The Enigma of Ultra-High Energy Cosmic Rays

General facts and the experimental situation
Acceleration ("bottom-up" scenario)
The role of magnetic fields
Neutrinos: Connection to cosmic rays and detection
"New physics"

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

Further reading:

short review: Science **291** (2001) 73

long reviews: Physics Reports **327** (2000) 109

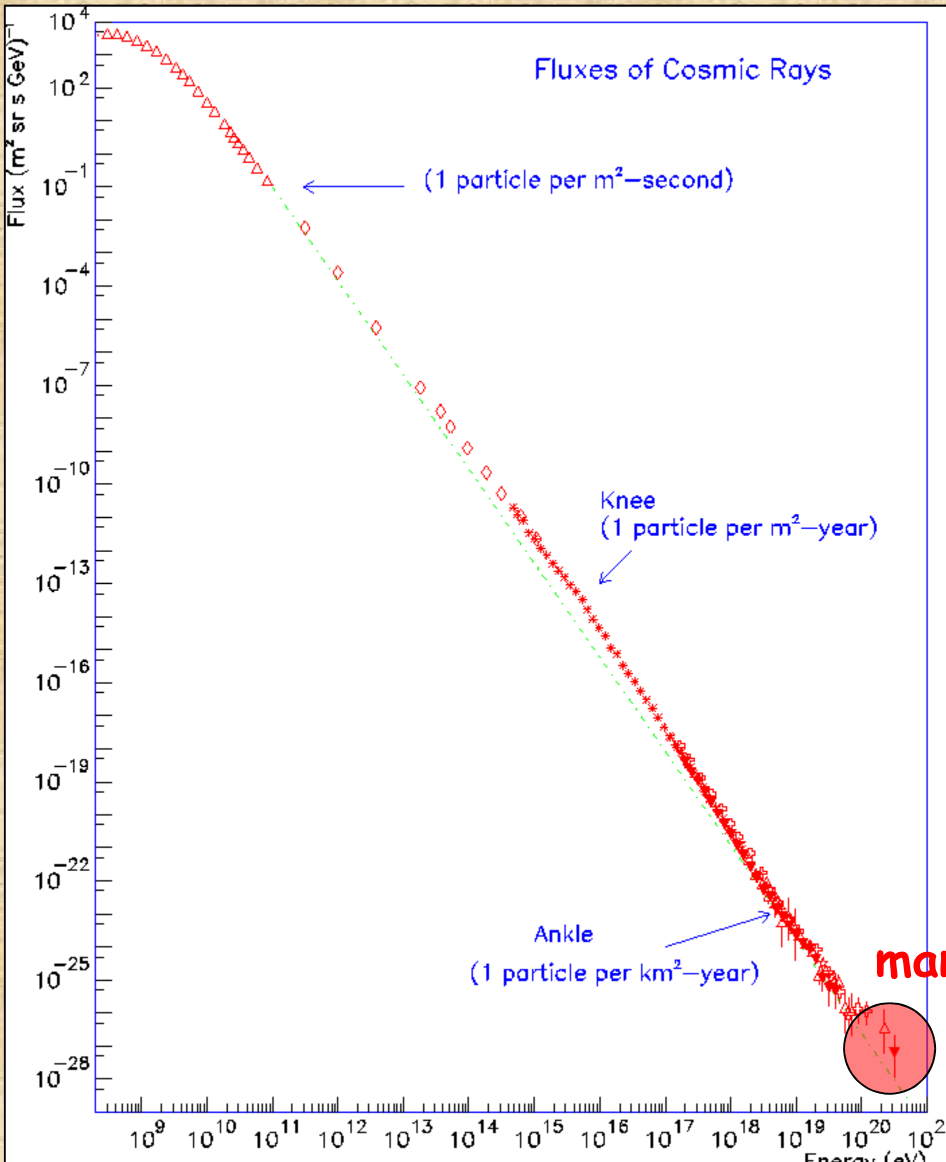
Torres and Anchordoqui, Rep.Prog.Phys 67, 1663.

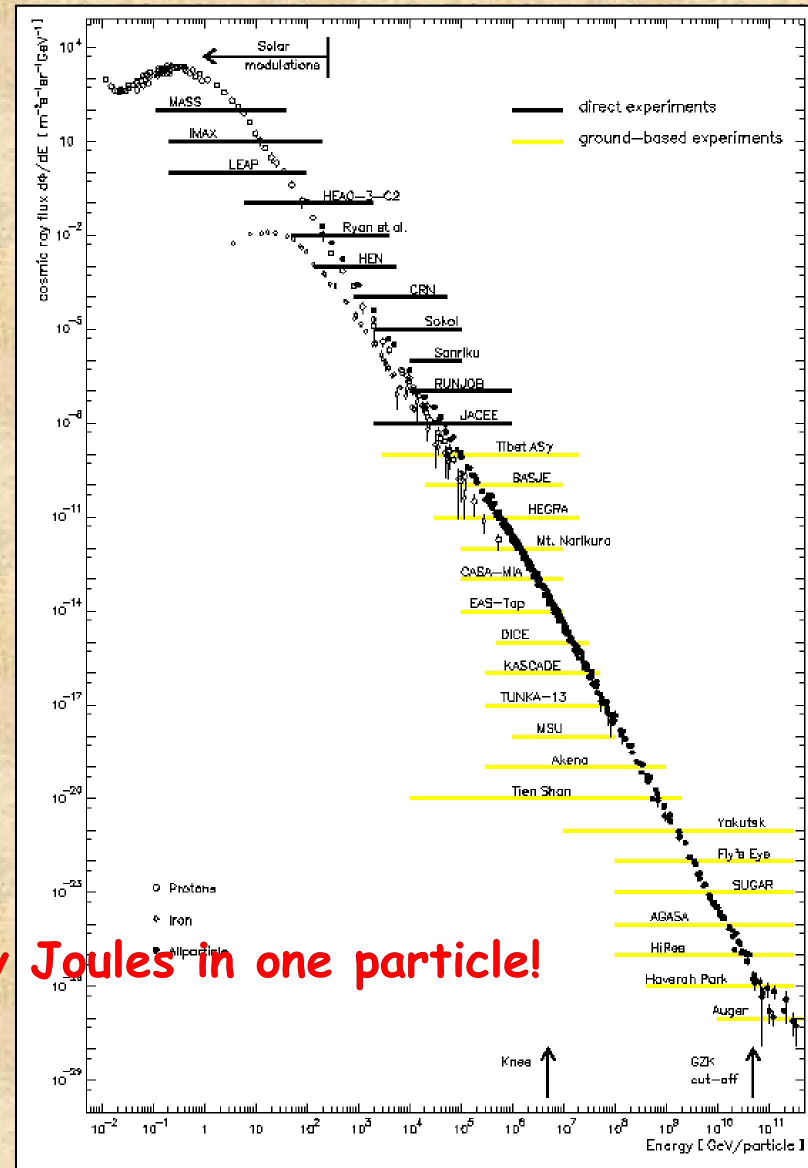
review collections:

Lecture Notes in Physics **576** (2001) (eds.: M.Lemoine, G.Sigl)

Comptes Rendus, Académie des Sciences, Vol 5, issue 4 (2004) (eds.: M.Boratav, G.Sigl)

The cosmic ray spectrum stretches over some 12 orders of magnitude in energy and some 30 orders of magnitude in differential flux:

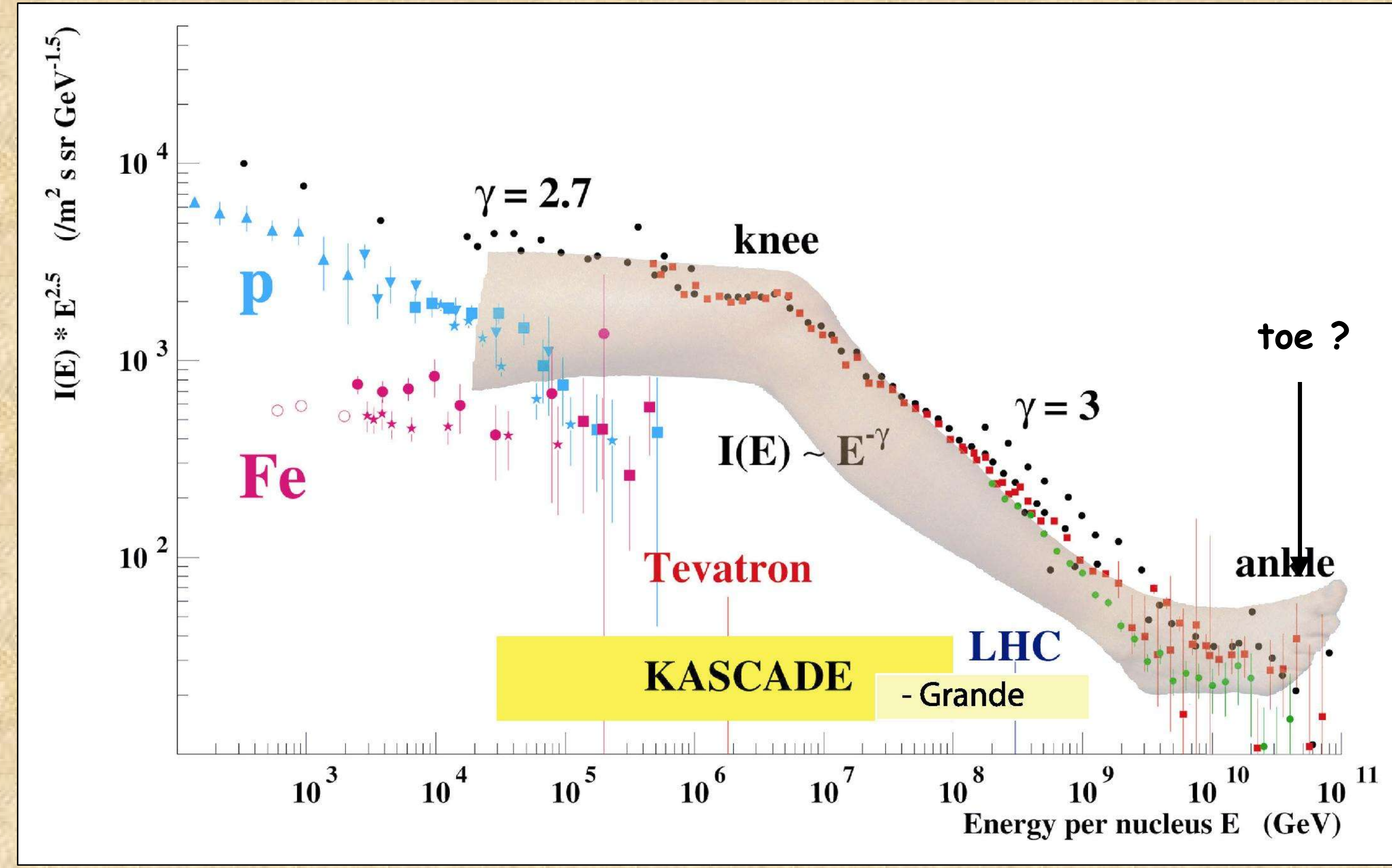




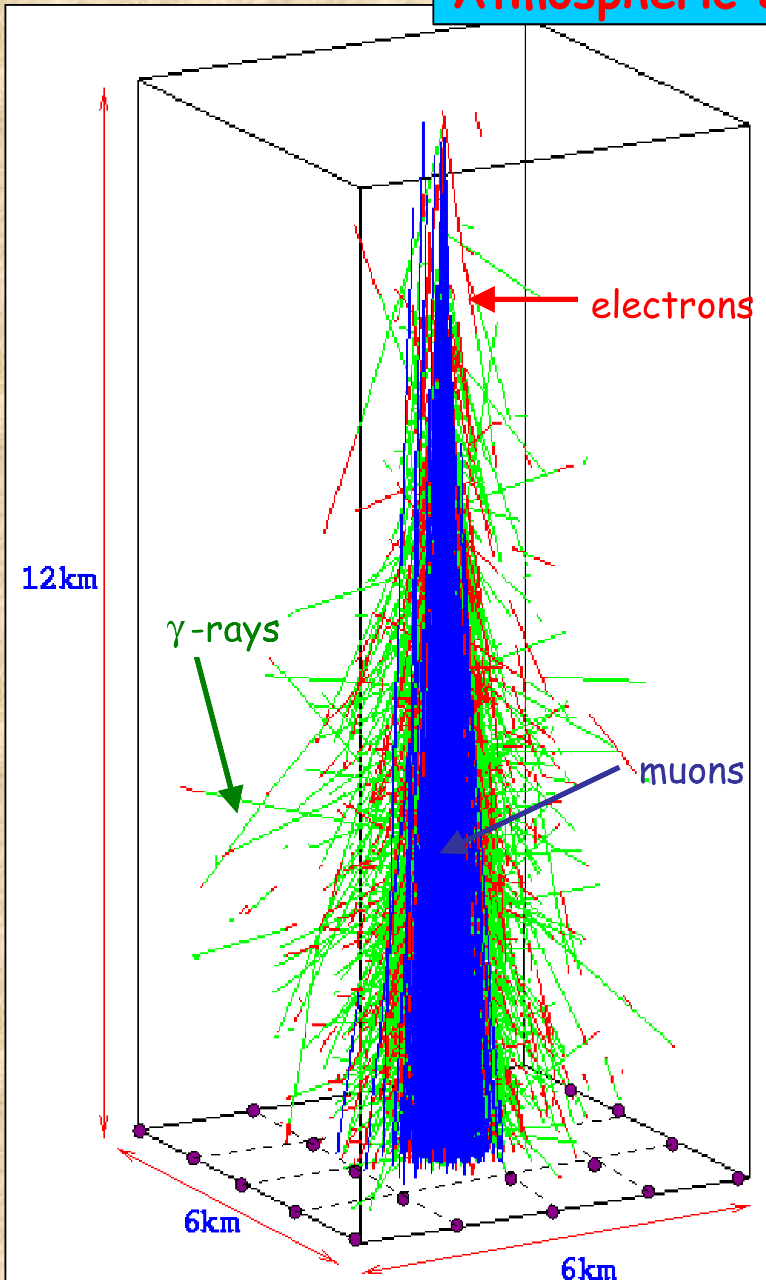
many Joules in one particle!

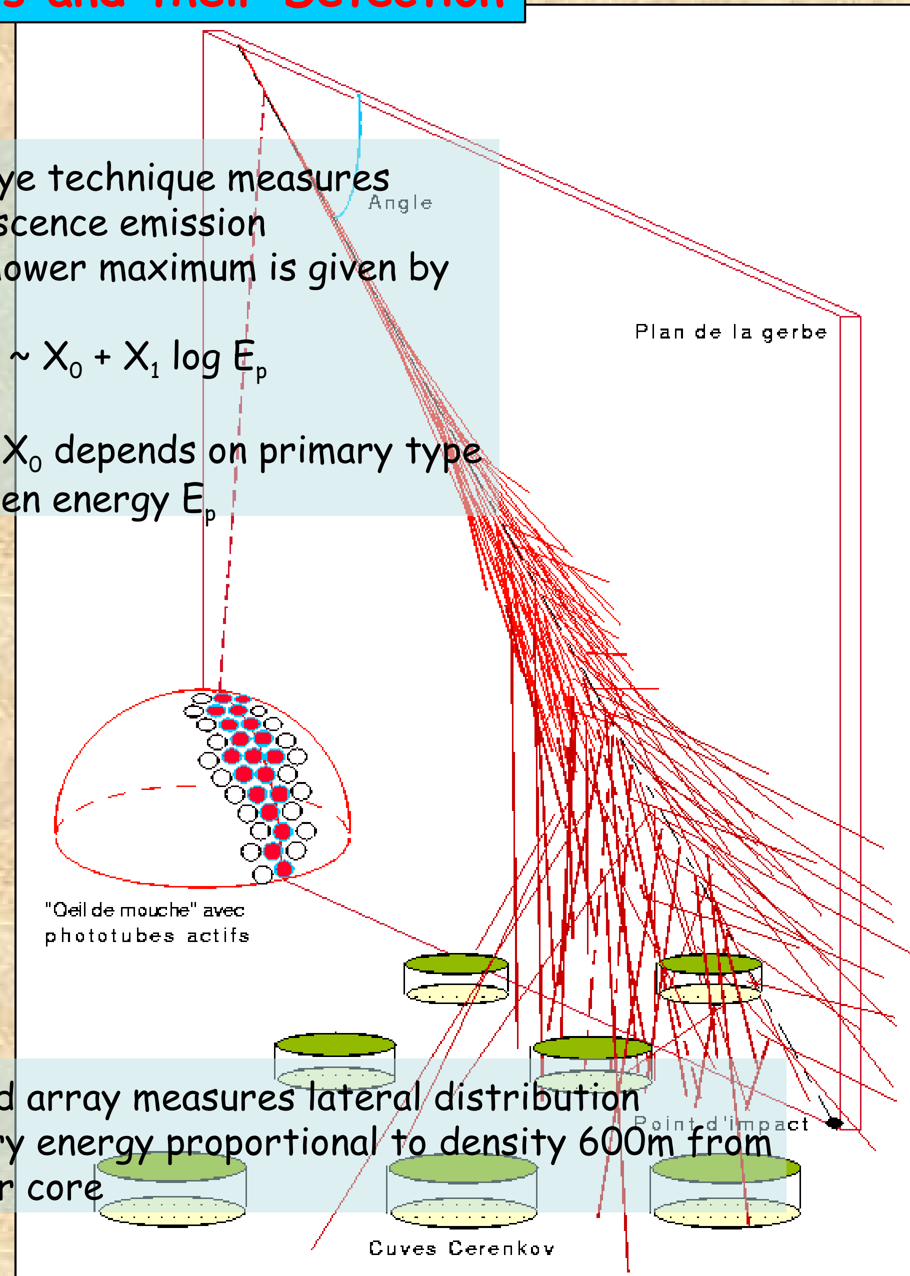
The structure of the spectrum and scenarios of its origin

supernova remnants — wind supernovae — AGN, top-down ??



