Origin and Acceleration of High Energy Cosmic Rays

Günter Sigl

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

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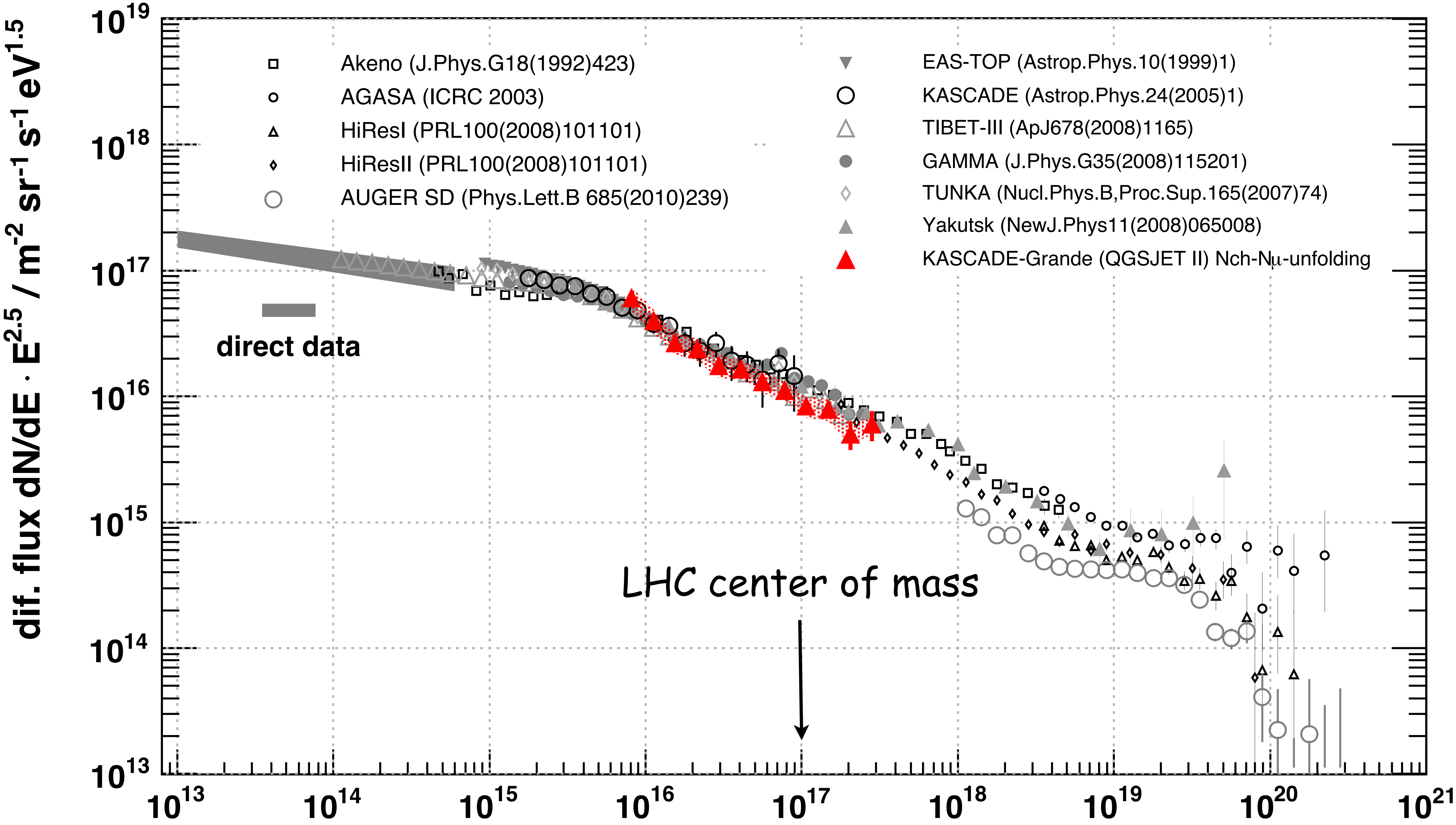
The All Particle Cosmic Ray Spectrum

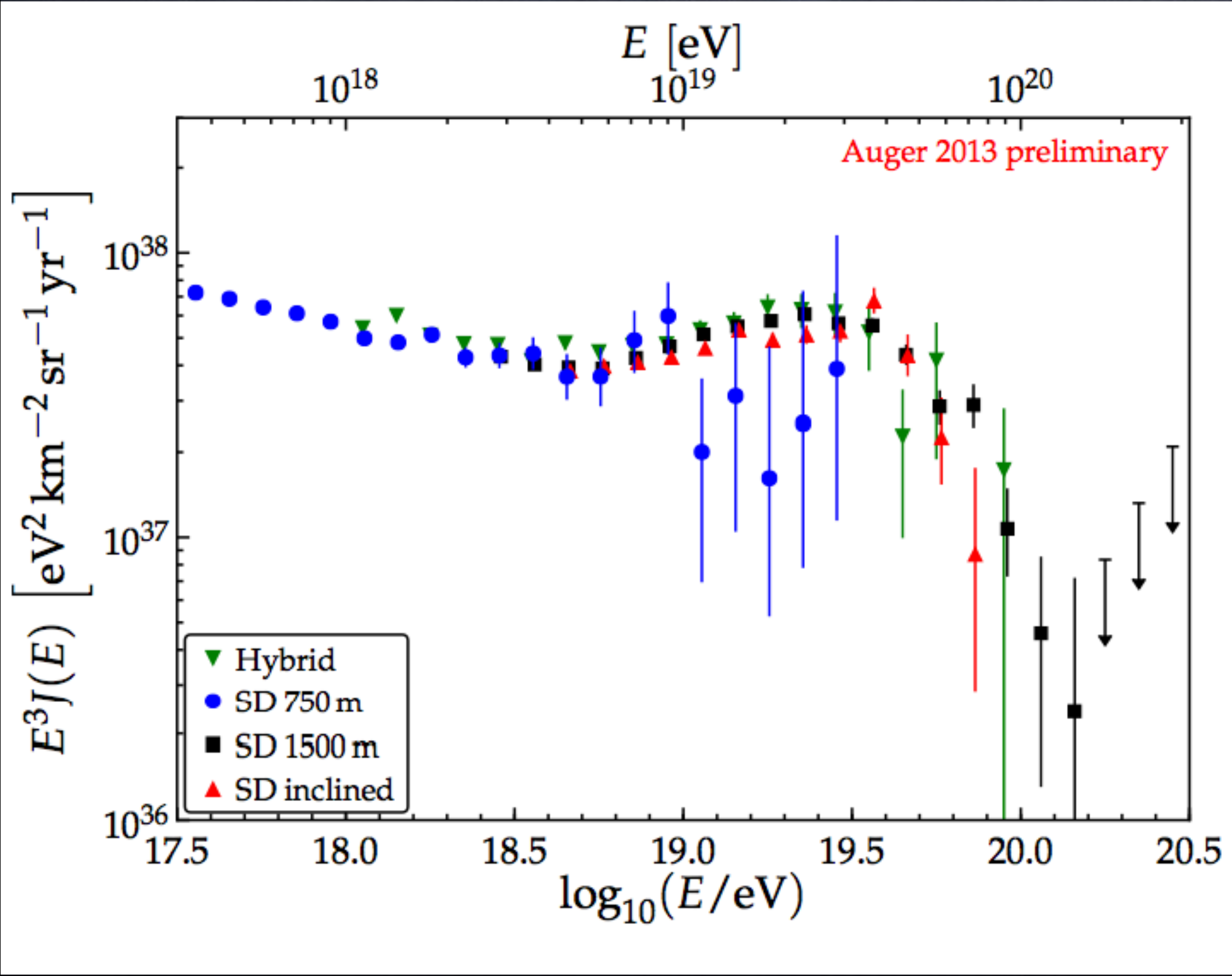


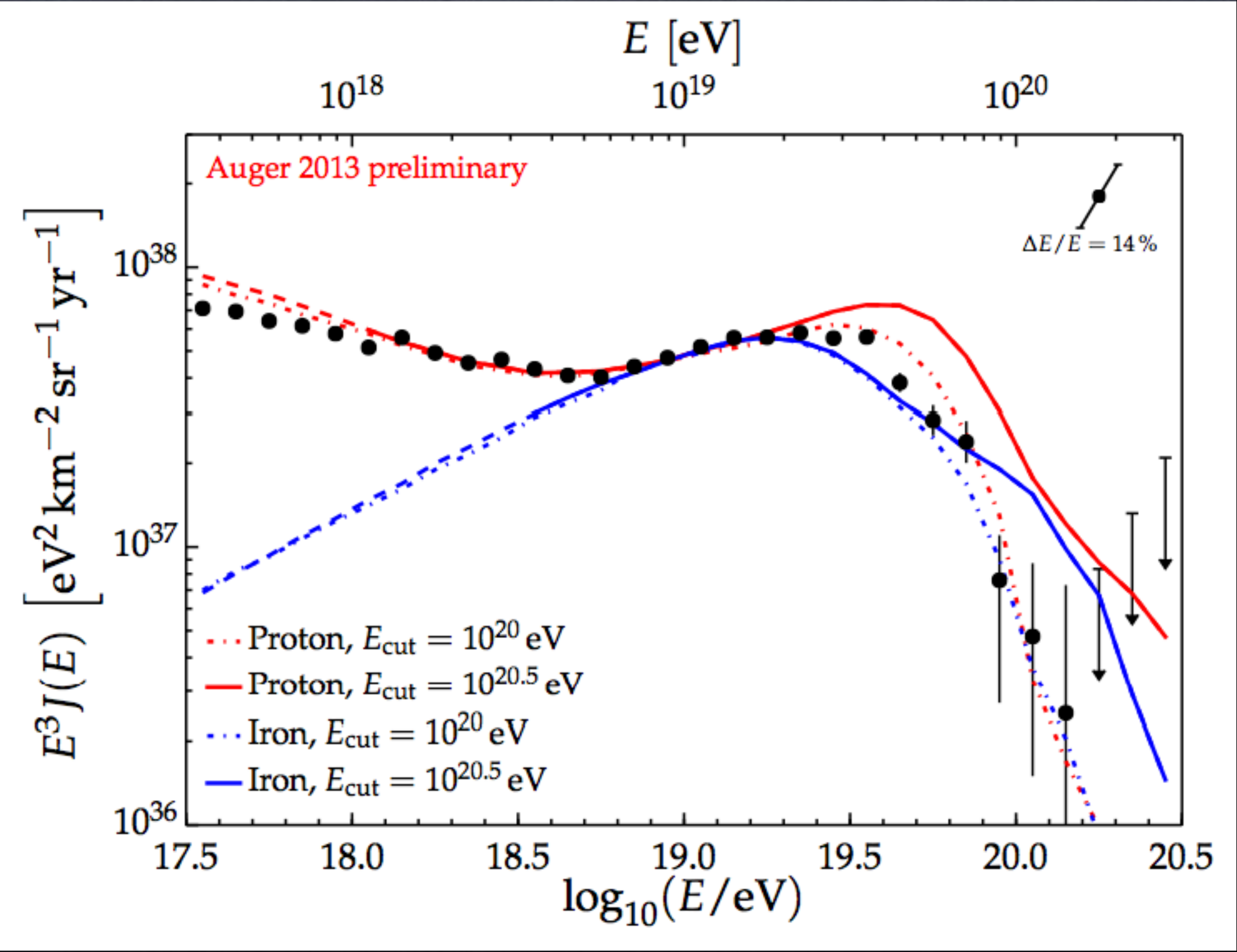
KASCADE-Grande collaboration, arXiv:1111.5436

Pierre Auger Spectra

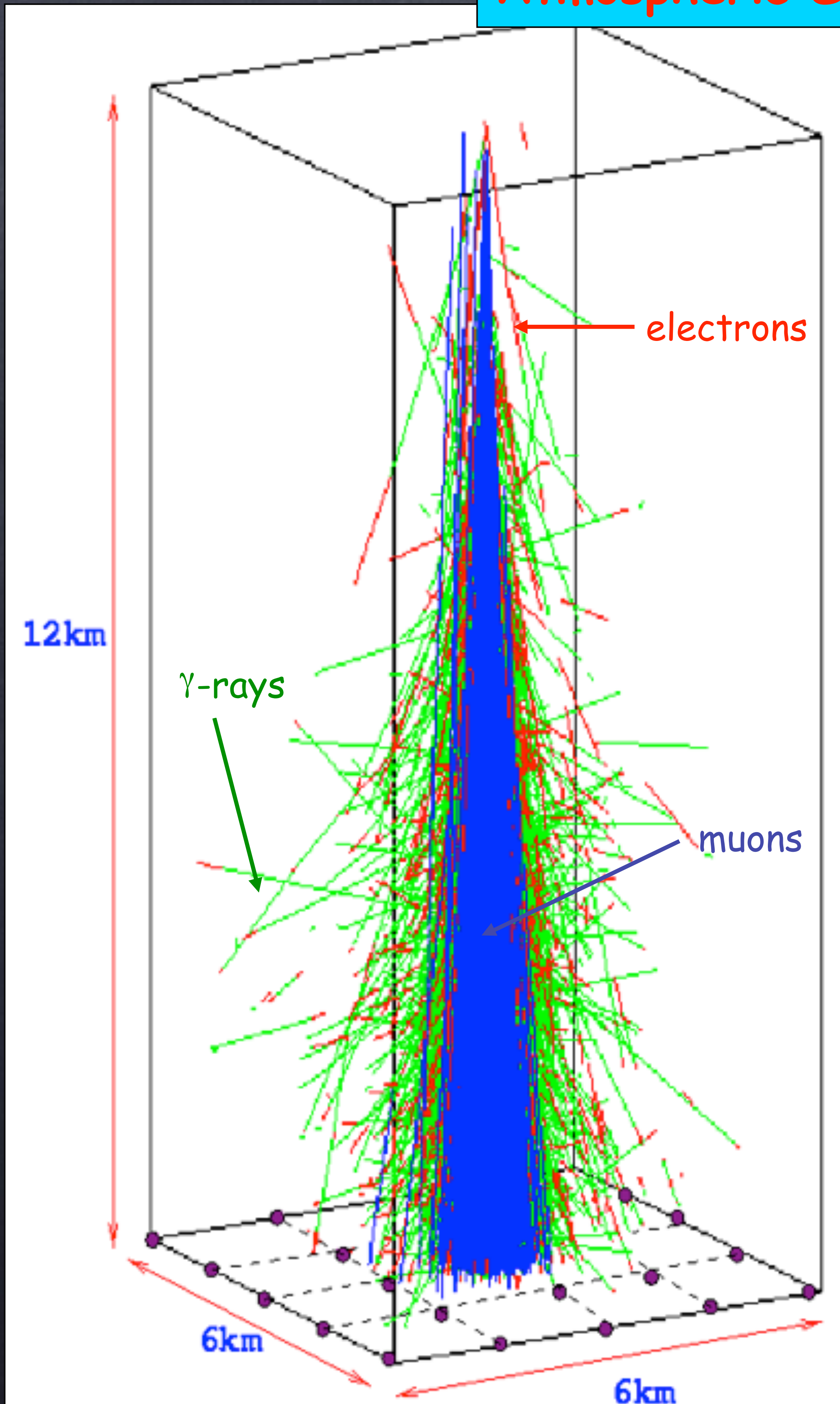
Auger exposure = 31645 km^2 sr yr
up to December 2012

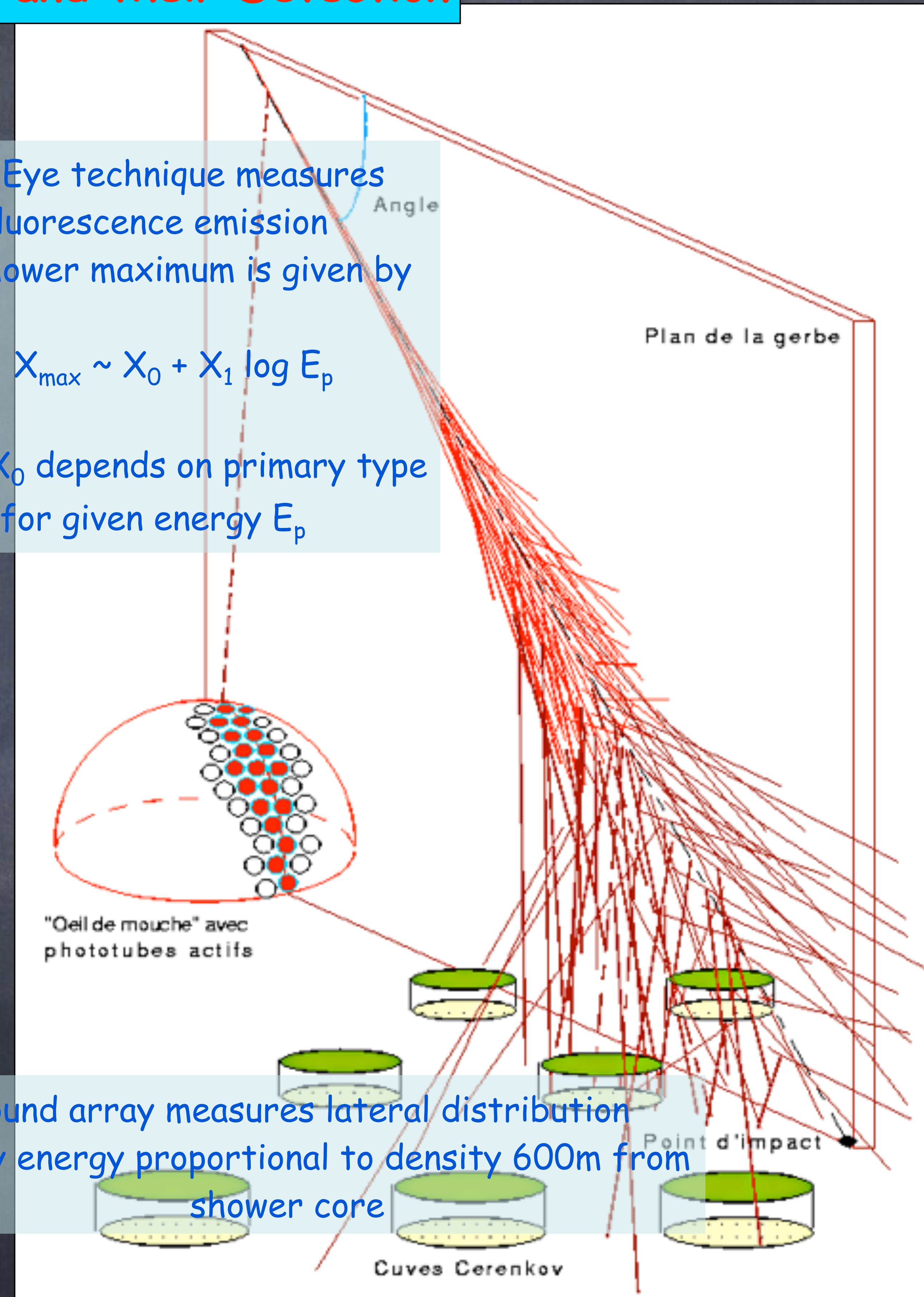
Pierre Auger Collaboration, PRL 101, 061101 (2008)
and Phys.Lett.B 685 (2010) 239
and ICRC 2013, arXiv:1307.5059, higlight talk Letessier-Selvon





Atmospheric Showers and their Detection



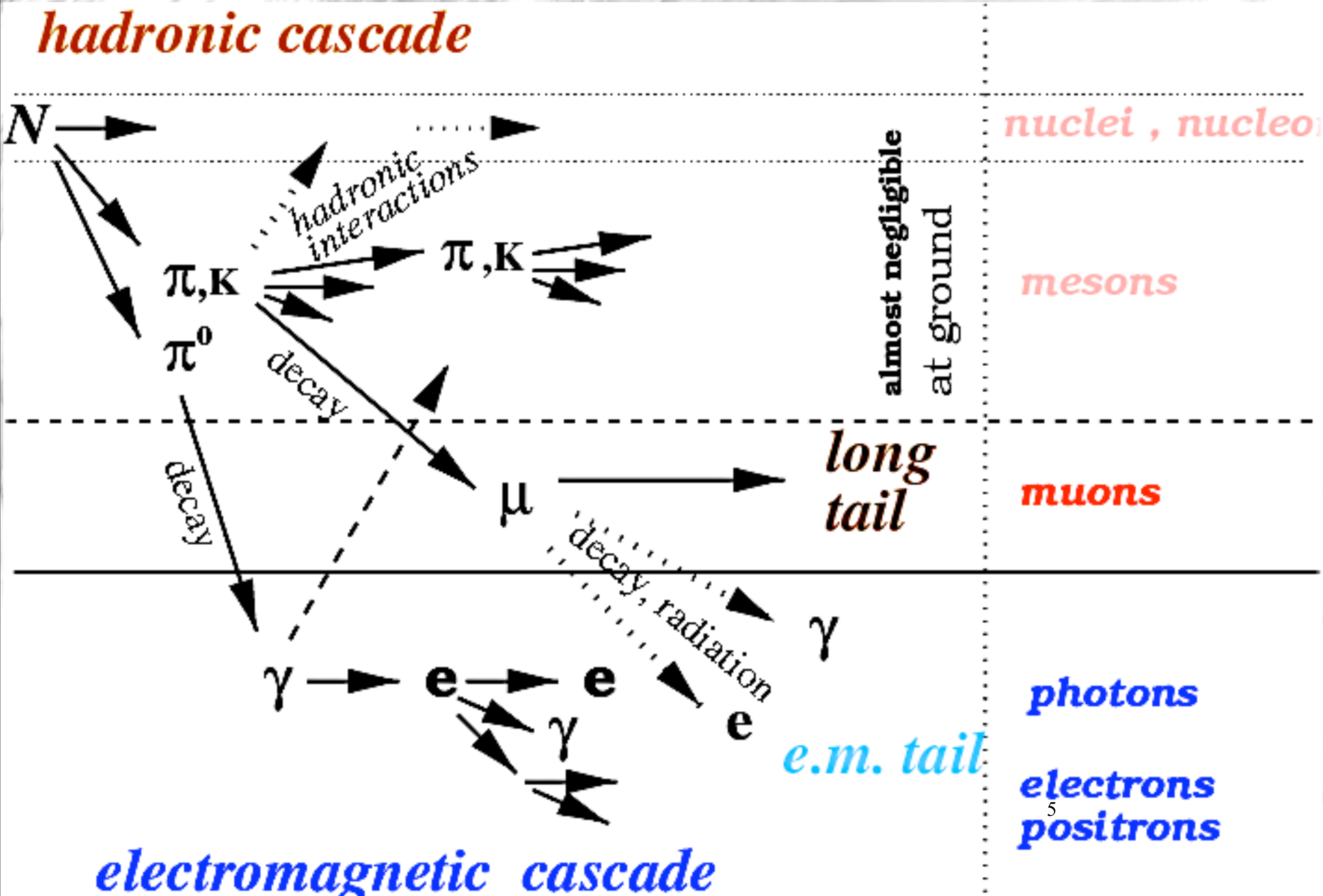


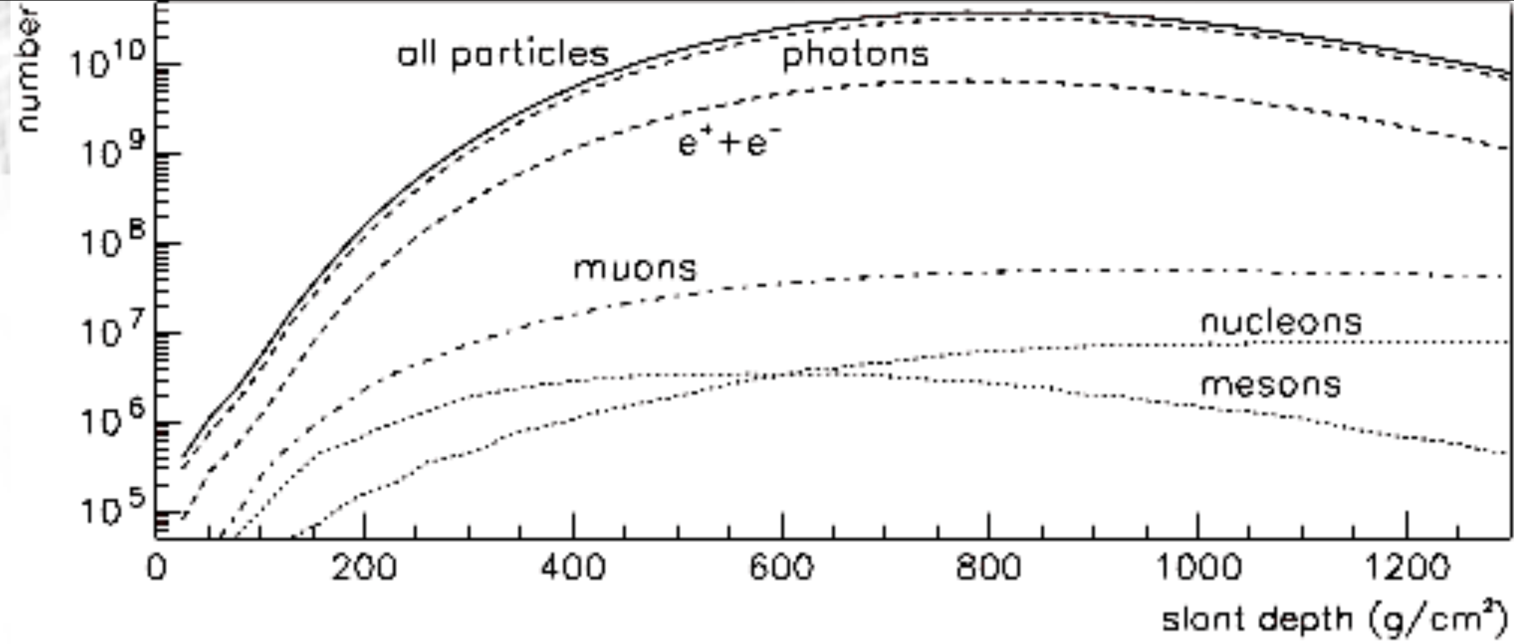
Fly's Eye technique measures fluorescence emission
The shower maximum is given by

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

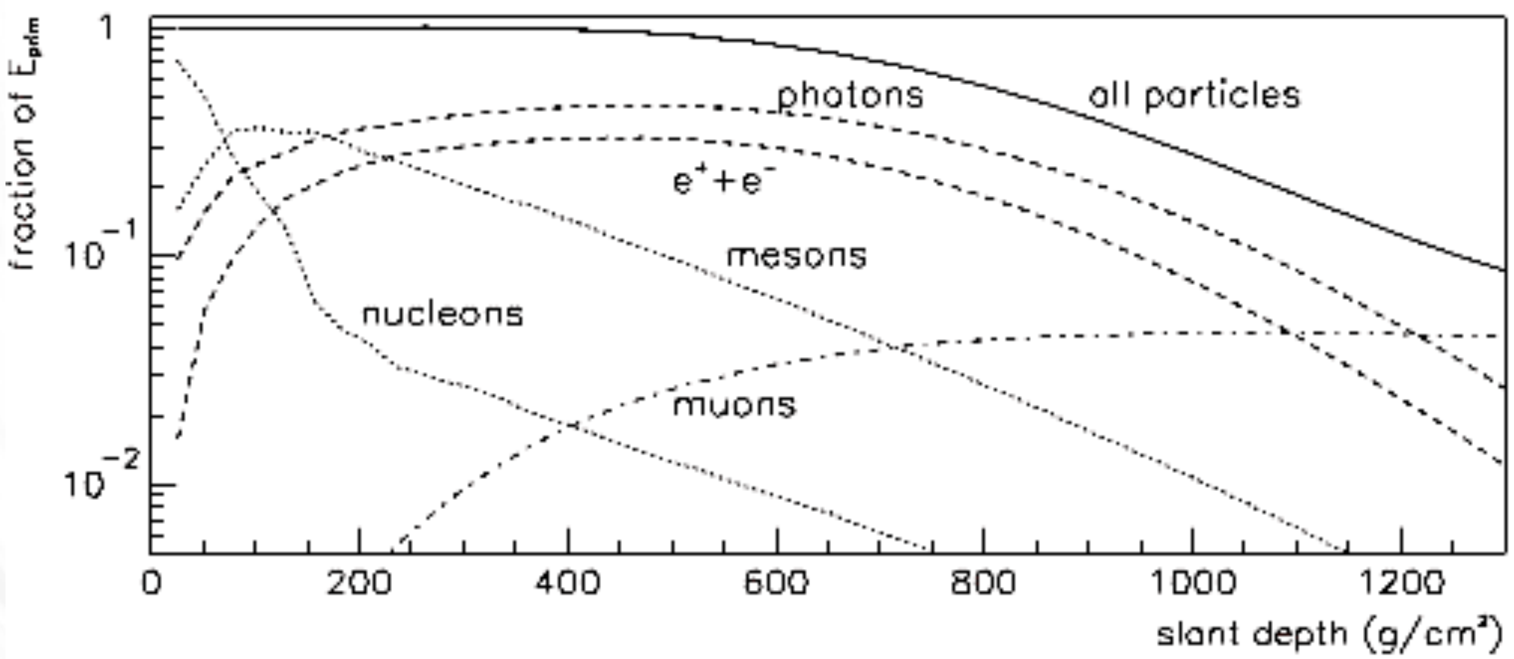
where X_0 depends on primary type for given energy E_p

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

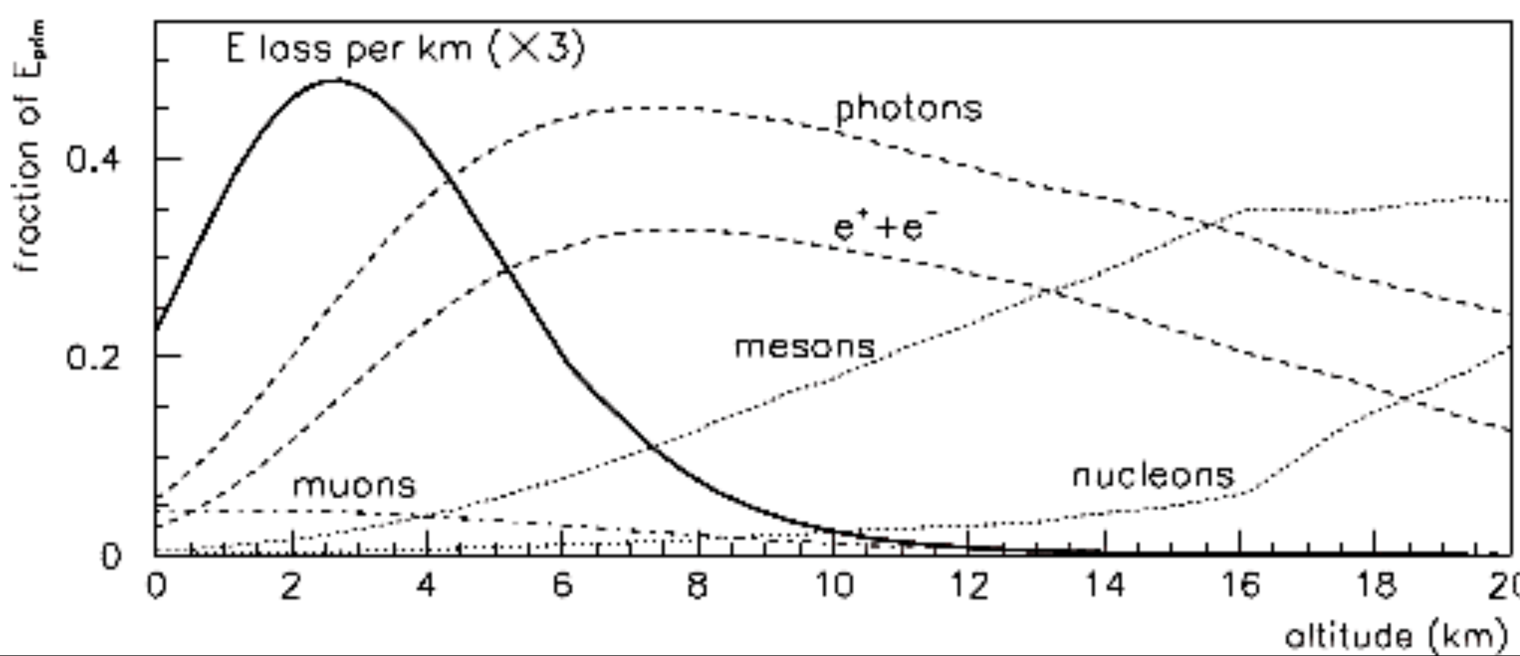

hadronic cascade
N
hadronic interactions
π,K
π,K
π⁰
decay
decay
almost negligible at ground
μ
long tail
decay, radiation
γ
γ
e
e
γ
e
e.m. tail
electromagnetic cascade
nuclei , nucleo
mesons
muons
photons
electrons
positrons



number
all particles
photons
e⁺+e⁻
muons
nucleons
mesons
slant depth (g/cm²)

