Fundamental Physics with Ultra-High Energy Cosmic Ray

- (Very short) reminder on Cosmic Ray experimental situation and current understanding
- Interpretations of Correlation with Large Scale Structure
- Implications for source candidates
- Secondary gamma rays and neutrinos
- Tests of new physics: Lorentz symmetry violations and cross sections

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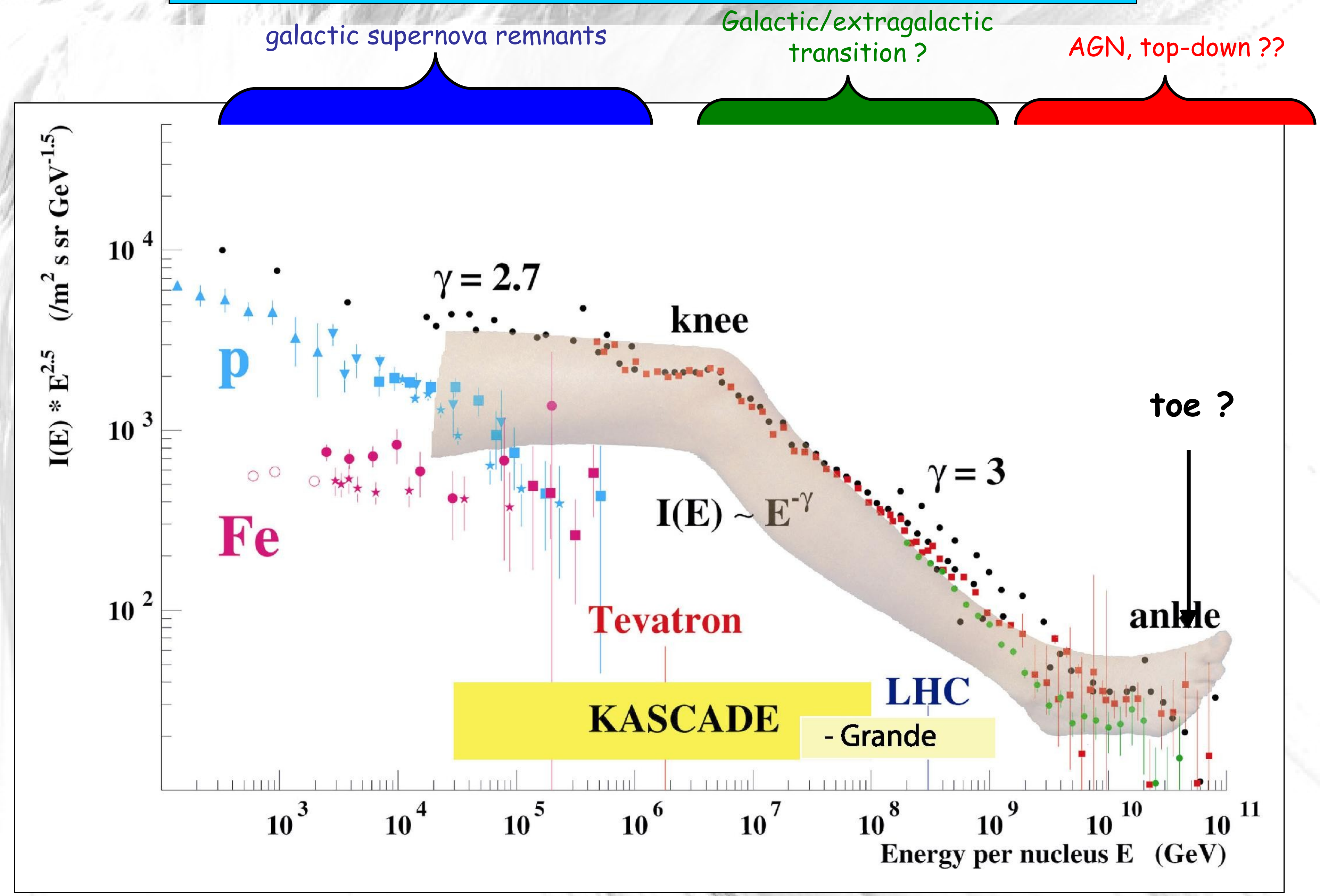
http://www2.iap.fr/users/sigl/homepage.html

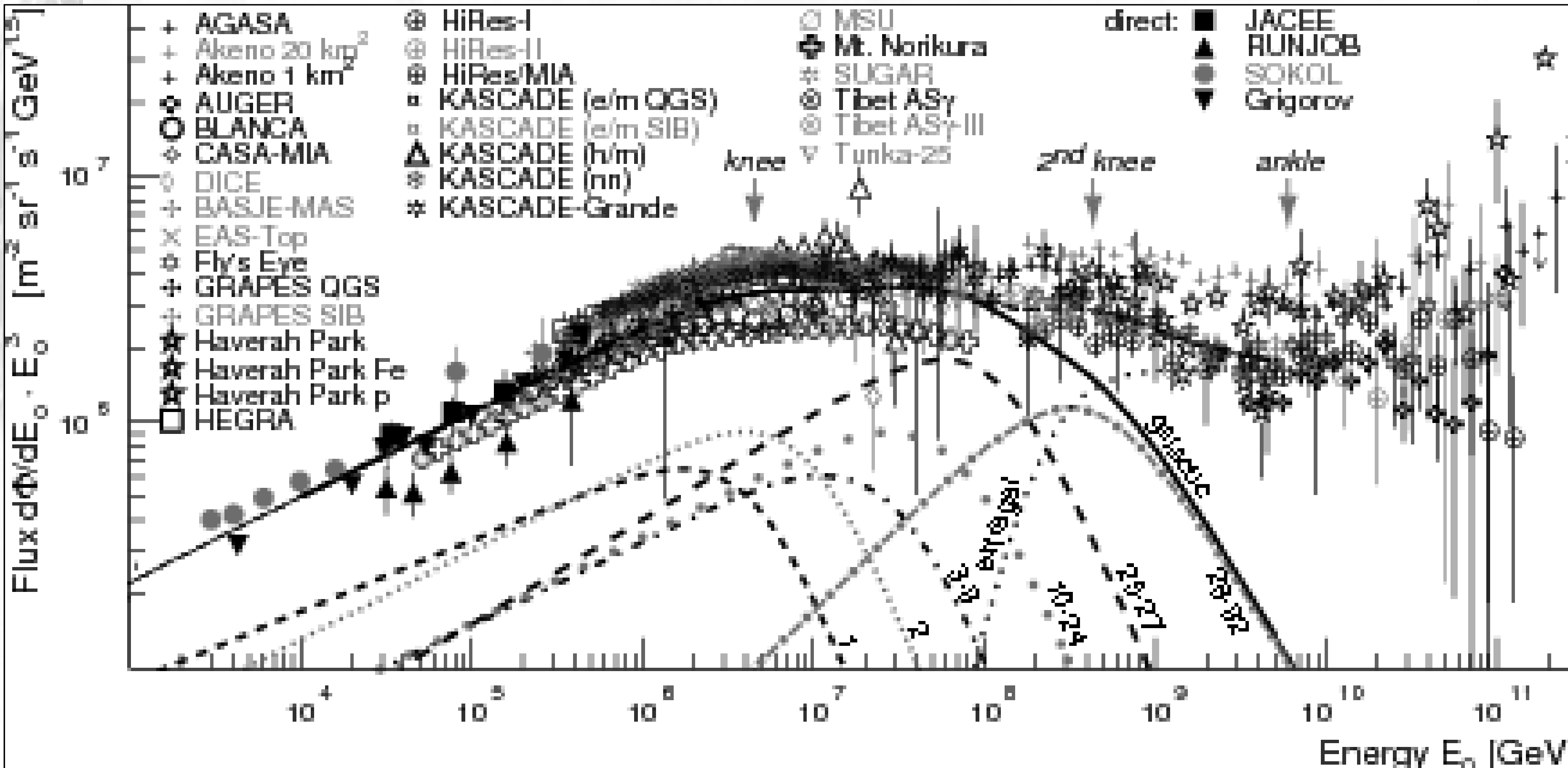
The structure of the spectrum and scenarios of its origin



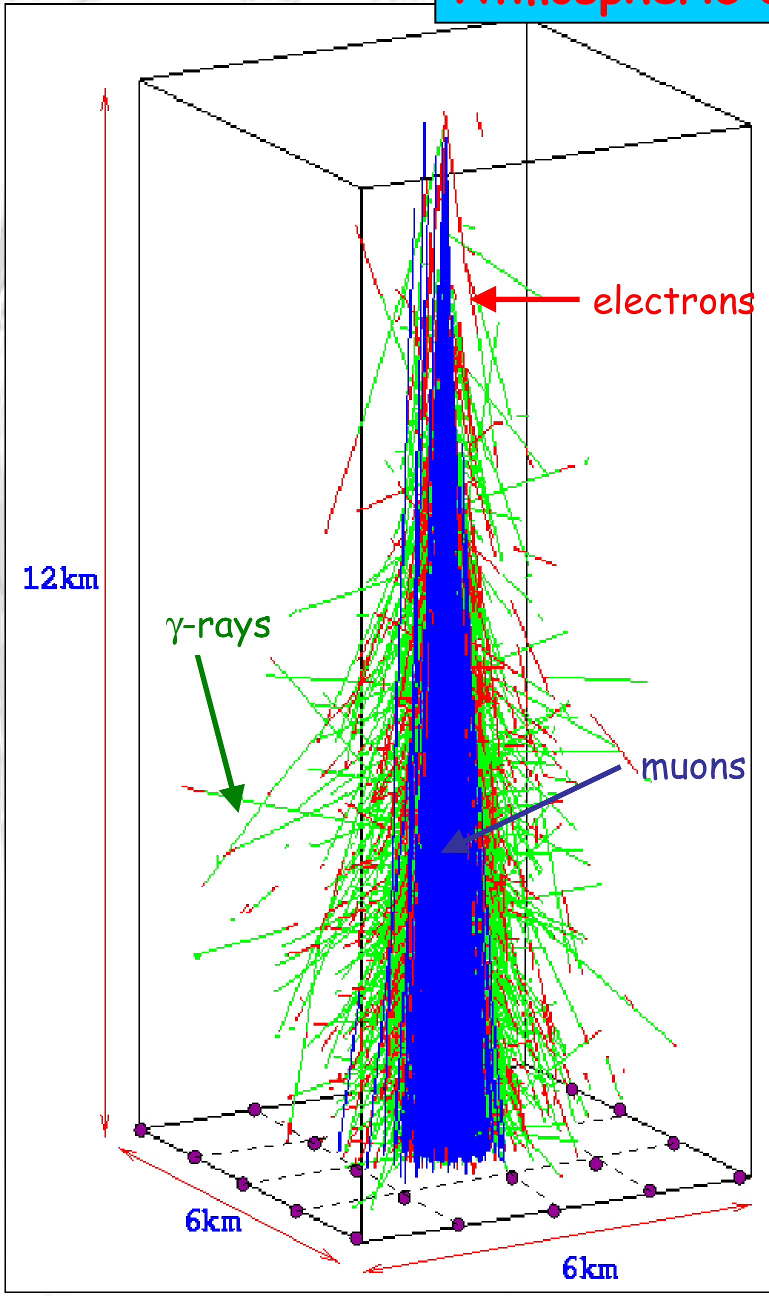
All Particle Spectrum and chemical Composition

Heavy elements start to dominate above knee
Rigidity (E/Z) effect: combination of deconfinement and maximum energy

Hoerandel, astro-ph/0702370



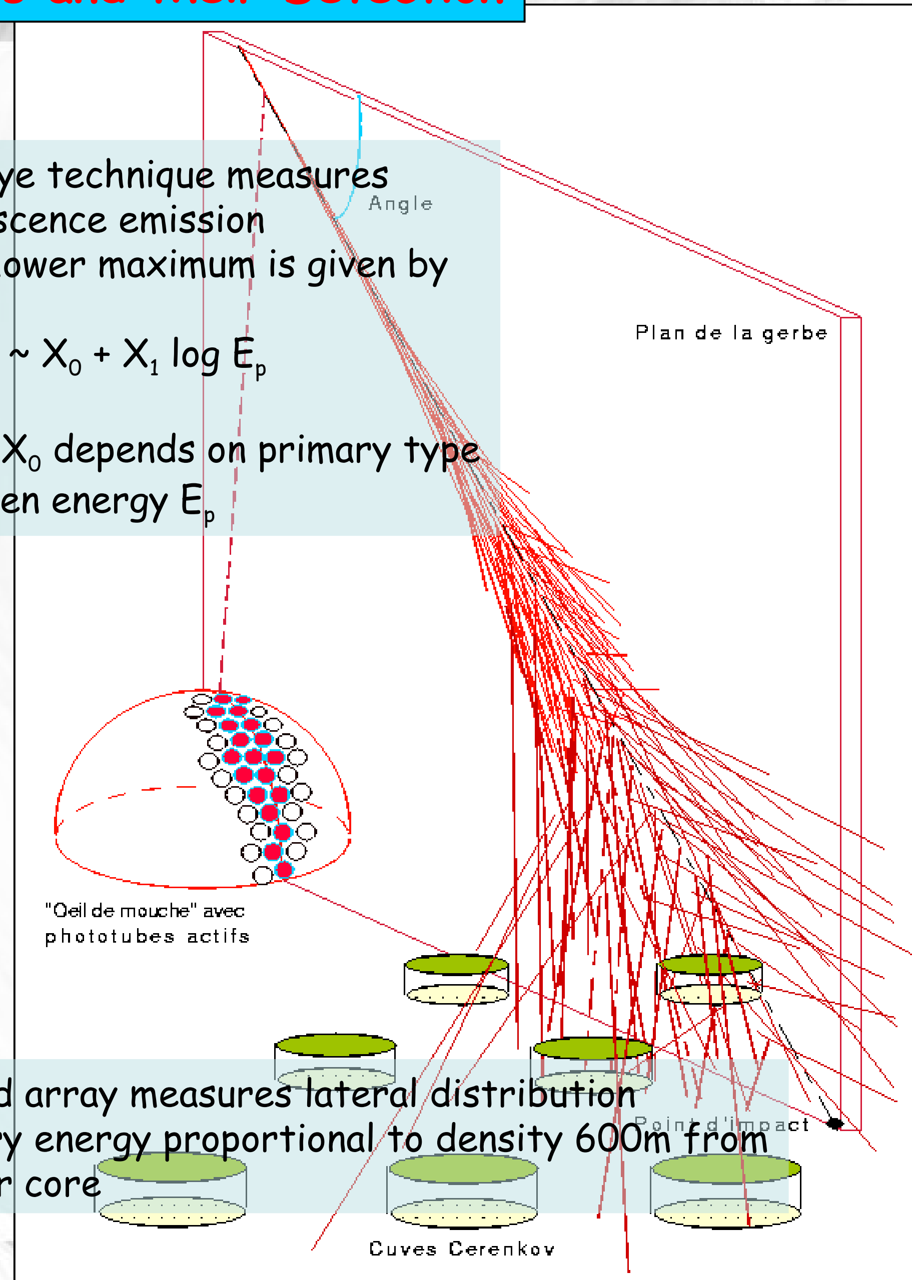
Atmospheric Showers and their Detection



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

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

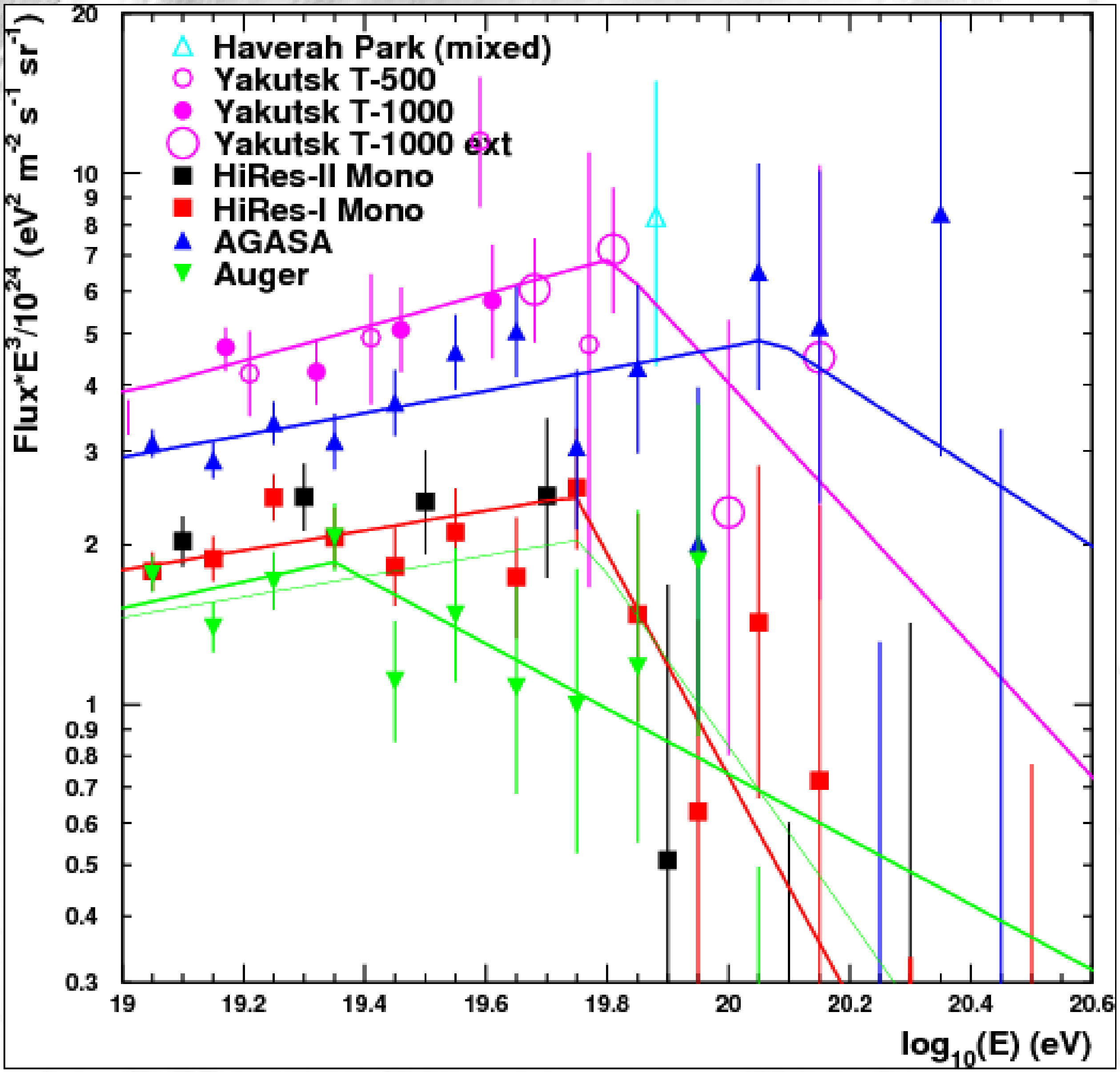
where X_0 depends on primary type for given energy E_p



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

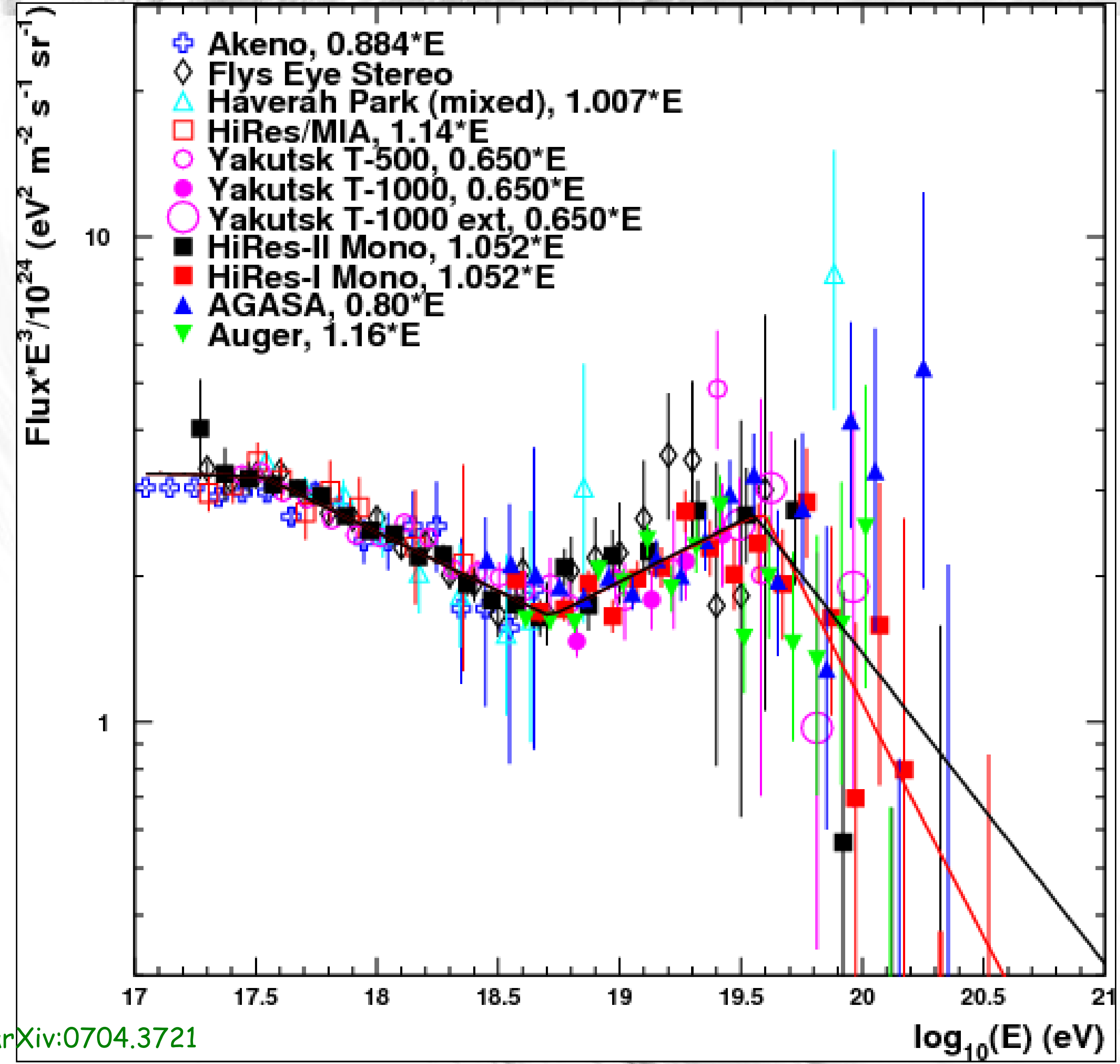
Lowering AGASA energy scale by about 20% brings it in accordance with HiRes up to the GZK cut-off, but maybe not beyond ?

