Multi Messenger Astrophysics

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ISAPP School 2019
Cosmic Ray Vision from the Southern Sky

Malargue, march 3rd 2019

“High Energy Universe”

The ensemble of astrophysical objects, environments and mechanisms that generate and store very high energy particles in the Milky Way and in the entire universe.

This field is one of the most significant and fascinating “Frontiers” in Science today.

1. Understanding the *“COSMOS*" where we live

2. The sources of the High Energy radiation can be the “laboratories” where we test *(in conditions that are not achievable in “Earth based laboratories”)* our Fundamental Laws of Physics.

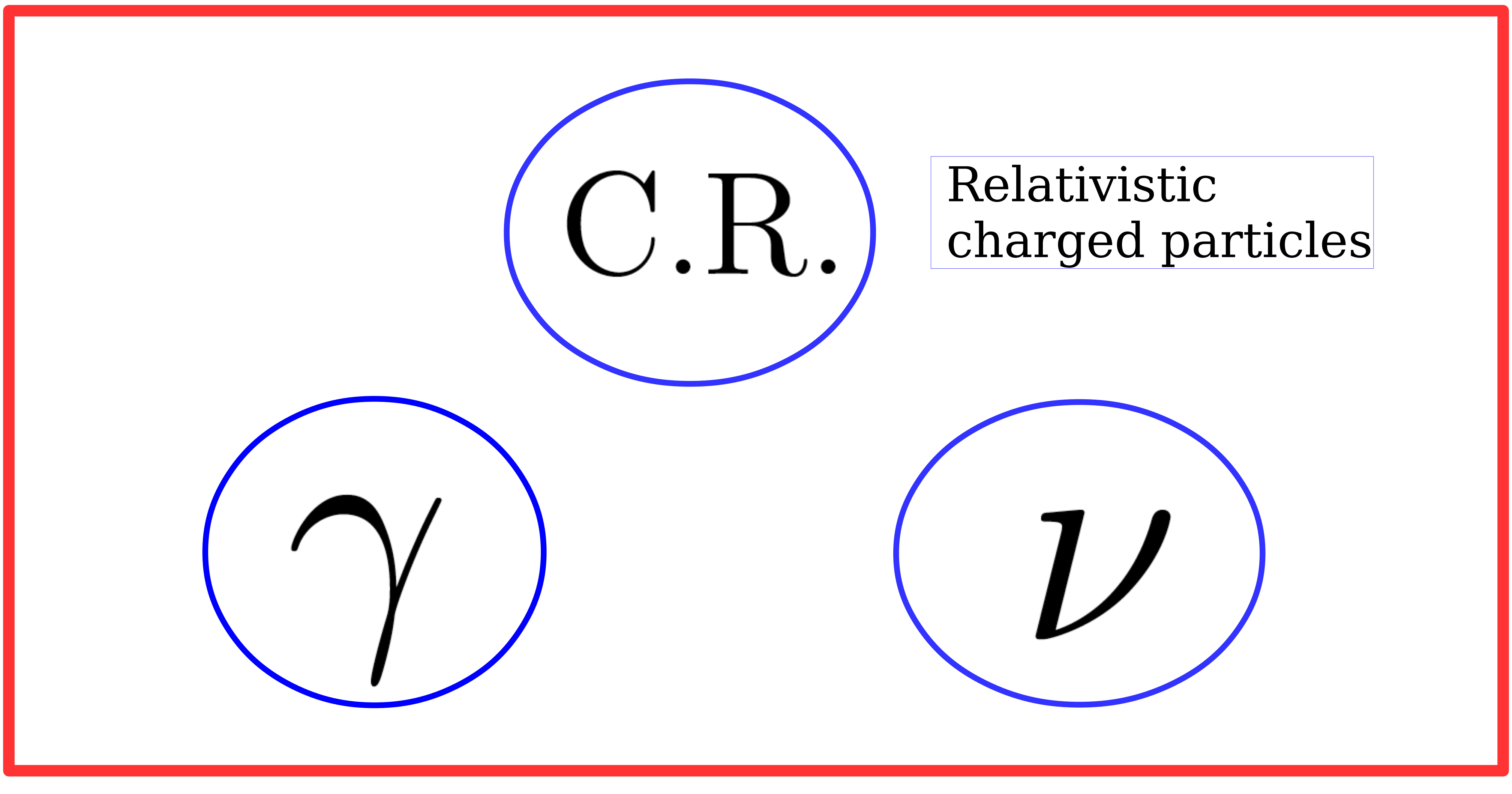
Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

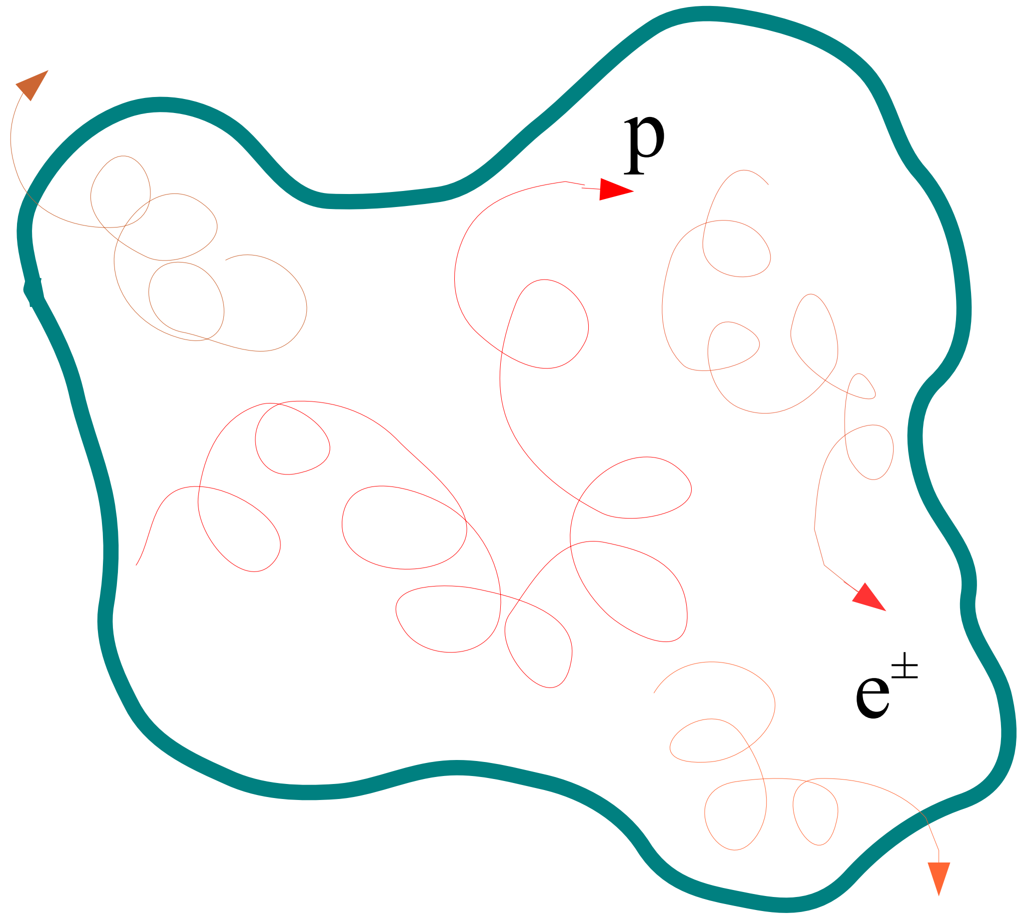
4 Messengers
for the study of the
“High Energy Universe”

Three messengers are “inextricably” tied together

[Cosmic Rays, Gamma Rays, High Energy Neutrinos can really be considered as three probes that study the same underlying physical phenomena]



Cosmic Ray Accelerator



Astrophysical object accelerating particles to relativistic energies

Contains populations of relativistic protons, Nuclei electrons/positrons

Emission of

COSMIC RAYS

PHOTONS

NEUTRINOS

Fundamental Mechanism:

Acceleration of Charged Particles

to Very High Energy ("non thermal processes")
in astrophysical objects (or better "events").

Creation of Gamma Rays and Neutrinos
via the interactions of these relativistic charged particles.

"Hadronic " "Leptonic "

$$p + \mathrm{X} \to \pi^+ \; \pi^- \; \pi^\circ \; \ldots$$

$$\pi^\circ \to \gamma \; \gamma$$

$$\pi^+ \to \mu^+ \; \nu_\mu$$

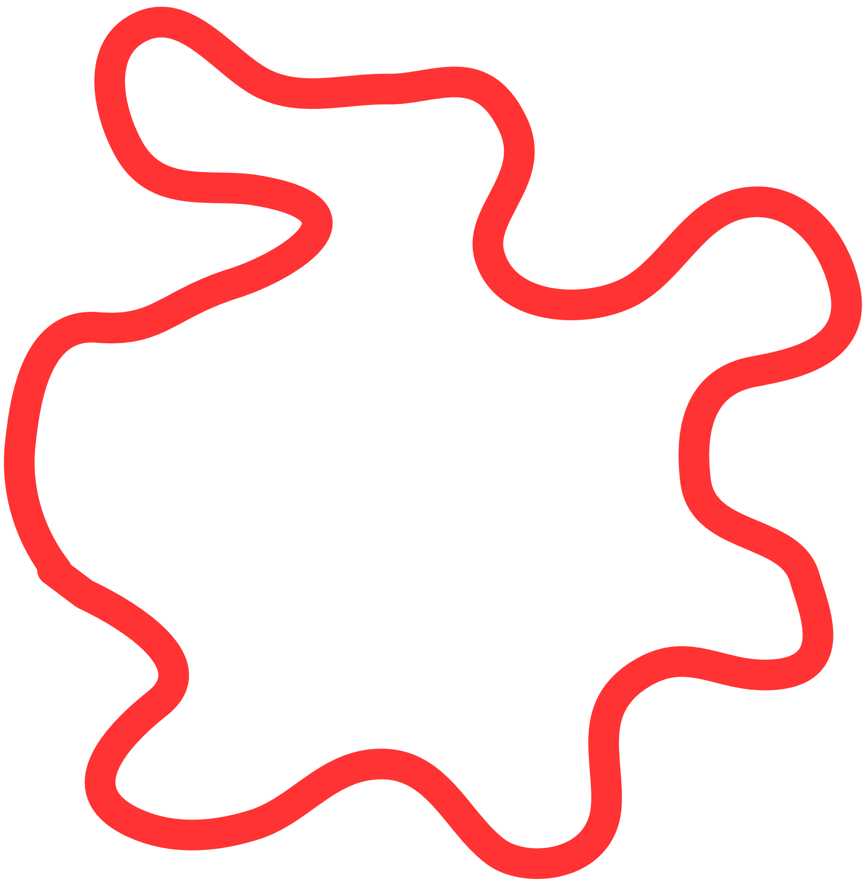
$$\hookrightarrow e^+ \; \nu_e \; \overline{\nu}_\mu$$

$$e^\pm \; \gamma_{\mathrm{soft}} \to e^\pm \; \gamma$$

$$e^\pm \; Z \to e^\pm \; \gamma \; Z$$

$$e^\pm \; \vec{B} \to e^\pm \; \gamma_{\mathrm{syn}}$$

High Energy Source



$$n_{\text{gas}}(\vec{x}, t)$$

$$\vec{B}(\vec{x}, t)\,\vec{E}(\vec{x}, t)$$

$$n_\gamma(\varepsilon, \hat{u}_\gamma, \vec{x}, t)$$

Structure

$$N_p(E, \vec{x}, t)$$

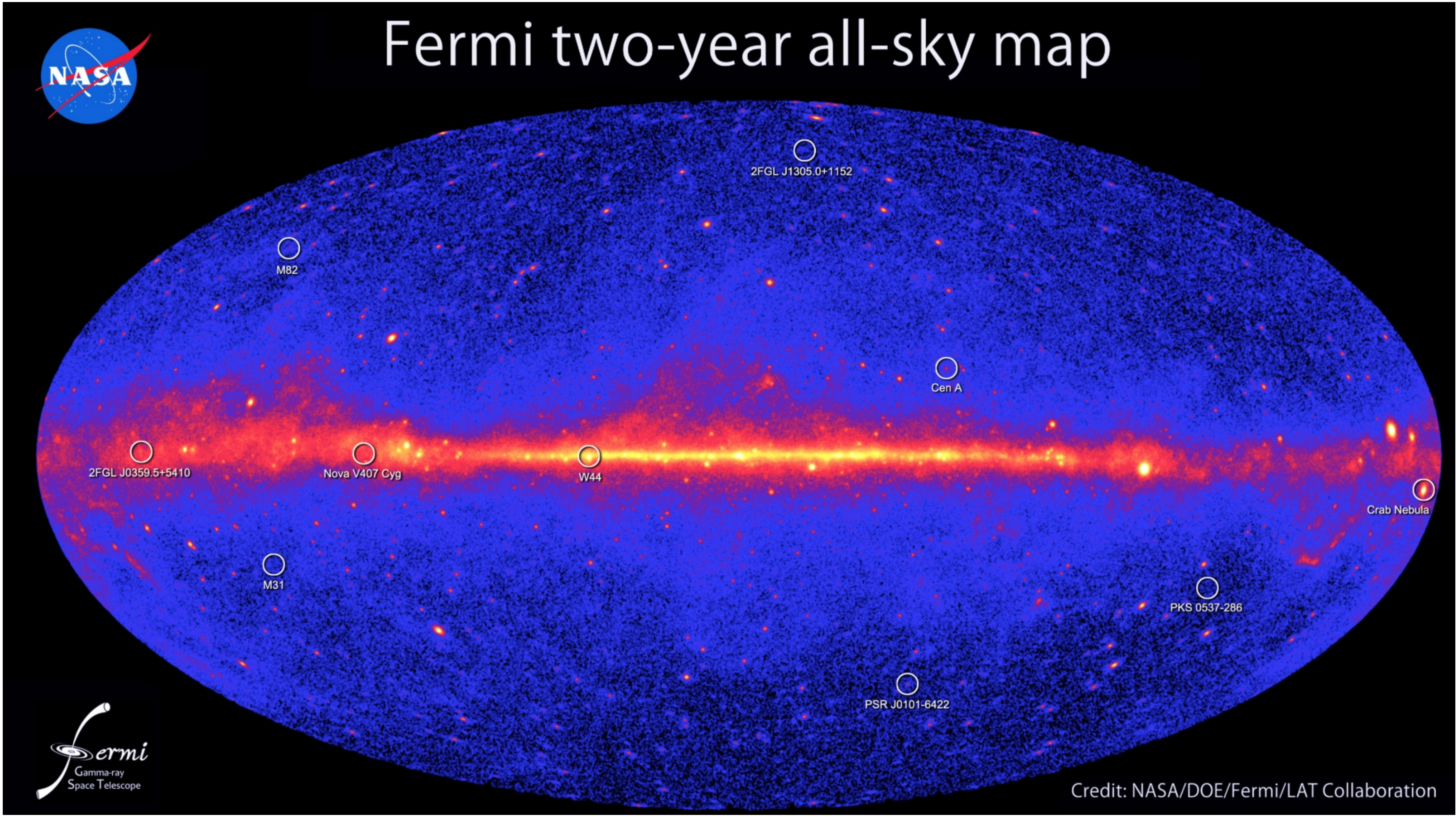
$$N_A(E, \vec{x}, t)$$

$$N_e(E, \vec{x}, t)$$

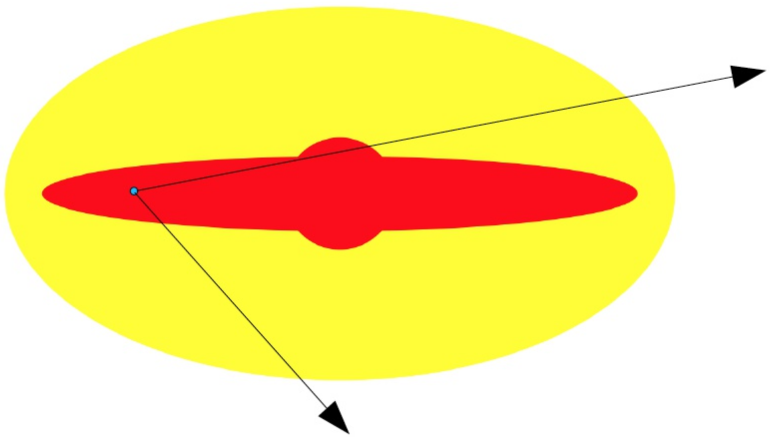
Relativistic Particles

$E_\gamma \geq 100$ MeV

Gamma Ray Sky

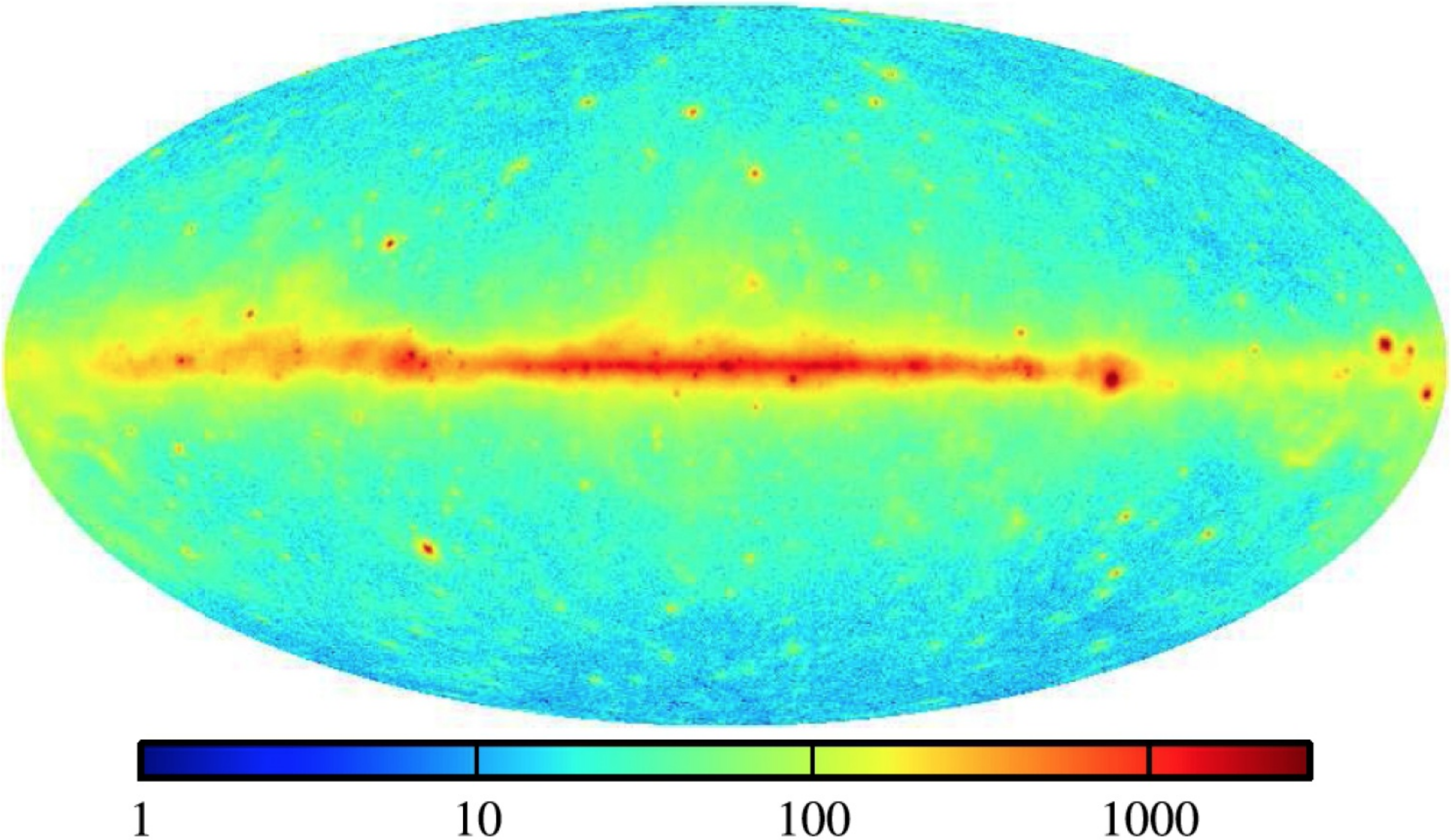


Diffuse Emission



Fermi–LAT counts

Galactic coordinates



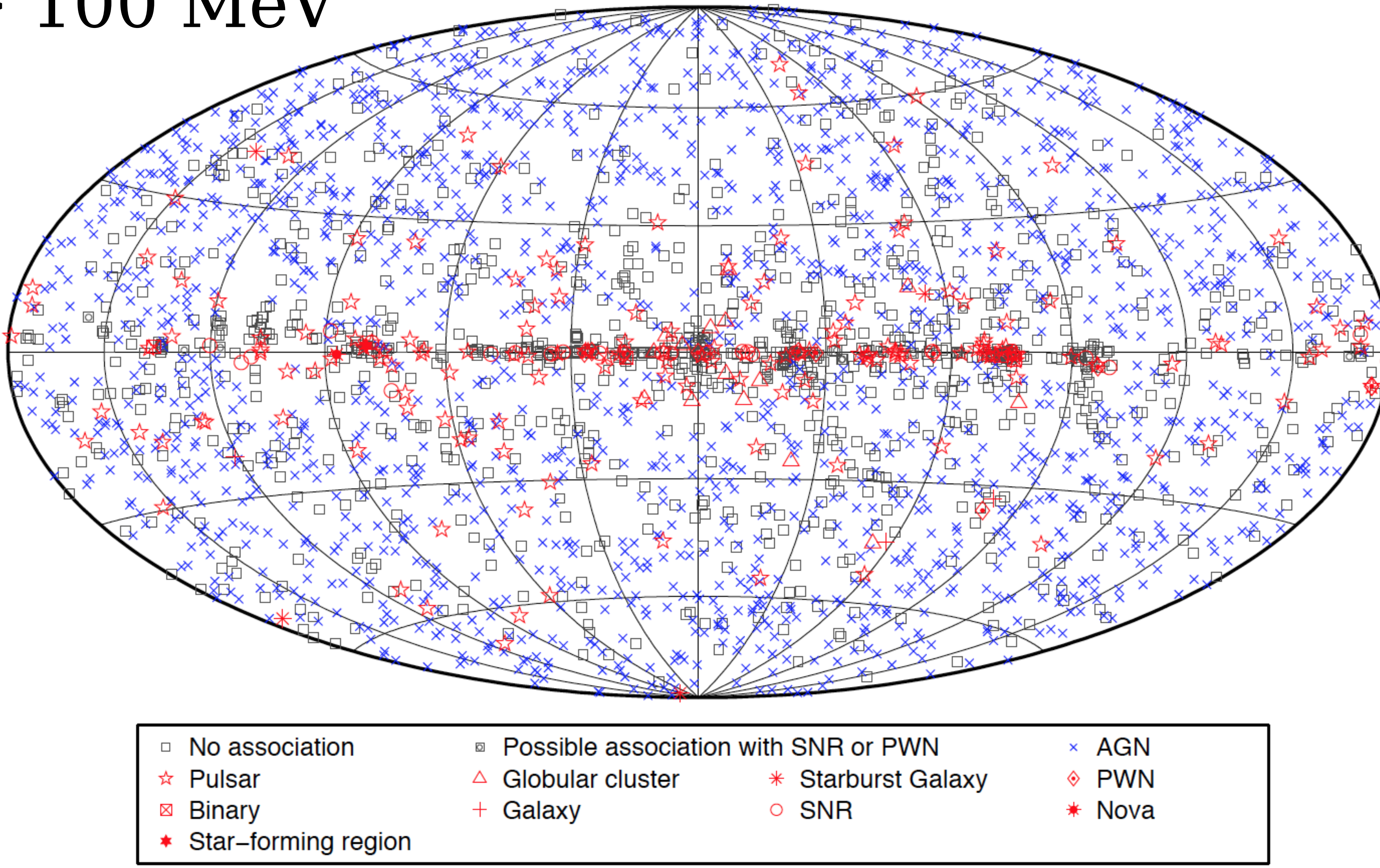
energy range 200 MeV to 100 GeV

Cosmic Ray interactions in the Interstellar Medium

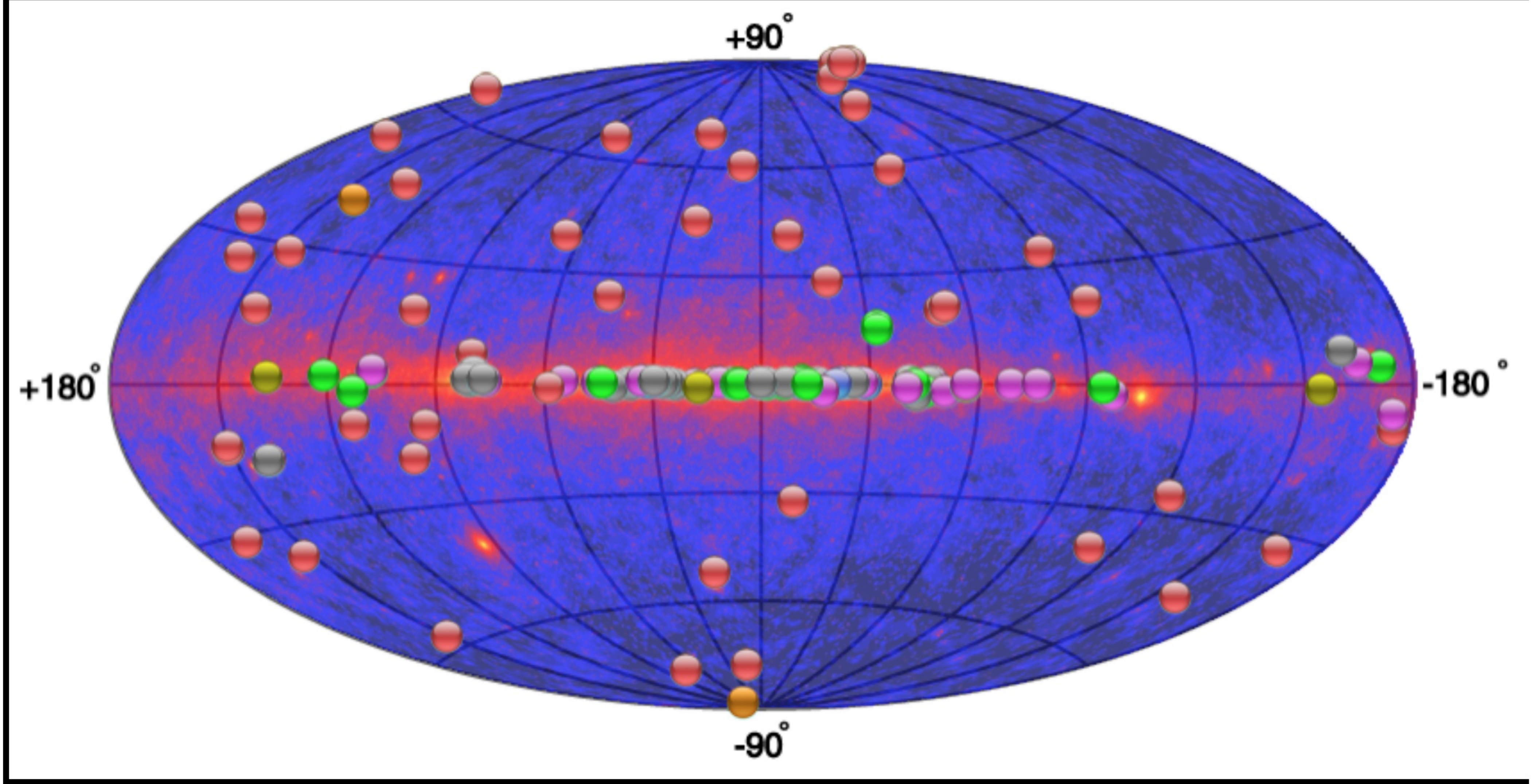
50% of flux
+- 5 degrees
around equator
[Galactic gas]

3^{rd} FERMI Catalog 3034 sources

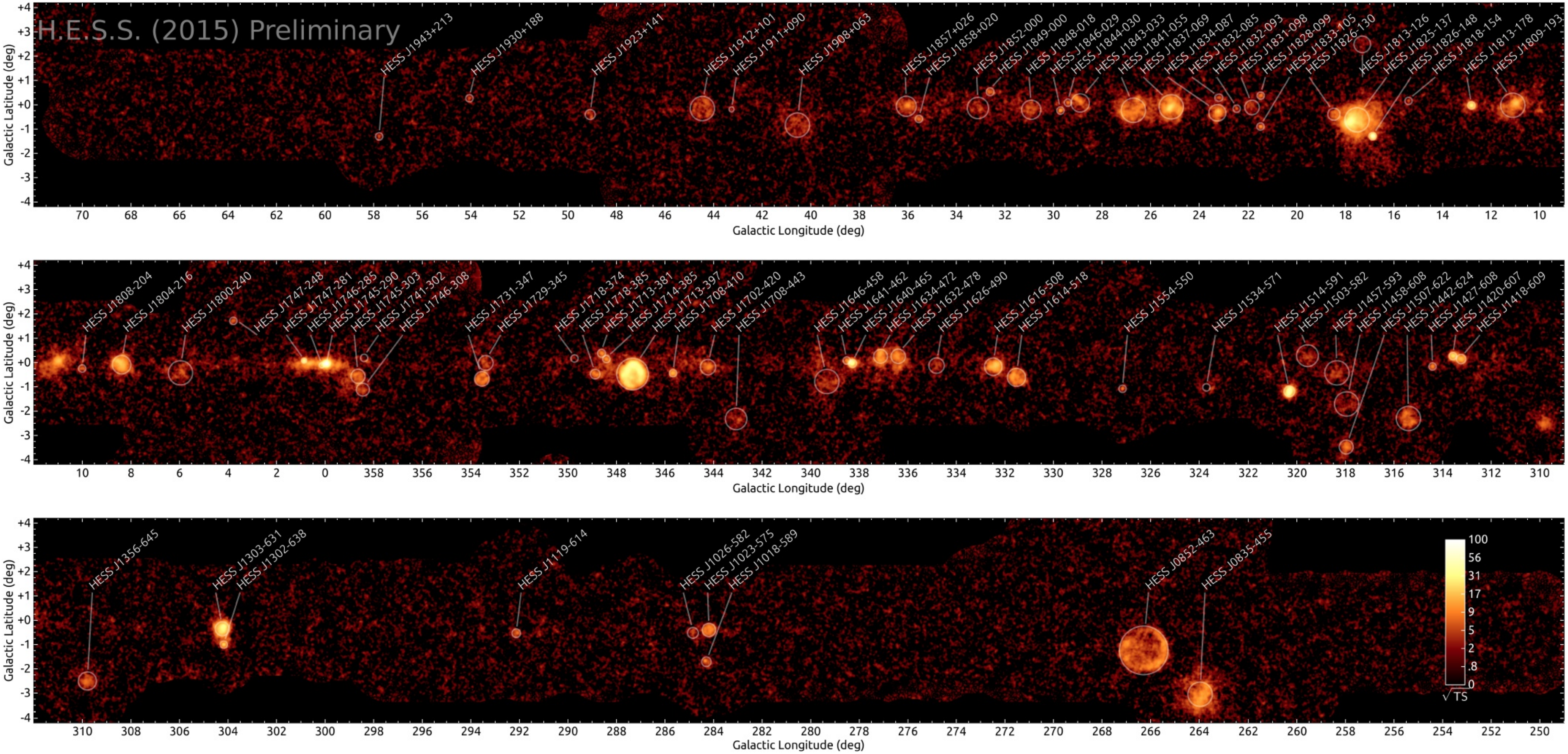
E > 100 MeV



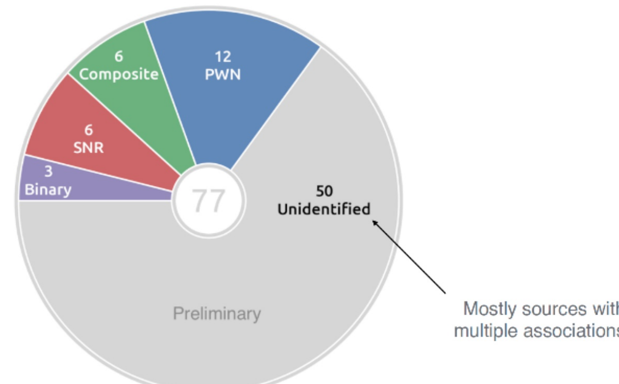
TeV Sky 170 → 200 Sources



blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky

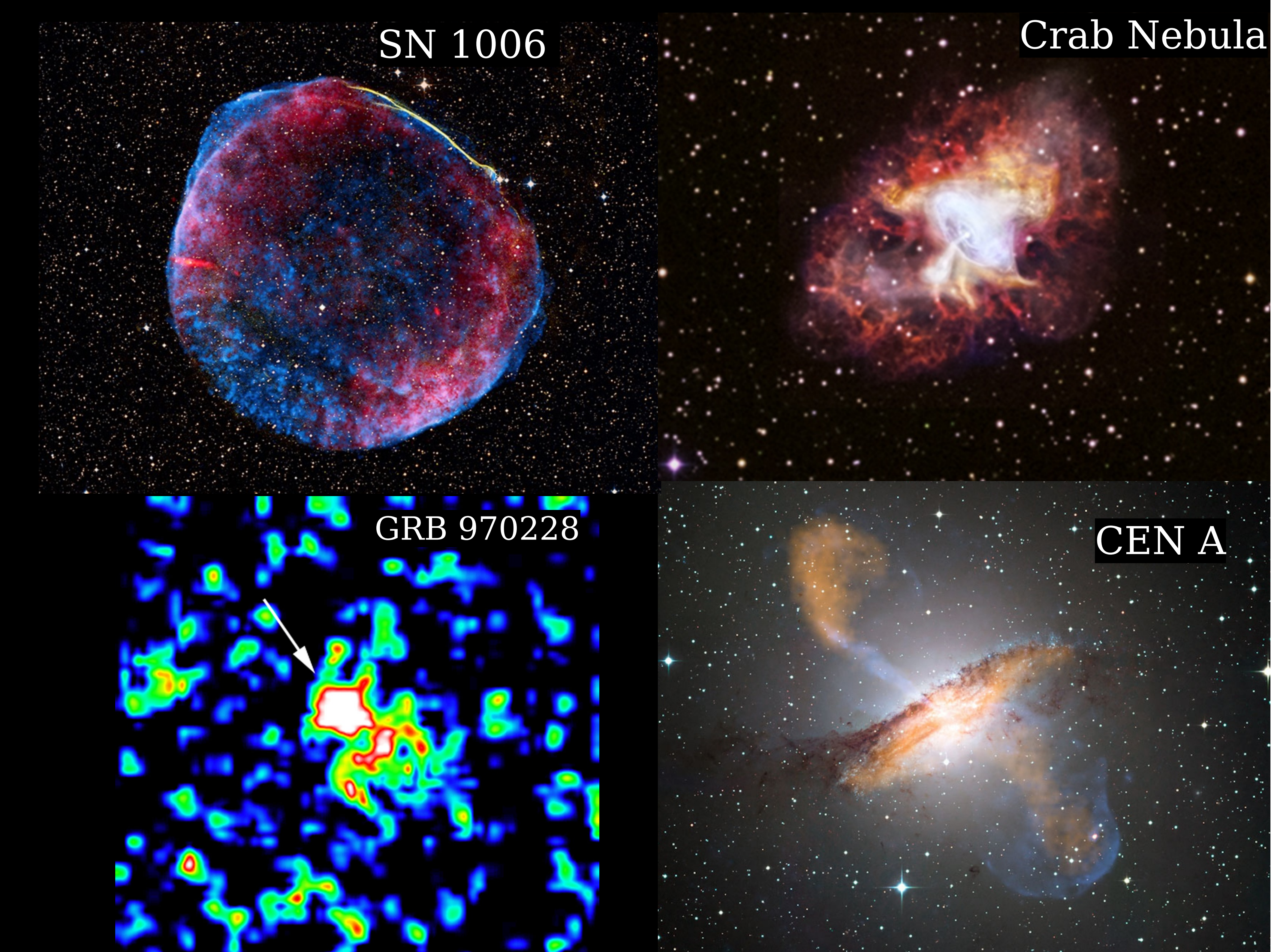


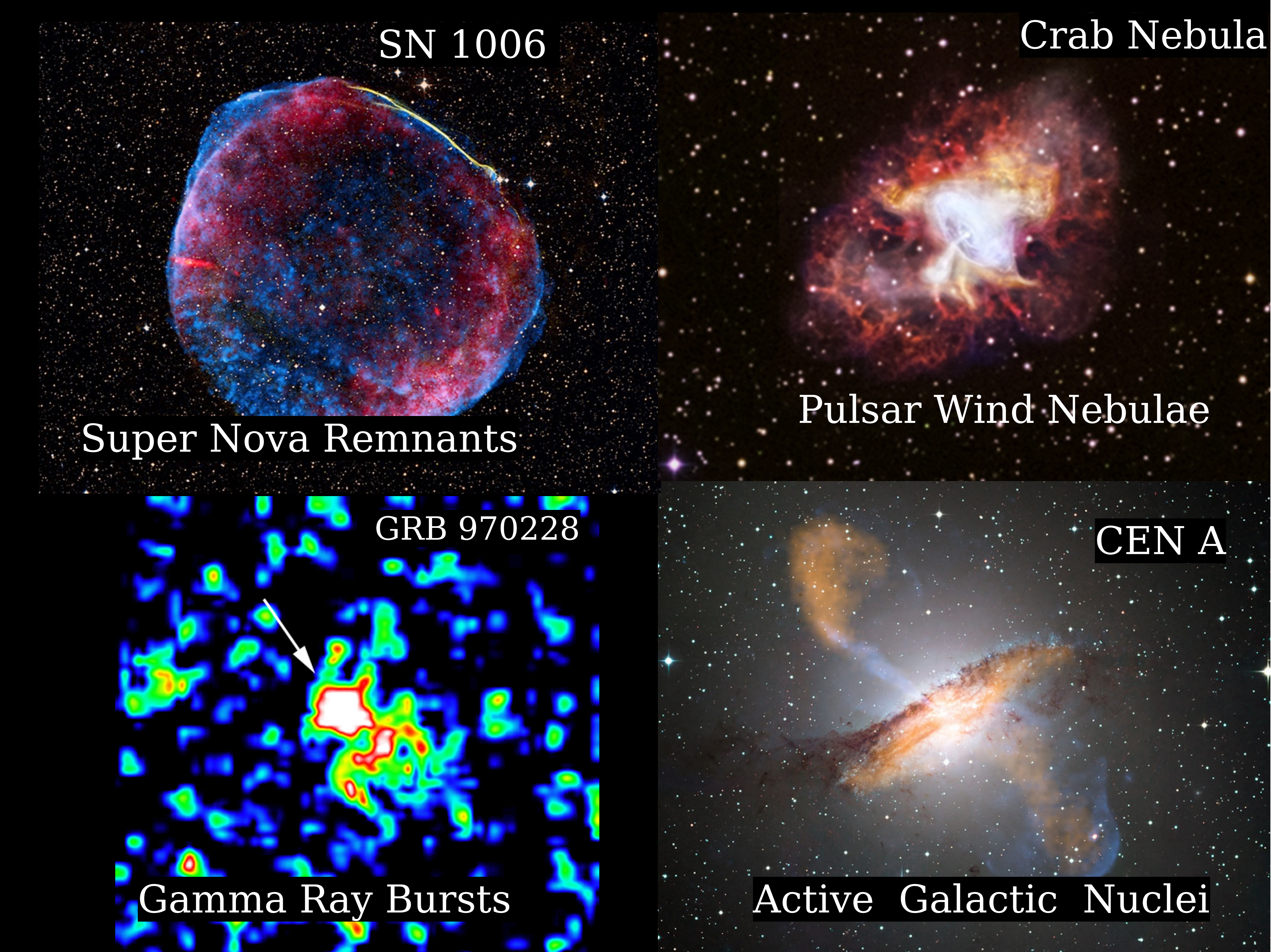
Firm identifications



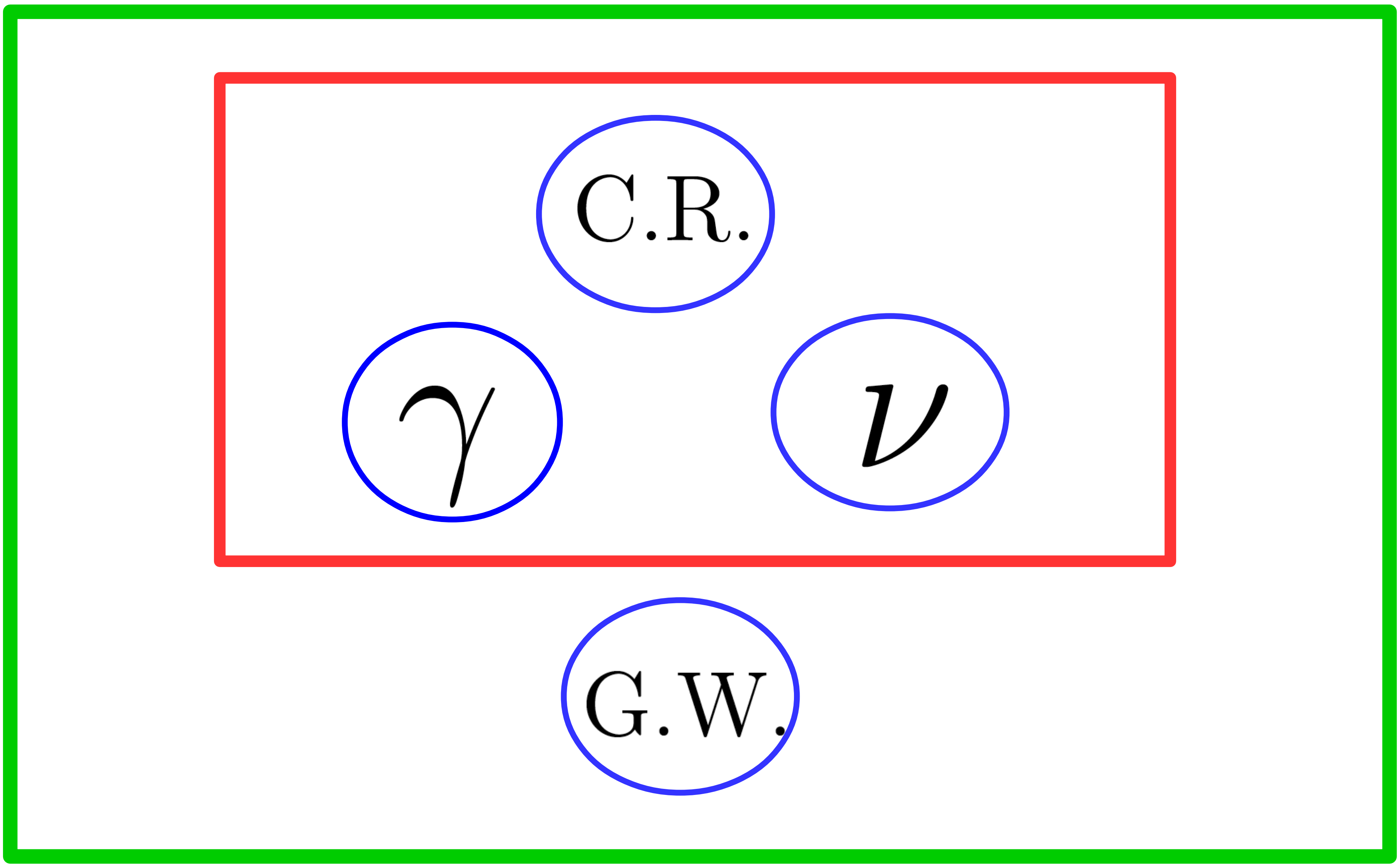
HESS survey of Galactic Plane [ICRC 2015] 77 “firm identifications”

Extraordinary beasts in the sky


SN 1006
Crab Nebula
GRB 970228
CEN A


SN 1006
Super Nova Remnants
Crab Nebula
Pulsar Wind Nebulae
GRB 970228
Gamma Ray Bursts
CEN A
Active Galactic Nuclei

Gravitational Waves Studies
Entering a new exciting era with LIGO/VIRGO



Sources are transients

[with a variety of time scales
from a small fraction of a second to thousands of years]

Associated to Compact Objects

Neutron stars,
Black Holes (stellar and Supermassive)

FORMATION of Compact Objects
(very large acceleration of very large masses)

Natural connection to Gravitational Waves

Sources are transients

[with a variety of time scales
from a small fraction of a second to thousands of years]

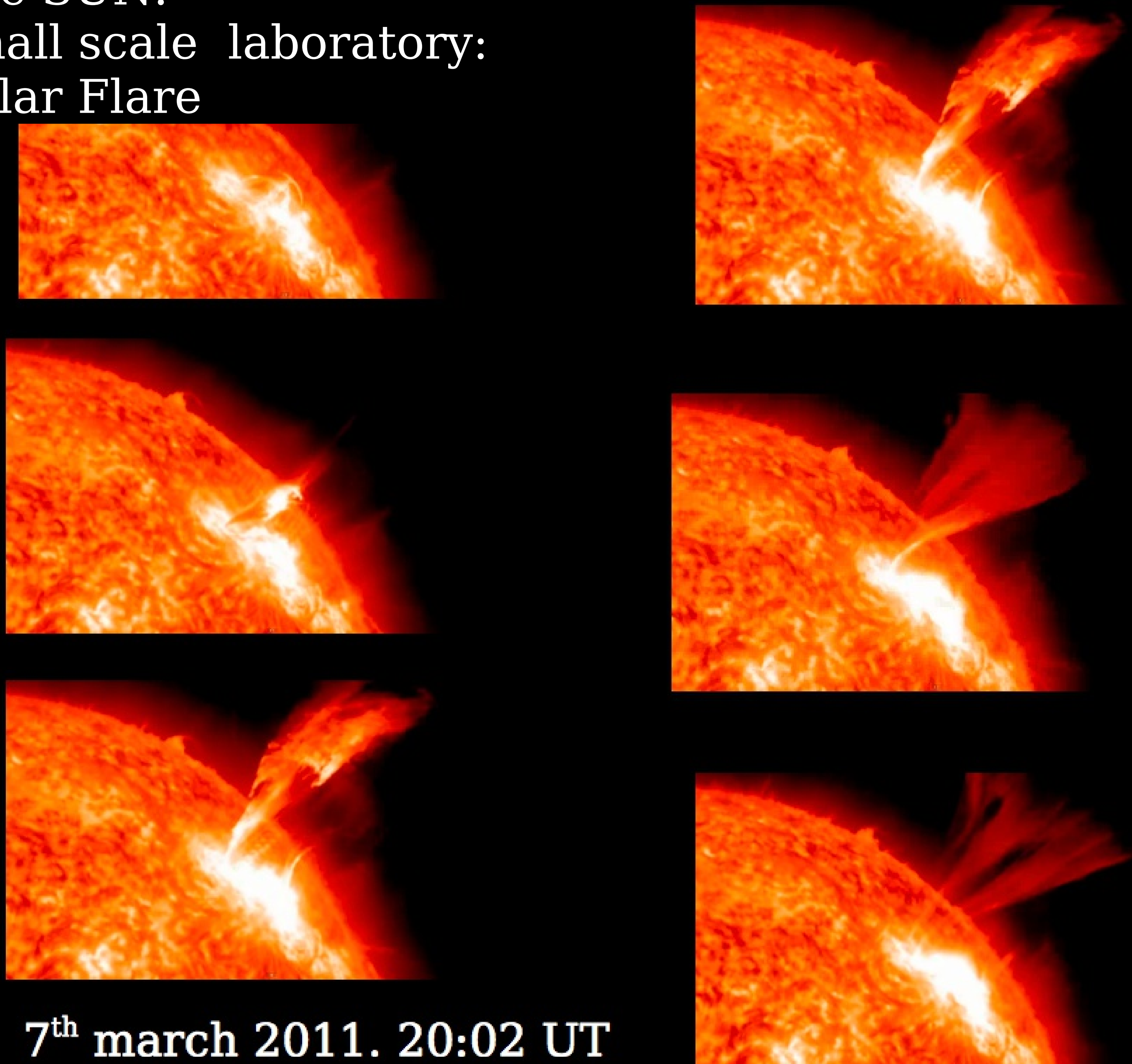
Associated to Compact Objects

Neutron stars,
Black Holes (stellar and Supermassive)

FORMATION of Compact Objects
(very large acceleration of very large masses)

Natural connection to Gravitational Waves

The SUN:
small scale laboratory:
Solar Flare



Aurora detected
in Canada same night

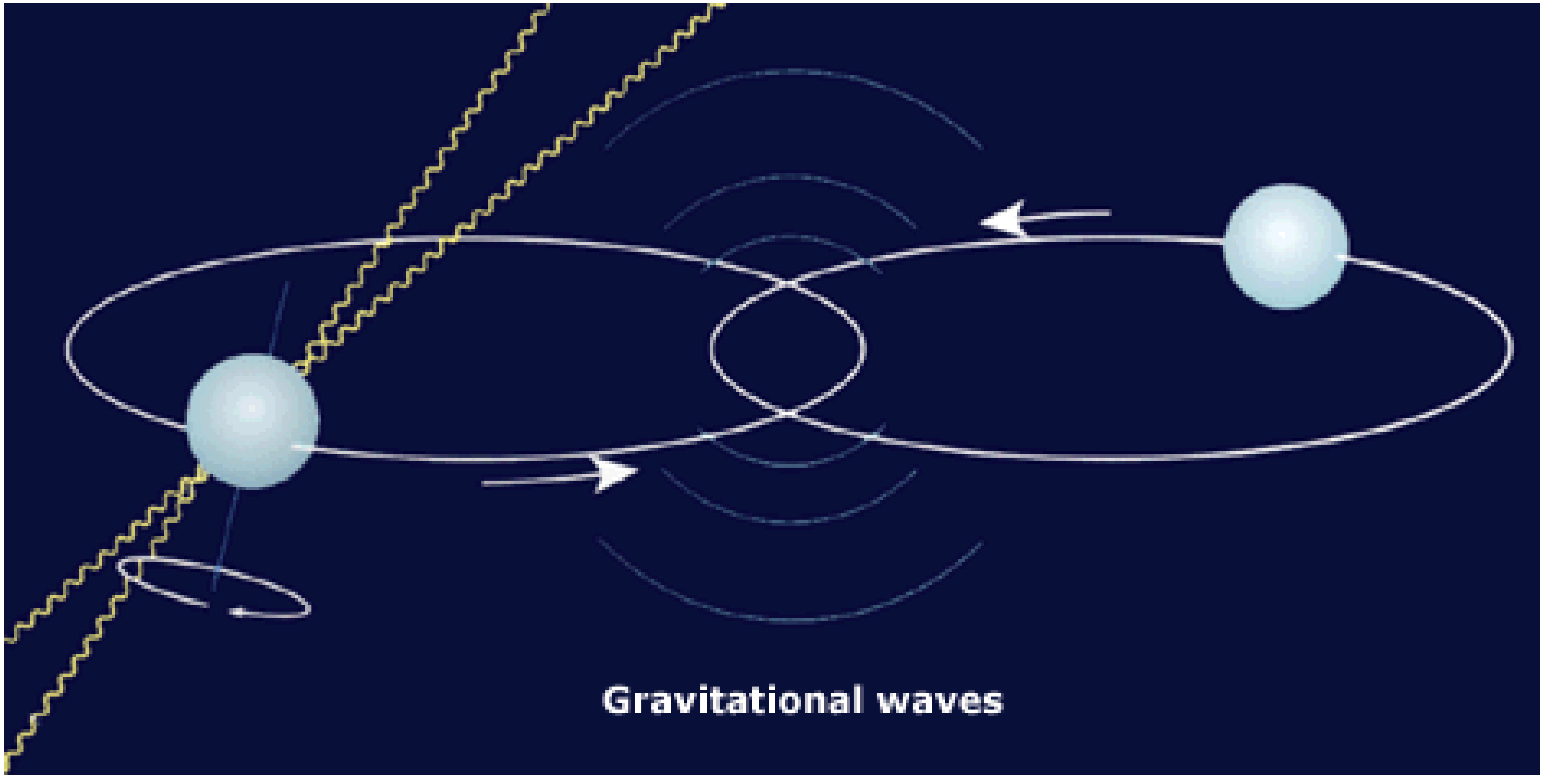
Binary Pulsars
(PSR 1913+16)
(discovery Hulse & Taylor (1978)
(Nobel prize 1993)
[Pulsar 17 rotation/second]

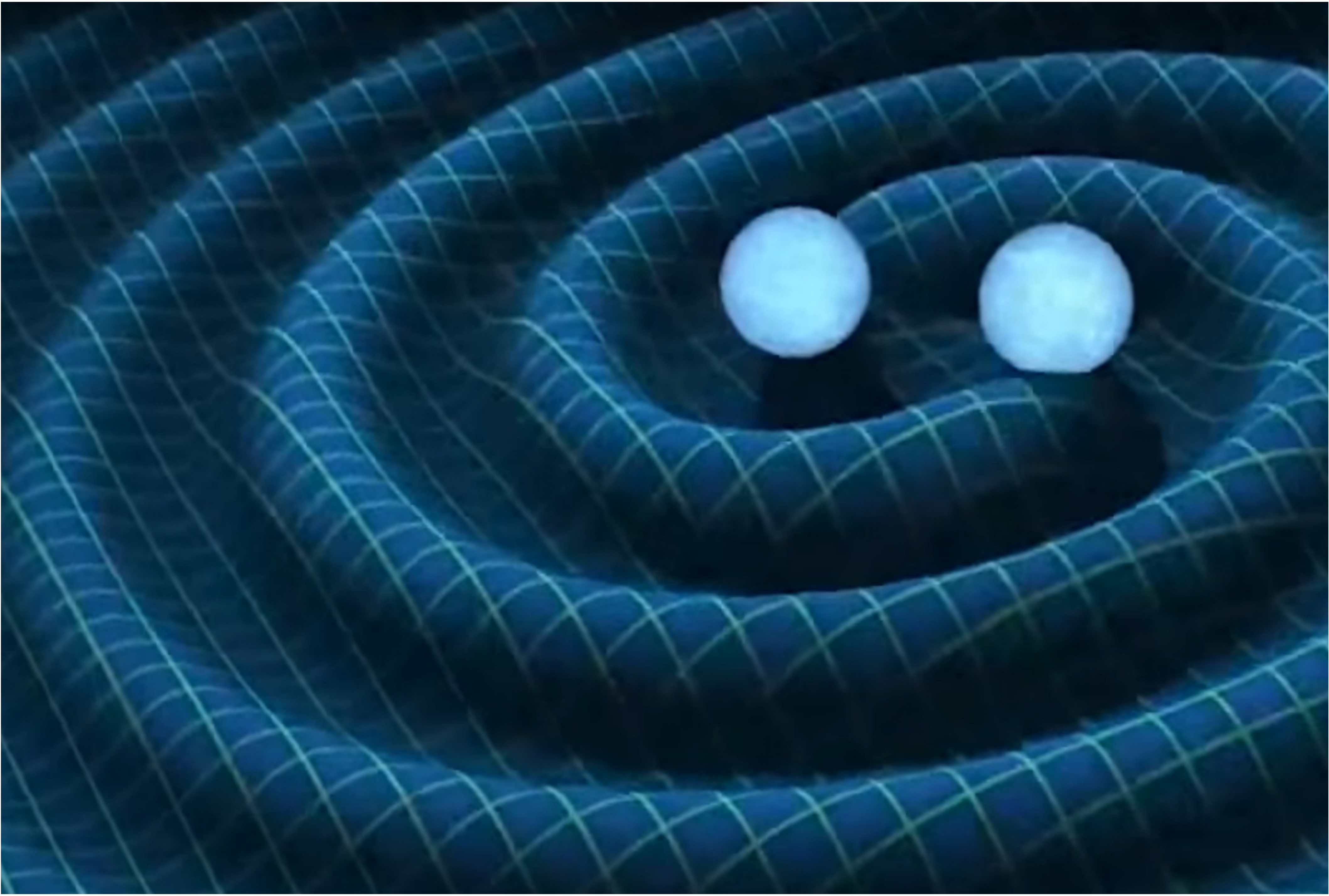
300 Myr
two neutron star coalesce

Orbit : 1.1 – 4.8 solar radii

Rotation period 7.75 hours
Period shorter
76.5 microsecond/year

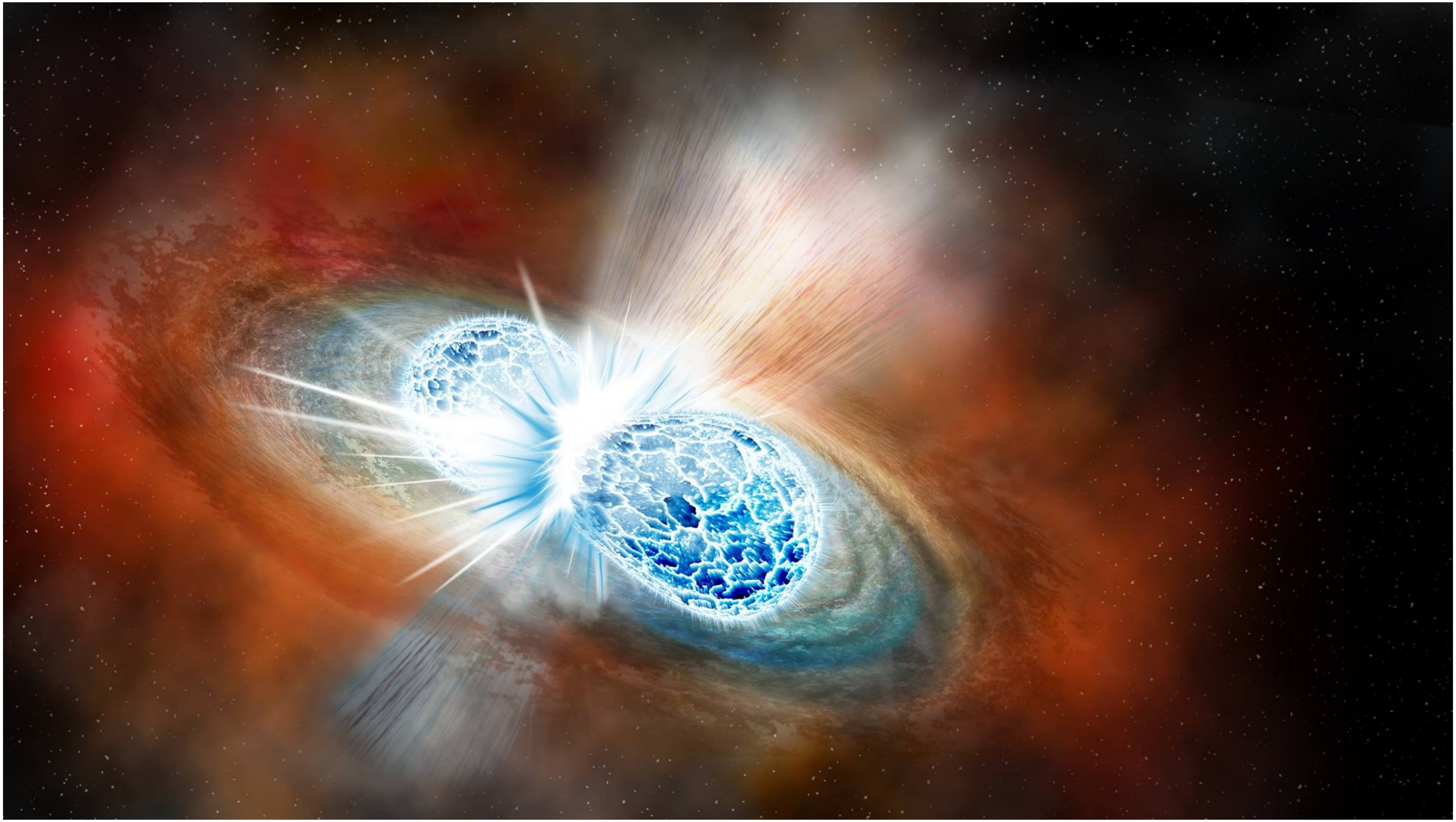
Orbit smaller
3.5 m/year

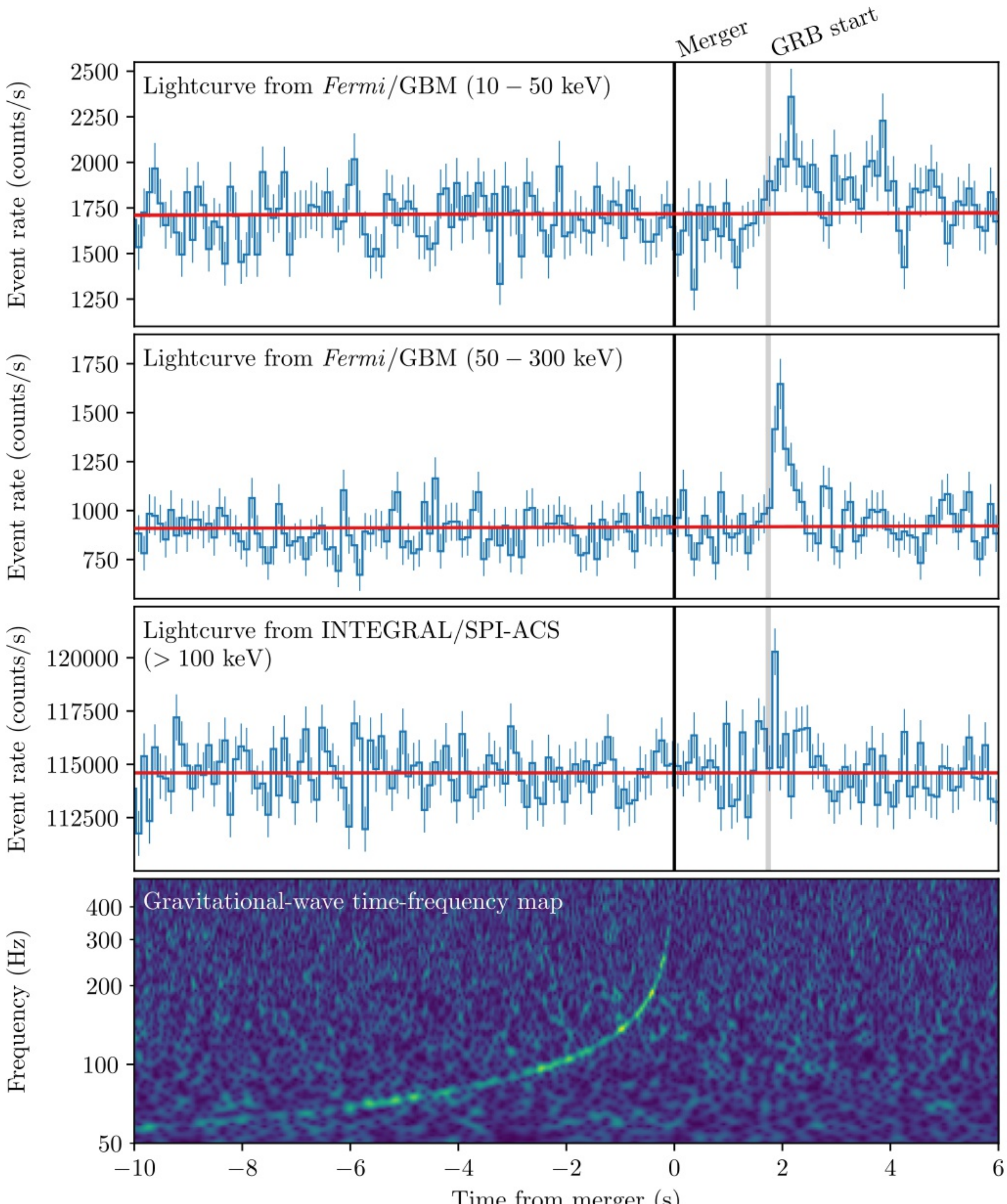




“Analogy”

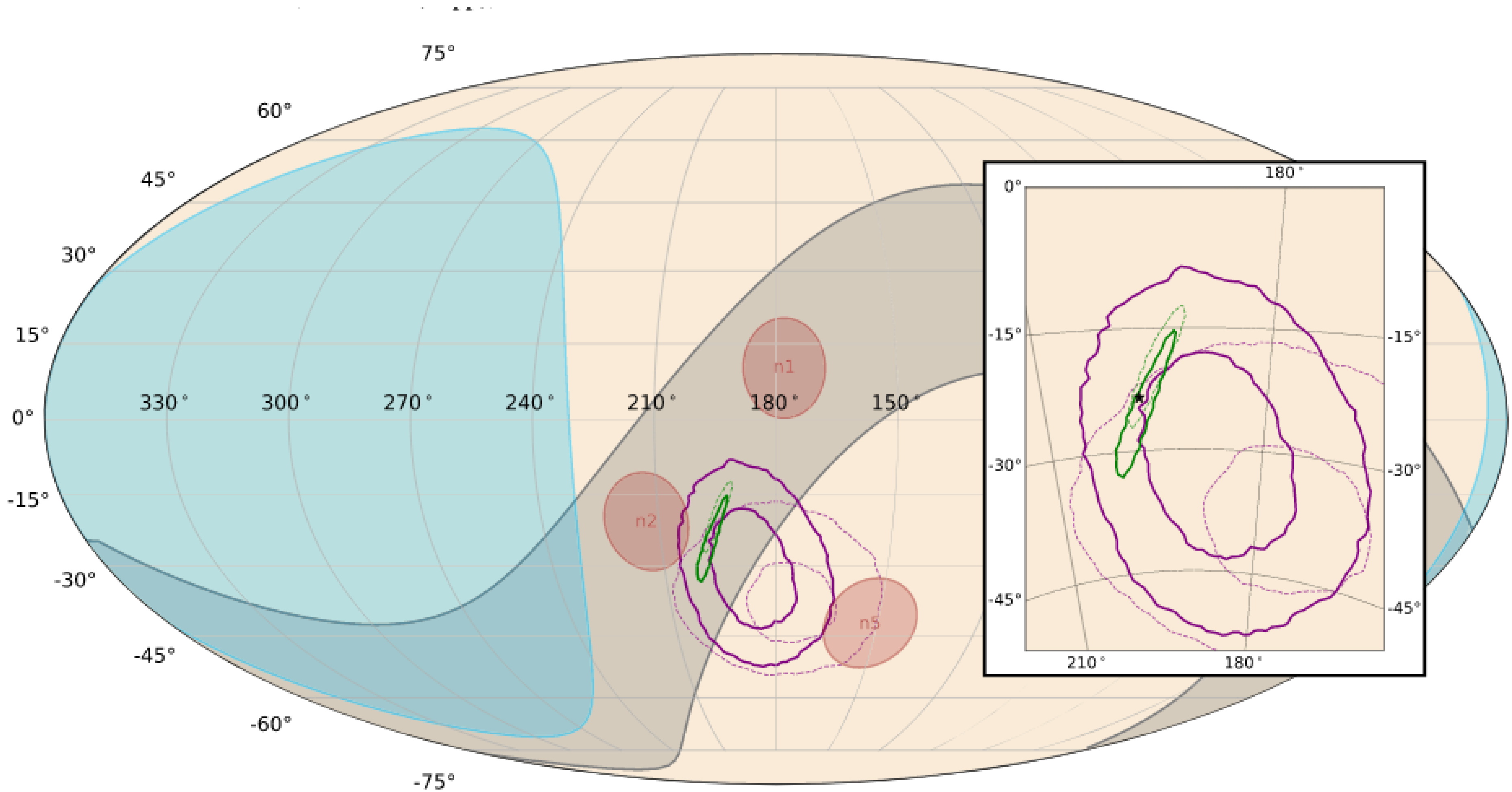
On a very different scale ……   GW 170817



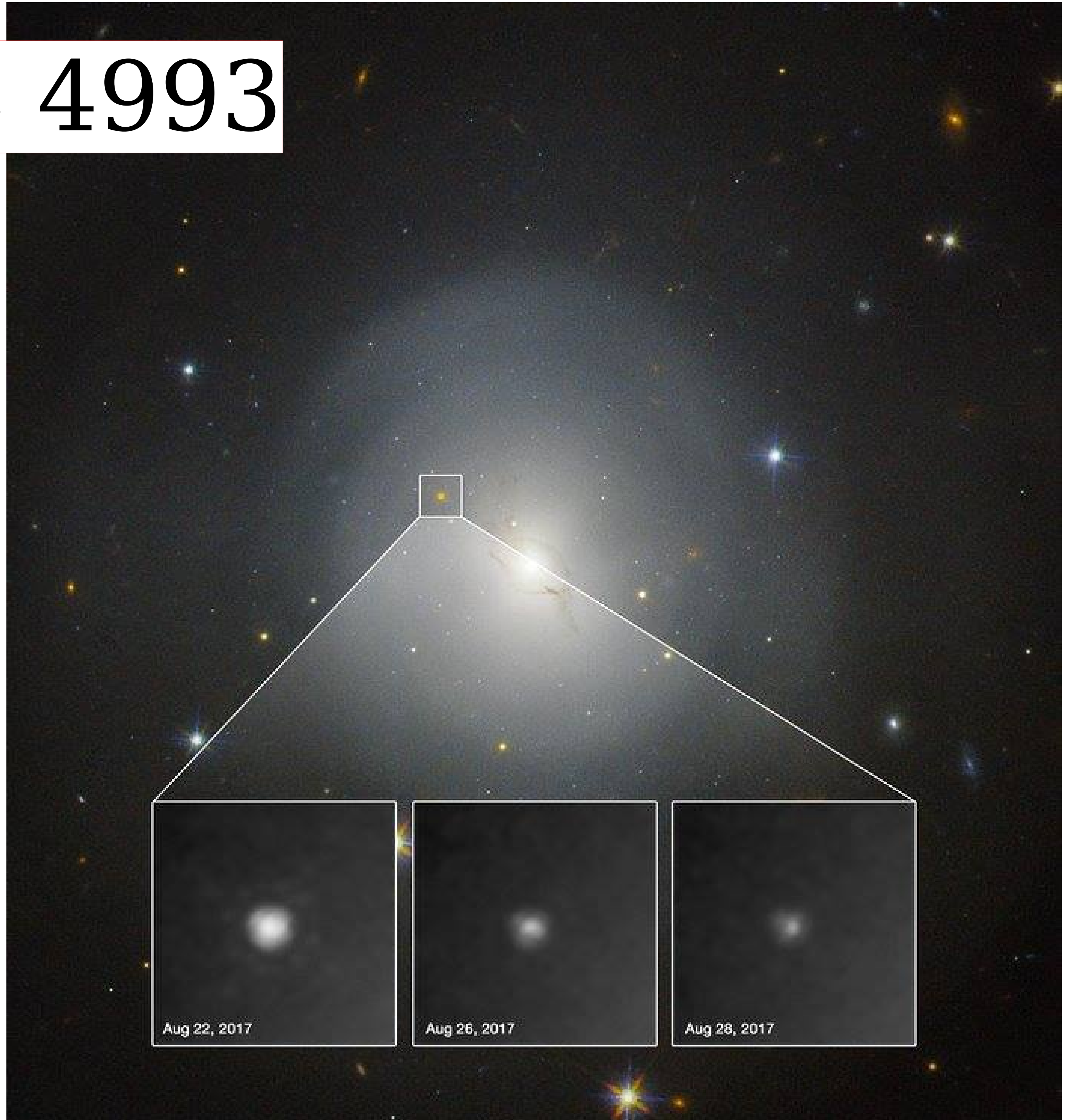


GRB 170817A

GW 170817


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
330°
300°
270°
240°
210°
180°
150°
n1
n2
n5
0°
180°
-15°
-30°
-45°
210°
180°

NGC 4993



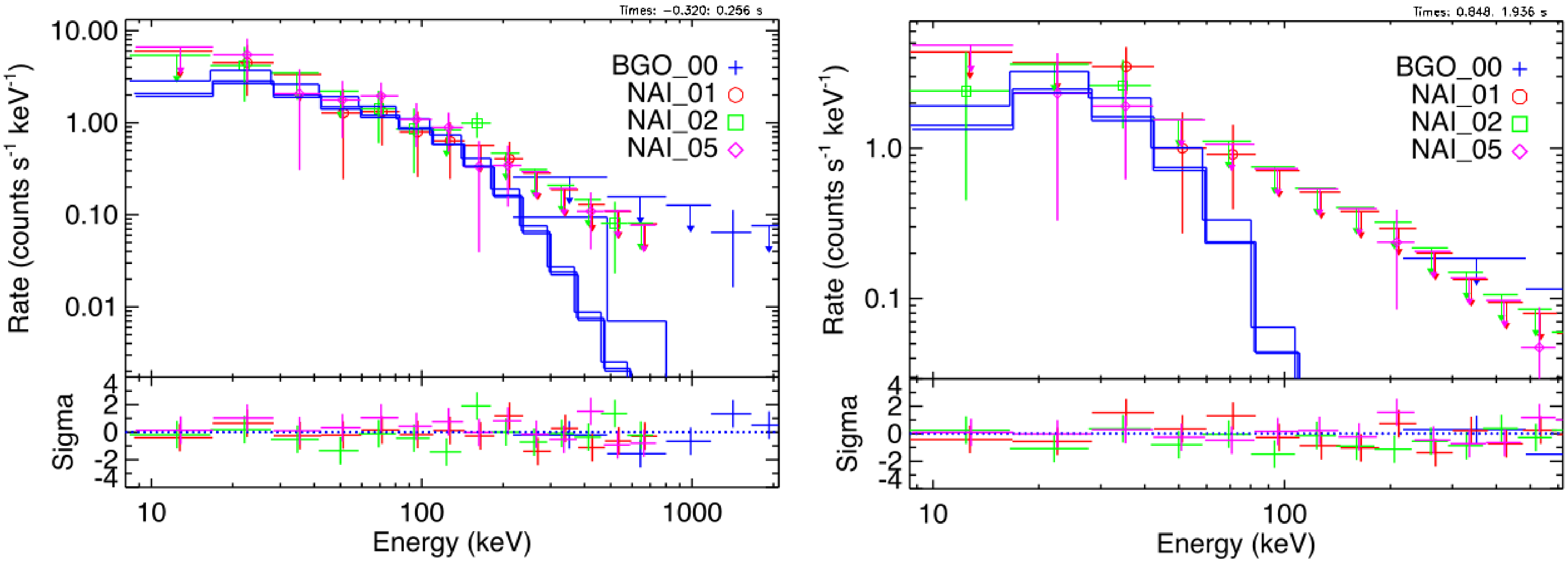
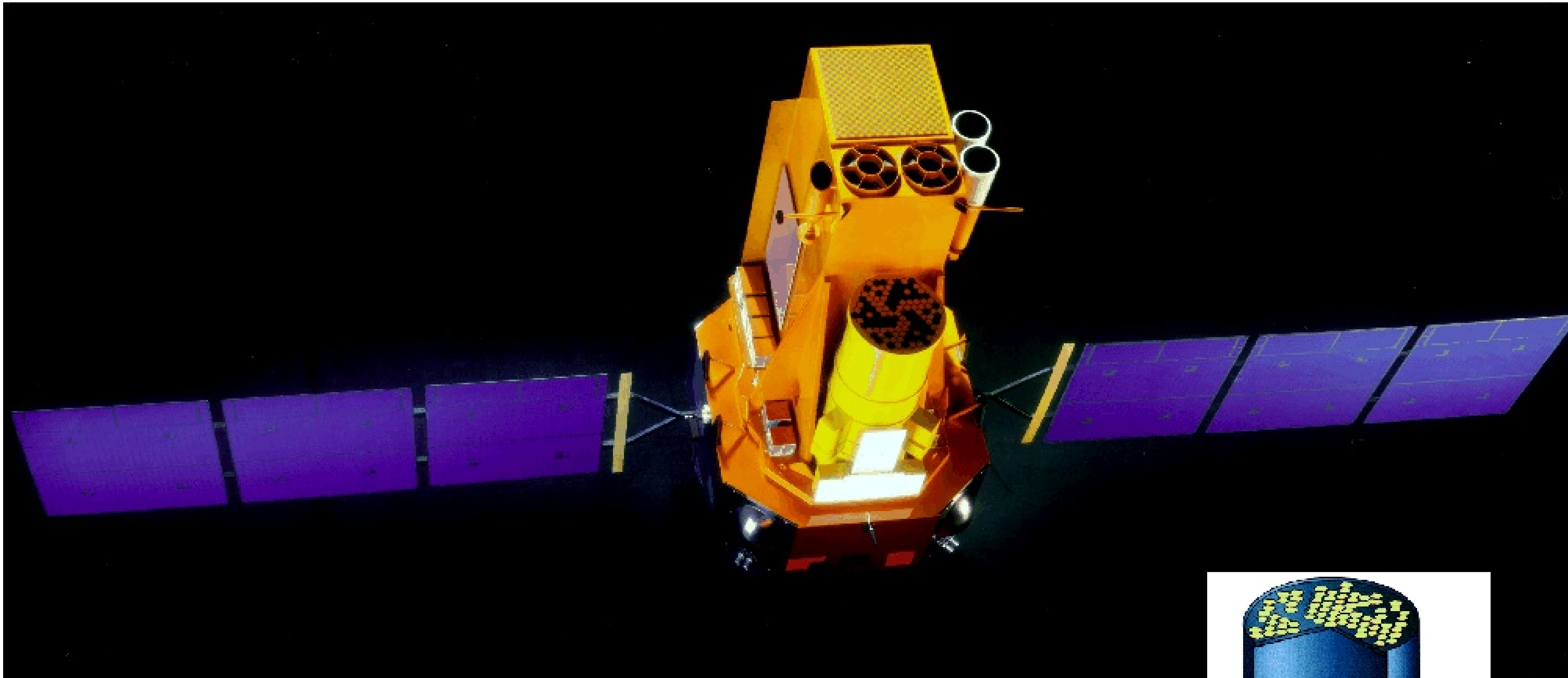
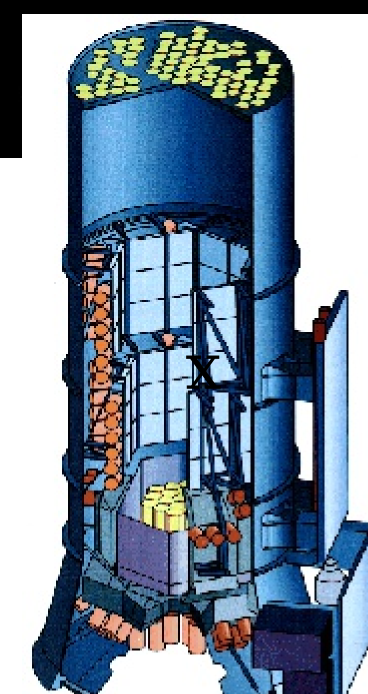
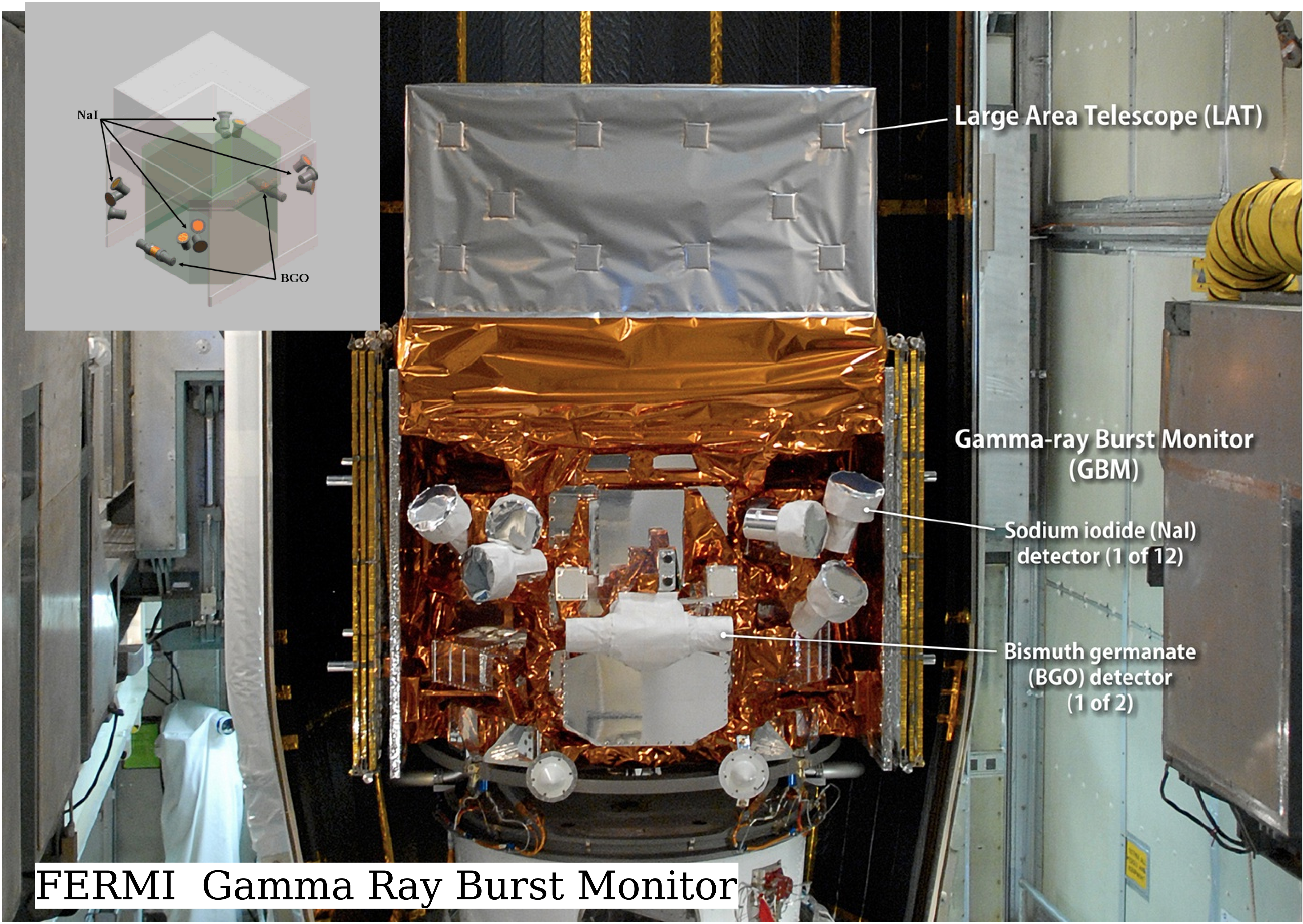


Figure 8. Spectral fits of the count rate spectrum for the (left) main pulse (Comptonized) and (right) softer emission (blackbody). The blue bins are the forward-folded model fit to the count rate spectrum, the data points are colored based on the detector, and 2σ upper limits estimated from the model variance are shown as downward-pointing arrows. The residuals are shown in the lower subpanels.

