Ultra High Energy Cosmic Radiation: Experimental and Theoretical Status

- (Very short) introduction on Cosmic Ray experimental situation and current understanding
- 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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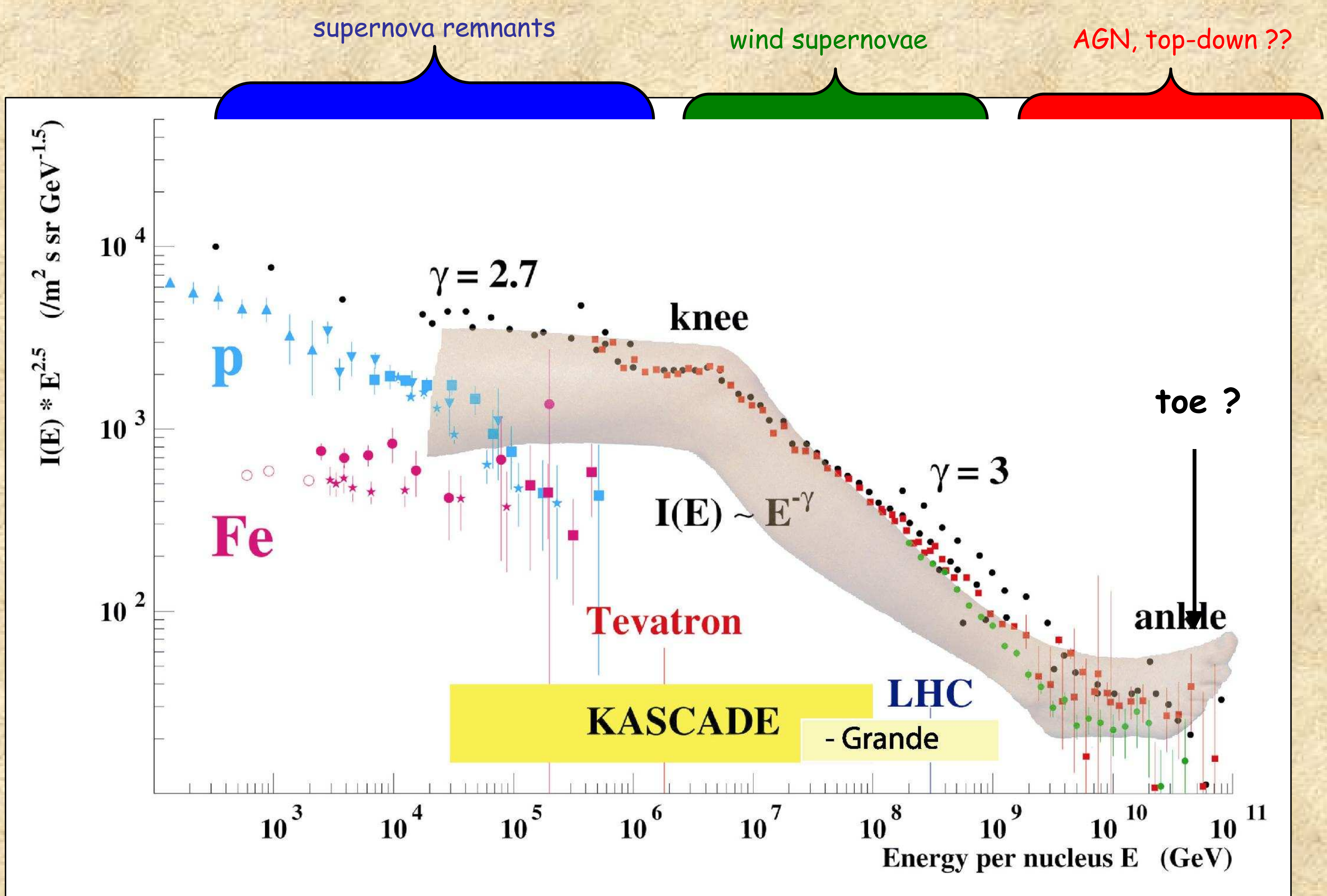
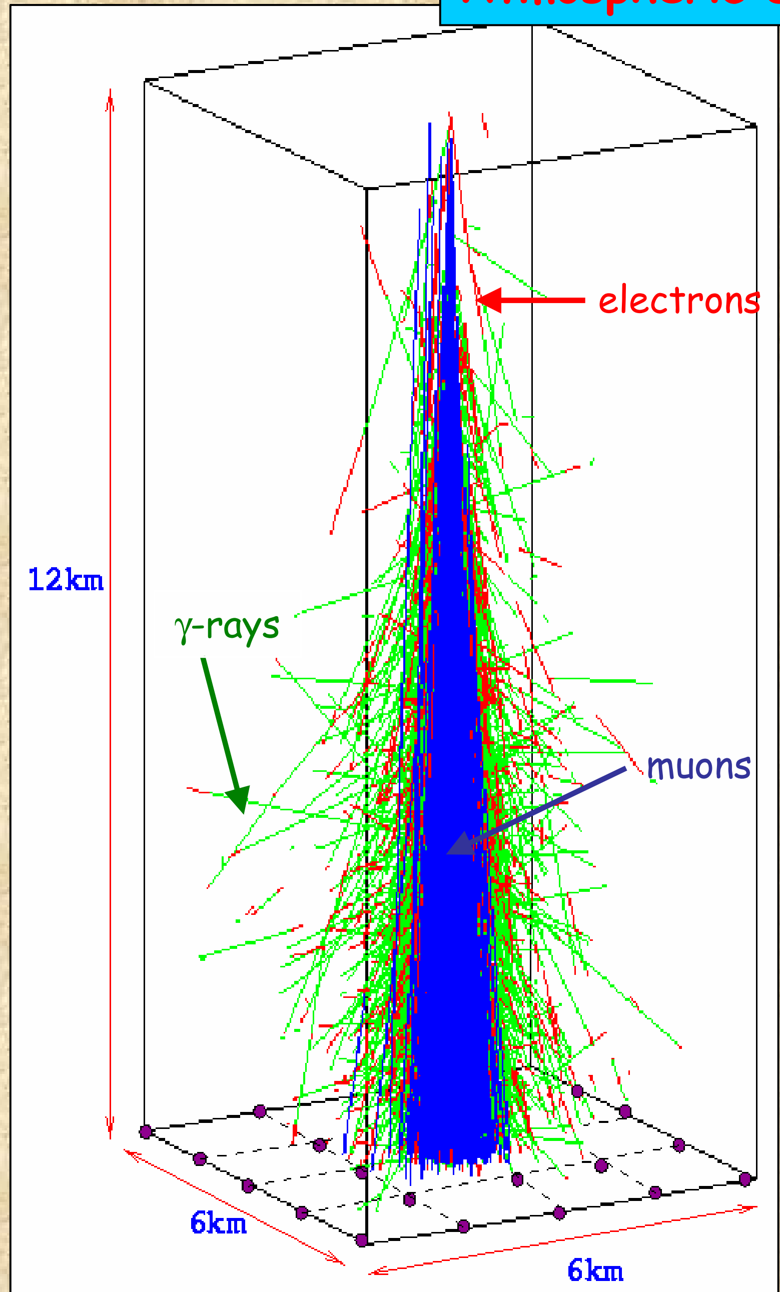
http://www2.iap.fr/users/sigl/homepage.html

The structure of the spectrum and scenarios of its origin



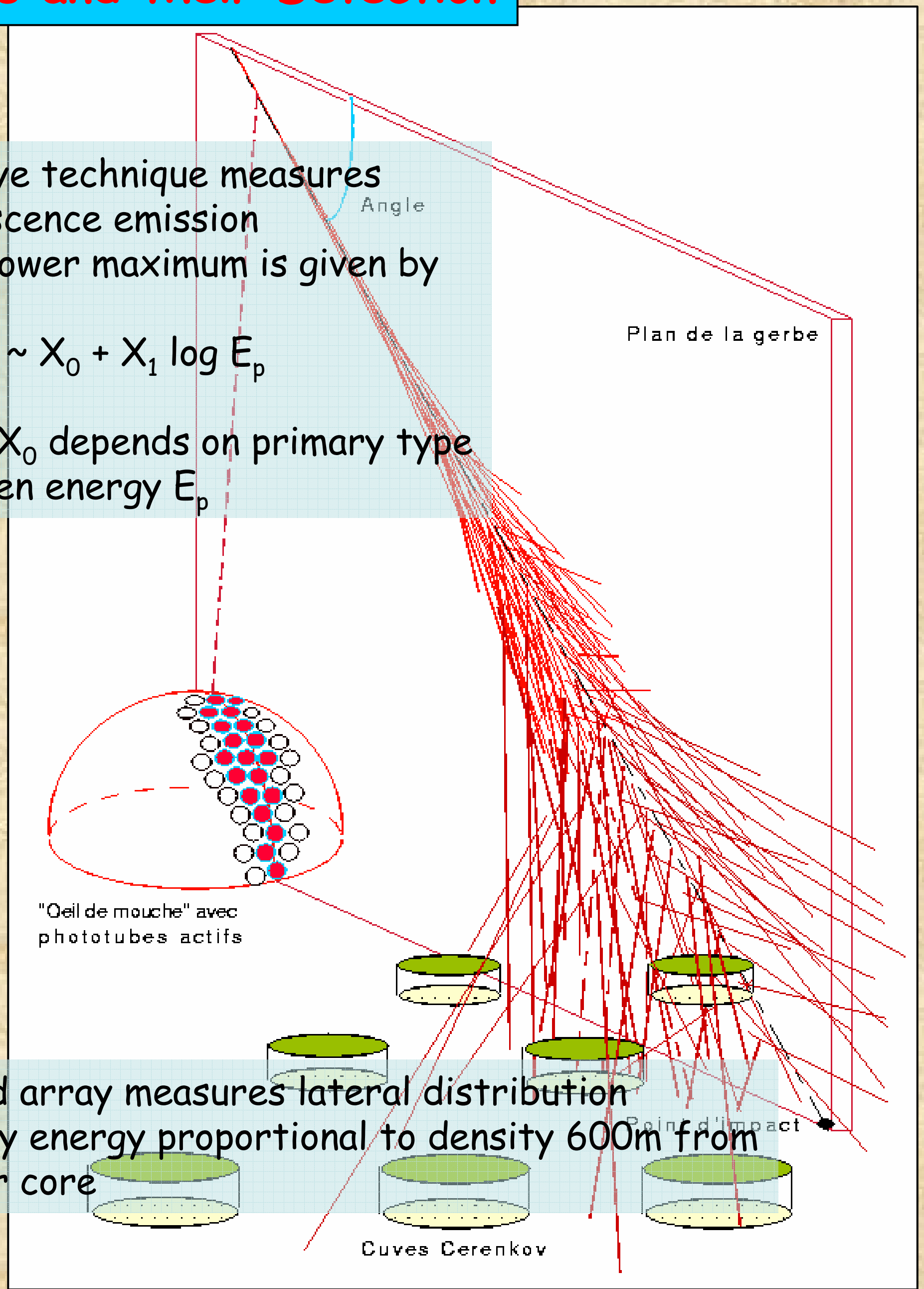
Atmospheric Showers and their Detection



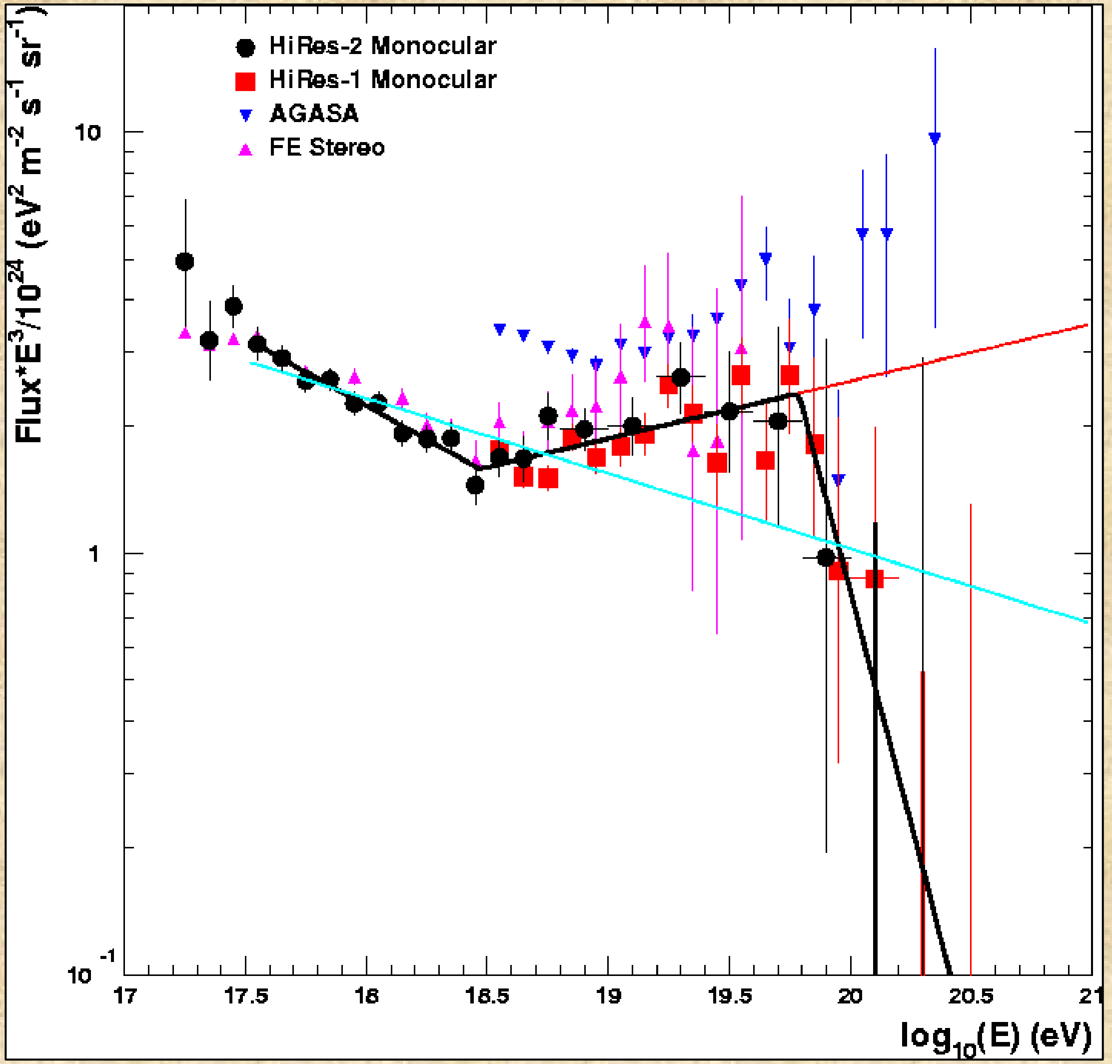
Fly's Eye technique measures fluorescence emission
The shower maximum is given by

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

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

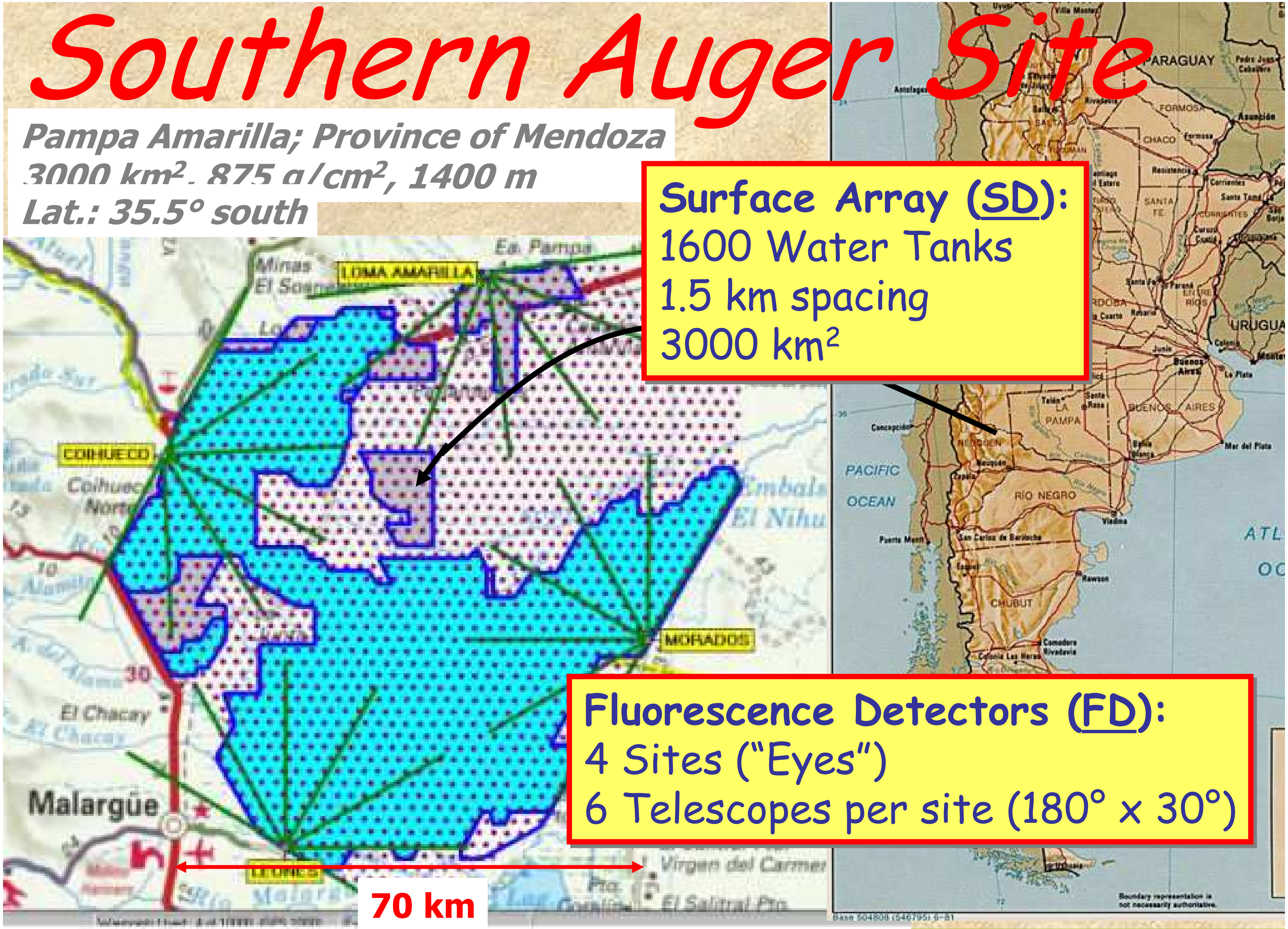
May need an experiment combining ground array with fluorescence such as the Auger project to resolve this issue.