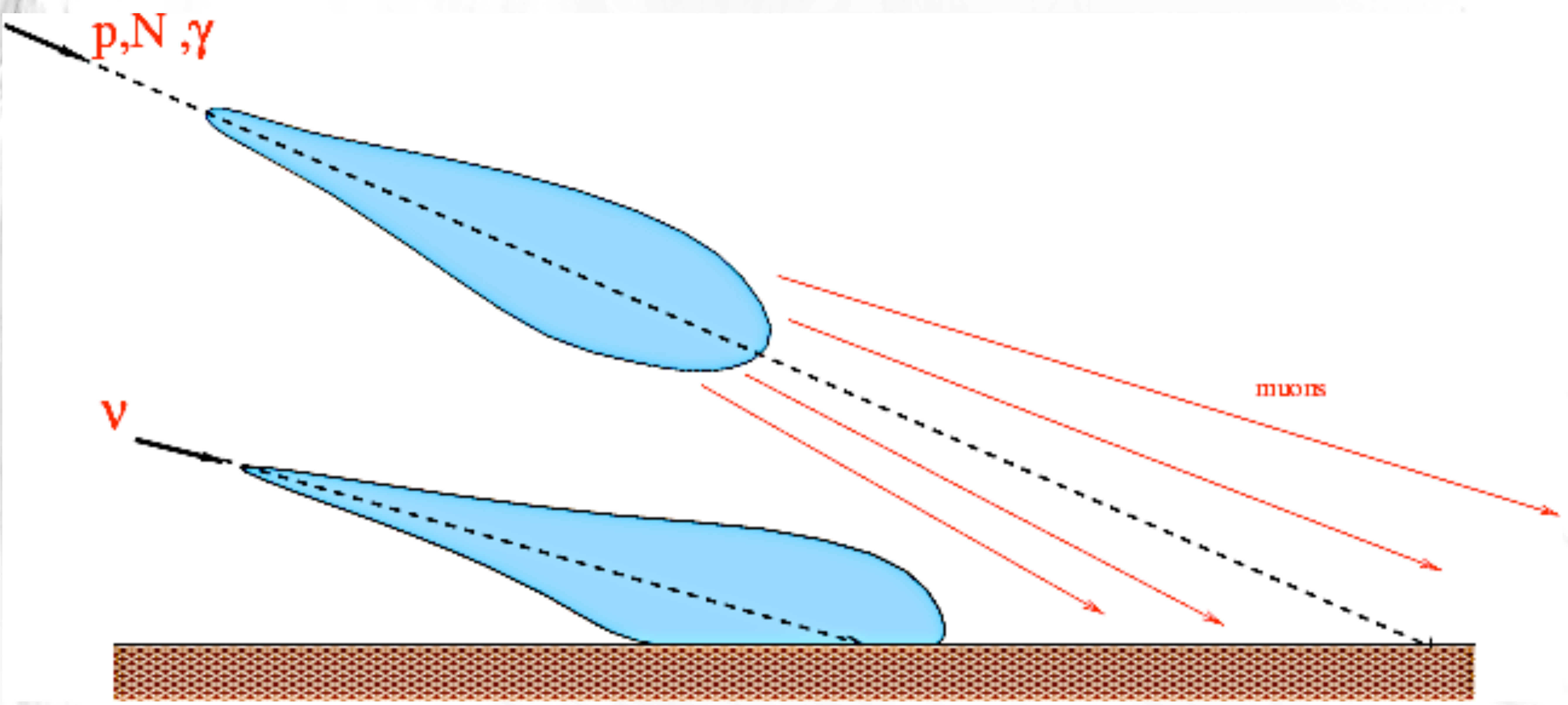


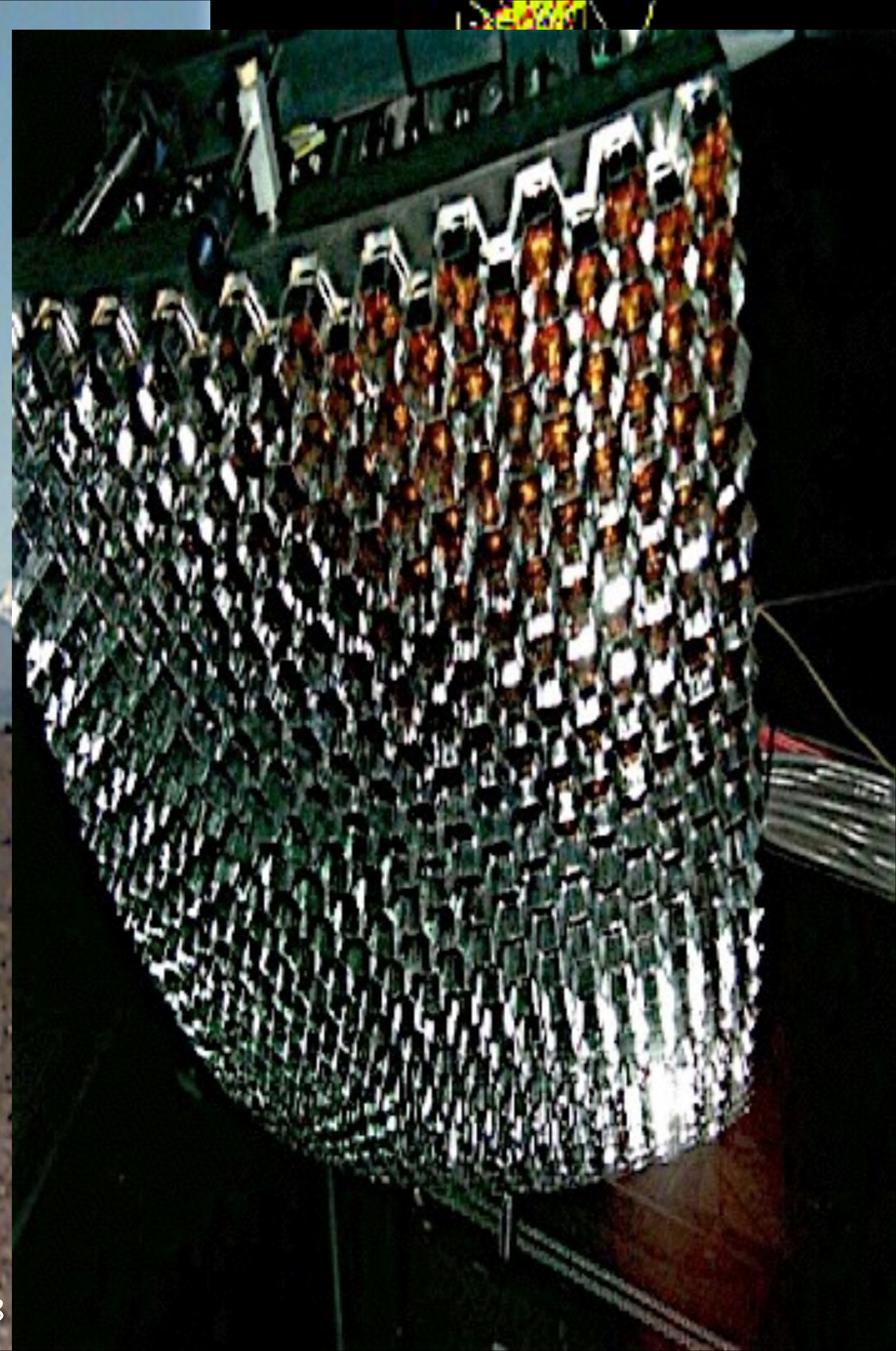
fraction of E_prim
photons
all particles
e⁺+e⁻
mesons
nucleons
muons
slant depth (g/cm²)



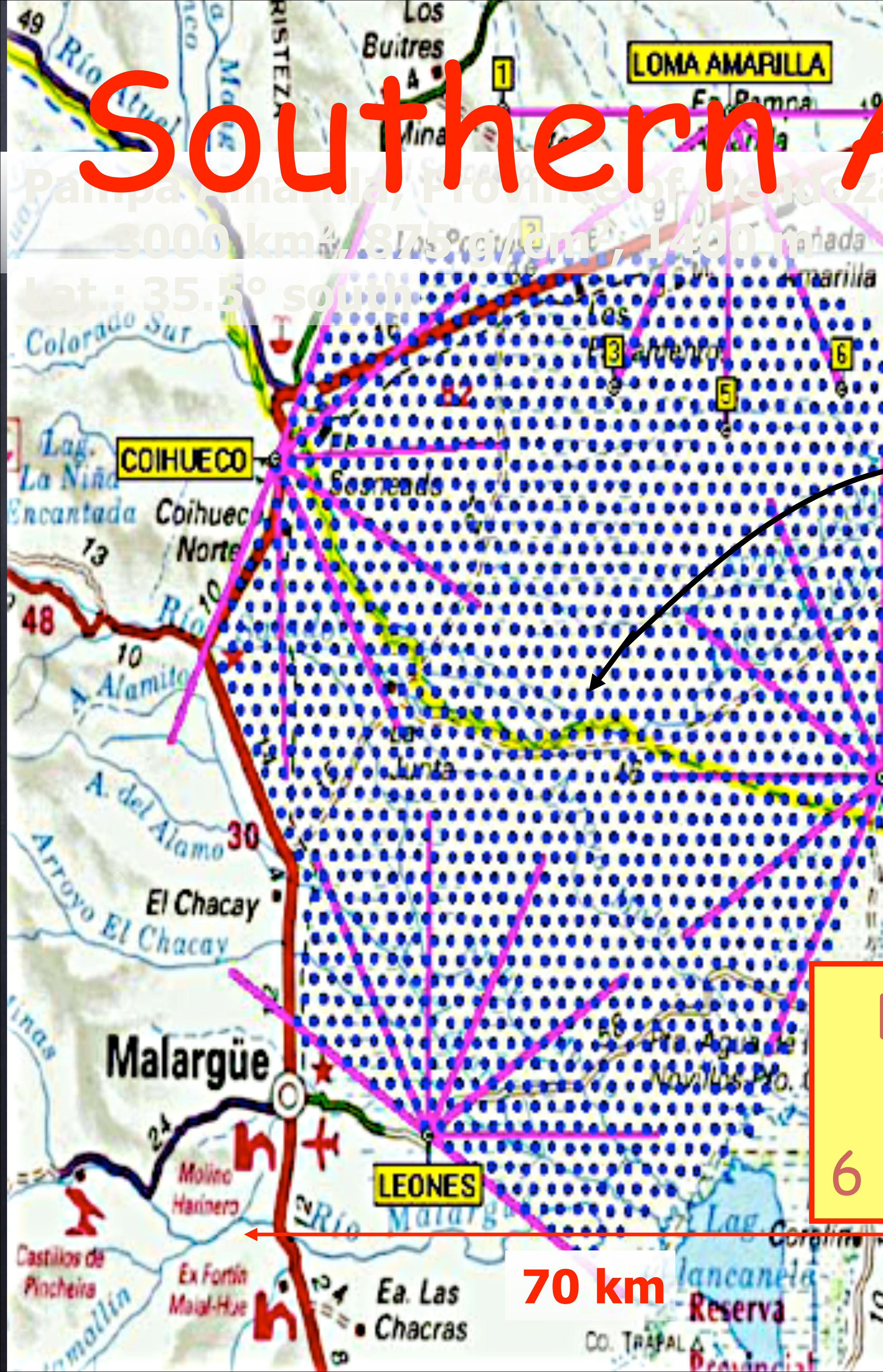
fraction of E_prim
E loss per km (×3)
photons
e⁺+e⁻
mesons
muons
nucleons
altitude (km)

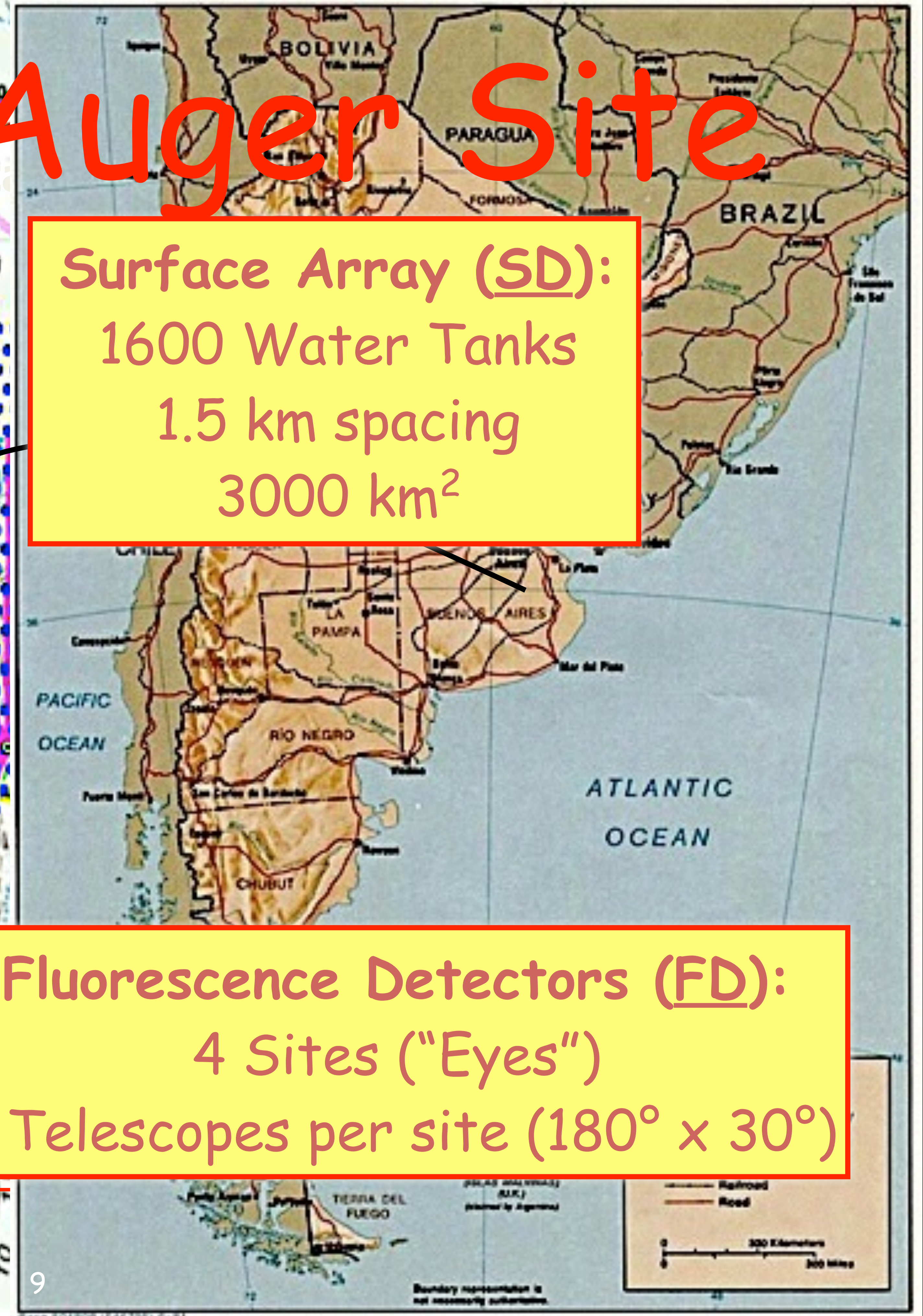
Cosmic ray versus neutrino induced air showers





Southern Auger Site





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°)

The Ultra-High Energy Cosmic Ray Mystery consists of (at least) Four Interrelated Challenges

1.) electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 50 Mpc.

2.) in most conventional scenarios exceptionally powerful acceleration sources within that distance are needed.

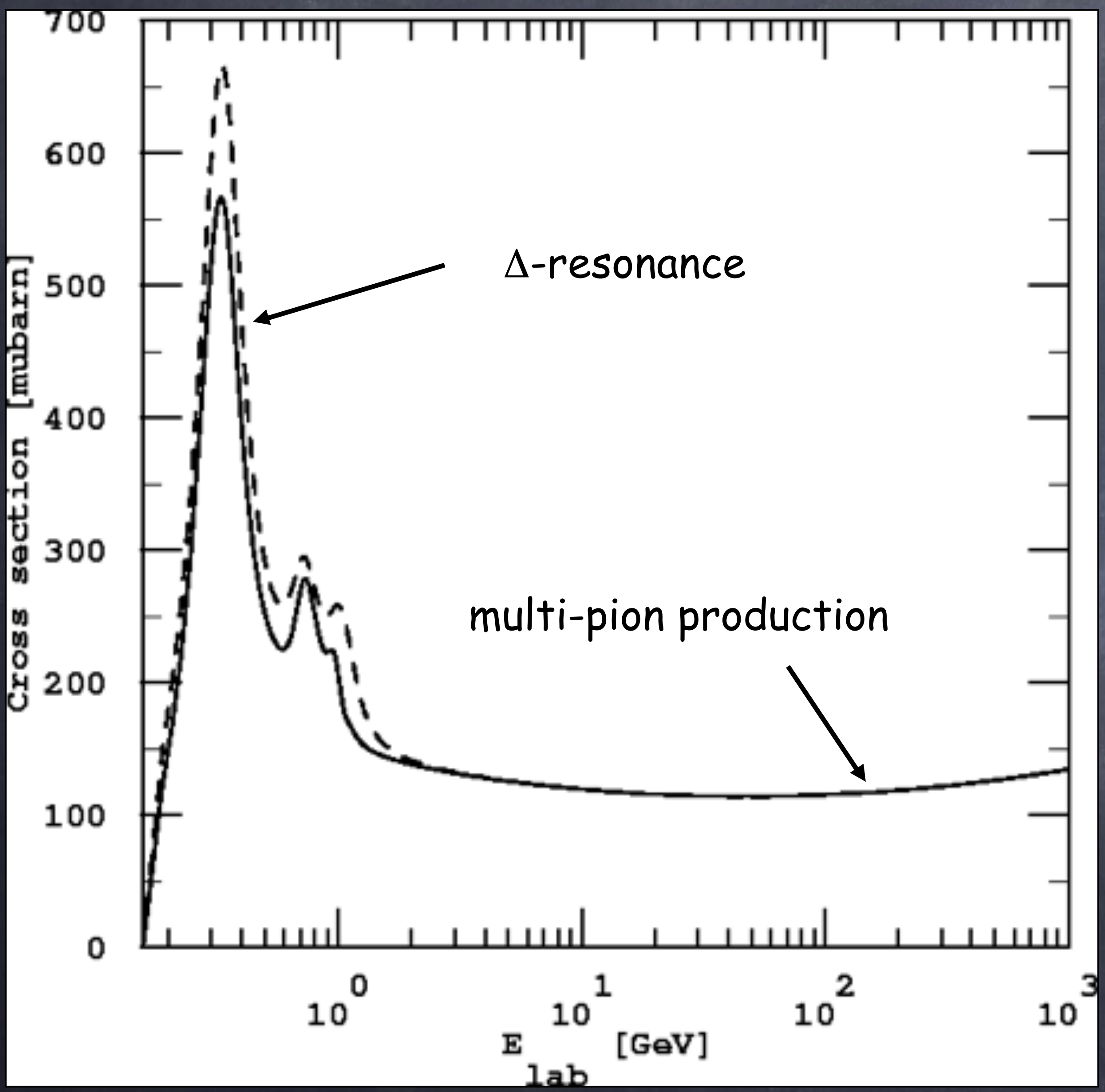
3.) The observed distribution does not yet reveal unambiguously the sources, although there are hints of correlations with local large scale structure

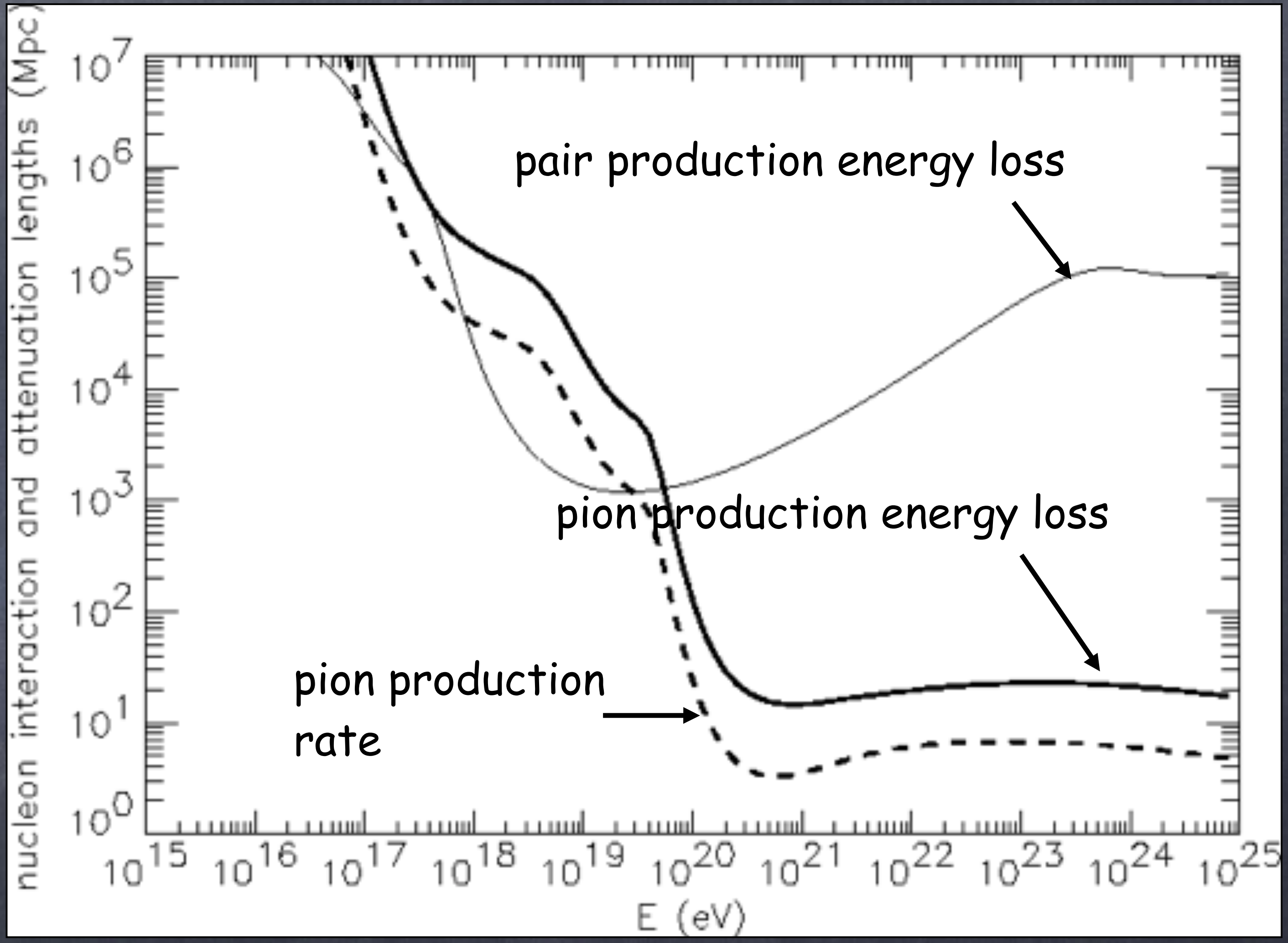
4.) The observed mass composition may become heavy toward highest energies, but no completely clear picture yet between experiments and air shower models

The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background

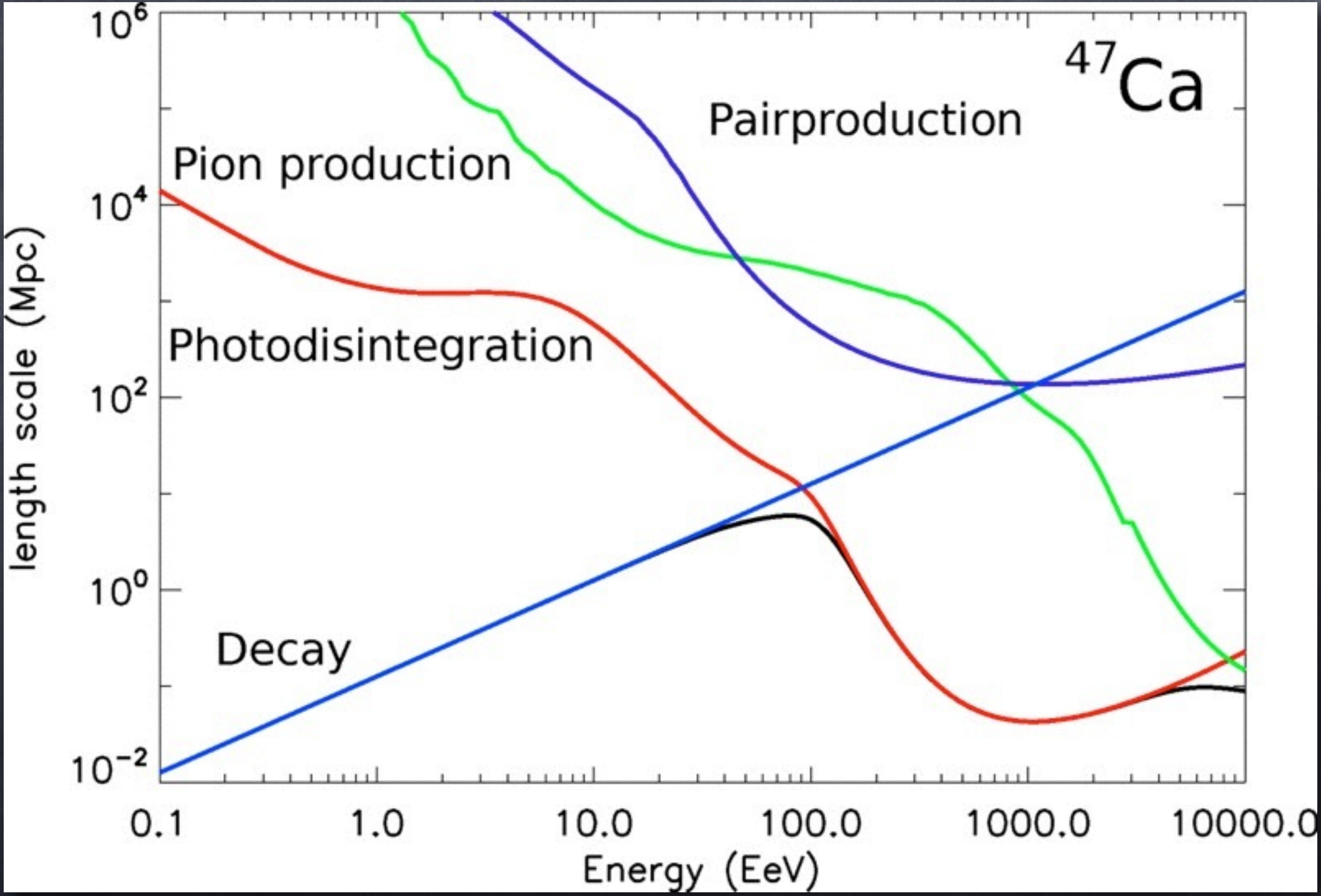
$$E_{\rm th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \simeq 4 \times 10^{19}\,{\rm eV}$$



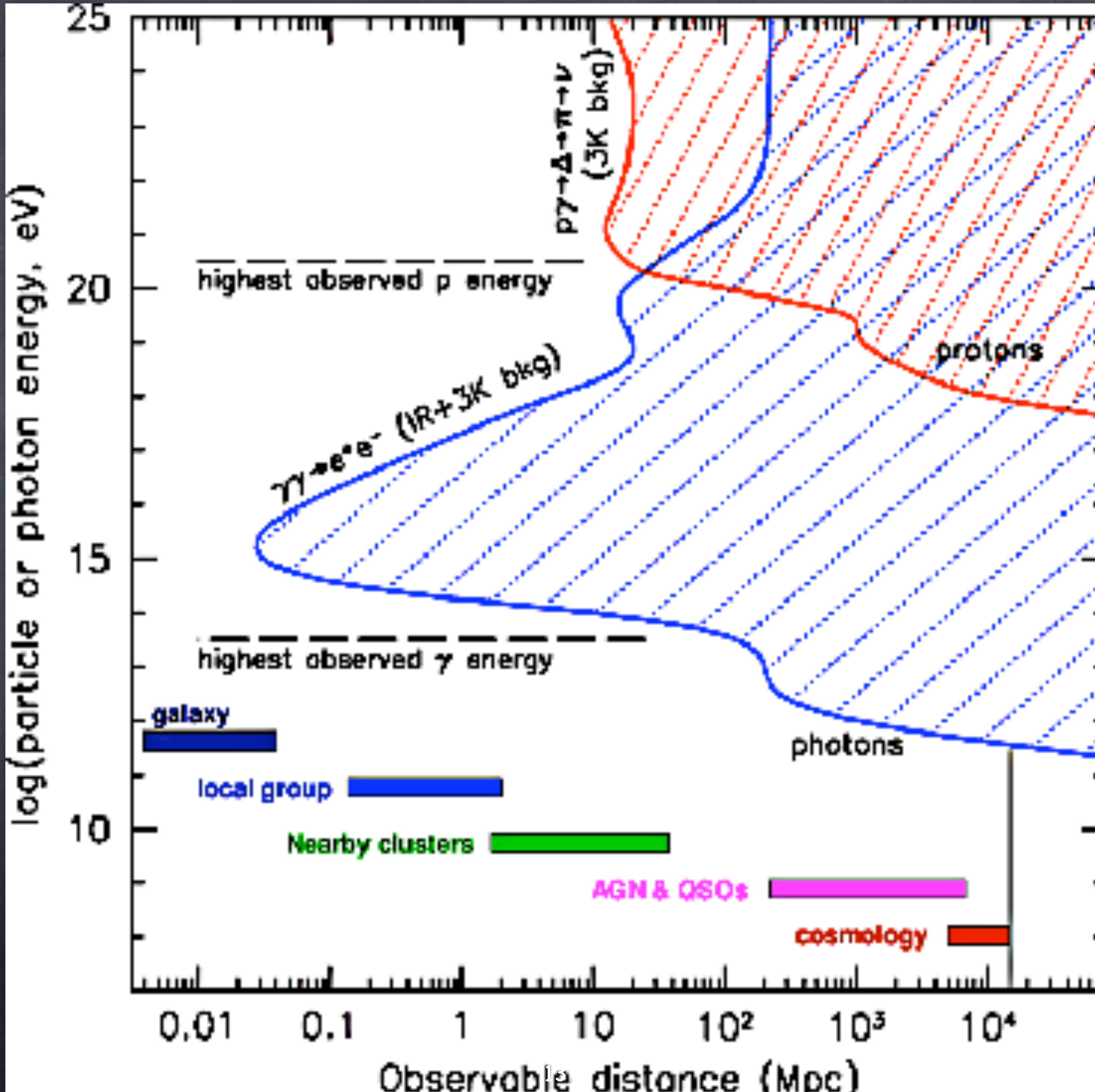


sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma > 10^{11}$ could avoid this conclusion.

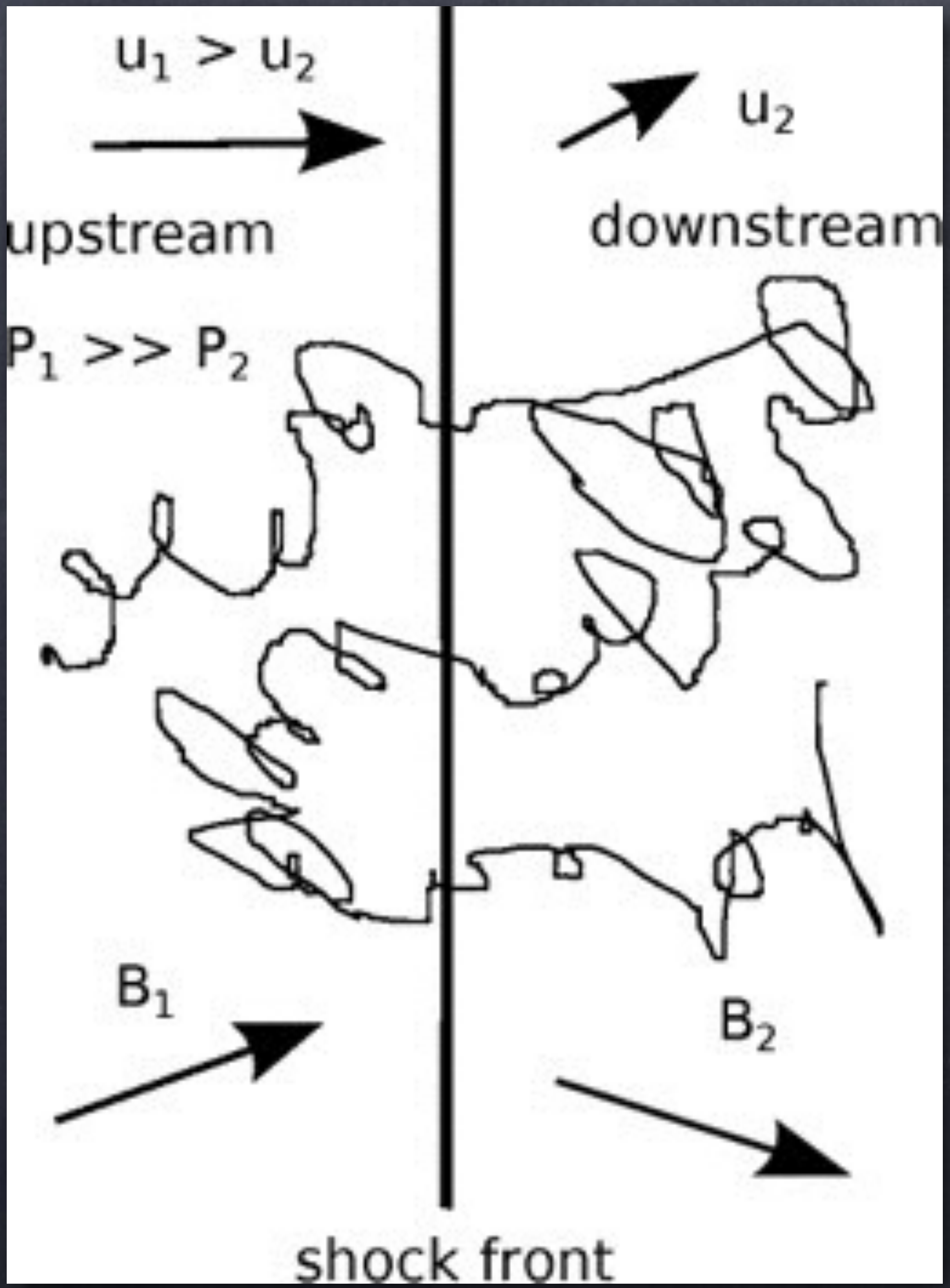
Length scales for relevant processes of a typical heavy nucleus

