High Energy Cosmic Rays, Gamma-Rays and Neutrinos

- (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.

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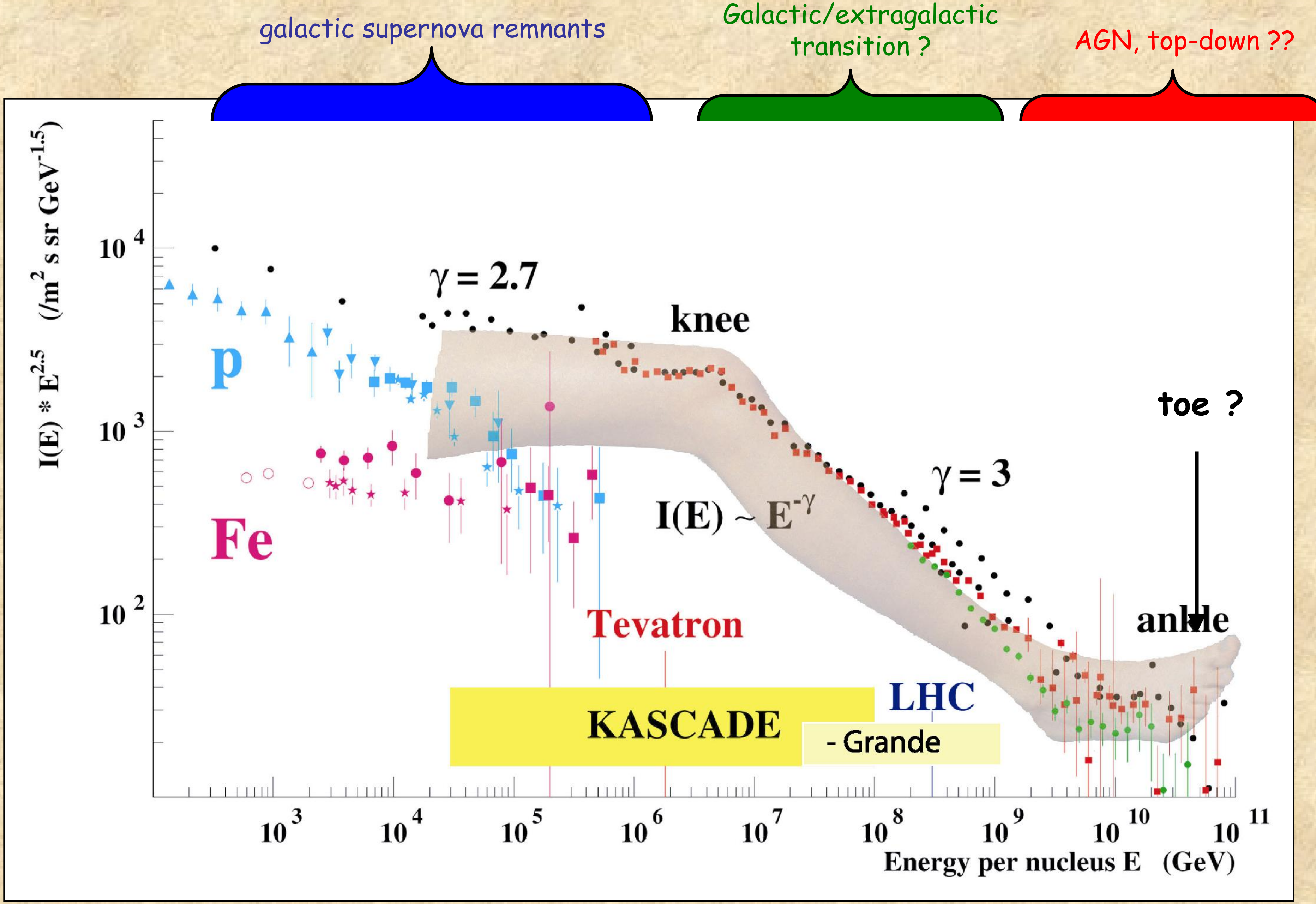
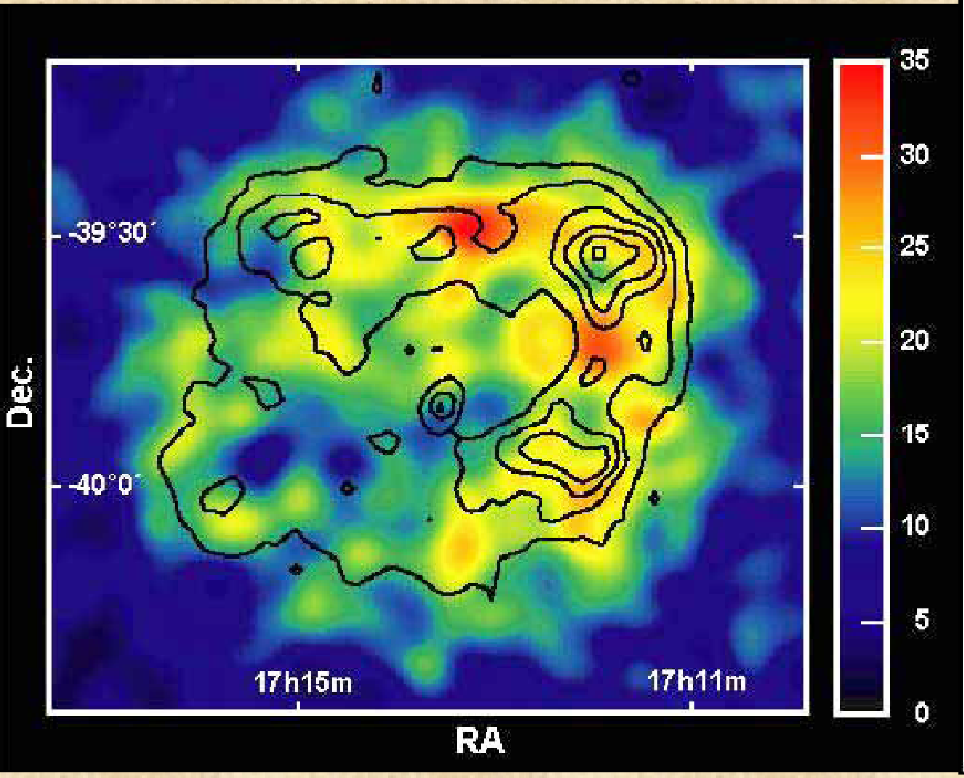
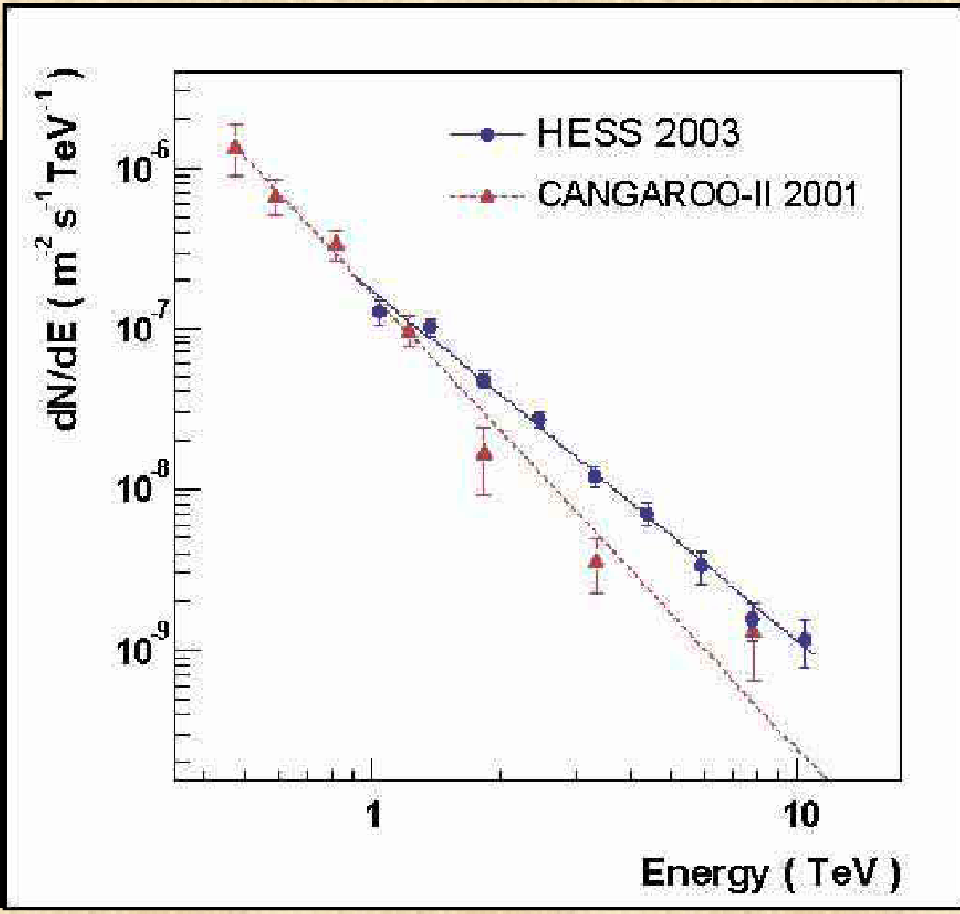
http://www2.iap.fr/users/sigl/homepage.html

The structure of the spectrum and scenarios of its origin



Supernova Remnants and Galactic Cosmic and γ-Rays

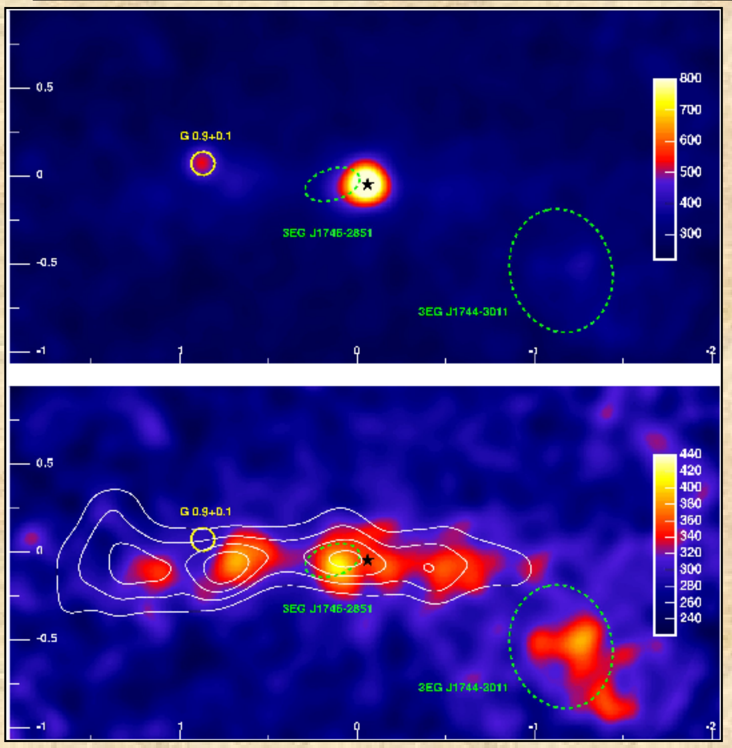




Aharonian et al., Nature 432 (2004) 75

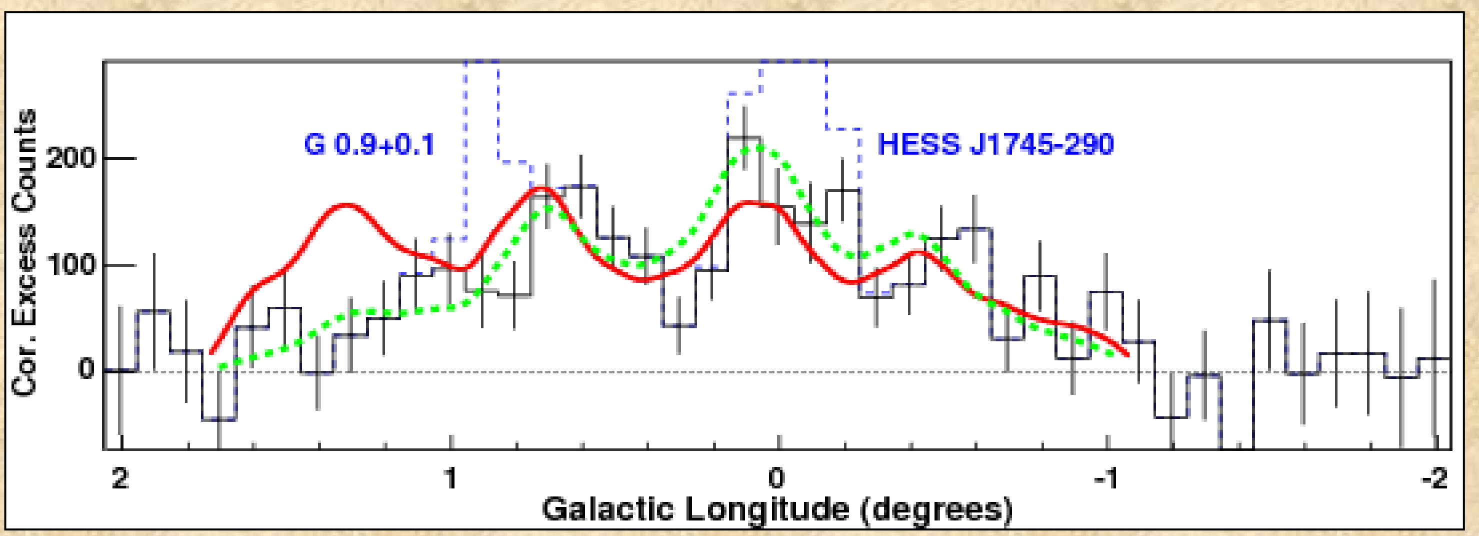
Supernova remnants have been seen by HESS in γ-rays: The remnant RXJ1713-3946 has a spectrum ~$E^{-2.2}$: => Charged particles have been accelerated to > 100 TeV. Also seen in 1-3 keV X-rays (contour lines from ASCA)

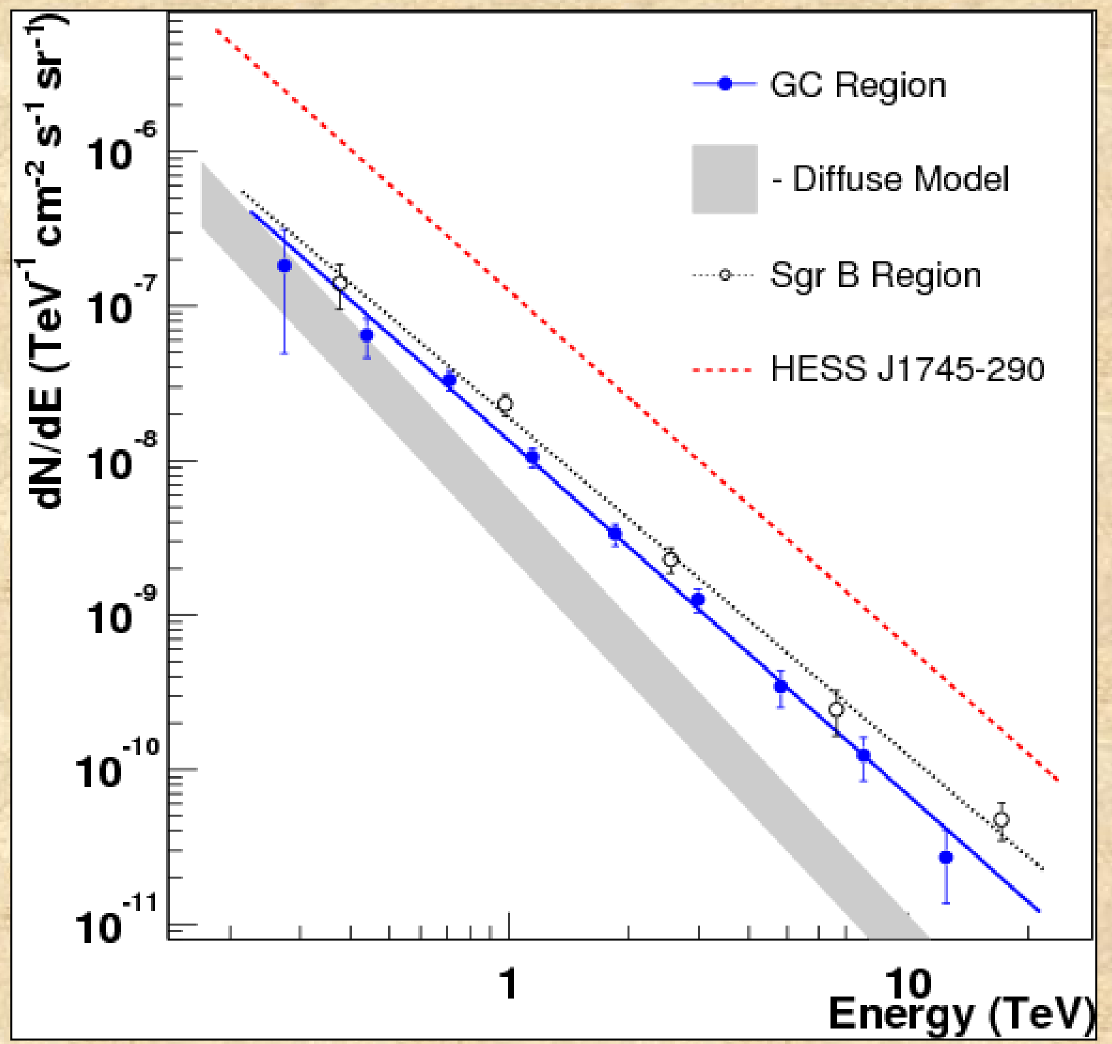
Hadronic Interactions and Galactic Cosmic and γ-Rays



HESS has observed γ-rays from objects around the galactic centre which correlate well with the gas density in molecular clouds for a cosmic ray diffusion time of $T \sim R^2/D \sim 3\times10^3\,(\theta/1^o)^2/\eta$ years where $D = \eta\, 10^{30}\ \mathrm{cm^2/s}$ is the diffusion coefficient for protons of a few TeV.