Atmospheric Showers and their Detection





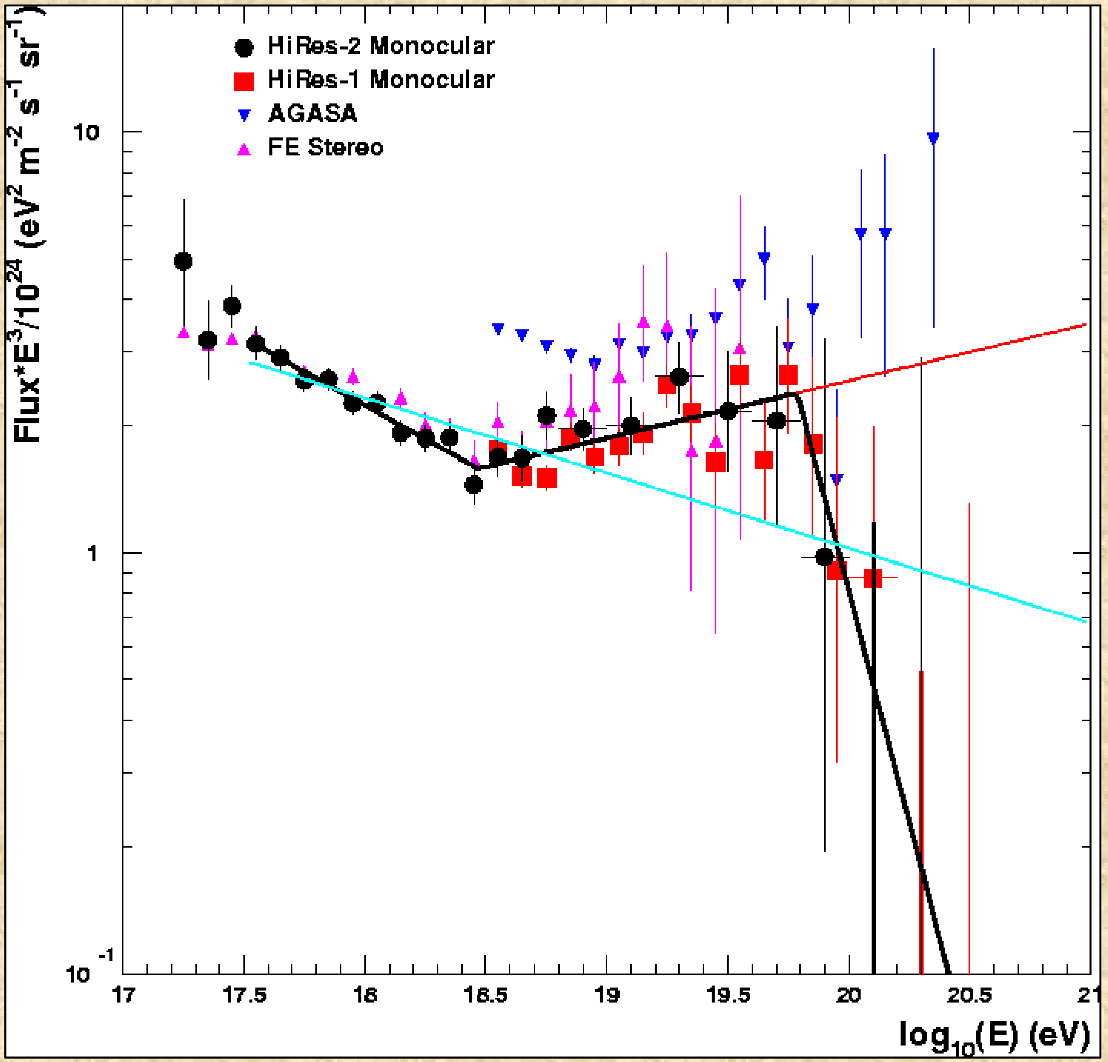
Fly's Eye technique measures fluorescence emission
The shower maximum is given by

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

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

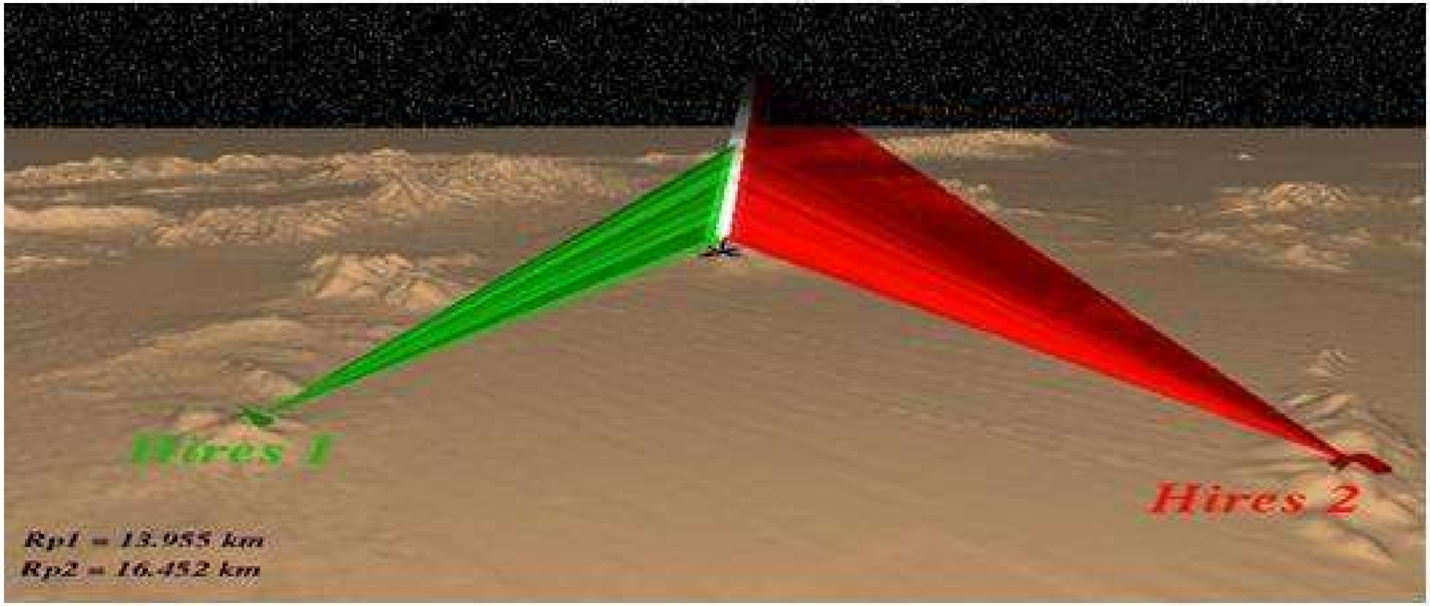
Lowering the AGASA energy scale by about 20% brings it in accordance with HiRes up to the GZK cut-off, but not beyond.

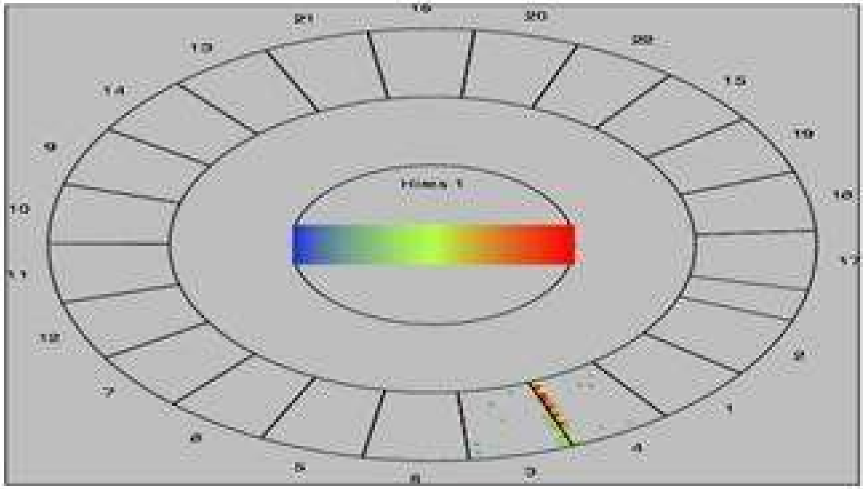


HiRes collaboration, astro-ph/0501317

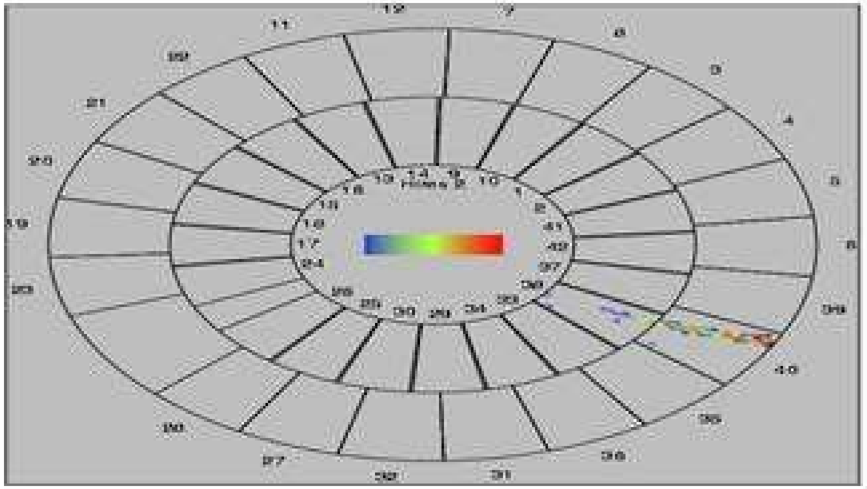
May need an experiment combining ground array with fluorescence such as the Auger project to resolve this issue.

Stereo Event E ~50 EeV





HiRes1



HiRes2

Southern Auger Site

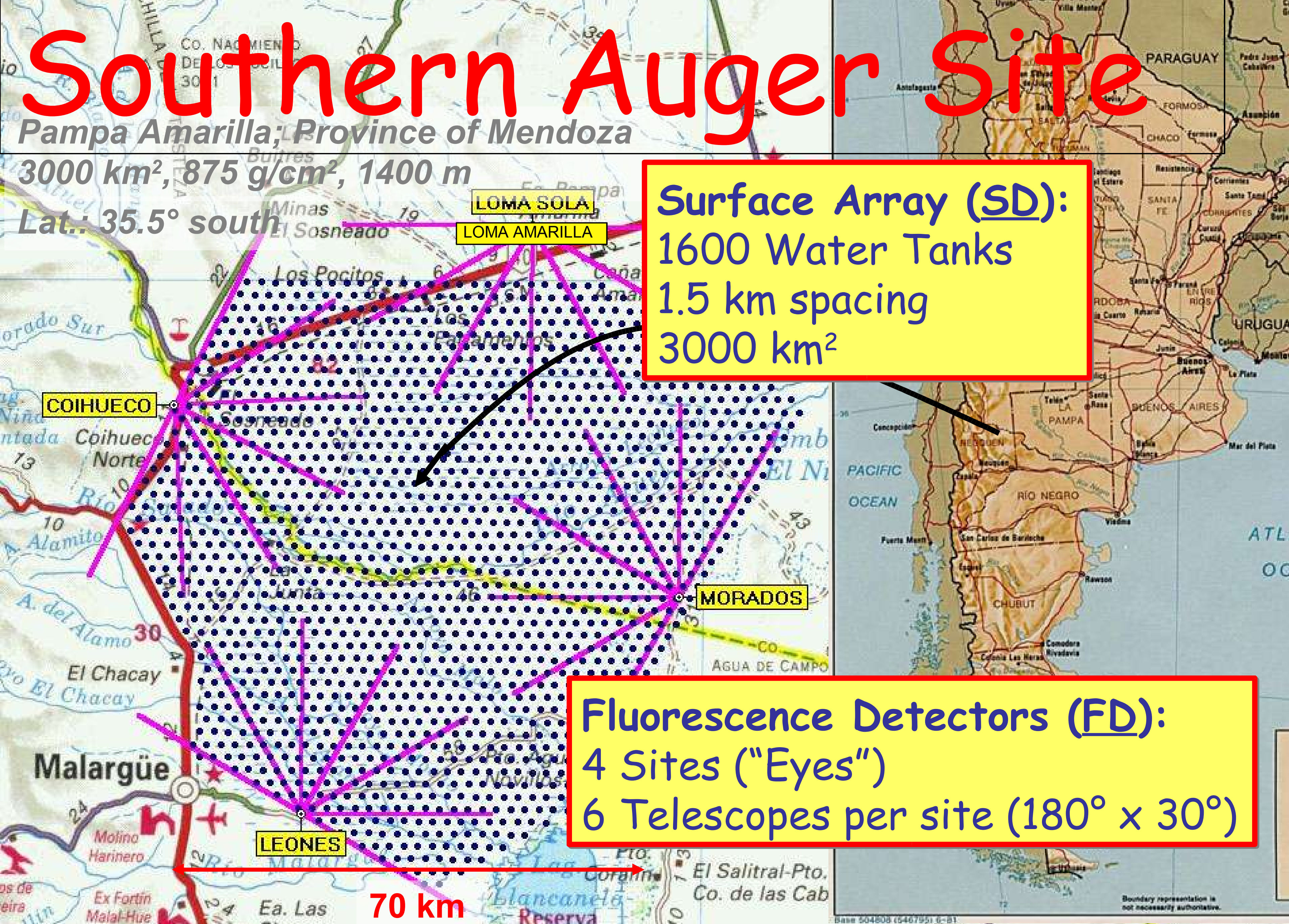
Pampa Amarilla; Province of Mendoza

3000 km², 875 g/cm², 1400 m

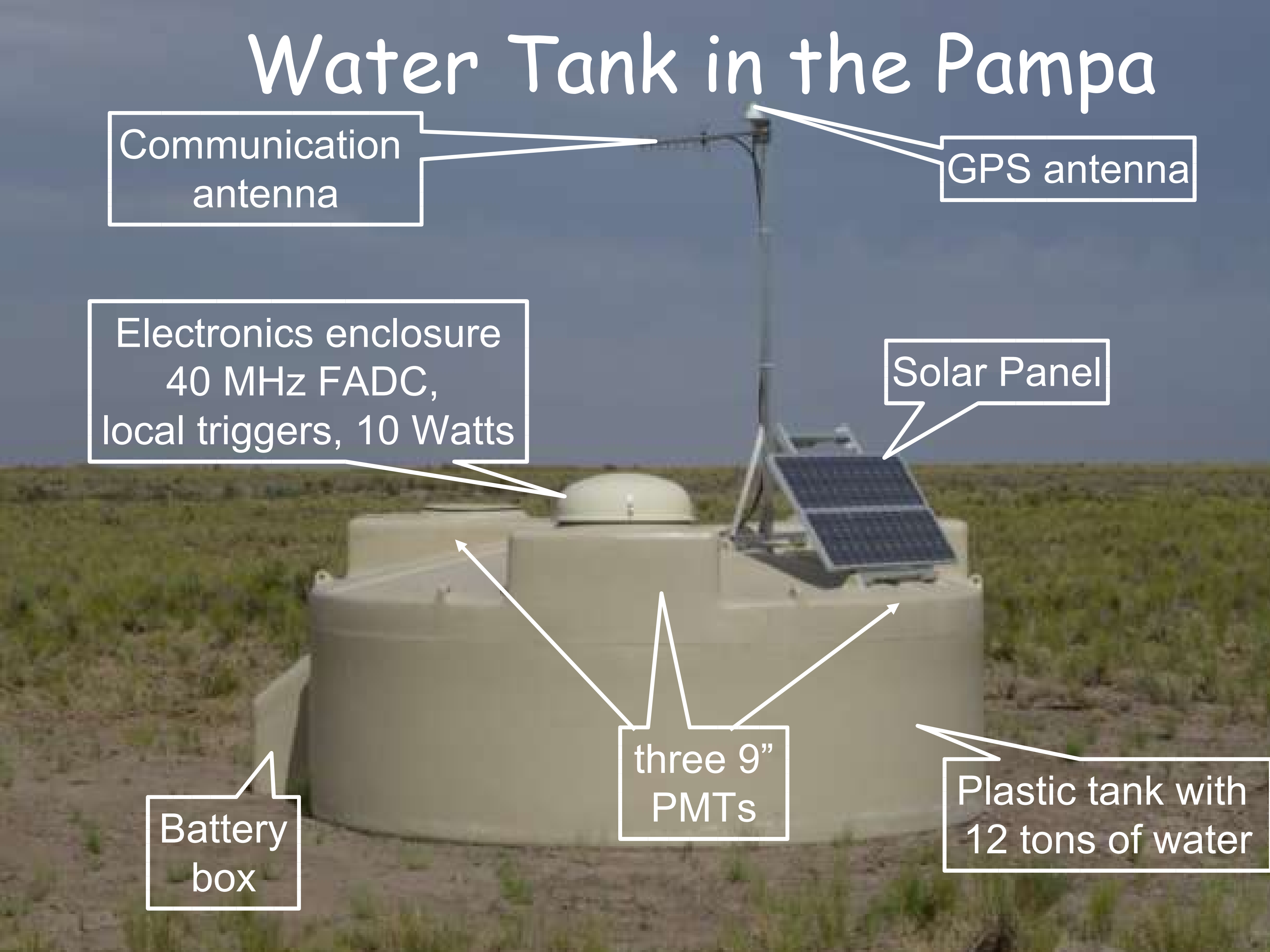
Lat.: 35.5° south

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°)

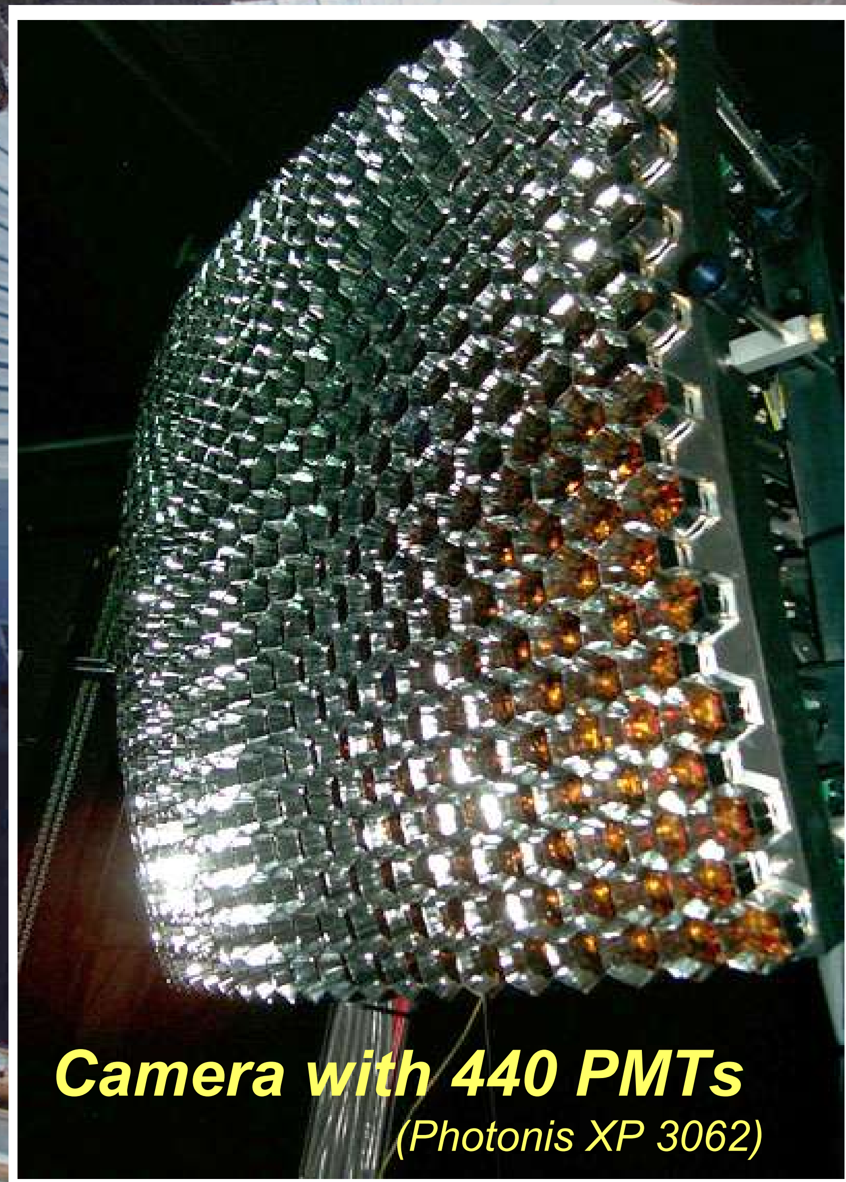


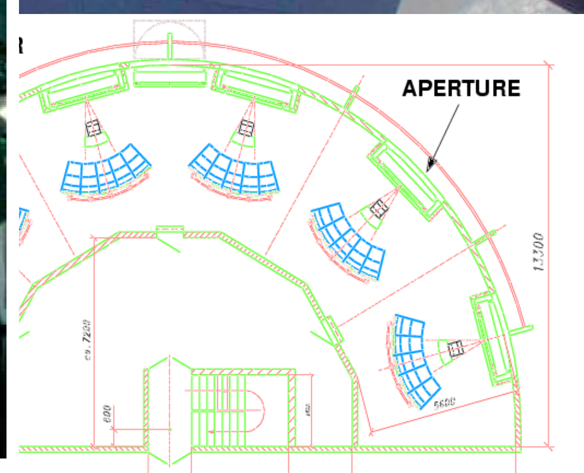
Water Tank in the Pampa



Installation Chain

Six Telescopes viewing 30°x30°

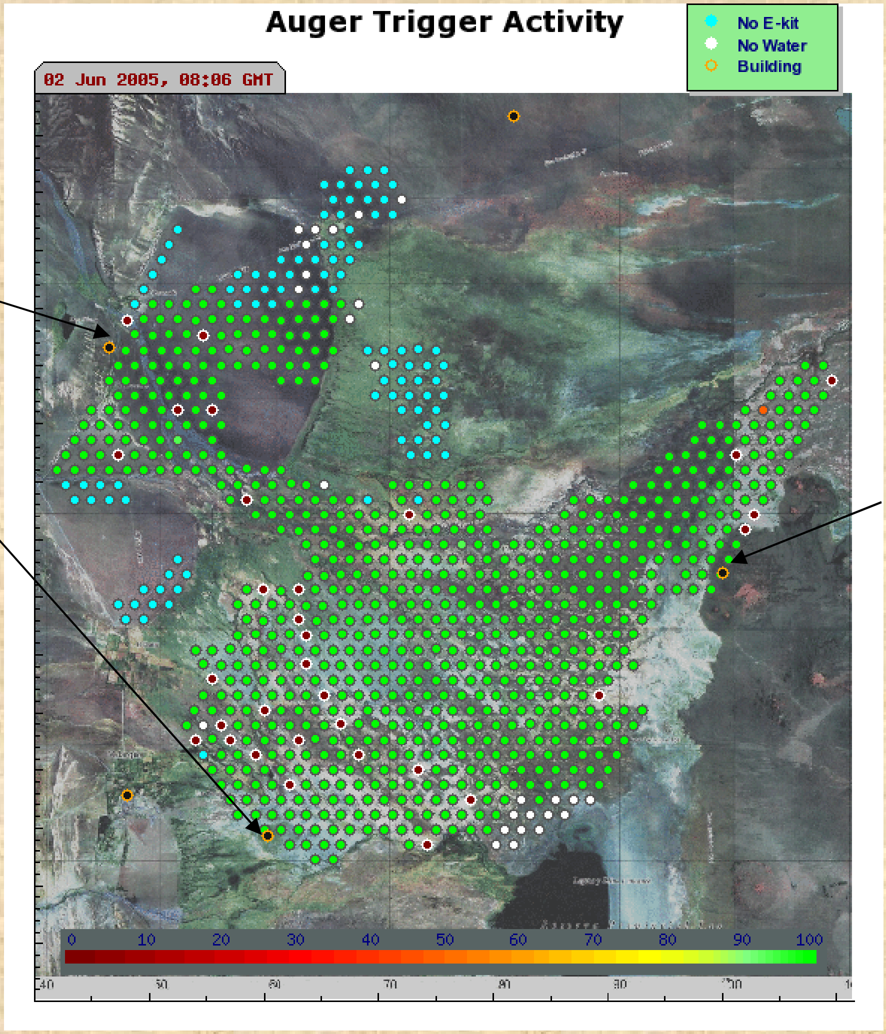




Current state of Observatory

Coihueco (FD)