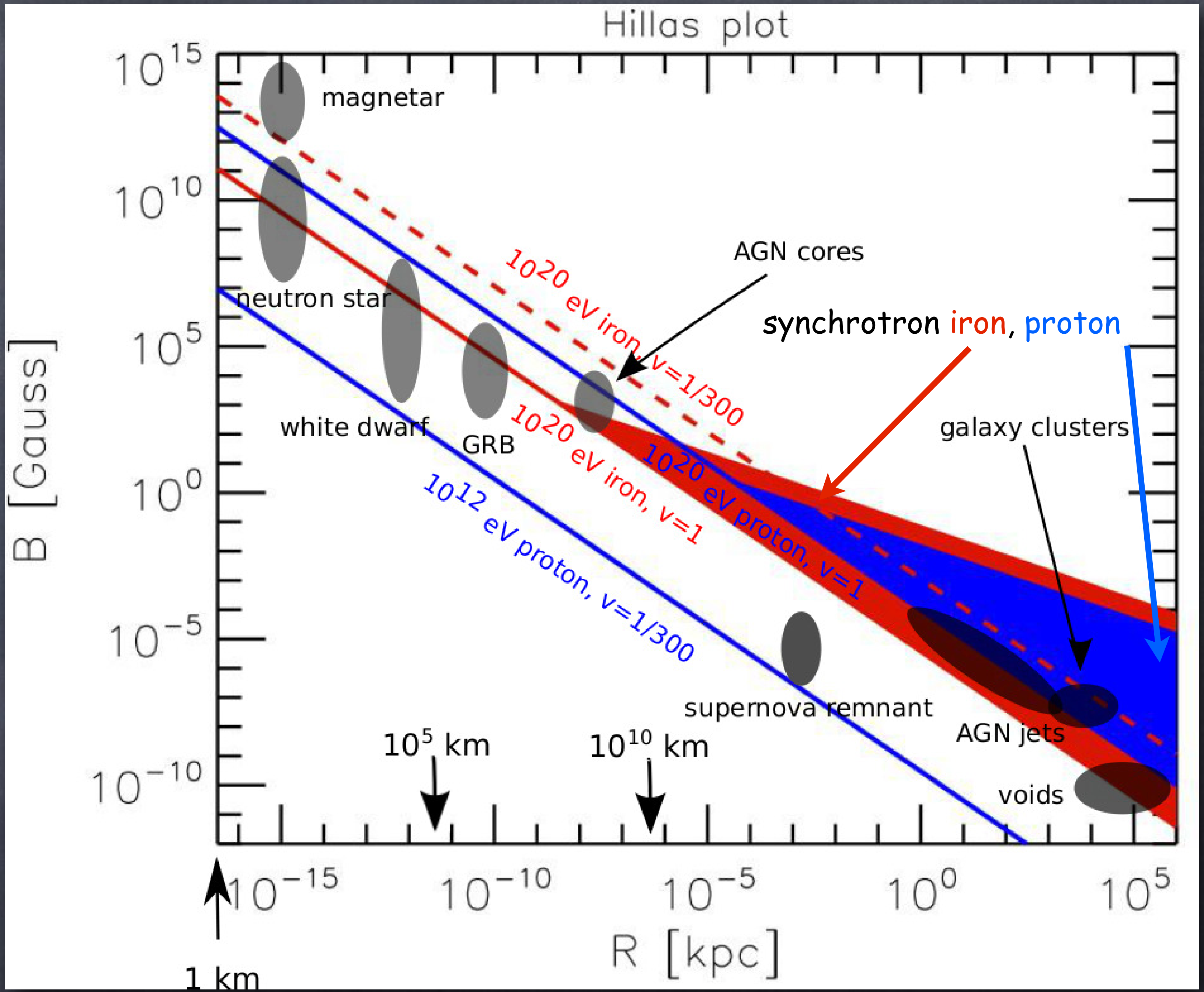


Interaction Horizons



1^{st} Order Fermi Shock Acceleration





Fractional energy gain per shock crossing ~ $u_1 - u_2$ 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

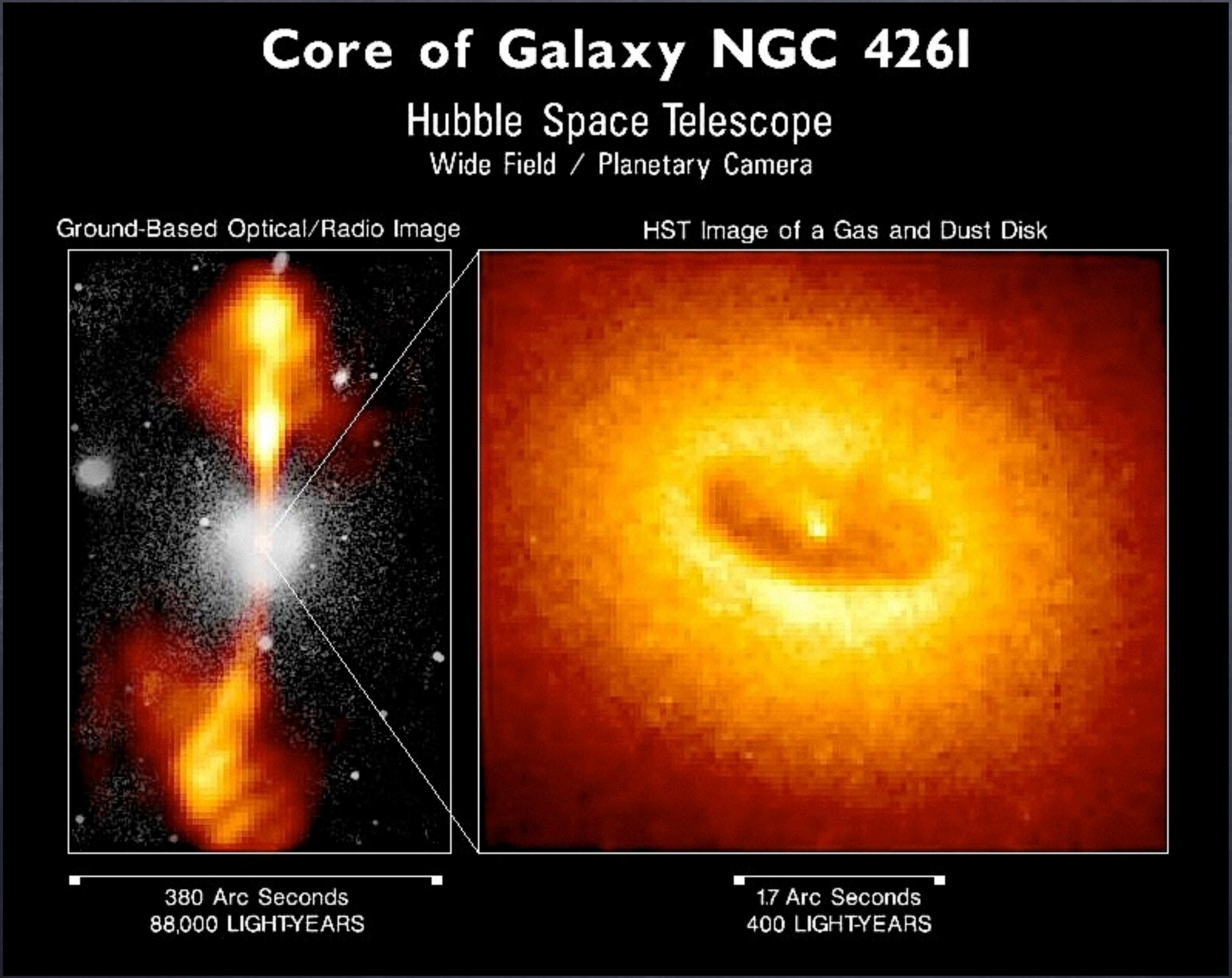
$$L_{\rm min} \sim \frac{\epsilon^2}{Z_0} \simeq 10^{45}\, Z^{-2} \left(\frac{E_{\rm max}}{10^{20}\,{\rm eV}}\right)^2\, {\rm erg\,s^{-1}}$$

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

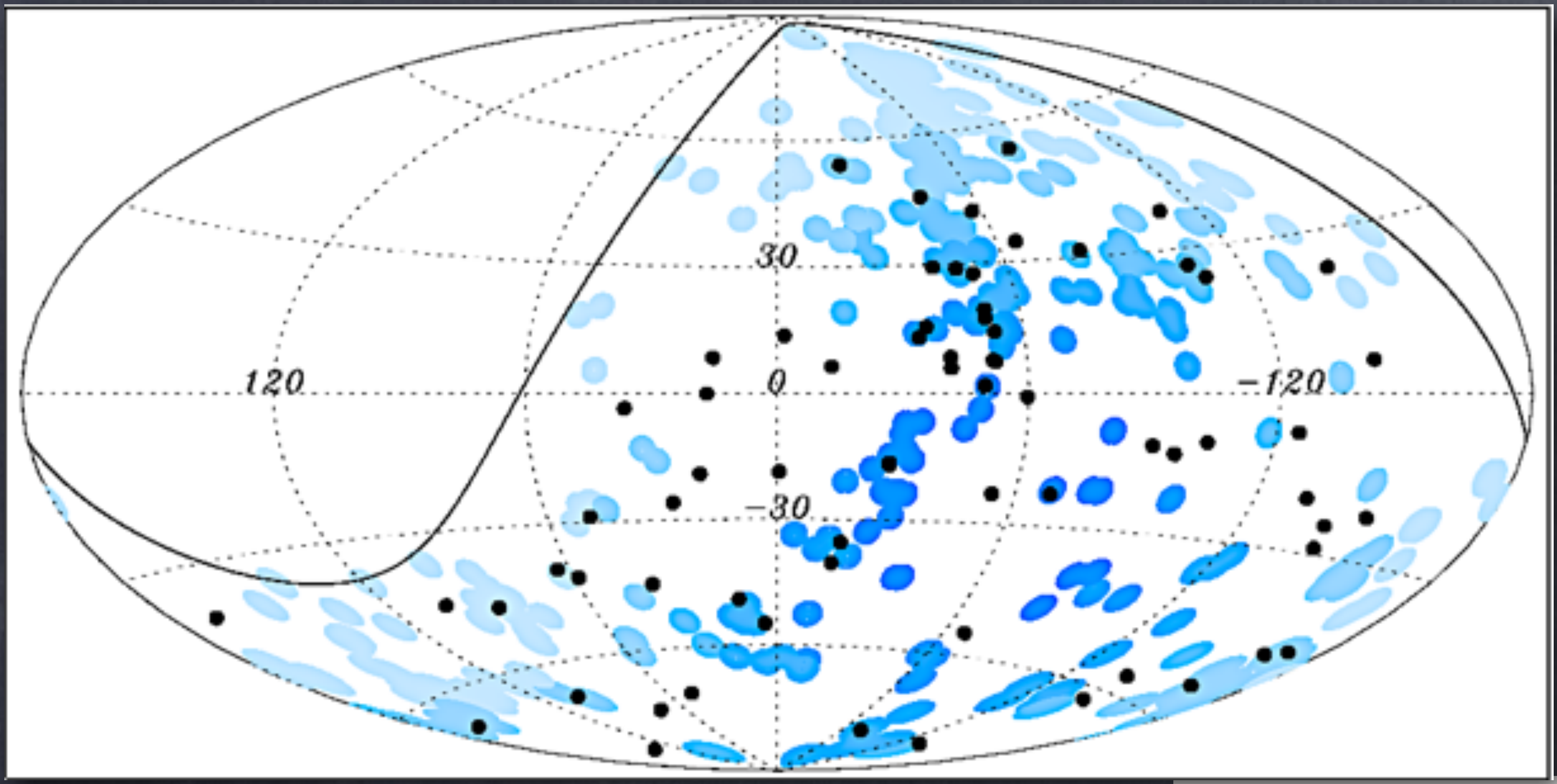
$$BR > 3\times 10^{17}\,\Gamma^{-1}\left(\frac{E_{\rm max}/Z}{10^{20}\,{\rm eV}}\right)\,{\rm Gauss\,cm}$$

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.

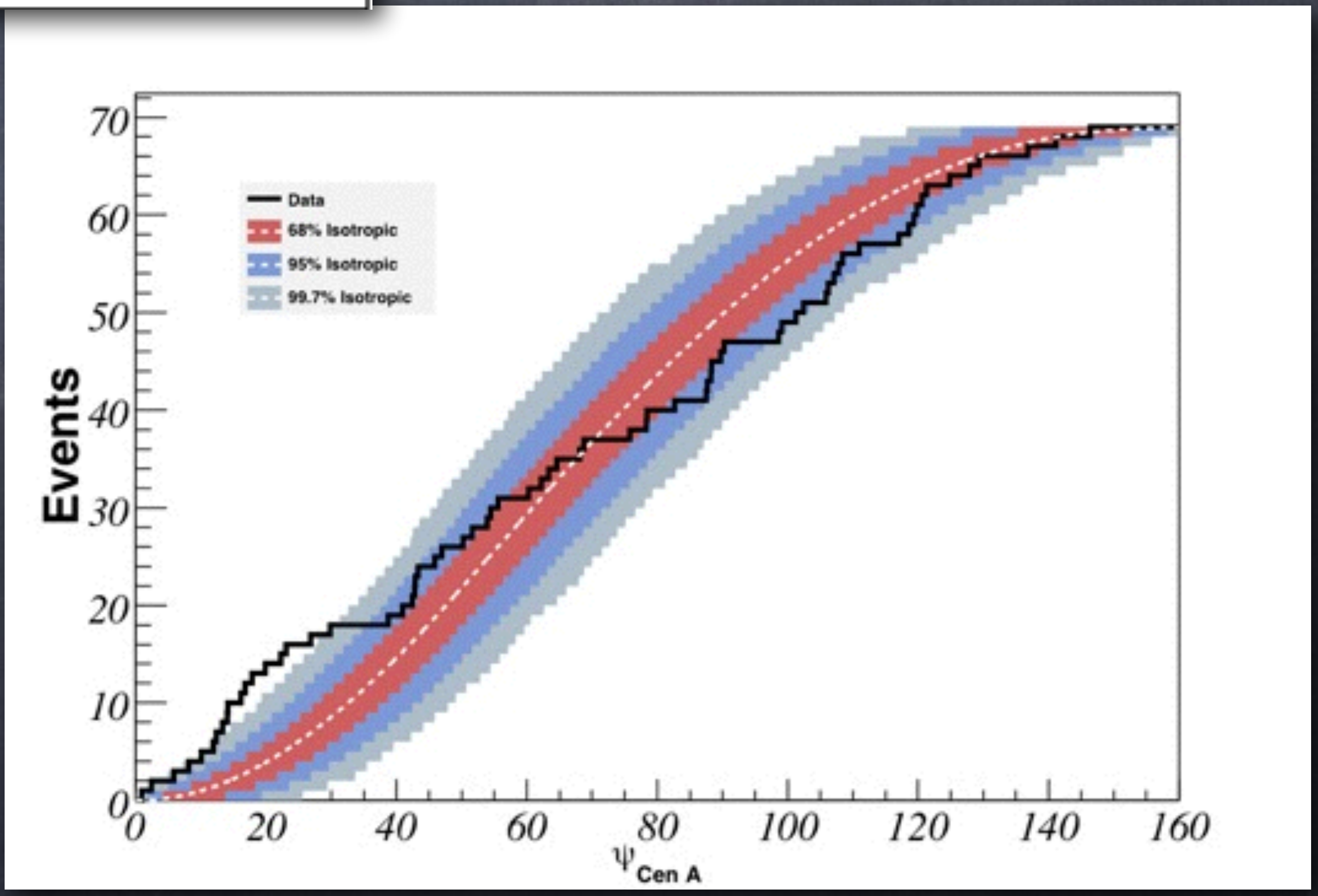
A possible acceleration site associated with shocks in hot spots of active galaxies



Centaurus A is a UHECR source candidate

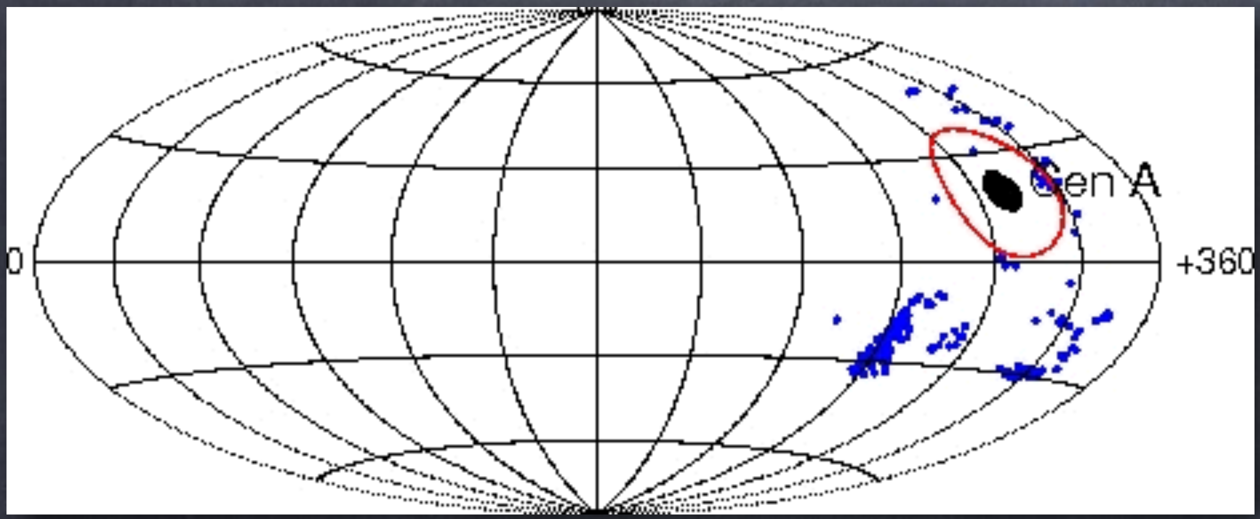


Pierre Auger sees an excess
in the direction of Centaurus A
above 55 EeV

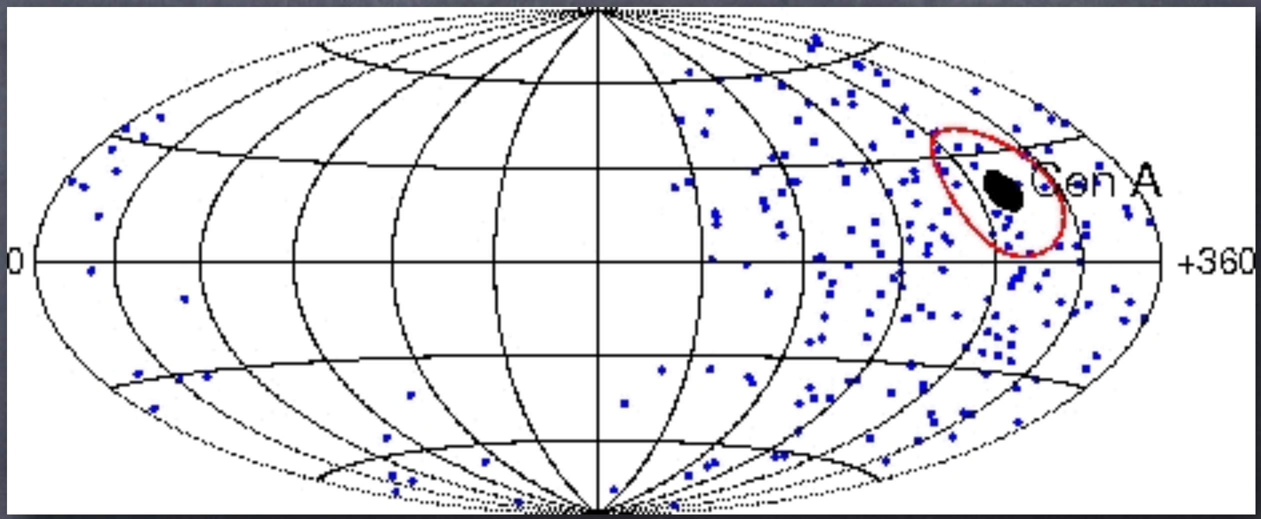


Pierre Auger Collaboration, Astropart.Phys. 34 (2010) 314

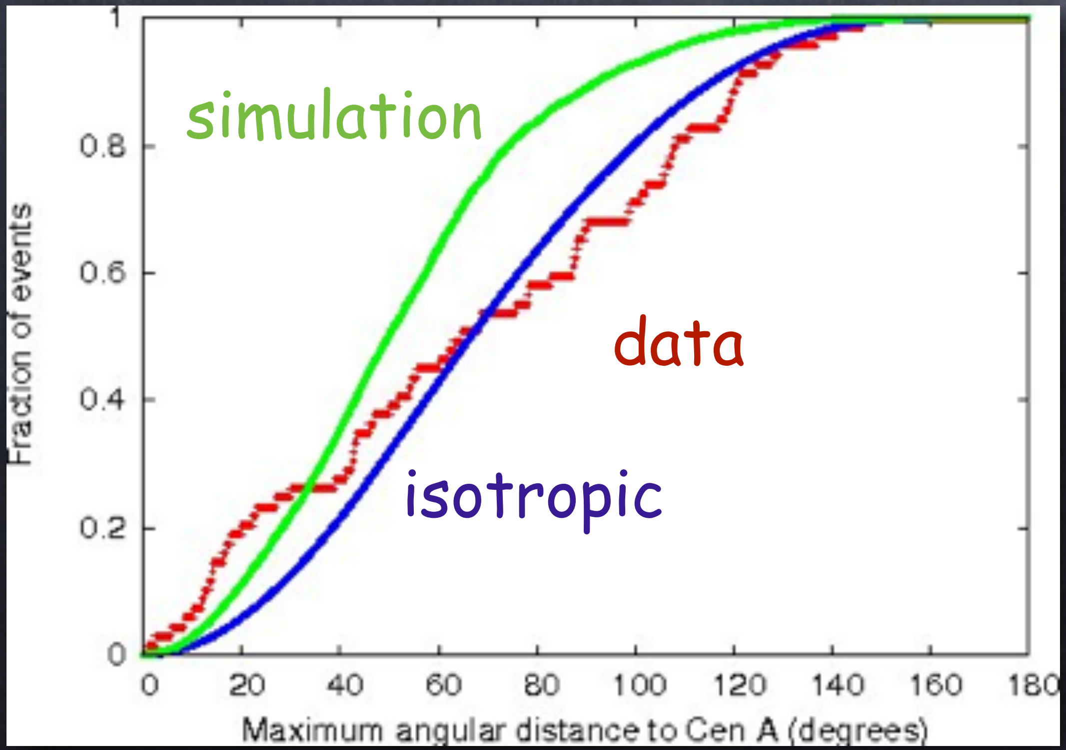
But even for iron primaries Centaurus A can not be the only UHECR source



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

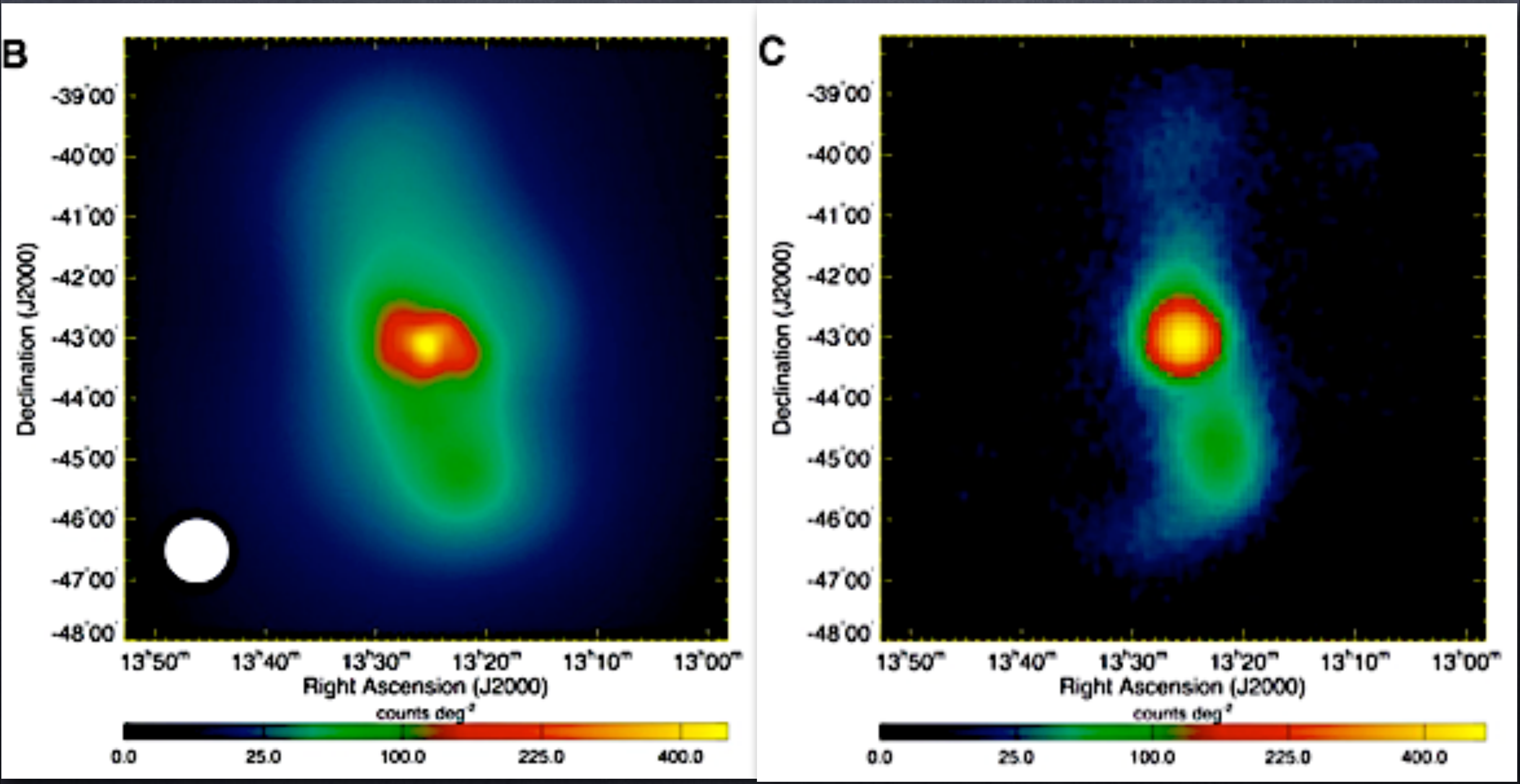


Including an extreme choice for the turbulent Galactic field component with strength 10 μG, coherence length 50 pc, 10 kpc halo extension



