Multi Messenger Astrophysics

Lecture 2.

Paolo Lipari
INFN Roma Sapienza

ISAPP School 2019
Cosmic Ray Vision from the Southern Sky

Malargue, march 8th 2019

Plan of this lecture

[1.] Dark Matter

[2.] Radiation mechanisms

[3.] Interpretation of
“Low Energy Cosmic Rays”

DARK MATTER

[a] Dynamical evidence for

[b] Nature of

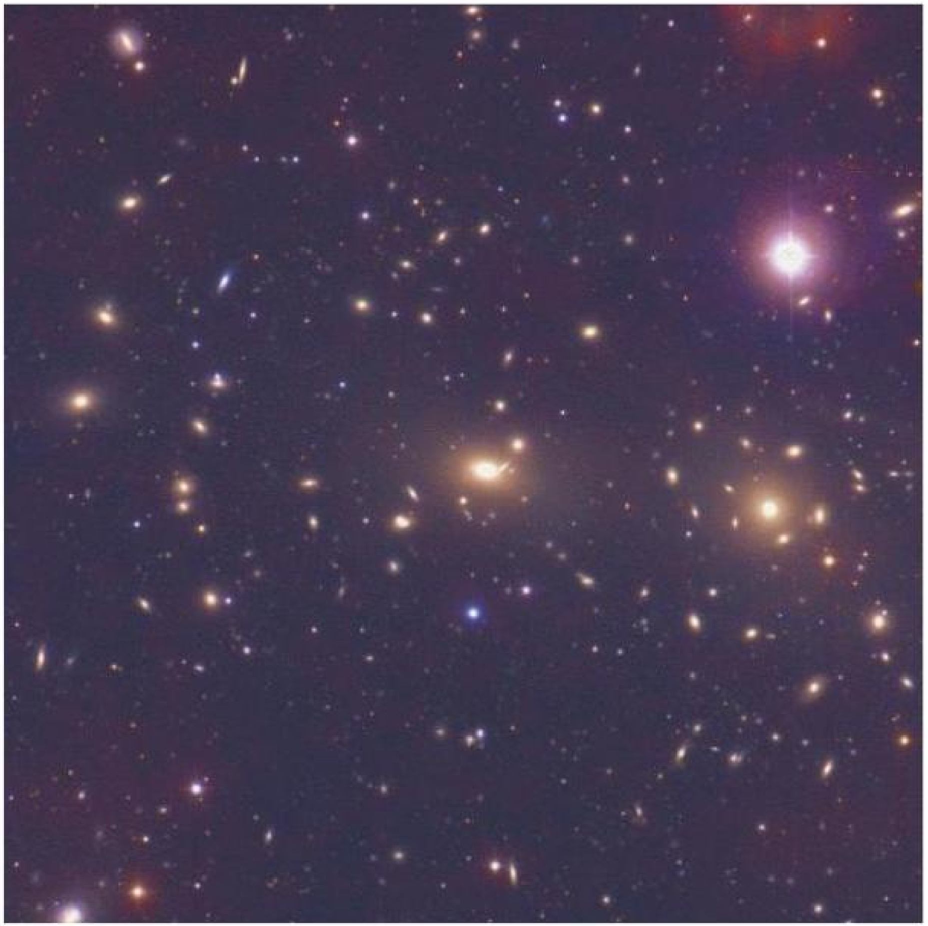
Dynamical Evidence for Dark Matter

- Galaxies
- Clusters of Galaxies
- The entire Universe

The Dark Matter is "non baryonic"
an "exotic" substance

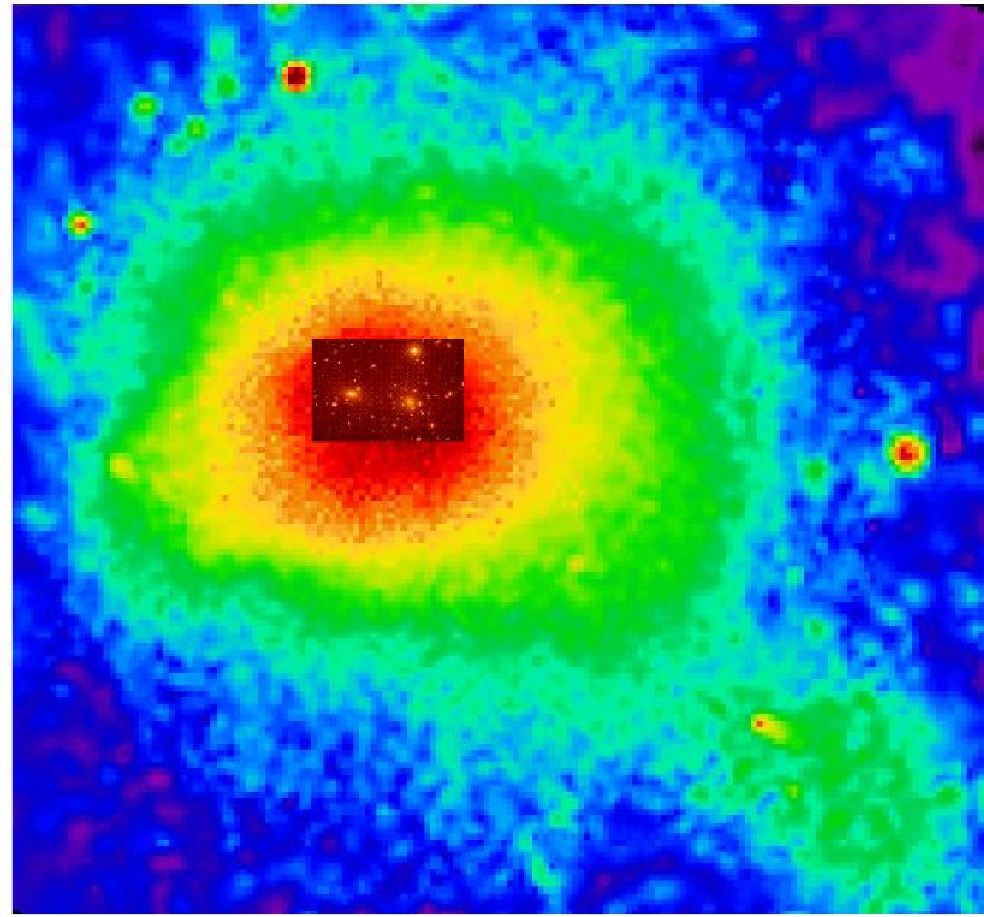
A field that is not contained
in the Standard Model of Particle Physics [!]

COMA Galaxy Cluster



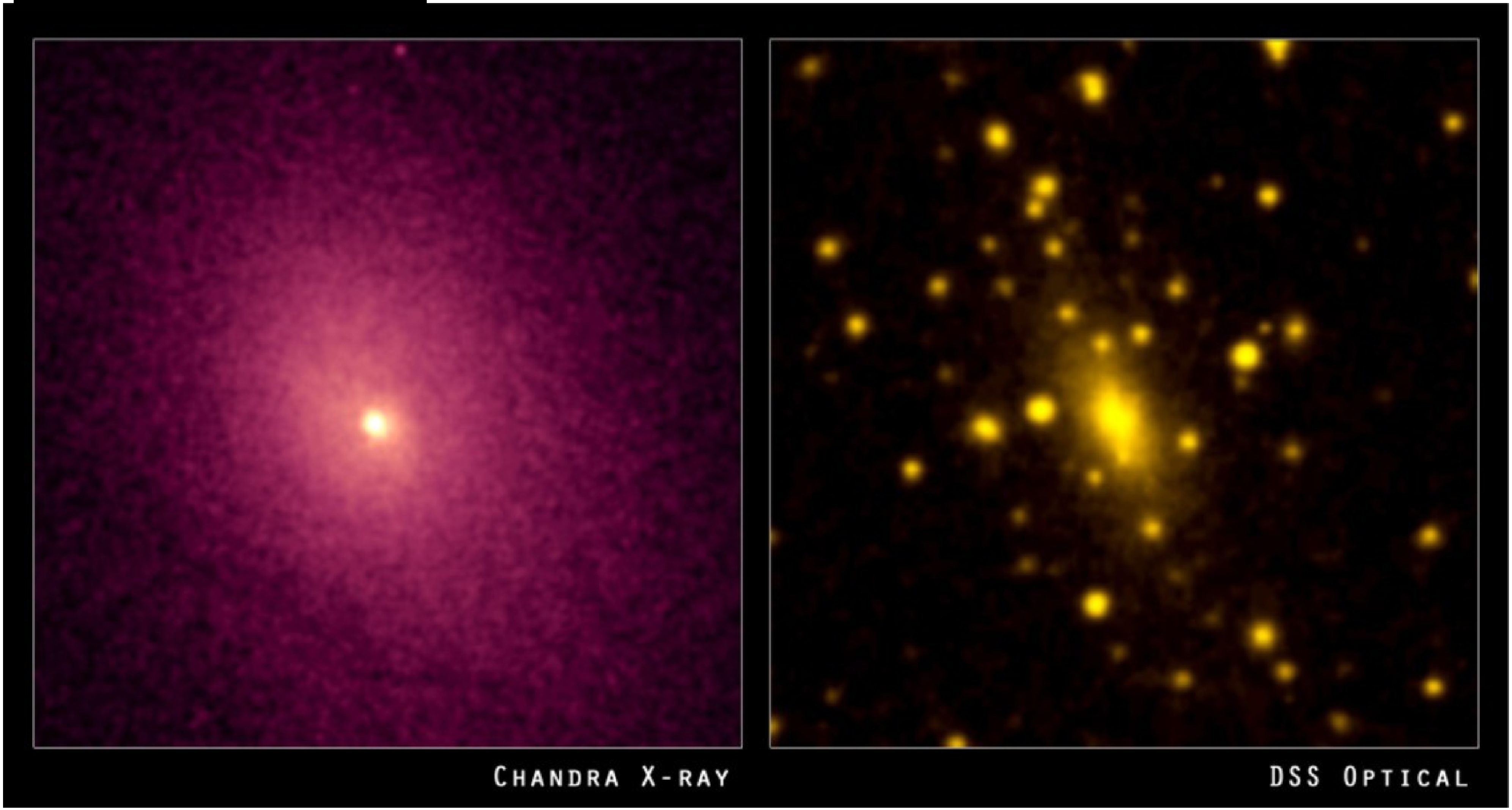
Optical

Fritz Zwicky 1933
First argument for Dark Matter
Virial theorem

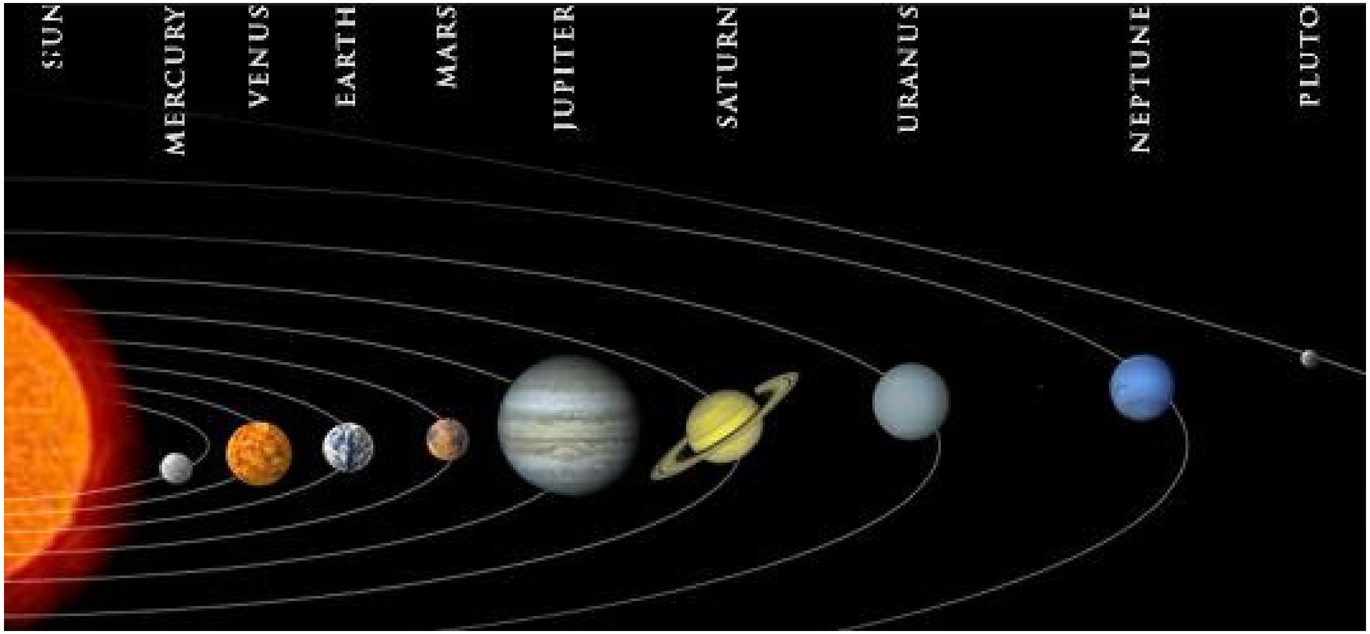


X-ray
[hot gas confined by
deep gravitational well]

ABELL 2029



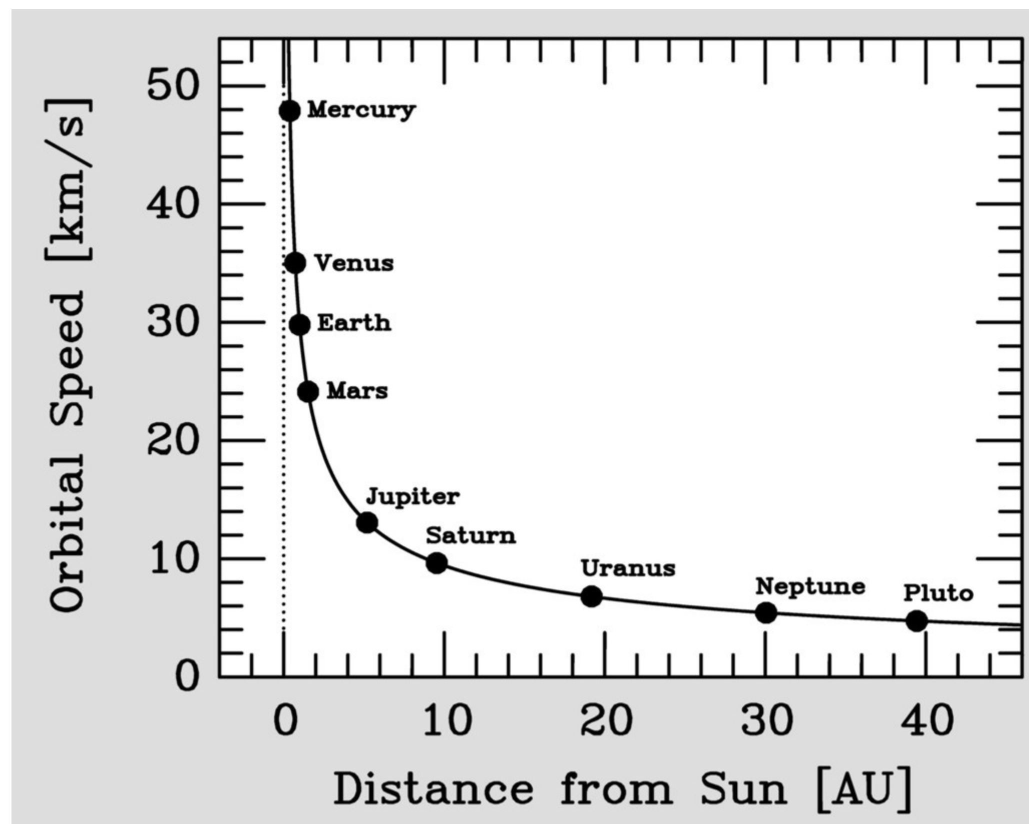
Most of the baryonic mass in a Galaxy cluster
Resides in a hot (temperature T ~ few KeV) intergalactic gas
Hydrostatic Equilibrium.

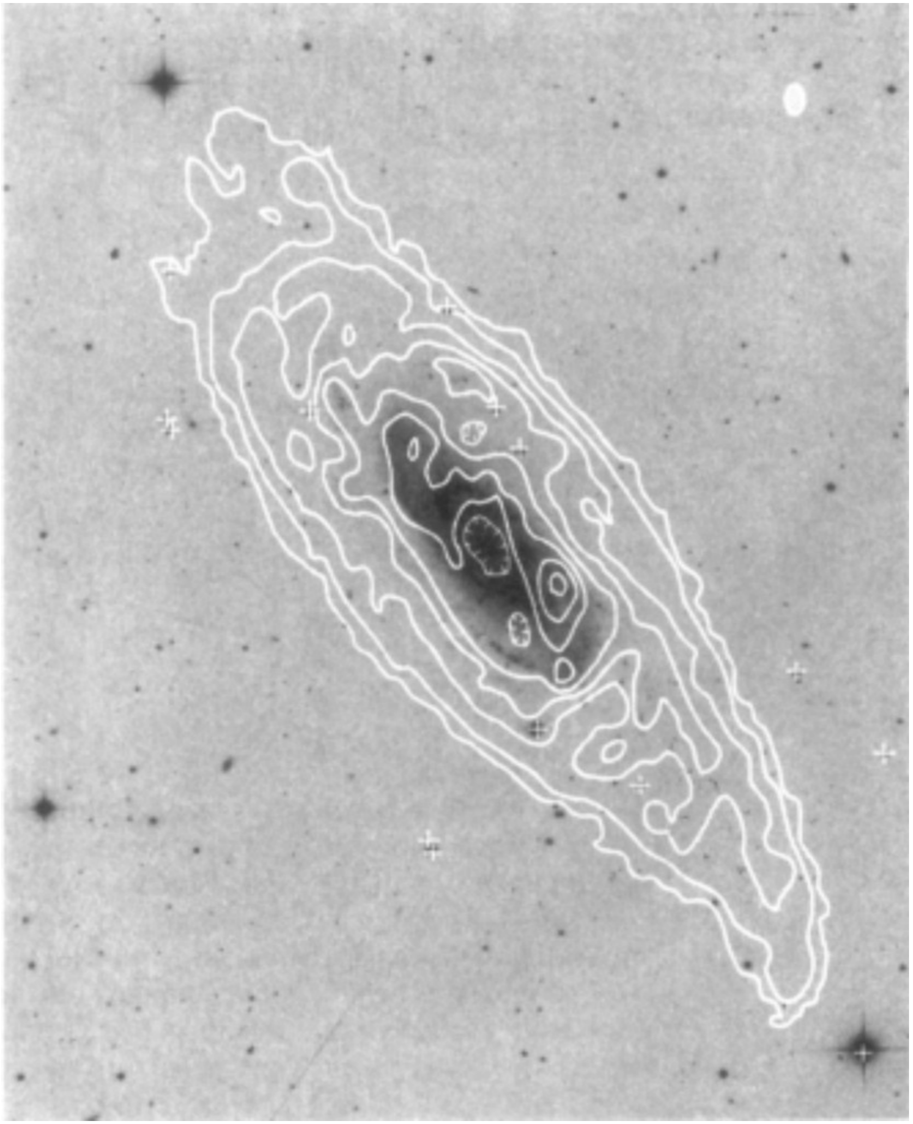


Keplerian circular motion:

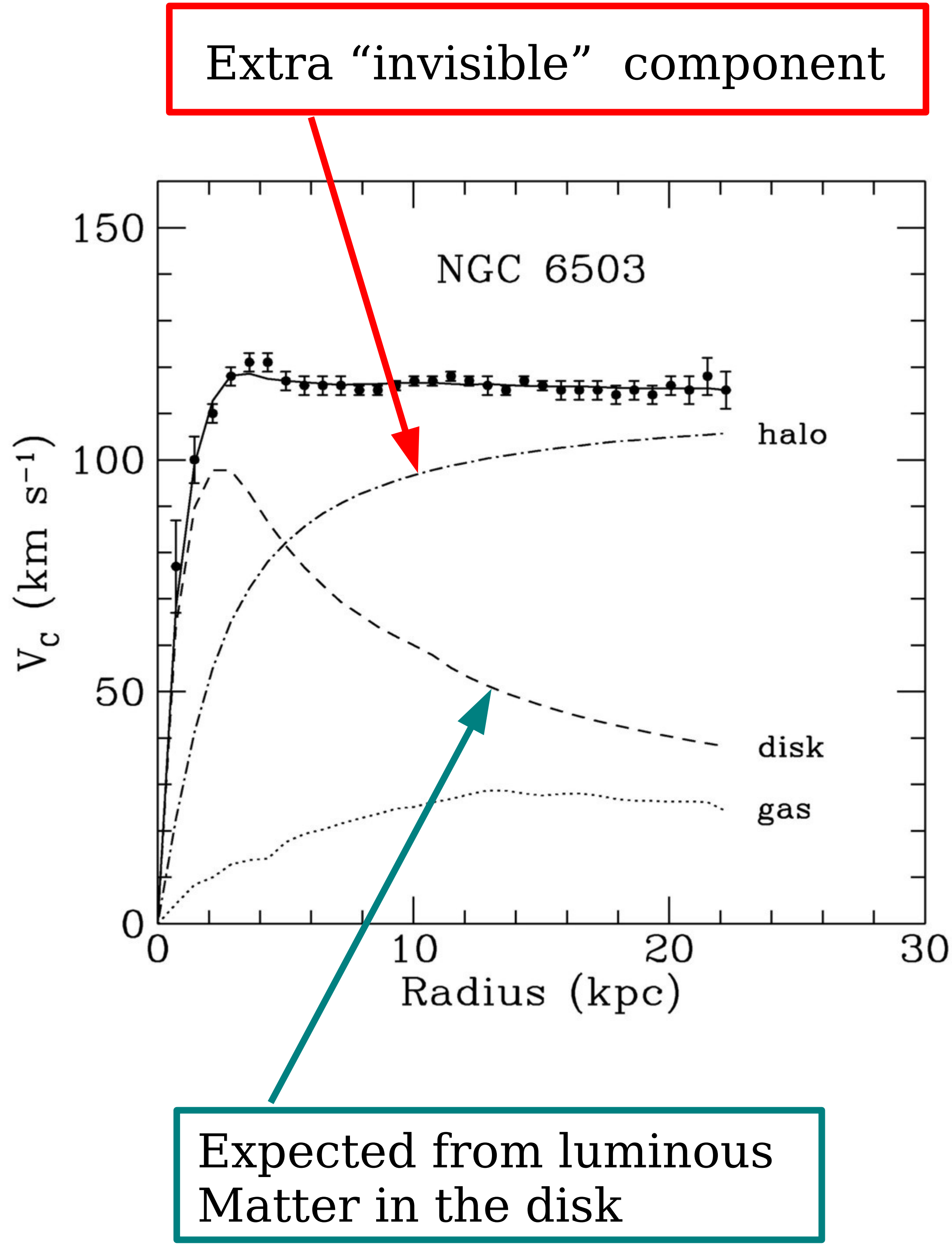
$$\frac{G\,M}{r^2} = \frac{v^2}{r}$$

$$v_{\mathrm{rot}} = \sqrt{\frac{G\,M}{r}}$$





Spiral galaxy NGC 3198
overlaid with hydrogen
column density [21 cm]
[ApJ 295 (1905) 305



M31: ANDROMEDA

M31 Rotation curve (1975)

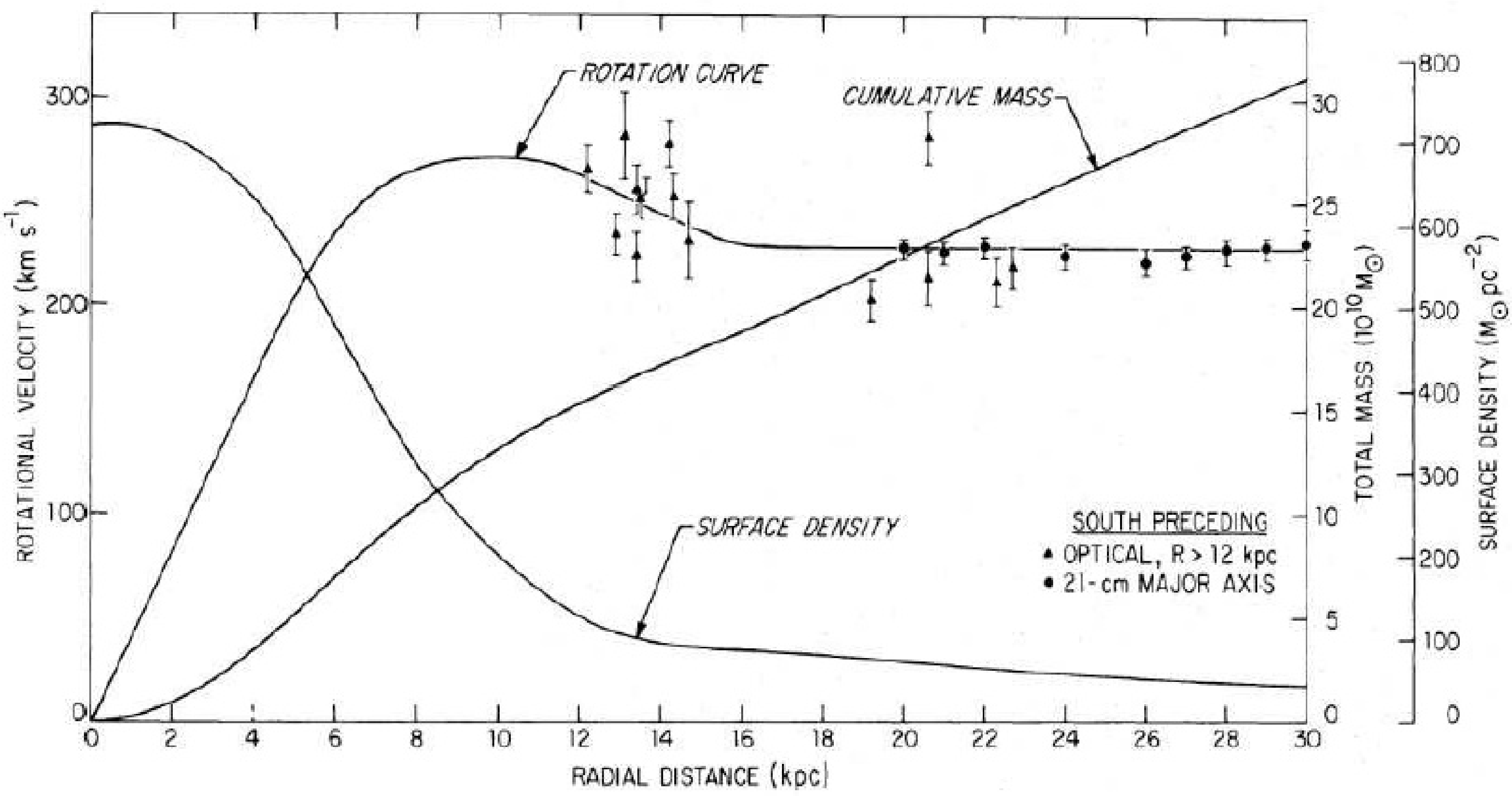
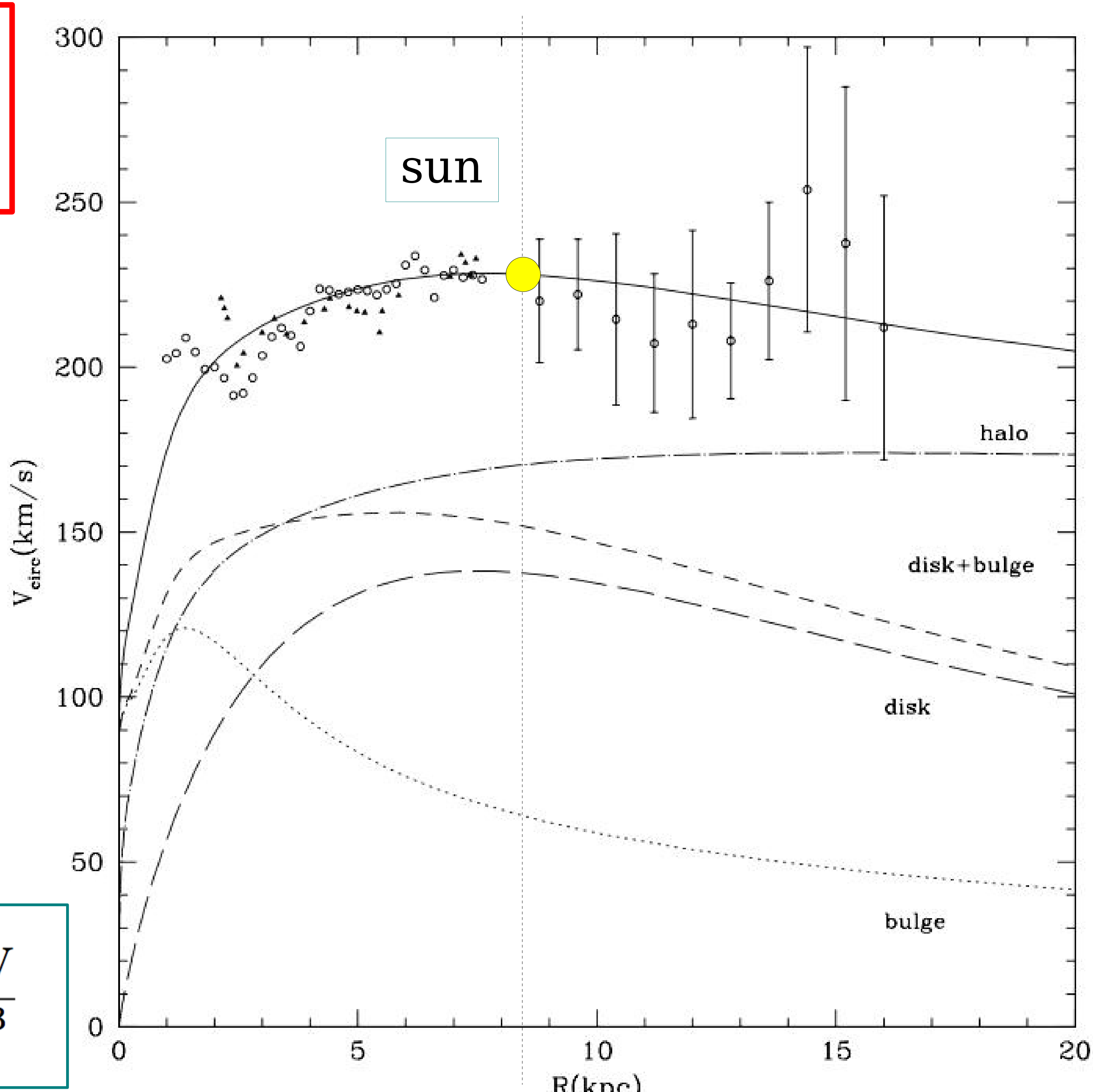


Figure 1: The rotation curve of M31 by Roberts & Whitehurst (1975). The filled triangles show the optical data from Rubin & Ford (1970), the filled circles show the 21-cm measurements made with the 300-ft radio telescope (reproduced by permission of the AAS and the author).

Milky Way

DARK HALO

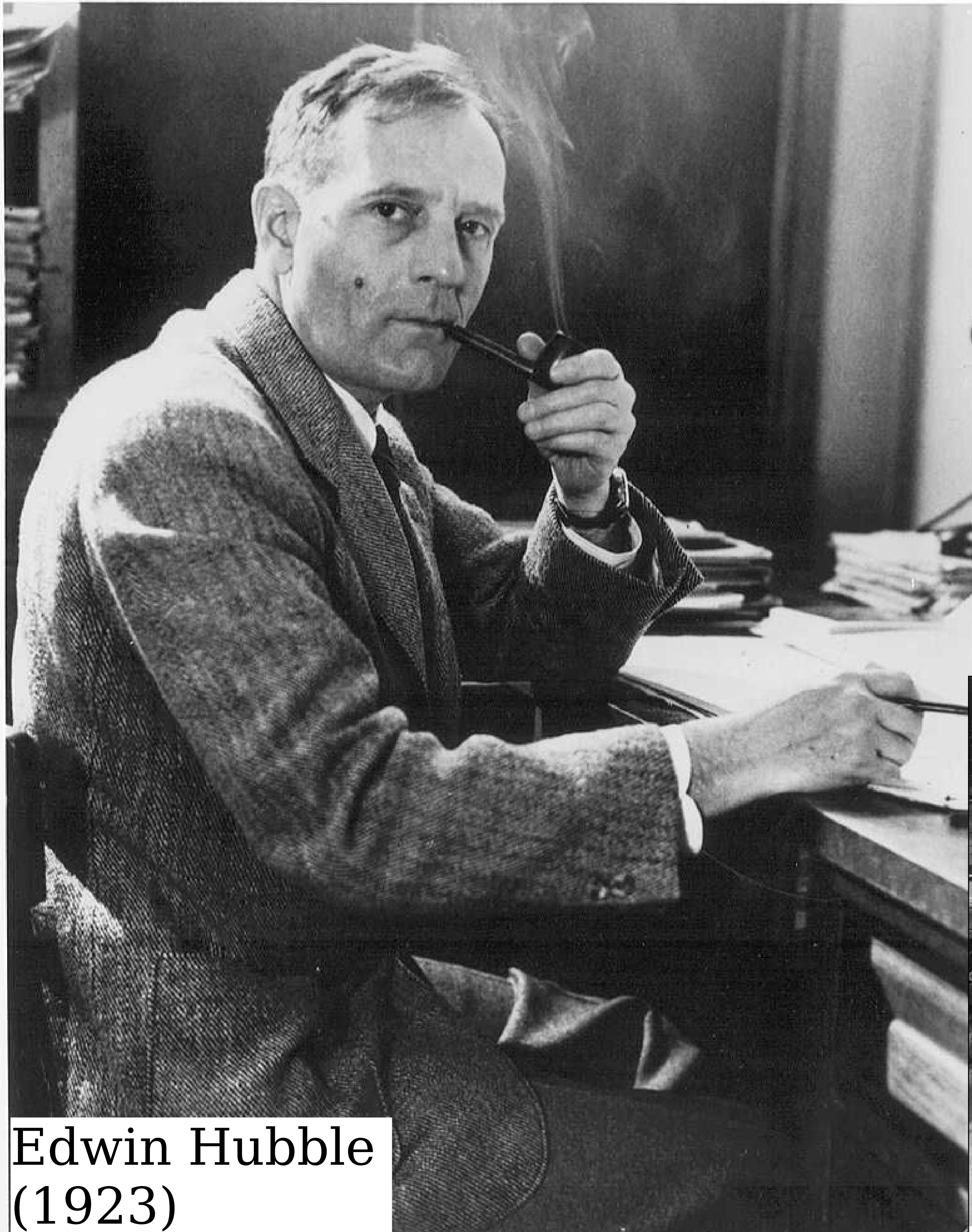
MILKY WAY



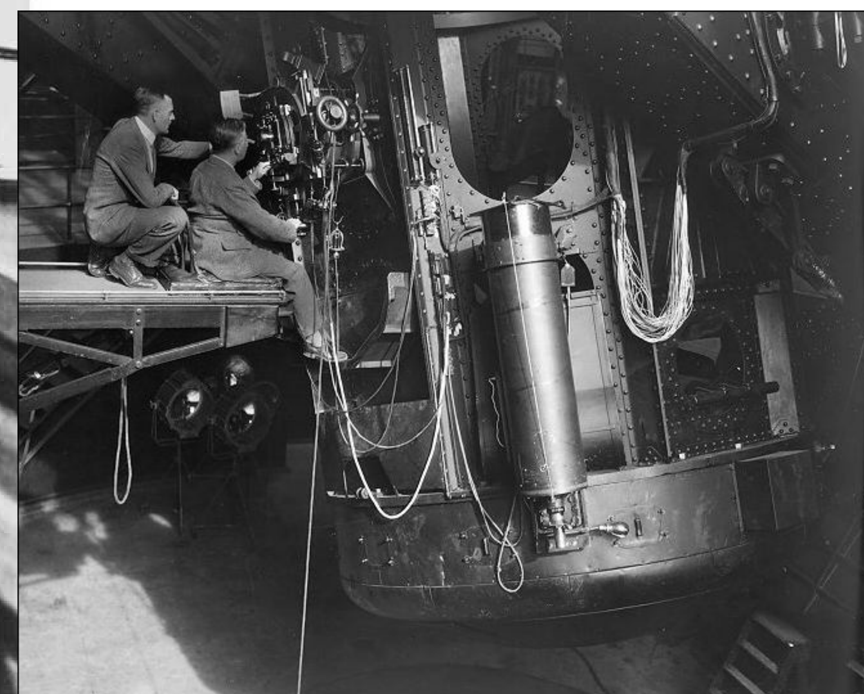
$$\rho_{\oplus} \simeq 0.3 \ \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

Discovery of the
Expansion of the
Universe.

Velocity of
Galaxies.



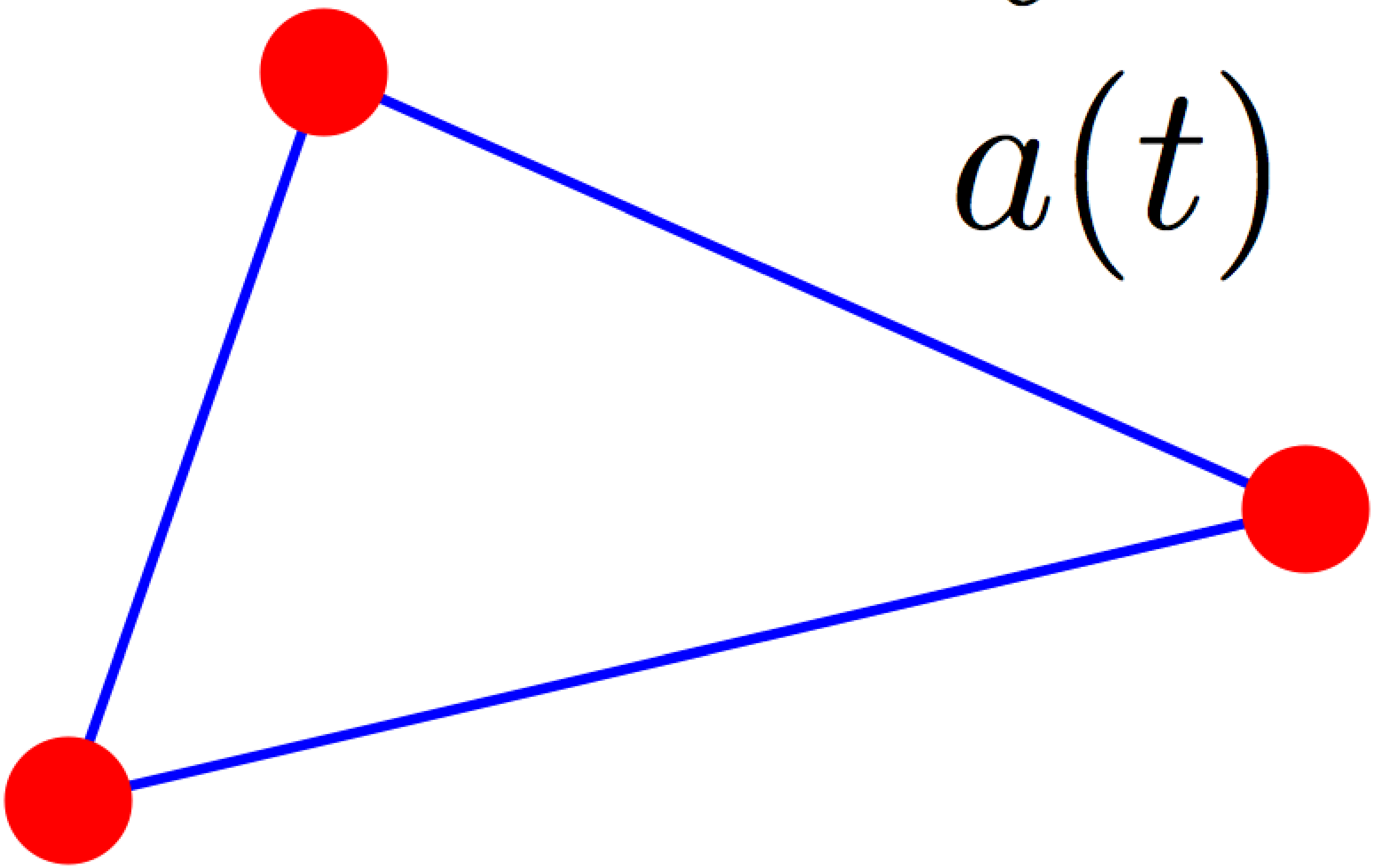
Edwin Hubble
(1923)



Rescaling of all distances.

t : Universal time

$a(t)$: Scale function



t_0 : present

$a(t_0) = 1$

$$\vec{R}_{ij}(t) = a(t)\ \vec{r}_{jk}$$

Expansion and Redshift

$$\lambda_{\text{emission}} \qquad t$$

Photon emitted at time t

$$\lambda_{\text{observed}} = \lambda_{\text{emission}} \frac{a(t_0)}{a(t)}$$

Wavelength "stretched" by the expansion

$$\lambda_{\text{observed}} = \lambda_{\text{emission}} \frac{1}{a(t)}$$

$$p \simeq \frac{1}{\lambda}$$ all particles

$$\lambda_{\text{observed}} = \lambda_{\text{emission}} (1+z)$$

Definition of redshift z

$$z(t) = \frac{1}{a(t)} - 1$$

Relation between Redshift z and scale a(t)

Dynamics of the expansion:

$$\left[\frac{da(t)}{dt}\right]^2 = \frac{8\,\pi\,G\,\rho(t)}{3}\,a^2(t) - K$$

Friedmann's equation.

[obtained from
Einstein equations
of General Relativity]

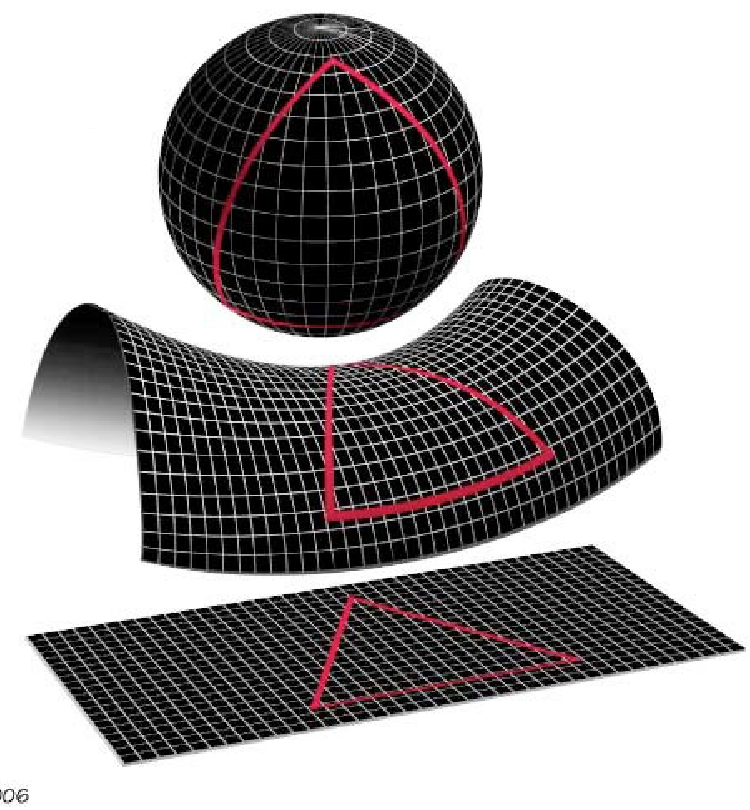
Constant K
Geometry of Space

$$K = \frac{c^2}{R_0^2}$$

$K > 0$

$K < 0$

$K = 0$



Derivation from elementary Newtonian dynamics
[wrong motivation, but right answer]:

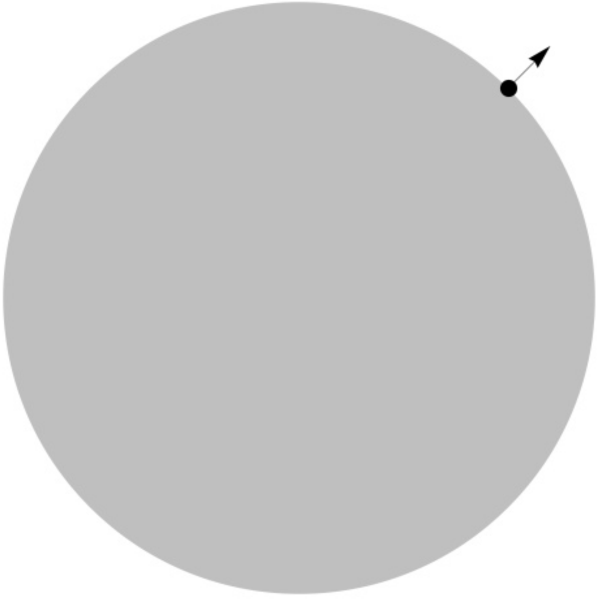
Spherical symmetry:
choose an arbitrary center point.
Energy = Kinetic + Potential

$$\frac{1}{2}\, m \left(\frac{dr}{dt}\right)^2 - \frac{G\, M(r)\, m}{r} = E$$

$$M(r) = \frac{4\,\pi}{3}\,\rho(t)\, r^3$$

$$r = R_0\, a(t)$$

$$K = \frac{2\,E}{m\, R_0^2}$$



$$\left[\frac{da(t)}{dt}\right]^2 = \frac{8\,\pi\,G\;\rho(t)}{3}\;a^2(t) - K$$

Substitute: $t = t_0$

$$H_0^2 = \frac{8\,\pi\,G\;\rho_0}{3} - K$$

$K = 0$

Flat space

$$\Longrightarrow$$

$$\rho_0 = \rho_{\text{critical}} = \frac{3\,H_0^2}{8\,\pi\,G}$$

$$1 = \frac{8\,\pi\,G\,\rho_0}{3\,H_0^2} - \frac{c^2}{R_0^2\,H_0^2}$$

$$1 = \frac{\rho_0}{\rho_c} - \frac{c^2}{R_0^2\,H_0^2}$$

$$\Omega_k = -\frac{c^2}{R_0^2\,H_0^2}$$

Curvature term

$$1 = \Omega_0 + \Omega_k$$

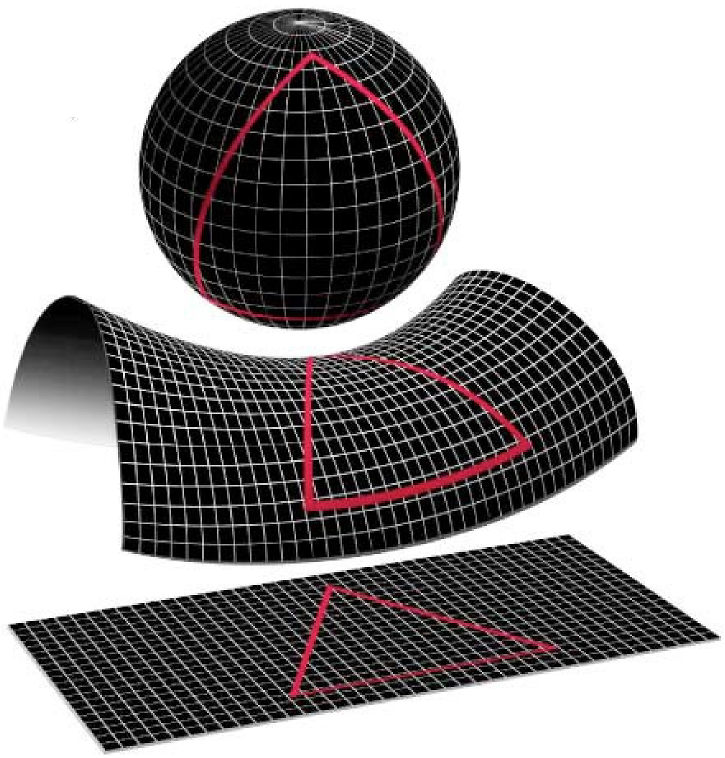
Geometry defined by Ω_0

$$\Omega_0 = \frac{\rho_0}{\rho_c}$$

$$\Omega_0 > 1$$

$$\Omega_0 < 1$$

$$\Omega_0 = 1$$



$$\left[\frac{da(t)}{dt}\right]^2 = \frac{8\pi G\,\rho(t)}{3}\,a^2(t) - K$$

$$\rho_0 = \rho_{\rm matter} + \rho_{\rm radiation} + \rho_{\rm vacuum}$$

$$\rho(t) = \frac{\rho_{\rm matter}}{a^3(t)} + \frac{\rho_{\rm radiation}}{a^4(t)} + \rho_{\rm vacuum}$$

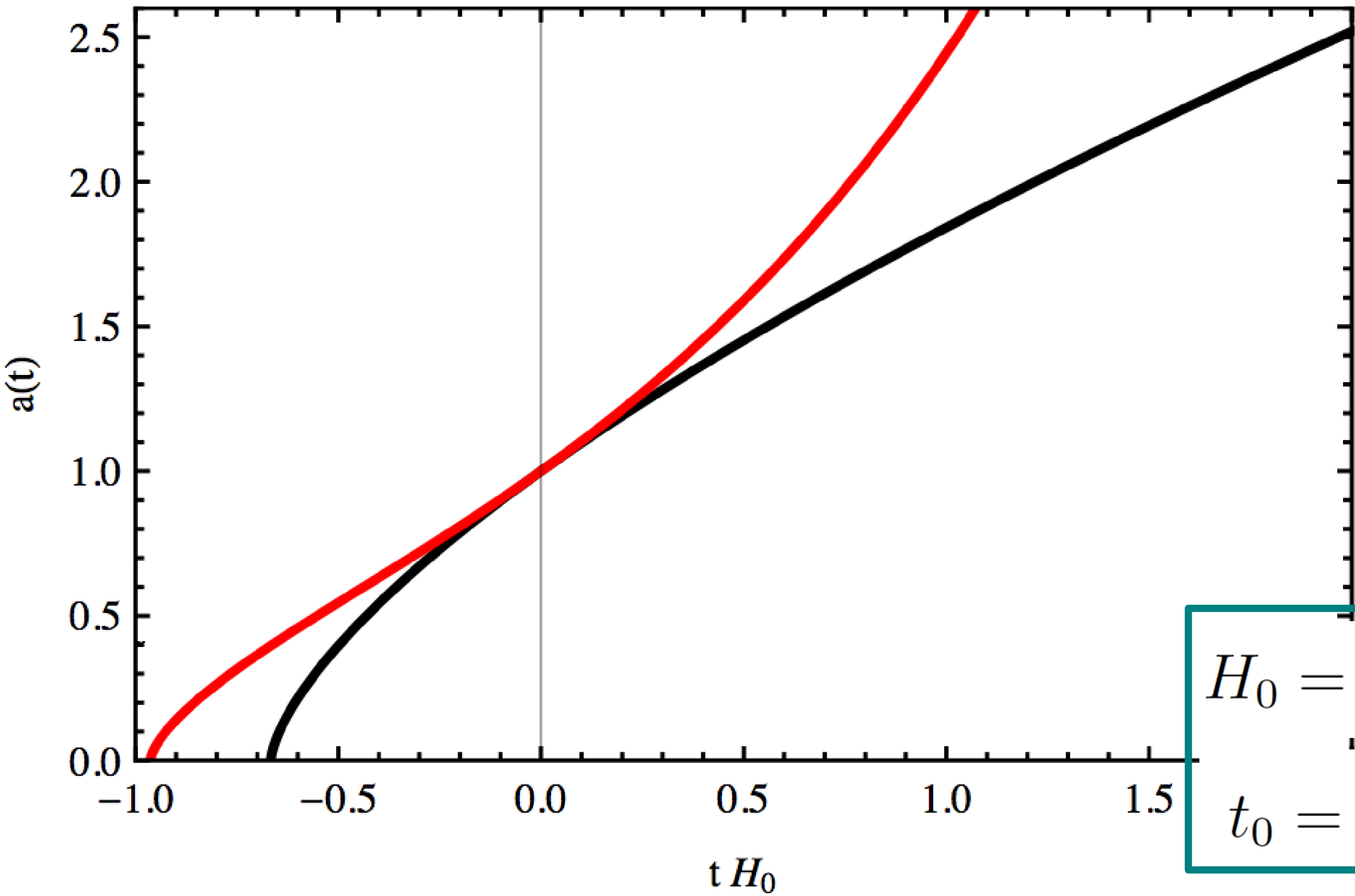
Particle conservation

Particle conservation + momentum redshift

.... the vacuum is the vacuum...

$$\frac{1}{H_0^2}\left[\frac{da(t)}{dt}\right]^2 = a^2(t)\left[\frac{\Omega_m}{a^3(t)} + \frac{\Omega_r}{a^4(t)} + \Omega_\Lambda + \frac{\Omega_k}{a^2(t)}\right]$$

$$1 = \Omega_{mat} + \Omega_{rad} + \Omega_\Lambda + \Omega_k$$



$\Omega_m = 1$

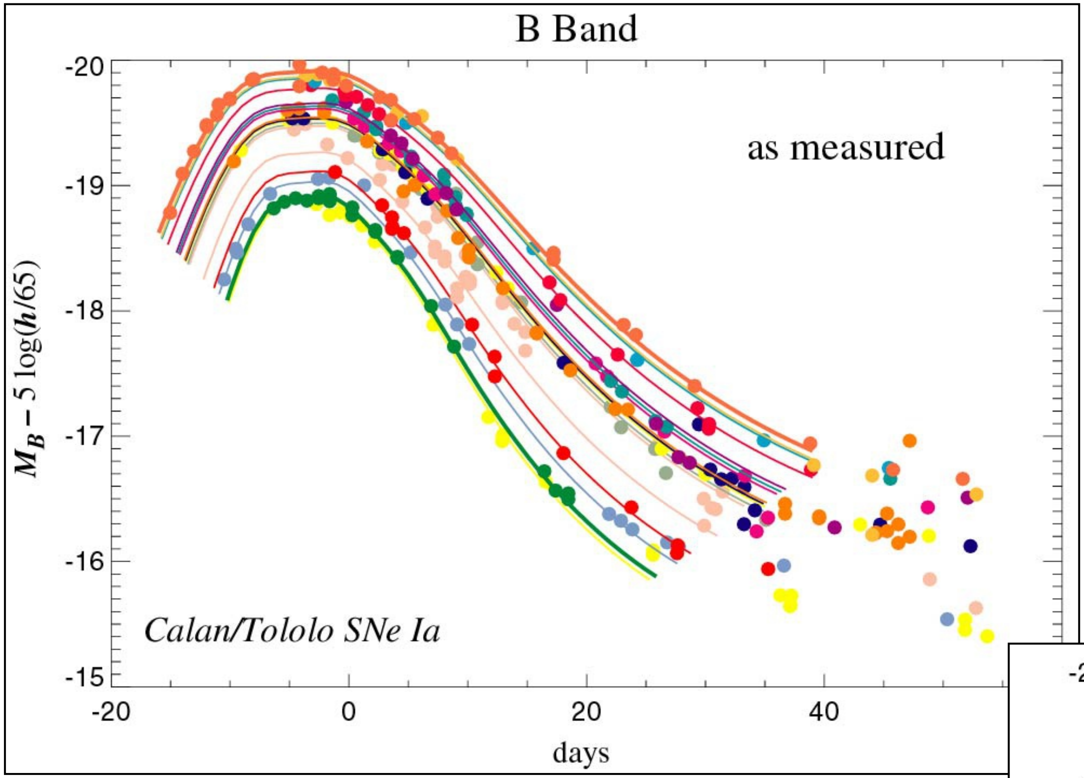
$\Omega_\Lambda = 0$

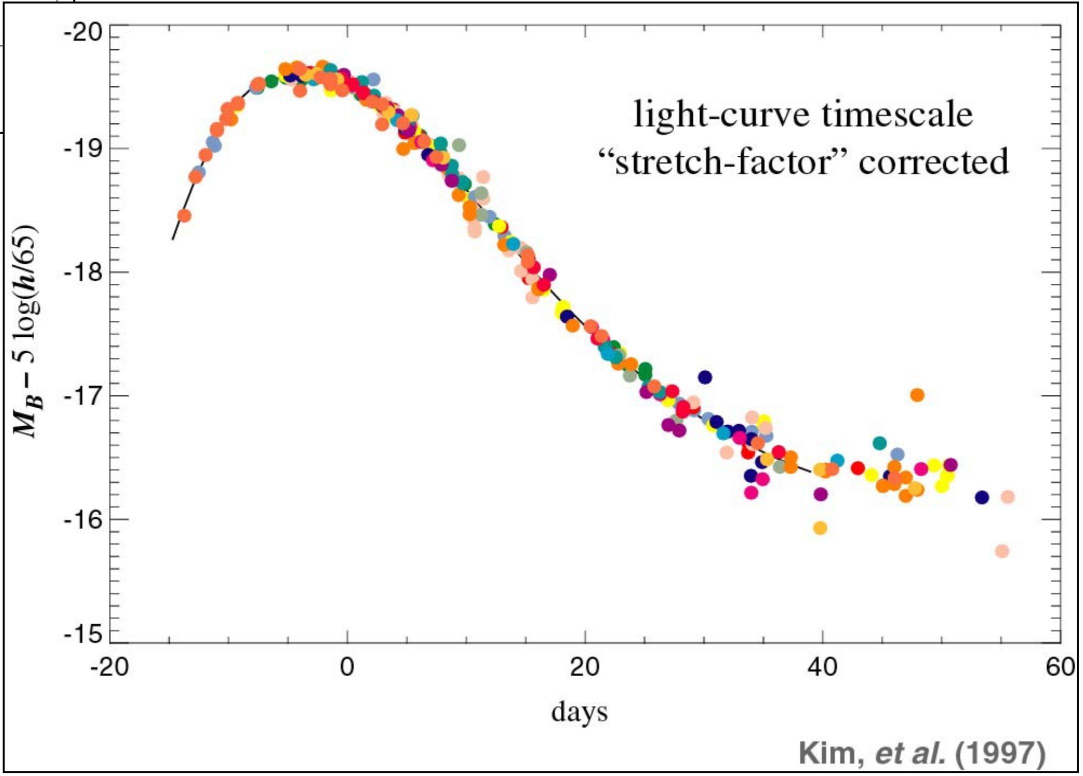
$\Omega_m = 0.3$

$\Omega_\Lambda = 0.7$

$H_0 = 70.2 \pm 1.4$ Km/s/Mpc

$t_0 = 13.76 \pm 0.11$ Gyr

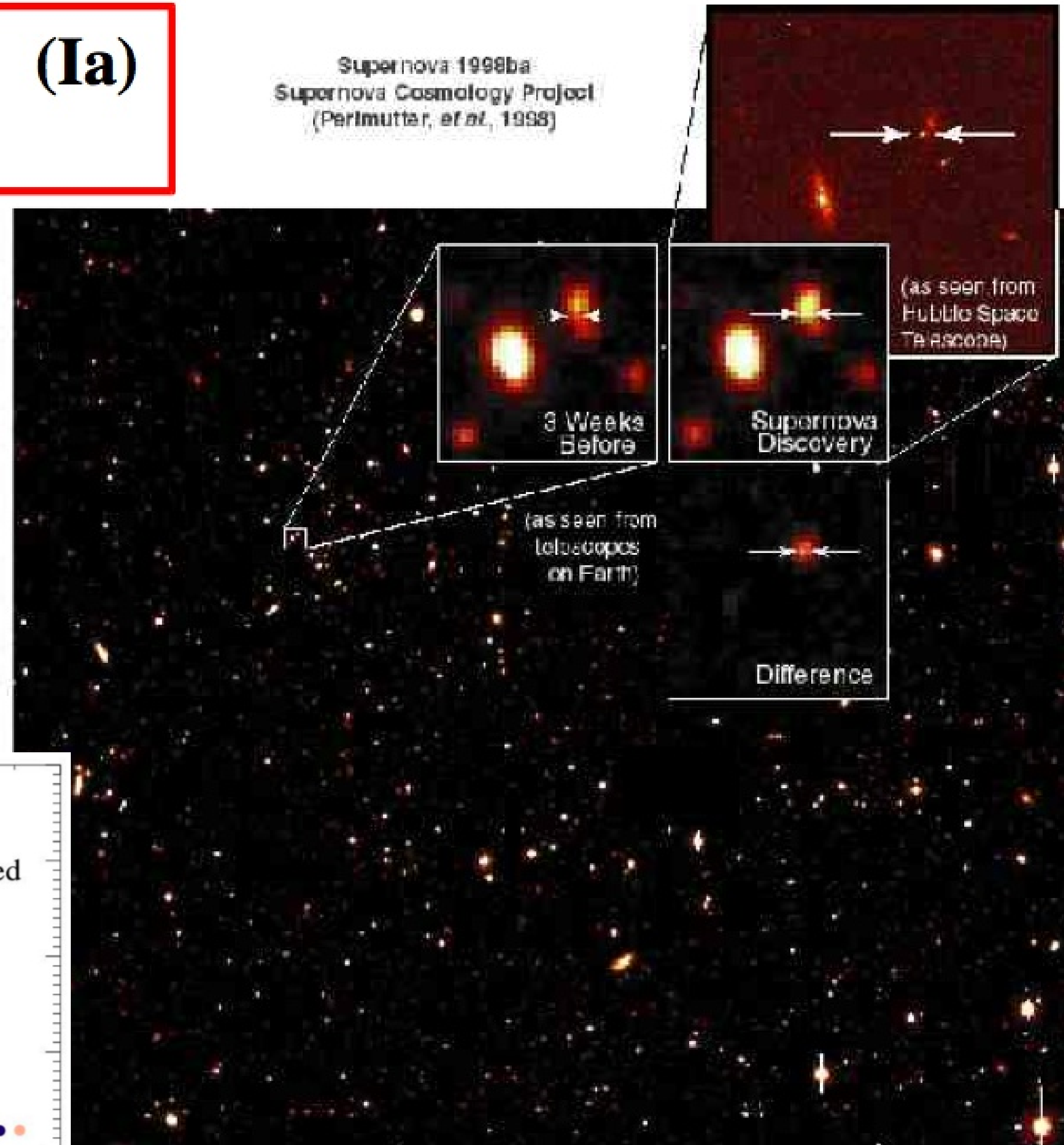




SuperNovae Ia
are a standard candle.

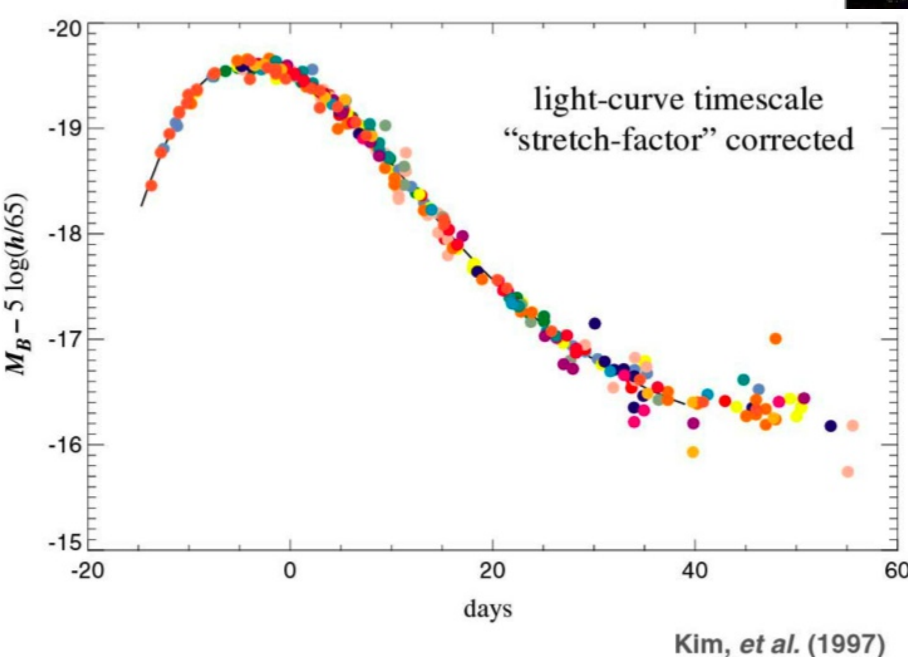
(universal light curve)
[dimming + broadening]

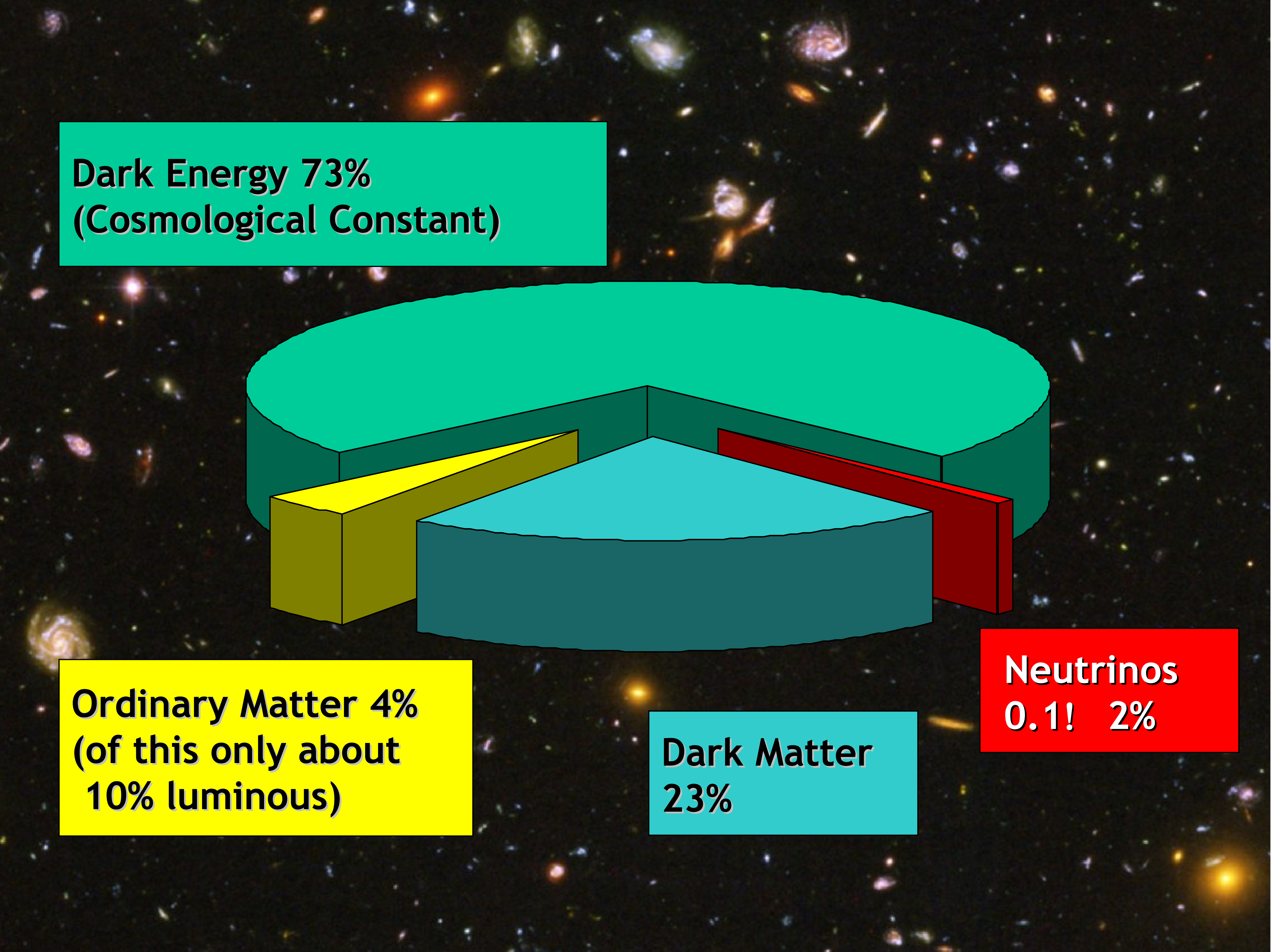
SUPERNOVAE (Ia) STUDIES



$$a(t) \leftrightarrow \ell(z)$$

SN1a as
standard candles




Dark Energy 73%
(Cosmological Constant)
Ordinary Matter 4%
(of this only about
10% luminous)
Dark Matter
23%
Neutrinos
0.1! 2%

$$\Omega_b = 0.0458 \pm 0.0016$$

$$\Omega_{cold} = 0.229 \pm 0.015$$

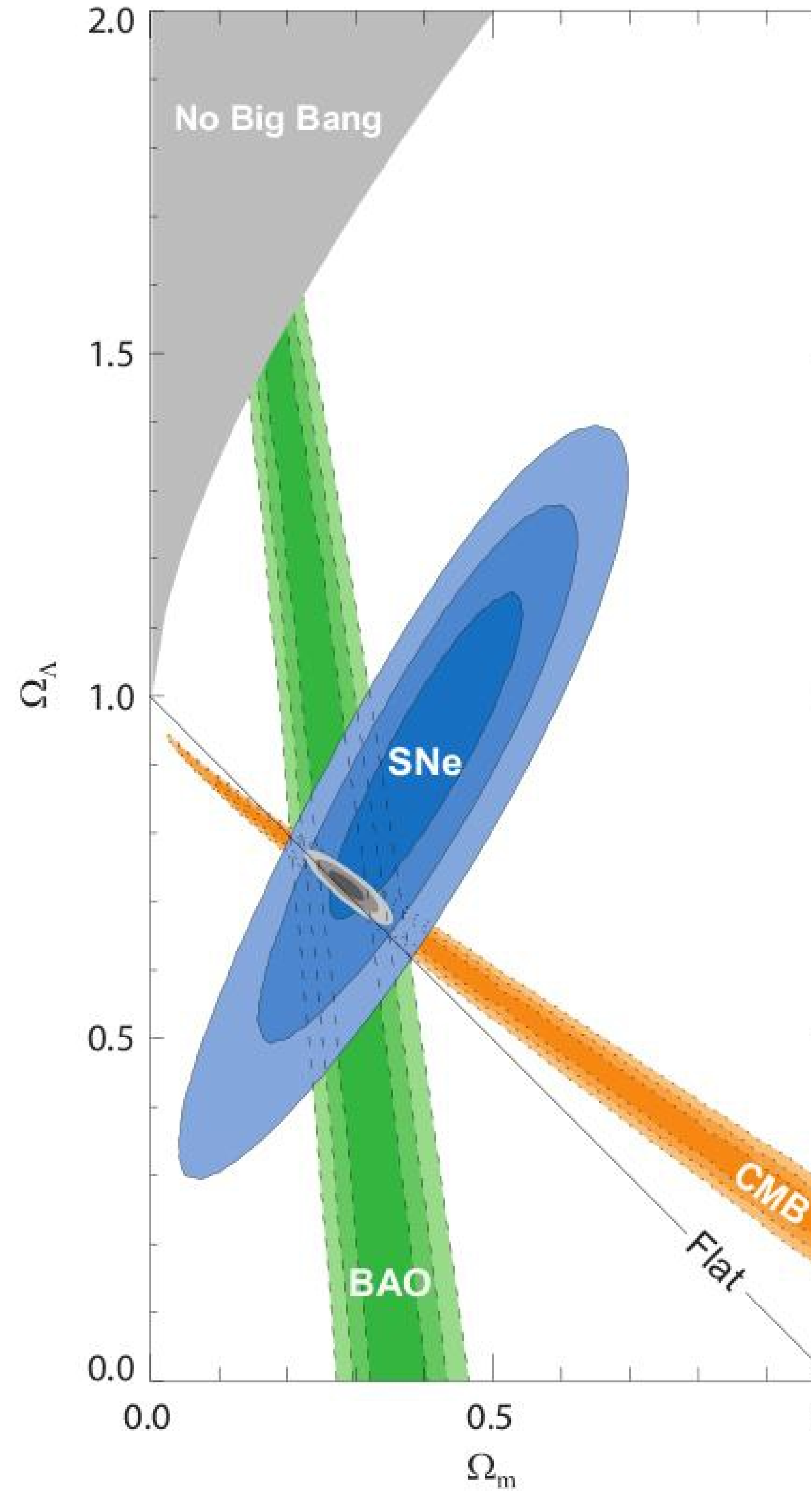
$$\Omega_\Lambda = 0.725 \pm 0.016$$

$$\Omega_k = 1 - \Omega_{total} = -\frac{c^2}{H_0^2\ R_0^2}$$

$$-0.0133 \leq \Omega_k \leq 0.0084$$

$$|R_0| > 37\ \mathrm{Gpc}$$

The Universe is FLAT !



Mysteries of the DARK UNIVERSE

DARK MATTER:

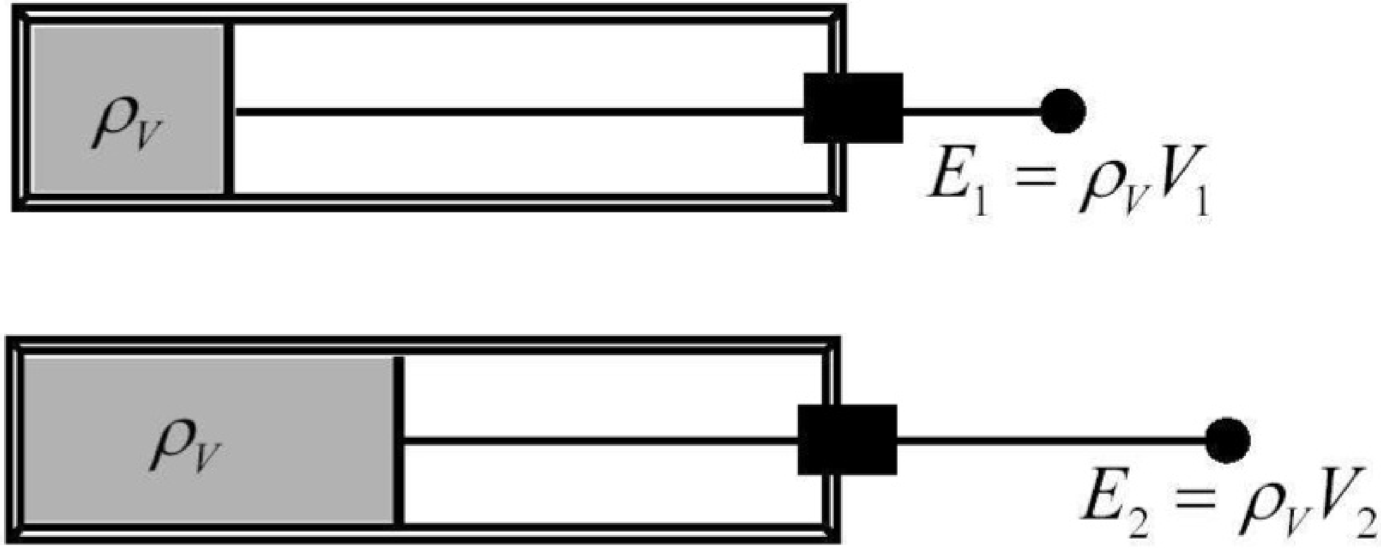
Holds together galaxies
and other large scale structures
[A new elementary particle ?]

DARK ENERGY :

Drives apart galaxies
And other large scale structures
[The energy of vacuum itself ?]

$$\ddot{a}(t) = -\frac{4\pi G}{3} \left[\rho(t) + 3\,p(t)\right] a(t)$$

Vacuum Pressure



$$\Delta E = \rho_{\text{vacuum}} \, \Delta V$$

$$W = -p_{\text{vacuum}} \, \Delta V$$

Need to "pull" the piston

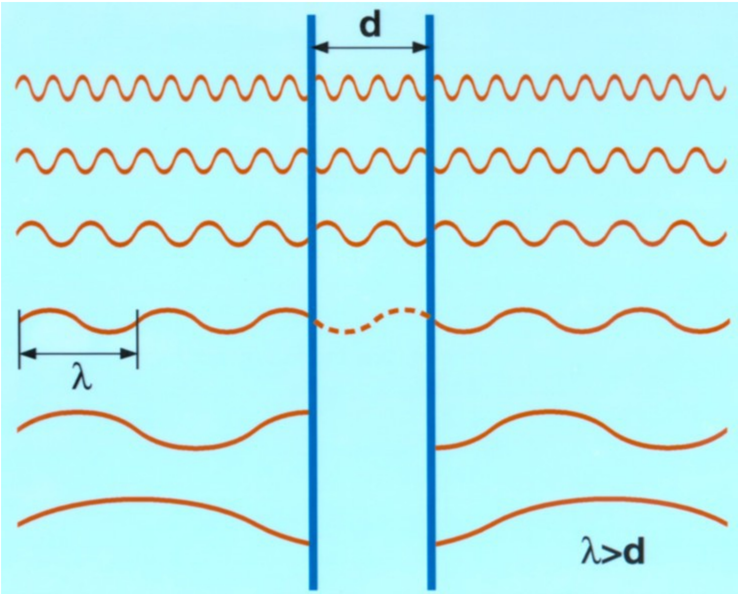
$$\rho_{\text{vacuum}} = -p_{\text{vacuum}}$$

Harmonic oscillator

$$E_n = \left(\frac{1}{2} + n\right)\ \hbar\,\omega$$

Electromagnetic field vacuum E

$$\langle \text{energy} \rangle = \left\langle \frac{E^2 + B^2}{8\pi} \right\rangle = \sum_k \frac{\hbar\,\omega_k}{2} \to \infty$$



Hendrik Casimir
(1909, 2000)

$$F_{\text{Casimir}} = \frac{\pi^2\,\hbar\,c}{240\,d^4}\ A \simeq 1.3 \times 10^{-7}\ \left(\frac{1\ \mu\text{m}}{d}\right)^4\ \left(\frac{A}{1\ \text{cm}^2}\right)\ \text{Newton}$$

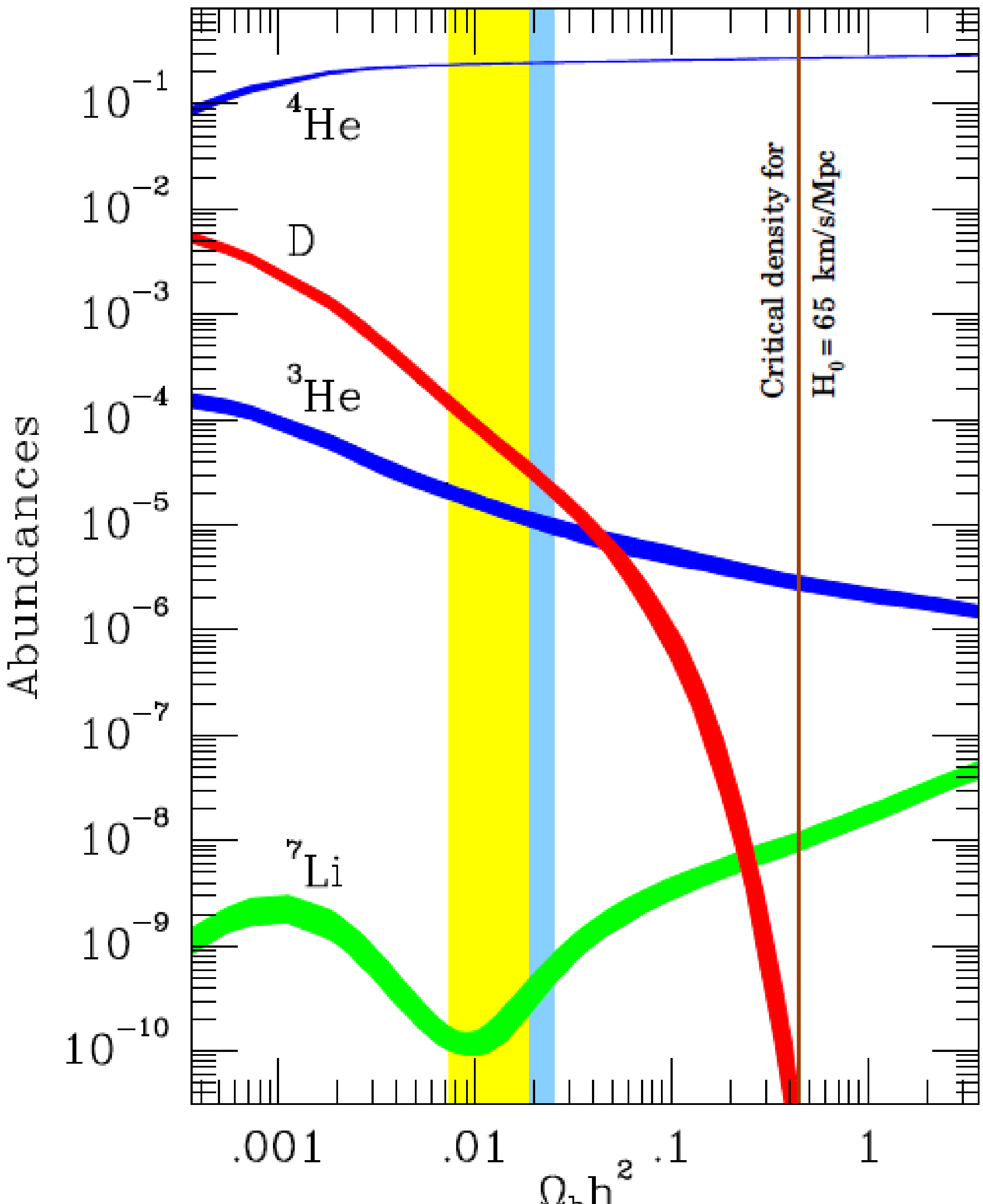
The DARK MATTER is “Non Baryonic”

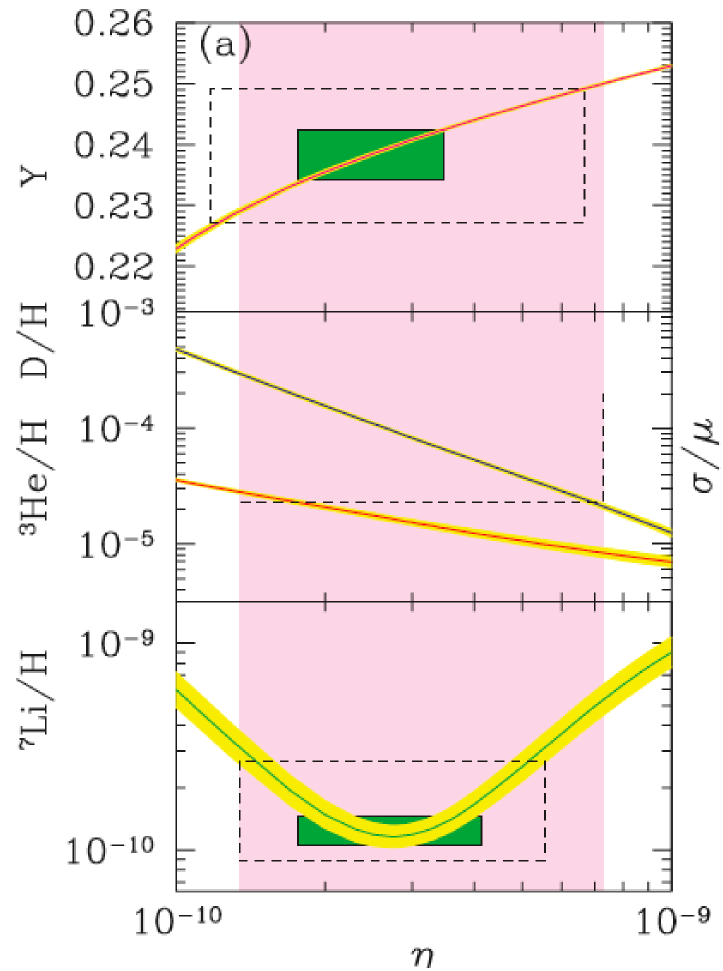
Nucleosynthesis

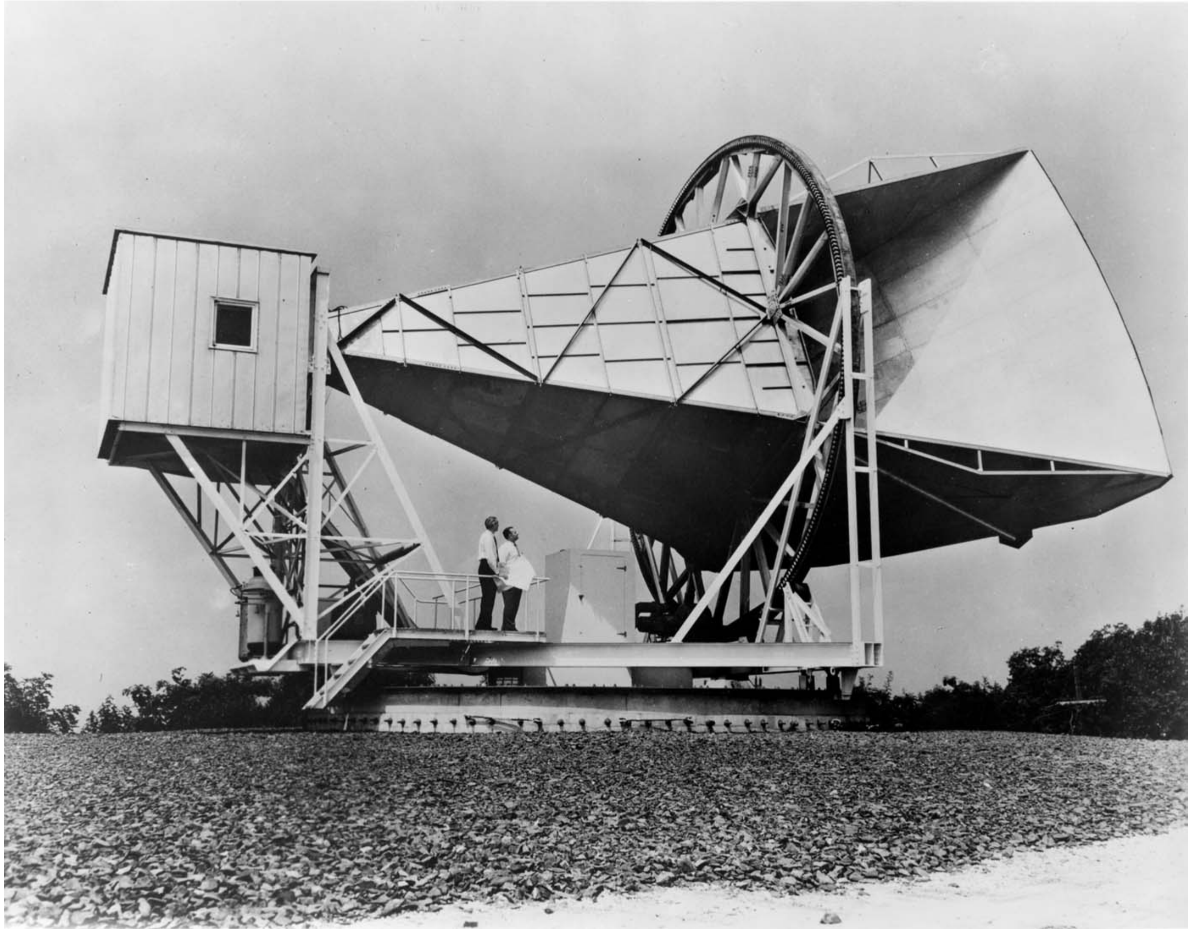
Structure Formation

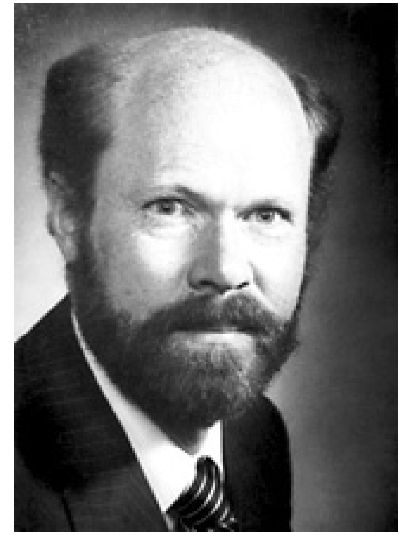
BigBang
Nucleo-synthesis
constraints

on ordinary
("baryonic") matter



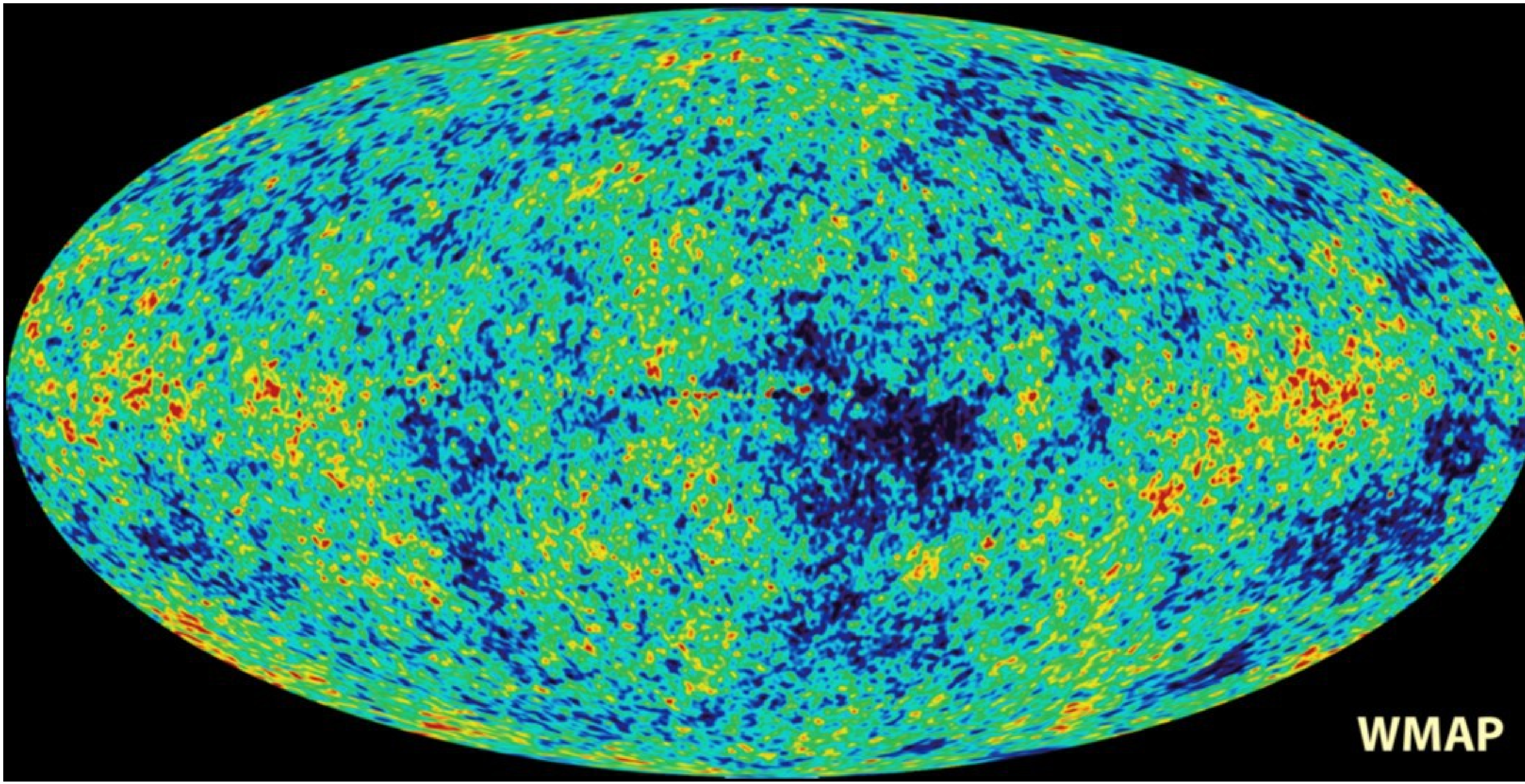




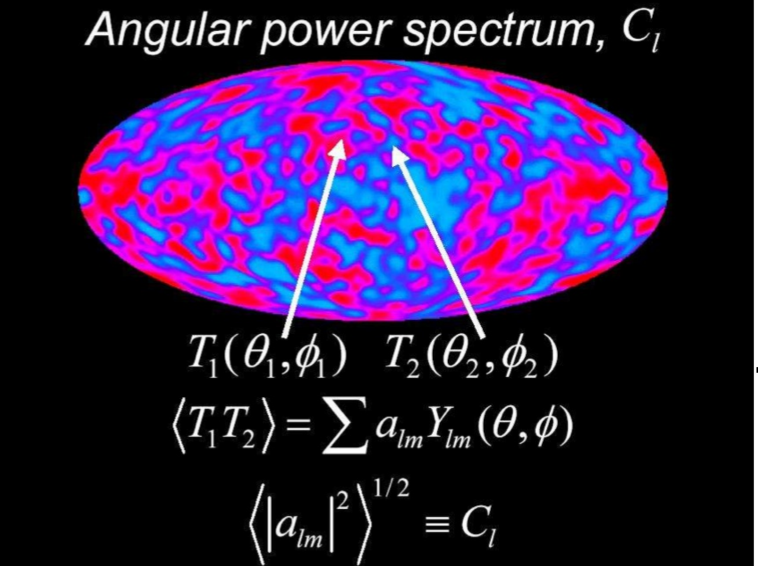


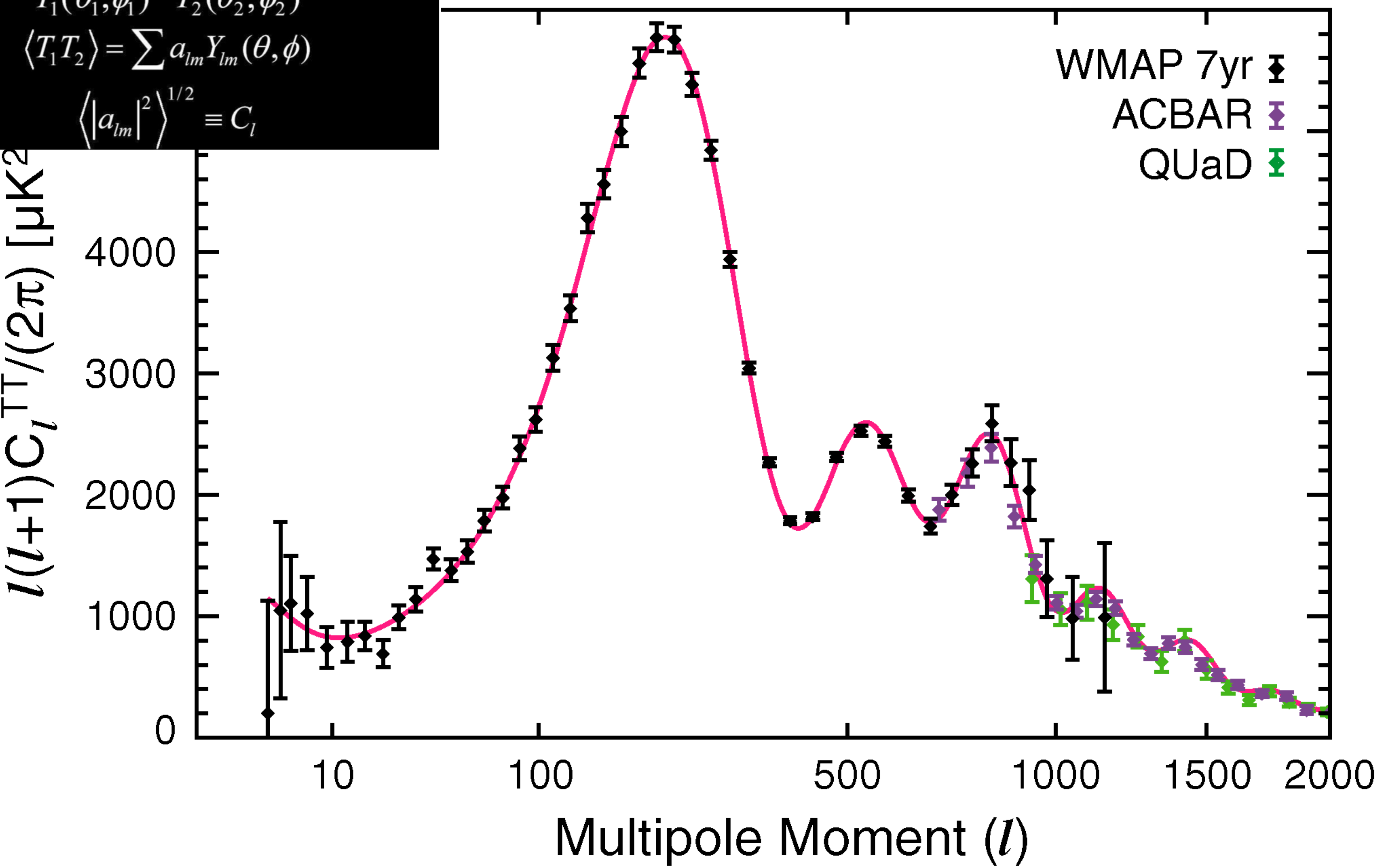
Robert W. Wilson Arno.A. Penzias

Discovery of the 2.7 Kelvin
Cosmic Microwave Background Radiation
By Penzias and Wilson (1965), [Nobel 1978]


WMAP

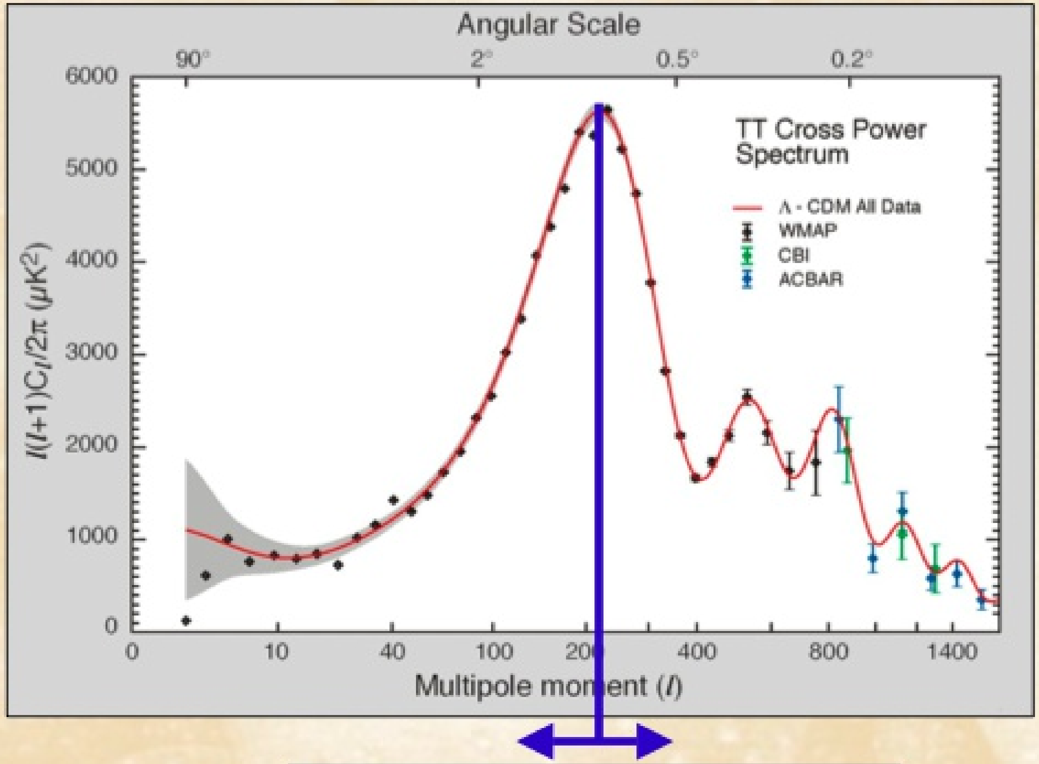
The "Rosetta stone"
Of the Early Universe





Flat Universe from CMBR Angular Fluctuations

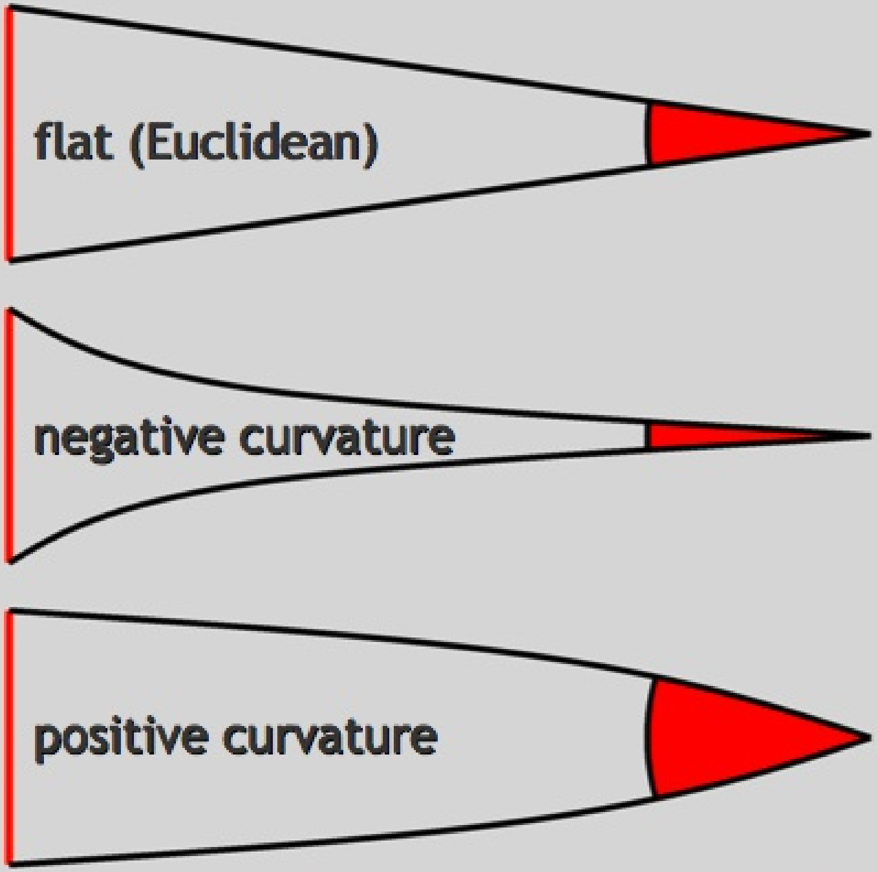
Spergel et al. (WMAP Collaboration)
astro-ph/0302209



$$\ell_{max} \approx 200/\sqrt{\Omega_{tot}}$$

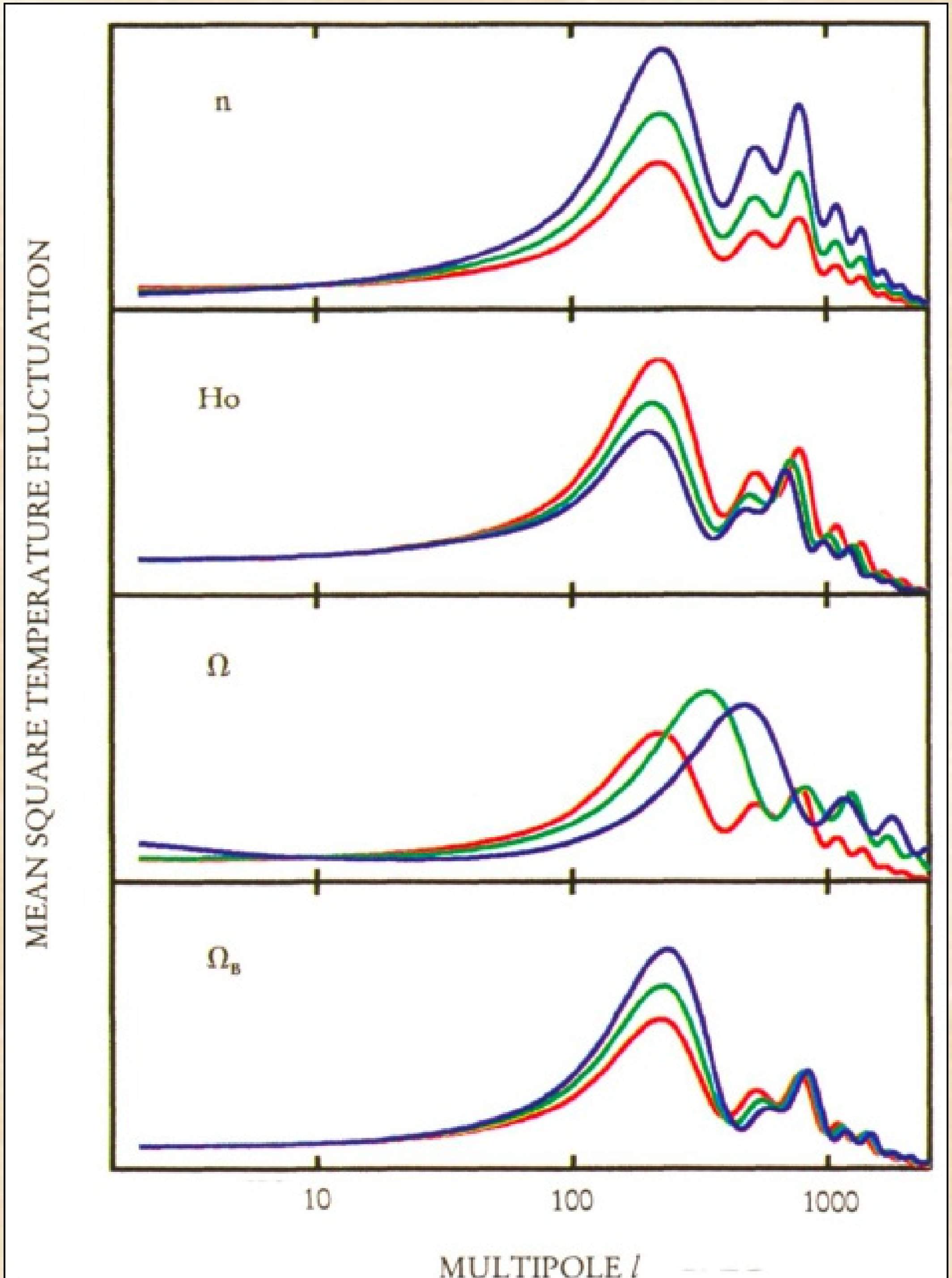
$$\Omega_{tot} = 1.02 \pm 0.02$$

Triangulation with acoustic peak



Known physical size of acoustic peak at decoupling ($z \approx 1100$)

