Links between High Energy Cosmic Rays, Gamma-Rays and Neutrinos

Günter Sigl

(supported by DFG, BMBF, Germany and Forschungs- und Wissenschaftsstiftung Hamburg)

1. Introduction and Experimental Situation
2. Astrophysics of Sources and Propagation
3. Particle Physics at High Energies

DFG Deutsche Forschungsgemeinschaft
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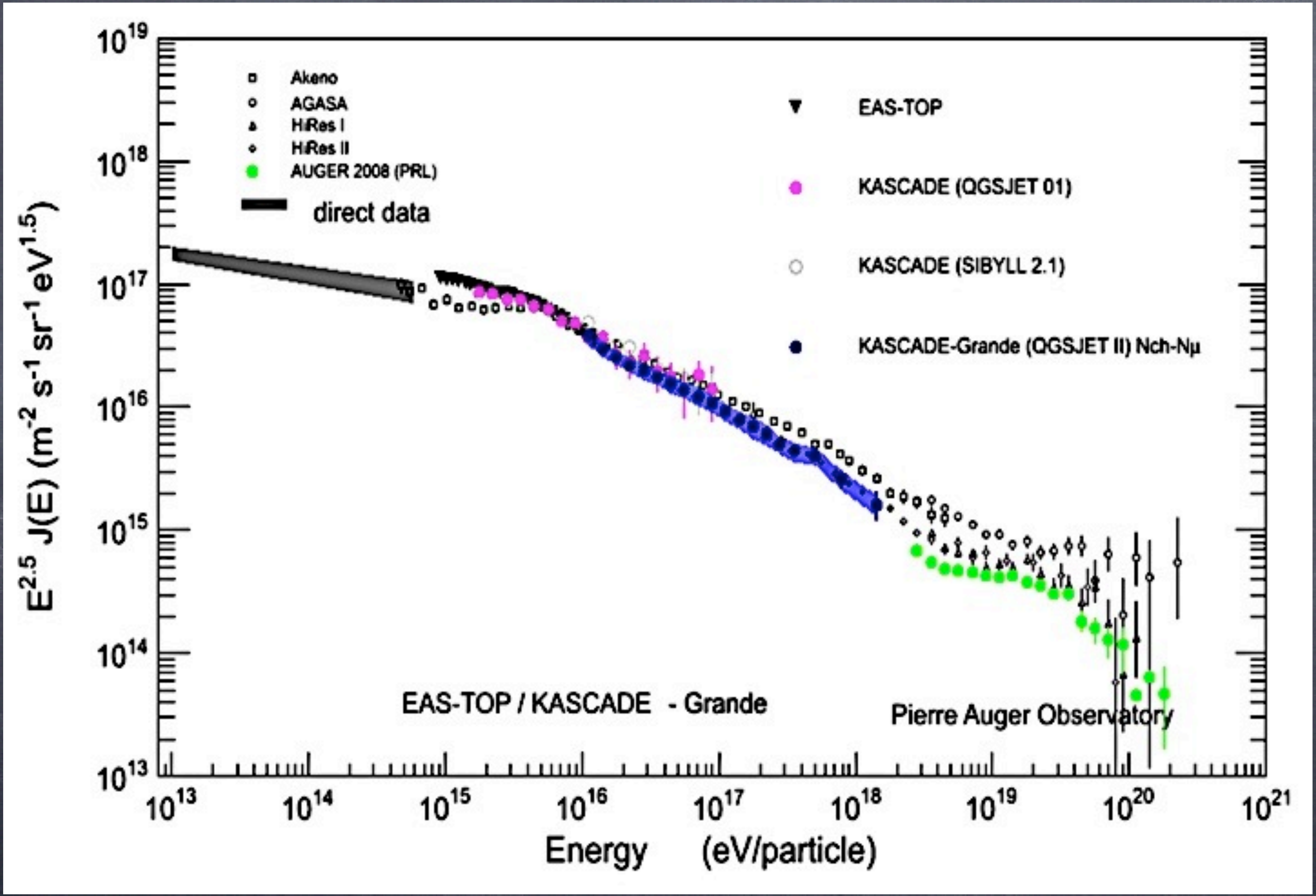
http://www2.iap.fr/users/sigl/homepage.html

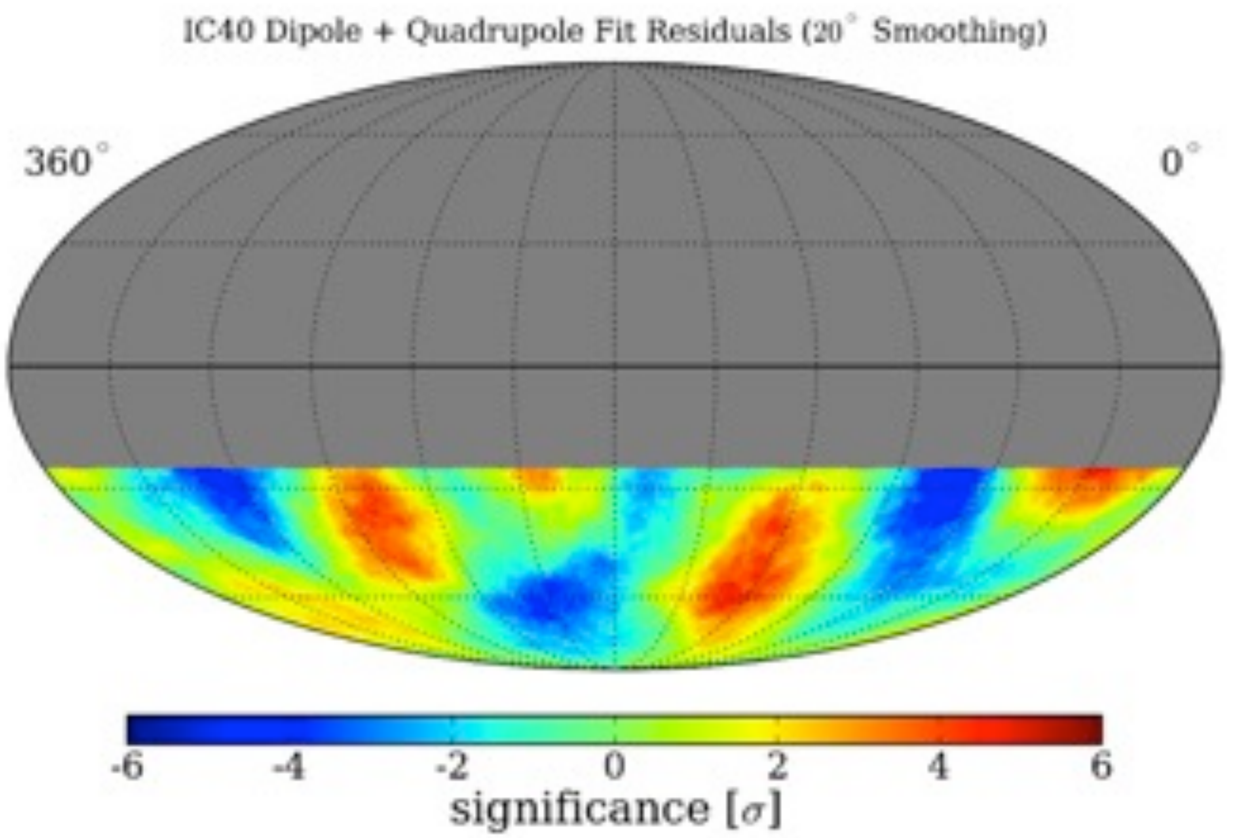
The All Particle Cosmic Ray Spectrum

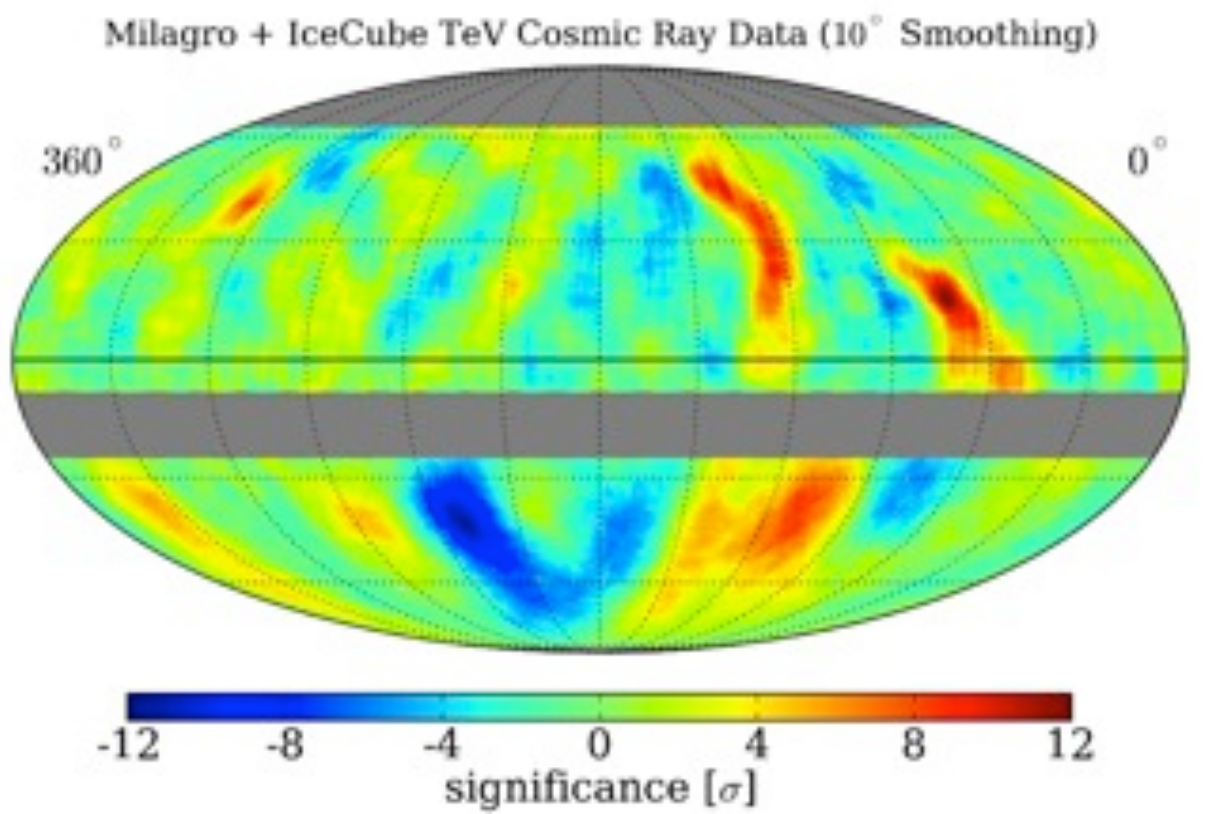


KASCADE-Grande collaboration, arXiv:1009.4716

An Example from Galactic Cosmic Rays: Do Cosmic Ray Anisotropies at 1-100 TeV reveal the Sources ?

R. Abbasi et al, ICECUBE collaboration, ApJ. 740 (2011) 16





Observed level ~ 10^{-3} can be explained by a cosmic rays gradient from nearby sources, but in diffusion theory only gives dipoles

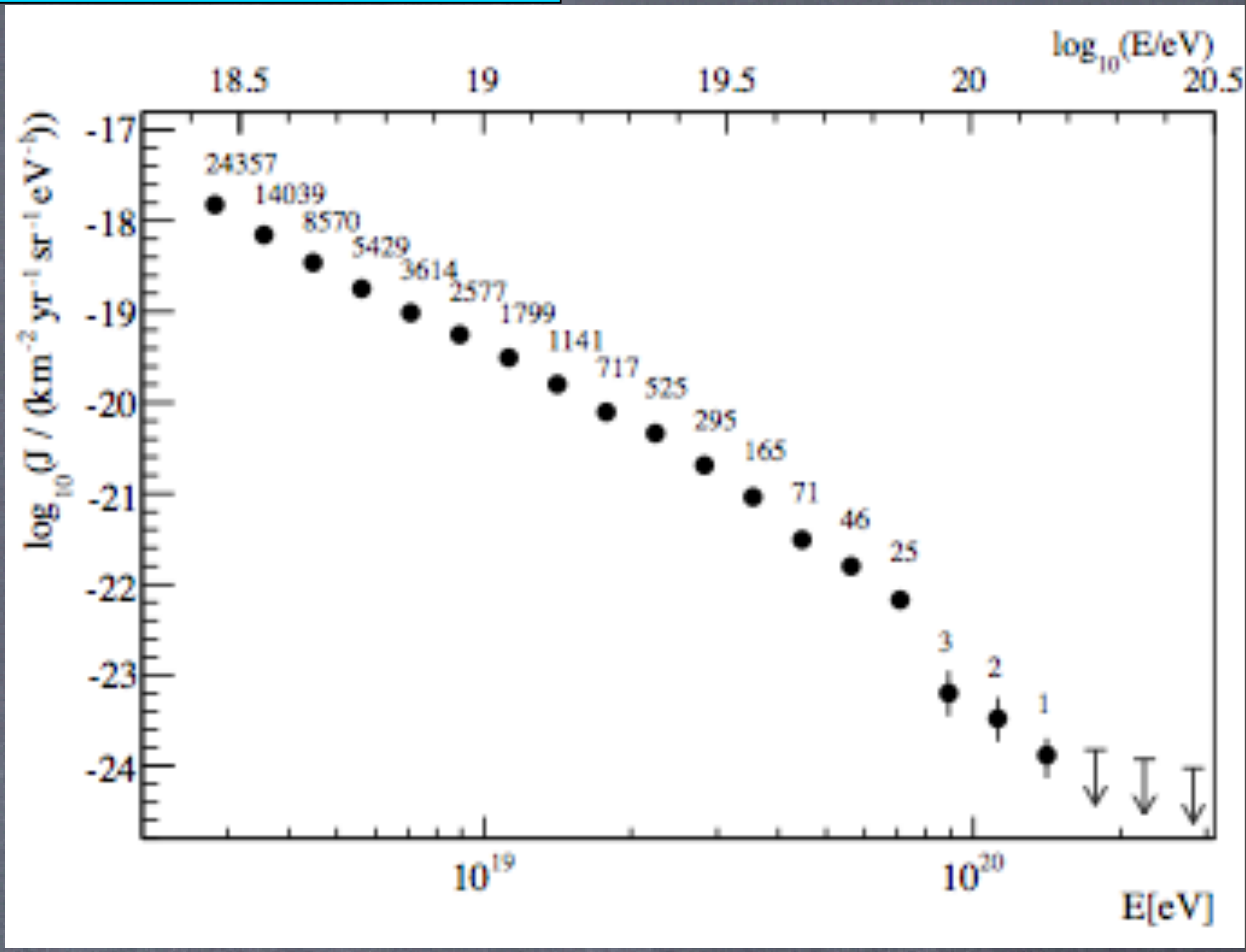
wrong structure for Compton-Getting effect

propagation mode, magnetic field structure: it may just reveal the magnetic field structure within one scattering length which can not be described by diffusion equation: Giacinti and Sigl, arXiv:1111.2536

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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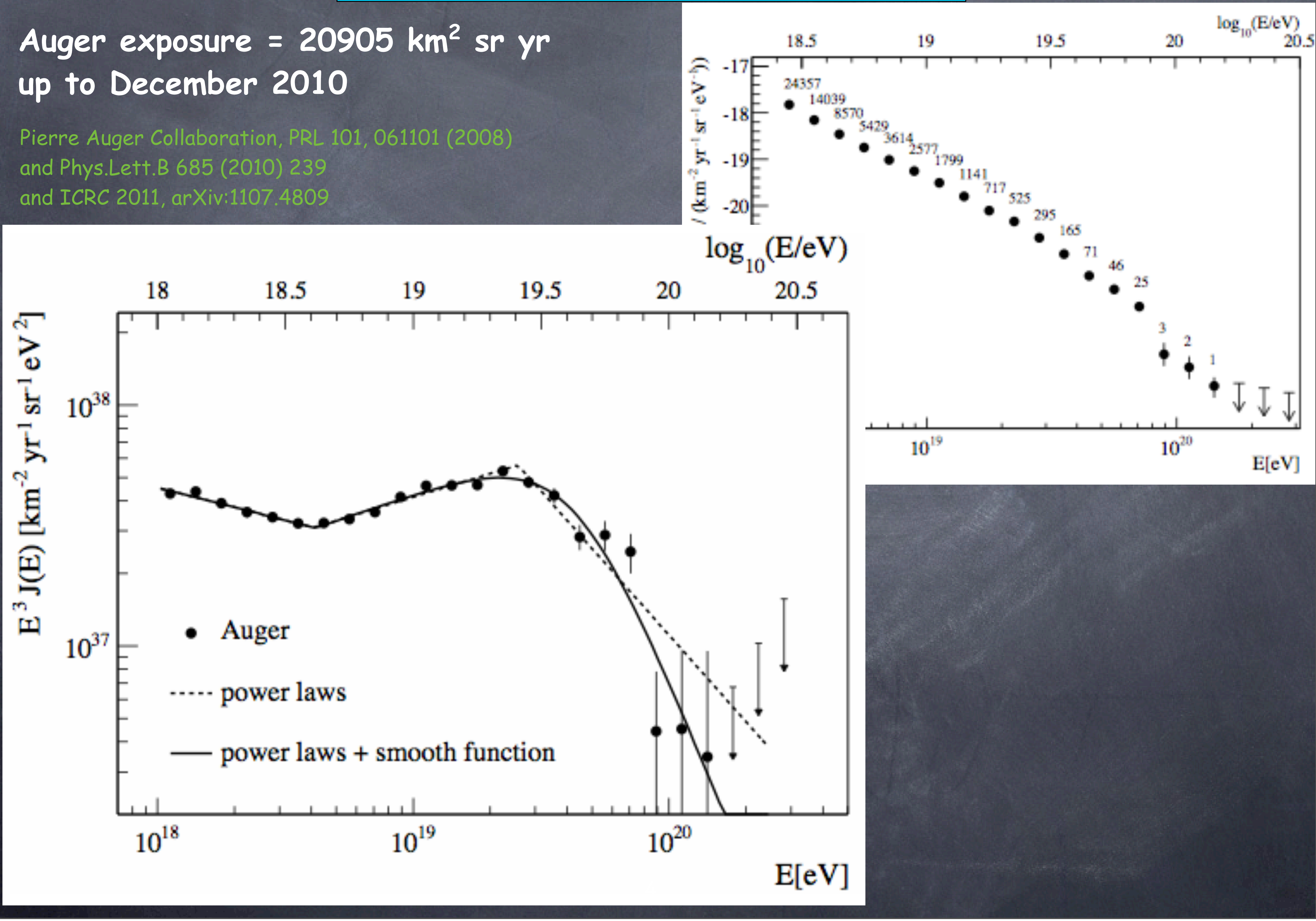
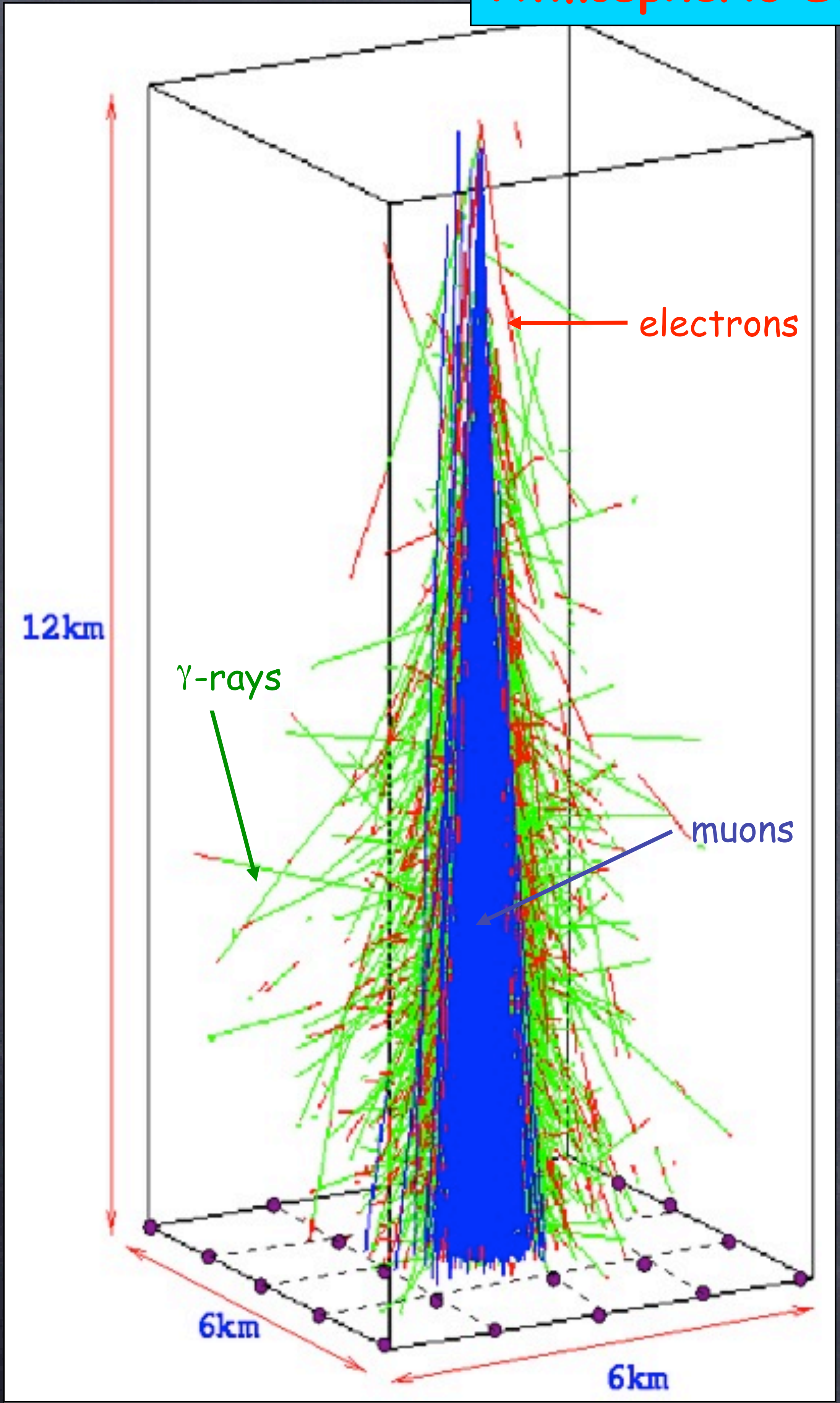


Atmospheric Showers and their Detection



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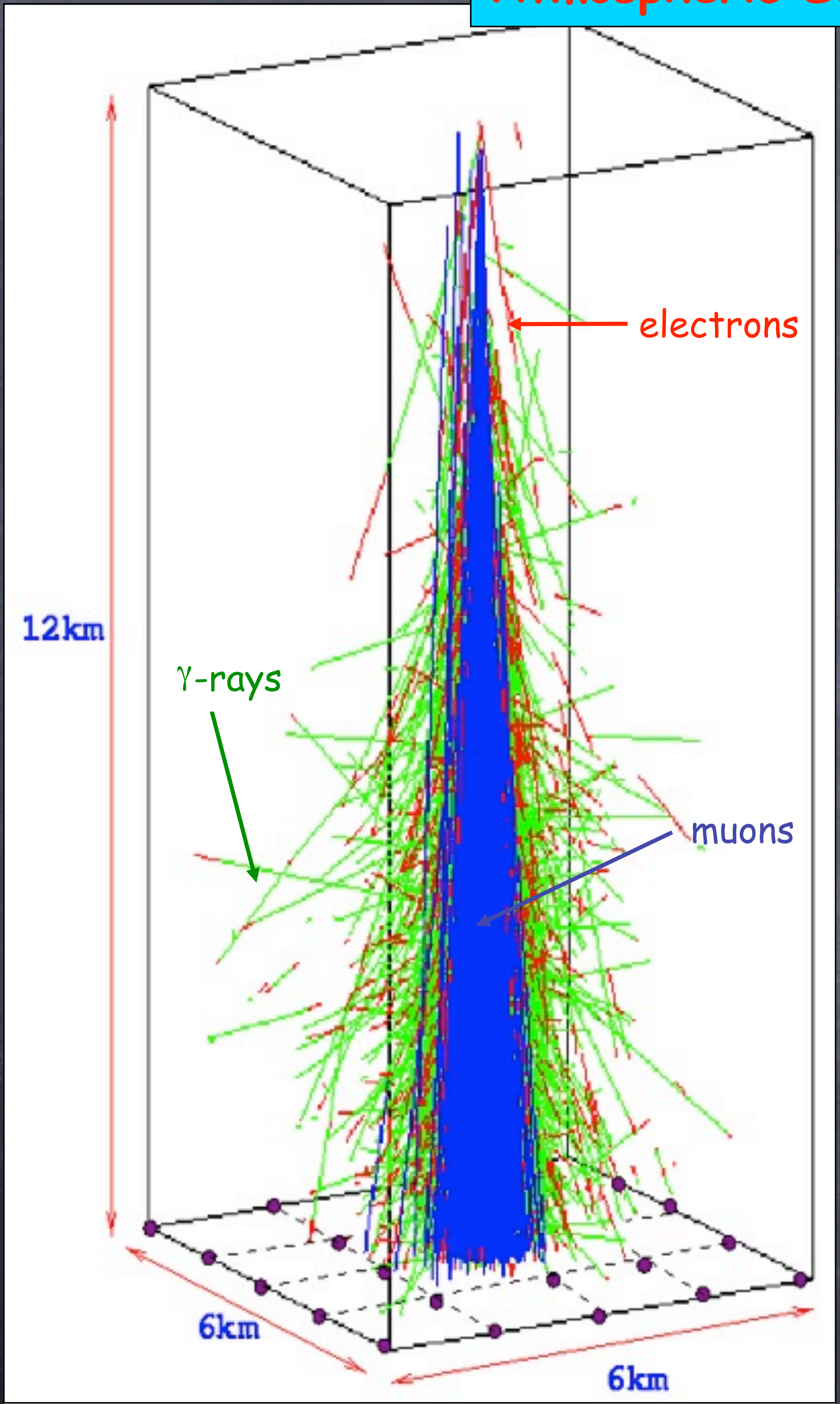

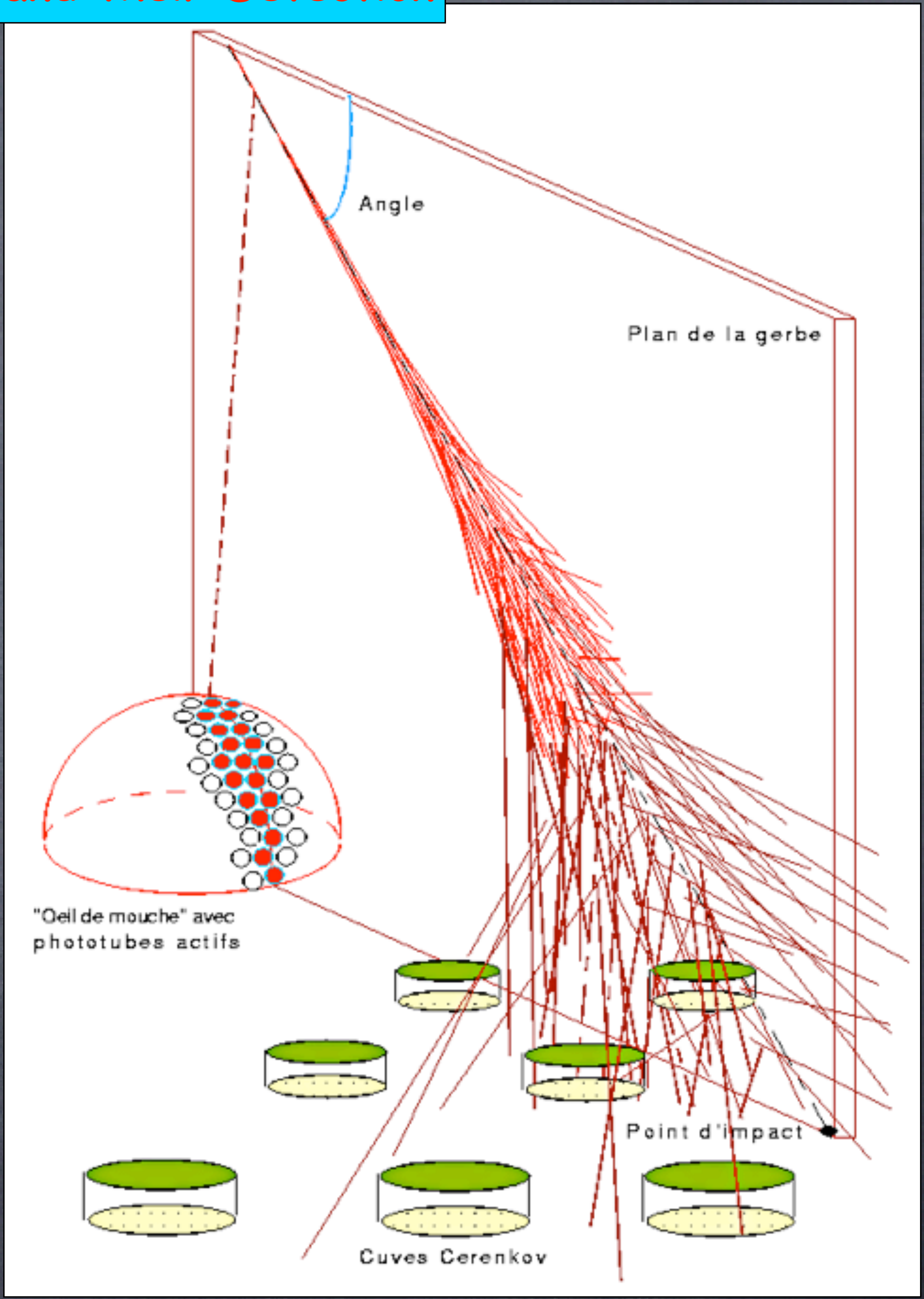

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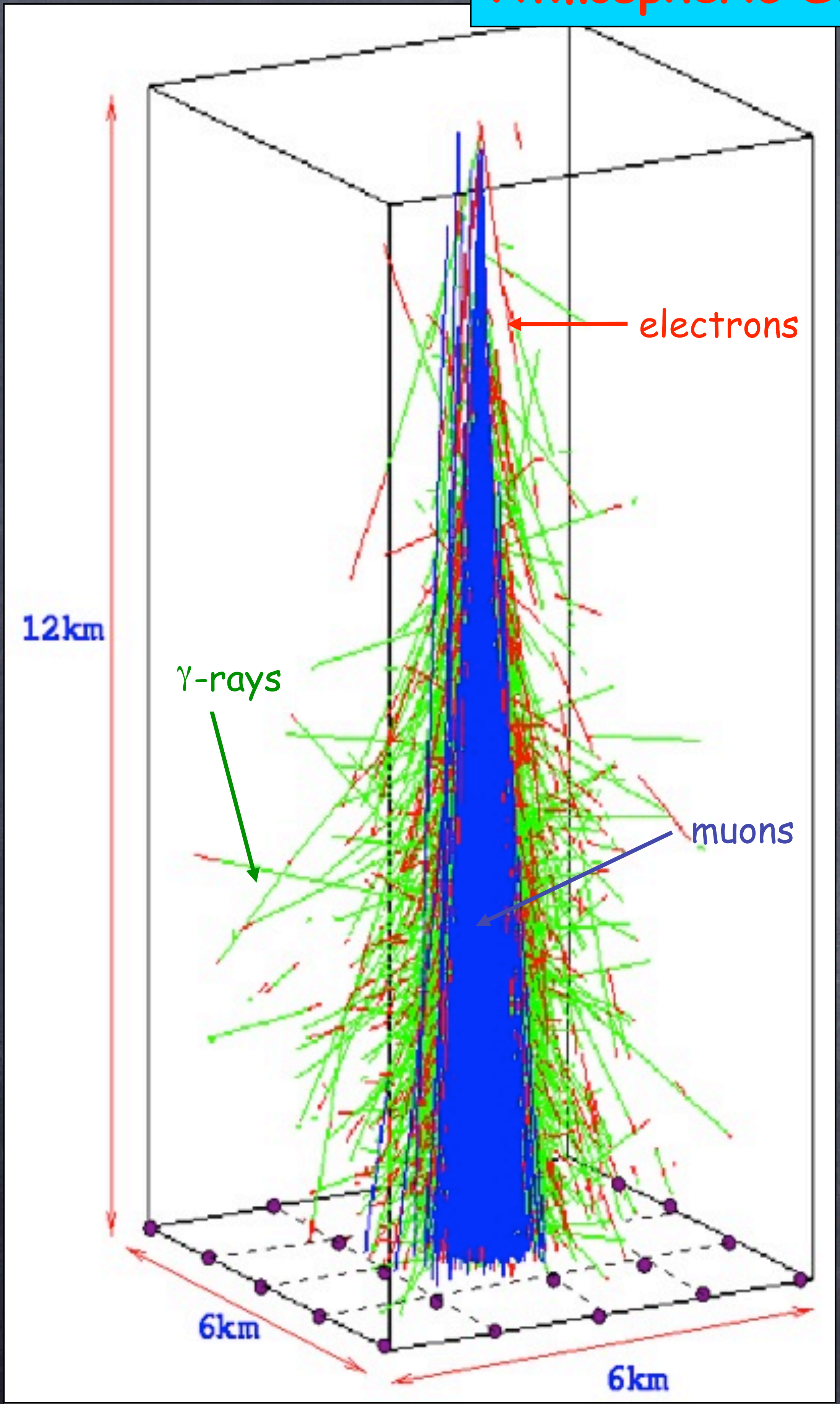

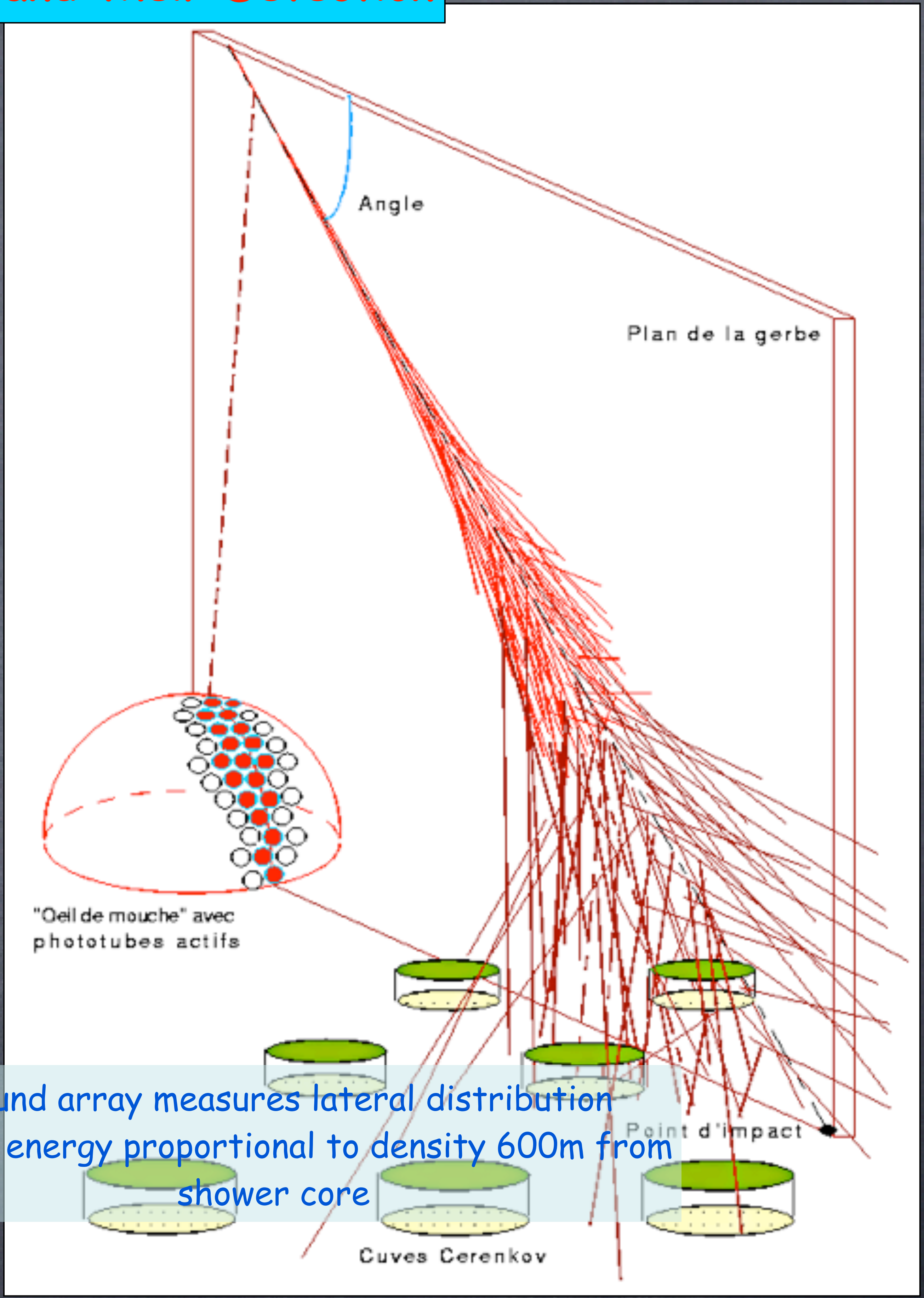

Ground array measures lateral distribution
Primary energy proportional to density 600m from shower core