Southern Auger Site

Pampa Amarilla; Province of Mendoza
3000 km^2, 875 g/cm^2, 1400 m
Lat.: 35.5° south

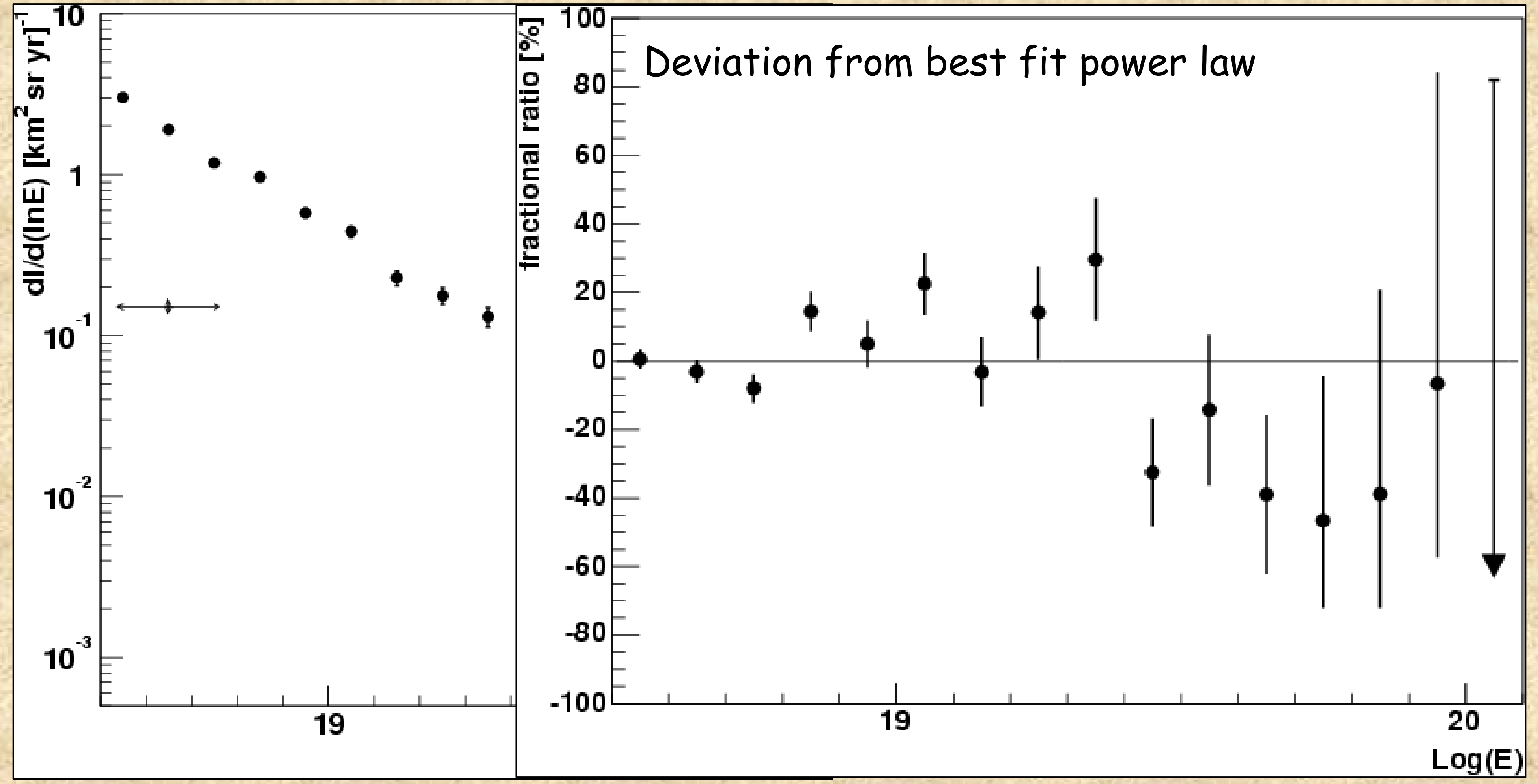
Surface Array (SD):
1600 Water Tanks
1.5 km spacing
3000 km^2

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

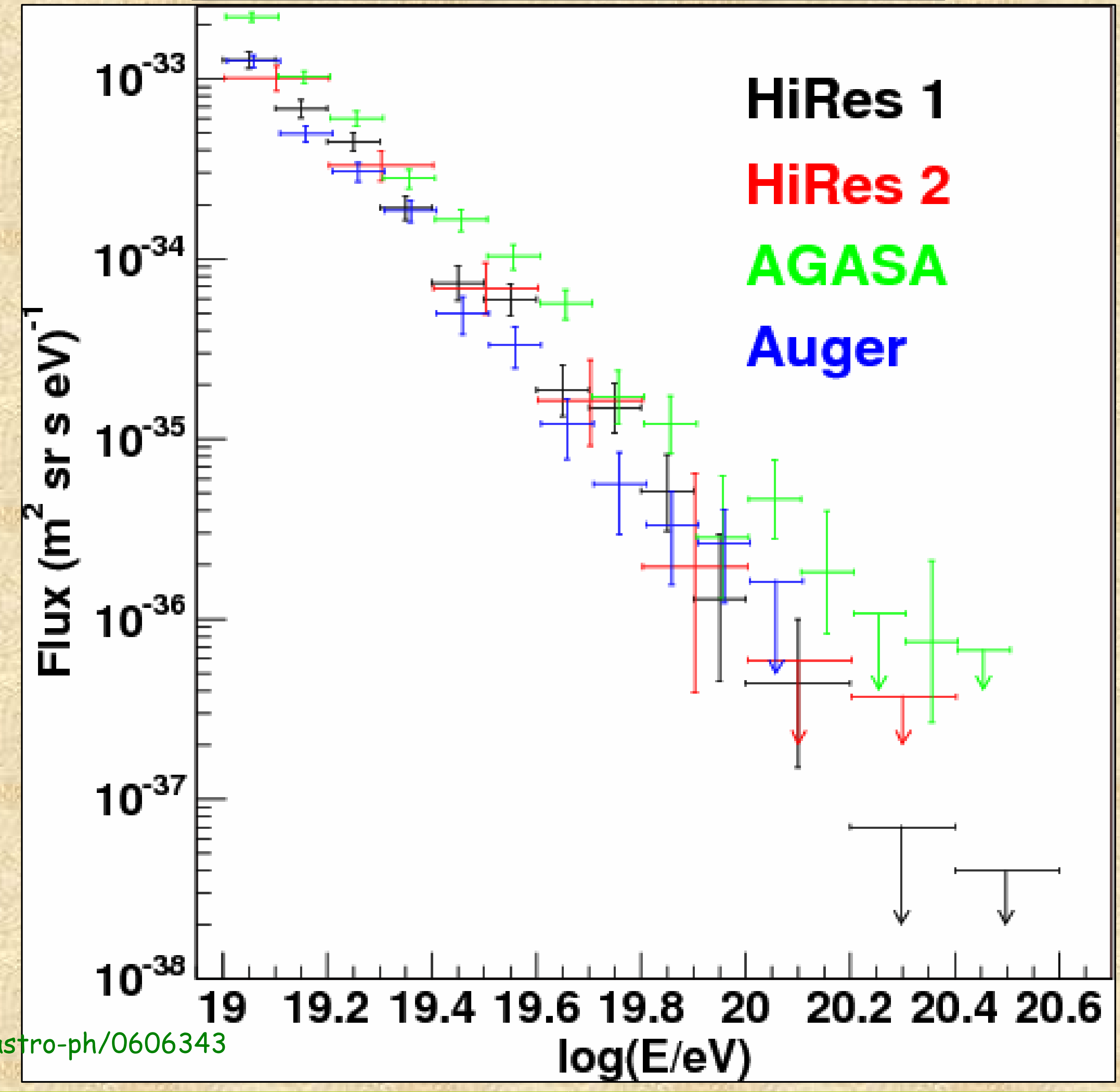


First Auger Spectrum !!

107% AGASA exposure
Statistics as yet insufficient to draw conclusion on GZK cutoff



Comparison of Experimental Spectra



Connolly et al., astro-ph/0606343

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

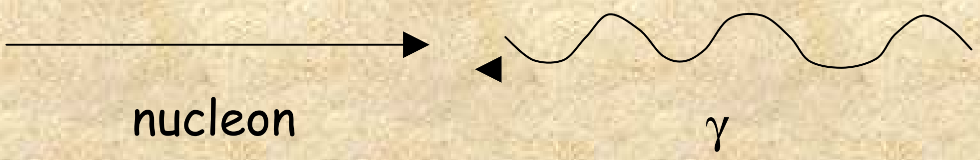
1.) electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 50 Mpc.

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

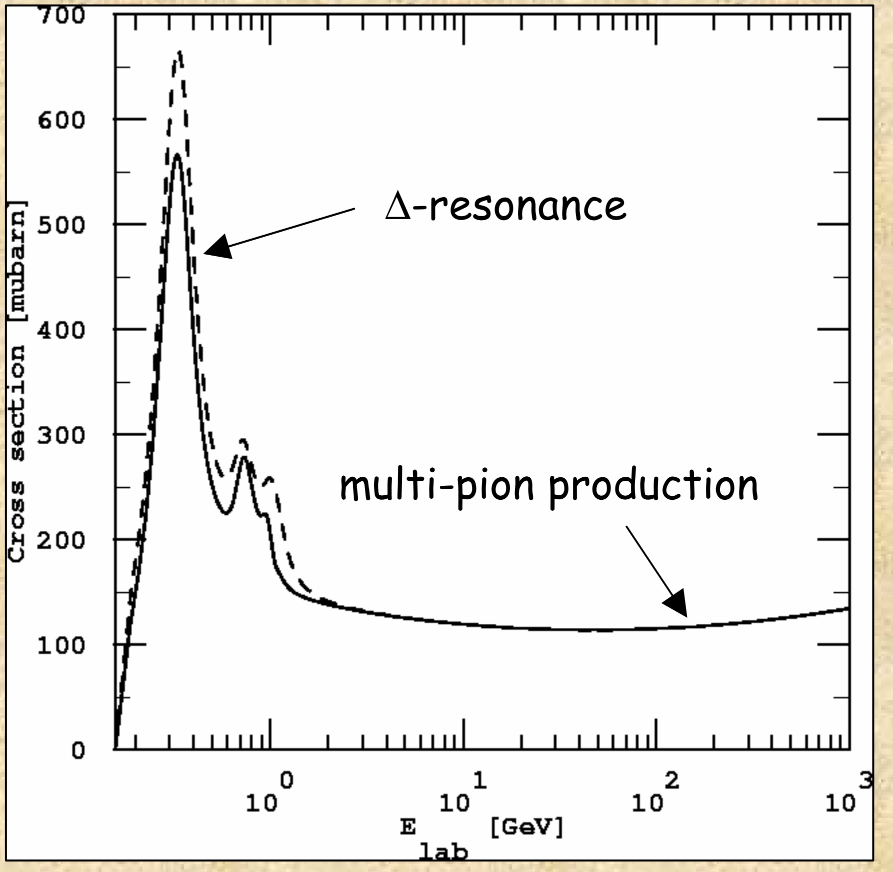
3.) The observed distribution seems to be very isotropic (except for a possible interesting small scale clustering)

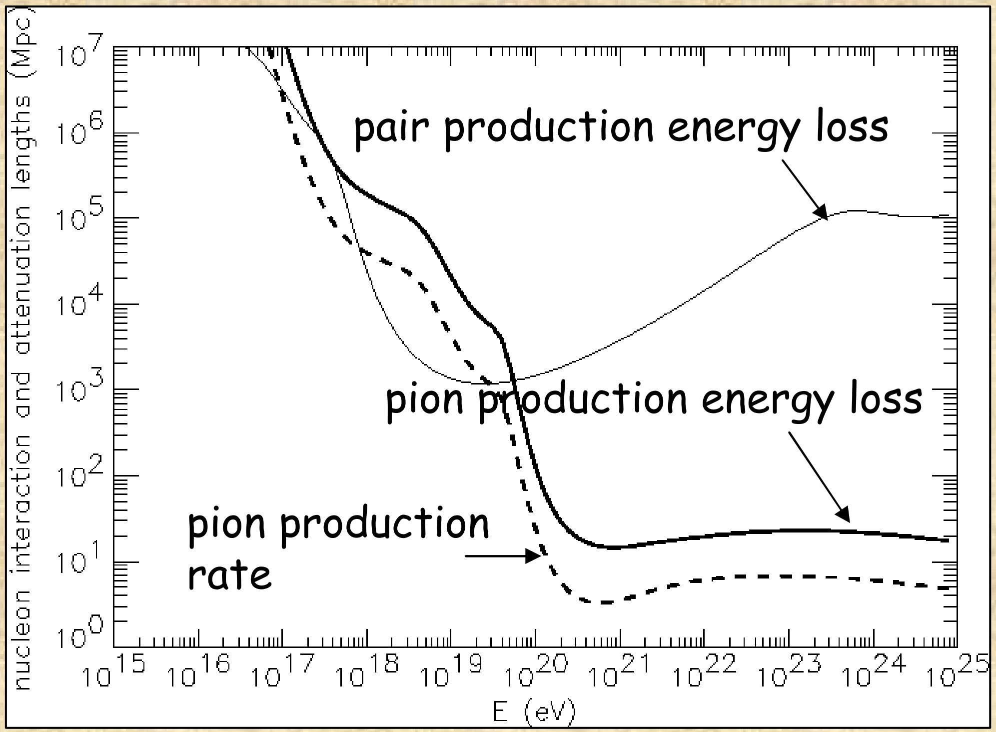
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



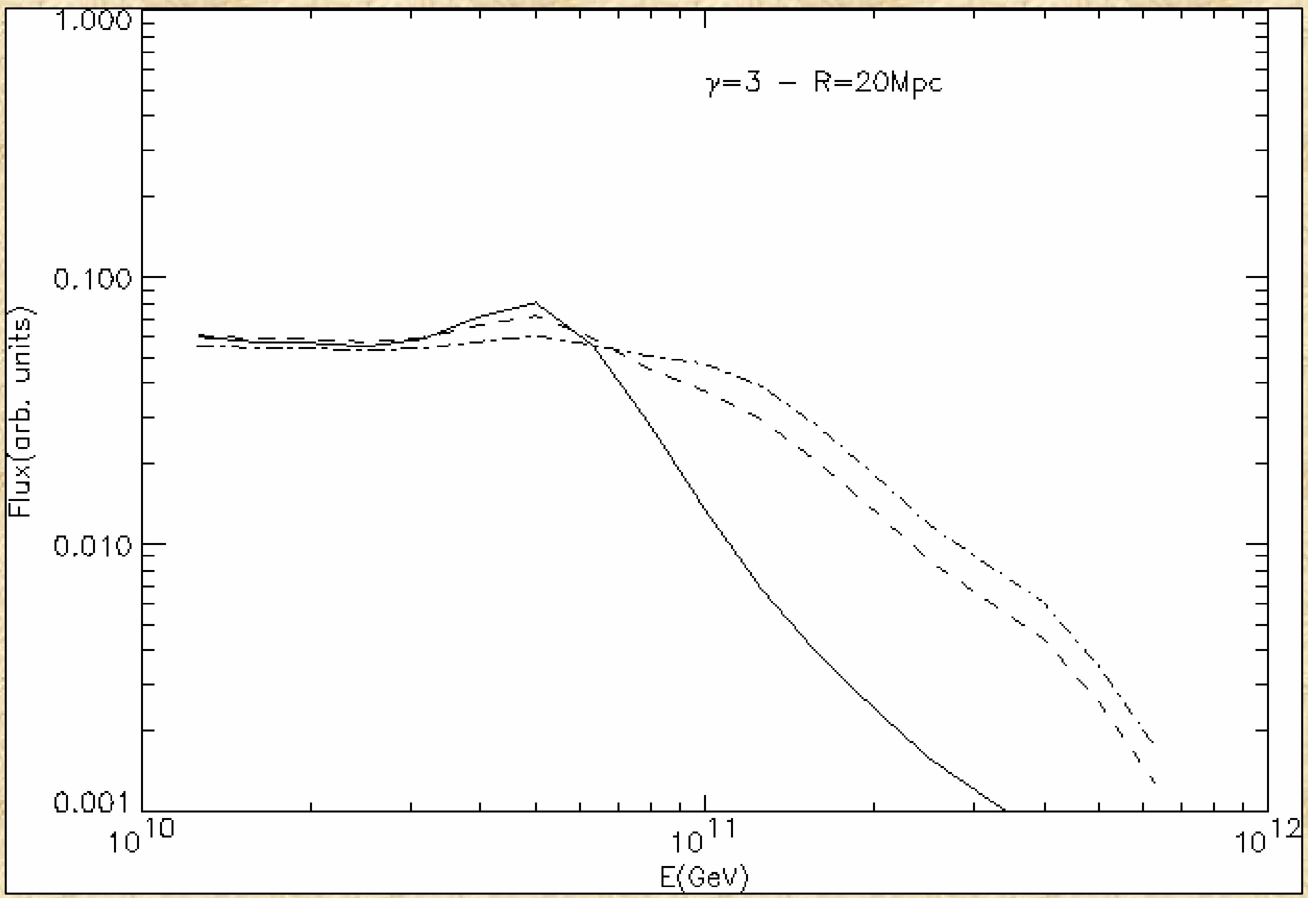
$$E_{\rm th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4 \cdot 10^{19}\,\mathrm{eV}$$





⇒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)

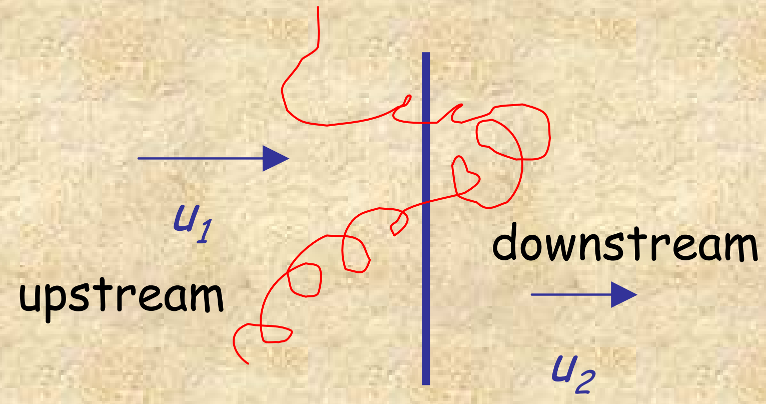


Observable spectrum for an E^{-3} injection spectrum for a distribution of sources with overdensities of 1, 10, 30 (bottom to top) within 20 Mpc, and otherwise homogeneous.