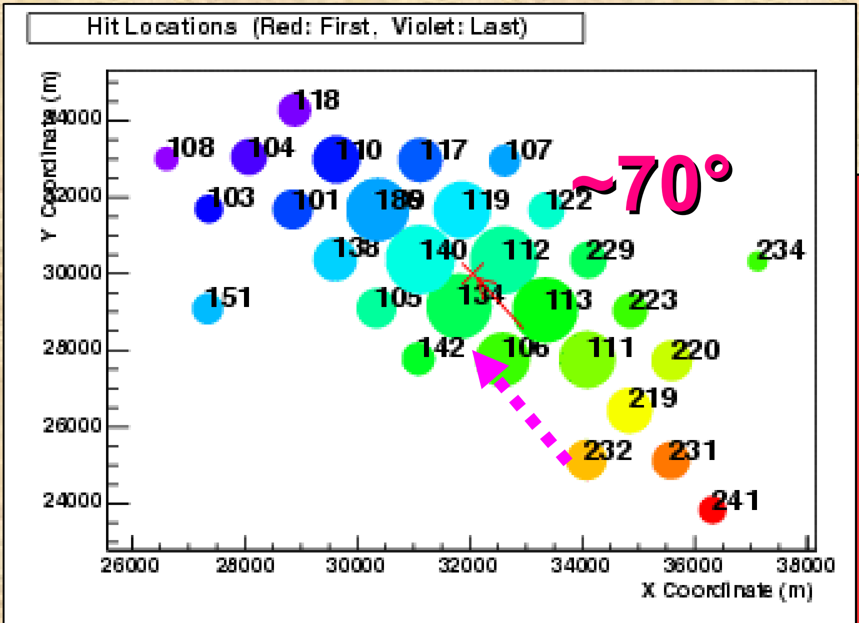
Los Leones (FD)



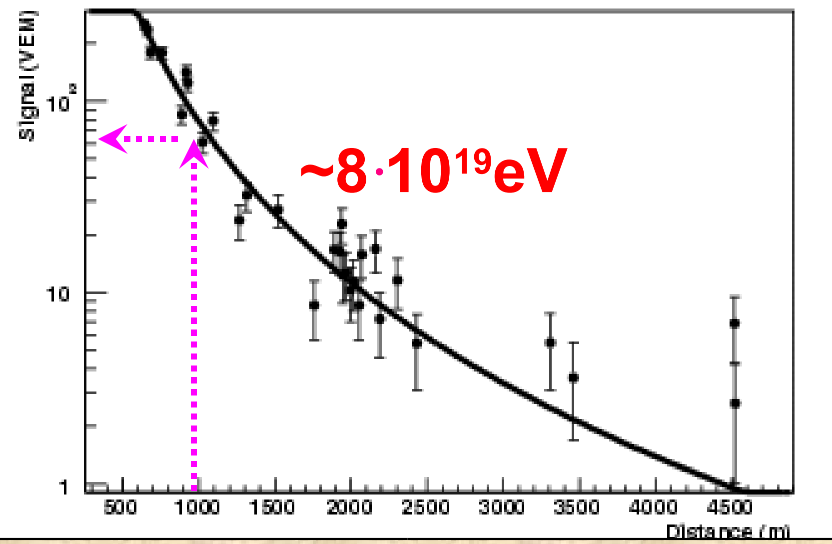
Los Morados (FD)

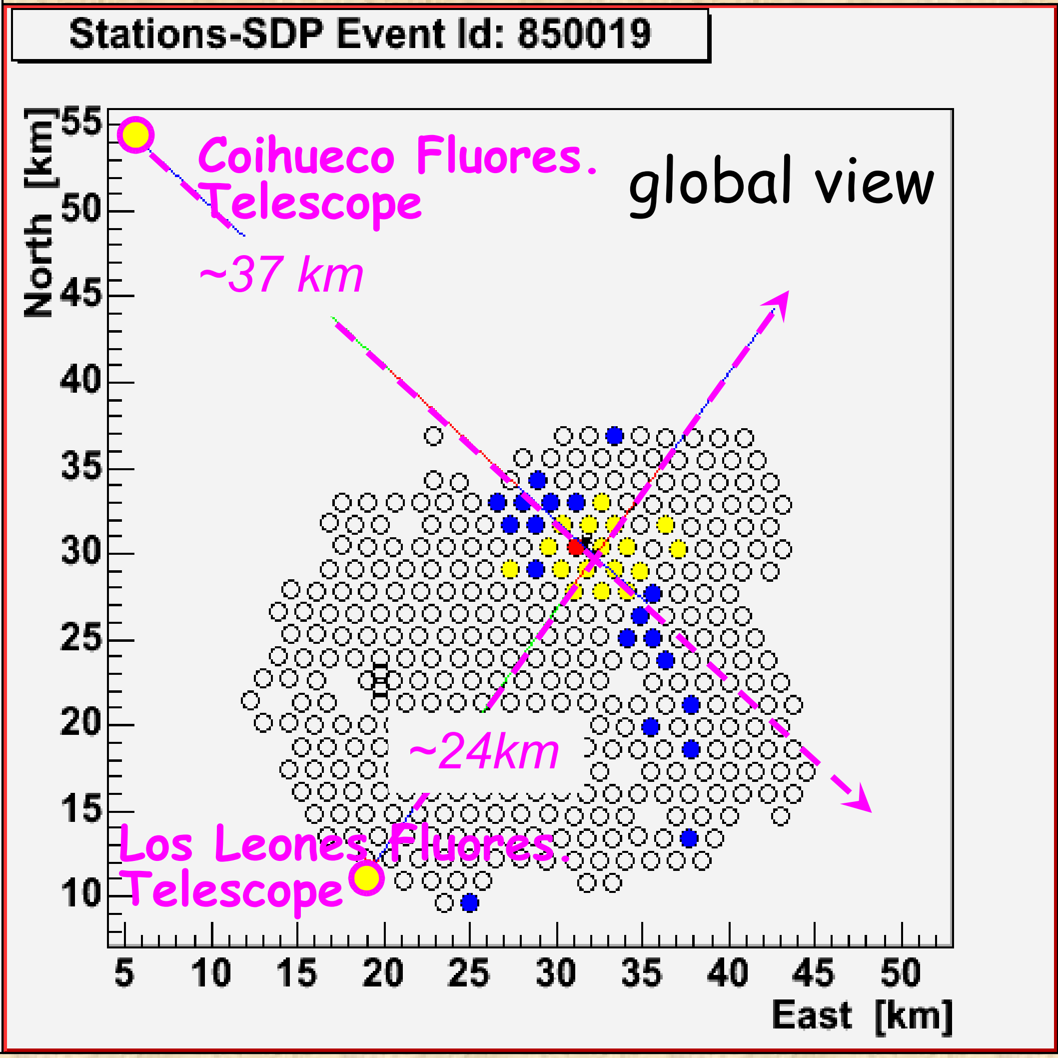
- 2/4 FD telescope sites fully running
- ~750/1600 tanks working in the fields

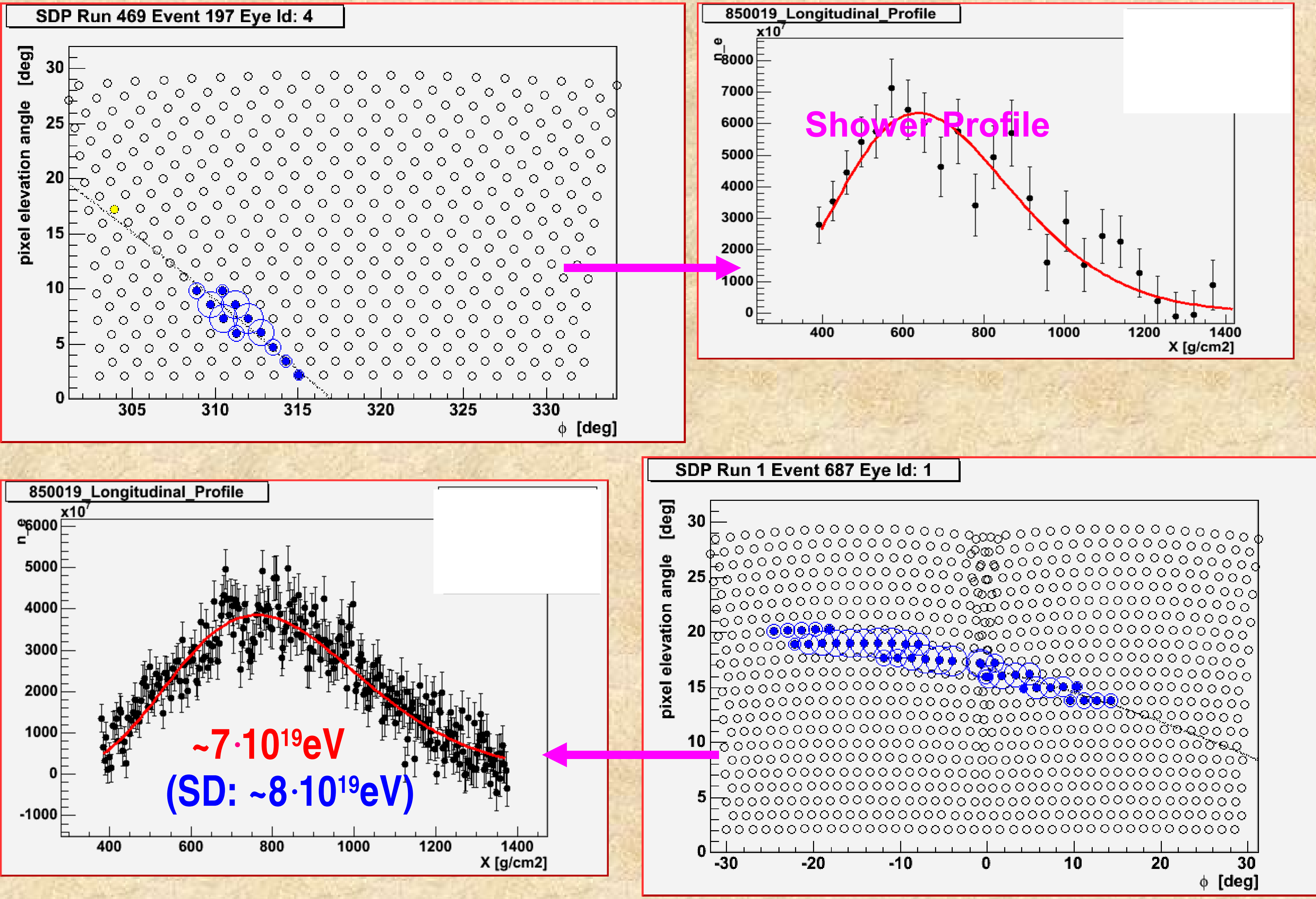
A stereo hybrid event



Lateral Distribution Function

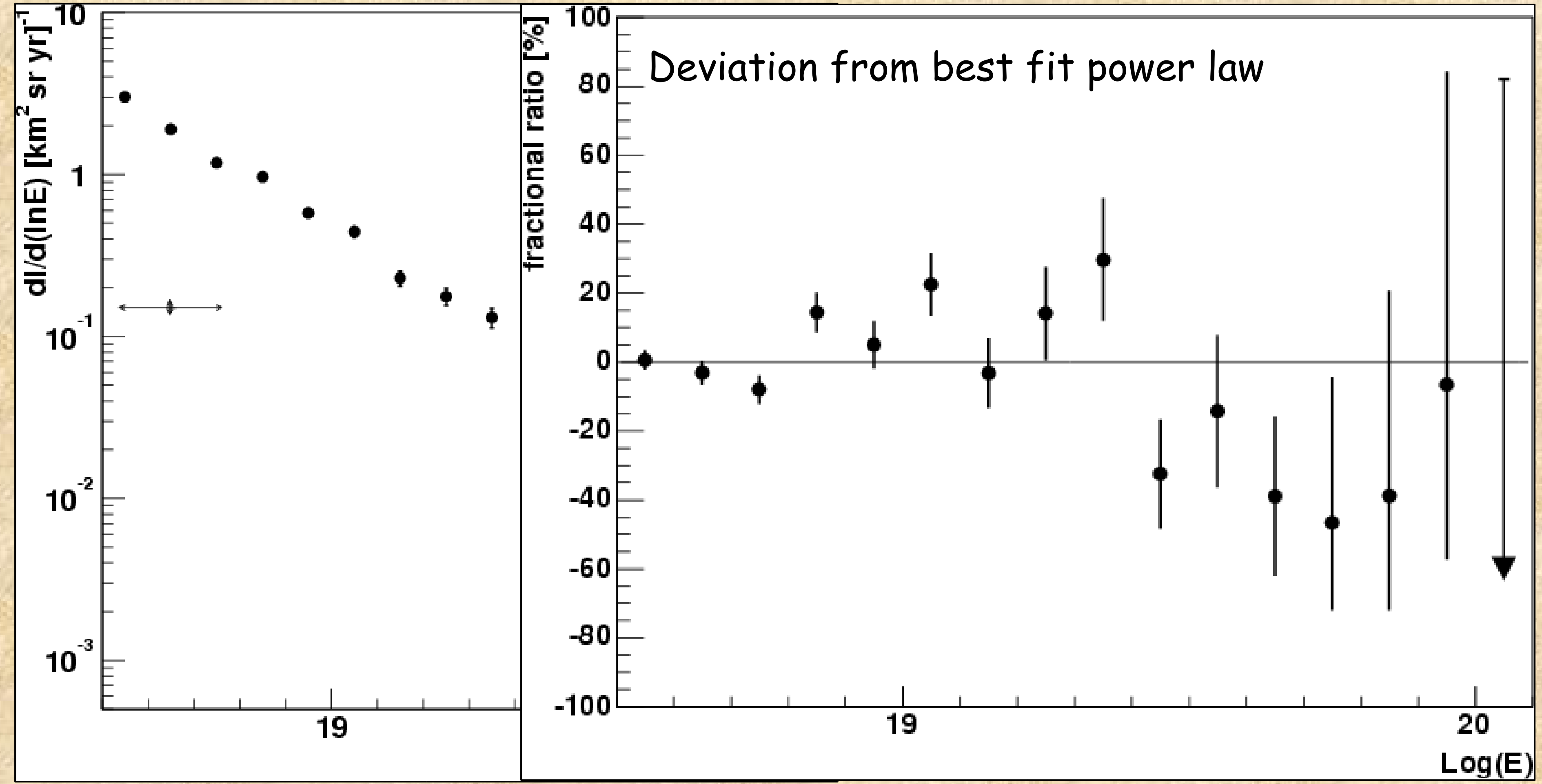




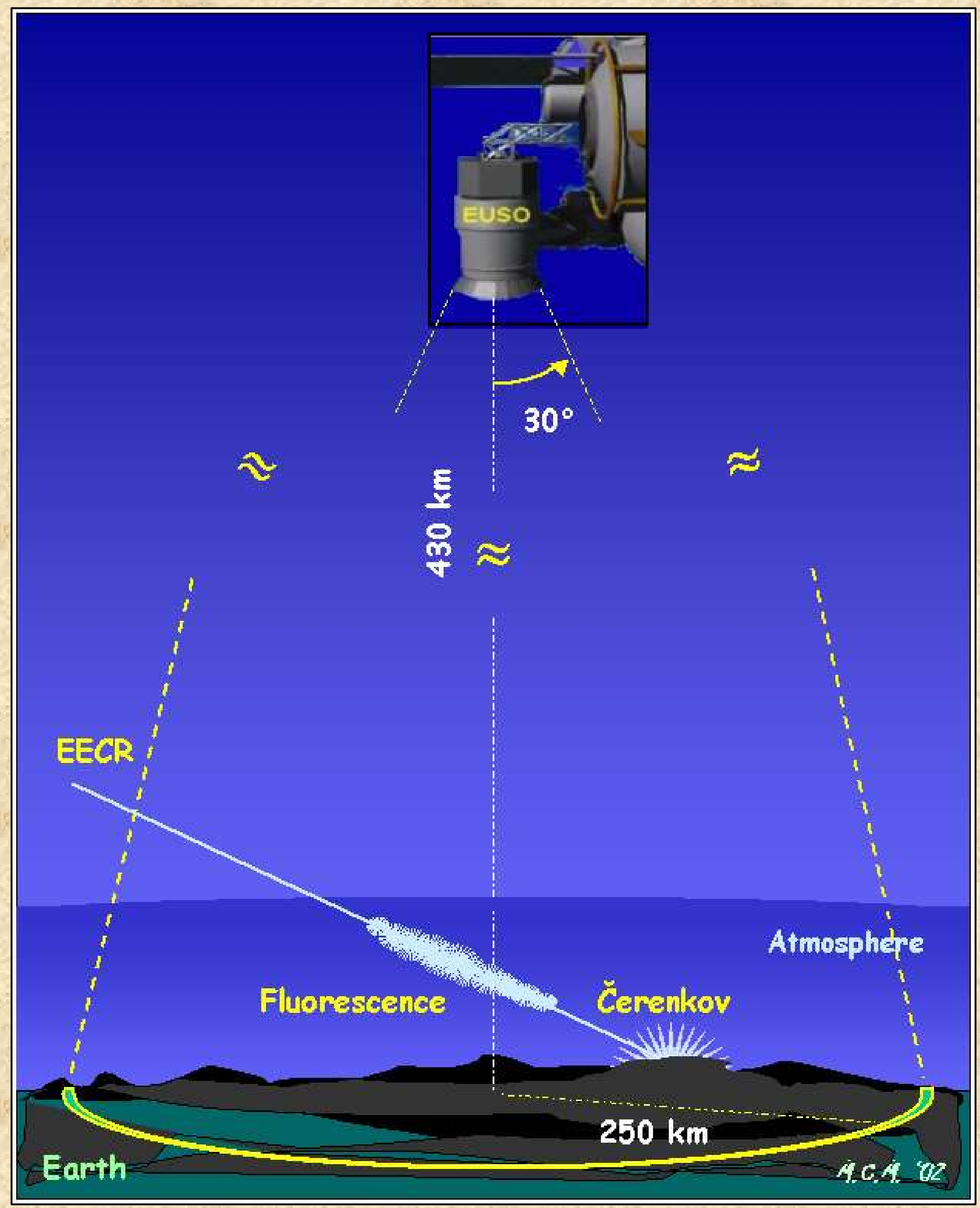

SDP Run 469 Event 197 Eye Id: 4
pixel elevation angle [deg]
ϕ [deg]
850019_Longitudinal_Profile
n_e
x10^7
X [g/cm2]
Shower Profile
850019_Longitudinal_Profile
n_e
x10^7
X [g/cm2]
~7·10^19eV
(SD: ~8·10^19eV)
SDP Run 1 Event 687 Eye Id: 1
pixel elevation angle [deg]
ϕ [deg]

First Auger Spectrum !!