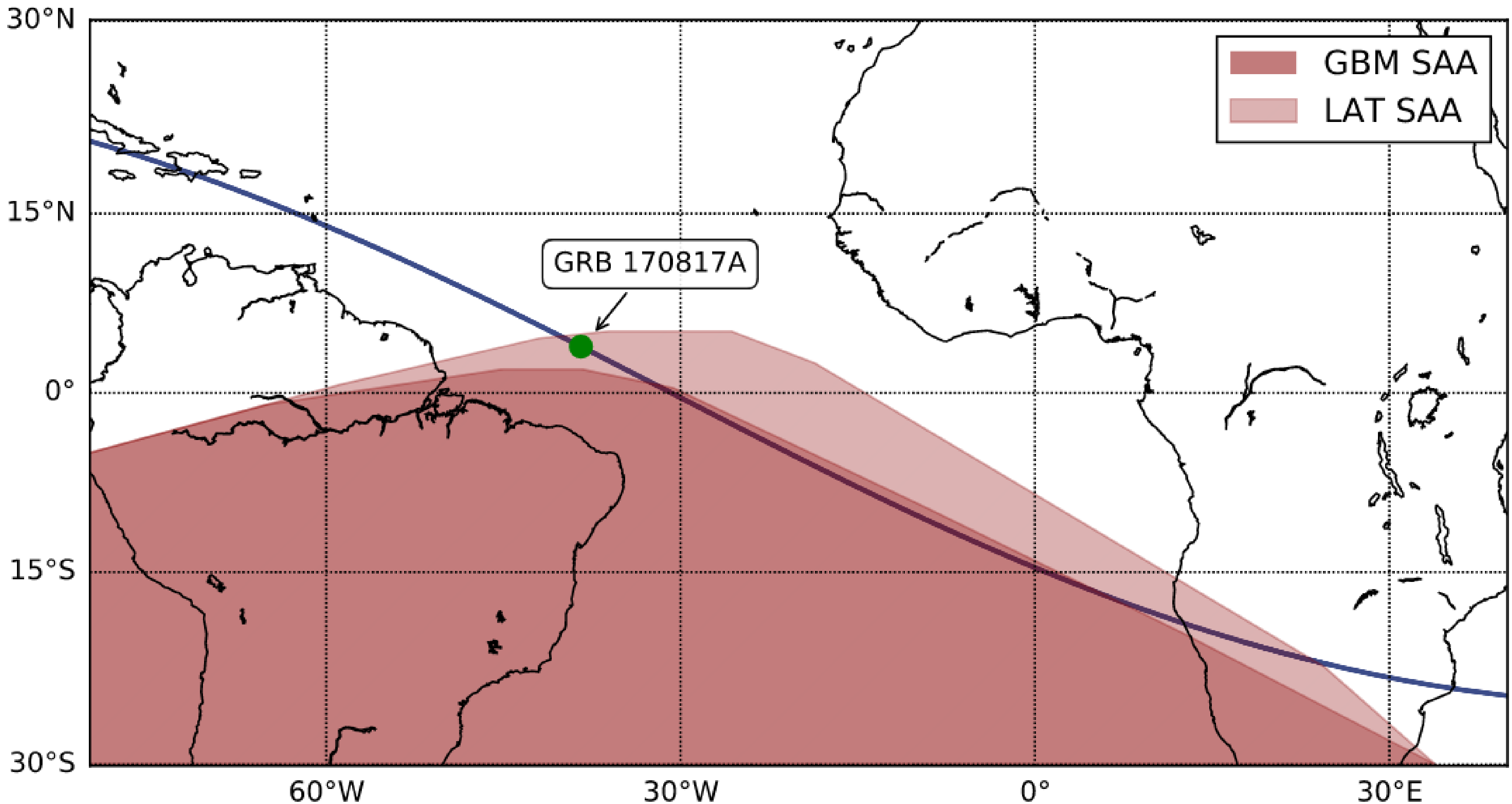




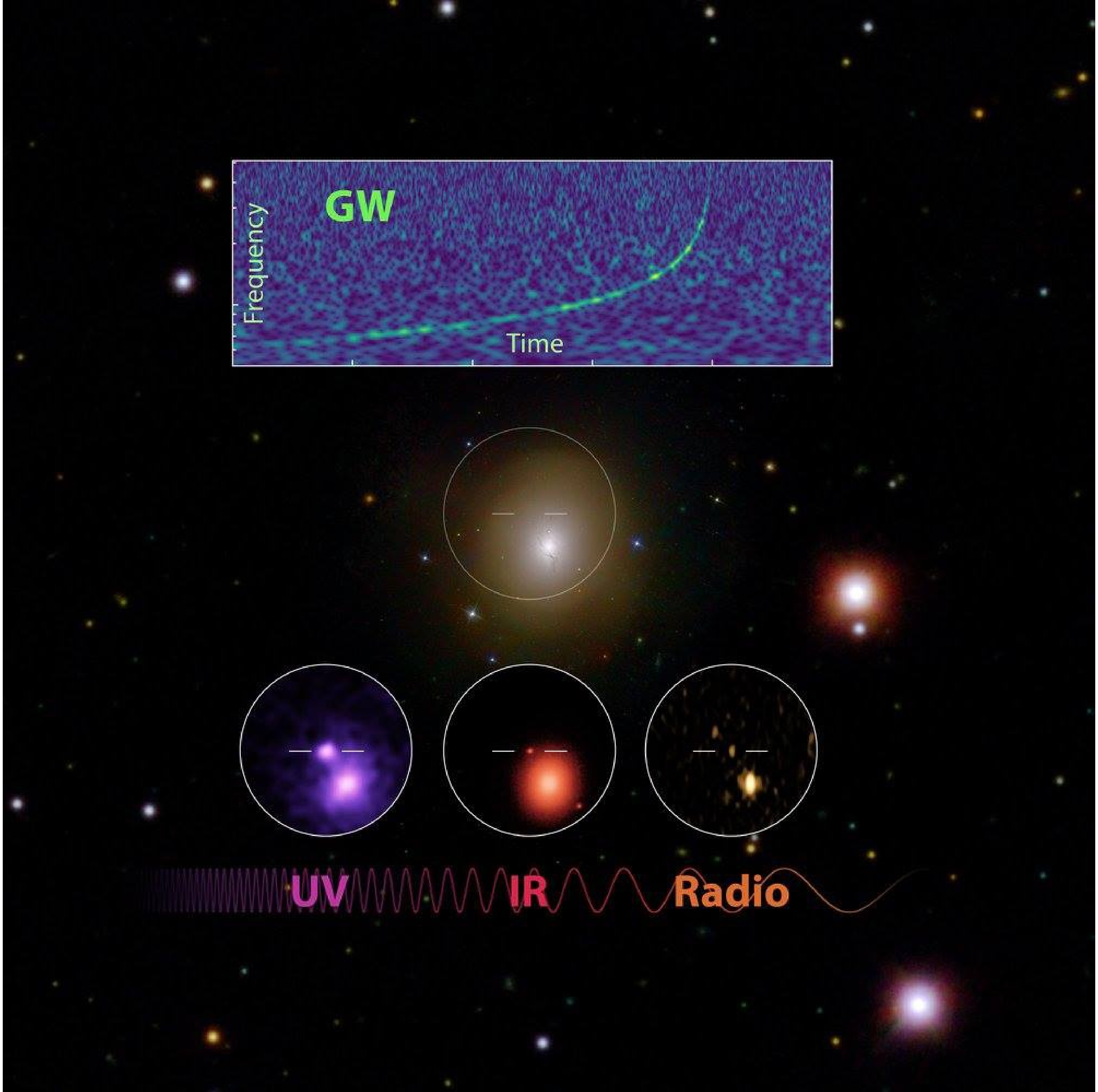
INTEGRAL
SPI-ADC



FERMI Gamma Ray Burst Monitor



30°N
15°N
0°
15°S
30°S
60°W
30°W
0°
30°E
GRB 170817A
GBM SAA
LAT SAA


GW
Frequency
Time
UV
IR
Radio

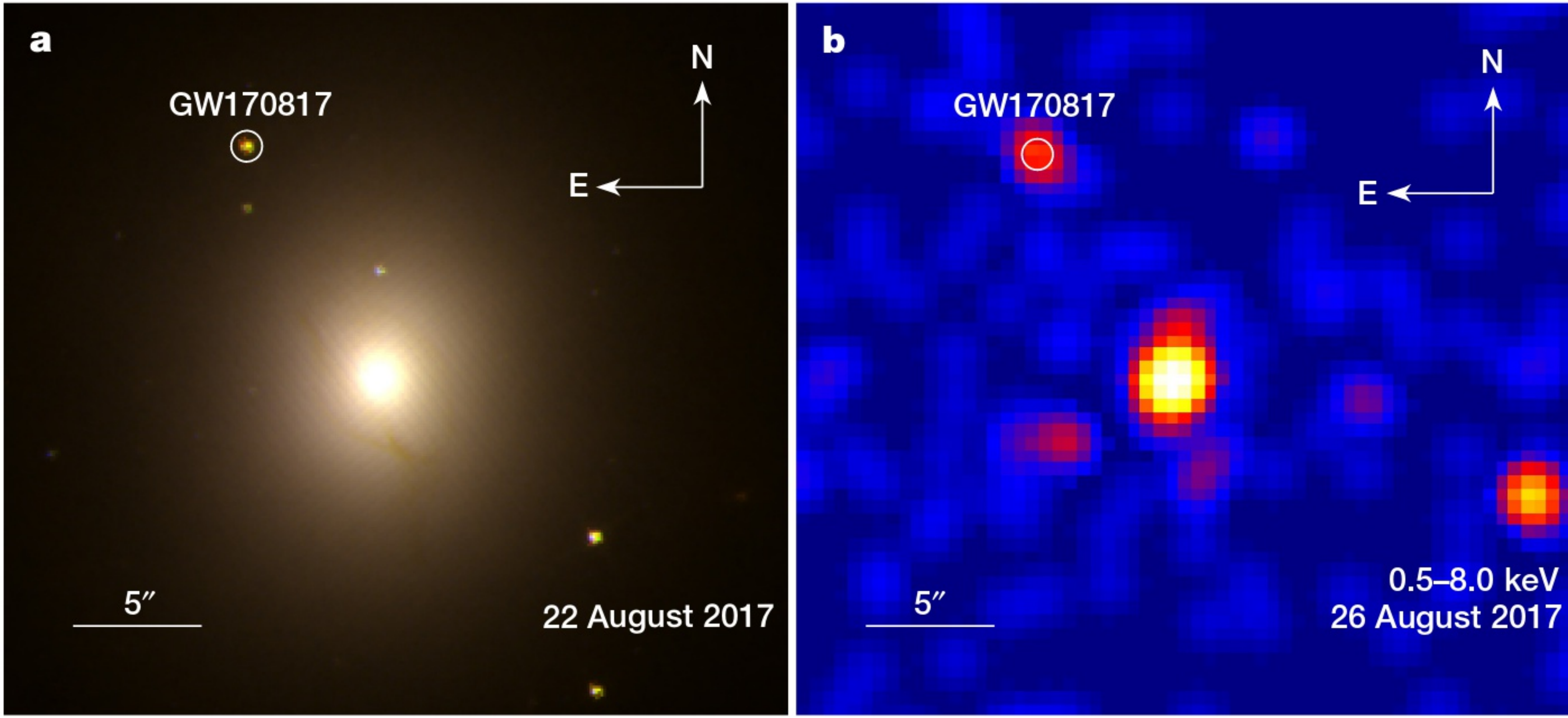
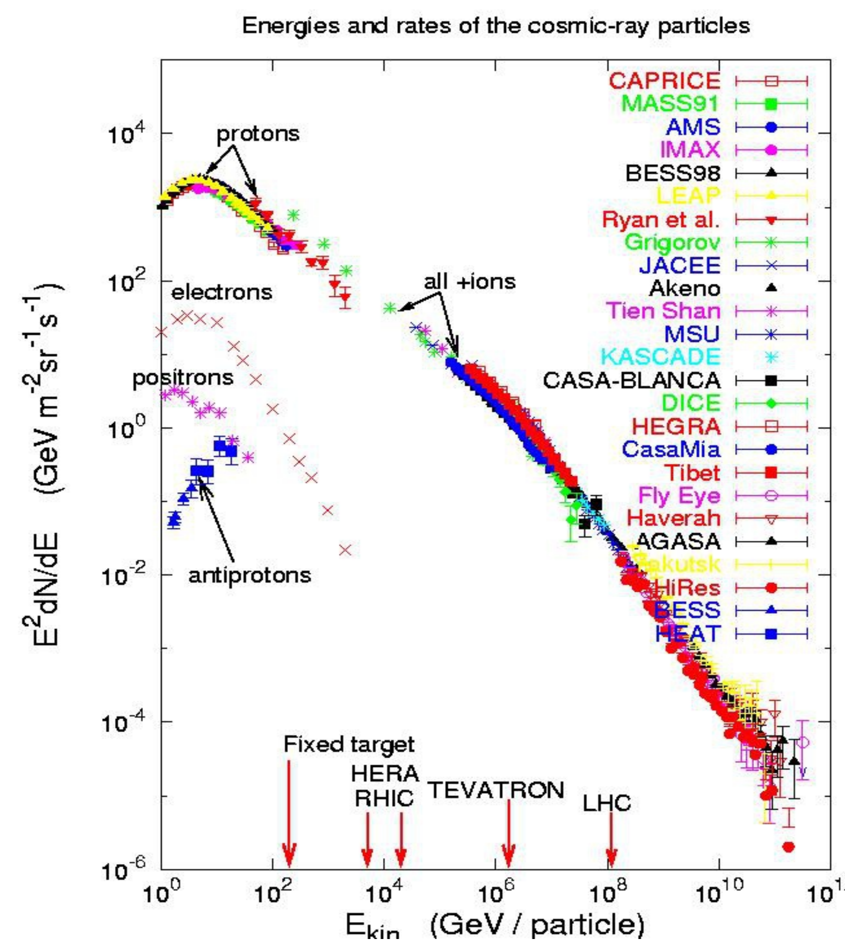


Figure 1 | Optical/infrared and X-ray images of the counterpart of GW170817. a, Hubble Space Telescope observations show a bright and red transient in the early-type galaxy NGC 4993, at a projected physical offset of about 2 kpc from its nucleus. A similar small offset is observed in less than a quarter of short GRBs[5]. Dust lanes are visible in the inner regions, suggestive of a past merger activity (see Methods). **b**, Chandra observations revealed a faint X-ray source at the position of the optical/infrared transient. X-ray emission from the galaxy nucleus is also visible.

Cosmic Rays

Discovery of Cosmic Rays
beginning of
High Energy Astrophysics

Victor Hess
before the balloon flight of 1912



Observations at the beginning of 1900

Discharge of electroscopes

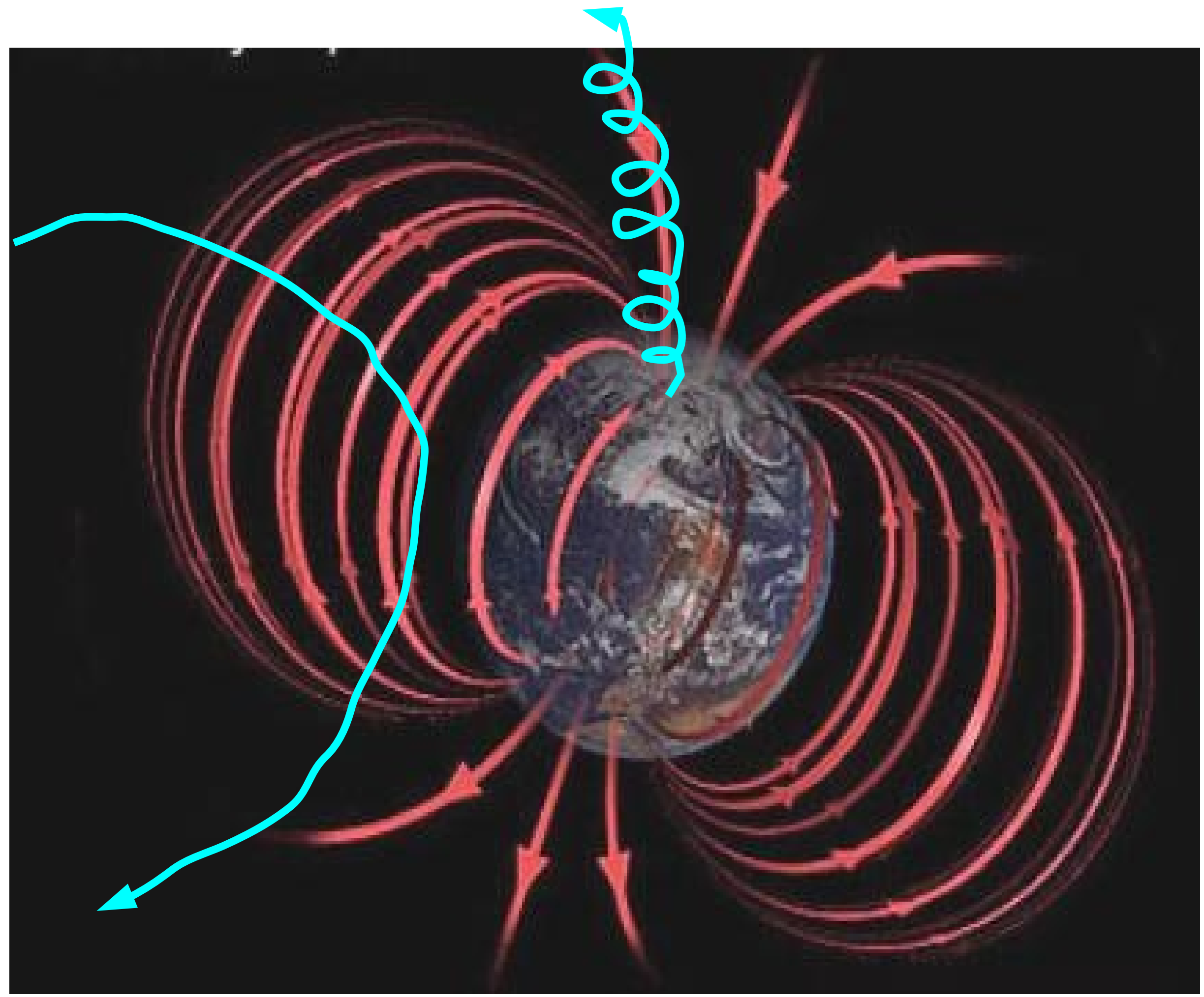
Why electroscopes are discharged ?
Existence of IONIZING RADIATION

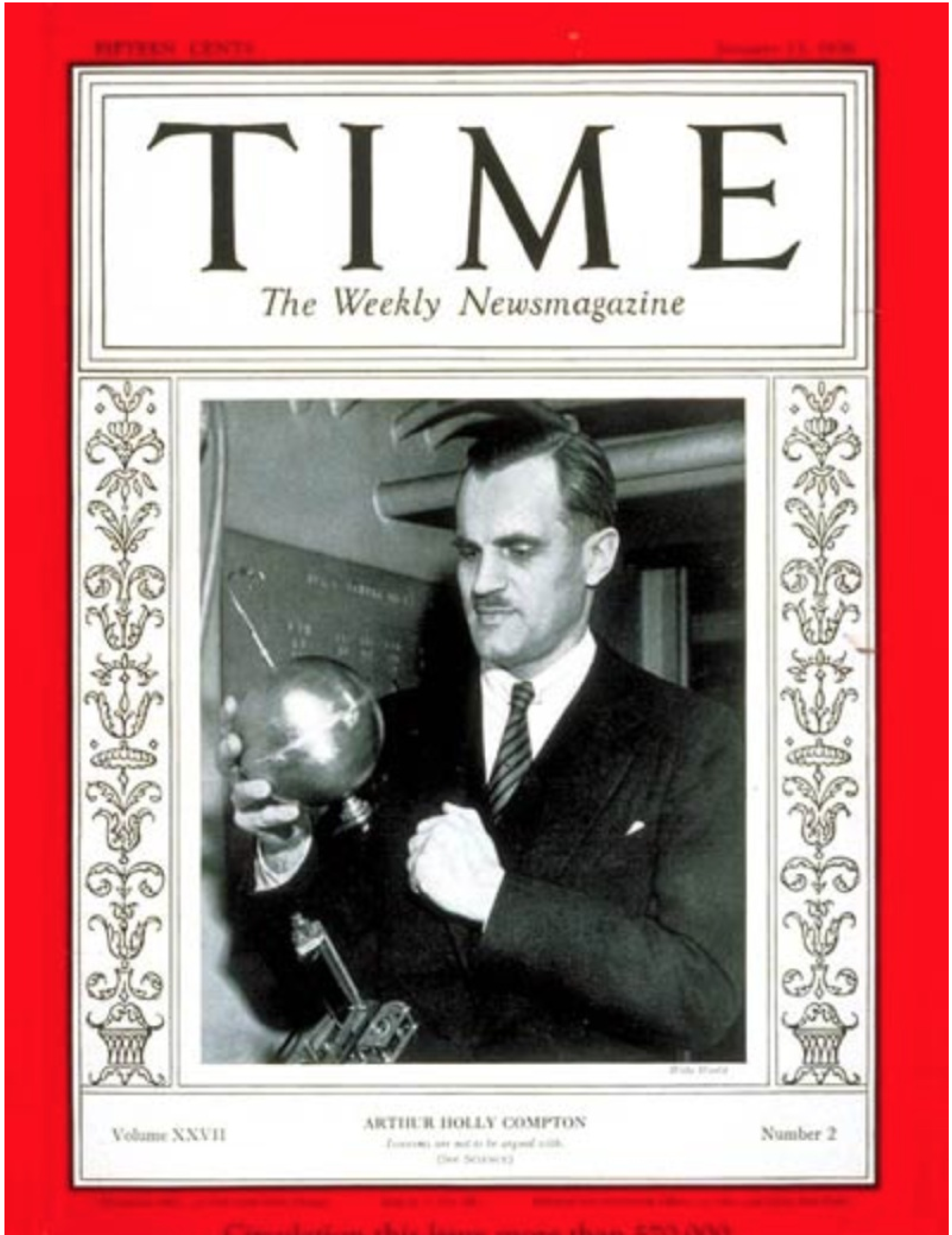
From where the ionization radiation is coming ?
Radioactivity is the natural explanation.

1896 Bequerel discovers radioactivity in Uranium
1898 – 1900 Pierre and Marie Curie, E Rutherford …

Relativistic charged particles. [Latitude effect]

Mostly protons (+ ionized nuclei) [East-West effect]





Arthur Compton

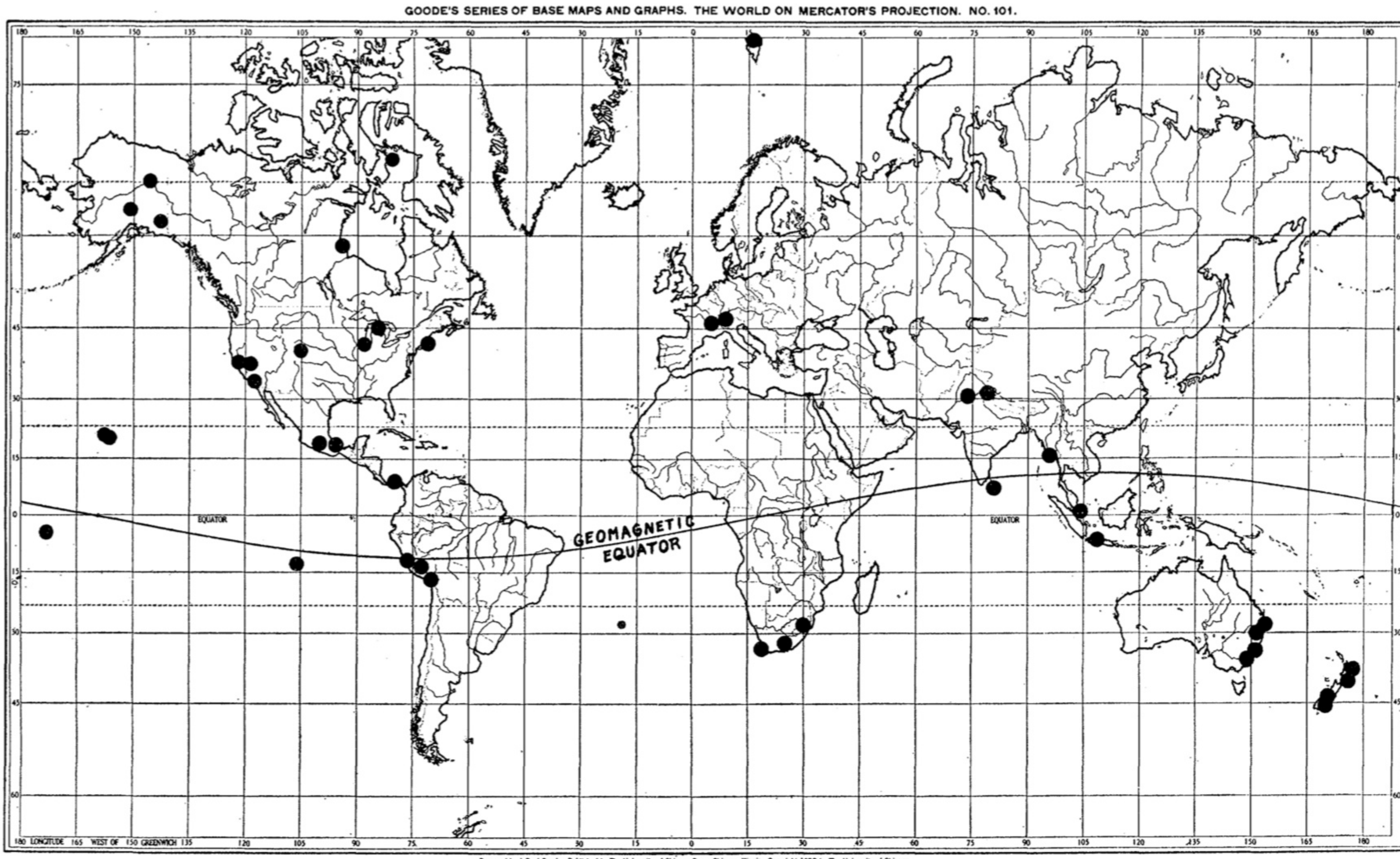


FIG. 1. Map showing location of our major stations for observing cosmic rays.

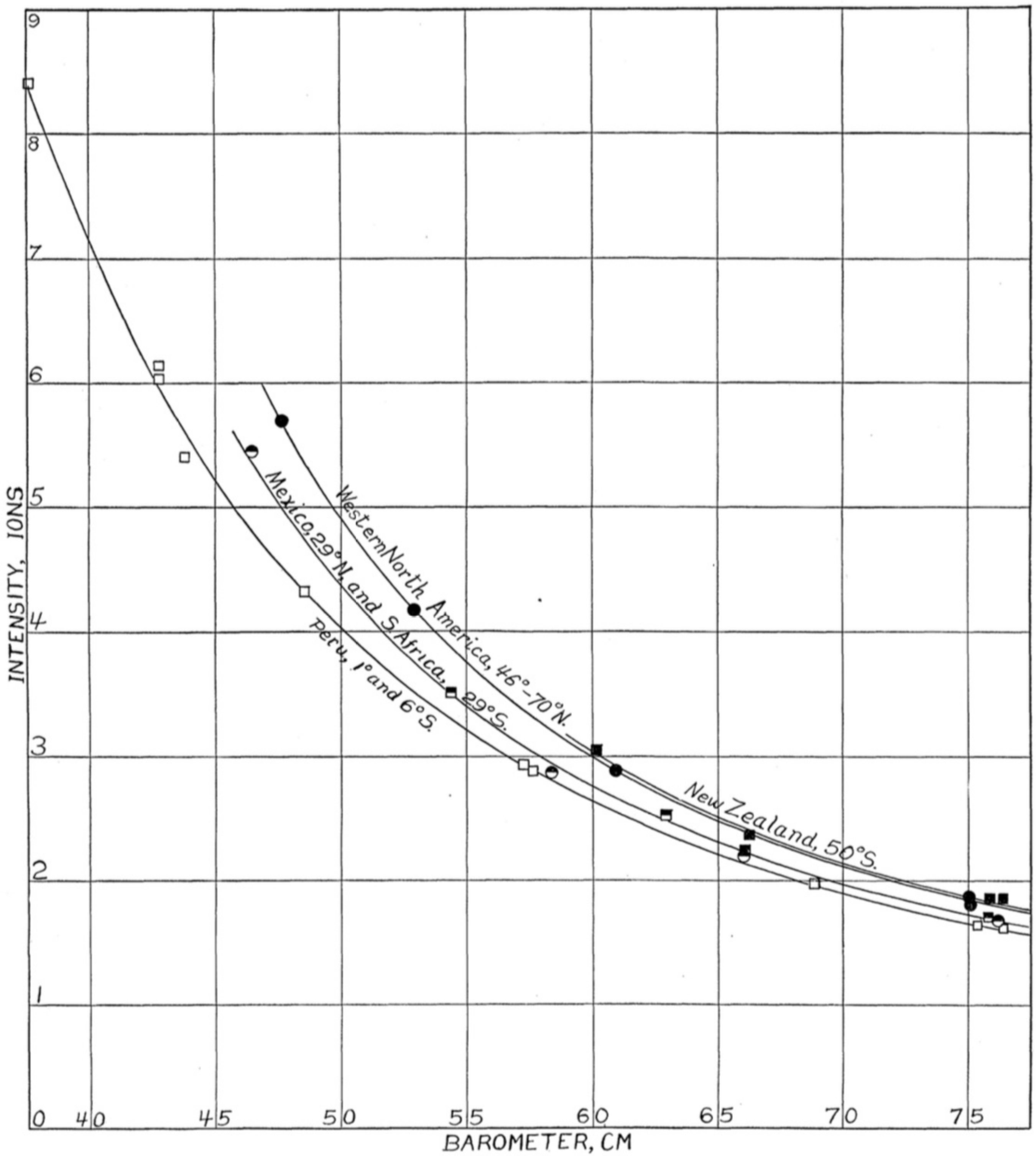


FIG. 5. Typical intensity *vs.* altitude curves for various latitudes.

A Geographic Study of Cosmic Rays

ARTHUR H. COMPTON, *University of Chicago*

(Received January 30, 1933)

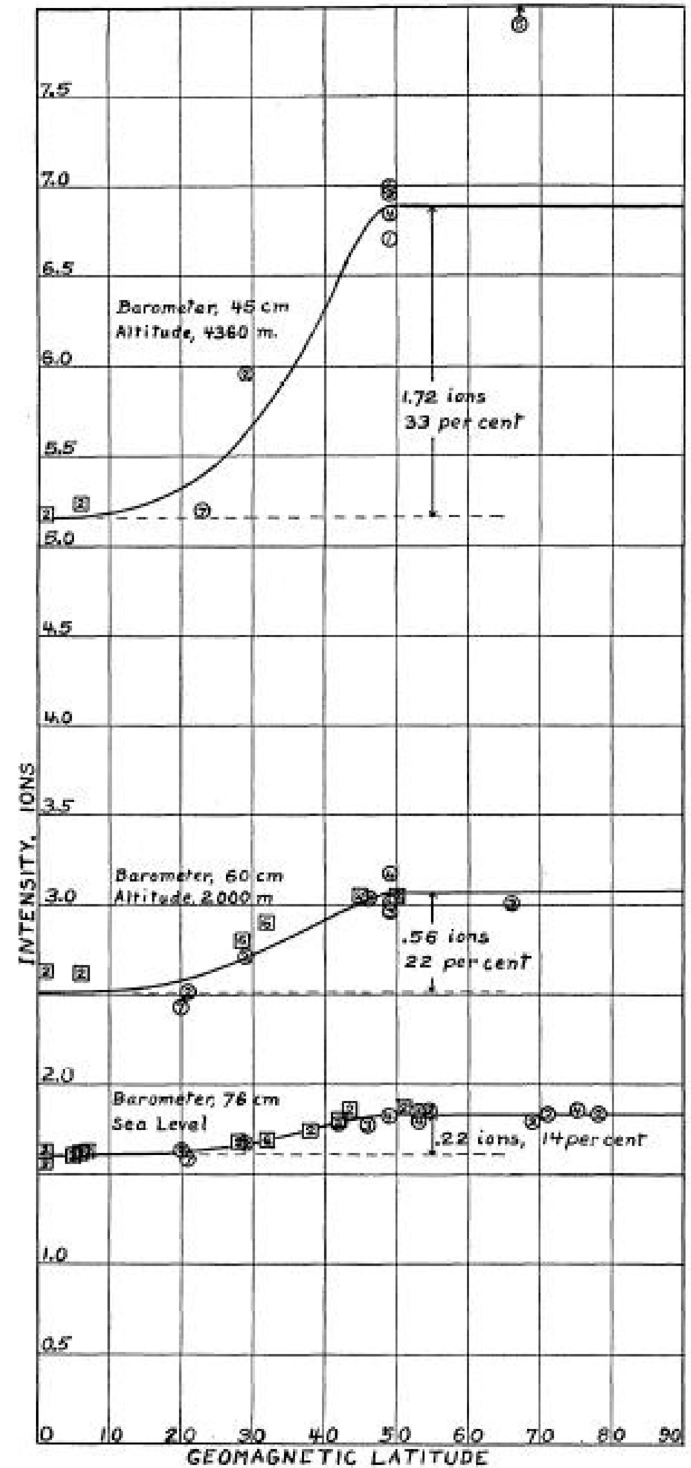
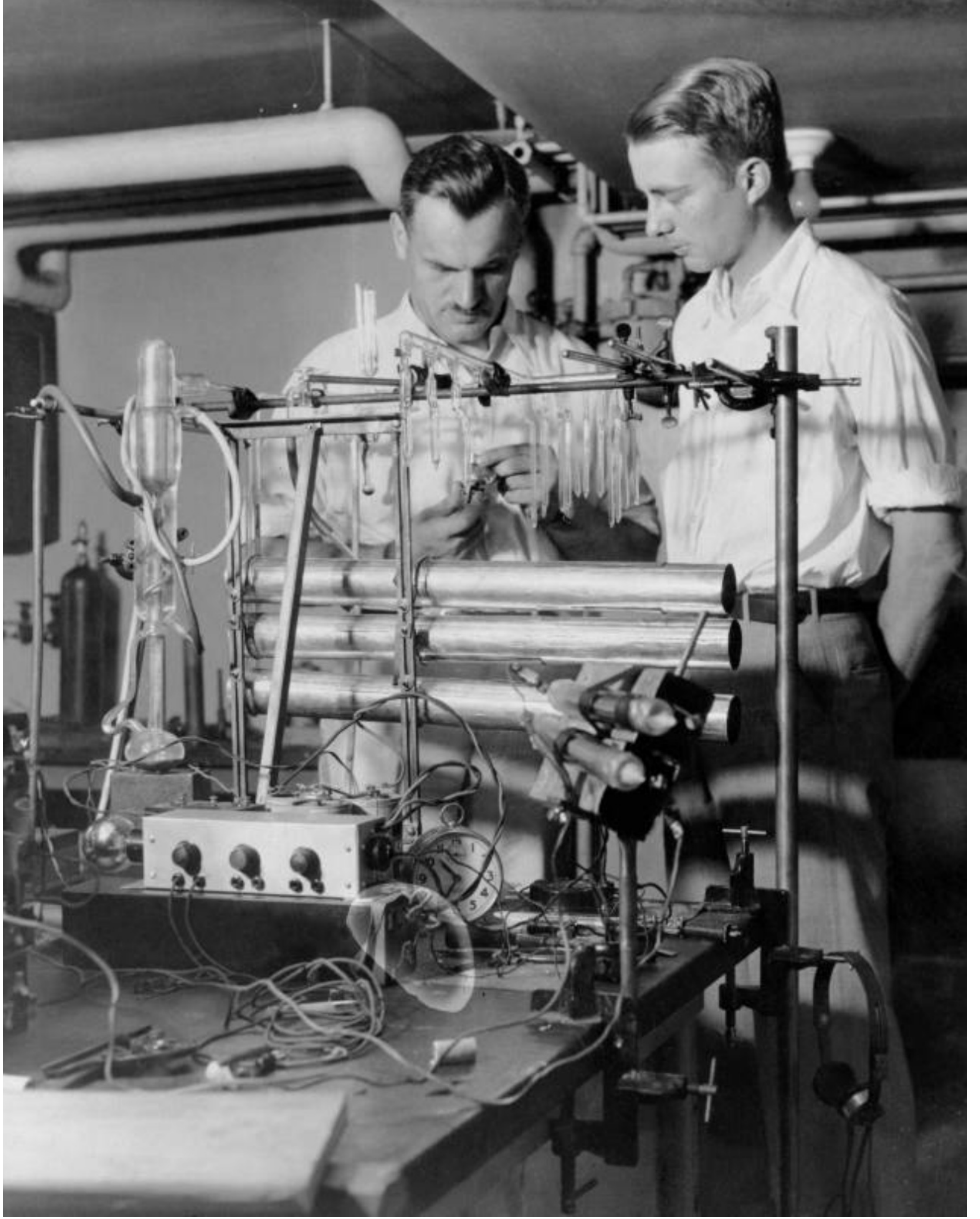


FIG. 6. Intensity *vs.* geomagnetic latitude for different elevations.

LATITUDE EFFECT

Arthur Compton

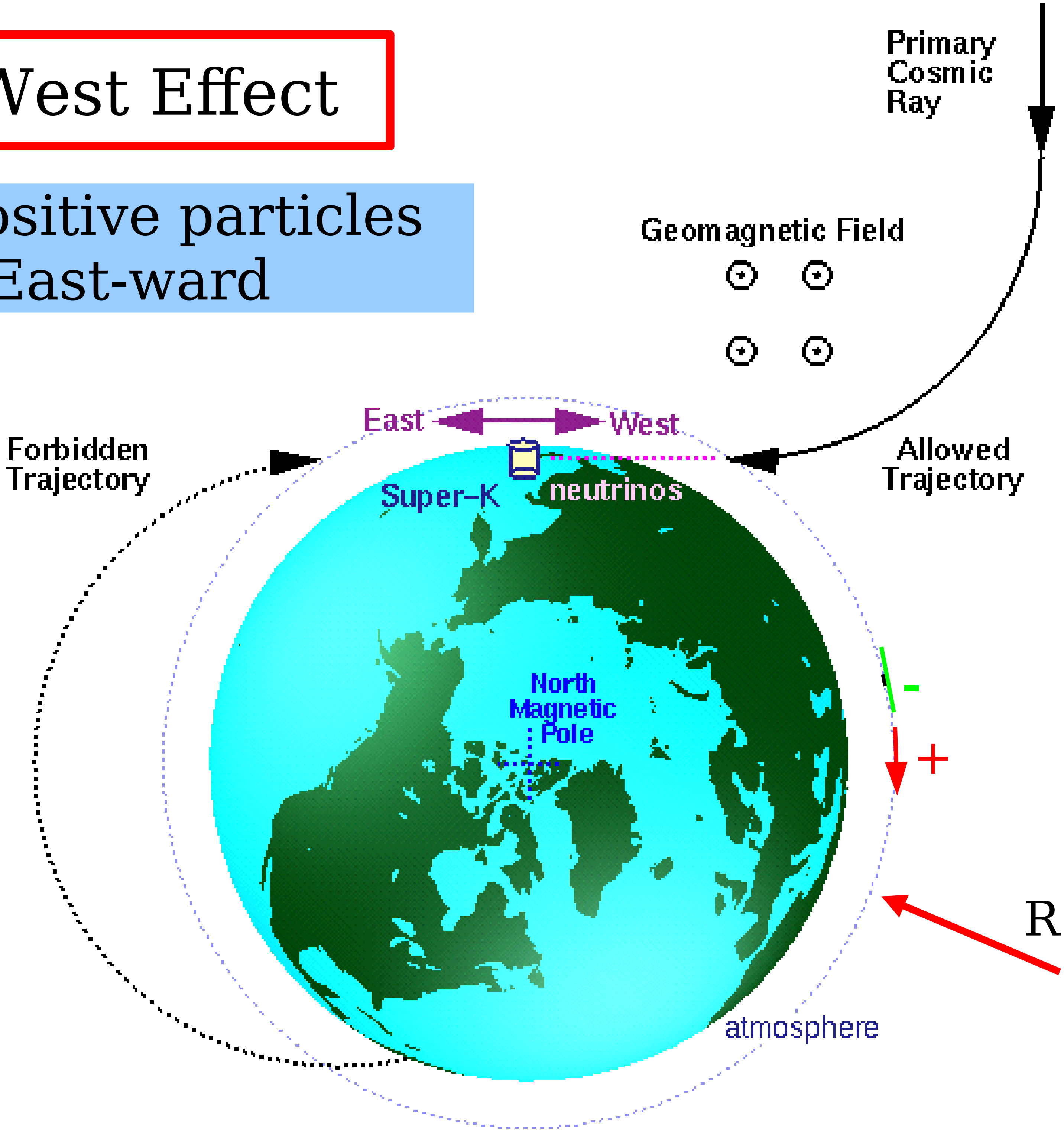
Luis Alvarez



East-West effect

East-West Effect

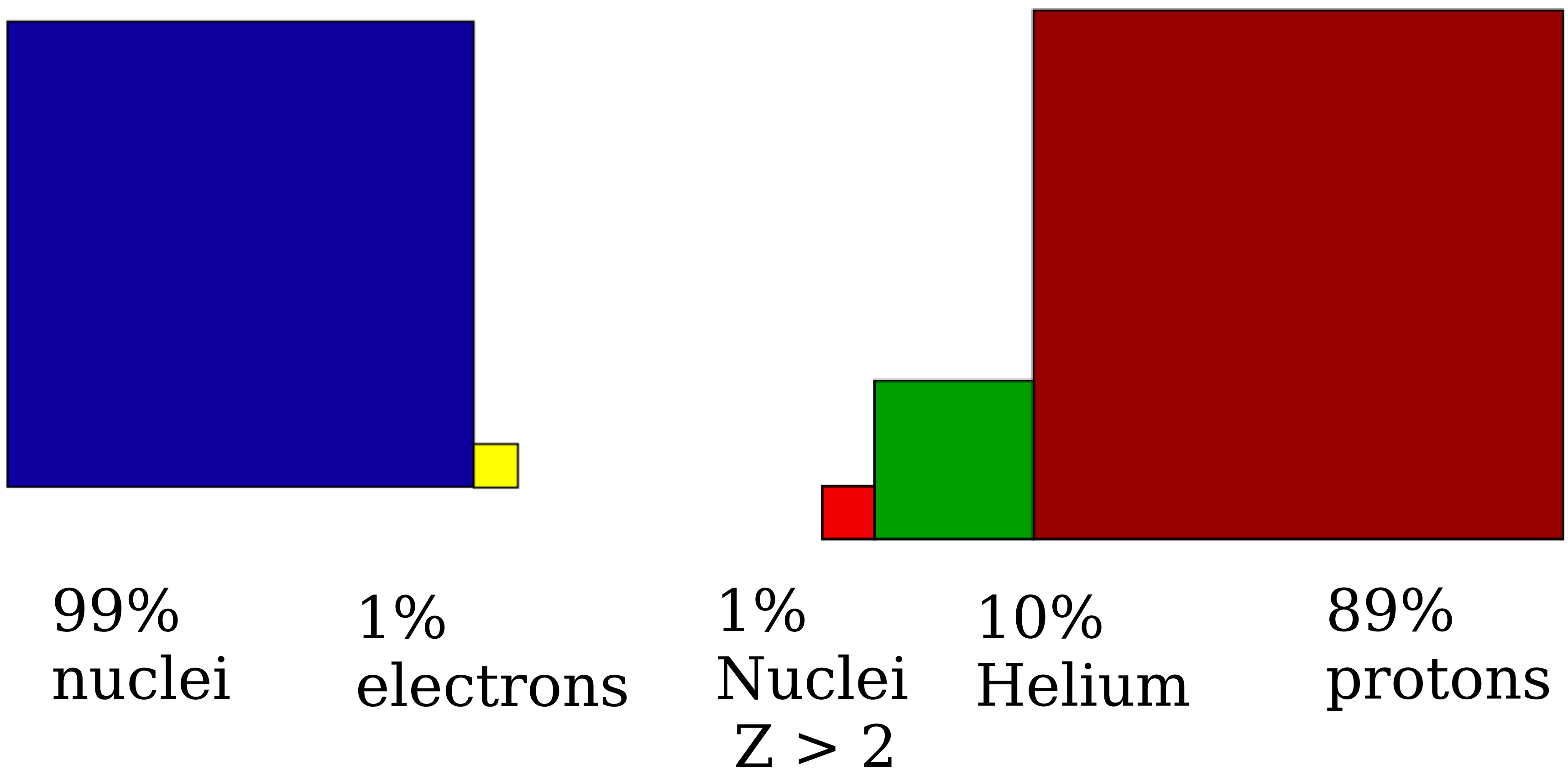
More positive particles going East-ward



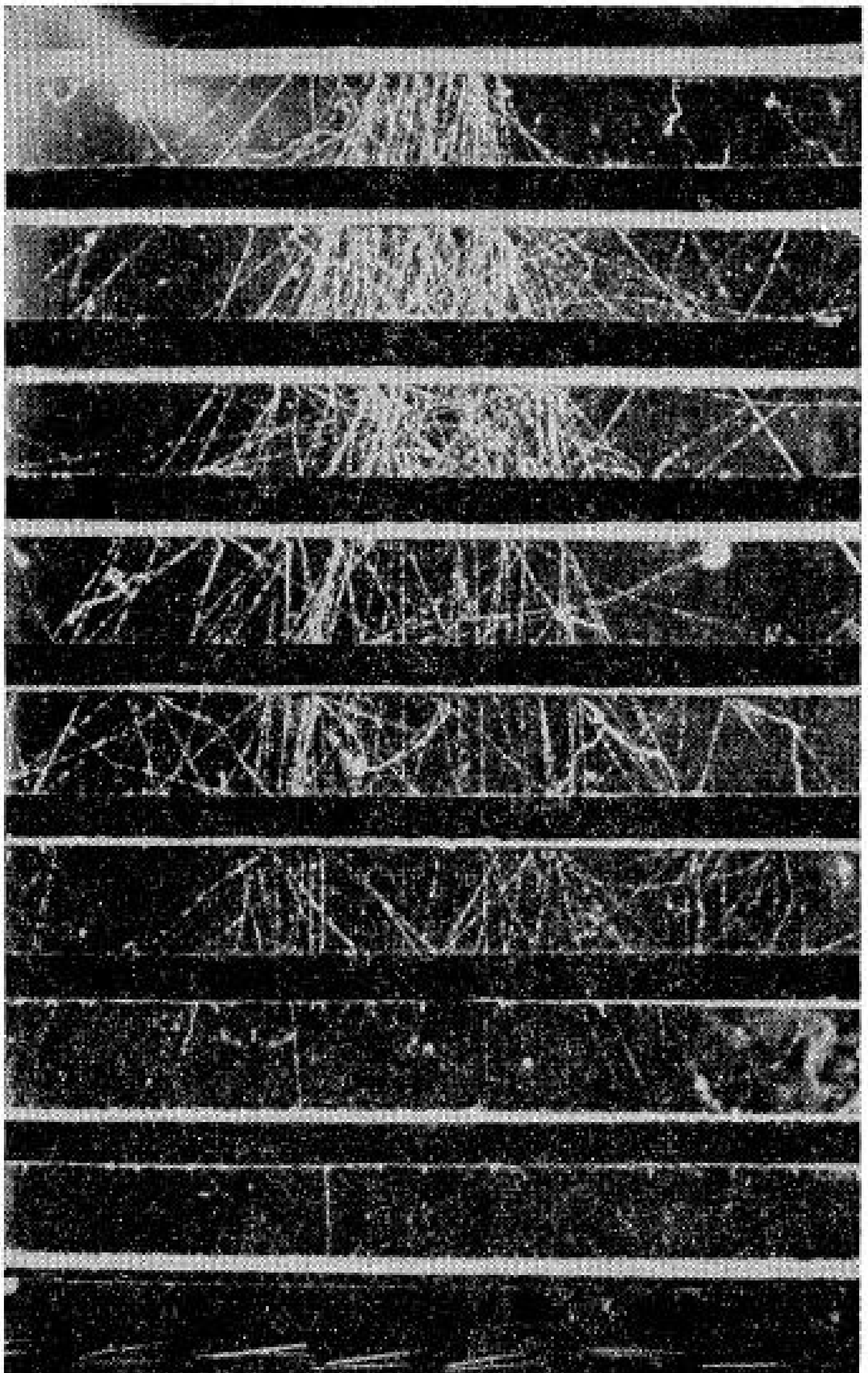
R = 59 GV

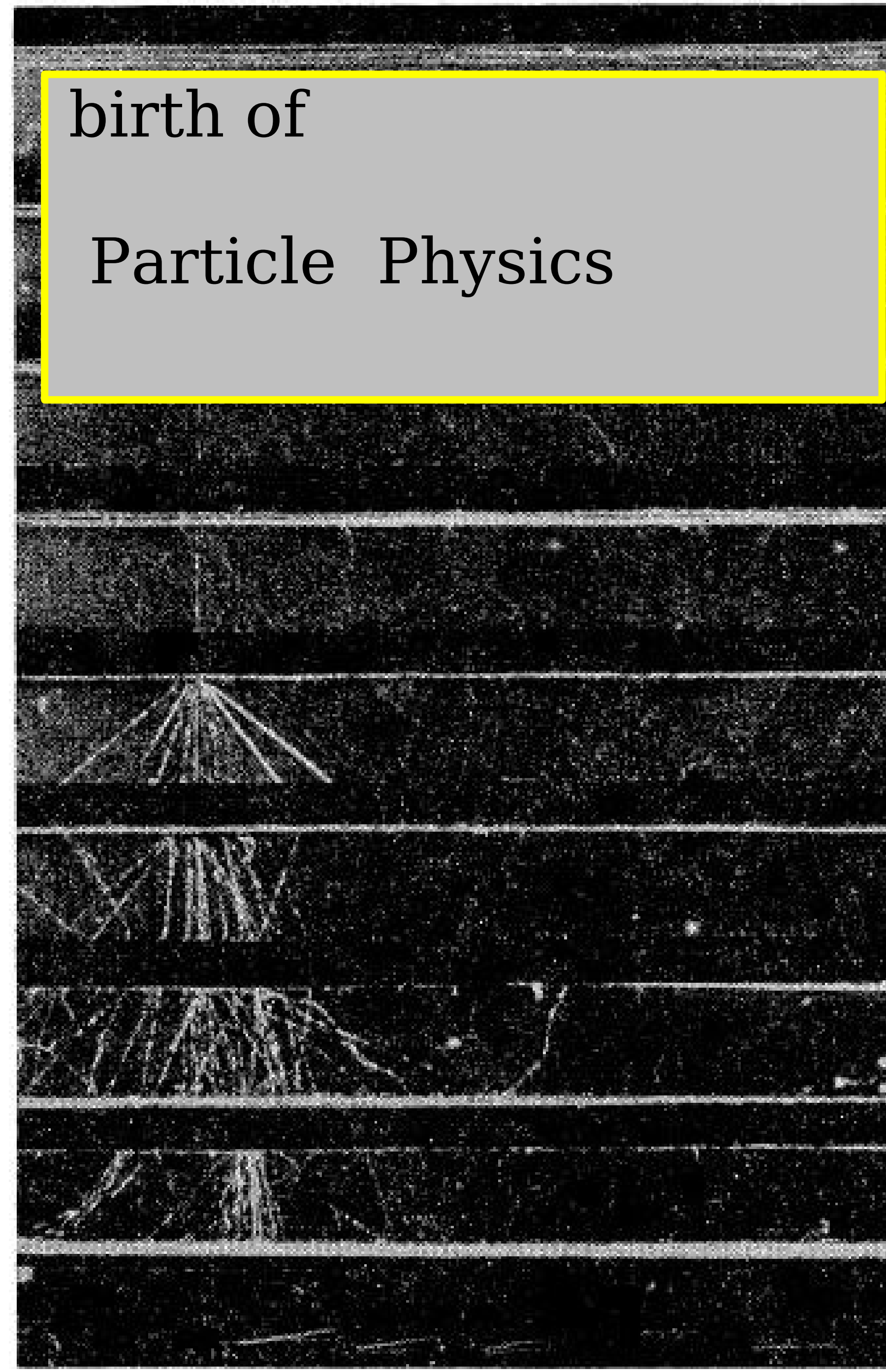
Relativistic charged particles. [Latitude effect]

Mostly protons (+ ionized nuclei) [East-West effect]

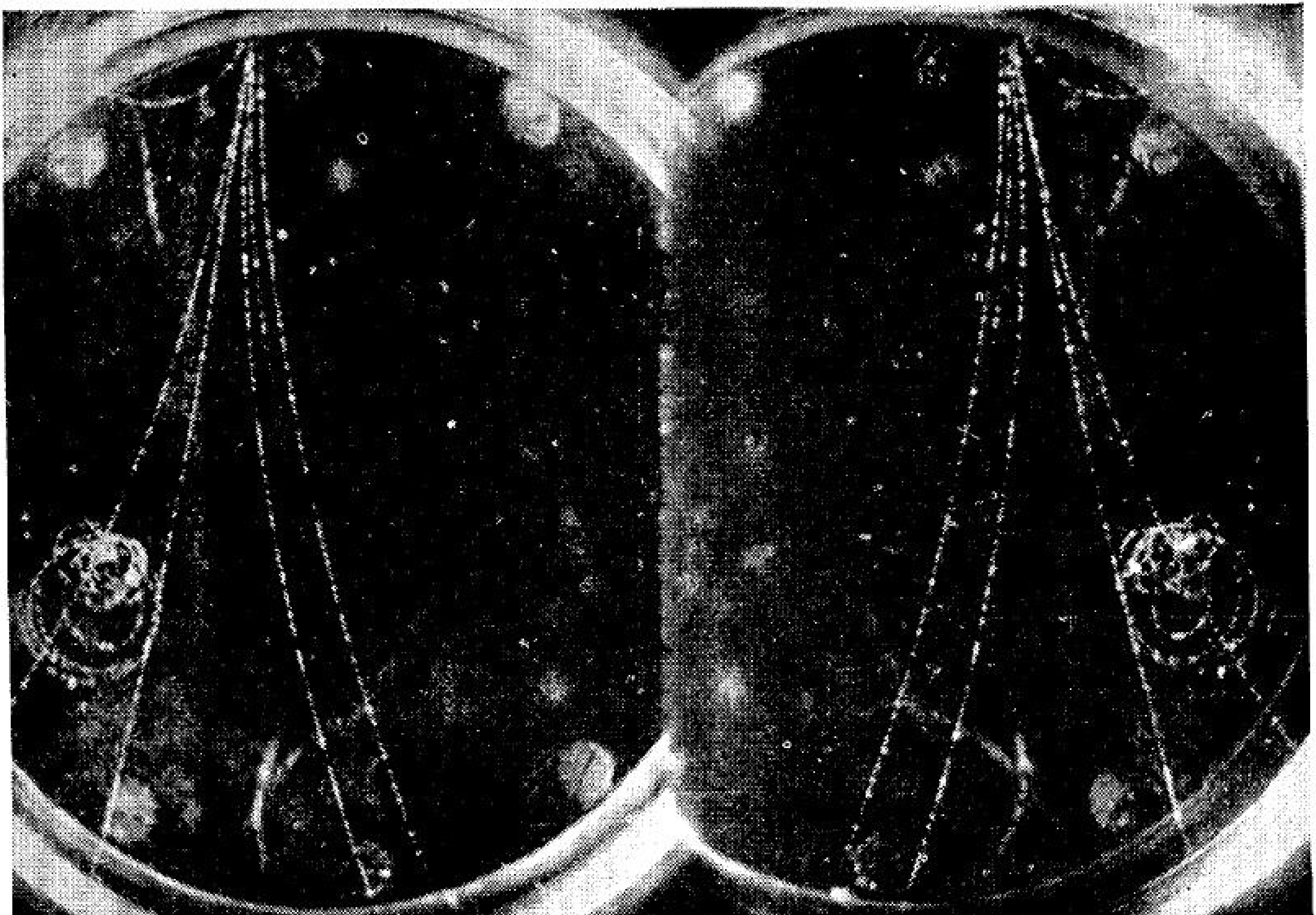


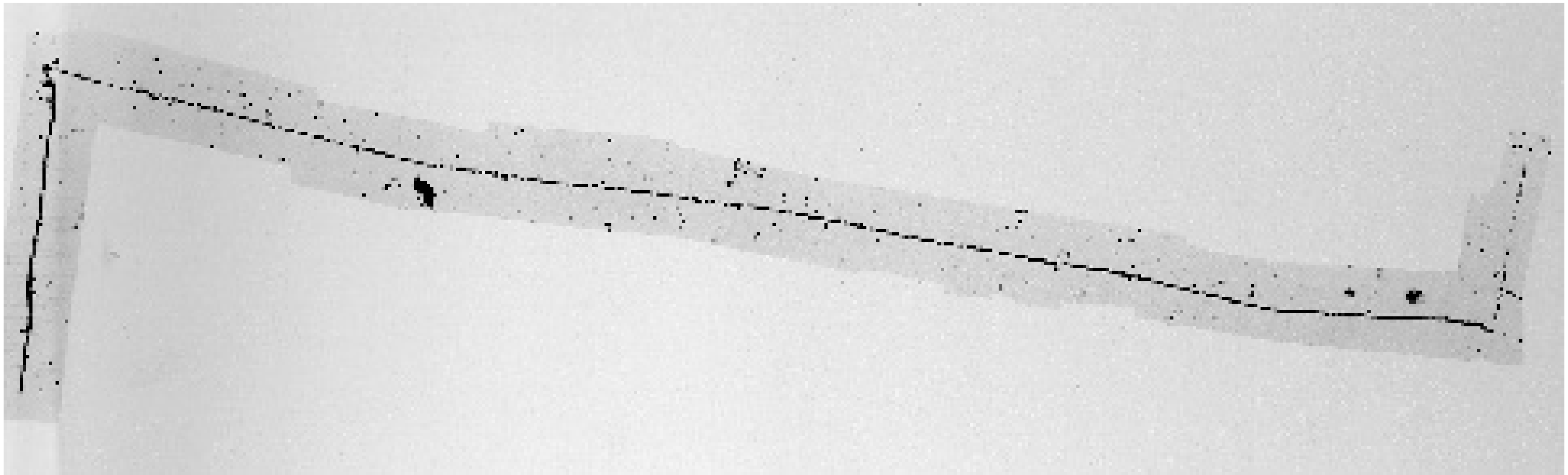
small quantities : positrons + anti-protons




birth of
Particle Physics

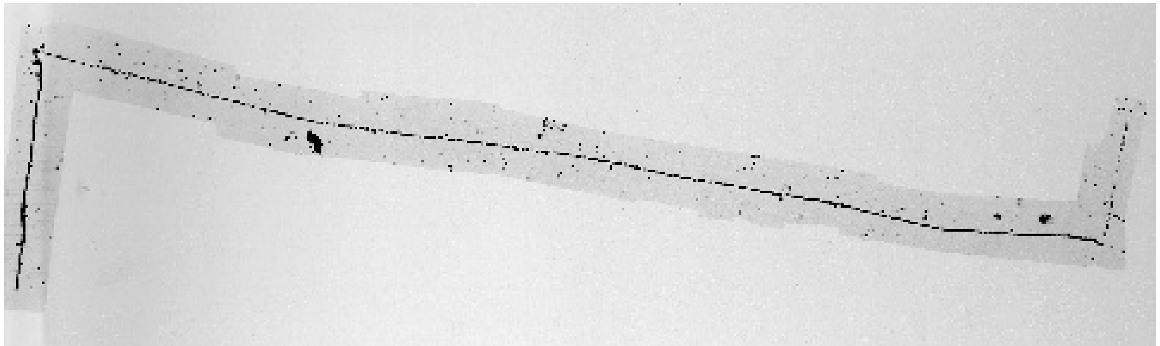
ELECTRONS and POSITRONS





$$\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$$

(1947) Powell, Occhialini and Lattes



$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

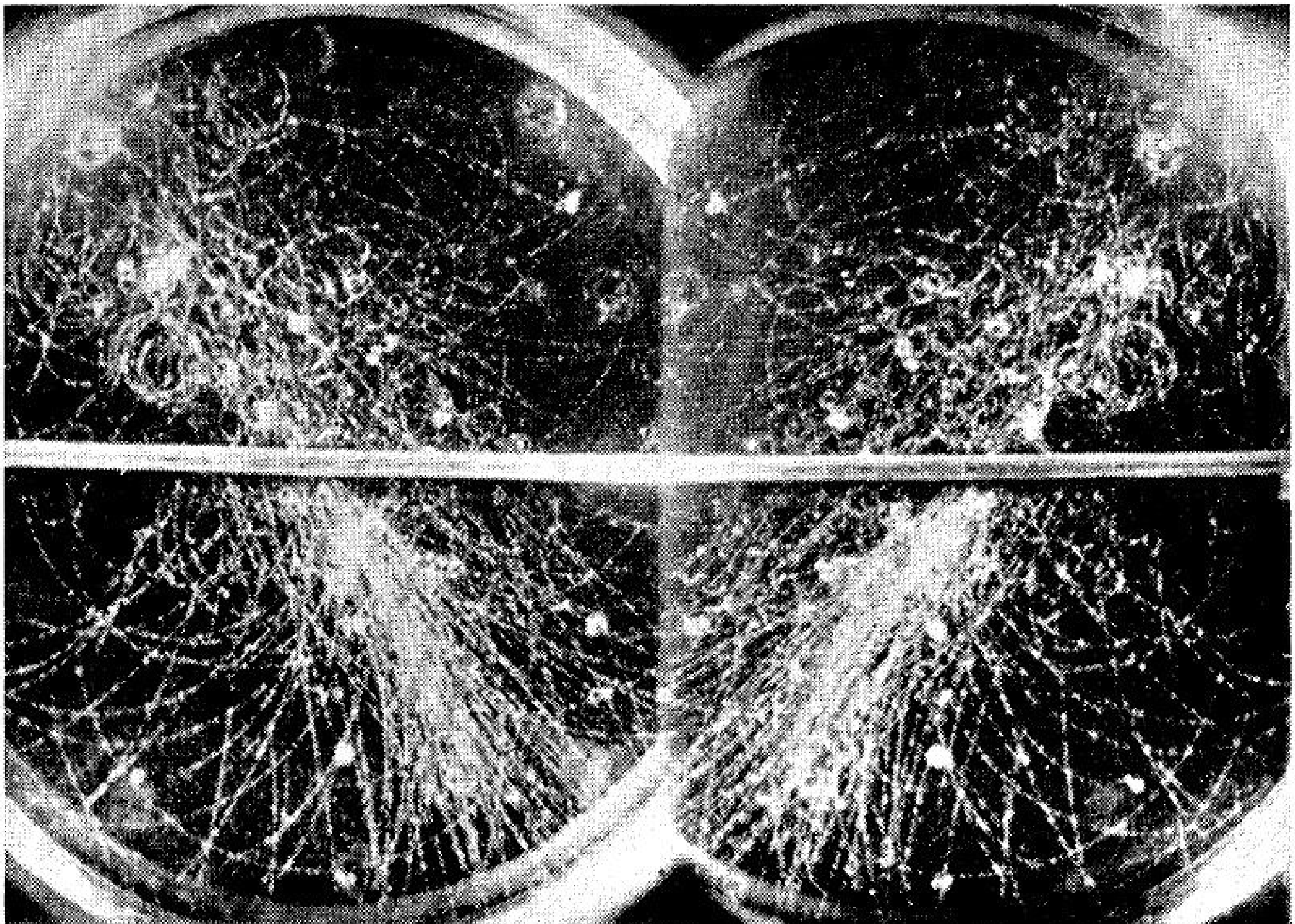
$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

$$\pi^\circ \rightarrow \gamma + \gamma$$

Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level

CARL D. ANDERSON AND SETH H. NEDDERMEYER, *Norman Bridge Laboratory of Physics, California Institute of Technology*

(Received June 9, 1936)



Hadronic Interactions

$$p + {}^{14}\mathrm{N} \rightarrow \ \pi^+ \ , \ \pi^- \ , \ \pi^0 \ , \ \ \ldots$$

$$p \ , \ n \ , \ \overline{p} \ , \ \overline{n}$$

$$K^+ \ , \ K^- \ , \ K^0 \ , \ \overline{K}^0$$

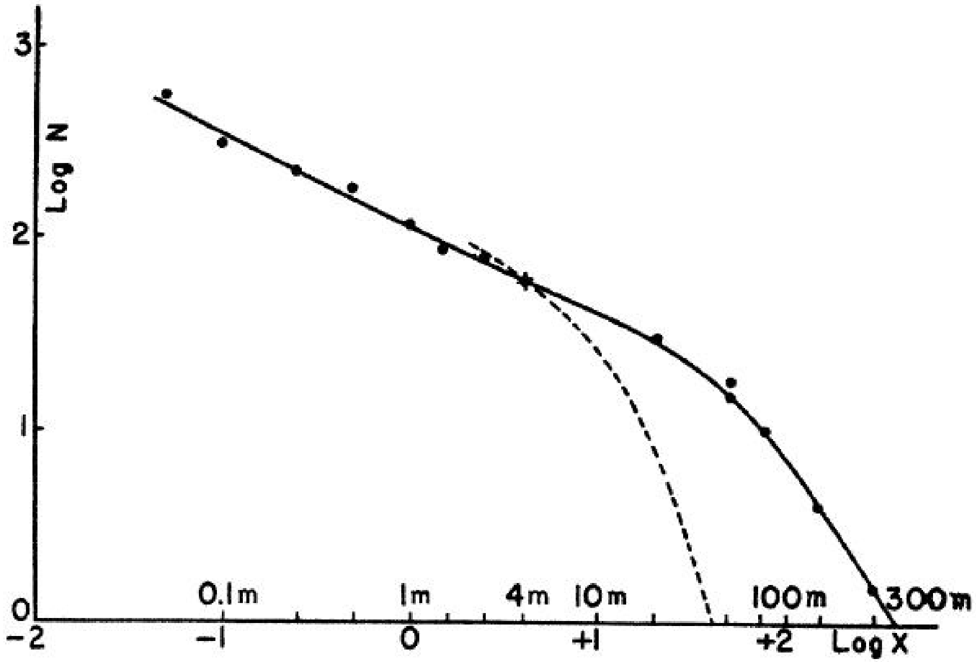
$$, \ \ \ldots$$

Extraordinary energy (!)

(10^{15}, 10^{16} eV) now: 10^{20}eV

[Extensive Air Showers]

Pierre Auger

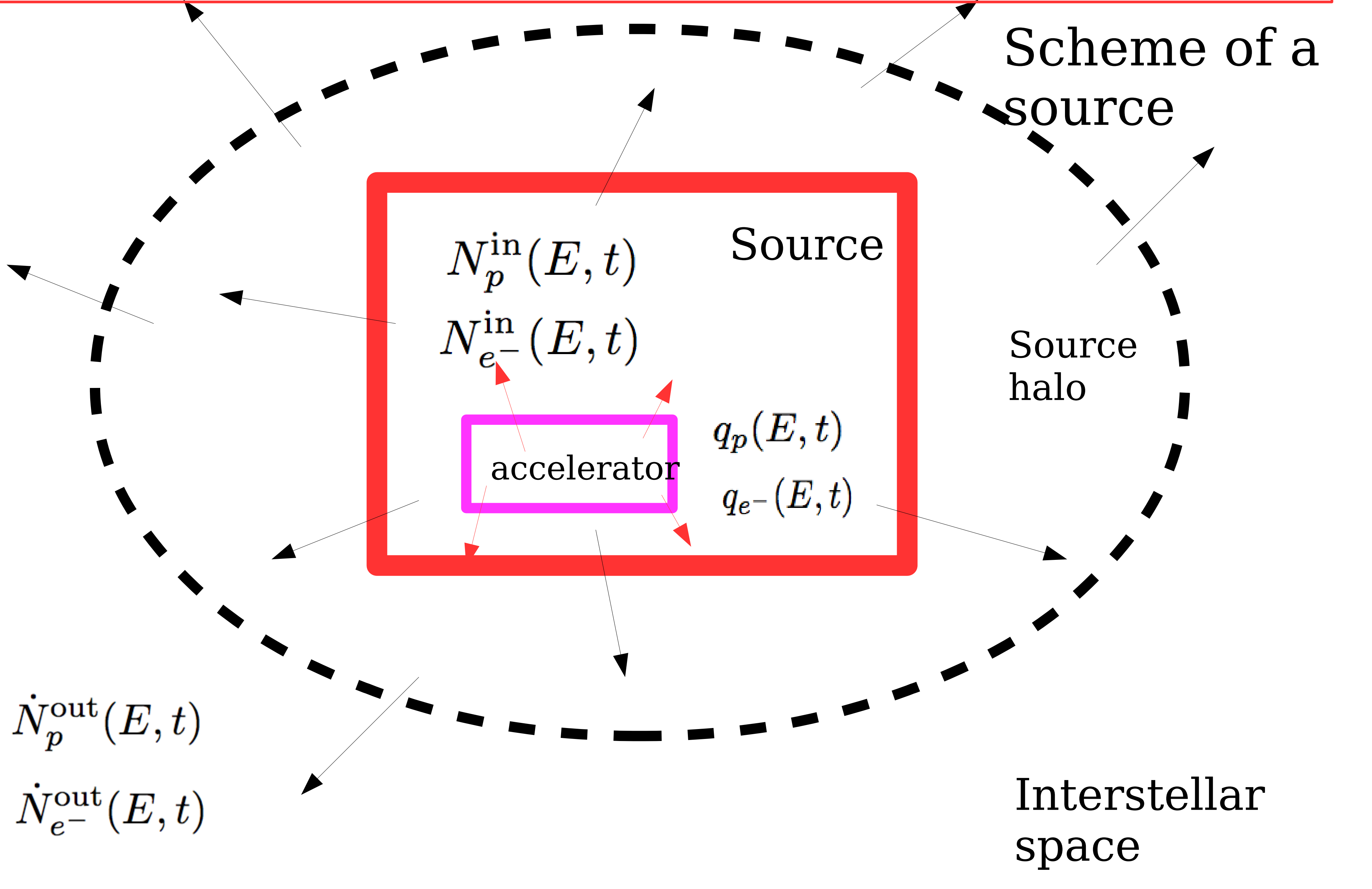


Phys.Rev. 1939

Acceleration of Cosmic Rays

[electrically charged particles]

Emission of Cosmic Rays from the Sources requires “escape”

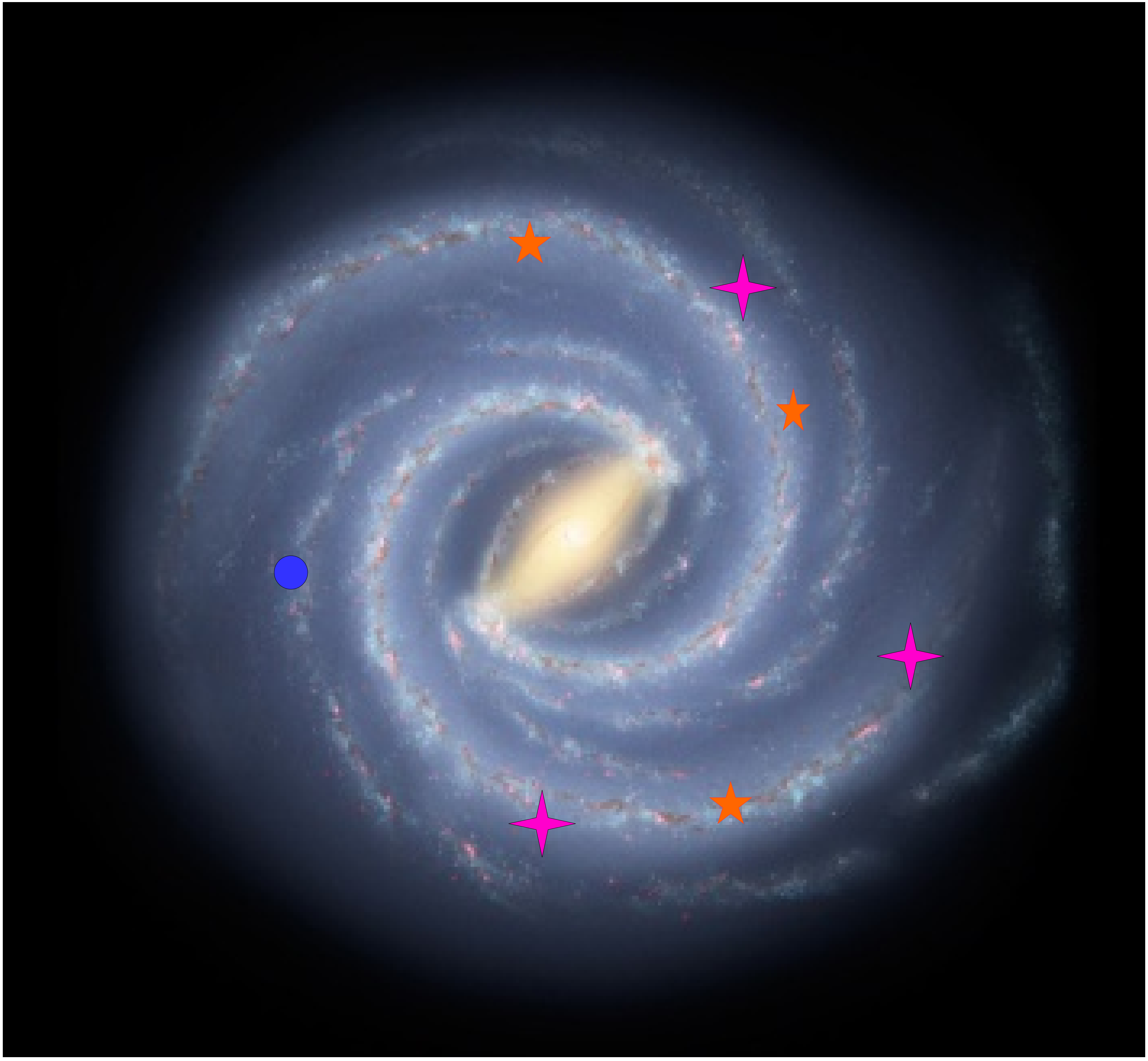


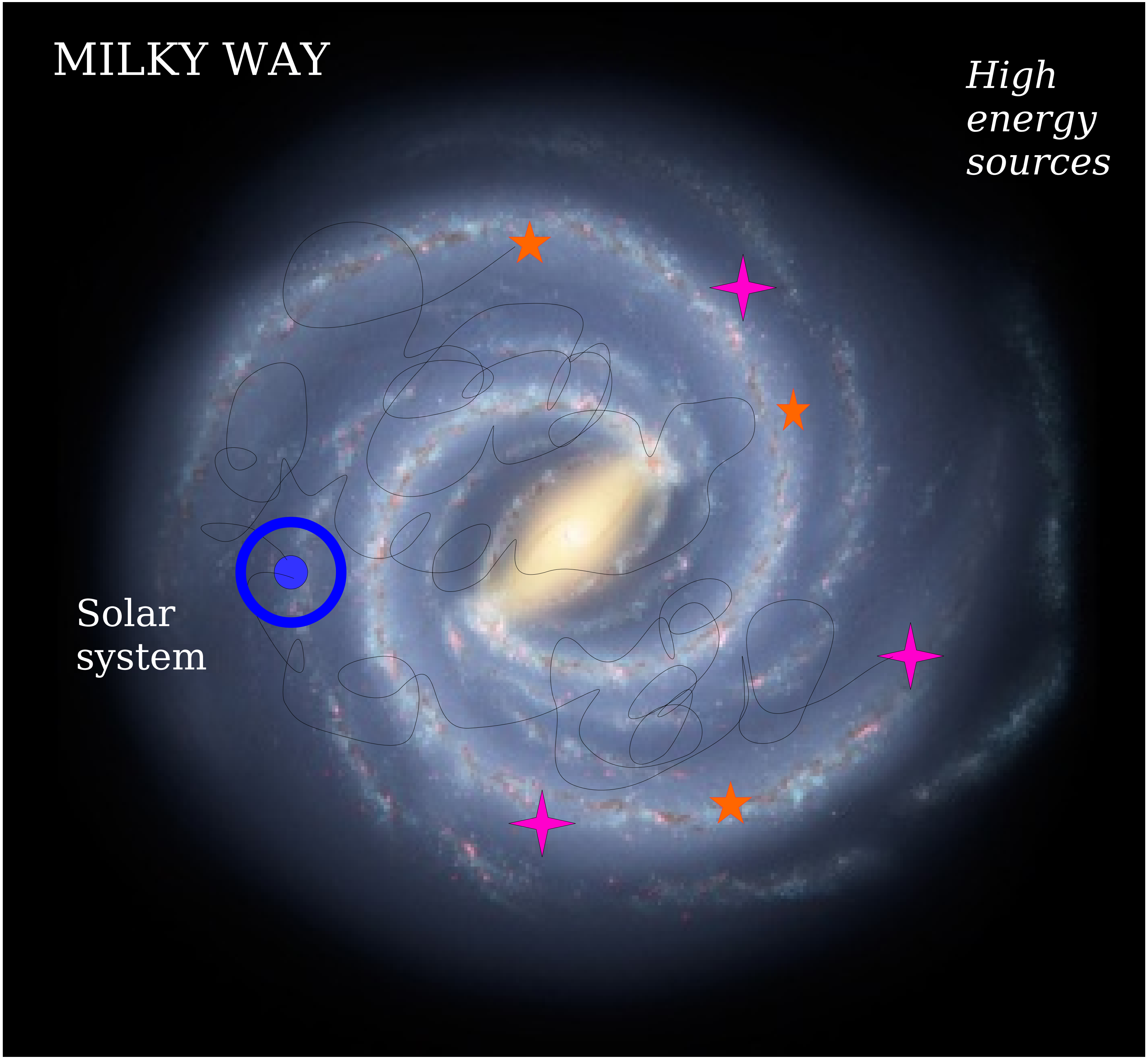
COSMIC RAYS

Space and time integrated average of particles generated by many sources in the Galaxy and in the universe, *also shaped by propagation effects*.

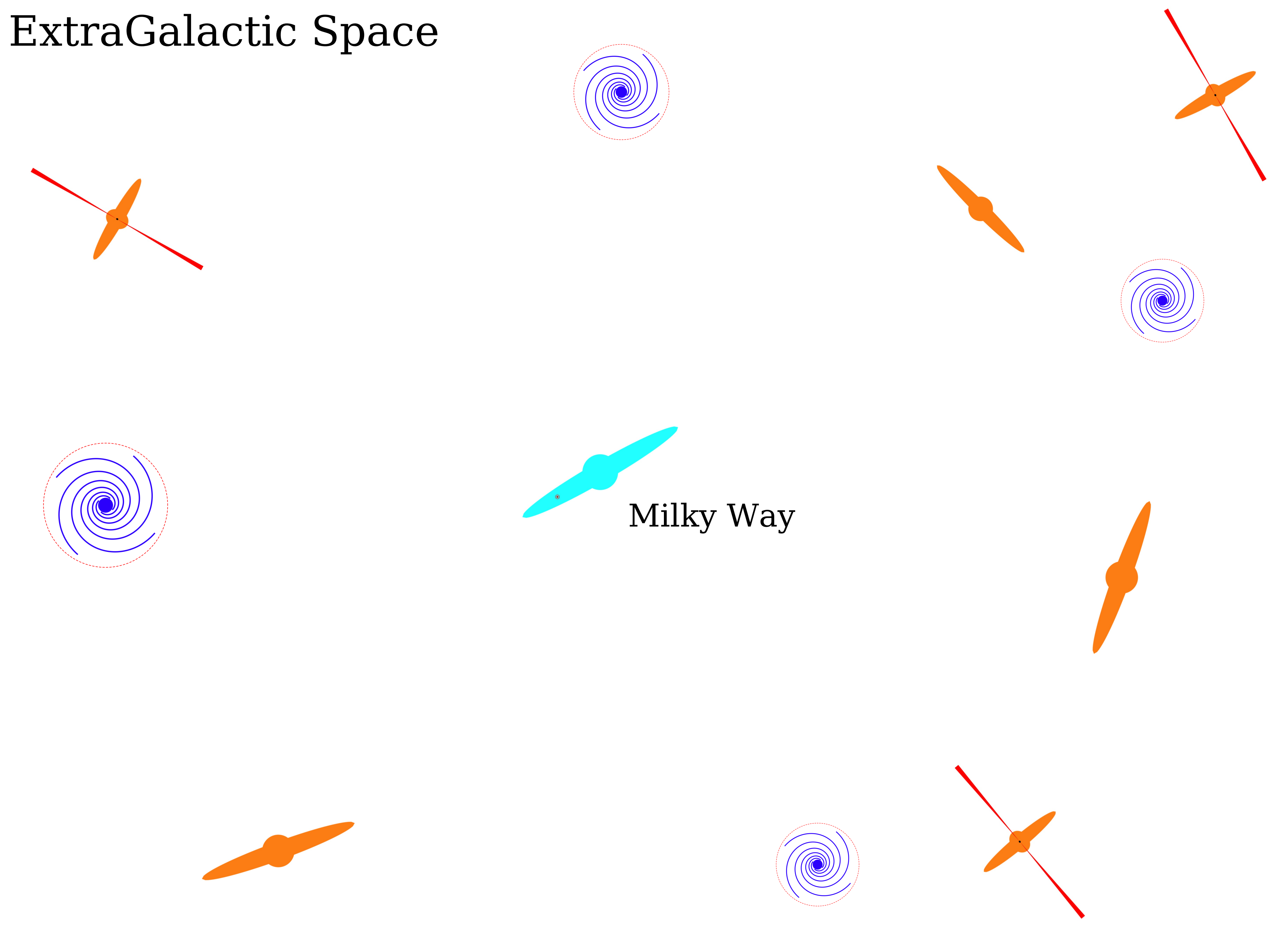
Measurement at
single point, and (effectively) single time.

