Quellen für kosmische, γ-Strahlung und Neutrinos bei hohen Energien

Astroteilchenphysik in Deutschland, DESY, Zeuthen, Oktober 4-6, 2005

- (Very short) introduction on Cosmic Ray experimental situation. For γ-rays and neutrinos see subsequent speakers.
- Large scale magnetic fields and their effects on UHECR.
- Ultra-High Energy Cosmic Rays and secondary γ-rays and neutrinos: detection prospects with different experiments.

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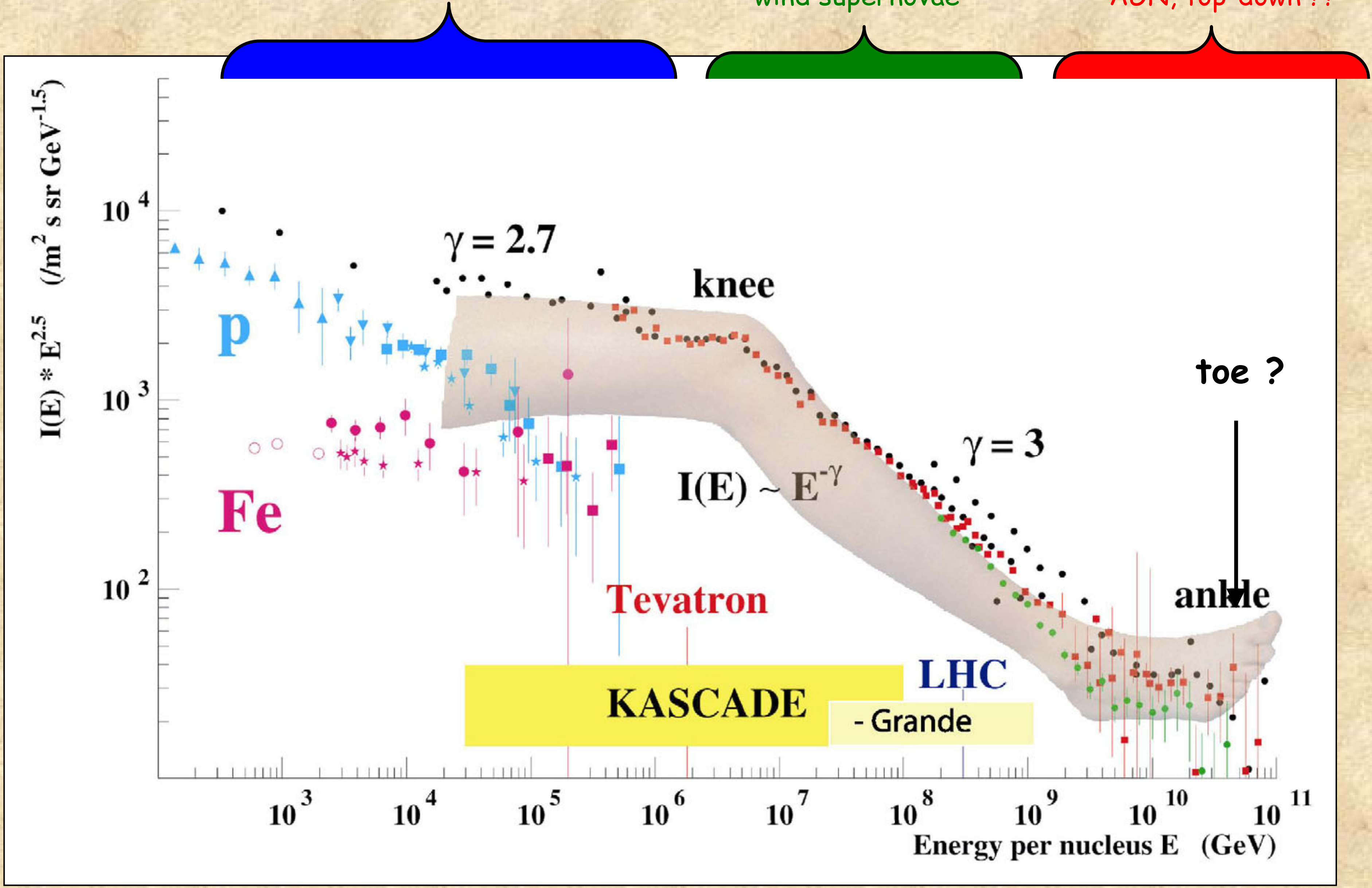
http://www2.iap.fr/users/sigl/homepage.html

The structure of the spectrum and scenarios of its origin

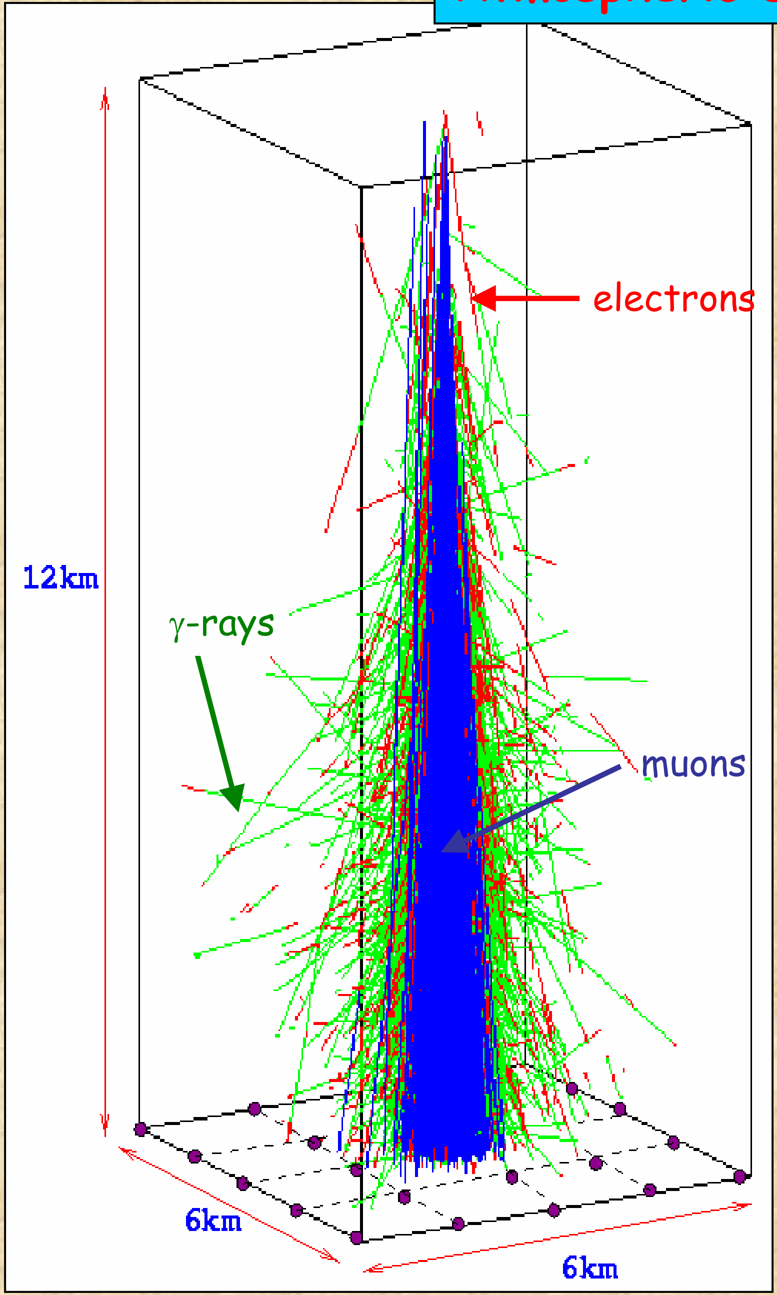
supernova remnants

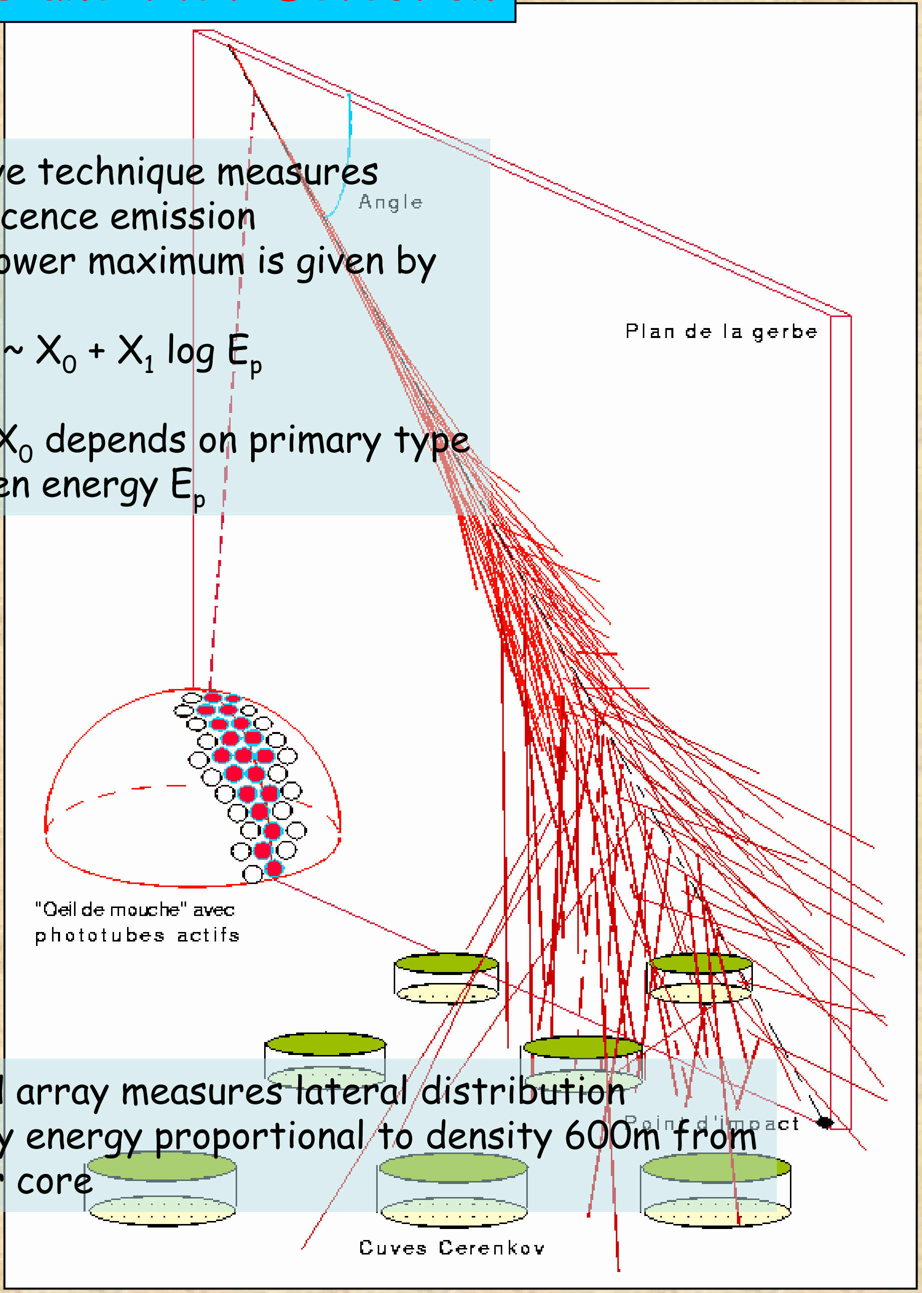
wind supernovae

AGN, top-down ??