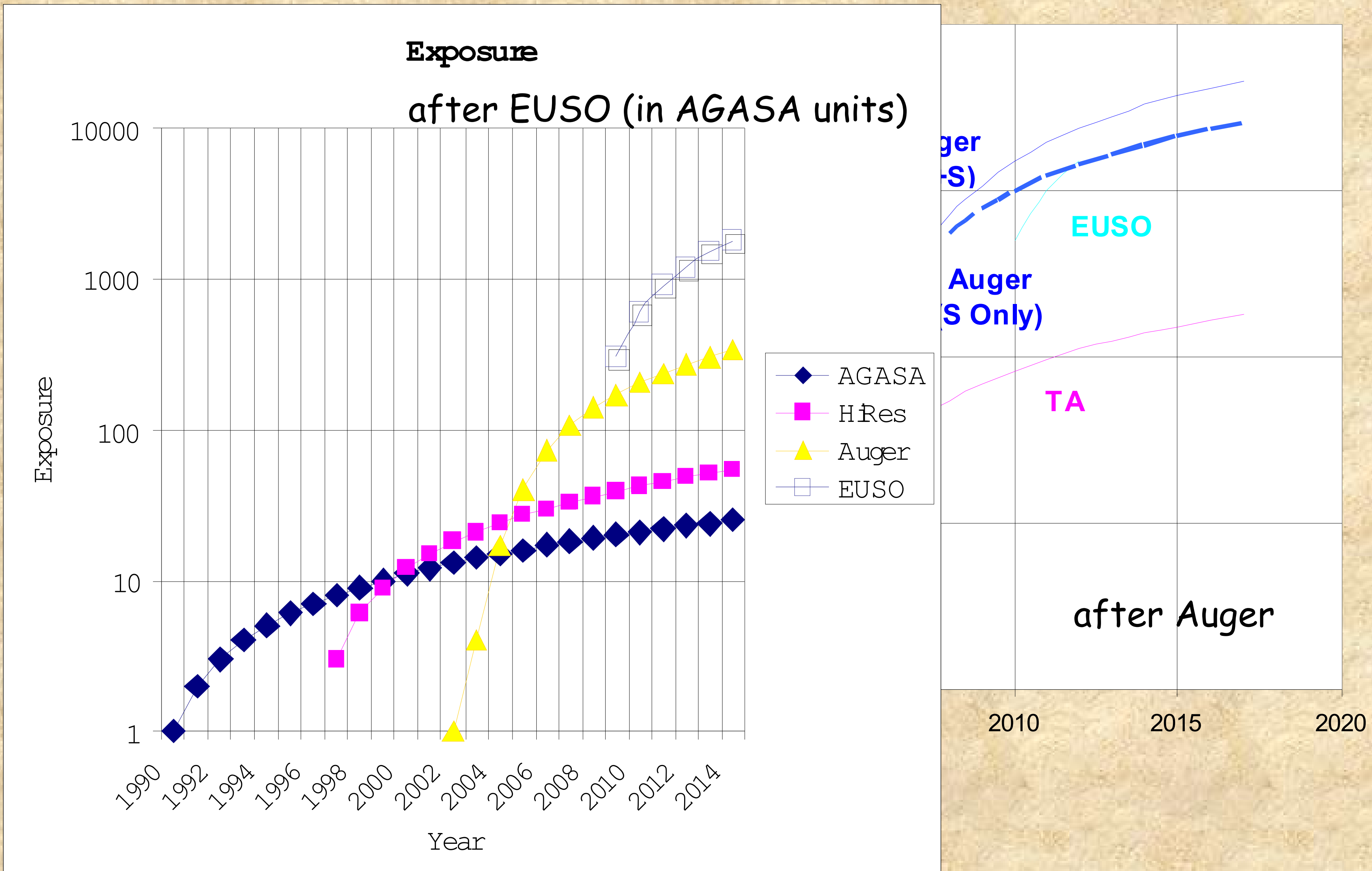
107% AGASA exposure
Statistics as yet insufficient to draw conclusion on GZK cutoff



EUSO concept: Detecting air showers from space.



Next-Generation Ultra-High Energy Cosmic Ray Experiments



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

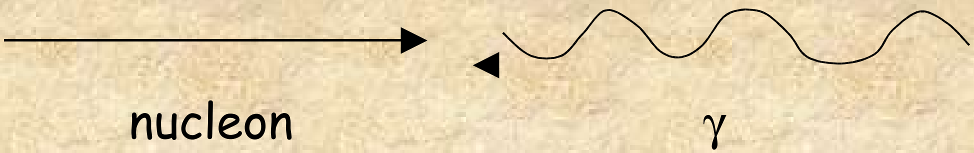
1.) electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 50 Mpc.

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

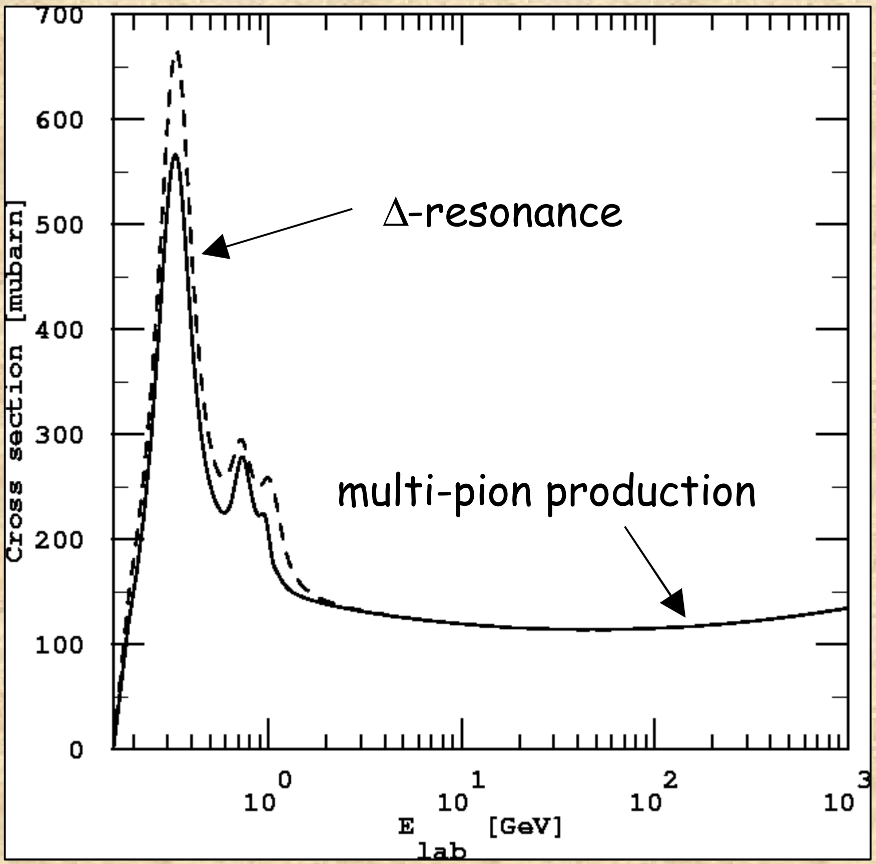
3.) The observed distribution seems to be very isotropic (except for a possible interesting small scale clustering)

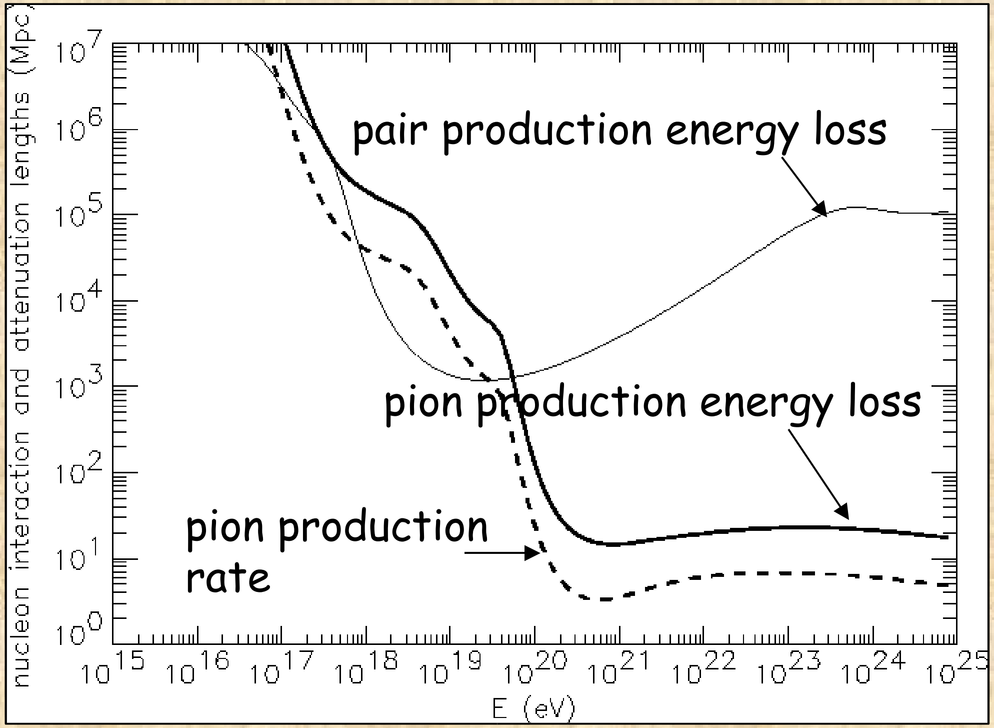
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



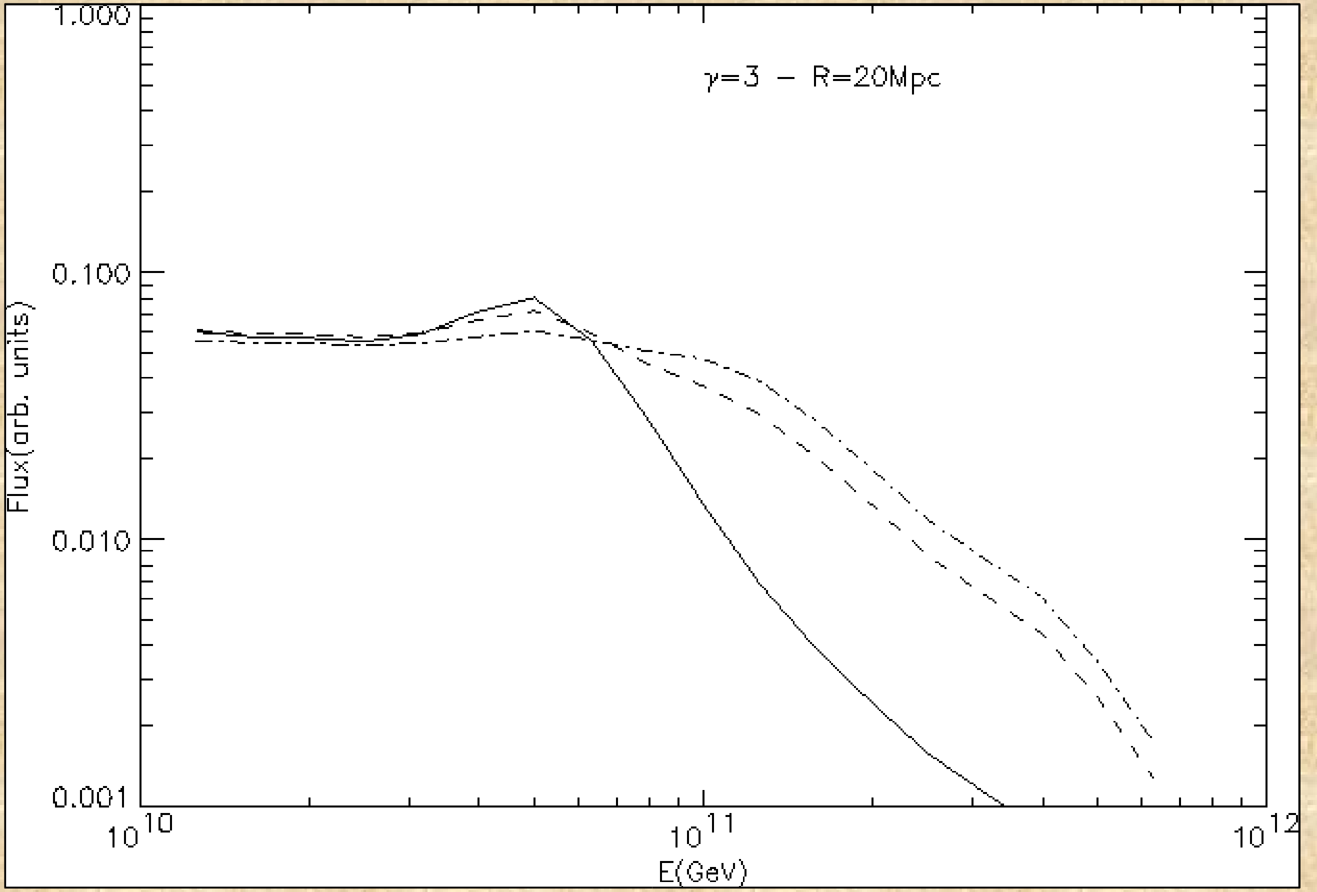
$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4 \cdot 10^{19}\,\mathrm{eV}$$





⇒sources must be in cosmological backyard
Only Lorentz symmetry breaking at Γ>10[11] could avoid this conclusion.

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

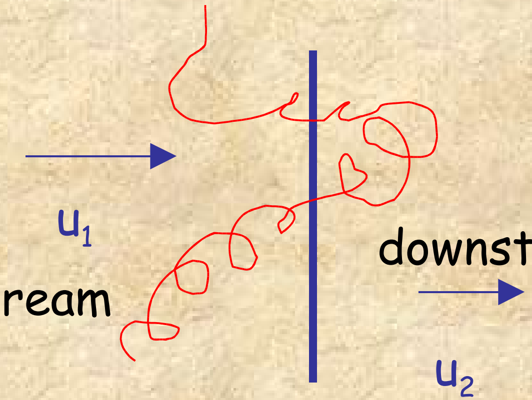


Observable spectrum for an E^{-3} injection spectrum for a distribution of sources with overdensities of 1, 10, 30 (bottom to top) within 20 Mpc, and otherwise homogeneous.

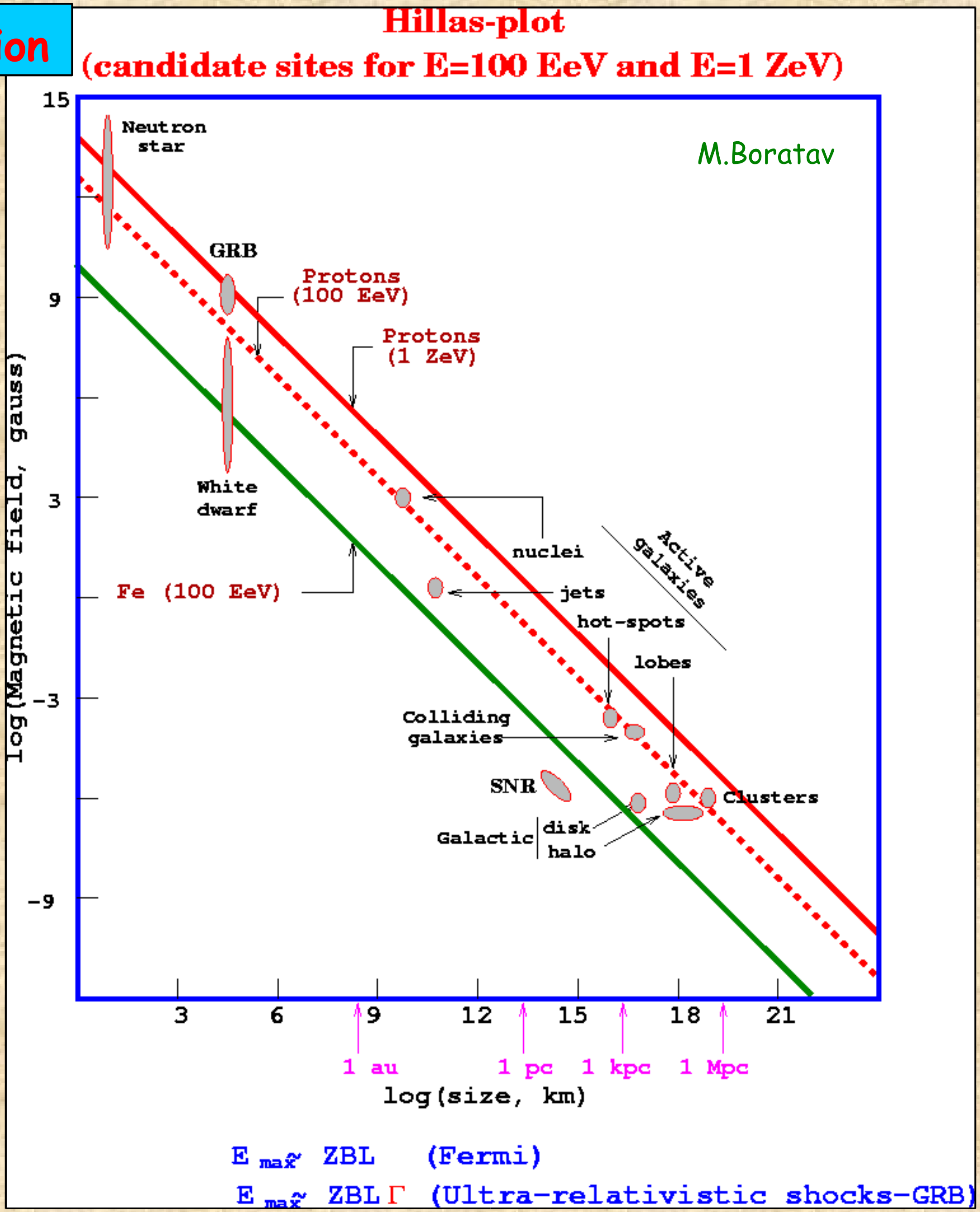
Blanton, Blasi, Olinto, Astropart.Phys. 15 (2001) 275