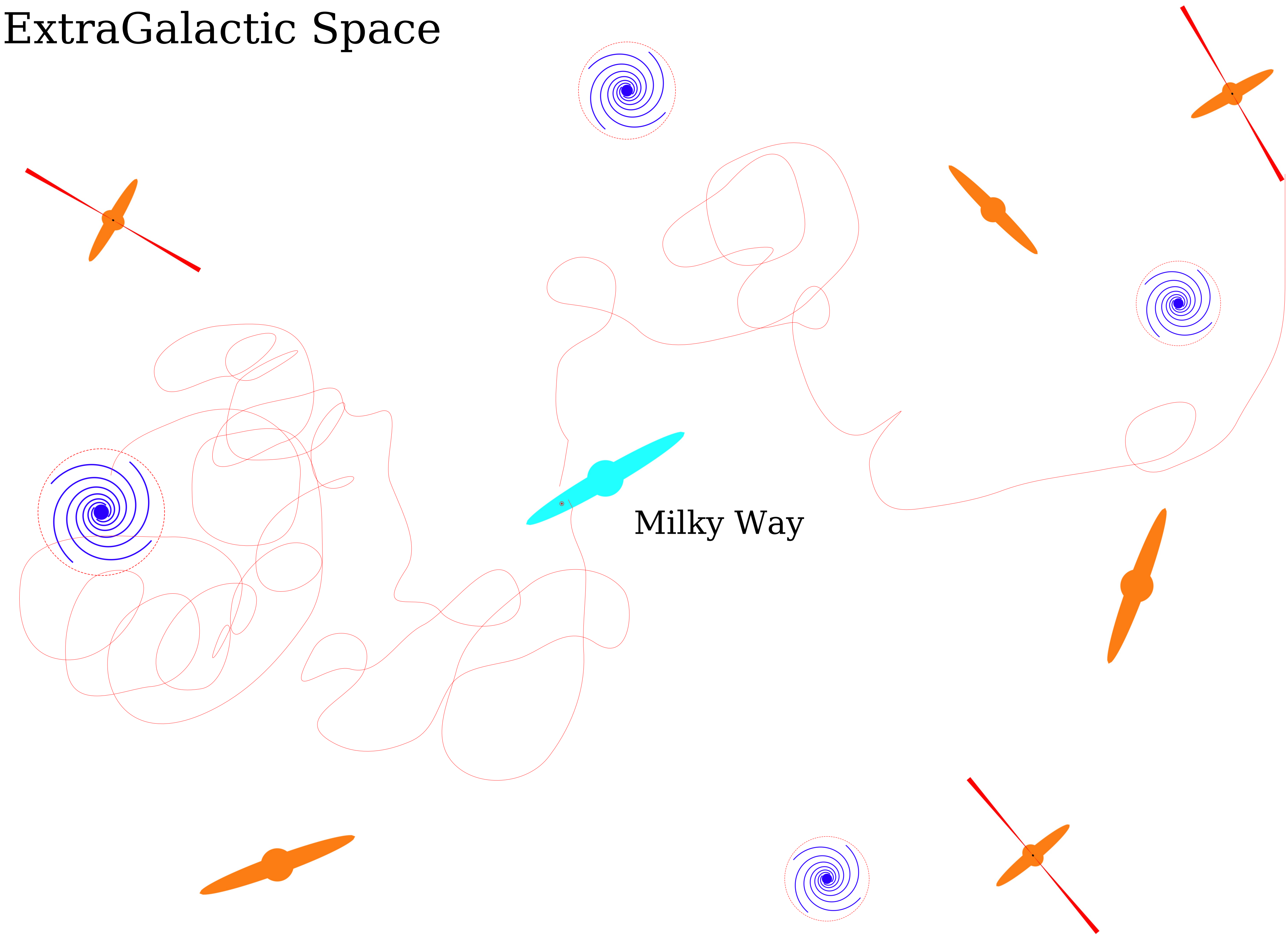
[slow time variations,
geological record carries some information]

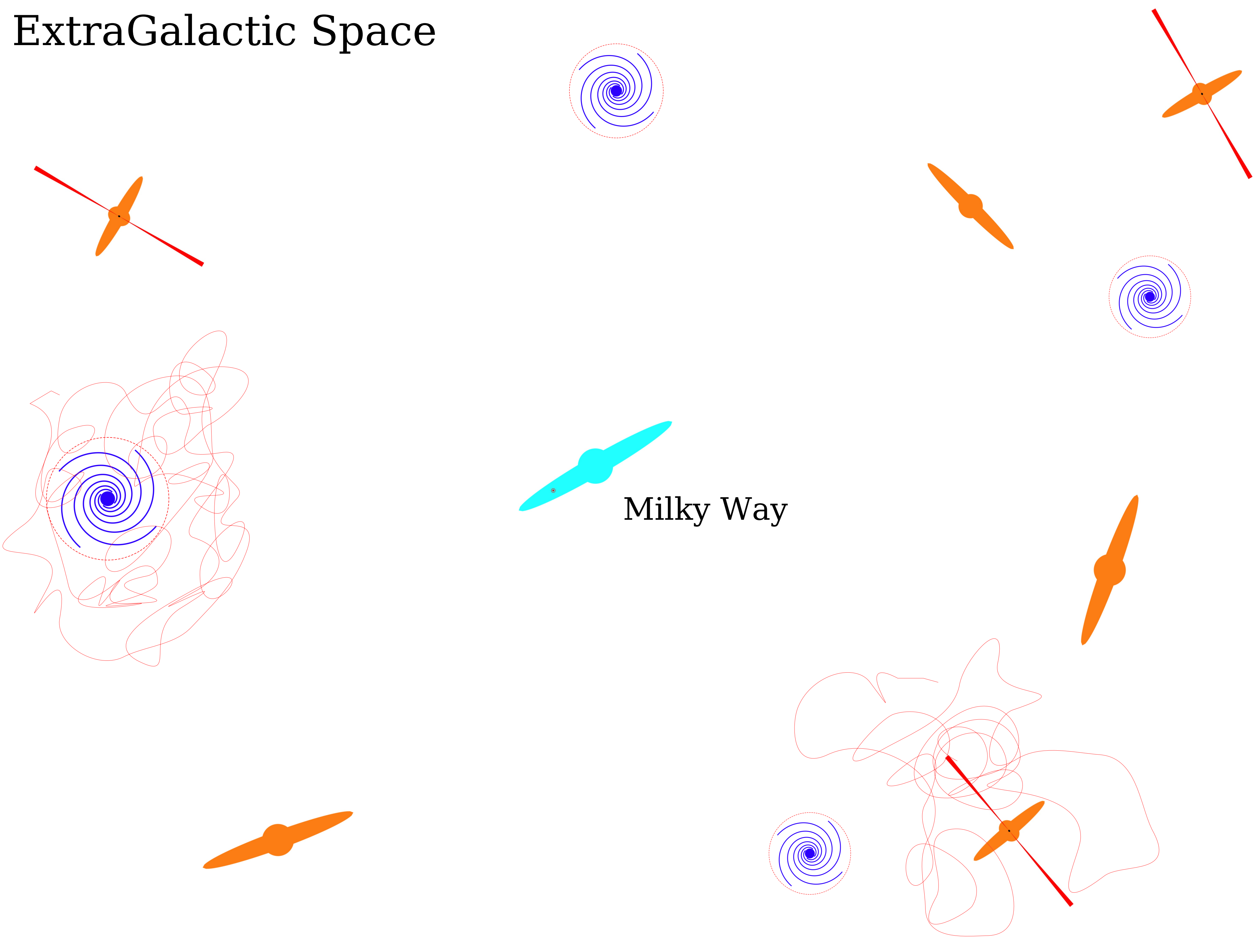




MILKY WAY
High energy sources
Solar system

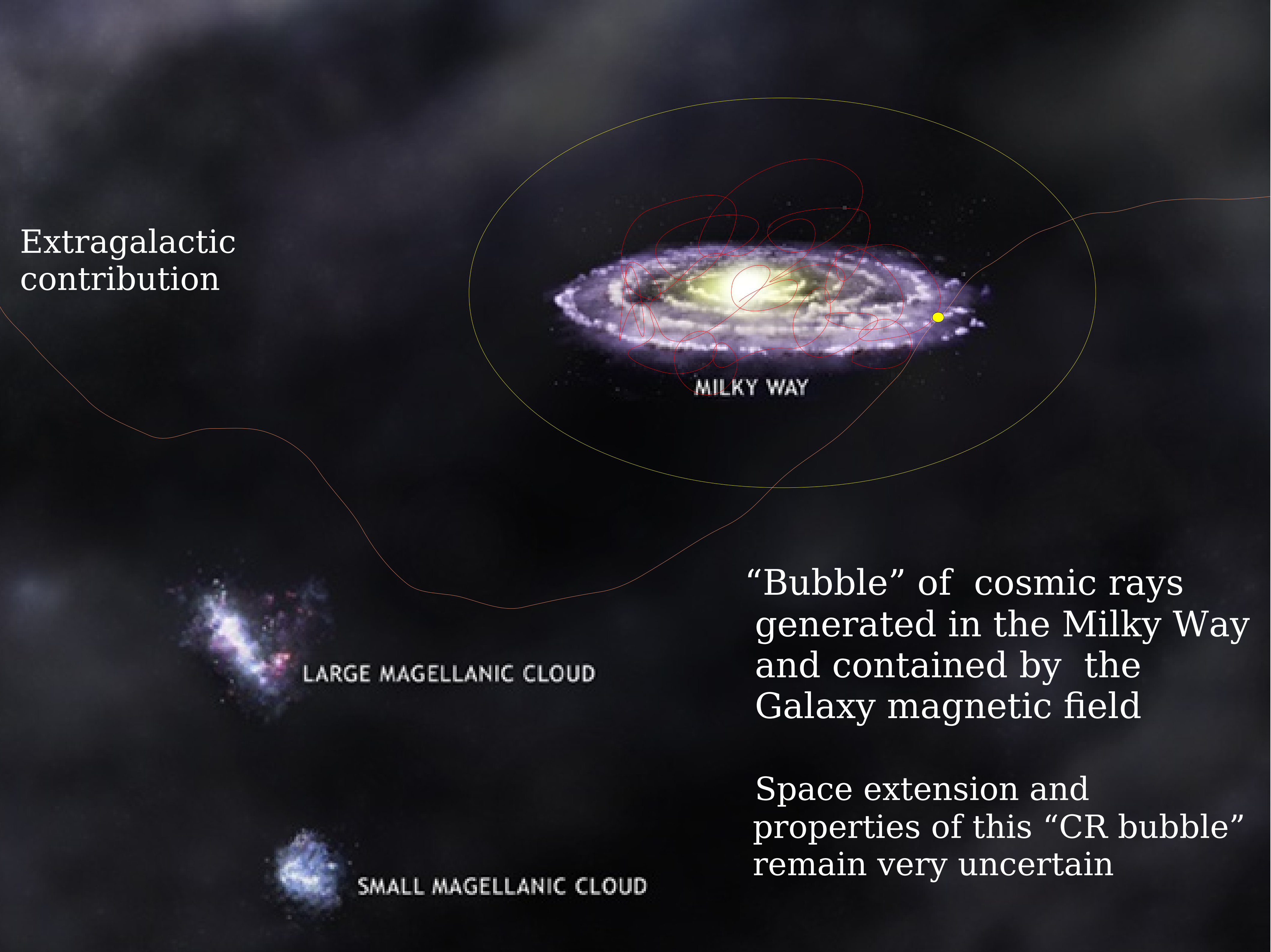

ExtraGalactic Space
Milky Way


ExtraGalactic Space
Milky Way



ExtraGalactic Space
Milky Way

Extragalactic contribution

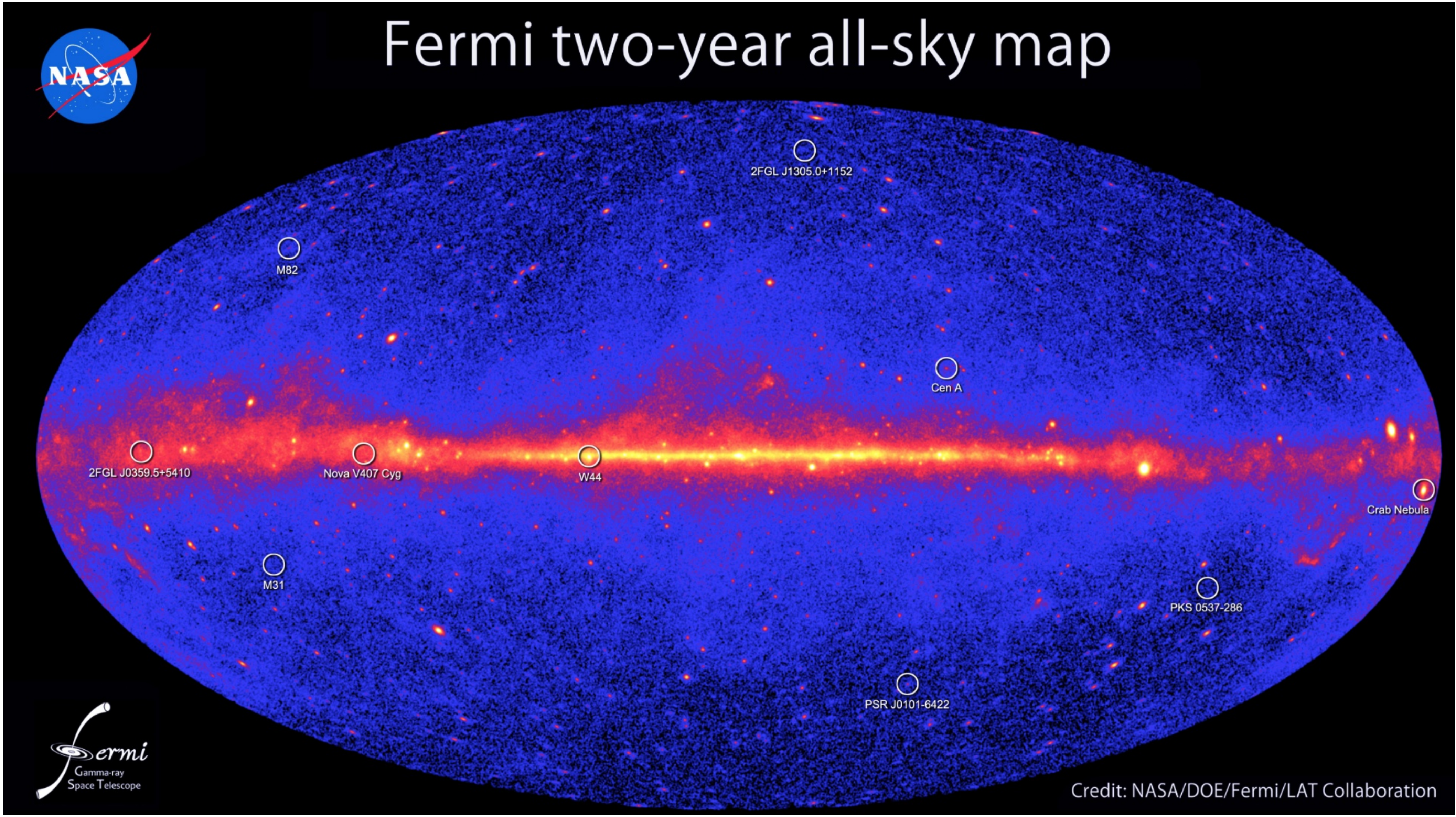


"Bubble" of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field

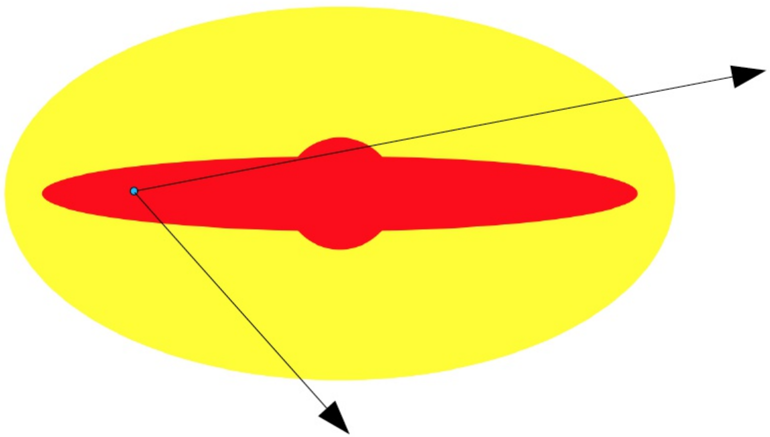
Space extension and properties of this "CR bubble" remain very uncertain

$E_\gamma \geq 100$ MeV

Gamma Ray Sky

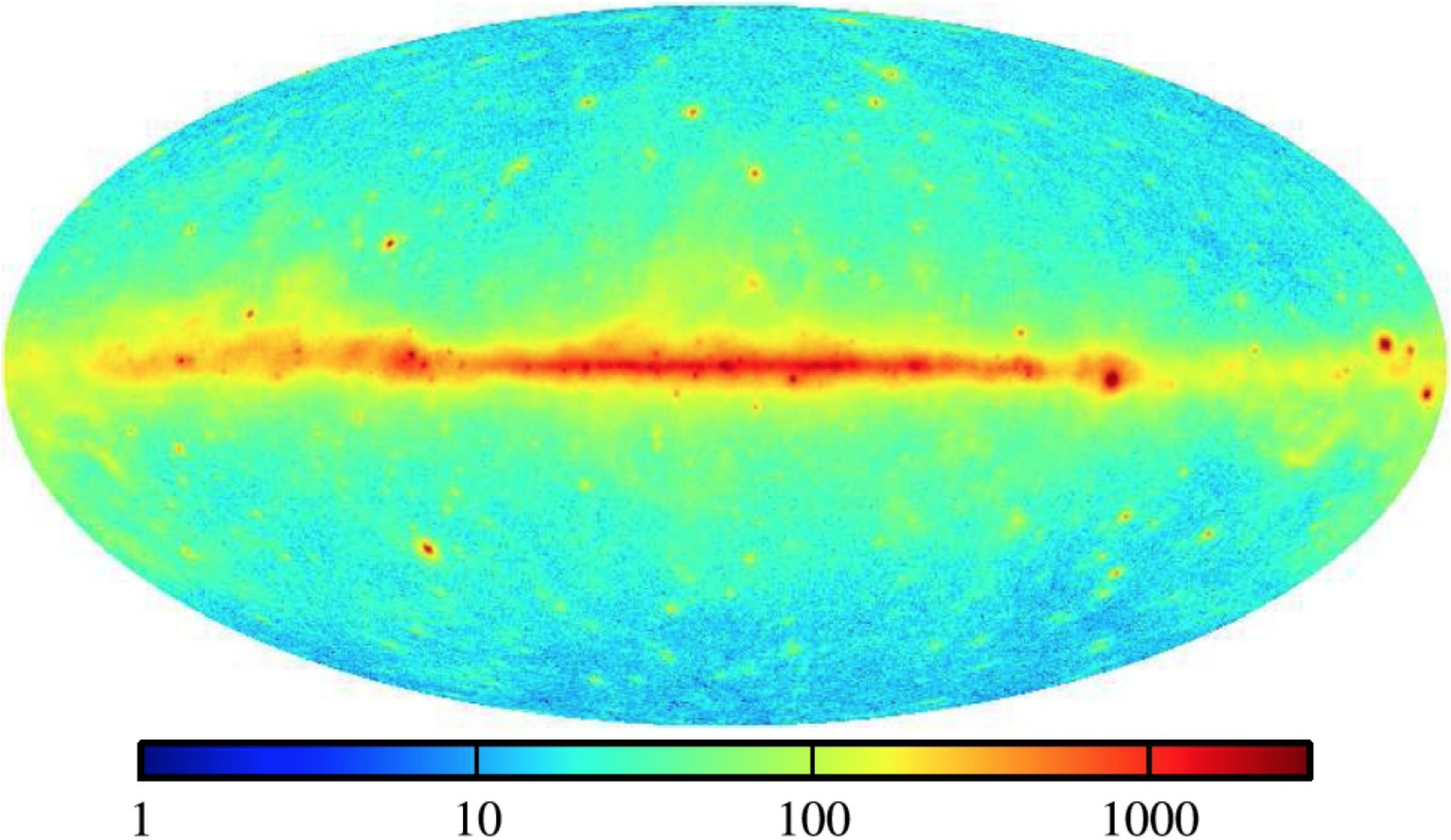


Diffuse Emission



Fermi–LAT counts

Galactic coordinates



energy range 200 MeV to 100 GeV

Cosmic Ray interactions in the Interstellar Medium

50% of flux
+- 5 degrees
around equator
[Galactic gas]

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

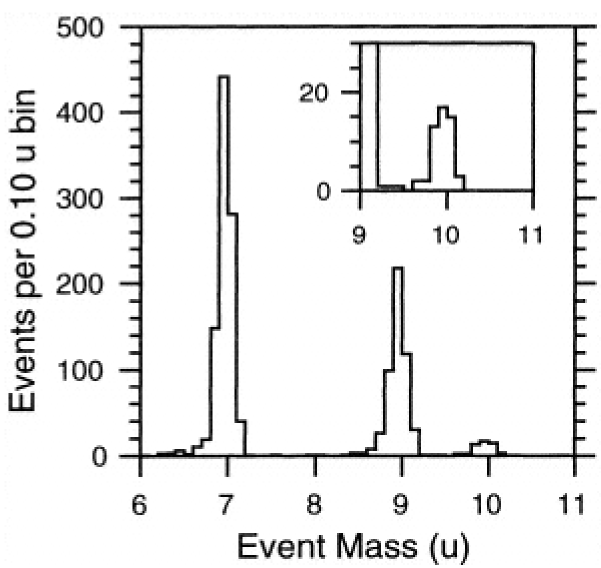
$$N_j(E) = \int d^3x \; n_j(E, \vec{x})$$

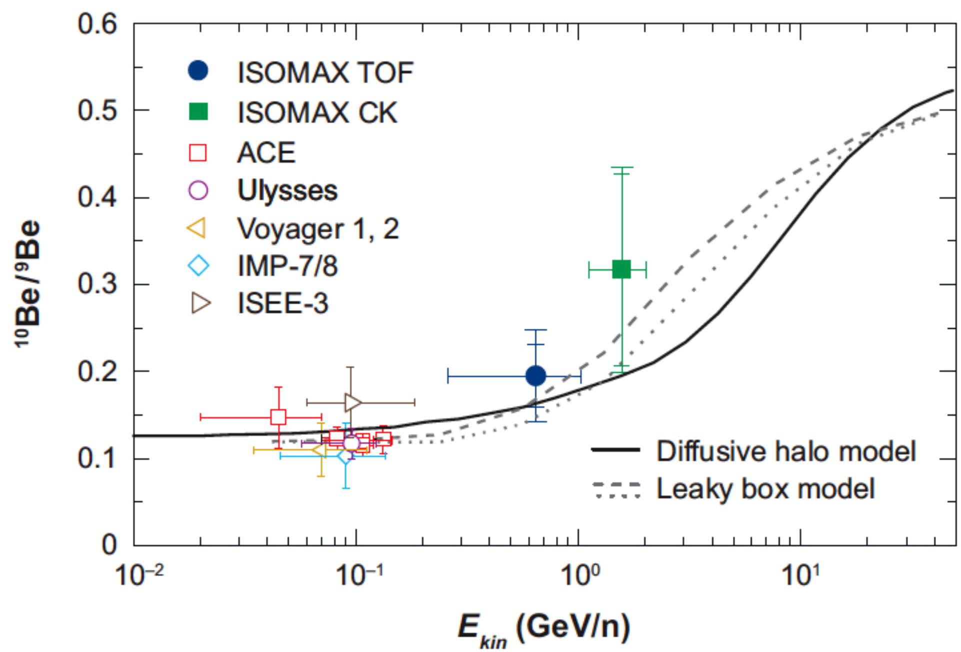
$$\phi_j(E) = \frac{c}{4\pi} \, n_j(E)$$

Determination of the "confinement time" $T(p/Z)$

"Cosmic clock" (Beryllium-10)

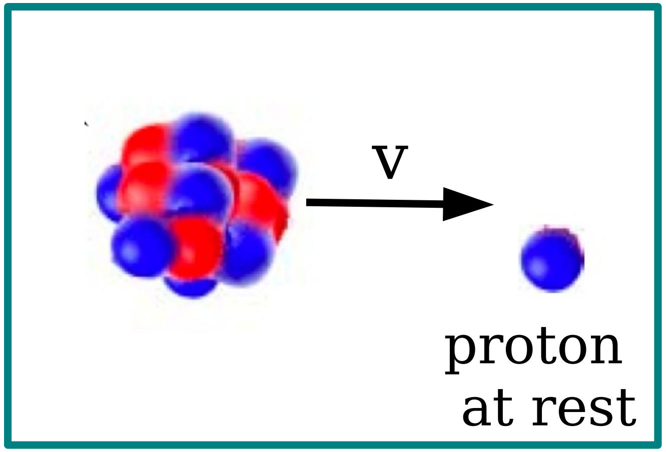
$$T_{1/2}\left[{}^{10}\mathrm{Be}\right] = 1.39 \times 10^6 \text{ years}$$

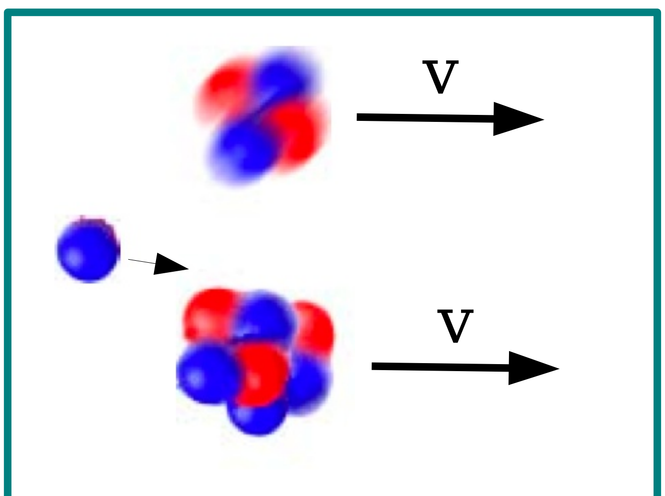


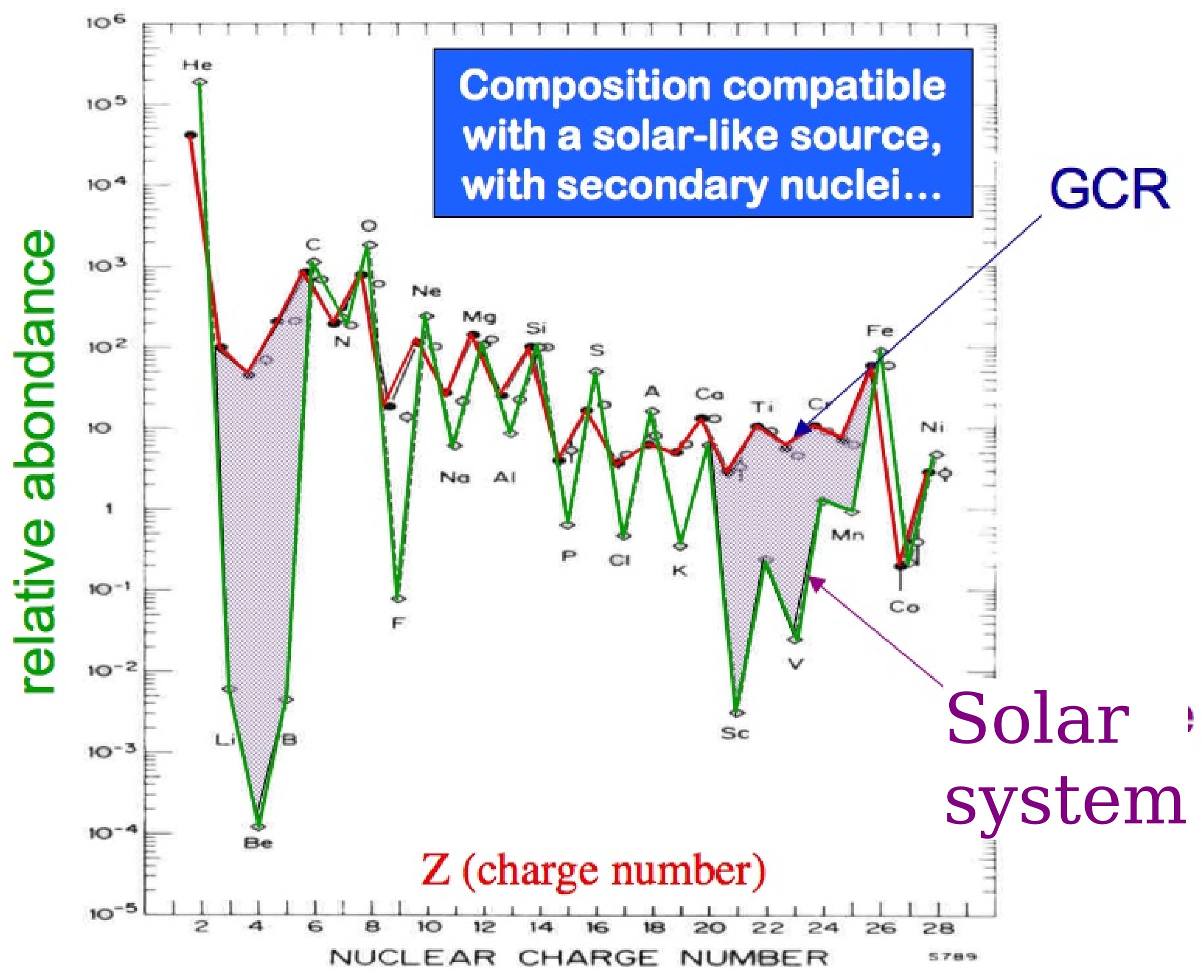


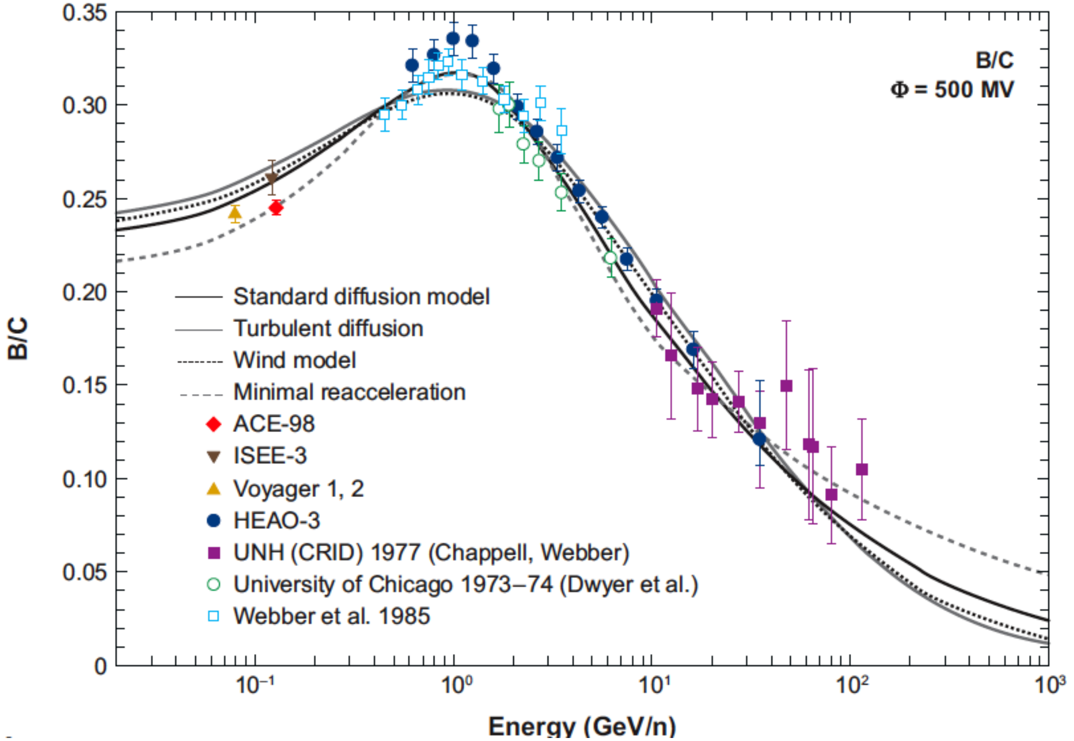
$$T \simeq 10 \text{ Myr}$$

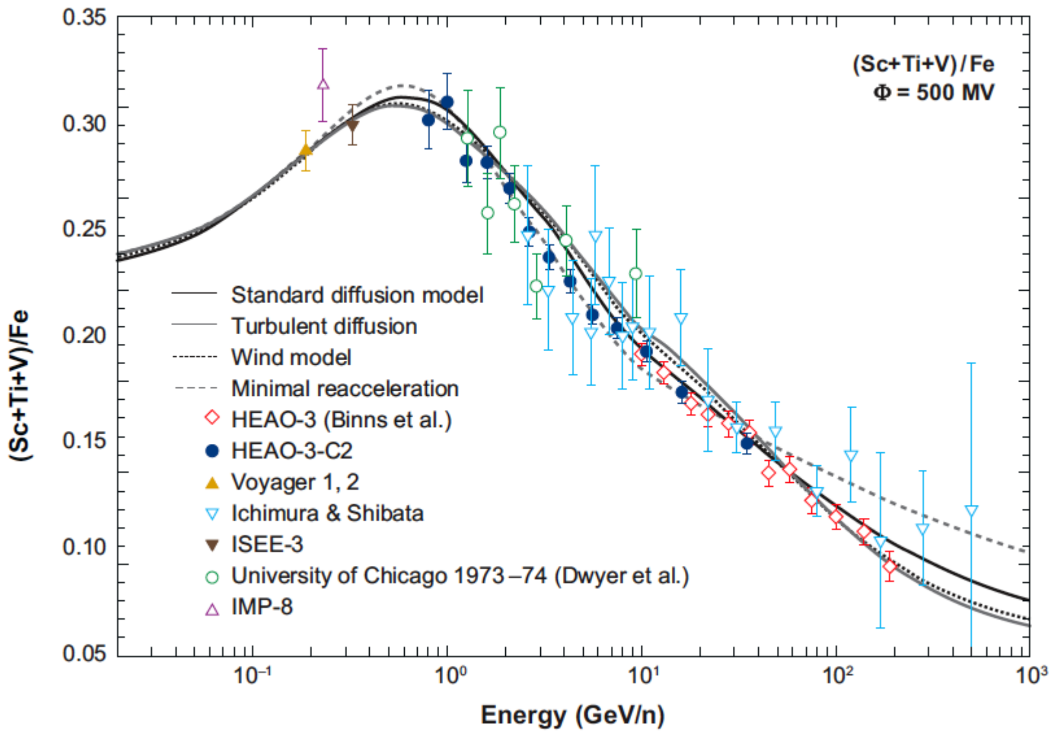
Nuclear Fragmentation
(collisions with the Inter Stellar Medium)











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

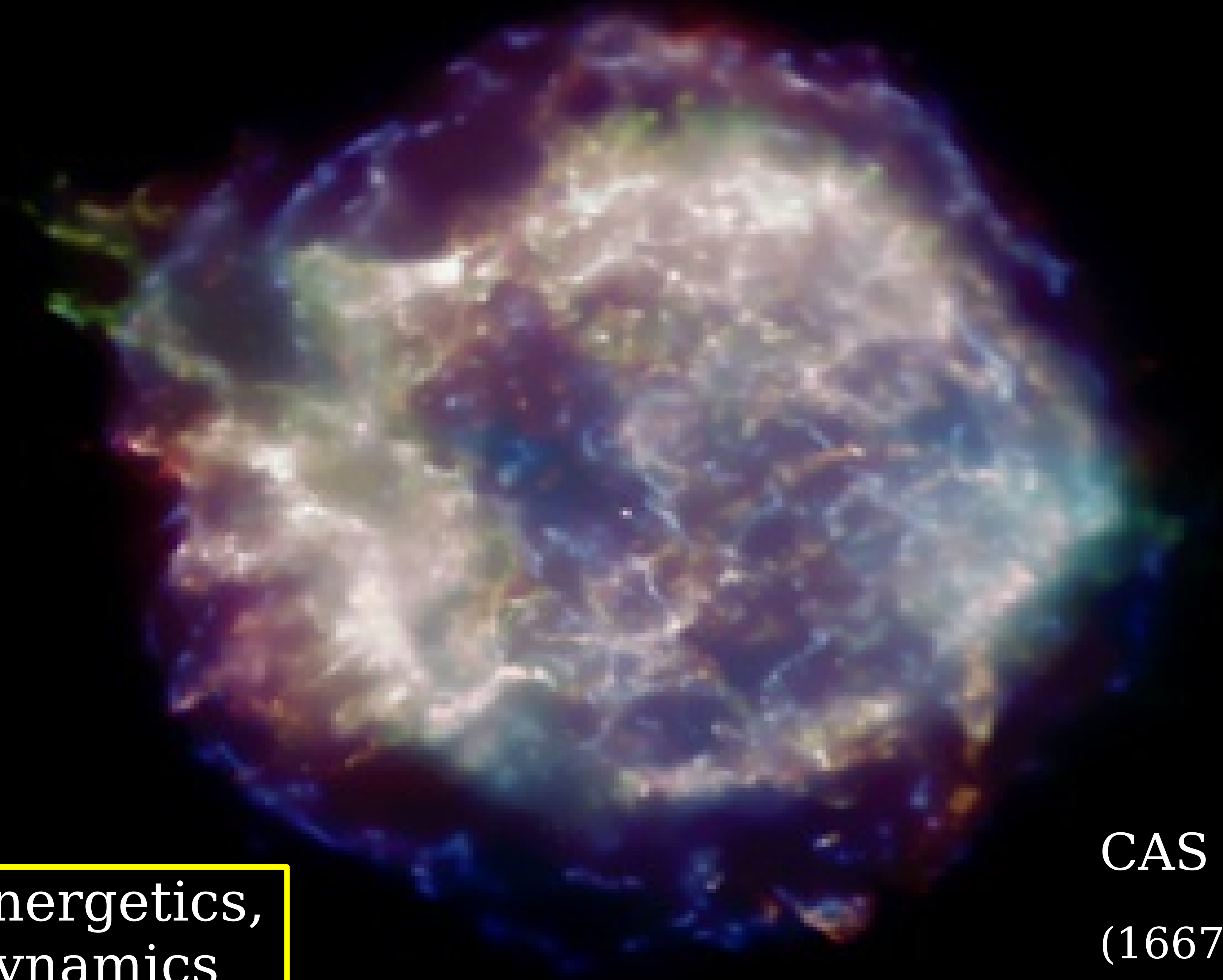
Spectral Shape
[Dynamics
of acceleration process]

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

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

Source Identification

The SuperNova “Paradigm” for CR acceleration

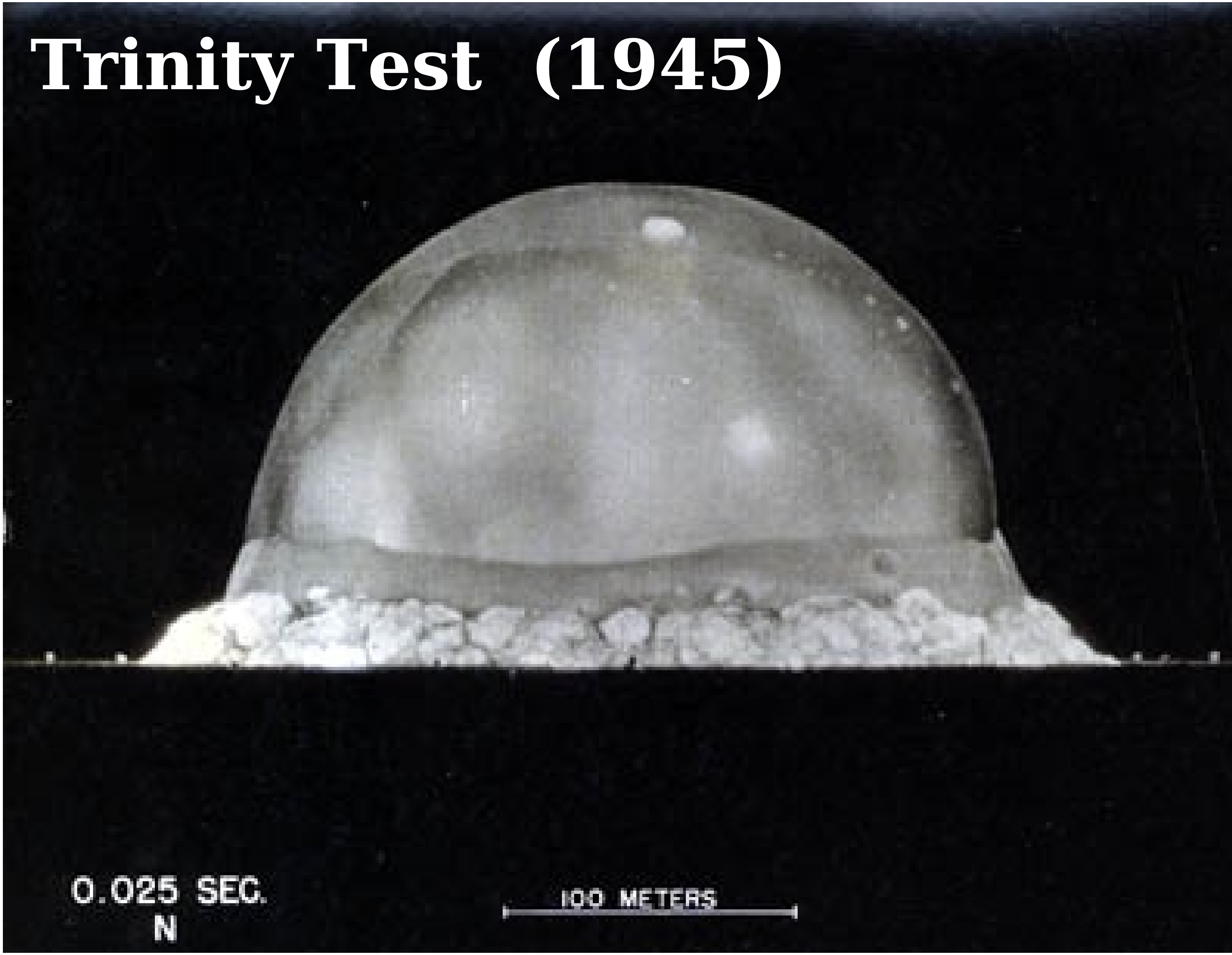


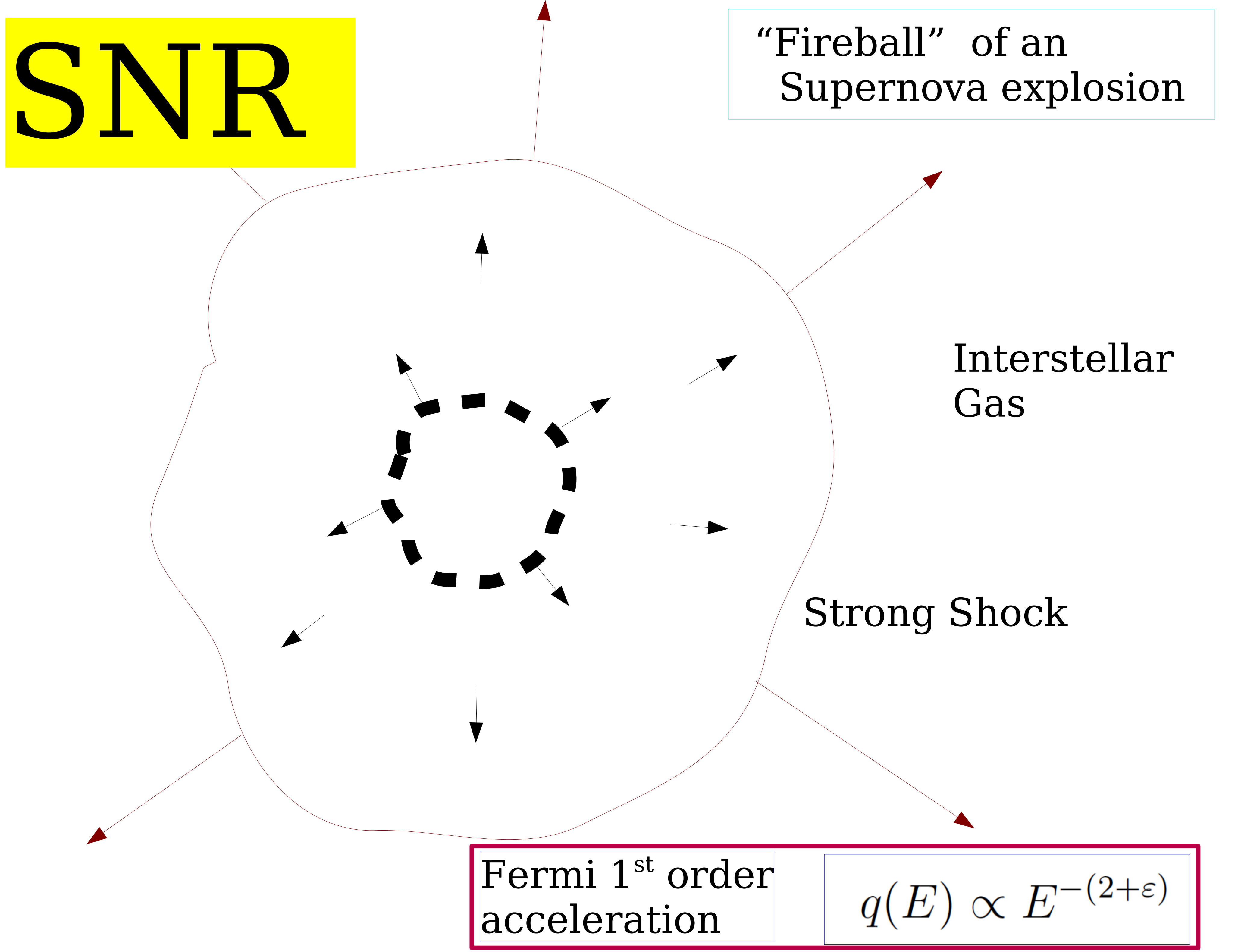
CAS A

(1667)

Energetics,
Dynamics

Trinity Test (1945)




SNR
“Fireball” of an Supernova explosion
Interstellar Gas
Strong Shock
Fermi 1st order acceleration
$q(E) \propto E^{-(2+\varepsilon)}$

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq E_{\text{SN}}^{\text{Kinetic}} \; f_{\text{SN}}$$

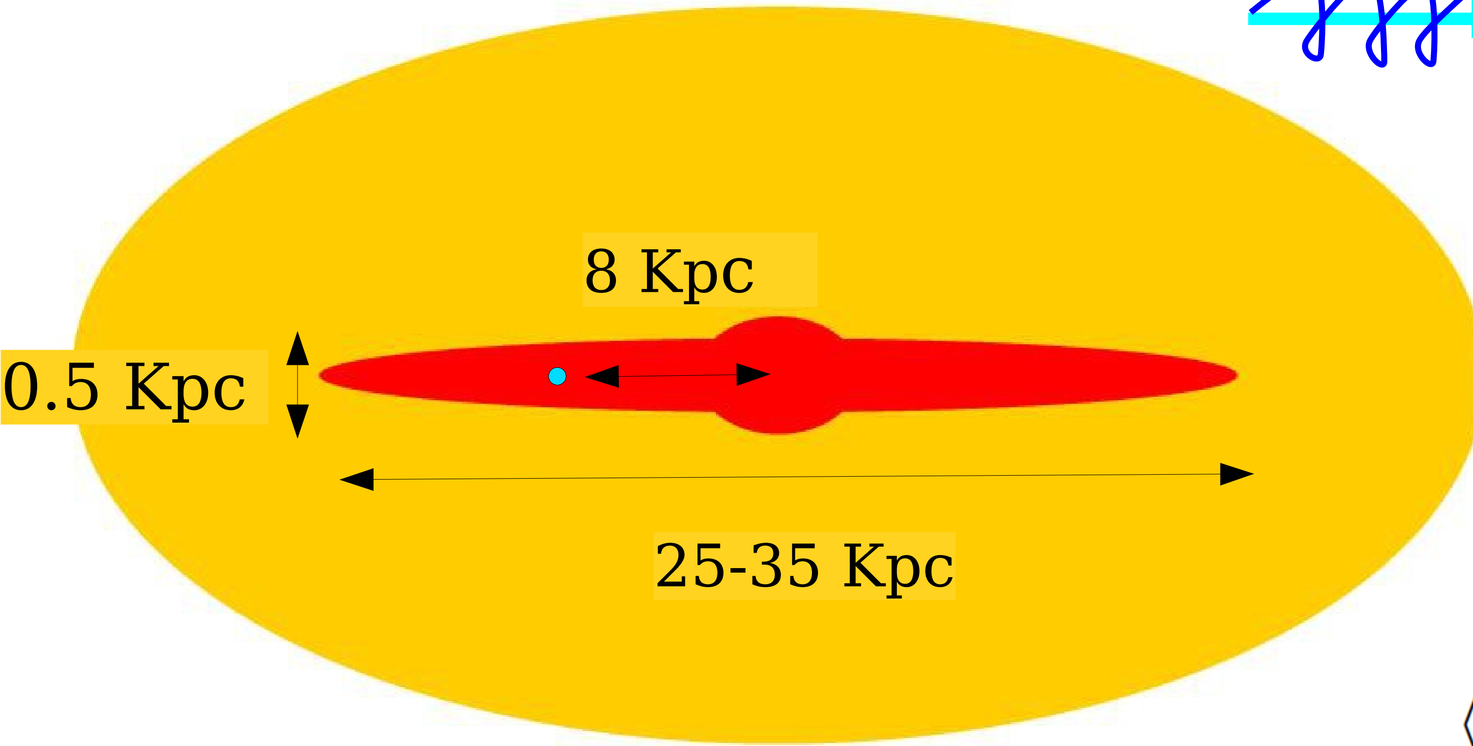
$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq \left[1.6 \times 10^{51} \text{ erg}\right] \; \left[\frac{3}{\text{century}}\right]$$

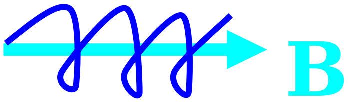
$$M = 5 \; M_{\odot}$$

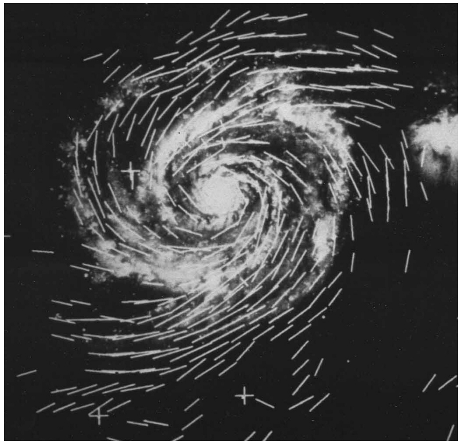
$$v \simeq 5000 \text{ Km/s}$$

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq 1.5 \times 10^{42} \; \frac{\text{erg}}{\text{s}}$$

Power Provided by SN is sufficient
with a conversion efficiency of 15-20 %
in relativistic particles







$$r_L = \frac{p_\perp c}{q\,B}$$

$$\langle B_{\rm MW} \rangle \simeq 3\ \mu{\rm Gauss}$$

$$r_L = \frac{1.08\ {\rm Kpc}}{Z} \left[\frac{E}{10^{18}\,{\rm eV}}\right] \left[\frac{\mu{\rm Gauss}}{B}\right]$$

$$r^p_{\rm Larmor}(100\ {\rm GeV}) \simeq 3.6 \times 10^{-8}\ {\rm Kpc}$$

$$r^p_{\rm Larmor}(10^{20}\ {\rm eV}) \simeq 36\ {\rm Kpc}$$

$$r^{\rm Fe}_{\rm Larmor}(10^{20}\ {\rm eV}) \simeq 1.4\ {\rm Kpc}$$

- Diffusion approximation
- Maximum energy for containment

Fermi Acceleration

COSMIC RAY ACCELERATION

Very important paper of Enrico Fermi (1949)

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

The theory originally proposed by Fermi is NOT correct
But this work contains a **fundamental idea** that
it is believed to be valid for cosmic ray acceleration.

On the Origin of the Cosmic Radiation

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A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

A theory of the origin of the Cosmic Rays is proposed according to which cosmic rays are accelerated primarily in the interstellar space of the galaxy by **collisions against moving magnetic fields [moving "clouds"]**

One of the features of the theory is that **it yields naturally an inverse power law** for the spectral distribution of the cosmic rays

FERMI ORIGINAL MODEL:

- General structure:

  Single acceleration event:
  Particle with Energy E
  in the event it gains an energy proportional to E

$$\Delta E = \xi \ E$$

- The events are iterated with probability 1-P
  The iteration is stopped with probability P

Two parameters ξ P

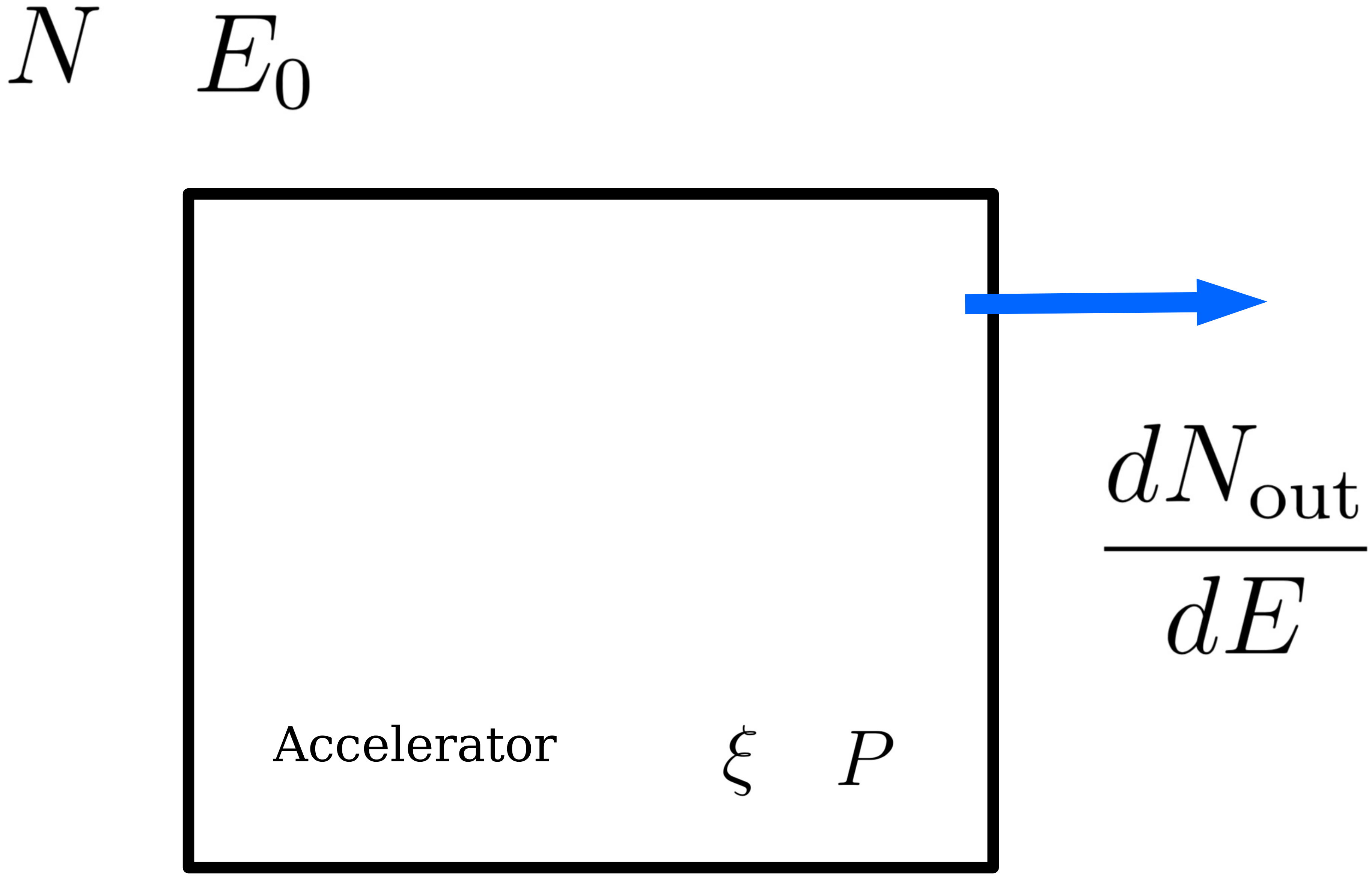
Problem:

We have a number N of particles all withe Energy E_0 inside an "accelerator". At regular intervals the particles acquire an energy $\Delta E = \xi\, E$, but with probability P the particle will exit the accelerators, and the acceleration process stops.

What is the energy Spectrum of the particles that exit from the accelerator:

$$\Delta E = \xi \; E$$

$$E \to E\,(1+\xi) \to E\,(1+\xi)\,(1+\xi) \to \ldots$$


N
E_0
Accelerator
ξ
P
$\frac{dN_{\mathrm{out}}}{dE}$

$$
\begin{aligned}
&E_0 \\
&E_1 = E_0\,(1+\xi) \\
&E_2 = E_0\,(1+\xi)^2 \\
&\ldots \\
&E_k = E_0\,(1+\xi)^k
\end{aligned}
$$

The Probability to have energy E_k is the probability of having received the acceleration *exactly* k times:

$$
\begin{aligned}
P_k &= (1-P)\,(1-P)\ldots(1-P)\;P \\
&= (1-P)^k\;P
\end{aligned}
$$

$$E_k = E_0\ (1+\xi)^k$$

$$n_k = N\ P_k = N_0\ P(1-P)^k$$

$$k\ =\ \log_{1+\xi}\left[\frac{E_k}{E_0}\right] \qquad =\ \frac{\ln(E_k/E_0)}{\ln(1+\xi)}$$

$$
\begin{aligned}
n_k &\equiv n(E_k) = N_0 \, P \, (1-P)^k \\
&= N_0 \, P \, (1-P)^{\frac{\ln(E_k/E_0)}{\ln(1+\xi)}} \\
&= N_0 \, P \, \exp\left[\frac{\ln(1-P) \, \ln(E_k/E_0)}{\ln(1+\xi)}\right] \\
&= N_0 \, P \, \left(\frac{E_k}{E_0}\right)^{\frac{\ln(1-P)}{\ln(1+\xi)}}
\end{aligned}
$$

$$n(E_k) = N_0 \; P \quad \left(\frac{E_k}{E_0}\right)^{\frac{\ln(1-P)}{\ln(1+\xi)}}$$

$$\frac{dn}{dE} \simeq \frac{n(E_k)}{\Delta E_k} \propto E^{\frac{\ln(1-P)}{\ln(1+\xi)}-1}$$

$$\frac{dn(E)}{dE} \propto E^{-(\gamma+1)}$$

$$n(E_k) = N_0 \; P \; \left(\frac{E_k}{E_0}\right)^{\frac{\ln(1-P)}{\ln(1+\xi)}}$$

Discrete Spectrum of the toy model

$$\frac{dn}{dE} \simeq \frac{n(E_k)}{\Delta E_k} \propto E^{\frac{\ln(1-P)}{\ln(1+\xi)}-1}$$

Differential Spectrum slope $\alpha = \gamma + 1$

$$n(>E) \propto E^{-\gamma}$$

Integral Spectrum slope γ

$$\frac{dn(E)}{dE} \propto E^{-(\gamma+1)}$$

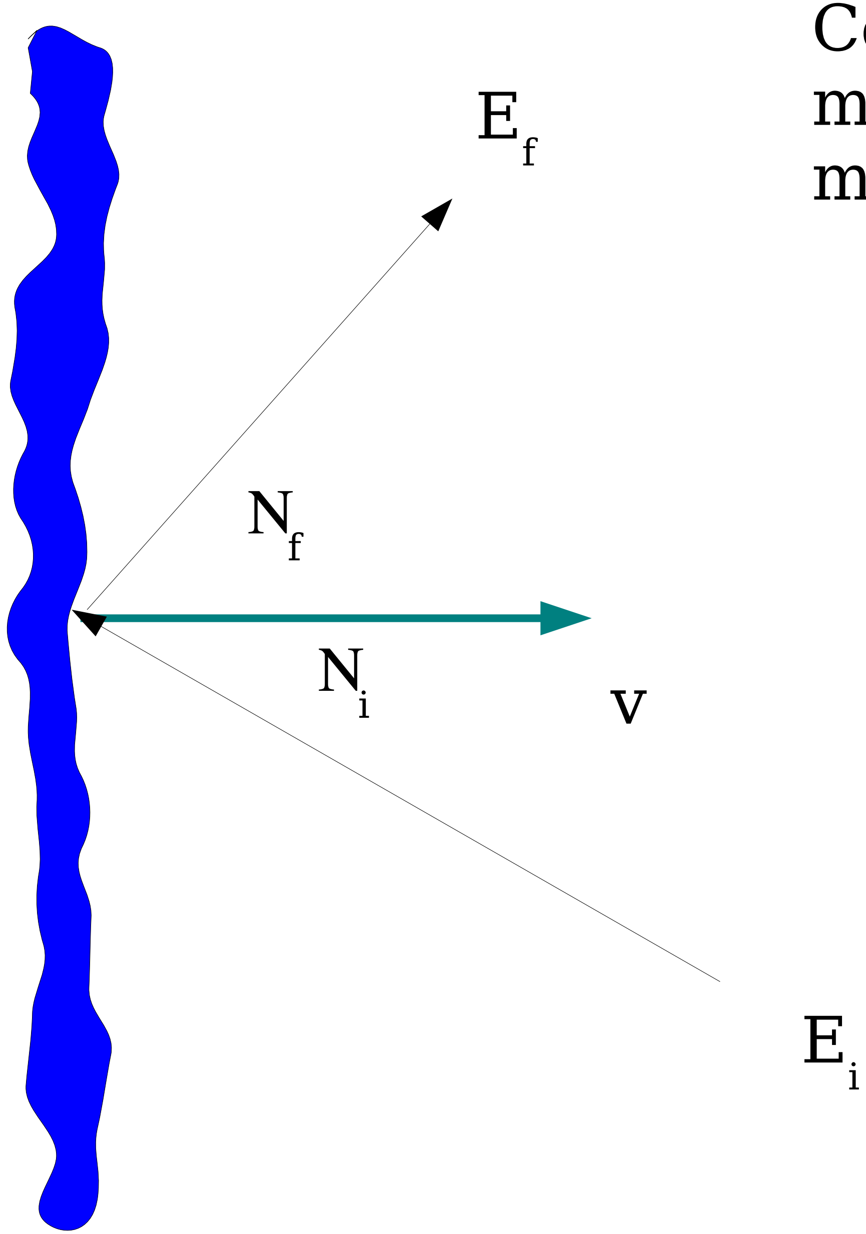
$$\gamma = -\frac{\ln(1-P)}{\ln(1+\xi)} \simeq \frac{P}{\xi}$$

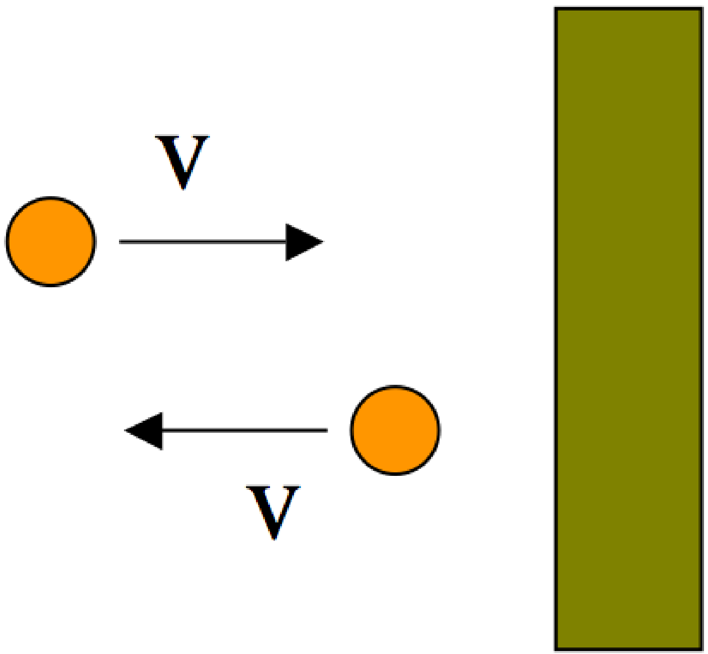
$$\ln(1+x) \simeq x + \frac{x^2}{2} - \frac{x^3}{3} + \dots$$

$$\ln(1-P) \simeq -P + \dots$$

$$\ln(1+\xi) \simeq \xi + \dots$$

Collisions with a macroscopic Object moving with velocity v

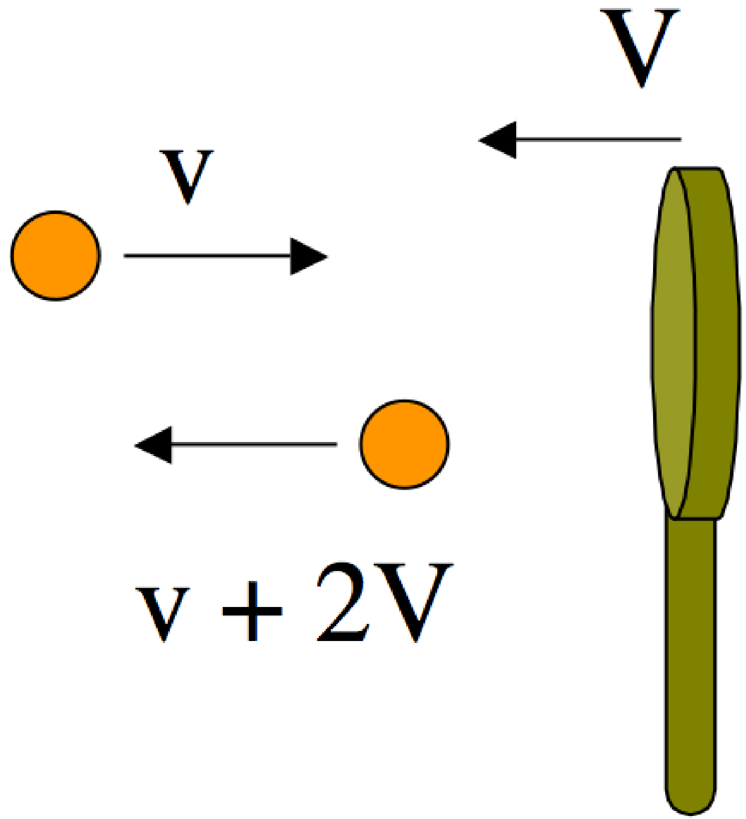




Elastic scattering
of a particle

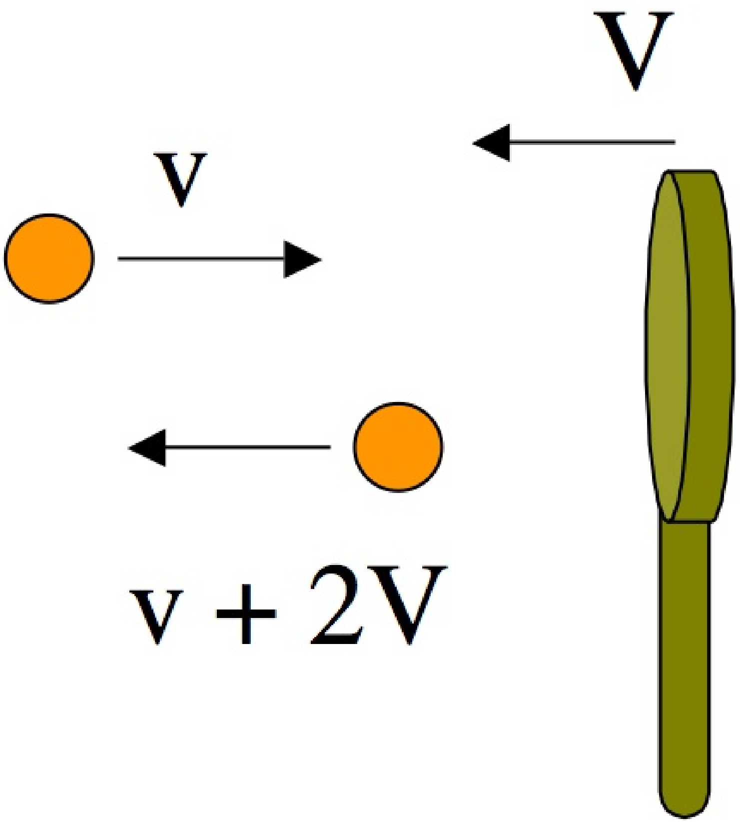
Wall at rest.

[Non relativistic velocities]



Elastic scattering:
the particle is
accelerated!

Moving Racket
(velocity V)



Why the final velocity is $v_{ball} + 2\ V_{racket}$?

2 Galilean transformations

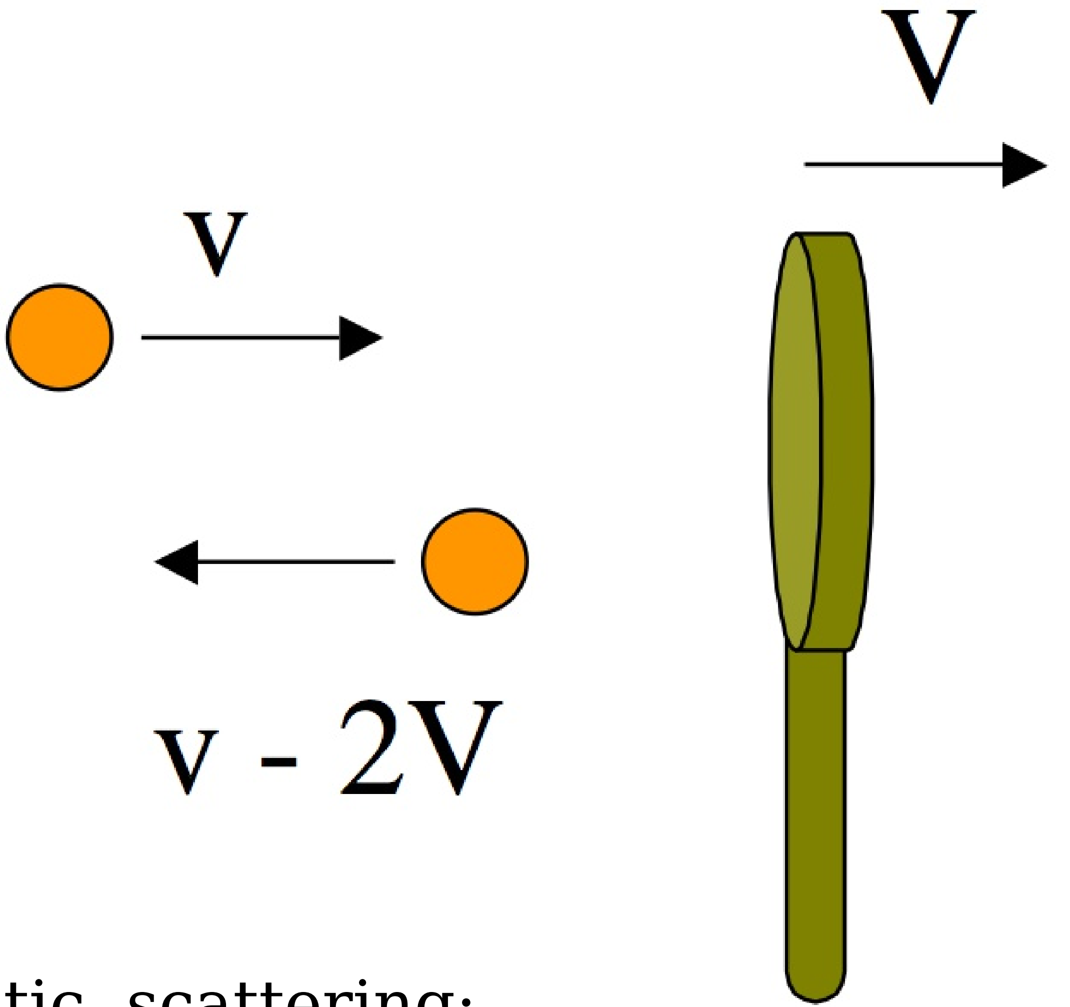
1. Go to frame where The racket is at rest. The ball in this frame has velocity:

   $v_{ball} + V_{racket}$

2. Transform back to the Original frame adding V_{racket}. The result is.

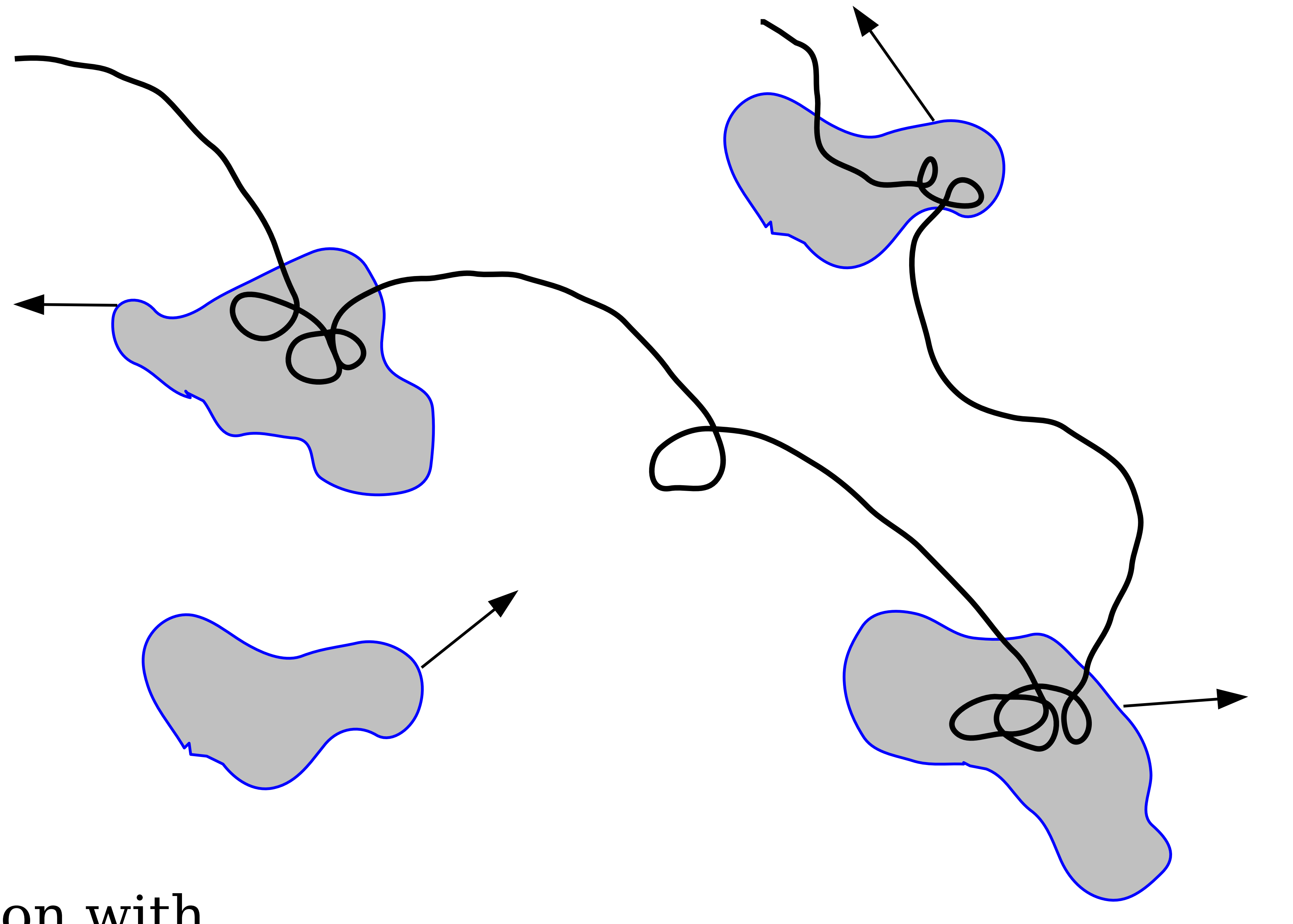
   $v_{ball} + 2\ V_{racket}$

“Drop Shot” slow down the ball

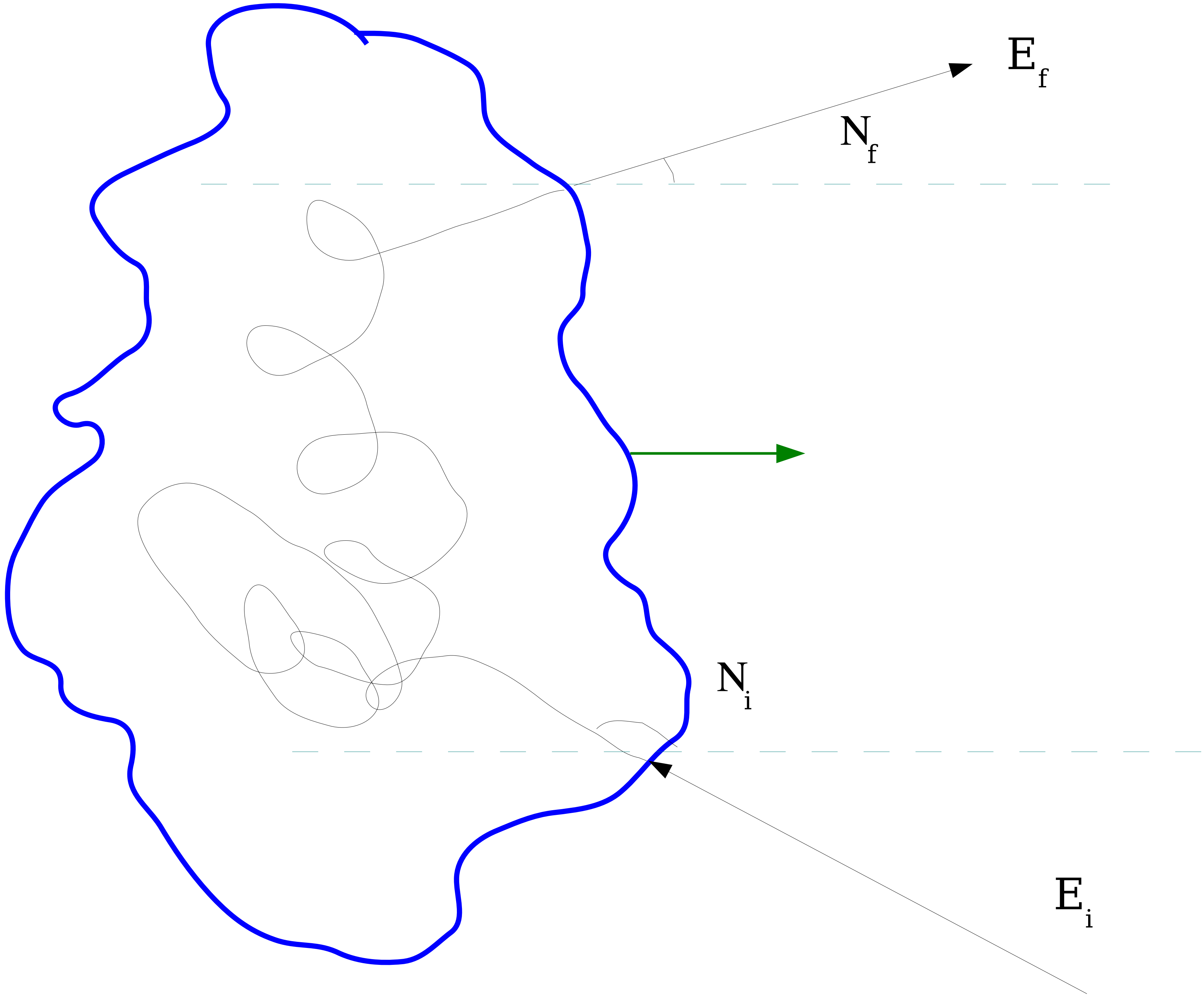


Elastic scattering:
the particle is
decelerated.

Moving Racket
(velocity -V)



Collision with
moving Plasma Clouds
in the Galaxy



E f
N f
N i
E i

Scattering on Plasma Clouds
Elastic Scattering of a particle of mass m on a "moving WALL" with mass $M \gg m$

Problem :A Particle scatters on a moving wall (a moving MACROSCOPIC OBJECT $M \gg m$) The particle has initial Energy E_i and initial direction (with respect to the wall velocity) θ_i.

Compute the final state energy E_f as a function of θ_f (the scattering angle).

In the system where the wall is at rest (indicated by $*$) the problem is of course trivial: $E_f^* = E_i^*$.

$$
\begin{aligned}
E_i^* &= \gamma\,(E_i - \beta\, p_{z,i}) \\
&\simeq \gamma\, E_i (1 - \beta\, \cos\theta_i)
\end{aligned}
$$

$$
\begin{aligned}
E_f &= \gamma\, E_i^*\, (1 + \beta\, \cos\theta_f^*) \\
&= \gamma^2\, (1 - \beta\, \cos\theta_i)(1 + \beta\, \cos\theta_f^*)\ \mathrm{E_i}
\end{aligned}
$$

$$\langle E_f \rangle = E_i \, \gamma^2 \, (1 - \beta \, \langle \cos \theta_i \rangle) \, (1 + \beta \, \langle \cos \theta_f^* \rangle)$$

$$\langle cos\theta_f^* \rangle = 0$$

The computation of $\langle cos\theta_i \rangle$ is a little more difficult, but it is obvious that "front" encounters are more likely that "back" encounters and therefore $\langle cos\theta_i \rangle < 0$. In fact the probability of θ_i is proportional to the *relative velocity* between the particle and the cloud.

$$v_{\rm rel} = \left|\vec{v}_{\rm cloud} - \vec{v}_{\rm particle}\right|$$

$$= \sqrt{(c - v\ \cos\theta_i)^2 + v^2\ \sin^2\theta_i}$$

$$= c\ \sqrt{(1 - \beta\cos\theta_i)^2 + \beta^2\ \sin^2\theta_i}$$

$$= c\ \sqrt{1 + \beta^2 - 2\beta\ \cos\theta_i}$$

$$\simeq c\ \sqrt{(1 - 2\beta\ \cos\theta_i}$$

$$\simeq c\ (1 - \beta\ \cos\theta_i) \qquad \beta \ll 1$$

$$\frac{dN}{d\cos\theta_i} \propto v_{\mathrm{rel}} \propto (1 - \beta\,\cos\theta_i)$$

$$\langle\cos\theta_i\rangle = \frac{\int_{-1}^{+1} d\cos\theta_i\;\;\cos\theta_i\;(1 - \beta\cos\theta_i)}{\int_{-1}^{+1} d\cos\theta_i\;(1 - \beta\cos\theta_i)} = -\frac{\beta}{3}$$

$$
\begin{aligned}
\frac{\langle E_f \rangle}{E_i} &= \gamma^2 \left(1 - \beta \langle \cos\theta_i \rangle\right) \left(1 + \beta \langle \cos\theta_f^* \rangle\right) \\
&\simeq \gamma^2 \left(1 - \beta \left(-\frac{\beta}{3}\right)\right) \left(1 + \beta \times 0\right) \\
&\simeq \frac{1}{1-\beta^2} \left(1 + \frac{\beta^2}{3}\right) \\
&\simeq \left(1 + \beta^2 + \ldots\right) \left(1 + \frac{\beta^2}{3}\right) \\
&\simeq 1 + \frac{4}{3}\,\beta^2 + \ldots
\end{aligned}
$$

$$
\boxed{\frac{\langle E_f \rangle}{E_i} \simeq 1 + \frac{4}{3}\,\beta^2 + \ldots}
$$

In the original form of the Fermi acceleration, the accelerator is the entire Galaxy and therefore the probability $P_{\rm esc}$ to "exit" from the accelerator is the simply the probability to exit from the galaxy between one encounter with a cloud and the next or:

$$P_{\rm esc} \sim \frac{(\Delta t)_{\rm encounters}}{T_{\rm conf}}$$

$$\Delta t \simeq \left[n_{\rm clouds}\ (\pi r^2_{\rm cloud})\, c\right]^{-1}$$

$$\gamma = \frac{P_{\rm esc}}{\xi} \simeq \frac{\Delta t / T_{\rm conf}}{4/3\ \beta^2}$$

$$\beta \sim 10^{-4}$$

$$T_{\rm conf} \simeq 10^7 \ \text{years} \simeq 10^{15} \ \text{sec}$$

$$\Delta t \simeq 10^8 \ \text{sec}$$

$$\gamma = \frac{P_{\rm esc}}{\xi} \simeq \frac{\Delta t / T_{\rm conf}}{4/3 \ \beta^2}$$

$$\boxed{\gamma \sim 10}$$

Spectrum too soft

MODIFICATION of the original FERMI Model

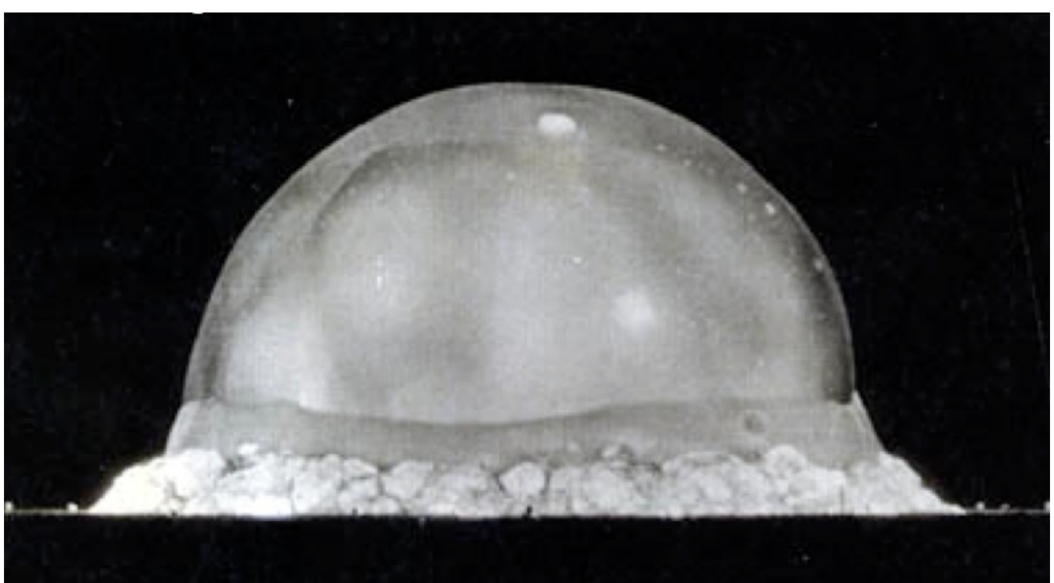
ACCELERATION at SHOCK FRONTS

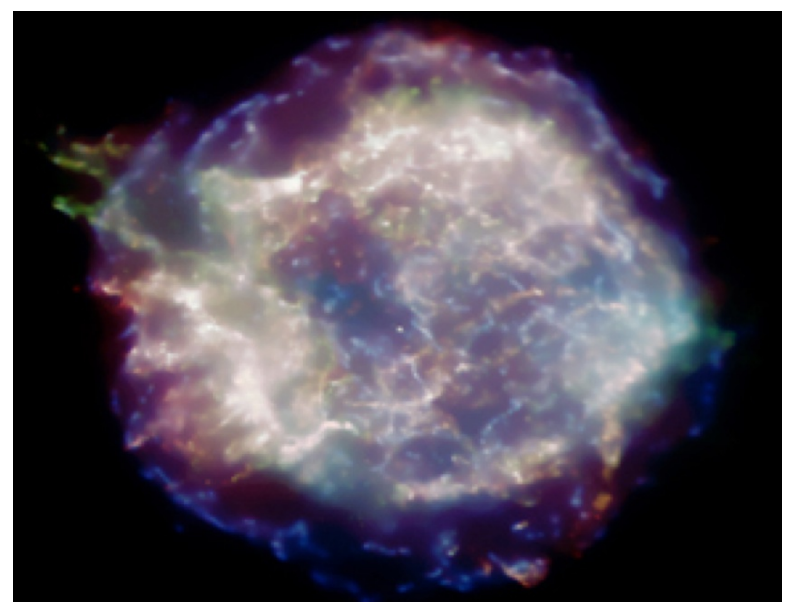
FERMI 1^{st} ORDER ACCELERATION

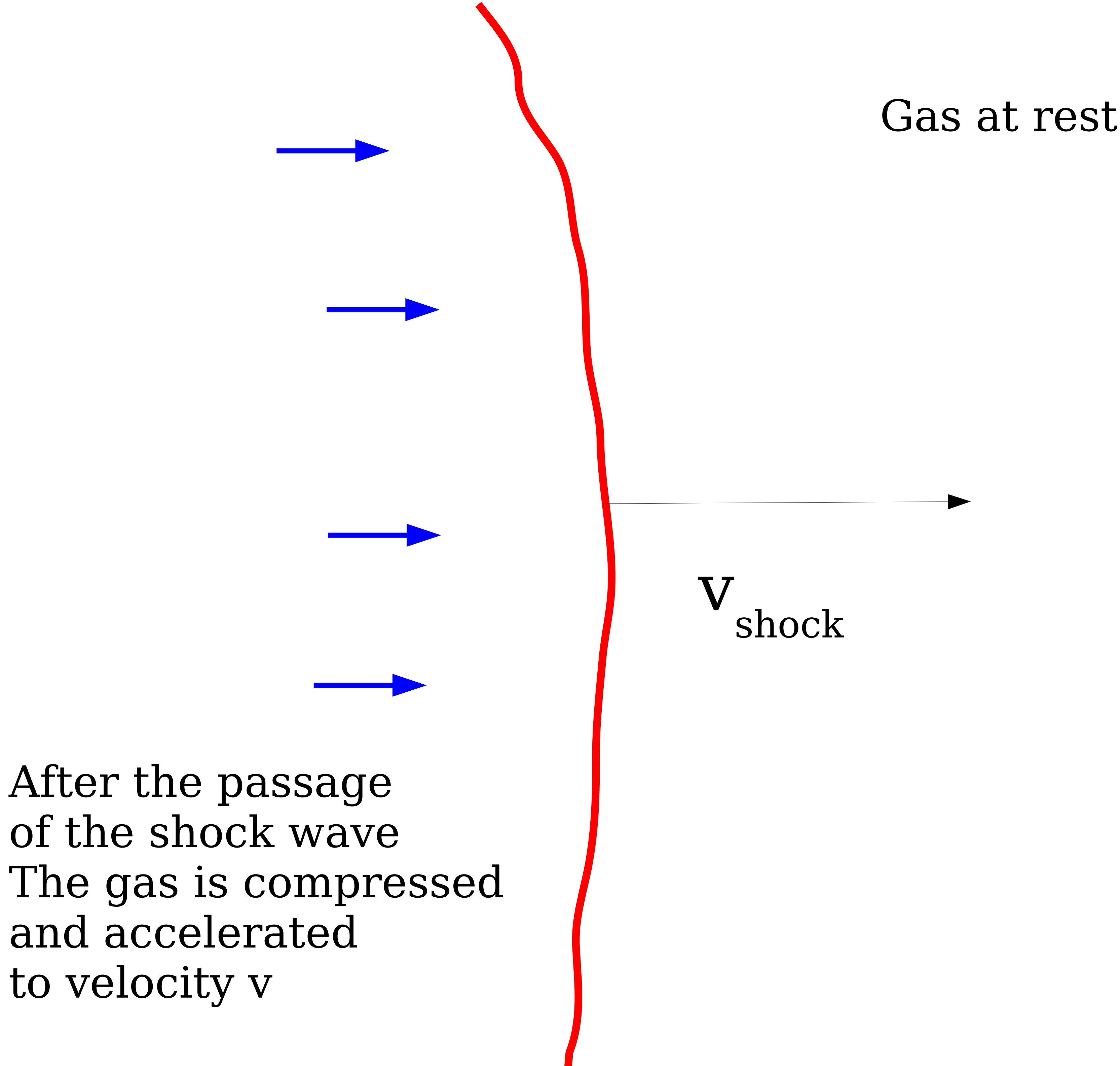
SHOCK in a fluid

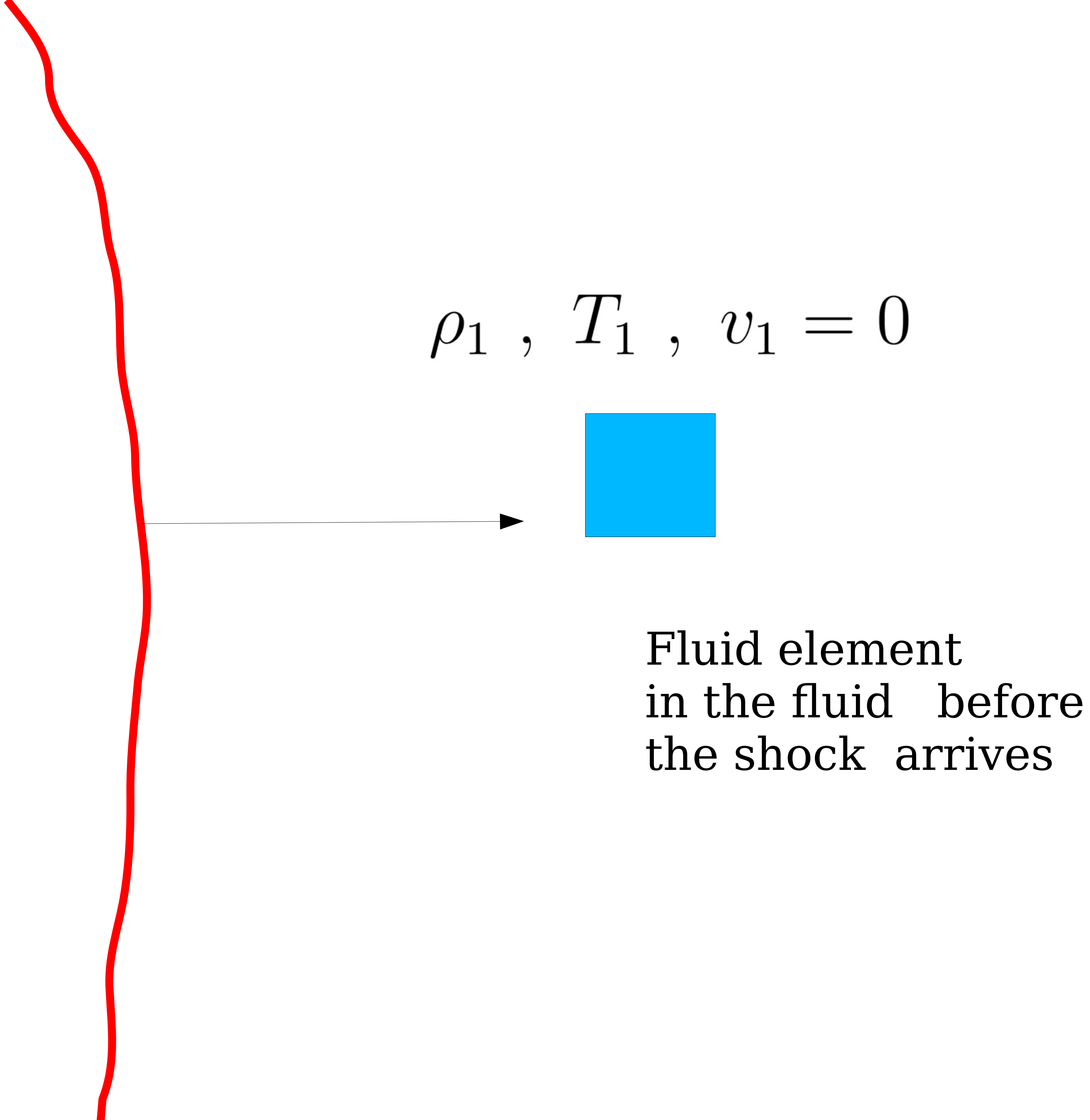
Surface of discontinuity in the thermodynamics quantities