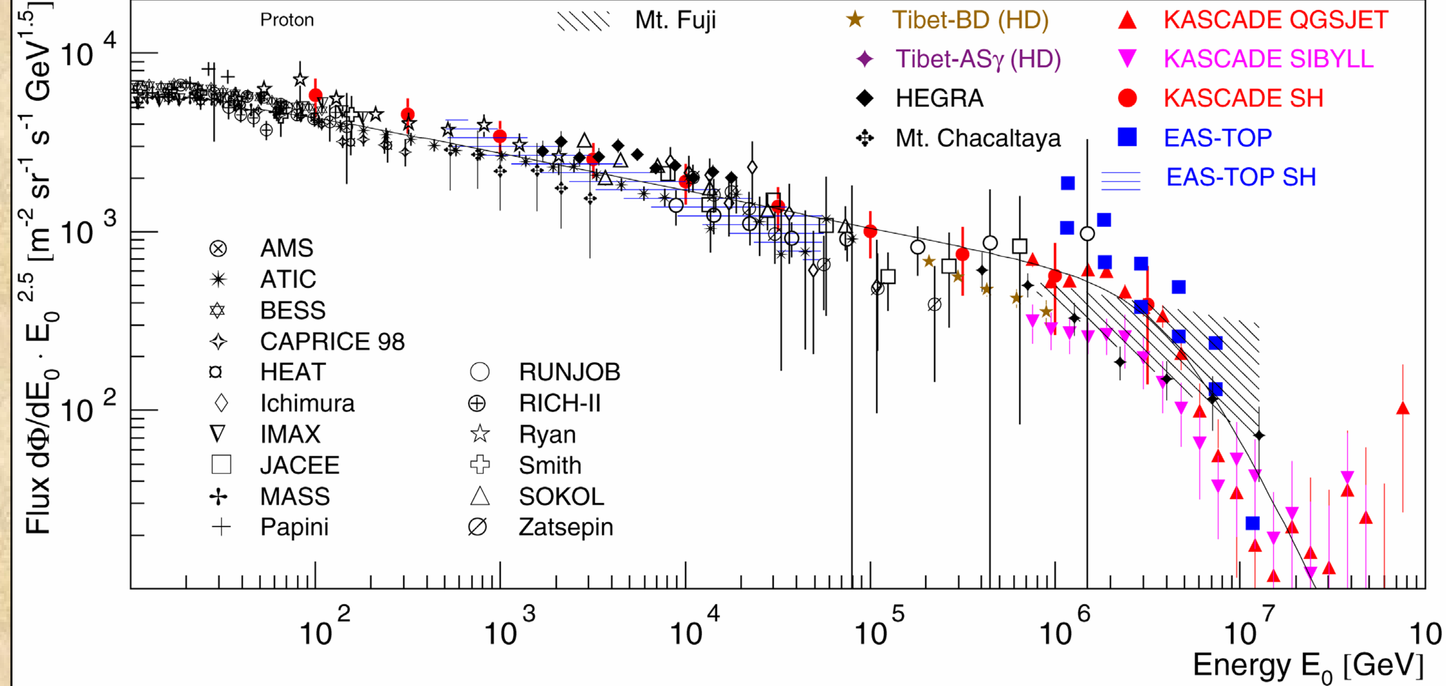
Aharonian et al., Nature 439 (2006) 695

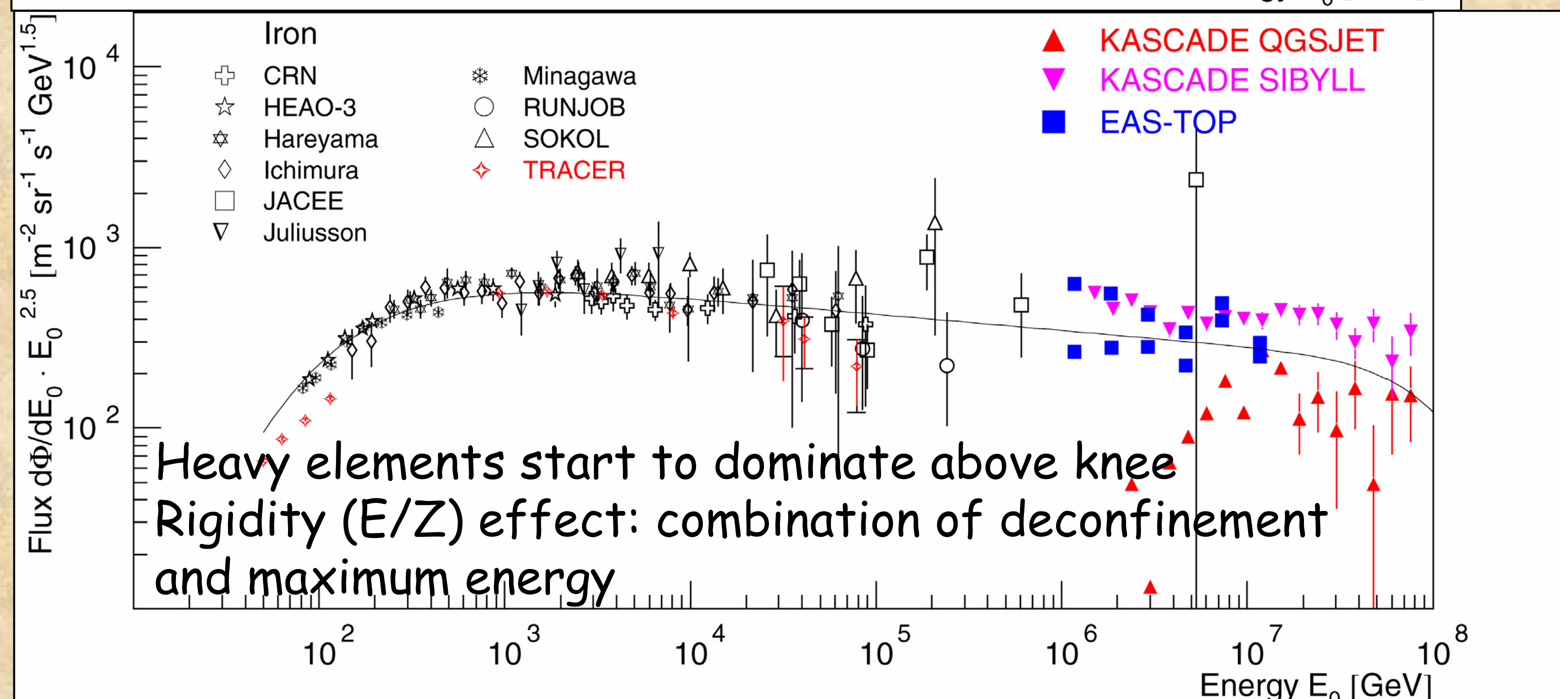




Given the observed spectrum $E^{-2.3}$, this can be interpreted as photons from π^0 decay produced in pp interactions where the TeV protons have the same spectrum and could have been produced in a SN event.

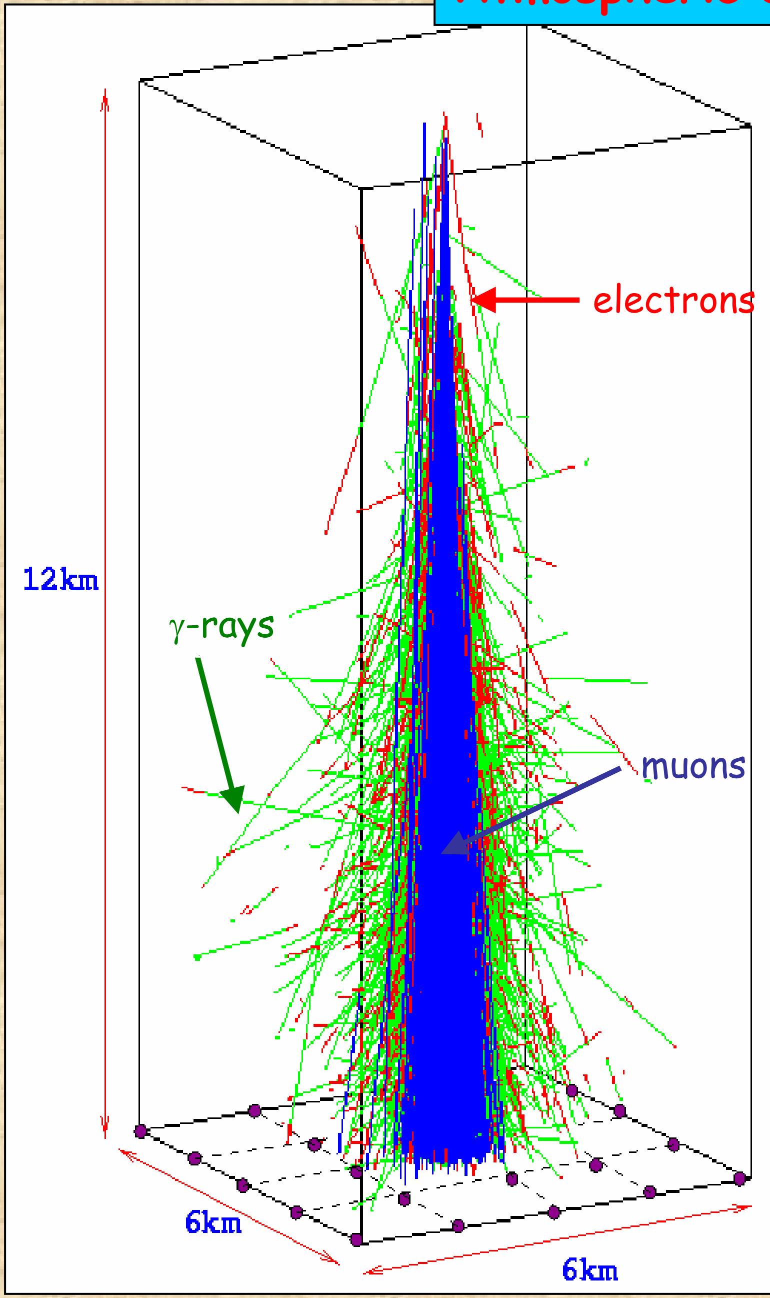
Note that this is consistent with the source spectrum both expected from shock acceleration theory and from the cosmic ray spectrum observed in the solar neighborhood, $E^{-2.7}$, corrected for diffusion in the galactic magnetic field, $j(E) \sim Q(E)\tau_{conf}(E) \sim Q(E)/D(E)$.

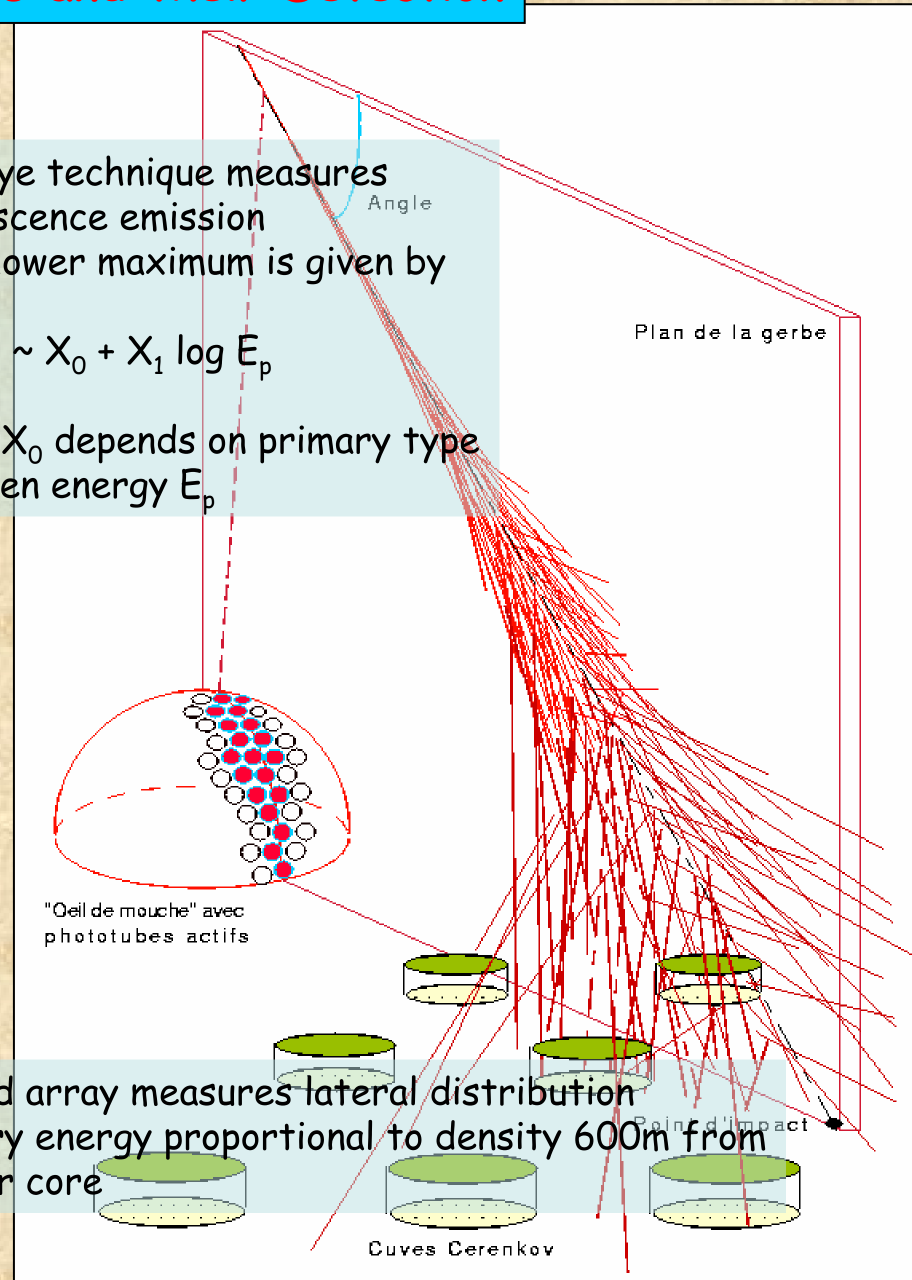




Heavy elements start to dominate above knee
Rigidity (E/Z) effect: combination of deconfinement and maximum energy

Atmospheric Showers and their Detection



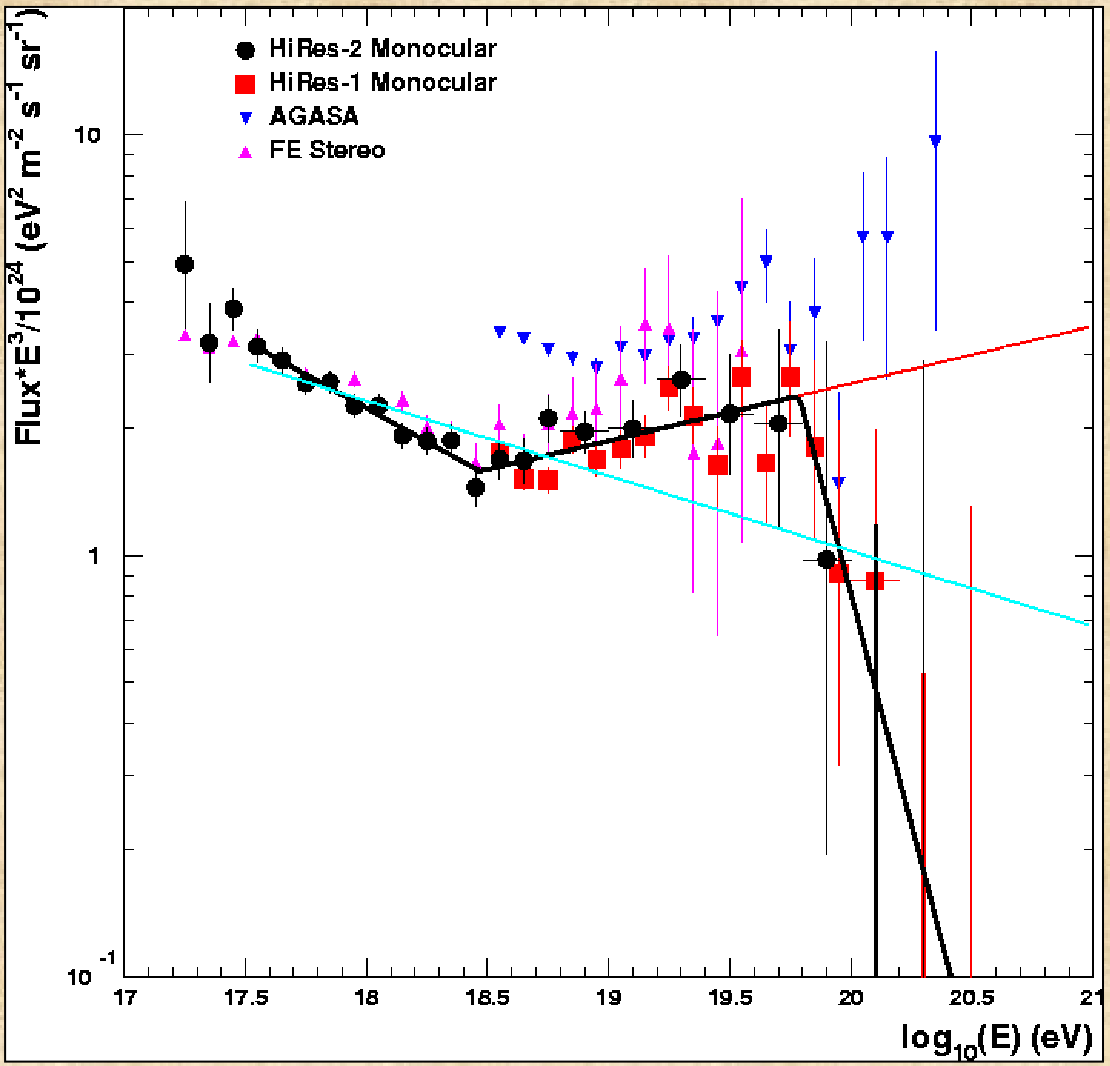


Fly's Eye technique measures fluorescence emission
The shower maximum is given by

