The Energy Frontier in Nature: Highest Energy Cosmic Radiation

Günter Sigl

1. Introduction and Overview
2. Astrophysics
3. Particle Physics at High Energies

DFG Deutsche Forschungsgemeinschaft

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UHH Universität Hamburg

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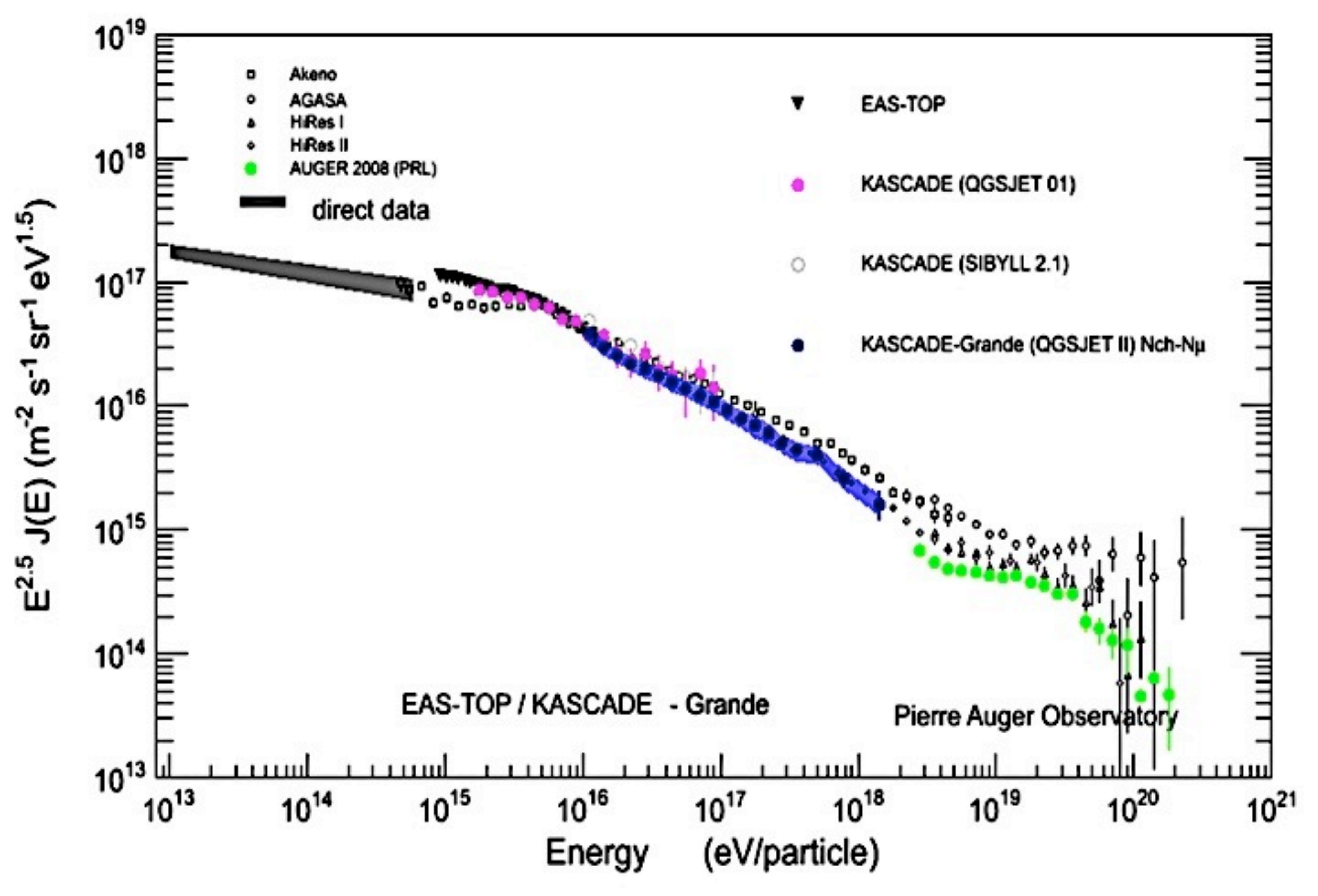
http://www2.iap.fr/users/sigl/homepage.html

The All Particle Cosmic Ray Spectrum

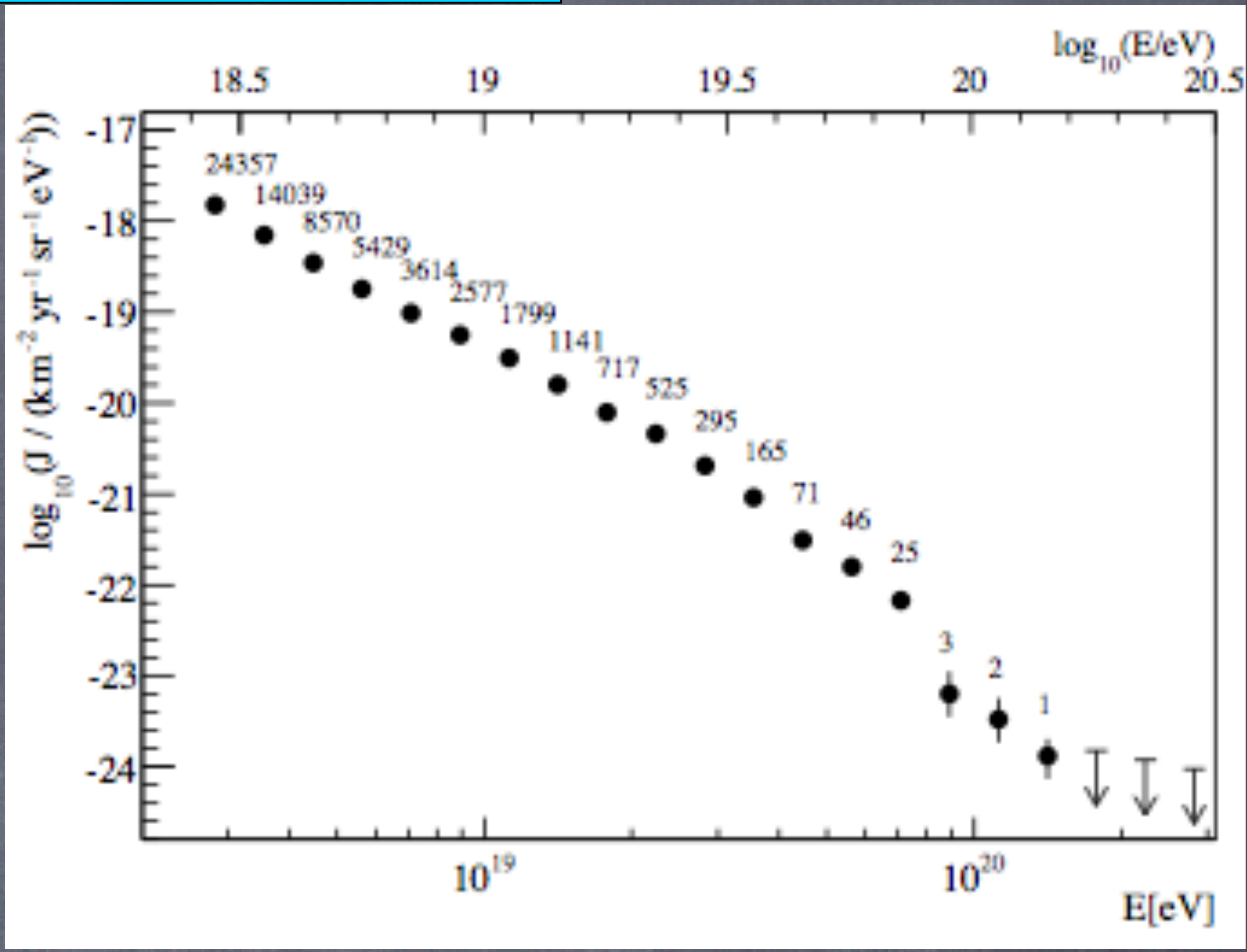


KASCADE-Grande collaboration, arXiv:1009.4716

Auger and HiRes Spectra

Auger exposure = 20905 km^2 sr yr up to December 2010

Pierre Auger Collaboration, PRL 101, 061101 (2008)
and Phys.Lett.B 685 (2010) 239
and ICRC 2011, arXiv:1107.4809



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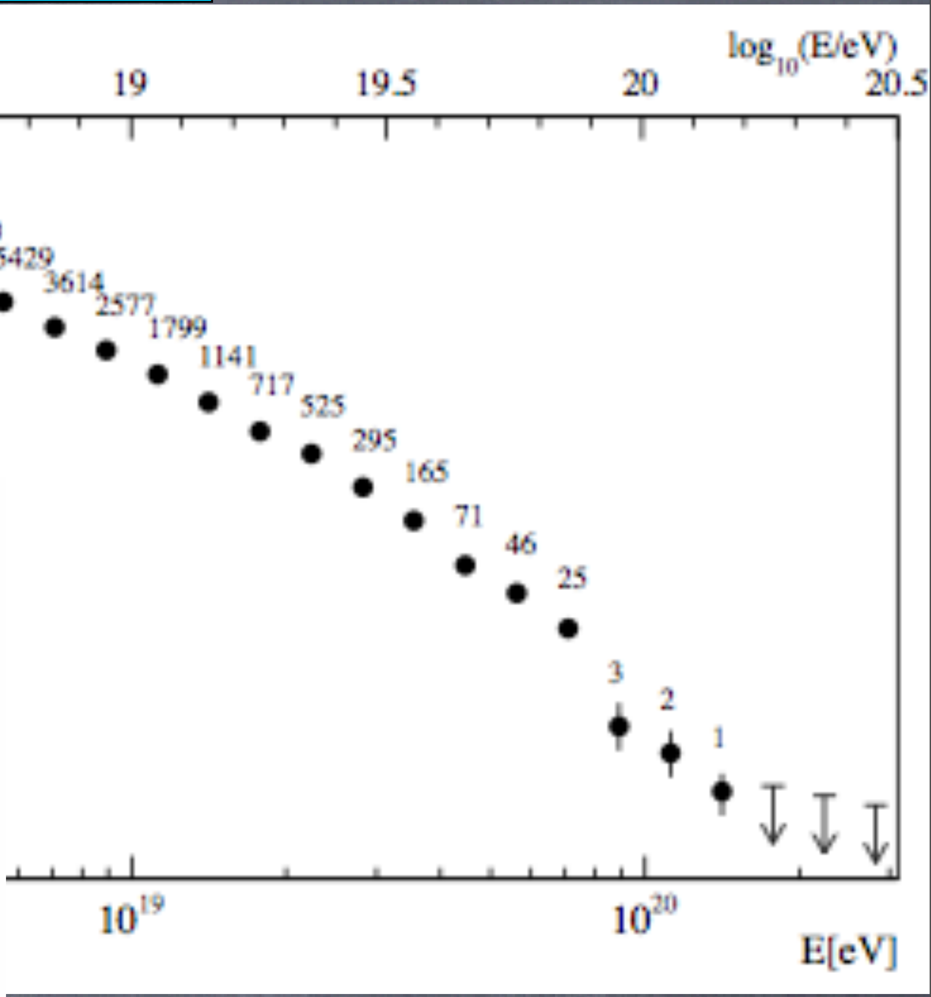
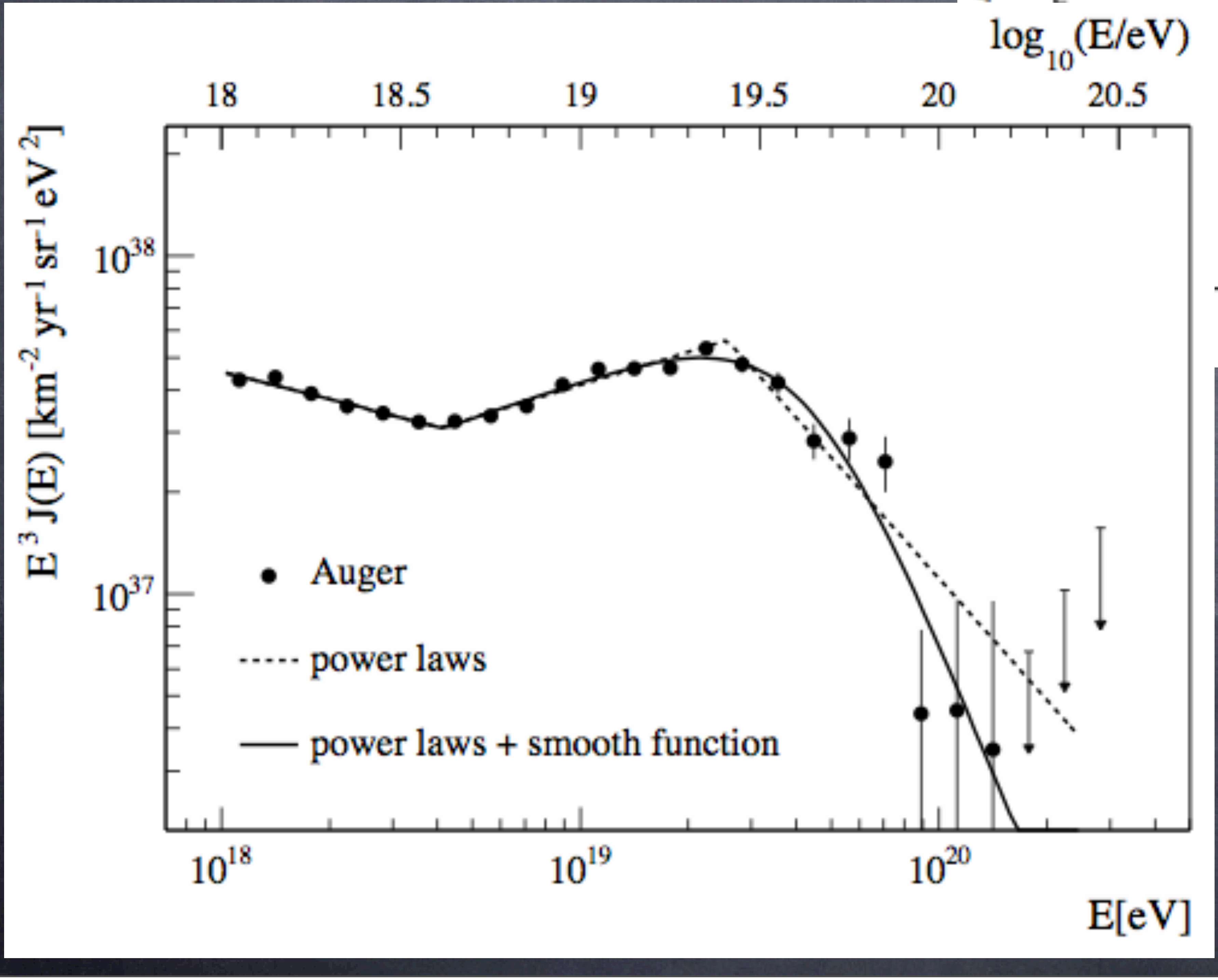
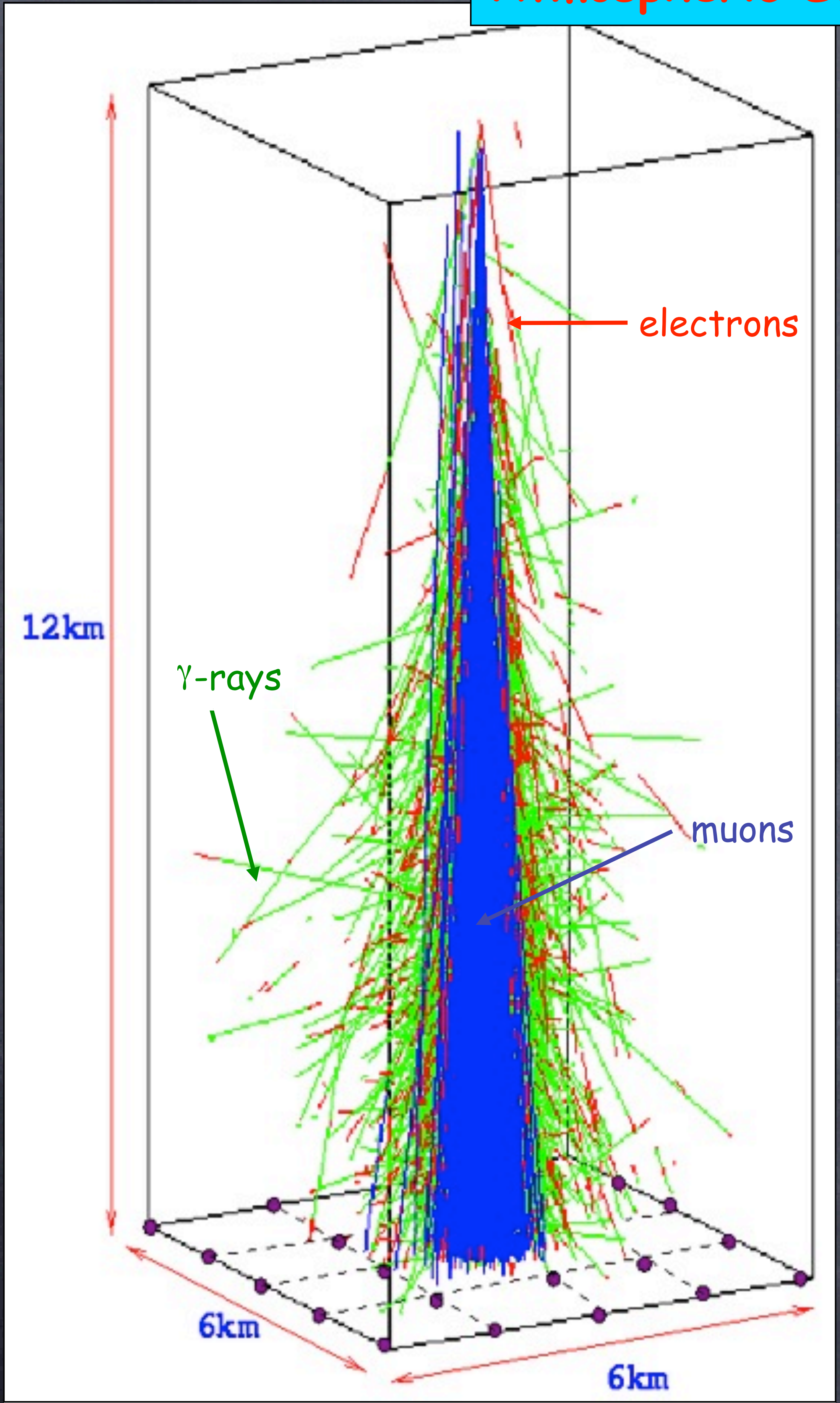




Atmospheric Showers and their Detection



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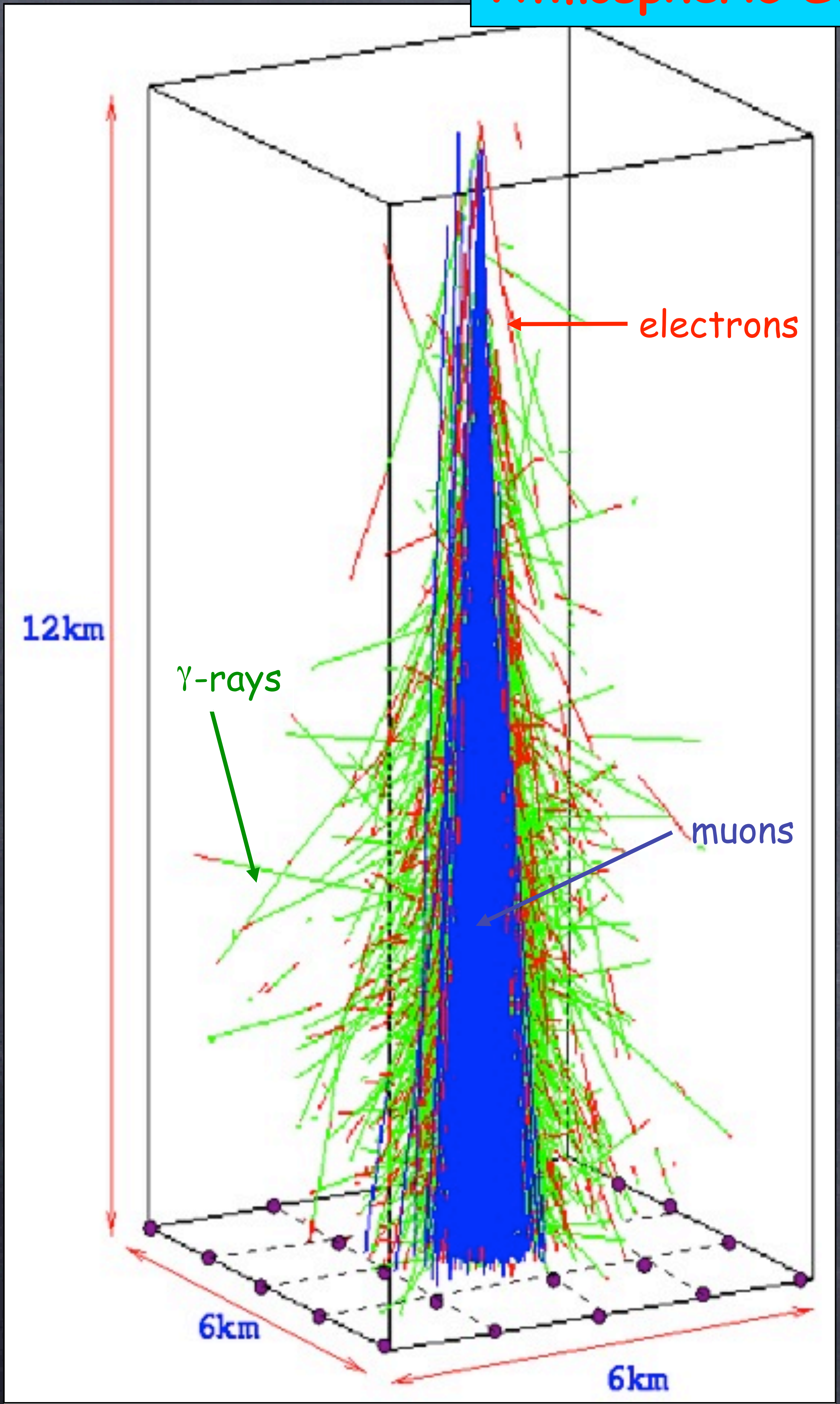

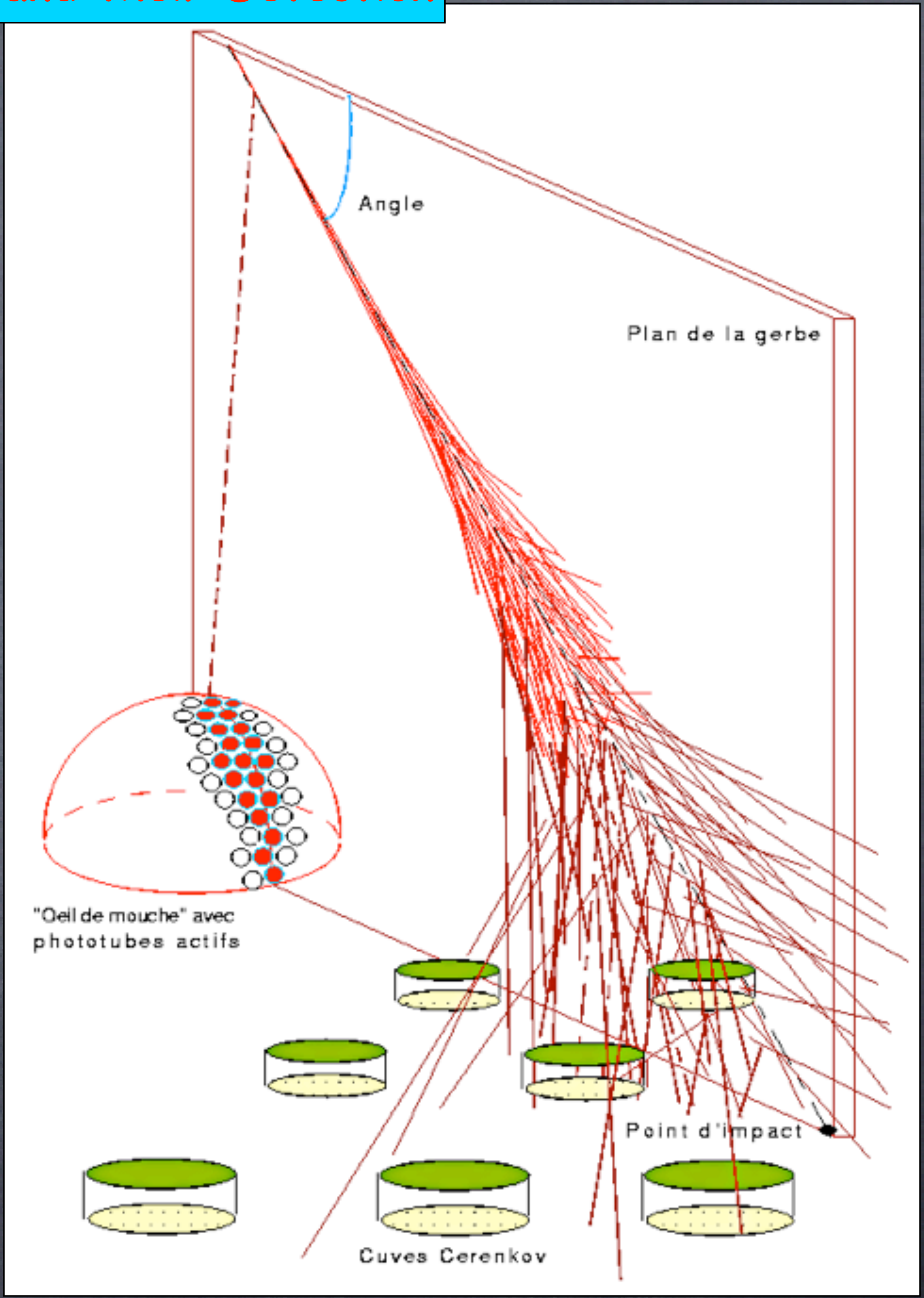

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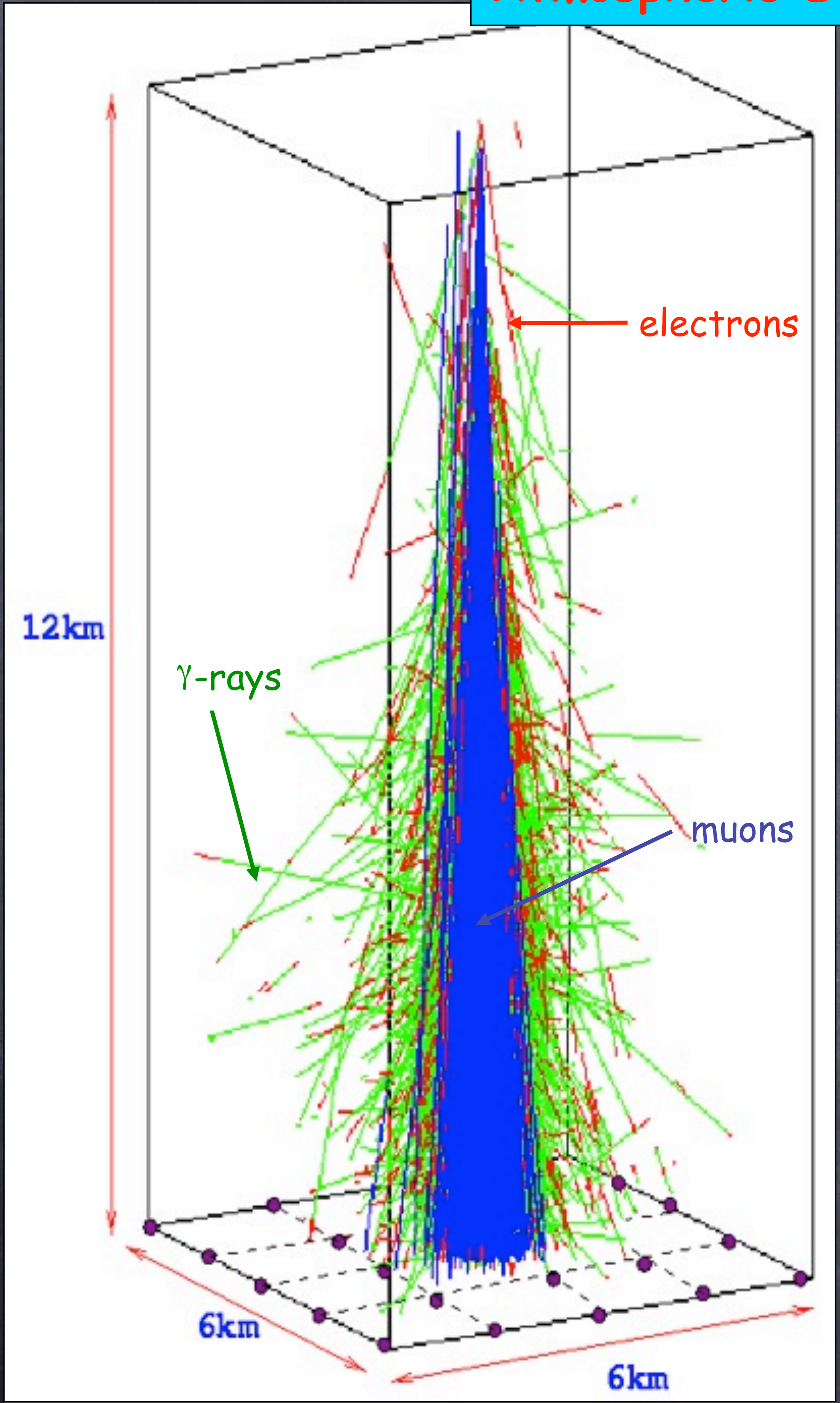

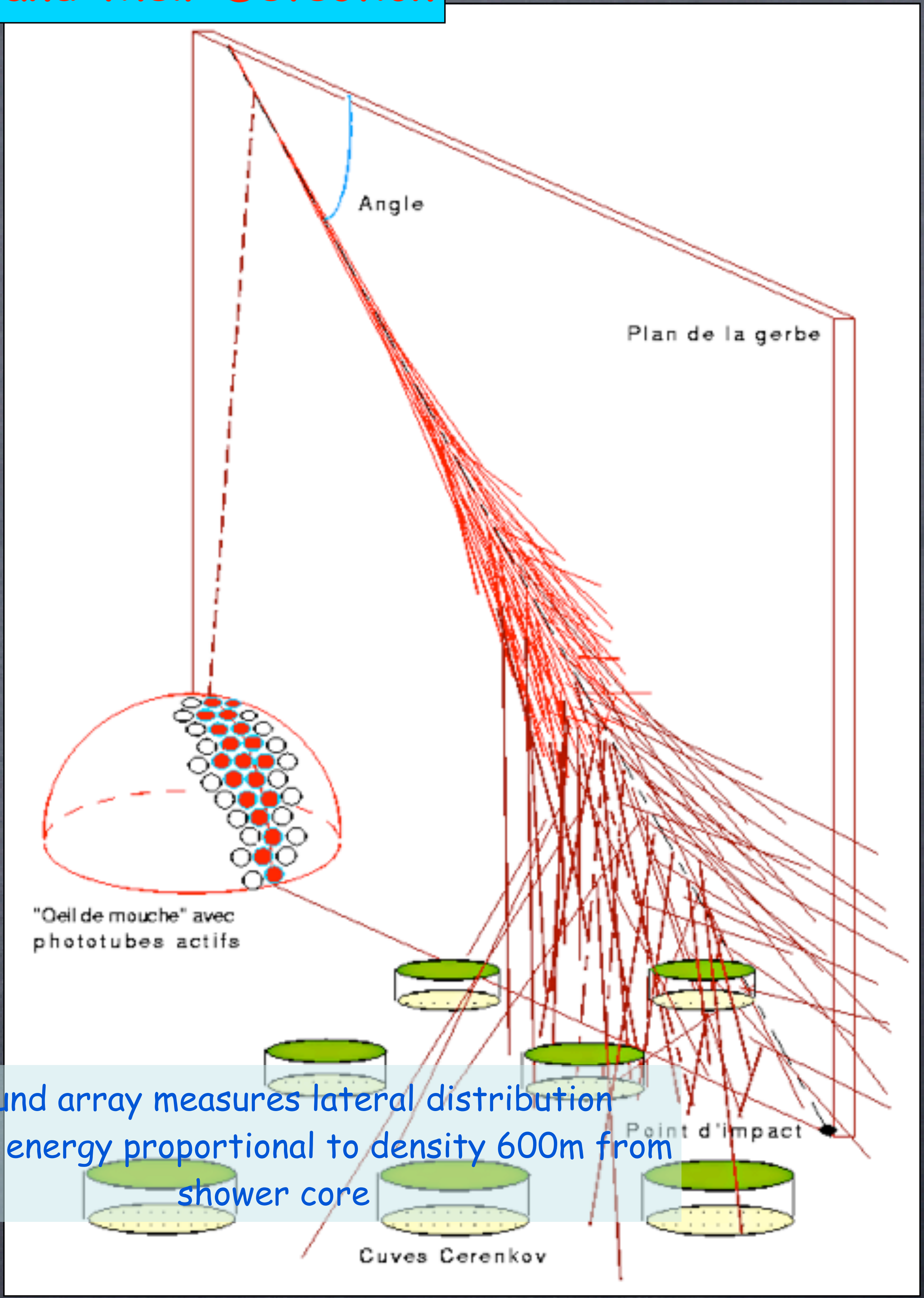

Ground array measures lateral distribution
Primary energy proportional to density 600m from shower core