(Density, Temperature, Velocity)

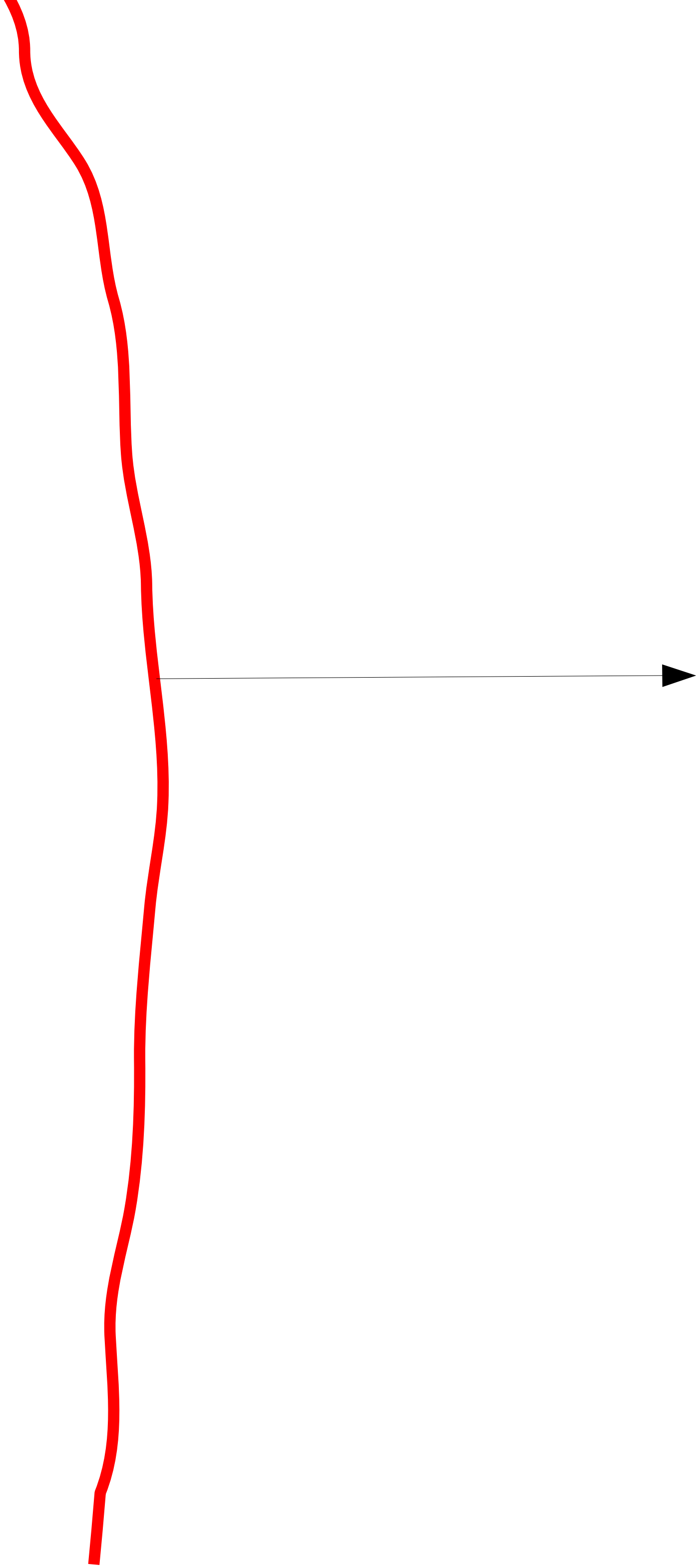





Gas at rest
v shock
After the passage
of the shock wave
The gas is compressed
and accelerated
to velocity v


$\rho_1 \ , \ T_1 \ , \ v_1 = 0$
Fluid element
in the fluid before
the shock arrives

$$\rho_2 \ , \ T_2 \ , \ v_2$$



Fluid element
After the shock
has passed:

- Set in motion
- Compressed
- Heated

Shock arrive with velocity V_{shock}

$$\rho_1 \ , \ T_1 \ , \ v_1 = 0$$

Compute the fluid properties after the shock:

$$\rho_2 \ , \ T_2 \ , \ v_2$$

$$V_{\text{shock}} > v_{\text{sound}}$$

$$M = \frac{V_{\text{shock}}}{v_{\text{sound}}}$$

Mach Number

$M \gg 1$ Strong shocks

Kinematics Relation at the Shock

Rankine Huguniot Relations

Conservation of MASS (number of Particles),
MOMENTUM,
ENERGY

$$\rho_1 \, v_1 = \rho_2 \, v_2$$

$$\rho_1 \, v_1^2 + P_1 = \rho_2 \, v_2^2 + P_2$$

$$\frac{1}{2} \, v_1^2 + \frac{P_1 + U_1}{\rho_1} = \frac{1}{2} \, v_2^2 + \frac{P_2 + U_2}{\rho_2}$$

$$r = \frac{\gamma - 1}{\gamma + 1}$$

$$\gamma = \frac{2}{f} + 1$$

$$\rho_2 = r\ \rho_1$$

$$M \gg 1$$

$$v_2 = \frac{V_{\text{shock}}}{r}$$

$$T \approx m\ V_s^2\ \frac{(r - 1)}{r^2}$$

$$r = \frac{\gamma - 1}{\gamma + 1}$$

$$\gamma = \frac{2}{f} + 1$$

$$\rho_2 = r \ \rho_1$$

$$M \gg 1$$

$$v_2 = \frac{V_{\text{shock}}}{r}$$

Monoatomic gas

$$\gamma = \frac{5}{3} \qquad r = 4$$

$$T \approx m \ V_s^2 \ \frac{(r-1)}{r^2}$$

$$r = \frac{\gamma - 1}{\gamma + 1}$$

$$\gamma = \frac{2}{f} + 1$$

$$\rho_2 = r\ \rho_1$$

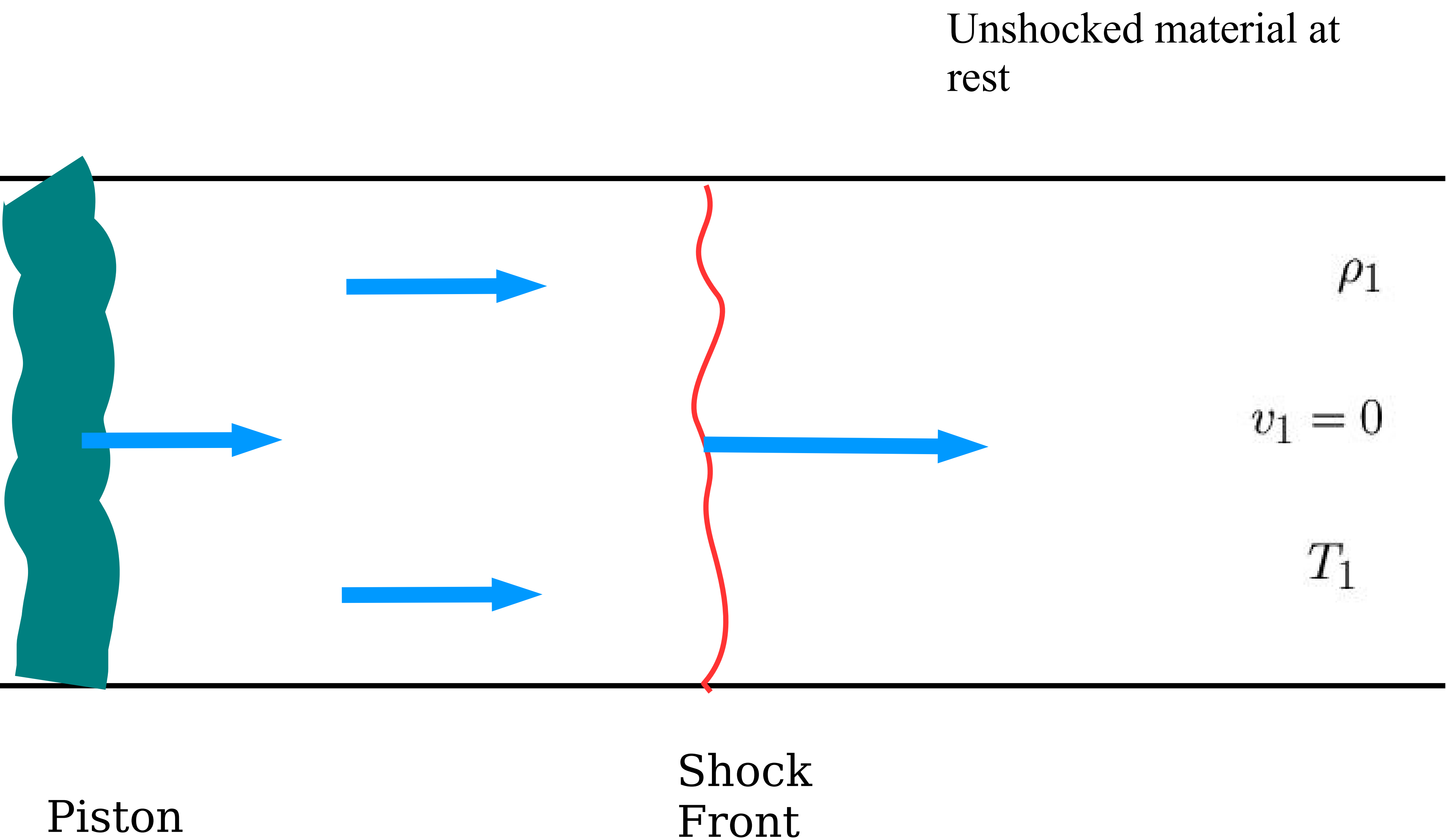
$$M \gg 1$$

$$v_2 = \frac{V_{\rm shock}}{r}$$

Biatomic gas

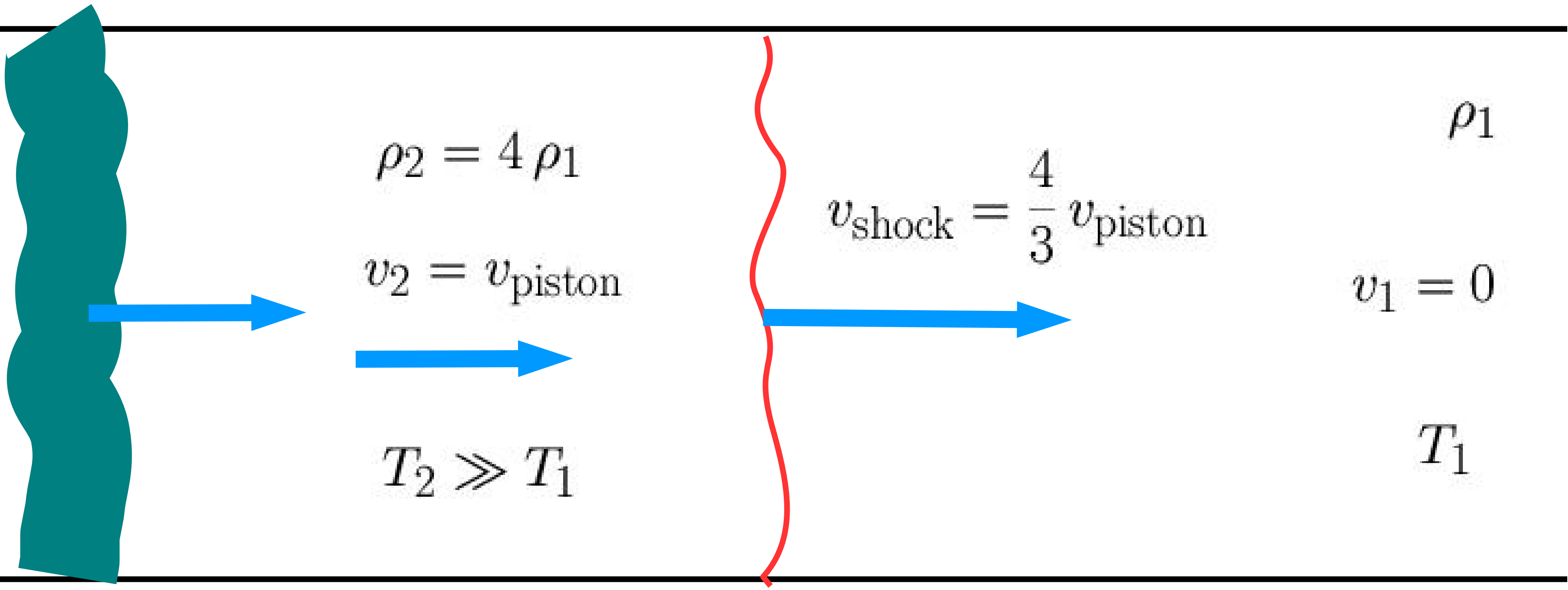
$$\gamma = \frac{7}{5} \qquad r = 6$$

$$T \approx m\ V_s^2\ \frac{(r-1)}{r^2}$$


Unshocked material at rest
ρ_1
$v_1 = 0$
T_1
Shock Front
Piston

STRONG SHOCK

Unshocked material at rest



shocked material

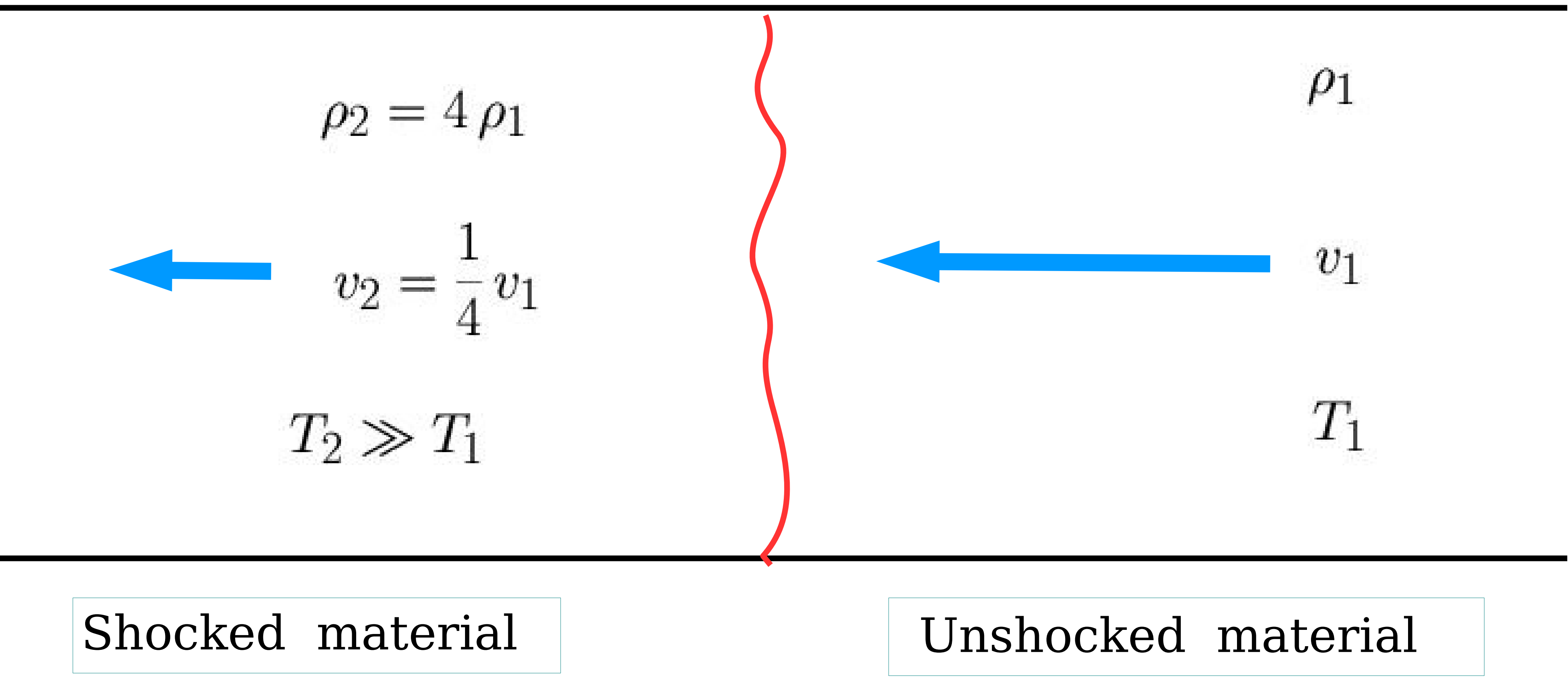
Unshocked material

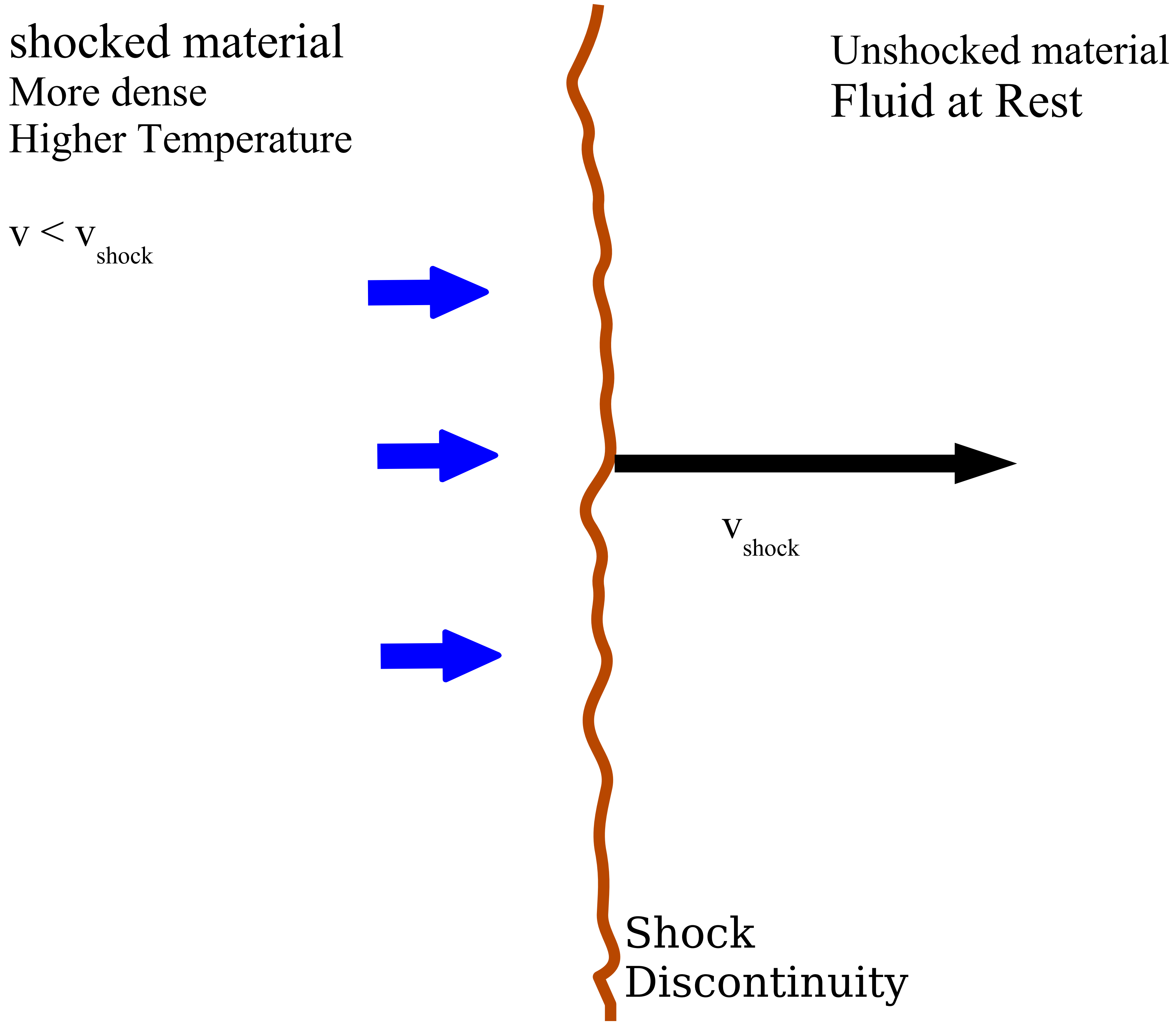
Compression factor r

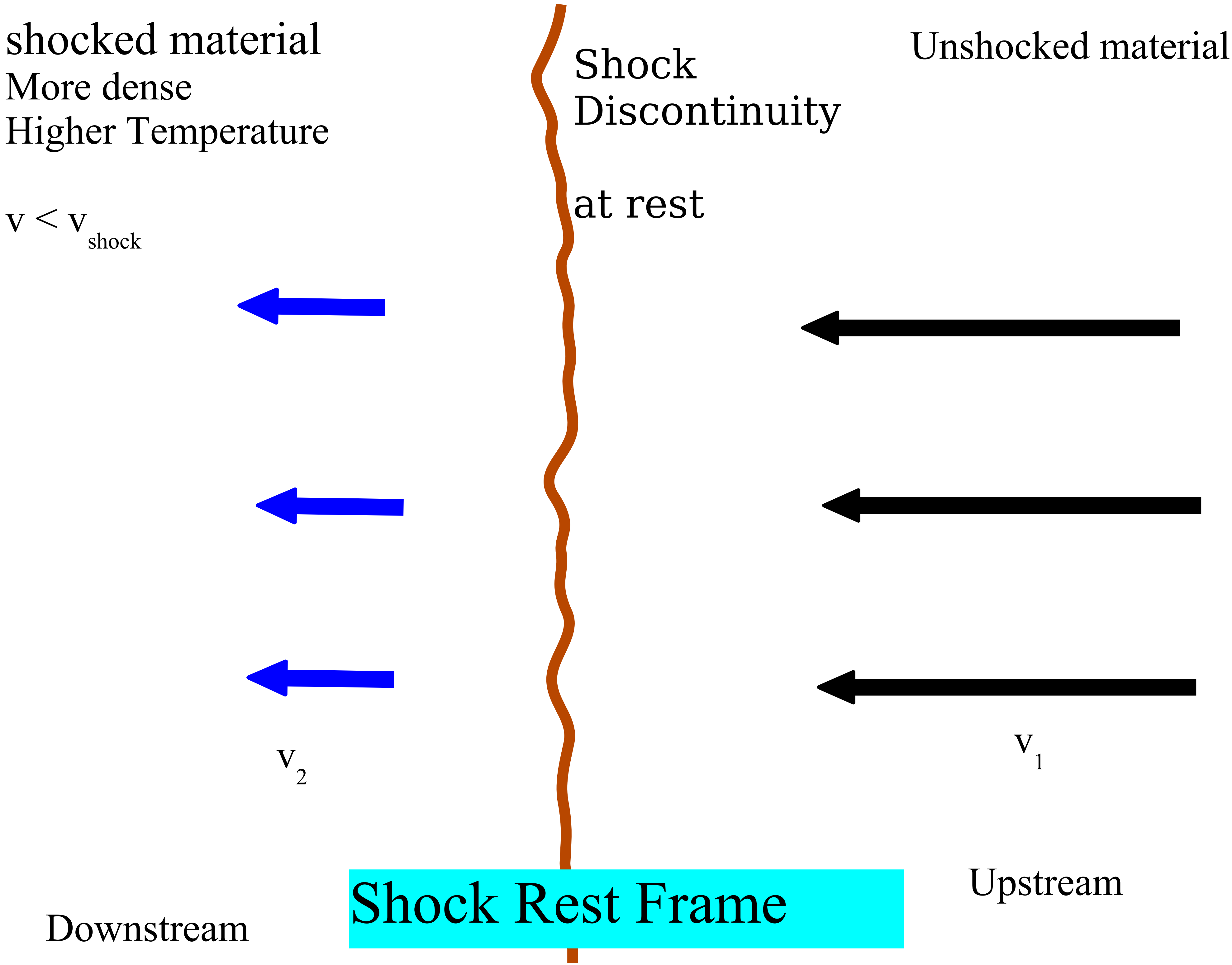
$$r \to \frac{\gamma + 1}{\gamma - 1} = 4$$

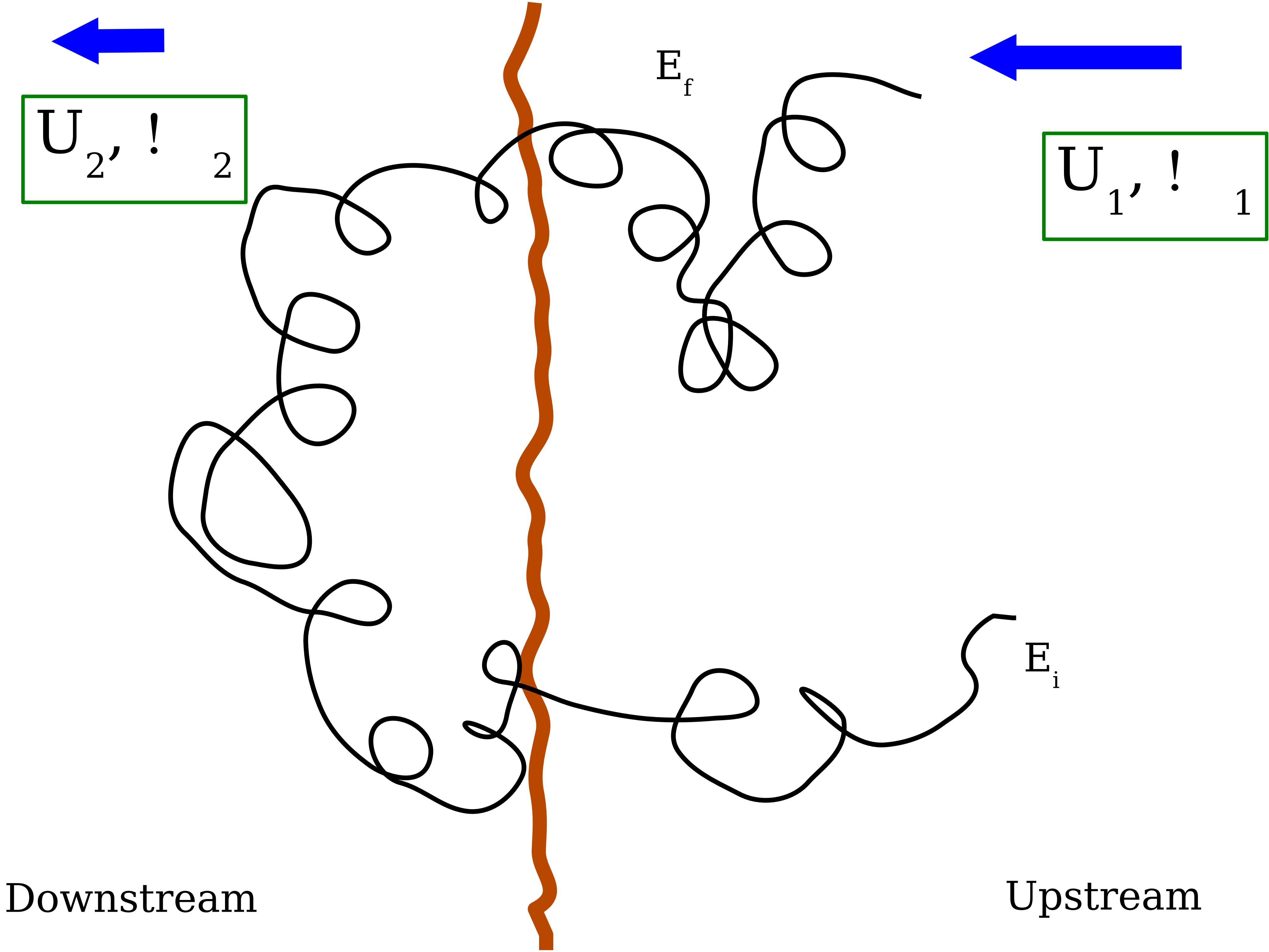
STRONG SHOCK

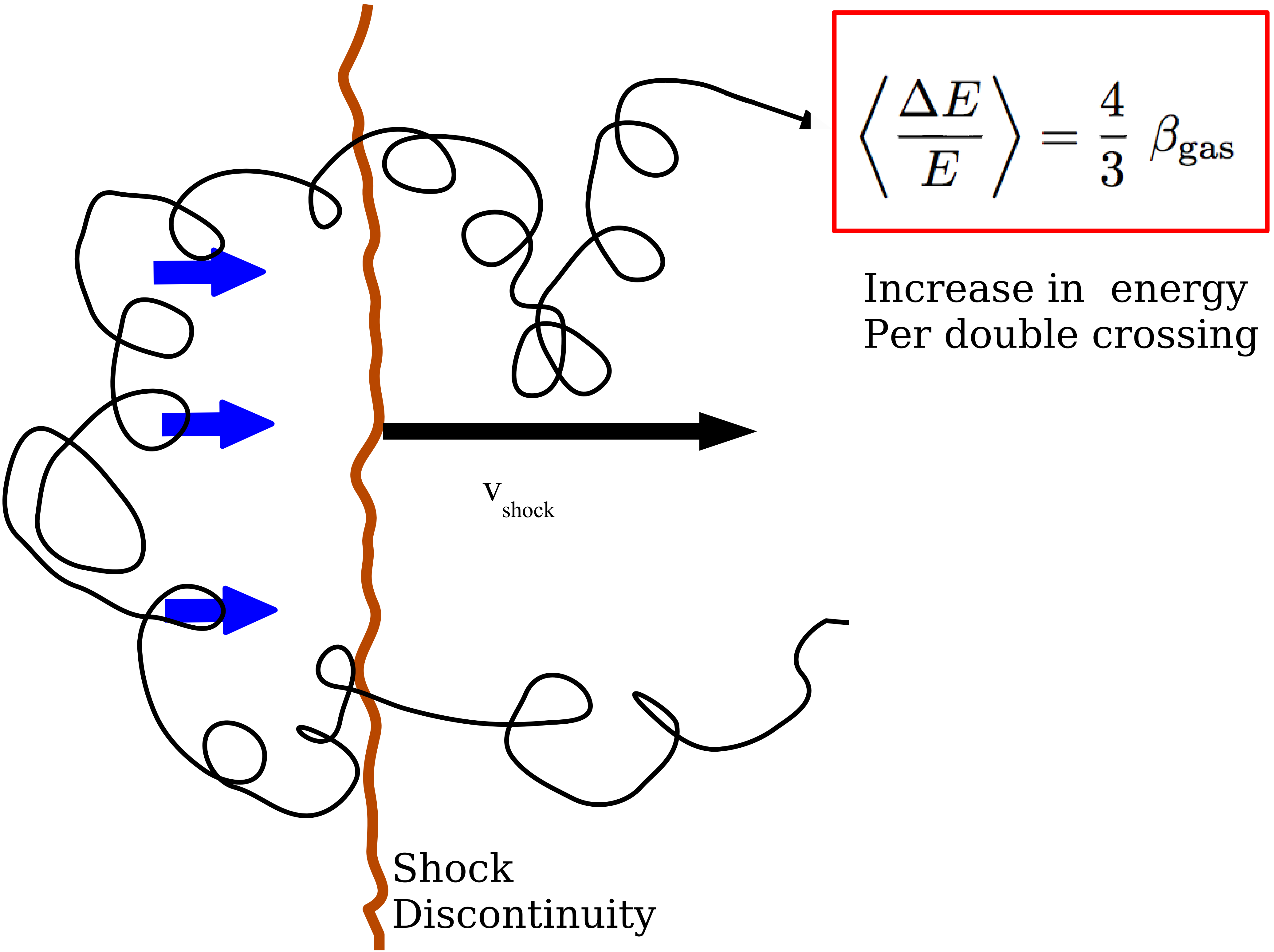
Shock Rest Frame

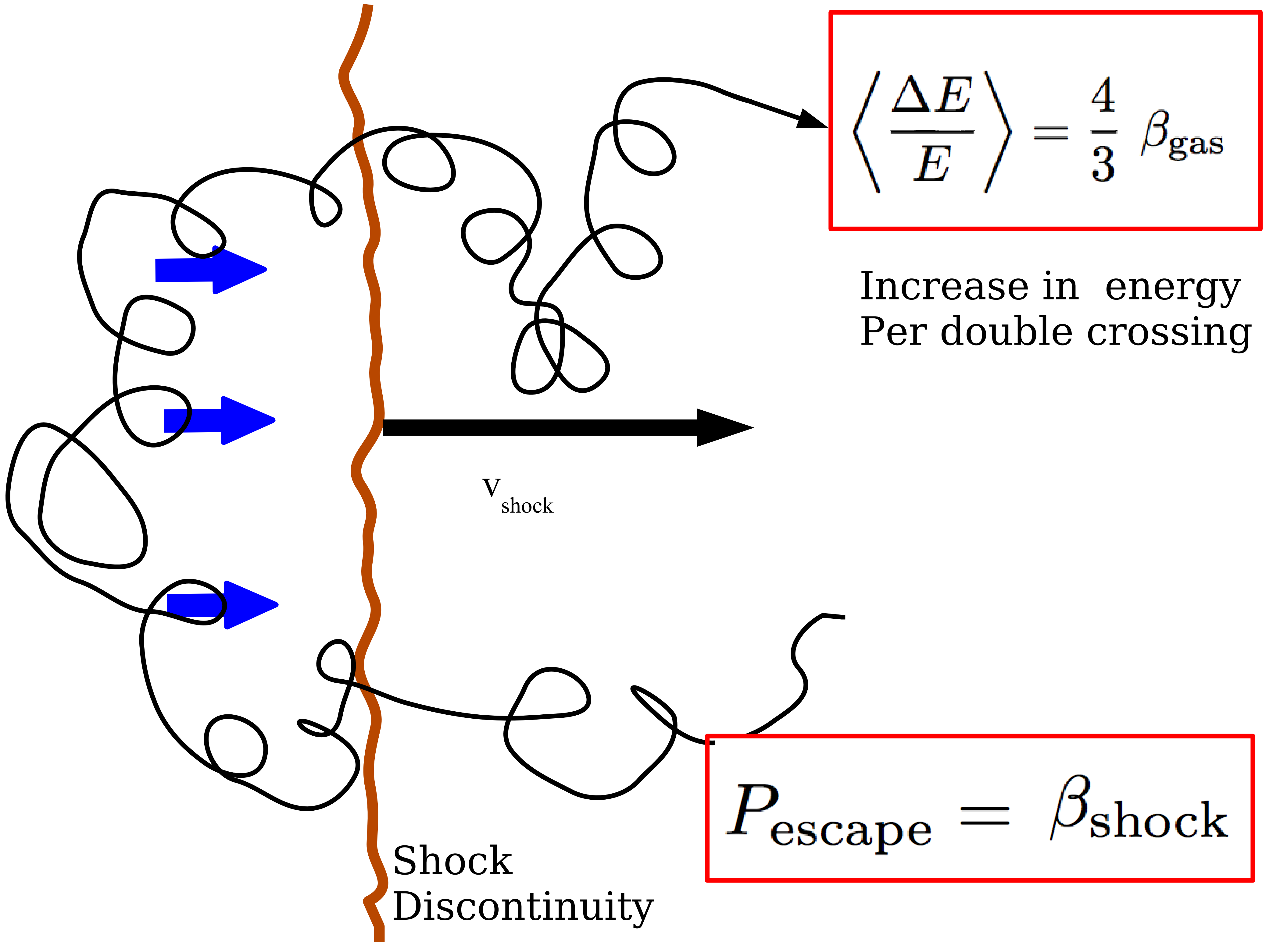



shocked material
More dense
Higher Temperature
$v < v_{shock}$
Unshocked material
Fluid at Rest
v_{shock}
Shock
Discontinuity


shocked material
More dense
Higher Temperature
v < v shock
Shock
Discontinuity
at rest
Unshocked material
v 2
v 1
Downstream
Shock Rest Frame
Upstream


U_2, ! $_2$
E_f
U_1, ! $_1$
E_i
Downstream
Upstream


$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\ \beta_{\mathrm{gas}}$
Increase in energy
Per double crossing
v_{shock}
Shock
Discontinuity



$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\, \beta_{\mathrm{gas}}$
Increase in energy
Per double crossing
v_{shock}
$P_{\mathrm{escape}} = \beta_{\mathrm{shock}}$
Shock
Discontinuity

$$\alpha = 1 + \frac{P_{\mathrm{esc}}}{\xi}$$

$$\alpha = 1 + \frac{\beta_{\mathrm{shock}}}{\frac{4}{3}\,\beta_{\mathrm{gas}}}$$

Strong shock

$$\alpha = 2 + \epsilon$$

Universal Spectral shape !

Demonstration that : $\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\, \beta_{\text{gas}}$

$$E_f = \gamma^2\, [1 - \beta \cos\theta_i]\, [1 + \beta\, \cos\theta_f^*]$$

$$-1 \leq \cos\theta_i \leq 0$$

$$0 \leq \cos\theta_f \leq 1$$

$$\frac{dN}{d\cos\theta_i} \propto \cos\theta_i$$

$$\frac{dN}{d\cos\theta_f^*} \propto \cos\theta_f^*$$

$$\phi_{\mathrm{in}} = n\,c \;\int_{-1}^{\beta} \frac{d\cos\theta}{2}\;[-\cos\theta + \beta]$$

$$= \frac{n\,c}{2}\;\left[-\frac{(\cos\theta)^2}{2} + \beta\;\cos\theta\right]_{-1}^{\beta}$$

$$= \frac{n\,c}{4}\;\left[\frac{1-\beta^2}{2} + \beta(1+\beta)\right] = \frac{n\,c}{4}\;(1+\beta)^2$$

$$\langle \cos\theta_i \rangle = \frac{\int_1^0 \; dz \;\; z \;\; z}{\int_1^0 \; dz \;\; z} = \frac{-1/3}{1/2} = -\frac{2}{3}$$

$$\langle \cos\theta_f^* \rangle = \frac{\int_0^1 \; dz \;\; z \;\; z}{\int_0^1 \; dz \;\; z} = \frac{+1/3}{1/2} = +\frac{2}{3}$$

$$\begin{aligned}
\frac{E_f}{E_i} &= \gamma^2 \left[1 - \beta \, \langle \cos\theta_i \rangle\right] \left[1 + \beta \, \langle \cos\theta_f^* \rangle\right] \\
&= \frac{1}{1-\beta^2} \left(1 + \beta \, \frac{2}{3}\right) \left(1 + \beta \, \frac{2}{3}\right) \\
&\simeq 1 + \frac{4}{3} \, \beta + O(\beta^2)
\end{aligned}$$

Demonstration $P_{\text{escape}} = \beta_{\text{shock}}$

When a particle is on the "upstream" side of the shock, it will cross the shock with probability unity, however, when it is on the downstream side (shocked fluid region) it will have a finite probability P to be advected to the fluid without ever recrossing the shock.

To compute this probability we can consider a surface that moves at the same velocity of the shock in the down–stream region of the shock.

We can also assume that the relativisitic particles have a uniform density n and are isotropic in the rest frame of the shocked gas.

In the rest frame of the shocked gas the surface moves with velocity $v = v_2$

The flux ϕ_{in} that enters the surface corresponds to angles θ (with respect to the velocity of the surface) corresponds to

ϕ_{in}

$$v_z^{\text{particle}} \leq v$$

$$c \cos\theta \leq v$$

ϕ_{out}

$$v_z^{\text{particle}} \geq v$$

$$c \cos\theta \geq v$$

$$\phi_{\rm out} = n\,c \int_{\beta}^{1} \frac{d\cos\theta}{2}\,[\cos\theta - \beta] = \frac{n\,c}{4}\,(1-\beta)^2$$

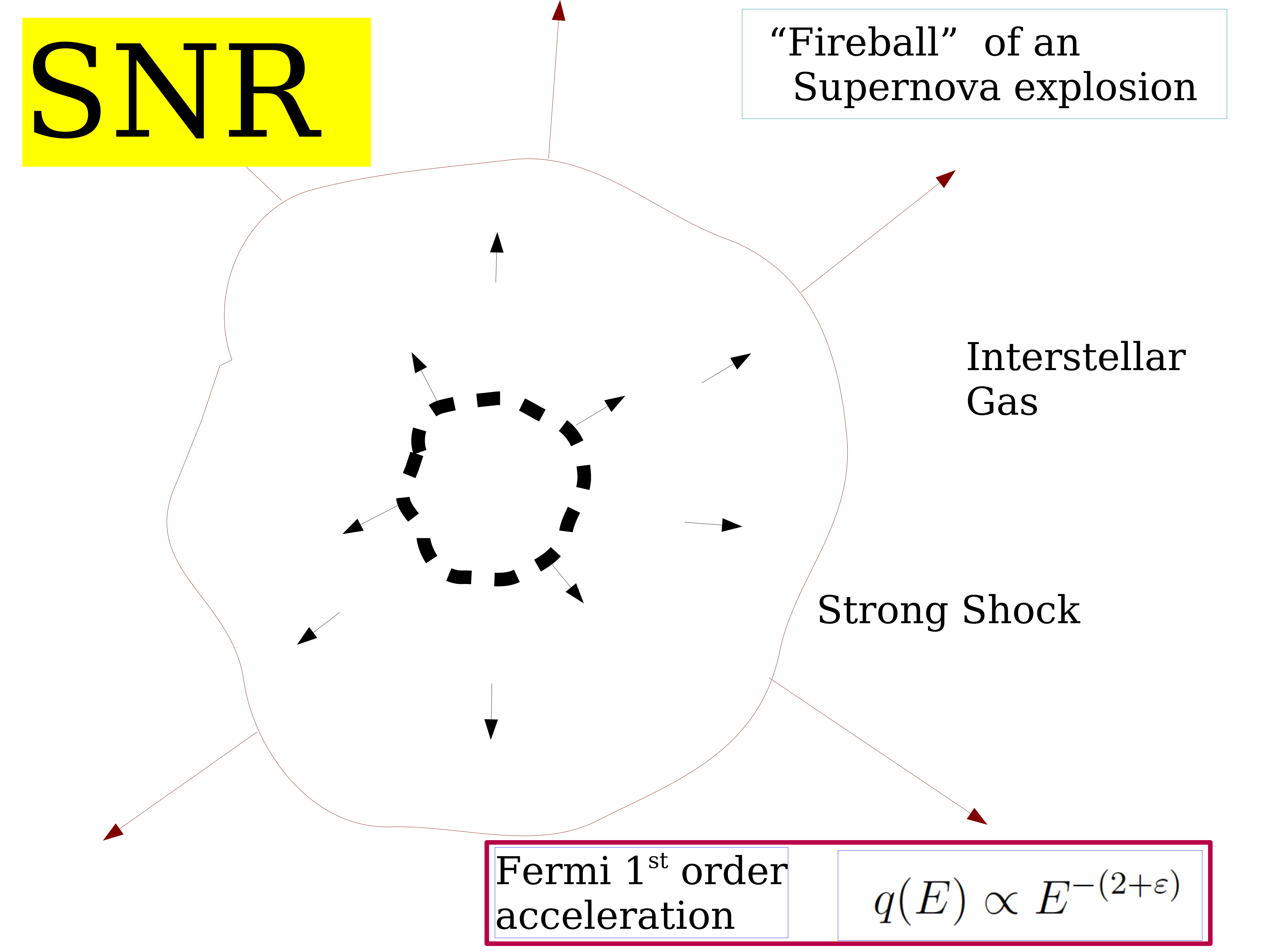
$$\frac{\phi_{\rm out}}{\phi_{\rm in}} = 1 - P_{\rm esc} = \frac{(1-\beta)^2}{(1+\beta)^2} \simeq 1 - 4\beta$$

$$P_{\rm esc} = 4\,\beta_2 = \beta_1 = \beta_{\rm shock}$$

Fermi 2nd order versus Fermi 1st order

Fermi 2nd order

Fermi 1st order
“shock in traffic”


SNR
“Fireball” of an Supernova explosion
Interstellar Gas
Strong Shock
Fermi 1st order acceleration
$q(E) \propto E^{-(2+\varepsilon)}$

$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq E_{\rm SN}^{\rm Kinetic}\ f_{\rm SN}$$

$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq \left[1.6 \times 10^{51}\ {\rm erg}\right]\ \left[\frac{3}{\rm century}\right]$$

$$M = 5\ M_\odot$$

$$v \simeq 5000\ {\rm Km/s}$$

$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq 1.5 \times 10^{42}\ \frac{\rm erg}{\rm s}$$

Power Provided by SN is sufficient
with a conversion efficiency of 15-20 %
in relativistic particles

Non accelerator sources of High Energy Particles

Dark Matter

(in form of WIMP's self annihilation or decay)

Super Massive Particles

[Very High mass scales ($M_{GUT,}$ ...)]

Production of high energy particles of all types $\gamma\ ,\ \nu\ ,\ e^+\ ,\ e^-\ ,\ p\ ,\ \ldots$

DARK MATTER

Dynamical evidence
Nature

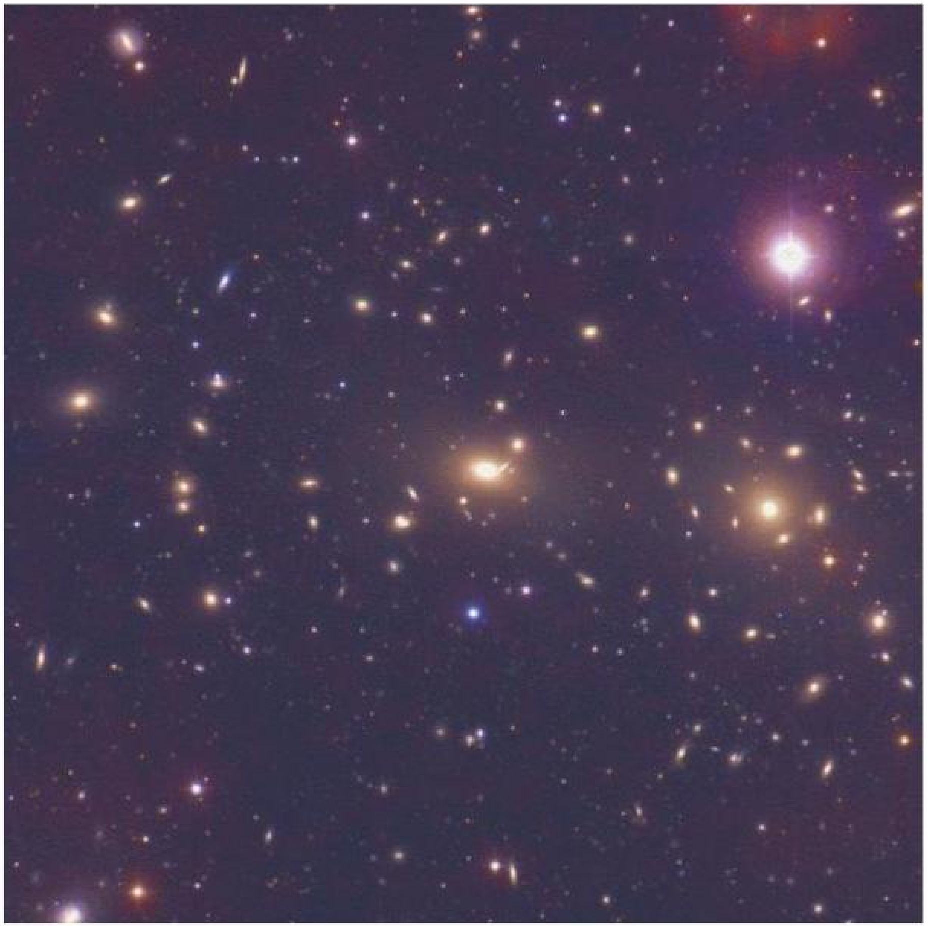
Dynamical Evidence for Dark Matter

- Galaxies
- Clusters of Galaxies
- The entire Universe

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

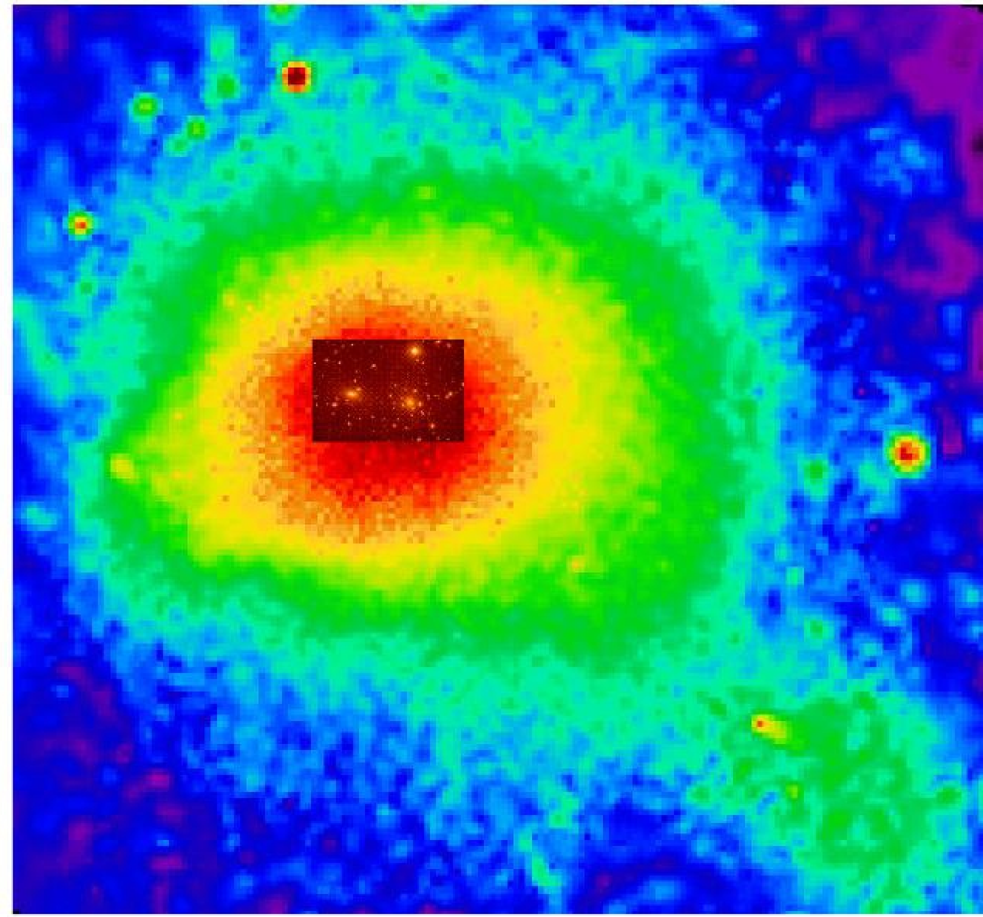
A field that is not contained
in the Standard Model of Particle Physics [!!]

COMA Galaxy Cluster



Optical

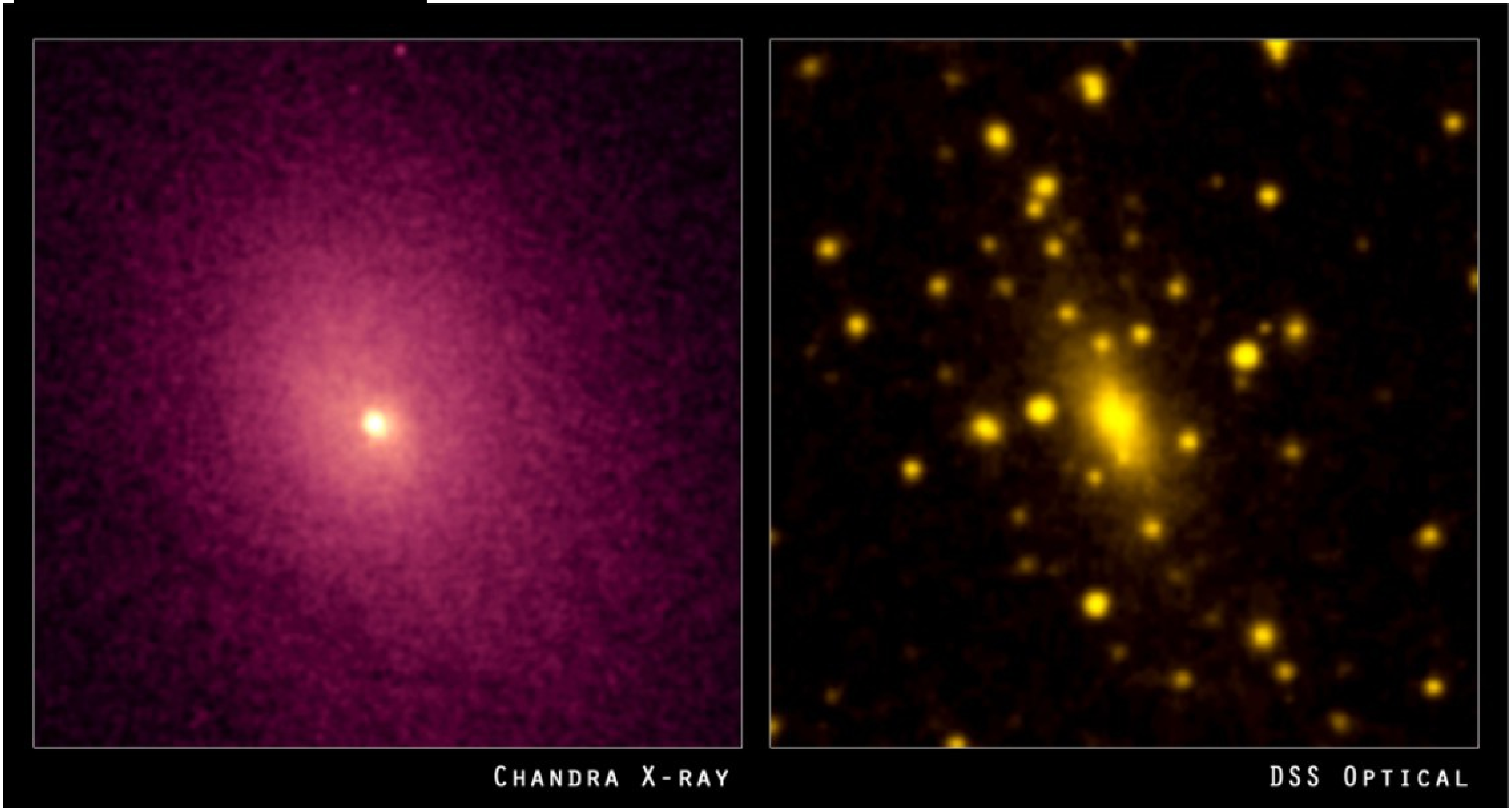
Fritz Zwicky 1933
First argument for Dark Matter
Virial theorem



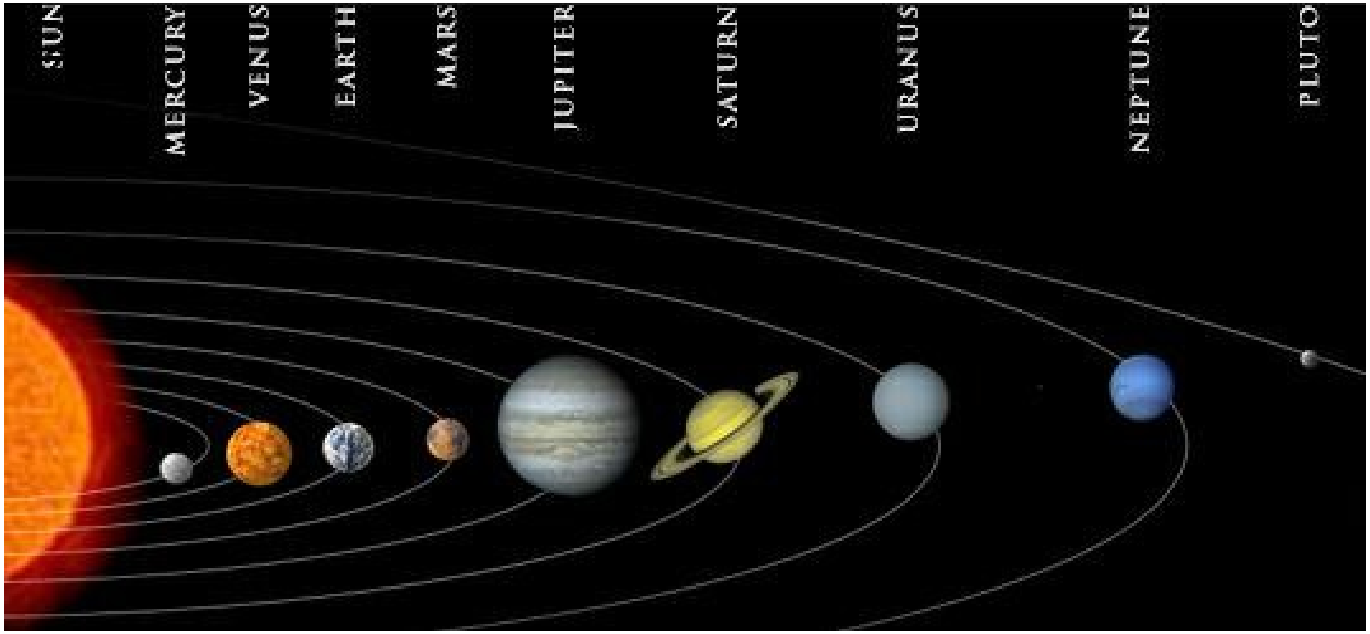
X-ray
[hot gas confined by
deep gravitational well]


VIRGO
CLUSTER
Virgo Cluster
Intes Mk69@900mm
St10XME L265min 300sec sub RGB 60/57/62min 200sec bin2x2
Gahberg 20080427/0507/0508
www.kerschhuber.astronomie.at

ABELL 2029



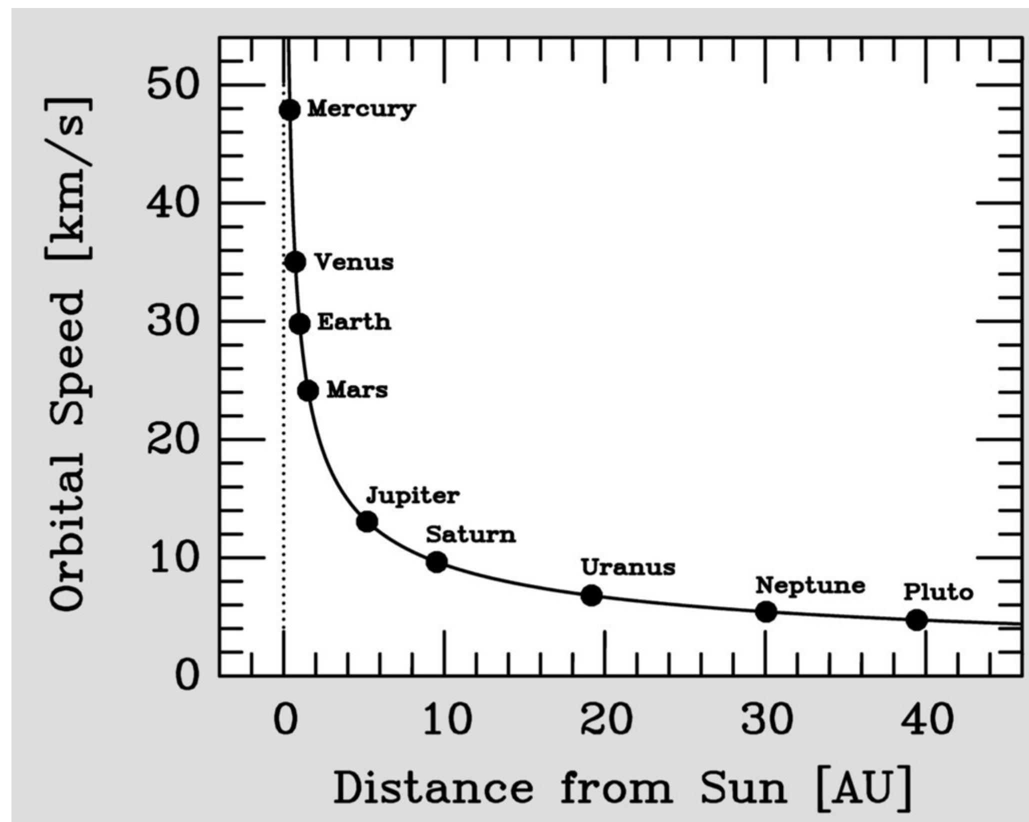
Most of the baryonic mass in a Galaxy cluster
Resides in a hot (temperature T ~ few KeV) intergalactic gas
Hydrostatic Equilibrium.

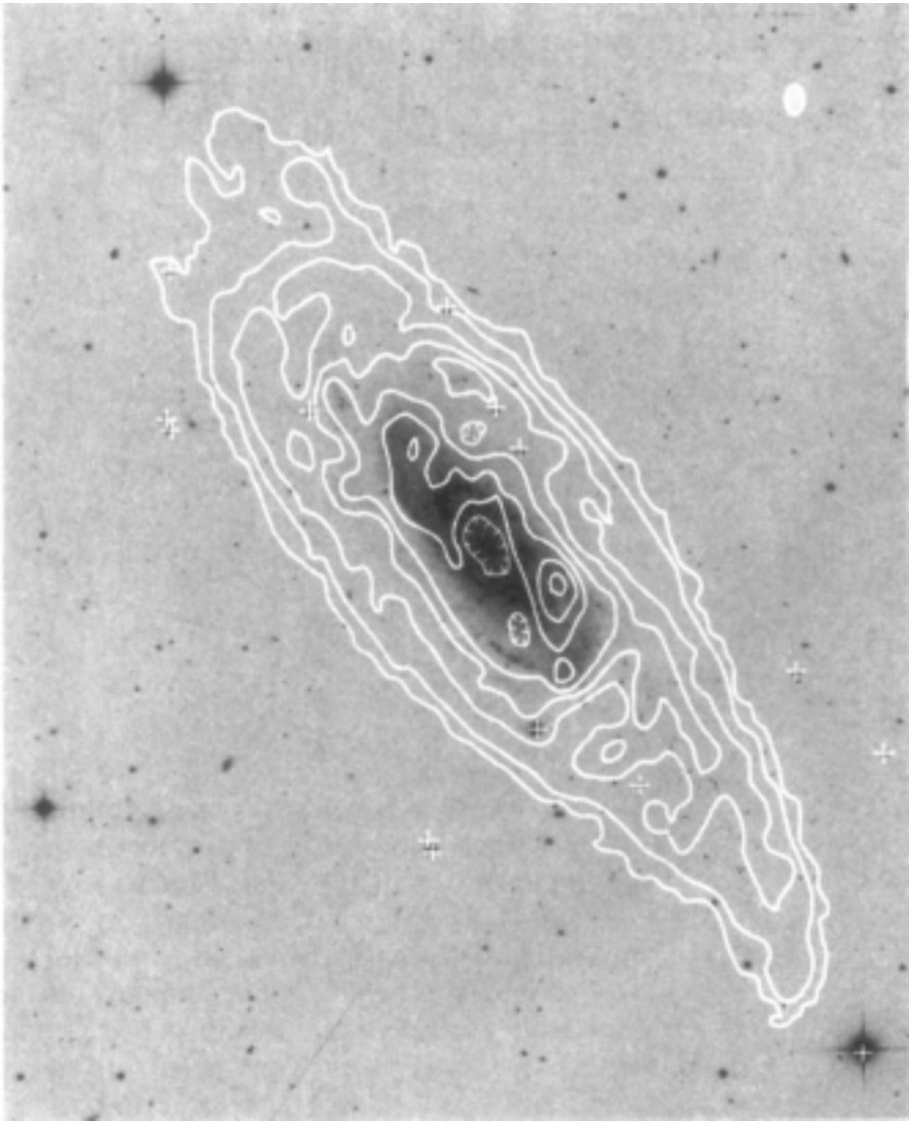


Keplerian circular motion:

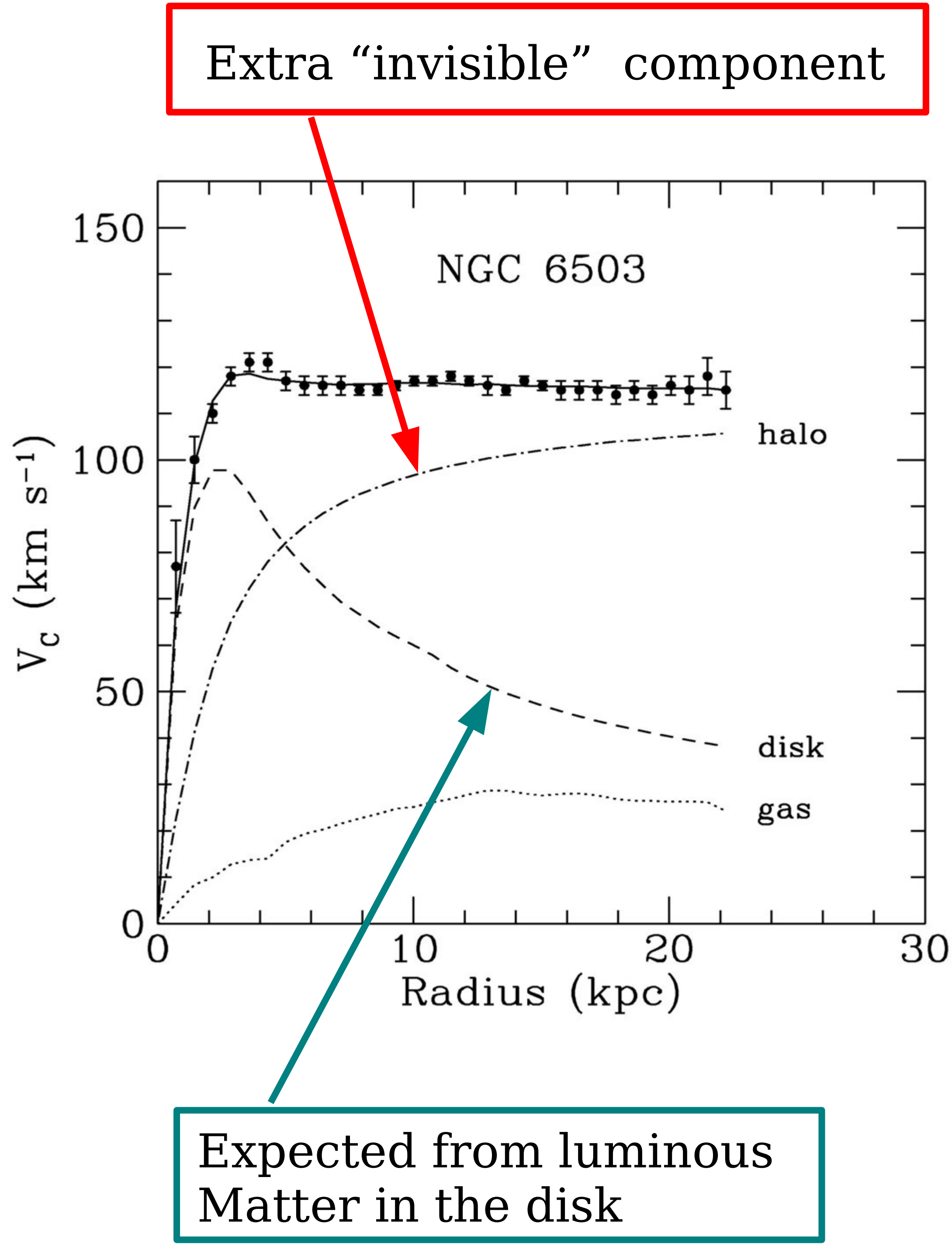
$$\frac{G\,M}{r^2} = \frac{v^2}{r}$$

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





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



M31: ANDROMEDA

M31 Rotation curve (1975)

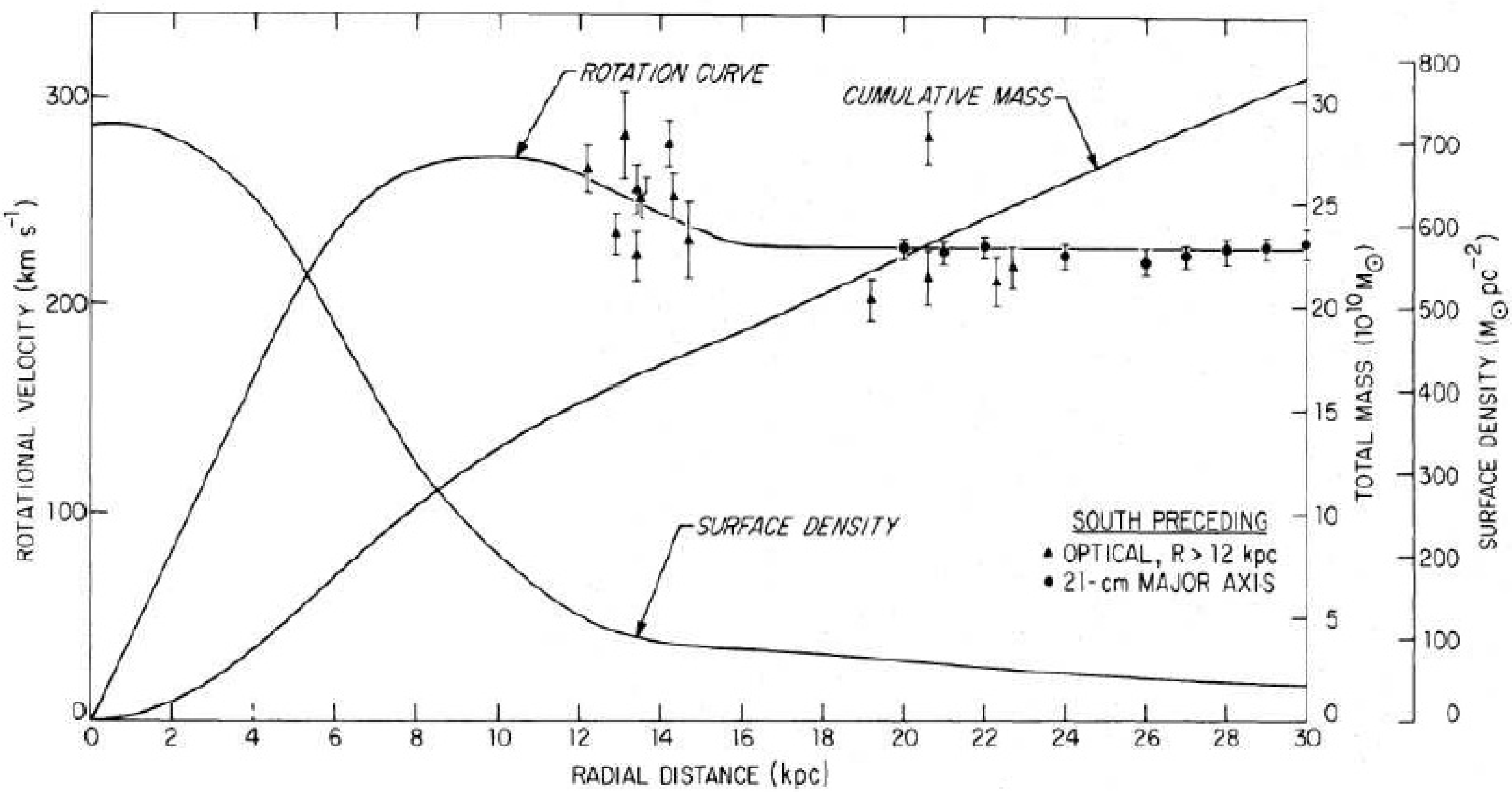
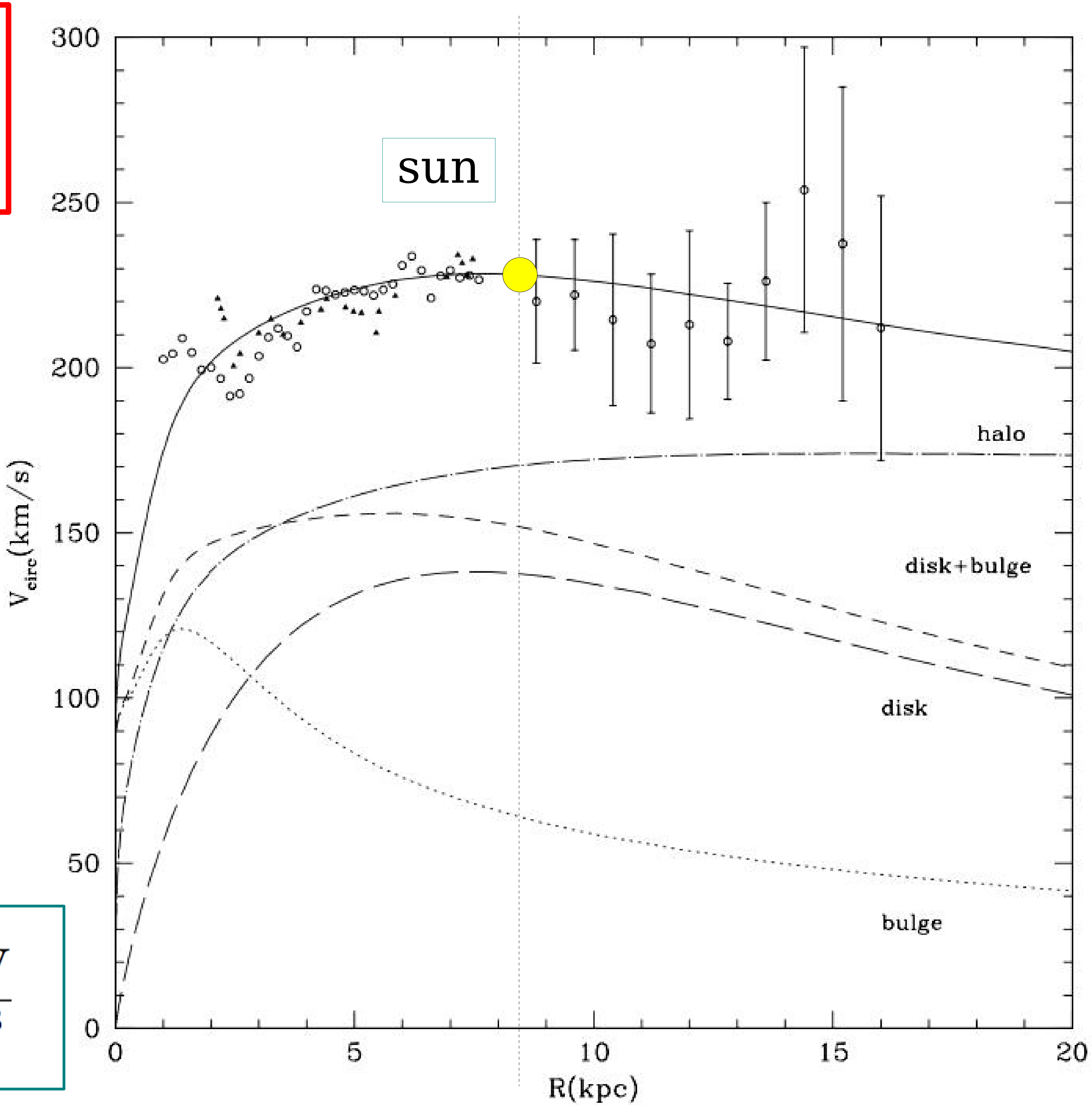


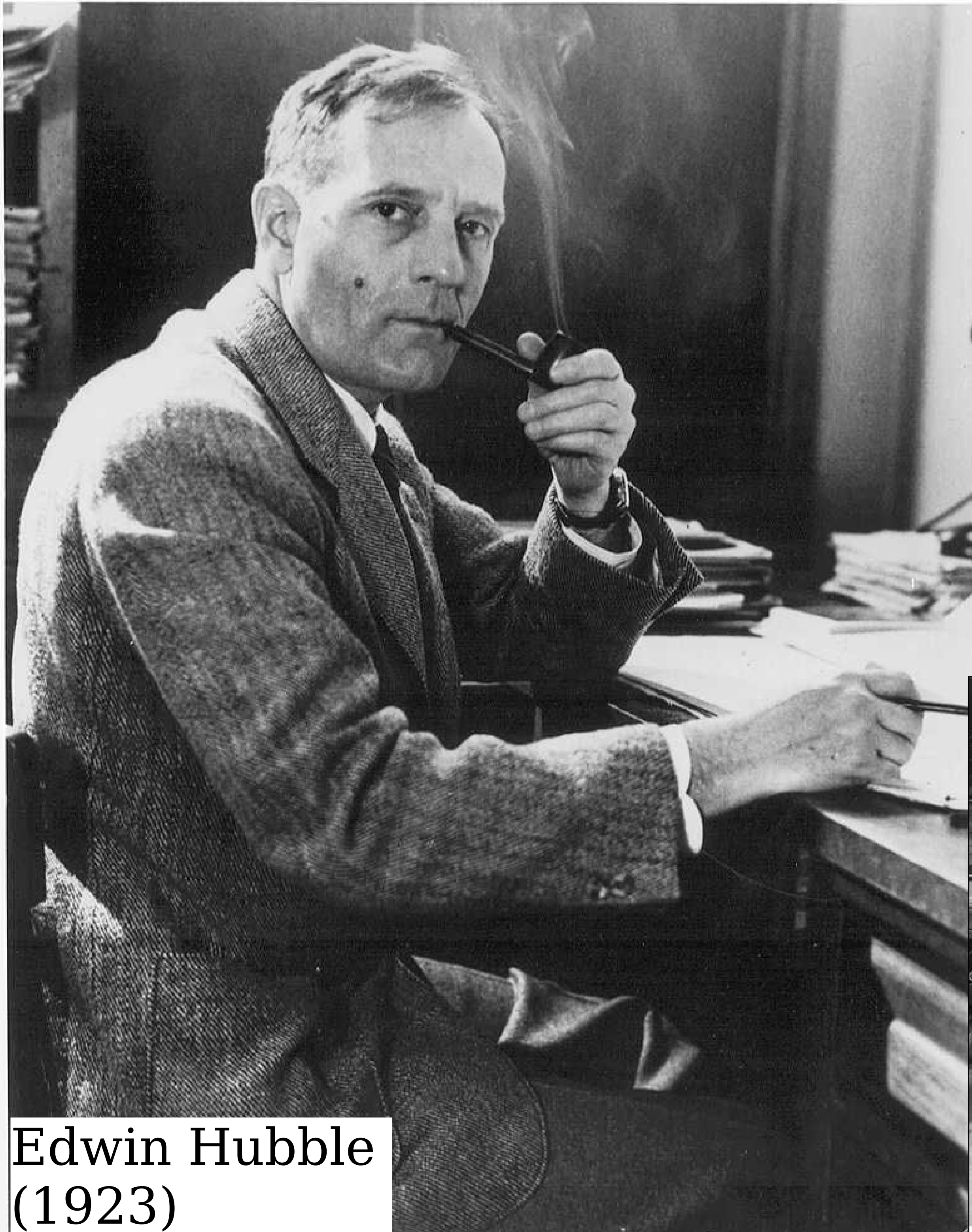
Figure 1: The rotation curve of M31 by Roberts & Whitehurst (1975). The filled triangles show the optical data from Rubin & Ford (1970), the filled circles show the 21-cm measurements made with the 300-ft radio telescope (reproduced by permission of the AAS and the author).

DARK
Galactic
HALO

MILKY WAY



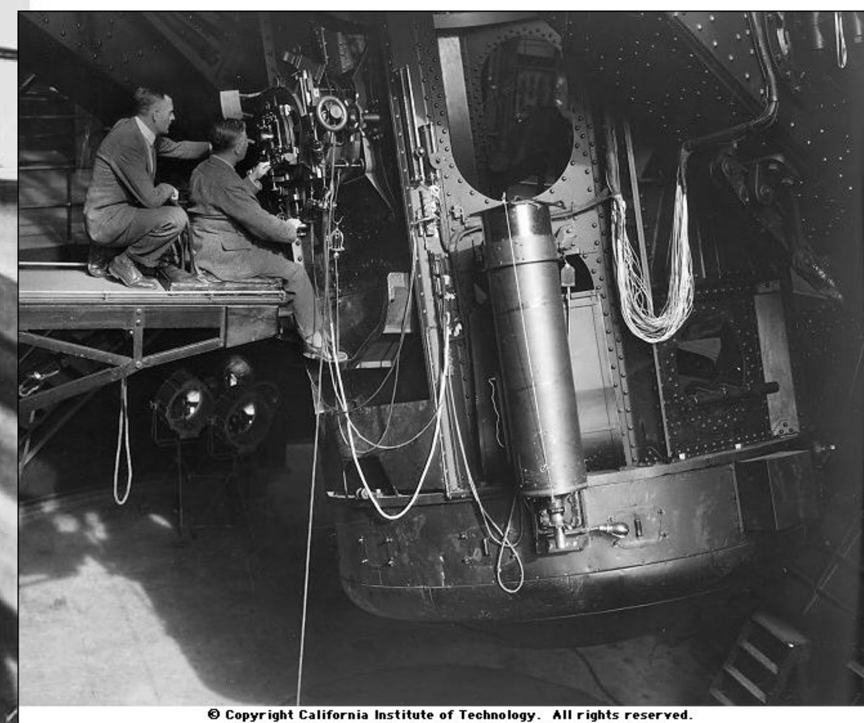
$$\rho_{\oplus} \simeq 0.3 \ \frac{\text{GeV}}{\text{cm}^3}$$



Edwin Hubble (1923)

Discovery of the Expansion of the Universe.

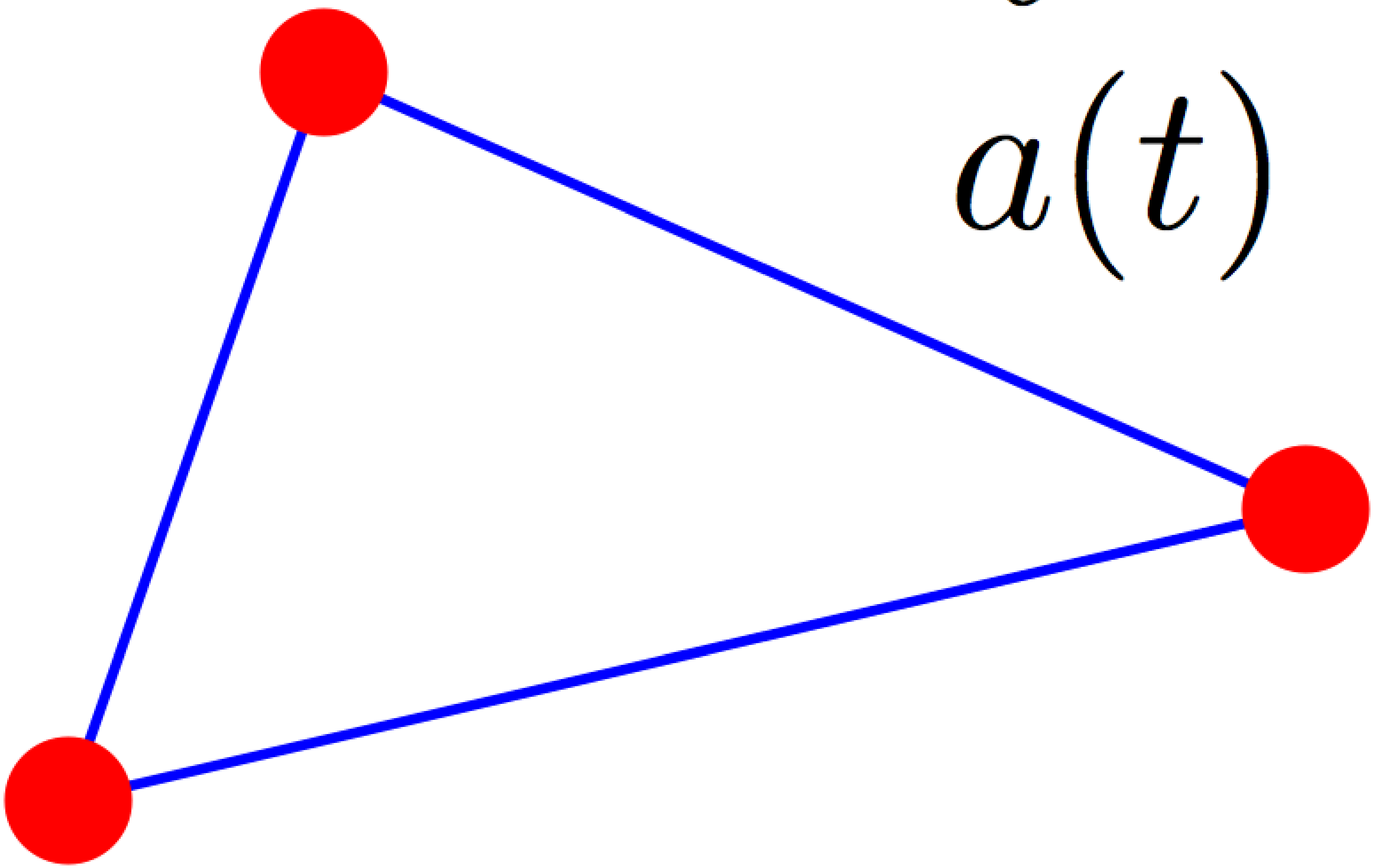
Velocity of Galaxies.



