Theoretical Developments in Ultra-High Energy Cosmic Radiation

- (Very short) introduction on Cosmic Ray experimental situation and current understanding
- Gamma Rays as a Cosmic Ray Source Diagnostic
- Large scale magnetic fields and their effects on UHECR.
- Ultra-High Energy Cosmic Rays and secondary γ-rays and neutrinos: Constraints and detection prospects with different experiments.
- Limits on Lorentz invariance violations

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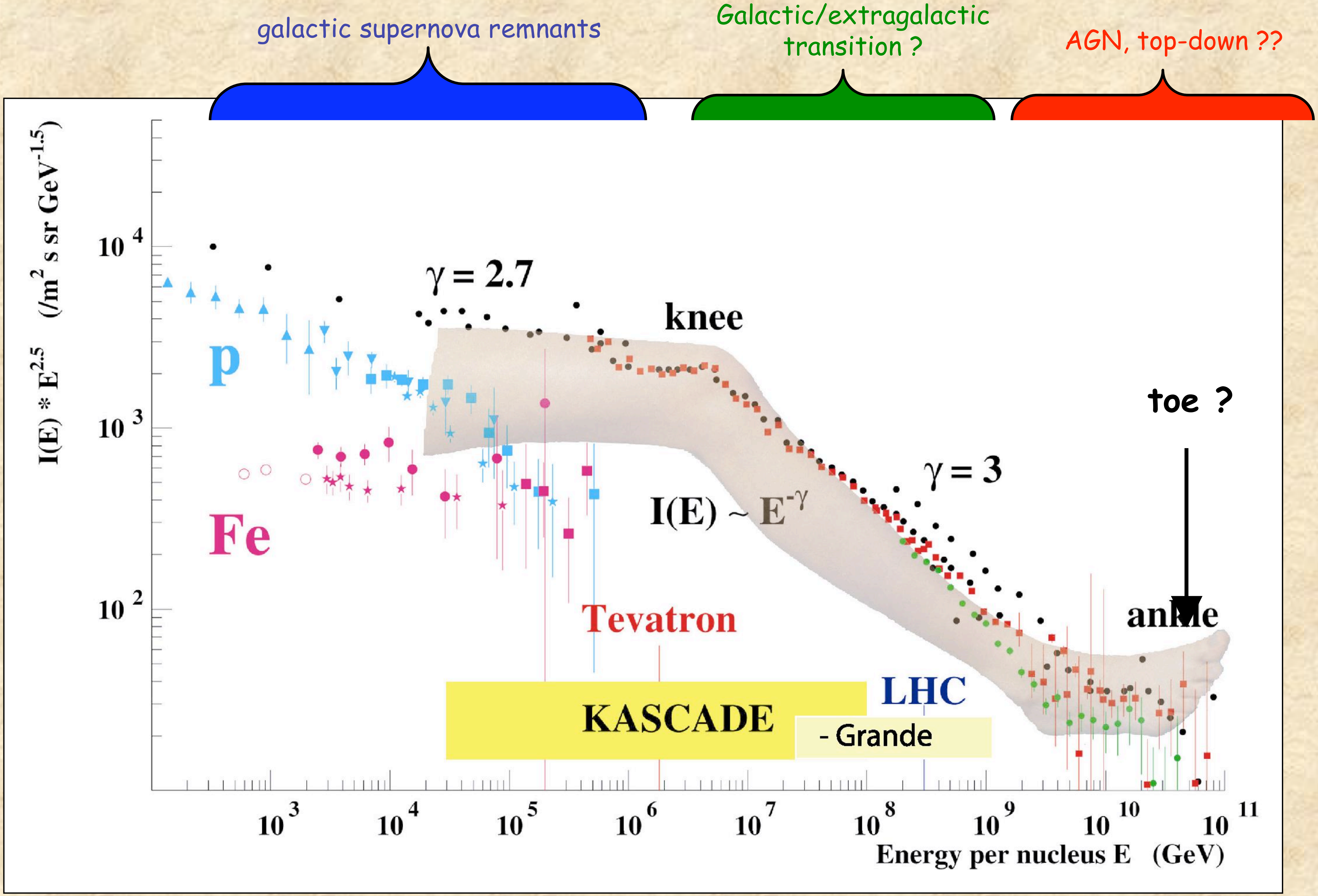
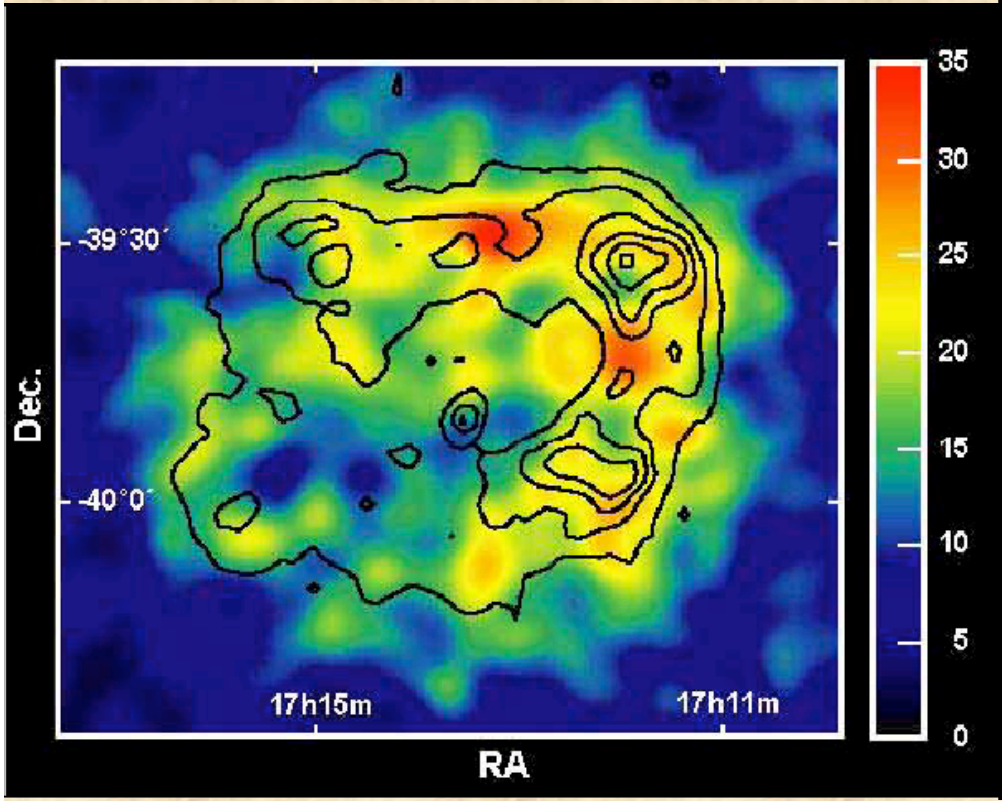
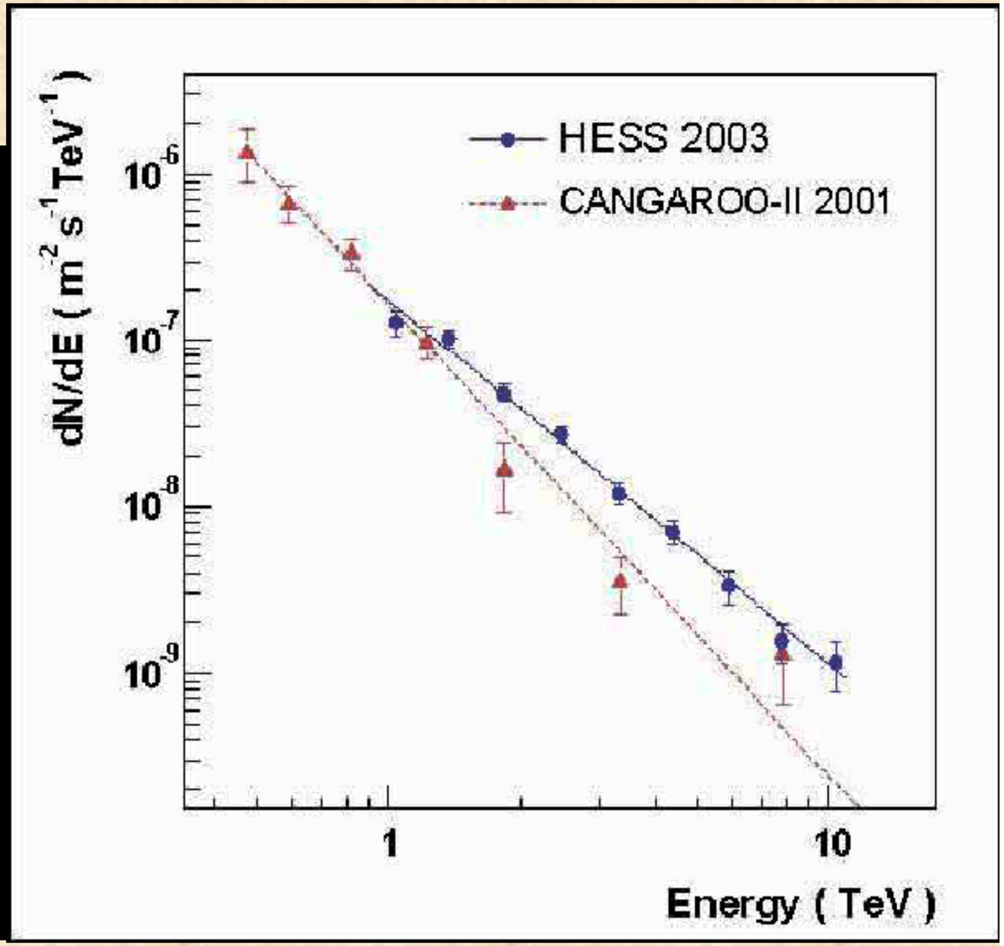
http://www2.iap.fr/users/sigl/homepage.html

The structure of the spectrum and scenarios of its origin



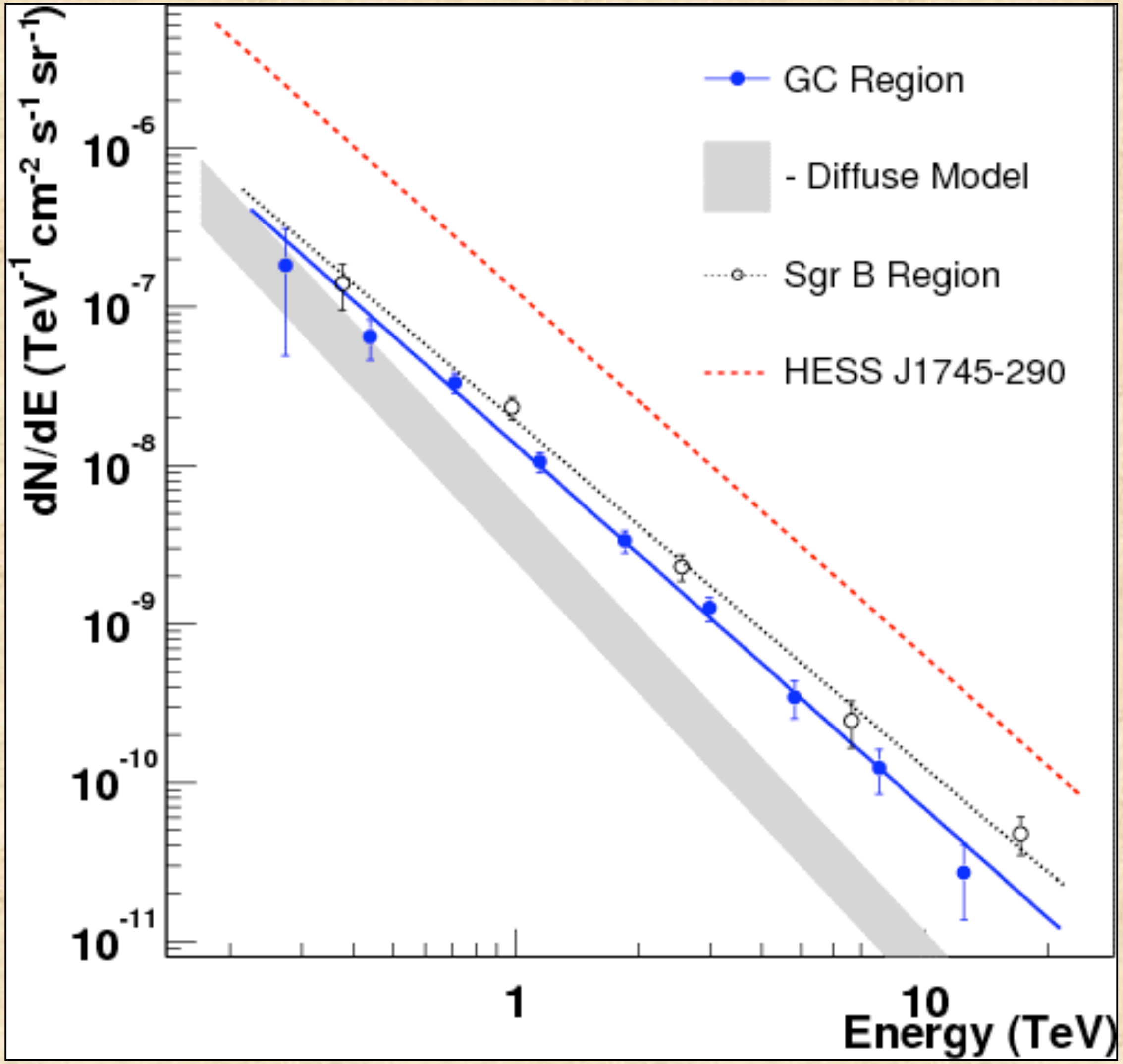
Supernova Remnants and Galactic Cosmic and γ-Rays





Aharonian et al., Nature 432 (2004) 75

Supernova remnants have been seen by HESS in γ-rays: The remnant RXJ1713-3946 has a spectrum ~$E^{-2.2}$: => Charged particles have been accelerated to > 100 TeV. Also seen in 1-3 keV X-rays (contour lines from ASCA)