Bergmann, Belz, J.Phys.G34 (2007) R359



May need an experiment combining ground array with fluorescence such as the Auger project to resolve this issue.

Comparison with earlier Experimental Spectra

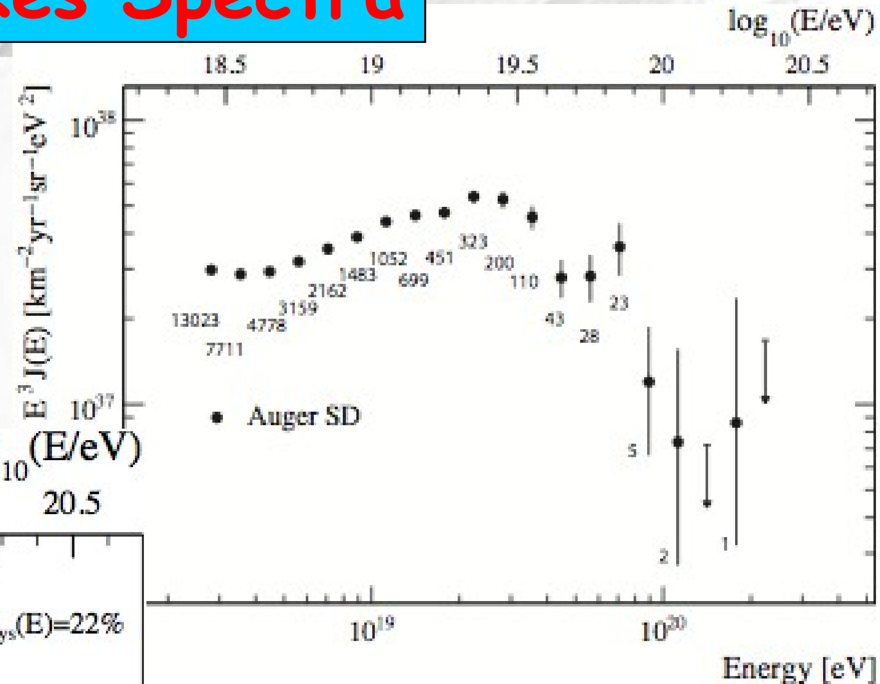


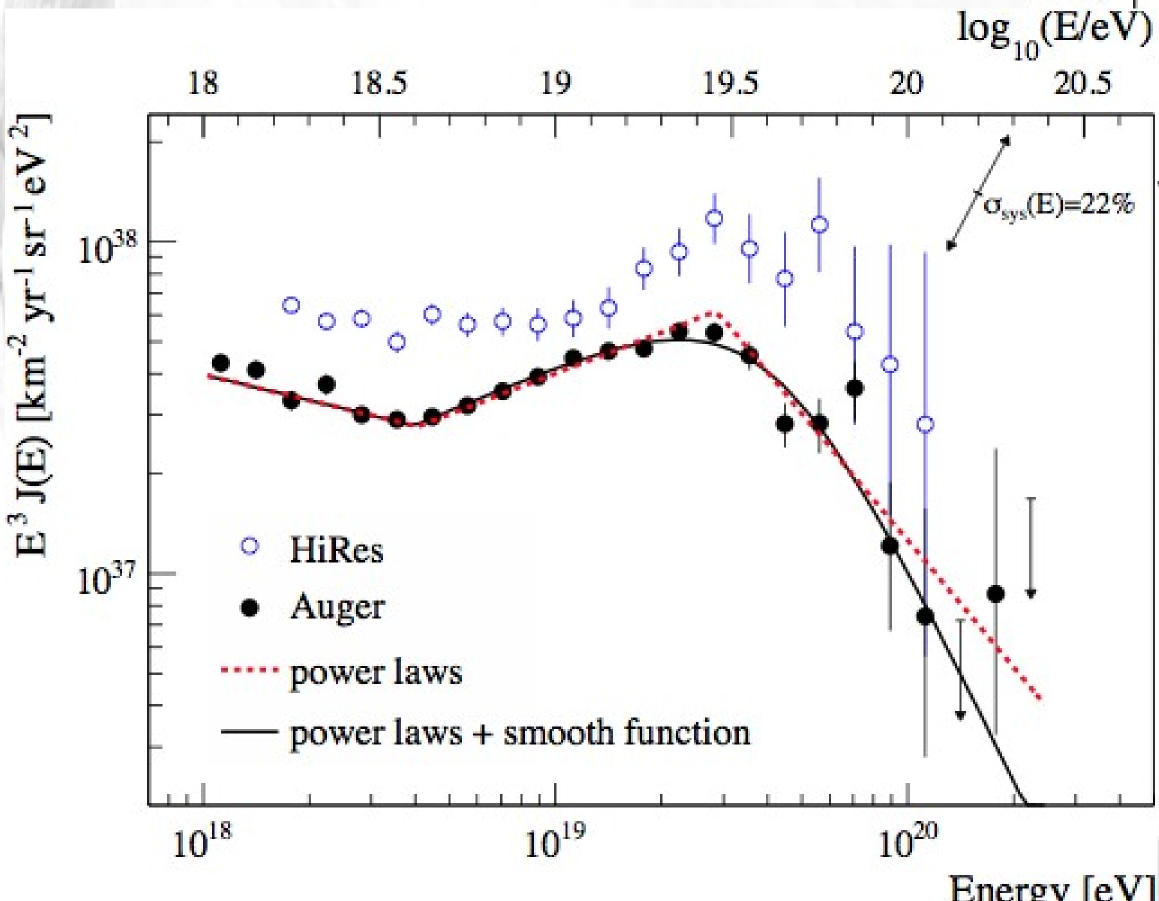
Bergmann, Belz, arXiv:0704.3721

Auger and HiRes Spectra

Auger exposure = 12,790 km^2 sr yr up to December 2008

Pierre Auger Collaboration, PRL 101, 061101 (2008) and Phys.Lett.B 2010, to appear





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

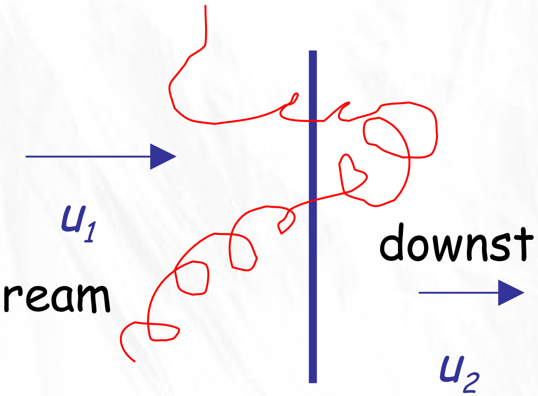
1.) electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 50 Mpc.

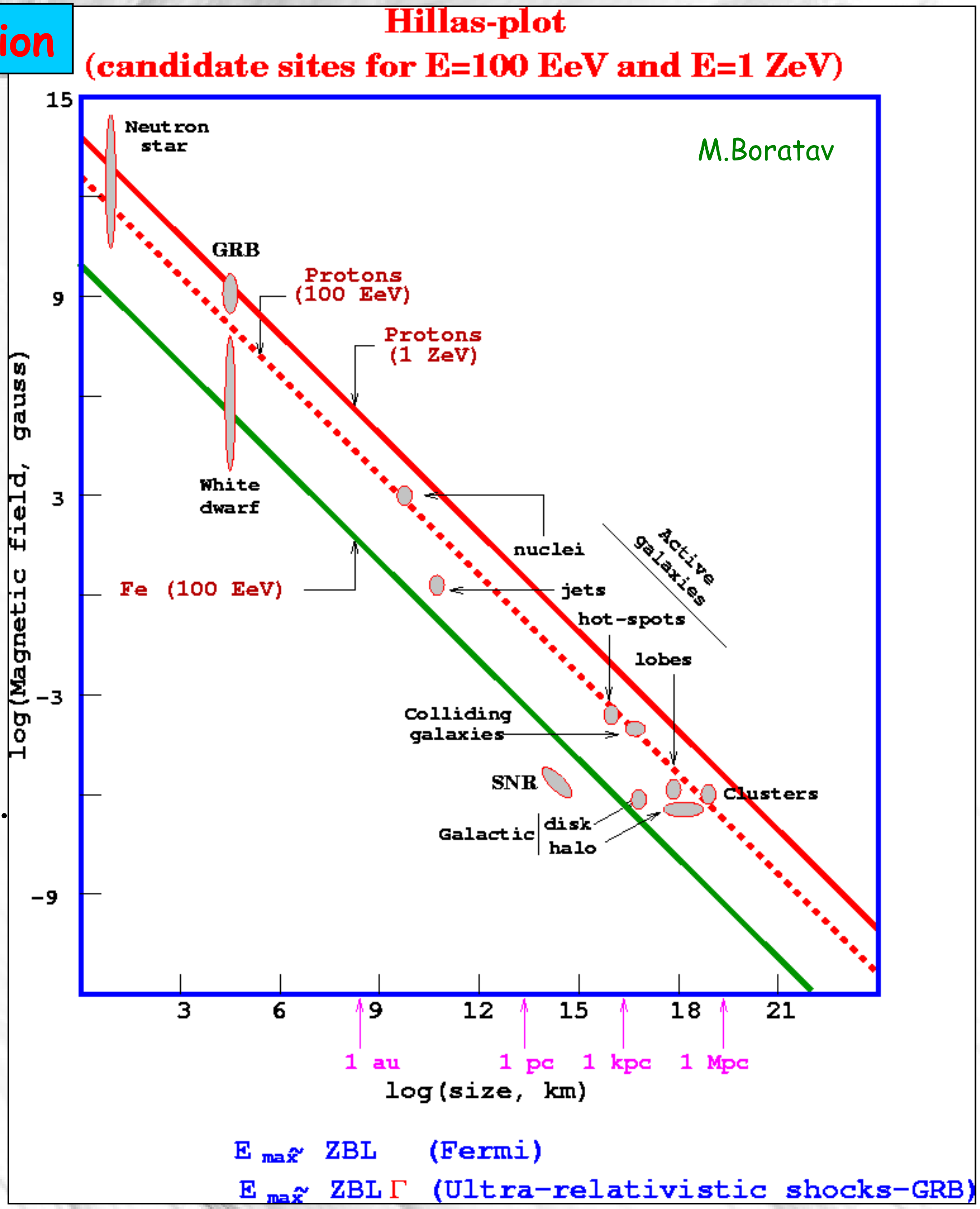
2.) in most conventional scenarios exceptionally powerful acceleration sources within that distance are needed.

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

1^{st} Order Fermi Shock Acceleration

The most widely accepted scenario of cosmic ray acceleration





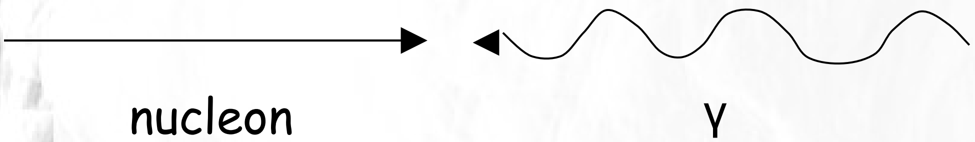
Fractional energy gain per shock crossing ~u_1-u_2 on time scale ~r_L/u_2.

This leads to a spectrum E^{-q} with $q > 2$ typically.

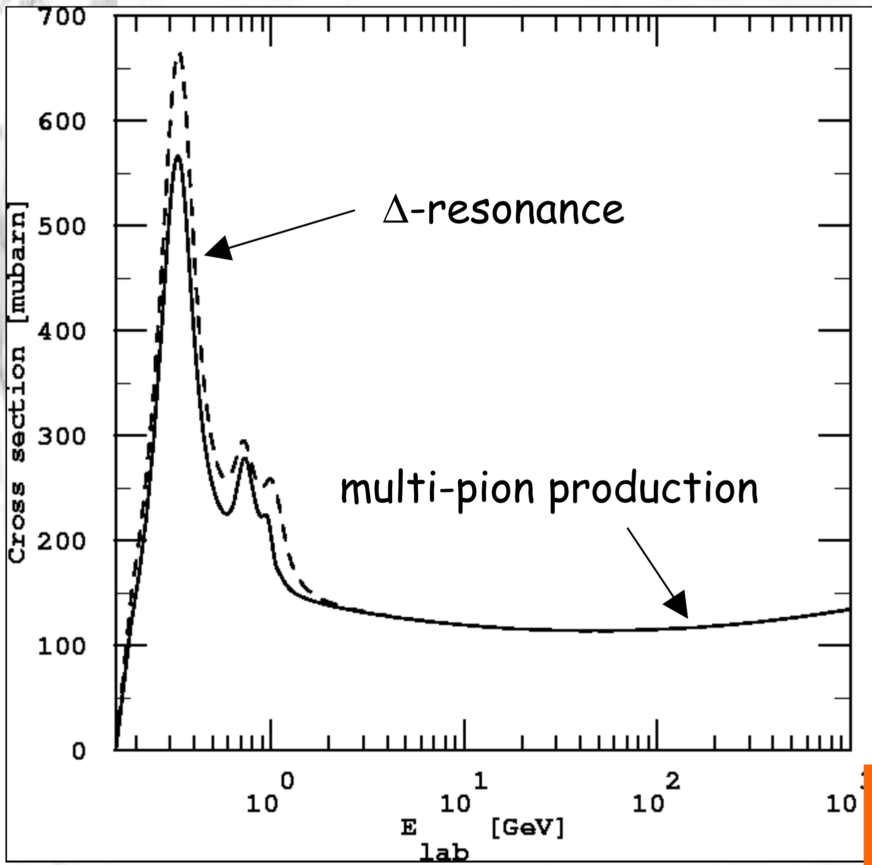
When the gyroradius r_L becomes comparable to the shock size L, the spectrum cuts off.

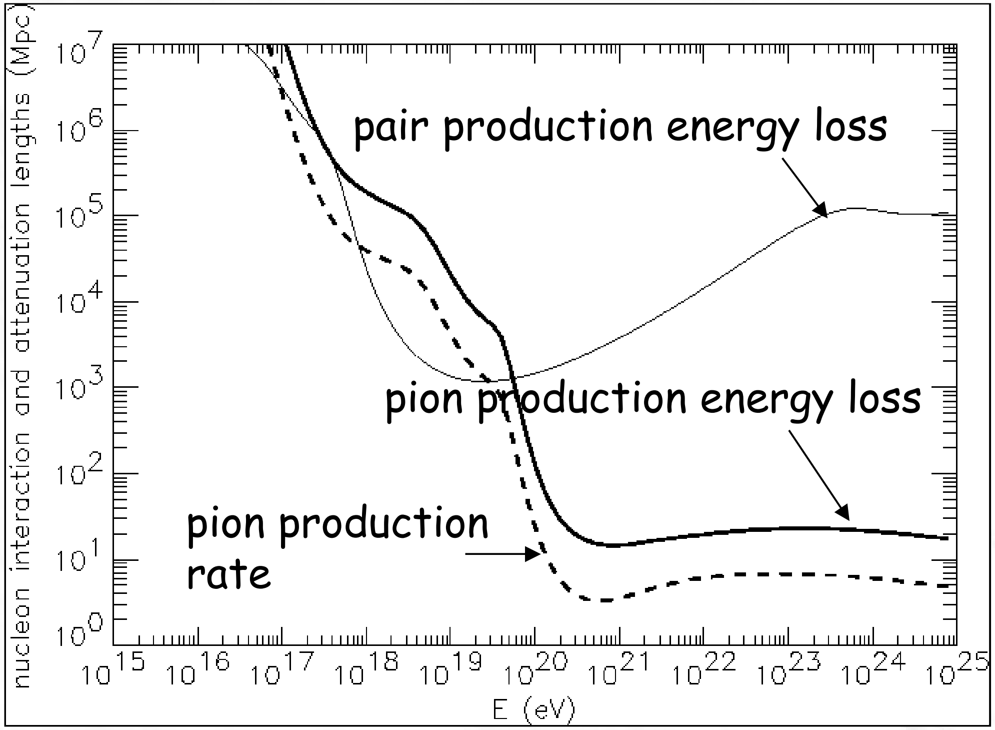
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



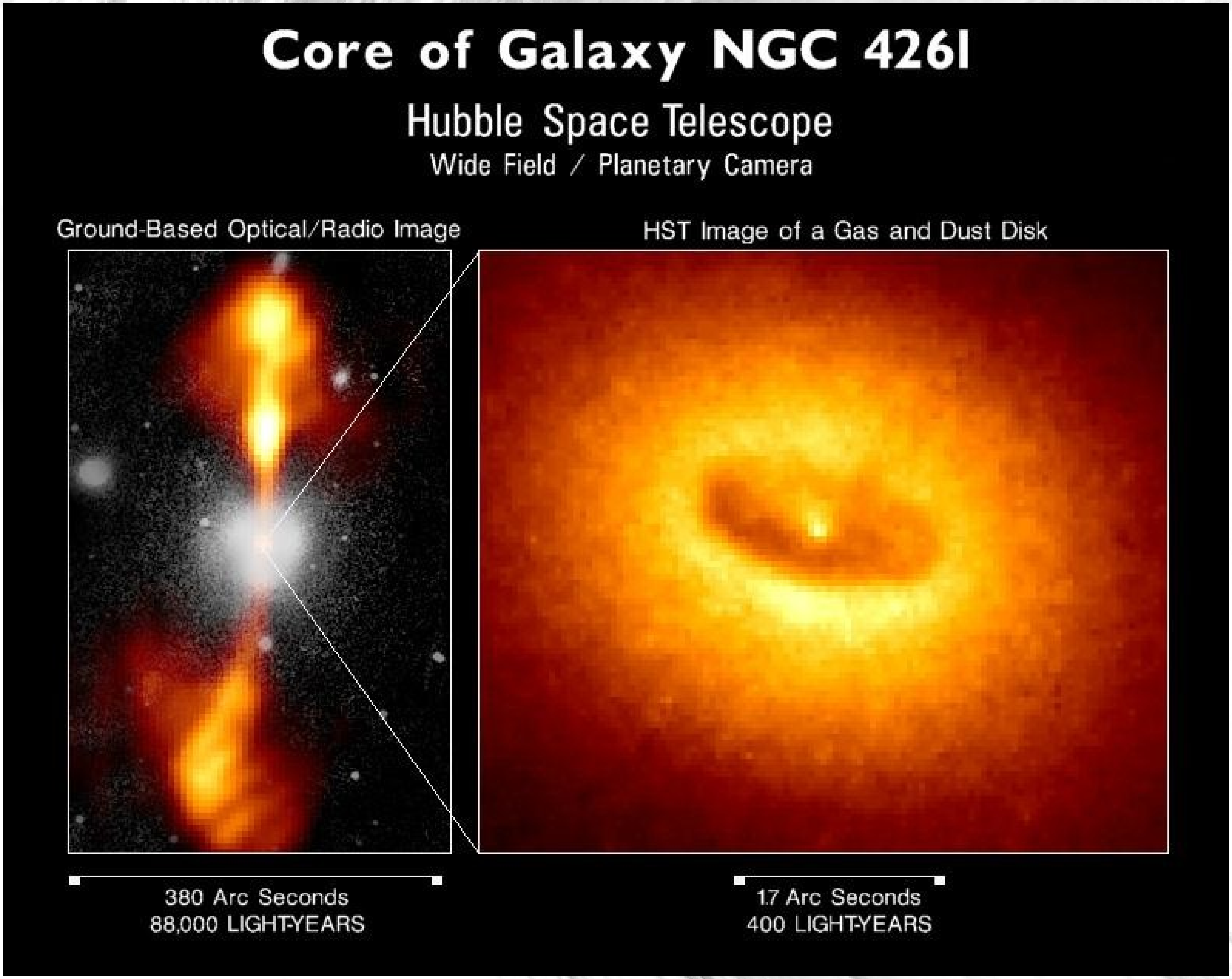
$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\epsilon} \approx 4\,x\,10^{19}\,\mathrm{eV}$$





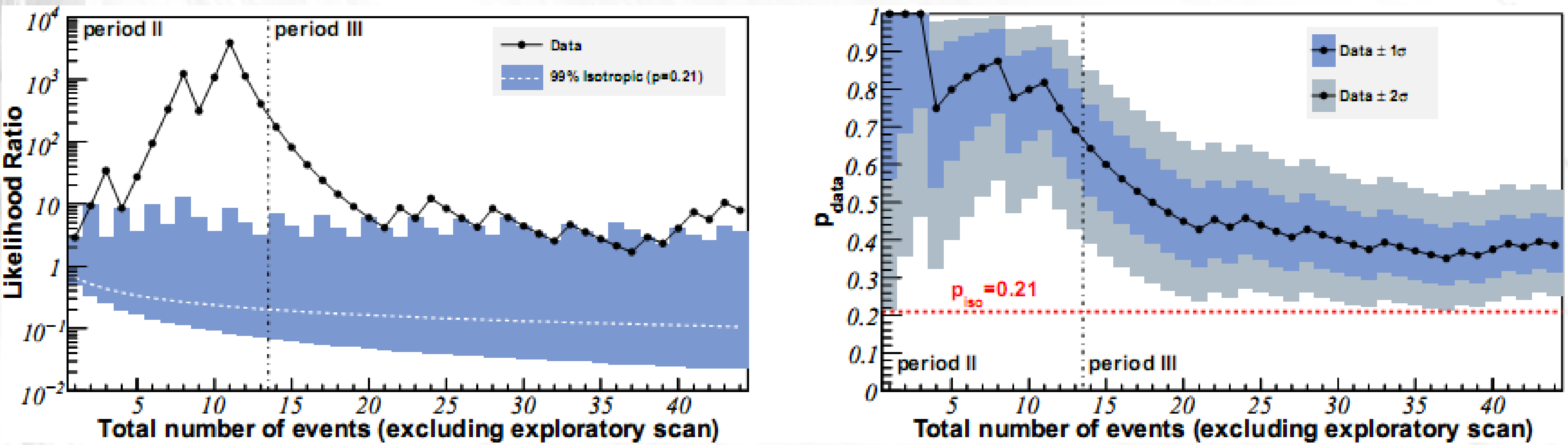
sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma > 10^{11}$ could avoid this conclusion.