Measured angular size today ($z = 0$)



Power-law index (tilt)
$n = 1.0, 1.1, 1.2$

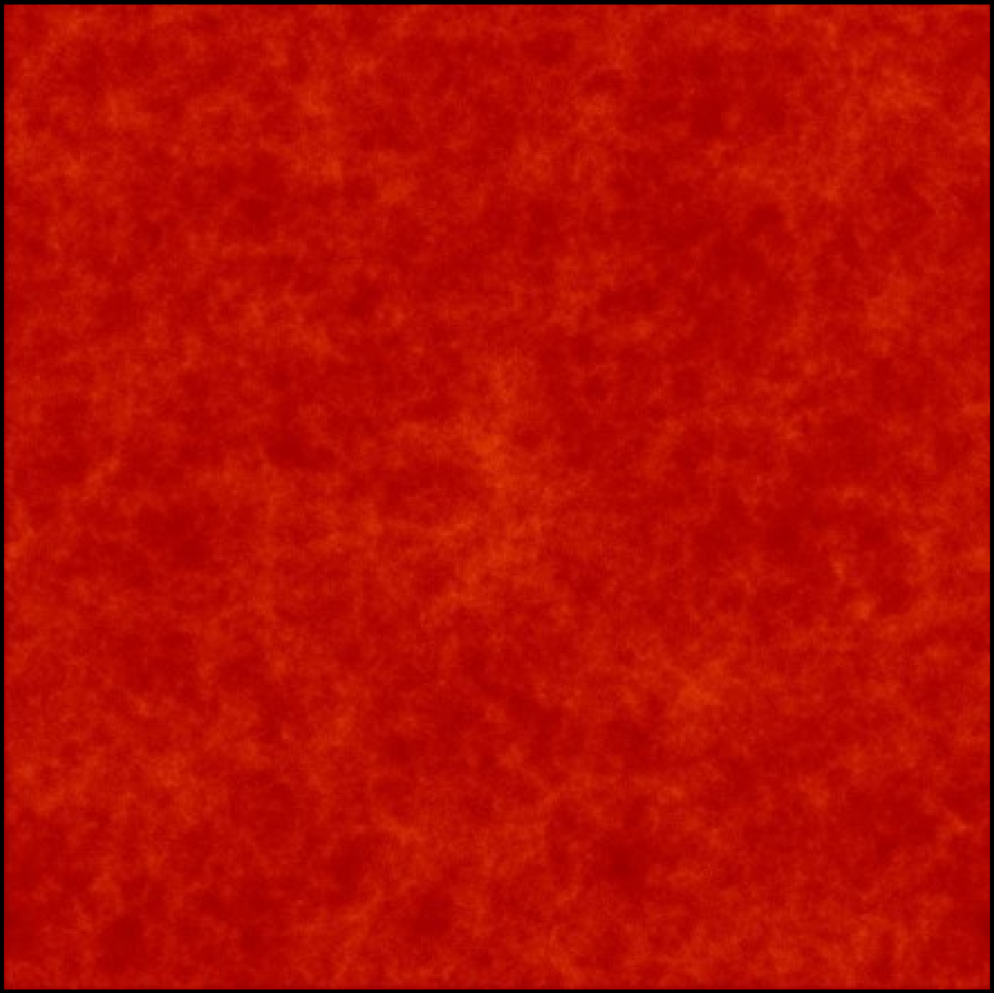
Hubble constant
$H_0 = 50, 60, 70$

Total density
$\Omega_{tot} = 1.0, 0.5, 0.3$

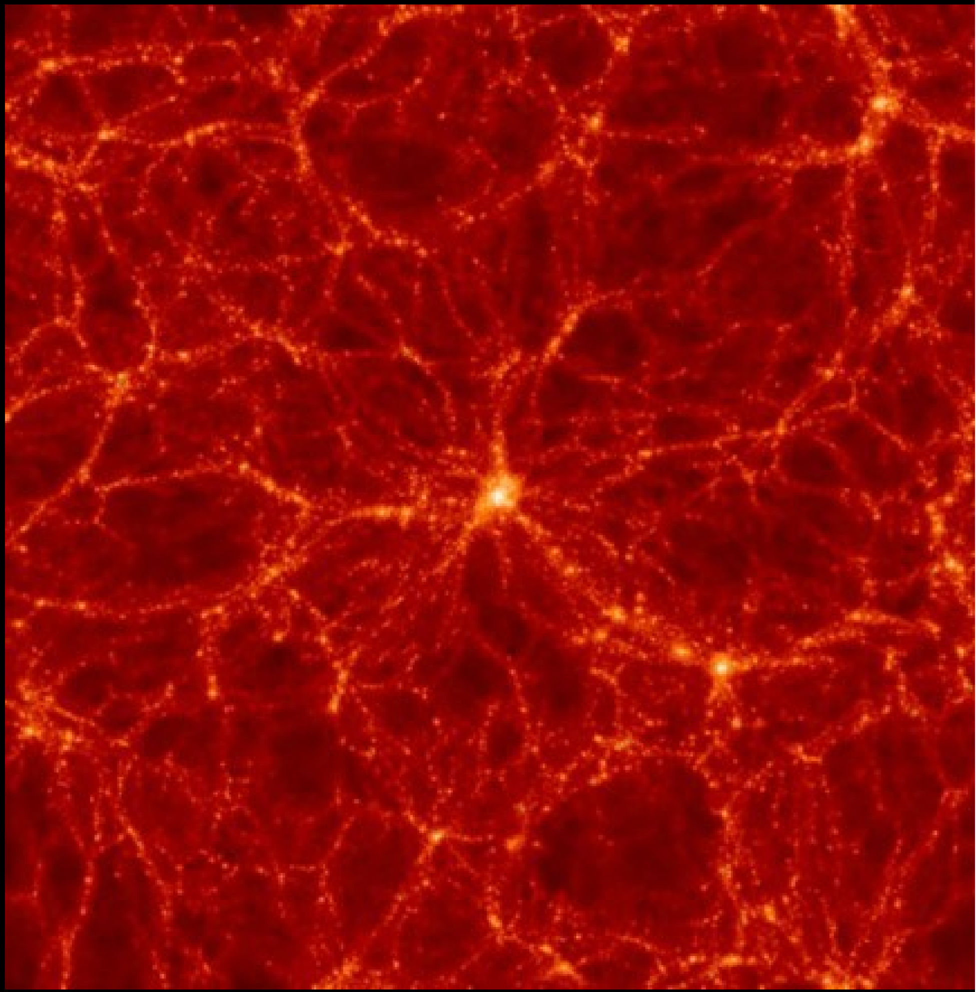
Baryon density
$\Omega_B = 5, 7.5, 10 \times 10^{-3}$

Physics Today 1997:11, 32

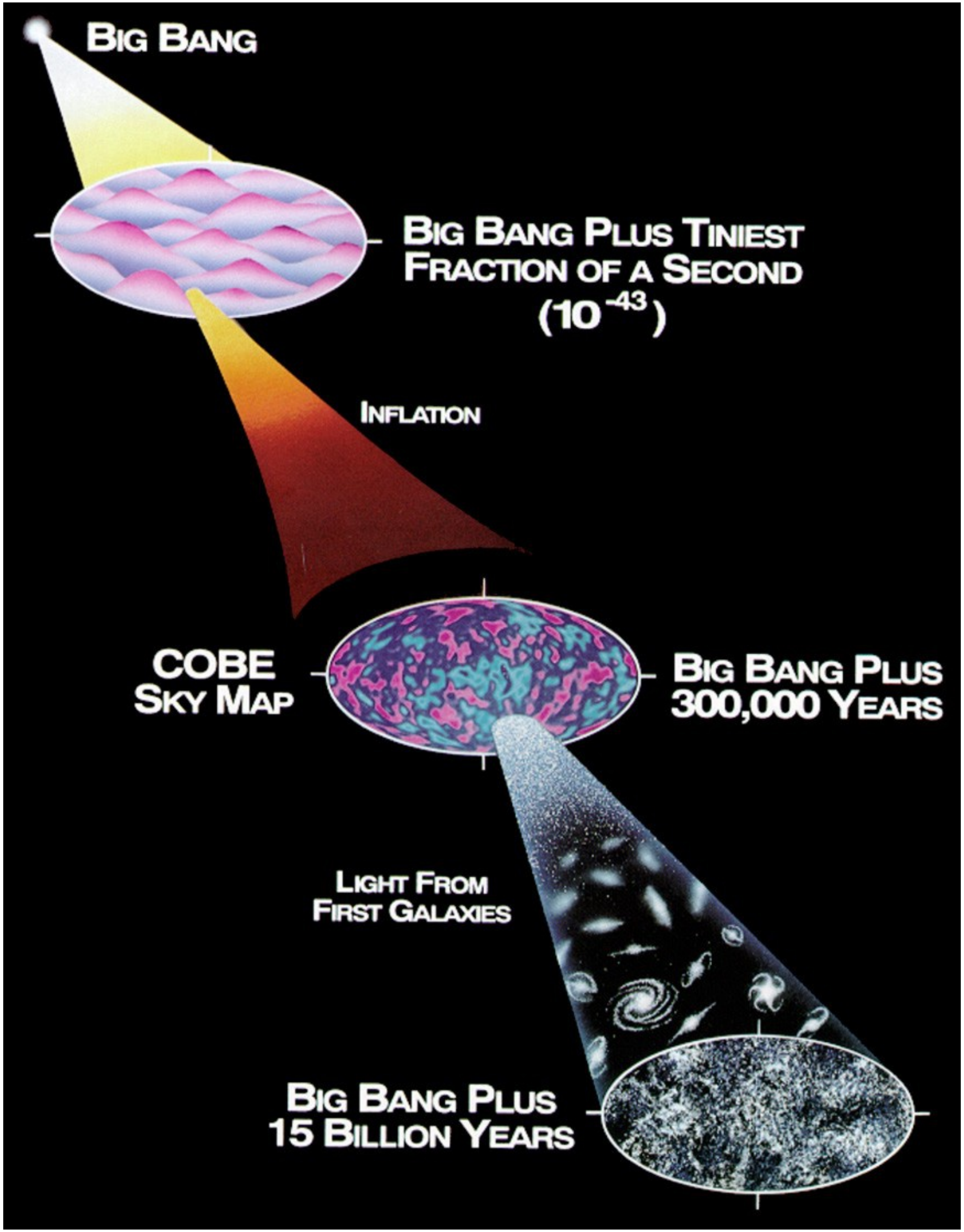
GRAVITATIONAL INSTABILITY



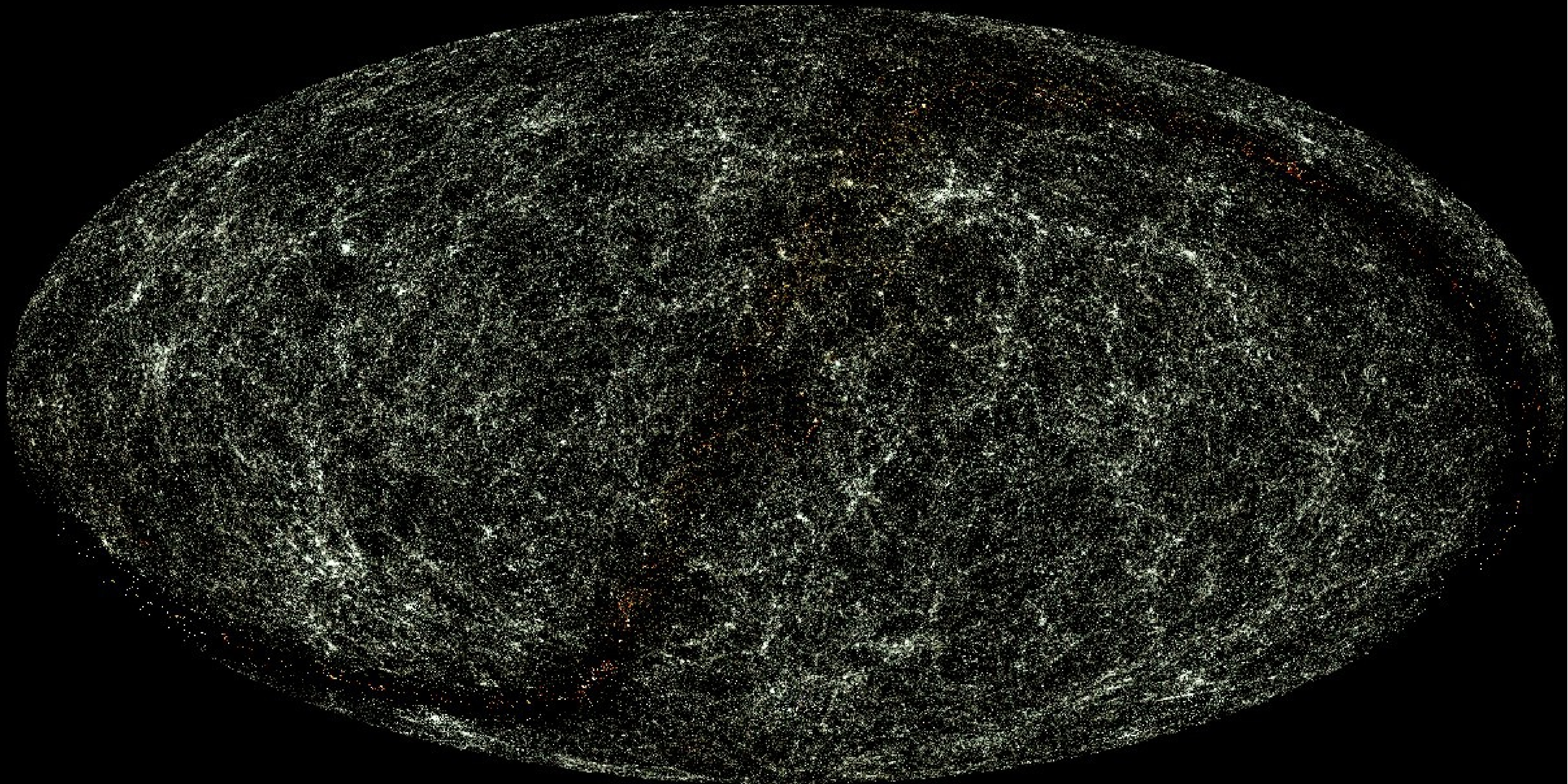
Smooth



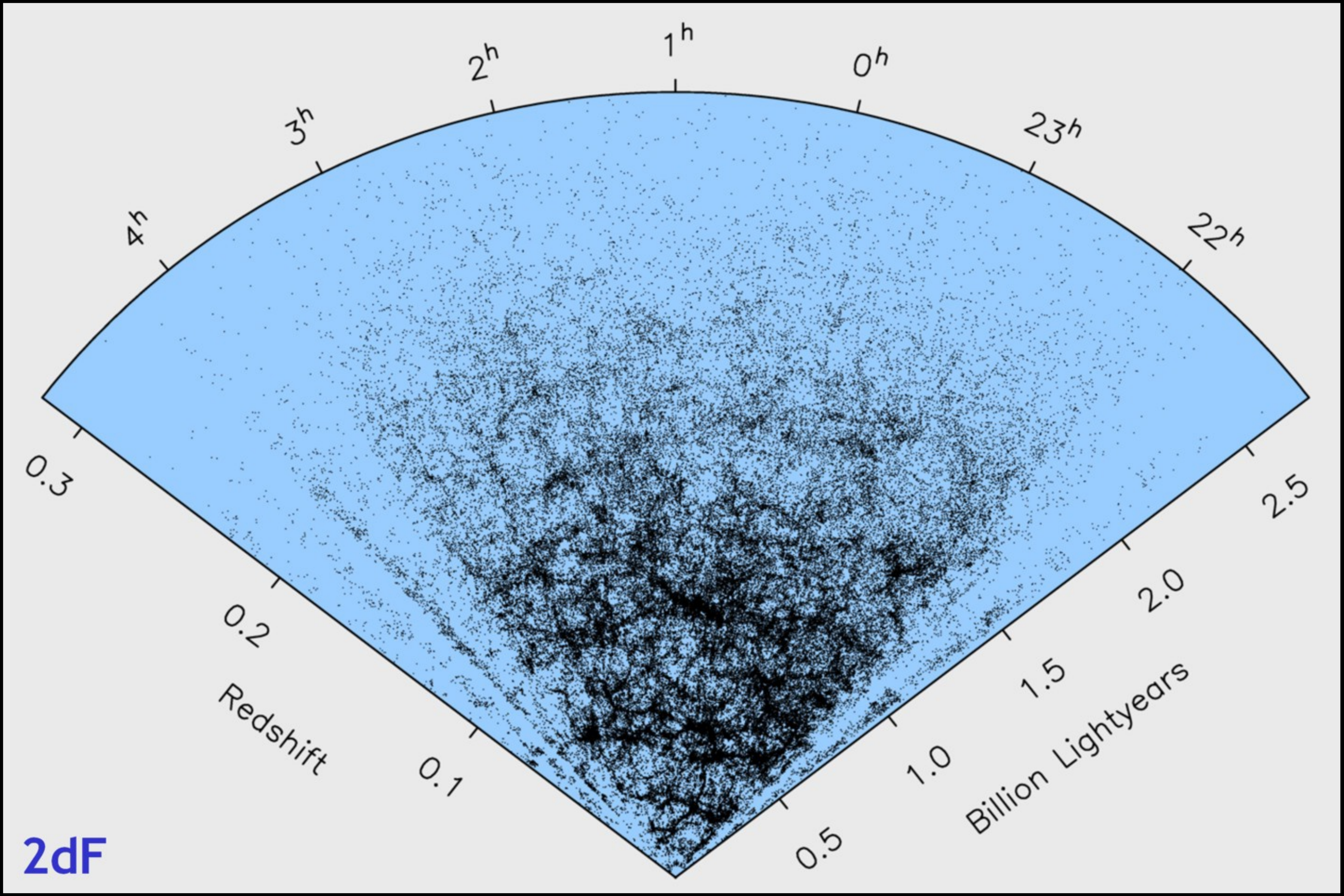
Structured

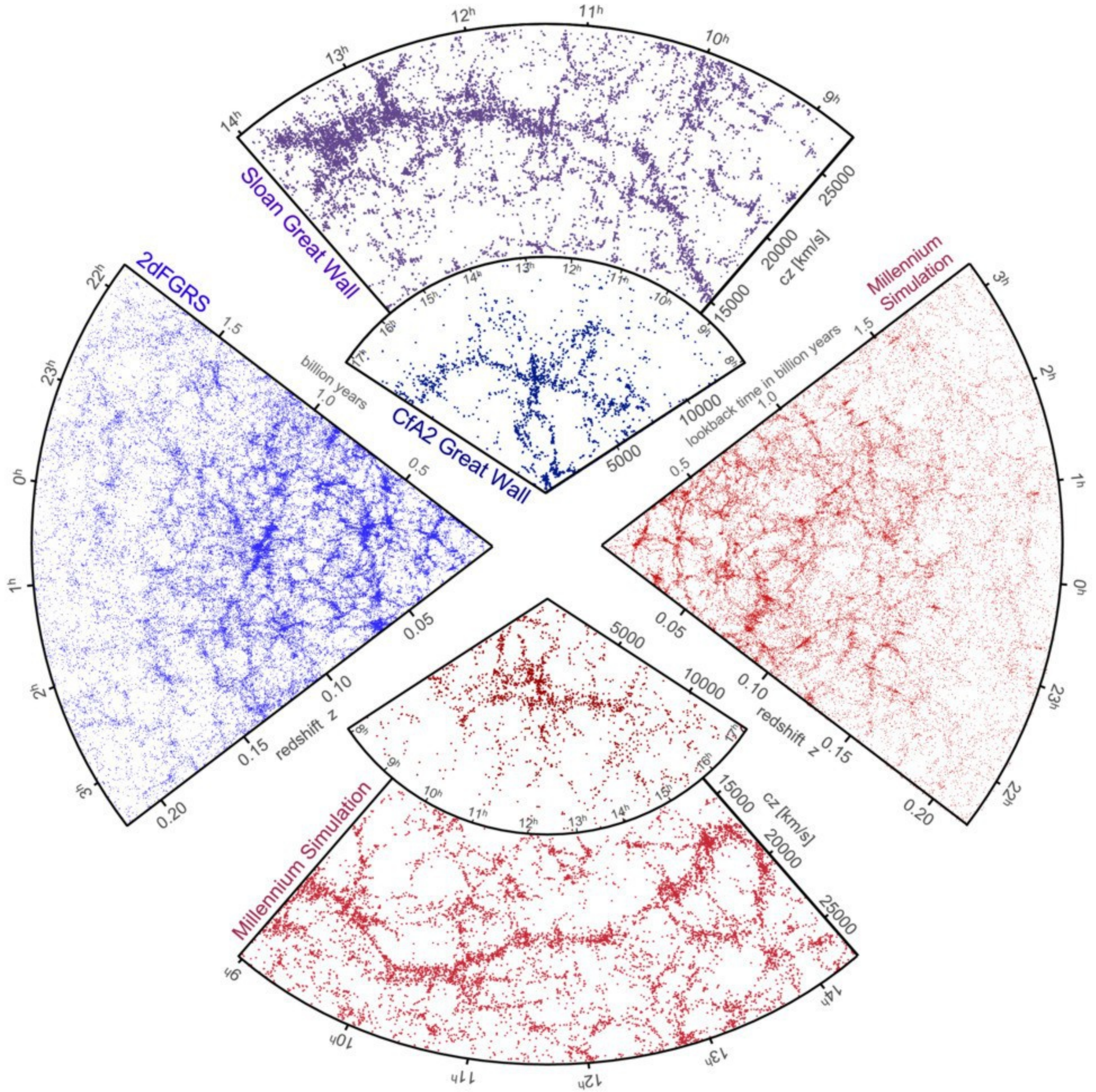

BIG BANG
BIG BANG PLUS TINIEST FRACTION OF A SECOND (10^{-43})
INFLATION
COBE SKY MAP
BIG BANG PLUS 300,000 YEARS
LIGHT FROM FIRST GALAXIES
BIG BANG PLUS 15 BILLION YEARS

Distribution of Galaxies in the SKY (XMASS)

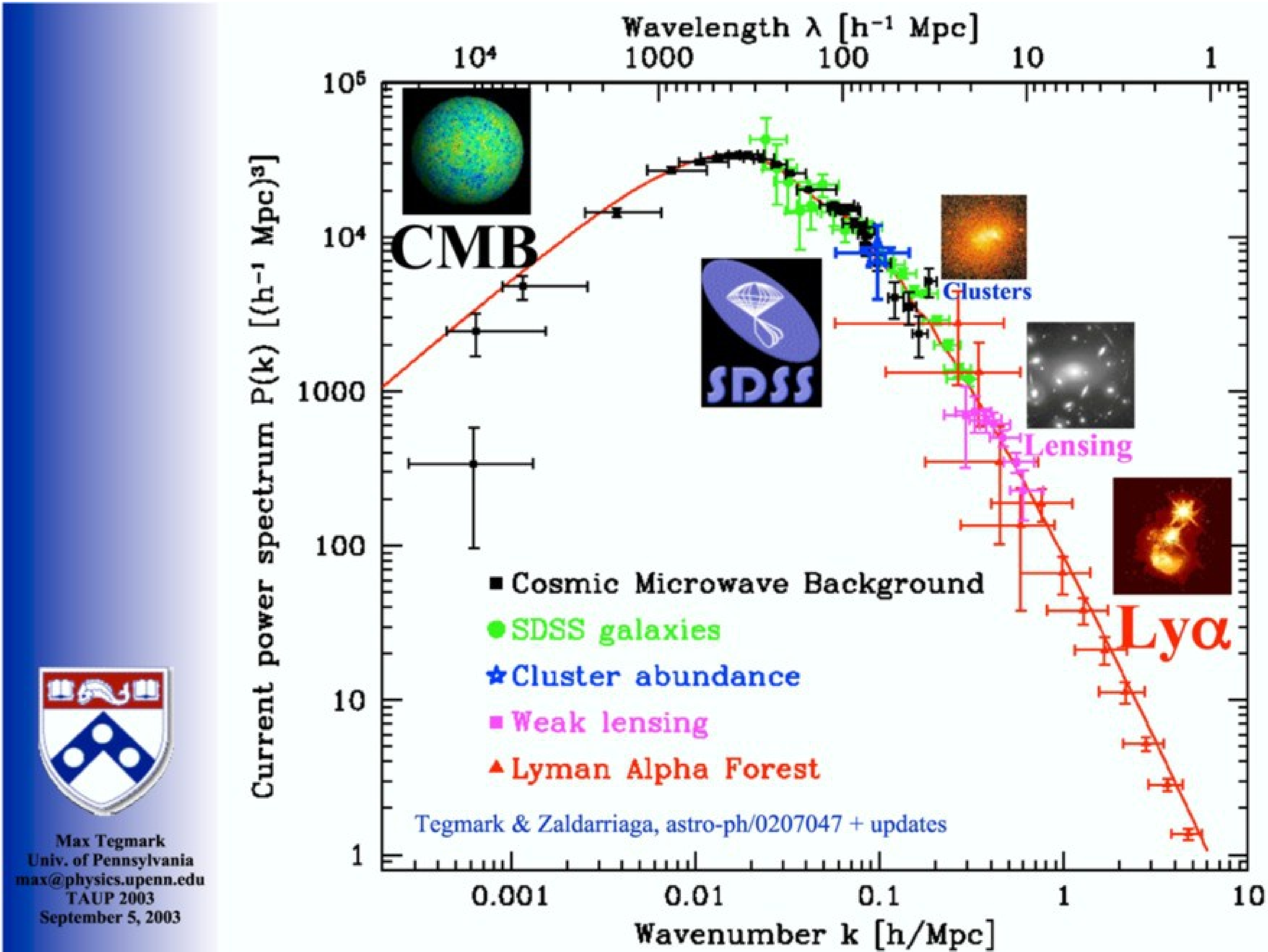


2dF Galaxy Redshift Survey





Sloan Great Wall
CfA2 Great Wall
2dFGRS
Millennium Simulation
Millennium Simulation
cz [km/s]
cz [km/s]
15000
20000
25000
5000
10000
billion years
lookback time in billion years
1.5
1.0
0.5
redshift z
redshift z
0.05
0.10
0.15
0.20


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
CMB
SDSS
Clusters
Lensing
Lyα
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
Tegmark & Zaldarriaga, astro-ph/0207047 + updates
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]
Max Tegmark
Univ. of Pennsylvania
max@physics.upenn.edu
TAUP 2003
September 5, 2003

NEUTRINOS

$$n_\nu = 6 \times \left(\frac{3}{4} \frac{\zeta(3)}{\pi^2} \frac{4}{11} T_\gamma^3 \right)$$

$$\sum m_\nu \gtrsim 0.05 \text{ eV}$$

Oscillation studies

$$n_\nu = 6 \times 56 \text{ cm}^{-3}$$

$$\Omega_\nu \simeq 0.021 \sum m_\nu (\text{eV})$$

$$\sum m_\nu \lesssim 1.3 \text{ eV}$$

Structure formation

Too much neutrinos erase Large Scale structure

$$0.001 \lesssim \Omega_\nu \lesssim 0.02$$

Does Dark Matter Really Exist ?

THE ASTROPHYSICAL JOURNAL, **270**:365–370, 1983 July 15

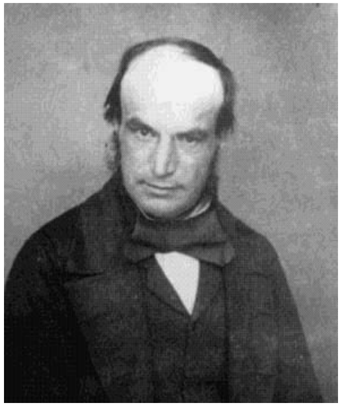
A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

M. MILGROM
Department of Physics, The Weizmann Institute of Science, Rehovot, Israel; and
The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

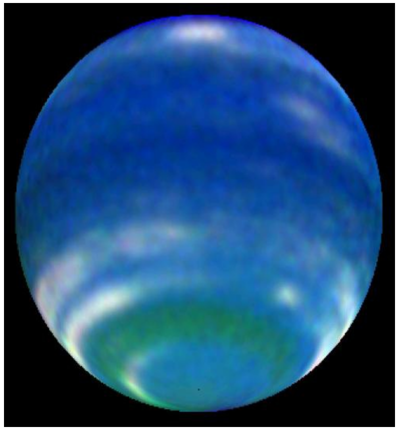
Uranus orbital anomalies

Prediction + Discovery of Neptune (23/24 september 1846)

Urbain Le Verrier

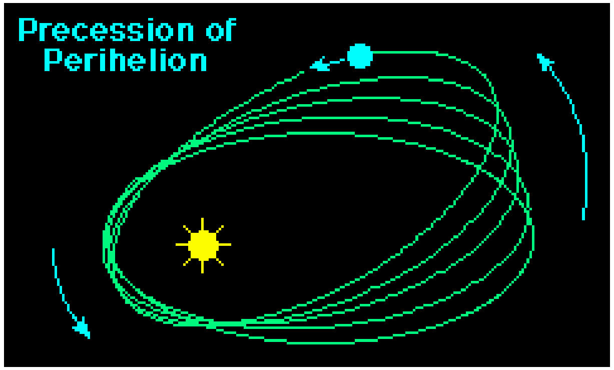


John Couch Adams

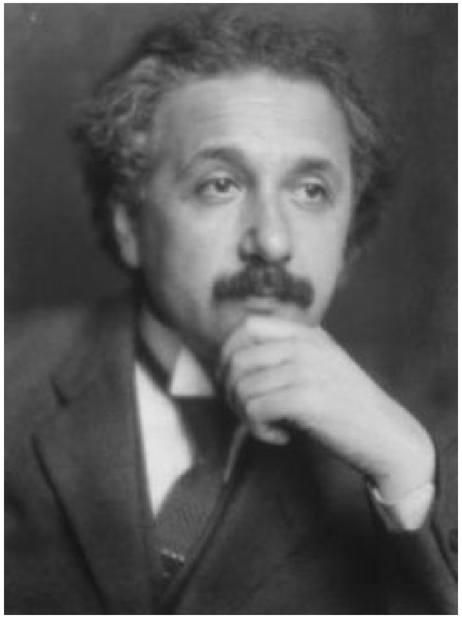


Mercury orbital anomalies

Extra 43''/century perihelion precession



New dynamics
General Relativity
(1916 Albert Einstein)



MOdified Newtonian Dynamics [MOND]

$$a_0 \simeq 10^{-8}\ \mathrm{cm/s^2}$$

$$F_{\rm grav} = \begin{cases} ma & \text{for } a >> a_0 \\ m\,\dfrac{a^2}{a_0} & \text{for } a << a_0 \end{cases}$$

Fundamental acceleration

$a_0 \simeq c\,H_0/5$

Coincidence?

$$\frac{G\,M}{r^2} = \frac{v^2}{r}$$

"Newtonian"

$v_{\rm rot}^2 \to GM/r$

$$\frac{G\,M}{r^2} = \left(\frac{v^2}{r}\right)^2 \frac{1}{a_0}$$

Modified Newtonian (small acceleration)

$v_{\rm rot}^4 \to GM\,a_0$

$v_{\rm rot} \propto M^{1/4} \propto L^{1/4}$

J. D. Bekenstein,
"Alternatives to dark matter: Modified gravity as an alternative to dark matter,"
arXiv:1001.3876 [astro-ph.CO].

1. Introduction

A look at the other papers in this volume will show the present one to be singular. Dark matter is a prevalent paradigm. So why do we need to discuss alternatives ? While observations seem to suggest that disk galaxies are embedded in giant halos of dark matter (DM), this is just an *inference* from accepted Newtonian gravitational theory. Thus if we are missing understanding about gravity on galactic scales, the mentioned inference may be deeply flawed. And then we must remember that, aside for some reports which always seem to contradict established bounds, DM is not seen directly. Finally, were we to put all our hope on the DM paradigm, we would be ignoring a great lesson from the history of science: accepted understanding of a phenomenon has usually come through confrontation of rather contrasting paradigms.

Theoretical Objections: "Phenomenology, Not Theory"

Mordehai Milgrom (SciAmi august 2002).

Successful as it may be, MOND is, at the moment, a limited phenomenological theory. By phenomenological, I mean that it has not been motivated by, and is not constructed on, fundamental principles. It was born from a direct need to describe and explain a body of observations, much as quantum mechanics (and, indeed, the concept of dark matter) developed. And MOND is limited, because it cannot be applied to all the relevant phenomena at hand. [Cosmology, Structure formation]

The main reason is that MOND has not been incorporated into a theory that obeys the principles of relativity, either special or general. Perhaps it is impossible to do so; perhaps it is simply a matter of time.

After all it took many years for the quantum idea, as put forth by Max Planck, Einstein and Niels Bohr, to be encapsulaed into the Scrödinger equation, and more time still to be made compatible with special relativity. Even today, despite long, concentrated efforts, theorists have not made quantum physics compatible with general relativity.

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The main reason is that MOND has not been incorporated into a theory that obeys the principles of relativity, either special or general. Perhaps it is impossible to do so; perhaps it is simply a matter of time.

Recent Development of a covariant relativistic theory

J. D. Bekenstein,
"Relativistic gravitation theory for the MOND paradigm," Phys. Rev. **D70**, 083509 (2004). [astro-ph/0403694].

[More than 450 references]

Why is "DARK MATTER" the "prevalent paradigm"

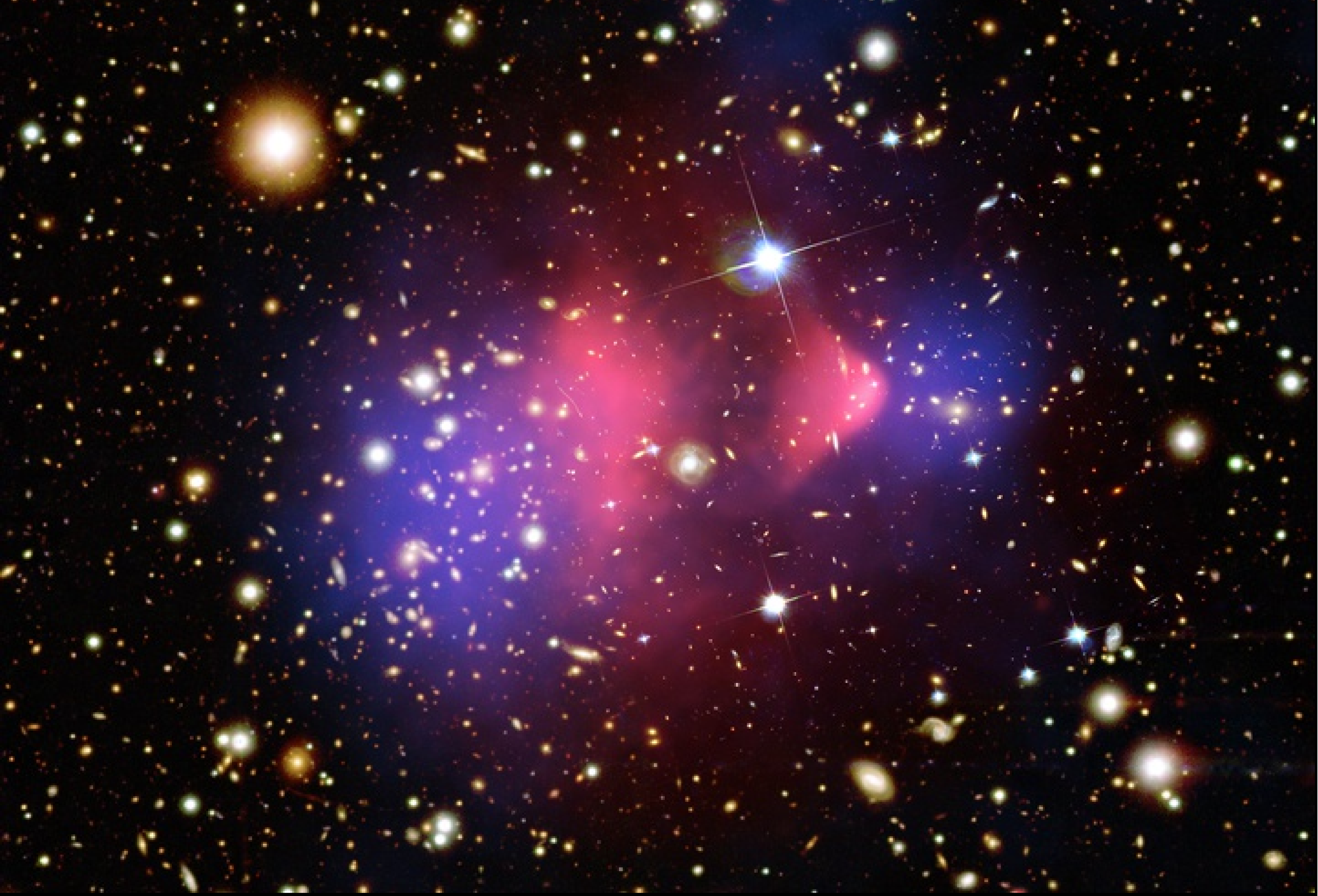
1. Theoretical Difficulties in constructing
   a consistent, covariant theory.

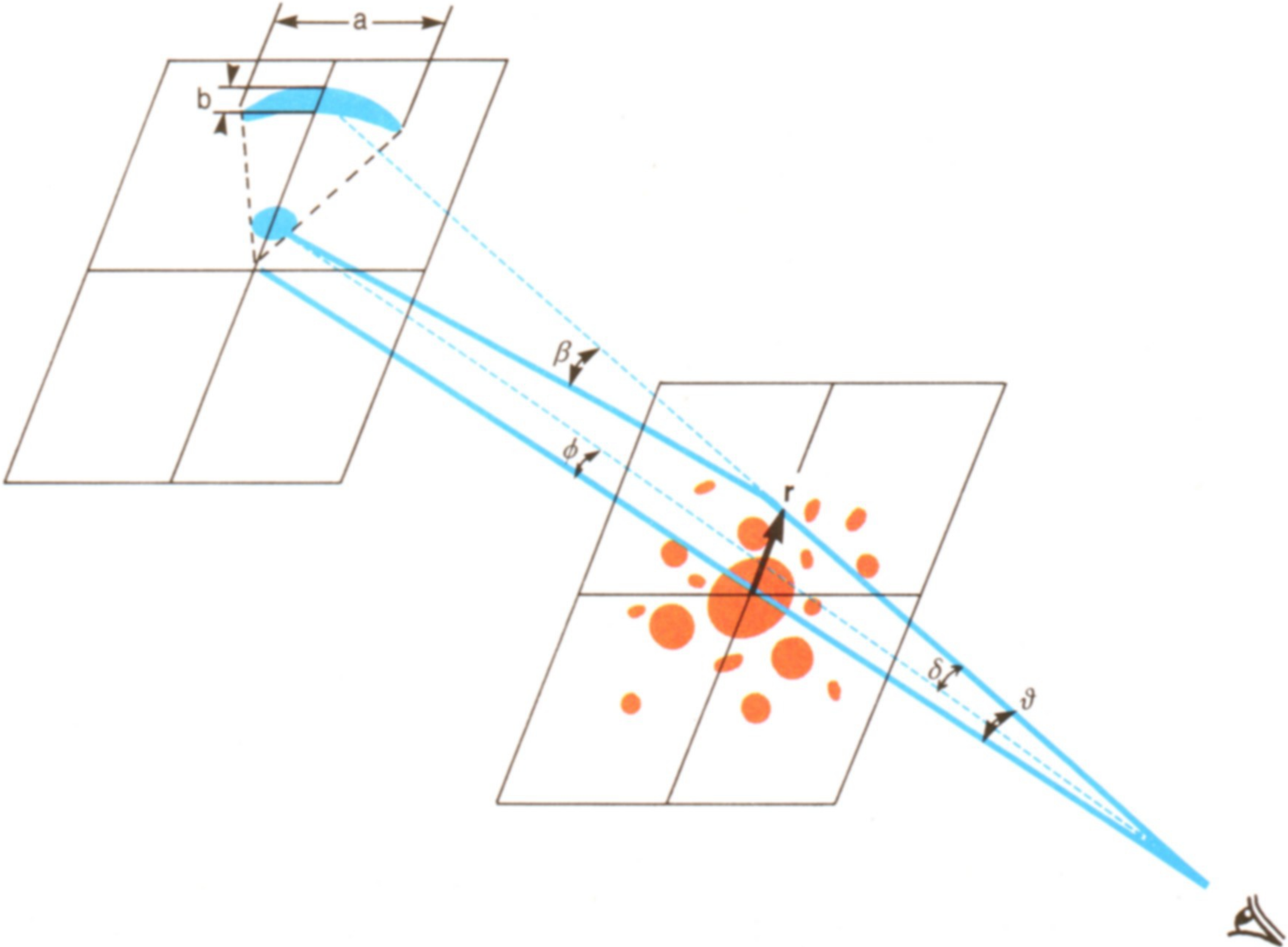
2. Remarkable success of the "Dark Matter" paradigm
   In describing the structure formation in our universe.
   Relation between the
   Large scale galaxy distribution.
   Anisotropies in the Cosmic Background Radiation.

3. The "BULLET CLUSTER"
   (Cluster 1E0657-558: 2 colliding clusters at z=0.296)
   Clear separation between Baryons and Mass.
   [other similar objects discovered (MACS J0025.4-1222)]

D. Clowe, M. Bradac, A. H. Gonzalez *et al.*,
"A direct empirical proof of the existence of dark matter,"
Astrophys. J. **648**, L109-L113 (2006). [astro-ph/0608407].

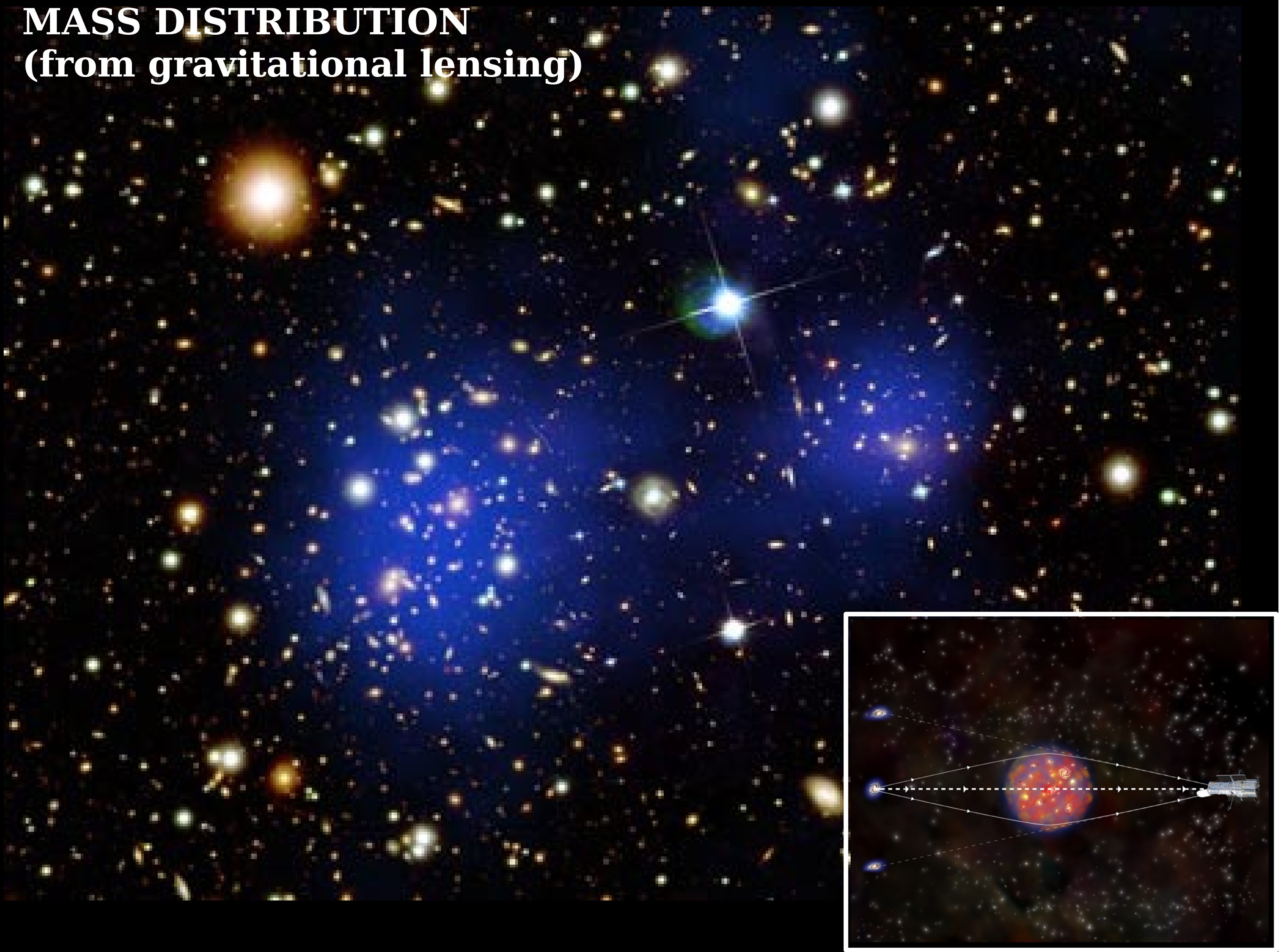
Bullet CLUSTER (2 colliding clusters)





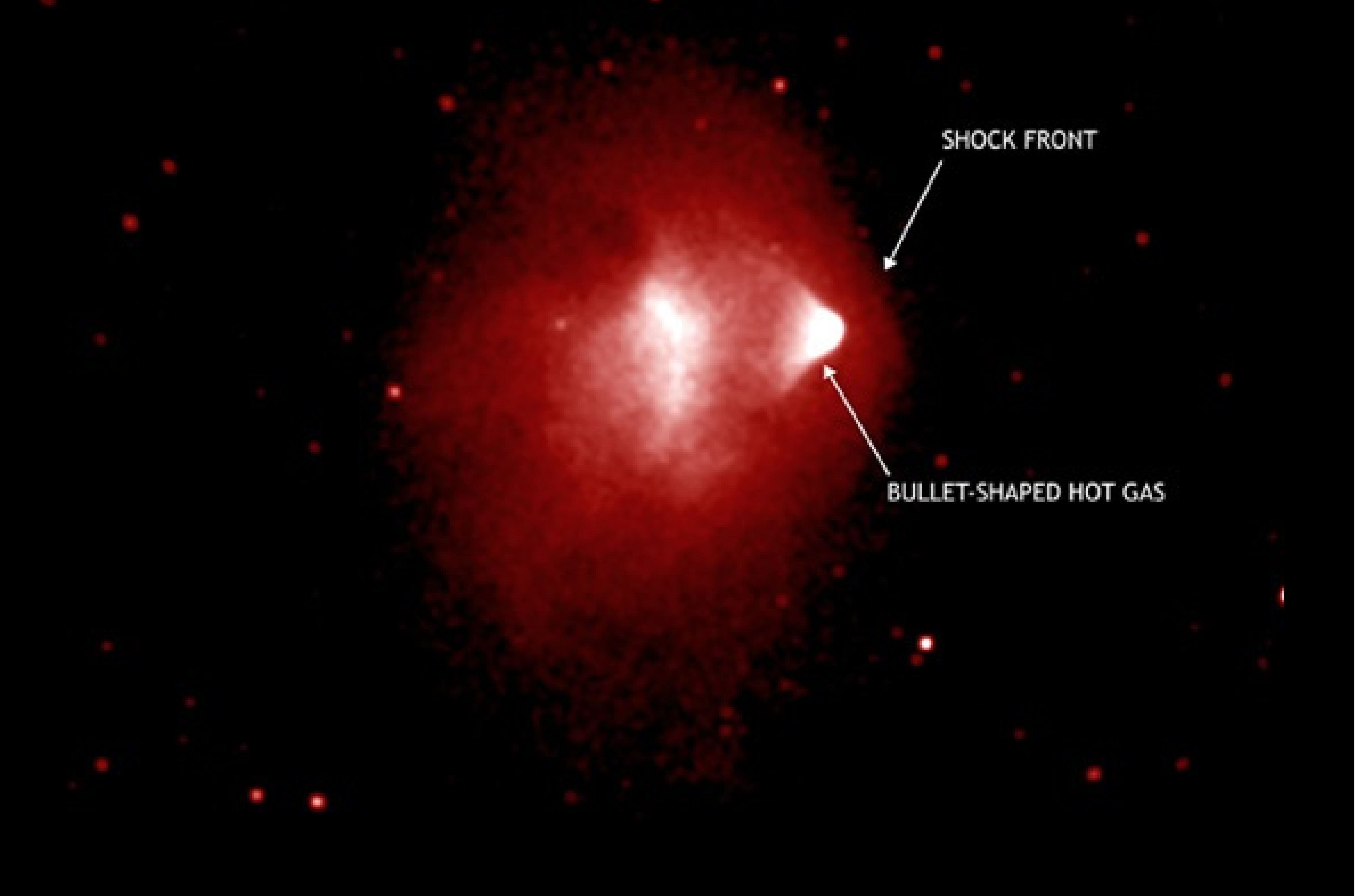
A.Tyson, Physics Today, 1992:6, pg.24

MASS DISTRIBUTION
(from gravitational lensing)



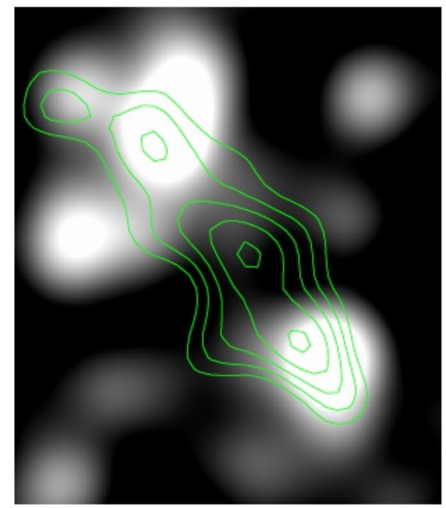
X-RAY Emission

(gas of ordinary matter)

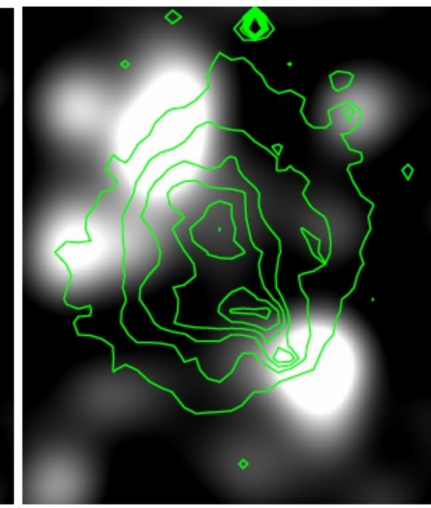


In recent years a lot of attention has been given to the "train wreck cluster" [Abell 520] (z=0.21)

A "counter example" to the Bullet cluster



White: galaxies
Contour: mass



White: galaxies
Contour: X rays

Contours = Mass
Red: X Rays (Chandra)

DARK MATTER: we know a lot :

...but we
do NOT know
much more...

It exists (no modified gravity for the bullet cluster)

Good estimate of the cosmological average (~23%)

Most of it is non baryonic

Most of it is “cold”

It cannot be explained by the Standard Model
in Particle Physics !

What is the Dark Matter ?

Cold Dark Matter
(Tate Gallery. London)

Artists and Dark Matter

Cornelia Parker

What is the Dark Matter ?

Possible theoretical ideas

Thermal Relic

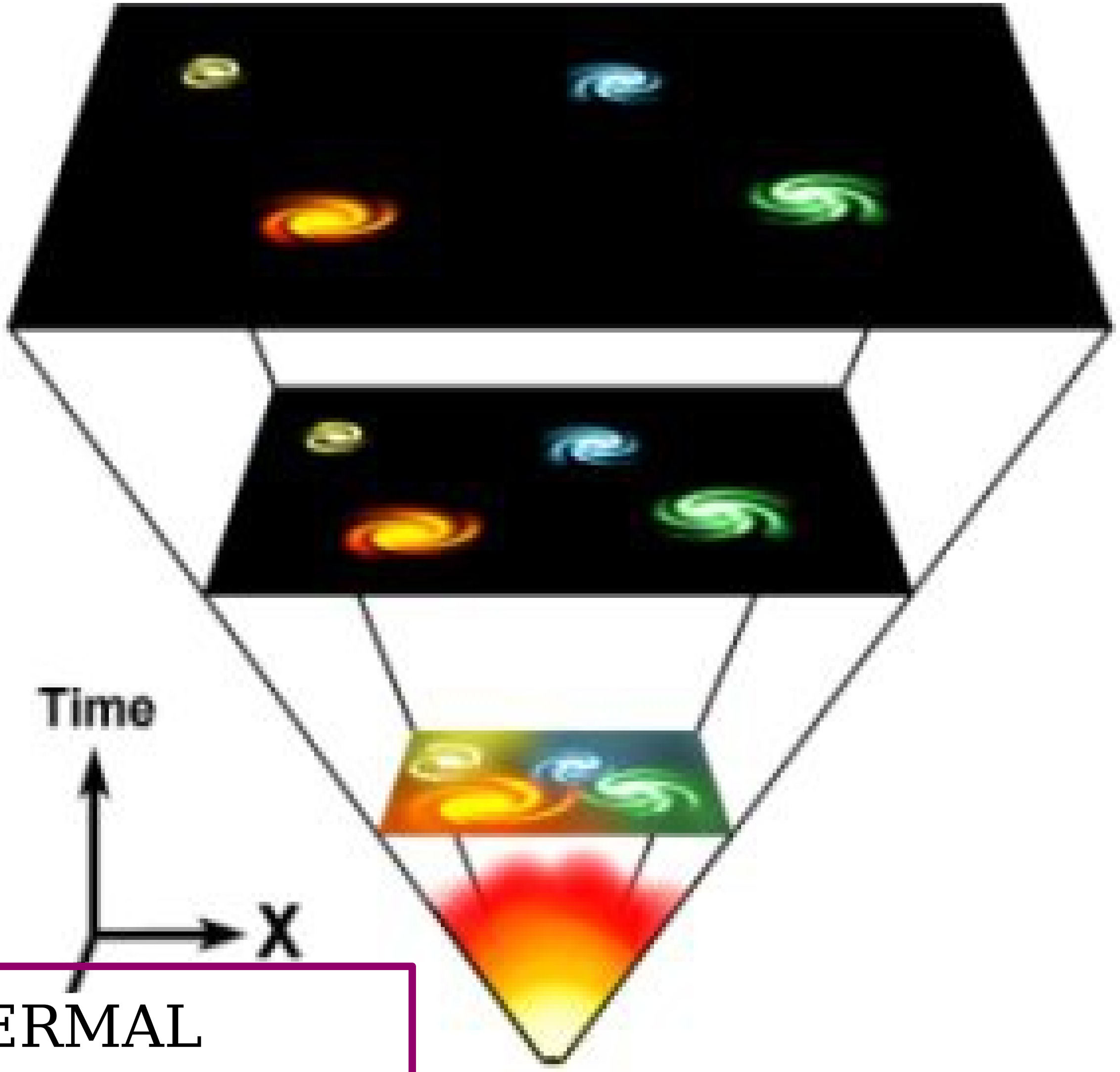
Axion

Super-massive particles

Discuss only this idea
[perhaps the best motivated]
[offers the best chances of discovery]

Early Universe was HOT

[Adiabatic compression of a fluid]



THERMAL EQUILIBRIUM

$$a + b \leftrightarrow c + d$$

"COSMIC SOUP"

$$n_j = n_{\bar{j}}$$

Thermal equilibrium
Distribution

$$\frac{dN_j}{d^3x\, d^3p} = \frac{g_j}{(2\,\pi\,\hbar\,c)^3}\,\frac{1}{e^{E/T} \mp 1}$$

Boson
fermion

$$n_j \neq n_{\bar{j}}$$

$$\frac{dN_j}{d^3x\, d^3p} = \frac{g_j}{(2\,\pi\,\hbar\,c)^3}\,\frac{1}{e^{(E-\mu_j)/T} \mp 1}$$

$$n(T) = \int d^3p \, \frac{dN}{d^3x \, d^3p}$$

$$\rho(T) = \int d^3p \; E(p) \, \frac{dN}{d^3x \, d^3p}$$

High Temperature

$$T \gg m_\chi$$

$$n_{\text{boson}}(T) = g \, \frac{\zeta(3)}{\pi^2} T^3$$

$$n_{\text{fermion}}(T) = g \, \frac{\zeta(3)}{\pi^2} T^3 \times \frac{3}{4}$$

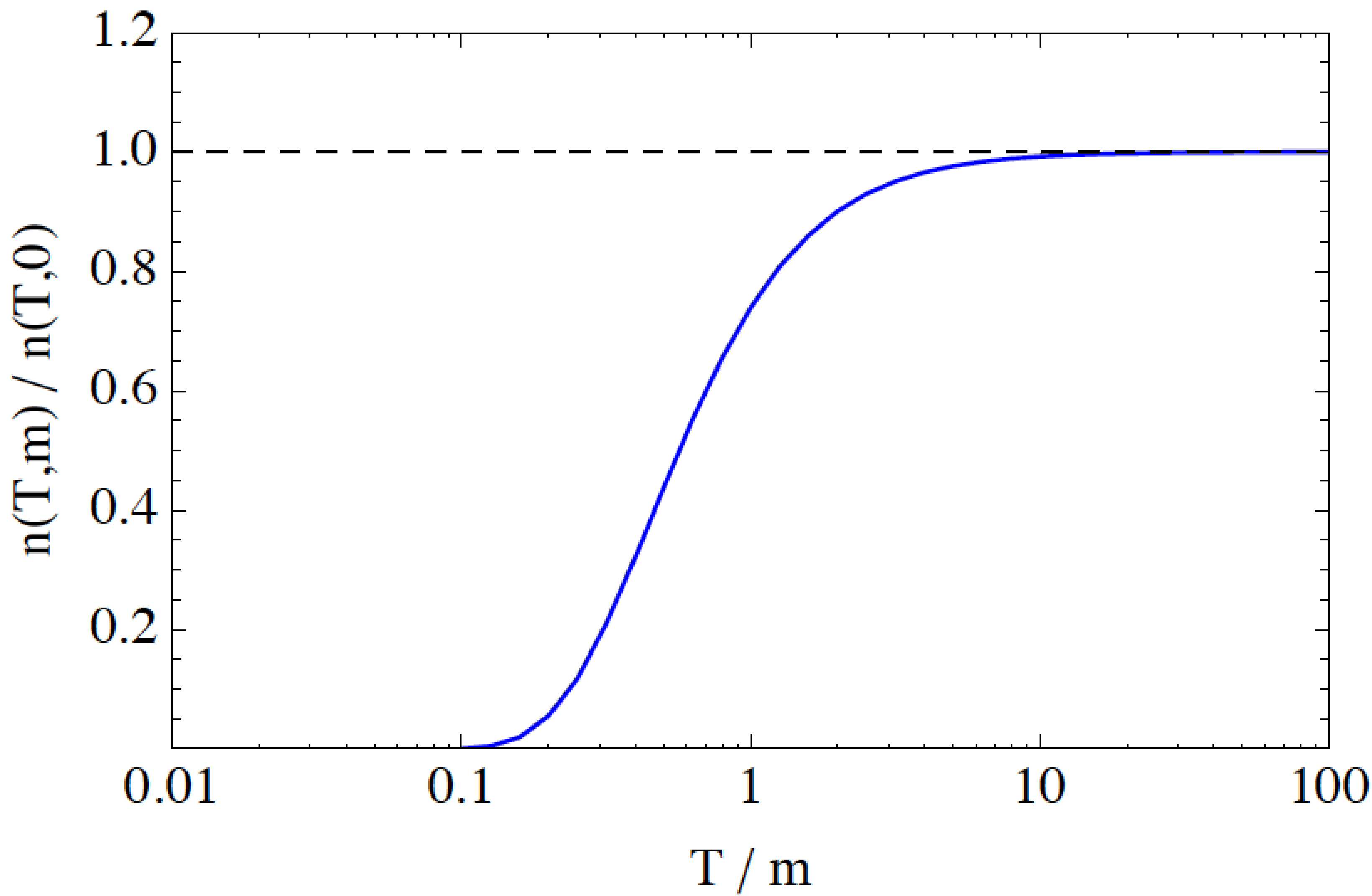
$$\rho_{\text{boson}}(T) = g \, \frac{\pi^2}{30} T^4$$

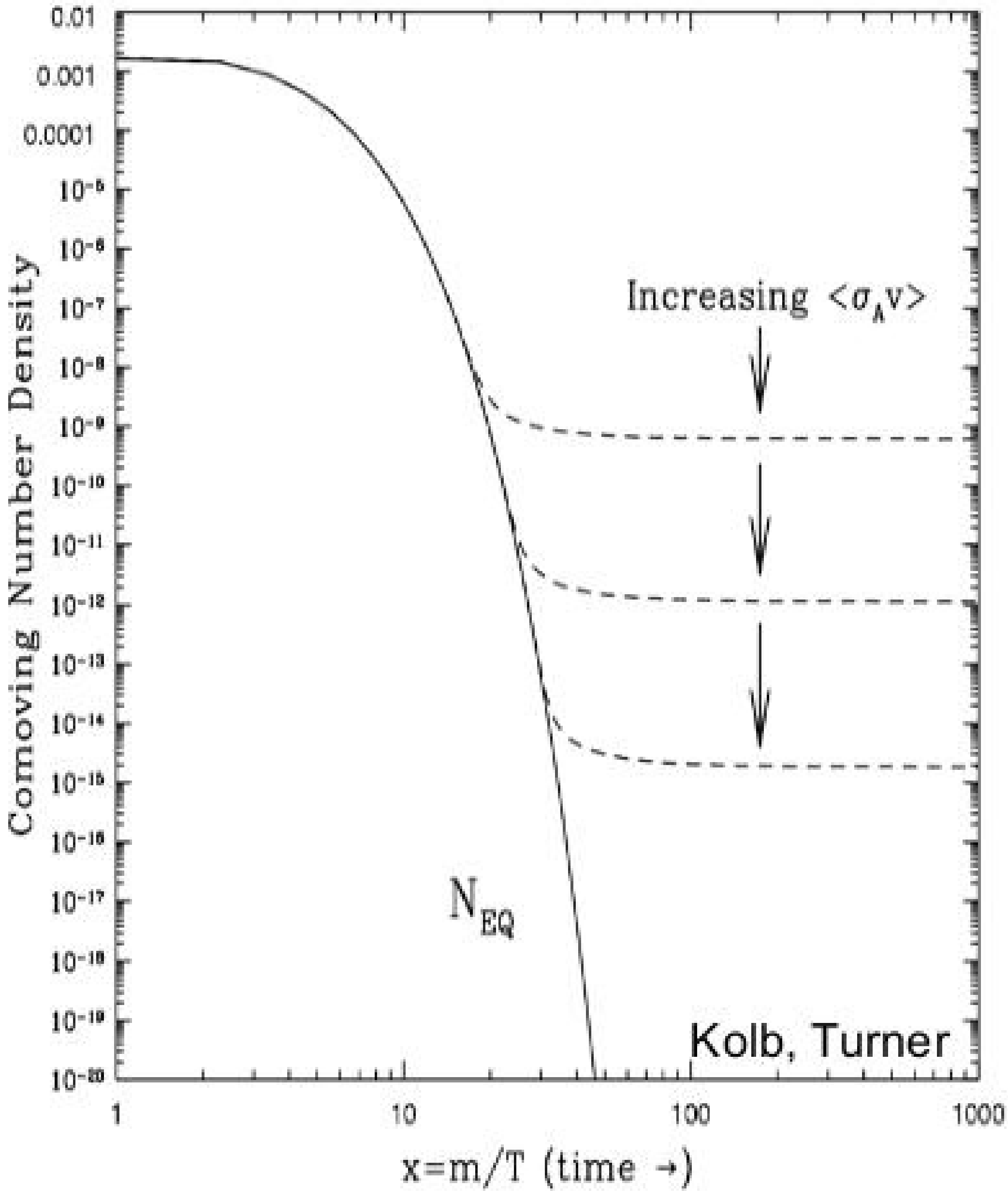
$$\rho_{\text{fermion}}(T) = g \, \frac{\pi^2}{30} T^4 \times \frac{7}{8}$$

$$n(T) = g\,\frac{e^{-m/T}\,(m\,T)^{3/2}}{2\sqrt{2}\,\pi^{3/2}}$$

$$\begin{array}{lll} \chi + \overline{\chi} & \rightarrow & q + \overline{q} \\ \chi + \overline{\chi} & \rightarrow & g + g \\ \chi + \overline{\chi} & \rightarrow & \gamma + \gamma \end{array} \qquad \begin{array}{lll} \chi + \overline{\chi} & \leftarrow & q + \overline{q} \\ \chi + \overline{\chi} & \leftarrow & g + g \\ \chi + \overline{\chi} & \leftarrow & \gamma + \gamma \end{array}$$

m < T





$$\Omega_j^0 \simeq 0.3 \left[\frac{3\times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma\, v\rangle}\right]$$

Annihilation cross section
Determines the
"relic abundance"

$$\chi + \chi \leftarrow f + \overline{f}$$

$$\chi + \chi \rightarrow f + \overline{f}$$

Exercise:

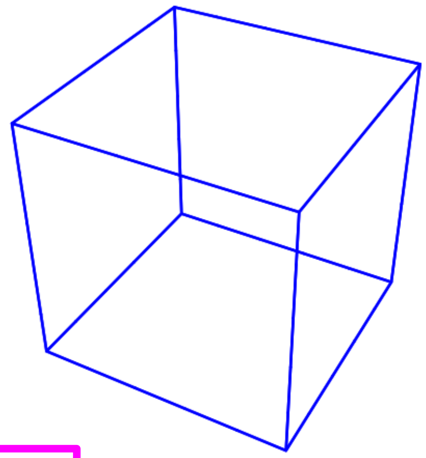
Compute the "Relic abundance" of a particle of mass M.

Input :

Hubble Constant now
Temperature of the CMBR
Annihilation cross section
[All particles of the standard Model]

Particle anti-particle annihilation and the "Relic Density"

[Pedagogical discussion]
"box" of constant volume.
Equal distributions for particle and anti-particle



$$dP_{\rm distruction} = n_\chi \; \langle \sigma_{\chi\chi \to {\rm anything}} \; v \rangle \; dt$$

Probability of disappearance per unit time

$$\langle \sigma \; v \rangle = \int d^3 v_1 \; \int d^3 v_2 \; f_\chi(\vec{v}_1) \; f_\chi(\vec{v}_2) \; \sigma(|\vec{v}_1 - \vec{v}_2|) \; |\vec{v}_1 - \vec{v}_2|$$

Velocity averaged cross section
[in many cases $\sigma(v) \; v = {\rm constant}$]

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$$\langle \sigma \, v \rangle = \int d^3v_1 \int d^3v_2 \, f_\chi(\vec{v}_1) \, f_\chi(\vec{v}_2) \, \sigma(|\vec{v}_1 - \vec{v}_2|) \, |\vec{v}_1 - \vec{v}_2|$$

Velocity averaged cross section
[in many cases $\sigma(v) \, v = {\rm constant}$]

$$dn_\chi = -n_\chi \, dP_{\rm dist} = -n_\chi^2 \, \langle \sigma v \rangle \, dt$$

Evolution of the Particle density

$$\frac{dn(t)}{dt} = -n^2(t)\,\langle\sigma\, v\rangle$$

Time evolution
Of the density

$$n(t_i) = n_i$$

Initial condition

$$\frac{dn}{n^2} = -\langle\sigma\, v\rangle\, dt$$

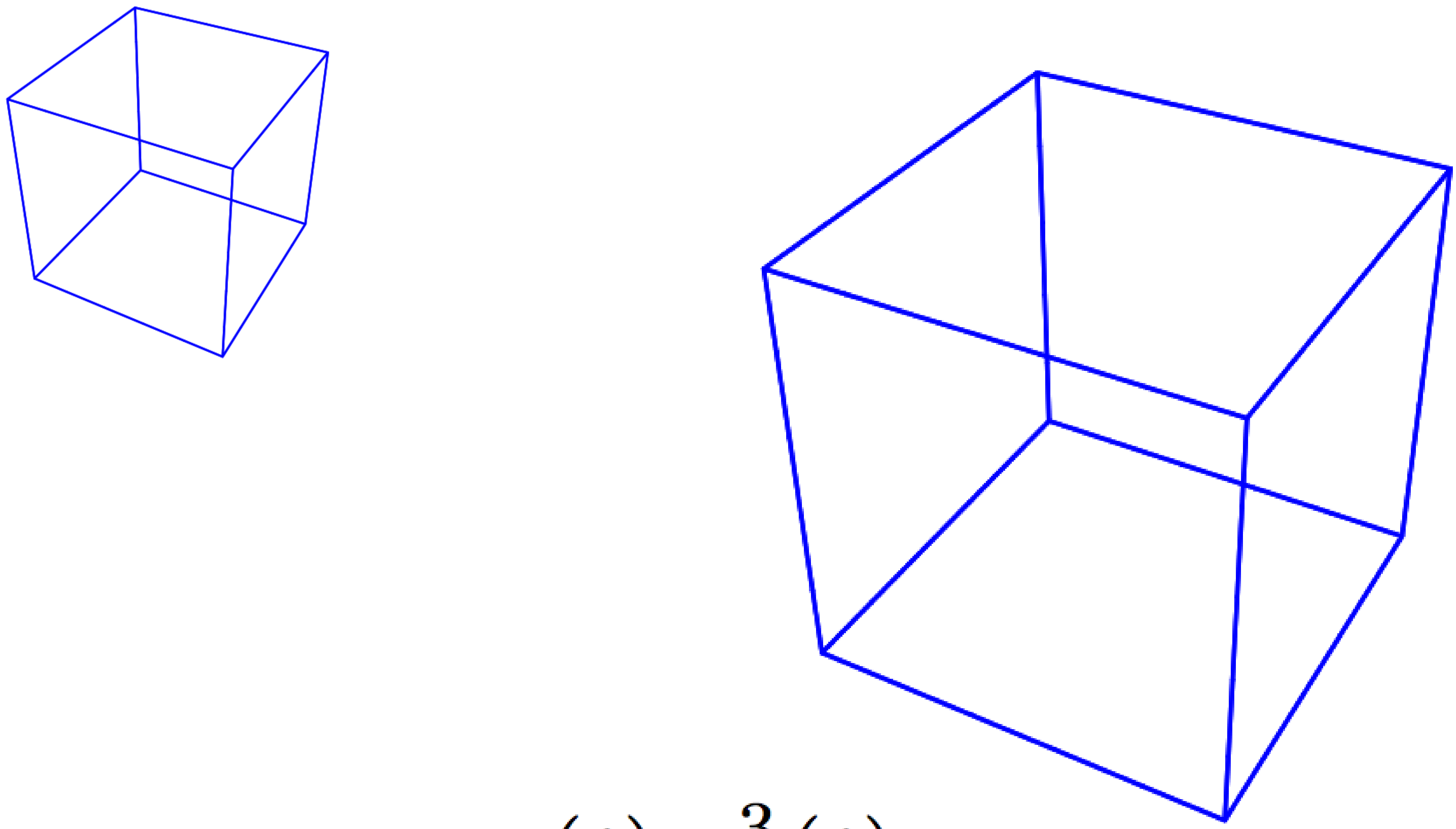
$$n(t) = \frac{n_i}{1 + n_i\,\langle\sigma\, v\rangle\,(t - t_i)}$$

Solution

$$\lim_{t\to\infty} n(t) = 0$$

All particles annihilate.

Annihilation in an Expanding Universe



$$n_{\text{comoving}} = n(t)\, a^3(t)$$

$$\frac{d[n(t)\,a^3(t)]}{dt} = -n^2(t)\,a^3(t)\,\langle\sigma\,v\rangle$$

Evolution equation for the comoving density

$$n(t)\,a^3(t) = \frac{n_i\,a_i^3}{1 + n_i\,a_i^3\,\langle\sigma\,v\rangle\,\int_{t_i}^{t} dt\,[a(t)]^{-3}}$$

Solution

$$(t - t_i) \rightarrow a^3(t_i)\,\int_{t_i}^{t} \frac{dt}{a(t)^3}$$

Difference with respect to the case of constant volume

$$\frac{d[n(t)\,a^3(t)]}{dt} = -n^2(t)\,a^3(t)\,\langle\sigma\,v\rangle$$

Evolution equation for the comoving density

$$n(t)\,a^3(t) = \frac{n_i\,a_i^3}{1 + n_i\,a_i^3\,\langle\sigma\,v\rangle\,\int_{t_i}^{t} dt\,\,[a(t)]^{-3}}$$

Solution

$$(t - t_i) \rightarrow a^3(t_i)\int_{t_i}^{t}\frac{dt}{a(t)^3}$$

Difference with Respect to the case of constant volume

Possible convergent integral For $t \rightarrow \infty$ Finite relic density

$$T(t) \propto \frac{1}{a(t)}$$

$$T(t) \propto t^{-1/2}$$

$$a(t) \propto t^{1/2}$$

$$T^2(t) = \frac{K}{t}$$

$$K = \left[\frac{32}{3}\, G \left(\frac{\pi^2}{30\hbar^3 c^5}\right) g^*\right]^{-1}$$

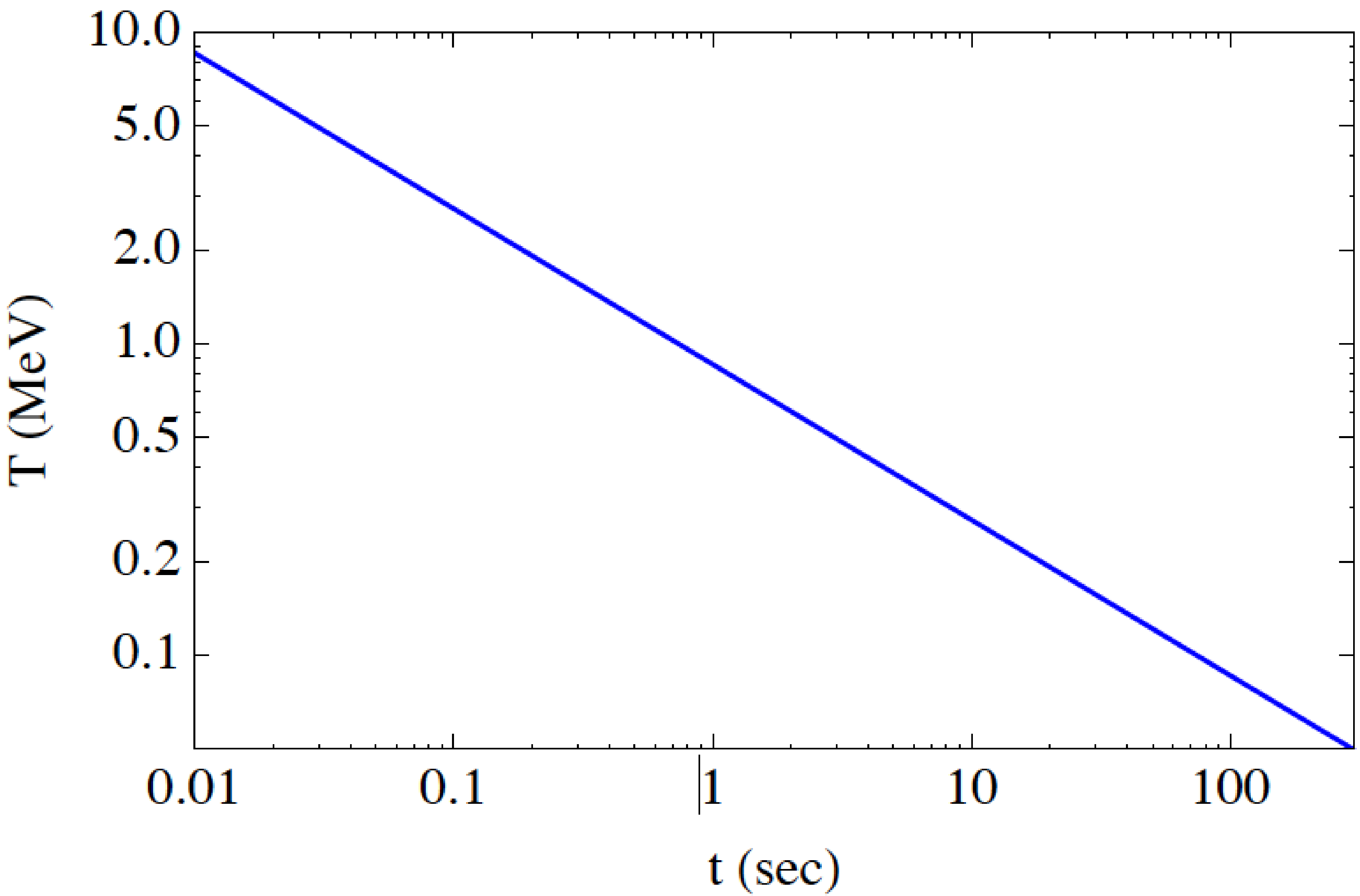
$$g^* = N_{\text{bosons}} + \frac{7}{8} N_{\text{fermions}}$$

$$a_i^3 \int_{t(M)}^{\infty} \frac{dt}{a^3(t)} = a_i^3 \int_M^0 dT' \, \frac{dt}{dT} \, \frac{1}{a^3(T)} = \frac{2K}{m^2}$$

$$\left[n(t)\, a^3(t)\right]_{\text{asymptotic}} = \frac{n_i\, a_i^3}{1 + n_i \langle \sigma v \rangle \, 2K/m^2}$$

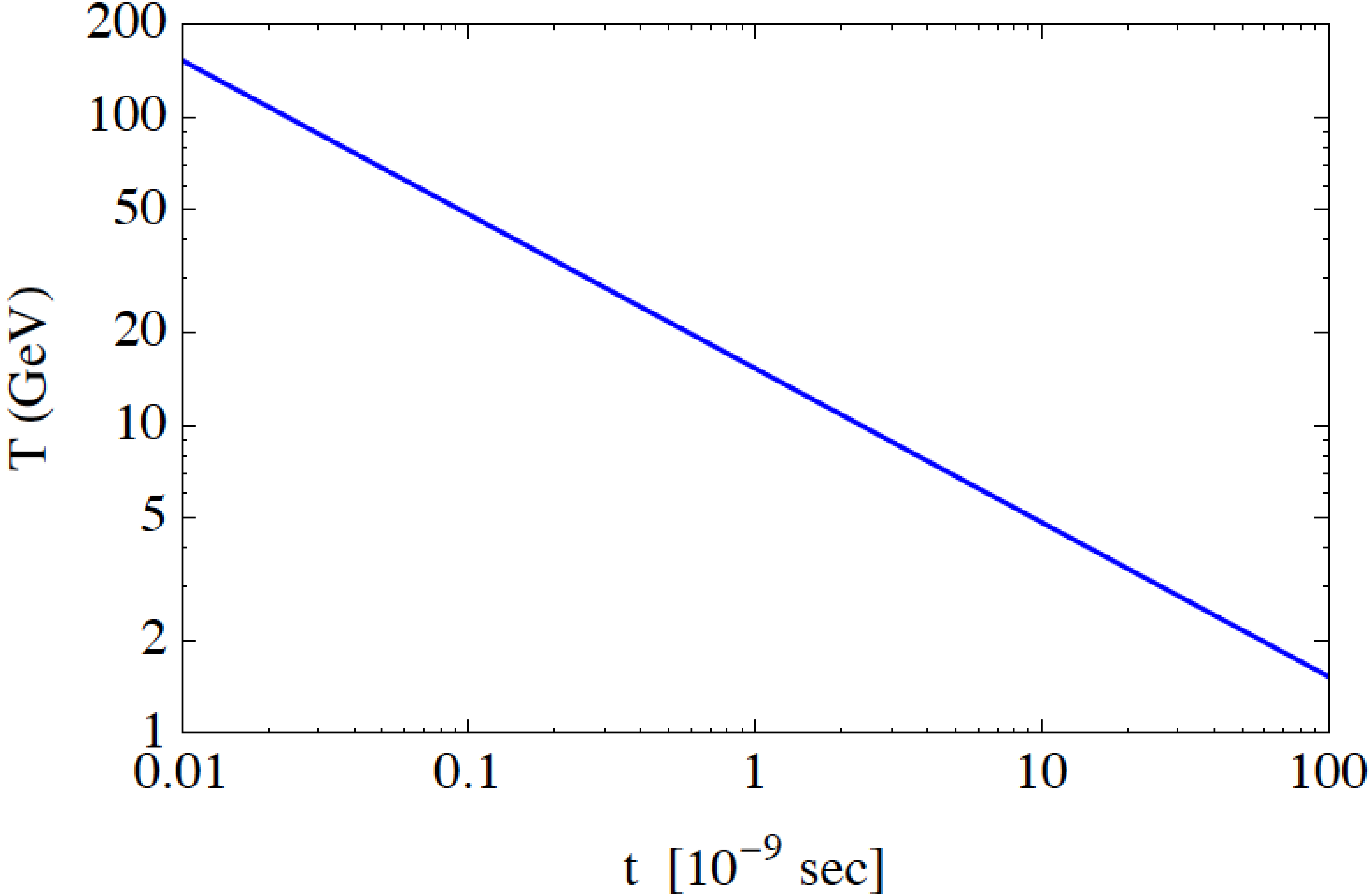
Relation between time and temperature during the nucleosynthesis
"the first three minutes"

$$T^2(t) = \frac{K}{t}$$



Extrapolation to early time

$$T^2(t) = \frac{K}{t}$$



Language of "freeze-out"

There is a time when the dark matter particles
Comoving density "freezes out", remain constant.

$$t_{\text{annihilation}} = \left(\langle \sigma \, v \rangle \; n_\chi \right)^{-1}$$

$$t_{\text{expansion}} = \left[(dL/dt)/L \right]^{-1}$$

$$t_{\text{expansion}} = \left[\dot{a}(t)/a(t) \right]^{-1} = 2\,t$$

$$a(t) \propto \sqrt{t}$$

$$t_{\text{annihilation}}(t^*) = t_{\text{expansion}}(t^*)$$

$$t^* \equiv t_{\text{freeze}}$$

Annihilation stops.

$$n_\chi^{\text{freeze}} \simeq \frac{1}{\langle \sigma\, v \rangle\ 2t_{\text{freeze}}} \simeq \frac{m_\chi^2}{\langle \sigma\, v \rangle\ 2K_g}$$

$$n_\chi^{\text{today}} \simeq n_\chi^{\text{freeze}} \quad \frac{T_0^3}{m_\chi^3}$$

$$= \frac{m_\chi^2}{\langle \sigma\, v \rangle\ 2K_g}\ \frac{T_0^3}{m_\chi^3}$$

$$\rho_\chi^{\text{today}} \simeq n_\chi^{\text{today}}\ m_\chi \simeq \frac{T_0^3}{\langle \sigma\, v \rangle\ 2K_g}$$

$$\rho_\chi^{\text{today}} \simeq n_\chi^{\text{today}}\ m_\chi \simeq \frac{T_0^3}{\langle \sigma\, v\rangle\ 2K_g}$$

$$\rho_c = 3\, H_0^2/(8\pi G)$$

$$\Omega_\chi \simeq \left(\frac{16\,\pi^{5/2}}{9\,\sqrt{\pi}}\right)\ \frac{G^{3/2}\ T_0^3}{H_0^2\ (\hbar c)^{3/2}\ c^3}\ \frac{\sqrt{g_{\text{eff}}}}{\langle \sigma\, v\rangle}$$

$$\Omega_\chi^{\text{analytic}} = 0.173\ \left(\frac{3\times 10^{-26}\ \text{cm}^3\,\text{s}^{-1}}{\langle \sigma\, v\rangle_{\text{f}}}\right)\ \sqrt{\frac{g_{\text{eff}}}{106.75}}$$

$$\Omega_j^0 \simeq 0.3 \left[\frac{3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma\, v \rangle} \right]$$

The "relic density" of a particle
is determined by its annihilation cross section

(several complications are possible)

$$\sigma(\chi\chi \to \mathrm{anything}) \simeq 10^{-36}\ \mathrm{cm}^2$$

$$\sigma \simeq \frac{\alpha^2}{M^2}\,(\hbar\, c)^2$$

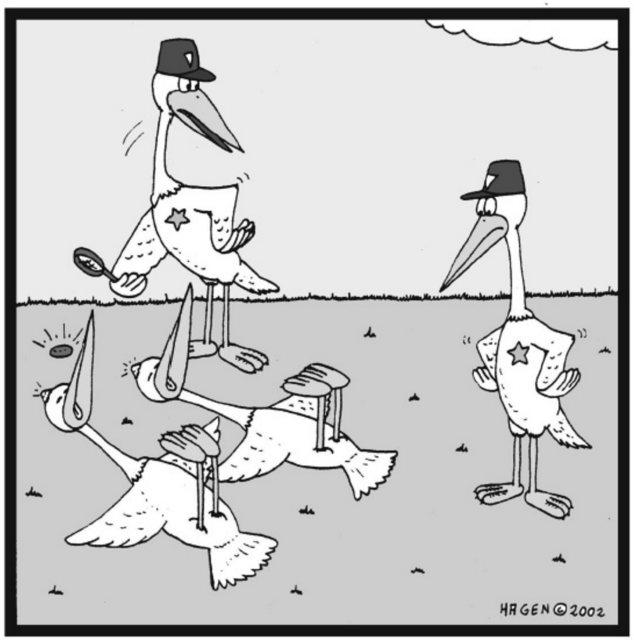
Weak interaction mass scale

$$M \simeq 200\ \mathrm{GeV}$$

Weakly Interacting Massive Particles (WIMP's)

the WIMP's "miracle"

"Killing two birds with a single stone"



Unbelievable! It looks like they've both been killed by the same stone...

Dark Matter Puzzle

Direct observational problem

Theories Beyond the Standard Model
(in particular Supersymmetry)
predict new particles that have
the right properties to form the DM

"Theoretical" motivation

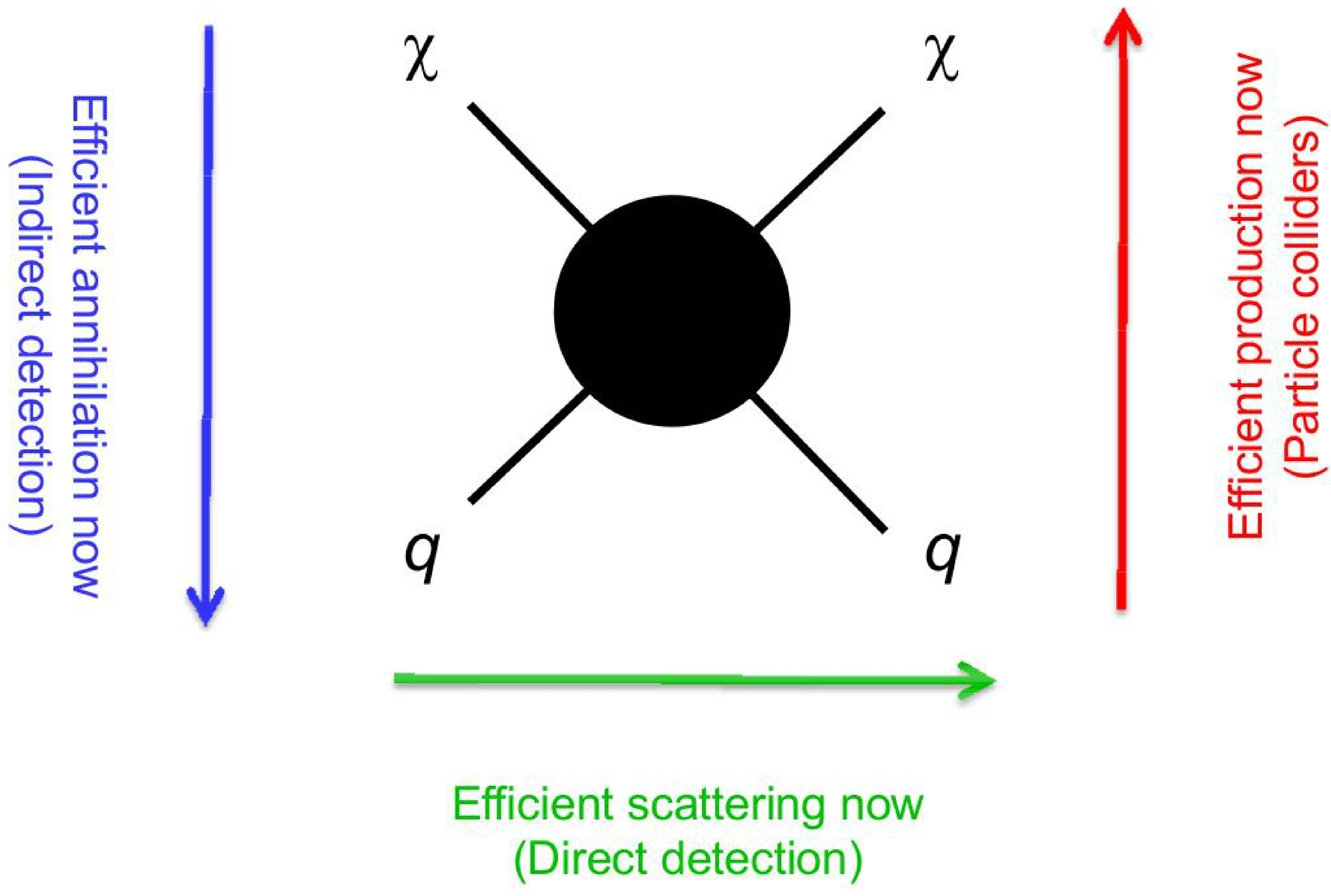
	Standard Model fields	Super-symmetric extension	
fermions	quarks	Squarks	New bosons (scalar) spin 0 S....
	leptons	Sleptons	
	neutrinos	Sneutrinos	
bosons	photon	photino	New fermions spin 1/2 ...ino
	W	Wino	
	Z	Zino	
	gluons	gluinos	
	Higgs	Higgsino	
2 Higgs →	H h	$\tilde{H}$ $\tilde{h}$	

Weak (~100 GeV) Mass scale ?

one stable new particle (R-parity conserved)

$$|\chi\rangle = c_1\ |\tilde{\gamma}\rangle + c_2\ |\tilde{z}\rangle + c_3\ |\tilde{H}\rangle + c_4\ |\tilde{h}\rangle$$

Three roads to the DM (WIMP) discovery



$$\chi + \chi \rightarrow q + \overline{q}$$

Annihilation

$$q + \overline{q} \rightarrow \chi + \chi$$

Creation

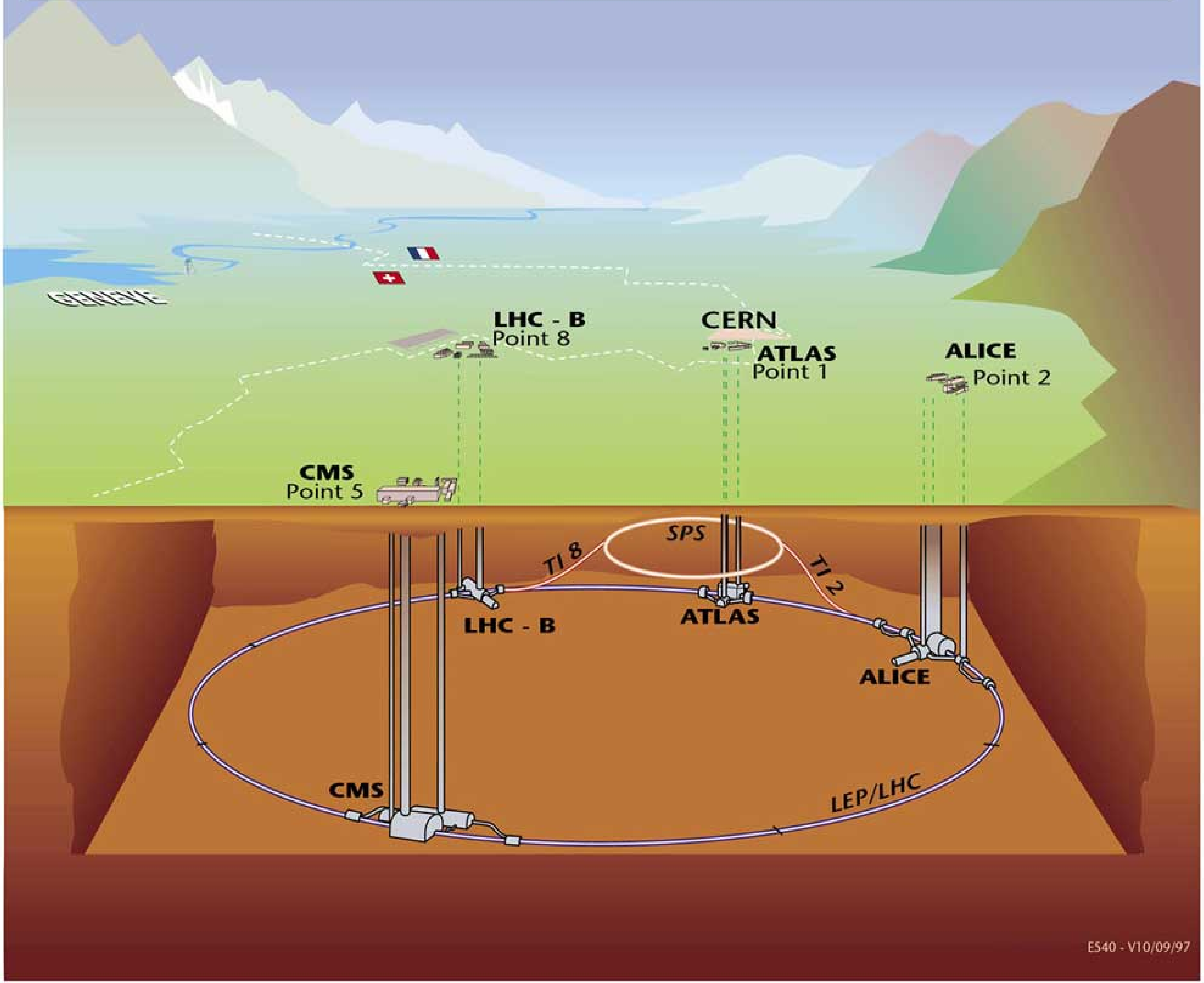
Time reversal

$$\chi + q \rightarrow \chi + q$$

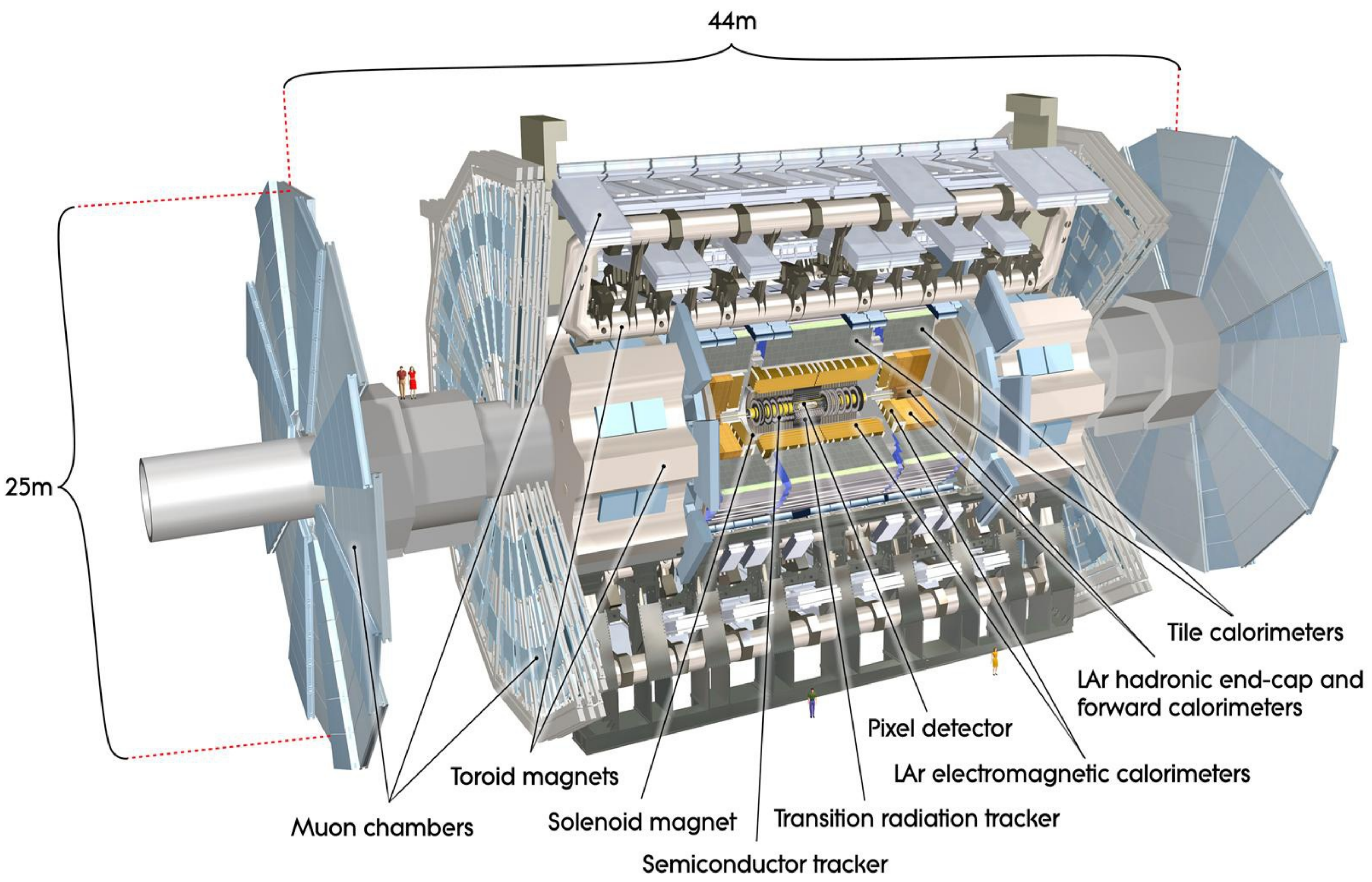
Elastic

Crossing symmetry

Overall view of the LHC experiments.

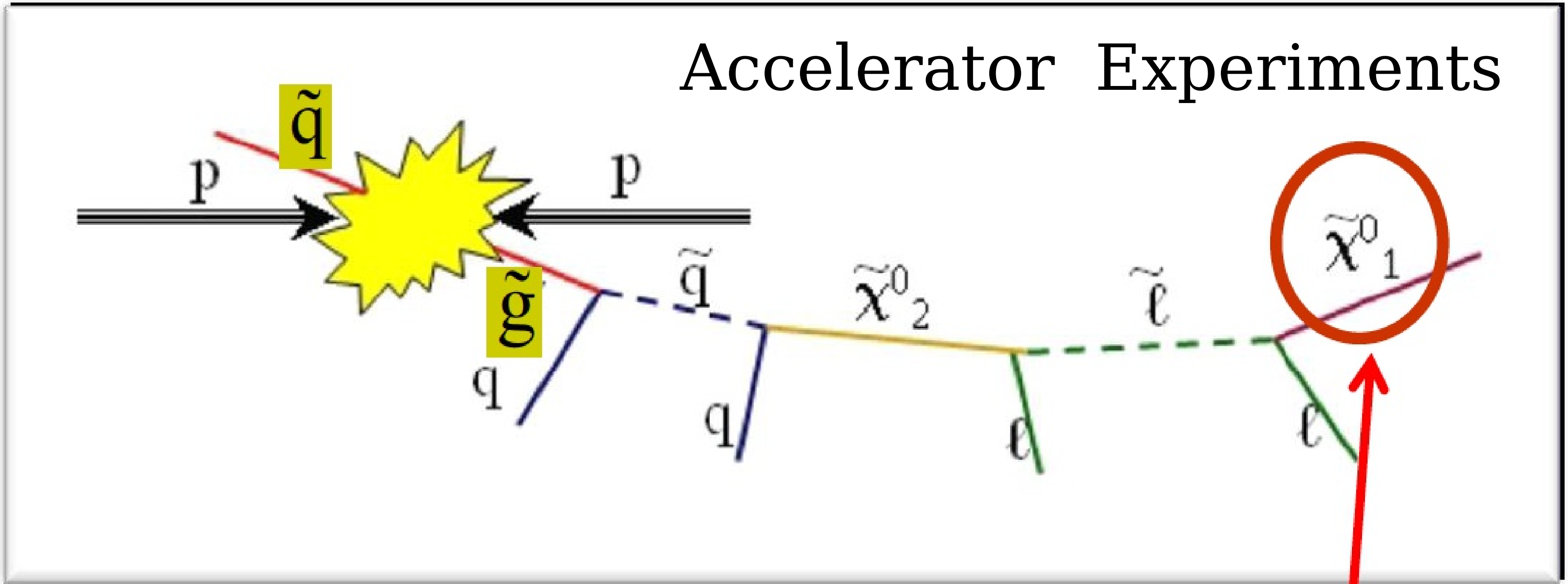


ATLAS detector at LHC

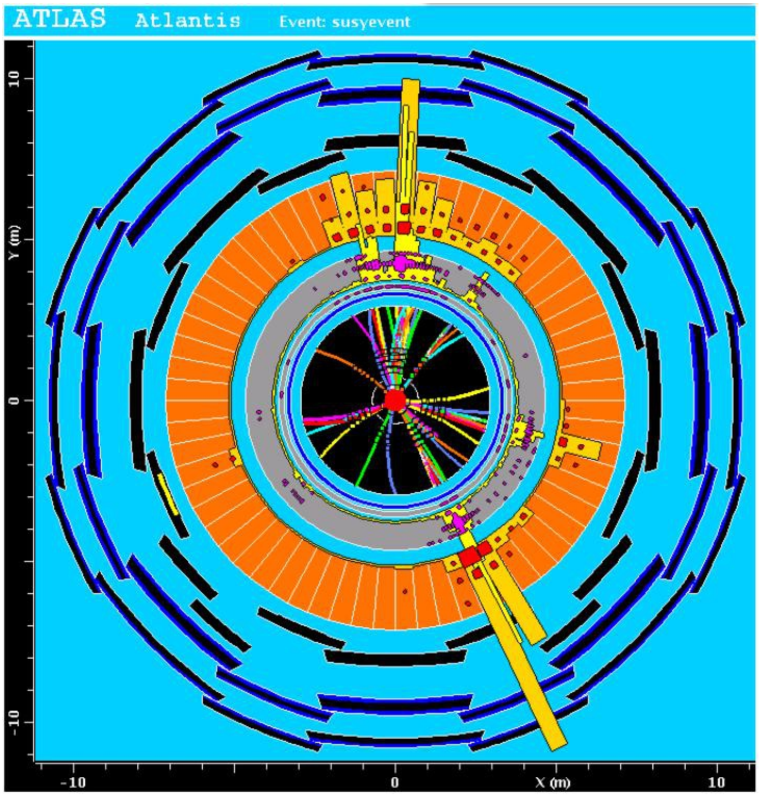


How do you see a Dark Matter (therefore invisible) particle ?