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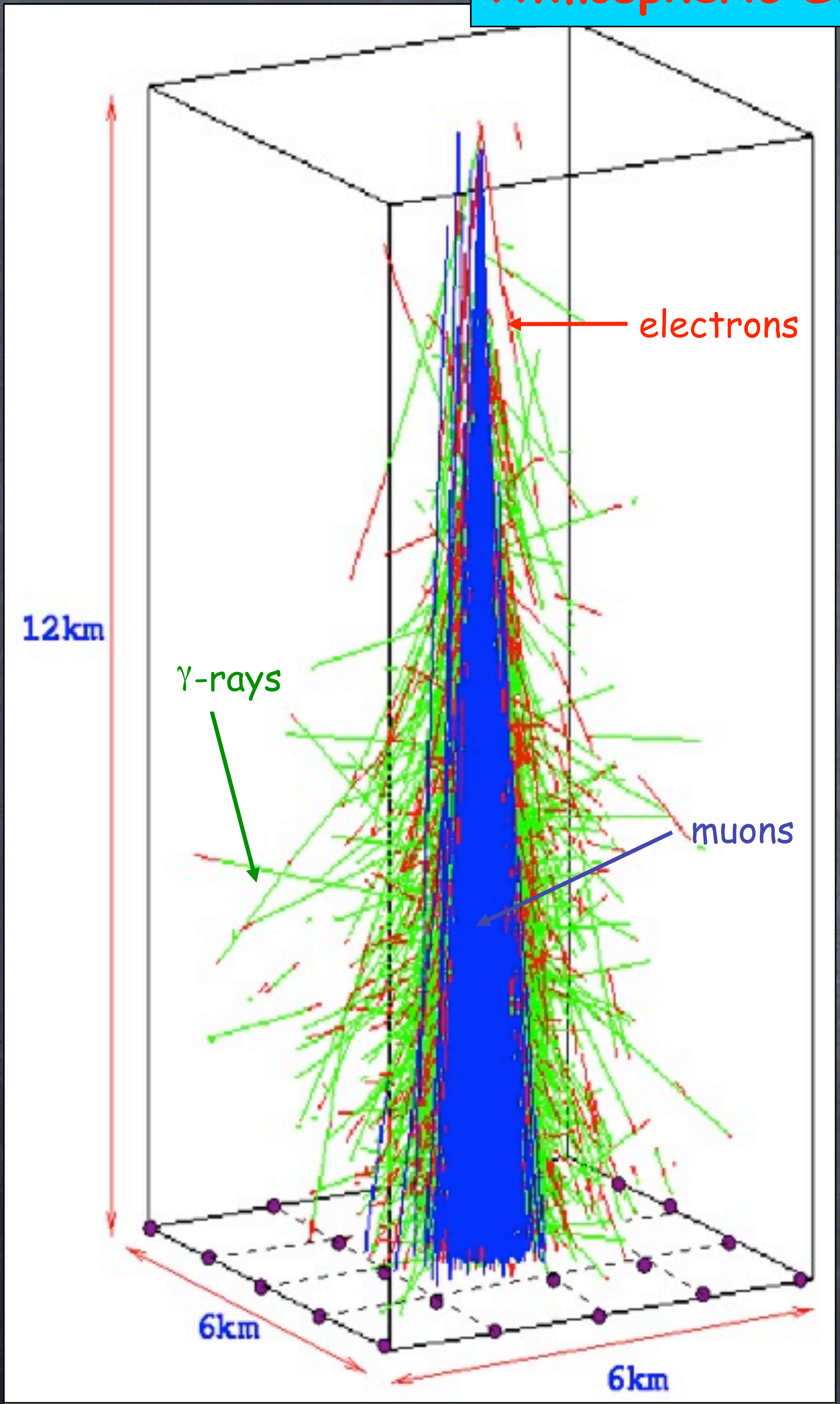
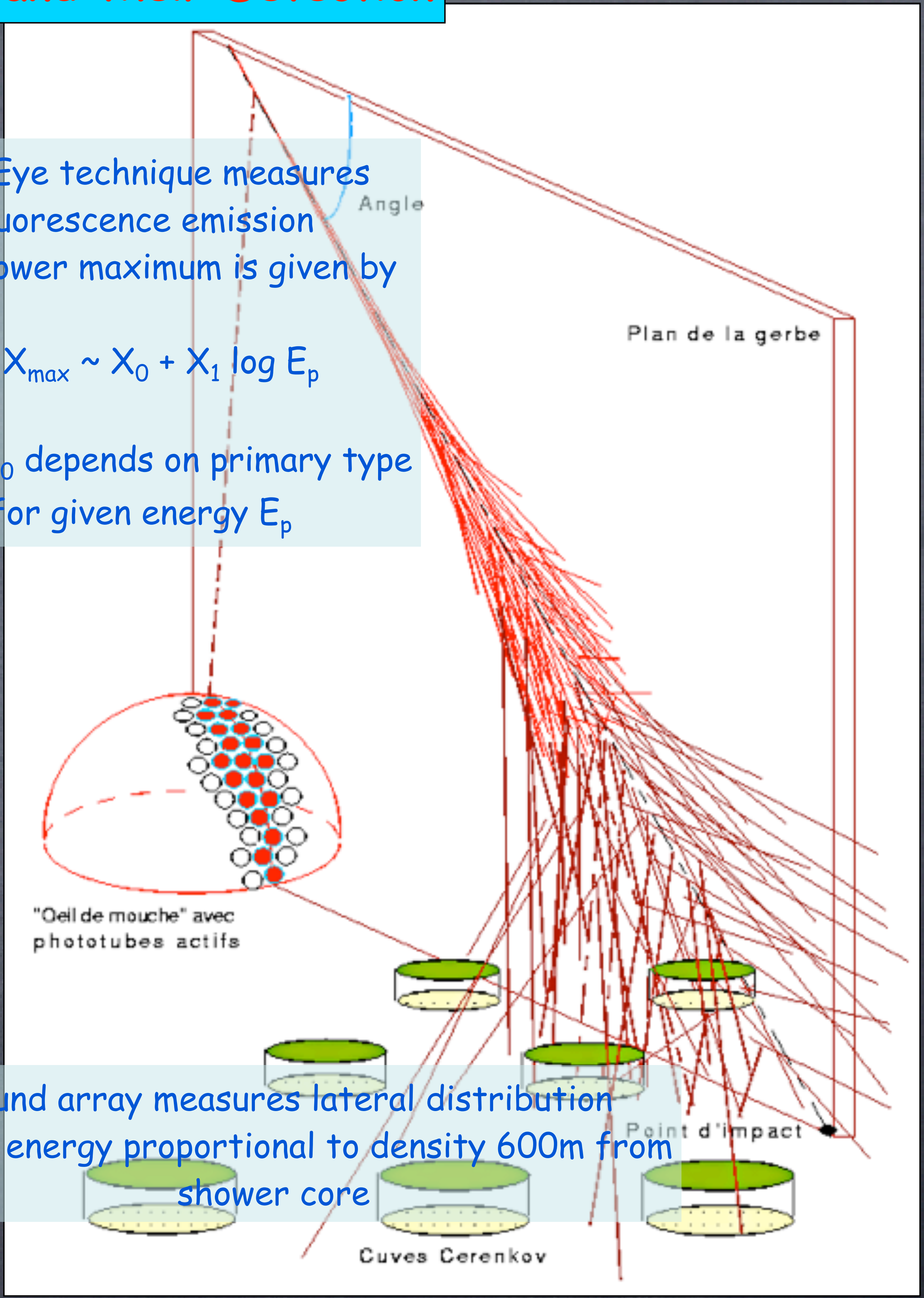


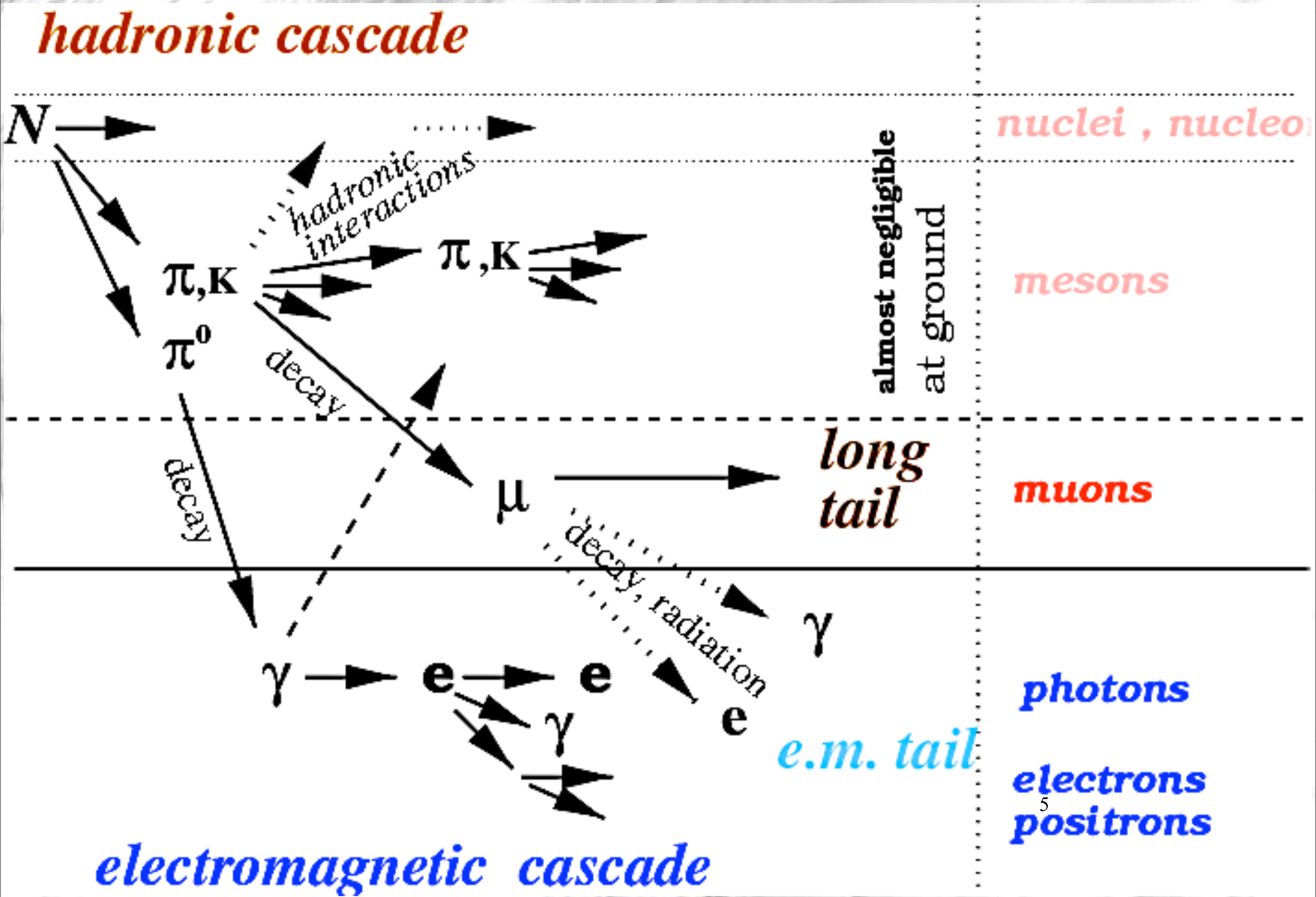


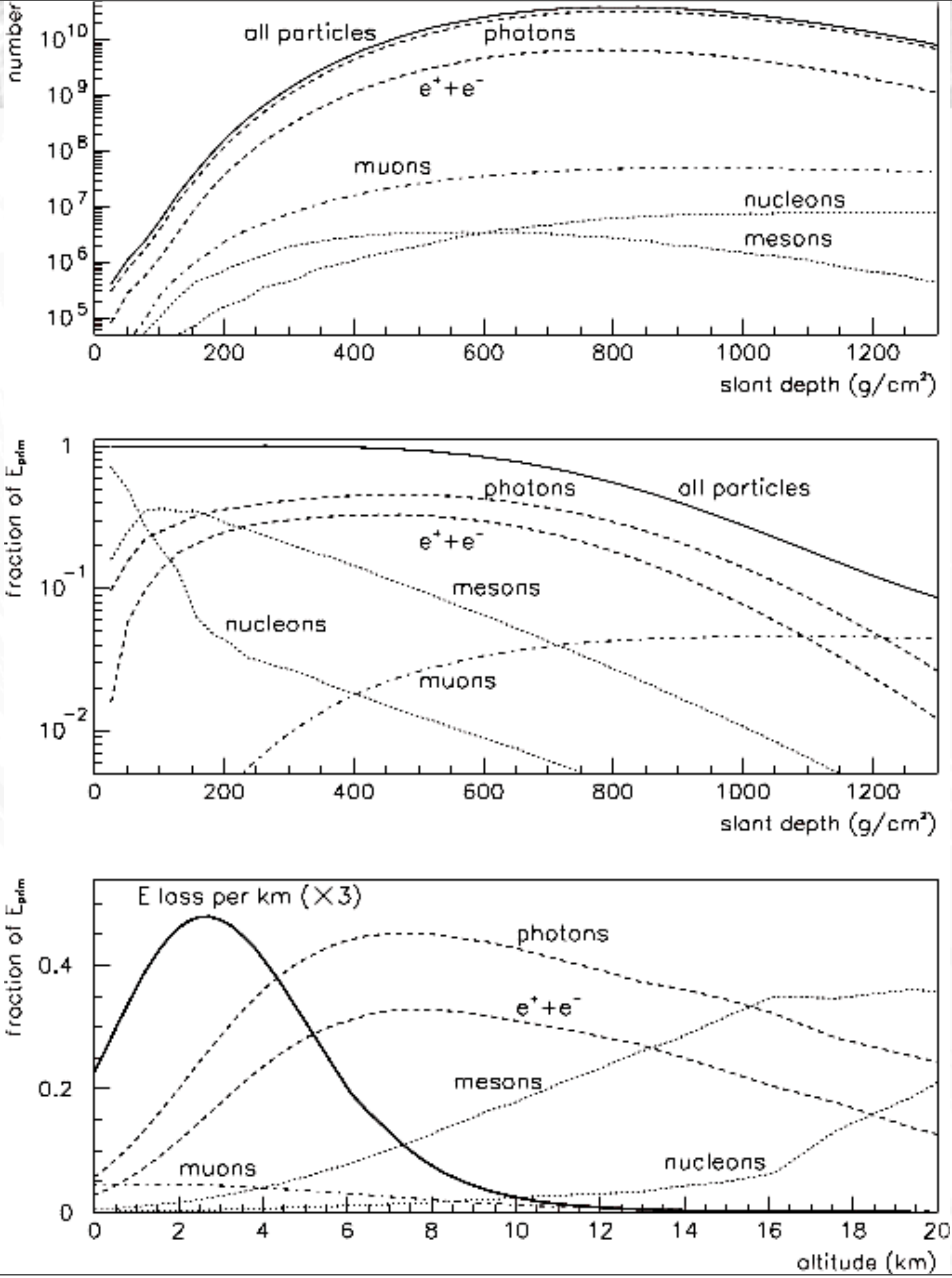
Fly's Eye technique measures fluorescence emission
The shower maximum is given by

$$X_{max} \sim X_0 + X_1 \log E_p$$

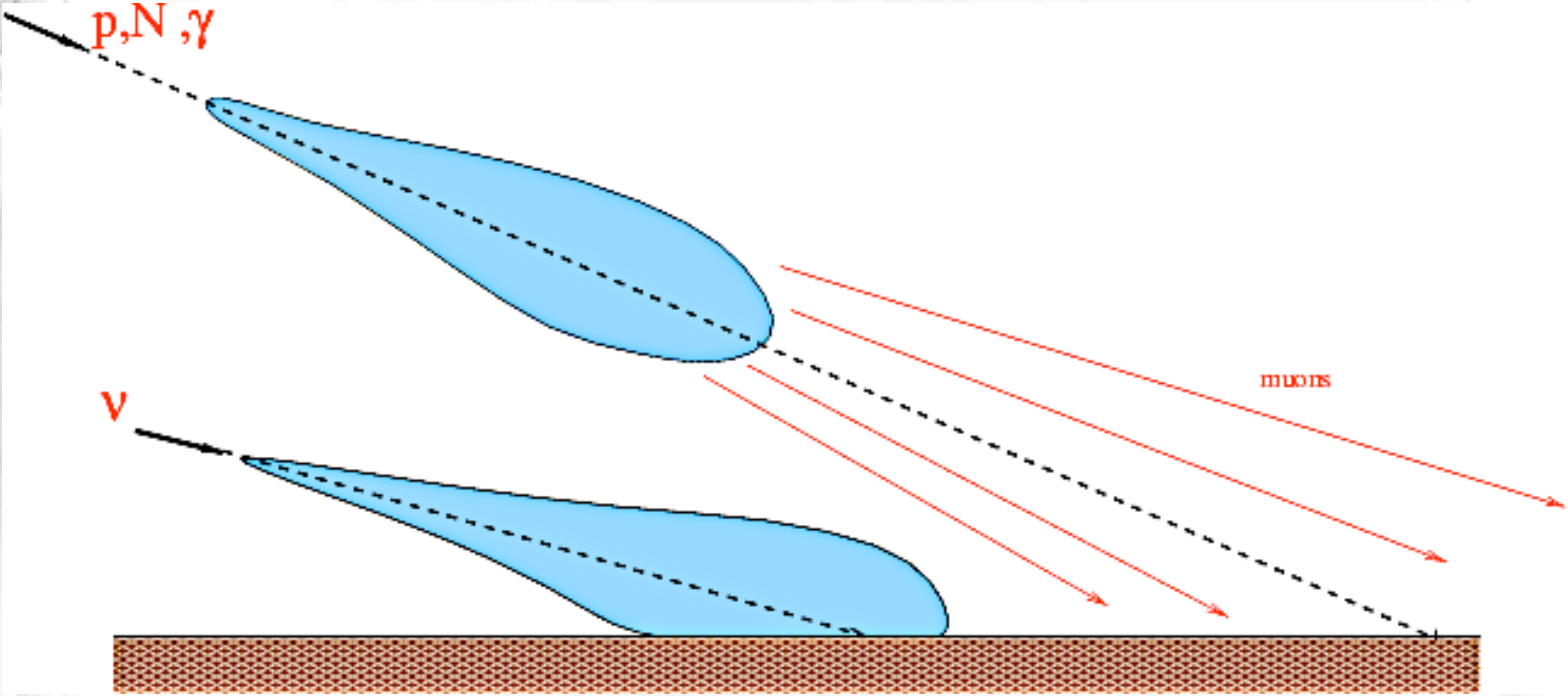
where X_0 depends on primary type for given energy E_p

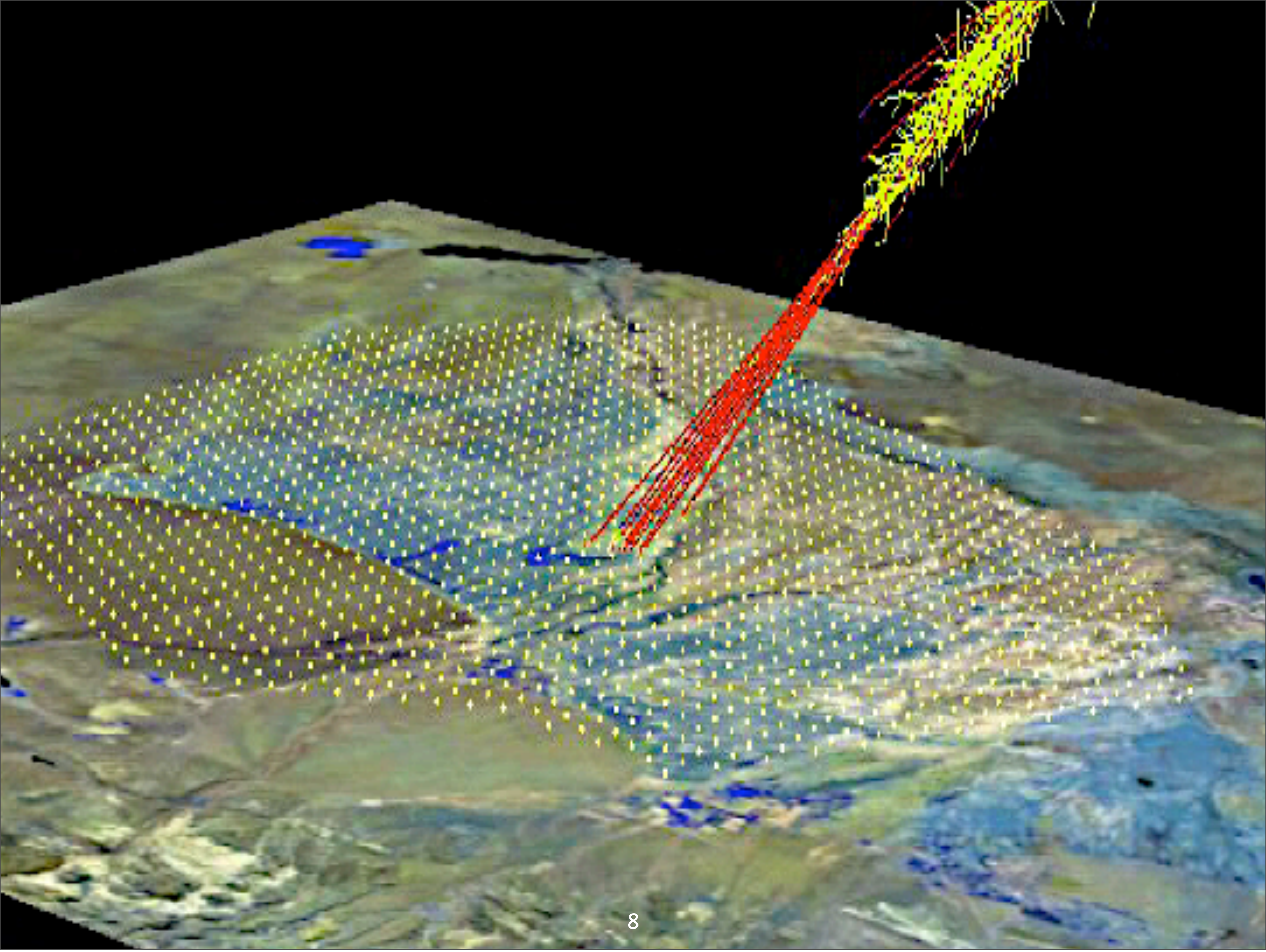
Ground array measures lateral distribution
Primary energy proportional to density 600m from shower core

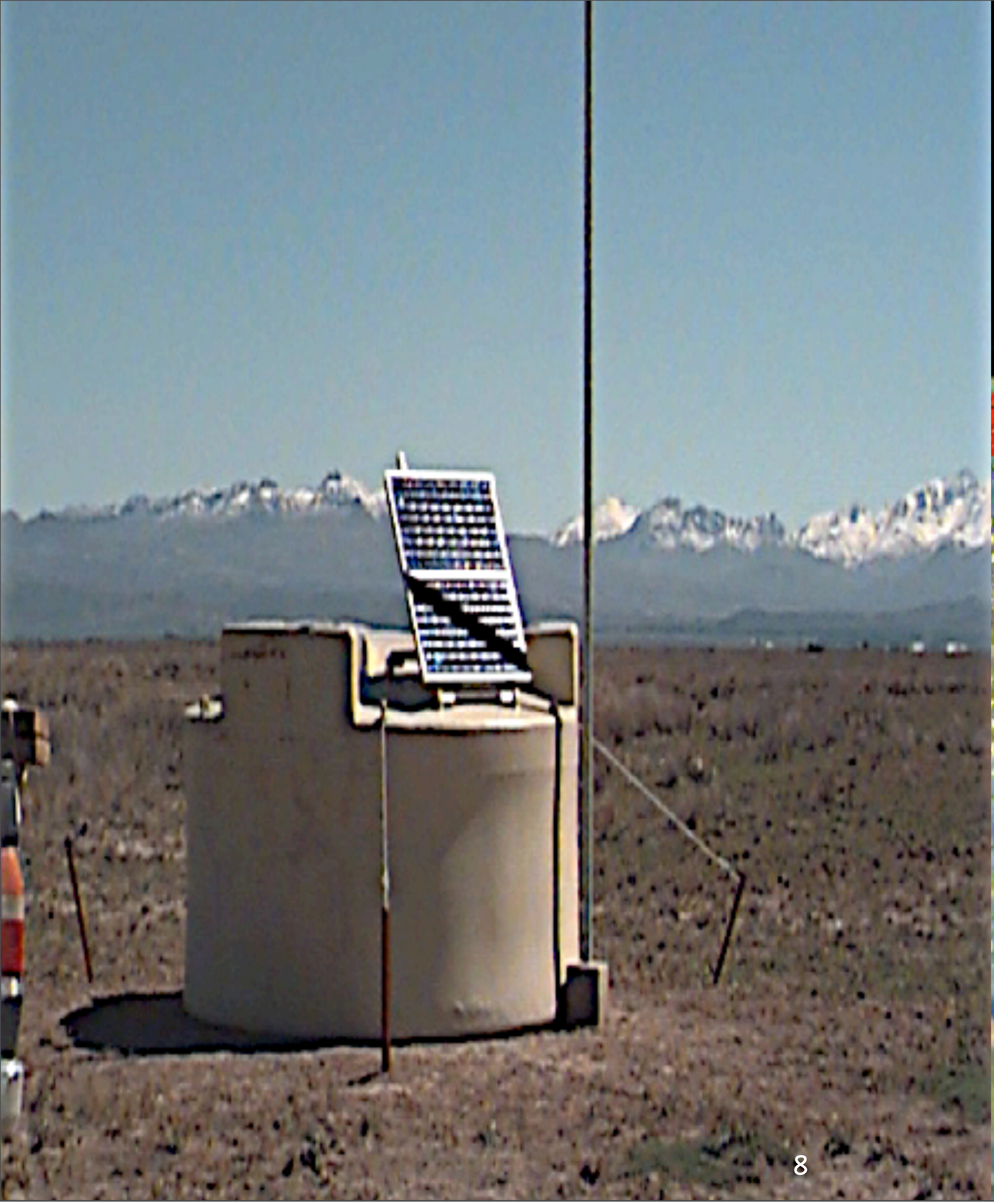

hadronic cascade
N
nuclei , nucleo
hadronic interactions
π,K
π ,K
π^0
mesons
almost negligible
at ground
decay
decay
μ
long tail
muons
decay, radiation
γ
γ
e
e
γ
e
e.m. tail
photons
electrons
positrons
electromagnetic cascade

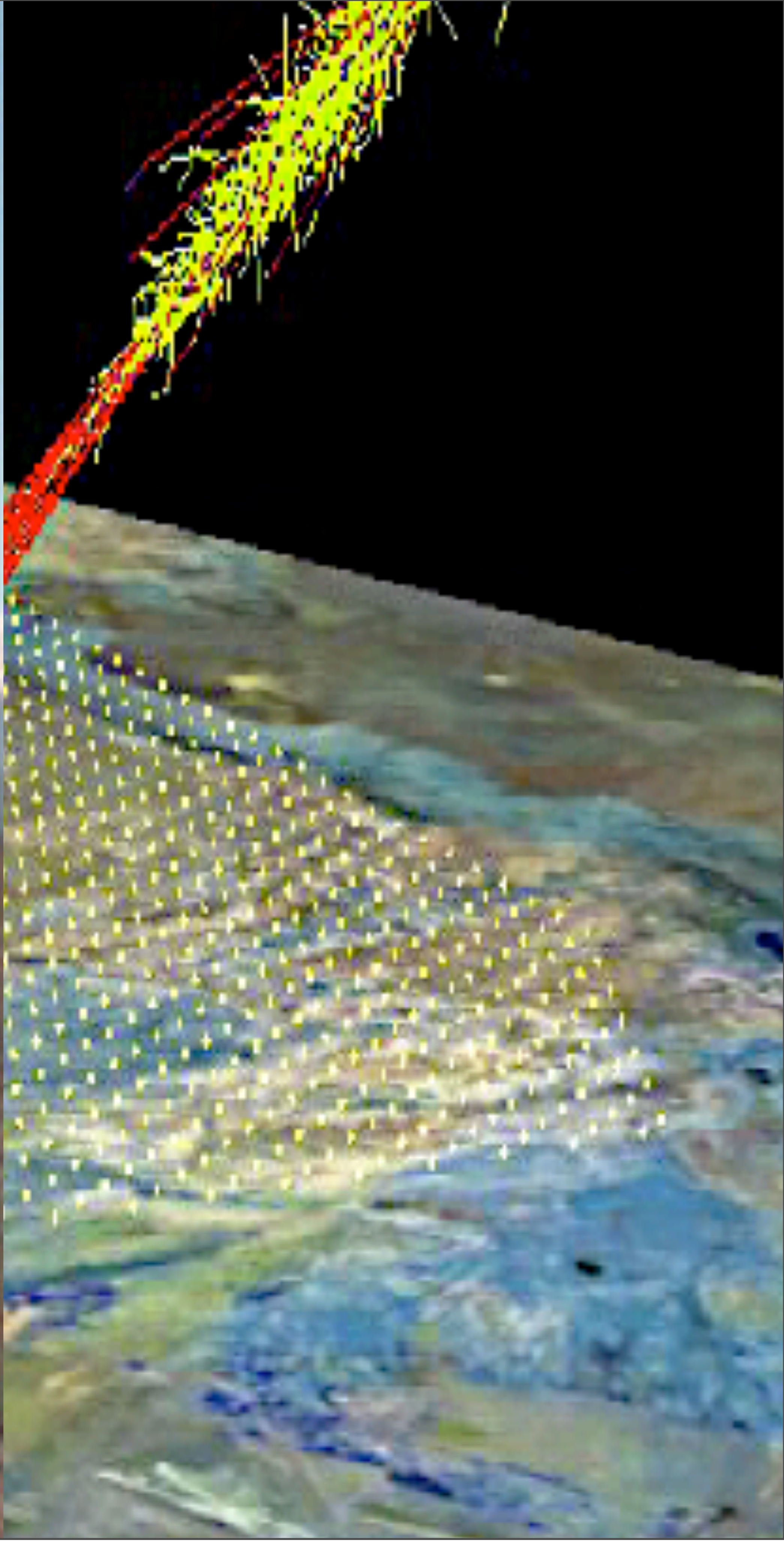

number
all particles
photons
$e^+ + e^-$
muons
nucleons
mesons
10^5
10^6
10^7
10^8
10^9
10^{10}
0
200
400
600
800
1000
1200
slant depth (g/cm²)
fraction of E_{prim}
1
10^{-1}
10^{-2}
photons
all particles
$e^+ + e^-$
mesons
nucleons
muons
0
200
400
600
800
1000
1200
slant depth (g/cm²)
fraction of E_{prim}
E loss per km (×3)
photons
$e^+ + e^-$
mesons
muons
nucleons
0
0.2
0.4
0
2
4
6
8
10
12
14
16
18
20
altitude (km)

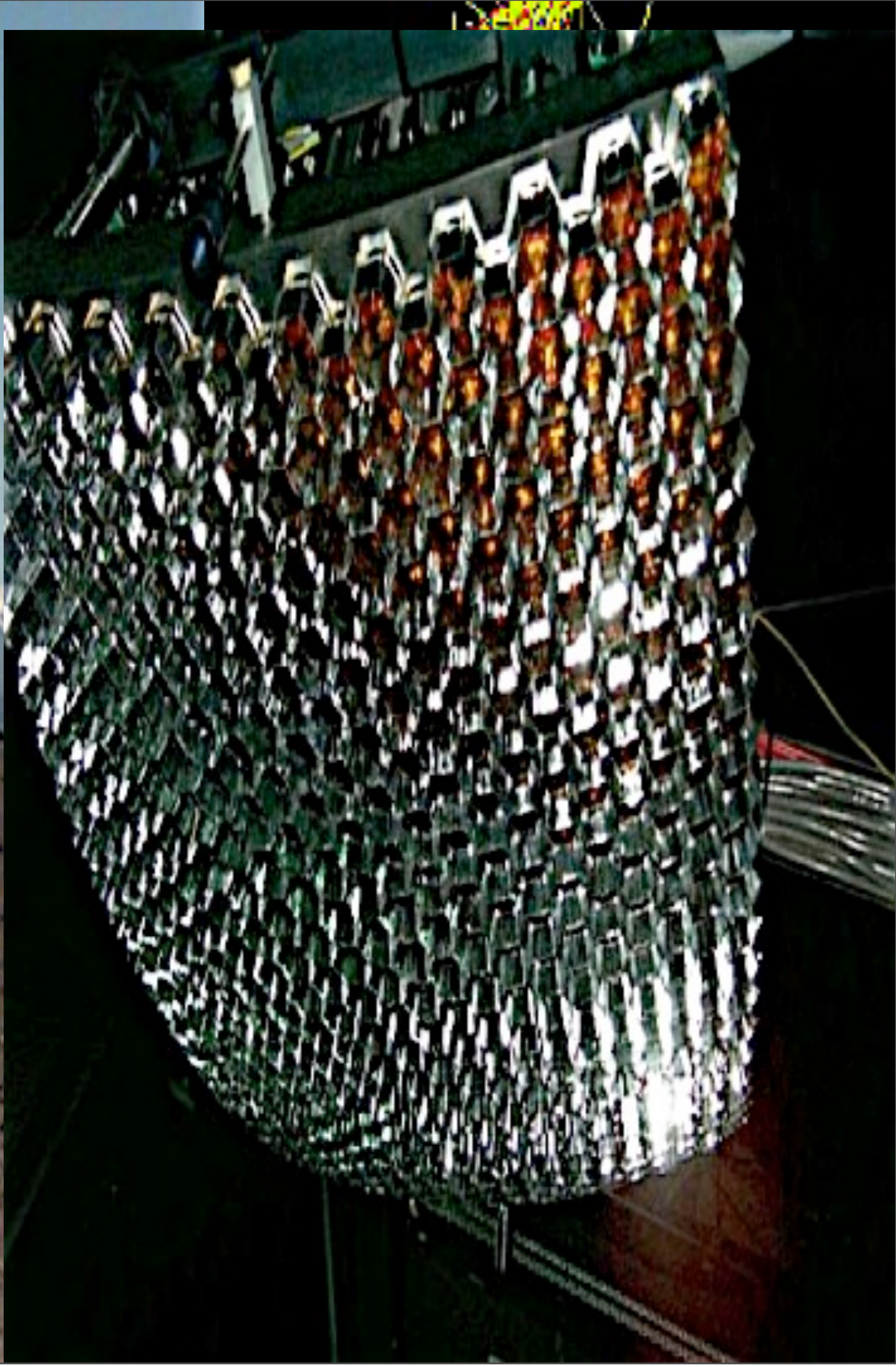
Cosmic ray versus neutrino induced air showers