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



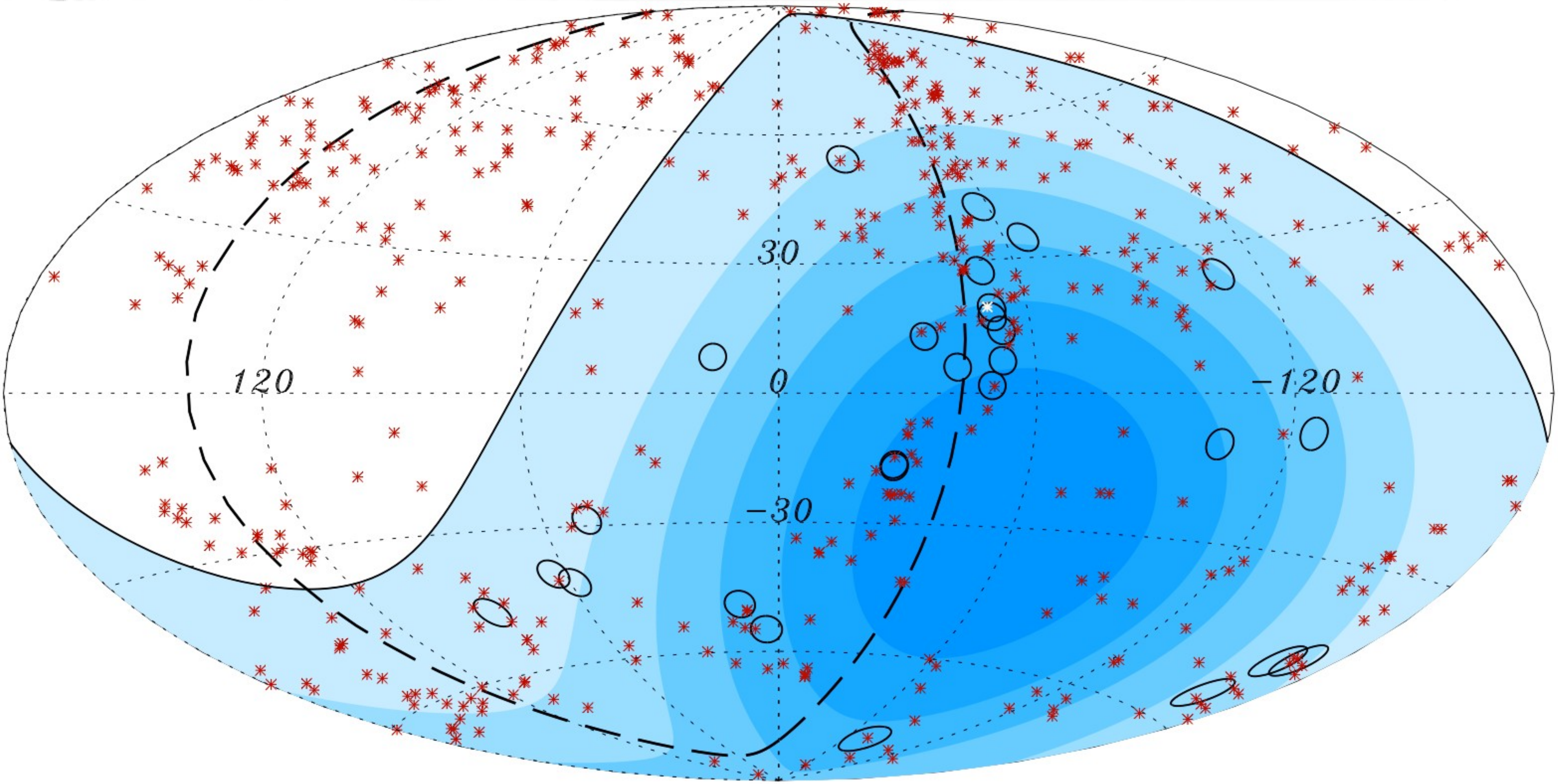
Ultra-High Energy Cosmic Ray Sources and Composition

New results from the Pierre Auger Observatory presented at the International Cosmic Ray Conference in Krakow, Poland



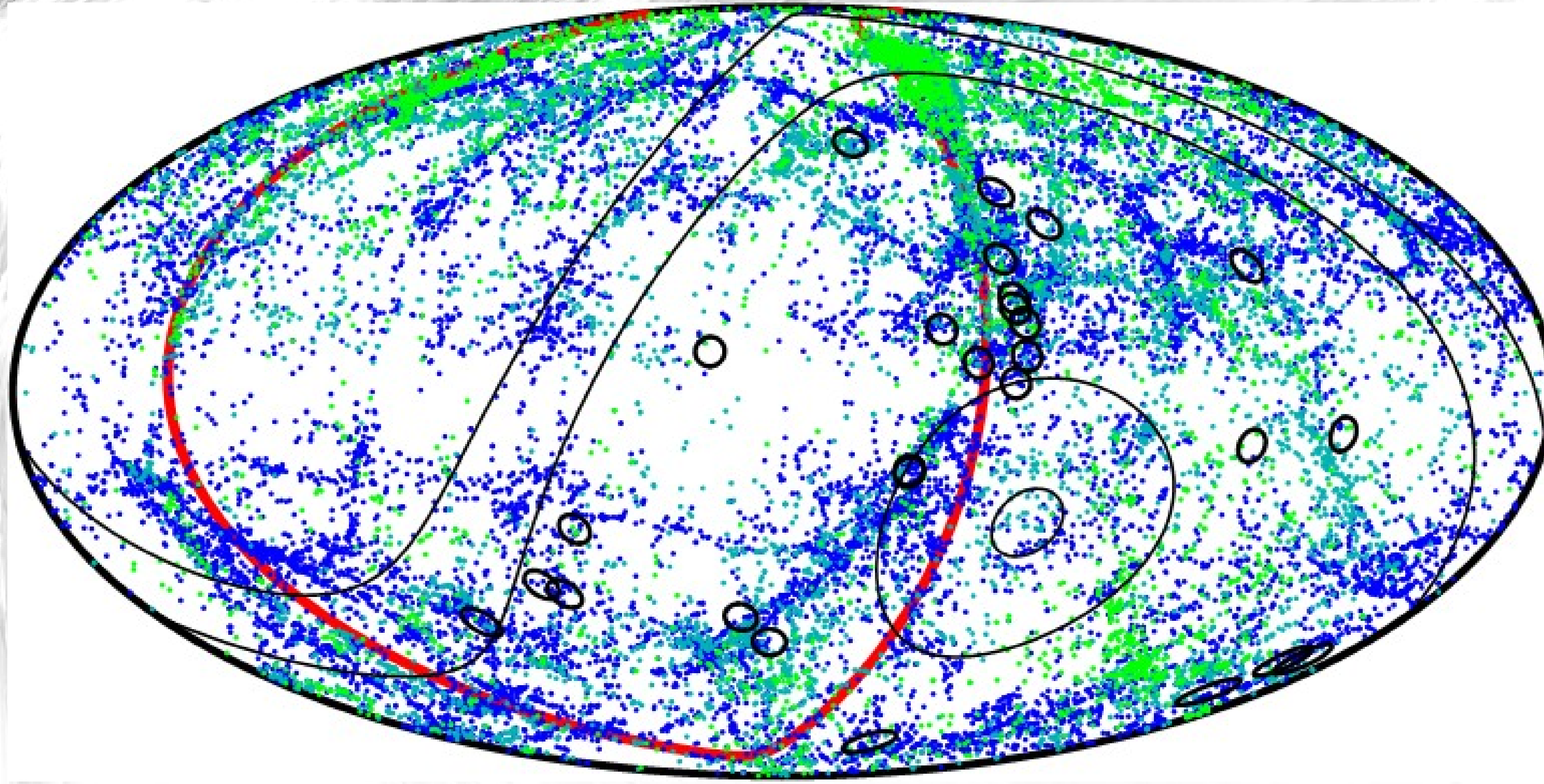
The case for anisotropy does not seem to have strengthened with more data

Auger sees Correlations with AGNs !



Red crosses = 472 AGNs from the Veron Cetty catalogue for z < 0.018
circles = 27 highest enery events above 57 EeV.
20 events correlated within 3.1°, 7 uncorrelated of which most in galactic plane

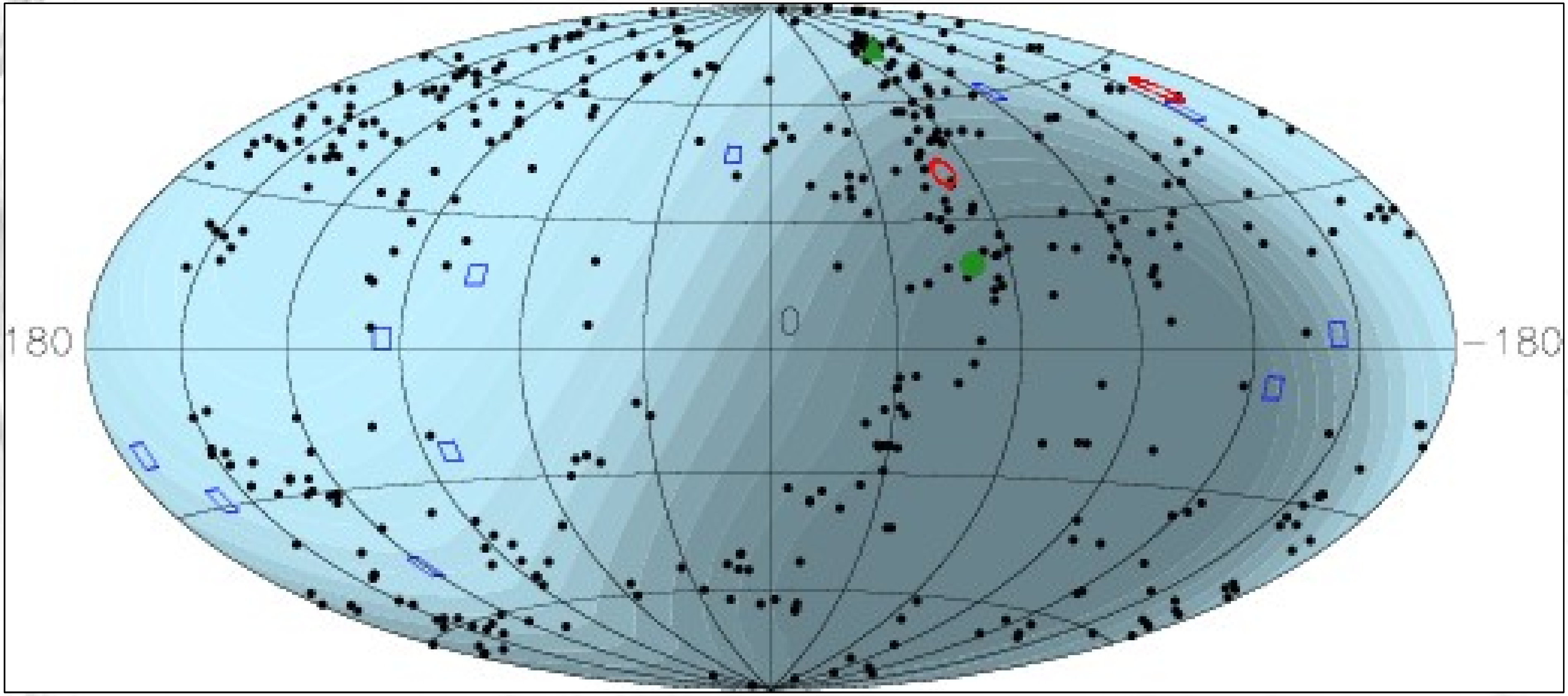
Pierre Auger Collaboration, Science 318 (2007) 938



Points = galaxies with $z < 0.015$
Black circles = Auger events above 60 EeV.
Black lines = equal exposure contours
red line= supergalactic plane

Lipari, arXiv:0808.0417

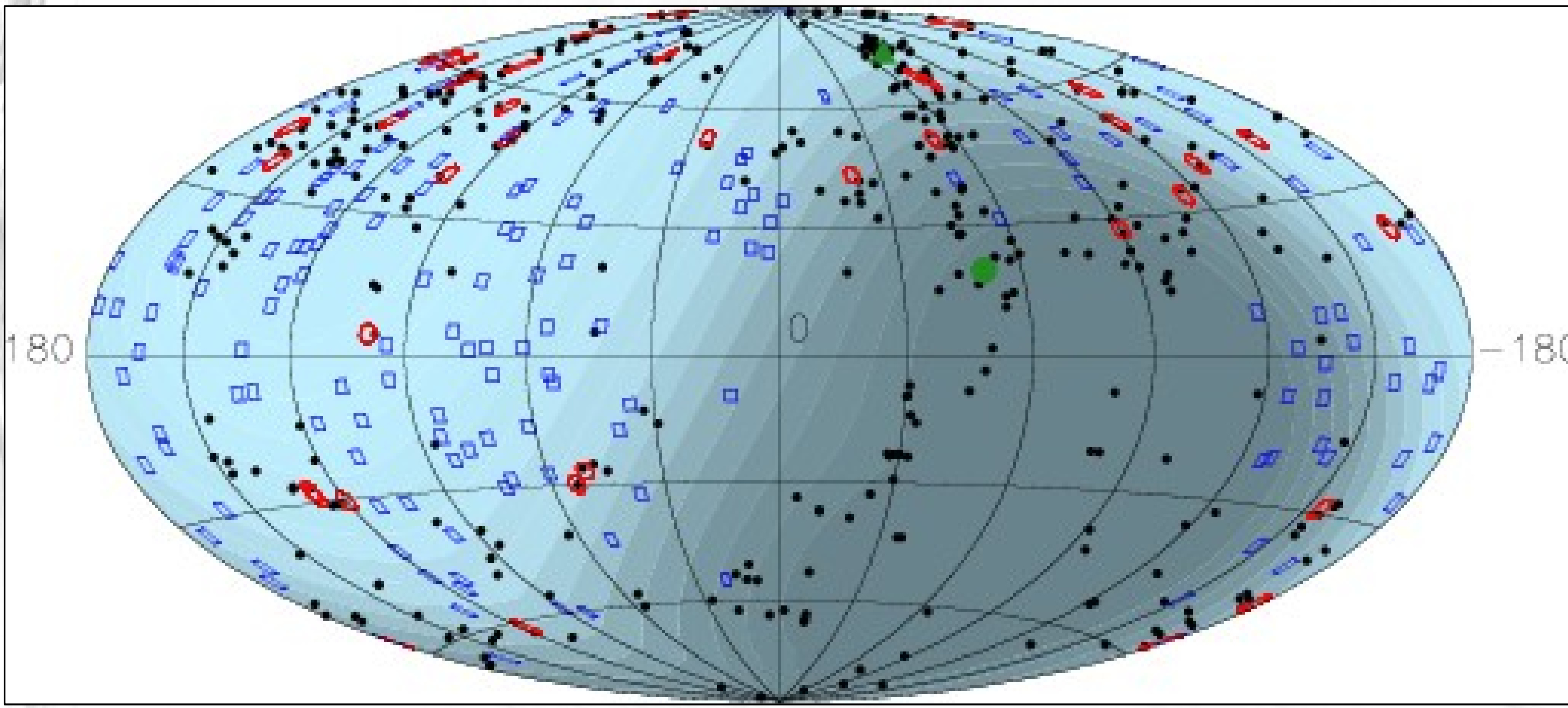
But HiRes sees no Correlations !



Black dots = 457 AGNs + 14 QSOs from the Veron Cetty catalogue for z < 0.018
red circles = 2 correlated events above 56 EeV within 3.1°,
blue squares = 11 uncorrelated events

HiRes Collaboration, arXiv:0804.0382

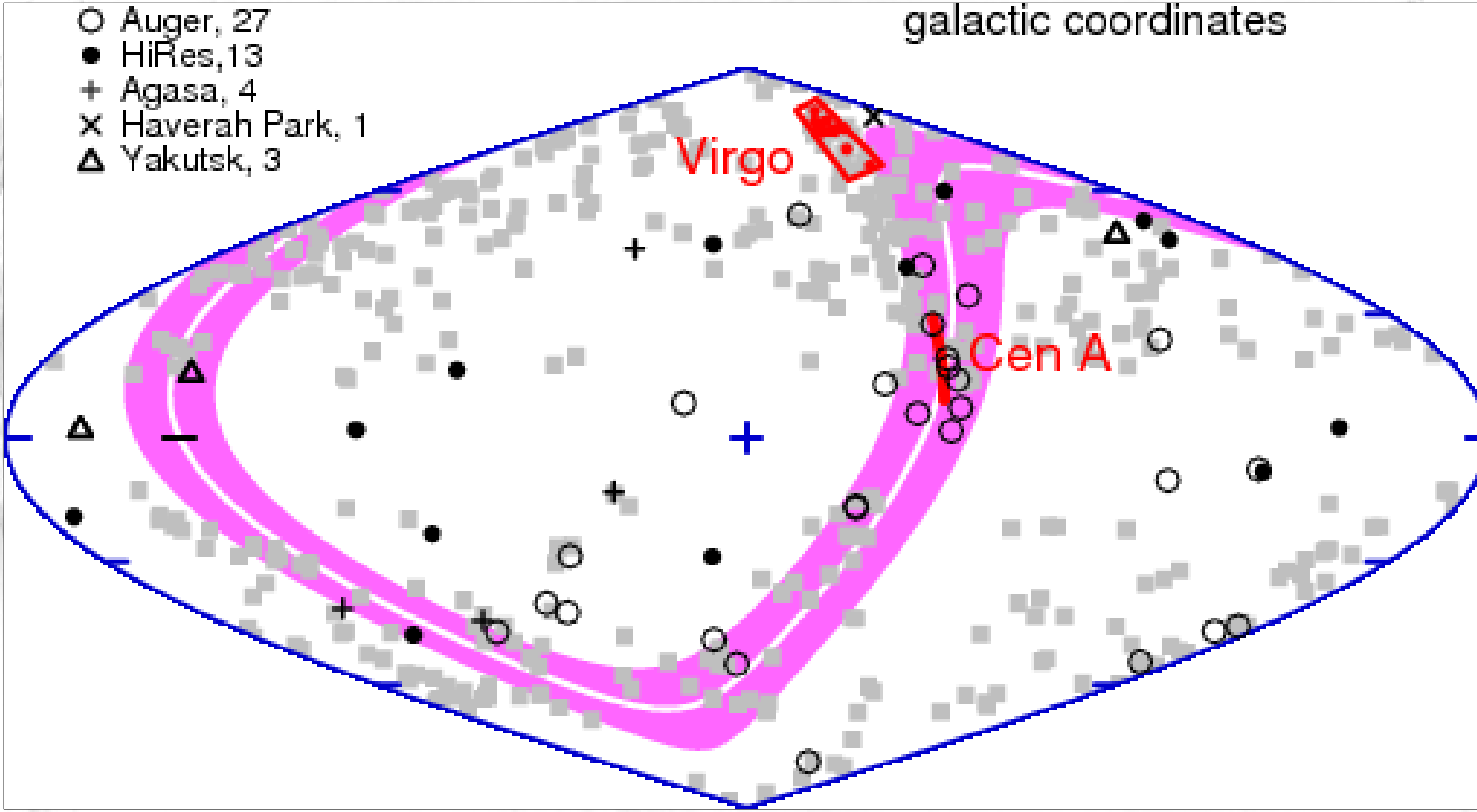
But HiRes sees no Correlations !



Black dots = 389 AGNs + 14 QSOs from the Veron Cetty catalogue for z < 0.016
red circles = 36 correlated events above 15.8 EeV within 2.0°,
blue squares = 162 uncorrelated events

HiRes Collaboration, arXiv:0804.0382

Correlation with supergalactic plane



Correlation with supergalactic plane within 10° (15°) is improved from 2.0 (2.4) sigma to 3.6 (3.2) sigma when definition relates to structure within 70 Mpc.