Accelerator Experiments



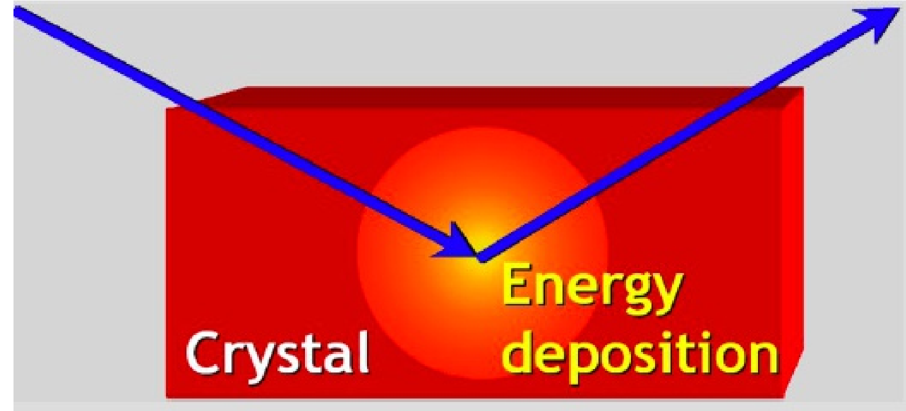
Lowest mass,
stable,
(super-symmetric)
Particle [LSP]



This particle interacts WEAKLY therefore (effectively always) traverse the detector invisibly.

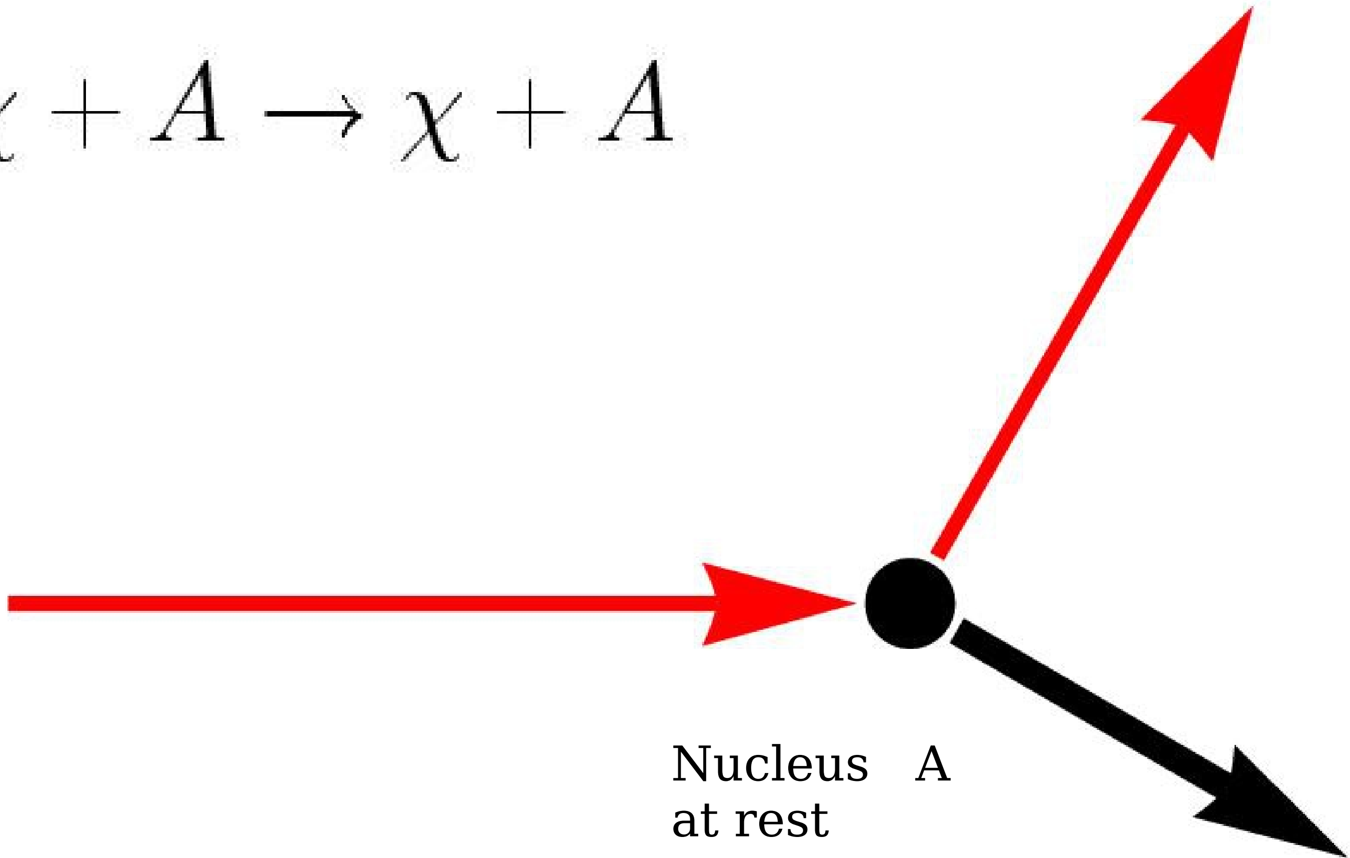
Detection via 4-momentum conservation ["Missing energy and (transverse) momentum"]

“Direct” Search
for Dark Matter



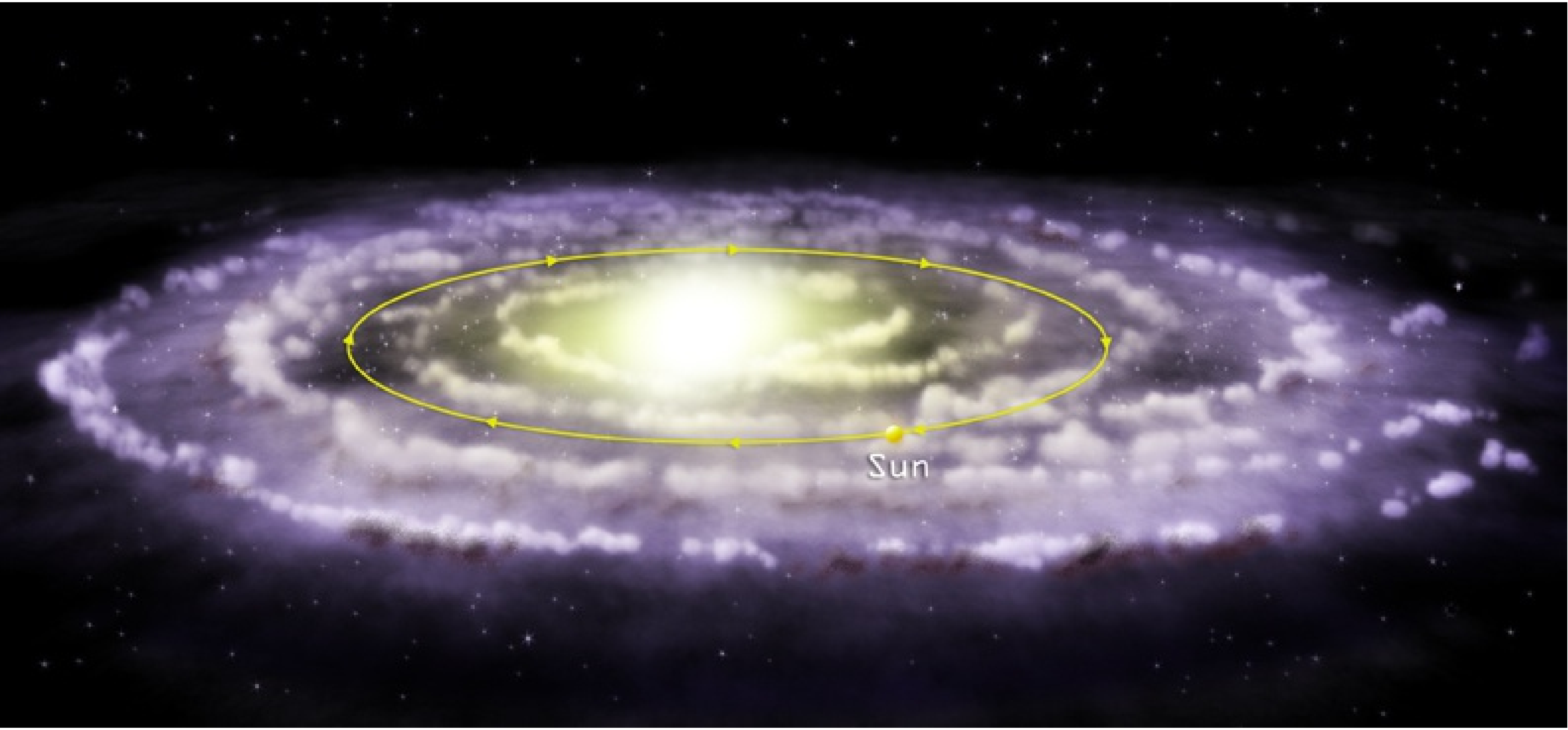
Elastic scattering

$$\chi + A \rightarrow \chi + A$$

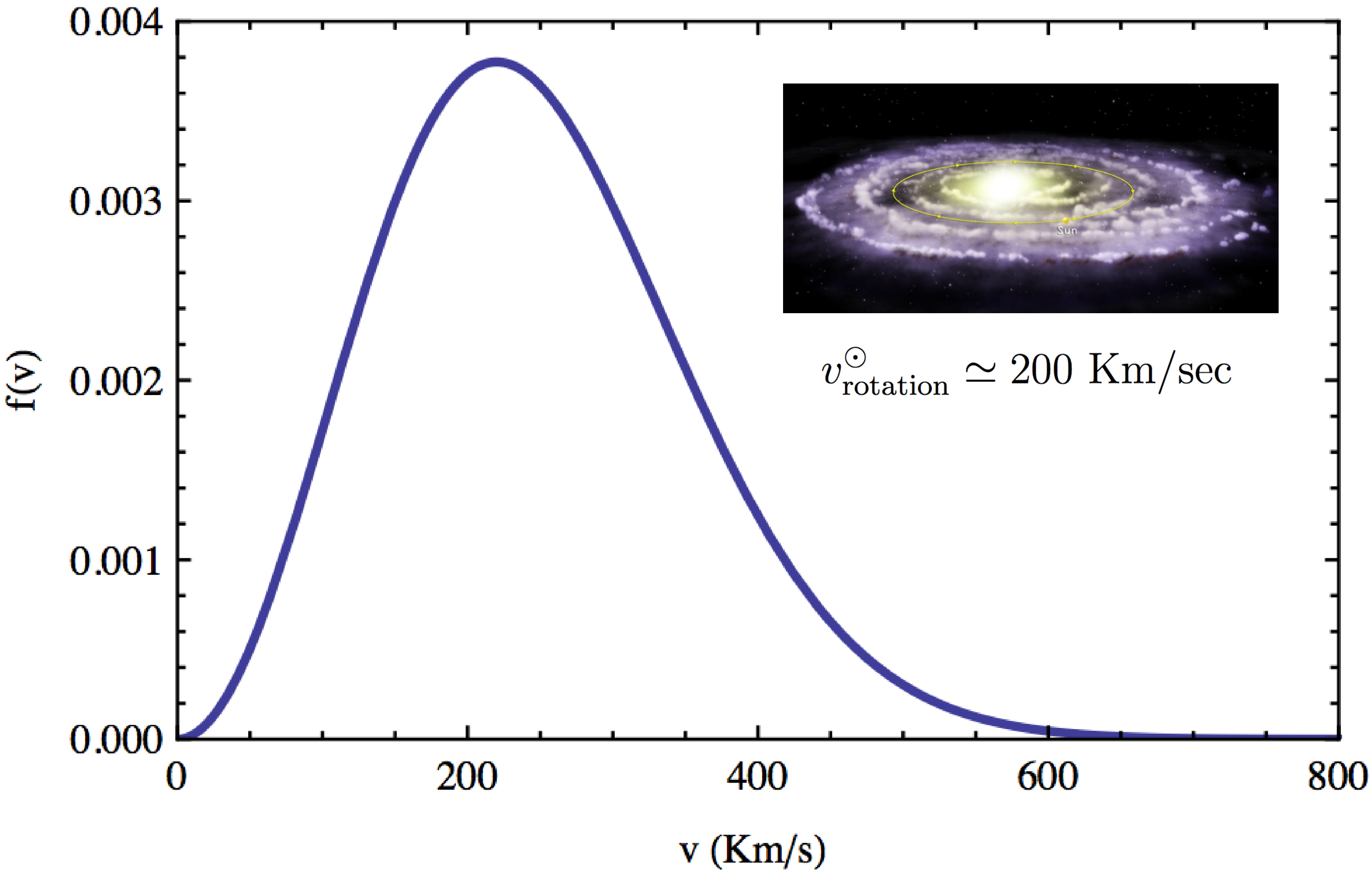


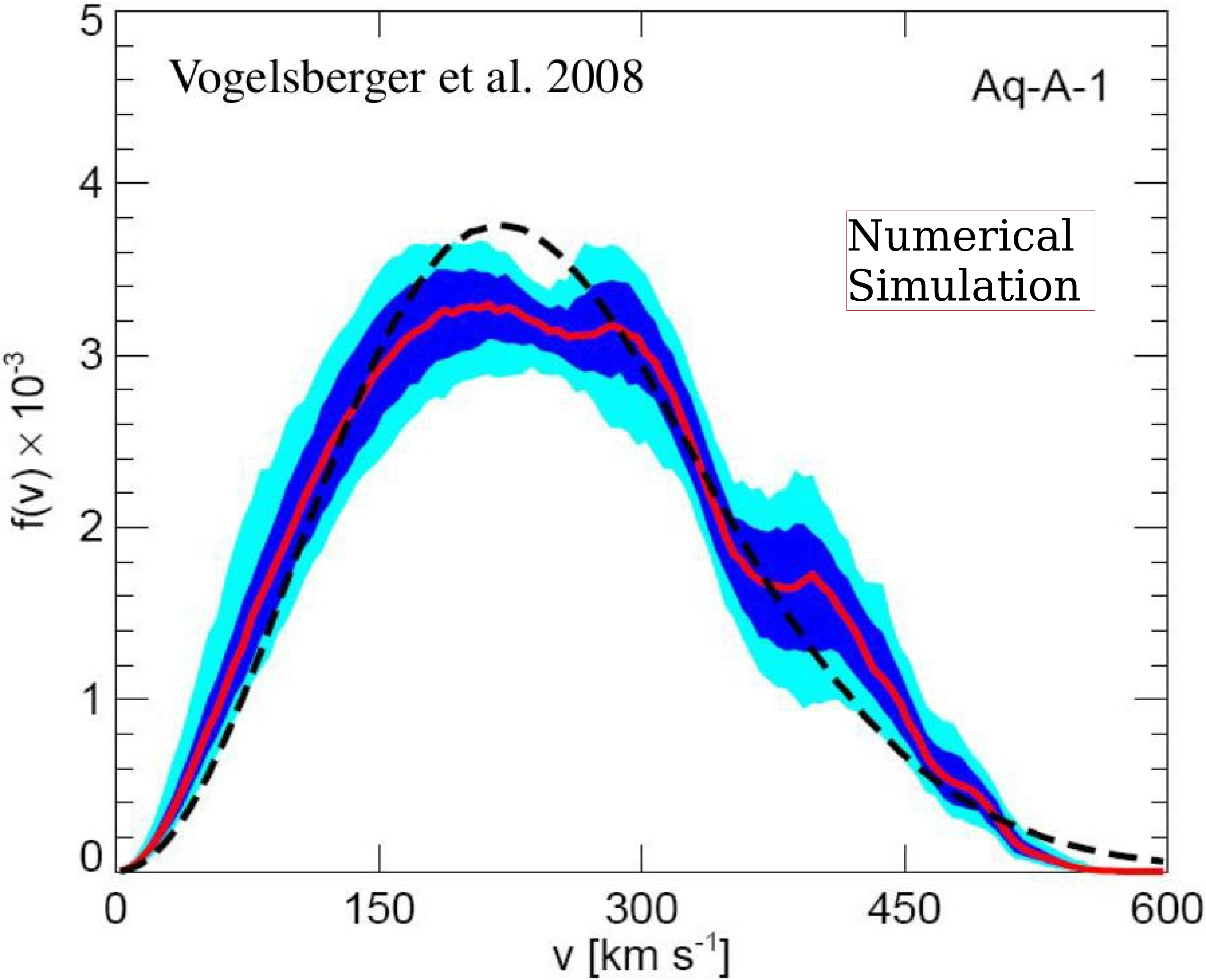
SUN – rotation around the galactic center.

$$v^{\odot}_{\text{rotation}} \simeq 200\ \text{Km/sec}$$

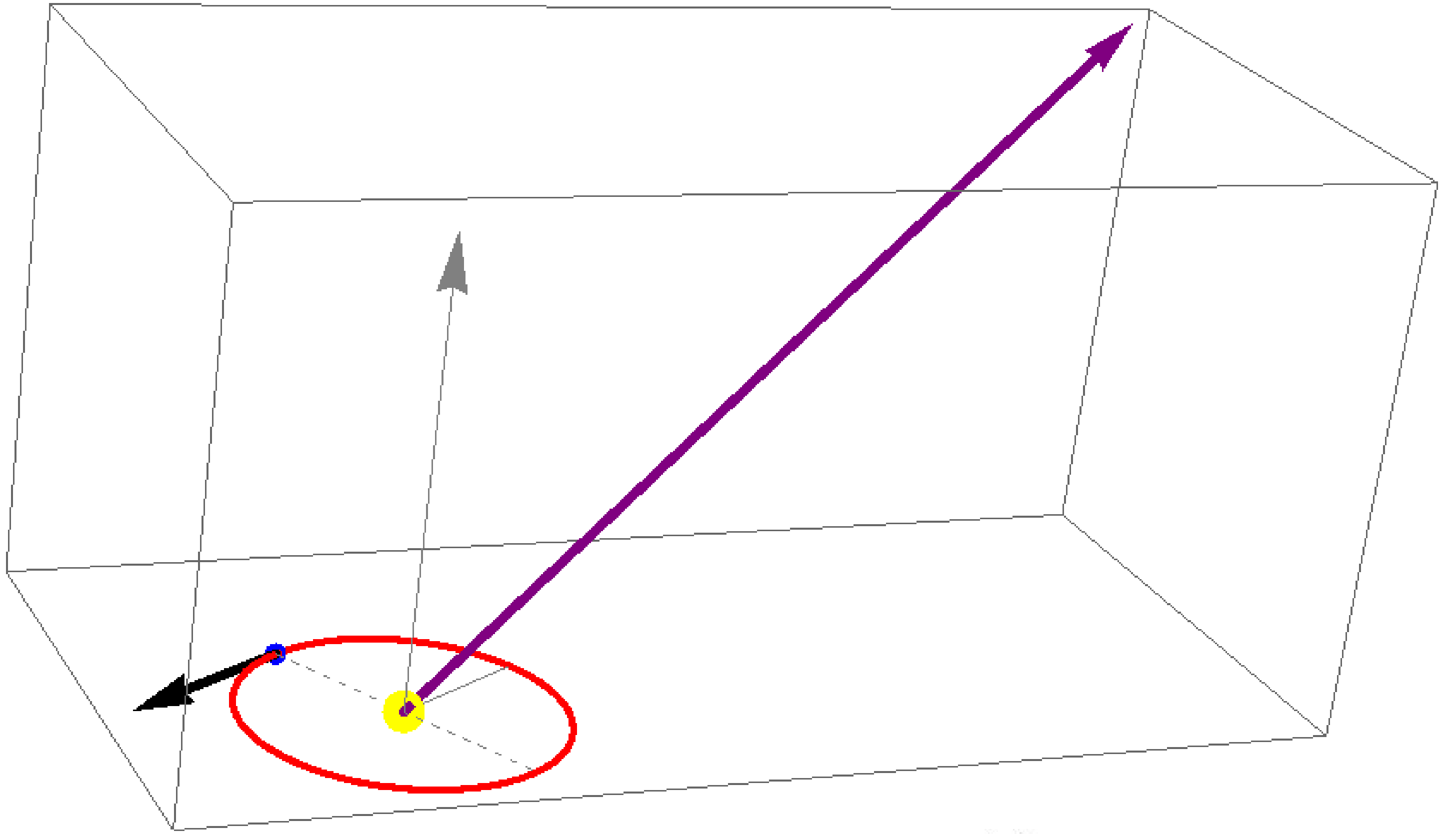


Predicted velocity distribution of DM particles
In the "Halo Frame"
Maxwellian form $\langle v_{\rm wimp} \rangle \simeq 250$ km/sec





Vogelsberger et al. 2008
Aq-A-1
Numerical Simulation
5
4
3
2
1
0
f(v) × 10^-3
0
150
300
450
600
v [km s^-1]



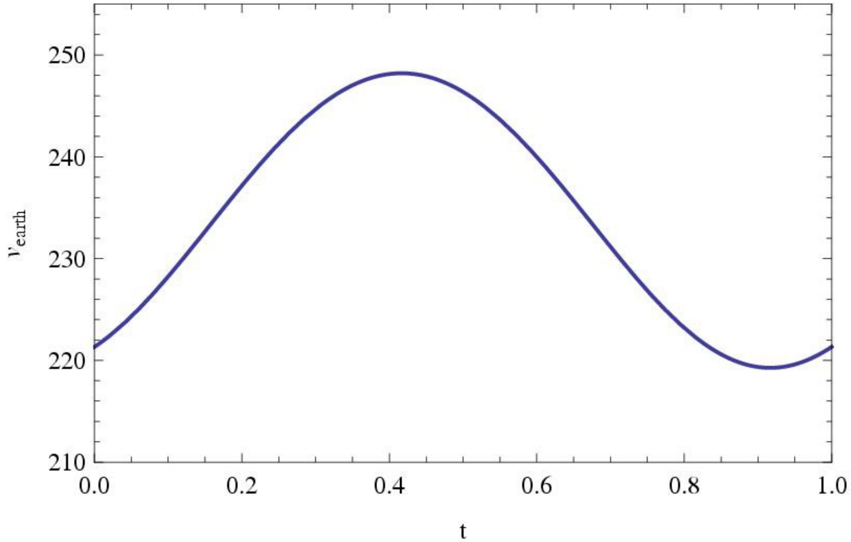
$$w_\oplus(t) \simeq w_\odot + \sin\gamma \; v_{\rm orbit} \;\; \cos[\omega(t-t_0)]$$

$$\vec{w}_\oplus(t) = \vec{w}_\odot + \vec{v}_{\rm orbit}(t)$$

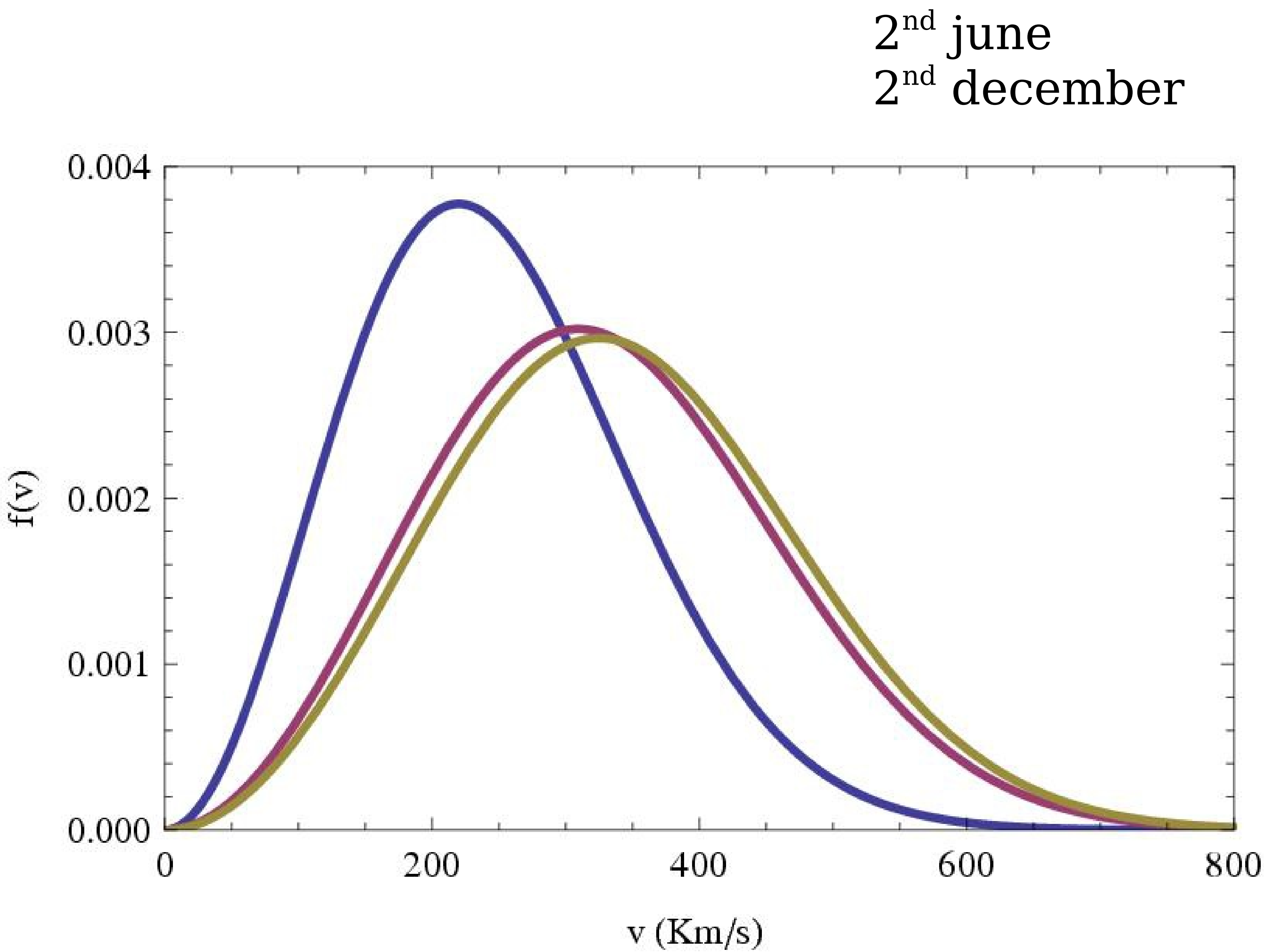
“Halo rest frame”

Velocity of Earth in the Halo rest frame

[Co-rotation ?]



Velocity distribution in the Earth Framexs



Expected flux of Dark Matter particles (here !) :

$$\phi_\chi = \frac{\rho_\chi}{m_\chi} \langle v_\chi \rangle$$

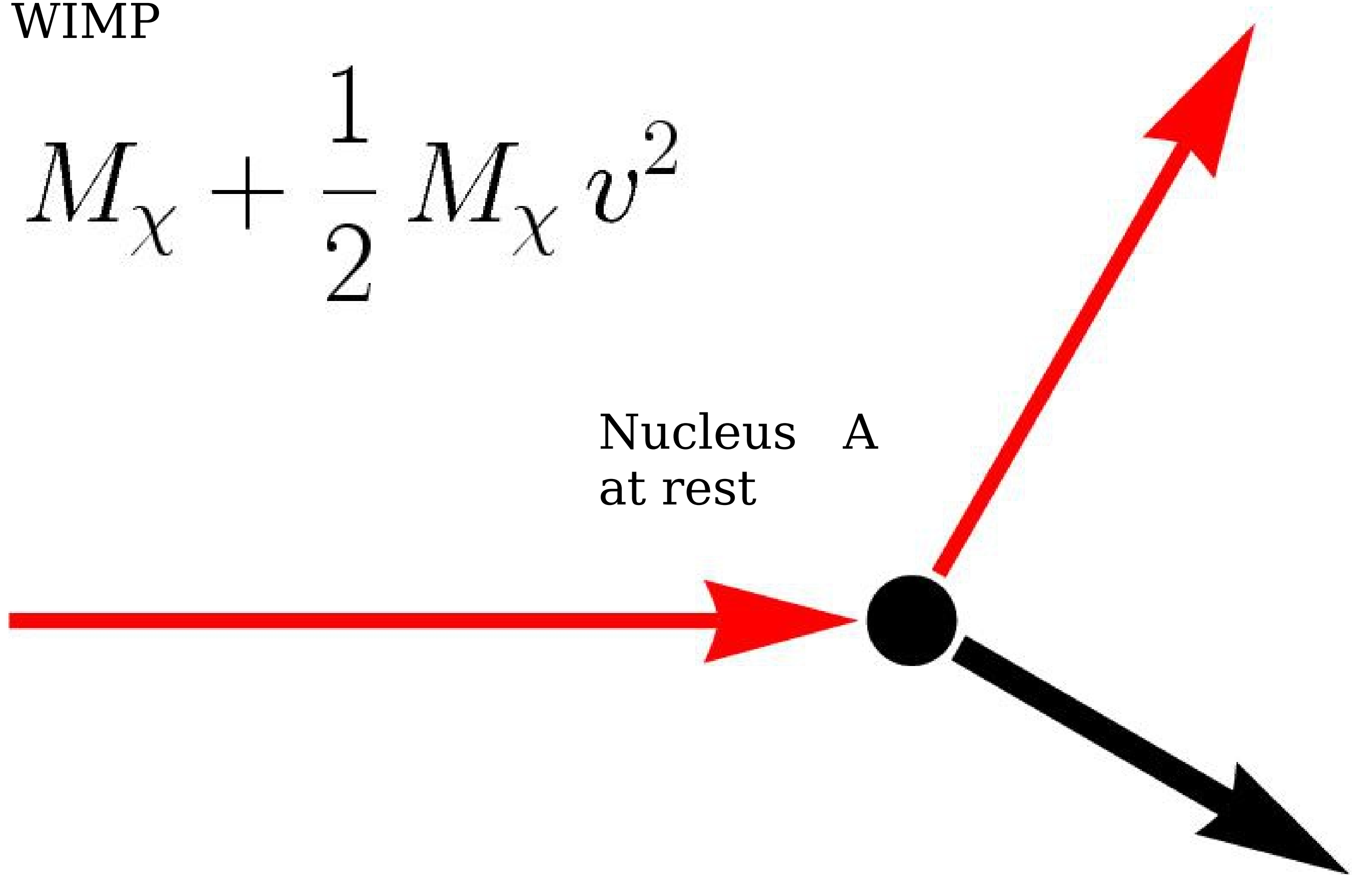
$$\simeq 1000 \left[\frac{100\ \mathrm{GeV}}{m_\chi}\right] \quad (\mathrm{cm}^2\ \mathrm{s})^{-1}$$

“Direct” Search for Dark Matter

$$\chi + A \rightarrow \chi + A$$

Non relativistic WIMP

$$E_{\rm wimp} \simeq M_\chi + \frac{1}{2} M_\chi v^2$$

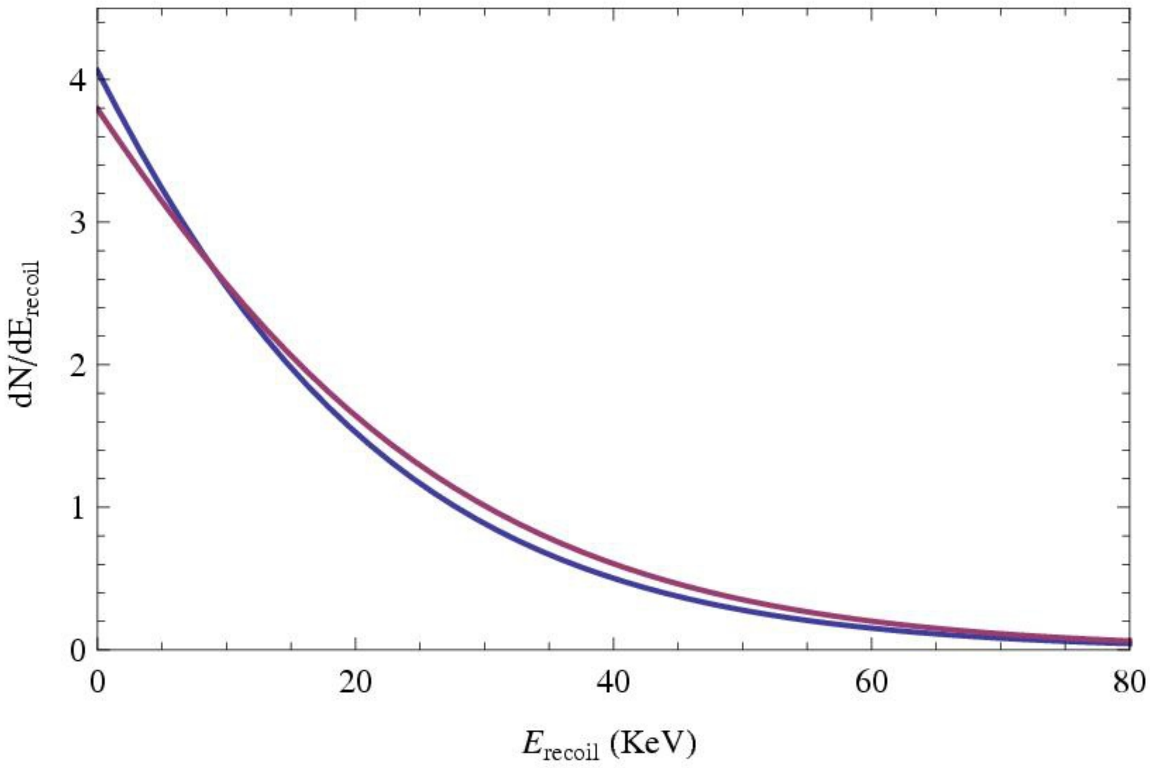


$$E_{\rm nucleus} = M_A + \left[\frac{1}{2} M_\chi v^2\right] \frac{4 M_A M_\chi}{(M_A + M_\chi)^2} \left(\frac{1 - \cos\theta^*}{2}\right)$$

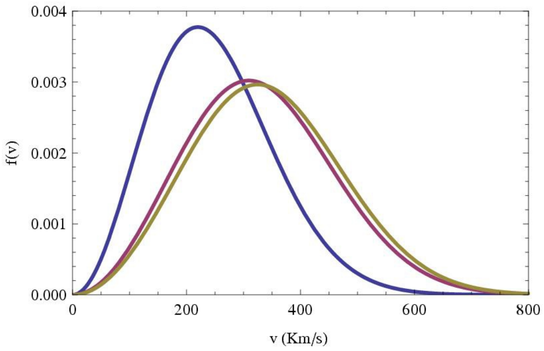
A = 127 (Iodium)
M_{wimp} = 50 GeV

Scattering RATE

Quasi exponential distribution



2nd june
2nd december



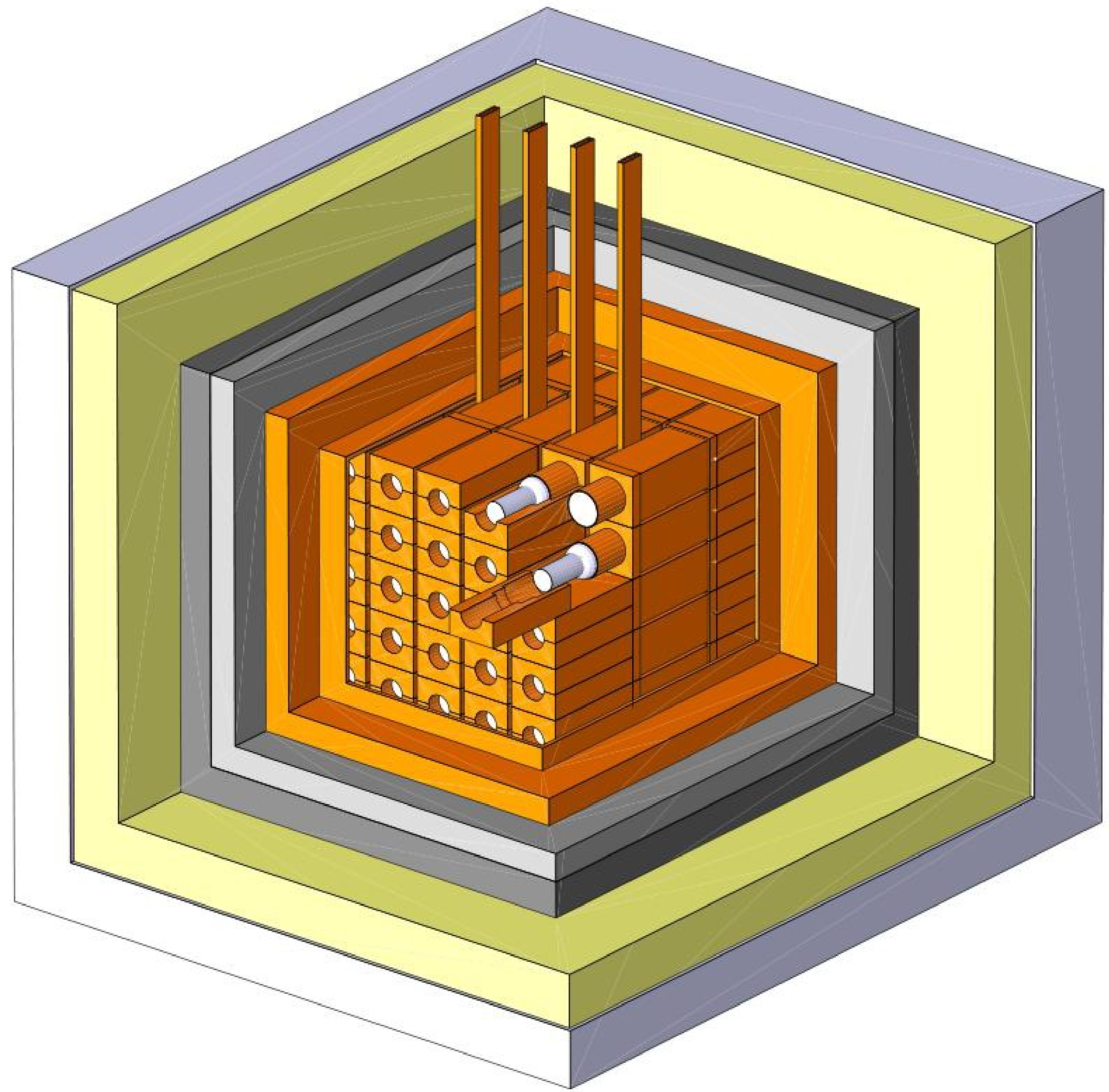
$$\frac{dR}{dE_{\rm recoil}}(E_{\rm recoil}, t) = R_0(E_{\rm recoil}) + A(E_{\rm recoil})\ f(t)$$

DAMA-LIBRA (Gran Sasso underground Laboratory)

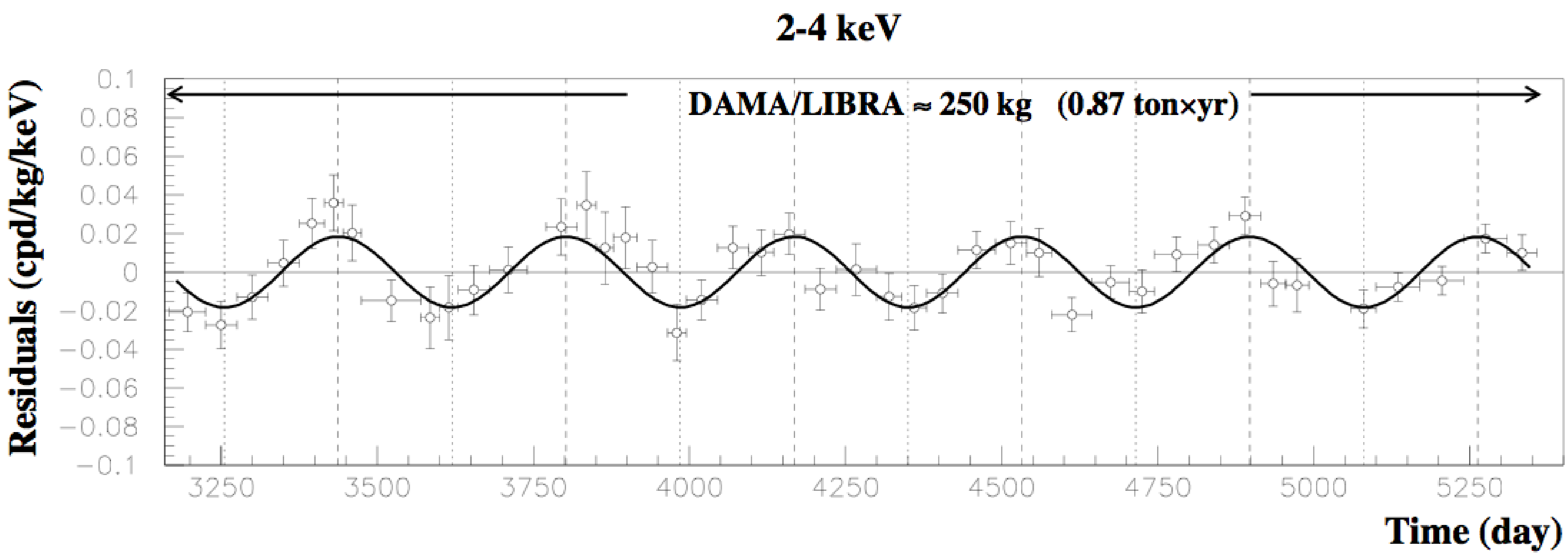
250 Kg NaI scintillator.

Observation of sinusoidal time-modulation of the Energy Deposition Rate

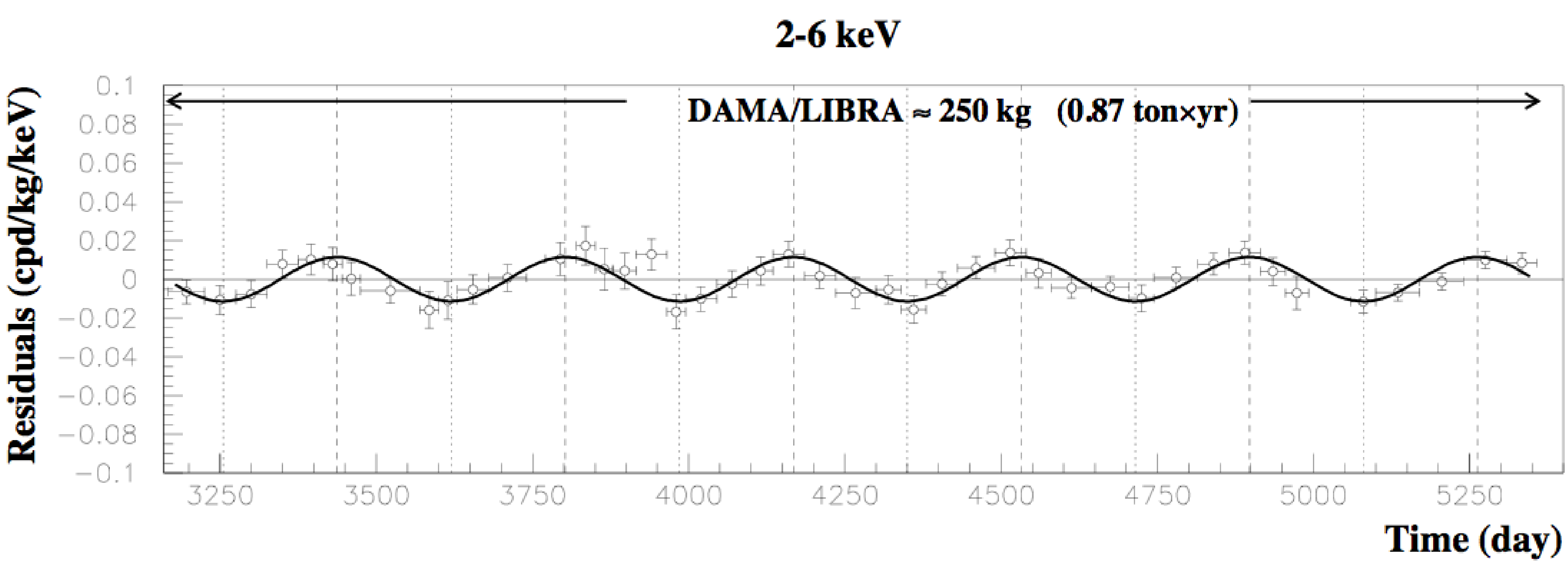
(controversial) claim of evidence of detection of Galactic Dark Matter



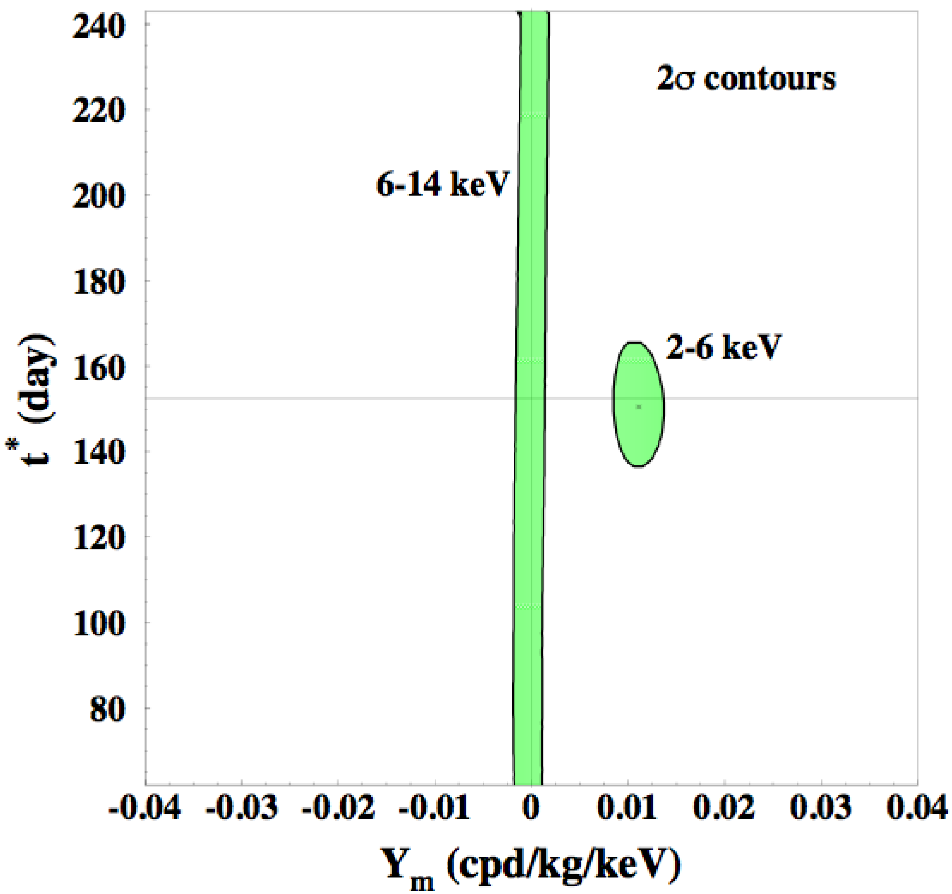
$$1.17 \text{ ton} \times \text{yr}$$



2-4 keV
DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)



2-6 keV
DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)



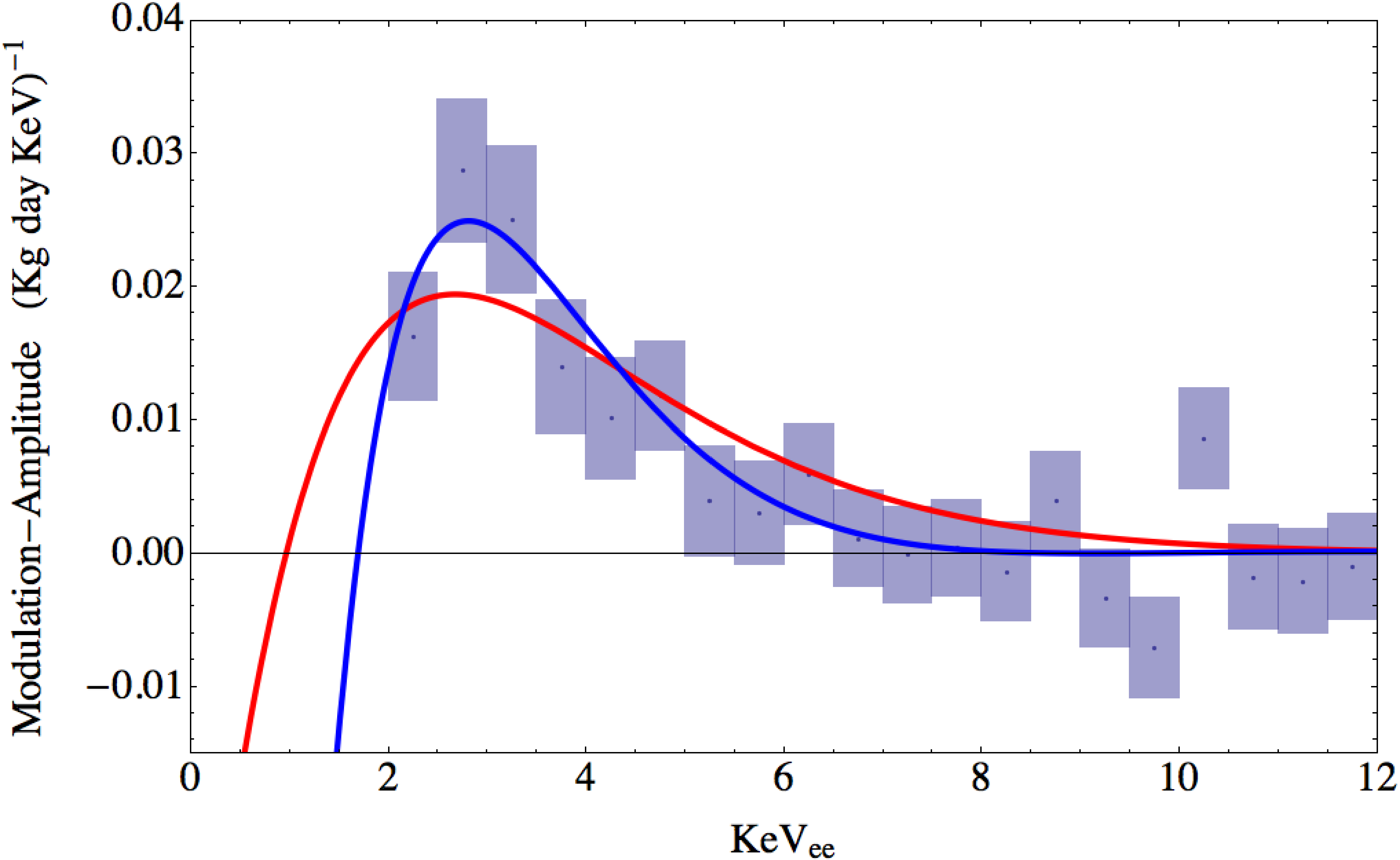
Period one year.
(... well obvious...)

"Phase"
Is centered
At the "right" value (!)

Maximum
The 2nd june
day: (146 ± 7)

Fundamental discovery ?!

Unknown background
(with coincident phase) ?


Modulation−Amplitude (Kg day KeV)−1
0.04
0.03
0.02
0.01
0.00
−0.01
0
2
4
6
8
10
12
KeVee

First results from DAMA/LIBRA and the combined results with DAMA/NaI

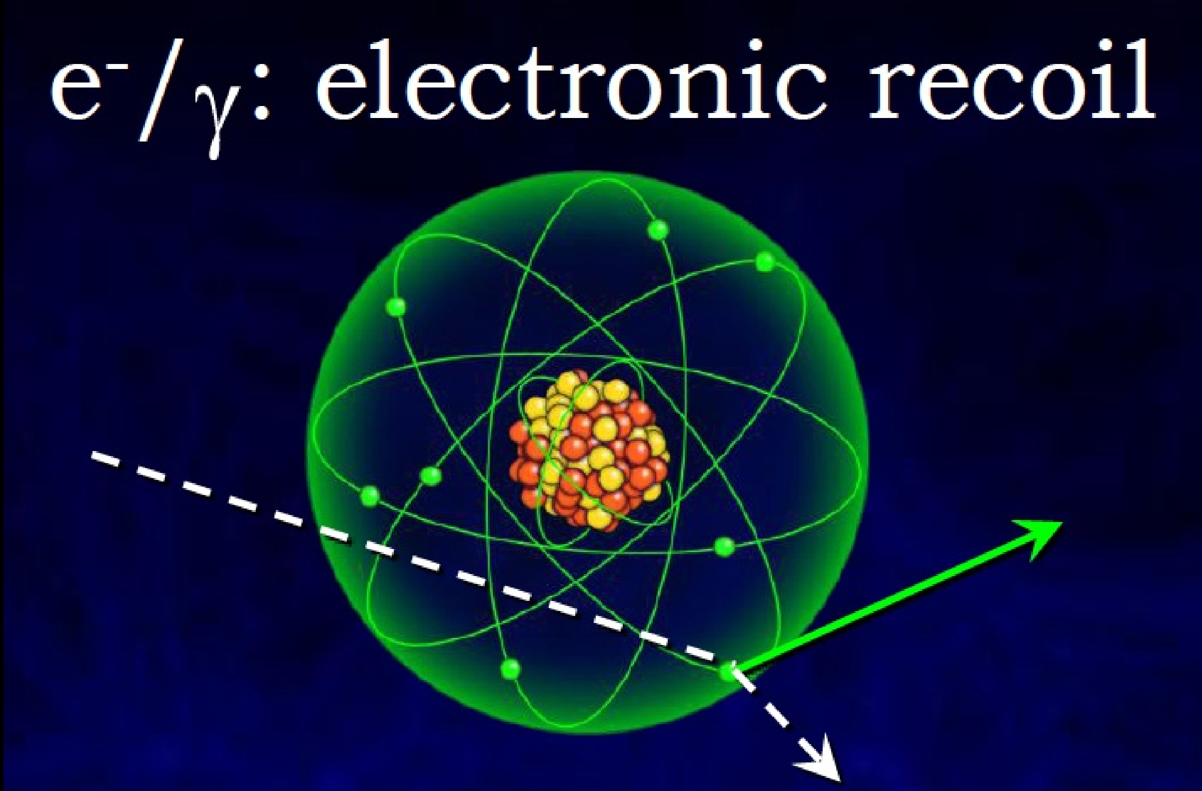
Abstract

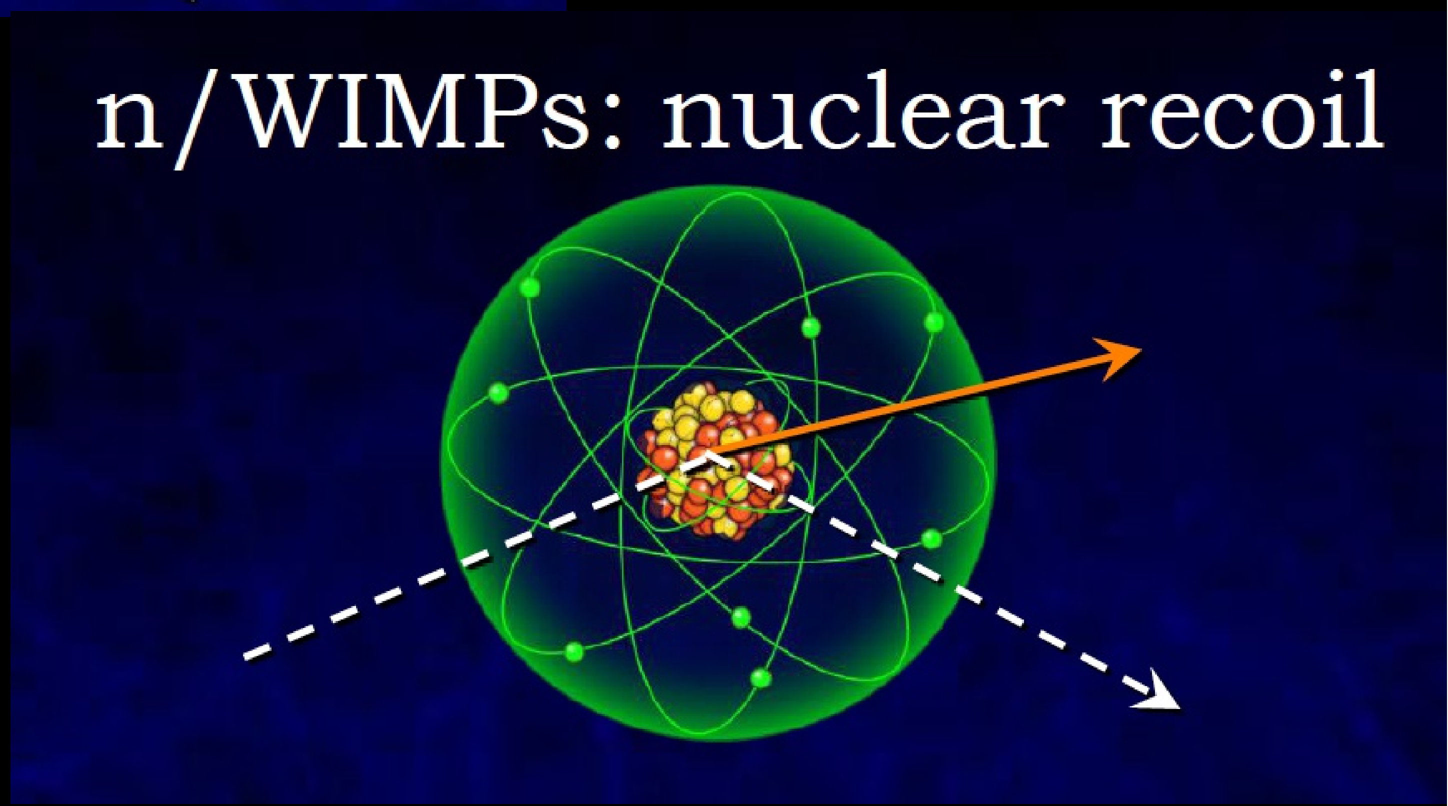
The highly radiopure $\simeq$ 250 kg NaI(Tl) DAMA/LIBRA set-up is running at the Gran Sasso National Laboratory of the I.N.F.N.. In this paper the first result obtained by exploiting the model independent annual modulation signature for Dark Matter (DM) particles is presented. It refers to an exposure of 0.53 ton$\times$yr. The collected DAMA/LIBRA data satisfy all the many peculiarities of the DM annual modulation signature. Neither systematic effects nor side reactions can account for the observed modulation amplitude and contemporaneously satisfy all the several requirements of this DM signature. Thus, the presence of Dark Matter particles in the galactic halo is supported also by DAMA/LIBRA and, considering the former DAMA/NaI and the present DAMA/LIBRA data all together (total exposure 0.82 ton$\times$yr), the presence of Dark Matter particles in the galactic halo is supported at 8.2 σ C.L..

New results from DAMA/LIBRA

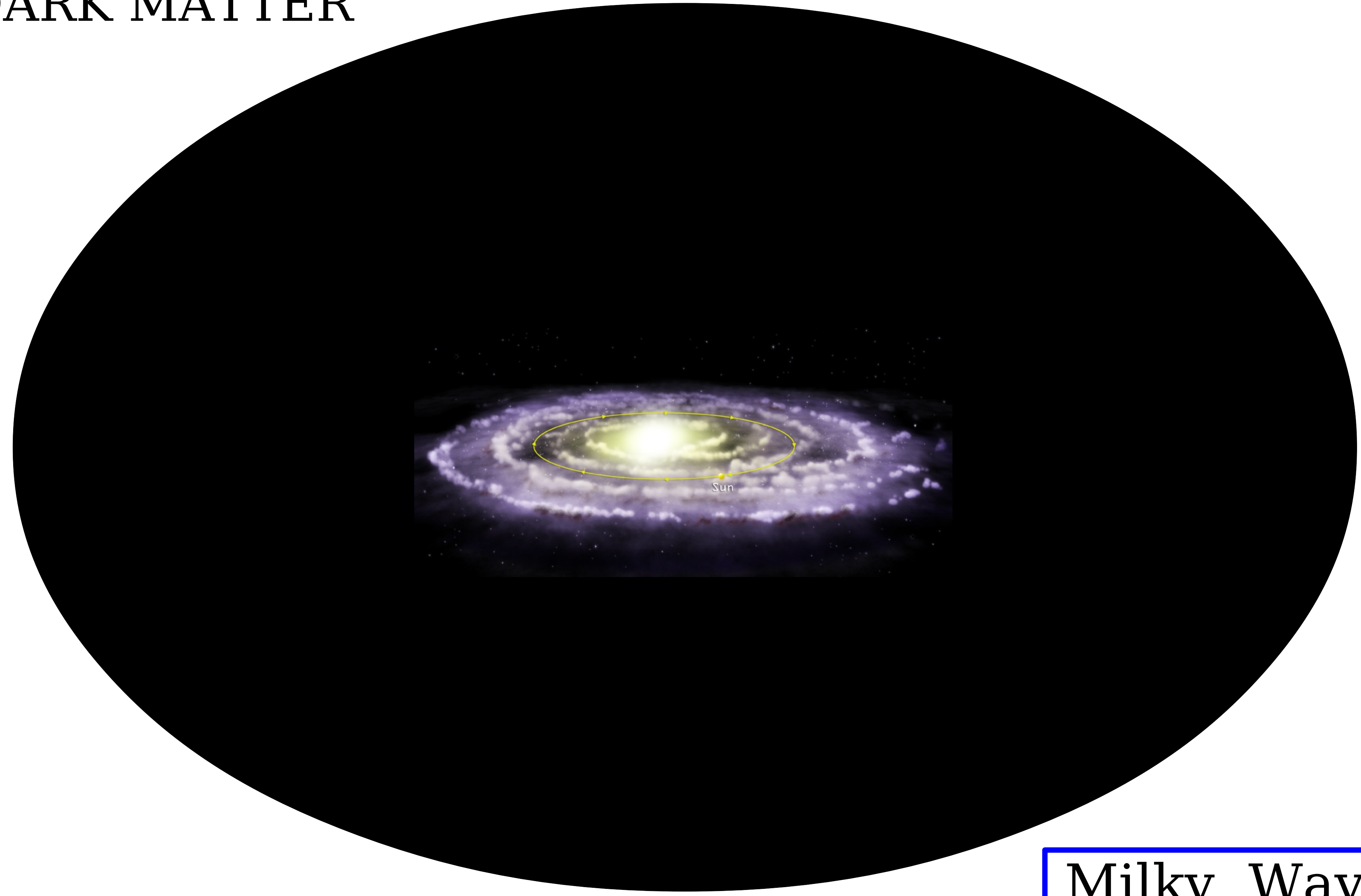
Abstract

DAMA/LIBRA is running at the Gran Sasso National Laboratory of the I.N.F.N.. Here the results obtained with a further exposure of 0.34 ton $\times$ yr are presented. They refer to two further annual cycles collected one before and one after the first DAMA/LIBRA upgrade occurred on September/October 2008. The cumulative exposure with those previously released by the former DAMA/NaI and by DAMA/LIBRA is now 1.17 ton $\times$ yr, corresponding to 13 annual cycles. The data further confirm the model independent evidence of the presence of Dark Matter (DM) particles in the galactic halo on the basis of the DM annual modulation signature (8.9 σ C.L. for the cumulative exposure). In particular, with the cumulative exposure the modulation amplitude of the *single-hit* events in the $(2-6)$ keV energy interval measured in NaI(Tl) target is (0.0116 ± 0.0013) cpd/kg/keV; the measured phase is (146 ± 7) days and the measured period is (0.999 ± 0.002) yr, values well in agreement with those expected for the DM particles.


e^-/γ: electronic recoil


n/WIMPs: nuclear recoil

Indirect searches for DARK MATTER



Milky Way
with DM halo

In the "WIMP paradigm" Dark Matter is NOT really dark

point in the Milky Way with dark matter mass density

$$\rho_\chi(\vec{x})$$

Number density of DM particles

$$n_\chi(\vec{x}) = \frac{\rho_\chi(\vec{x})}{m_\chi}$$

cosmology

Release of energy

$$(2\, m_\chi) \left[\frac{1}{2}\, n_\chi^2(\vec{x}) \langle \sigma\, v \rangle \right] d^3x\ dt$$

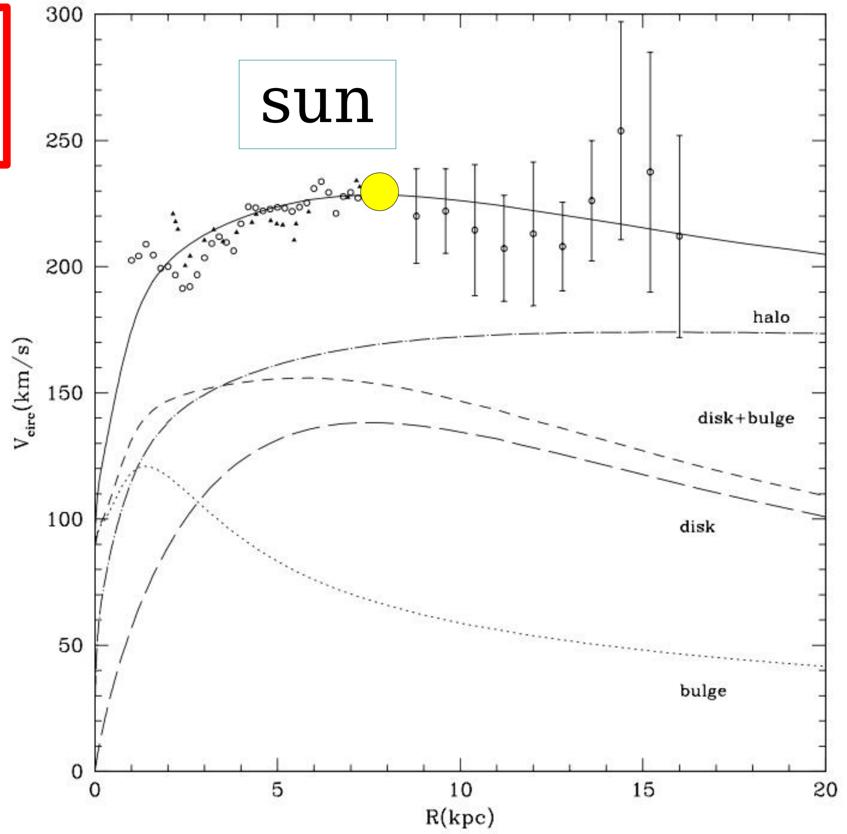
[assume here DM particle is of Majorana nature $\chi = \overline{\chi}$]

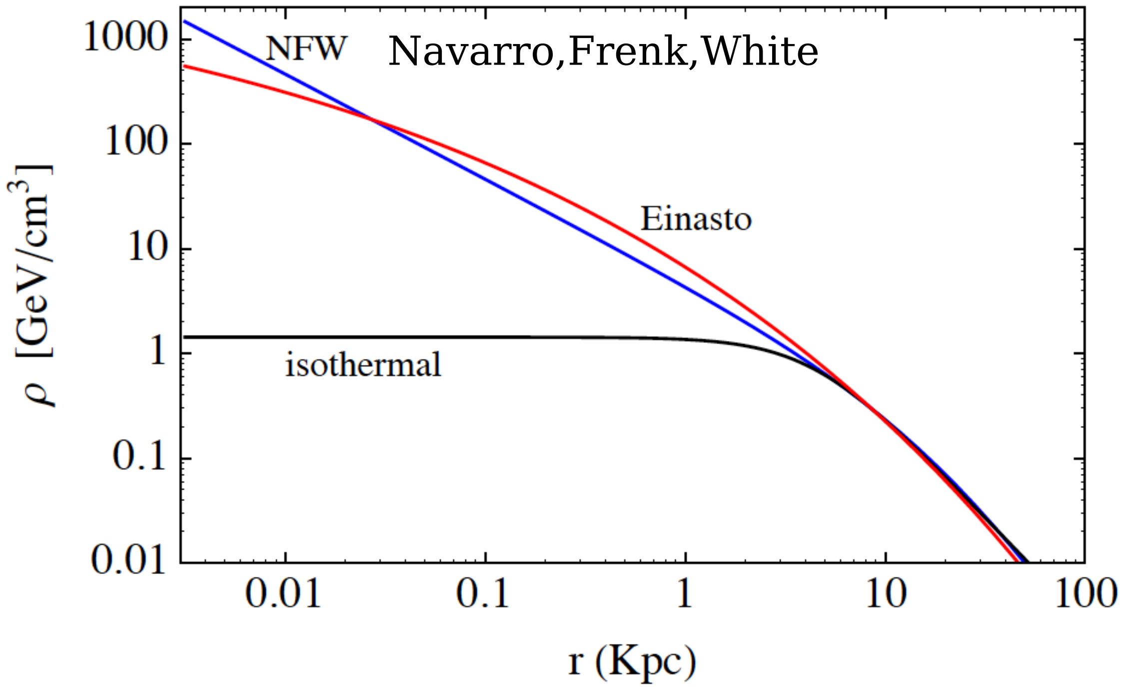
DM in the Milky Way

$$\rho_{\rm isothermal}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

$$\rho_{\rm Einasto}(r) = \rho_s \exp\{-(2/\alpha)[(r/r_s)^\alpha - 1]\}$$





Density distribution
determined by
Rotation velocity measurements

"Cusp" at GC
derived by N-body simulations

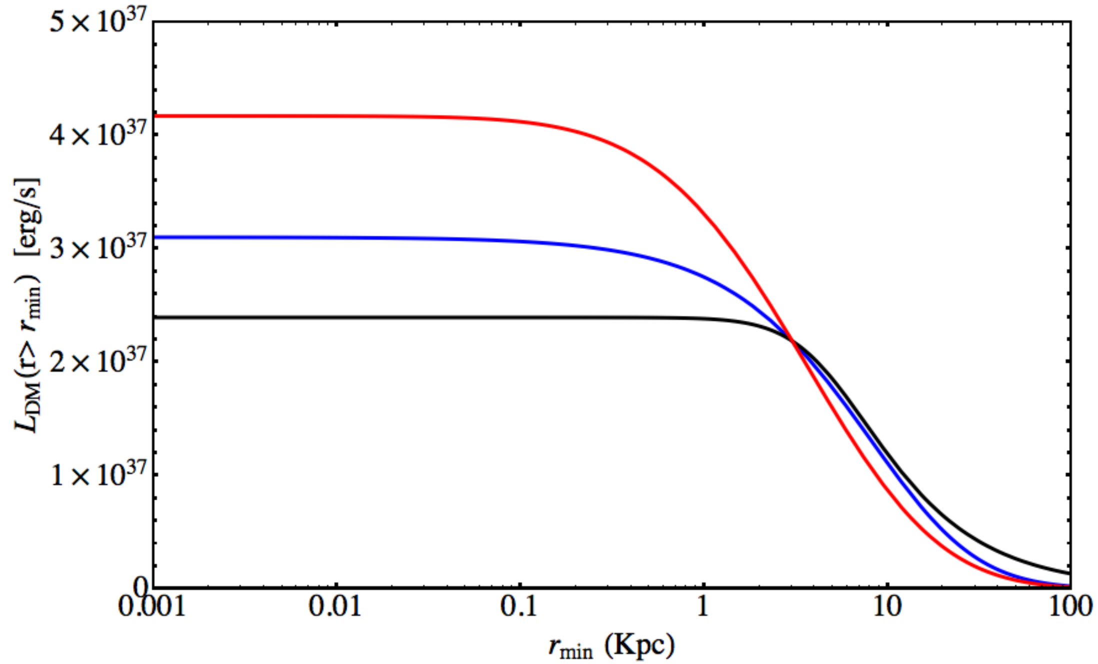
Power generated by DM annihilations in the Milky Way halo

$$L_{\rm DM} \simeq 3 \times 10^{37} \text{ erg s}^{-1} \left[\frac{\langle \sigma v \rangle}{3 \times 10^{-26}\ (\text{cm}^3\text{s})^{-1}}\right] \left[\frac{100 \text{ GeV}}{m_\chi}\right]$$

For comparison,
for Cosmic Ray protons

$$\frac{dL_{\rm DM}}{d^3x}(\vec{x}) = \frac{\rho^2(\vec{x})}{m_\chi} \langle \sigma v \rangle$$

$$L_p \simeq 10^{41} \frac{\text{erg}}{\text{s}}$$



small effect
of "Cusp" on
total luminosity

What is the final state of DM annihilations ?

... well we do not know, we have to build a model (for example supersymmetry).

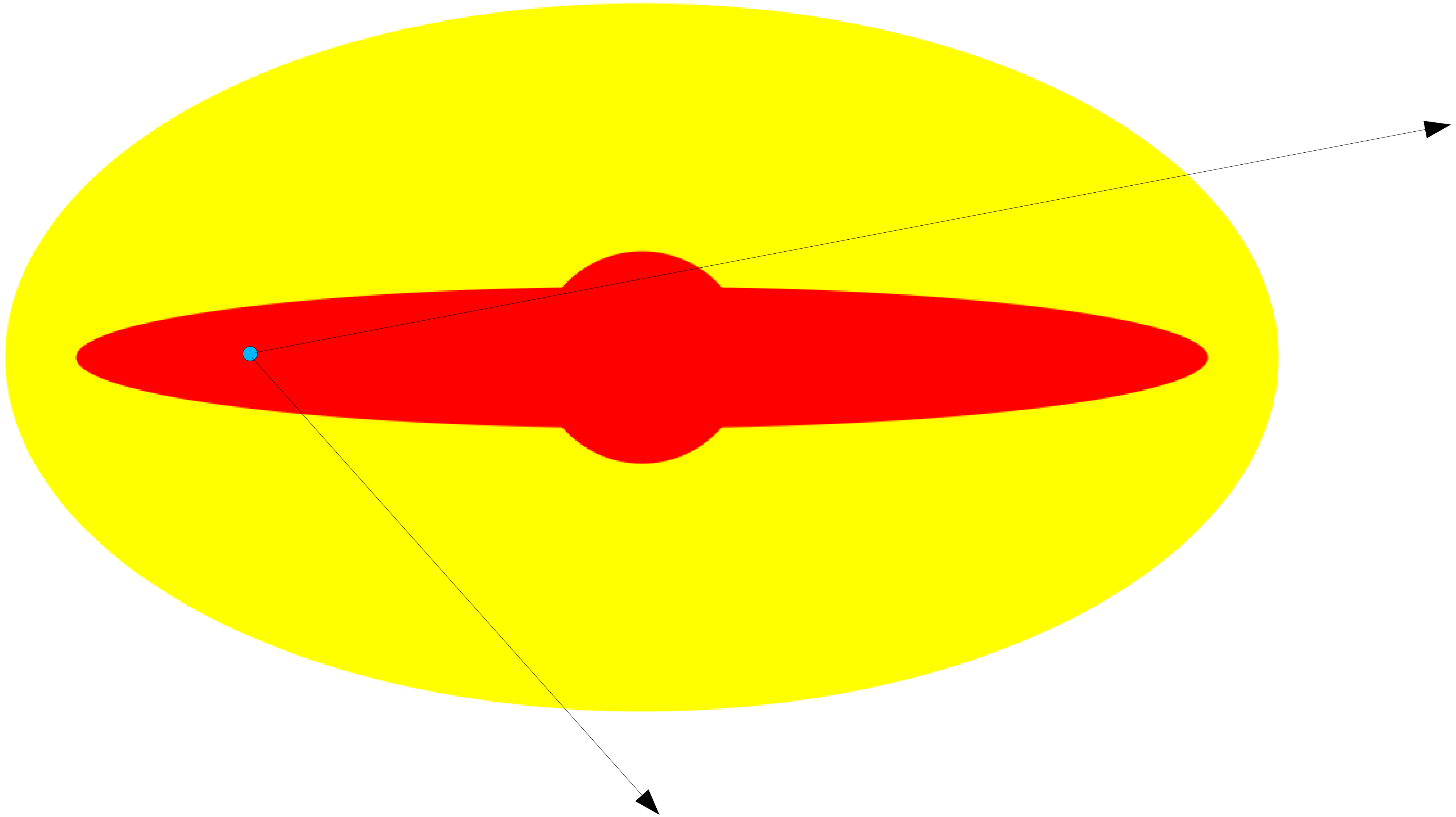
But it is plausible that the Dark Matter particle will (or could) produce all particles (and anti-particles) that we know.

Most promising for detection:

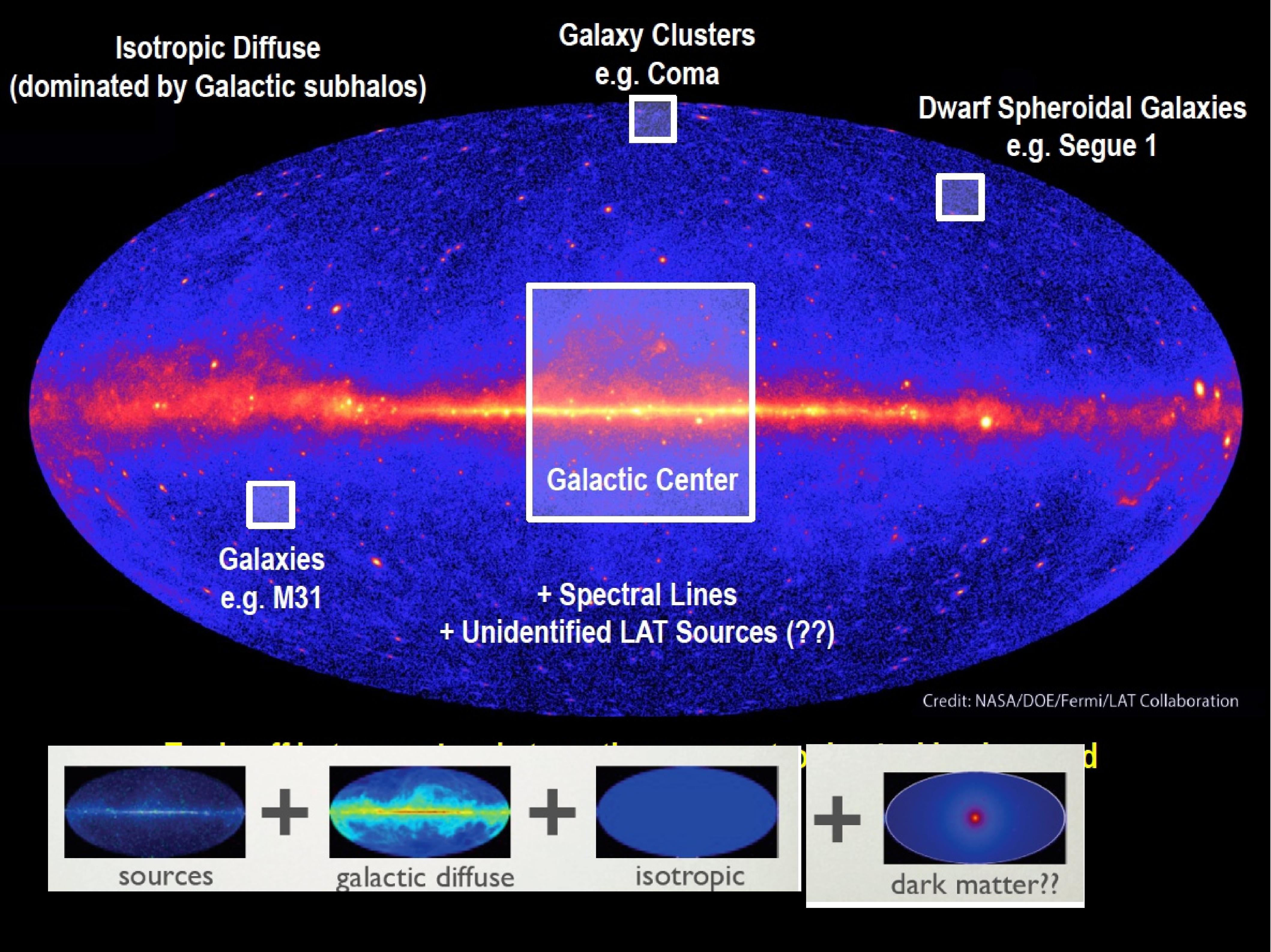
$$\chi + \chi \rightarrow \gamma \quad e^{+} \quad \bar{p} \quad \nu_{\alpha}$$

photons | Charged (anti)particles | Neutrinos

Photon emission from DM annihilation



$$\phi_\gamma(E_\gamma,\Omega) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \left(\int d\ell\, \rho^2(\ell,\Omega) \right) \left. \frac{dN_\gamma}{dE_\gamma} \right|_{\chi\chi\to\gamma}$$


Isotropic Diffuse
(dominated by Galactic subhalos)
Galaxy Clusters
e.g. Coma
Dwarf Spheroidal Galaxies
e.g. Segue 1
Galactic Center
Galaxies
e.g. M31
+ Spectral Lines
+ Unidentified LAT Sources (??)
Credit: NASA/DOE/Fermi/LAT Collaboration
sources
+
galactic diffuse
+
isotropic
+
dark matter??

No evidence for Dark Matter signal

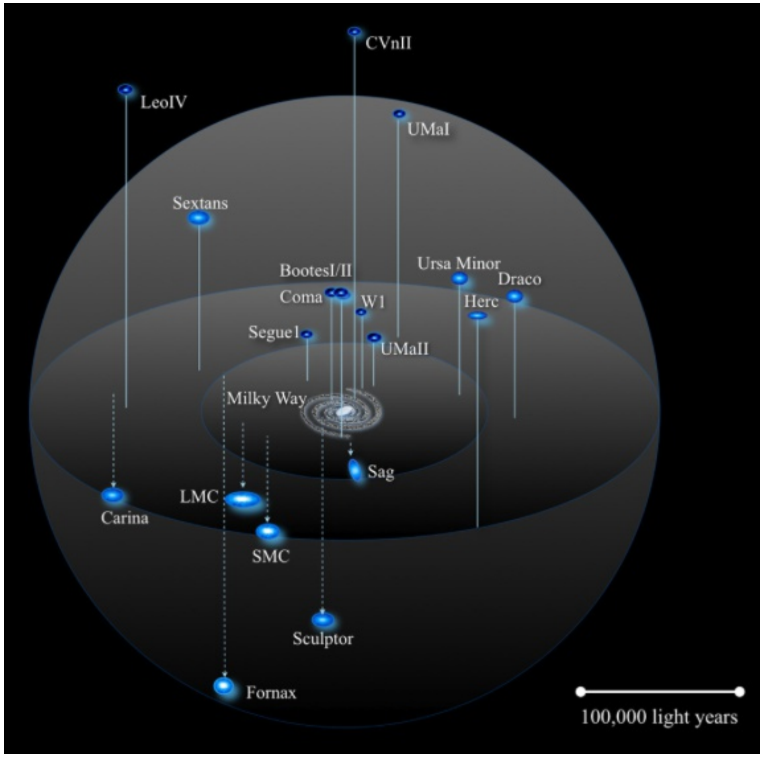
1. Galactic Center

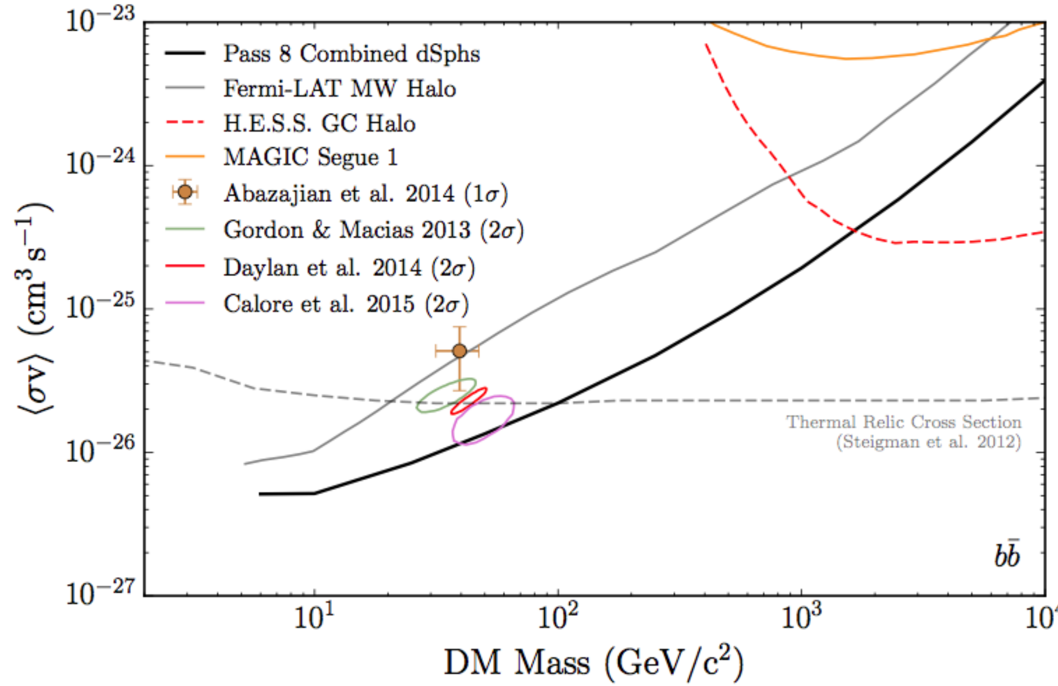
2. Dwarf Galaxies

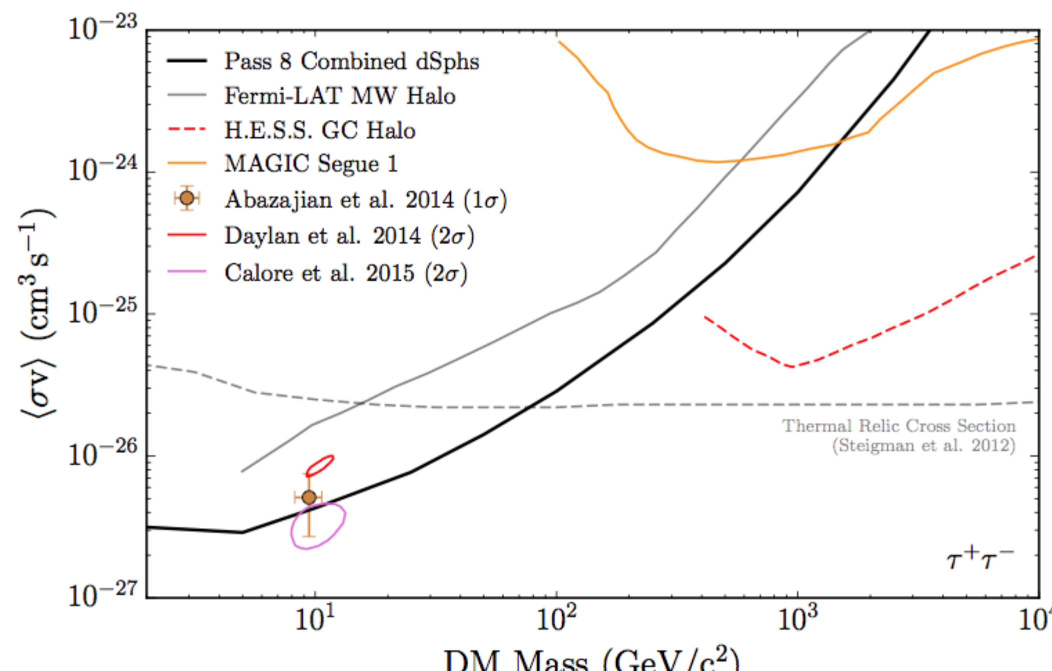
3. Spectral lines

M. Ackermann *et al.* [Fermi-LAT Collaboration],
"The Fermi Galactic Center GeV Excess and Implications for Dark Matter,"
Astrophys. J. **840**, no. 1, 43 (2017)
[arXiv:1704.03910 [astro-ph.HE]].

M. Ackermann *et al.* [Fermi-LAT Collaboration],
"Searching for Dark Matter Annihilation from Milky Way
Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data,"
Phys. Rev. Lett. **115**, no. 23, 231301 (2015)
[arXiv:1503.02641 [astro-ph.HE]].





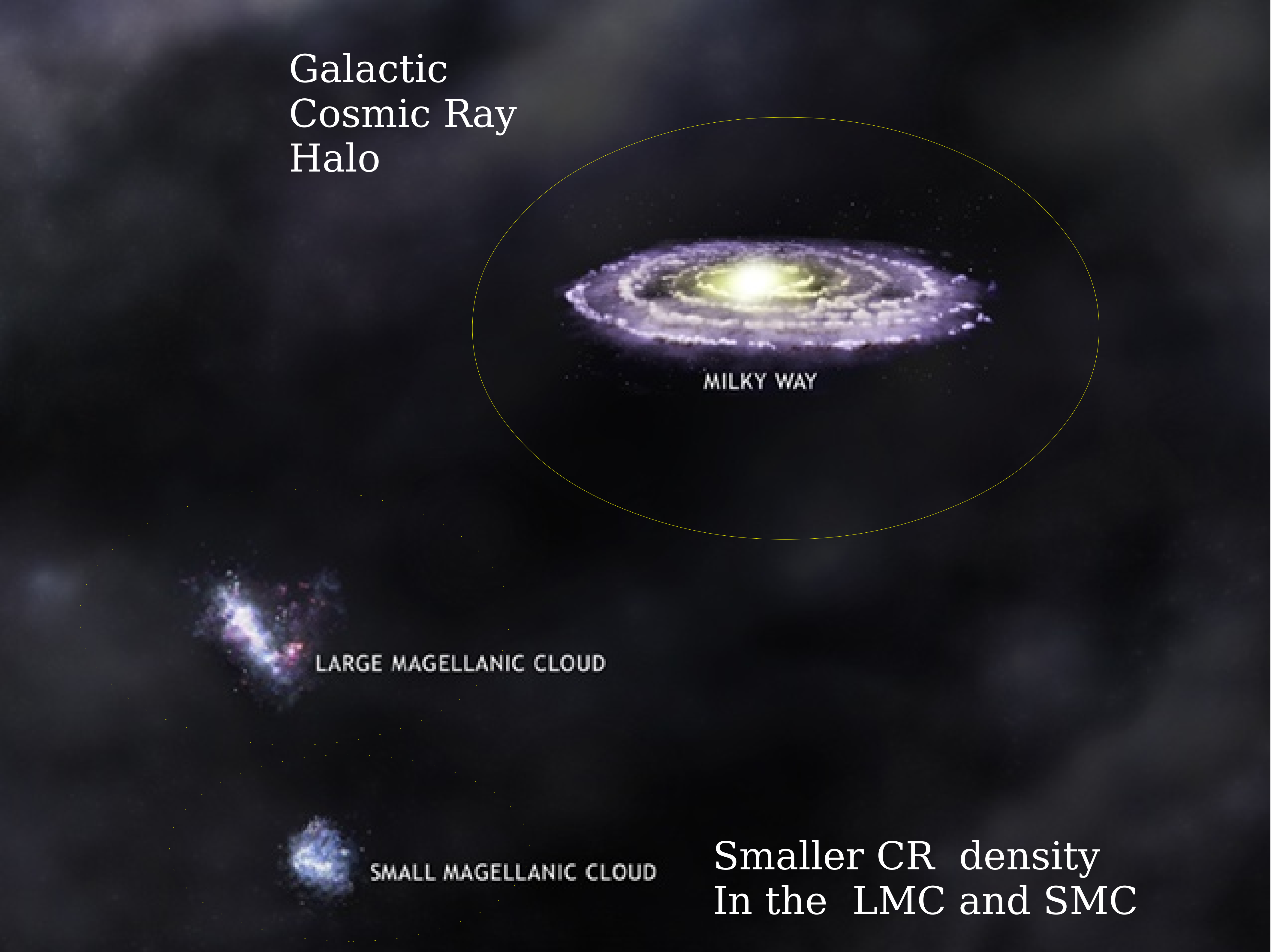


M. Ackermann *et al.* [Fermi-LAT Collaboration],

"Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data,"

Phys. Rev. Lett. **115**, no. 23, 231301 (2015)

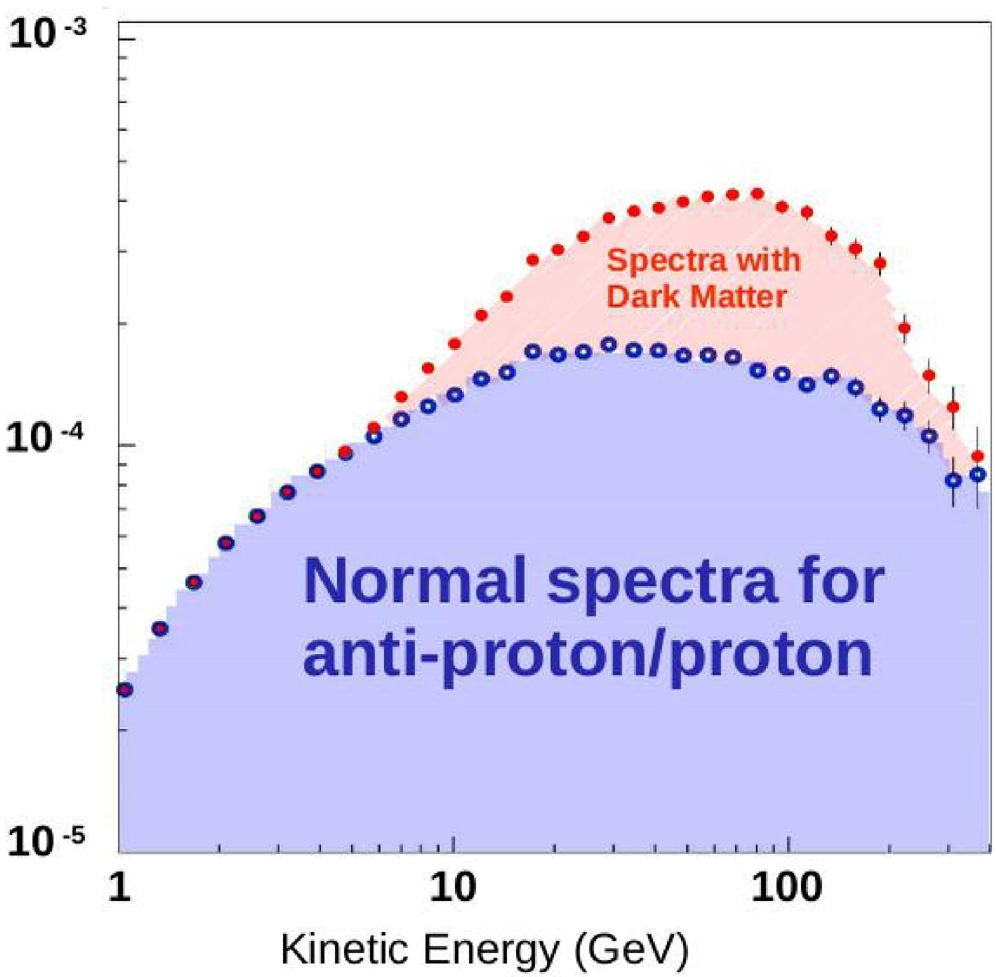
[arXiv:1503.02641 [astro-ph.HE]].