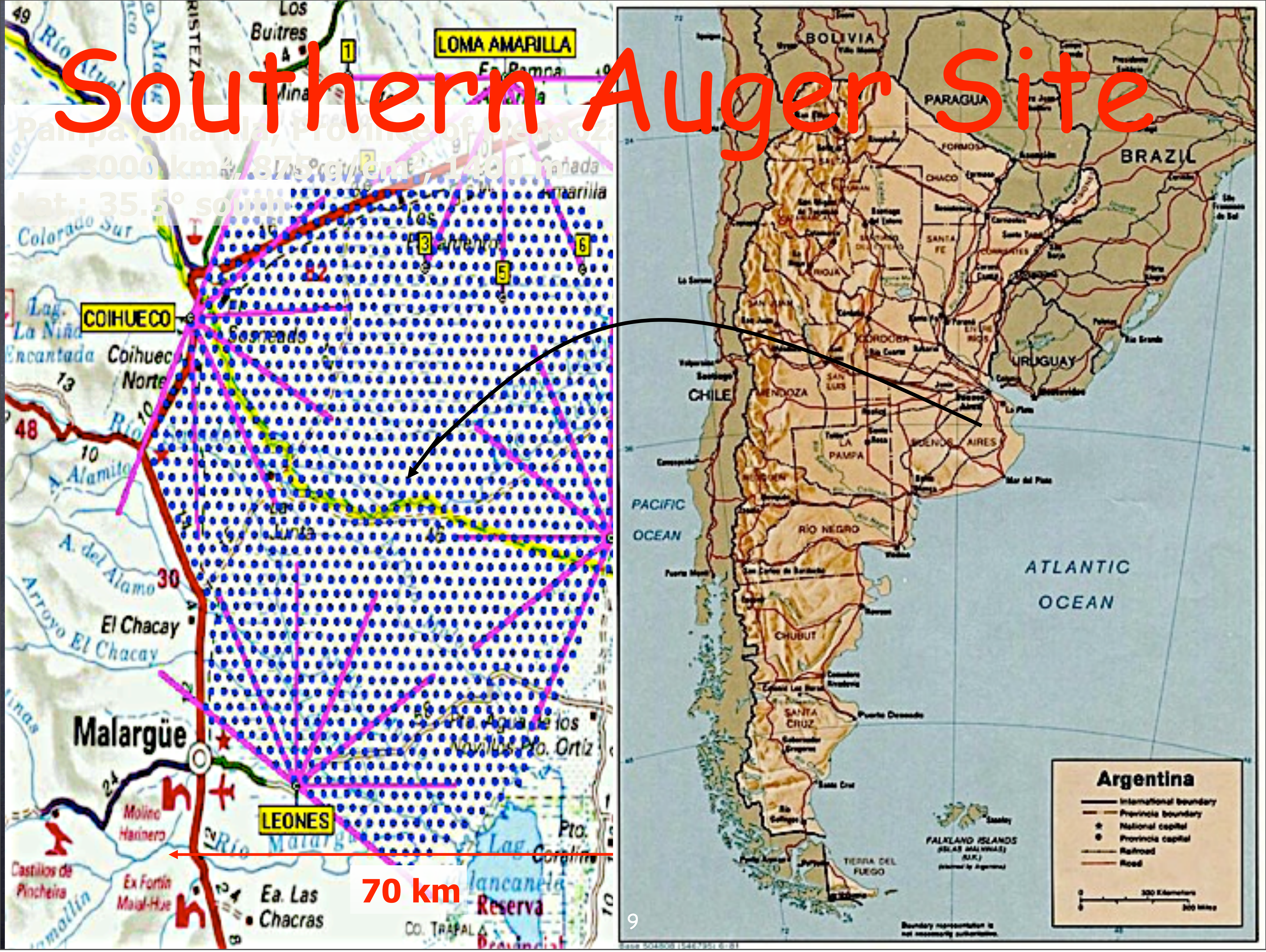


Southern Auger Site

Pampa Amarilla, Province of Mendoza

3000 km², 875 g/cm², 1400 m

Lat.: 35.5° south



70 km

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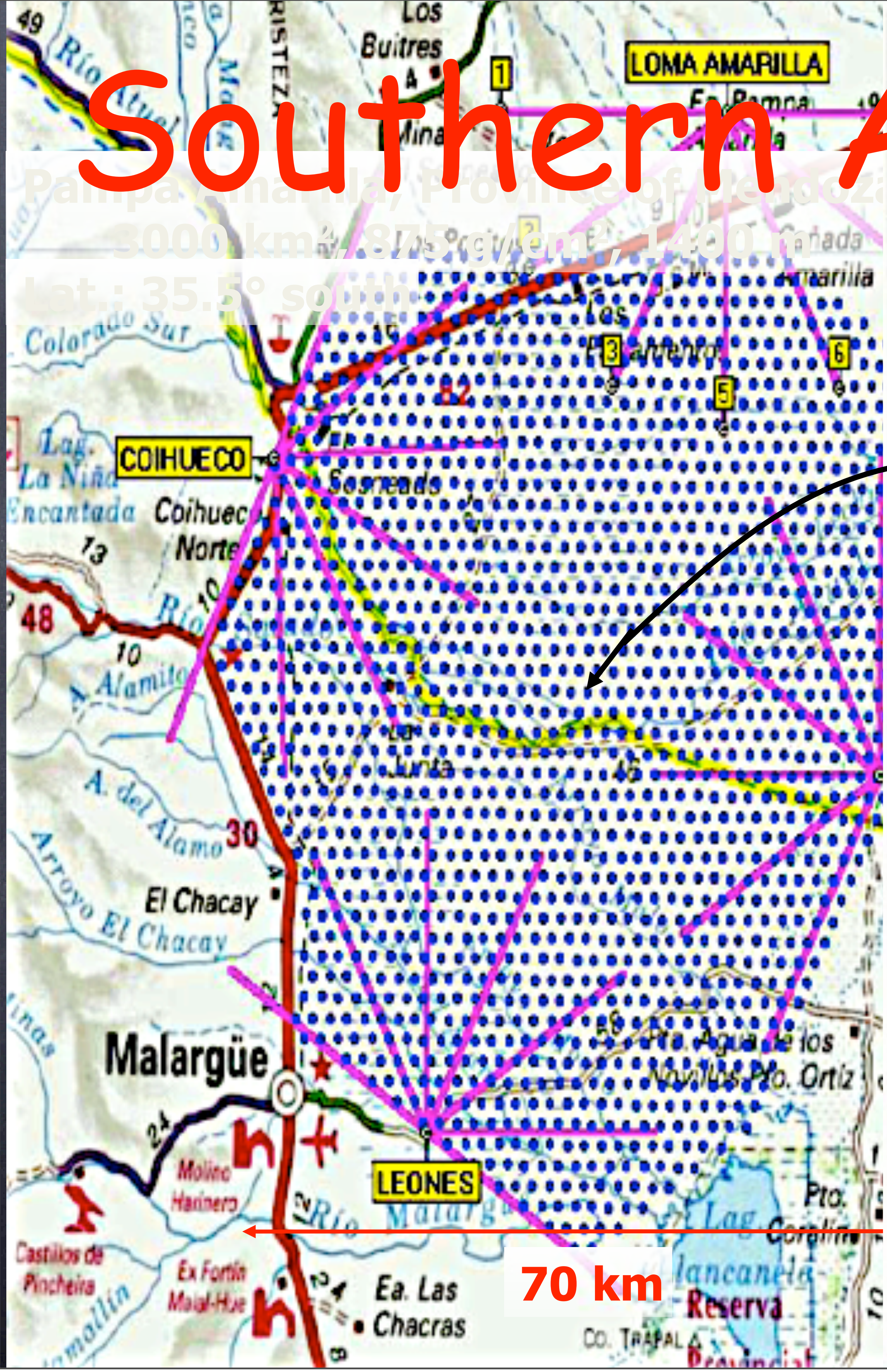

Surface Array (SD):
1600 Water Tanks
1.5 km spacing
3000 km²

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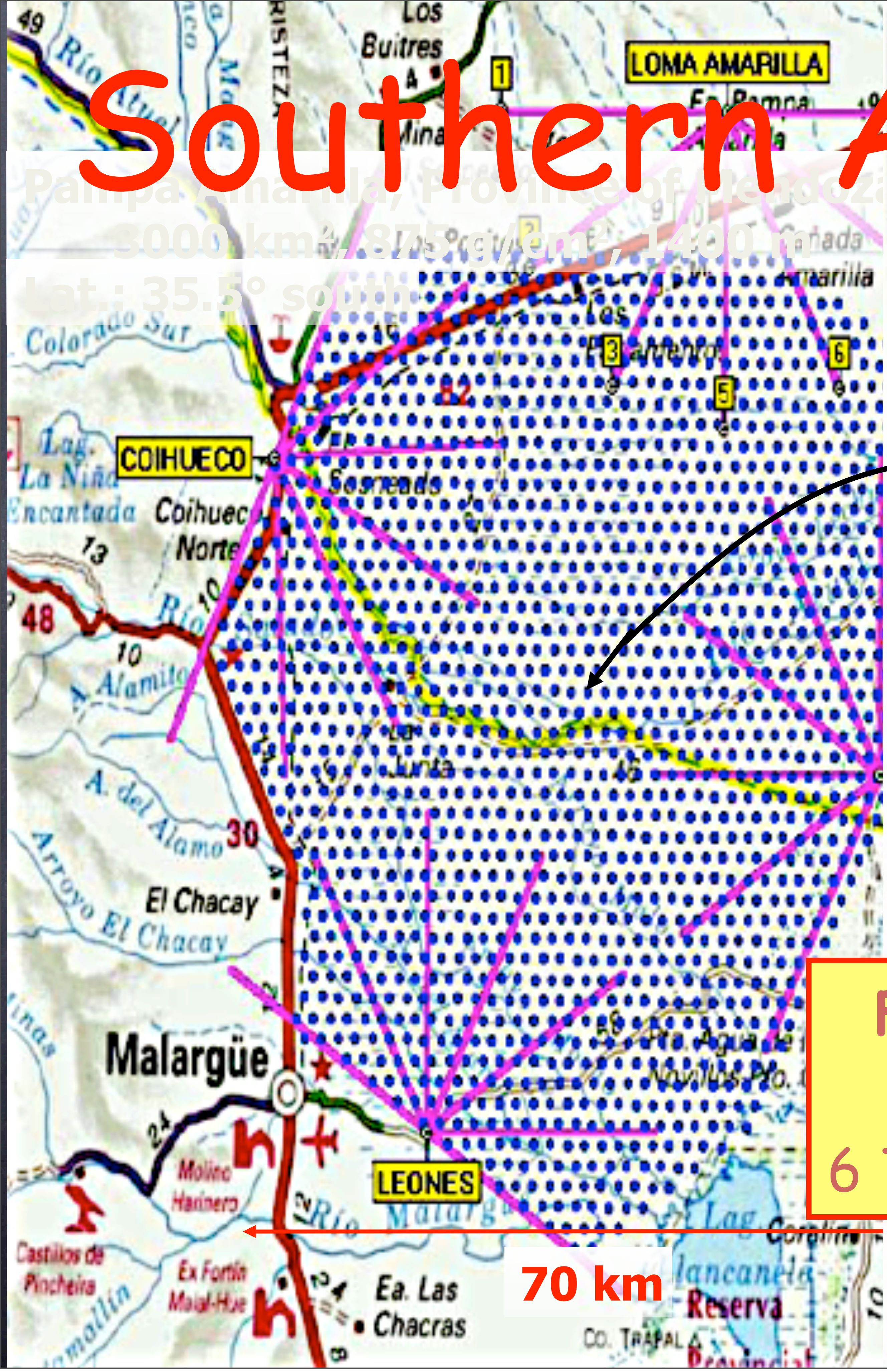

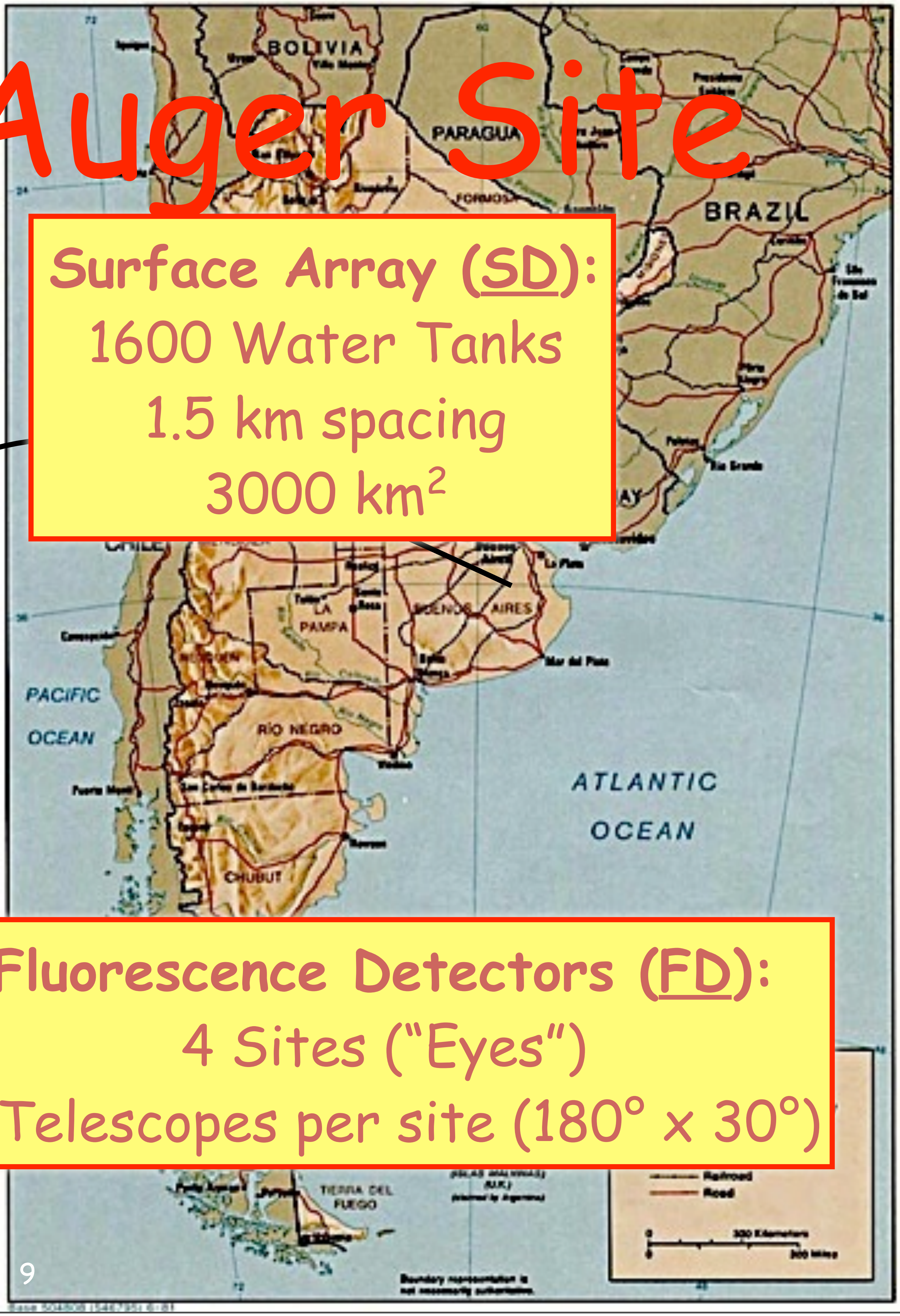

Surface Array (SD):
1600 Water Tanks
1.5 km spacing
3000 km^2

Fluorescence Detectors (FD):
4 Sites ("Eyes")
6 Telescopes per site (180° x 30°)

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3.) The observed distribution does not yet reveal unambiguously the sources, although there is some correlation with local large scale structure

4.) The observed mass composition may become heavy toward highest energies, but no consistent picture yet between experiments and air shower models

The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background

$$E_{\rm th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \simeq 4\times 10^{19}\,{\rm eV}$$

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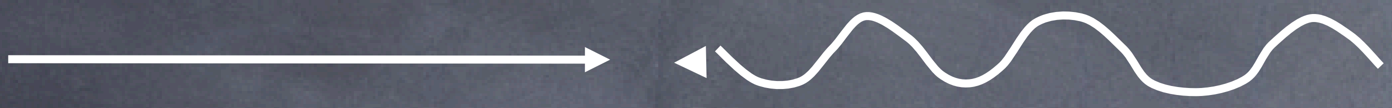

nucleon

γ

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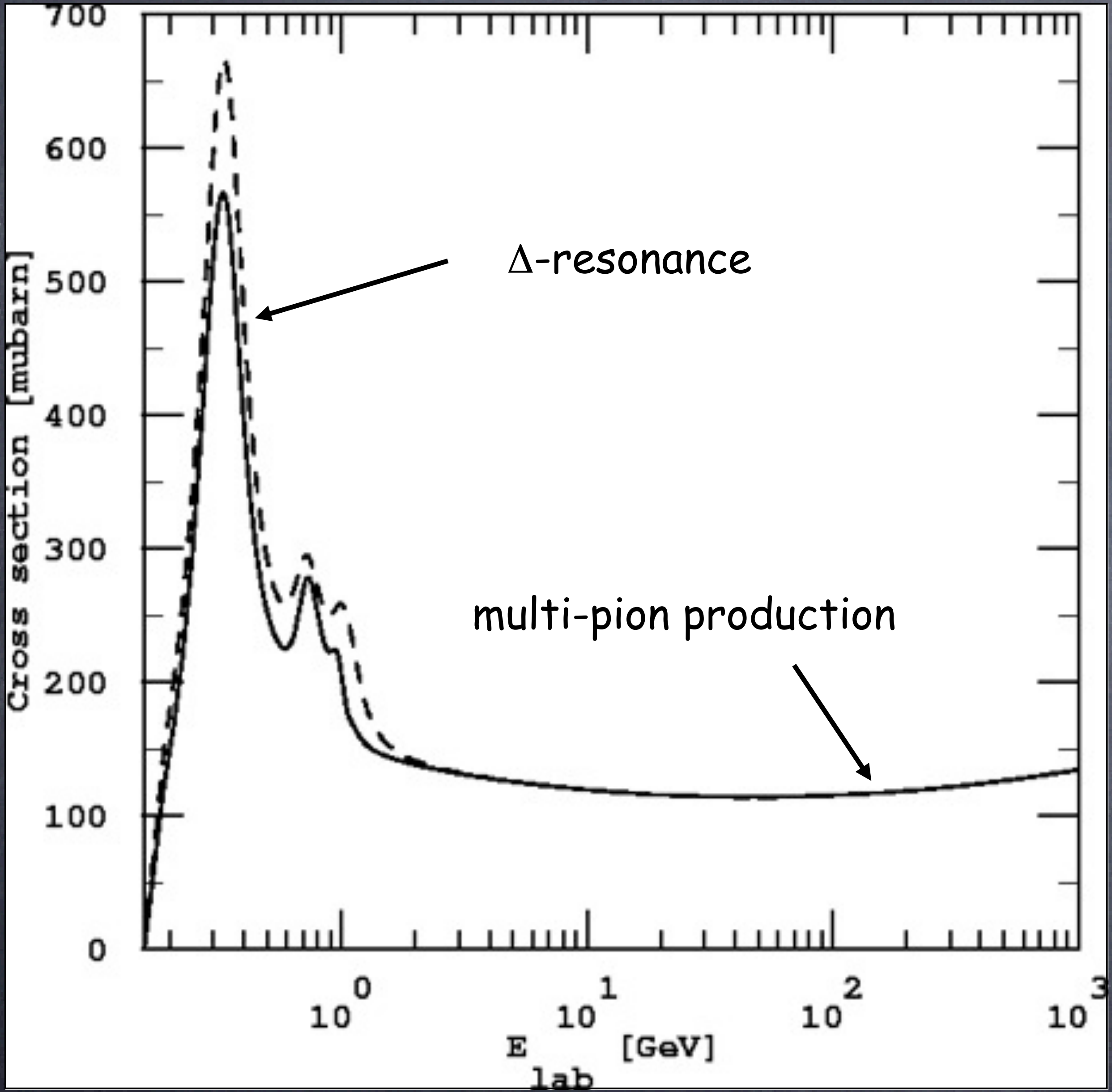

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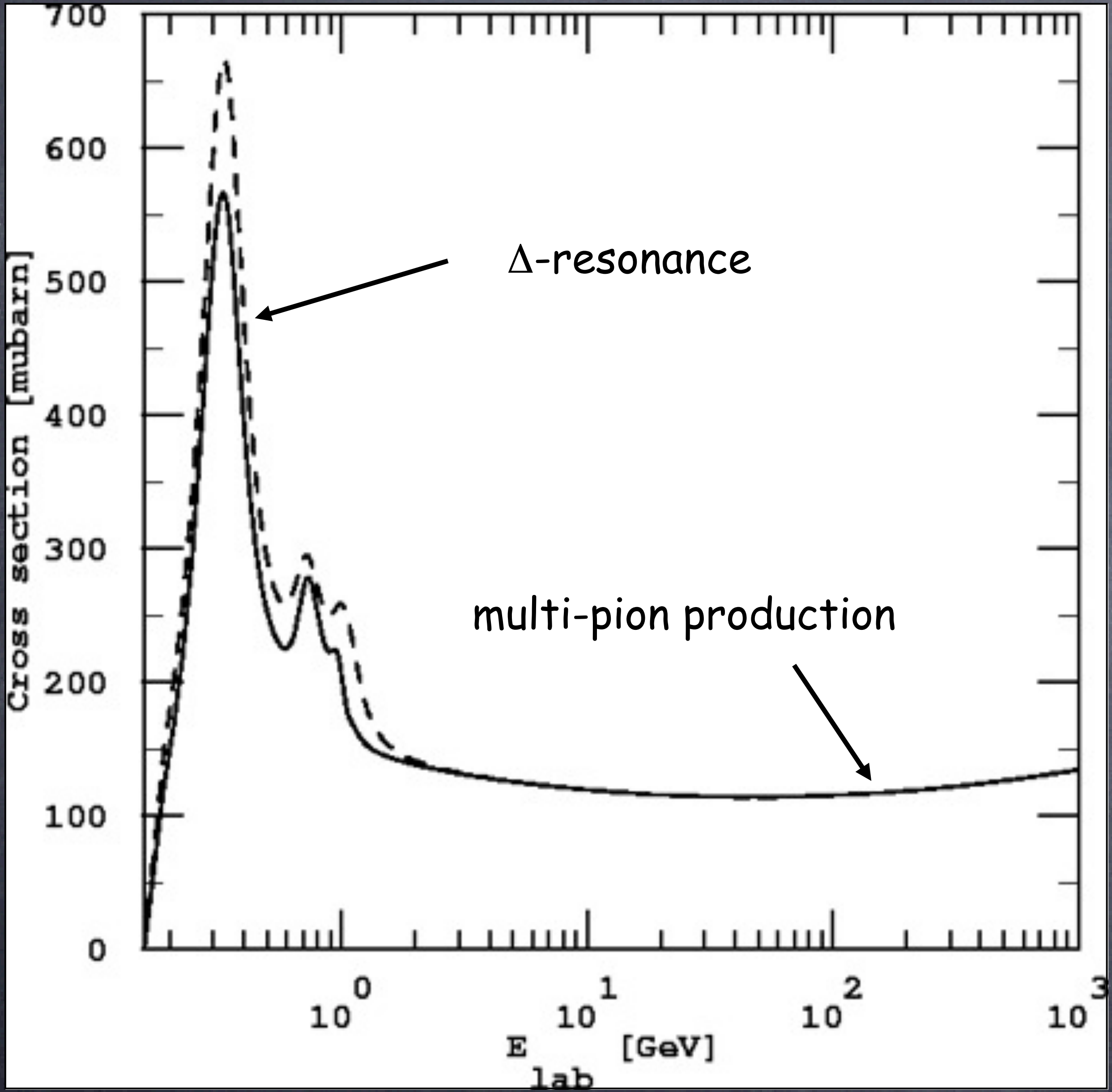
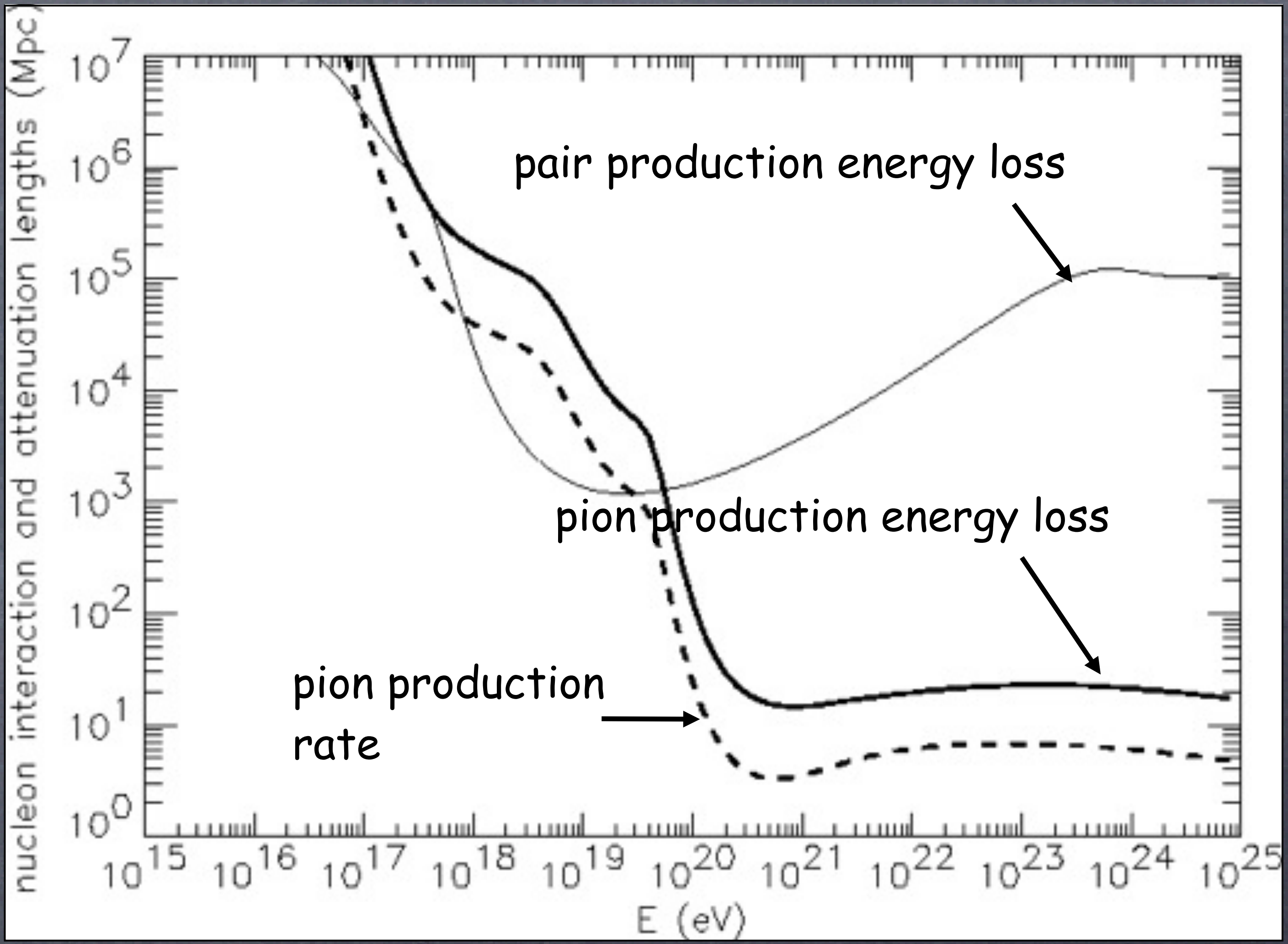


Δ-resonance

multi-pion production



pair production energy loss

pion production energy loss

pion production rate

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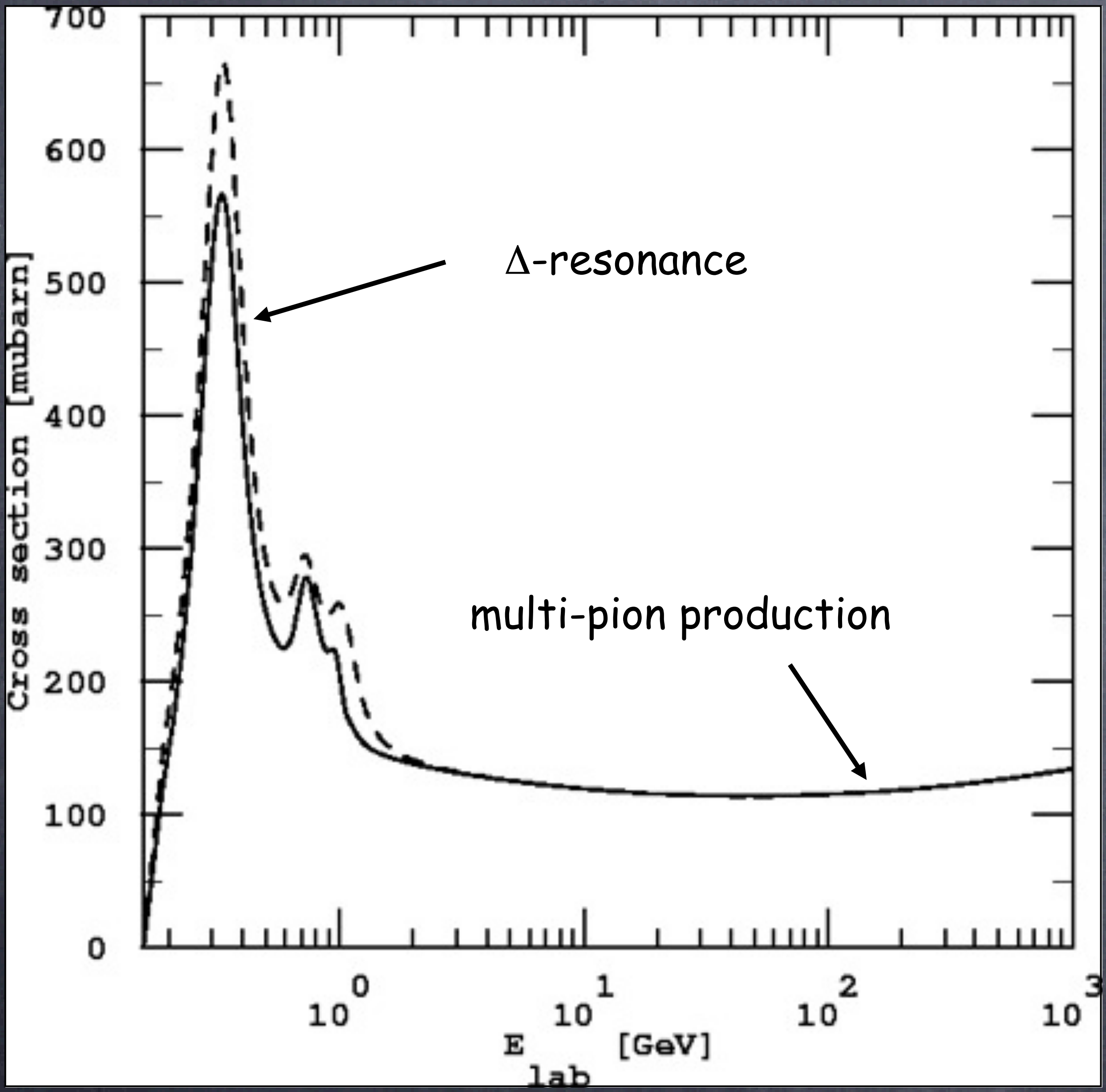
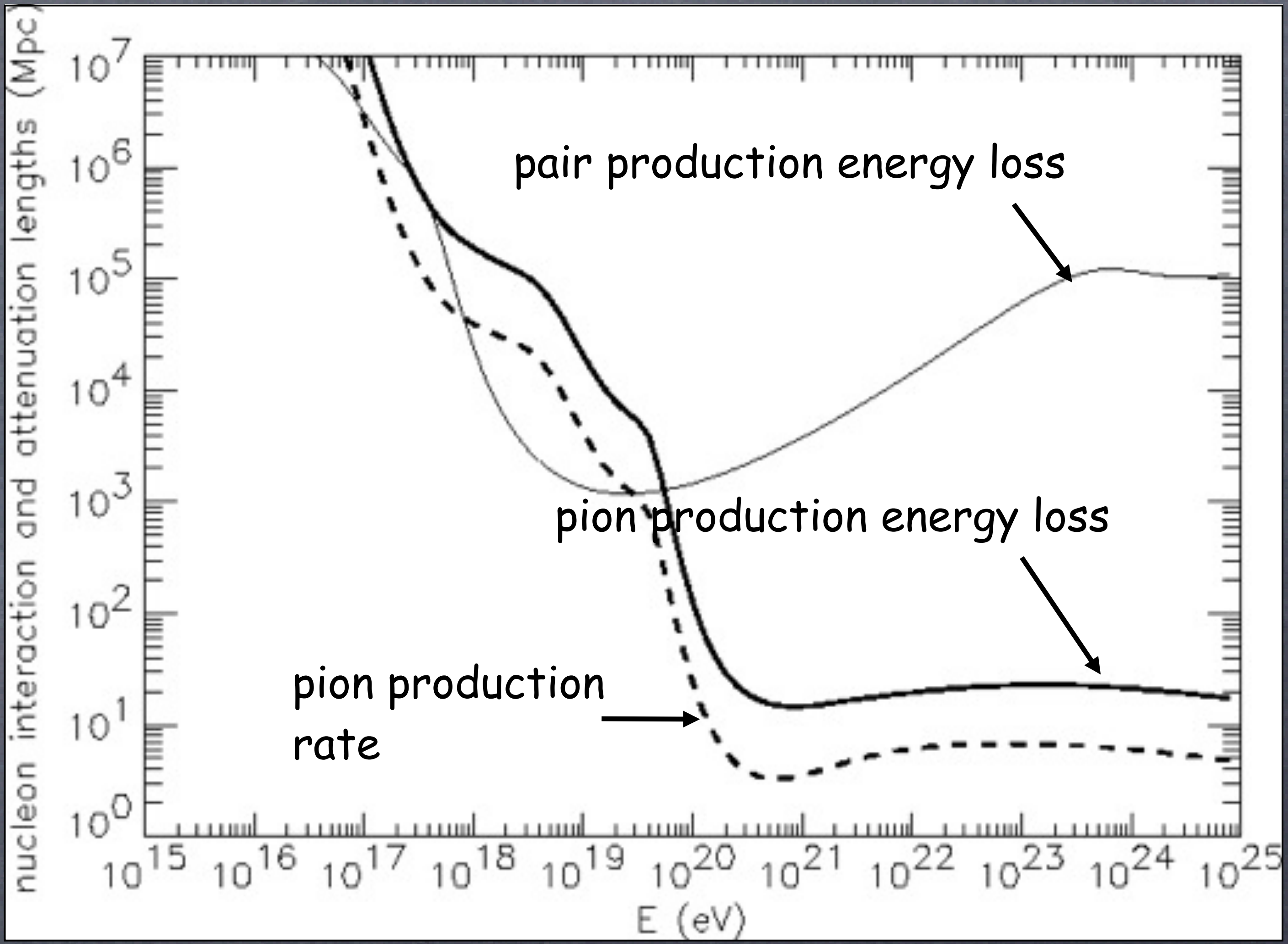
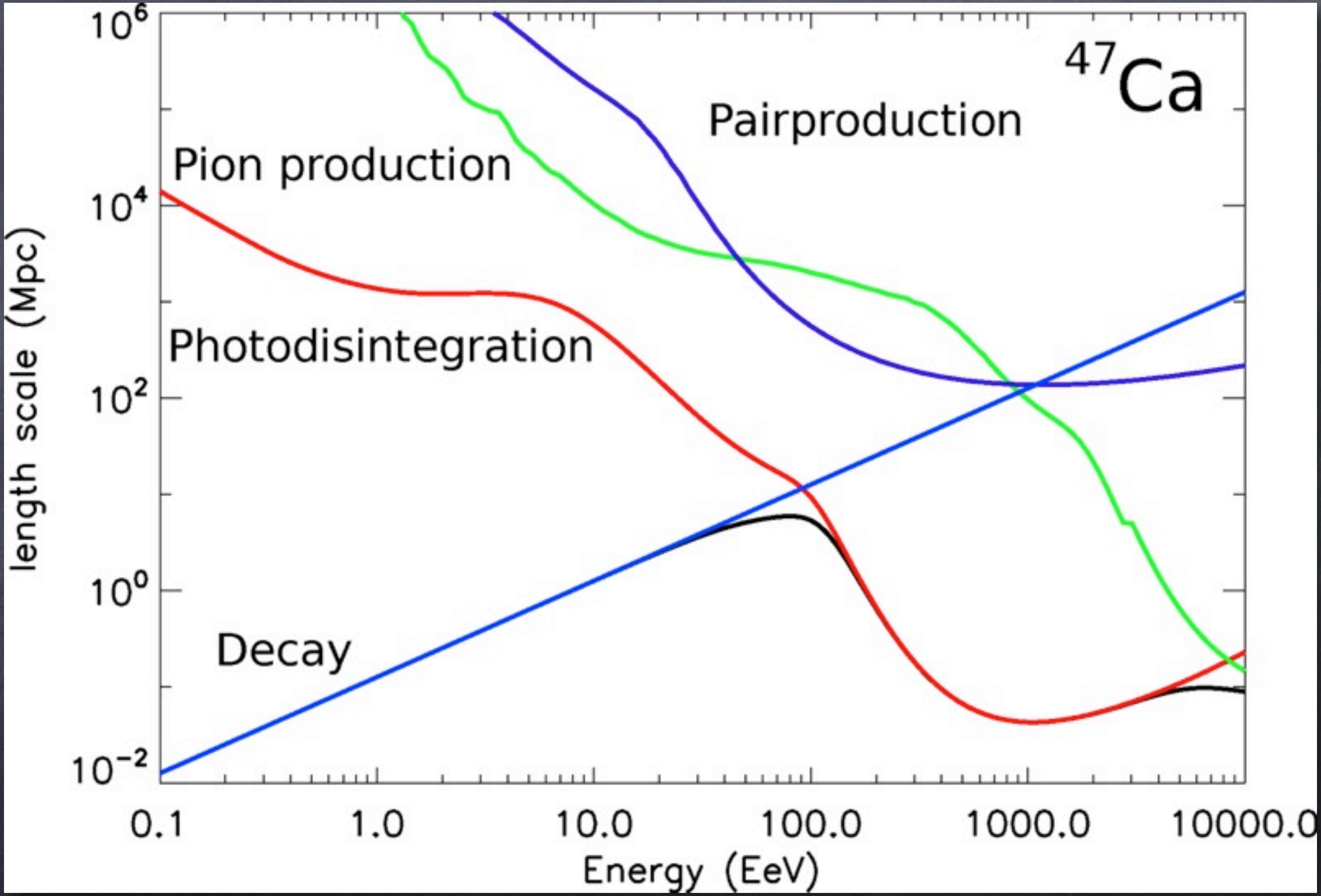