Stanev, arXiv:0805.1746

Some general estimates 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 bolometric power of

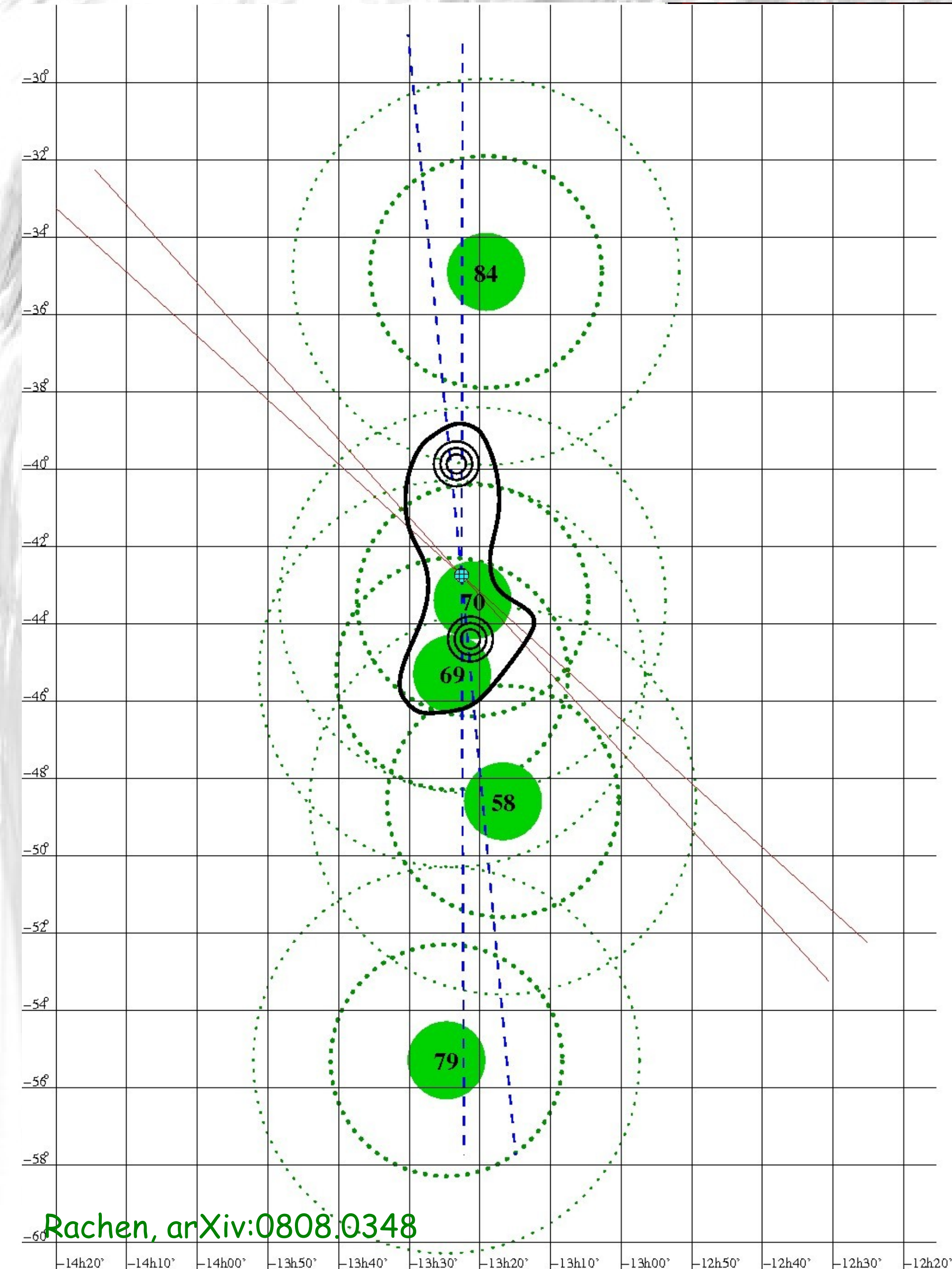
$$L_{\min} \approx \epsilon^2 / Z_0 \approx 10^{45}\, Z^{-2} \left(\frac{E_{\max}}{10^{20}\,\mathrm{eV}} \right)^2 \mathrm{erg\,s^{-1}}$$

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

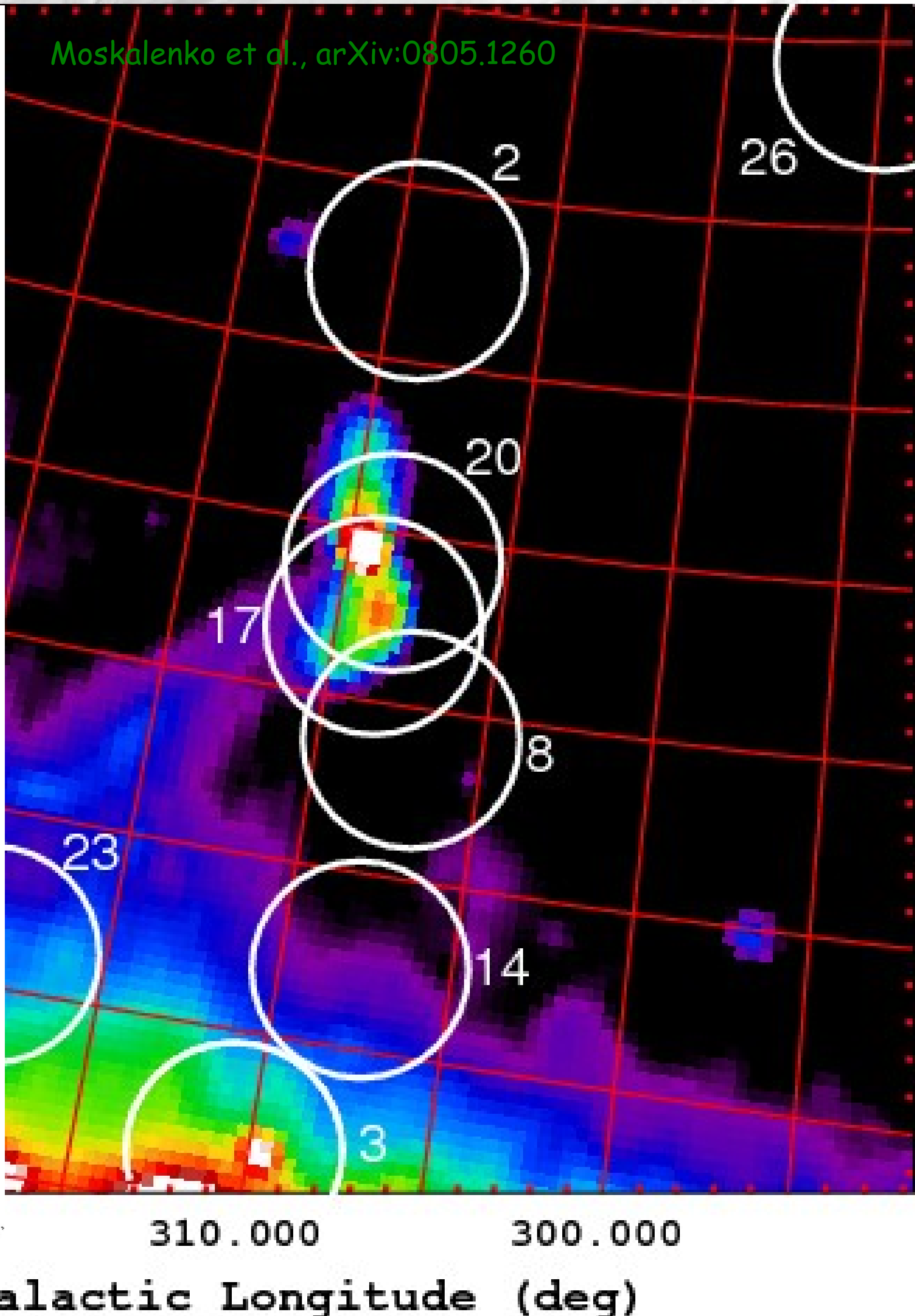
$$BR \; > \; 3 \times 10^{17}\, \Gamma^{-1} \left(\frac{E_{\max}}{10^{20}\,\mathrm{eV}} \right) \mathrm{Gauss\,cm}$$

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.

Centaurus A

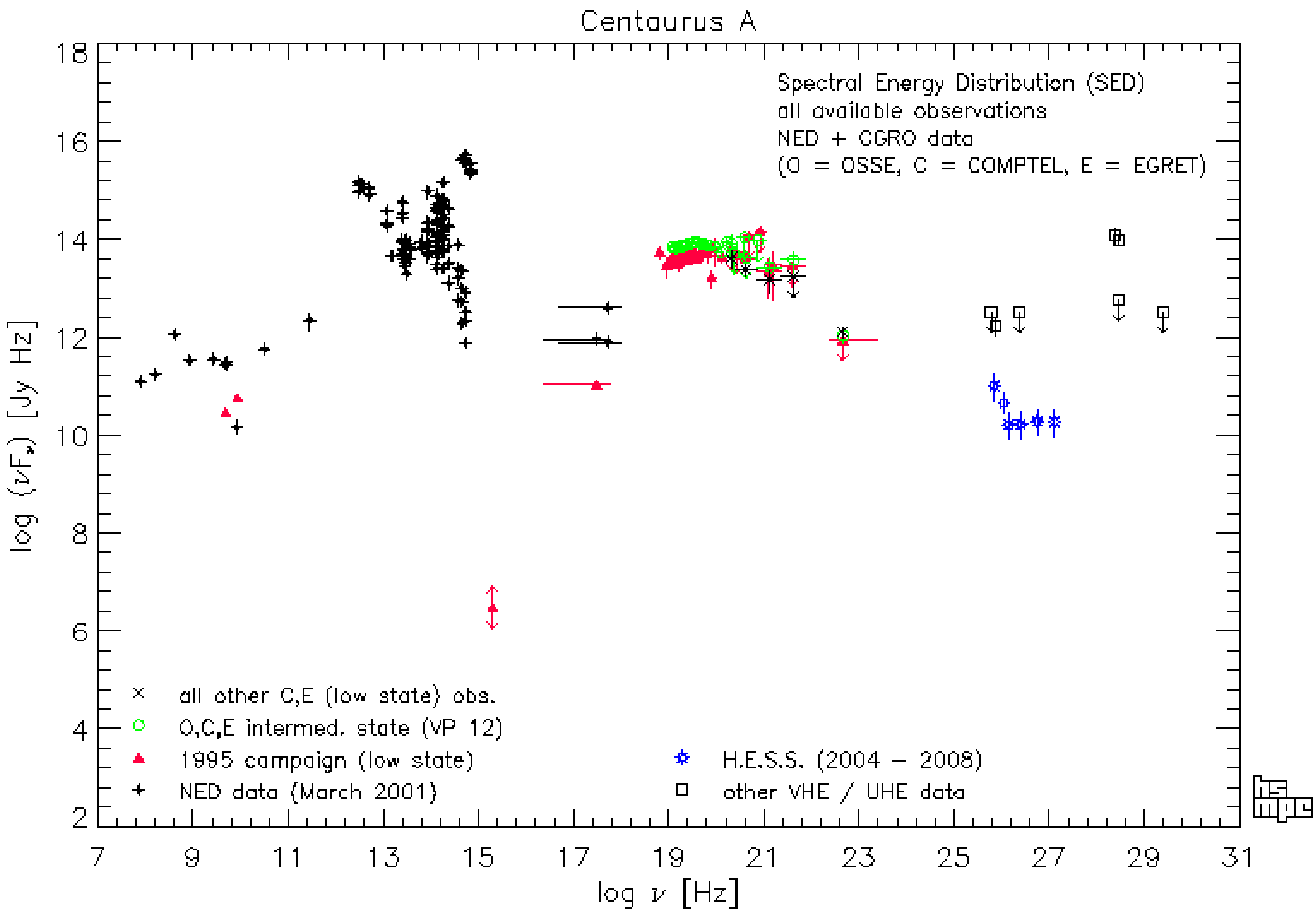


-30°
-32°
-34°
-36°
-38°
-40°
-42°
-44°
-46°
-48°
-50°
-52°
-54°
-56°
-58°
-60°
84
70
69
58
79
-14h20'
-14h10'
-14h00'
-13h50'
-13h40'
-13h30'
-13h20'
-13h10'
-13h00'
-12h50'
-12h40'
-12h30'
-12h20'
Rachen, arXiv:0808.0348

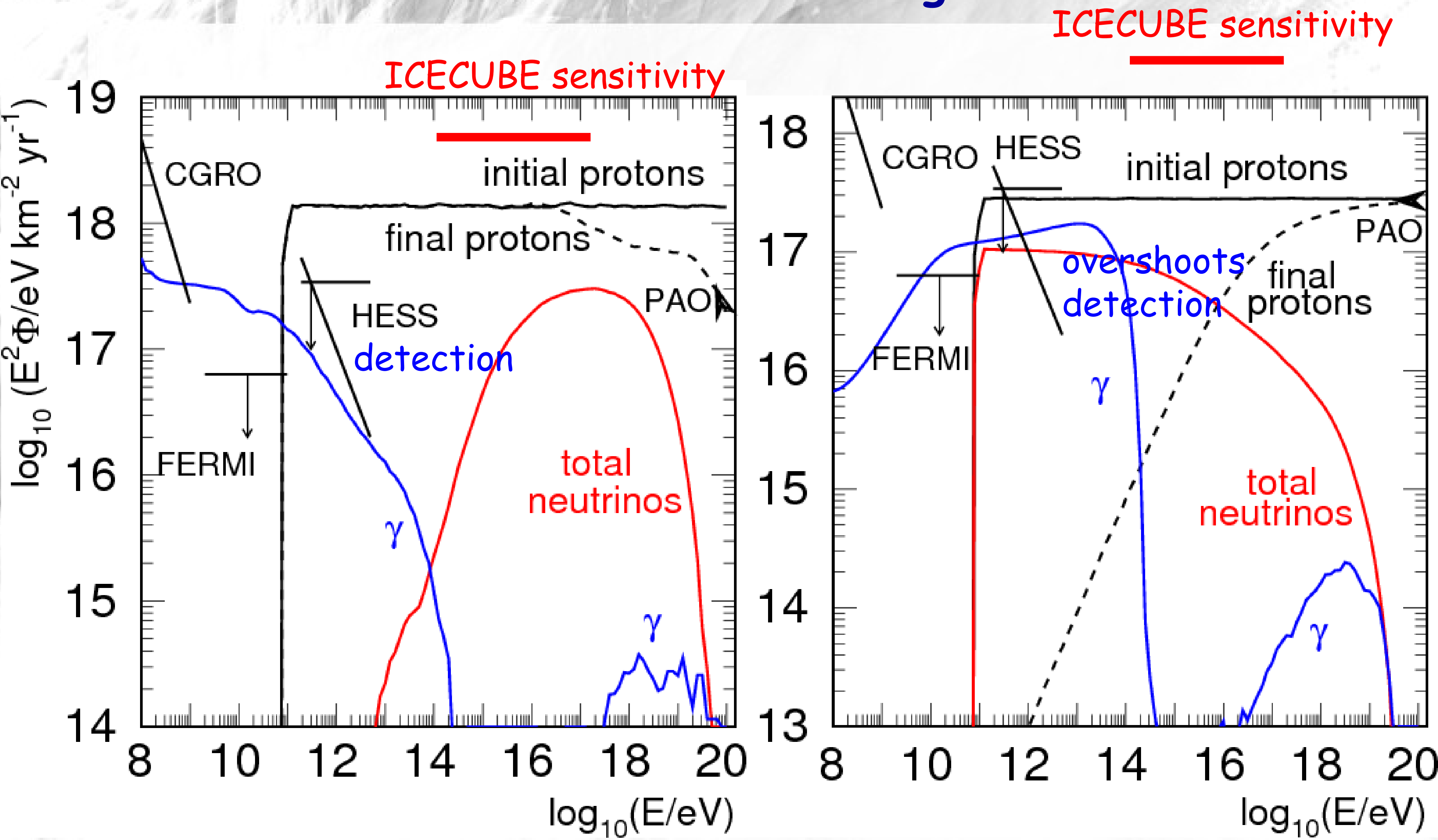


Moskalenko et al., arXiv:0805.1260
2
26
20
17
8
23
14
3
310.000
300.000
Galactic Longitude (deg)

Centaurus A was recently seen by H.E.S.S.



Centaurus A as Multimessenger Source

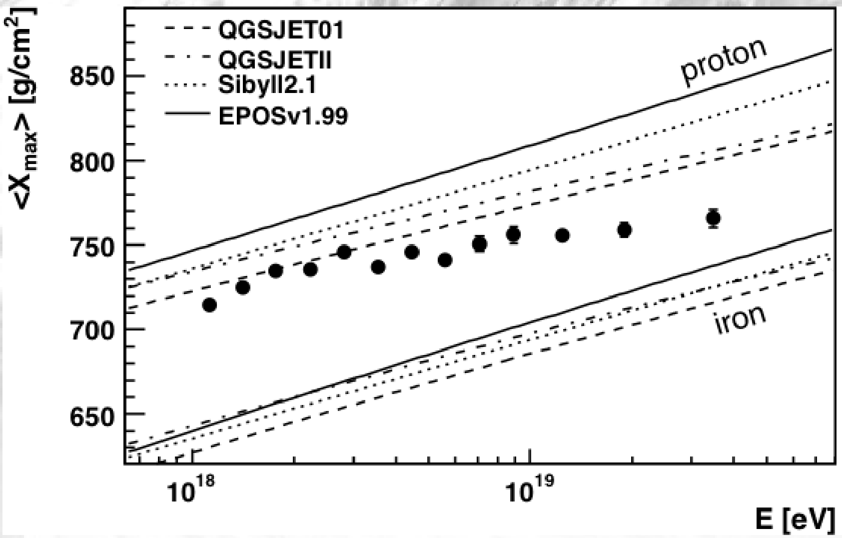


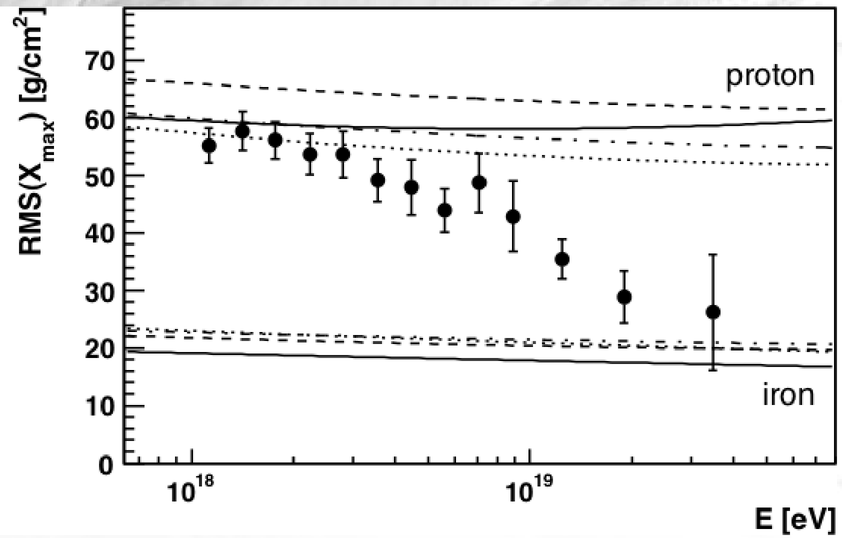
E^{-2} acceleration of protons around the core

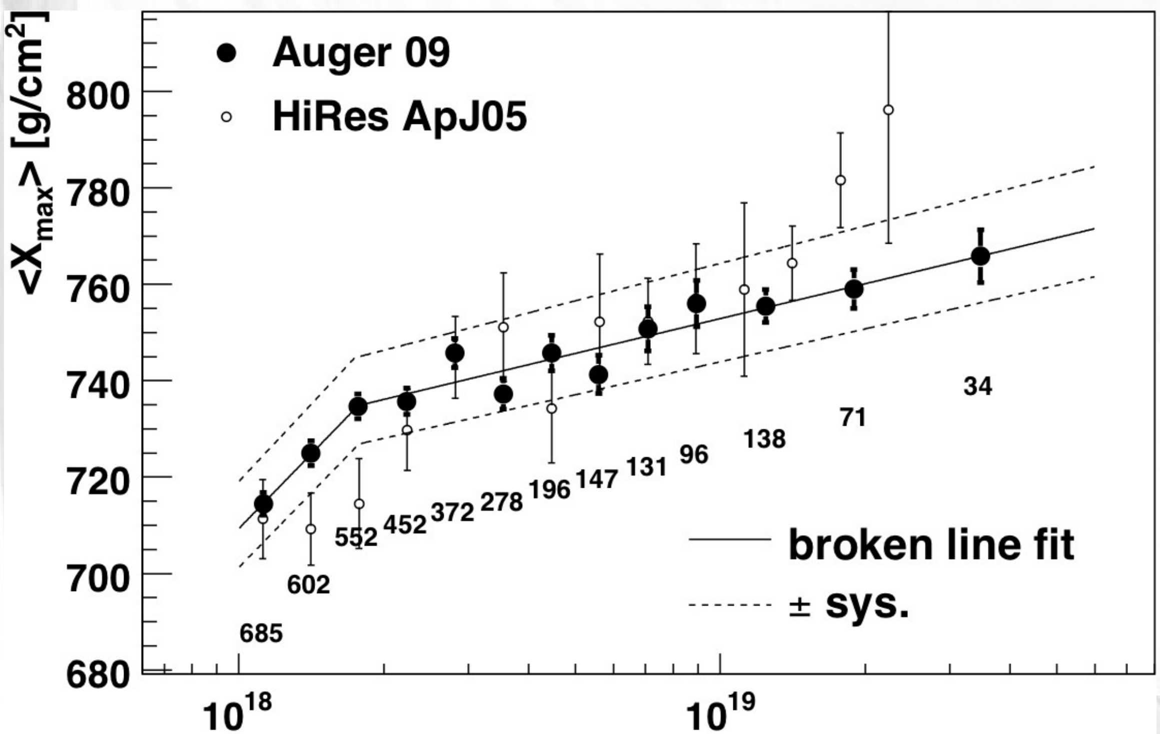
E^{-2} acceleration of protons in the jet

Kachelriess, Ostapchenko, Tomas, NJP 11 (2009) 065017

There may be a significant heavy component at the highest energies:



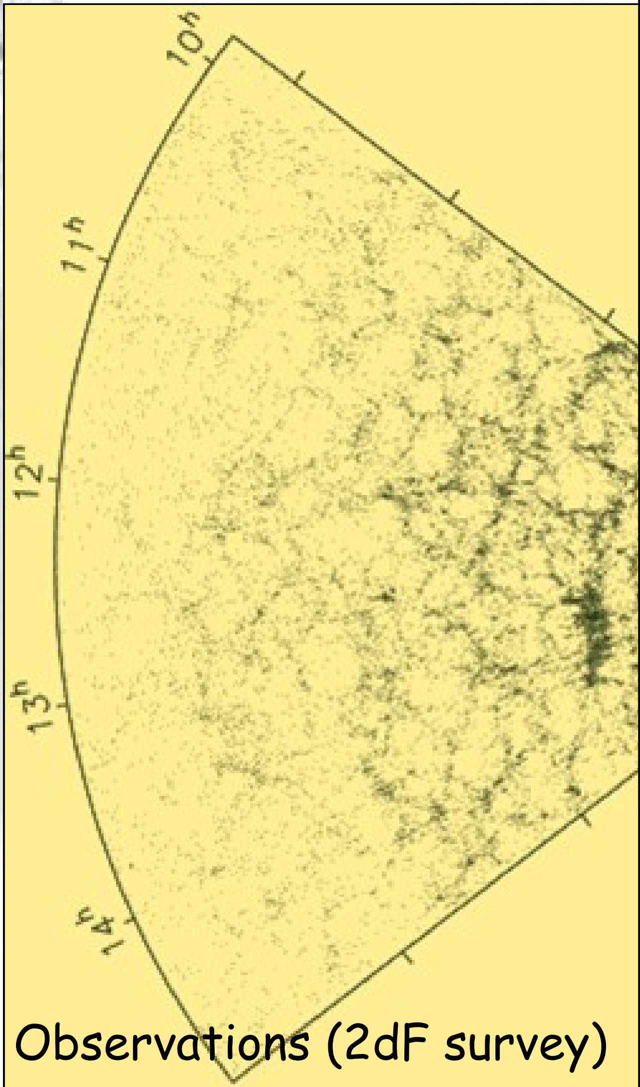




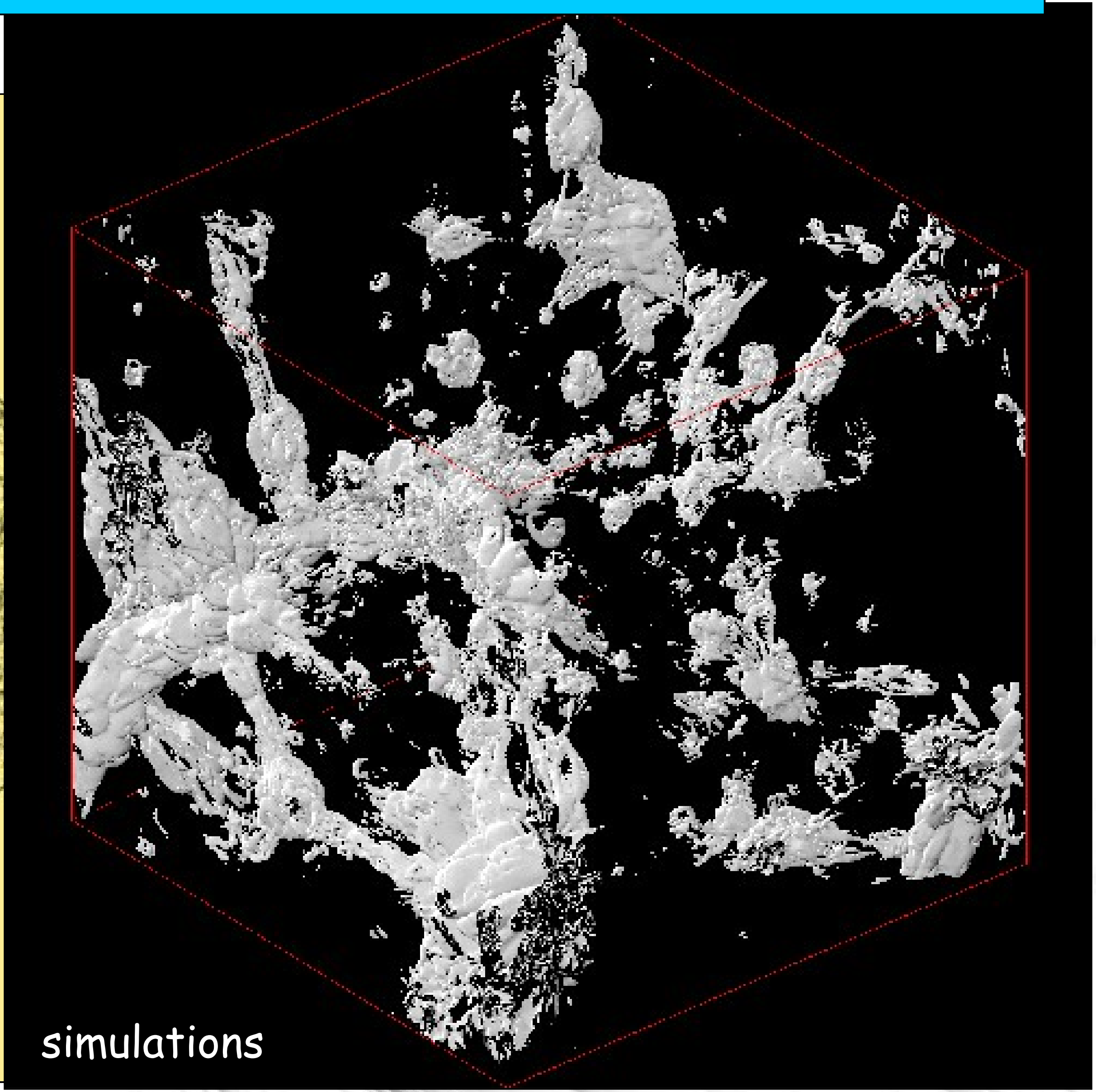
Auger data on composition seem to point to a quite heavy composition at the highest energies, whereas HiRes data seem consistent with a light composition.

Pierre Auher Collaboration, Phys.Rev.Lett., to appear, arXiv:1002.0699

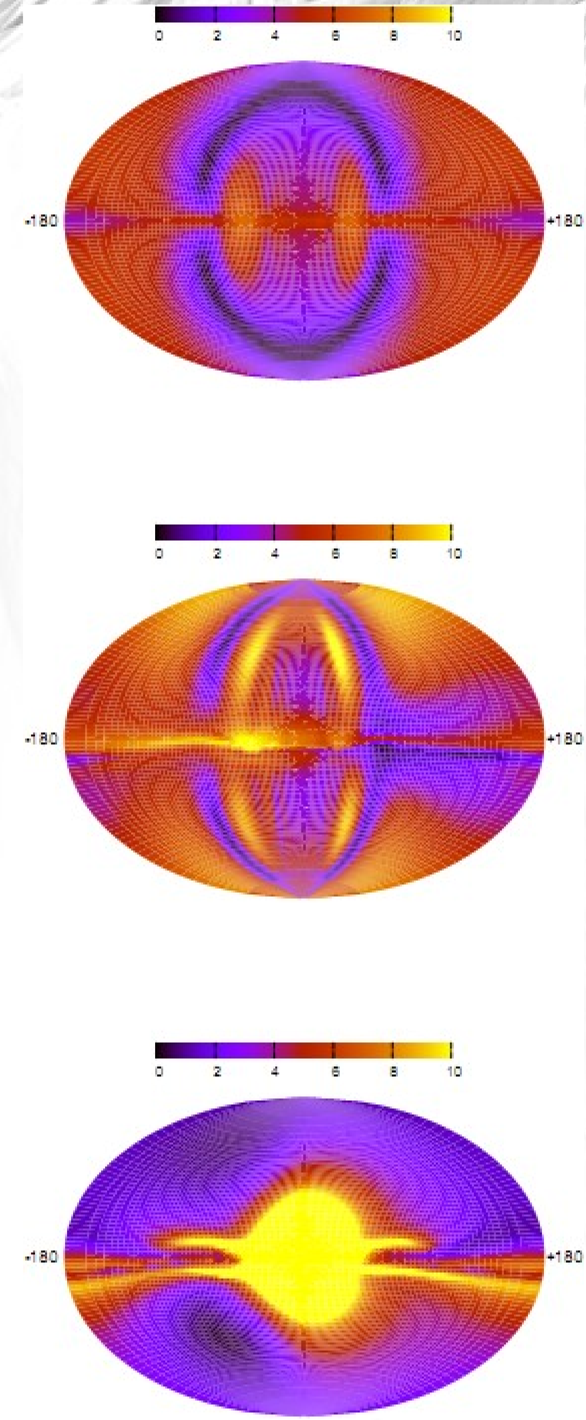
Ultra-High Energy Cosmic Ray Propagation in a structured Universe



Observations (2dF survey)


simulations

First, what about the Galactic deflection ?



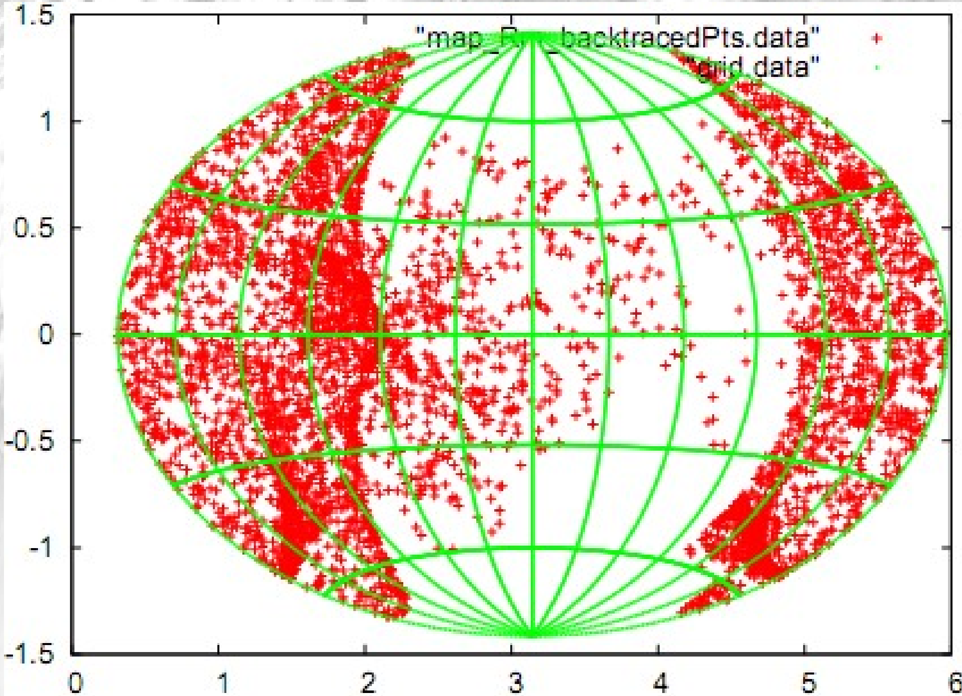
Deflection in **galactic magnetic field** is rather model dependent, here for $E/Z=4\ 10^{19}$ eV for Models of

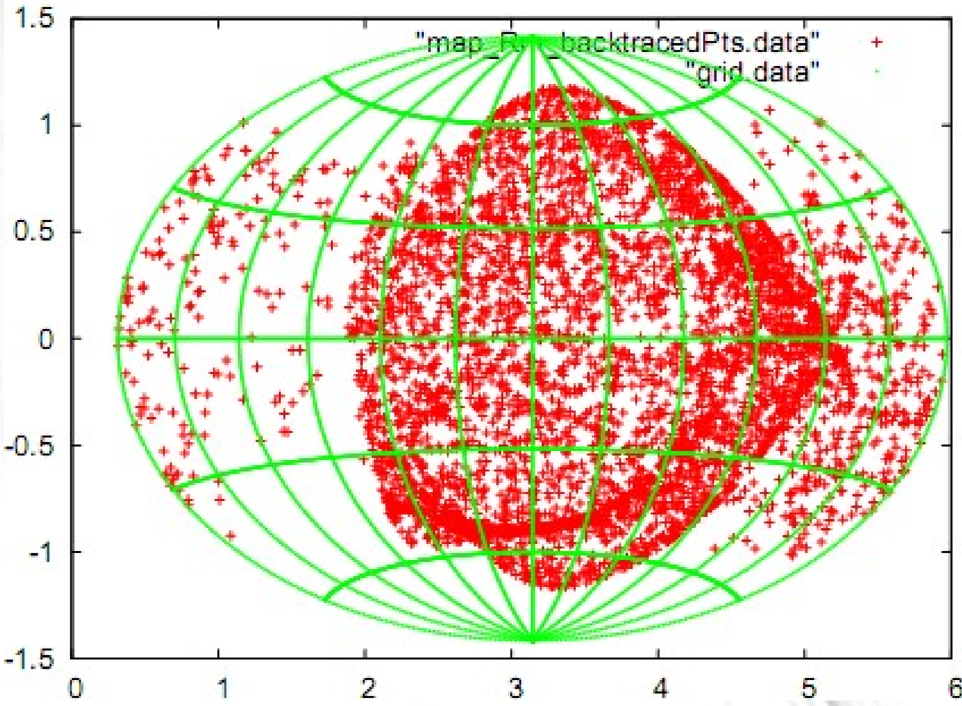
Tinyakov, Tkachev (top)

Harrari, Mollerach, Roulet (middle)

Prouza, Smida (bottom)

Kachelriess, Serpico, Teshima Astropart. Phys. 26 (2006) 378





Back-tracking of iron at $6\ 10^{19}$ eV through Galactic field according to Prouza-Smida model gives highly anisotropic picture

Top: toward galactic centre

Bottom: toward galactic anti-centre

Giacinti, Kachelriess, Semikoz, Sigl

"Conundrum":

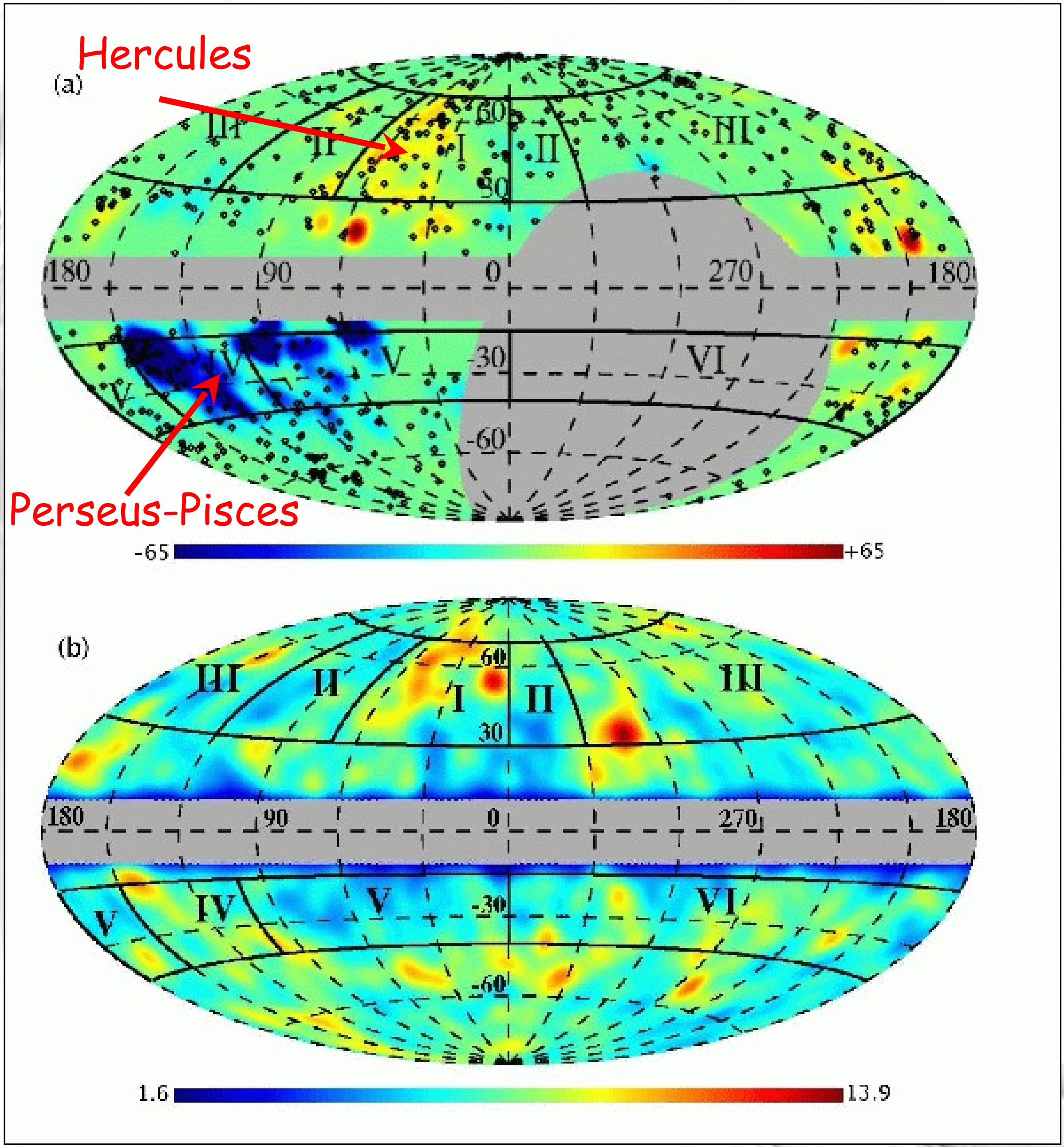
If deflection is small and correlated AGN are sources then

a) primaries should be protons to avoid too much deflection in galactic field

b) but air shower measurements by Pierre Auger (but not HiRes) indicate mixed or heavy composition

c) Theory of AGN acceleration seem to necessitate heavier nuclei to reach observed energy

Propagation in structured extragalactic magnetic fields



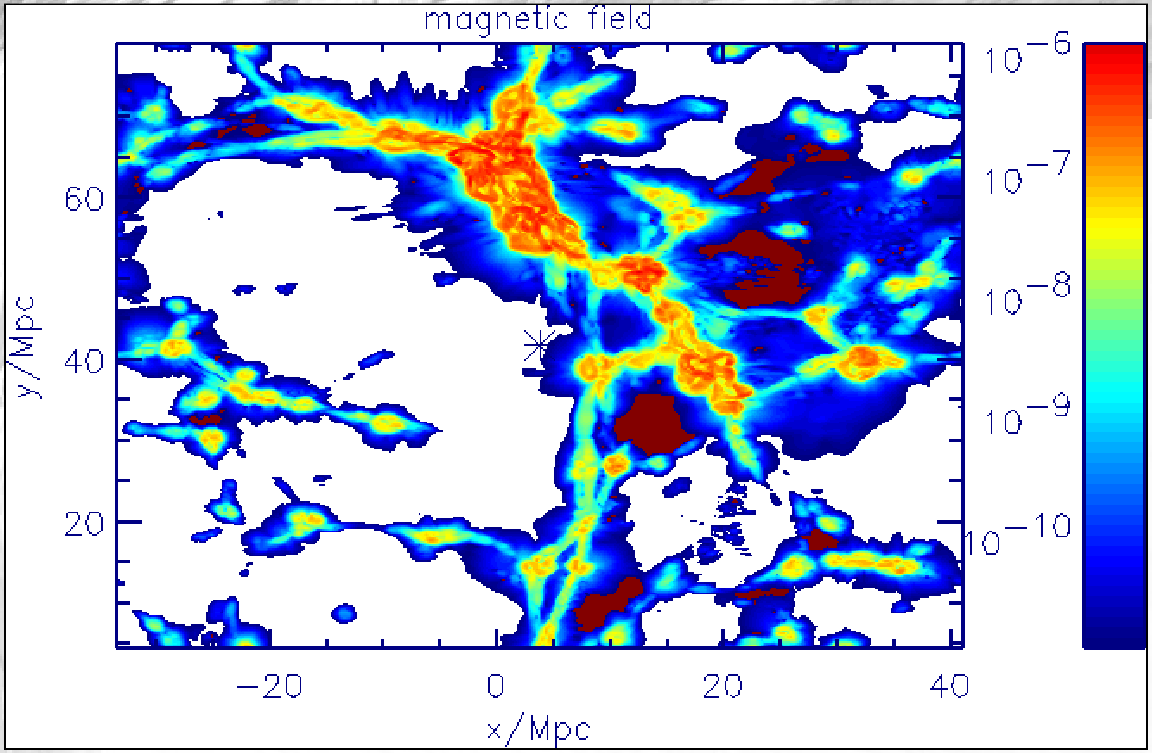
Smoothed rotation measure:
Possible signatures of ~0.1μG level on super-cluster scales!