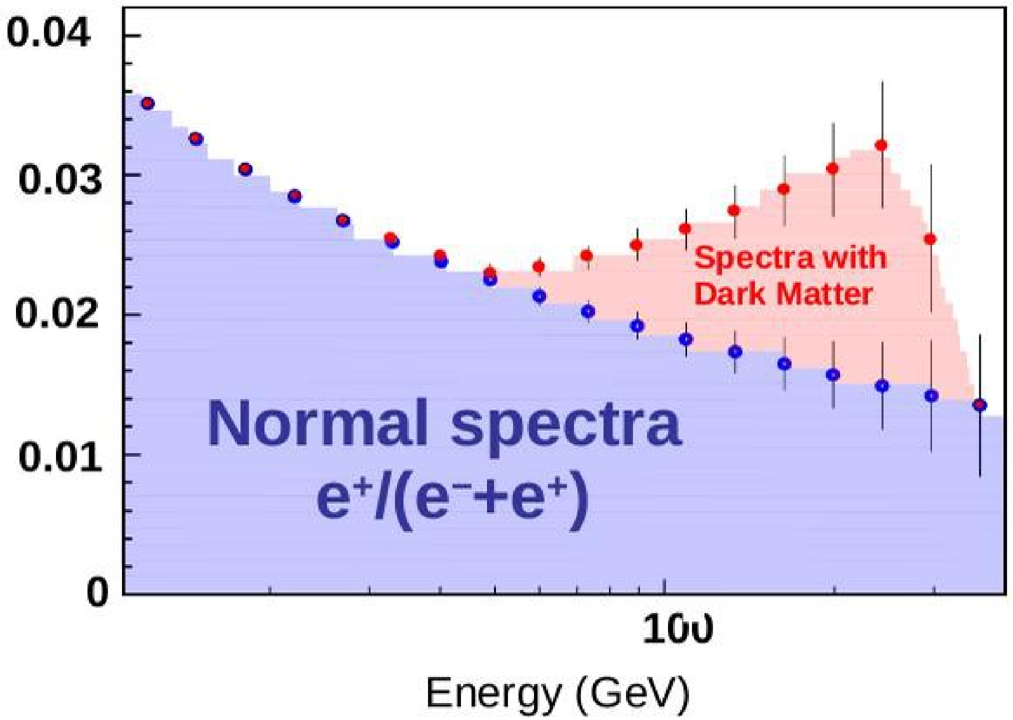

Galactic
Cosmic Ray
Halo
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
Smaller CR density
In the LMC and SMC

Charged particles:
positrons and
anti-protons

Trapped by the
Galactic magnetic field

Extra contribution to
the cosmic ray fluxes

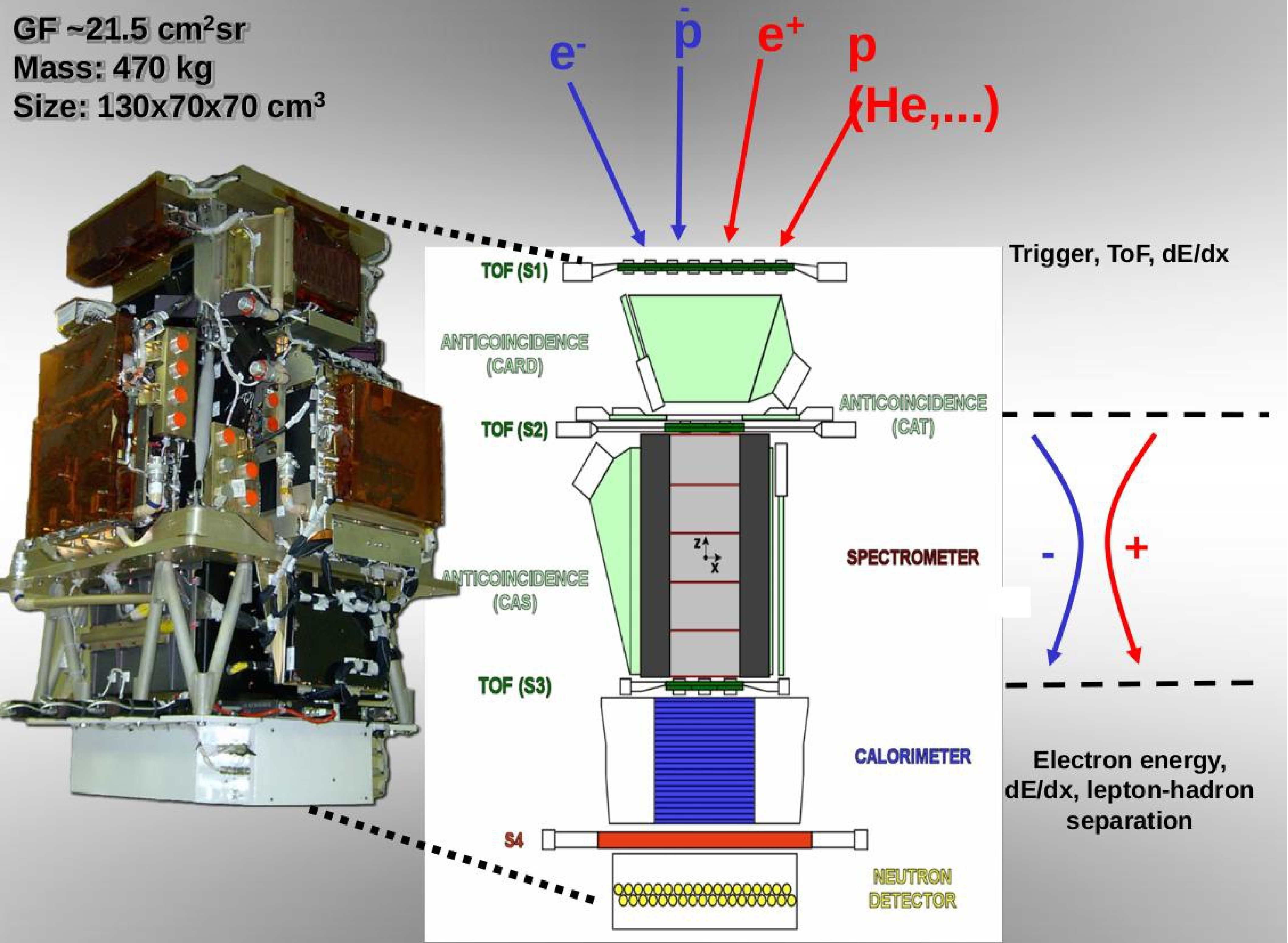


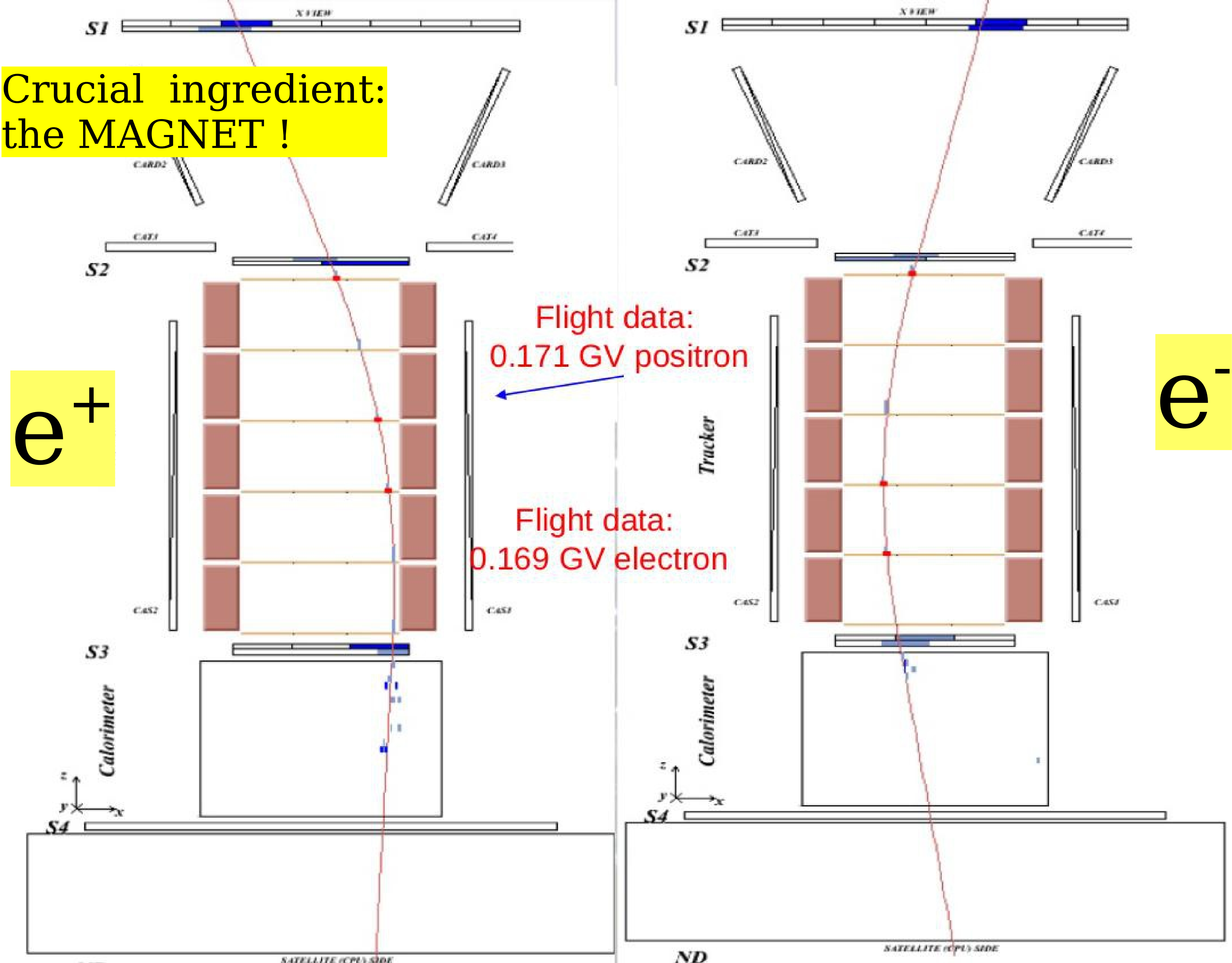


PAMELA

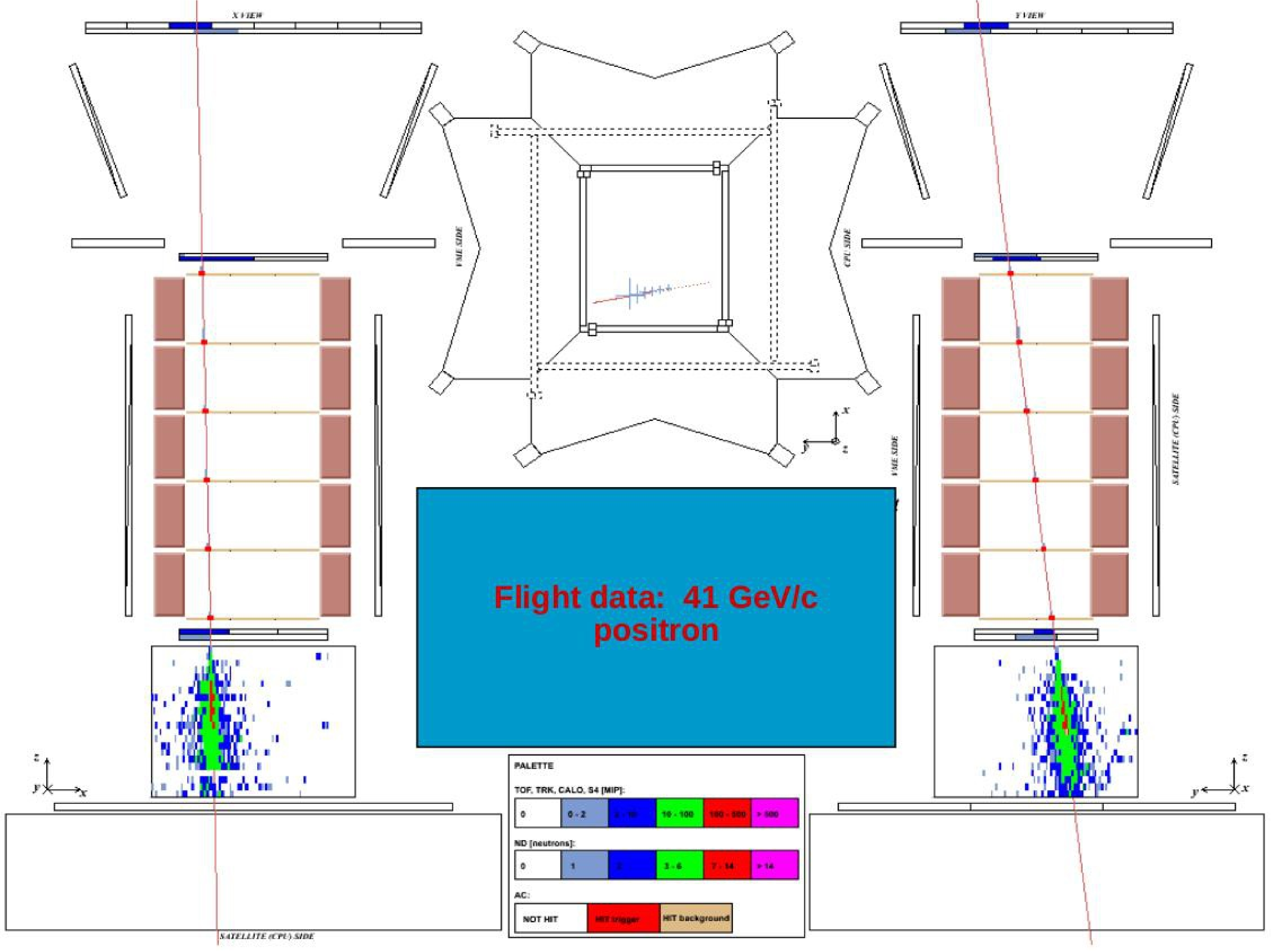
detector

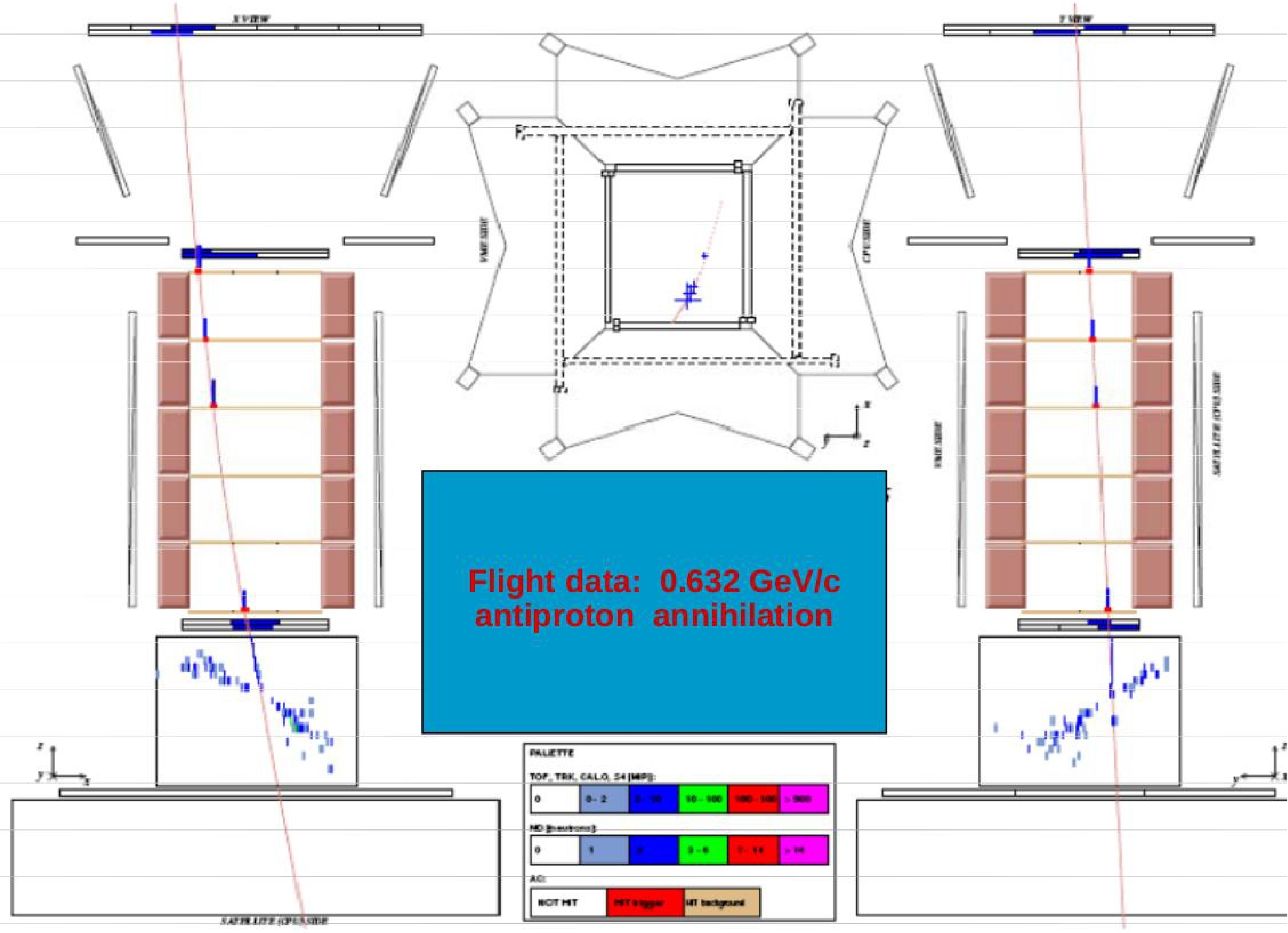
Launch
15th june 2006


GF ~21.5 cm²sr
Mass: 470 kg
Size: 130x70x70 cm³
e⁻
p̄
e⁺
p
(He,...)
Trigger, ToF, dE/dx
TOF (S1)
ANTICOINCIDENCE
(CARD)
ANTICOINCIDENCE
(CAT)
TOF (S2)
SPECTROMETER
-
+
ANTICOINCIDENCE
(CAS)
TOF (S3)
CALORIMETER
Electron energy,
dE/dx, lepton-hadron
separation
S4
NEUTRON
DETECTOR

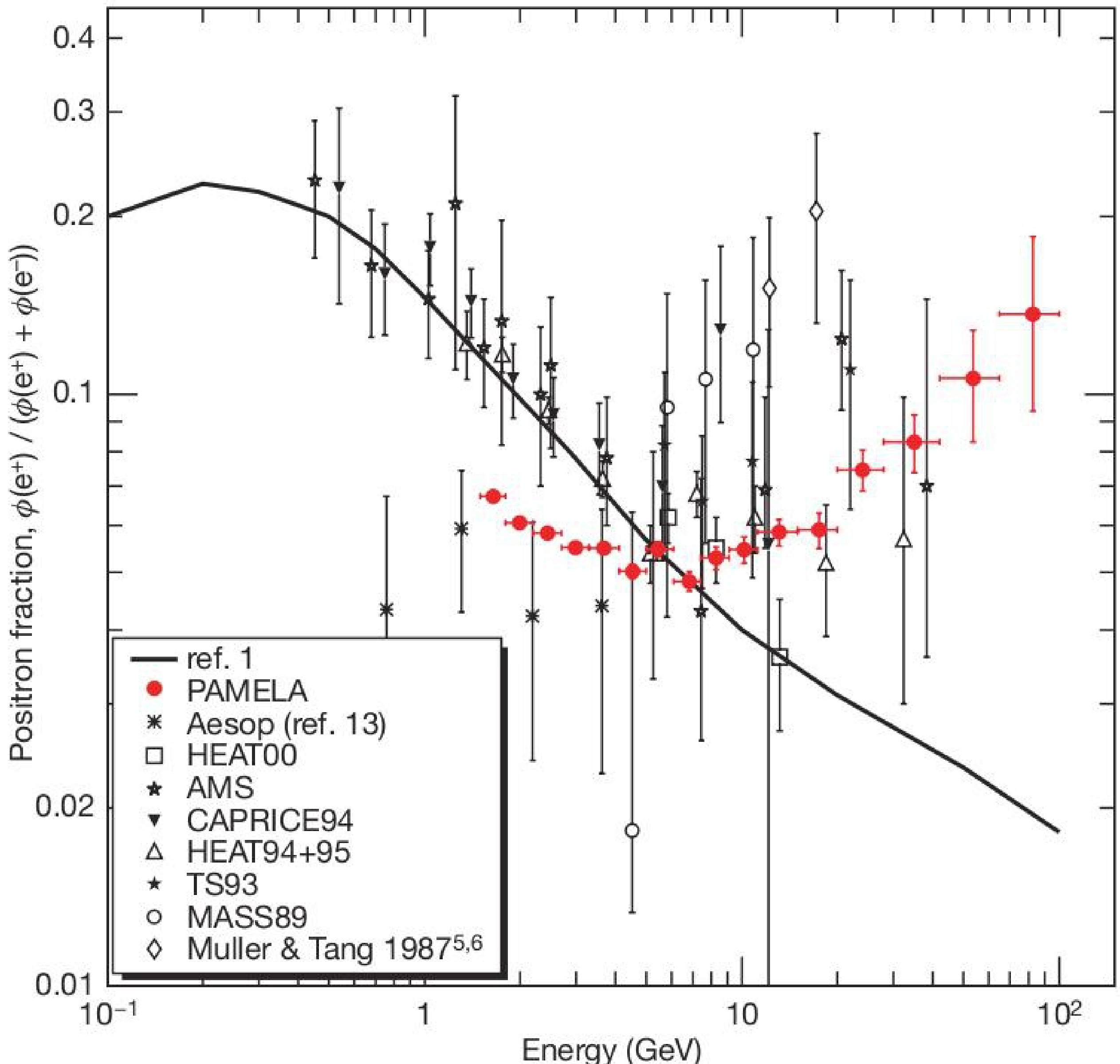


Crucial ingredient:
the MAGNET !
e+
e-
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron
S1
S2
S3
S4
Tracker
Calorimeter
ND


X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Flight data: 41 GeV/c positron
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background


X VIEW
Y VIEW
Flight data: 0.632 GeV/c
antiproton annihilation
PALETTE
AC:
NOT HIT
HIT trigger
HIT background

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV



"Positron Excess" !

[2.] Radiation Mechanisms

[a] Hadronic

[b1] Leptonic, Compton
[b2] Leptonic, Synchrotron

Gamma Ray Emission by Proton interaction

via production and decay of neutral pions

$$p + p \rightarrow \pi^{\circ} + \ldots$$

$$\pi^{\circ} \rightarrow \gamma\gamma$$

Gamma Ray Emission by Proton interaction

via production and decay of neutral pions

$$p + p \rightarrow \pi^{\circ} + \ldots$$

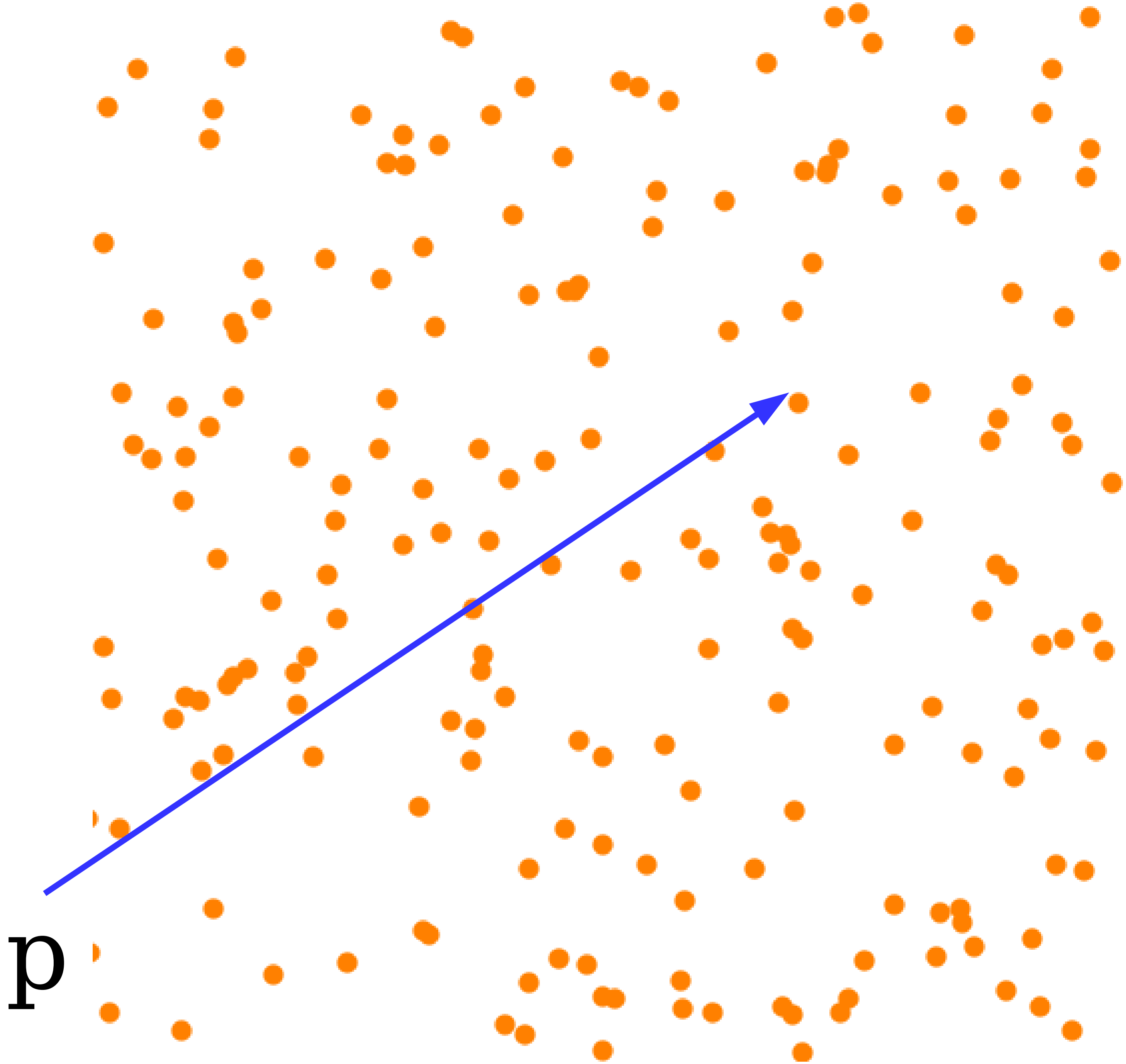
$$\pi^{\circ} \rightarrow \gamma\gamma$$

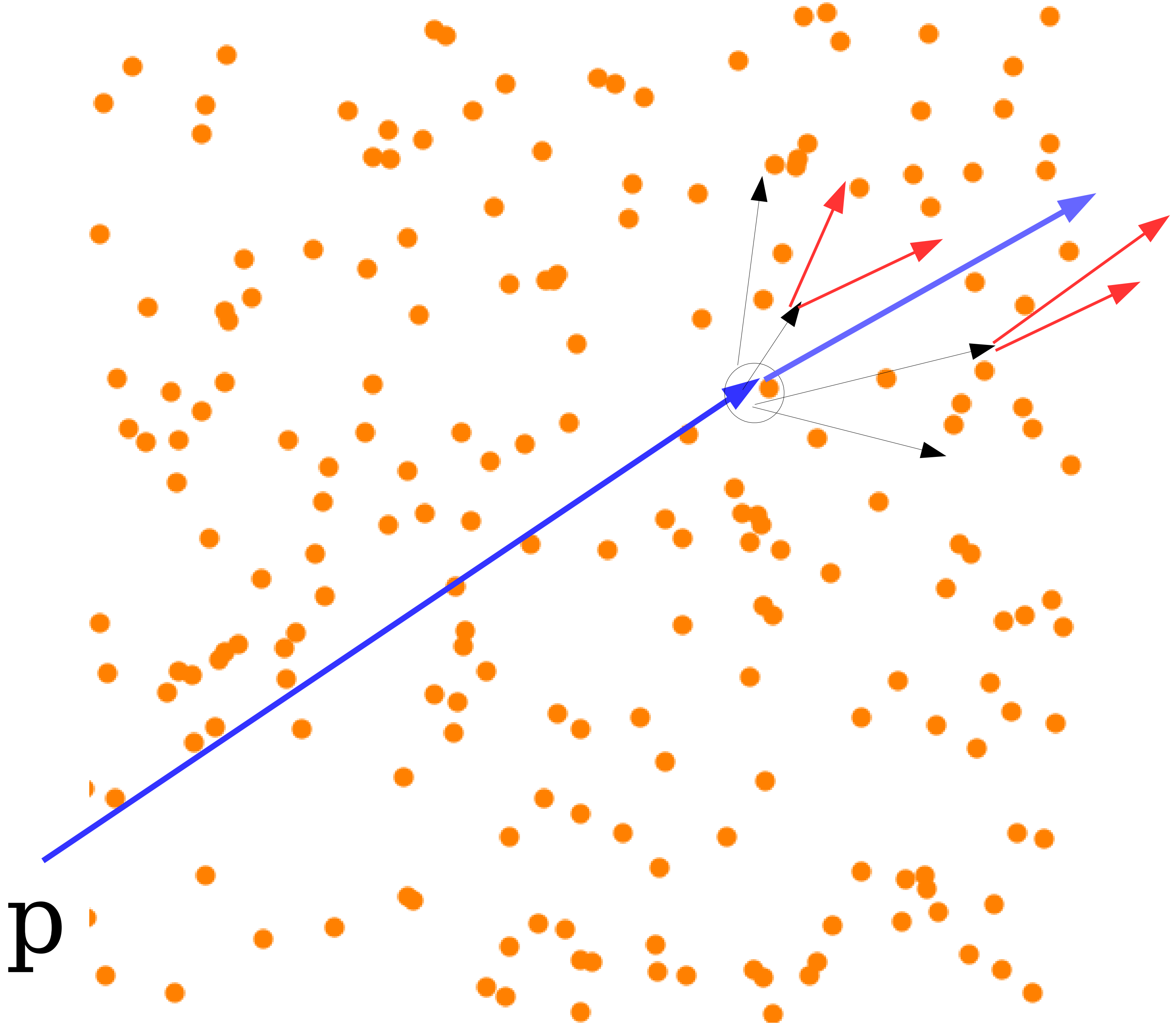
Smaller contributions from decay of other particles

$$\eta \rightarrow \gamma + \ldots$$

$$\eta' \rightarrow \gamma + \ldots$$

$[u\overline{u}]$ $[d\overline{d}]$ $[s\overline{s}]$


p


p

Hadronic mechanism:
(emission of photons by proton interaction).

$$N_p(E) \simeq K\; E^{-\alpha}$$

Relativistic protons
Population in the source.

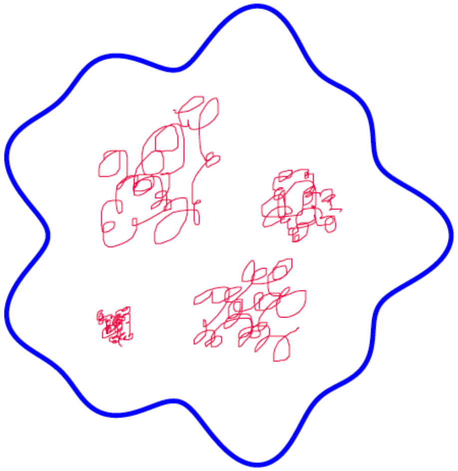
Expect (in most cases)
a power law spectrum

A proton in the source has a probability of interacting
in a time dt :

$$dP_{\rm int}(E_p) = \sigma_{pp}(E_p)\, n_p\, \beta c\, dt$$

proton-proton
inelastic cross section

Gas density in the target



$$\phi_\gamma(E_\gamma) = \frac{1}{4\pi d^2}\ \dot{N}_\gamma(E_\gamma)$$

Flux observed at the Earth

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p\ N_e(E_p)\ \frac{dP_{\rm int}(E_p)}{dt}\ \frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma}$$

Number of photons of energy Eg produced in an interaction of a proton of energy Ep

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \; N_e(E_p) \; \frac{dP_{\rm int}(E_p)}{dt} \; \frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma}$$

$$N_p(E) \simeq K \; E^{-\alpha}$$

$$\frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma} \simeq \frac{1}{E_\gamma} \; F_{p\to\gamma}\left(\frac{E_\gamma}{E_p}\right)$$

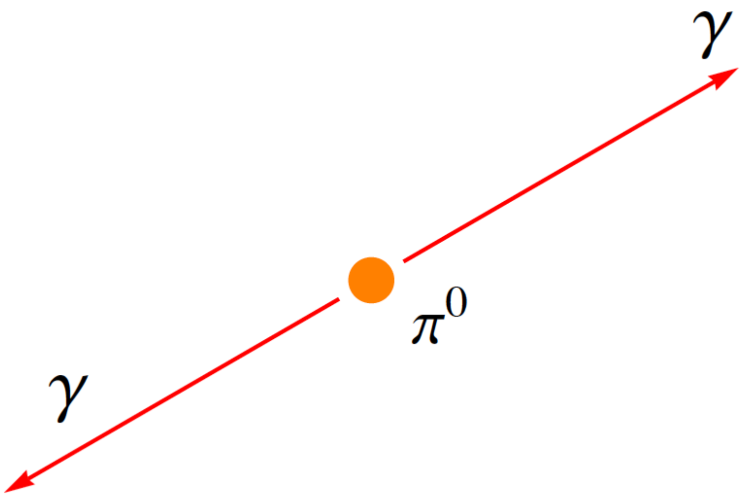
"Scaling function"

$$\frac{dP_{\rm int}(E_p)}{dt} = \sigma_{pp}(E_p)\, n_p \; \beta c$$

Convolution of the probability of creating a neutral pion of a certain energy + probability that the pion decay into a photon of energy E_γ

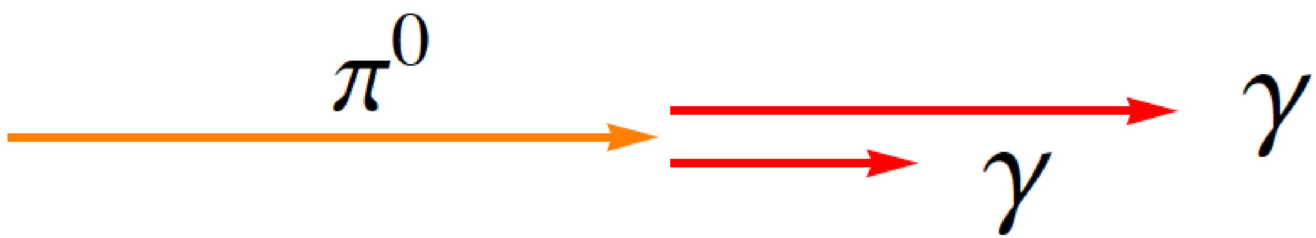
Pion decay into photons:

$$\pi^{\circ} \rightarrow \gamma\gamma$$



Rest Frame $$E_{\gamma} = \frac{m_{\pi}}{2}$$

Photons are emitted isotropically
and monochromatically with a fixed energy.



Frame where the pion is moving

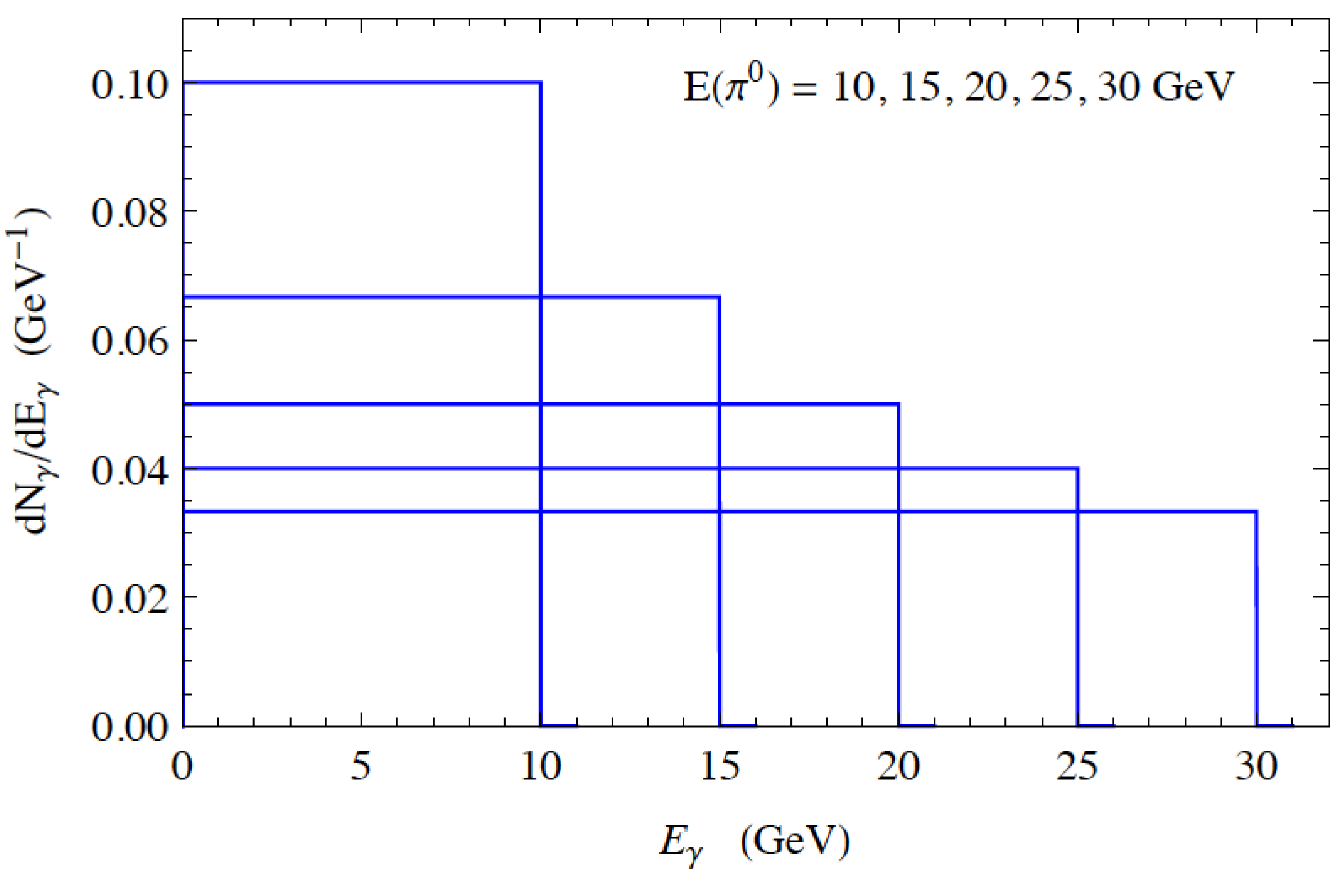
$$\frac{dN_\gamma}{dE_\gamma}(E_\gamma; E_\pi)$$

$$E_{\gamma,\min} = \frac{E_\pi}{2}(1 - \beta_\pi)$$

$$E_{\gamma,\max} = \frac{E_\pi}{2}(1 + \beta_\pi)$$

$$E_{\gamma,\min} \simeq 0$$

$$E_{\gamma,\max} \simeq E_\pi$$

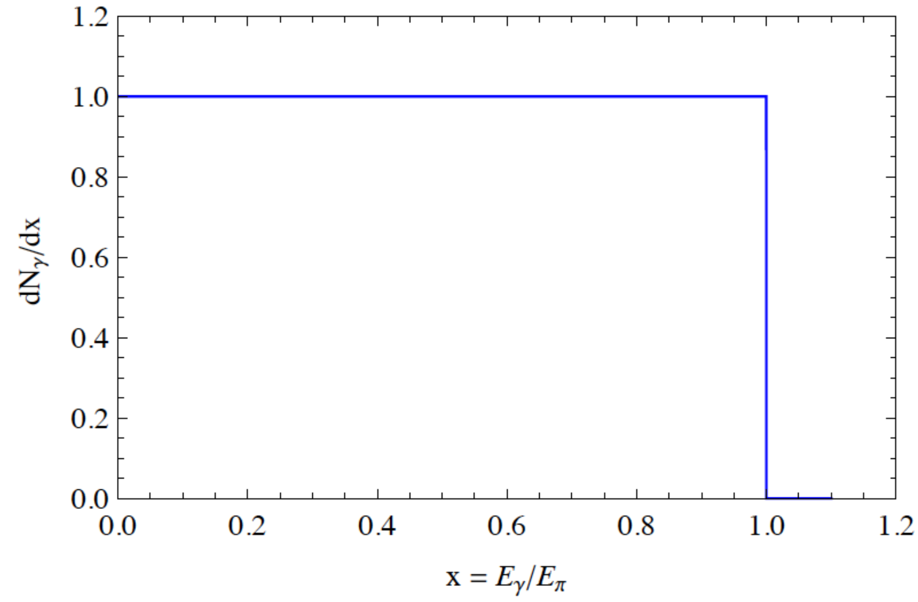


The spectrum of the photons has a

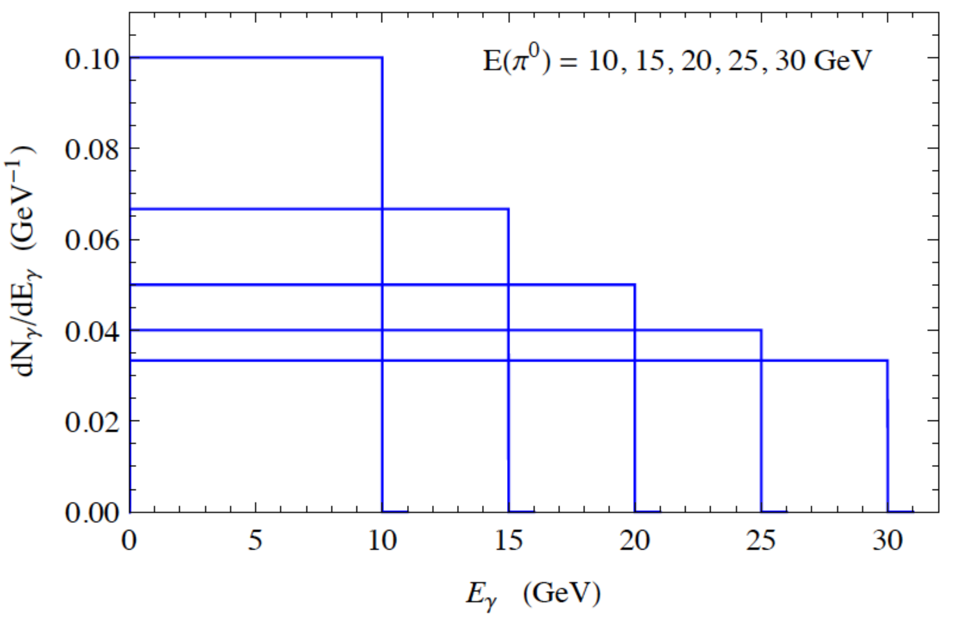
"scaling form"

$$\left.\frac{dN_\gamma}{dE_\gamma}(E_\gamma; E_\pi)\right|_{\pi^0\to\gamma\gamma} = \frac{1}{E_\pi}\, F_{\pi^0\to\gamma}\left(\frac{E_\gamma}{E_\pi}\right)$$

$$F_{\pi^0\to\gamma} = \begin{cases} 1 & \text{for} \quad x < 1 \\ 0 & \text{for} \quad x > 1 \end{cases}$$

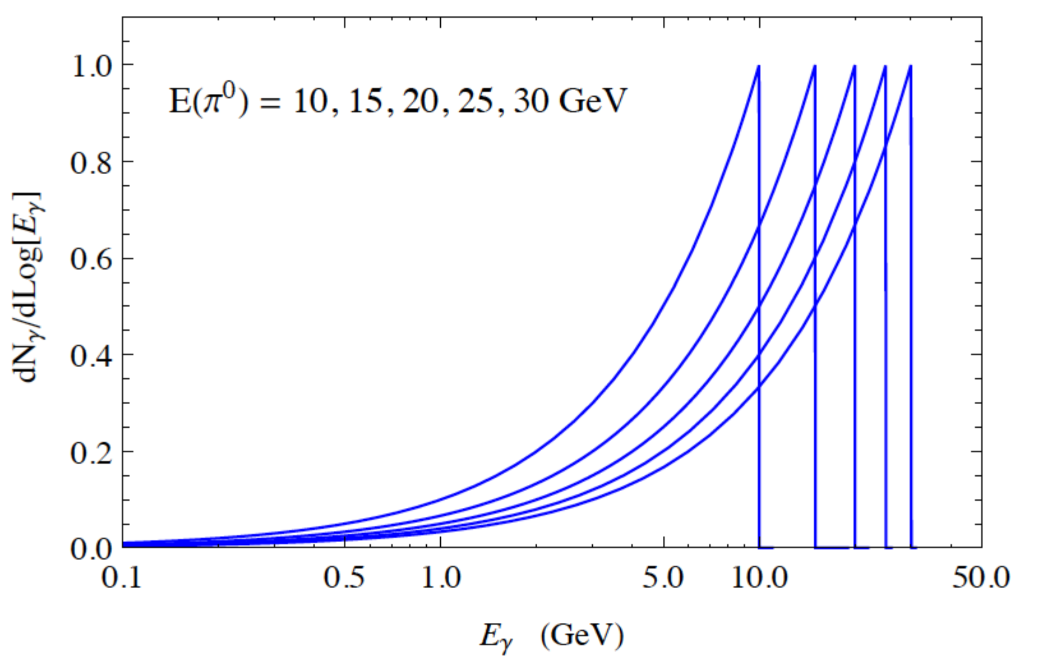


$$\frac{dN_\gamma}{dE_\gamma}$$



$$\frac{dN_\gamma}{d\ln E_\gamma} = E_\gamma \; \frac{dN_\gamma}{dE_\gamma}$$

Functions of same shape

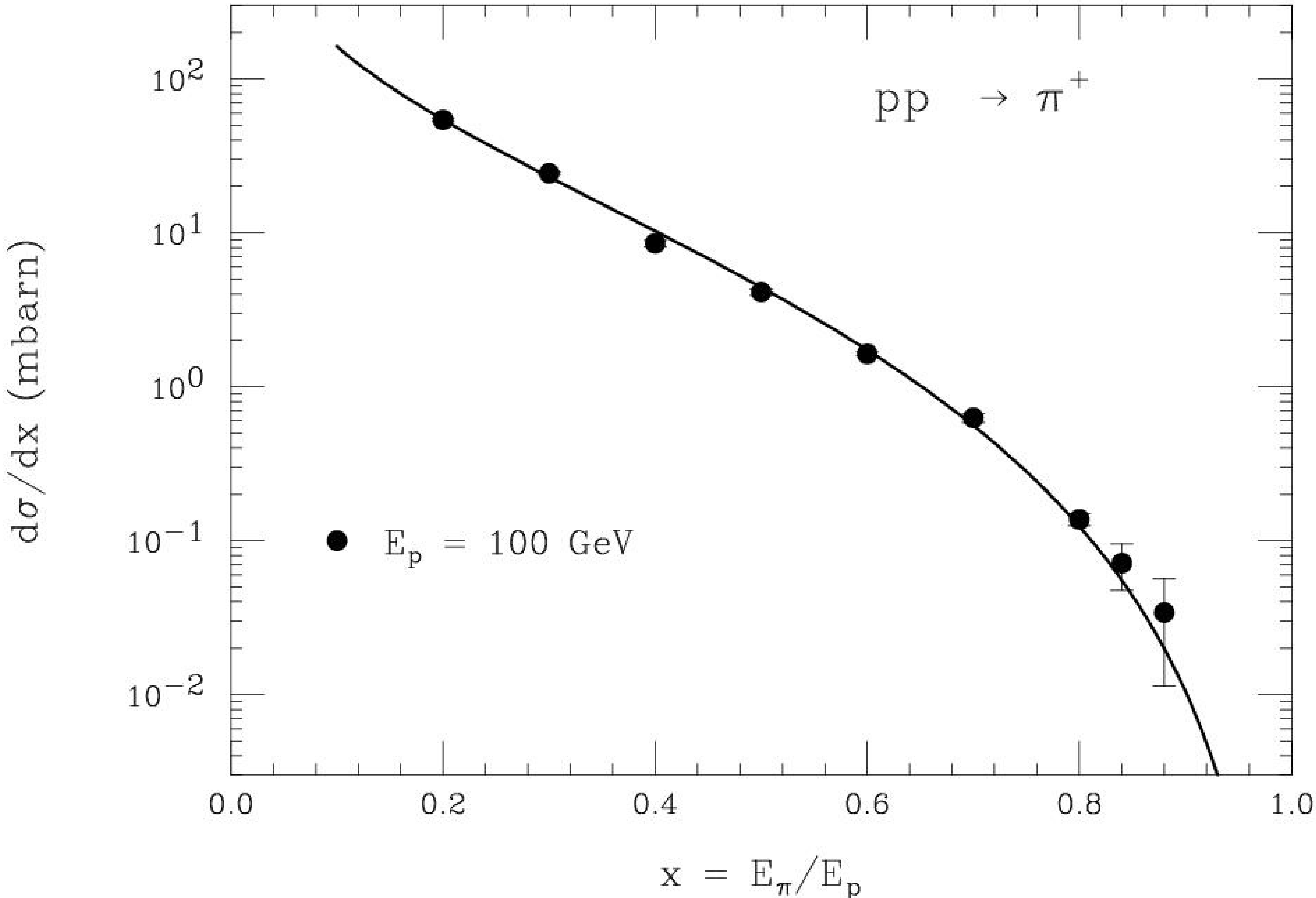


$$\frac{dN_{p\to\gamma}}{dE_\gamma}(E_\gamma;E_p) = \frac{dN_{p\to\pi}}{dE_\pi}(E_\pi,E_p) \otimes \frac{dN_{\pi^0\to\gamma}}{dE_\gamma}(E_\gamma;E_\pi)$$

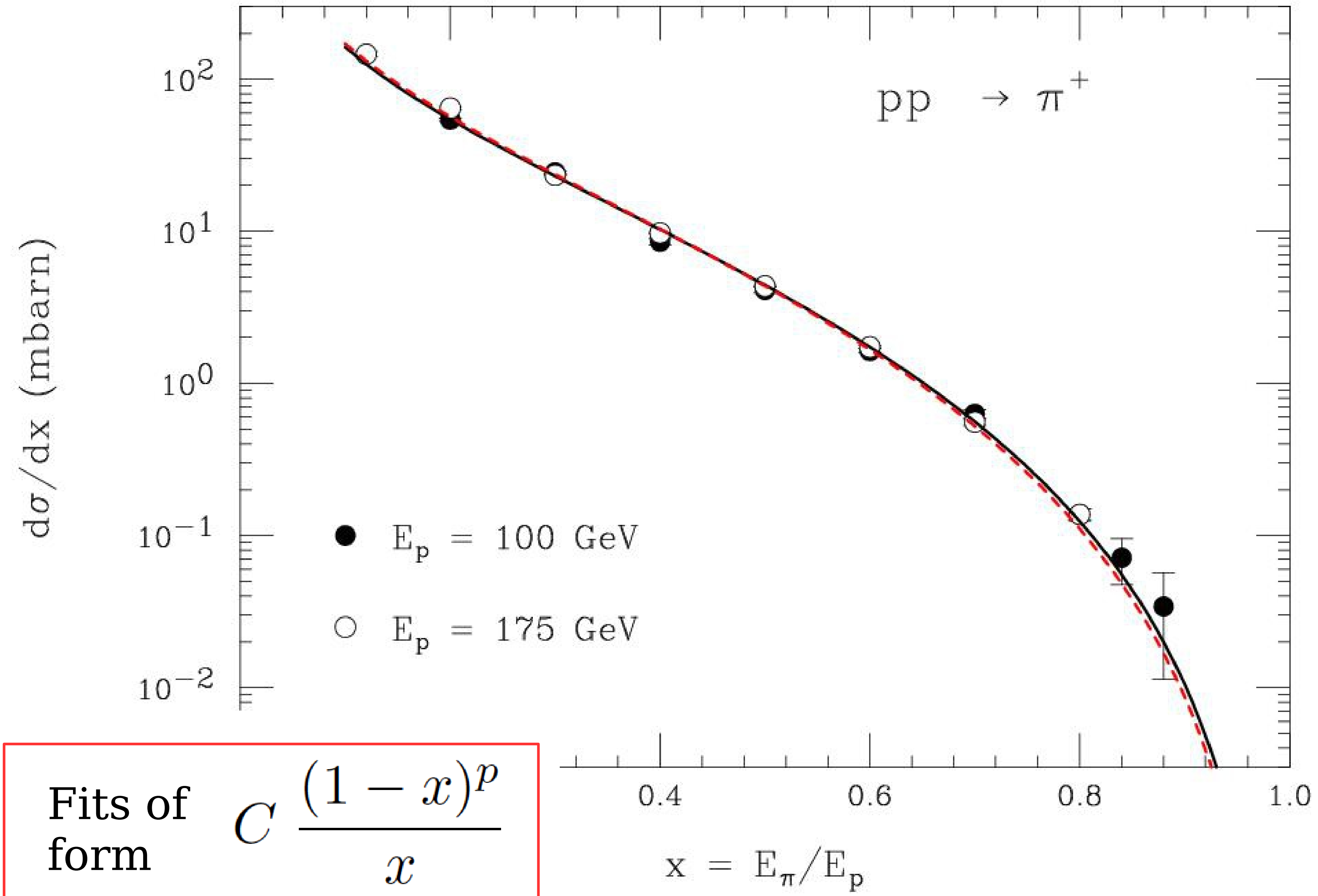
Inclusive distribution of pions
Produced in proton interactions

Fermilab Experiment

A.Brenner et al. Phys.Rev D26, 1497, (1982).



Two different Energies (100, 175 GeV)



Fits of form $C\,\dfrac{(1-x)^p}{x}$

Feynman Scaling

$$\frac{dn_{p\to\pi}}{dE_\pi}(E_\pi;E_0) = \frac{1}{E_0}\ F_{p\to\pi}\left(\frac{E_\pi}{E_0}\right)$$

(Only approximate validity)

But very useful as "guide"
(and with important consequences)

$$\frac{dN_{p\to\gamma}}{dE_\gamma}(E_\gamma; E_p) = \frac{dN_{p\to\pi}}{dE_\pi}(E_\pi, E_p) \otimes \frac{dN_{\pi^0\to\gamma}}{dE_\gamma}(E_\gamma; E_\pi)$$

Inclusive distribution of pions
Produced in proton interactions

Note :
The convolution of two scaling functions
is again a scaling function

Important consequence :

A Power-Law spectrum of primary protons generates
a power law spectrum of same exponent.

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \; N_e(E_p) \; \frac{dP_{\rm int}(E_p)}{dt} \; \frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma}$$

Number of photons emitted per unit time and unit energy at energy Eg

=

Number of protons in the source with Energy Ep

*

Probability that one proton interact per unit time

*

Number of photons of energy Eg produced in the interaction of a proton of Energy Ep

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \; N_e(E_p) \; \frac{dP_{\rm int}(E_p)}{dt} \; \frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma}$$

$$N_p(E) \simeq K \; E^{-\alpha}$$

$$\frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma} \simeq \frac{1}{E_\gamma} \; F_{p\to\gamma}\left(\frac{E_\gamma}{E_p}\right)$$

$$\frac{dP_{\rm int}(E_p)}{dt} = \sigma_{pp}(E_p)\, n_p \; \beta c$$

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \; \left[K \; E_p^{-\alpha}\right] \; \left[n_p \; \sigma_{pp}(E) \, \beta c\right] \; \left[\frac{1}{E_p} \; F_{p\to\gamma}\left(\frac{E_\gamma}{E_p}\right)\right]$$

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \;\left[K\; E_p^{-\alpha}\right]\;\left[n_p\,\sigma_{pp}(E)\,\beta c\right]\;\left[\frac{1}{E_p}\;F_{p\to\gamma}\left(\frac{E_\gamma}{E_p}\right)\right]$$

$$x = \frac{E_\gamma}{E_p}$$

$$dE_p = -dx\;\frac{E_\gamma}{x^2}$$

change of variables

Approximations:

v = c

$$\sigma_{pp}(E) \simeq \sigma_{pp}$$

$$\dot{N}_\gamma(E_\gamma) = n_p\,\sigma_{pp}\,c\int_0^1 dx\;\frac{E_\gamma}{x}\;K\;\left(\frac{E_\gamma}{x}\right)^{-\alpha}\;\left[\frac{x}{E_\gamma}\;Fp\to\gamma\,(x)\right]$$

$$\dot{N}_\gamma(E_\gamma) = n_p\,\sigma_{pp}\,c \int_0^1 dx\; \frac{E_\gamma}{x}\; K\; \left(\frac{E_\gamma}{x}\right)^{-\alpha}\; \left[\frac{x}{E_\gamma}\; Fp \to \gamma\,(x)\right]$$

$$\dot{N}_\gamma(E_\gamma) = n_p\,\sigma_{pp}\,c\; K\; E_\gamma^{-\alpha} \int_0^1 dx\; x^{\alpha-1}\; F_{p\to\gamma}\,(x)$$

$$\int_0^1 dx\; x^{\alpha-1}\; F_{p\to\gamma}\,(x) = Z_{p\to\gamma}(\alpha)$$

$$\dot{N}_\gamma(E_\gamma) = [K_p\,\sigma_{pp}\,c\,n_p\,Z_{p\to\gamma}]\; E_\gamma^{-\alpha}$$

$$\dot{N}_\gamma(E_\gamma) = \quad K_\gamma\; E_\gamma^{-\alpha}$$

IF the population of relativistic protons inside an astrophysical source is a power law of esponent alpha

$$N_p(E) \simeq K \; E^{-\alpha}$$

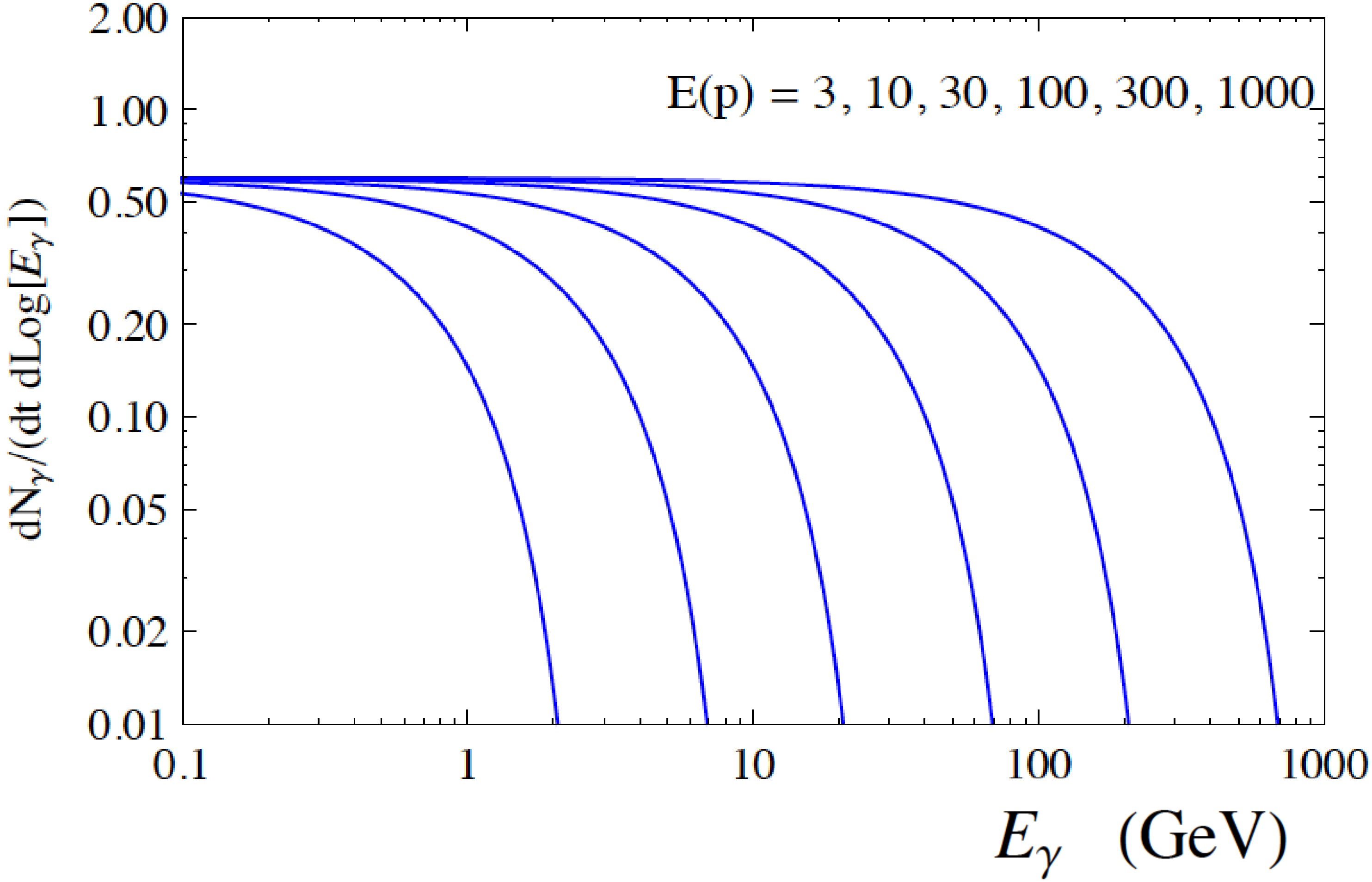
Then the photon emission is also a power law with the same exponent.
The emission is proportional to the gas density in the source

$$\dot{N}_\gamma(E_\gamma) = K_\gamma \; E_\gamma^{-\alpha}$$

$$\dot{N}_\gamma(E_\gamma) = [K_p \, n_p \, \sigma_{pp} \, c \, Z_{p\to\gamma}(\alpha)] \; E_\gamma^{-\alpha}$$

“Geometric demonstration”

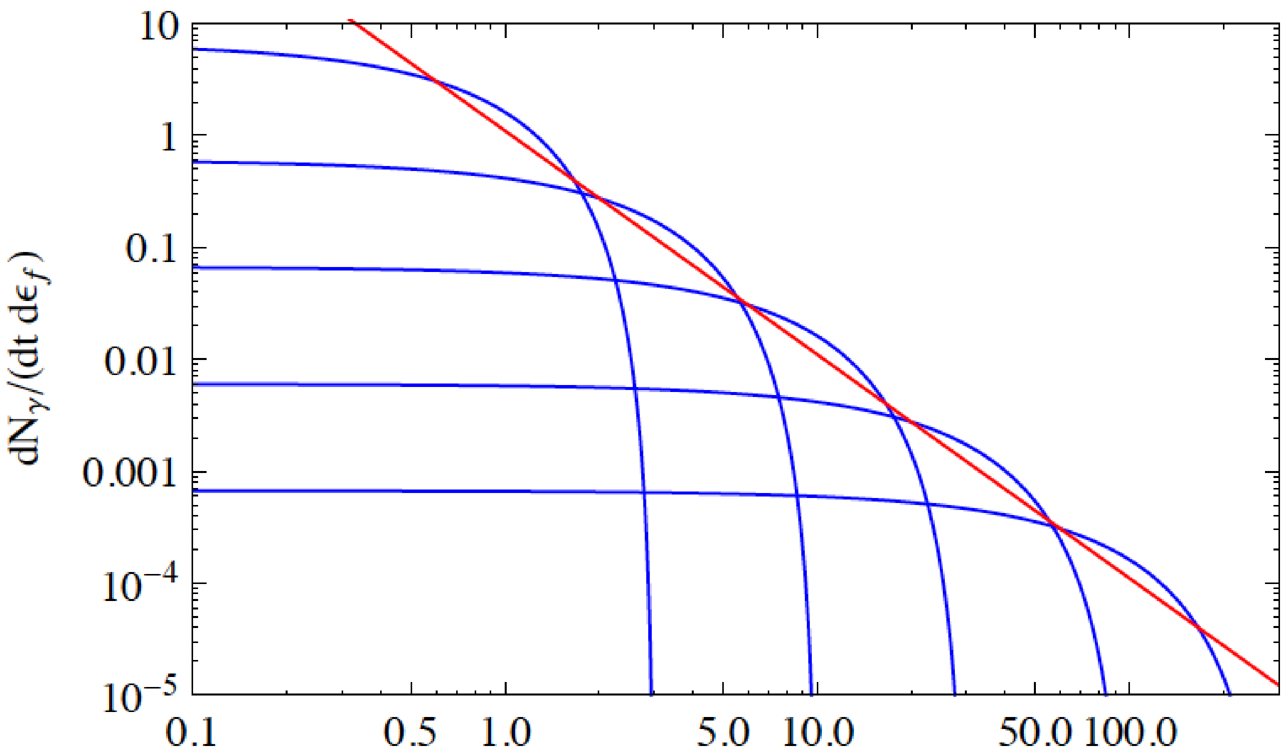
$$\left.\frac{dN_\gamma}{d\ln E_\gamma}\right|_{pp\to\gamma}(E_\gamma, E_p)$$



$$E_p^{-2} \quad \frac{dN_\gamma}{d\ln E_\gamma}\bigg|_{pp\to\gamma} (E_\gamma, E_p)$$

Weight all contributions
With a power Law

Sum all contributions:
obtain power Law
of same esponent



E_γ (GeV)

“Signature” of the hadronic mechanism:

The mass m_{π° leaves its “imprint”

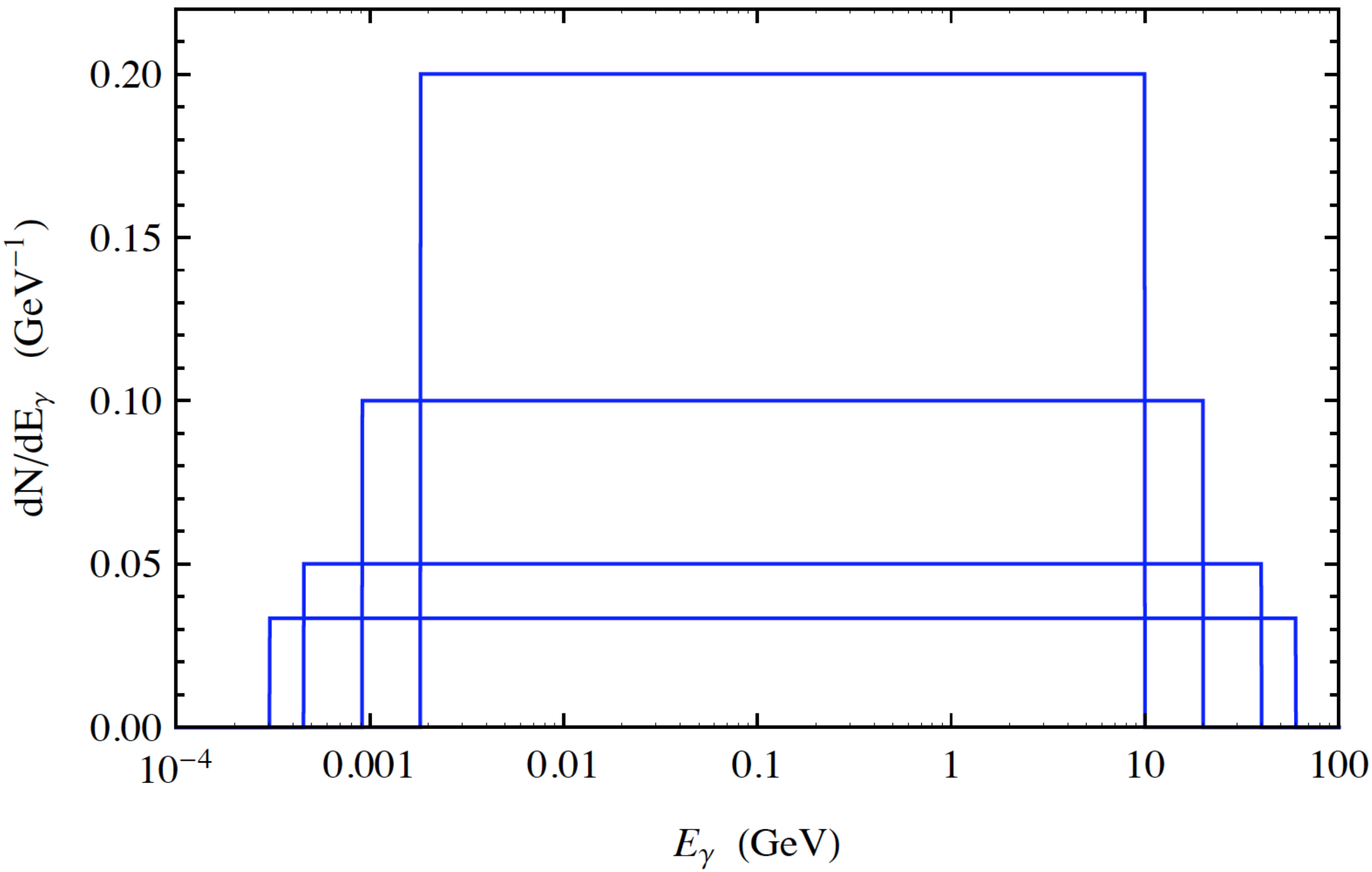
on the photon spectrum

Look again to the decay spectrum

$$E_{\gamma,\min} = E_\pi \; (1 - \beta_\pi)$$

$$E_{\gamma,\max} = E_\pi \; (1 + \beta_\pi)$$

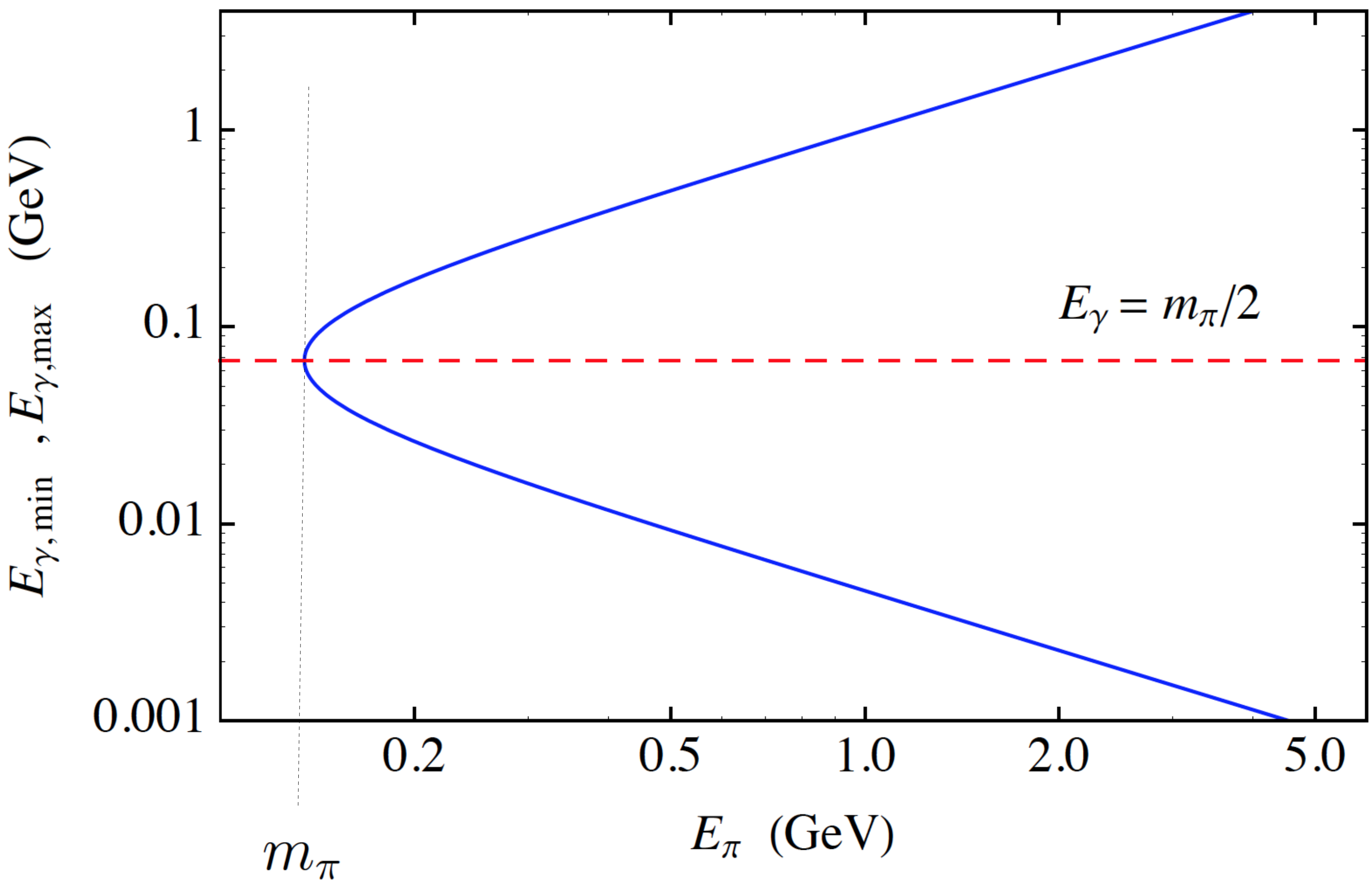
$$E_{\gamma \;\; \min,(\max)} = E_\pi \; \left(1 \mp \sqrt{1 - \frac{m_\pi^2}{E_\pi^2}}\right)$$



Low energy photons can only be produced by High energy pions

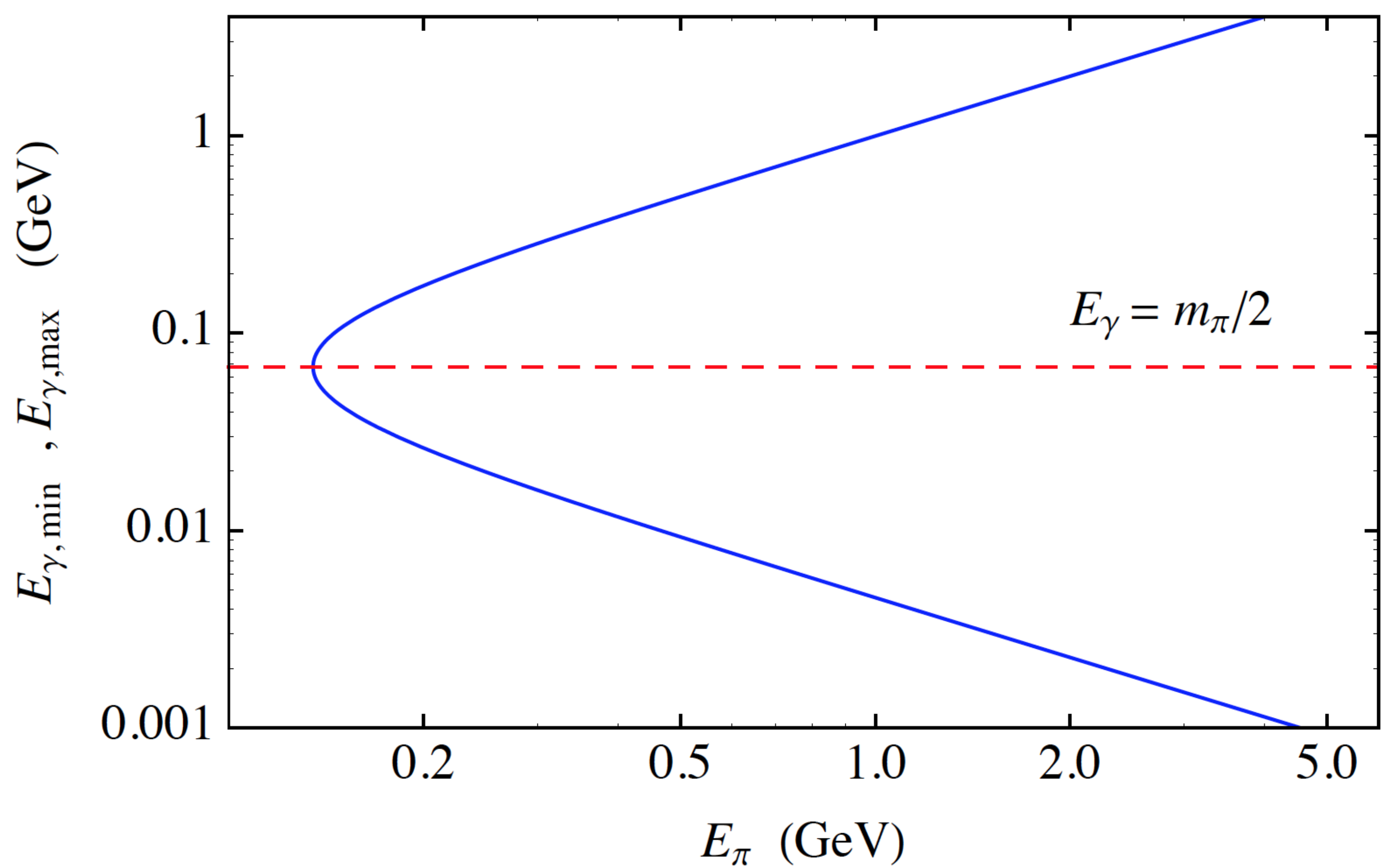
$$E_{\gamma,\min} = E_\pi \, (1 - \beta_\pi)$$

$$E_{\gamma,\max} = E_\pi \, (1 + \beta_\pi)$$



$$E_{\pi,\min}(E_\gamma) = E_\gamma + \frac{m_\pi^2}{4\,E_\gamma} \;=\; \frac{m_\pi}{2}\;\left[\frac{2E_\gamma}{m_\pi} + \frac{m_\pi}{2\,E_\gamma}\right]$$

[symmetry for "reflections" around $E_\gamma = m_{\pi^\circ}/2$]



Gamma ray spectrum as convolution of the π° spectra

$$\frac{d\dot{N}_\gamma}{dE_\gamma}(E_\gamma) = \int_{E_{\pi,\min}(E_\gamma)}^{\infty} dE_\pi \; \frac{dN_\pi}{dE_\pi}(E_\pi) \; \frac{dN_{\pi^\circ\to\gamma}}{dE_\gamma}(E_\gamma, E_\pi)$$

$$= \int_{E_\gamma + m_\pi^2/(4\,E_\gamma)}^{\infty} dE_\pi \; \frac{dN_\pi}{dE_\pi}(E_\pi) \; \frac{1}{\sqrt{E_\pi^2 - m_\pi^2}}$$

$$\frac{d\dot{N}_\gamma}{dE_\gamma}(E_\gamma) = \frac{d\dot{N}_\gamma}{dE_\gamma}(E'_\gamma)$$

$$\frac{2E_\gamma}{m_\pi} = \frac{m_\pi}{2\,E'_\gamma}$$

For the *hadronic emission mechanism*:

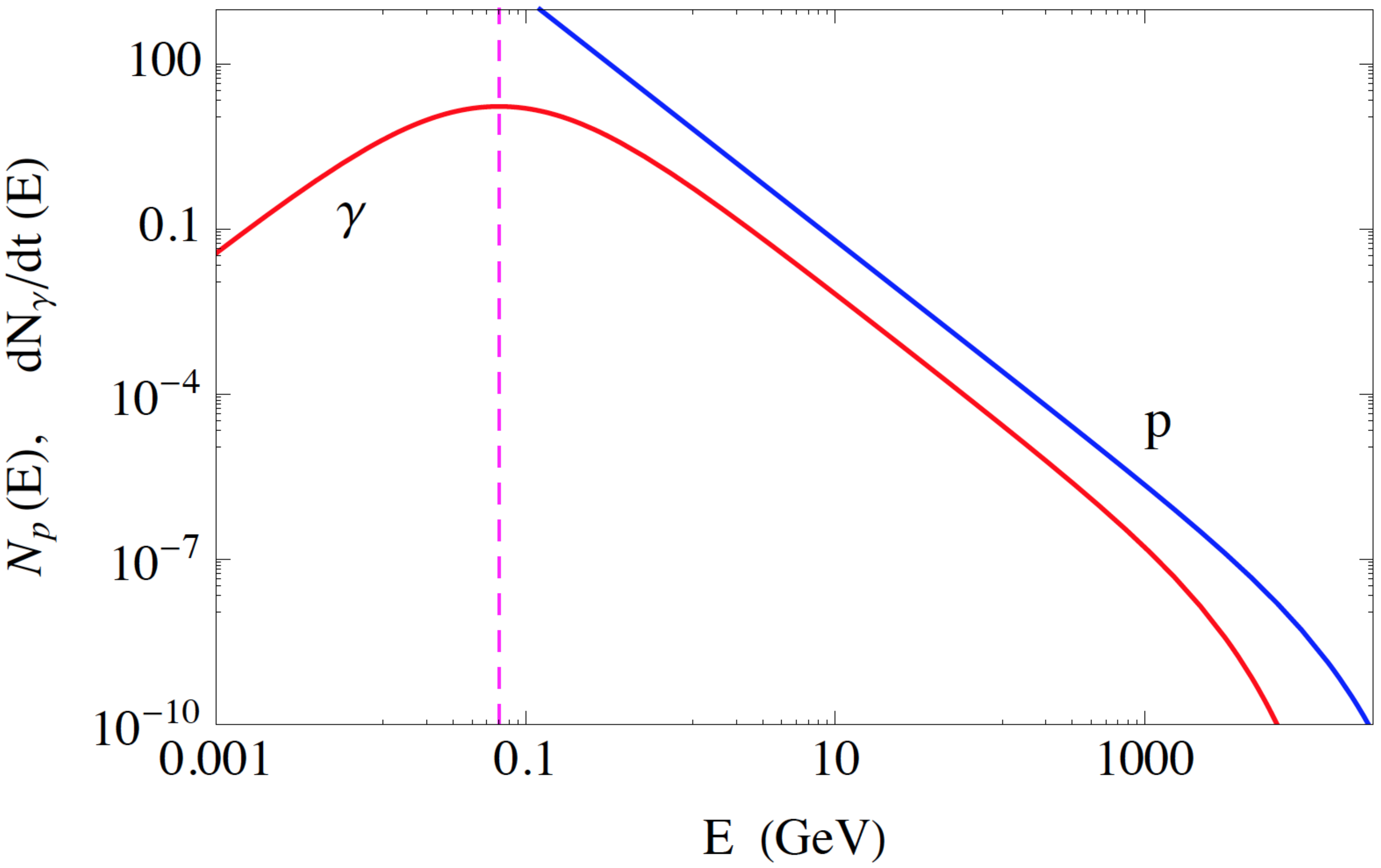
The photon spectra at energies E_γ and E'_γ symmetric around $m_{\pi^\circ}/2$ are *equal*.

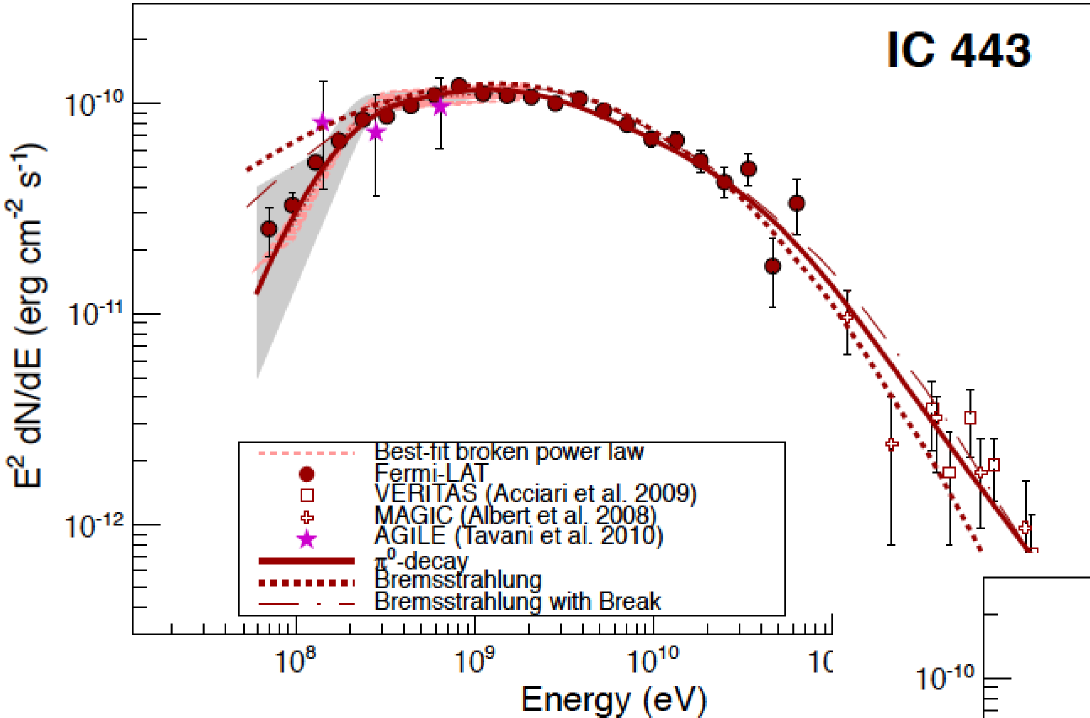
Low energy cutoff

Consequence of
The pion mass = 0.135 GeV

High energy cutoff:

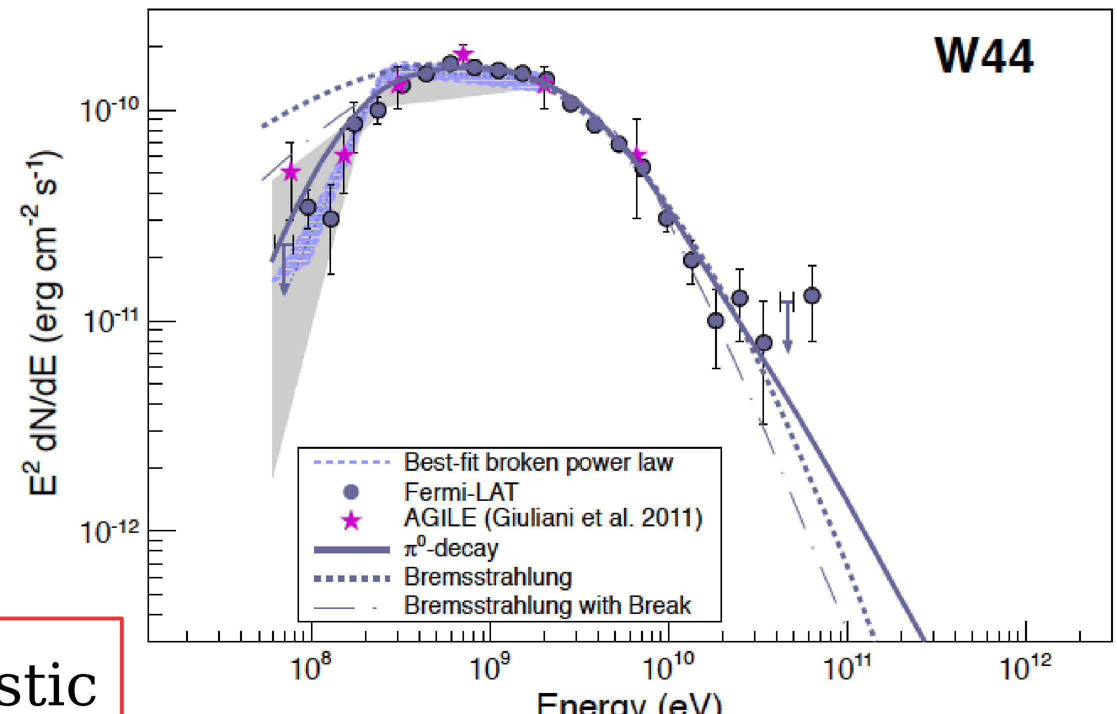
Reflects a possible cutoff in the
Proton spectrum





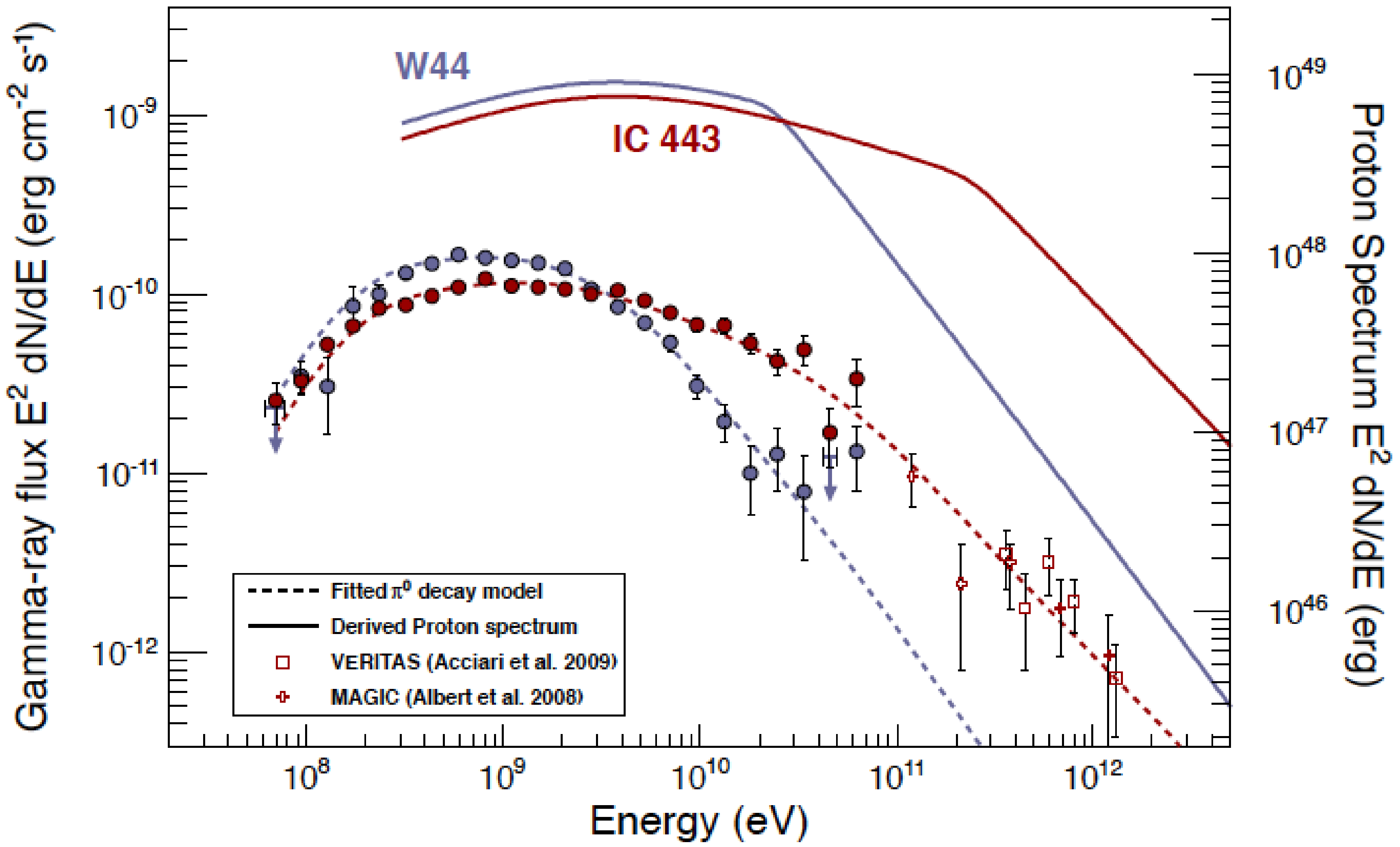
Result of the FERMI collaboration

SCIENCE feb. 2013



"Detection of the characteristic Pion-decay signature in Supernova Remnants"

Reconstruction of the Proton population
Inside the two SuperNova shells



"Conventional mechanism"
for the production of positrons and antiprotons:

Creation of secondaries in the inelastic hadronic interactions of cosmic rays in the interstellar medium

$$pp \to \overline{p} + \ldots$$

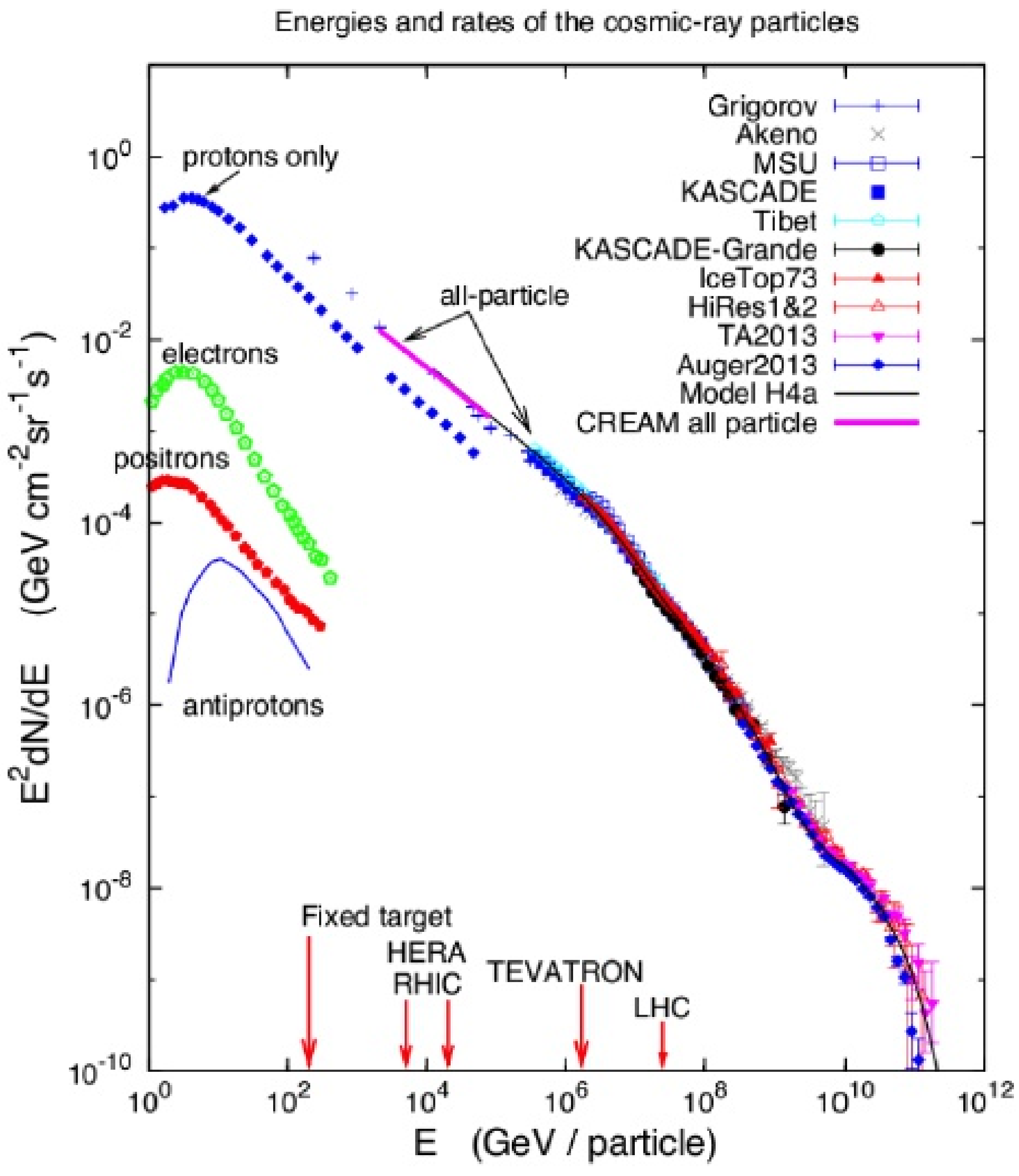
$$pp \to \pi^+ + \ldots$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$pp \to \pi^\circ + \ldots$$
$$\hookrightarrow \gamma + \gamma$$

"Standard mechanism" for the generation of positrons and anti-protons

Dominant mechanism for the generation of high energy gamma rays

intimately connected



Electron flux is smaller and *softer* than the proton flux.

Smaller contributions of positrons and antiprotons

Straightforward [hadronic physics] exercise:

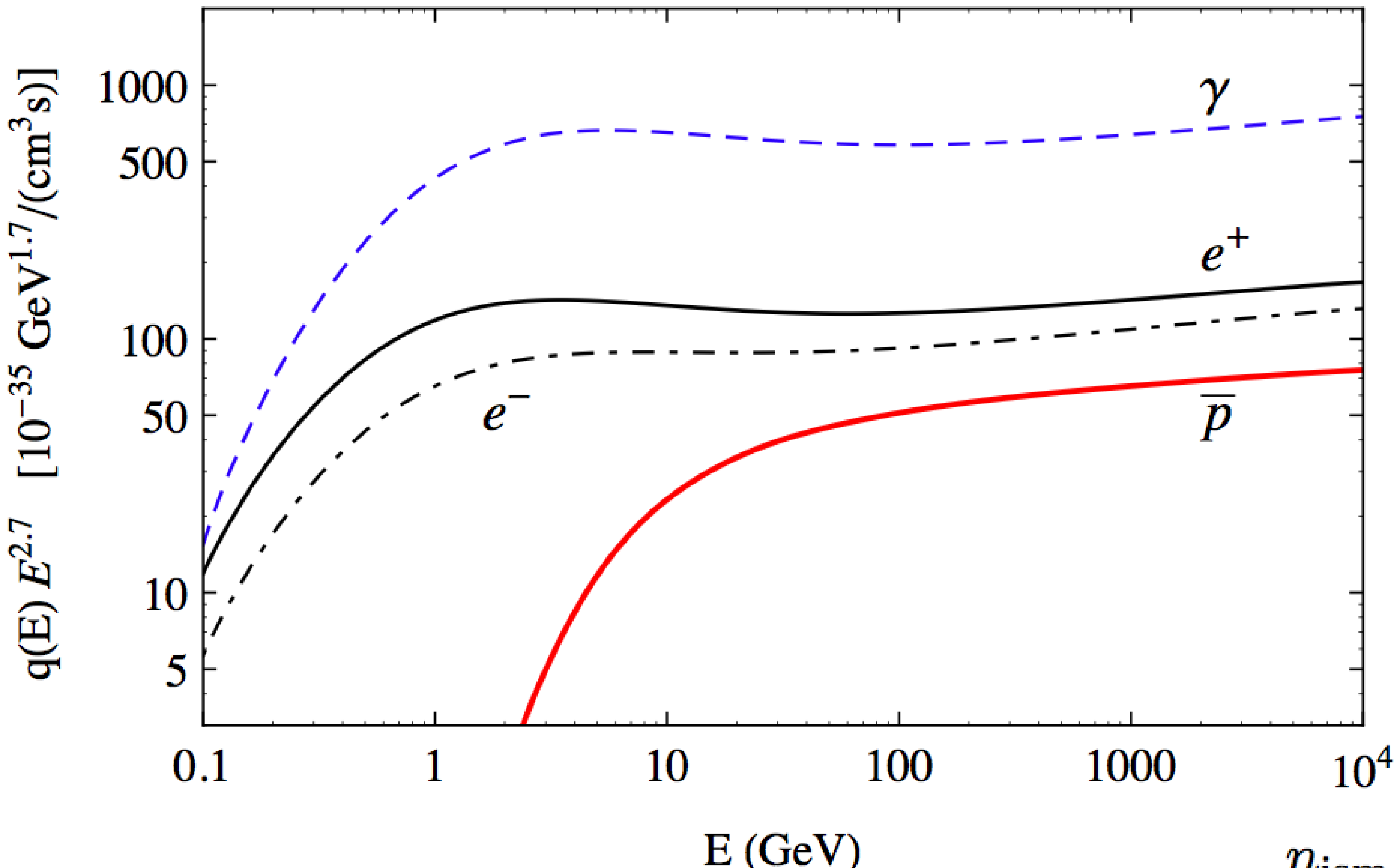
[1] Take spectra of cosmic rays (protons + nuclei) observed at the Earth

[2] Make them interact in the local interstellar medium (pp, p-He, He-p,...)

[3] Compute the rate of production of secondaries

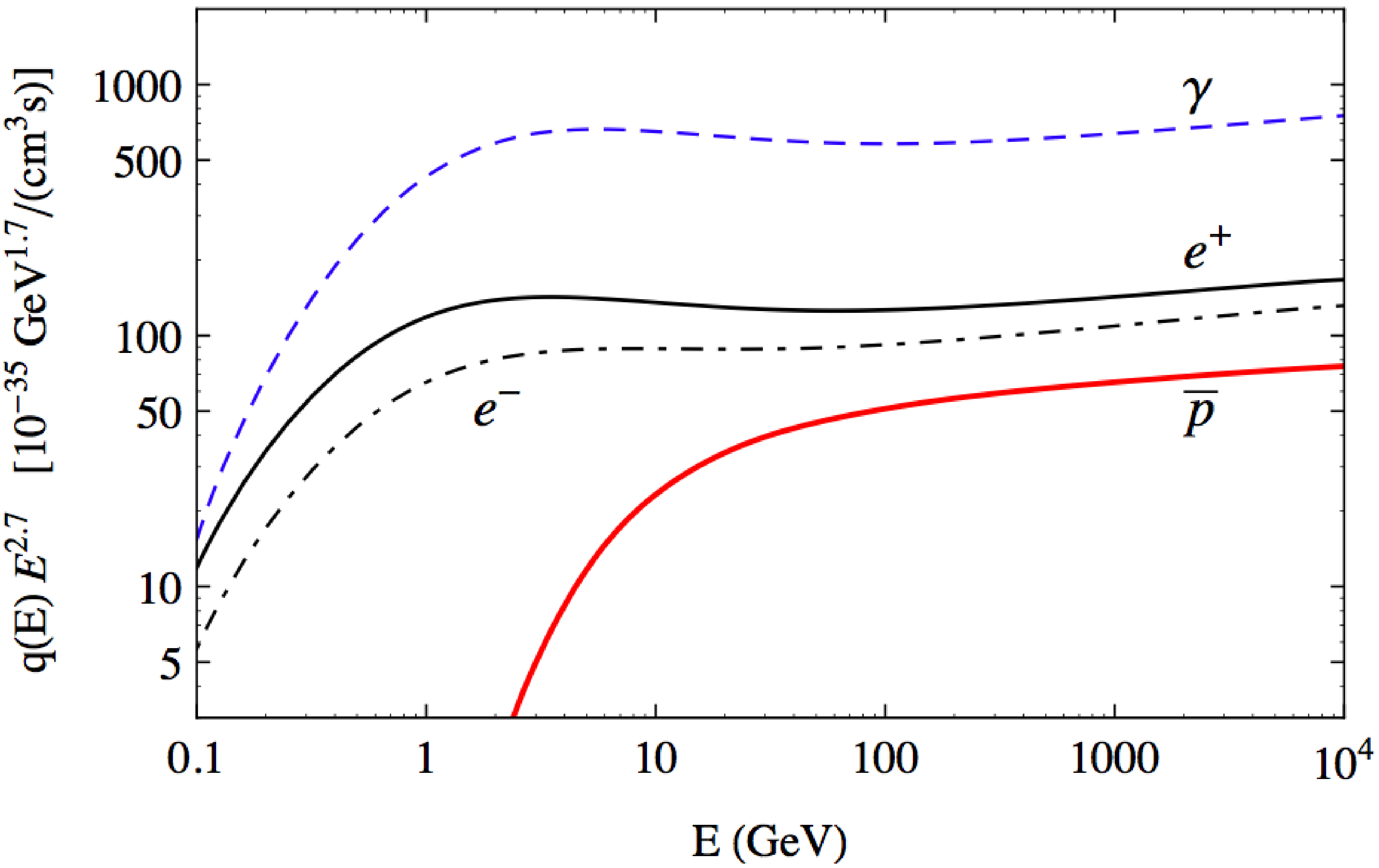
$$q_j(E, \vec{x}_\odot)$$

$[\text{cm}^3 \text{ s GeV}]^{-1}$



$$n_{\text{ism}}(\vec{x}_\odot) = 1 \text{ cm}^{-3}$$

"Local" Rate of production of secondaries



$$\frac{\gamma}{e^+} \approx 5.5$$

$$\frac{e^-}{e^+} \approx 0.8$$

$$\frac{e^+}{\overline{p}} \approx 2.0$$

Different low energy behaviors
(low energy antiproton production suppressed)

Power Law behavior at high energy

Radiation Mechanisms for Electrons and Positrons:

SYNCHROTRON

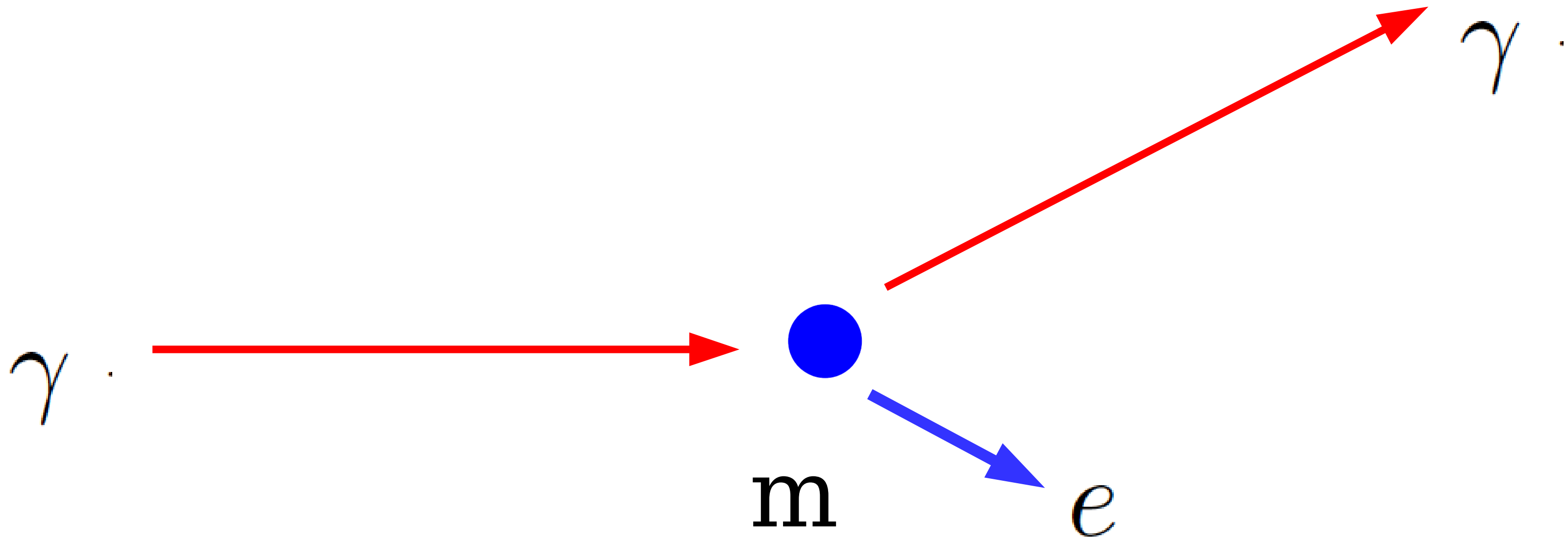
INVERSE COMPTON scattering

Compton scattering

$$e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma$$

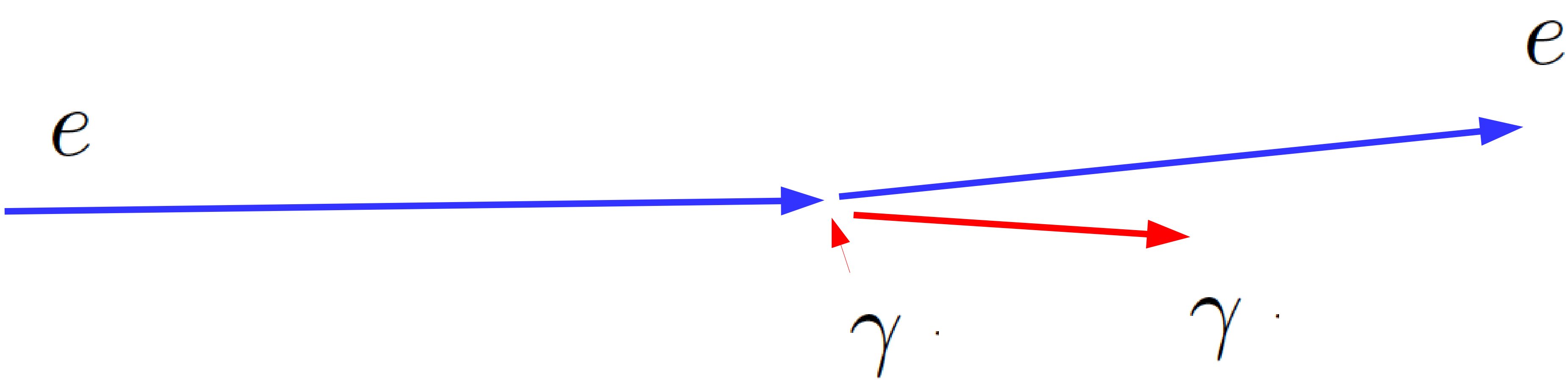
Scattering between an electron (or positron) and a photon.

“Normally” (and historically) it is studied experimentally in the electron rest frame



Here the photon loses energy to the electron.

In astrophysics it is important when a high energy, relativistic electron (E >> m) scatter with a "soft photon" such as a visible light photon (of a few eV) or a photon of the Cosmic Microwave Background Radiation [T = 2.725 Kelvin = 0.000234 eV]



The electron loses energy, and generates Gamma rays.