1^{st} Order Fermi Shock Acceleration

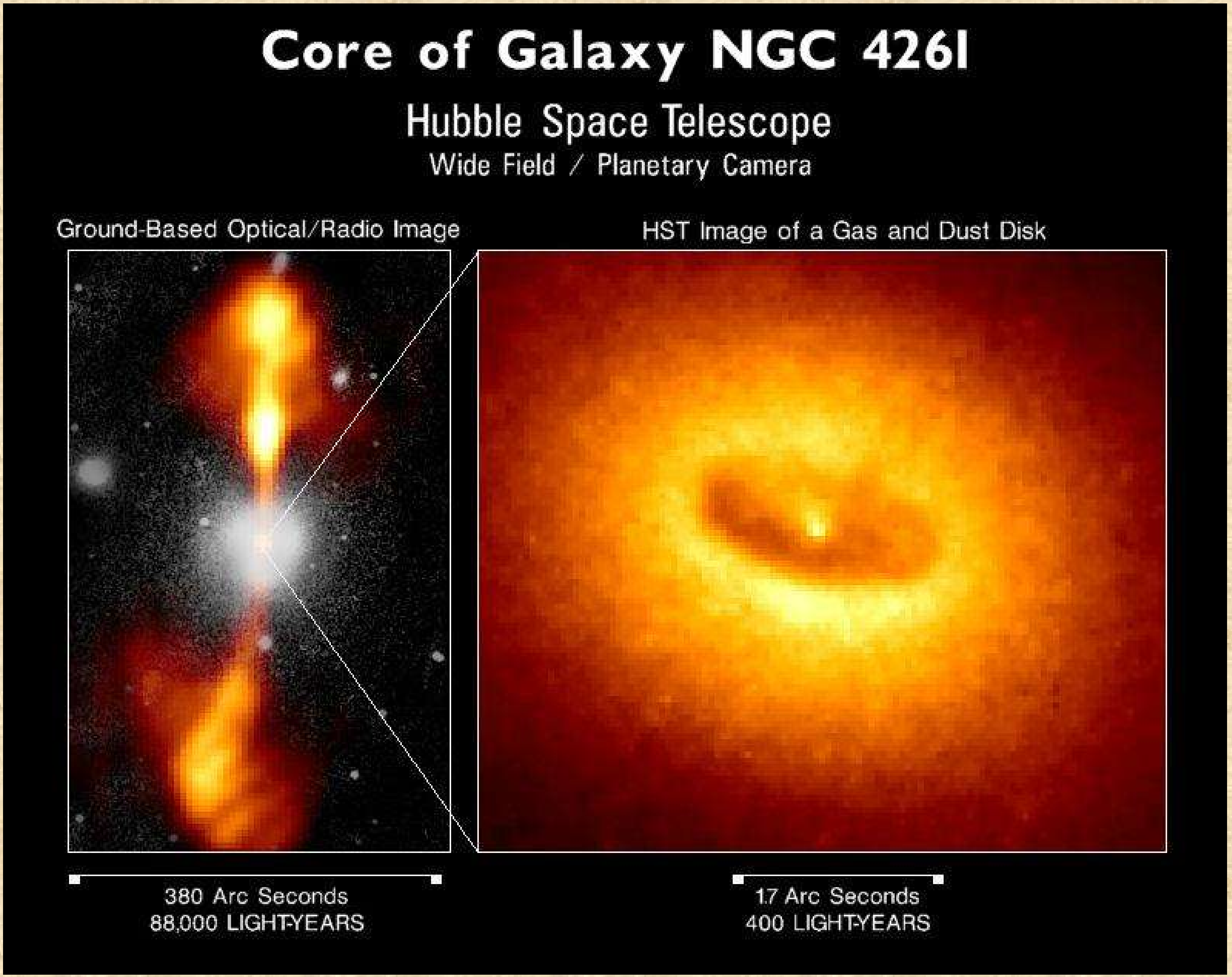
The most widely accepted scenario of cosmic ray acceleration



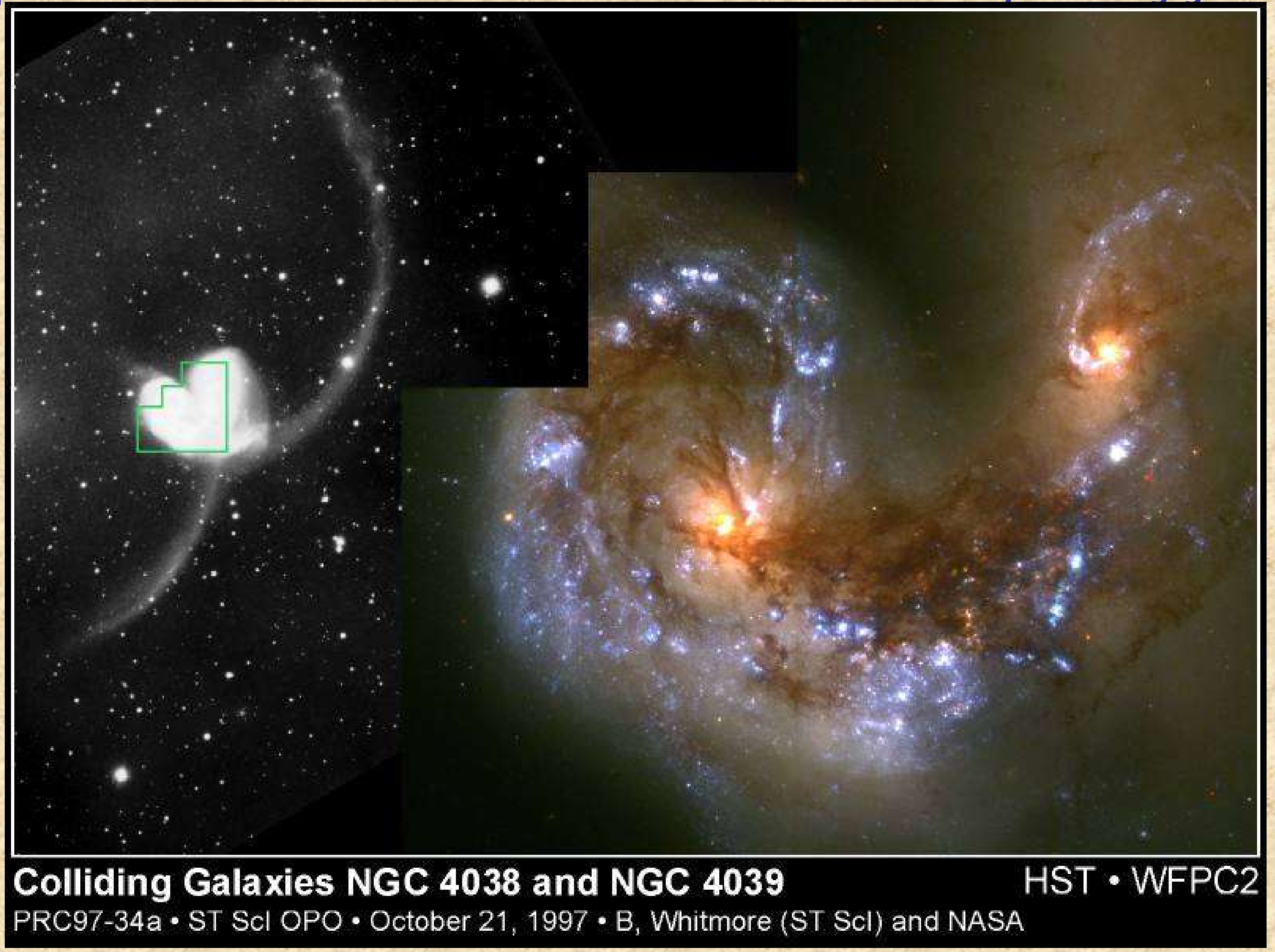
Fractional energy gain per shock crossing $\propto u_1 - u_2$ on a time scale r_L/u_2.
Together with downstream losses this leads to a spectrum E^{-q} with $q > 2$ typically.
When the gyroradius r_L becomes comparable to the shock size L, the spectrum cuts off.



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

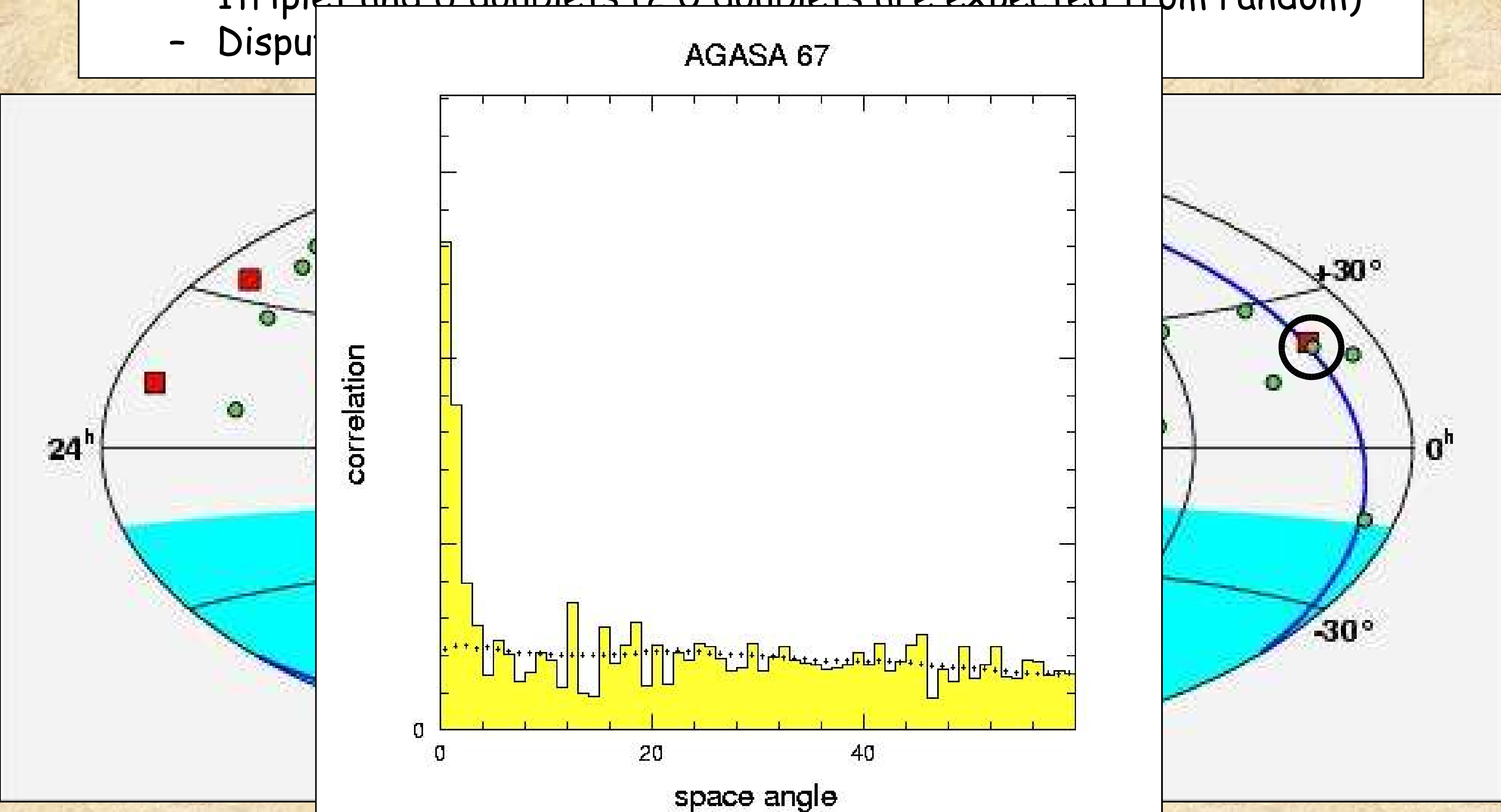


A possible acceleration site associated with shocks formed by colliding galaxies



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)
  - Disput

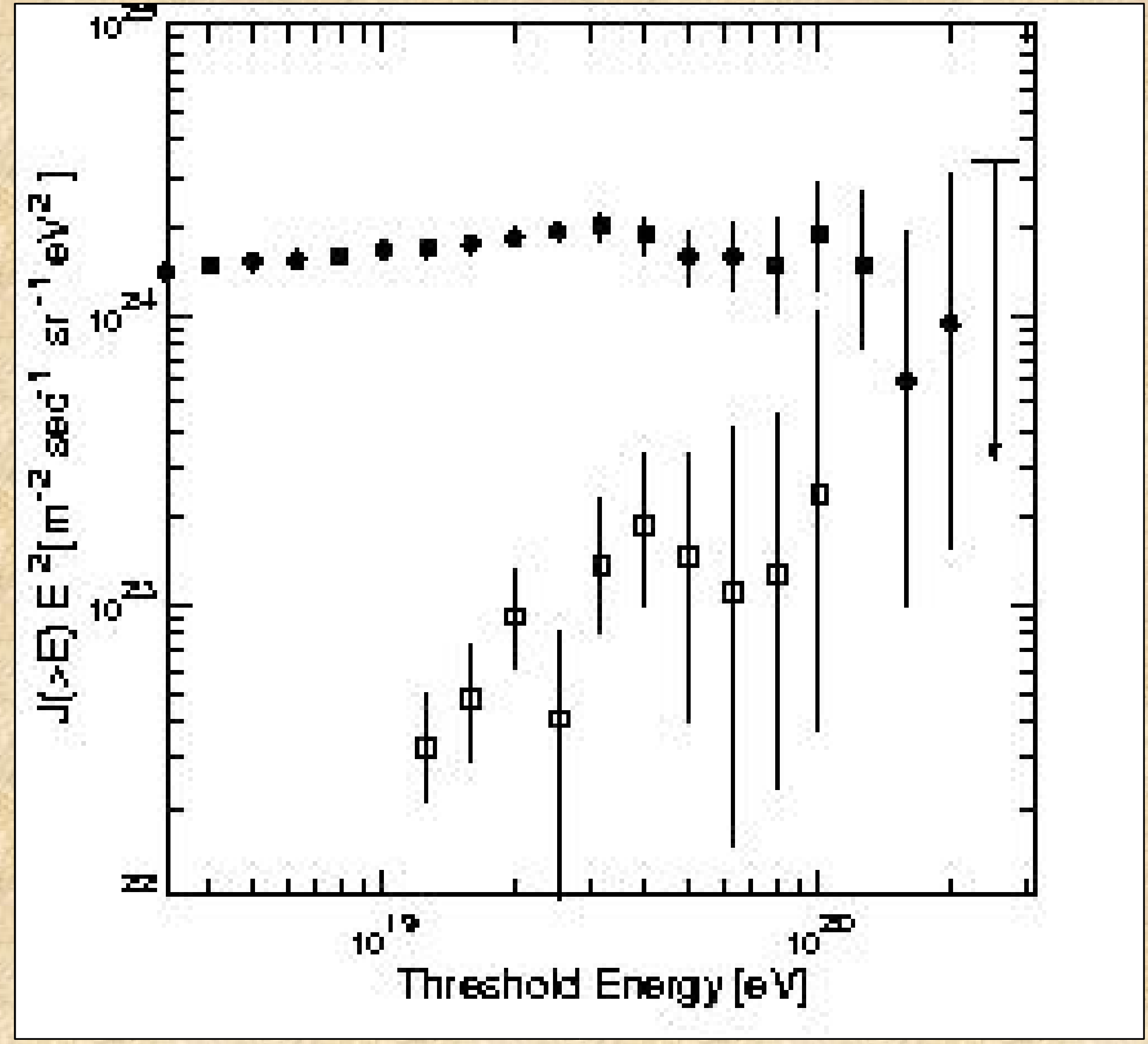


Spectrum of the clustered component in the AGASA data

Custered component has spectrum $E^{-1.8\pm0.5}$

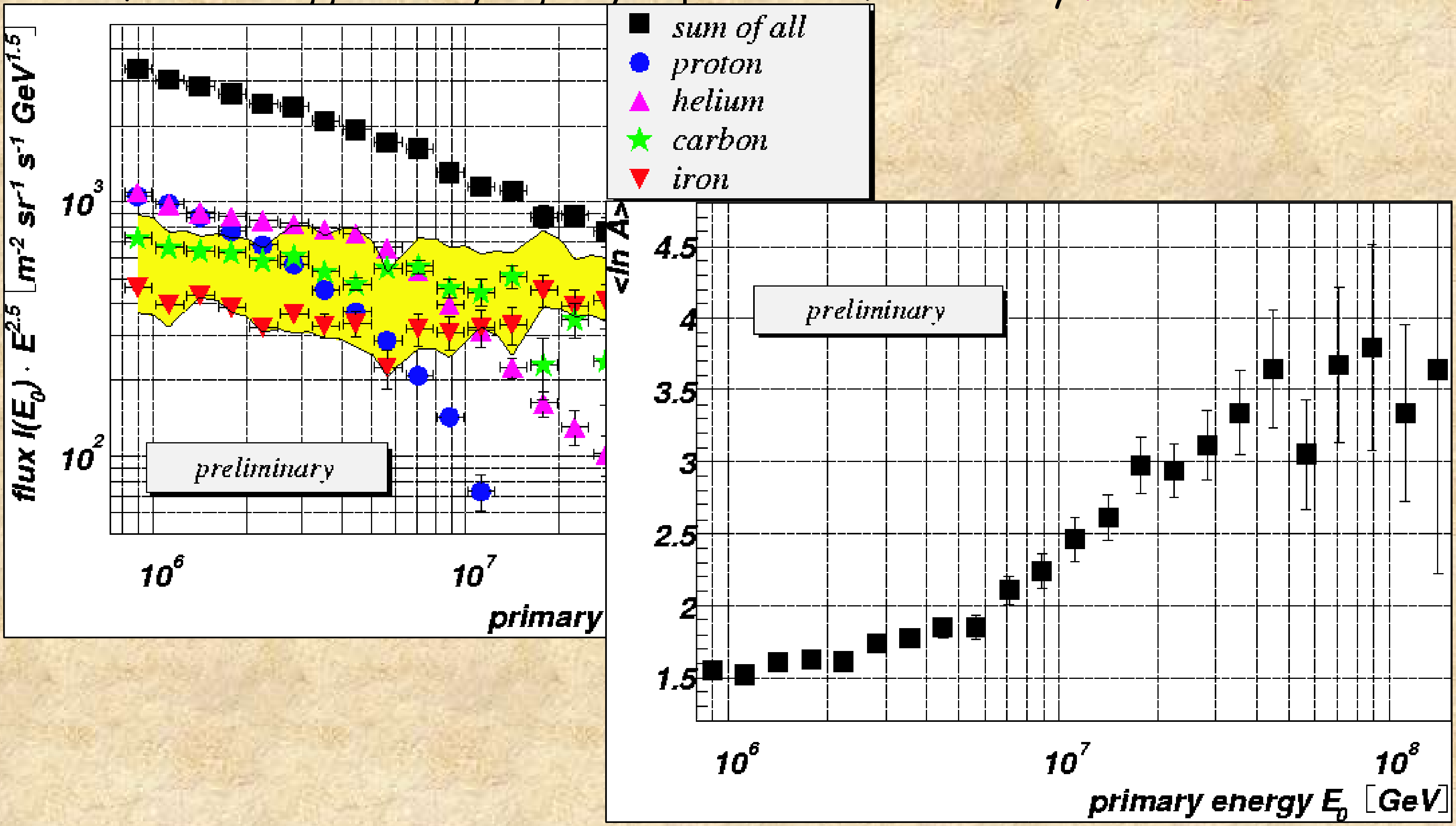
Possible explanations of clustering:

* point-like sources of charged particles in case of insignificant magnetic deflection
* point-like sources of neutral primaries
* magnetic lensing of charged primaries



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.