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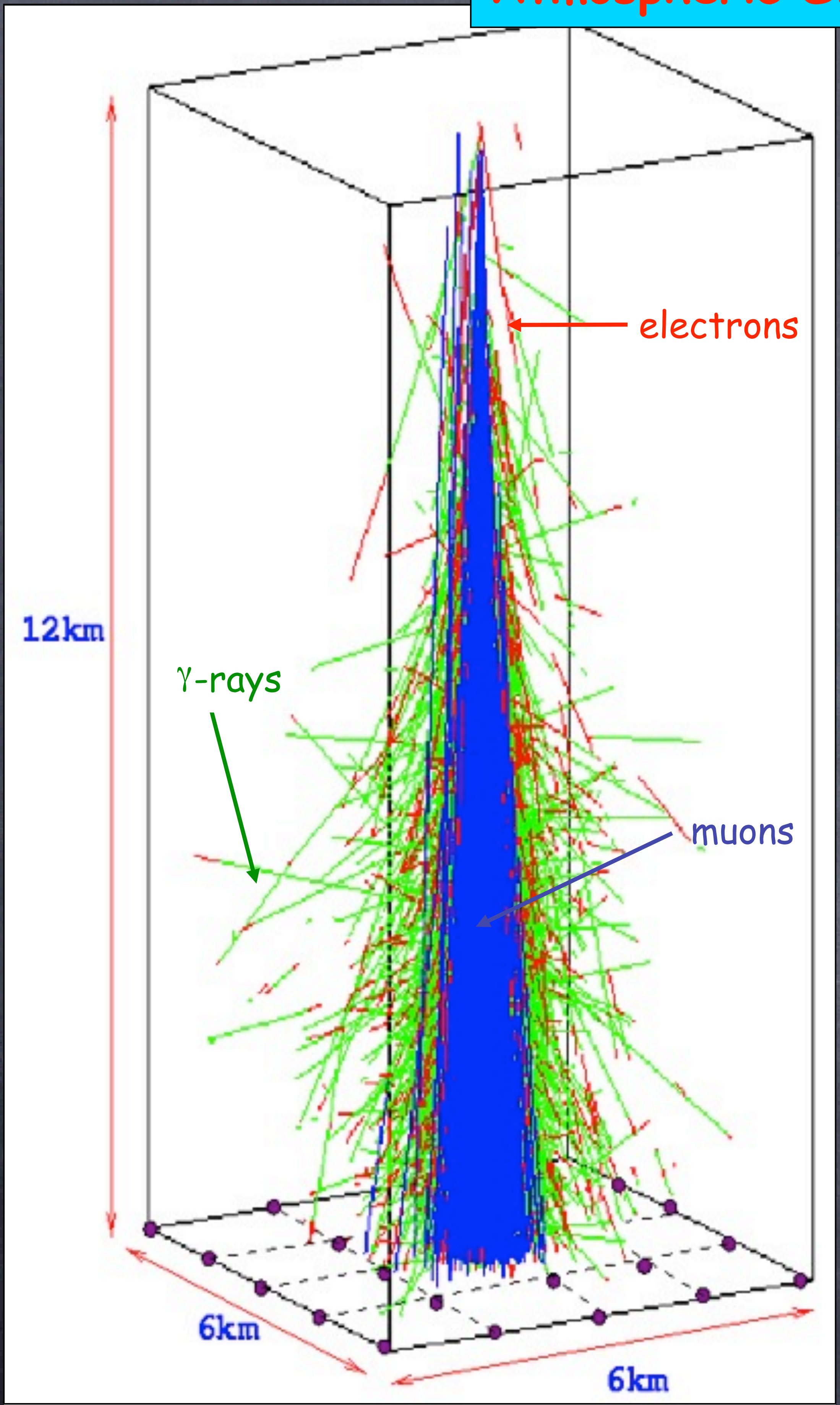
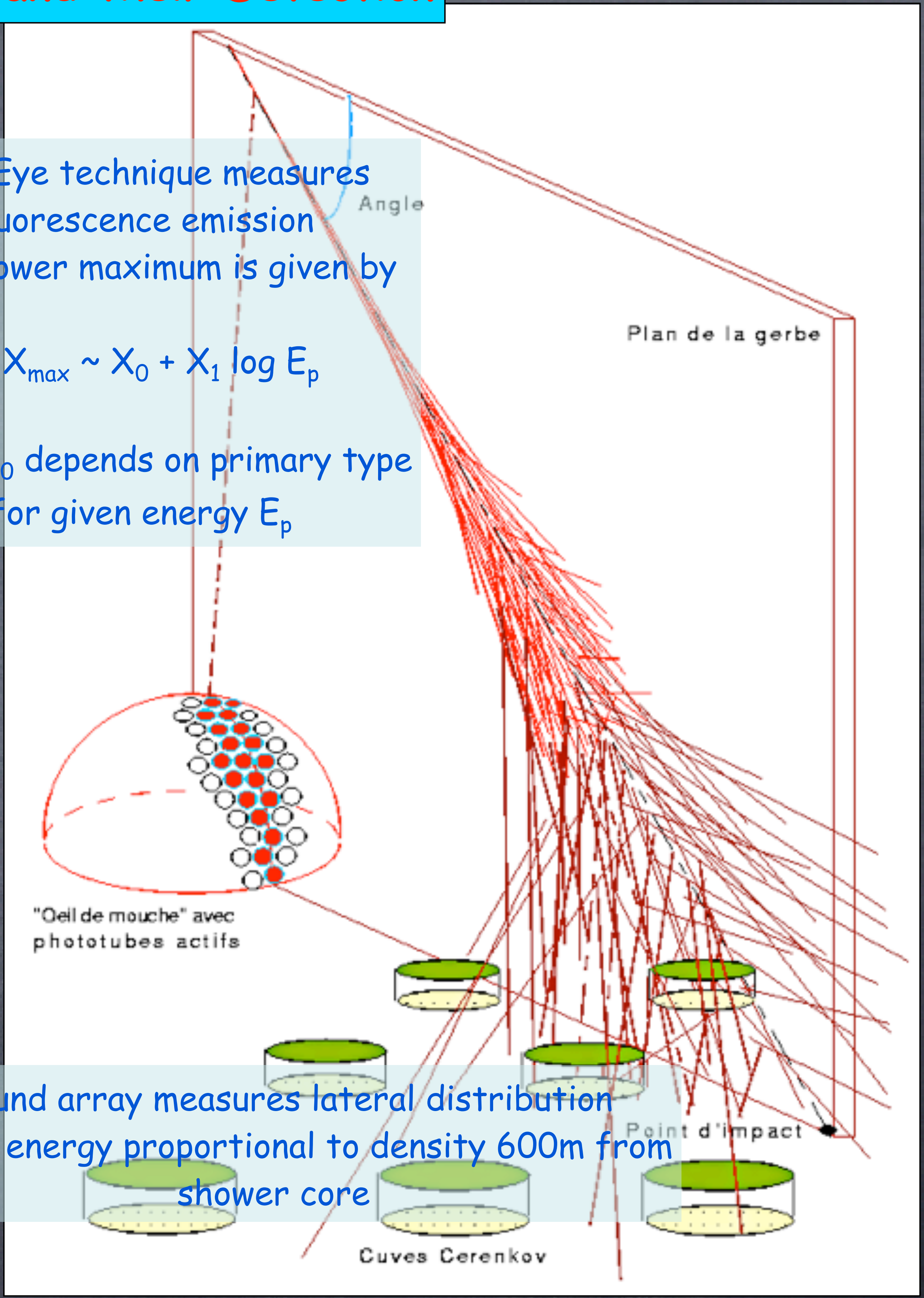


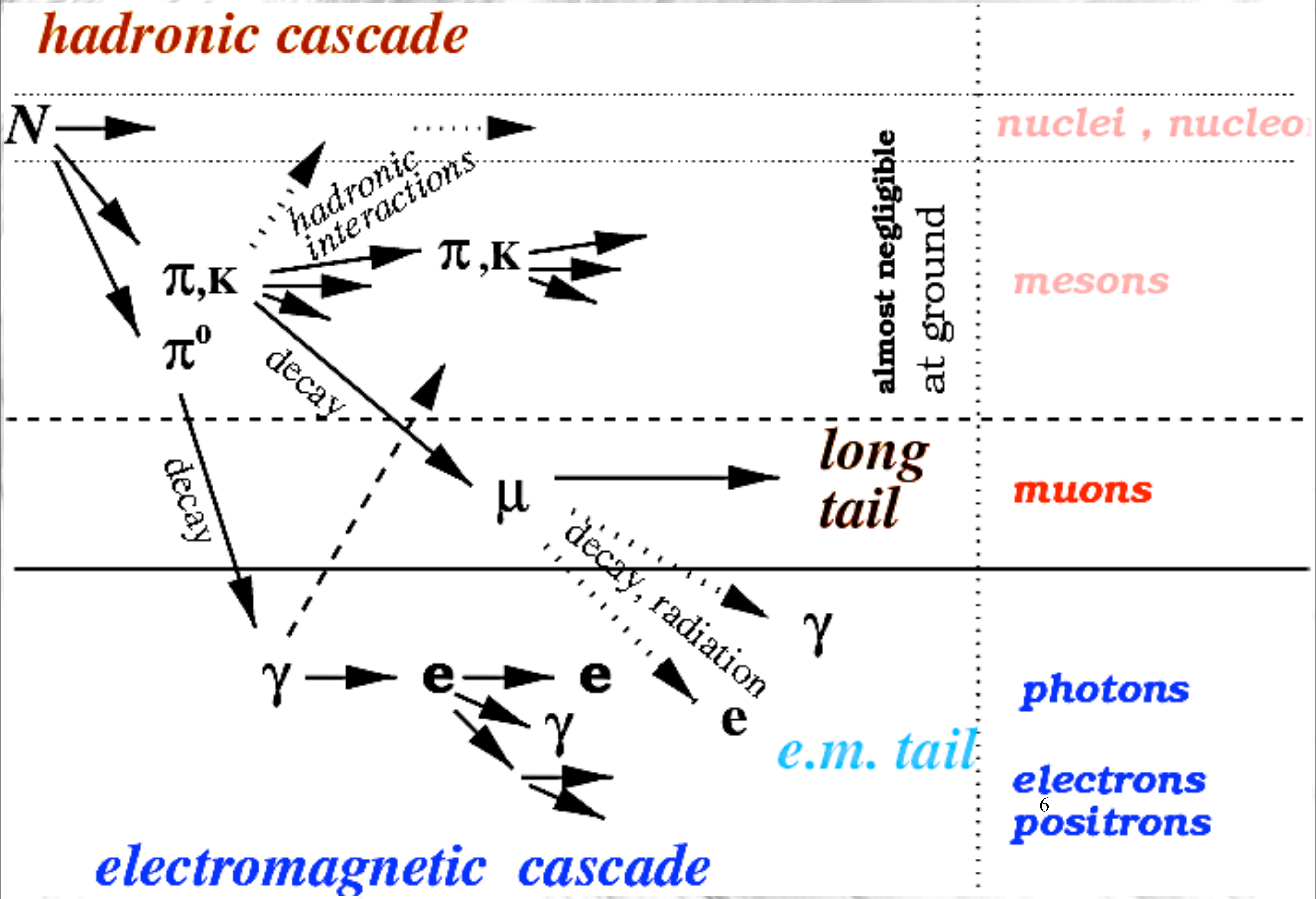


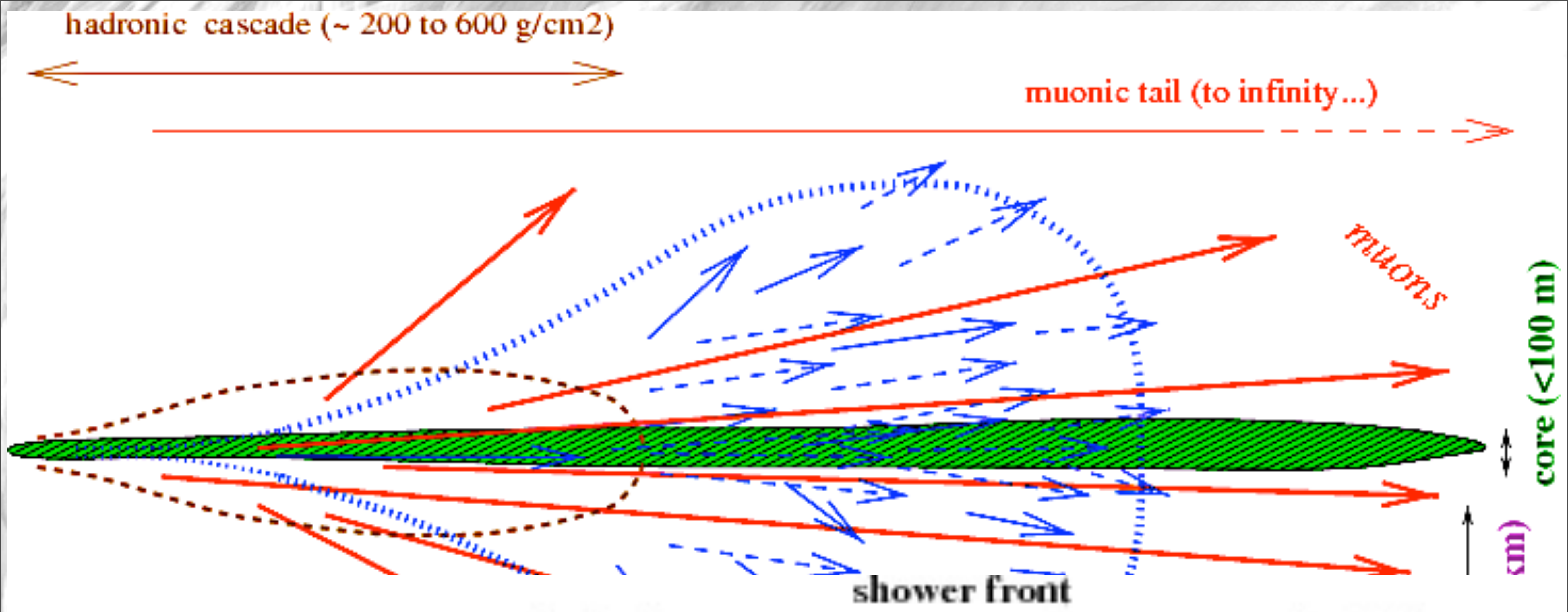
Fly's Eye technique measures fluorescence emission
The shower maximum is given by

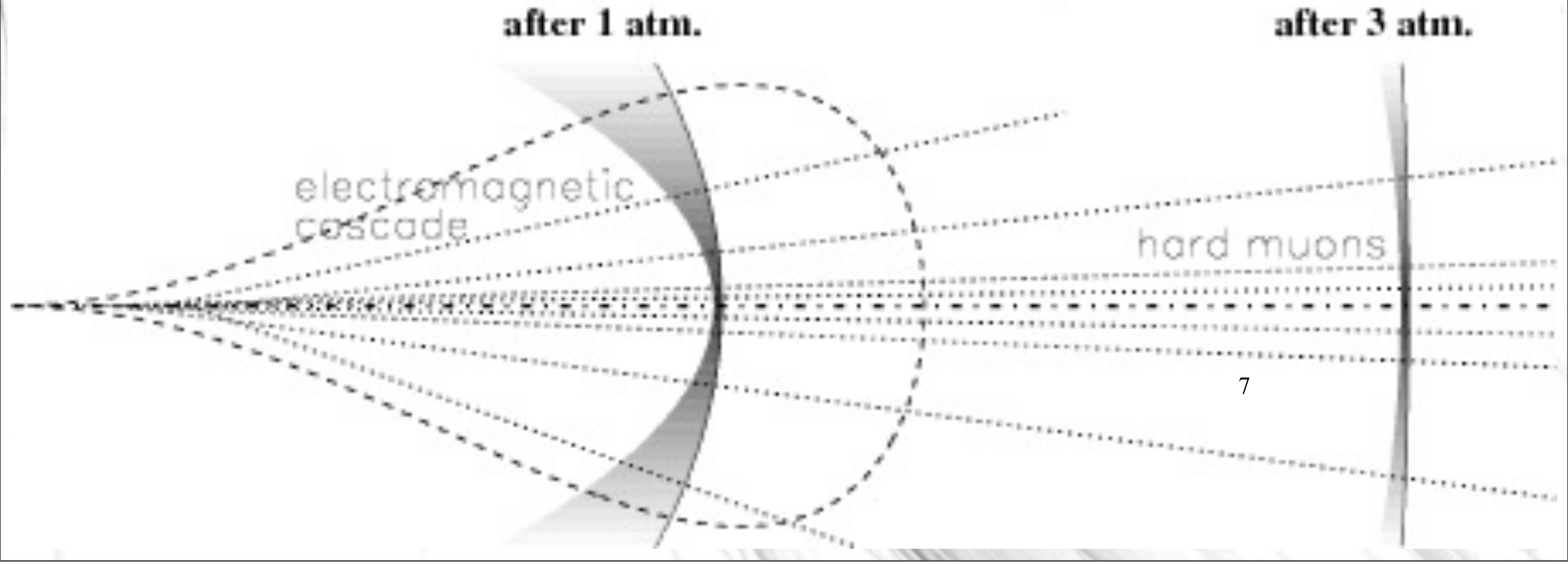
$$X_{max} \sim X_0 + X_1 \log E_p$$

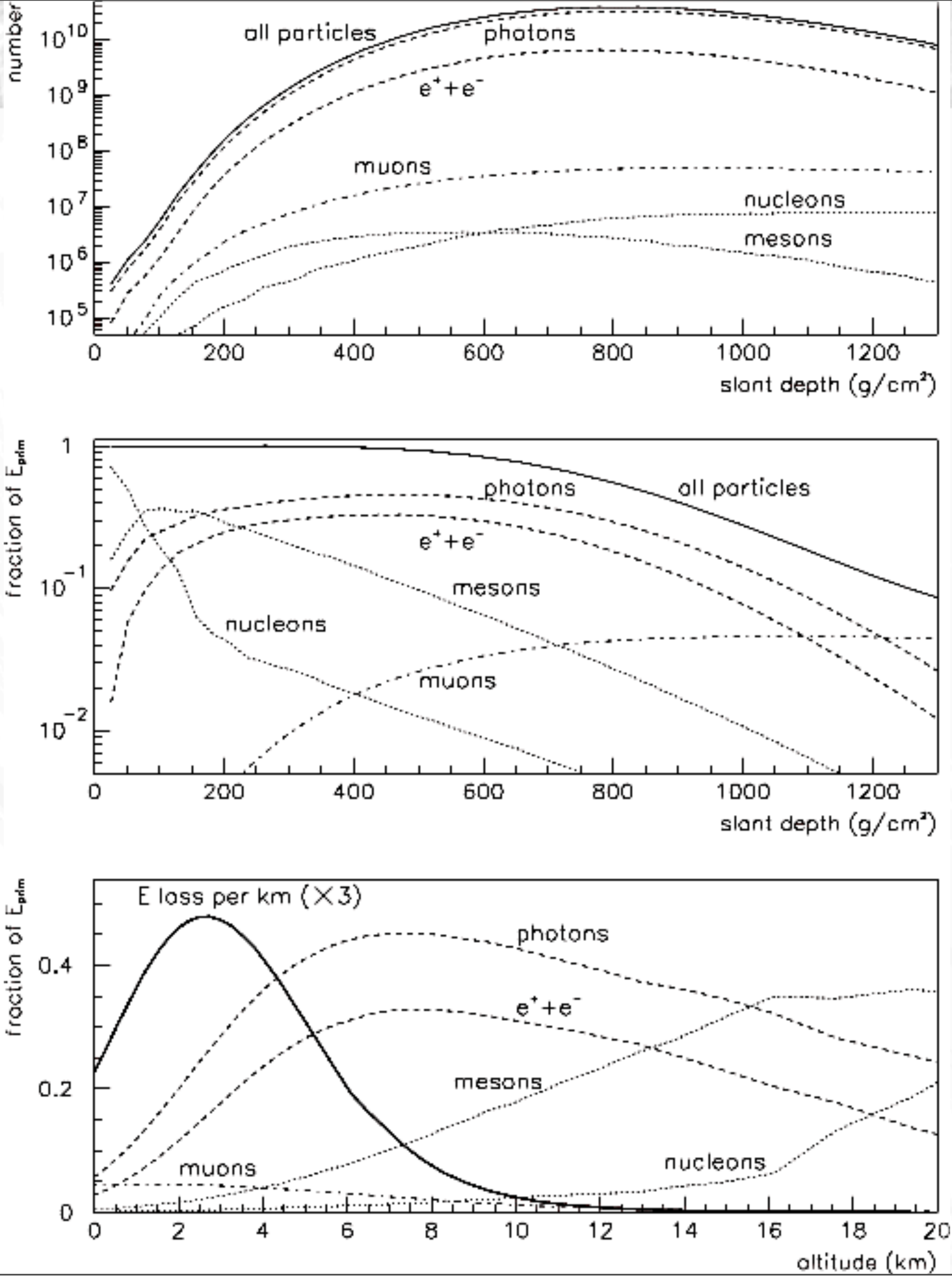
where X_0 depends on primary type for given energy E_p

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

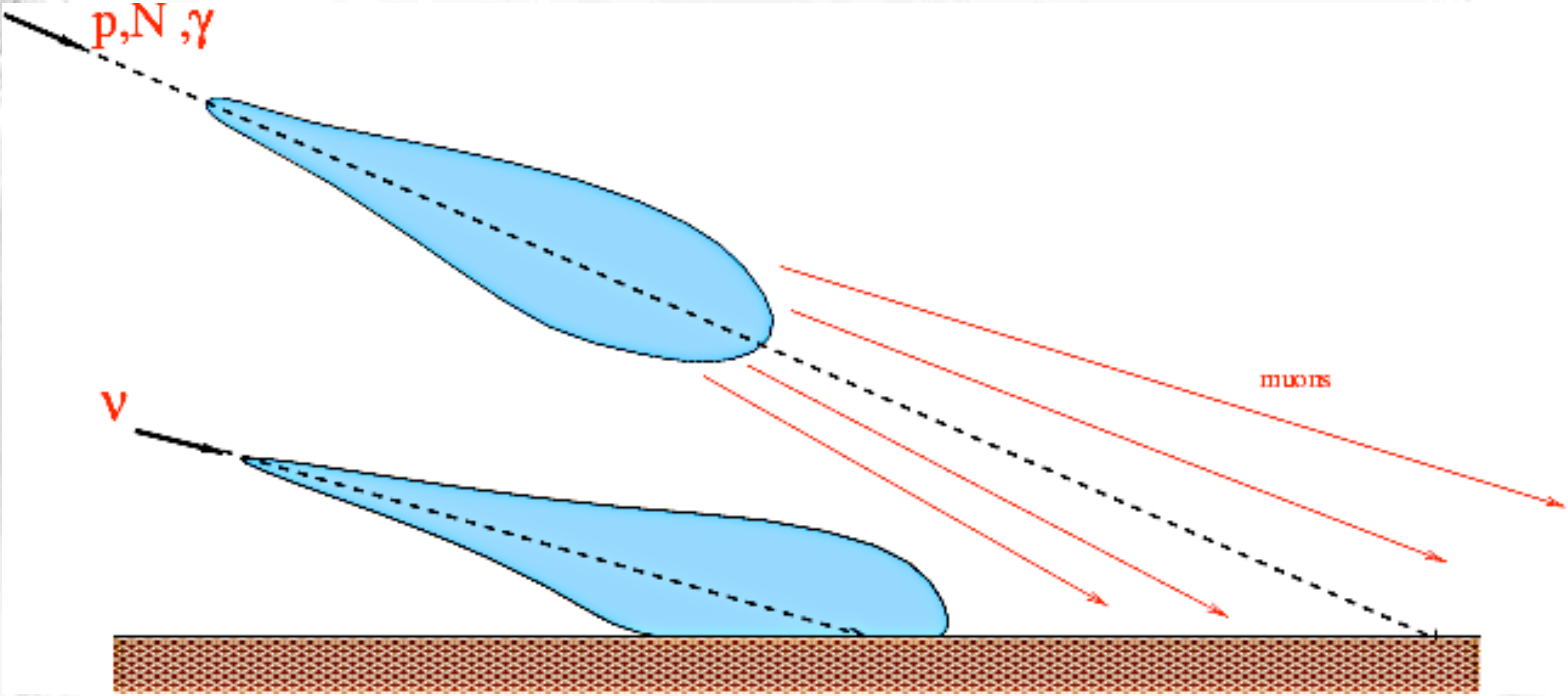

hadronic cascade
N
hadronic interactions
π,K
π,K
π⁰
decay
decay
almost negligible at ground
μ
long tail
decay, radiation
γ
γ
e
e
γ
e
e.m. tail
electromagnetic cascade
nuclei , nucleo
mesons
muons
photons
electrons
positrons

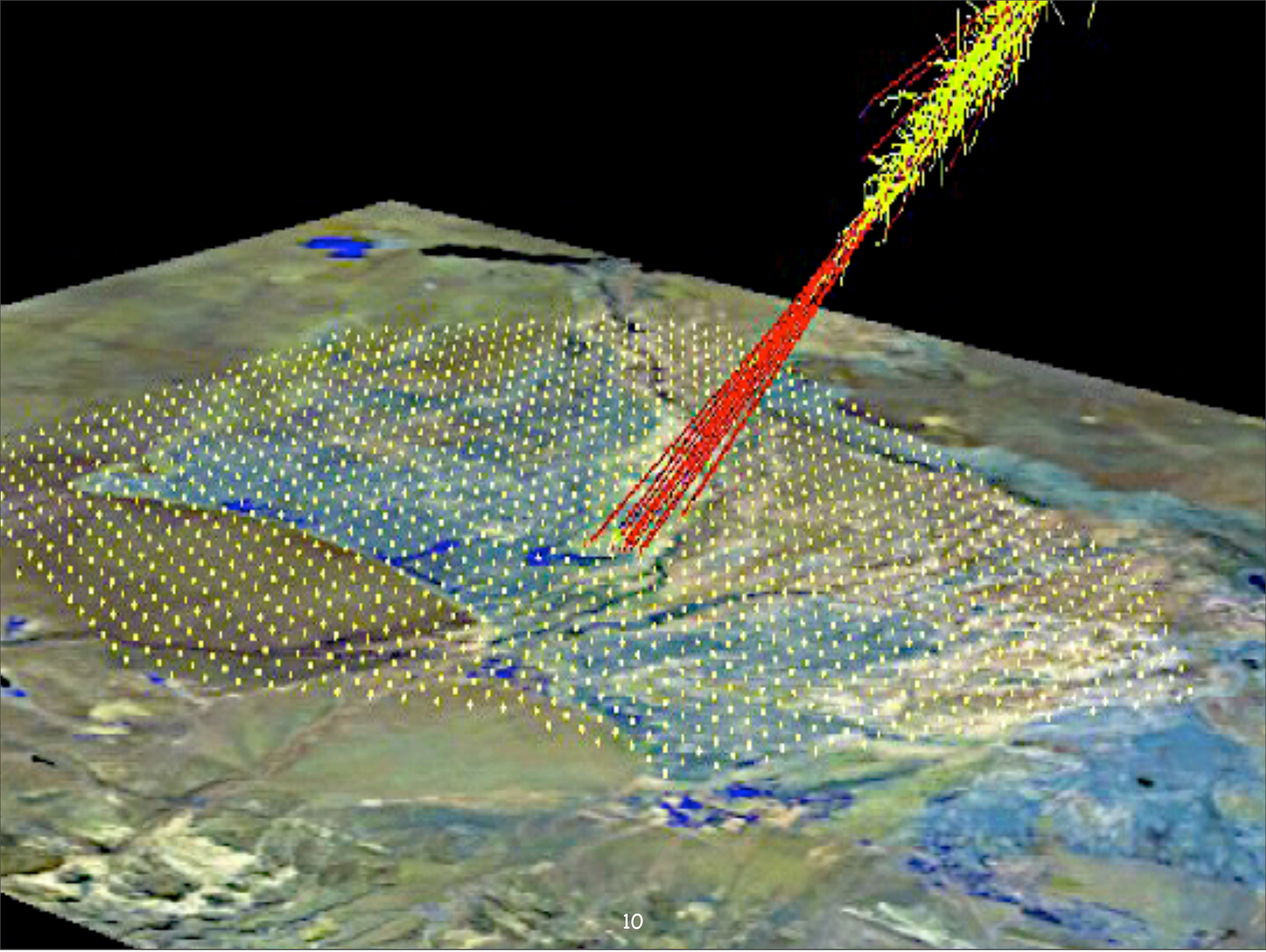

hadronic cascade (~ 200 to 600 g/cm2)
muonic tail (to infinity...)
muons
core (<100 m)
shower front

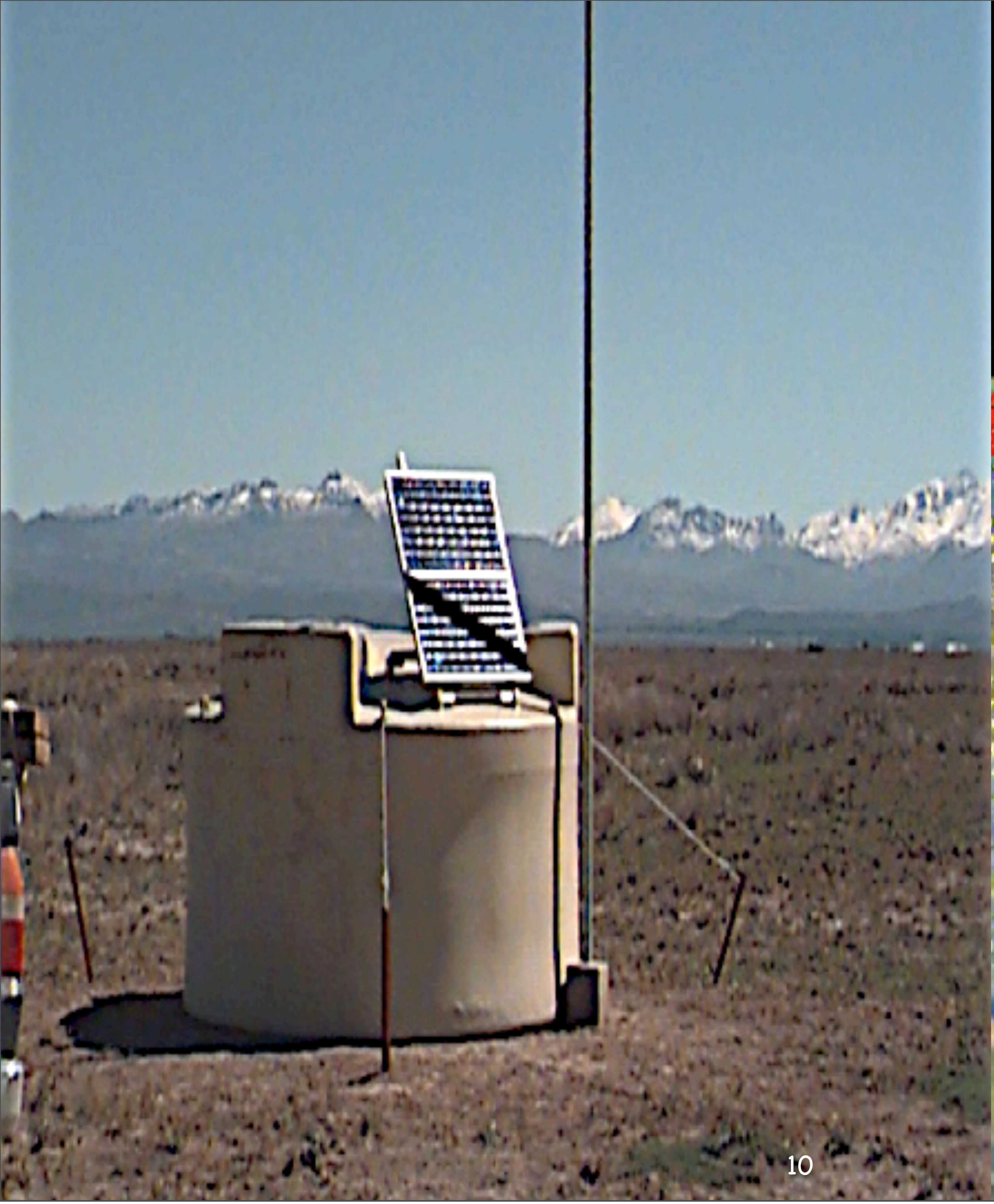

after 1 atm.
after 3 atm.
electromagnetic cascade
hard muons

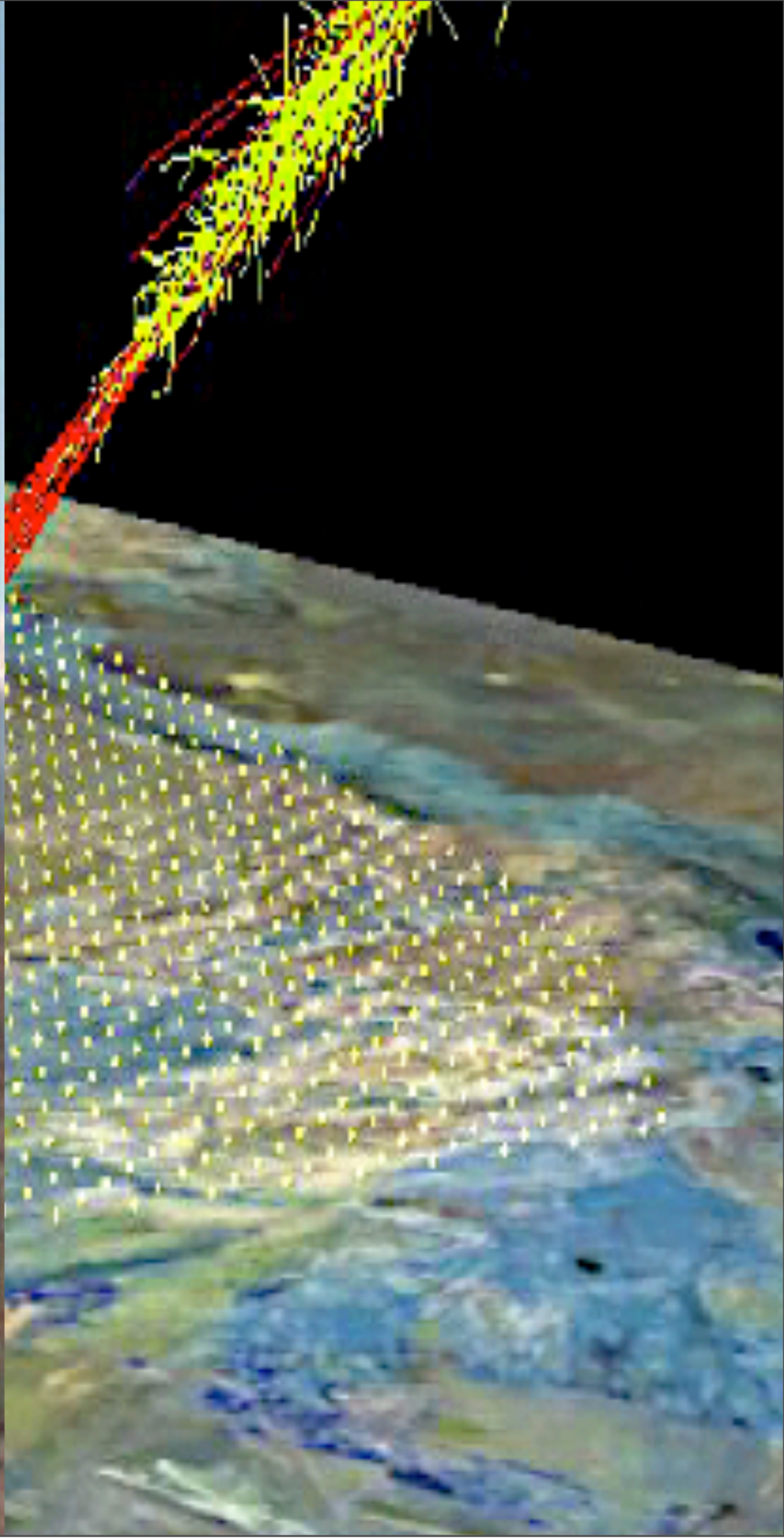

number
all particles
photons
e⁺+e⁻
muons
nucleons
mesons
10^5
10^6
10^7
10^8
10^9
10^10
0
200
400
600
800
1000
1200
slant depth (g/cm²)
fraction of E_prim
1
10^-1
10^-2
photons
all particles
e⁺+e⁻
mesons
nucleons
muons
0
200
400
600
800
1000
1200
slant depth (g/cm²)
fraction of E_prim
E loss per km (×3)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