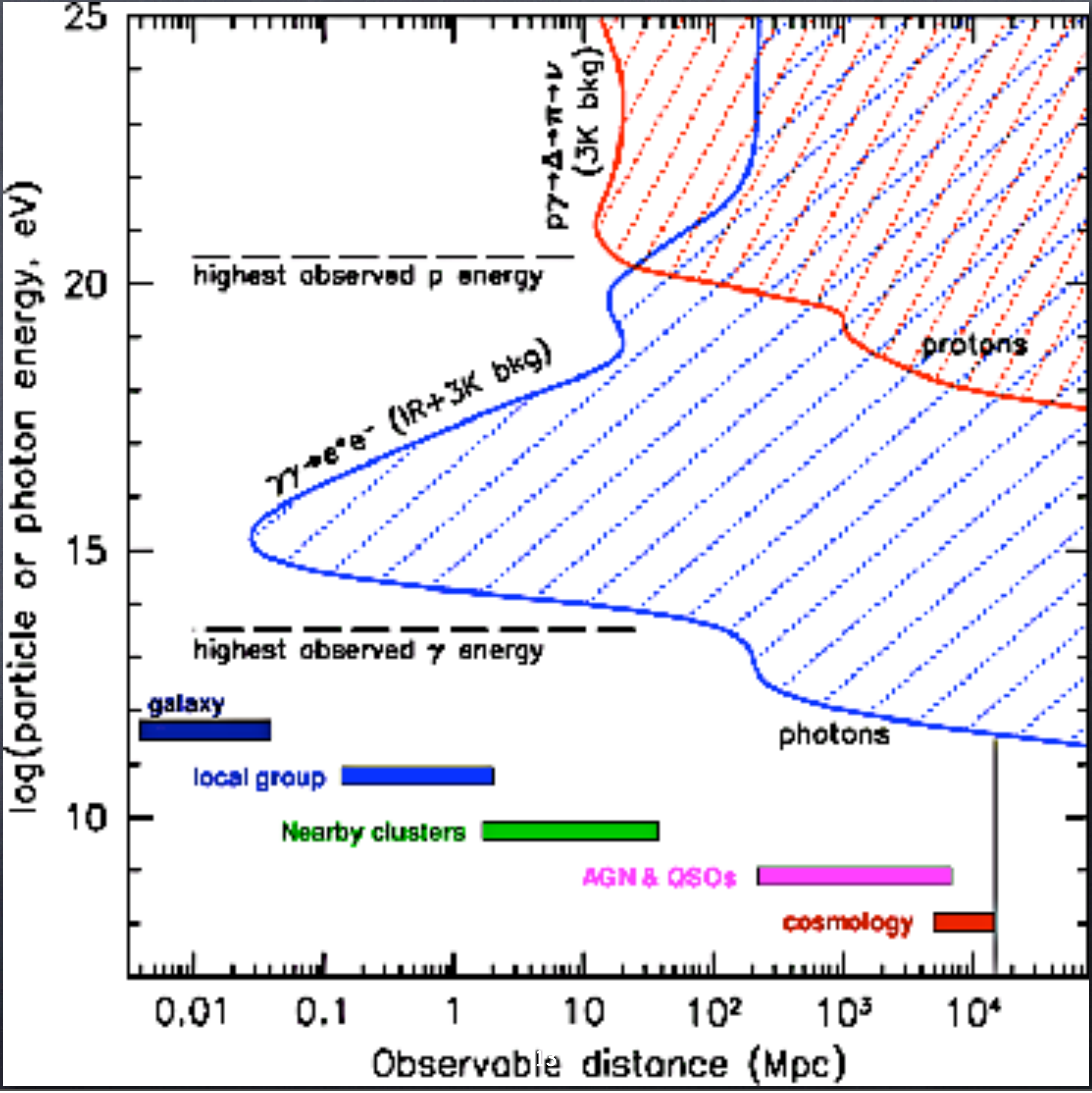


sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma > 10^{11}$ could avoid this conclusion.

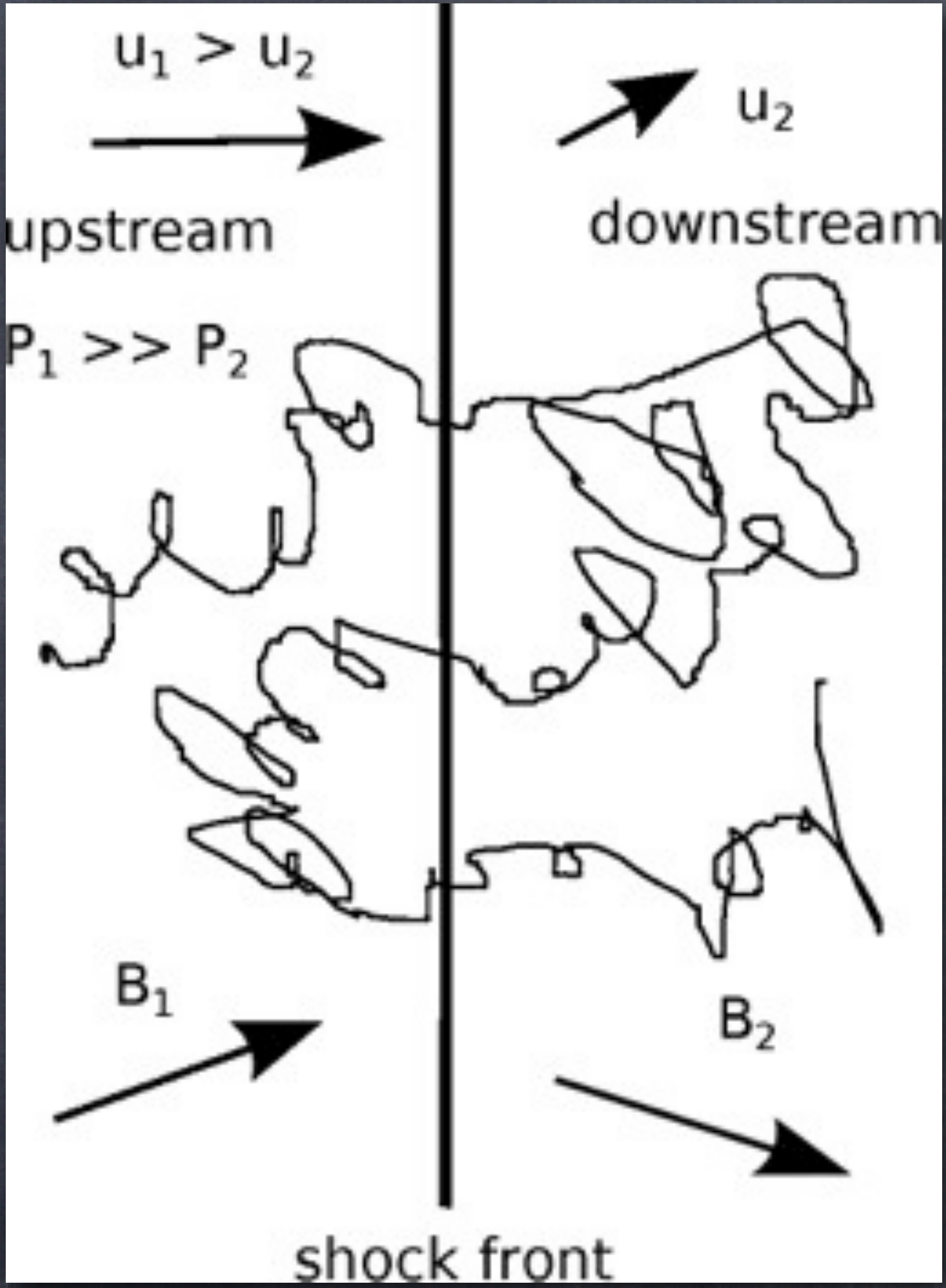
Length scales for relevant processes of a typical heavy nucleus

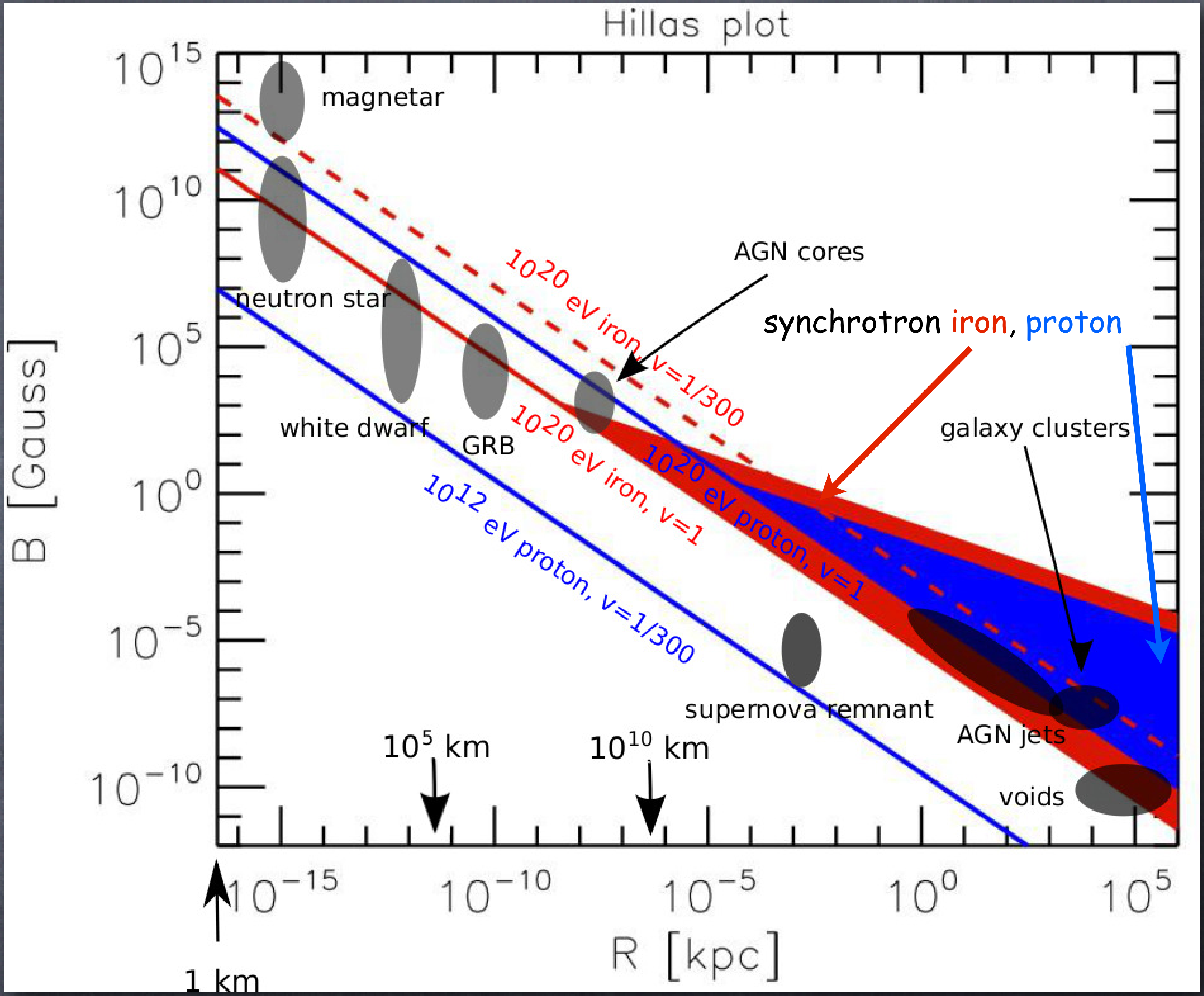


Interaction Horizons



1st Order Fermi Shock Acceleration





Fractional energy gain per shock crossing ~ $u_1 - u_2$ on a time scale r_L/u_2 .

Together with downstream losses this leads to a spectrum E^{-q} with $q > 2$ typically.

Confinement, gyroradius < shock size, and energy loss times define maximal energy

Some general Requirements for Sources

Accelerating particles of charge eZ to energy E_{max} requires induction $\varepsilon > E_{max}/eZ$. With $Z_0 \sim 100\Omega$ the vacuum impedance, this requires dissipation of minimum power of

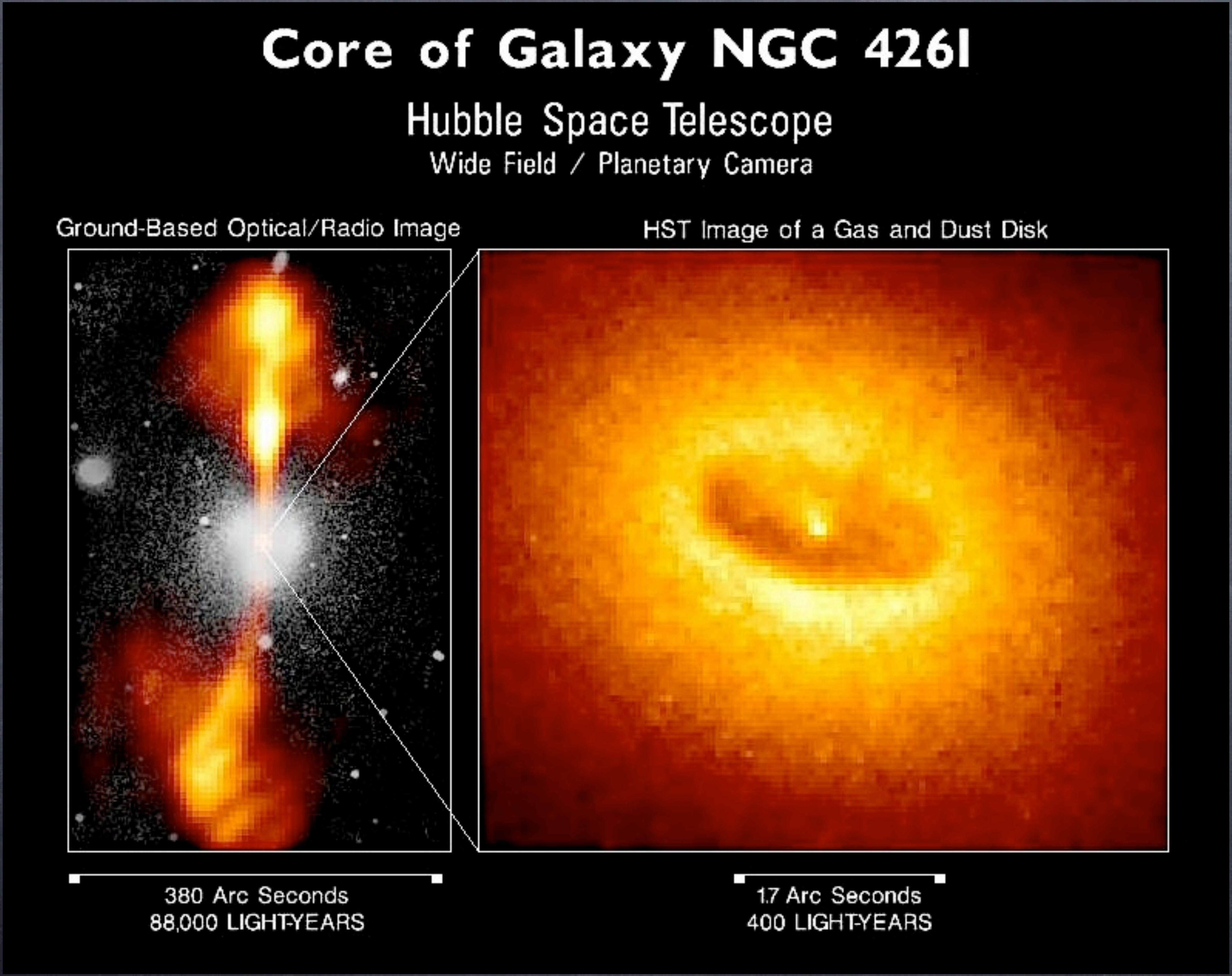
$$L_{\rm min} \sim \frac{\epsilon^2}{Z_0} \simeq 10^{45}\, Z^{-2} \left(\frac{E_{\rm max}}{10^{20}\,{\rm eV}}\right)^2 \;{\rm erg\,s}^{-1}$$

This „Poynting" luminosity can also be obtained from $L_{min} \sim (BR)^2$ where BR is given by the „Hillas criterium":

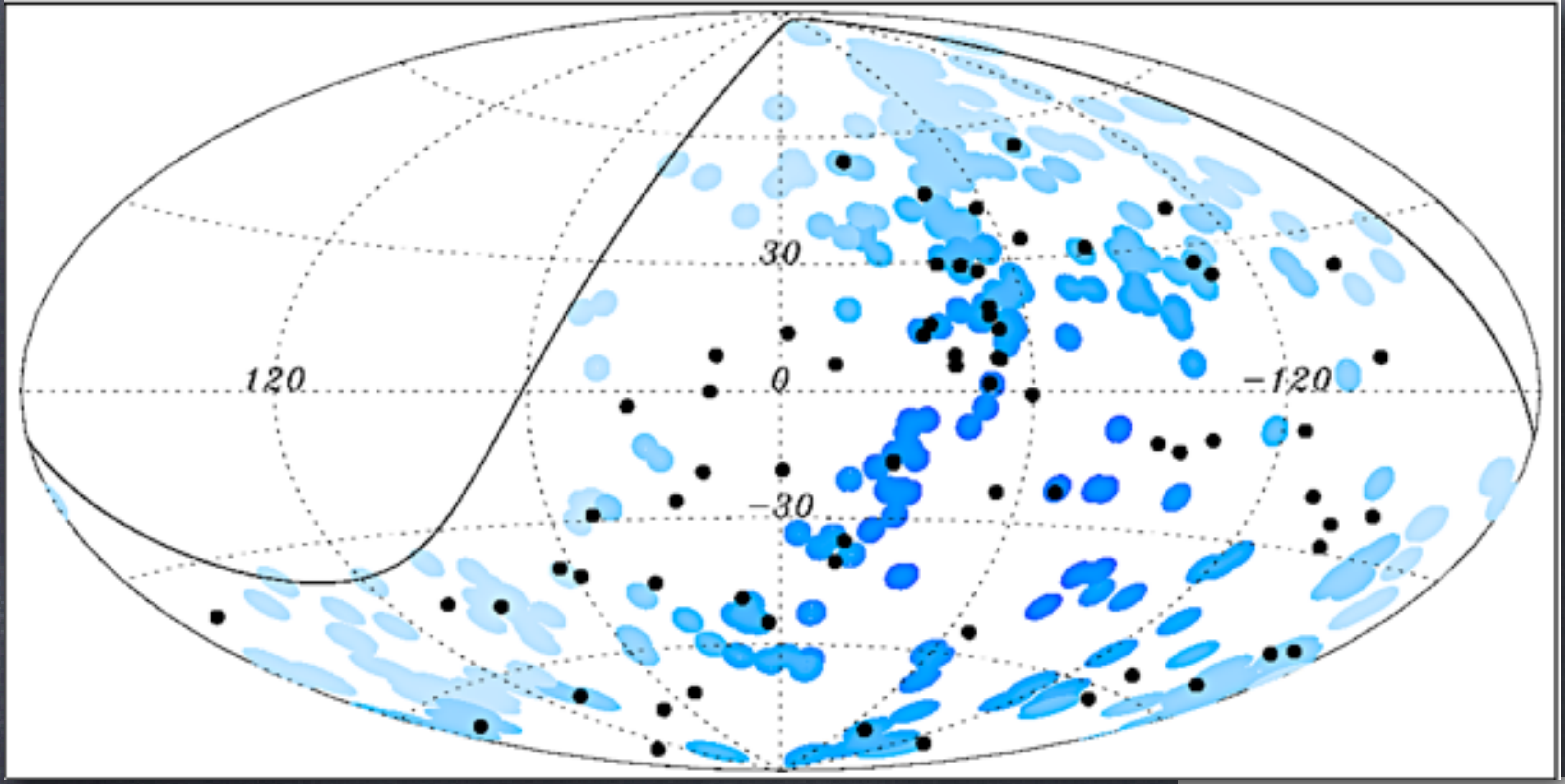
$$BR > 3 \times 10^{17}\,\Gamma^{-1} \left(\frac{E_{\rm max}/Z}{10^{20}\,{\rm eV}}\right) {\rm Gauss\,cm}$$

where Γ is a possible beaming factor.
If most of this goes into electromagnetic channel, only AGNs and maybe gamma-ray bursts could be consistent with this.

A possible acceleration site associated with shocks in hot spots of active galaxies