Atmospheric Showers and their Detection





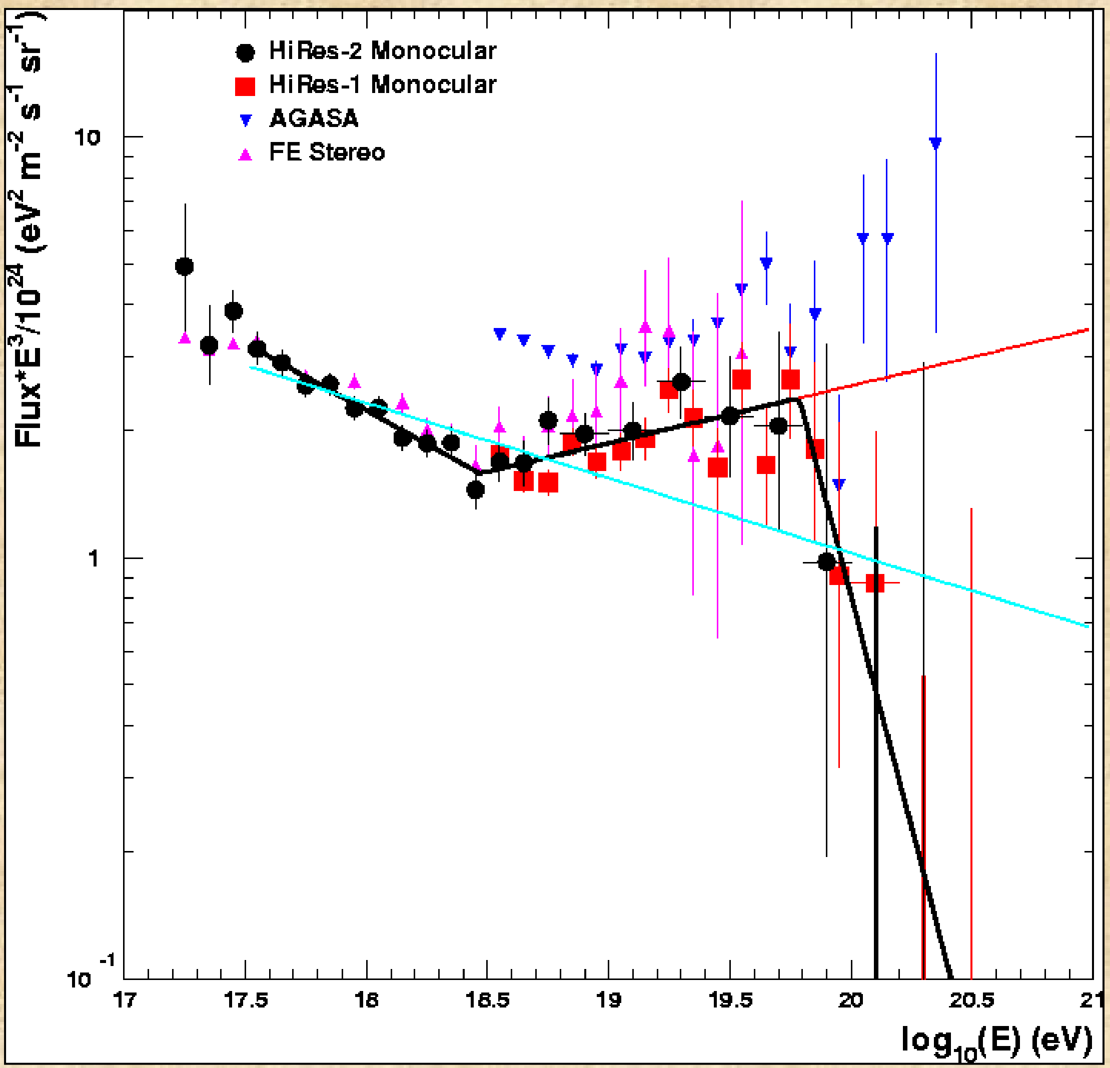
Fly's Eye technique measures fluorescence emission
The shower maximum is given by

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

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



HiRes collaboration, astro-ph/0501317

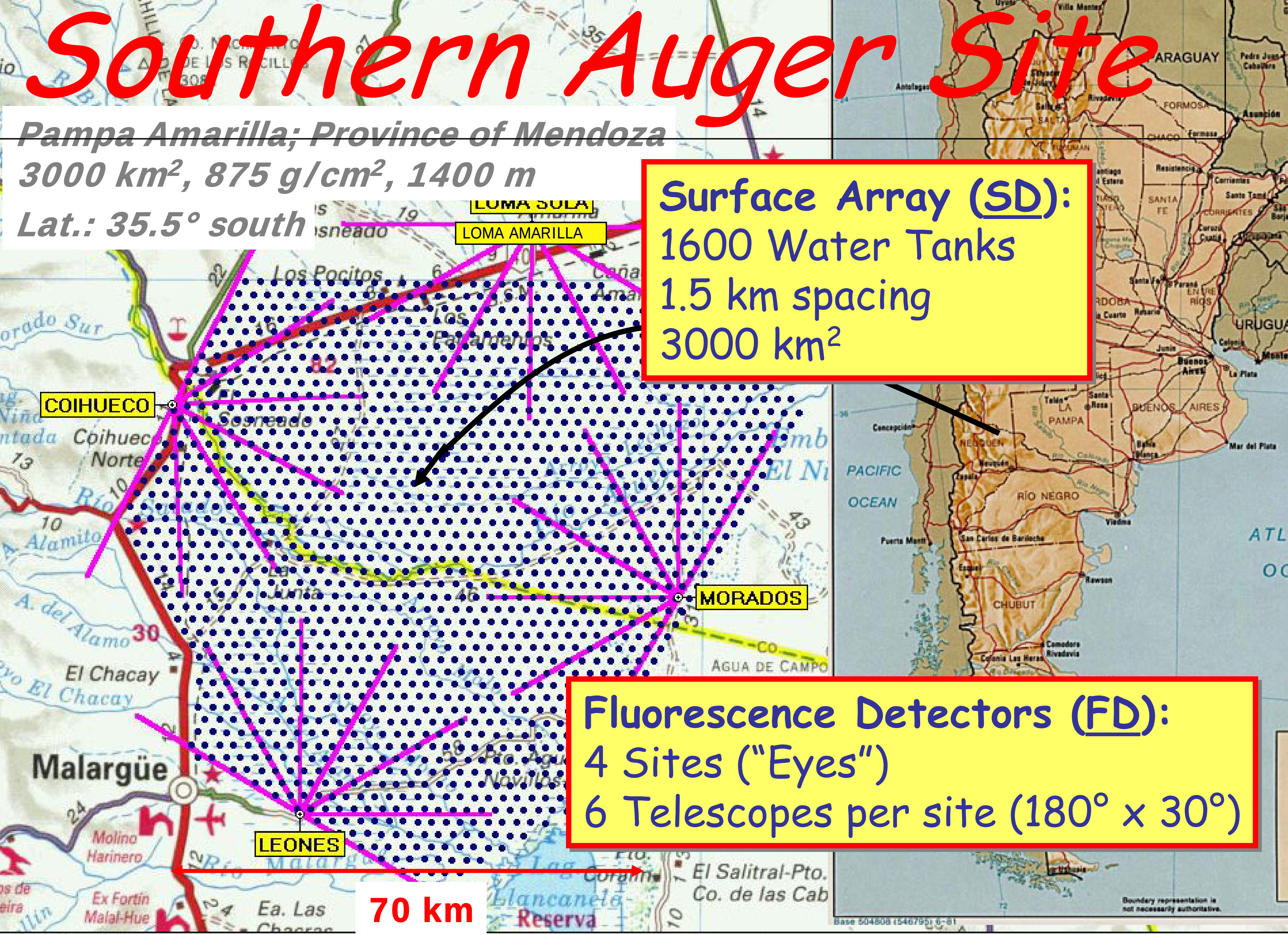
May need an experiment combining ground array with fluorescence such as the Auger project to resolve this issue.

Southern Auger Site

Pampa Amarilla; Province of Mendoza

3000 km², 875 g/cm², 1400 m

Lat.: 35.5° south



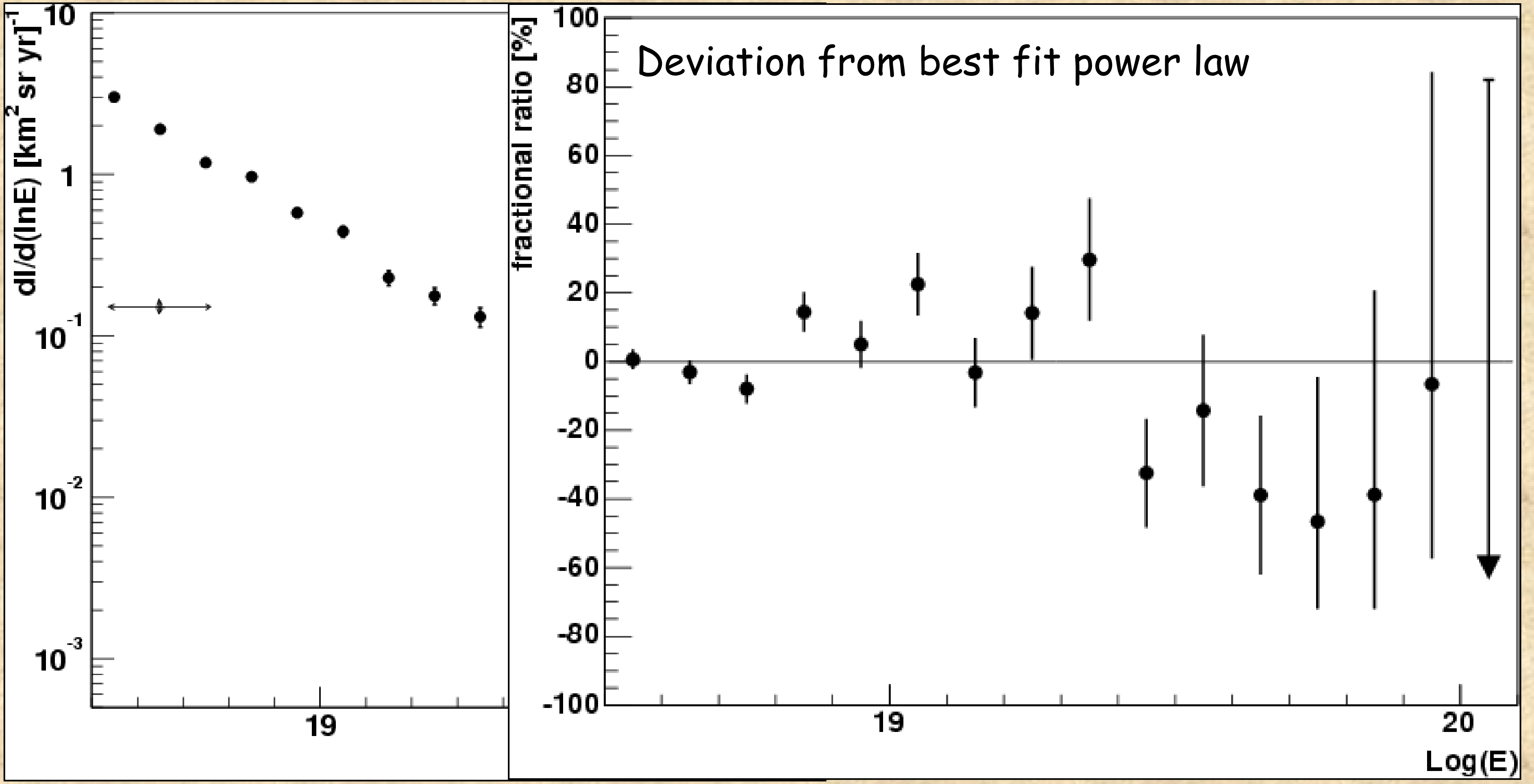
Surface Array (SD):
1600 Water Tanks
1.5 km spacing
3000 km²

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

First Auger Spectrum !!

107% AGASA exposure

Statistics as yet insufficient to draw conclusion on GZK cutoff



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

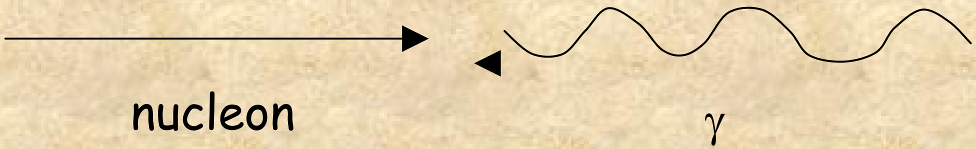
1.) electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 50 Mpc.