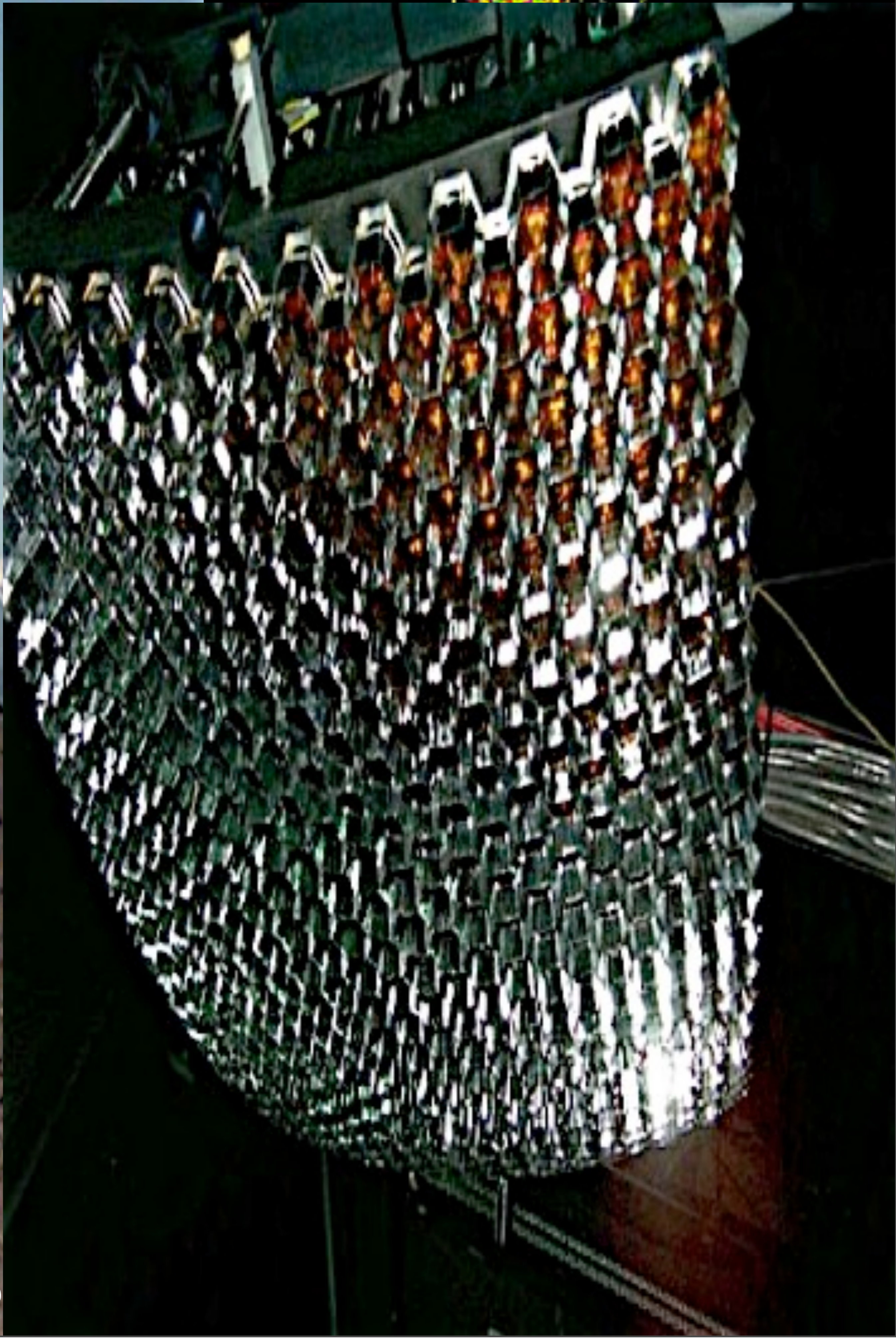
Cosmic ray versus neutrino induced air showers









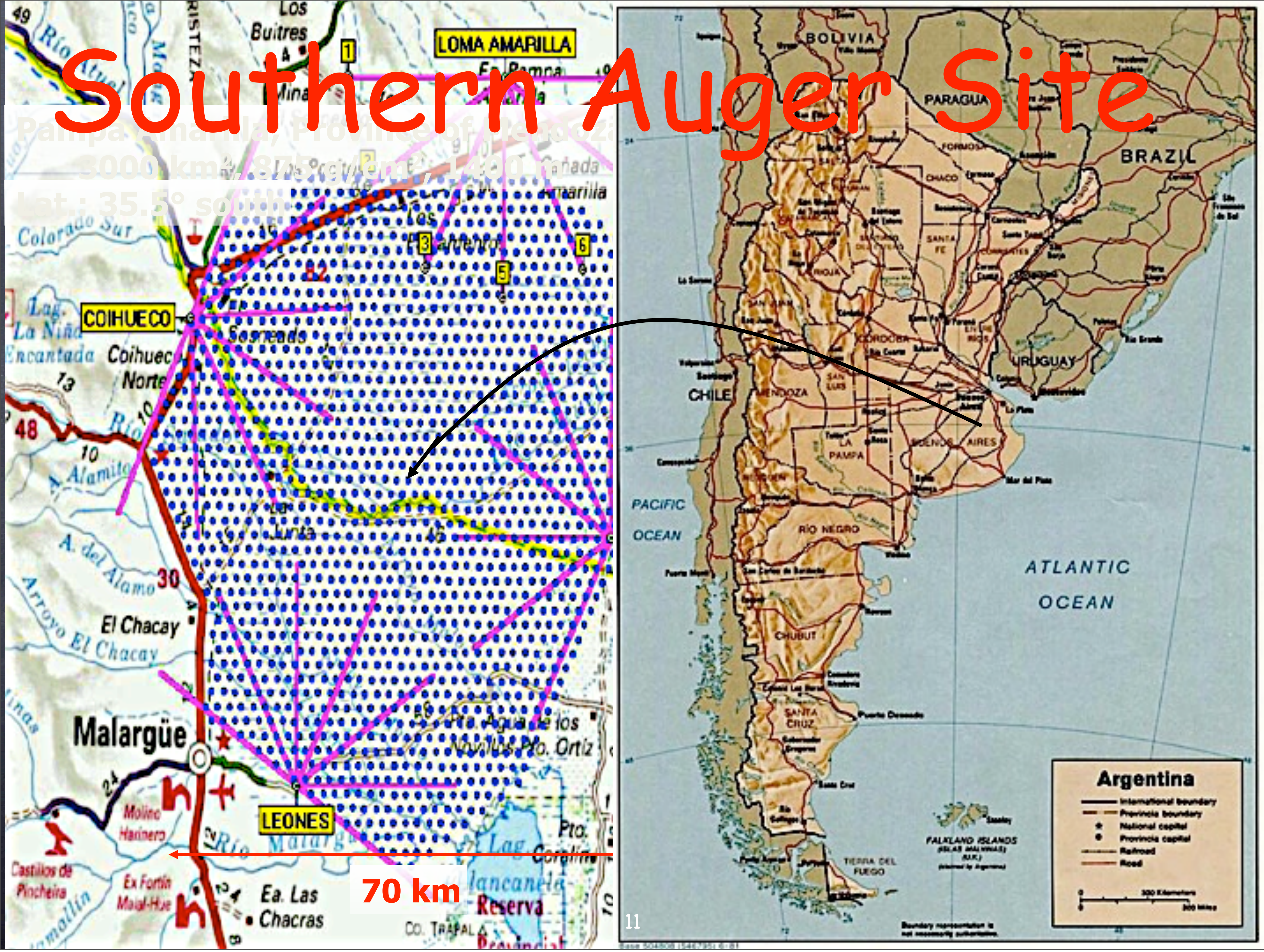


Southern Auger Site

Pampa Amarilla, Province of Mendoza

3000 km², 875 g/cm², 1400 m

Lat.: 35.5° south



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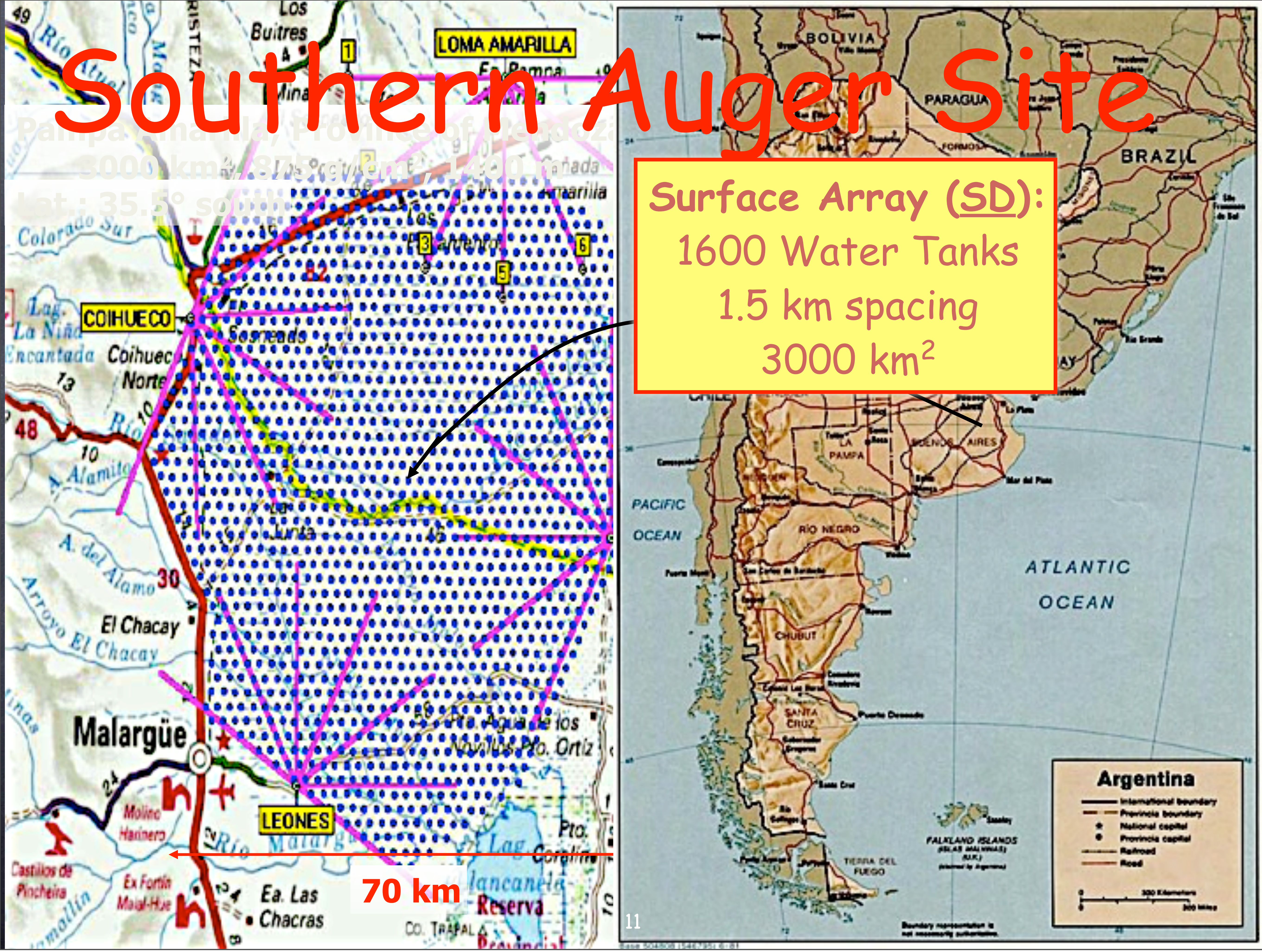

Surface Array (SD):
1600 Water Tanks
1.5 km spacing
3000 km²

70 km

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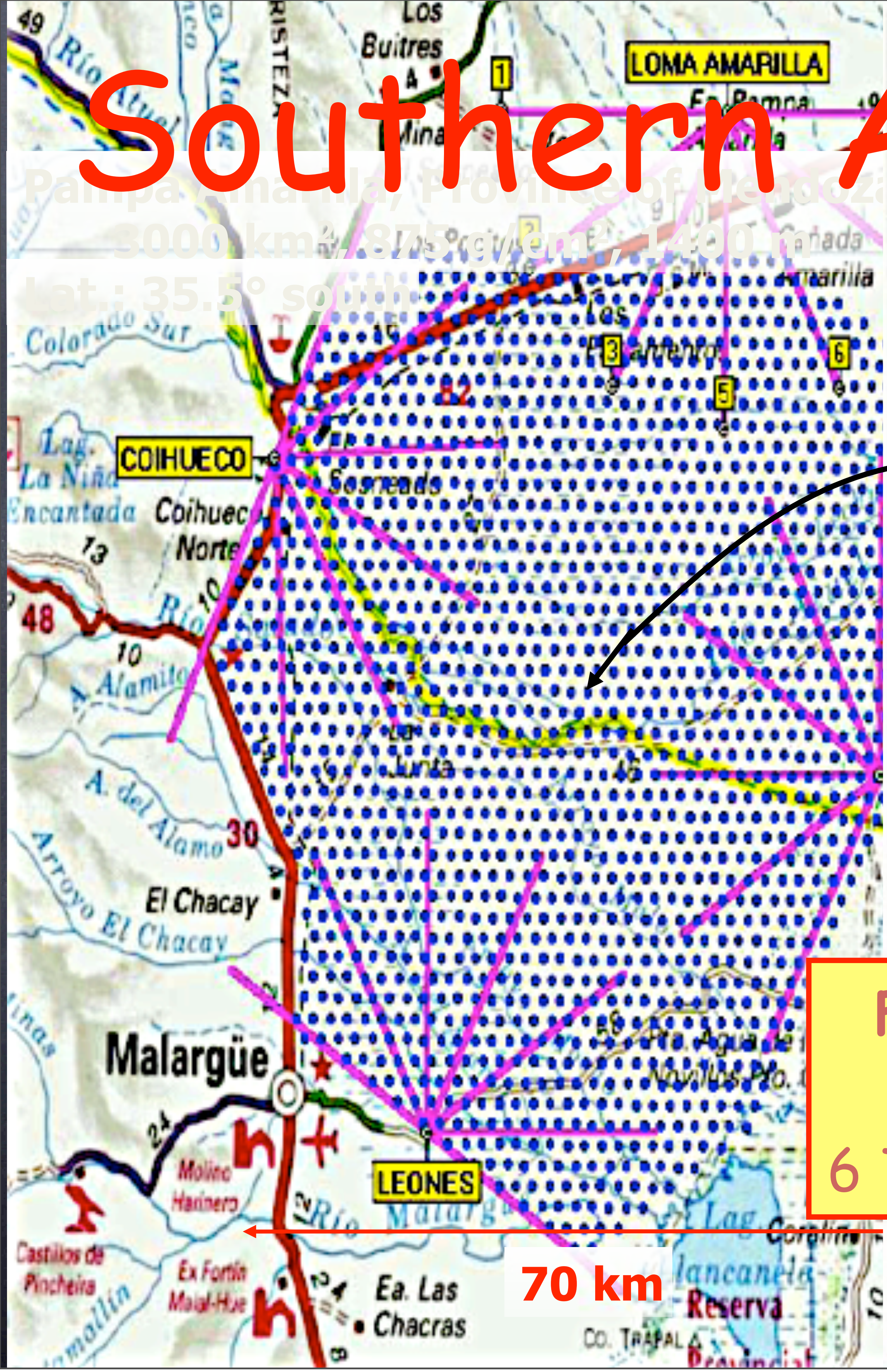

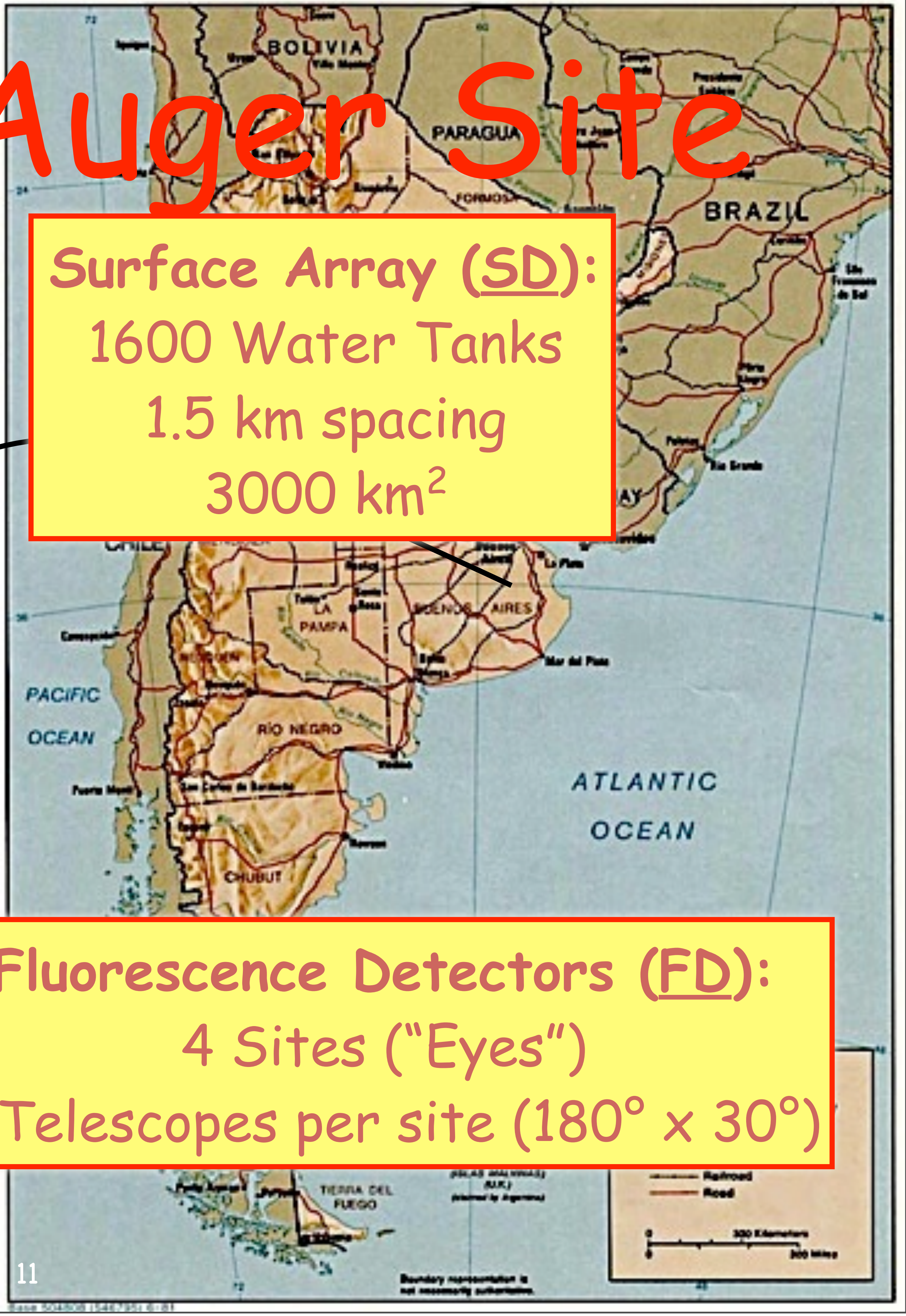

Surface Array (SD):
1600 Water Tanks
1.5 km spacing
3000 km²

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

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4.) Within standard hadronic air shower theory the shape of observed air showers is not easy to explain with pure or mixed mass primary composition

The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background

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

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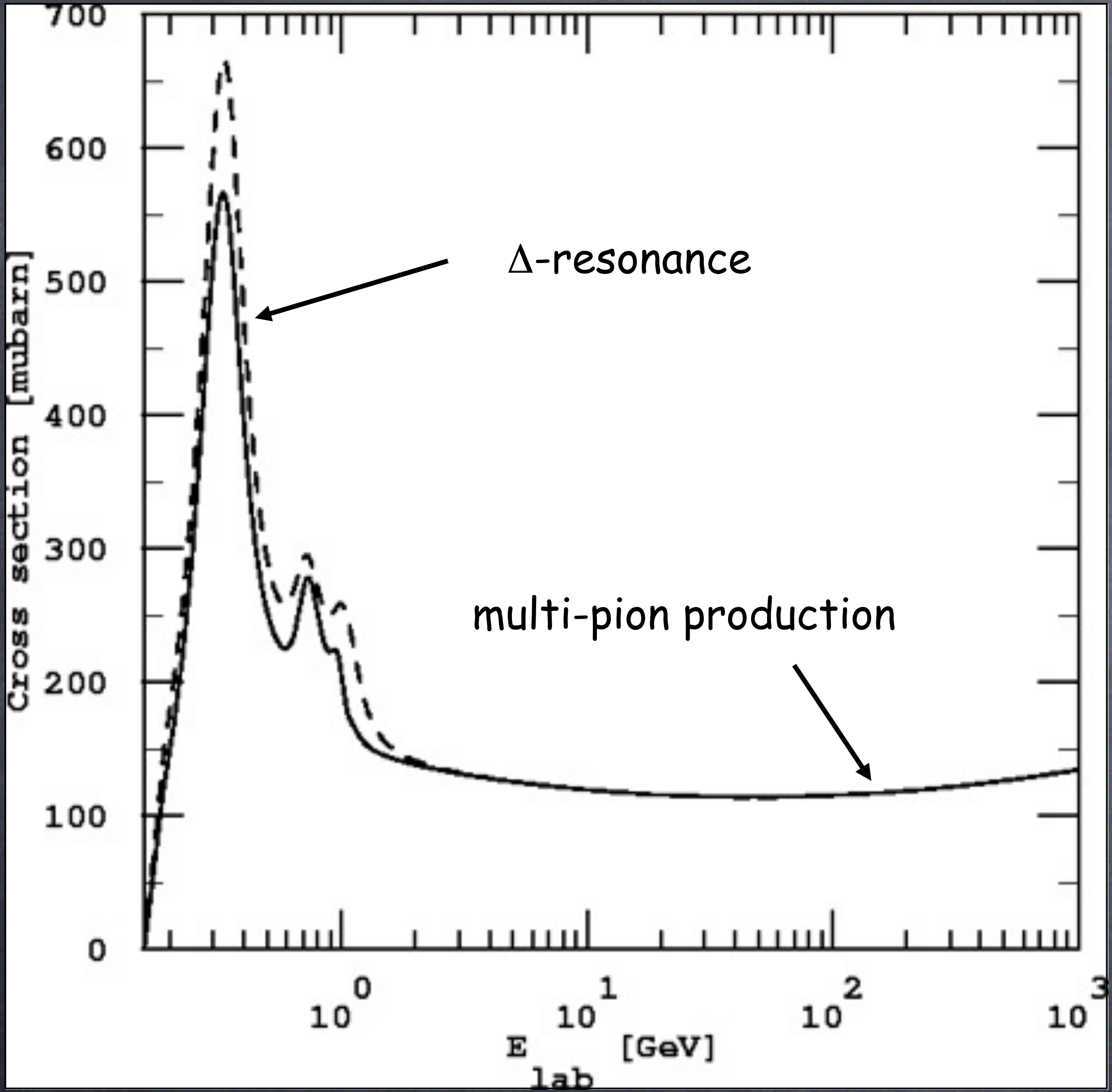

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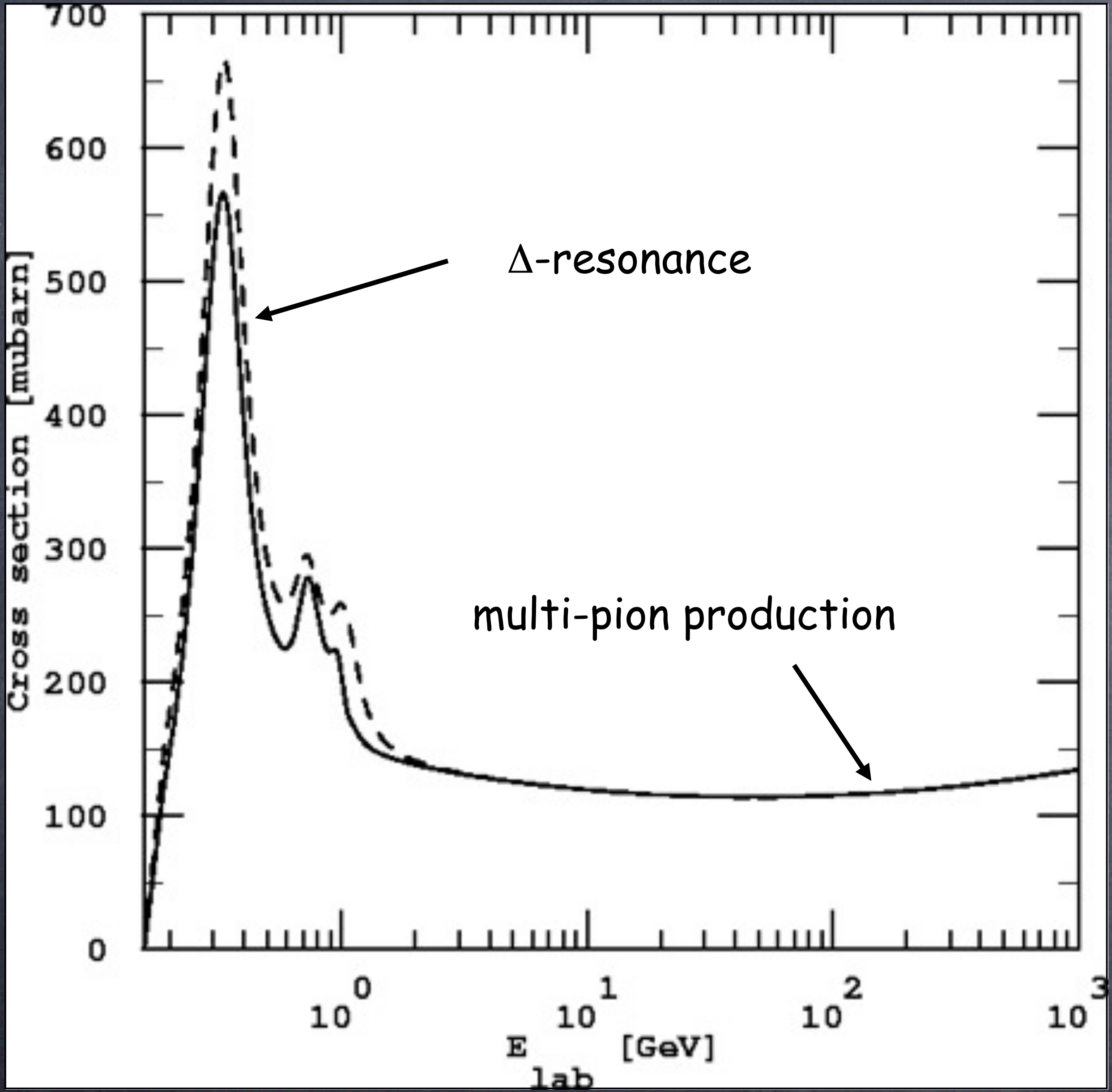
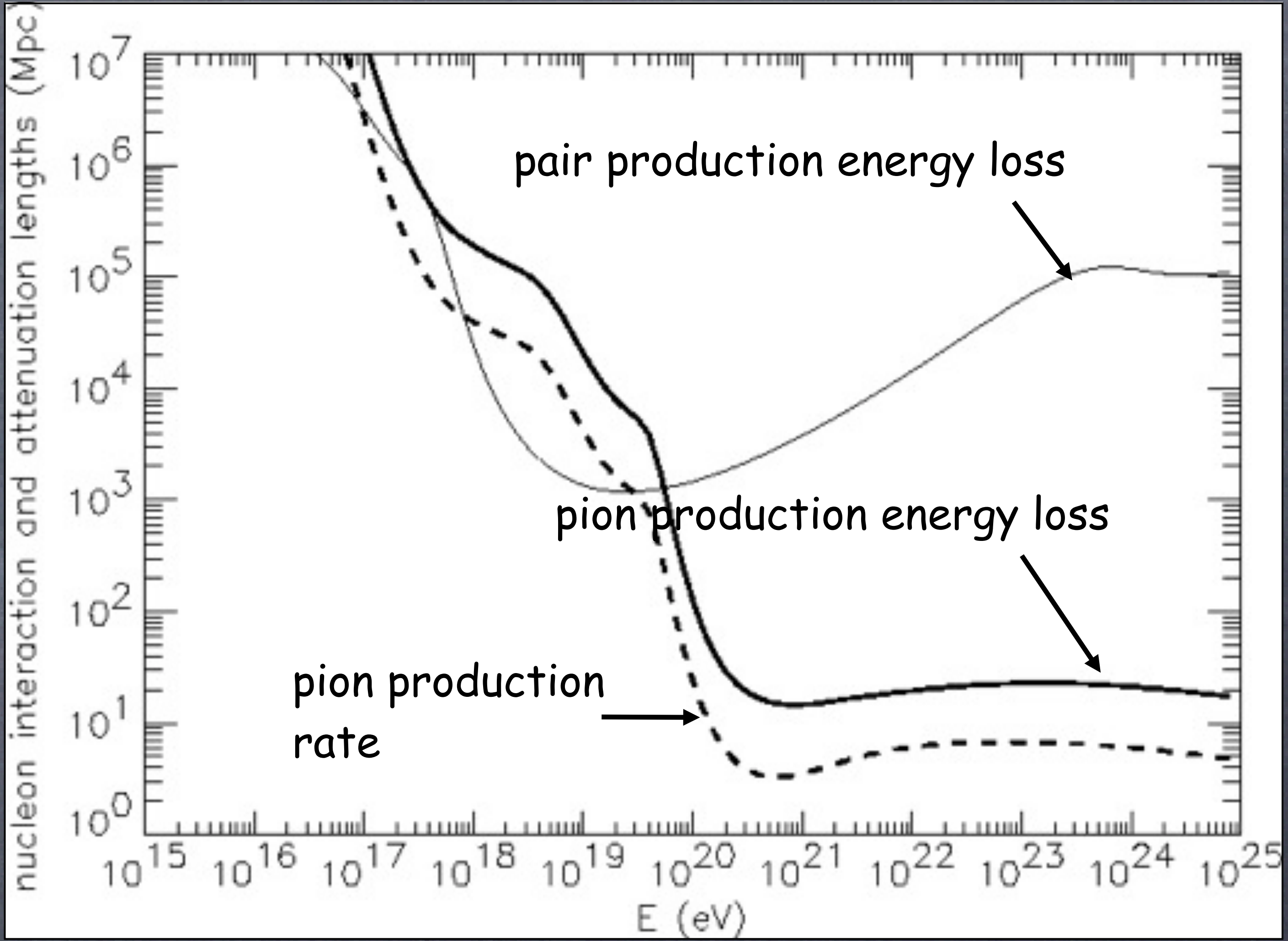


Δ-resonance

multi-pion production



pair production energy loss

pion production energy loss

pion production rate

The Greisen-Zatsepin-Kuzmin (GZK) effect

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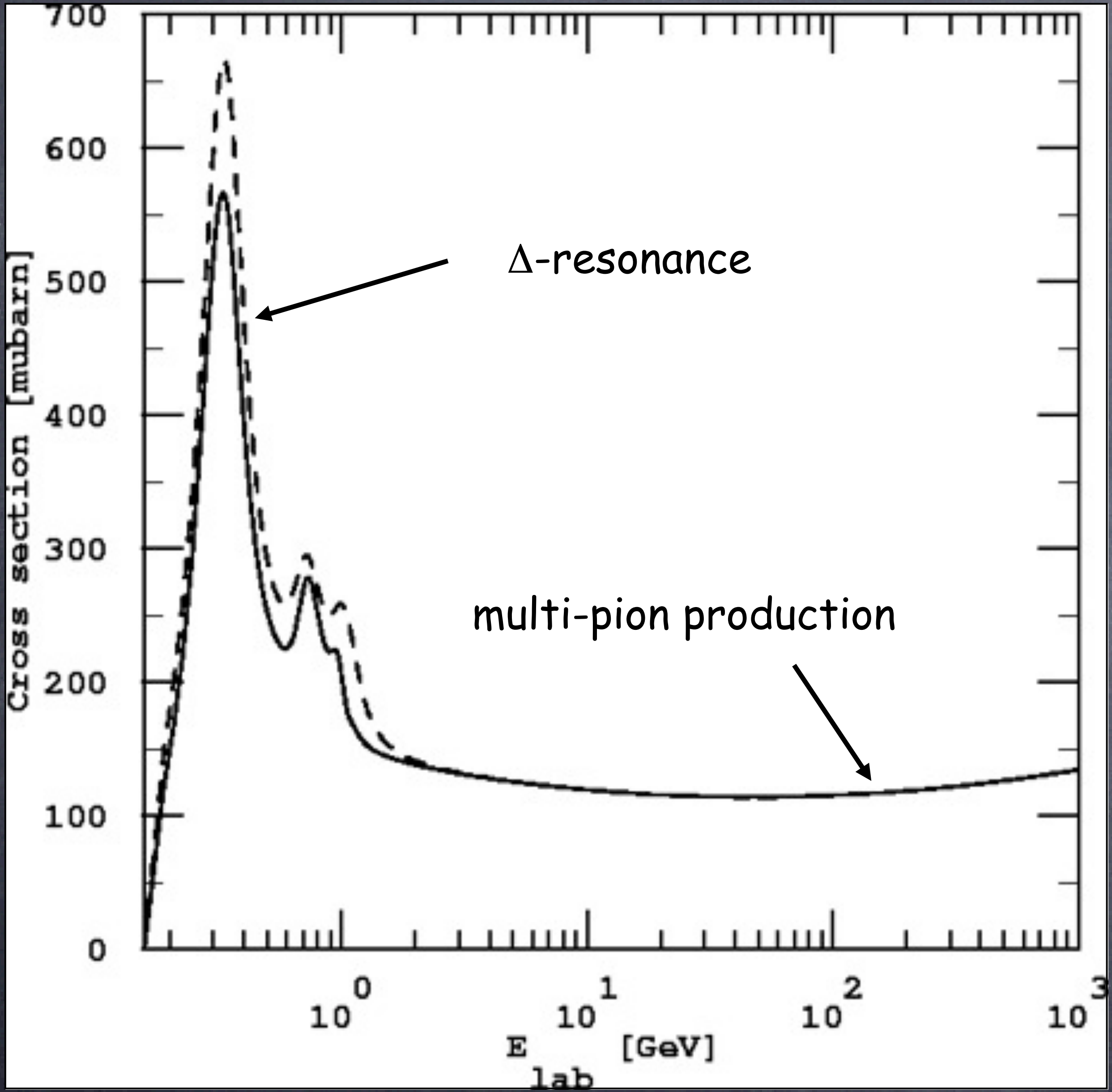
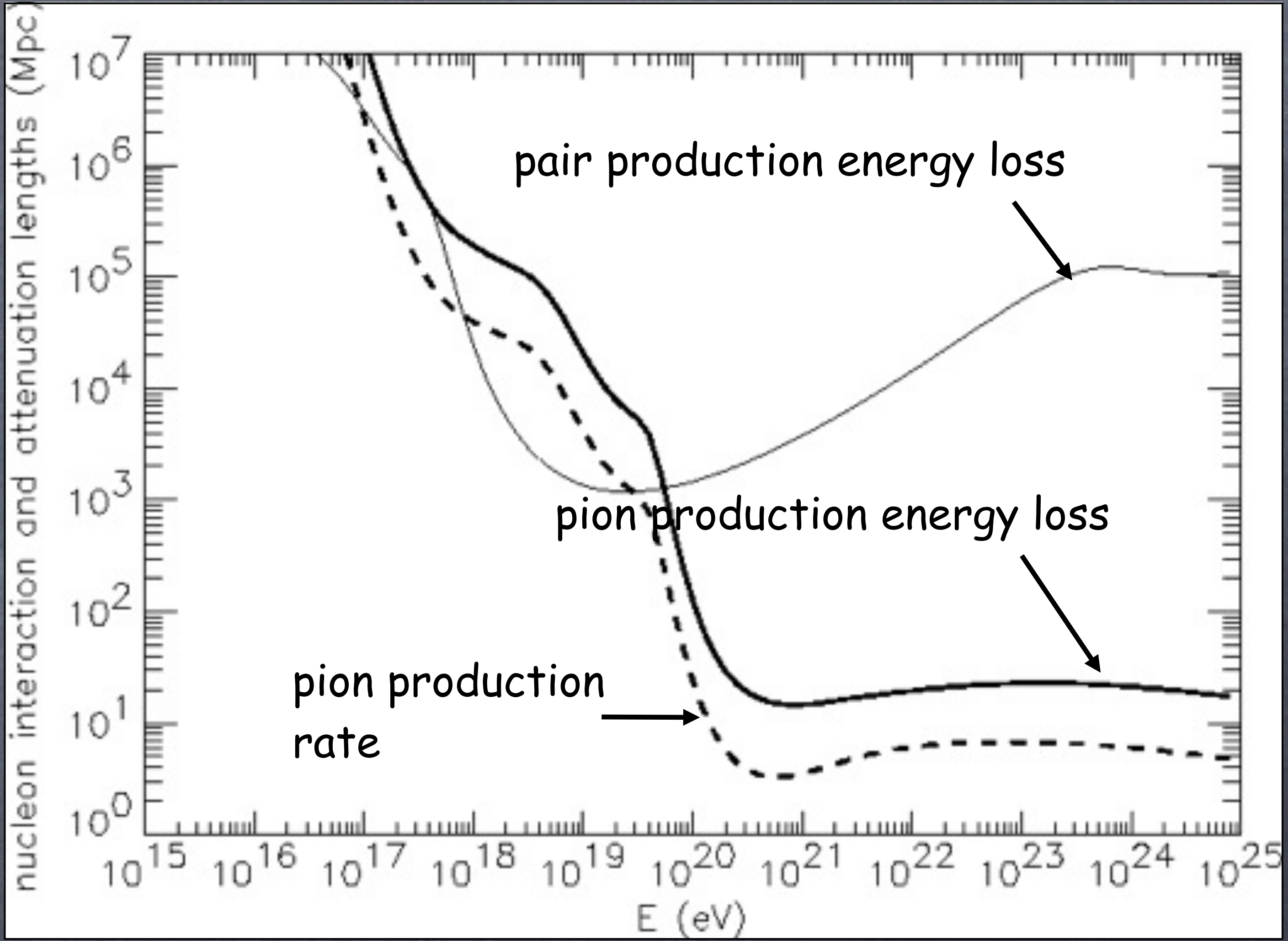
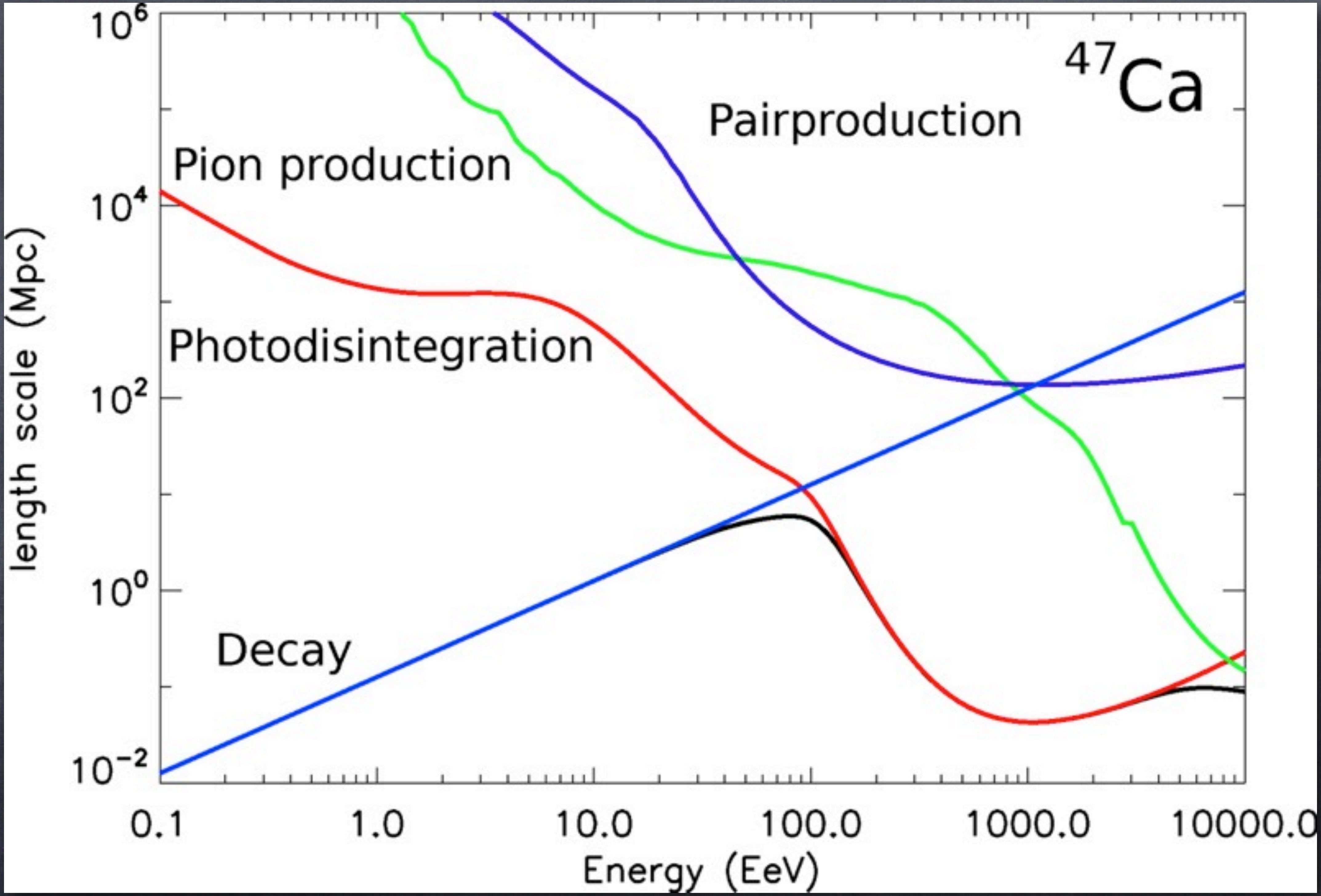