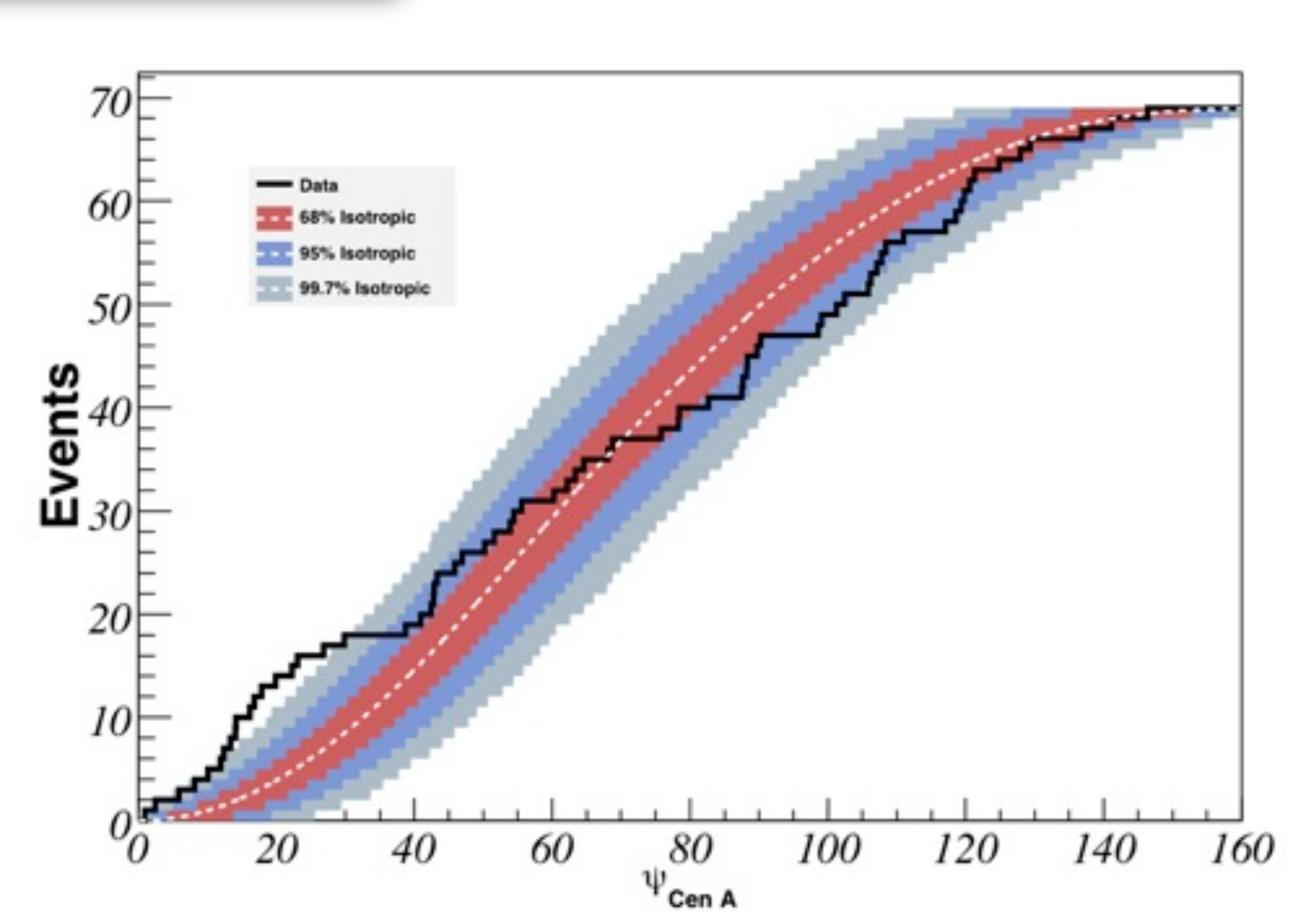


Centaurus A is a UHECR source candidate

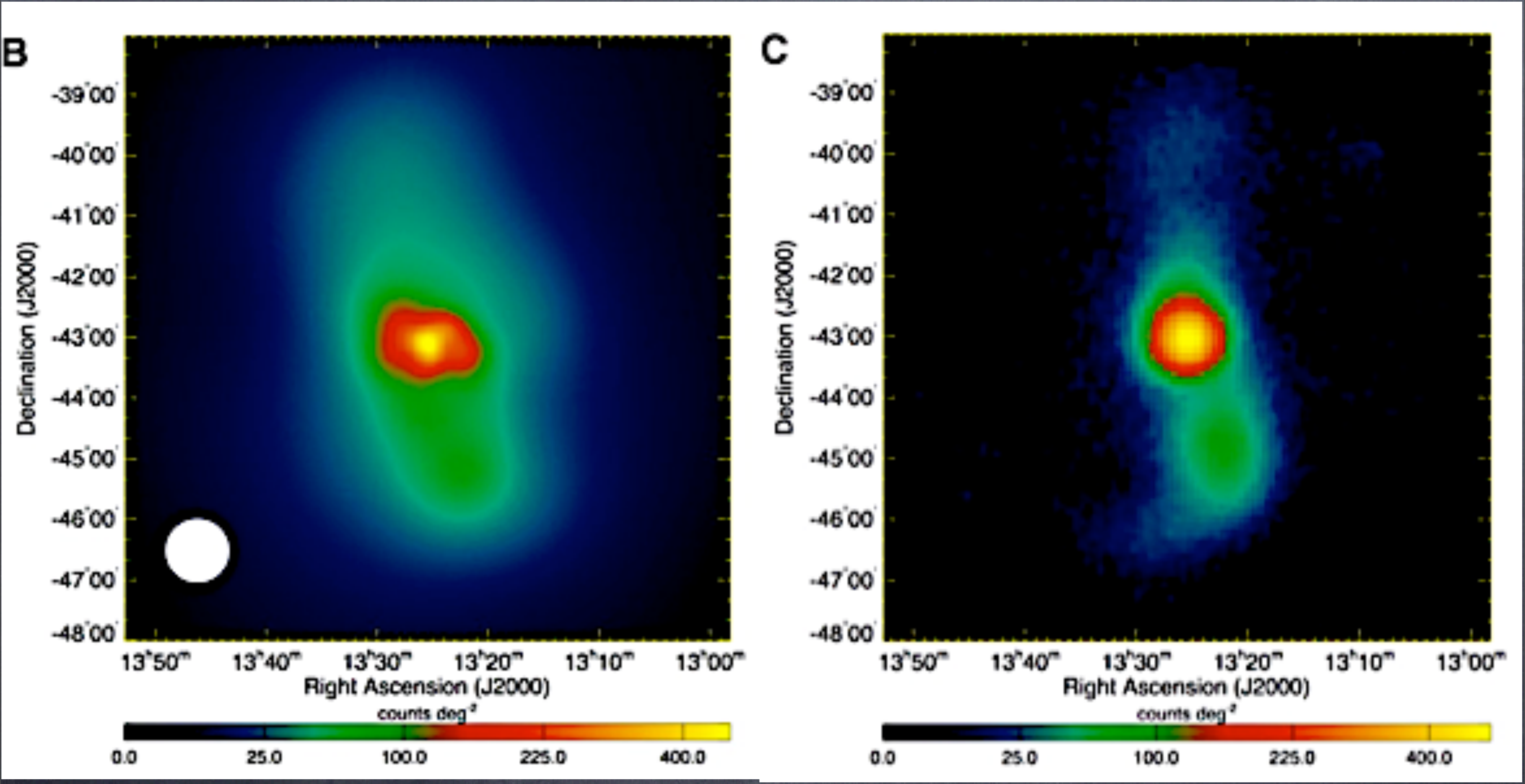


Pierre Auger sees an excess
in the direction of Centaurus A

Pierre Auger Collaboration, Astropart.Phys. 34 (2010) 314



Lobes of Centaurus A seen by Fermi-LAT

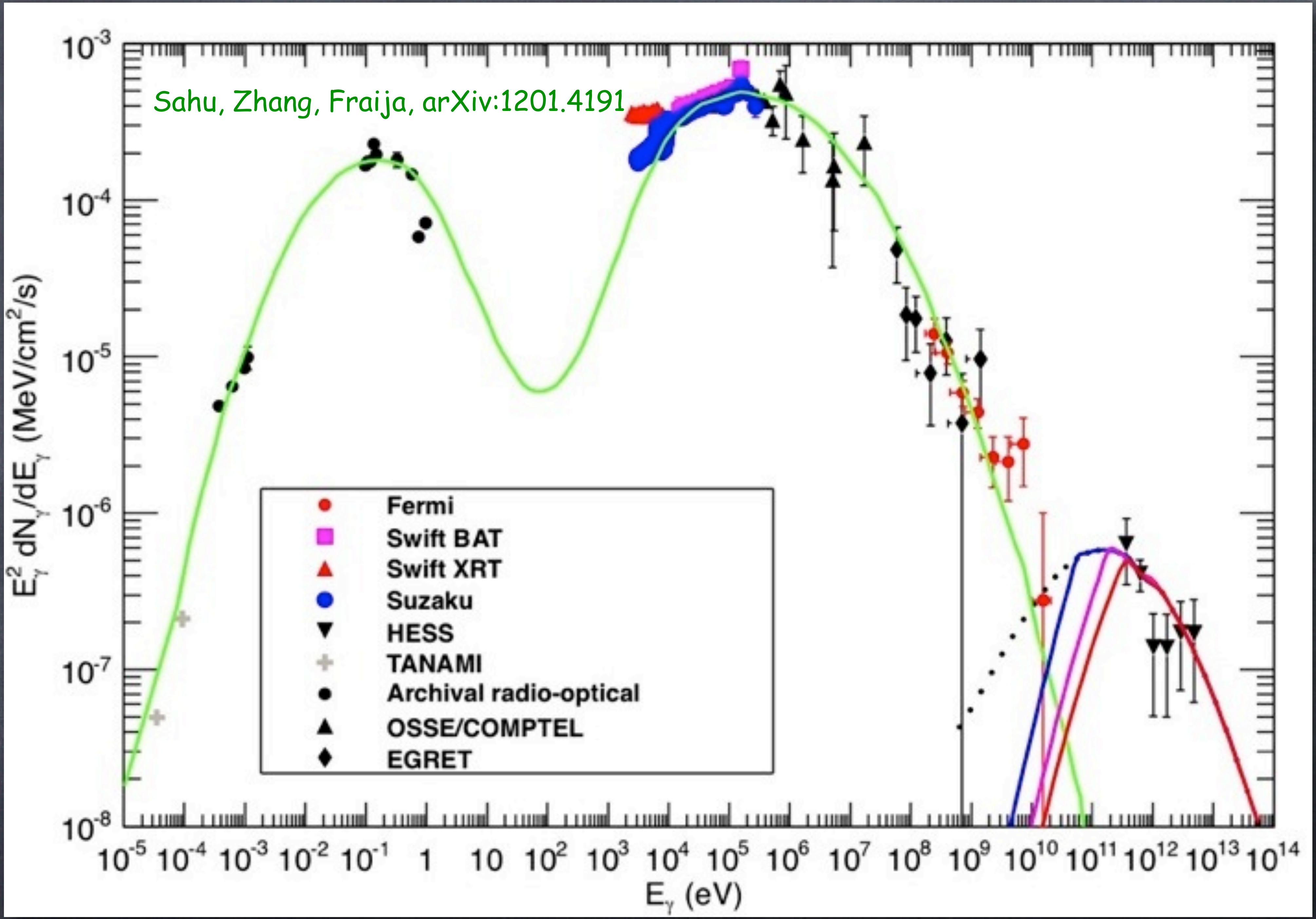


> 200 MeV γ-rays

Radio observations

Abdo et al., Science Express 1184656, April 1, 2010

Centaurus A as Multimessenger Source: A Mixed hadronic+leptonic Model


Sahu, Zhang, Fraija, arXiv:1201.4191

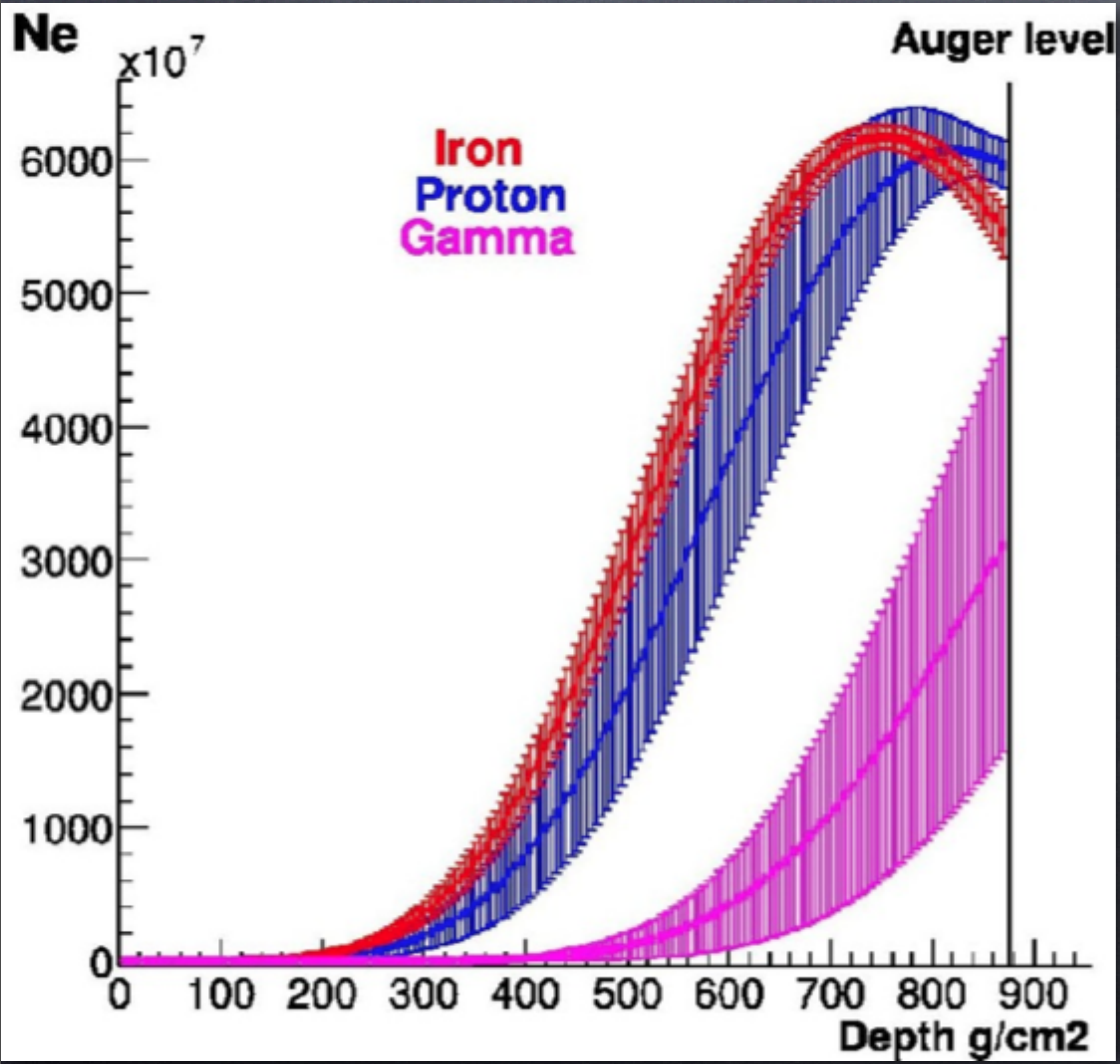
Low energy bump = synchrotron

high energy bump = synchrotron self-Compton

TeV-γ-rays: pγ interactions of shock-accelerated protons

Mass Composition

Depth of shower maximum and its distribution contain information on primary mass composition



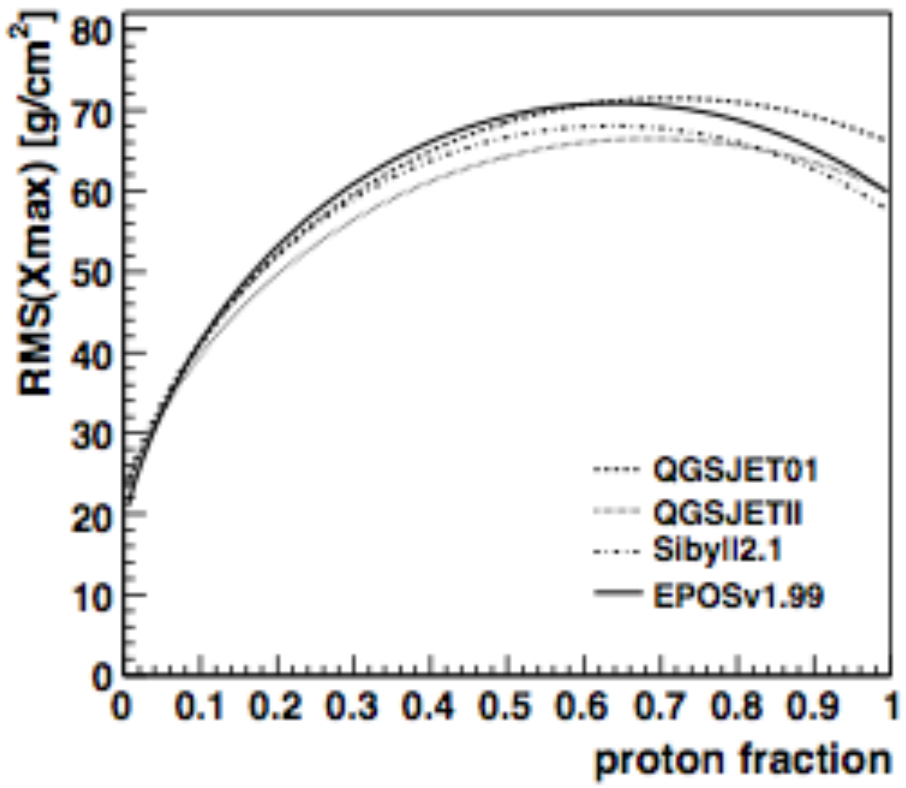
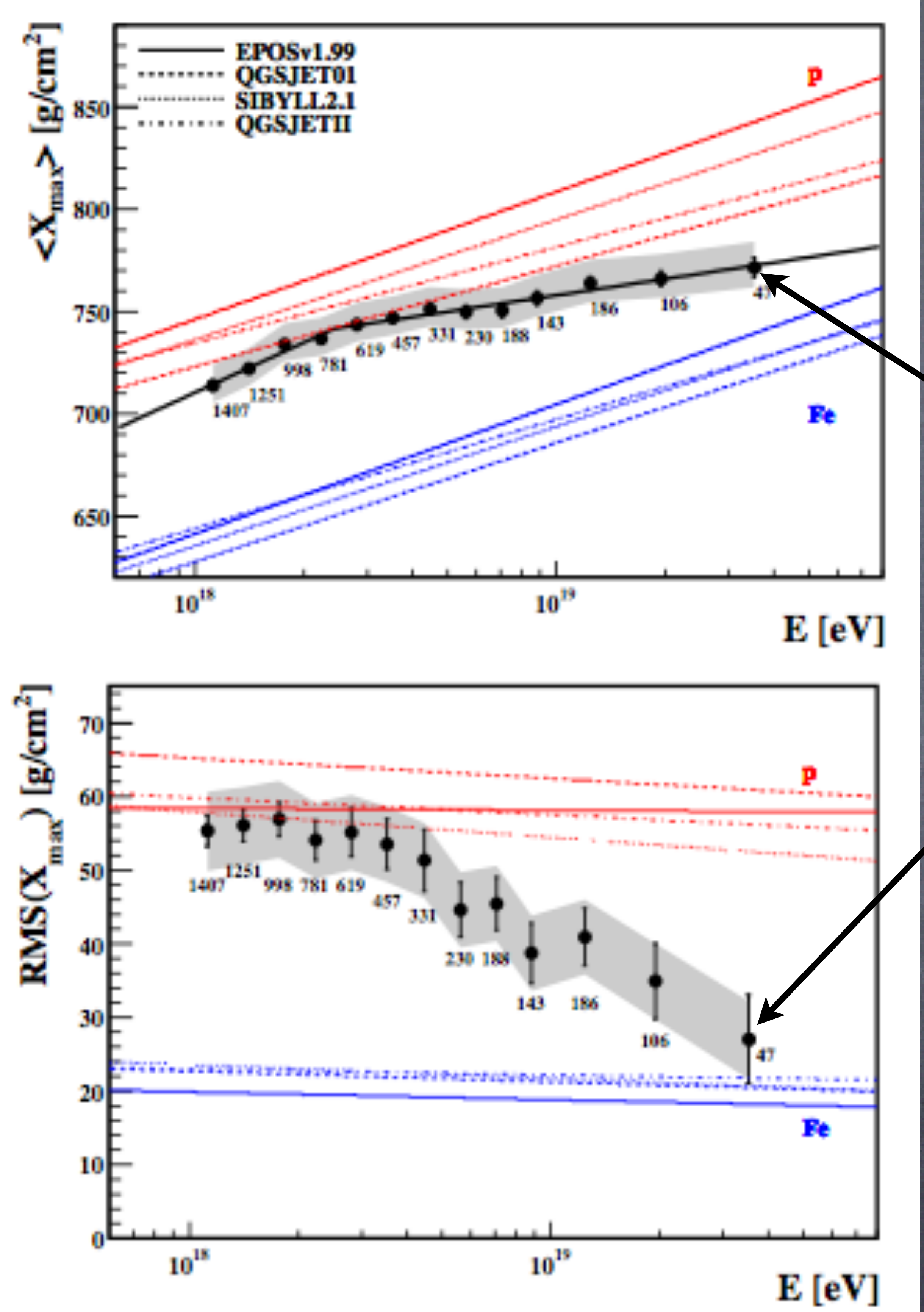


FIGURE 1. RMS($X_{\max}$) from different hadronic interaction models [23] and a two-component p/Fe composition model ($E = 10^{18}$ eV).

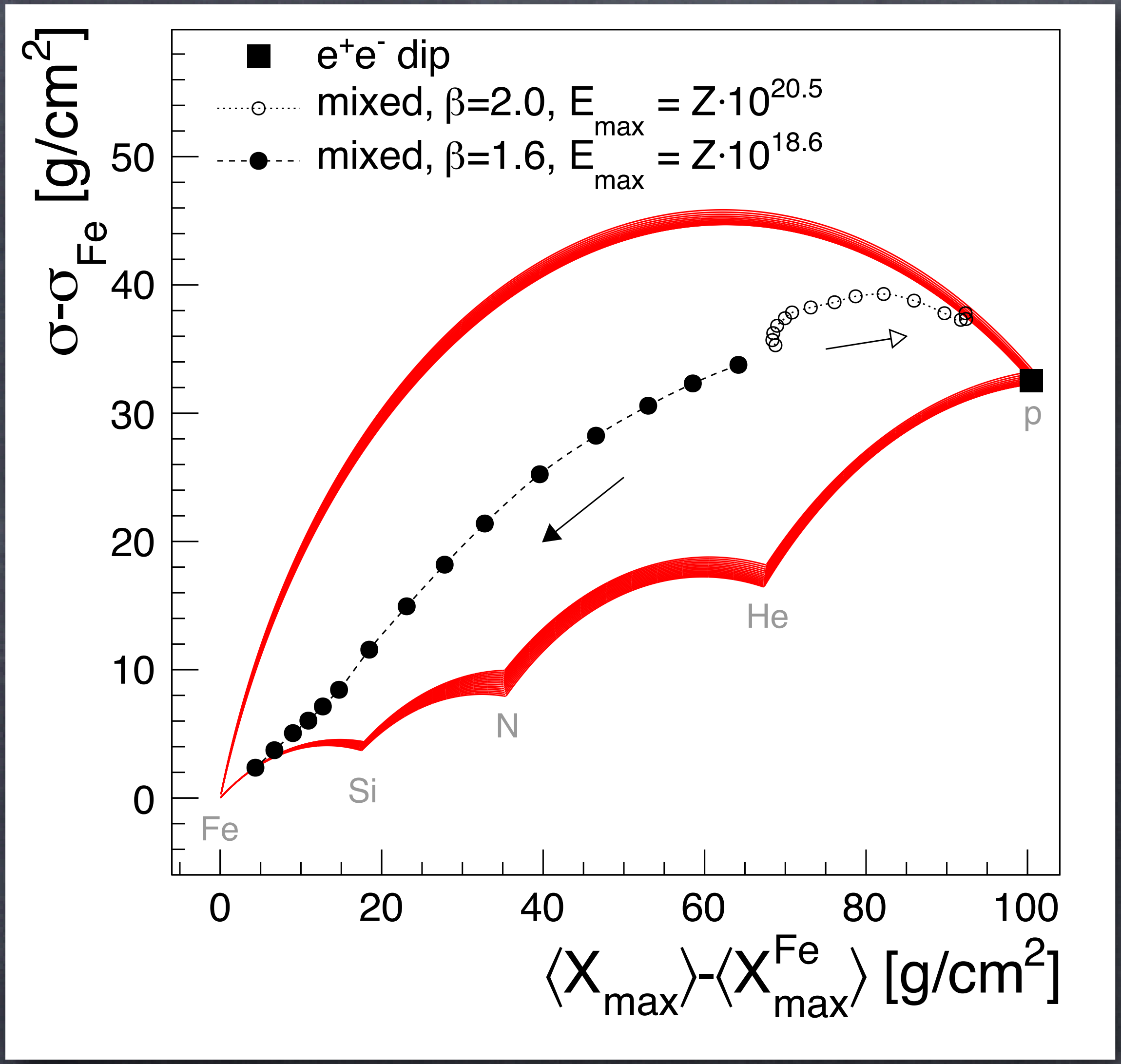
Pierre Auger data suggest a heavier composition toward highest energies:

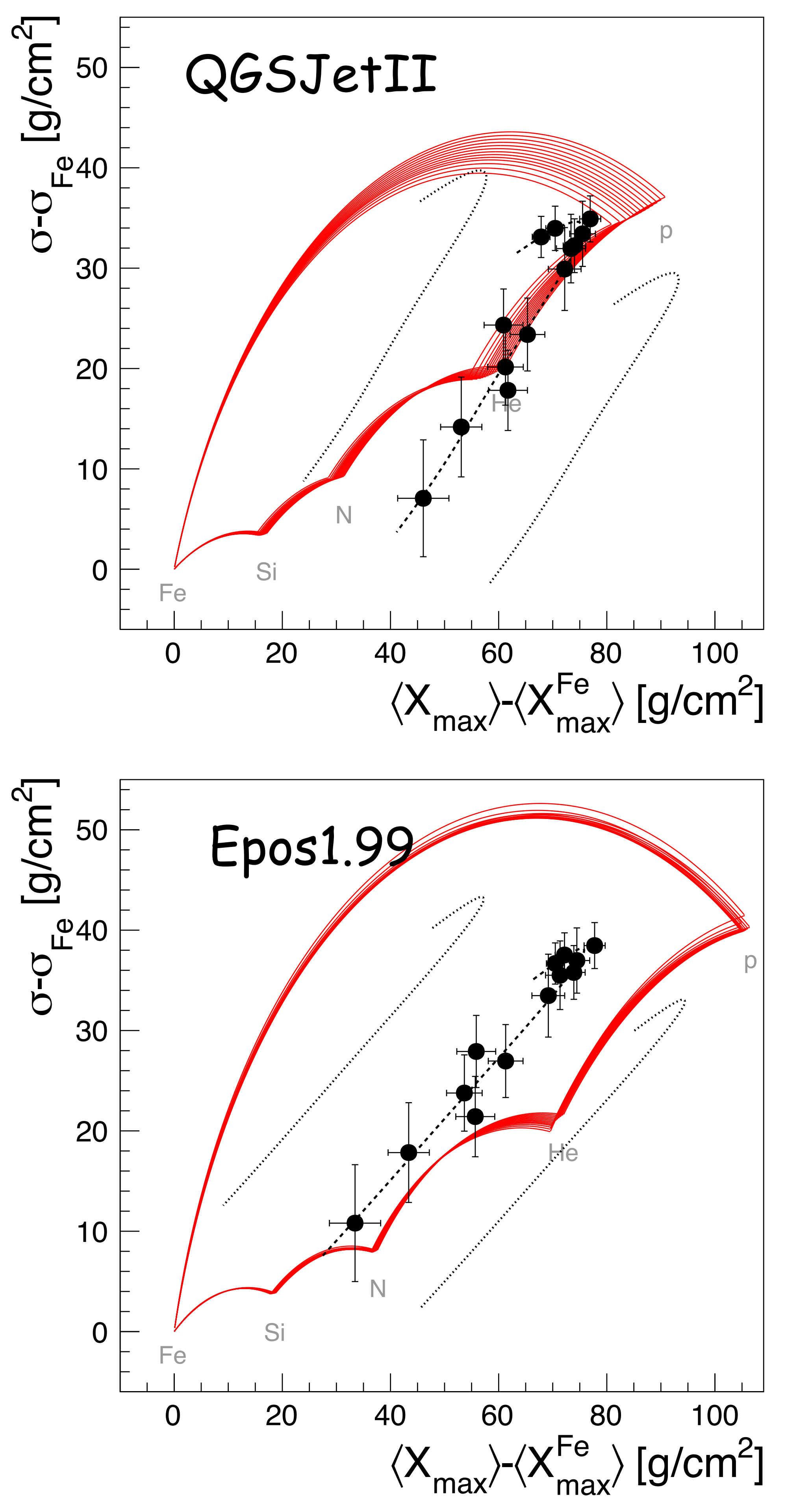


but not confirmed on the northern hemisphere by HiRes and Telescope Array which are consistent with protons

potential tension with air shower simulations and some hadronic interaction models because a mixed composition would predict larger RMS(X_{max})

Pierre Auger Collaboration,
Phys.Rev.Lett., 104 (2010) 091101,
and ICRC 2011, arXiv:1107.4804

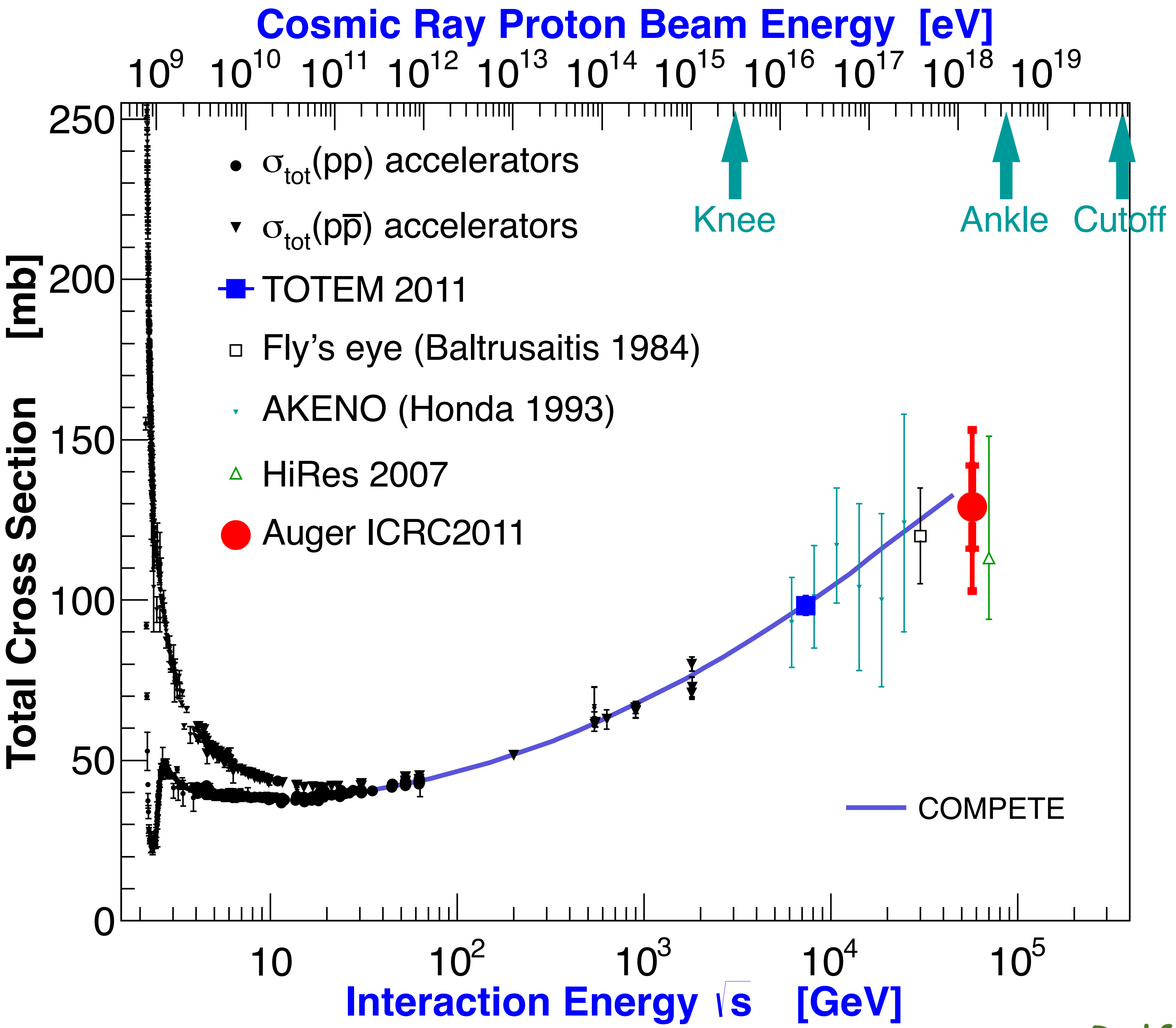




combined measurement of X_{max} and its fluctuation σ constrains composition **within a given hadronic interaction model**

Kampert and Unger, arXiv:1201.0018

Hadronic Cross-Sections

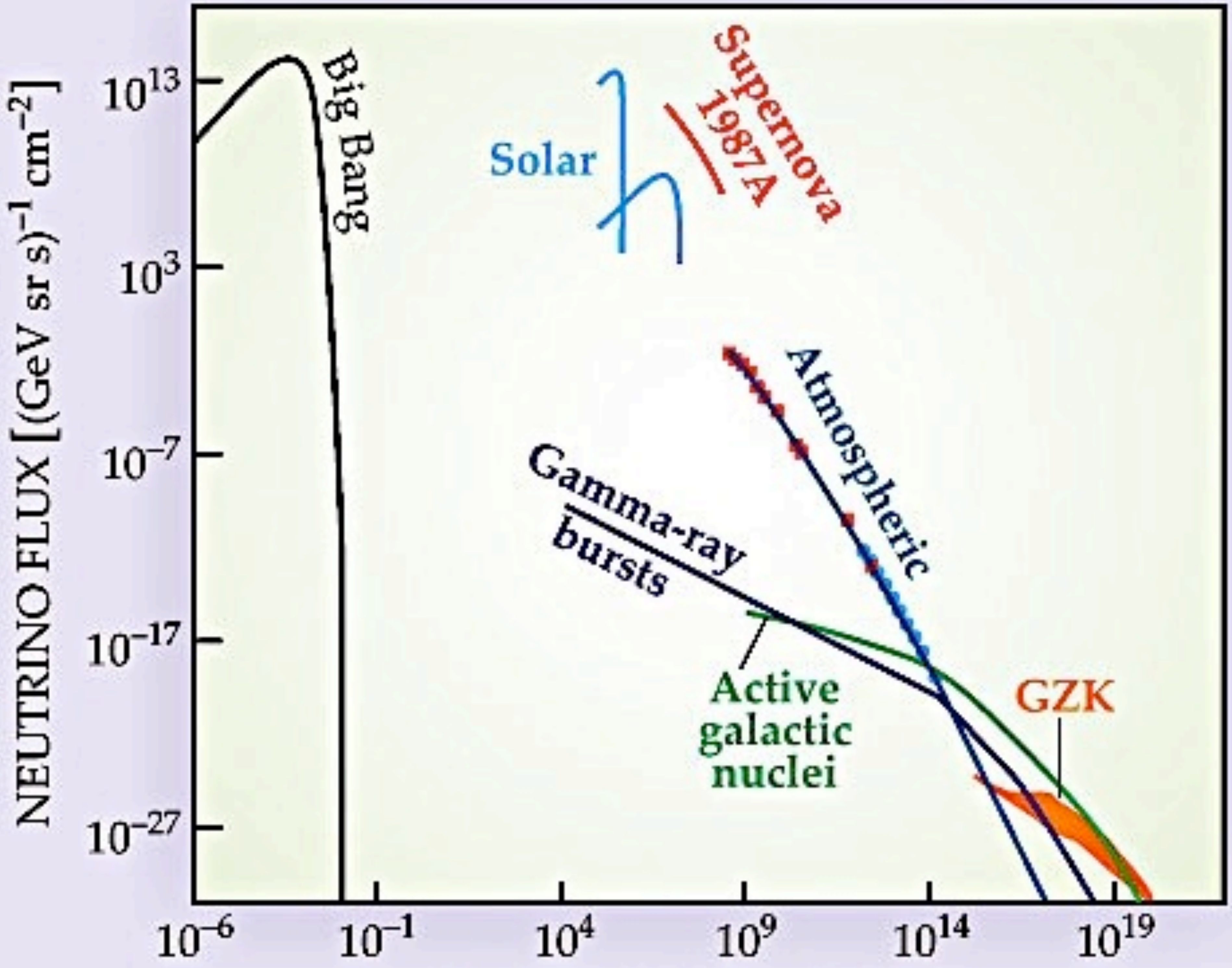


Ralf Ulrich

The high-energy frontier. No indications of missing physics.