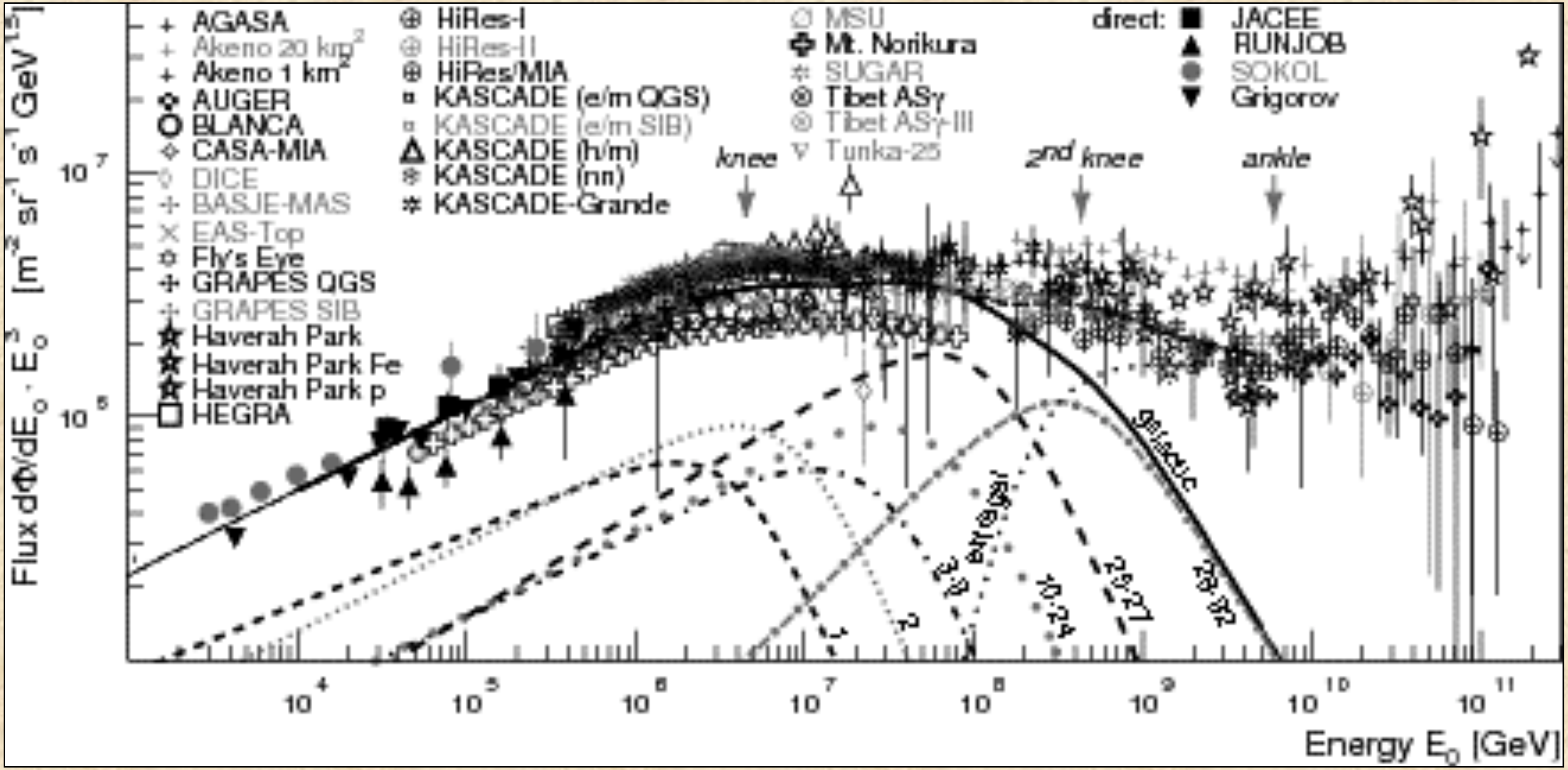
Given the observed spectrum $E^{-2.3}$, this can be interpreted as photons from π^0 decay produced in pp interactions where the TeV protons have the same spectrum and could have been produced in a SN event.

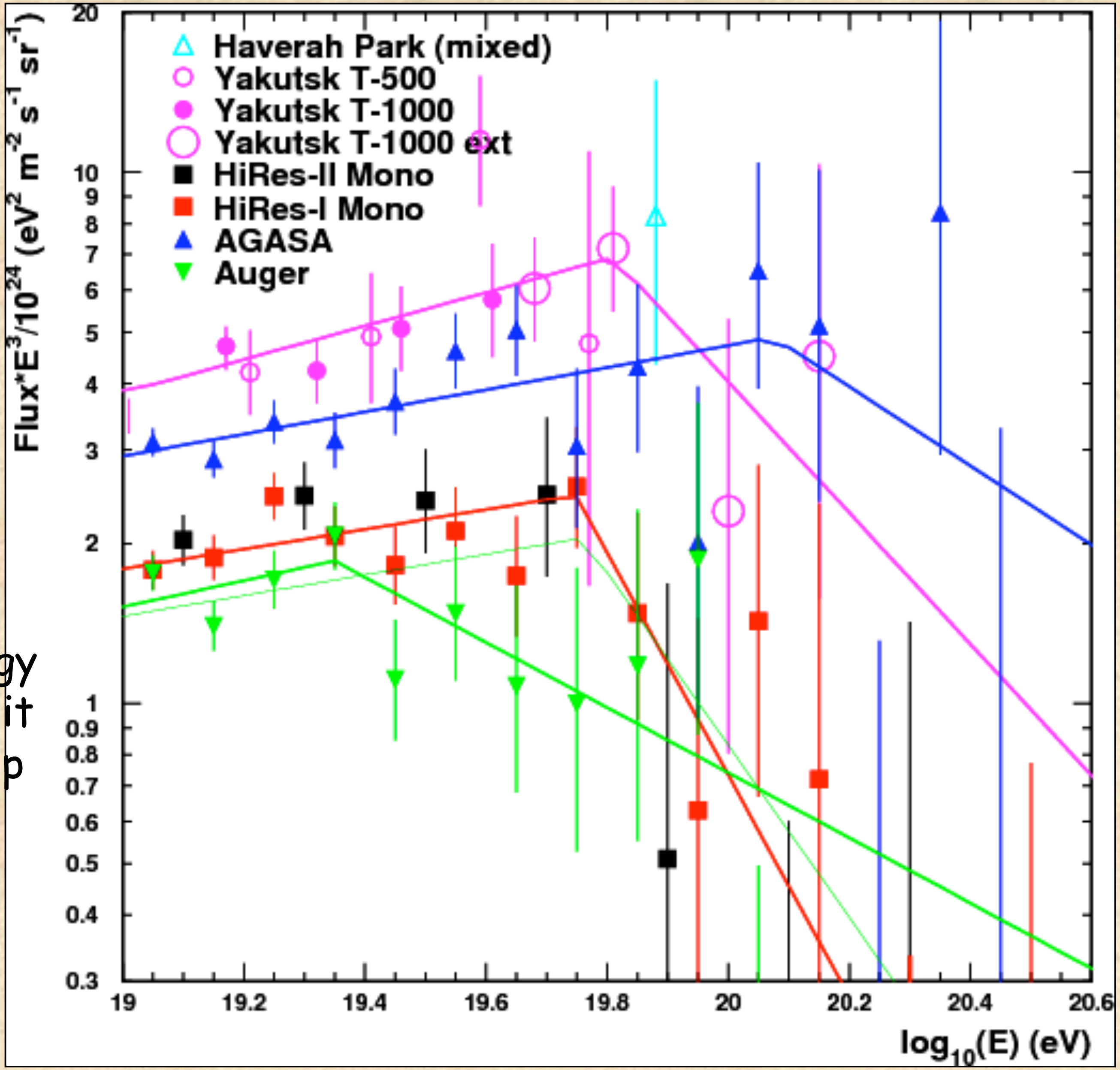
Note that this is consistent with the source spectrum both expected from shock acceleration theory and from the cosmic ray spectrum observed in the solar neighborhood, $E^{-2.7}$, corrected for diffusion in the galactic magnetic field, $j(E) \sim Q(E)\tau_{conf}(E) \sim Q(E)/D(E)$.

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



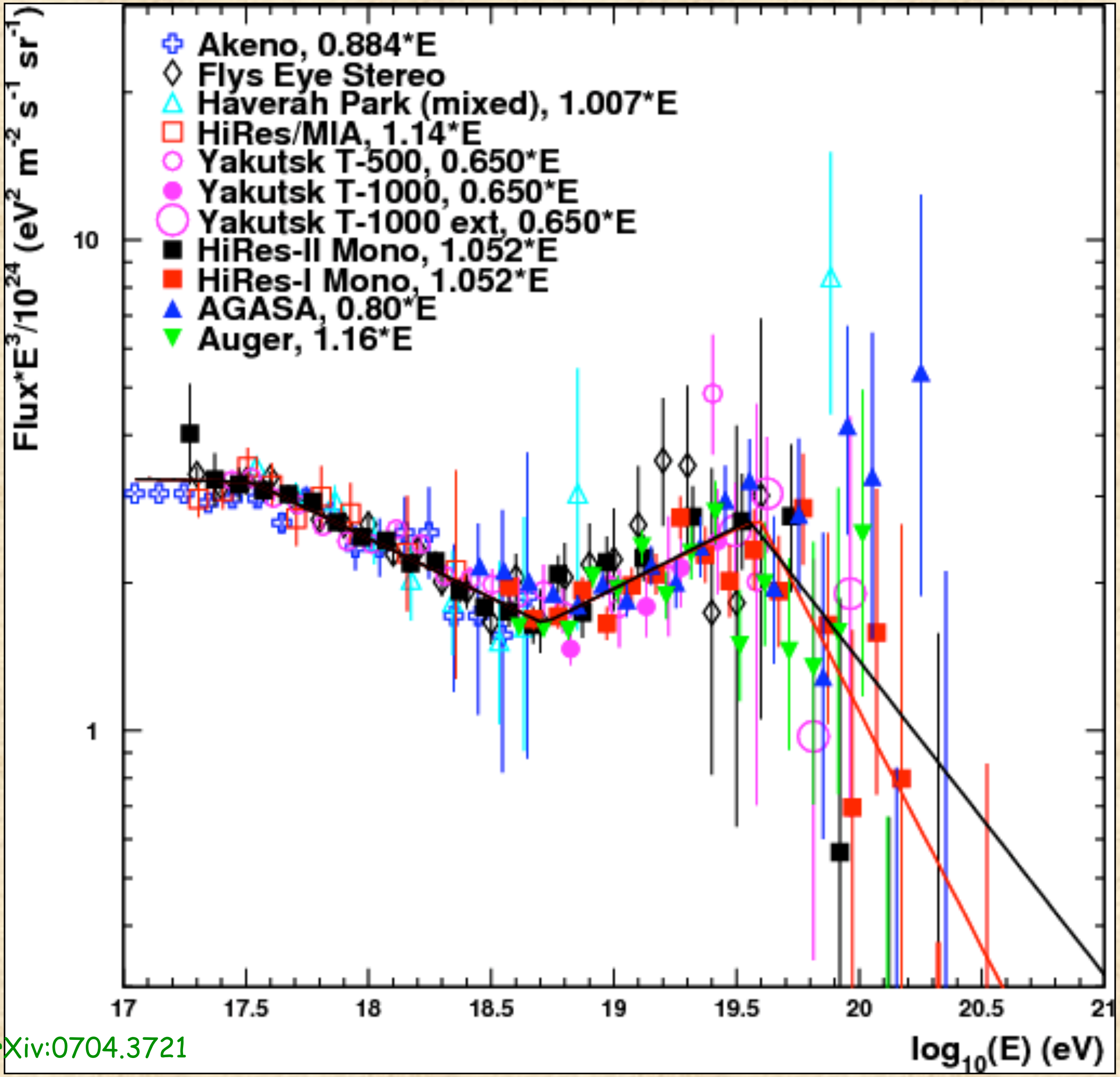


Lowering the AGASA energy scale by about 20% brings it in accordance with HiRes up to the GZK cut-off, but maybe not beyond ?

Bergmann, Belz, arXiv:0704.3721

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

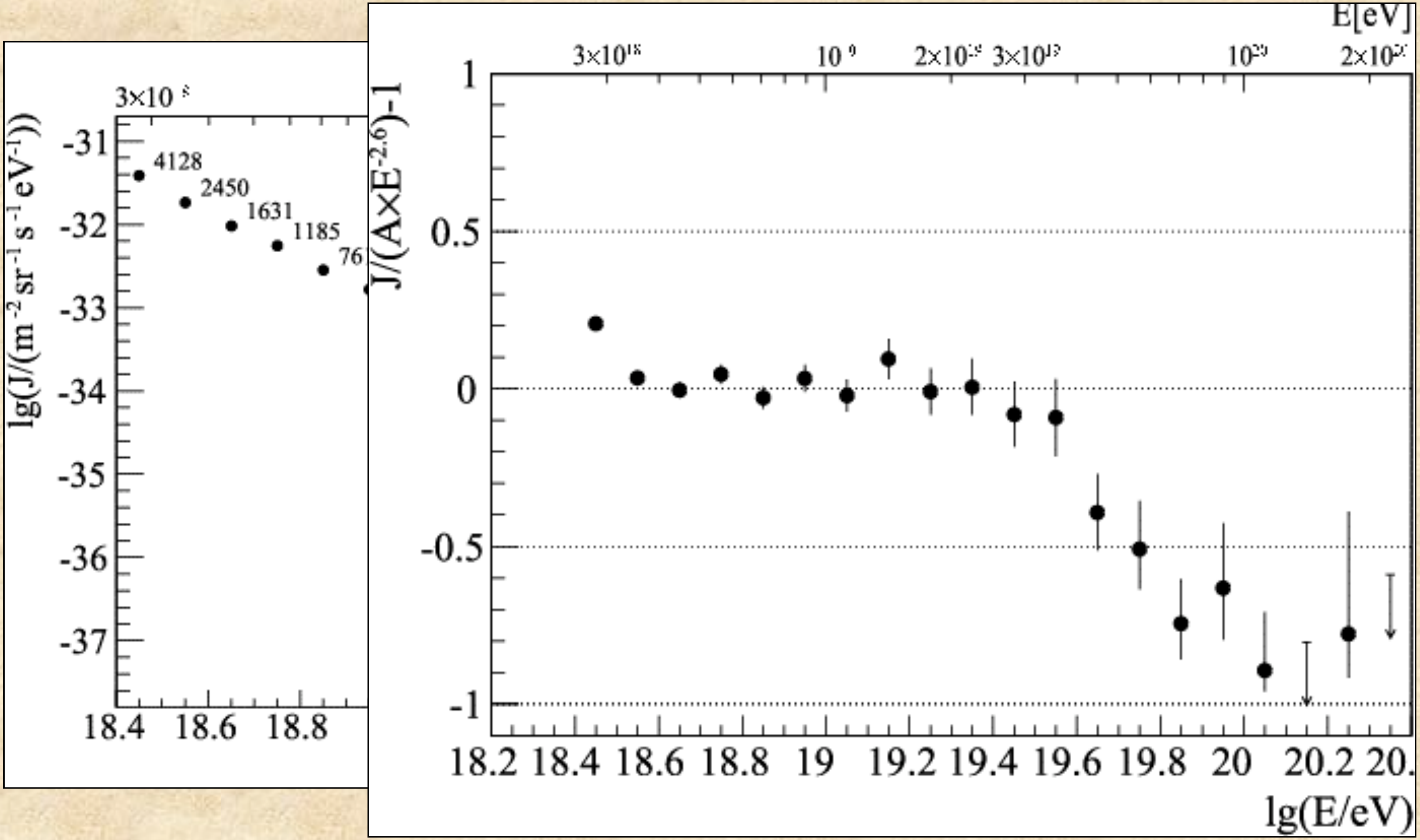
Comparison of Experimental Spectra



Bergmann, Belz, arXiv:0704.3721

Auger Spectrum

3 times AGASA exposure



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

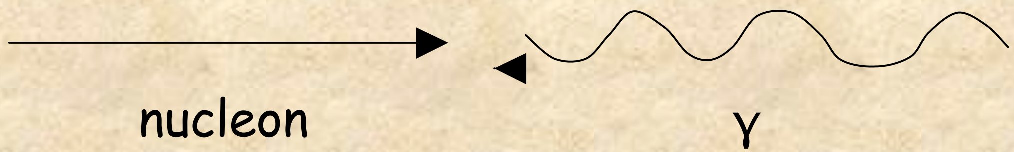
1.) electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 50 Mpc.