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

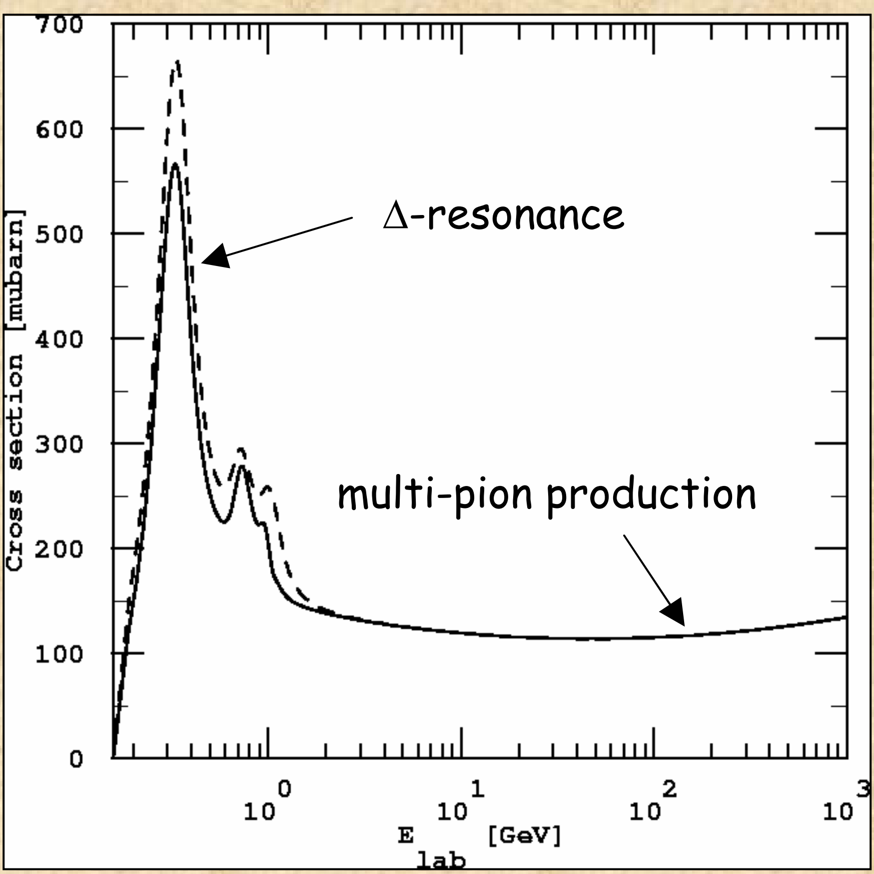
3.) The observed distribution seems to be very isotropic (except for a possible interesting small scale clustering)

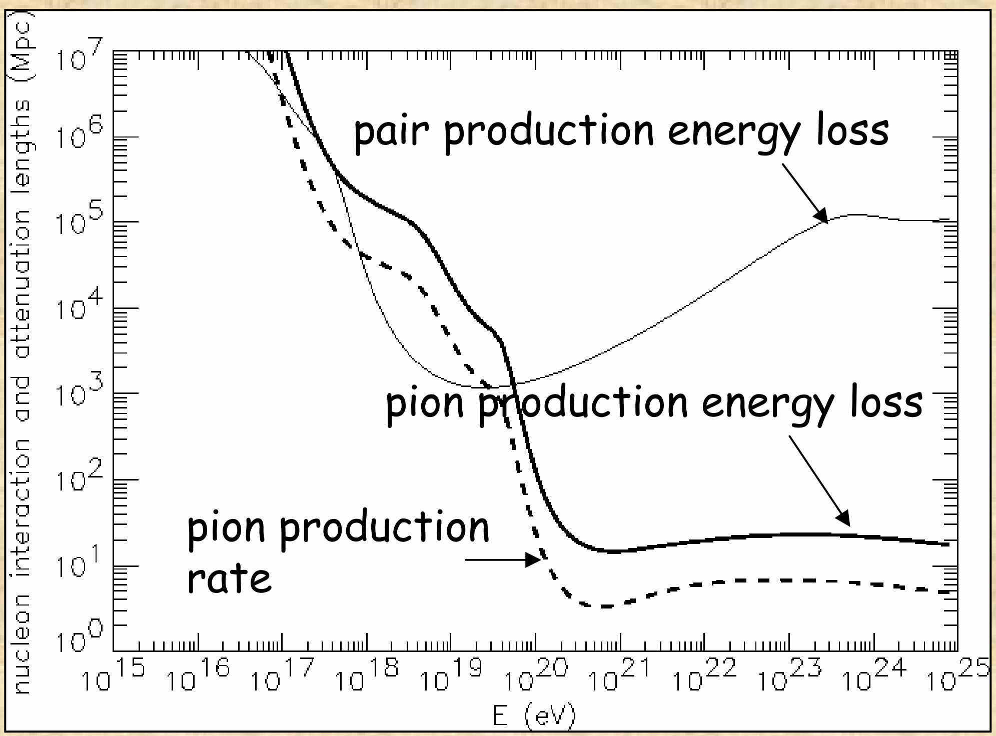
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



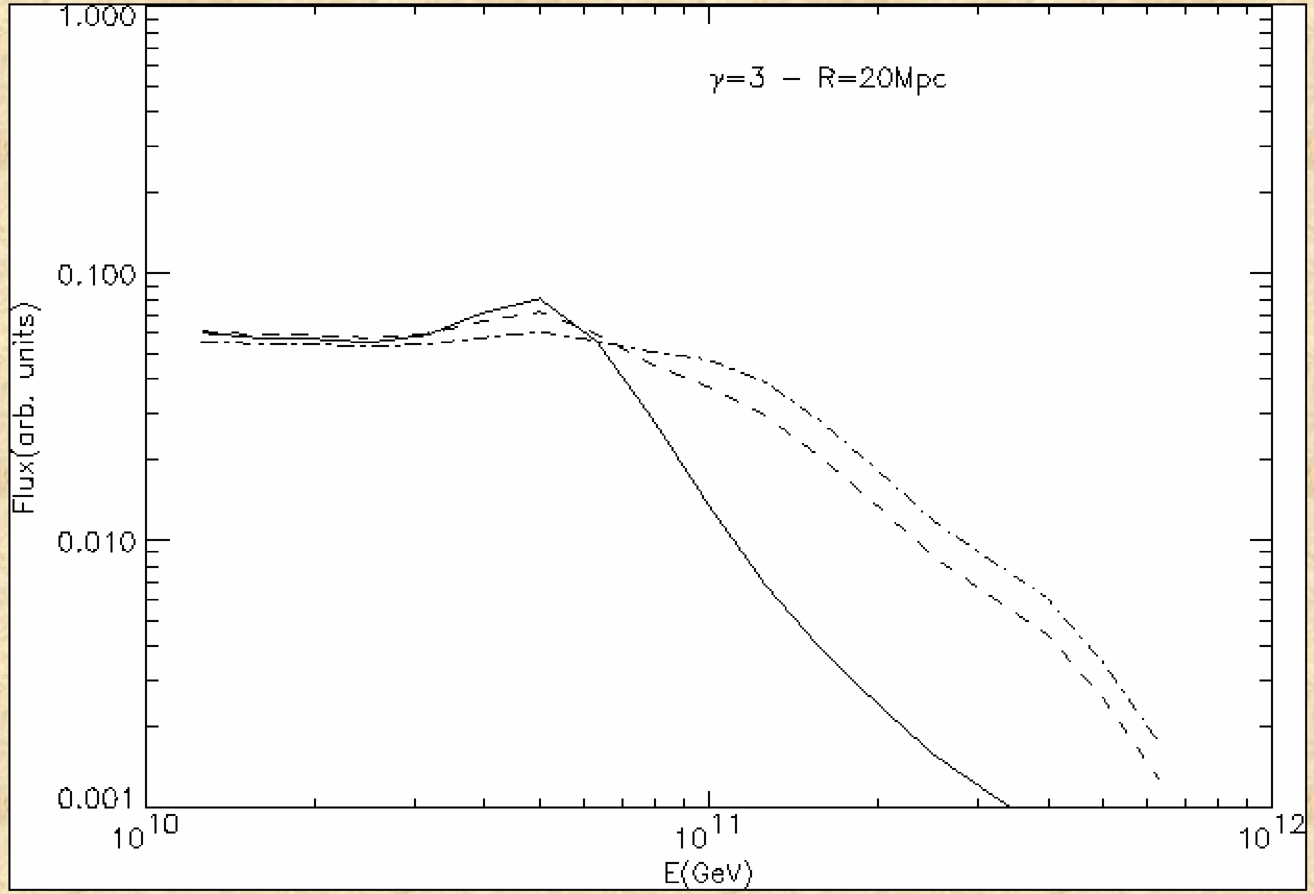
$$E_{\rm th} = \frac{2m_N m_\pi + m_\pi^{\;2}}{4\varepsilon} \approx 4\cdot 10^{19}\,{\rm eV}$$





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

What the GZK effect tells us about the source distribution (in the absence of strong magnetic deflection)

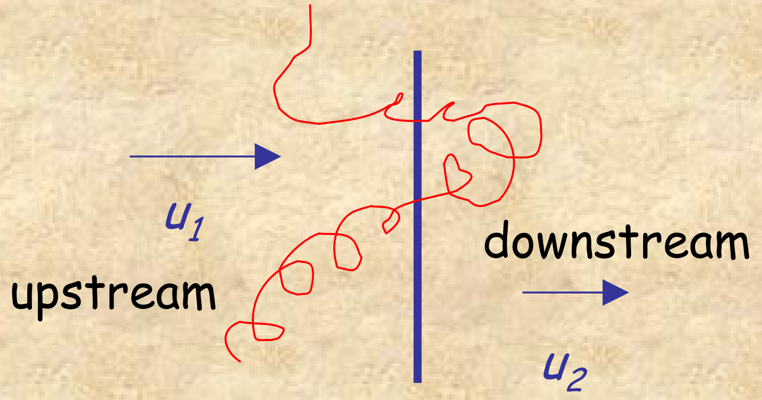


Observable spectrum for an E^3 injection spectrum for a distribution of sources with overdensities of 1, 10, 30 (bottom to top) within 20 Mpc, and otherwise homogeneous.