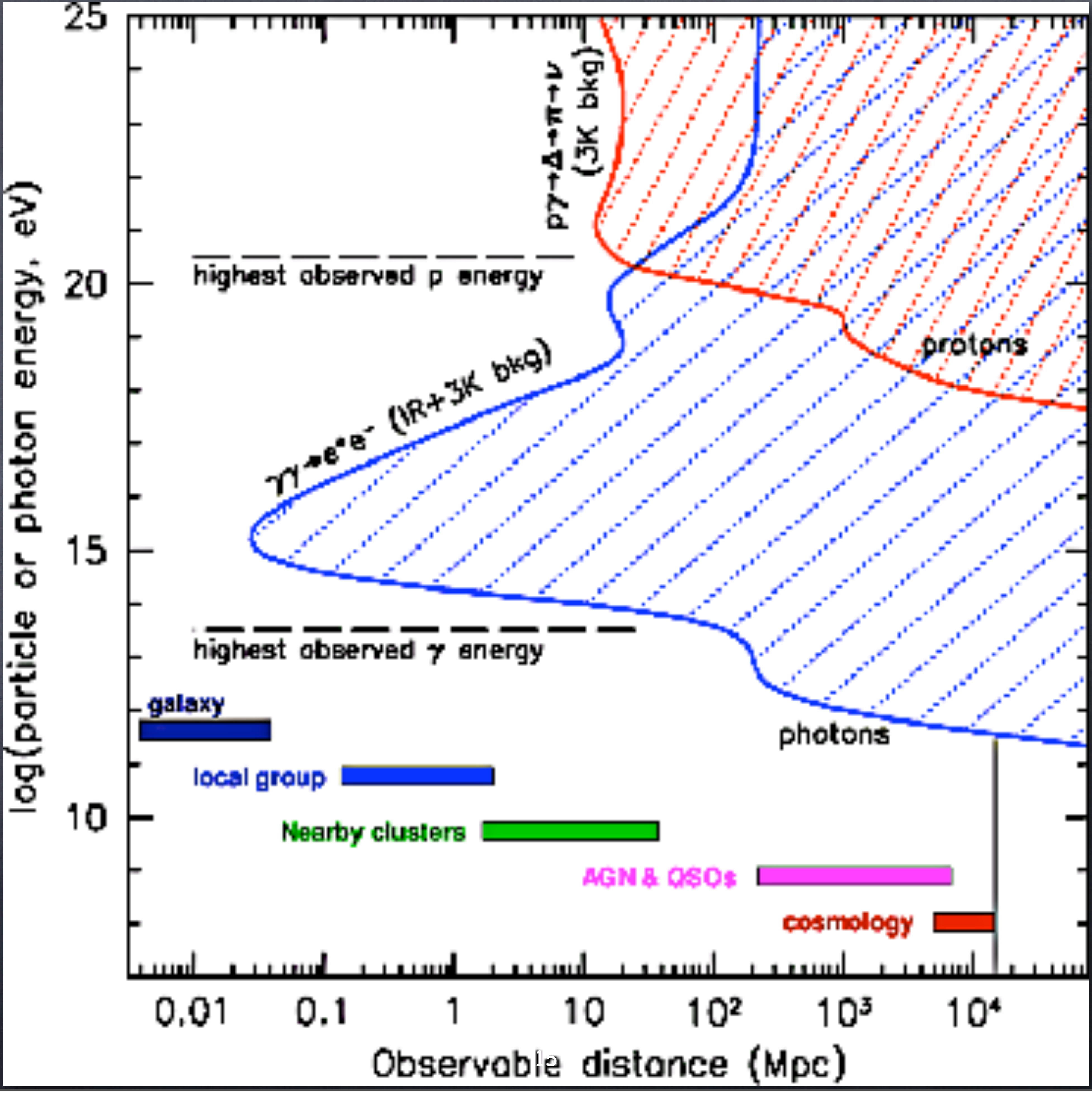


sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma>10^{11}$
could avoid this conclusion.

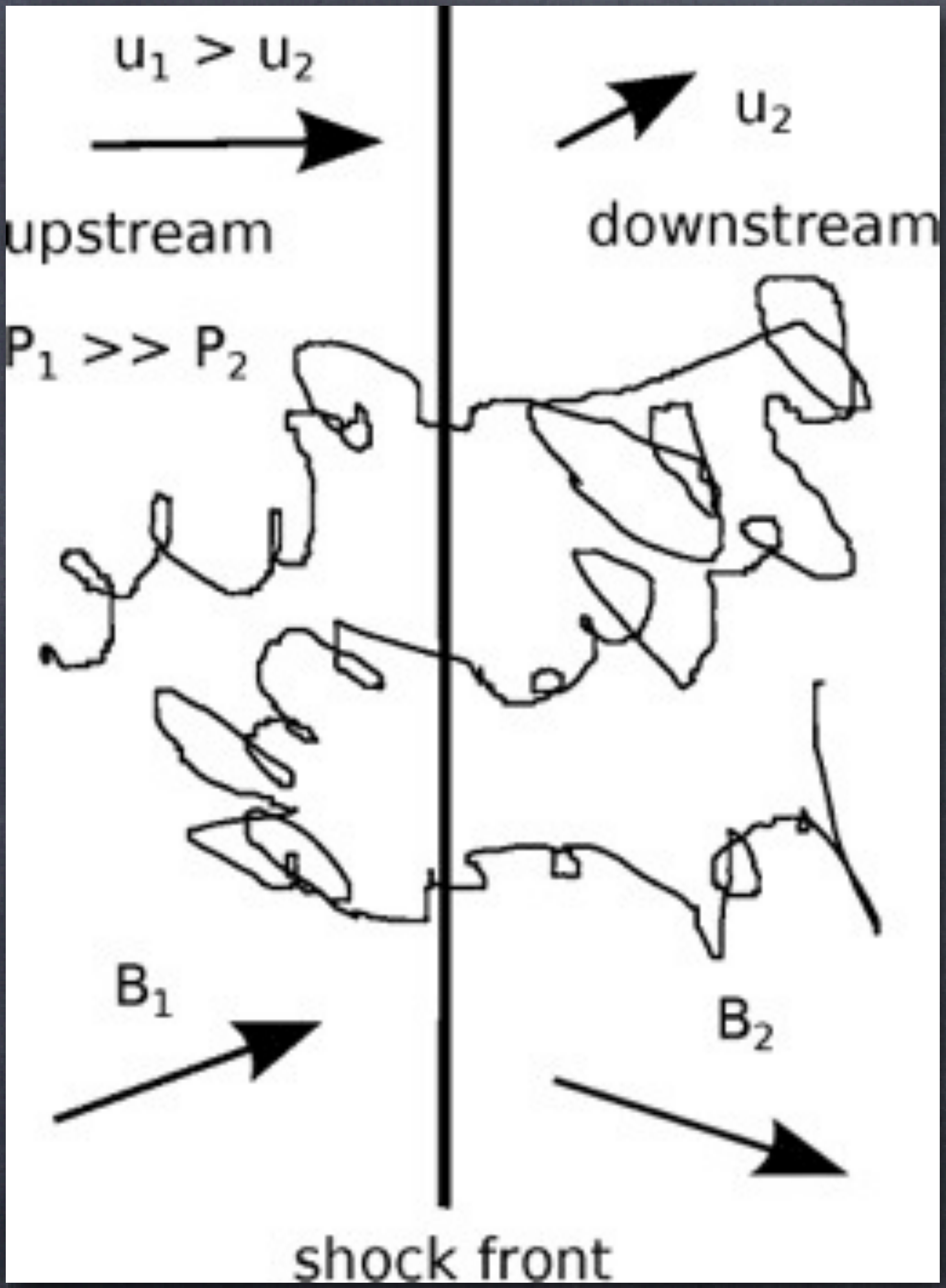
Length scales for relevant processes of a typical heavy nucleus

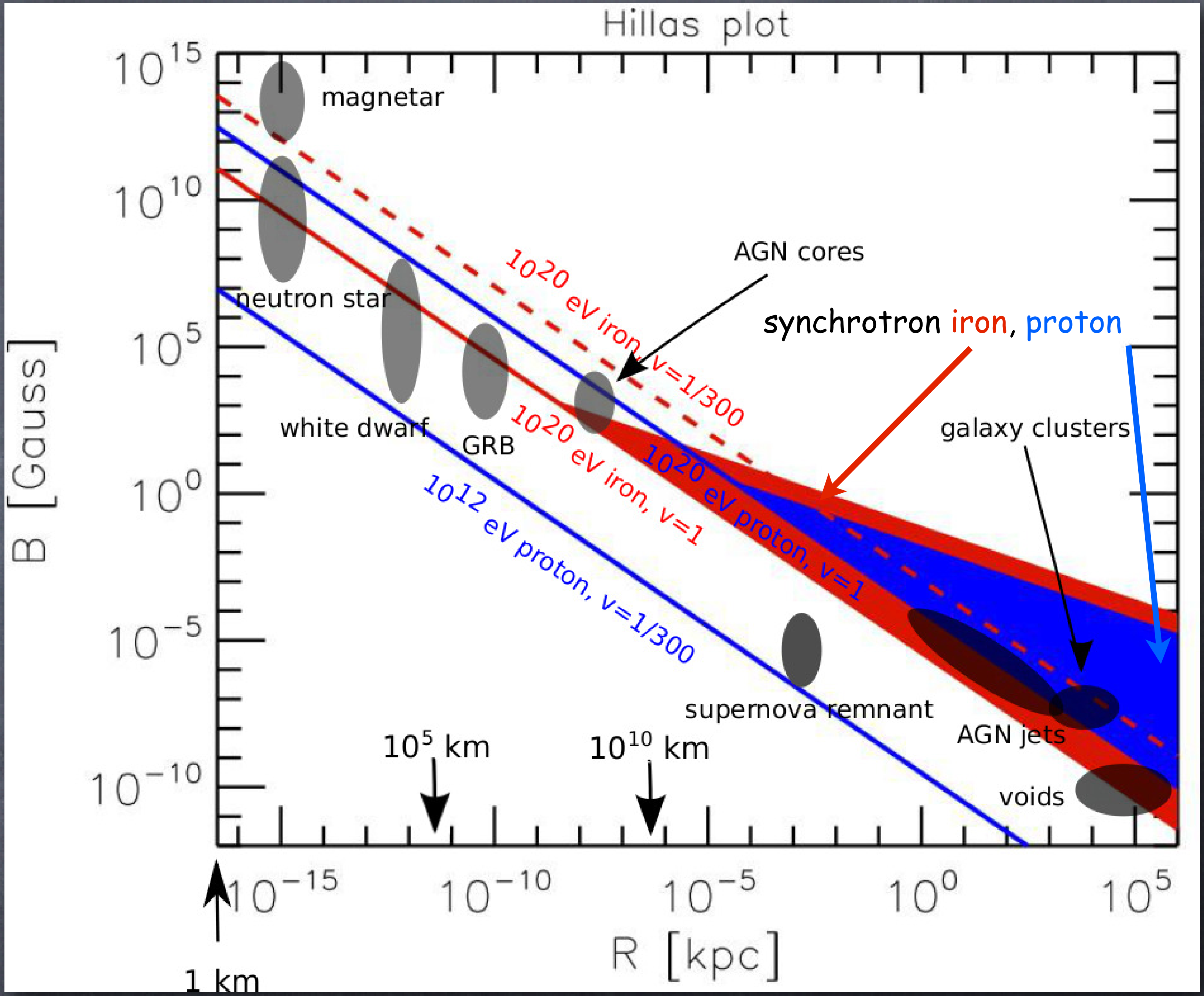


Interaction Horizons



1^{st} Order Fermi Shock Acceleration





Fractional energy gain per shock crossing $\sim u_1 - u_2$ 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

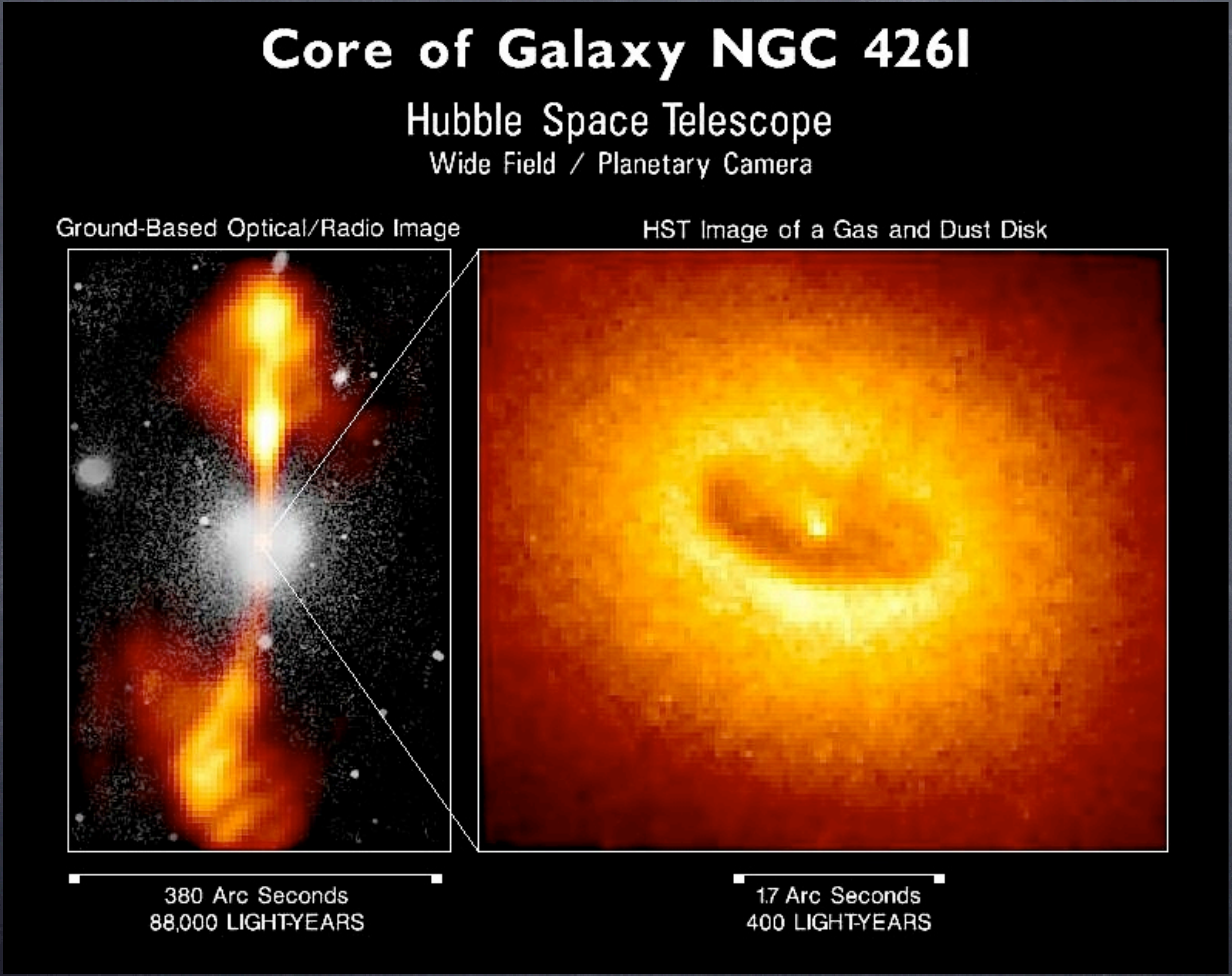
$$L_{\rm min} \sim \frac{\epsilon^2}{Z_0} \simeq 10^{45}\, Z^{-2} \left(\frac{E_{\rm max}}{10^{20}\,{\rm eV}}\right)^2 \;{\rm erg\,s}^{-1}$$

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

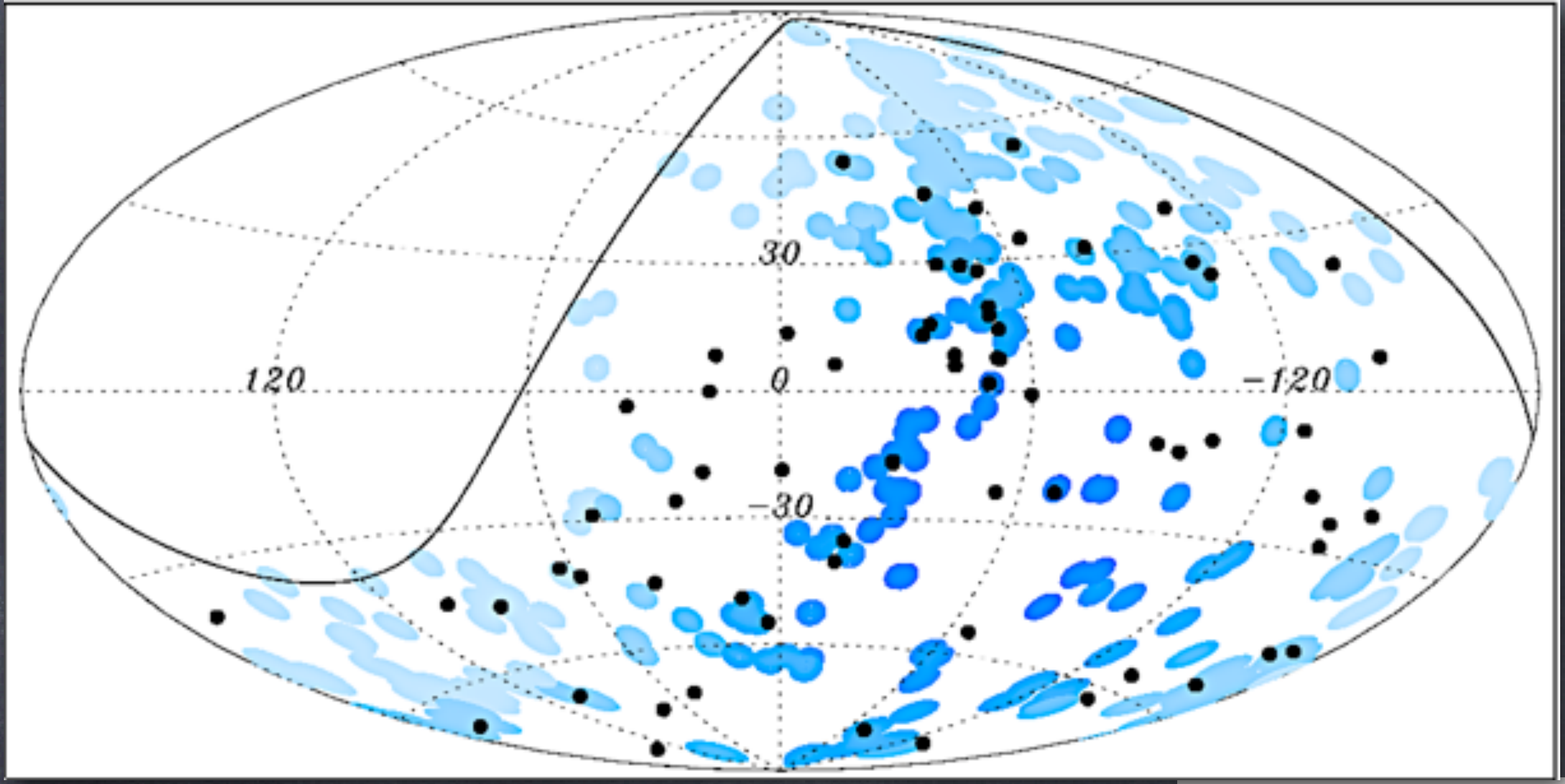
$$BR > 3 \times 10^{17}\,\Gamma^{-1} \left(\frac{E_{\rm max}/Z}{10^{20}\,{\rm eV}}\right) \,{\rm Gauss\,cm}$$

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.

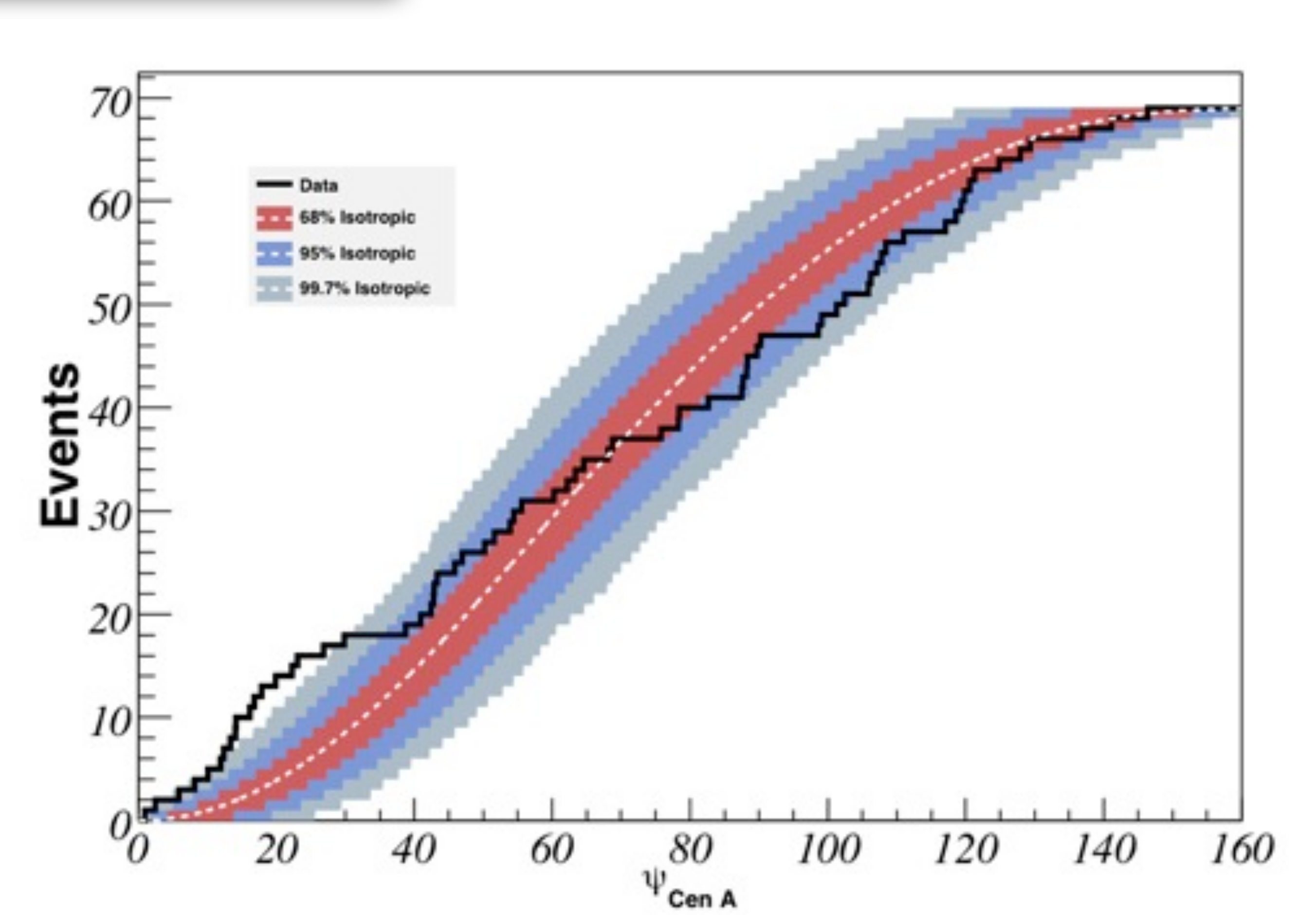
A possible acceleration site associated with shocks in hot spots of active galaxies



Centaurus A is a UHECR source candidate

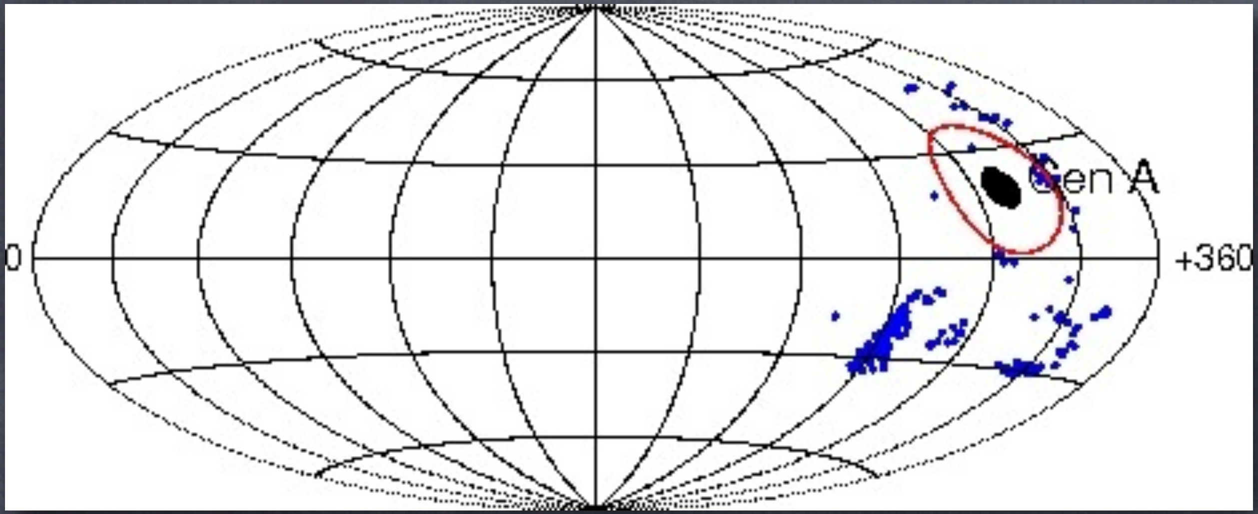


Pierre Auger sees a clear excess
in the direction of Centaurus A

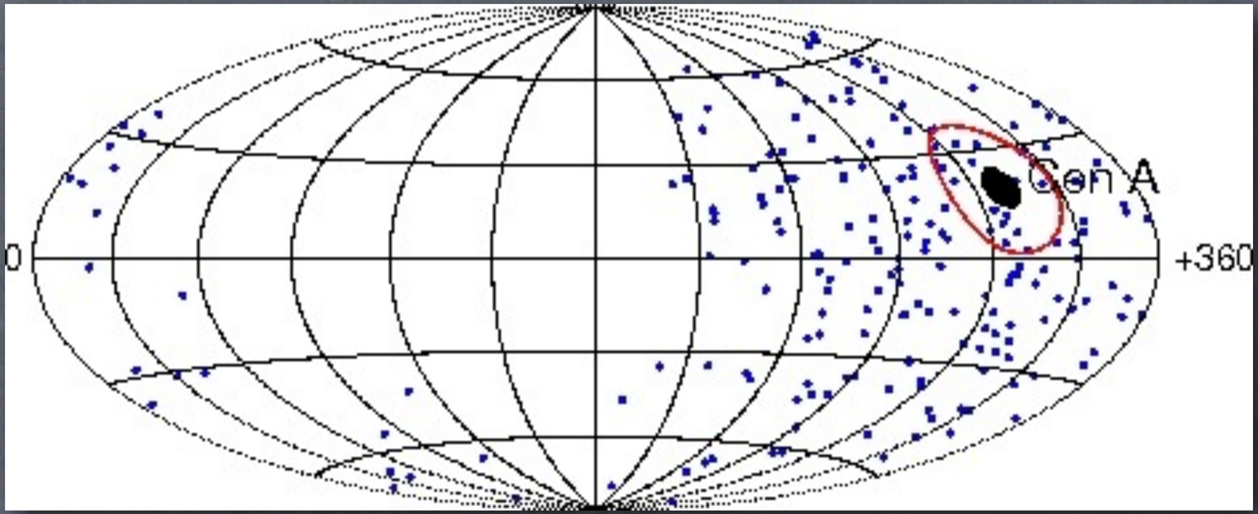


Pierre Auger Collaboration, Astropart.Phys. 34 (2010) 314

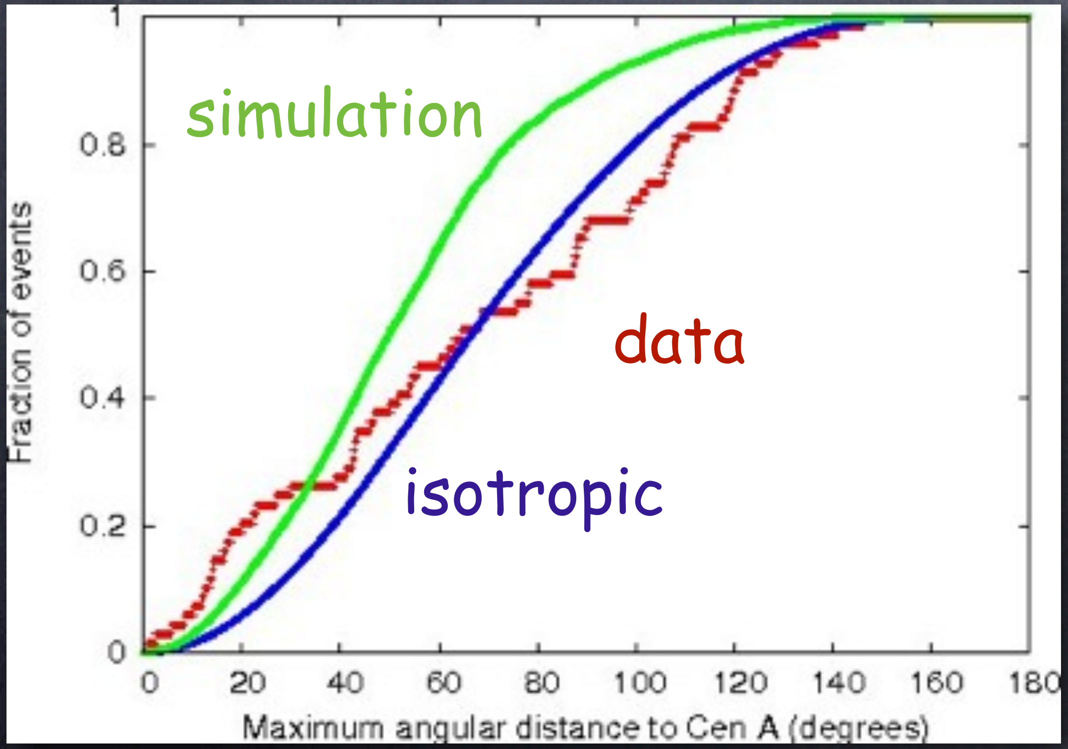
But even for iron primaries Centaurus A can not be the only UHECR source



Iron Image of Cen A in the Prouza-Smida Galactic magnetic field model

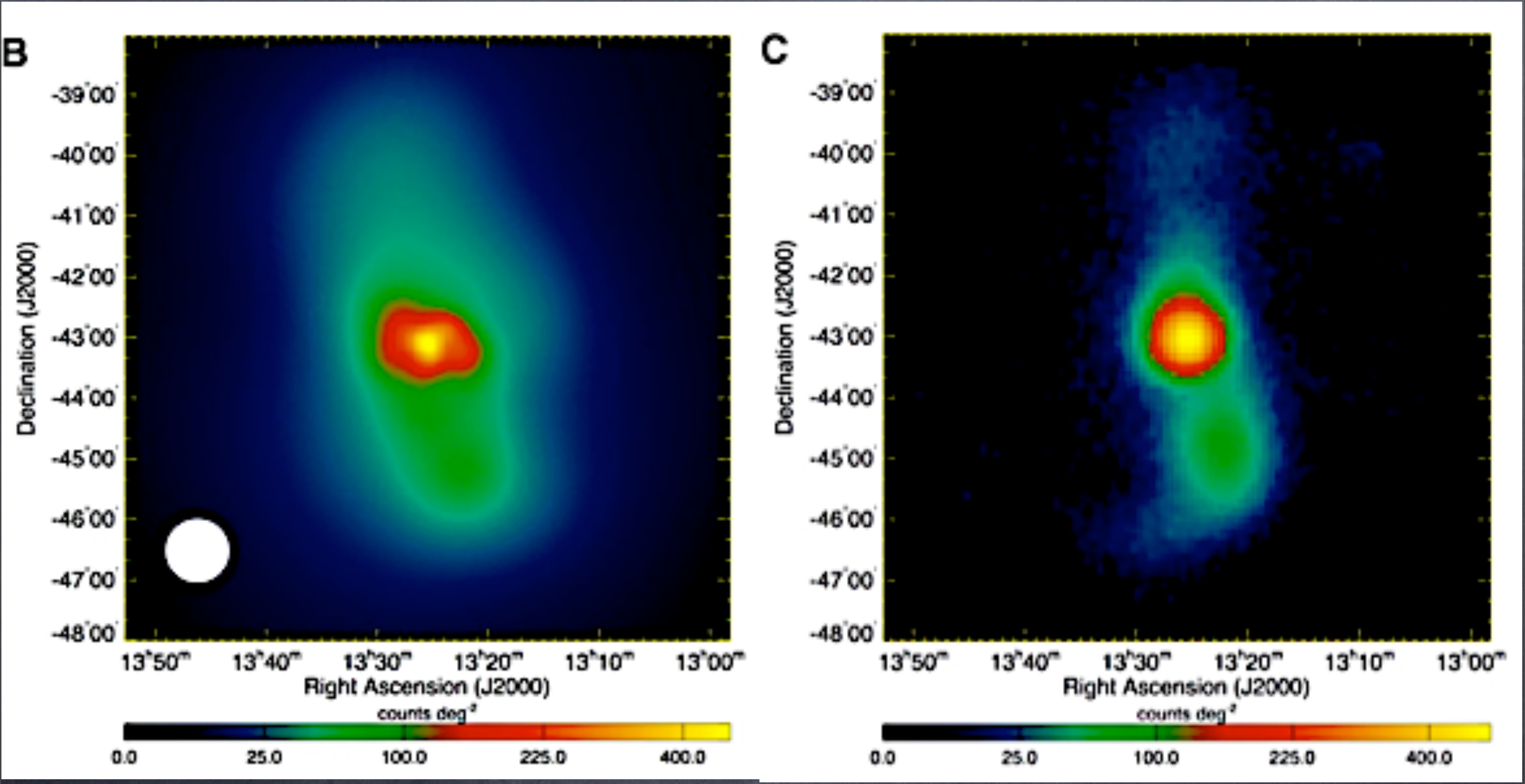


Including an extreme choice for the turbulent Galactic field component with strength 10 μG, coherence length 50 pc, 10 kpc halo extension



