The Enigma of the Highest Energy Particles in the Universe

1. Observations
2. Anisotropies and Mass Composition
3. Secondary Neutrinos
4. Tests of Lorentz Symmetry
5. Cosmic Rays and the Structured Universe

DFG Deutsche Forschungsgemeinschaft

PROJEKTTRÄGER FÜR DAS Bundesministerium für Bildung und Forschung

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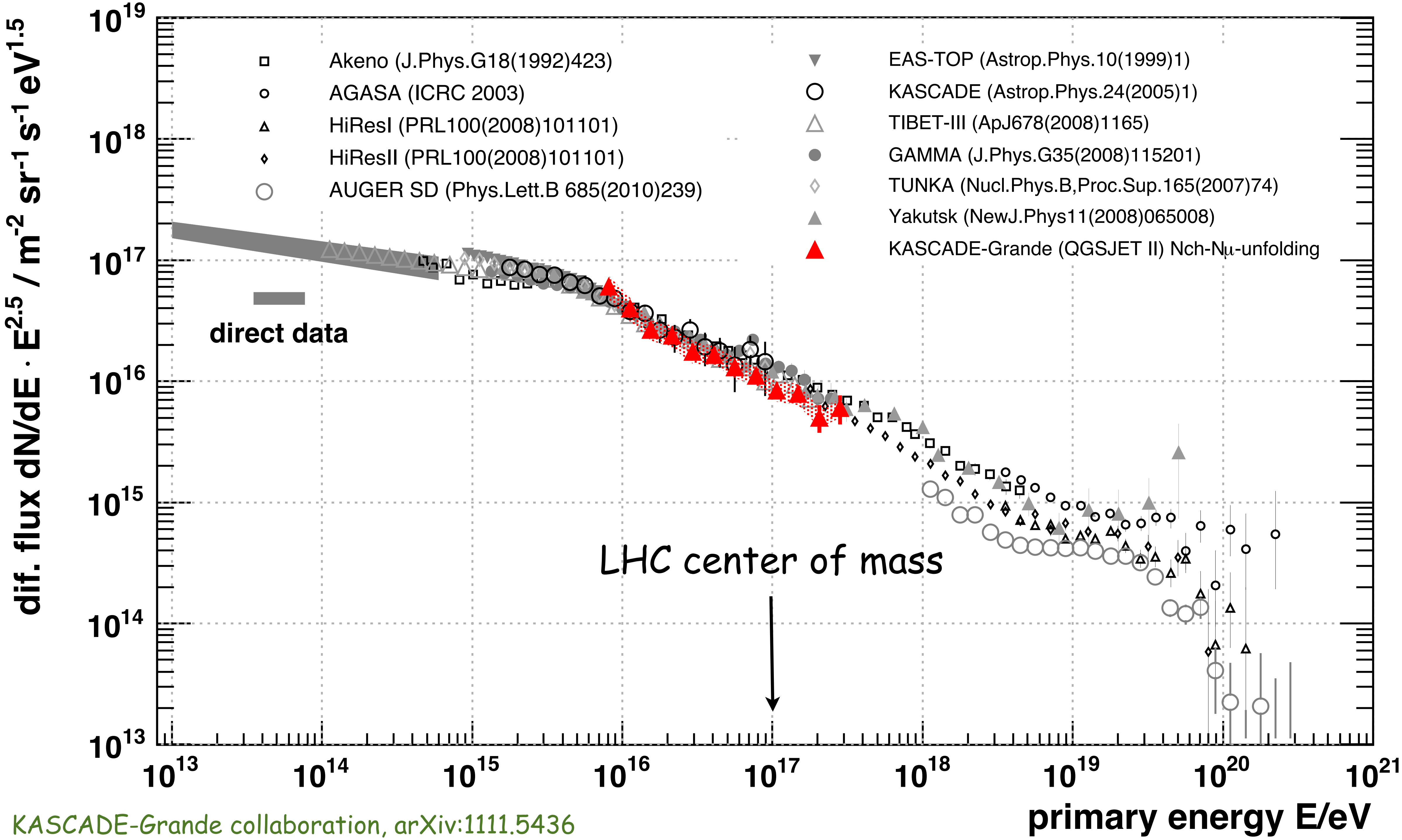
UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

The All Particle Cosmic Ray Spectrum

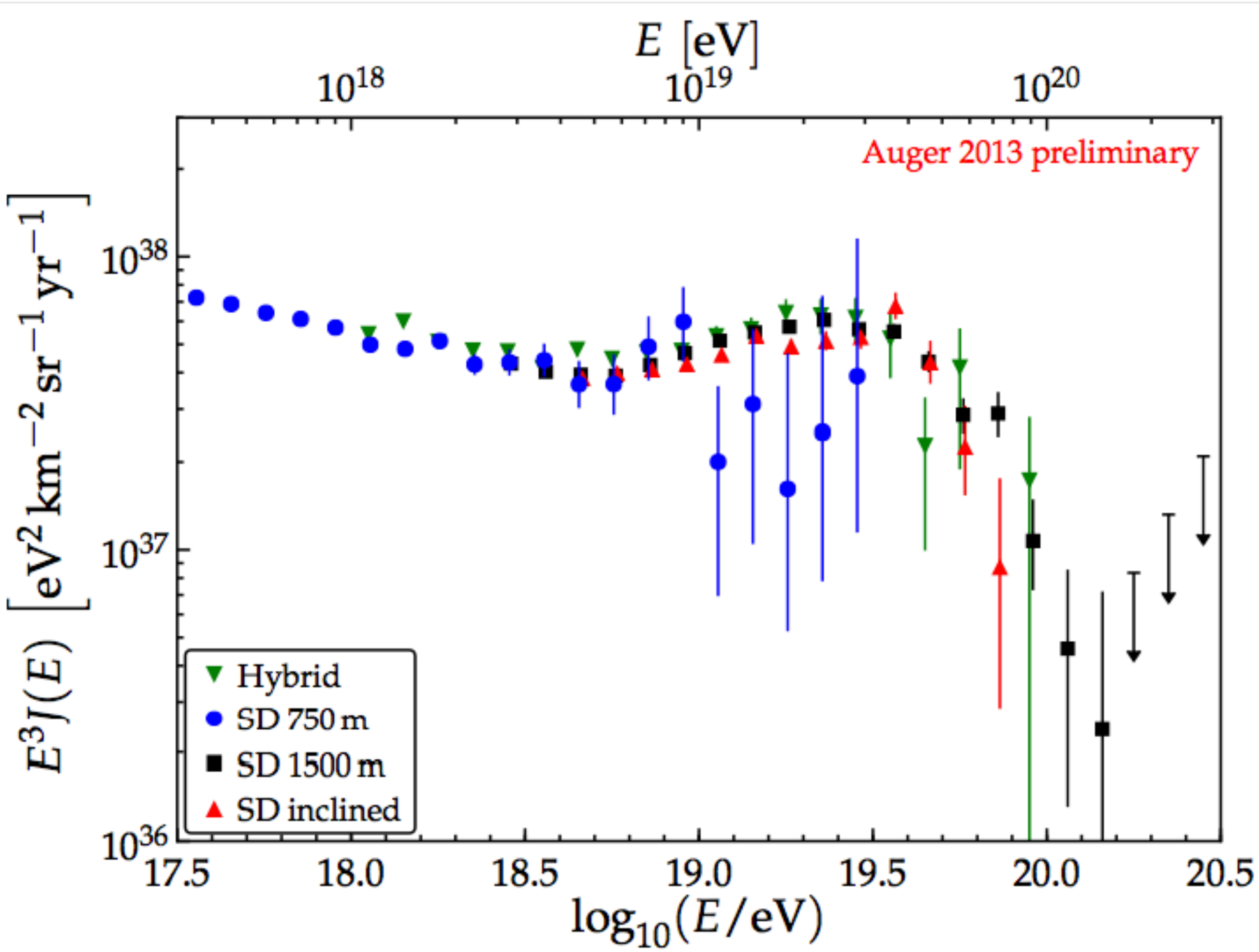


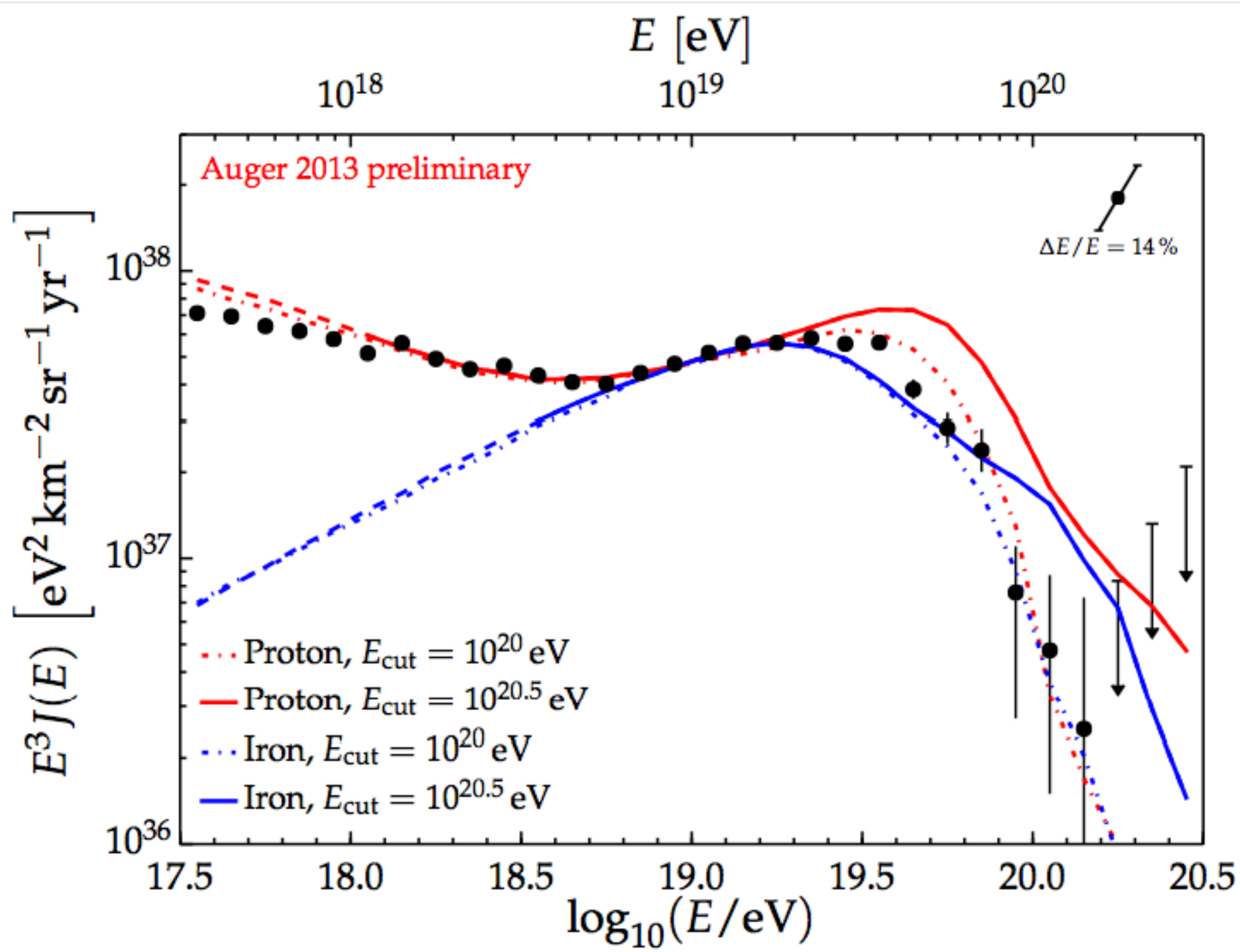
KASCADE-Grande collaboration, arXiv:1111.5436

Pierre Auger Spectra

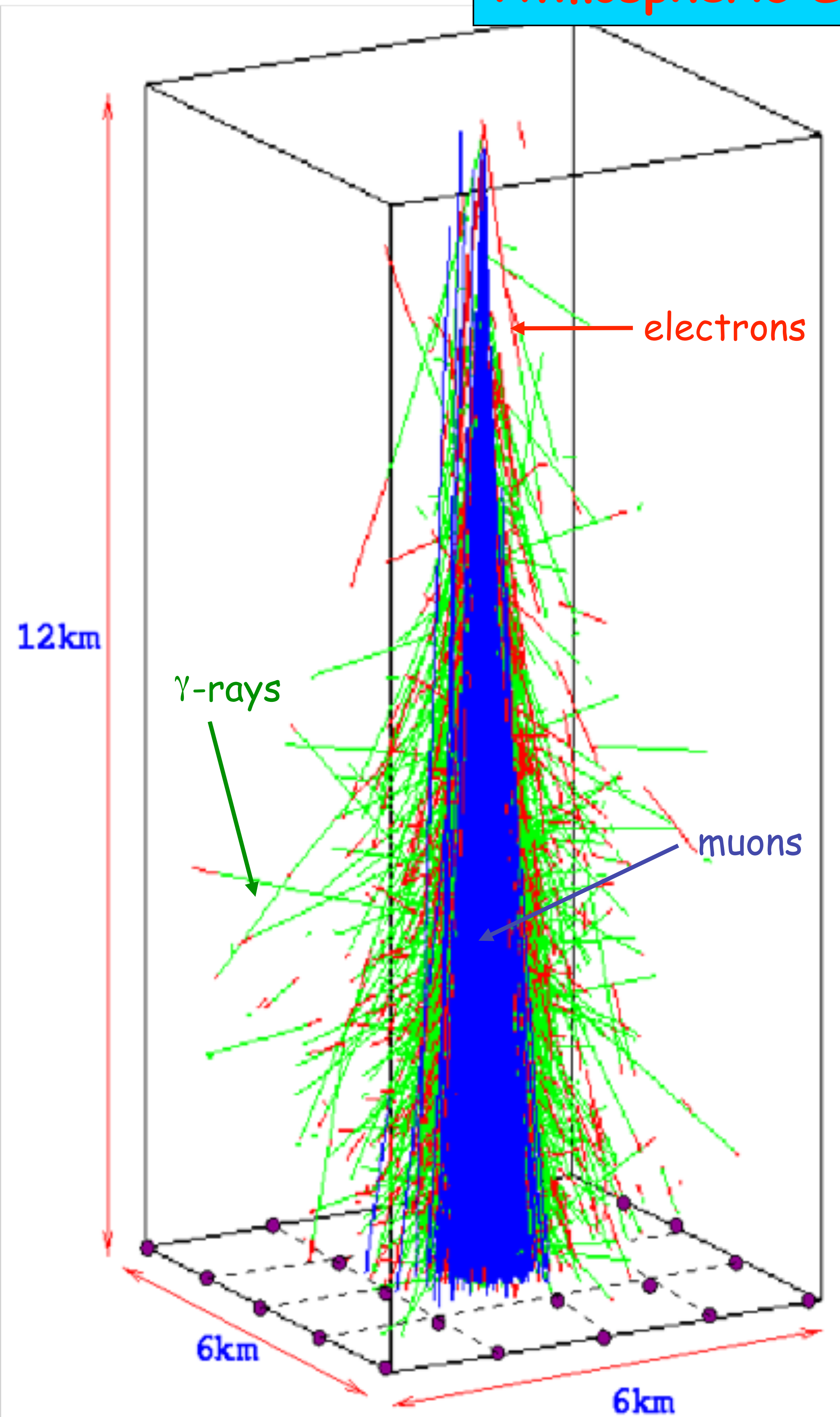
Auger exposure = 31440 km^2 sr yr, 8259 events above 10^{19} eV up to December 2012

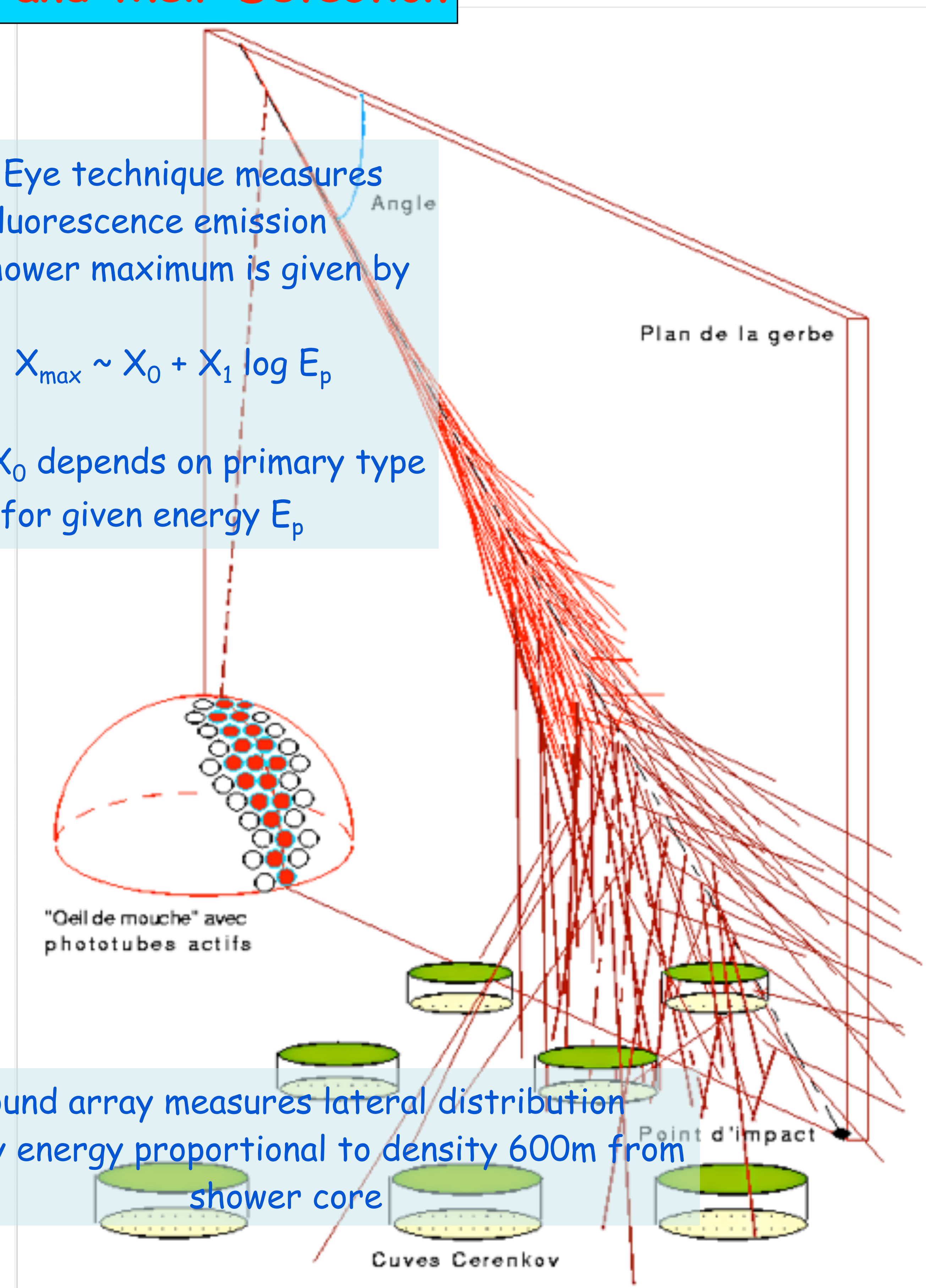
Pierre Auger Collaboration, PRL 101, 061101 (2008)
and Phys.Lett.B 685 (2010) 239
and ICRC 2013, arXiv:1307.5059, higlight talk Letessier-Selvon





Atmospheric Showers and their Detection





Fly's Eye technique measures fluorescence emission

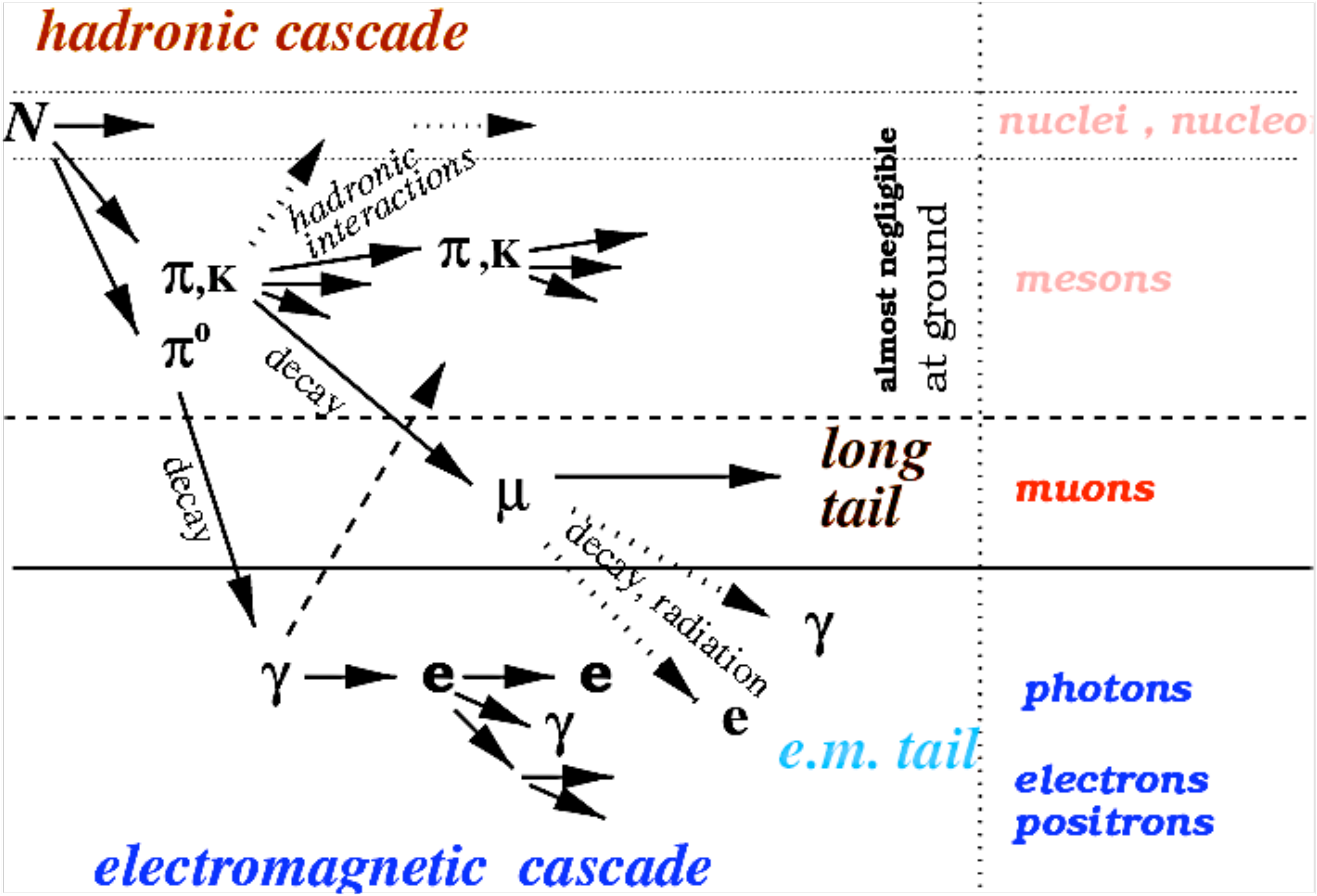
The shower maximum is given by

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

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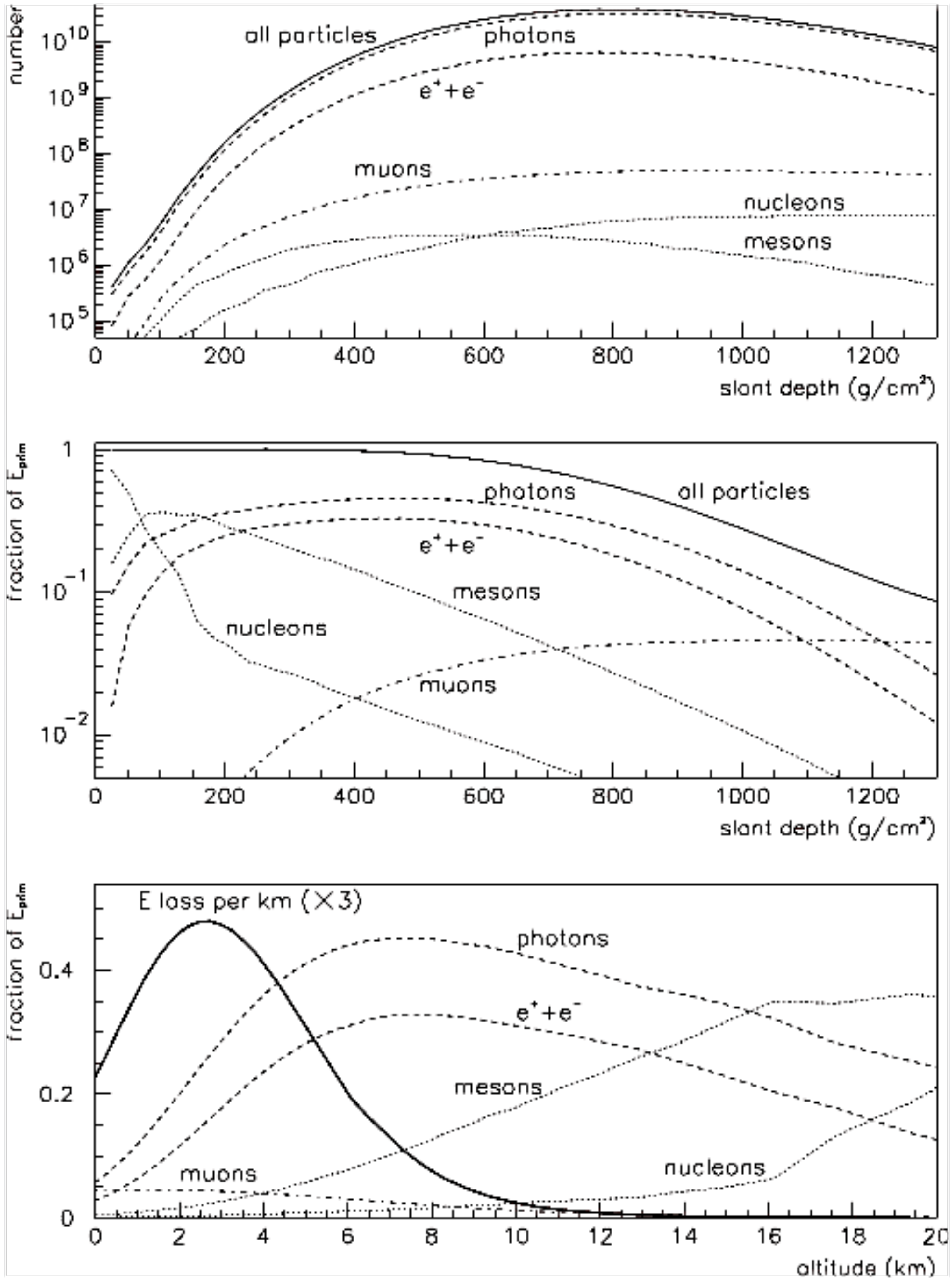
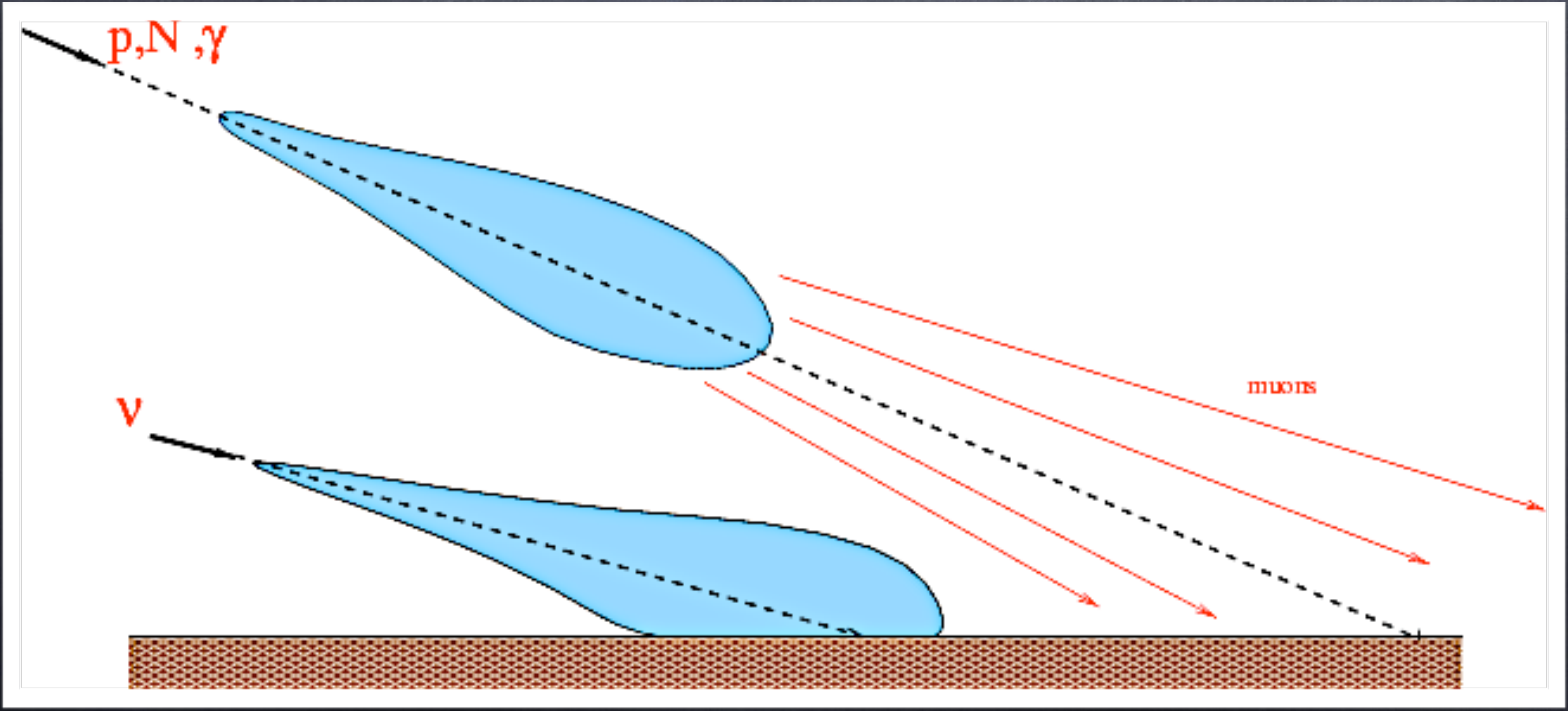
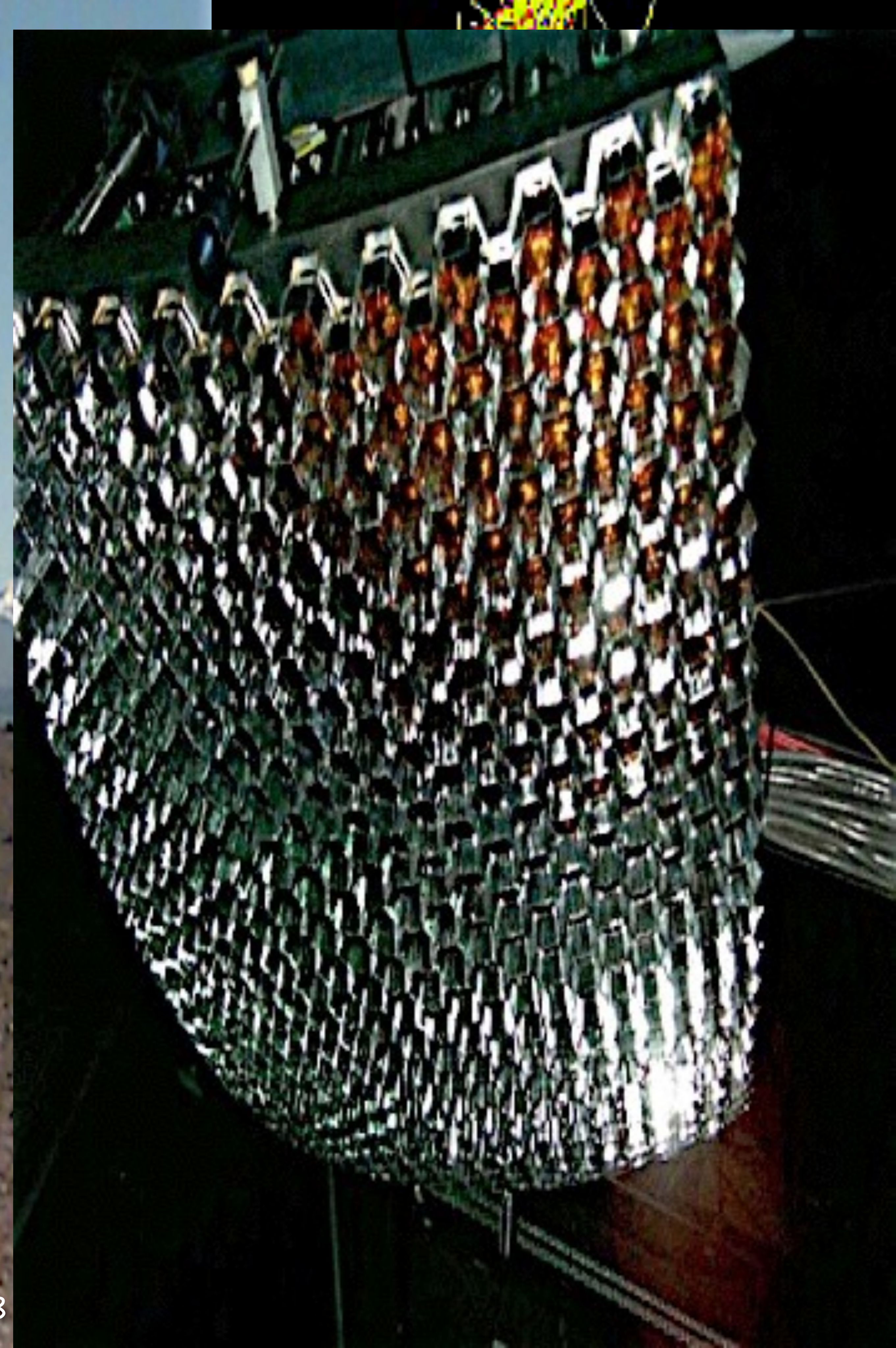
e
e
γ
e.m. tail
photons
electrons
positrons
electromagnetic cascade



number
all particles
photons
e⁺+e⁻
muons
nucleons
mesons
slant depth (g/cm²)
fraction of E_prim
all particles
photons
e⁺+e⁻
mesons
nucleons
muons
slant depth (g/cm²)
fraction of E_prim
E loss per km (×3)
photons
e⁺+e⁻
mesons
nucleons
muons
altitude (km)

Cosmic ray versus neutrino induced air showers



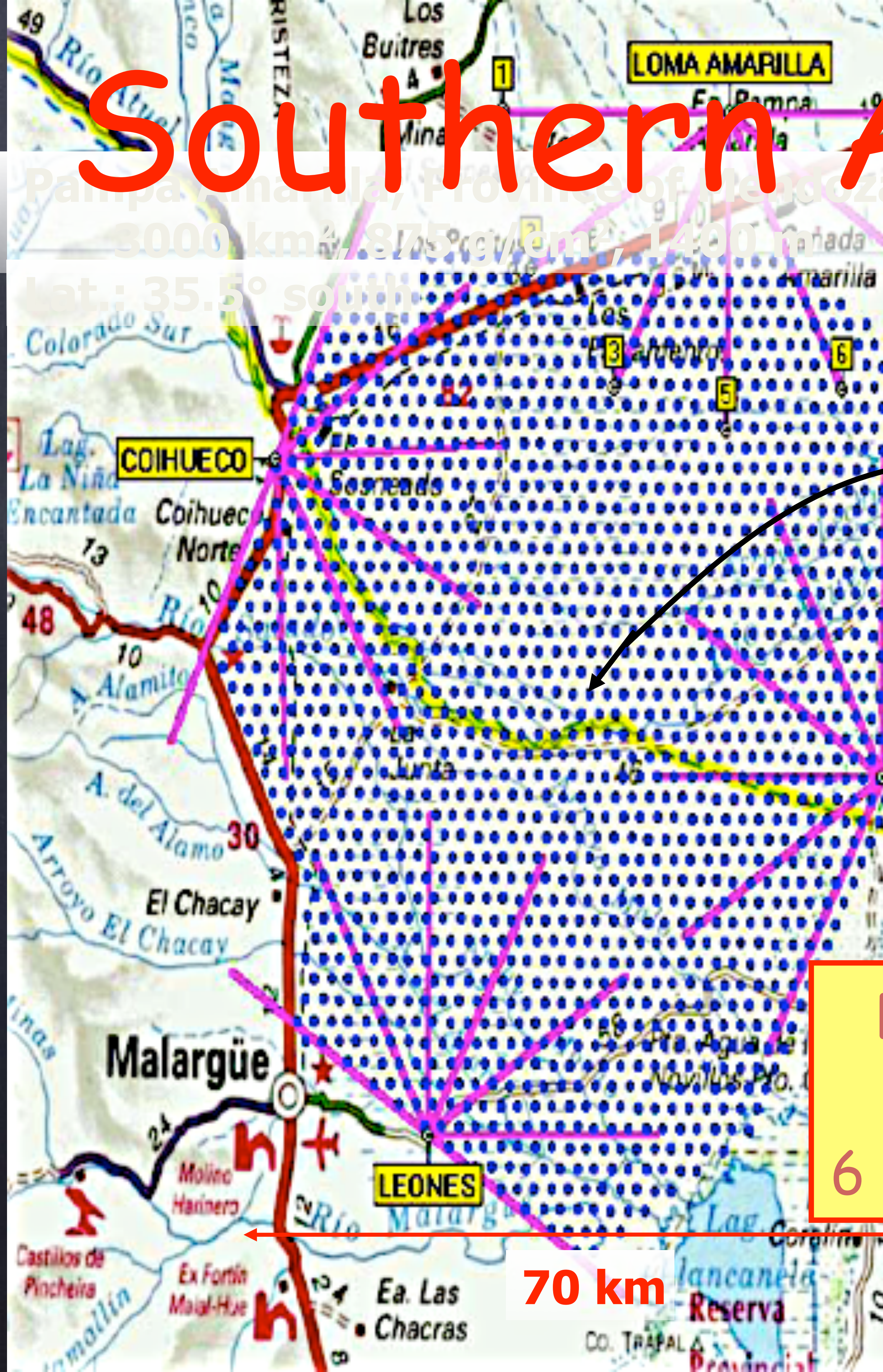


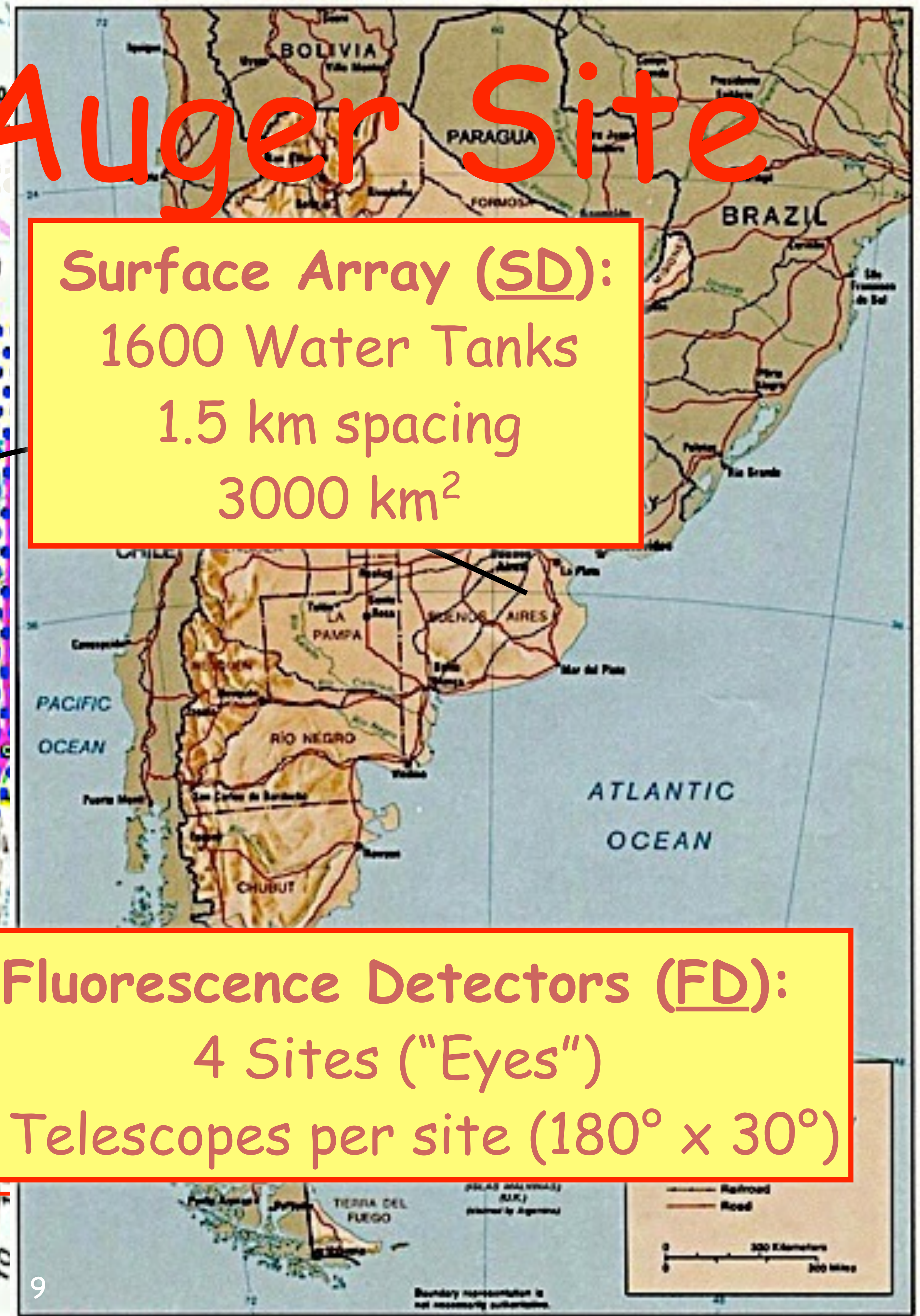
Southern Auger Site

Pampa Amarilla, Province of Mendoza
3000 km², 875 g/cm², 1400 m
Lat.: 35.5° south

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.