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

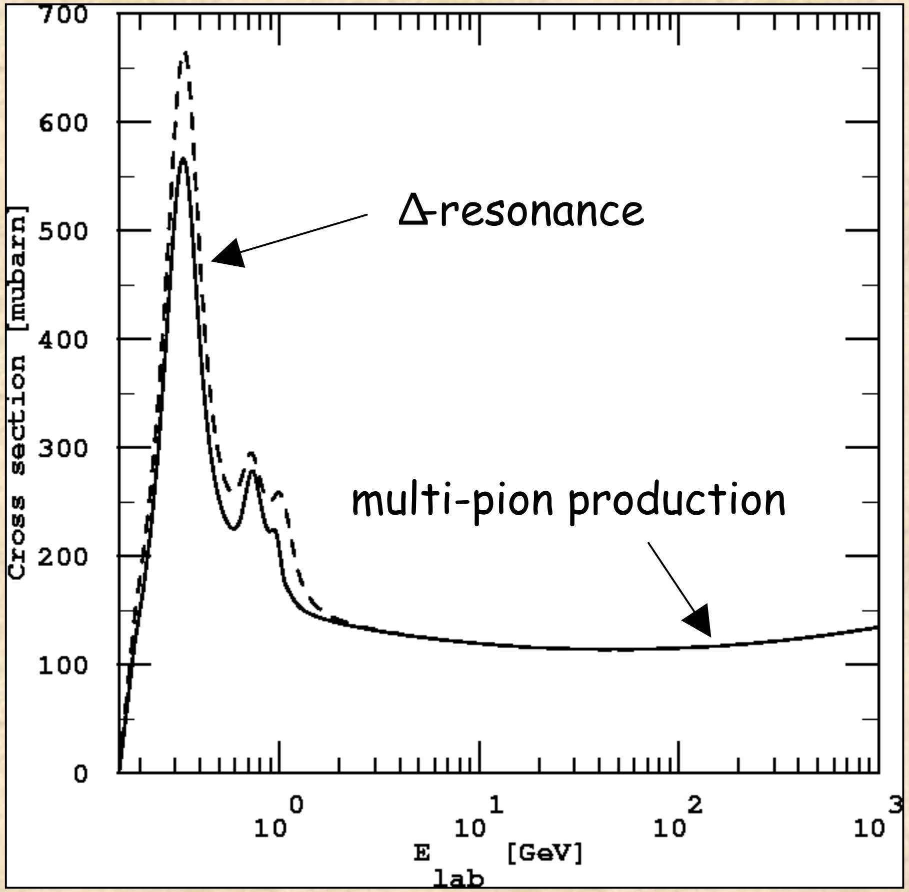
3.) The observed distribution seems to be very isotropic (except for a possible interesting small scale clustering)

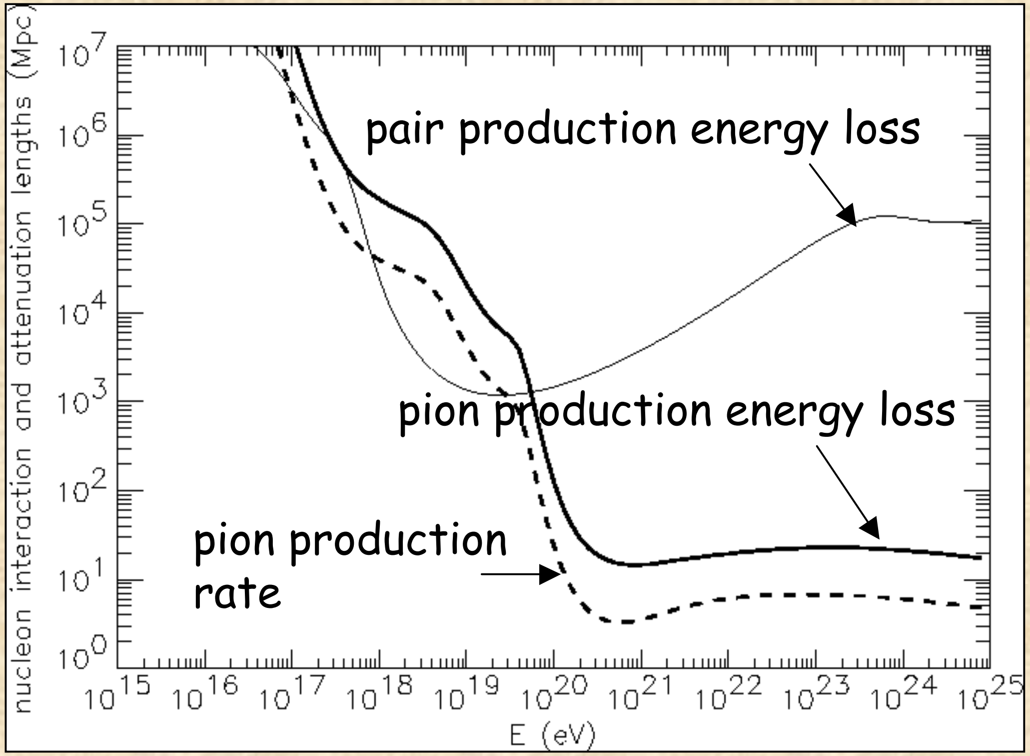
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



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

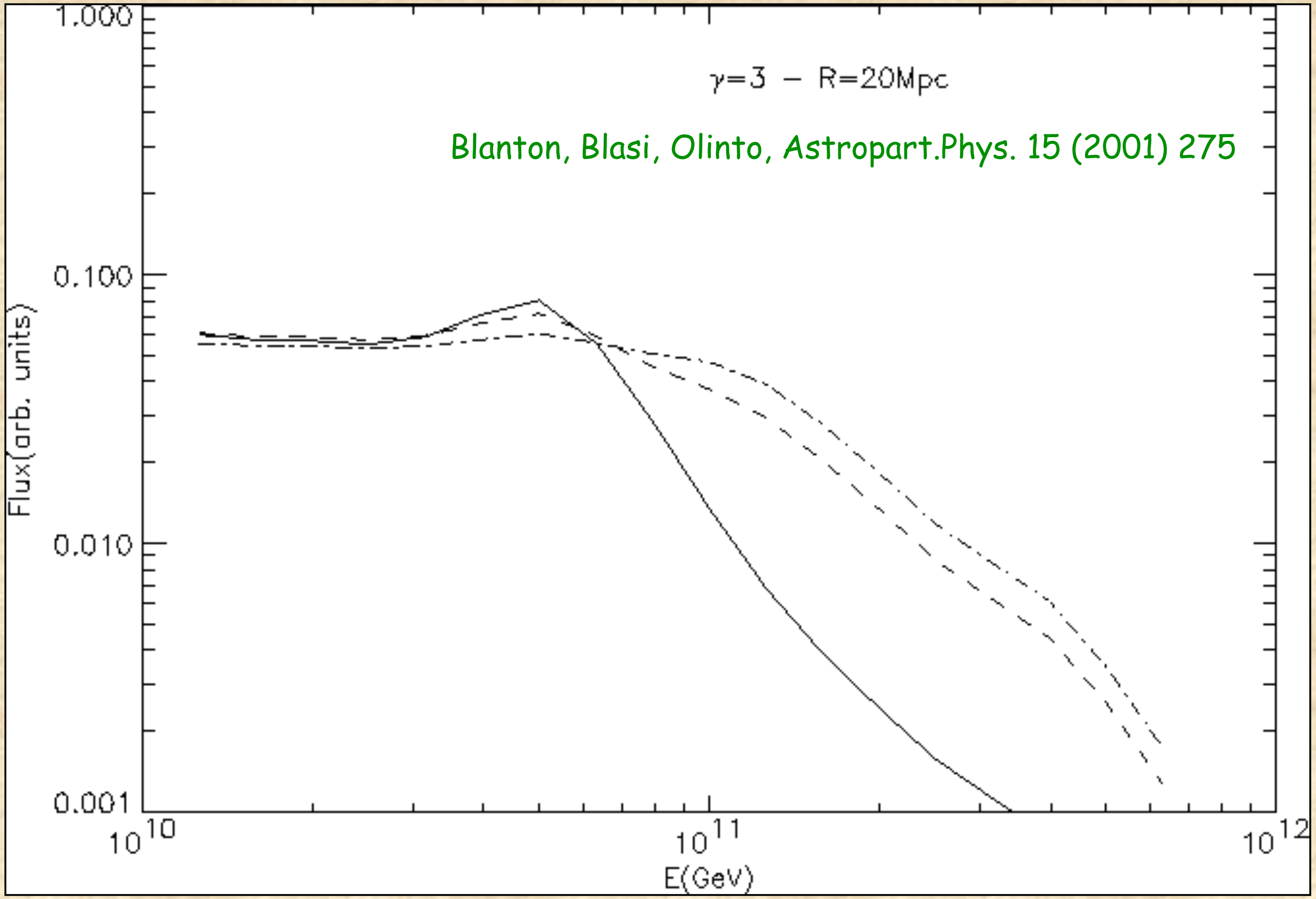




⇒sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma > 10^{11}$
could avoid this conclusion.

GZK "cut-off" is a misnomer because "conventional" astrophysics can create events above the "cut-off"

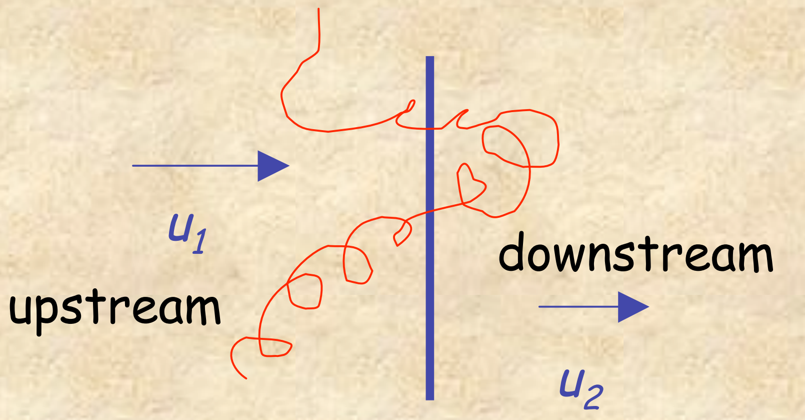
The GZK effect may tell us about the source distribution (in the absence of strong magnetic deflection)



Observable spectrum for an E^{-3} injection spectrum for a distribution of sources with overdensities of 1, 10, 30 (bottom to top) within 20 Mpc, and otherwise homogeneous.

1^{st} Order Fermi Shock Acceleration

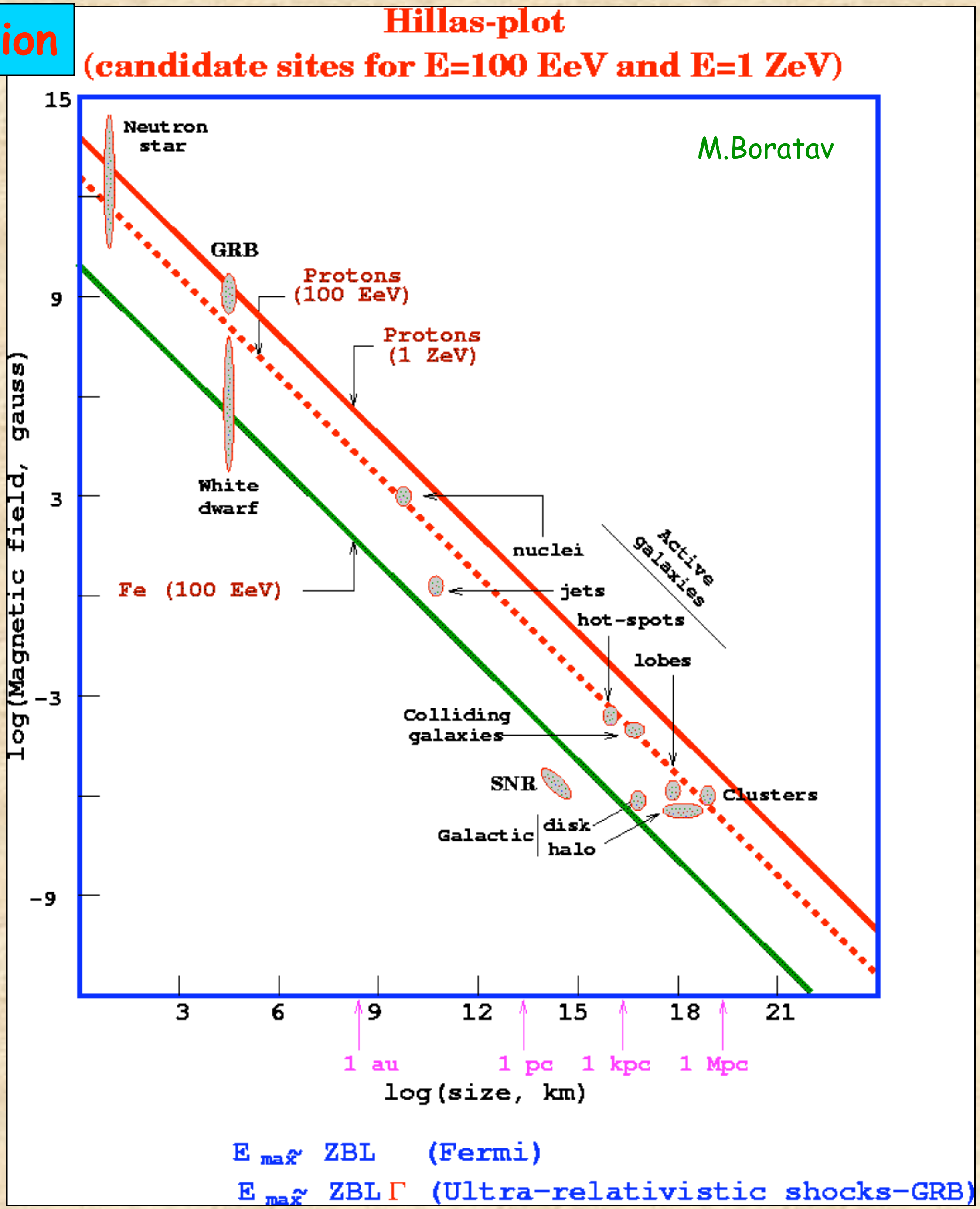
The most widely accepted scenario of cosmic ray acceleration



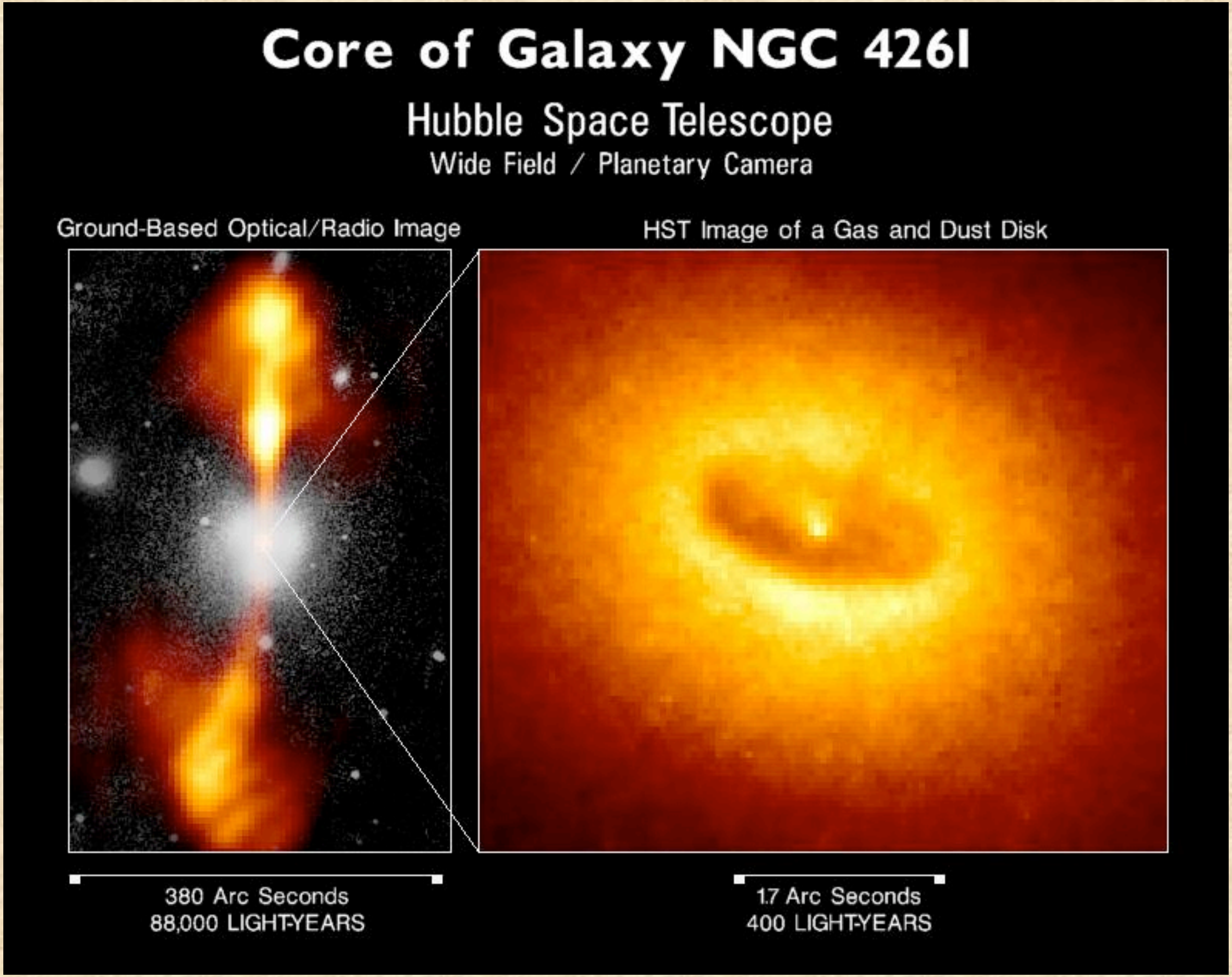
Fractional energy gain per shock crossing $\sim u_1 - u_2$ on time scale $\sim r_L/u_2$

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.