"Inverse Compton"

$$\varepsilon_i(\text{rest frame}) = \varepsilon'$$

$$m_e \; \varepsilon'_i = \varepsilon_i \; E_i \; (1 - \cos\theta_{\gamma e})$$

“Thomson regime”

Quantum mechanics result is identical to the classical result

$$\varepsilon_i^{\text{rest frame}} < m_e$$

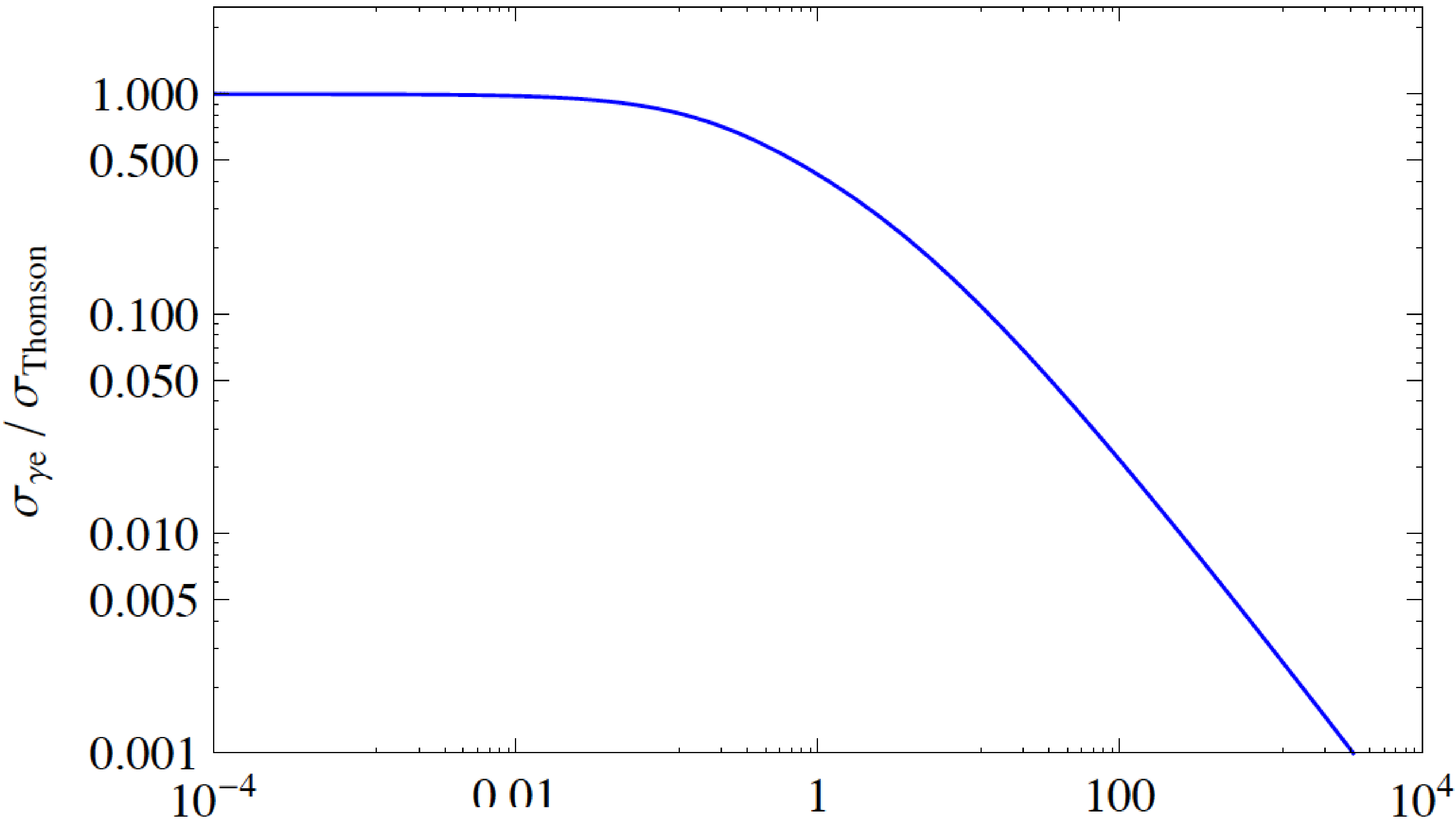
$$\varepsilon_i \; E_{e,i} < m_e^2$$

“Klein-Nishina regime”

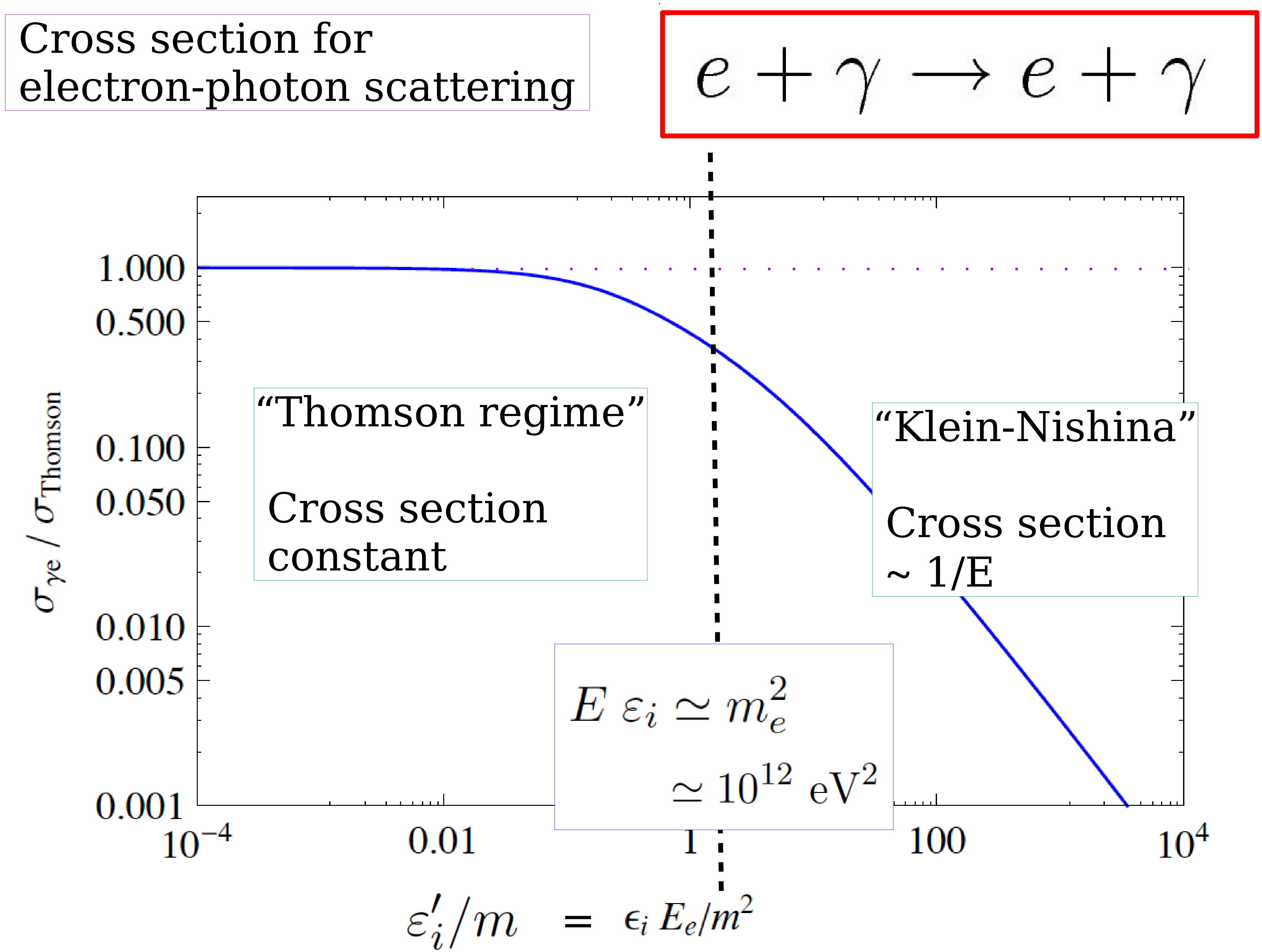
$$\varepsilon_i \; E_{e,i} >> m_e^2$$

Cross section for electron-photon Compton scattering

$$e + \gamma \rightarrow e + \gamma$$



$$\varepsilon'_i/m = \epsilon_i \, E_e/m^2$$



Cross section for electron-photon scattering
$e + \gamma \to e + \gamma$
1.000
0.500
0.100
0.050
0.010
0.005
0.001
$\sigma_{\gamma e} / \sigma_{\mathrm{Thomson}}$
"Thomson regime"
Cross section constant
"Klein-Nishina"
Cross section ~ 1/E
$E\, \varepsilon_i \simeq m_e^2$
$\simeq 10^{12}$ eV^2
10^{-4}
0.01
1
100
10^4
$\varepsilon_i'/m = \epsilon_i E_e/m^2$

$$\sigma_{\text{Thomson}} = \frac{8\pi}{3} \frac{e^2}{(m_e\, c^2)^2} = \frac{8\pi}{3}\, r_0^2$$

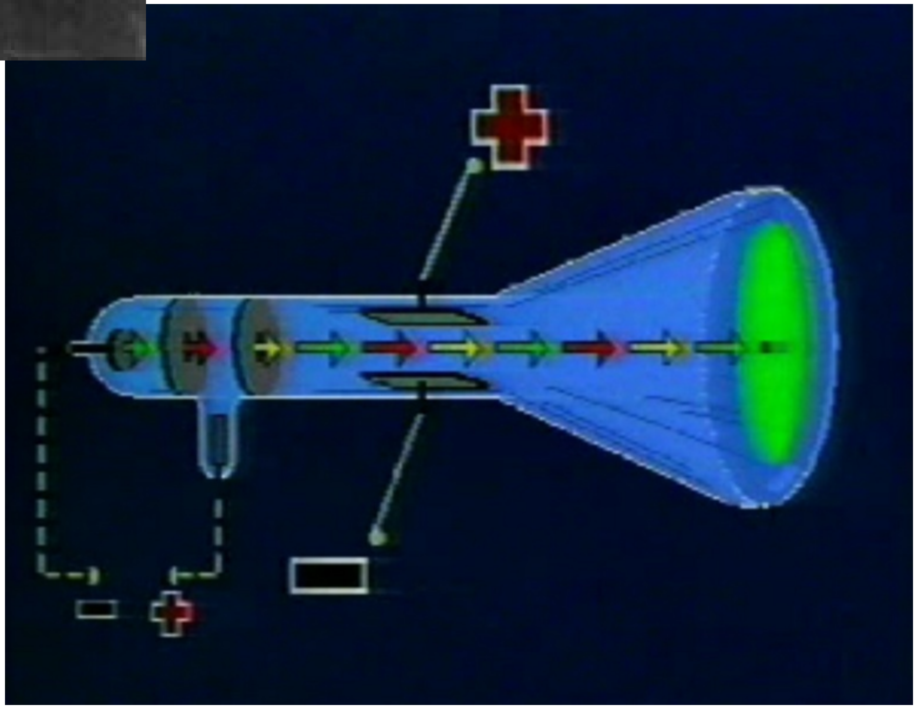
$$\simeq 6.65 \times 10^{-25}\ \text{cm}^2$$

$$\sigma \propto \frac{1}{m^2}$$

Scattering process important only for electrons/positrons

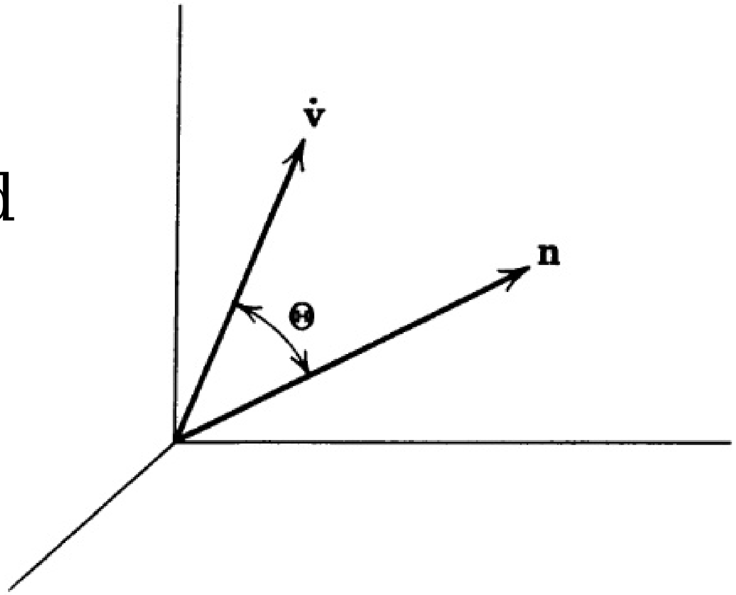
J.J Thomson (1897)

Discovery of the electron



Thomson regime

Classical results
of radiation from an accelerated
electric charge that has
a small velocity (v/c << 1)



$$\frac{dP}{d\Omega} = \frac{e^2}{4\pi c^3} |\dot{\mathbf{v}}|^2 \sin^2\Theta$$

Power emitted
per unit solid angle

$$P = \frac{2}{3}\frac{e^2}{c^3} |\dot{\mathbf{v}}|^2$$

Total emitted power

Larmor's formula

Jackson, Classical Electrodynamics, sec.14.8

Thomson Scattering of Radiation

If a plane wave of monochromatic electromagnetic radiation is incident on a free particle of charge e and mass m, the particle will be accelerated and so emit radiation. This radiation will be emitted in directions other than that of the incident plane wave, but for nonrelativistic motion of the particle it will have the same frequency as the incident radiation. The whole process may be described as scattering of the incident radiation.

$$\frac{d\sigma}{d\Omega} = \frac{\text{Energy radiated/unit time/unit solid angle}}{\text{Incident energy flux in energy/unit area/unit time}}$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{mc^2}\right)^2 \cdot \frac{1}{2}(1 + \cos^2\theta)$$

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2$$

$$\sigma_{\text{Thomson}} = 6.65 \times 10^{-25}\ \text{cm}^2$$

Average over polarization
of incident wave,
sum over polarization
of scattered wave

Classically, the scattered radiation has the same frequency of the incident wave.

Quantum mechanically,
in the scattering between particles
this cannot be exactly true, because
of conservation of energy and momentum.

$$\varepsilon_f(\cos\theta) = \frac{\varepsilon_i}{1 + \frac{\varepsilon_i}{m}(1-\cos\theta)}$$

Variables in electron rest frame

Classically, the scattered radiation has the same frequency of the incident wave.

Quantum mechanically,
in the scattering between particles this cannot be exactly true, because of conservation of energy and momentum.

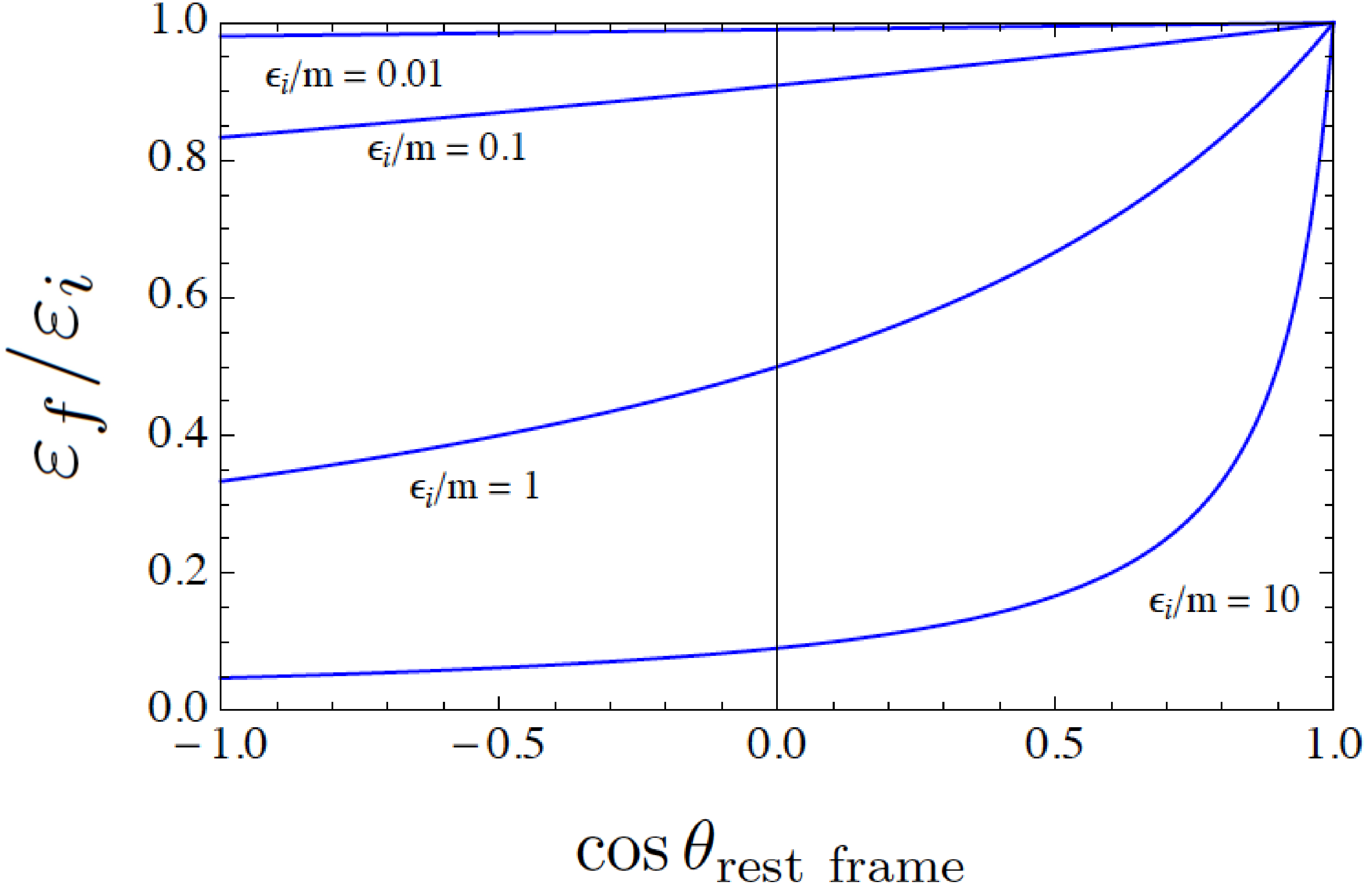
$$\varepsilon_f(\cos\theta) = \frac{\varepsilon_i}{1 + \frac{\varepsilon_i}{m}(1 - \cos\theta)}$$

Variables in electron rest frame

COMPTON experiment confirms Einstein/Planck theory !
Scattered light changes its wavelength

Kinematics of Compton Scattering in the electron rest frame

$$\varepsilon_f(\cos\theta) = \frac{\varepsilon_i}{1 + \frac{\varepsilon_i}{m}(1 - \cos\theta)}$$



$$\varepsilon_f(\cos\theta) = \frac{\varepsilon_i}{1 + \frac{\varepsilon_i}{m}(1 - \cos\theta)}$$

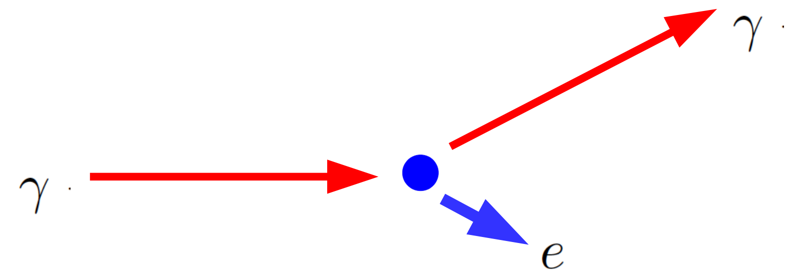
$$\frac{\varepsilon_i}{m} << 1$$

$$\varepsilon_f \simeq \varepsilon_i$$

Variables in electron rest frame

Kinematically this is simple to understand
("scattering of a light particle on a very massive object")

$$\varepsilon_f \simeq \varepsilon_i$$



Variables in electron rest frame

What happens in a frame where the electron is ultra-relativistic with Lorentz factor gamma ?

$$0 \lesssim \varepsilon_f \leq 4\,\varepsilon_i\,\gamma^2$$

Combination of two Lorentz transformation

$$\varepsilon_i' = \gamma \varepsilon_i (1 + \beta)$$

Lorentz transformation to get rest-frame Energy

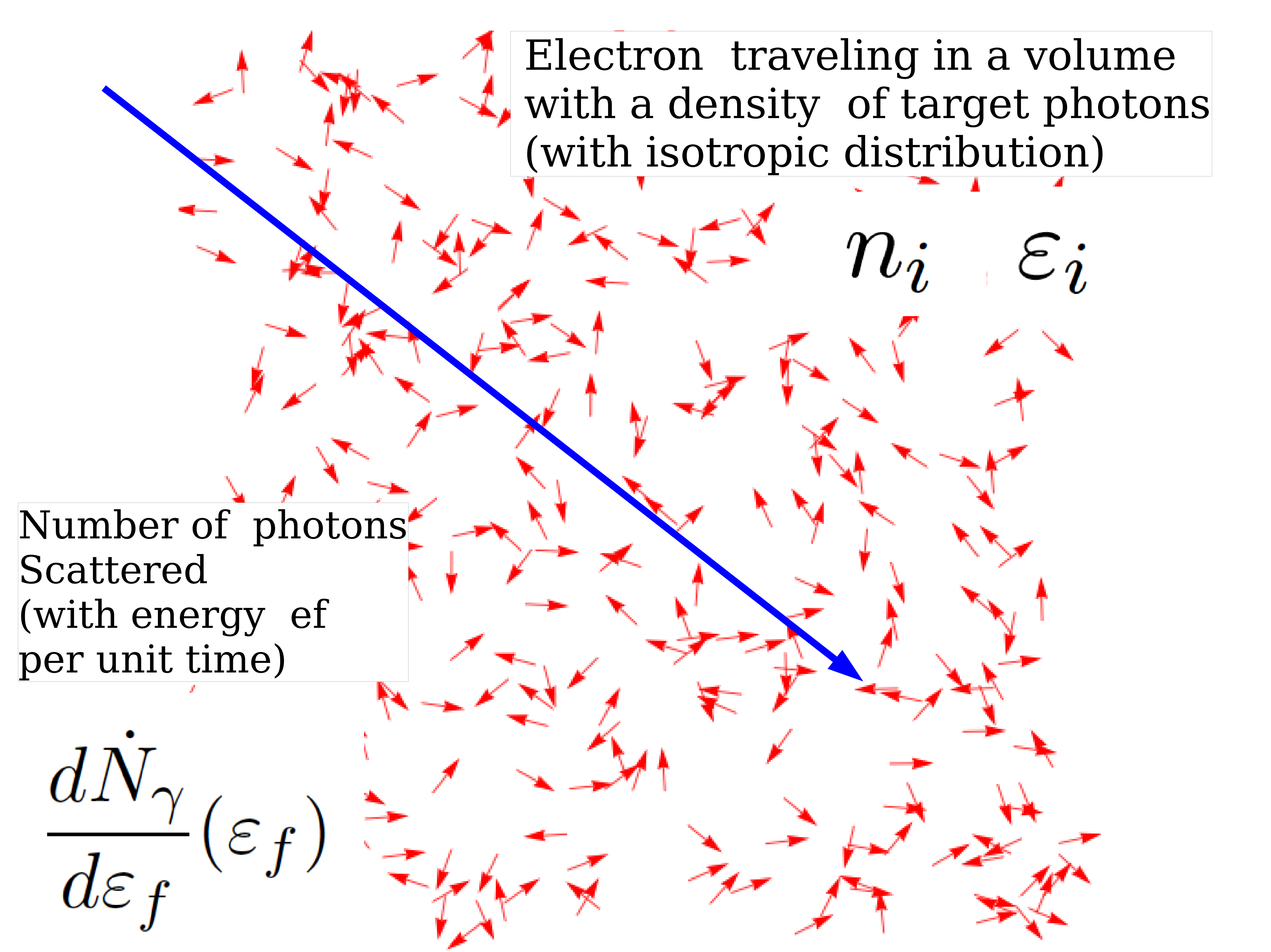
$$\varepsilon_f = \gamma \varepsilon'_f (1 + \beta)$$

Backward scattering

$$\varepsilon'_f = \varepsilon_i'$$

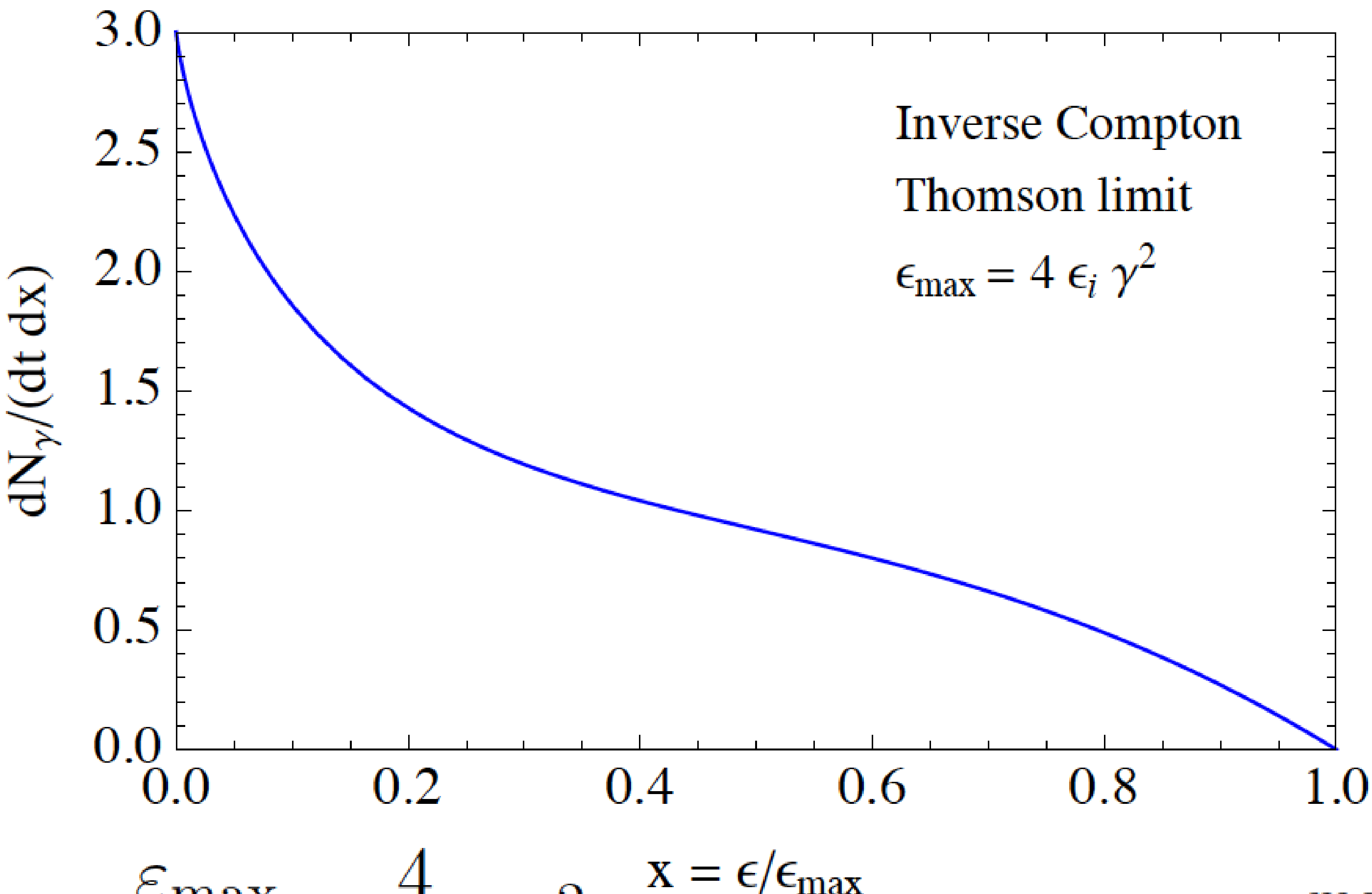
Second transformation to go back to lab. frame

$$\varepsilon_f = \gamma^2 \varepsilon_i (1 + \beta)^2 \simeq 4\gamma^2 \varepsilon_i$$


Electron traveling in a volume
with a density of target photons
(with isotropic distribution)
n_i ε_i
Number of photons
Scattered
(with energy ef
per unit time)
$\frac{d\dot{N}_\gamma}{d\varepsilon_f}(\varepsilon_f)$

$$\frac{d\dot{N}_\gamma}{d\varepsilon_f}(\varepsilon_f) = \sigma_{\rm th}\, c\, \frac{1}{4\gamma^2\,\varepsilon_i}\, F_{\rm th}\left(\frac{\varepsilon_f}{4\gamma^2\varepsilon_i}\right)$$

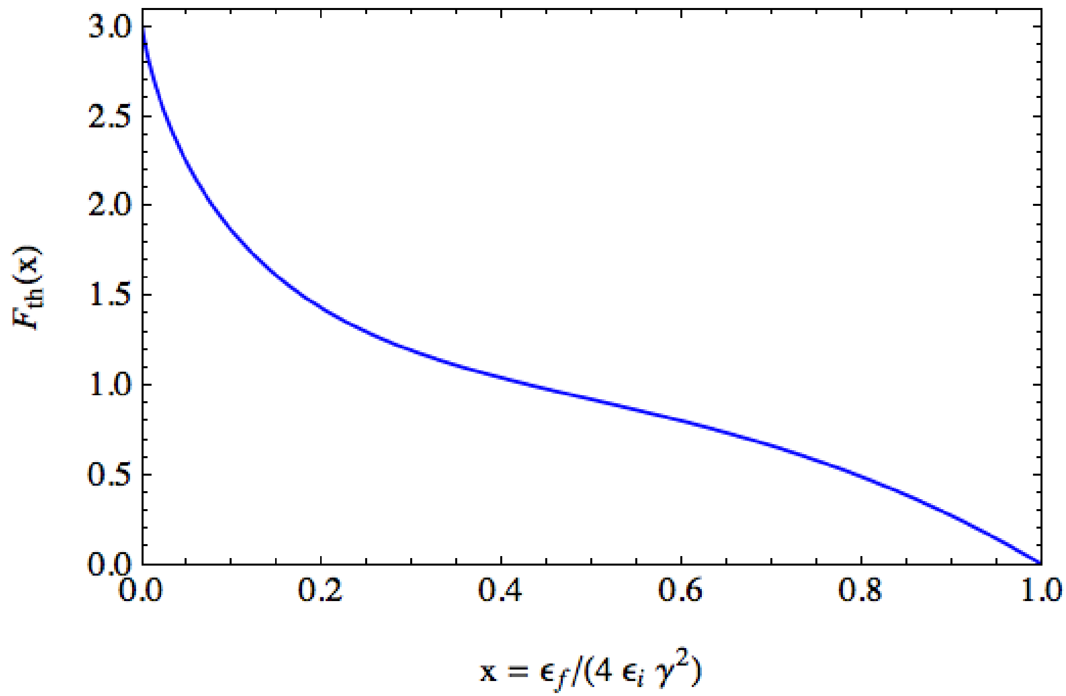
See Blumenthal + Gould Rev.Mod.Phys. Apr. 1970



$$\langle \varepsilon_f \rangle = \frac{\varepsilon_{\rm max}}{3} = \frac{4}{3}\varepsilon_i\,\gamma^2$$

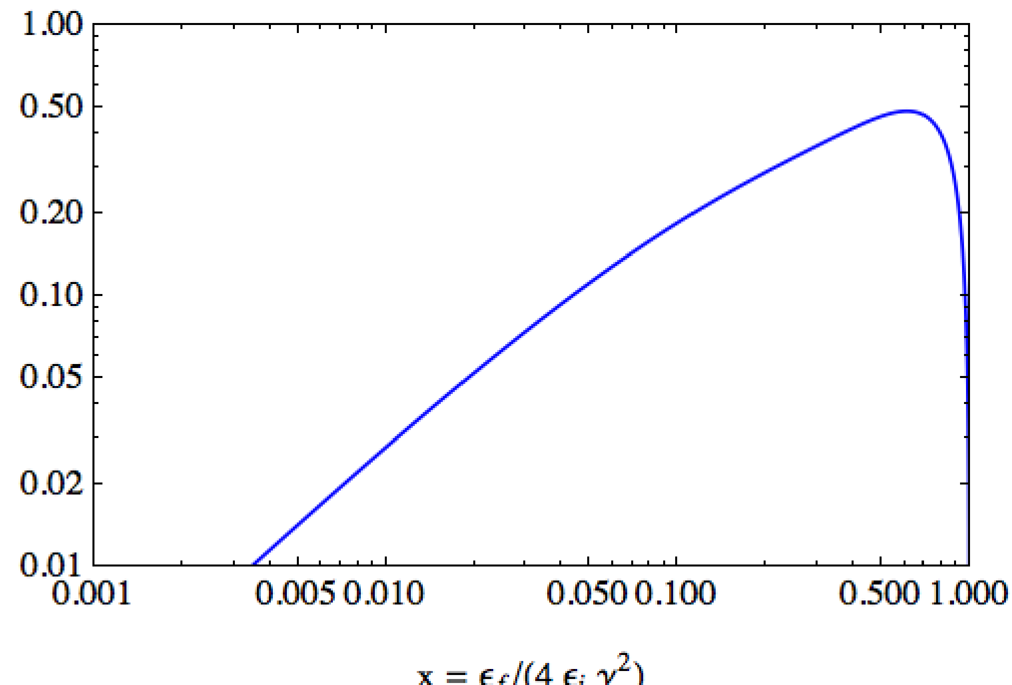
$$\varepsilon_f^{\rm max} \simeq 4\,\varepsilon_i\,\gamma^2$$

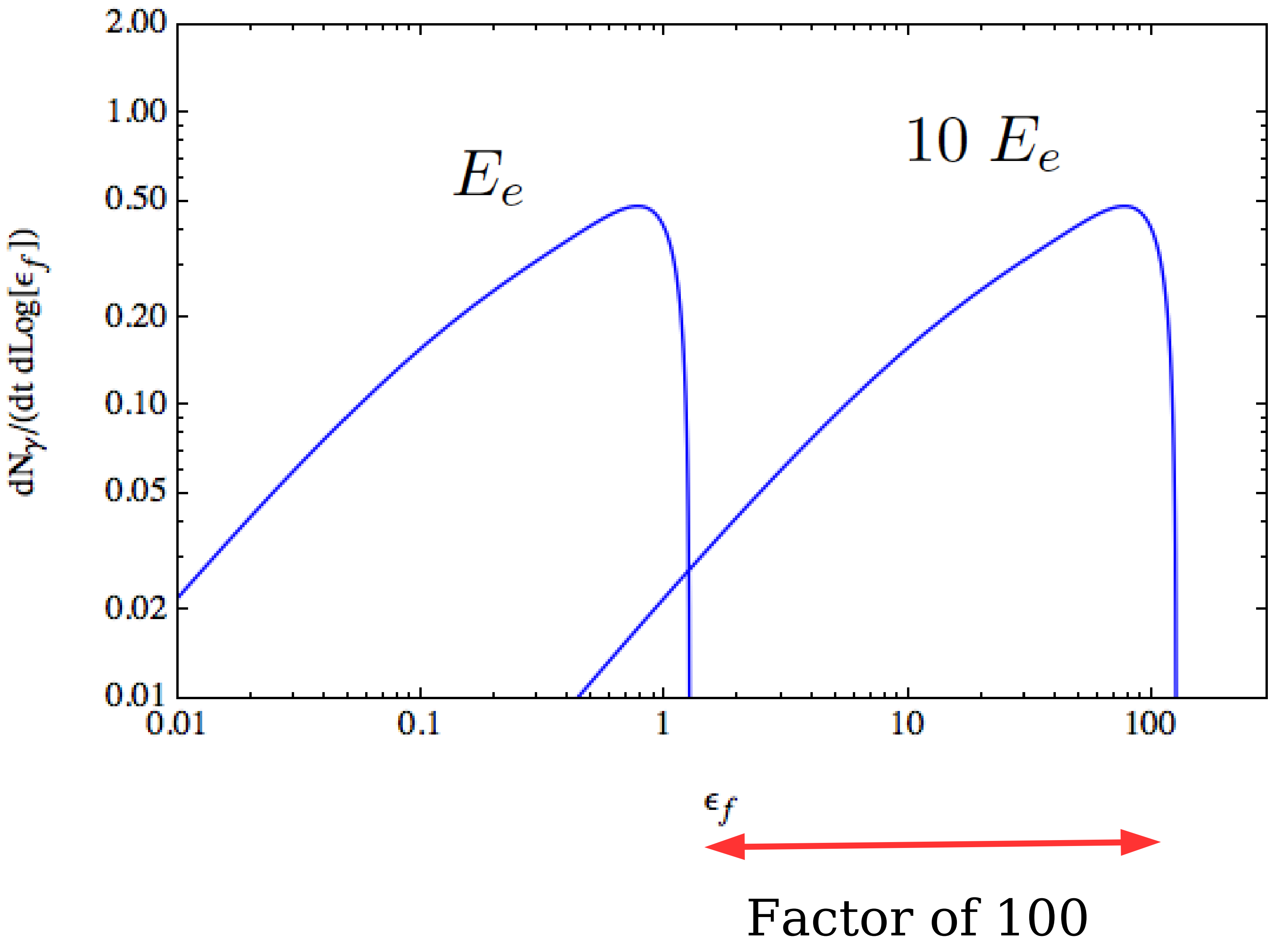
$$F_{\rm Th}(x) = 3\ \left[2x\,\log x + x + 1 - 2x^2\right]$$



$$\frac{dN_\gamma}{dx}$$

$$\frac{dN_\gamma}{d\log x}$$





E_e
$10\ E_e$
dN$_\gamma$/(dt dLog[ϵ_f])
2.00
1.00
0.50
0.20
0.10
0.05
0.02
0.01
0.01
0.1
1
10
100
ϵ_f
Factor of 100

Inverse Compton Scattering

Radiation Field: Density: n_γ^{target}

Photon energy: ε_i

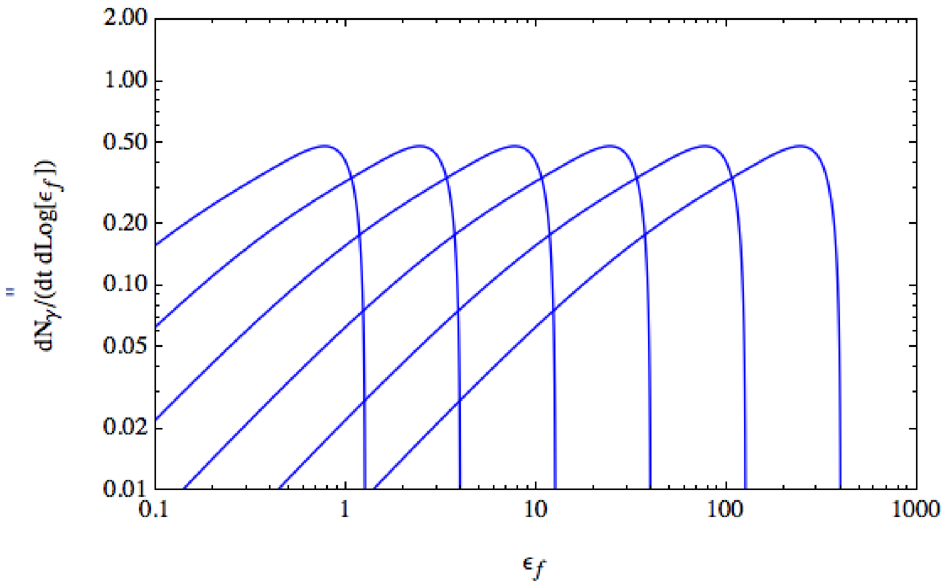
$$\dot{N}_\gamma^{[\text{Inv.Compt.}]} = (\sigma_{\text{Th}}\, c)\; n_\gamma^{\text{target}}$$

Interaction rate

$$\langle \varepsilon_f \rangle = \frac{4}{3} \varepsilon_i\, \gamma^2 \qquad \gamma = E/m$$

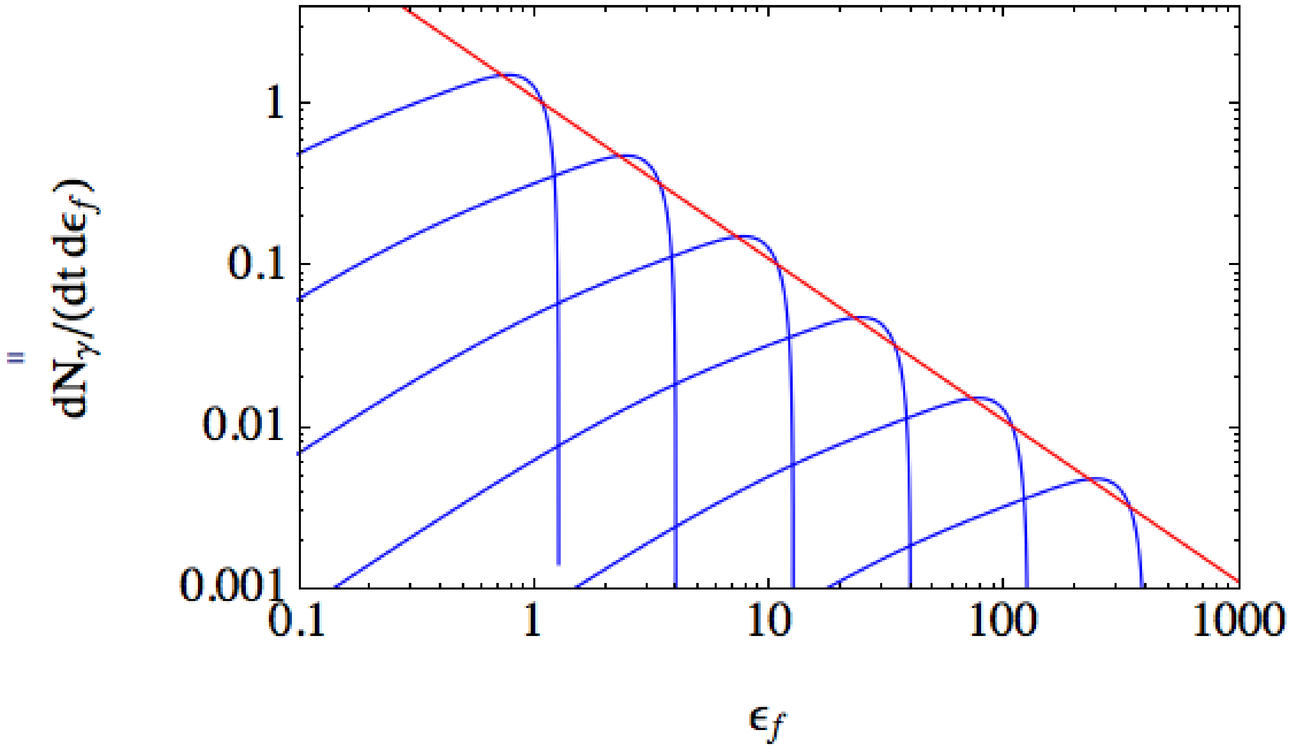
Average energy of scattered photon

$$\left[\frac{dE}{dt}\right]_{\text{Inv.Compt.}} = \dot{N}_\gamma\, \langle \varepsilon_f \rangle = \frac{4}{3}\, (\sigma_{\text{Th}}\, c)\, (n_\gamma^{\text{target}}\, \varepsilon_i)\, \gamma^2$$

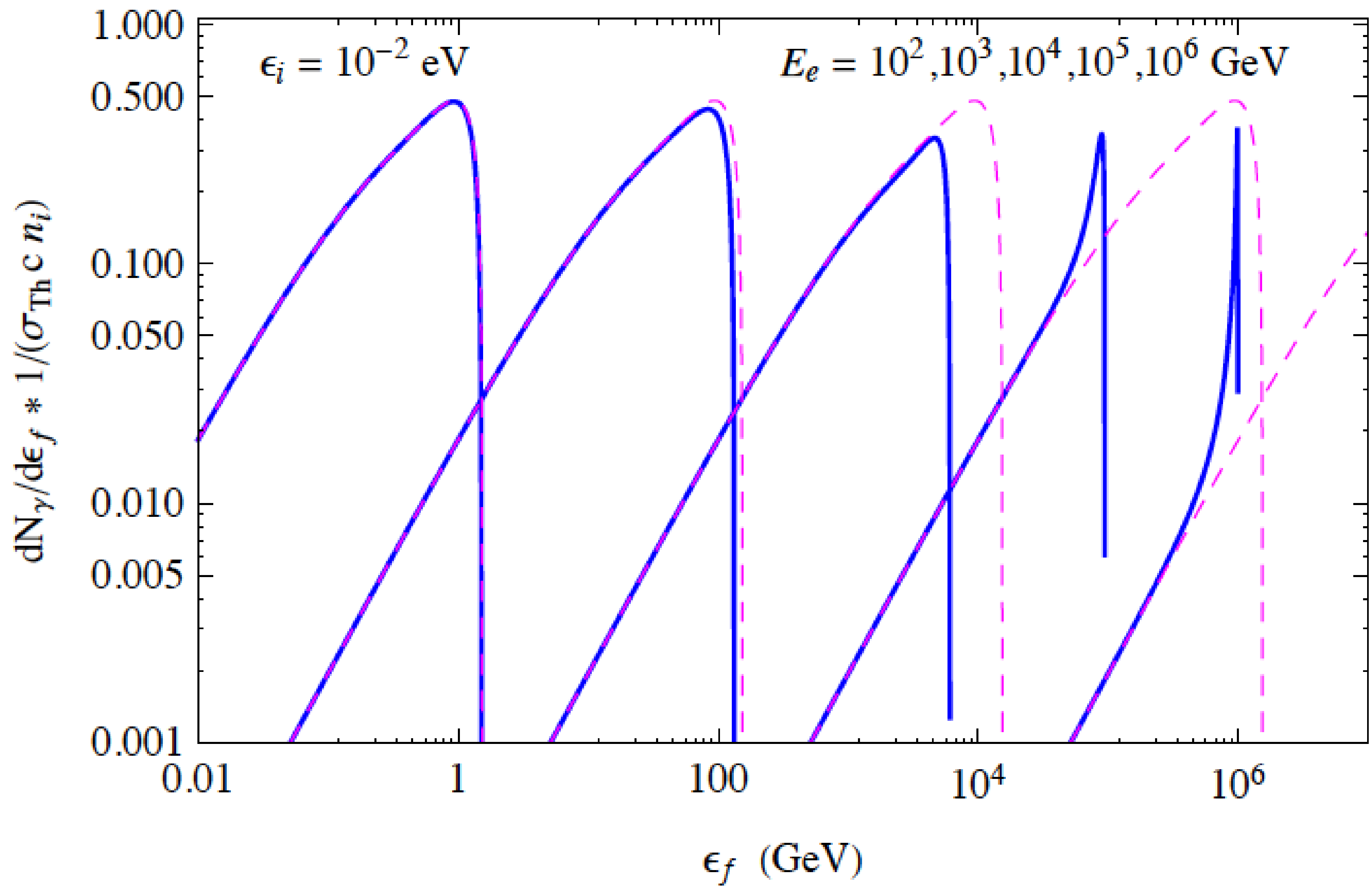


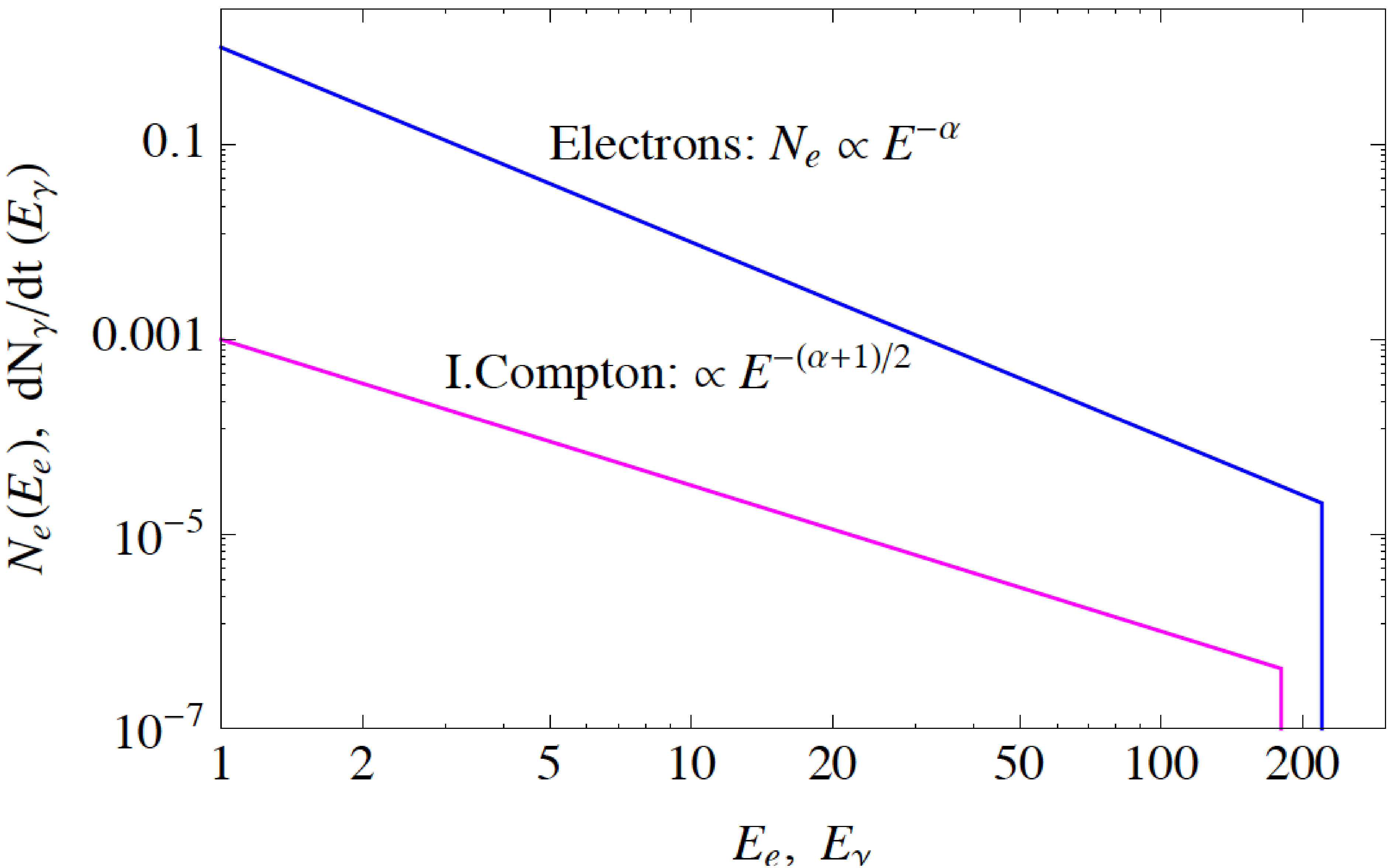
Contributions of
different electron energy

Power Law
of electrons



$$\frac{d\dot{N}_\gamma}{d\varepsilon_f}(\varepsilon_f) = \sigma_{\rm th}\, c\, \frac{1}{4\gamma^2\,\varepsilon_i}\, F_{\rm th}\left(\frac{\varepsilon_f}{4\gamma^2\varepsilon_i}\right)$$





Electrons: $N_e \propto E^{-\alpha}$
I.Compton: $\propto E^{-(\alpha+1)/2}$
0.1
0.001
10^{-5}
10^{-7}
1
2
5
10
20
50
100
200
$N_e(E_e)$, $dN_\gamma/dt\,(E_\gamma)$
E_e, E_ν

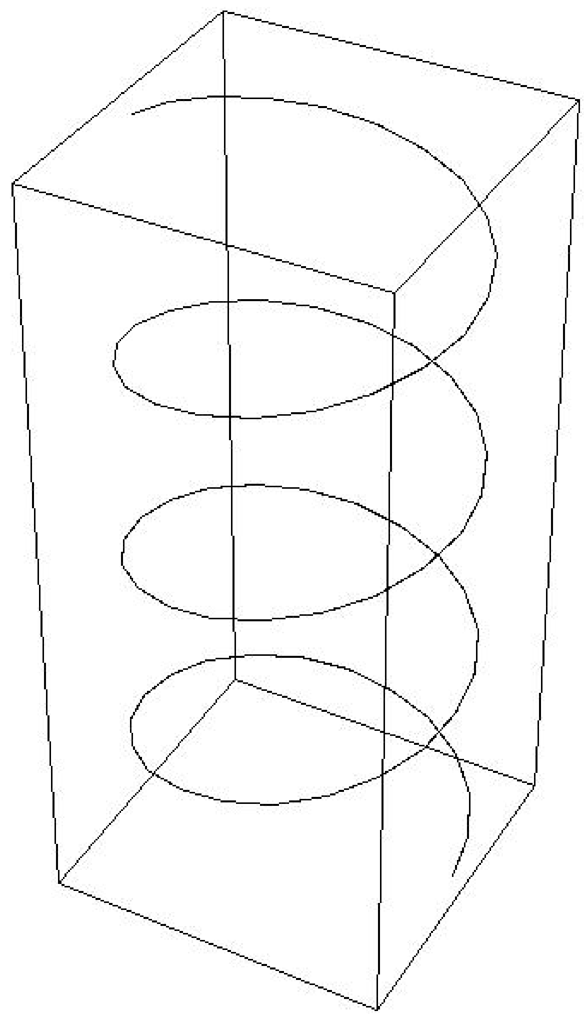
$$N_e(\gamma) = K_e\,\gamma^{-\alpha}$$

$$\frac{d\dot{N}_\gamma}{d\varepsilon_f} = K_\gamma\;\varepsilon_f^{-(\alpha+1)/2}$$

$$\frac{d\dot{N}_\gamma}{d\varepsilon_f} = \left[K_e\,a(\alpha)\,\left[\sigma_{Th}\,c\,n_\gamma^{\rm target}\right]\,\varepsilon_i^{(\alpha-1)/2}\right]\;\varepsilon_f^{-(\alpha+1)/2}$$

$$a(\alpha) = \frac{12(11+4\alpha+\alpha^2)}{(1+\alpha)(4+\alpha)(3+\alpha)^2}$$

Synchrotron radiation



Emission of radiation
from relativistic
charged particles
propagating in
in a magnetic field

Classical and
Quantum Mechanical treatments
give the same results for
all astrophysical problems
(identifying frequency and energy)

$$-\left.\frac{dE}{dt}\right|_{\rm syn}(E,B) = \frac{4}{3}\left(\frac{8\pi}{3}\,\frac{e^4}{m^2c^4}\right)\,\frac{B^2}{8\pi}\,\left(\frac{E}{m\,c^2}\right)^2$$

$\sigma_{\rm Th}$ [energy density] γ^2

$$-\left.\frac{dE}{dt}\right|_{\rm syn} \propto \frac{E^2\;B^2}{m^4}$$

$$-\frac{dE}{dt} \propto \sin^2\alpha$$

$$\langle \sin^2\alpha \rangle = \frac{2}{3}$$

Energy loss for synchrotron grows proportionally to B^2 E^2 m^{-4}

Average for random orientation of the field

Important only for electrons and positrons (except for very extraordinary circumstances)

Total Energy Loss for Synchrotron Radiation:

$$-\frac{dE}{dt} = \frac{2}{3}\frac{e^2}{c^3}\ a^2$$

$$a = |\dot{\vec{v}}|$$

Larmor Formula

valid for acceleration
of particle at rest
(or v << c)

Result valid in frame where the particle is non relativistic
+ need to boost in the laboratory frame

Total Energy Loss for Synchrotron Radiation:

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Larmor Formula

$$a = |\dot{\vec{v}}|$$

valid for acceleration
of particle at rest
(or v << c)

Result valid in frame where the particle is non relativistic
+ need to boost in the laboratory frame

$$-\frac{dE}{dt} = \frac{2}{3}\frac{e^2}{c^3}\left[\frac{1}{m^2c^2}\left(\frac{dp^\alpha}{d\tau}\frac{dp_\alpha}{d\tau}\right)\right]$$

Write in
relativistic
invariant form

$$-\frac{dE}{dt} = \frac{2}{3}\left(\frac{e^4}{m^2\,c^4}\right)\frac{1}{c}\;\gamma^2\,B^2\,v_\perp^2$$

transverse=
orthogonal to B

$$\frac{dp^\alpha}{d\tau}\frac{dp_\alpha}{d\tau} = \left(\frac{d\vec{p}}{d\tau}\right)^2 - \frac{1}{c^2}\left(\frac{dE}{d\tau}\right)^2$$

$$d\tau = \frac{dt}{\gamma}$$

$$\frac{d\vec{p}}{dt} = e\frac{\vec{v}}{c} \wedge \vec{B}$$

Motion in a Magnetic field

$$\frac{1}{m^2\,c^2}\frac{dp^\alpha}{d\tau}\frac{dp_\alpha}{d\tau} = \gamma^2\left|e\frac{\vec{v}}{c} \wedge \vec{B}\right| = \gamma^2\,\frac{e^2 B^2\,v_\perp^2}{c^2}$$

$$-\left.\frac{dE}{dt}\right|_{\rm syn}(E,B) = \frac{4}{3}\left(\frac{8\pi}{3}\,\frac{e^4}{m^2c^4}\right)\,\frac{B^2}{8\pi}\,\left(\frac{E}{m\,c^2}\right)^2$$

$\sigma_{\rm Th}$ [energy density] γ^2

$$-\left.\frac{dE}{dt}\right|_{\rm syn} \propto \frac{E^2\;B^2}{m^4}$$

$$-\frac{dE}{dt} \propto \sin^2\alpha$$

$$\langle \sin^2\alpha \rangle = \frac{2}{3}$$

Energy loss for synchrotron grows proportionally to B^2 E^2 m^{-4}

Average for random orientation of the field

Important only for electrons and positrons (except for very extraordinary circumstances)

Angular distribution of the radiation

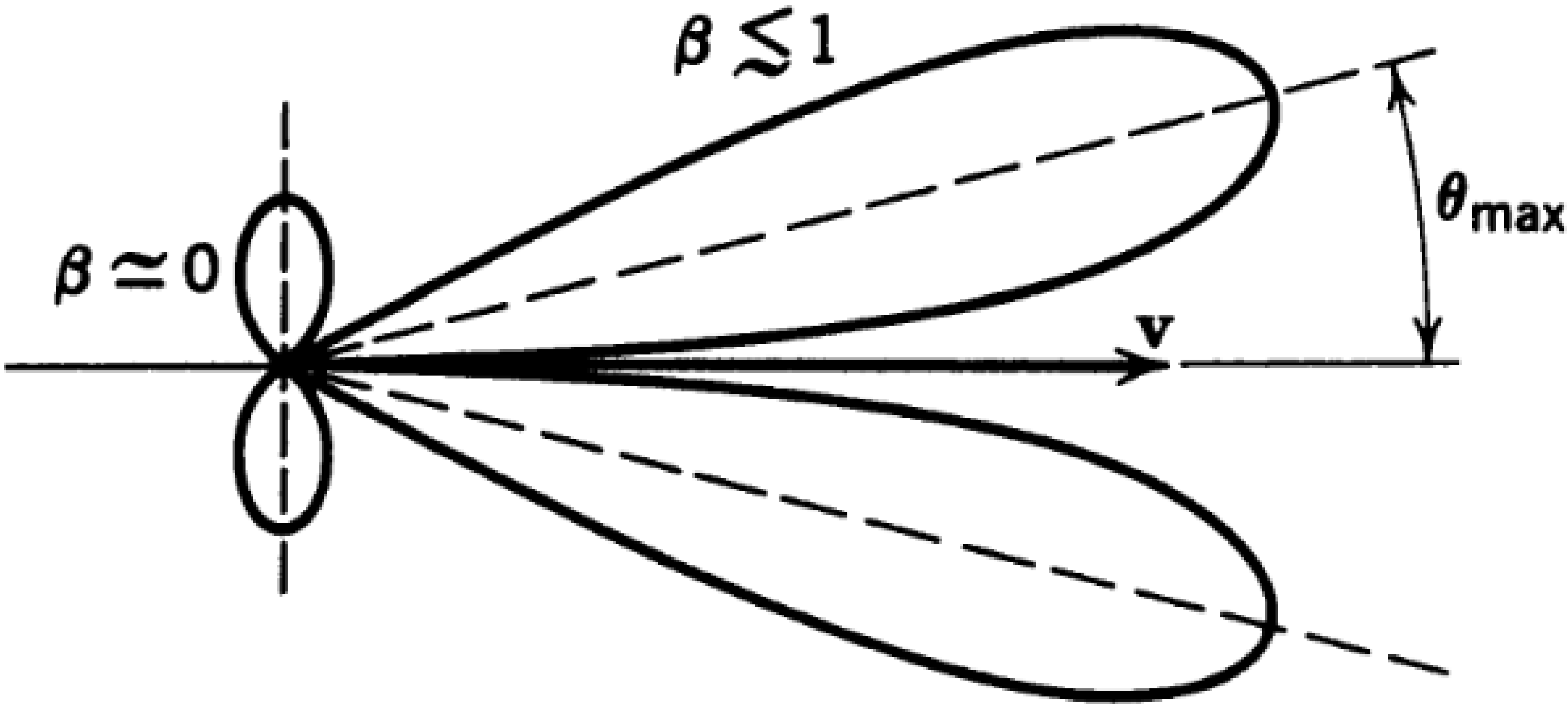
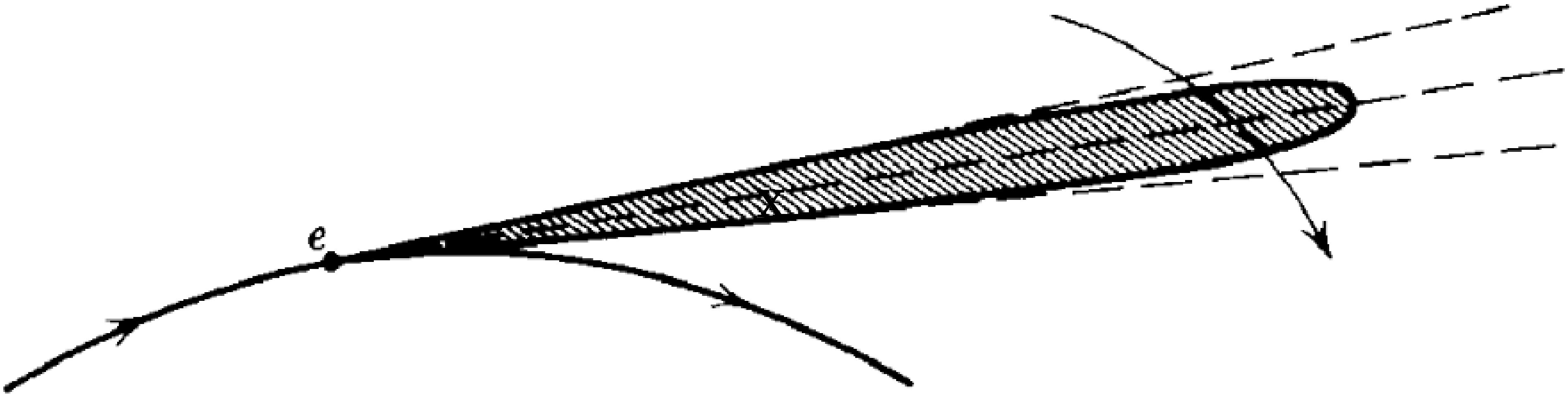


Figure 14.4 Radiation pattern for charge accelerated in its direction of motion. The two patterns are not to scale, the relativistic one (appropriate for $\gamma \sim 2$) having been reduced by a factor $\sim 10^2$ for the same acceleration.

From: Jackson
"Classical Electrodynamics"



Synchrotron radiation is emitted in cone of
Narrow angle along the instantaneous direction of
motion of the particle

$$\theta \sim \frac{1}{\gamma} = \frac{m}{E}$$

Dependence on the energy (or frequency) of the emitted photon.

$$\left.\frac{dL}{d\nu}\right|_{\rm syn} (\nu, B, \gamma, \alpha)$$

Classical electrodynamics (for example chapter 14 of Jackson)

$$\left.\frac{d\dot{N}_\gamma}{d\varepsilon_f}\right|_{\rm syn} (\varepsilon_f, \gamma, B, \alpha)$$

Quantum mechanical calculation

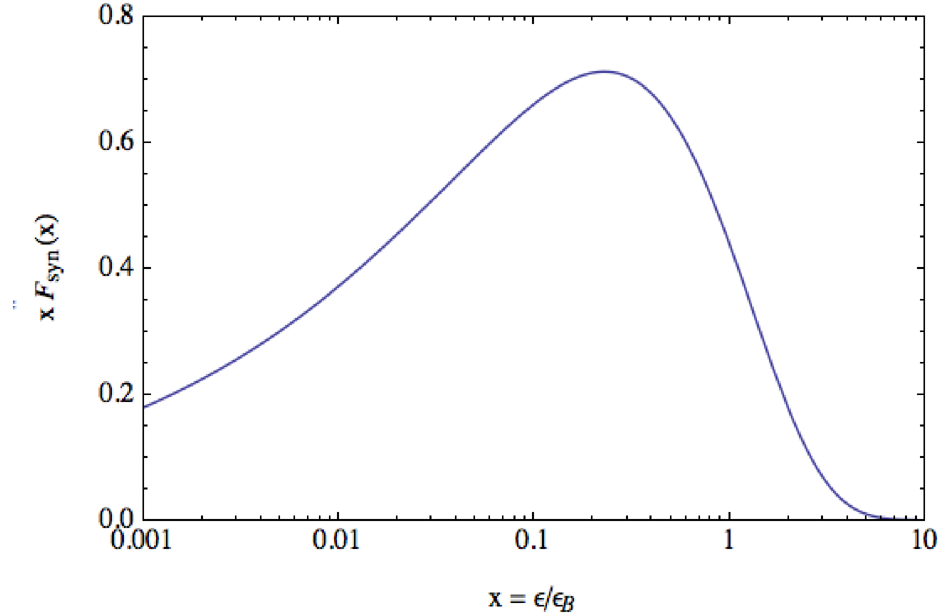
$$\varepsilon_f = 2\pi \hbar \nu \qquad \frac{dL}{d\varepsilon_f} = \varepsilon_f \, \frac{d\dot{N}_\gamma}{d\varepsilon_f}$$

$$\left.\frac{d\dot{N}_\gamma}{d\varepsilon_f}\right|_{\text{syn}} (\varepsilon_f, \gamma, B, \alpha) = \frac{\sqrt{3}}{2\pi} \; \frac{e^3\, B}{m\, c^2\, \hbar} \; \frac{1}{\varepsilon_c} F_{\text{syn}} \left(\frac{\varepsilon}{\varepsilon_c\; \sin\alpha} \right)$$

Characteristic (or “critical”) energy

$$\varepsilon_c = \frac{3}{2}\; \frac{e\, B}{m\, c^2}\, \hbar c\, \gamma^2$$

$$F_{\text{syn}}(x) = \int_y^\infty dy\; K_{5/3}(y)$$



α = “Pitch angle”
angle between the velocity of the particle
and the magnetic field

$$\varepsilon_c = \frac{3}{2} \frac{e B}{m c^2} \hbar c \gamma^2$$

Critical energy
for synchrotron emission

$$\varepsilon_c \simeq 0.0665 \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{E}{\mathrm{TeV}}\right)^2 \mathrm{eV}$$

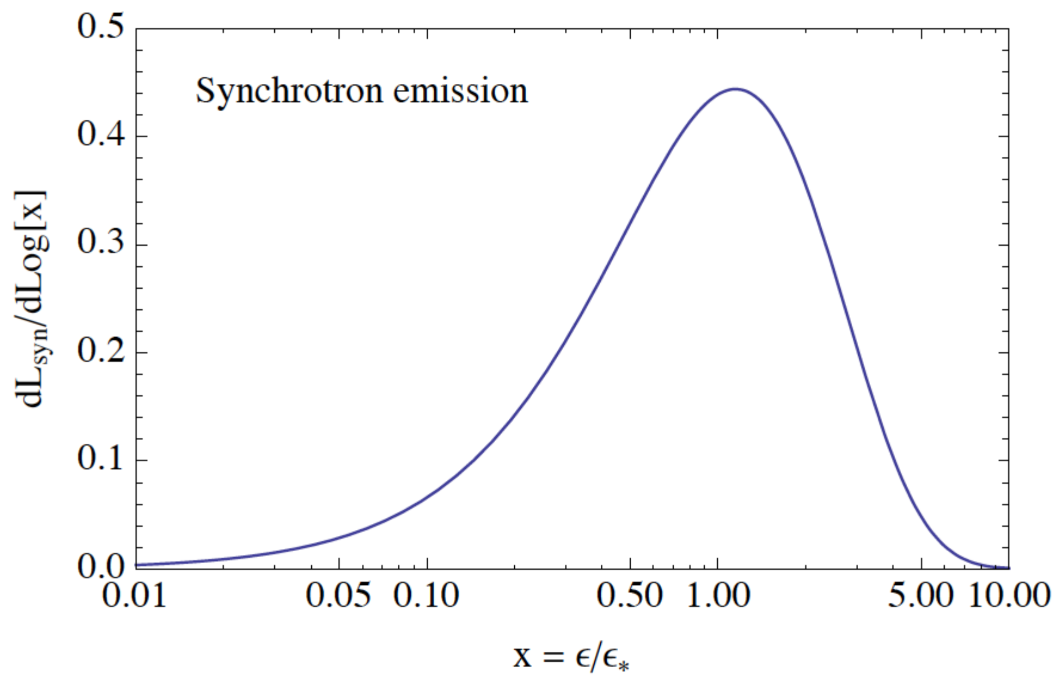
Most of the power
emitted around the
critical energy

Example of
CRAB nebula

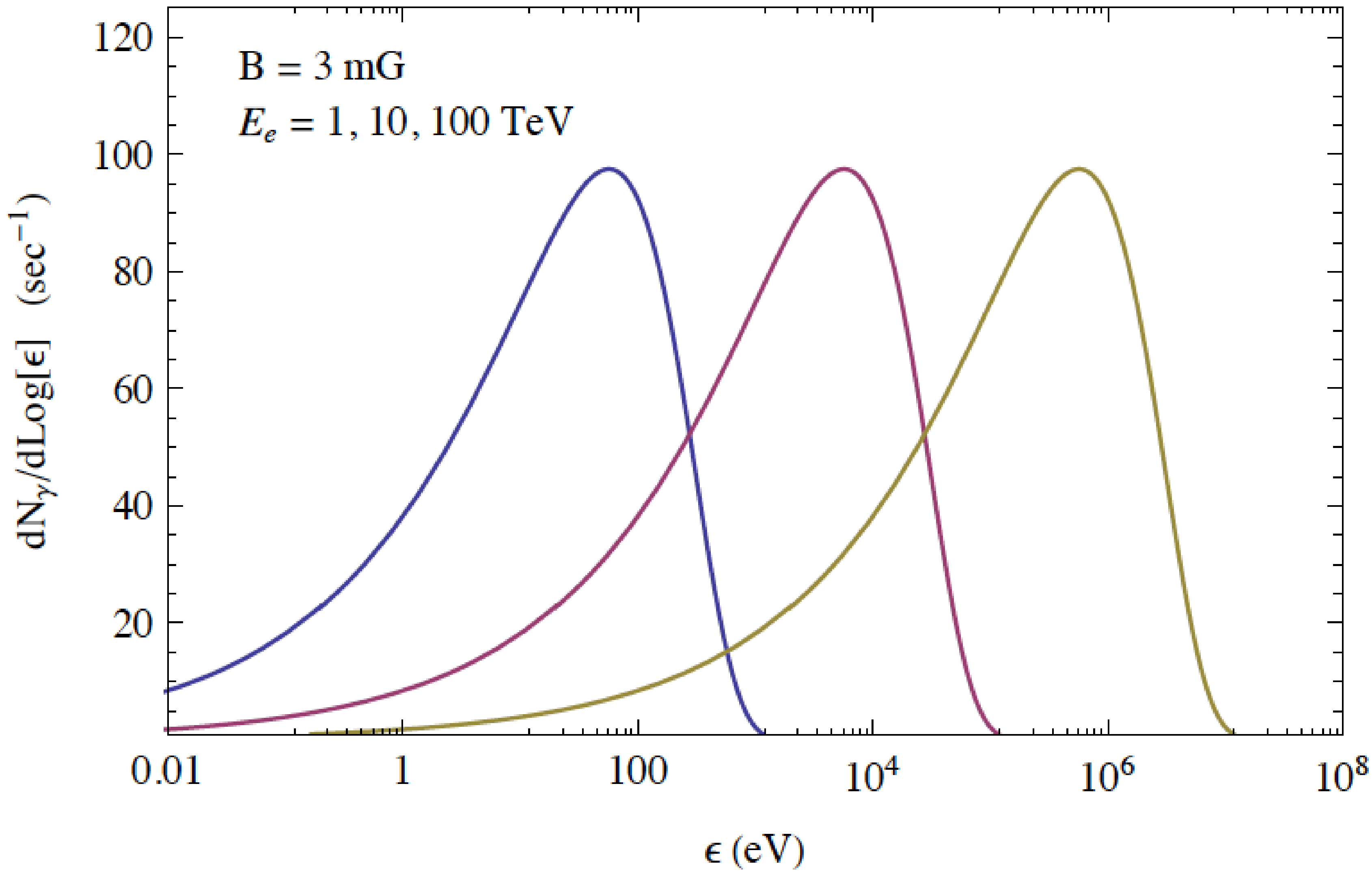
$$E_{\mathrm{max}} \simeq 3 \times 10^{15} \mathrm{eV}$$

$$B_{\mathrm{Crab}} \simeq 120 \mu\mathrm{Gauss}$$

$$\varepsilon_{\mathrm{syn,max}} \simeq 70 \mathrm{MeV}$$

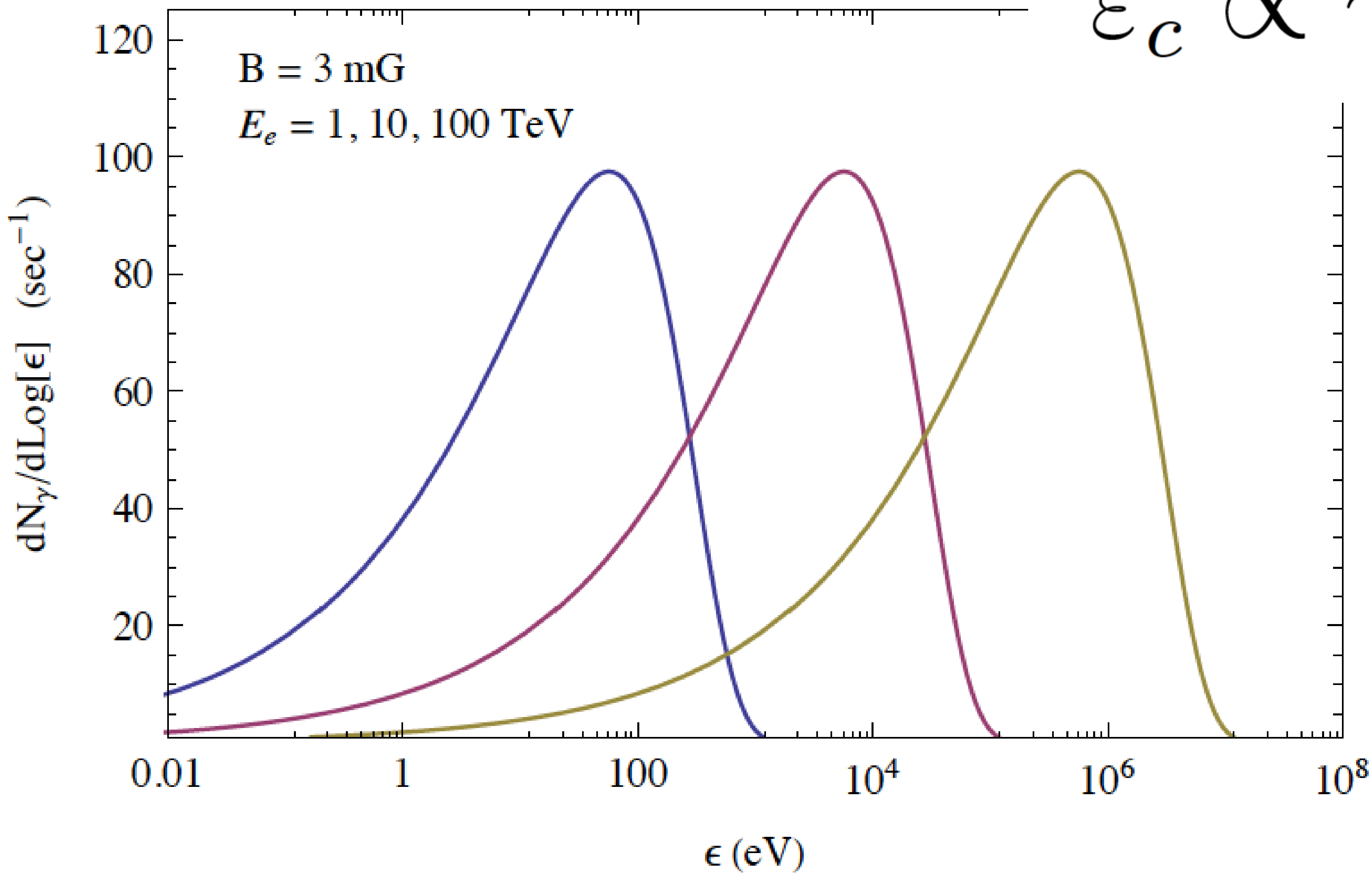


Number of synchrotron photons emitted as
as a function of the Logarithm of the photon energy



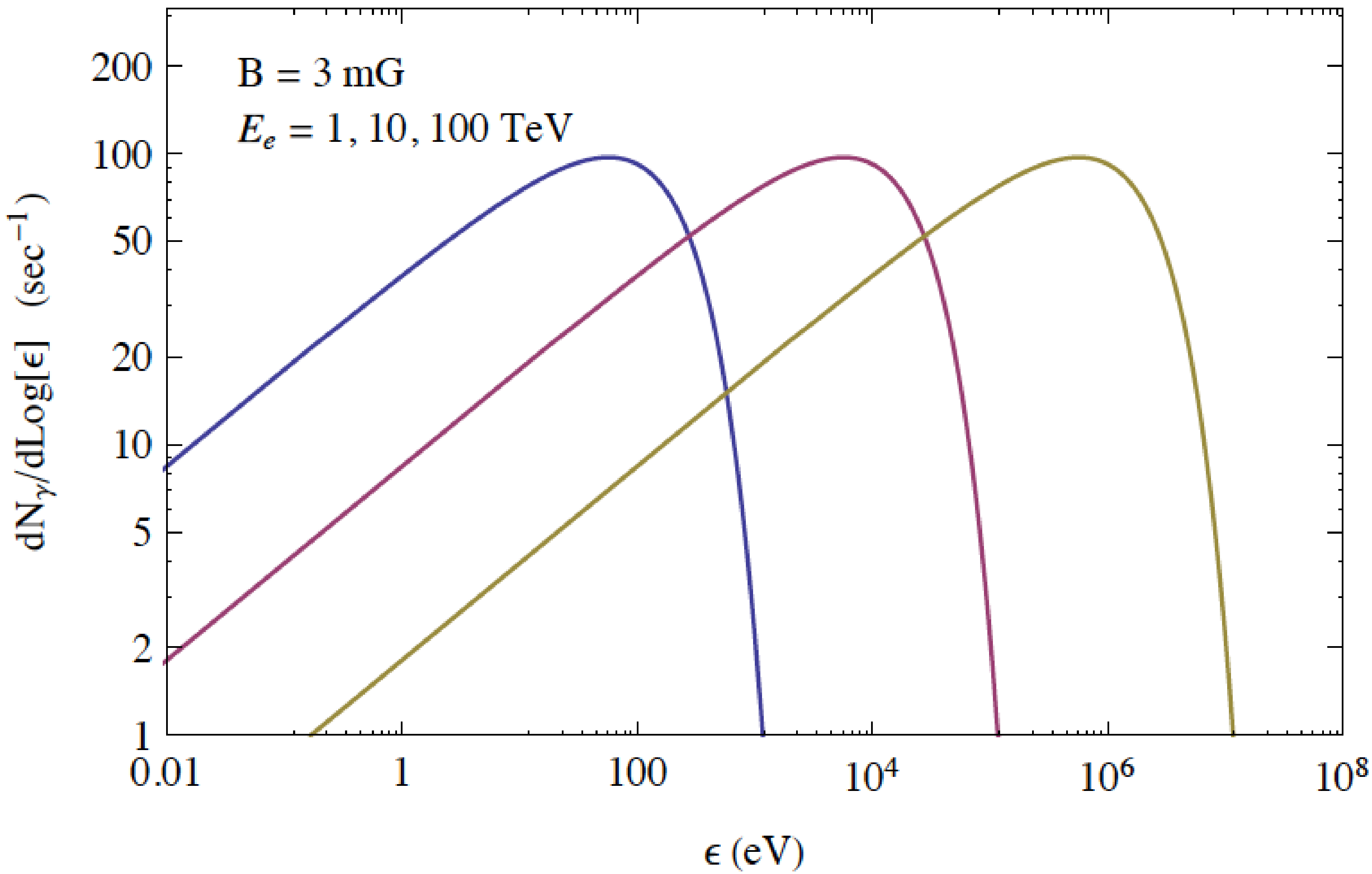
Number of synchrotron photons emitted as
as a function of the Logarithm of the photon energy

$$\varepsilon_c \propto \gamma^2$$



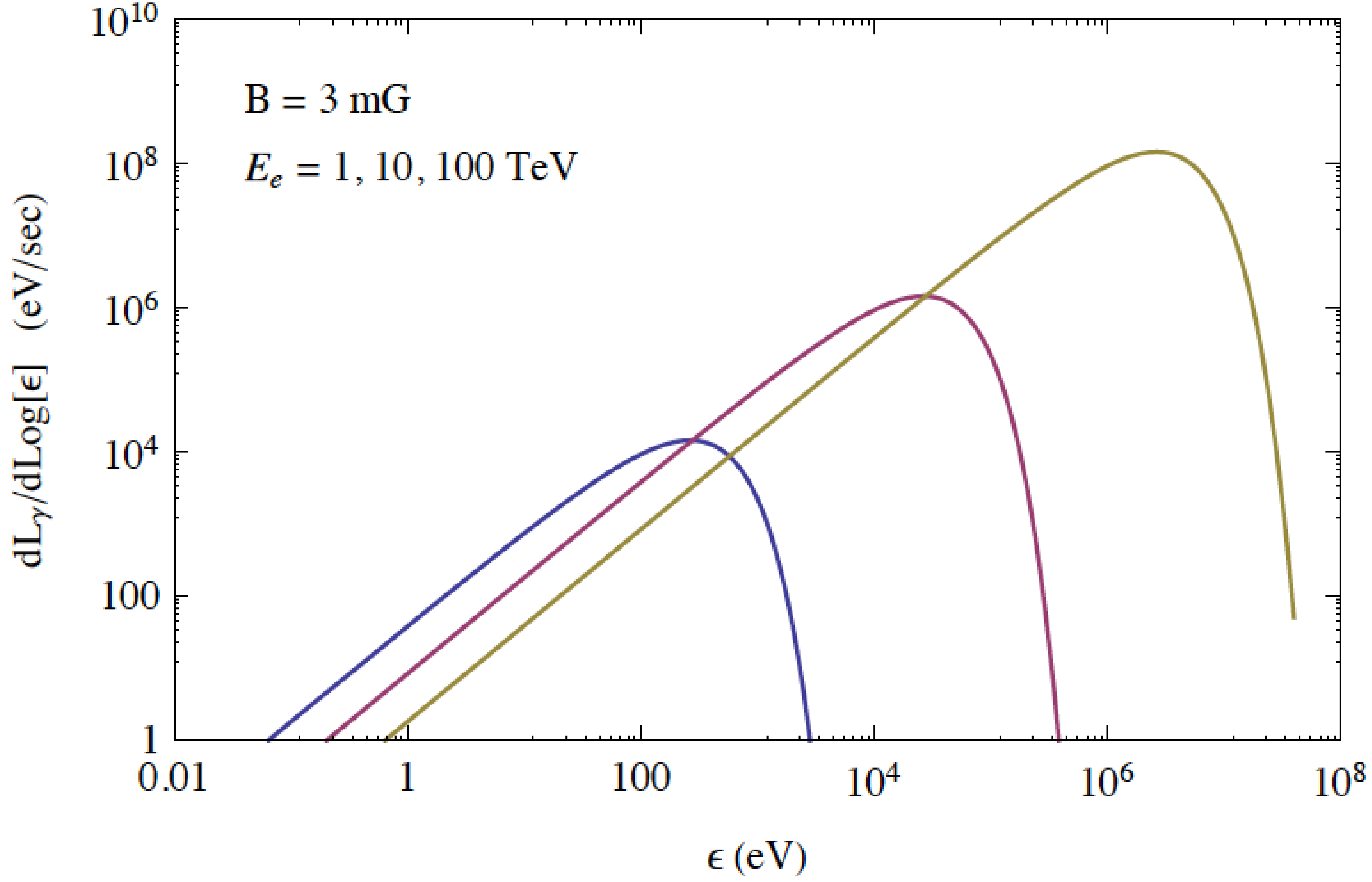
Number of synchrotron photons emitted as
as a function of the Logarithm of the photon energy

[As previous picture but with a logarithmic vertical scale]

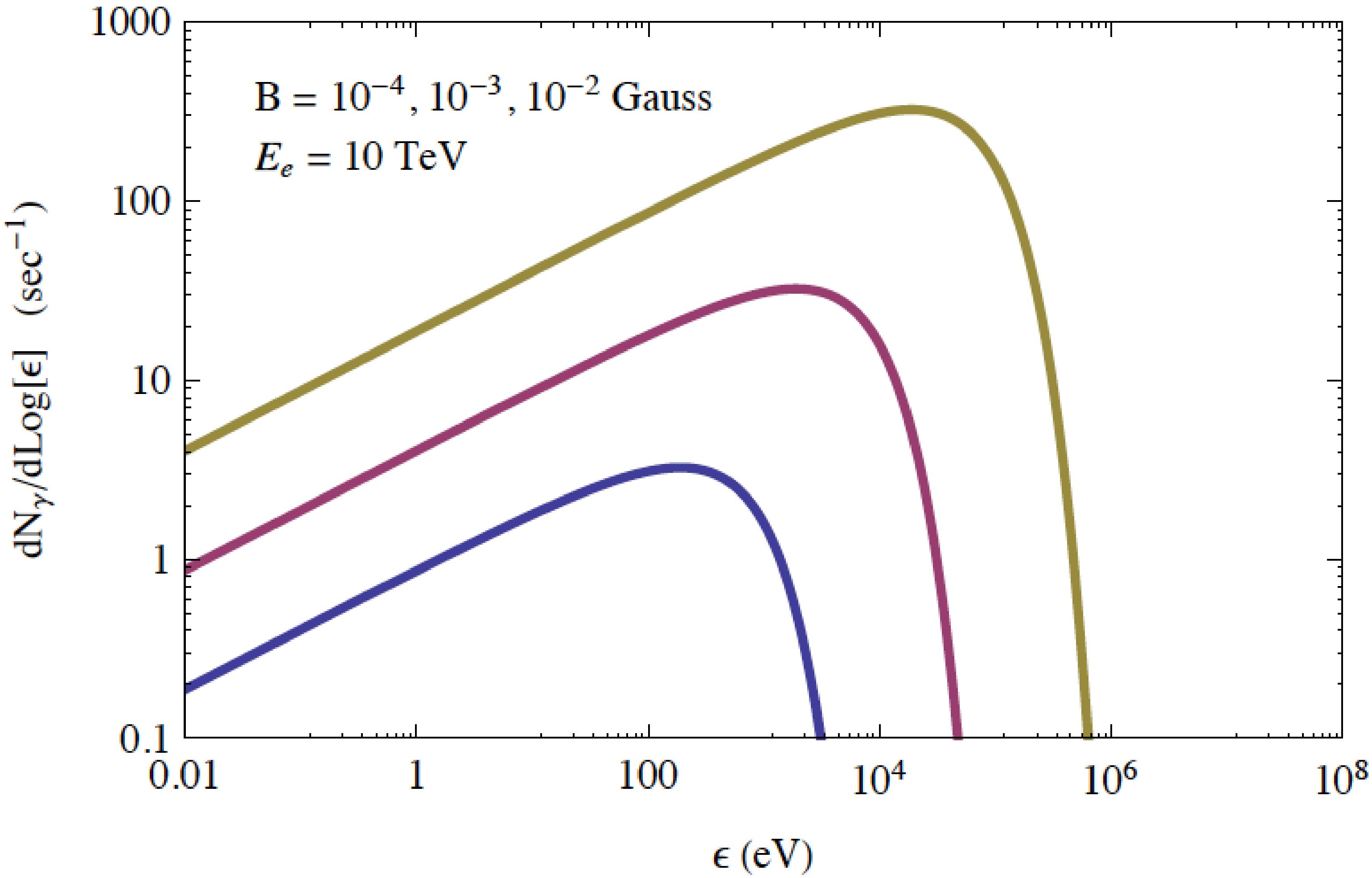


Differential Power

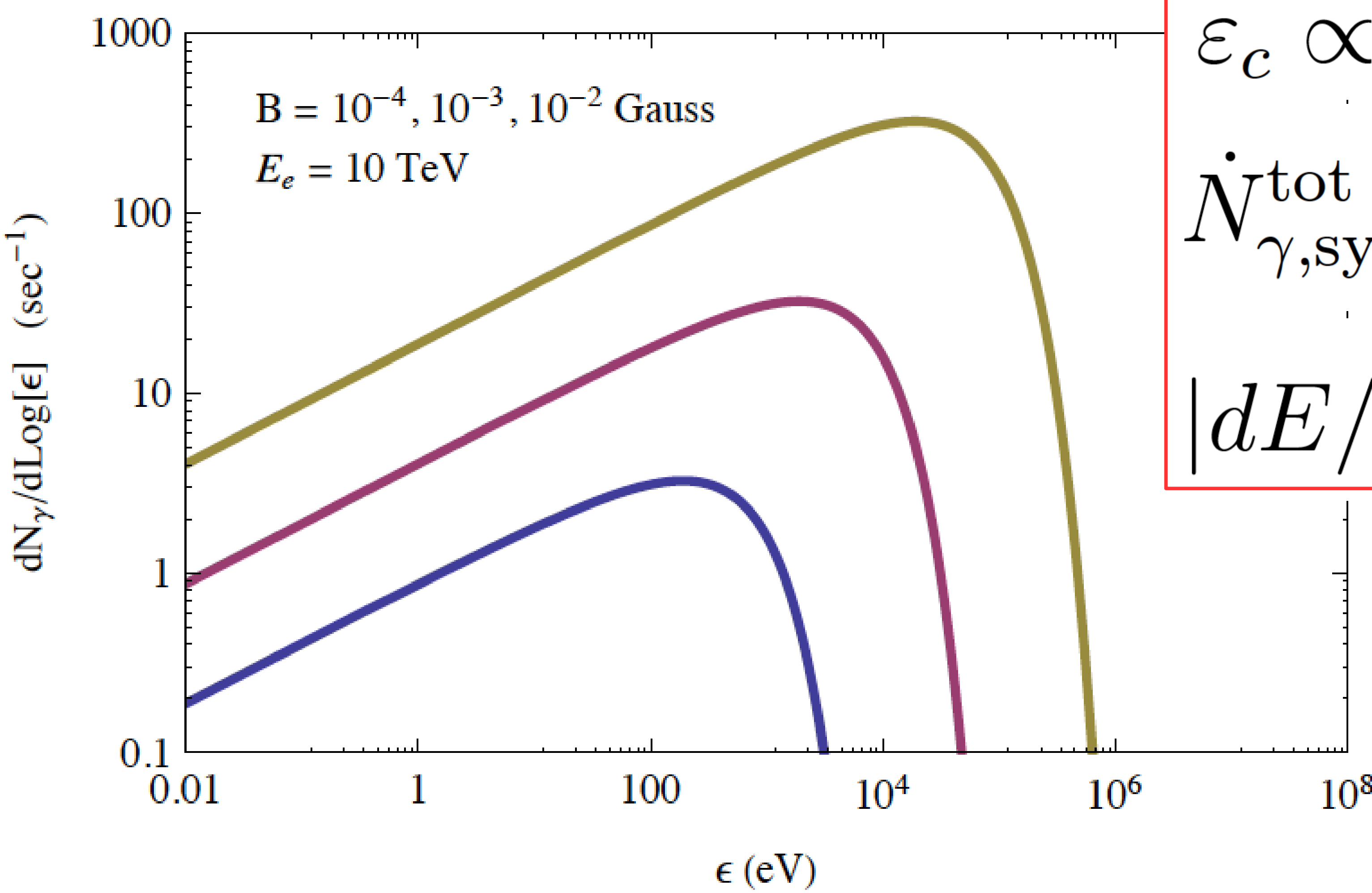
emitted in synchrotron radiation
as a function of the Logarithm [photon energy]



Number of synchrotron photons emitted as
as a function of the Logarithm of the photon energy.
Different values of the Magnetic Field



Number of synchrotron photons emitted as
as a function of the Logarithm of the photon energy.
Different values of the Magnetic Field



$$\varepsilon_c \propto B$$

$$\dot{N}^{\rm tot}_{\gamma,{\rm syn}} \propto B$$

$$|dE/dt| \propto B^2$$

Synchrotron Radiation

$$\dot{N}_\gamma = \frac{5}{2\sqrt{3}} \; \frac{e^3 \, B}{m \, c^2 \, \hbar} \, \sin \alpha$$

$$\langle \varepsilon_f \rangle = \frac{4}{5\sqrt{3}} \; \frac{\hbar c}{m \, c^2} \, e \, B \;\; \gamma^2 \; \sin \alpha$$

Synchrotron Radiation

$$\dot{N}_\gamma = \frac{5}{2\sqrt{3}} \frac{e^3 B}{m c^2 \hbar} \sin\alpha$$

$$\langle \varepsilon_f \rangle = \frac{4}{5\sqrt{3}} \frac{\hbar c}{m c^2} e B \; \gamma^2 \; \sin\alpha$$

Inverse Compton

$$(\sigma_{\mathrm{Th}}\, c)\; n_\gamma^{\mathrm{target}}$$

$$\frac{4}{3}\varepsilon_i\, \gamma^2$$

The magnetic field can be seen as an ensemble of virtual photons.

Synchrotron Radiation can be seen as the Inverse Compton scattering on these background photons

$$n_\gamma^{\rm target} \simeq \frac{5\sqrt{3}}{16\pi}\,\frac{mc^2}{\hbar c\,e} B\ \sin\alpha$$

$$n_\gamma^{\rm target} \propto B$$

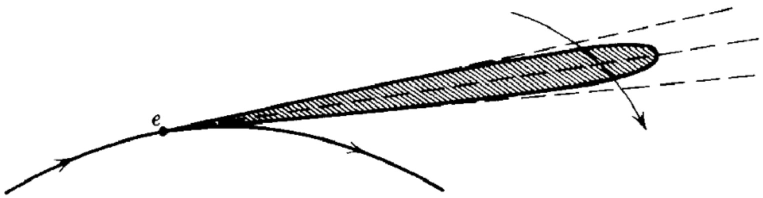
$$\langle \varepsilon_i \rangle \simeq \frac{4}{5\sqrt{3}}\,\frac{\hbar c}{mc^2} e\,B\ \sin\alpha$$

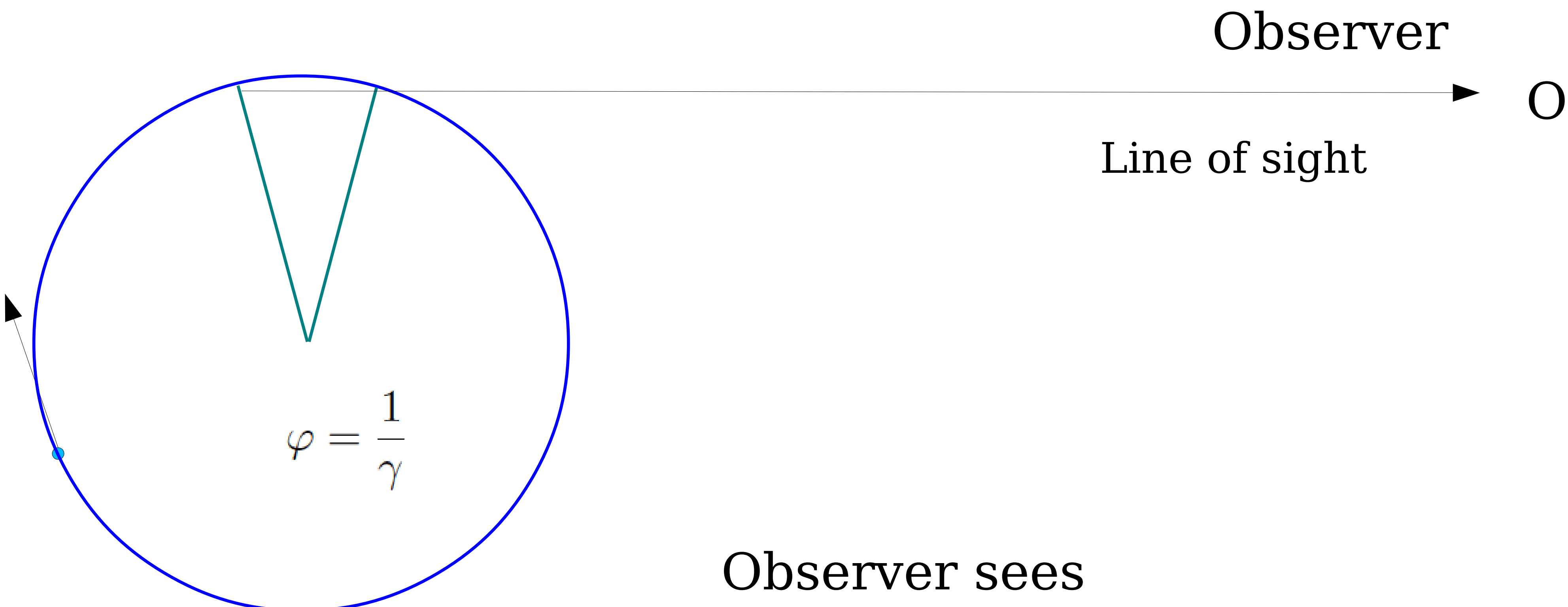
$$\langle \varepsilon_i \rangle \simeq\propto B$$

see: Blumenthal & Gould
Rev. Mod. Phys. 42, 237 (1970)

$$\rho_B = \frac{B^2}{8\pi}$$

Classical Physics method to estimate the Frequency (that is the energy) of synchrotron radiation



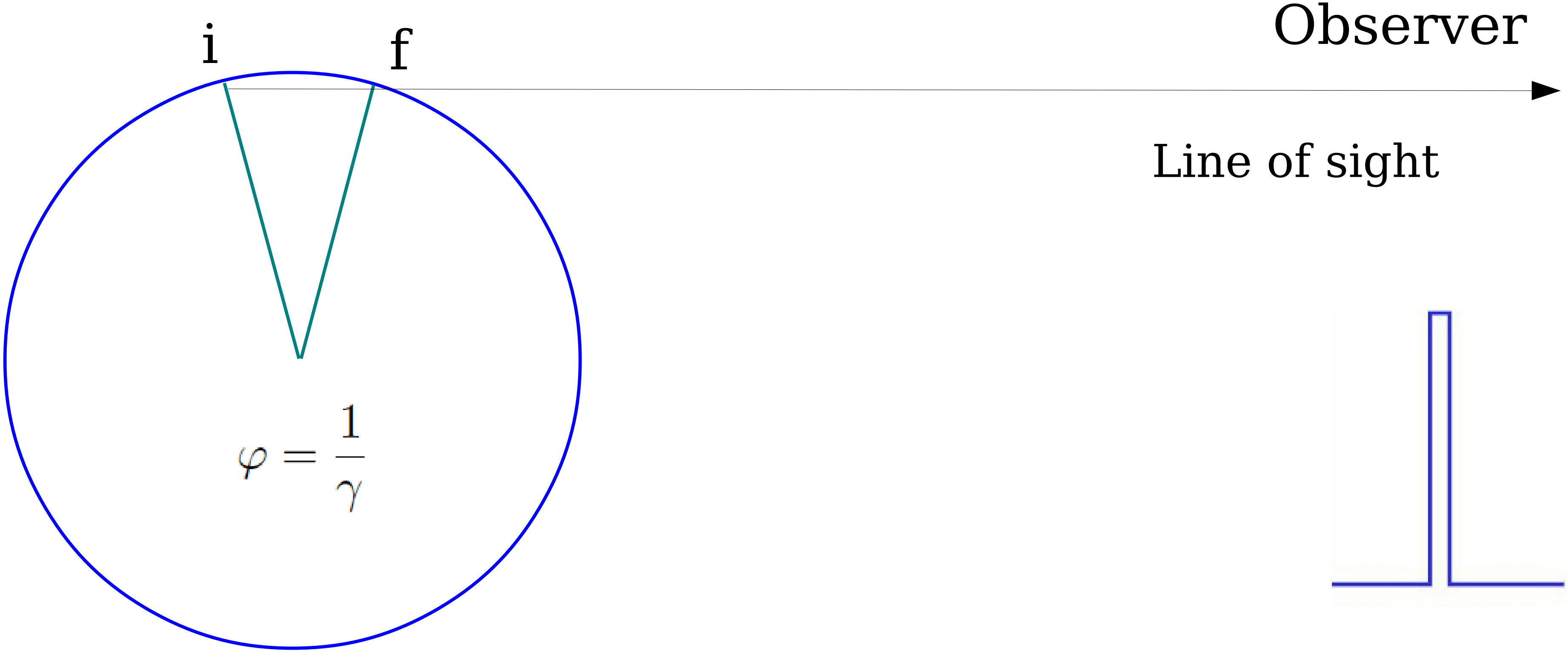


Observer sees
a sequence of narrow pulses
of radiation

First photon emitted at time t_i

Last photon emitted at time $t_f = t_i + \frac{r}{\gamma\, v}$

$$t_i^{\rm obs} \;=\; t_i + \frac{L}{c}$$

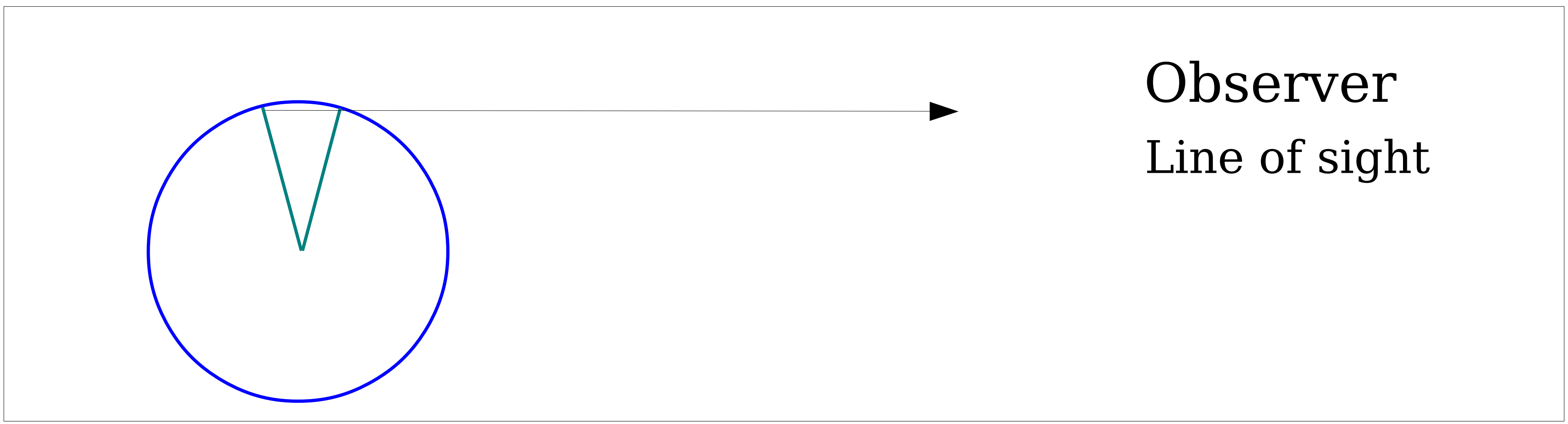


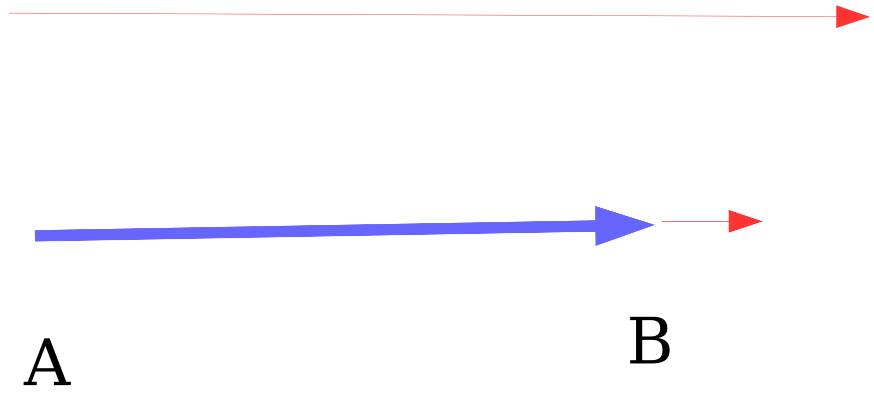
$$\Omega = \frac{eB}{m\gamma c}$$

Frequency of the
Circular (elicoidal) motion

$$\varphi = \frac{1}{\gamma} = \Omega \; (\Delta t)_{\text{emission}}$$

$$(\Delta t)_{\text{emission}} = \frac{1}{\gamma \, \Omega} = \frac{mc}{eB}$$

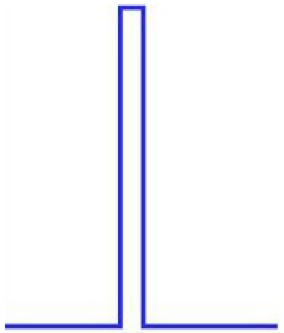




$$(\Delta t)_{\text{obs}} = (\Delta t)_{\text{emission}}\ (1 - \beta)$$

$$(\Delta t)_{\text{obs}} = (\Delta t)_{\text{emission}}\ \frac{2}{\gamma^2}$$

$$(\Delta t)_{\text{obs}} = \frac{2mc}{q\,B\,\gamma^2}$$



Fourier analysis of a pulse of length δt
Frequency of largest component

$$\omega \sim \frac{1}{\delta t}$$

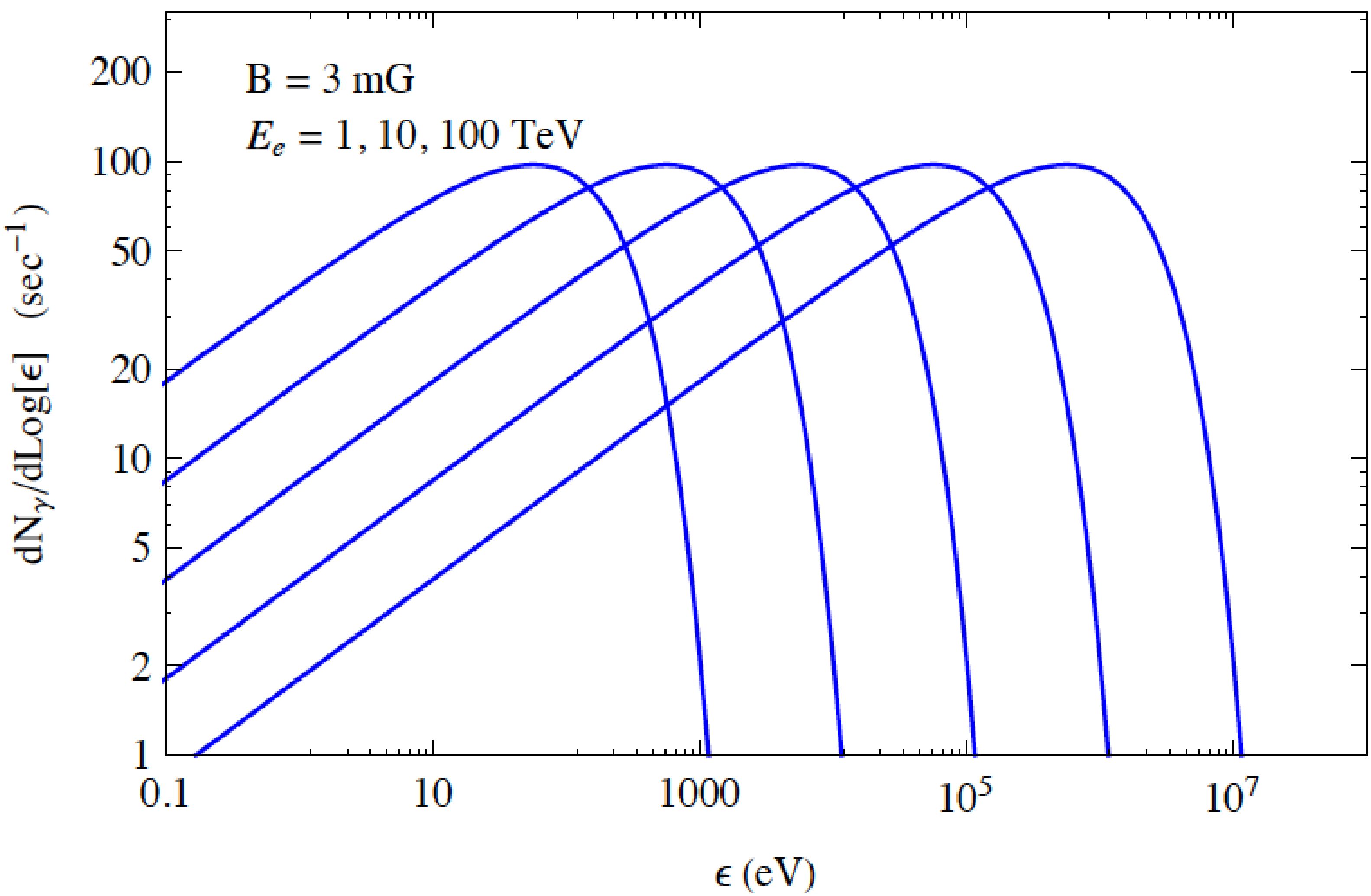
Dominant energy of Synchrotron emission

$$\varepsilon = \hbar\omega \simeq \frac{eB}{mc}\,\gamma^2$$

Synchrotron emission from
an ensemble of
relativistic electrons/positrons.

Sum the contributions of all particles.