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

Lobes of Centaurus A seen by Fermi-LAT

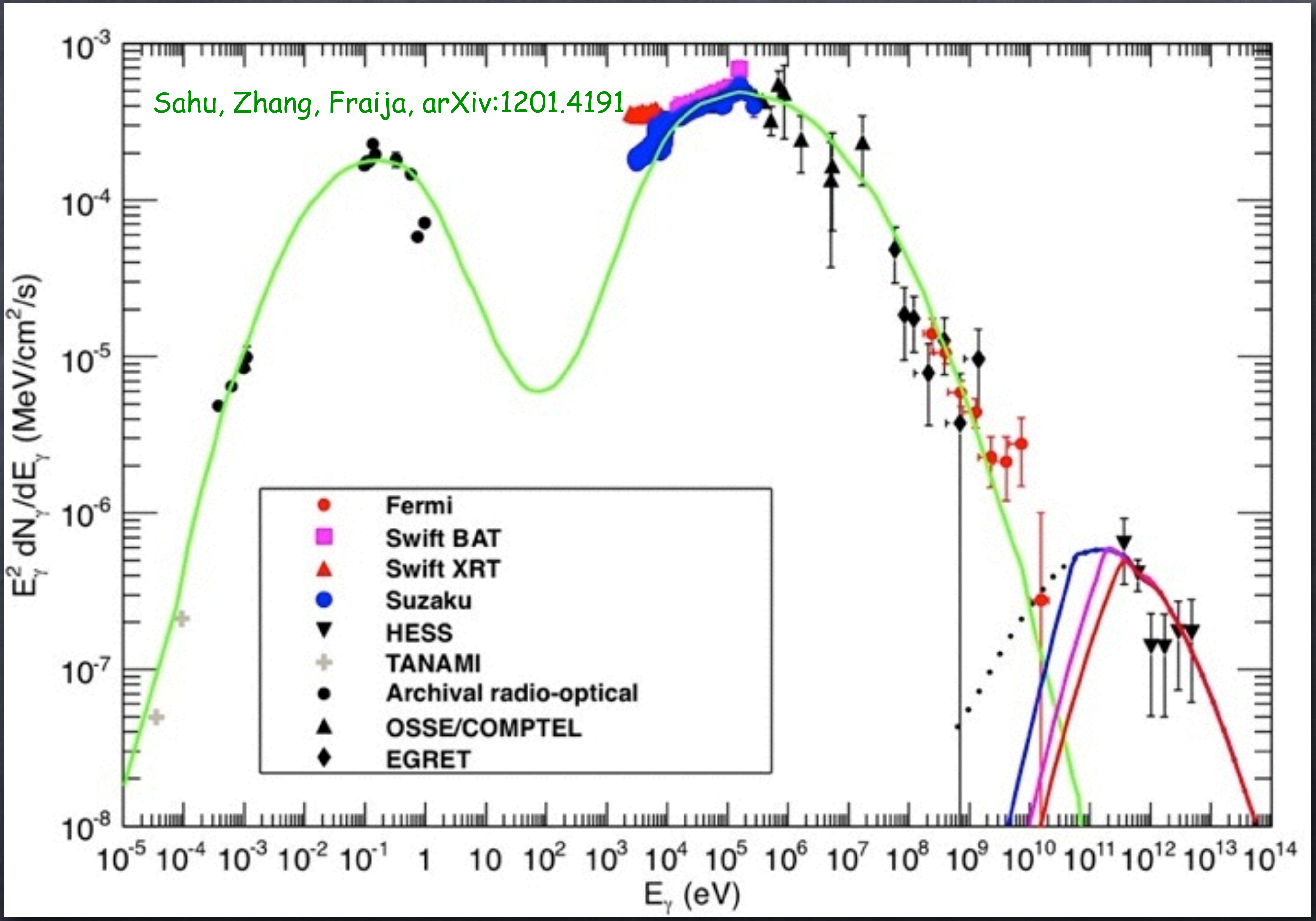


> 200 MeV γ-rays

Radio observations

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

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



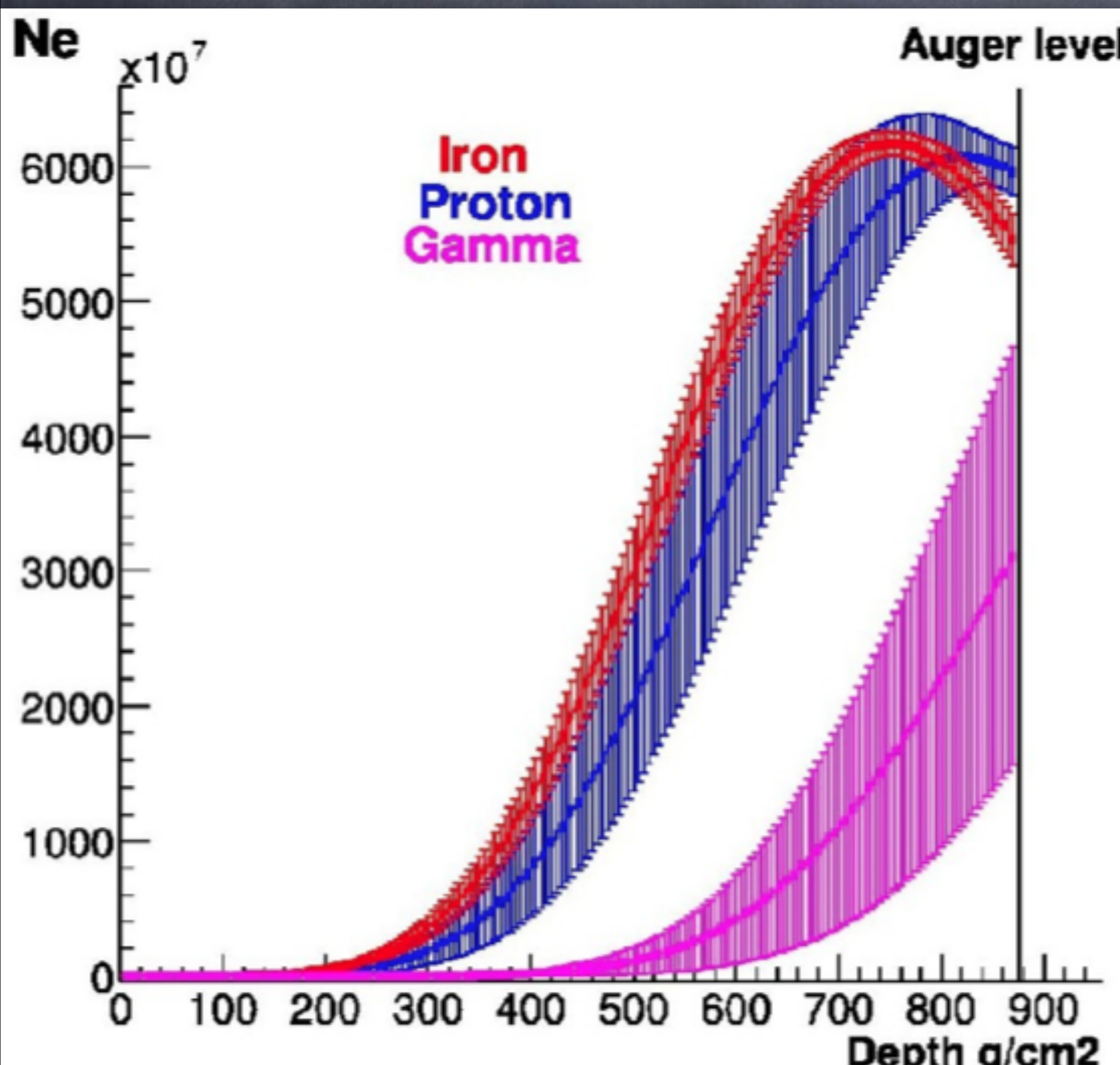
Low energy bump = synchrotron

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



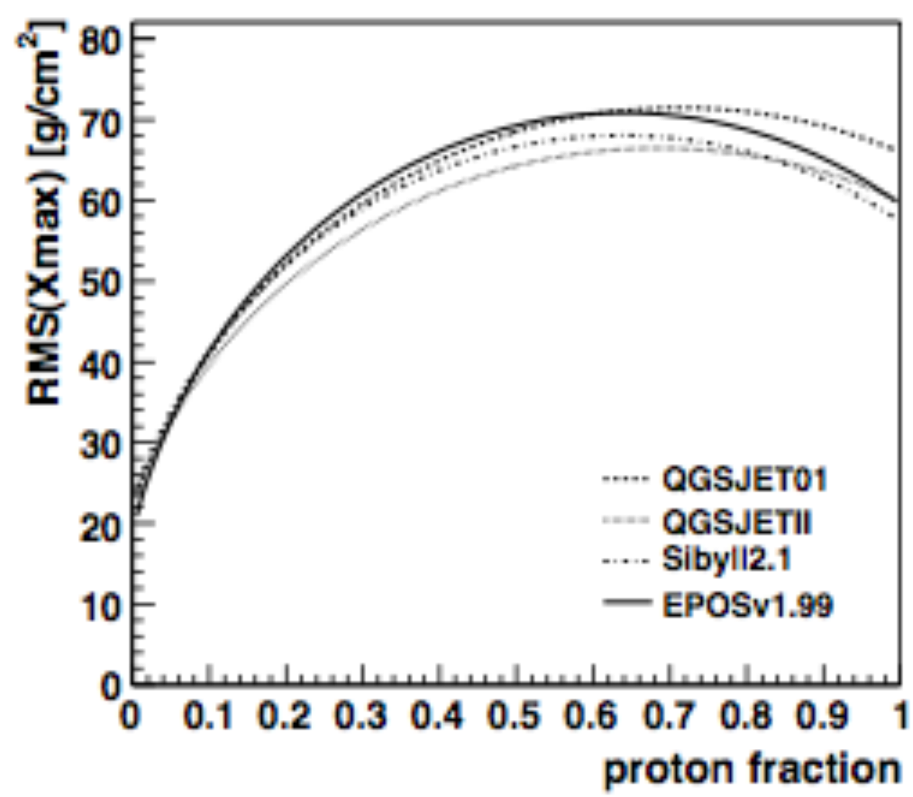
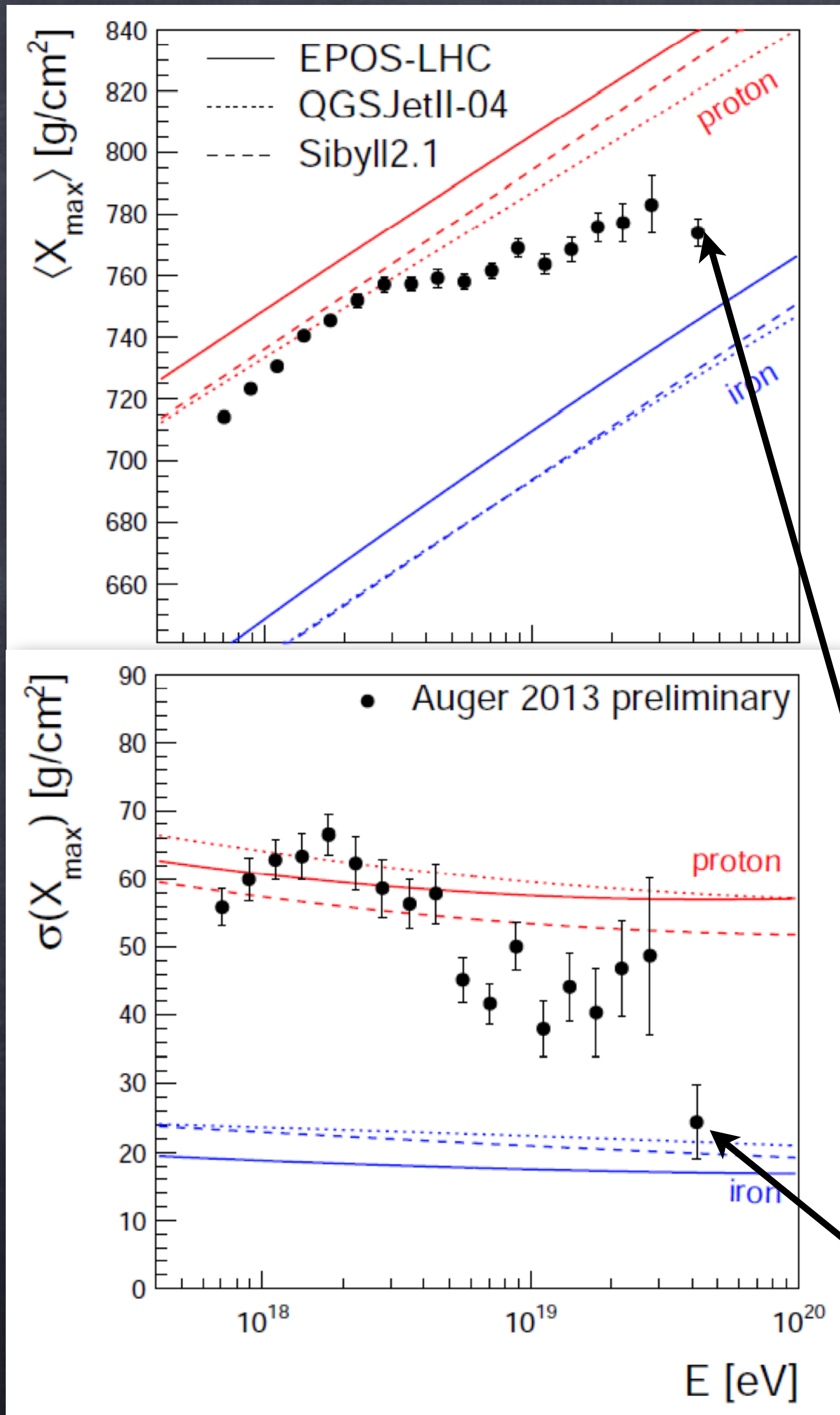
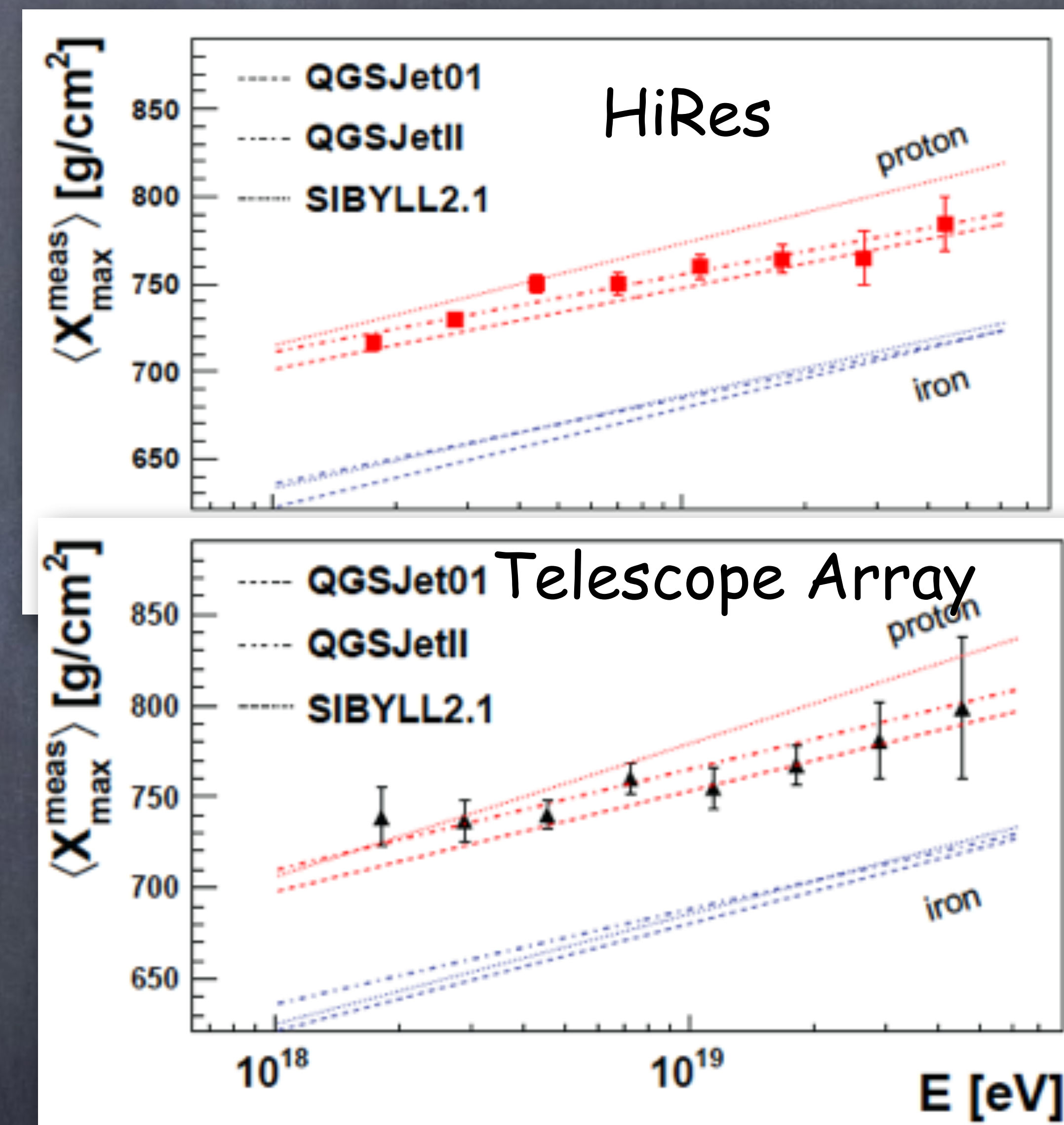


FIGURE 1. RMS(X_{max}) from different hadronic interaction models [23] and a two-component p/Fe composition model ($E = 10^{18}$ eV).

Pierre Auger data suggest a heavier composition toward highest energies:

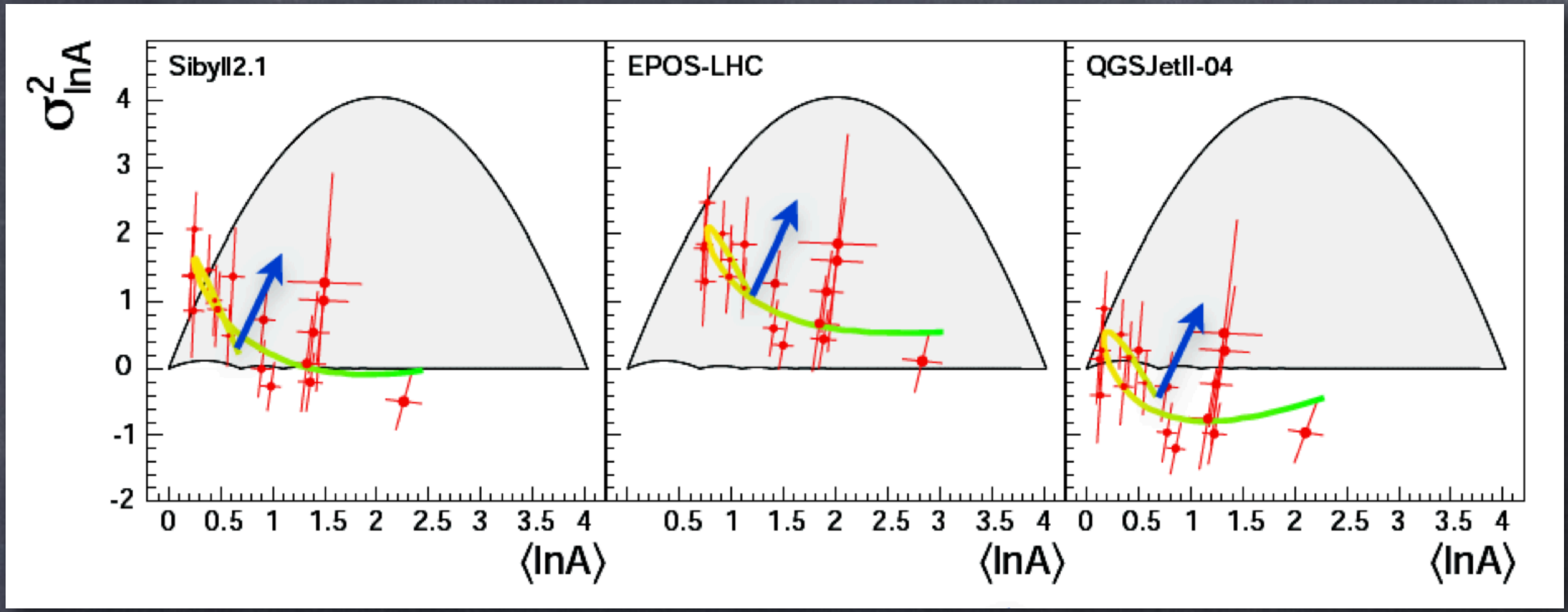


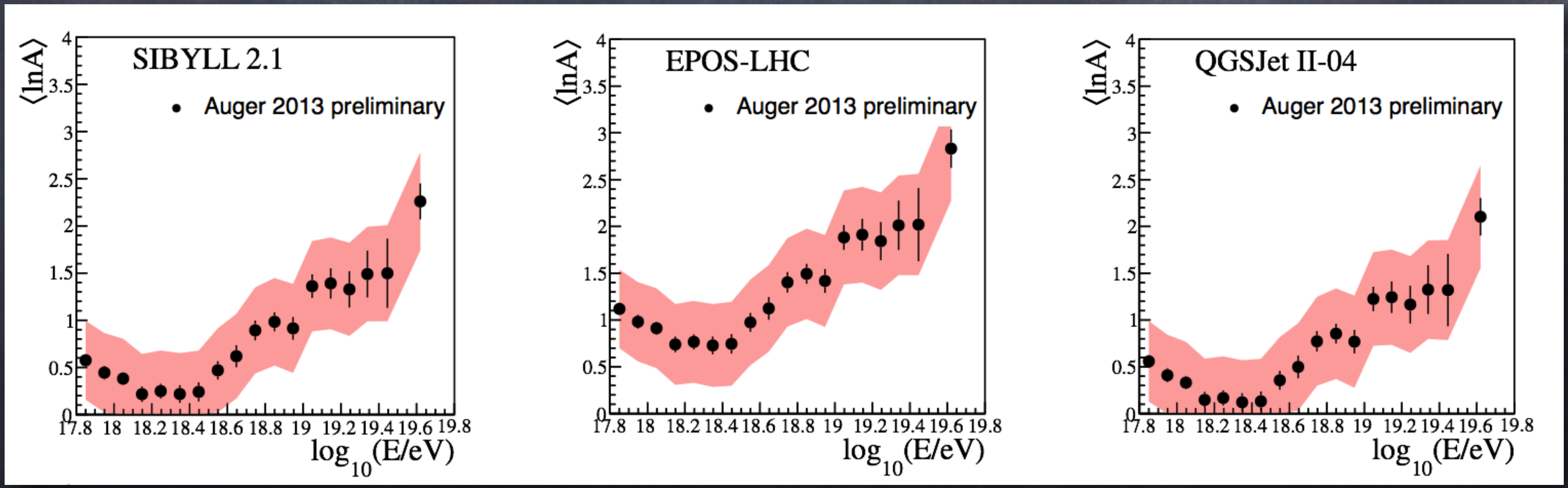
but not confirmed on the northern hemisphere by HiRes and Telescope Array which are consistent with protons



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

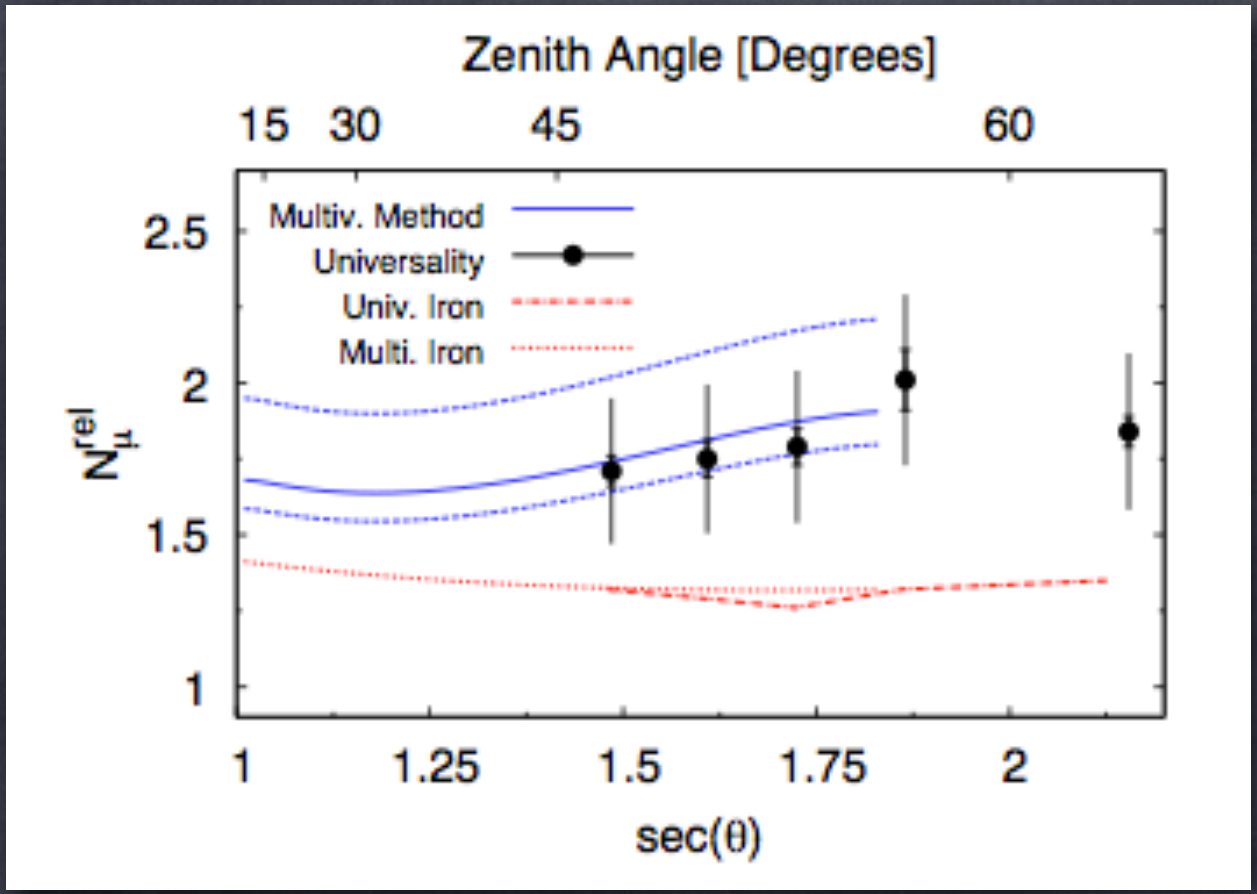
Pierre Auger Collaboration, Phys.Rev.Lett., 104 (2010) 091101, and ICRC 2013, arXiv:1307.5059 combined measurement of X_{max} and its fluctuation σ constrains composition **within a given hadronic interaction model**



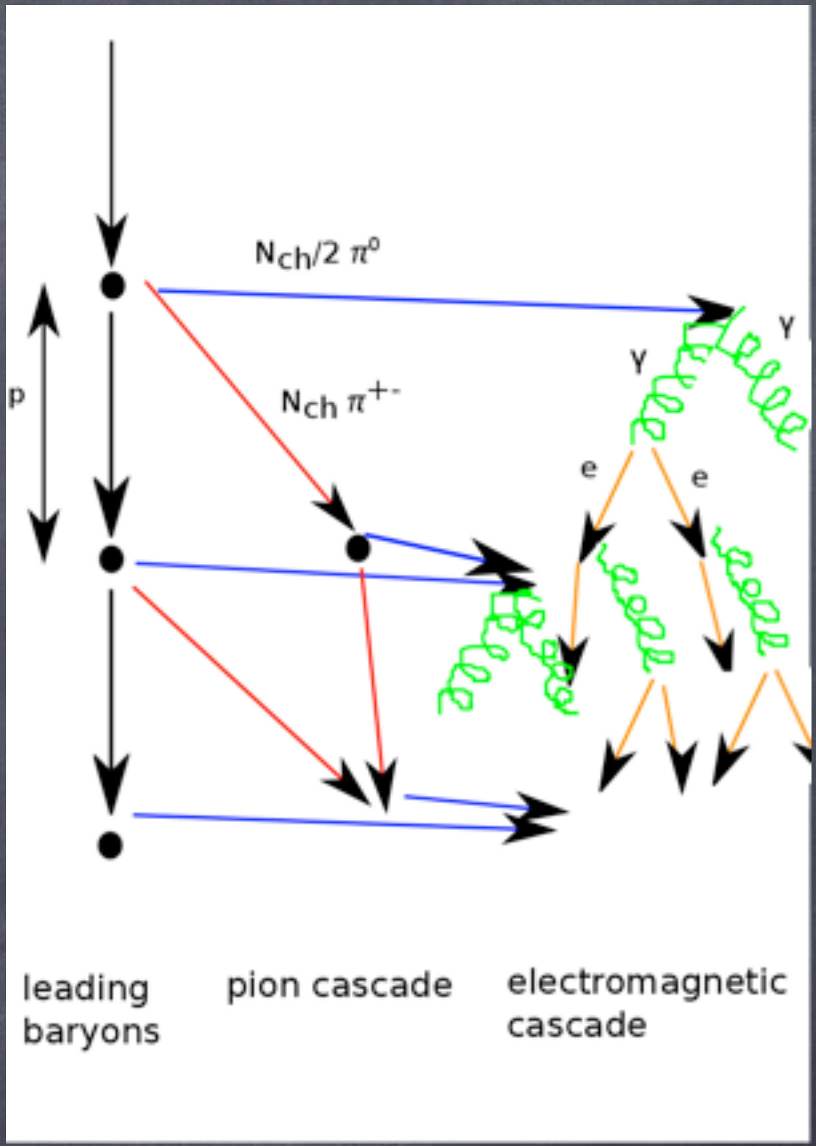


Kampert and Unger, arXiv:1201.0018, M. Roth at TeVPA 2013 and ICRC 2013

Muon number measured at 1000 m from shower core a factor ~2 higher than predicted



Pierre Auger Collaboration, ICRC 2011, Allen et al., arXiv:1107.4804



The muon number scales as

$$N_\mu \propto E_{\rm had} \propto (1 - f_{\pi^0})^N \ ,$$

with the fraction going into the electromagnetic channel $f_{\pi^0} \simeq \frac{1}{3}$ and the number of generations N strongly constrained by $X_{\rm max}$. Larger N_μ thus requires smaller f_{π^0} !

KASCADE data suggest a heavy composition below ~10^{18} eV possibly becoming lighter around 10^{18} eV

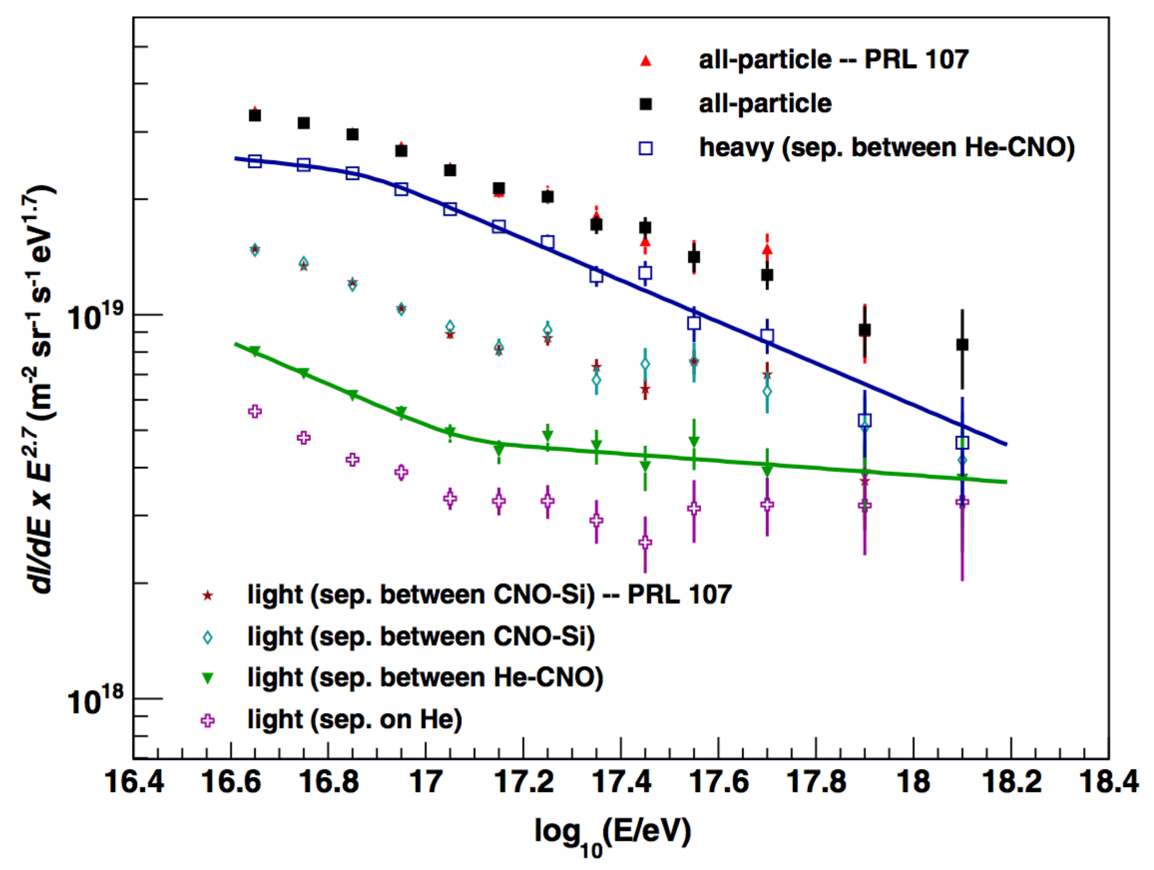
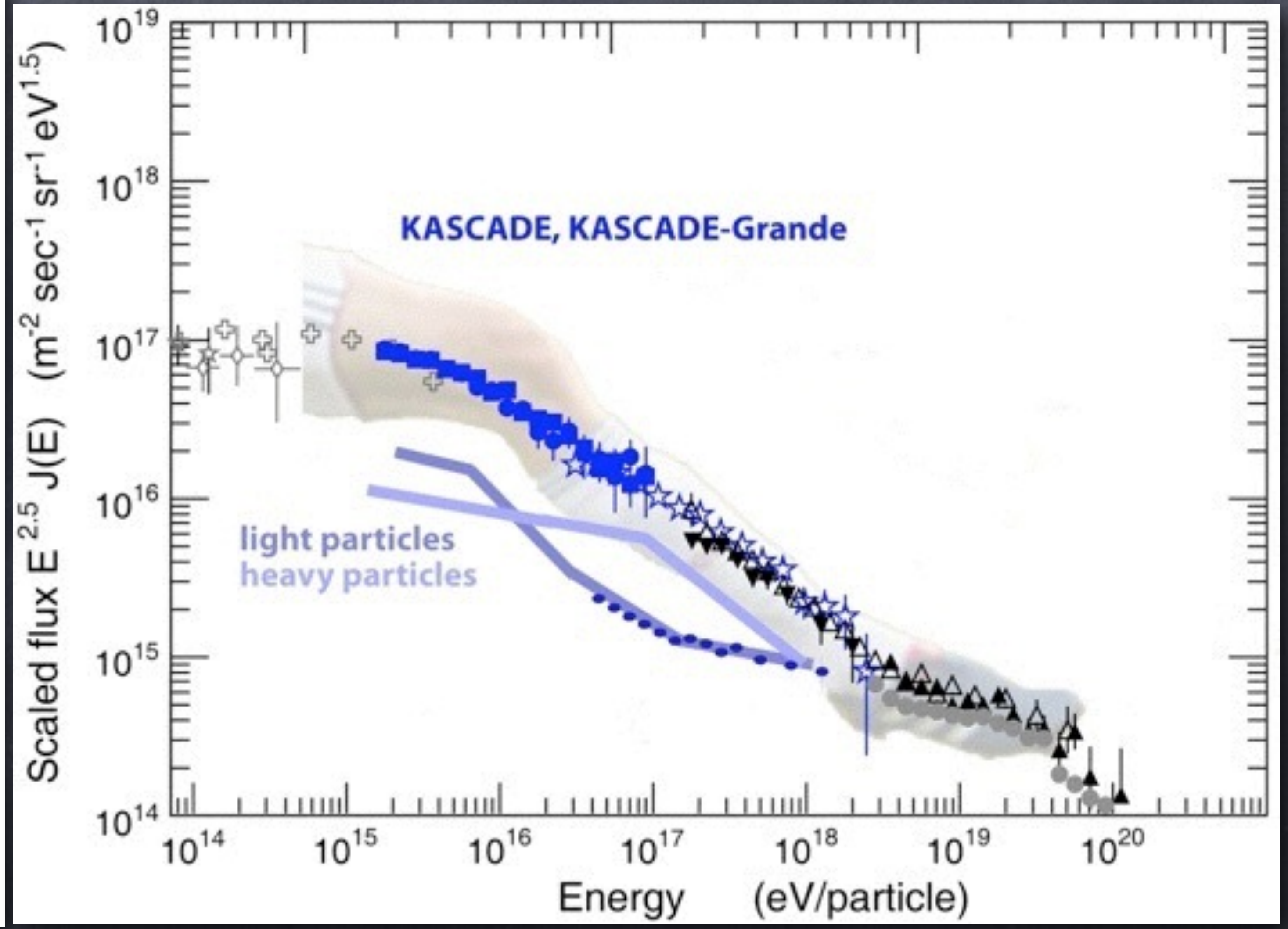
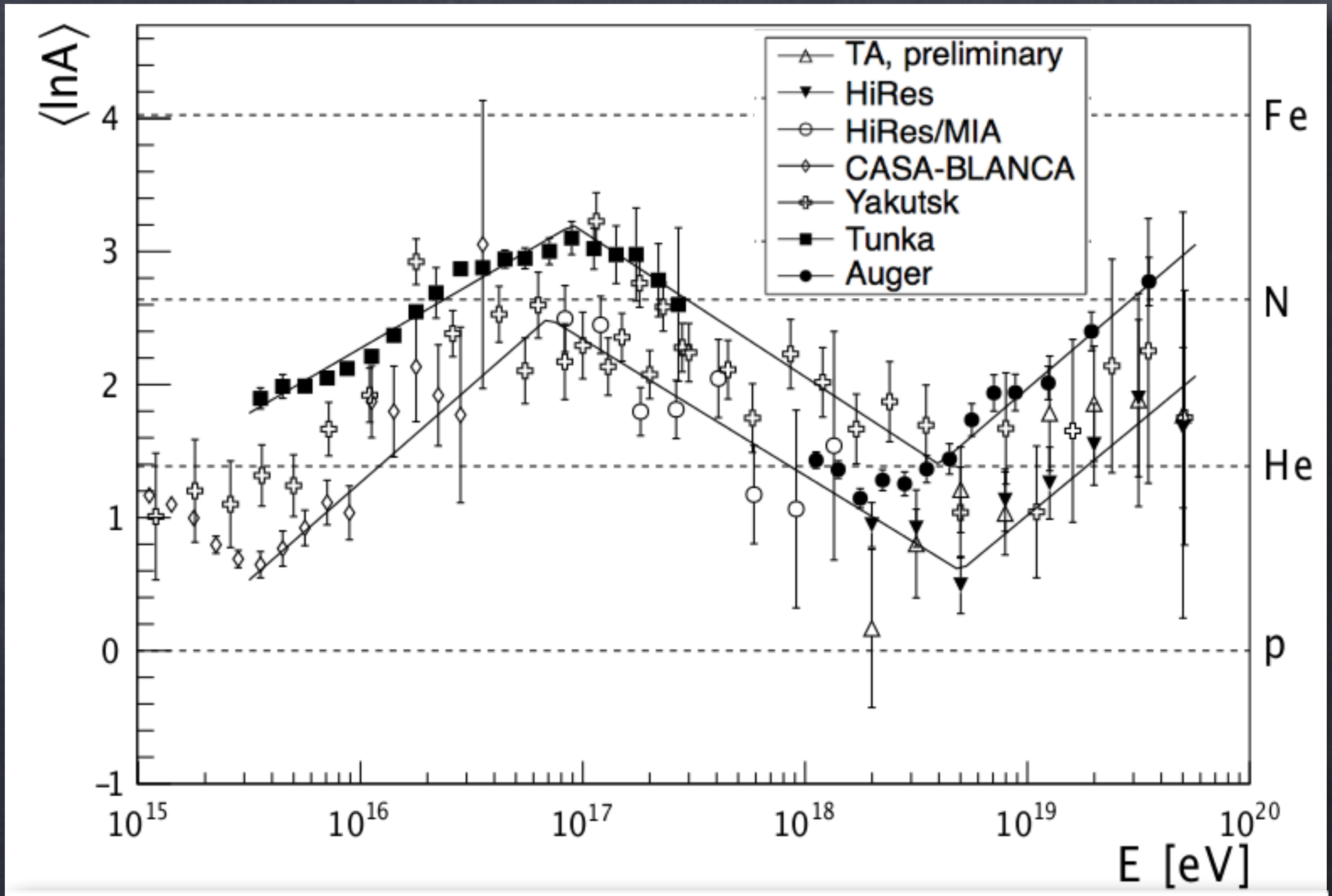


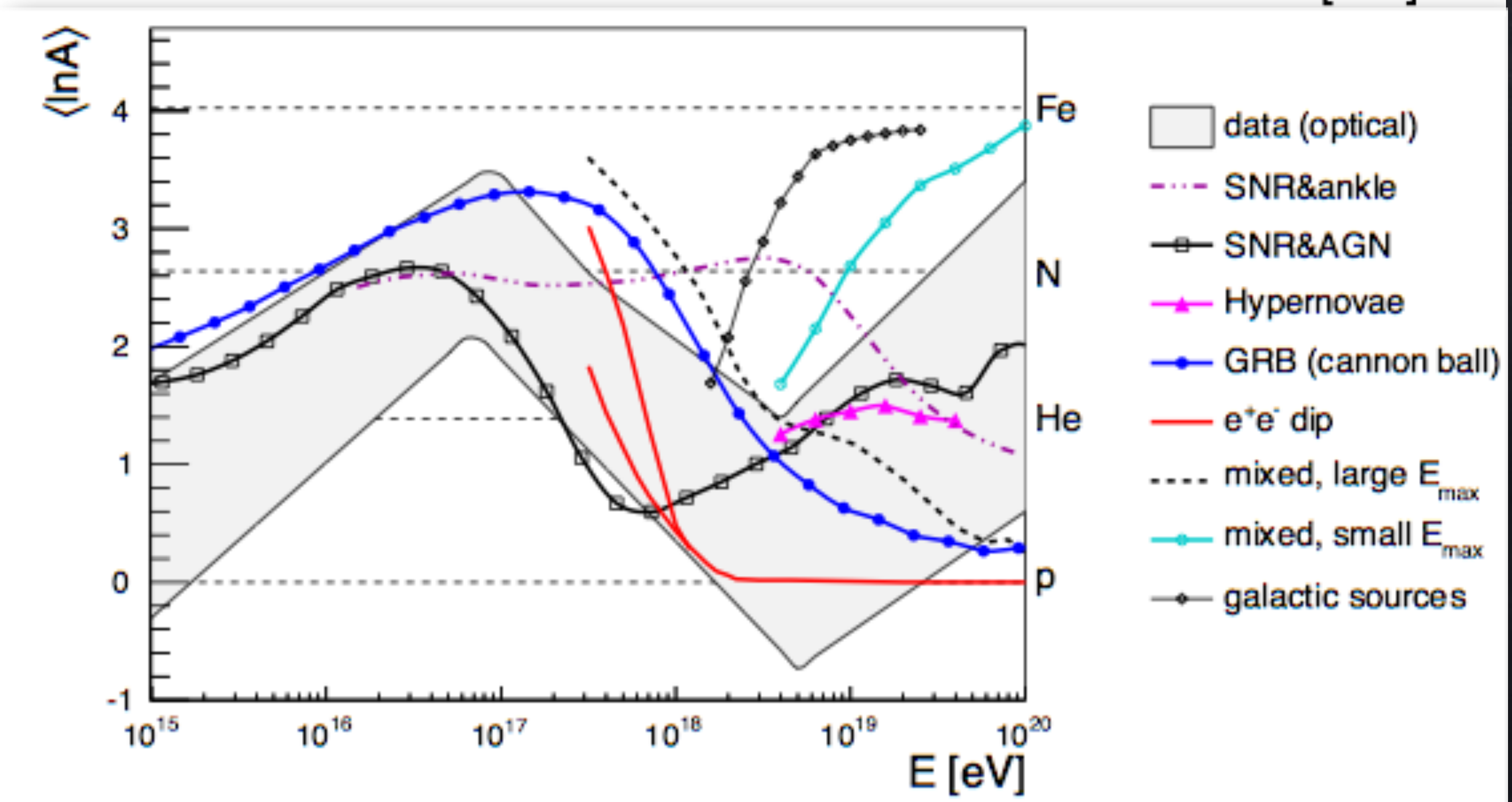
FIG. 4 (color online). The all-particle and electron-rich spectra from the analysis [8] in comparison to the results of this analysis with higher statistics. In addition to the light and heavy spectrum based on the separation between He and CNO, the light spectrum based on the separation on He is also shown. The error bars show the statistical uncertainties.