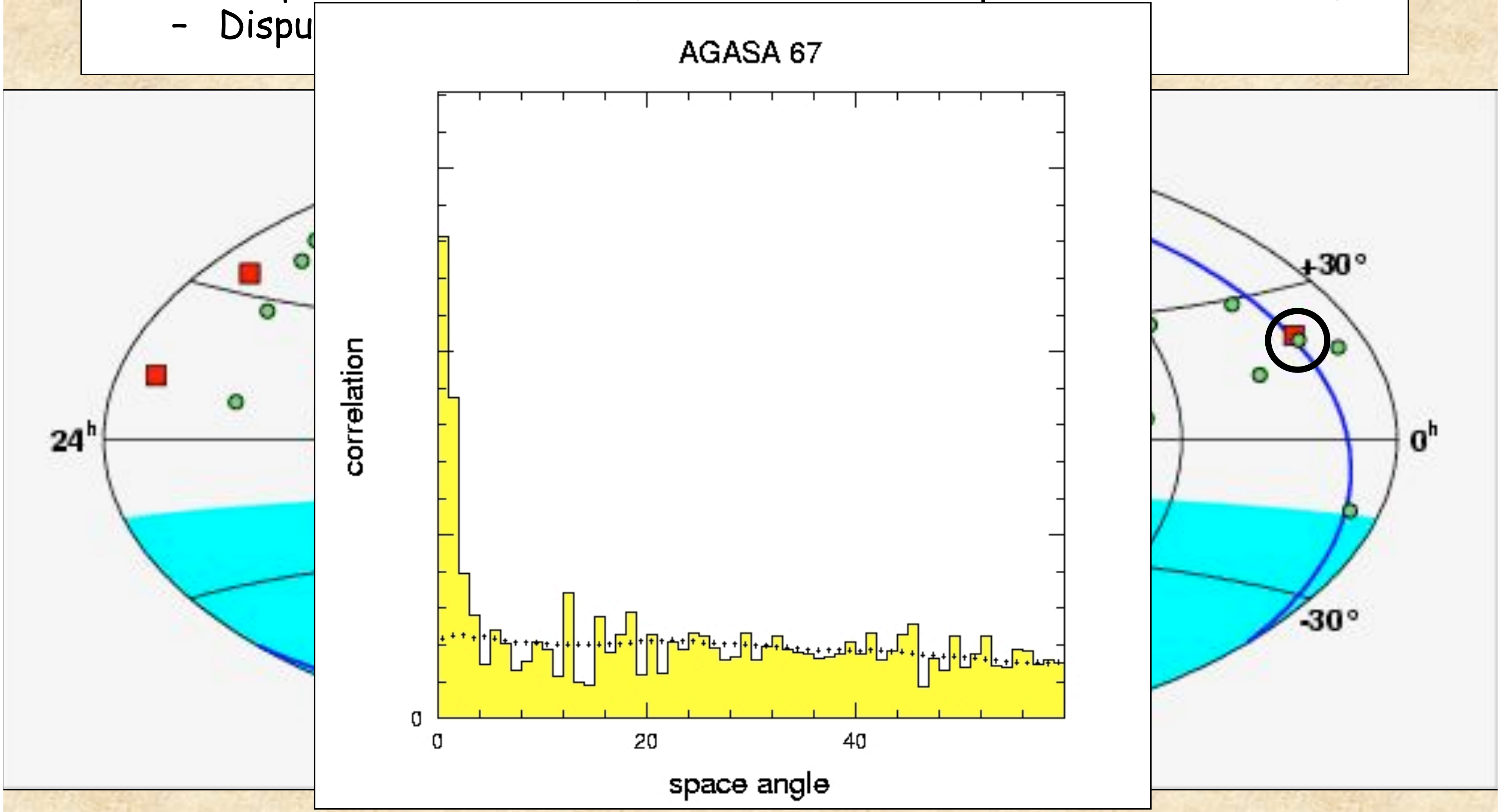


A possible acceleration site associated with shocks in hot spots of active galaxies



Arrival Direction Distribution $>4\times10^{19}$eV zenith angle <50deg.

- Isotropic on large scales → Extra-Galactic
- But AGASA sees clusters in small scale ($\Delta\theta$<2.5deg)
  - 1triplet and 6 doublets (2.0 doublets are expected from random)
  - Dispu



Ultra-High Energy Cosmic Ray Propagation and Magnetic Fields

Cosmic rays above ~10^{19} eV are probably extragalactic and may be deflected mostly by extragalactic fields B_{XG} rather than by galactic fields.

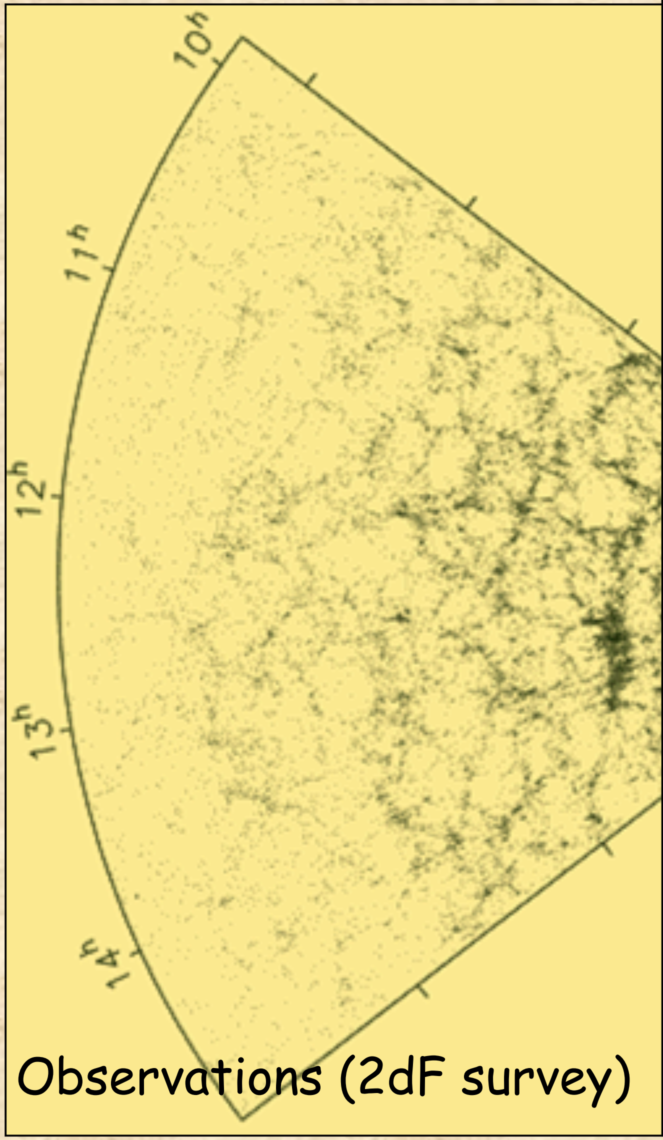
However, very little is known about about B_{XG}: It could be as small as 10^{-20} G (primordial seeds, Biermann battery) or up to fractions of micro Gauss if concentrated in clusters and filaments (equipartition with plasma).

Transition from rectilinear to diffusive propagation over distance d in a field of strength B and coherence length Λ_c at:

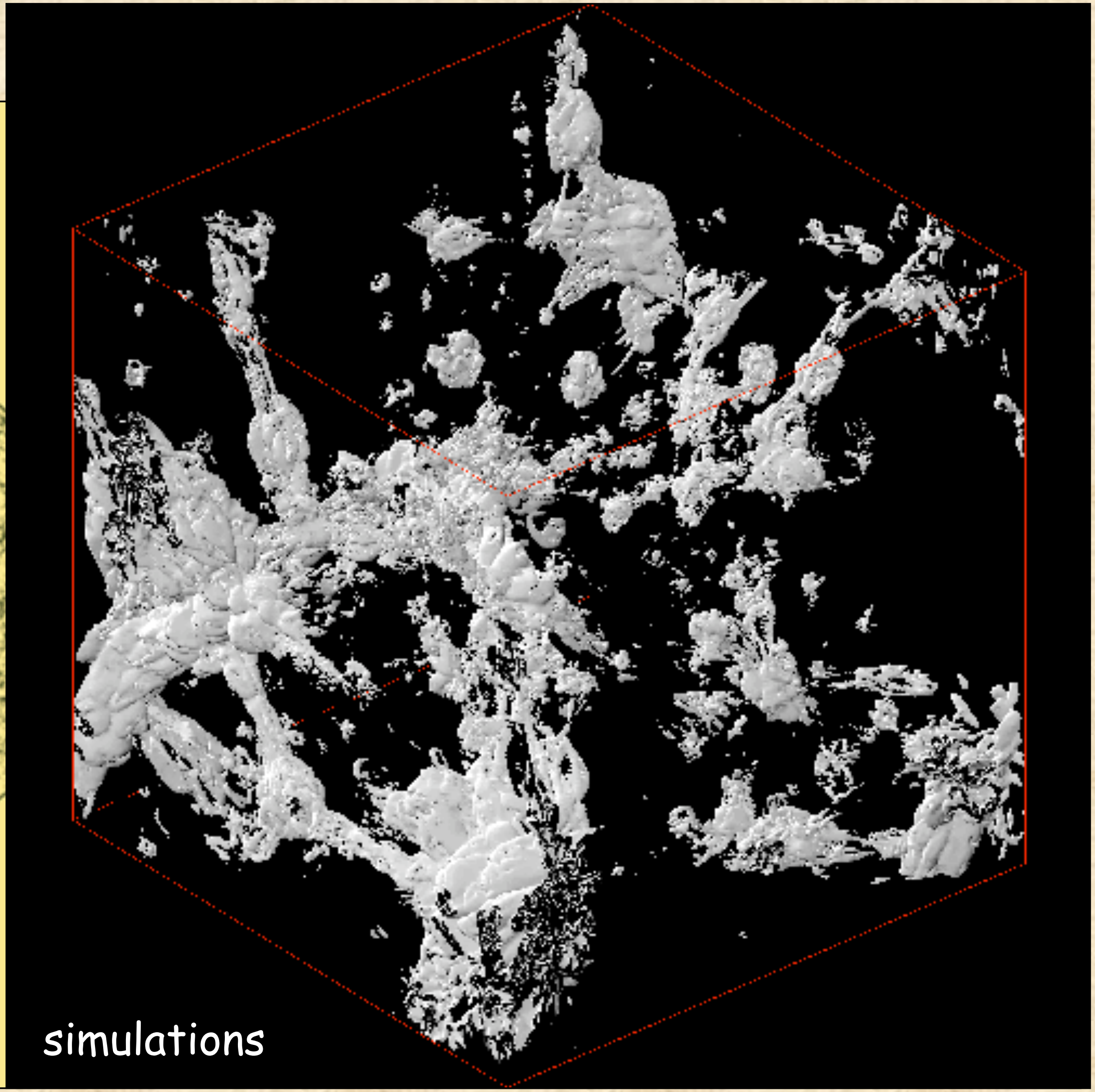
$$E_c \simeq 1.2 \times 10^{19} \left(\frac{Z}{26}\right) \left(\frac{d}{10\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B_{rms}}{\mathrm{nG}}\right) \left(\frac{\lambda_c}{1\,\mathrm{Mpc}}\right)^{1/2} \mathrm{eV}$$

In this transition regime Monte Carlo codes are in general indispensable.