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

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



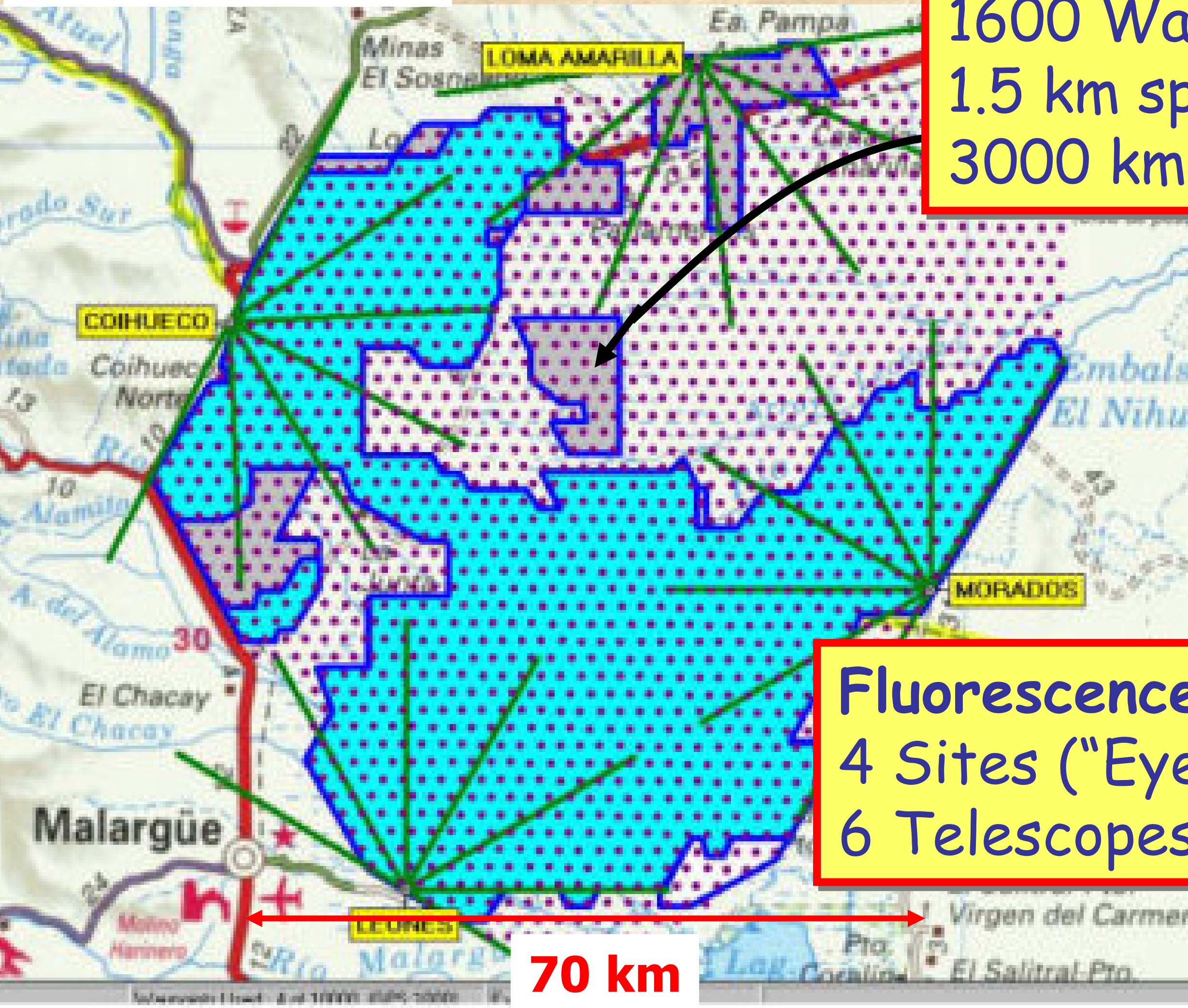
Lowering the AGASA energy scale by about 20% brings it in accordance with HiRes up to the GZK cut-off, but not beyond.

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

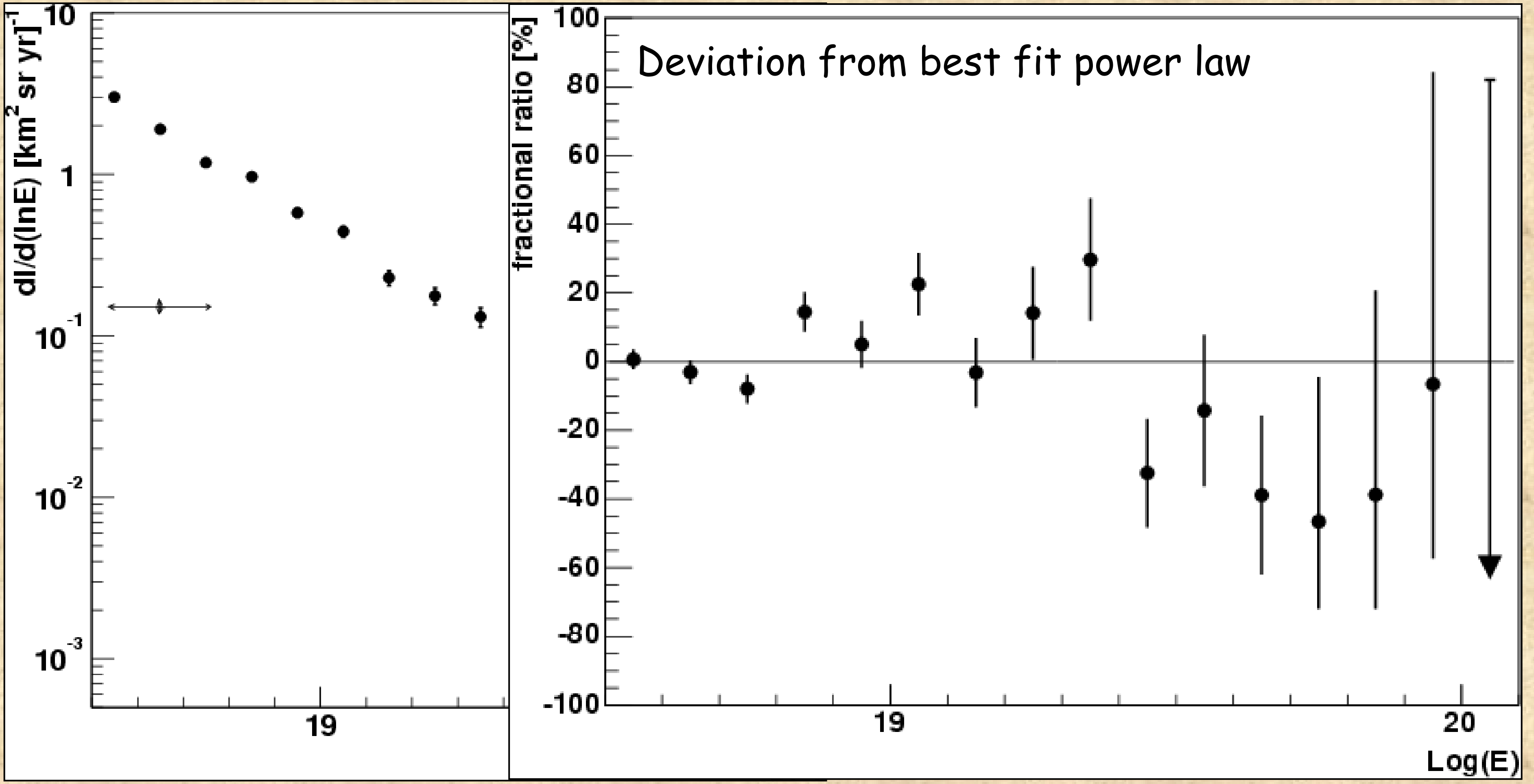


Surface Array (SD):
1600 Water Tanks
1.5 km spacing
3000 km²

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

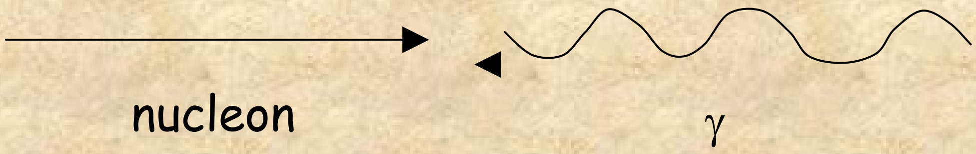
1.) electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 50 Mpc.

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

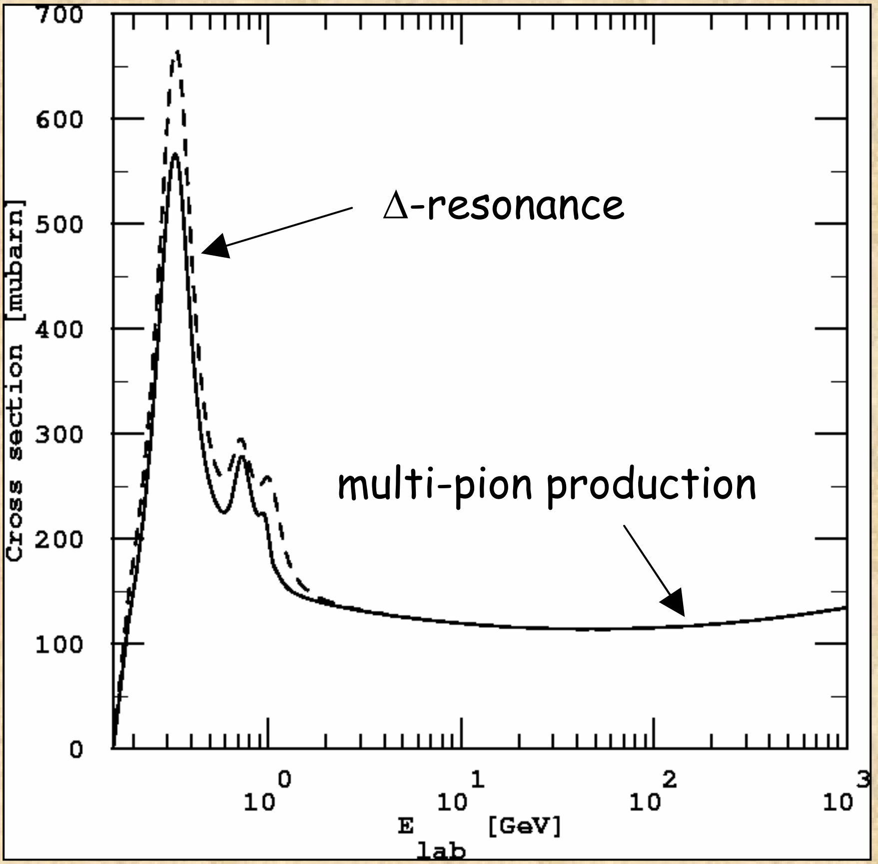
3.) The observed distribution seems to be very isotropic (except for a possible interesting small scale clustering)

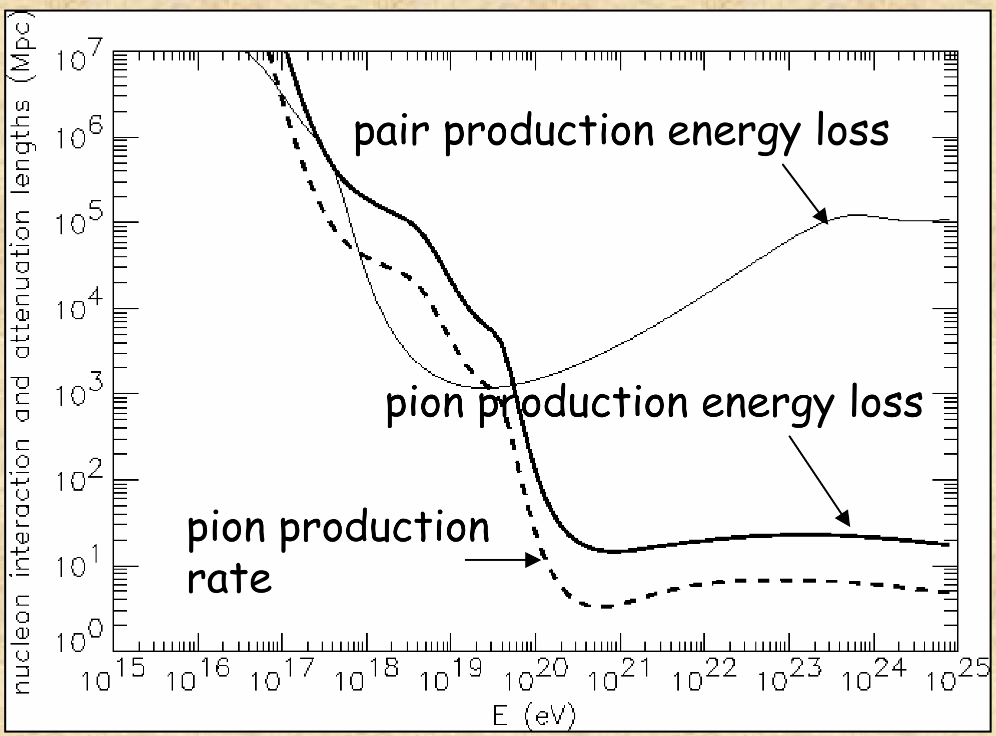
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



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

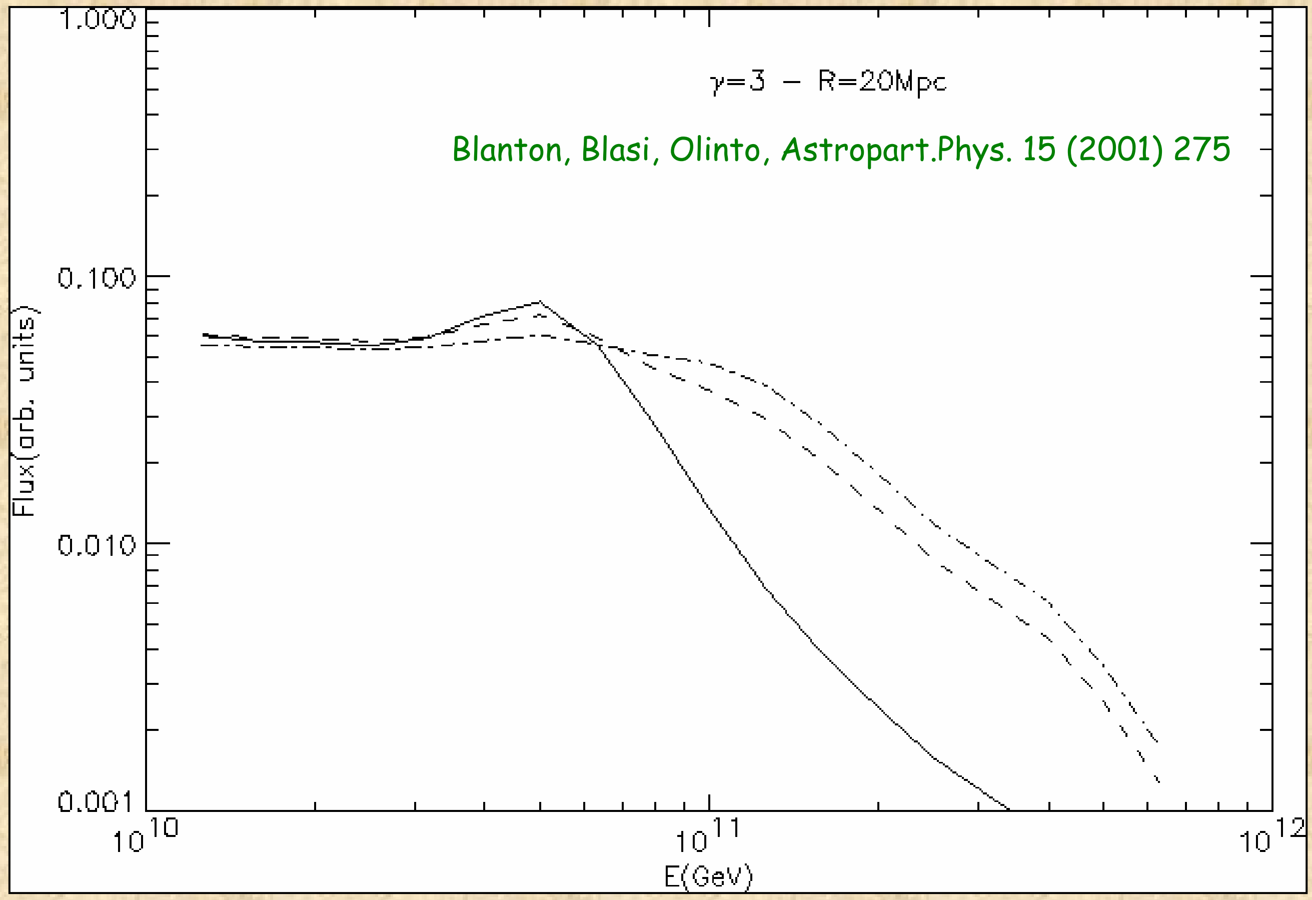




⇒sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma > 10^{11}$ could avoid this conclusion.

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

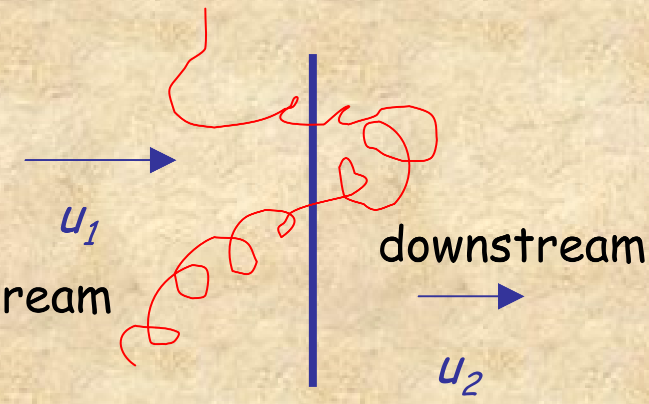
The GZK effect may tell us about the source distribution (in the absence of strong magnetic deflection)

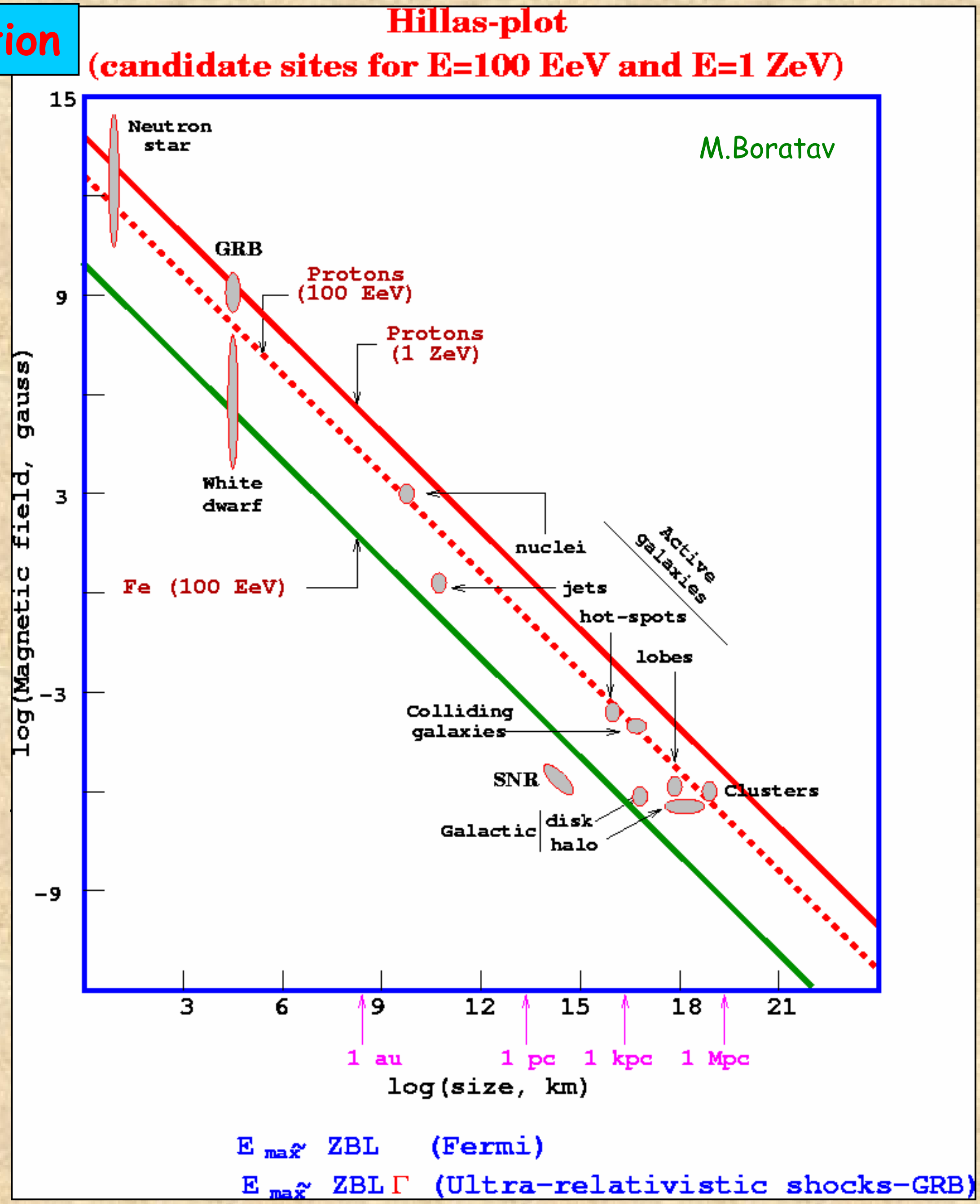


Observable spectrum for an E^{3} injection spectrum for a distribution of sources with overdensities of 1, 10, 30 (bottom to top) within 20 Mpc, and otherwise homogeneous.