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]

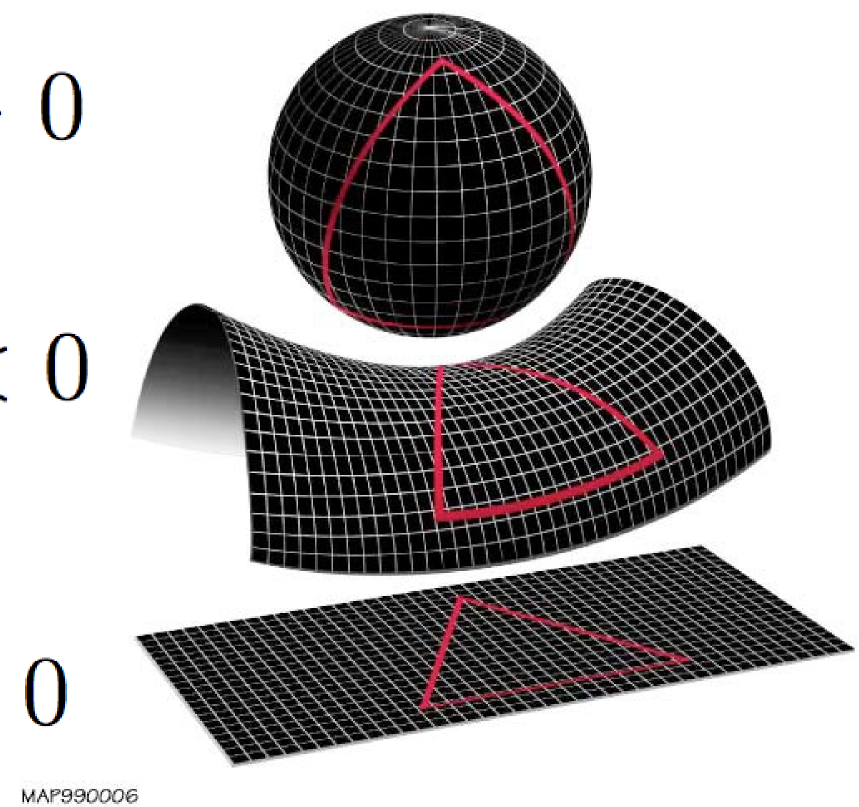
Constant K
Geometry of Space

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

$K > 0$

$K < 0$

$K = 0$



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

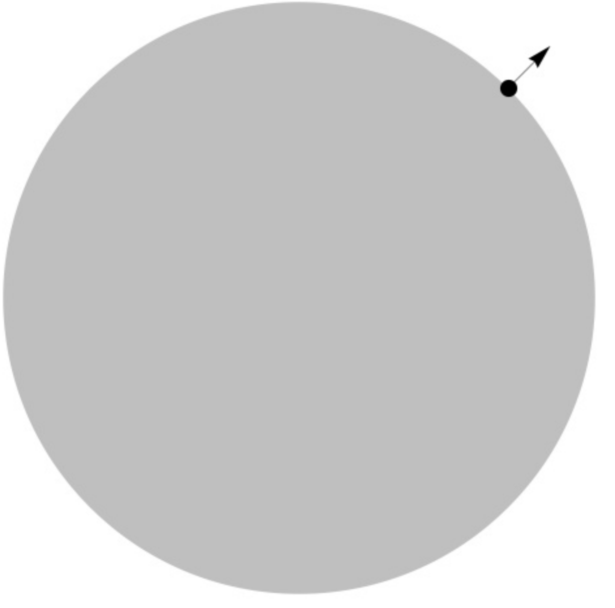
Spherical symmetry:
choose an arbitrary center point.
Energy = Kinetic + Potential

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

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

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

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



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

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

$$1 = \Omega_0 + \Omega_k$$

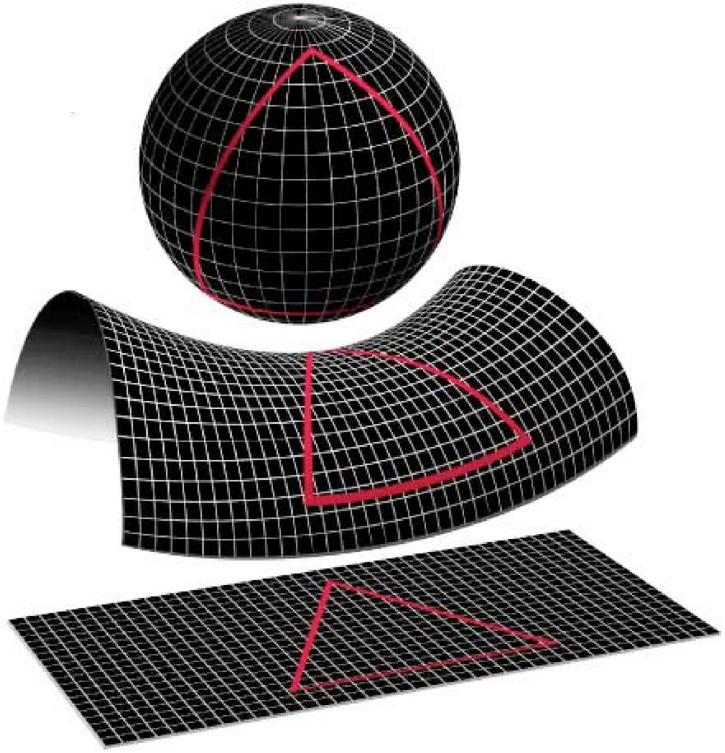
Geometry defined by Ω_0

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

$\Omega_0 > 1$

$\Omega_0 < 1$

$\Omega_0 = 1$



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

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

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

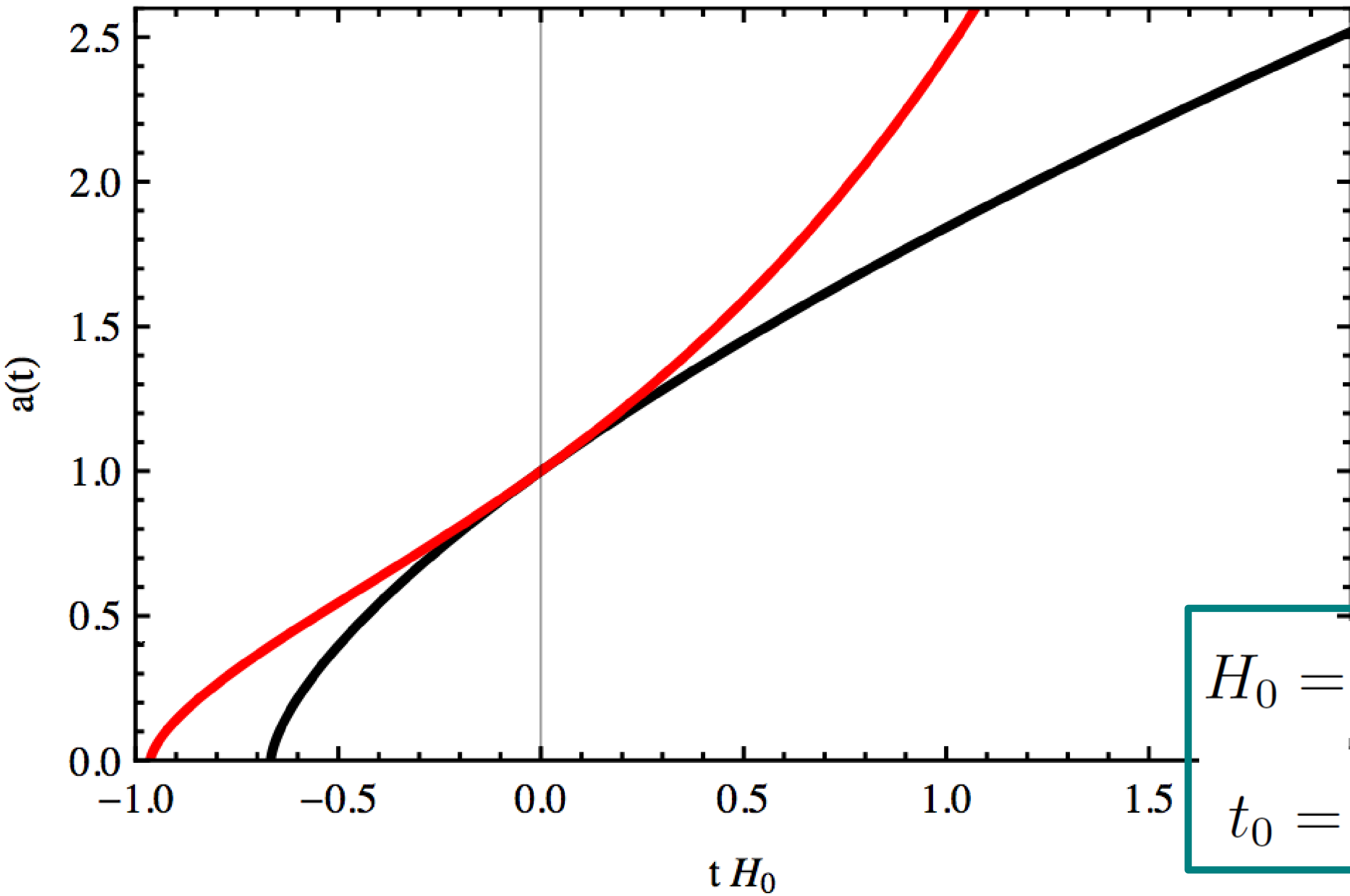
Particle conservation

Particle conservation + momentum redshift

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

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

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



$\Omega_{\rm m} = 1$

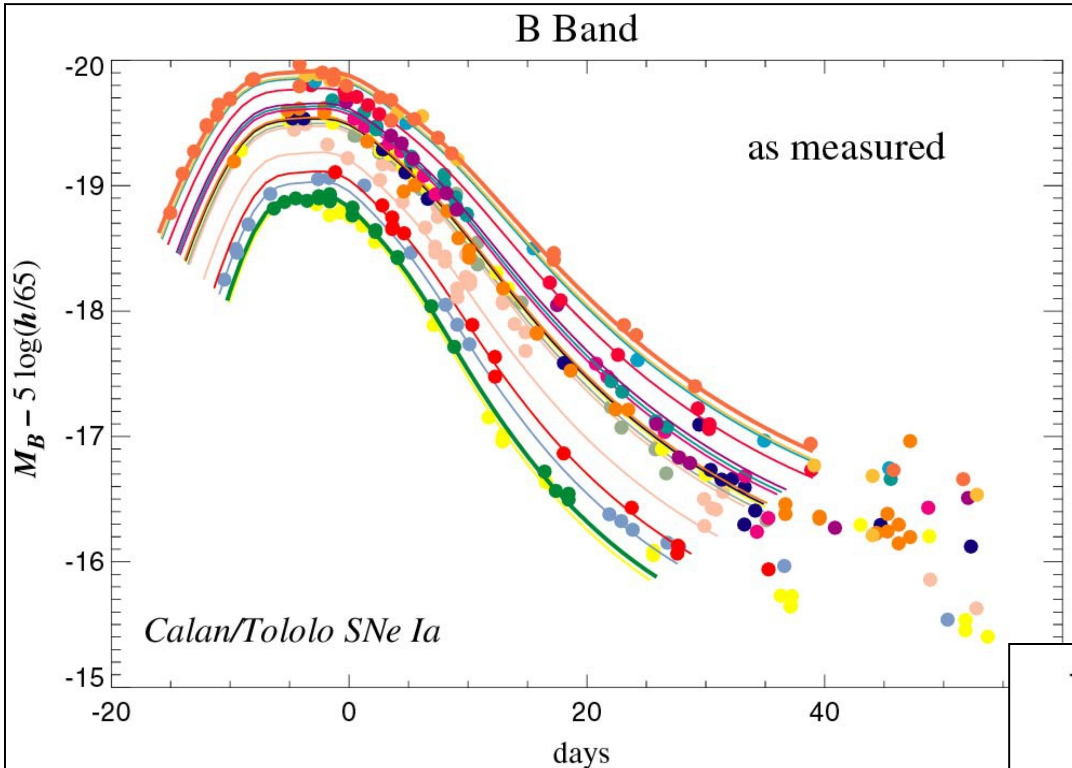
$\Omega_\Lambda = 0$

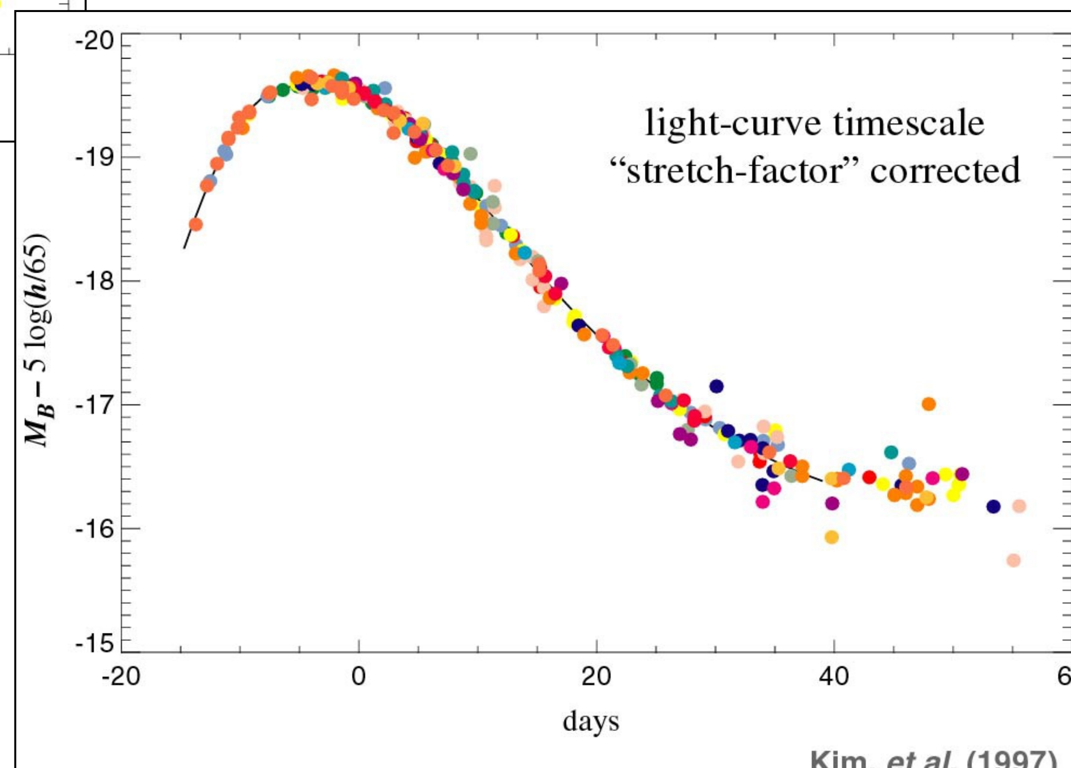
$\Omega_{\rm m} = 0.3$

$\Omega_\Lambda = 0.7$

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

$t_0 = 13.76 \pm 0.11$ Gyr





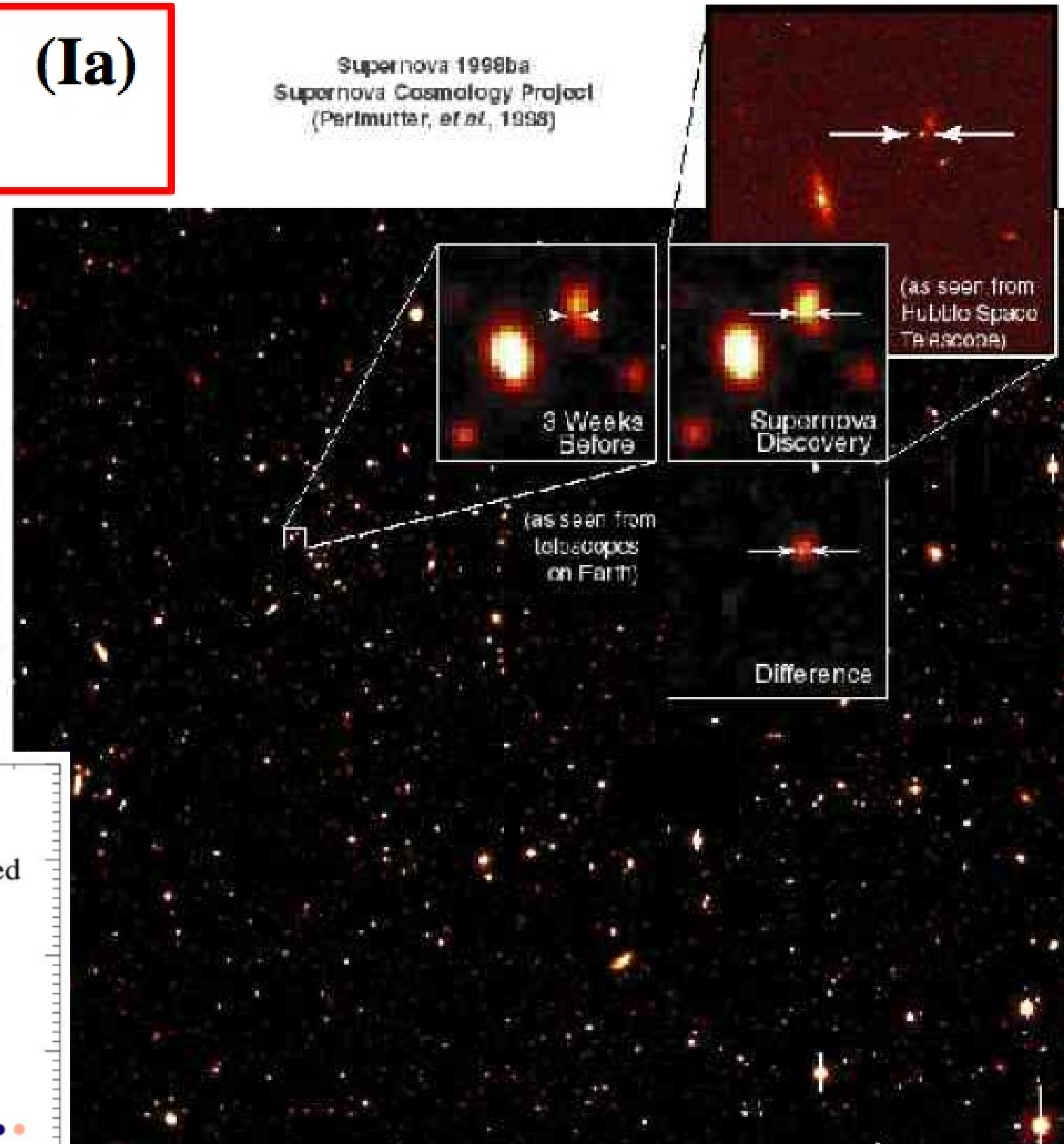
SuperNovae Ia
are a standard candle.

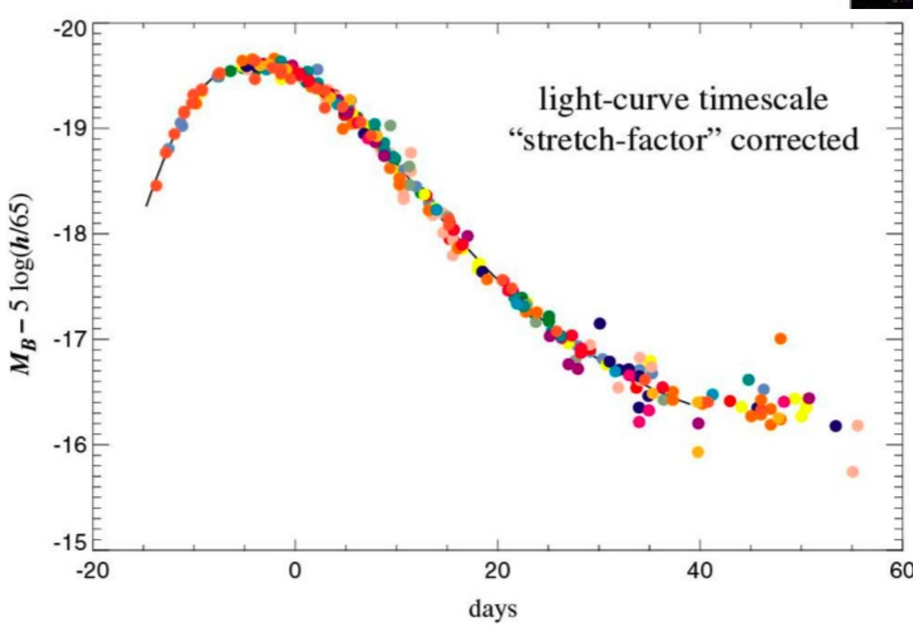
(universal light curve)
[dimming + broadening]

SUPERNOVAE (Ia) STUDIES

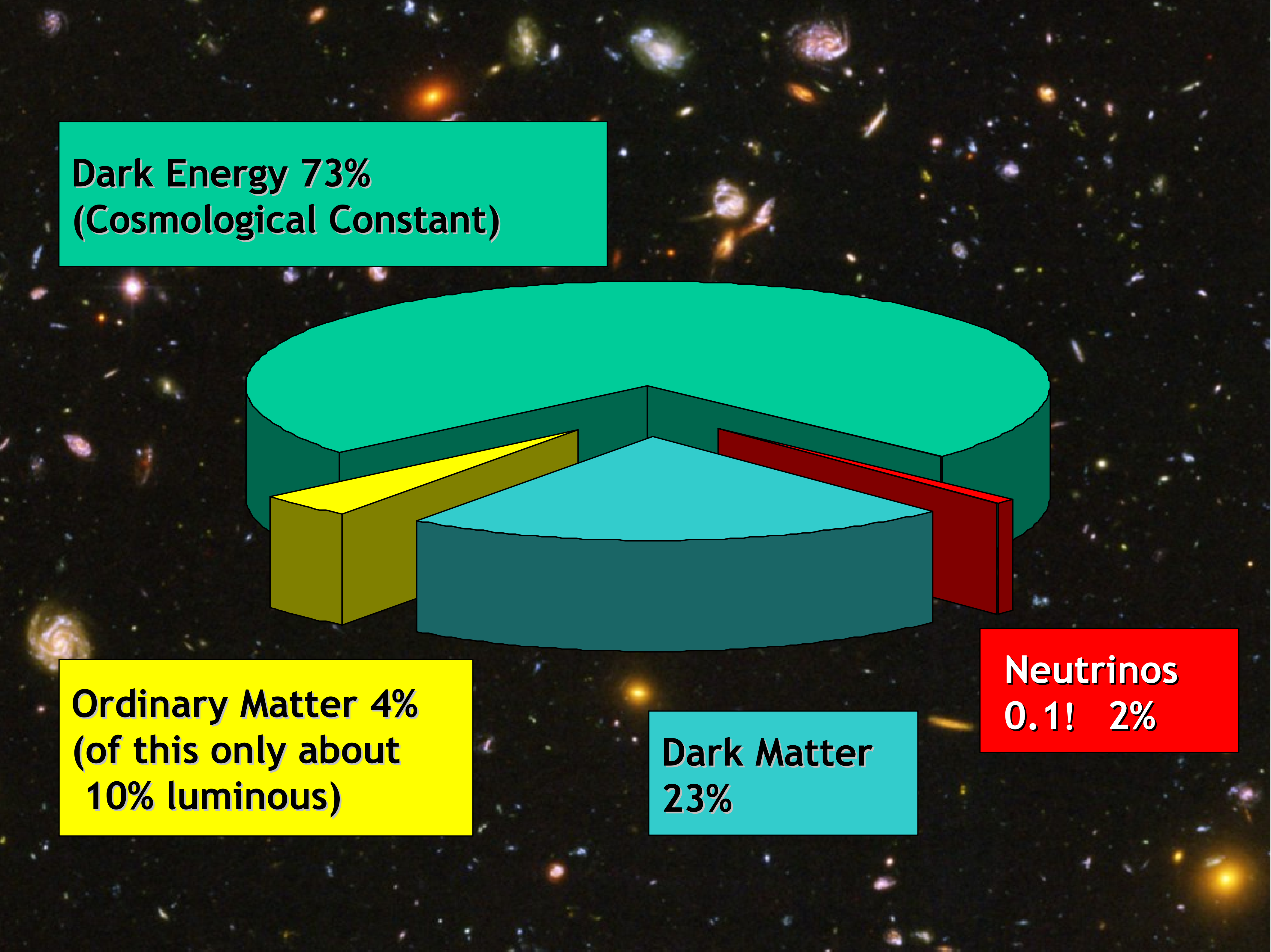
$$a(t) \leftrightarrow \ell(z)$$

SN1a as standard candles





Kim, *et al.* (1997)


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

$$\Omega_b = 0.0458 \pm 0.0016$$

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

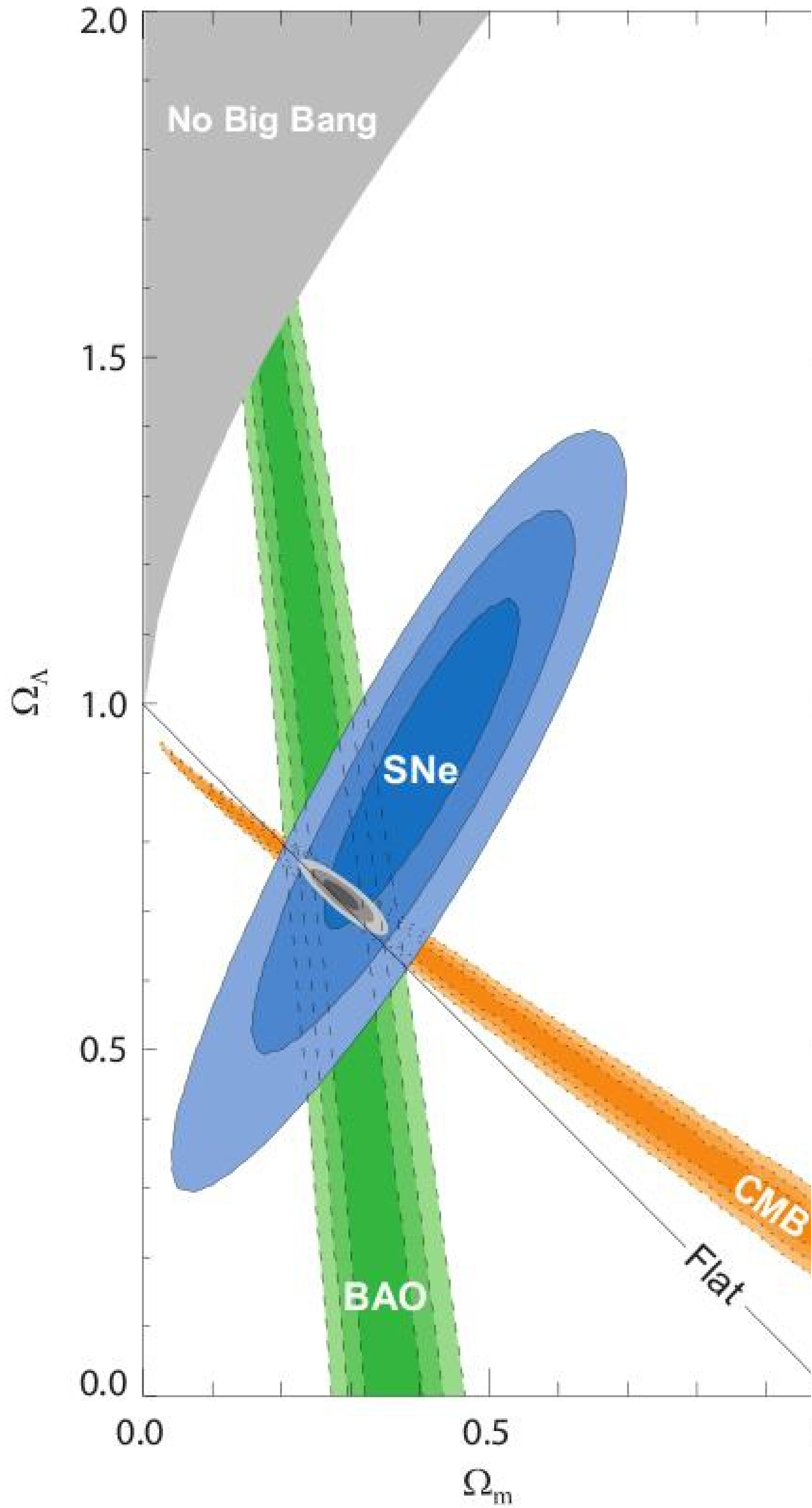
$$\Omega_\Lambda = 0.725 \pm 0.016$$

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

$$-0.0133 \le \Omega_k \le 0.0084$$

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

The Universe is FLAT !



Mysteries of the DARK UNIVERSE

DARK MATTER:

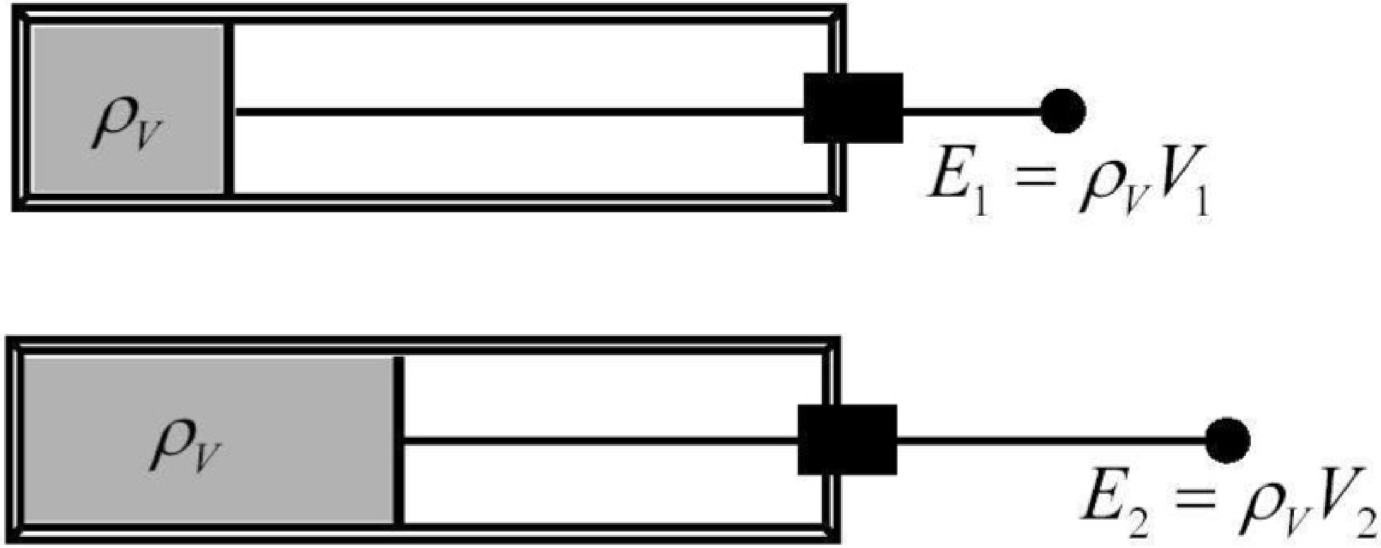
Holds together galaxies
and other large scale structures
[A new elementary particle ?]

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

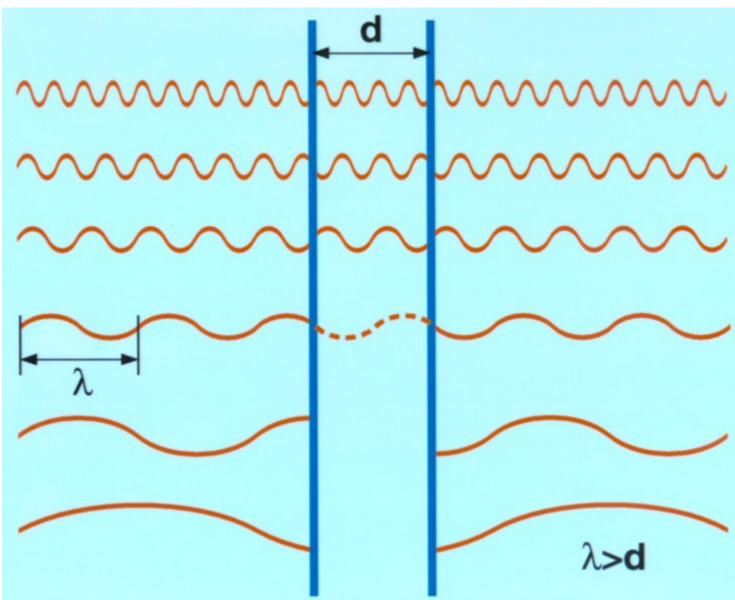
$$\rho_{\text{vacuum}} = -p_{\text{vacuum}}$$

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)

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

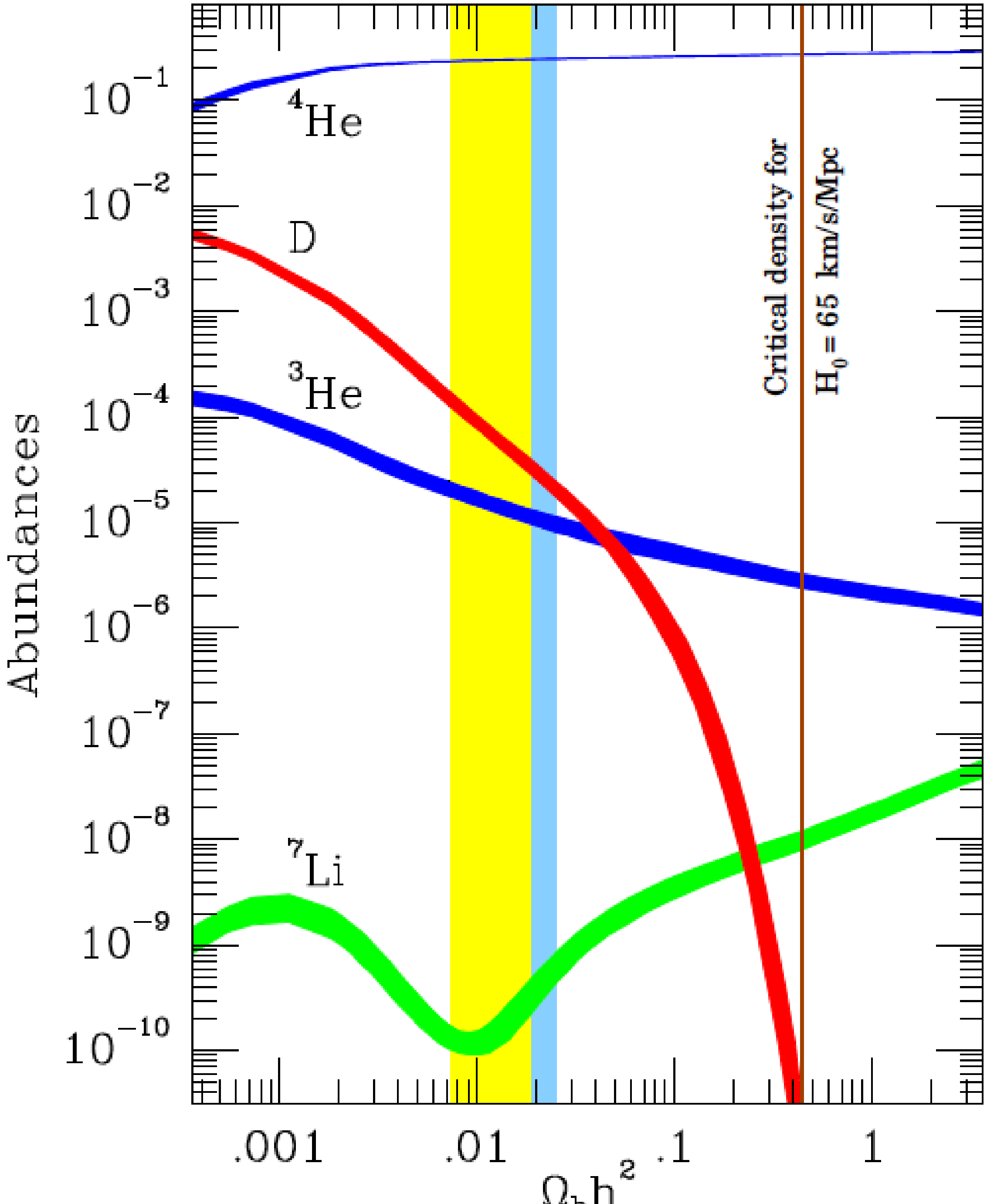
The DARK MATTER is "Non Baryonic"

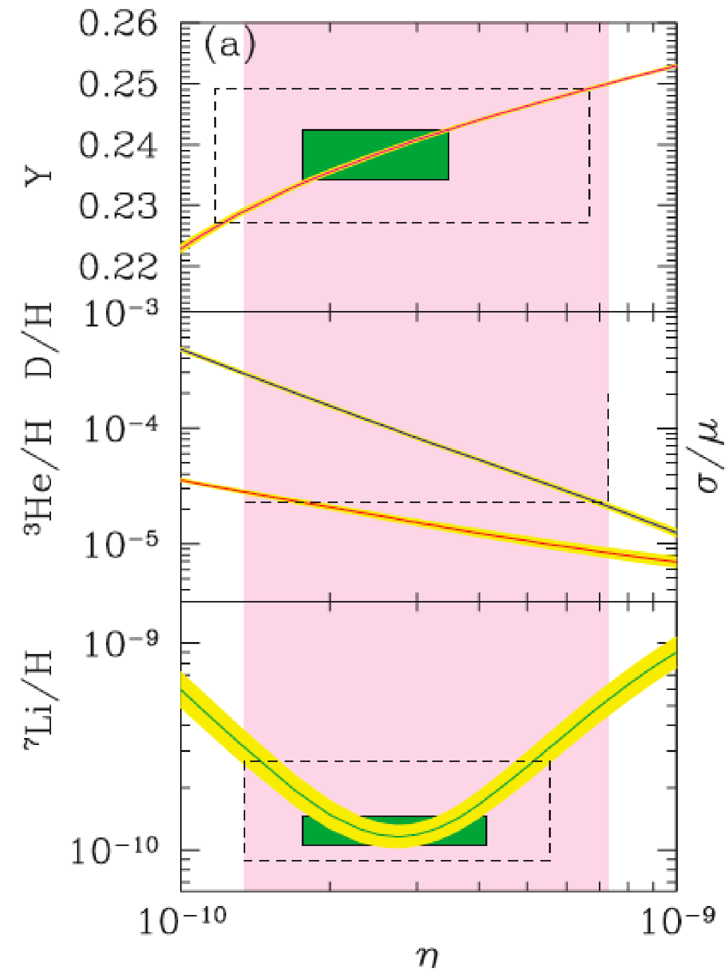
Nucleosynthesis

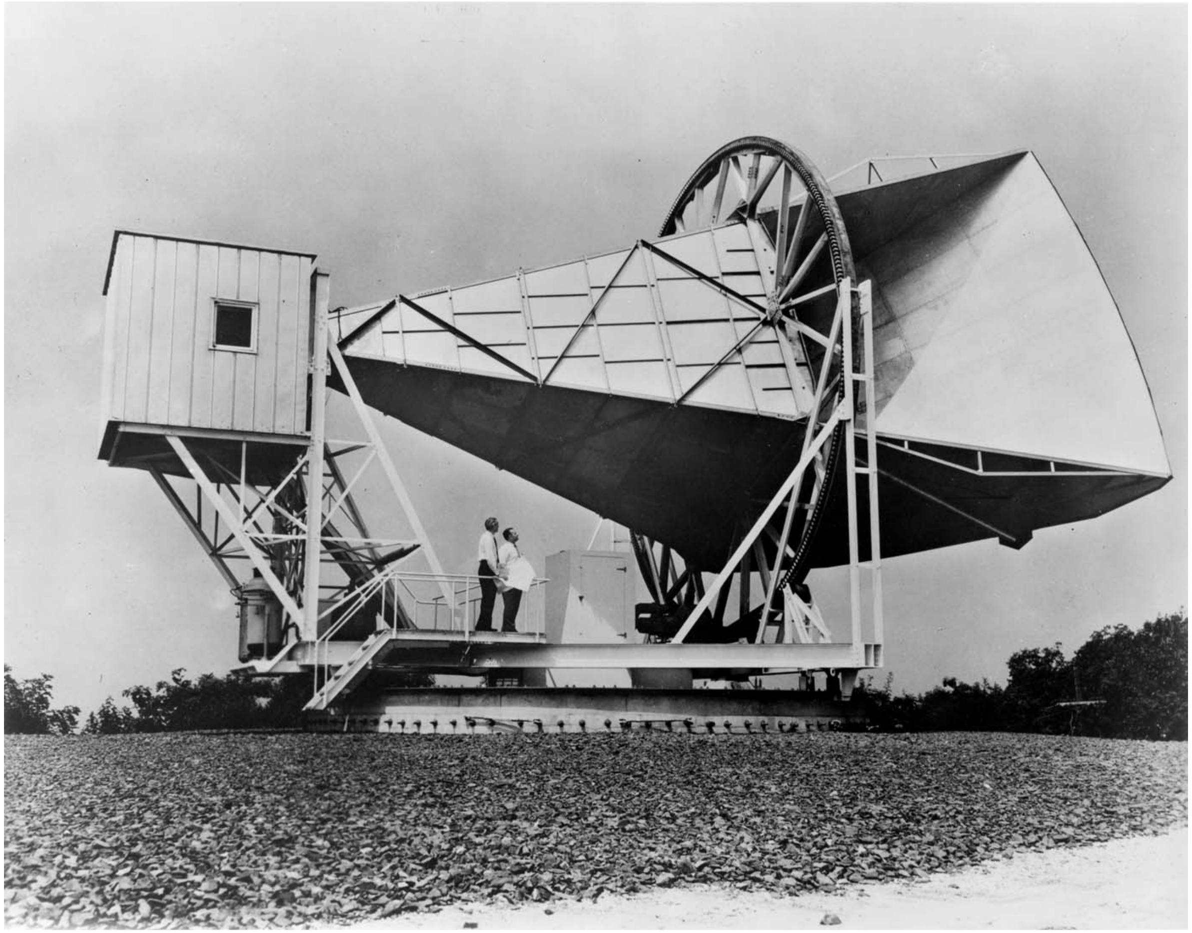
Structure Formation

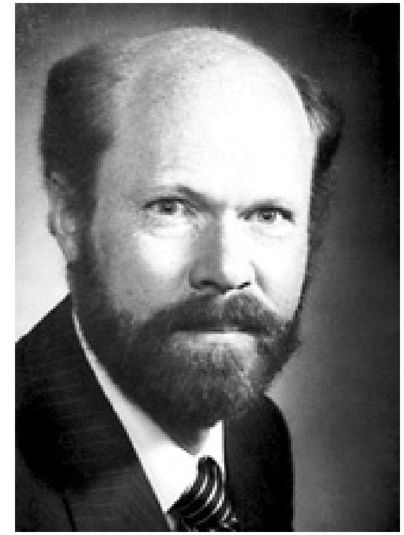
BigBang Nucleo-synthesis constraints

on ordinary (“baryonic”) matter





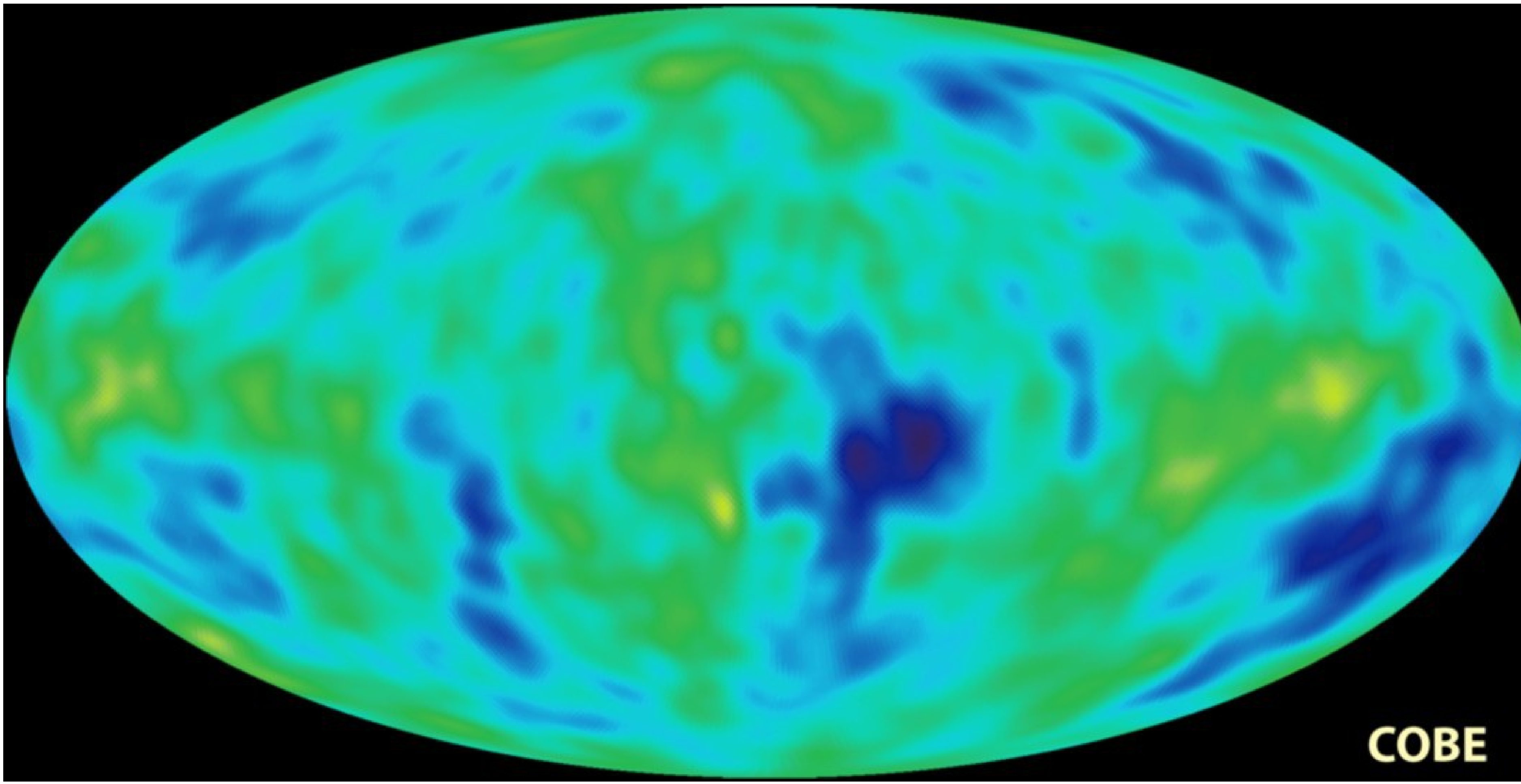


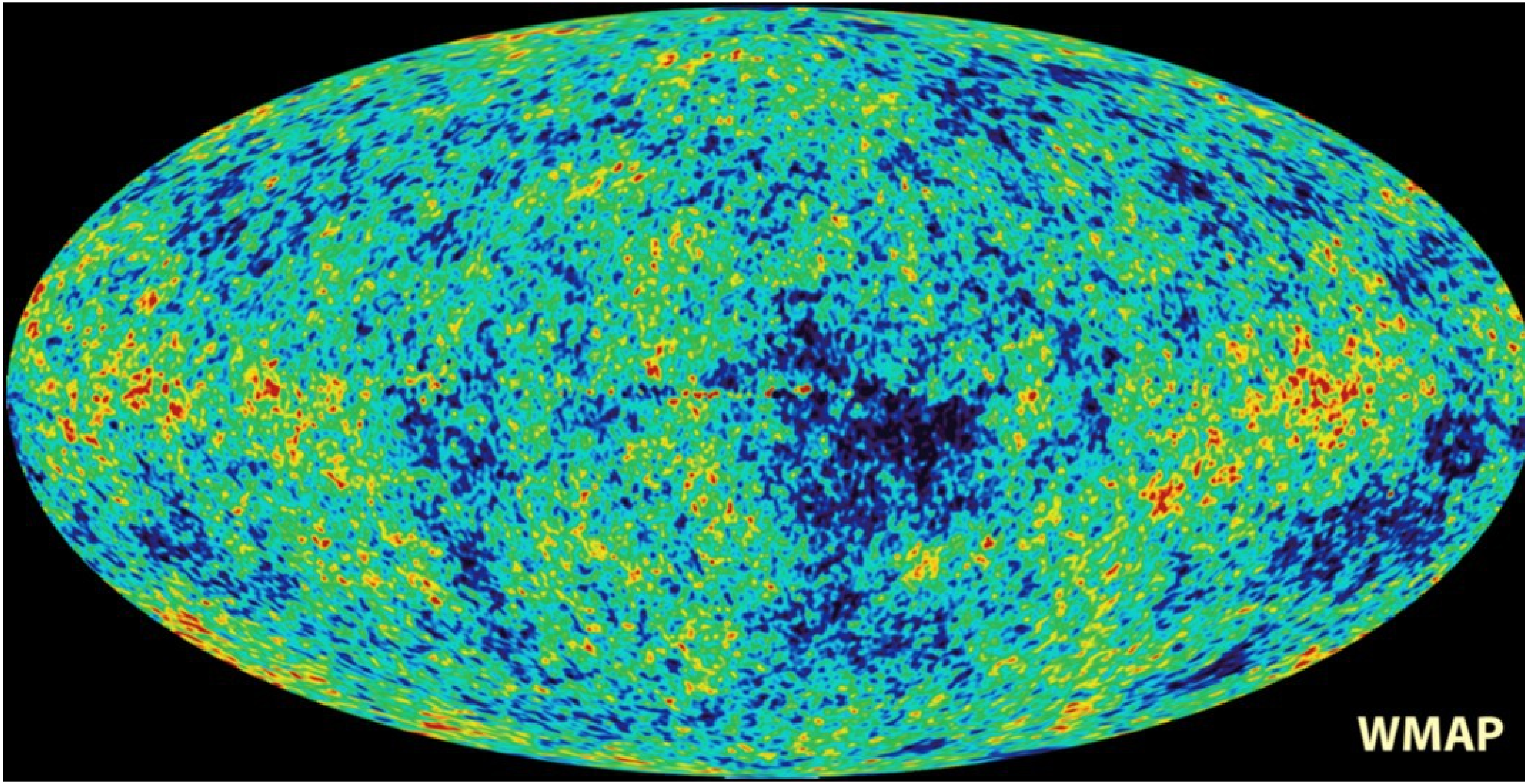


Robert W. Wilson

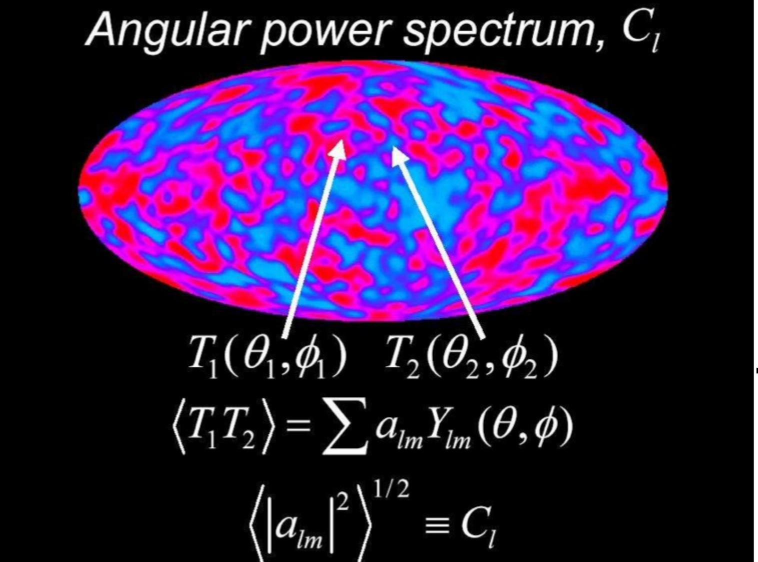
Arno.A. Penzias

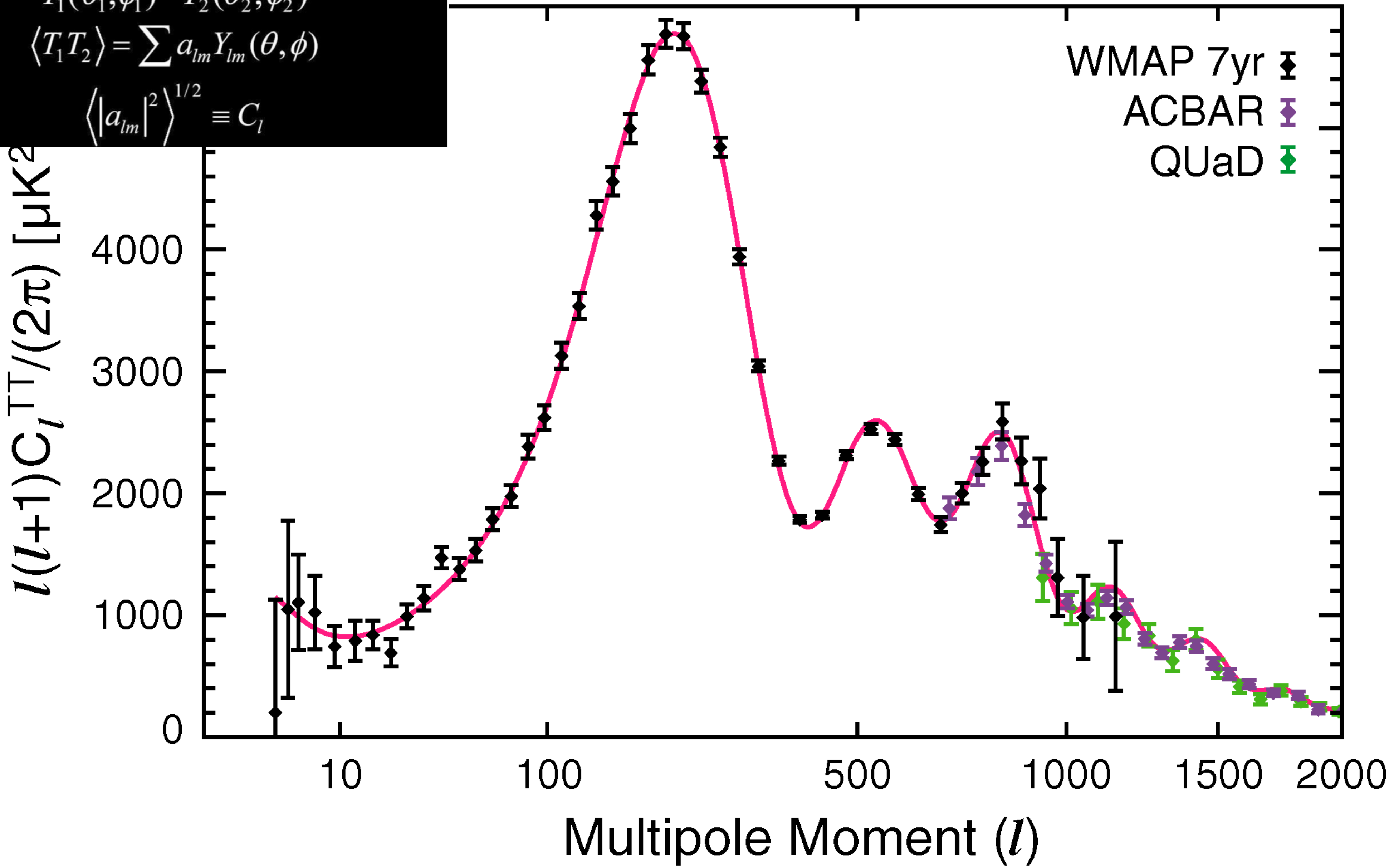
Discovery of the 2.7 Kelvin
Cosmic Microwave Background Radiation
By Penzias and Wilson (1965), [Nobel 1978]


COBE


WMAP

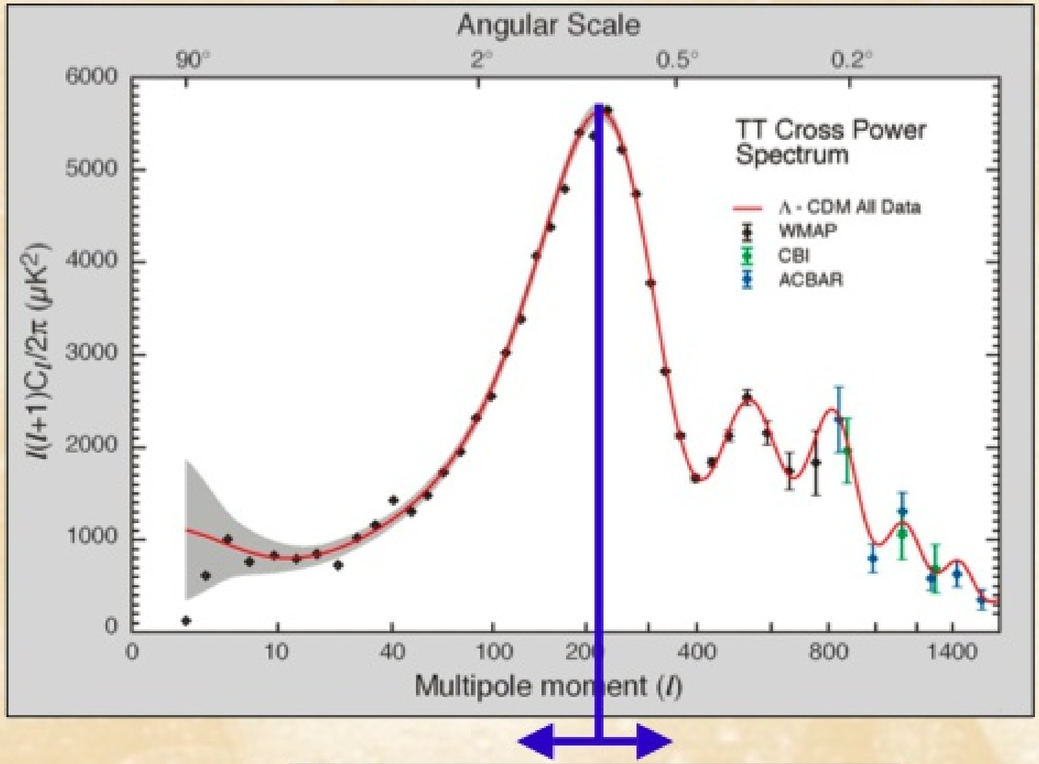
The “Rosetta stone”
Of the Early Universe





Flat Universe from CMBR Angular Fluctuations

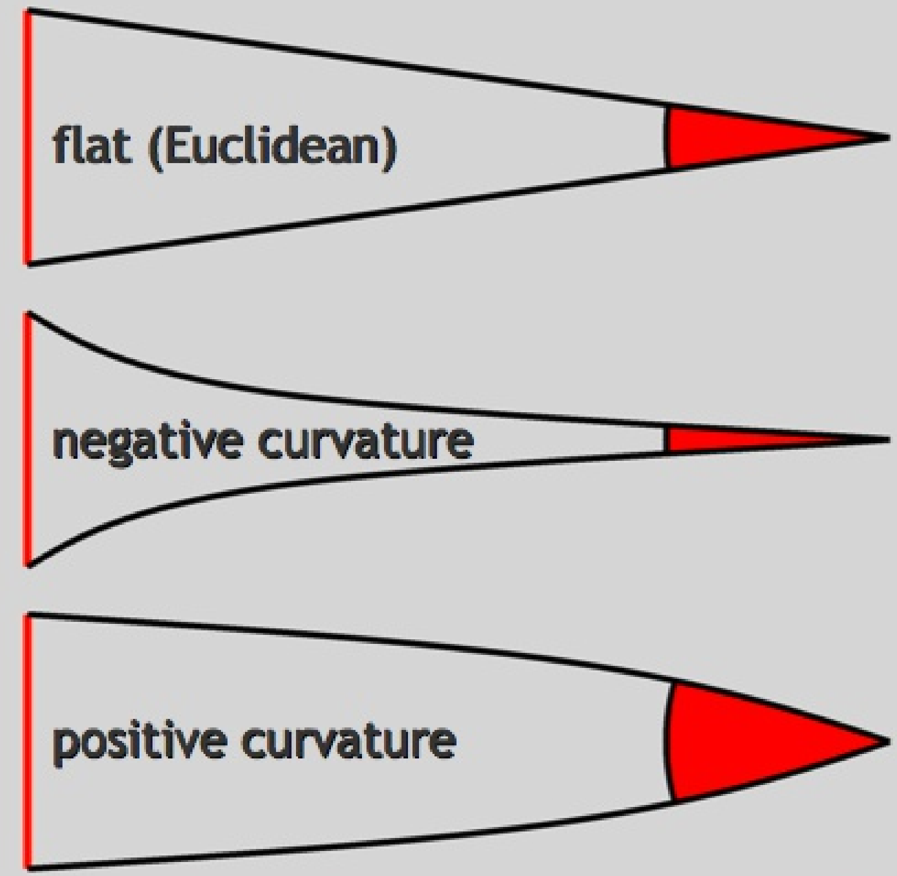
Spergel et al. (WMAP Collaboration)
astro-ph/0302209



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

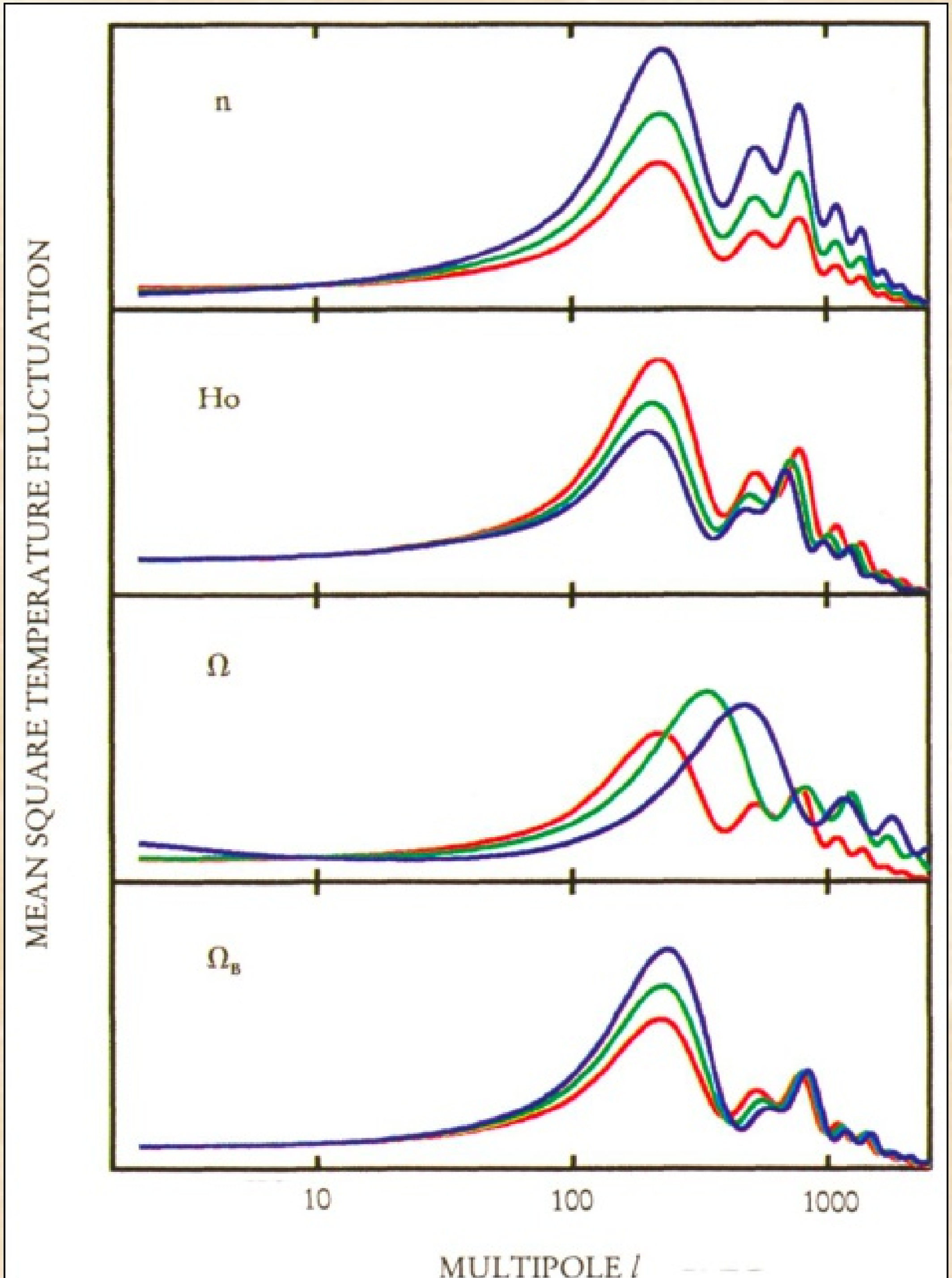
$$\Omega_{tot} = 1.02 \pm 0.02$$

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

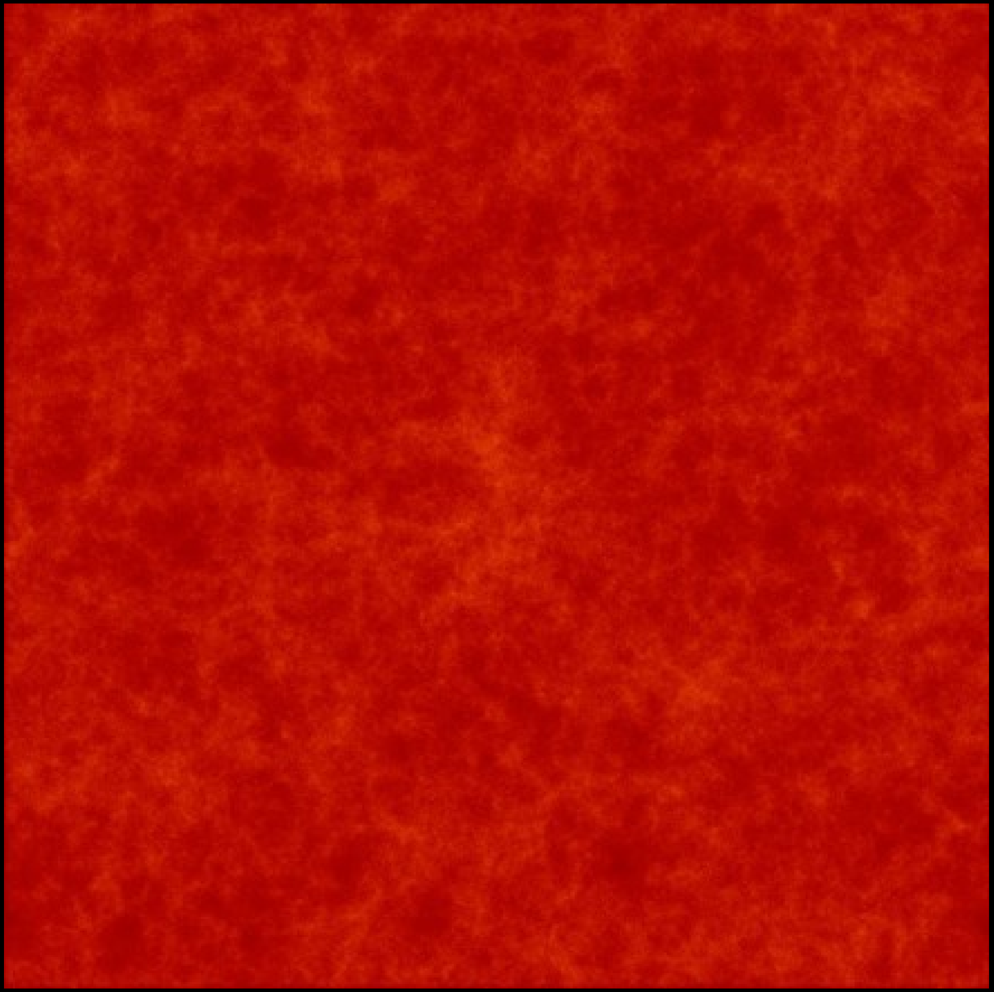
Hubble constant
H_0 = 50, 60, 70

Total density
Ω_{tot} = 1.0, 0.5, 0.3

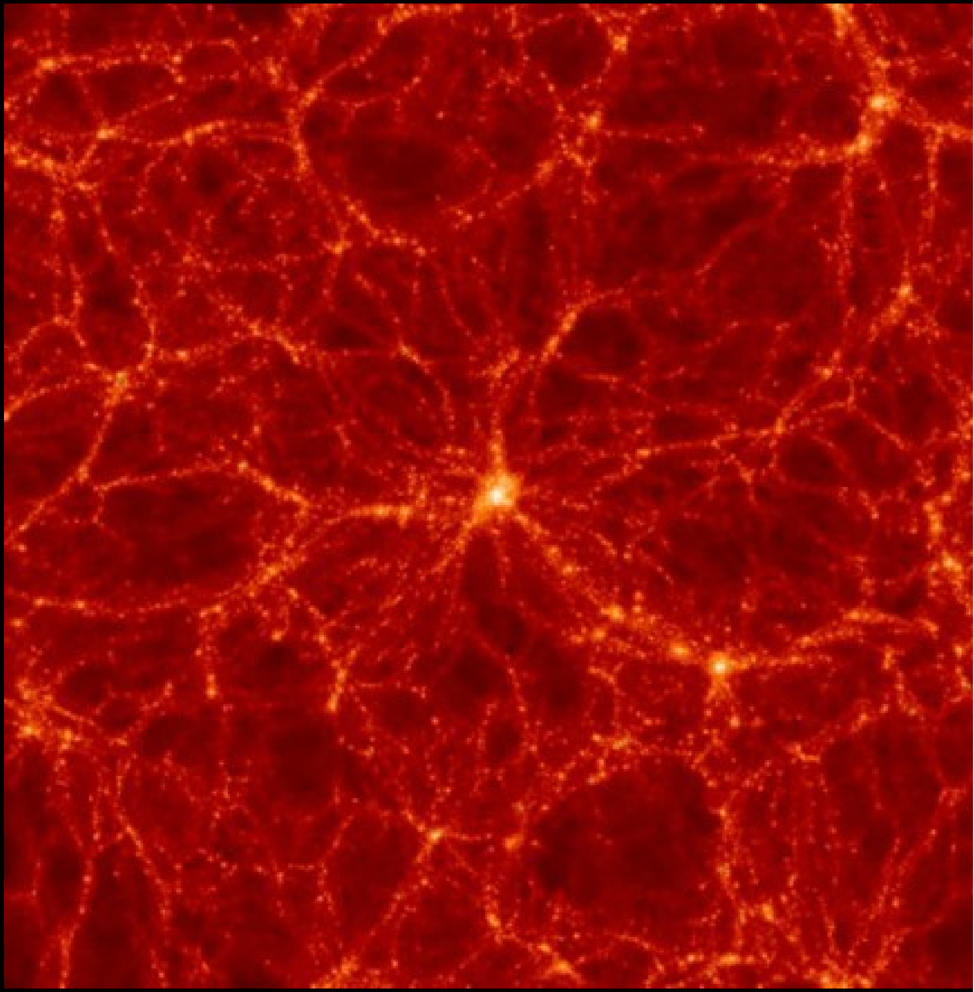
Baryon density
Ω_B = 5, 7.5, 10×10^{-3}

Physics Today 1997:11, 32

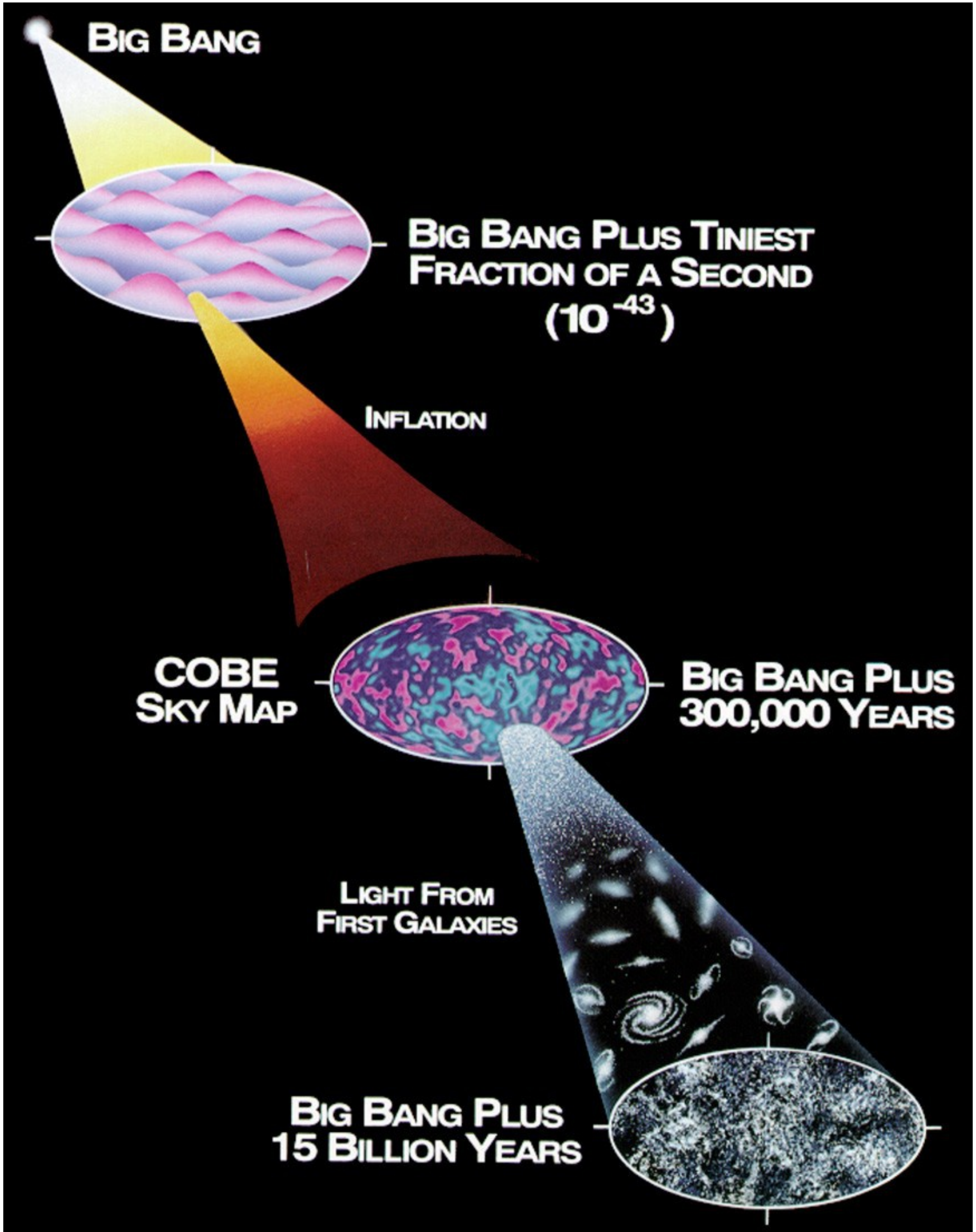
GRAVITATIONAL INSTABILITY



Smooth

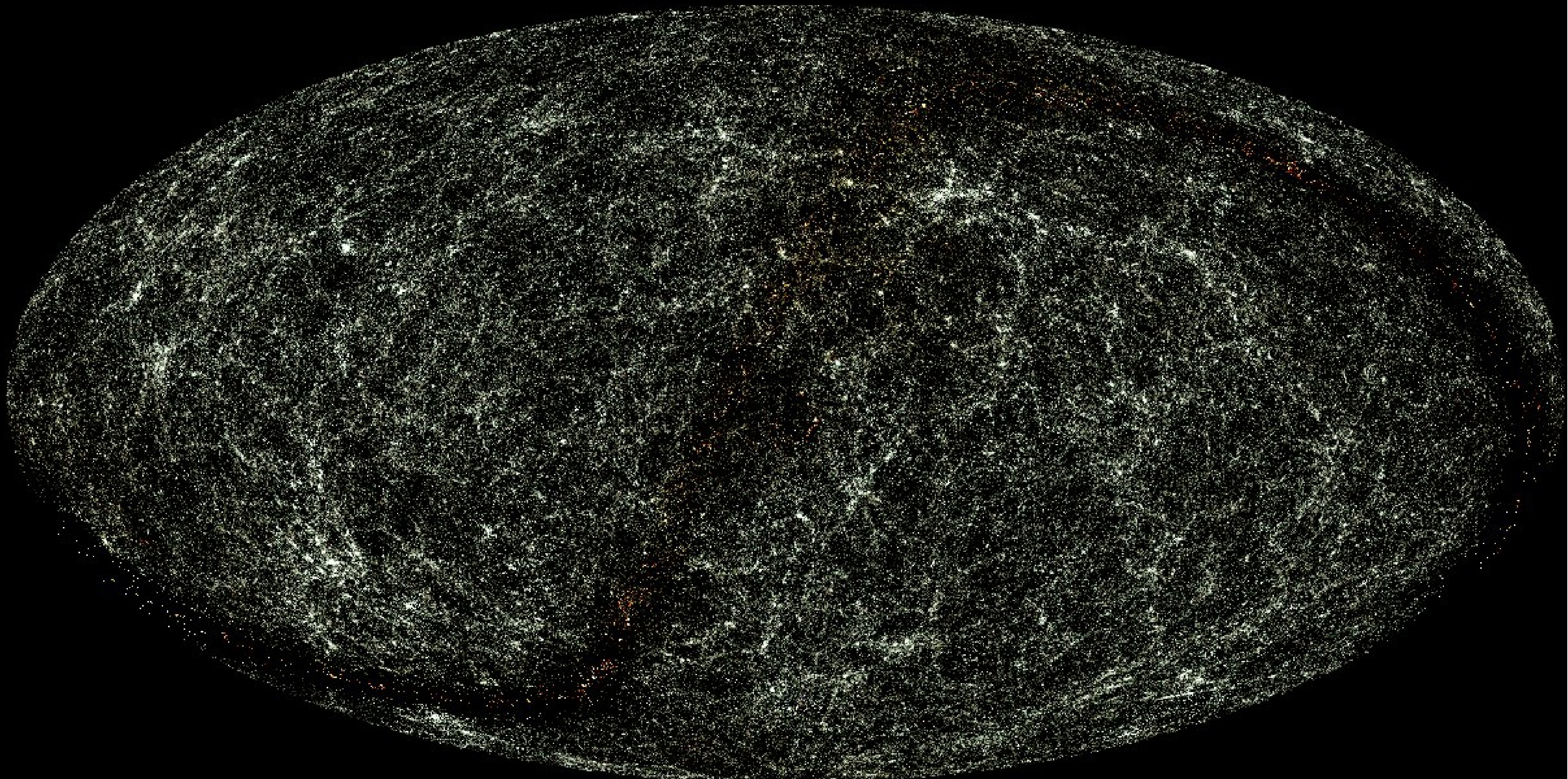


Structured

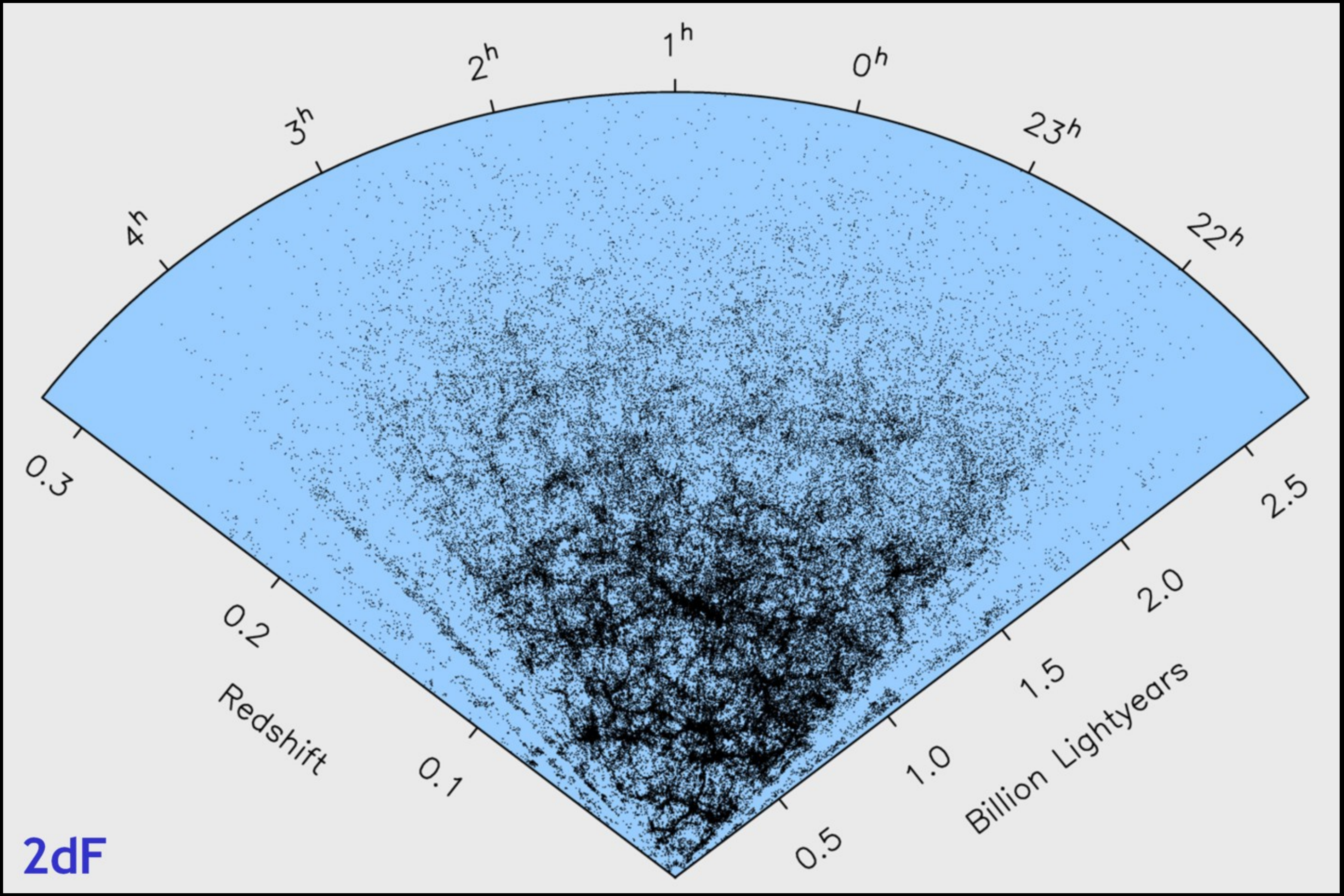


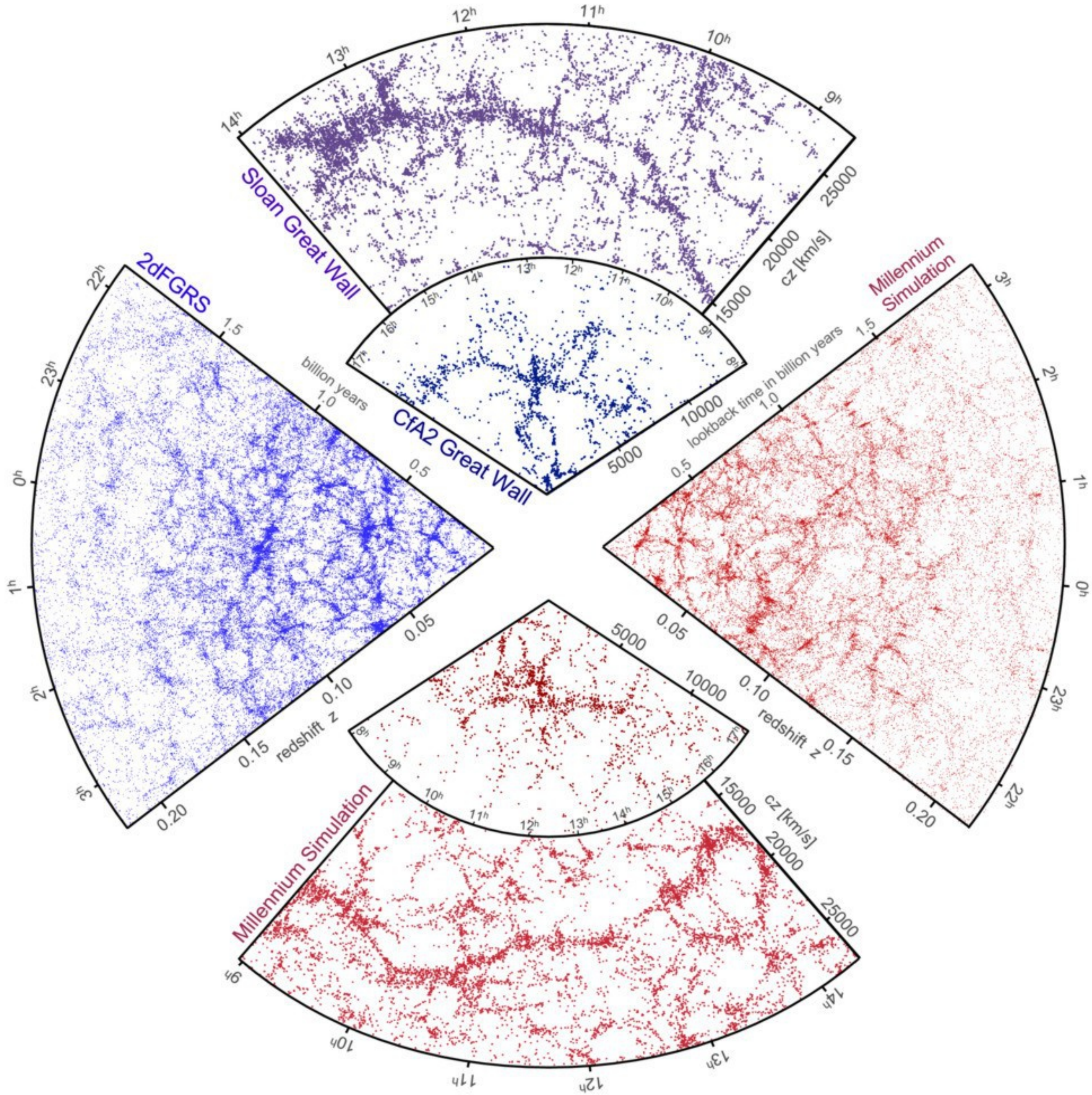
BIG BANG
BIG BANG PLUS TINIEST FRACTION OF A SECOND (10^{-43})
INFLATION
COBE SKY MAP
BIG BANG PLUS 300,000 YEARS
LIGHT FROM FIRST GALAXIES
BIG BANG PLUS 15 BILLION YEARS

Distribution of Galaxies in the SKY (XMASS)

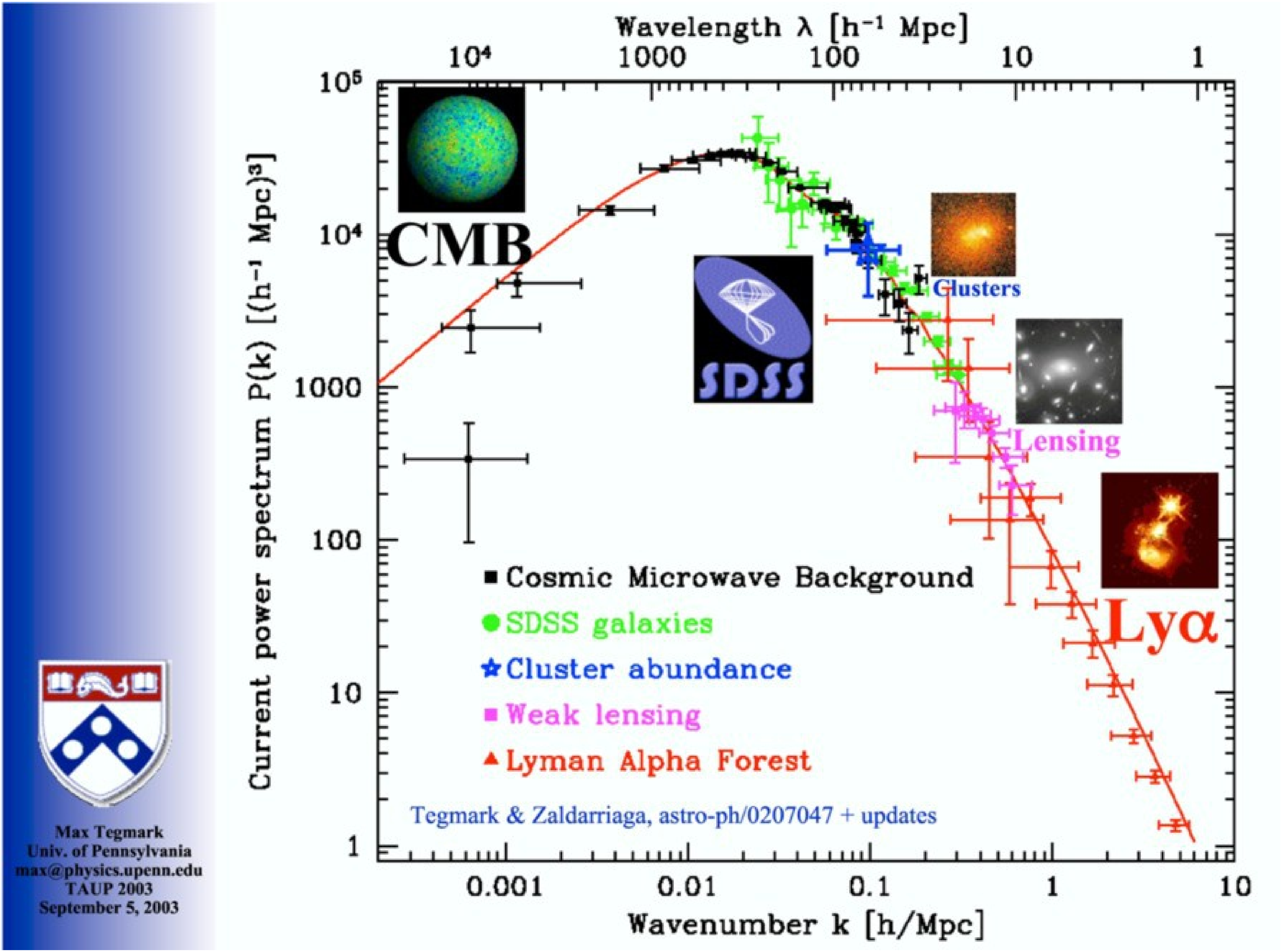


2dF Galaxy Redshift Survey





Sloan Great Wall
CfA2 Great Wall
2dFGRS
Millennium Simulation
Millennium Simulation
cz [km/s]
lookback time in billion years
billion years
redshift z


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
CMB
SDSS
Clusters
Lensing
Lyα
Current power spectrum P(k) [(h⁻¹ Mpc)³]
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

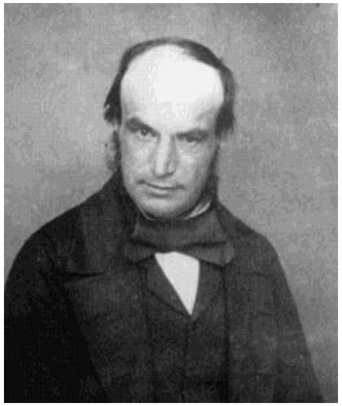
A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

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

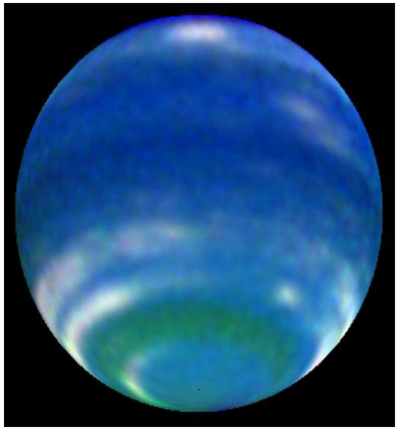
Uranus orbital anomalies

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

Urbain Le Verrier

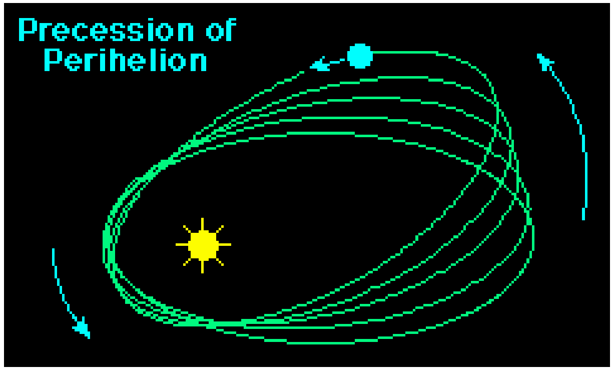


John Couch Adams

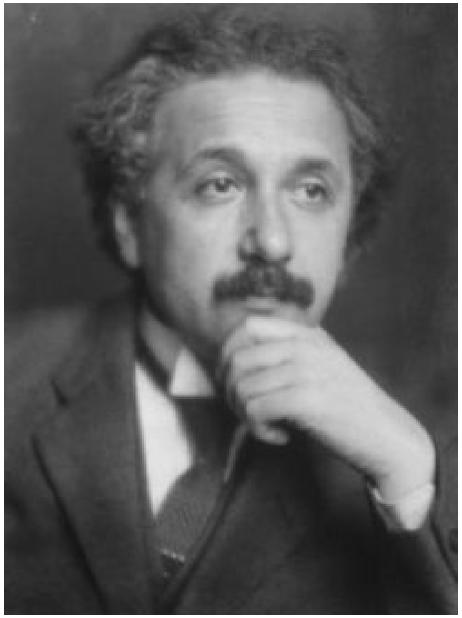


Mercury orbital anomalies

Extra 43''/century perihelion precession



New dynamics
General Relativity
(1916 Albert Einstein)



MOdified Newtonian Dynamics [MOND]

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

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

Fundamental acceleration

$$a_0 \simeq c\,H_0/5$$

Coincidence?