KASCADE Collaboration, Phys.Rev. D87 (2013) 081101,

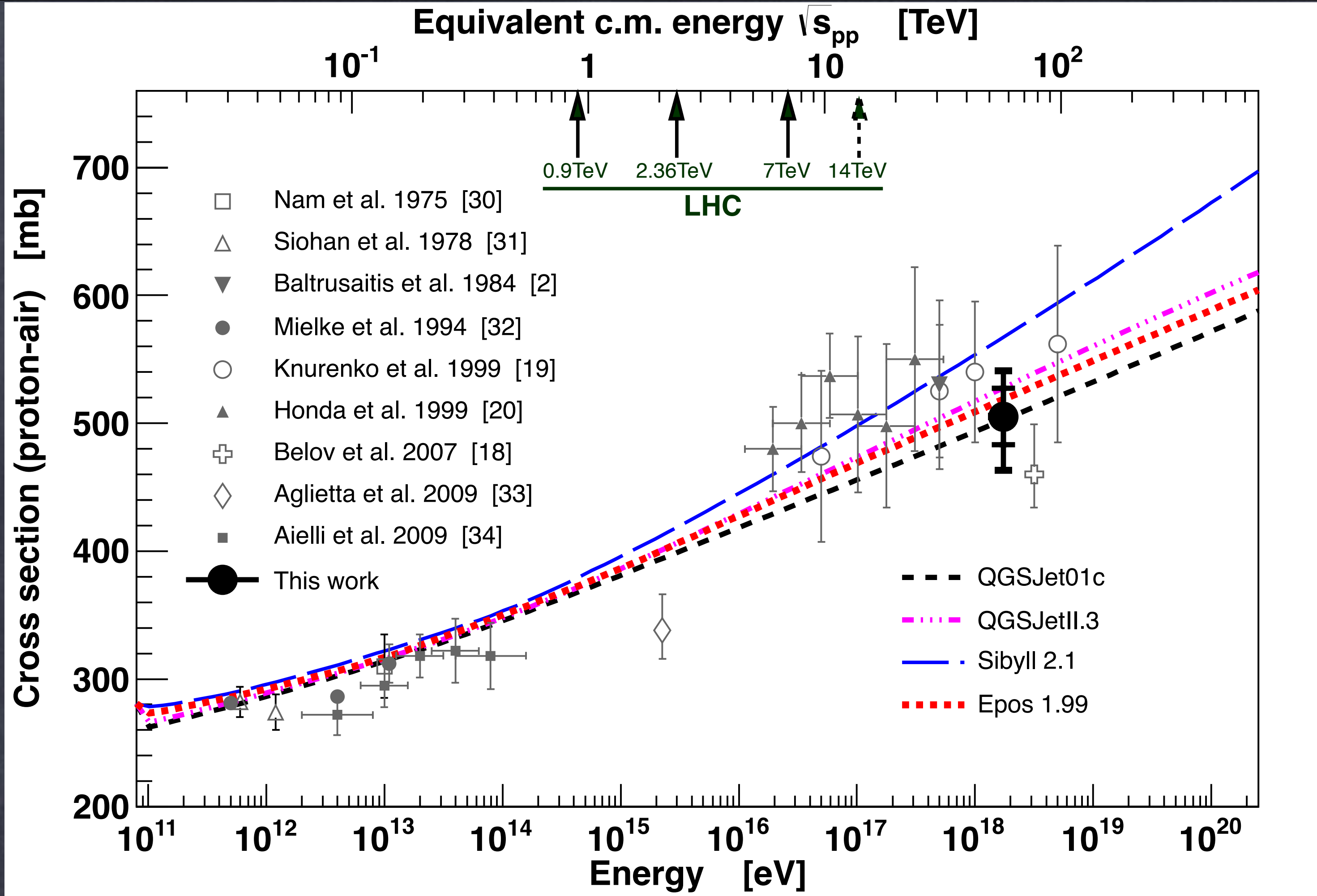


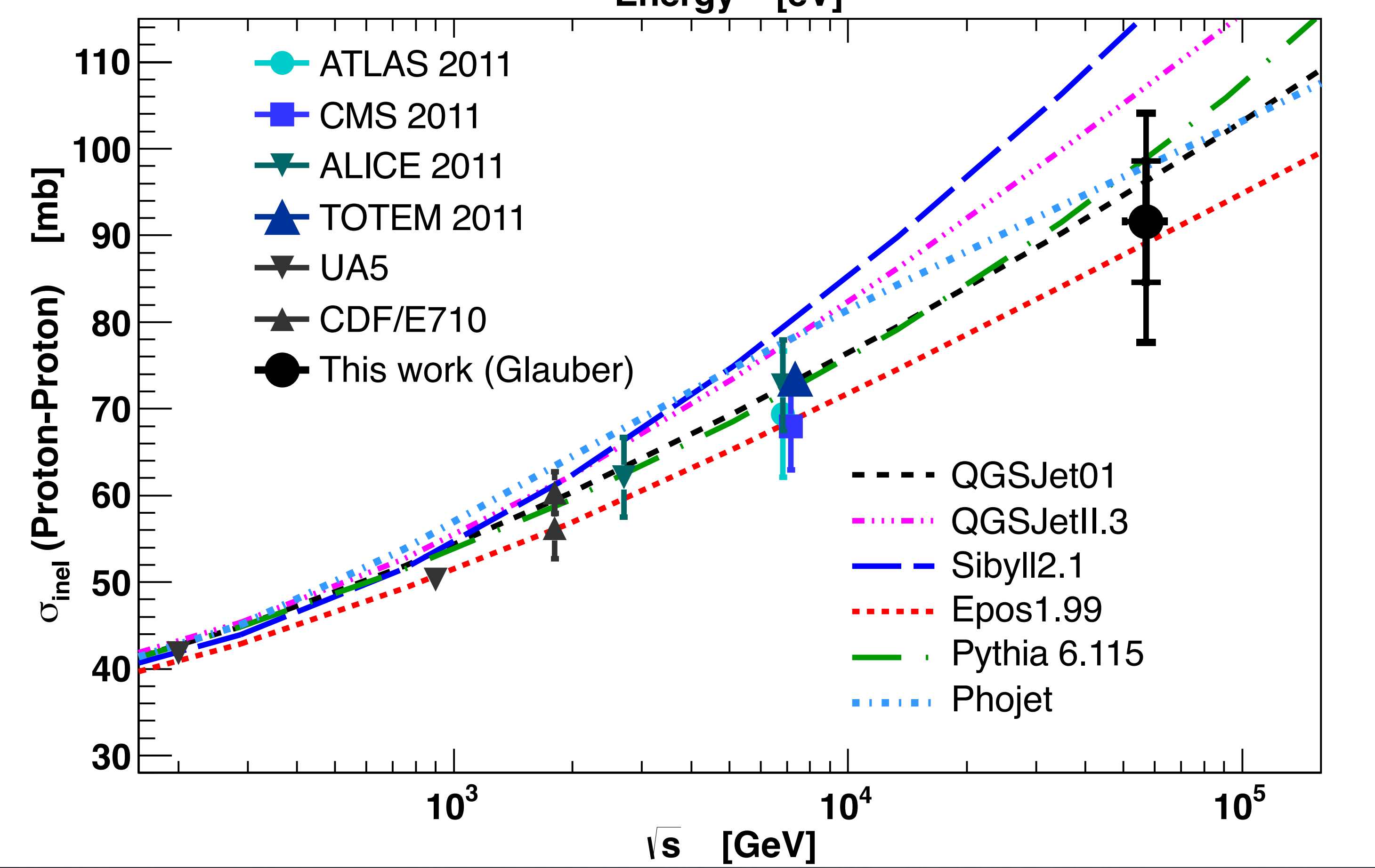
The global picture for the mass composition



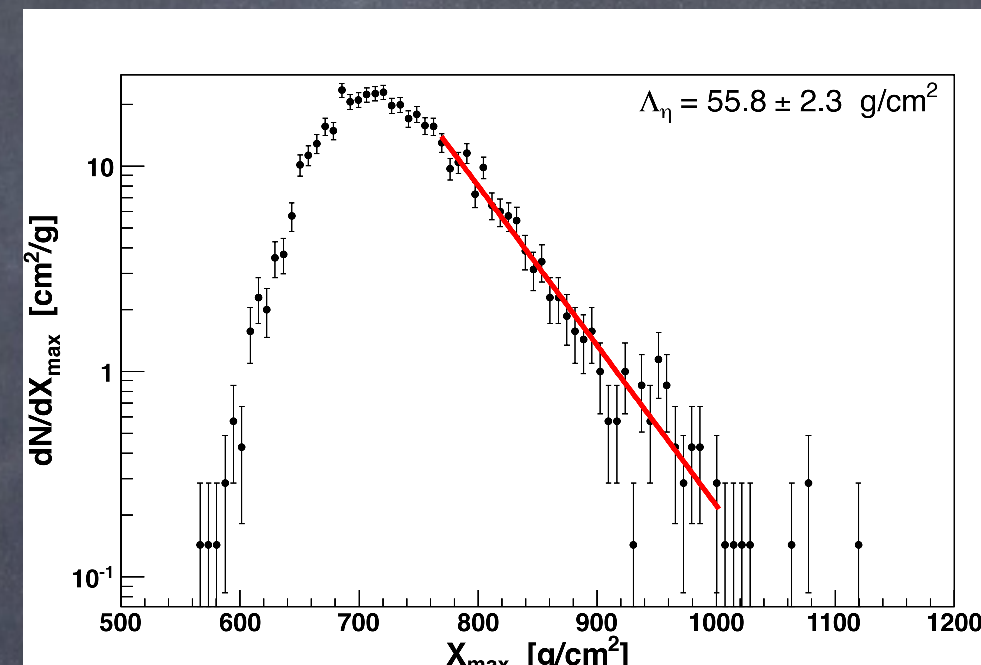


K.-H.Kampert and M.Unger, Astropart.Phys. 35 (2012) 660





p-air cross section derived from exponential tail of depth of shower maxima

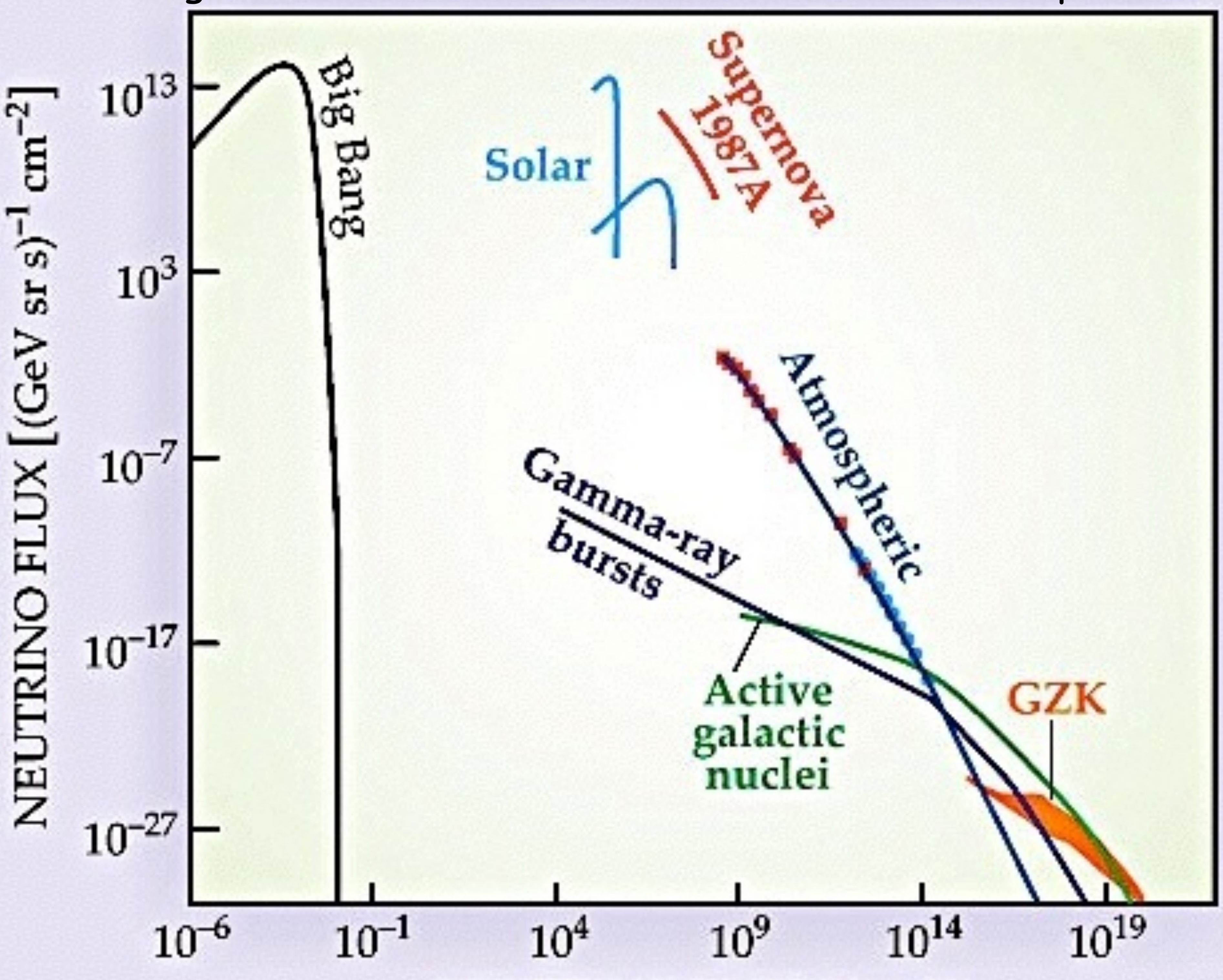


pp cross section derived from Glauber model

Pierre Auger Collaboration, PRL 109, 062002 (2012)

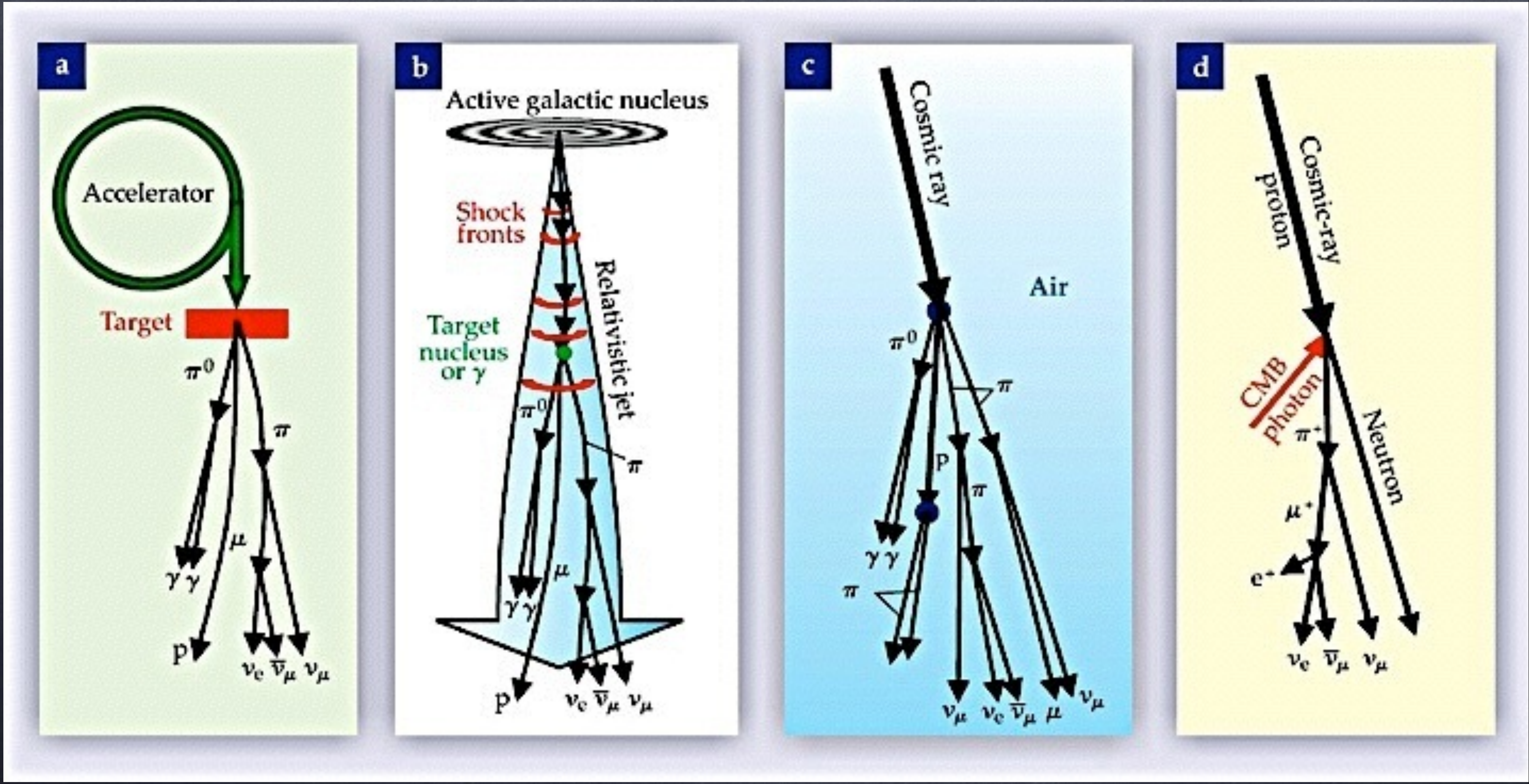
Very High High Energy Neutrinos

The „grand unified“ differential neutrino number spectrum



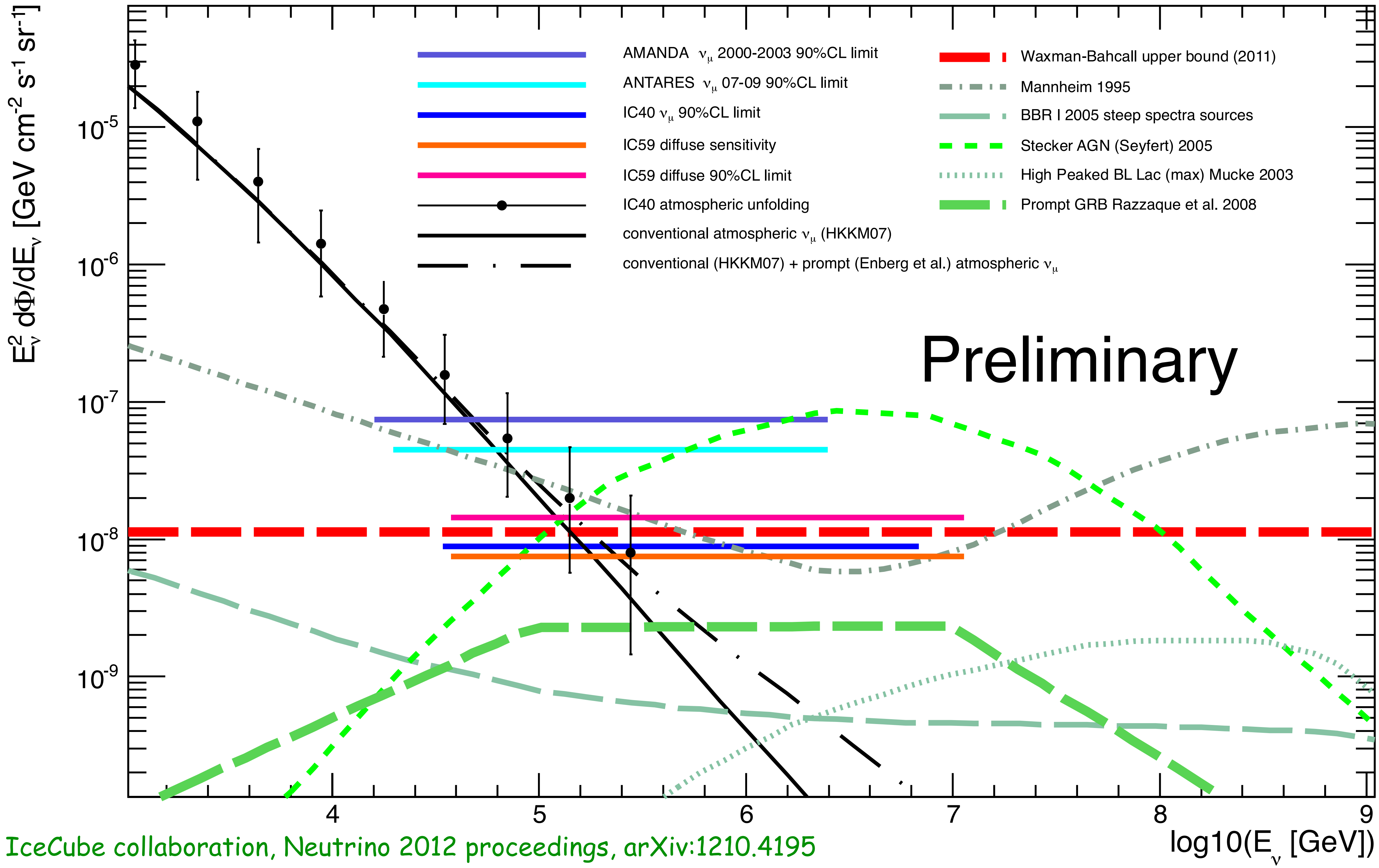
From Physics Today

Summary of neutrino production modes



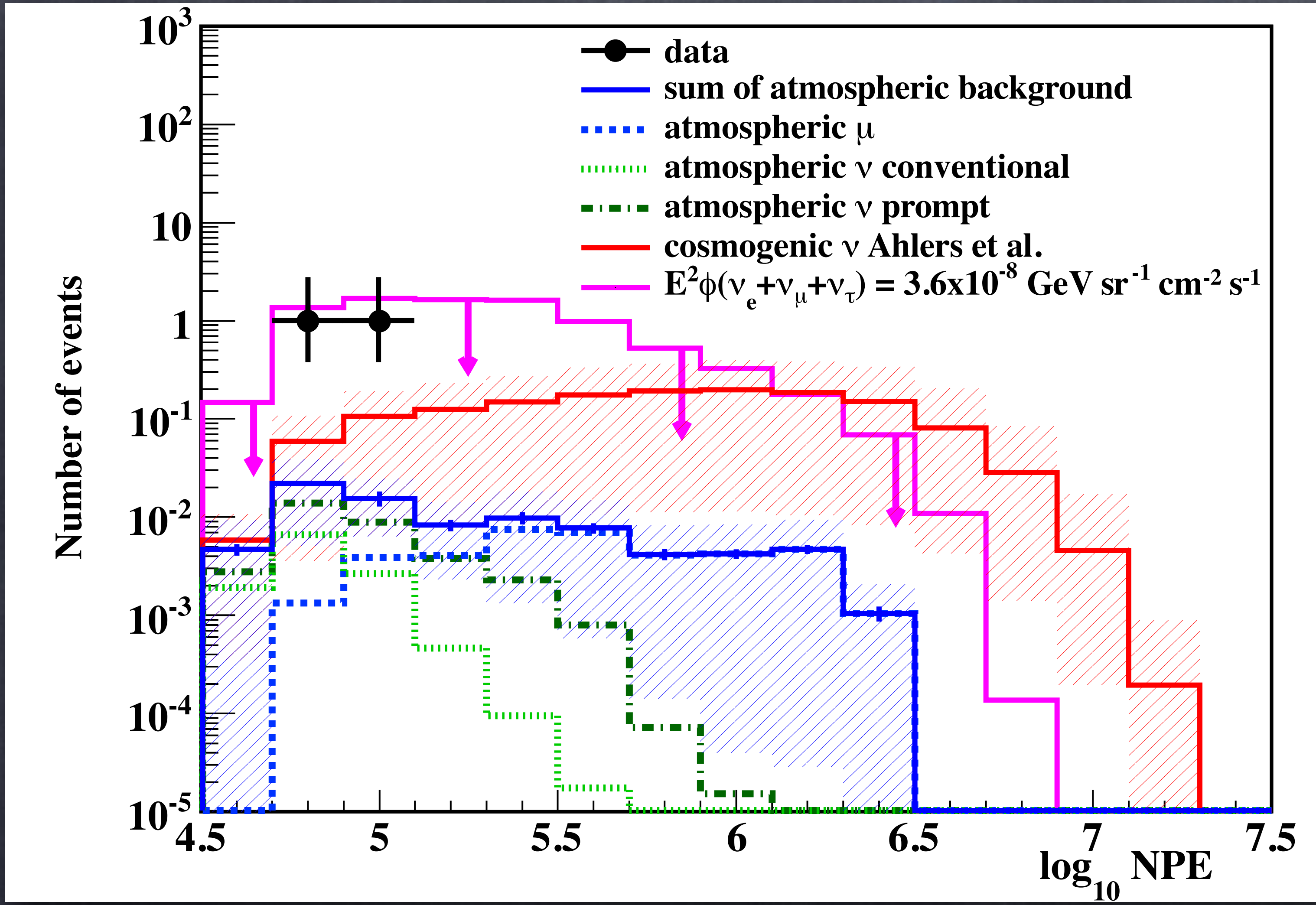
From Physics Today

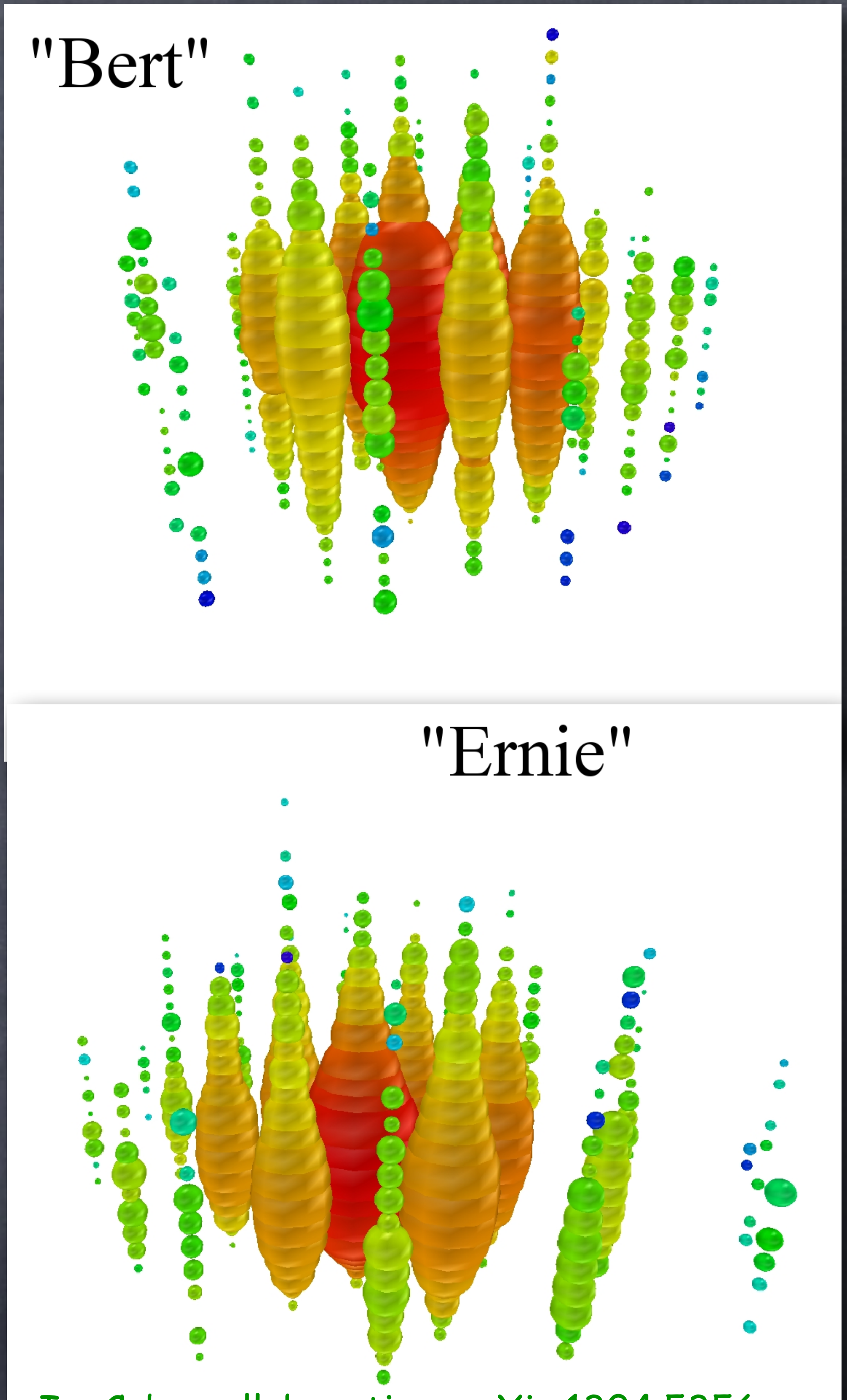
Current Neutrino Flux Upper Limits at TeV-EeV energies



IceCube collaboration, Neutrino 2012 proceedings, arXiv:1210.4195

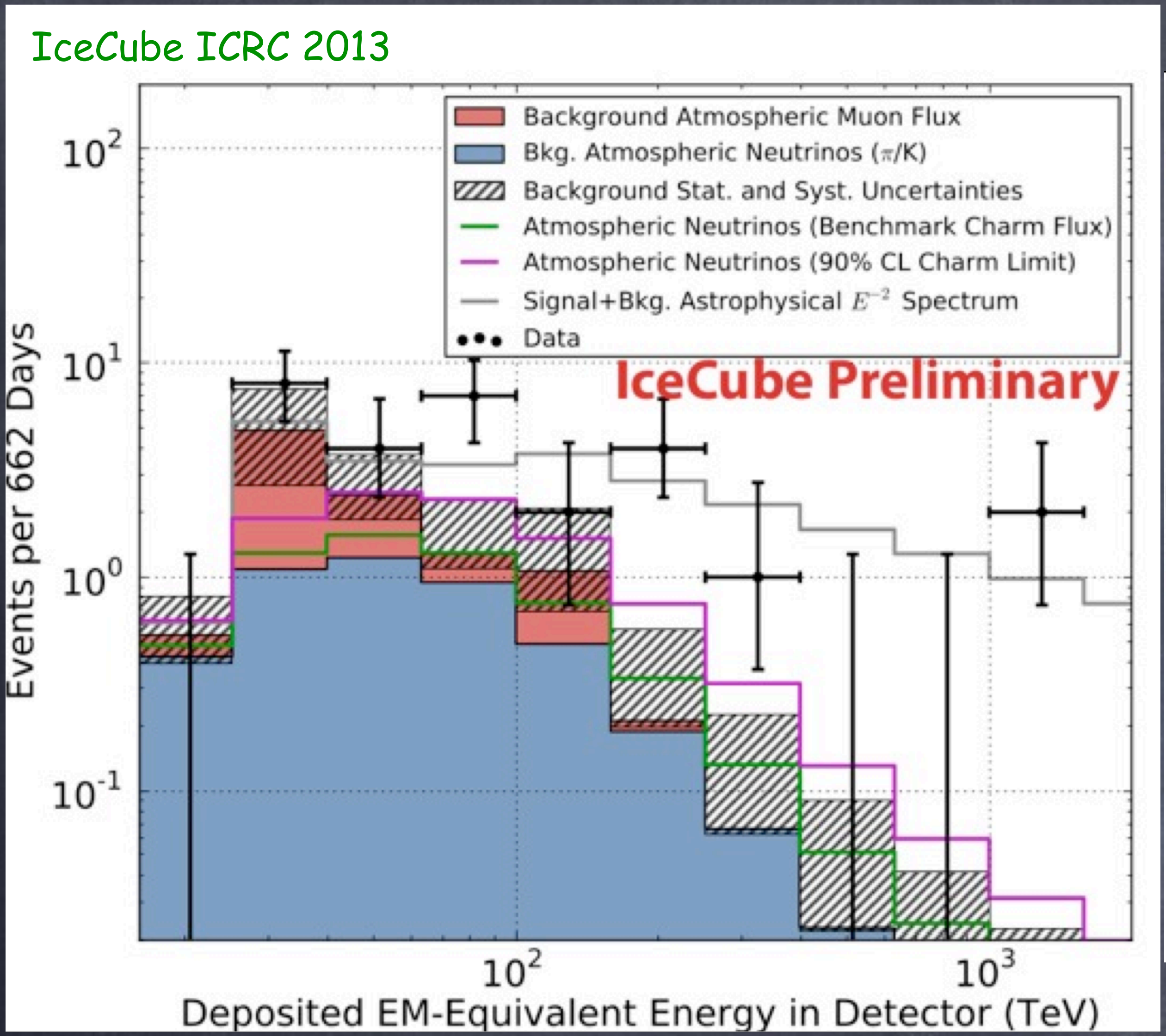
But now two PeV energy candidate neutrinos observed by IceCube