Blanton, Blasi, Olinto, Astropart.Phys. 15 (2001) 275

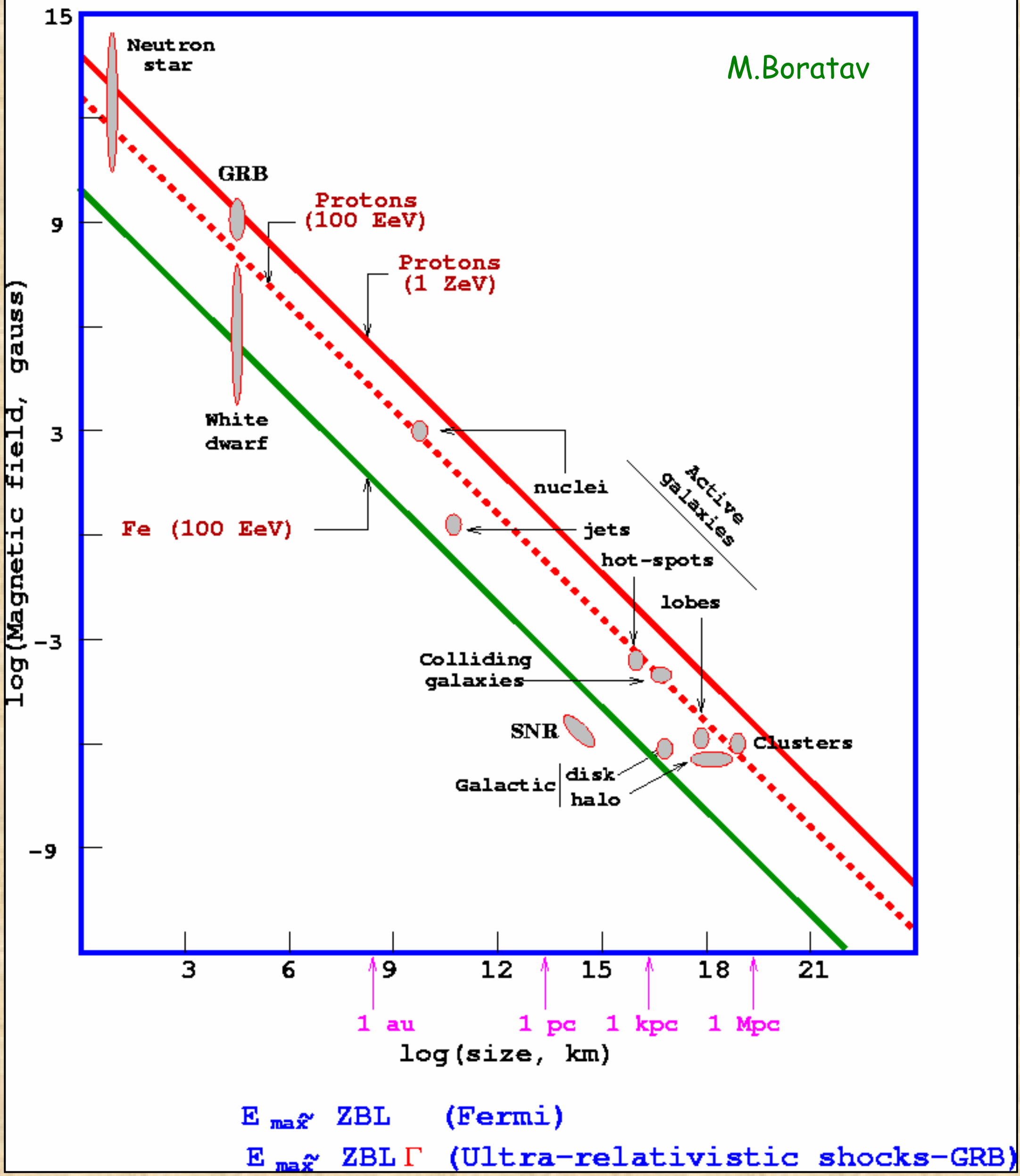
1st Order Fermi Shock Acceleration

The most widely accepted scenario of cosmic ray acceleration

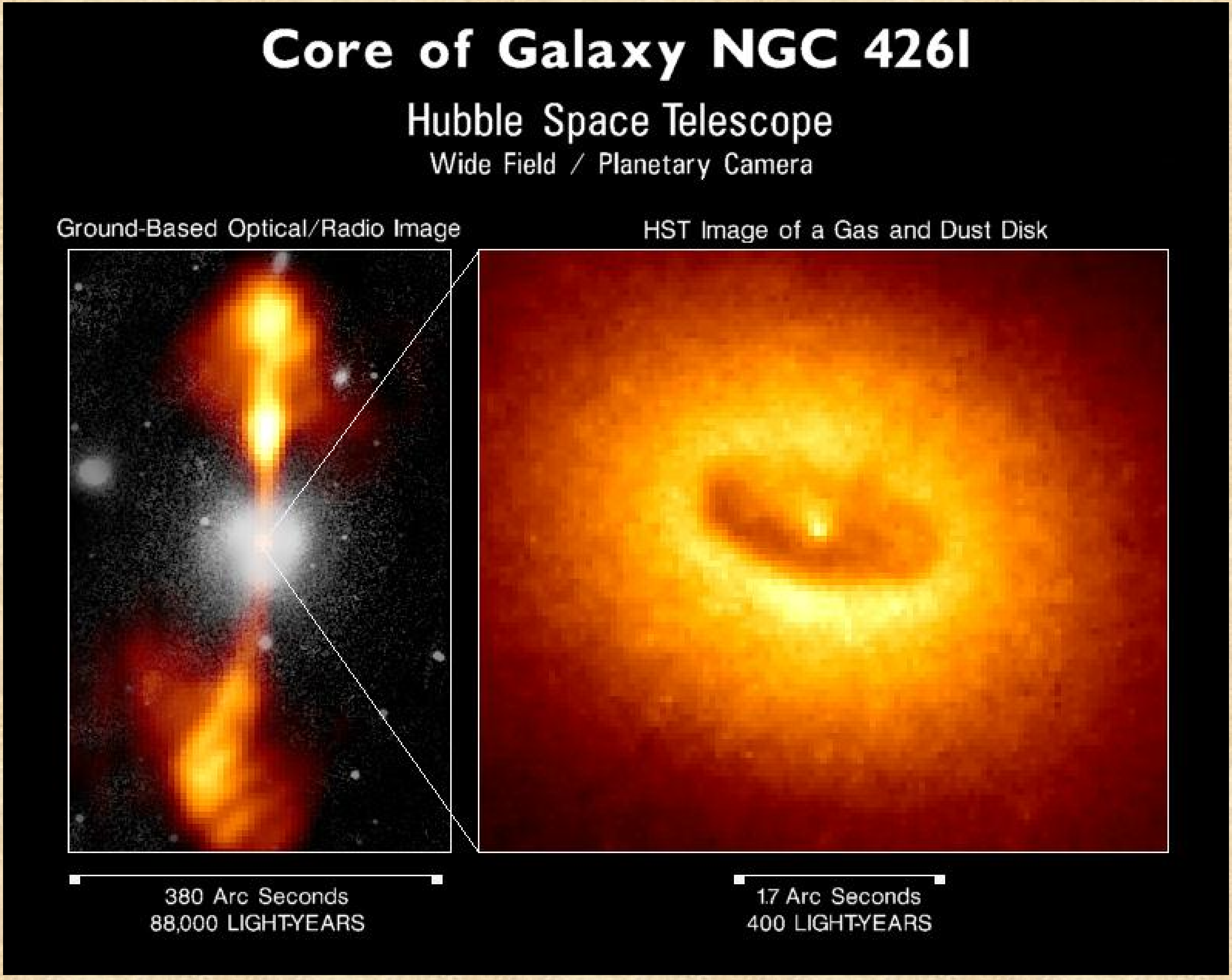


Fractional energy gain per shock crossing $\propto u_1 - u_2$ on a time scale r_L/u_2.
Together with downstream losses this leads to a spectrum E^{-q} with $q > 2$ typically.
When the gyroradius r_L becomes comparable to the shock size L, the spectrum cuts off.

Hillas-plot
(candidate sites for E=100 EeV and E=1 ZeV)

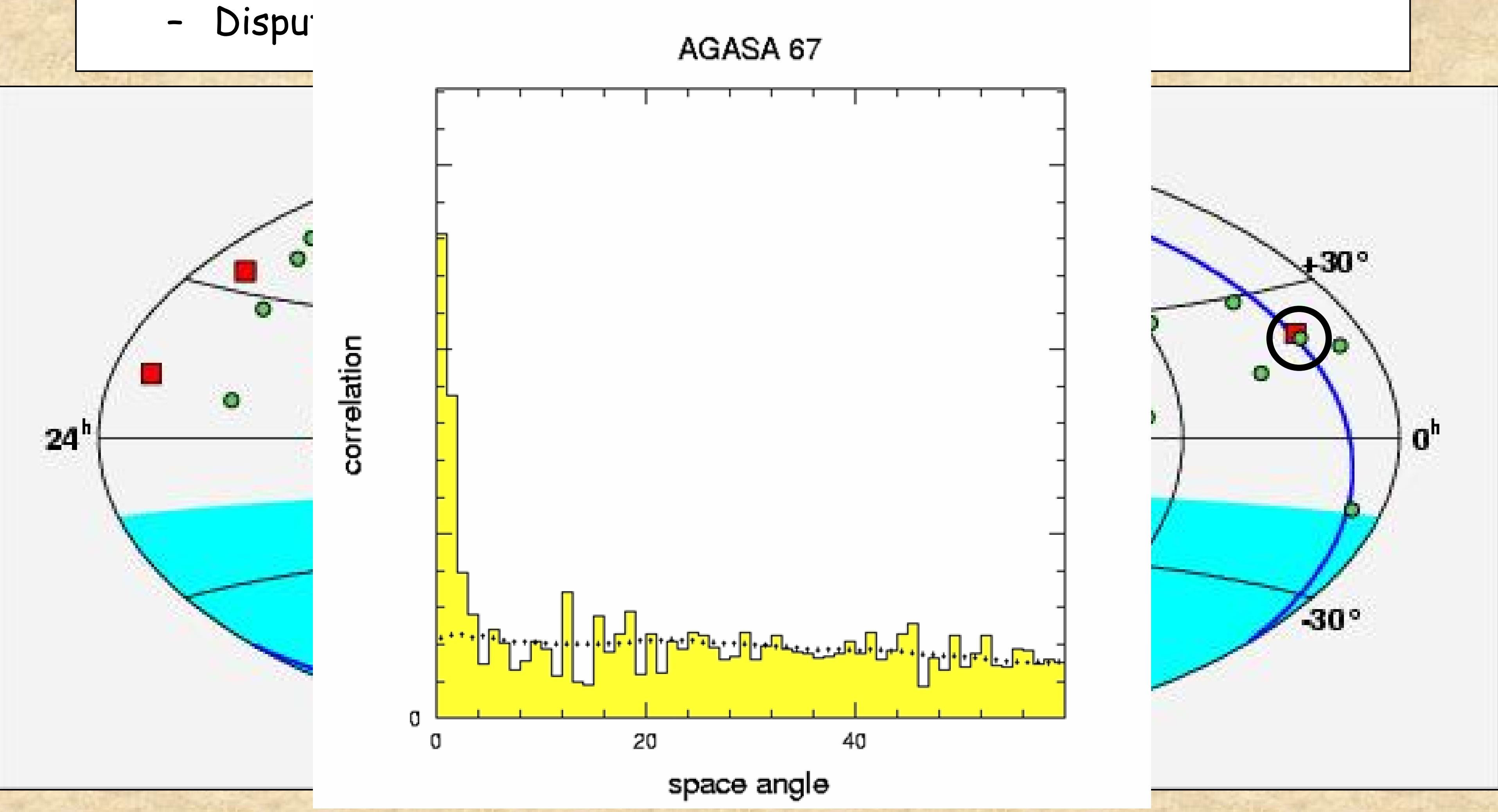


A possible acceleration site associated with shocks in hot spots of active galaxies



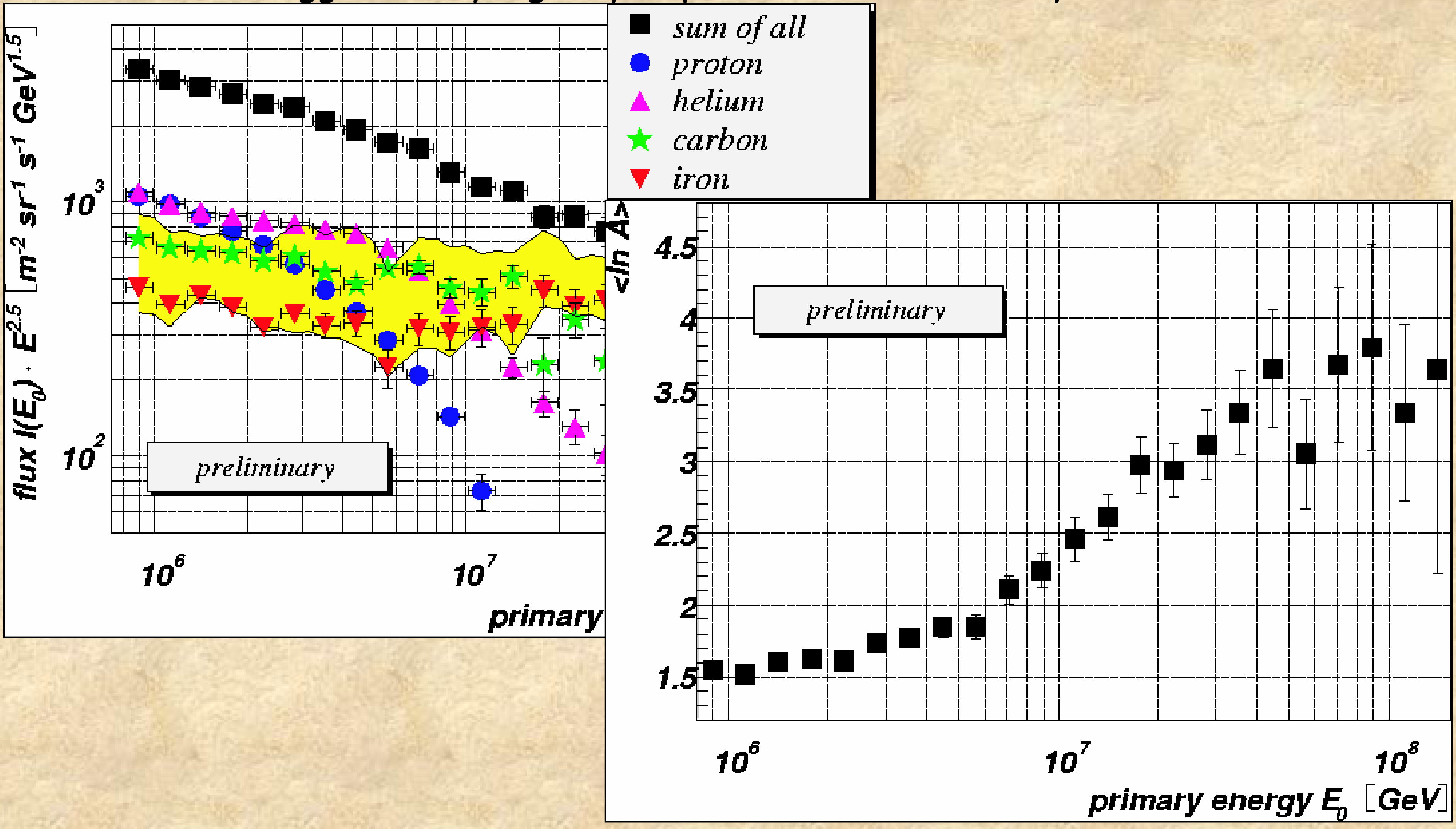
Arrival Direction Distribution >4×10^{19}eV zenith angle <50deg.