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

1st Order Fermi Shock Acceleration

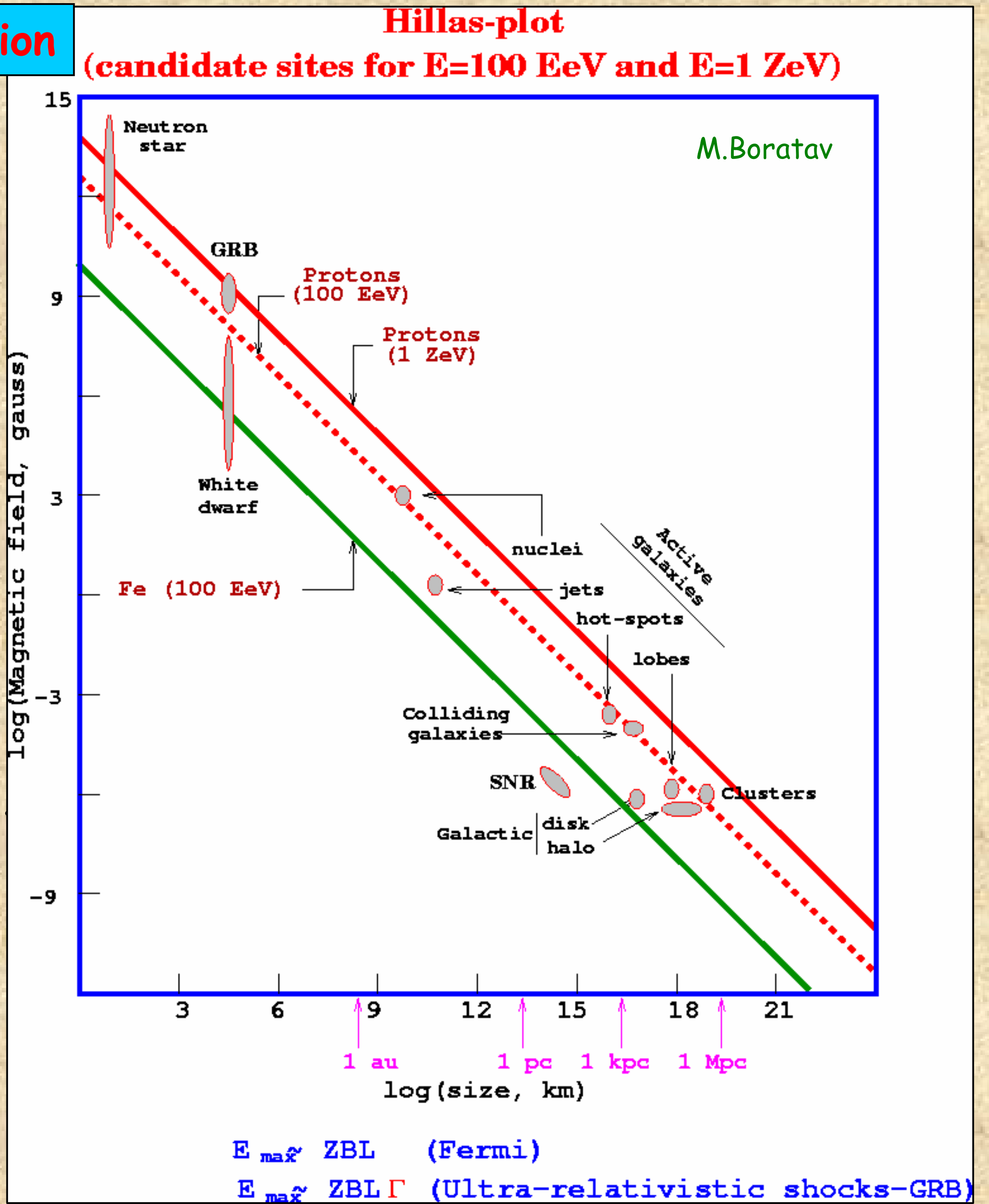
The most widely accepted scenario of cosmic ray acceleration



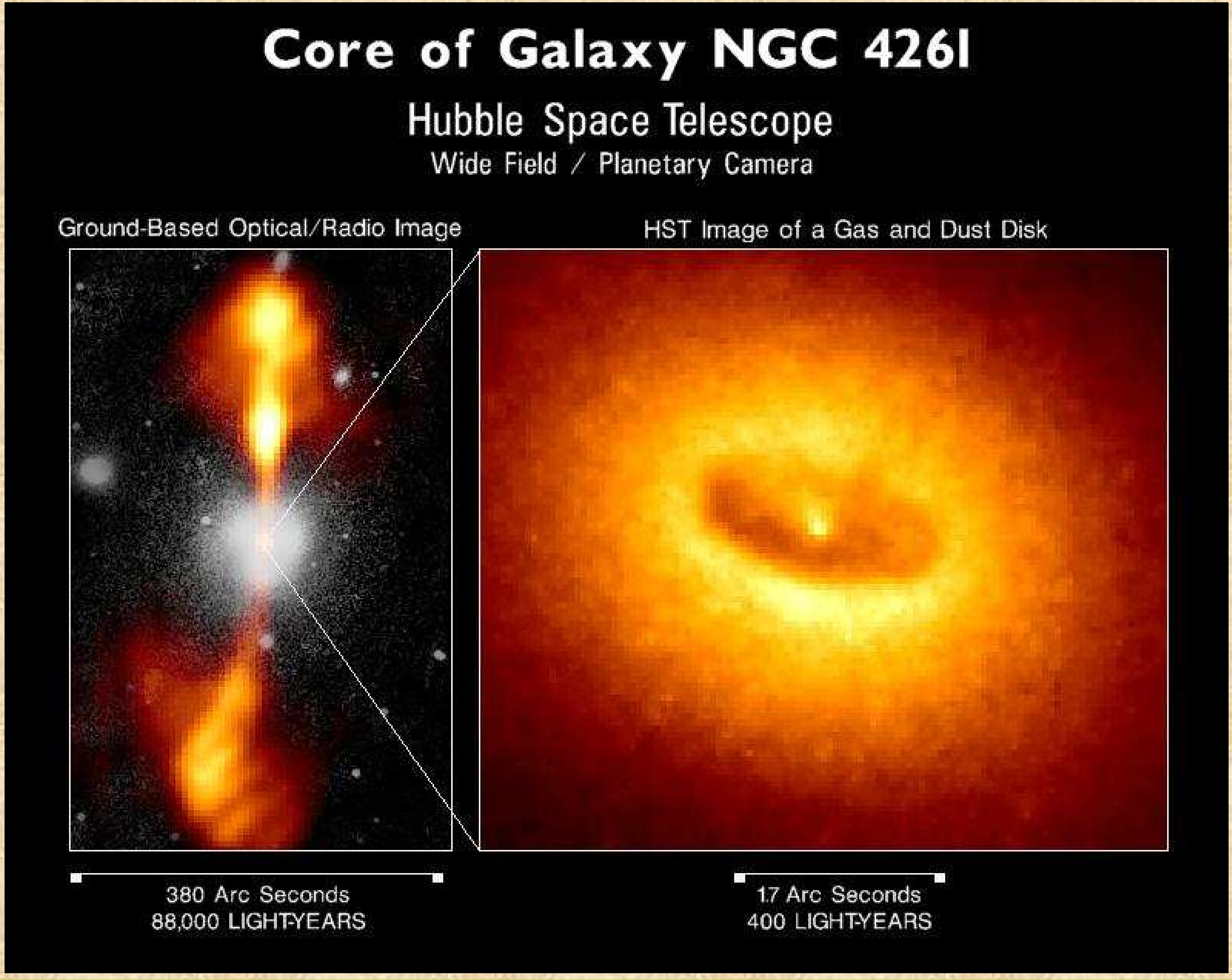
Fractional energy gain per shock crossing $\sim u_1 - u_2$ on time scale $\sim r_L / u_2$.

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.

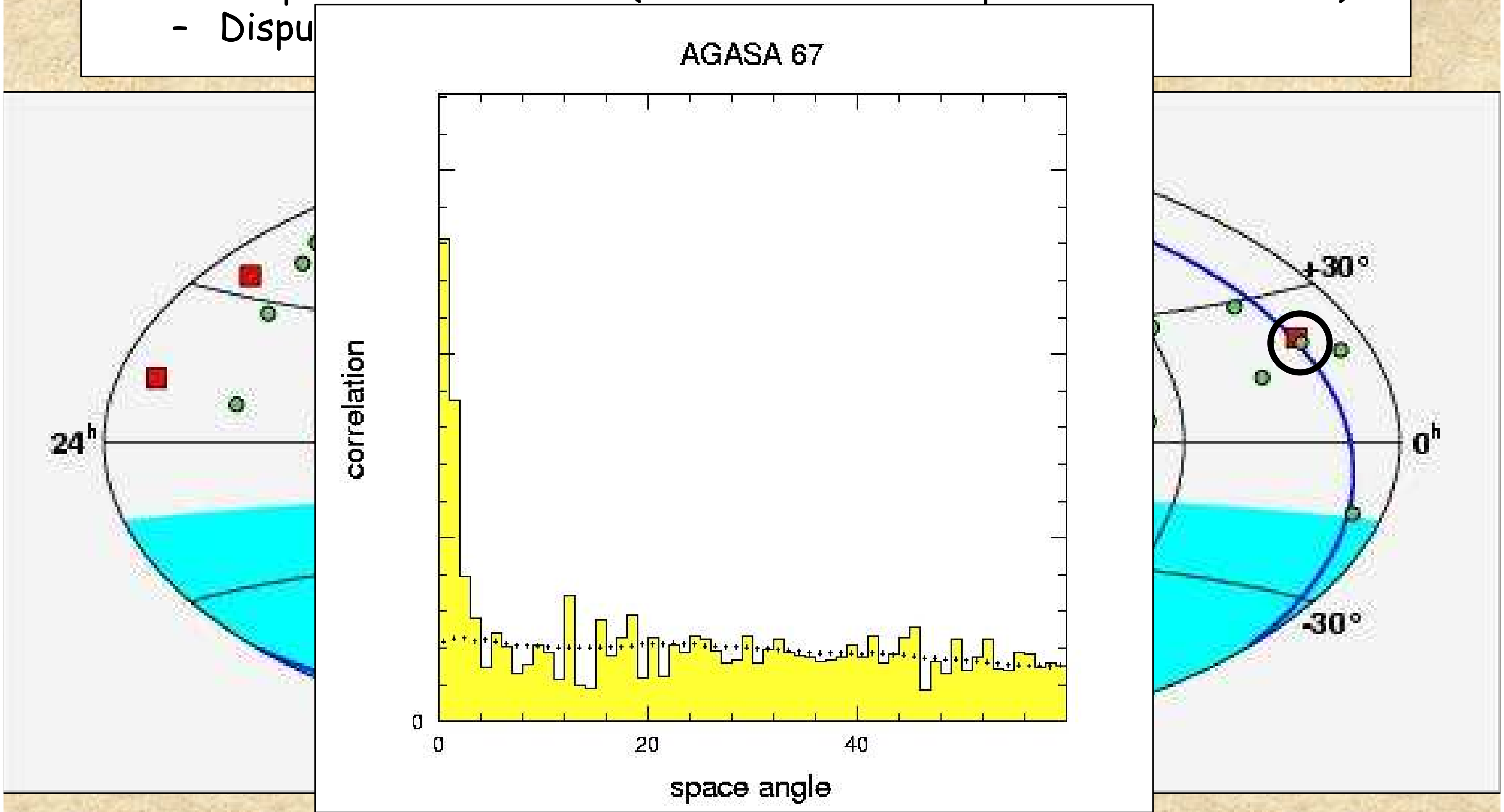


A possible acceleration site associated with shocks in hot spots of active galaxies



Arrival Direction Distribution >4×10^{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.

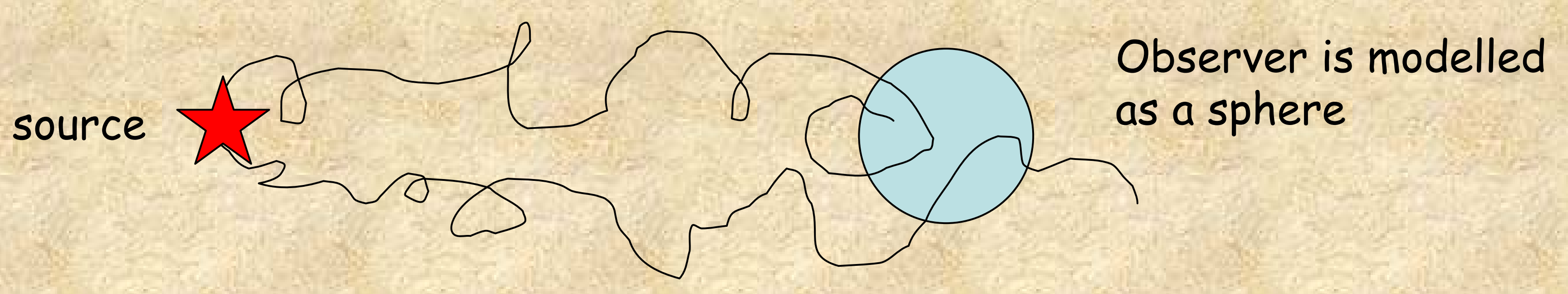
However, very little is known about about B_{XG}: It could be as small as 10^{-20} G (primordial seeds, Biermann battery) or up to fractions of micro Gauss if concentrated in clusters and filaments (equipartition with plasma).

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

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

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

Principle of deflection Monte Carlo code

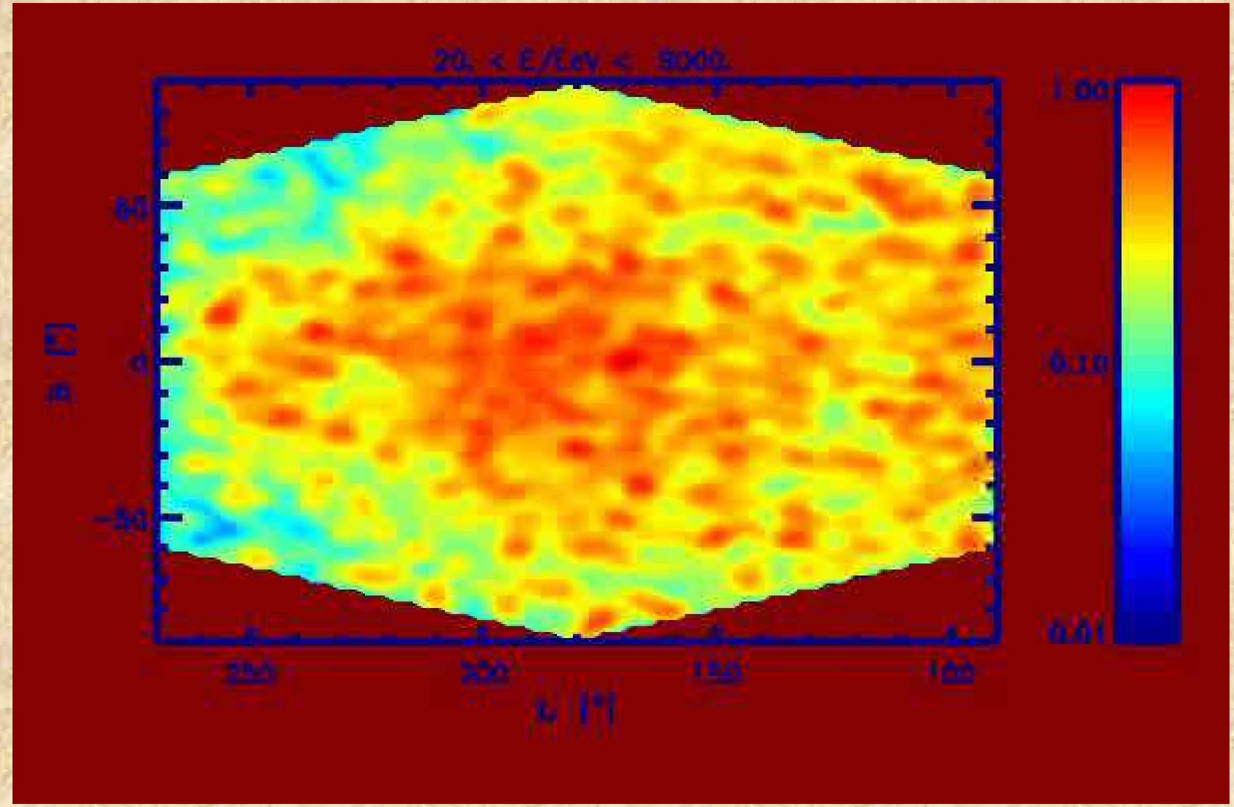


A particle is registered every time a trajectory crosses the sphere around the observer. This version to be applied for individual source/magnetic field realizations and inhomogeneous structures.