1st Order Fermi Shock Acceleration

The most widely accepted scenario of cosmic ray acceleration



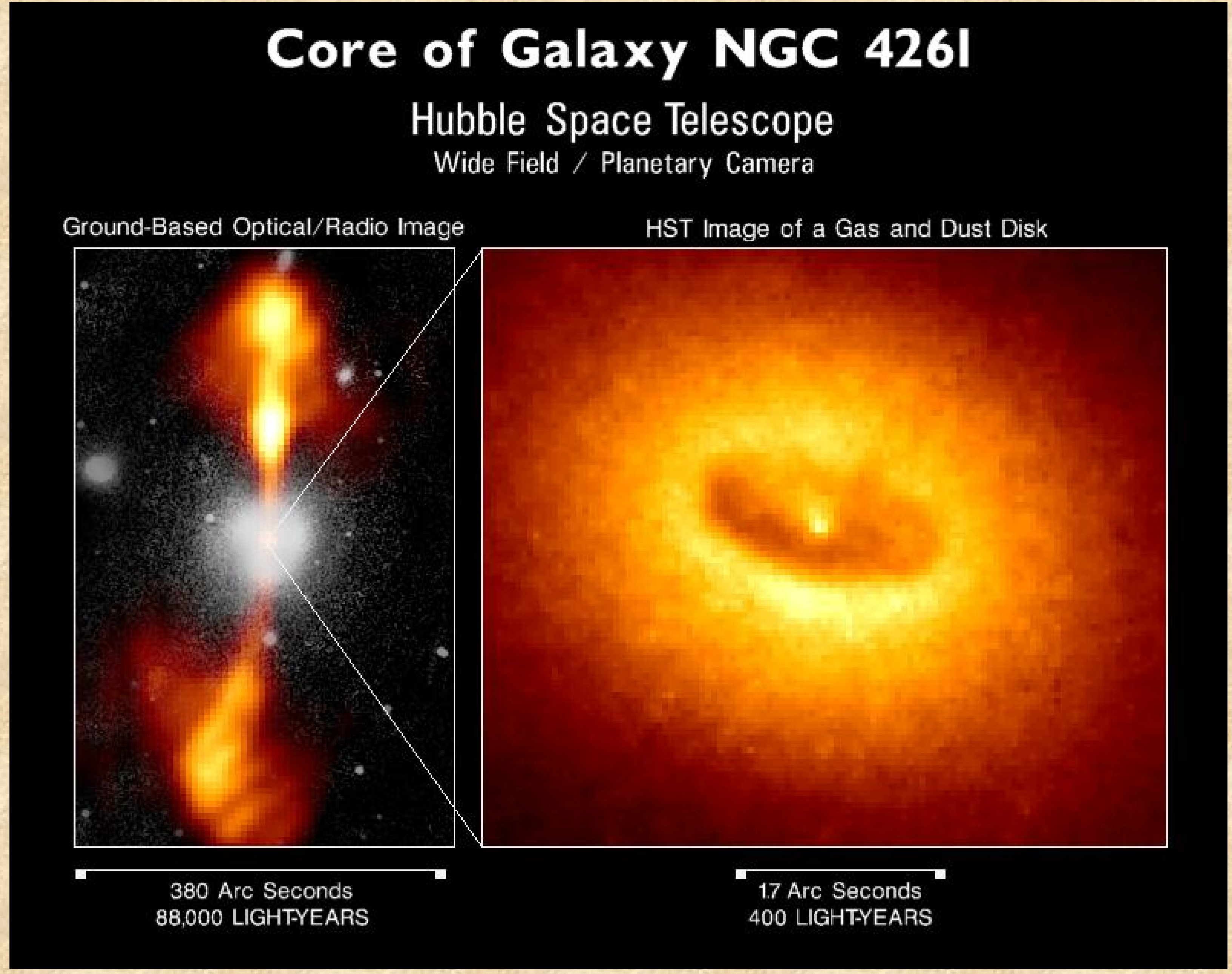


Fractional energy gain per shock crossing $\sim u_1 - u_2$ on time scale $\sim r_L / u_2$.

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

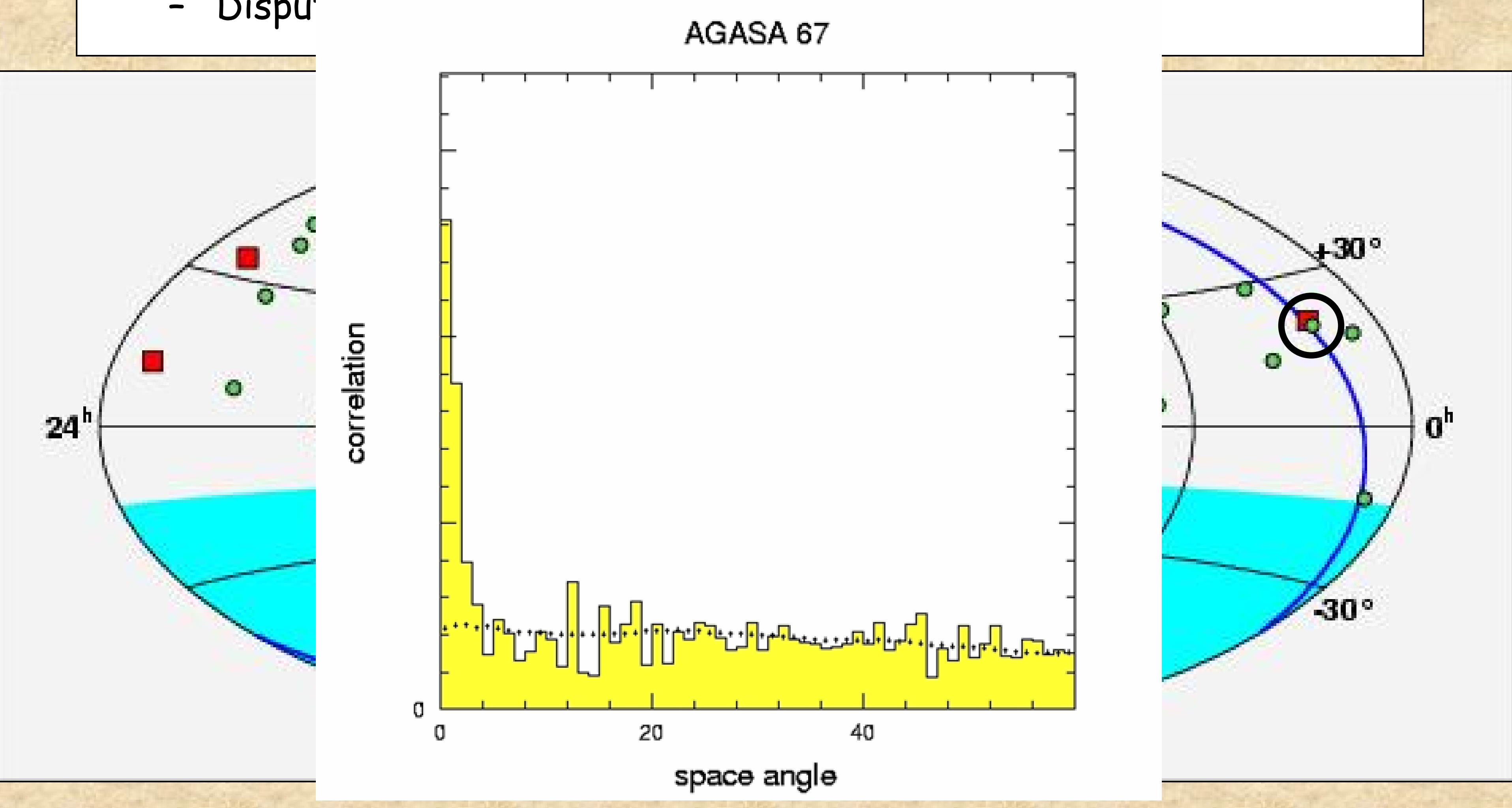
When the gyroradius r_L becomes comparable to the shock size L, the spectrum cuts off.

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



Arrival Direction Distribution >4x10^{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

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

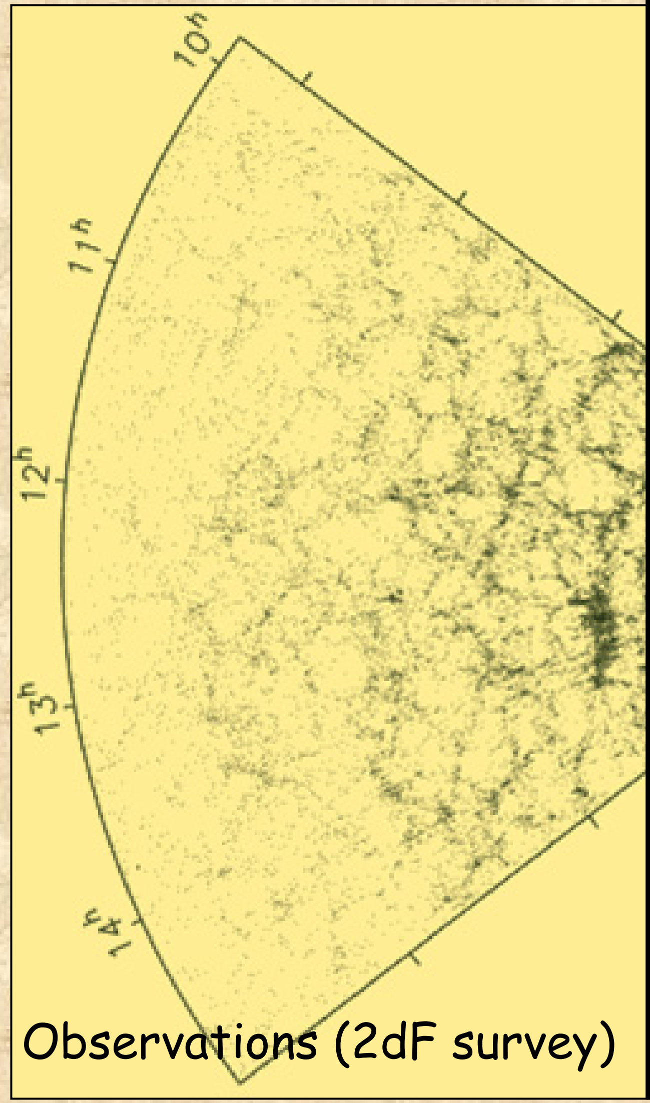
However, very little is known about about B_{XG}: It could be as small as 10^{-20} G (primordial seeds, Biermann battery) or up to fractions of micro Gauss if concentrated in clusters and filaments (equipartition with plasma).

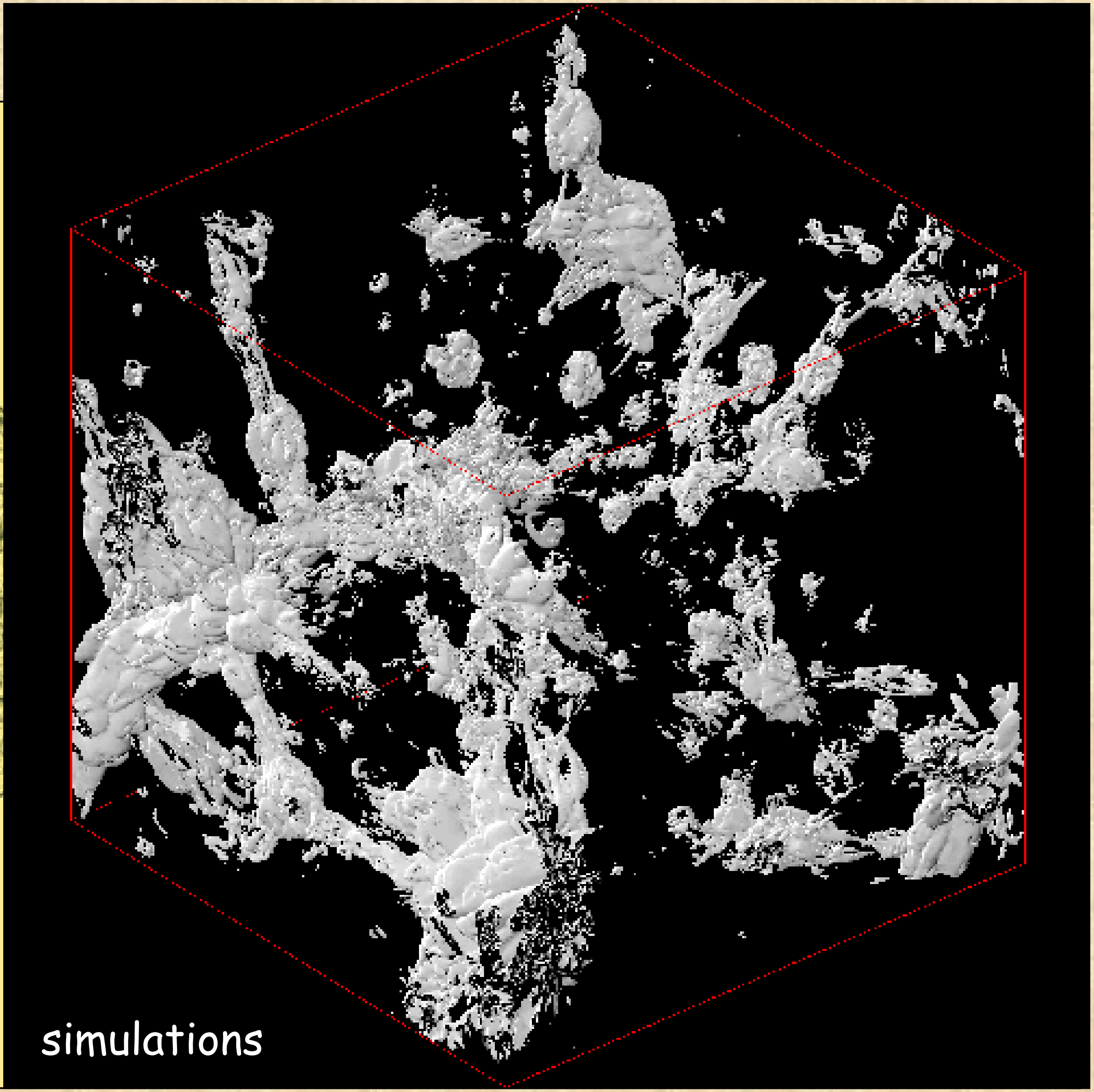
Transition from rectilinear to diffusive propagation over distance d in a field of strength B and coherence length Λ_c at:

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

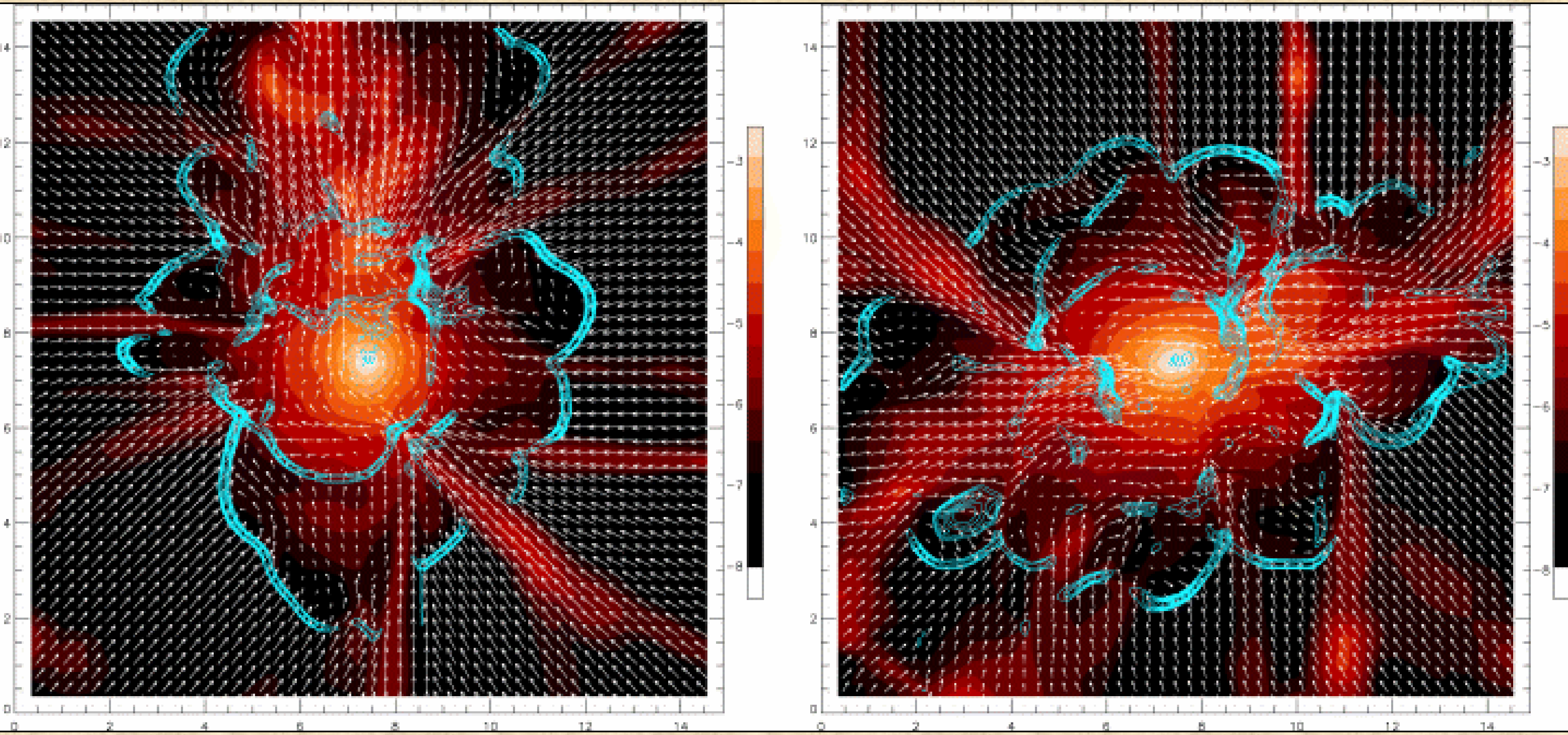
In this transition regime Monte Carlo codes are in general indispensable.