Theoretical motivations from the Weibel instability which tends to drive field to fraction of thermal energy density

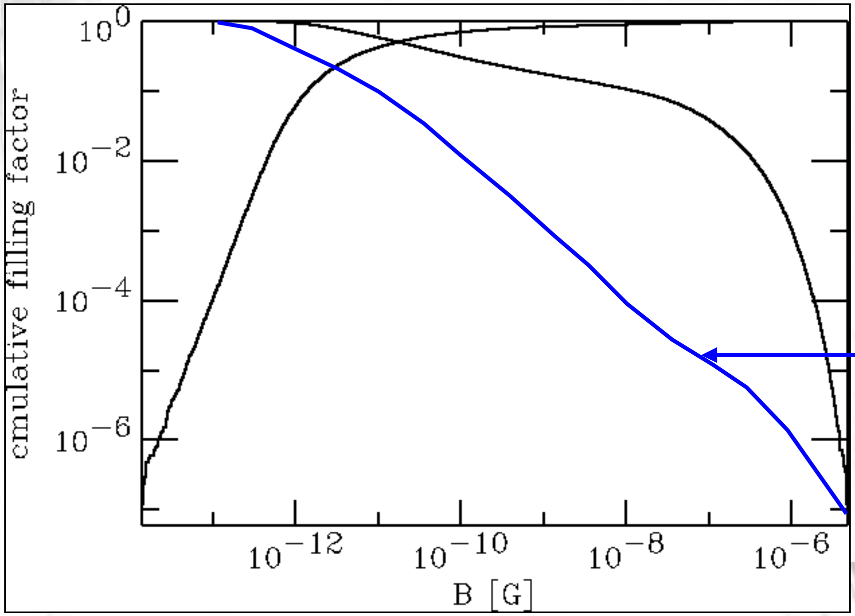
But need much more data from radio astronomy, e.g. Lofar, SKA

2MASS galaxy column density

Xu et al., astro-ph/0509826

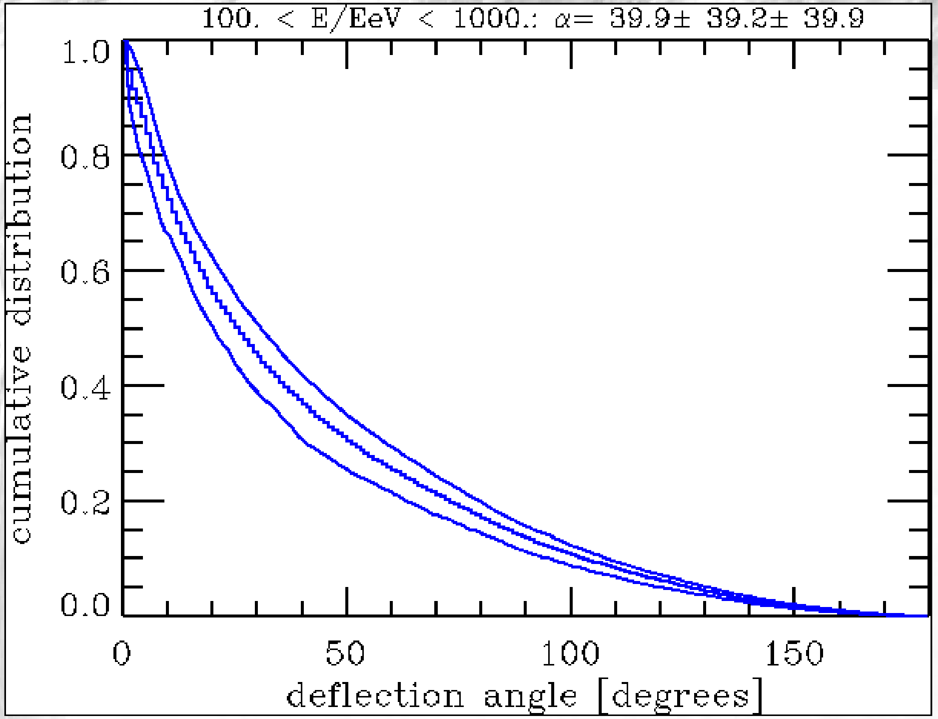


Observer immersed in fields of ~10^{-11} Gauss:
Cut thru local magnetic field strength



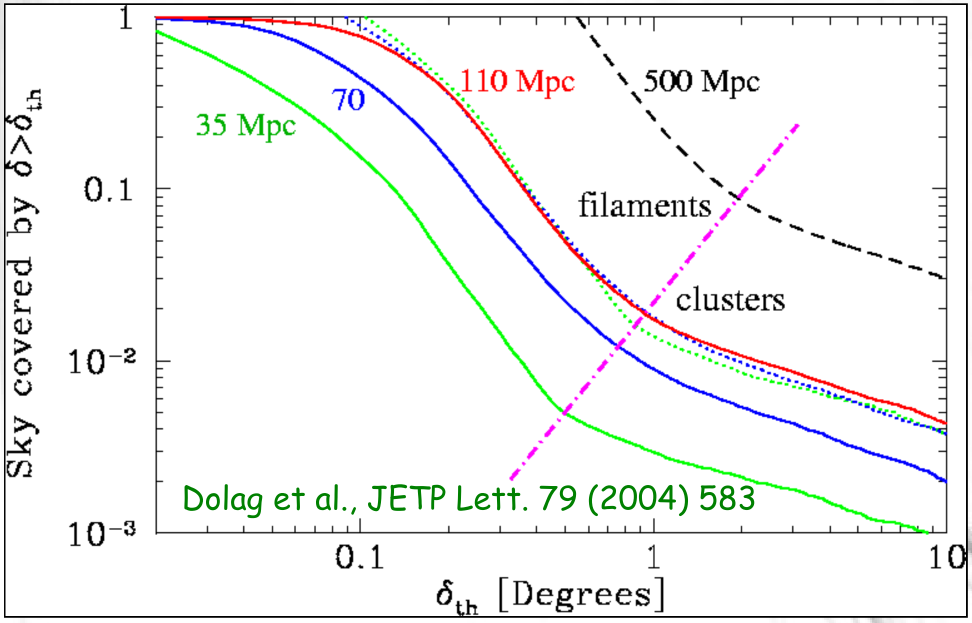
Filling factors of magnetic fields from the large scale structure simulation.

Note: MHD code of Dolag et al., JETP Lett. 79 (2004) 583 gives much smaller filling factors for strong fields.



Deflection in magnetized structures surrounding the sources lead to off-sets of arrival direction from source direction up to >10 degrees up to 10^{20} eV in our simulations. This is contrast to Dolag et al., JETP Lett. 79 (2004) 583.

Particle astronomy not necessarily possible, especially for nuclei !



Cumulative deflection angle distributions for proton primaries

Conclusion:

A correleation with the local large scale structure is not necessarily destroyed by relatively large deflection, not even for iron, provided the field correlates with the large scale structure and deflection is mainly within that structure

It would mean that any correlation with specific sources does not identify particular sources, but only a source class that is distributed as the large scale structure

Instead of AGN it could be e.g. due to GRBs or magnetars

Neutral Secondaries of Ultra-High Energy Cosmic Rays Are sensitive to their Composition

accelerated nuclei interact:

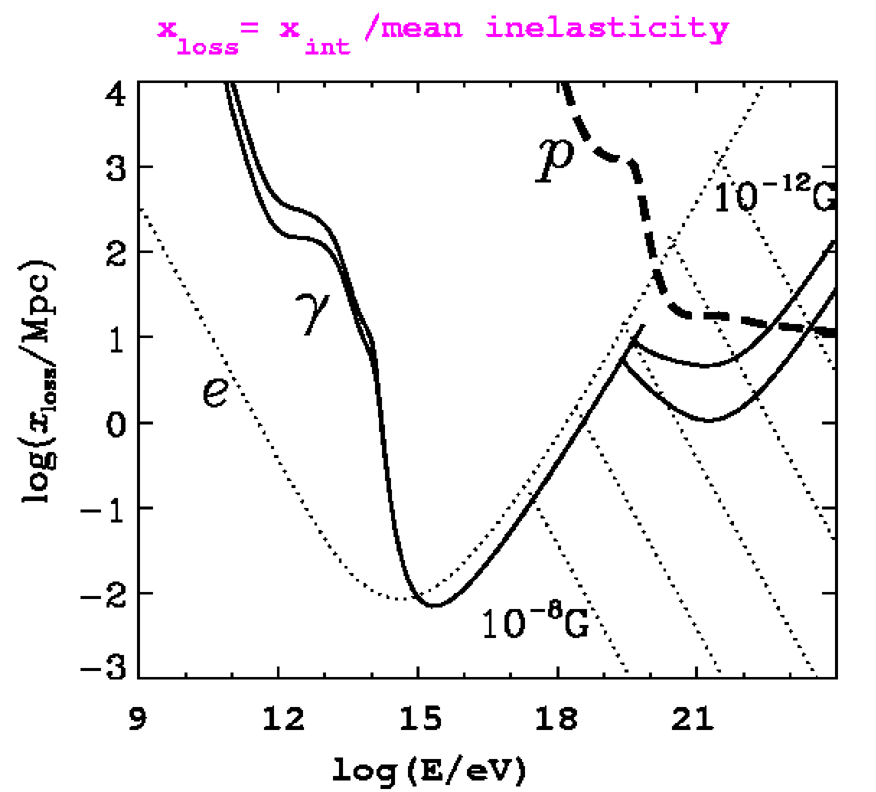
$$ {}^{A}_{Z} + N, \gamma \rightarrow X + \begin{array}{l} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{0} \rightarrow \gamma - \text{rays} \end{array} $$

during propagation ("cosmogenic") or in sources (AGN, GRB, ...)

=> energy fluences in γ-rays and neutrinos are comparable due to isospin symmetry.

Neutrino spectrum is unmodified, γ-rays pile up below pair production threshold on CMB at a few 10^{14} eV.

Universe acts as a calorimeter for total injected electromagnetic energy above the pair threshold.
=> neutrino flux constraints.



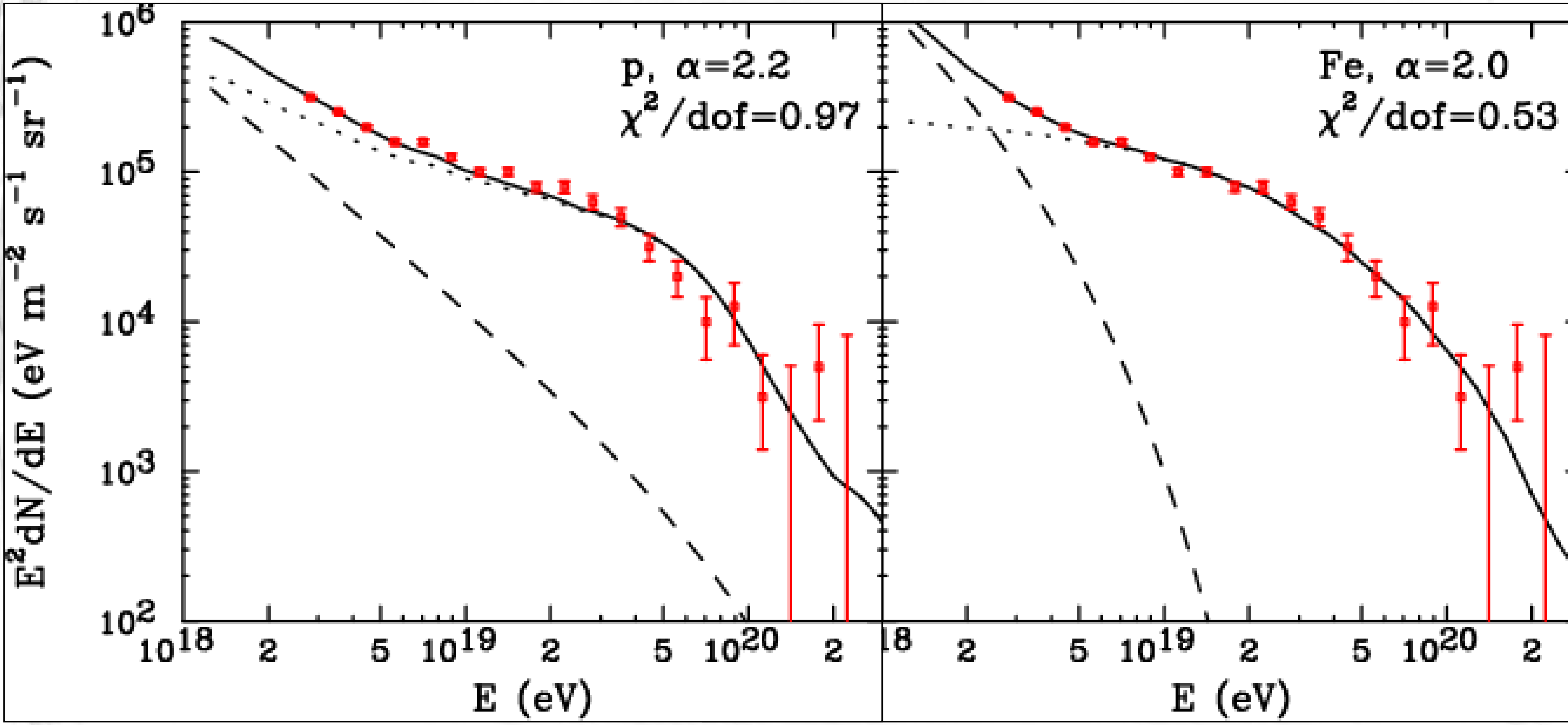
Included processes:

Electrons: inverse Compton; synchrotron rad (for fields from pG to 10 nG)

Gammas: pair-production through IR, CMB, and radio backgrounds

Protons: Bethe-Heitler pair production, pion photoproduction

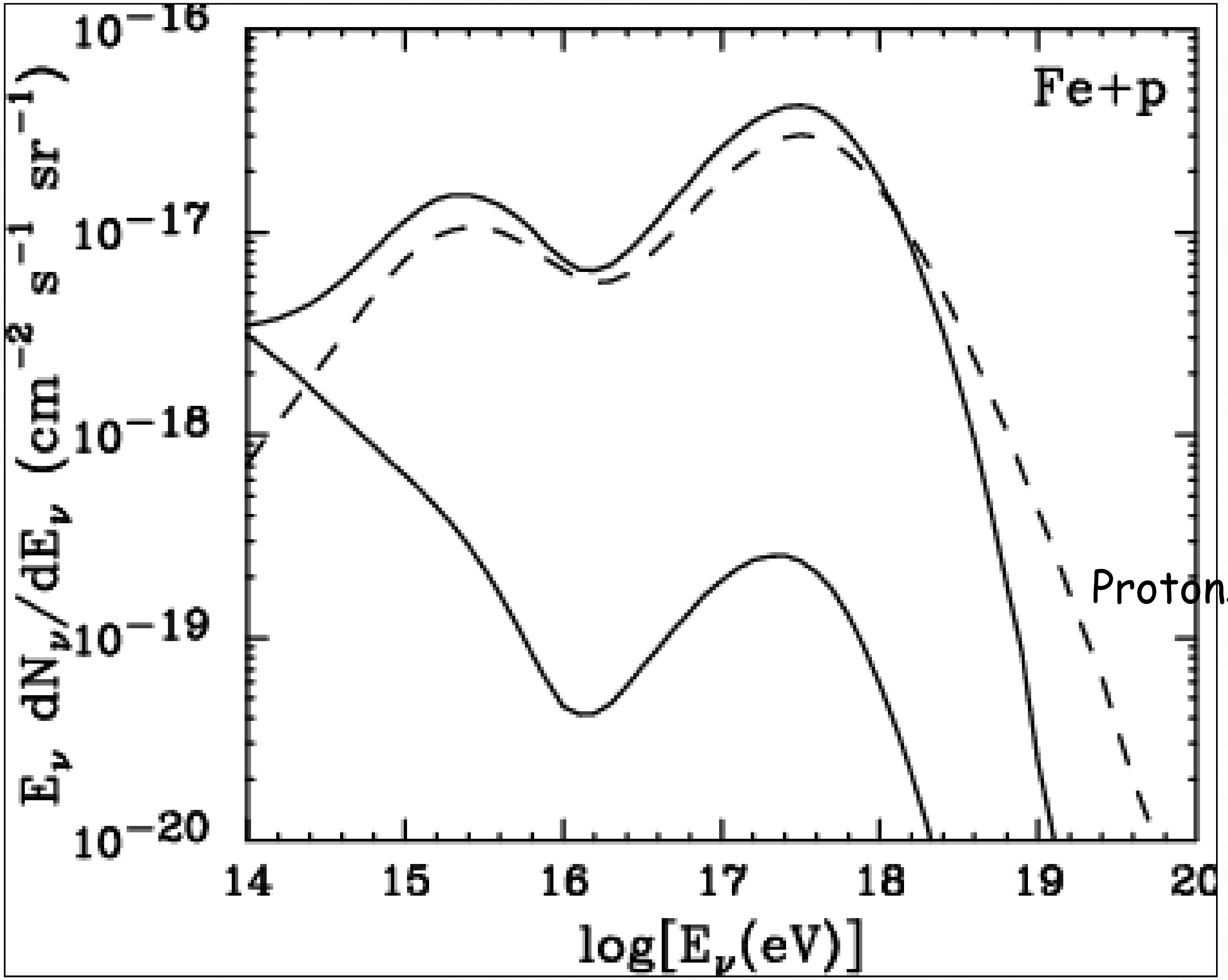
Chemical Composition and Cosmogenic Neutrino Flux



Best fits to Auger spectrum for proton and iron injection with $E_{max}=(Z/26)10^{22}$ eV

Anchordoqui, Hooper, Sarkar, Taylor, Astropart.Phys. 29 (2008) 1

Range of cosmogenic neutrino fluxes consistent with PAO spectrum and composition



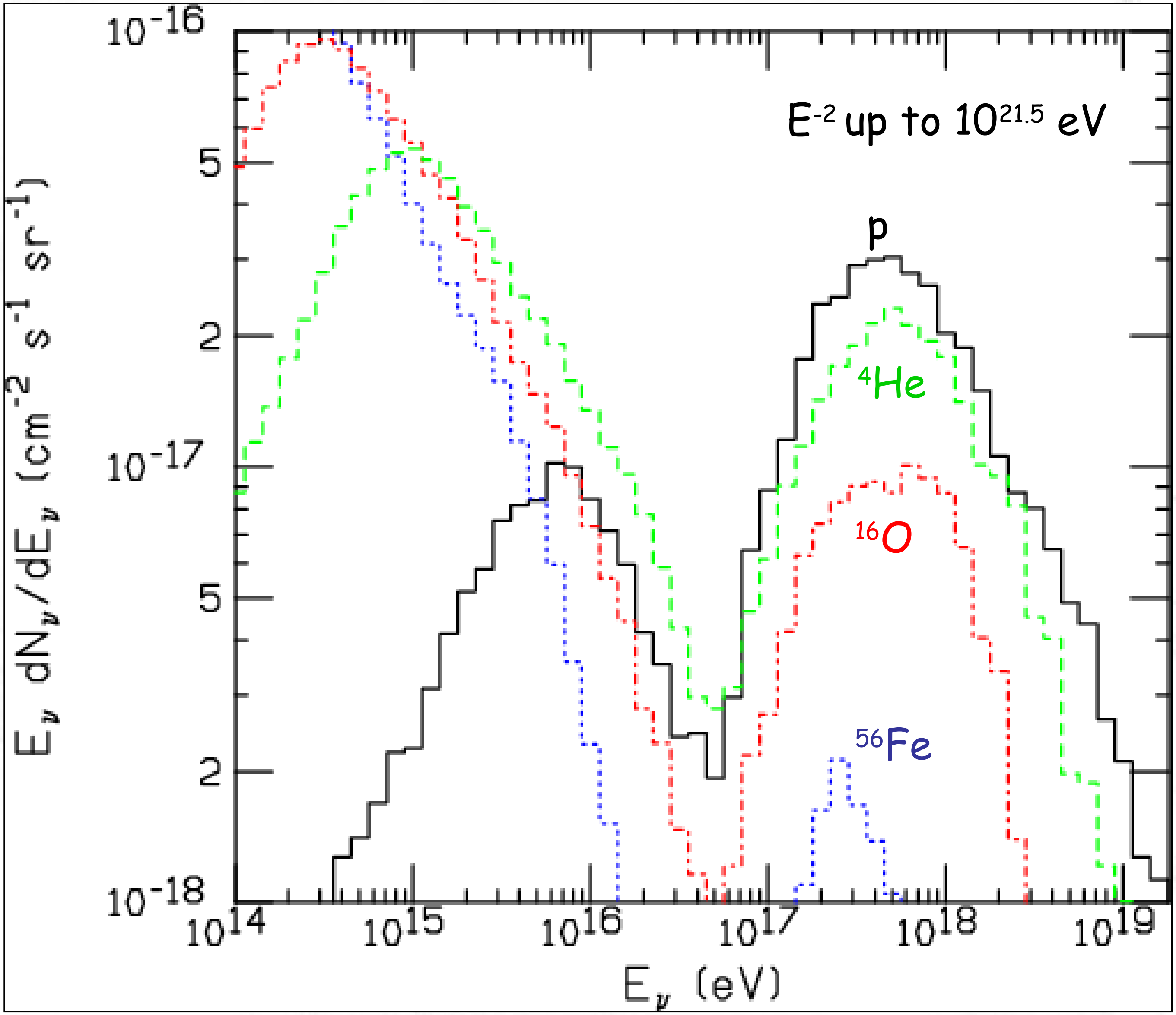
Protons only

Anchordoqui, Hooper, Sarkar, Taylor, Phys.Rev.D 76 (2007) 123008

Influence of Composition on Cosmogenic Neutrinos

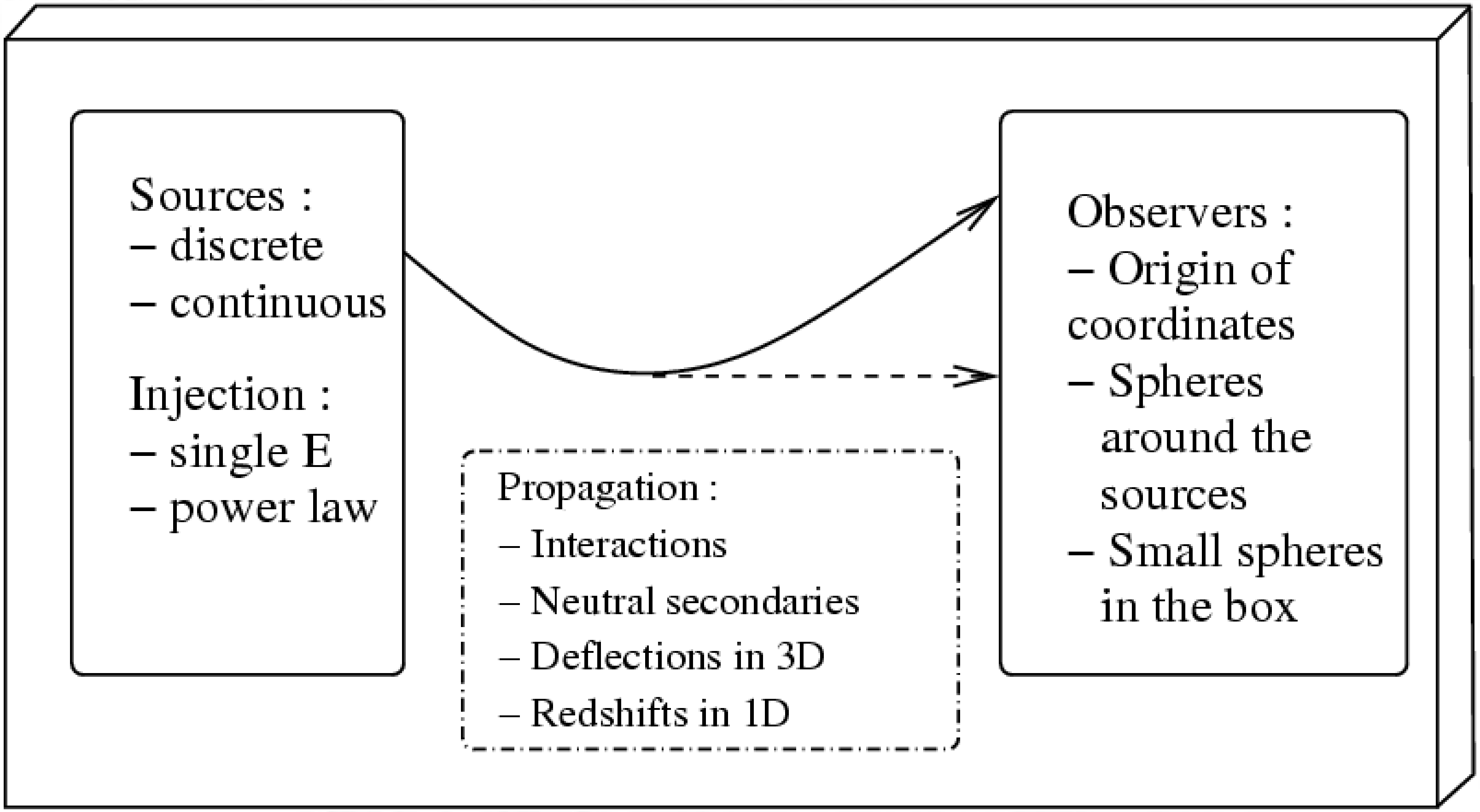
The highest rates are 1 event/year in ICECUBE for protons

Rates comparable if E_{max}/Z = const, but 10-30 times lower for iron if E_{max} independent of Z.