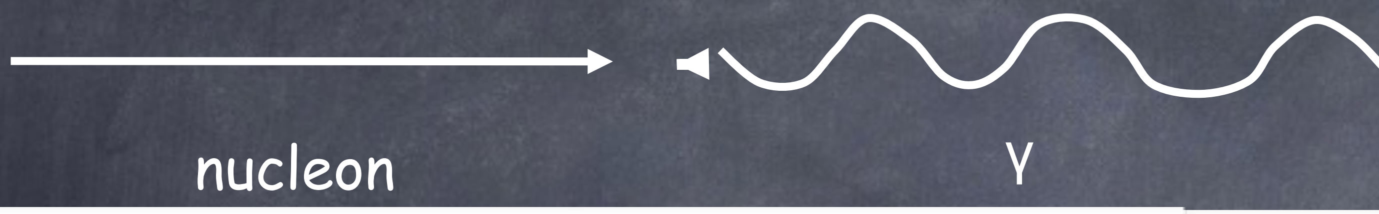
2.) in most conventional scenarios exceptionally powerful acceleration sources within that distance are needed.

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

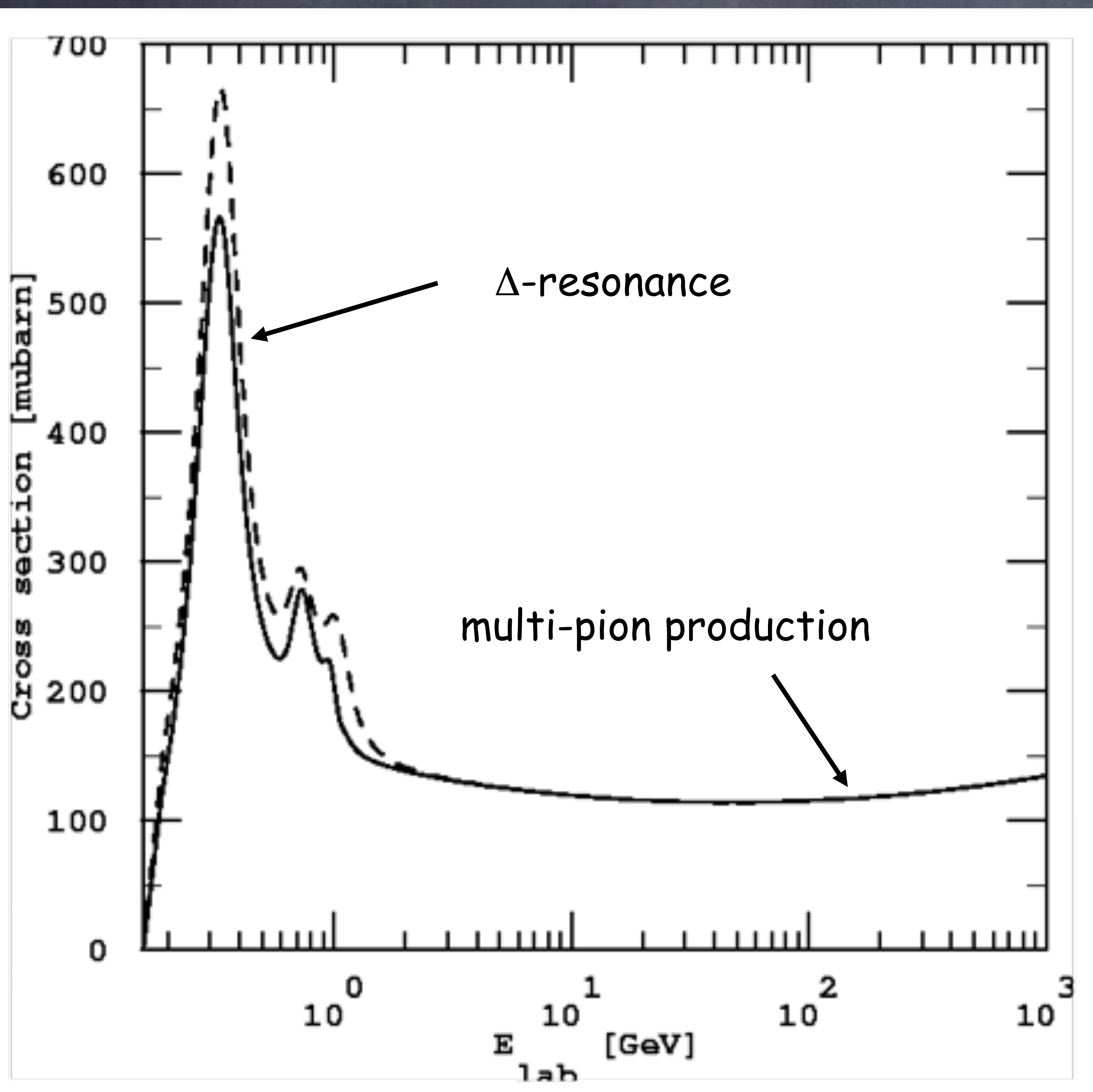
4.) The observed mass composition may become heavy toward highest energies, but no completely clear picture yet between experiments and air shower models

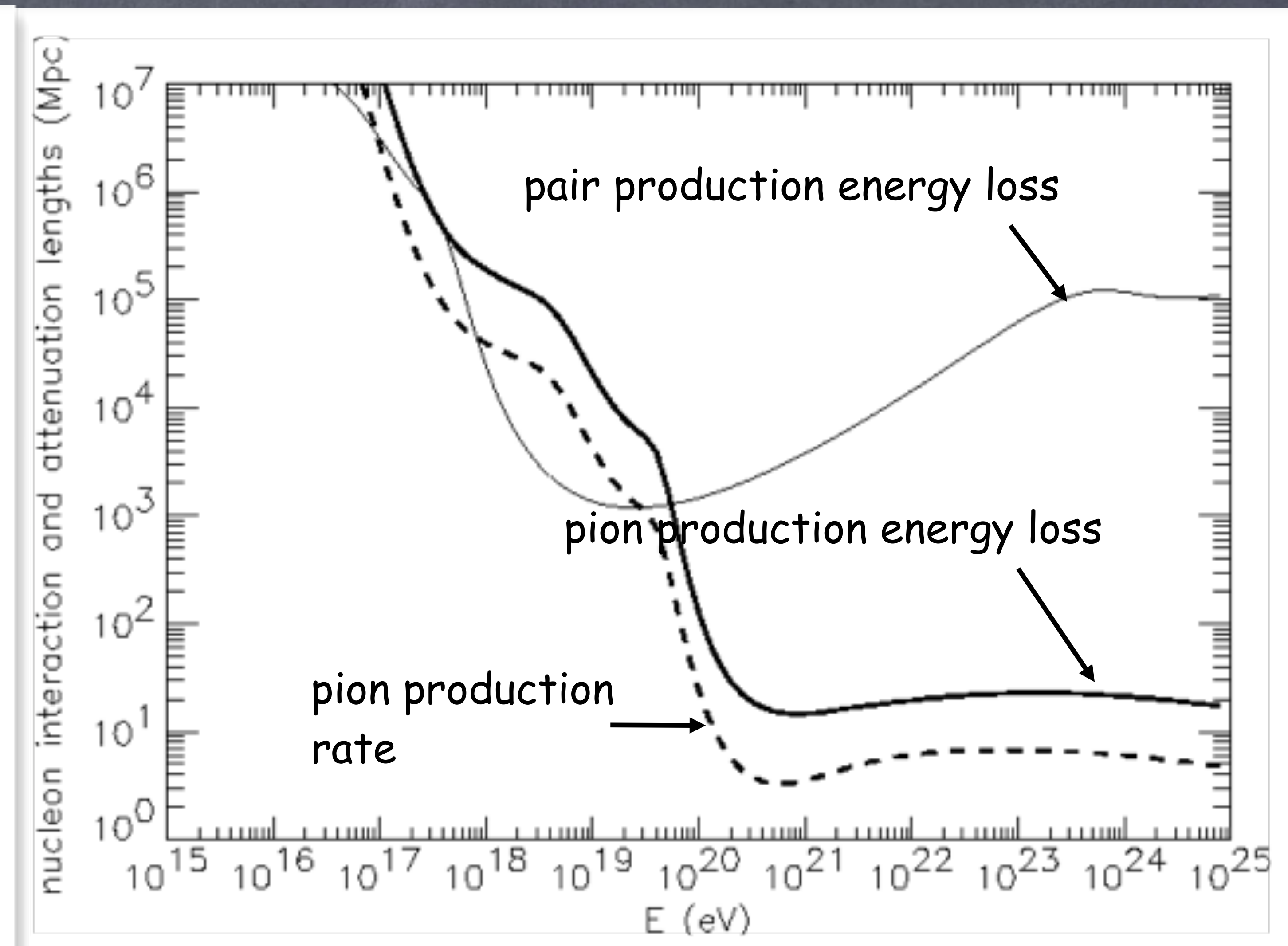
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



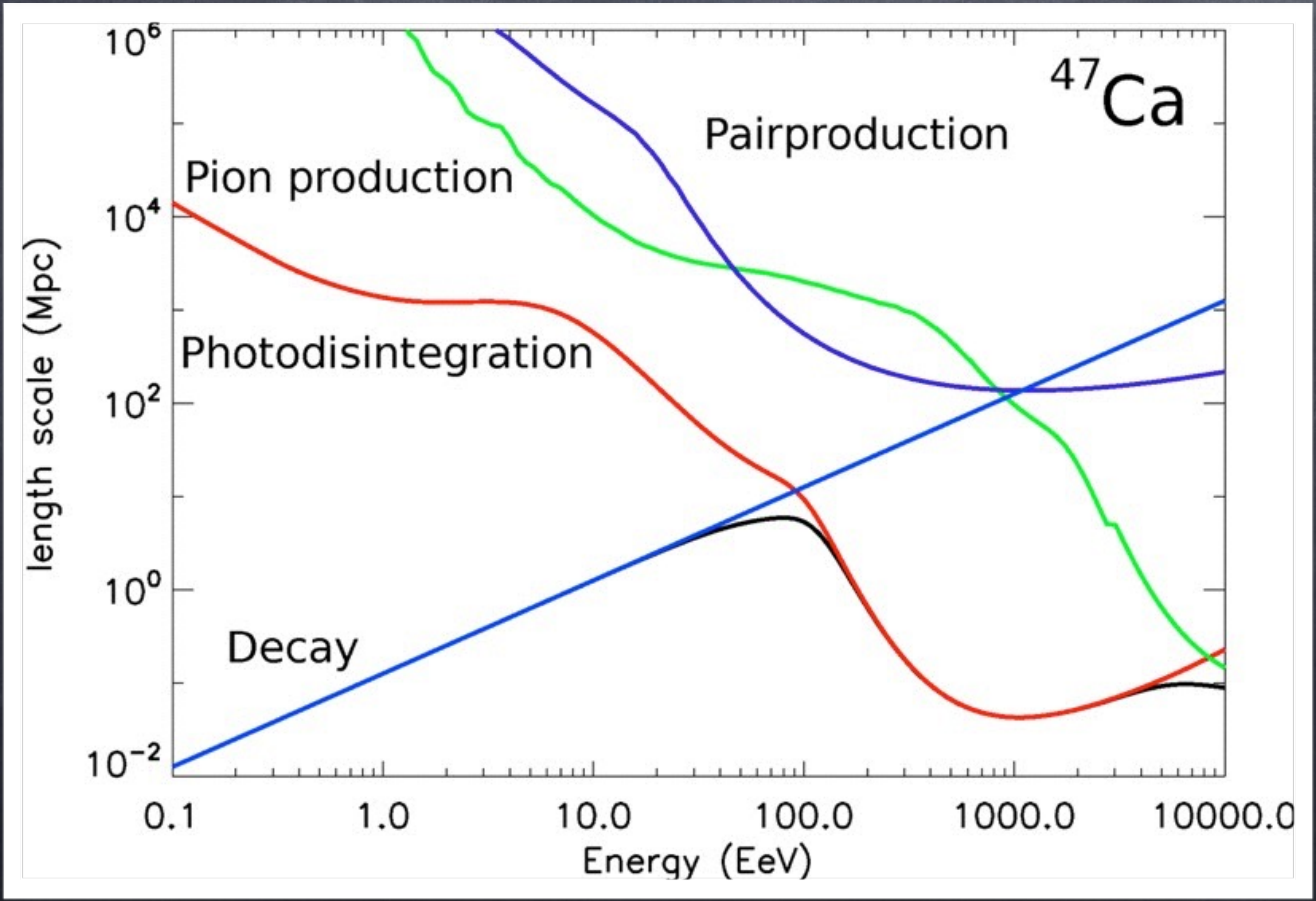
$$E_{\text{th}} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \simeq 4 \times 10^{19}\,\text{eV}$$



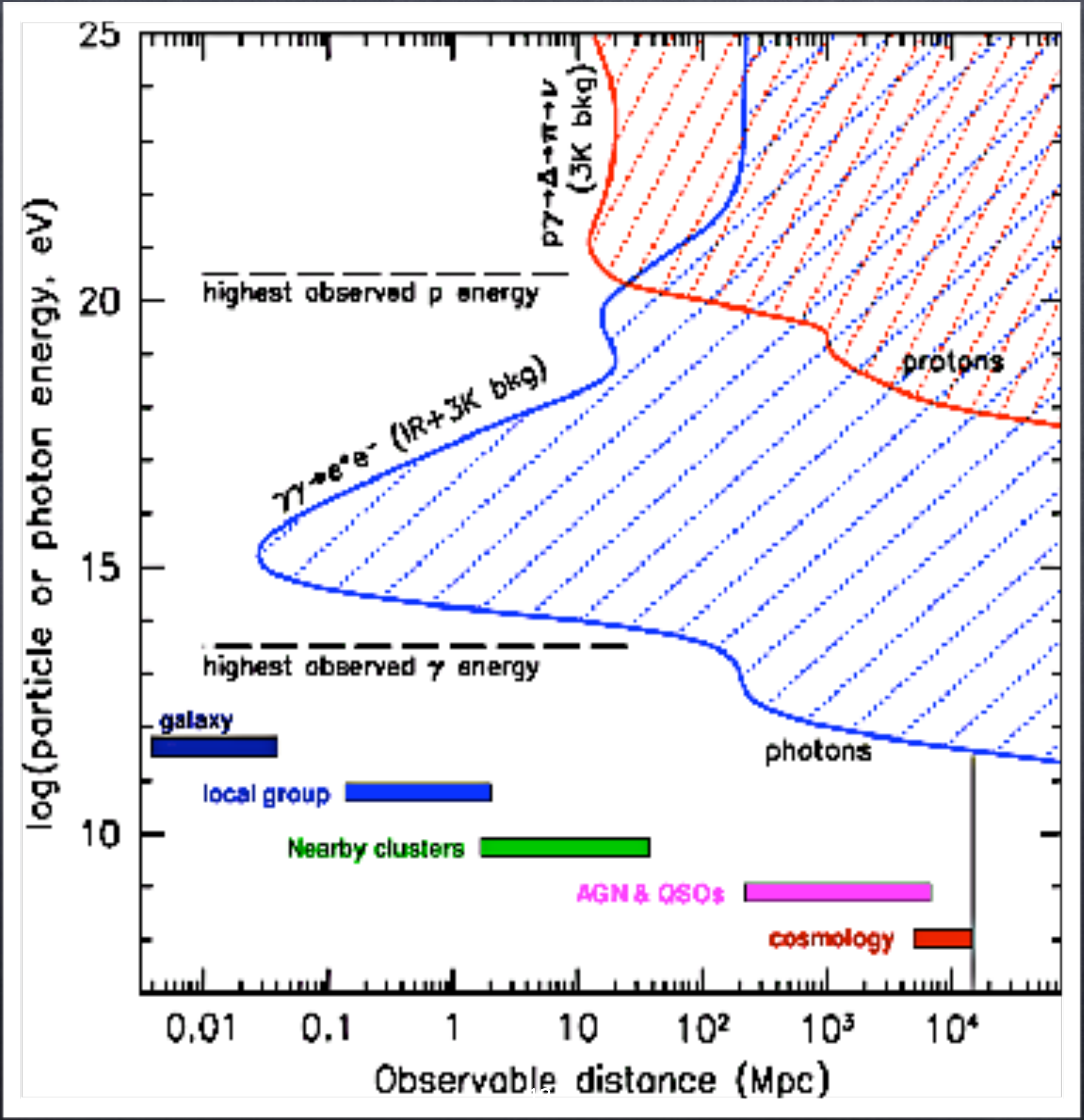


sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma > 10^{11}$
could avoid this conclusion.

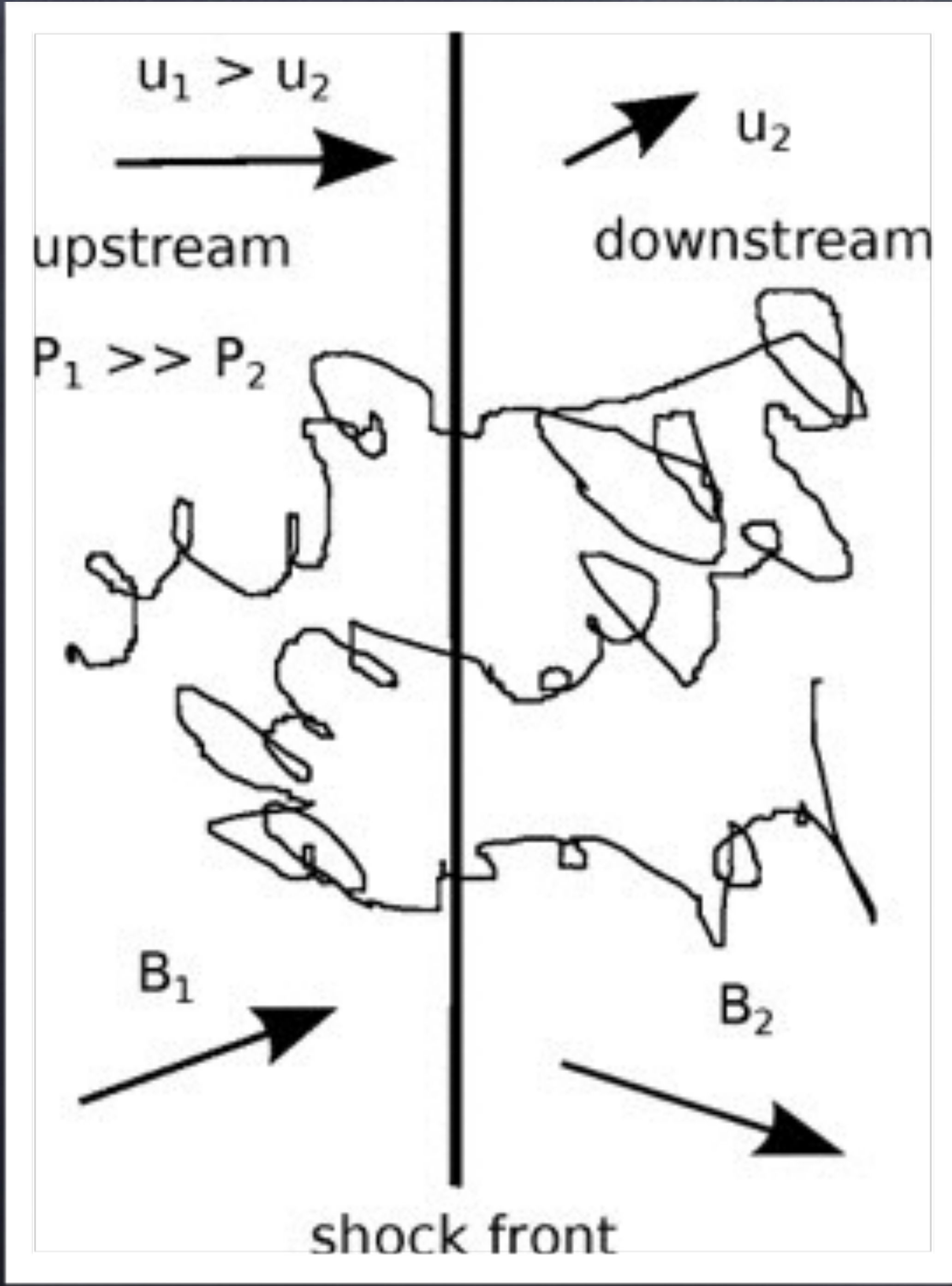
Length scales for relevant processes of a typical heavy nucleus

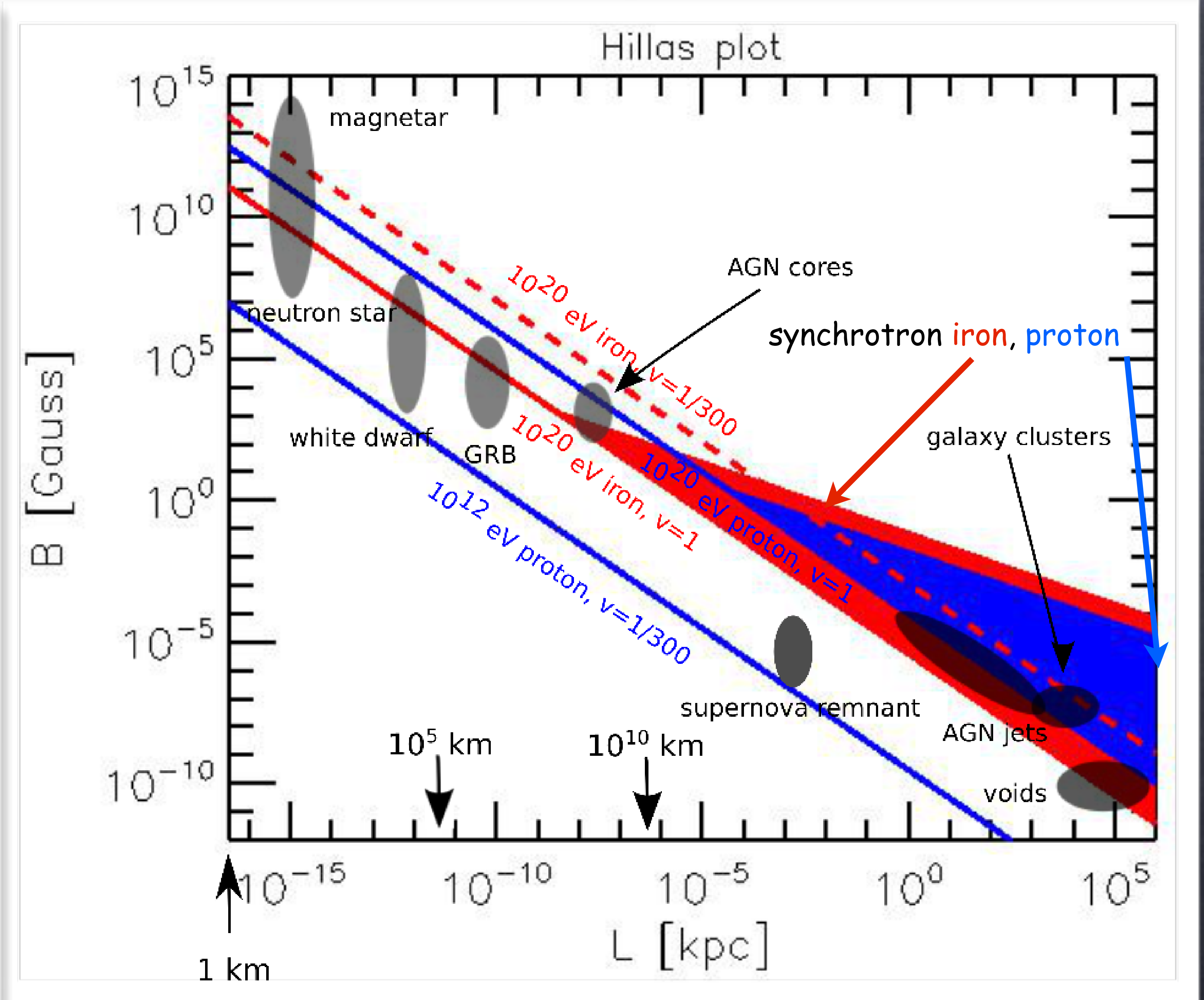


Interaction Horizons



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

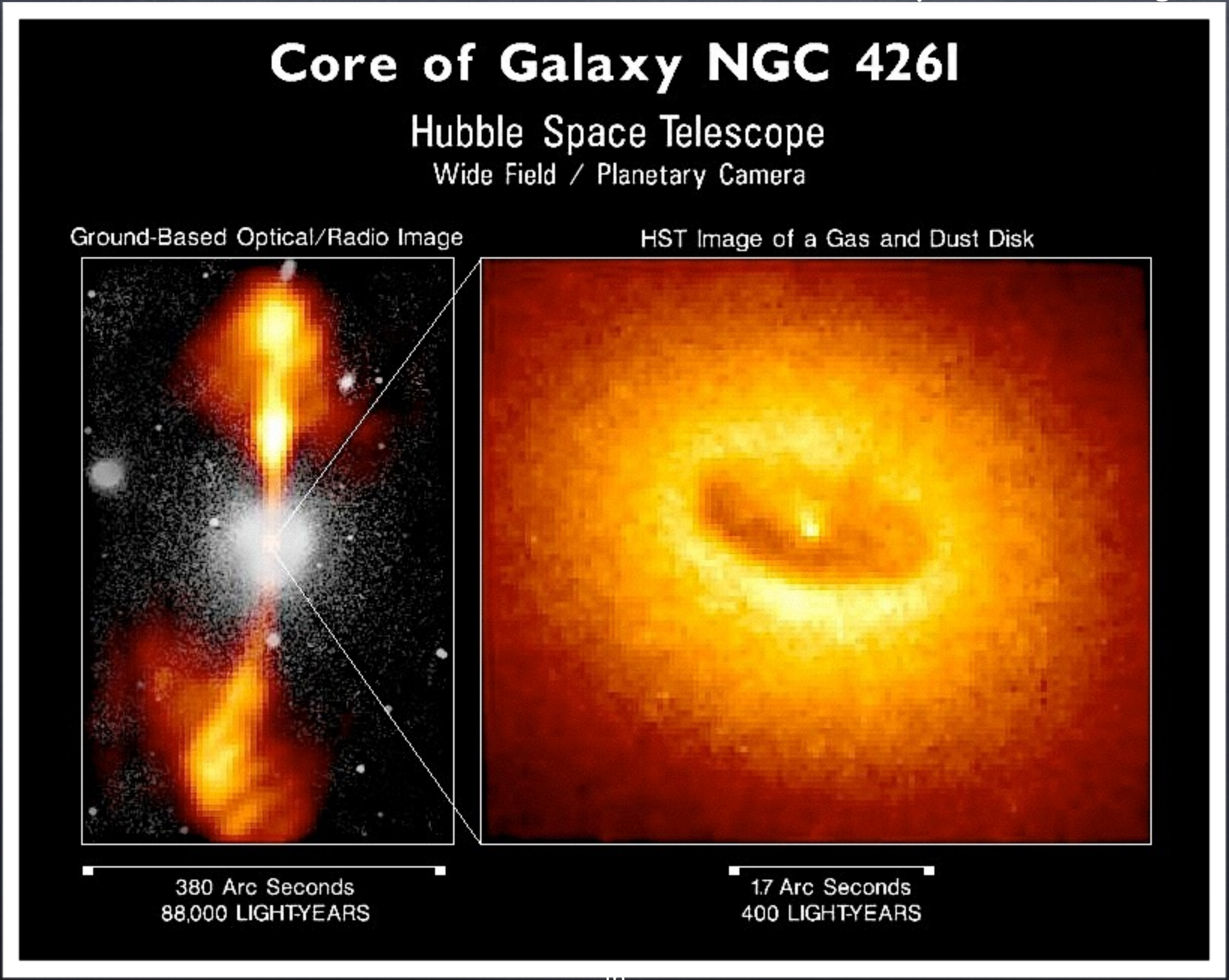
$$L_{\rm min} \sim \frac{\epsilon^2}{Z_0} \simeq 10^{45}\, Z^{-2} \left(\frac{E_{\rm max}}{10^{20}\,{\rm eV}}\right)^2 \,{\rm erg\,s^{-1}}$$

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

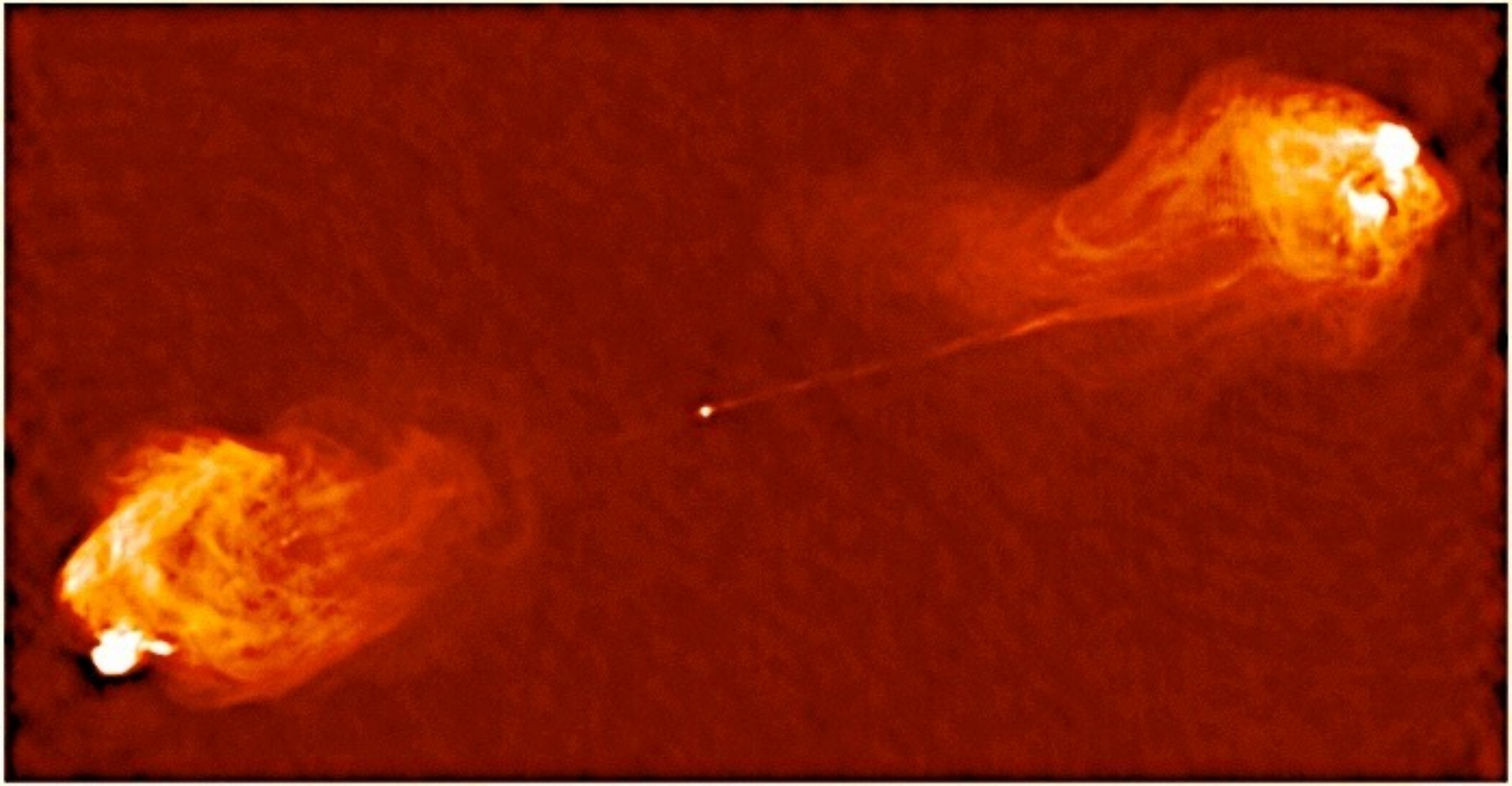
$$BR > 3 \times 10^{17}\,\Gamma^{-1} \left(\frac{E_{\rm max}/Z}{10^{20}\,{\rm eV}}\right) {\rm Gauss\,cm}$$

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.

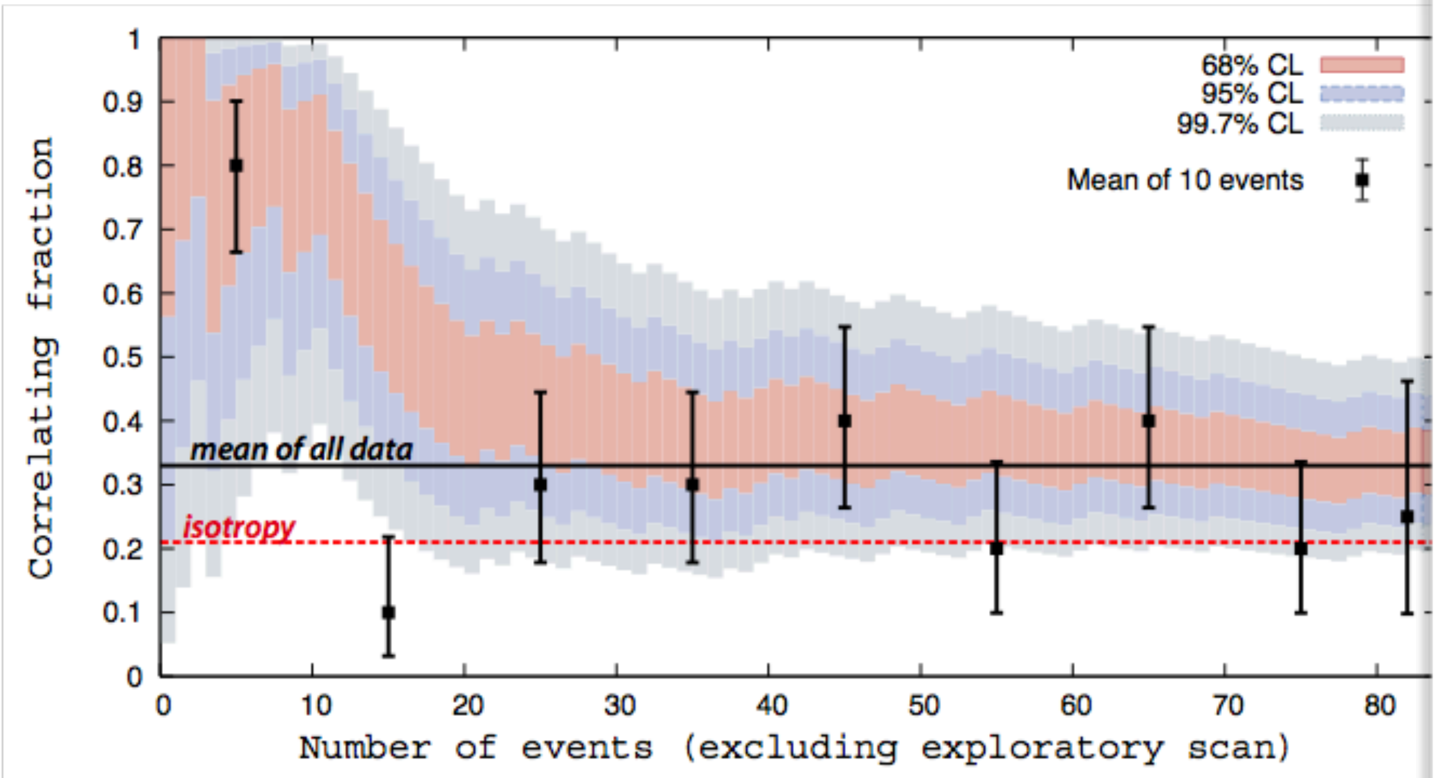
A possible acceleration site associated with shocks in hot spots of active galaxies