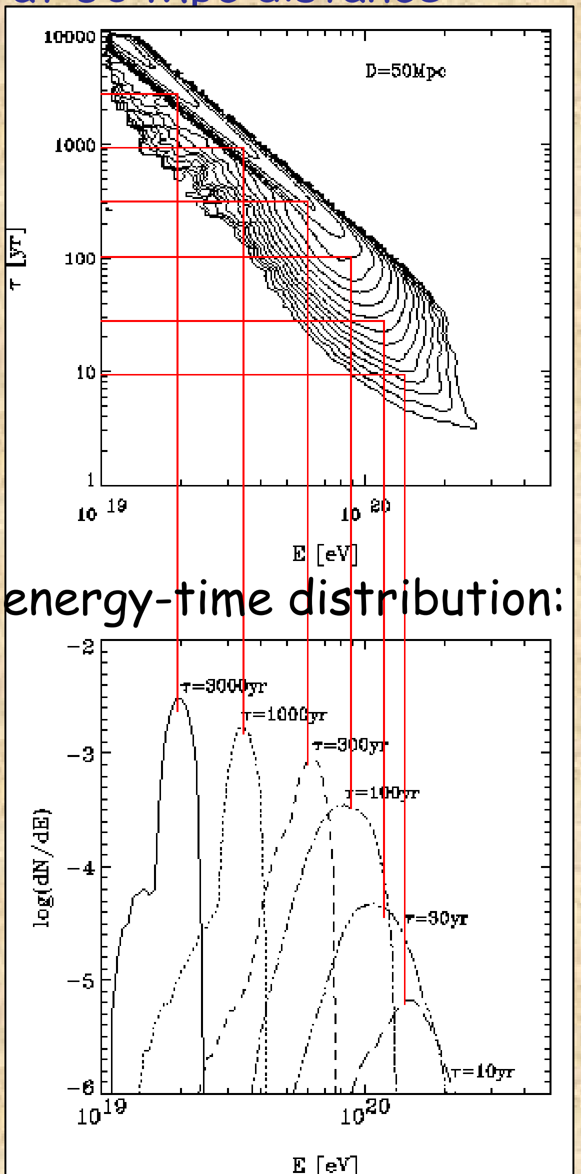
Example: Magnetic field of 10^{-10} Gauss,
coherence scale 1 Mpc,
burst source at 50 Mpc distance

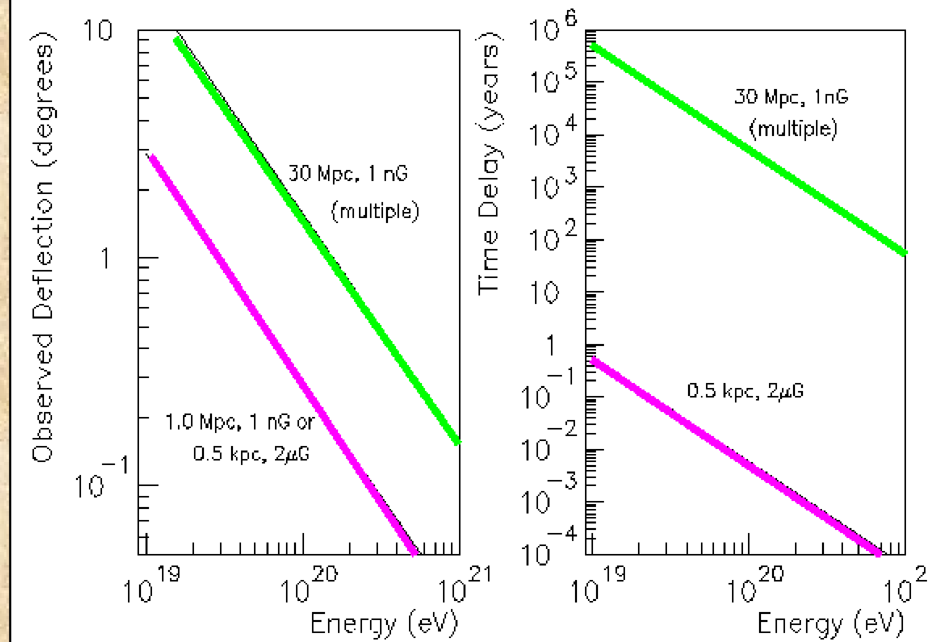
Typical numbers:

time delay

cuts through energy-time distribution:

differential spectrum



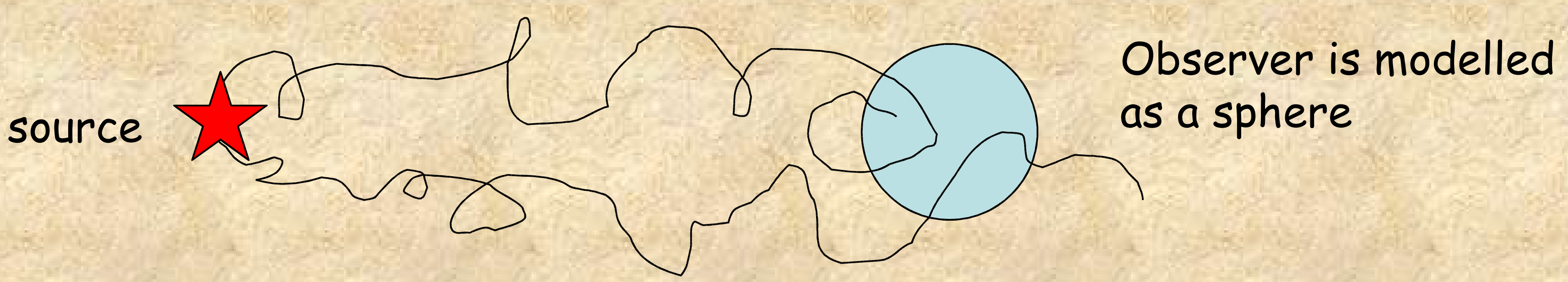


Δθ for a vertical shower:

	10 EeV	100 EeV
Array alone	2°	<1°
Hybrid	0.25°	0.20°

Lemoine, Sigl

Principle of deflection Monte Carlo code

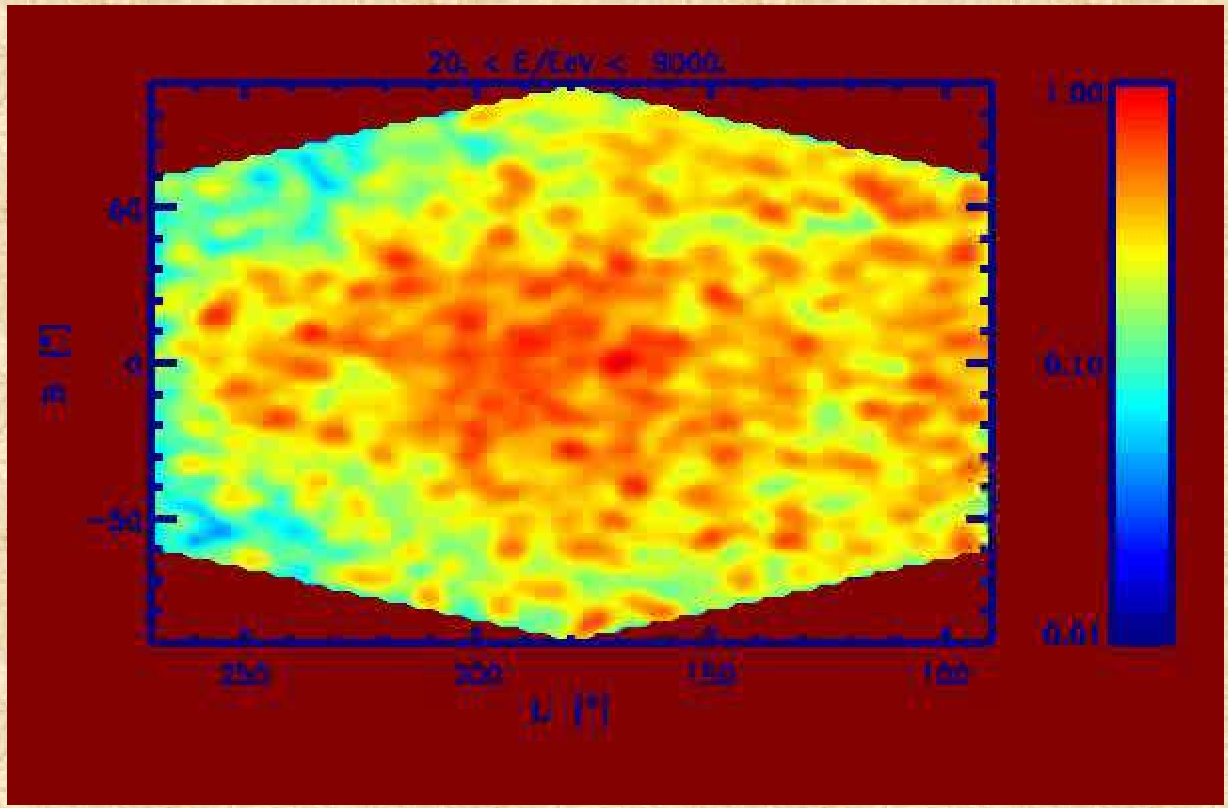


A particle is registered every time a trajectory crosses the sphere around the observer. This version to be applied for individual source/magnetic field realizations and inhomogeneous structures.

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.



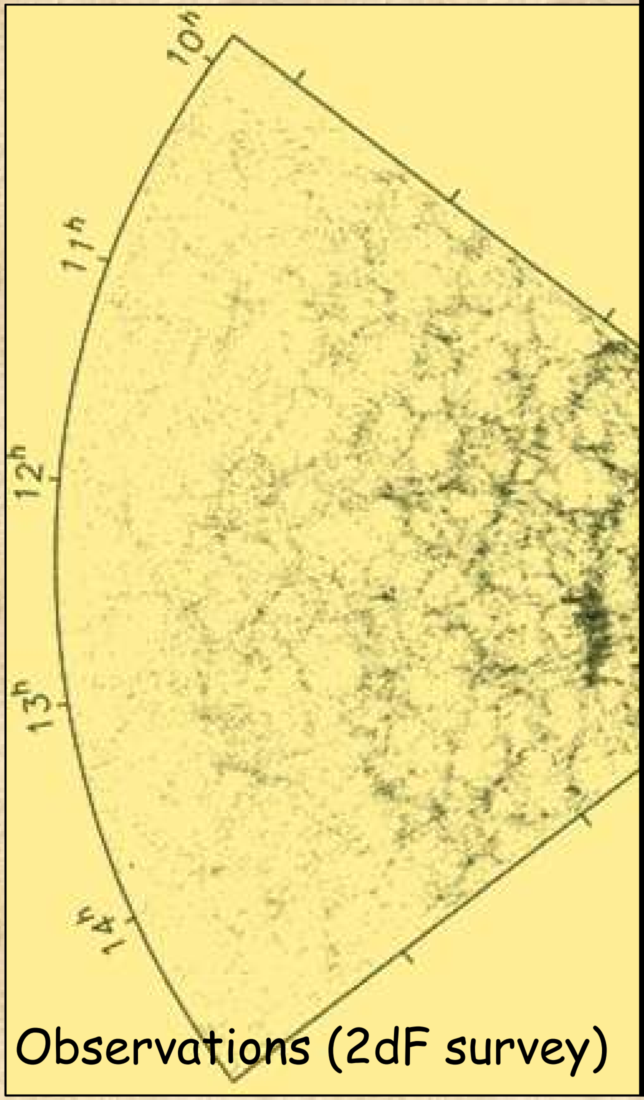
10^5 trajectories,
251 images between
20 and 300 EeV,
2.5° angular resolution

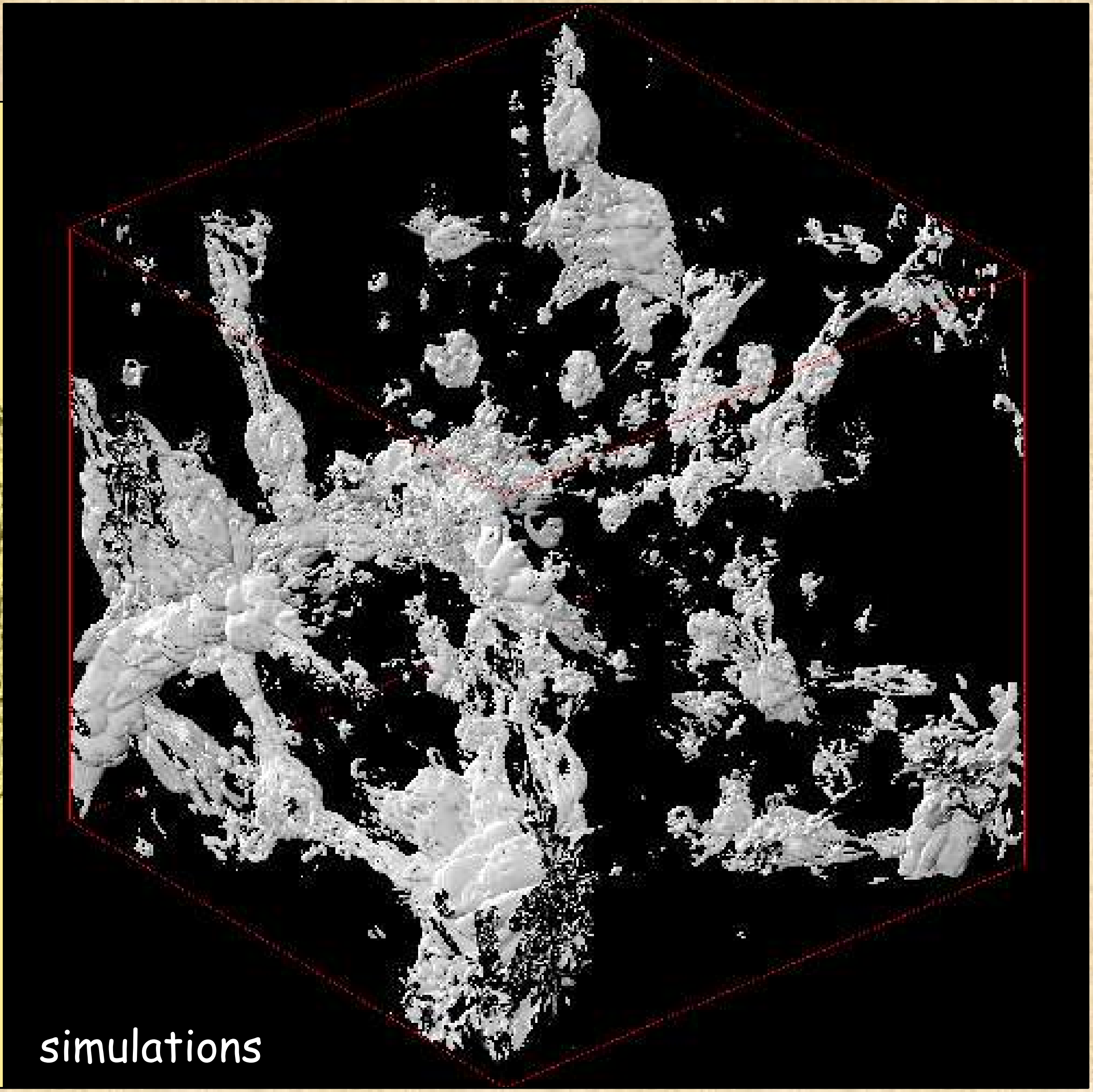
Isola, Lemoine, Sigl

Conclusions:

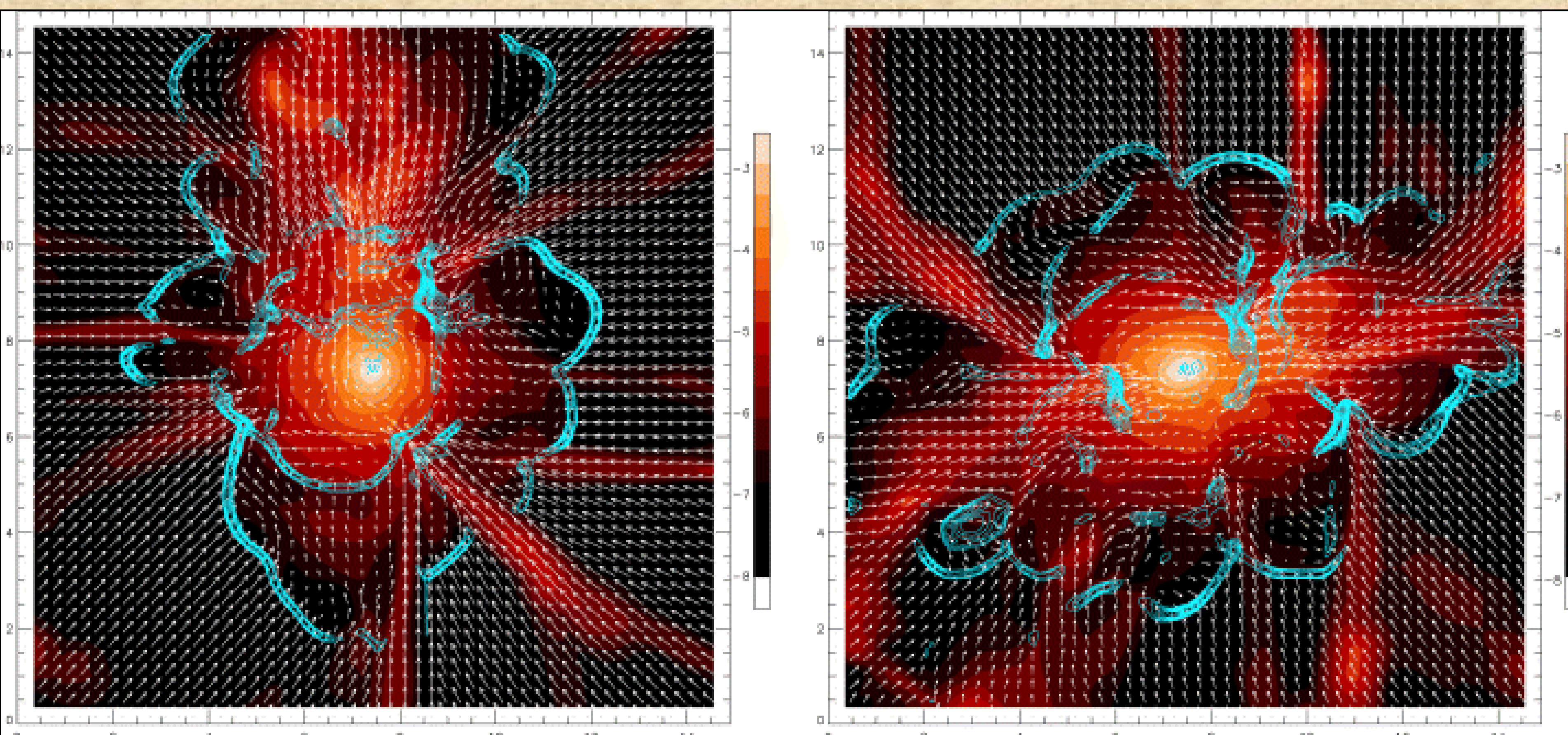
1.) Isotropy is inconsistent with only one source.
2.) Strong fields produce interesting lensing (clustering) effects.

The Universe is structured





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



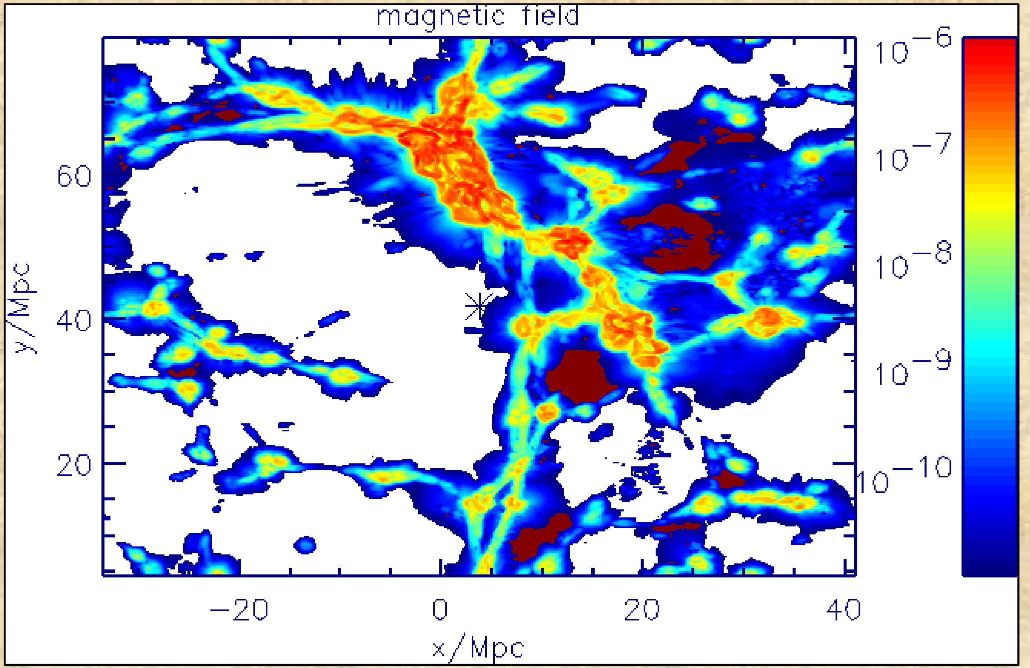
Miniati, MNRAS 342, 1009

Some results on propagation in structured extragalactic magnetic fields

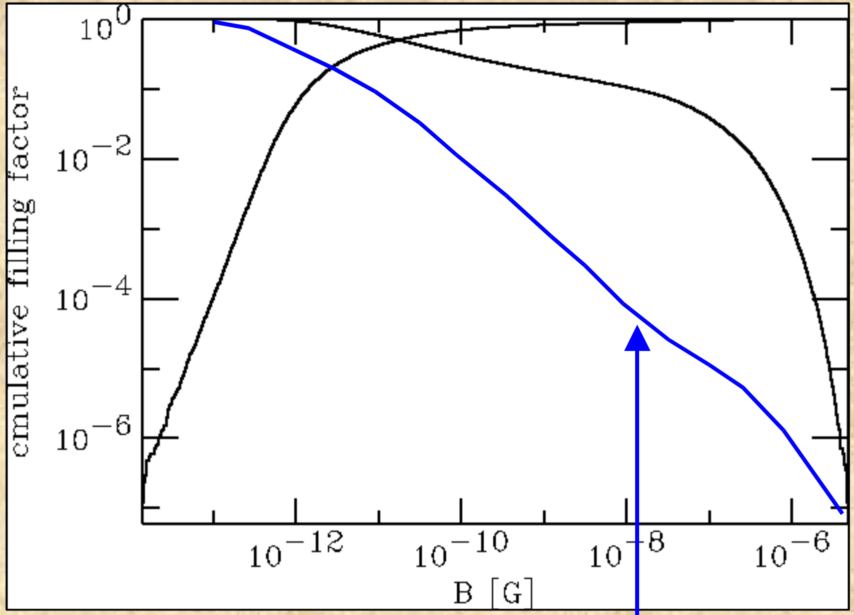
Scenarios of extragalactic magnetic fields using large scale structure simulations with magnetic fields followed passively and normalized to a few micro Gauss in galaxy clusters.