Main Drawback: CPU-intensive if deflections are considerable because most trajectories are “lost”. But inevitable for accurate simulations in highly structured enivornments without symmetries.

Effects of a single source: Numerical simulations

A source at 3.4 Mpc distance injecting protons with spectrum $E^{-2.4}$ up to 10^{22} eV
A uniform Kolmogorov magnetic field, $\langle B^2(k)\rangle \sim k^{-11/3}$, of rms strength 0.3 μG, and largest turbulent eddy size of 1 Mpc.



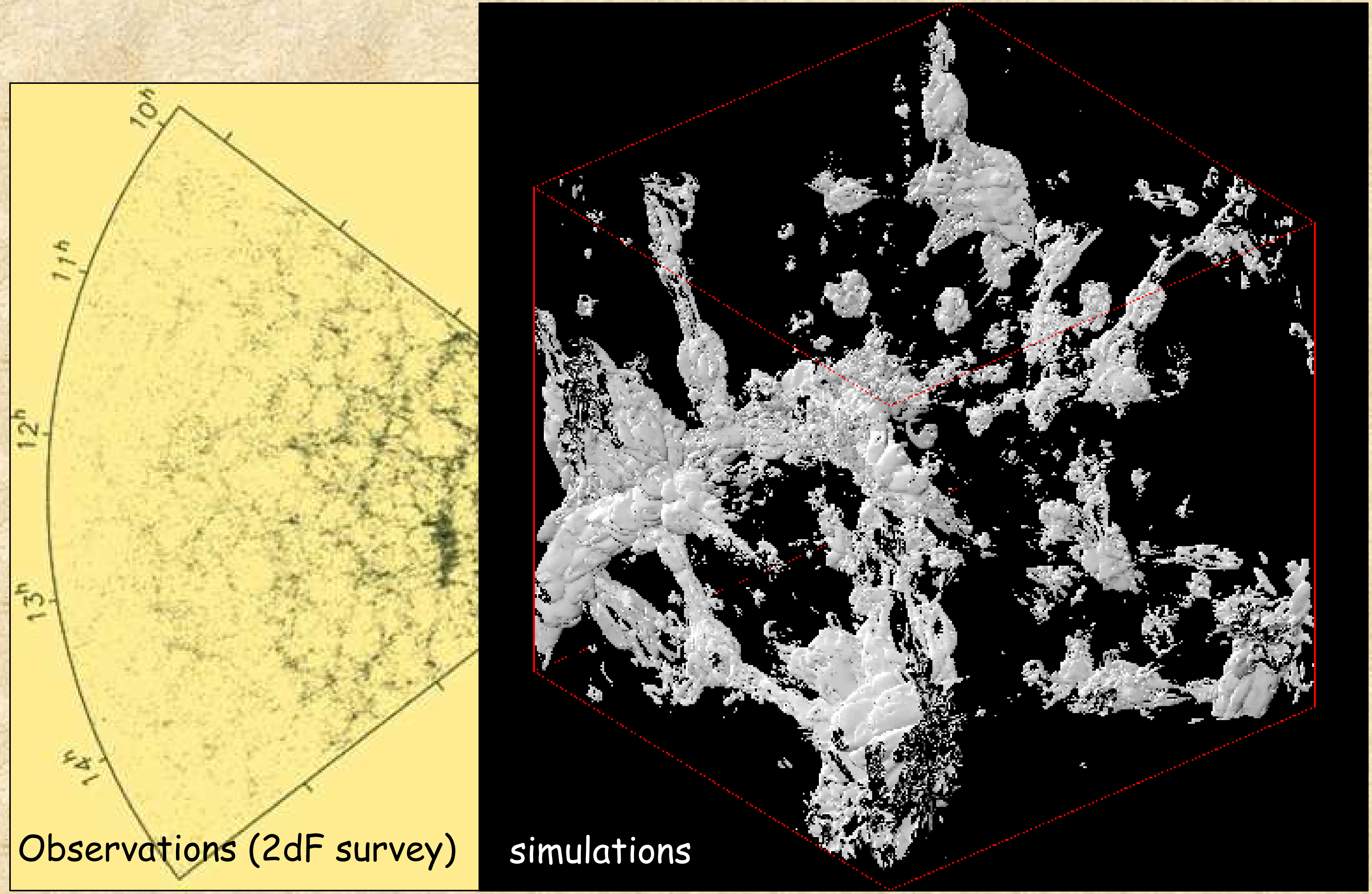
10^5 trajectories,
251 images between
20 and 300 EeV,
2.5° angular resolution

Isola, Lemoine, Sigl

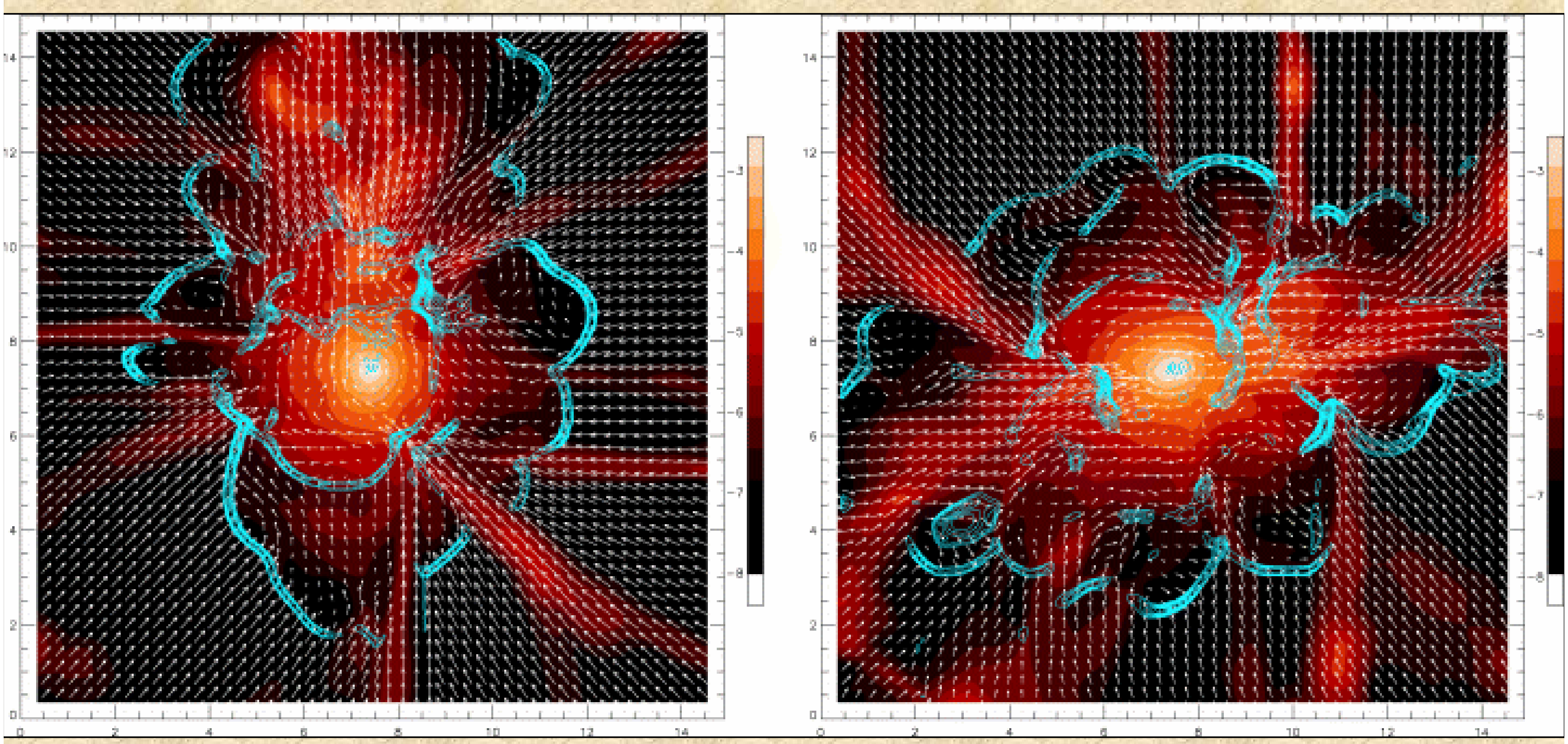
Conclusions:

1.) Isotropy is inconsistent with only one source.
2.) Strong fields produce interesting lensing (clustering) effects.

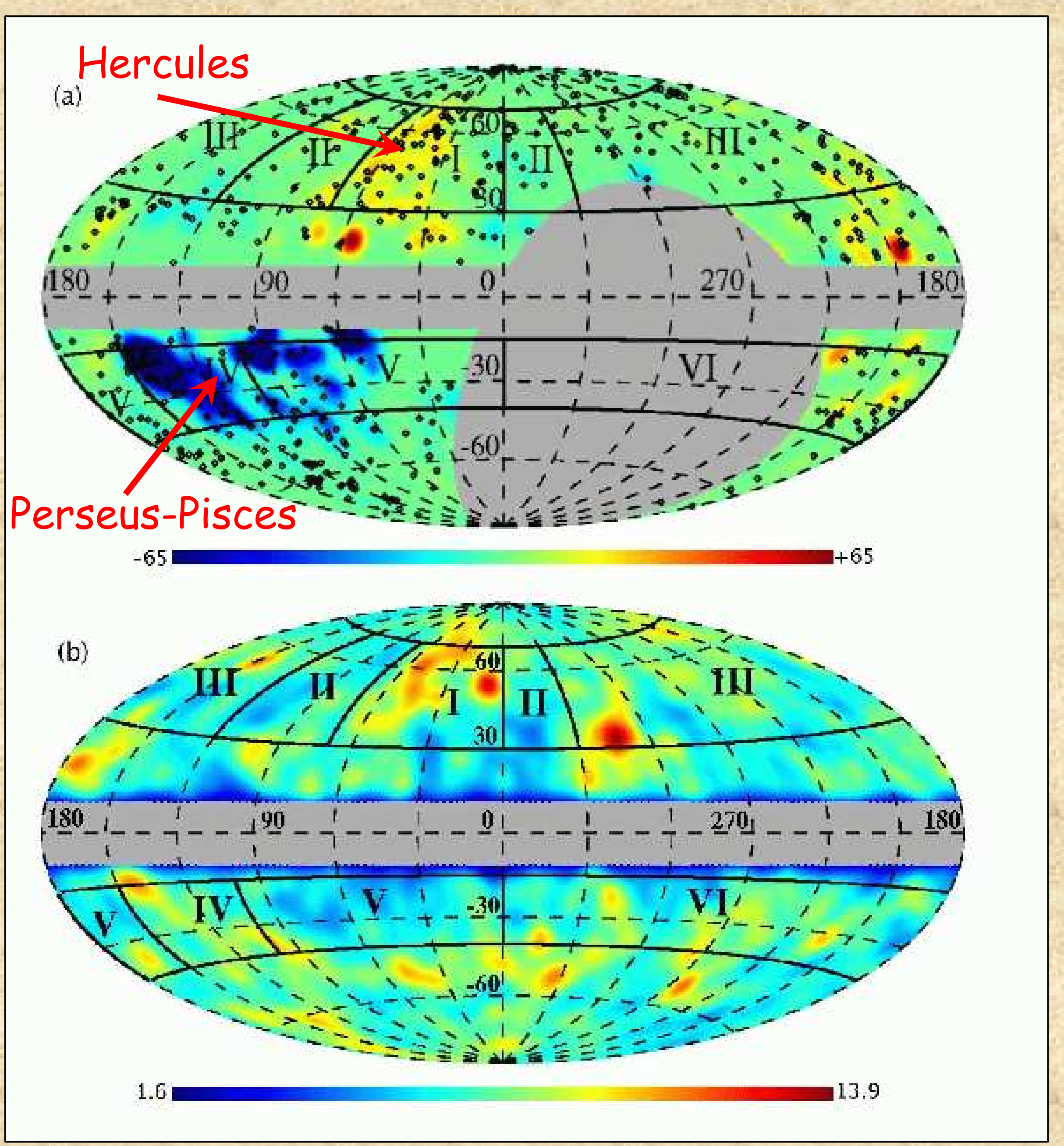
The Universe is structured



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!

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

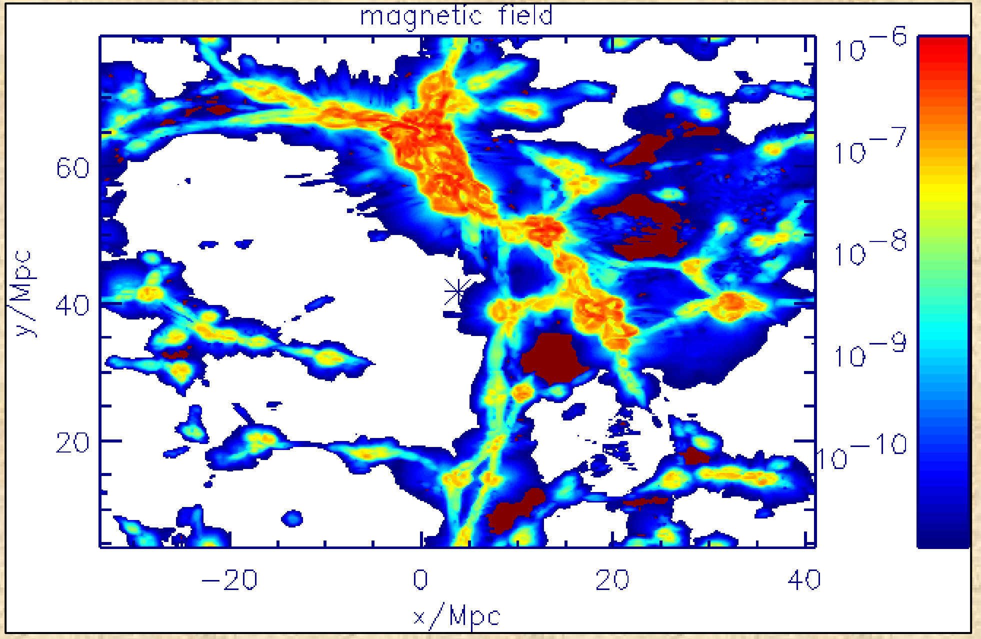
2MASS galaxy column density

Xu et al., astro-ph/0509826

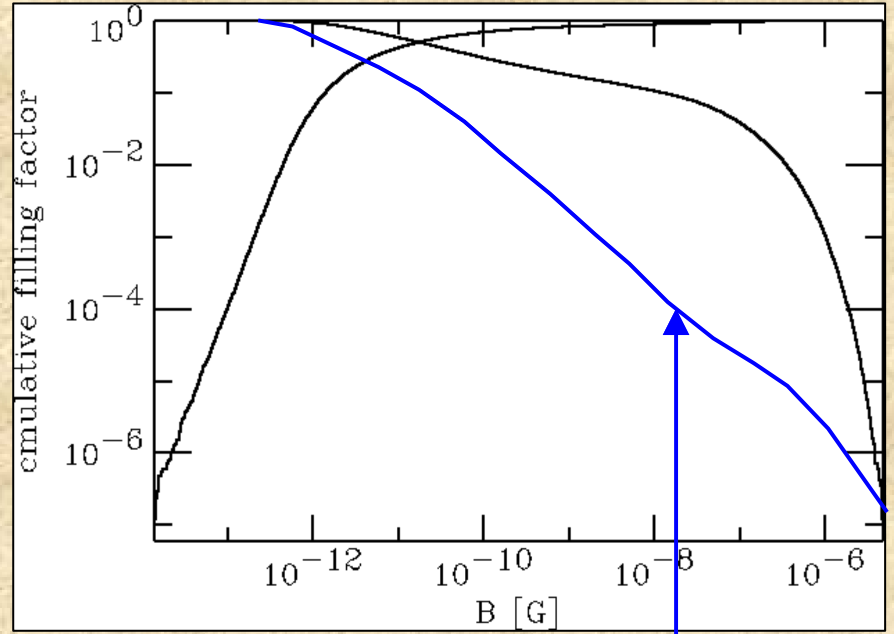
Some results on propagation in structured extragalactic magnetic fields