The Universe is structured

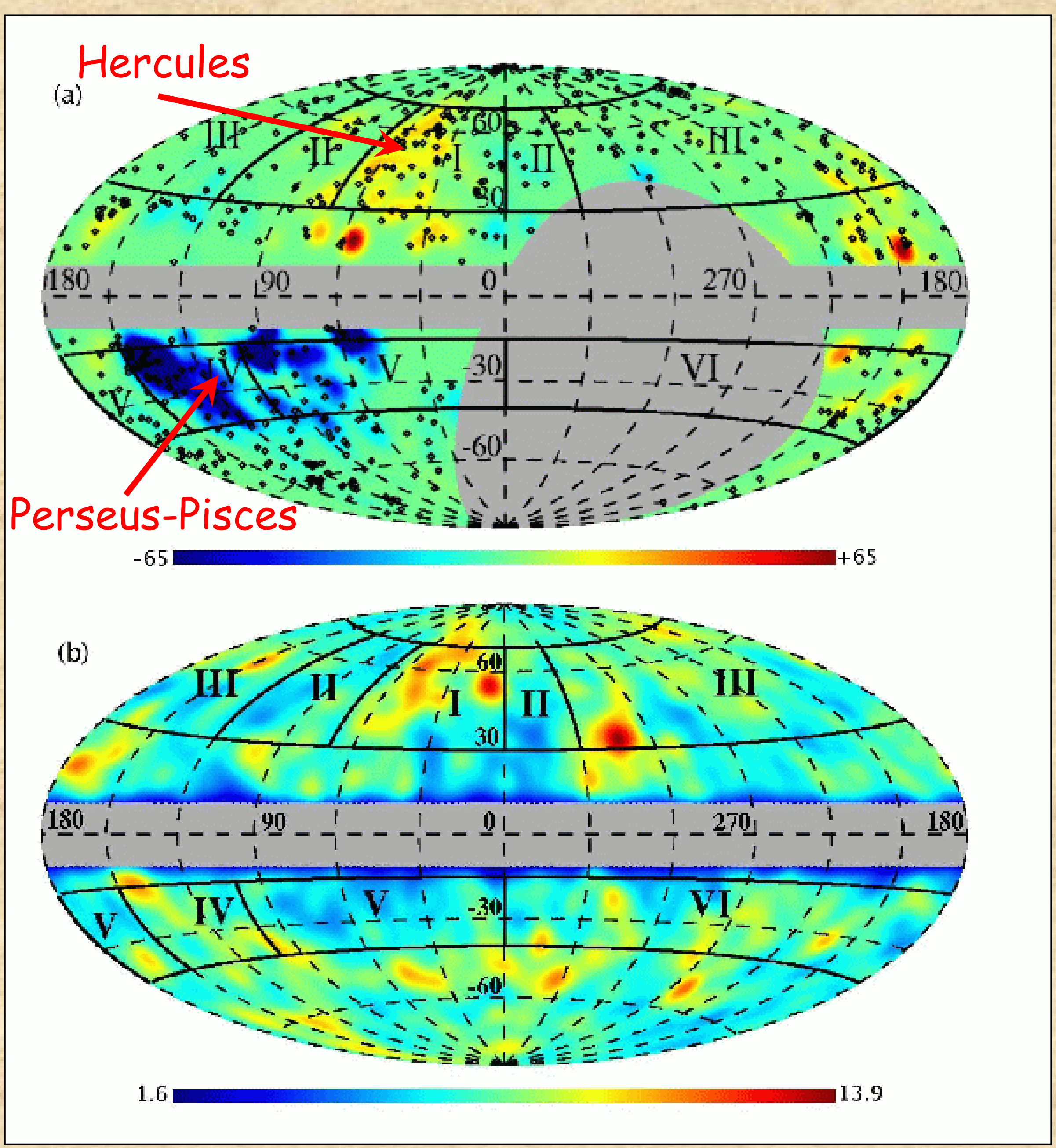




The Sources may be immersed in Magnetized Structures such as Galaxy Clusters



Miniati, MNRAS 342, 1009



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

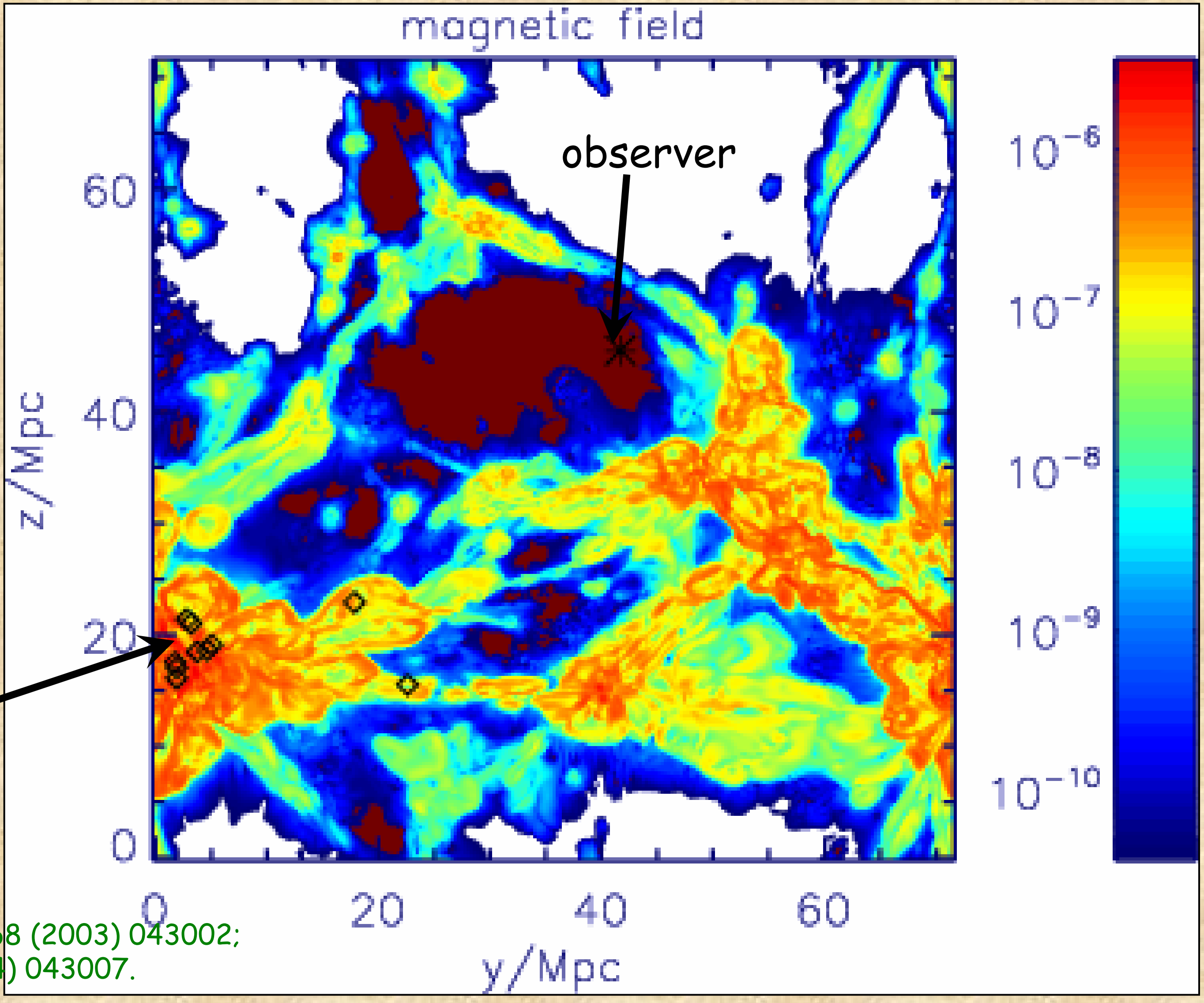
2MASS galaxy column density

Xu et al., astro-ph/0509826

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

Propagation in structured extragalactic magnetic fields

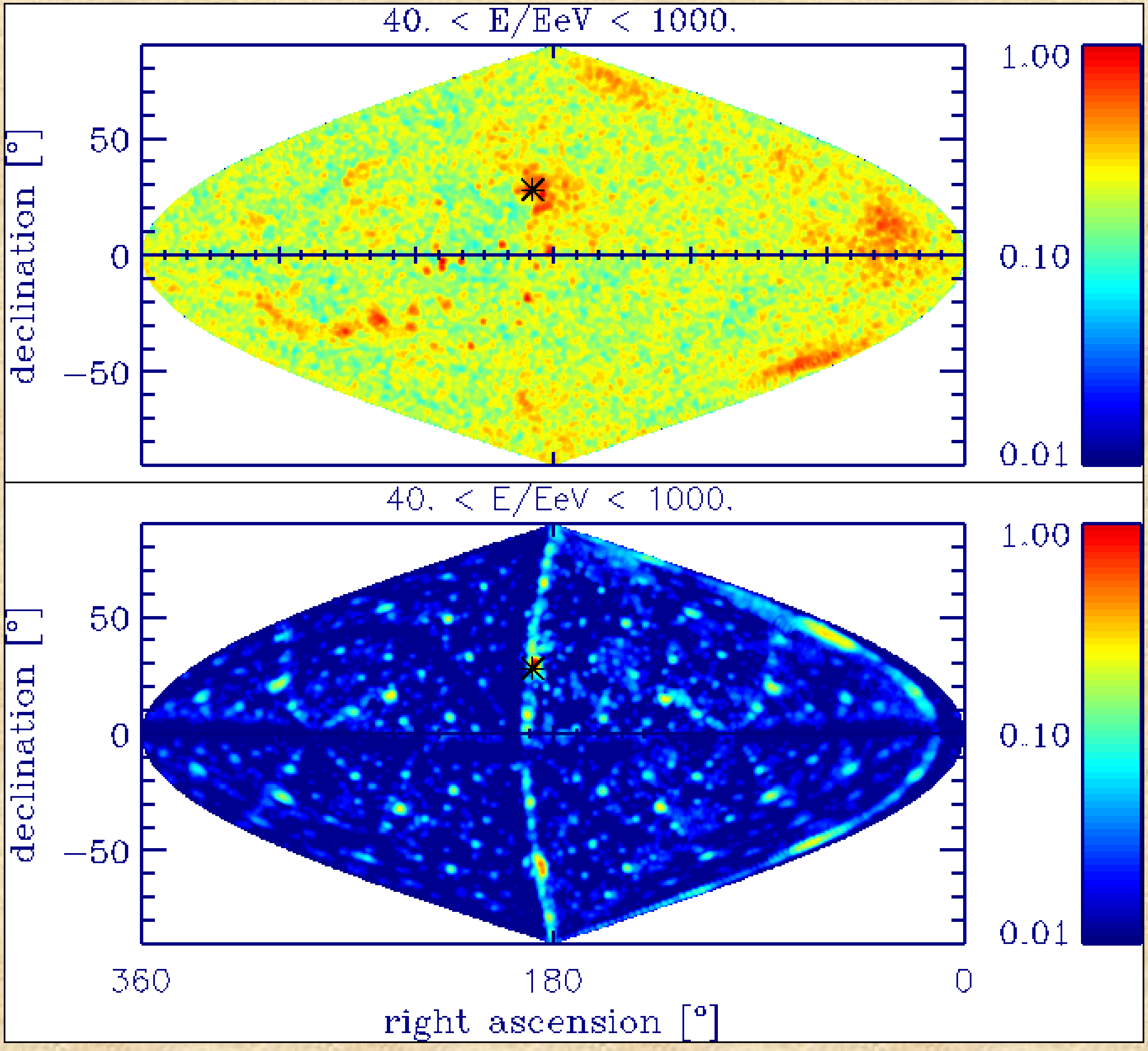
Scenarios of extragalactic magnetic fields using large scale structure simulations with magnetic fields reaching few micro Gauss in galaxy clusters.



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

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

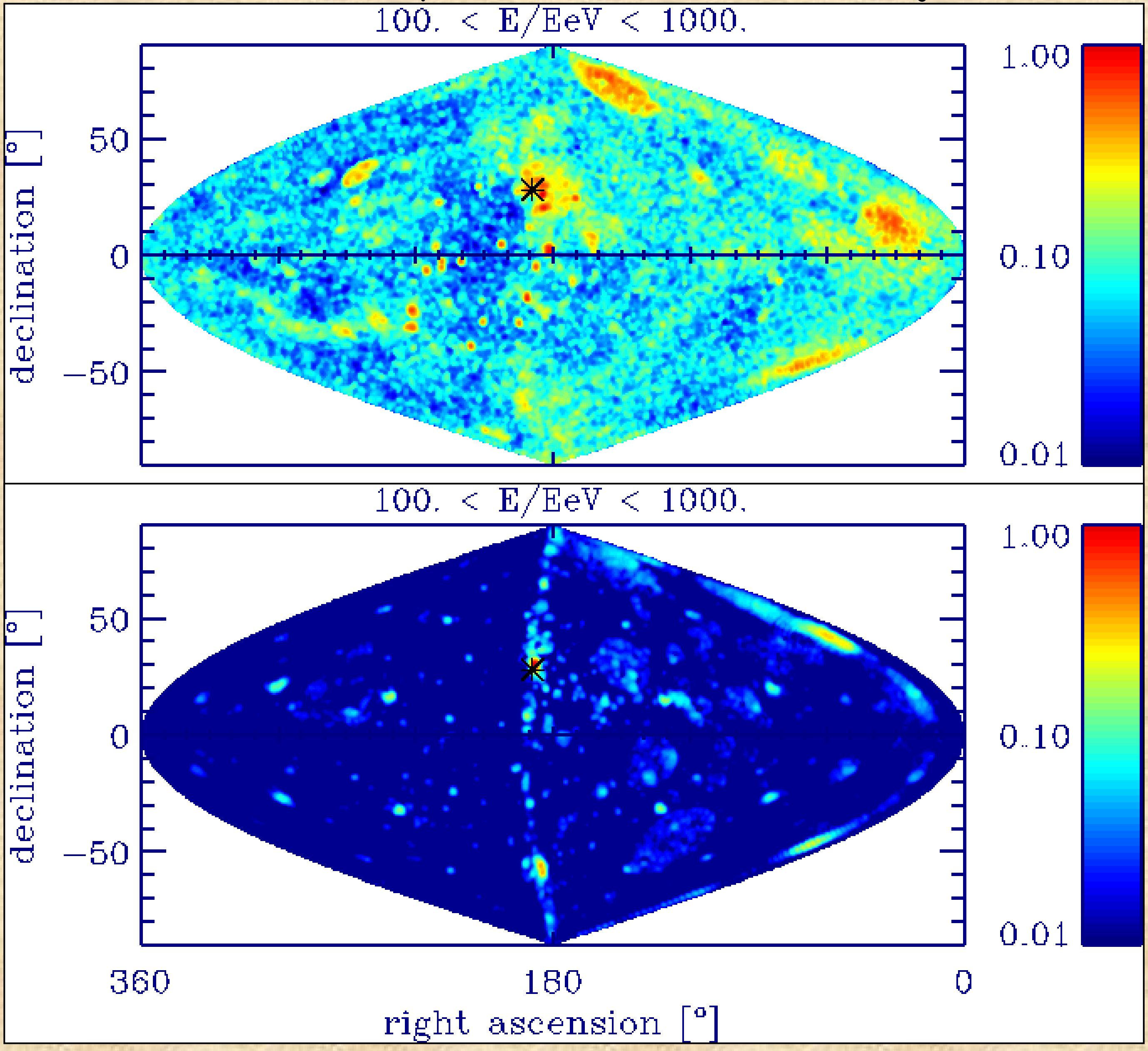
The simulated sky above 4×10^{19} eV with structured sources of density 2.4×10^{-5} Mpc^{-3} : ~2×10^{5} simulated trajectories above 4×10^{19} eV.