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

"Newtonian"

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

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

Modified Newtonian (small acceleration)

$$v_{\mathrm{rot}}^4 \to G M\, a_0$$

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

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.

Theoretical Objections: "Phenomenology, Not Theory"

Mordehai Milgrom (SciAmi august 2002).

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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"

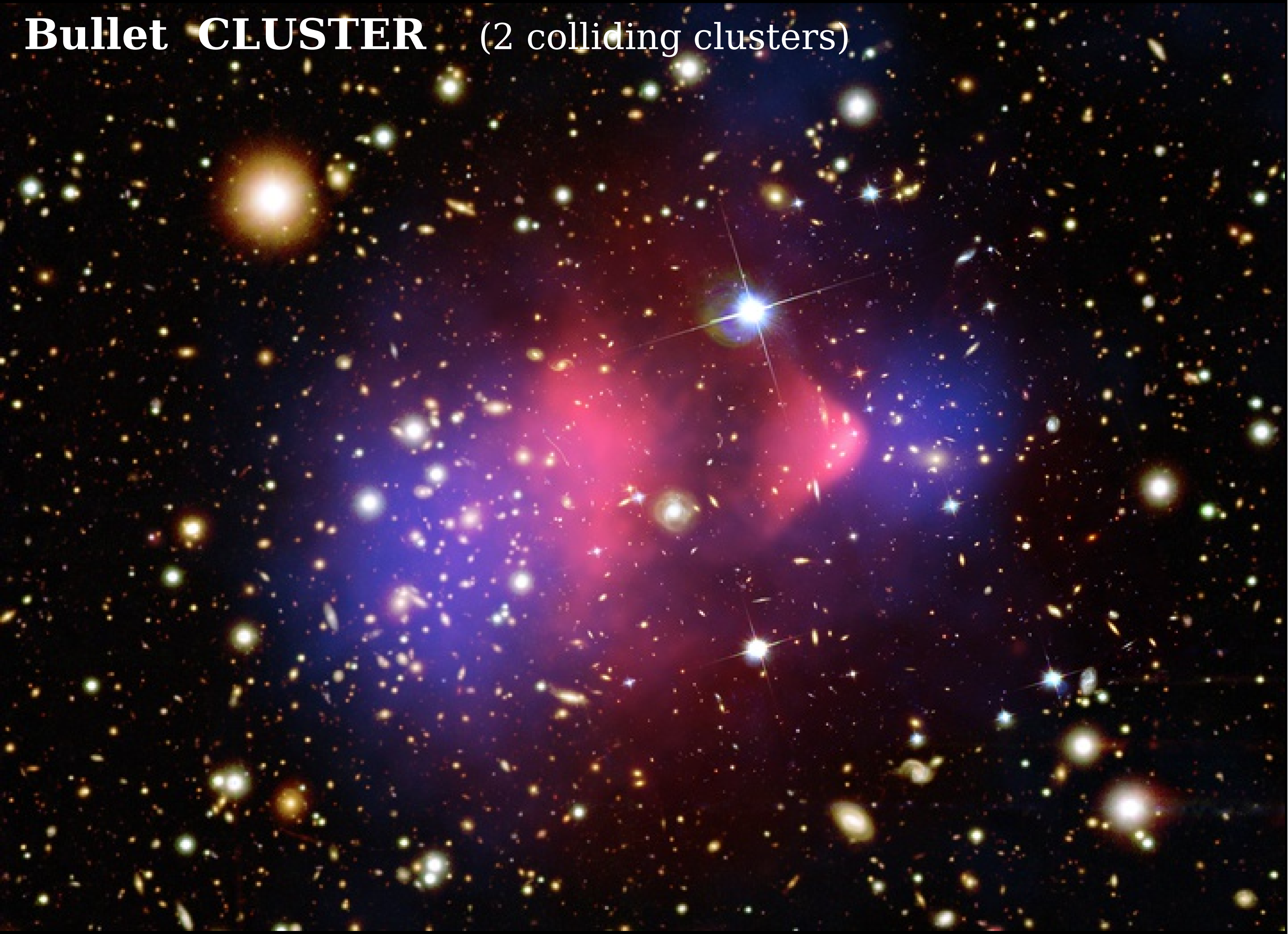
1. Theoretical Difficulties in constructing
   a consistent, covariant theory.

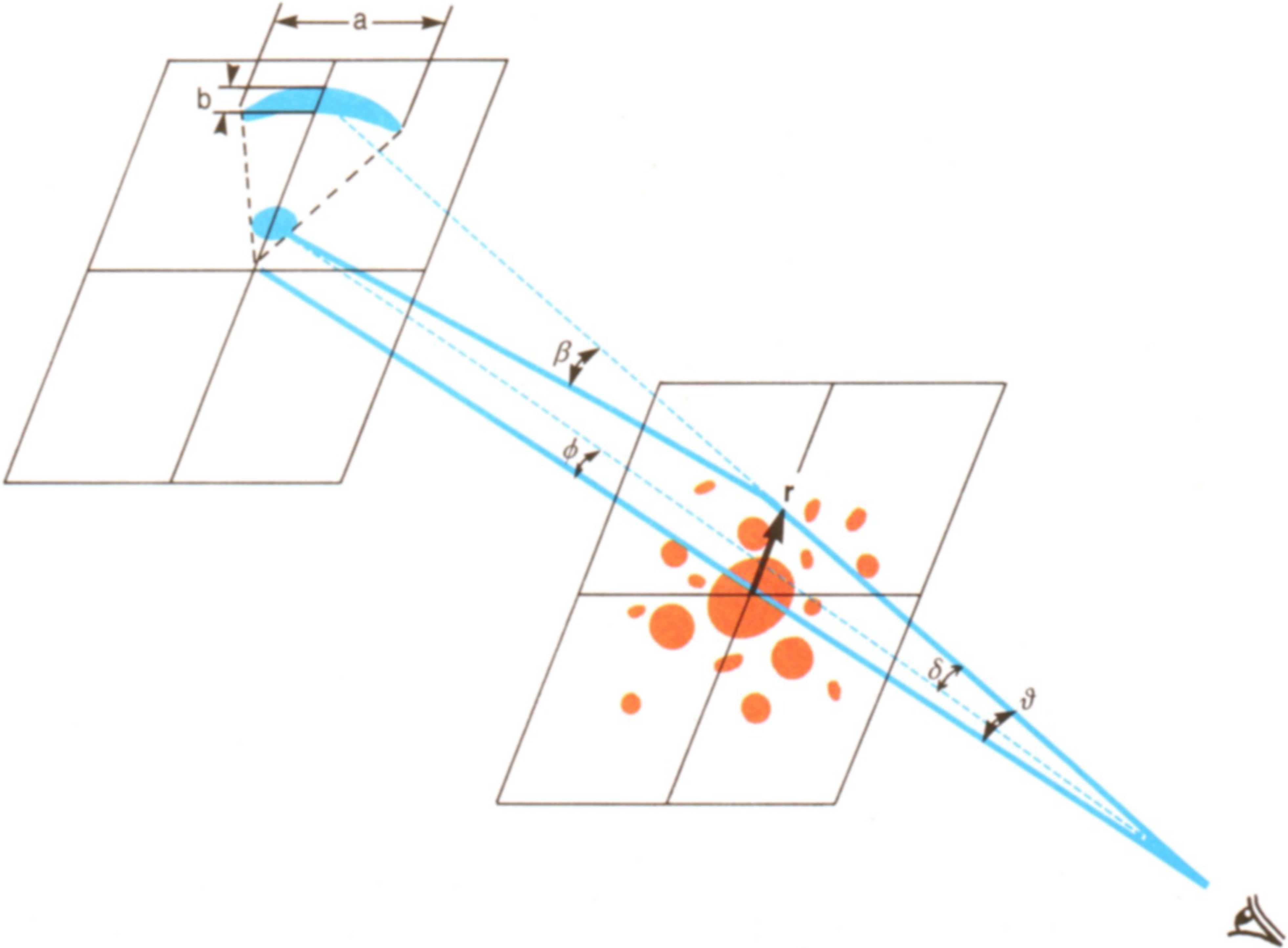
2. Remarkable success of the "Dark Matter" paradigm
   In describing the structure formation in our universe.
   Relation between the
   - Large scale galaxy distribution.
   - Anisotropies in the Cosmic Background Radiation.

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].

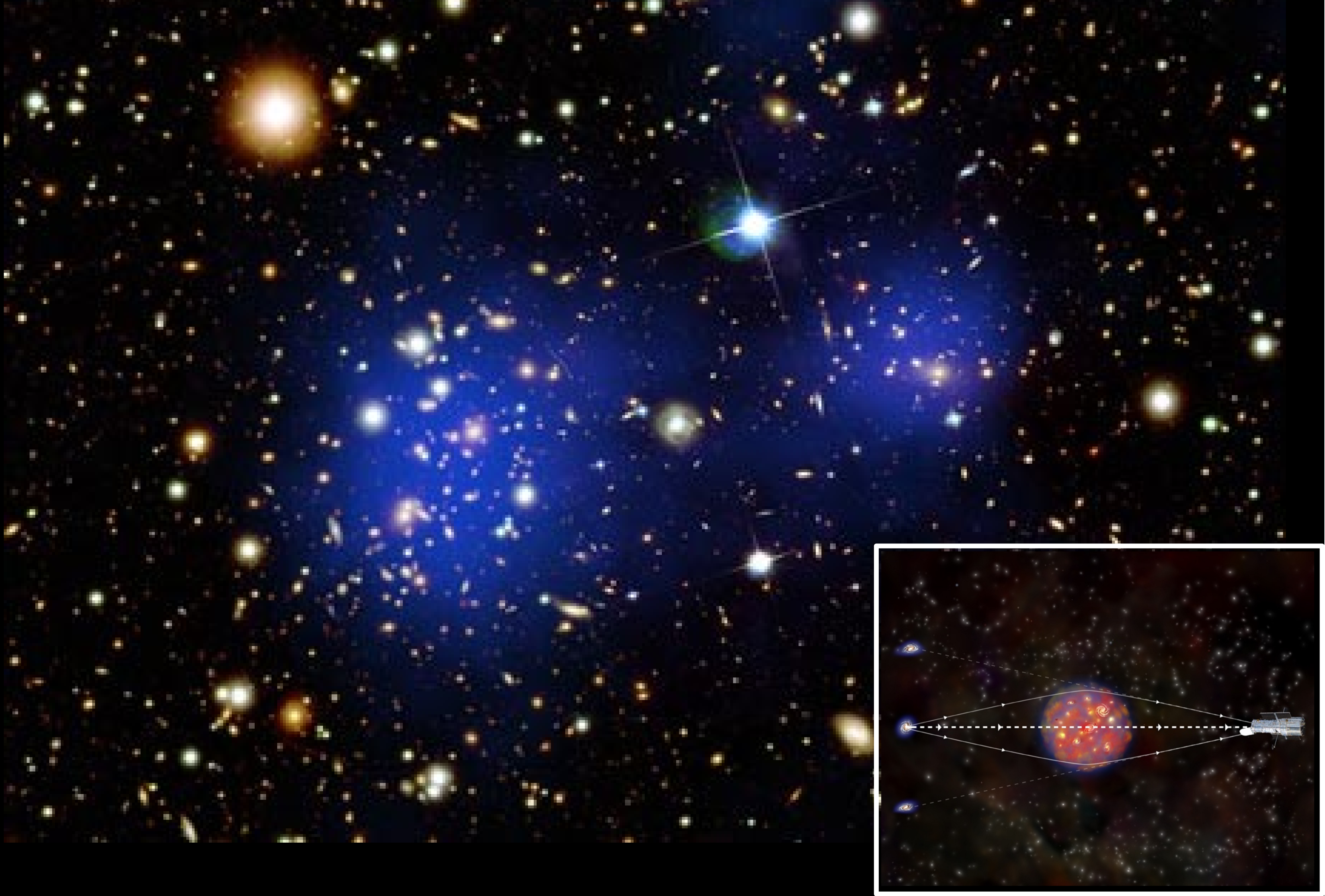
Bullet CLUSTER (2 colliding clusters)



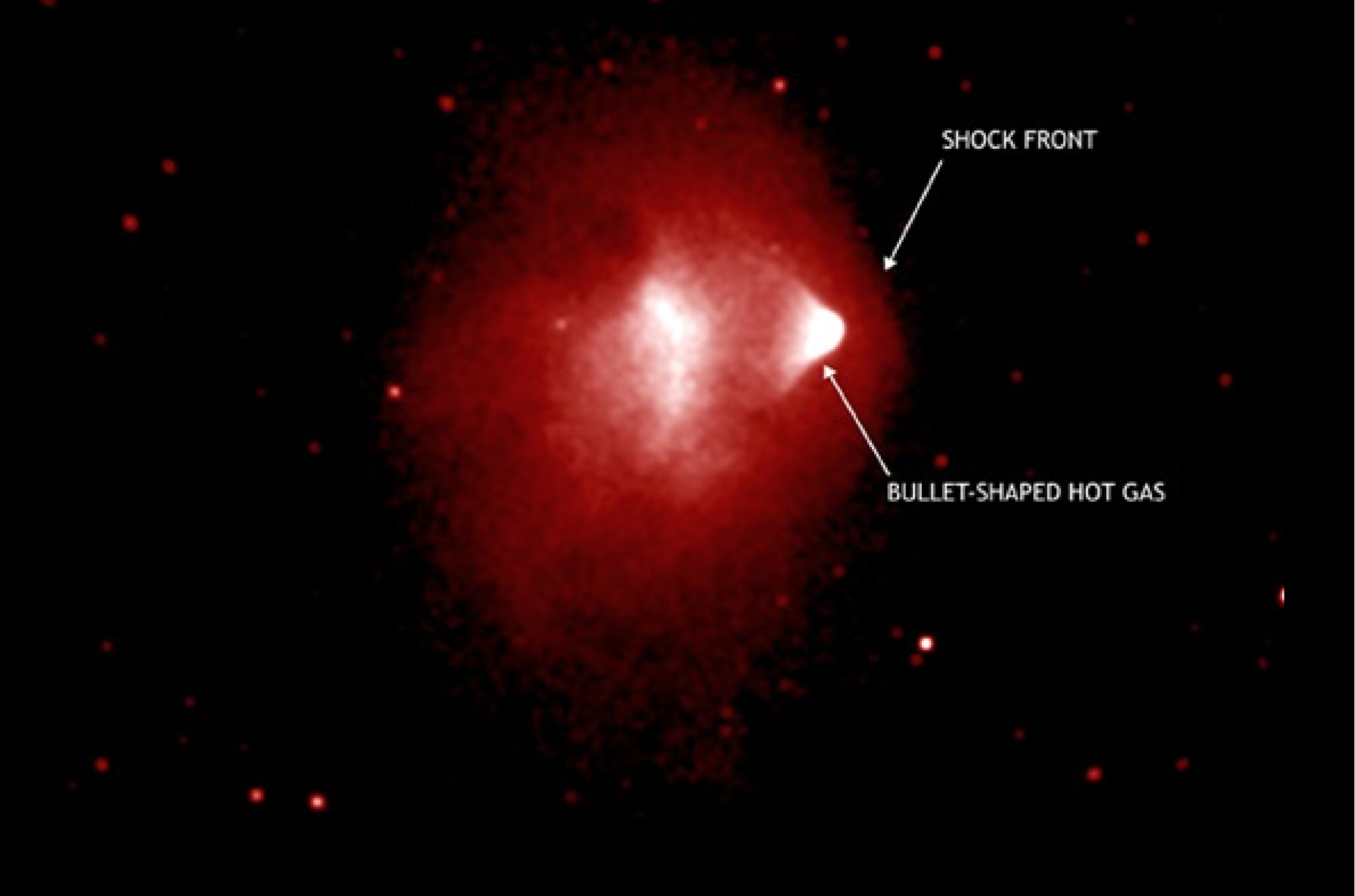


A.Tyson, Physics Today, 1992:6, pg.24

MASS DISTRIBUTION
(from gravitational lensing)

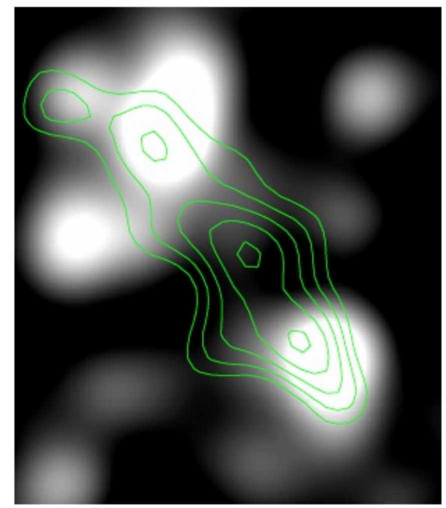


X-RAY Emission
(gas of ordinary matter)

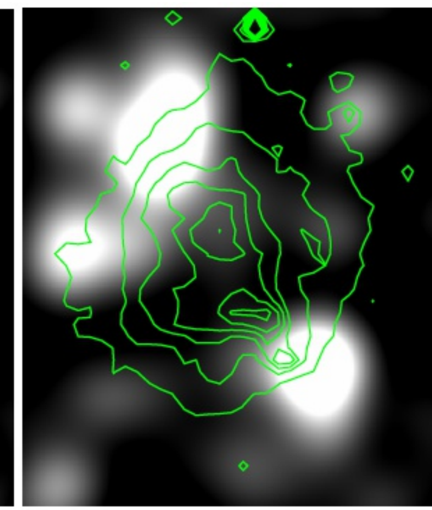


In recent years a lot of attention has been given to the "train wreck cluster" [Abell 520] (z=0.21)

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

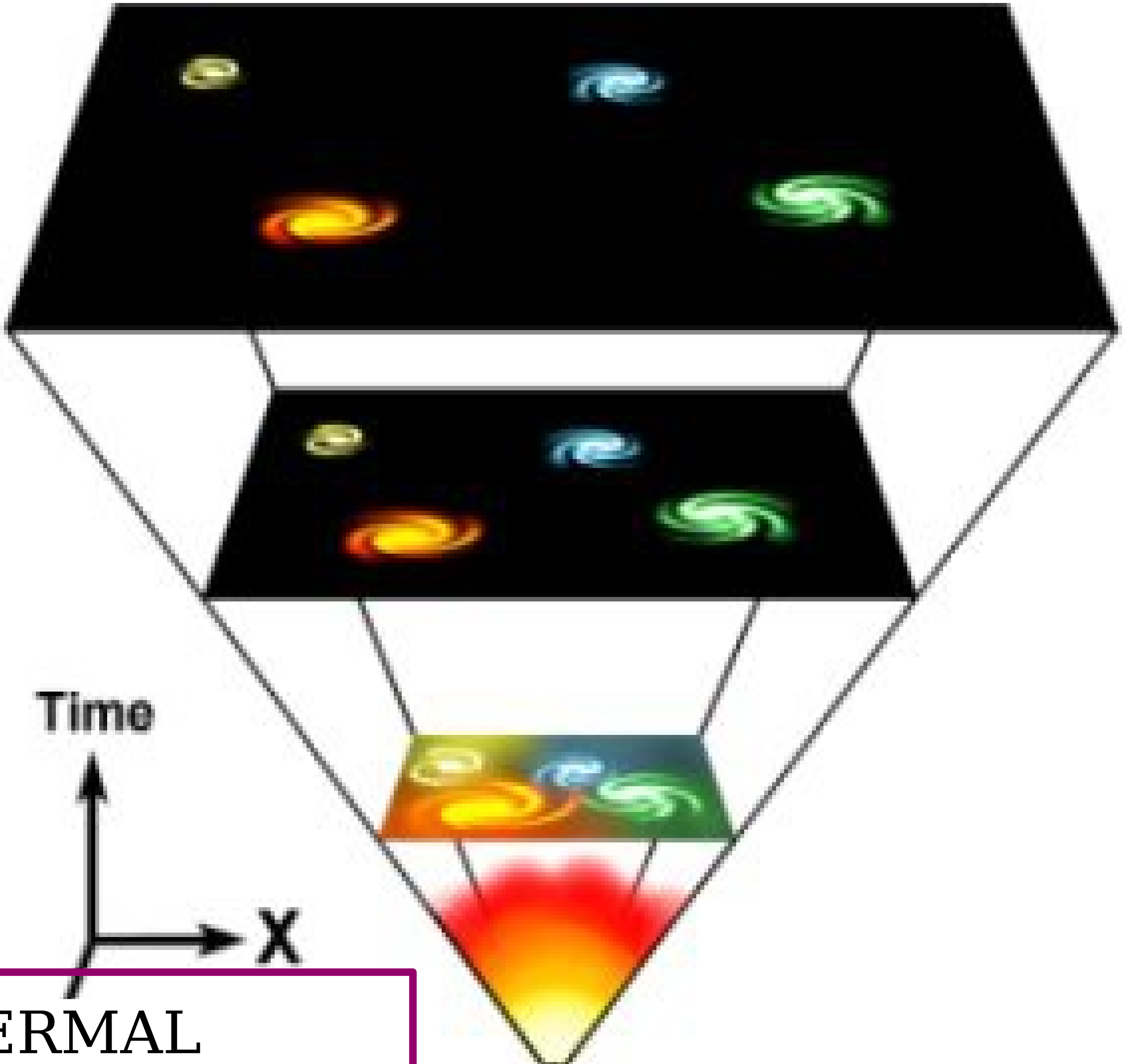
Axion

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

$$T \gg m_\chi$$

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

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

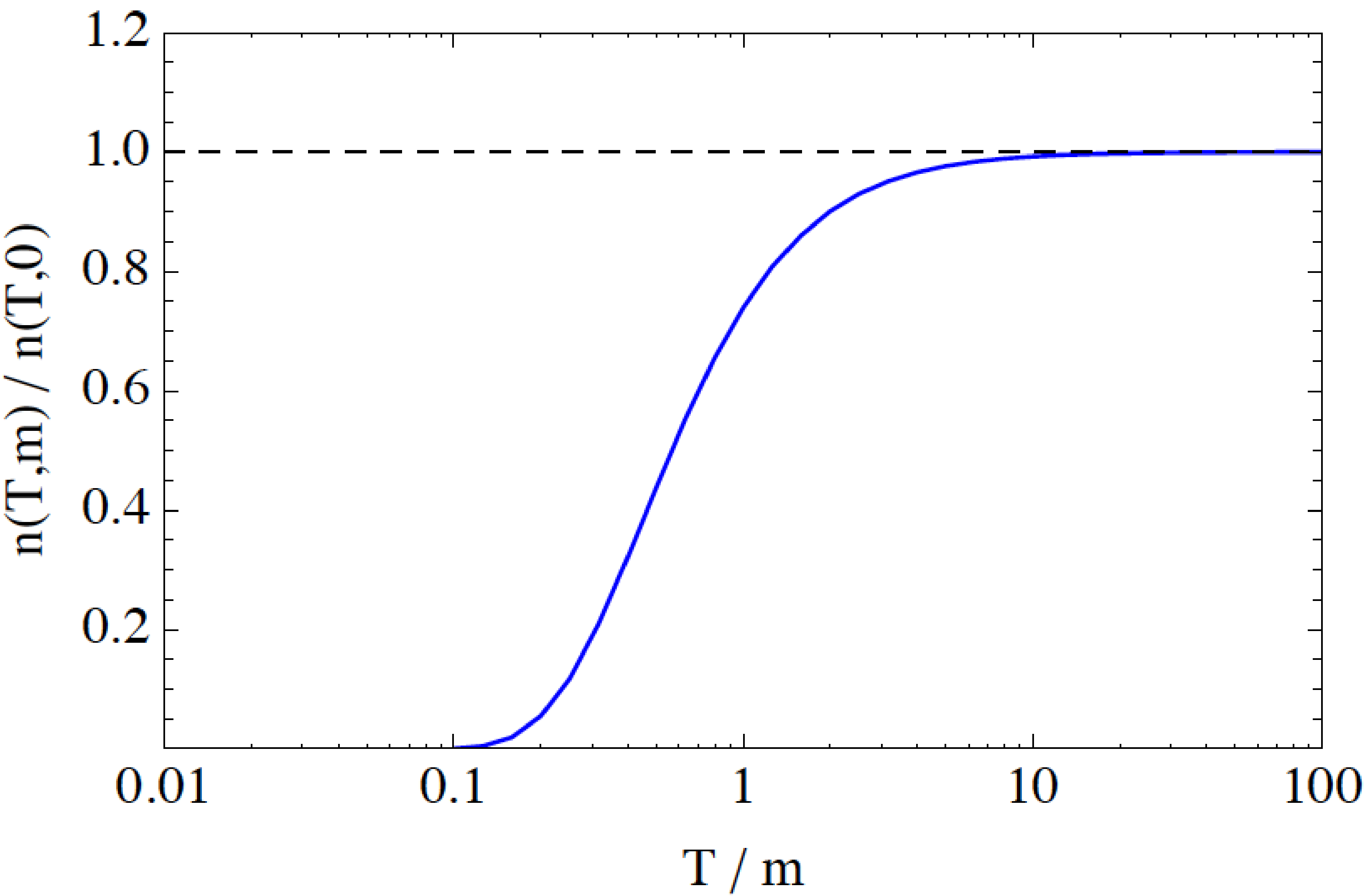
$$\rho_{\mathrm{boson}}(T) = g \, \frac{\pi^2}{30} T^4$$

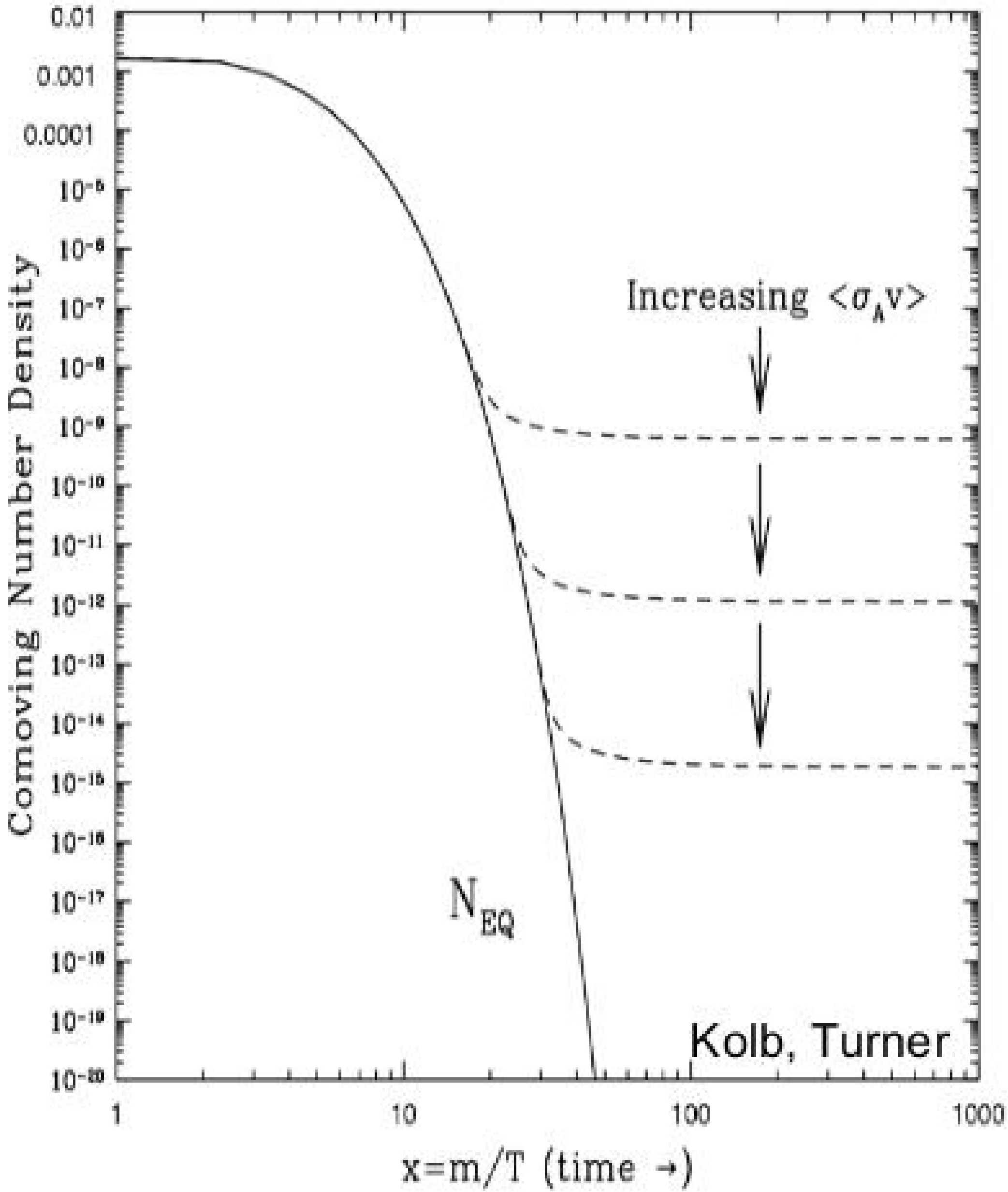
$$\rho_{\mathrm{fermion}}(T) = g \, \frac{\pi^2}{30} T^4 \times \frac{7}{8}$$

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

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

m < T





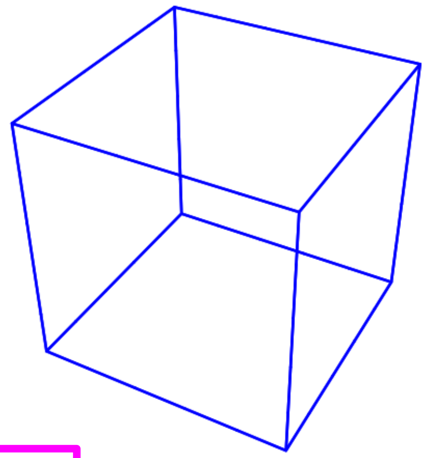
$$\Omega_j^0 \simeq 0.3 \left[\frac{3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma\, v \rangle} \right]$$

Annihilation cross section
Determines the
"relic abundance"

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

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

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 $\sigma(v) \; v = {\rm constant}$]

Particle anti-particle annihilation and the "Relic Density"

[Pedagogical discussion]
"box" of constant volume.
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Velocity averaged cross section
[in many cases $\sigma(v) \; v = \text{constant}$]

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

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

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

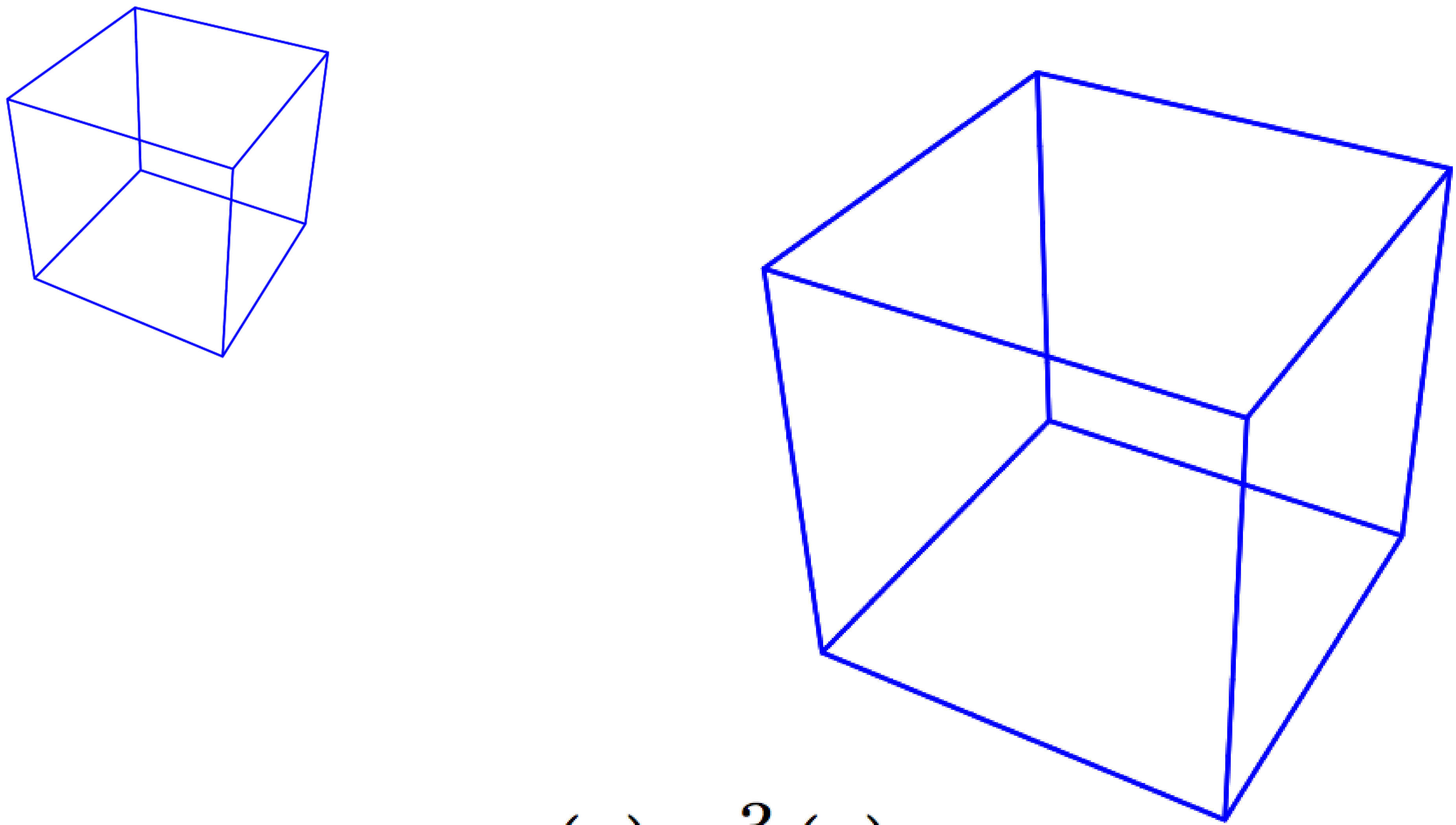
$$n(t) = \frac{n_i}{1 + n_i \langle \sigma\, v \rangle (t - t_i)}$$

Solution

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

All particles annihilate.

Annihilation in an Expanding Universe



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

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

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

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

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

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

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

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

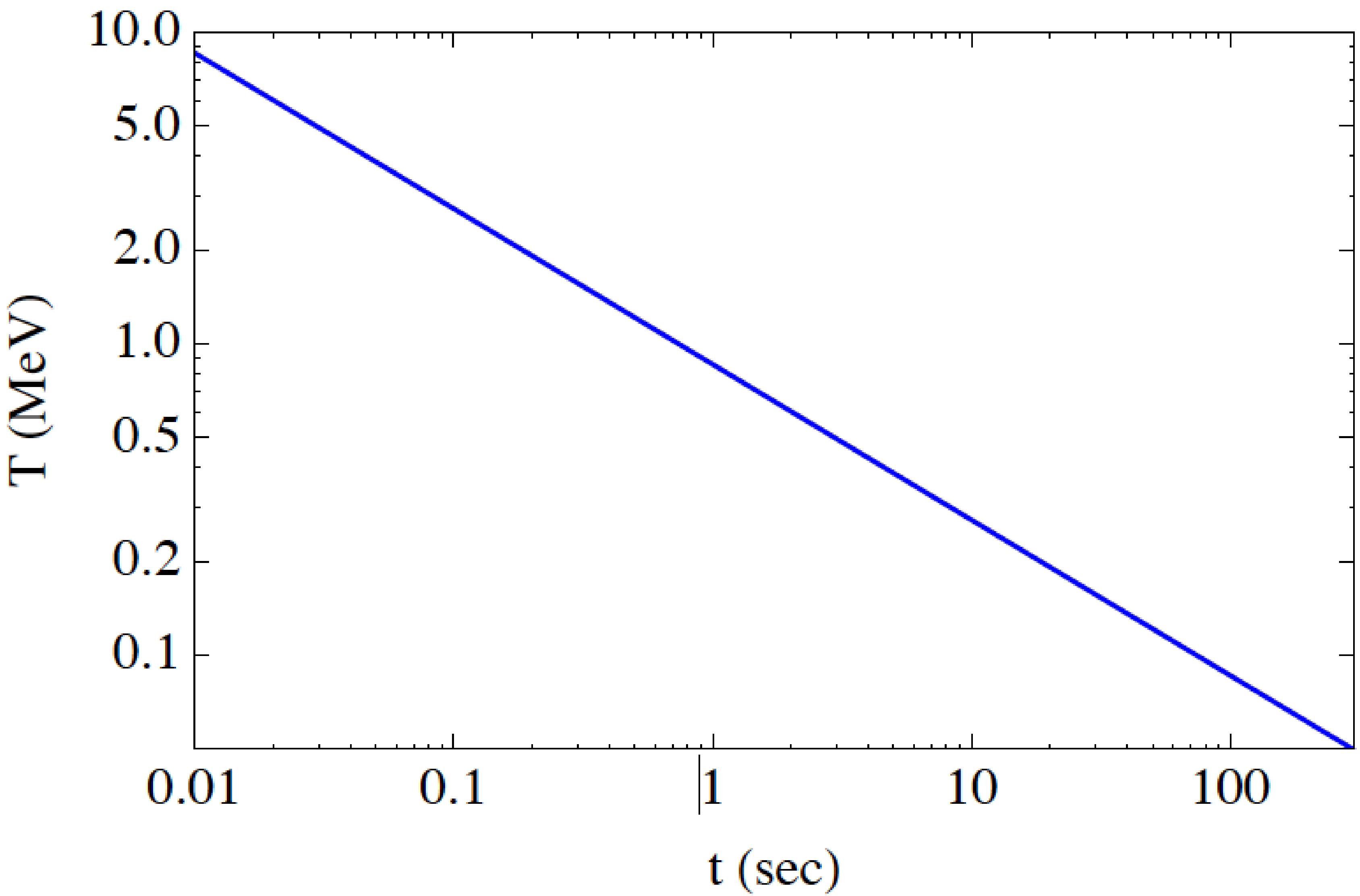
$$g^* = N_{\text{bosons}} + \frac{7}{8} N_{\text{fermions}}$$

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

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

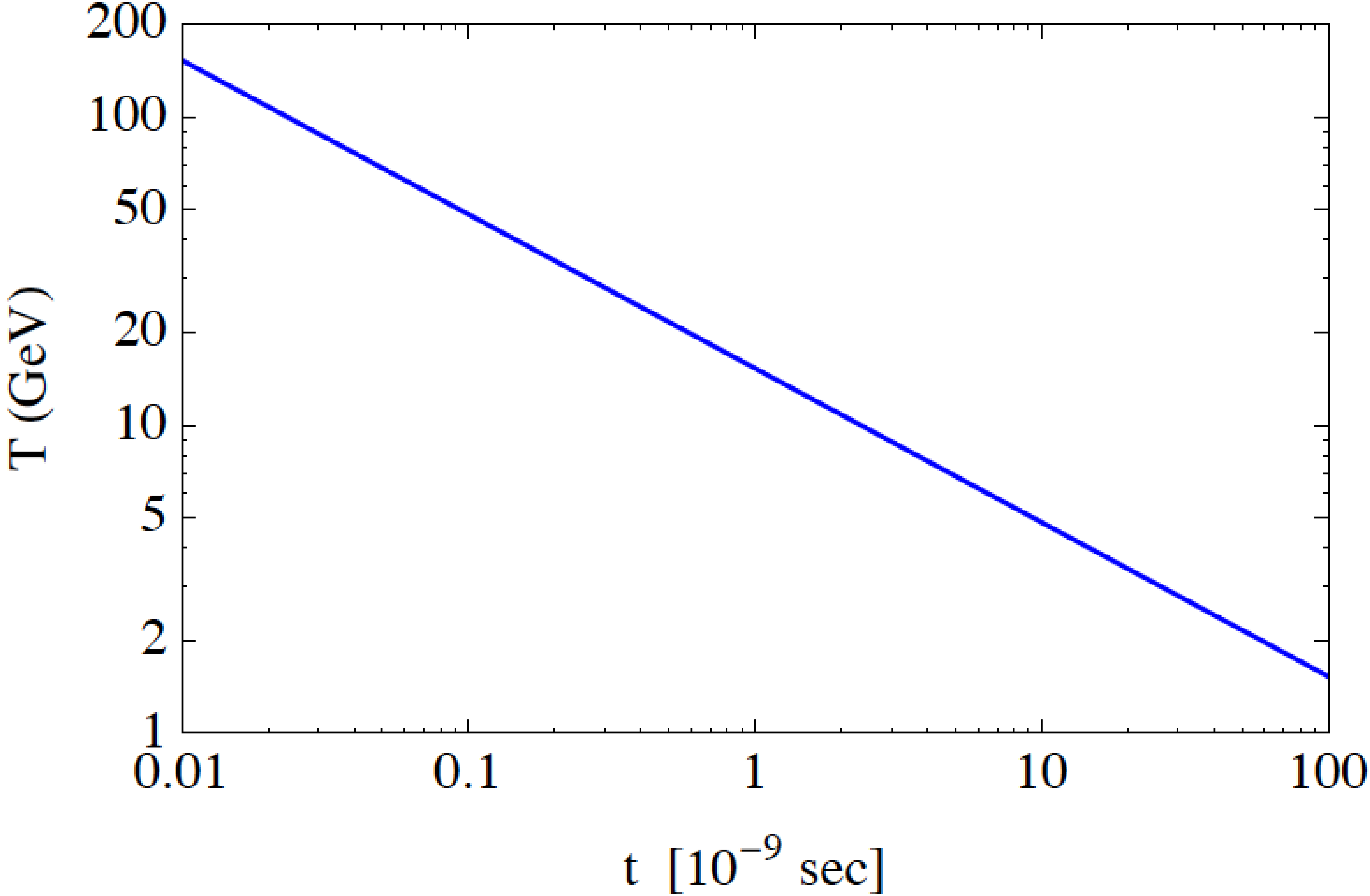
Relation between time and temperature
during the nucleosynthesis
“the first three minutes”

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



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.

$$t_{\rm annihilation} = (\langle \sigma\, v \rangle\, n_\chi)^{-1}$$

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

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

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

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

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

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)

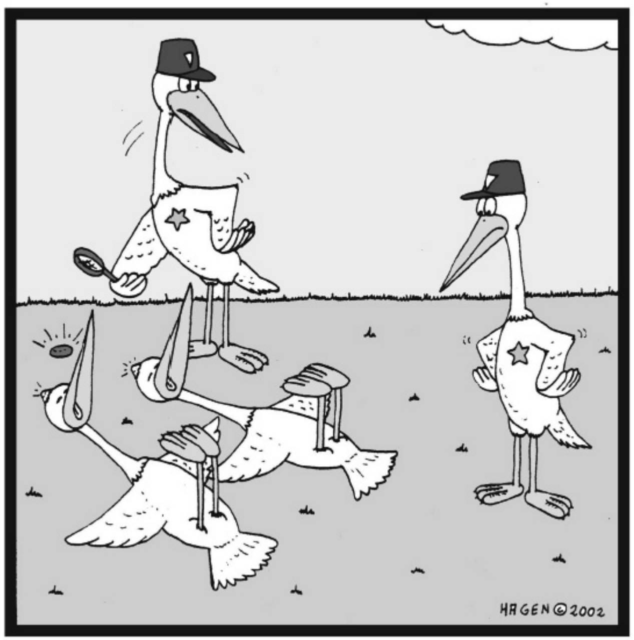
$$\sigma(\chi\chi \to \mathrm{anything}) \simeq 10^{-36} \ \mathrm{cm}^2$$

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

Weak interaction mass scale

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

Weakly Interacting Massive Particles (WIMP's)



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

the WIMP's "miracle"

"Killing two birds with a single 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
	leptons	Sleptons
	neutrinos	Sneutrinos
bosons	photon	photino
	W	Wino
	Z	Zino
	gluons	gluinos
	Higgs	Higgsino
2 Higgs →	H h	$\tilde{H}$ $\tilde{h}$

New bosons (scalar) spin 0 S....

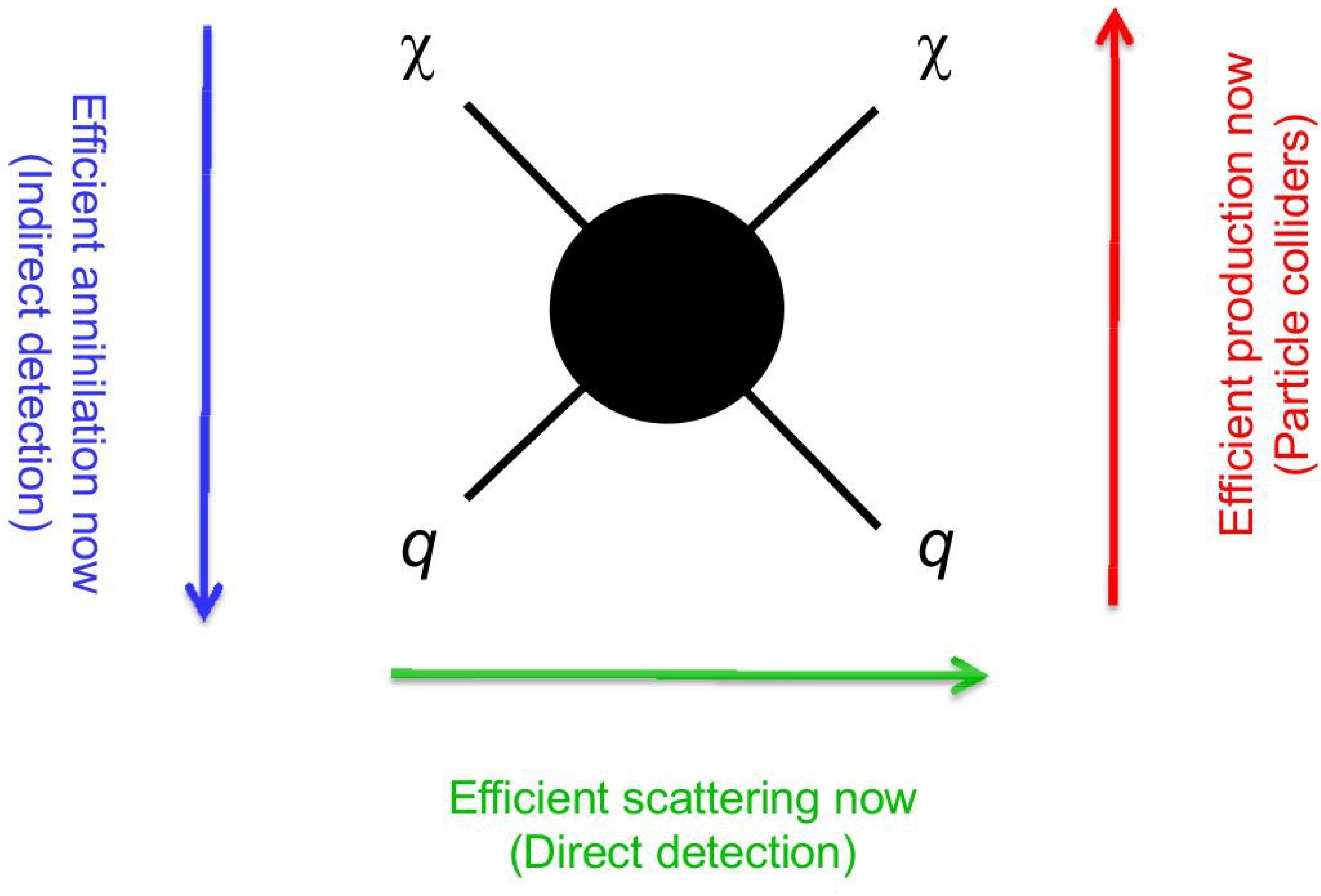
New fermions spin 1/2 ...ino

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

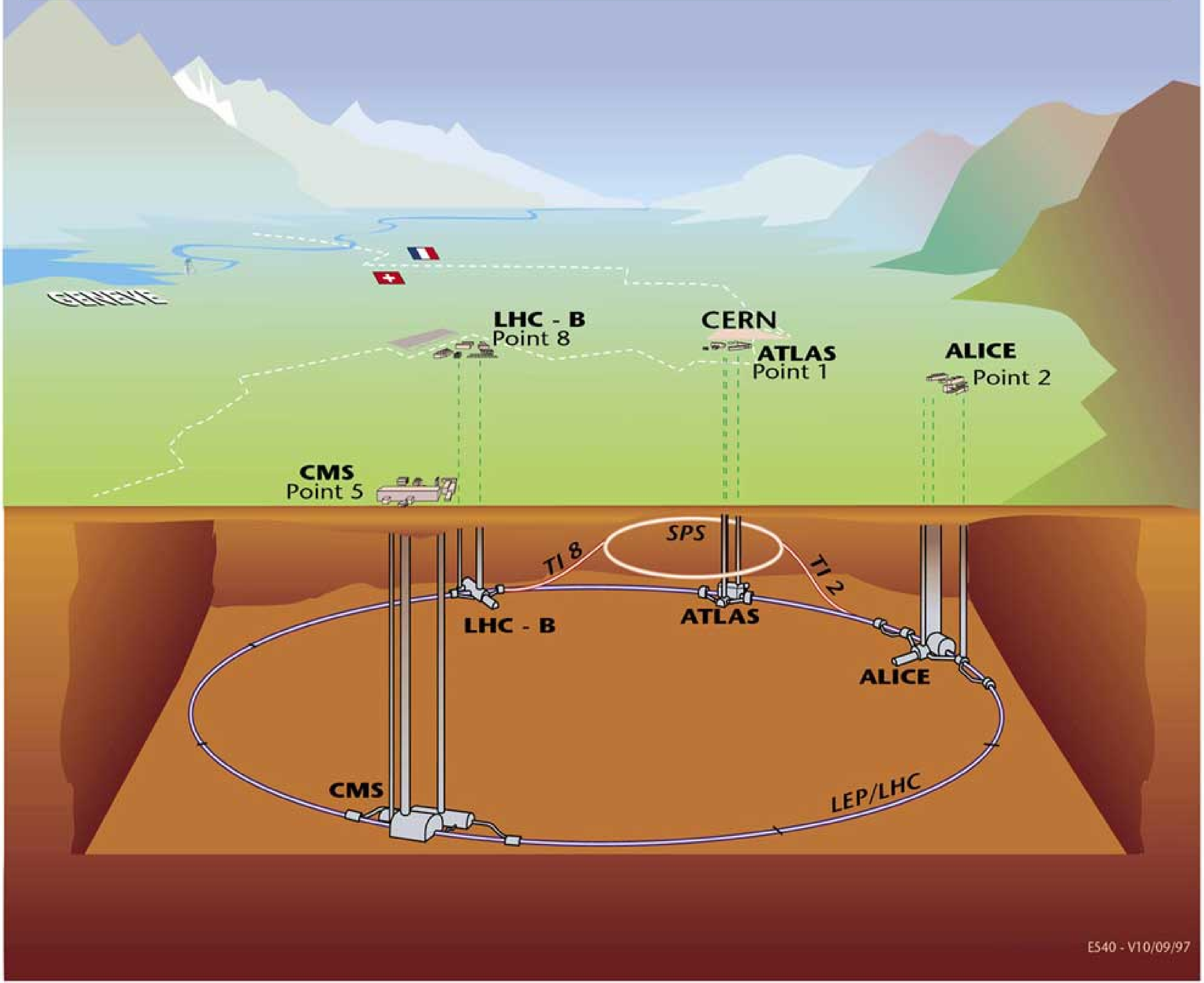
Time reversal

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

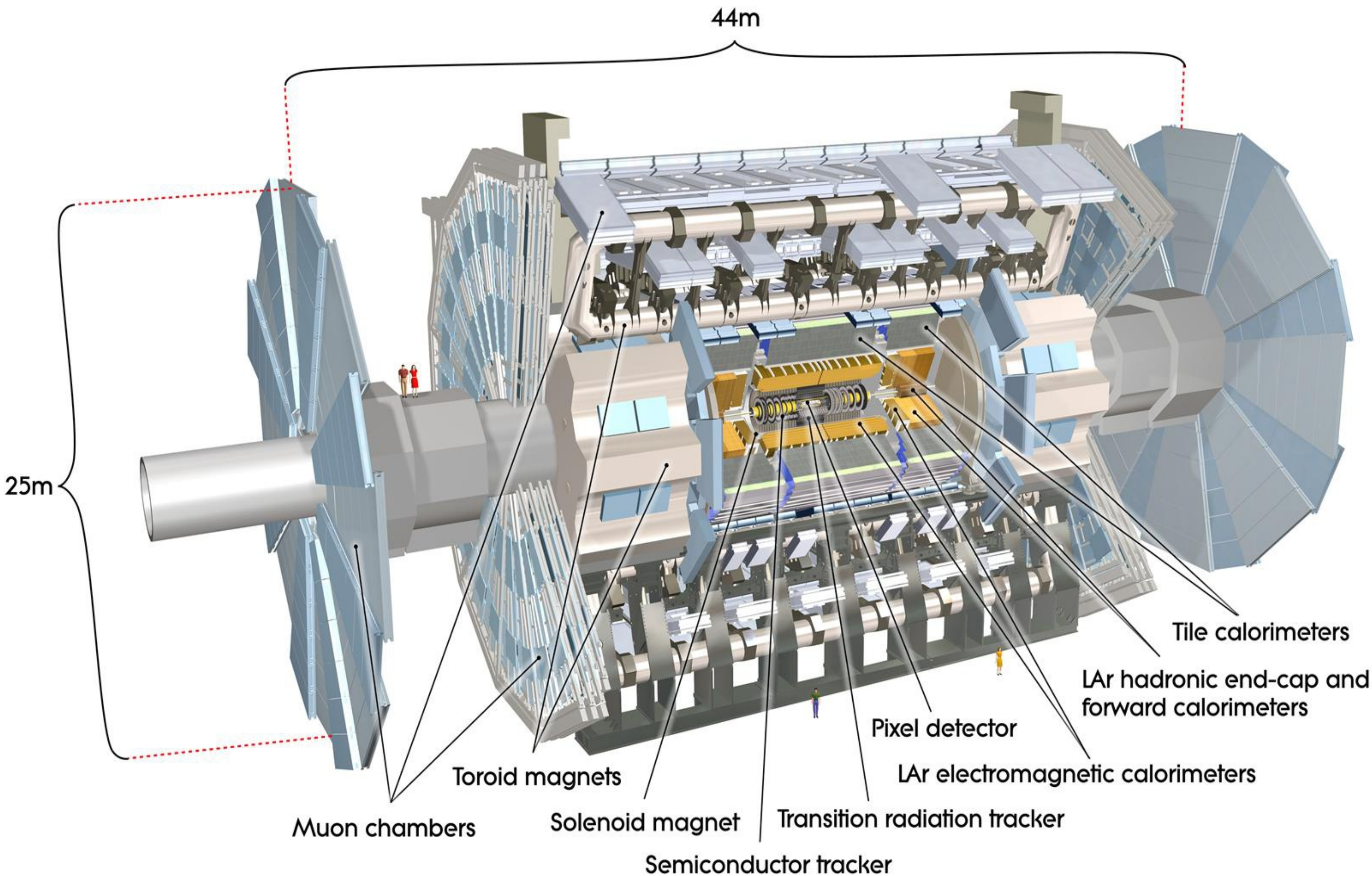
Elastic

Crossing symmetry

Overall view of the LHC experiments.

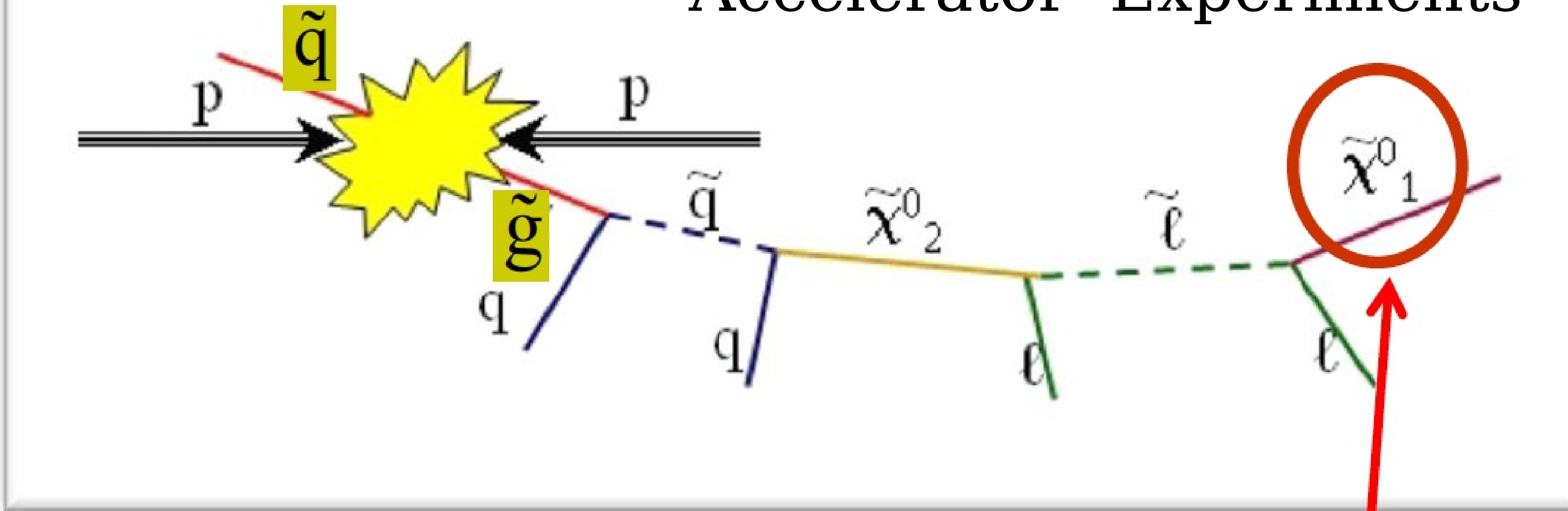


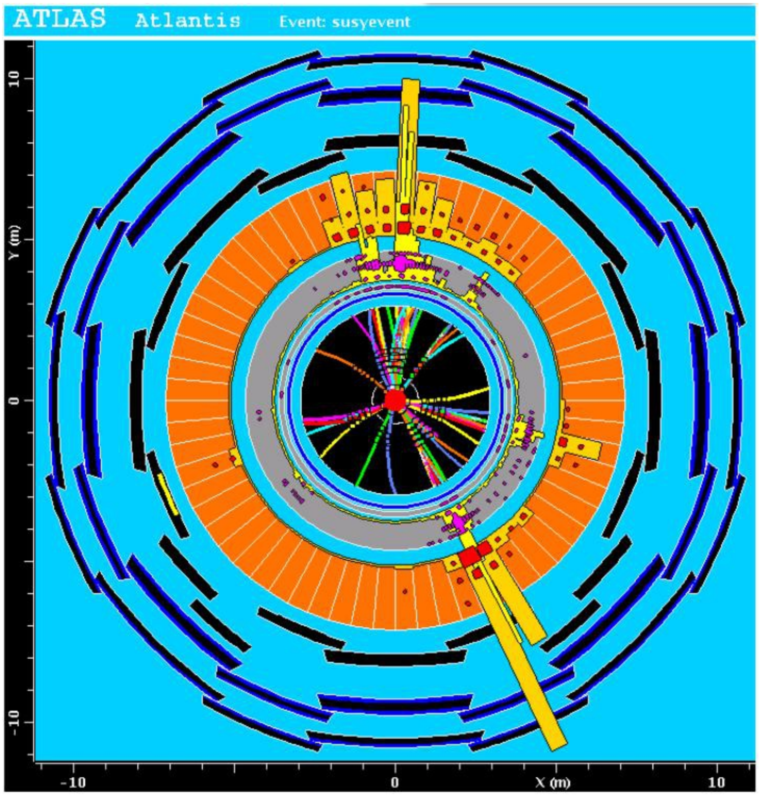
ATLAS detector at LHC



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

Accelerator Experiments





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

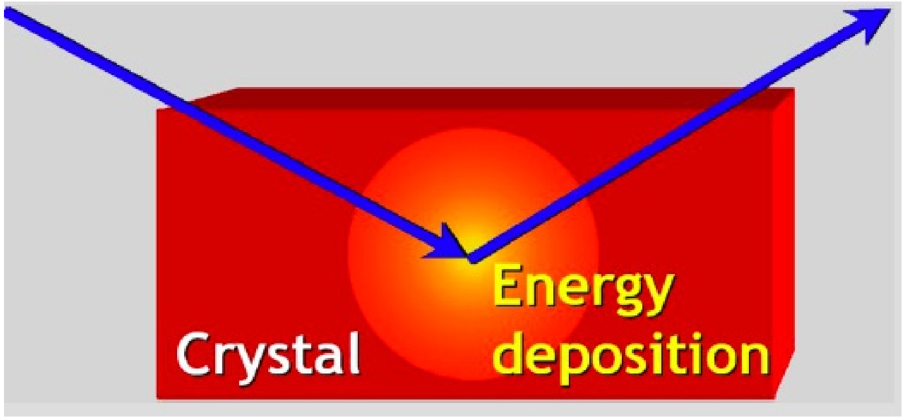
This particle interacts WEAKLY therefore (effectively always) traverse the detector invisibly.

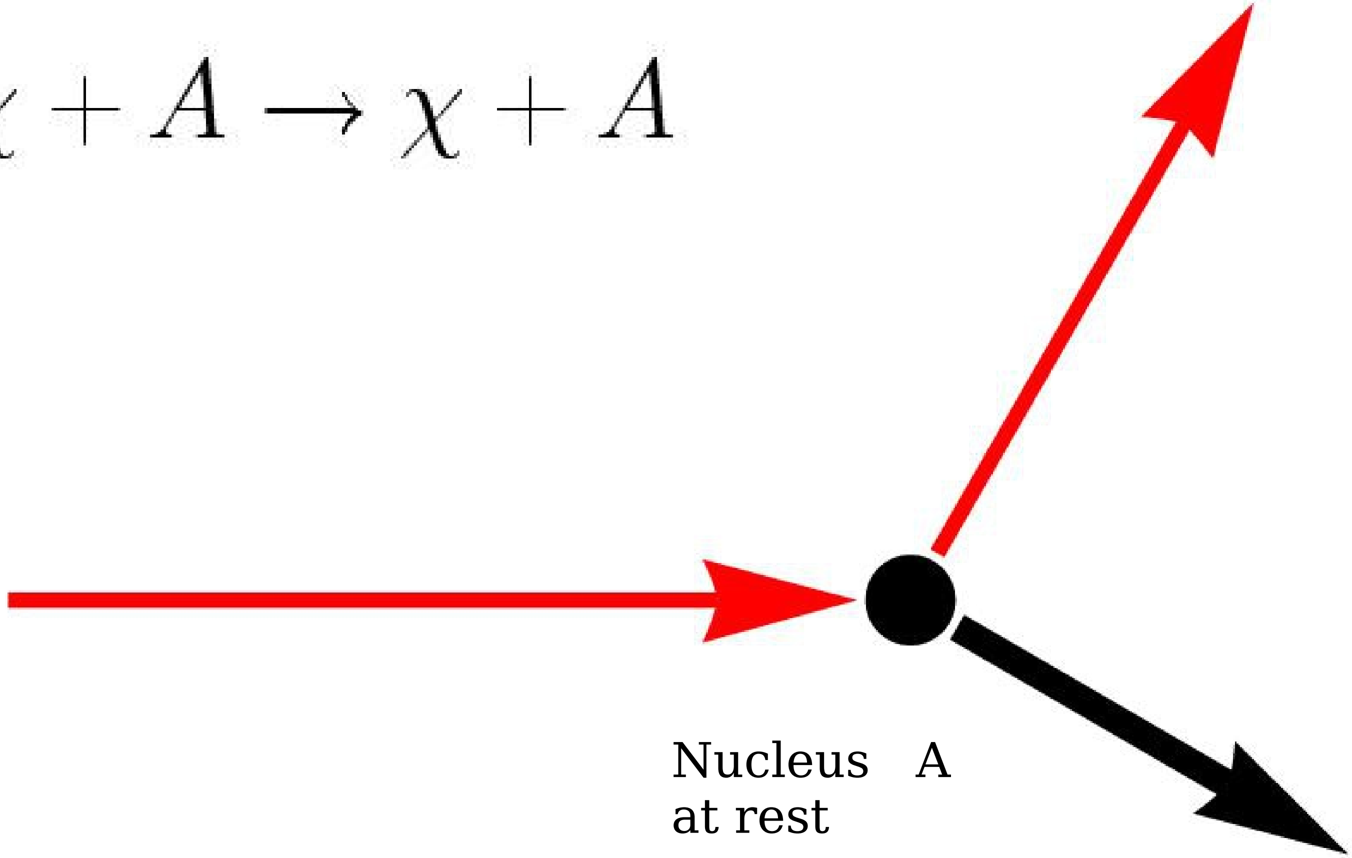
Detection via 4-momentum conservation
["Missing energy and
(transverse) momentum"]

“Direct” Search for Dark Matter

Elastic scattering

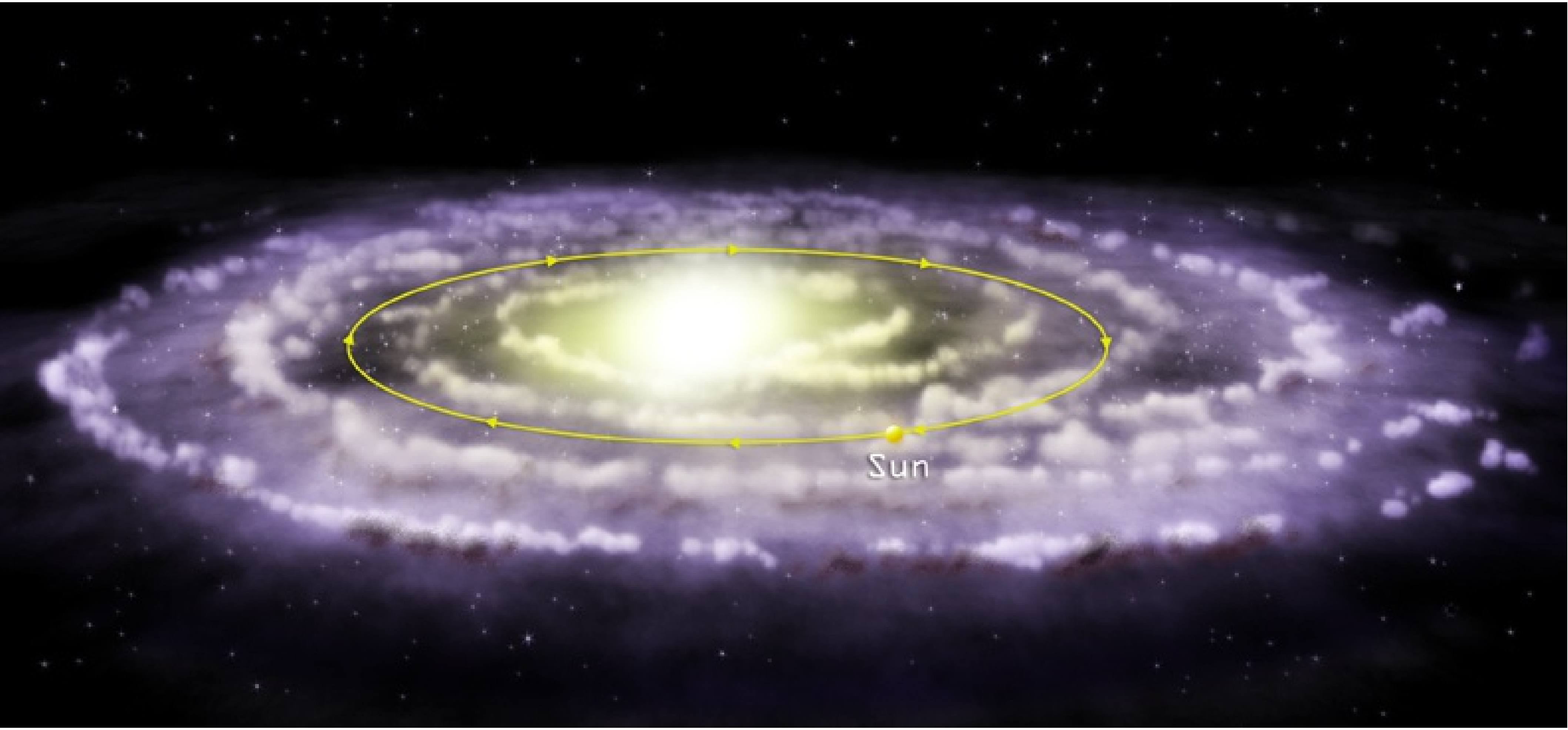
$$\chi + A \to \chi + A$$



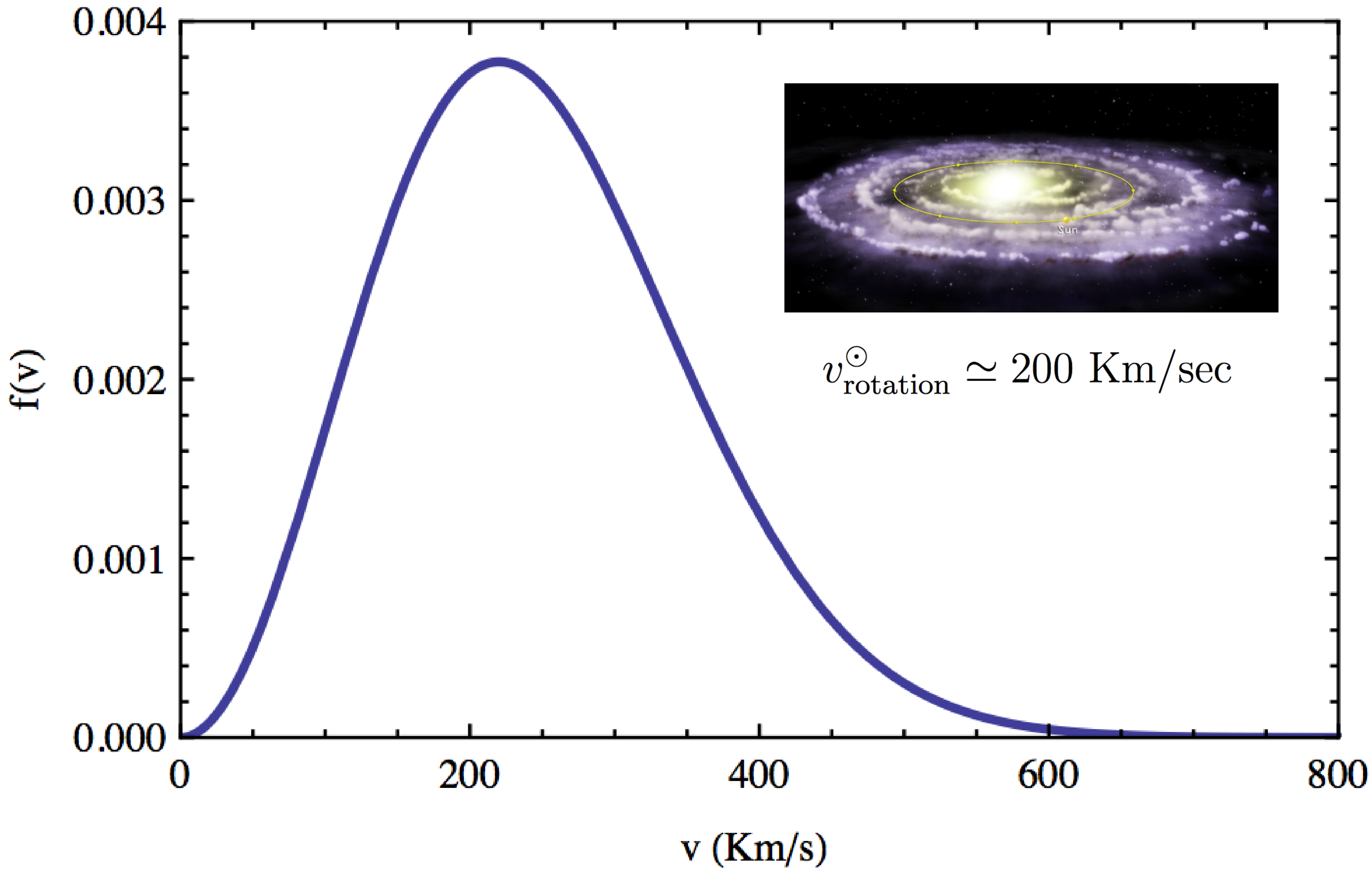


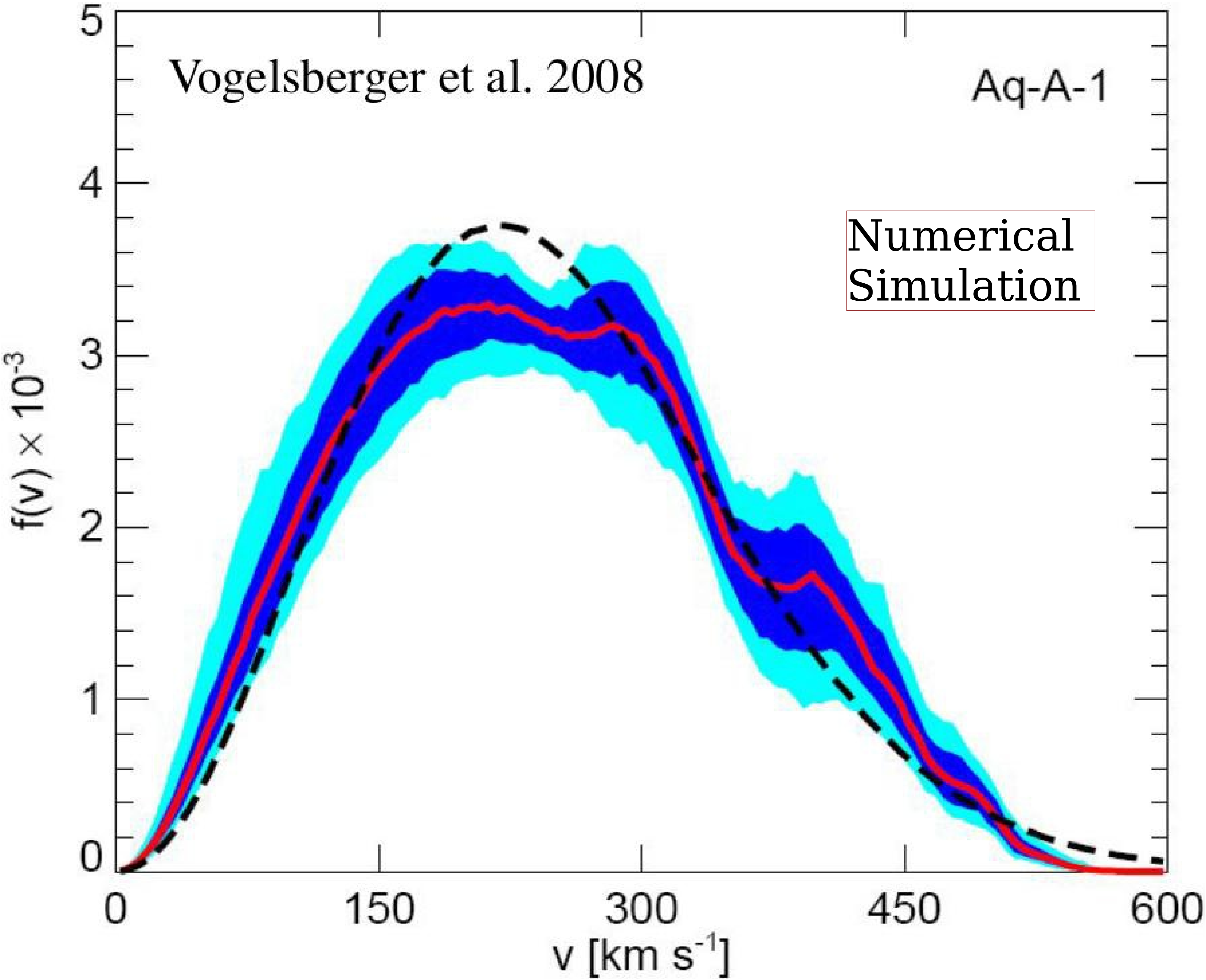
SUN – rotation around the galactic center.