Emission of electrons/positrons of different energy :



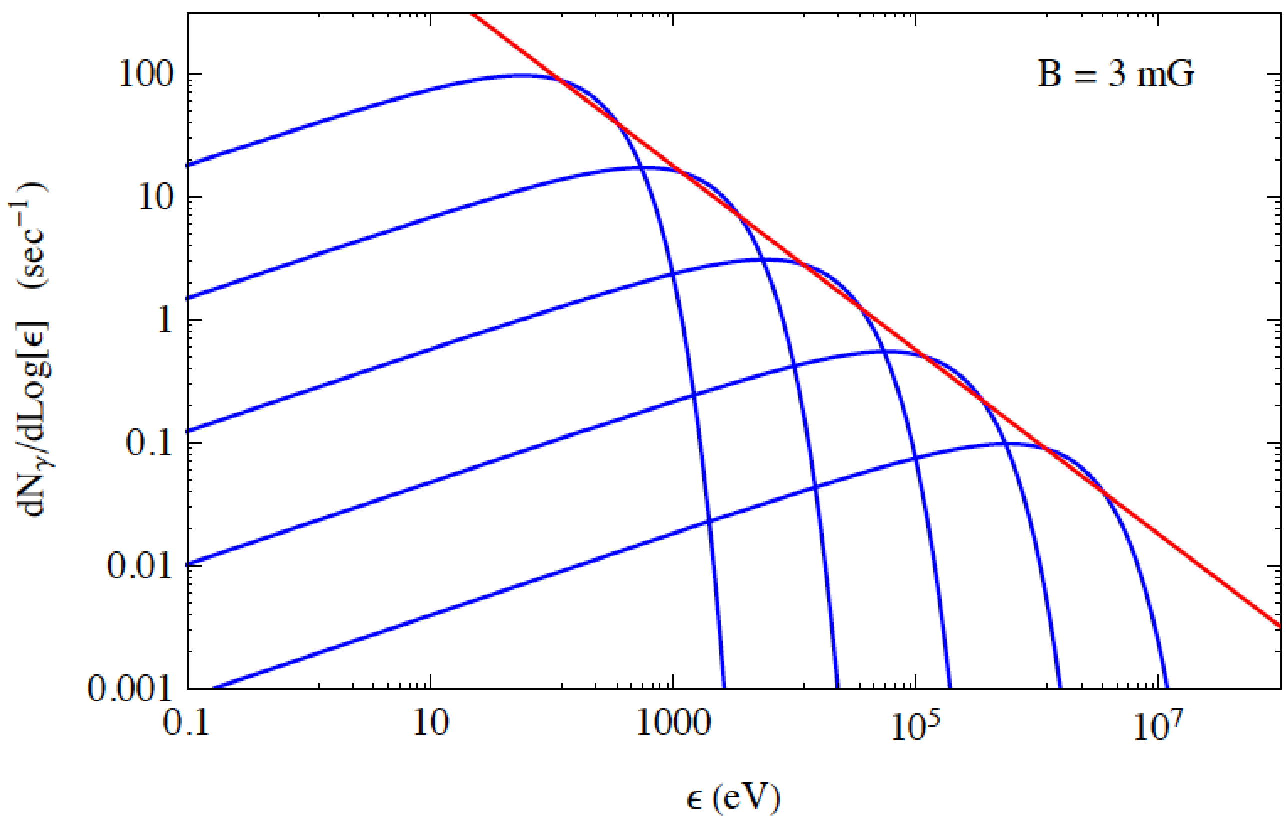
Sum all emission spectra with appropriate weights
Weight = [electron energy distribution]

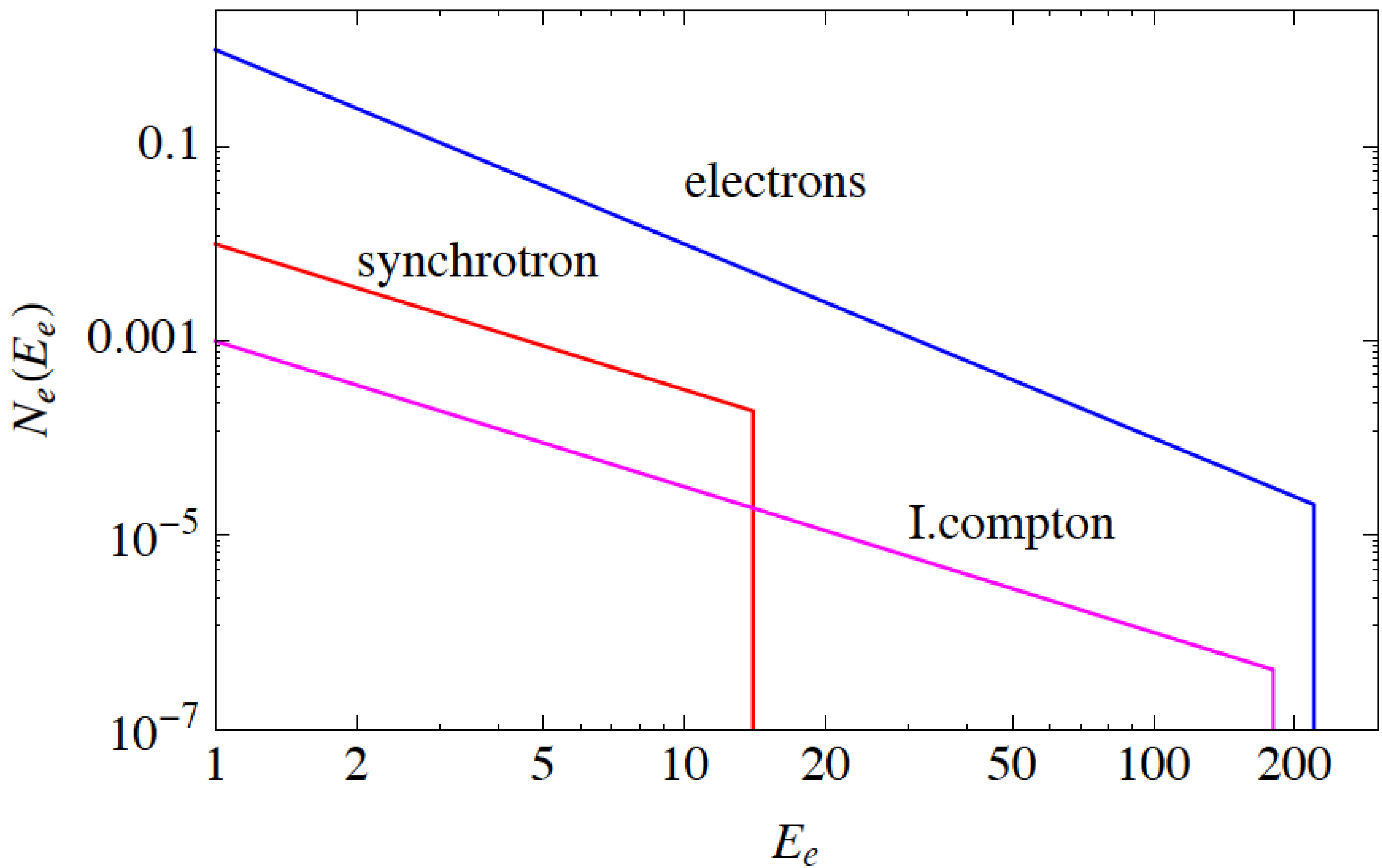
$$N_e(E_e) \propto E_e^{-\alpha}$$

Electron spectrum
power law of exponent α

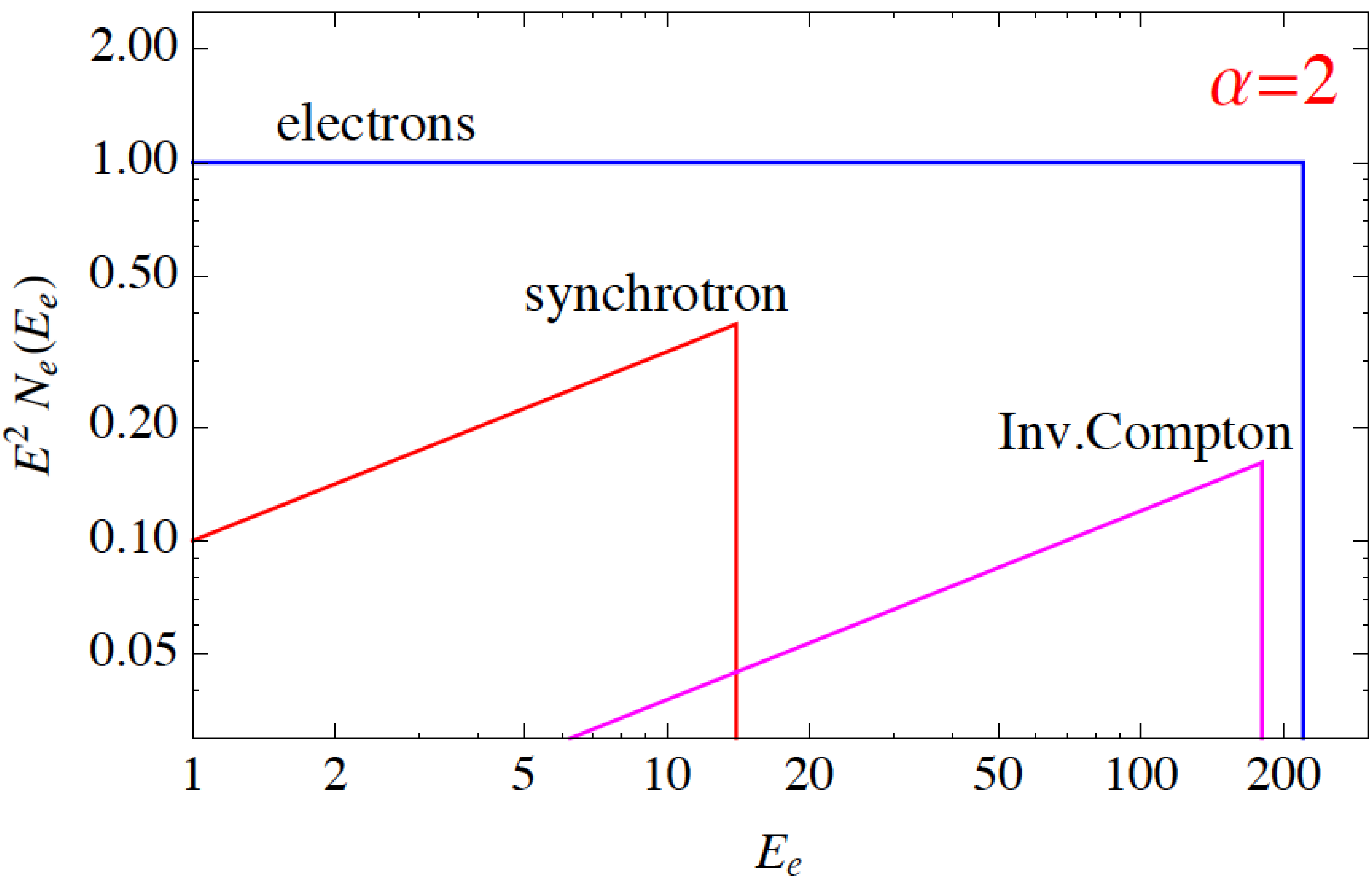
$$\dot{N}_\gamma(E_\gamma) \propto E_\gamma^{-(\alpha+1)/2}$$

Synchrotron spectrum
power law of exponent $\dfrac{\alpha+1}{2}$



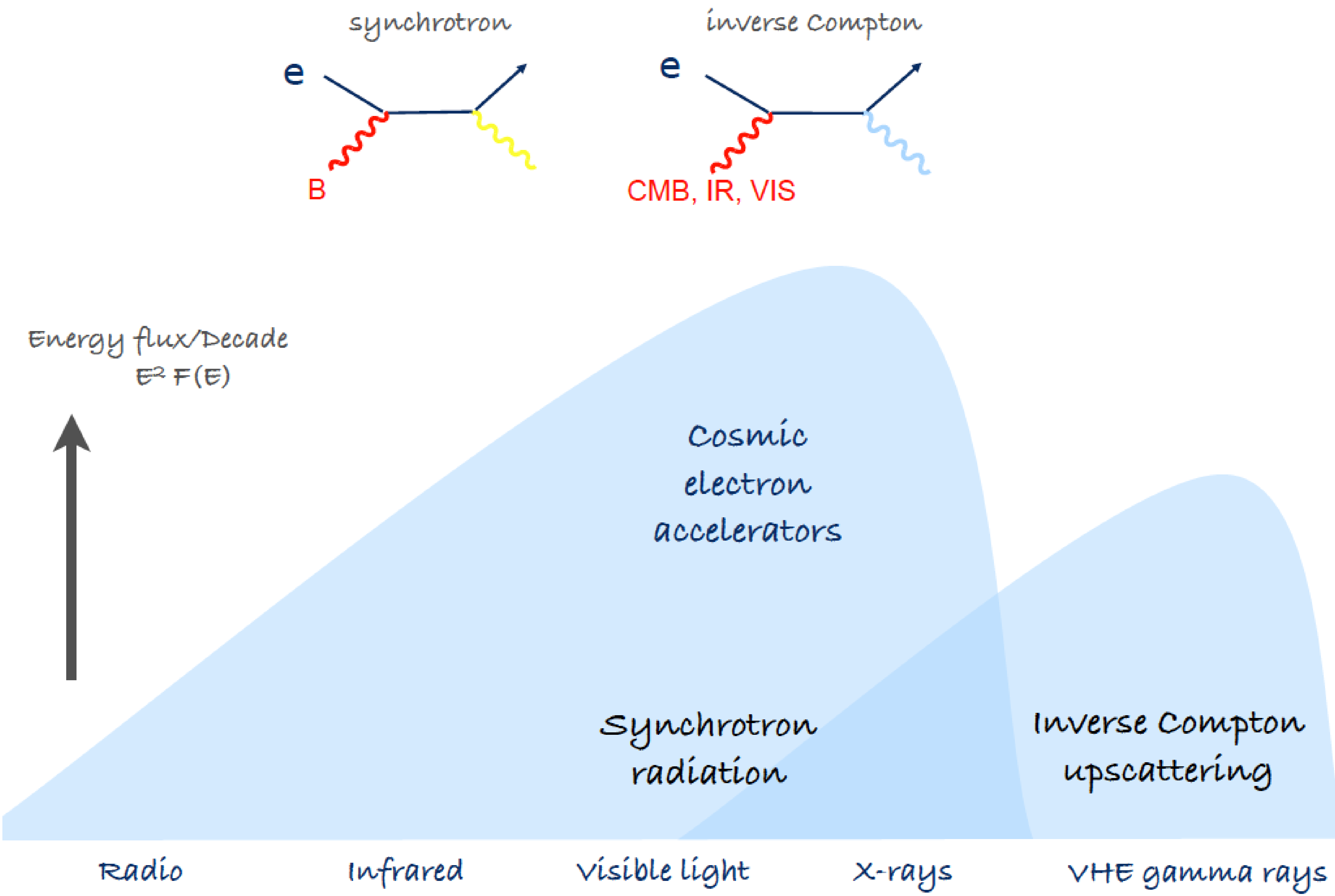


0.1
0.001
10^{-5}
10^{-7}
$N_e(E_e)$
electrons
synchrotron
I.compton
1
2
5
10
20
50
100
200
E_e

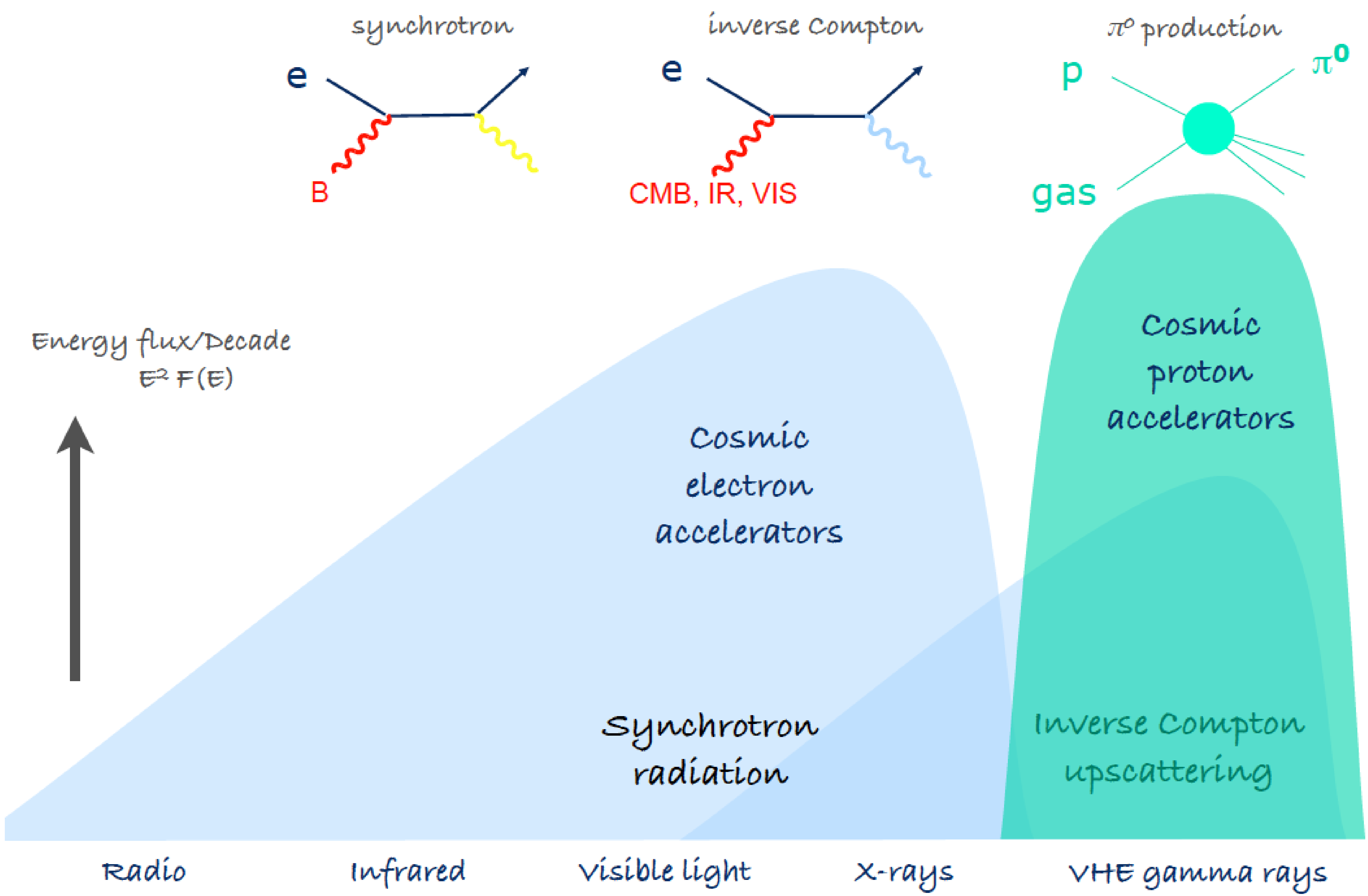


2.00
1.00
0.50
0.20
0.10
0.05
1
2
5
10
20
50
100
200
electrons
synchrotron
Inv.Compton
α=2
$E^2\, N_e(E_e)$
E_e

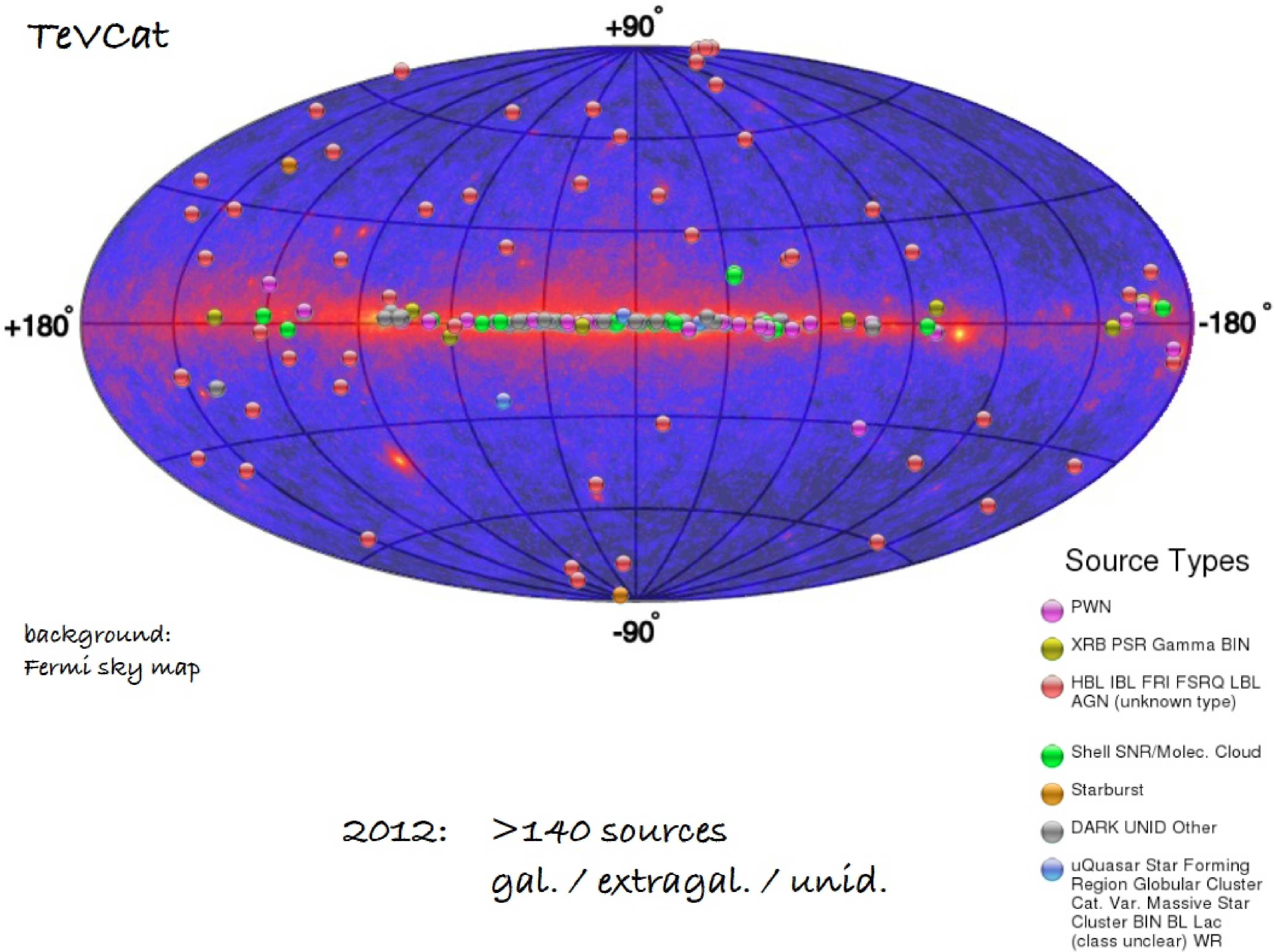
From particles to radiation



From particles to radiation



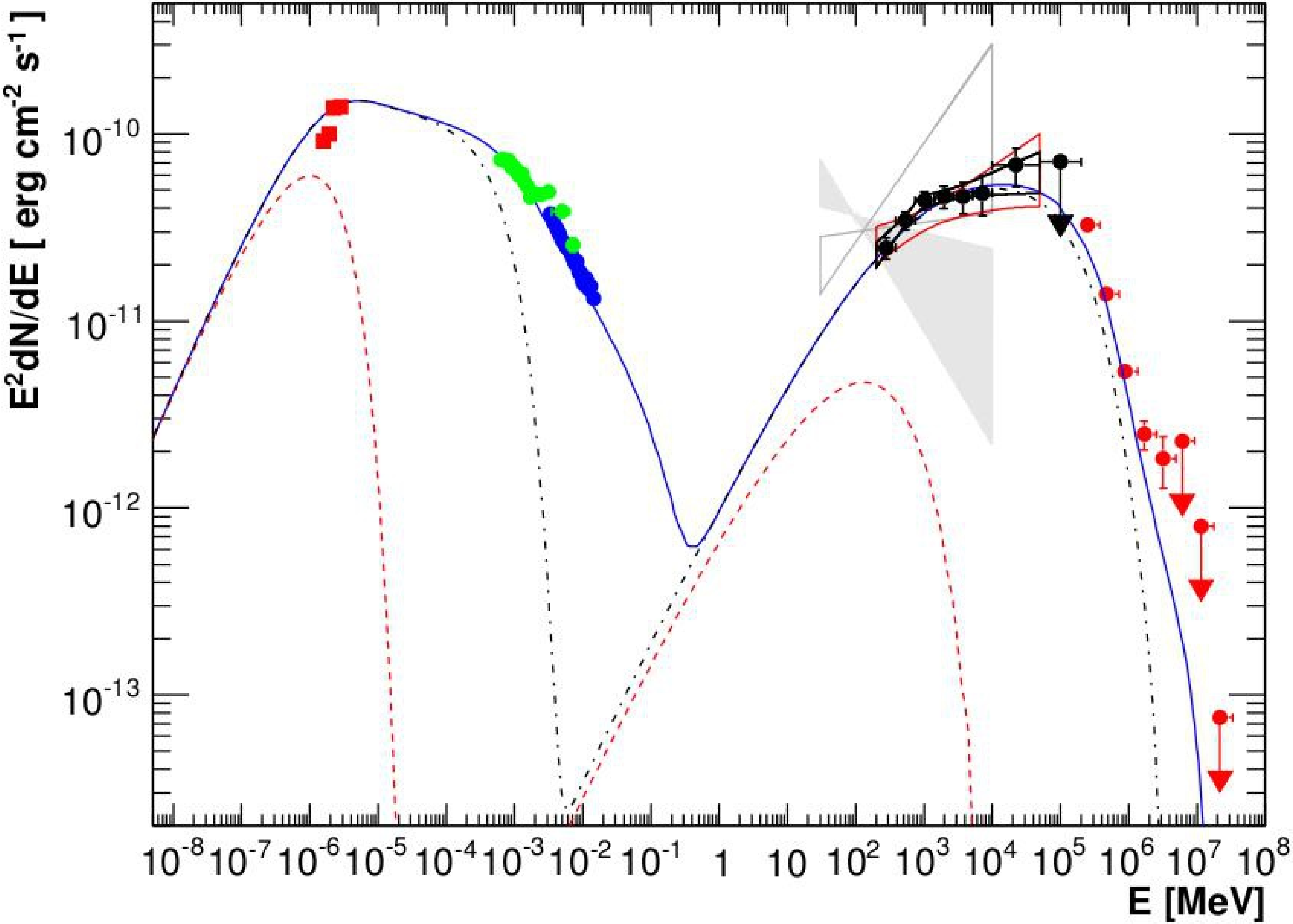
TeVCat



background:
Fermi sky map

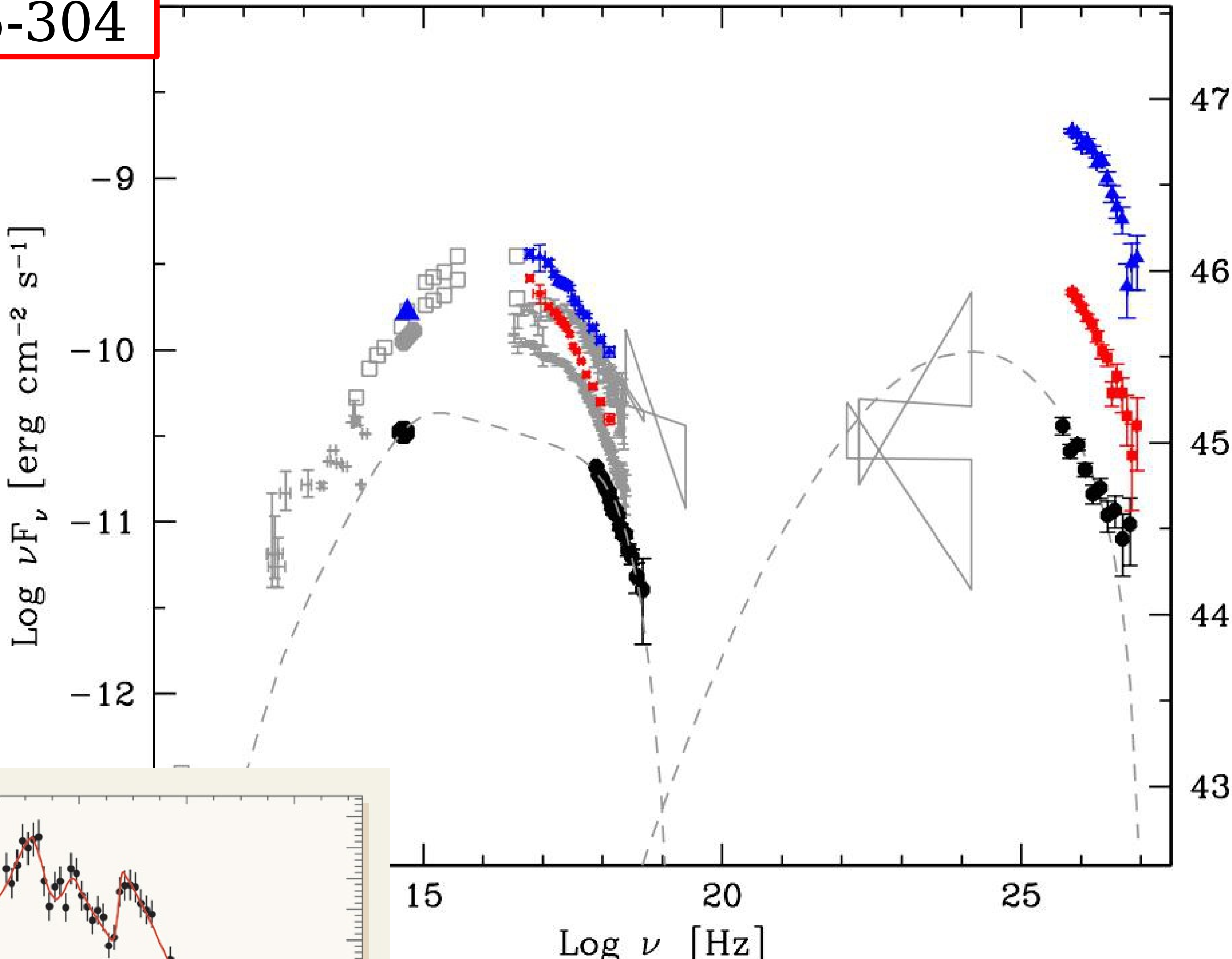
2012: >140 sources
gal. / extragal. / unid.

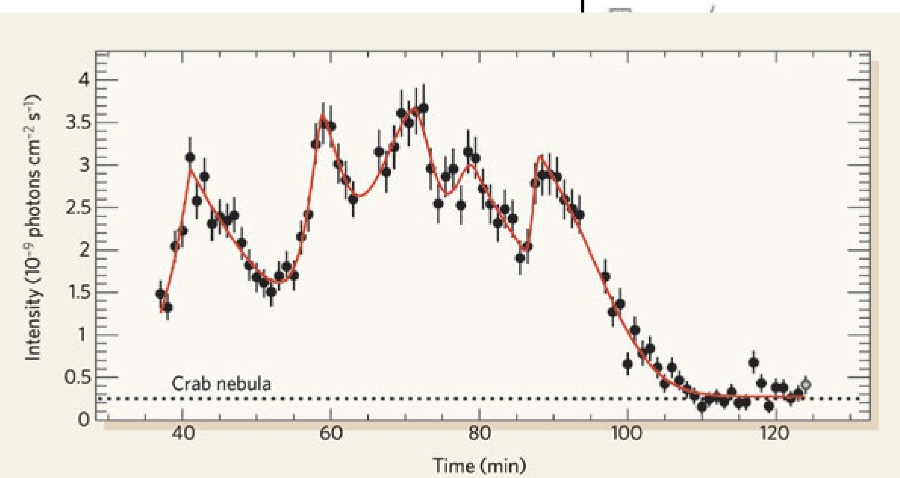
PKS 2155-304



E^{2}dN/dE [erg cm^{-2} s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
E [MeV]

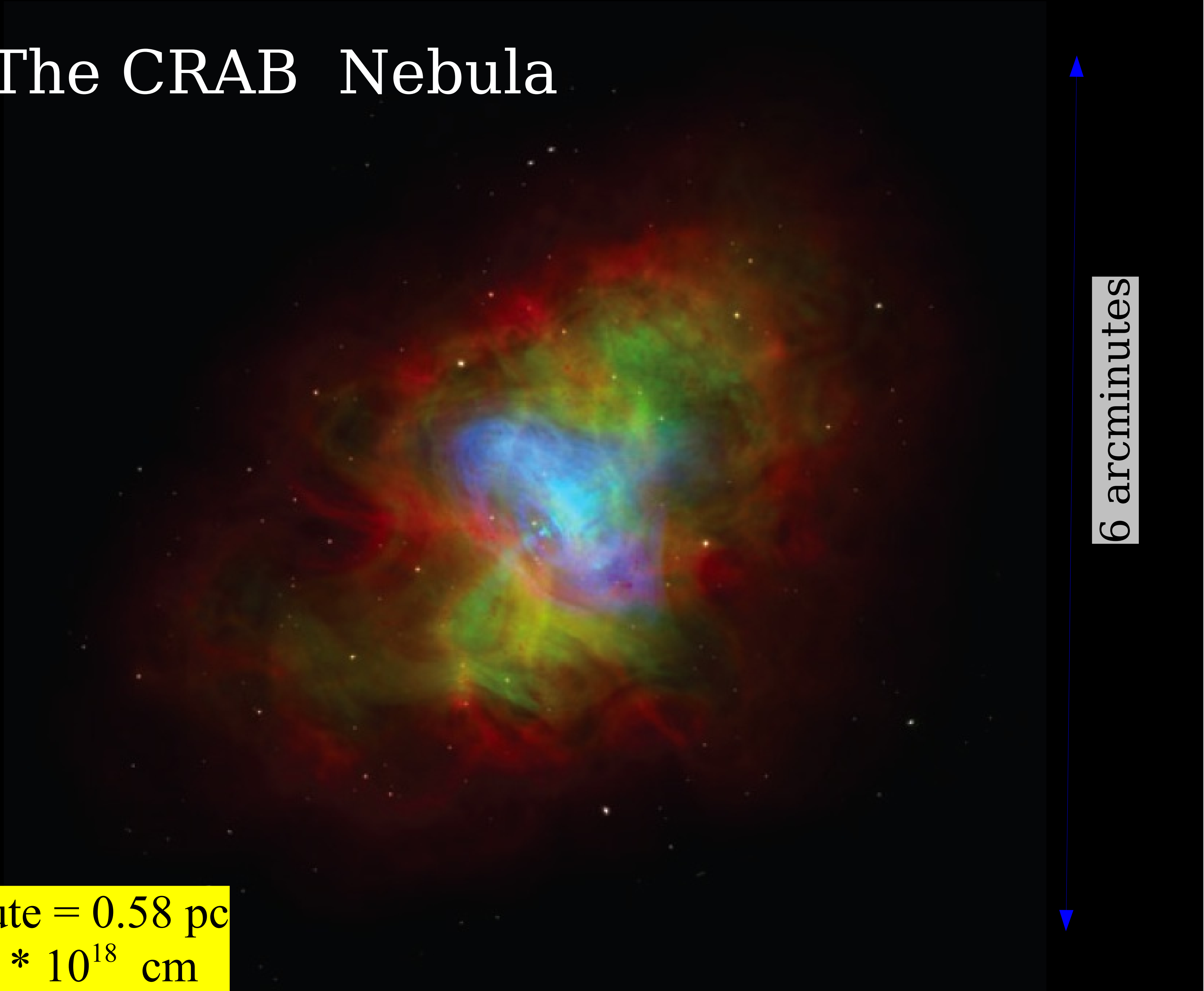
PKS 2155-304





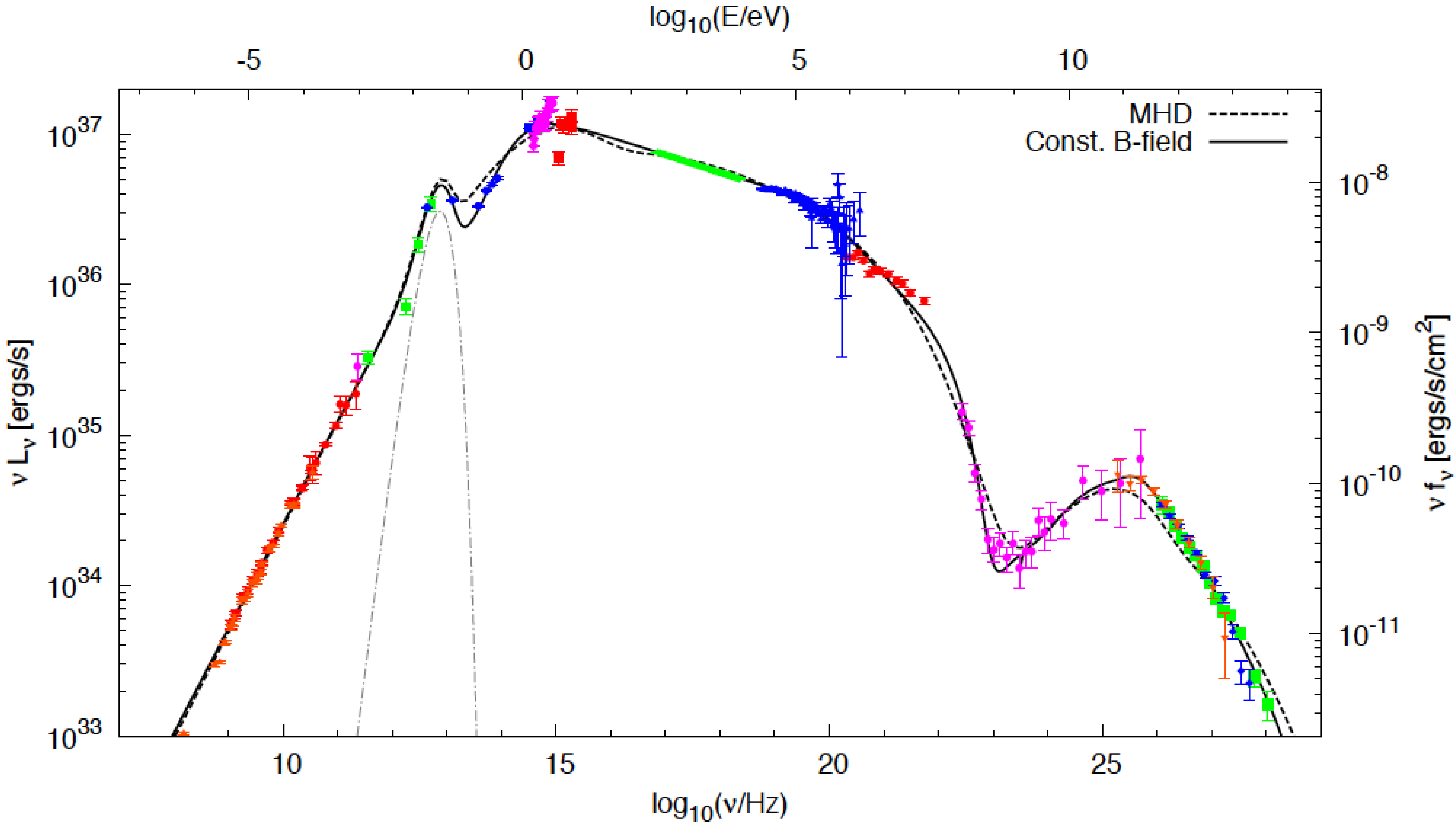
(Very rapid time variations)

The CRAB Nebula



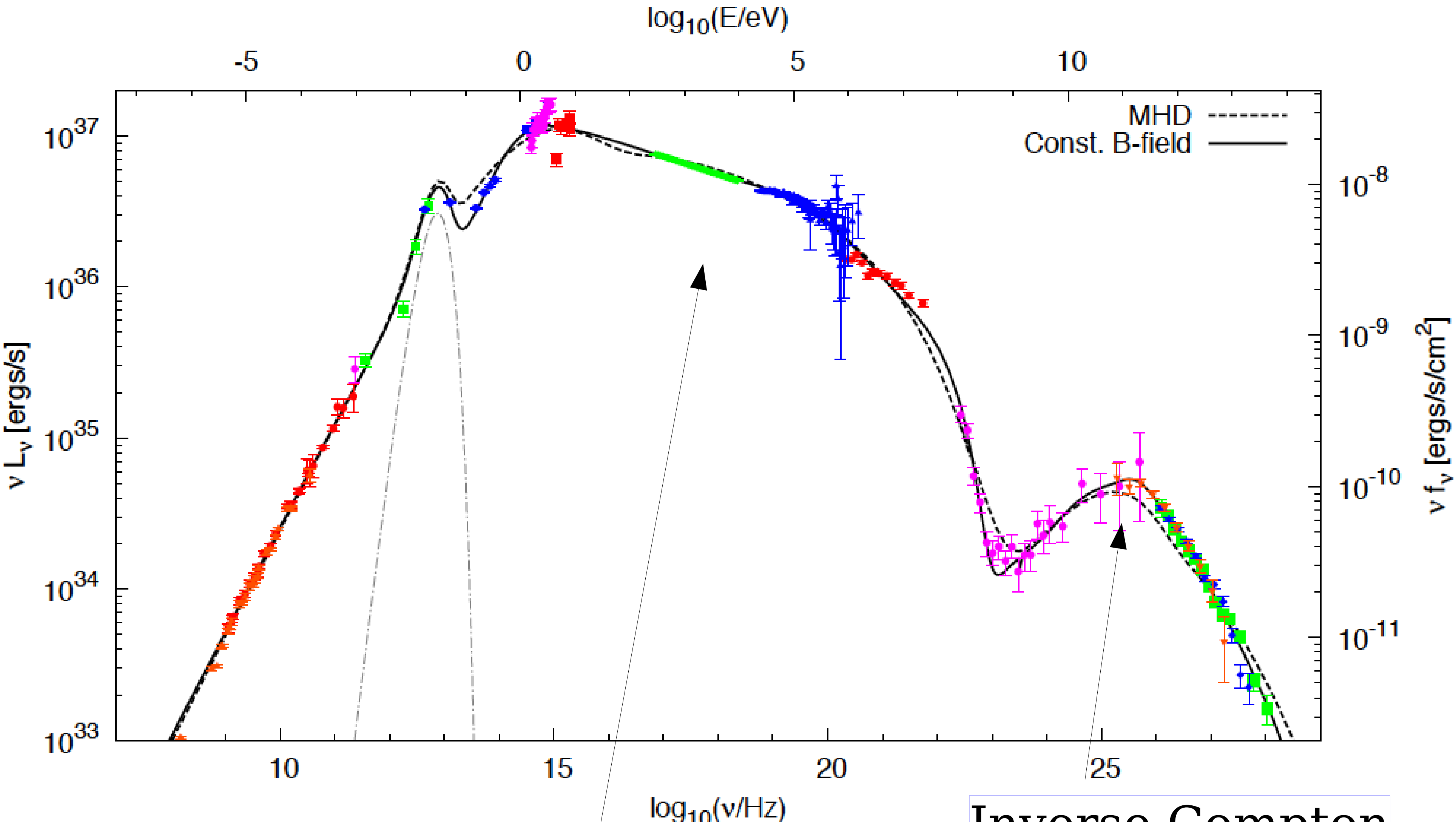
1 minute = 0.58 pc
= 1.8 * 10^{18} cm

Spectral Energy Distribution of the CRAB nebula



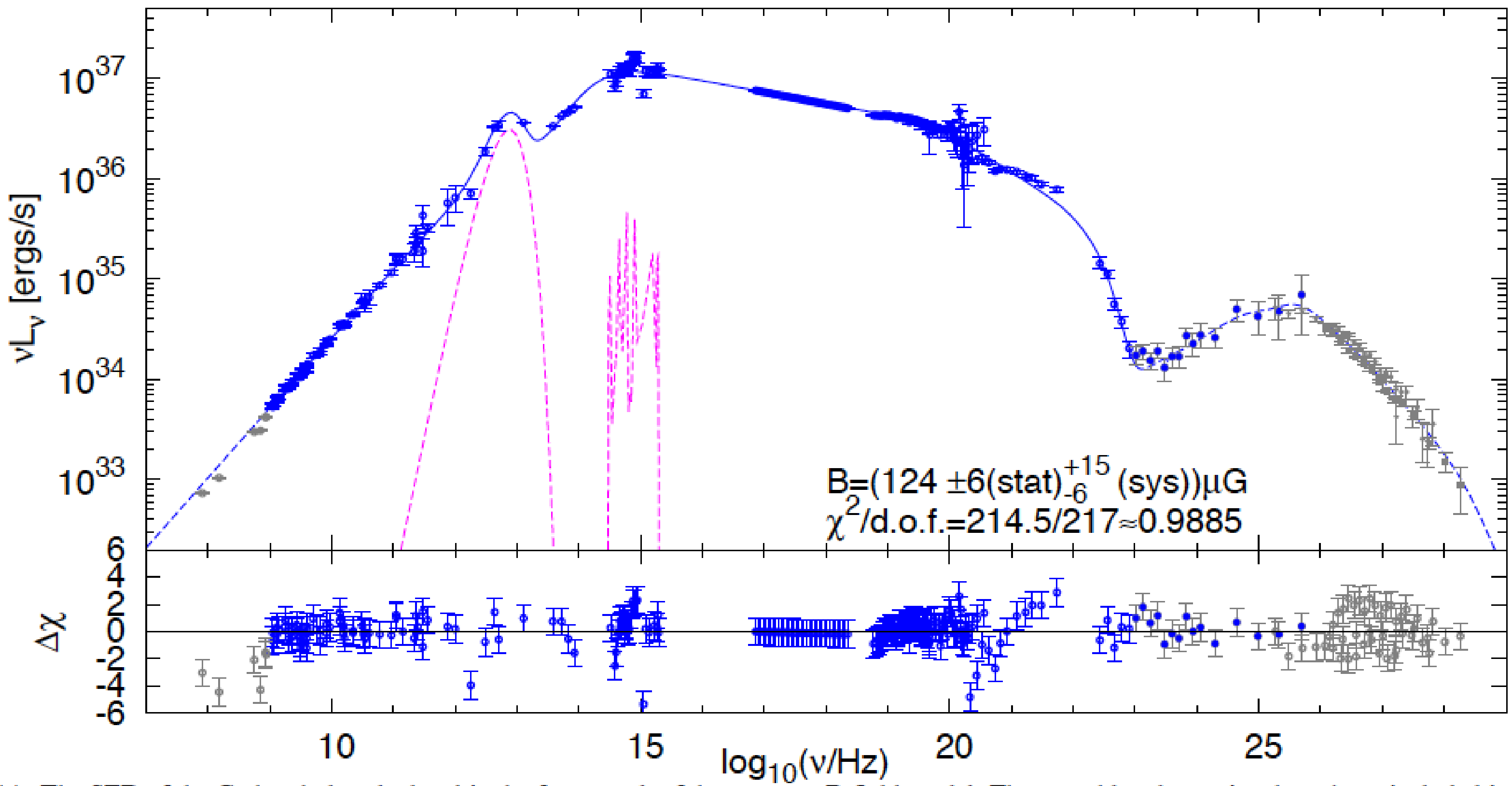
CRAB Nebula Energy Spectrum

SSC (Self Synchrotron Coompton) model emission



Synchrotron Radiation

Inverse Compton Scattering



(a) The SED of the Crab nebula calculated in the framework of the constant B-field model. The open blue data points have been included in the fit for the synchrotron part and the filled blue points used to determine the best-fitting magnetic field.

[3.] Interpretation of the "Low Energy Cosmic Ray Spectra"

(direct measurements)

$$E \lesssim 30 \text{ TeV}$$

Measurements of *at the Earth:* Cosmic Rays

$$\phi_p(E,\Omega)\ ,\quad \phi_{\rm He}(E,\Omega)\ ,\quad \ldots\ ,\ \phi_{\{\rm A,Z\}}(E,\Omega)$$

protons+ nuclei

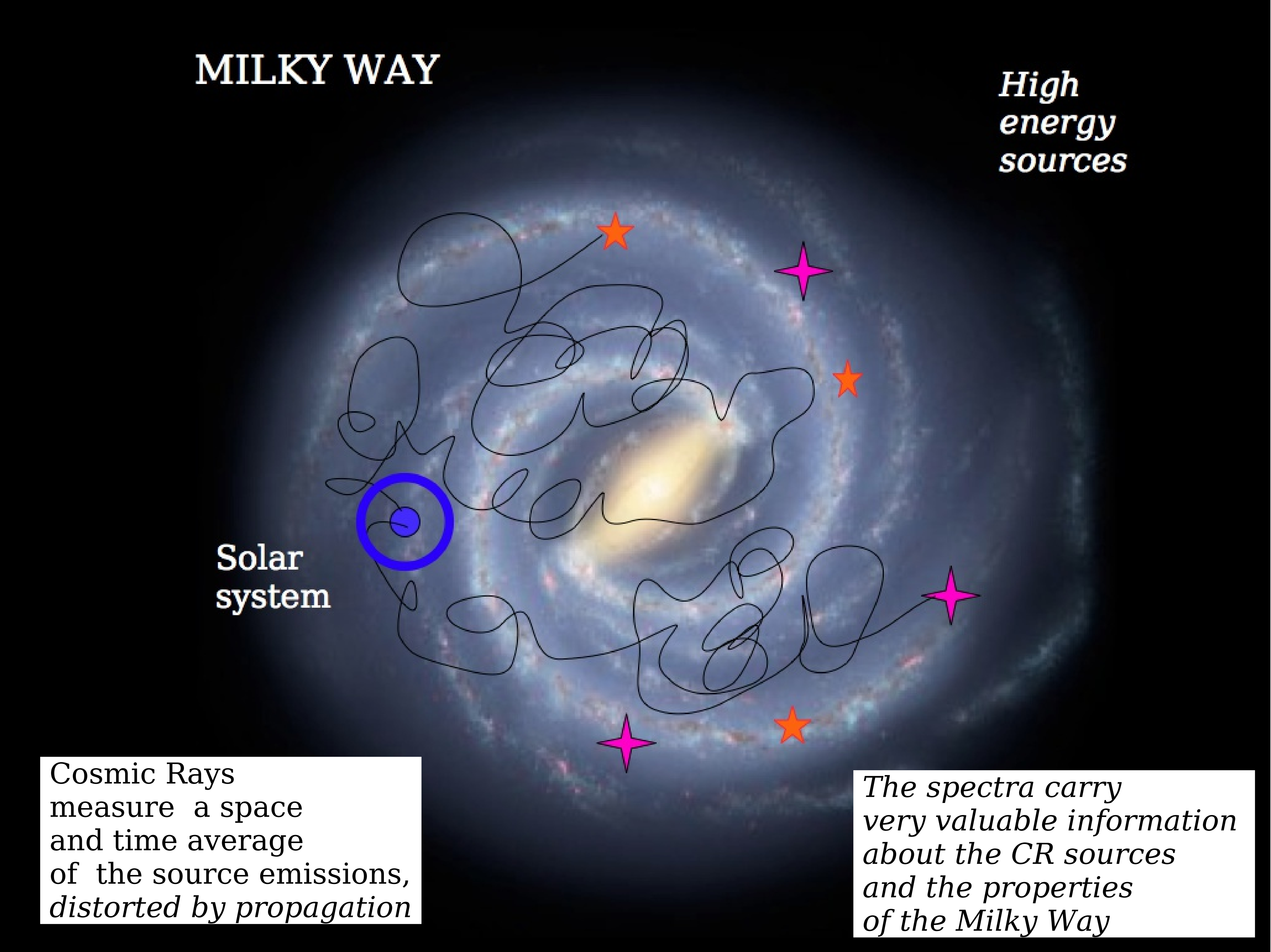
$$\phi_{e^-}(E,\Omega)$$

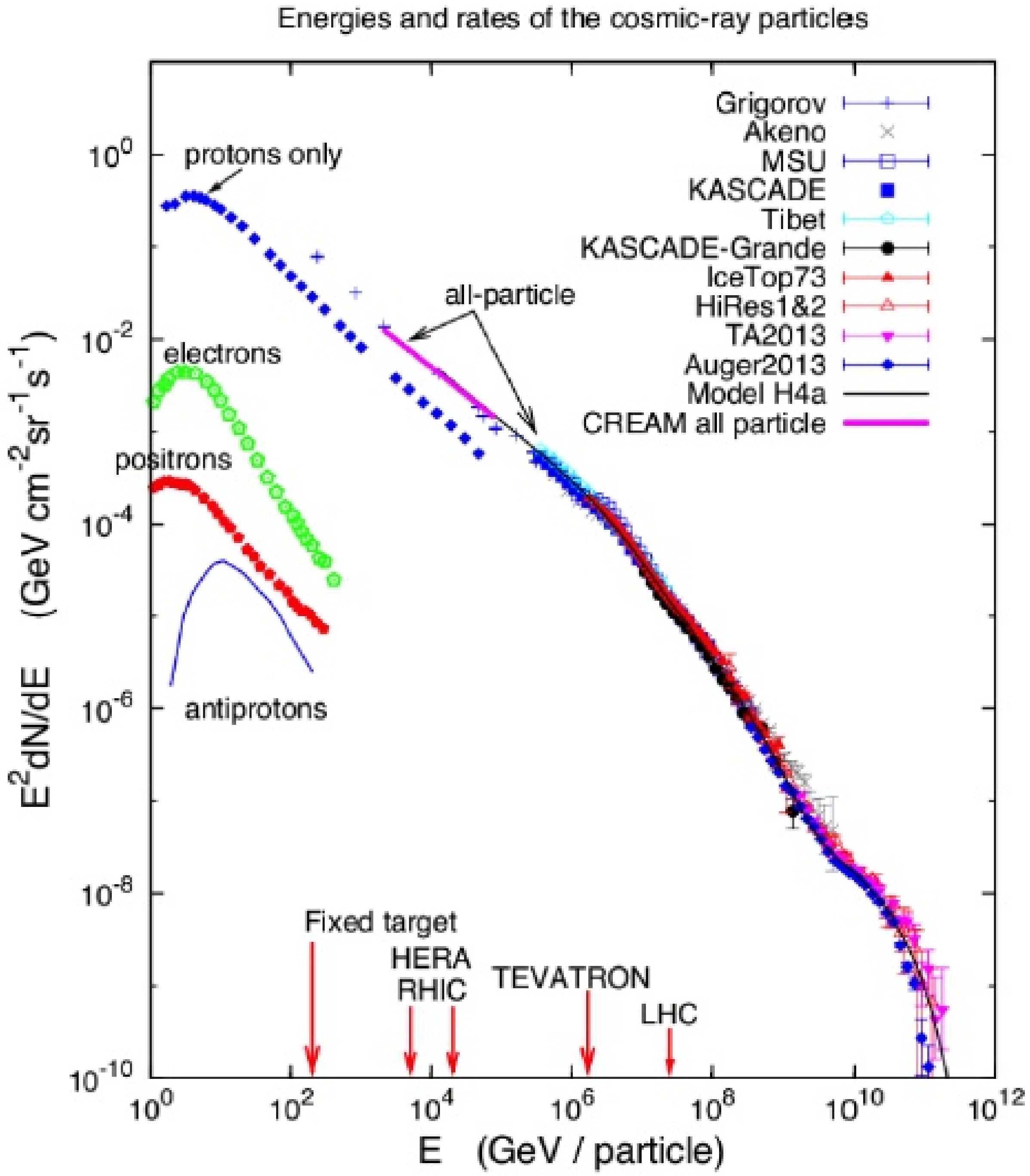
electrons

$$\phi_{e^+}(E,\Omega)$$

$$\phi_{\overline{p}}(E,\Omega)$$

anti-particles

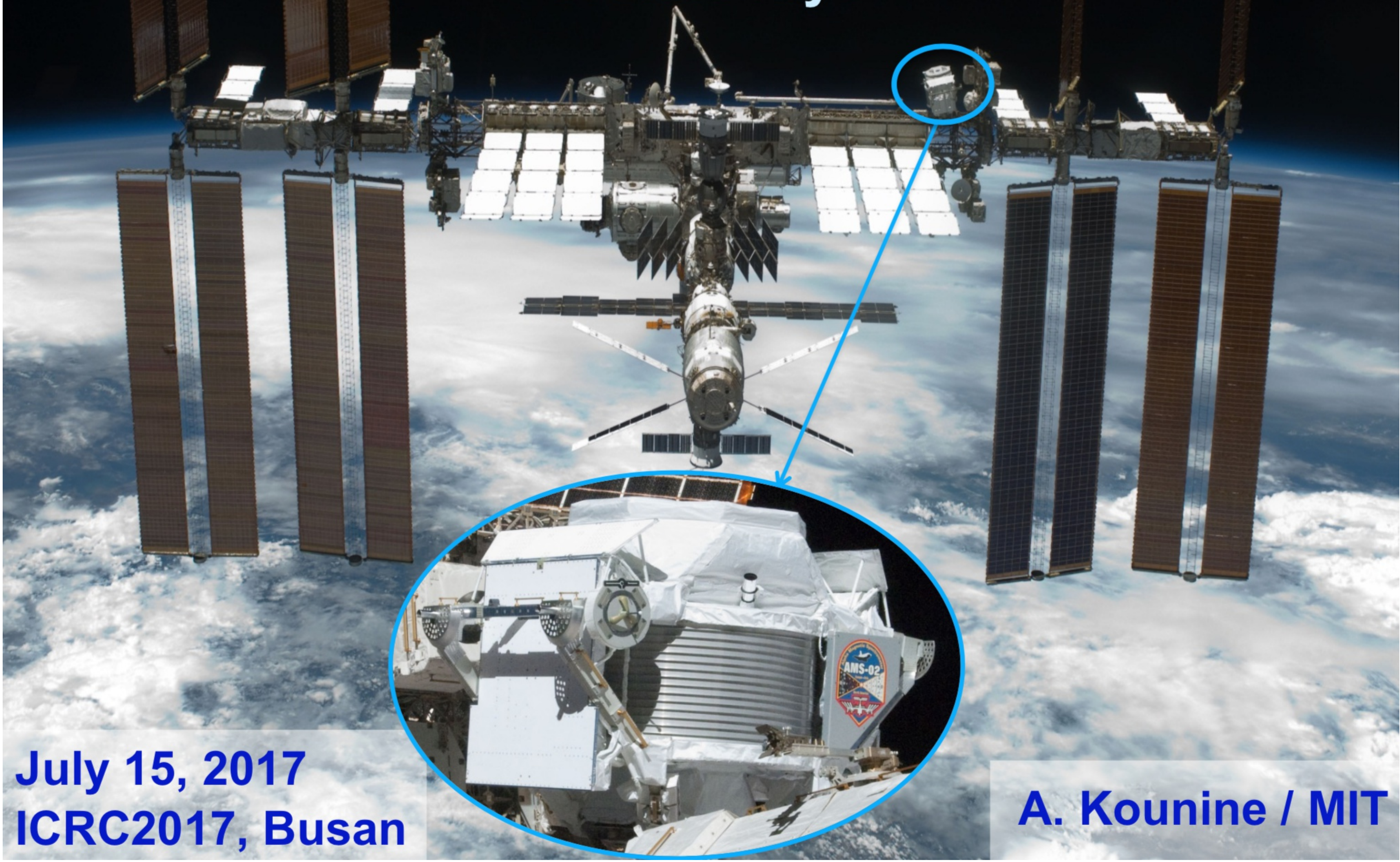

MILKY WAY
High energy sources
Solar system
Cosmic Rays measure a space and time average of the source emissions, *distorted by propagation*
The spectra carry very valuable information about the CR sources and the properties of the Milky Way



Electron flux is smaller and *softer* than the proton flux.

Smaller contributions of positrons and antiprotons

AMS results on the properties of the fluxes of elementary particles and nuclei in primary cosmic rays

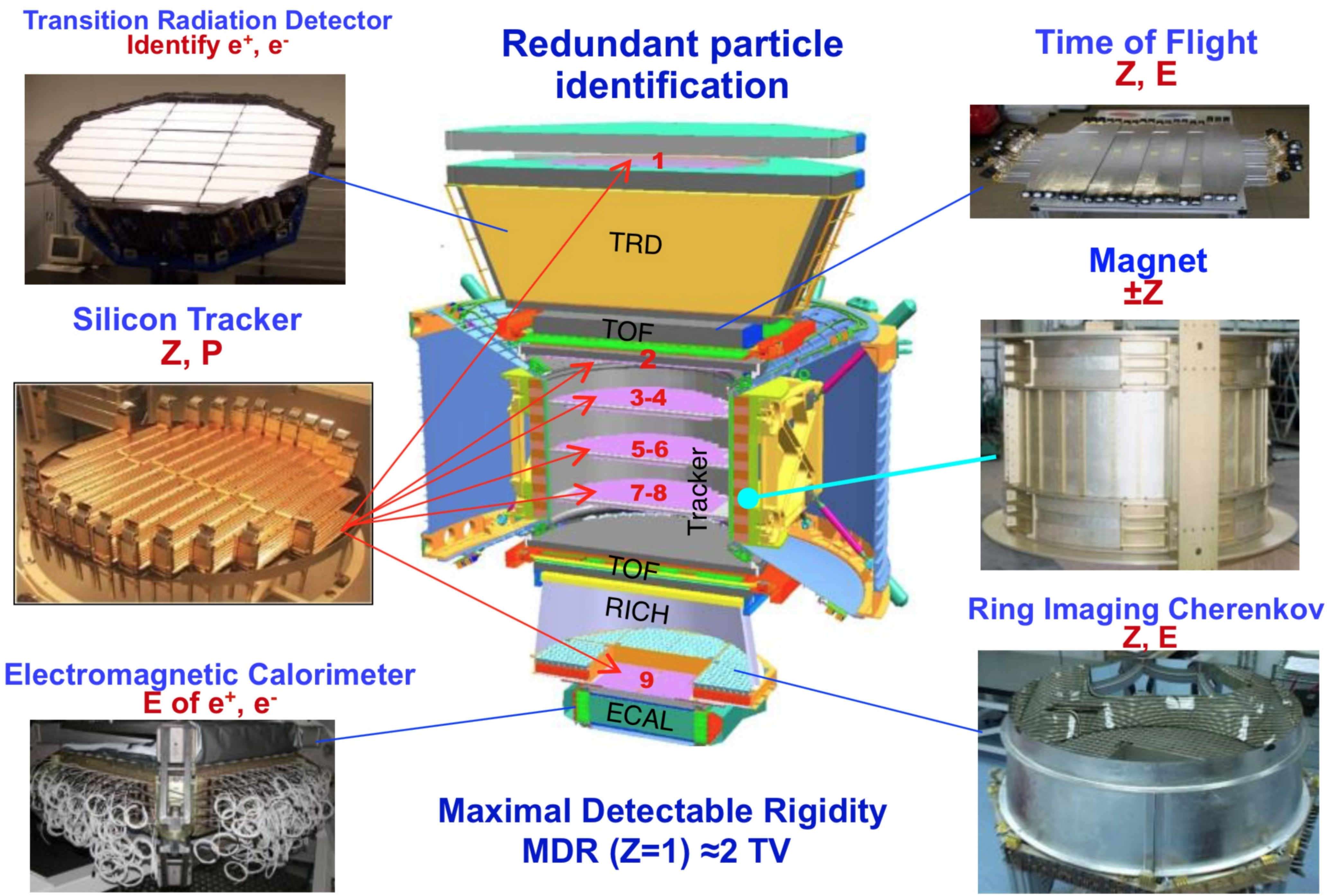


July 15, 2017
ICRC2017, Busan

A. Kounine / MIT


AMS will continue to at least 2024
ELC2
AMS installed on the ISS at
5:15 CDT May 19, 2011
AMS taking data since
9:35 CDT May 19, 2011
ELC4

AMS: A TeV precision, multipurpose magnetic spectrometer



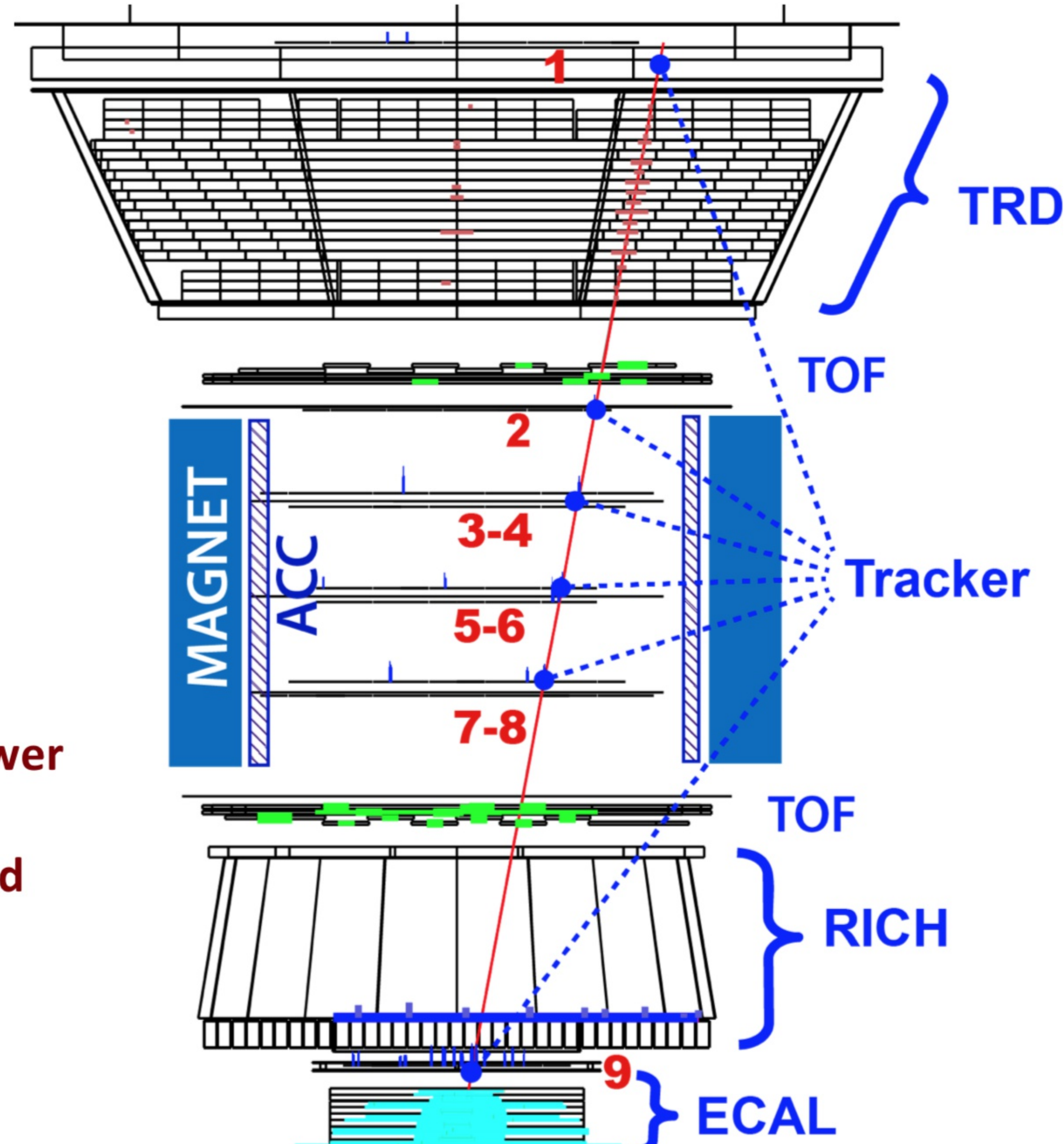
2.4 TeV Electron measured by AMS

An electron is identified by:

① an electron signal in the TRD

② an electron signal in the ECAL

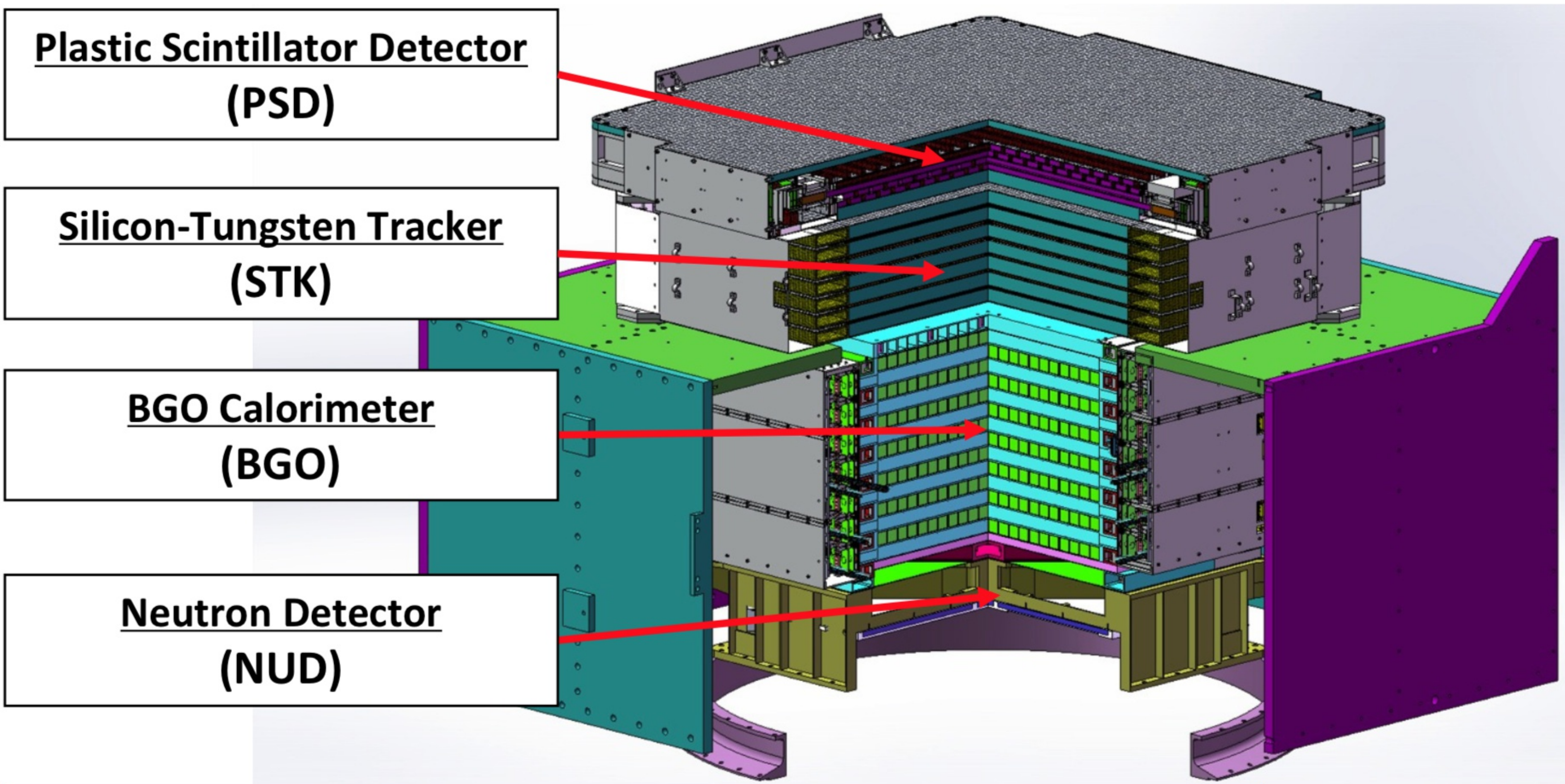
③ the matching of the ECAL shower energy and the momentum measured with the tracker and the magnet.



DAMPE (Dark Matter Particle Explorer)

Launch : 17th December 2015

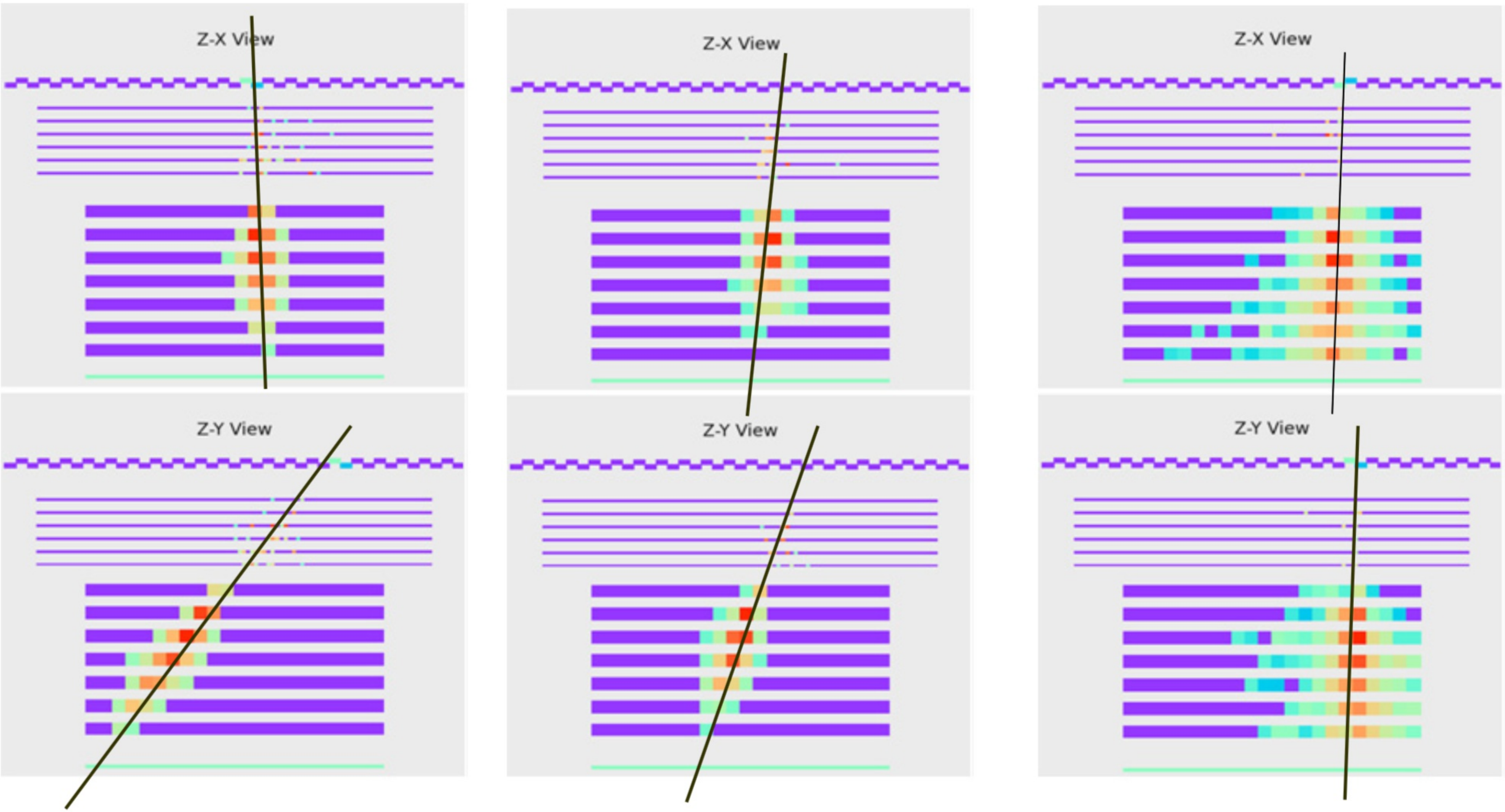
Instrument Design



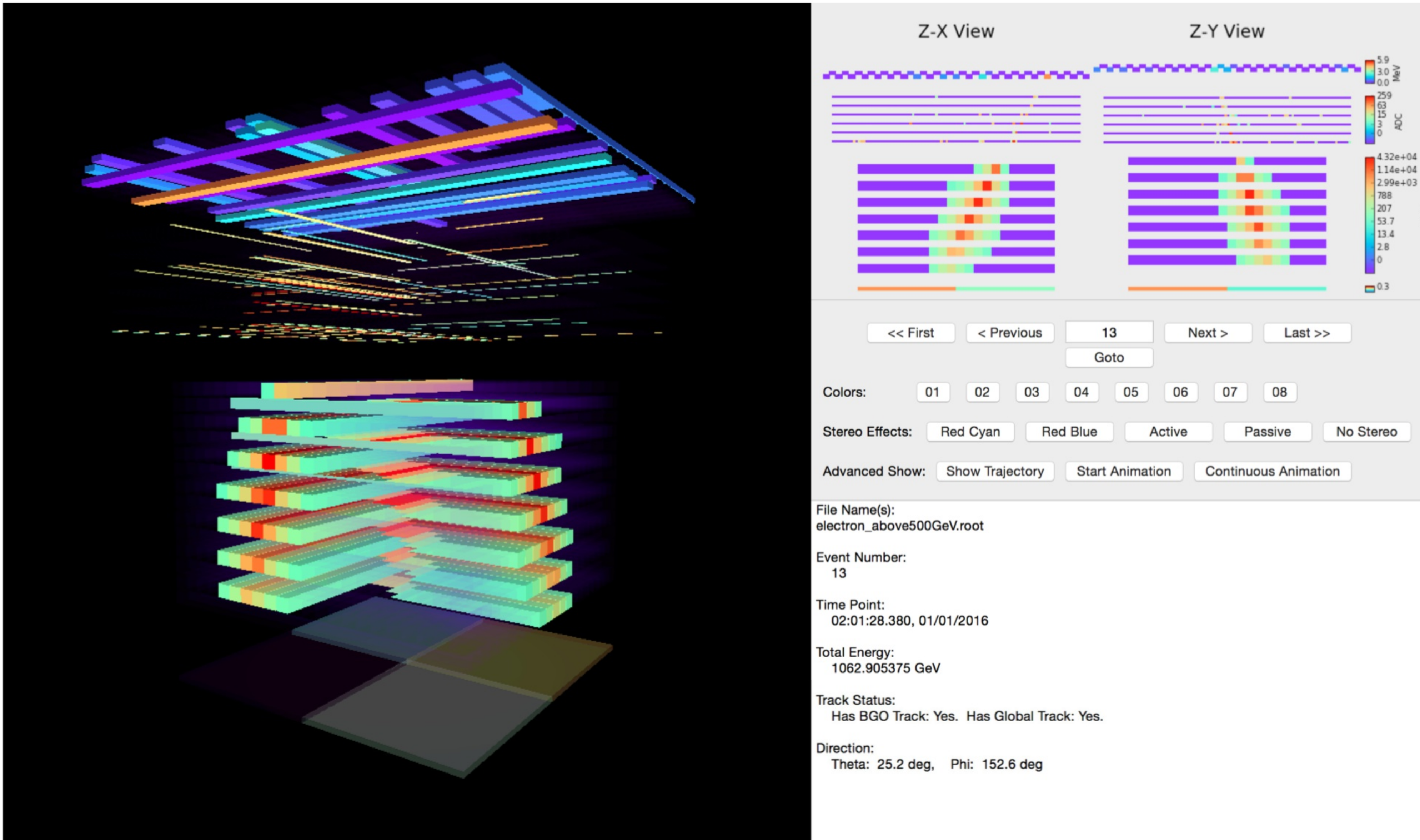
- Charge measurement (dE/dx in PSD, STK and BGO)
- Pair production and precise tracking (STK and BGO)
- Precise energy measurement (BGO bars)
- Particle identification (BGO and NUD)

Signals for different particles

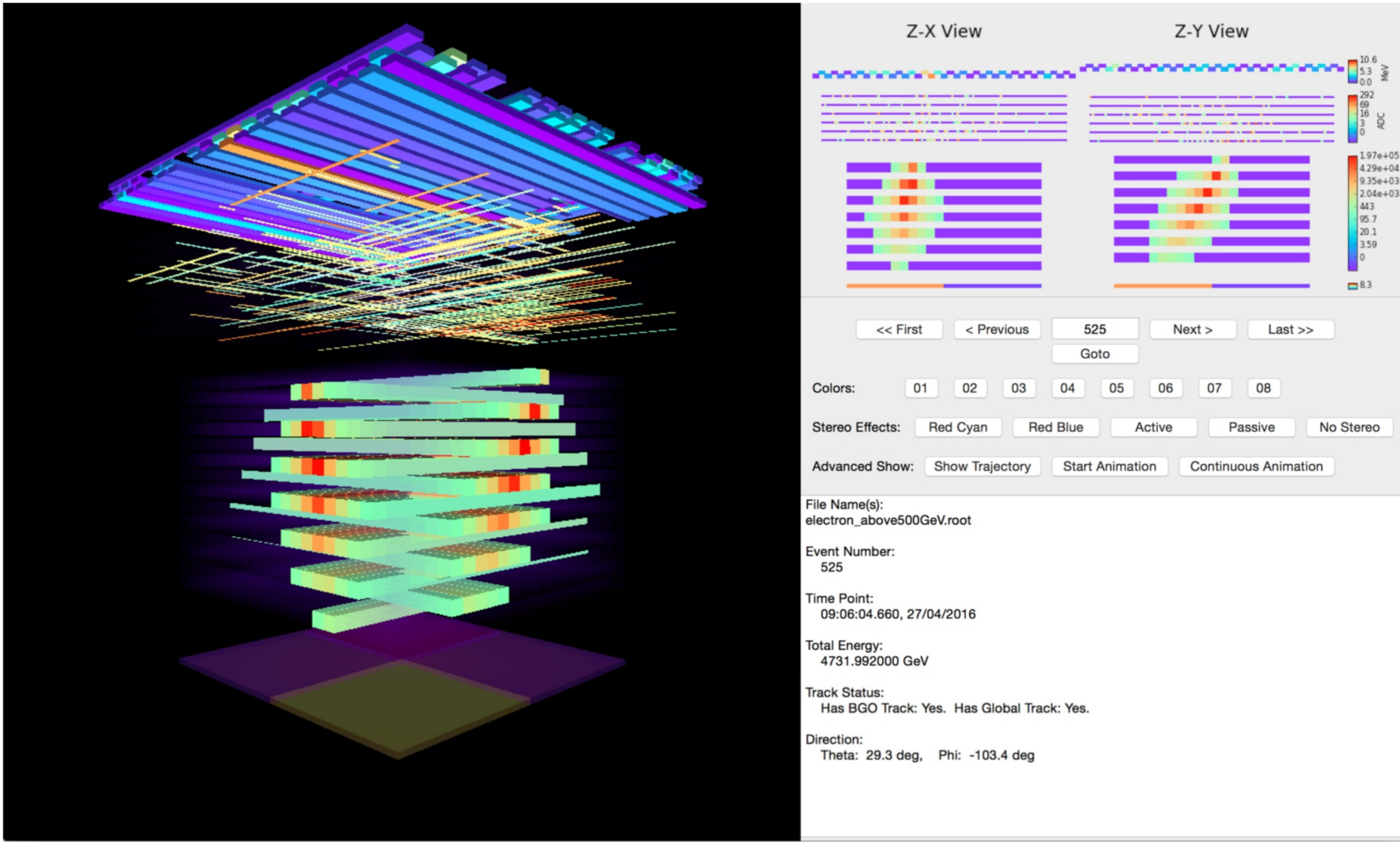
electron gamma proton



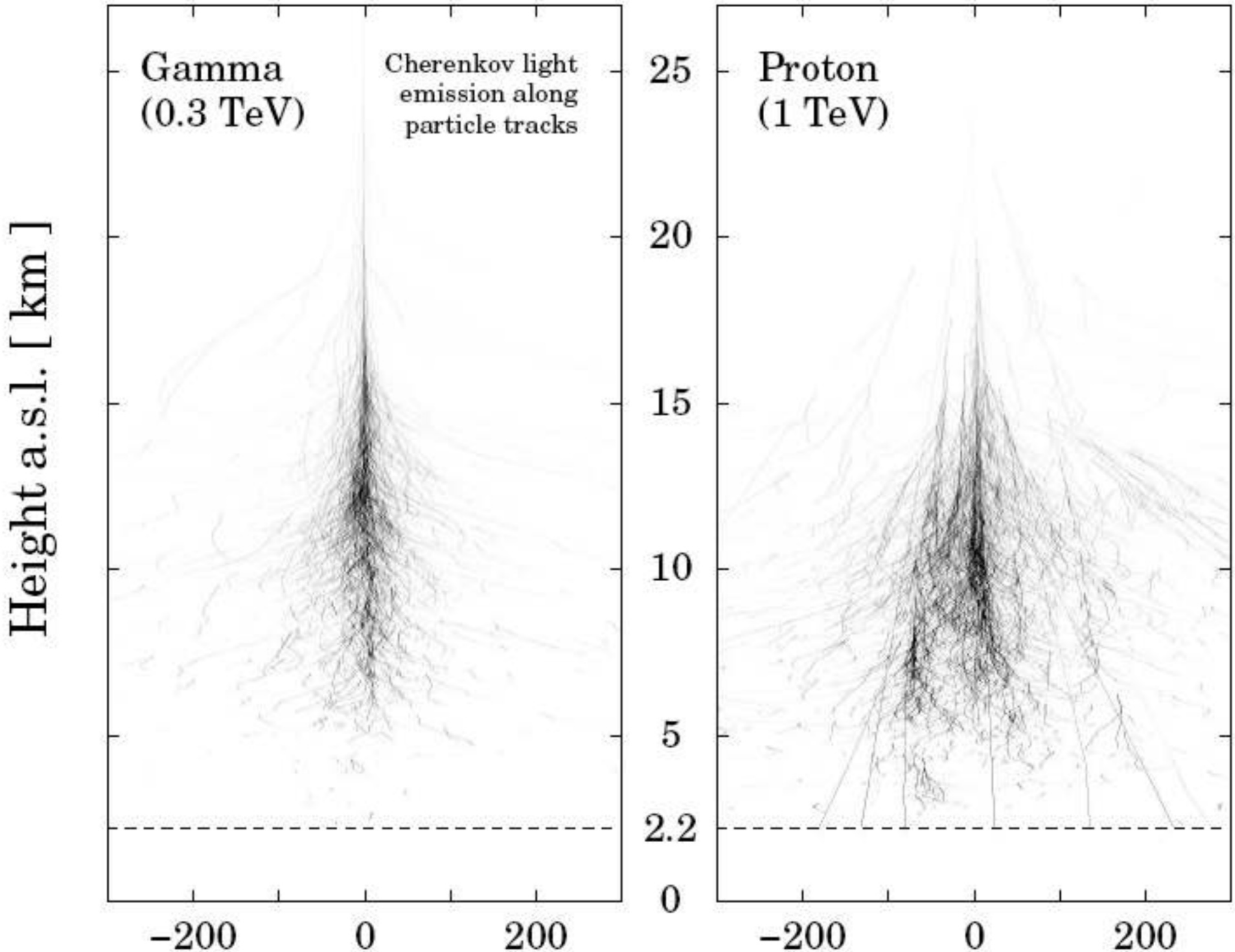
Event: ~1 TeV electron candidate



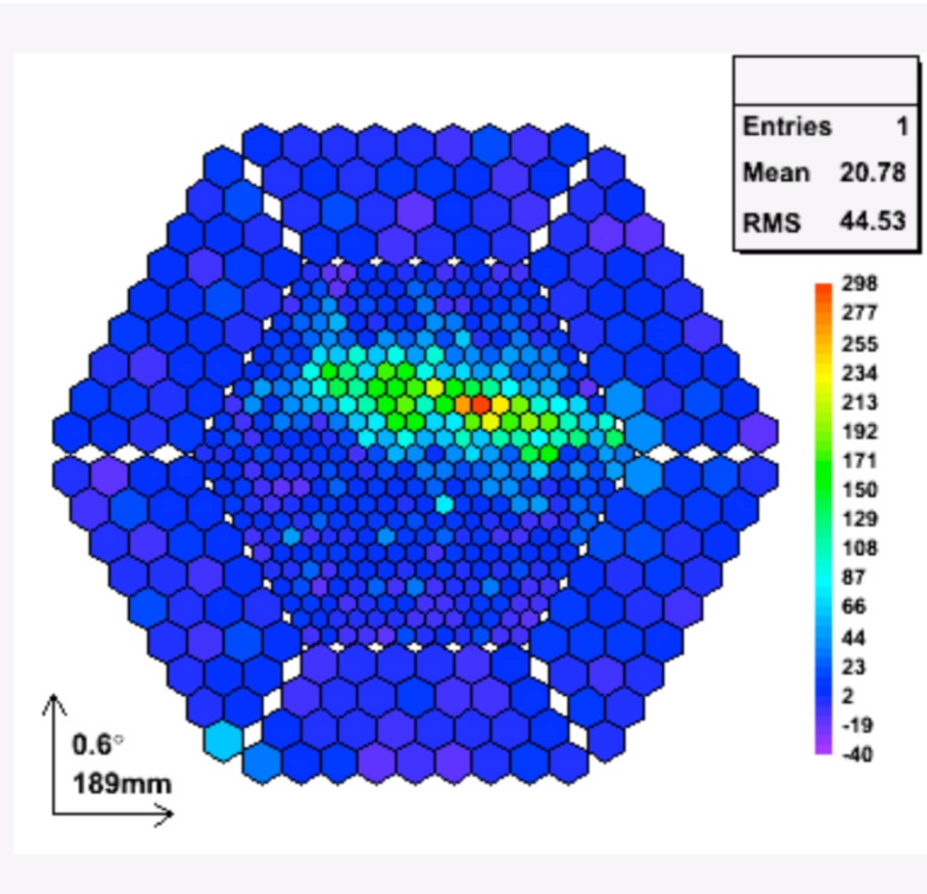
Event: ~5 TeV electron candidate



HESS Cherenkov detector


Gamma
(0.3 TeV)
Cherenkov light
emission along
particle tracks
Proton
(1 TeV)
Height a.s.l. [km]
25
20
15
10
5
2.2
0
−200
0
200
−200
0
200

MAGIC camera



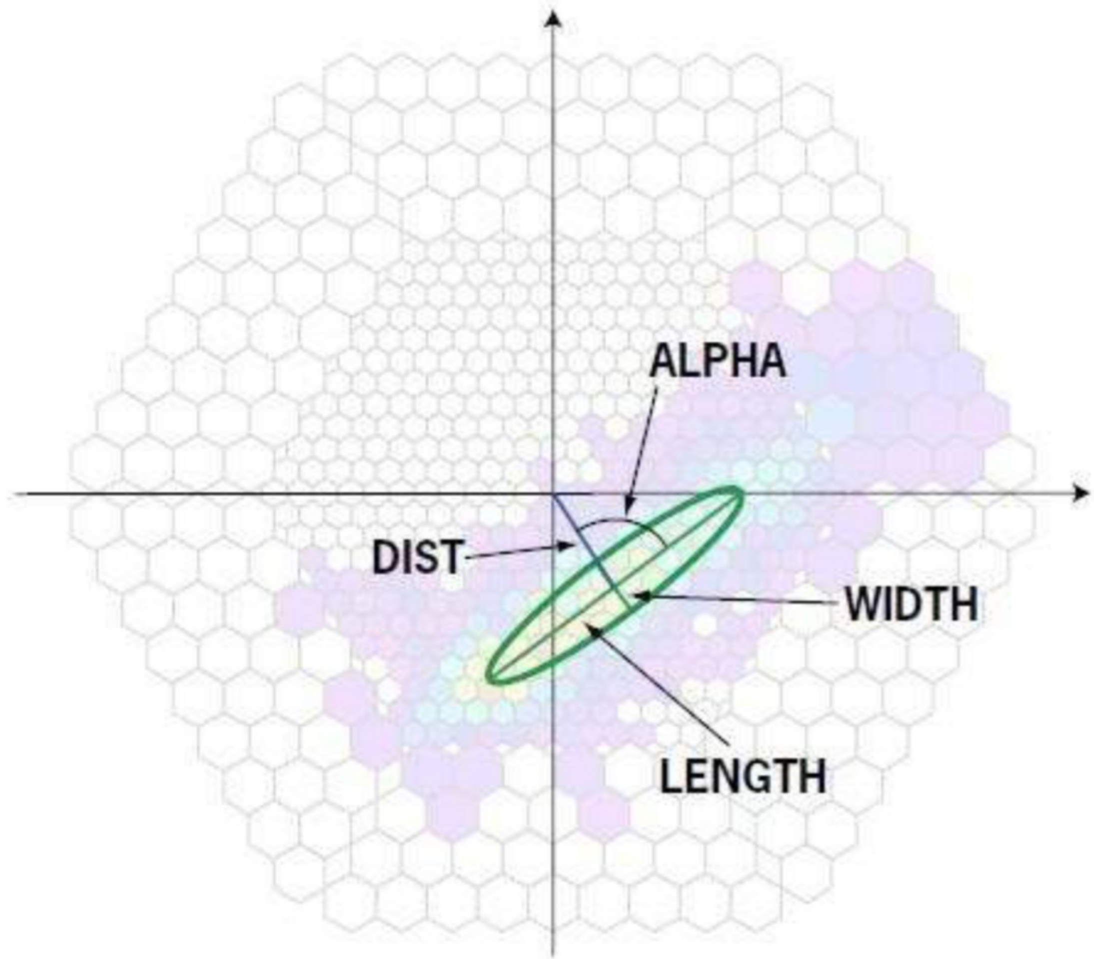
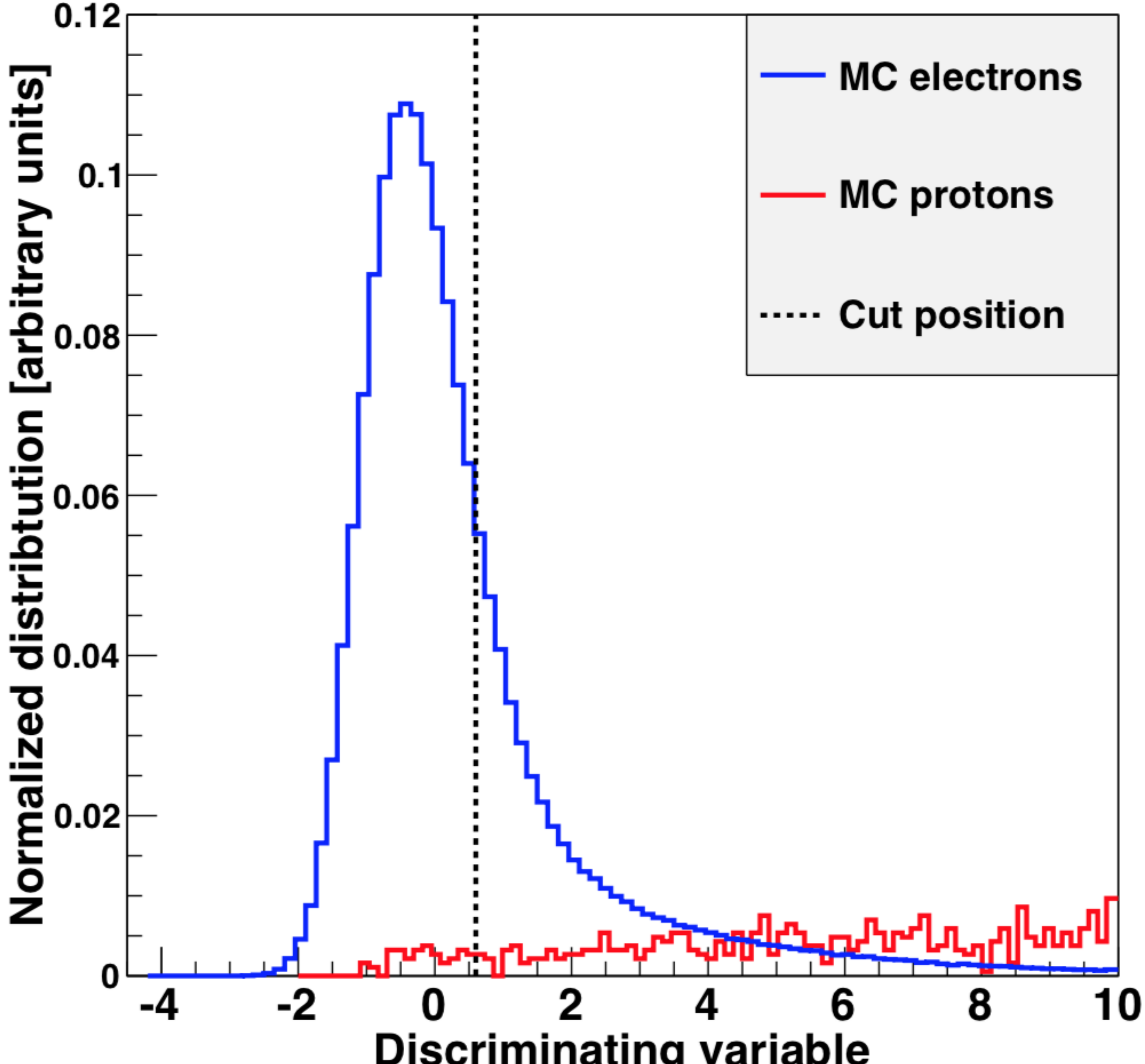


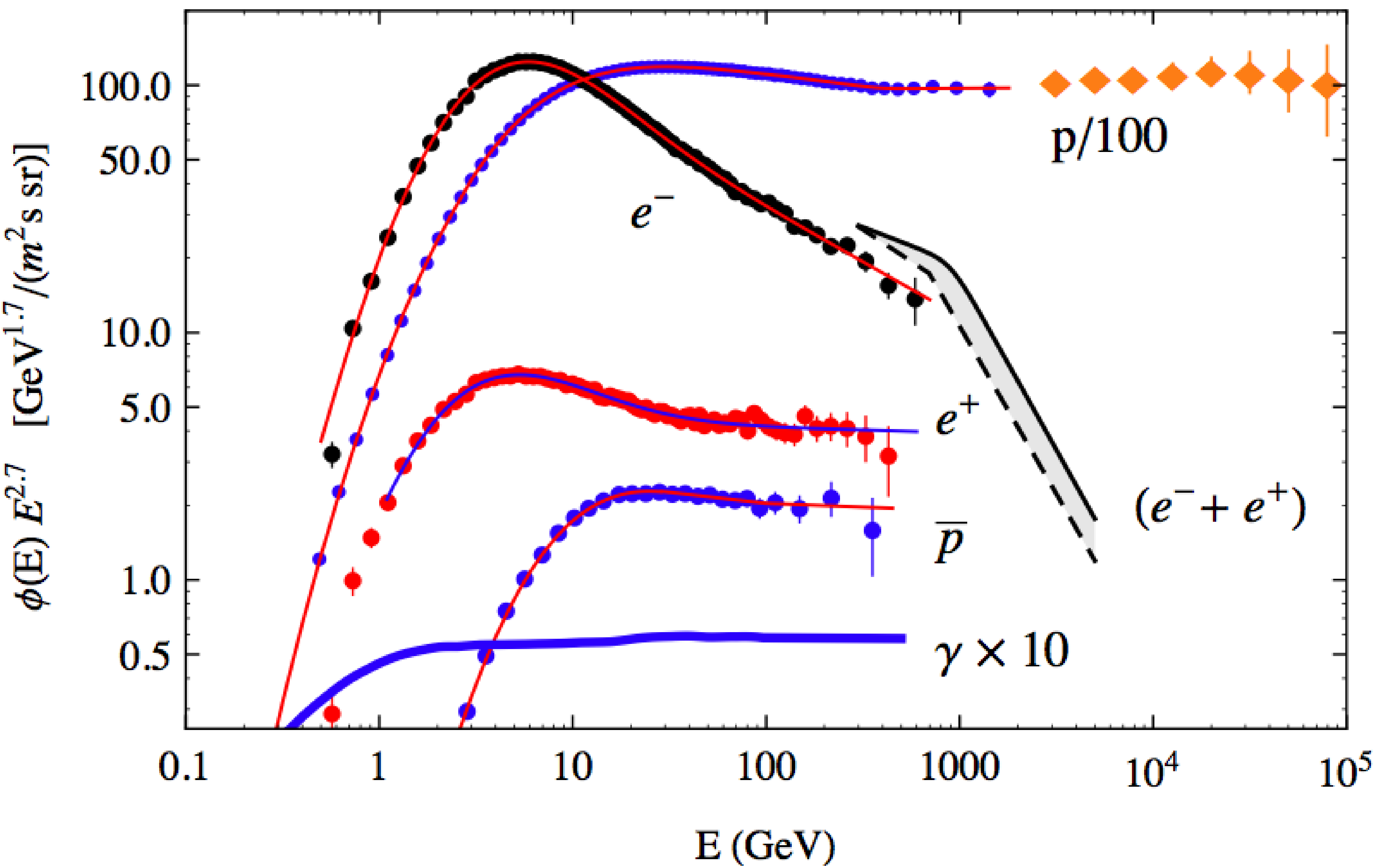
image analysis:
form and orientation



MC electrons
MC protons
Cut position
Normalized distribtution [arbitrary units]
Discriminating variable
0.12
0.1
0.08
0.06
0.04
0.02
0
-4
-2
0
2
4
6
8
10

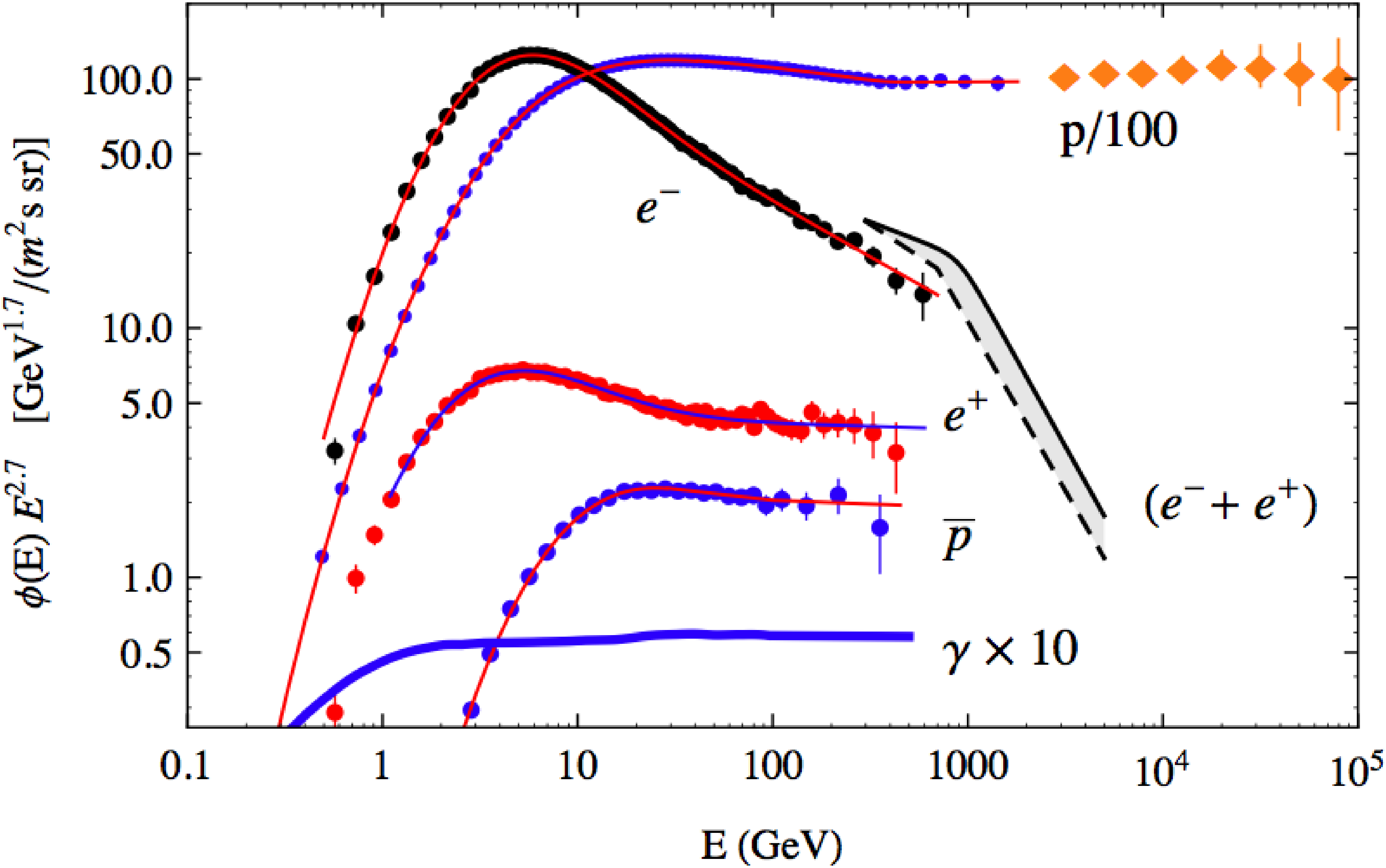
AMS02 p e^- e^+ $\overline{p}$

CREAM p data



angle averaged diffuse Galactic gamma ray flux (Fermi)

CREAM p data

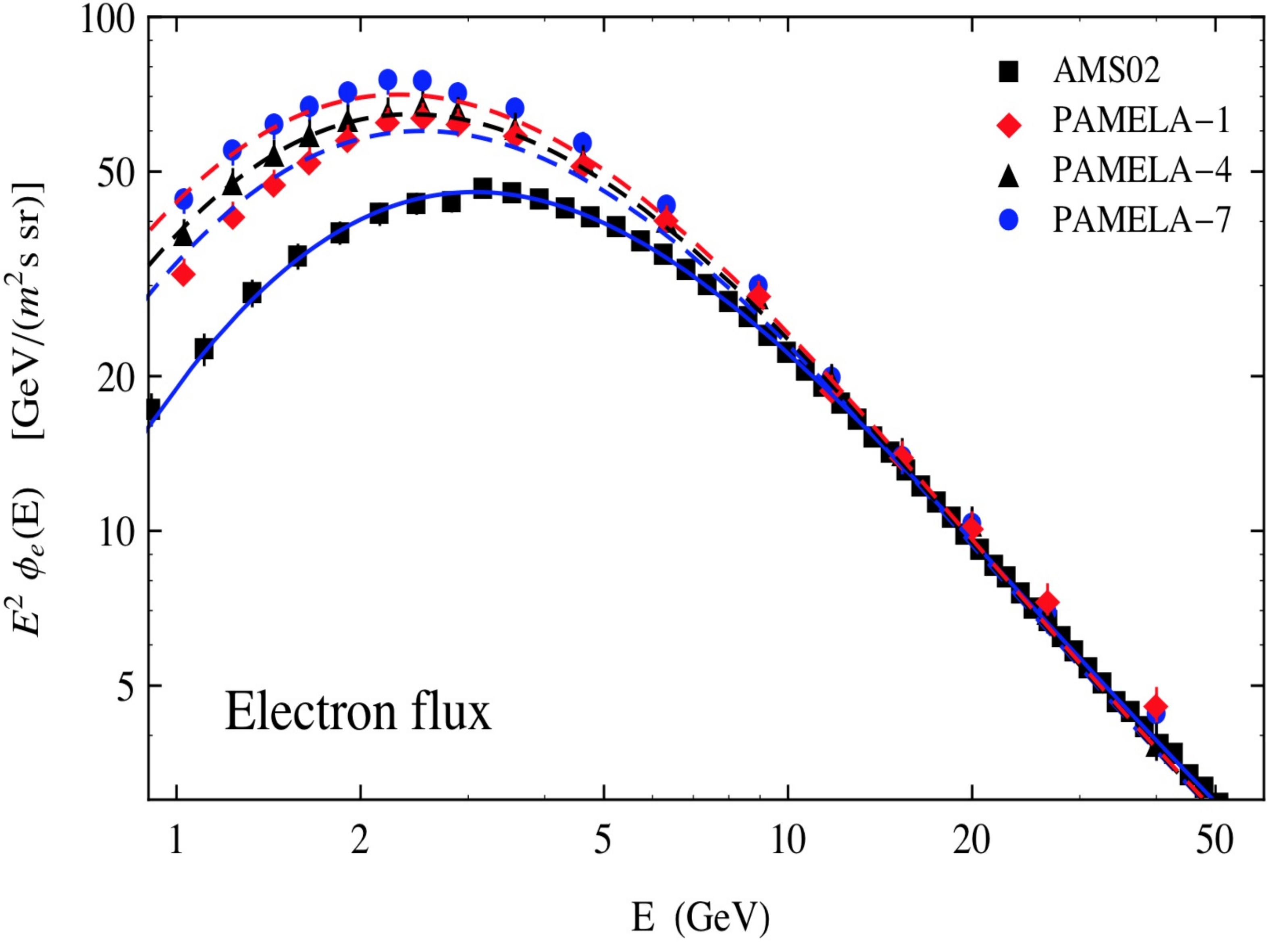


soft electron spectrum

4 spectra
have approximately
the same slope

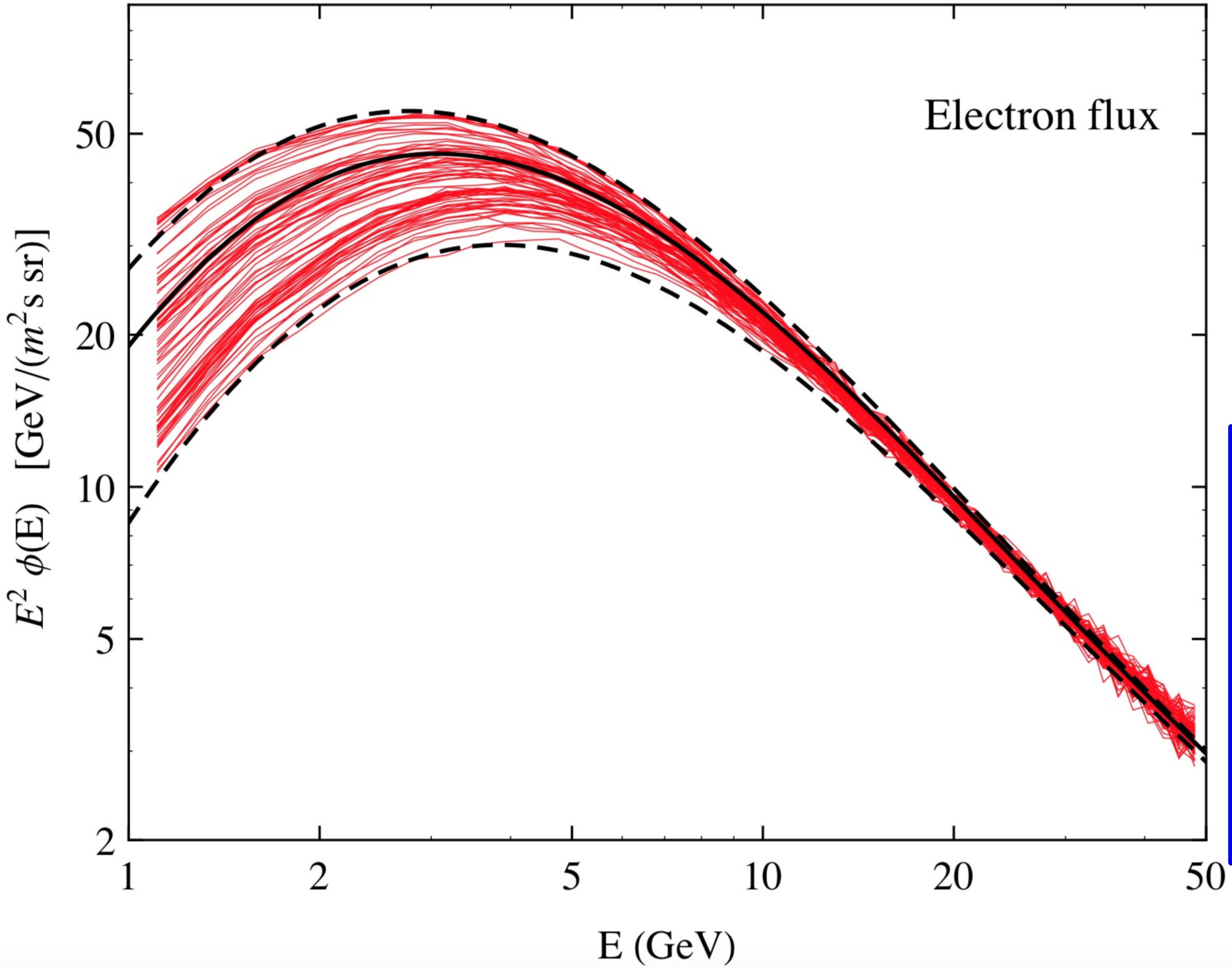
Solar Modulations

Electron spectra
at different times



Recent AMS02
[79 spectra of e+ and e-]
[27 days periods]

What is the shape of the **interstellar spectrum** ?