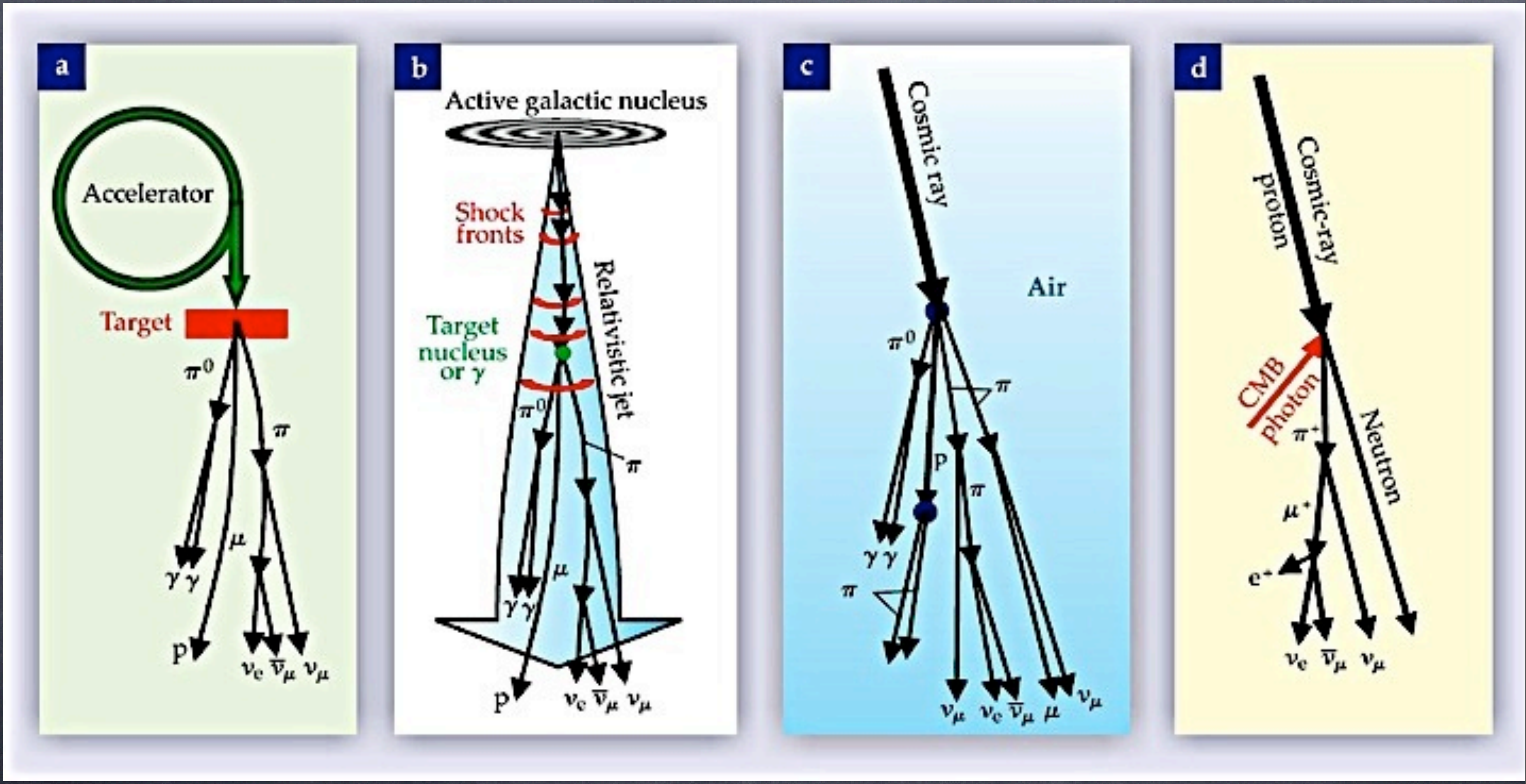
Very High High Energy Neutrinos

The „grand unified“ differential neutrino number spectrum



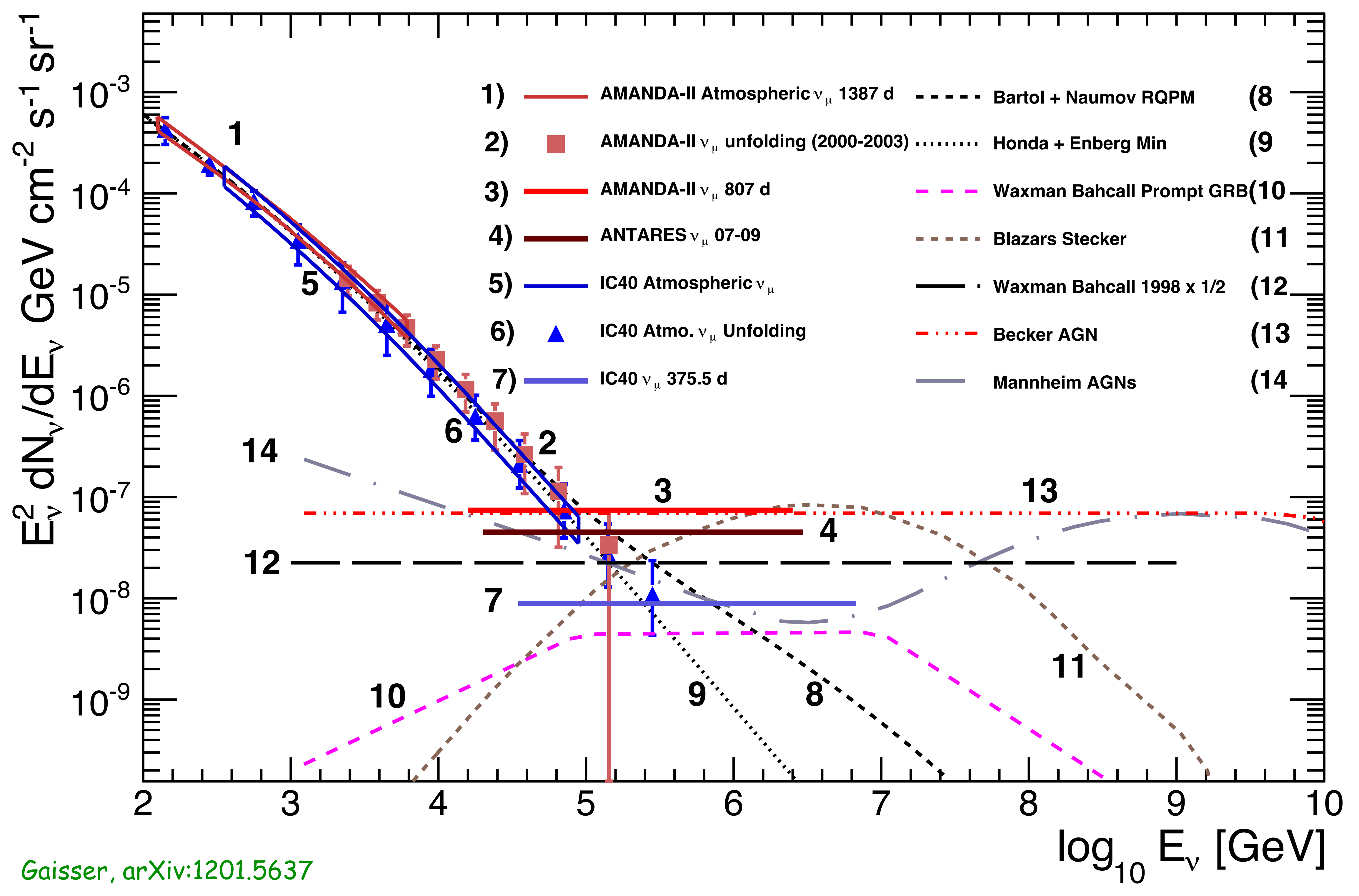
From Physics Today

Summary of neutrino production modes



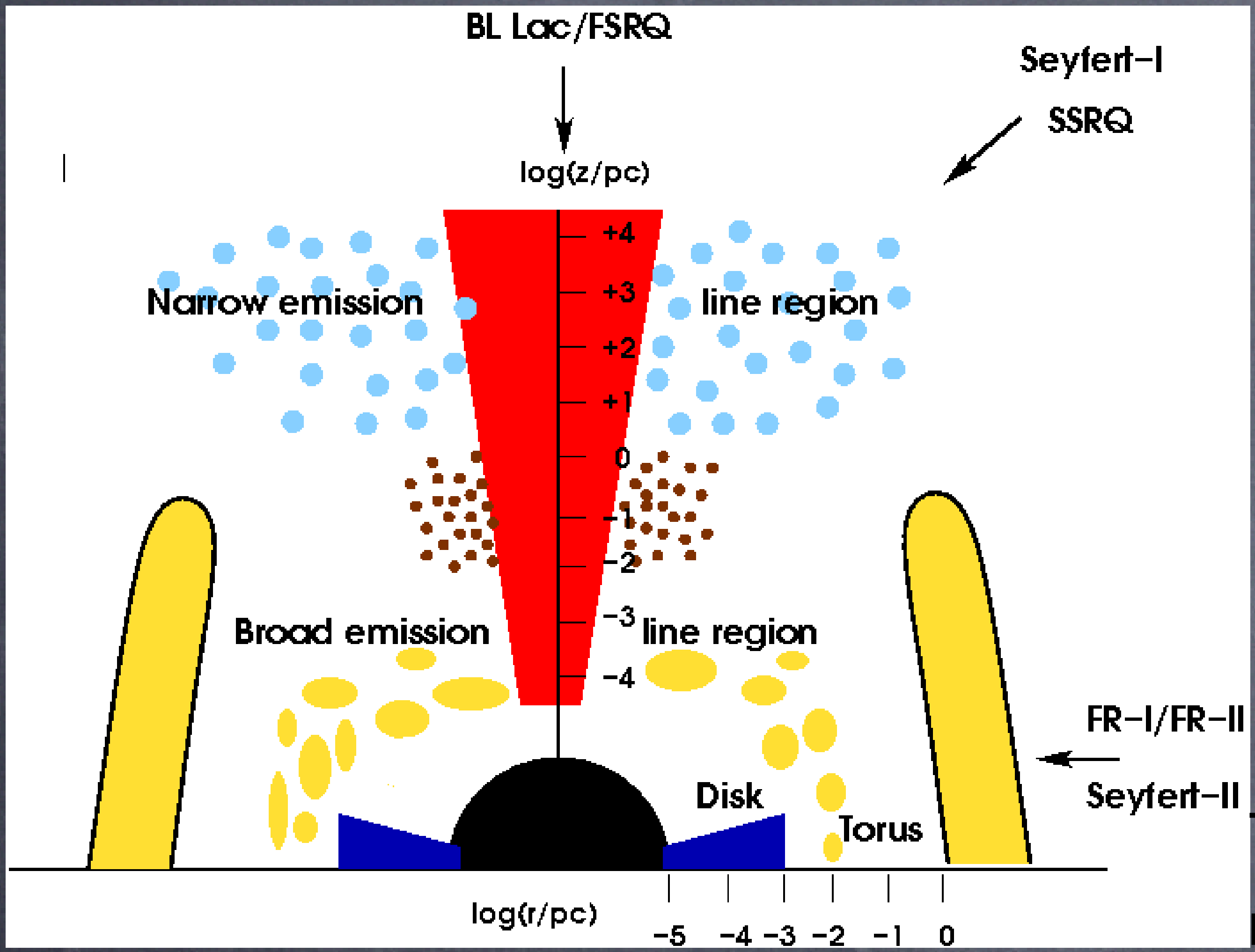
From Physics Today

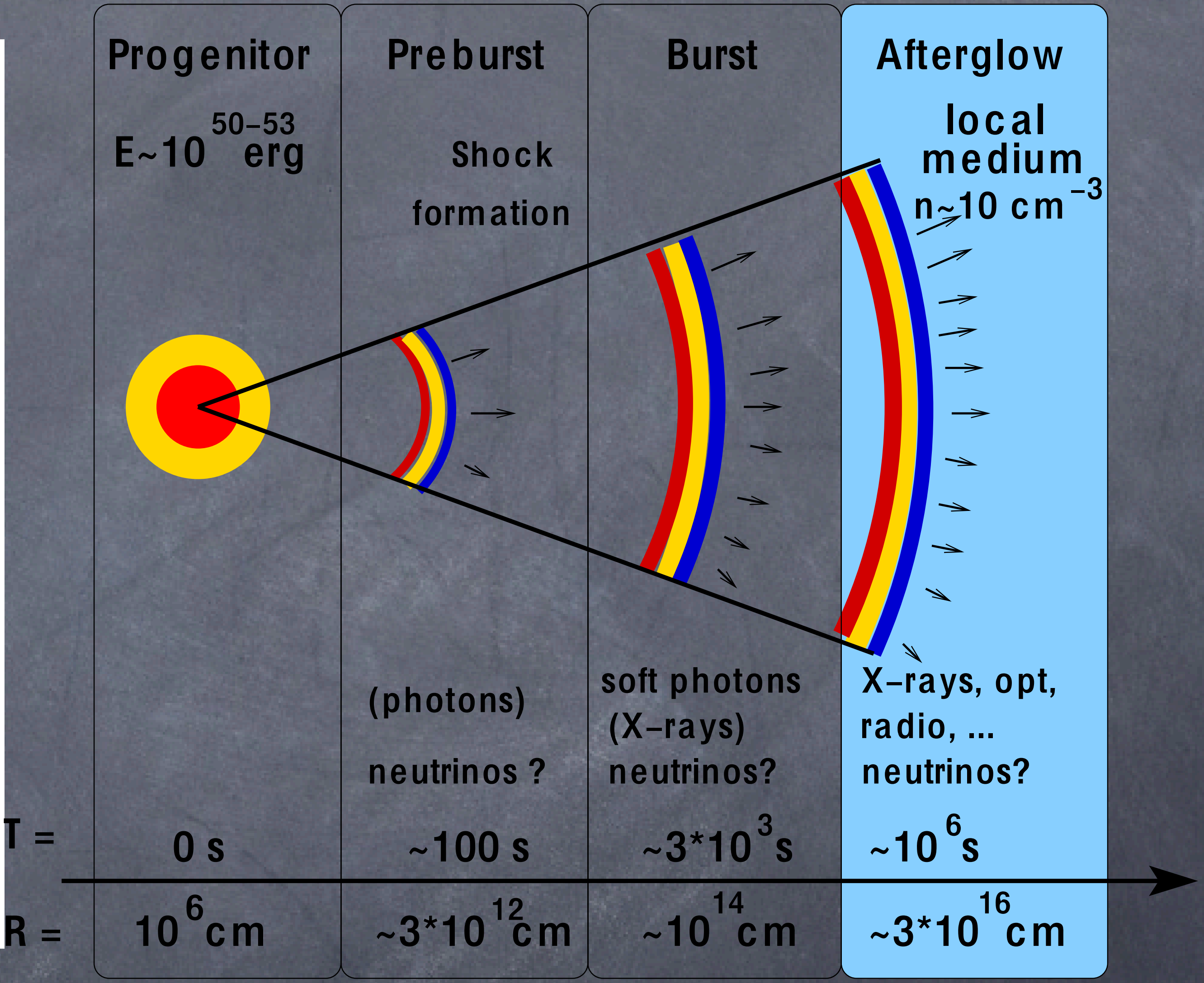
Current Neutrino Flux Upper Limits at TeV-EeV energies



Gaisser, arXiv:1201.5637

Discrete Extragalactic High Energy Neutrino Sources





active galaxies

gamma ray bursts

Figures from J. Becker, Phys.Rep. 458 (2008) 173

Neutrino Fluxes from Gamma-Ray Bursts

GRBs are optically thick to charged cosmic rays and nuclei are disintegrated => only neutrons escape and contribute to the UHECR flux by decaying back into protons

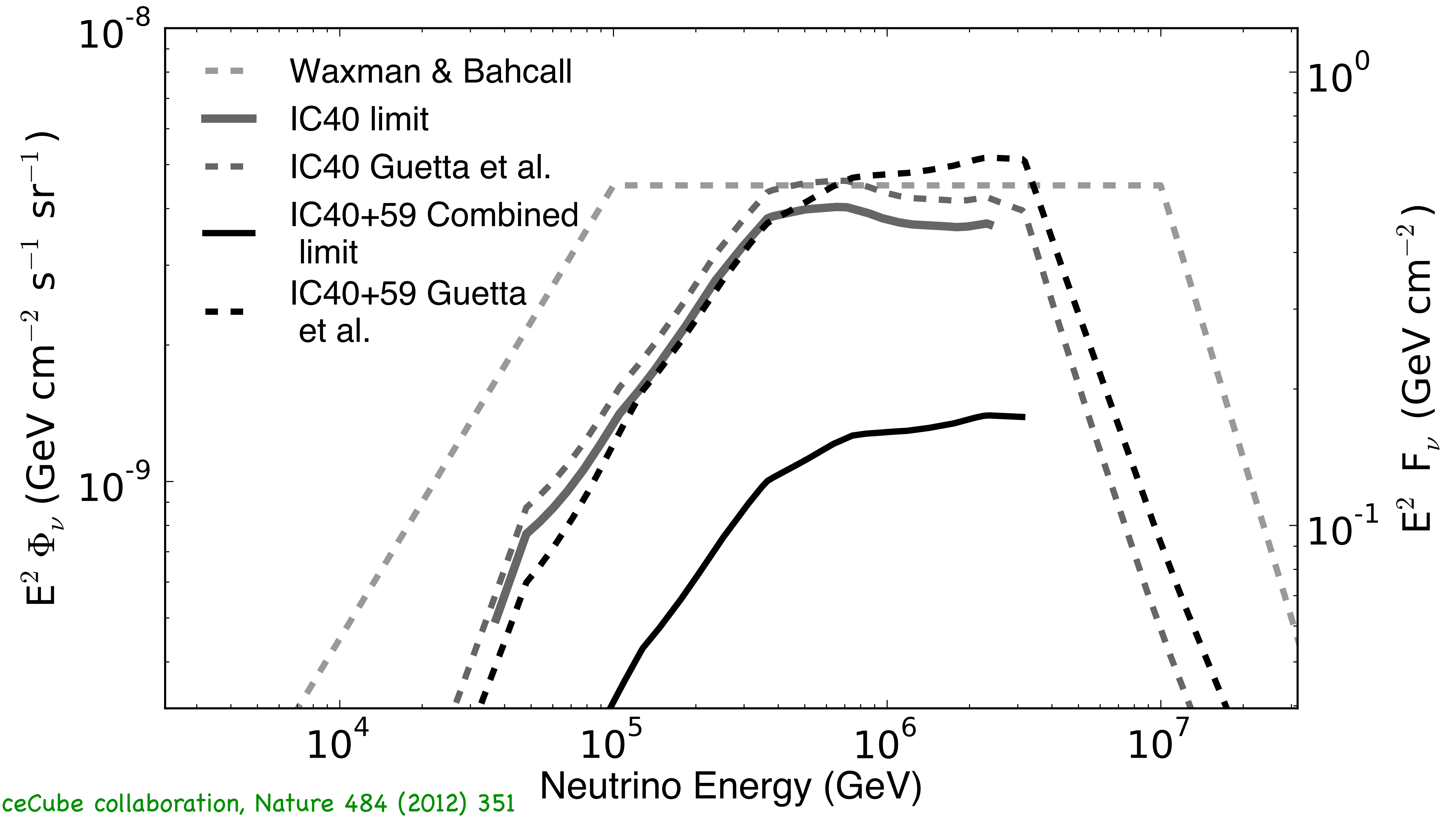
Diffuse neutrino flux from GRBs can thus be linked to UHECR flux (if it is dominantly produced by GRBs)

$$\Phi_\nu(E_\nu) \sim \frac{1}{\eta_\nu}\Phi_p\left(\frac{E}{\eta_\nu}\right) \,,$$

where $\eta_\nu \simeq 0.1$ is average neutrino energy in units of the parent proton energy.

Above ~ 10^{17} eV neutrino spectrum is steepened by one power of E_ν because pions/muons interact before decaying

GRBs as UHECR sources now strongly challenged by non-observation of neutrinos by IceCube



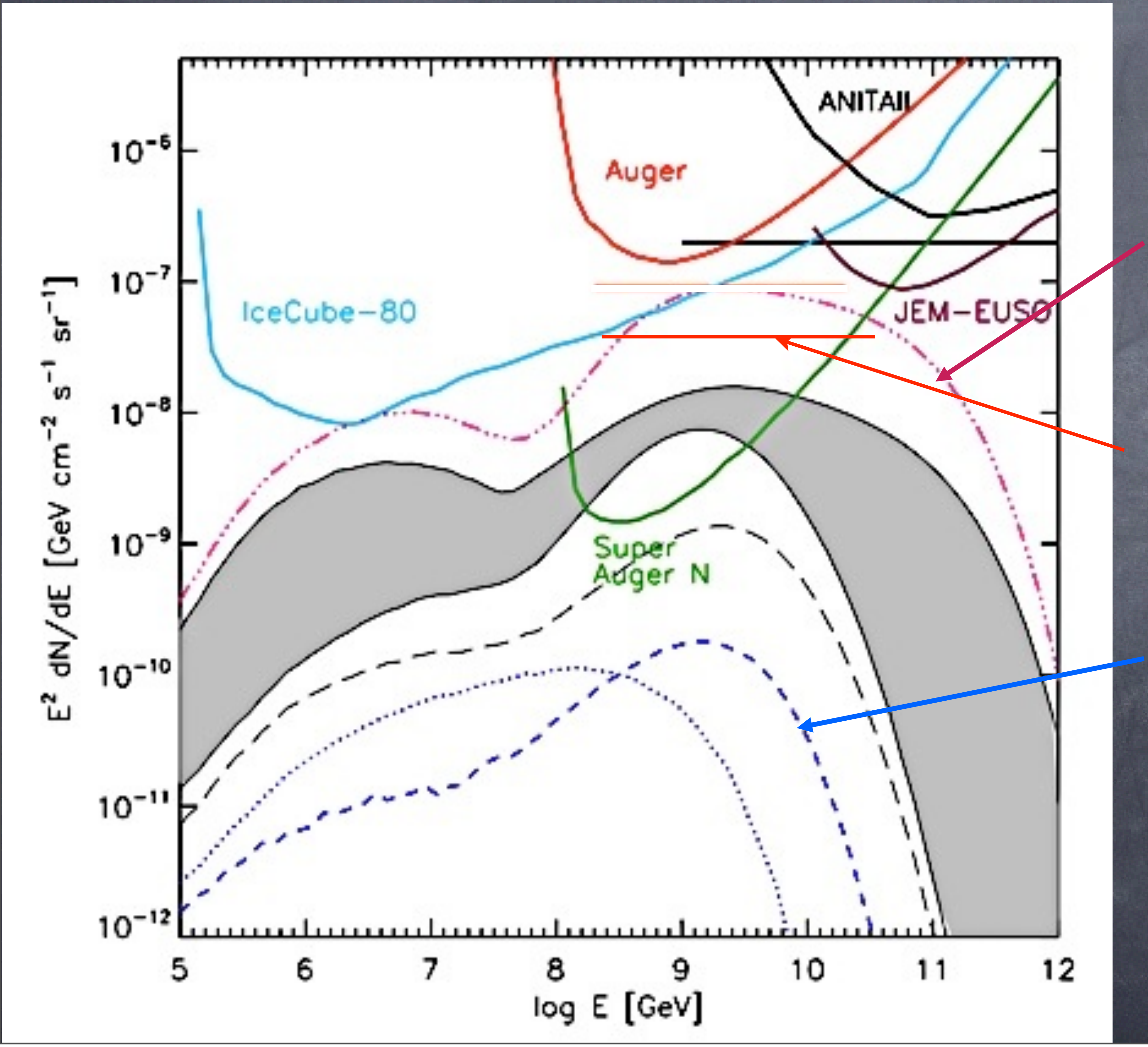
IceCube collaboration, Nature 484 (2012) 351

Halzen, NUSKY2011

Physics with Diffuse Cosmogenic Neutrino Fluxes

Cosmogenic neutrino fluxes depend on number of nucleons produced above GZK threshold which is proportional to E_{max}/A

Further suppressed for heavy nuclei due to increased pair production



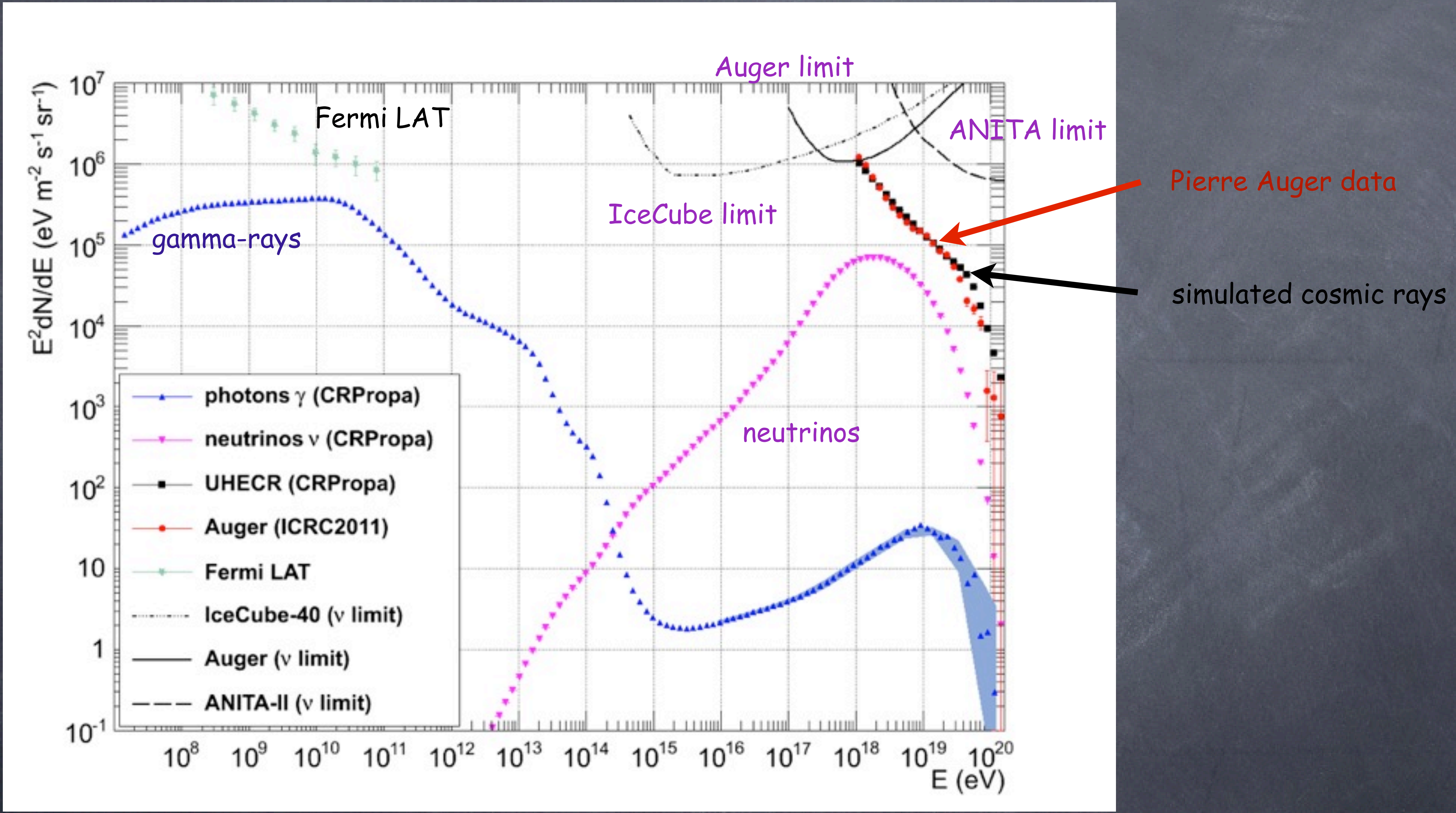
Pure protons, E_{max}=3 10^{21} eV, strong evolution

current Auger limit on Earth-skimming neutrinos

Pure iron, E_{max}= 10^{20}/26 eV, no evolution

Kotera, Allard, Olinto, JCAP 1010 (2010) 013

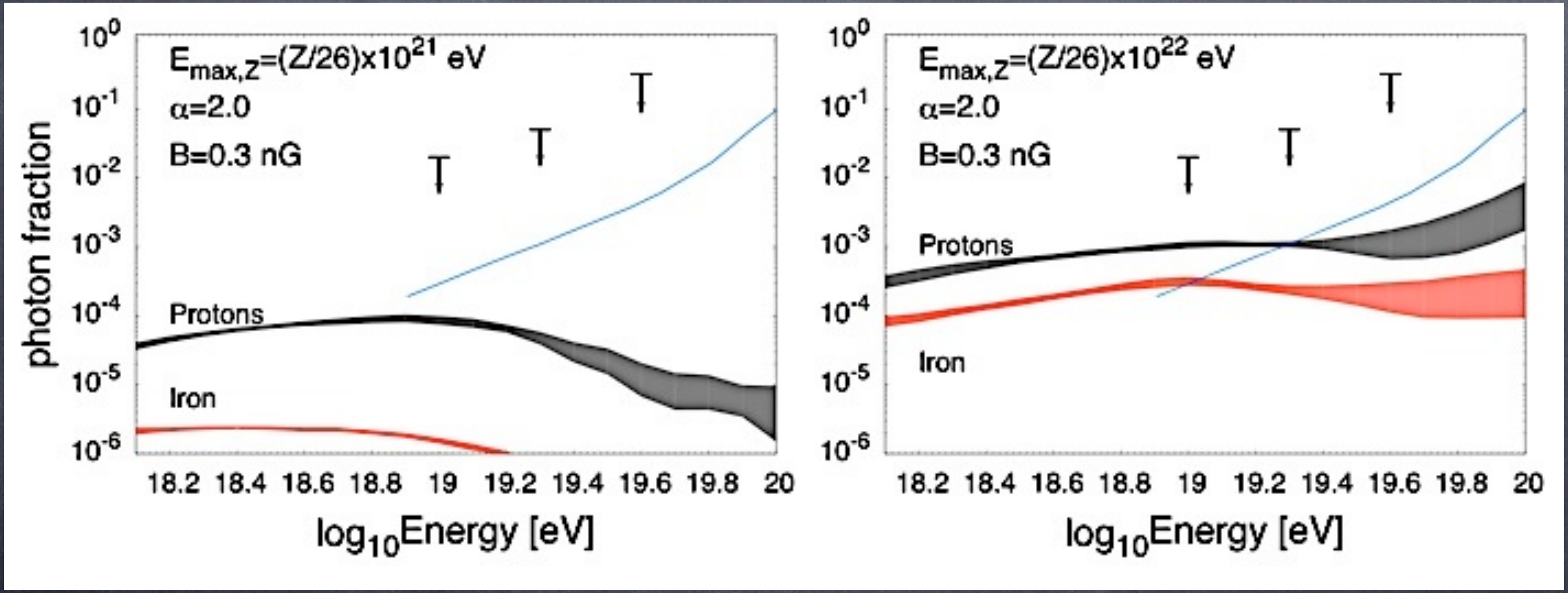
TeV γ-ray fluxes also constrain cosmogenic neutrino fluxes sensitive to redshift evolution; complementary to UHE γ-ray fluxes



comoving injection rate scaling as $(1+z)^4$ up to z=2 injection spectral slope α=2.2 up to $E_{max} = Z \times 3.86 \times 10^{20}$ eV for a galactic composition at the sources

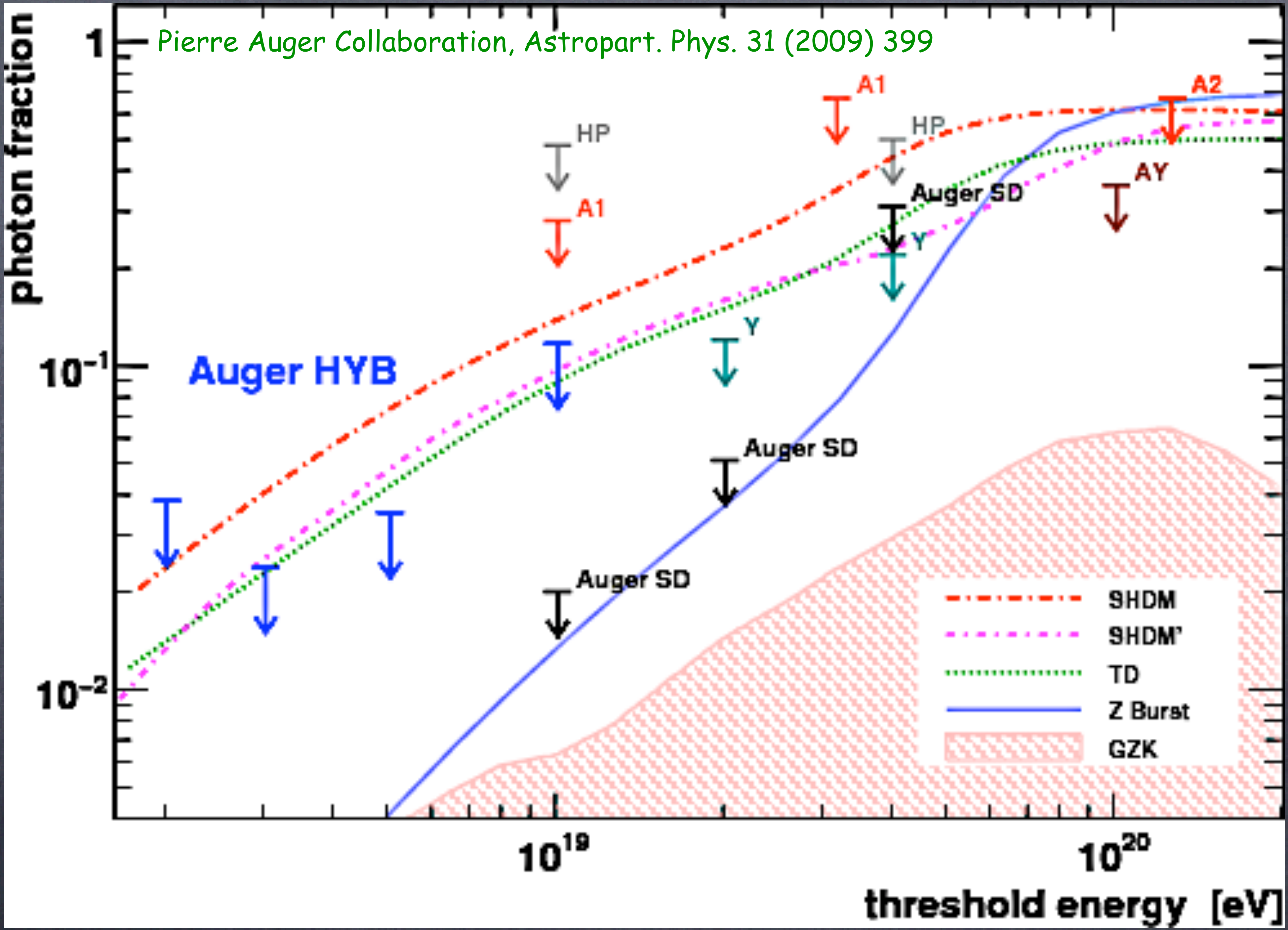
Physics with Diffuse Secondary Gamma-Ray Fluxes

- UHE gamma-ray fluxes depend on number of nucleons locally produced above GZK threshold which is proportional to E_{max}/A
- Further suppressed for heavy nuclei due to increased pair production
- complementary to cosmogenic neutrinos: does not depend on redshift evolution



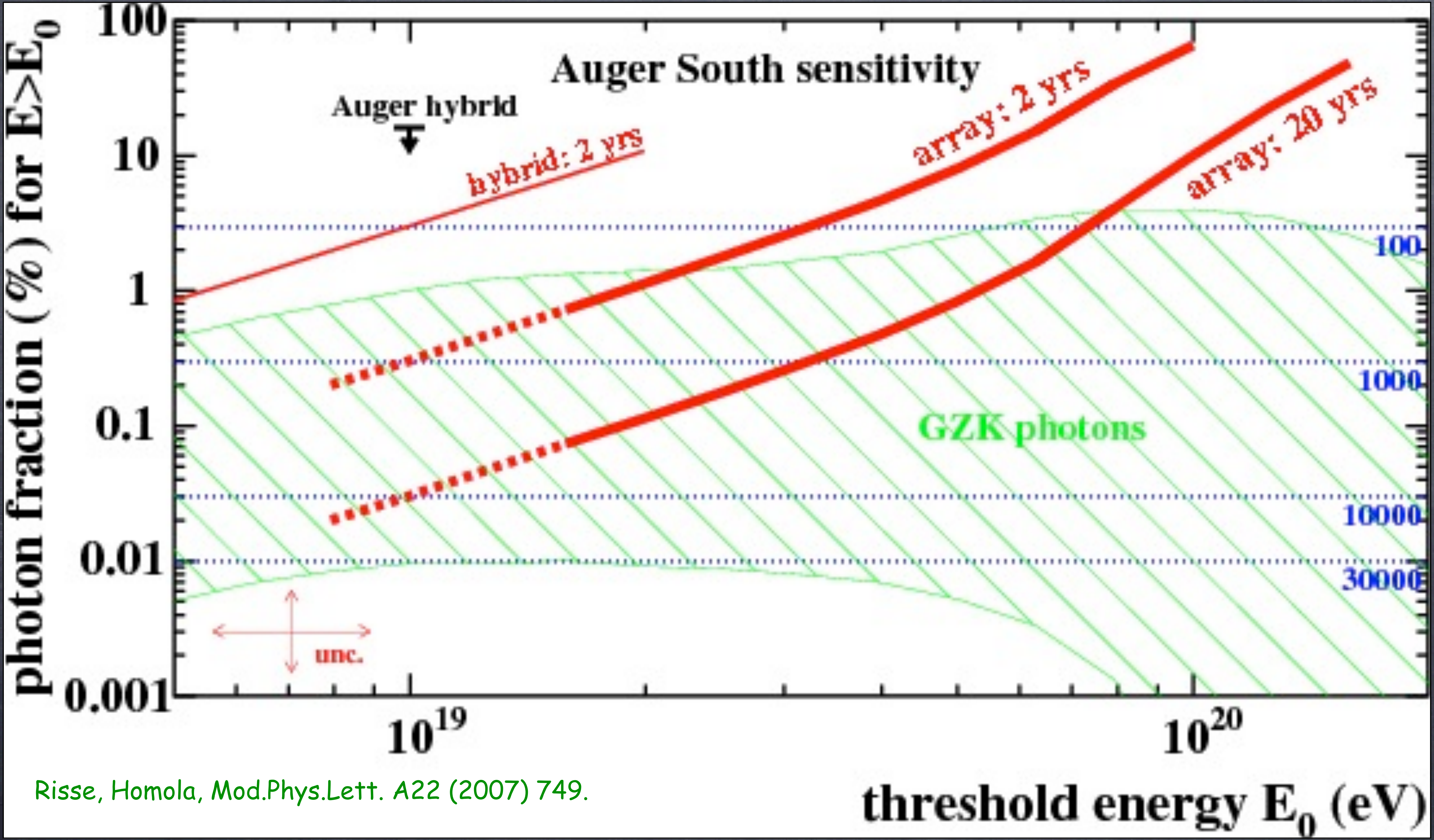
Hooper, Taylor, Sarkar, Astropart.Phys. 34 (2011) 340

Current upper limits on the photon fraction are of order 2% above 10^{19} eV from latest results of the Pierre Auger experiments (ICRC) and order 30% above 10^{20} eV.



Pierre Auger Collaboration, Astropart. Phys. 31 (2009) 399

Future data will allow to probe smaller photon fractions and the GZK photons



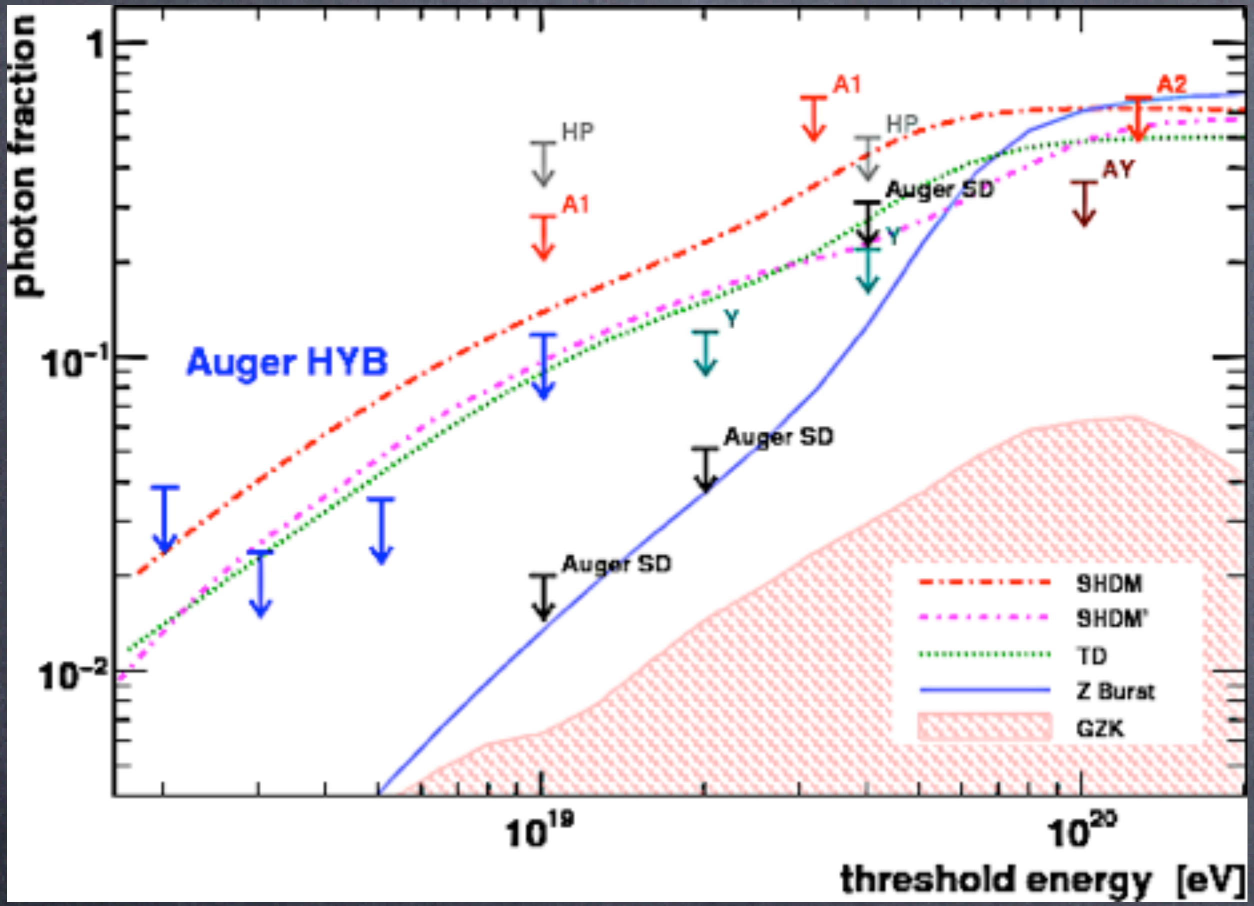
Risse, Homola, Mod.Phys.Lett. A22 (2007) 749.