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

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



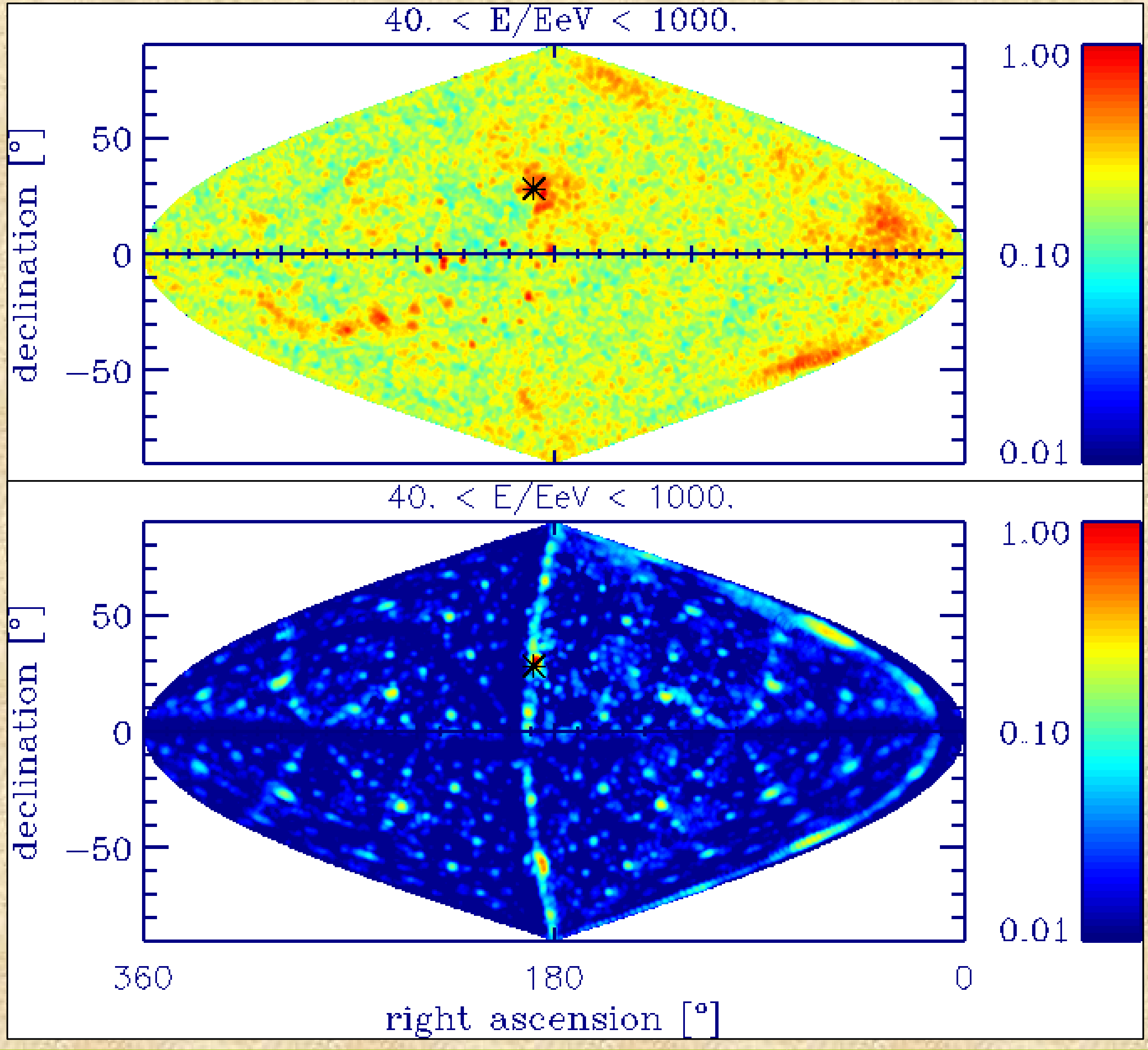
Magnetic field filling factors



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

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

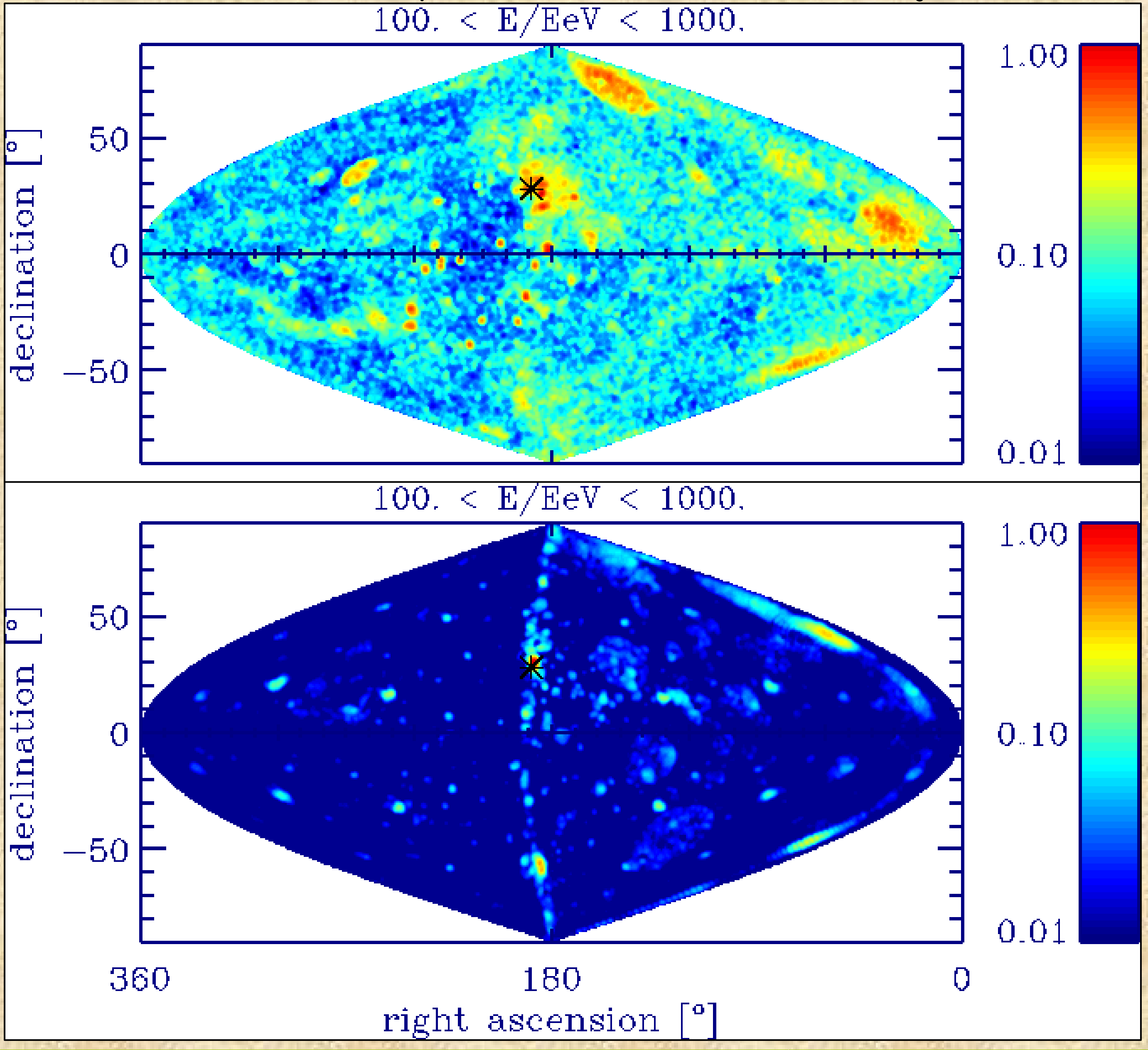
The simulated sky above 4×10^{19} eV with structured sources of density 2.4×10^{-5} Mpc^{-3} : $\sim2\times10^{5}$ simulated trajectories above 4×10^{19} eV.



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.

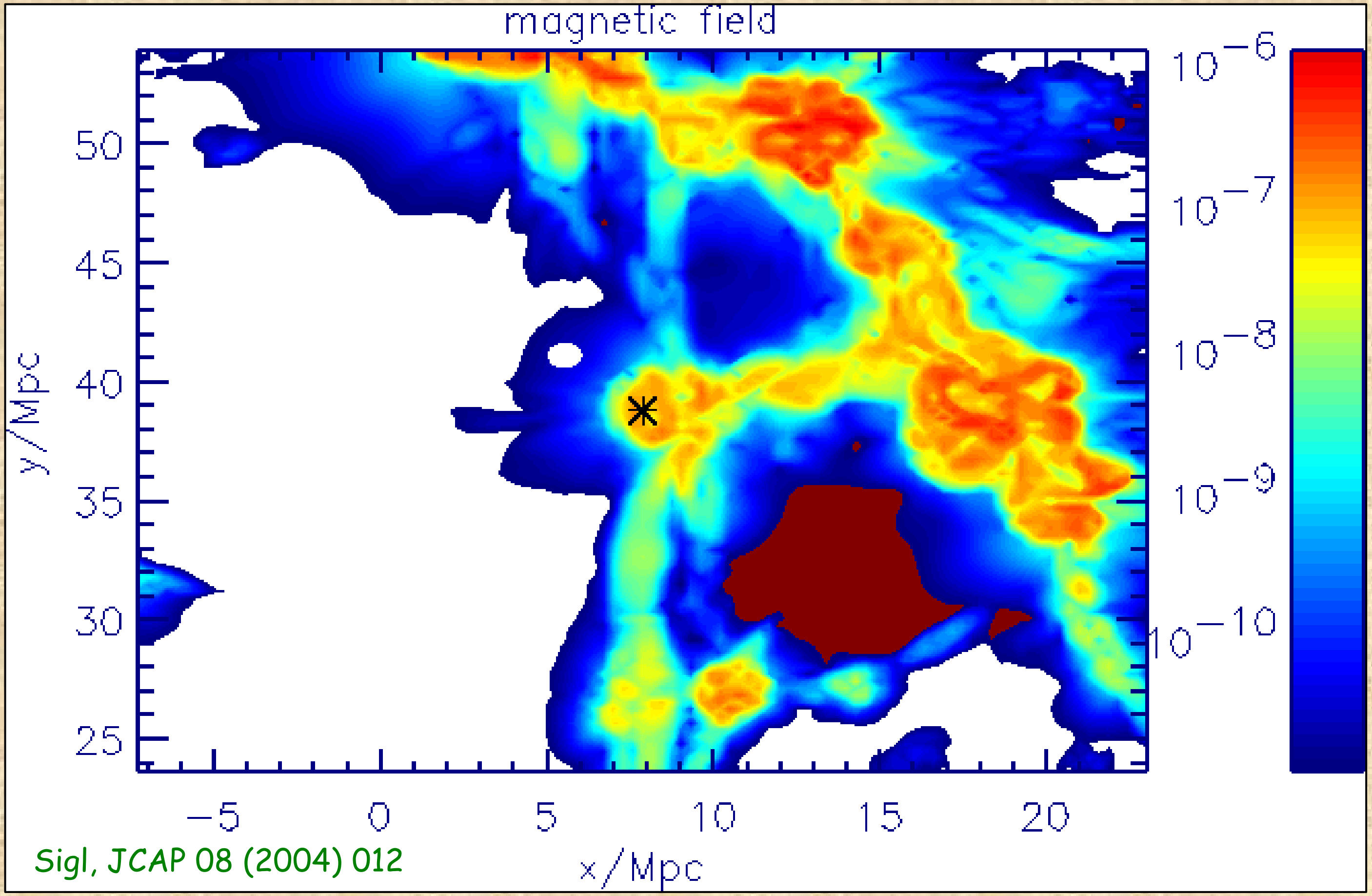


With field

Without field

Heavy Nuclei: Structured Fields and Individual Sources

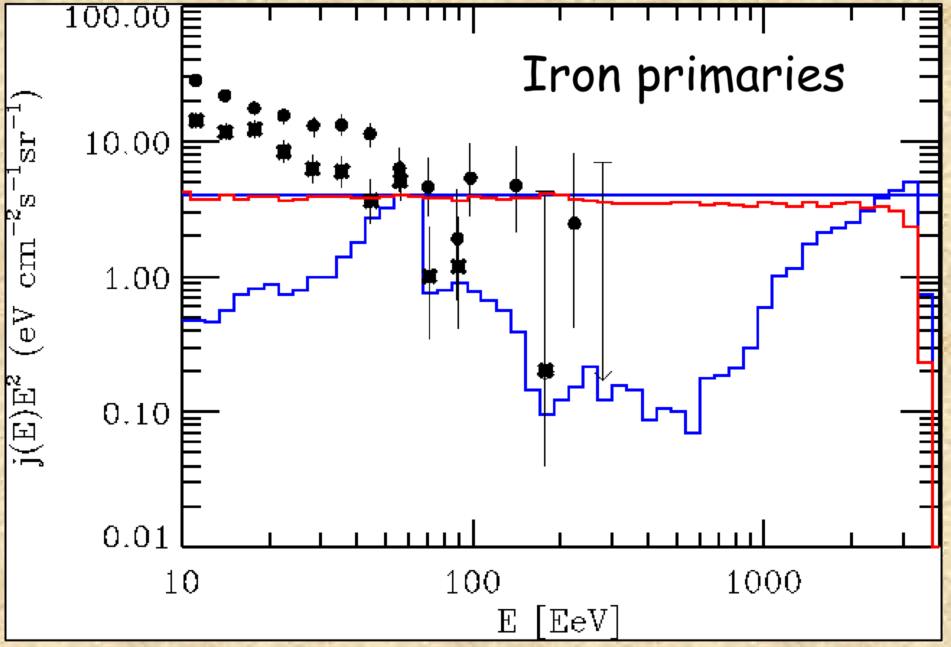
Spectra and Composition of Fluxes from Single Discrete Sources considerably depend on Source Magnetization, especially for Sources within a few Mpc.

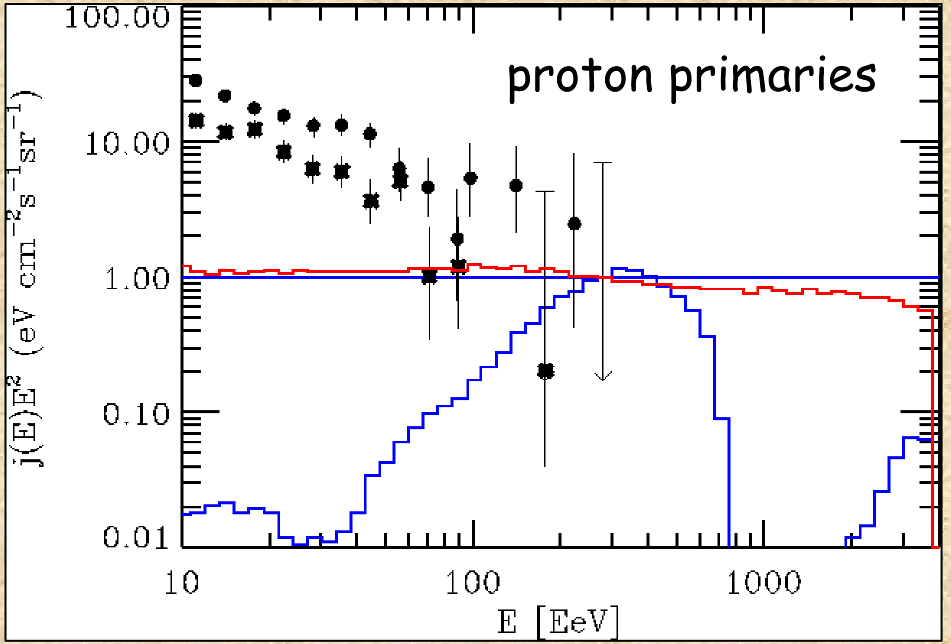


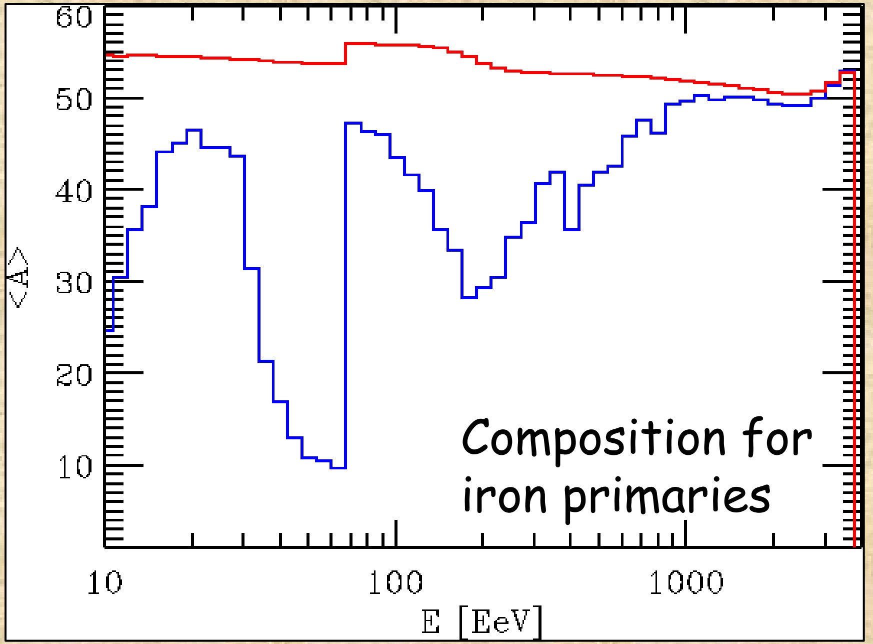
Sigl, JCAP 08 (2004) 012

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

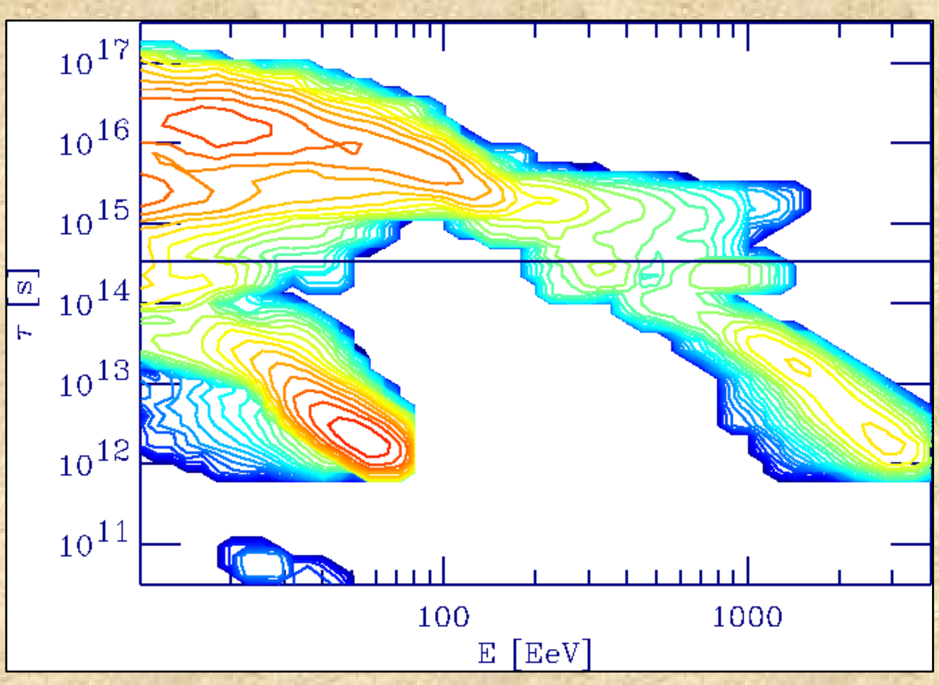
With field = blue
Without field = red
Injection spectrum = horizontal line