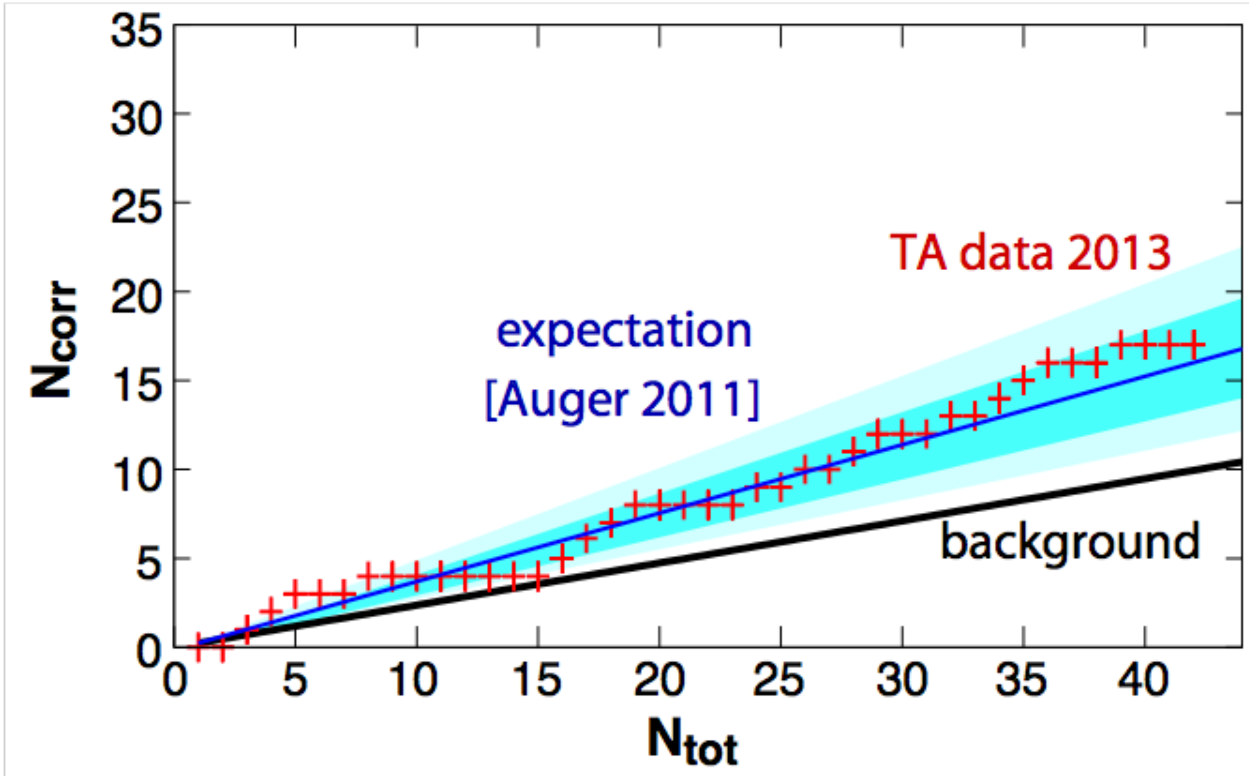


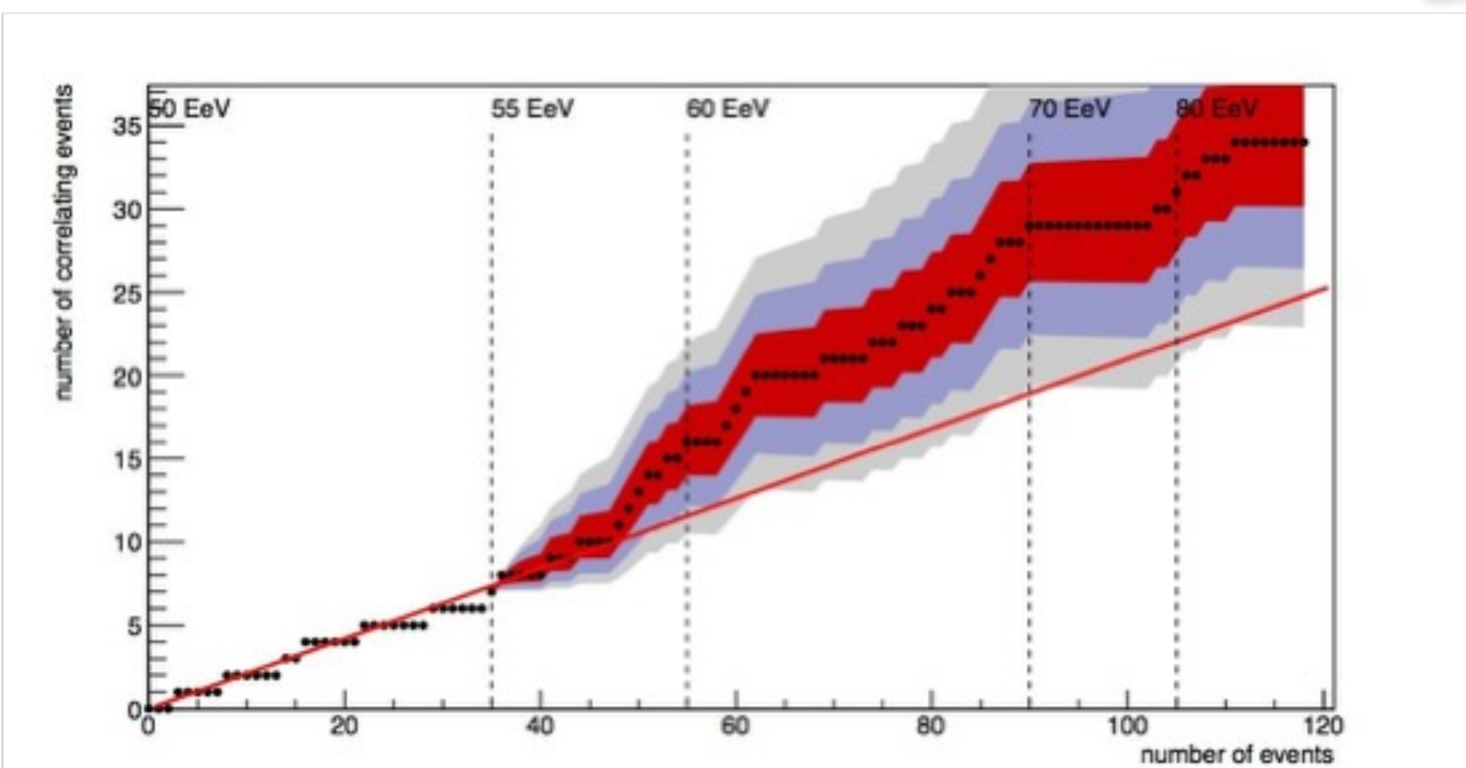
Or Cygnus A



Status of Large Scale UHECR Anisotropy







Kampert and Tinyakov,arXiv:1405.0575

All Sky View from Pierre Auger and Telescope Array

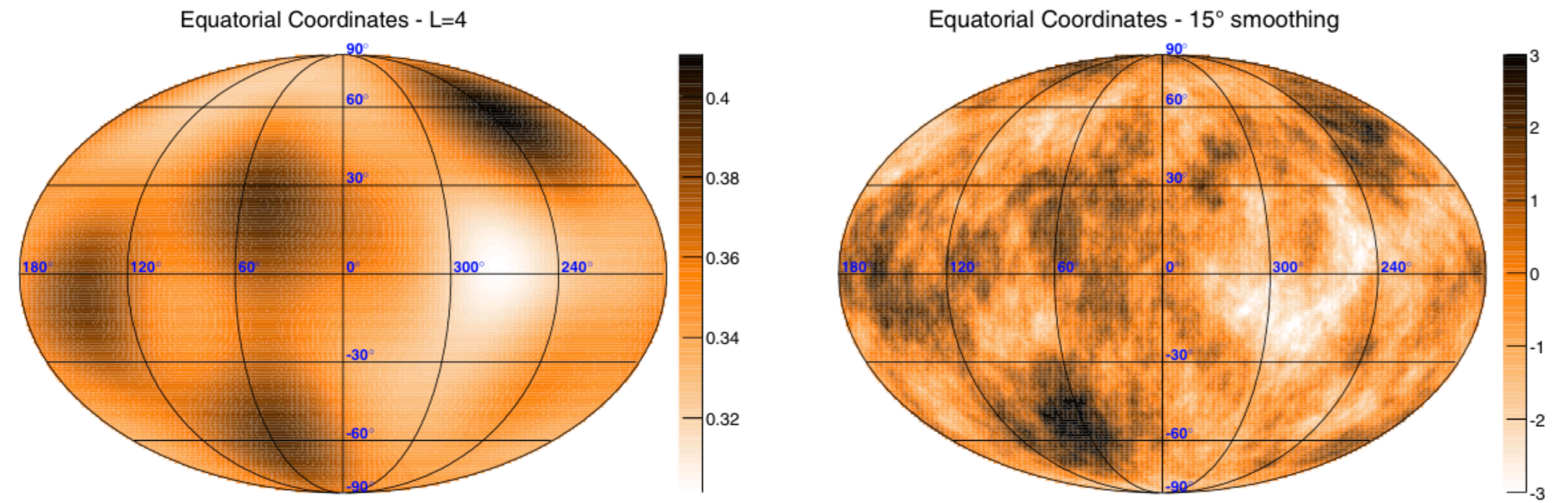
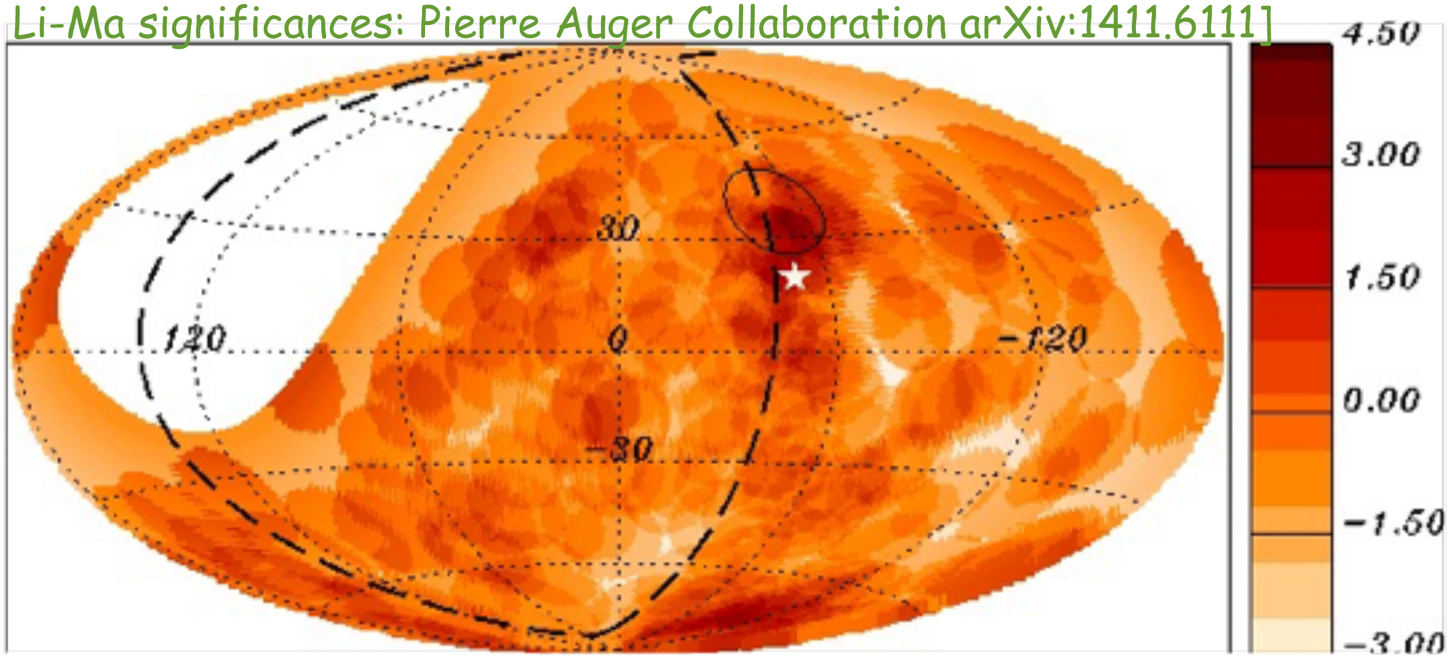
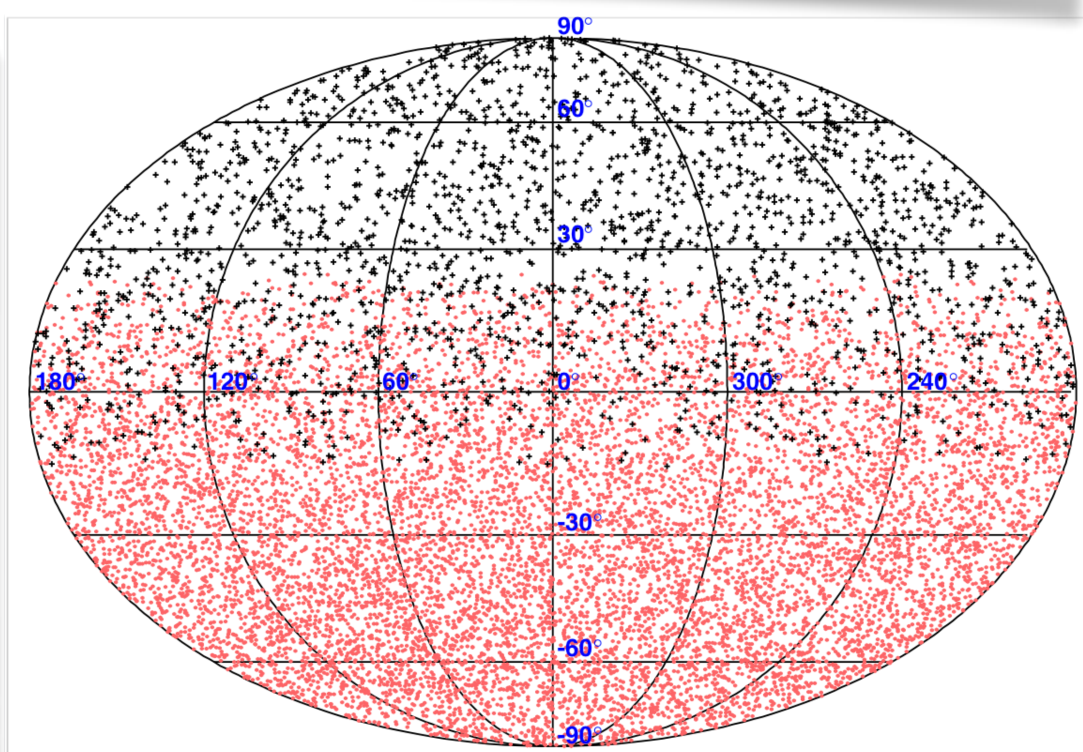


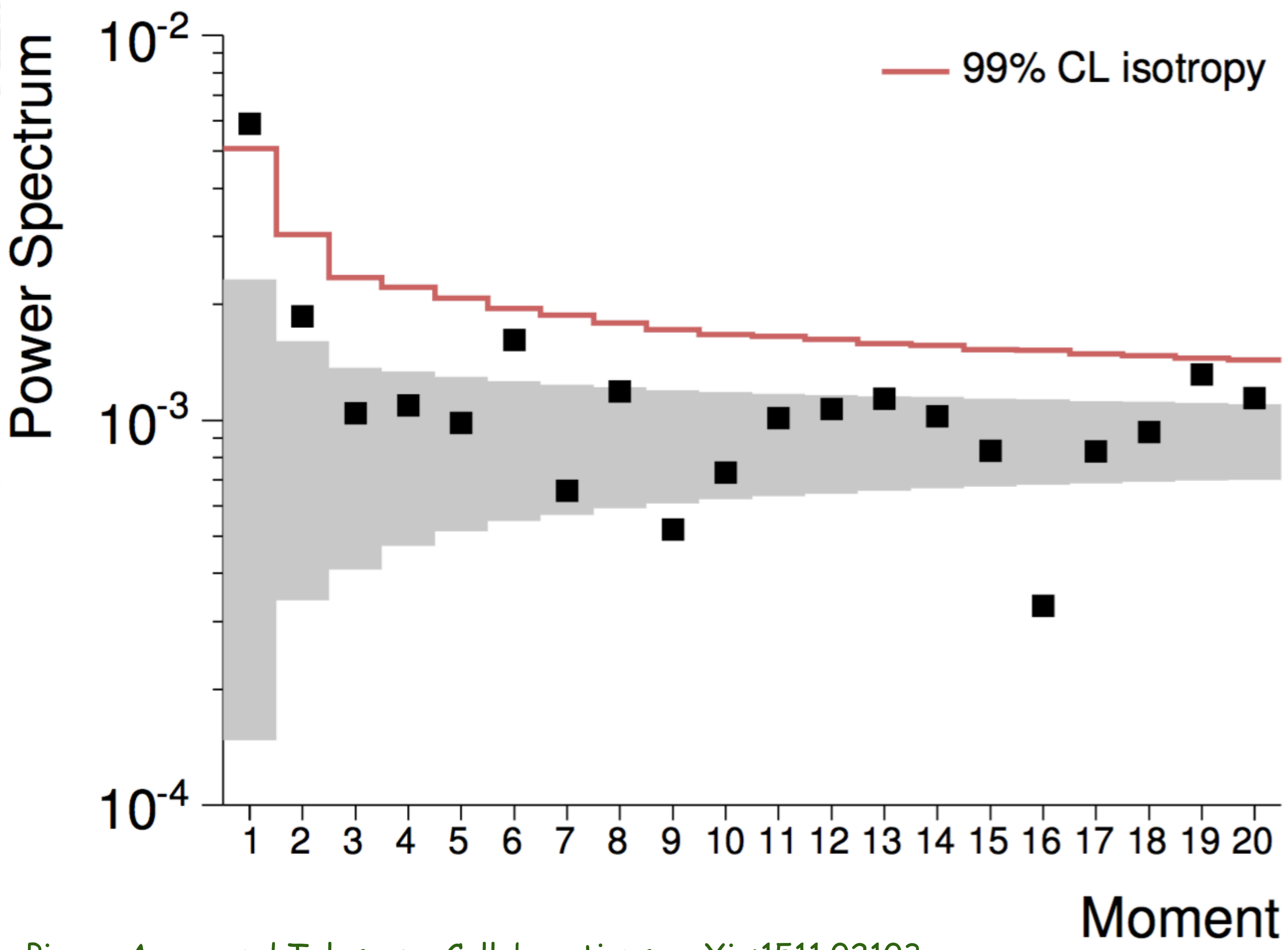
Figure 9. Left: flux sky map in km^{-2} yr^{-1} sr^{-1} units, using a multipolar expansion up to $\ell = 4$. Right: significance sky map smoothed out at a 15° angular scale.
(A color version of this figure is available in the online journal.)

Pierre Auger and Telescope Collaborations, ApJ 794 (2014) 172 [arXiv:1409.3128]

Li-Ma significances: Pierre Auger Collaboration arXiv:1411.6111]

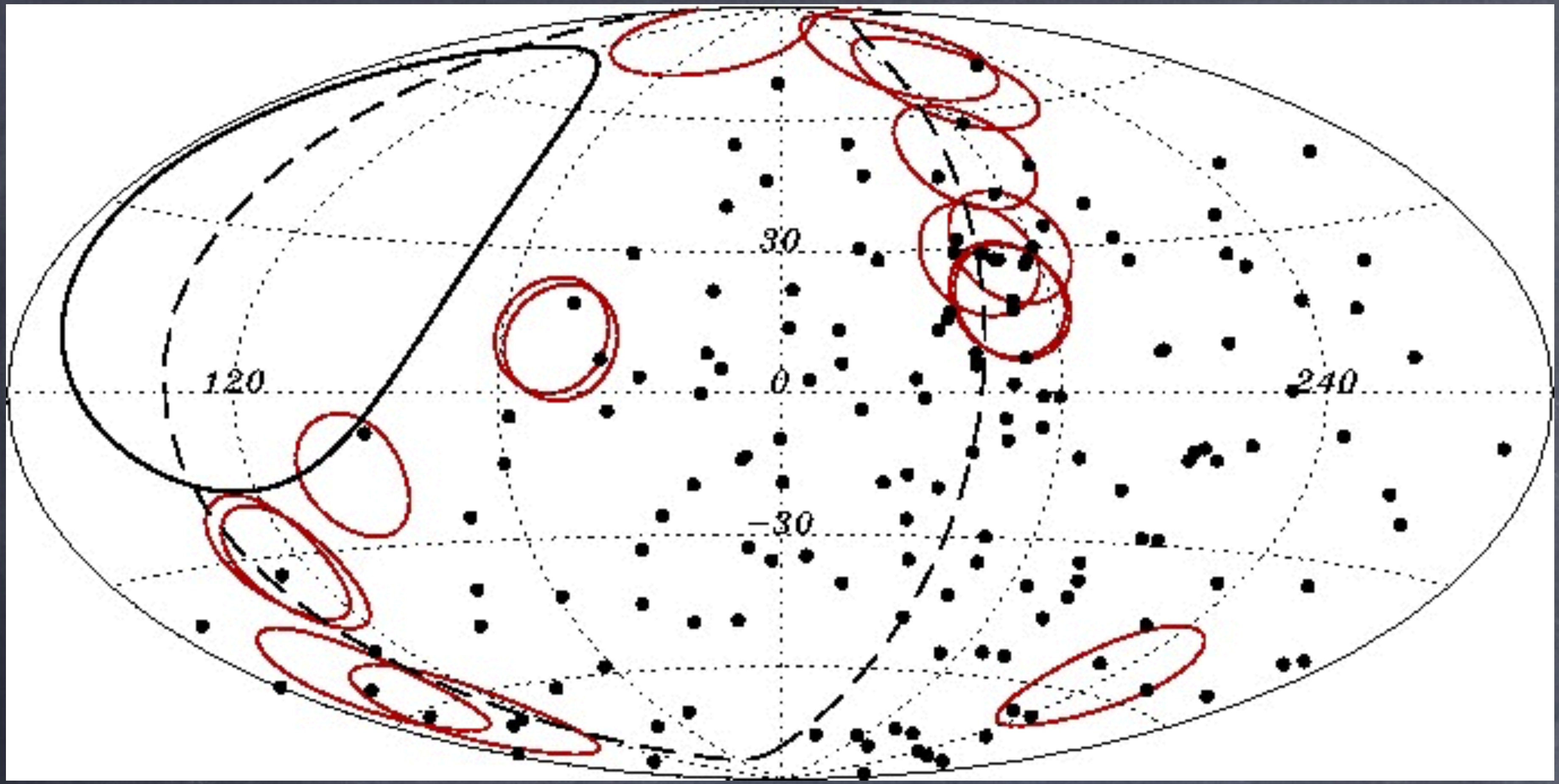






Pierre Auger and Telescope Collaborations, arXiv:1511.02103

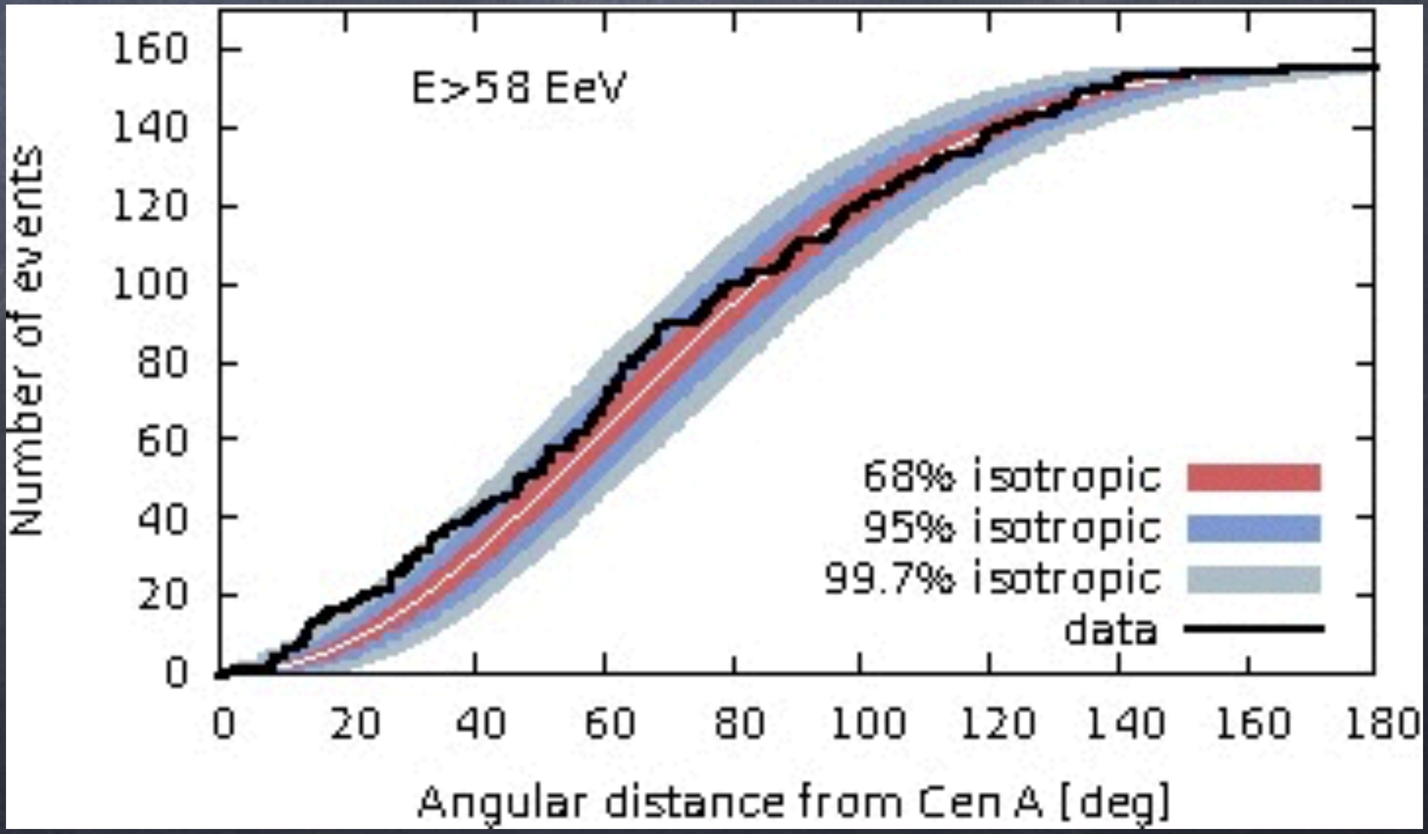
Centaurus A is a UHECR source candidate



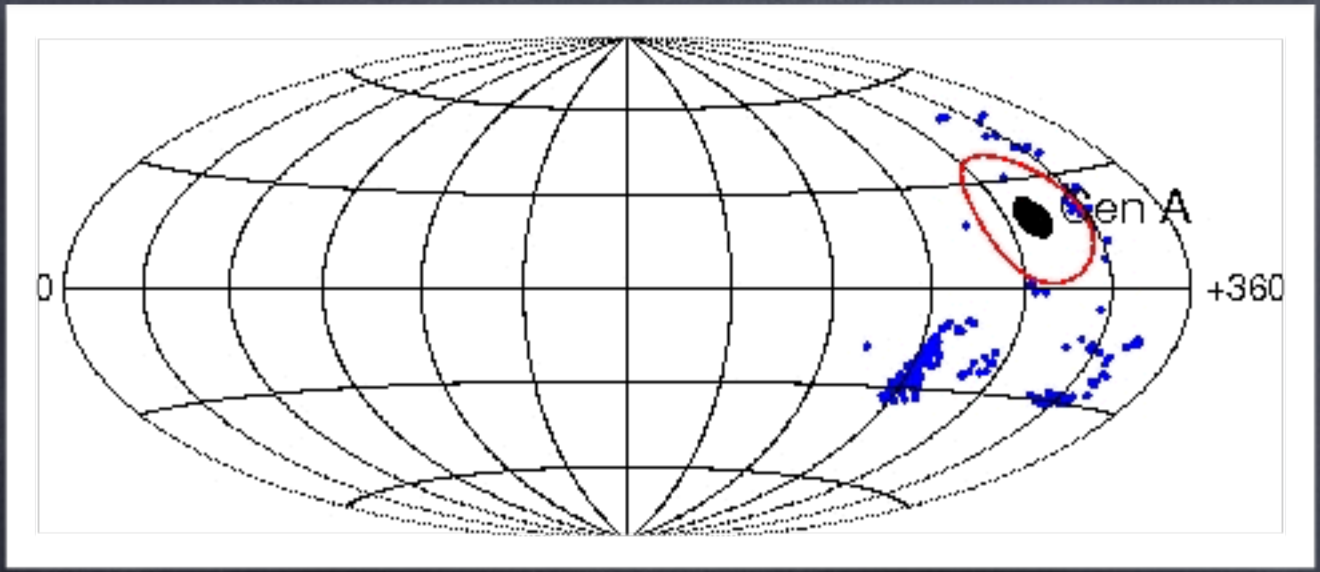
Pierre Auger Collaboration, arXiv:1411.6111

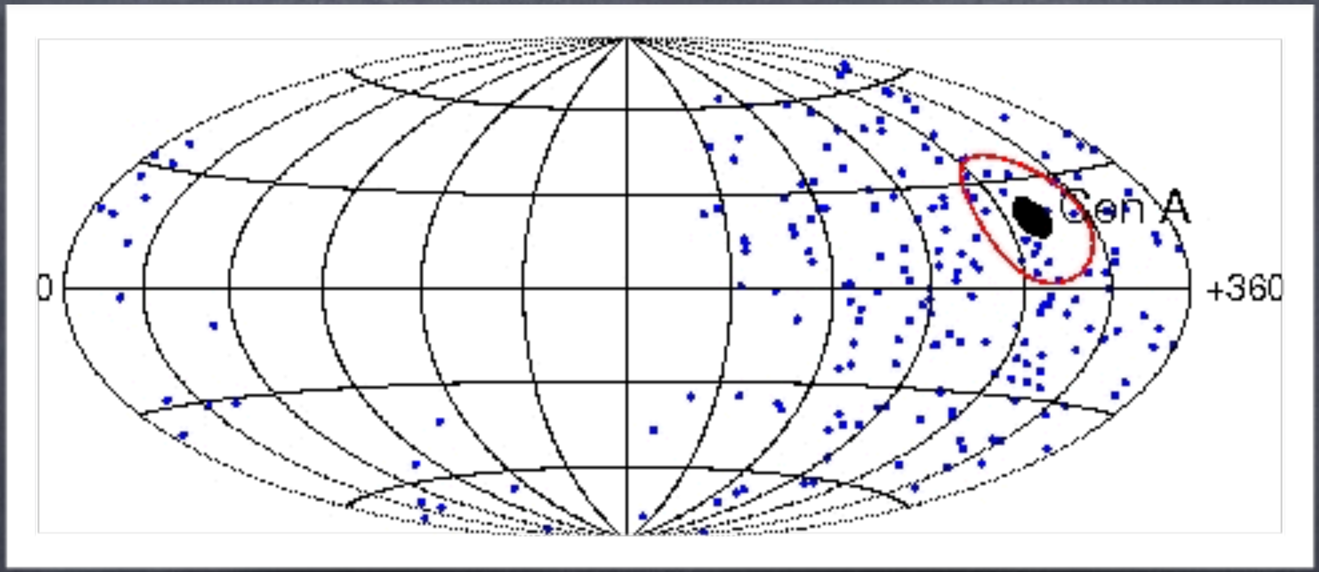
Events above 58 EeV against radio galaxies brighter than 10^{40} erg/s within 90 Mpc (red circles)

Pierre Auger sees a slight excess in the direction of Centaurus A above 58 EeV



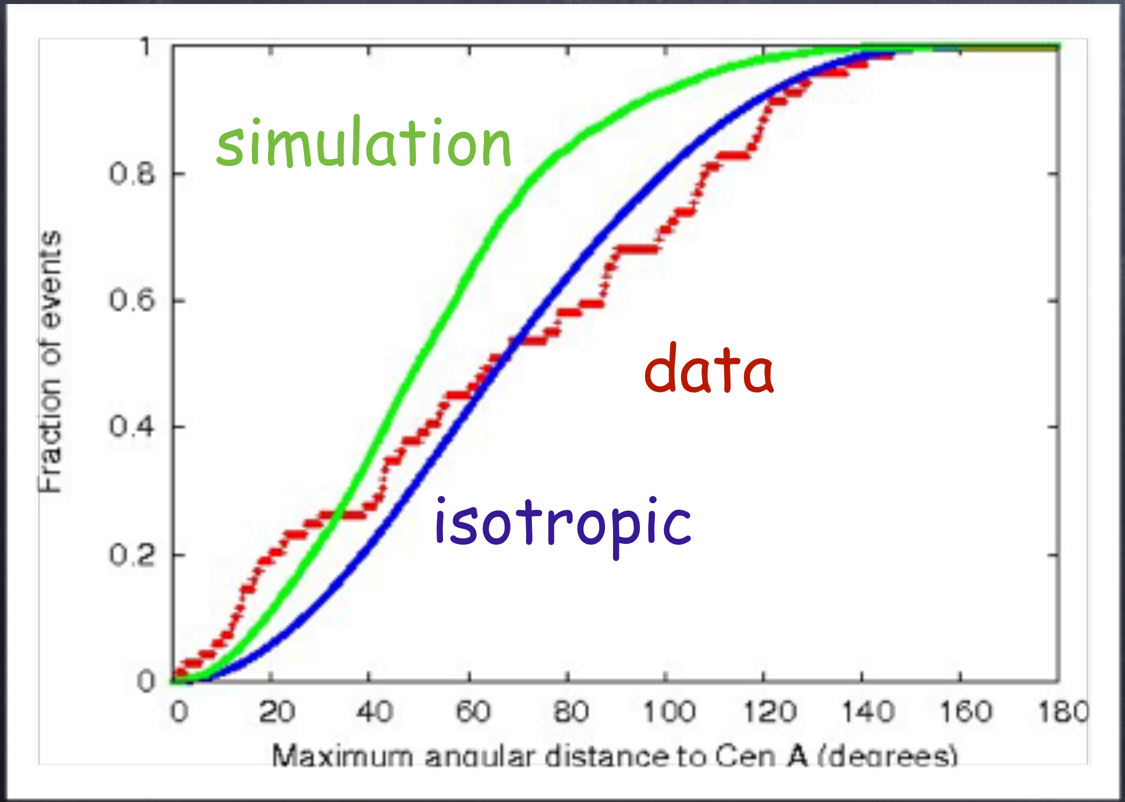
But even for iron primaries Centaurus A can not be the only UHECR source





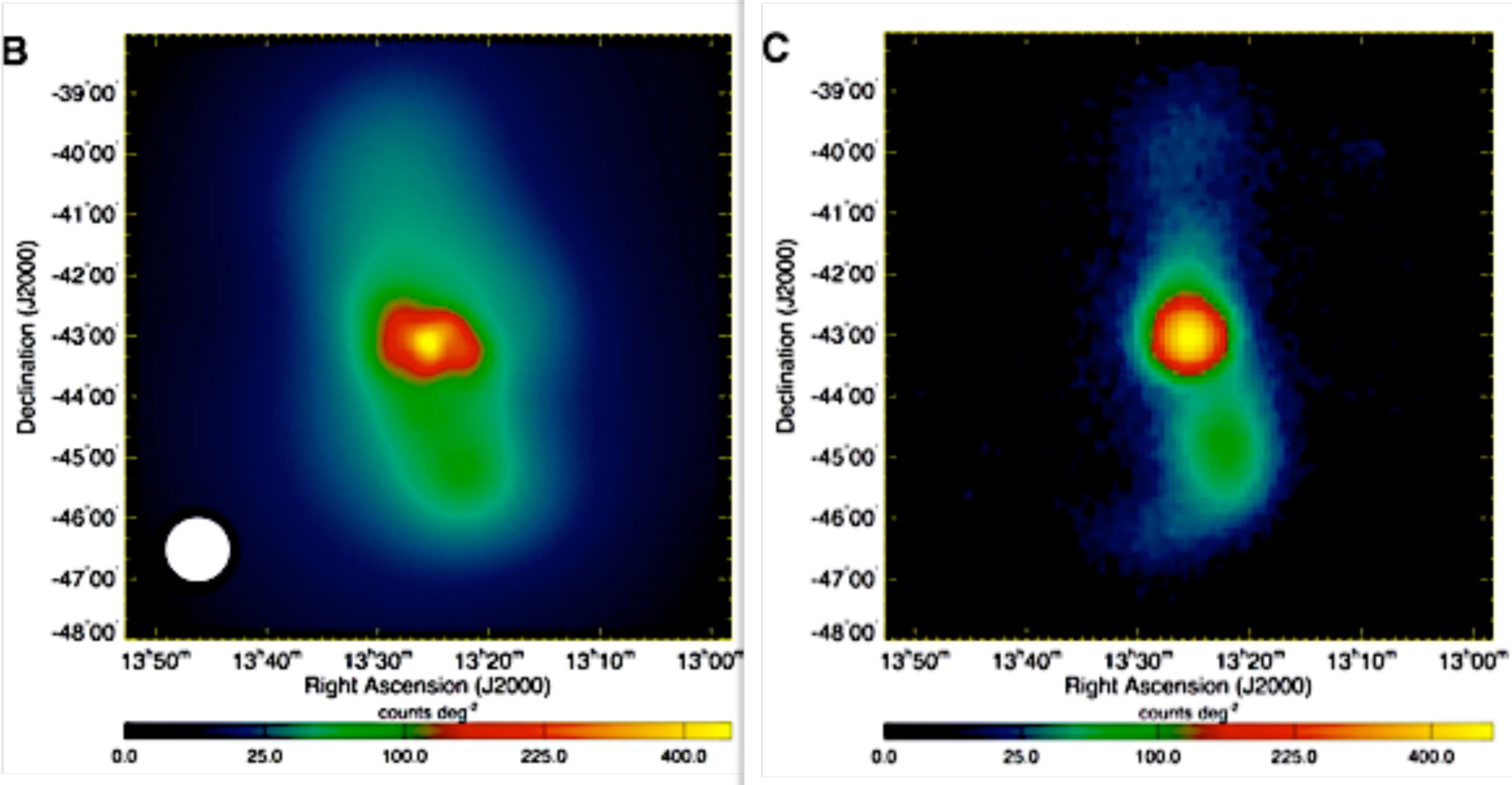
Iron Image of Cen A in the Prouza-Smida Galactic magnetic field model

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

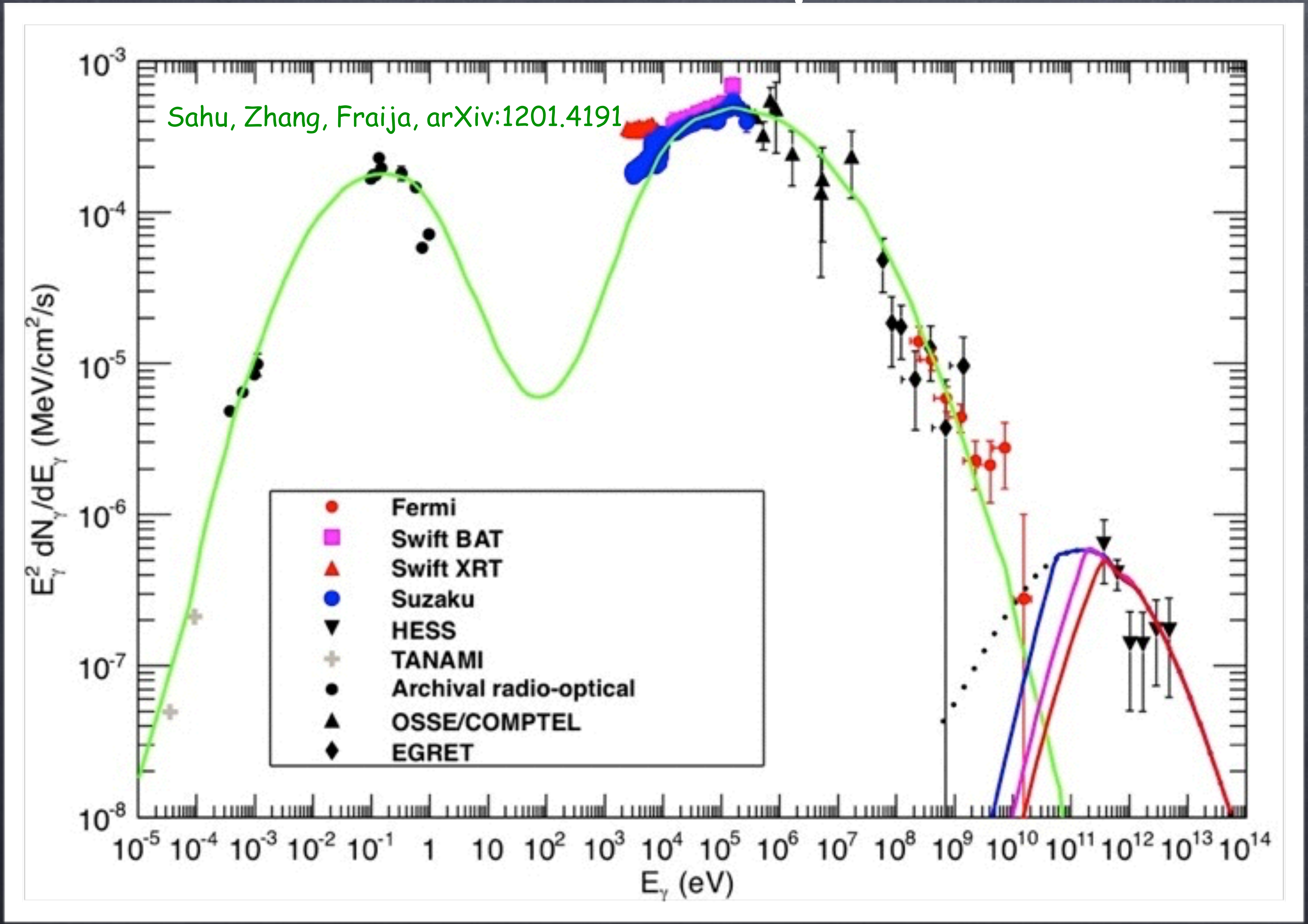


> 200 MeV γ-rays

Radio observations

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

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



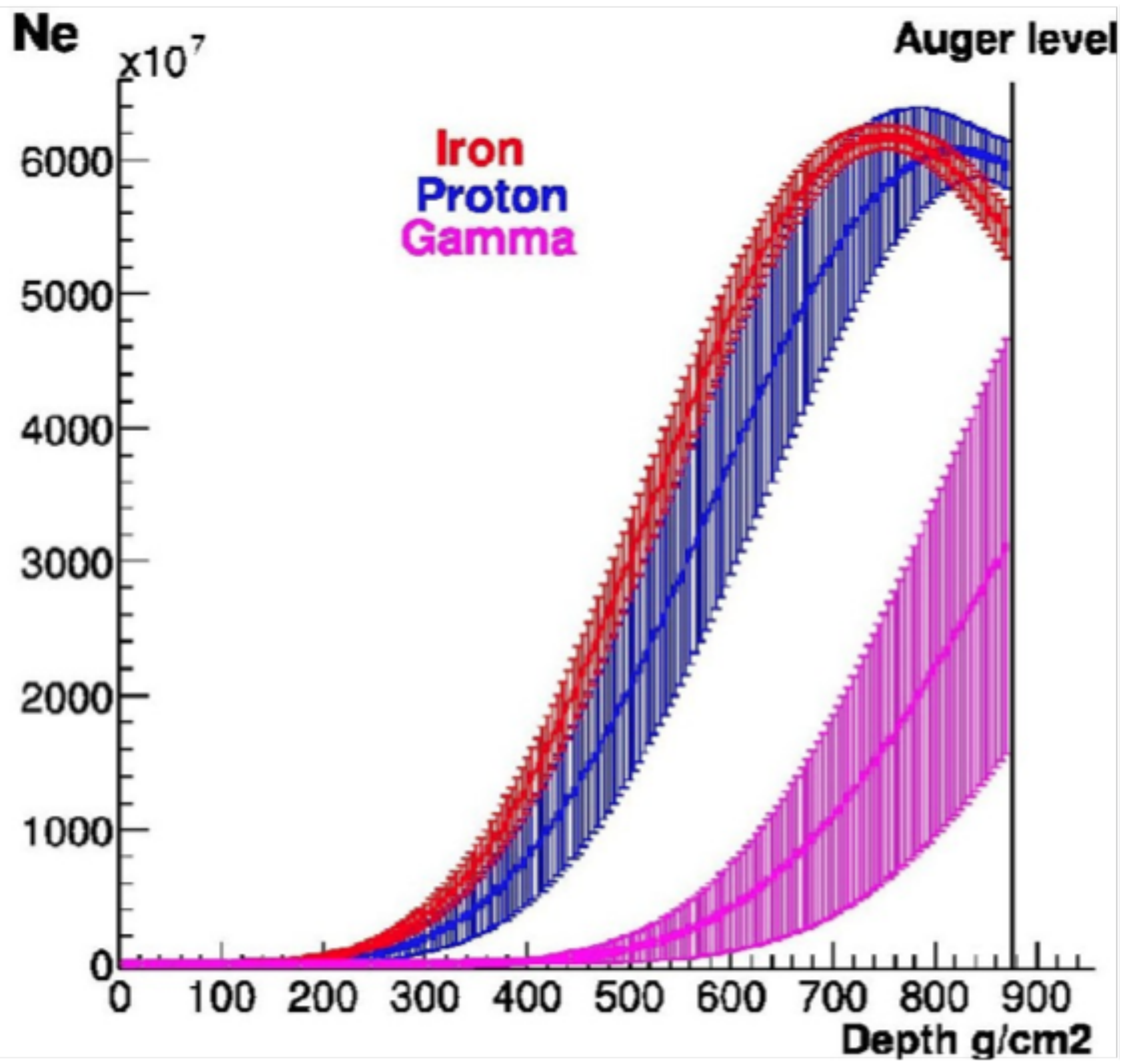
Low energy bump = synchrotron

high energy bump = synchrotron self-Compton

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

Mass Composition

Depth of shower maximum X_{max} and its distribution contain information on primary mass composition