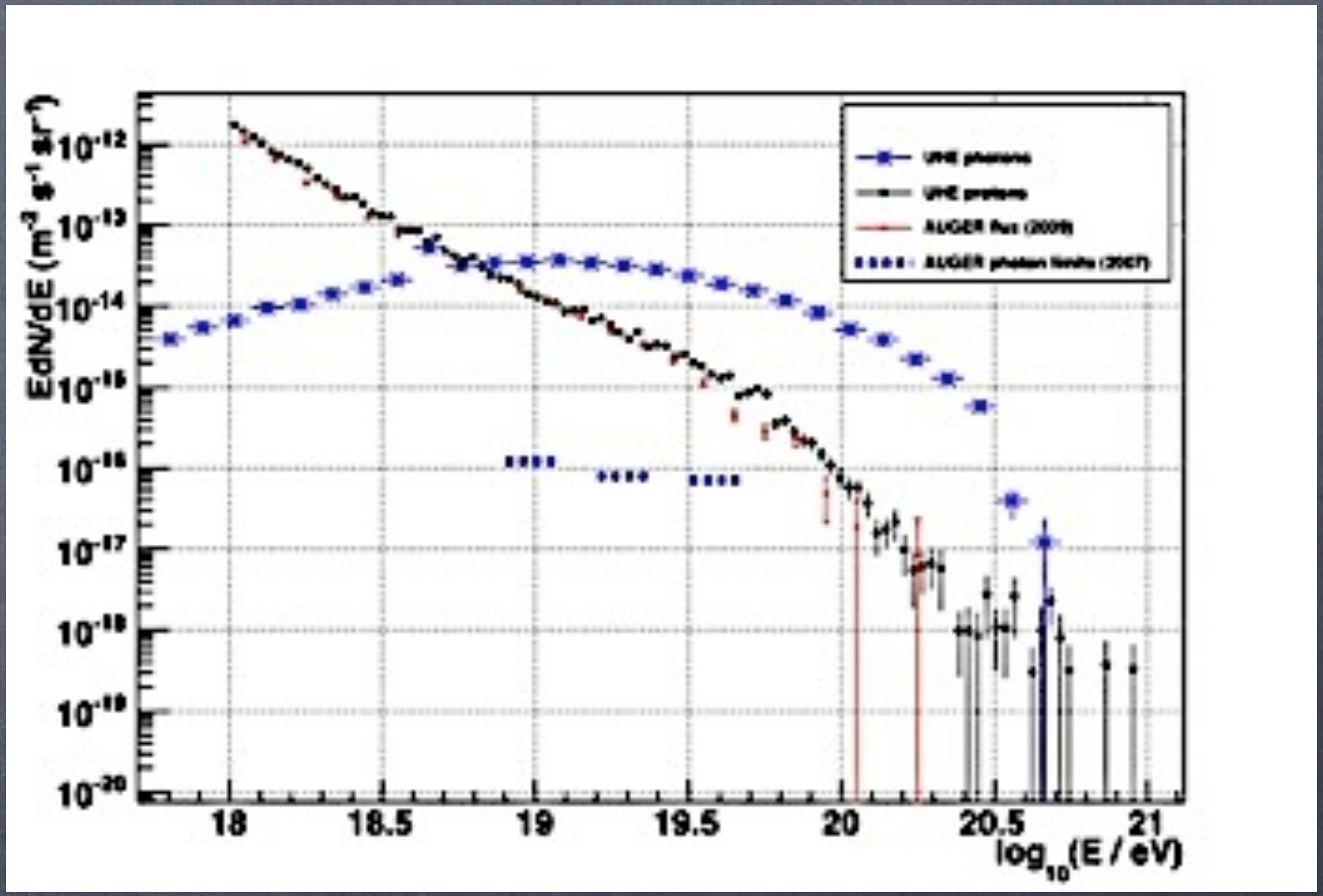
Lorentz Symmetry Violation in the Electromagnetic Sector

The idea:

Experimental upper limits on UHE photon fraction

Contradict predictions if pair production is absent





Pierre Auger Collaboration, Astropart. Phys. 31 (2009) 399

Maccione, Liberati, Sigl, PRL 105 (2010) 021101

For photons we assume the dispersion relation

$$\omega_{\pm}^2 = k^2 + \xi_n^{\pm} k^2 \left(\frac{k}{M_{\mathrm{Pl}}}\right)^n , n \geq 1 \,,$$

and for electrons

$$E_{e,\pm}^2 = p_e^2 + m_e^2 + \eta_n^{e,\pm} p_e^2 \left(\frac{p_e}{M_{\mathrm{Pl}}}\right)^n , n \geq 1 \,,$$

with only one term present. Polarizations denoted with ±. For positrons, effective field theory implies $\eta_n^{p,\pm} = (-1)^n \eta_n^{e,\mp}$. Furthermore, $\xi_n^+ = (-1)^n \xi_n^-$, so that the problem depends on three parameters which in the following we denote by

$$\xi_n \,, \eta_n^+ \,, \eta_n^-$$

for each n.

Consider pair production on a background photon of energy k_b and assume kinematics with ordinary energy-momentum conservation, with $p_- = (1-y)k$, $p_+ = yk$. Using $x = 4y(1-y)k/k_{LI}$ with the threshold in absence of Lorentz invariance (LI) violation, $k_{LI}=m_e^2/\omega_b$, the condition for pair production is then

$$\alpha_n x^{n+2} + x - 1 \geq 0$$

where

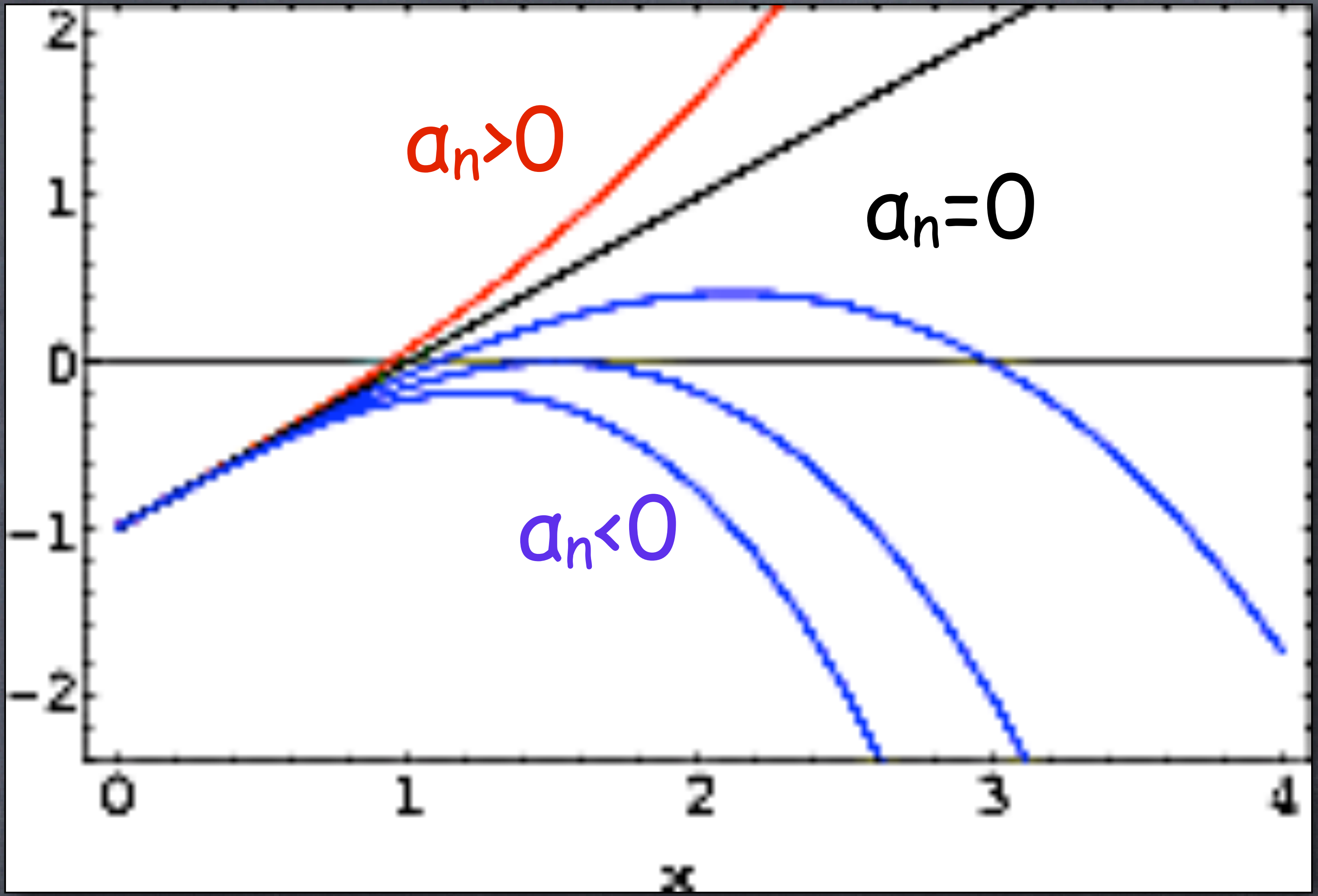
$$\alpha_n = \frac{\xi_n - (-1)^n \eta_n^{\mp} y^{n+1} - \eta_n^{\pm}(1-y)^{n+1}}{2^{2(n+2)} y^{n+1}(1-y)^{n+1}} \frac{m_e^{2(n+1)}}{k_b^{n+2} M_{\rm Pl}^n} .$$

All combinations of $\xi_n, \eta_n^+, \eta_n^-$ can occur, depending on the partial wave of the pair, governed by total angular momentum conservation. All partial waves are allowed away from the thresholds.

The condition for photon decay is

$$\alpha_n x^{n+2} - 1 \geq 0$$

There are at least two real solutions $0 \leq x_n^l \leq x_n^r$ for pair production (lower and upper thresholds)



Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

For photon decay there is at most one positive real threshold.

Minimize/maximize these wrt. y

A given combination $\xi_n, \eta_n^+, \eta_n^-$ is ruled out if, for 10^{19} eV < ω < 10^{20} eV, at least one photon polarization state is stable against decay and does not pair produce for any helicity configuration of the final pair.

In the absence of LIV in pairs for n=1, this yields:

$$\xi_1 \leq 2.4 \times 10^{-15}$$

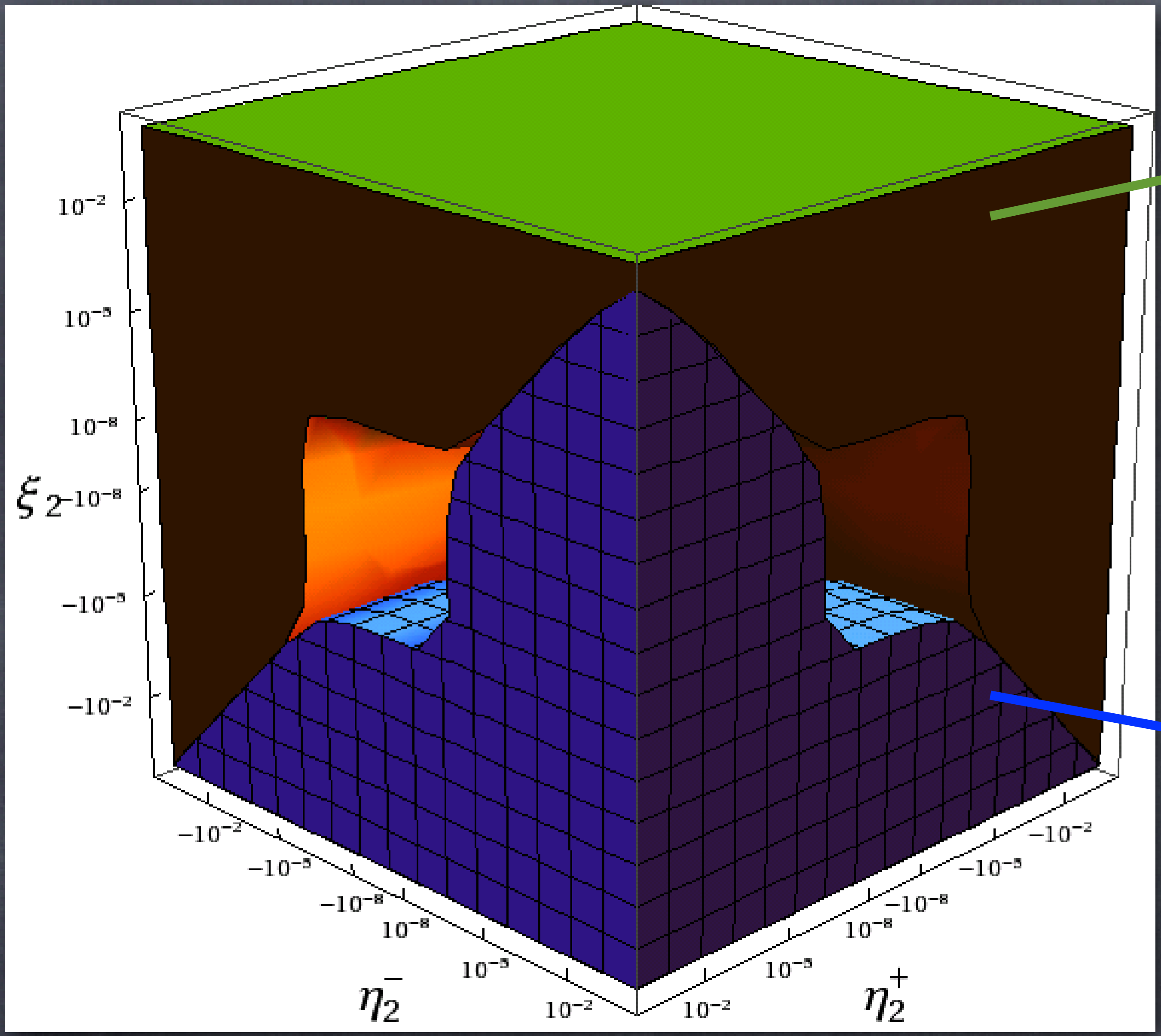
and for n=2:

$$\xi_2 \geq -2.4 \times 10^{-7}$$

If a UHE photon were detected, any LIV parameter combination would be ruled out for which photon decay is allowed for both photon polarizations for at least one helicity configuration of the final pair.

For n = 1, all parameters of absolute value < 10^{-14} ruled out

For n = 2, if absolute value of both the photon and one of the electron parameters is < 10^{-6}, the second electron parameter can be arbitrarily large even once a UHE photon is seen.



UHE photons are detected

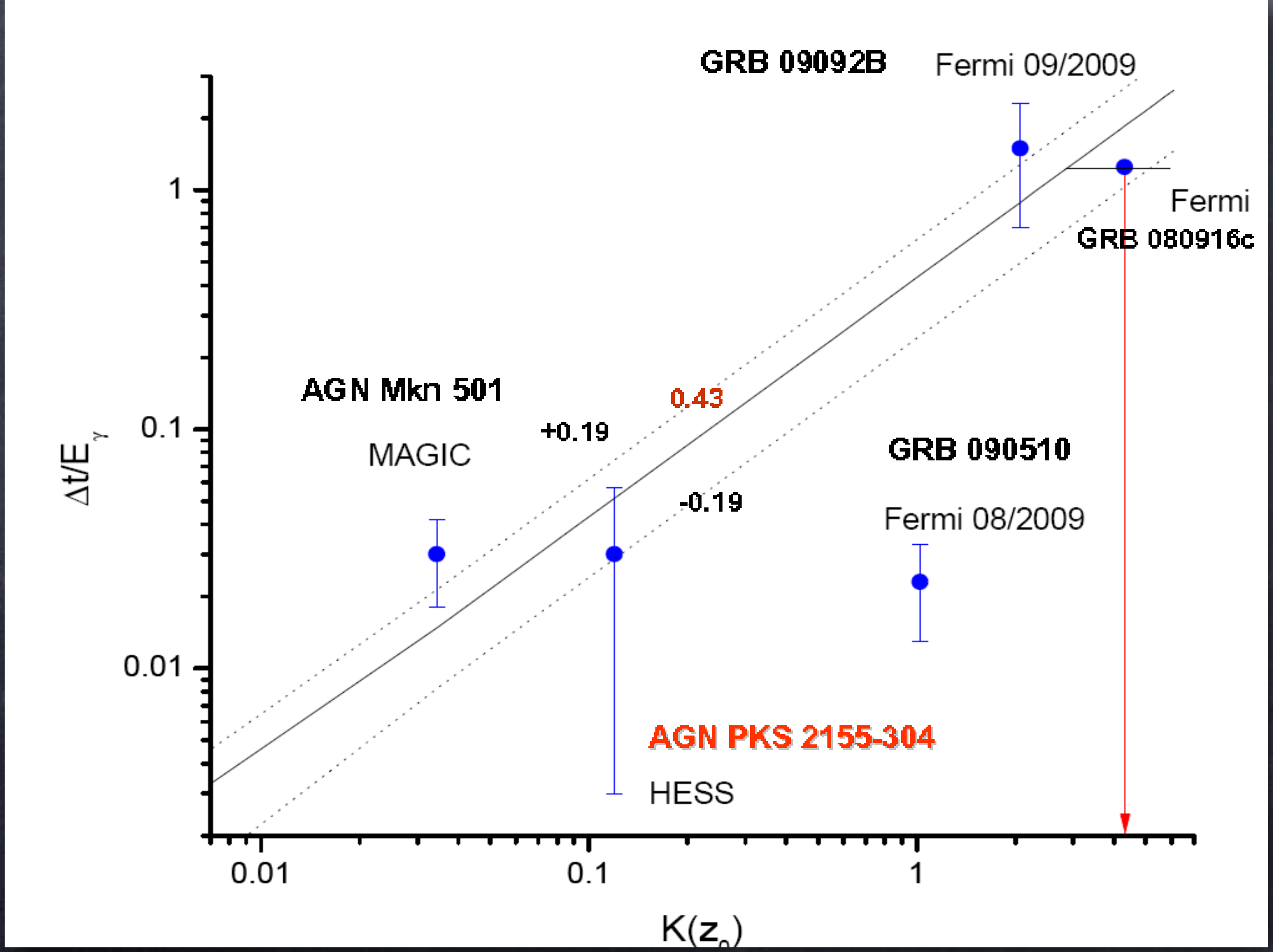
UHE photon absorption takes place

Such strong limits suggest that Lorentz invariance violations are completely absent !

The modified dispersion relation also leads to energy dependent group velocity V=∂E/∂p and thus to an energy-dependent time delay over a distance d:

$$\Delta t = -\xi\, d \frac{E}{M_{\mathrm{Pl}}} \simeq -\xi \left(\frac{d}{100\,\mathrm{Mpc}} \right) \left(\frac{E}{\mathrm{TeV}} \right) \mathrm{sec}$$

for linearly suppressed terms. GRB observations in TeV γ-rays can therefore probe quantum gravity and may explain that higher energy photons tend to arrive later (Ellis et al.).

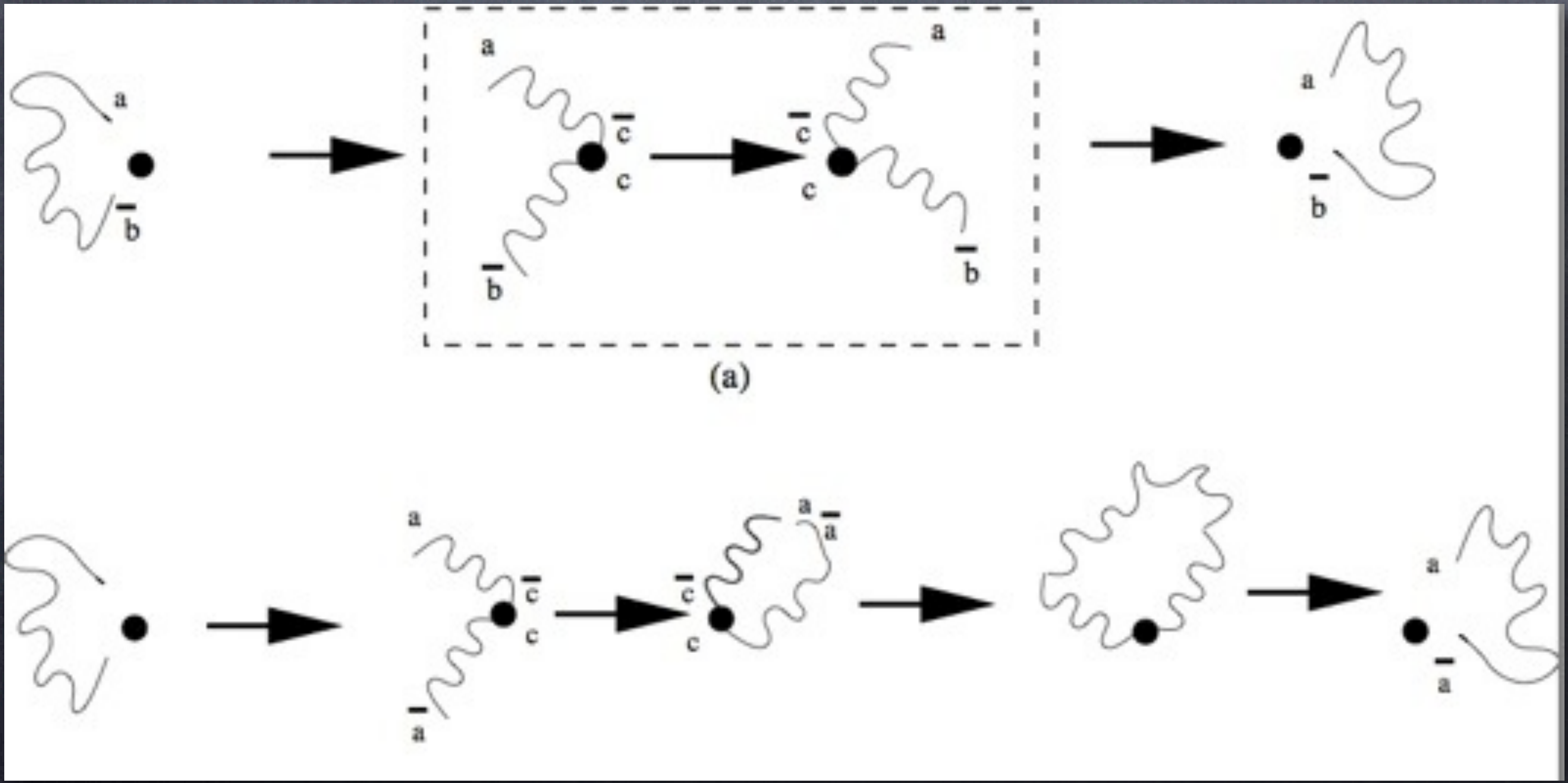


But the UHE photon limits are inconsistent with interpretations of time delays of high energy gamma-rays from GRBs within quantum gravity scenarios based on effective field theory

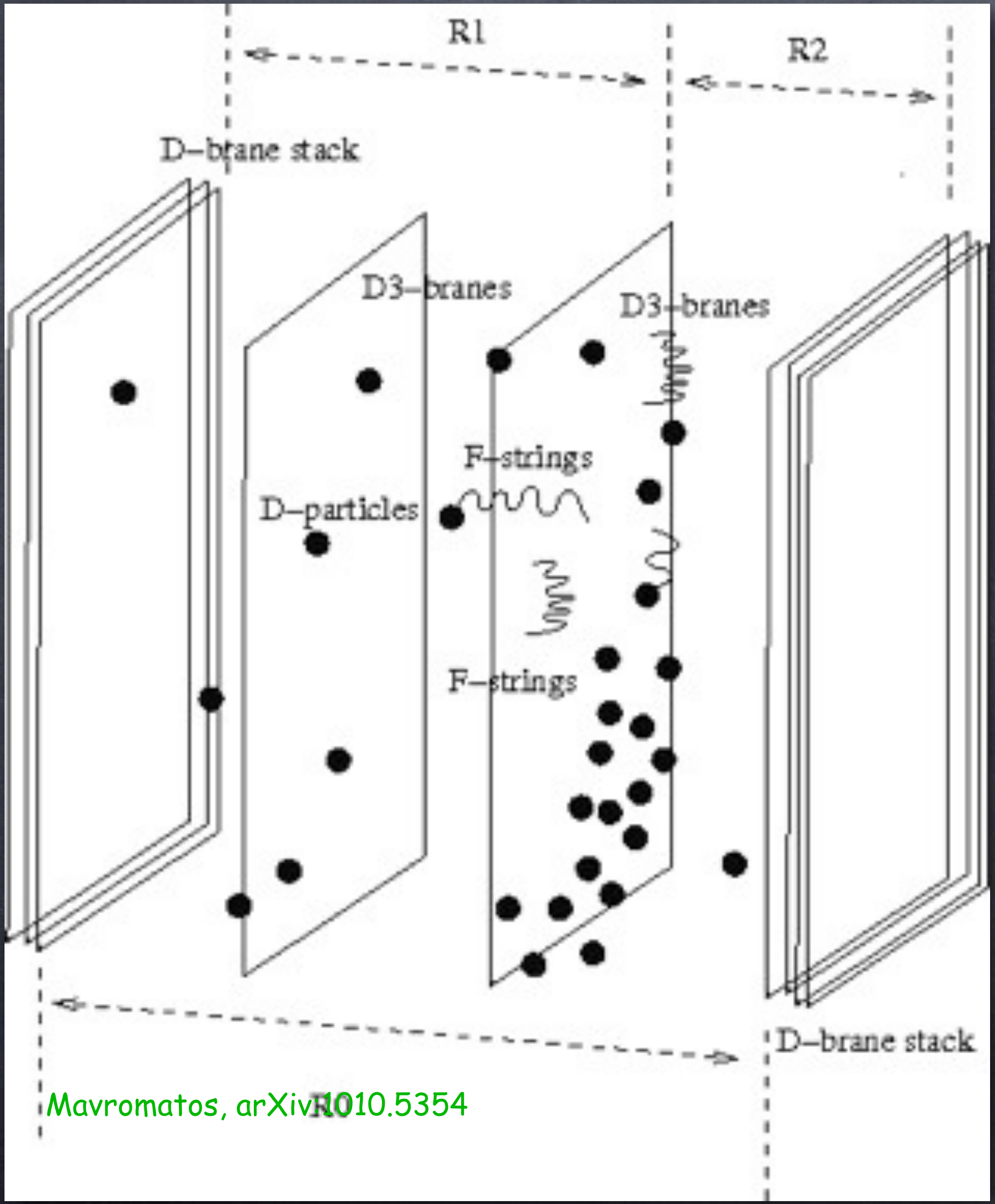
Maccione, Liberati, Sigl, PRL 105 (2010) 021101

Possible exception in space-time foam models,

Ellis, Mavromatos, Nanopoulos, arXiv:1004.4167

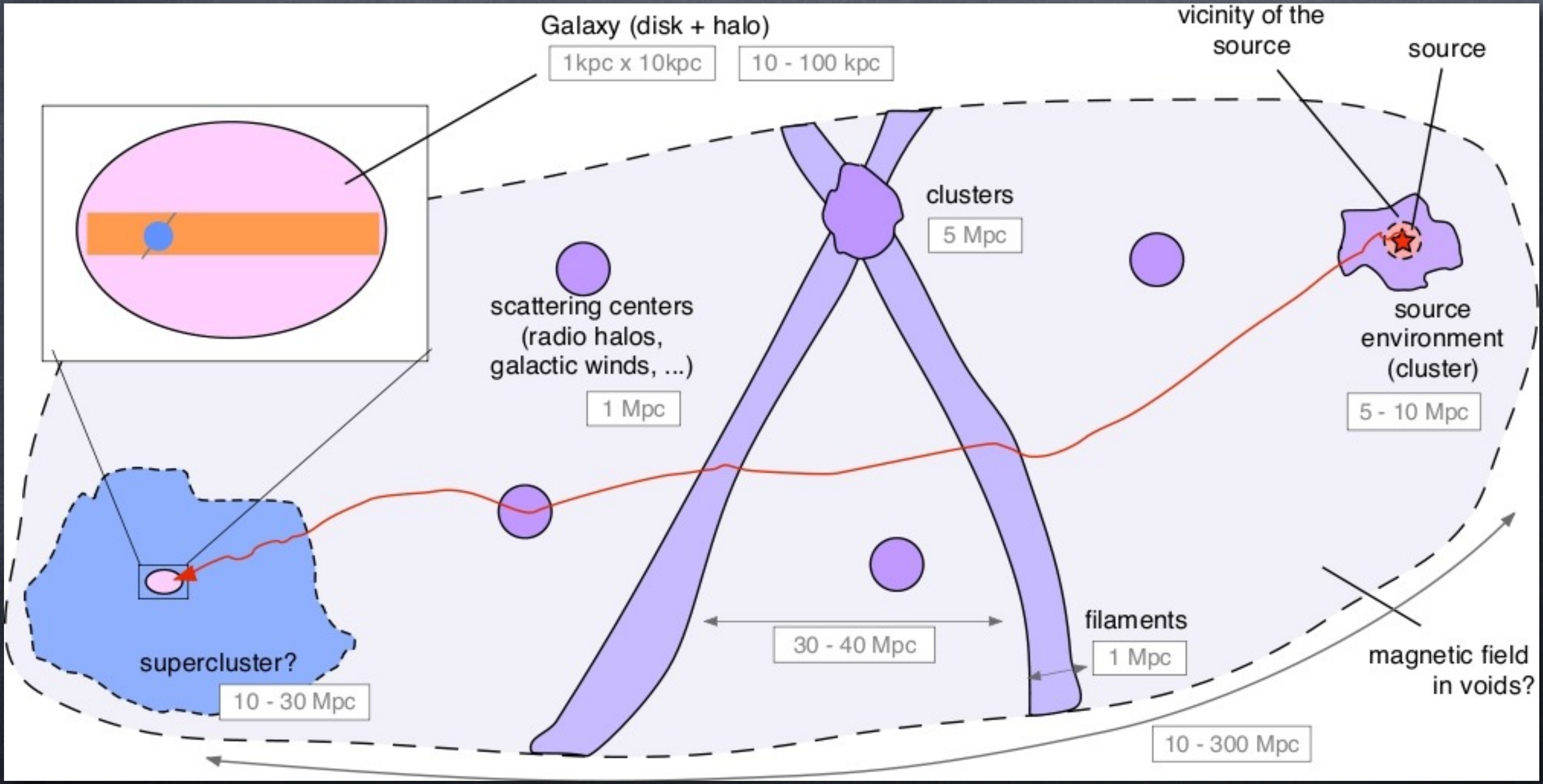


In space-time foam models there may be fluctuating terms in dispersion relation, thus no strict energy-momentum conservation. This could circumvent pair production limits, allowing to interpret time dispersion by quantum gravity effects