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



Ultra-High Energy Cosmic Ray Propagation and Magnetic Fields

1.) The knee is probably a deconfinement effect in the galactic magnetic field as suggested by rigidity dependence measured by KASCADE:



2.) 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:

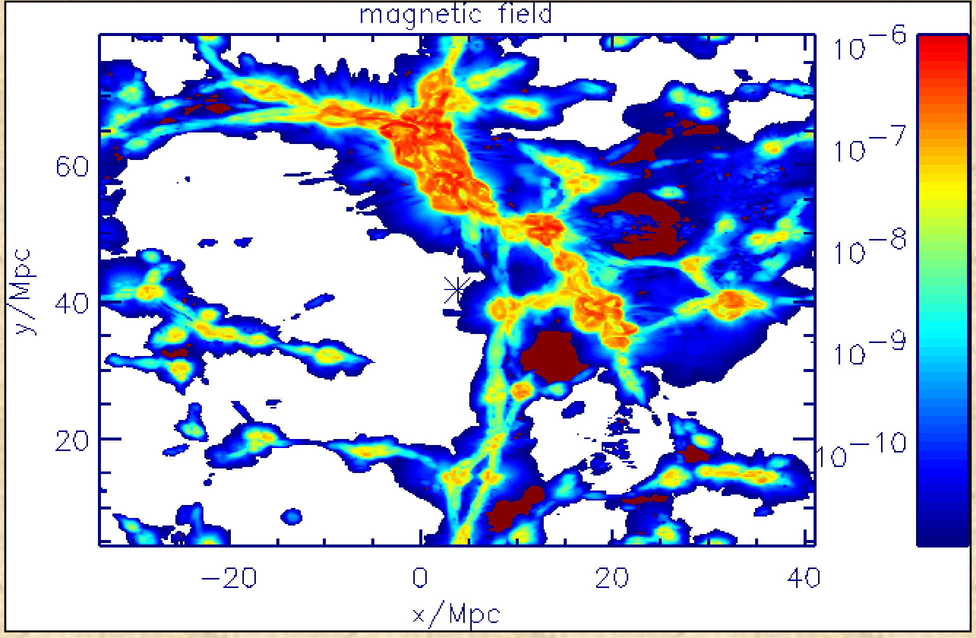
$$E_{\rm c} \cong 4.7\times10^{19}\left(\frac{d}{10\,{\rm Mpc}}\right)^{1/2}\left(\frac{B_{\rm rms}}{10^{-7}\,{\rm G}}\right)\left(\frac{\lambda_{\rm c}}{1\,{\rm Mpc}}\right)^{1/2}\,{\rm eV}$$

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

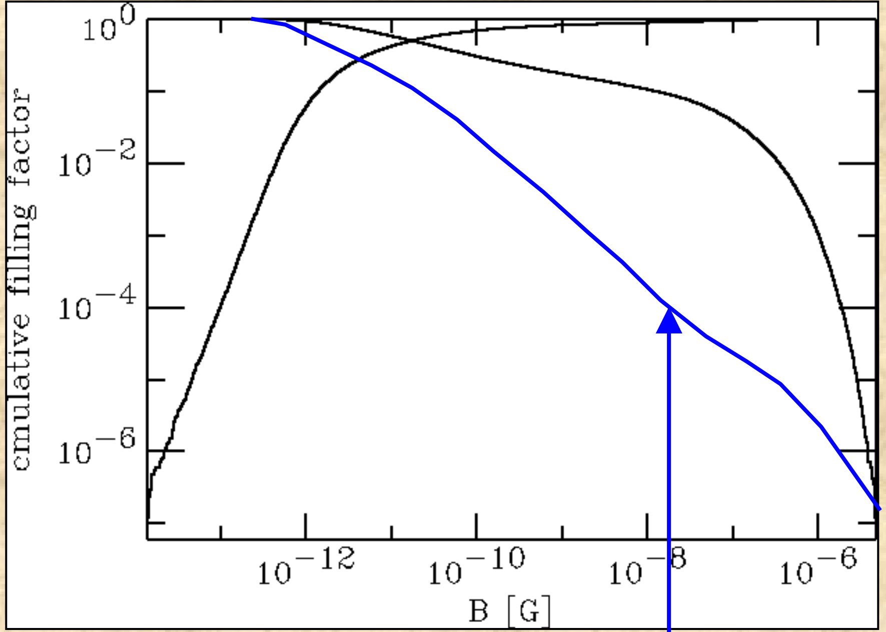
Some results on propagation in structured extragalactic magnetic fields

Scenarios of extragalactic magnetic fields using large scale structure simulations with magnetic fields followed passively and normalized to a few micro Gauss in galaxy clusters.

Sources of density ~10^{-5} Mpc^{-3} follow baryon density, field at Earth ~10^{-11} G.



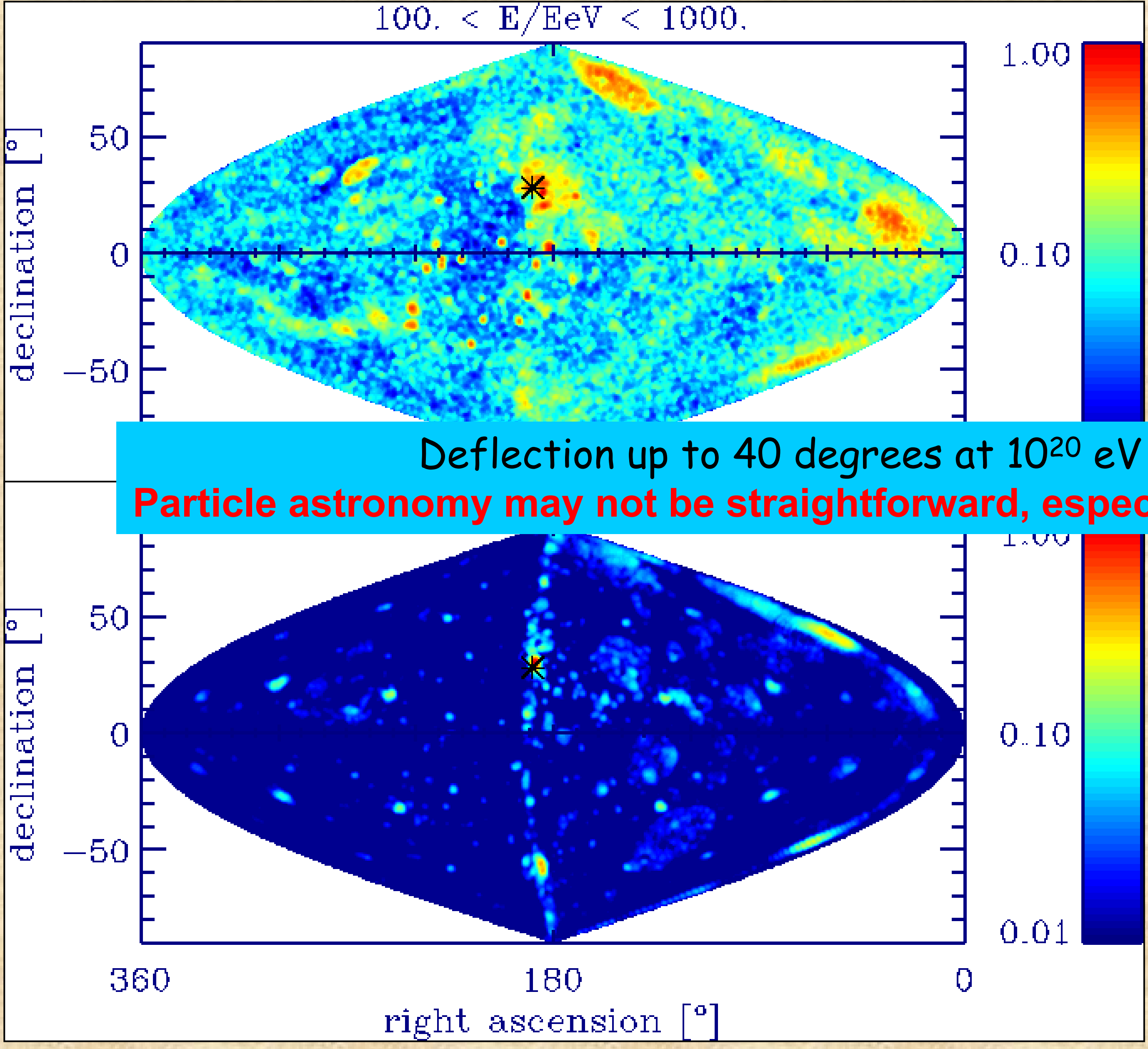
Magnetic field filling factors



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

Sigl, Miniati, Ensslin, Phys.Rev.D 68 (2003) 043002; astro-ph/0309695; PRD 70 (2004) 043007.

The simulated sky above 10^{20} eV with structured sources of density 2.4×10^{-5} Mpc^{-3} : ~2×10^{5} simulated trajectories above 10^{20} eV .



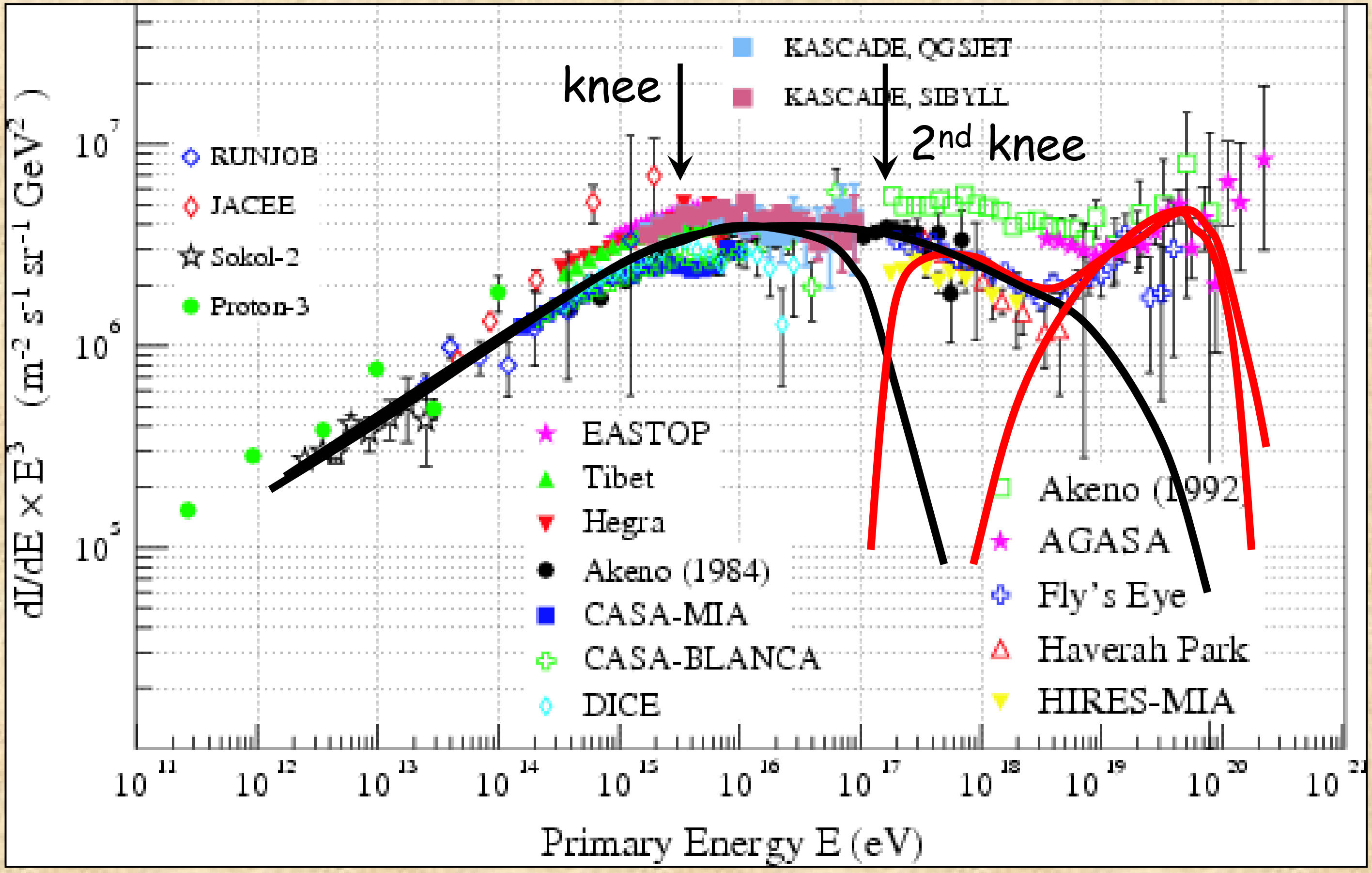
With field

Without field

Deflection up to 40 degrees at 10^{20} eV !