D.Hooper, A.Taylor, S.Sarkar, Astropart.Phys.23 (2005) 11

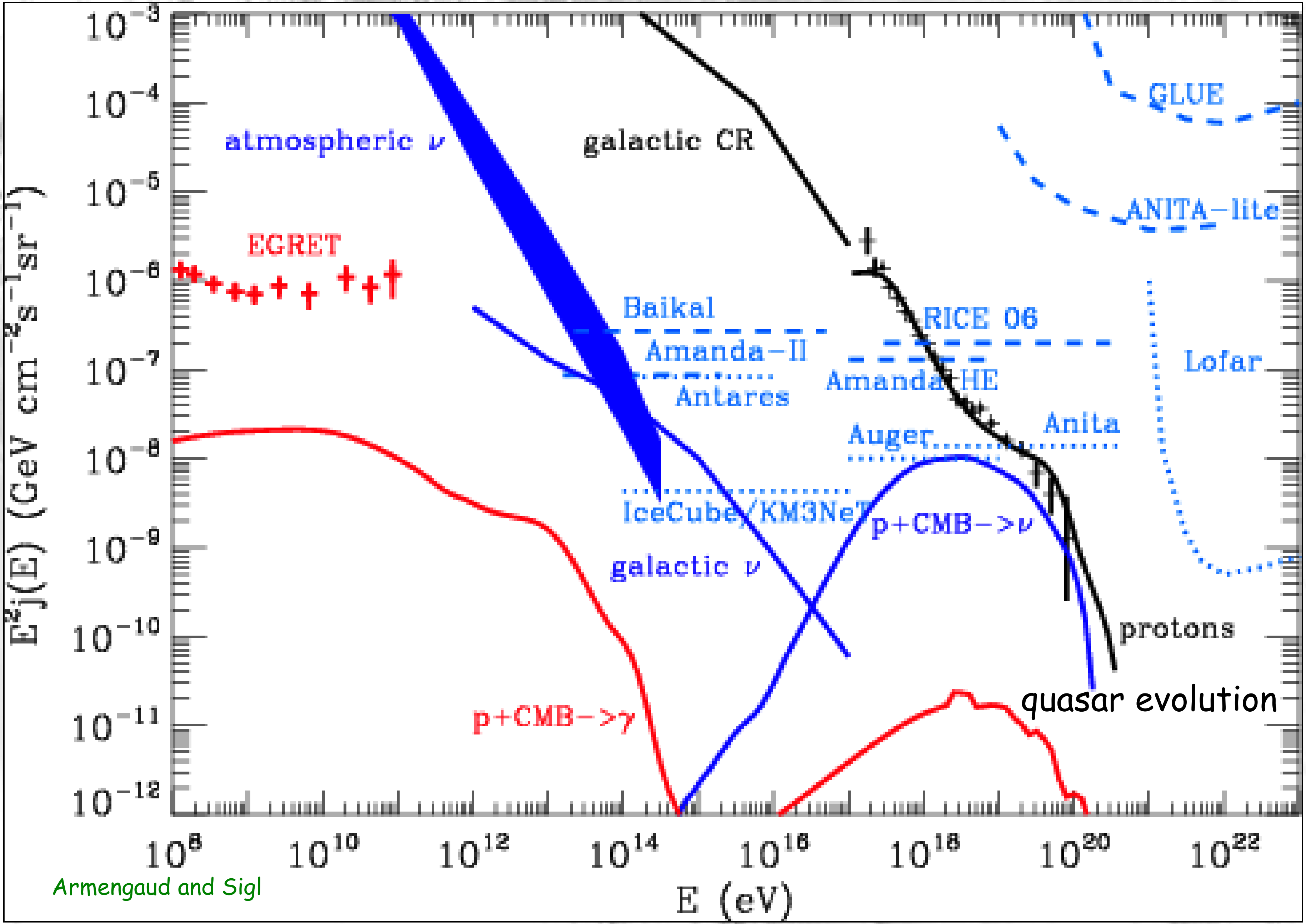
CRPropa is a public code for UHE cosmic rays, neutrinos and γ-Rays



Eric Armengaud, Tristan Beau, Günter Sigl, Francesco Miniati, Astropart.Phys.28 (2007) 463.
http://apcauger.in2p3.fr/CRPropa/index.php

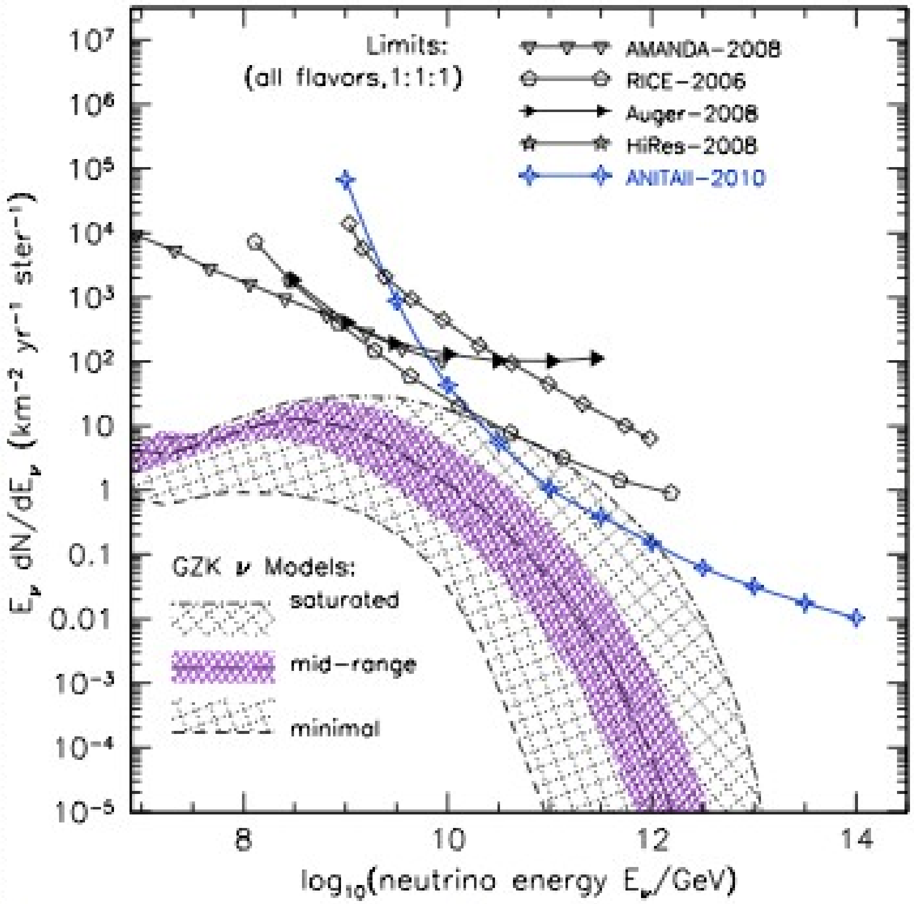
Now including: Jörg Kulbartz, Luca Maccione, Nils Nierstenhöfer, Karl-Heiz Kampert ...

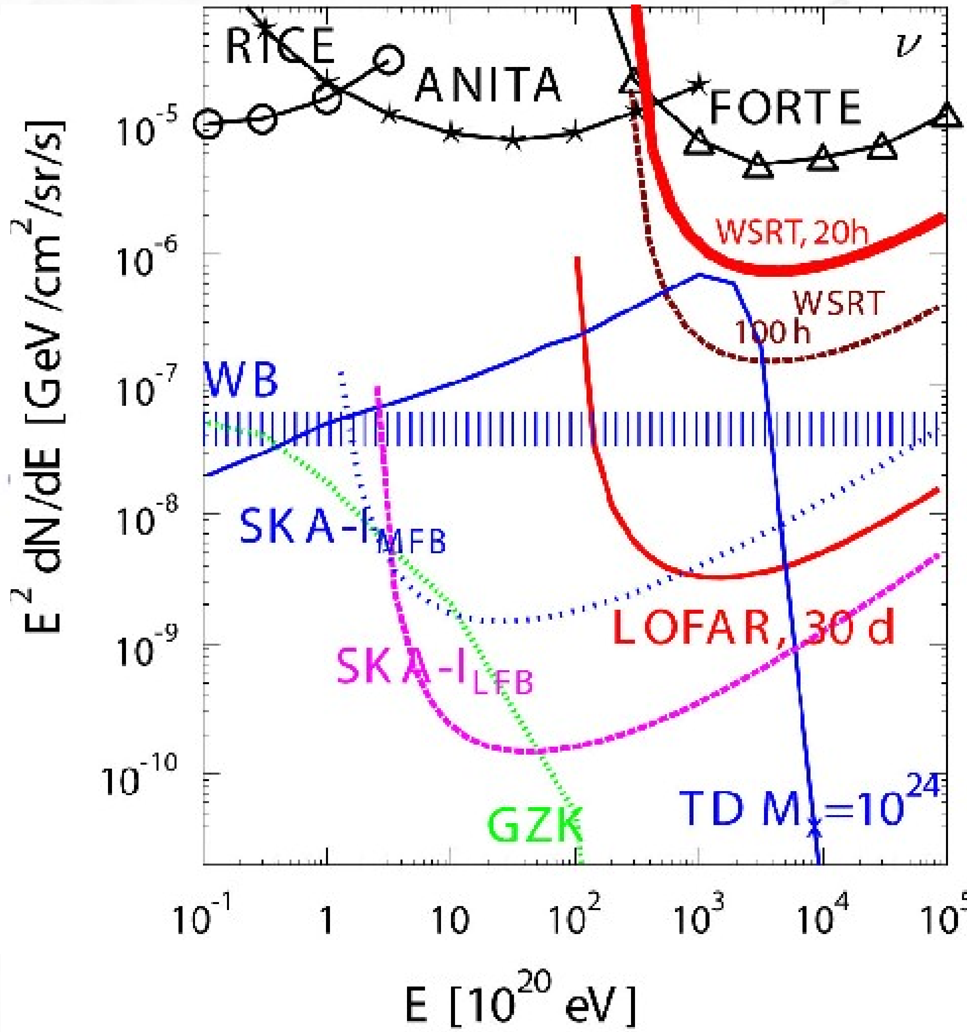
Theoretical Limits, Sensitivities, and "Realistic" Diffuse Fluxes: A Summary



Armengaud and Sigl

Limits and future Sensitivities to UHE neutrino fluxes





P. Gorham et al, arXiv:1003.2961

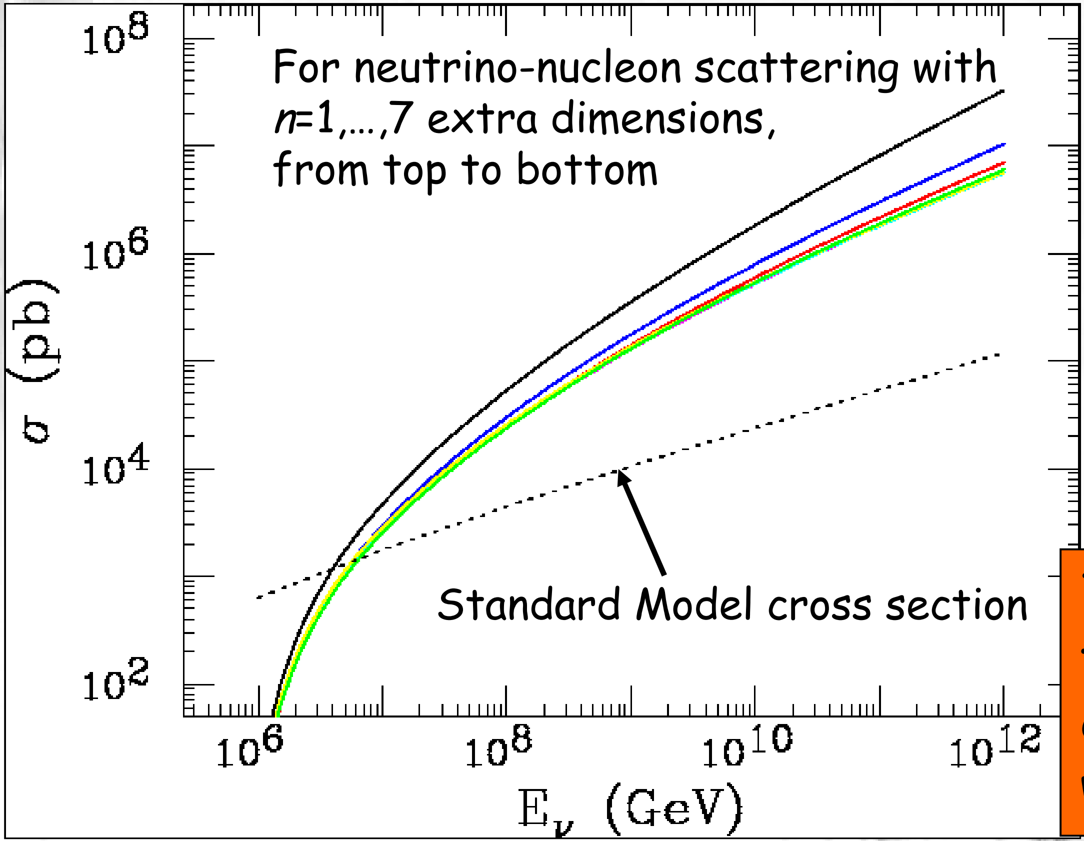
A. Haungs, arXiv:0811.2361

Probes of Neutrino Interactions beyond the Standard Model

Note: For primary energies around 10^{20} eV:

- Center of mass energies for collisions with relic backgrounds
  ~100 MeV – 100 GeV —> physics well understood
- Center of mass energies for collisions with nucleons in the atmosphere
  ~100 TeV – 1 PeV —> probes physics beyond reach of accelerators

Example: microscopic black hole production in scenarios with a TeV string scale:



Feng, Shapere, PRL 88 (2002) 021303

This increase is not sufficient to explain the highest energy cosmic rays, but can be probed with deeply penetrating showers.

Clues on the neutrino-nucleon cross section
From different types of neutrino-induced showers

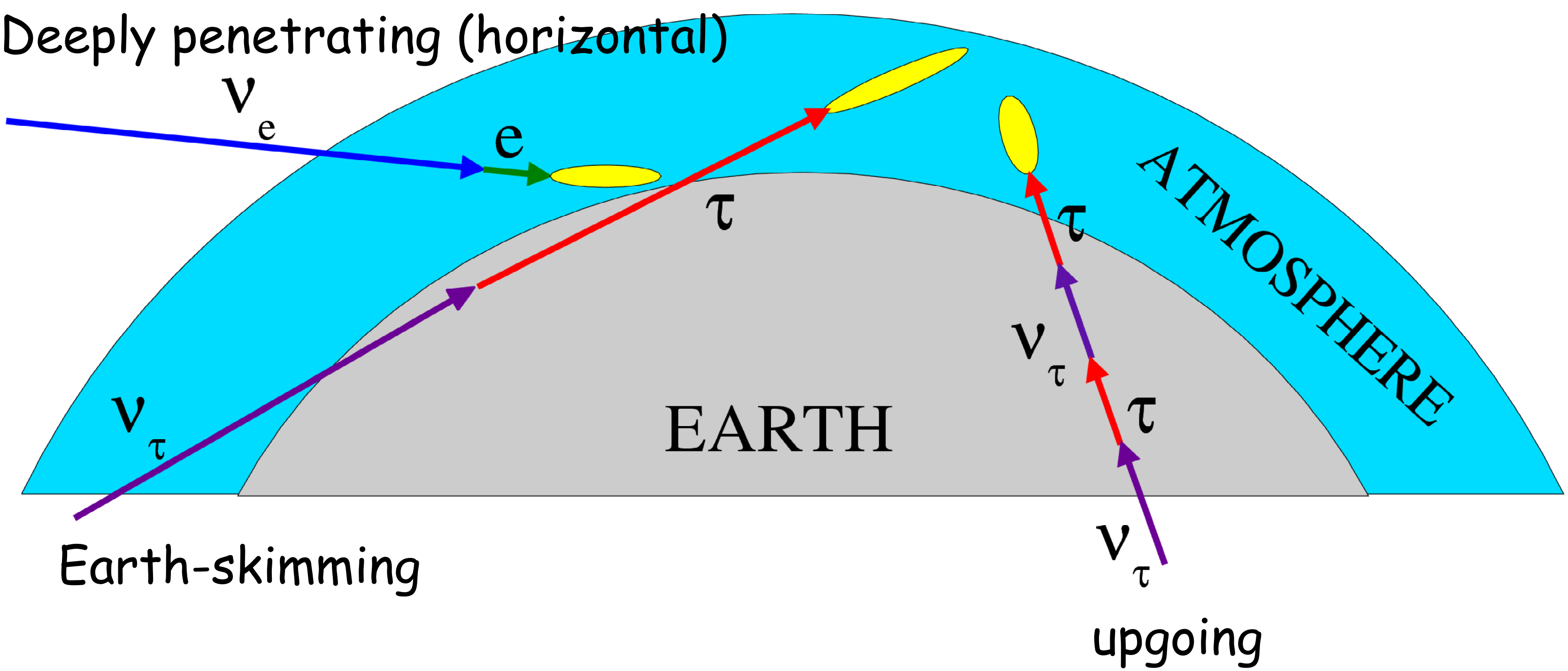
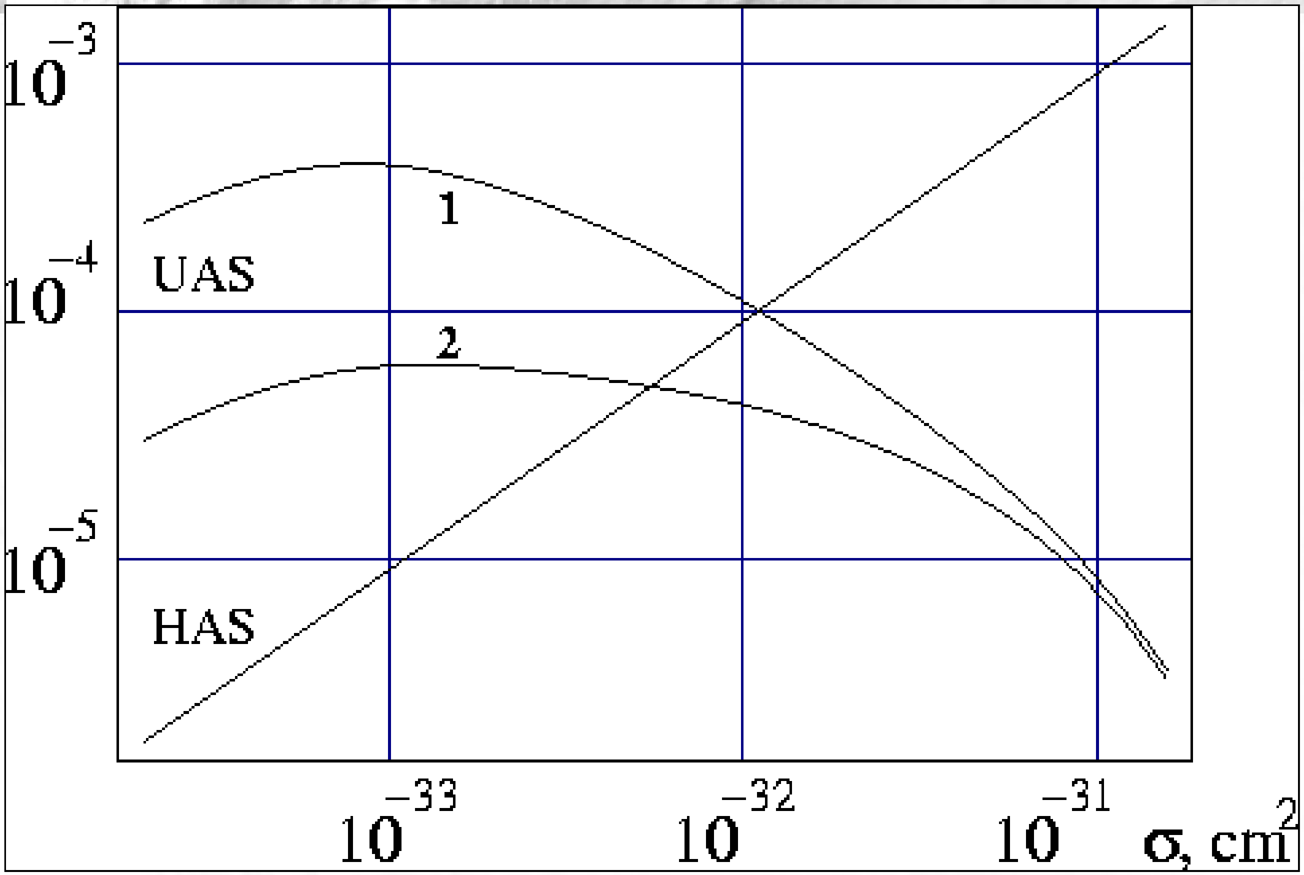


Figure from Cusumano

Earth-skimming τ-neutrinos



Air-shower probability per τ-neutrino at 10^{20} eV for 10^{18} eV (1) and 10^{19} eV (2) threshold energy for space-based detection.