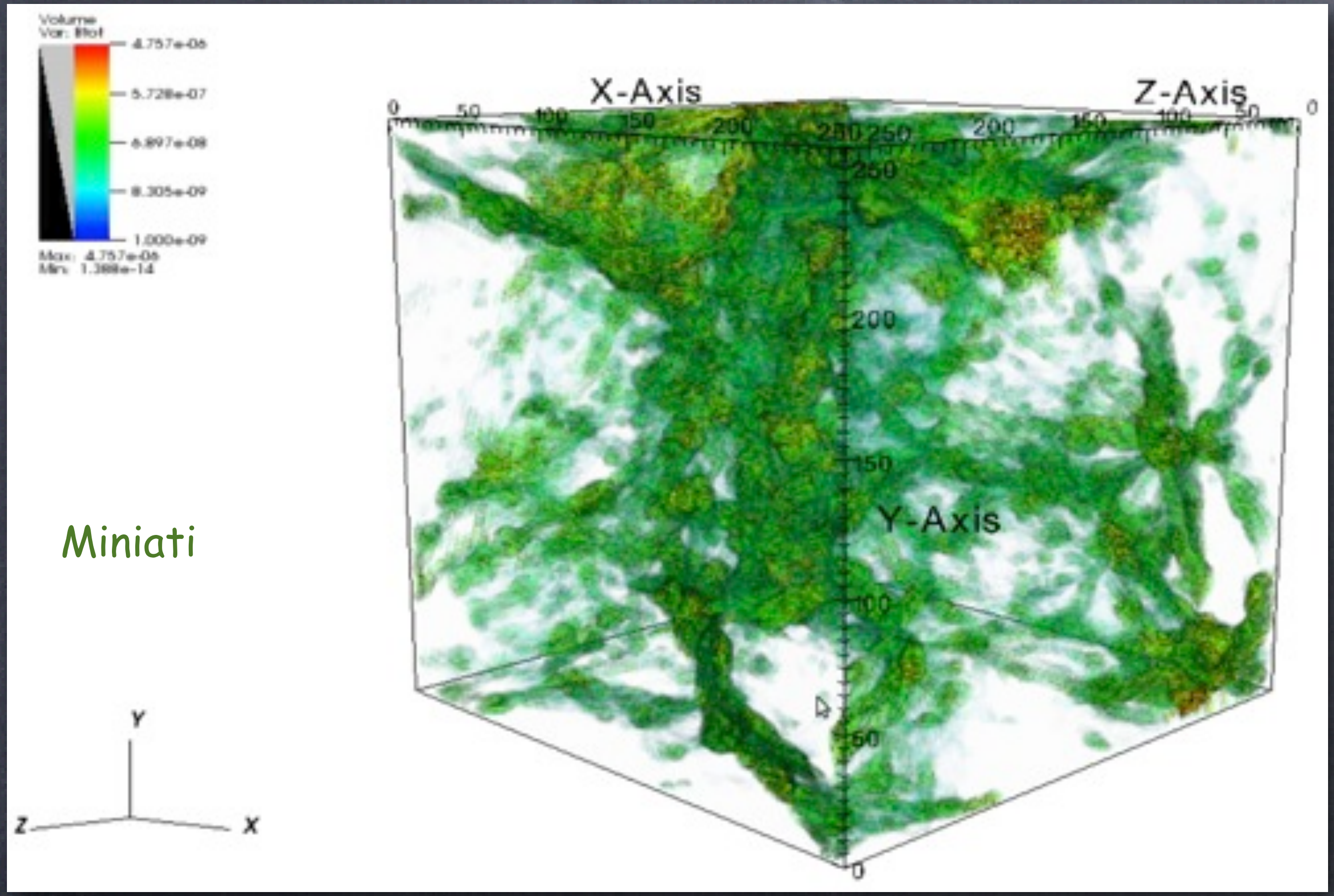
Mavromatos, arXiv:1010.5354

3-Dimensional Effects in Propagation

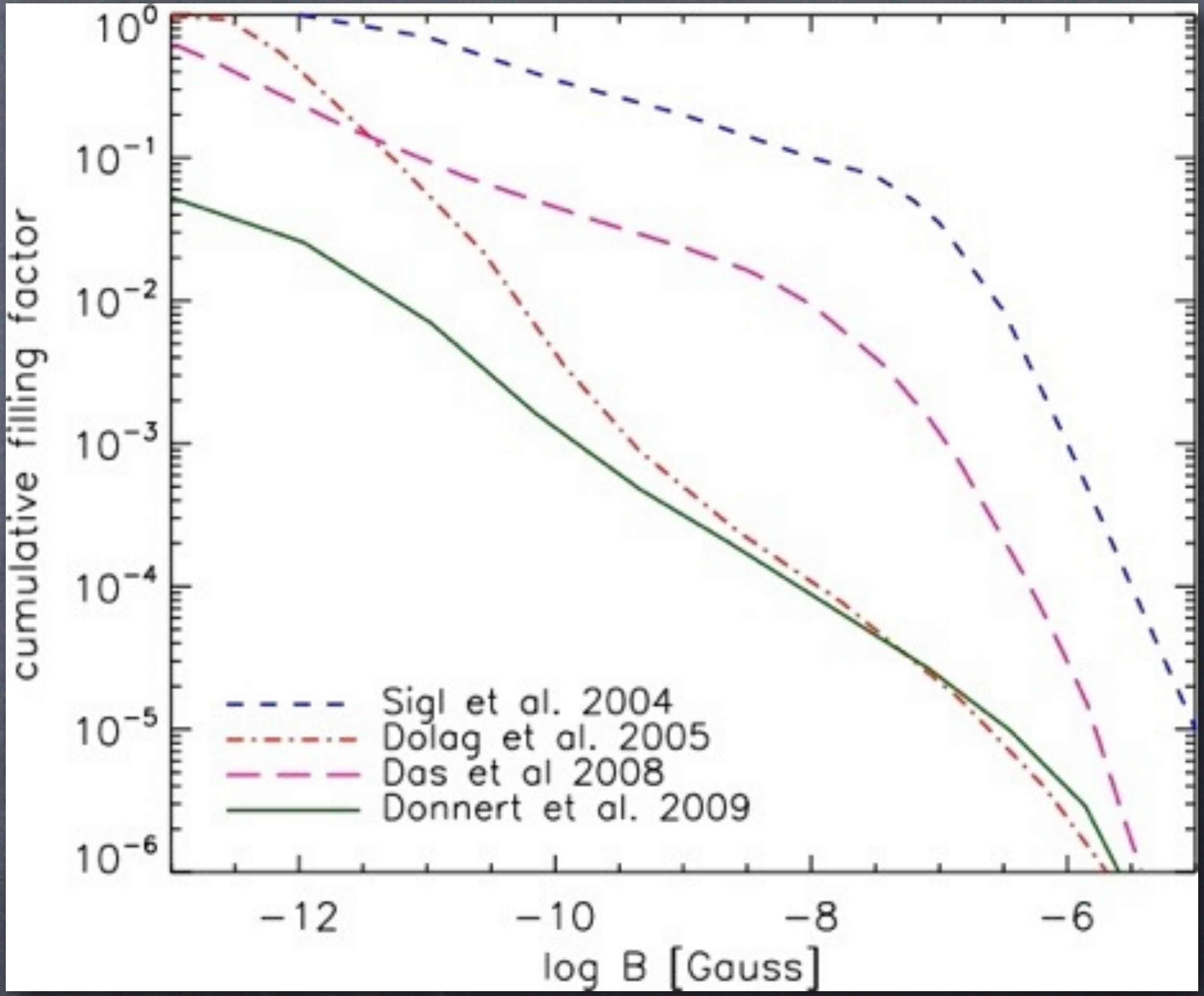


Kotera, Olinto, Ann.Rev.Astron.Astrophys. 49 (2011) 119

Structured Extragalactic Magnetic Fields



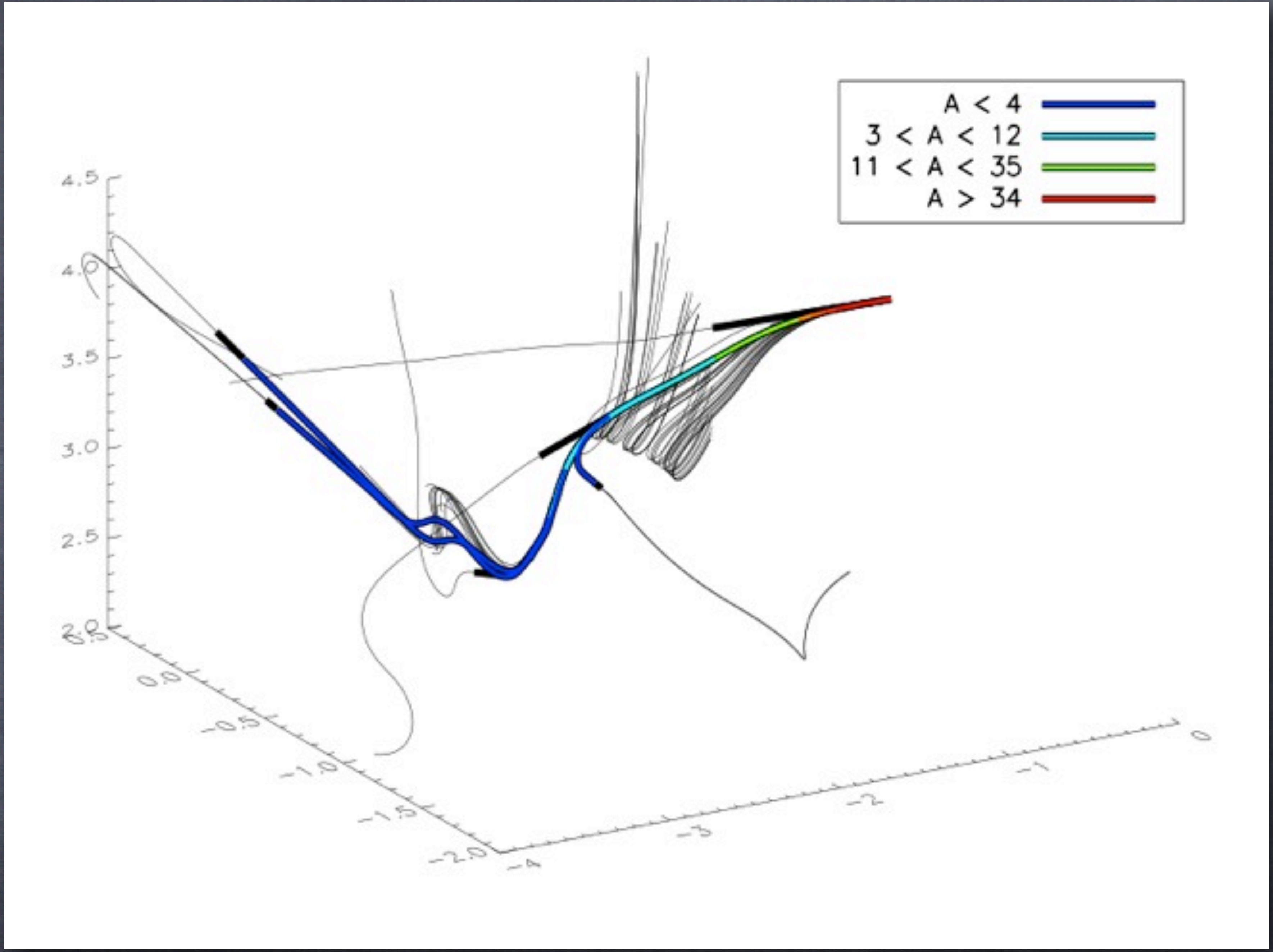
Miniati



Kotera, Olinto, Ann.Rev.Astron.Astrophys. 49 (2011) 119

Filling factors of extragalactic magnetic fields are not well known and come out different in different large scale structure simulations

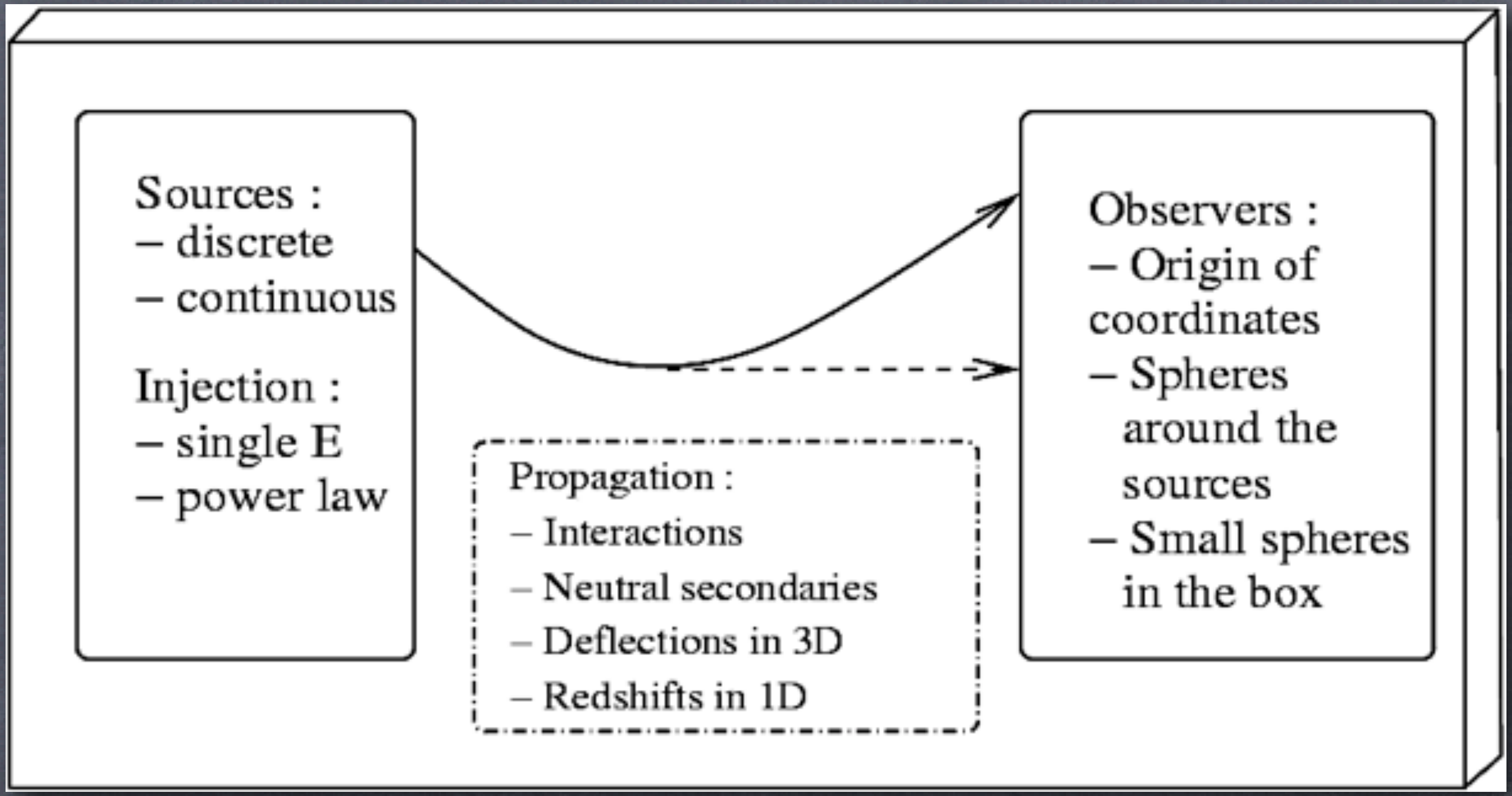
Extragalactic iron propagation produces nuclear cascades in structured magnetic fields:



Initial energy 1.2×10^{21} eV, magnetic field range 10^{-15} to 10^{-6} G. Color-coded is the mass number of secondary nuclei

CRPropa 2.0

CRPropa is a public code for UHE cosmic rays, neutrinos and γ-rays being extended to heavy nuclei and hadronic interactions



Eric Armengaud, Tristan Beau, Günter Sigl, Francesco Miniati,
Astropart.Phys.28 (2007) 463.

Version 1.4 at http://apcauger.in2p3.fr/CRPropa/index.php

Now including: Jörg Kulbartz, Luca Maccione,
Nils Nierstenhoefer, Karl-Heinz Kampert, Peter Schiffer, Arjen van Vliet

ask for beta version CRPropa 2.0 !

The main part of the code is written in C++ and calls some Fortran routines (mainly SOPHIA for interactions photo-pion production of nucleons)
nuclear interactions based on TALYS

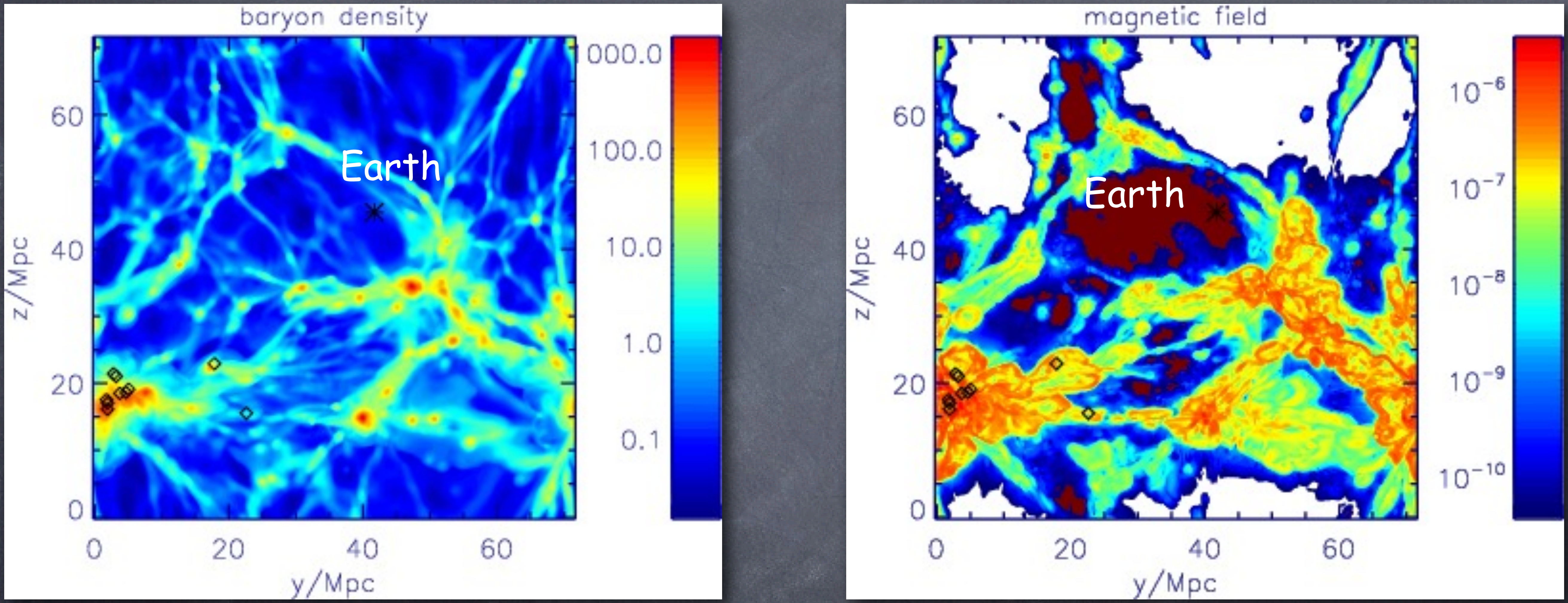
Electromagnetic cascades are treated by solving one-dimensional transport equations

The set-up (source distributions, environment, magnetic fields, low energy photon backgrounds, injection spectrum, arbitrary composition at fixed energy per nucleon, which interactions/secondaries to take into account)
can be provided with xml files.

Output can be in form of whole trajectories or events; possible output formats are ASCII, FITS or ROOT.

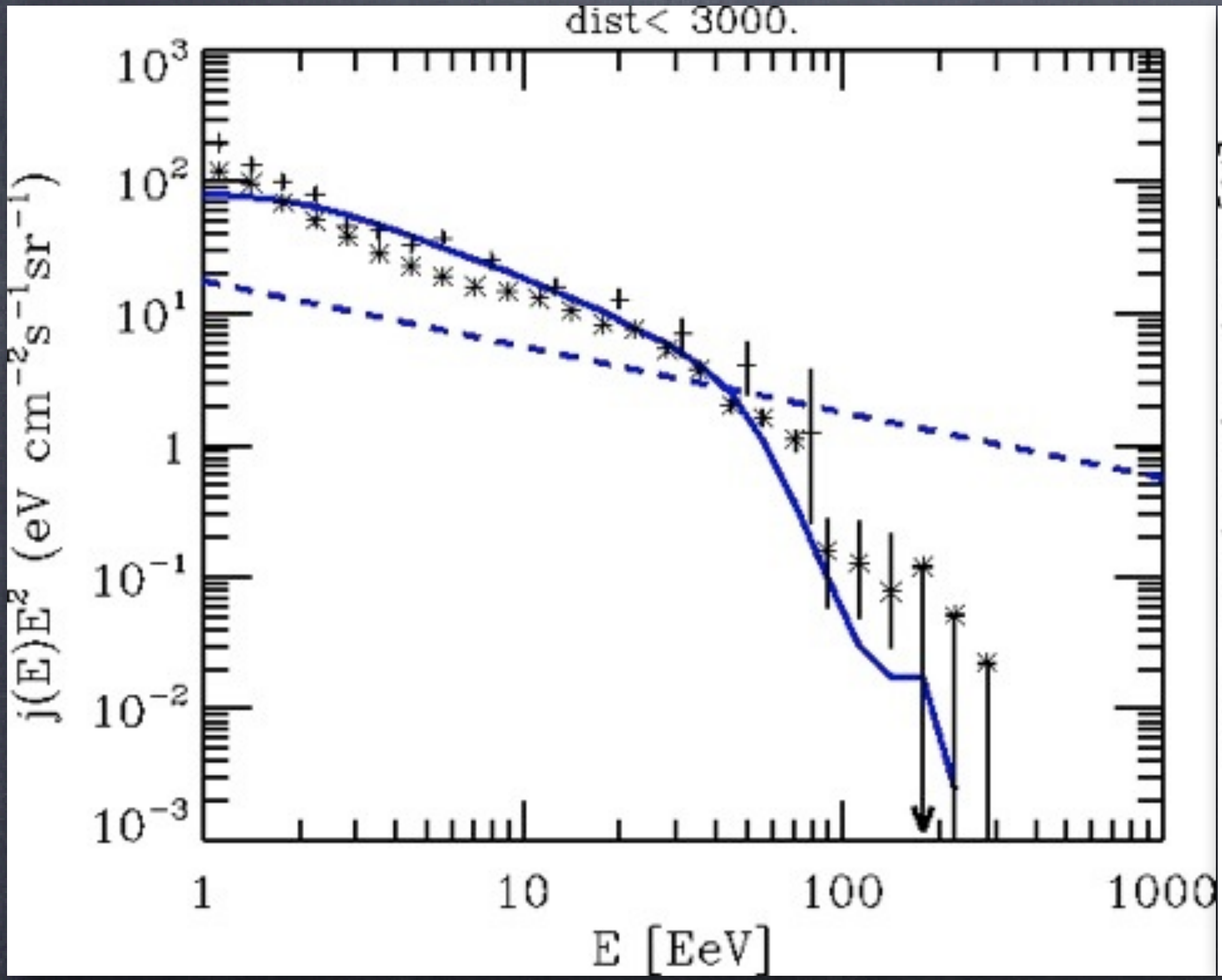
Presented are two examples for 1D and 3D simulations

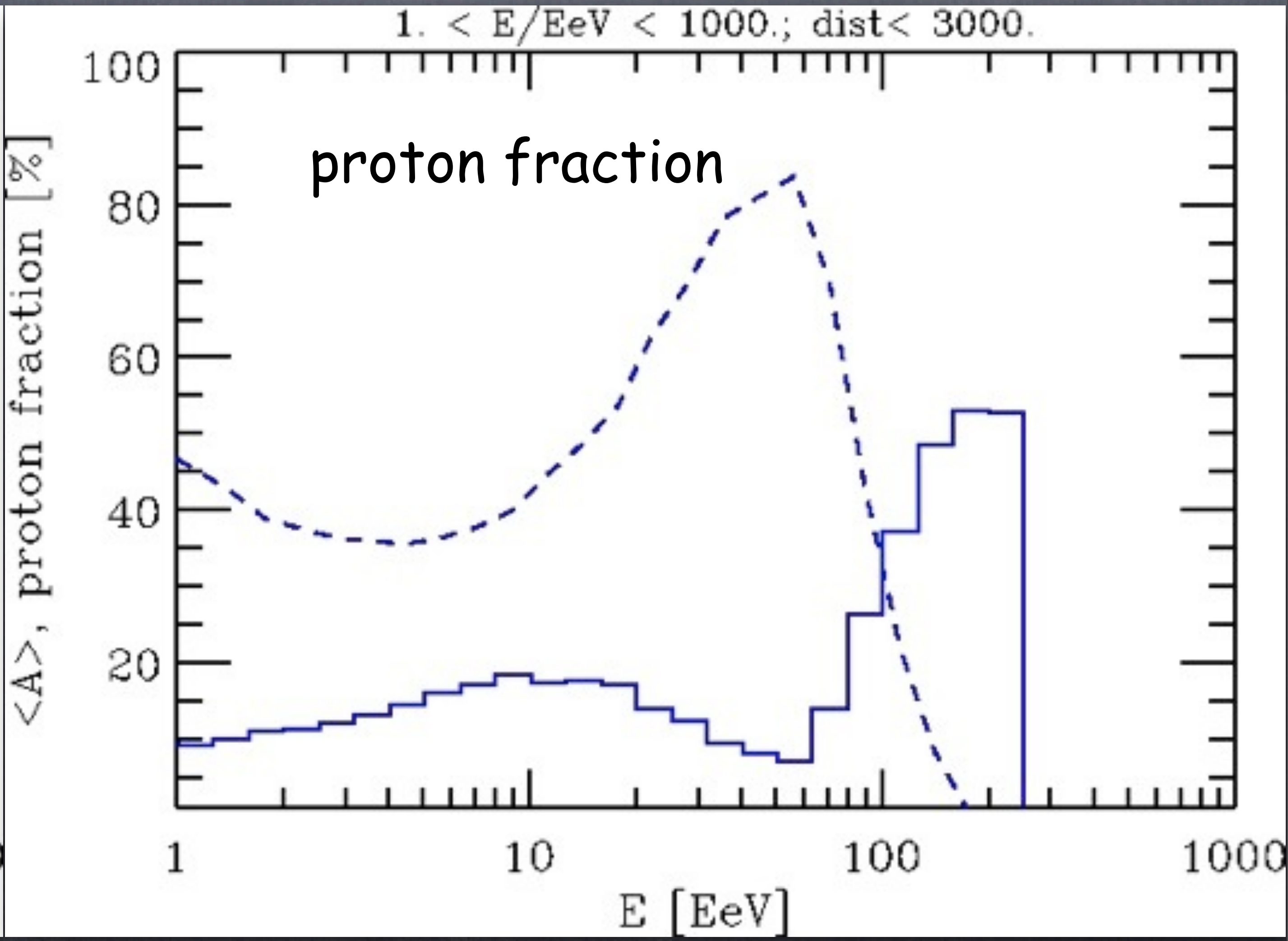
Discrete Sources in nearby large scale structure



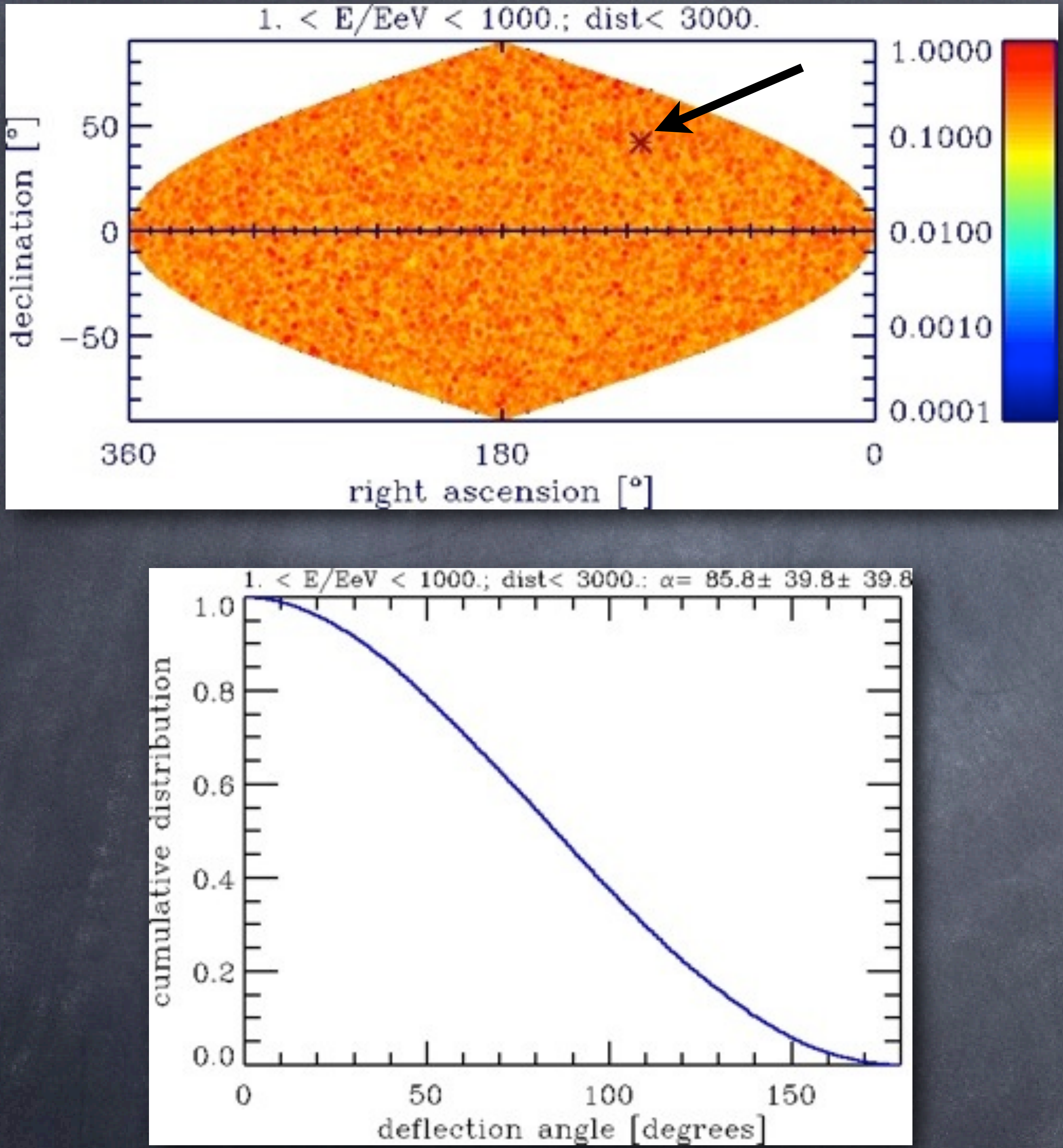
10 sources per (75 Mpc)^3 box, concentrated in a galaxy cluster at ≃30 Mpc, injecting $E^{-2.5}$ spectra up to 200xZ EeV with 10 x galactic abundance;
+ one source @ 4Mpc of 0.002 relative strength injecting E^{-2} spectrum up to 10xZ EeV.

Results: Spectra and Composition

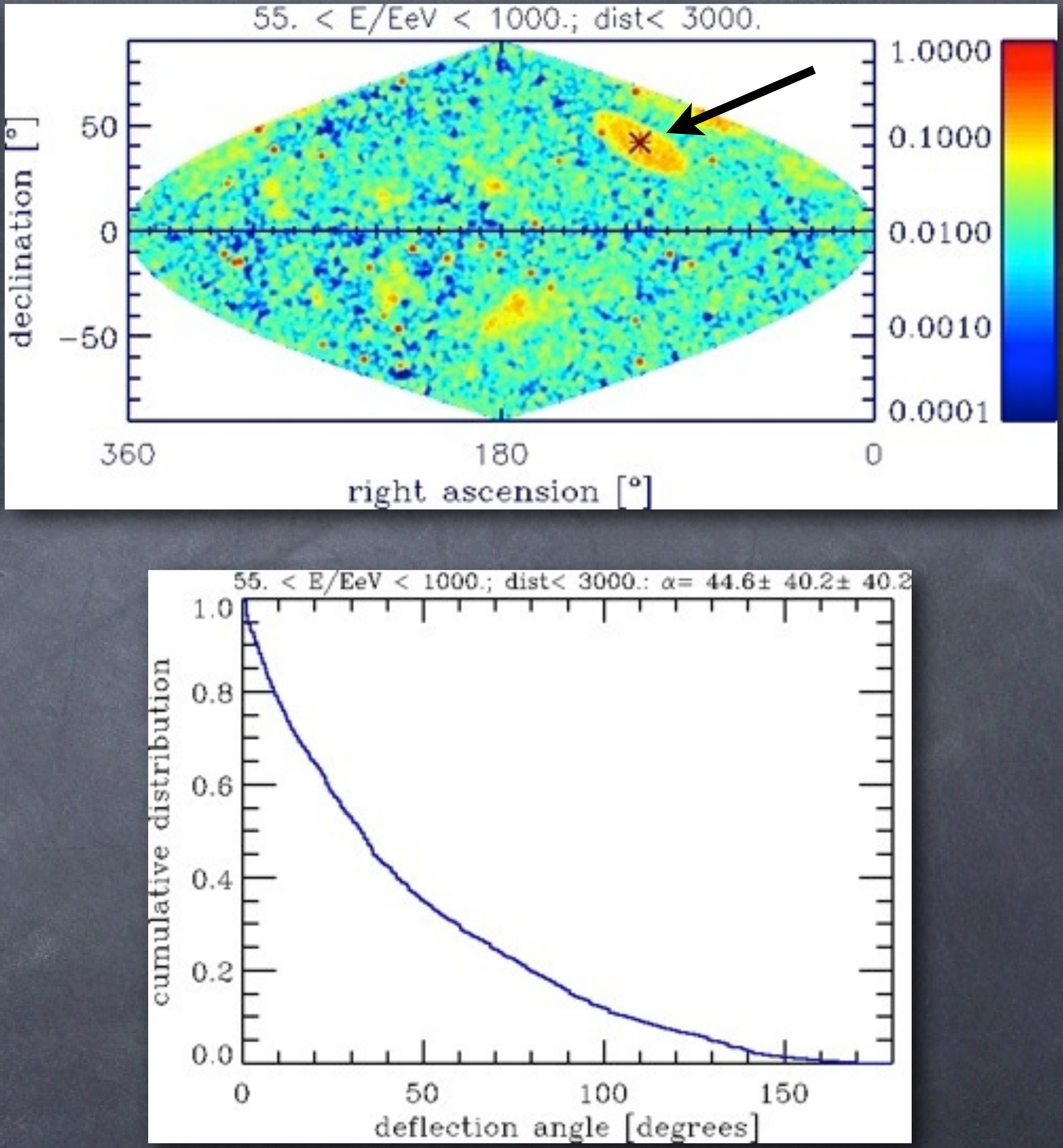




Results: Sky Distributions and Anisotropies



above 1 EeV



above 55 EeV

It is surprisingly difficult to construct simple scenarios with structured sources and magnetic fields that reproduce all observations: spectra, energy dependent composition and anisotropy; to explain them separately is quite easy

Conclusions

1.) It is surprisingly difficult to construct simple scenarios with structured sources and magnetic fields that reproduce all observations: spectra, energy dependent composition and anisotropy; to explain them separately is quite easy

2.) The observed X_{max} distribution of air showers provides potential constraints on hadronic interaction models: Some models are in tension even when “optimizing” unknown mass composition; however, systematic uncertainties are still high.

Conclusions

3.) Both diffuse cosmogenic neutrino and photon fluxes mostly depend on chemical composition, maximal acceleration energy and redshift evolution of sources

4.) Multi-messenger modeling sources including gamma-rays and neutrinos start to constrain the source and acceleration mechanisms

5.) Highest Energy Cosmic Rays, Gamma-rays, and Neutrinos give the strongest constraints on violations of Lorentz symmetry => terms suppressed to first and second order in the Planck mass would have to be unnaturally small