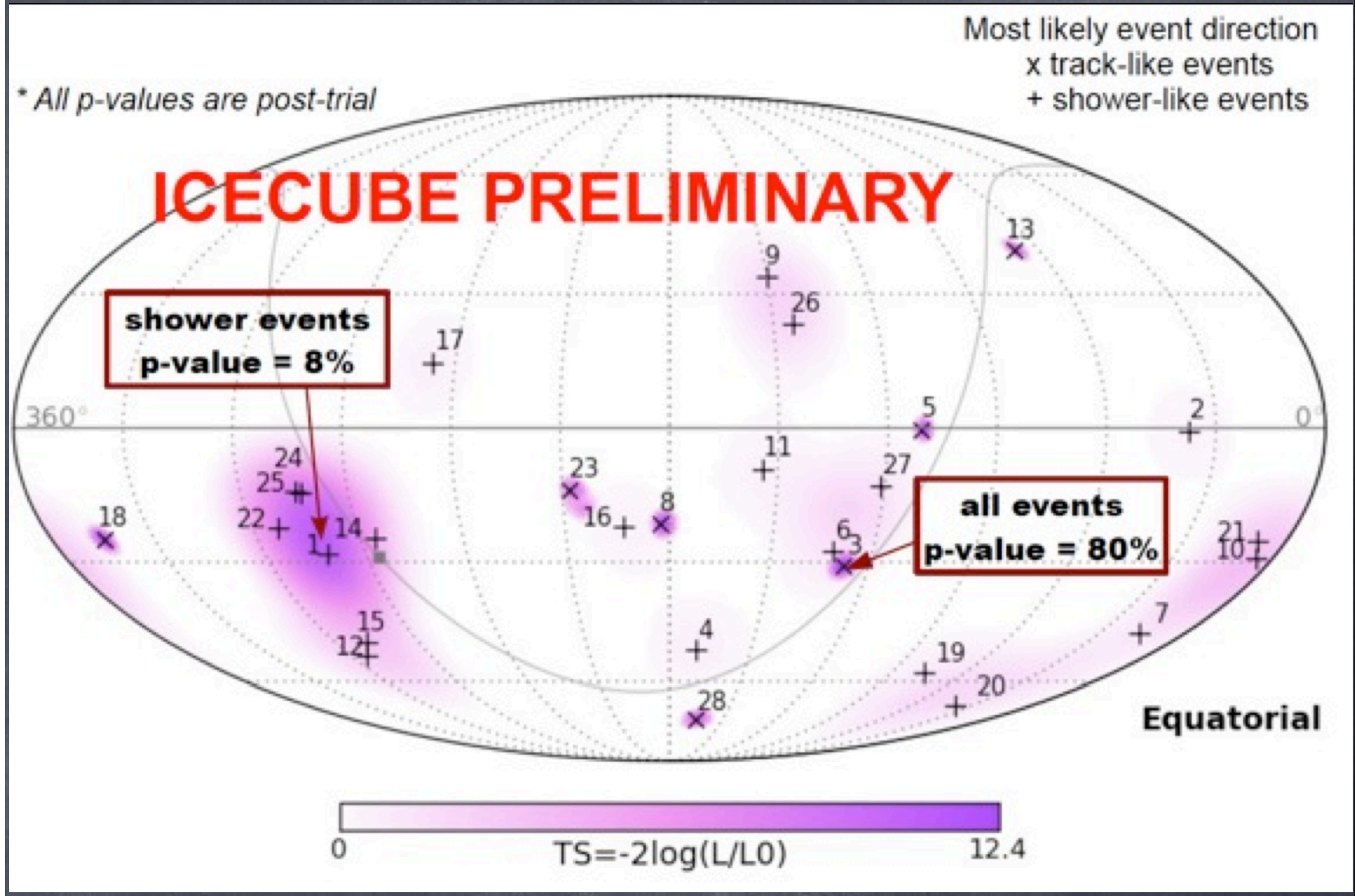




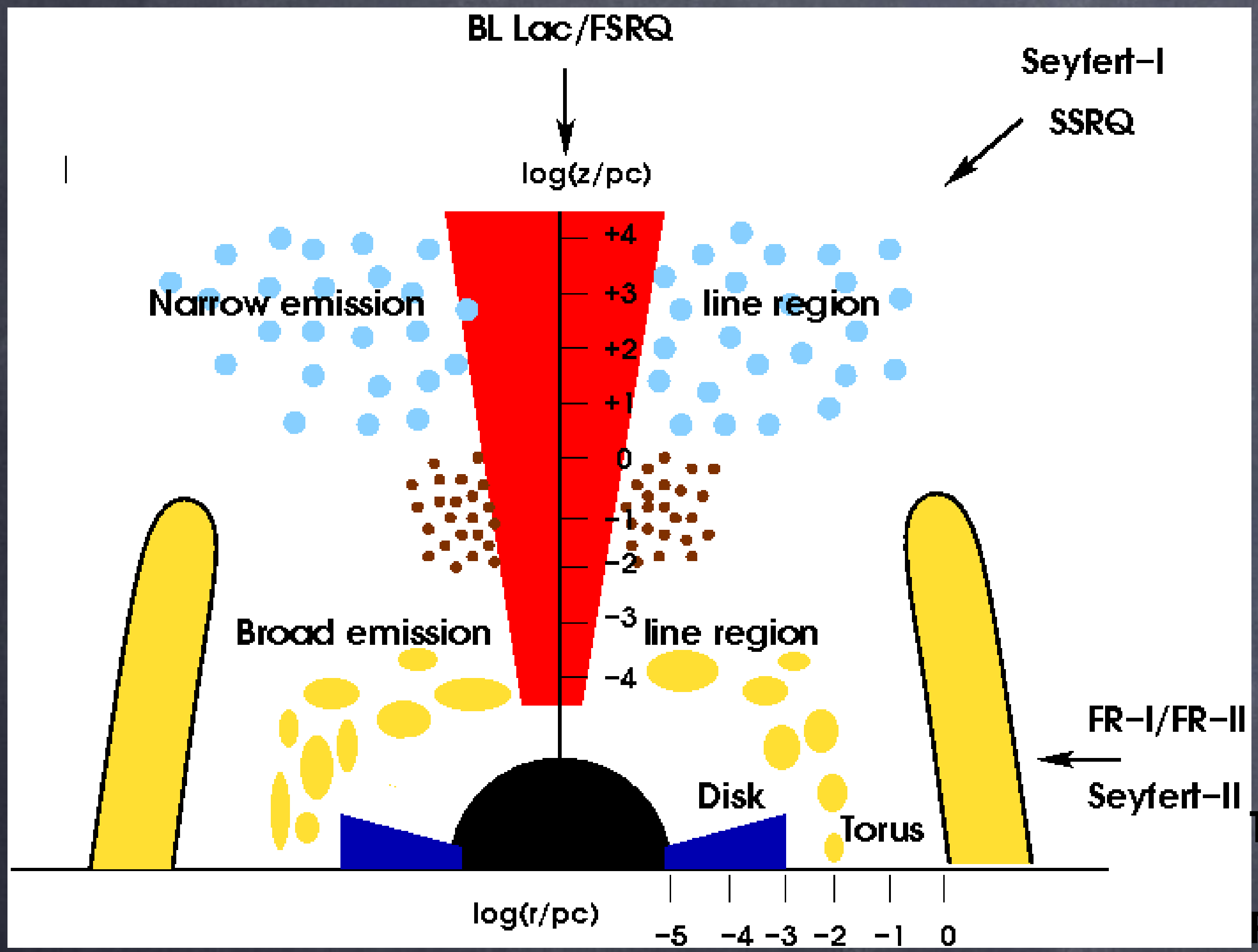
IceCube collaboration, arXiv:1304.5356

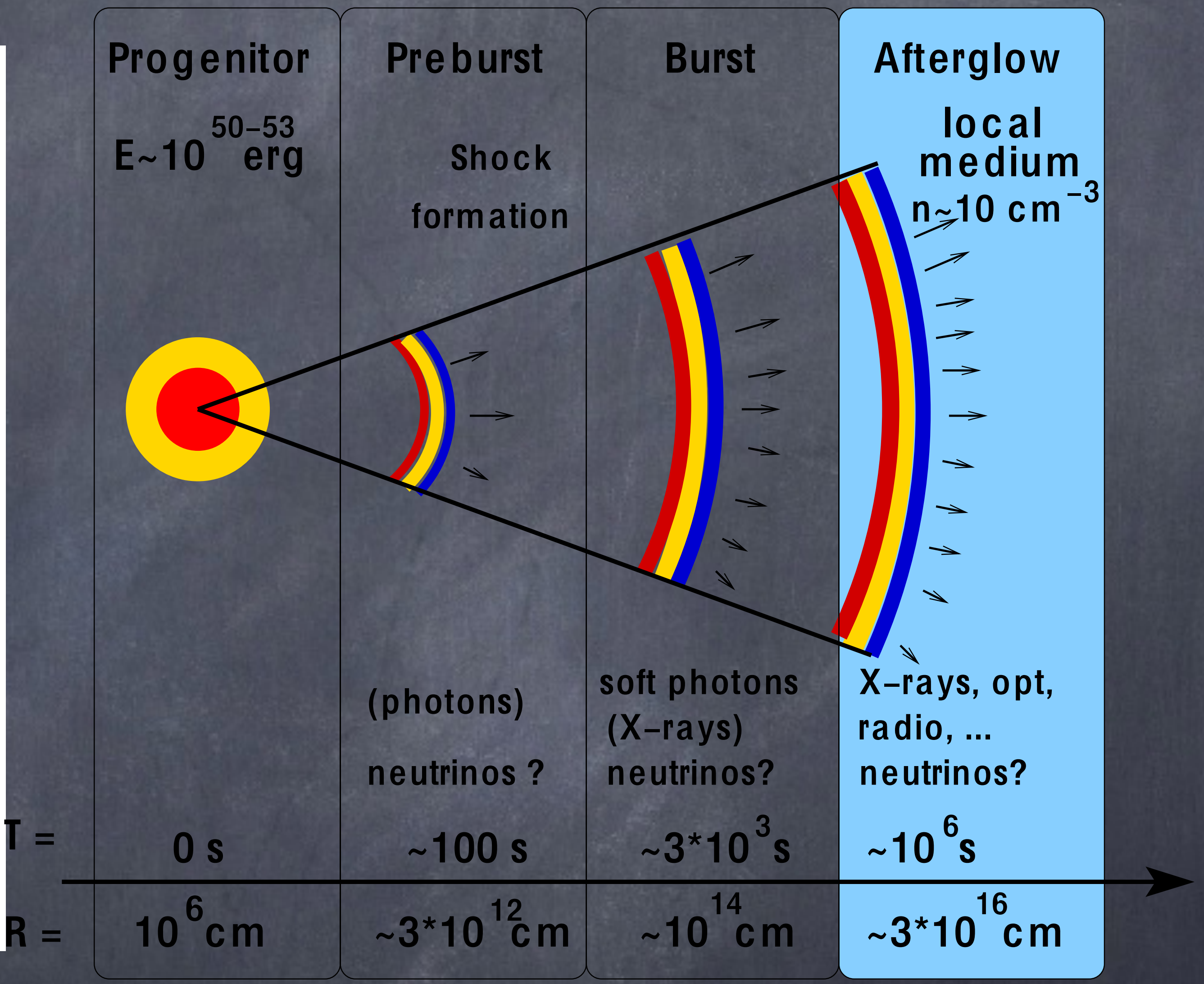
and even more events at few 100 TeV: preliminary IceCube results





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

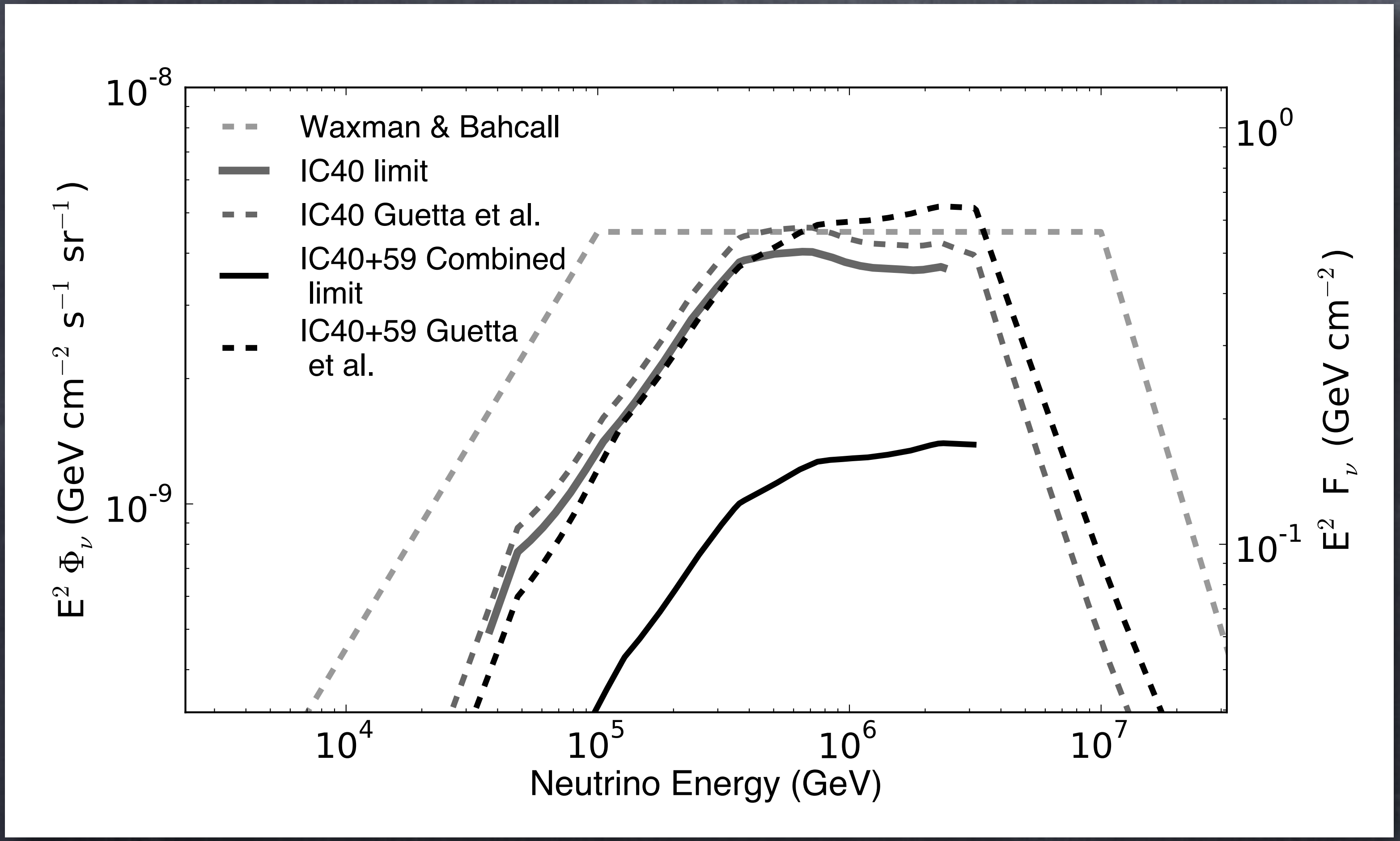
Diffuse neutrino flux from GRBs can thus be linked to UHECR flux (if it is dominantly produced by GRBs)

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

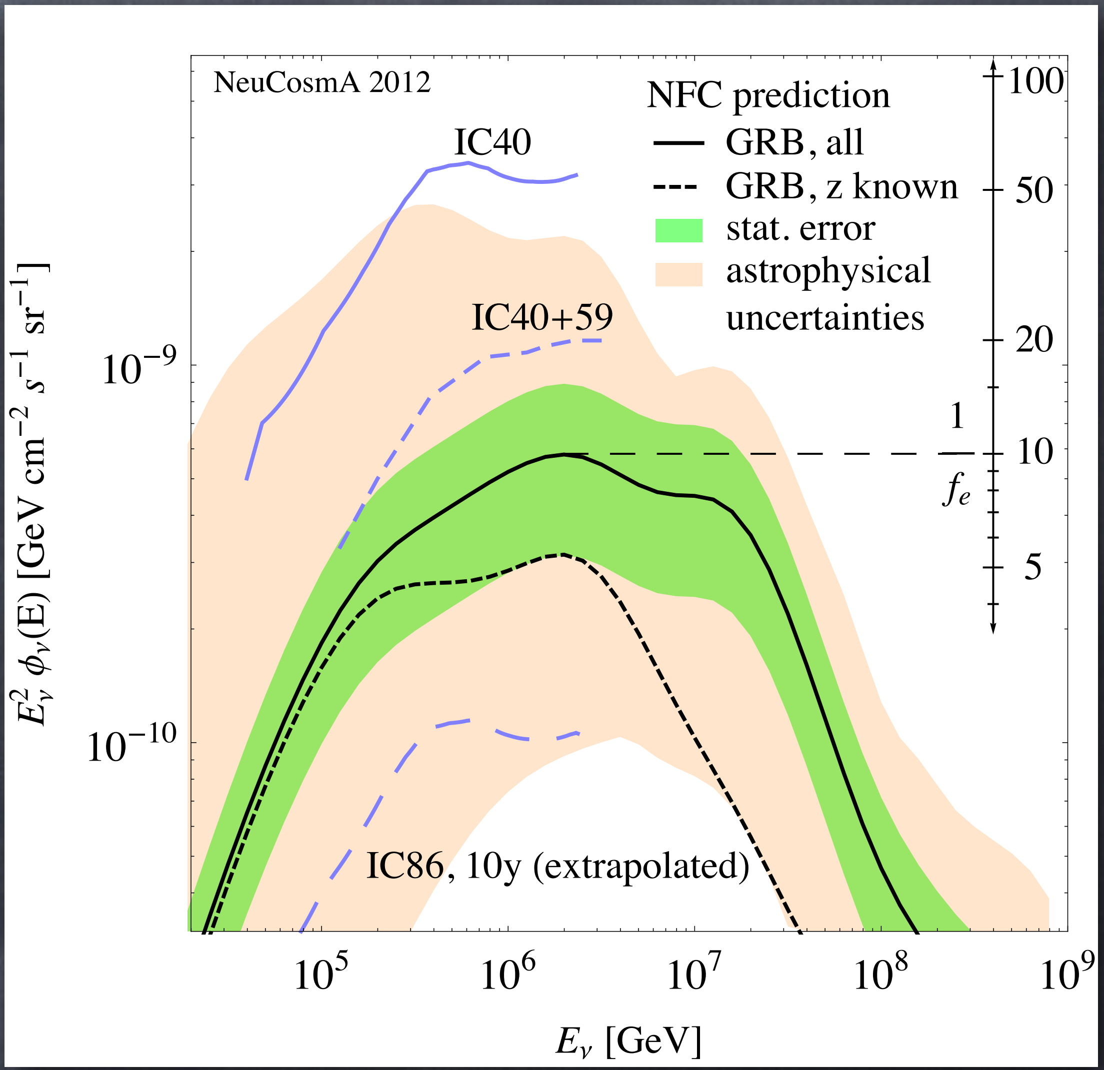
where $\eta_\nu \simeq 0.1$ is average neutrino energy in units of the parent proton energy.

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 constrained by non-observation of neutrinos by IceCube



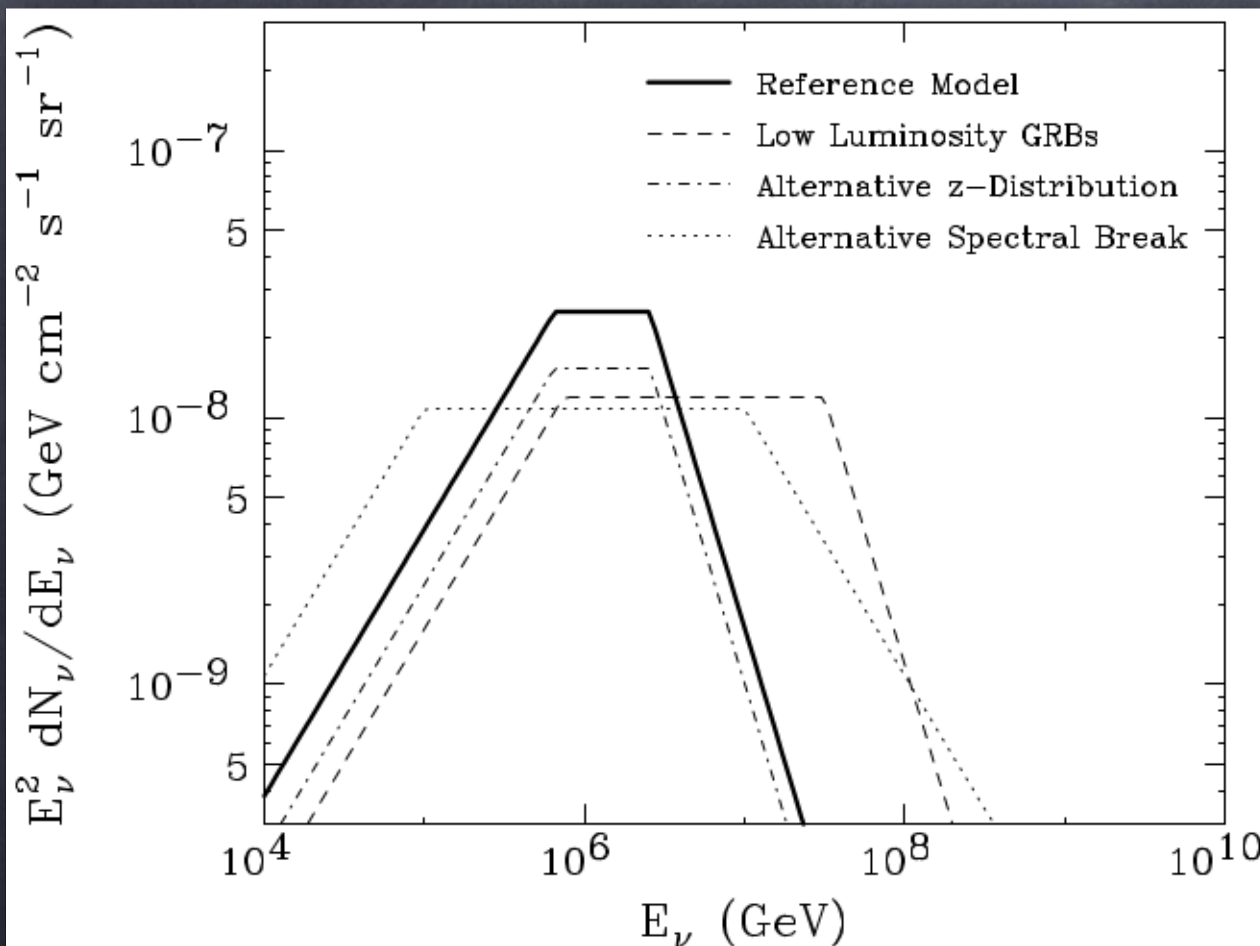
IceCube collaboration, Nature 484 (2012) 351



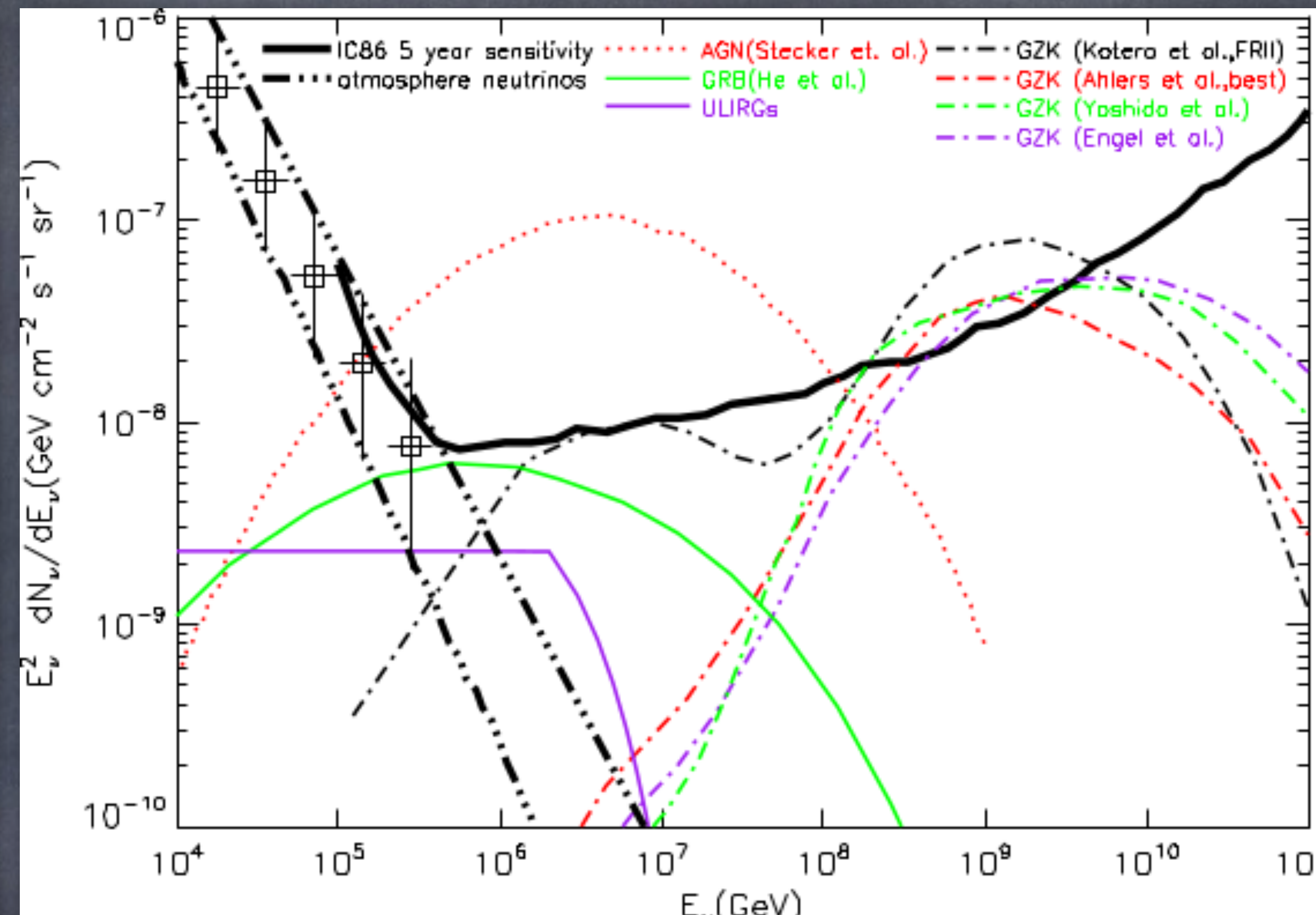
but re-evaluation of diffuse neutrino flux from GRBs gave factor ~10 smaller fluxes

Hümmer, Baerwald, Winter, PRL 108 (2012) 231101

But GRB models can still be tweaked to explain the IceCube events



Cholis and Hooper, arXiv:1211.1974



He et al., arXiv:1303.1253

IceCube events are unlikely to be produced during UHECR propagation ("cosmogenic neutrinos")

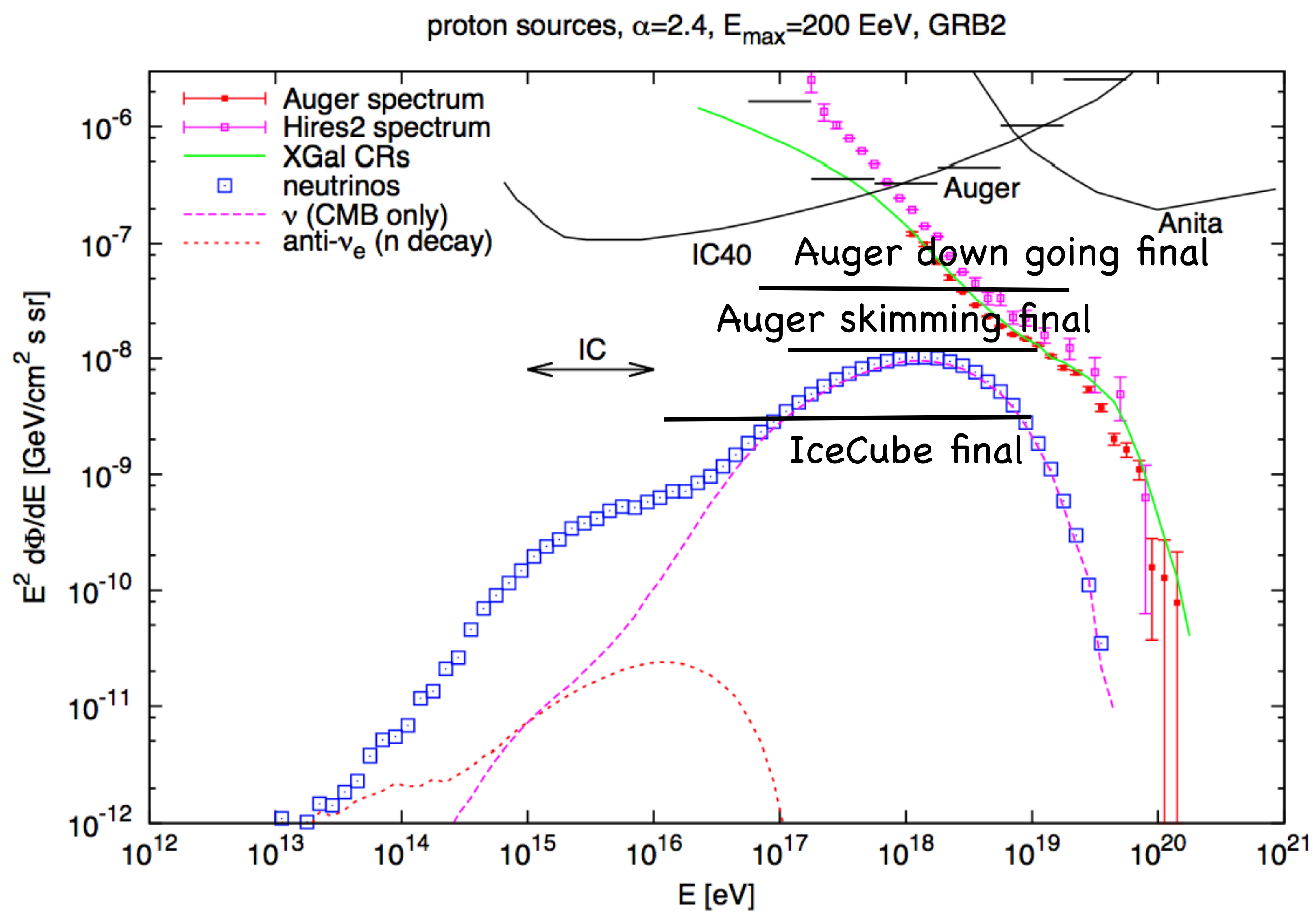


Figure 1. Proton 'dip' scenario with source spectral index $\alpha = 2.4$ and $E_{\rm max} = 200\,{\rm EeV}$. Indicated are the propagated proton spectrum and the resulting all flavor neutrino fluxes (obtained with CR-Propa). We also show separately the neutrino backgrounds due to interactions with CMB alone as well as those resulting from n decays. The CR flux measured by Auger and Hires and the neutrino limits from IceCube, Auger and Anita are displayed. We also indicate the energy range and approximate flux level suggested by the two observed IceCube events.

Roulet, Sigl, van Vliet, Mollerach, JCAP 1301, 028

IceCube events are unlikely to be produced during UHECR propagation ("cosmogenic neutrinos")

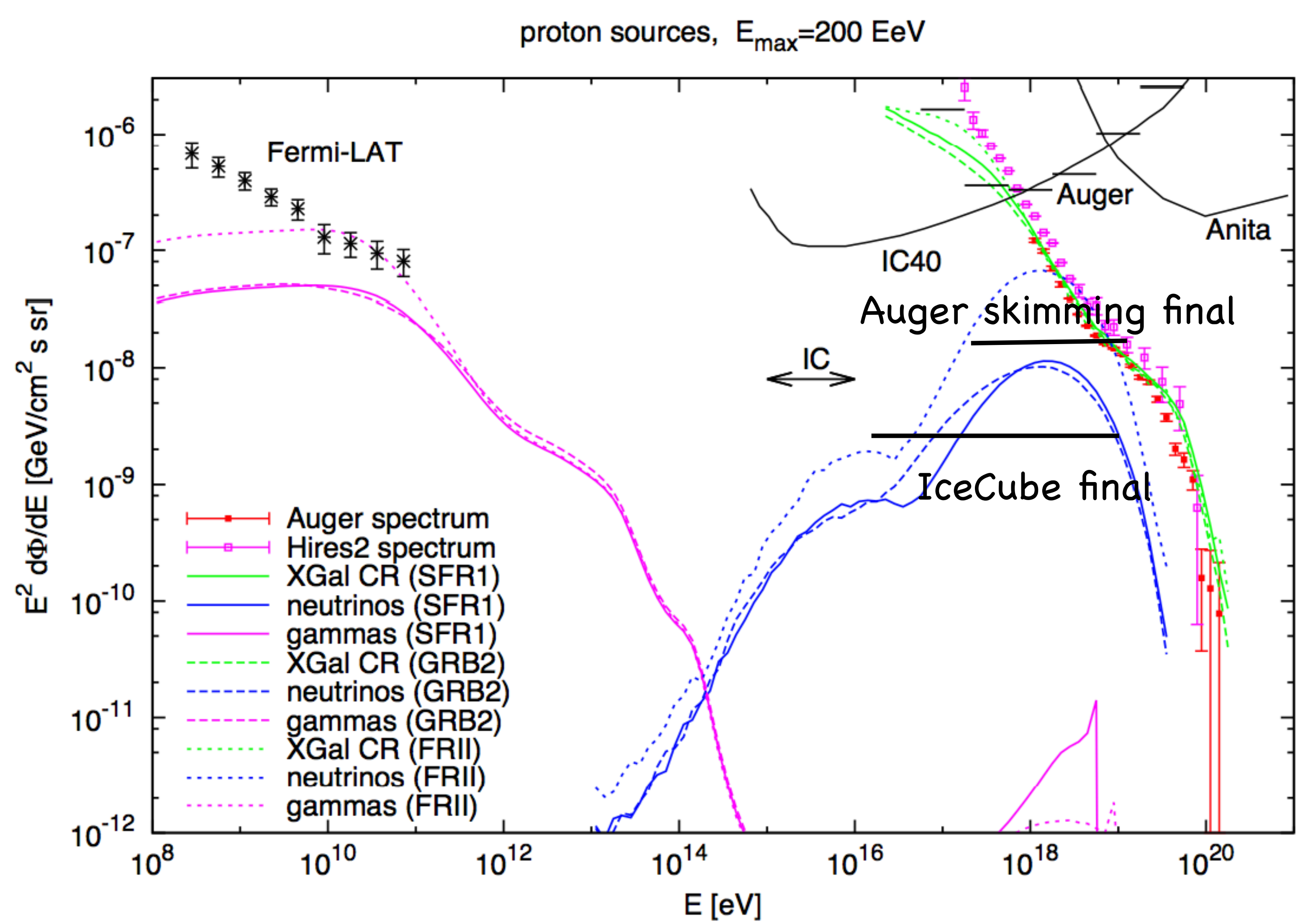


Figure 2. Proton scenario with $E_{\rm max} = 200\,$EeV for different source evolution models (SFR1, GRB2 and FRII). The source spectral index is $\alpha = 2.4$ for the SFR1 and GRB2 models, while $\alpha = 2.2$ for the FRII model. Indicated are the propagated proton spectrum, the resulting (all flavor) neutrino and the photon fluxes. The photon background measured by Fermi-LAT [10] is indicated, besides the CR spectra and ν bounds included in figure 1.