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

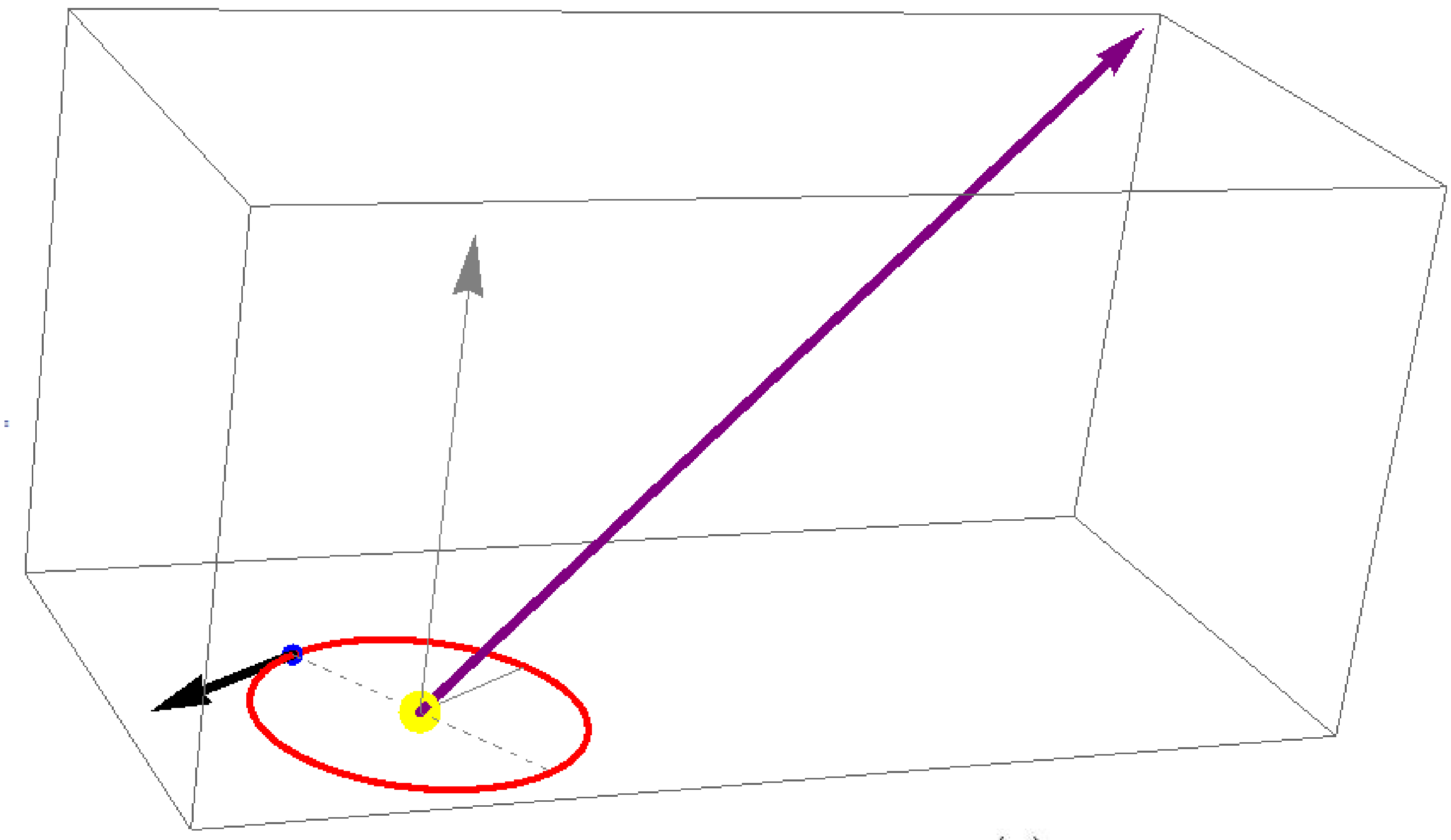


Predicted velocity distribution of DM particles
In the "Halo Frame"
Maxwellian form $\langle v_{\rm wimp} \rangle \simeq 250 \text{ km/sec}$





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



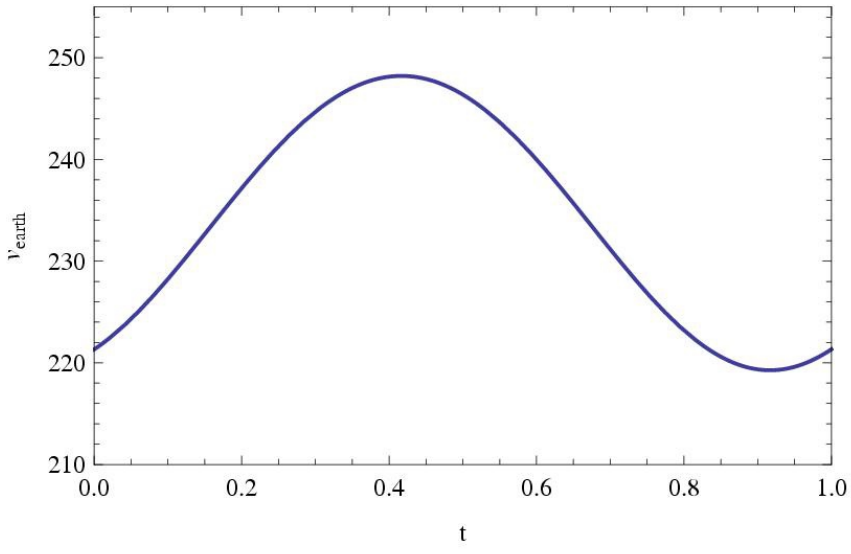
$$w_{\oplus}(t) \simeq w_{\odot} + \sin\gamma\ v_{\mathrm{orbit}}\ \cos[\omega(t-t_0)]$$

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

"Halo rest frame"

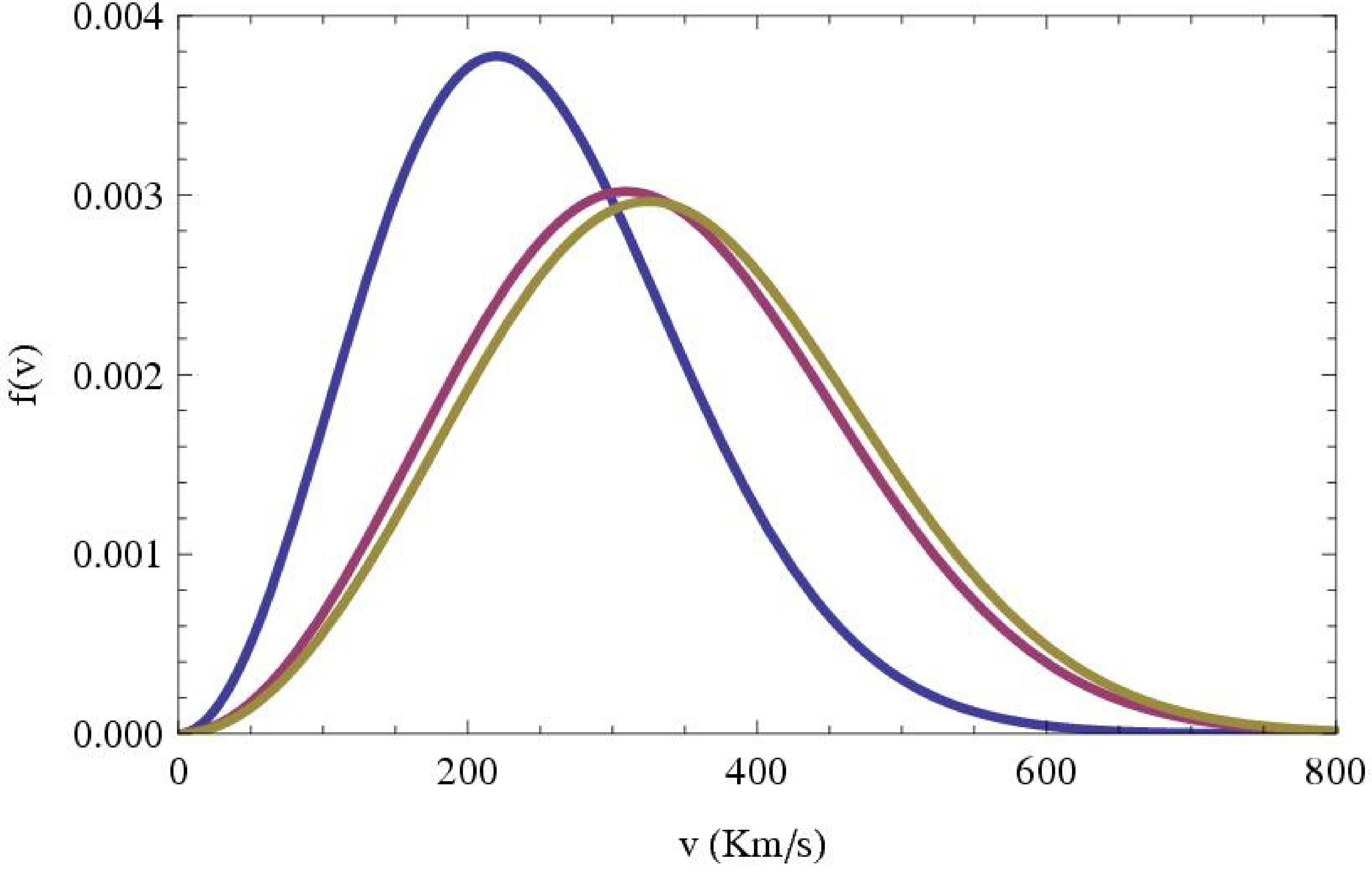
Velocity of Earth in the Halo rest frame

[Co-rotation ?]



Velocity distribution in the Earth Framexs

2nd june
2nd december



Expected flux of Dark Matter particles (here !) :

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

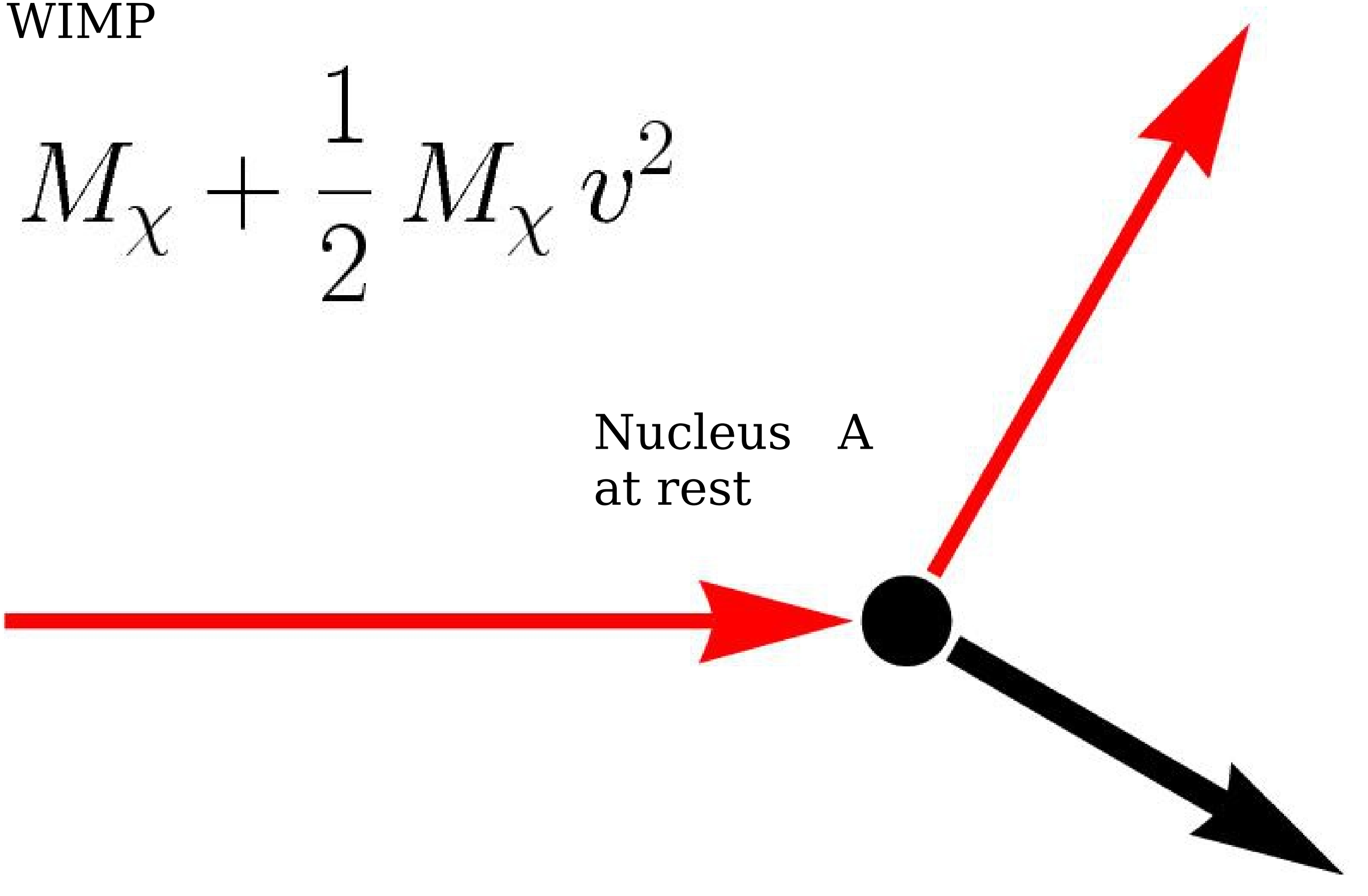
$$\simeq 1000 \left[\frac{100 \text{ GeV}}{m_\chi}\right] \quad (\text{cm}^2 \text{ s})^{-1}$$

"Direct" Search for Dark Matter

$$\chi + A \to \chi + A$$

Non relativistic WIMP

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

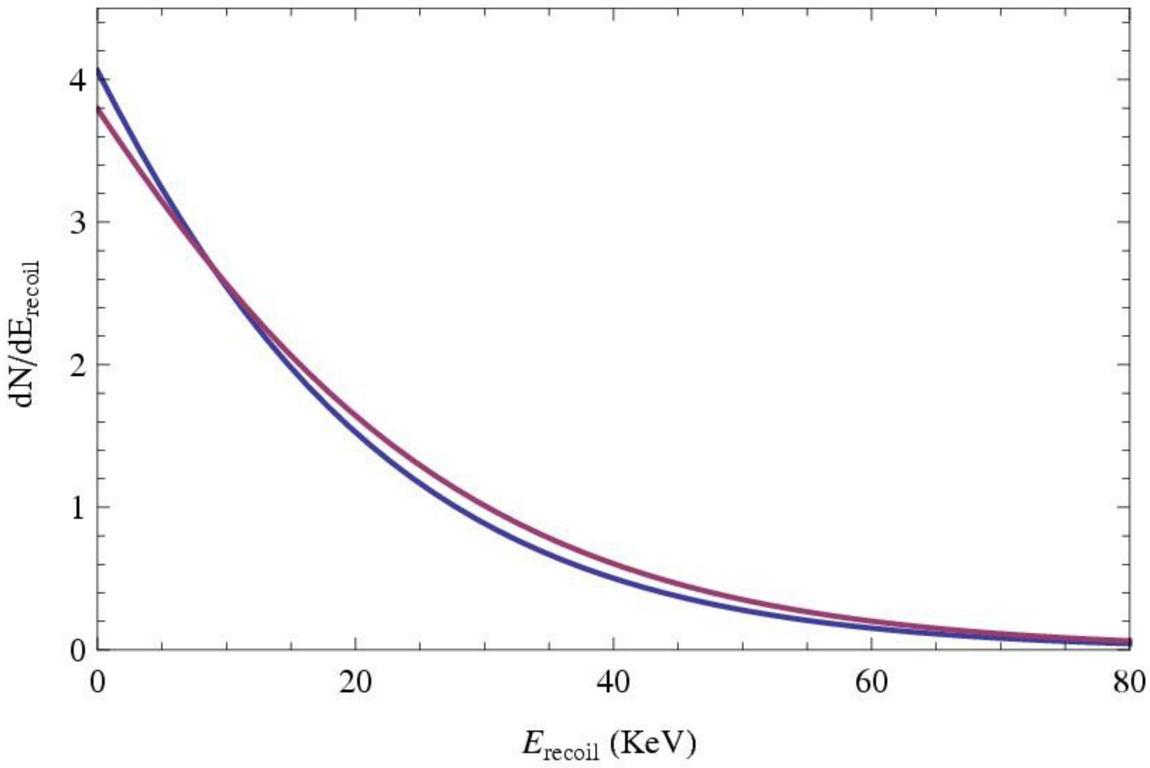


$$E_{\rm nucleus} = M_A + \left[\frac{1}{2} M_\chi v^2\right] \frac{4\, M_A\, M_\chi}{(M_A + M_\chi)^2} \left(\frac{1-\cos\theta^*}{2}\right)$$

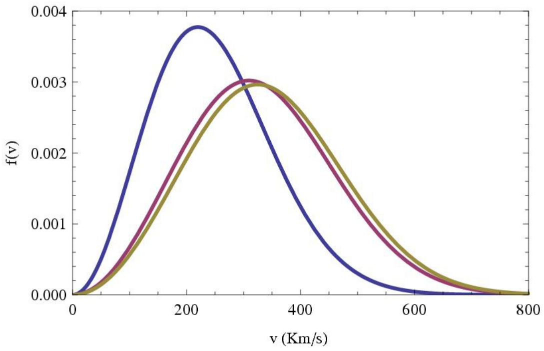
A = 127 (Iodium)
M_{wimp} = 50 GeV

Scattering RATE

Quasi exponential distribution



2nd june
2nd december



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

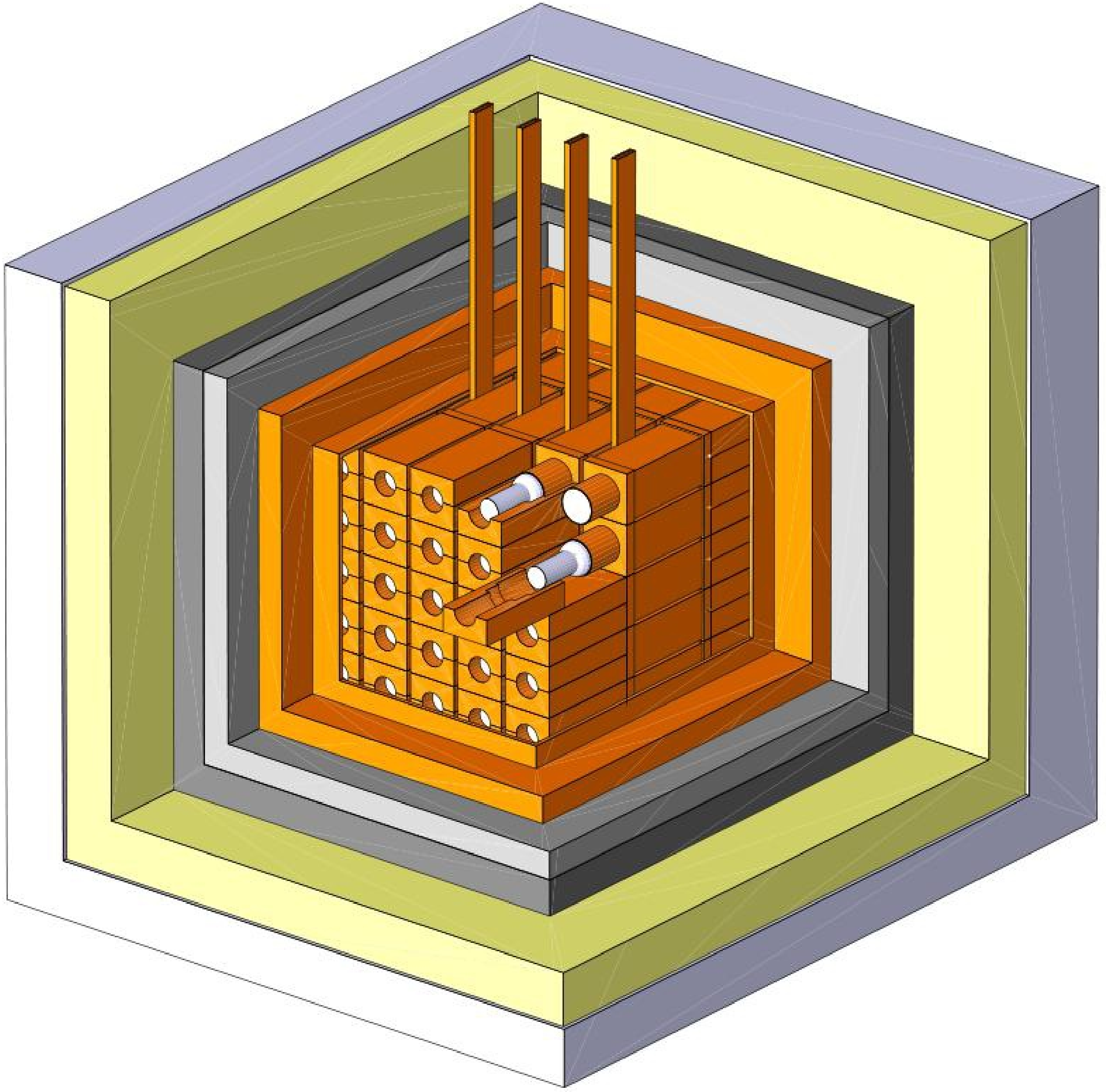
DAMA-LIBRA (Gran Sasso underground Laboratory)

250 Kg NaI scintillator.

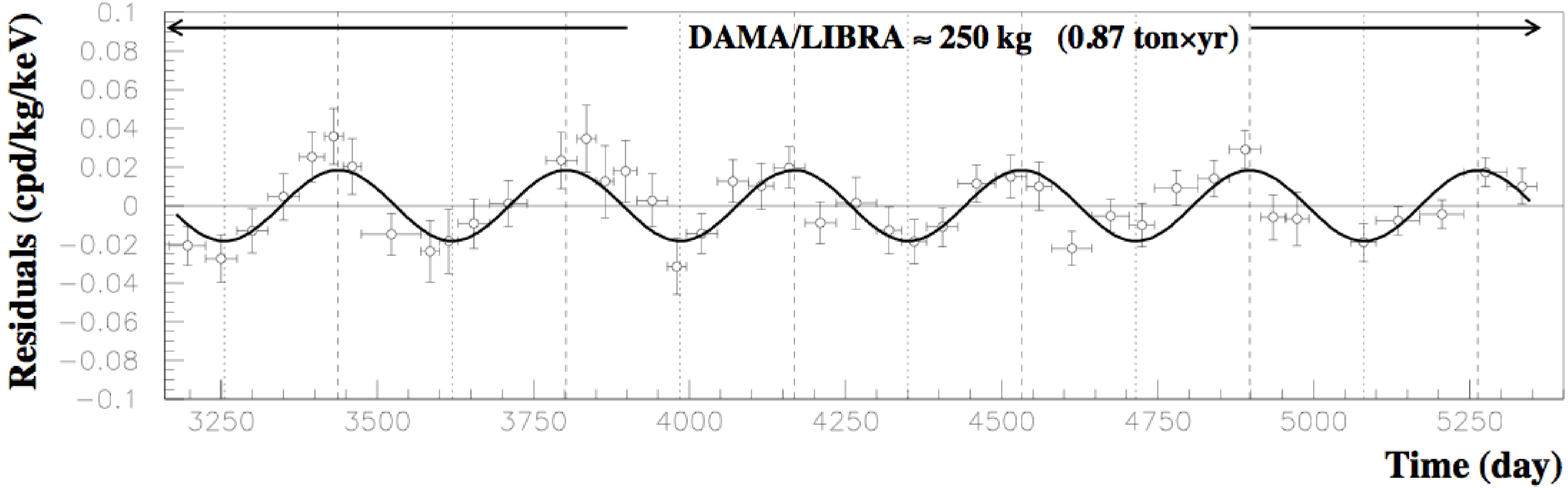
Observation
of sinusoidal
time-modulation of the
Energy Deposition Rate

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

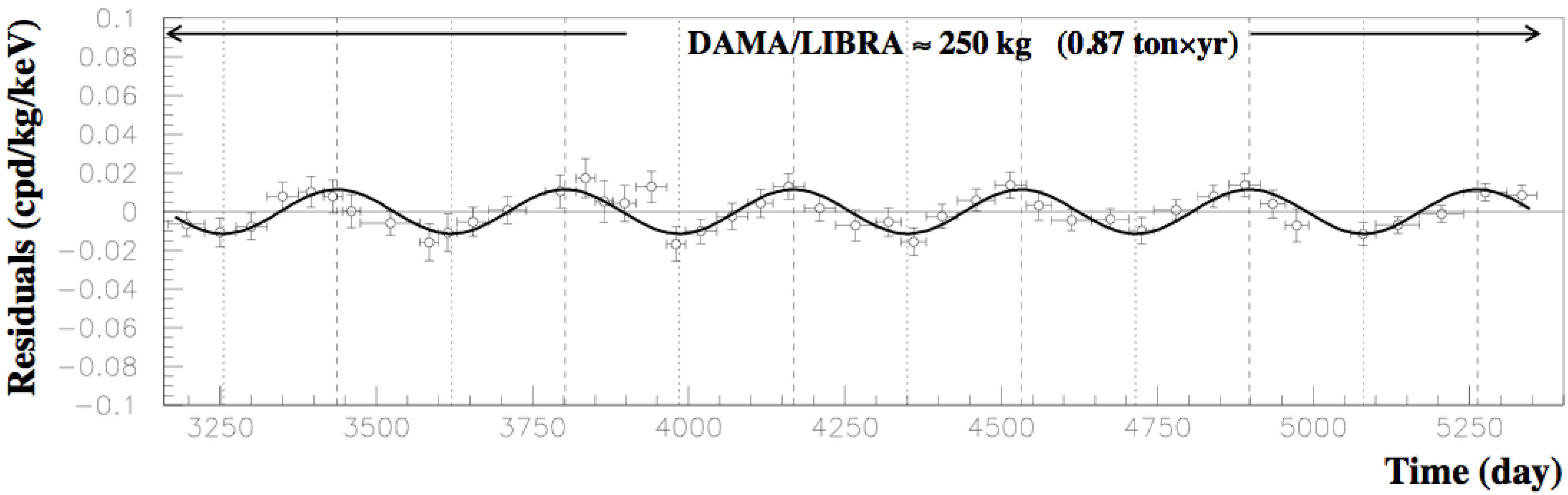
$1.17 \text{ ton} \times \text{yr}$

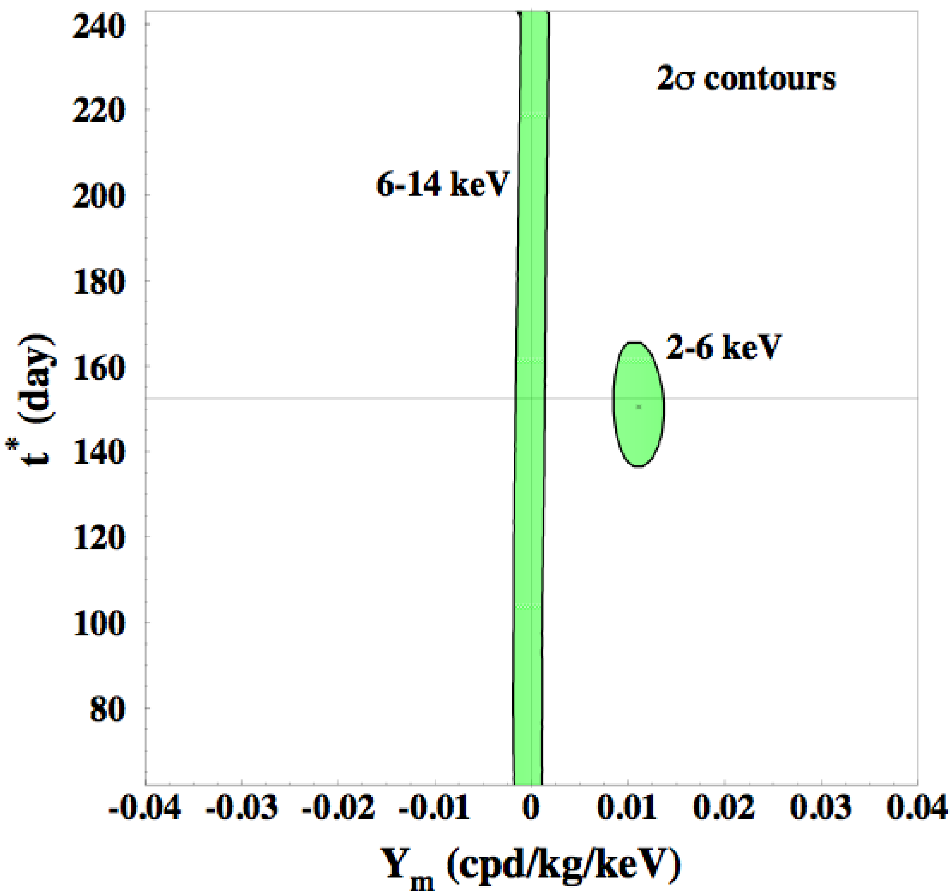


2-4 keV


DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
3250
3500
3750
4000
4250
4500
4750
5000
5250
Time (day)

2-6 keV


DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
3250
3500
3750
4000
4250
4500
4750
5000
5250
Time (day)



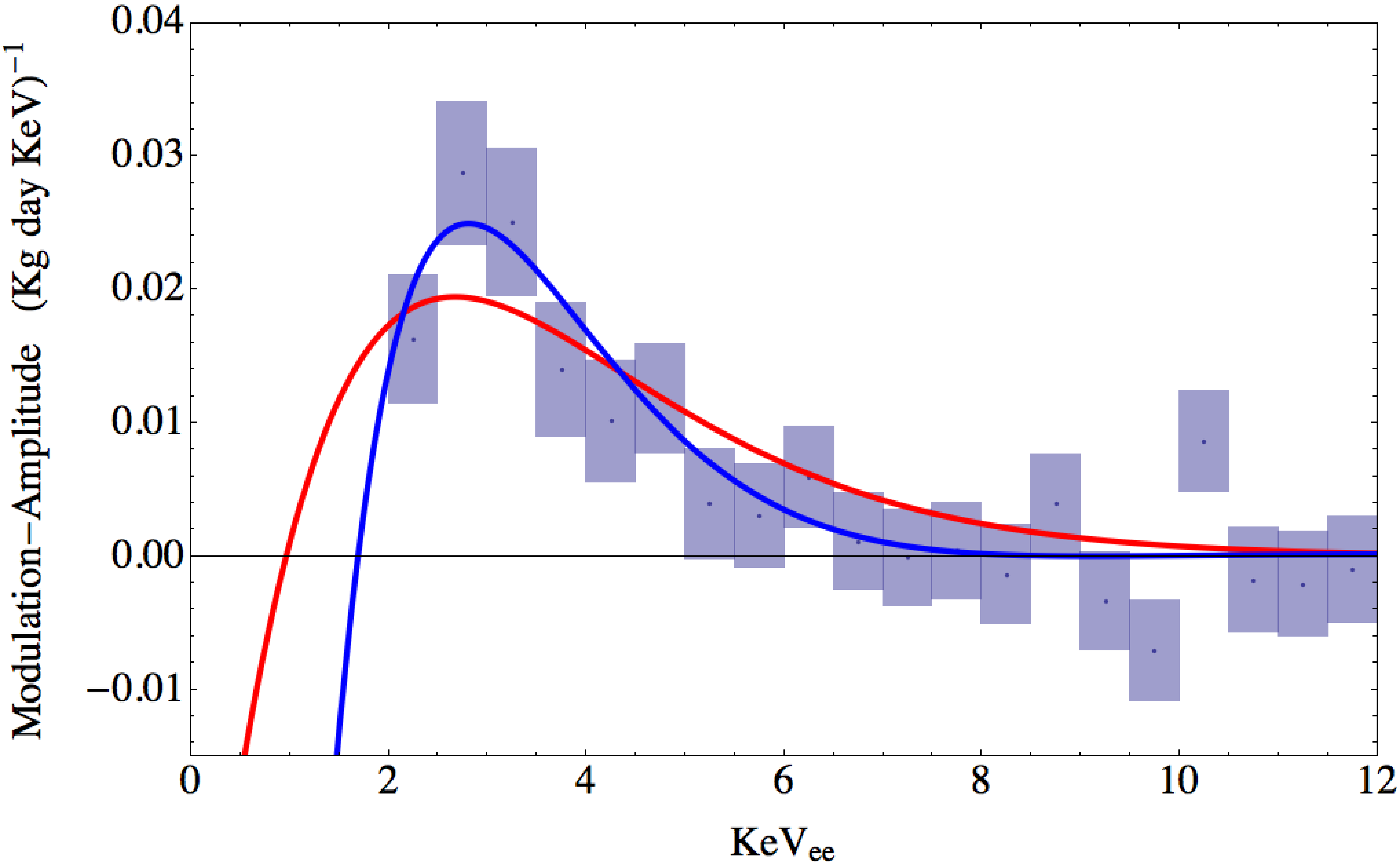
Period one year.
(… well obvious…)

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

Maximum
The 2nd june
day: (146 ± 7)

Fundamental discovery ?!

Unknown background
(with coincident phase) ?



0.04
0.03
0.02
0.01
0.00
−0.01
Modulation−Amplitude (Kg day KeV)$^{-1}$
0
2
4
6
8
10
12
KeV$_{ee}$

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

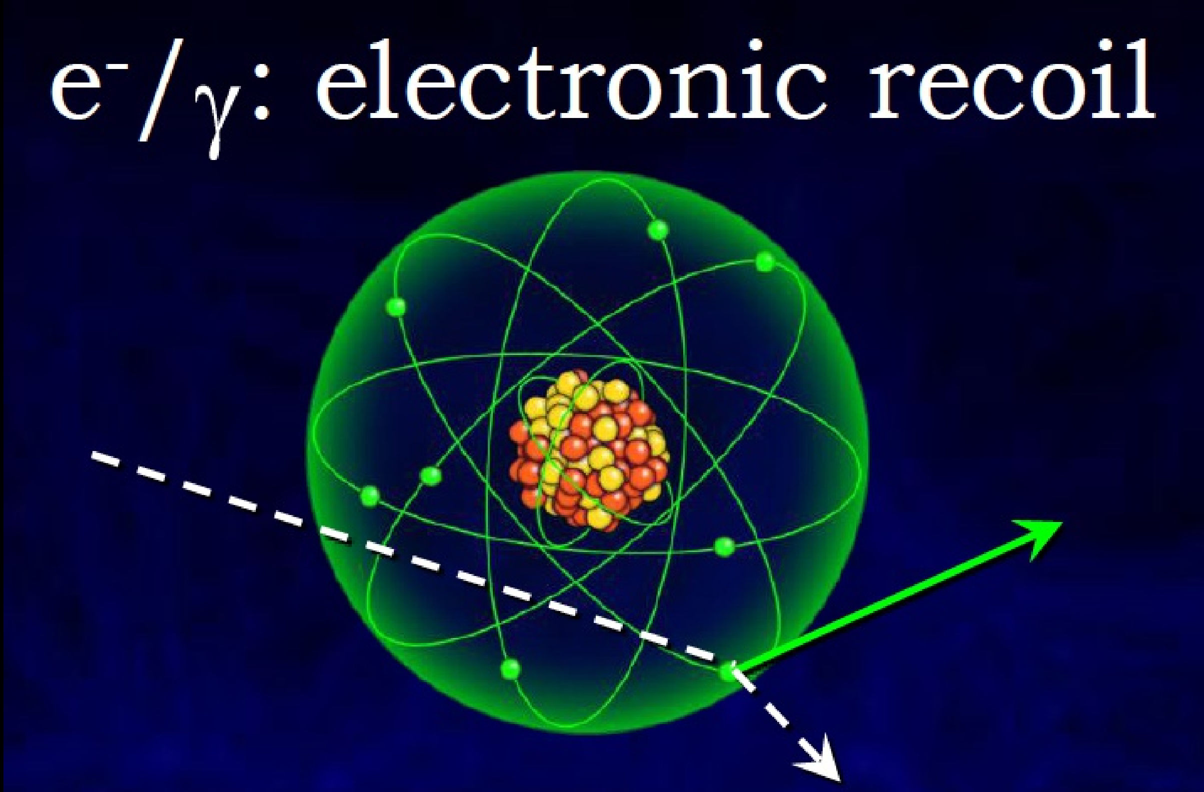
Abstract

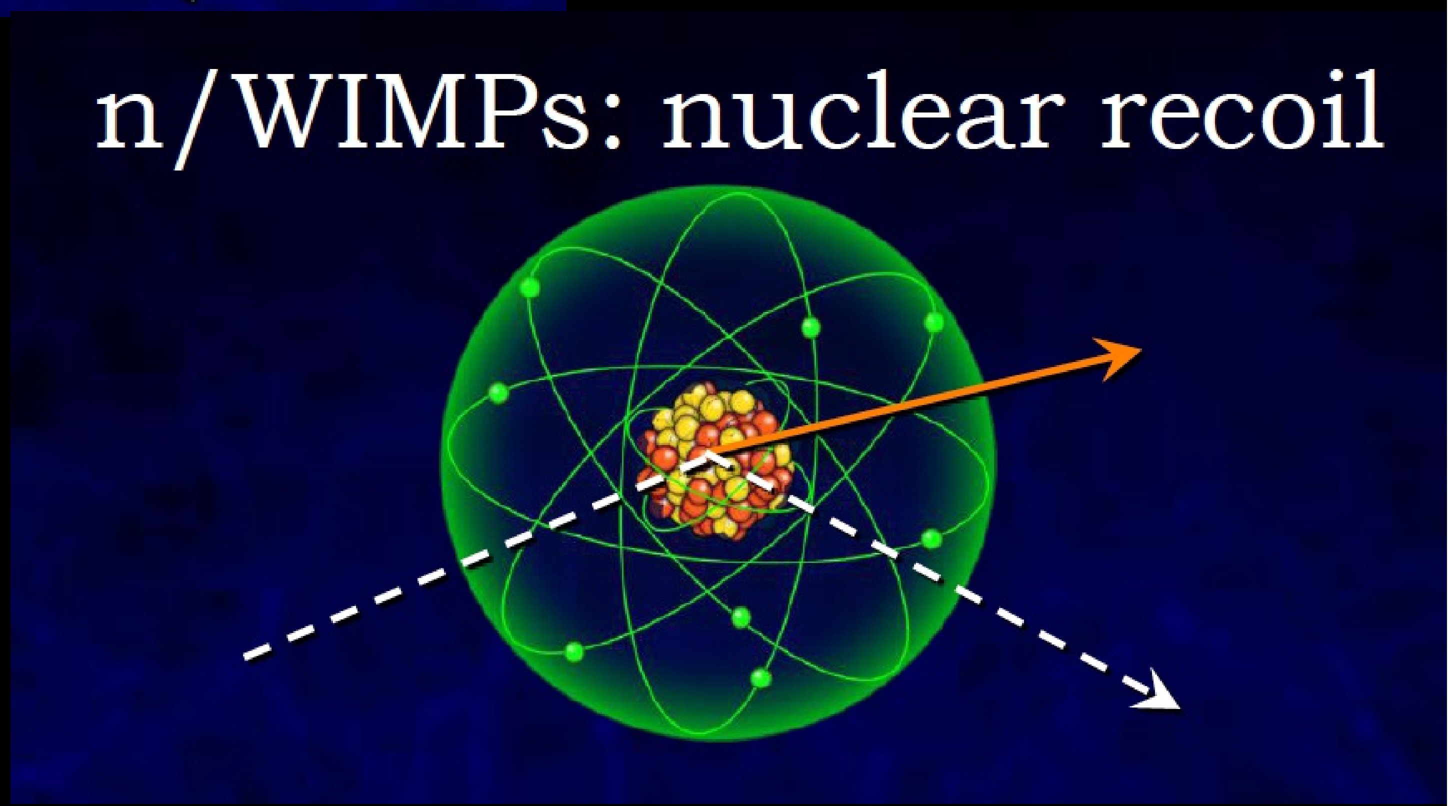
The highly radiopure $\simeq 250$ kg NaI(Tl) DAMA/LIBRA set-up is running at the Gran Sasso National Laboratory of the I.N.F.N.. In this paper the first result obtained by exploiting the model independent annual modulation signature for Dark Matter (DM) particles is presented. It refers to an exposure 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

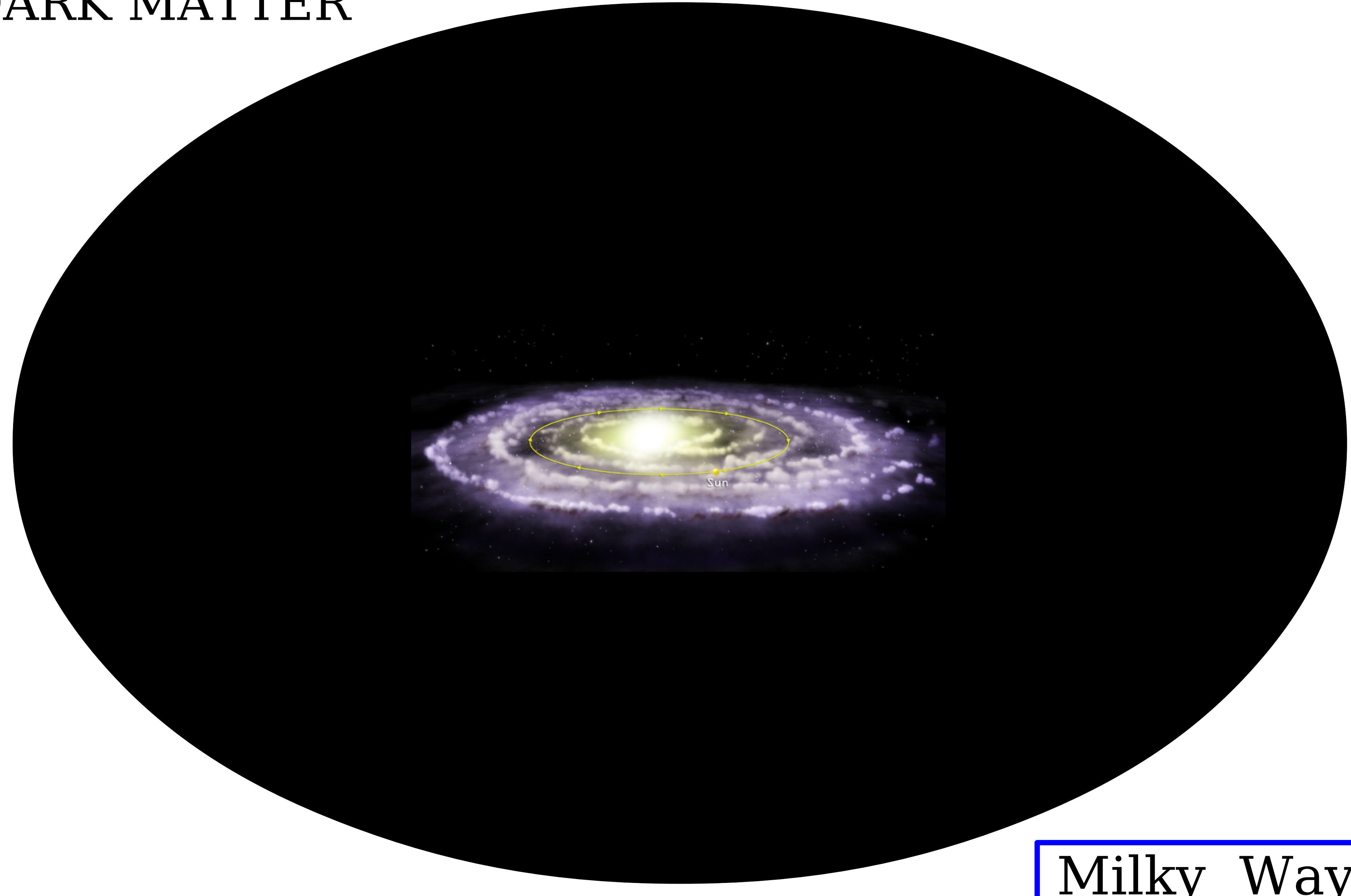
Abstract

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

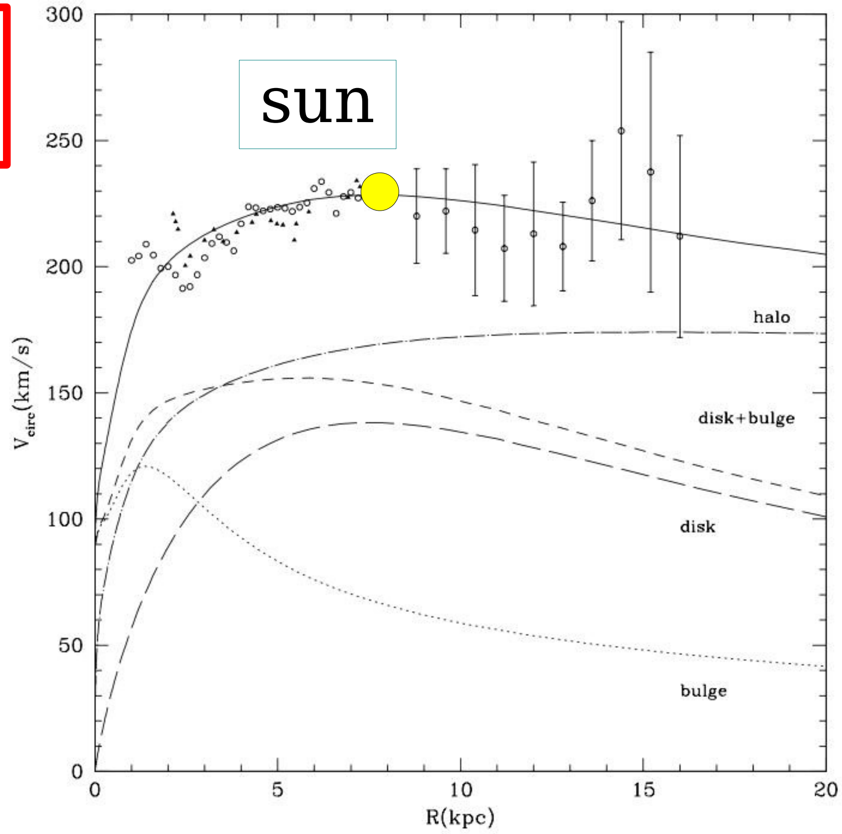
[assume here DM particle is of Majorana nature $\chi = \overline{\chi}$]

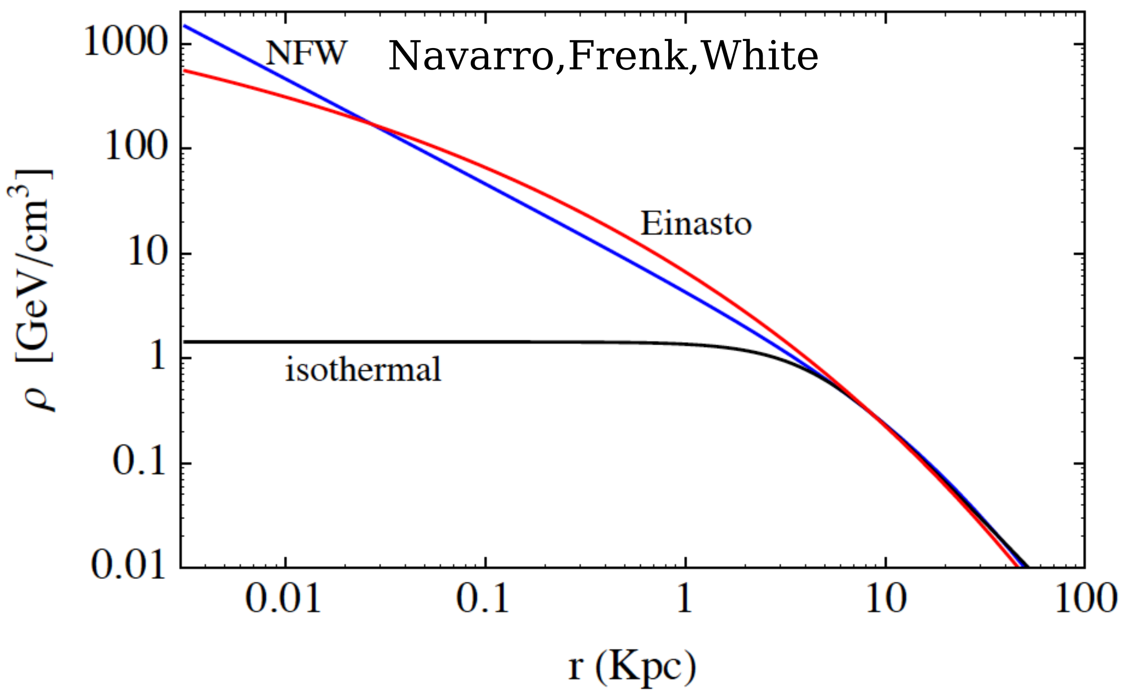
DM in the Milky Way

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

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

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





Density distribution

determined by
Rotation velocity measurements

“Cusp” at GC
derived by N-body simulations

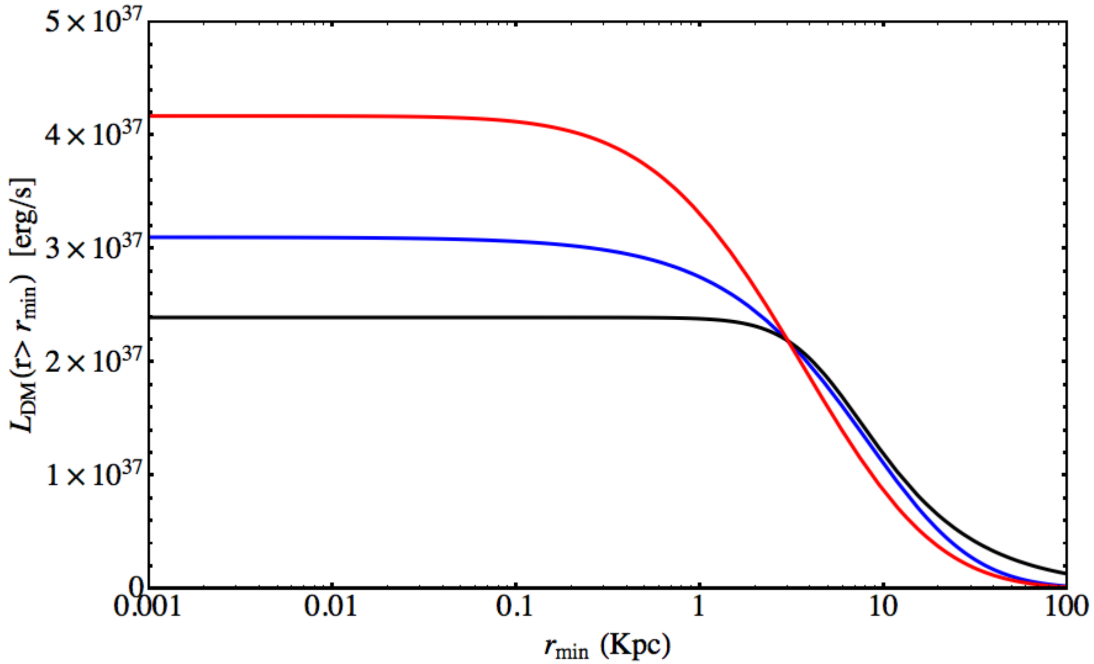
Power generated by DM annihilations in the Milky Way halo

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

For comparison,
for Cosmic Ray protons

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

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



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:

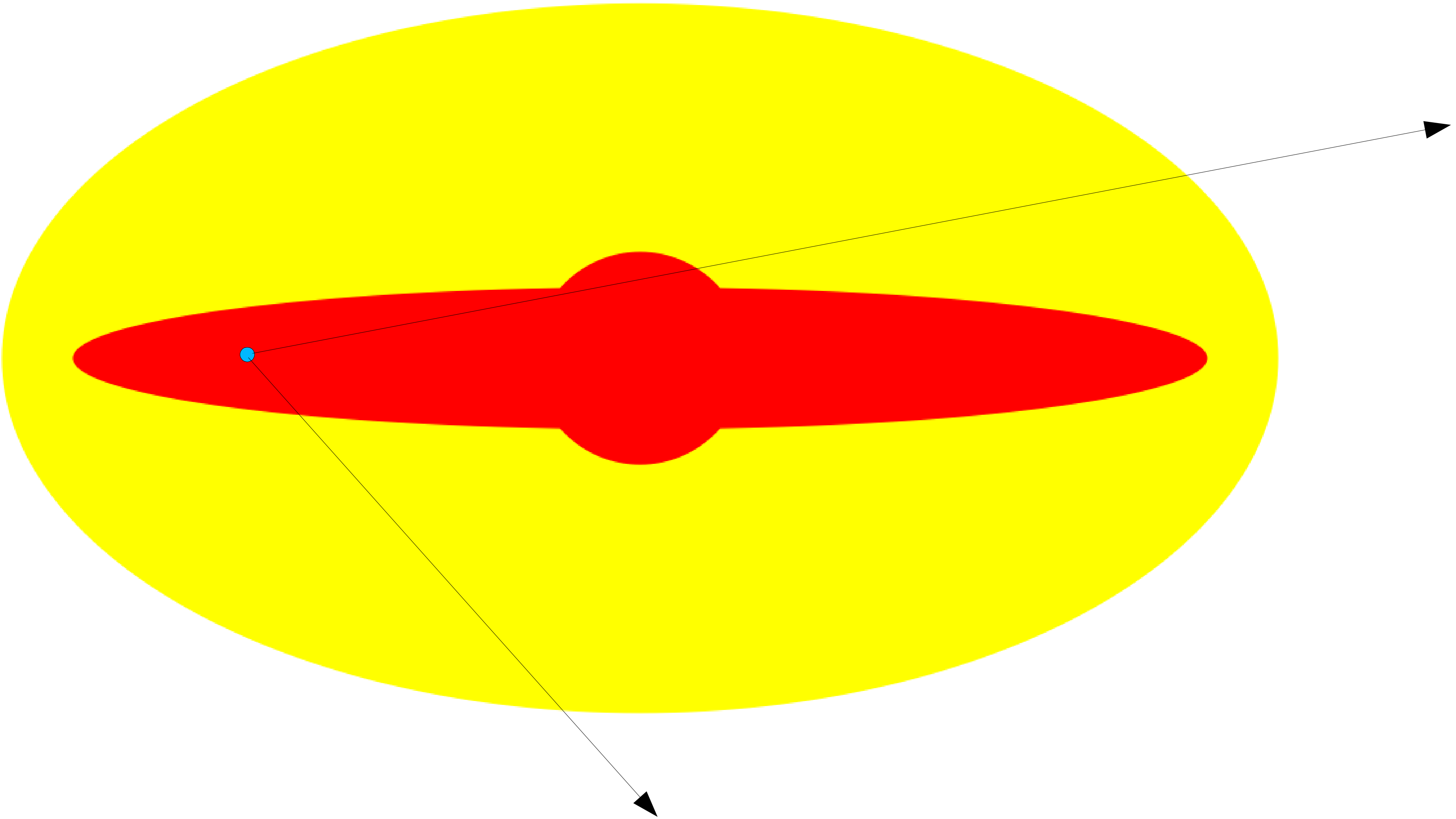
$$\chi + \chi \to \gamma \quad e^+ \quad \bar{p} \quad \nu_\alpha$$

photons

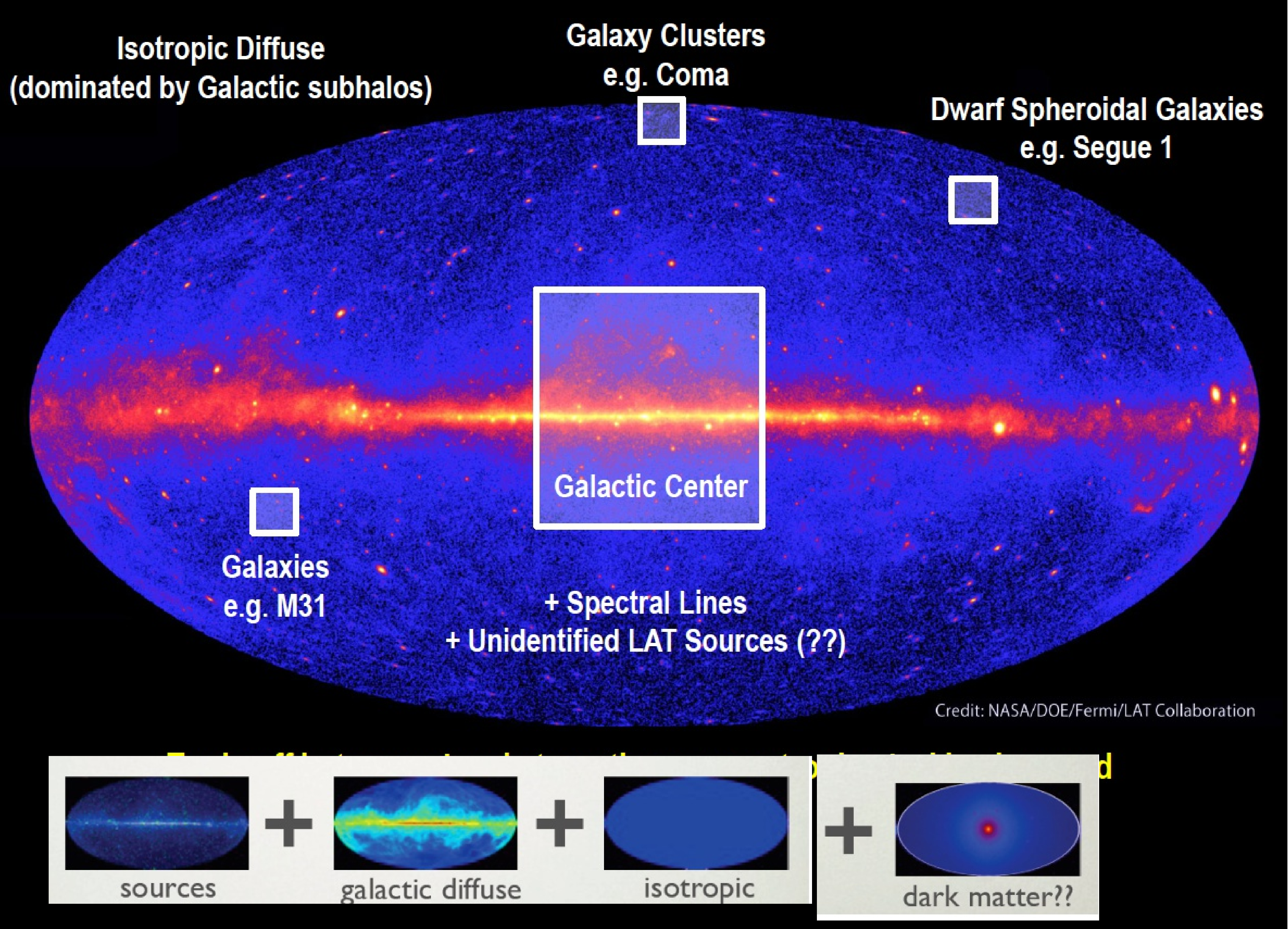
Charged (anti)particles

Neutrinos

Photon emission from DM annihilation



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


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

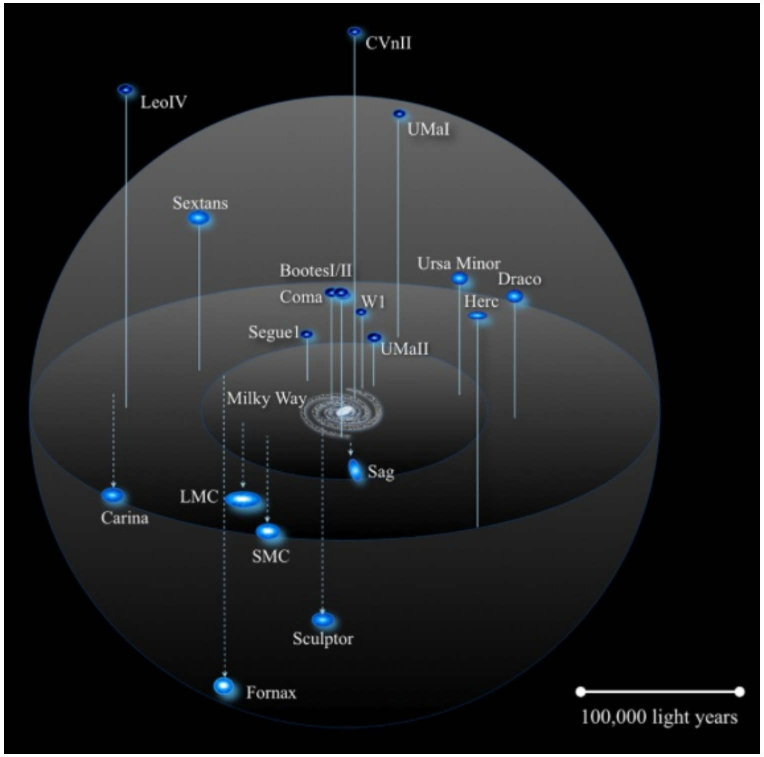
1. Galactic Center

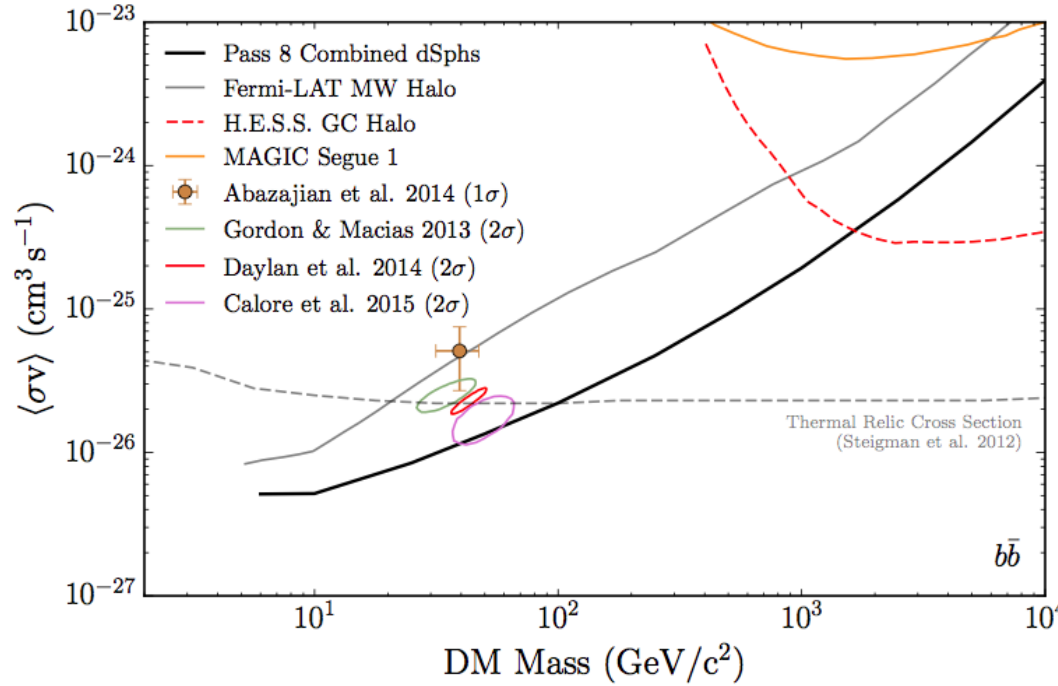
2. Dwarf Galaxies

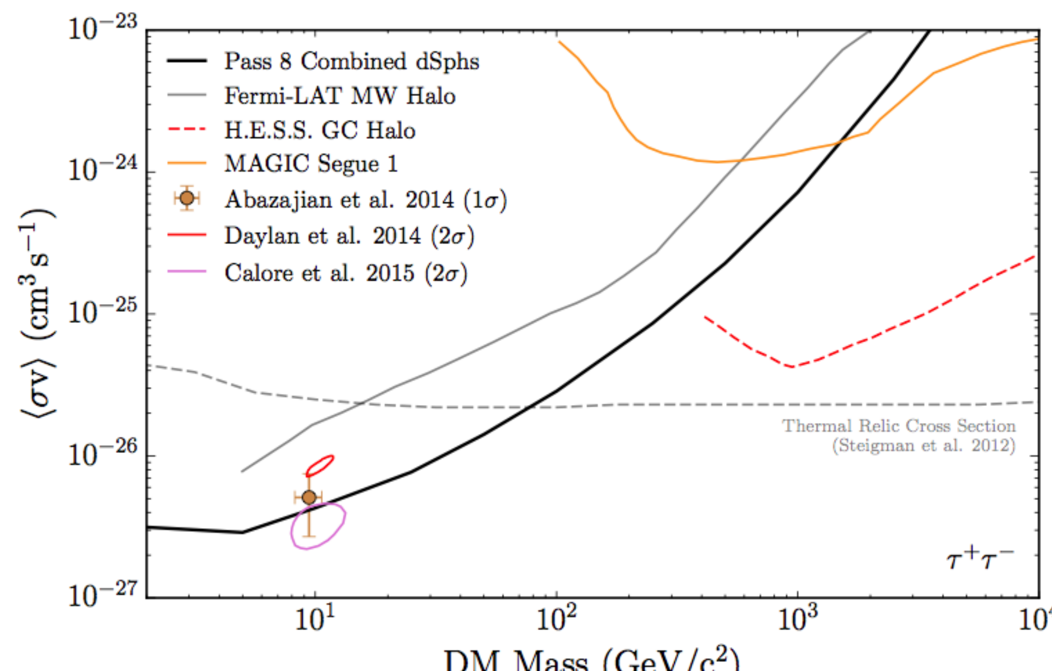
3. Spectral lines

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]].







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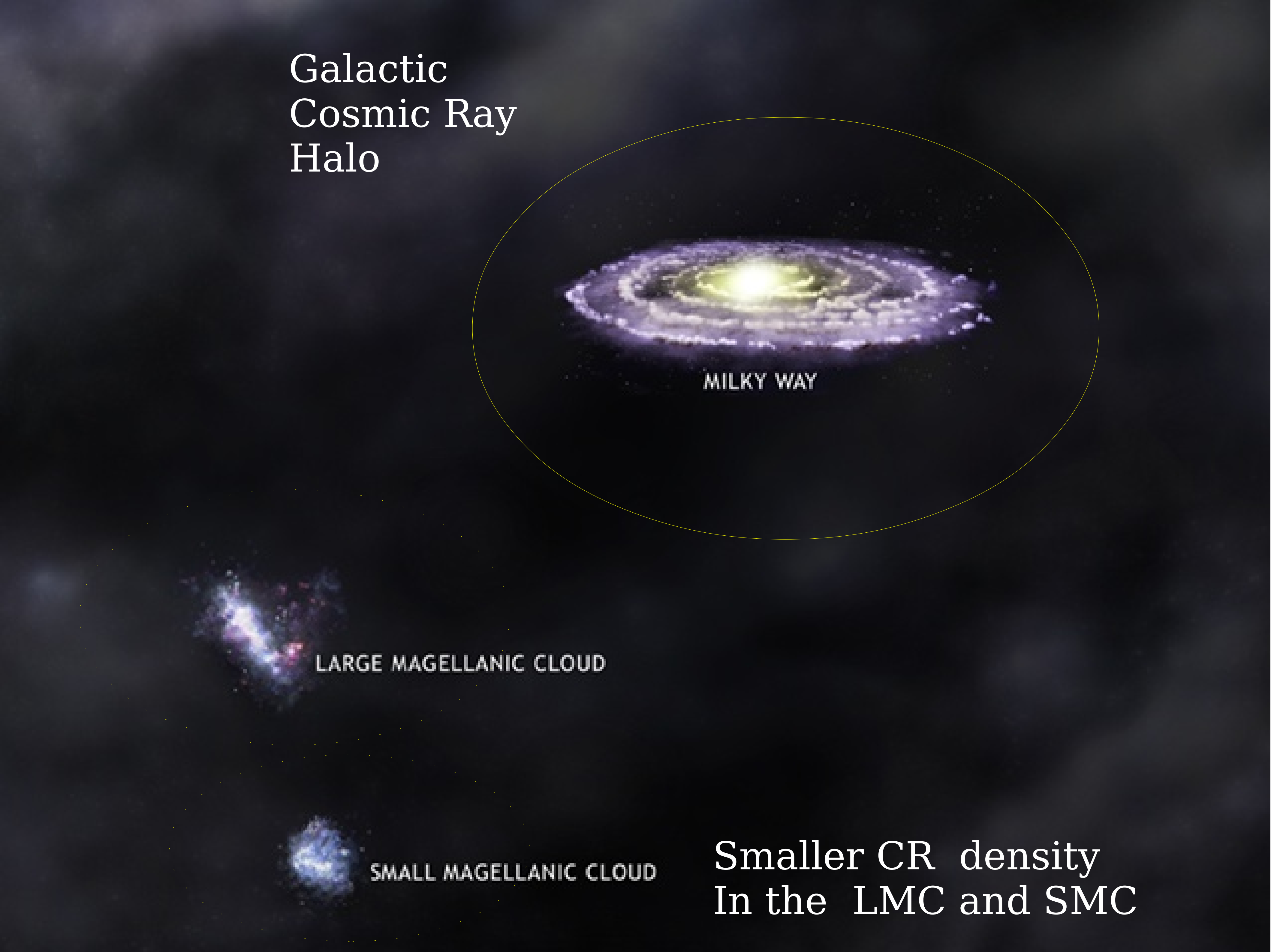
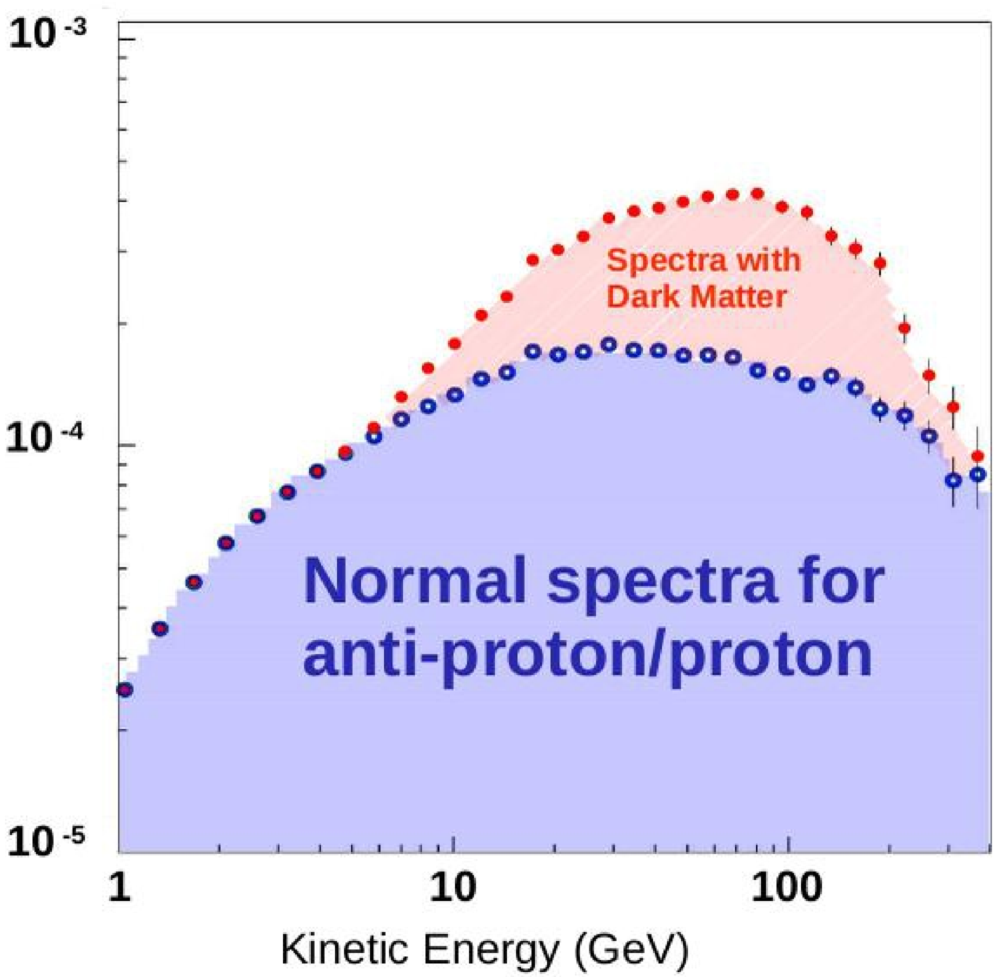
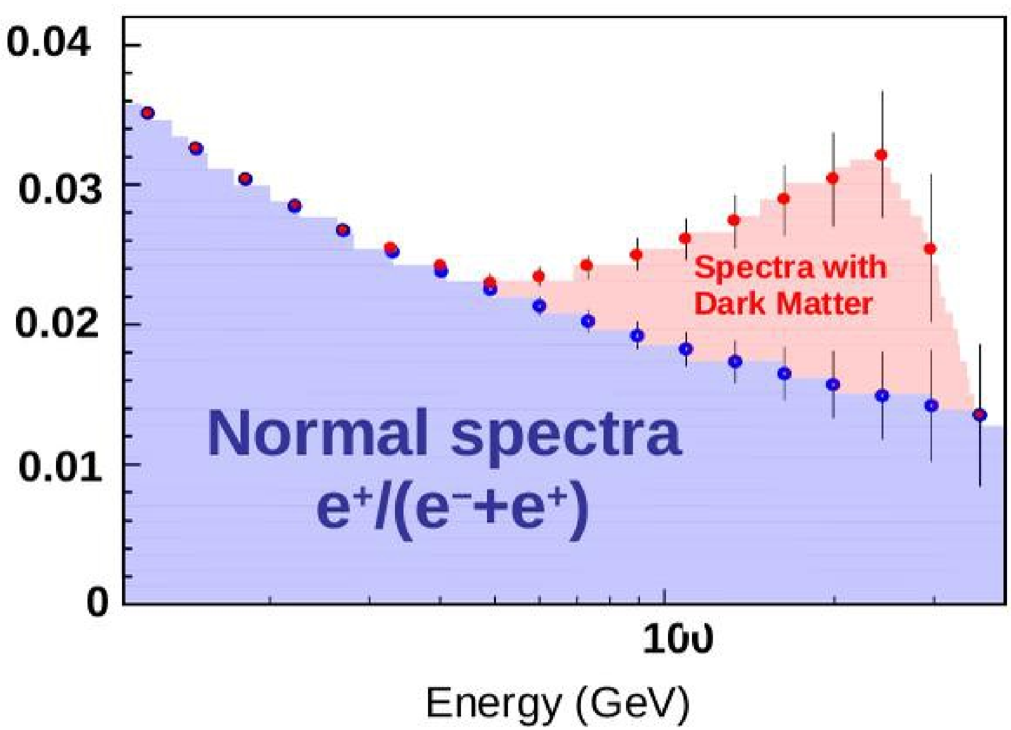

Galactic
Cosmic Ray
Halo
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
Smaller CR density
In the LMC and SMC

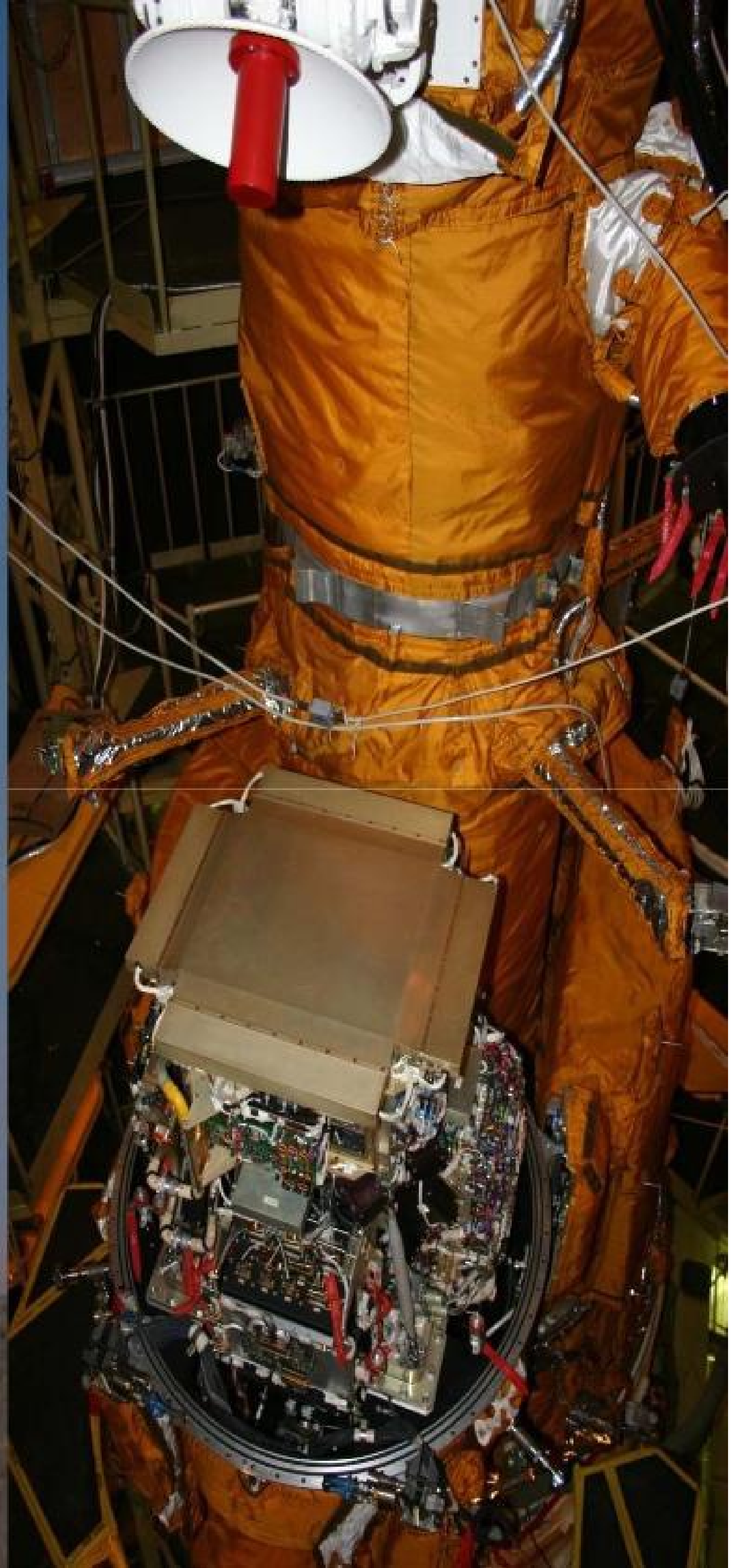
Charged particles:
positrons and
anti-protons

Trapped by the
Galactic magnetic field

Extra contribution to
the cosmic ray fluxes





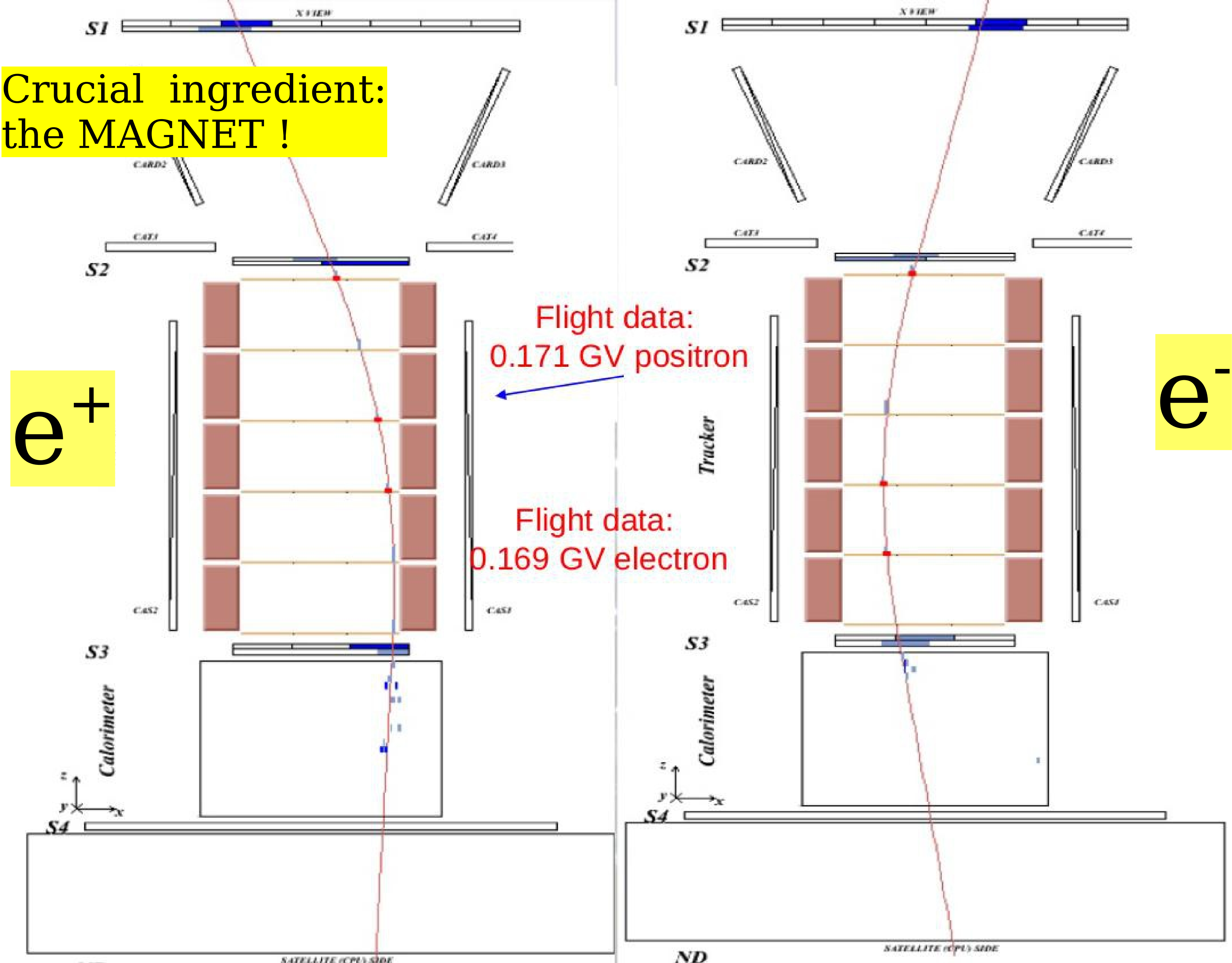


PAMELA

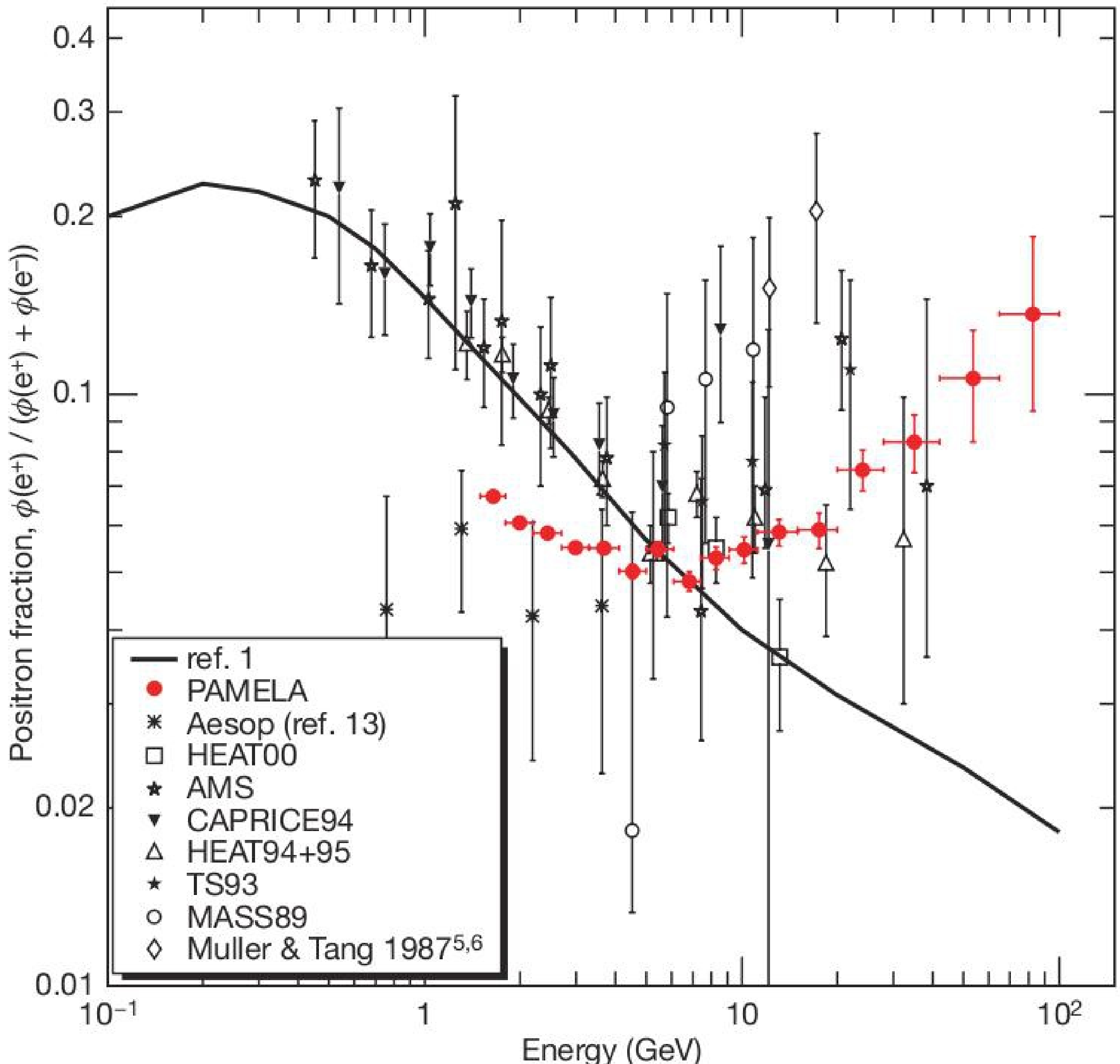
detector

Launch
15^{th} june 2006

The "positron excess":
Evidence for DM
or astrophysical effect ?


Crucial ingredient:
the MAGNET !
e^+
e^-
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron
S1
S2
S3
S4
CARD2
CARD3
CAT3
CAT4
CAS2
CAS3
Tracker
Calorimeter
ND
SATELLITE (CPU) SIDE

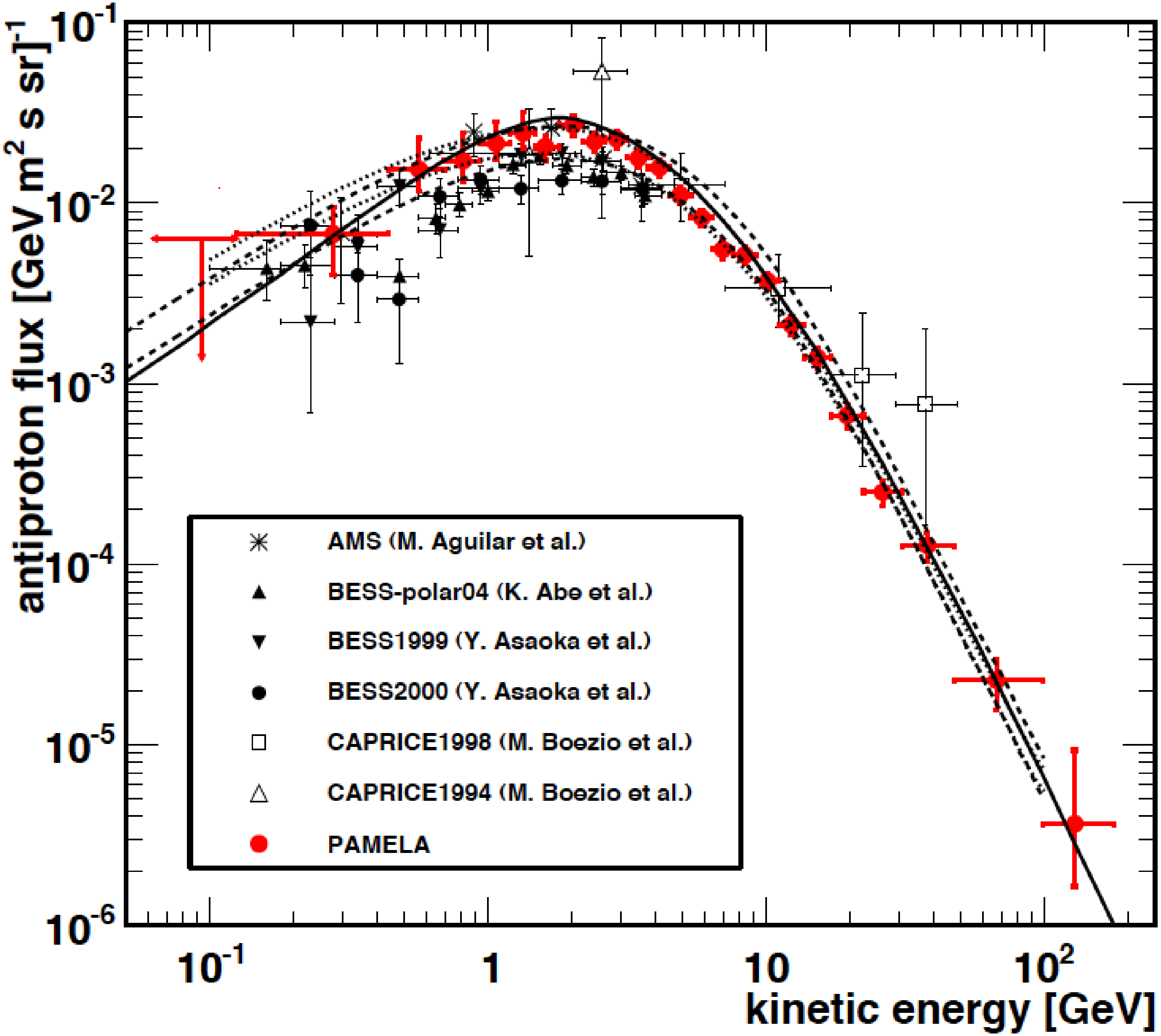
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV



"Positron Excess" !