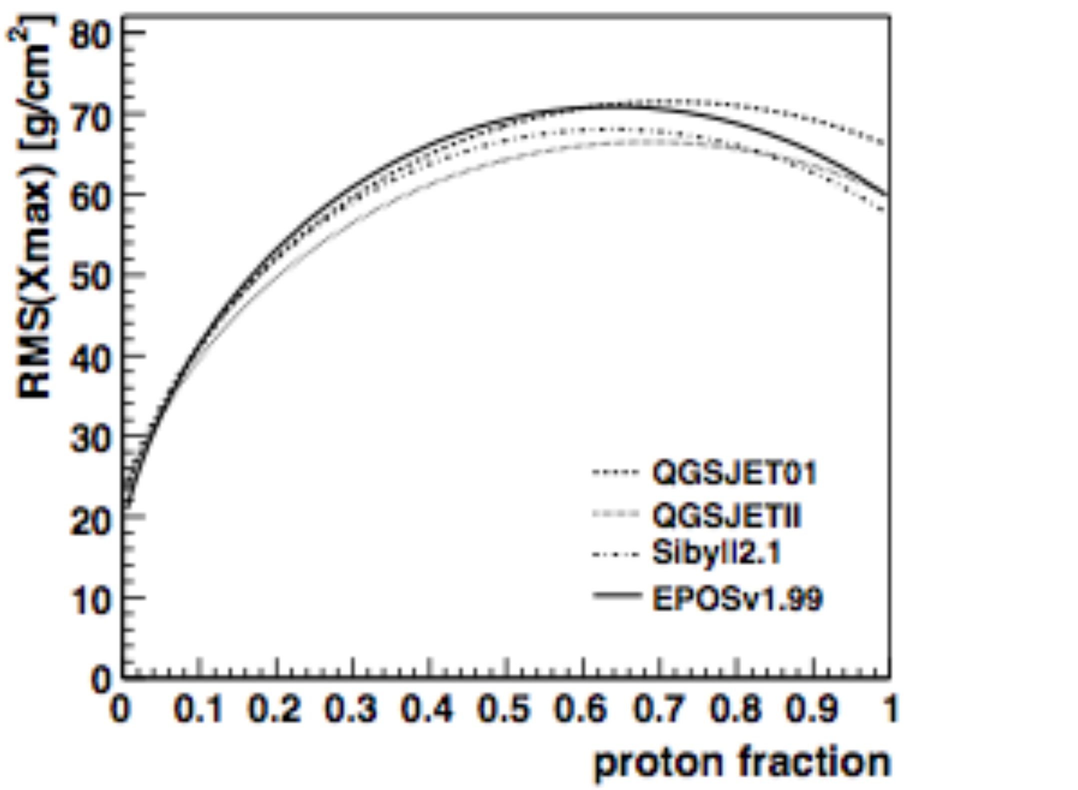
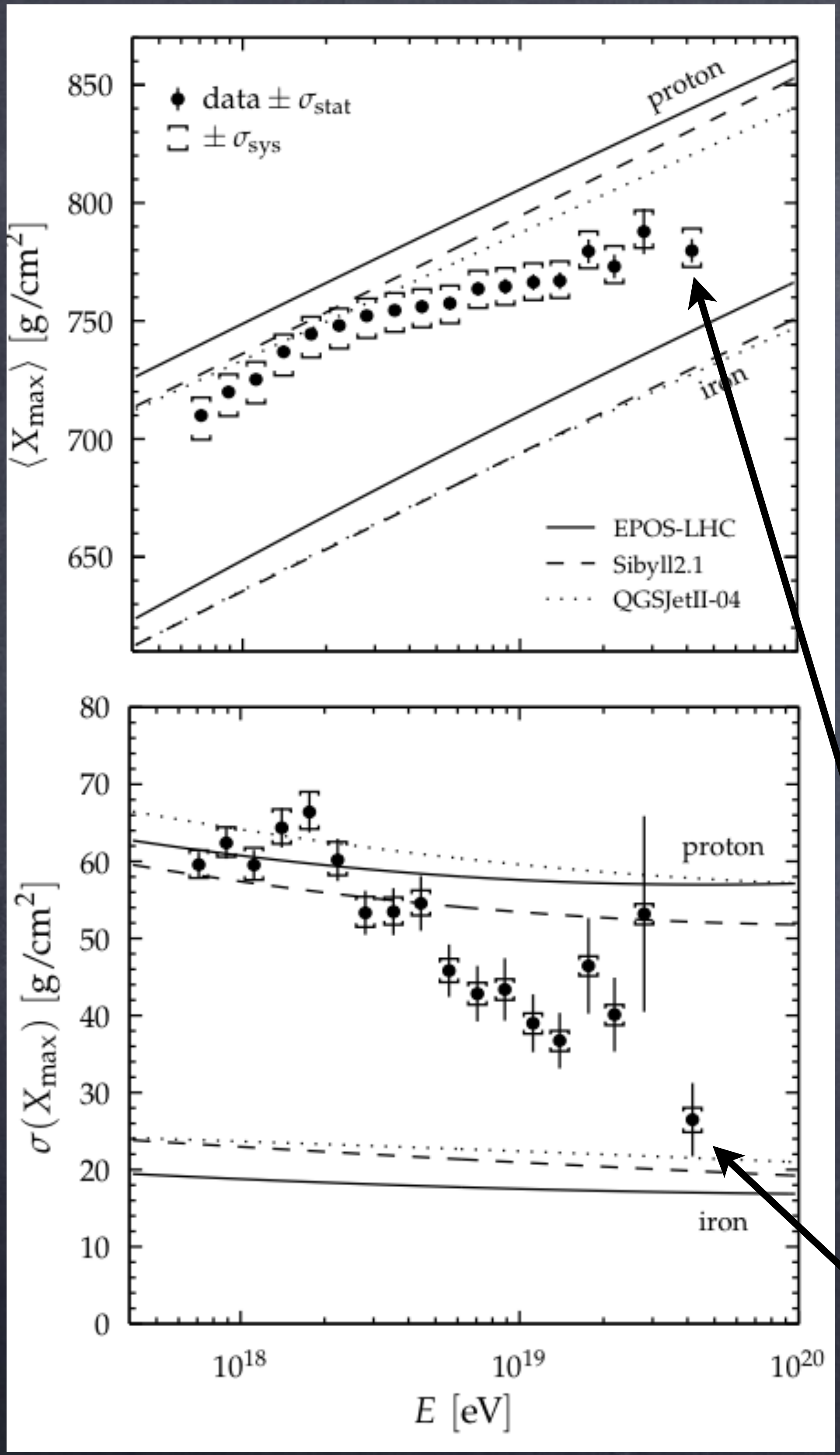


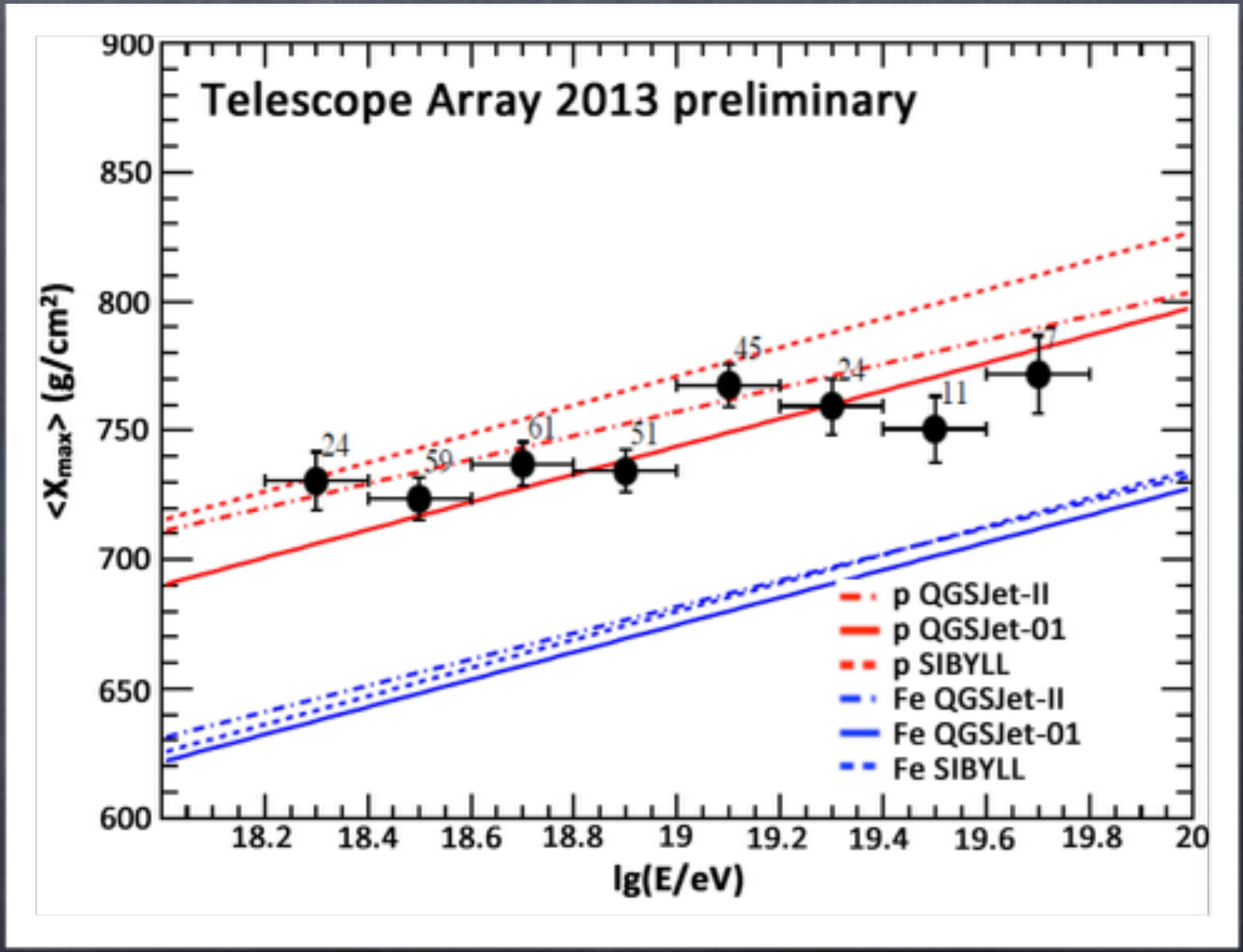
FIGURE 1. RMS(X_{max}) from different hadronic interaction models [23] and a two-component p/Fe composition model ($E = 10^{18}$ eV).

Pierre Auger data suggest a heavier composition toward highest energies:



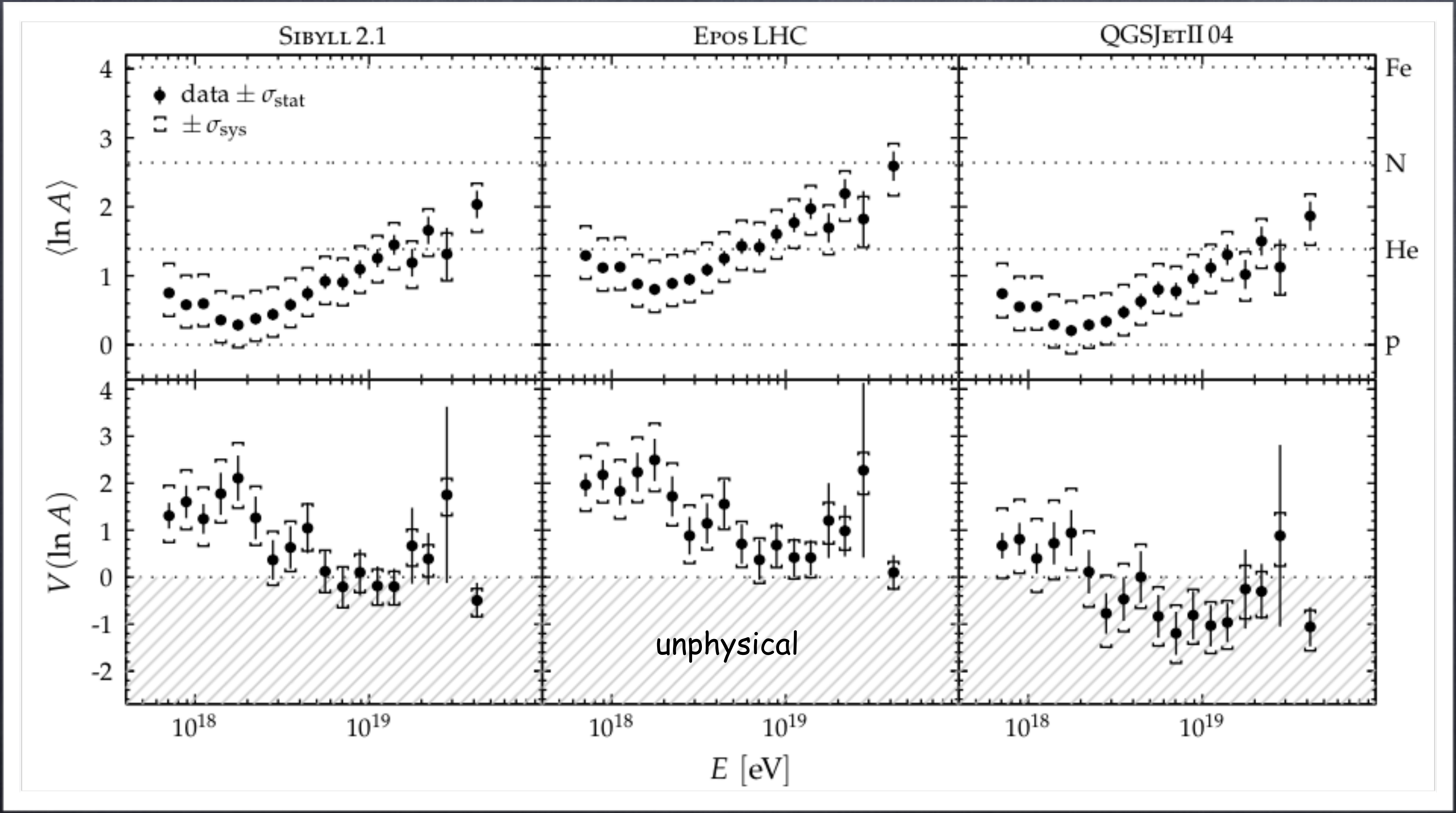
Pierre Auger Collaboration, arXiv:1409.4809

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})

combined measurement of X_{max} and its fluctuation $\sigma(X_{max})$ can be translated to distribution of atomic mass A **within a given hadronic interaction model**



Pierre Auger Collaboration, arXiv:1409.4809

would imply that fluctuations predicted by a pure composition already higher than observed

An attempt to reconstruct individual elements

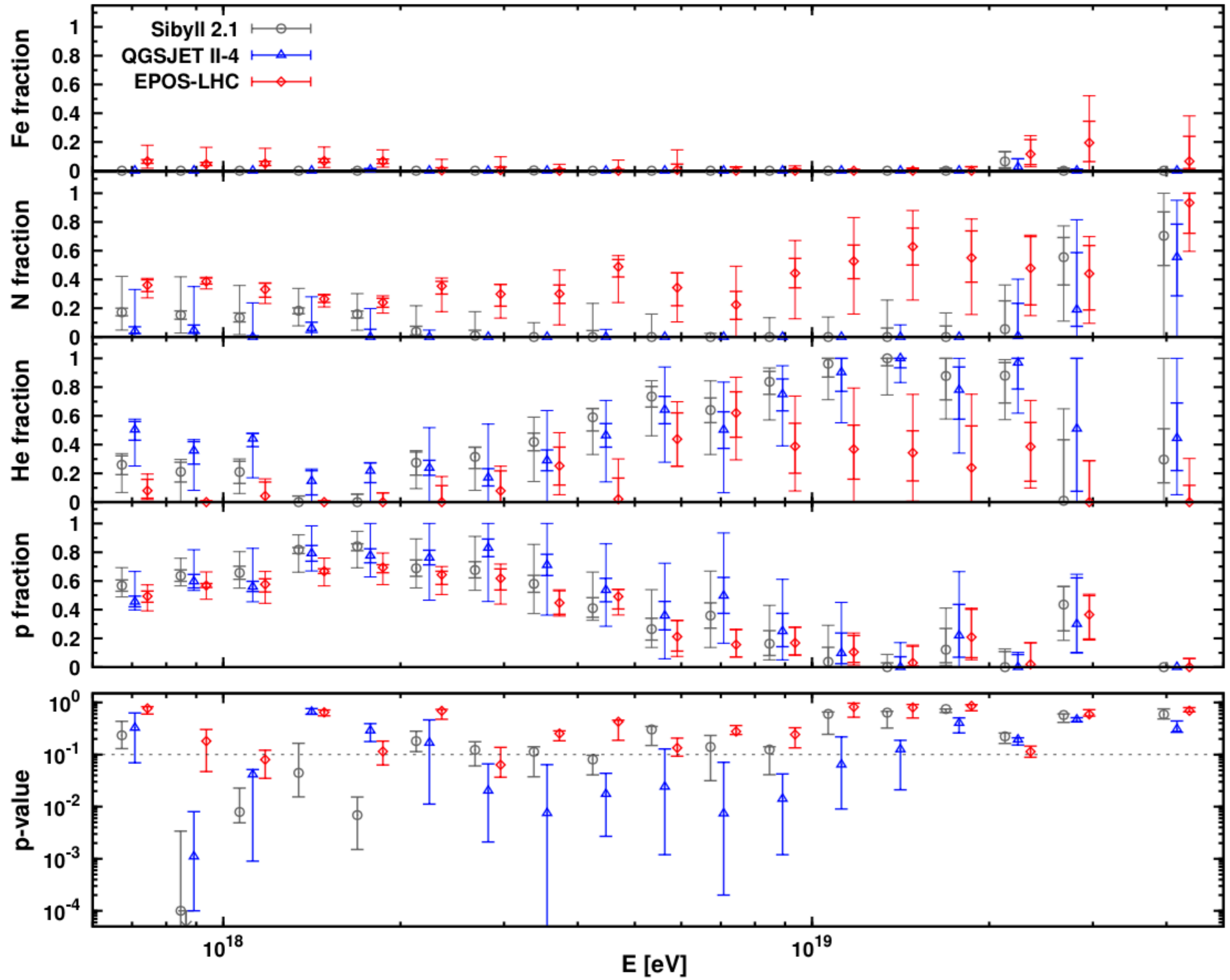
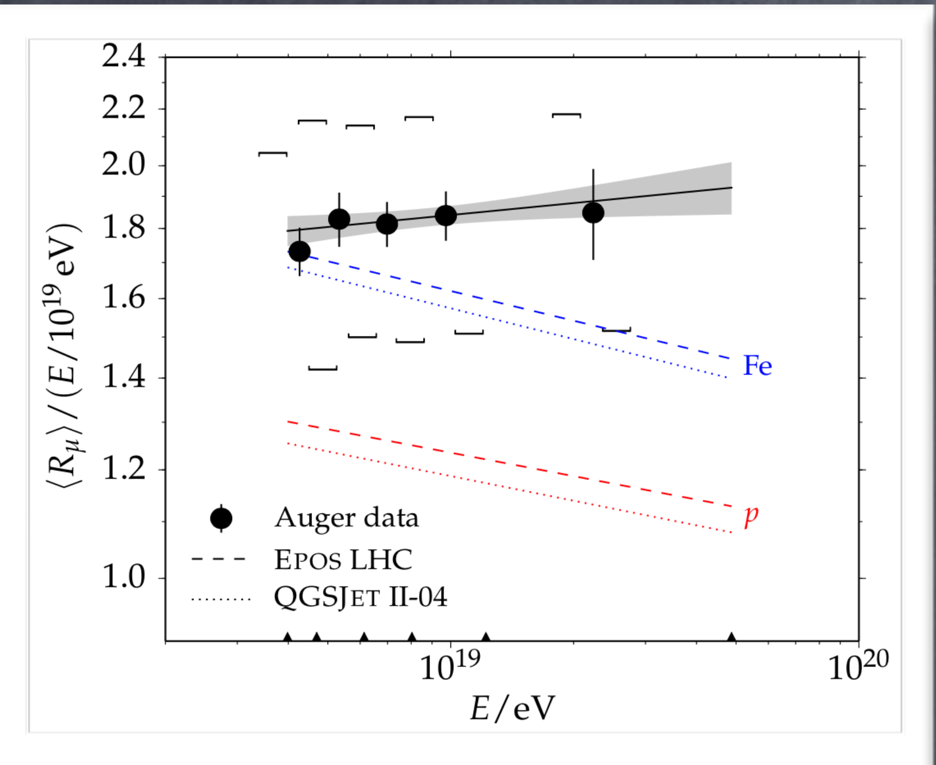
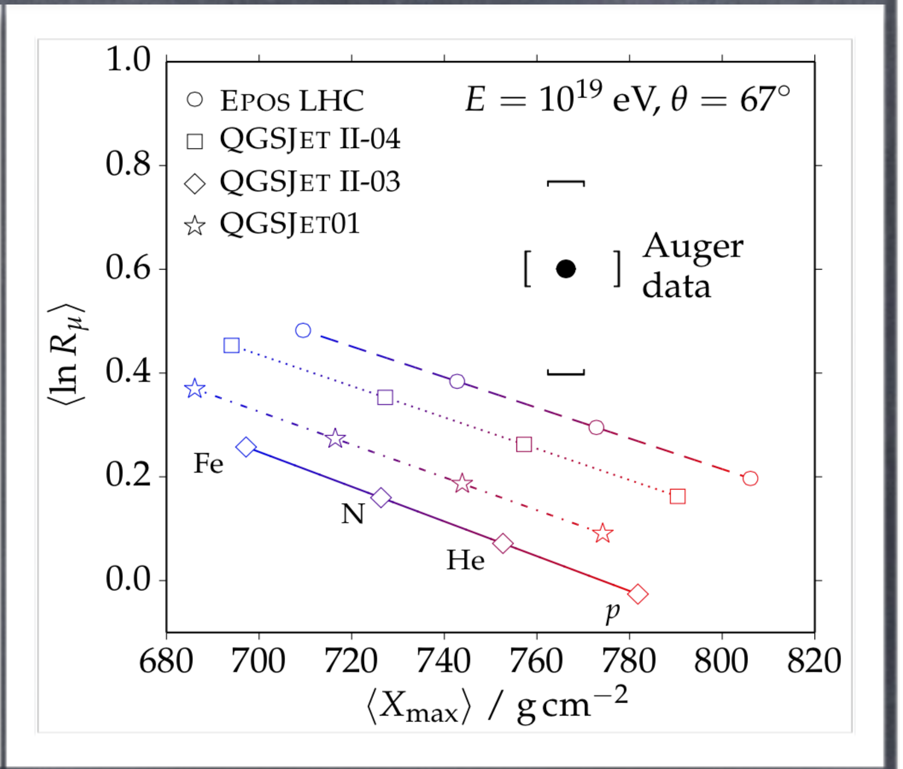


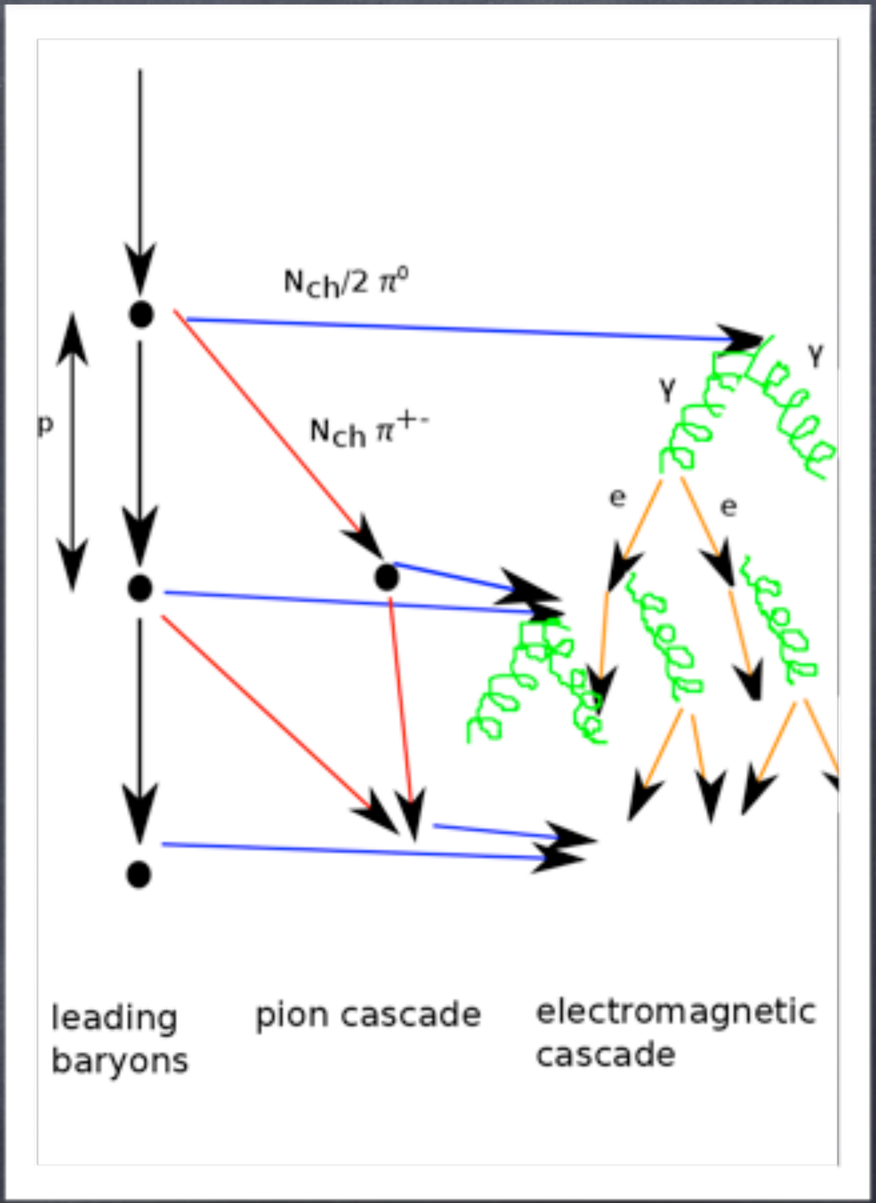
FIG. 4: Fitted fraction and quality for the scenario of a complex mixture of protons, helium nuclei, nitrogen nuclei, and iron nuclei. The upper panels show the species fractions and the lower panel shows the p-values.

Pierre Auger Collaboration, arXiv:1409.5083

Muon number measured at 1000 m from shower core systematically higher than predicted







Pierre Auger Collaboration, arXiv:1408.1421

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

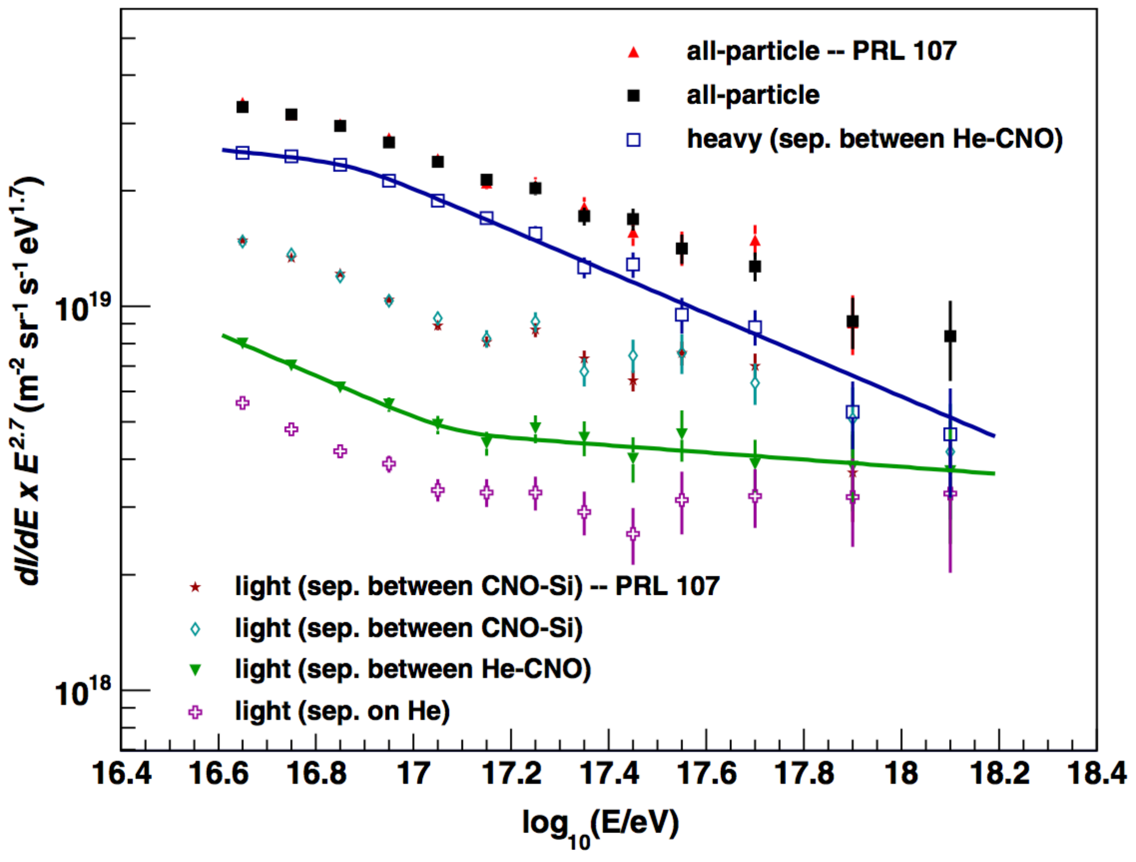
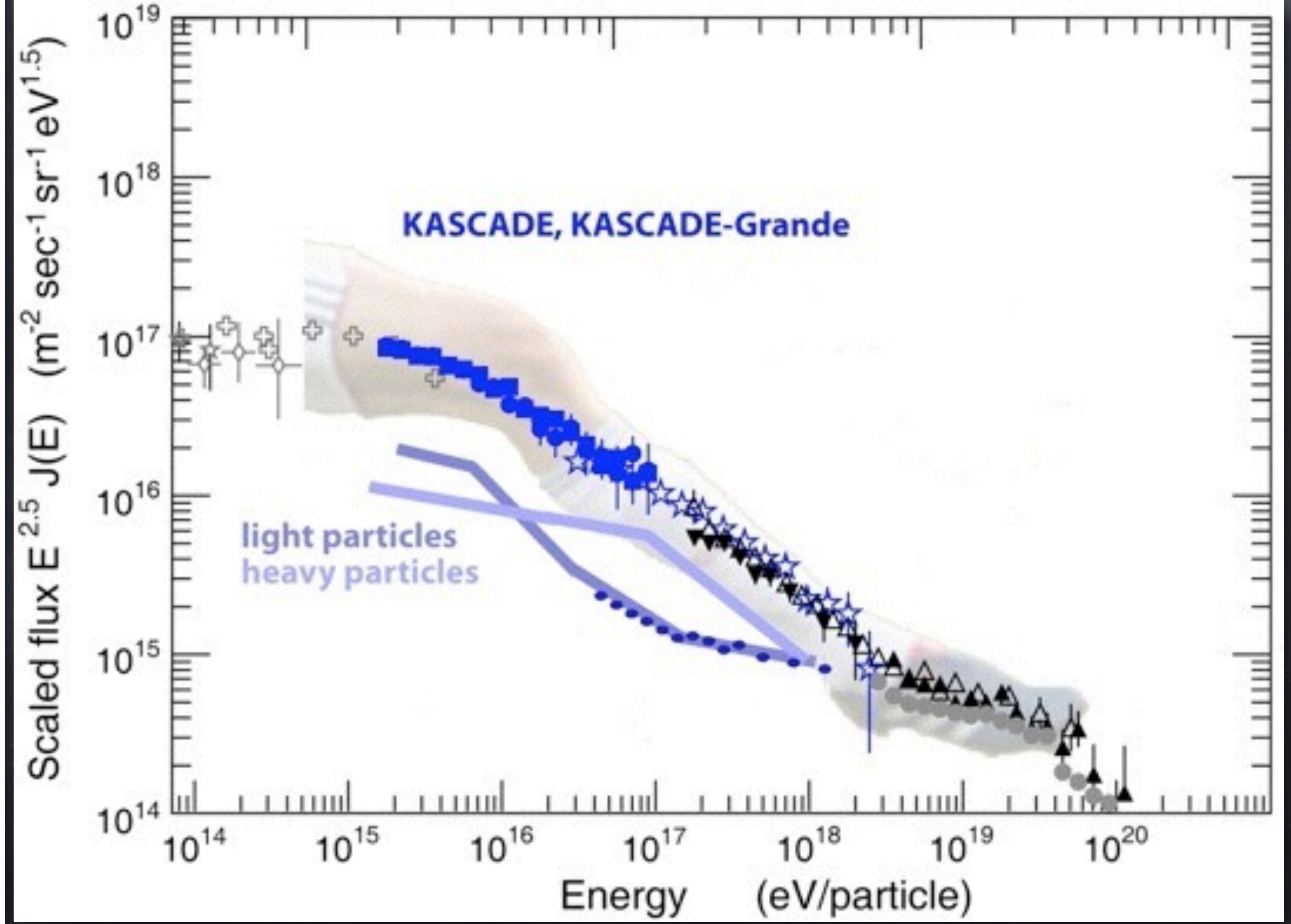
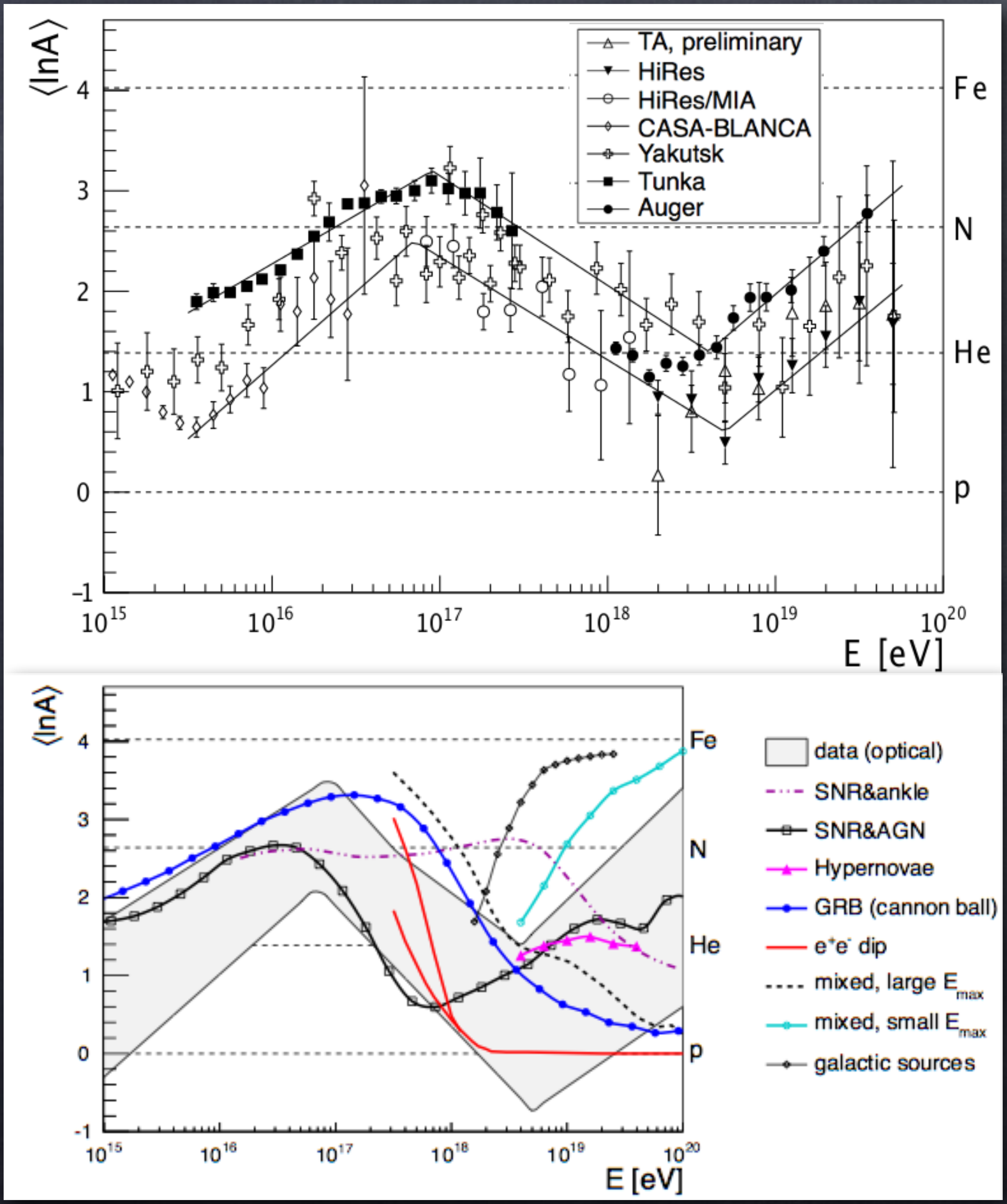


FIG. 4 (color online). The all-particle and electron-rich spectra from the analysis [8] in comparison to the results of this analysis with higher statistics. In addition to the light and heavy spectrum based on the separation between He and CNO, the light spectrum based on the separation on He is also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

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

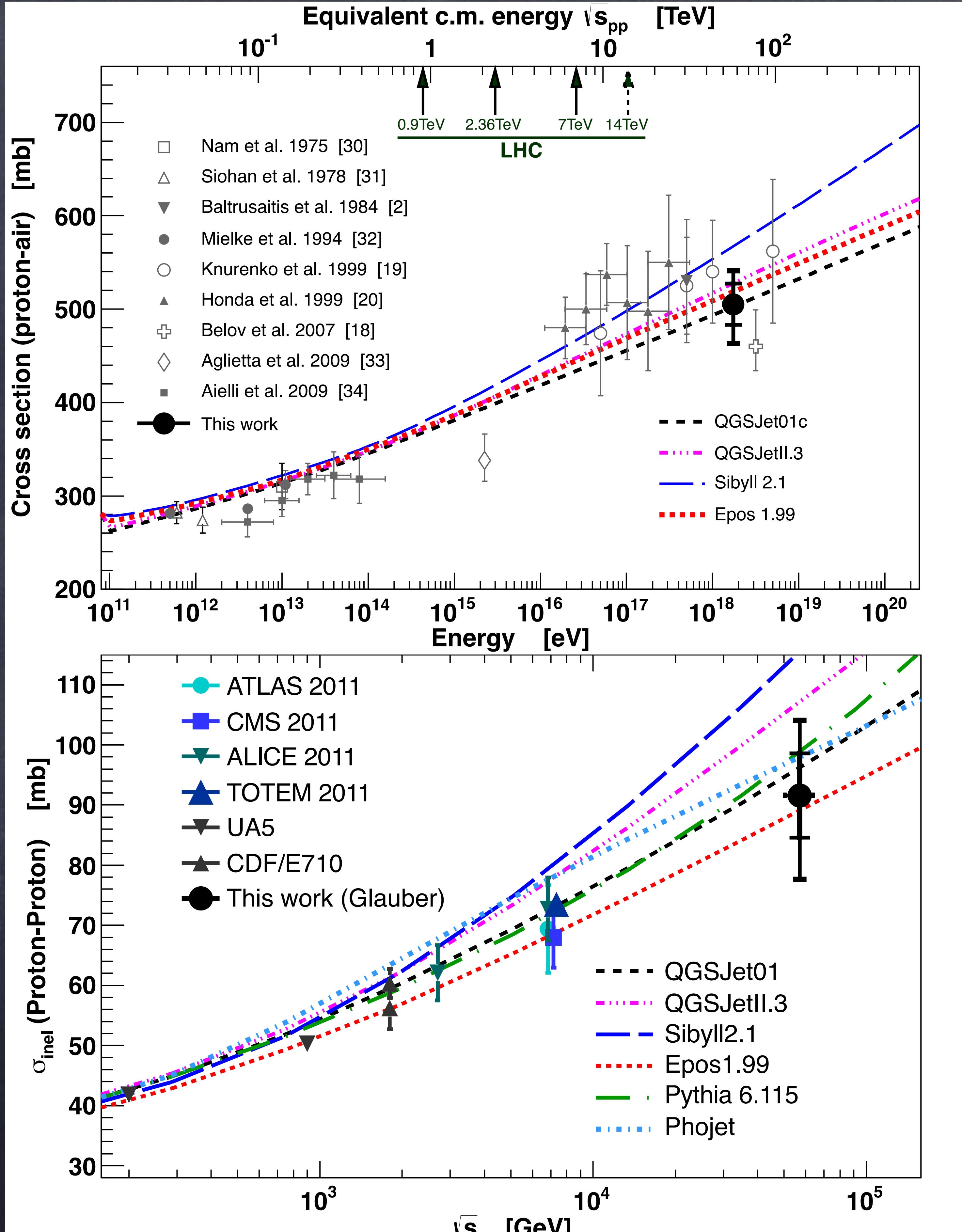


The global picture for the mass composition

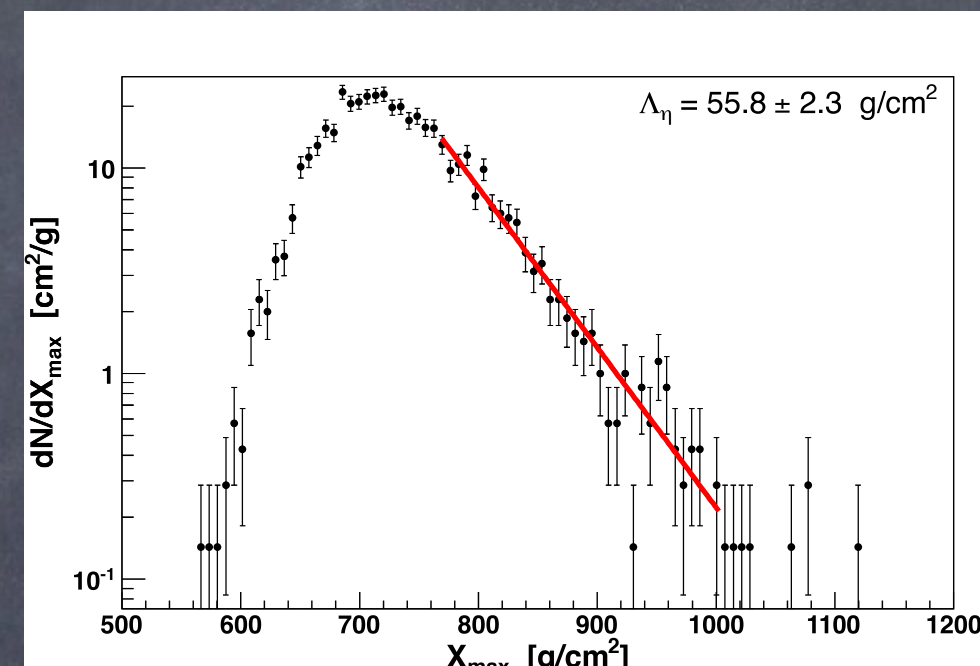


K.-H.Kampert and M.Unger, Astropart.Phys. 35 (2012) 660

Indications of "Peters cycles" for galactic and extragalactic sources whose maximal energies are proportional to the charge Z and extend up to ~ 10^{17} and 10^{20} eV, respectively