Comparison of earth-skimming and horizontal shower rates allows to measure the neutrino-nucleon cross section in the 100 TeV range.

Kusenko, Weiler, PRL 88 (2002) 121104

Lorentz Symmetry Violation in the Photon Sector

For photons we assume the dispersion relation

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

and for electrons

$$E_{e,\pm}^{2} = p_{e}^{2} + m_{e}^{2} + \eta_{n}^{e,\pm} \, p_{e}^{2} \left(\frac{p_{e}}{M_{\mathrm{Pl}}} \right)^{n}, \quad n \geq 1 ,$$

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

$$\xi_{n}, \eta_{n}^{+}, \eta_{n}^{-}$$

for each *n*.

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

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

where

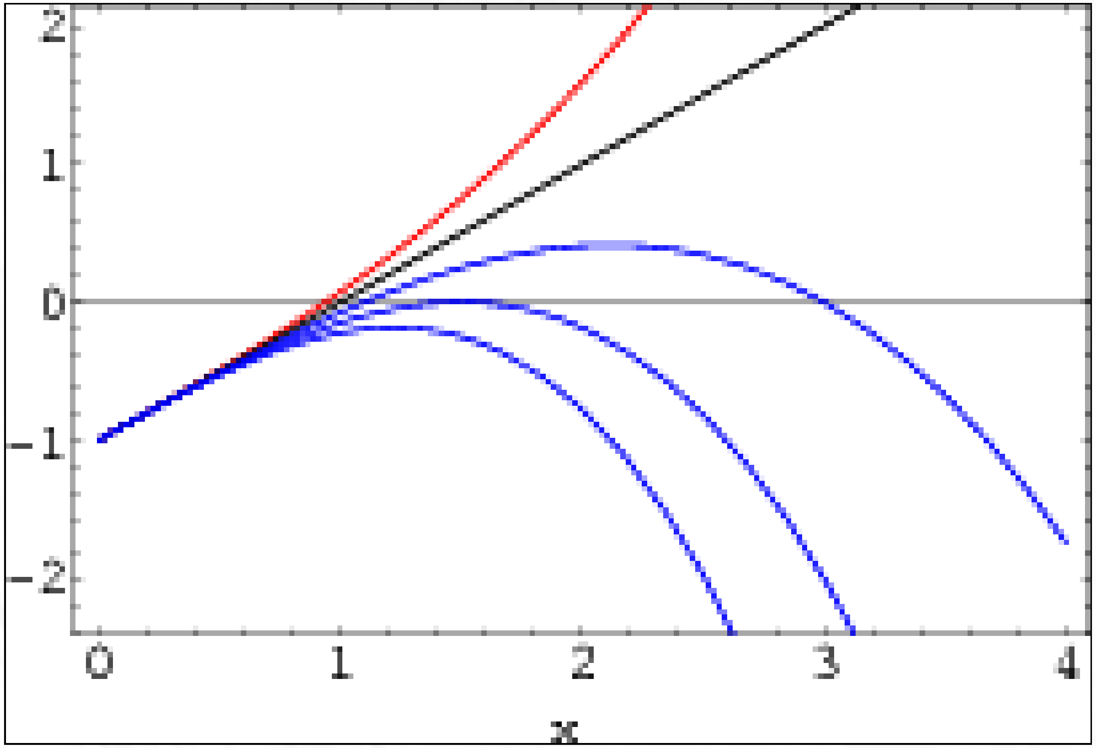
$$\alpha_n = \frac{\xi_n - (-1)^n \eta_n^{\mp} y^{n+1} - \eta_n^{\pm} (1-y)^{n+1}}{2^{2(n+2)} y^{n+1} (1-y)^{n+1}} \frac{m_e^{2(n+1)}}{k_b^{n+2} M_{\mathrm{Pl}}^n}.$$

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

The condition for photon decay is

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

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

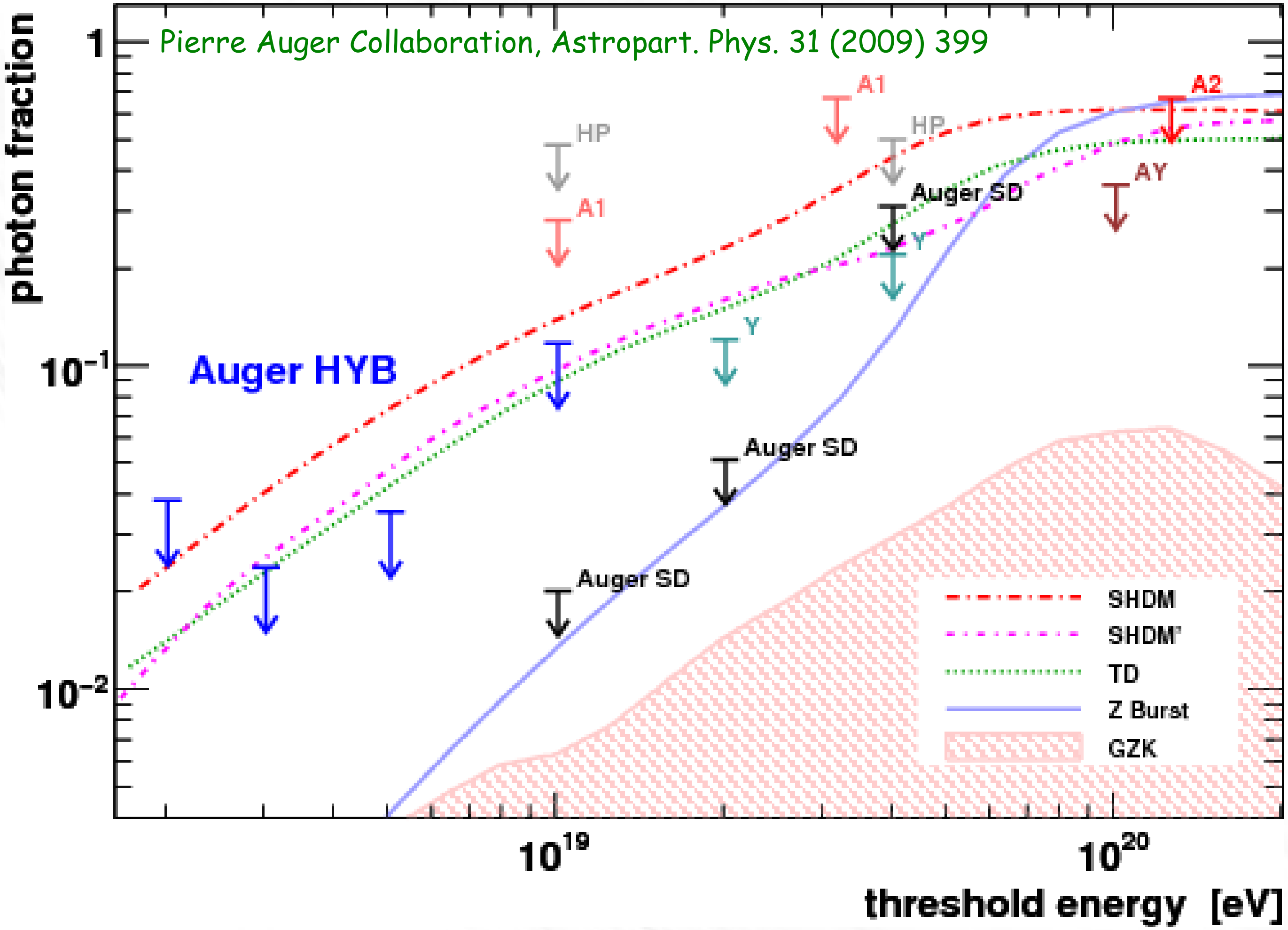


Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

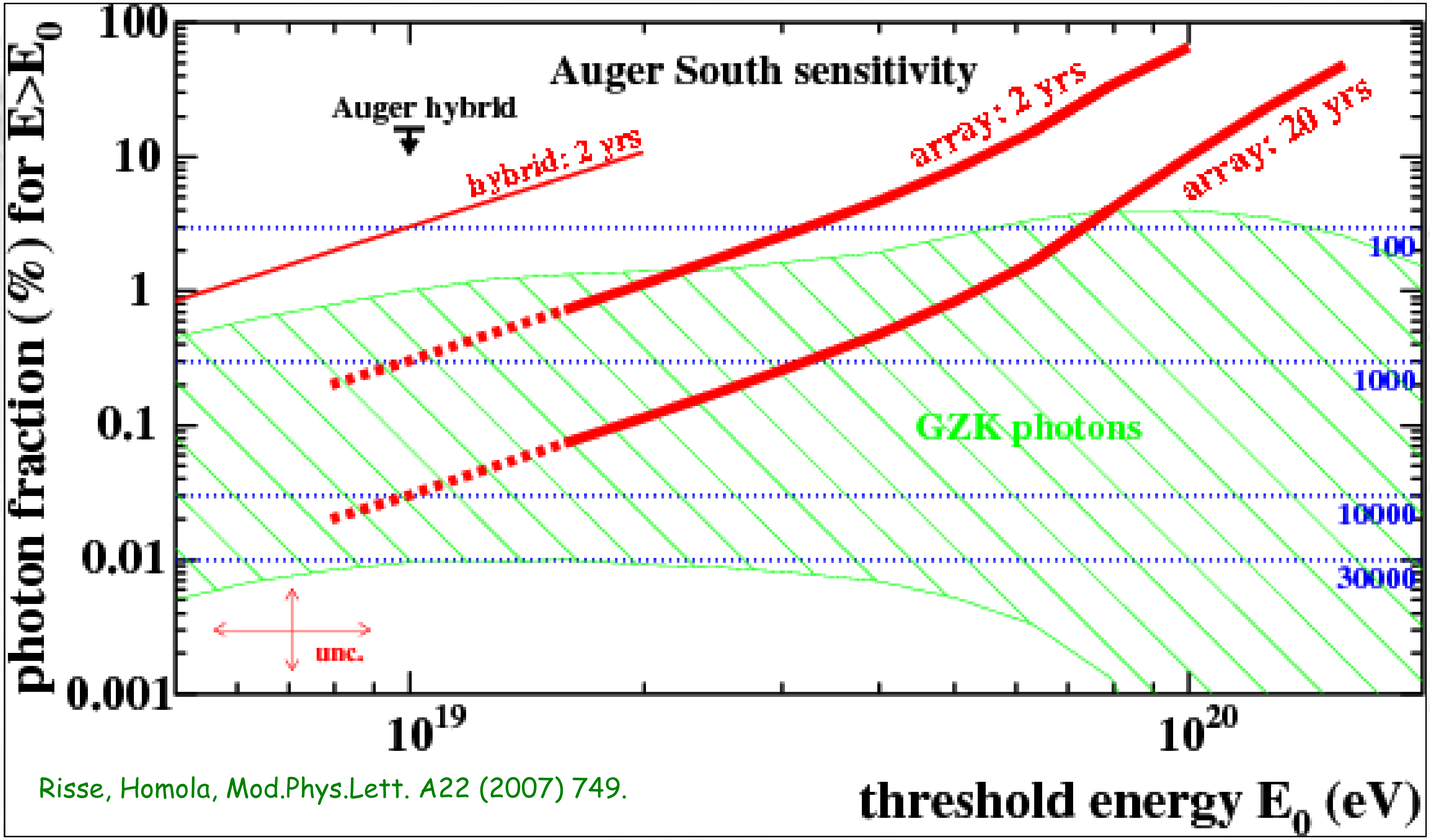
For photon decay there is at most one positive real threshold.

Minimize/maximize these wrt. y

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.

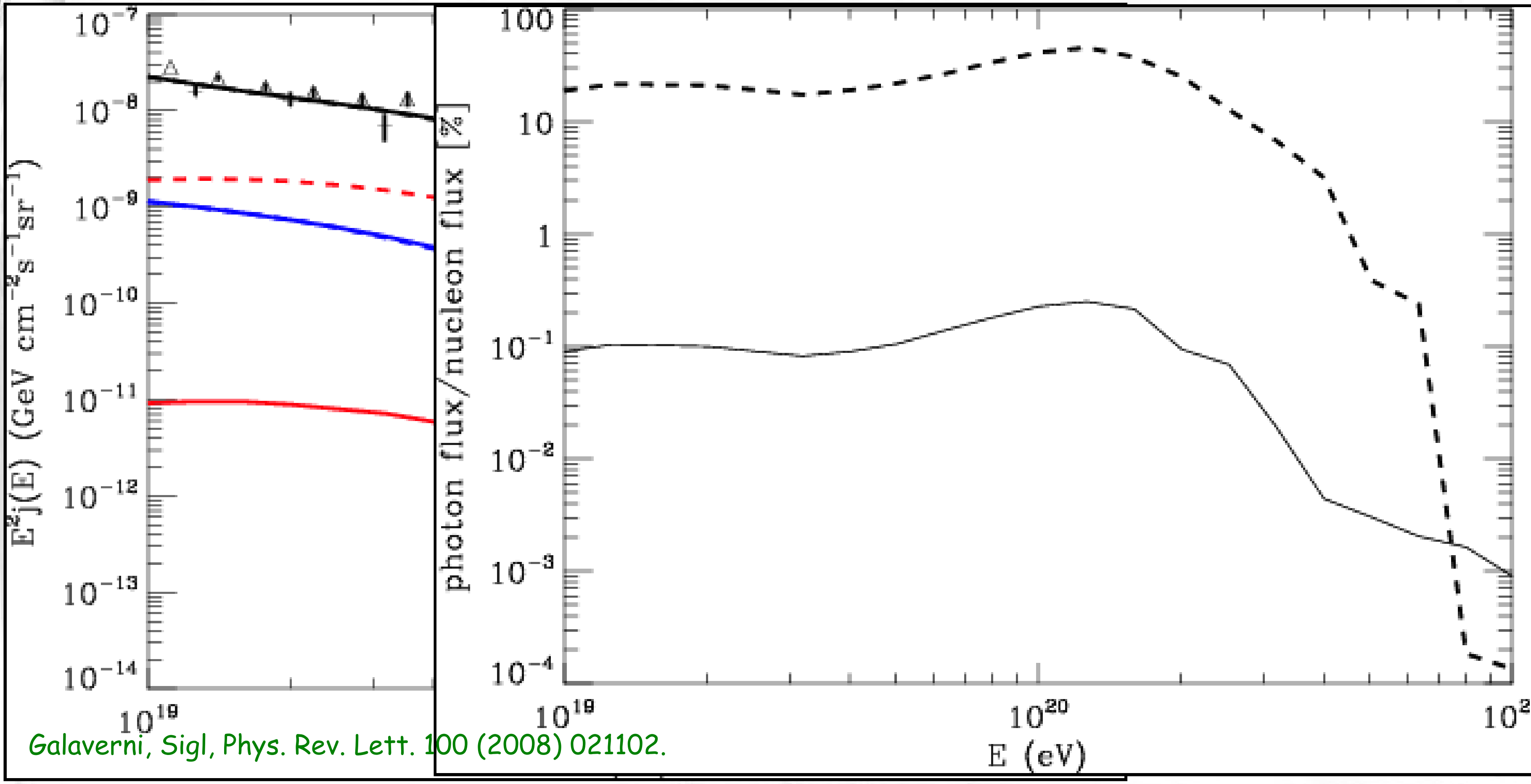


Future data will allow to probe smaller photon fractions and the GZK photons



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

In absence of pair production for 10^{19} eV < ω < 10^{20} eV the photon fraction would be ~20% and would thus violate experimental bounds:



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

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

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

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

and for n=2:

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

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

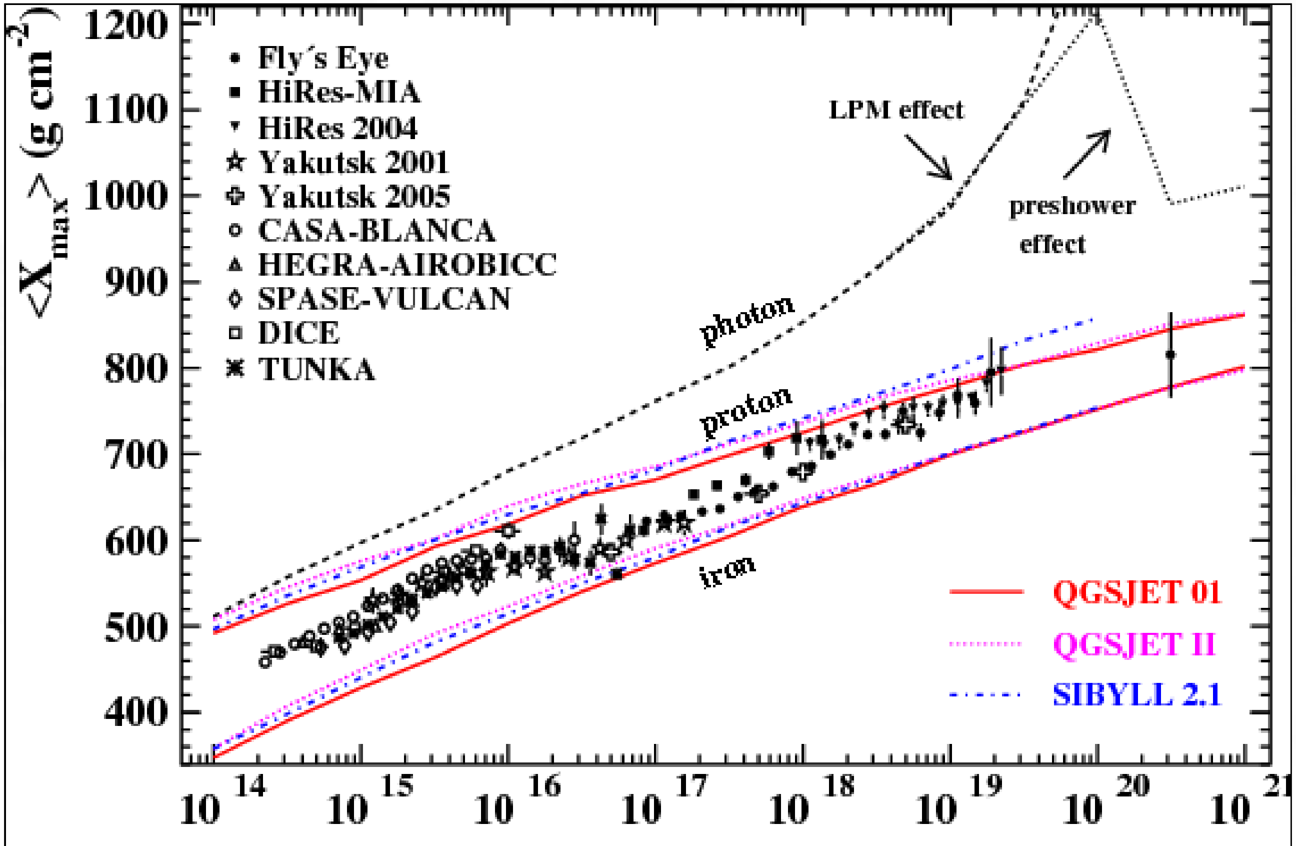
For $n = 1$, all parameters of absolute value < 10^{-14} ruled out

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

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

Possible Caveats

1.) Air shower physics of photon primaries not well understood ?



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

2.) Our constraints do not apply to supersymmetric QED which implies LI violating terms suppressed by the electron mass, $\xi_n m^2(k/M_{Pl})^n$.

Conclusions1

1.) The origin of very high energy cosmic rays is still one of the fundamental unsolved questions of astroparticle physics.
This is especially true at the highest energies, but even the origin of Galactic cosmic rays is not resolved beyond doubt.

2.) Above 60 EeV, arrival directions correlate with the local cosmic large scale structure.

3.) It is currently not clear what the sources are within these structures. Potential sources closest to the arrival directions require heavier nuclei to attain observed energies. Air shower characteristics also seem to imply a mixed composition.

4.) This is surprising because larger deflections would be expected for nuclei already in the Galactic magnetic field.

Conclusions2

5.) The large Lorentz factors involved in cosmic radiation at energies above ~ 10^{19} eV provides a magnifier into possible Lorentz invariance violations (LIV).

6.) Once UHE photons are detected, all LIV parameters in the electromagnetic sector suppressed to first order in the Planck scale can be constrained to be $\leq 10^{-6}$. At second order, one of the parameters can be large.

7.) At energies above ~10^{18} eV, the center-of mass energies are above a TeV and thus beyond the reach of accelerator experiments. Especially in the neutrino sector, where Standard Model cross sections are small, this probes potentially new physics beyond the electroweak scale, including possible quantum gravity effects.

8.) Many new interesting ideas on a modest cost scale for ultra-high energy neutrino detection are currently under discussion.