With field

Without field

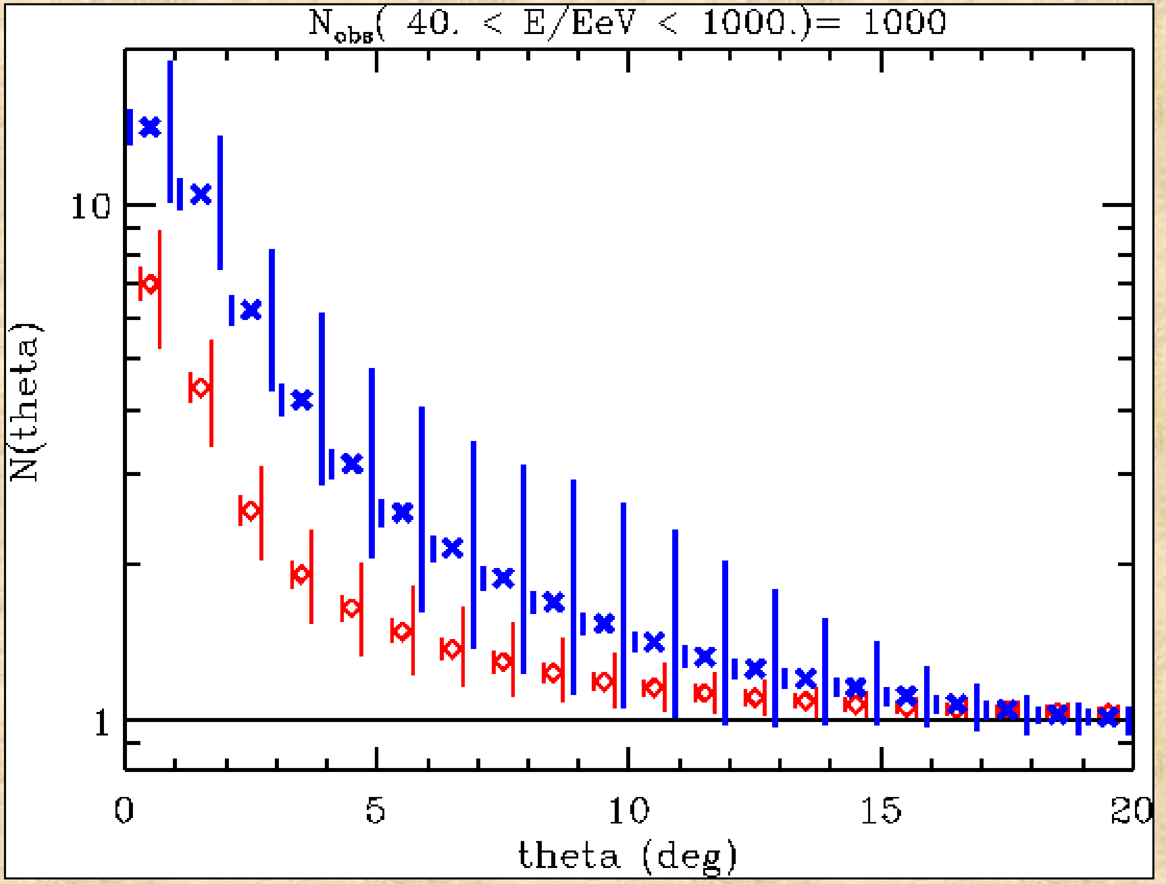
The simulated sky above 10^{20} eV with structured sources of density 2.4×10^{-5} Mpc^{-3} : ~2×10^5 simulated trajectories above 10^{20} eV.



With field

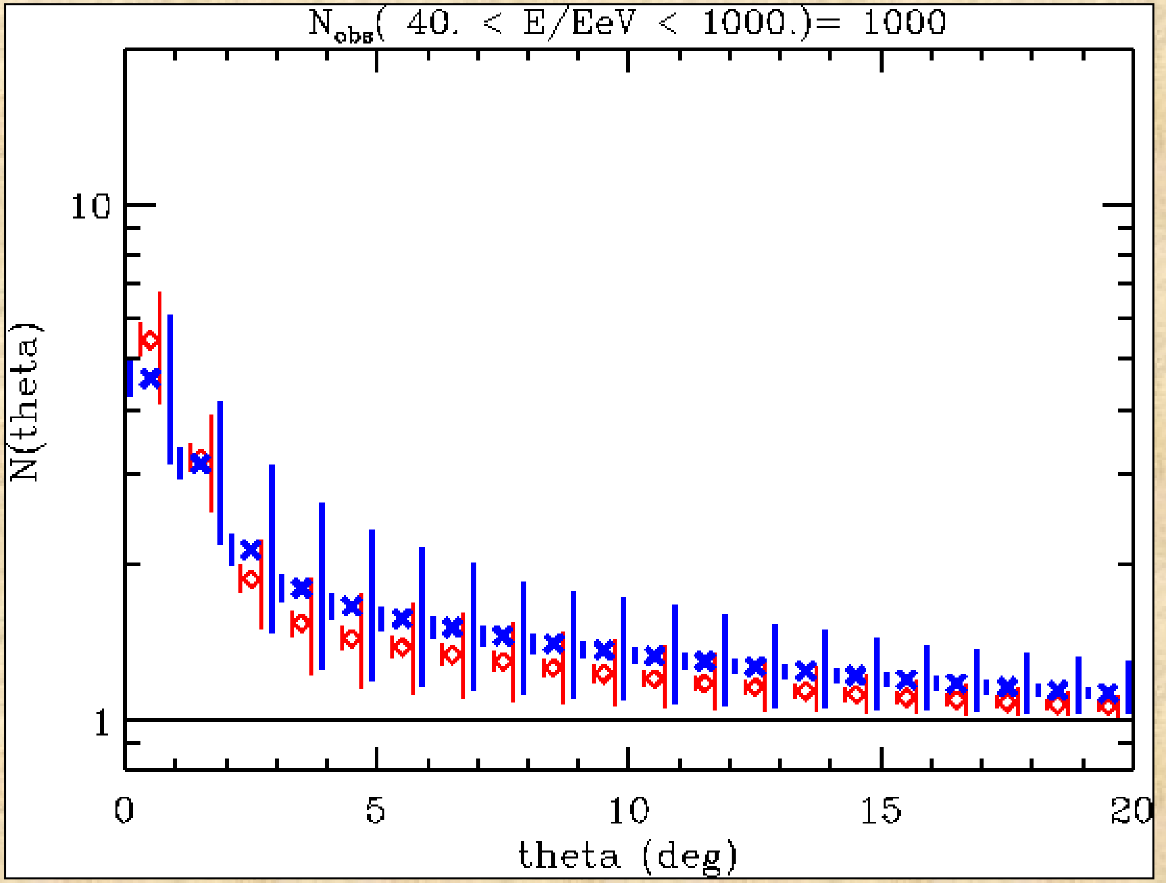
Without field

Unmagnetized, Structured Sources: Future Sensitivities



Comparing predicted autocorrelations for source density = 2.4×10^{-4} Mpc^{-3} (red set) and 2.4×10^{-5} Mpc^{-3} (blue set) for an Auger-type exposure.

Magnetized, Structured Sources: Future Sensitivities

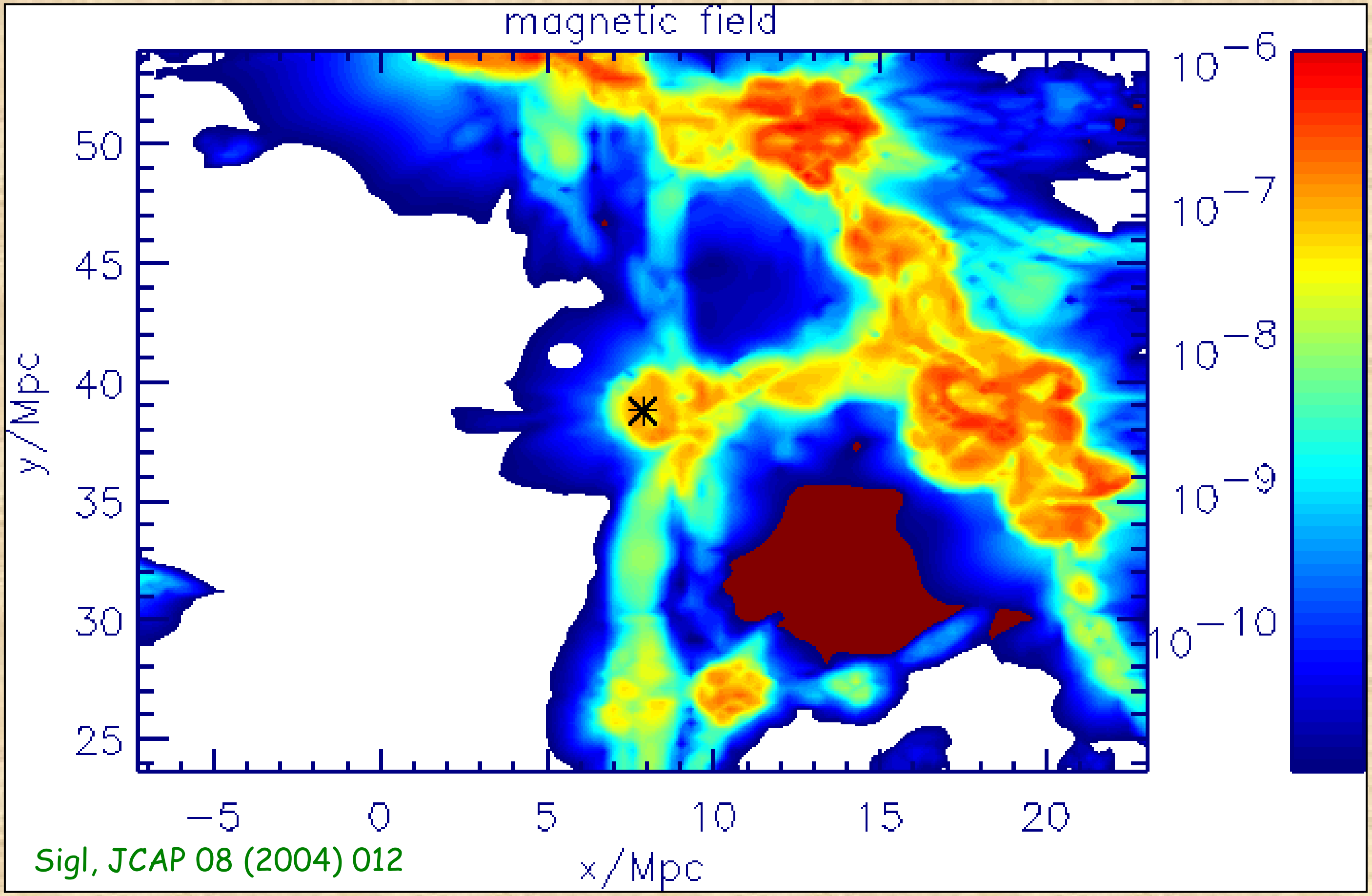


Comparing predicted autocorrelations for source density = 2.4×10^{-4} Mpc^{-3} (red set) and 2.4×10^{-5} Mpc^{-3} (blue set) for an Auger-type exposure.

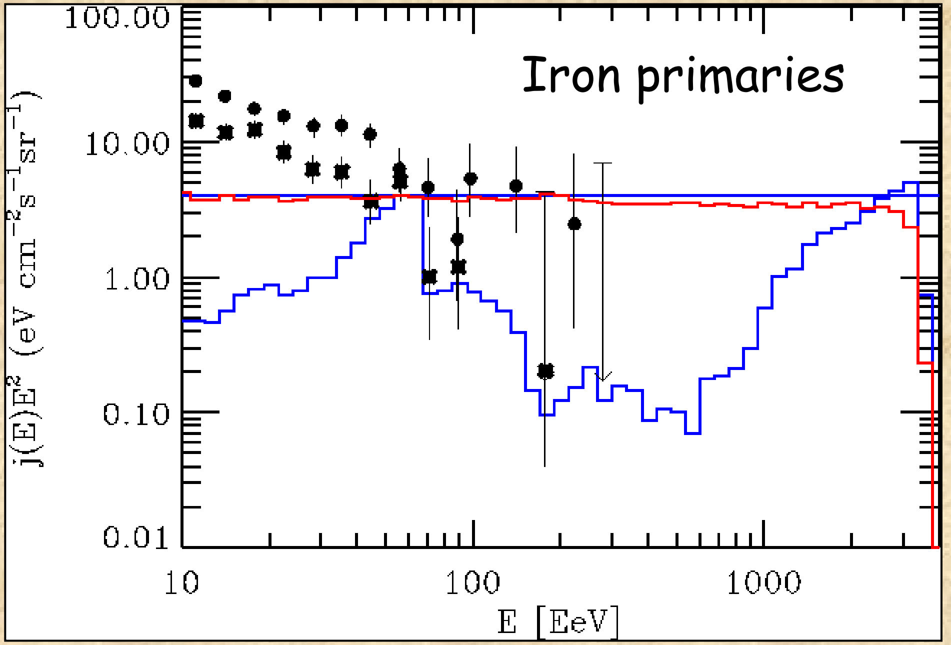
Deflection in magnetic fields makes autocorrelation and power spectrum much less dependent on source density and distribution !

Heavy Nuclei: Structured Fields and Individual Sources

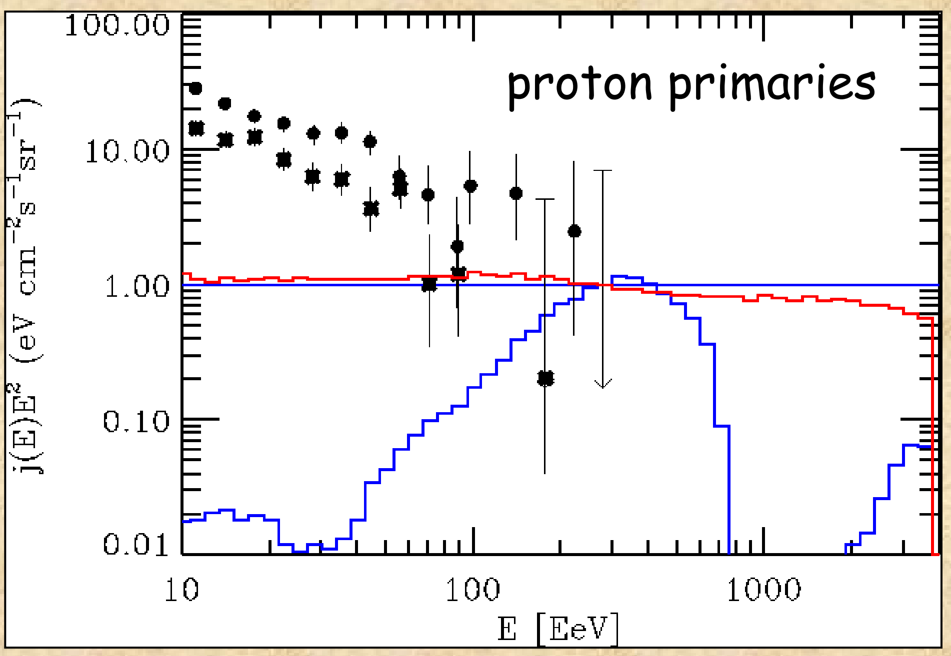
Spectra and Composition of Fluxes from Single Discrete Sources considerably depend on Source Magnetization, especially for Sources within a few Mpc.

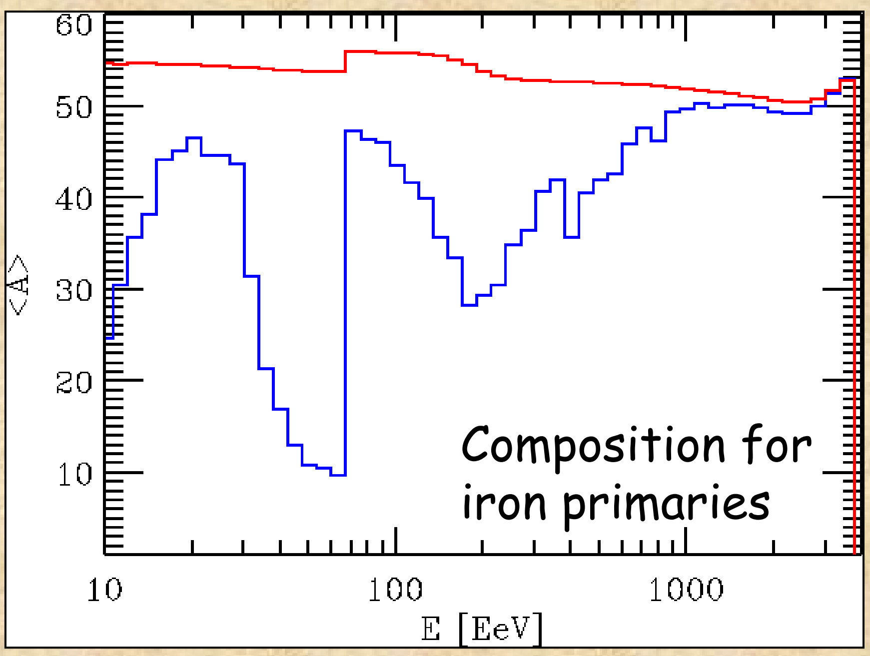


Source in the center; weakly magnetized observer modelled as a sphere shown in white at 3.3 Mpc distance.