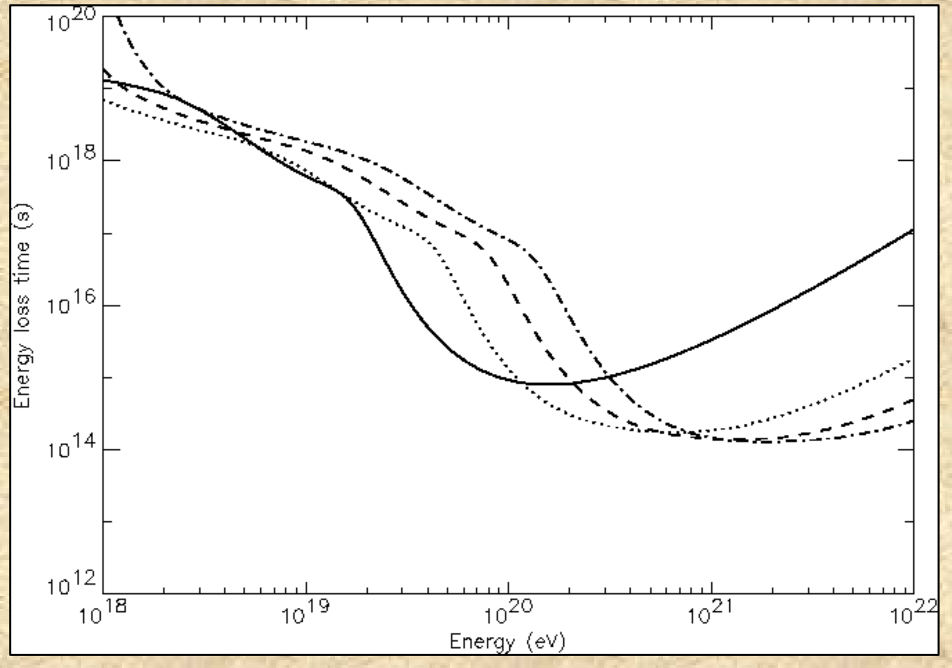






Importance of deflection obvious from comparing energy loss/spallation time scales with delay times

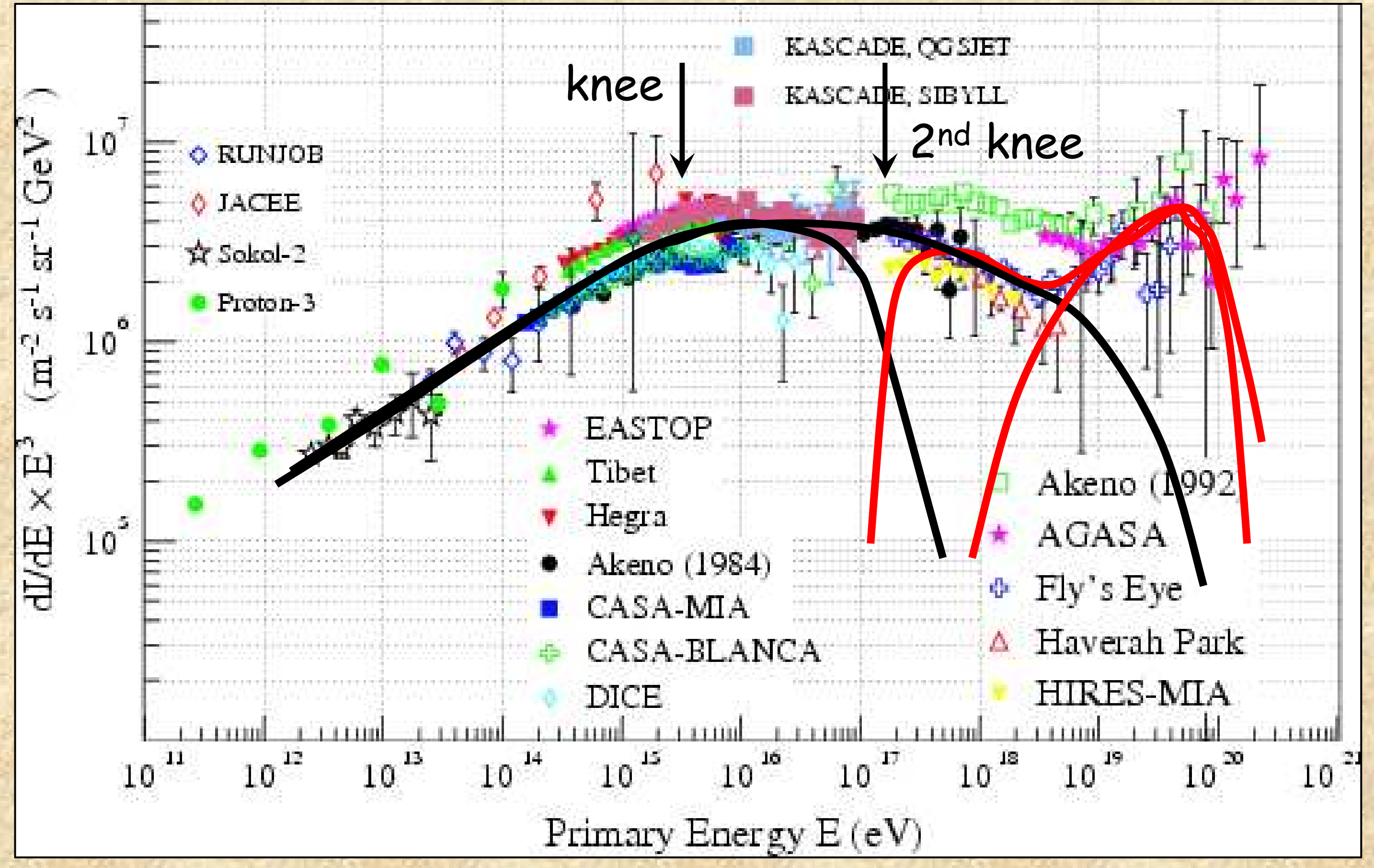




horizontal line=straight line propagation time
low delay-time spike at ~50 EeV due to spallation nucleons produced outside source field.

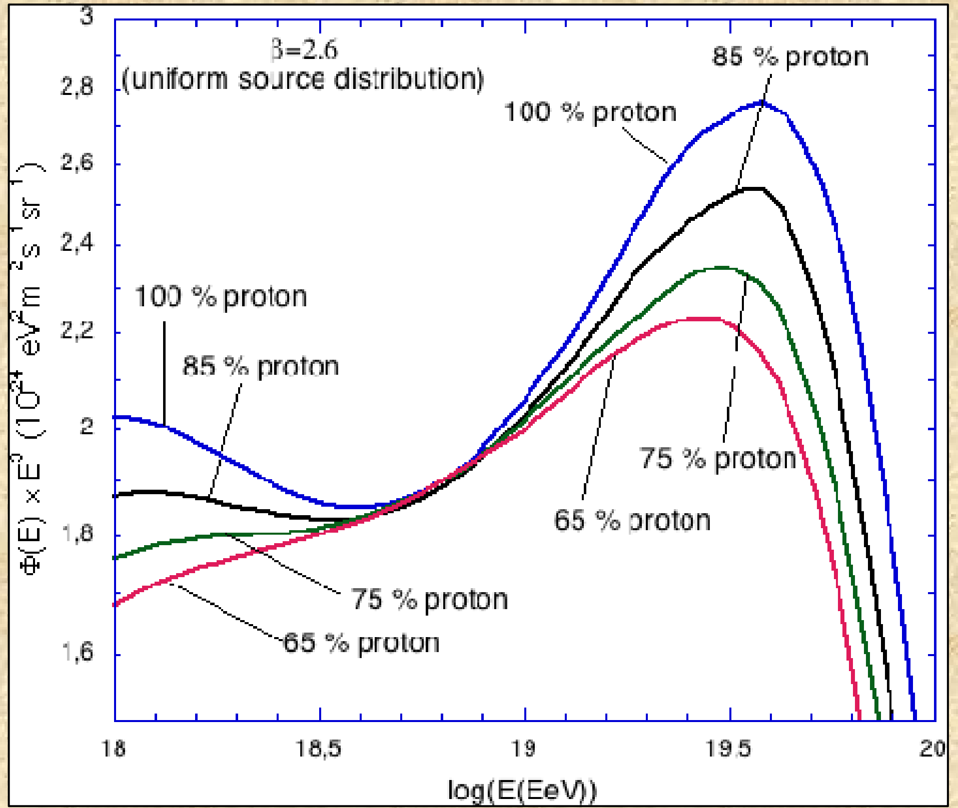
Energy loss times for helium (solid), carbon (dotted), silicon (dashed), and iron (dash-dotted).

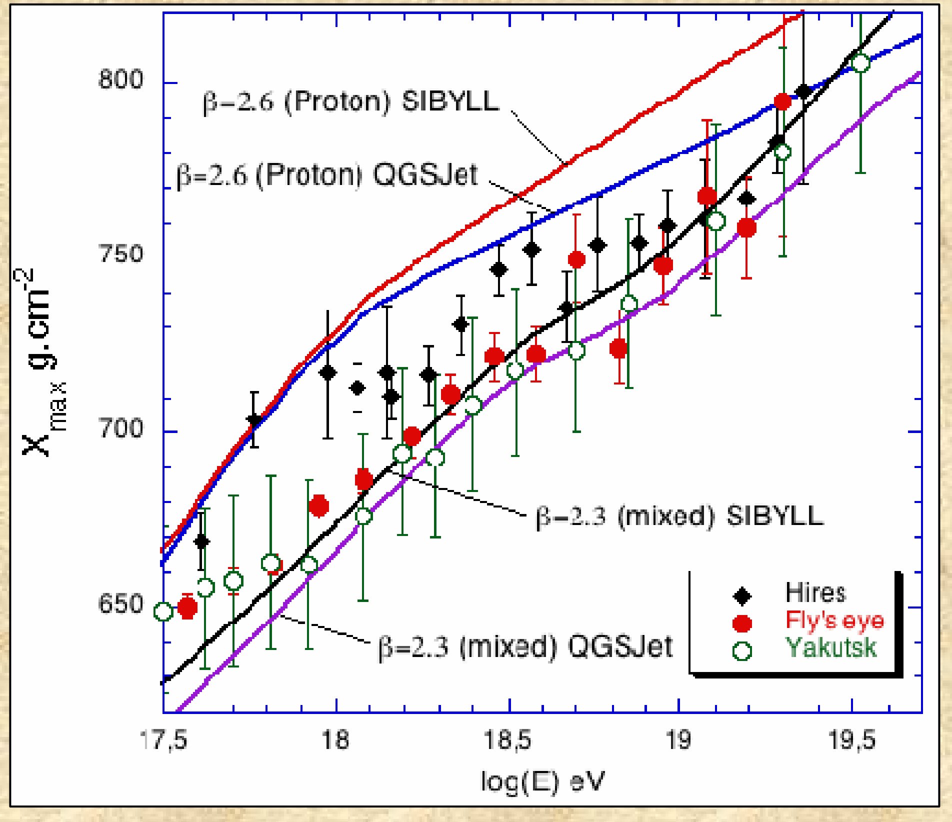
Chemical Composition, Magnetic Fields, Nature of the Ankle



"Conventional Scenario":
The ankle at ~5×10^{18} eV is a cross-over from a 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.

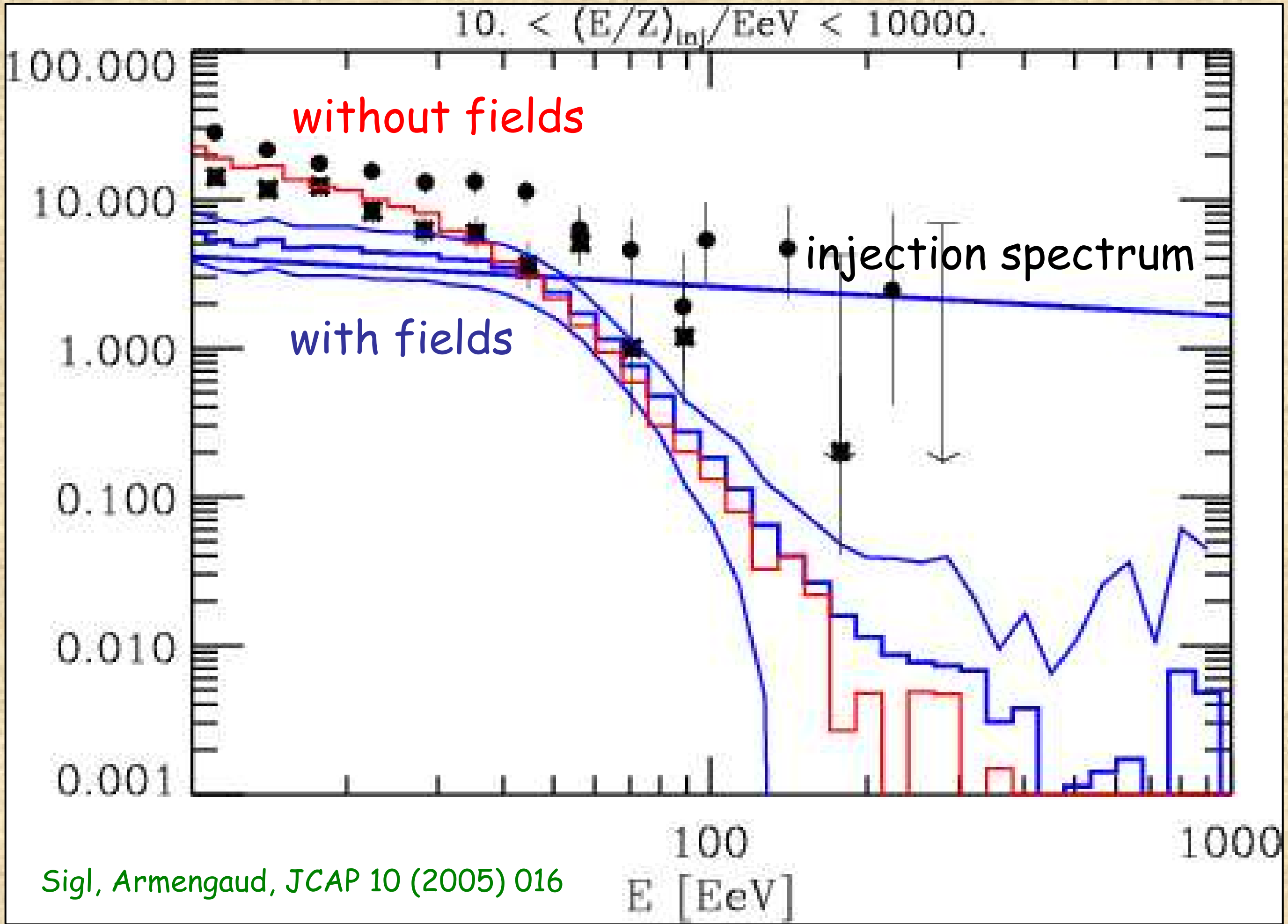




A significant iron admixtures does not reproduce the ankle in the absence of magnetic fields.

Experimental situation on chemical abundances is unsettled.

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



Injection of mixed composition (solar metallicity) with spectrum $E^{-2.2}$ up to 10^{21} eV and a source density ~ 2.4×10^{-5} Mpc^{-3}.

Conclusion: In the absence of fields, flux observed above 10^{19} eV requires too hard an injection spectrum to fit 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:

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

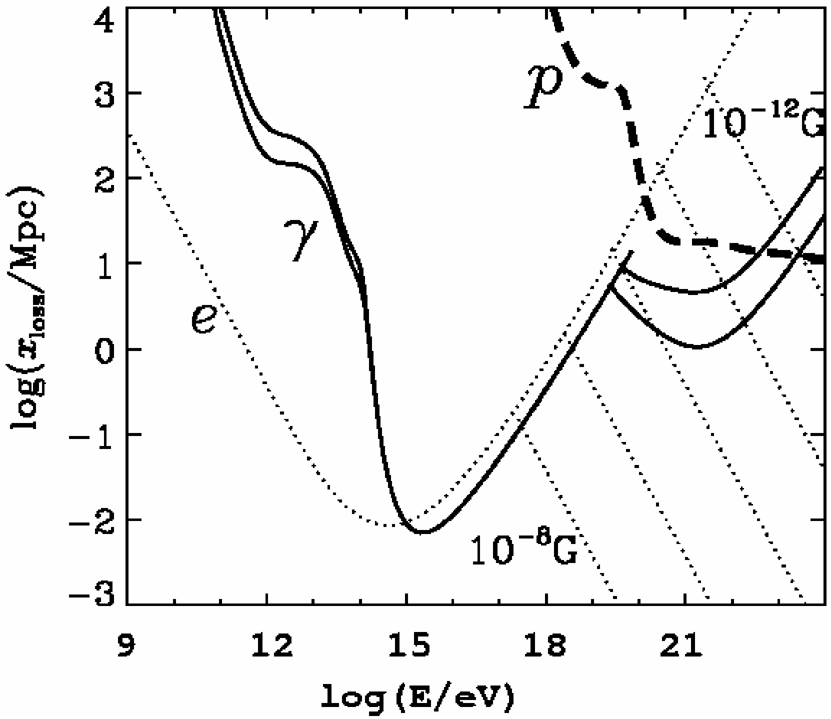
during propagation ("cosmogenic") or in sources (AGN, GRB, ...)