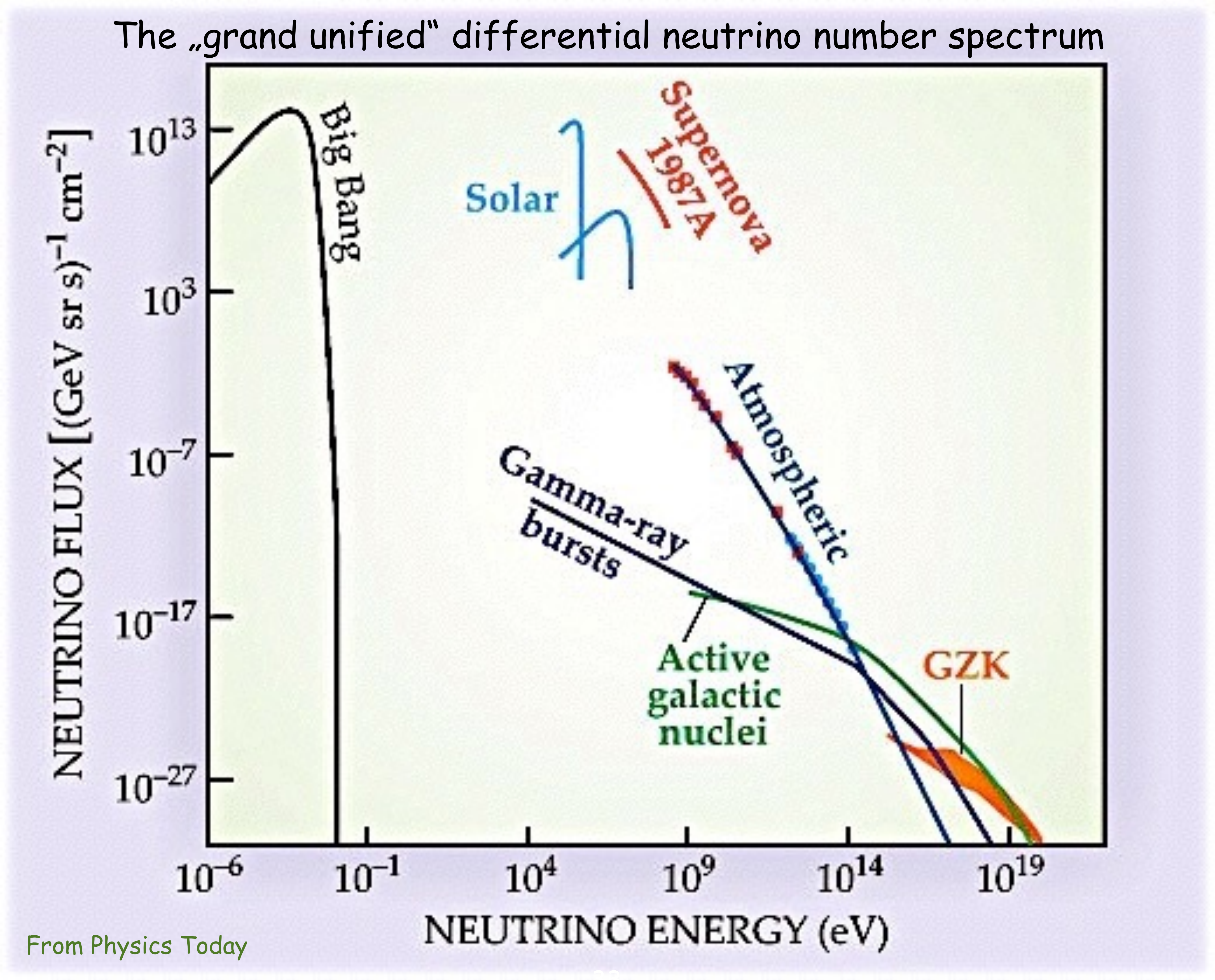
p-air cross section derived from exponential tail of depth of shower maxima



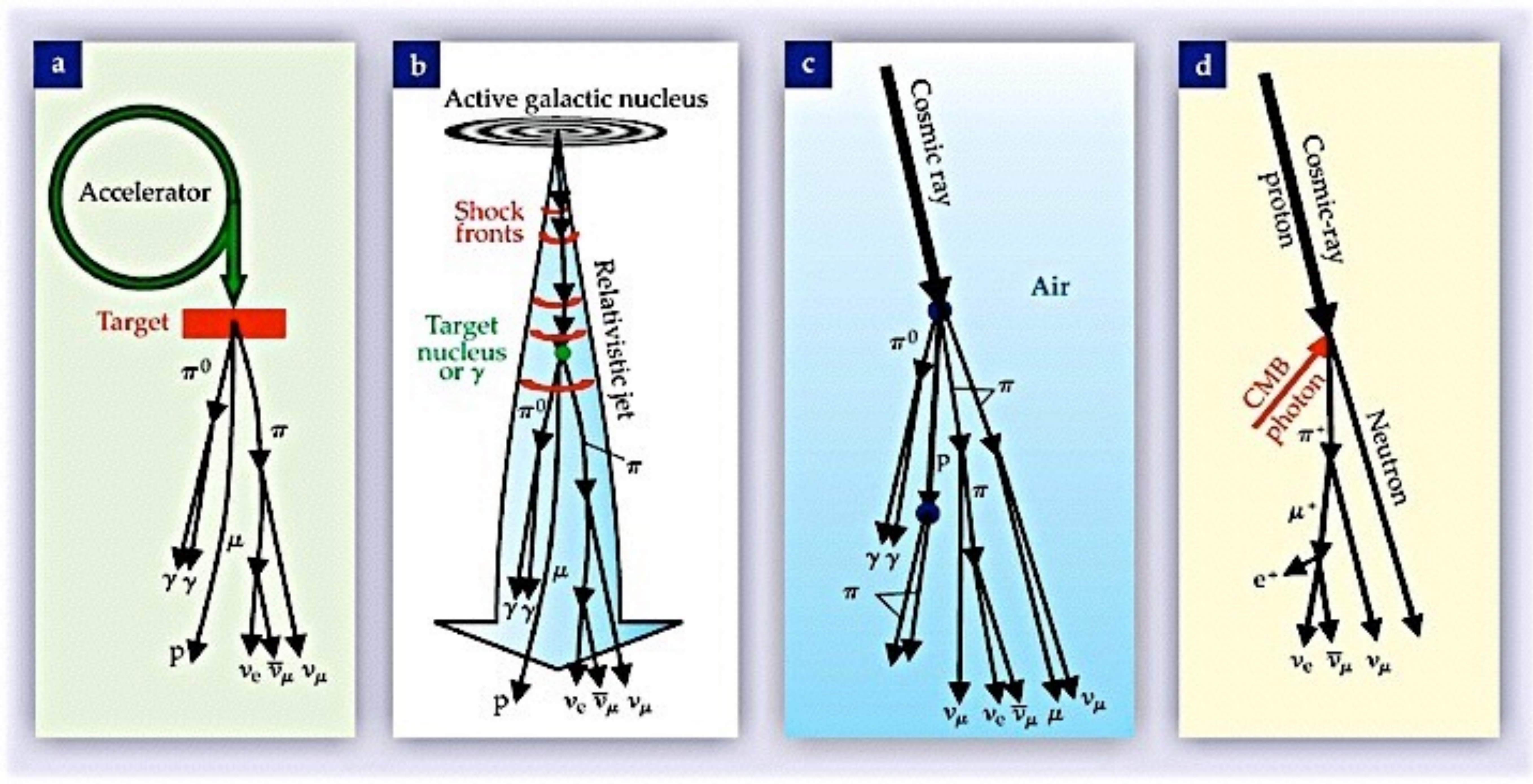
pp cross section derived from Glauber model

Pierre Auger Collaboration, PRL 109, 062002 (2012)

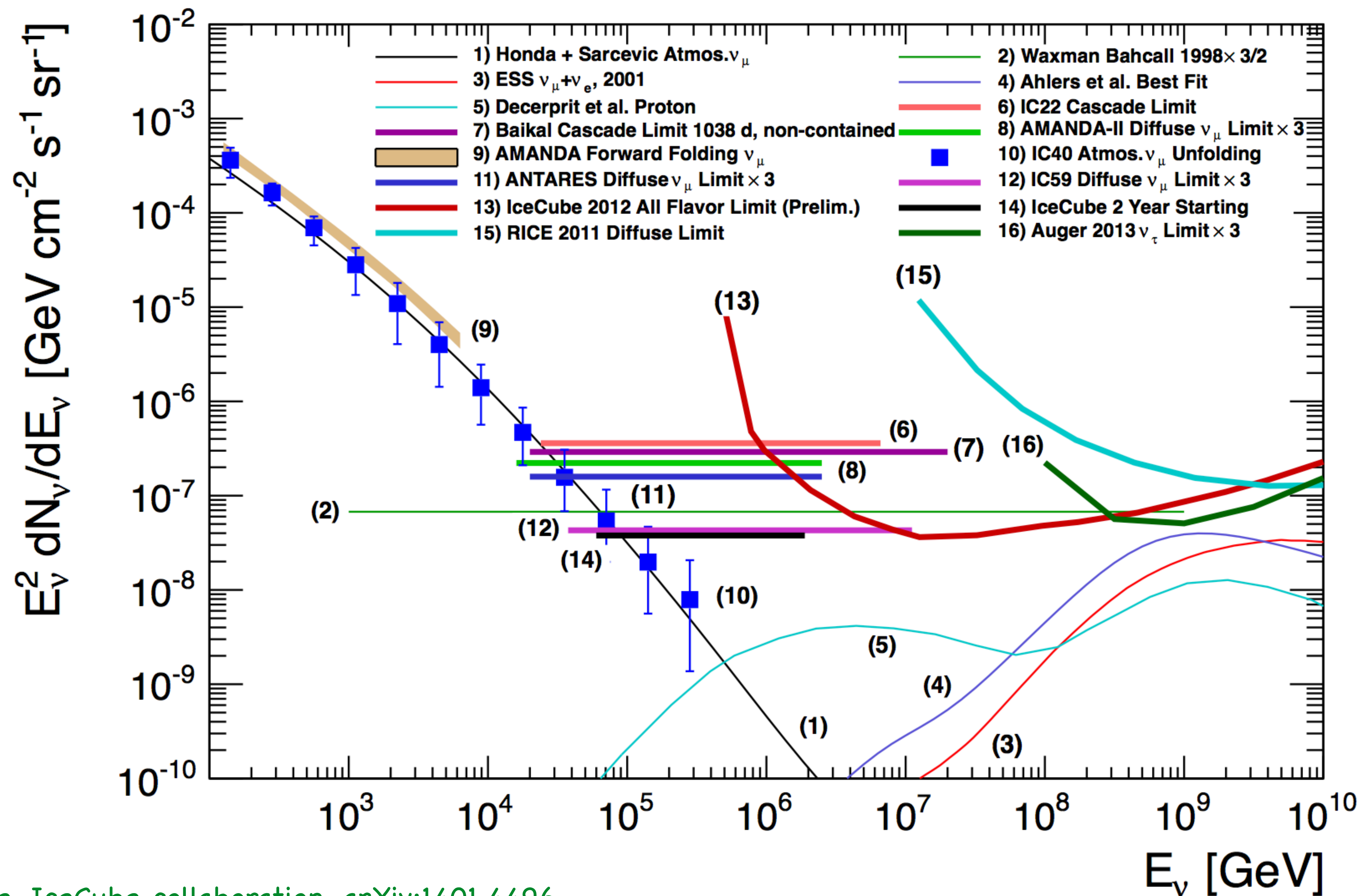
Very High High Energy Neutrinos



Summary of neutrino production modes

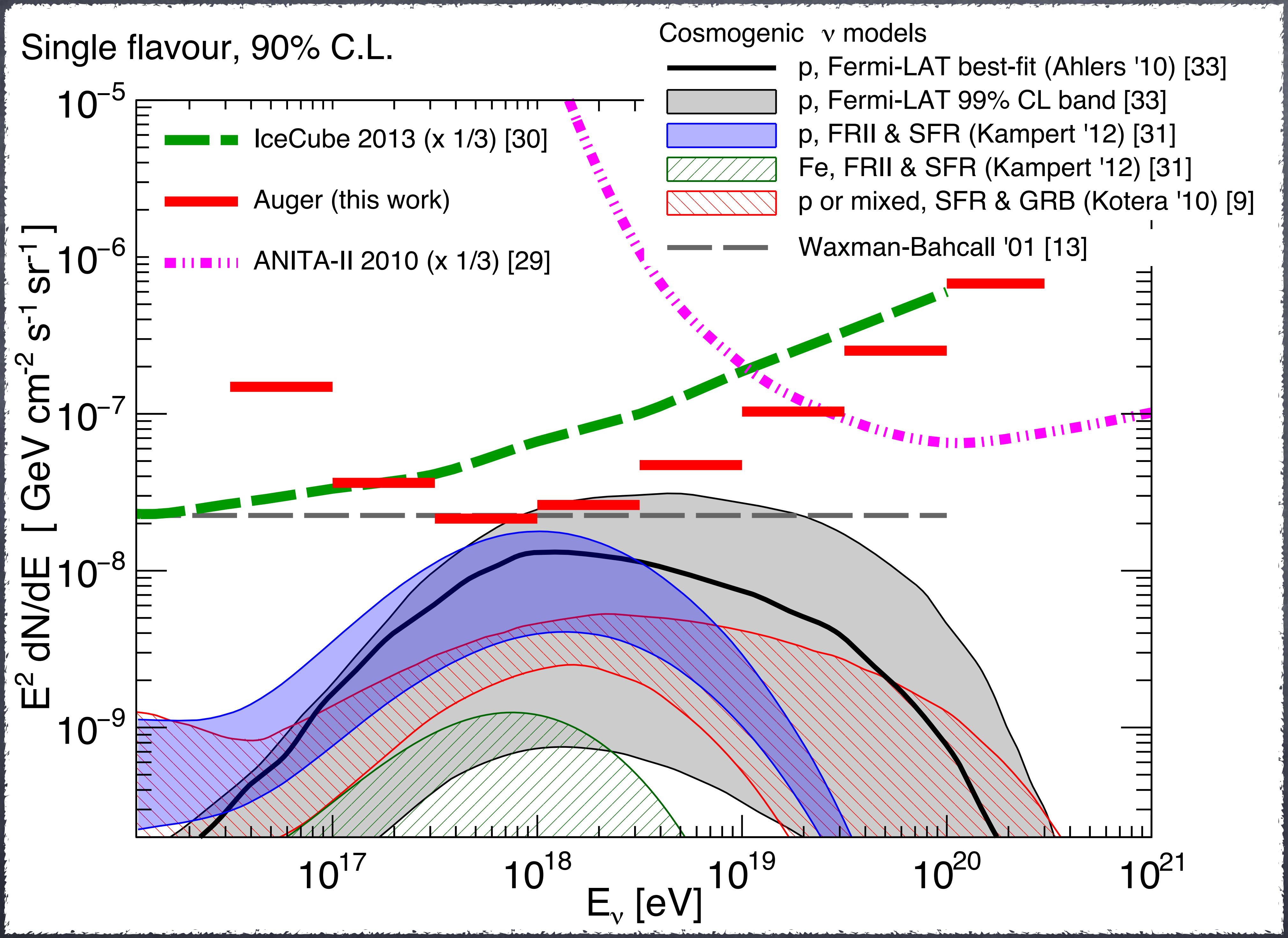


From Physics Today



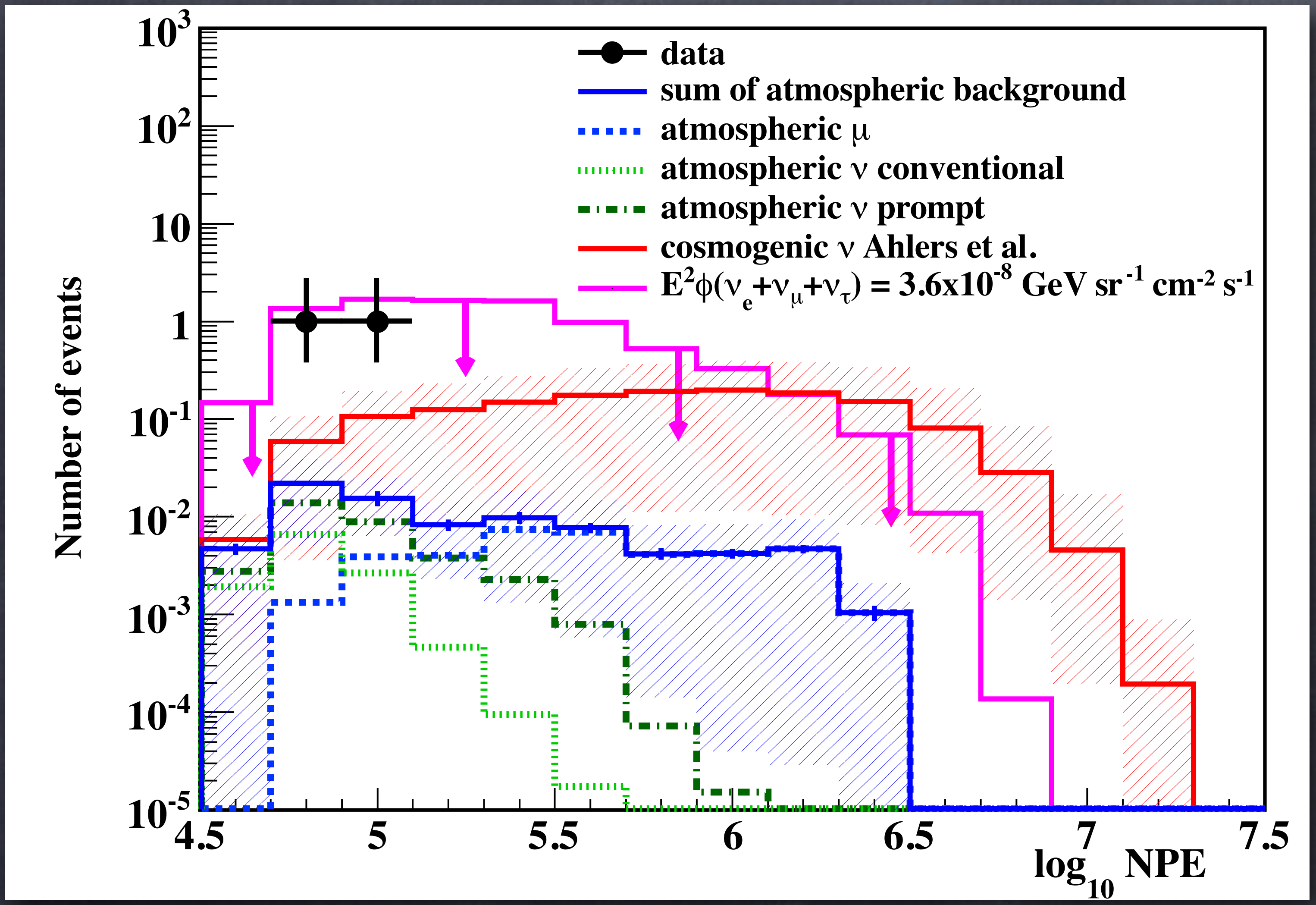
A.Karle, IceCube collaboration, arXiv:1401.4496

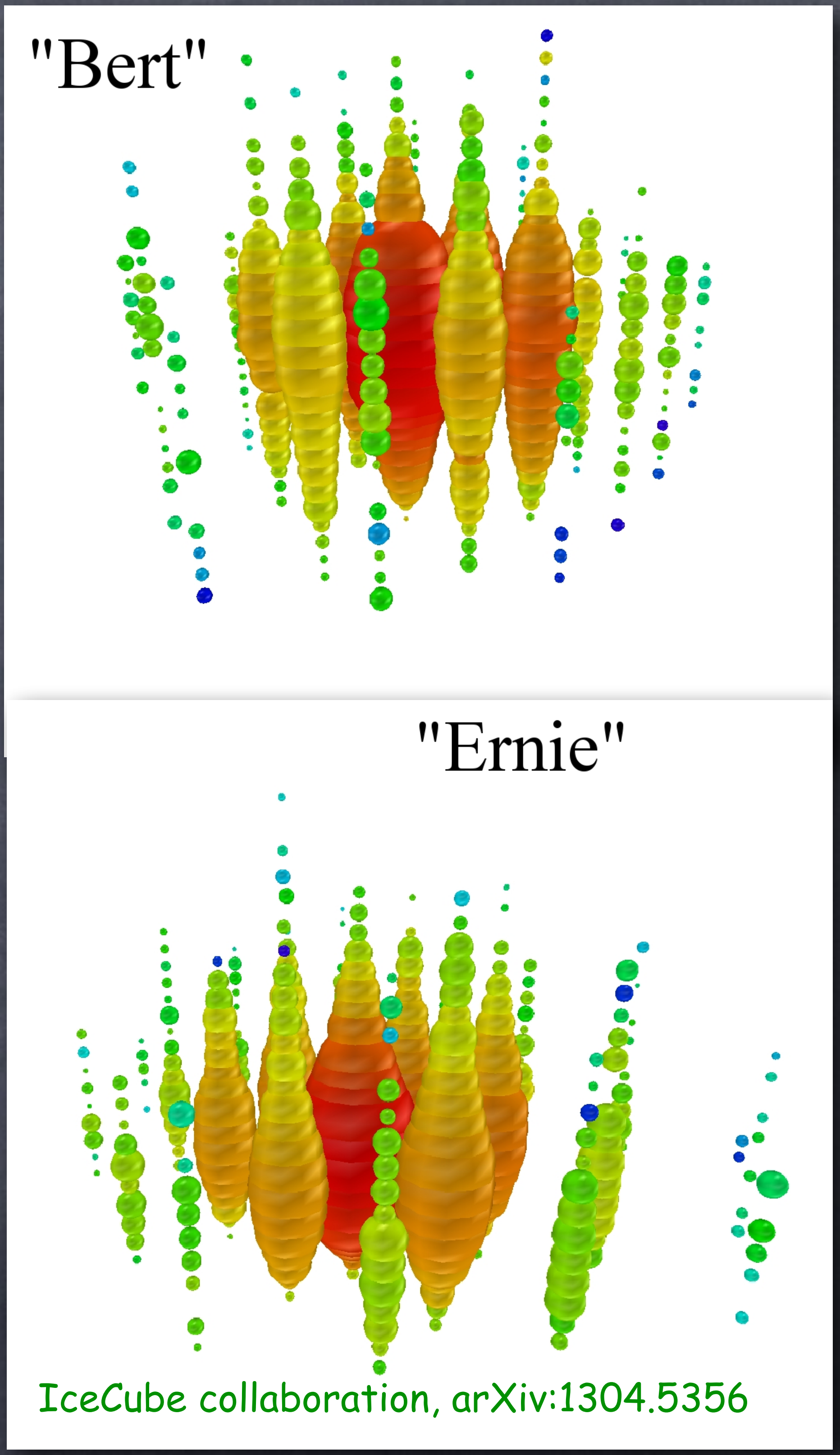
Figure 7: An overview is presented of observed atmospheric neutrino fluxes, upper limits to diffuse fluxes and models. The IceCube 2012 differential upper limit (11) turn up sharply at 1PeV because of observed PeV events. The best fit diffuse flux using starting events in IceCube (12) forms evidence for a diffuse astrophysical flux up to PeV energies above the atmospheric neutrino spectrum extending to a few 100 TeV.



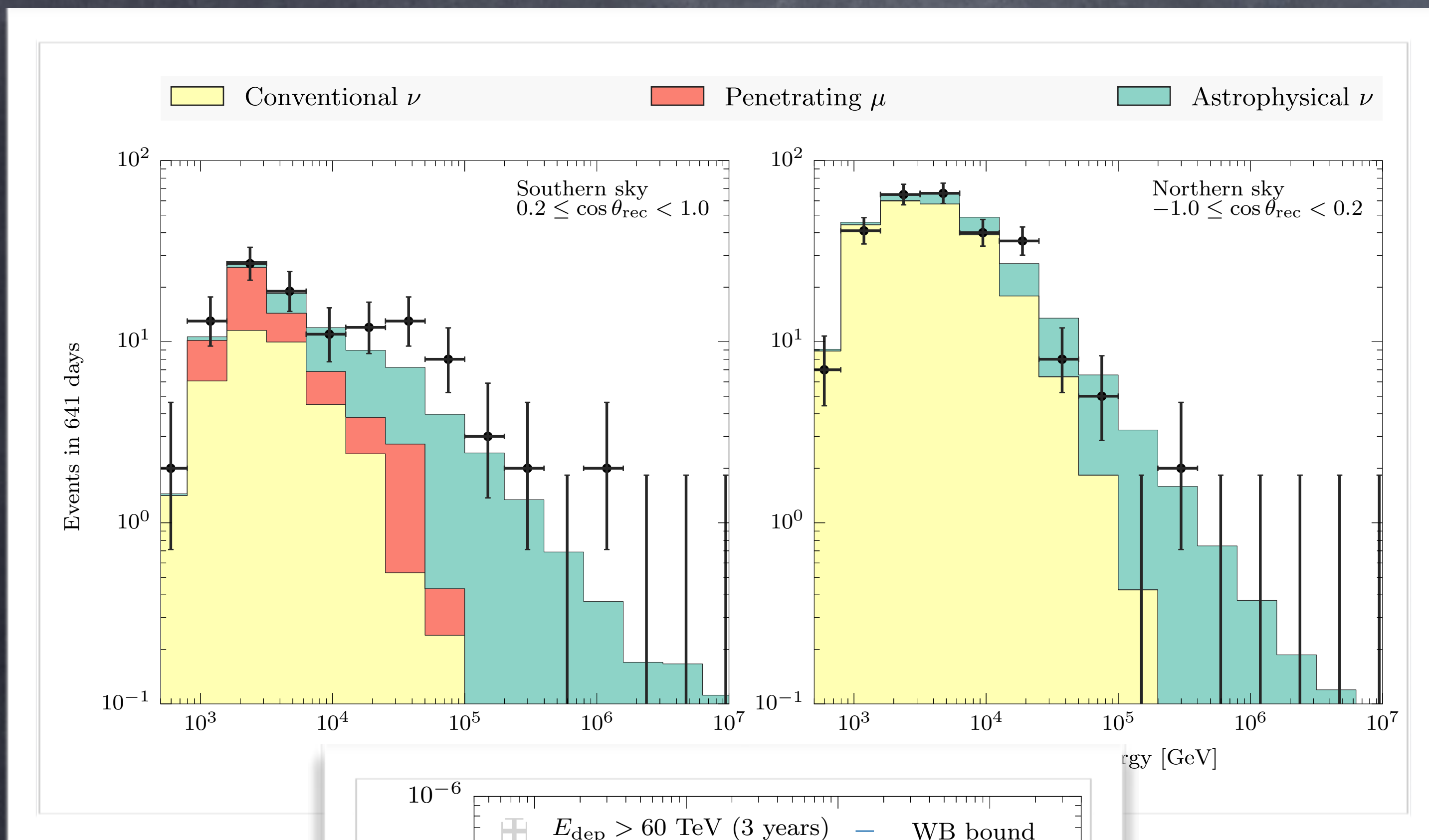
Pierre Auger collaboration, arXiv:1504.05397

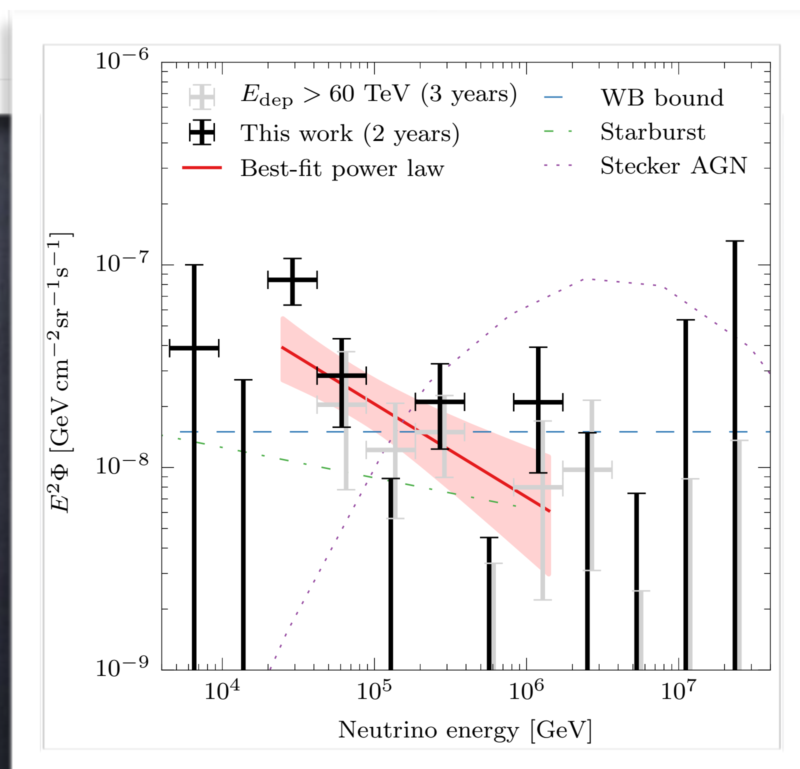
But now two PeV energy candidate neutrinos observed by IceCube

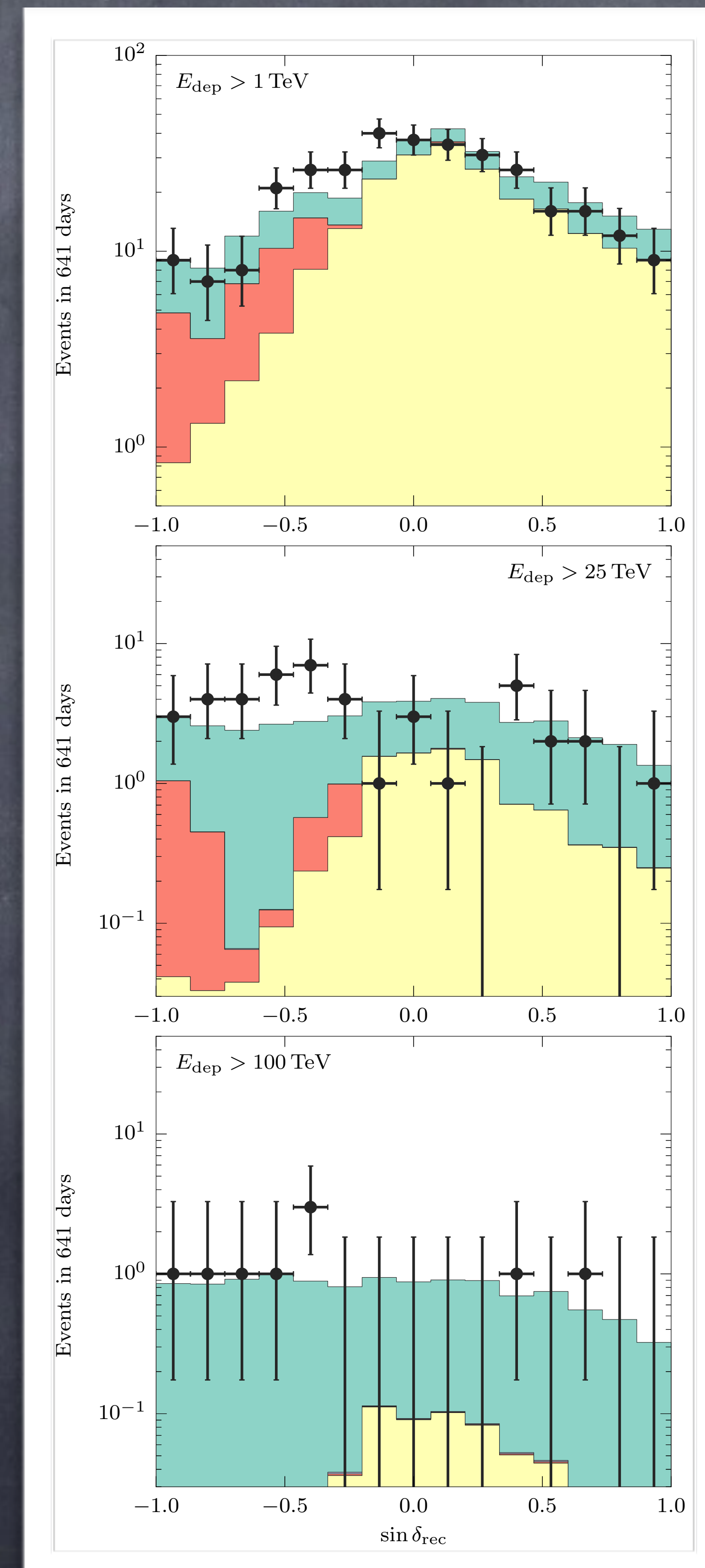




IceCube observed 283 cascade and 105 track events from the Southern sky above 1 TeV deposited energy:







IceCube collaboration, Phys.Rev. D 91 (2015) 022001 [arXiv:1410.1749]

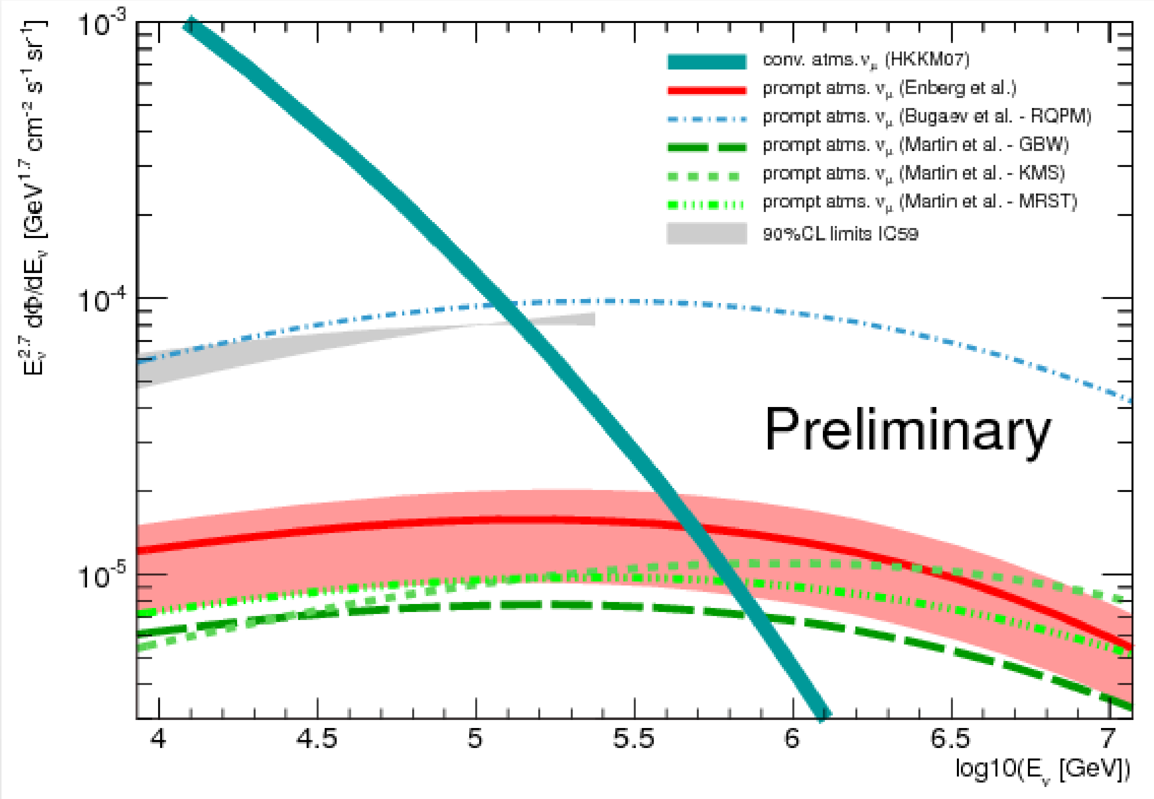
The "background": atmospheric ν

* To assess the entity of an IceCube diffuse signal of purely astrophysical origin an accurate estimation of the background is mandatory.

* Atmospheric neutrinos are a source of background:

Cosmic Rays + Atmospheric Nuclei → hadrons → neutrinos

* Two contributing mechanisms, following two different power-law regimes:
  - conventional ν flux from the decay of $\pi^{\pm}$ and $K^{\pm}$
  - prompt ν flux from charmed and havier hadrons (D, B)



Garzelli, Moch, Sigl, JHEP 1510 (2015) 115

Transition point: still subject of investigation ([IceCube collab., [arXiv:1302.0127]]).