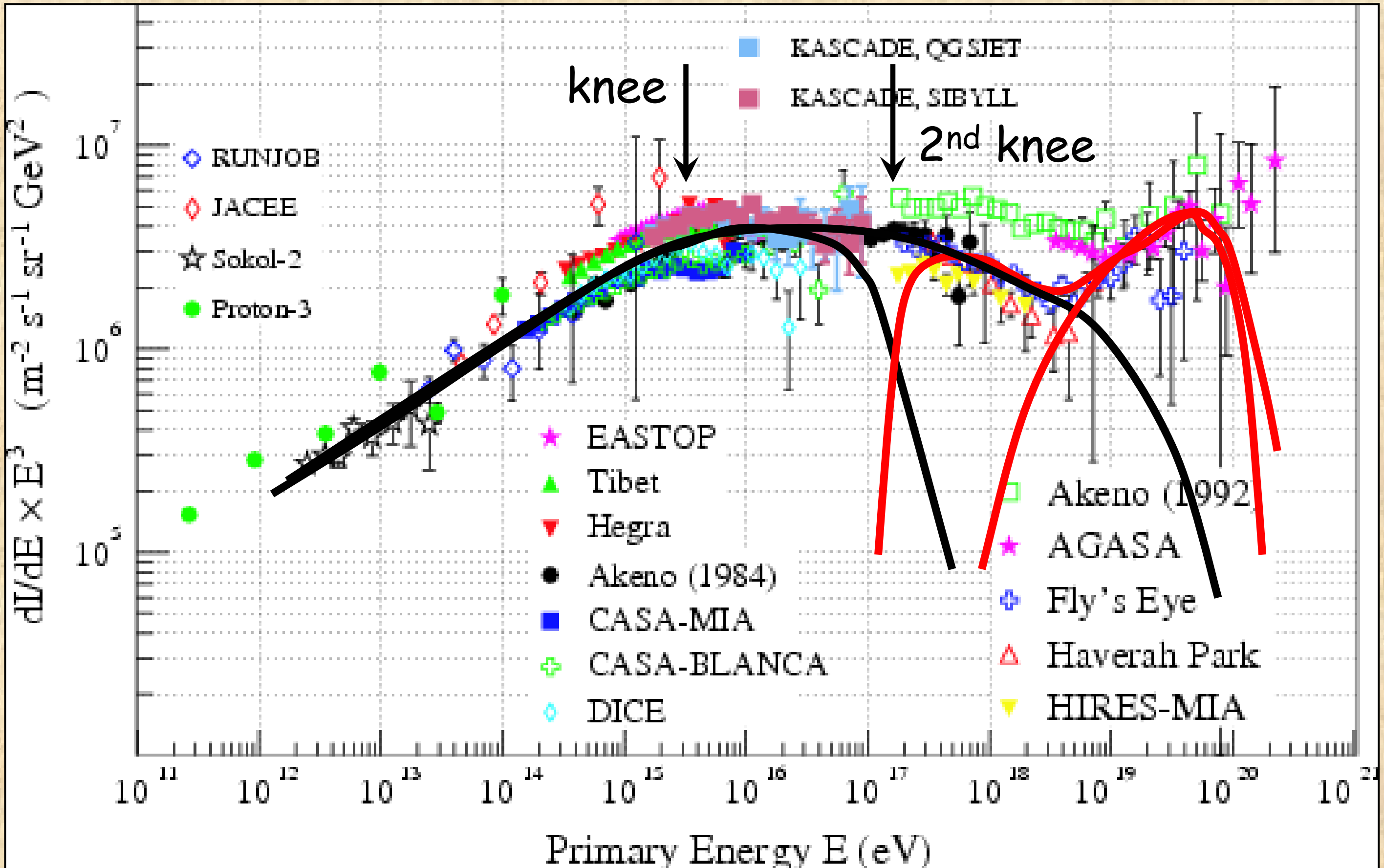


With field = blue
Without field = red
Injection spectrum = horizontal line





Chemical Composition, Magnetic Fields, Nature of the Ankle



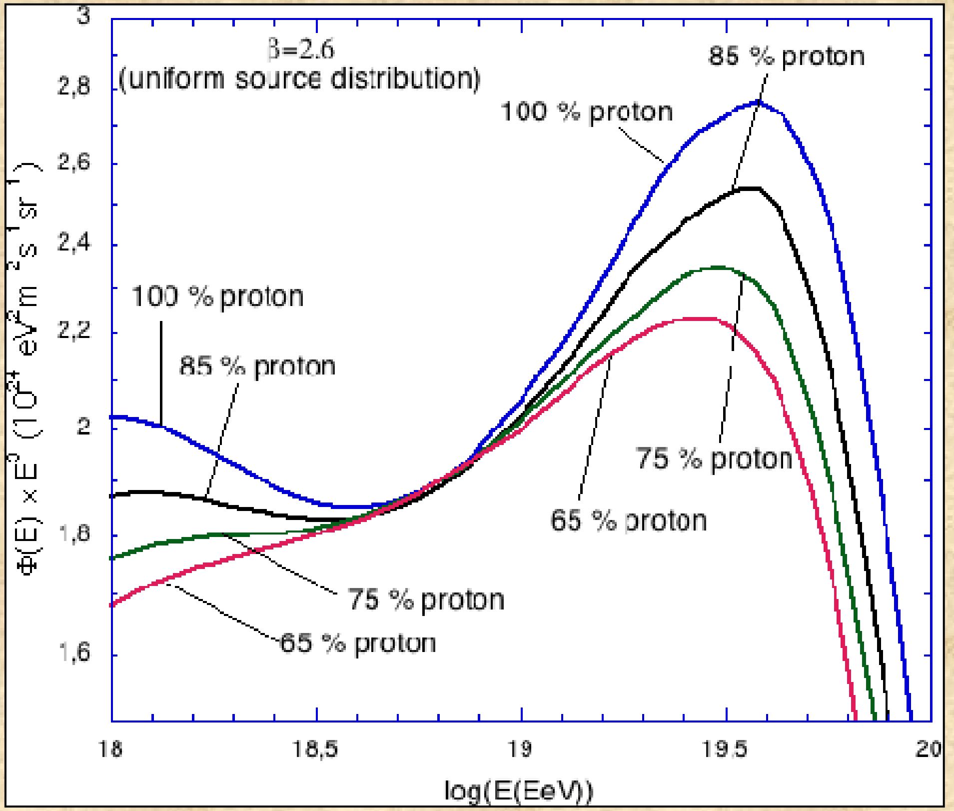
"Conventional Scenario":

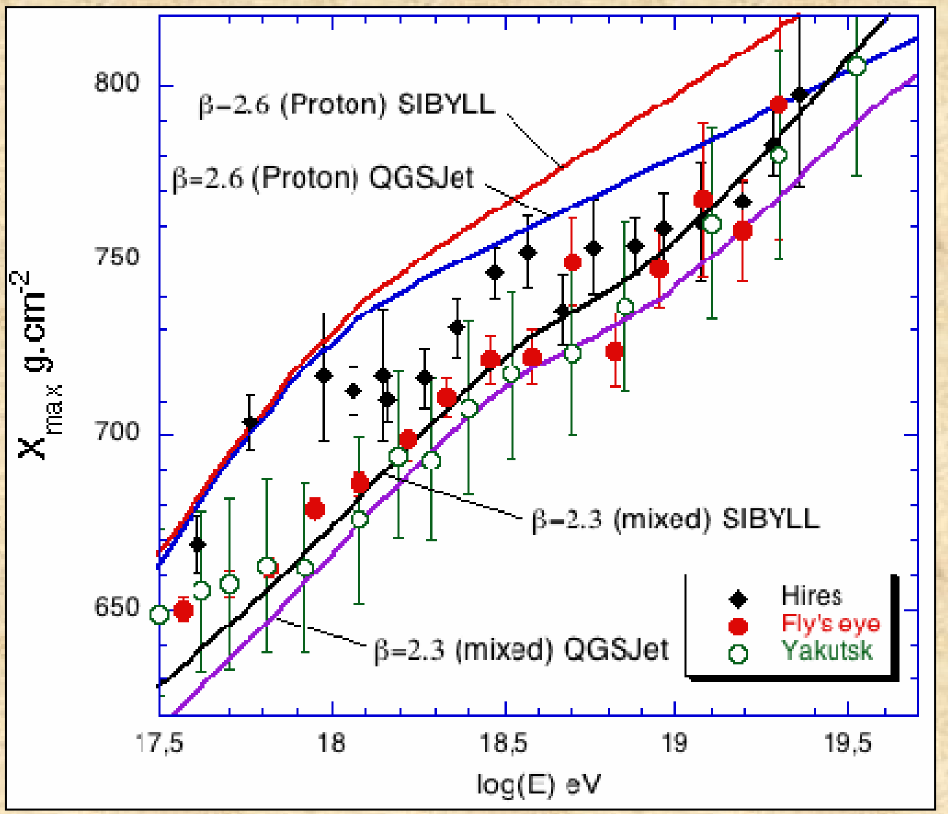
The ankle at ~5×10^{18} eV is a cross-over from a heavy Galactic to a light extragalactic component.

Scenario of Berezinsky et al.:

Galactic cosmic rays level out at the 2nd knee at ~4×10^{17} eV where dominated by heavy nuclei.

The ankle at ~5×10^{18} eV is due to pair production of extragalactic protons on the CMB. Requires >85% protons at the ankle.





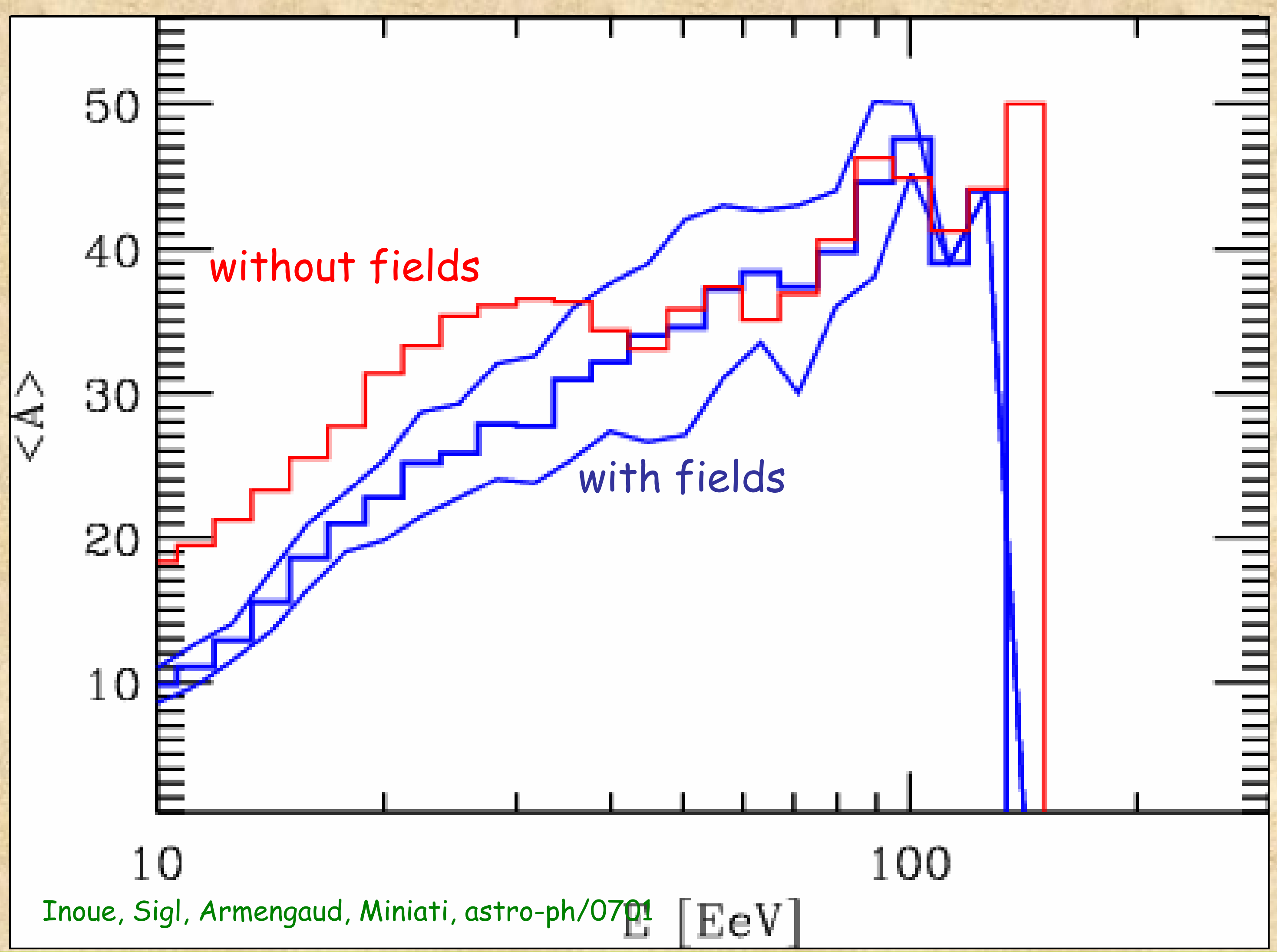
A significant iron admixture does not reproduce the ankle in the absence of magnetic fields.

Experimental situation on chemical abundances is unsettled.

Allard et al., astro-ph/0505566, 0508465

Example: Acceleration of Mixed (Solar Metallicity) Composition at Cluster Accretion Shocks

Injection spectrum $E^{1.7}$ with rigidity $E/Z < 10^{19}$ eV (consistent with cluster shock properties) and a source density ~ 2.4×10^{-6} Mpc^{-3}.



Inoue, Sigl, Armengaud, Miniati, astro-ph/0701

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

accelerated protons interact:

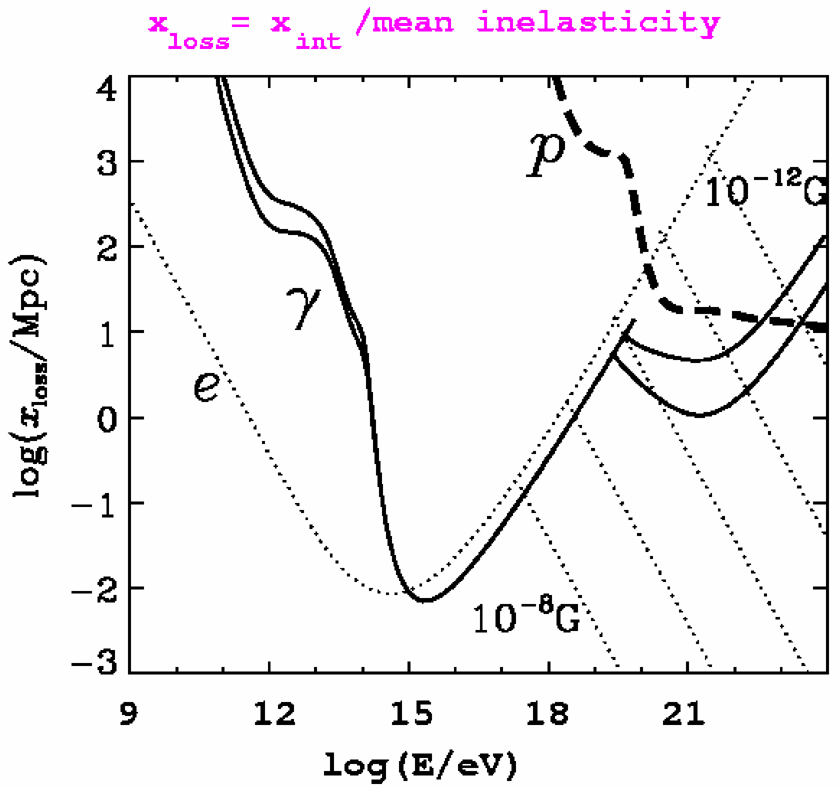
$$p + \begin{matrix} N \\ \gamma \end{matrix} \rightarrow X + \left. \begin{matrix} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{o} \rightarrow \gamma - \text{rays} \end{matrix} \right\}$$

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.



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

Propagation of nucleons, photons, electrons, and neutrinos

In one dimension propagation is governed by Boltzmann equations for differential spectrum of species i, $n_i(E)$:

$$\frac{\partial n_i(E)}{\partial t} = \Phi_i(E) - n_i(E)\int d\varepsilon n_b(\varepsilon)\int_{-1}^{+1} d\mu \frac{1-\mu\beta_b\beta_i}{2}\sum_j \sigma_{i\to j}\Big|_{s=\varepsilon E(1-\mu\beta_b\beta_i)}$$

$$+\int dE'\int d\varepsilon n_b(\varepsilon)\int_{-1}^{+1} d\mu \sum_j \frac{1-\mu\beta_b\beta_j'}{2} n_j(E')\left.\frac{d\sigma_{j\to i}(s,E)}{dE}\right|_{s=\varepsilon E'(1-\mu\beta_b\beta_j)},$$

where:

$\Phi_i(E)$ =injection spectrum,

$n_b(\varepsilon)$ =diffuse background neutrino or photon density at energy ε,

μ = cos(angle between background and in-particle),

β =particle velocities,

$\sigma_{i\to j}$ = cross sections for processes $i \to j$,

s =center of mass energy.

Background spectrum between $\sim 10^{-8}$ eV and ~ 10 eV

propagated particles between 100 MeV and 10^{16} GeV (GUT scale)

transport equations (including cosmology, i.e. redshift-distance relation) solved by implicit methods.

Processes taken into account

Nucleons:

- (multiple) pion production: $N\gamma_b \to N(n\pi)$ with subsequent pion decays: leads to "GZK-effect".
- pair production by protons: $p\gamma_b \to pe^+e^-$: relevant below GZK threshold (similar to triplet pair production below)
- Neutron decay: $n \to pe^-\bar{\nu}_e$

Electromagnetic channel:

- pair production and inverse Compton scattering: $\gamma\gamma_b \to e^+e^-$ and $e\gamma_b \to e\gamma$: leading order processes with

$$\sigma_{\rm PP} \simeq 2\sigma_{\rm ICS} \simeq \frac{3}{2}\sigma_T \frac{m_e^2}{s} \ln\frac{s}{2m_e^2} \quad (s \gg m_e^2)\,.$$

- double pair production: $\gamma\gamma_b \to e^+e^-e^+e^-$: dominates at highest energies with

$$\sigma_{\rm DPP} \simeq \frac{43\alpha^2}{24\pi^2}\sigma_T \quad (s \gg m_e^2)\,.$$

- triplet pair production: $e\gamma_b \to ee^+e^-$: dominant at highest energies with

$$\sigma_{\rm TPP} \simeq \frac{3\alpha}{8\pi}\sigma_T\left(\frac{28}{9}\ln\frac{s}{m_e^2} - \frac{218}{27}\right) \quad (s \gg m_e^2)\,,$$

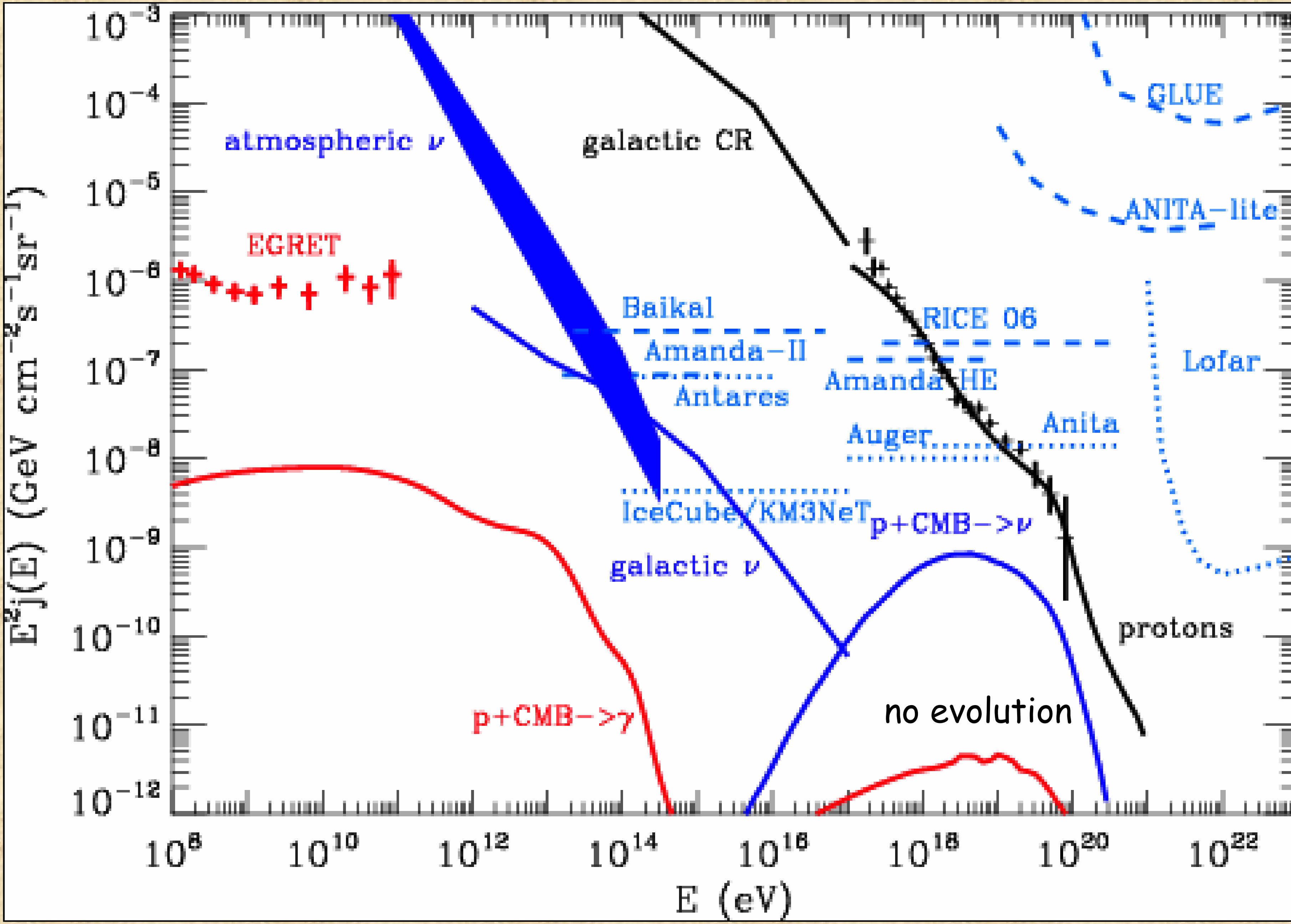
  with fractional energy loss η of leading e

$$\eta \simeq 1.768\left(\frac{s}{m_e^2}\right)^{-3/4} \quad (s \gg m_e^2)\,.$$

- synchrotron loss of electrons and positrons in cosmic magnetic fields: $eB \to e\gamma$. Energy loss given by