The Universe is structured

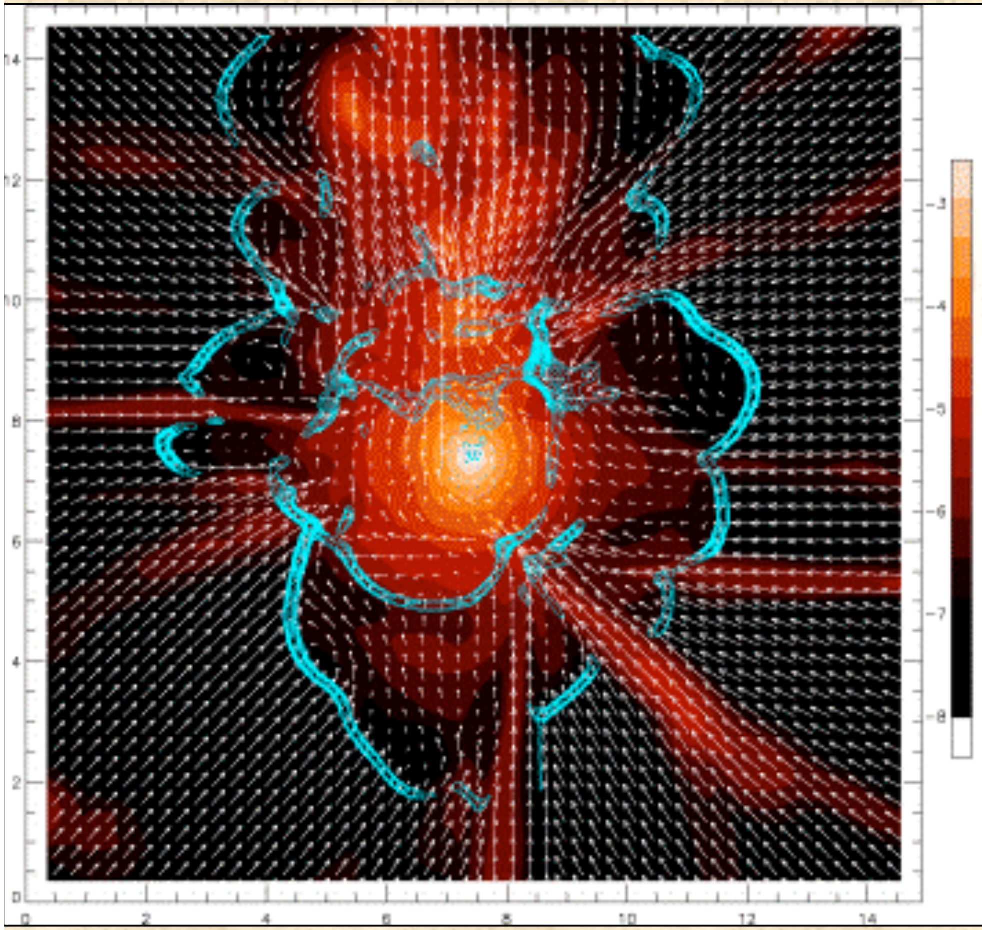


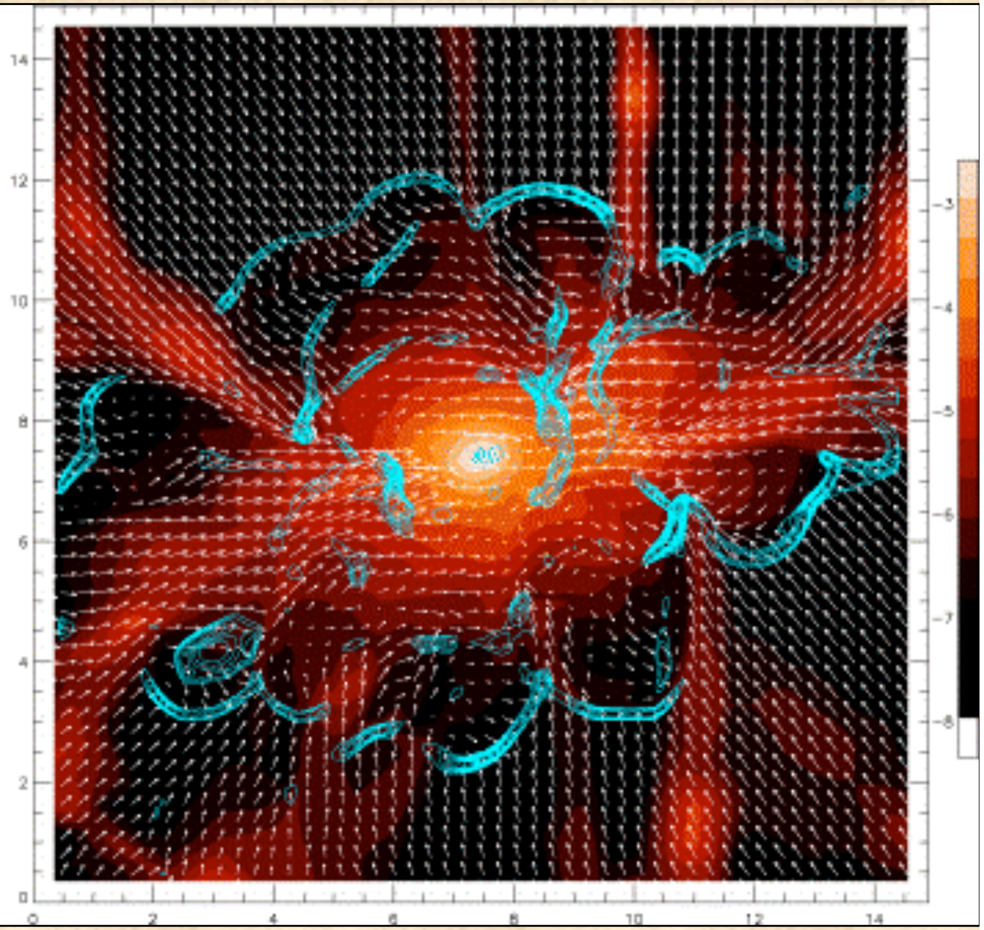
Observations (2dF survey)



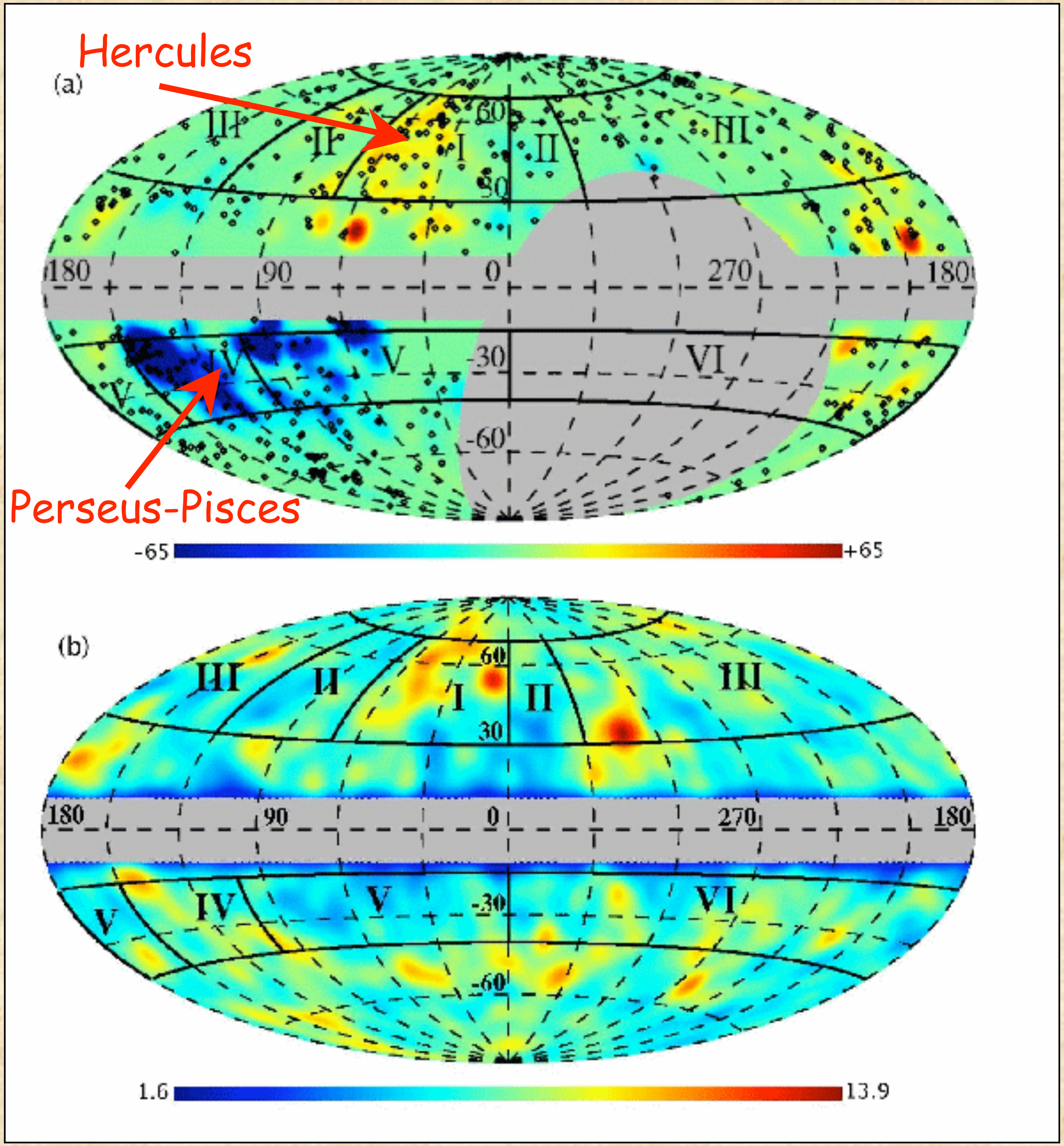
simulations

The Sources may be immersed in Magnetized Structures such as Galaxy Clusters





Miniati, MNRAS 342, 1009



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

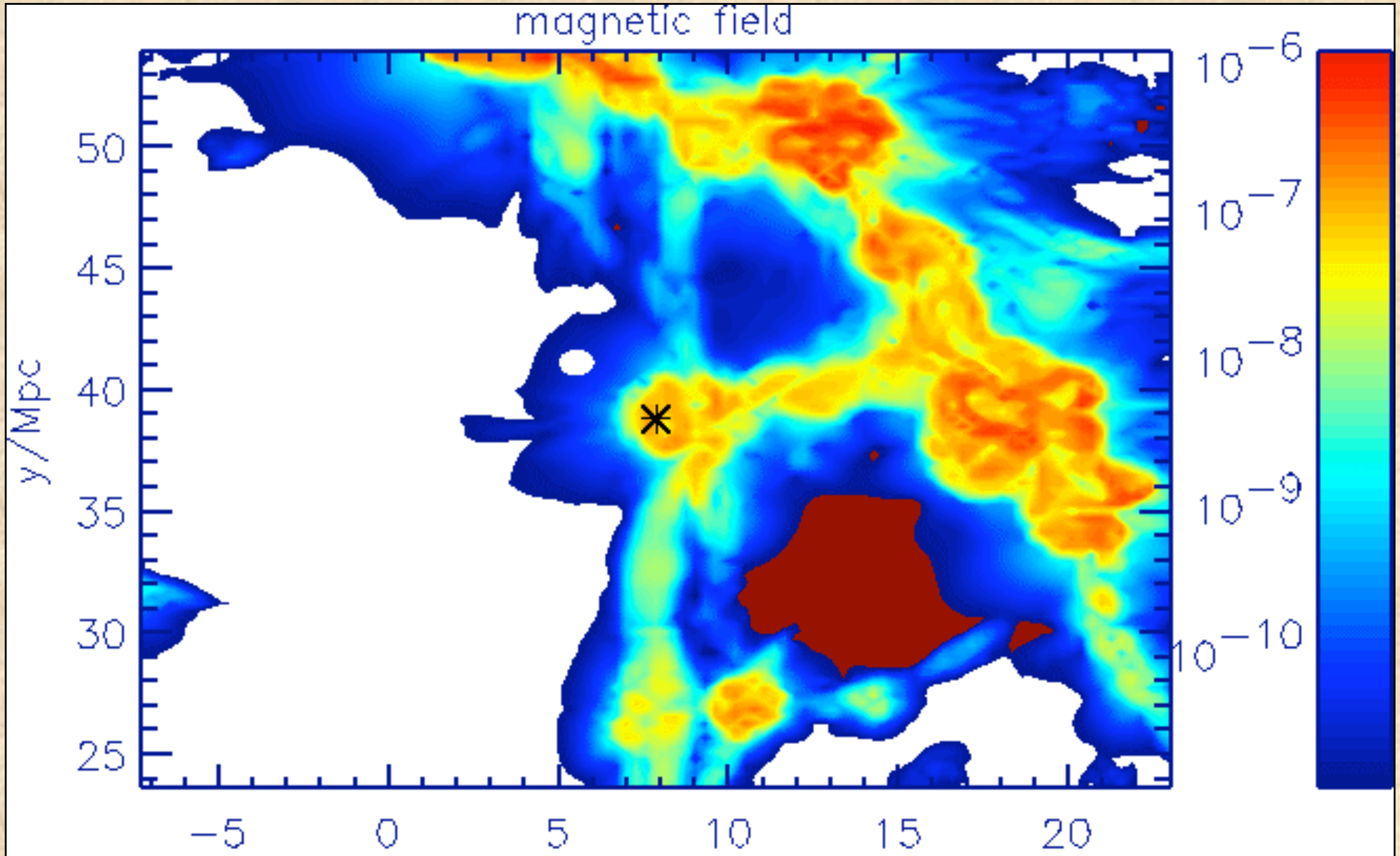
But need much more data from radio astronomy, e.g. Lofar, SKA

2MASS galaxy column density

Xu et al., astro-ph/0509826

Heavy Nuclei: Structured Fields and Individual Sources

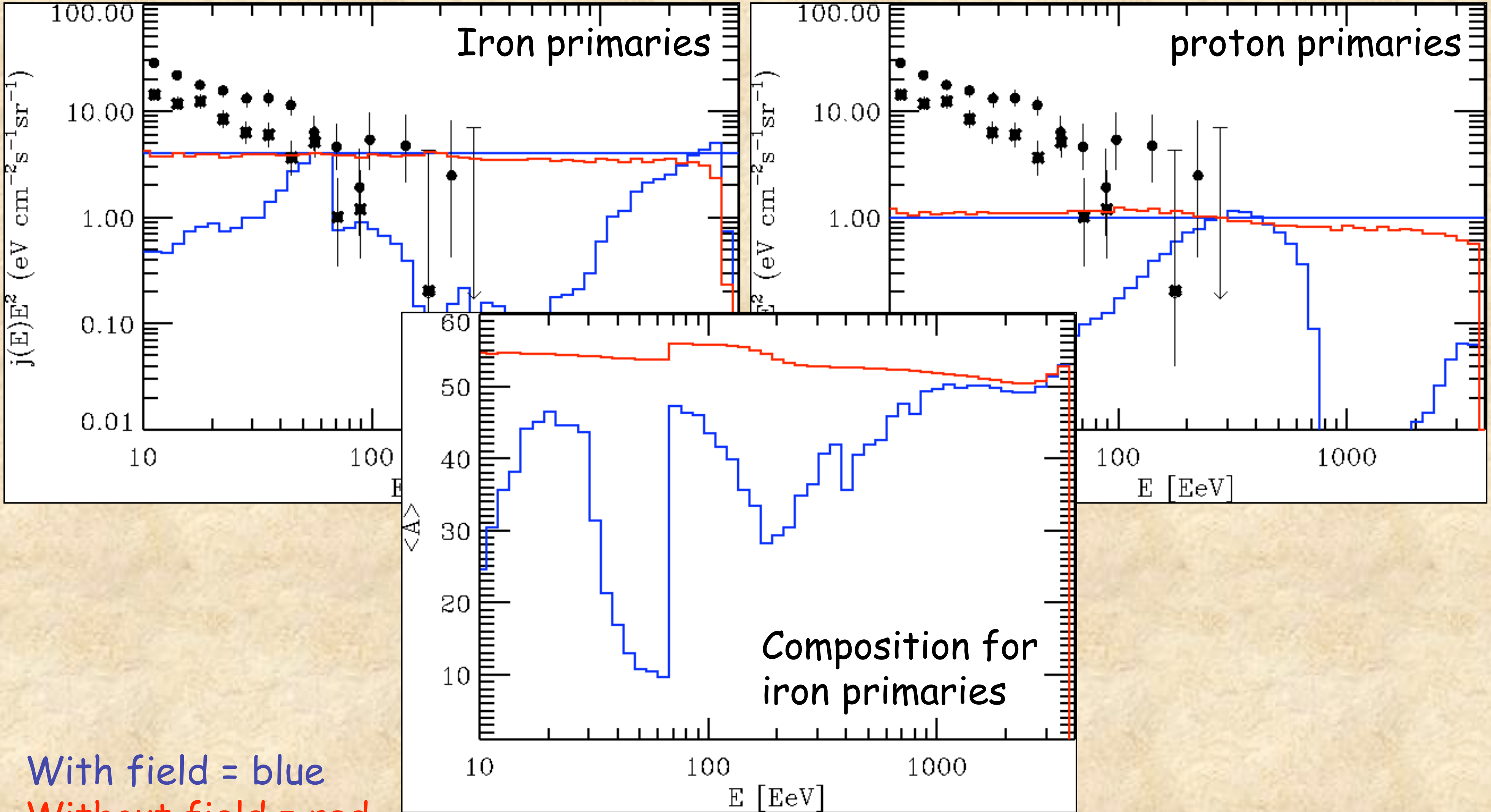
Spectra and Composition of Fluxes from Single Discrete Sources considerably depend on Source Magnetization, especially for Sources within a few Mpc.