Giacinti, Kachelriess, Semikoz, Sigl, Astropart.Phys. 35 (2011) 192

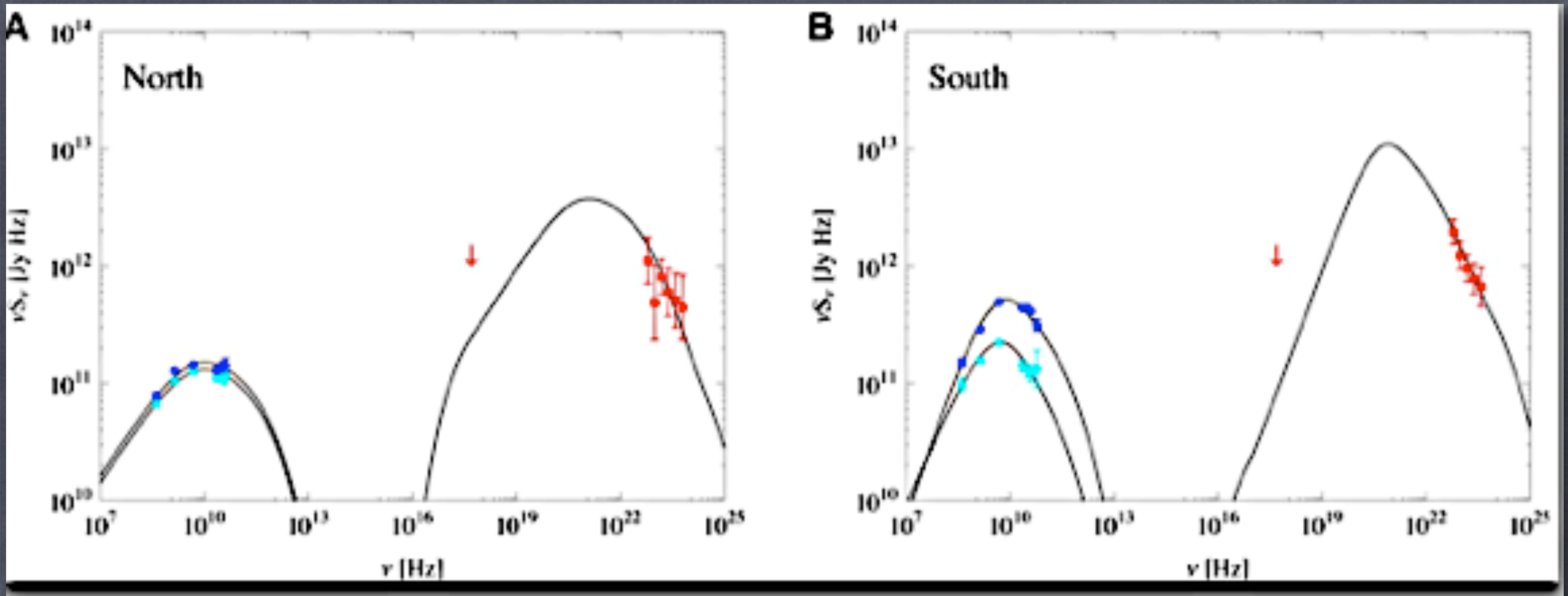
Lobes of Centaurus A seen by Fermi-LAT

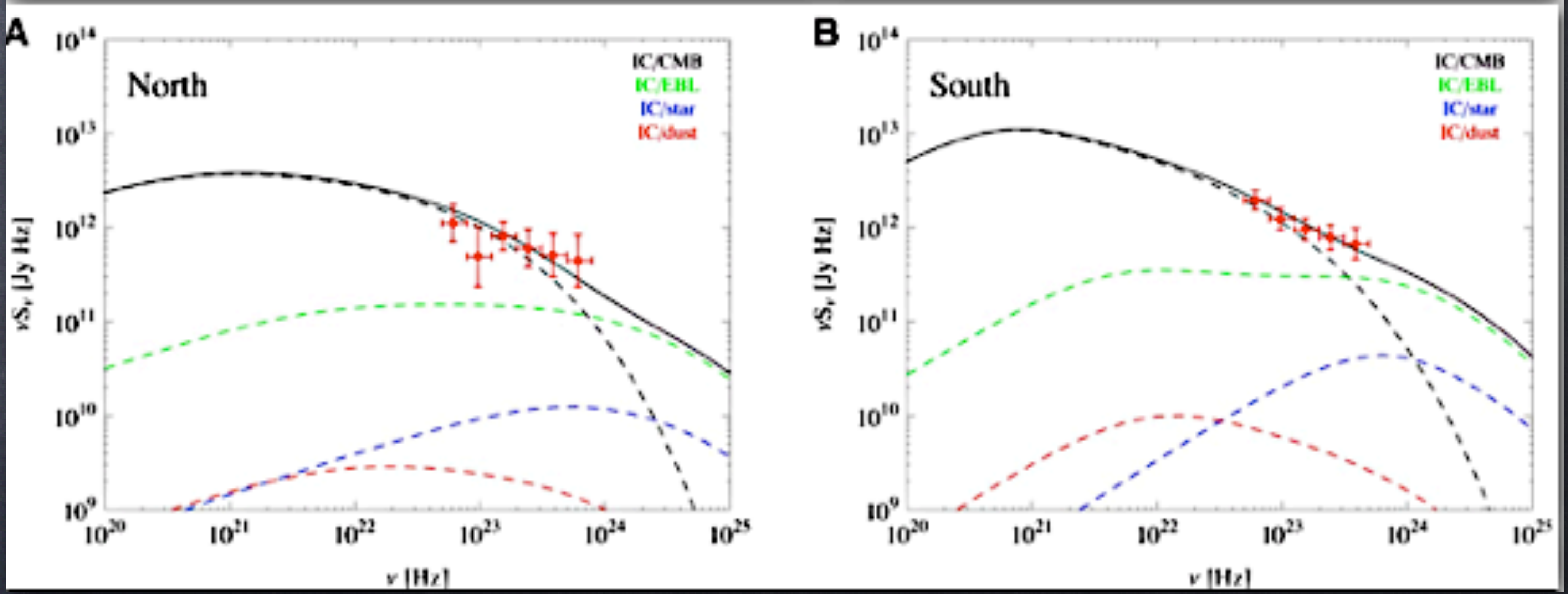


> 200 MeV γ-rays

Radio observations

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



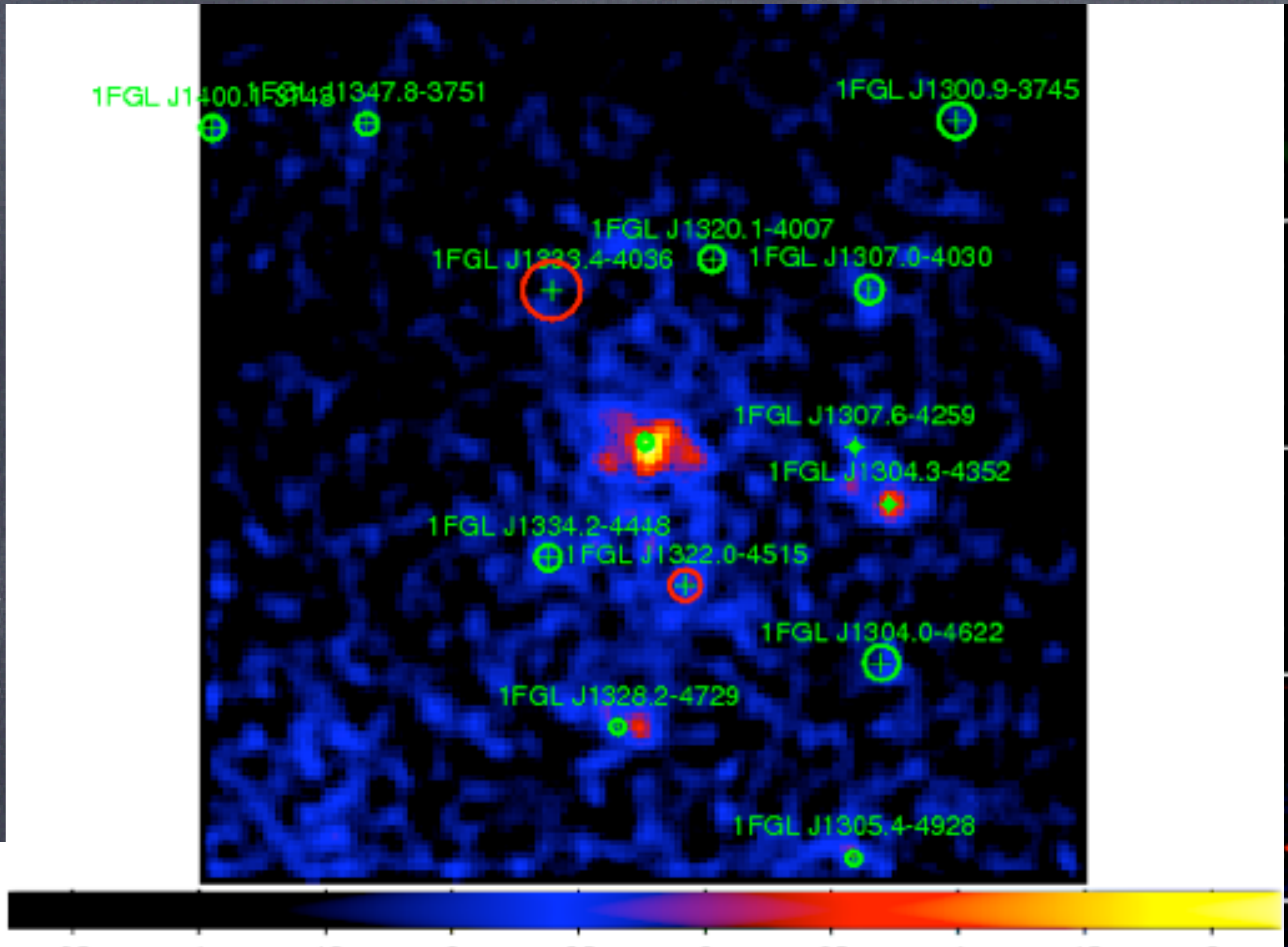


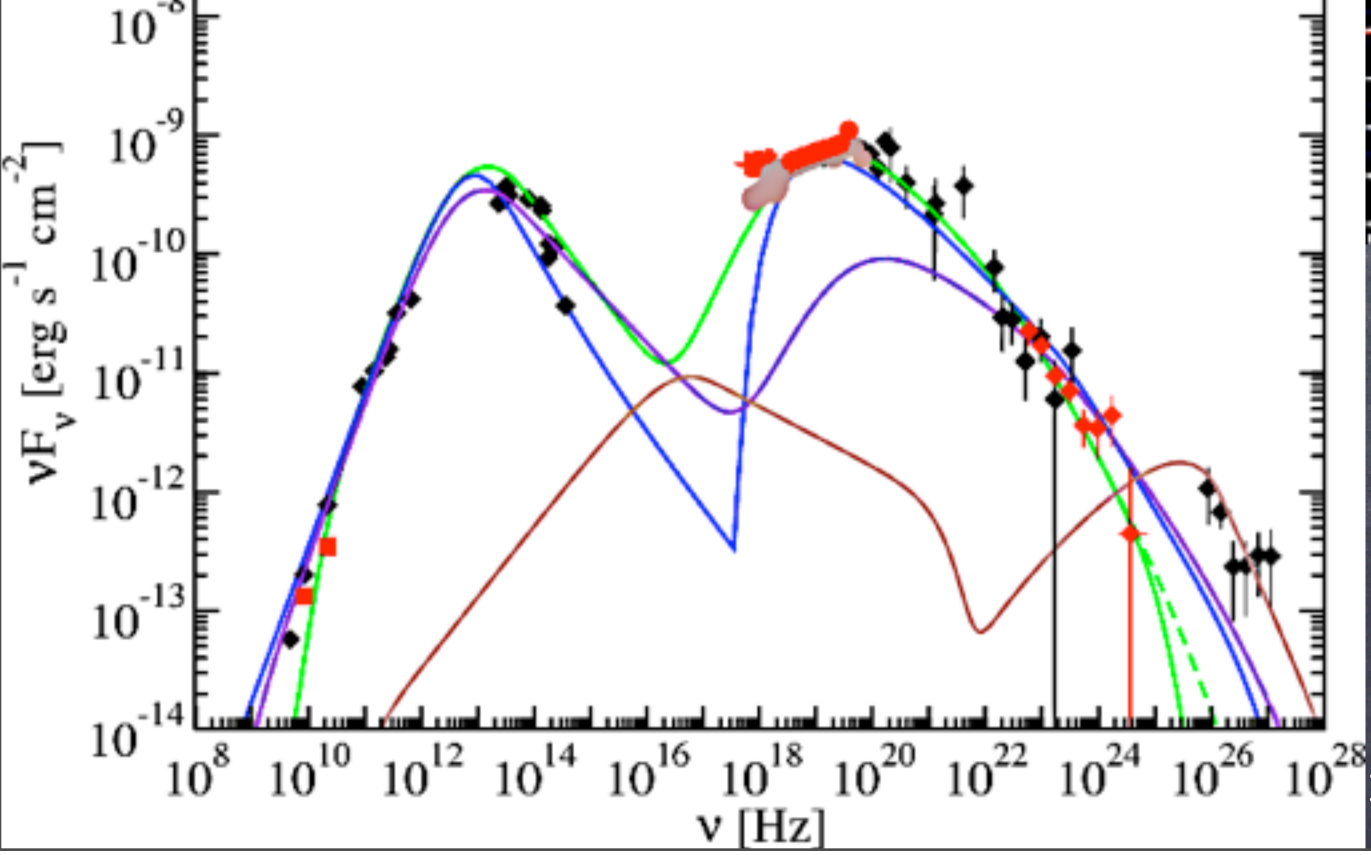
Low energy bump = synchrotron

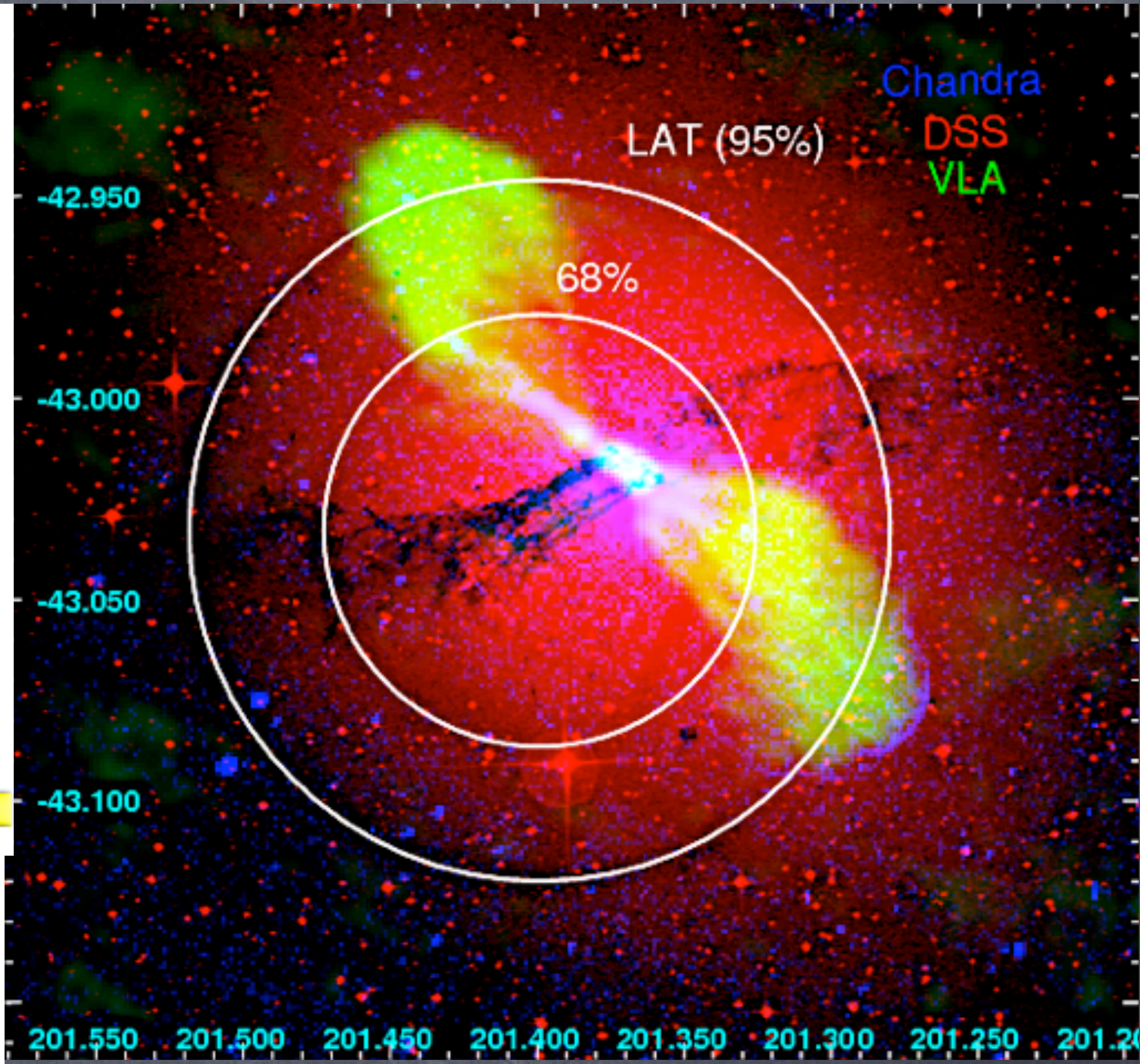
high energy bump = inverse Compton on CMB in ~0.85μG field

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

Core of Centaurus A seen by Fermi-LAT



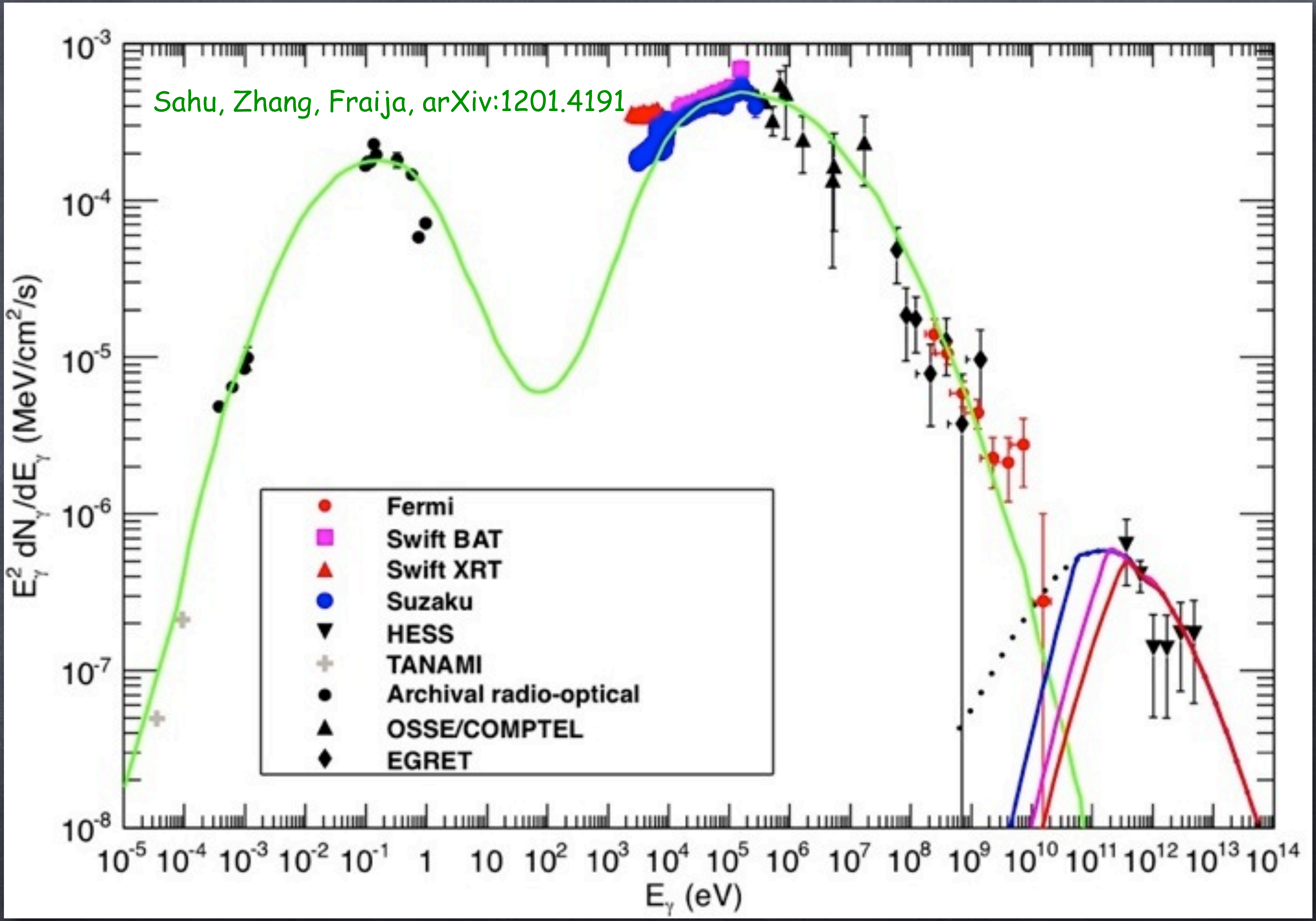




Can be explained by synchrotron self Compton except for HESS observation

Abdo et al., (Fermi LAT collaboration), arXiv:1006.5463

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

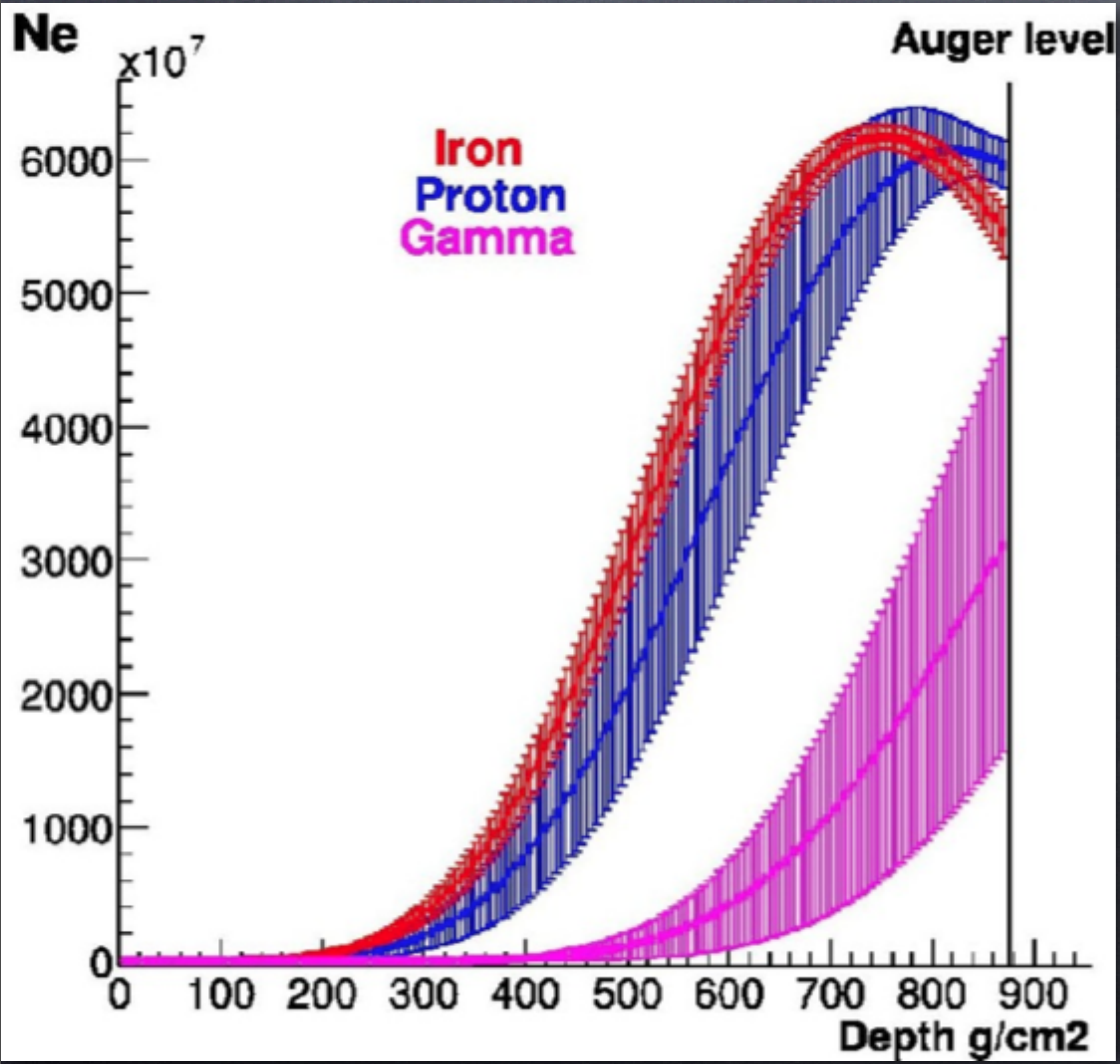

Sahu, Zhang, Fraija, arXiv:1201.4191

Low energy bump = synchrotron

high energy bump = synchrotron self-Compton

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

air shower characteristics suggest mixed or heavy chemical composition for E>10^{19} eV



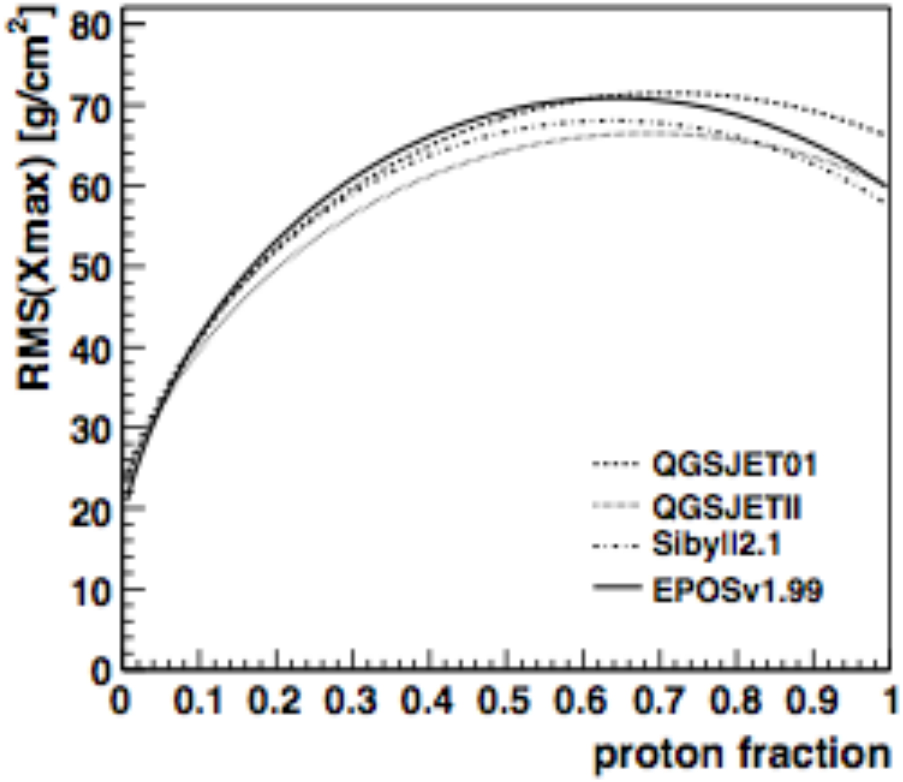


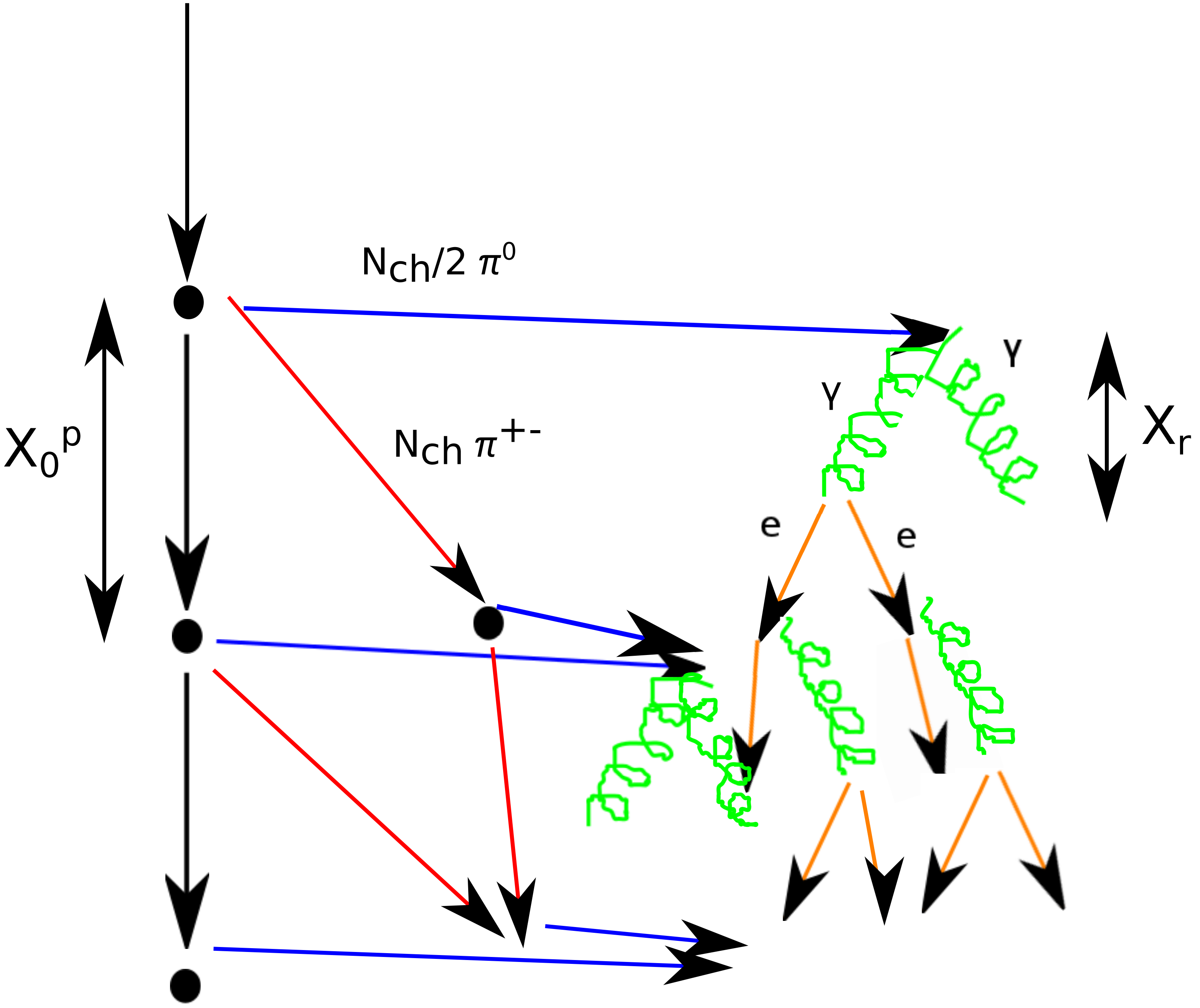
FIGURE 1. RMS($X_{\max}$) from different hadronic interaction models [23] and a two-component p/Fe composition model ($E = 10^{18}$ eV).

First two generations of a hadronic cascade in the Heitler model

Depth of shower maximum essentially determined by number of EM generations $X_{max} \sim X_r \ln(E/E_{cr})$;
in superposition model substitute E/A
=> air showers from heavier primaries peak higher in the atmosphere.

For a pure composition RMS(X_{max}) dominated by fluctuations of first interaction depth $X_0^p(E/A)/A^{1/2}$

No composition reproduces measured X_{max} and RMS(X_{max}) at the same time

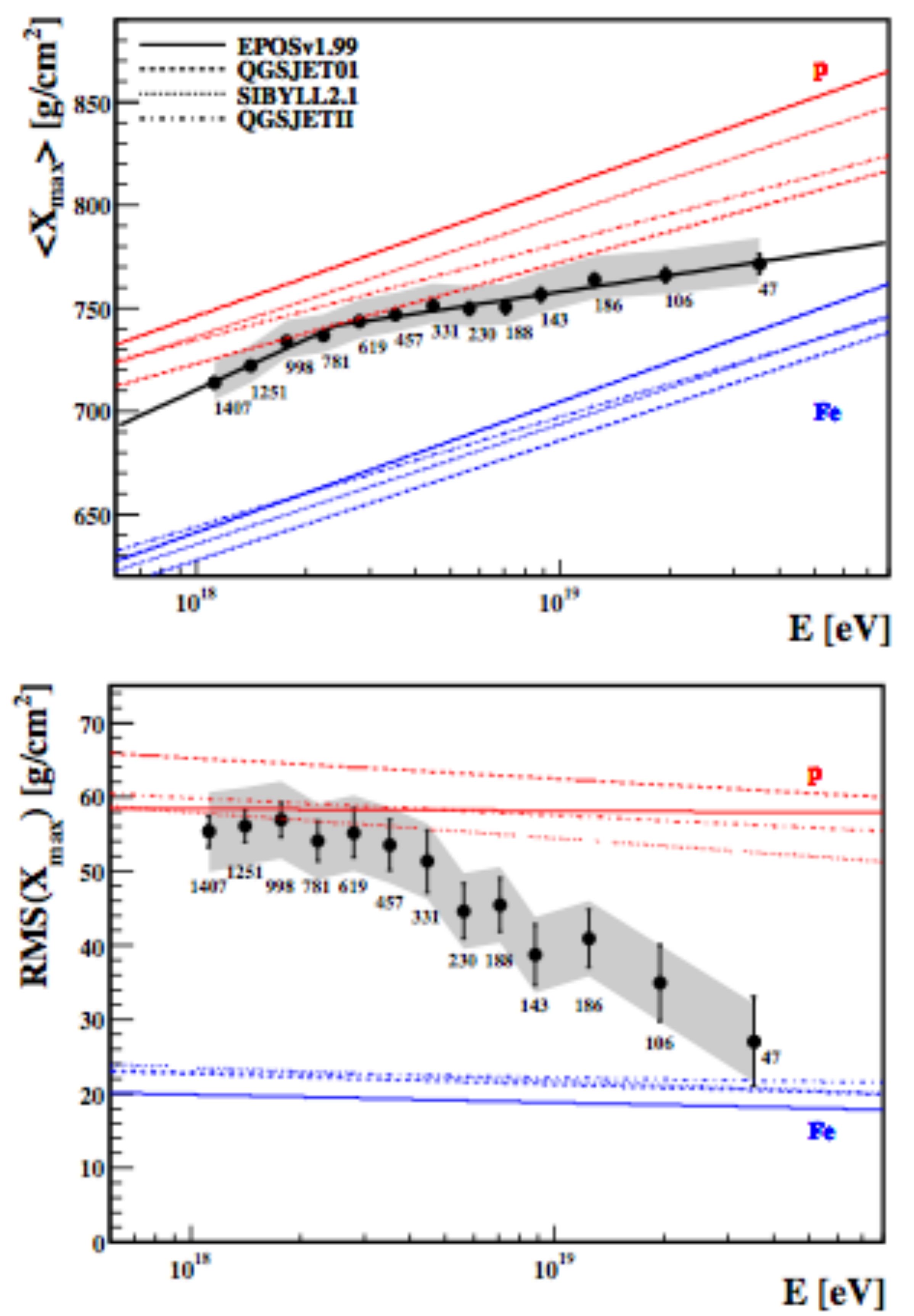


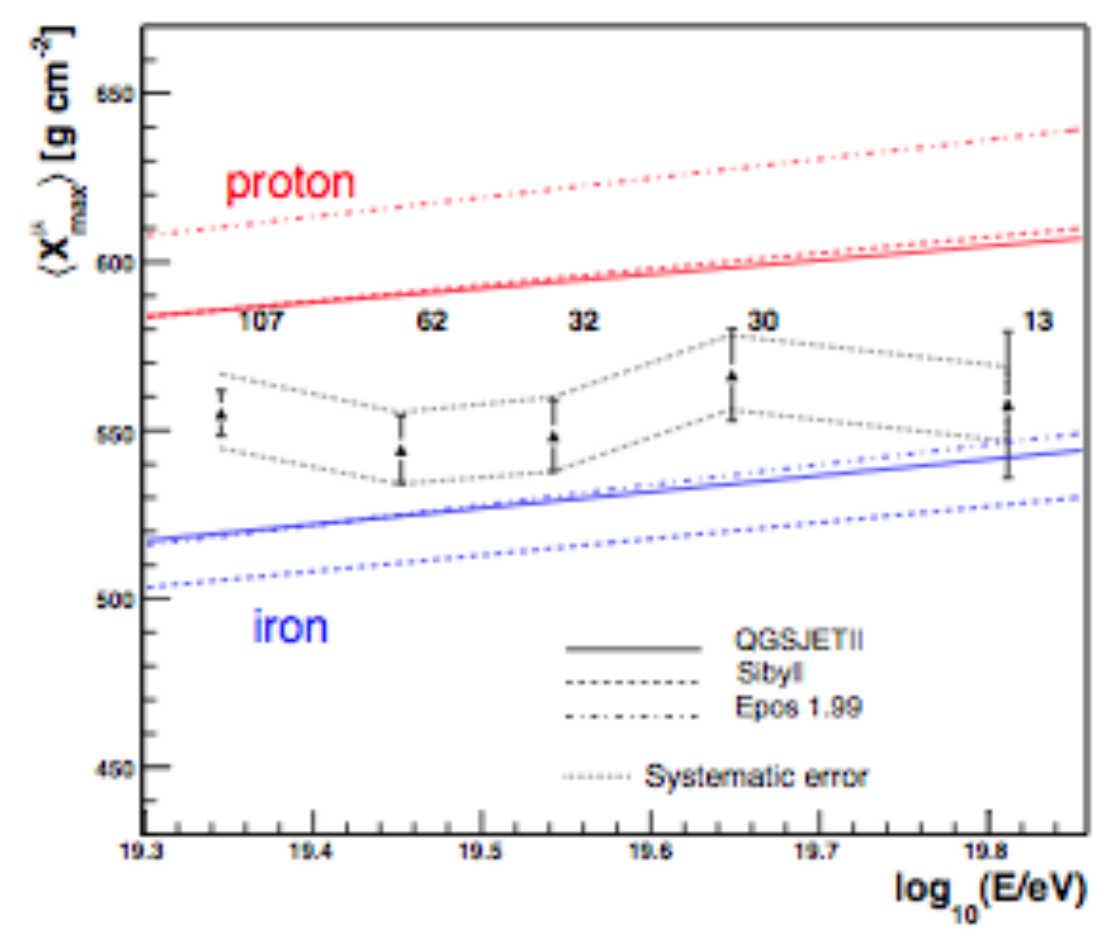
leading baryons

pion cascade

electromagnetic cascade

Pierre Auger data suggest a heavy component at the highest energies:

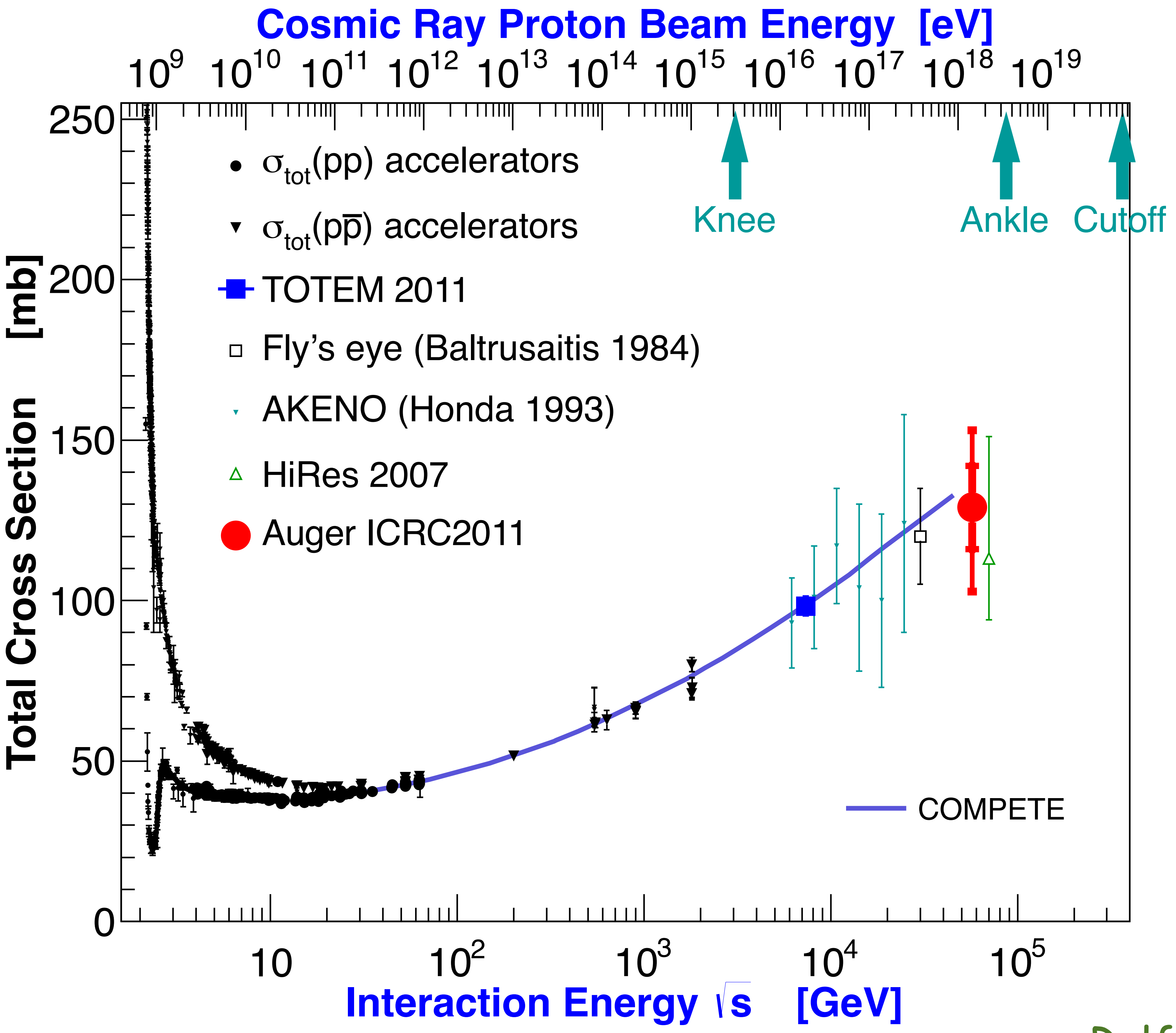




Auger data on composition seem to point to a quite heavy composition at the highest energies

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

Hadronic Cross-Sections

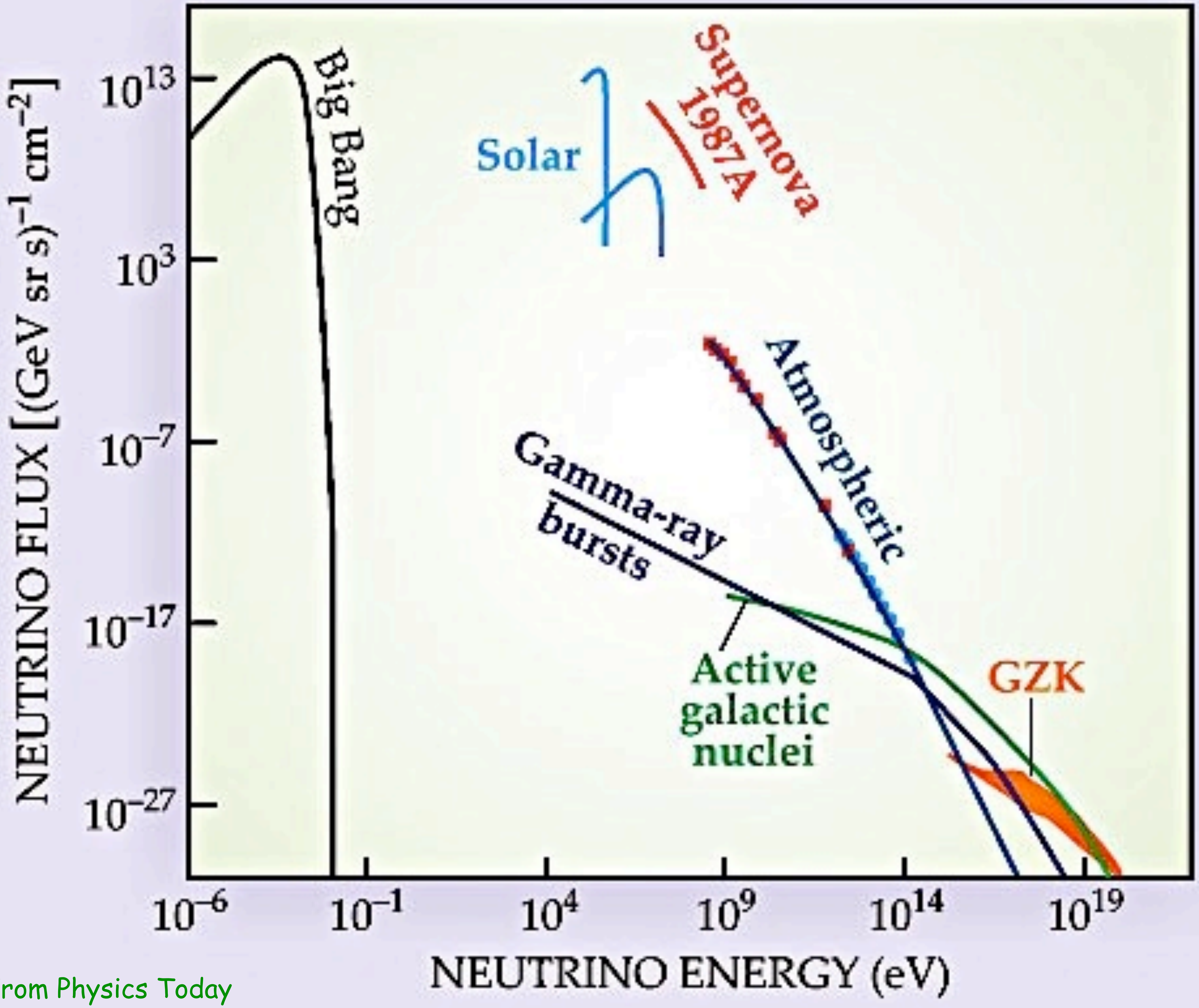


Ralf Ulrich

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

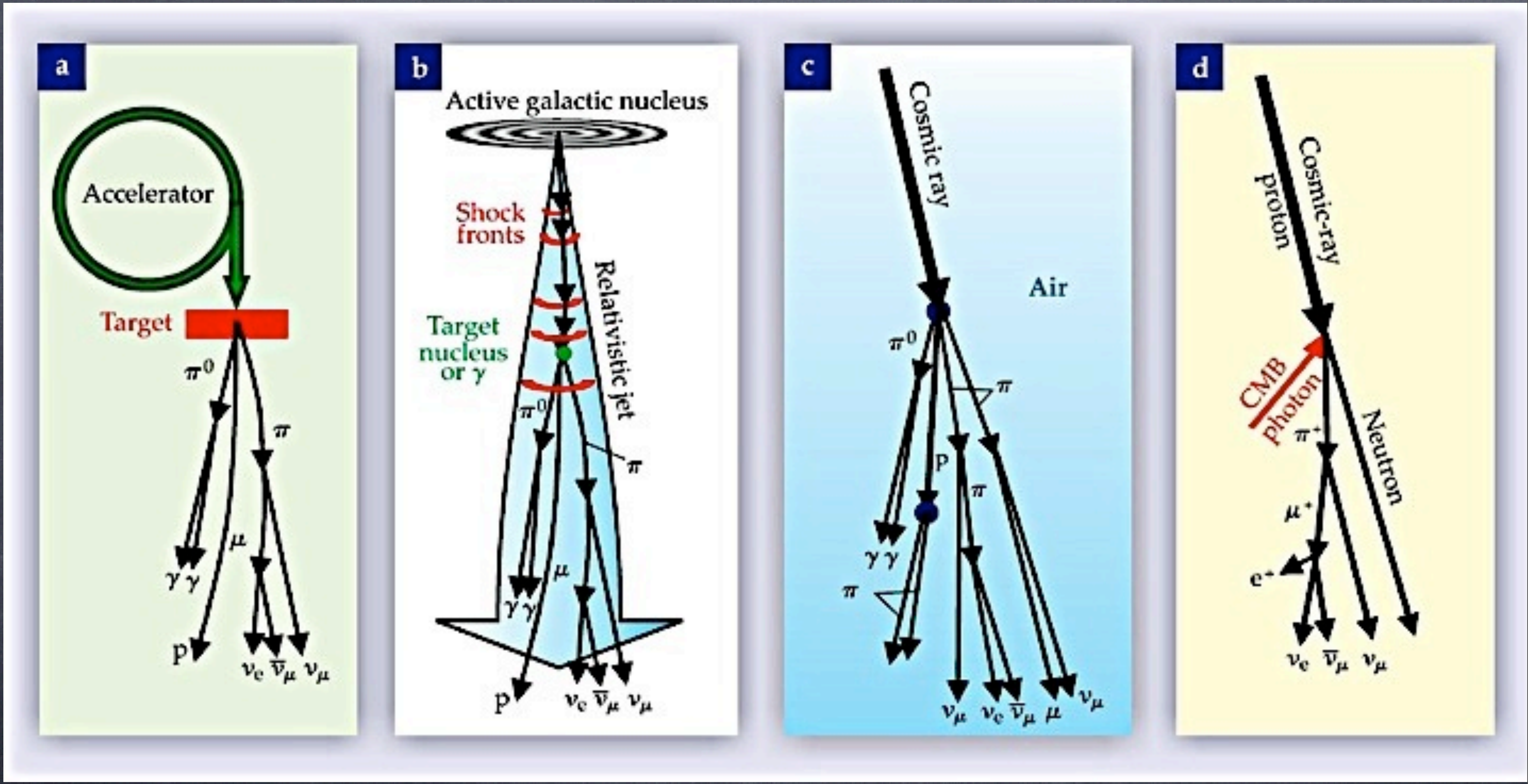
Very High High Energy Neutrinos

The „grand unified" differential neutrino number spectrum



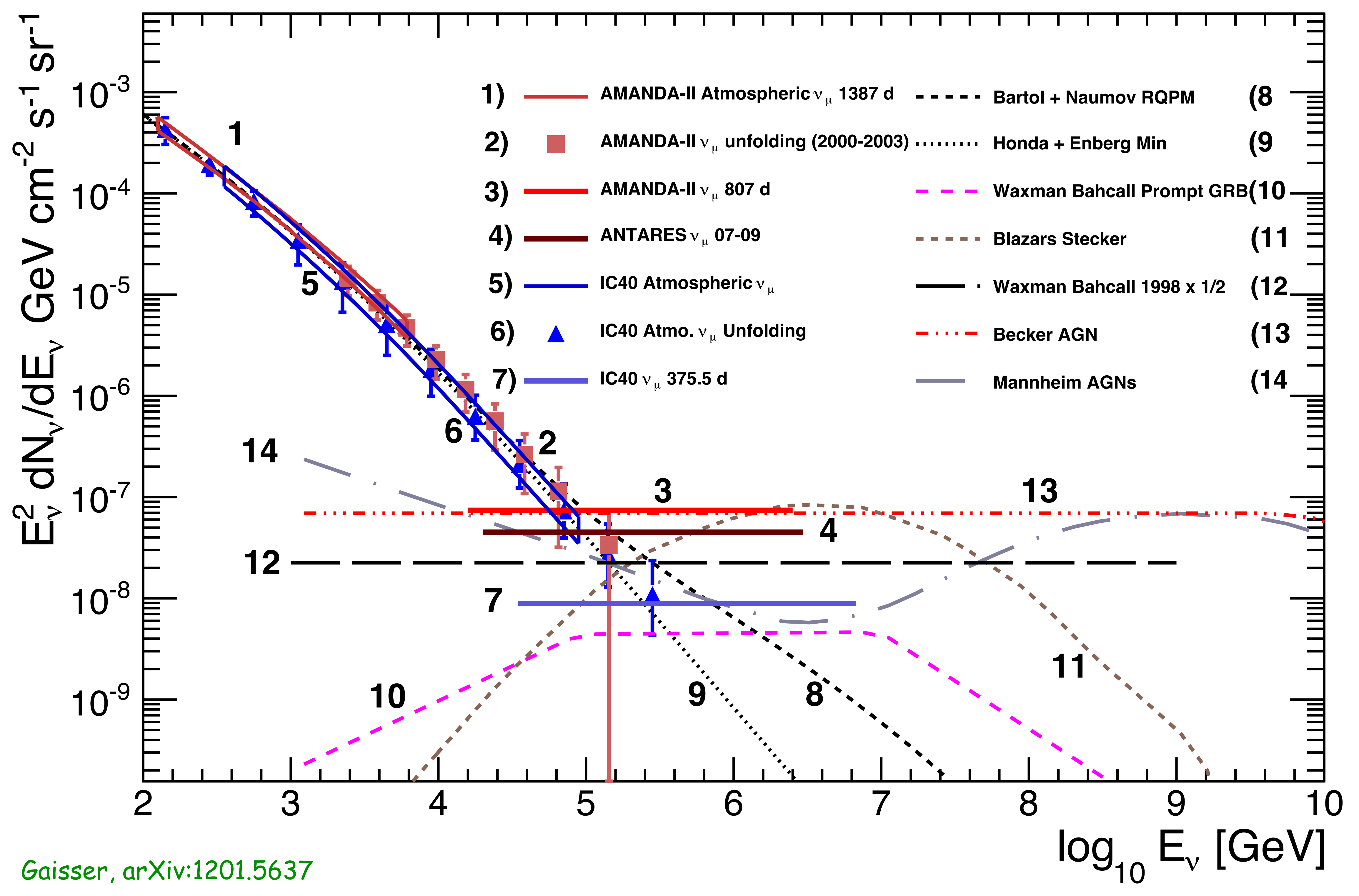
From Physics Today

Summary of neutrino production modes



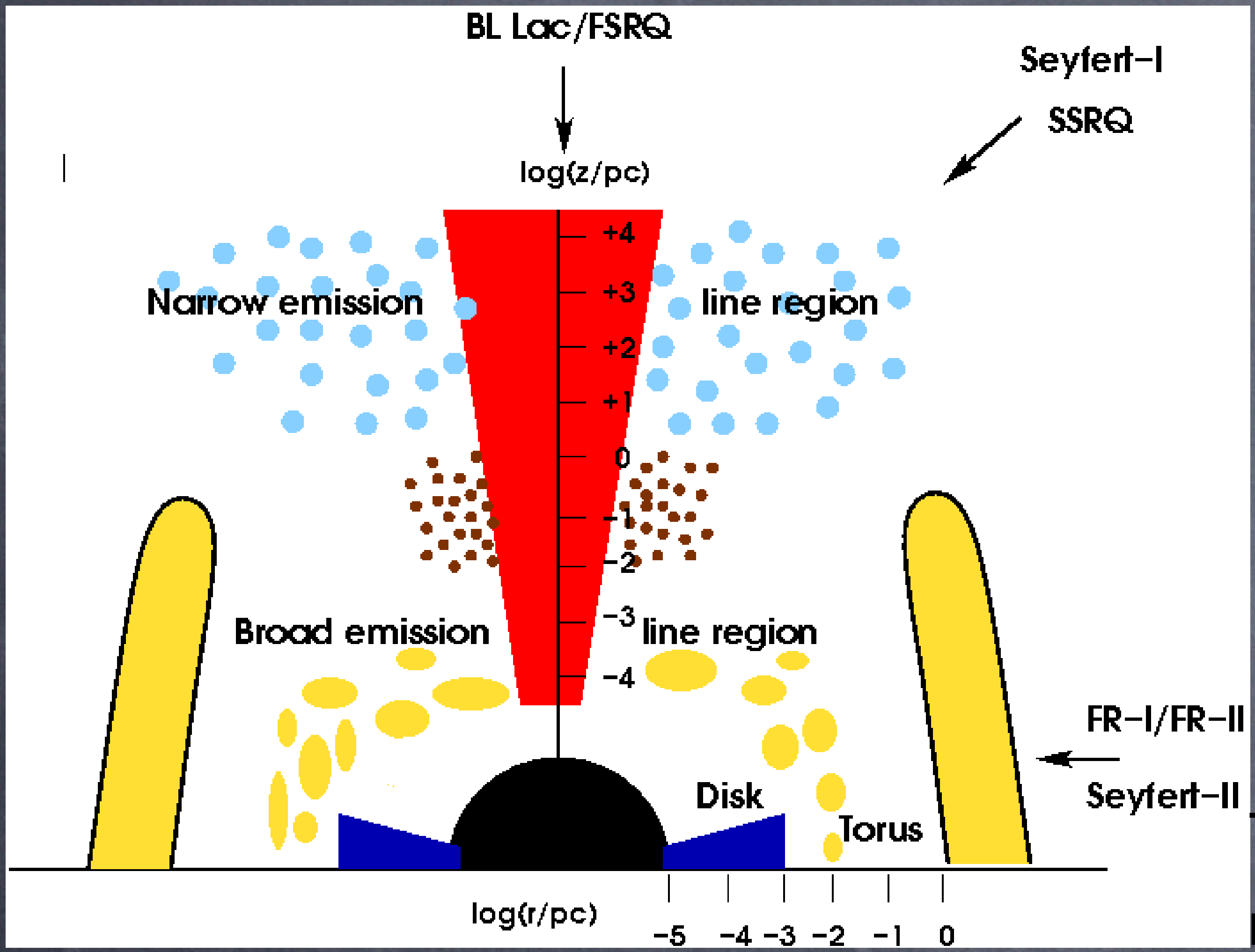
From Physics Today

Current Neutrino Flux Upper Limits at TeV-EeV energies

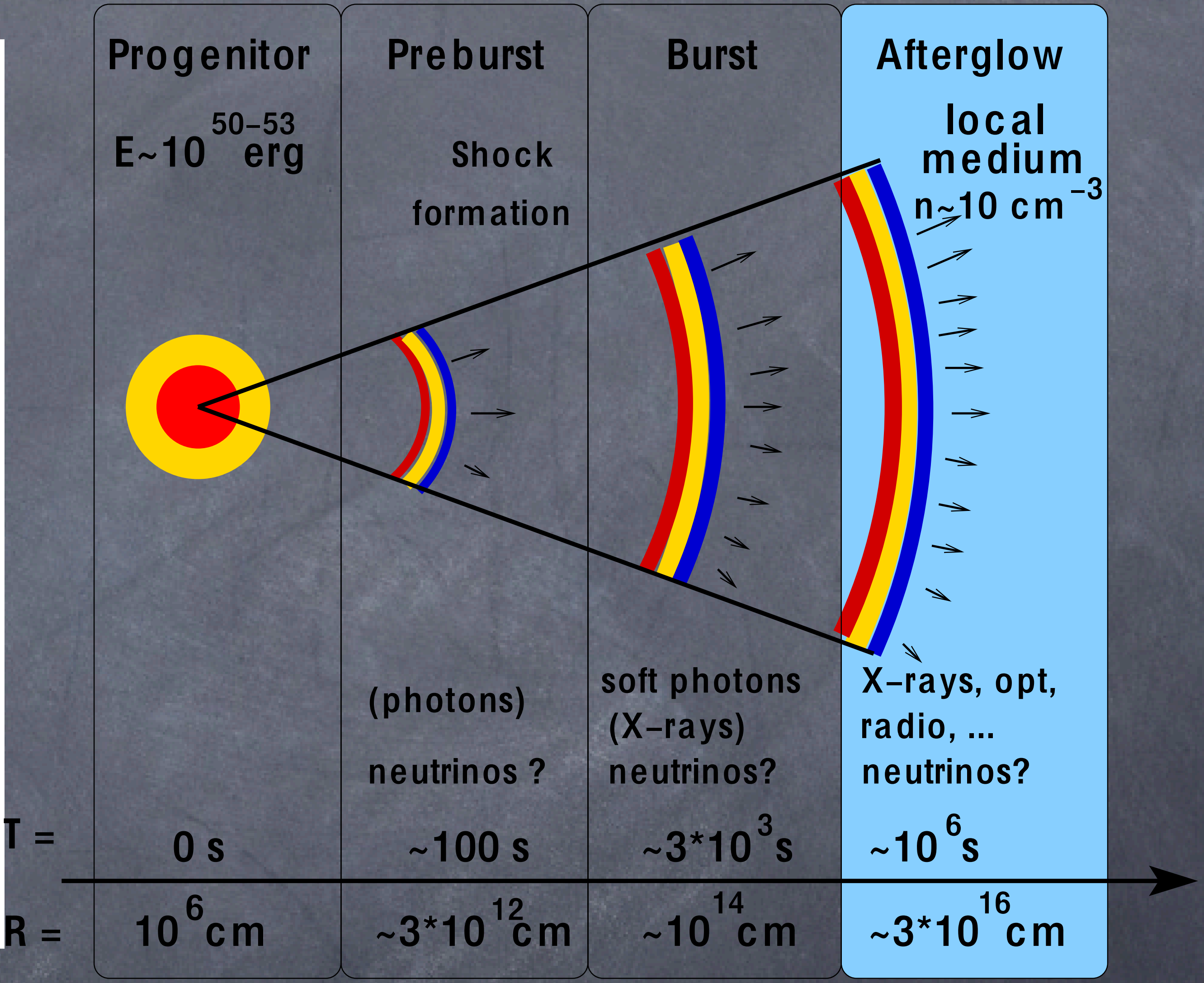


Gaisser, arXiv:1201.5637

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

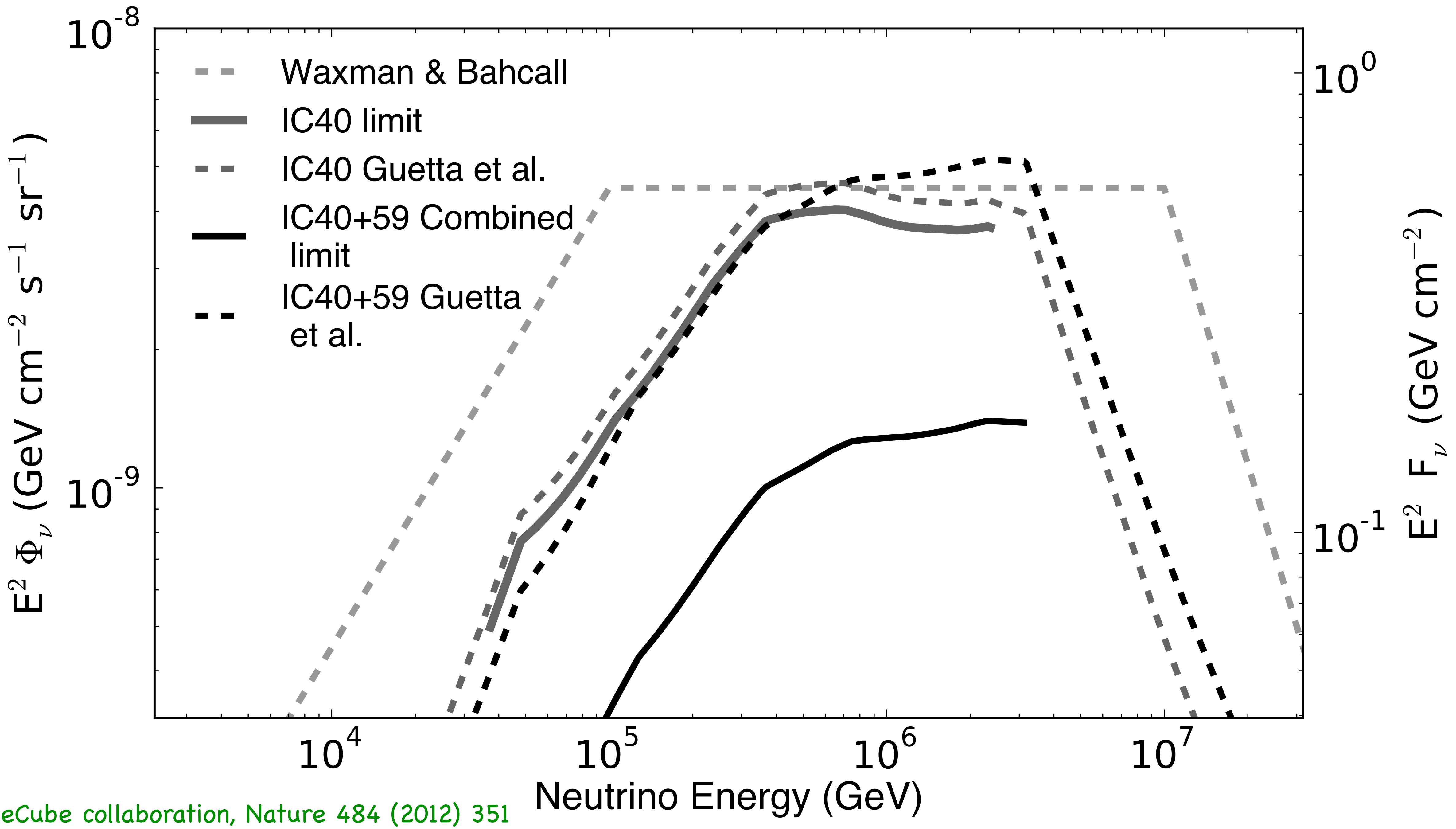
Diffuse neutrino flux from GRBs can thus be linked to UHECR flux (if it is dominantly produced by GRBs)

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

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



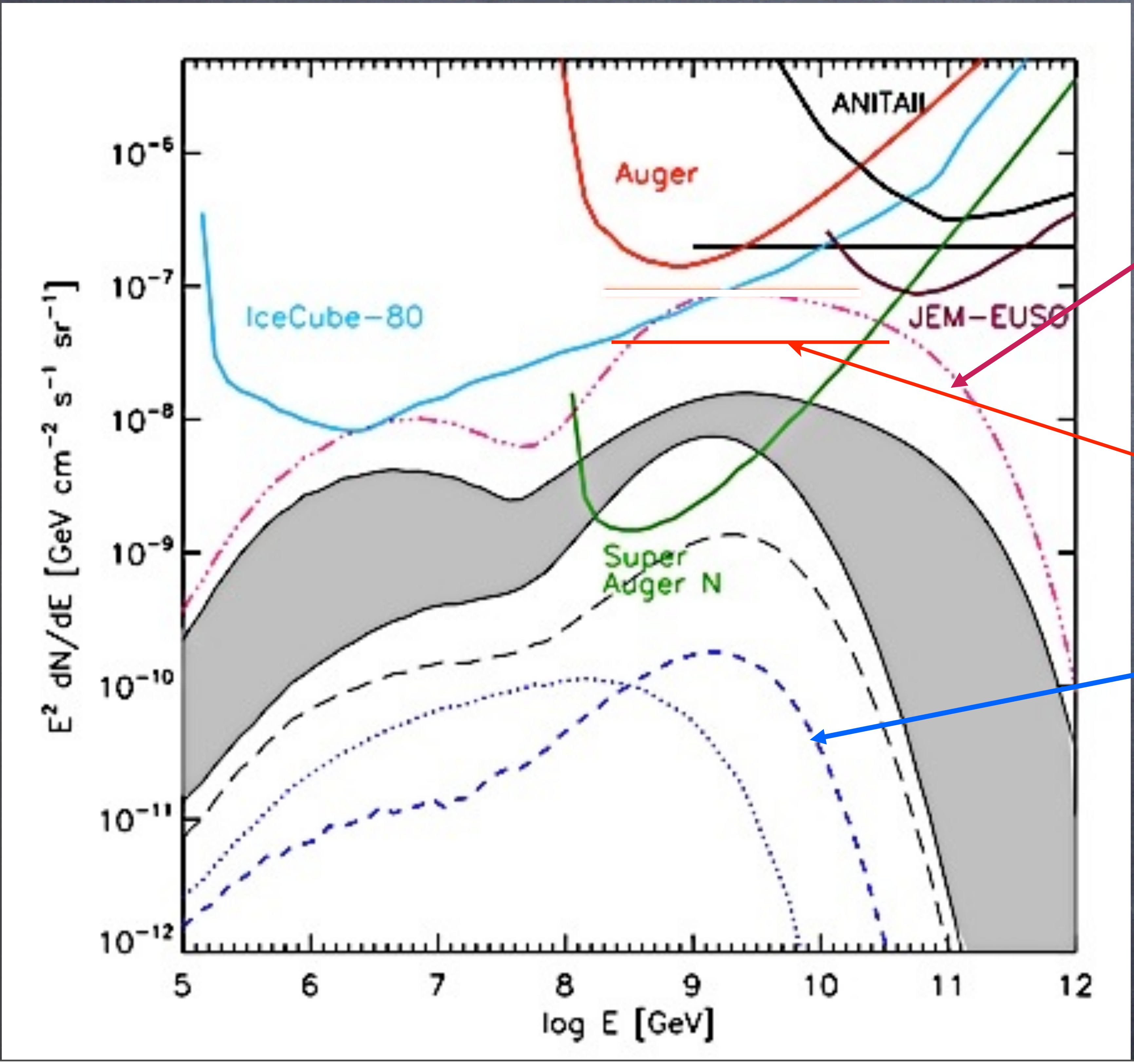
IceCube collaboration, Nature 484 (2012) 351

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

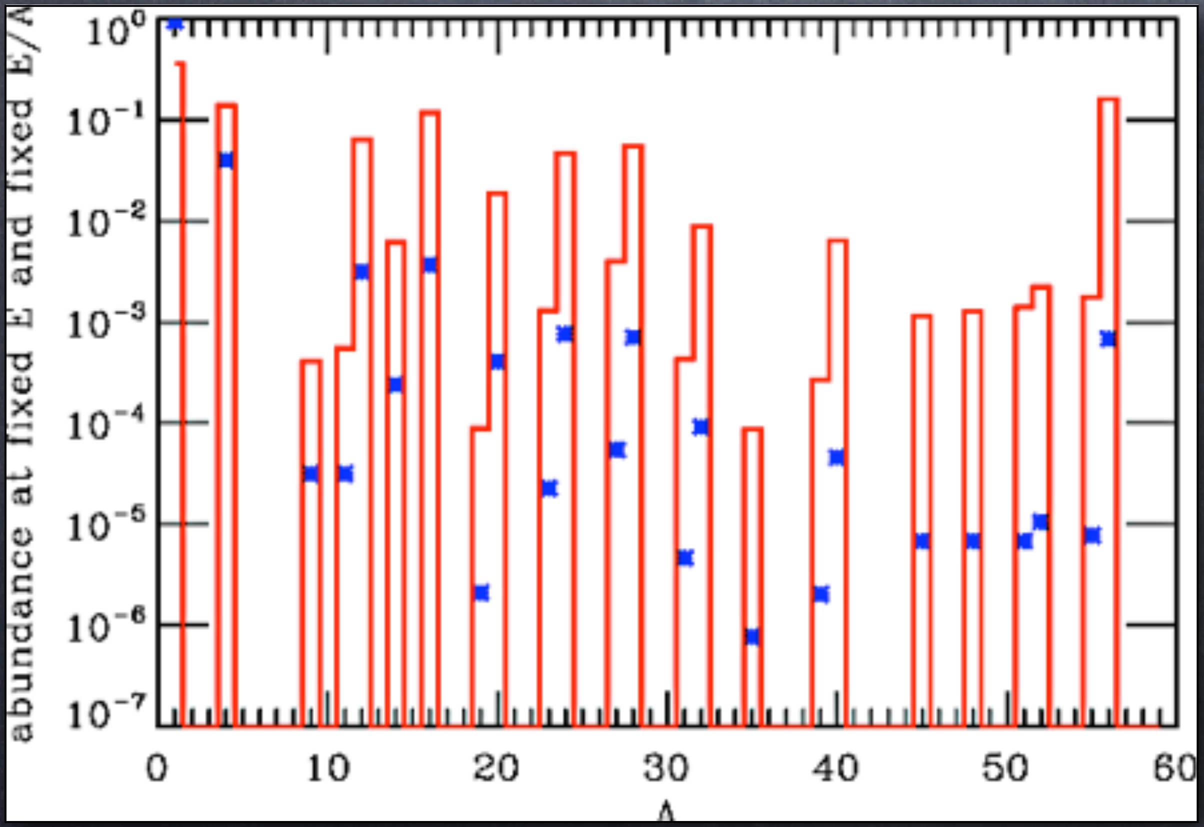
Kotera, Allard, Olinto, JCAP 1010 (2010) 013

Mixed chemical compositions

For an injection spectrum $E^{-\alpha}$ elemental abundance at given energy E is modified to

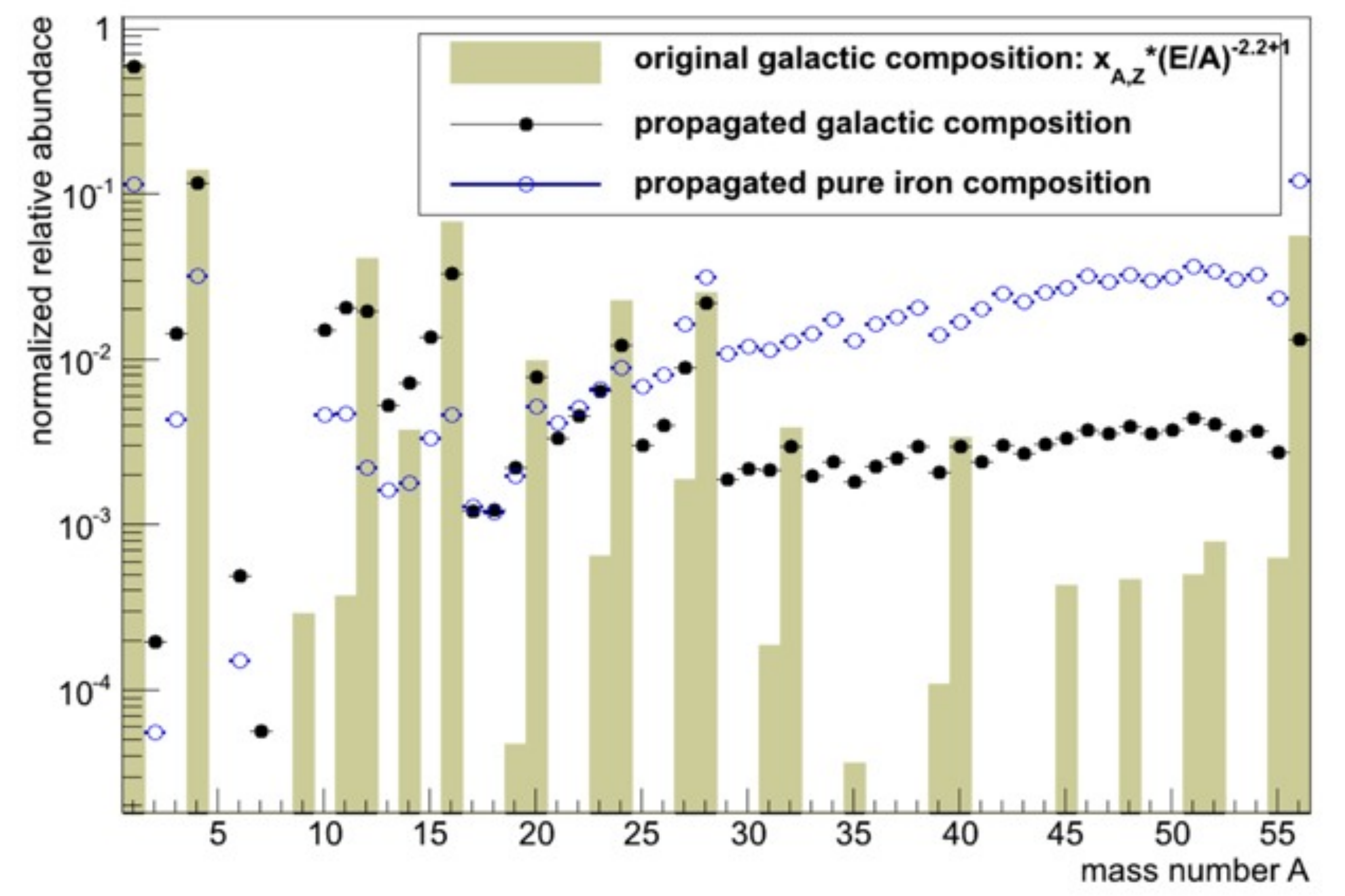
$$\frac{dn_A}{dE}(E) = N x_A \, A^{\alpha-1} \, E^{-\alpha}$$

where x_A is the abundance at given energy per nucleon E/A.