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T\frac{B^2}{8\pi}\left(\frac{Zm_e}{m}\right)^4\left(\frac{E}{m_e}\right)^2\,.$$

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



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

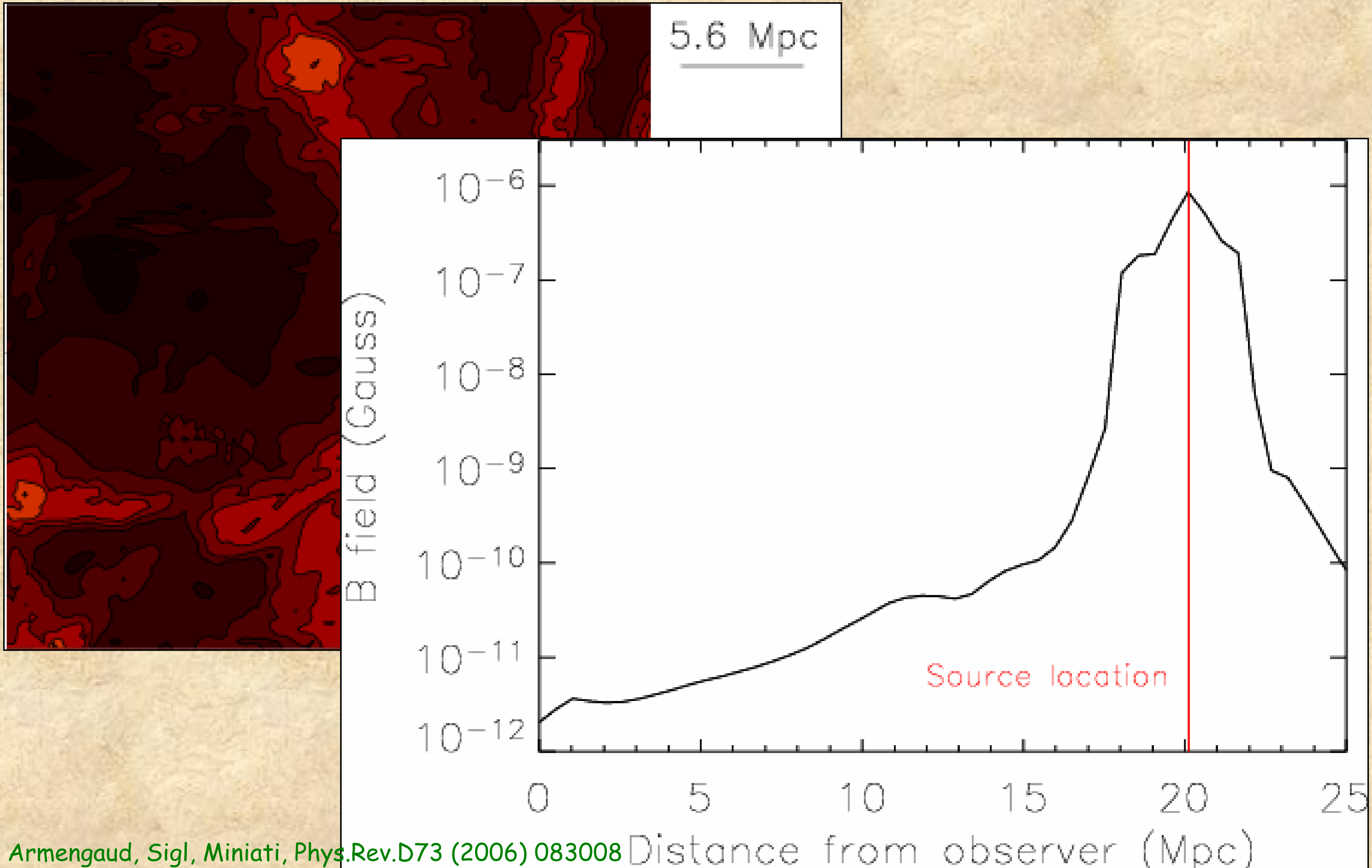
Numerous connections:

Magnetic fields influence propagation path lengths. This influences:

spallation of nuclei 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.

Discrete Source in a magnetized galaxy cluster injecting protons up to 10^{21} eV



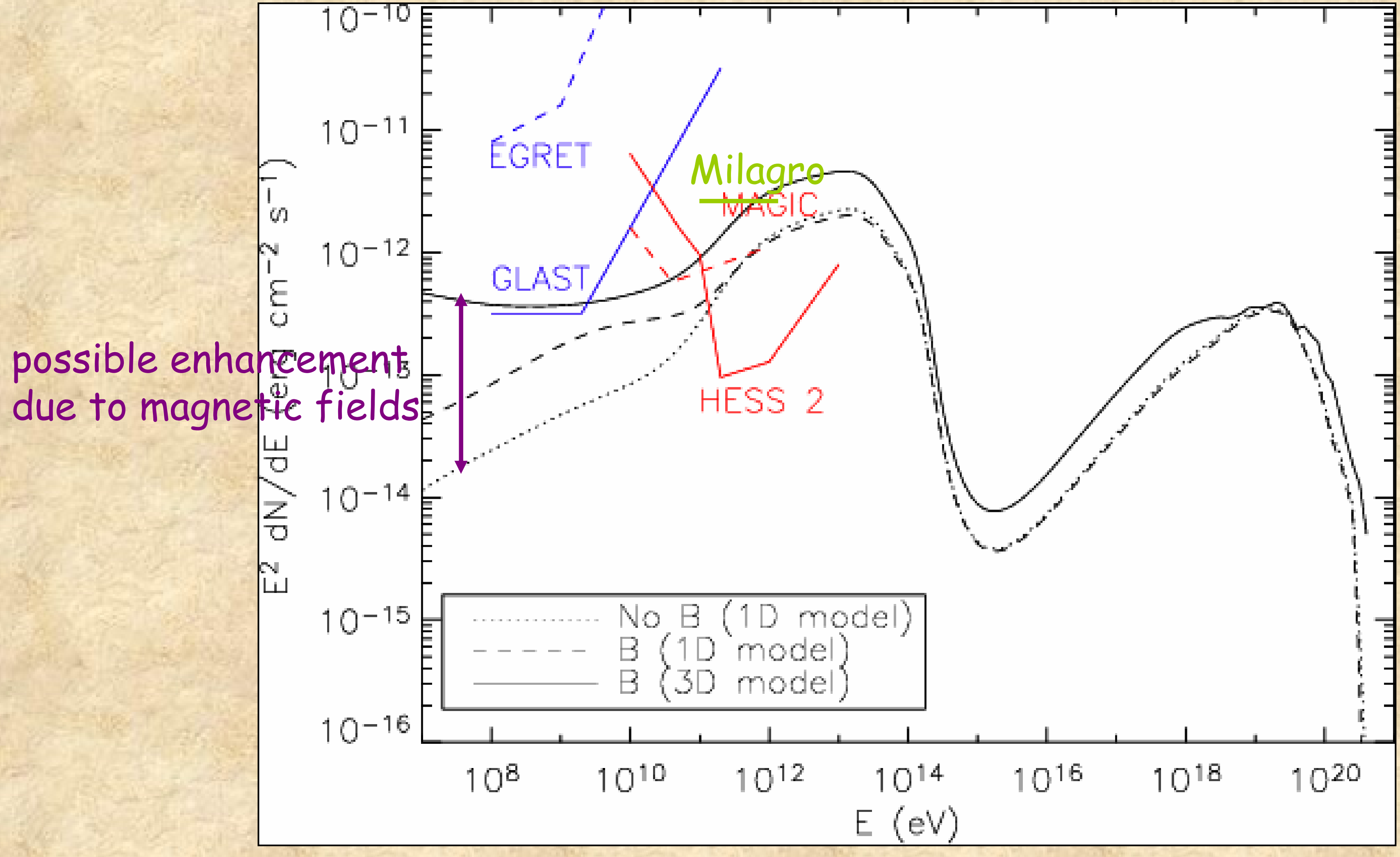
Armengaud, Sigl, Miniati, Phys.Rev.D73 (2006) 083008

In a magnetic field B, pairs emit synchrotron photons of typical energy

$$E_{\rm syn} \simeq 6.8 \times 10^{11} \left(\frac{E_e}{10^{19}\,{\rm eV}}\right)^2 \left(\frac{B}{0.1\,\mu{\rm G}}\right)\,{\rm eV}\,.$$

For proton spectra steeper than $\sim E^{-2}$, the sub-GeV photon flux is dominated by synchrotron photons from pair production. Pairs produced by protons appear below $\sim 10^{17}\,$eV which in $\sim 0.1\,$G fields ends up in synchrotron photons below $\sim 1\,$GeV.

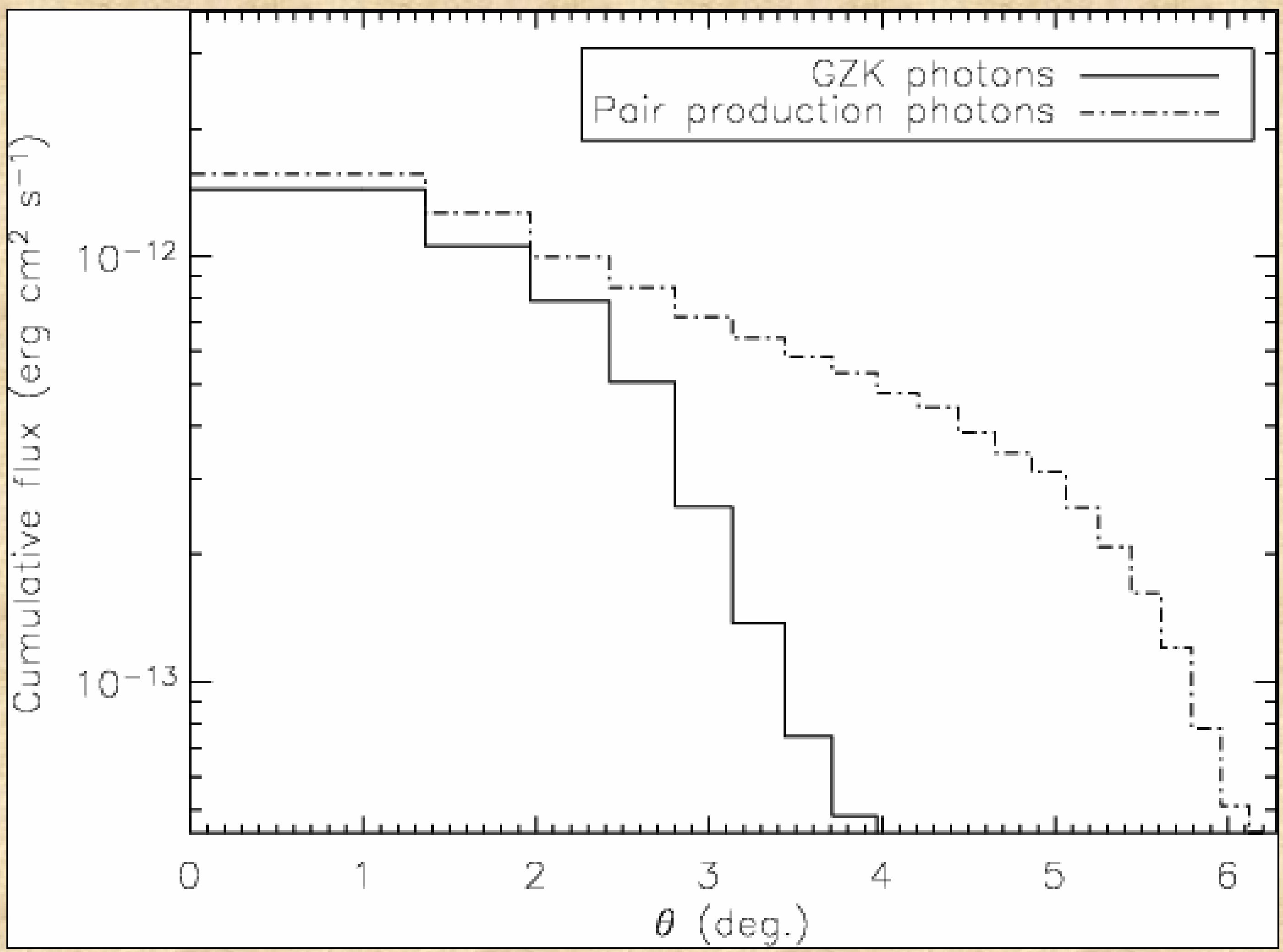
Source at 20 Mpc, $E^{2.7}$ proton injection spectrum with 4×10^{42} erg/s above 10^{19} eV



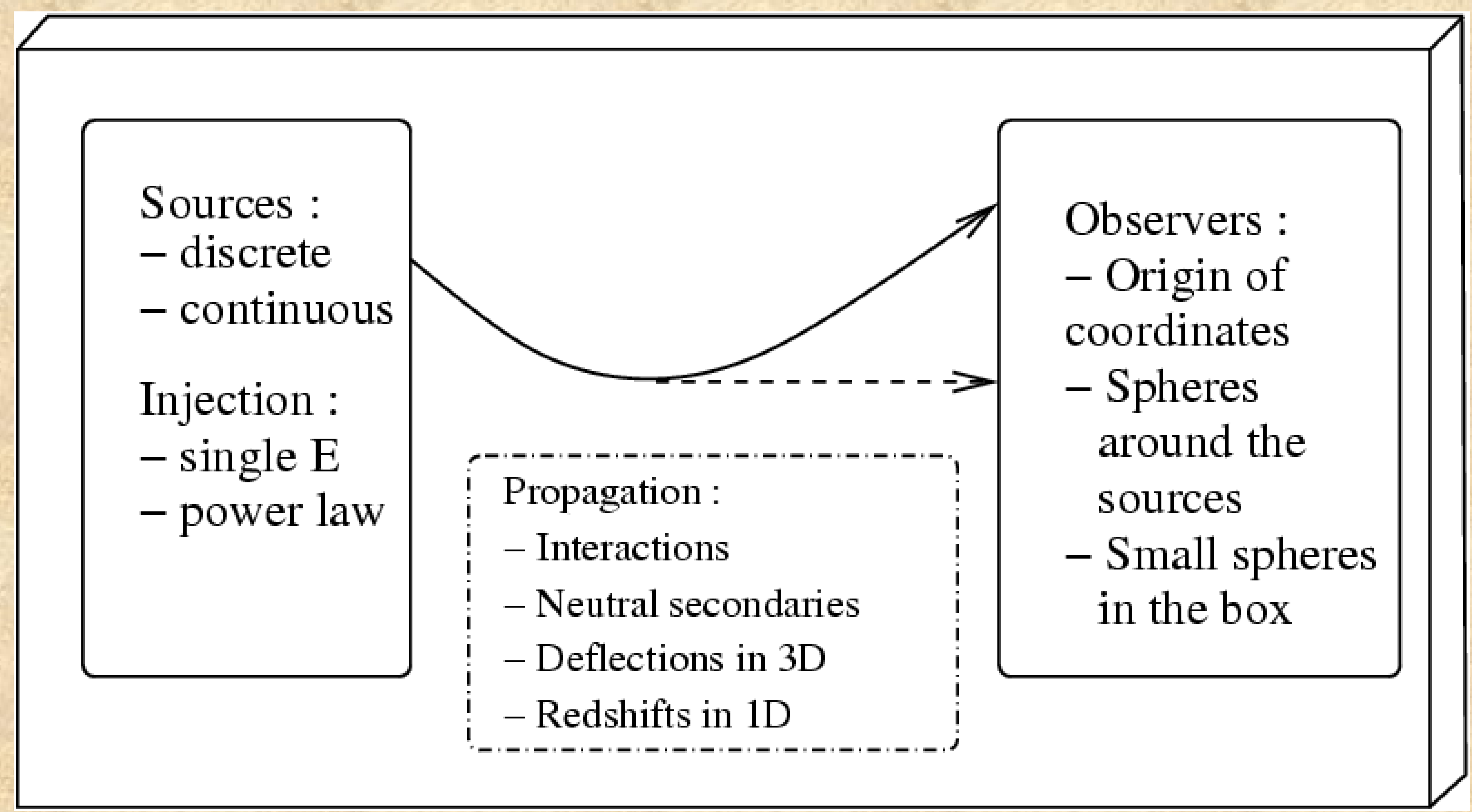
Note that the 3d structure of the field matters and leads to further enhancement of GeV γ-ray fluxes. Γ-rays from pp interactions neglected.

The source magnetic fields can give rise to a **GeV-TeV γ-ray halo** that would be easily resolvable by instruments such as HESS

In case of previous example, γ-rays above 1 TeV:



Short Advertizement: CRPropa a public code for UHE cosmic rays, Neutrinos and γ-Rays



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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.) 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.