Sigl, JCAP 08 (2004) 012

Source in the center; weakly magnetized observer modelled as a sphere shown in white at 3.3 Mpc distance.

$$E_c \approx 10^{21} \left(\frac{Z}{26}\right) \left(\frac{d}{1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B_{rms}}{0.1\,\mu\mathrm{G}}\right) \left(\frac{\lambda_c}{100\,\mathrm{kpc}}\right)^{1/2} \mathrm{eV}$$

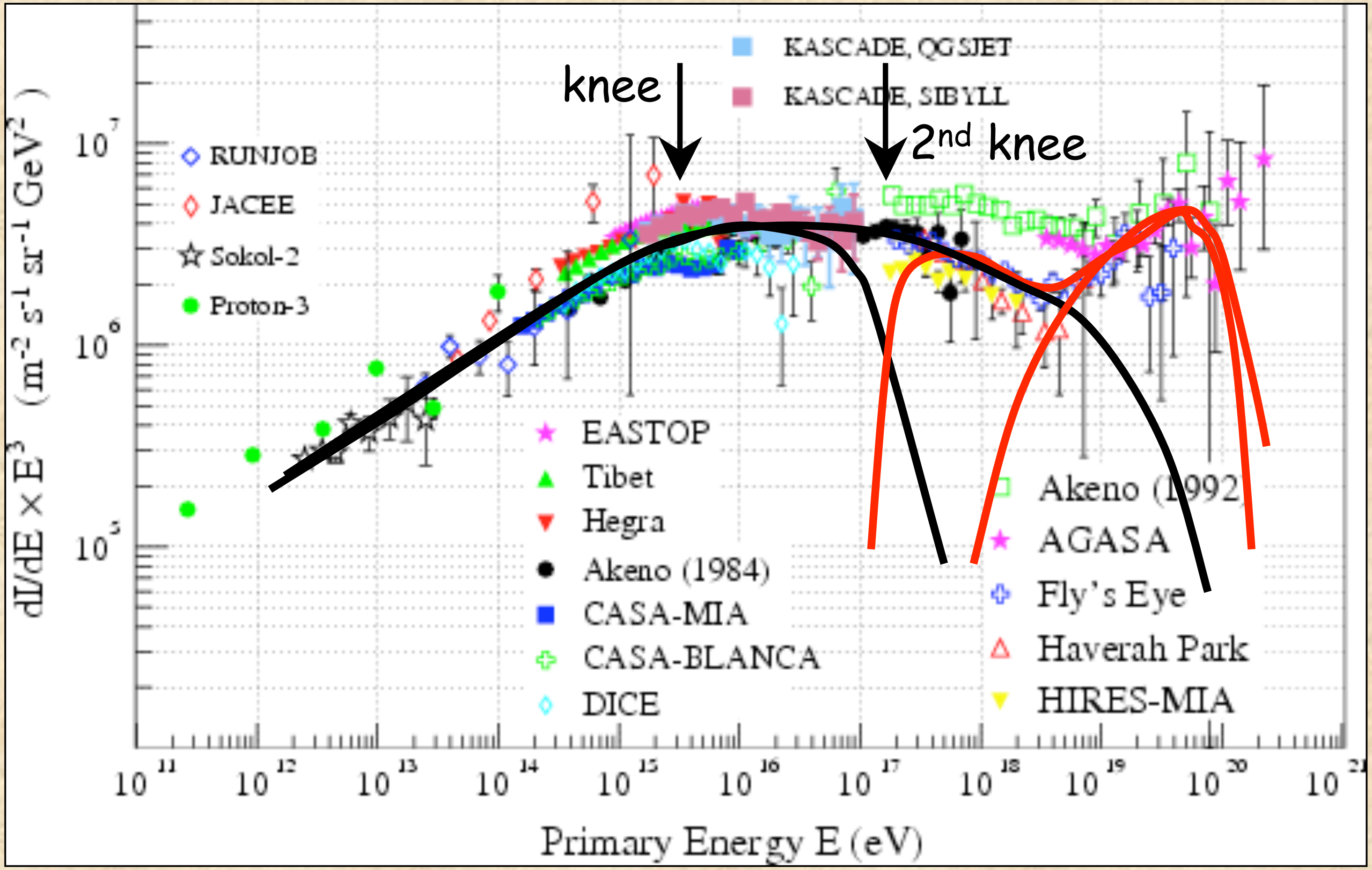


With field = blue

Without field = red

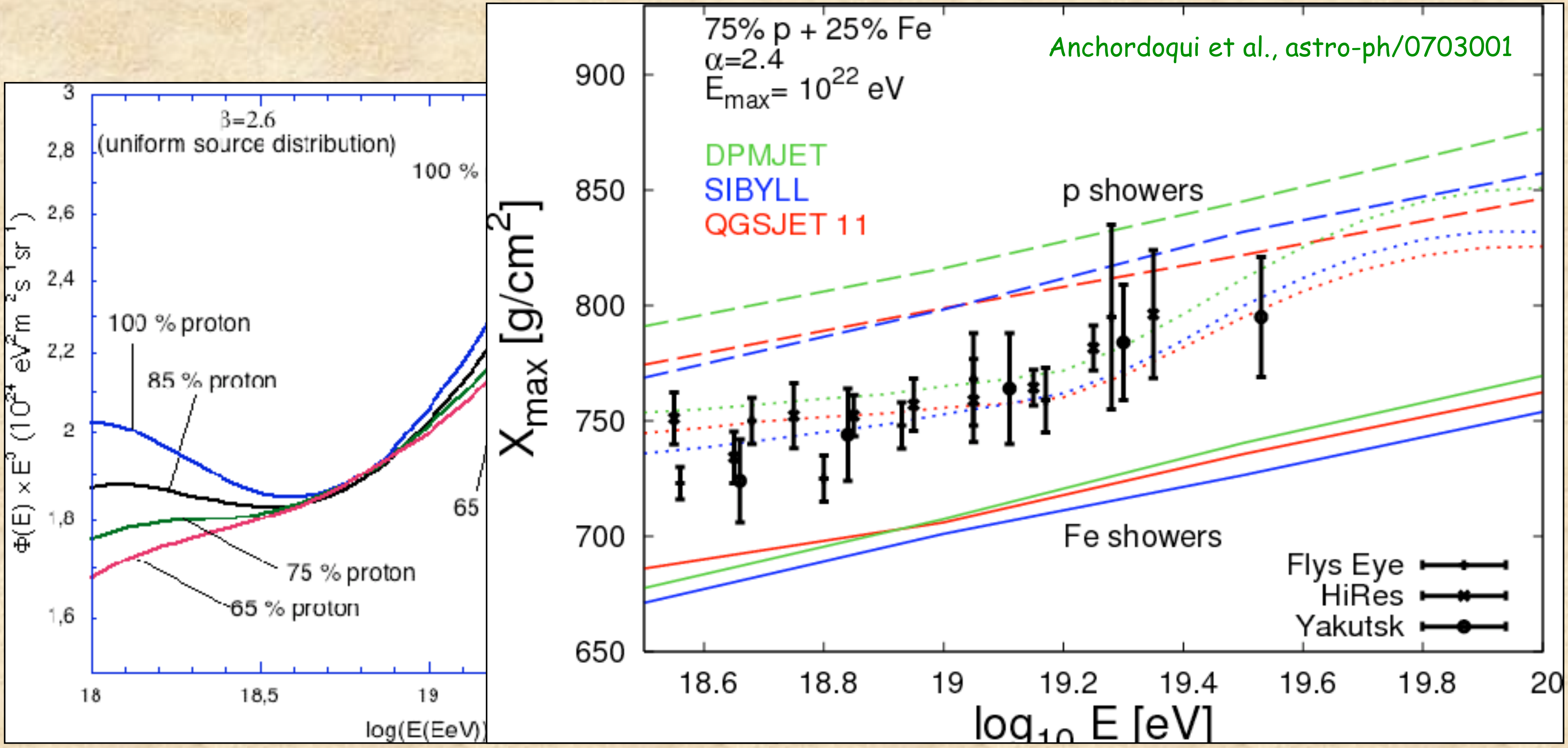
Injection spectrum = horizontal line

Chemical Composition, Magnetic Fields, Nature of the Ankle



"Conventional Scenario":
The ankle at ~5x10^{18} eV is a cross-over from a heavy Galactic to a light extragalactic component.

Scenario of Berezinsky et al.:
Galactic cosmic rays level out at the 2nd knee at ~4x10^{17} eV where dominated by heavy nuclei.
The ankle at ~5x10^{18} eV is due to pair production of extragalactic protons on the CMB. Requires >85% protons at the ankle.



Allard et al., A& 443, L29 (2005), astro-ph/0508465

A significant iron admixtures does not reproduce the ankle in the absence of magnetic fields.

But experimental situation on chemical abundances is unsettled.

Ultra-High Energy Cosmic Rays and the Connection to γ-ray and Neutrino Astrophysics

accelerated protons interact:

$$p + \begin{matrix} N \\ \gamma \end{matrix} \rightarrow X + \left. \begin{matrix} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{o} \rightarrow \gamma-\text{rays} \end{matrix} \right\}$$

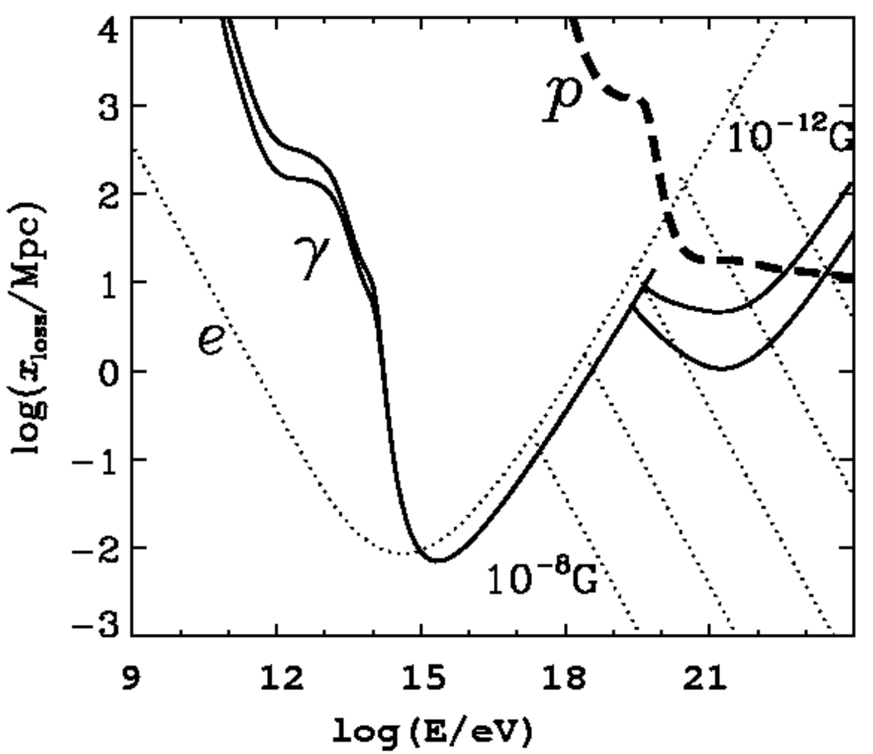
during propagation ("cosmogenic") or in sources (AGN, GRB, ...)

=> 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.

$x_{loss} = x_{int}$ /mean inelasticity



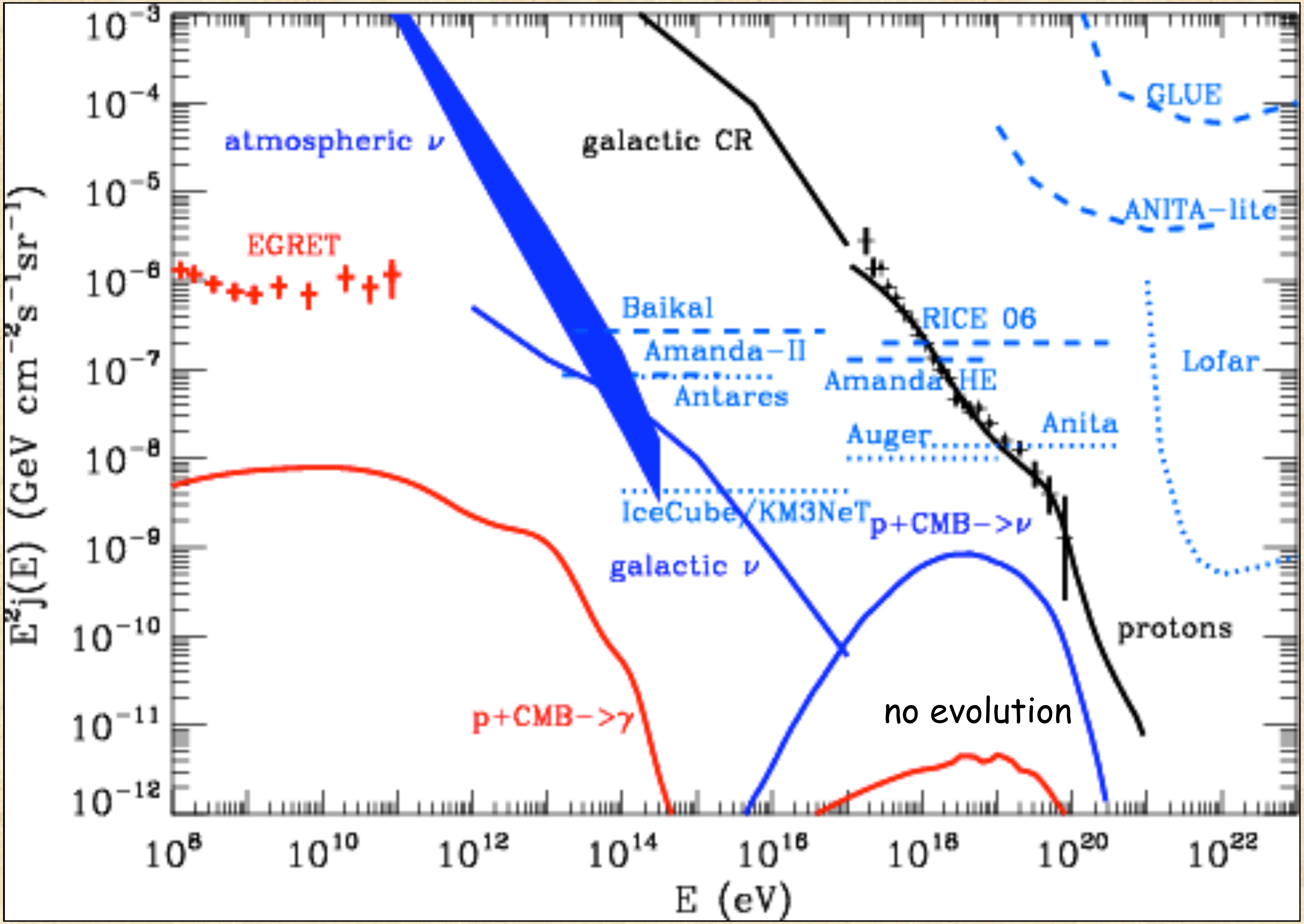
Included processes:

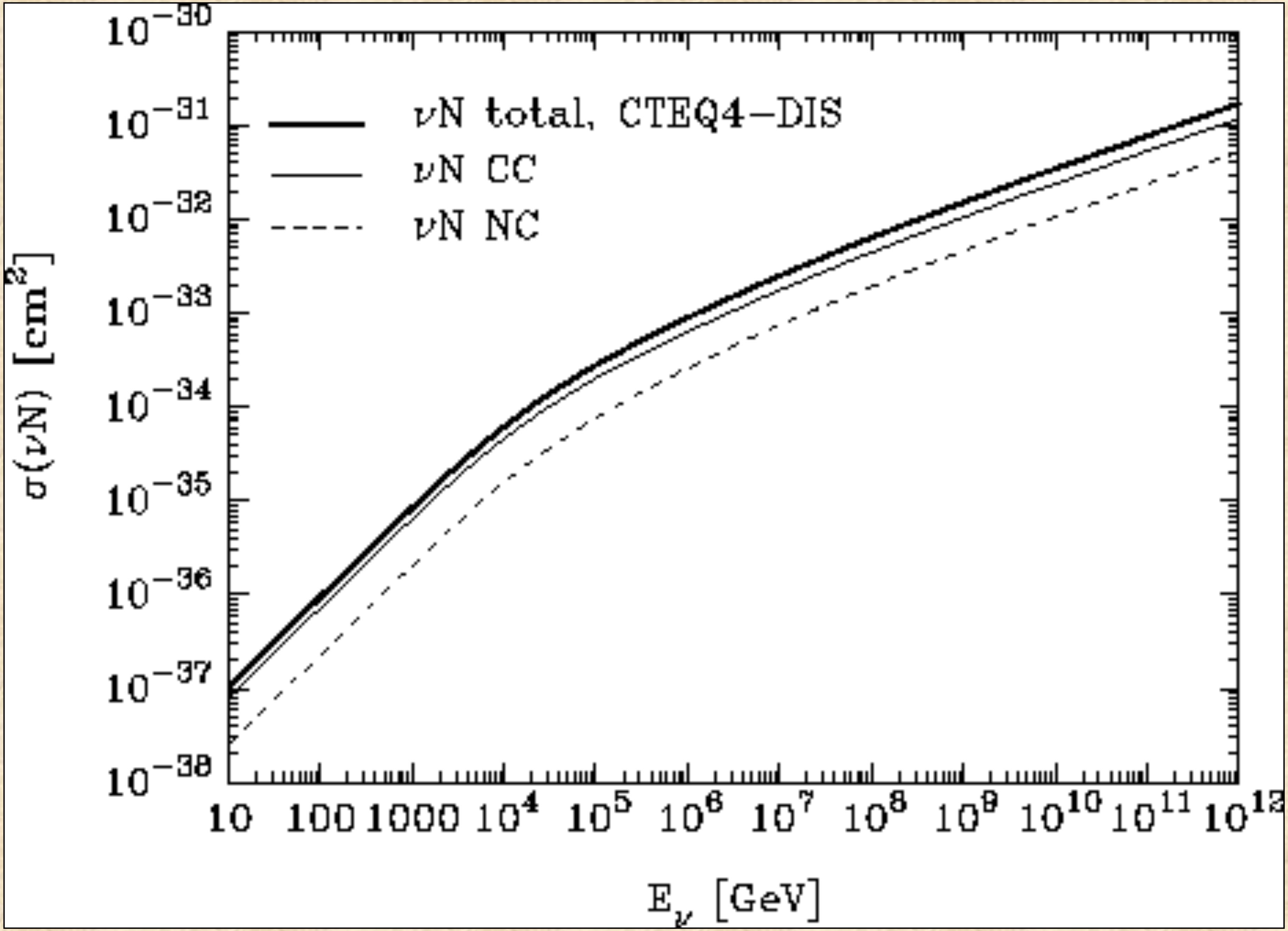
Electrons: inverse Compton; synchrotron rad (for fields from pG to 10 nG)

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

Protons: Bethe-Heitler pair production, pion photoproduction

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





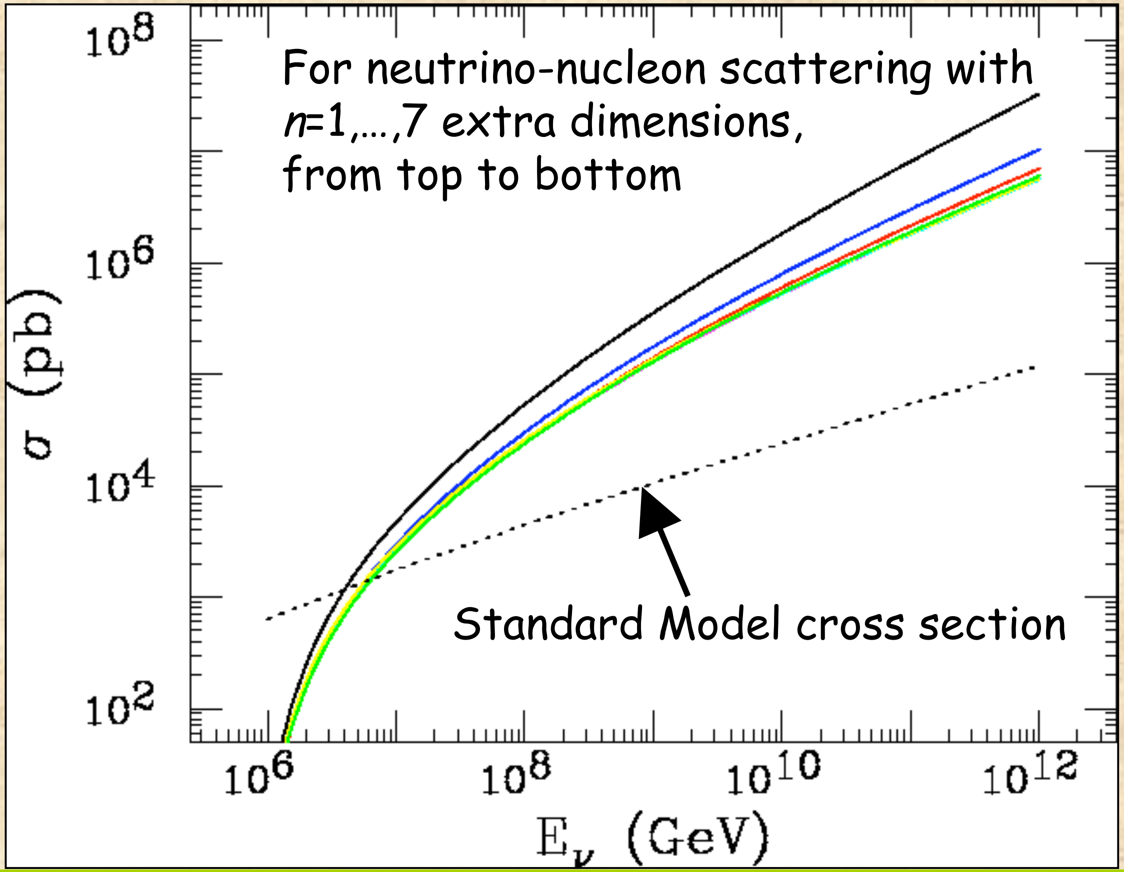
νN total, CTEQ4−DIS
νN CC
νN NC
$\sigma(\nu N)$ [cm^2]
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10 100 1000 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12}
E_ν [GeV]

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.

Solution: Compare rates of different types of neutrino-induced showers

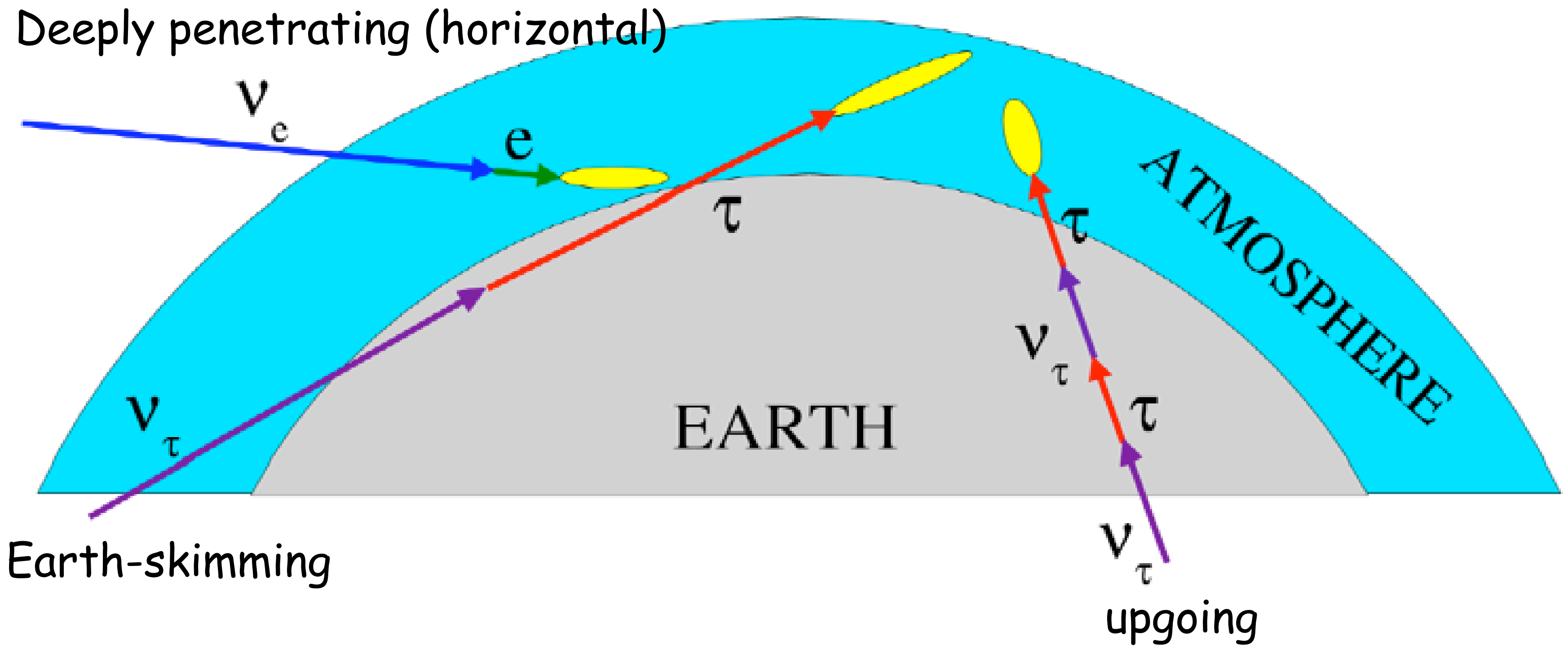
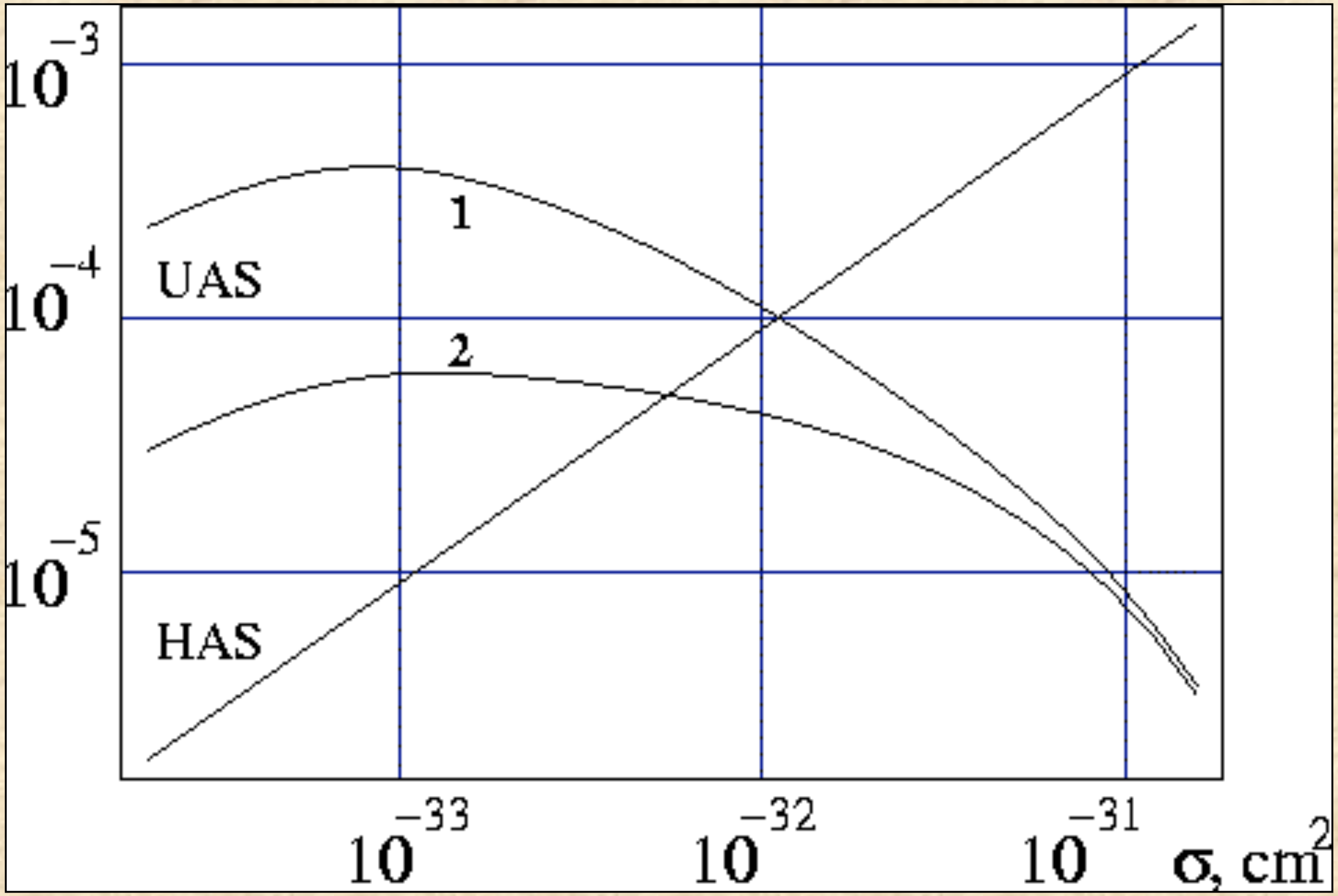


Figure from Cusumano

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 violations in the Nucleon Sector

Dispersion relation between energy E, momentum p, and mass m may be modified by non-renormalizable effects at the Planck scale M_{Pl},

$$E^2 - p^2 \approx m^2 - \xi \frac{p^3}{M_{\mathrm{Pl}}} - \zeta \frac{p^4}{M_{\mathrm{Pl}}^{\;2}} + \ldots,$$

where most models, e.g. critical string theory, predict ξ=0 for lowest order.

Introducing the standard threshold momentum for pion production, $N+\gamma \to N\pi$,

$$p_0 = \frac{2m_N m_\pi + m_\pi^{\;2}}{4\varepsilon},$$

the threshold momentum p_{th} in the modified theory is given by

$$-\frac{p_0^{\;3}}{(m_\pi^{\;2} + 2m_\pi m_N)M_{\mathrm{Pl}}} \frac{m_\pi m_N}{(m_\pi + m_N)^2} \left[2\xi \left(\frac{p_{\mathrm{th}}}{p_0} \right)^3 + 3\zeta \frac{p_0}{M_{\mathrm{Pl}}} \left(\frac{p_{\mathrm{th}}}{p_0} \right)^4 + \ldots \right] + \frac{p_{\mathrm{th}}}{p_0} = 1$$

Attention: this assumes standard energy-momentum conservation which is not necessarily the case.

Coleman, Glashow, PRD 59 (1999) 116008; Alosio et al., PRD 62 (2000) 053010

For $\xi \sim \zeta \sim 1$ this equation has no solution => No GZK threshold!

For $\zeta \sim 0$, $\xi \sim -1$ the threshold is at ~1 PeV!
For $\xi \sim 0$, $\zeta \sim -1$ the threshold is at ~1 EeV!