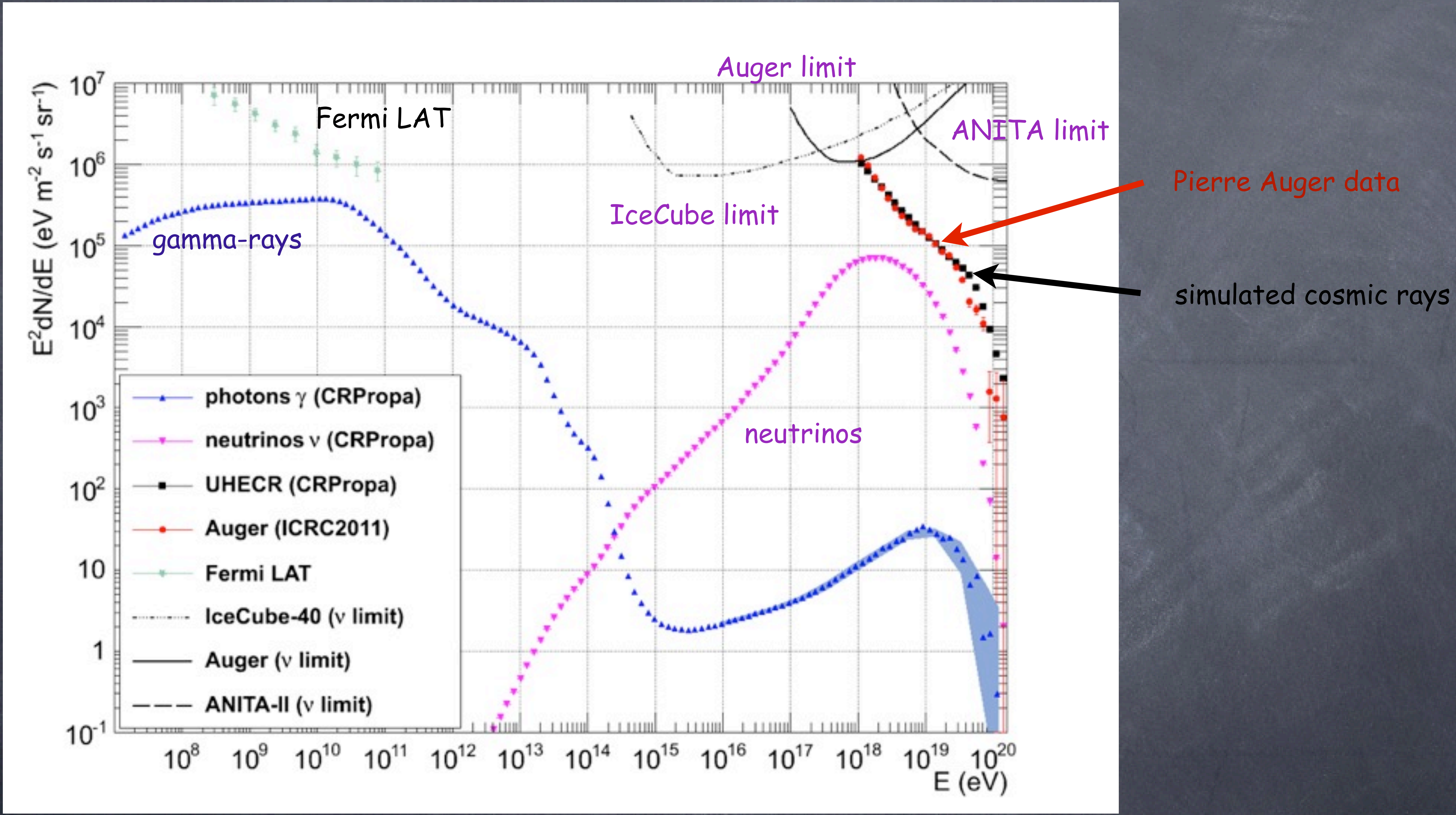
Composition at given E/A (blue) following elemental abundances in the Galaxy
Composition at given E for an $E^{-2.6}$ injection spectrum (red).

1D: Mass Composition after propagating a mixed Composition



comoving injection rate scaling as $(1+z)^4$ up to z=2
injection spectral slope α=2.2 up to E_{max} = $Z\times10^{21}$ eV

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

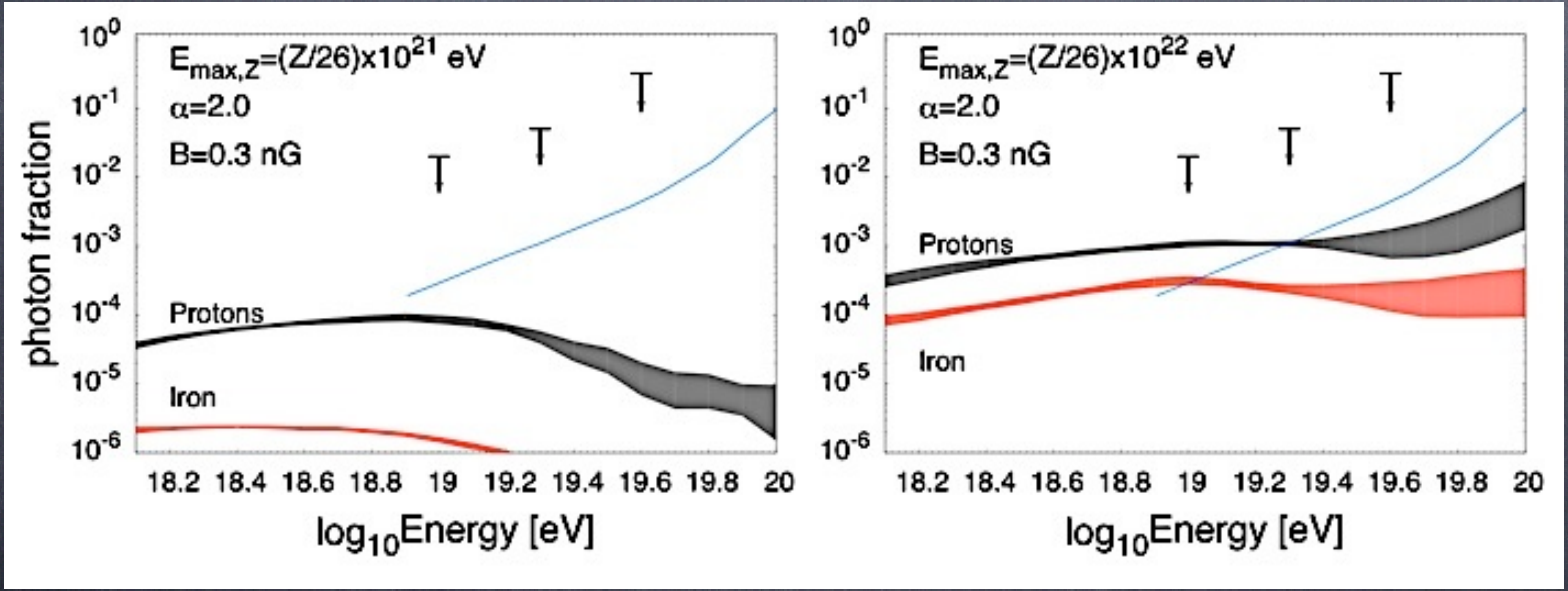


comoving injection rate scaling as $(1+z)^4$ up to z=2 injection spectral slope α=2.2 up to $E_{max} = Z \times 3.86 \times 10^{20}$ eV for a galactic mixed composition at the sources

Physics with Diffuse Secondary Gamma-Ray Fluxes

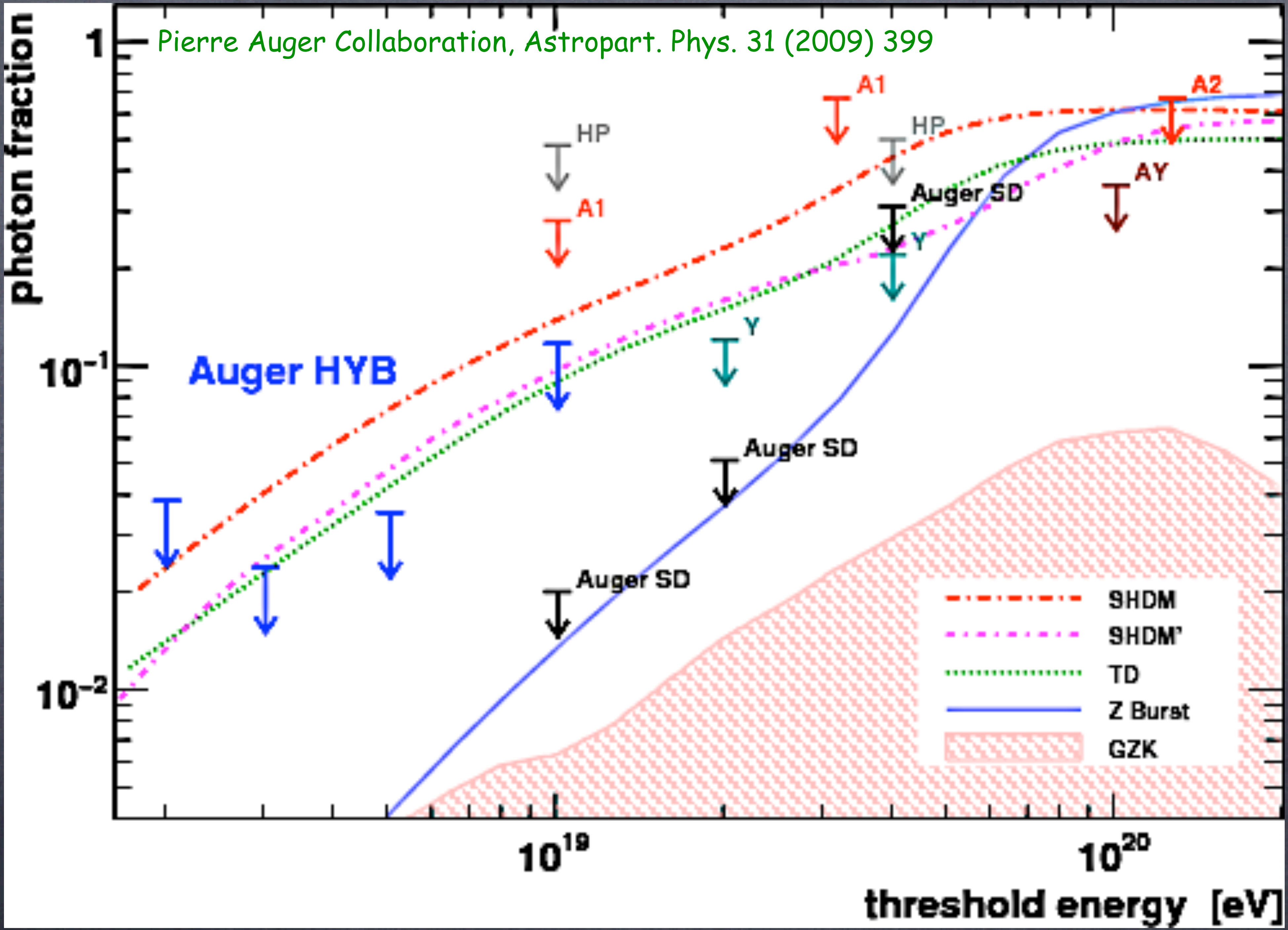
UHE gamma-ray fluxes depend on number of nucleons locally produced above GZK threshold which is proportional to E_{max}/A

Further suppressed for heavy nuclei due to increased pair production complementary to cosmogenic neutrinos: does not depend on redshift evolution

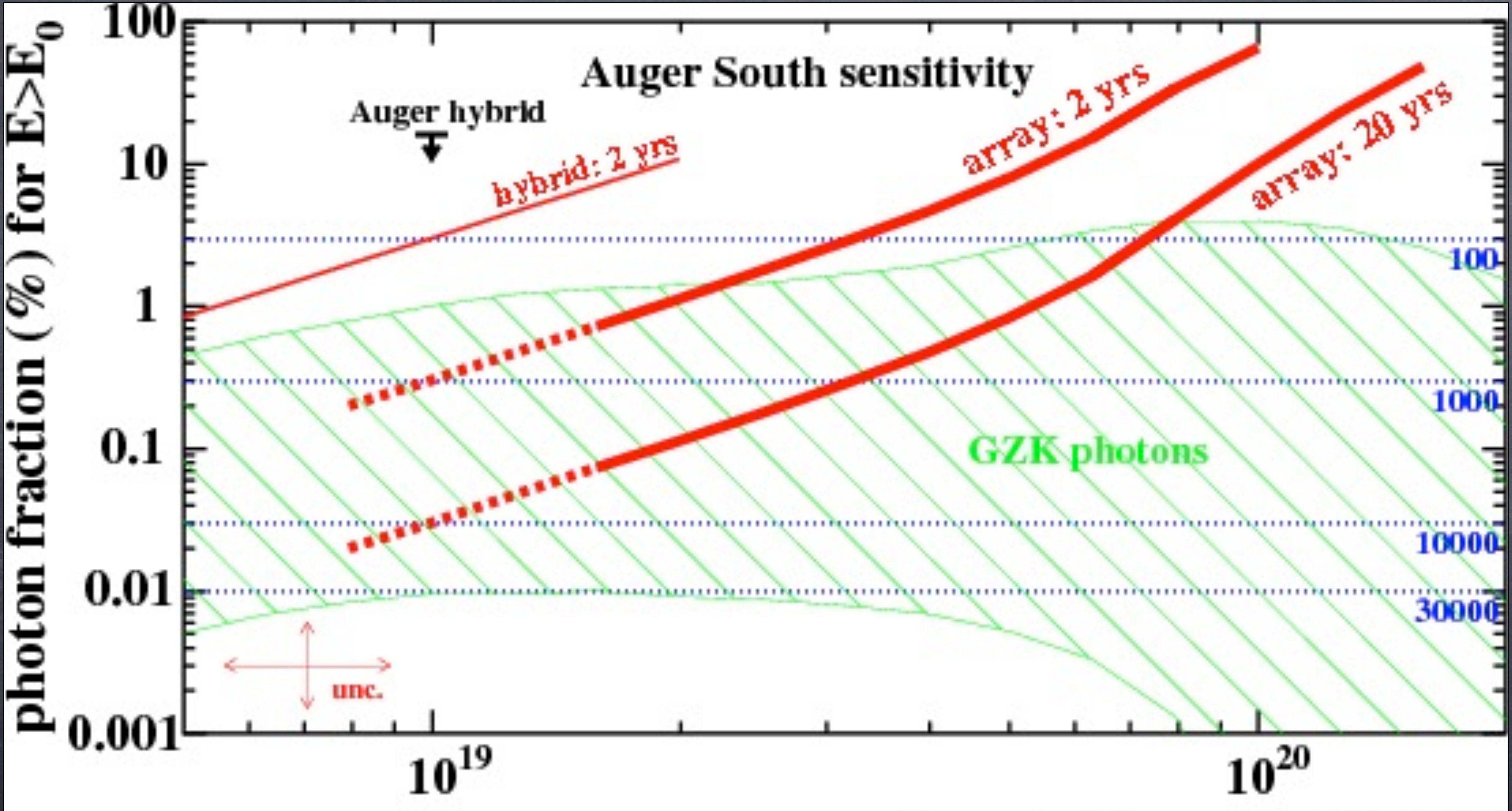


Hooper, Taylor, Sarkar, Astropart.Phys. 34 (2011) 340

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.



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



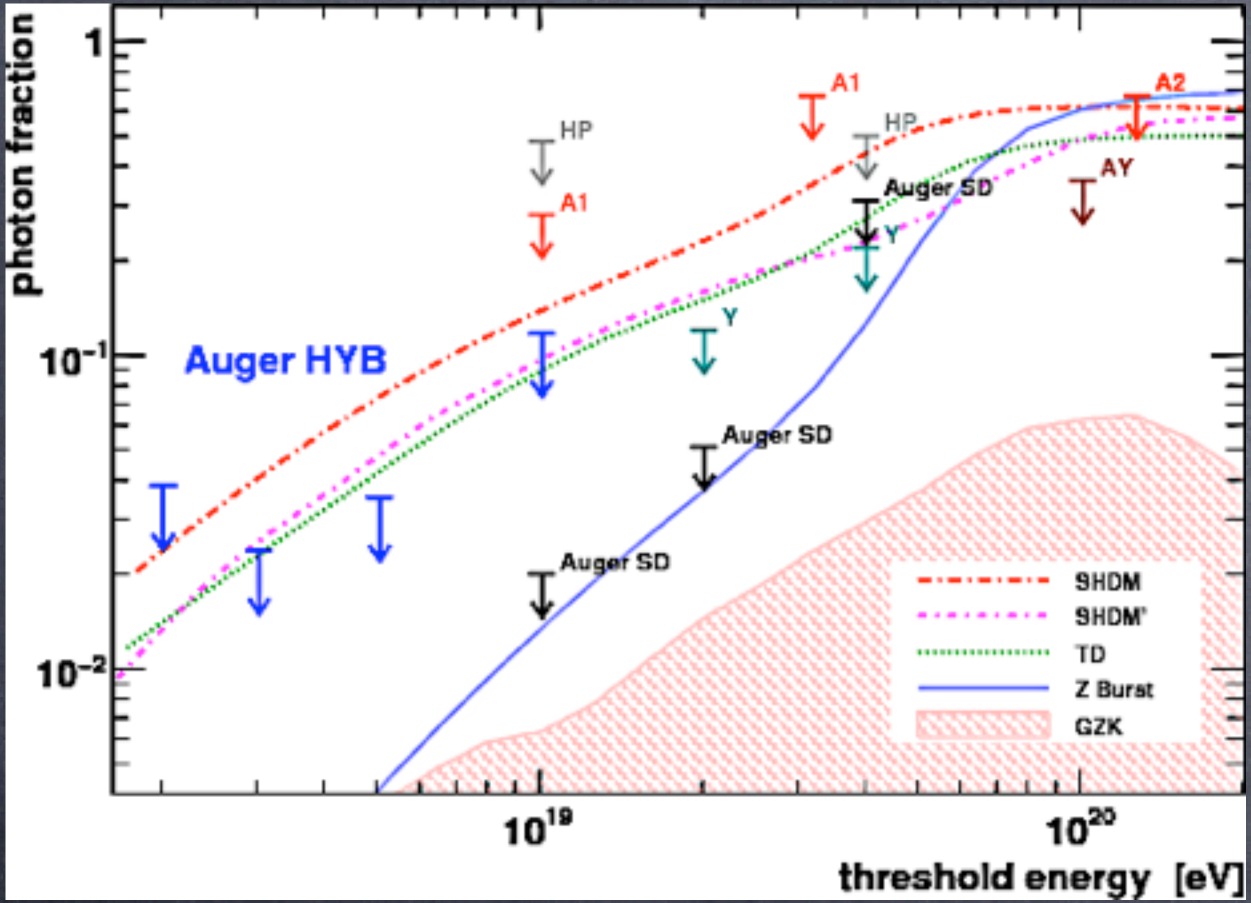
Risse, Homola, Mod.Phys.Lett. A22 (2007) 749.

Lorentz Symmetry Violation in the Electromagnetic Sector

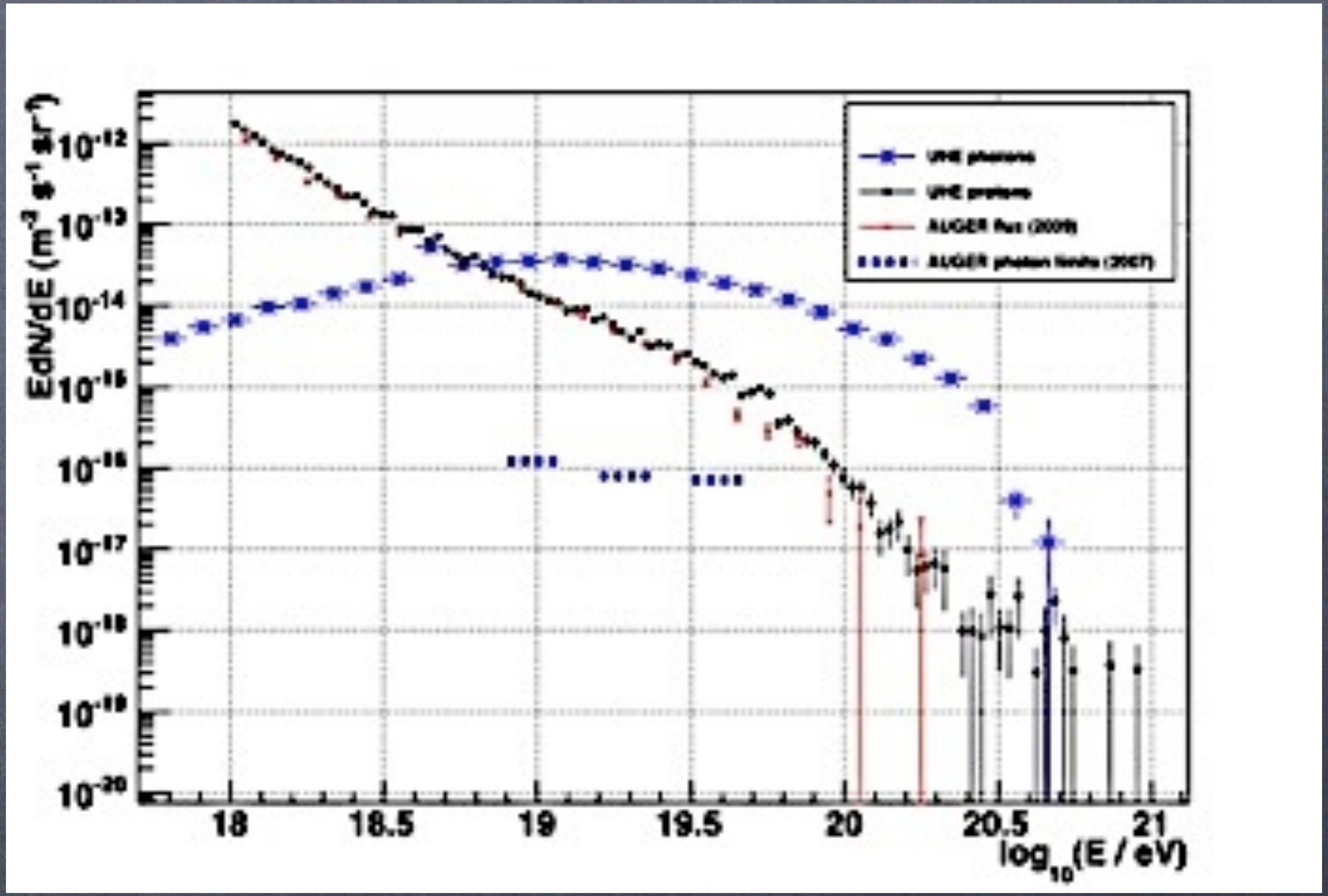
The idea:

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 a photon dispersion relation

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

pair production may become inhibited, increasing GZK photon fluxes above observed upper limits: **In the absence of LIV for electrons/positrons for n=1 this yields:**

$$\xi_1 \leq 10^{-12}$$

Such strong limits may indicate that Lorentz invariance violations are completely absent !

Lorentz Symmetry Violation in the Neutrino Sector

Define $\delta = v^2 - 1 > 0$, such that $m^2 = E^2 - p^2 = E^2(1 - v^2) = -\delta E^2$ is effective tachyonic mass

Superluminal neutrino velocities would predict vacuum Cherenkov radiation $\nu \rightarrow \nu\, e^+ e^-$ with an energy loss rate

$$\Gamma \simeq \frac{25}{448} \frac{G_{\rm F}^2}{192\pi^3} E^5 \delta^3$$

corresponding to an "effective mass" $|m^2| = \delta E^2$ and a Lorentz factor $\gamma = 1/\delta^{1/2}$, by dimensional analysis, Cohen and Glashow, PRL 107 (2011) 181803

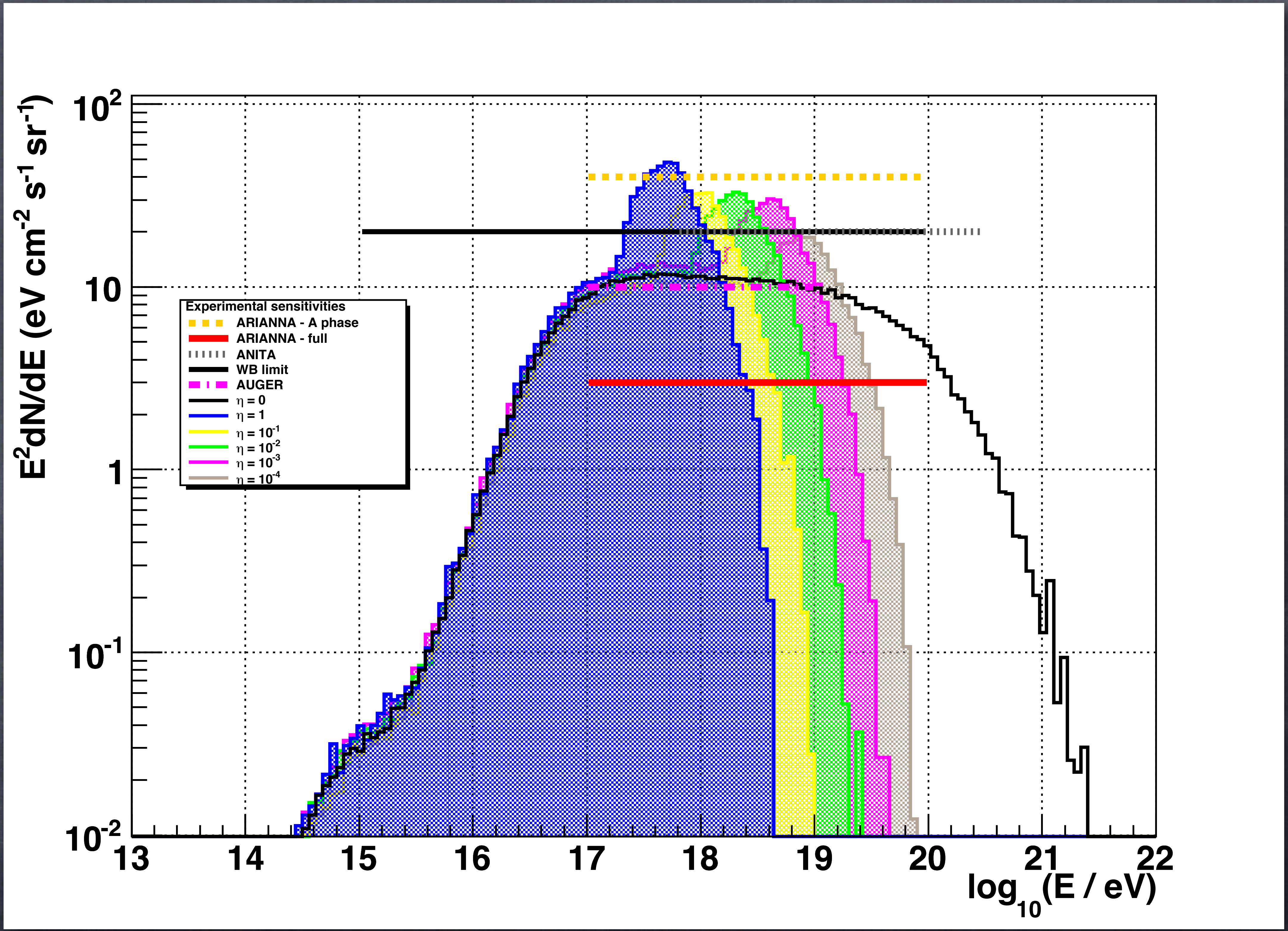
For terms $\eta_n p^2 (p/M_{\rm Pl})^{n-2}$ in the neutrino dispersion relation one has $\delta \sim \eta_n (E/M_{\rm Pl})^{n-2}$

In numbers

$$\Gamma^{-1} \simeq 15 \left(\frac{\mathrm{GeV}}{E}\right)^5 \delta^{-3}\,\mathrm{cm}$$

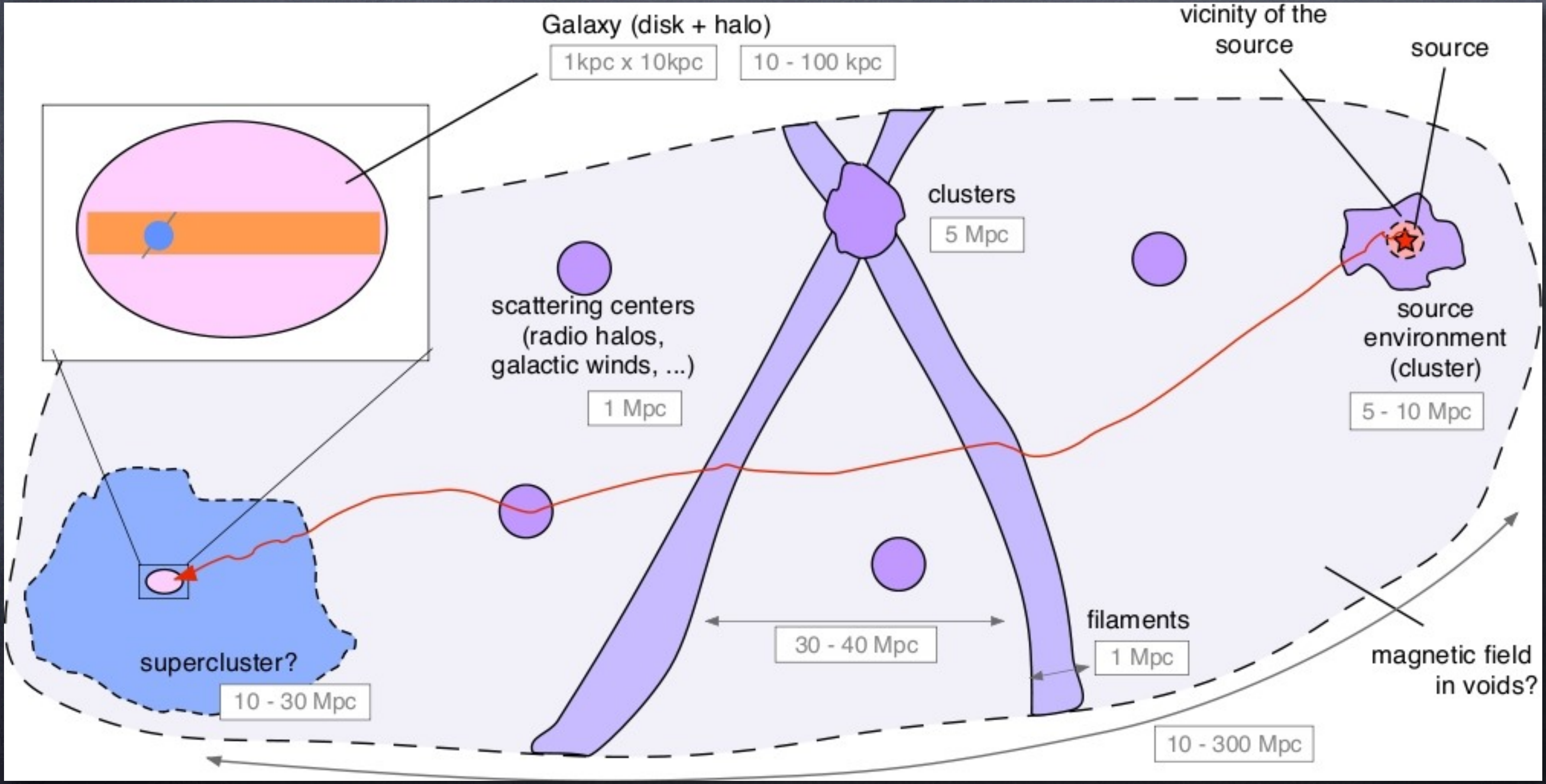
For the superluminality once claimed by OPERA, $E \gtrsim 17.5$ GeV and a length scale ~730 km one has $\delta \lesssim 5\mathrm{x}10^{-5}$.
Actual constraint in fact stronger because beam contains higher energies.
This was inconsistent with claimed effect !