=> 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

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

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

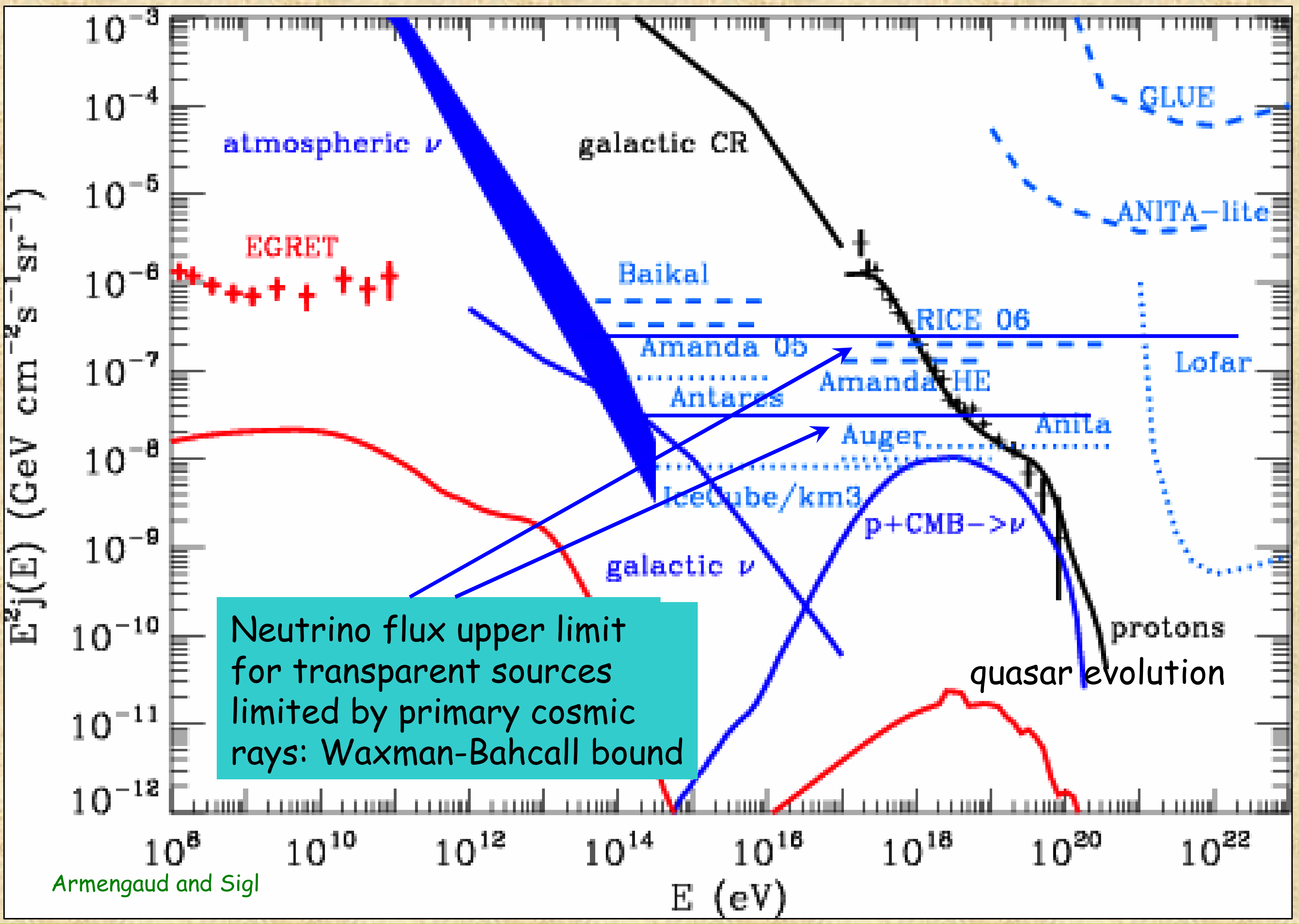
with fractional energy loss η of leading e

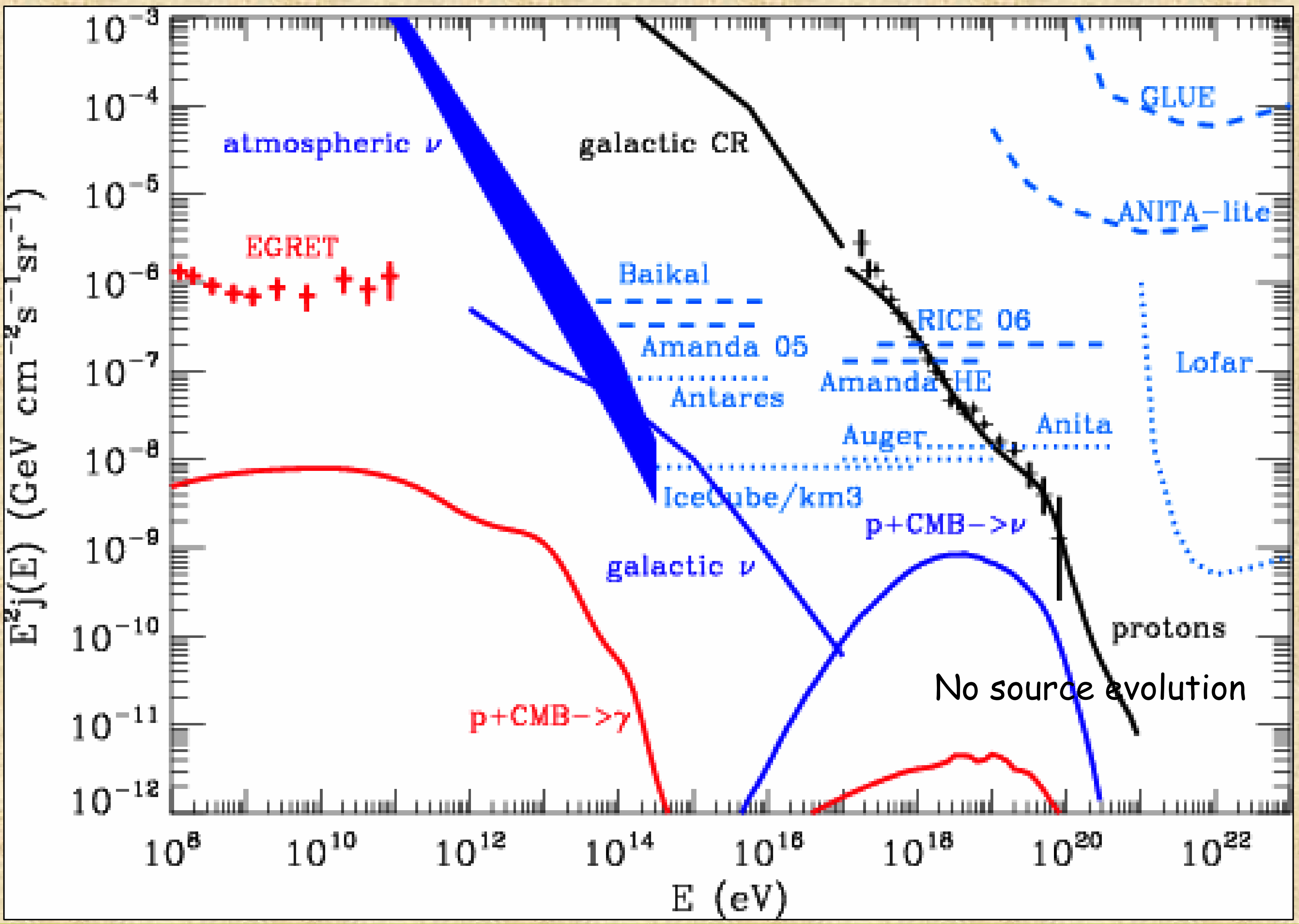
$$\eta \simeq 1.768\left(\frac{s}{m_e^2}\right)^{-3/4} \quad (s \gg m_e^2)\,.$$

- 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





atmospheric ν
galactic CR
GLUE
ANITA−lite
EGRET
Baikal
RICE 06
Amanda 05
Lofar
Amanda HE
Antares
Anita
Auger
IceCube/km3
p+CMB−>ν
galactic ν
protons
No source evolution
p+CMB−>γ
$E^2 j(E)$ (GeV cm^{-2}s^{-1}sr^{-1})
E (eV)

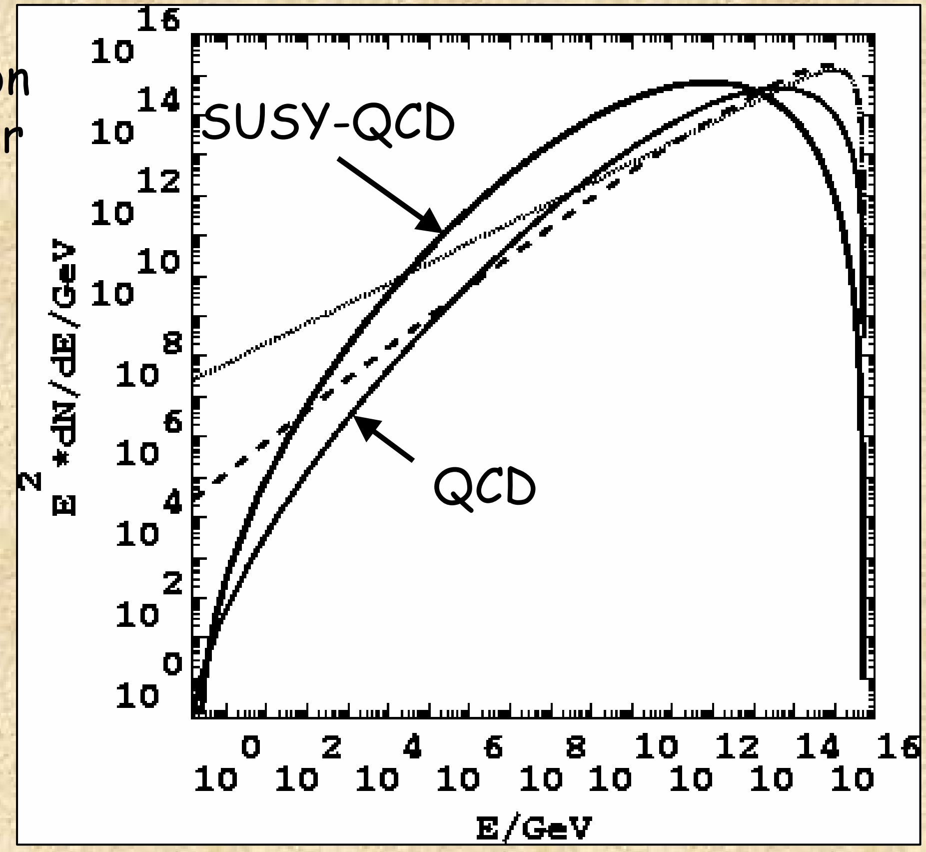
Application: Flux calculations in Top-Down scenarios

a) Assume mode of X-particle decay in GUTs

$$\text{Example}: X \rightarrow l + \underbrace{q + q}_{\text{hadronic jets}}$$

b) Determine hadronic quark fragmentation spectrum extrapolated from accelerator data within QCD:

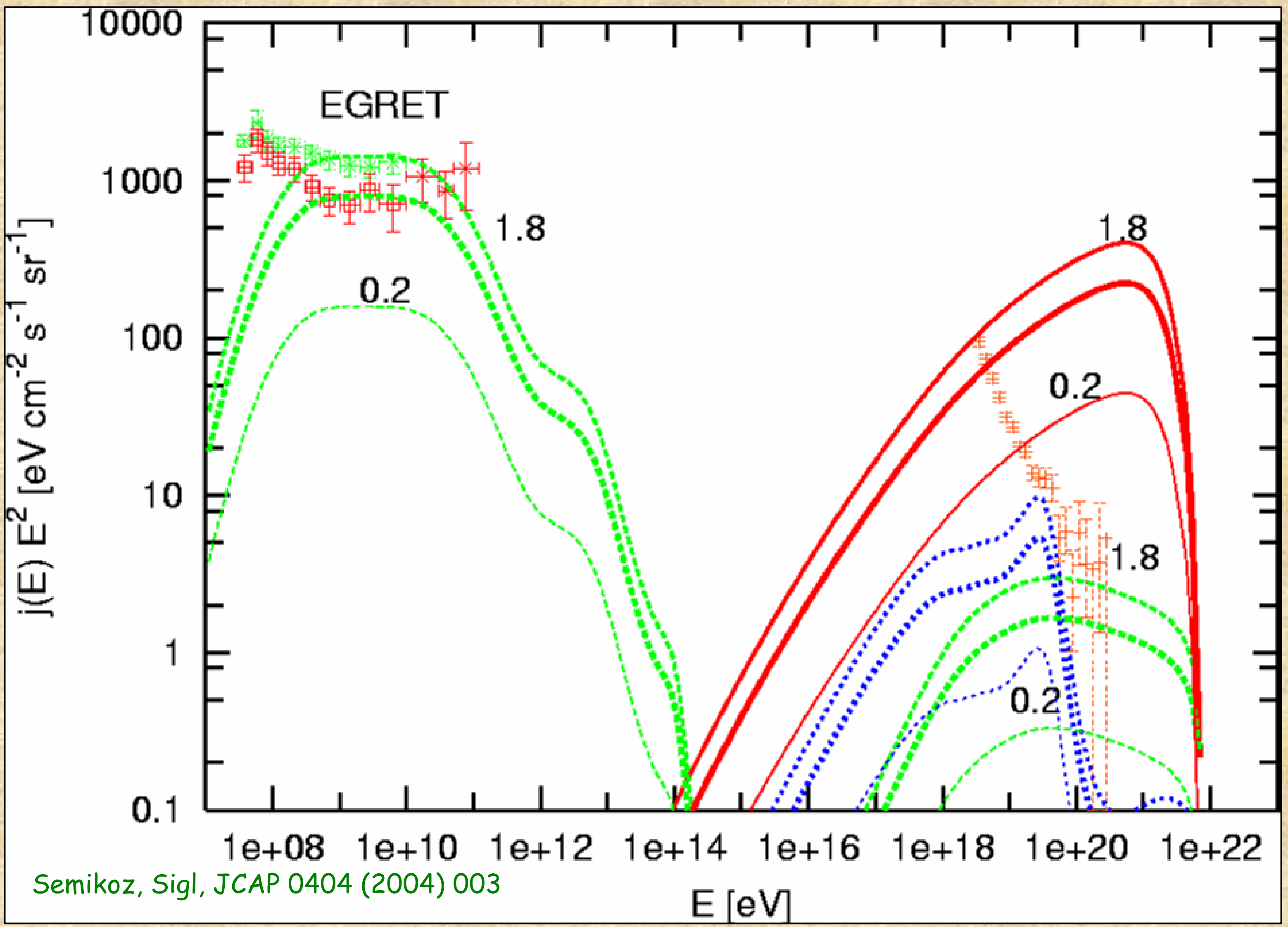
modified leading log approximation (Dokshitzer et al.) with and without supersymmetry versus older approximations (Hill). More detailed calculations by Kachelriess, Berezinsky, Toldra, Sarkar, Barbot, Drees: results not drastically different.



Fold in meson decay spectra into neutrinos and γ-rays.

c) fold in injection history and solve the transport equations for propagation.

A typical example:



Semikoz, Sigl, JCAP 0404 (2004) 003

In general, the ratio of γ-rays to nucleons is too high to explain highest energy cosmic rays without overproducing GeV γ-ray background.