Roulet, Sigl, van Vliet, Mollerach, JCAP 1301, 028

IceCube events are unlikely to be produced during UHECR propagation ("cosmogenic neutrinos")

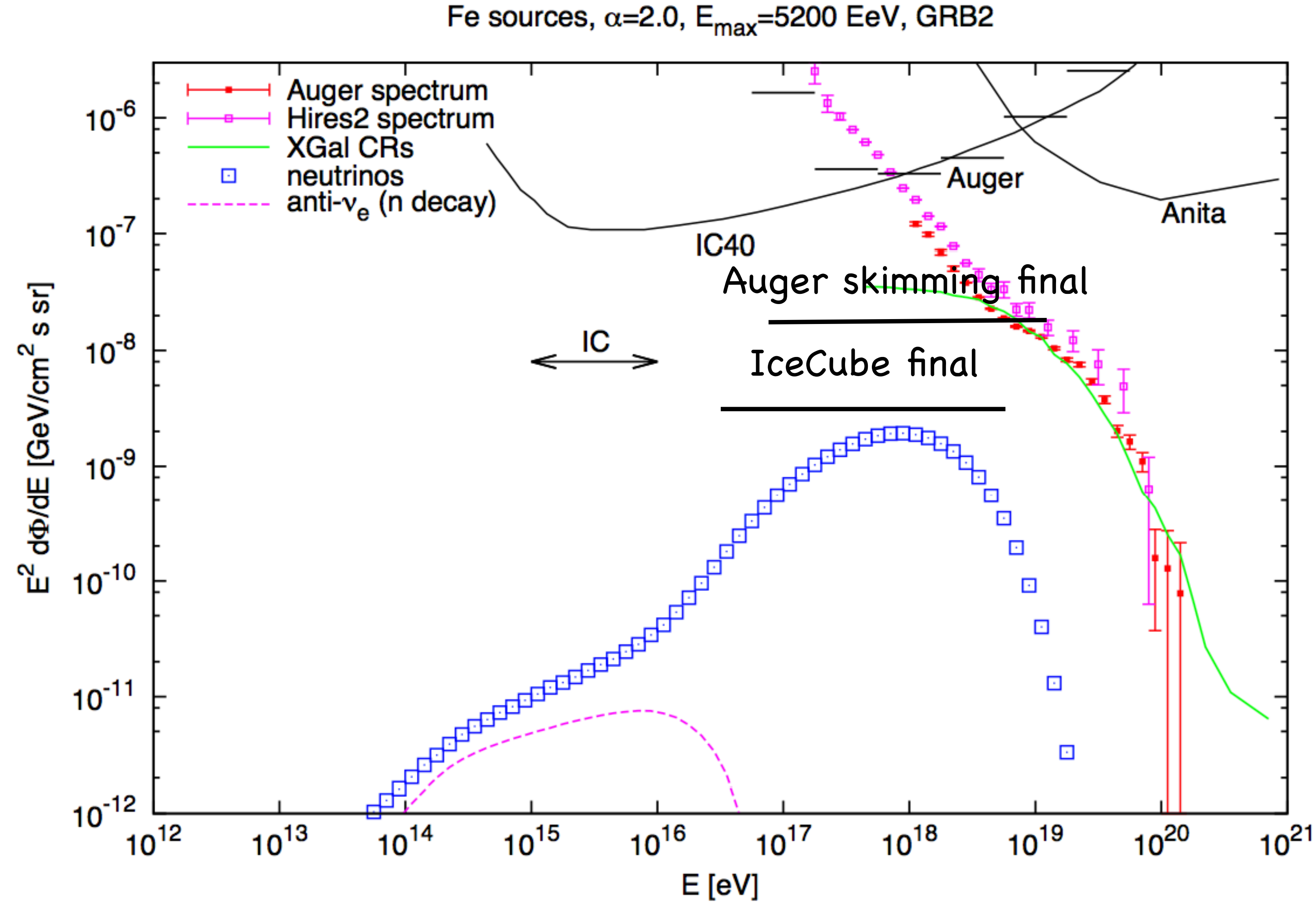


Figure 3. Extragalactic Fe scenario with source spectral index $\alpha = 2.0$ and $E_{\mathrm{max}} = 5200\,\mathrm{EeV}$. Indicated are the propagated CR spectrum and the resulting (all flavor) neutrino fluxes, as well as the neutrino background due to n-decays alone.

Roulet, Sigl, van Vliet, Mollerach, JCAP 1301, 028

IceCube events are unlikely to be produced during UHECR propagation ("cosmogenic neutrinos")

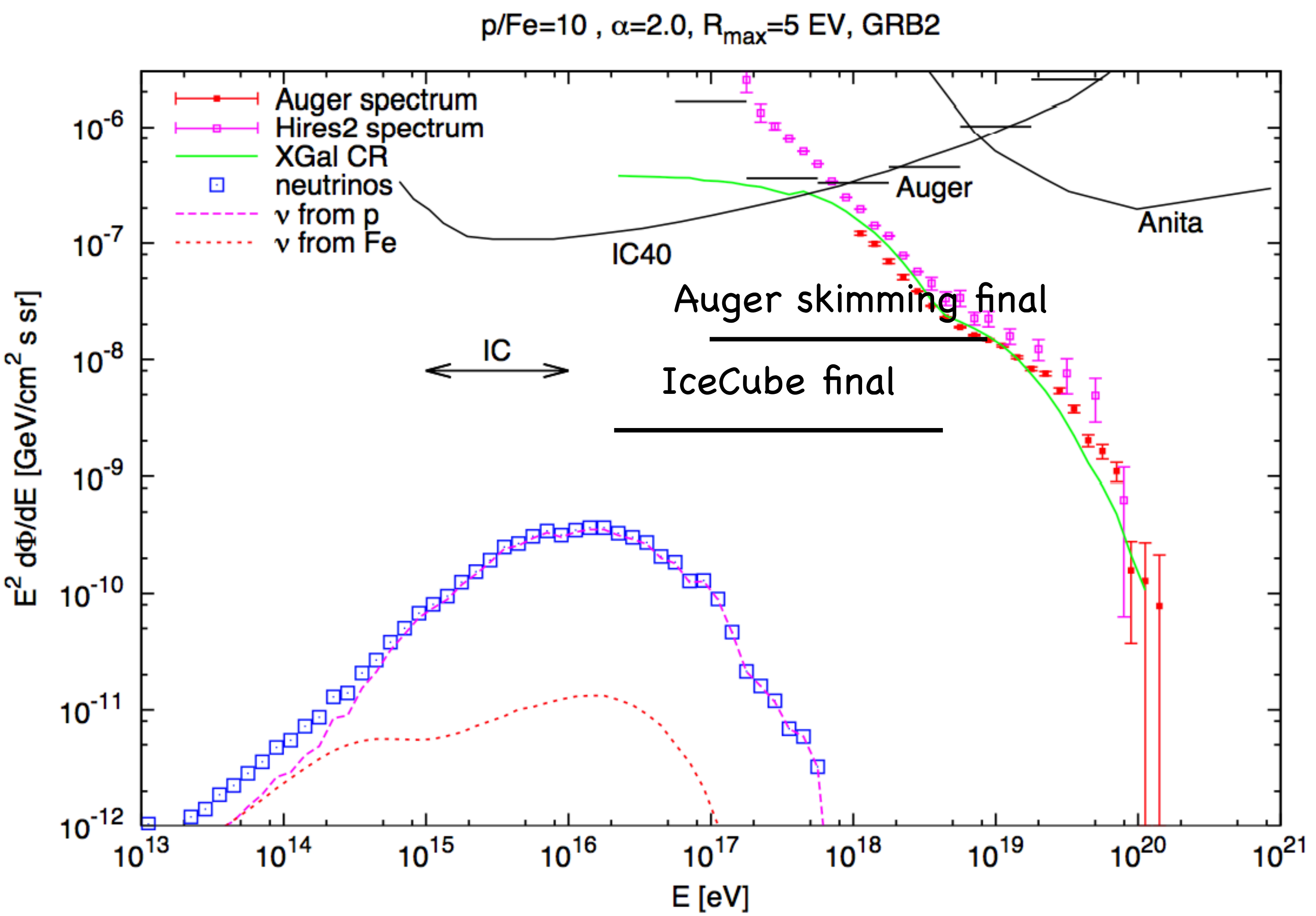


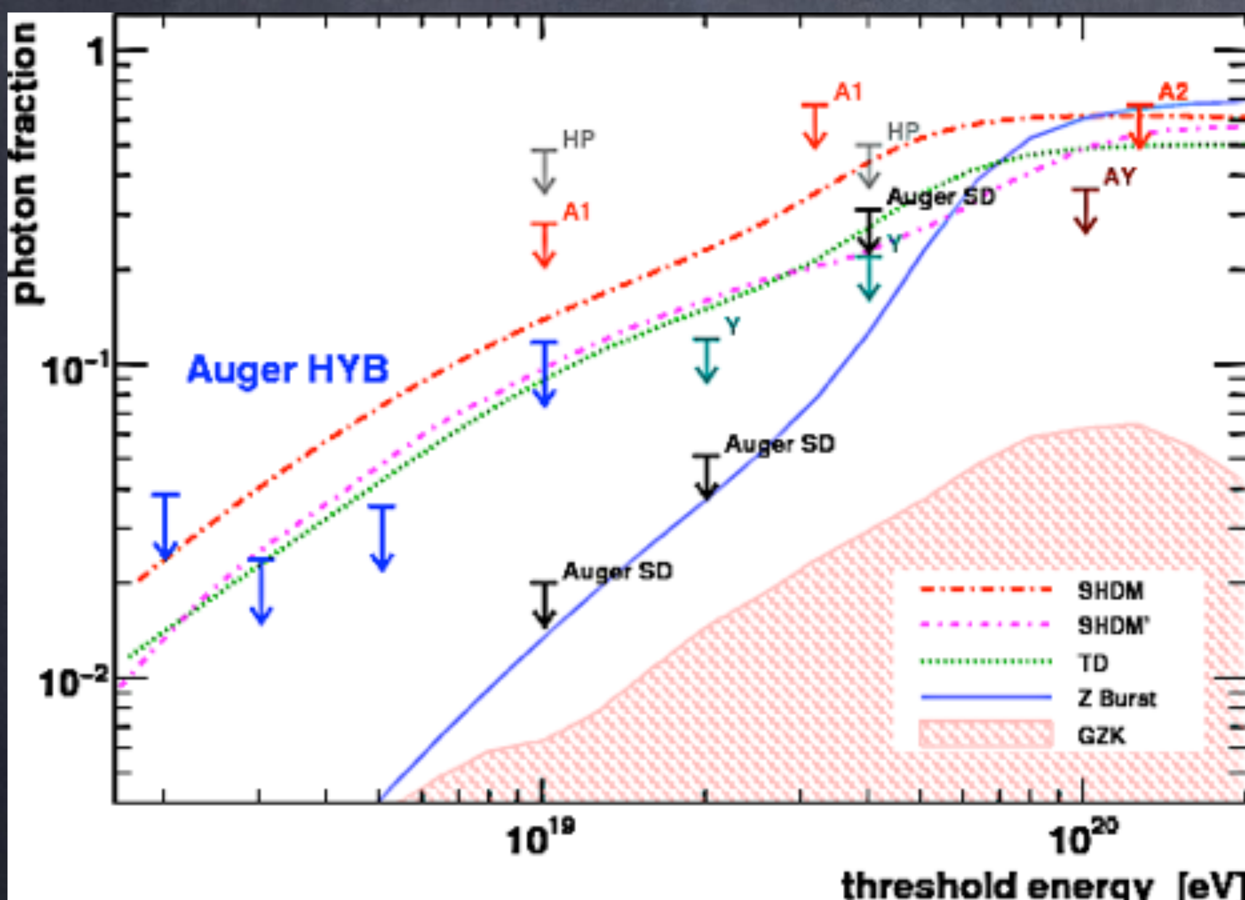
Figure 4. Mixed composition (p-Fe) scenario with source spectral index $\alpha = 2.0$ and $E_{\max} = 5\,Z\,\mathrm{EeV}$. Indicated are the propagated CR spectrum, the resulting (all flavor) neutrino fluxes and the separate contributions from p and Fe primaries.

Roulet, Sigl, van Vliet, Mollerach, JCAP 1301, 028

Lorentz Symmetry Violation in the Electromagnetic Sector

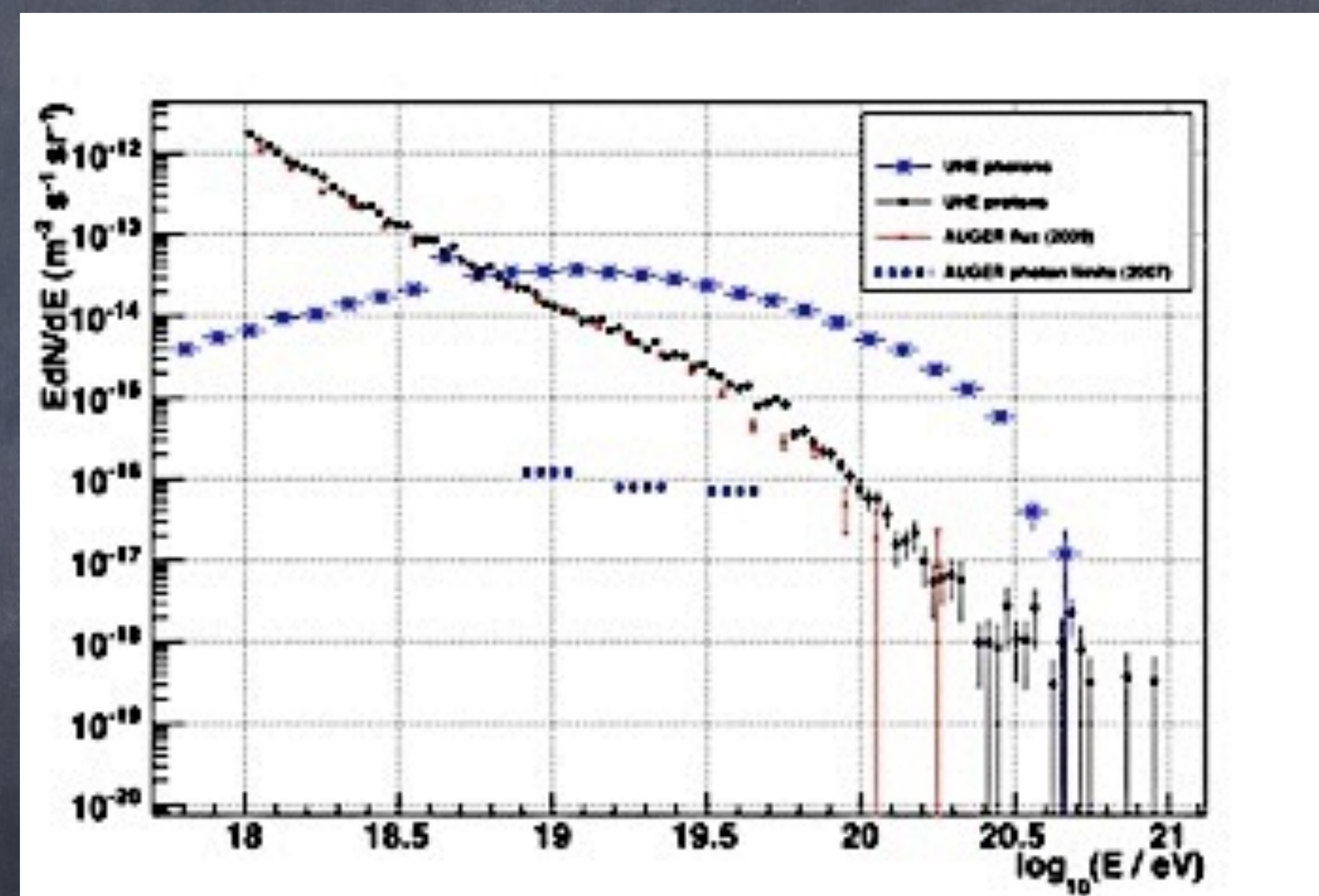
The idea:

Experimental upper limits on UHE photon fraction



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

Contradict predictions if pair production is absent



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

Lorentz Symmetry Violation in the Photon Sector

For a photon dispersion relation

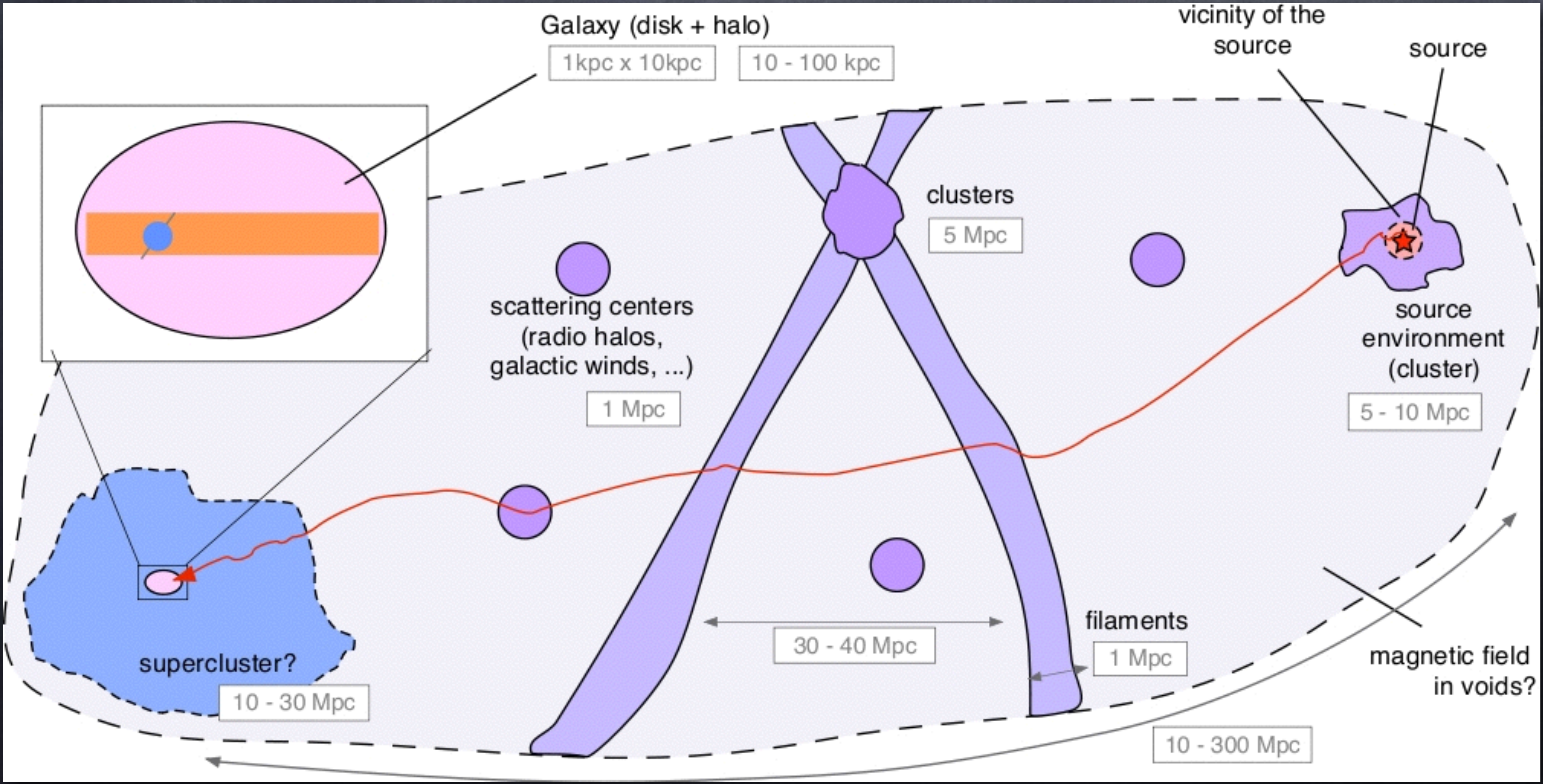
$$\omega_\pm^2 = k^2 + \xi_n^\pm k^2 \left(\frac{k}{M_{\rm Pl}}\right)^n \,, n \geq 1 \,,$$

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:**

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

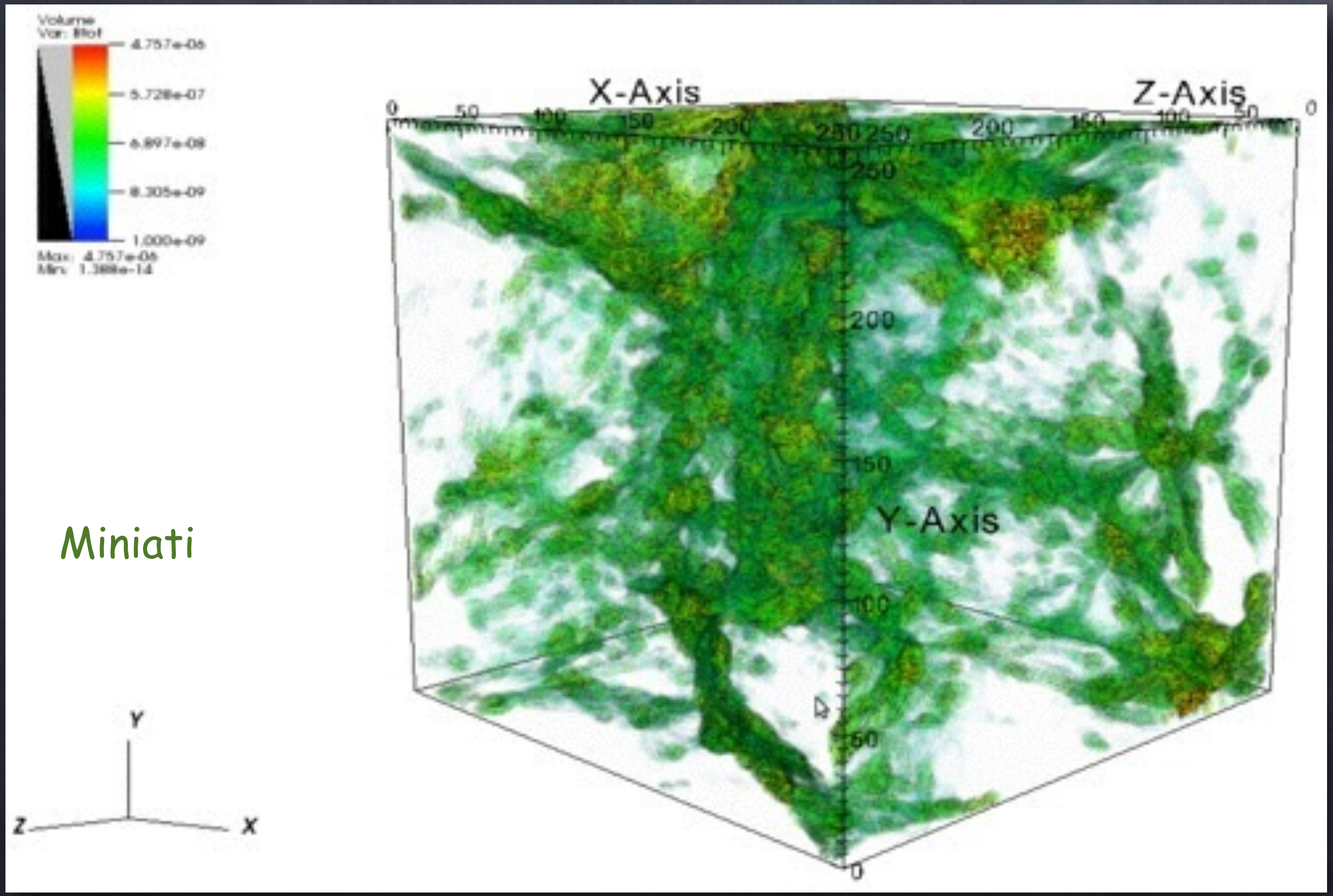
Such strong limits may indicate that Lorentz invariance violations are completely absent !

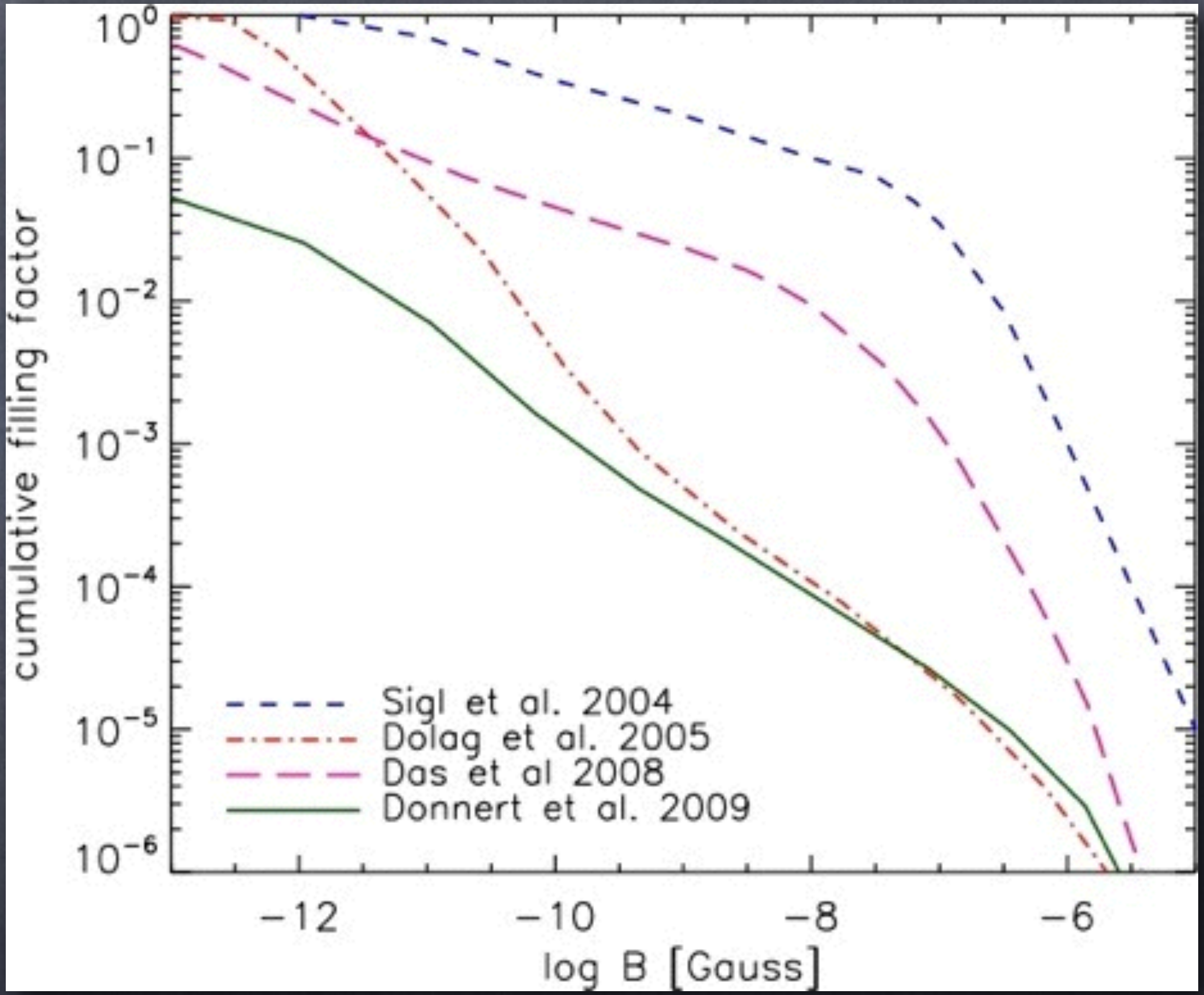
3-Dimensional Effects in Propagation



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

Structured Extragalactic Magnetic Fields

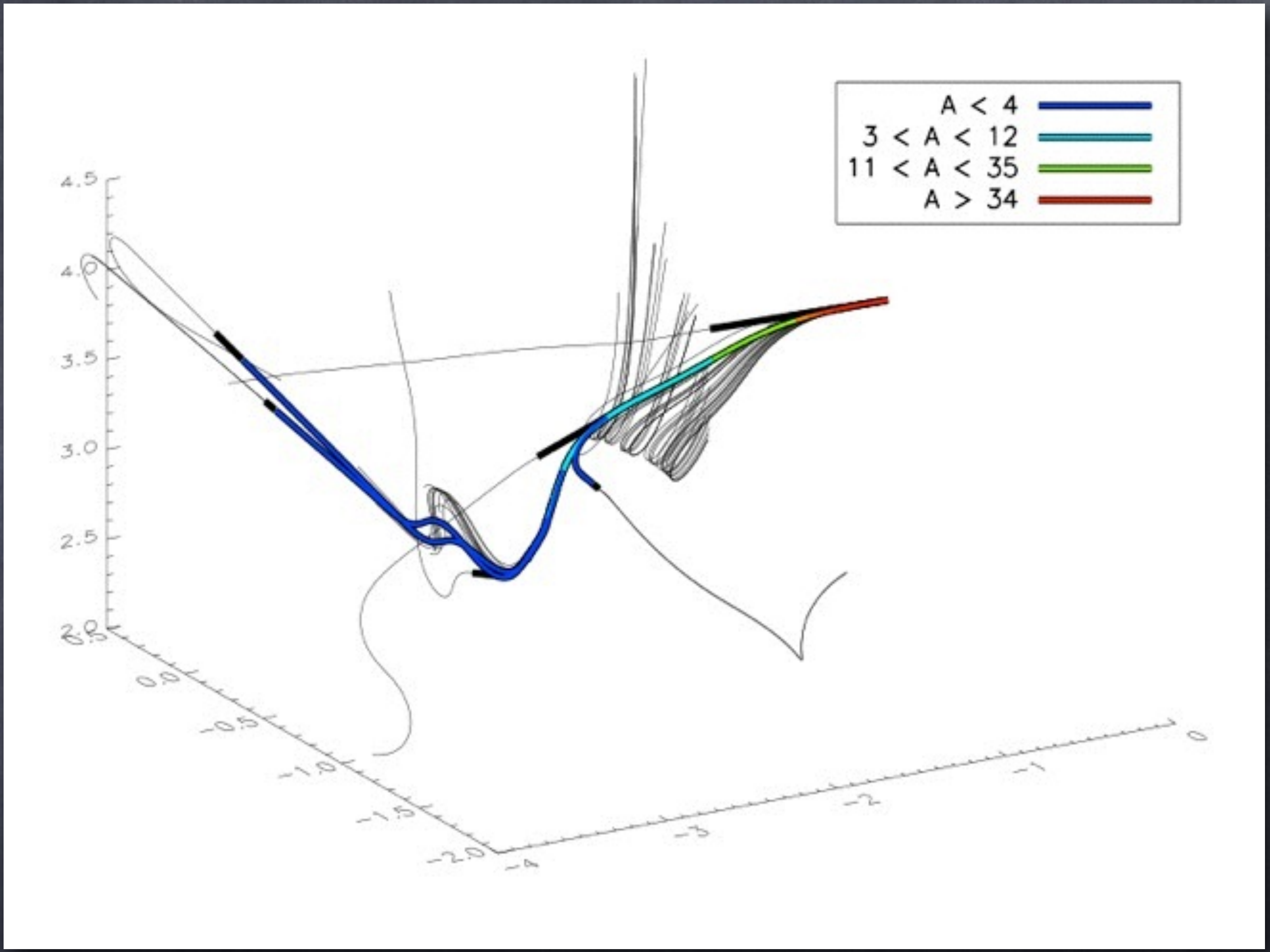




Kotera, Olinto, Ann.Rev.Astron.Astrophys. 49 (2011) 119

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

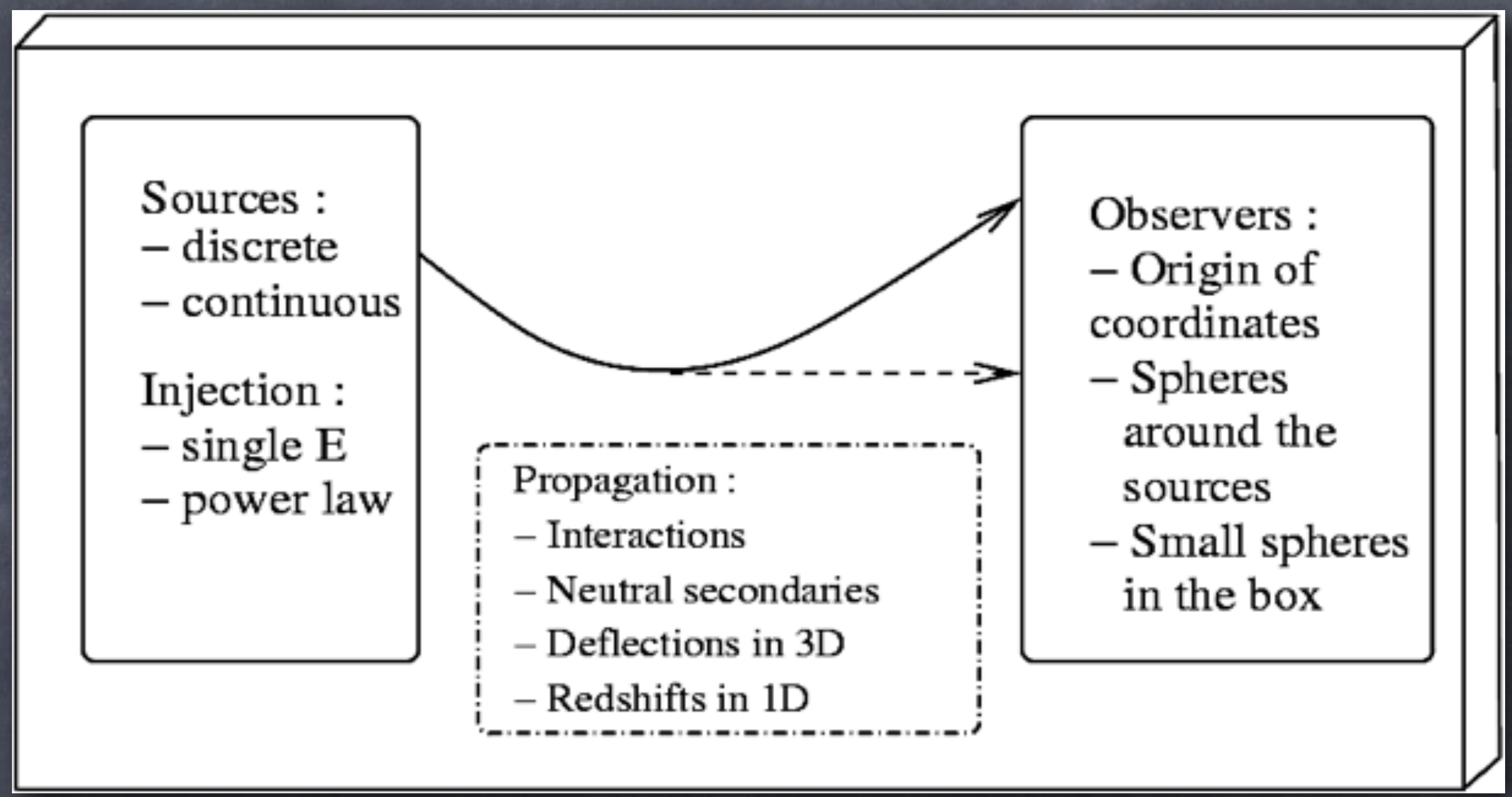
Extragalactic iron propagation produces nuclear cascades in structured magnetic fields:



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 2.0/3.0

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



Version 1.4: Eric Armengaud, Tristan Beau, Günter Sigl, Francesco Miniati, Astropart.Phys.28 (2007) 463.