Fit =

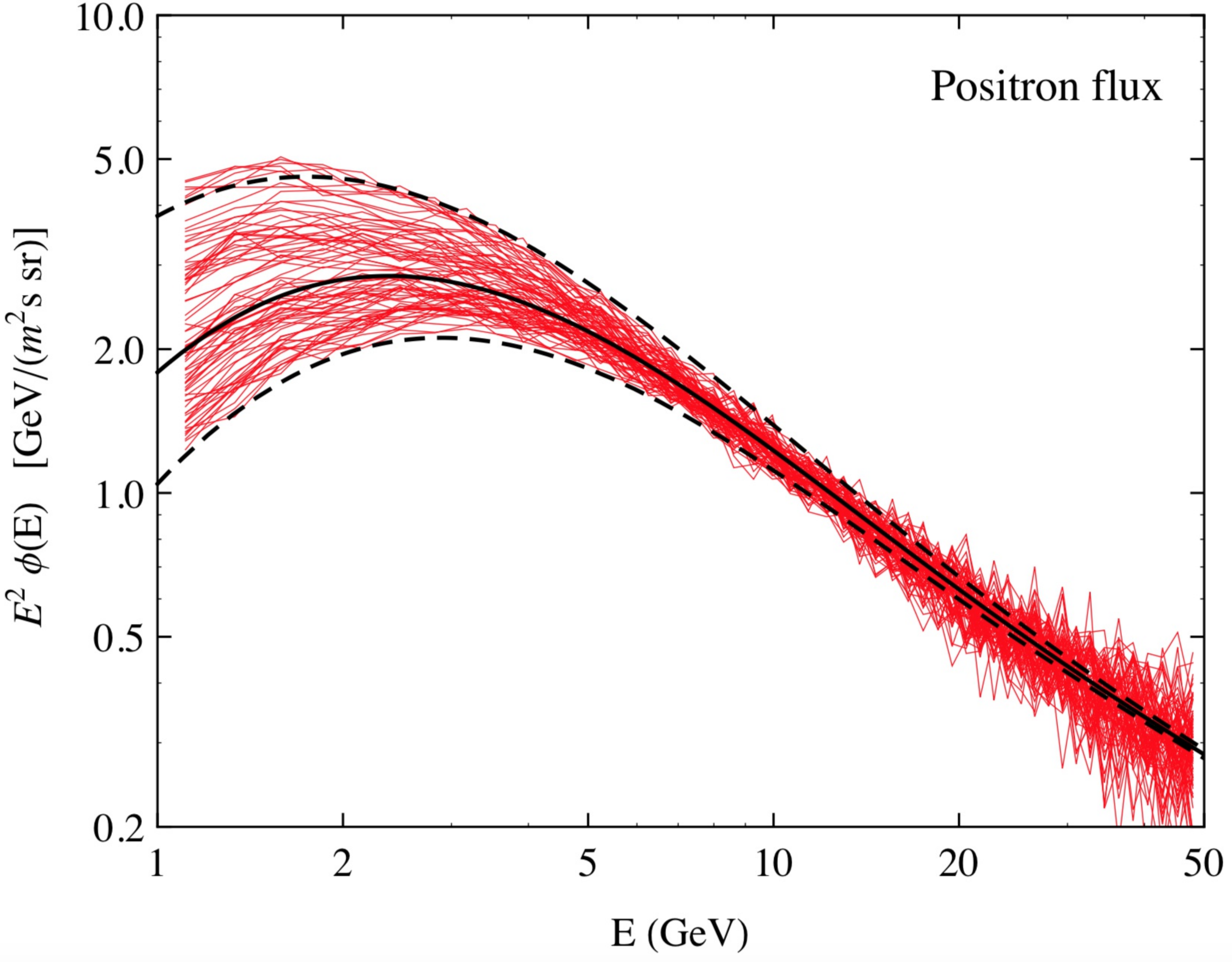
$K\ E^{-3.17}$

$\otimes$

FFA Solar Modulations

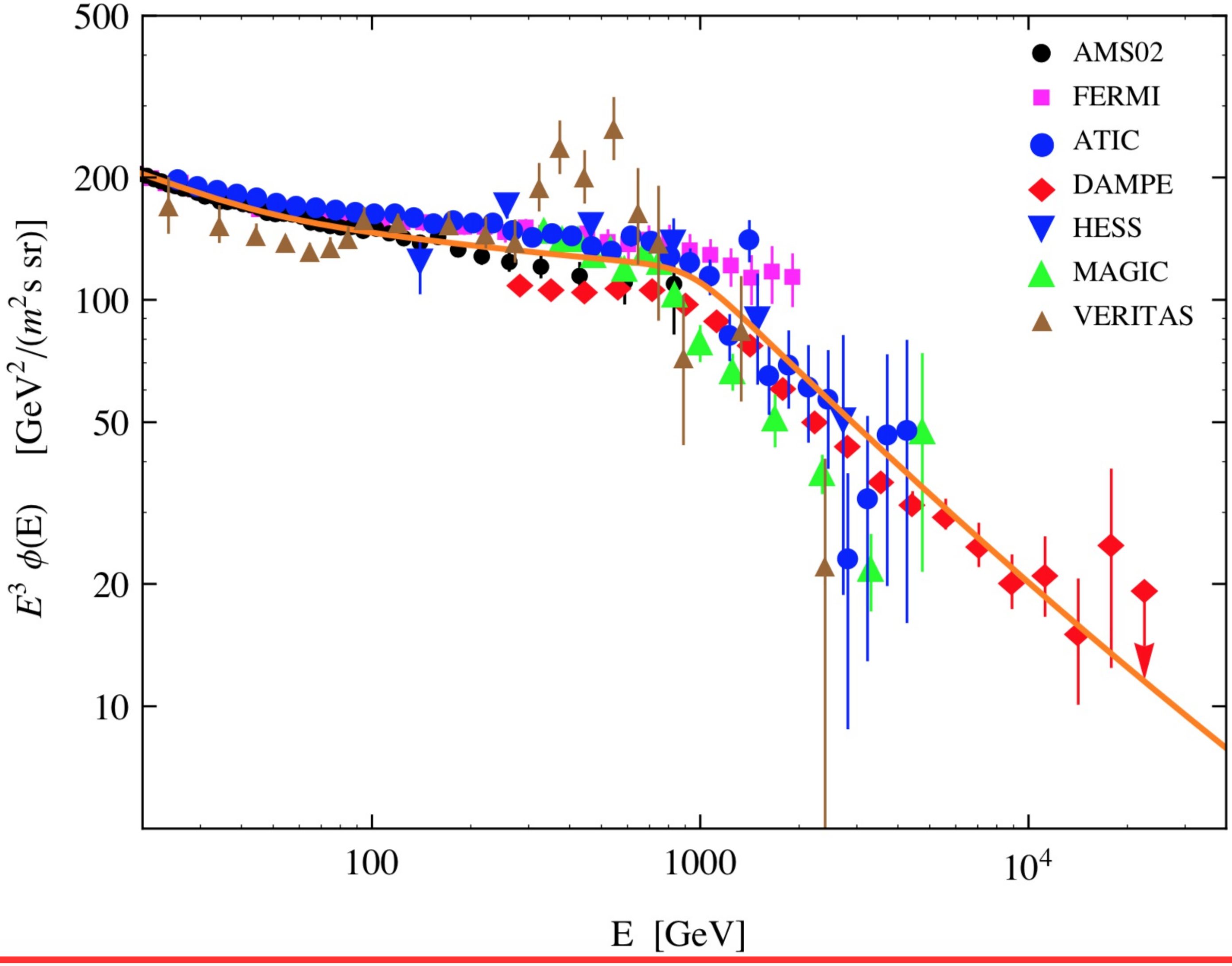
Positron flux

Unbroken power law
in interstellar space
+ Force Field Approximation
for solar modulations

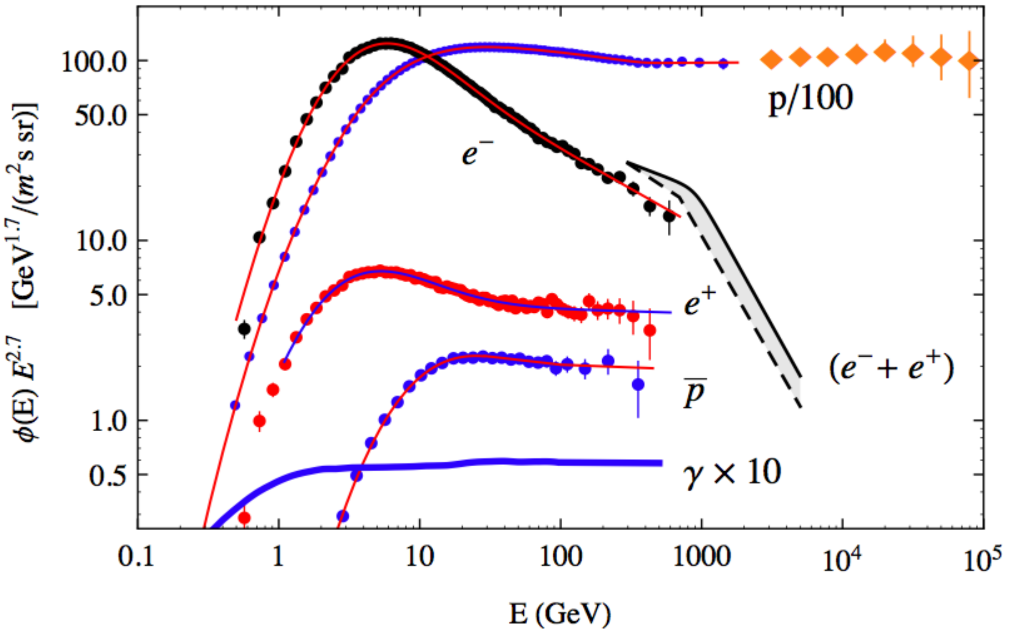


All electron spectrum $(e^- + e^+)$

Remarkable discovery of Cherenkov telescopes confirmed by satellites



Understanding this spectral structure is *important*



"striking" qualitative features that "call out" for an explanation

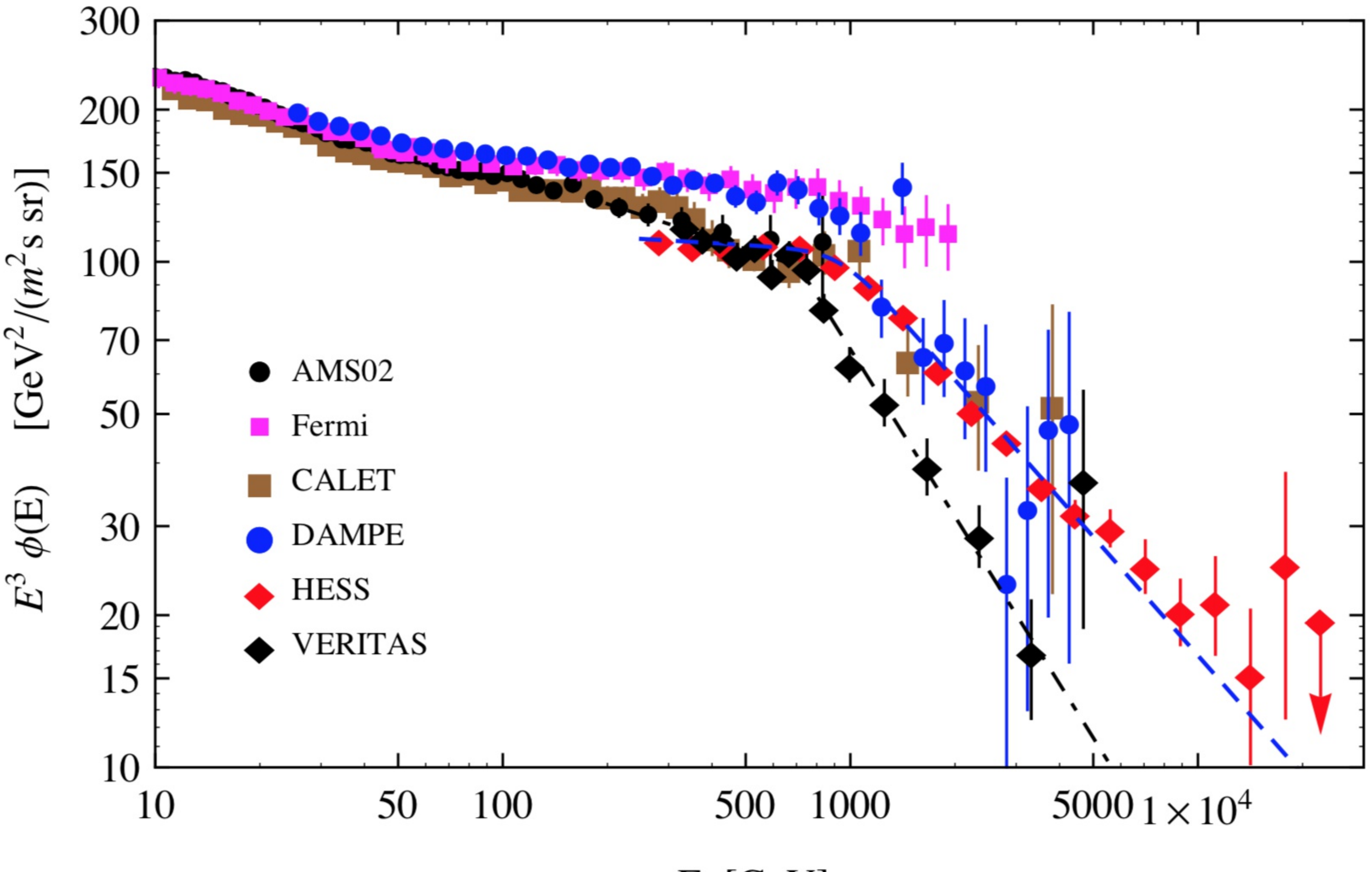
4 spectra have approximately the same slope

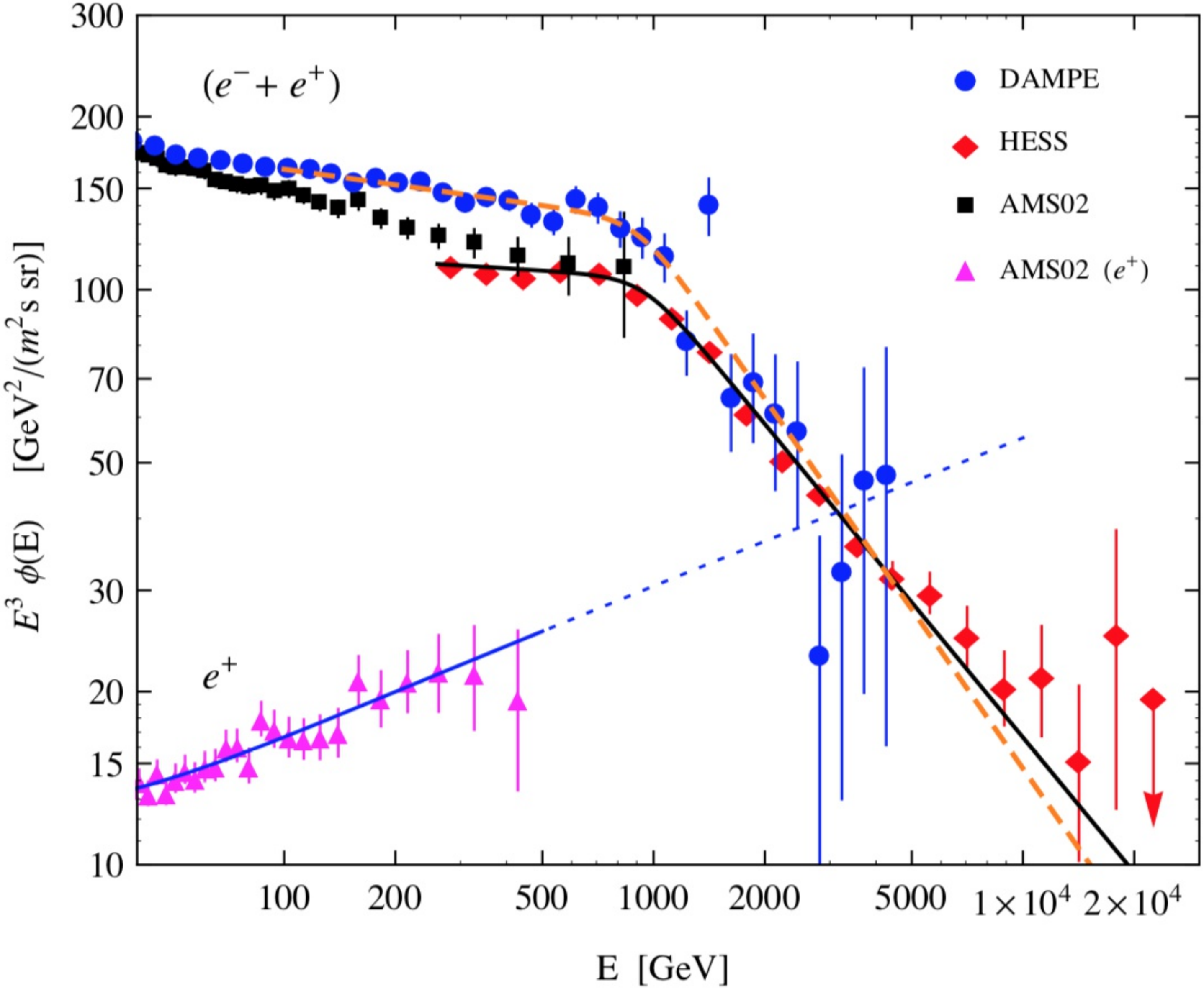
[A] *Proton* and *electron* spectra are very different.

- [a1] much smaller e- flux
- [a2] much *softer* electron flux
- [a3] evident "break" at 1 TeV in the $(e^+ + e^-)$ spectrum

[B] *positron* and *antiproton* for (E> 30 GeV) have the same power law behavior and differ by a factor 2 (of order unity)

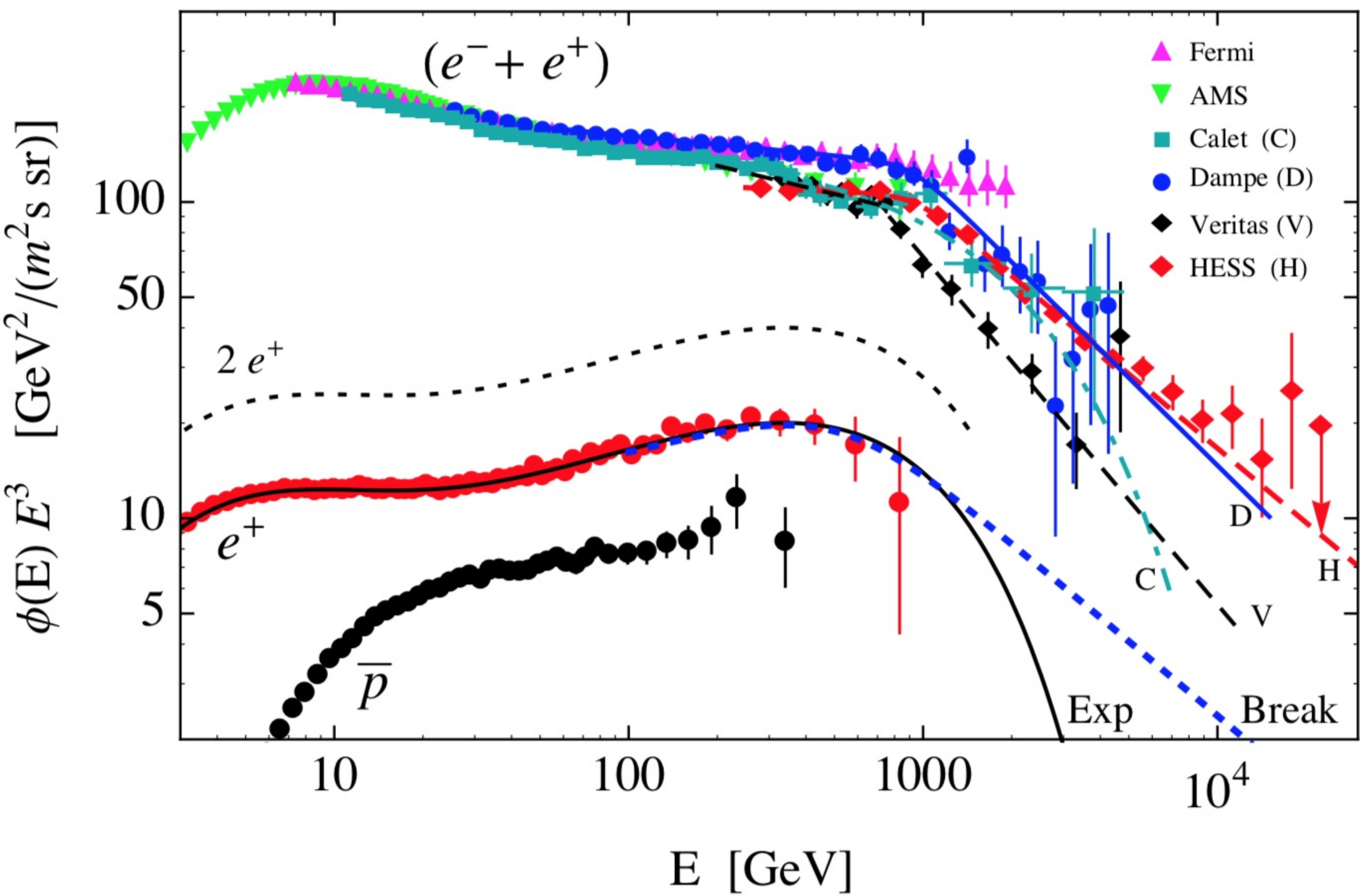
Veritas: break at 710 GeV,
stronger break





Positron component

Crucial to extend the measurement



$(e^- + e^+)$
Fermi
AMS
Calet (C)
Dampe (D)
Veritas (V)
HESS (H)
$\phi(E)\, E^3$ [GeV^2/(m^2s sr)]
100
50
10
5
$2\, e^+$
e^+
$\overline{p}$
D
H
C
V
Exp
Break
10
100
1000
10^4
E [GeV]

Energy Loss

main mechanisms

Synchrotron radiation
Compton scattering
strongly depend on the particle mass

quadratic in energy

$$-\frac{dE}{dt} \propto \frac{q^4}{m^4} E^2$$

$$T_{\rm loss}(E) = \frac{E}{|dE/dt|} \simeq \frac{1}{b\,E}$$

Characteristic time
for energy loss

$$T_{\rm loss}(E) \approx \frac{620}{E_{\rm GeV}}\ {\rm Myr}$$

$$\approx \frac{0.62}{E_{\rm TeV}}\ {\rm Myr}$$

Energy losses
can be the main
"sink" for e+/e- CR

or be negligible

depending on the residence time of the particles in the Galaxy

Rate of Energy Loss depends on the energy density in magnetic field and radiation (and therefore *is a function of position*)

$$T_{\rm loss}(E) = \frac{E}{|dE/dt|} \simeq \frac{3\, m_e^2}{4\, c\, \sigma_{\rm Th}\, \langle \rho_B + \rho_\gamma^*(E) \rangle \; E}$$

$$\simeq 621.6 \left(\frac{\rm GeV}{E} \right) \left(\frac{0.5 \ {\rm eV/cm^3}}{\rho} \right) \ {\rm Myr}$$

Average value for the particle confinement volume

$$\rho_b = \frac{B^2}{8\,\pi} \simeq 0.22 \ \left(\frac{B}{3\ \mu{\rm G}} \right)^2 \ \frac{\rm eV}{\rm cm^3}$$

$$\rho_{\rm CMBR} \simeq 0.26 \ \ \frac{\rm eV}{\rm cm^3}$$

Formation of the Galactic Cosmic Ray spectra
(for each particle type)
three elements are of fundamental importance:

1. Source spectrum

2. Magnetic confinement
   (CR residence (escape) time)

3. Energy losses
   (synchrotron + Compton scattering+ ….)

[4. hadronic + other interactions …..]

Galactic Cosmic Rays

$$N_j(E) = Q_j(E) \times T_j(E)$$

Different particles

$p, \quad \text{nuclei}(Z, A)$

$\overline{p}, \quad e^-, \quad e^+$

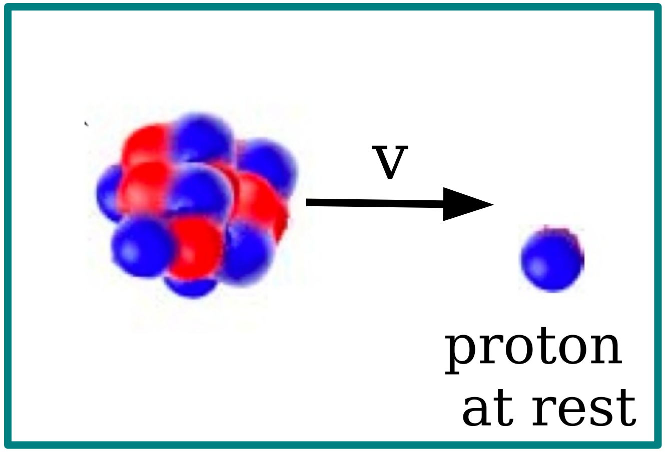
Injection of cosmic rays

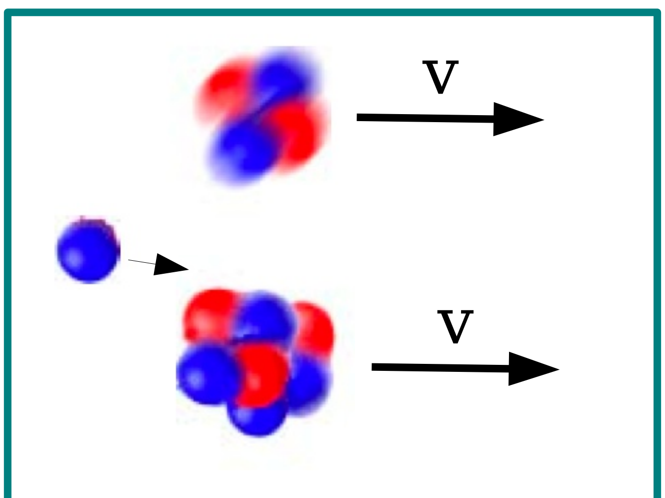
Containment time

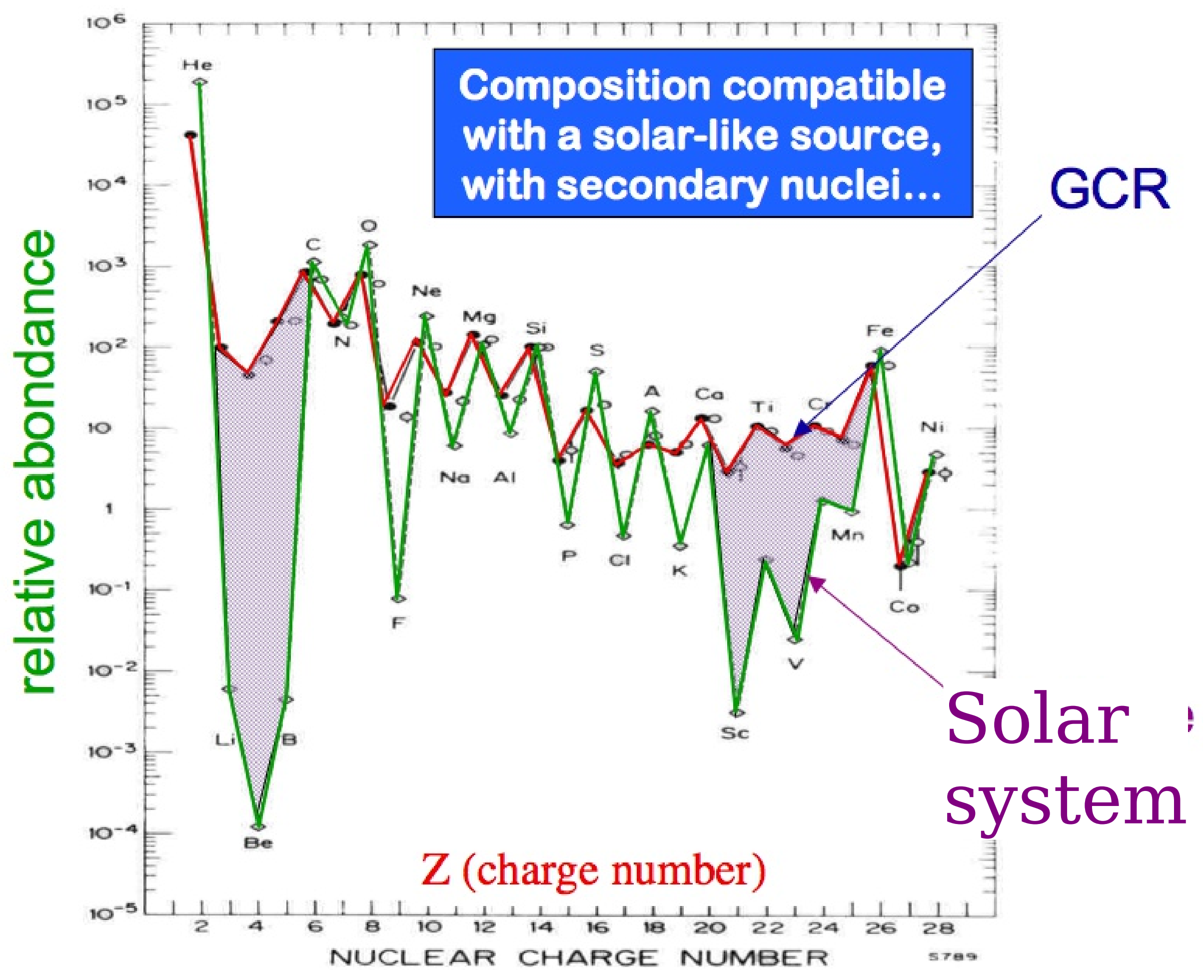
$$N_j(E) = \int d^3x \; n_j(E, \vec{x})$$

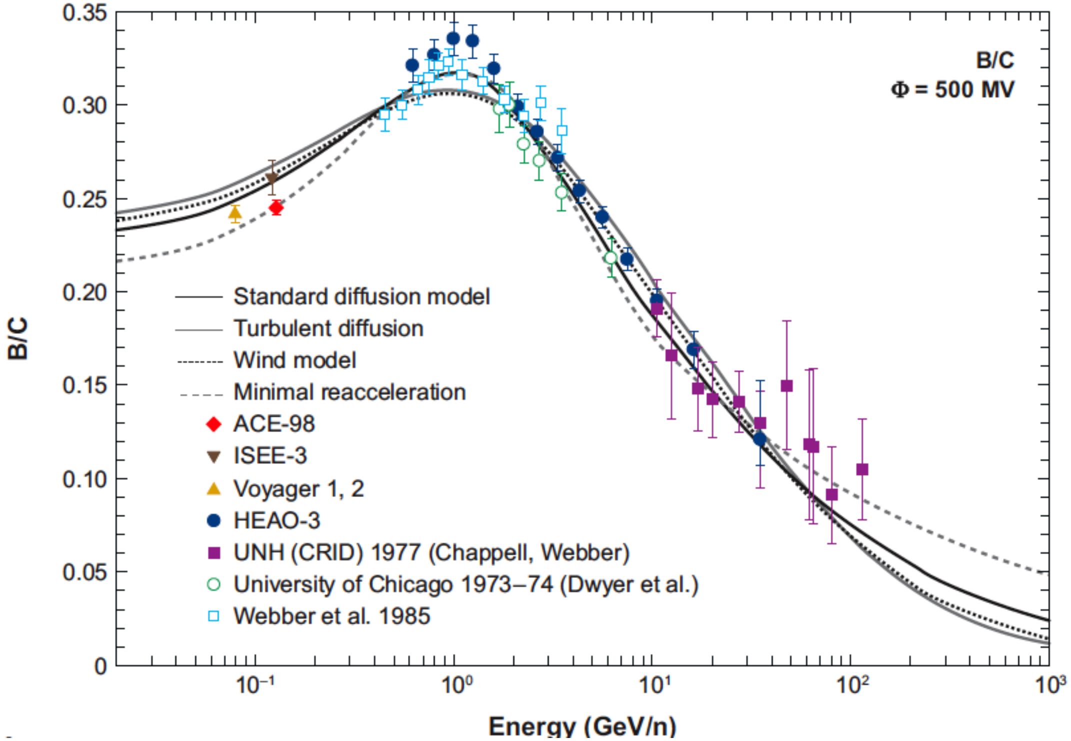
$$\phi_j(E) = \frac{c}{4\pi} \, n_j(E)$$

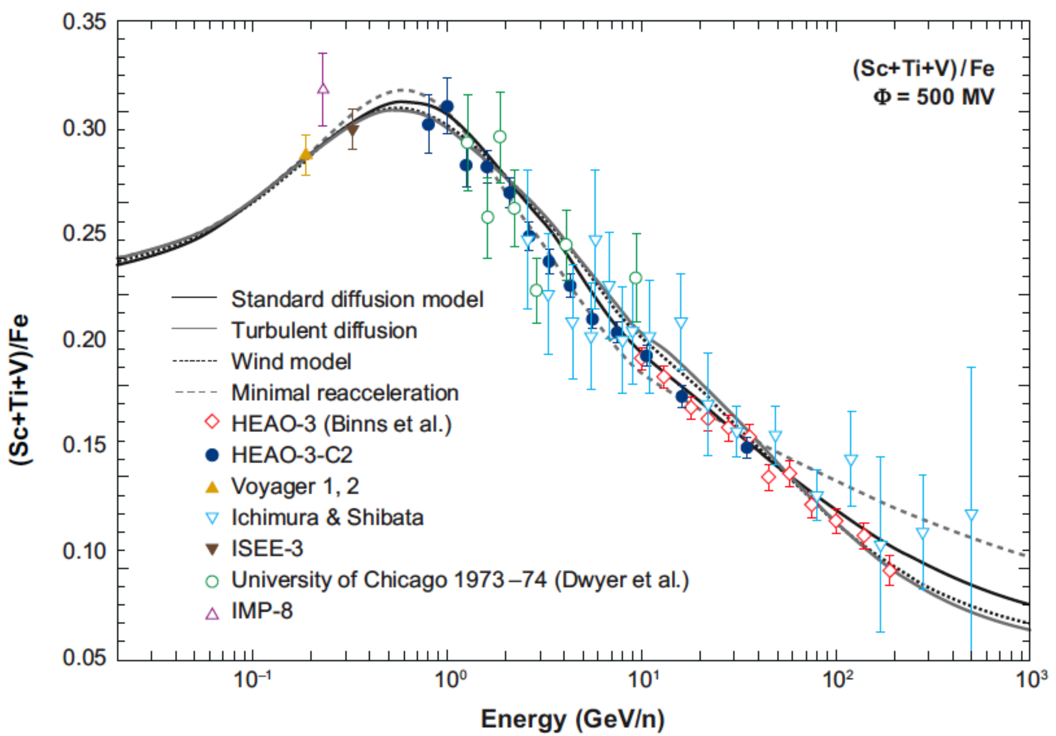
Nuclear Fragmentation
(collisions with the Inter Stellar Medium)











Column density

$$X(E) = \langle \rho \rangle \, T(E)$$

Escape faster at higher E

$$X(E) \propto E^{-\delta}$$

$$\delta \simeq 0.4 \div 0.6$$

$$\frac{\langle \rho \rangle}{m_p} \simeq 0.2 \text{ cm}^{-3}$$

(extended halo)

Injection
of cosmic rays

Containment
time

$$N_j(E) = Q_j(E) \times T_j(E)$$

$$L_j = \int dE\ E\ Q_j(E)$$

LARGE Power
Requirement

Spectral Shape
[Dynamics
of acceleration process]

$$L_{\rm cr}(\text{Milky Way}) \simeq 2 \times 10^{41}\ \text{erg/s}$$

$$\simeq 5 \times 10^{7}\ L_{\odot}$$

Source
Identification

“Secondary Nuclei” Li, Be, B

Rare nuclei created in the fragmentation of primary (directly accelerated) more massive nuclei

Some examples:

$$^{12}\mathrm{C} + p \to {}^{10}\mathrm{B} + 2\,p + n$$

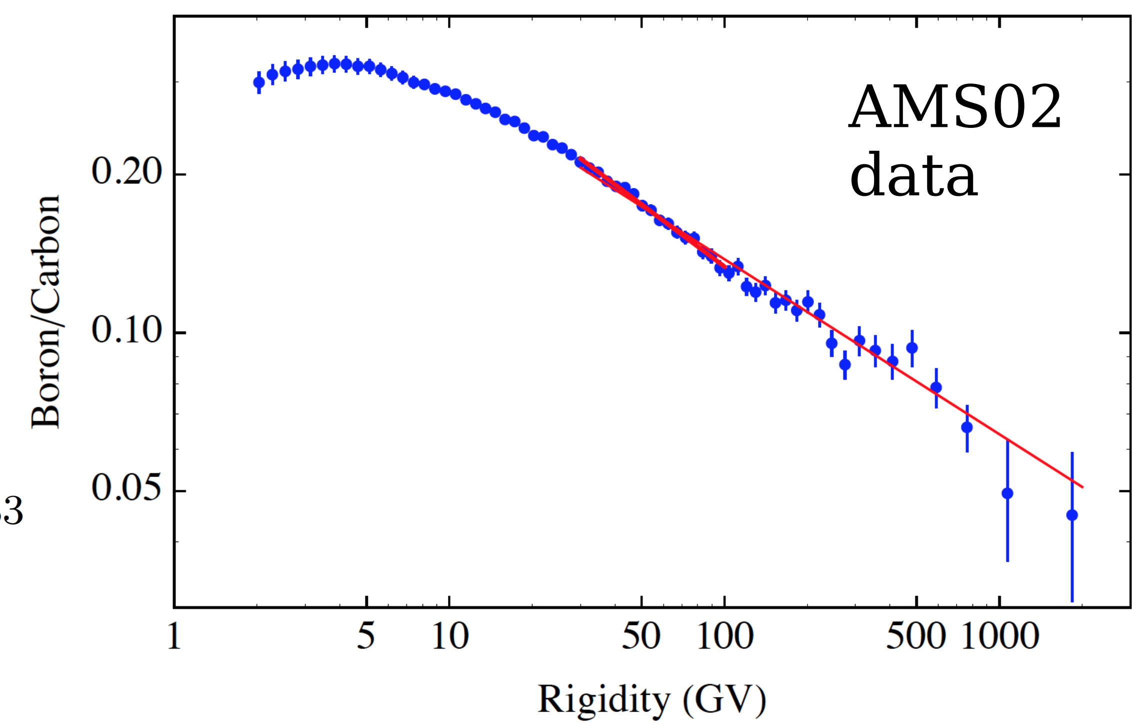
$$^{12}\mathrm{C} + p \to {}^{11}\mathrm{B} + 2\,p$$

$$^{16}\mathrm{O} + p \to {}^{11}\mathrm{B} + {}^{4}\mathrm{He} + 2\,p$$

....

$$\frac{\text{secondary nuclei}}{\text{primary nuclei}} \Longrightarrow$$

“grammage" traversed by the nuclei



$$\frac{\text{Boron}}{\text{Carbon}} \approx 0.21 \left(\frac{p/Z}{30\ \text{GV}}\right)^{-0.33}$$

$$\frac{\text{Boron}}{\text{Carbon}} \approx 0.21 \left(\frac{p/Z}{30\ \text{GV}}\right)^{-0.33}$$

Approximation
of constant fragmentation
cross sections

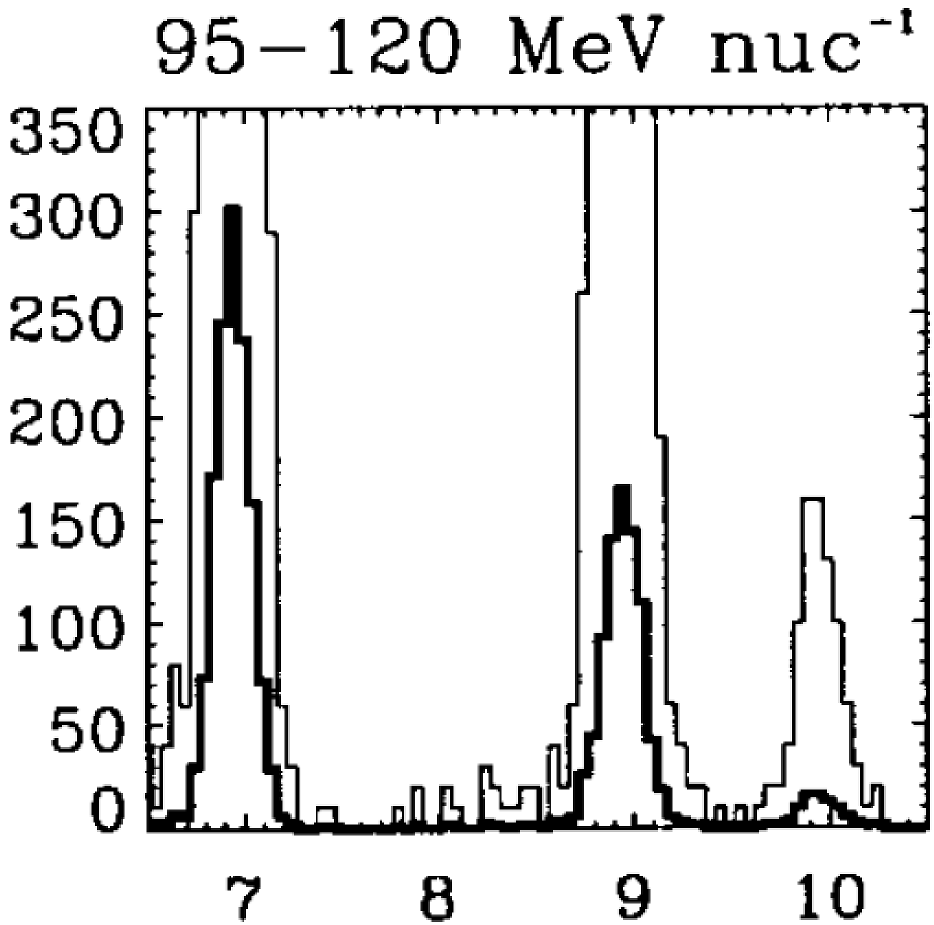
Interpretation in terms of Column density

$$\langle X \rangle \approx 4.7 \left(\frac{p/Z}{30\ \text{GV}}\right)^{-0.33} \frac{\text{g}}{\text{cm}^2}$$

[Assuming that the column density is accumulated during *propagation in interstellar space*]

$$\langle T_{\text{age}} \rangle \simeq 30\ \text{Myr} \left[\frac{0.1\ \text{g}\,\text{cm}^{-3}}{\langle n_{\text{ism}} \rangle}\right] \left(\frac{|p/Z|}{30\ \text{GV}}\right)^{-0.33}$$

Direct measurement of the cosmic ray "age"
unstable isotope Beryllium-10. $(T_{1/2} \simeq 1.51 \pm 0.04 \text{ Myr})$



N.E. Yanasak *et al.* Astrophys. J. **563**, 768 (2001).

Measurements
of Beryllium 10

Compare with
flux of stable isotopes

Decay suppression:
infer residence time

$$\langle P_{\rm surv} \rangle = 0.12 \pm 0.01$$

Estimate of suppression
in original paper

Extracting $\langle t_{\rm age} \rangle$ $\langle P_{\rm surv} \rangle$

is in general *model dependent*
[depends on the distribution of the age]

Single age for CR: $\langle P_{\rm surv} \rangle = e^{-t/\tau}$

Distribution of ages

$$\langle P_{\rm surv} \rangle = \int_0^\infty dt \, \boxed{F(t, \langle t \rangle)} \, e^{-t/\tau}$$

Work of

N.E. Yanasak *et al.*

Astrophys. J. **563**, 768 (2001).

$E_0 = 70\text{–}145\ \mathrm{MeV/nucleon}$

$$\langle P_{\rm surv} \rangle = 0.12 \pm 0.01$$

$$\langle t_{\rm age} \rangle \simeq 15.0 \pm 1.6\ \mathrm{Myr}$$

[Leaky Box framework]

Result reinterpreted with longer lifetimes in different frameworks

M. Kruskal, S. P. Ahlen and G. Tarlé,

Astrophys. J. **818**, no. 1, 70 (2016)

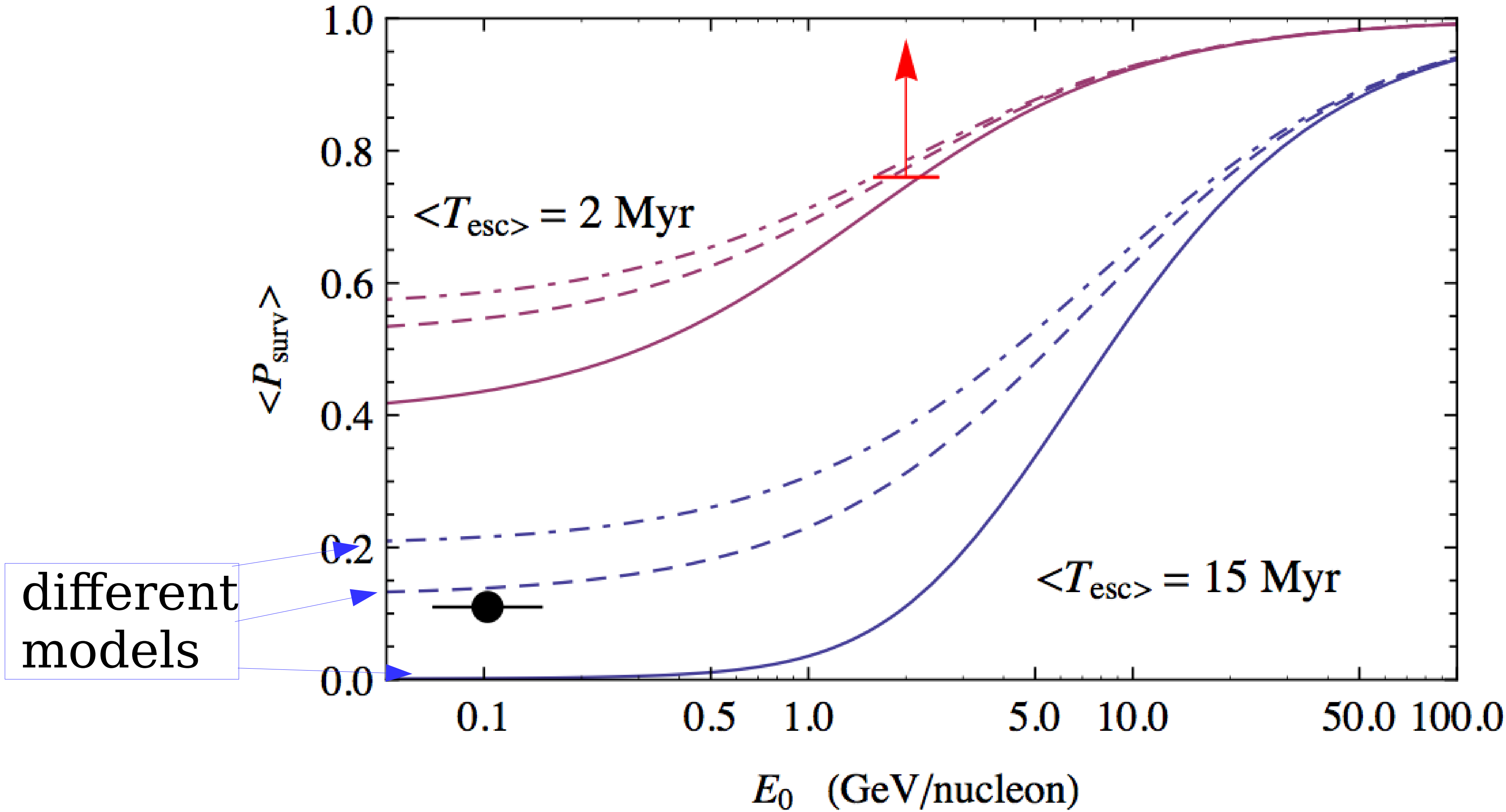
$E_0 = 2\ \mathrm{GeV/nucleon}$

very important to confirm !

$$\langle P_{\rm surv} \rangle \approx 1$$

$$\langle t_{\rm age} \rangle \leq 2.0\ \mathrm{Myr}$$

Much smaller sensitivity to the modeling “theory”



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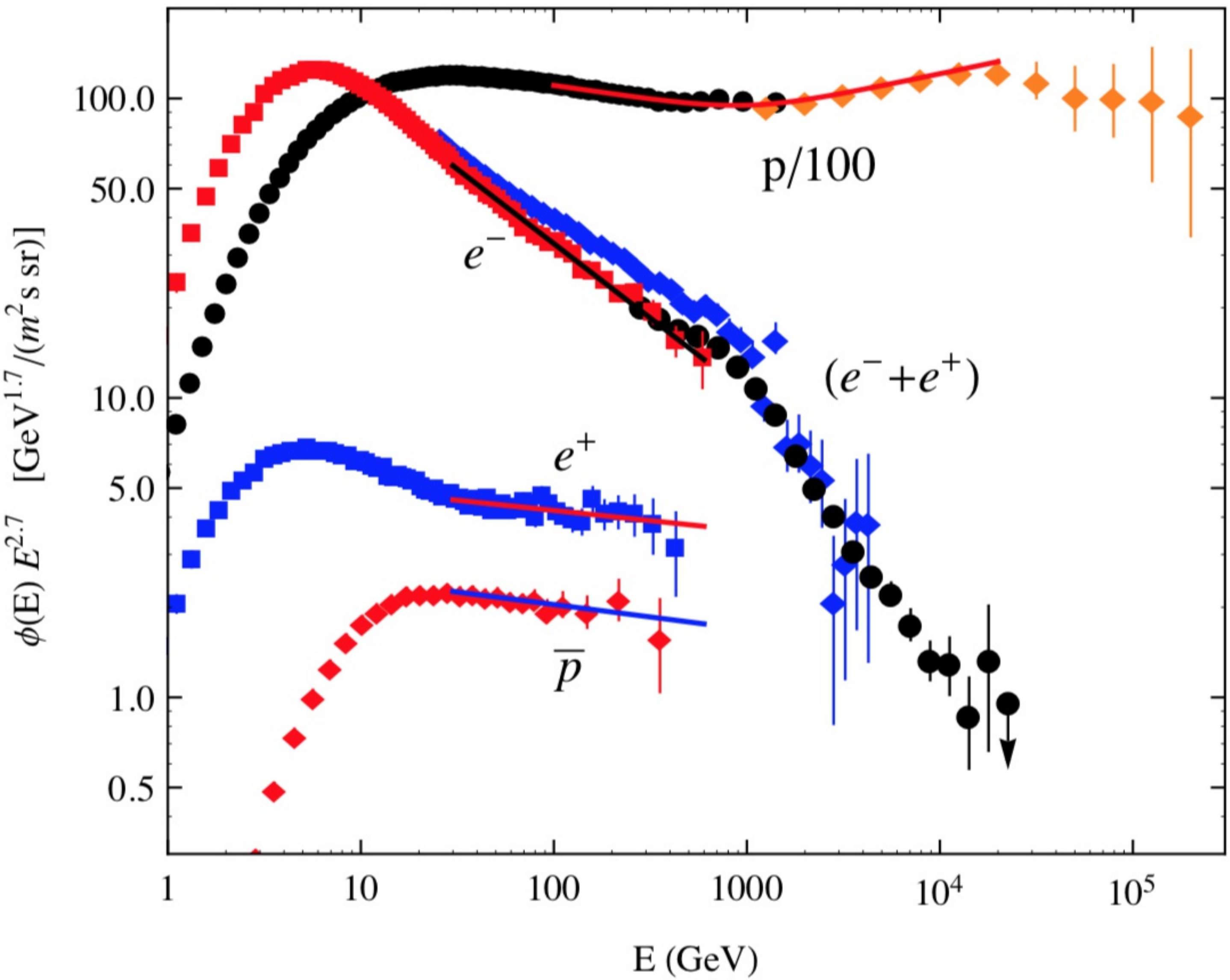
Astrophys. J. **563**, 768 (2001).

M. Kruskal, S. P. Ahlen and G. Tarlé,

Astrophys. J. **818**, no. 1, 70 (2016)

Profound astrophysical implications of the cosmic ray residence time.



e^- p

e^+ $\overline{p}$

"Conventional mechanism"

for the production of positrons and antiprotons:

Creation of secondaries in the inelastic hadronic interactions of cosmic rays in the interstellar medium

$$pp \to \overline{p} + \ldots$$

$$pp \to \pi^+ + \ldots$$
$$\quad\quad \hookrightarrow \mu^+ + \nu_\mu$$
$$\quad\quad\quad\quad \hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$pp \to \pi^\circ + \ldots$$
$$\quad\quad \hookrightarrow \gamma + \gamma$$

"Standard mechanism" for the generation of positrons and anti-protons

Dominant mechanism for the generation of high energy gamma rays

intimately connected

Straightforward [hadronic physics] exercise:

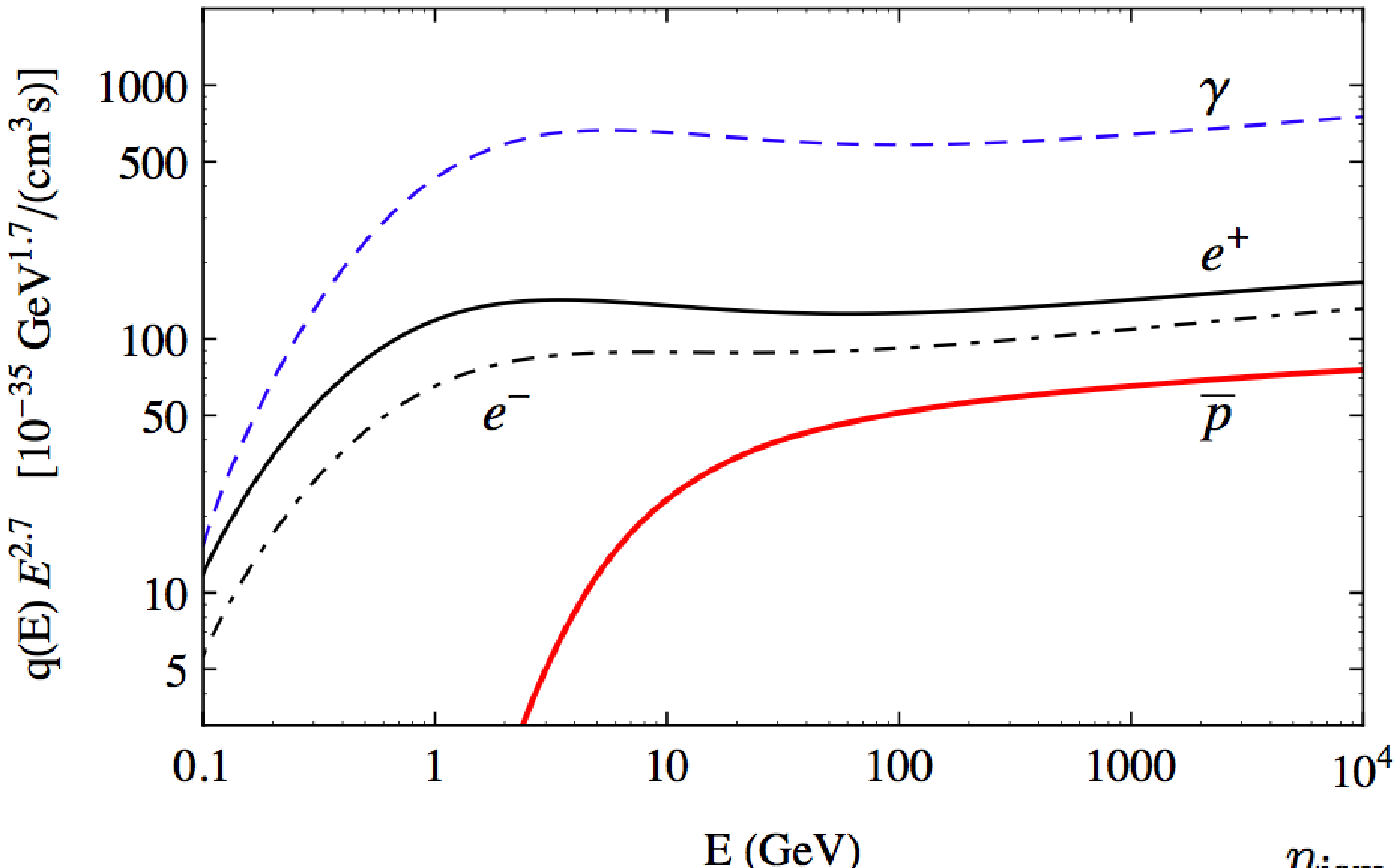
[1] Take spectra of cosmic rays (protons + nuclei) observed at the Earth

[2] Make them interact in the local interstellar medium (pp, p-He, He-p,...)

[3] Compute the rate of production of secondaries

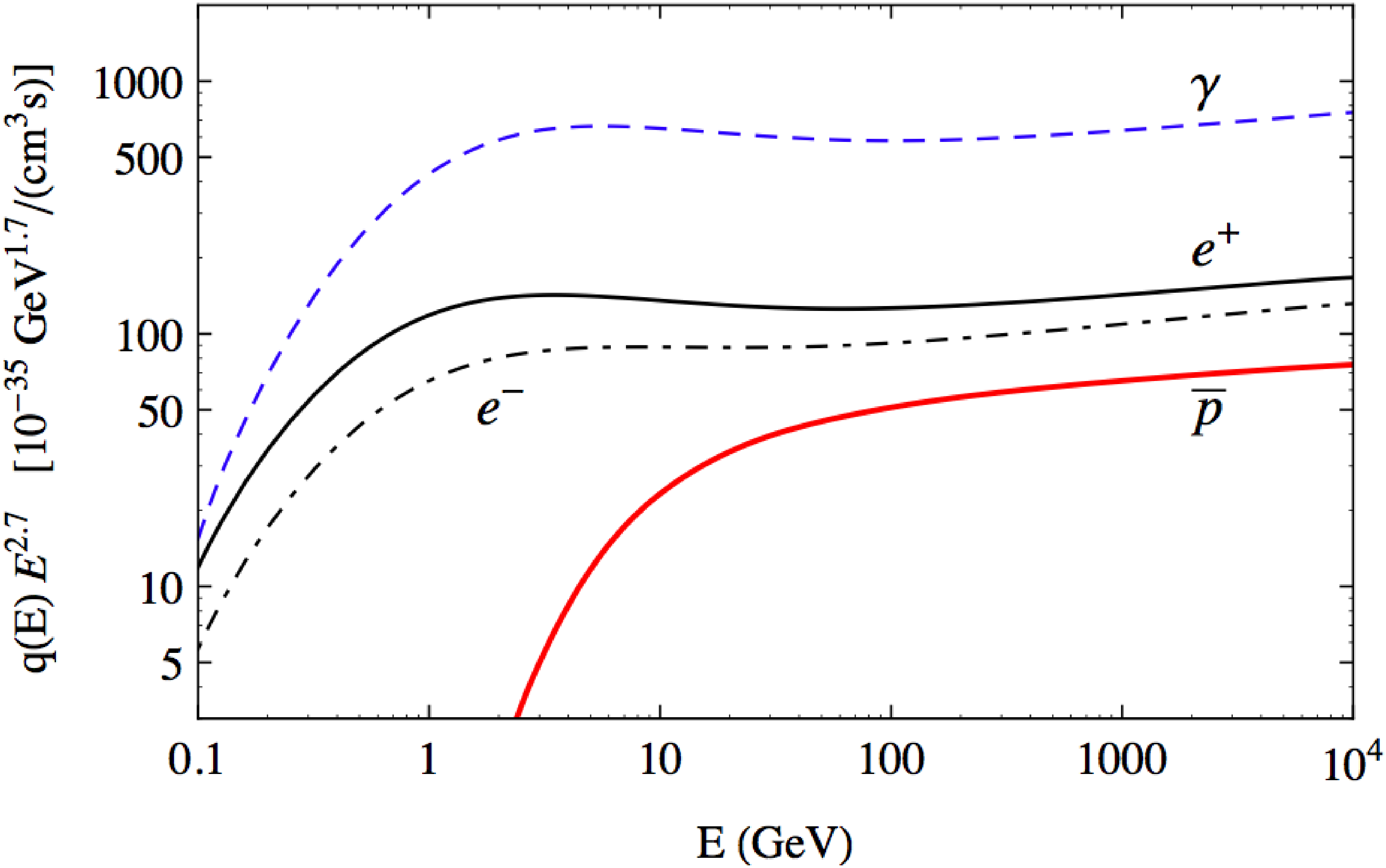
$$q_j(E, \vec{x}_\odot)$$

$$[\text{cm}^3 \text{ s GeV}]^{-1}$$



$$n_{\text{ism}}(\vec{x}_\odot) = 1 \text{ cm}^{-3}$$

“Local” Rate of production of secondaries



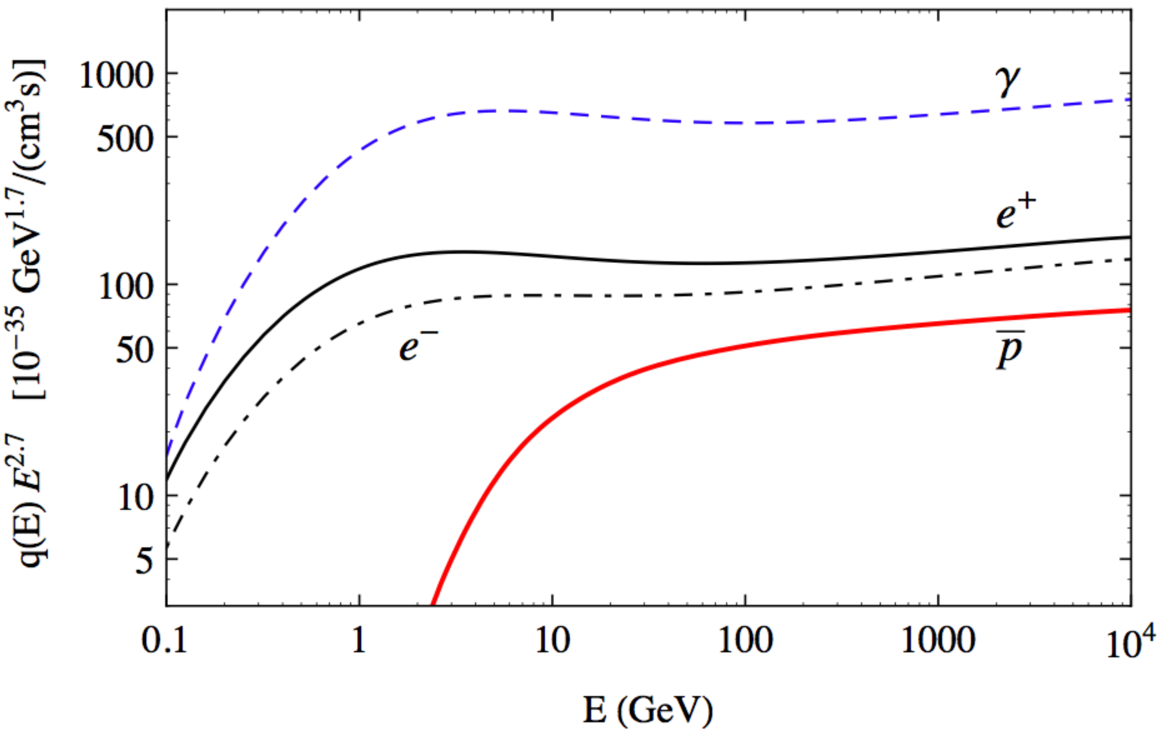
$$\frac{\gamma}{e^+} \approx 5.5$$

$$\frac{e^-}{e^+} \approx 0.8$$

$$\frac{e^+}{\overline{p}} \approx 2.0$$

Different low energy behaviors
(low energy antiproton production suppressed)

Power Law behavior at high energy

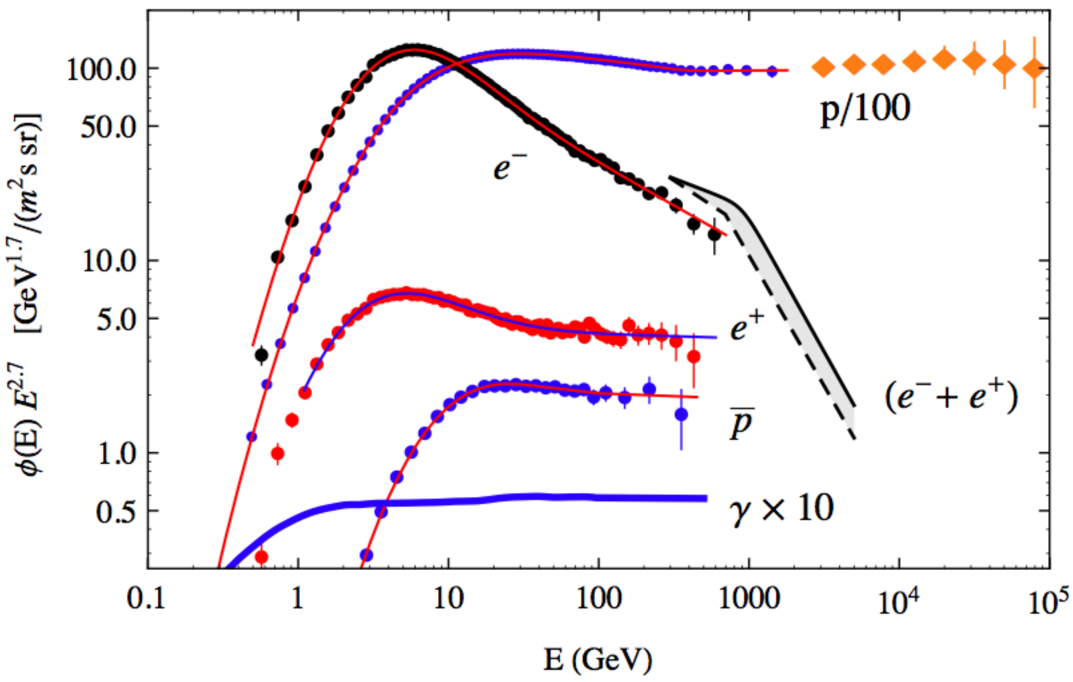


Local production rates of secondaries

$e^+ \quad \bar{p}$

“striking” similarity

Observed fluxes



$$\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \approx \frac{q_{e^+}^{\rm loc}(E)}{q_{\overline{p}}^{\rm loc}(E)}$$

The ratio positron/antiproton
Local source (secondary production)
(within systematic uncertainties)
is equal to the ratio of the observed fluxes

Does this result has a
"natural explanation" ?

There is a simple, natural interpretation that *"leaps out of the slide" :*

1. The "standard mechanism of secondary production is the main source of the antiparticles (and of the gamma rays)

2. Cosmic rays in the Galaxy (that generate the antiparticles and the photons) have spectra similar to what is observed at the Earth.

3. *The Galactic propagation effects for positrons and antiprotons are approximately equal*

4. The propagation effects have only a weak energy dependence.

The Logic of the discussion on the positron flux:

$$\phi_j(E) = q_j(E)\ \mathcal{P}_j(E)$$

Flux of particle type j is the source spectrum "distorted" by propagation effect.

Apply to positrons:

$$\phi_{e^+}(E) = [q_{e^+}^{\rm sec}(E) + q_{e^+}^{\rm new}(E)]\ \mathcal{P}_{e^+}(E)$$

DATA

model

New source of positrons (DM, pulsars,...)

model

Phenomenological observation

$$\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \approx \frac{q_{e^+}^{\rm sec}(E)}{q_{\overline{p}}^{\rm sec}(E)}$$

$$\phi_j(E) = q_j(E)\ \mathcal{P}_j(E)$$

Conventional scenario

Positrons have
an "energy loss sink"

$$\mathcal{P}_{e^+}(E) < \mathcal{P}_{\overline{p}}(E)$$

Meaningless (but strange)
numerical coincidence

$$[q_{e^+}^{\rm sec}(E) + q_{e^+}^{\rm new}(E)]\ \ \mathcal{P}_{e^+}(E) \approx$$

$$\approx q_{e^+}^{\rm sec}(E)\ \mathcal{P}_{\overline{p}}(E)$$

"Natural" explanation

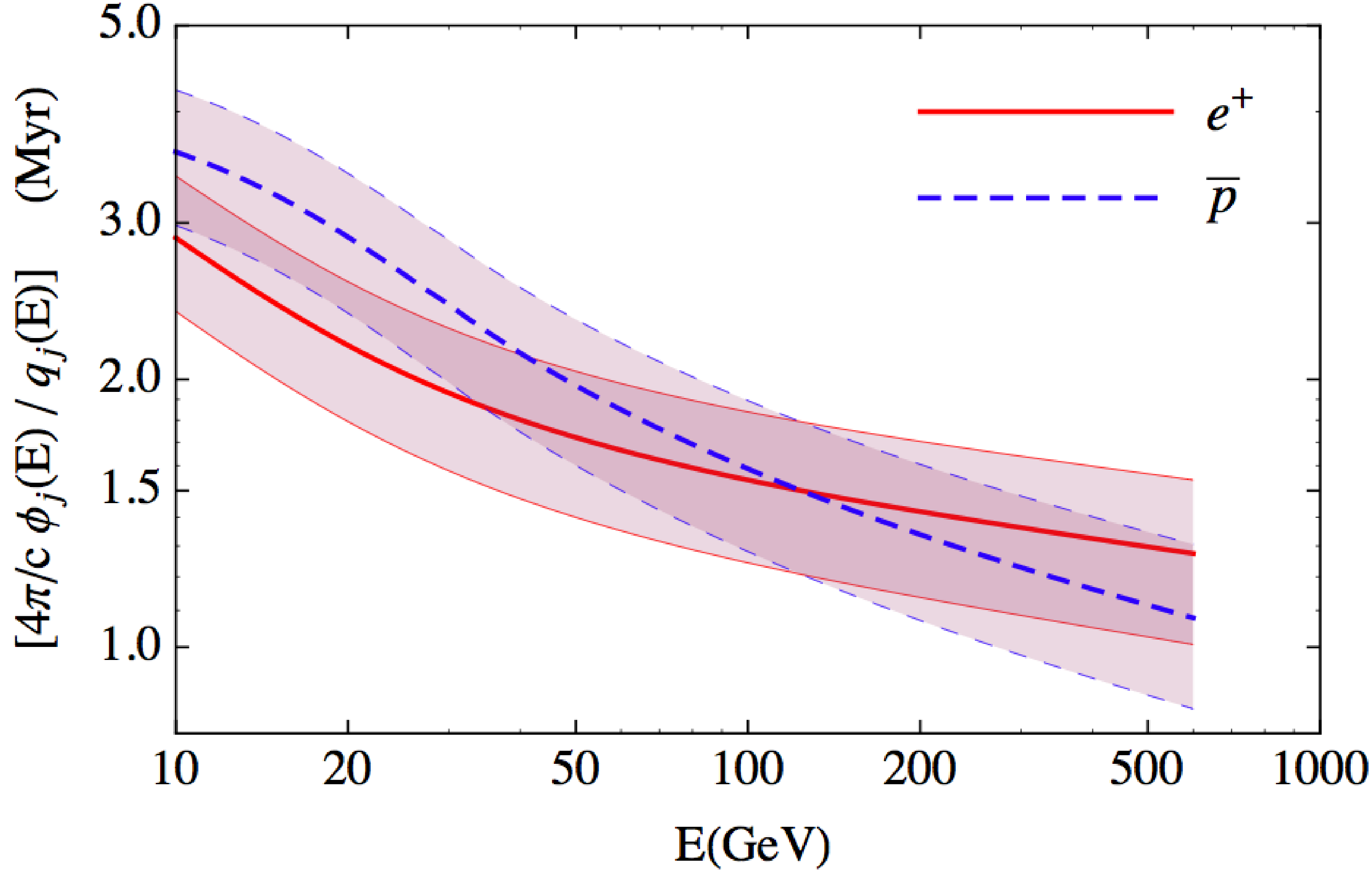
$$\mathcal{P}_{e^+}(E) \approx \mathcal{P}_{\overline{p}}(E)$$

$$q_{e^+}(E) \simeq q_{e^+}^{\rm sec}(E)$$

$$q_{\overline{p}}(E) \simeq q_{\overline{p}}^{\rm sec}(E)$$

$$\frac{\phi_{\overline{p}}(E)}{q^{\rm loc}_{\overline{p}}(E)} \approx \frac{\phi_{e^+}(E)}{q^{\rm loc}_{e^+}(E)}$$

Distortion of the source spectra created by propagation



Weak energy dependence of the propagation effects !

Formation of the Cosmic Rays spectra in the Galaxy:

Simplest Model:

LEAKY BOX

[No space variables. The Galaxy is considered as one single homogeneous volume (or point)]

Equation that describe the CR Galactic population

$$\frac{\partial n(E,t)}{\partial t} = q(E,t) - \frac{n(E,t)}{T_{\rm esc}(E)} + \frac{\partial}{\partial E}\left[\beta(E)\, n(E,t)\right]$$

Three functions of energy/rigidity define completely the model for one particle type

$q(E)$: Source spectrum (stationary)

$T_{\rm esc}(E)$ Escape time

$\beta(E) = -\frac{dE}{dt}$ Rate of energy loss $T_{\rm loss}(E) = E/\beta(E)$

$$\frac{\partial n(E,t)}{\partial t} = q(E,t) - \frac{n(E,t)}{T_{\rm esc}(E)} + \frac{\partial}{\partial E}\left[\beta(E)\, n(E,t)\right]$$

$$q(E,t)$$

Source

spectrum of cosmic rays

$$T_{\rm esc}(E)$$

Escape time

$$-\frac{dE}{dt} = \beta(E)$$

Rate of energy Loss

Propagation

$$n(E,t)$$

Observable CR density

$$q(E) = q_0 \; E^{-\alpha}$$

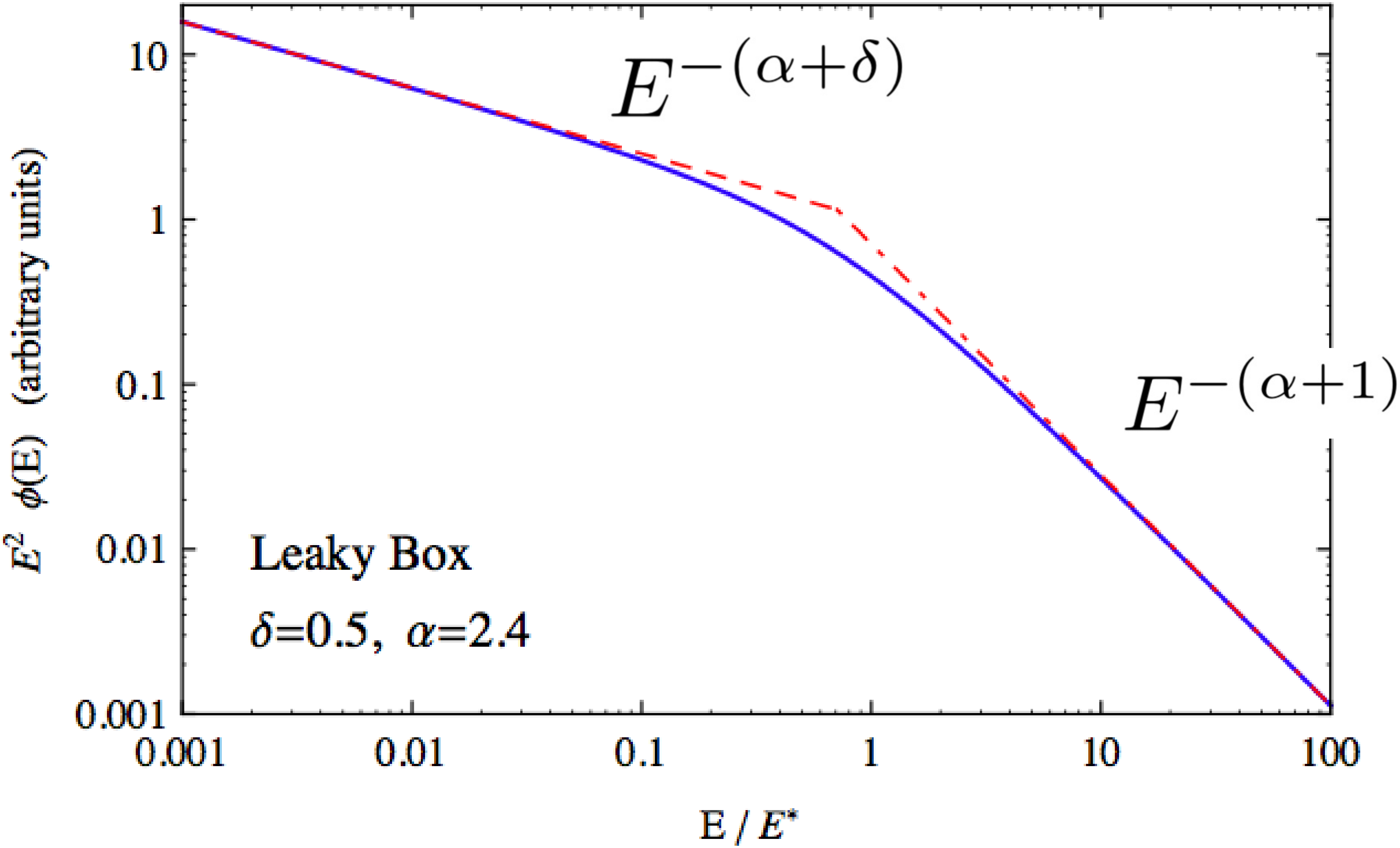
Source

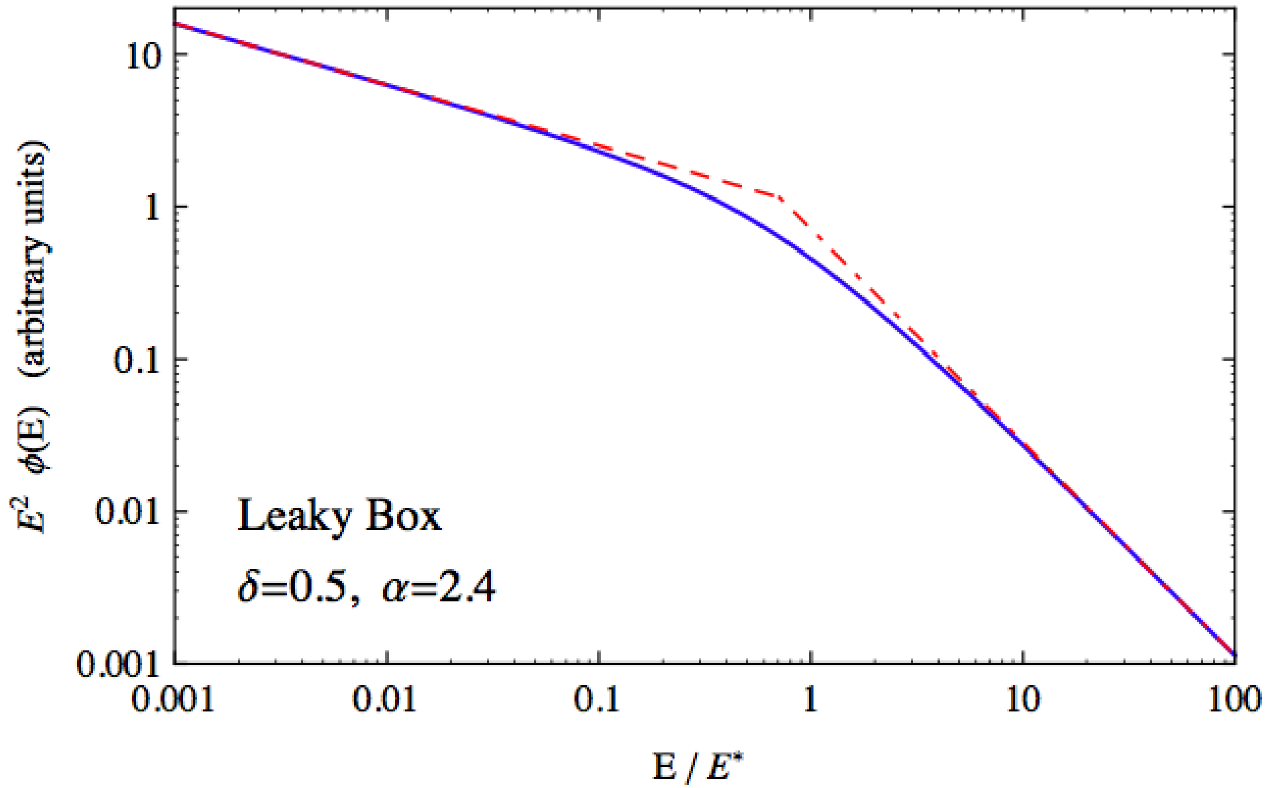
$$T_{\rm esc}(E) = T_0 \; E^{-\delta}$$

escape

$$\beta(E) = b\, E^2$$

Energy loss





$$q(E) = q_0 \; E^{-\alpha}$$

$$T_{\rm esc}(E) = T_0 \; E^{-\delta}$$

$$\beta(E) = b\, E^2$$

Spectral "feature"

Softening:

$$\Delta\gamma = 1 - \delta \qquad E_b \approx E^*$$

Critical energy E^*

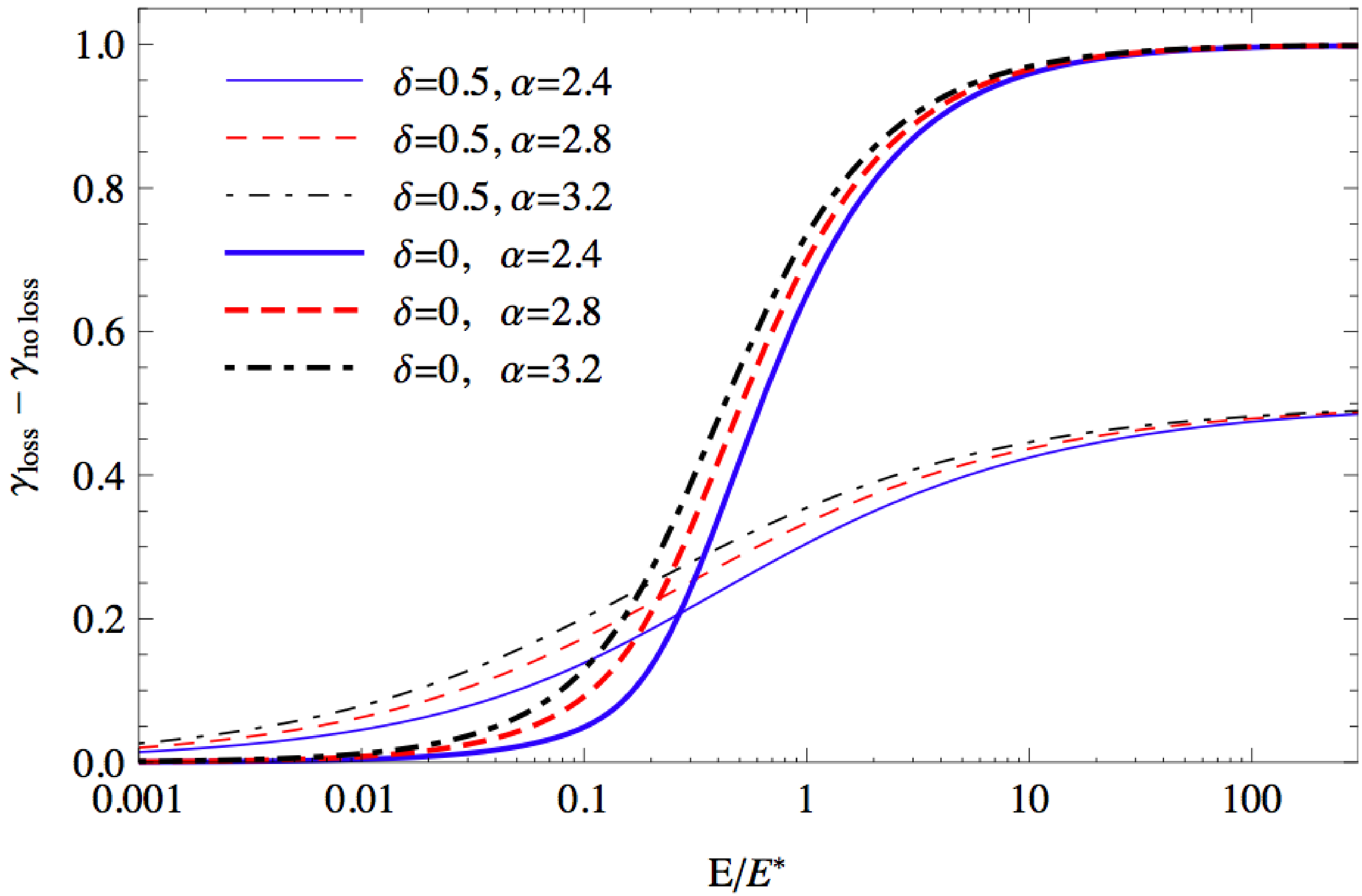
$$T_{\rm loss}(E^*) = T_{\rm esc}(E^*)$$

$$E^* = (T_0\, b)^{1/(\delta - 1)}$$

Exact solution:

$$n(E) = q(E)\, T_{\rm esc}(E) \times \int_0^{1/a} d\tau\, (1 - a\,\tau)^{\alpha-2}\, \exp\left[-\frac{1}{a\,(1-\delta)}\left[1 - (1 - a\,\tau)^{1-\delta}\right]\right]$$

$$a = \frac{T_{\rm esc}(E)}{T_{\rm loss}(E)} \simeq (T_0\, b)\, E^{1-\delta} = \left(\frac{E}{E^*}\right)^{1-\delta}$$



Idea of very general validity:

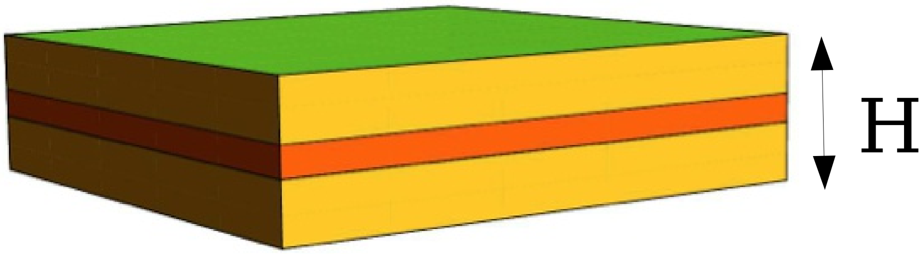
The Spectra of electrons and positrons
should contain a softening "spectral feature"
associated to the energy loss:
at a **critical energy** E^*

$$T_{\rm esc}(E) \simeq \langle t_{\rm esc}(E) \rangle$$

$$T_{\rm loss}(E) \simeq \frac{E}{\langle |dE/dt| \rangle}$$

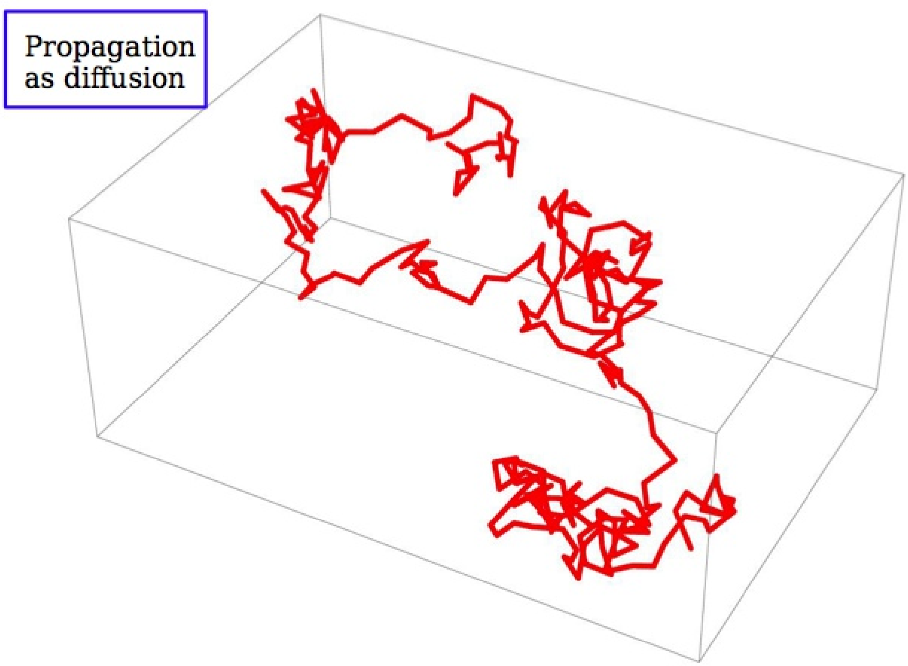
$$T_{\rm esc}(E^*) = T_{\rm loss}(E^*)$$

Diffusion Model ("minimal version")



Galaxy modeled as
a homogeneous slab
of a "diffusive medium"
with 2 absorption surfaces

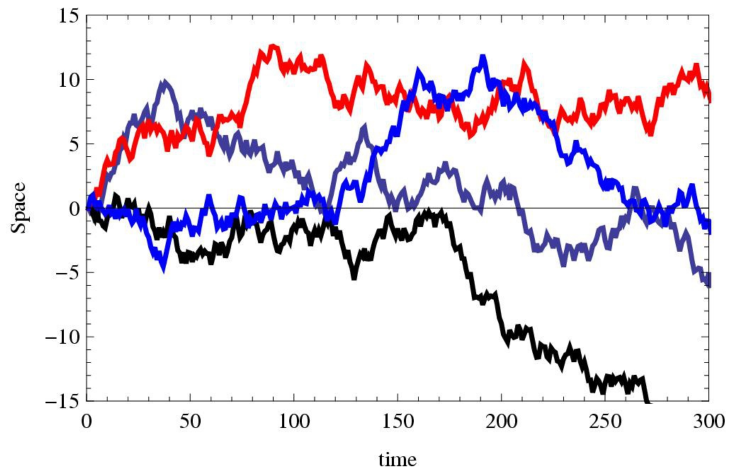
$z = \pm H$ (Halo thickness)



Propagation model
specified by H + 2 functions

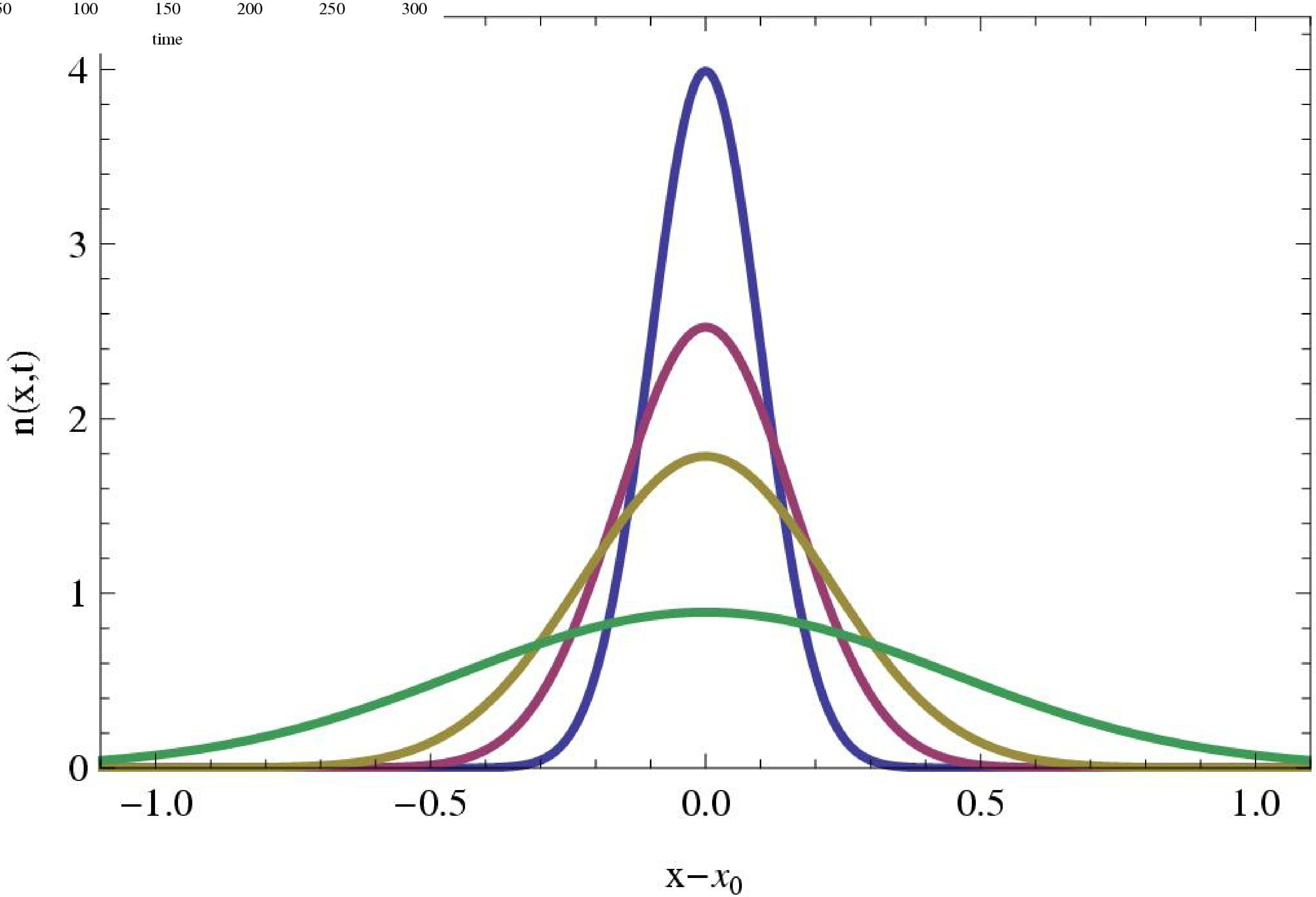
$$D(E) = D_0 \; E^{\delta}$$

$$\beta(E) = b \, E^2$$



Projection in x (or y or z)

$$\sigma_x^2 = 2\,D\,t$$



Average escape time for CR (no energy loss)

$$T_{\rm esc}(E) = \frac{H^2}{2\,D(E)} = \langle t_{\rm esc}(E) \rangle$$

$$T_{\rm esc}(E) = T_0 \; E^{-\delta}$$

$$D(E) = D_0 \; E^{\delta}$$

$$T_{\rm esc}(E^*) = T_{\rm loss}(E^*)$$

Critical energy

$$E^* = \left(\frac{H^2\, b}{2\, D_0} \right)^{1/(\delta - 1)}$$

$$q(E,\vec{x},t) = q_0\ E^{-\alpha}\ \delta[z]$$

Stationary emission from the Galactic plane

Exact solution:

$$n(E) = \begin{cases} \dfrac{q_0\ H}{2\,D_0}\ E^{-(\alpha+\delta)} & \text{for } E \ll E^* \\ \\ \dfrac{q_0}{\sqrt{2\,D_0\,b}}\ c(\alpha,\delta)\ E^{-[\alpha+(1+\delta)/2]} & \text{for } E \gg E^* \end{cases}$$

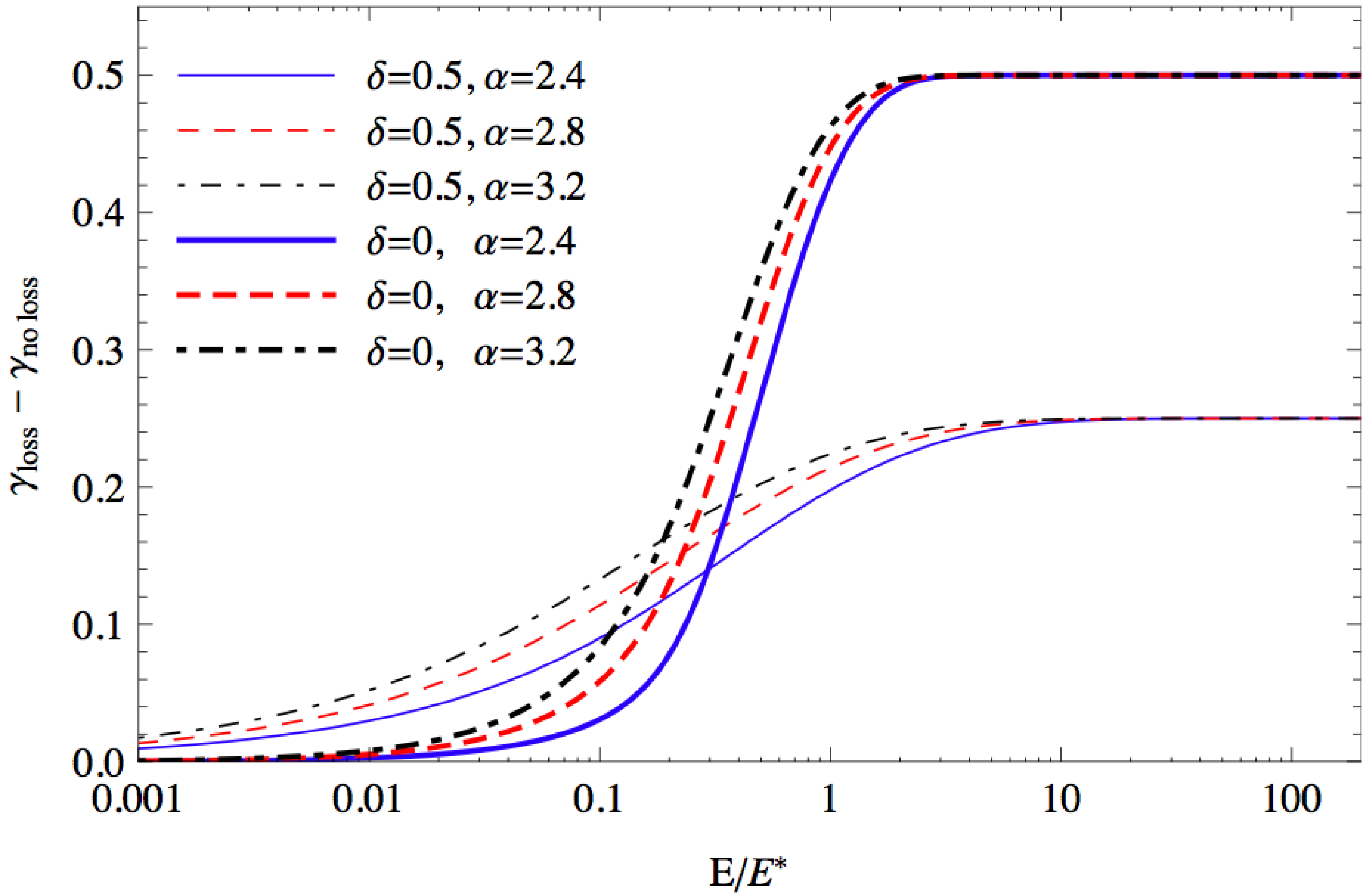
Energy losses negligible

Energy losses dominant

$$c(\alpha,\delta) = \sqrt{\frac{1-\delta}{2\pi}}\ \int_0^1 d\tau\ \frac{(1-\tau)^{\alpha-2}}{\sqrt{1-(1-\tau)^{1-\delta}}}$$

$$\Delta\gamma = \frac{1-\delta}{2}$$

Imprint of the energy losses on the spectral index



$$\Delta\gamma = \frac{1-\delta}{2}$$

$$E_b \approx E^*$$

$$E_b \simeq c(\alpha,\delta)^{2/(\delta-1)}\ E^*$$

The (Model independent) point :

The effects of energy loss during the propagation of electrons and positrons should leave an “imprint” on the spectra: a *softening feature.*

The characteristic energy of the softening has a simple physical meaning: (in good approximation) it is the energy where the Loss-Time is equal to the Escape Time (or age) of the cosmic rays.

$$T_{\rm loss}(E^*) = T_{\rm esc}(E^*)$$

Identification of E^*
corresponds to a measurement of the CR residence time

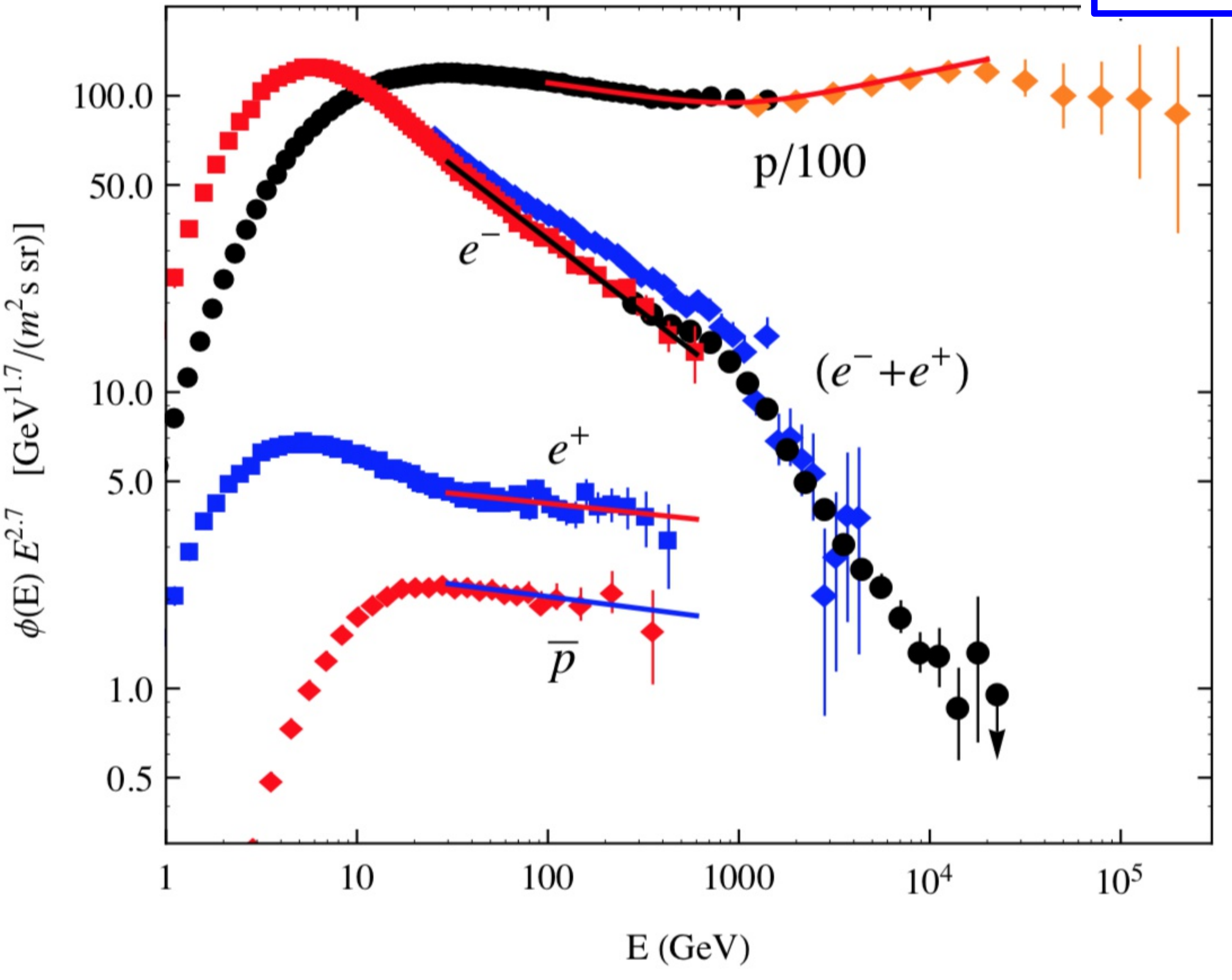
Where is the energy loss softening feature ?