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

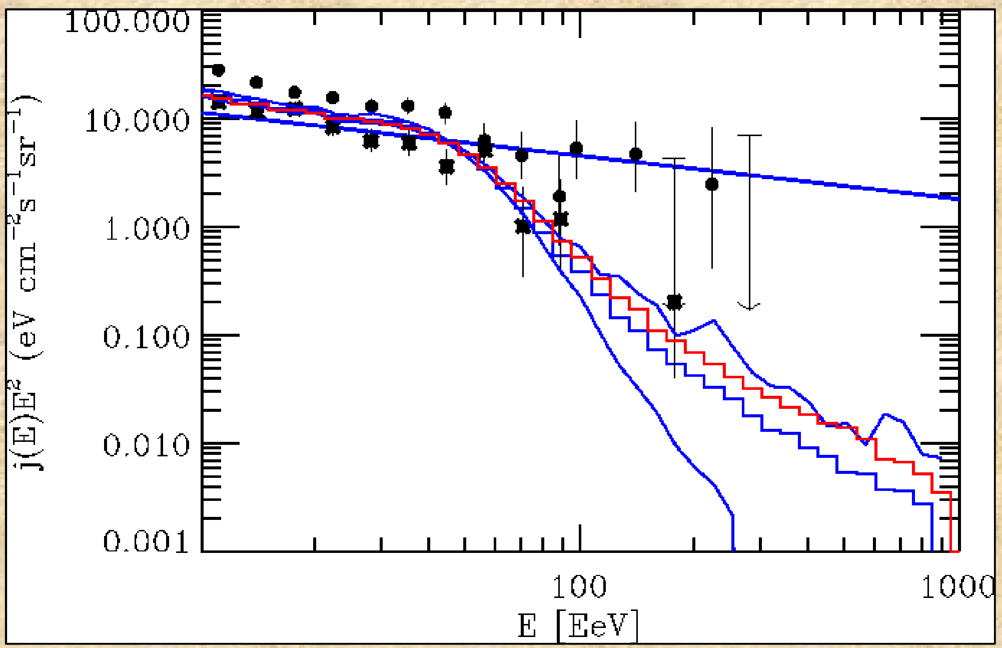
Sources of density ~10^{-5} Mpc^{-3} follow Baryon density, field at Earth ~10^{-11} G.



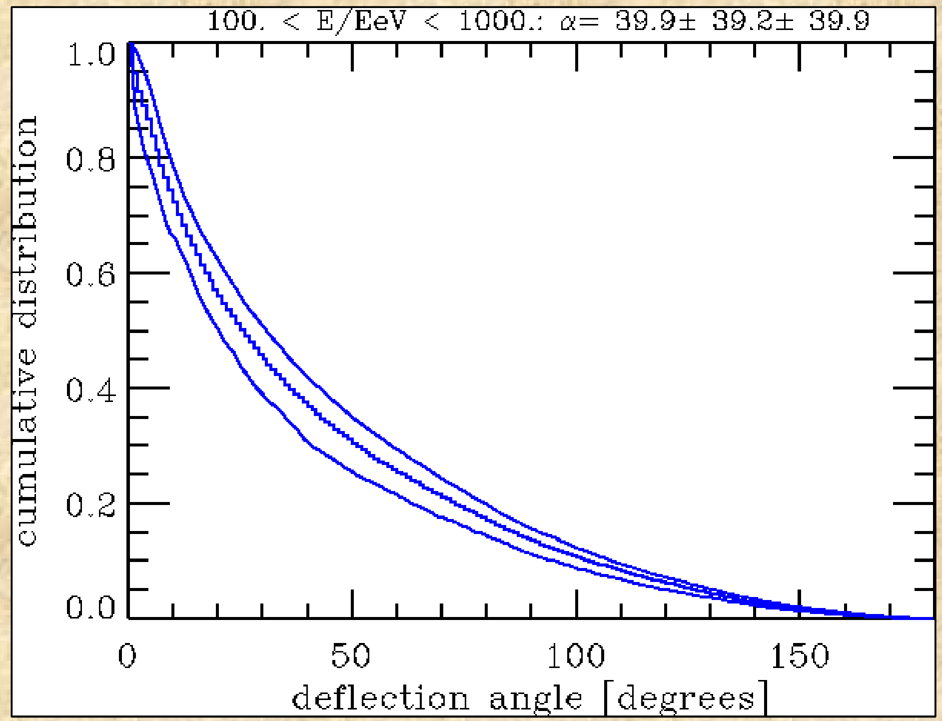
Magnetic field filling factors



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



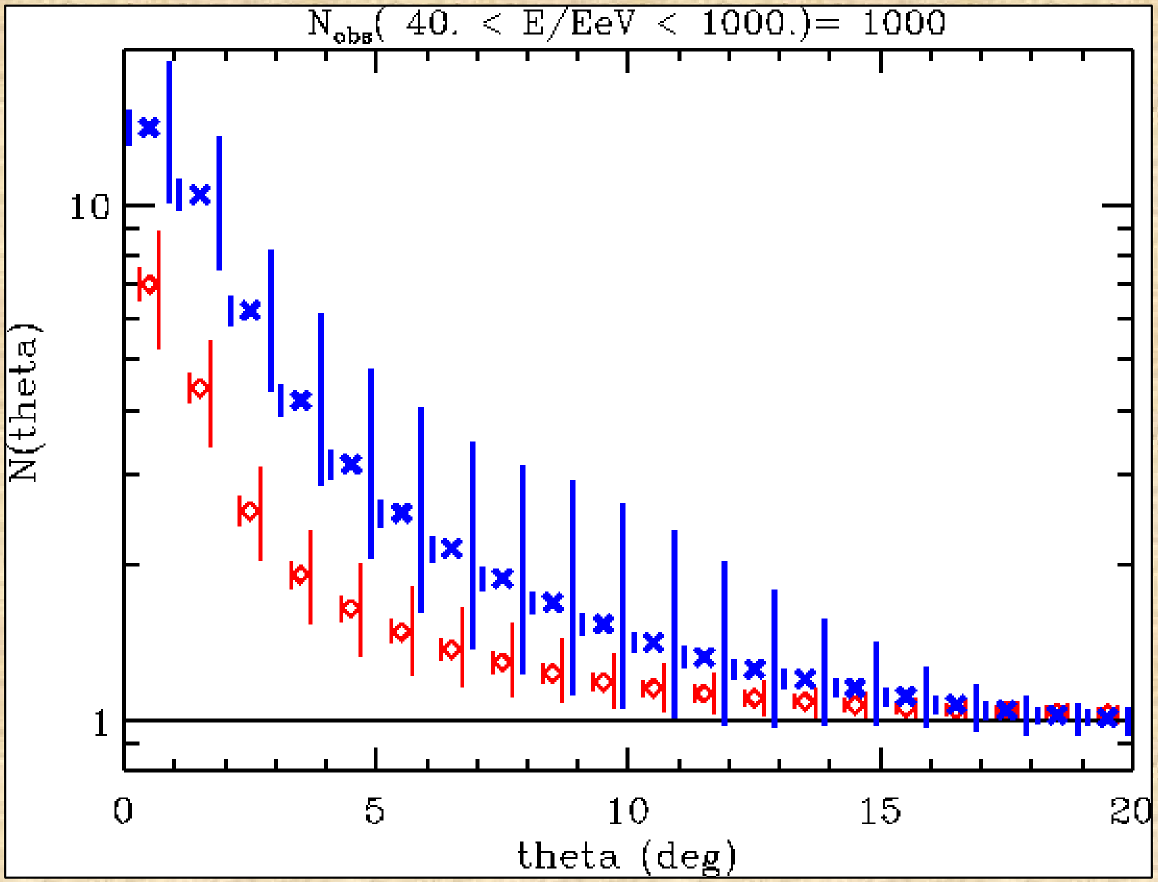
The spectrum in the magnetized source scenario shows a pronounced GZK cut-off with field as well as without field.



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.

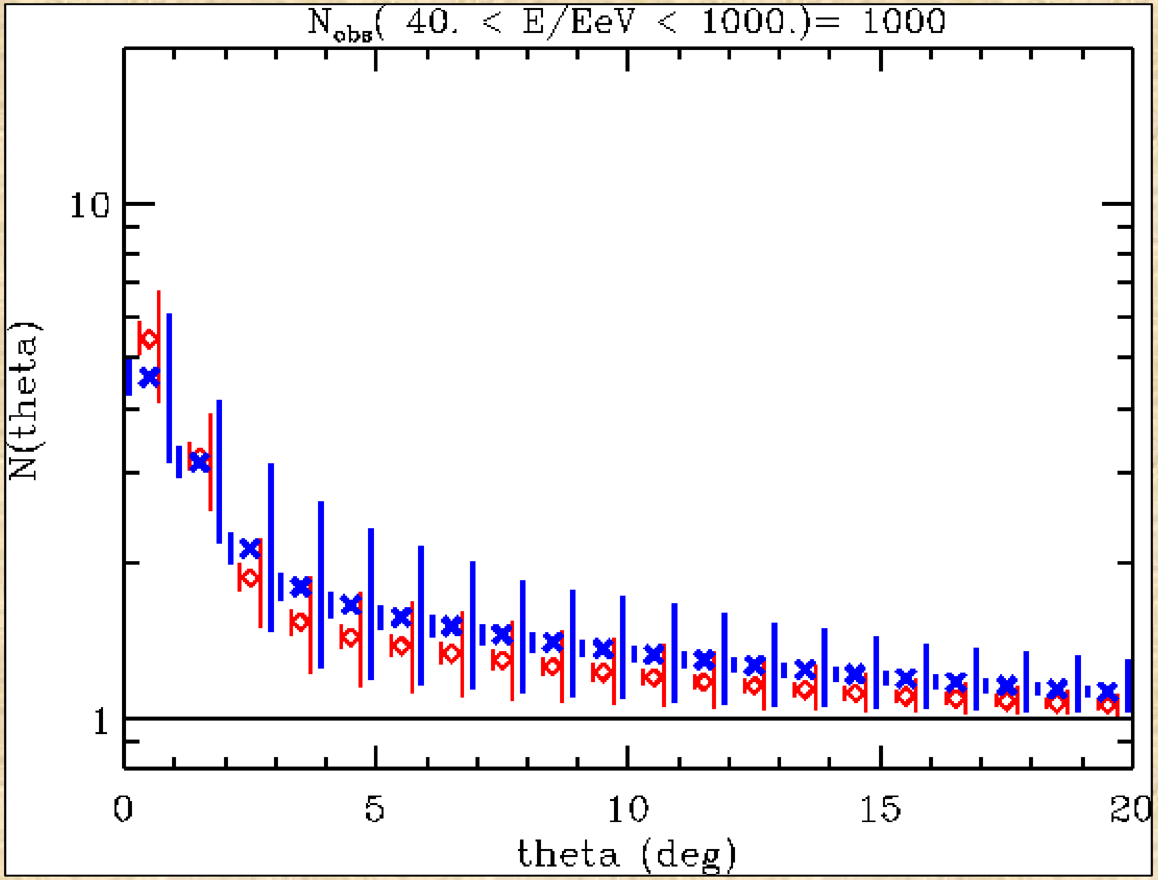
⇒**Particle astronomy not necessarily possible, especially for nuclei !**

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.

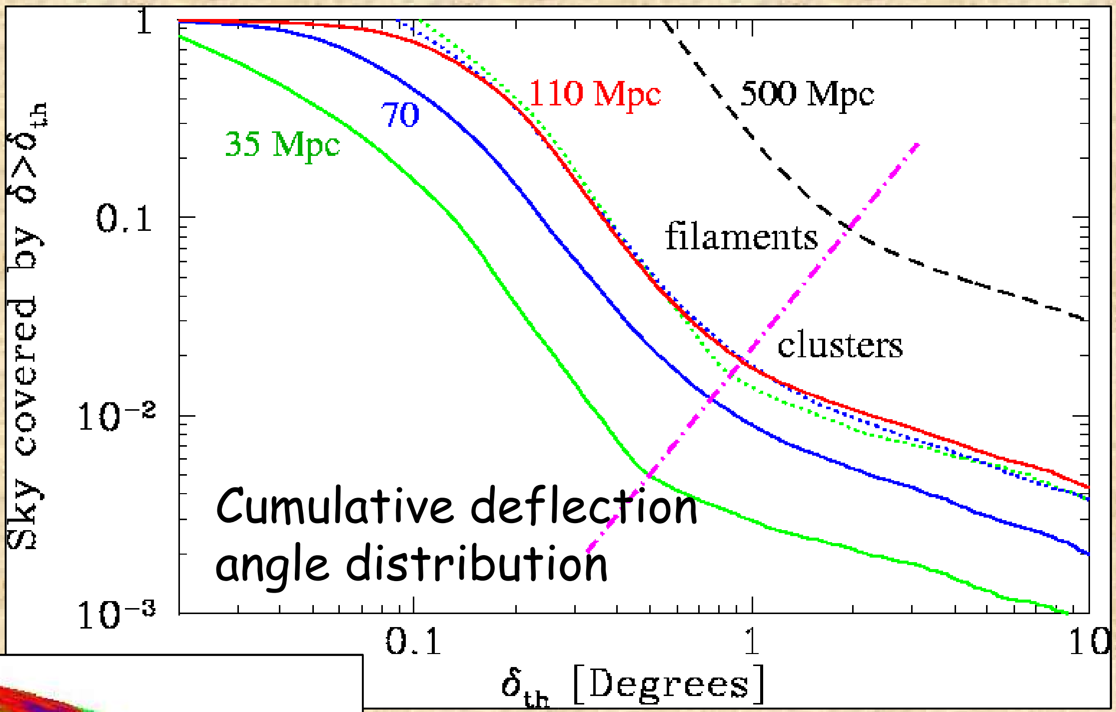
Magnetized, Structured Sources: Future Sensitivities

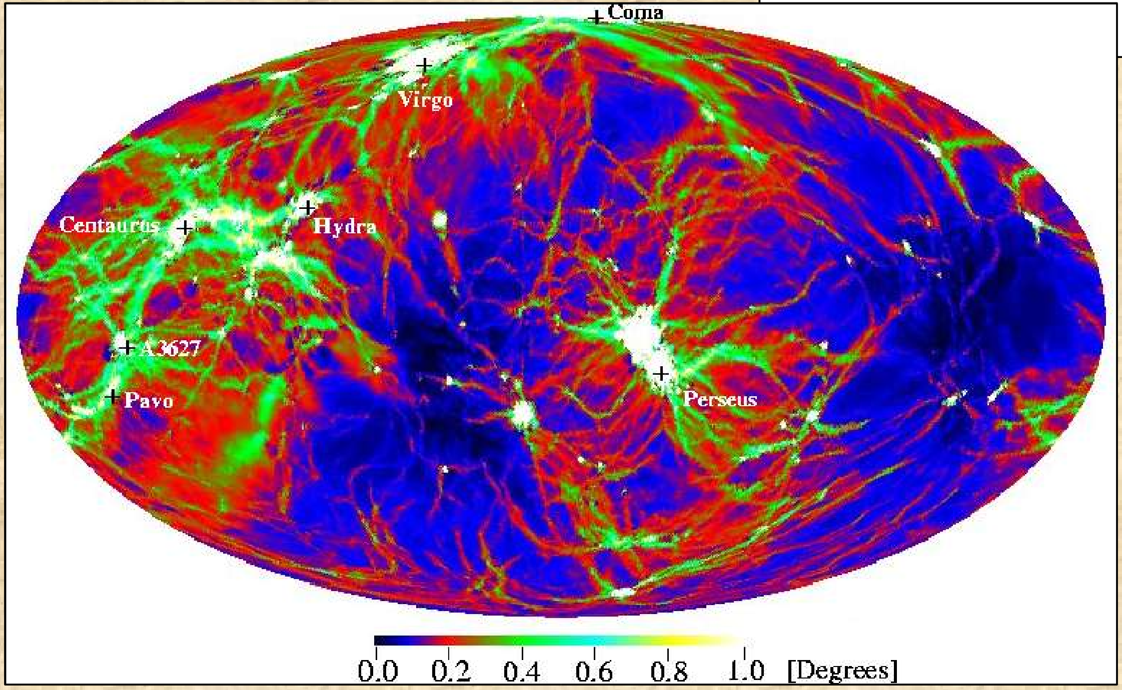


Comparing predicted autocorrelations for source density = 2.4x10^{-4} Mpc^{-3} (red set) and 2.4x10^{-5} Mpc^{-3} (blue set) for an Auger-type exposure.

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

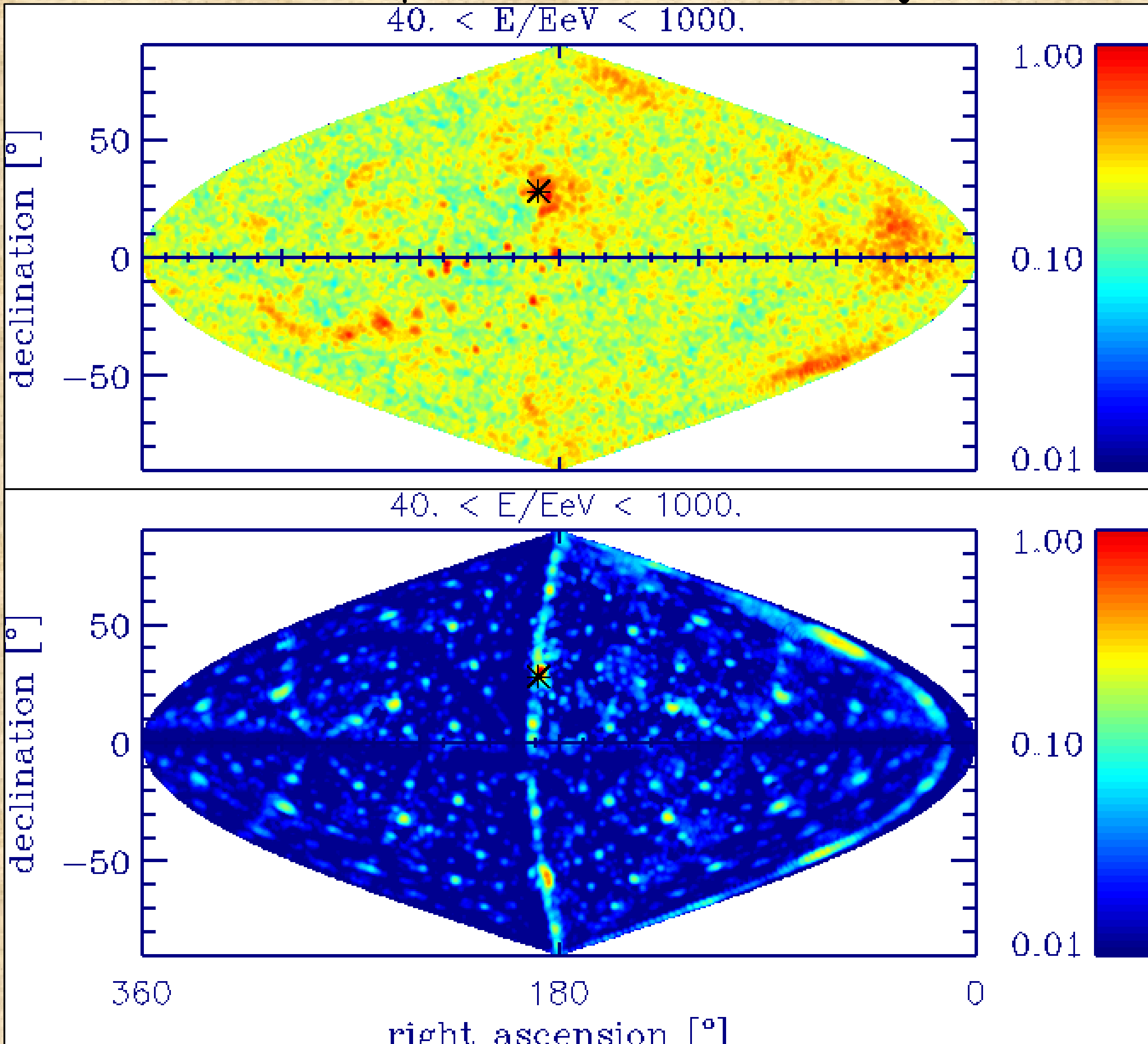
Comparison with Dolag et al.