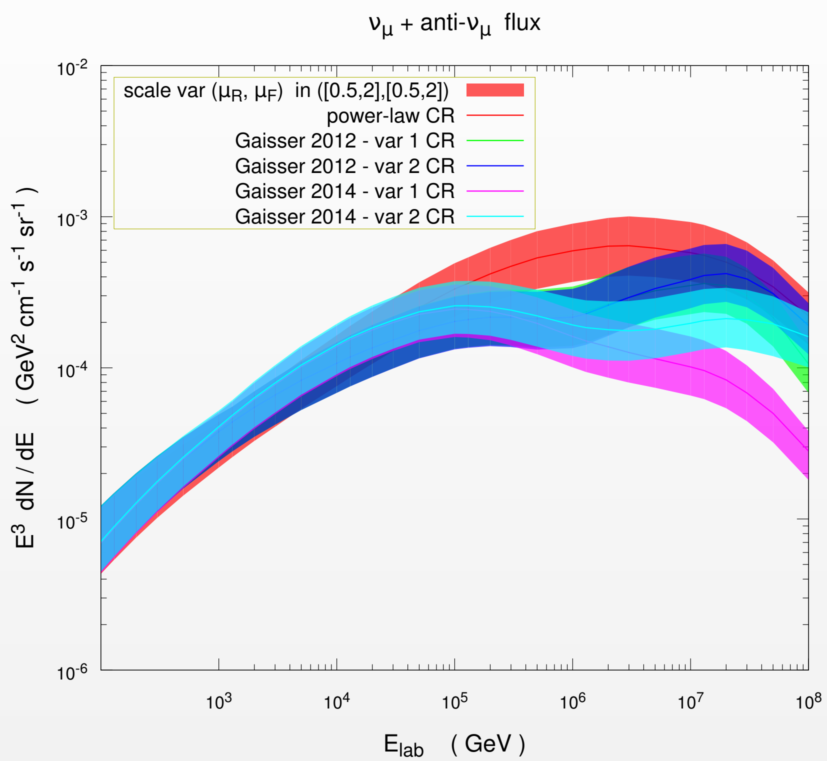
The QCD core of the Z-moments for prompt fluxes: $d\sigma(pp \to charmed\ hadrons)/dx_E$

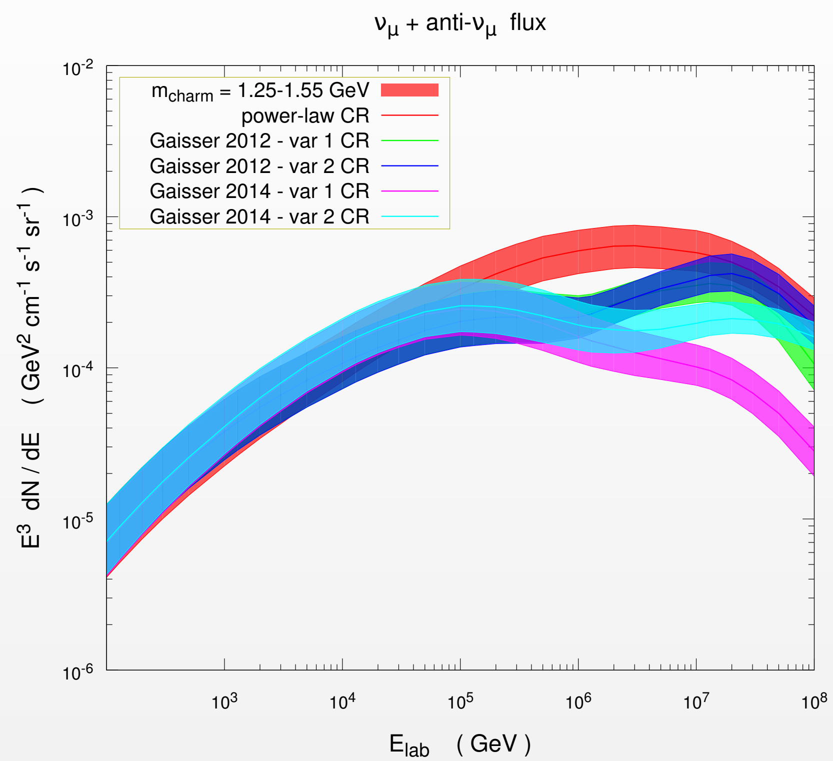
$$Z_{ph}(E_h) = \int_0^1 \frac{dx_E}{x_E} \frac{\phi_p(E_h/x_E, 0)}{\phi_p(E_h, 0)} \frac{\lambda_p(E_h)}{\lambda_p(E_h/x_E)} \frac{A_{air}}{\sigma^{tot,inel}_{p-Air}(E_h)} \frac{d\sigma_{pp\to c\bar{c}\to h+X}}{dx_E}(E_h/x_E)$$

We used a (NLO QCD + Parton Shower + Hadronization) approach, with central scale, PDF and m_{charm} choices driven by previous considerations (see LO/NLO/NNLO plots) and variations in the following intervals:

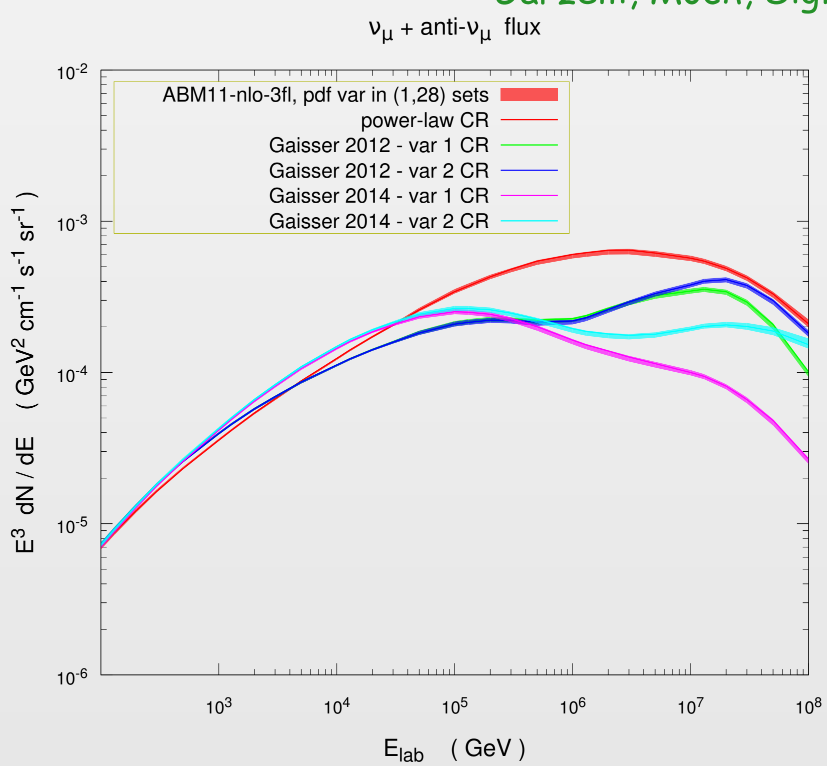
- central scale $(\mu_R, \mu_F) = \mu_0 = \sqrt{p^2_{T,charm} + 4m^2_{charm}}$, with independent variations of $\mu_R \in (0.5, 2)\mu_0$ and $\mu_F \in (0.5, 2)\mu_0$
- m^{pole}_{charm}= 1.40 GeV, with variation in [1.25,1.55] GeV
- PDFs:
  * ABM11-NLO-3fl full set (central + 28 variations)
  * CT10-nlo-3fl (central)
  * NNPDF3.0-3fl (central)

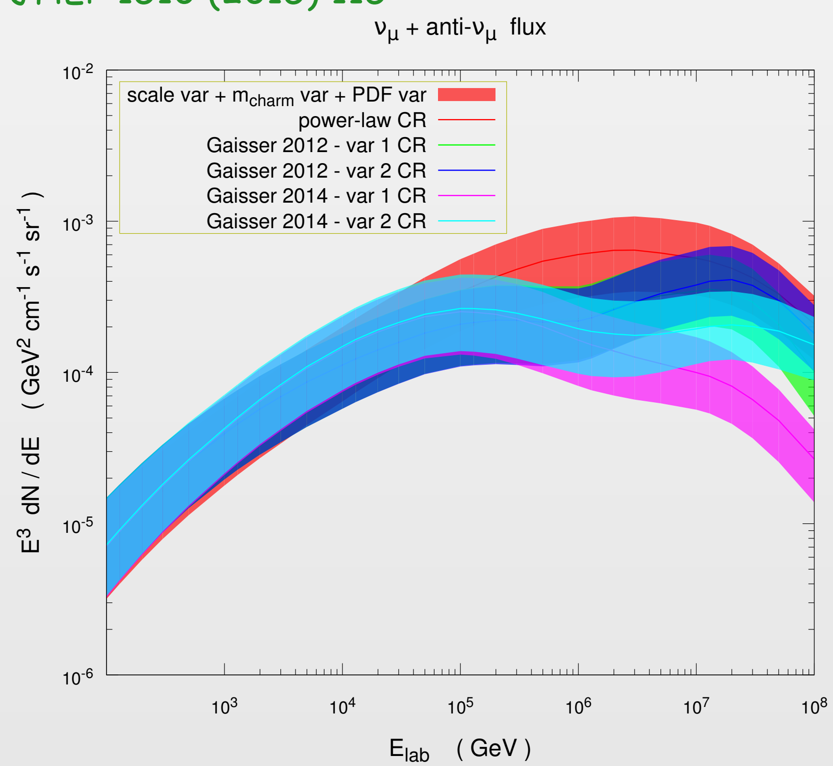
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: (scale + mass + PDF) variation summary



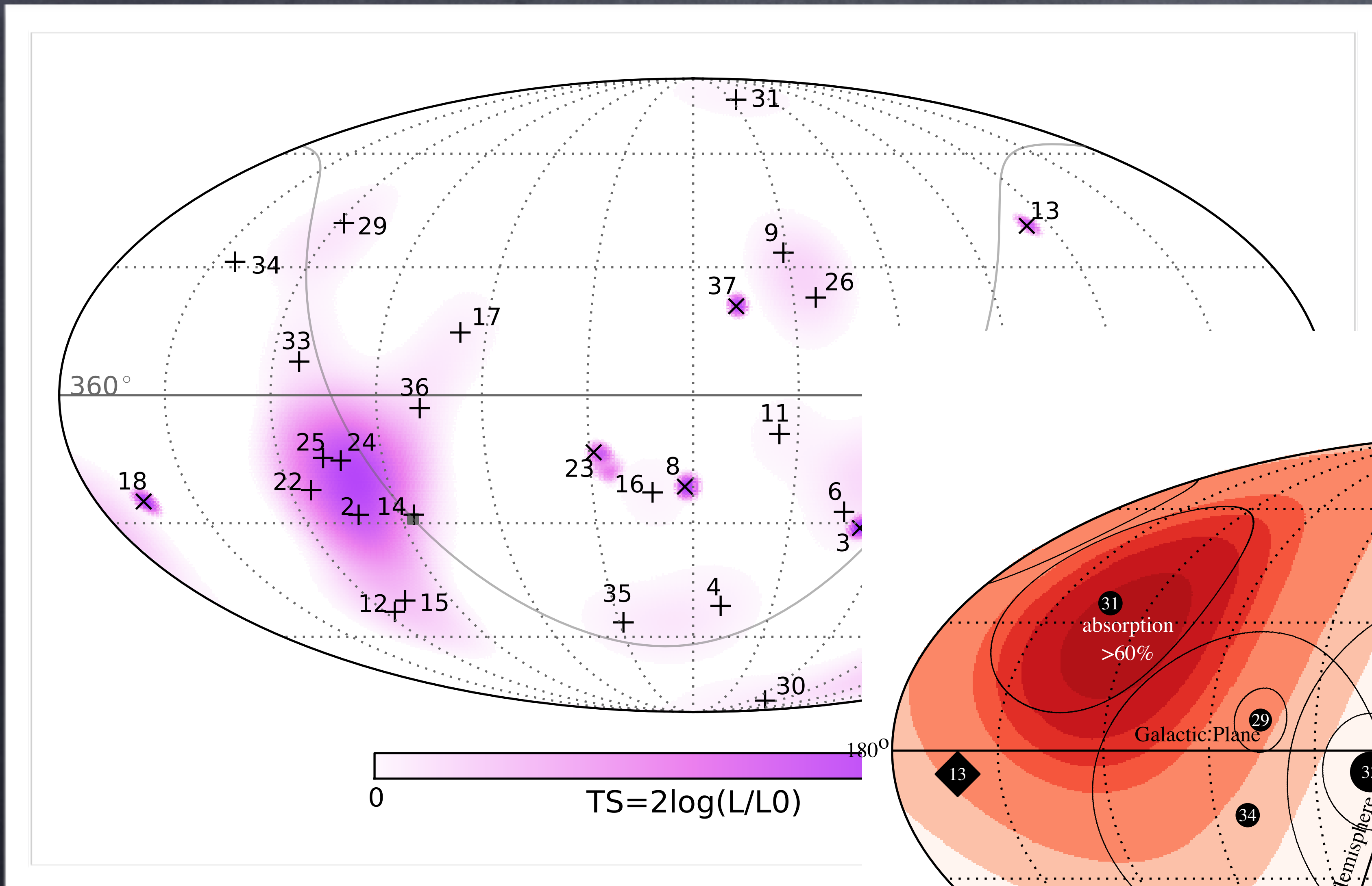


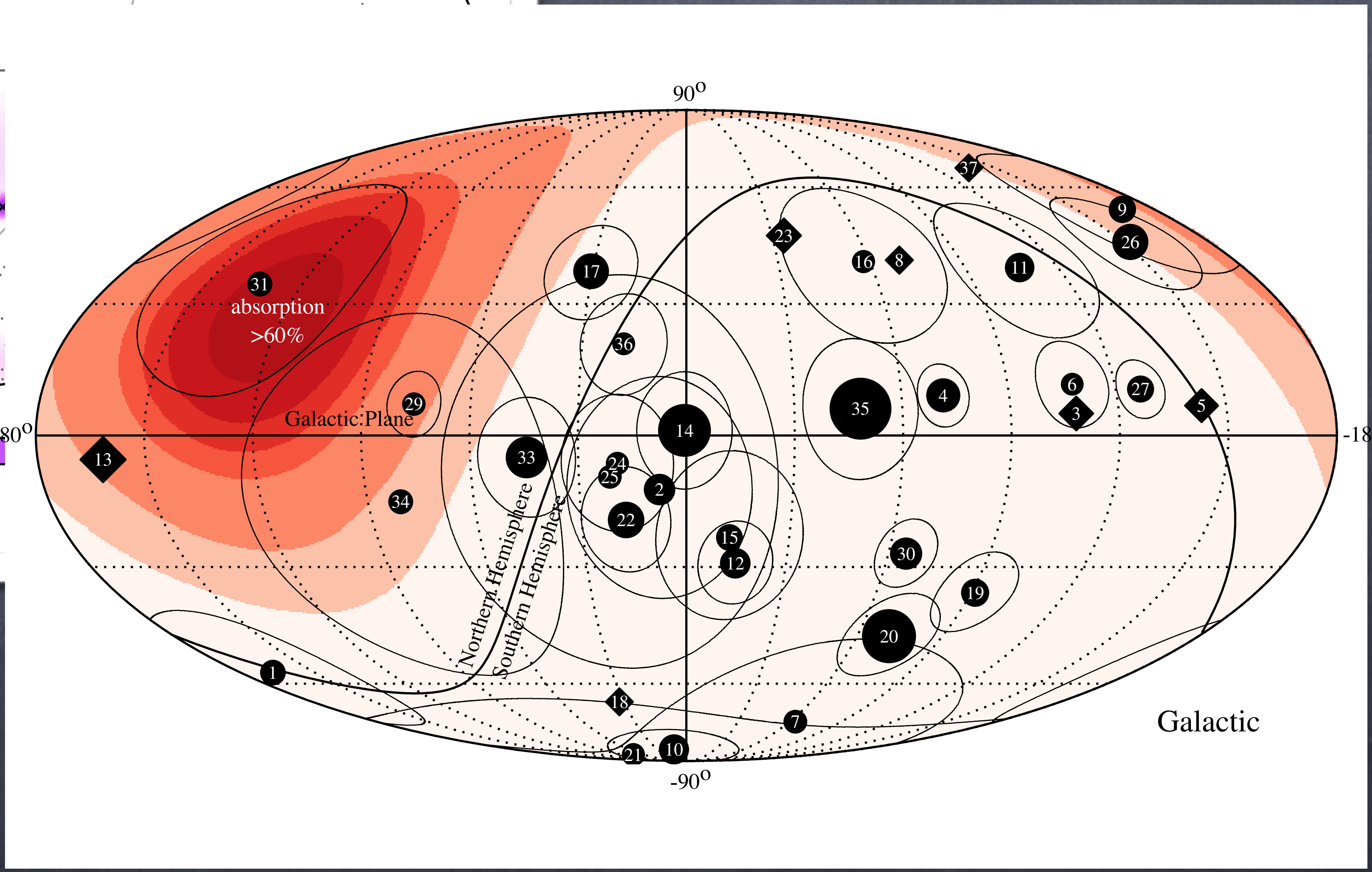
Garzelli, Moch, Sigl, JHEP 1510 (2015) 115





Neutrino sky distribution

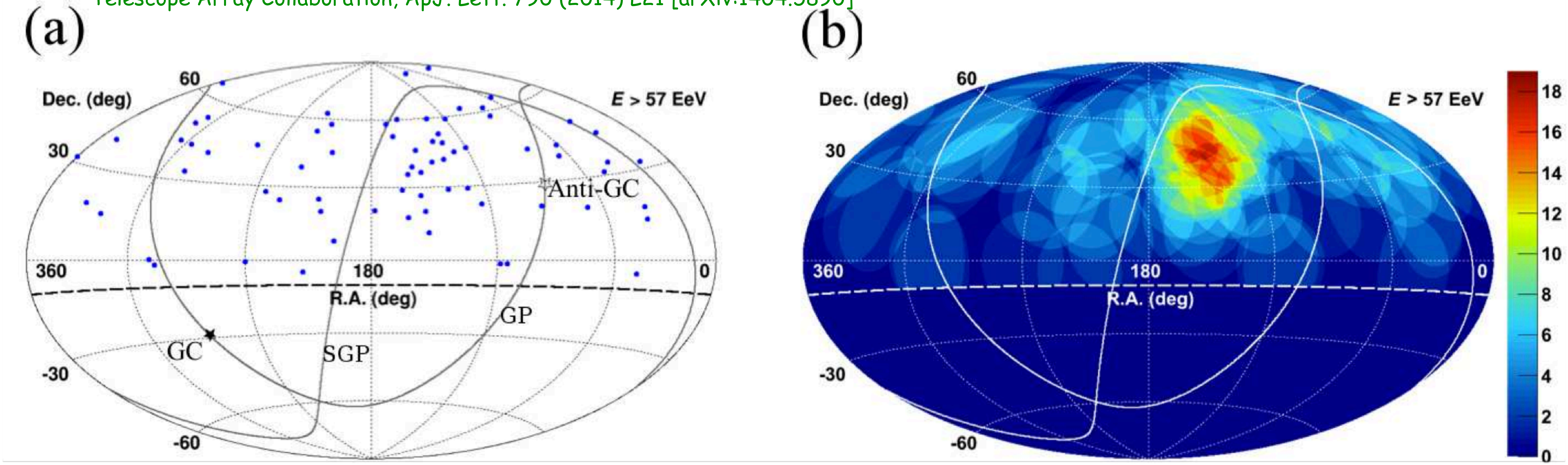




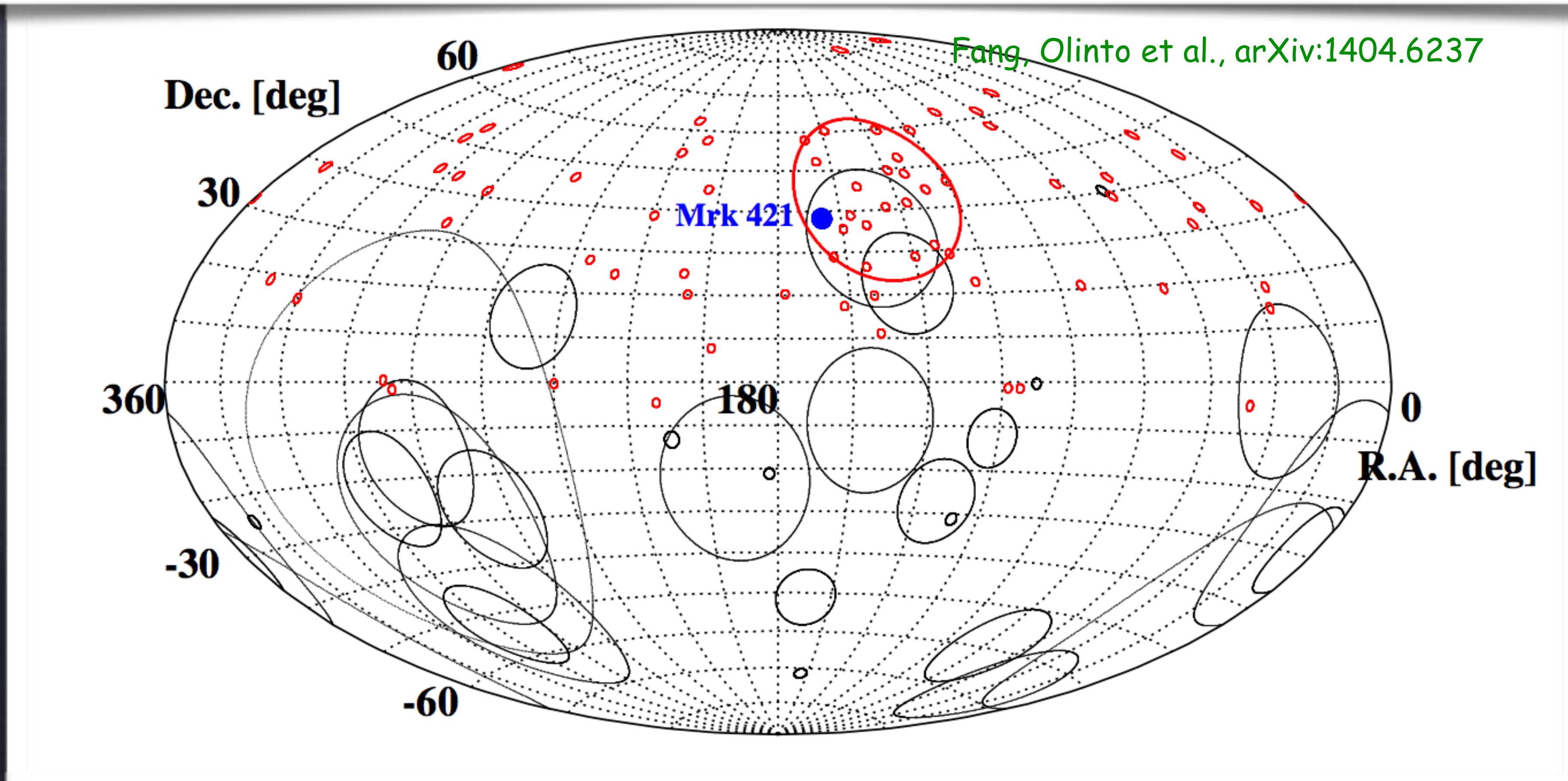
IceCube collaboration, Phys.Rev. Lett. 113 (2014) 101101 [arXiv:1405.5303]

A possible Correlation of IceCube Neutrinos with the Cosmic Ray Excess seen by Telescope Array ?

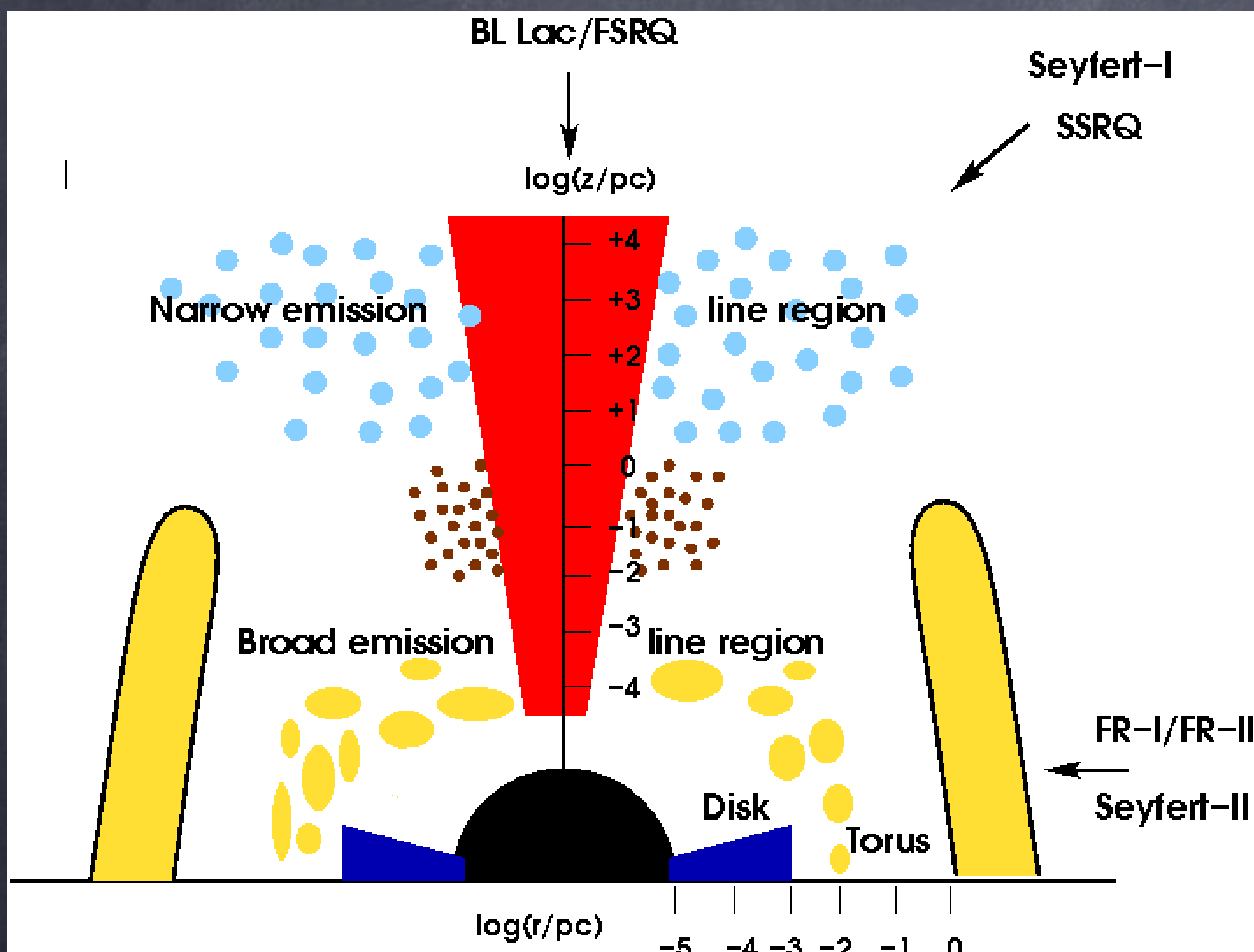
Telescope Array Collaboration, ApJ. Lett. 790 (2014) L21 [arXiv:1404.5890]

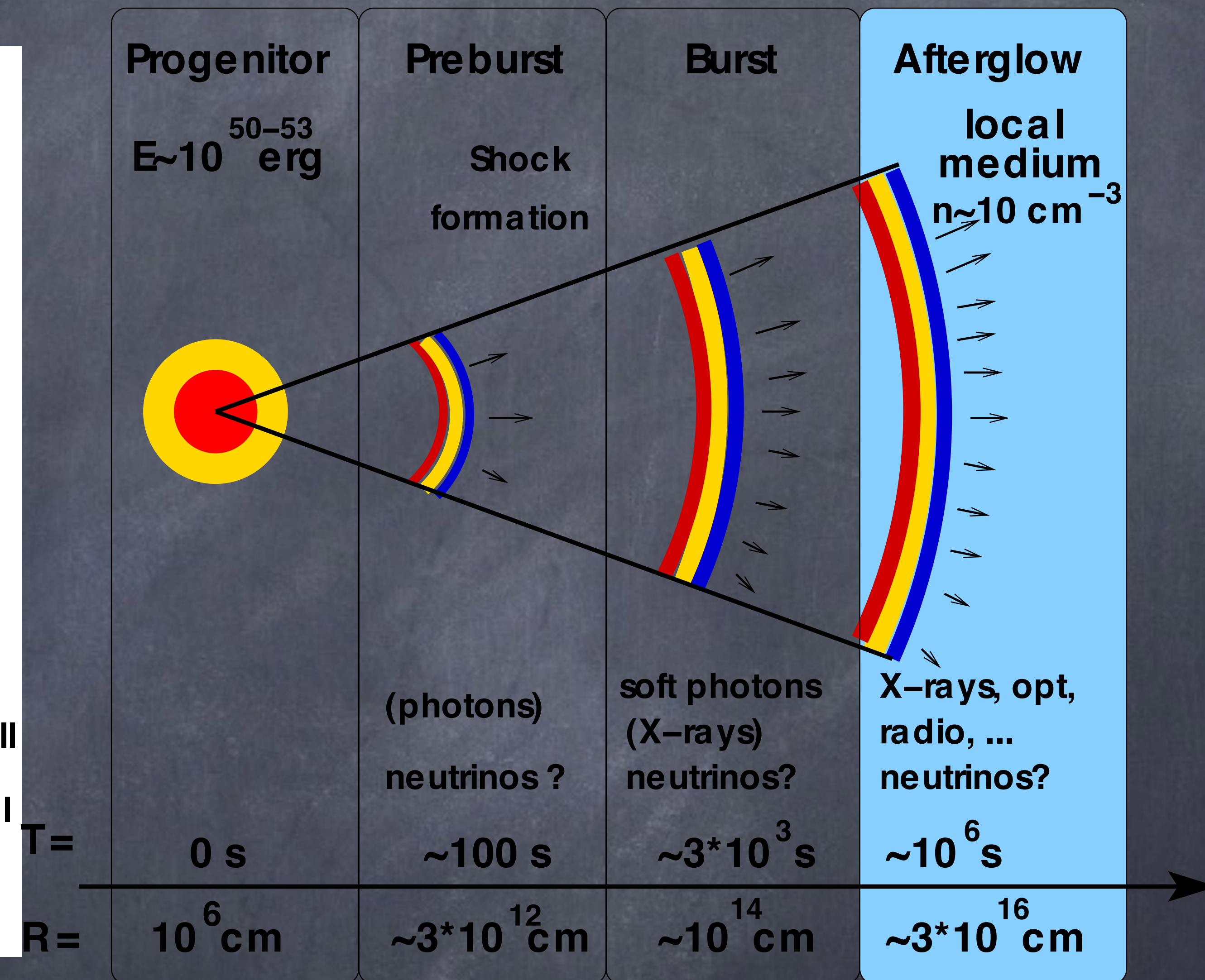


Fang, Olinto et al., arXiv:1404.6237



Discrete Extragalactic High Energy Neutrino Sources





active galaxies **gamma ray bursts**

Figures from J. Becker-Tjus, 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)

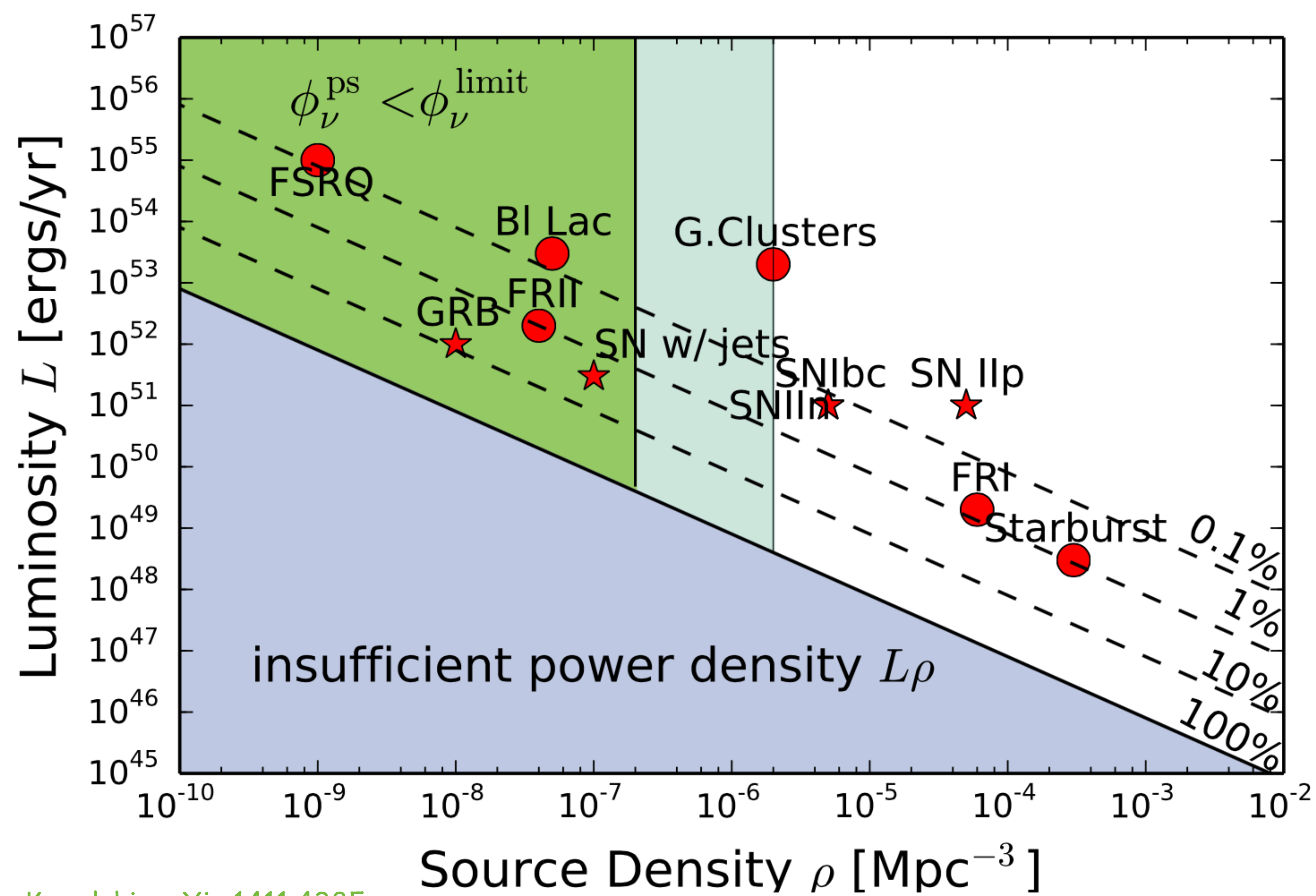
$$\Phi_\nu(E_\nu) \sim \frac{1}{\eta_\nu}\Phi_p\left(\frac{E}{\eta_\nu}\right) ,$$

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

Correlation studies with GRBs now constrain the GRB contribution to observed diffuse neutrino flux to < 1%, see IceCube collaboration arXiv:1601.06484; also implies subdominant contribution of GRBs to ultra-high energy cosmic rays

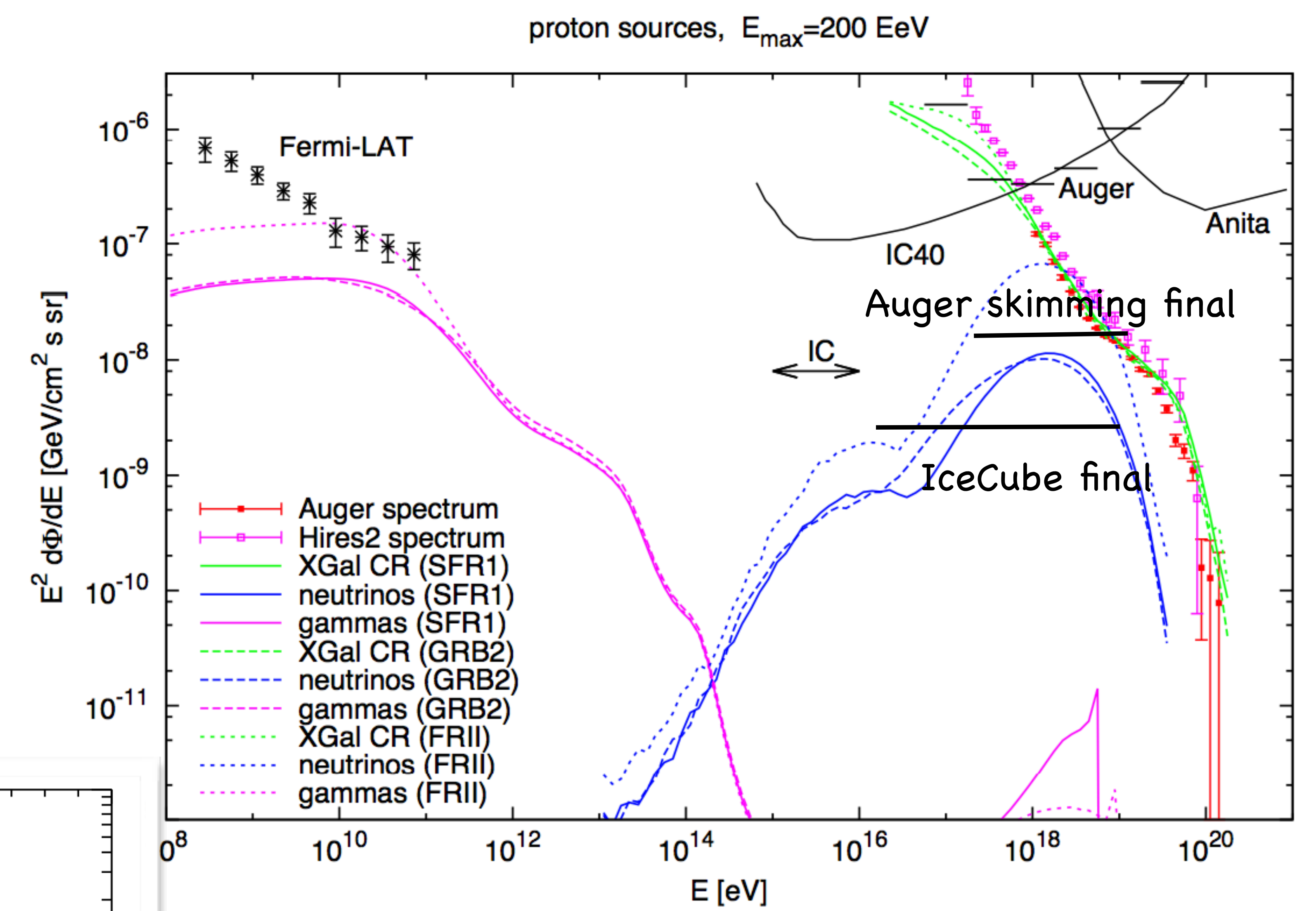
But a combination of the measured diffuse flux with upper limits on individual sources constrains source type



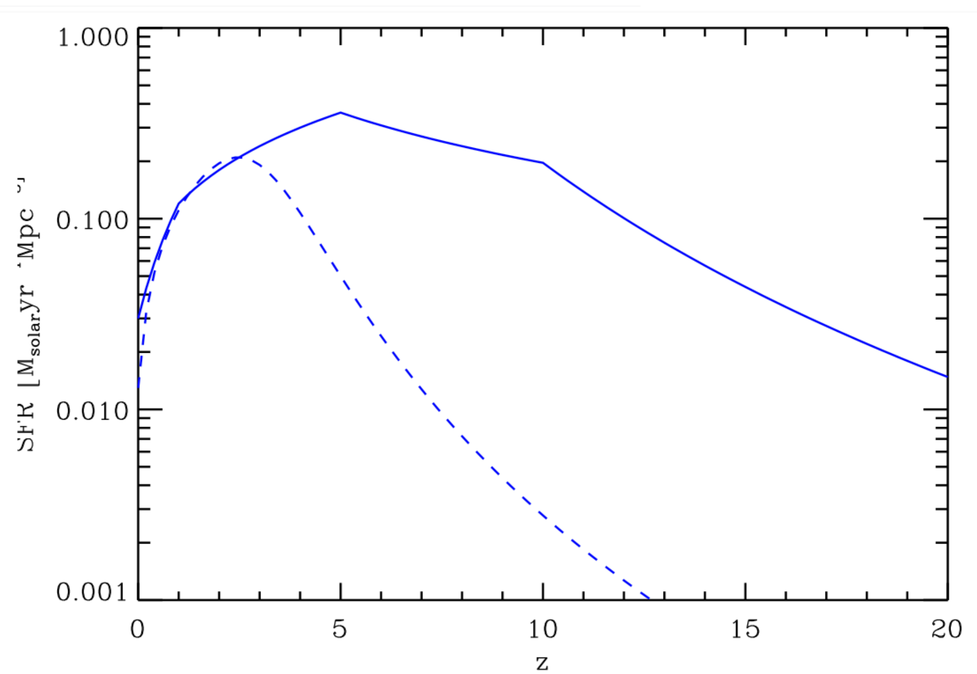
Kowalski, arXiv:1411.4385

Cosmogenic Neutrinos: Maximal Fluxes for Pure Proton Injection insufficient to explain IceCube neutrinos

- Including secondary photons
- strong source evolution is here constrained by Fermi-LAT results



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

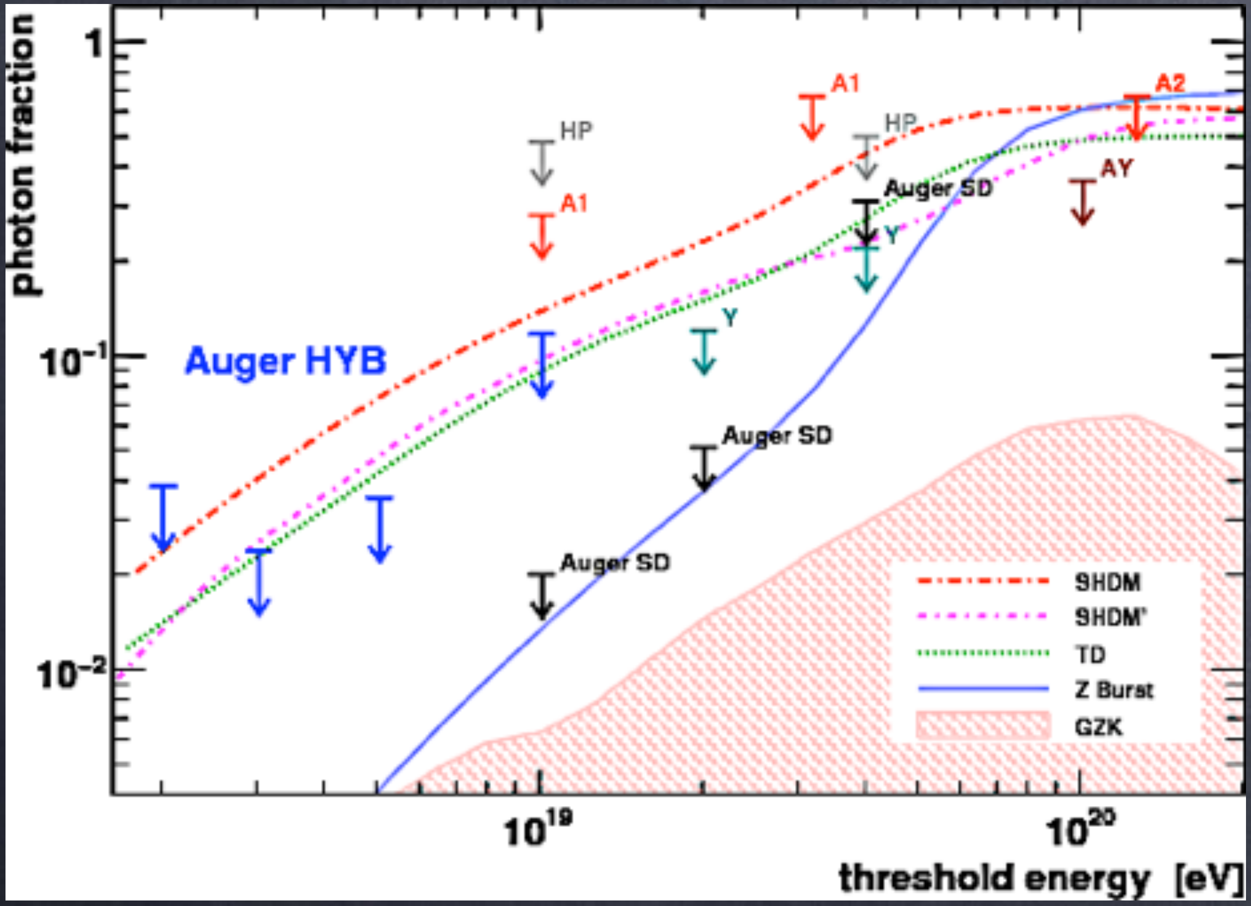


Roulet, Sigl, van Vliet, Mollerach, JCAP 1301, 028

Lorentz Symmetry Violation in the Electromagnetic Sector

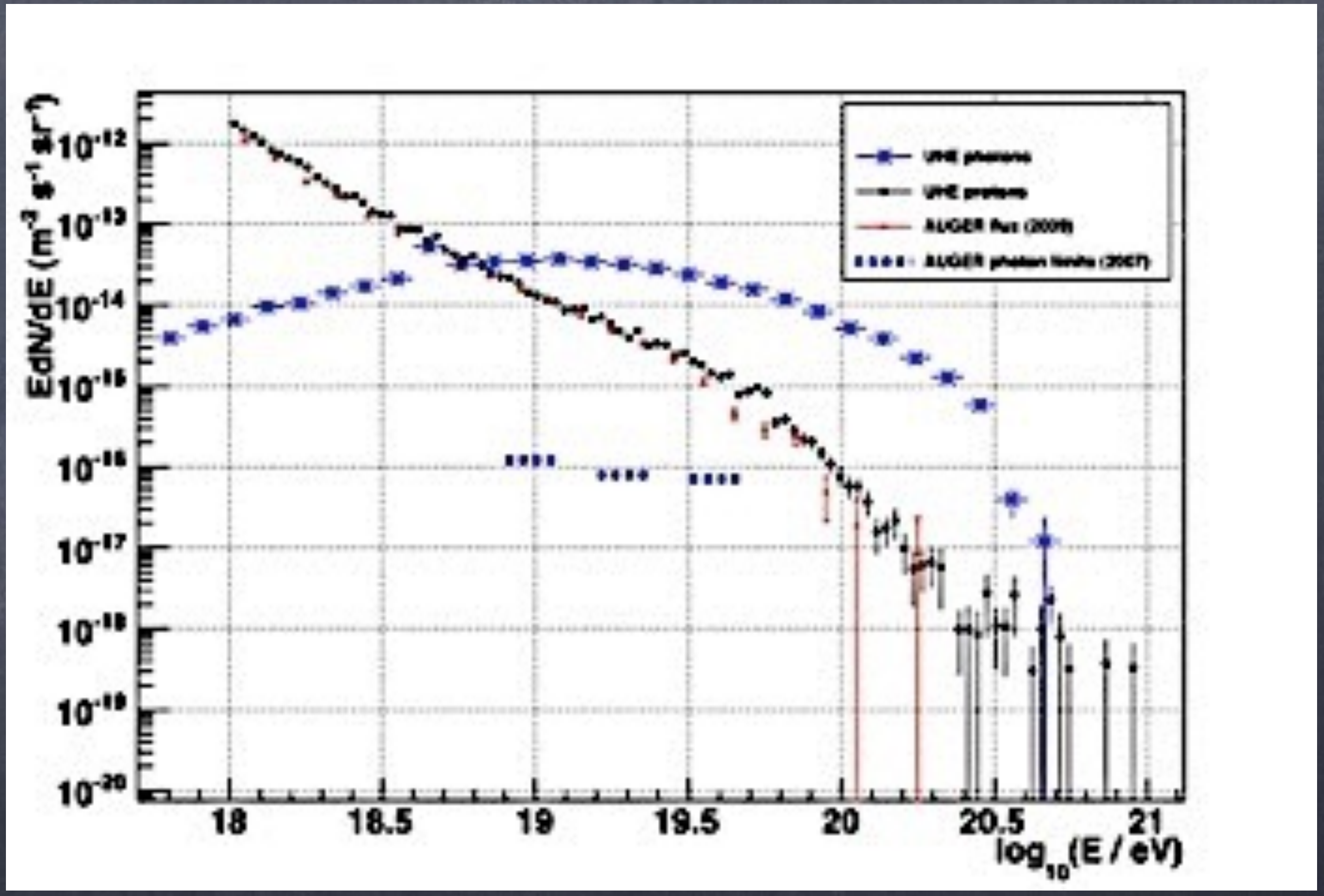
The idea:

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

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

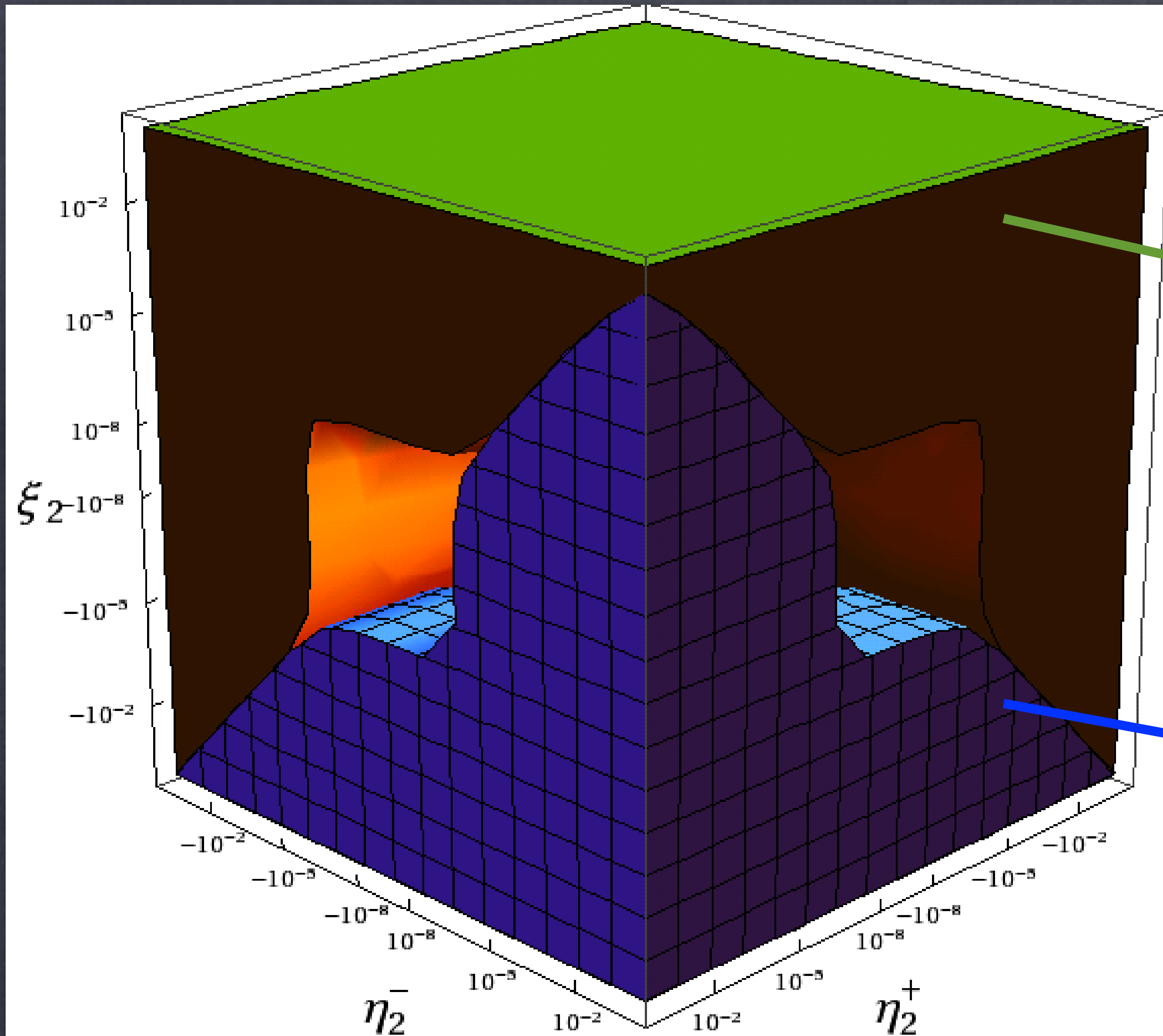
pair production may become inhibited, increasing GZK photon fluxes above observed upper limits: **In the absence of LIV for electrons/positrons for n=1 (CPT-odd terms) this yields:**

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

Even for n=2 (CPT-even) one has sensitivity to $\xi_2 \sim 10^{-6}$

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

Constraints for n=2



UHE photons are detected

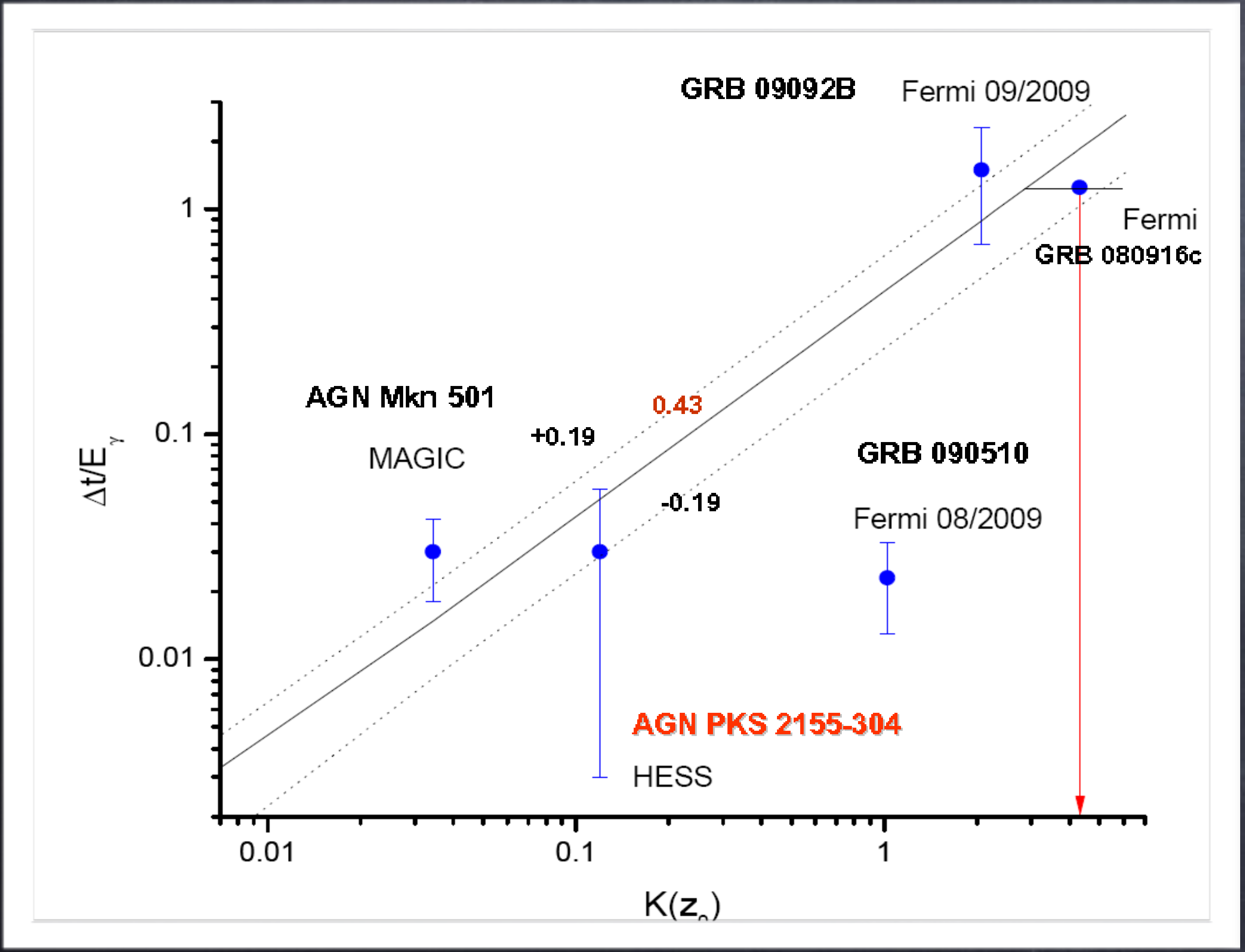
UHE photon absorption takes place

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

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

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

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.).

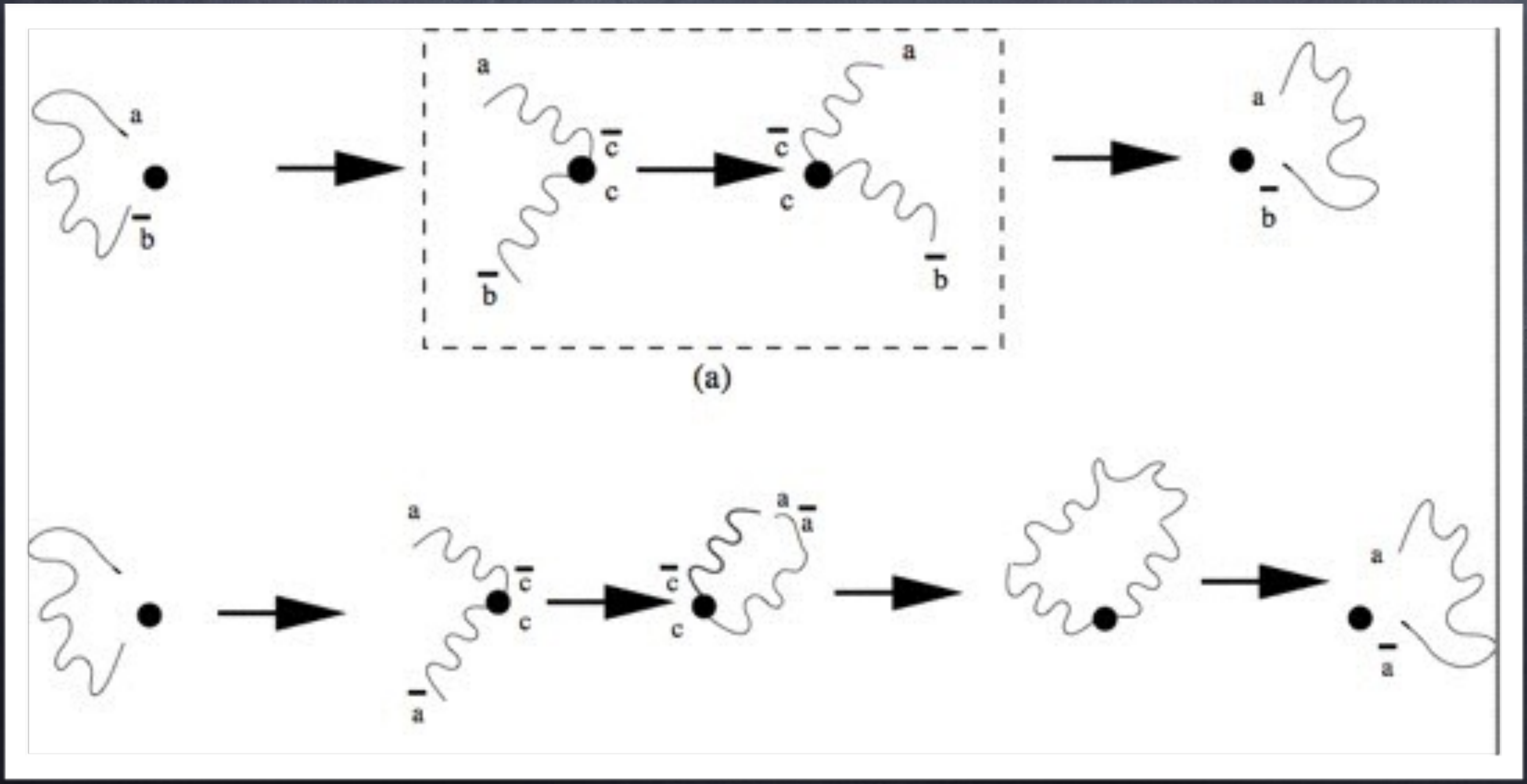


But the UHE photon limits are inconsistent with interpretations of time delays of high energy gamma-rays from GRBs within quantum gravity scenarios based on effective field theory

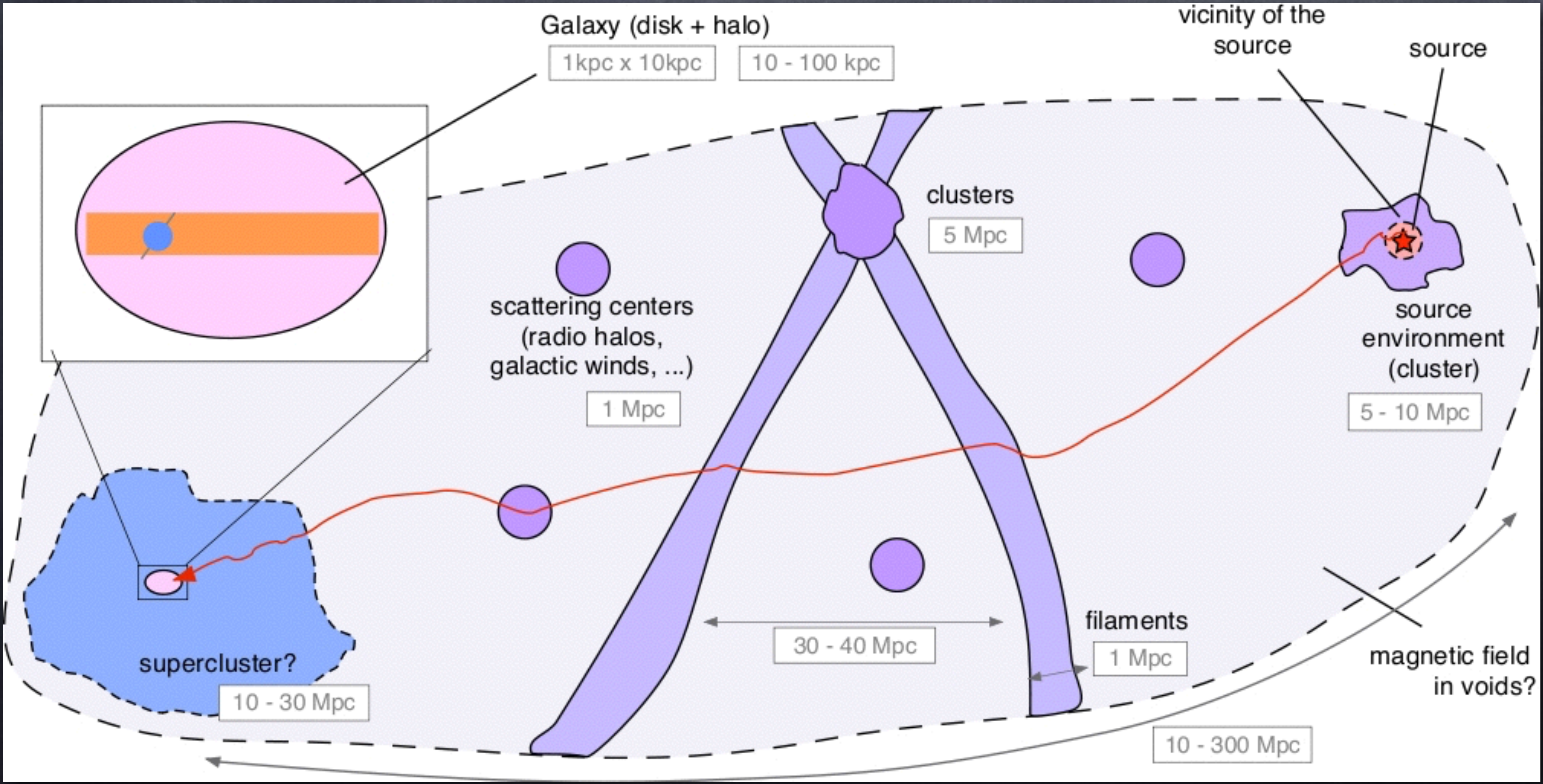
Maccione, Liberati, Sigl, PRL 105 (2010) 021101

Possible exception in space-time foam models,

Ellis, Mavromatos, Nanopoulos, arXiv:1004.4167

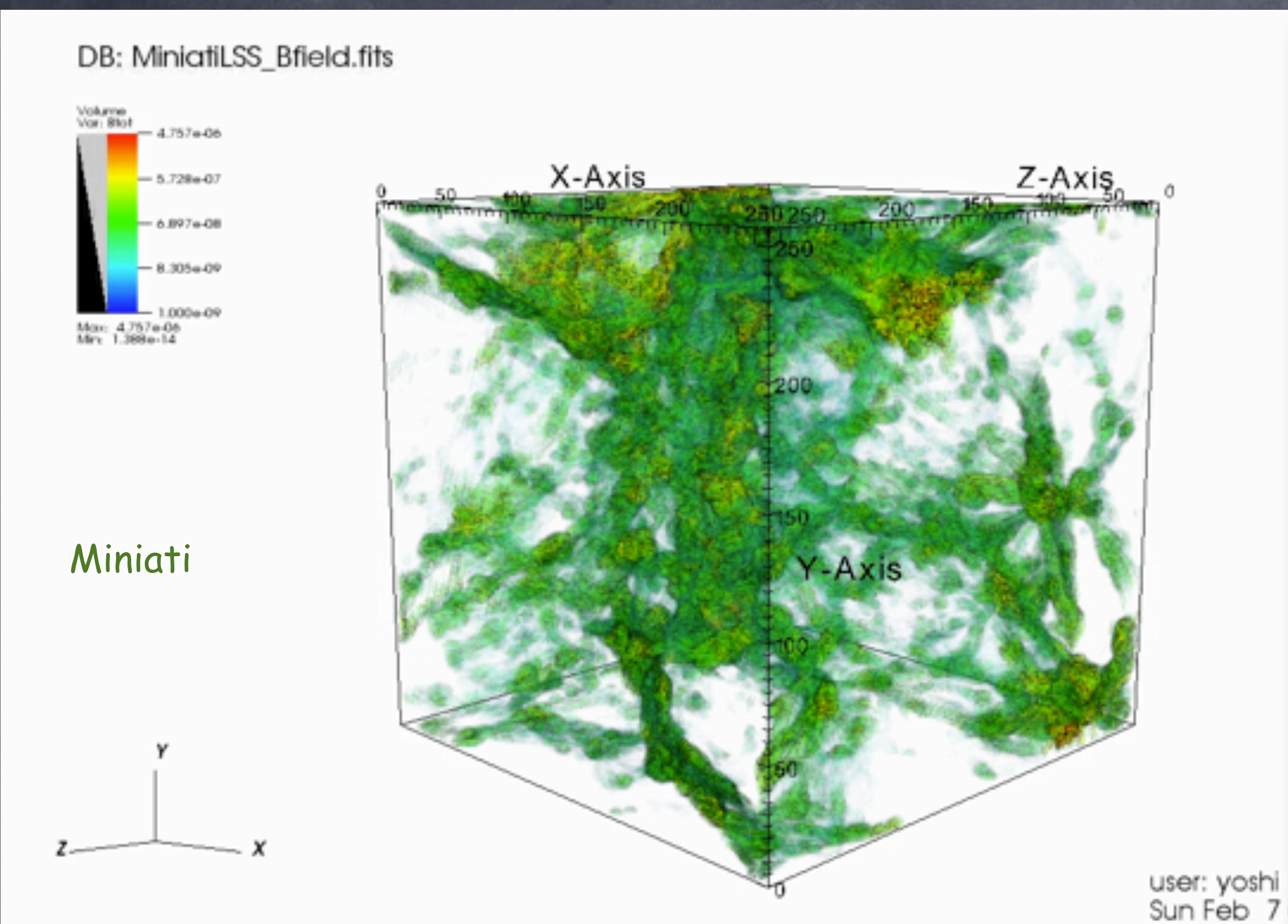


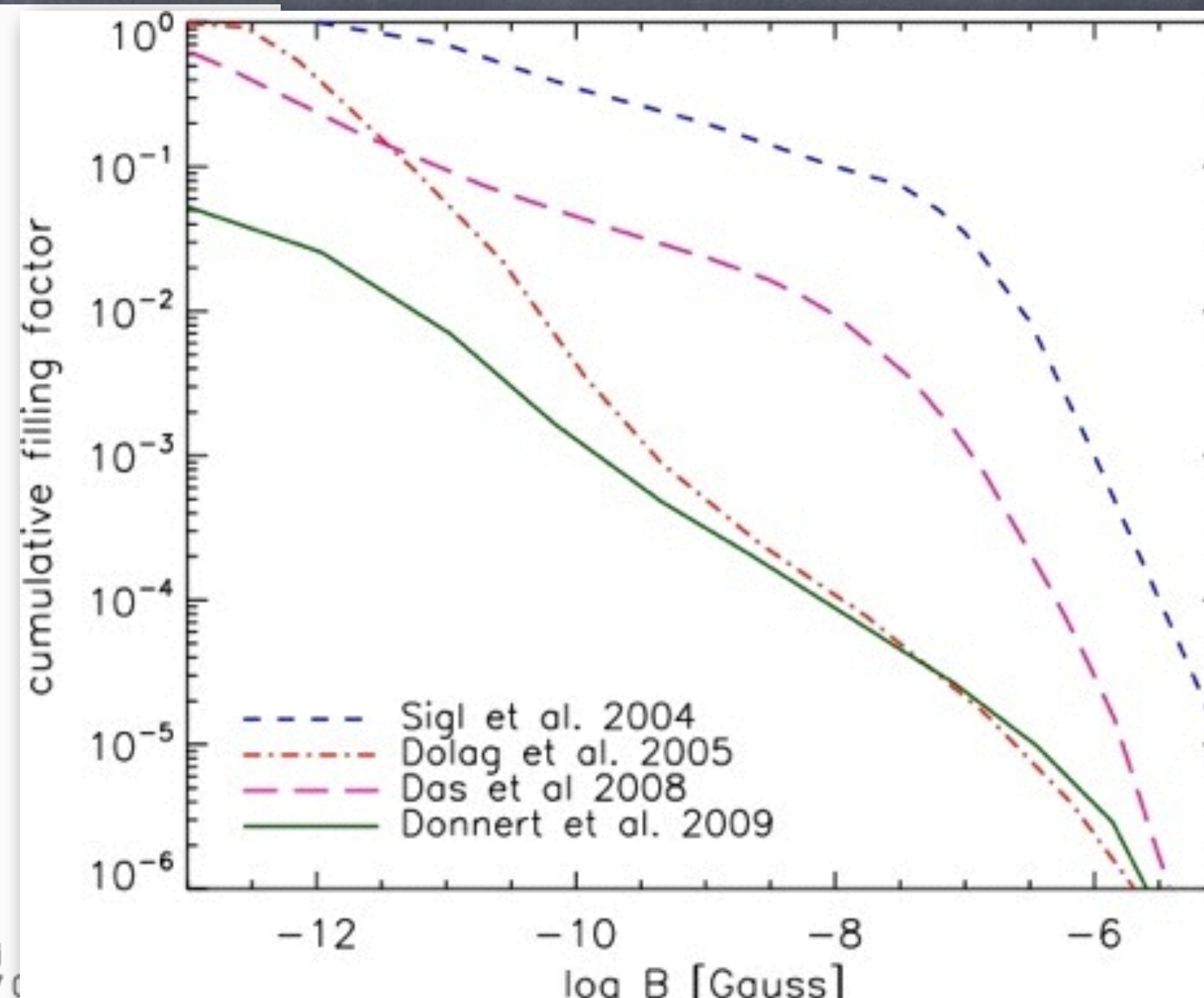
3-Dimensional Effects in Propagation



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

Structured Extragalactic Magnetic Fields

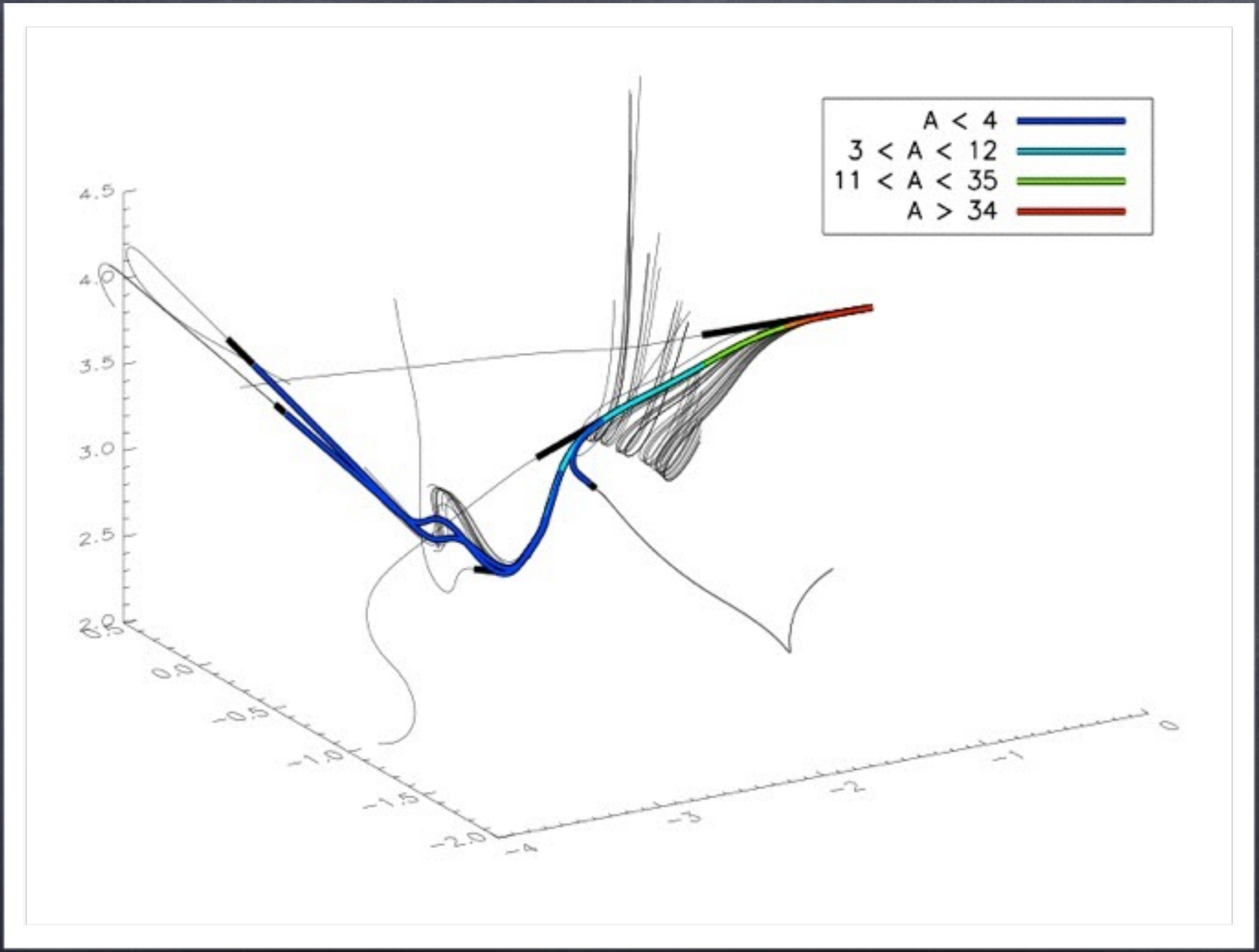




Kotera, Olinto, Ann.Rev.Astron.Astrophys. 49 (2011) 119

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

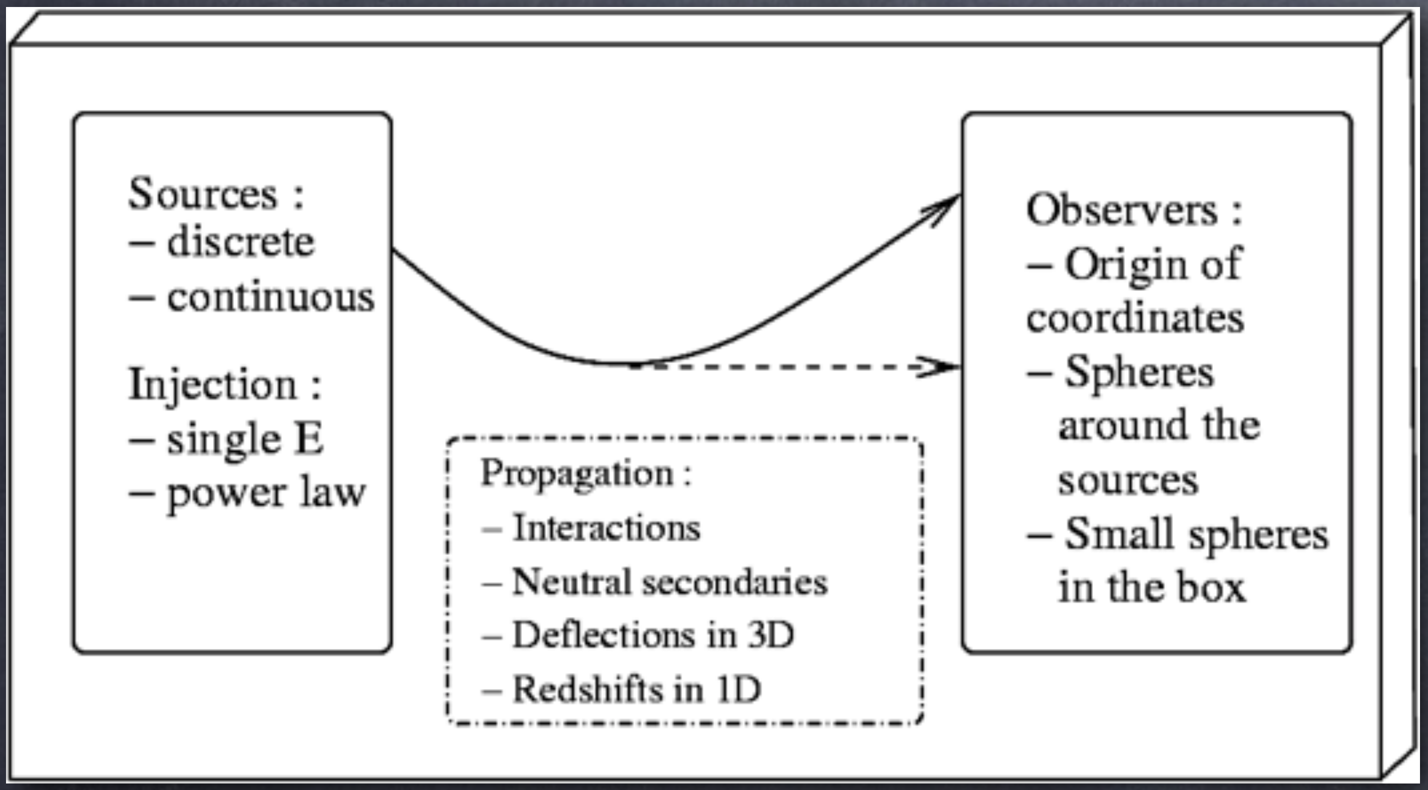
Extragalactic iron propagation produces nuclear cascades in structured magnetic fields:

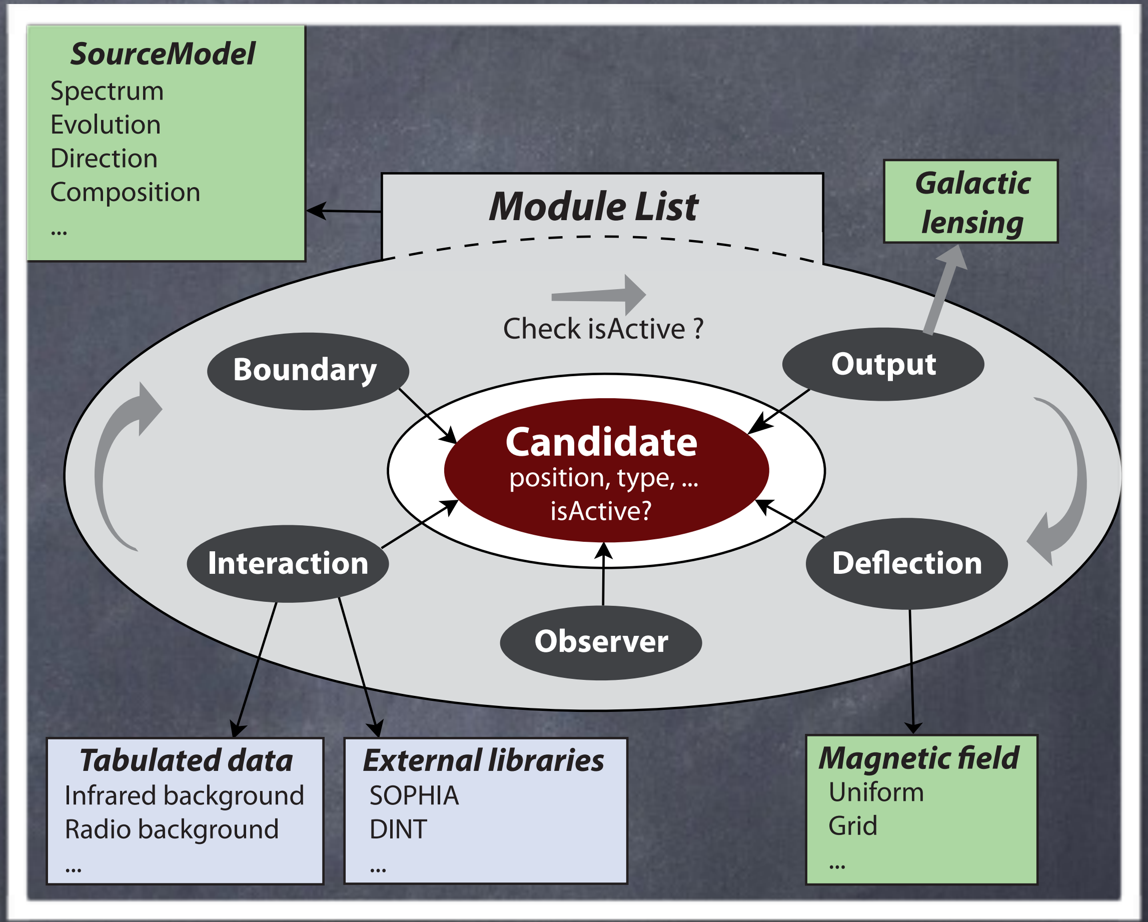


Initial energy 1.2 x 10^{21} eV, magnetic field range 10^{-15} to 10^{-6} G. Color-coded is the mass number of secondary nuclei

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

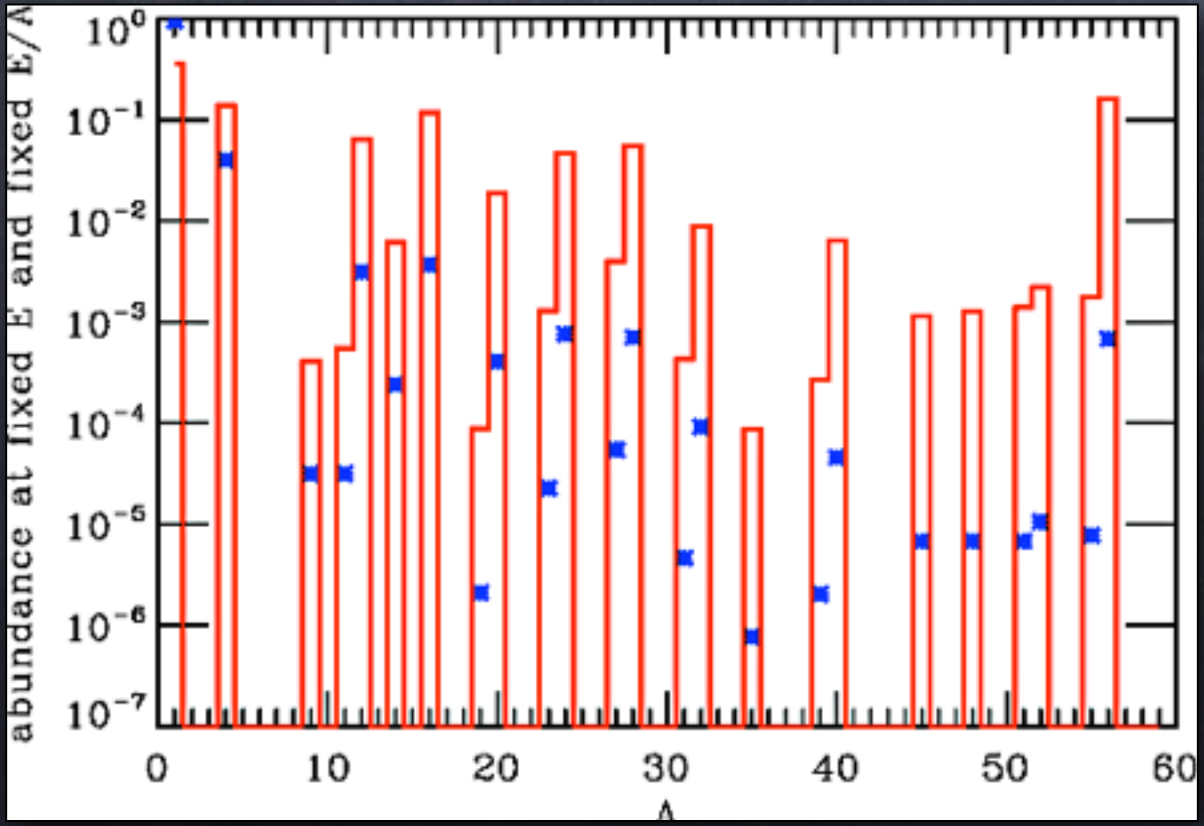
Version 3.0: Luca Maccione, Rafael Alves Batista, David Walz, Gero Müller, Nils Nierstenhoefer, Karl-Heinz Kampert, Peter Schiffer, Arjen van Vliet Astroparticle Physics 42 (2013) 41

Mixed mass compositions

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

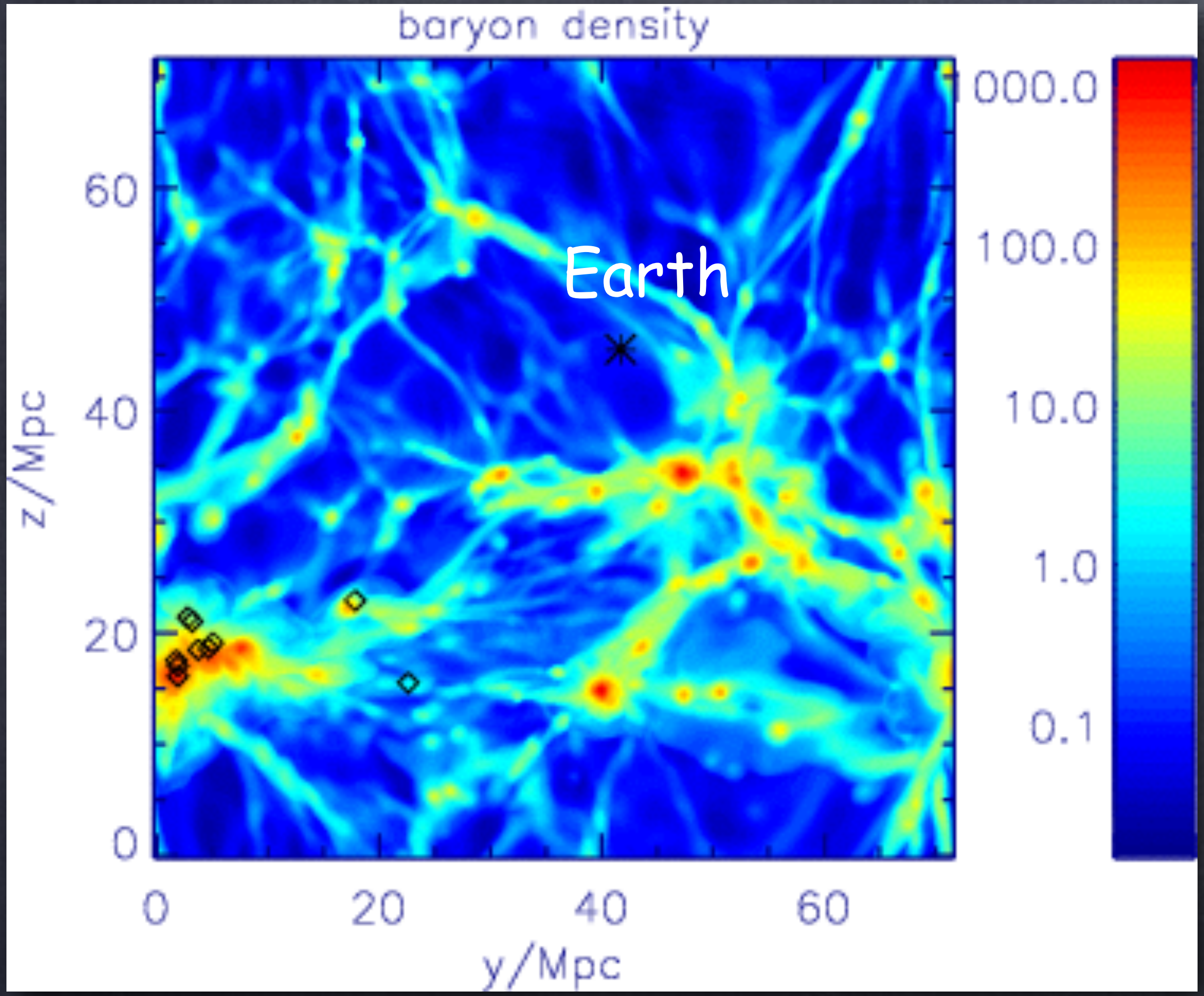
$$\frac{dn_A}{dE}(E) = N x_A \, A^{\alpha-1} \, E^{-\alpha} g(E)$$

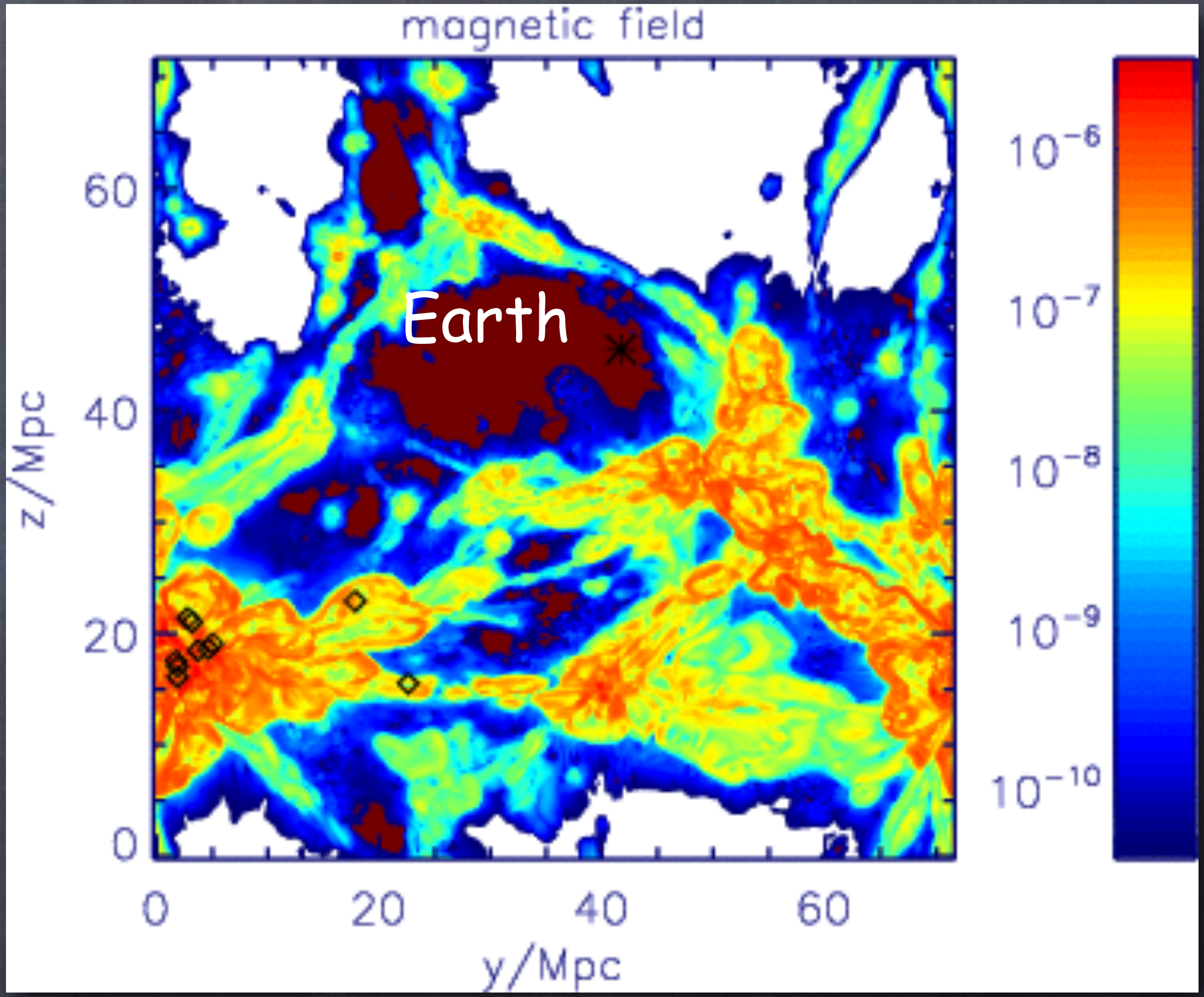
where x_A is the abundance at given energy per nucleon E/A and g(E) is the cut-off shape.