$X \rightarrow q + q$, $m_X = 2\times10^{13}\,\mathrm{GeV}$, $B = 10^{-12}\,\mathrm{G}$, homogeneous sources with $\dot{\rho}_X \propto t^{-3}$

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

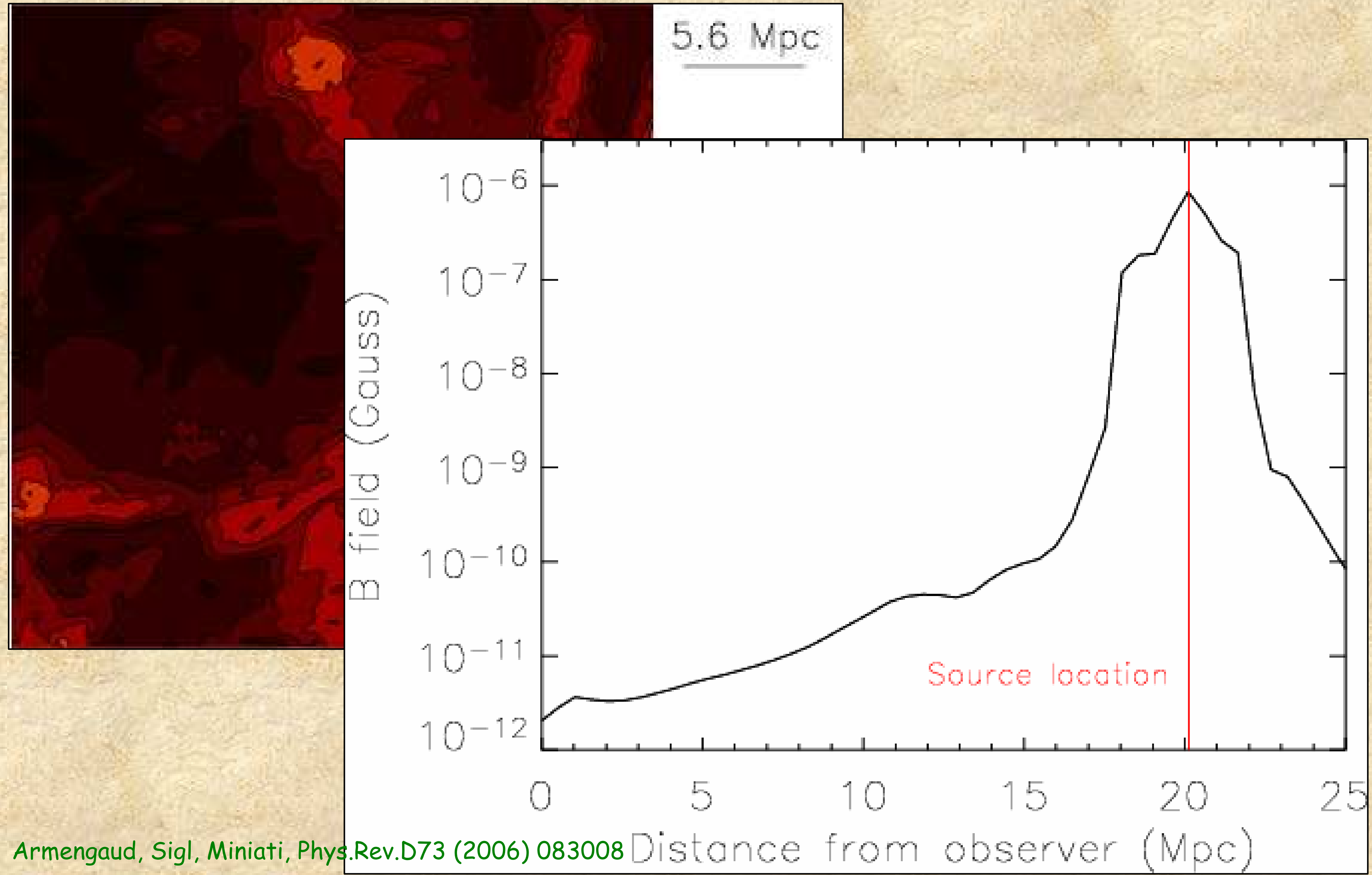
Numerous connections:

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

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

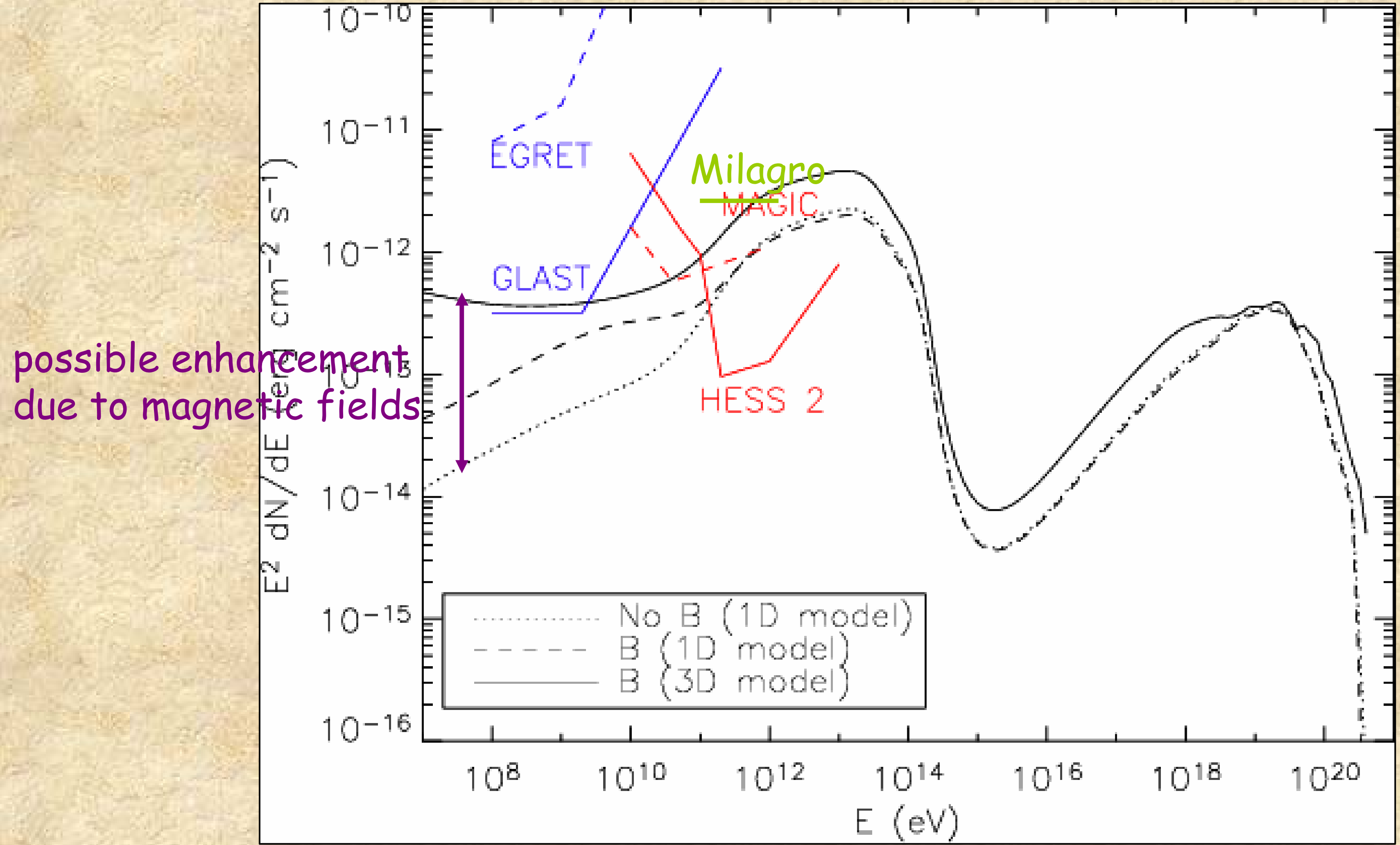
For proton spectra steeper than $\sim E^{-2}$, the sub-GeV photon flux is dominated by synchrotron photons from pair production. Pairs produced by protons appear below $\sim 10^{17}\,$eV which in $\sim 0.1\,$G fields ends up in synchrotron photons below $\sim 1\,$GeV.

Furthermore, the EGRET limit on $\gamma-$rays from clusters around 100 MeV gives the limit

$$\beta \lesssim 2.17 - 0.1\log_{10}(\eta/0.01)$$

on the low energy proton spectrum $E^{-\beta}$ contributing a fraction η to the CR flux at $10^{19}\,$eV to avoid overproduction from $pp \to \pi \to \gamma$ processes.

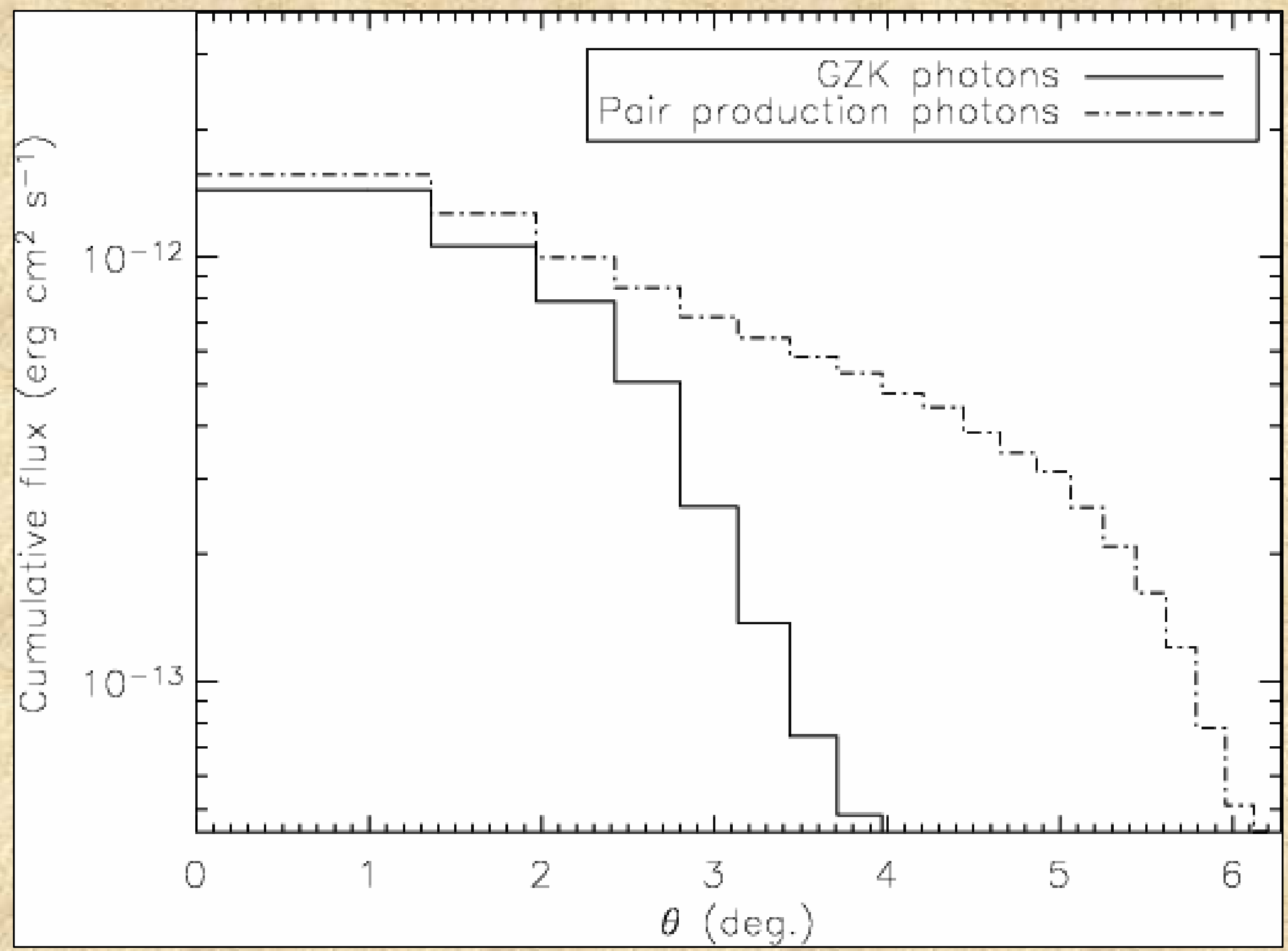
Source at 20 Mpc, $E^{2.7}$ proton injection spectrum with 4×10^{42} erg/s above 10^{19} eV



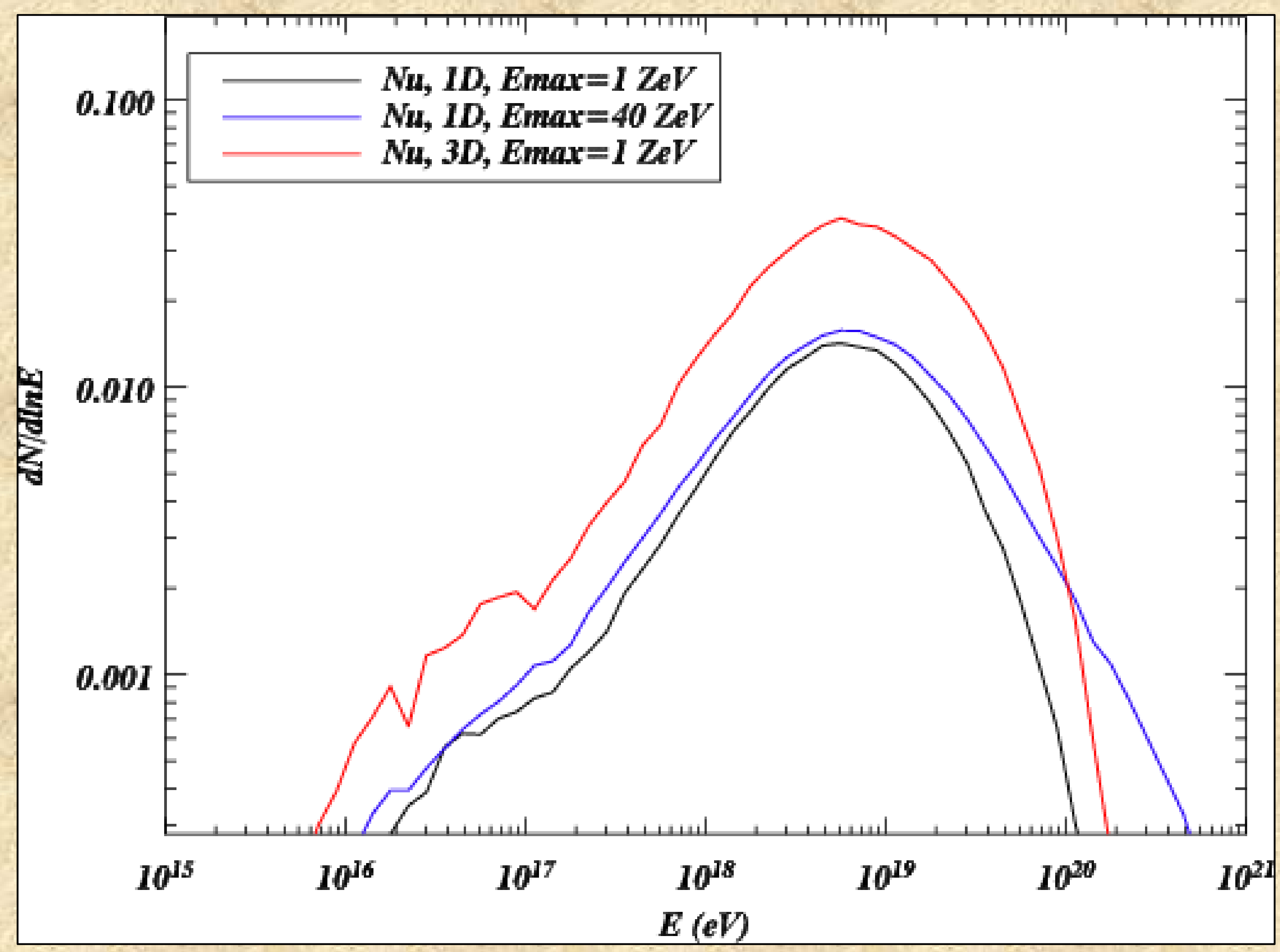
Note that the 3d structure of the field matters and leads to further enhancement of GeV γ-ray fluxes. Γ-rays from pp interactions neglected.

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

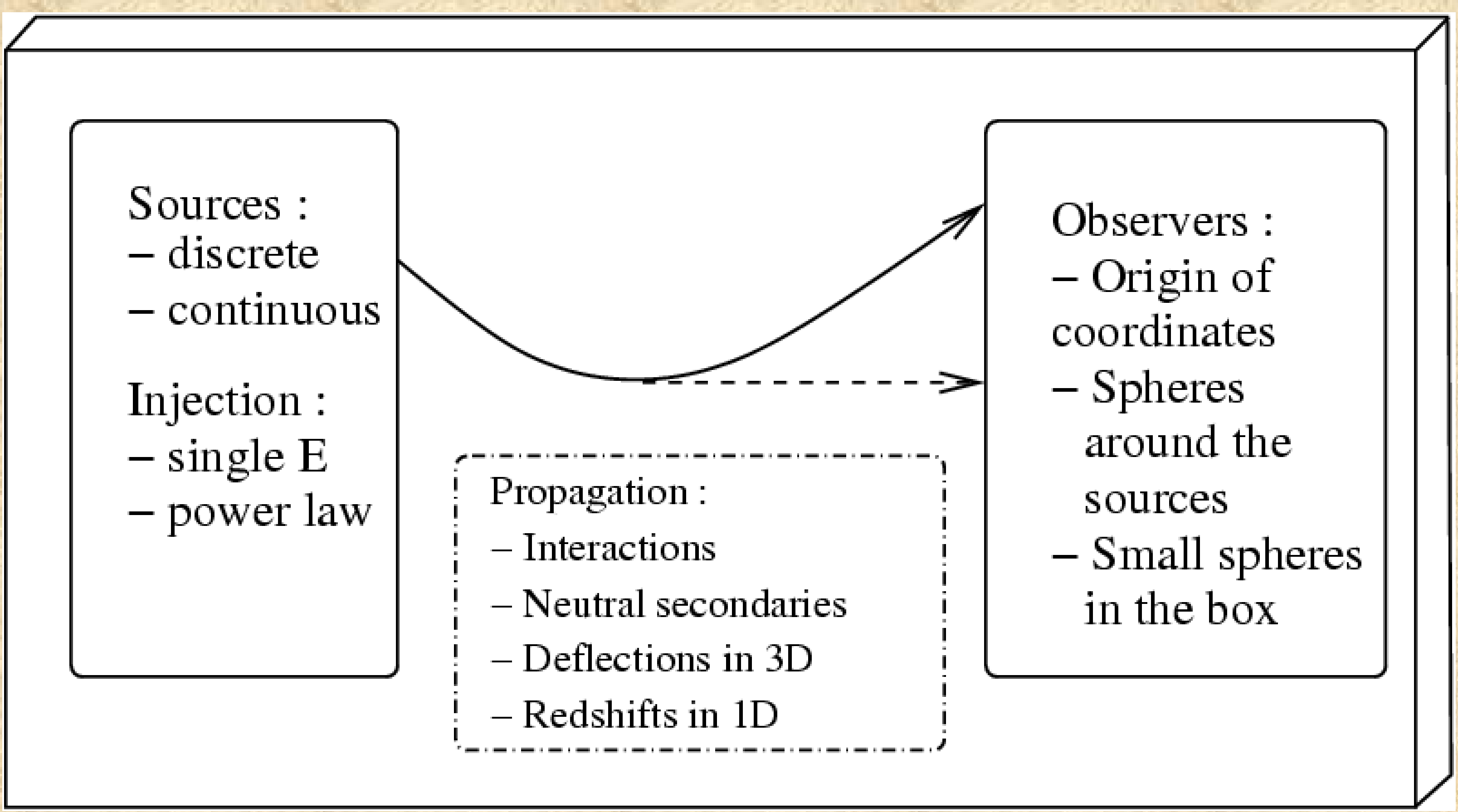
In case of previous example, γ-rays above 1 TeV:



The GZK neutrino flux can also be enhanced by magnetic fields



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



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astro-ph/0603675

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.) Secondary γ-ray and neutrino fluxes from discrete magnetized sources can also be enhanced considerably. This can be relevant for neutrino telescopes and γ-ray detectors such as GLAST, HESS, MAGIC

5.) 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.