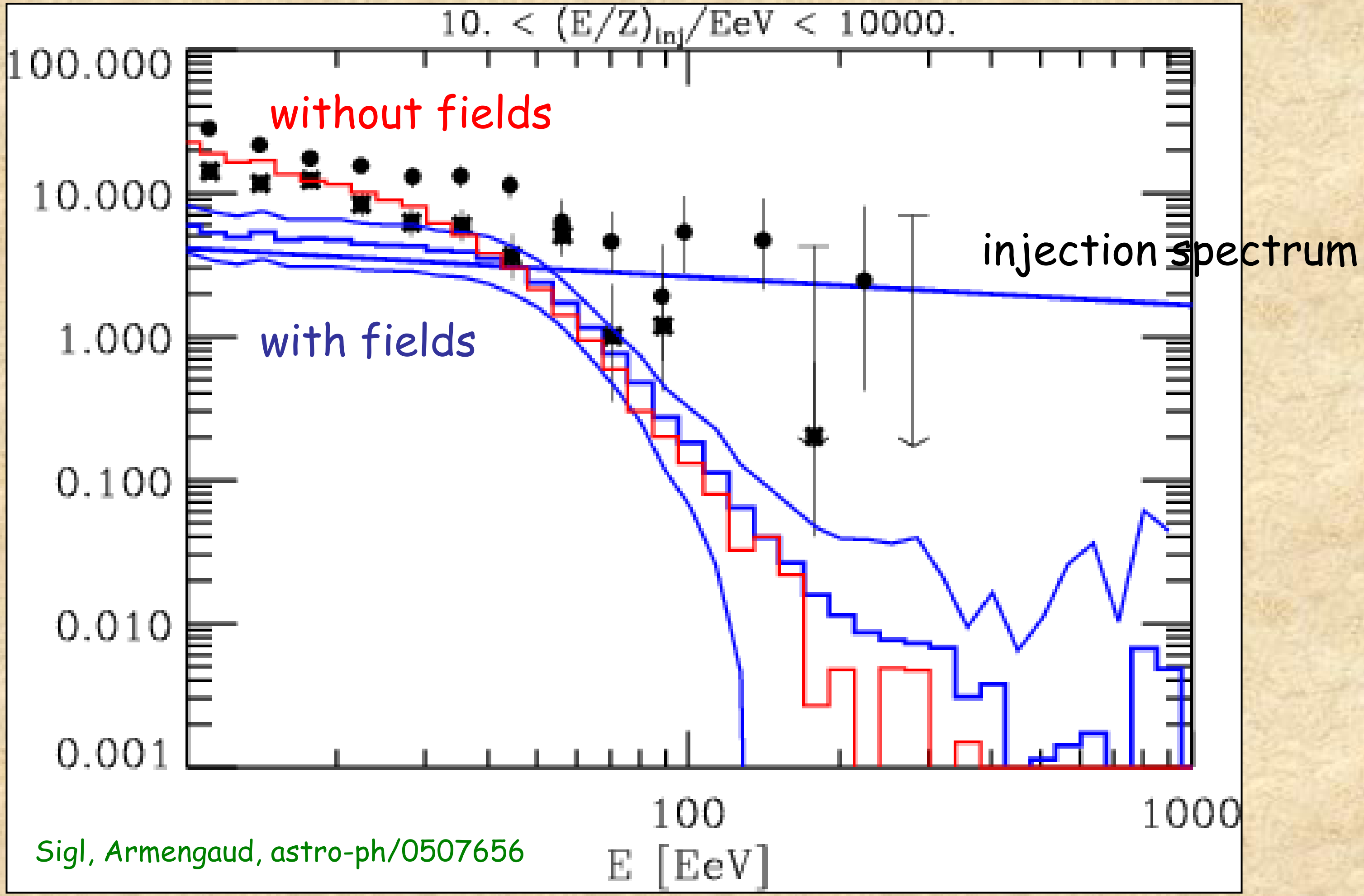
Particle astronomy may not be straightforward, especially for nuclei !

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.



Sigl, Armengaud, astro-ph/0507656

Injection of mixed composition (solar metallicity) with spectrum $E^{-2.2}$ and a source density ~ 10^{-5} Mpc^{-3}.

Conclusion: In the absence of fields too hard an injection spectrum is necessary to fit flux around the ankle and too many nuclei are predicted at the ankle (Allard et al., astro-ph/0505566).

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

accelerated protons interact:

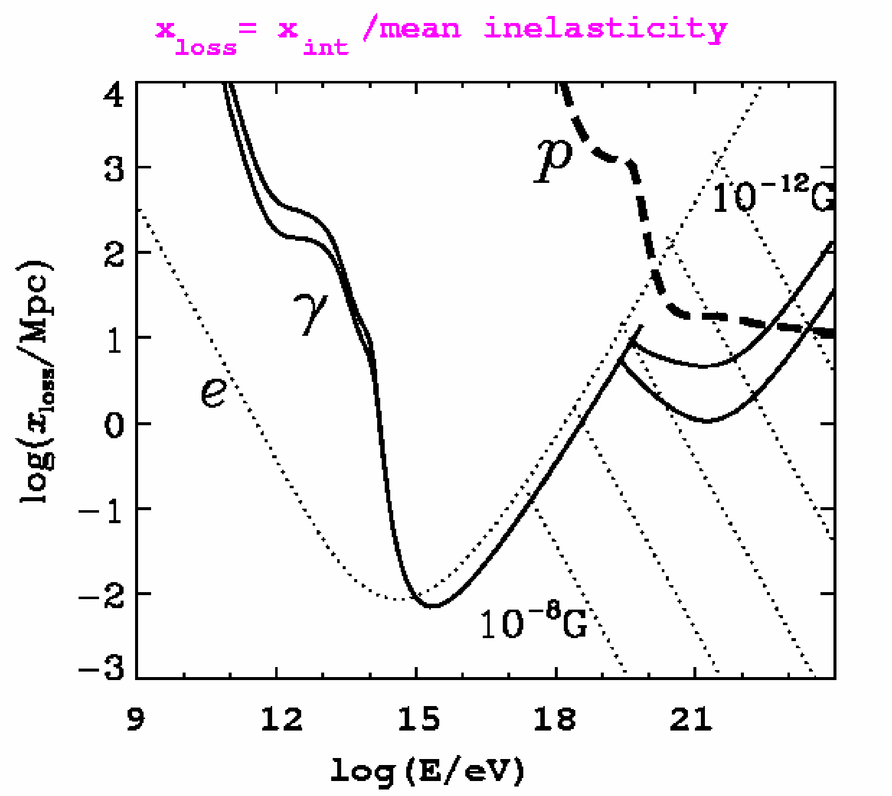
$$p + \begin{array}{c} N \\ \gamma \end{array} \rightarrow X + \left.\begin{array}{l} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{0} \rightarrow \gamma-\text{rays} \end{array}\right\}$$

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.



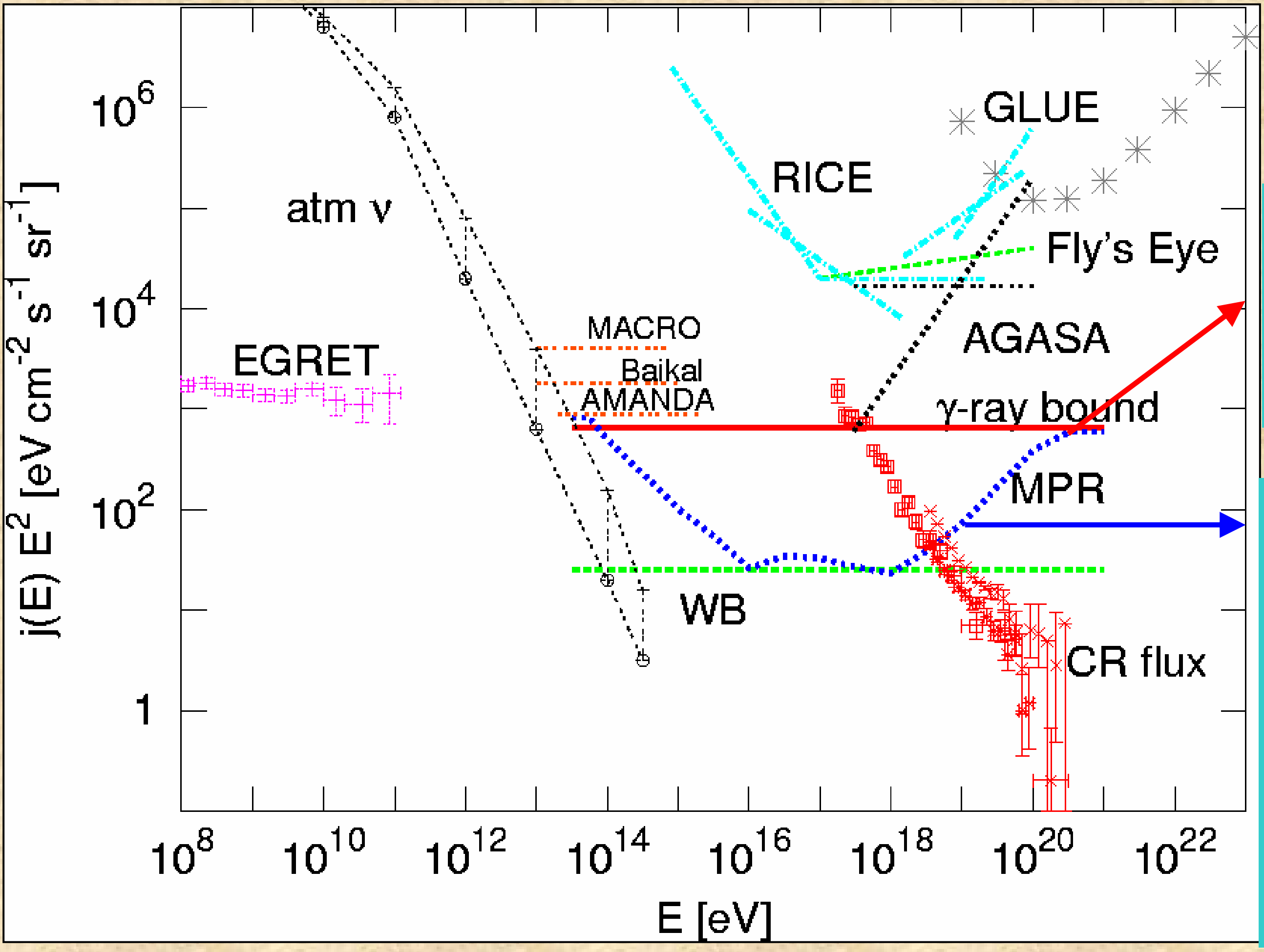
Included processes:

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

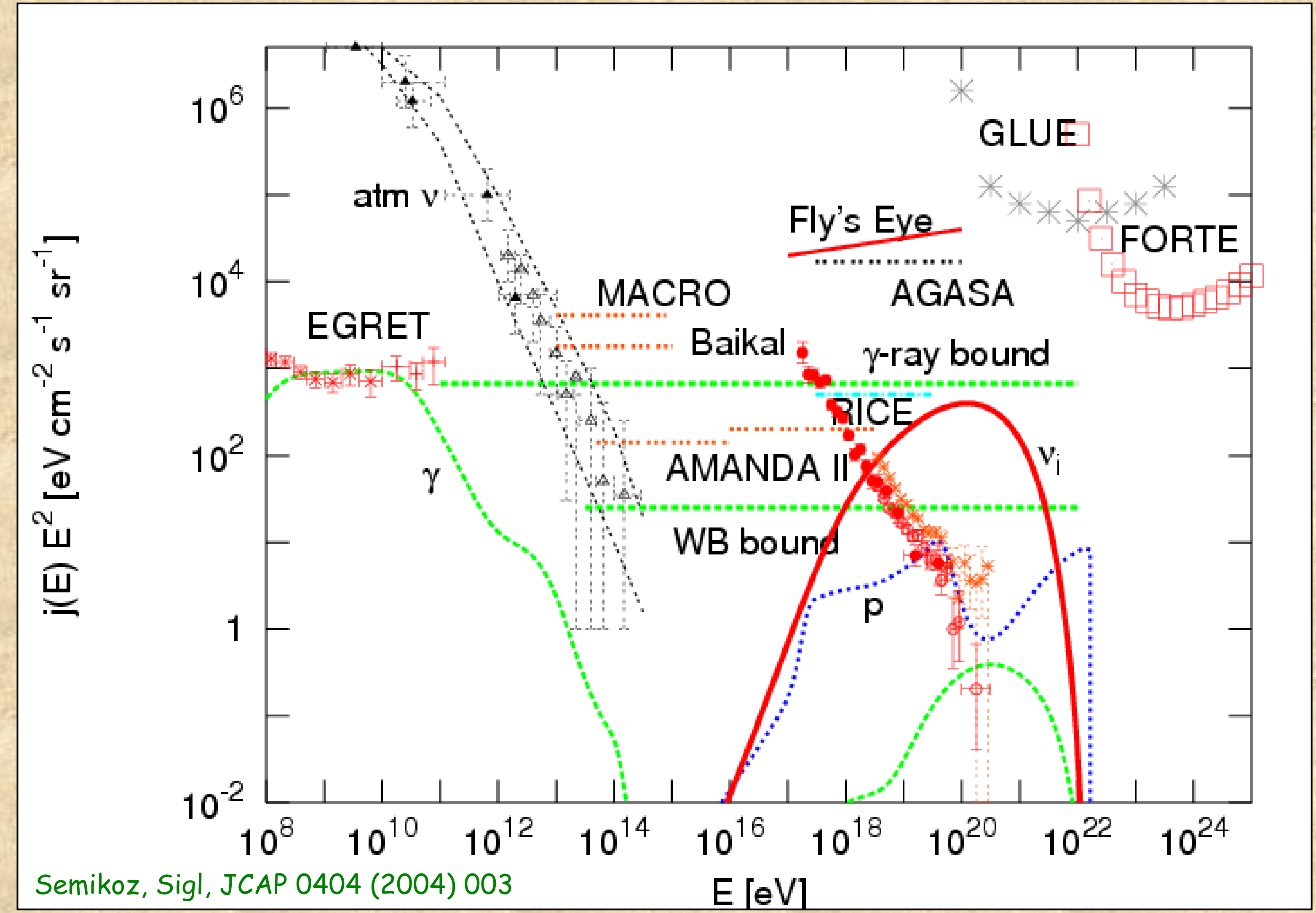
Total injected electromagnetic energy is constrained by the diffuse γ-ray flux measured by EGRET in the MeV – 100 GeV regime



Neutrino flux upper limit for opaque sources determined by EGRET bound

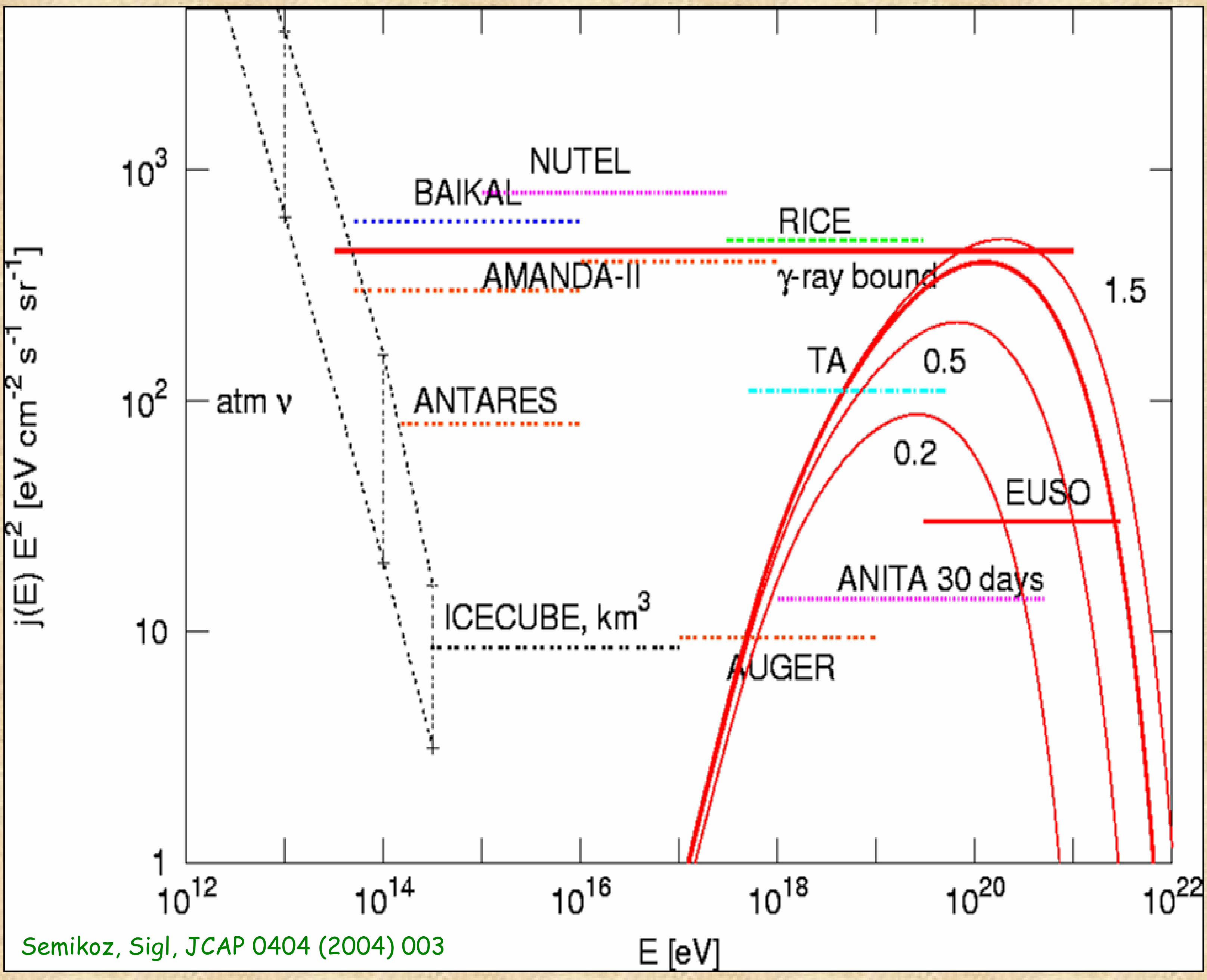
Neutrino flux upper limit for transparent sources more strongly constrained by primary cosmic ray flux at 10^{18} – 10^{19} eV (Waxman-Bahcall; Mannheim-Protheroe-Rachen)

Example: diffuse sources injecting E^{1} proton spectrum extending up to $2\text{x}10^{22}$ eV with $(1+z)^3$ up to redshift z=2. Shown are primary proton flux together with secondary γ-ray and neutrino fluxes.



Semikoz, Sigl, JCAP 0404 (2004) 003

Future neutrino flux sensitivities



Semikoz, Sigl, JCAP 0404 (2004) 003

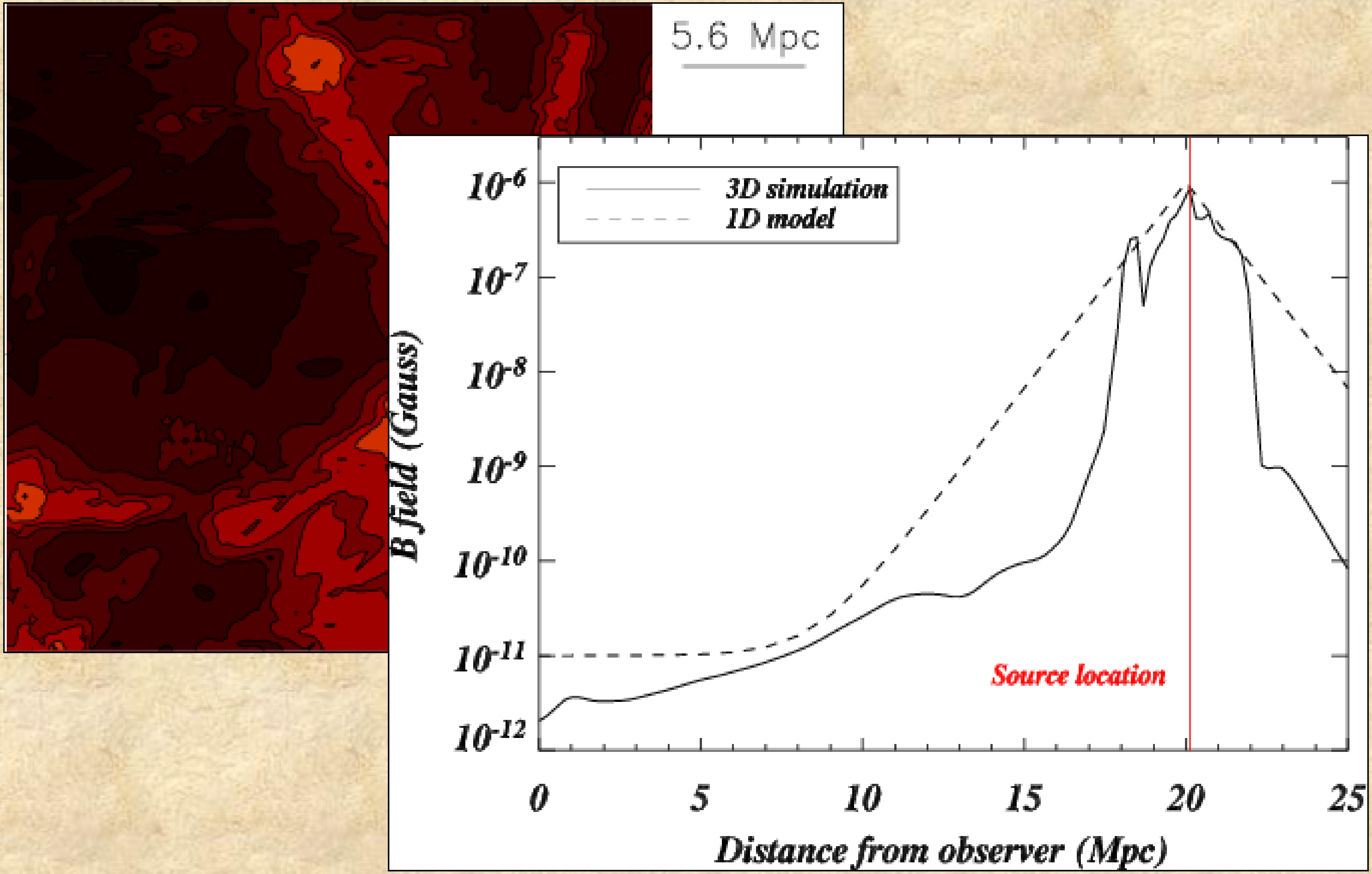
Putting Everything Together: Cosmic Rays, Gamma-Rays, Neutrinos, Magnetic Fields