Antiproton result

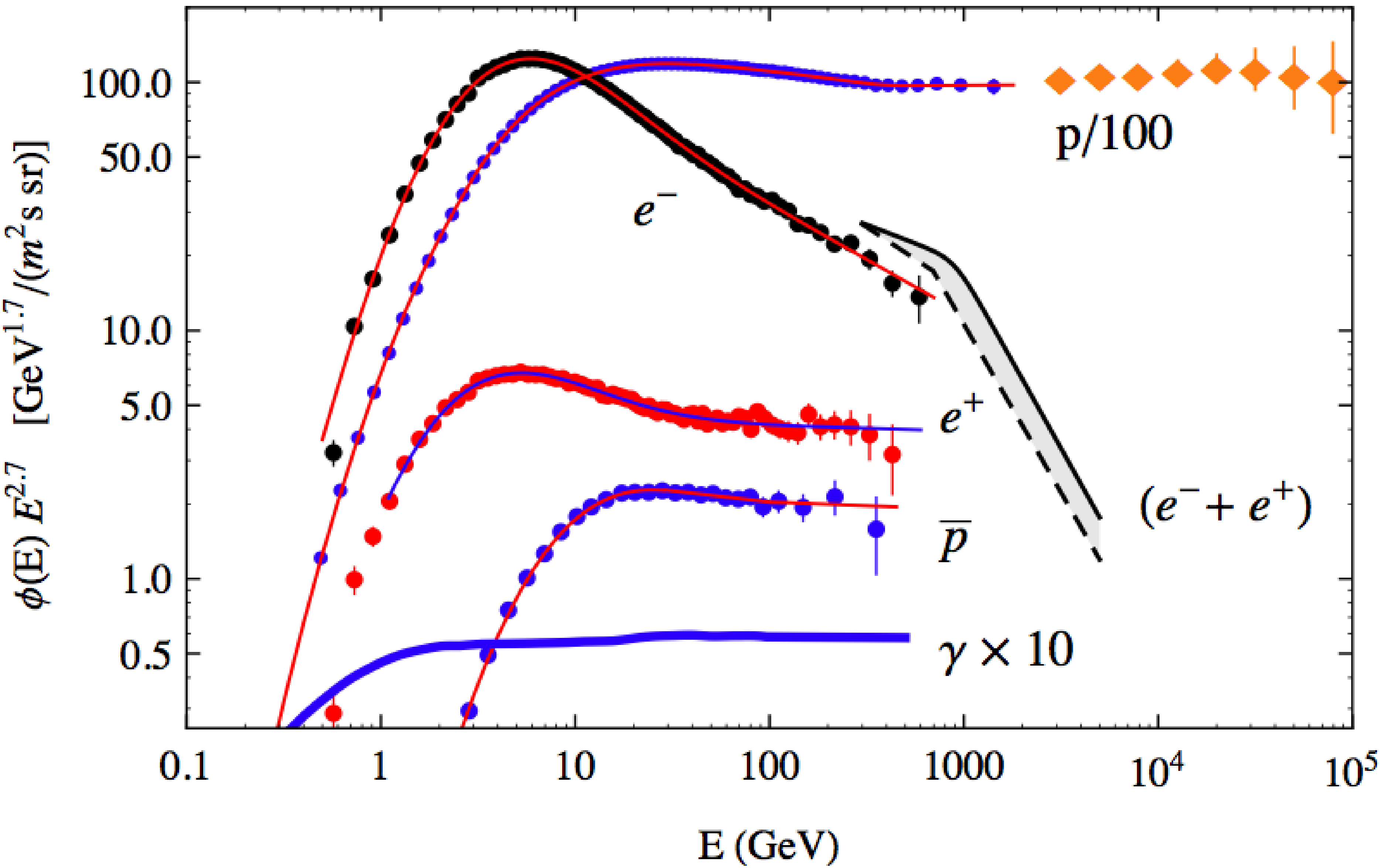
Agreement
With standard production mechanism



Cosmic Ray Spectra
AMS02

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

CREAM p data



angle averaged diffuse Galactic gamma ray flux (Fermi)

- Why the proton flux has its shape ?
- Why the electron flux has its shape ?
- Why the positron flux has its shape ?
- Why the $\overline{p}$ flux has its shape ?

Do the positron and antiproton fluxes contain a DM component ?

Formation of the COSMIC RAYS spectra

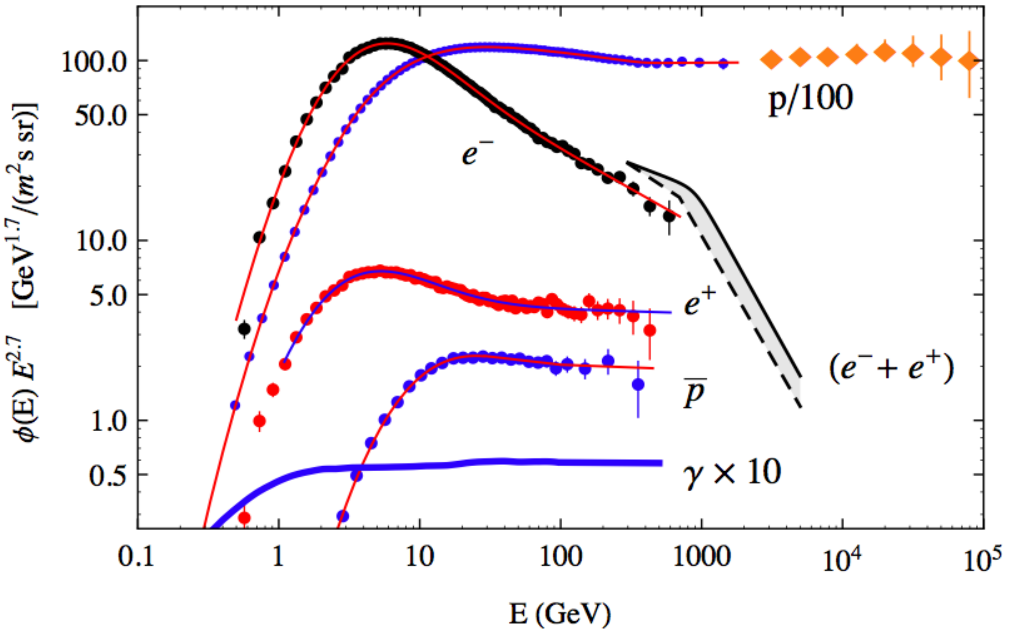
$$\phi_j(E, \vec{x}, t) \Longleftrightarrow q_j(E, \vec{x}, t)$$

Propagation

Observable fluxes (directly at the Earth)

Propagation

Spectra released in interstellar space by the CR sources



“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)

Why ?

(for E > 20-30 GeV)

$$\gamma_{e^-} \simeq \gamma_p + (0.41 \pm 0.02)$$

$$\gamma_{e^+} \simeq \gamma_{\overline{p}}$$

$$\gamma_{e^+} \simeq \gamma_{\overline{p}} \approx \gamma_p$$

Why ?

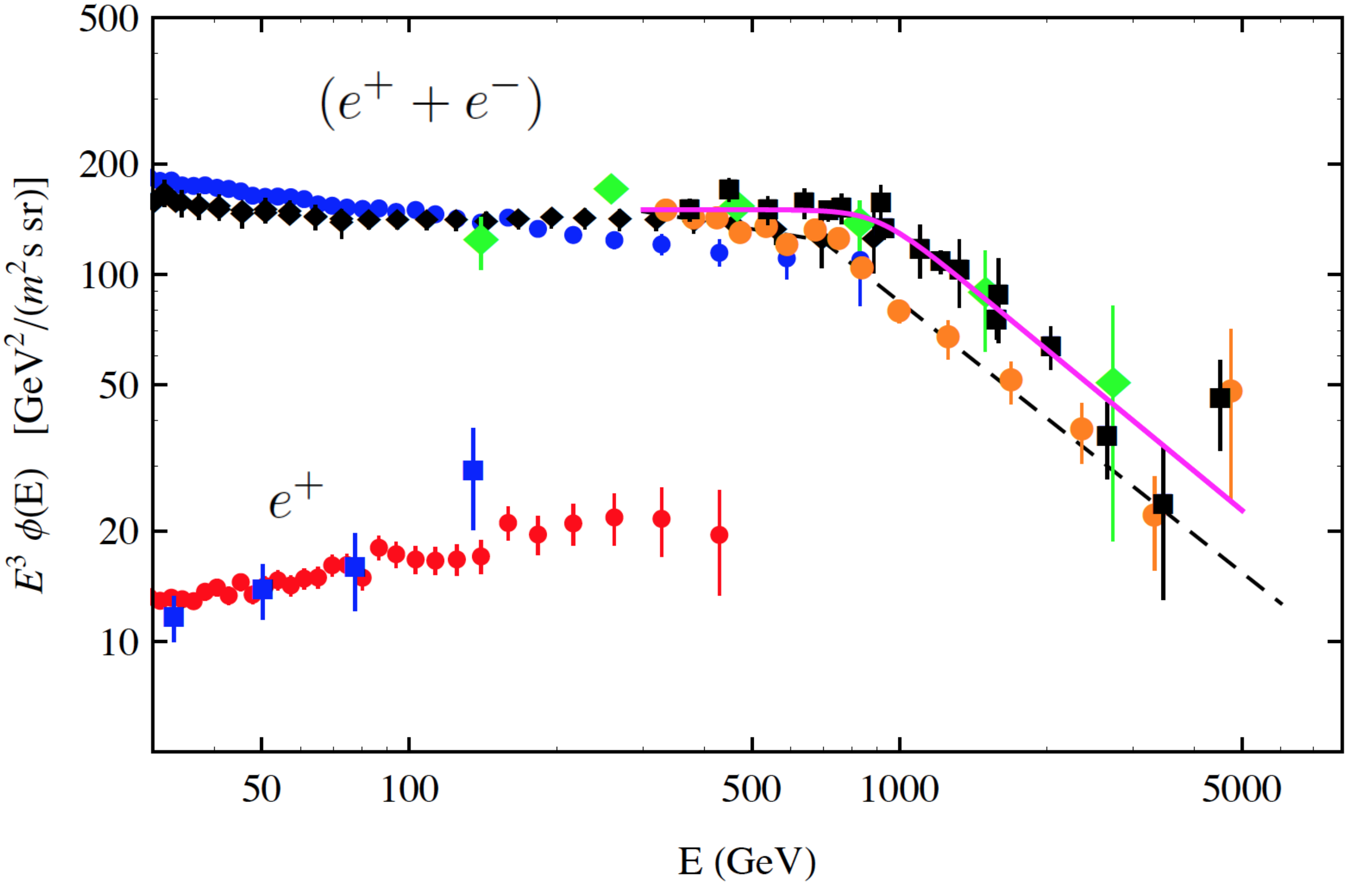
(for E > 20-30 GeV)

$$\gamma_{e^-} \simeq \gamma_p + (0.41 \pm 0.02)$$

$$\gamma_{e^+} \simeq \gamma_{\overline{p}}$$

Is there a
physical reason”,
or it is
“just a coincidence” ?

$$\gamma_{e^+} \simeq \gamma_{\overline{p}} \approx \gamma_p$$



$(e^+ + e^-)$

AMS02
FERMI-LAT

HESS
VERITAS
MAGIC

HESS fit

$\gamma_1 \simeq 3.0$

$\gamma_2 \simeq 4.1$

$E_{\mathrm{break}} = 900\ \ \mathrm{GeV}$

MAGIC fit

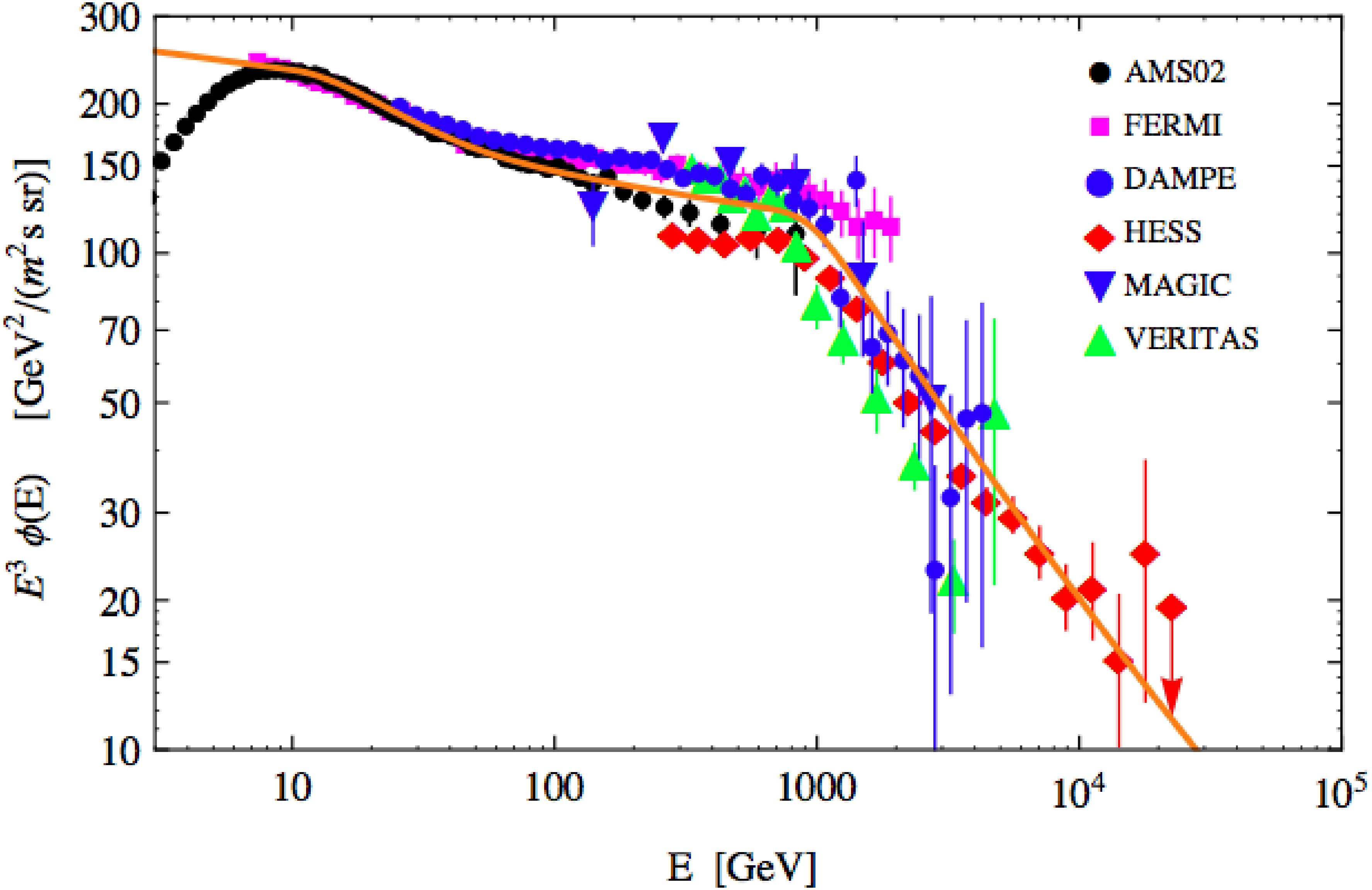
$\gamma_1 \simeq 3.2 \pm 0.01$

$\gamma_2 \simeq 4.1 \pm 0.01$

$E_{\mathrm{break}} = 710 \pm 40\ \mathrm{GeV}$

very prominent spectral feature

New data release (ICRC-2017) by HESS
Publication of DAMPE (chinese satellite)



proton versus *electron* spectra

Standard explanation for the
softer electron spectrum:

$$\gamma_{e^-} \simeq \gamma_p + (0.41 \pm 0.02)$$

Astrophysical Accelerators generate identical spectra
of electrons and protons (when ultra-relativistic)
[Injection in the acceleration mechanism
is mass dependent. Therefore different normalizations]

Propagation effect

due to the large rate of energy losses
of relativistic electrons, their spectrum
suffers more distortion

Energy losses

[synchrotron, Compton scattering]
strongly depend on the particle mass

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

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

Characteristic time
for energy loss

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

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

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

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

Conventional interpretation
for the proton/electron ratio [simplest discussion]

$$N_p(E) = Q_p(E) \times T_p(E)$$

$$N_{e^-}(E) = Q_{e^-}(E) \times T_e(E)$$

Accelerators generate spectra of electrons
and protons of similar shape (but different normalization)

$$Q_{e^-}(E) \approx K_{ep} \; Q_p(E)$$

$K_{ep} \simeq 0.01 \div 0.02$

Mass effect in
acceleration injection

$$\frac{N_{e^-}(E)}{N_p(E)} \approx \frac{T_{e^-}(E)}{T_p(E)} \approx E^{-0.4}$$

Conventional picture for the electron/proton ratio:

$$T_p(E) = T_{\rm escape}(E)$$

$$T_e(E) = T_{\rm escape}(E) \oplus T_{\rm loss}(E) \simeq T_{\rm loss}(E)$$

$$E \gtrsim 30 \ {\rm GeV}$$

$$\frac{T_{\rm loss}(E)}{T_{\rm escape}(E)} \propto \frac{\phi_{e^-}(E)}{\phi_p(E)} \propto E^{-0.41}$$

$$T_{\rm escape}(30 \ {\rm GeV}) \gtrsim T_{\rm loss}(30 \ {\rm GeV}) \simeq 30 \ {\rm Myr}$$

"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

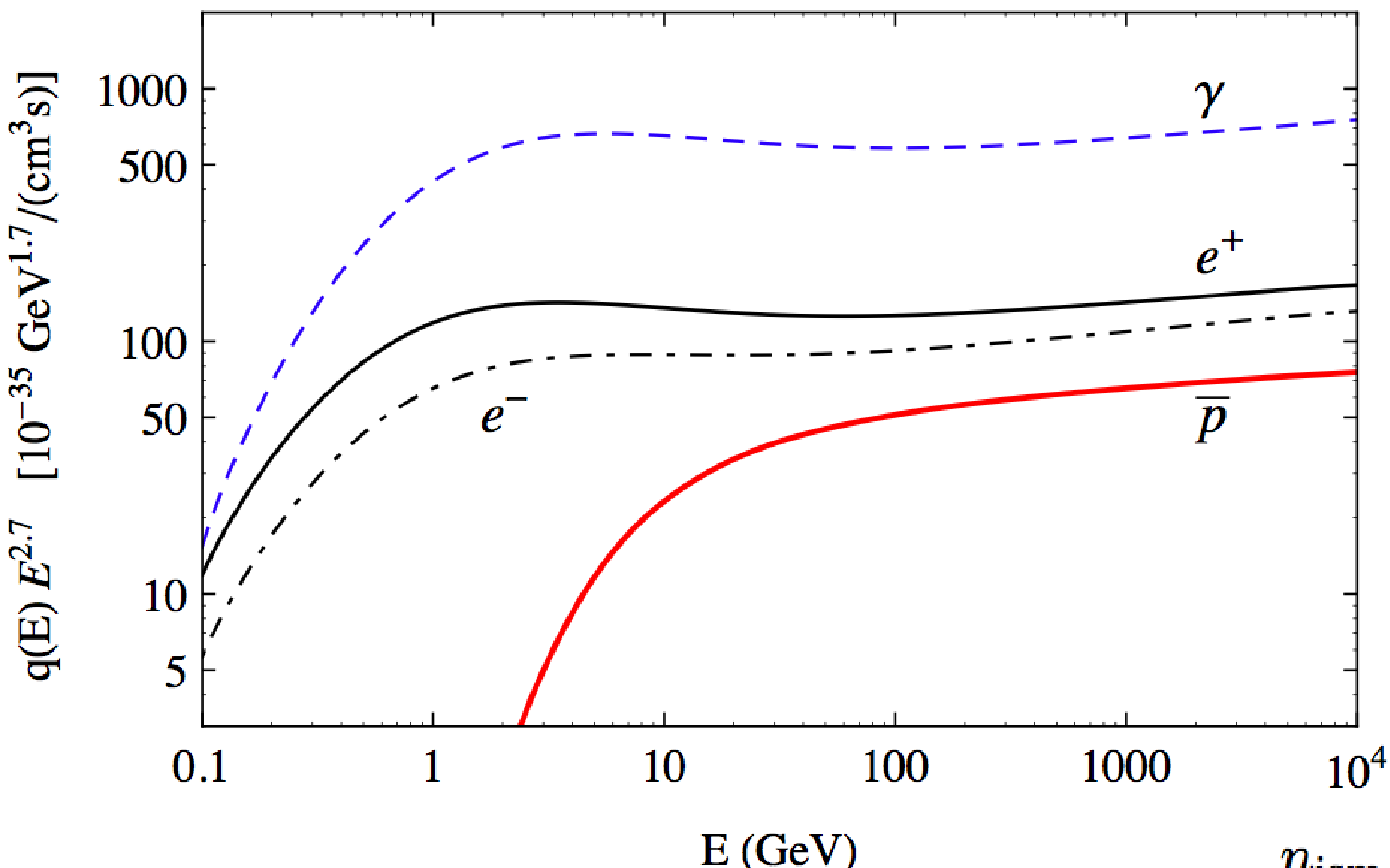
Straightforward [hadronic physics] exercise:

[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,...)

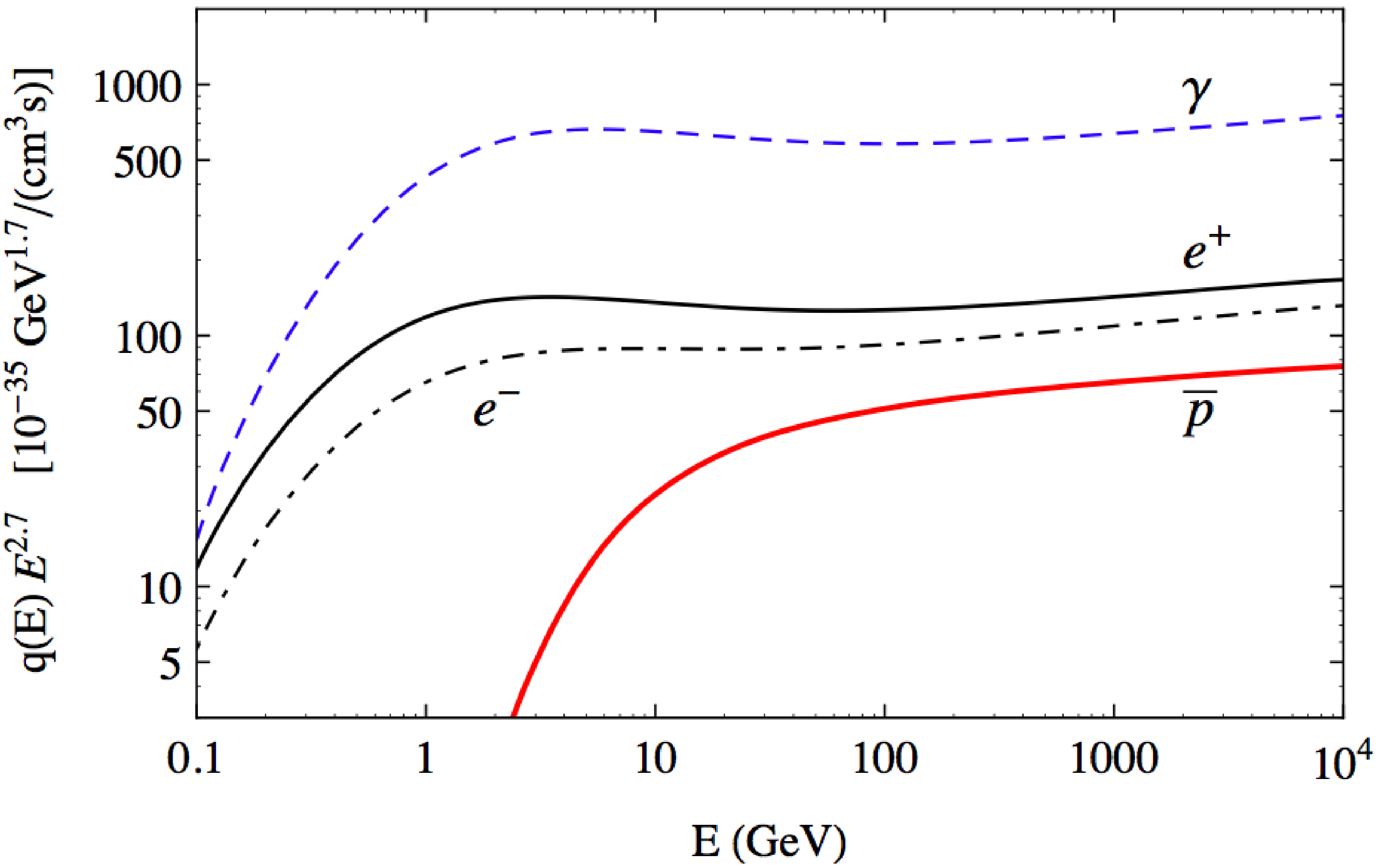
[3] Compute the rate of production of secondaries $q_j(E, \vec{x}_\odot)$

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



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

“Local” Rate of production of secondaries



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

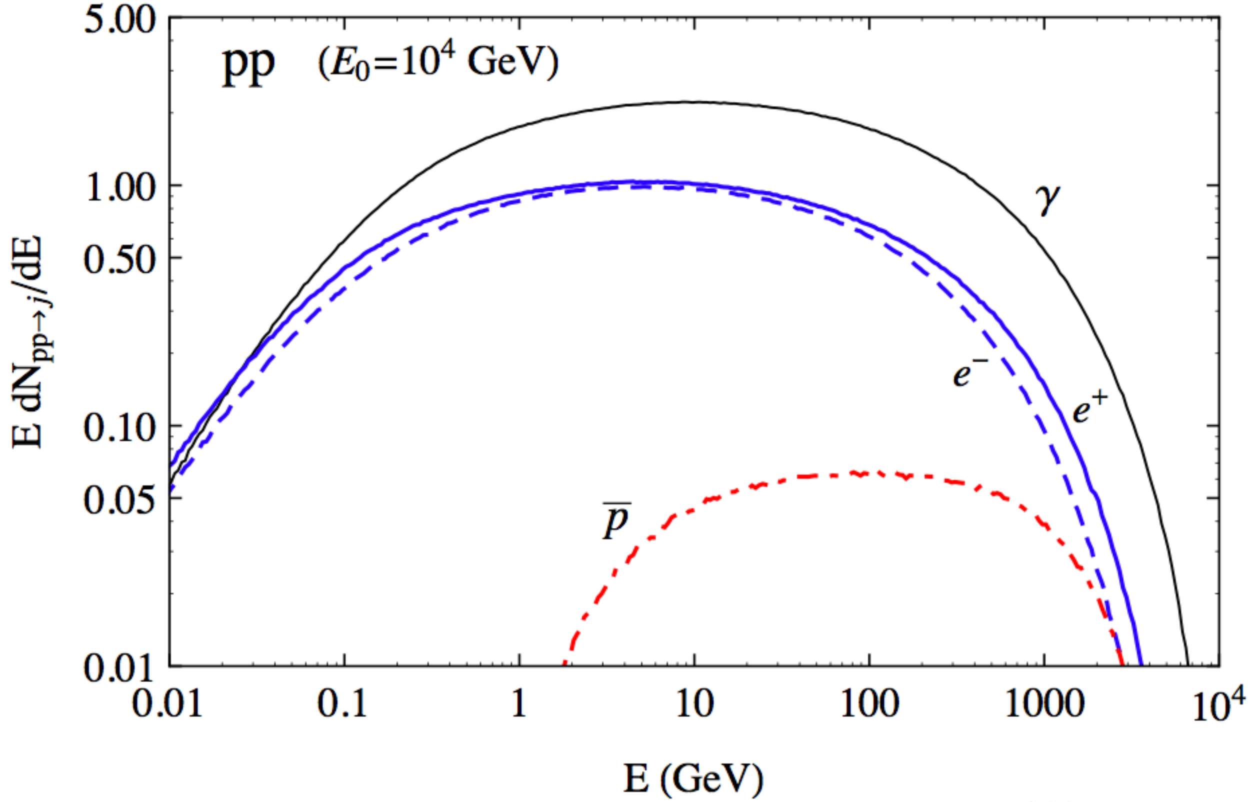
$$\frac{e^-}{e^+} \approx 0.8$$

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

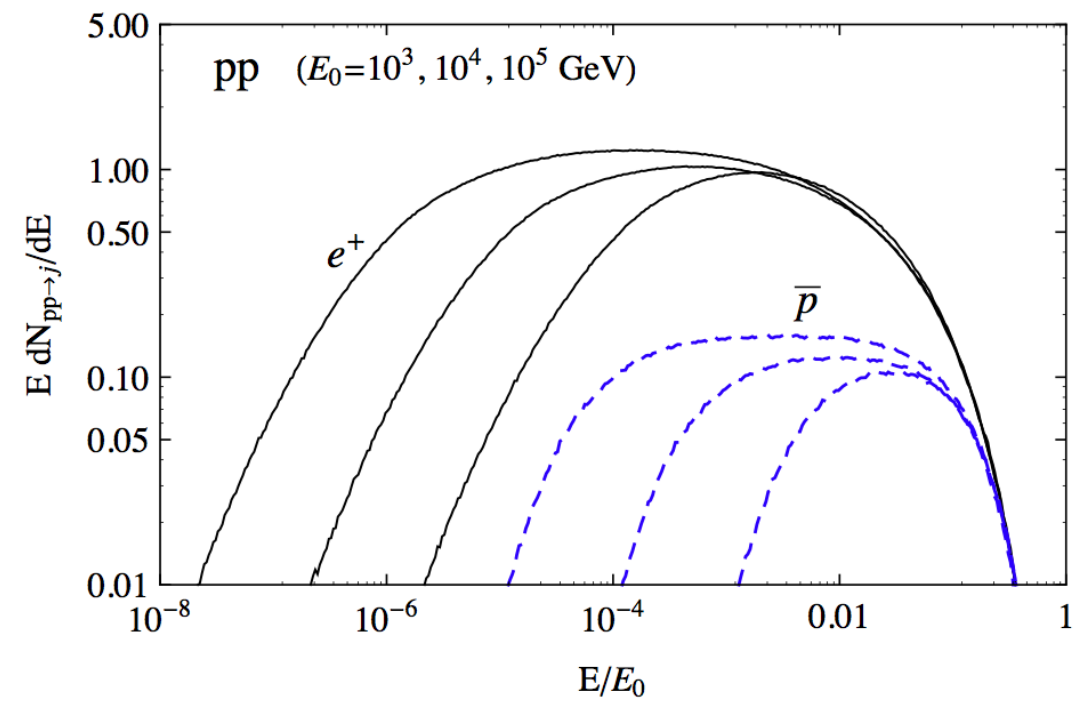
Different low energy behaviors
(low energy antiproton production suppressed)

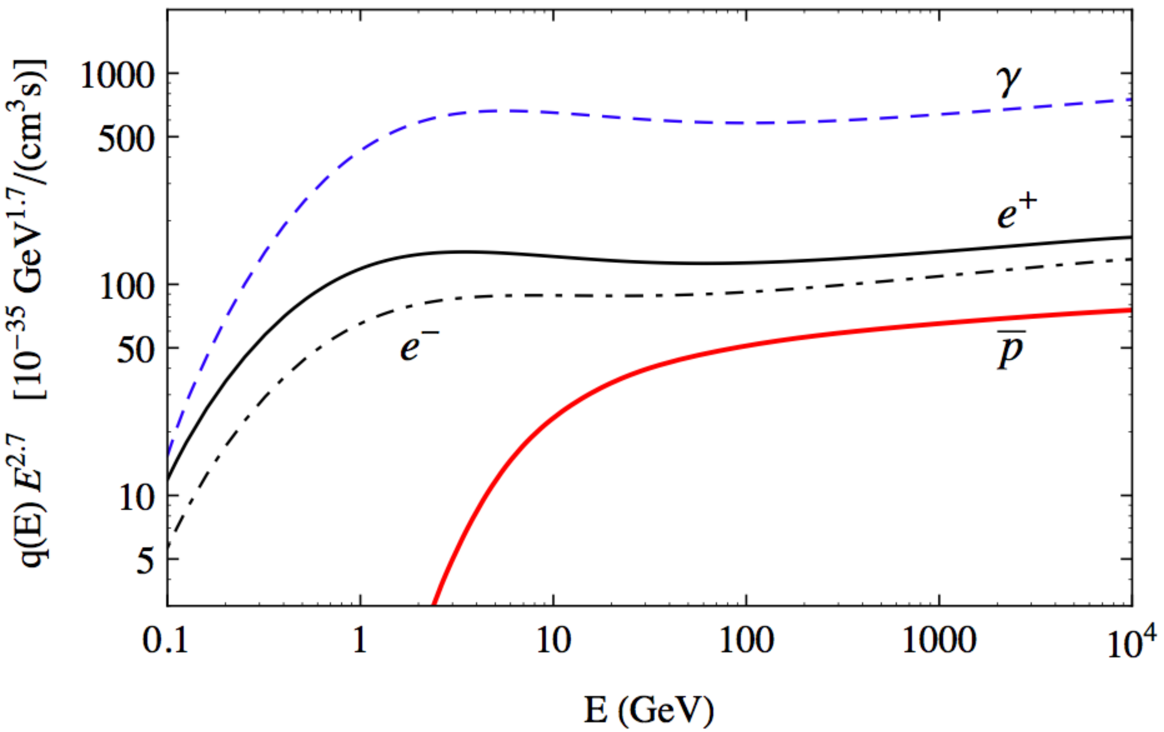
Power Law behavior at high energy

Secondary spectra



Scaling behavior

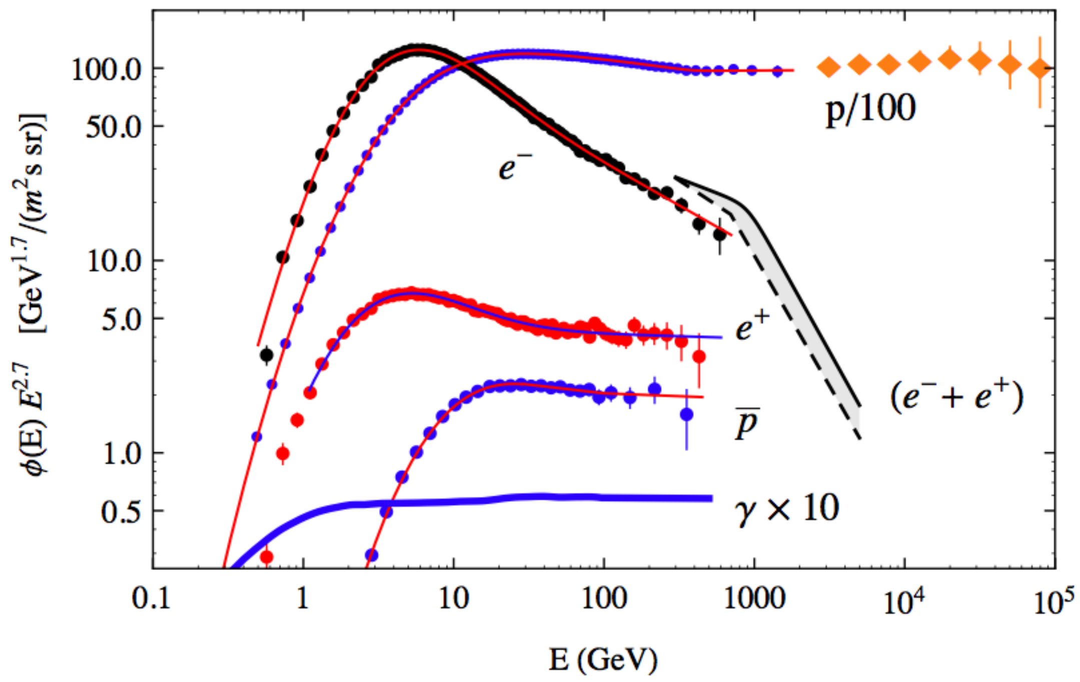




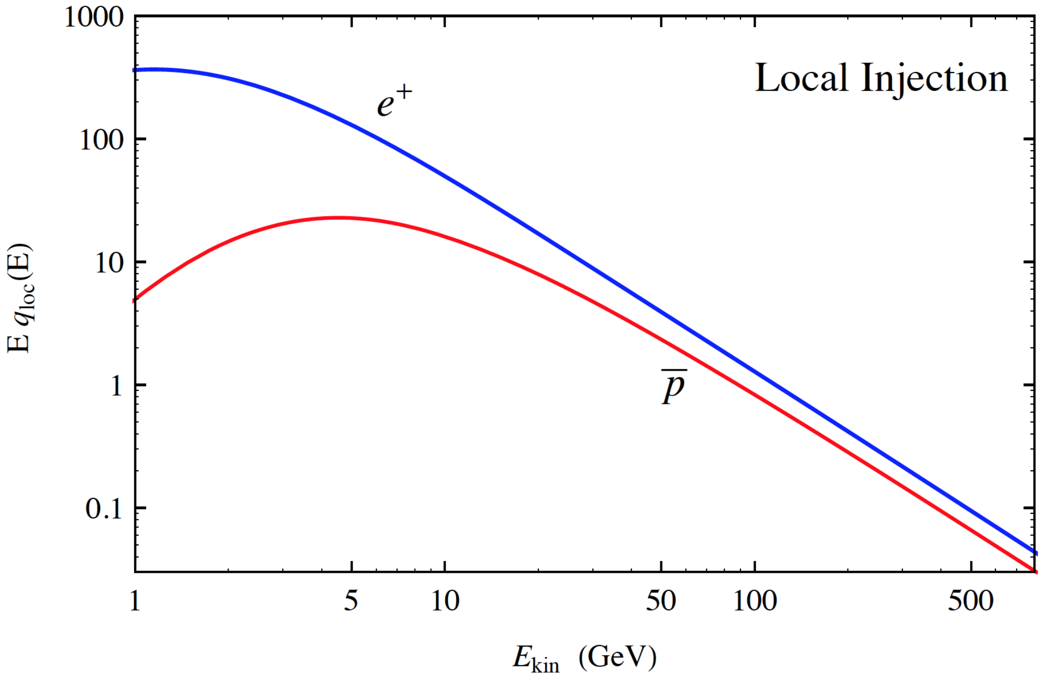
Local production rates of secondaries

e^+ $\overline{p}$

"striking" similarity

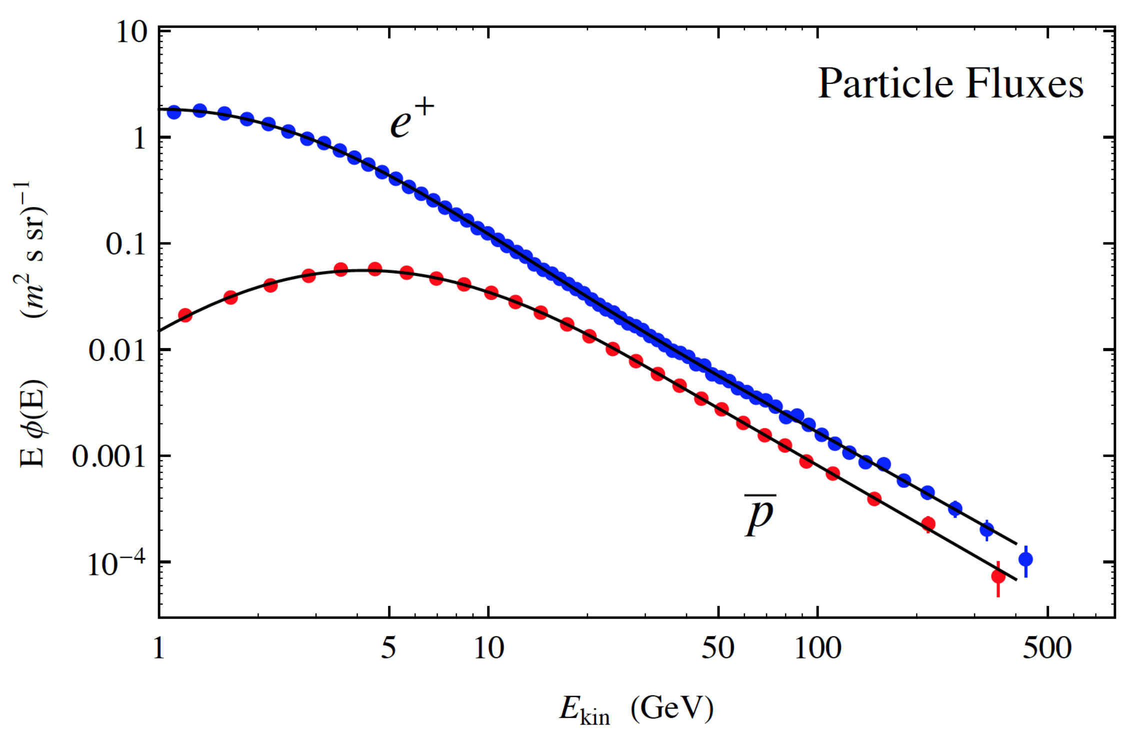


Observed fluxes



Local production rates of secondaries

“striking” similarity



Observed fluxes

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

The ratio positron/antiproton of the injection is *(within errors)* 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. The cosmic rays 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.

Relation between the production rate of a cosmic ray type and the observed flux at the Earth

$$\phi_j(E) = \frac{\beta\, c}{4\,\pi}\; Q_j(E)\; P_j(E)$$

Flux

Galactic Production Rate

Propagation Function

$$P_j(E) \approx \frac{T_j(E)}{V_j(E)} \approx \frac{\text{Average age}}{\text{Confinement volume}}$$

The study of the *diffuse gamma ray* flux allows to study the hypothesis that the shape of the CR spectra is approximately independent from position

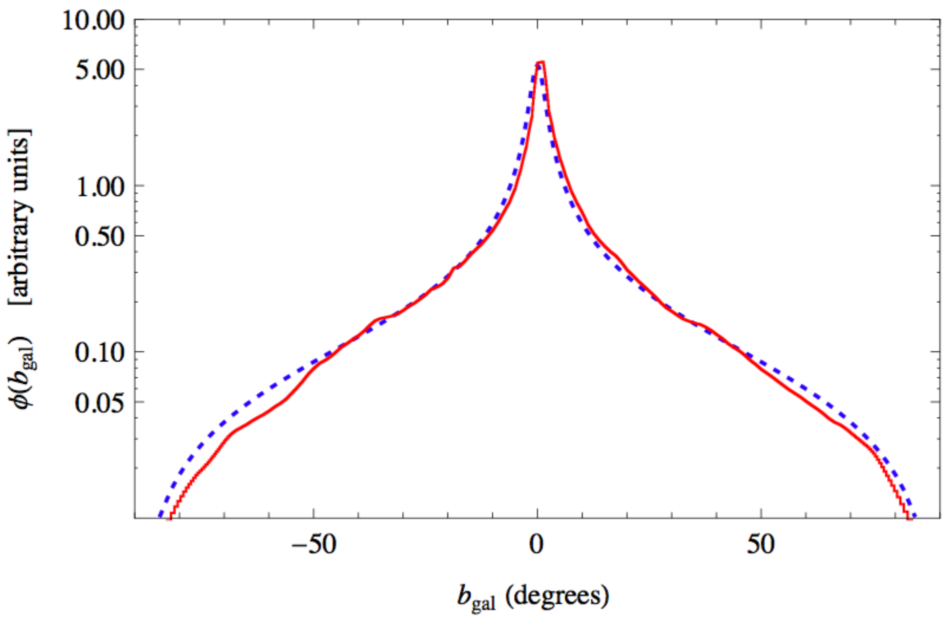
Flux : Integration of emission along the line of sight

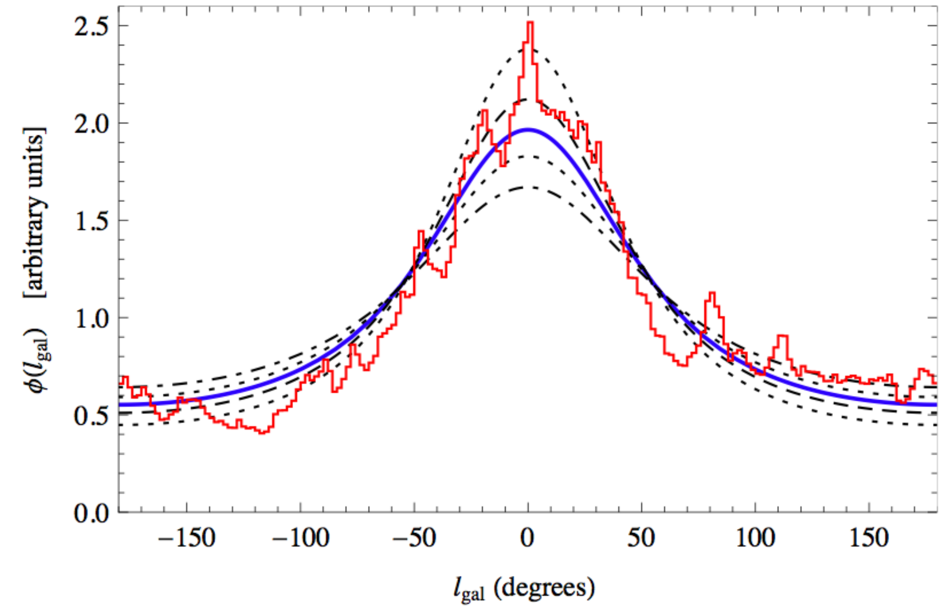
$$\phi_\gamma(E,\Omega) = \frac{1}{4\,\pi} \int_0^\infty d\ell \; q_\gamma[E, \vec{x}_\odot + \ell\,\hat{\Omega}]$$

$$\Phi_\gamma(E) = \int_{4\pi} d\Omega \; \phi_\gamma(E,\Omega)$$

$$= \frac{1}{4\,\pi} \int d^3x \; \frac{q_\gamma(E,\vec{x})}{|\vec{x} - \vec{x}_\odot|^2} \quad = \frac{Q_\gamma(E)}{4\,\pi\, L_{\rm eff}^2(E)}$$

The angular distribution of the gamma ray flux encodes the space distribution of the emission





Estimate of the space distribution of the emission

$$q_\gamma(E,\vec{x}) = \frac{Q_\gamma(E)}{(2\pi)^{3/2}\, R^2\, Z}\, \exp\left[-\frac{(x^2+y^2)}{2\,R^2} - \frac{z^2}{2\,Z^2}\right]$$

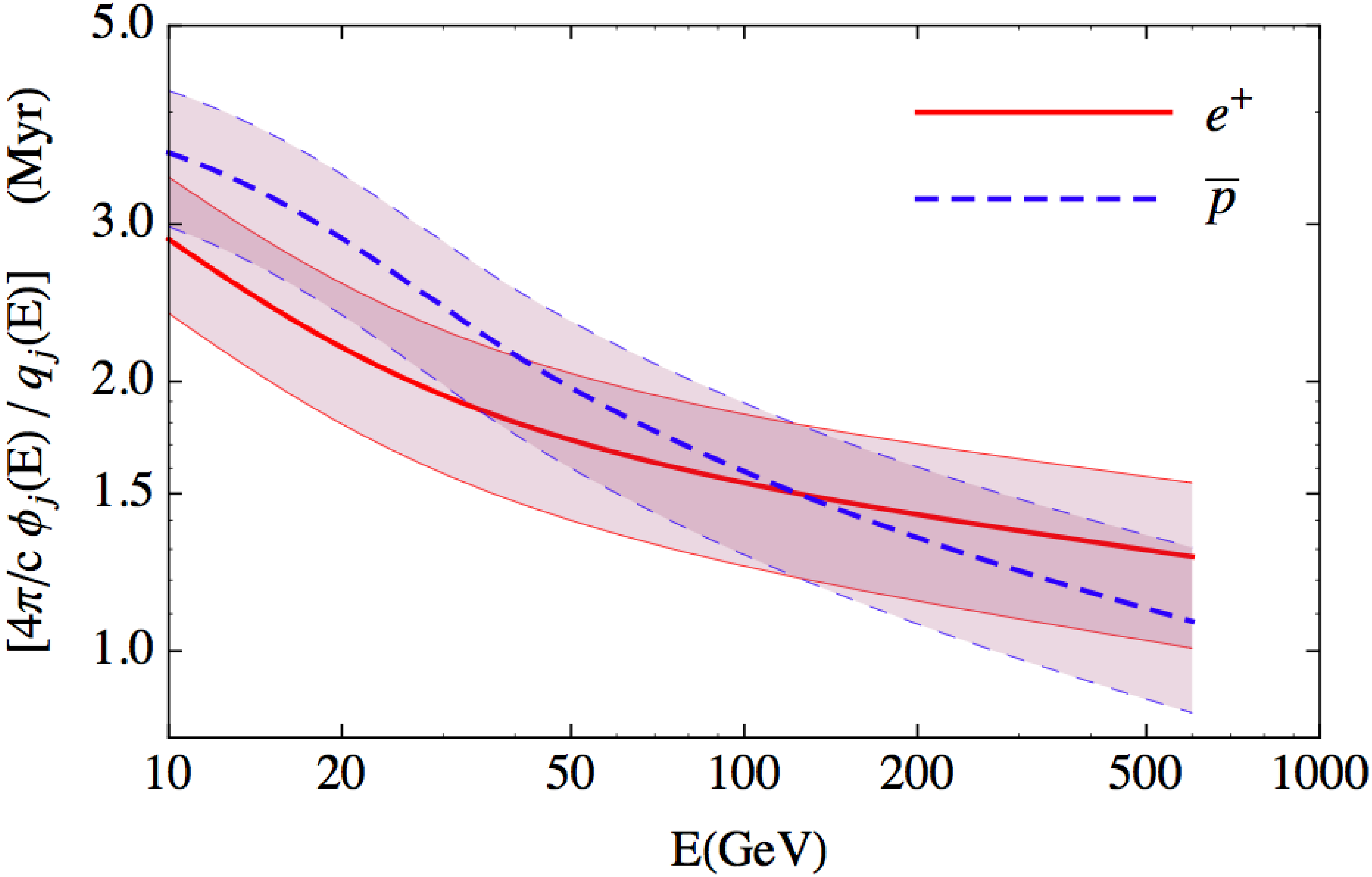
$Z \simeq 0.22$ kpc

$R \simeq 5.2$ kpc

$$V_Q \approx 160 \left[\frac{1\ \mathrm{cm}^{-3}}{n_{\rm ism}(\vec{x}_\odot)}\right]\ \mathrm{kpc}^3$$

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

Distortion of the source spectra created by propagation



Weak energy dependence of the propagation effects !

Two crucial problems emerge :

[1.] The energy dependence of the propagation effects is significantly smaller than expectations
[based on the B/C ratio]
[theoretically motivated]

Problem
also for antiprotons !

[2.] The propagation effects for positrons and antiprotons are approximately equal.

Is this possible ?

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

Rates of energy losses for positrons and antiprotons differ by many orders of magnitude

The much larger rate of energy loss for $e^{\pm}$ is irrelevant in propagation if the *time of residence* of the particles is sufficiently short, so that a particle loses only a small fraction of its energy before escape from the Galaxy

$$|dE/dt| \; T_{\rm age} \ll E$$

$$T_{\rm age} \ll \frac{E}{|dE/dt|} \equiv T_{\rm loss}(E)$$

Characteristic times for the propagation of Cosmic Rays in the Milky Way

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

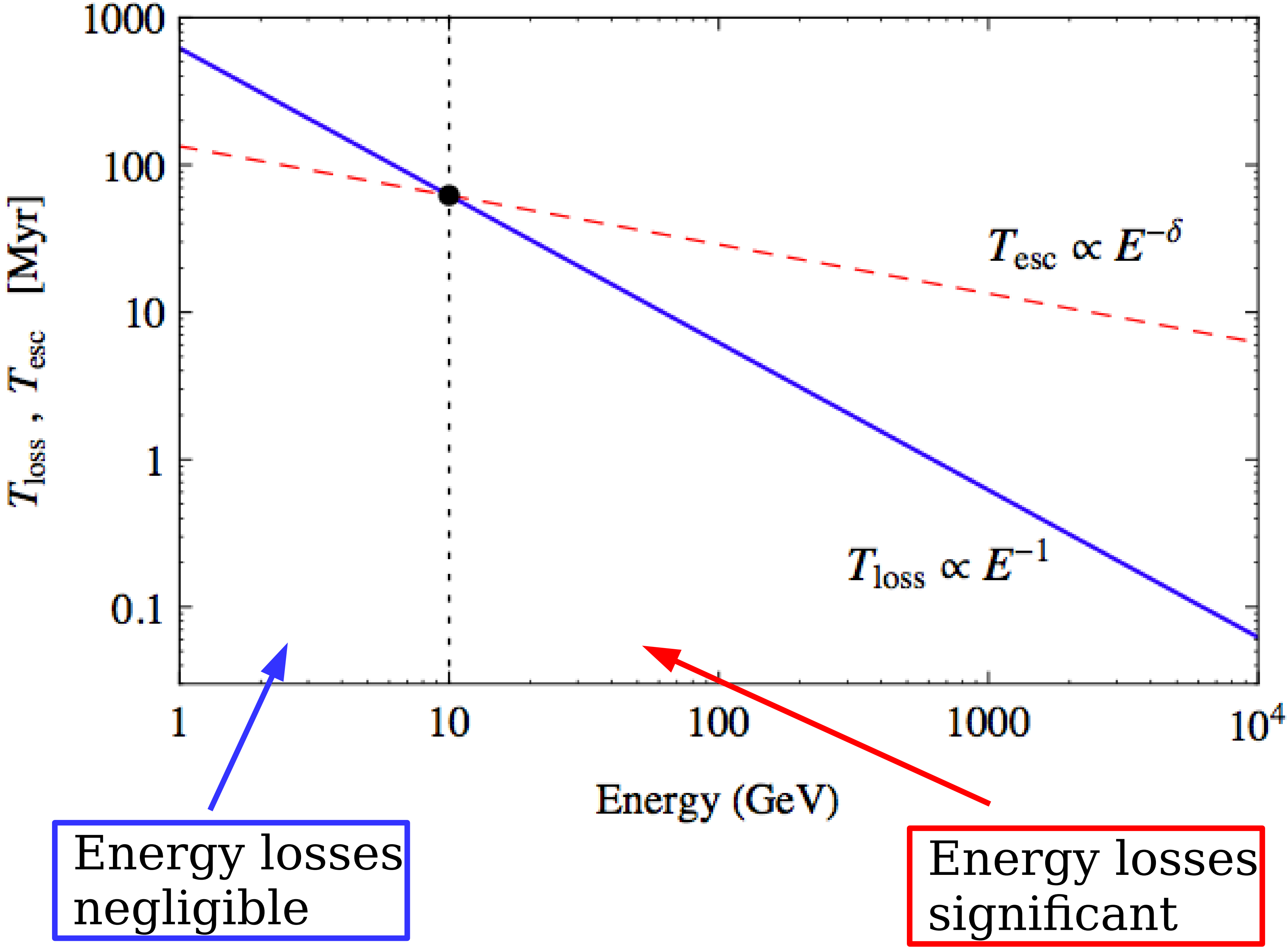
Time to escape from the Galaxy

$$T_{\rm loss}^{e}(E)$$

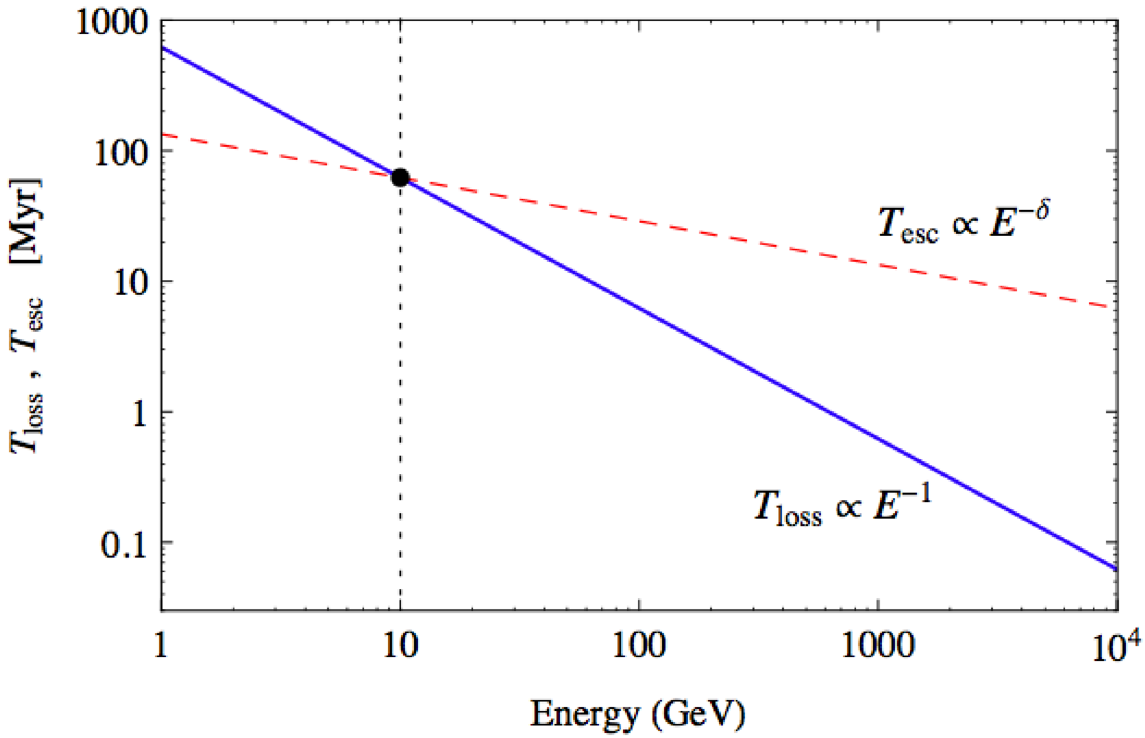
Time to lose a significant fraction of the initial energy (for electrons and positrons)

$$T_{\rm int}^{p}(E)$$

Interaction time (for protons)

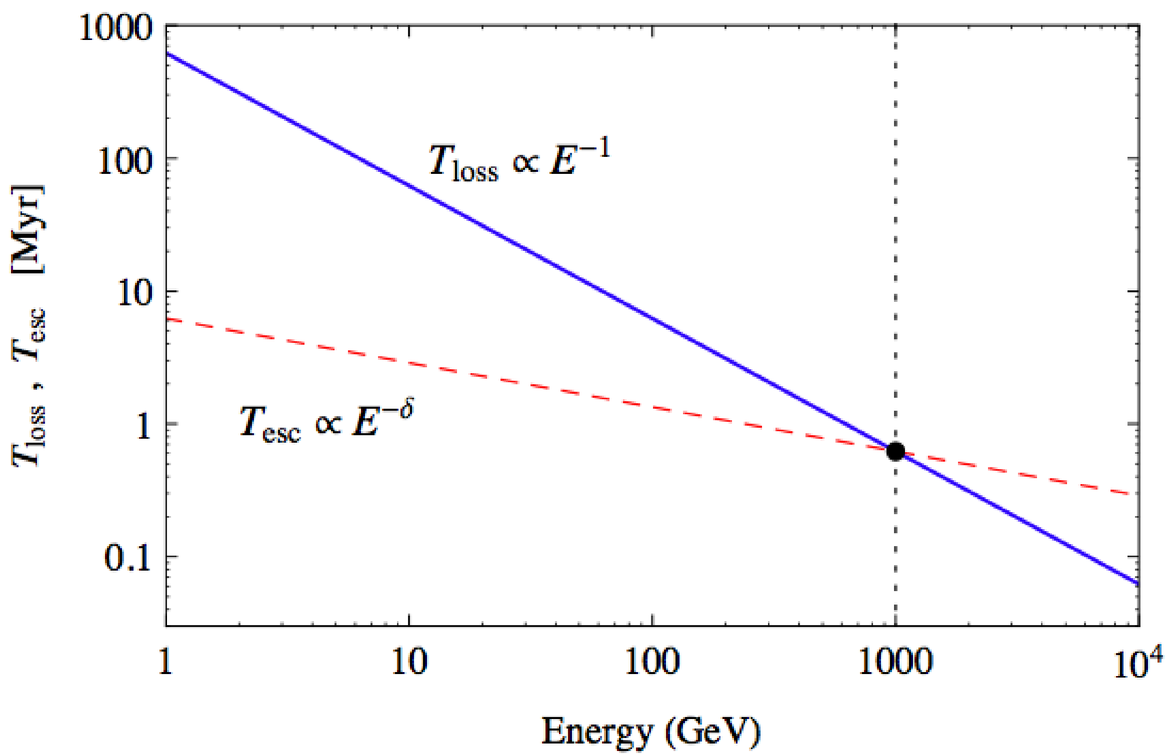


1000
100
10
1
0.1
T_{loss} , T_{esc} [Myr]
1
10
100
1000
10^4
Energy (GeV)
$T_{esc} \propto E^{-\delta}$
$T_{loss} \propto E^{-1}$
Energy losses negligible
Energy losses significant



"Standard picture"

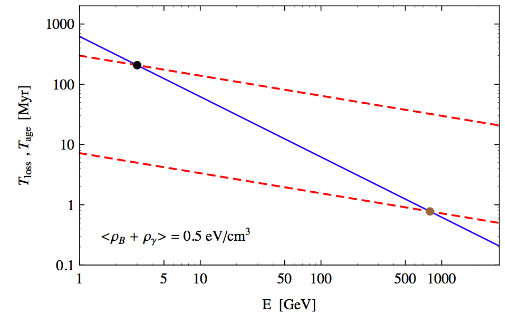
Energy losses important for E > few GeV



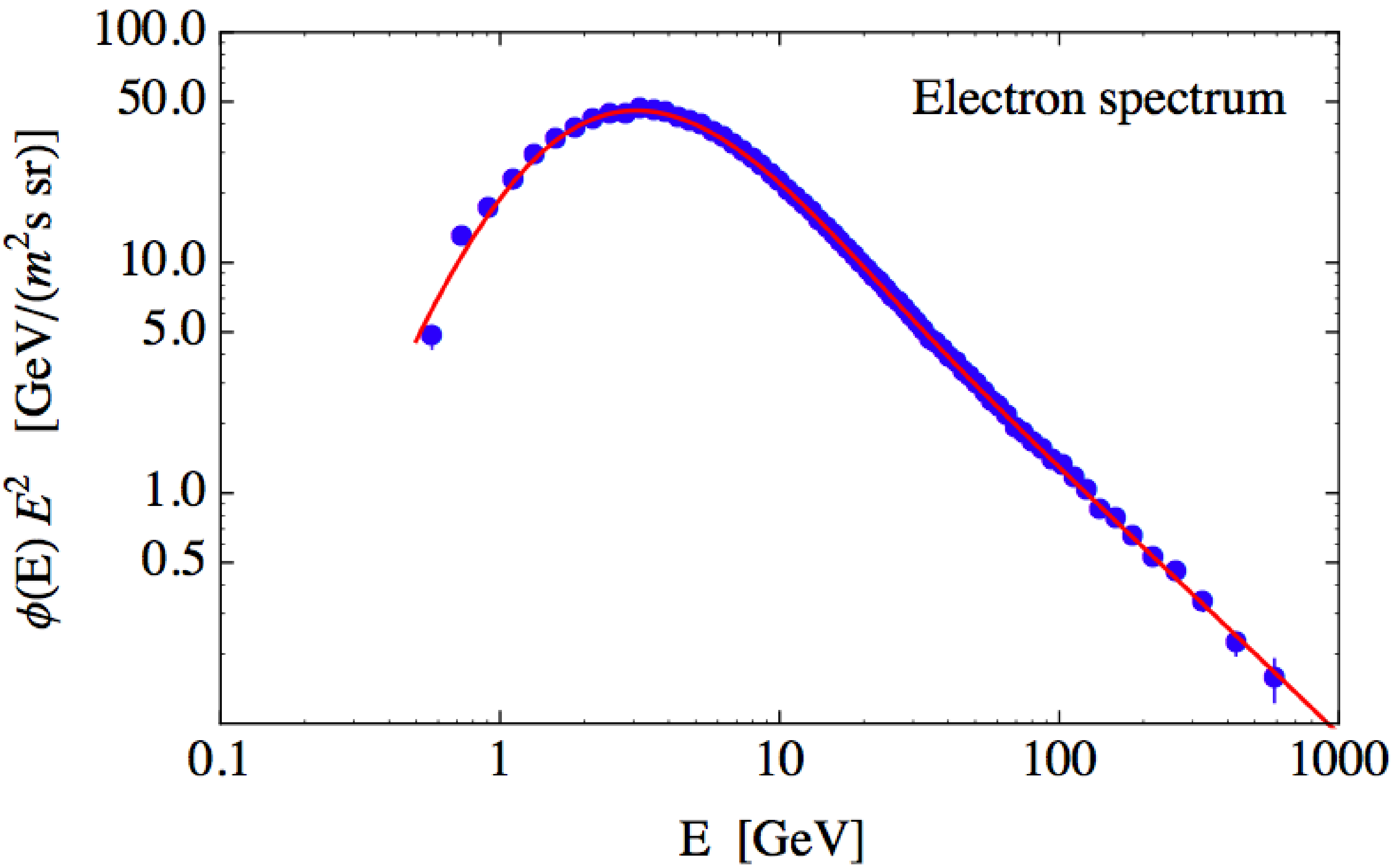
"Alternative picture"

Energy losses become important at $E \approx 1$ TeV

Use the electron spectrum
as a *"cosmic ray clock"*



Where is the spectral feature
associated to the critical energy ?



Very smooth electron spectrum

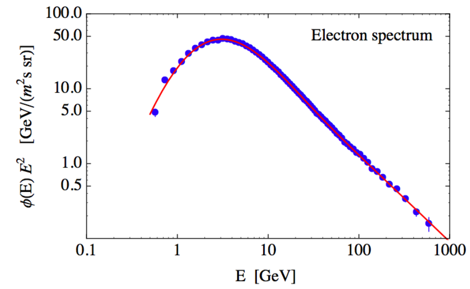
Fit =

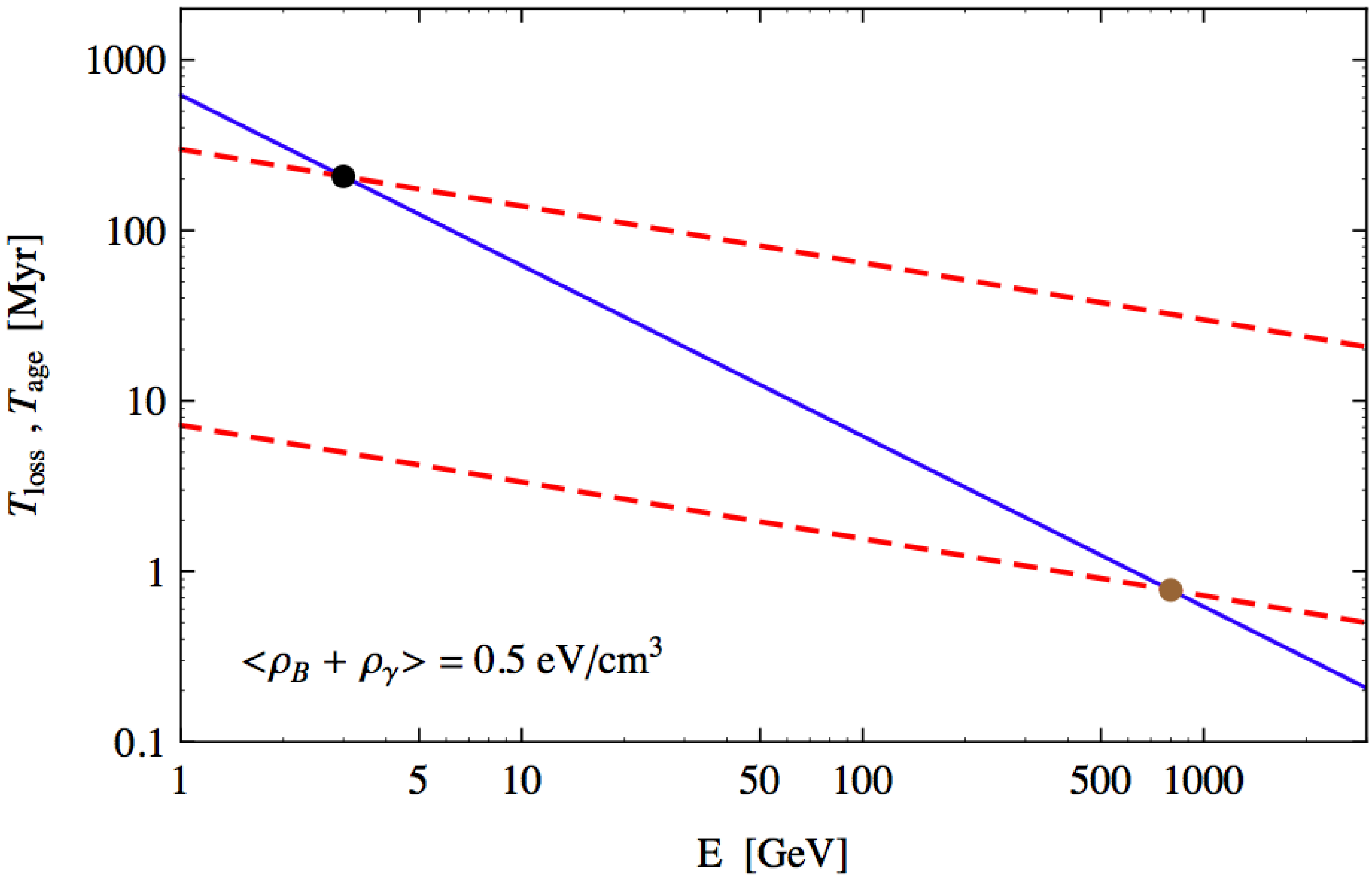
$$K\ E^{-3.17}$$

$$\otimes$$

FFA Solar Modulations (1.44GeV)]

Where is the critical energy: E^*
in the electron spectrum ?





Pull to very low energy

$E^* < 5$ GeV

Push to high energy

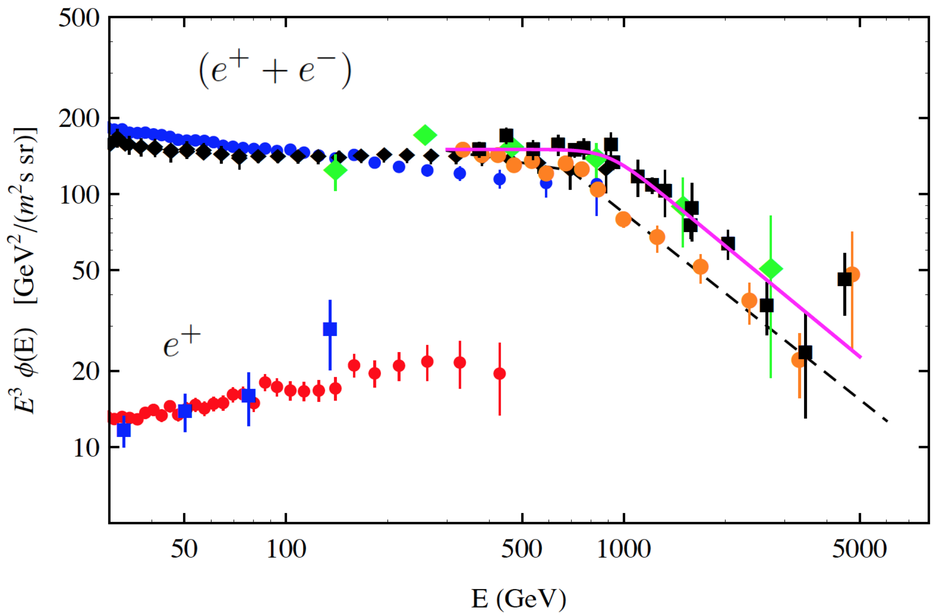
$E^* > 500$ GeV

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

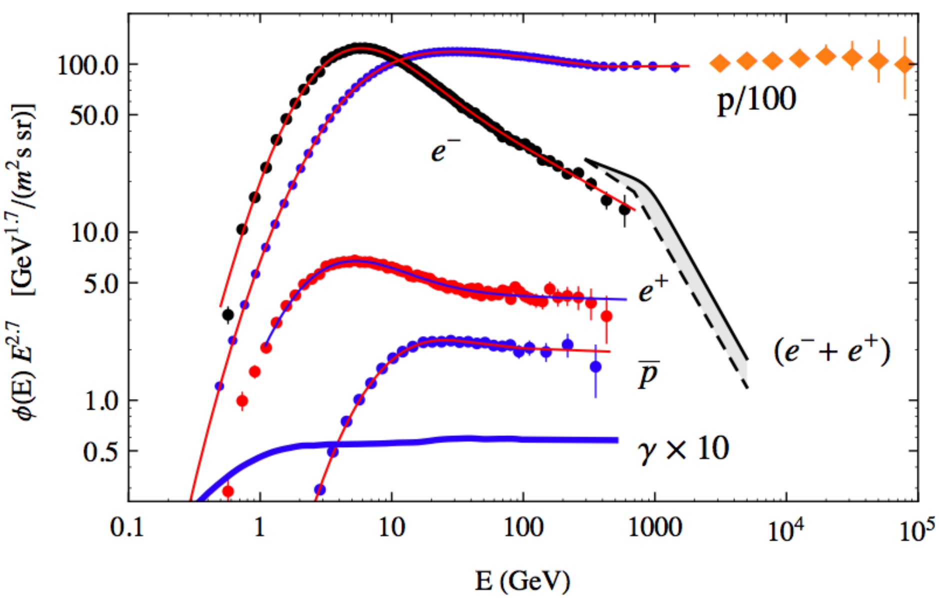
$$E \lesssim E^* \simeq 900 \text{ GeV}$$

This solution is simple and natural
but has a significant "theoretical" problem:

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 ?! (with electrons much softer).



The e/p difference must be generated by the sources

…. Can the sources release different spectra of e- and p without violating the “universality” of the acceleration mechanism ?….. yes !

Effects of Energy losses:

in the accelerators (perhaps SNR)

“Generation” =

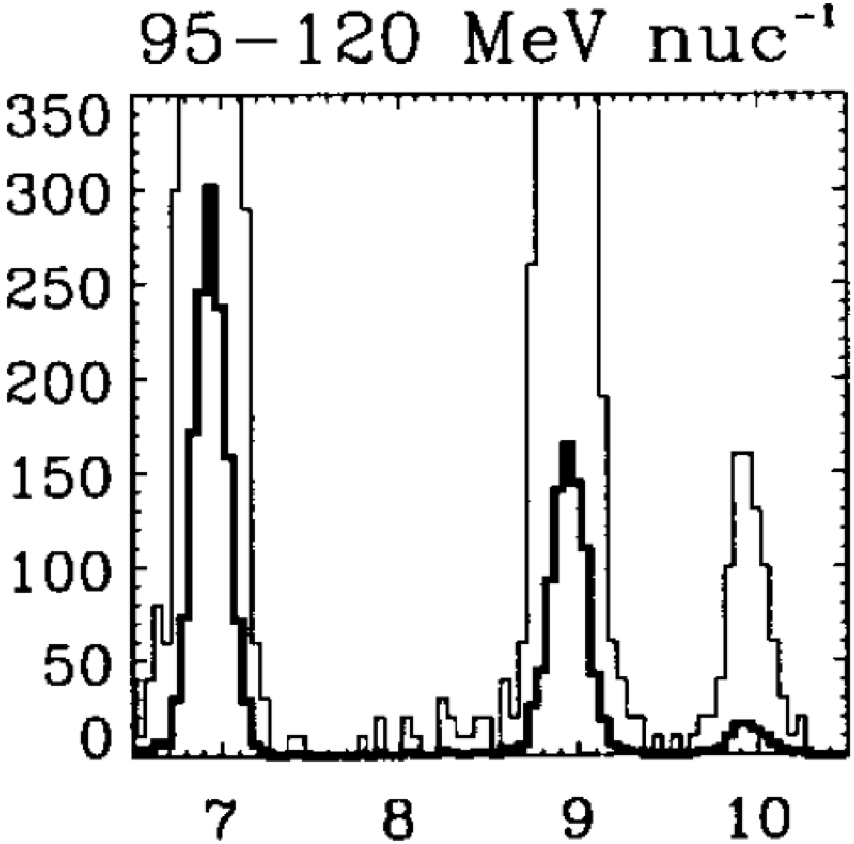
Injection in the acceleration process — mass dependence

$\otimes$

Acceleration

$\otimes$

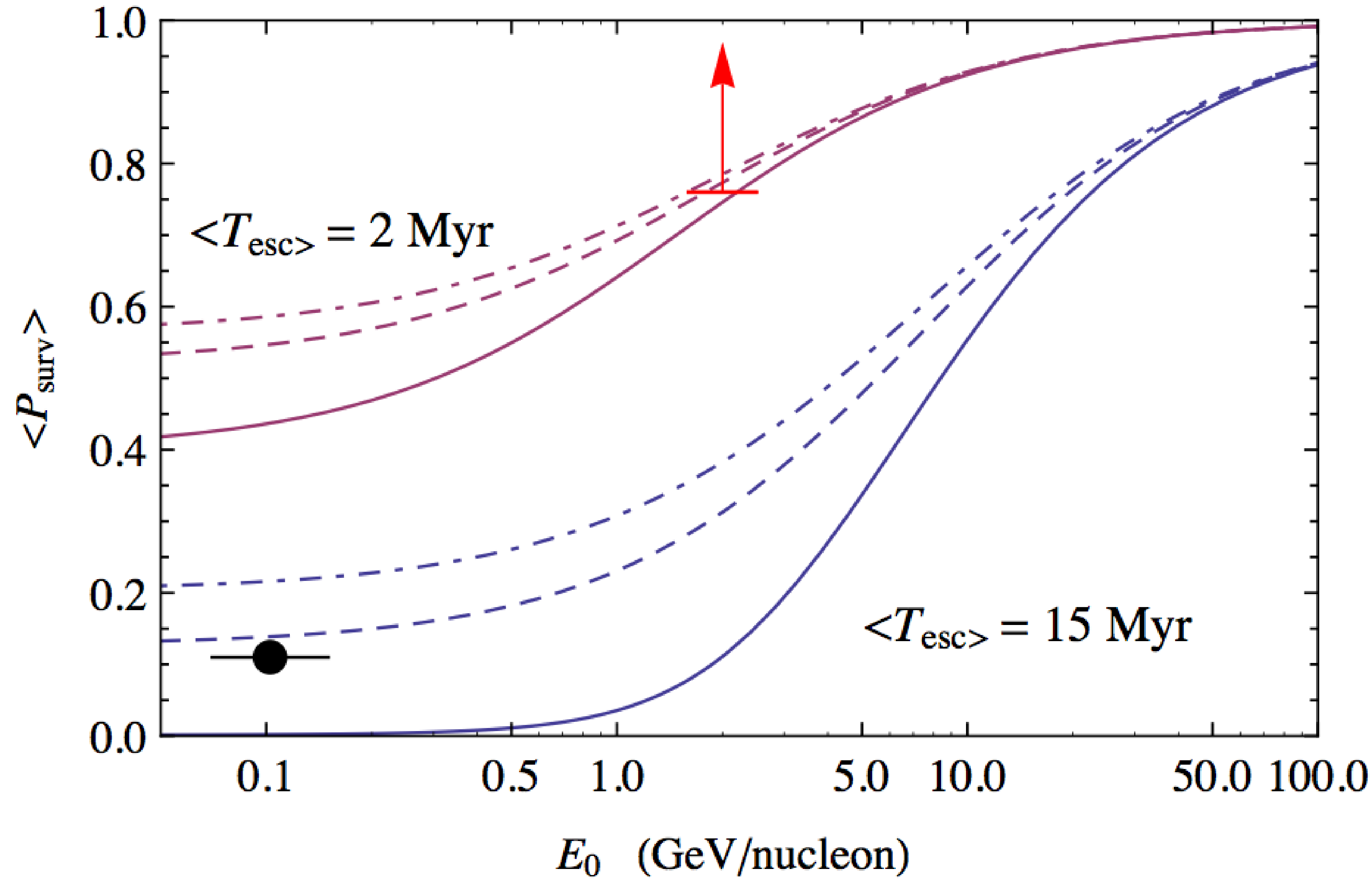
source Ejection (escape from accelerator) — mass dependence (energy loss)



Measurements of Beryllium 10

$(T_{1/2} \simeq 1.51 \pm 0.04\ \mathrm{Myr})$

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



N.E. Yanasak *et al.*

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

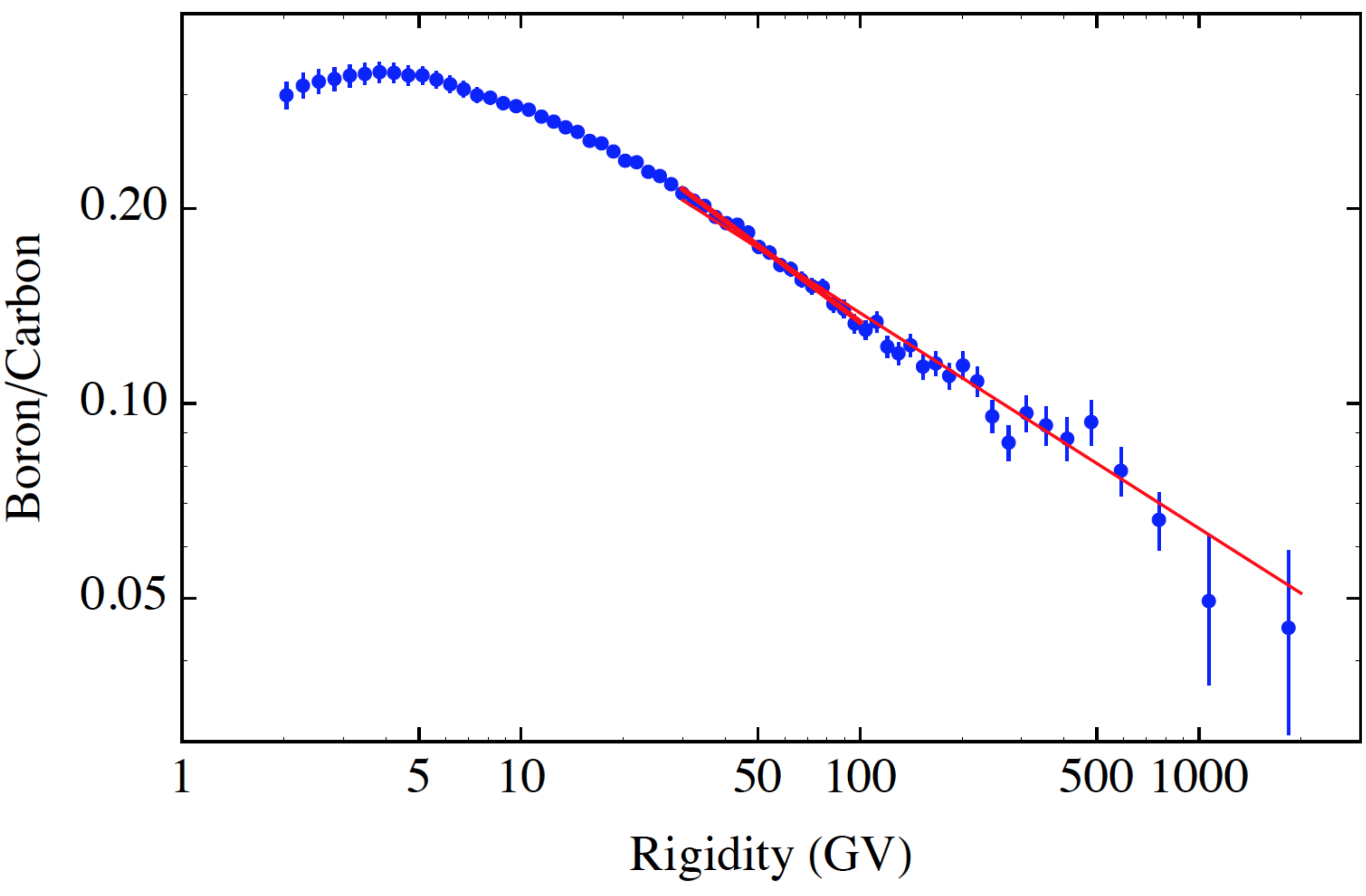
M. Kruskal, S. P. Ahlen and G. Tarlé,

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

What about secondary/primary nuclei ?

[normally the “cornerstone” of most propagation models]

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



AMS02 data

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

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*]

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

Residence time inferred from B/C ratio
assuming that the column density crossed by
the nuclei is accumulated in interstellar space

is *inconsistent* [as it is too long]
with the hypothesis that the energy losses of $e^{\pm}$
are negligibly small.

Possible solutions

1. [Energy dependence of fragmentation Cross sections]

2. Most of the column density inferred from the B/C ratio
   is integrated not in interstellar space
   but inside or in the envelope of the sources
   [Cowsik and collaborators]

Conventional (orthodox) *description :*

$$P_{e^+}(E) < P_{\overline{p}}(E)$$

The result :

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

is simply a (rather extraordinary)
but meaningless numerical coincidence

$$Q_{e^+}(E) = Q_{e^+}^{\rm secondary}(E) + Q_{e^+}^{\rm new}(E)$$

$$Q_{\overline{p}}(E) = Q_{\overline{p}}^{\rm secondary}(E)$$

Positrons
have an “extra source”
(dominant at high energy)

New source sufficiently “fine tuned” (in shape and normalization)

$$[Q_{e^+}^{\rm sec}(E) + Q_{e^+}^{\rm new}(E)]\ P_{e^+}(E) \approx Q_{e^+}^{\rm sec}(E)\ P_{\overline{p}}(E)$$

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 these two scenarios ?

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

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

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

4. 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 positron and antiproton fluxes is of central importance for High Energy Astrophysics.

This problem touches the cornerstones of Cosmic Ray astrophysics and it has profound and broad implications

[Possible new antiparticle sources,
Spectra released by accelerators,
Fundamental properties of propagation]

Crucial crossroad for the field.