Version 2.0 at https://crpropa.desy.de/Main_Page

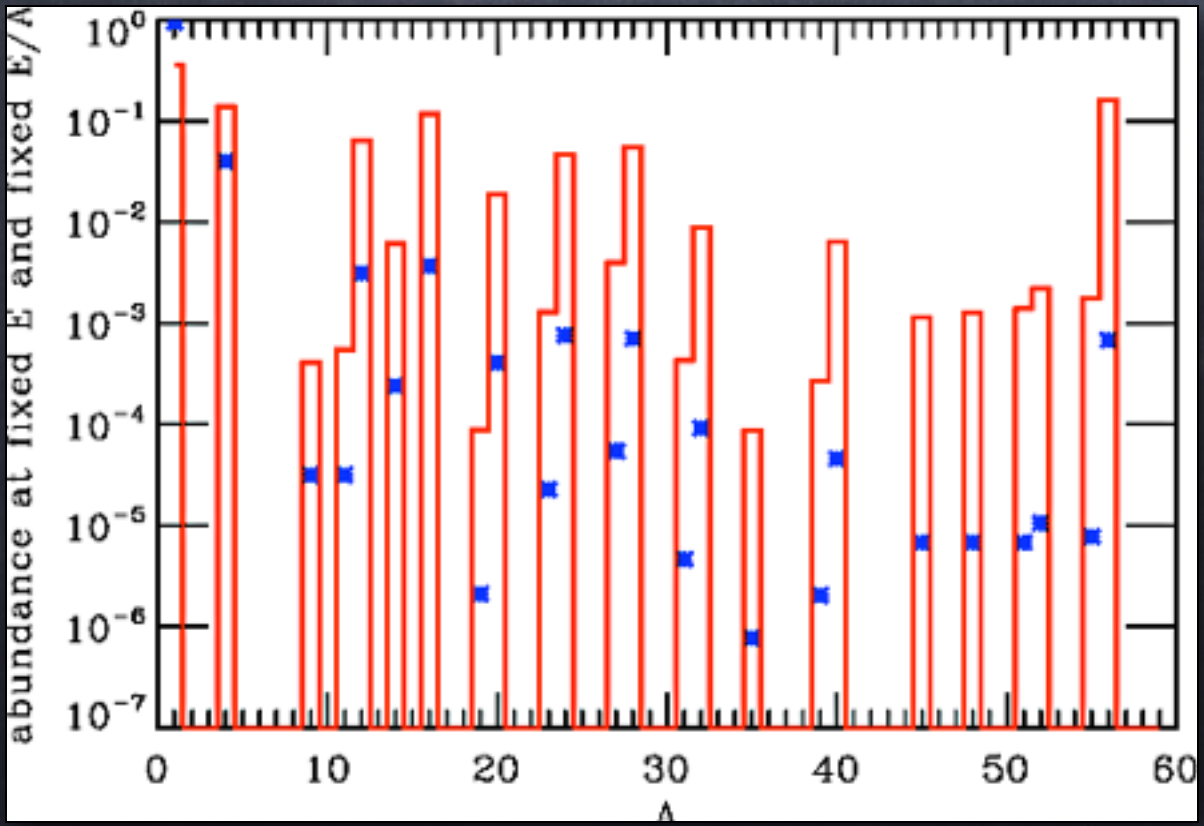
Now including: Jörg Kulbartz, Luca Maccione, Nils Nierstenhoefer, Karl-Heinz Kampert, Peter Schiffer, Arjen van Vliet arXiv:1206.3132, Astroparticle Physics

Mixed chemical compositions

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

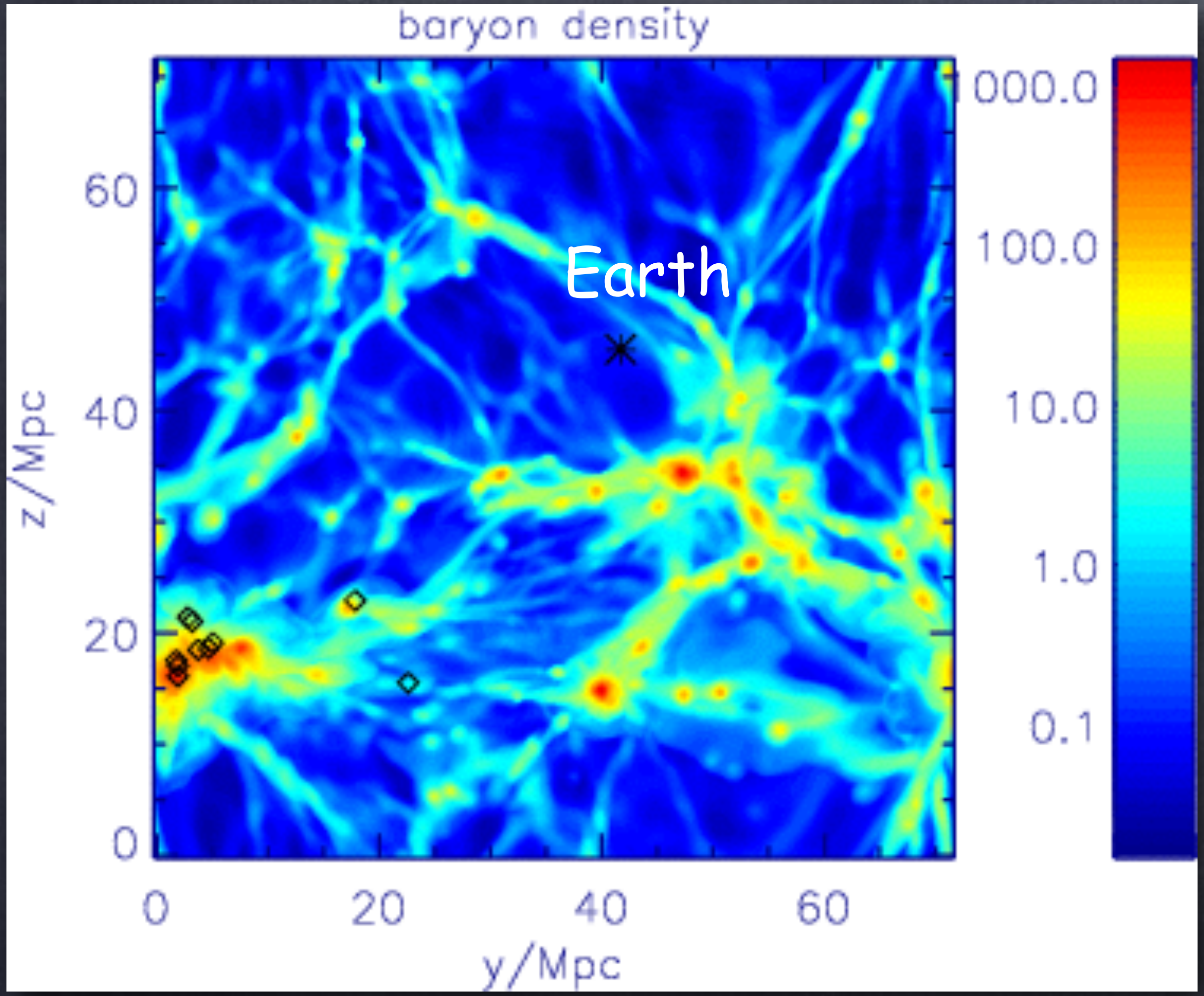
$$\frac{dn_A}{dE}(E) = N x_A \, A^{\alpha-1} \, E^{-\alpha} g(E)$$

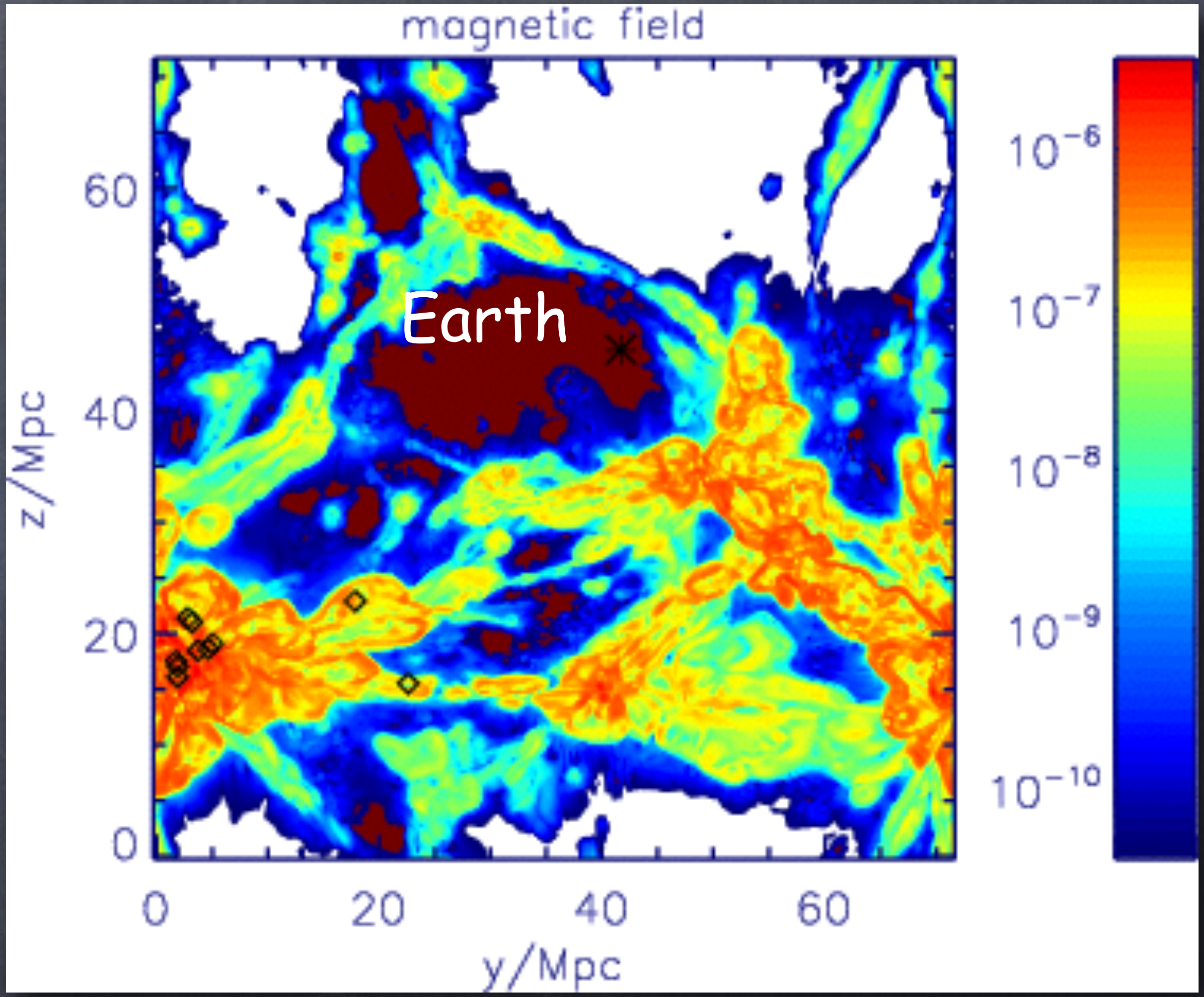
where x_A is the abundance at given energy per nucleon E/A and g(E) is the cut-off shape.



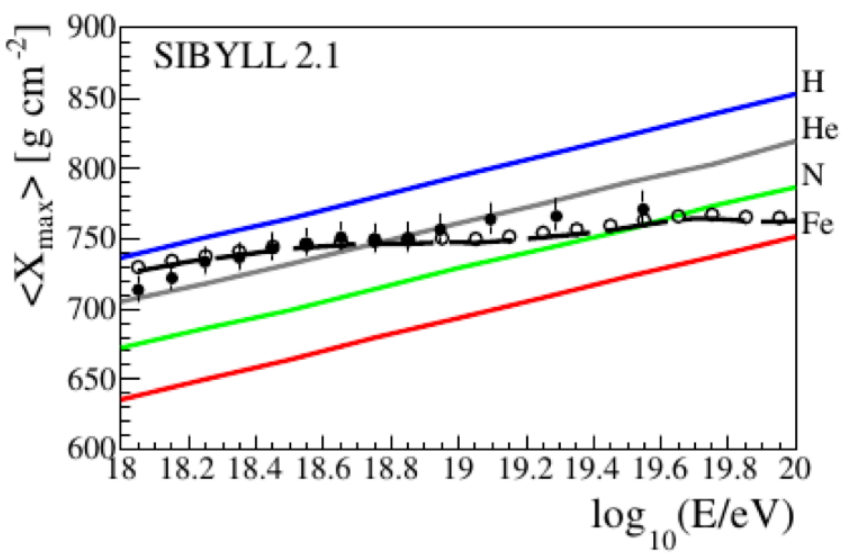
Composition at given E/A (blue) following elemental abundances in the Galaxy
Composition at given E for an $E^{-2.6}$ injection spectrum (red).

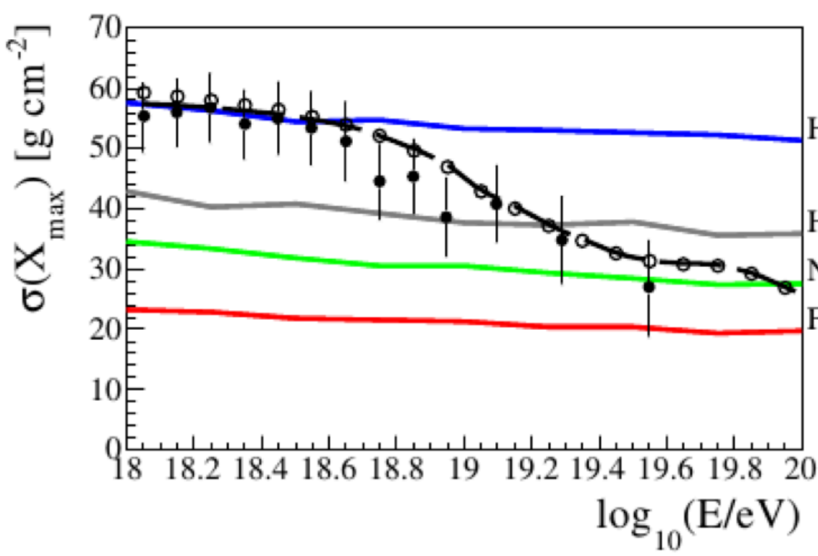
Discrete Sources in nearby large scale structure

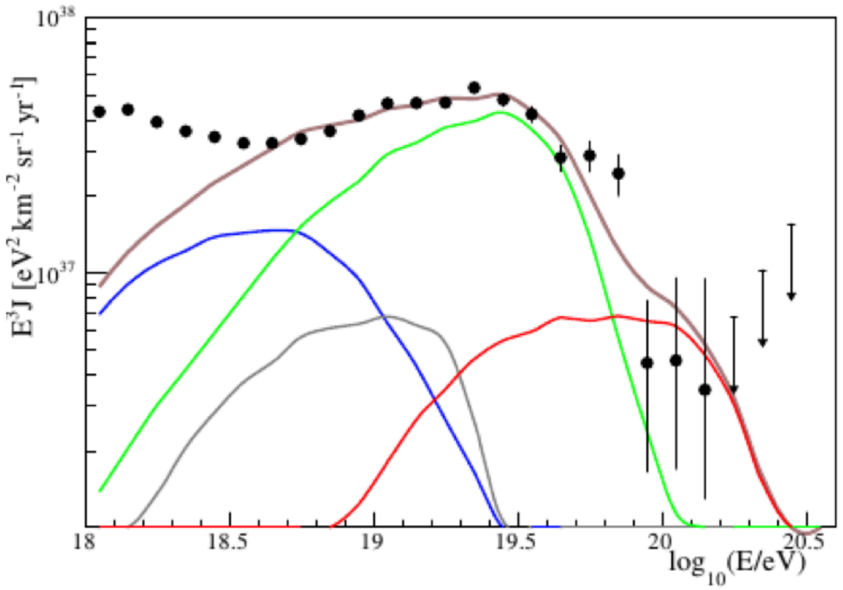


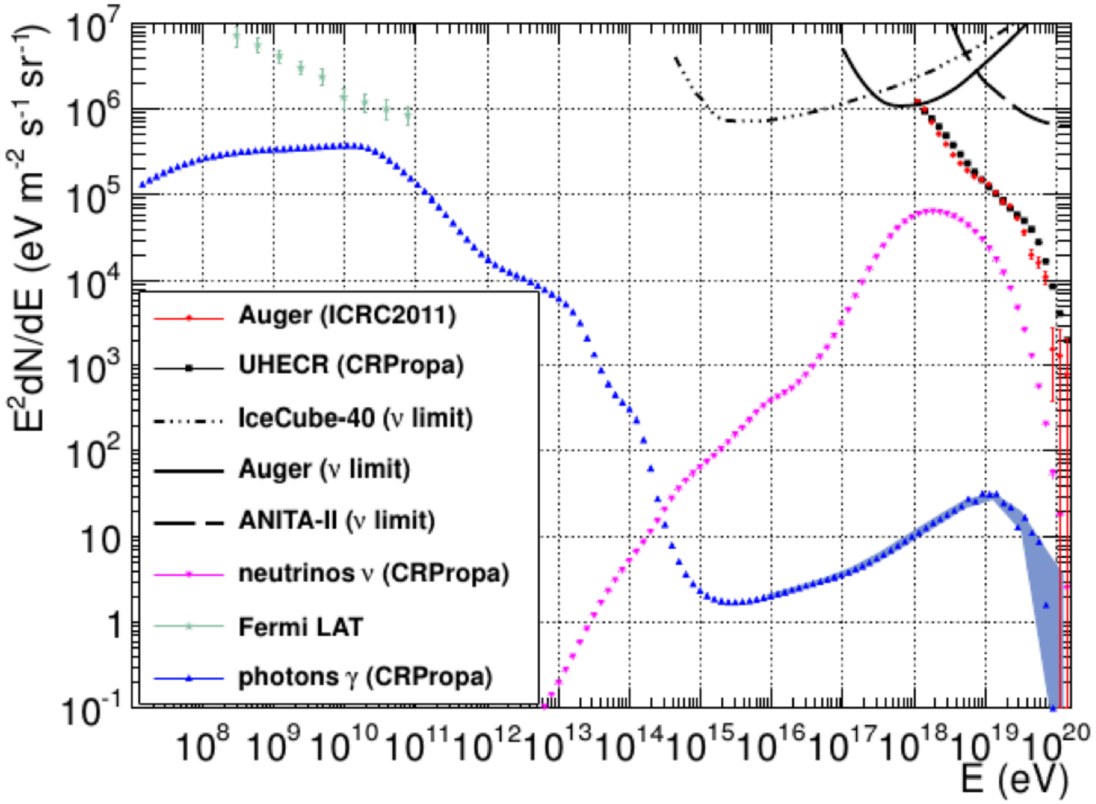


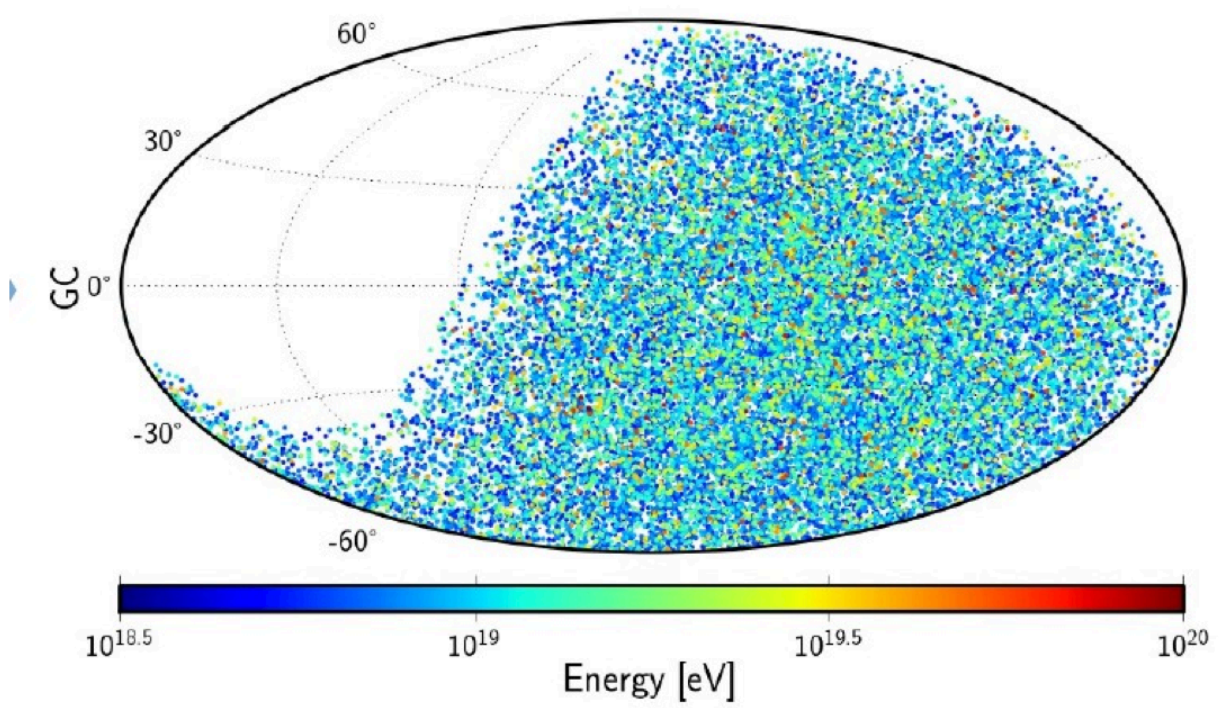
Building Benchmark Scenarios



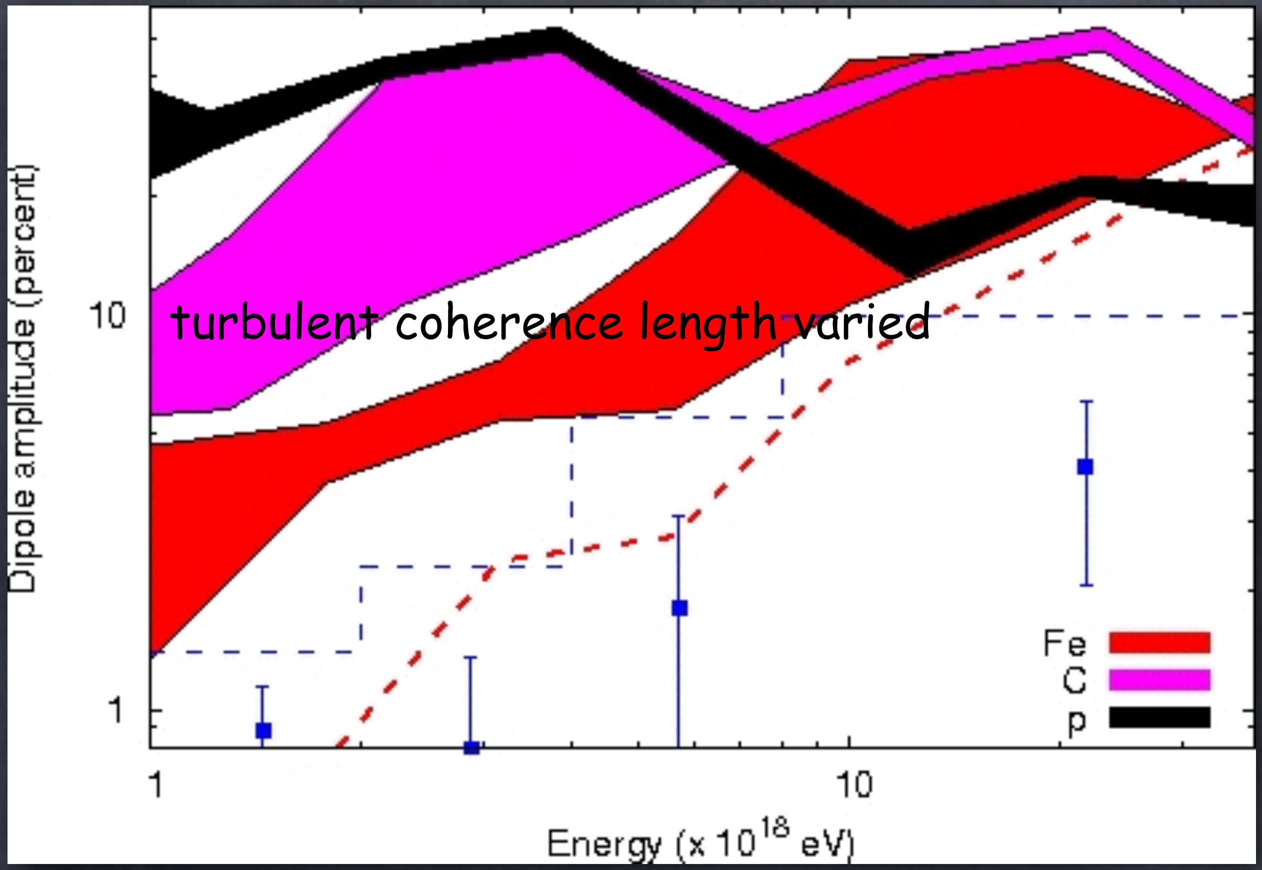


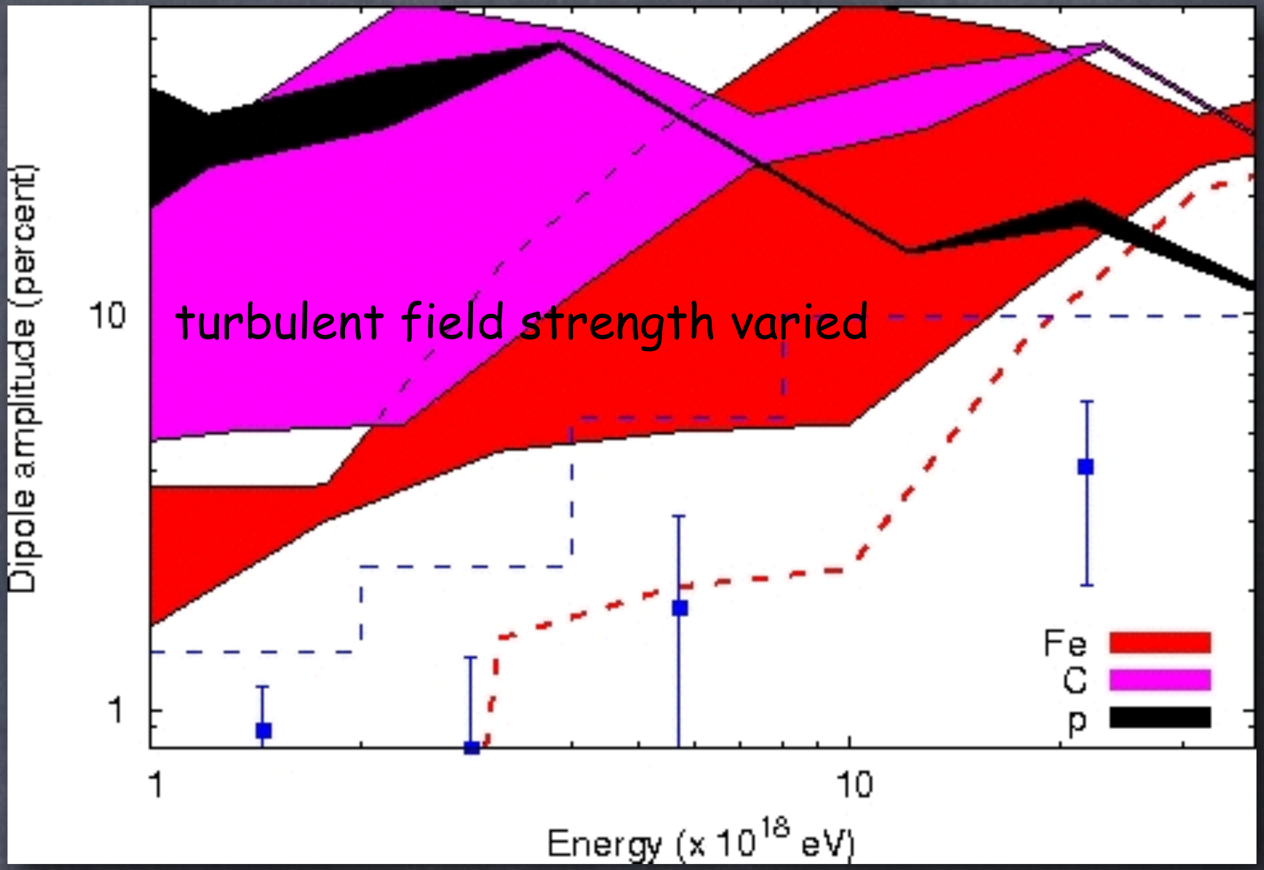






Composition and the Transition Galactic/Extragalactic Cosmic Rays





Giacinti, Kachelriess, Semikoz, Sigl, arXiv:1112.5599 and Pierre Auger Collaboration, Astrophys.J. 762 (2012) L13

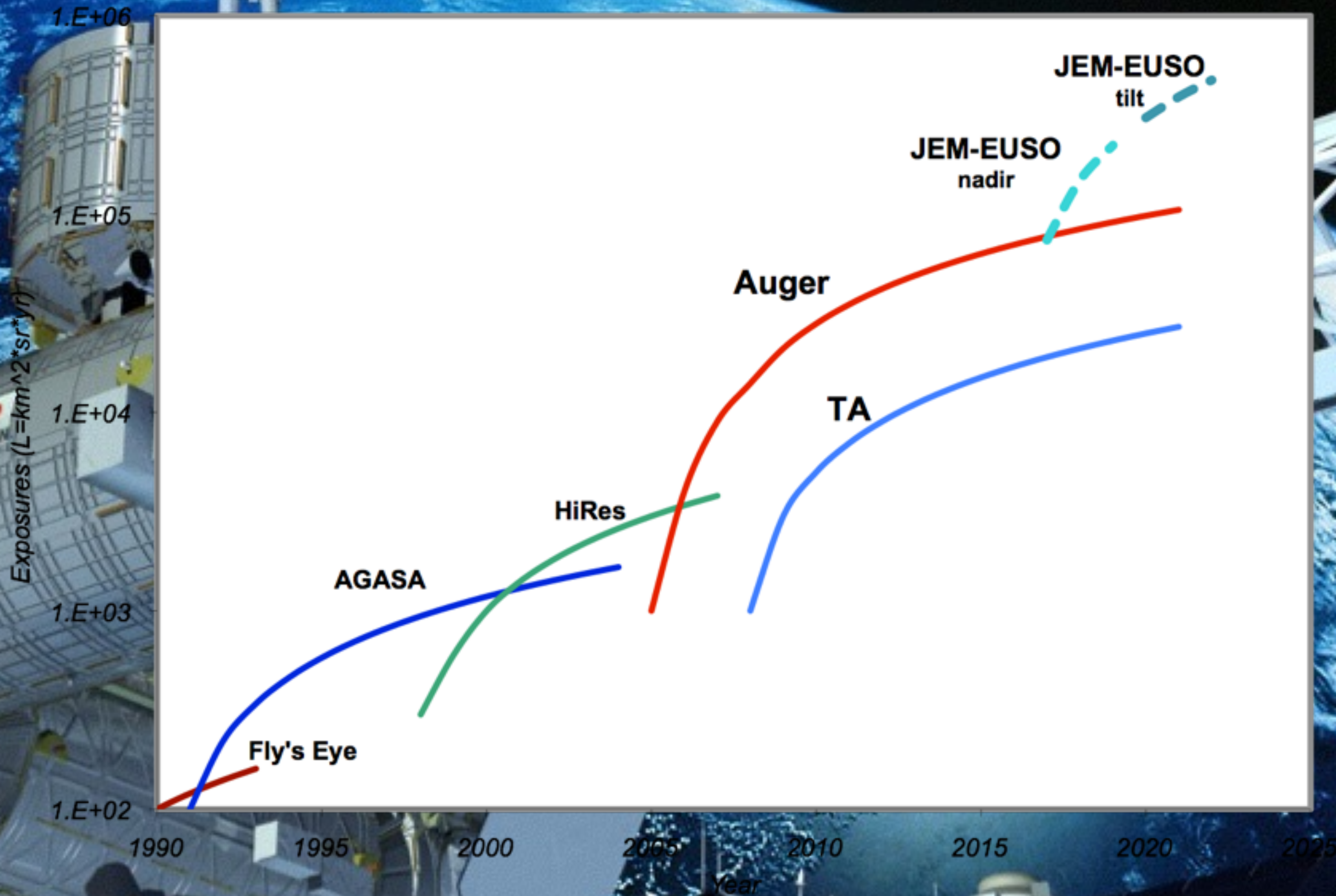
Light Galactic Nuclei produce too much anisotropy above $\simeq 10^{18}$ eV. This implies:

1.) if composition around 10^{18} eV is light => probably extragalactic (and ankle may be due to pair production by protons)
2.) if composition around 10^{18} eV is heavy => transition could be at the ankle if Galactic nuclei are produced by sufficiently frequent transients, e.g. magnetars

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

Relatively hard injection spectra and low maximal rigidities of few times 10^{18} eV seem to be favored

The future: JEM-EUSO



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