Use the lepton spectra as *"cosmic ray clocks"*

$$E^* \lesssim 3 \text{ GeV}$$

$$E^* \simeq 900 \text{ GeV}$$

Two possibilities

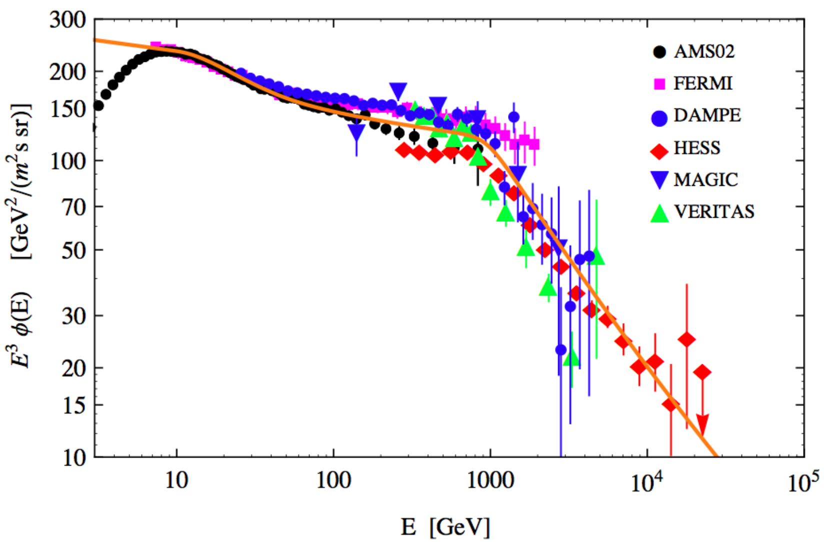


Possible (and “natural”) choice: identification of the sharp softening observed by the Cherenkov telescopes in the spectrum of $(e^+ + e^-)$ as the critical energy

$$E^* = E_{\rm HESS} \simeq 900 \text{ GeV}$$

$$T_{\rm confinement}[E \simeq 900 \text{ GeV}] \simeq 0.7 \div 1.3 \text{ Myr}$$

Range depends on volume of confinement



Propagation of positrons and antiprotons is approximately equal for

$$E \lesssim E^* \simeq 900 \text{ GeV}$$

Imprints of the

"Granular nature" of the CR sources
on the spectra of electrons

Imprints of the

“Granular nature” of the CR sources on the spectra of electrons

Prediction of large effects at sufficiently high energy

Large anisotropy

Large deviations from power law flux

$$E \gtrsim E^{\dagger}$$

“Critical energy for discrete sources effects”

How many sources contribute to the Cosmic Ray Flux ?

Assumption, for primary CR (p, e^-)

The CR sources are "events"
point-like and "short-lived" (on Galactic scales)
[*Supernova explosions*, Gamma Ray Bursts, Pulsars, ...]

$$T_{\rm sources}$$

time between events in the entire Galaxy

$$T_{\rm SNR} \approx 50 \text{ yr}$$

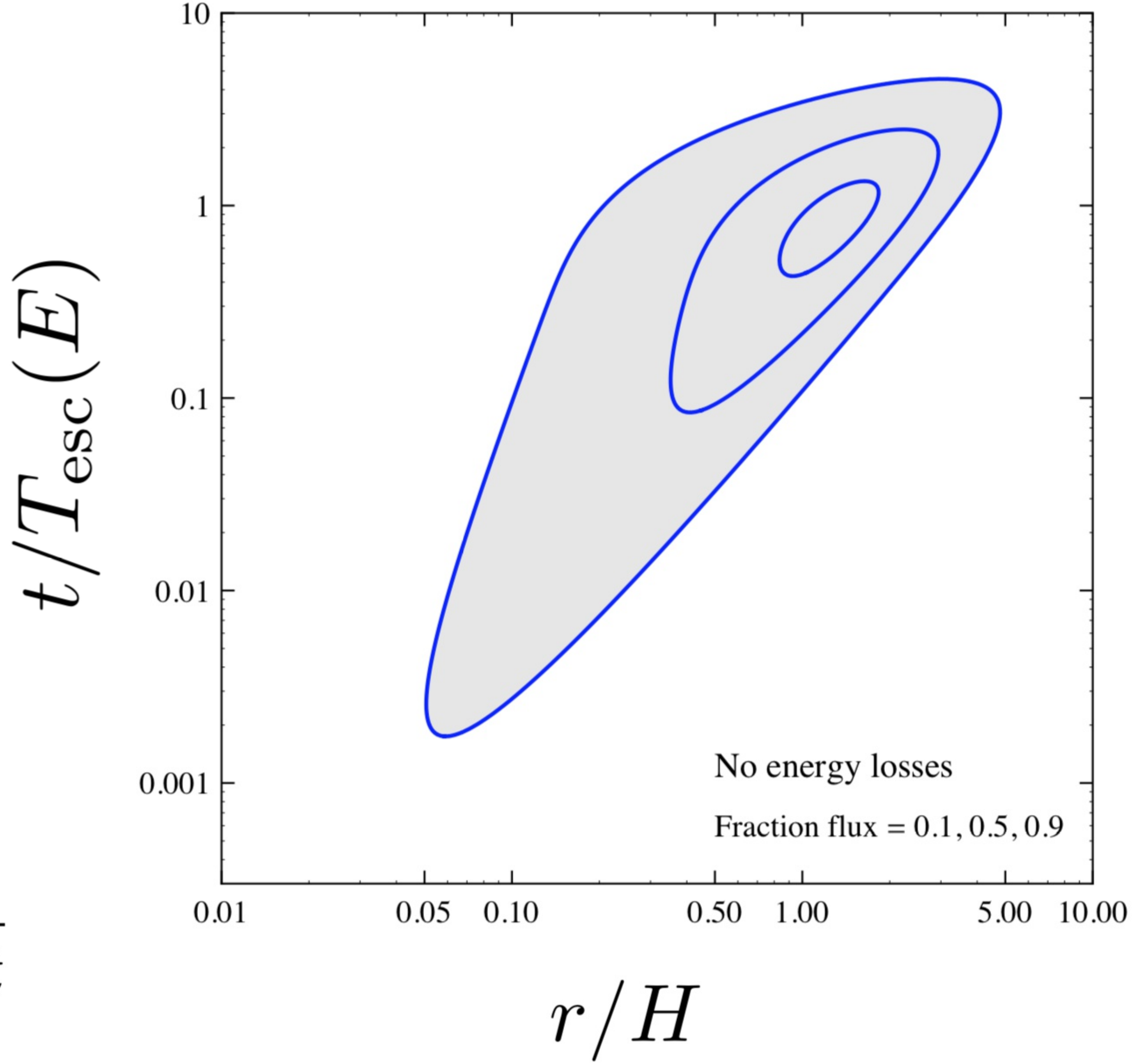
$$n_{\rm sources} \approx \frac{1}{\pi \, R_{\rm disk}^2} \simeq 0.0015 \text{ kpc}^{-2}$$

Number density in the disk

Assume continuous emission of protons

Space-time
origin of the flux

(in Diffusion
Model)



$$\frac{d\phi_p}{d\log r \ d\log t}$$

Protons (Nuclei)

Number of "source-events" that contribute to the flux

$$N^p_{\rm sources}(E) \approx \frac{n_s}{T_s} \; H^2 \; T_{\rm esc}(E)$$

All events at a distance: $r < H$

Age: $t < T_{\rm esc}(E)$

Numerical example: $\delta = 0.4$

$$N_{\rm sources}(E) \simeq 240 \; \left[\frac{T_s}{50 \text{ yr}}\right]^{-1} \; \left[\frac{H}{5 \text{ kpc}}\right]^2 \; \left[\frac{T_{\rm diff}(10 \text{ GeV})}{10 \text{ Myr}}\right] \; \left(\frac{E}{\rm PeV}\right)^{-0.4}$$

Maximum propagation time for electron and positrons

Evolution of energy with time:

$$-\frac{dE}{dt} = b\ E^2$$

$$E_i(E,t) = \frac{E}{1 - b\,E\,t}$$

Initial energy
(time t in the past)

$$t \to T_{\rm loss}(E) = \frac{1}{b\,E}$$

$$E_i(E,t) \to \infty$$

Maximum age for particle observed with energy E

$$t_{\rm max}(E) \simeq T_{\rm loss}(E) = \frac{1}{b\,E}$$

Maximum propagation distance

$$R_{\max}(E) = \frac{H}{\sqrt{1-\delta}} \left(\frac{E}{E^*}\right)^{-(1-\delta)/2}$$

Strong dependence on the critical energy

$H = 3 \text{ kpc} \qquad \delta = 0.4$

$E^* = 3 \text{ GeV}$

$$R_{\max}(E) = 0.67 \text{ kpc} \left(\frac{E}{\text{TeV}}\right)^{-0.3}$$

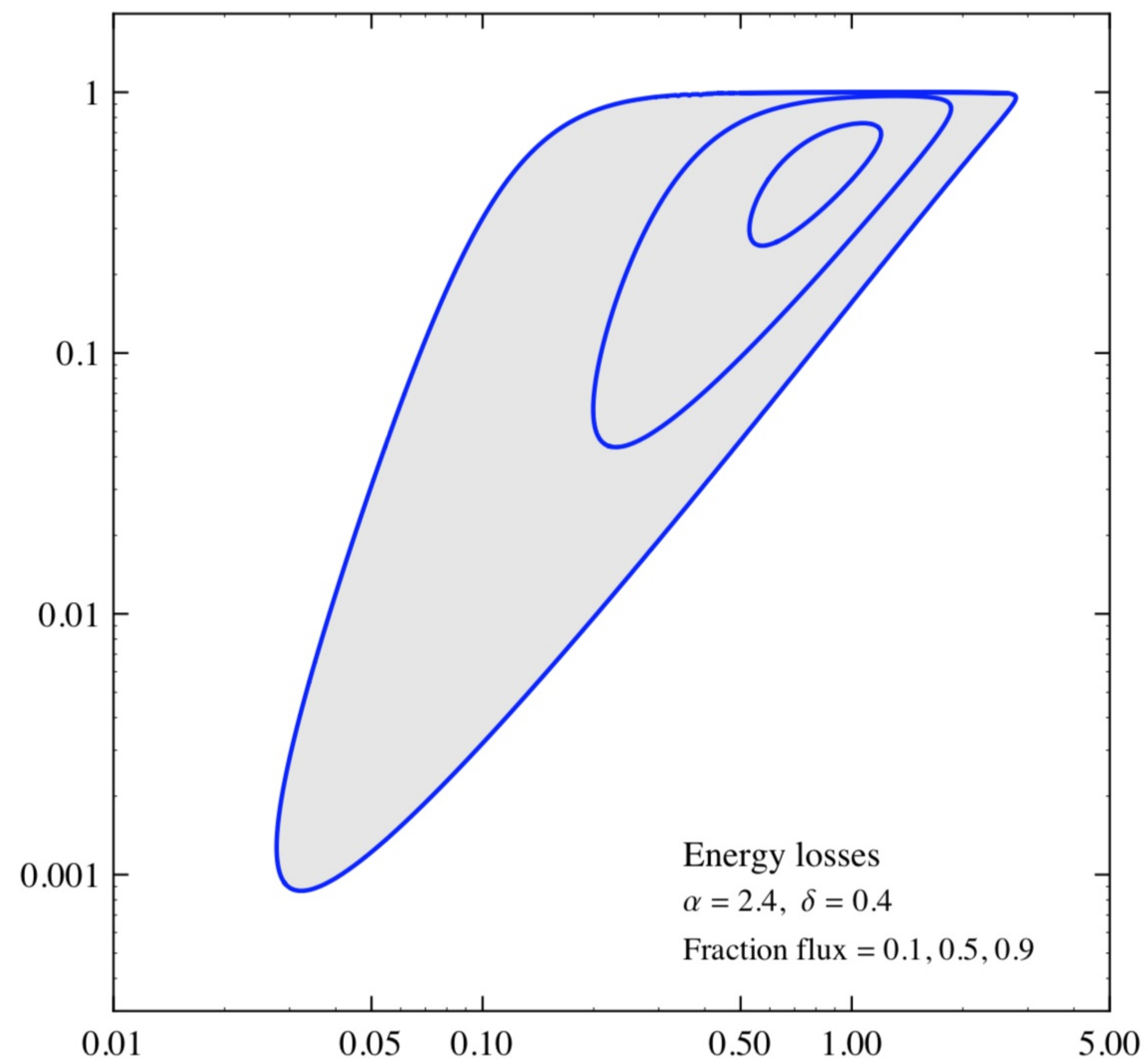
$E^* = 940 \text{ GeV}$

$$R_{\max}(E) = 3.80 \text{ kpc} \left(\frac{E}{\text{TeV}}\right)^{-0.3}$$

Assume continuous emission of electrons

Space-time origin of the flux

$$\frac{d\phi_{e^\mp}}{d\log r \;\; d\log t}$$



$t/T_{\rm loss}(E)$

$r/R_{\max}(E)$

Electrons

Number of "source-events" that contribute to the flux

$$N^{e^{\mp}}_{\rm sources}(E) \approx \frac{n_s}{T_s} \; R^2_{\rm max}(E) \; T_{\rm loss}(E)$$

All events at a distance: $r < H$

Age: $t < T_{\rm esc}(E)$

Numerical example: $\delta = 0.4$

$$N^{e^{\mp}}_{\rm sources}(E) \simeq 8.5 \; \left[\frac{T_s}{50 \text{ yr}}\right]^{-1} \; \left[\frac{H}{3 \text{ kpc}}\right]^{2} \; \left[\frac{E^*}{3 \text{ GeV}}\right]^{0.6} \; \left(\frac{E}{\text{TeV}}\right)^{-1.6}$$

"Stochastic effects critical Energy": "One single source"

[Brightest source contributes (on average)
½ the expected flux for a continuous source distribution]

$$E^{\dagger} \simeq 1.1 \left[\frac{T_s}{50 \text{ yr}}\right]^{-0.625} \left[\frac{H}{3 \text{ kpc}}\right]^{1.25} \left[\frac{E^*}{3 \text{ GeV}}\right]^{0.375} \text{TeV}$$

If the critical energy is low (GeV Range)
Expect to see the effects of granularity at TeV energy

If the critical energy is high (1 TeV)
expect to see the effects of granularity at 15-20 TeV

Problem of the “Local Sources"

If the CR residence time is long,
and therefore the diffusion coefficient is small:

for $E \gtrsim 1 \text{ TeV}$
one expects that only very near sources
contribute to the flux.

and therefore:

the spectrum should show evidence for the fact that only very few sources contribute.

What happens when only few sources contribute to the flux ?

The flux is generated by an ensemble o
of discrete "source events" that are
localized ("point like") and last a short time
(on Galactic time scales).

$$q_s(E, r, t) = q_0 \; E^{-\alpha} \; \delta[t - t_i] \; \delta[\vec{x} - \vec{r}_s]$$

Each source is defined by two parameters
and by its "age" and position

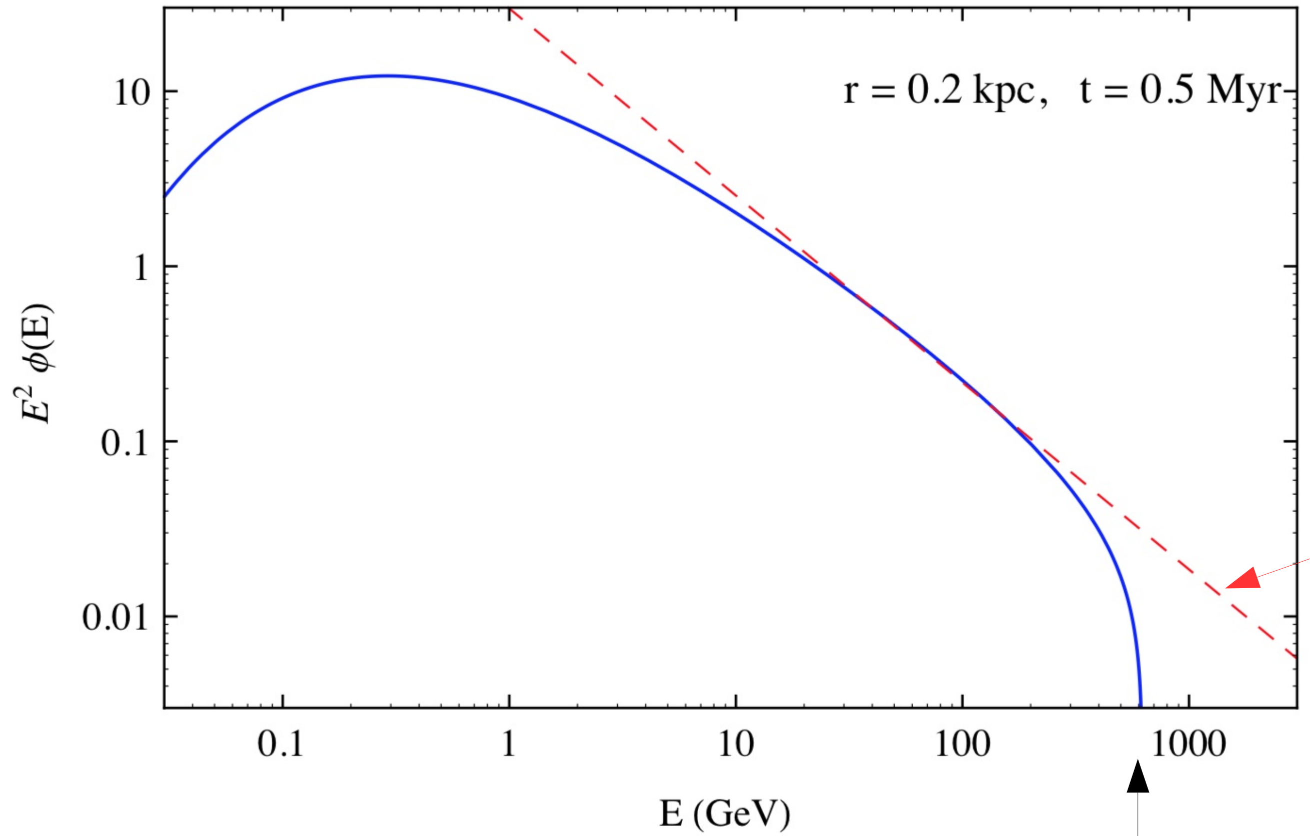
$$\{t_i \;,\; \vec{r}_s\} \qquad \{\mathcal{E} \;,\; \alpha\} \qquad q_0 \propto \mathcal{E}$$

Flux from an "
instantaneous explosive) source"

simple diffusive model)

$\{D_0\ ,\ \delta\ ,\ \ b\ ,\ \ H\}$

$$q_s(E) = q_0\ E^{-\alpha}\ \delta[t - t_i]$$



$E^{-\gamma}$

$\gamma = \alpha + 3/2\,\delta$

$$E_{\max} \simeq \frac{1}{b\,t}$$

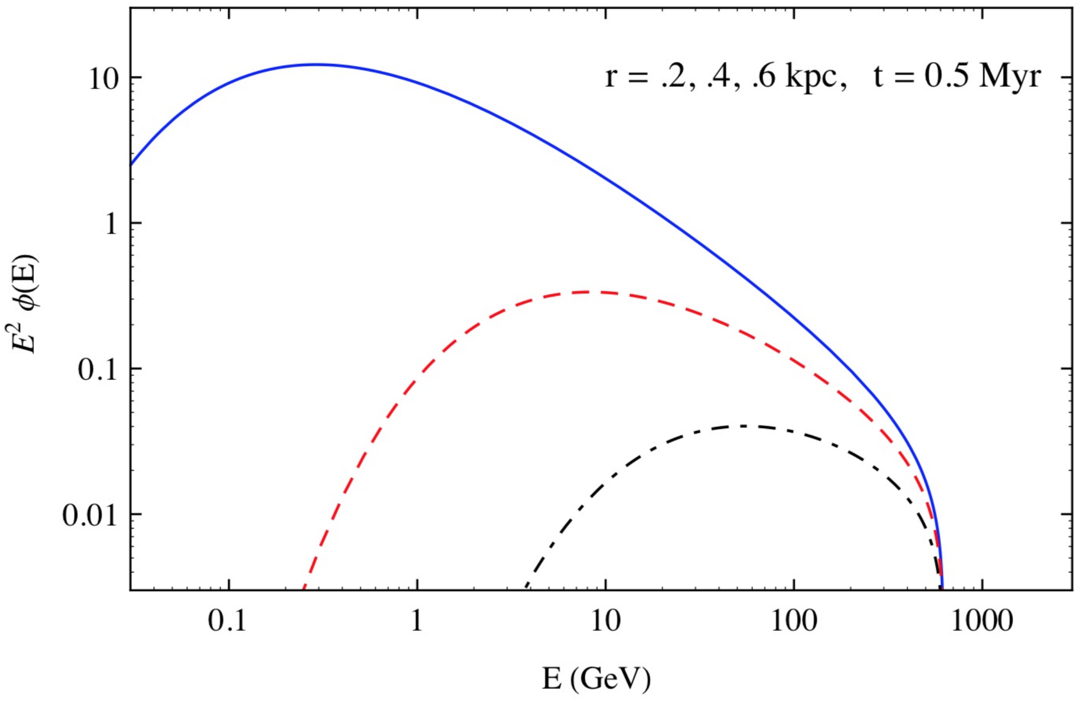
Simple analytic expression
(limit of negligible escape)

$$\phi_s(E,r,t) = \frac{c}{4\pi} \frac{q_0 \; E^{-\alpha}}{(2\,\pi)^{3/2} \; R^3(E,t)} \; \exp\left[-\frac{r^2}{2\;R^2(E,t)}\right]$$

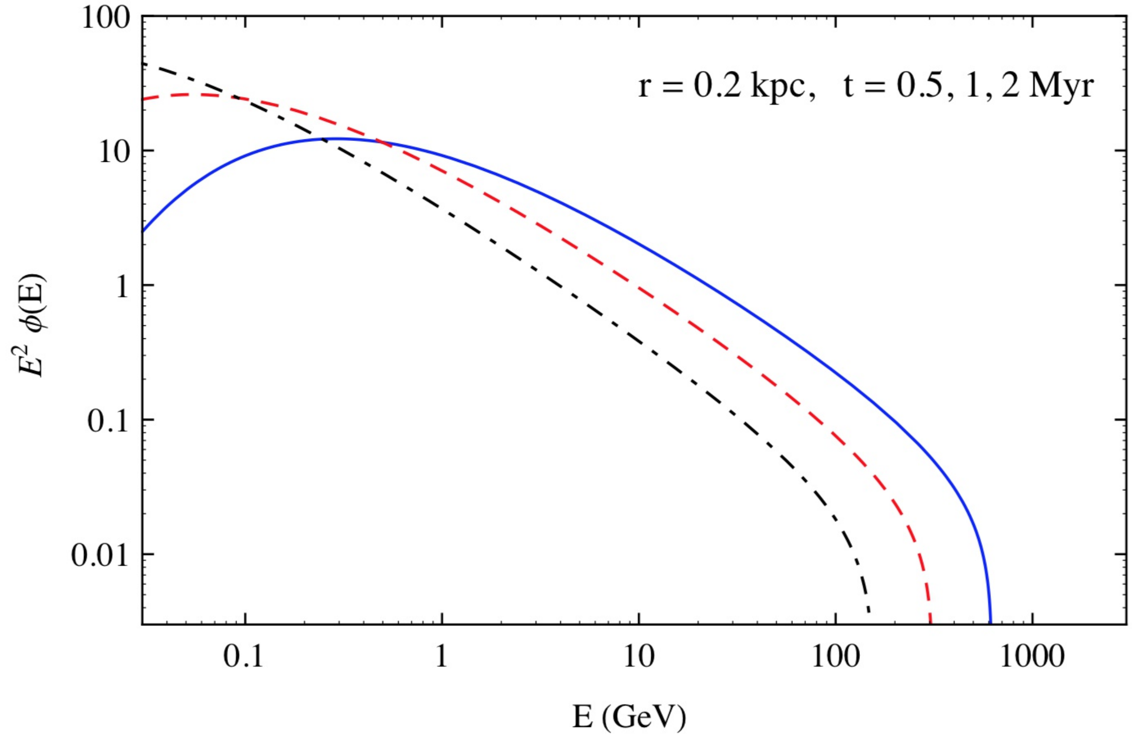
$$R^2(E,t) = 2\;D(E)\;t\;\rho(b\,E\,t)$$

$$\rho(x) = \frac{1-(1-x)^{(1-\delta)}}{(1-\delta)\;x}$$

$$1 \leq \rho(x) \leq (1-\delta)^{-1}$$



Changing r
(same age)



Changing t
(same distance)

An ensemble of many such sources
all equal to each other
uniformly distributed in a thin layer around
the Solar system
with a constant rate $f = 1/T_s$

Result (neglect escape) in a power law flux:

$$\phi(E) = \frac{c}{4\pi} \frac{k(\alpha,\delta)}{\sqrt{4\pi}} \frac{q_0}{T_s} \frac{1}{\sqrt{D_0\, b}} E^{-[\alpha+(1+\delta)/2]}$$

Identical fluxes can be generated by

Many weak sources, or
Few strong sources

But:
"granularity" effects
(discrete sources)

“MonteCarlo study of source configurations

Divide the space time into two regions:

Far, old sources

$$r > r_{\rm cut}$$

$$t > t_{\rm cut}$$

Treated as a continuous “smooth emission”

Near, young sources

$$r < r_{\rm cut}$$

$$t < t_{\rm cut}$$

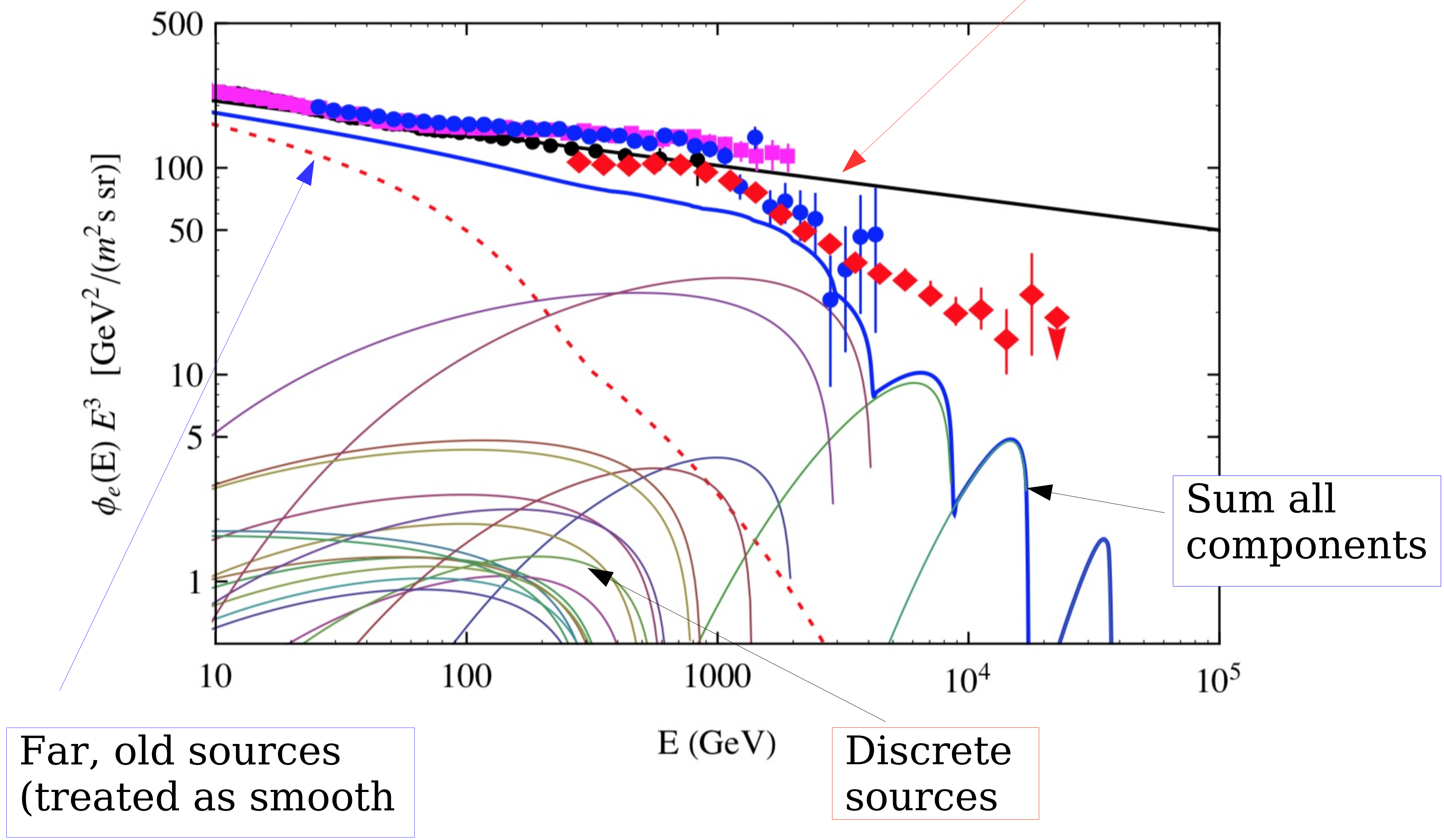
Treated as individual sources (generating randomly one configuration)

Randomly generated configuration of sources

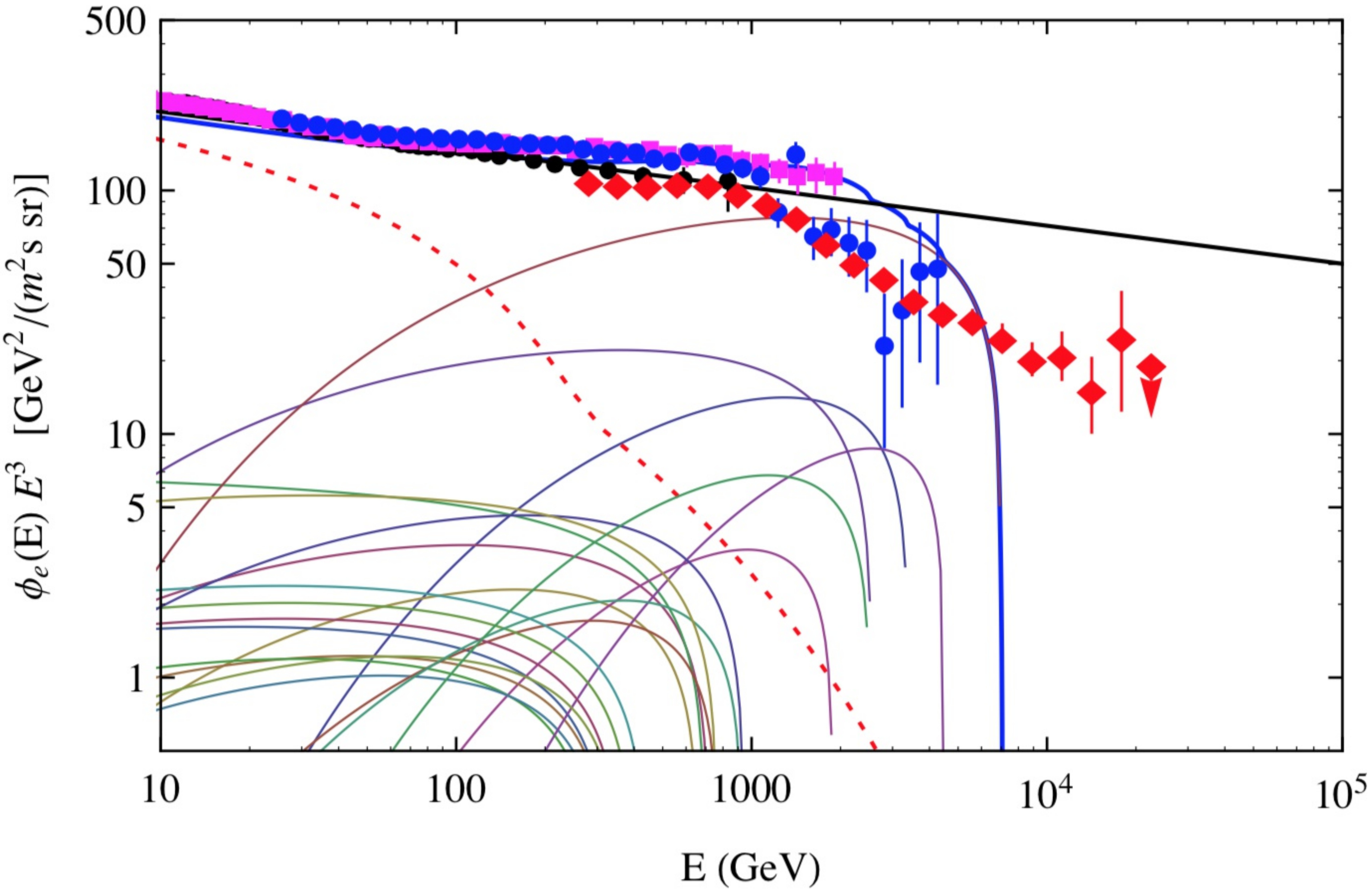
$T_s = 50$ yr

$R_{\text{disk}} = 15$ kpc

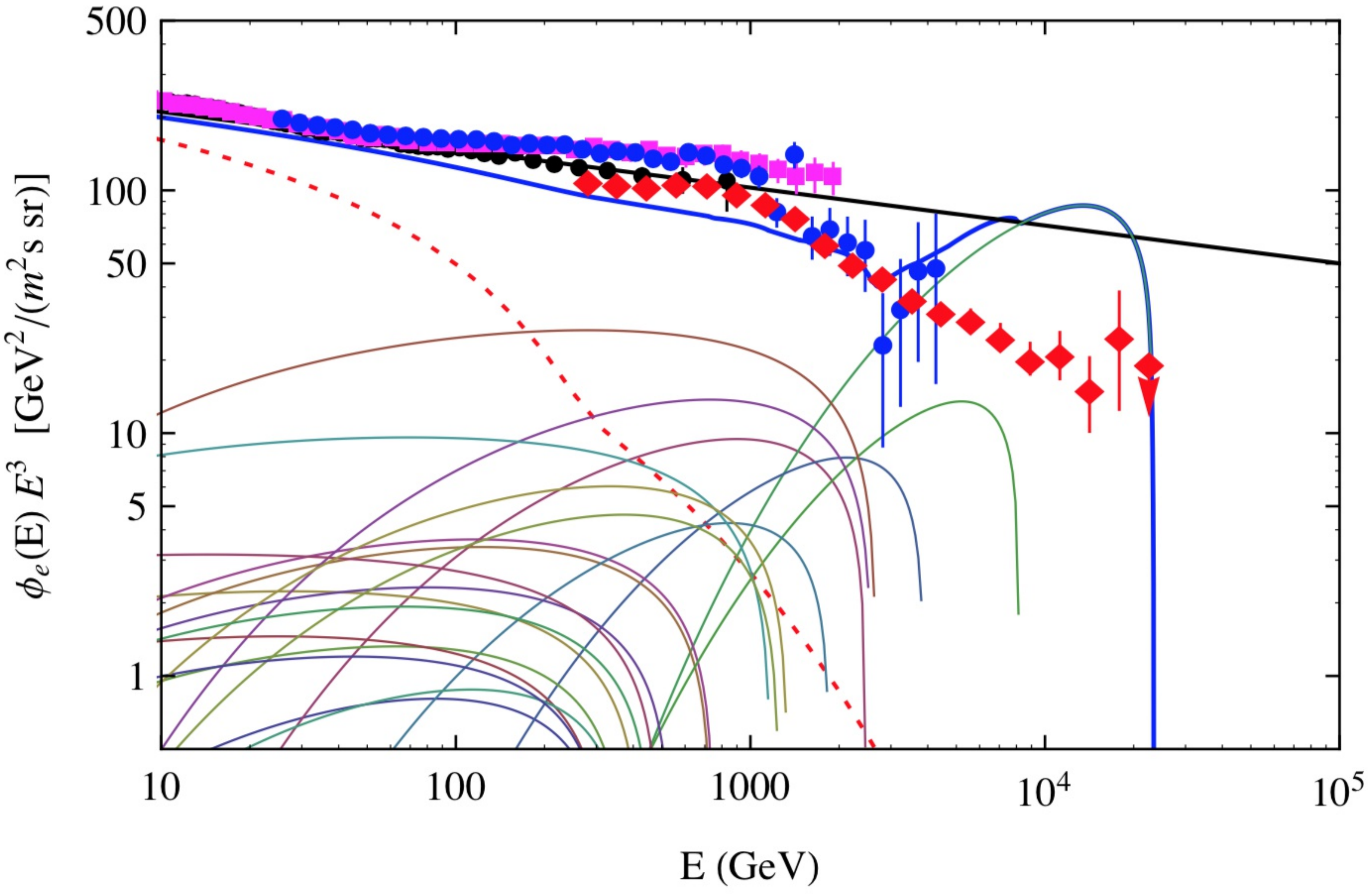
$D(10 \text{ GeV}) = 10^{28} \text{ cm}^2/\text{s}$



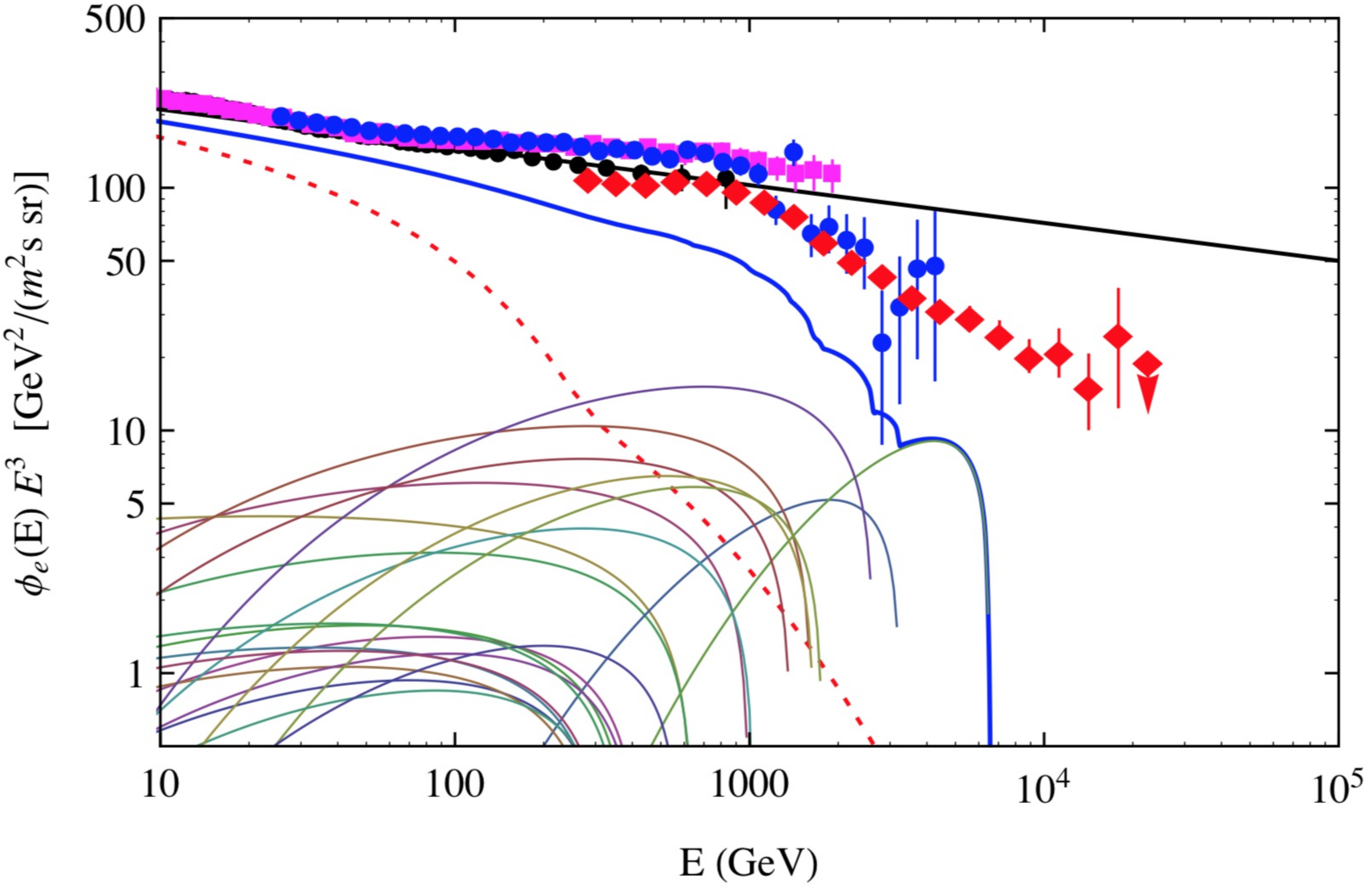
One more randomly generated configuration of sources [2]



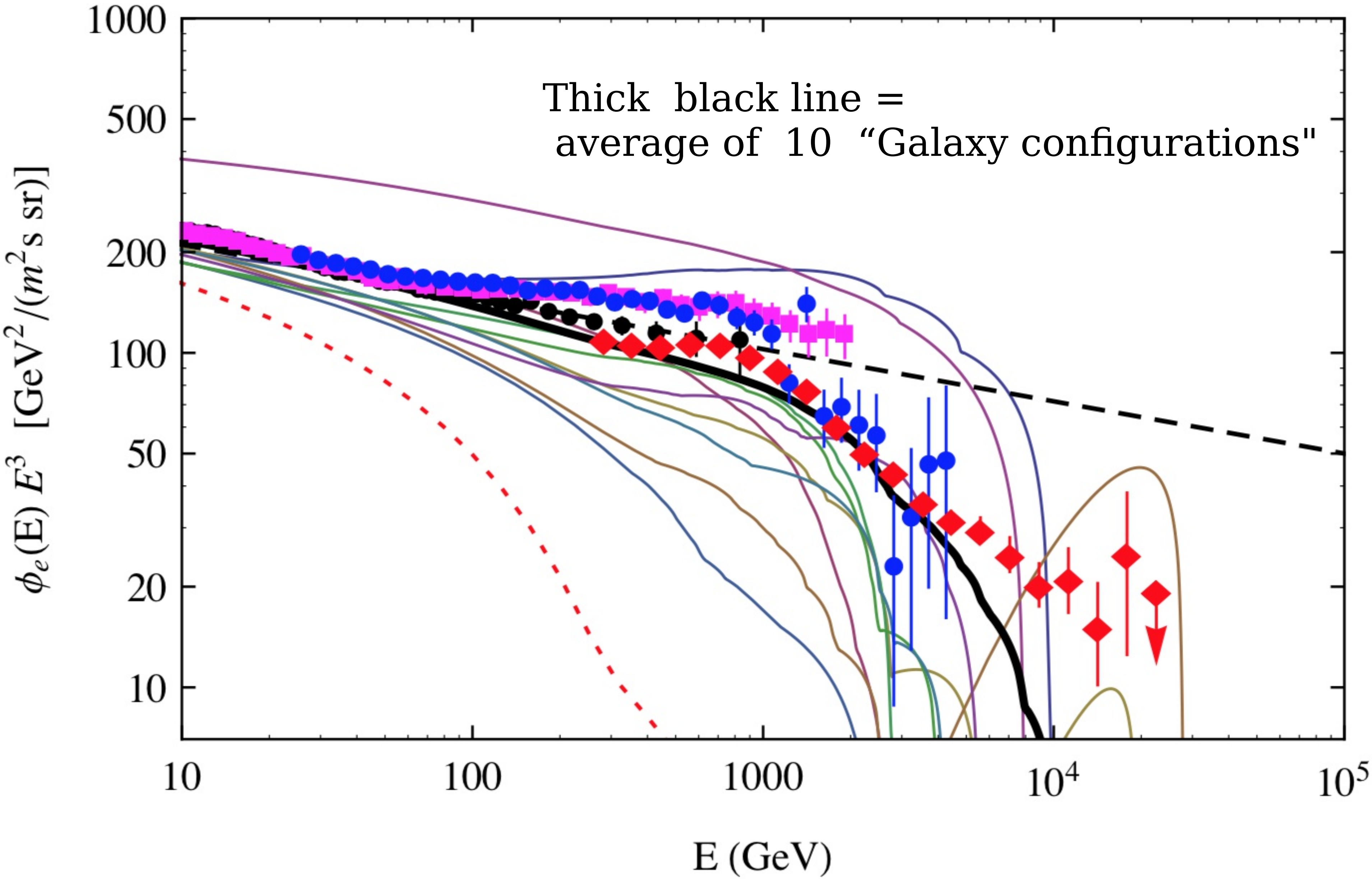
One more randomly generated configuration of sources [3]



One more randomly generated configuration of sources [4]



10 configurations [Sum of all contributions]



Conclusion from this numerical study

In the framework of the model described above
(short CR lifetime, explosive sources)

It is *very difficult* to explain the
observed spectral shape
with a sharp break to a steeper power law form

Conclusion from this numerical study

In the framework of the model described above
(short CR lifetime, explosive sources)

It is *very difficult* to explain the
observed spectral shape
with a sharp break to a steeper power law form

Solutions ….. ?

[1.] High critical energy (large propagation distance)

[2.] Modify the source model

The *“Just so”* solution to the *“local sources problem*"

Hypothesis: ONE single log duration source is responsible for the spectral break in the all-electron spectrum

R. López-Coto, R. D. Parsons, J. A. Hinton and G. Giacinti, “An undiscovered pulsar in the Local Bubble as an explanation of the local high energy cosmic ray electron spectrum,” arXiv:1811.04123 [astro-ph.HE].

S. Recchia, S. Gabici, F. A. Aharonian and J. Vink, “A local fading accelerator and the origin of TeV cosmic ray electrons,” arXiv:1811.07551 [astro-ph.HE].

Emission from a source is extended in time

Simplest hypothesis: a factorized spectrum

$$q_s(E,t) = q_0 \; E^{-\alpha} \; F(t-t_i)$$

Time dependence motivated by
the PULSAR breaking law

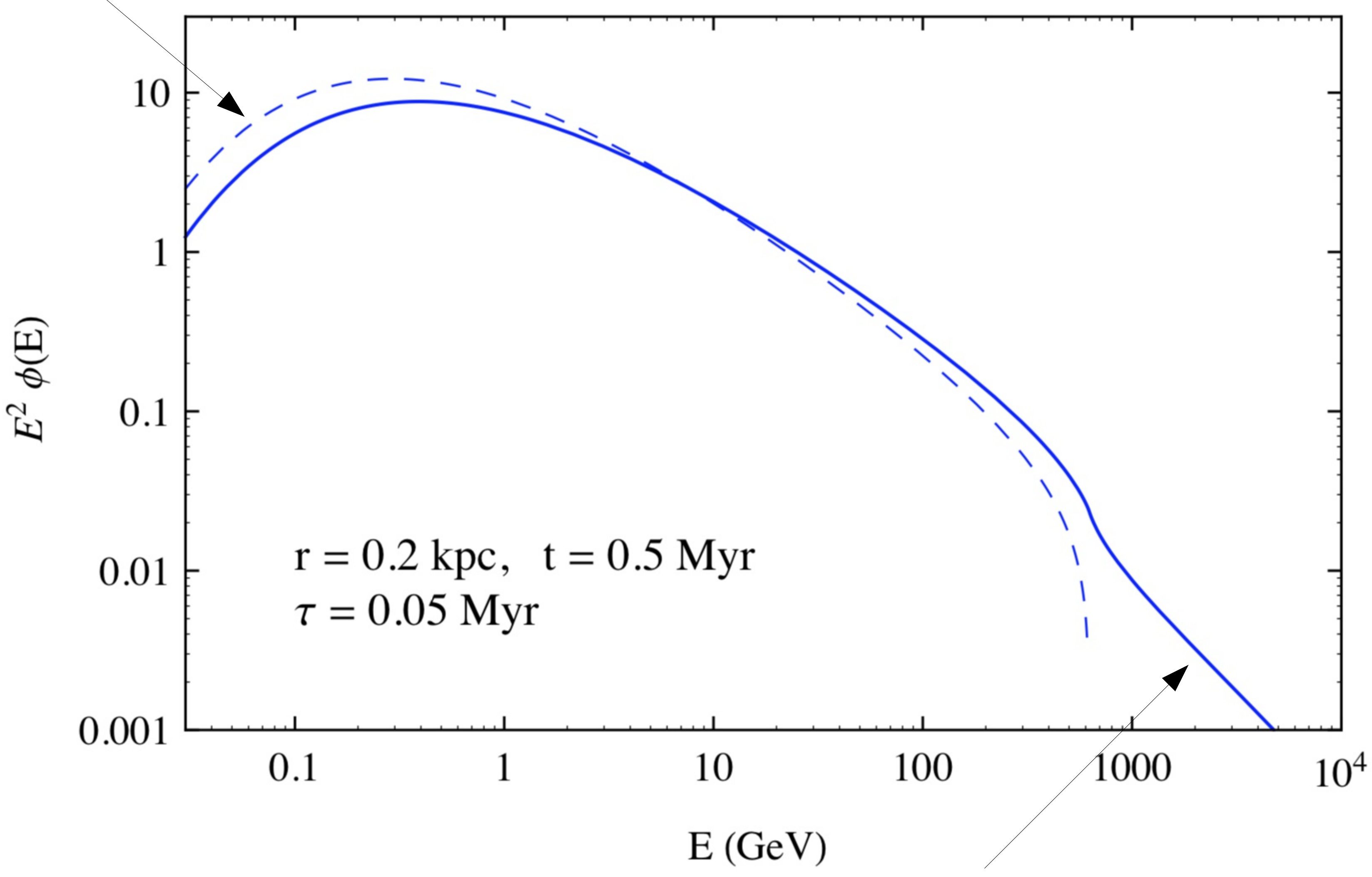
$$q_s(E,t) = q_0 \; E^{-\alpha} \; \frac{(p-1)}{\tau} \; \left[1 + \frac{(t-t_i)}{\tau}\right]^{-p}$$

$$p = \text{breaking index}$$

$$\int_0^\infty dt \; F(t) = 1$$

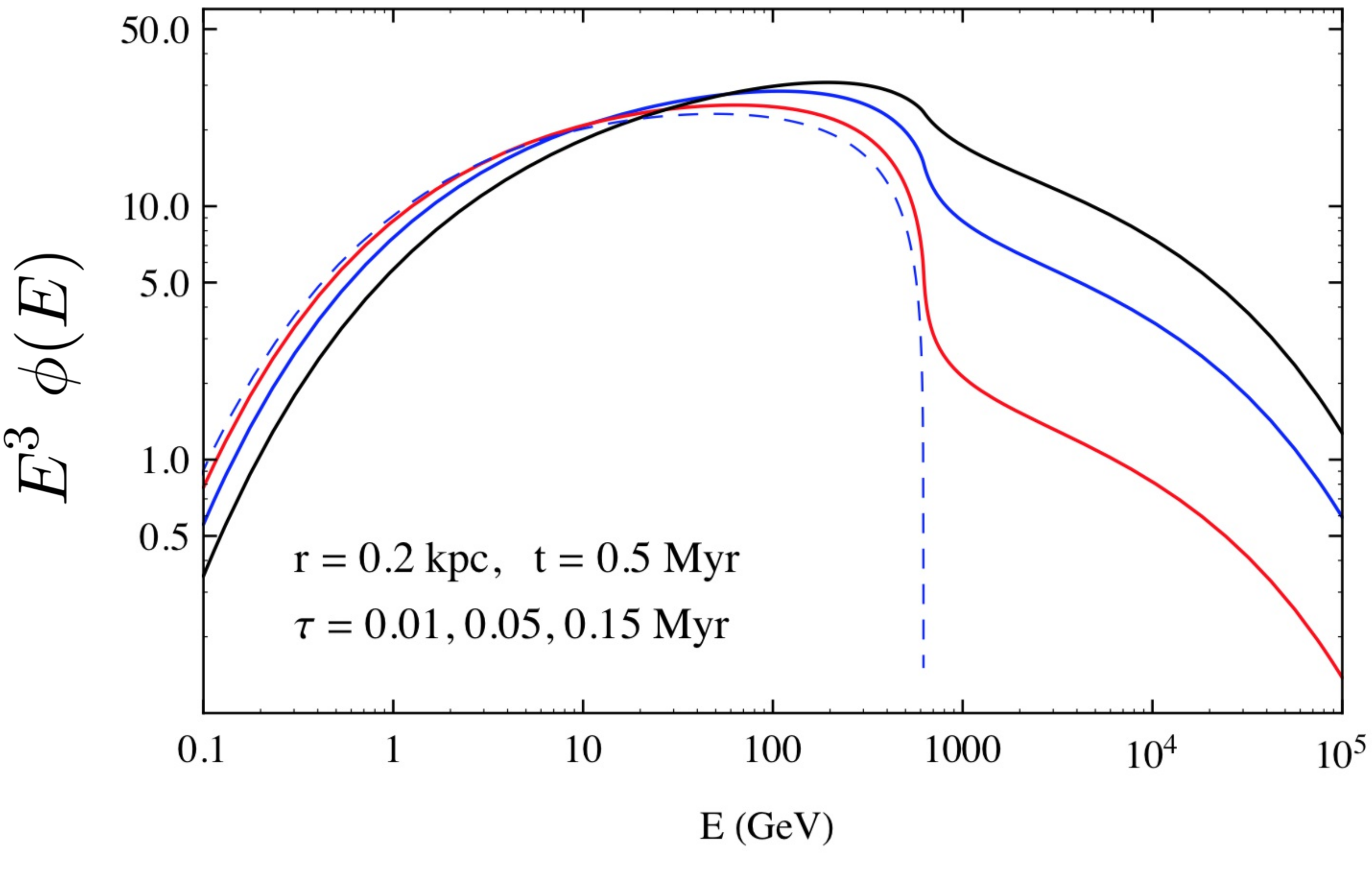
Fading source $p = 2$

Dashed line
Instantaneous source

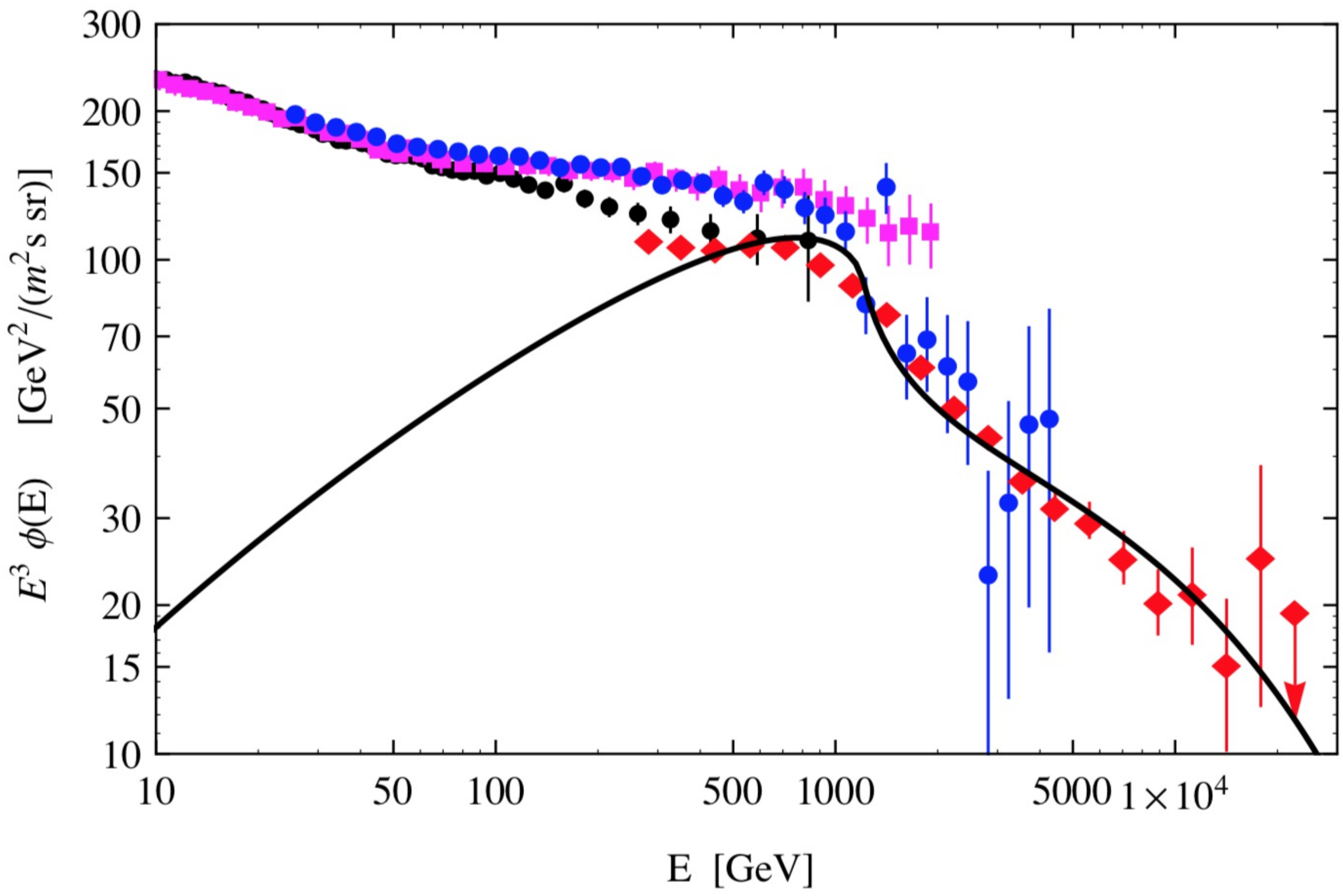


High energy tail

changing source decay time tau:



Matching the spectral break with ONE "fading" source



$r = 157$ kpc

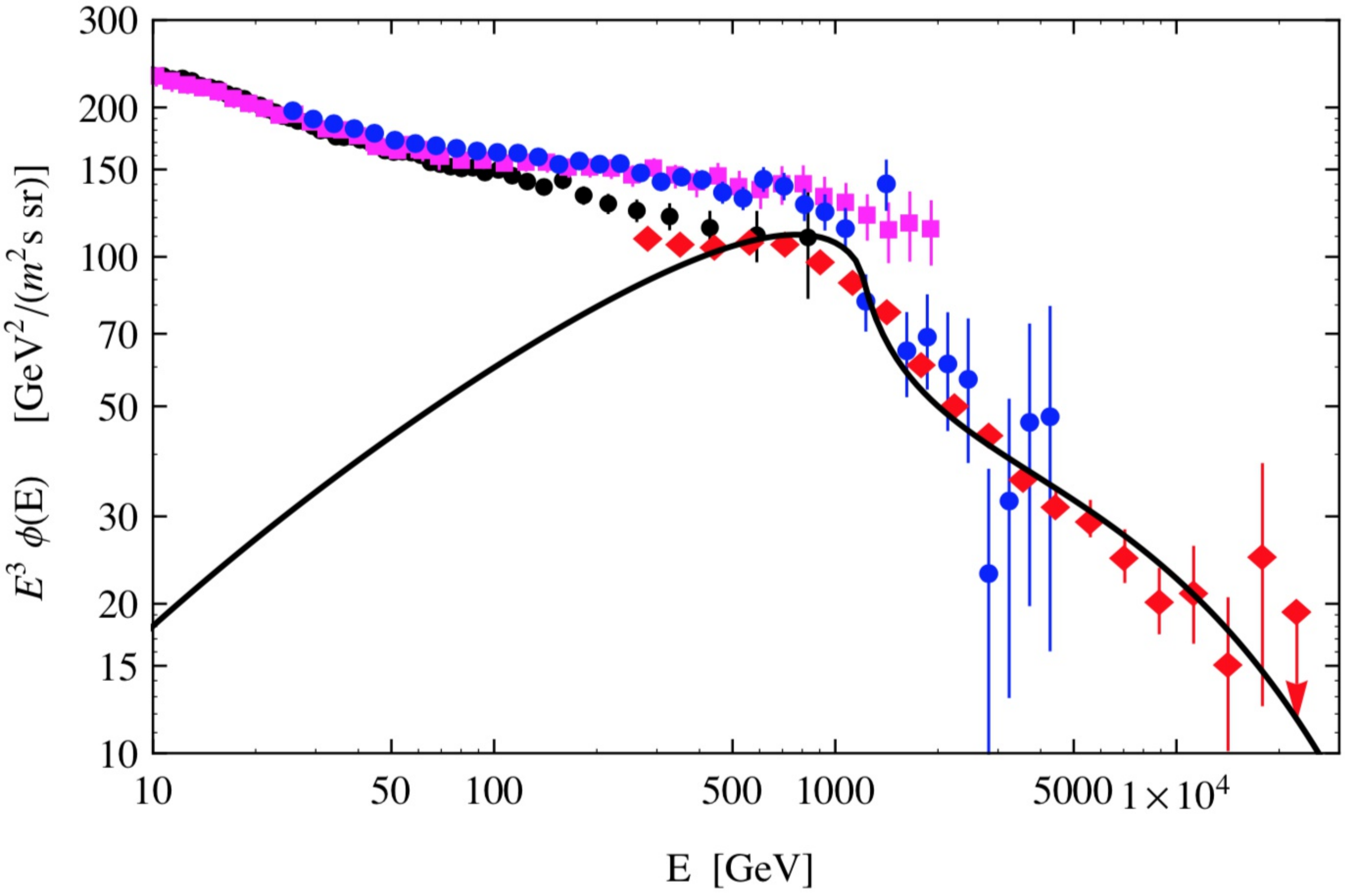
$t = 260$ kyr

$\tau = 40$ kyr

$\mathcal{E} = 1.1 \times 10^{48}$ erg

Possible to match the break with emission from one source

Matching the spectral break with ONE "fading" source



$r = 157$ kpc

$t = 260$ kyr

$\tau = 40$ kyr

$\mathcal{E} = 1.1 \times 10^{48}$ erg

Possible to match the break with emission from one source

[can one match the entire spectrum ?]

Note on the solution:

The source distance r
enters the flux
In the combination:

$$\frac{r^2}{D(E)\,t}$$

Flux absolute
Normalization

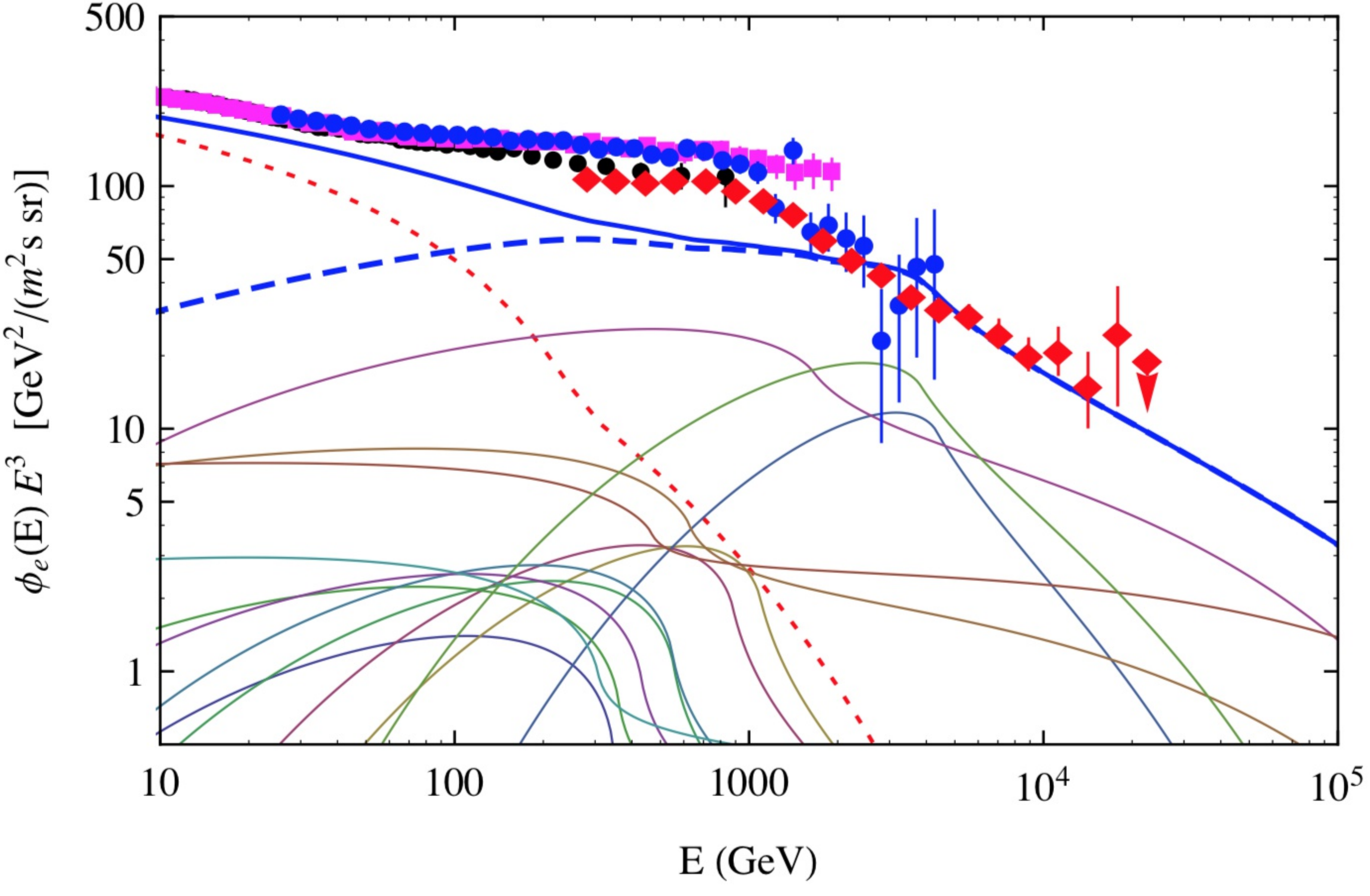
$$\propto \frac{\mathcal{E}}{(D_0)^3}$$

Infinite identical solutions:

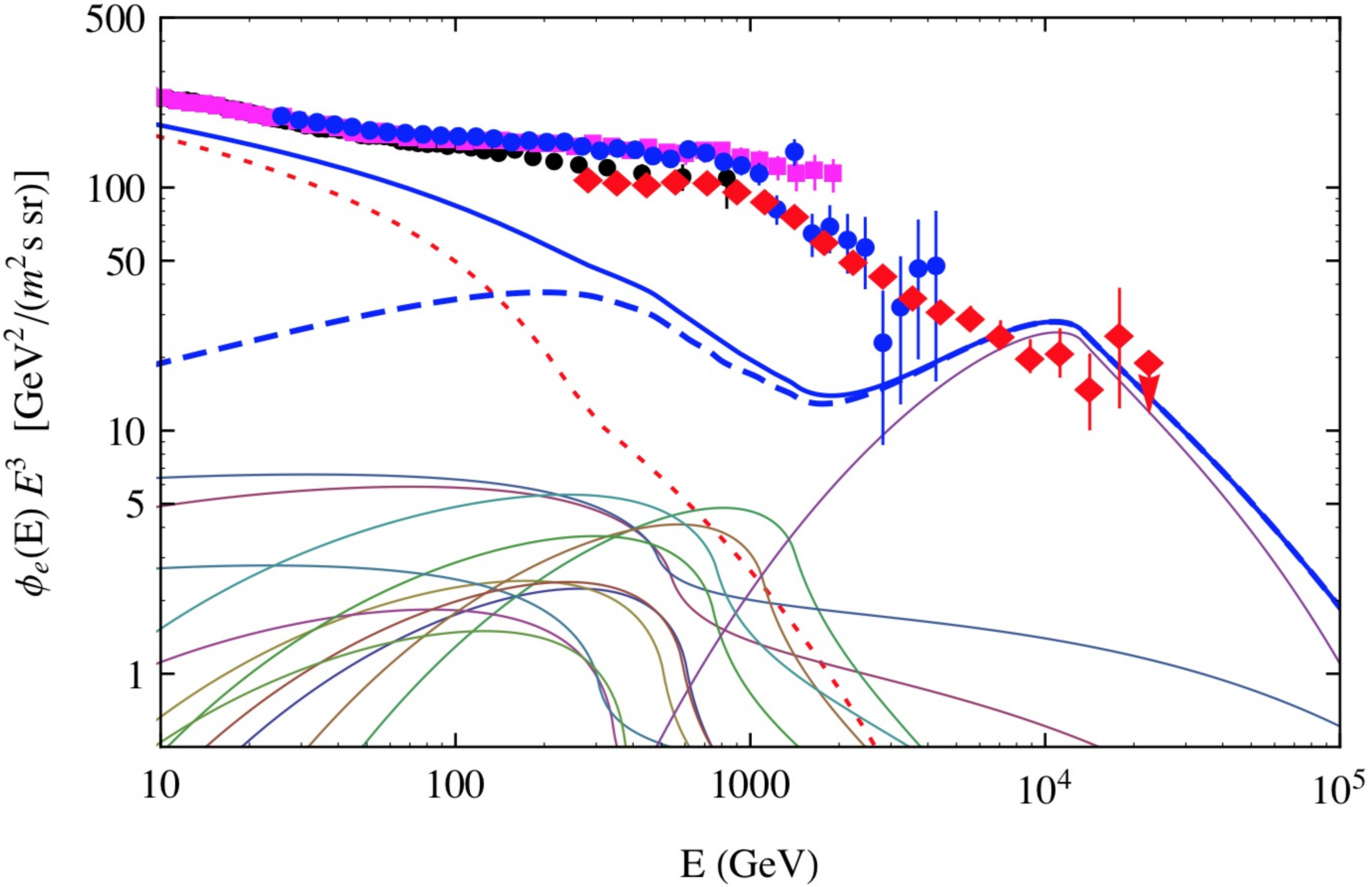
$$\{D_0\ ,\ r,\ \ \mathcal{E},\ \ \ldots\ \}$$

$$\{D_0'\ ,\ r\ (D_0'/D_0)^{1/2},\ \ \mathcal{E}\ (D_0'/D_0)^{3/2},\ \ \ldots\ \ \}$$

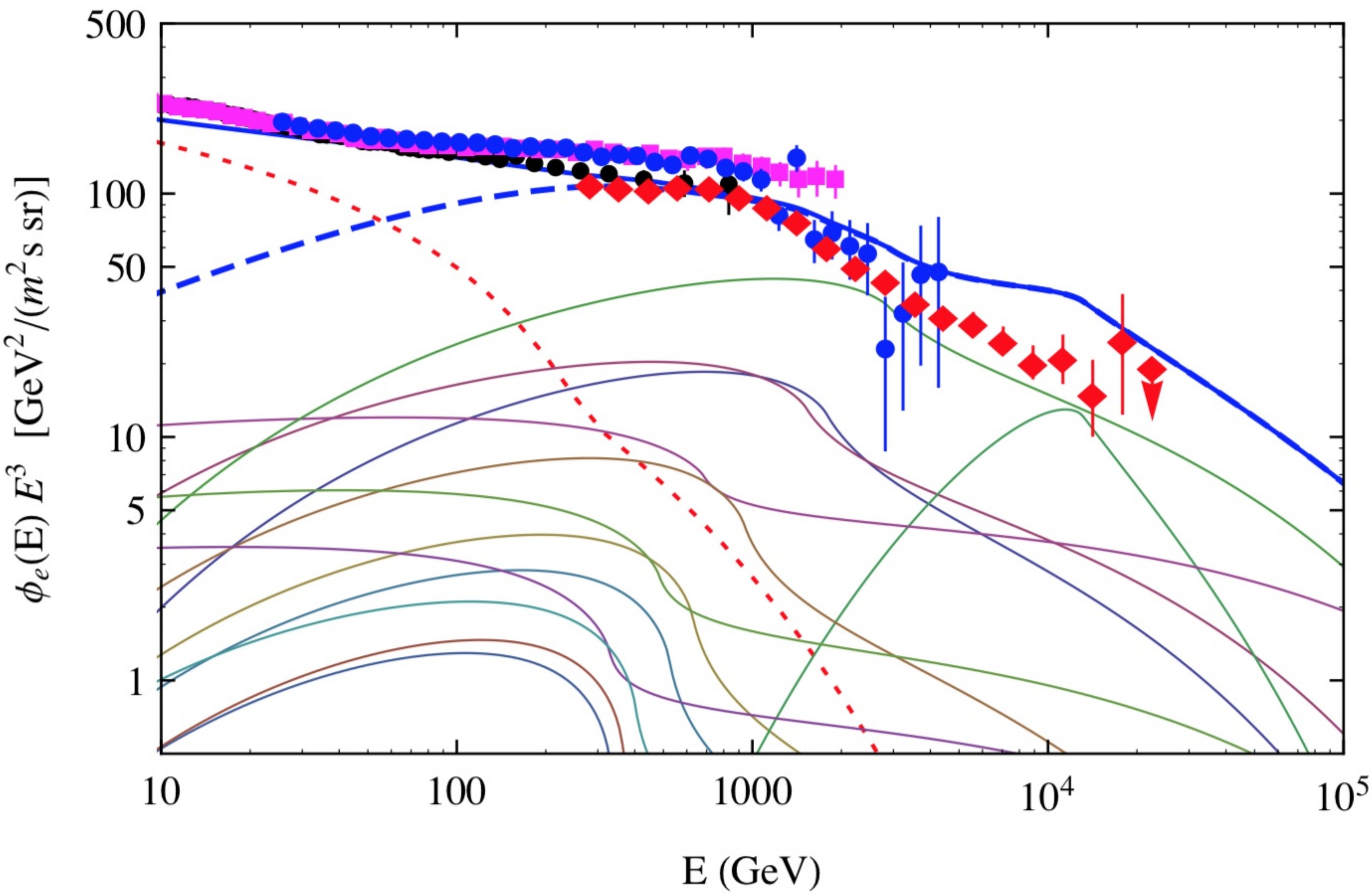
Study ensemble of fading sources



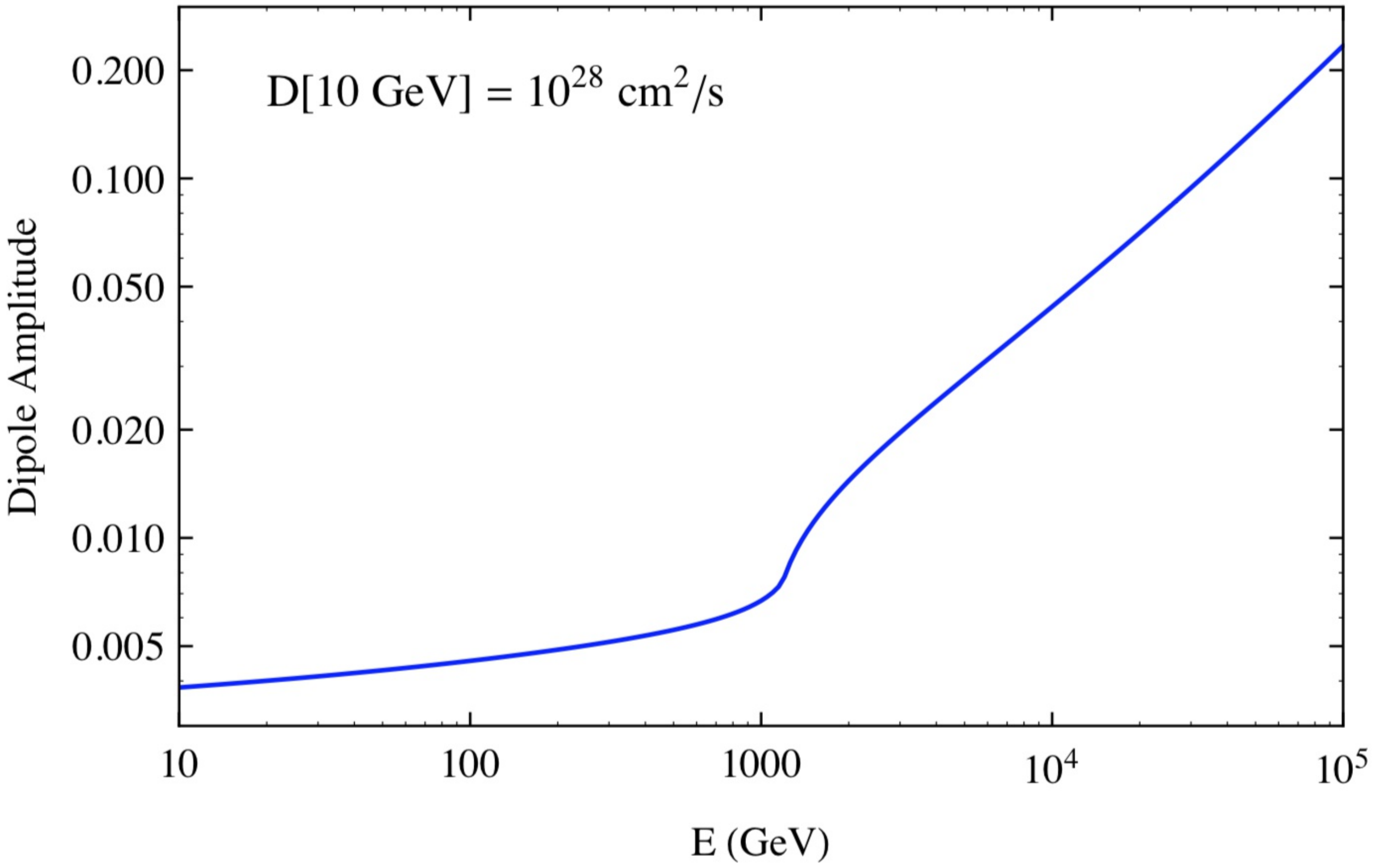
One random Galactic configuration [2]



One random Galactic configuration [e]



Dipole moment of the angular distribution



Comments:

Interesting solution,
But… still requires "significant fine tuning"
to generate a spectrum similar to the observed one
with no additional structure.
[transition many sources → One source]

Very important astrophysical implications:

Are Pulsar-like sources the main sources
of electrons ? [and also positrons ?]

Do Pulsars accelerate protons ?

What about Supernovae ?

Proton versus electron

Acceleration in sources

Cosmic Ray generation

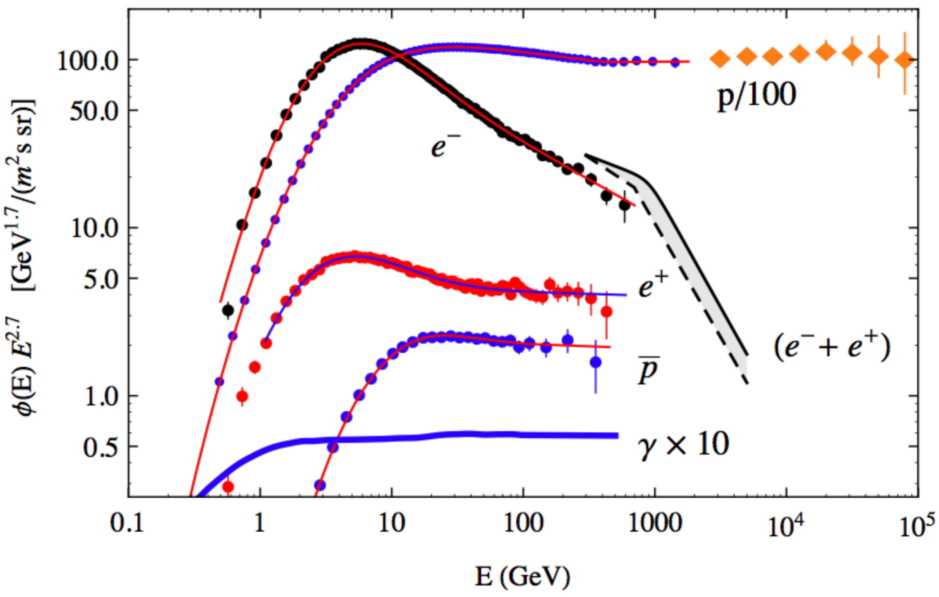
Problem of central importance in High Energy Astrophysics

If: positrons and antiprotons have equal propagation properties.

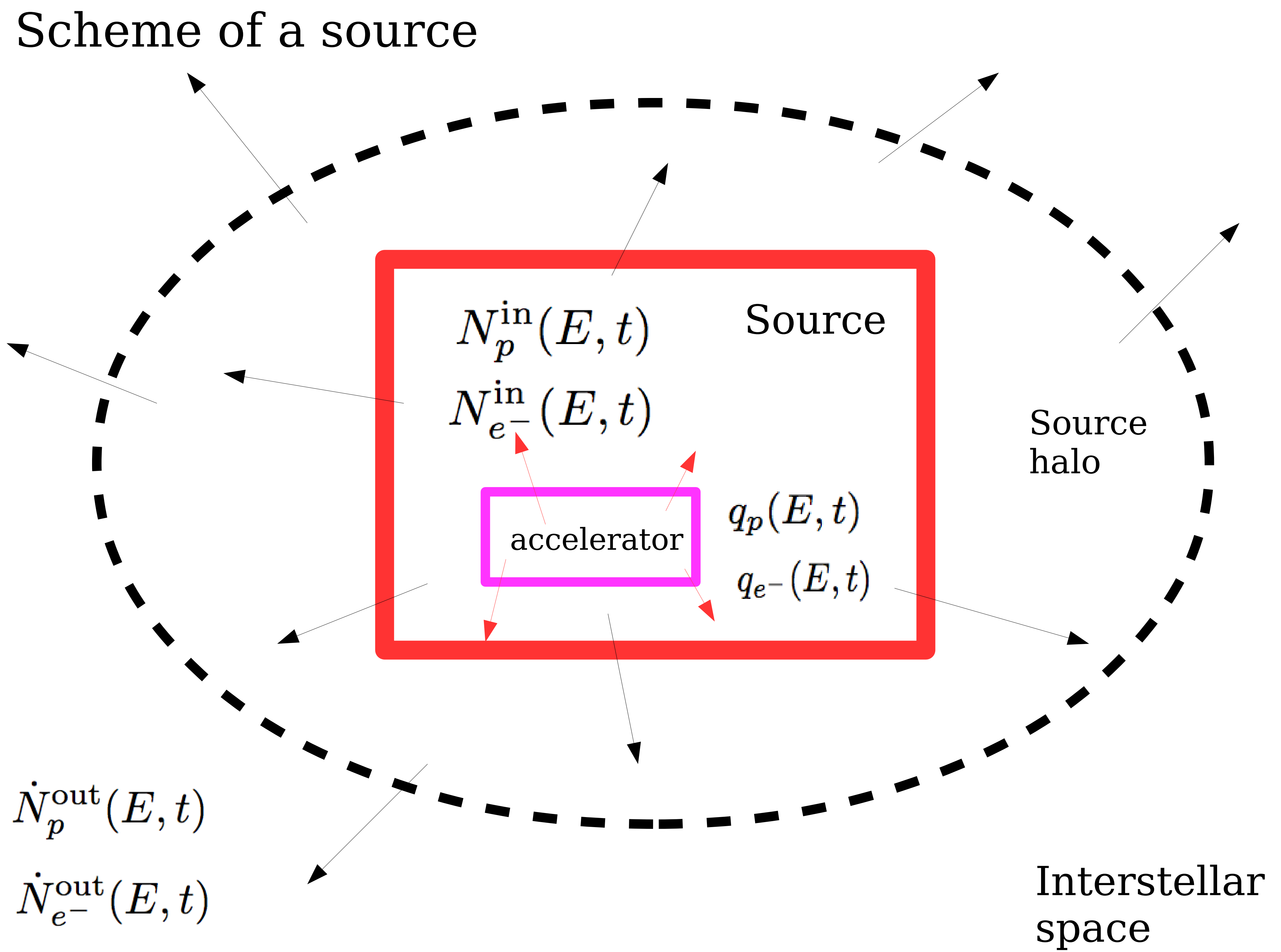
Then: also electron and protons have also the same propagation properties

But then:

why are the electron the proton spectra so different from each other ?!



The e/p difference must be generated by the sources


Scheme of a source
$N_p^{\rm in}(E,t)$
$N_{e^-}^{\rm in}(E,t)$
Source
accelerator
$q_p(E,t)$
$q_{e^-}(E,t)$
Source halo
$\dot{N}_p^{\rm out}(E,t)$
$\dot{N}_{e^-}^{\rm out}(E,t)$
Interstellar space

Primary Cosmic Rays:

understand the Accelerators

Nearly certainly the accelerators are *transients*

A single accelerator

t_i (Accelerator is born)

$t_i + T$ (Accelerator "disappears")

Integrating over its entire lifetime, the Accelerator "releases" in interstellar space populations of relativistic Particles.

$$N_p^{\rm out}(E) \quad , \quad N_{e^-}^{\rm out}(E) \quad , N_{\rm He}^{\rm out}(E) \quad , \ldots.$$

During its lifetime, $t_i < t < t_i + T$

the accelerator is a gamma ray and neutrino emitter

$$q_\gamma(E,t) \qquad q_\nu(E,t)$$

Infer the populations of relativistic particles inside (or near) the accelerators:

$$N_p^{\rm in}(E,t) \qquad N_{e^-}^{\rm in}(E,t)$$

Far from trivial to relate this information to the CR spectra released in interstellar space

$$N_p^{\rm out}(E) \quad , \quad N_{e^-}^{\rm out}(E)$$

The observations of the anti-particle fluxes

brings us to a *"Crossroad"*
in our studies of Cosmic Rays

electrons
positrons

protons
antiprotons

Propagation properties
in the Milky Way

[A] *"Conventional Scenario"*

Different propagation properties for $E \gtrsim 3 \text{ GeV}$

[B] *"Alternative Scenario"*

Equal propagation properties for $E \lesssim 900 \text{ GeV}$

Conventional propagation scenario:

A1. Very long lifetime for cosmic rays

A2. Difference between electron and proton spectra shaped by propagation effects

A3. New hard source of positrons is required

A4. Secondary nuclei generated in interstellar space

Alternative propagation scenario:

B1. Short lifetime for cosmic rays

B2. Difference between electron and proton spectra generated in the accelerators

B3. antiprotons and positrons of secondary origin

B4. Most secondary nuclei generated in/close to accelerators

How can one discriminate between the two scenarios ?

1. Extend measurements of e+- spectra
   Different cutoffs can confirm the conventional picture

2. More precise measuremens of (e+ + e-) spectra
   in the multi-TeV range

3. Extend measurements of secondary nuclei
   [B, Be, Li]. Look for signatures of
   nuclear fragmentation inside/near the accelerators.

4. Study the space and energy distributions
   of the relativistic e+- in the Milky Way
   [from the analysis of diffuse Galactic gamma ray flux]

5. Develop an understanding of the CR sources
   Study the populations of e- and p in young SNR
   (assuming that they are the main sources of CR)

Conclusions:

An understanding of the origin of the
electron, positron and antiproton fluxes
is of central importance for High Energy Astrophysics.

This problem touches the
"*cornerstones*" of the field
and has profound and broad implications

Discovery of Dark Matter !!?
Possible antiparticle accelerators
Spectra (e and p) released by CR accelerators,
Fundamental properties of CR Galactic propagation

Crucial crossroad for the field.

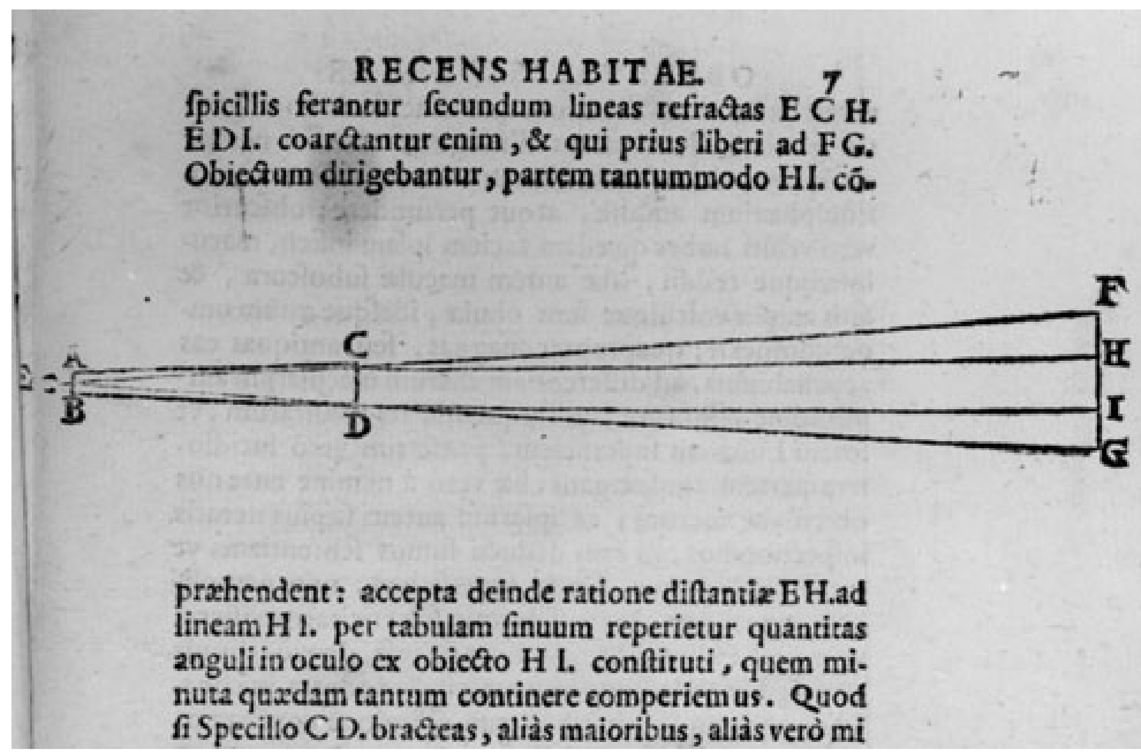

Korkoronke
El choique


© Nicholas Buer


Pleiades

410 years ago (dec-1609)

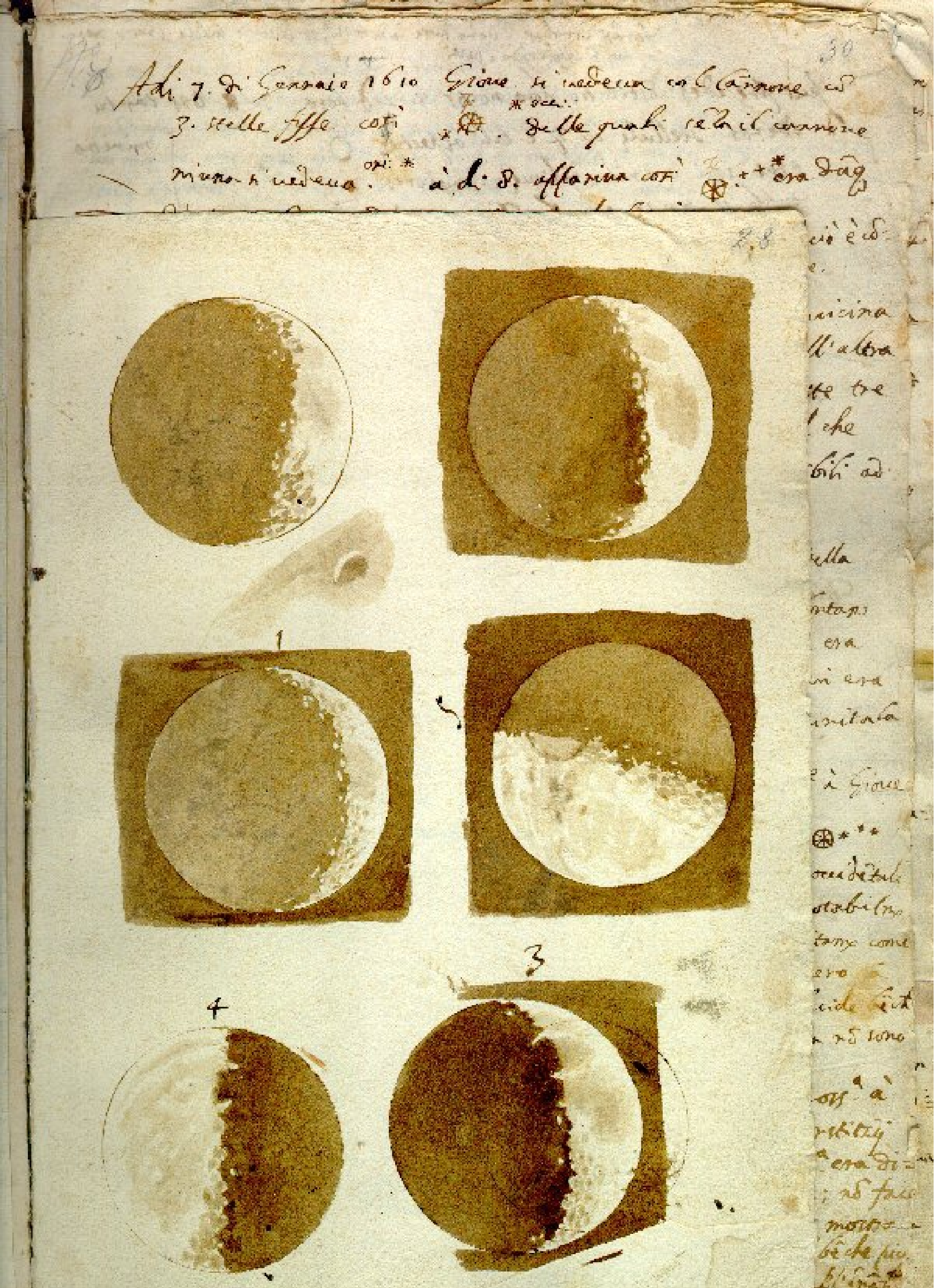
Galileo Galilei
started to observe
the sky with a telescope



RECENS HABITAE. 7

ſpicillis ferantur ſecundum lineas refractas E C H. E D I. coarctantur enim, & qui prius liberi ad F G. Obiectum dirigebantur, partem tantummodo H I. cō-

prehendent: accepta deinde ratione diſtantiæ E H. ad lineam H I. per tabulam ſinuum reperietur quantitas anguli in oculo ex obiecto H I. conſtituti, quem minuta quædam tantum continere comperiemus. Quod ſi Specillo C D. bracteas, aliàs maioribus, aliàs verò mi



It is extraordinarily beautiful and a source of great joy to observe the body of the Moon .....

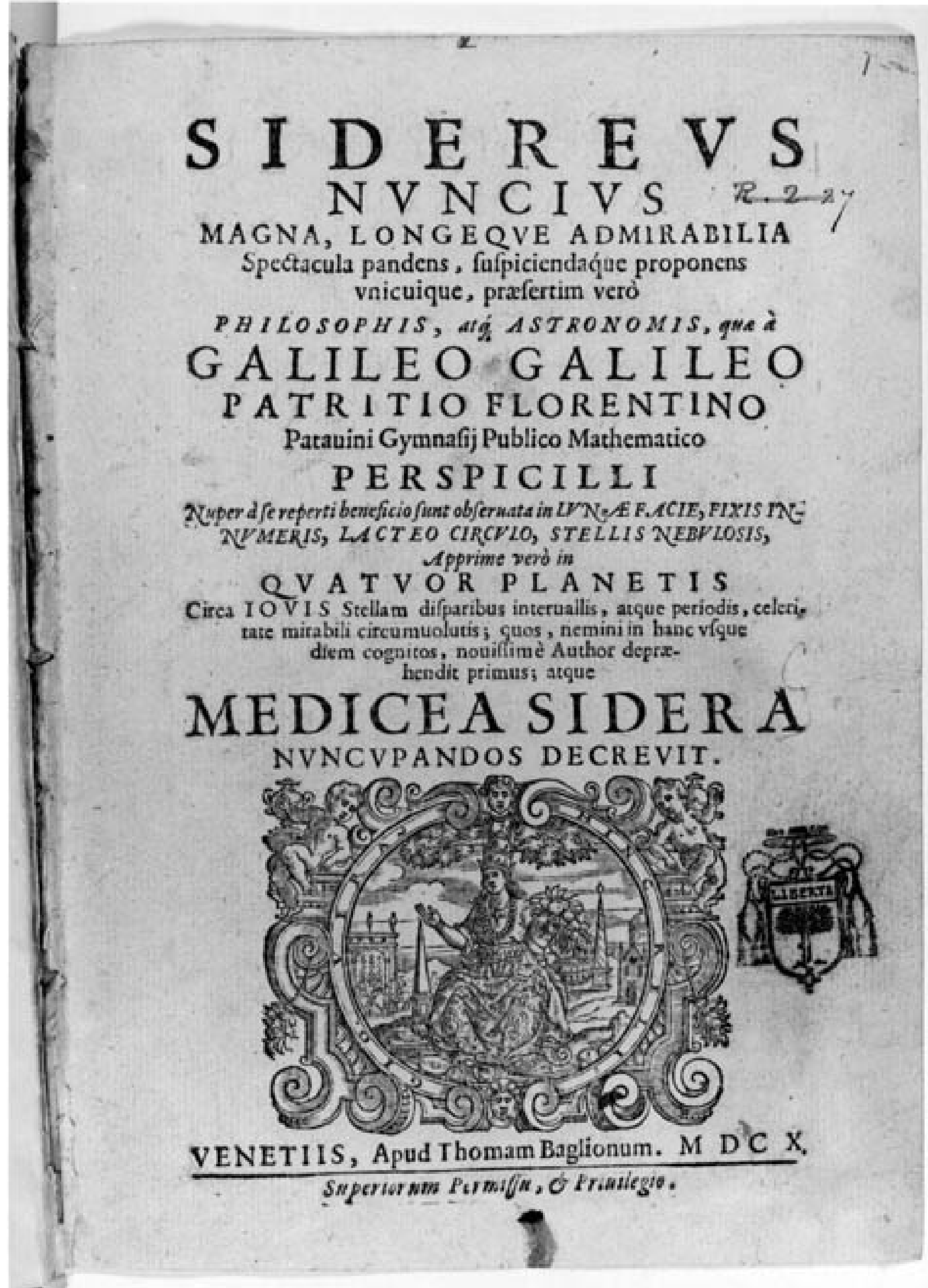
Pulcherrimum atque visu iucundissimum est, lunare corpus,......

In 1610,
Galileo published his observations under the title:

“SIDEREUS NUNCIUS”

“The messenger from the stars”

unfolding great and very wonderful sights
and displaying to the gaze of everyone,
but especially philosophers and astronomers,
the things that were observed by
GALILEO GALILEI,
Florentine patrician
and public mathematician of the University of Padua,
with the help of a
spyglass
lately devised by him,
about the face of the Moon, countless fixed stars,
the Milky Way, nebulous stars,
but especially about
four planets
flying around the star of Jupiter at unequal intervals
and periods with wonderful swiftness;
which, unknown by anyone until this day,
the first author detected recently
and decided to name
MEDICEAN STARS


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.


PLEIADVM CONSTELLATIO.

Quod tertio loco à nobis fuit obſeruatum, eſt ipſiuſ-
met LACTEI Circuli eſſentia, ſeu materies, quam Per-

PLEIADUM CONSTELLATIO


My best wishes to all of you !