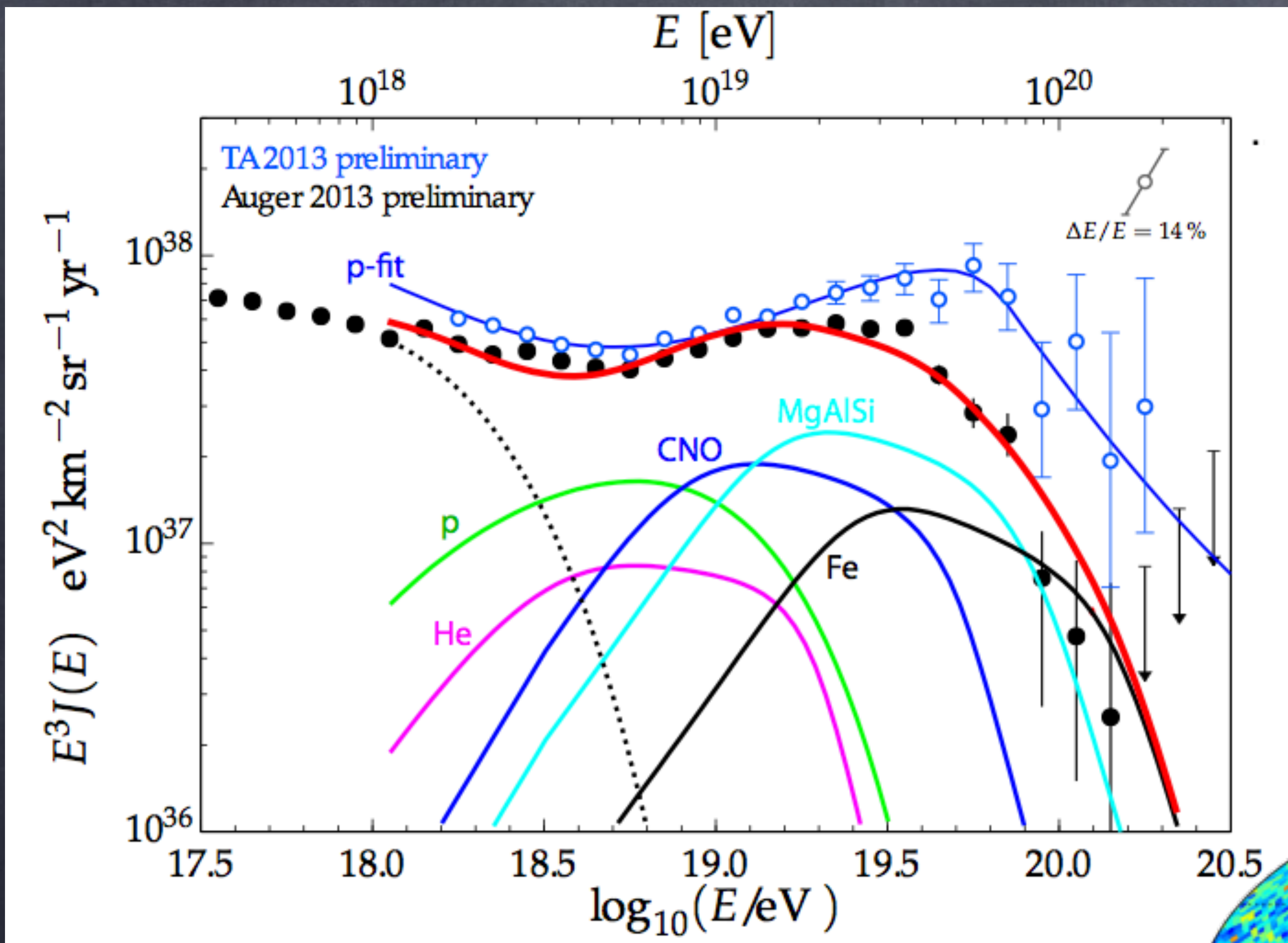
Composition at given E/A (blue) following elemental abundances in the Galaxy
Composition at given E for an $E^{-2.6}$ injection spectrum (red).

Discrete Sources in nearby large scale structure





Building Benchmark Scenarios

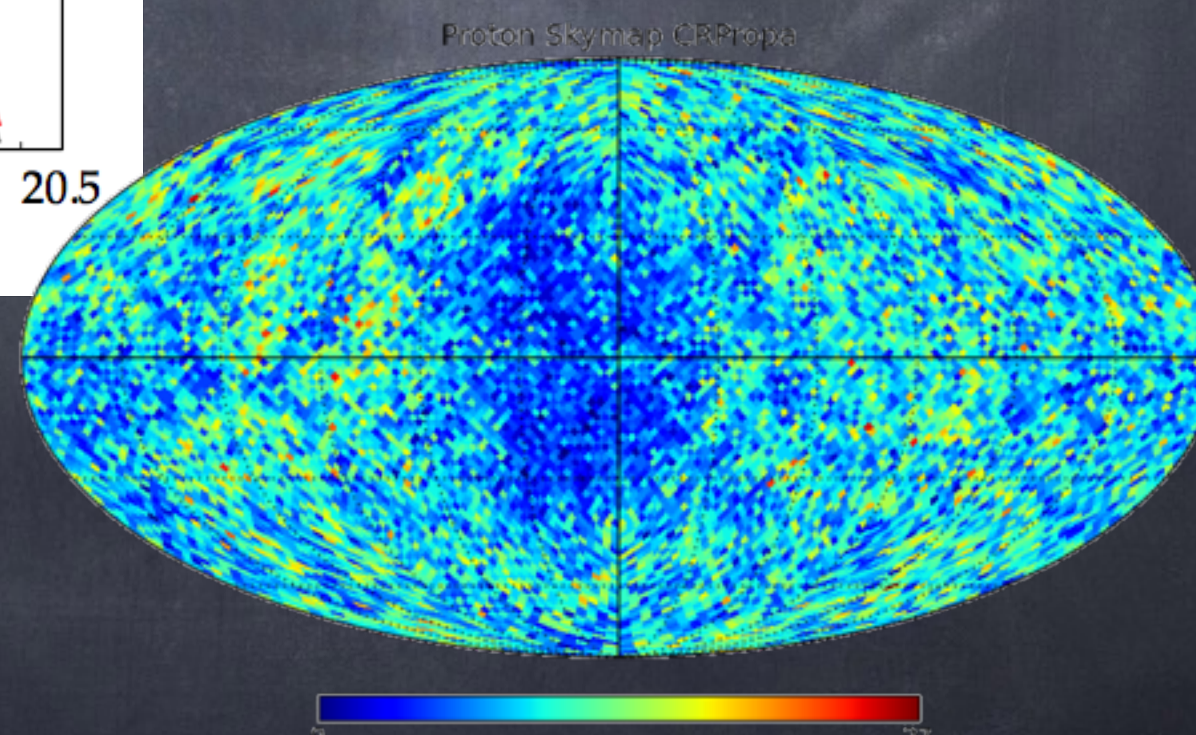


TA fit (red): pure proton injection

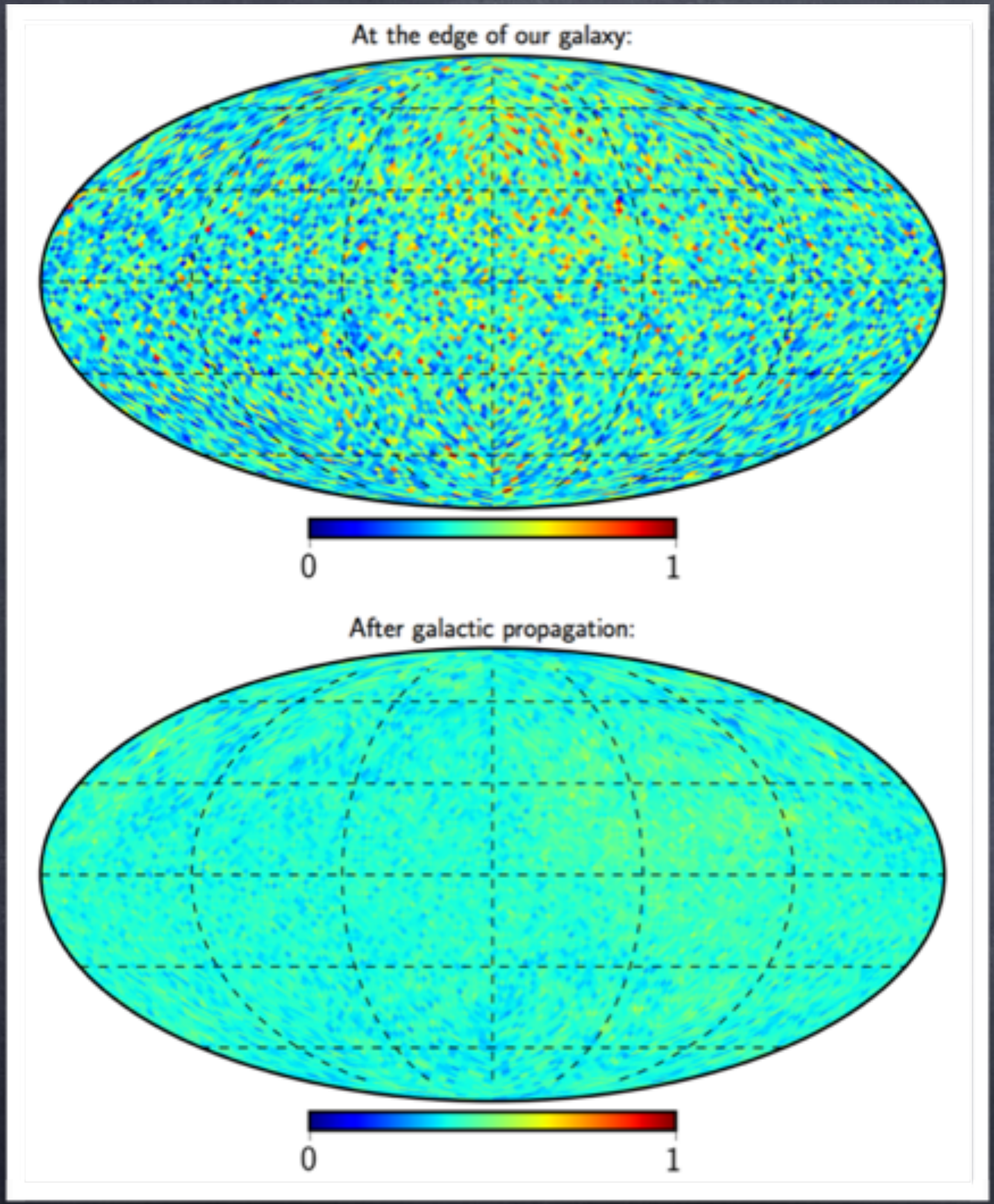
rate ∝ $(1+z)^{4.4}\,E^{-2.36}$

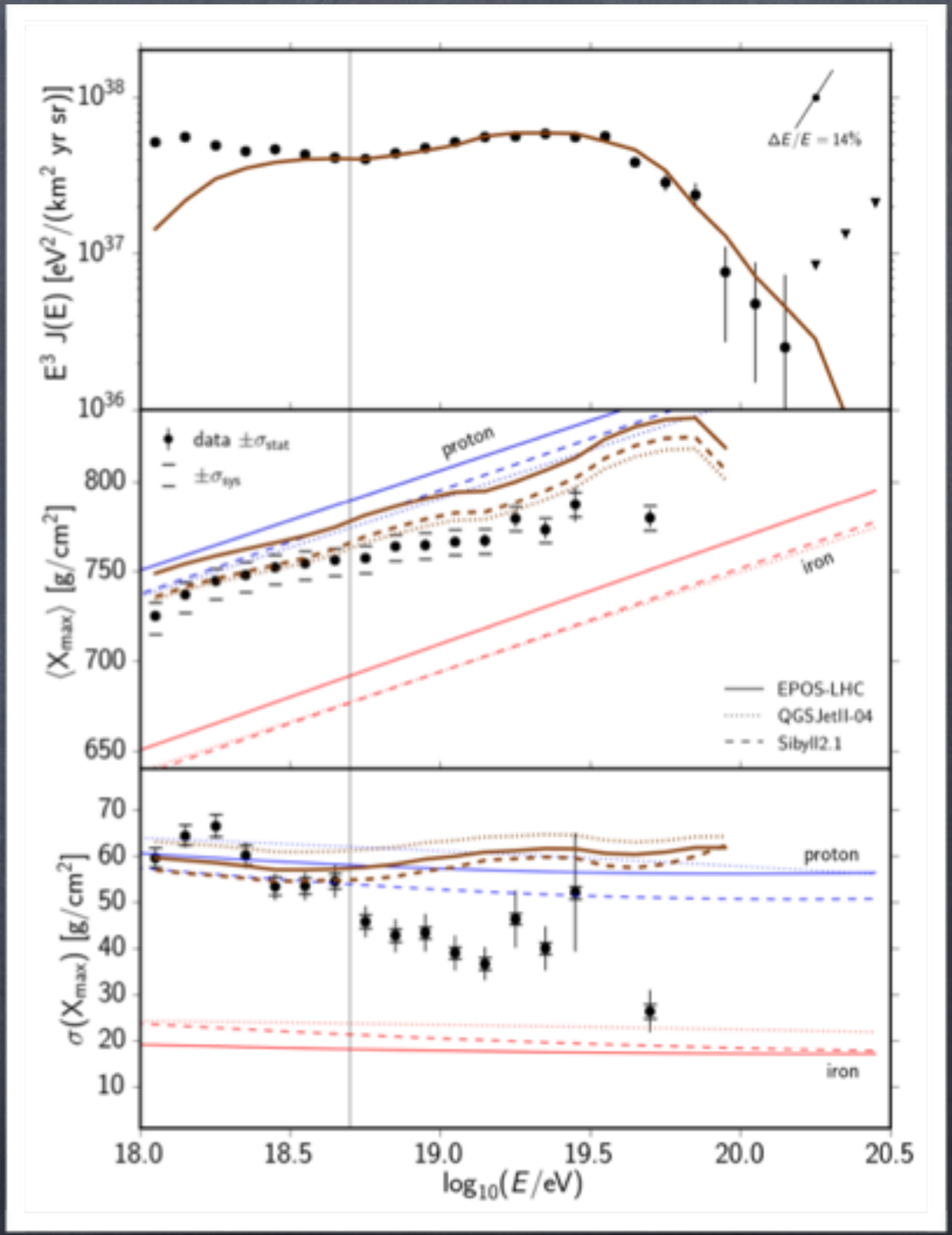
Auger fit: enhanced galactic

composition ∝ $E^{-1.8}$ up to $10^{18.7}$ eV*Z

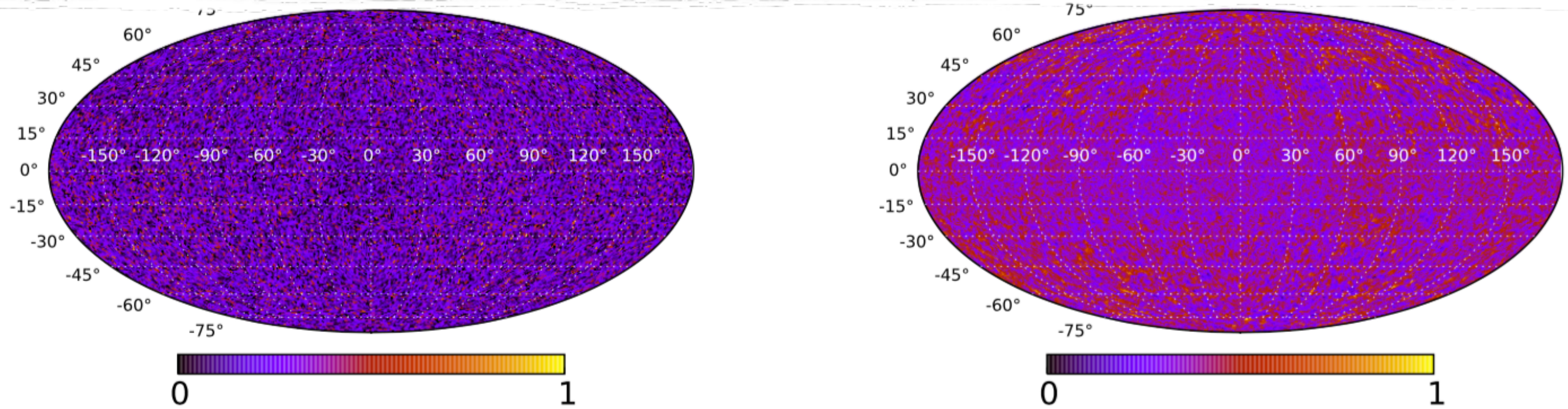


Building Benchmark Scenarios





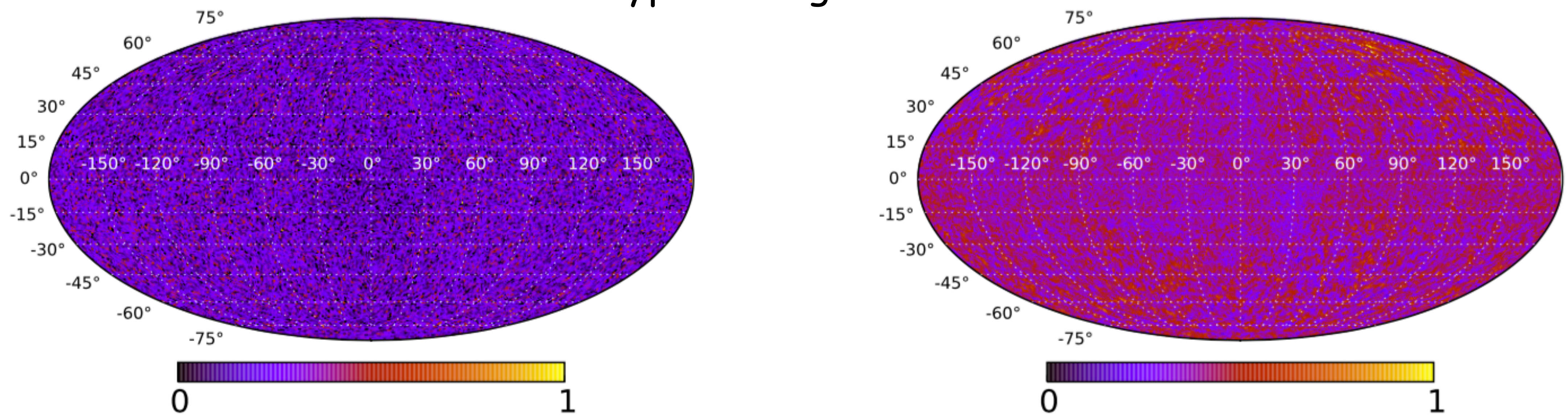
combining spectral and composition information with anisotropy can considerably strengthen constraints on source characteristics, distributions and magnetization



(a) 3D proton, no GMF

(b) 3D proton, with GMF

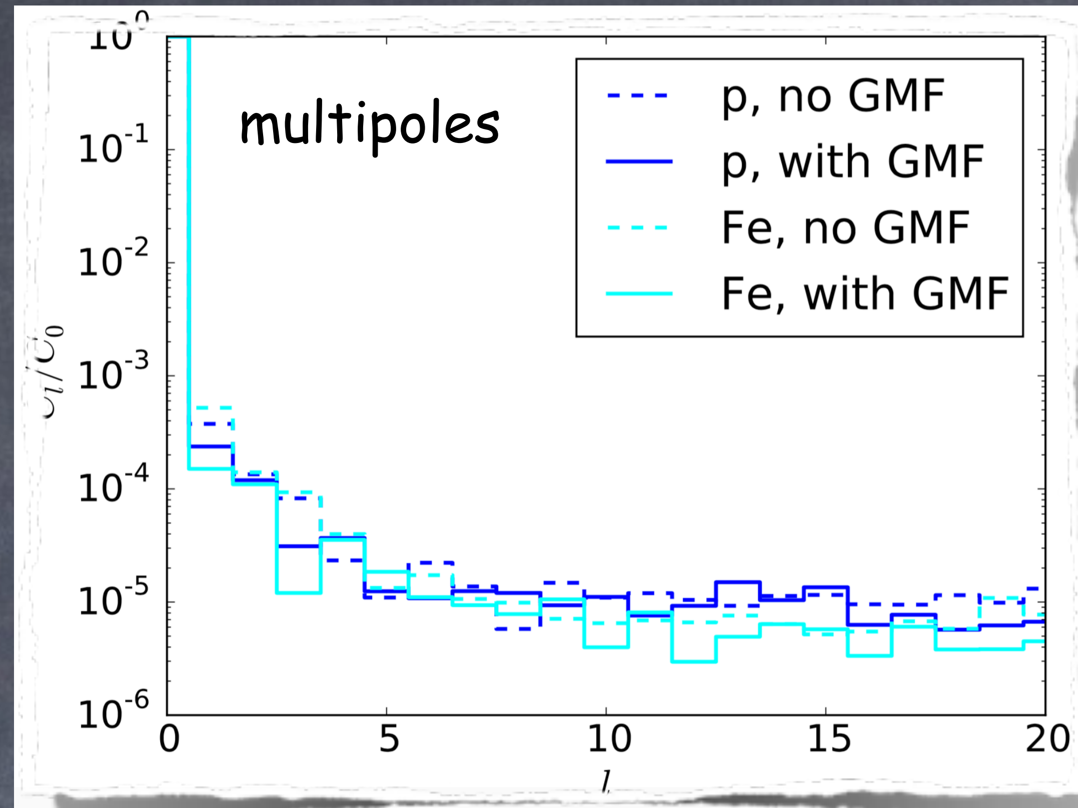
10^{-3} sources per Mpc^3 following the large scale structure;
Miniati-type extragalactic fields

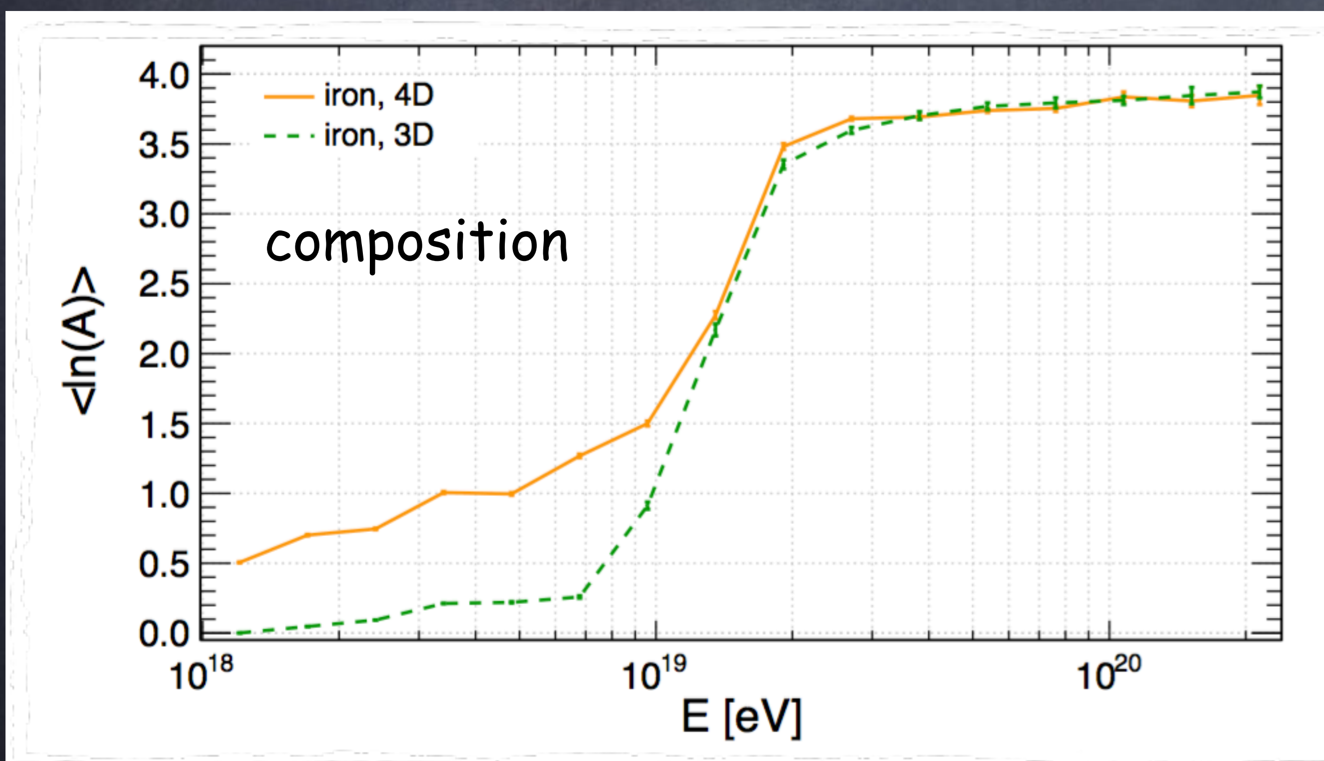


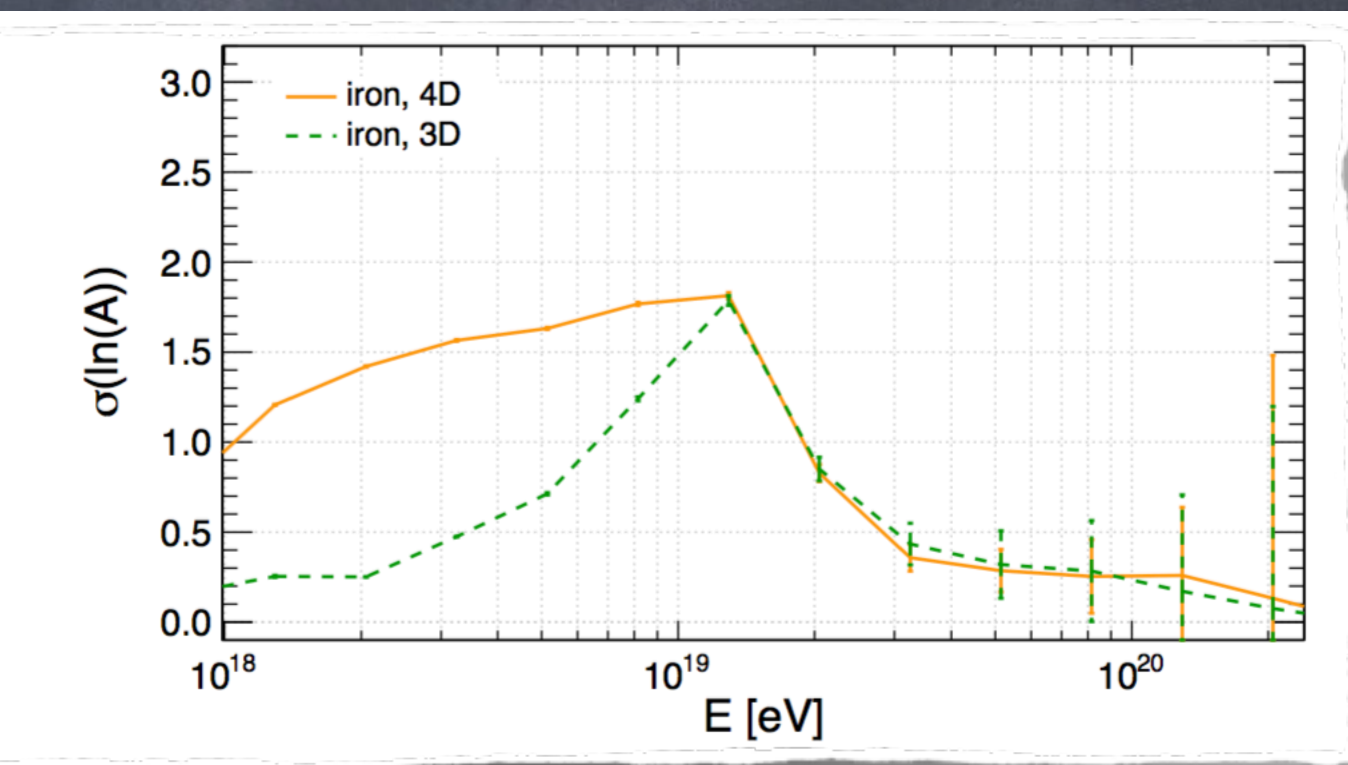
(c) 3D iron, no GMF

(d) 3D iron, with GMF

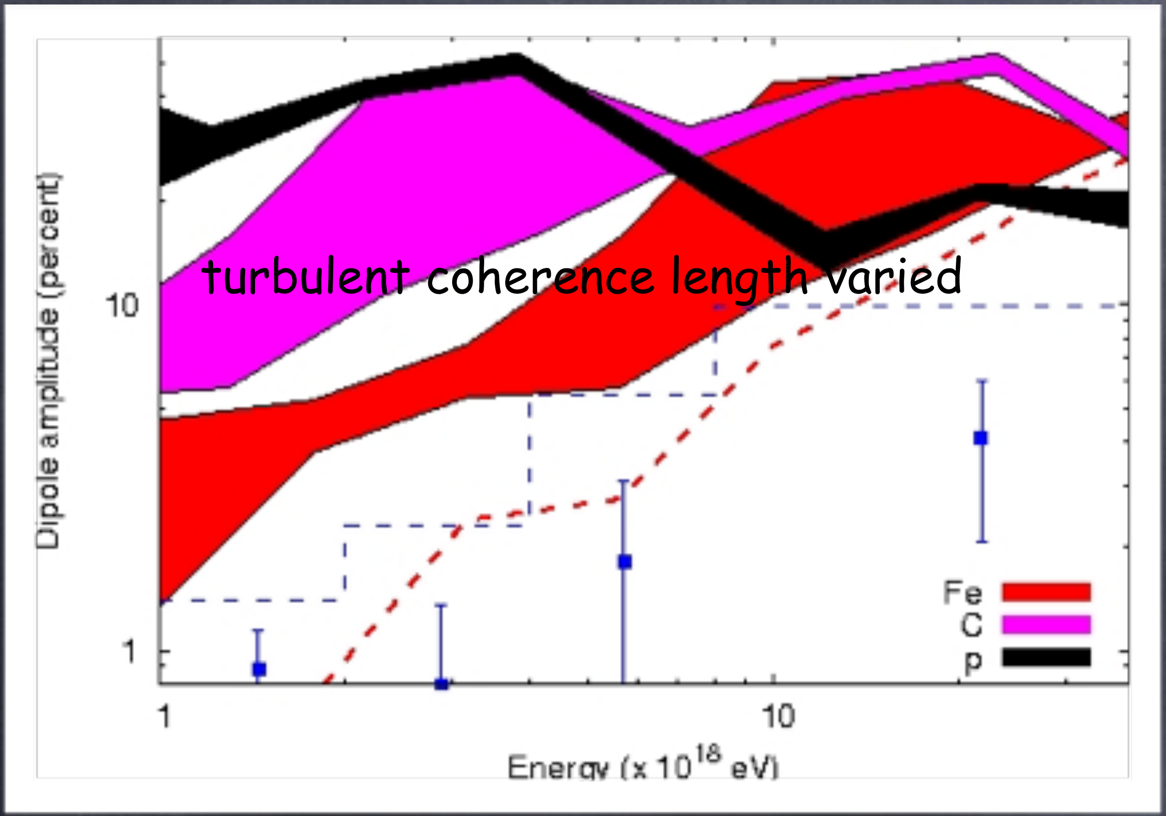
Figure 5. Sky maps for pure proton injection (top) and pure iron injection (bottom) before (left) and after (right) deflections in the galactic magnetic field taken into account using a spectral index of $\gamma = -1.5$ and maximum rigidity $R_{\max} = 500$ EV down to a minimum energy of $E_0 = 1$ EeV. See

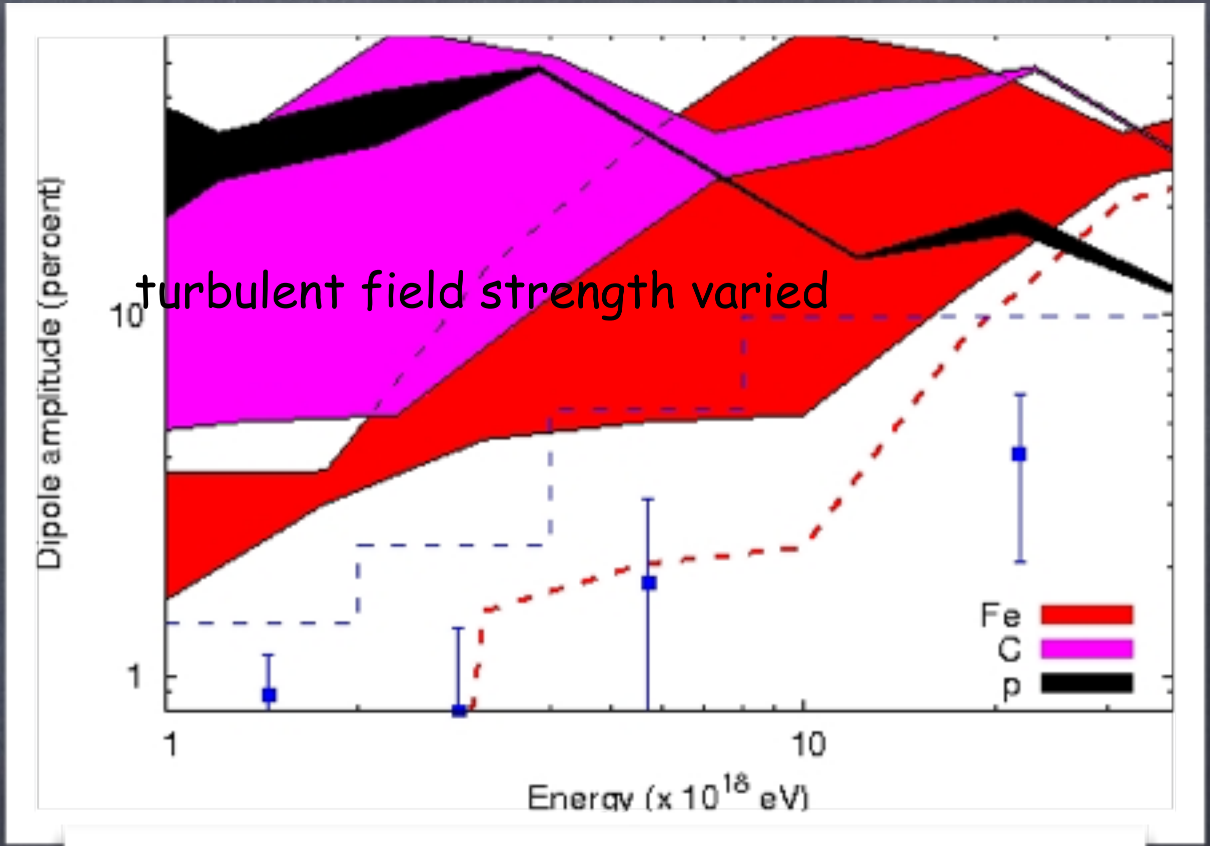

multipoles
p, no GMF
p, with GMF
Fe, no GMF
Fe, with GMF
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
5
10
15
20
l

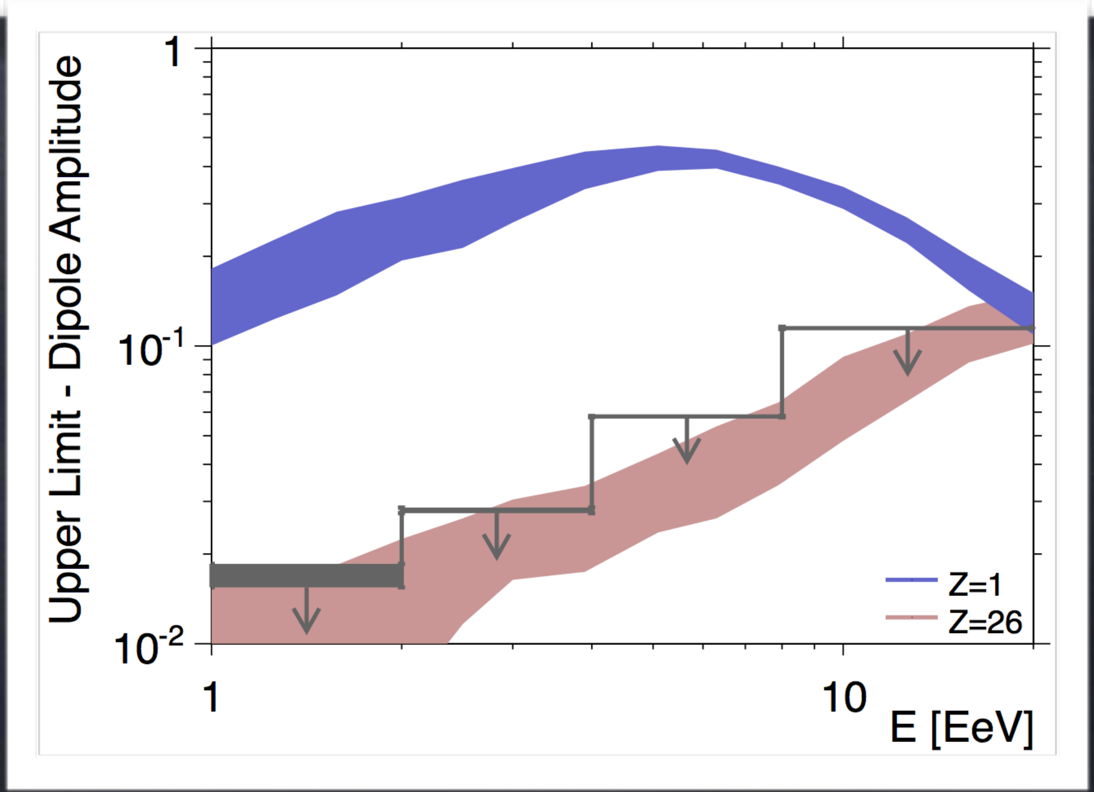

iron, 4D
iron, 3D
composition
<ln(A)>
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^18
10^19
10^20
E [eV]


iron, 4D
iron, 3D
σ(ln(A))
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^18
10^19
10^20
E [eV]

Composition and the Transition Galactic/Extragalactic Cosmic Rays







Giacinti, Kachelriess, Semikoz, Sigl,
JCAP 07 (2012) 031
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

Conclusions

1.) The sources of ultra-high energy cosmic rays are still not identified due to rather small anisotropies; composition seems to become heavier at the highest energies which appears economic in terms of shock acceleration power

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.) IceCube neutrinos already constrain their sources which should be sufficiently numerous: Gamma-ray bursts are unlikely as main 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