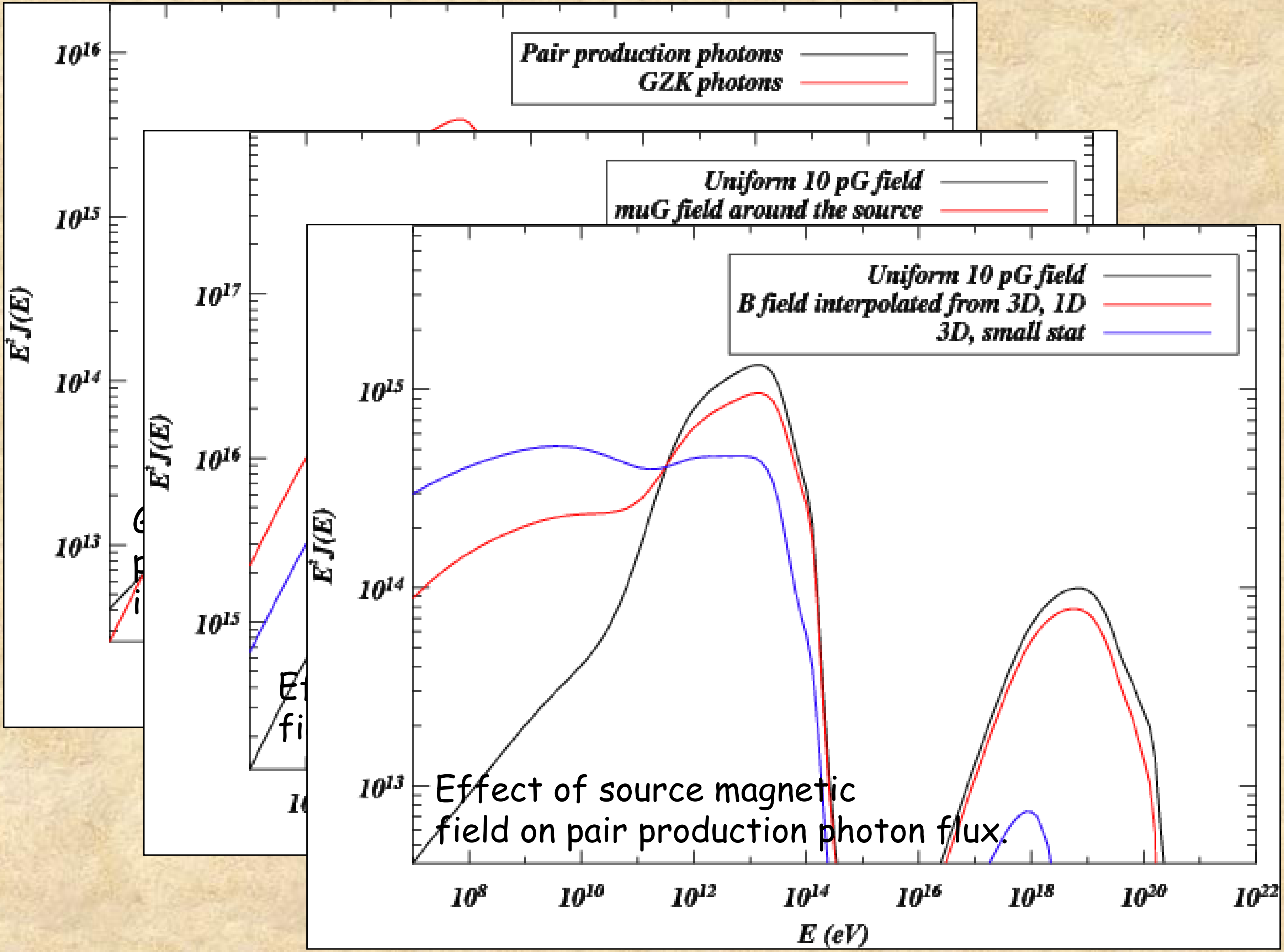
Various connections:
Magnetic fields influence propagation path lengths. This influences:

photo-spallation and thus observable composition, interpretation of ankle

production of secondary gamma-rays and neutrinos, thus detectability of their fluxes and identification of source mechanisms and locations.

Example: Source in a magnetized galaxy cluster at 20 Mpc, injecting protons with an $E^{-2.3}$ spectrum

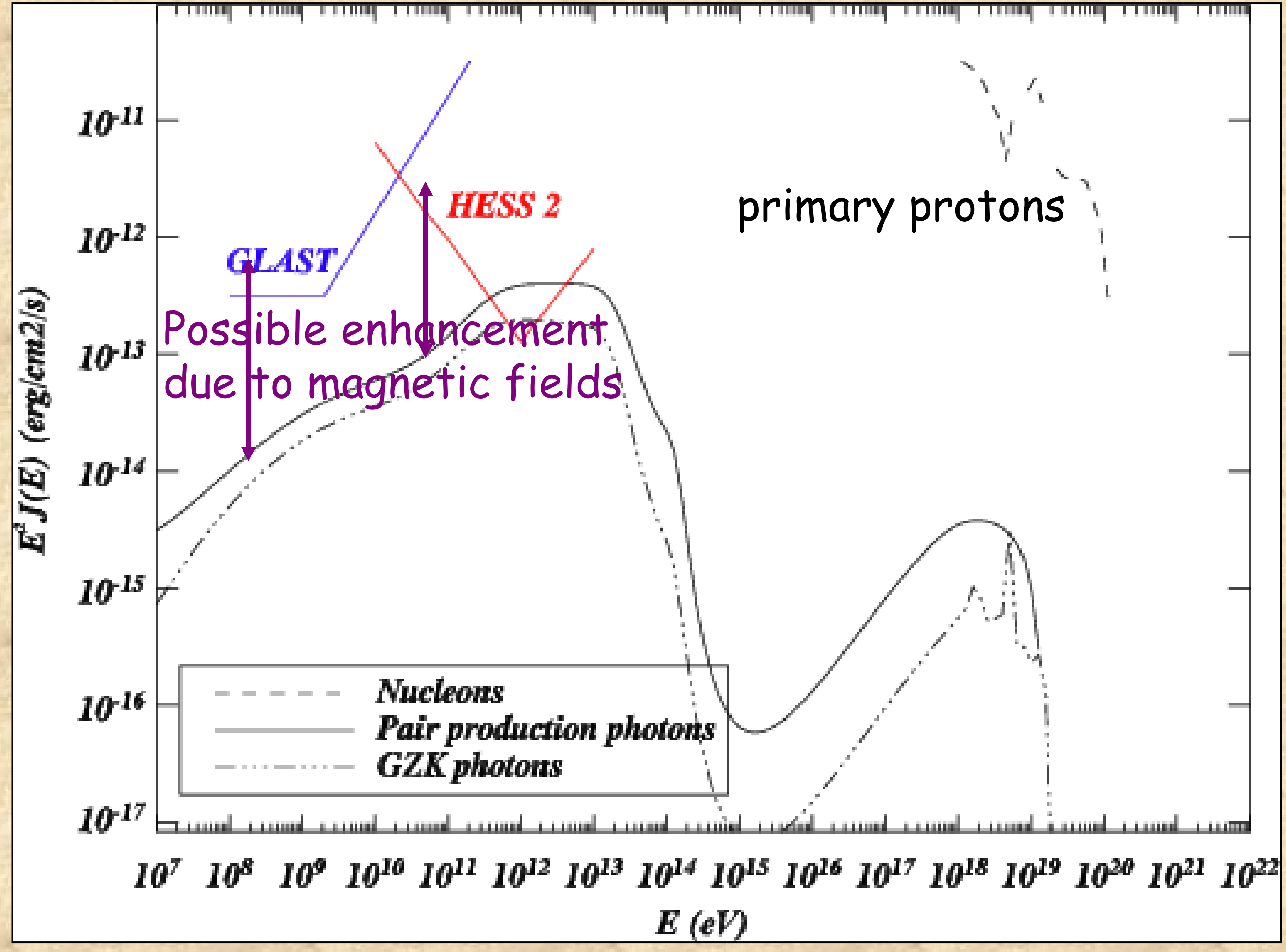




Effect of source magnetic field on pair production photon flux.

This is quite relevant for γ-ray astronomy in the GeV-TeV band

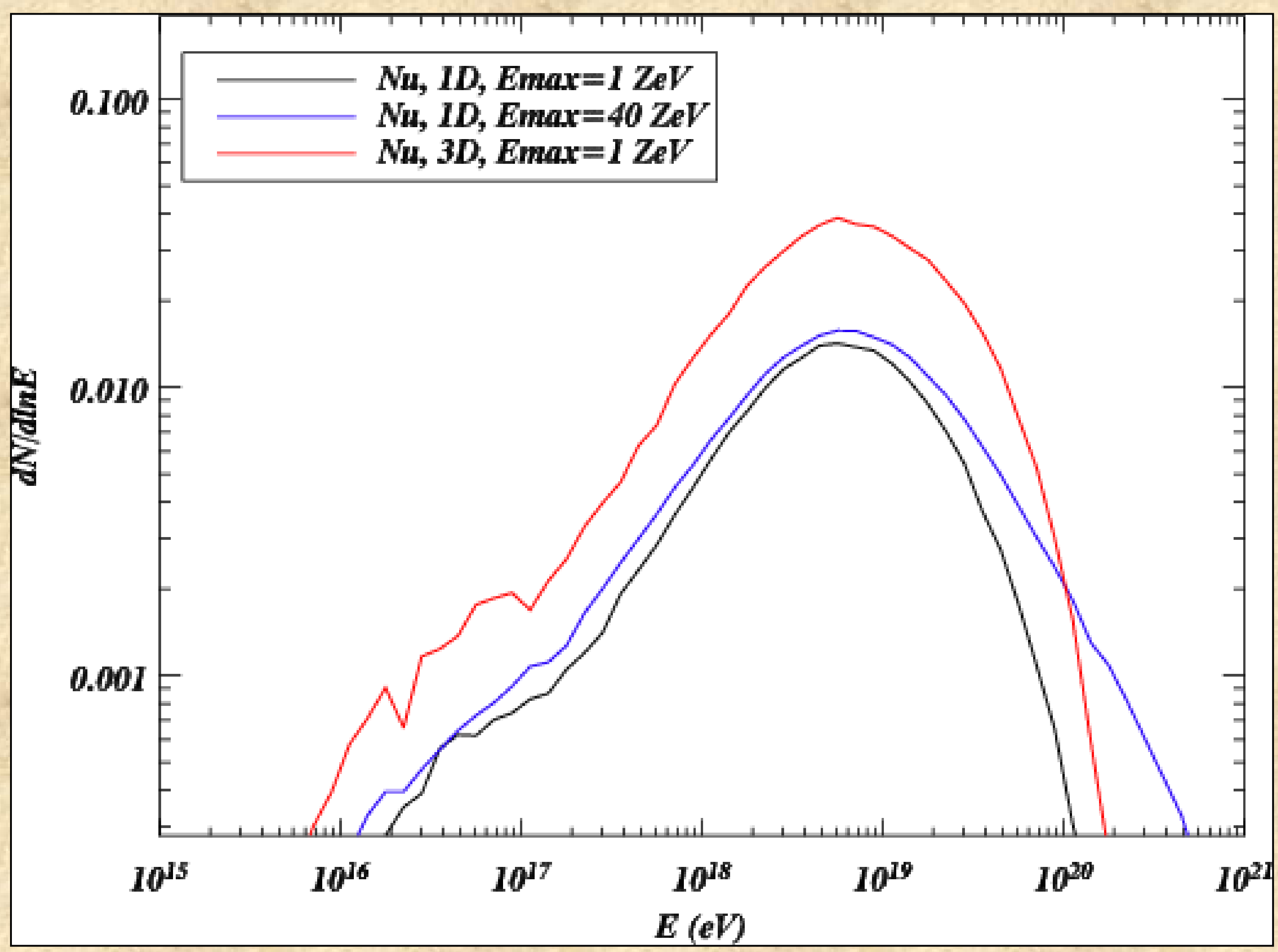
d=100 Mpc, no magnetic field, $E^{-2.7}$ injection spectrum



primary protons

Possible enhancement due to magnetic fields

The GZK neutrino flux can also be enhanced by magnetic fields



Conclusions

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.) Sources are likely immersed in (poorly known) 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.

3.) Future data (auto-correlation) will test source magnetization. Deflection angles are currently hard to quantify.

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.