But the strongest constraints would be obtained by observing “cosmogenic neutrinos”, $E \sim 10^{19}$ eV over Mpc length scales, corresponding to $\delta \lesssim 3\mathrm{x}10^{-25}$, or $\eta_4 \lesssim 3\mathrm{x}10^{-5}$



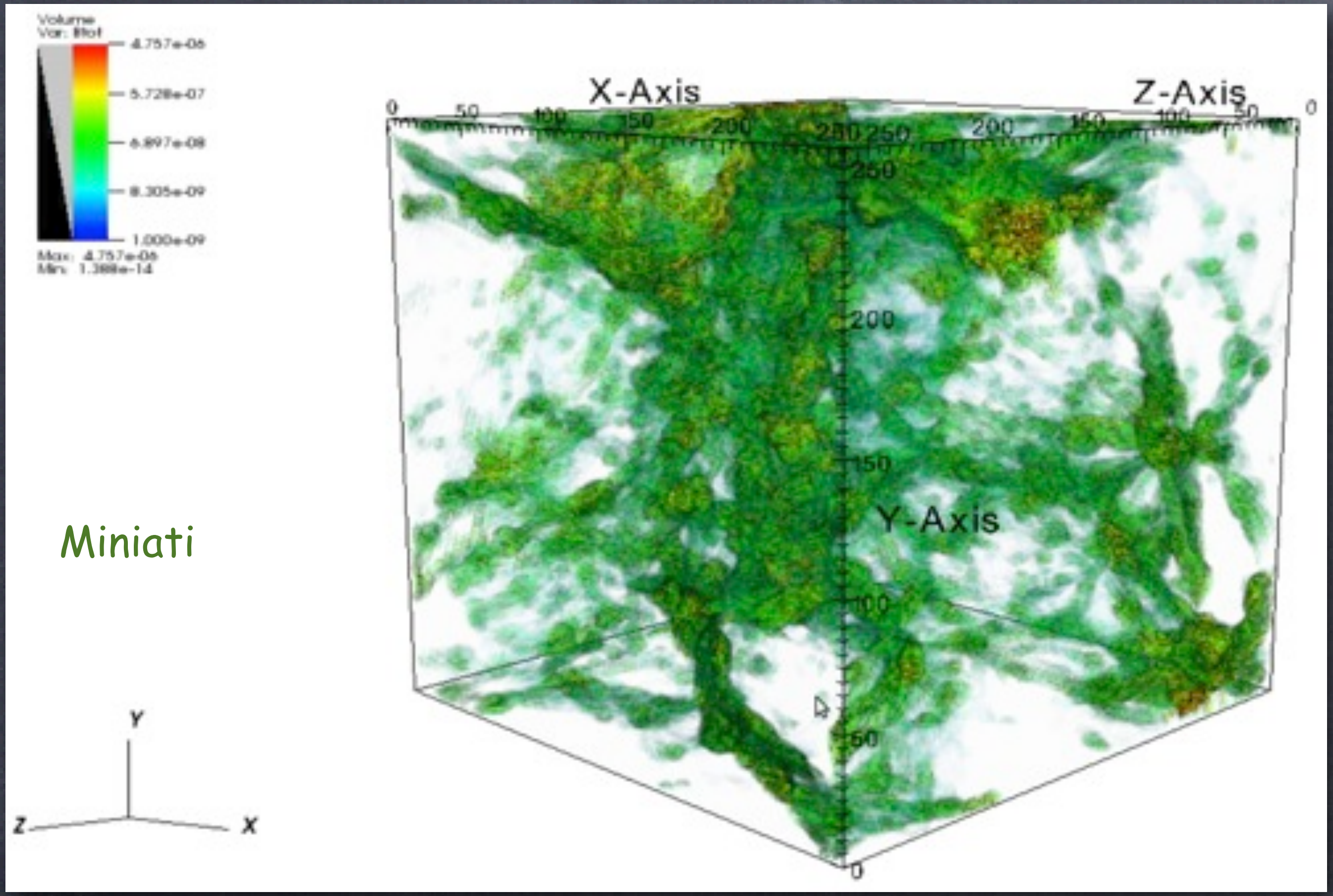
Mattingly, Maccione, Galaverni, Liberati, Sigl, JCAP 1002:007 (2010)

3-Dimensional Effects in Propagation

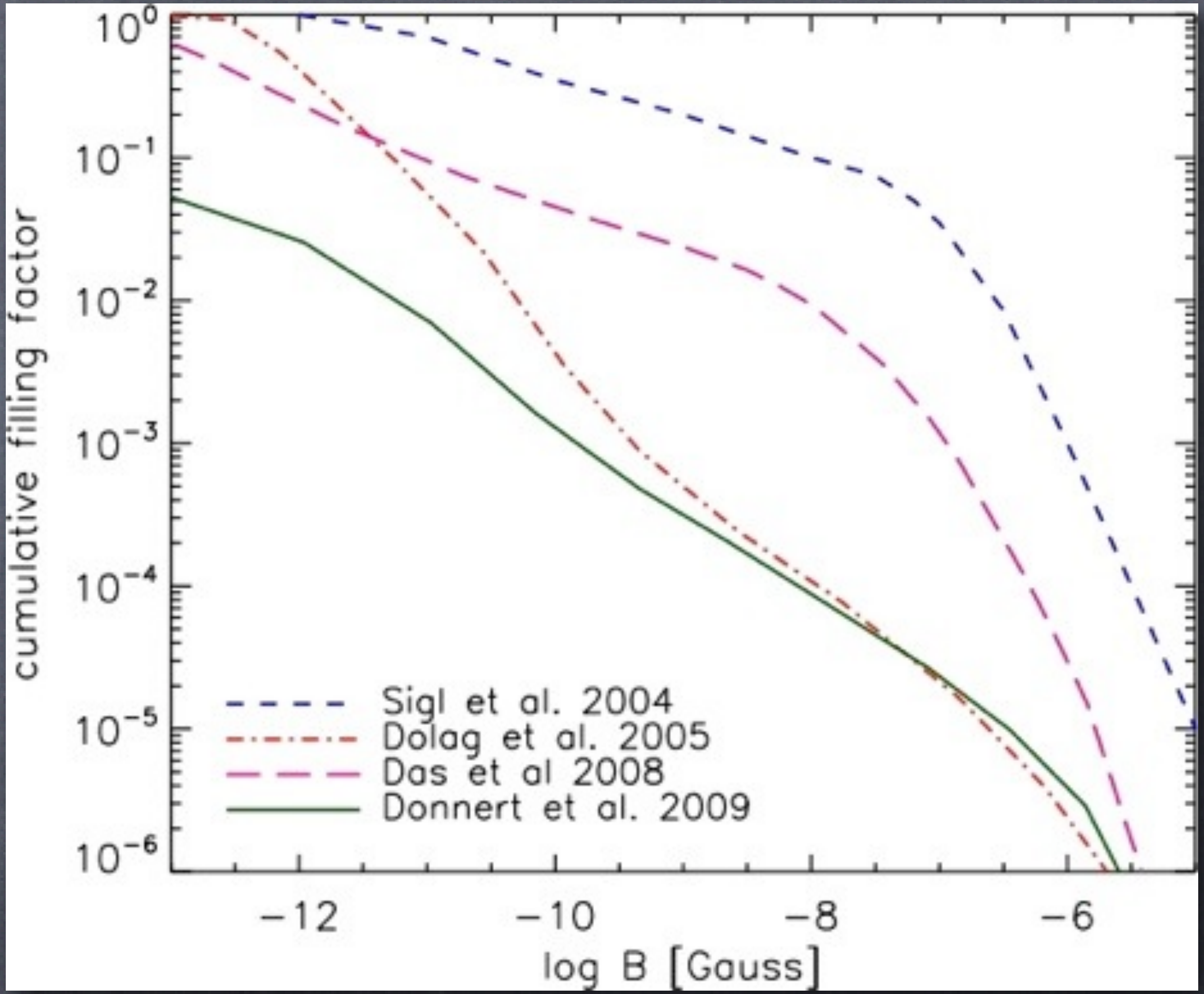


Kotera, Olinto, Ann.Rev.Astron.Astrophys. 49 (2011) 119

Structured Extragalactic Magnetic Fields



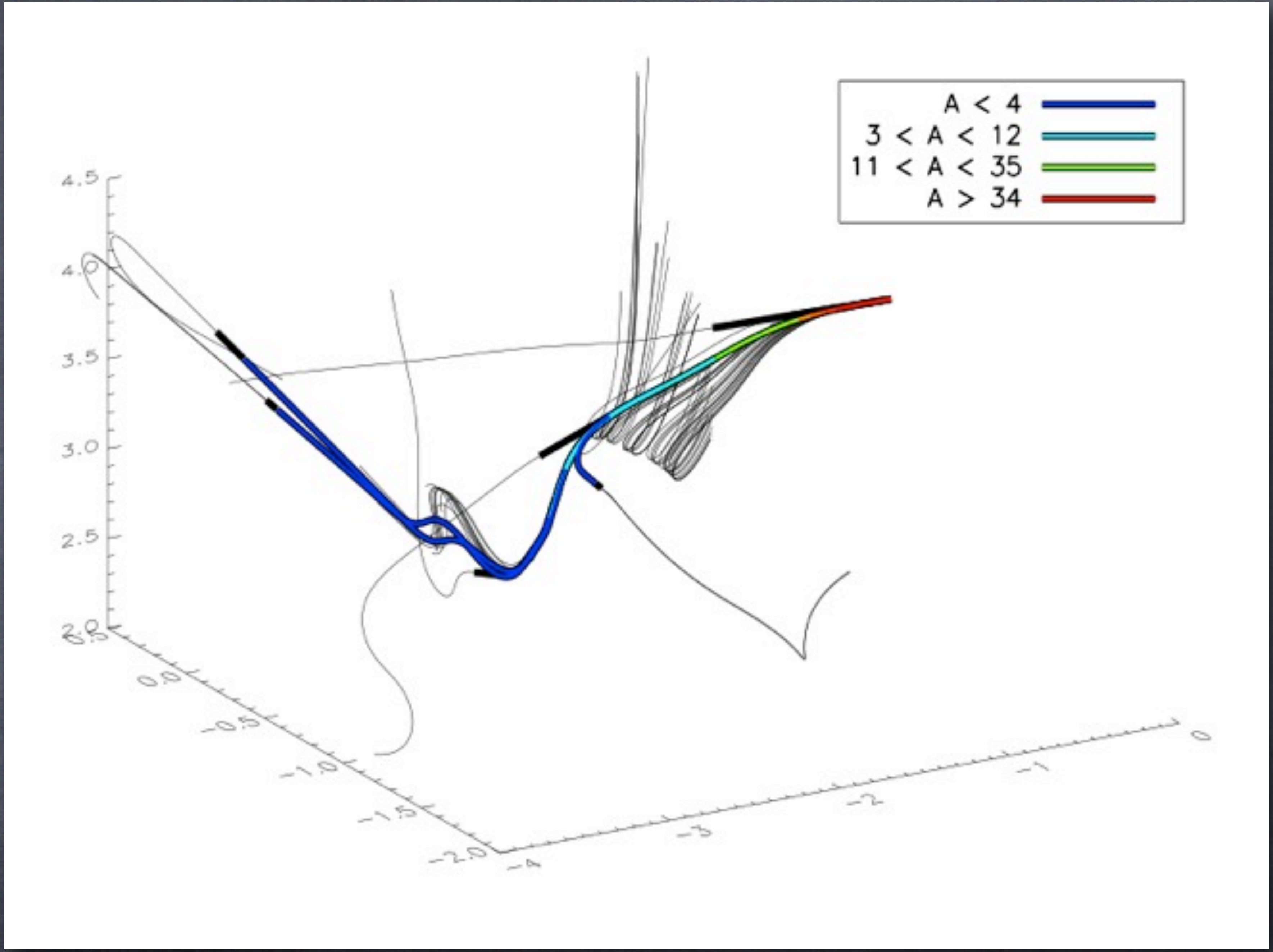
Miniati



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

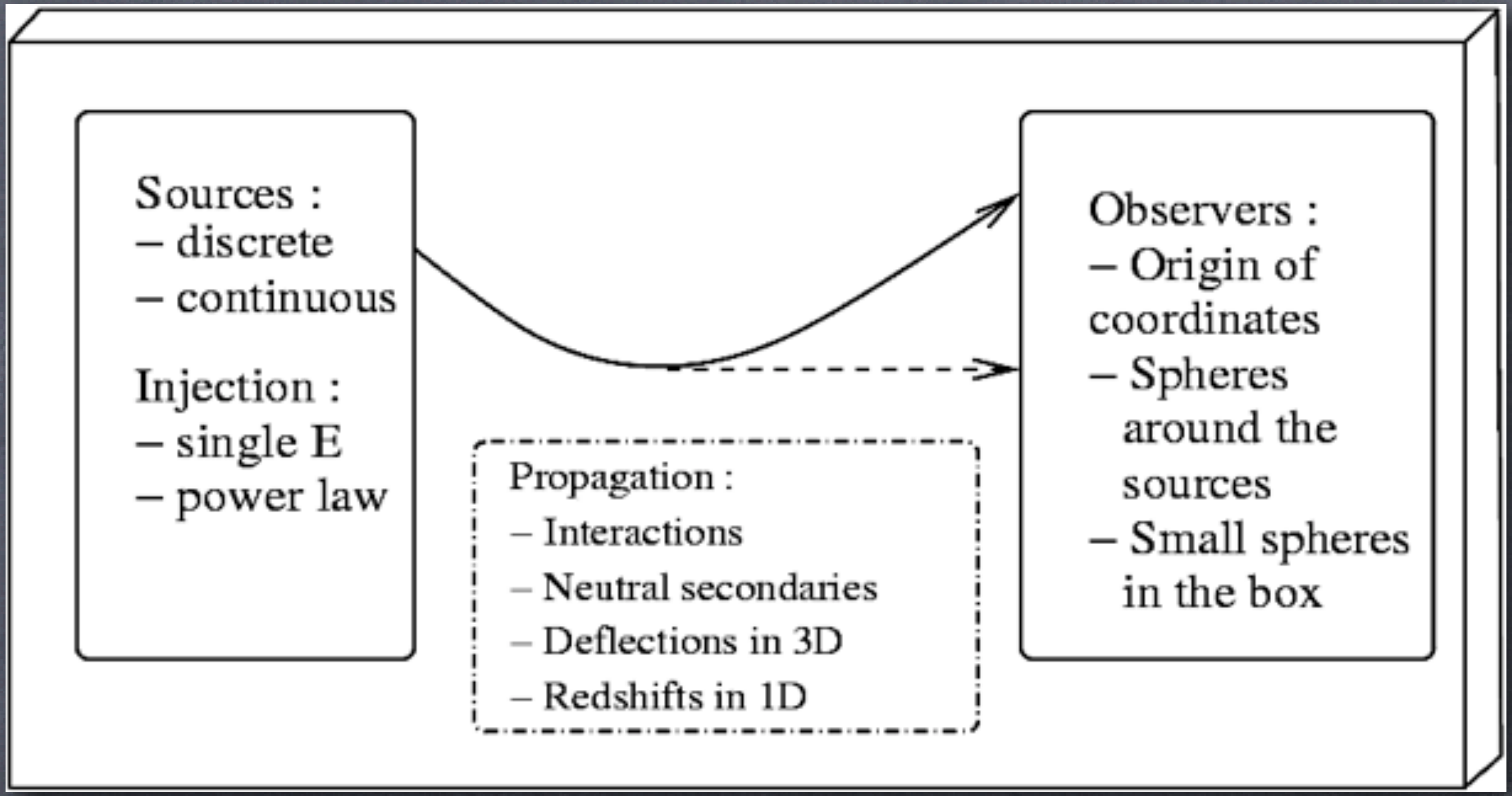
Extragalactic iron propagation produces nuclear cascades in structured magnetic fields:



Initial energy 1.2 x 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


Sources :
– discrete
– continuous

Injection :
– single E
– power law

Propagation :
– Interactions
– Neutral secondaries
– Deflections in 3D
– Redshifts in 1D

Observers :
– Origin of coordinates
– Spheres around the sources
– Small spheres in the box

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

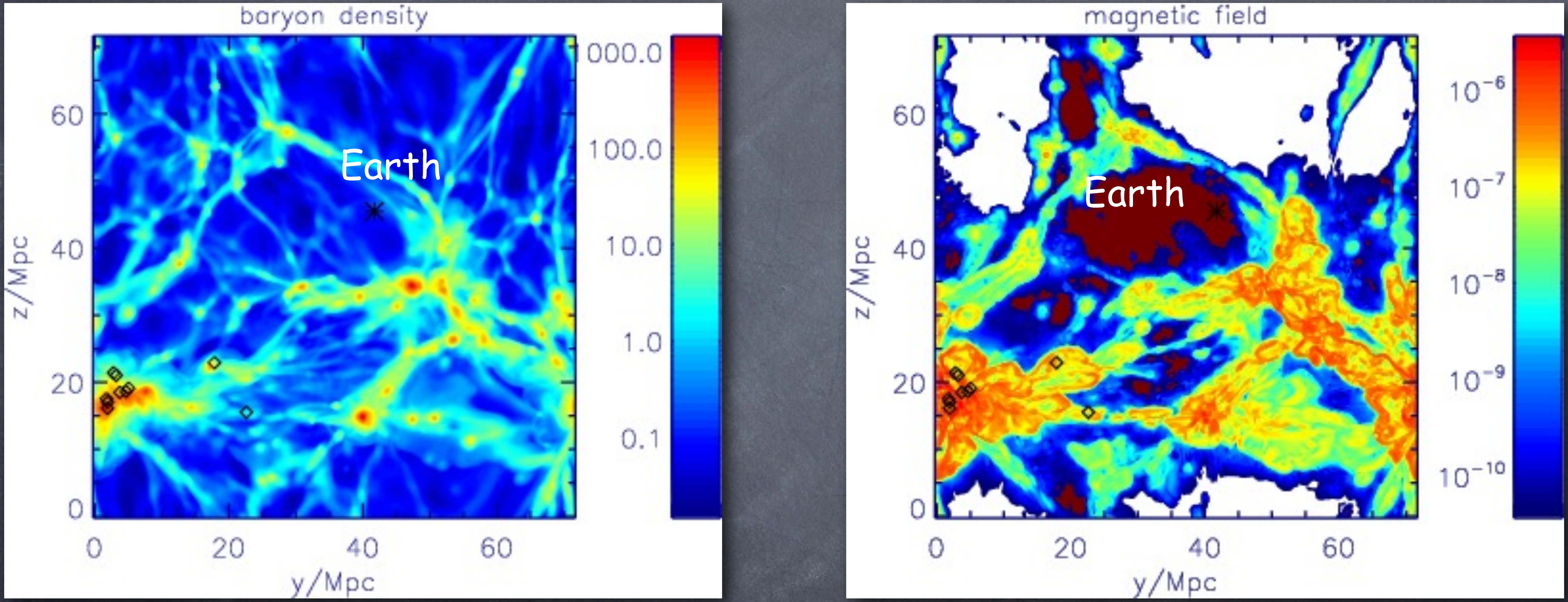
Electromagnetic cascades are treated by solving one-dimensional transport equations

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.

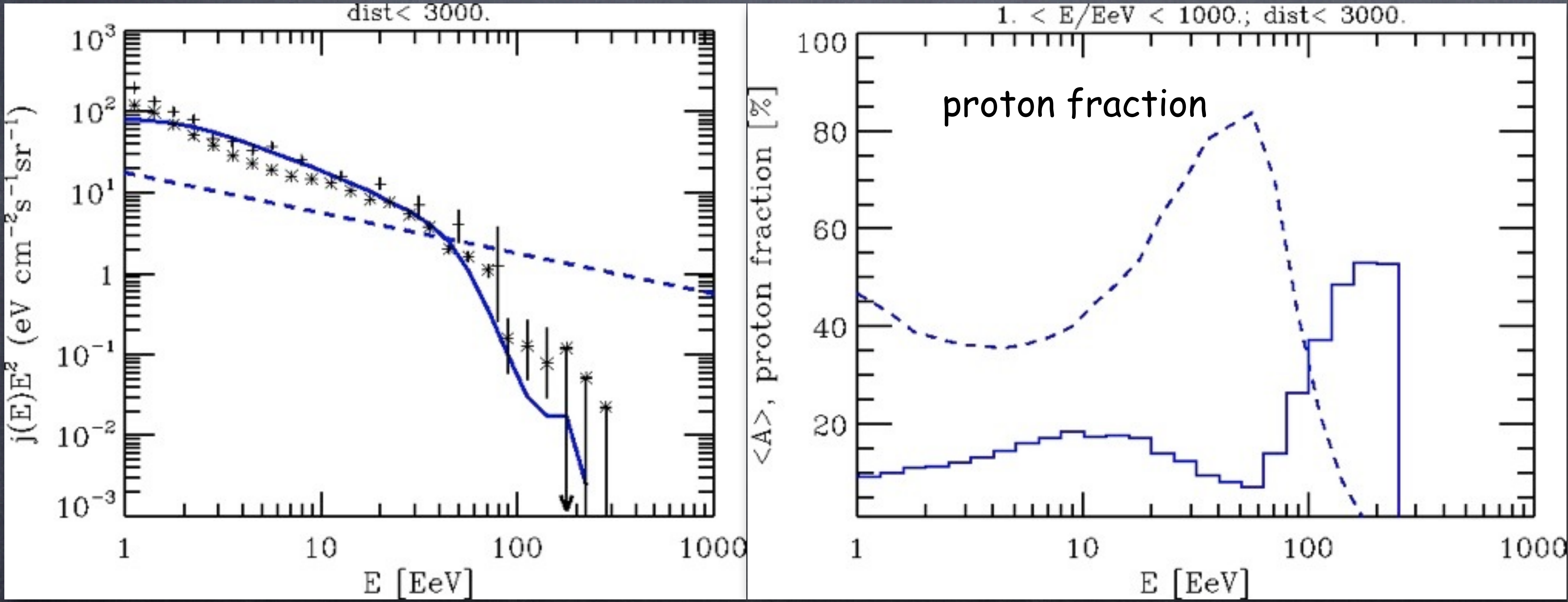
Presented are two examples for 1D and 3D simulations

Discrete Sources in nearby large scale structure

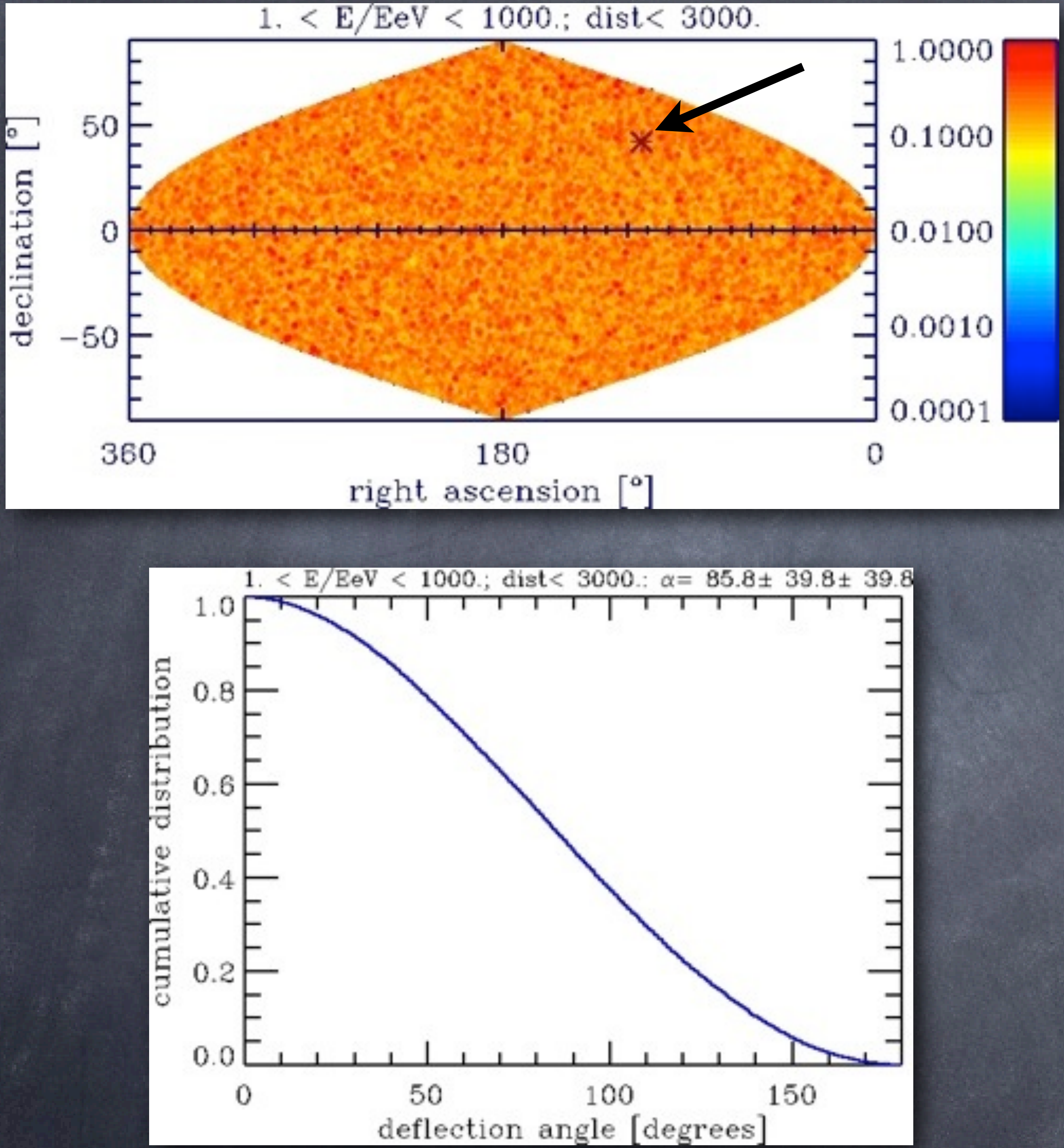


10 sources per (75 Mpc)^3 box, concentrated in a galaxy cluster at ≃30 Mpc, injecting $E^{-2.5}$ spectra up to 200xZ EeV with 10 x galactic abundance;
+ one source @ 4Mpc of 0.002 relative strength injecting E^{-2} spectrum up to 10xZ EeV.

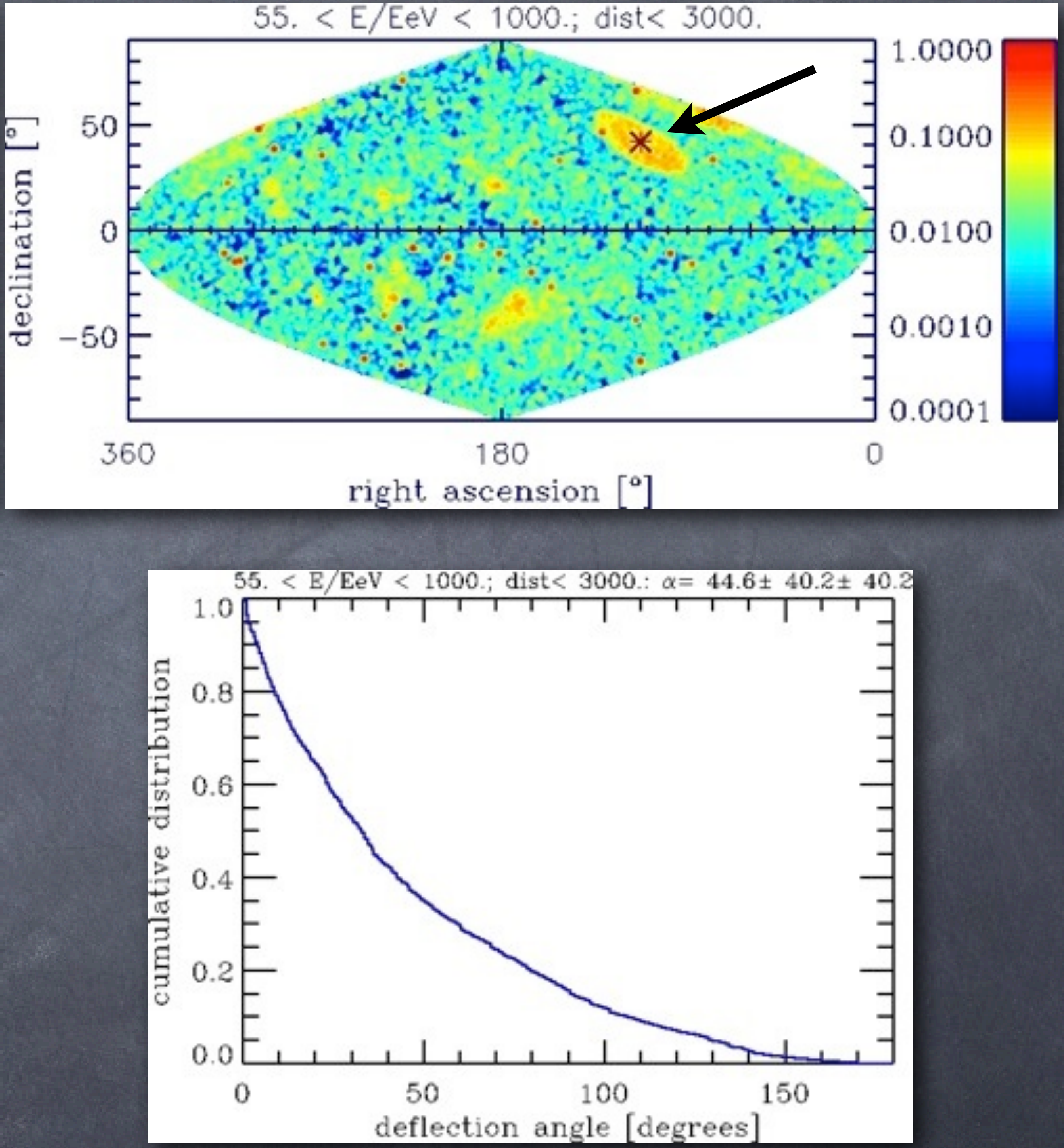
Results: Spectra and Composition



Results: Sky Distributions and Anisotropies



above 1 EeV

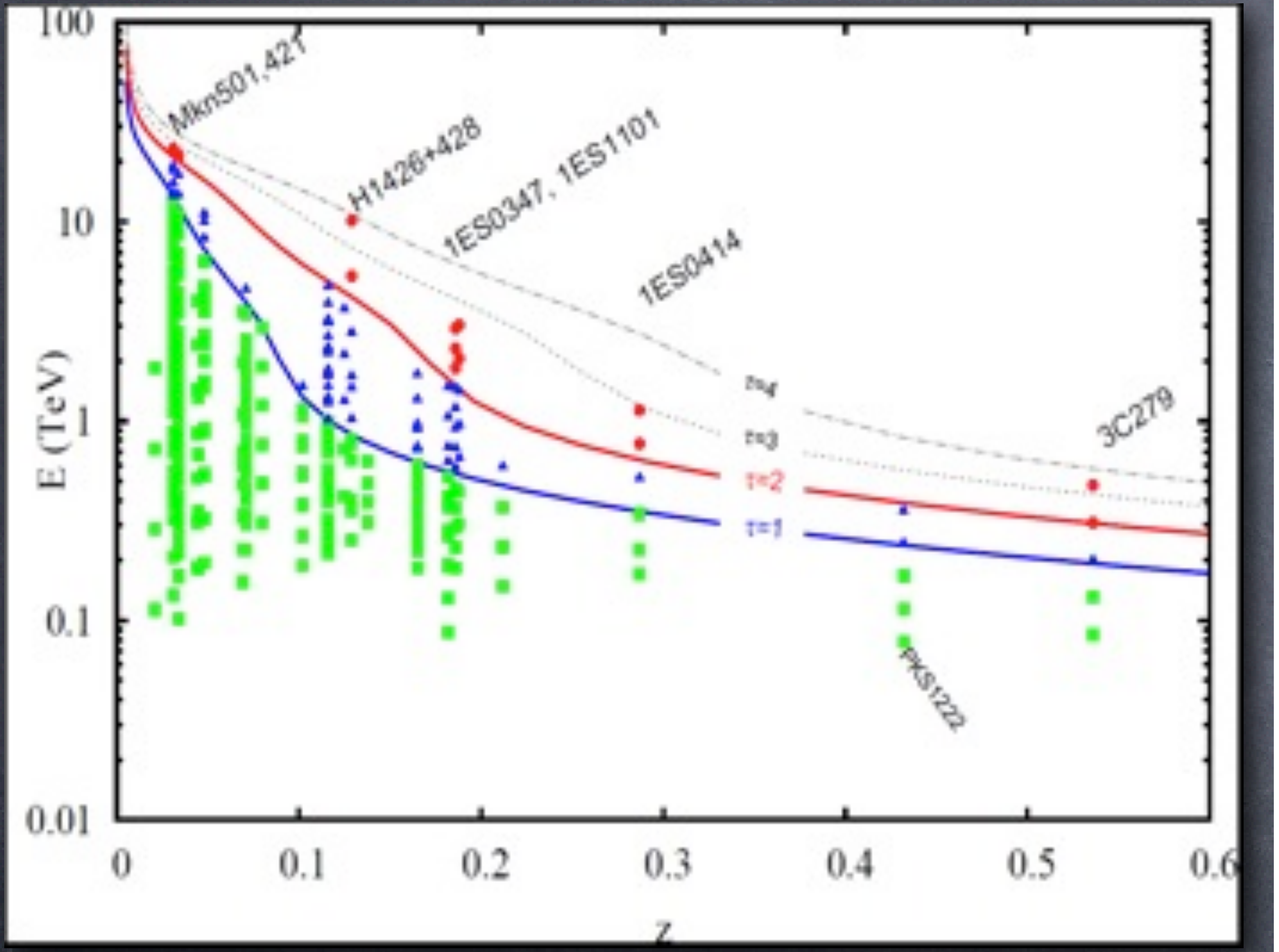


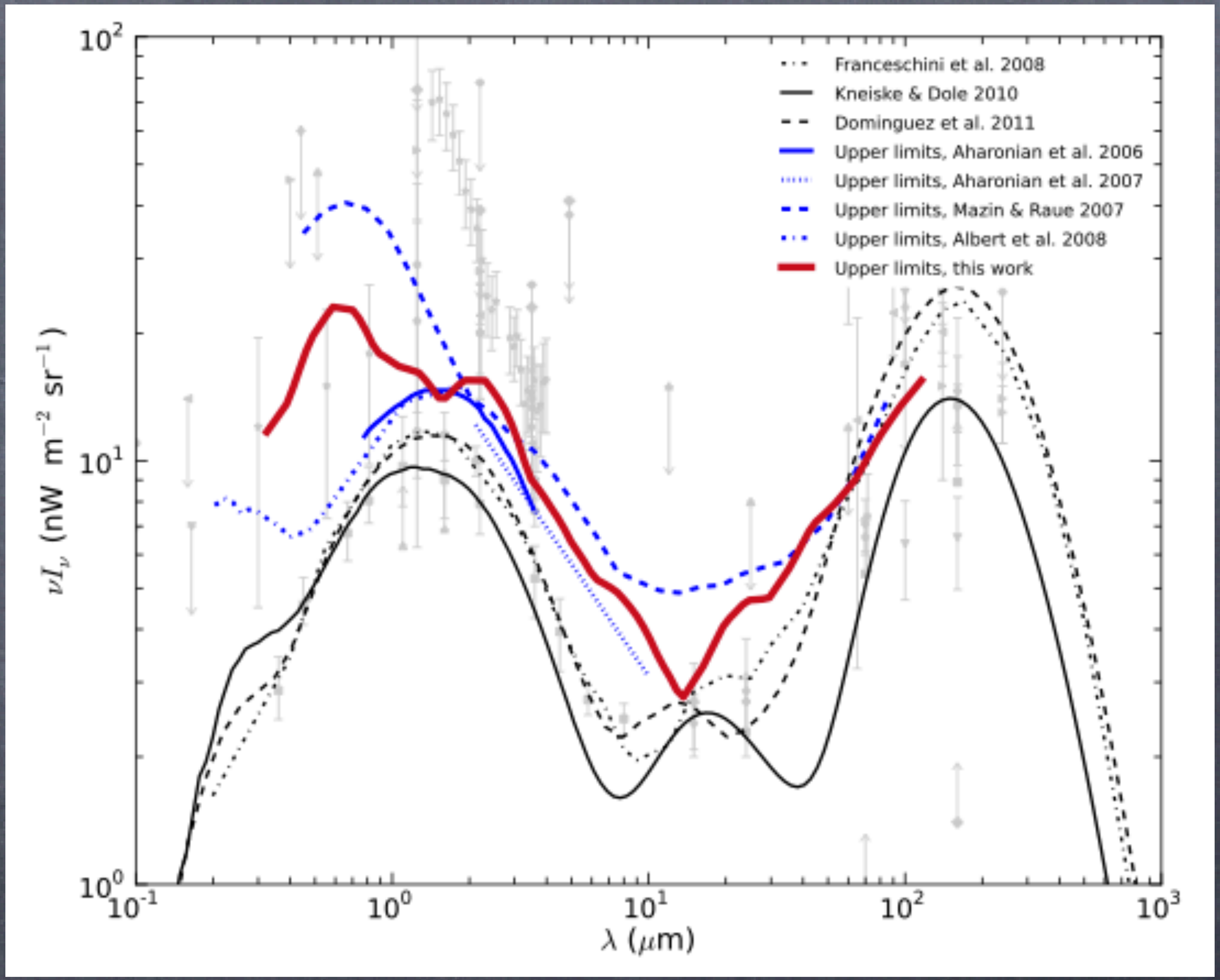
above 55 EeV

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

The γ-Ray Transparency of the Universe

TeV γ-ray spectra appear harder than expected from photon absorption by pair production in the infrared background

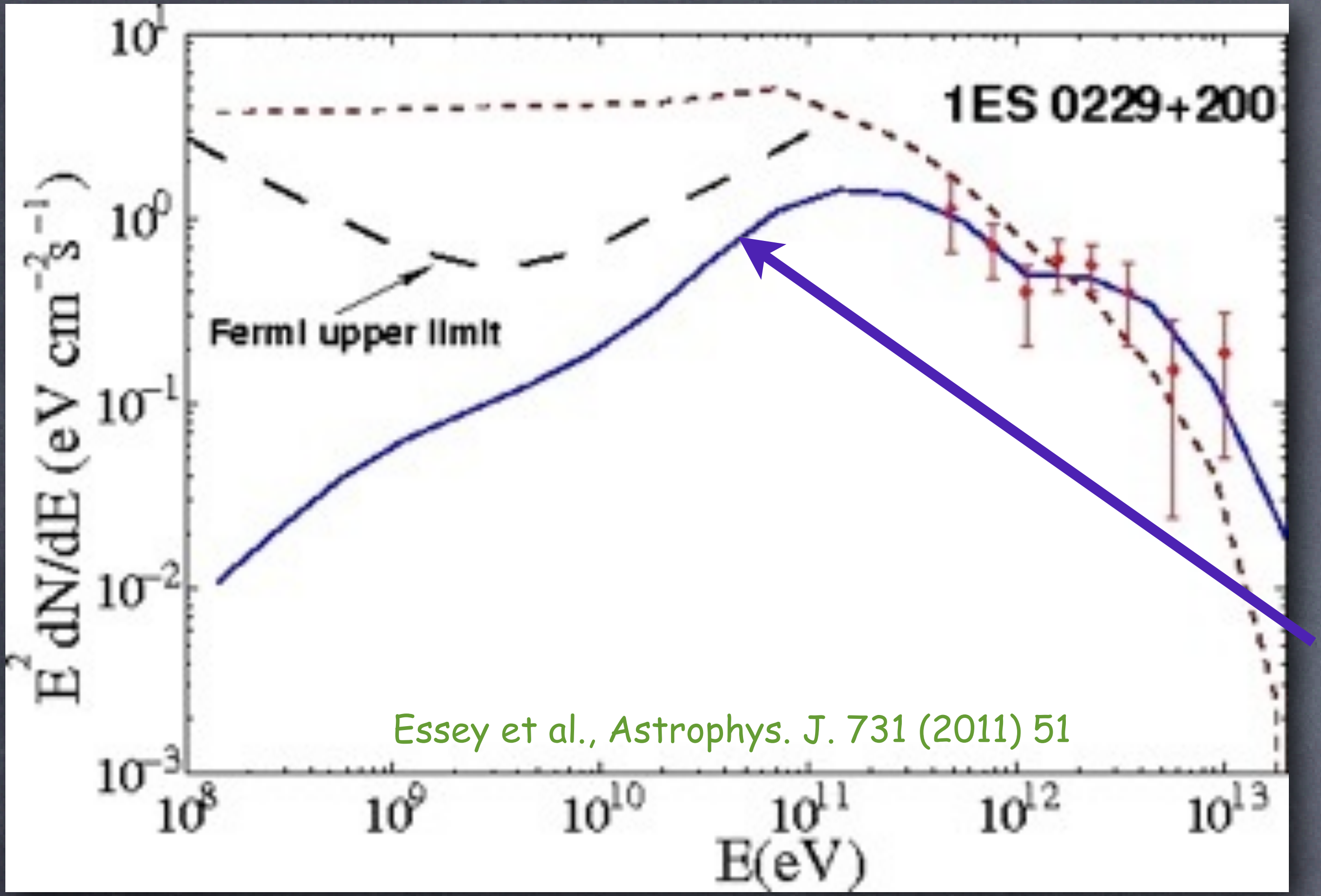




Horns, Meyer, arXiv:1201.4711

Meyer, Raue, Mazin, Horns arXiv:1202.2867

Electromagnetic Cascades and TeV γ-Rays



Essey et al., Astrophys. J. 731 (2011) 51

Pure γ-ray injection tends to underproduce "prompt" TeV γ-rays (observed by IACT) and overproduce GeV γ-ray cascades (not observed by Fermi LAT)

Solution 1:
magnetic fields > 10^{-17} G sufficiently disperse the GeV γ-ray cascades [Neronov et al.]

Solution 2:
cascade absorption by plasma beam instabilities [Broderick et al.]: conditions satisfied ?

Solution 3:
Primary cosmic rays produce TeV γ-rays continuously during propagation [Essey et al.]: variability ?

Solution 4:
γ-ray mixing with new light states (ALPS, hidden photons)
[Roncadelli, Montanino. De Angelis, Hooper, Serpico, Mirizzi ...]

Solution 5:
Lorentz invariance violation [Mavromatos...]: stronger constraints from UHE γ-rays

Physics 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 Xmax distribution of air showers is currently difficult to explain within standard hadronic interaction scenarios, even when "optimizing" unknown mass composition. New physics ?

Physics 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