Confirmation of a normal GZK threshold would imply the following limits:

$|\xi| < 10^{-13}$ for the first-order effects.
$|\zeta| < 10^{-6}$ for the second-order effects.

Energy-independent (renormalizable) corrections to the maximal speed $V_{max} = \lim_{E\to\infty} \partial E/\partial p = 1-d$ can be constrained by substituting $d \longrightarrow (\xi/2)(E/M_{Pl})+(\zeta/2)(E/M_{Pl})^2$.

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:

$$\Delta t = -\xi D \frac{E}{M} \approx -\xi \left(\frac{D}{100\,\mathrm{Mpc}}\right)\left(\frac{E}{\mathrm{TeV}}\right)\mathrm{sec}$$

for $\zeta = 0$. GRB observations in TeV γ-rays can therefore probe quantum gravity. The current limit is $M/\xi > 8\times10^{15}$ GeV (Ellis et al.).

Lorentz Symmetry Violation in the Photon Sector

For photons we assume the dispersion relation

$$\omega^2 = k^2 \pm \xi_n k^2 \left(\frac{k}{M_{Pl}}\right)^n \quad \text{with} \quad n \geq 1$$

with only one term present, whereas dispersion relations for other particles are unchanged.

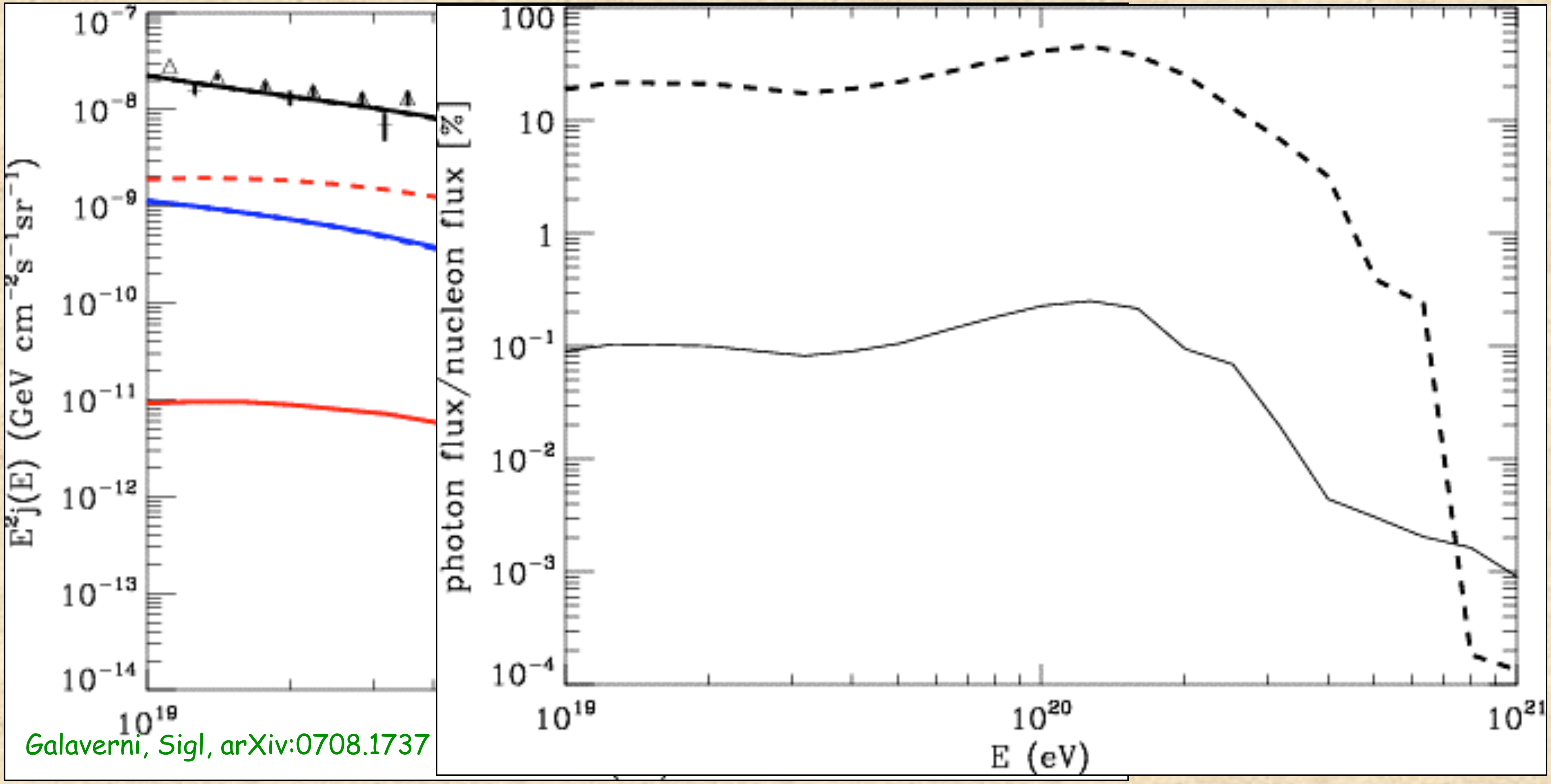
Consider pair production $\gamma\gamma \to e^+ e^-$, on a background photon of energy ω_b. Scaled to the threshold in absence of Lorentz invariance (LI) breaking, $k_{LI} \equiv m_e^2/\omega_b$, the threshold condition is

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

where

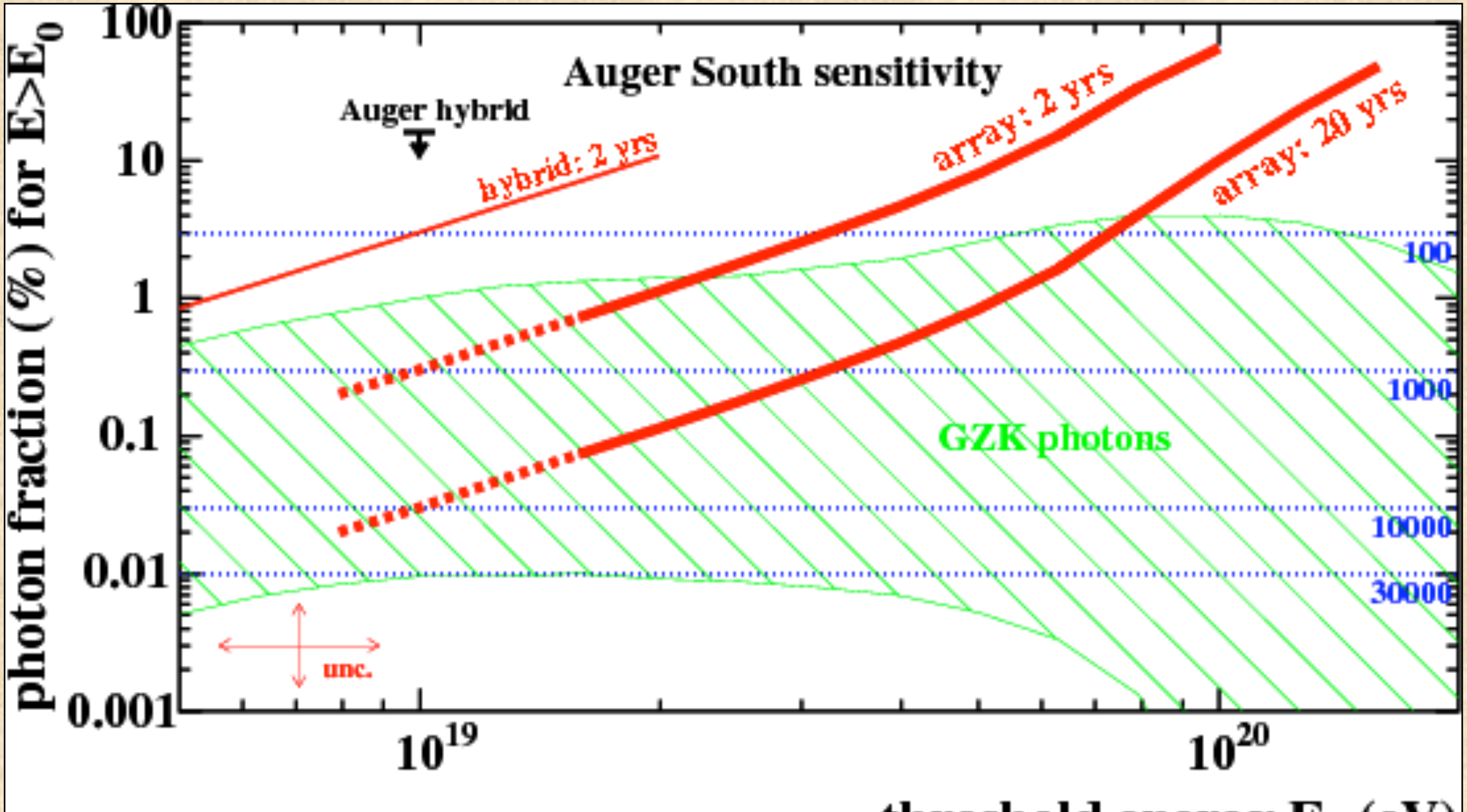
$$\alpha_n \equiv \xi_n \frac{k_{LI}^2}{4m_e^2}\left(\frac{k_{LI}}{M_{Pl}}\right)^n\,.$$

Since photon interaction length above 10^{19} eV is below a few Mpc, the fraction of secondary photons is expected to be . 1% above 10^{19} eV and . 10% above 10^{20} eV. But without pair production for 10^{19} eV . ! . 10^{20} eV the photon fraction would be ' 20%:



Galaverni, Sigl, arXiv:0708.1737

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.



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

Absence of pair production between 10^{19} eV and 10^{20} eV would thus violate experimental constraints.

Since a typical CMB photon energy is $\omega_b \sim 6\times 10^{-4}$ eV, pair production should be allowed for

$$2.3\times 10^4 \lesssim x \lesssim 2.3\times 10^5 \lesssim x_n^u(\alpha_n)\,.$$

For $n = 1$ this yields

$$\alpha_1 \lesssim \frac{1}{(2.5\times 10^5)^2} \simeq 1.9\times 10^{-11}\,, \quad \xi_1 \lesssim 2.4\times 10^{-15}\,.$$

For $n = 2$ this yields

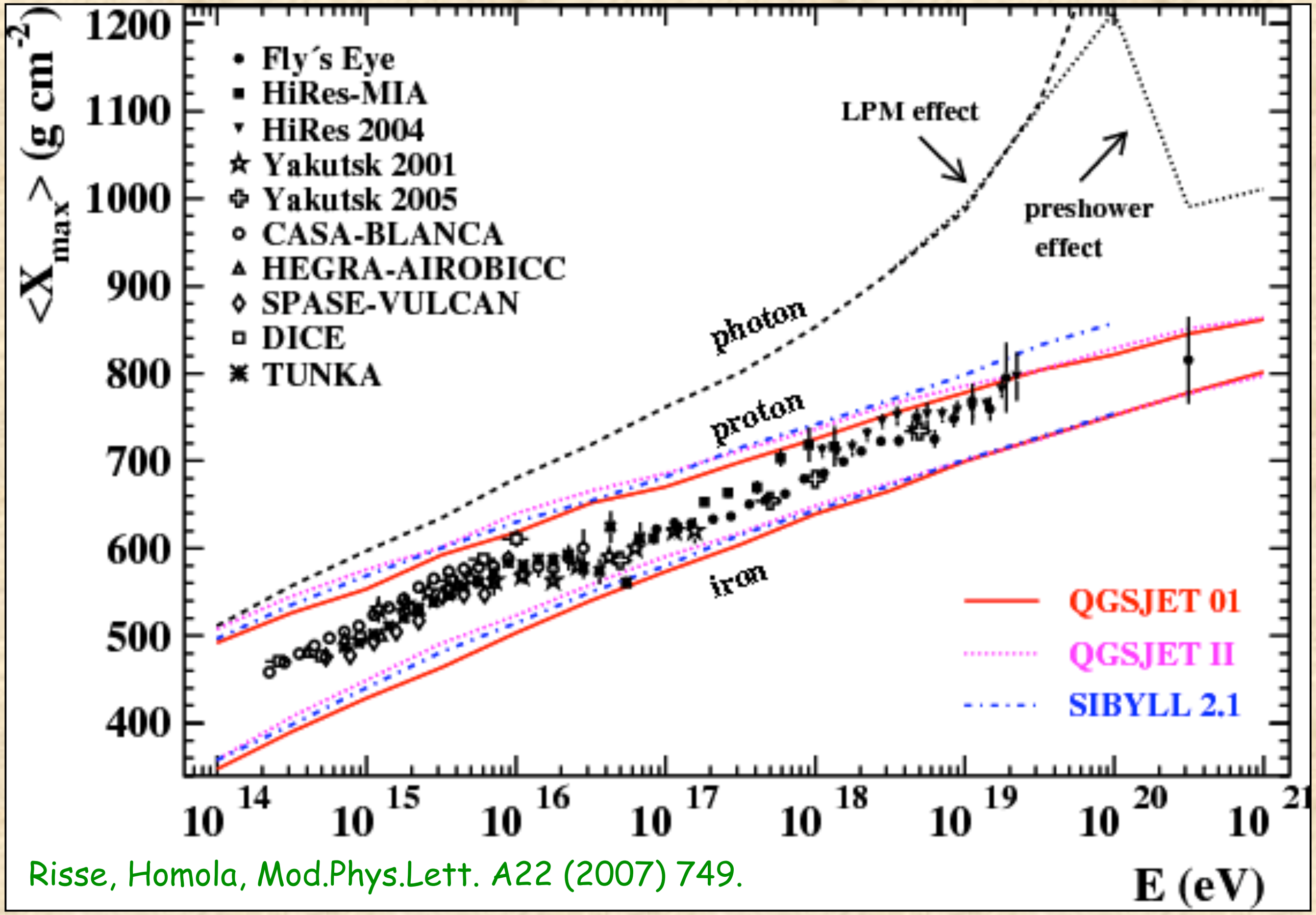
$$\alpha_2 \gtrsim -\frac{1}{(2.5\times 10^5)^3} \simeq -8.2\times 10^{-17}\,, \quad \xi_2 \gtrsim -2.4\times 10^{-7}\,.$$

Only for $n \geq 3$ the limits on ξ_n become larger than unity.

Galaverni, Sigl, arXiv:0708.1737

Possible Caveats

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



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

2.) LI violation in the electron sector can enable pair production if corresponding dimensionless parameters are considerably larger than in the photon sector.

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

Conclusions1

1.) The origin of very high energy cosmic rays is 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.) Acceleration and sky distribution of cosmic rays are strongly linked to the in part poorly known strength and distribution of cosmic magnetic fields.

3.) Sources are likely immersed in magnetic fields of fractions of a microGauss. Such fields can strongly modify spectra and composition even if cosmic rays arrive within a few degrees from the source direction.

4.) Pion-production establishes a very important link between the physics of high energy cosmic rays on the one hand, and γ-ray and neutrino astrophysics on the other hand. All three of these fields should be considered together. Strong constraints arise from γ-ray overproduction.

Conclusions2

5.) 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.

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

7.) The GZK effect produces secondary γ-rays whose fraction of the total particle flux above 10^{19} eV is expected to be below 1% due to pair production. Current experimental limits are of order 2%. In the absence of pair production in this energy range, the expected fraction would violate these limits.

8.) The coming 3-5 years promise an about 100-fold increase of ultra-high energy cosmic ray data due to experiments that are either under construction or in the proposal stage. This will constrain primary cosmic ray flux models.