Sky map of deflection angles

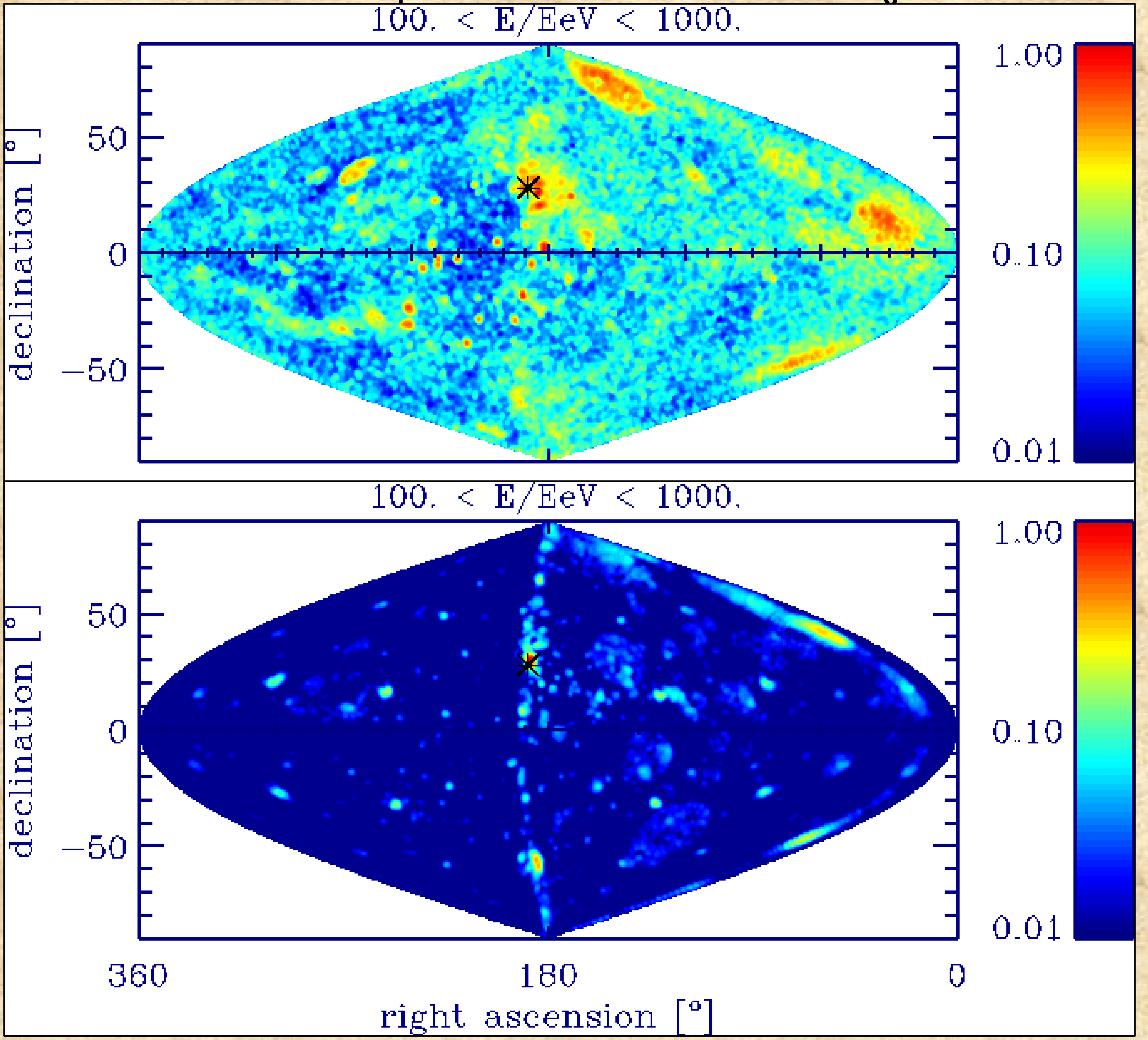
The simulated sky above 4×10^{19} eV with structured sources of density 2.4×10^{-5} Mpc^{-3} : ~2×10^{5} simulated trajectories above 4×10^{19} eV.



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 4×10^{19} eV.

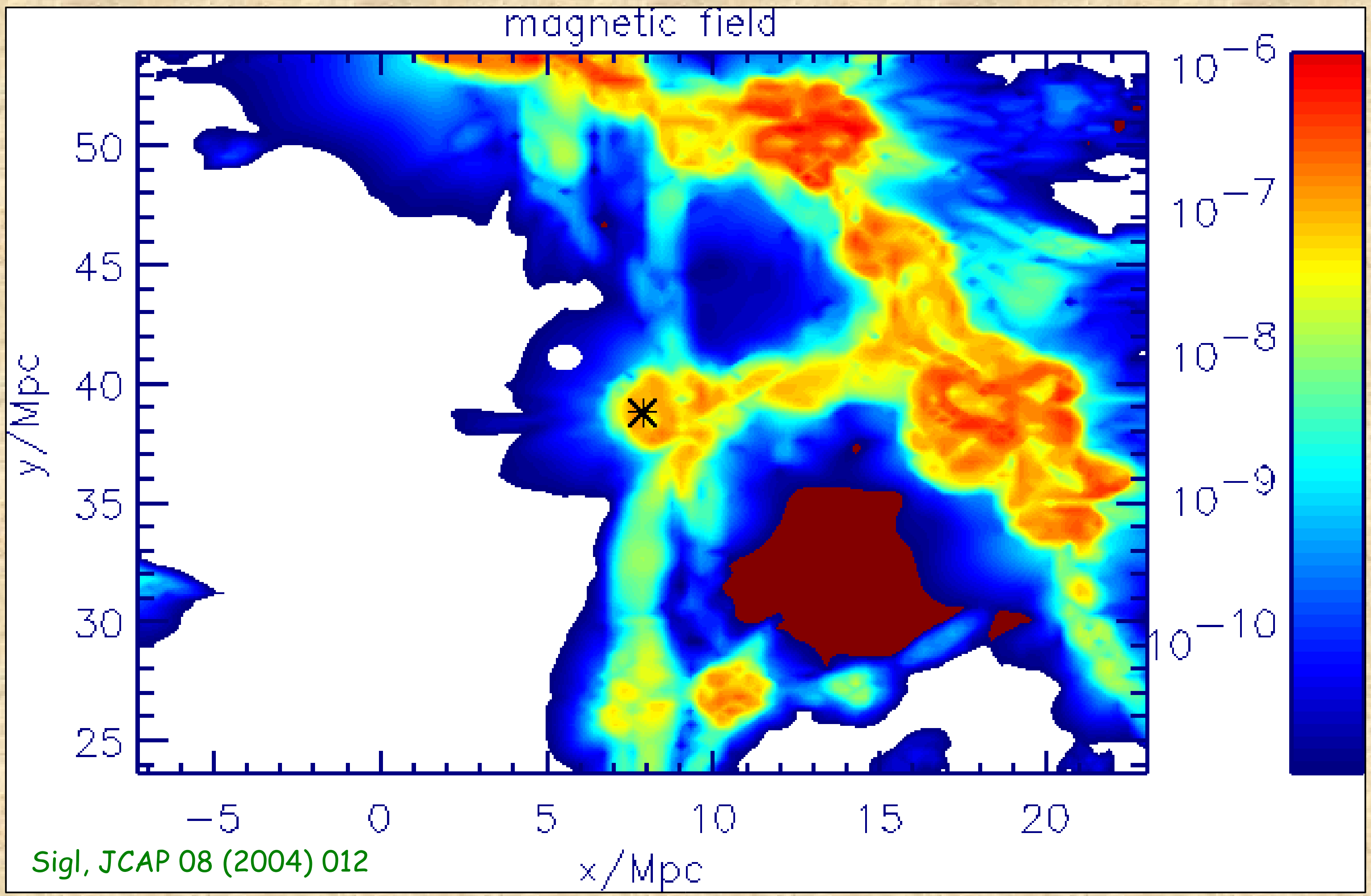


With field

Without field

Generalization to Heavy Nuclei: Structured Fields and Individual Sources

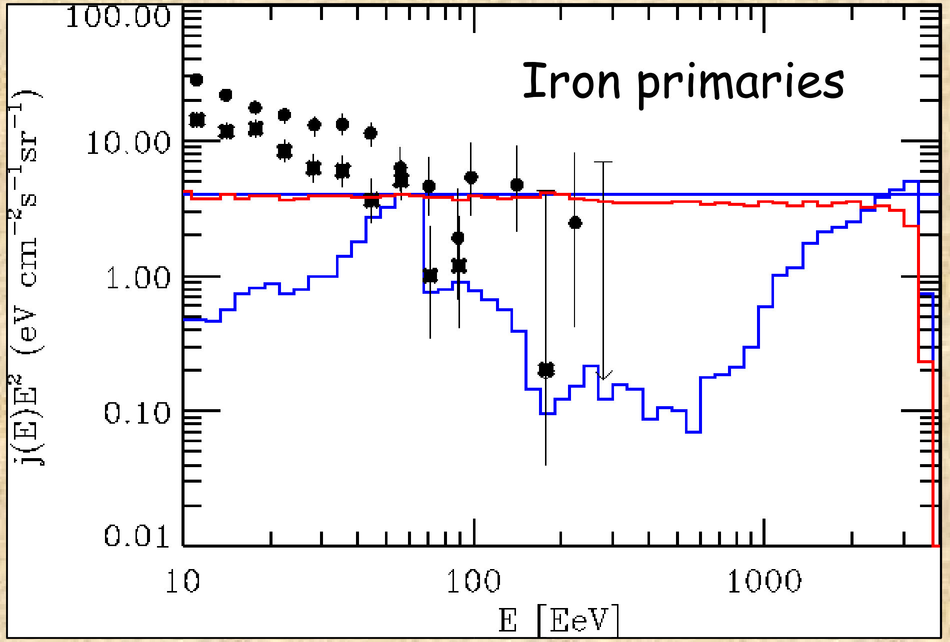
Spectra and Composition of Fluxes from Single Discrete Sources considerably depend on Source Magnetization, especially for Sources within a few Mpc

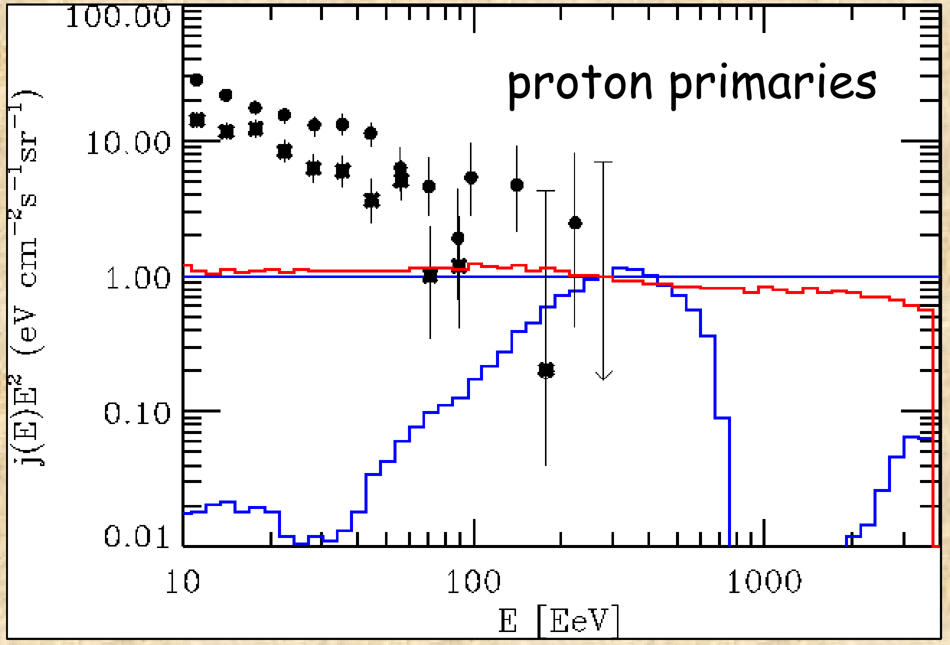


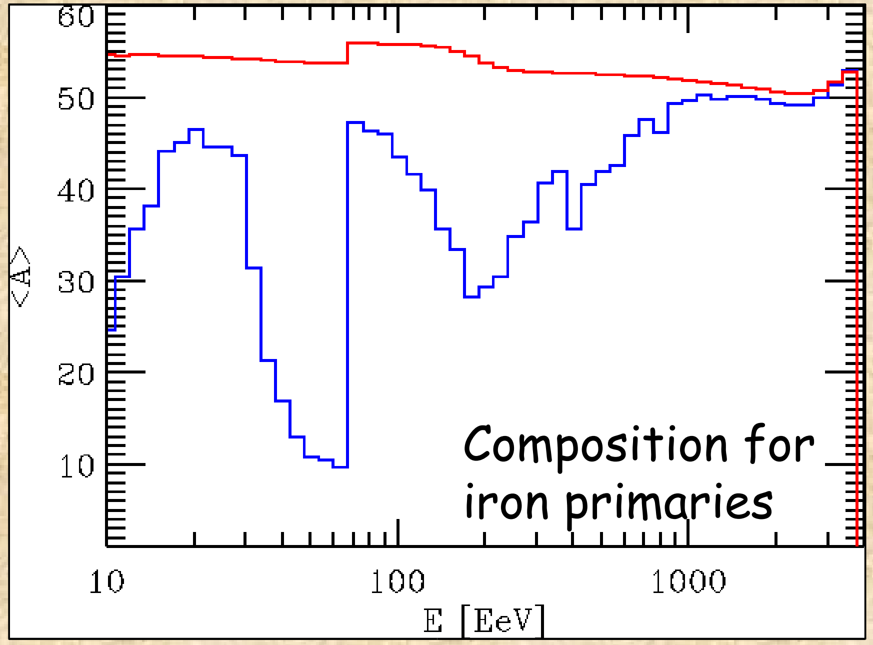
Sigl, JCAP 08 (2004) 012

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







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

accelerated protons interact:

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

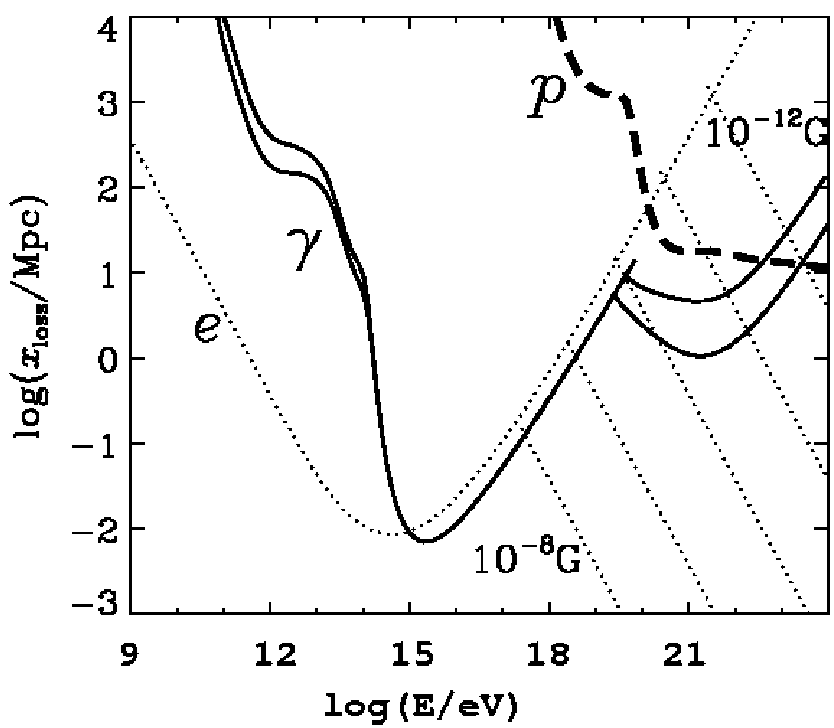
during propagation ("cosmogenic") or in sources (AGN, GRB, ...)

=> 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



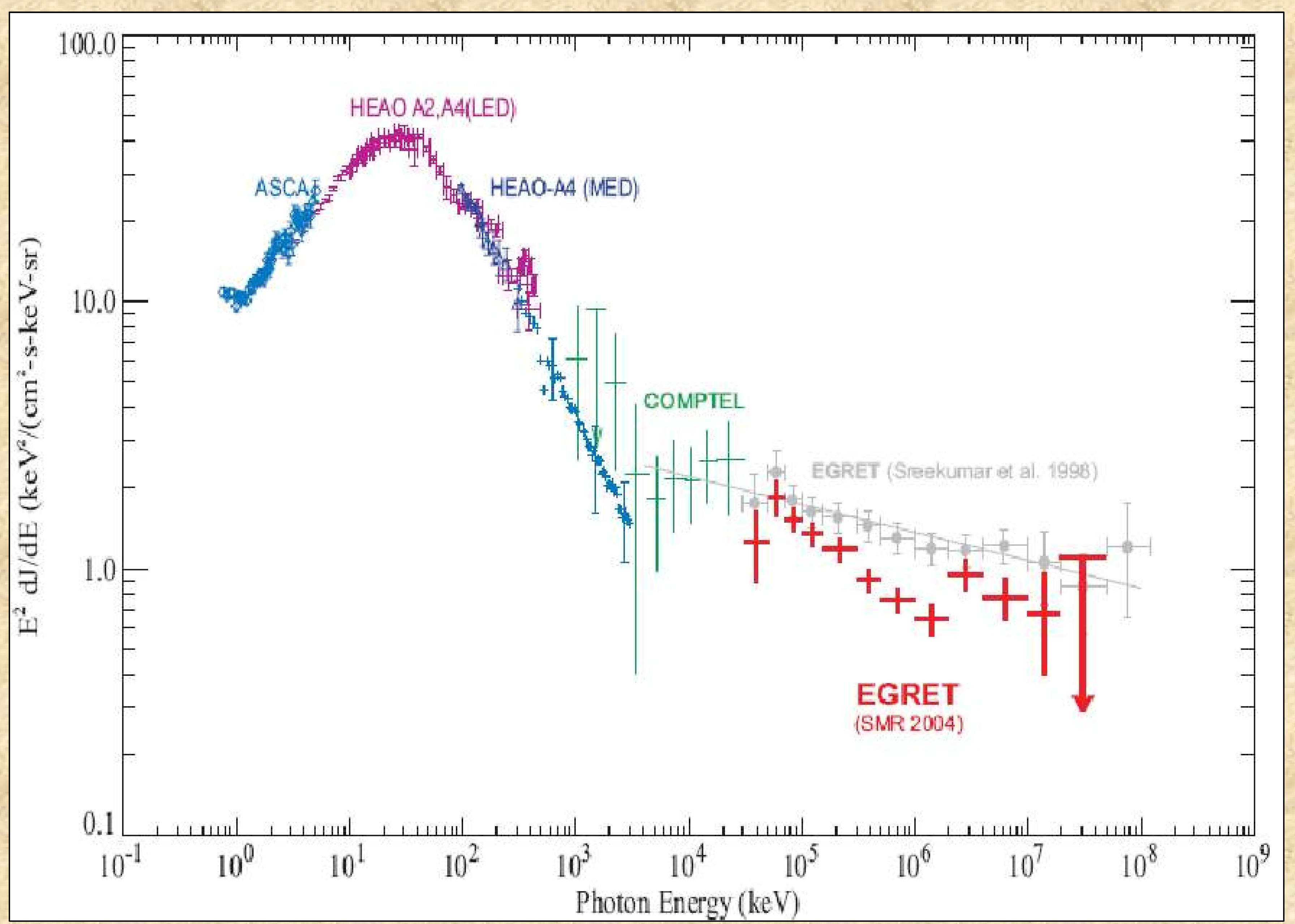
Included processes:

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

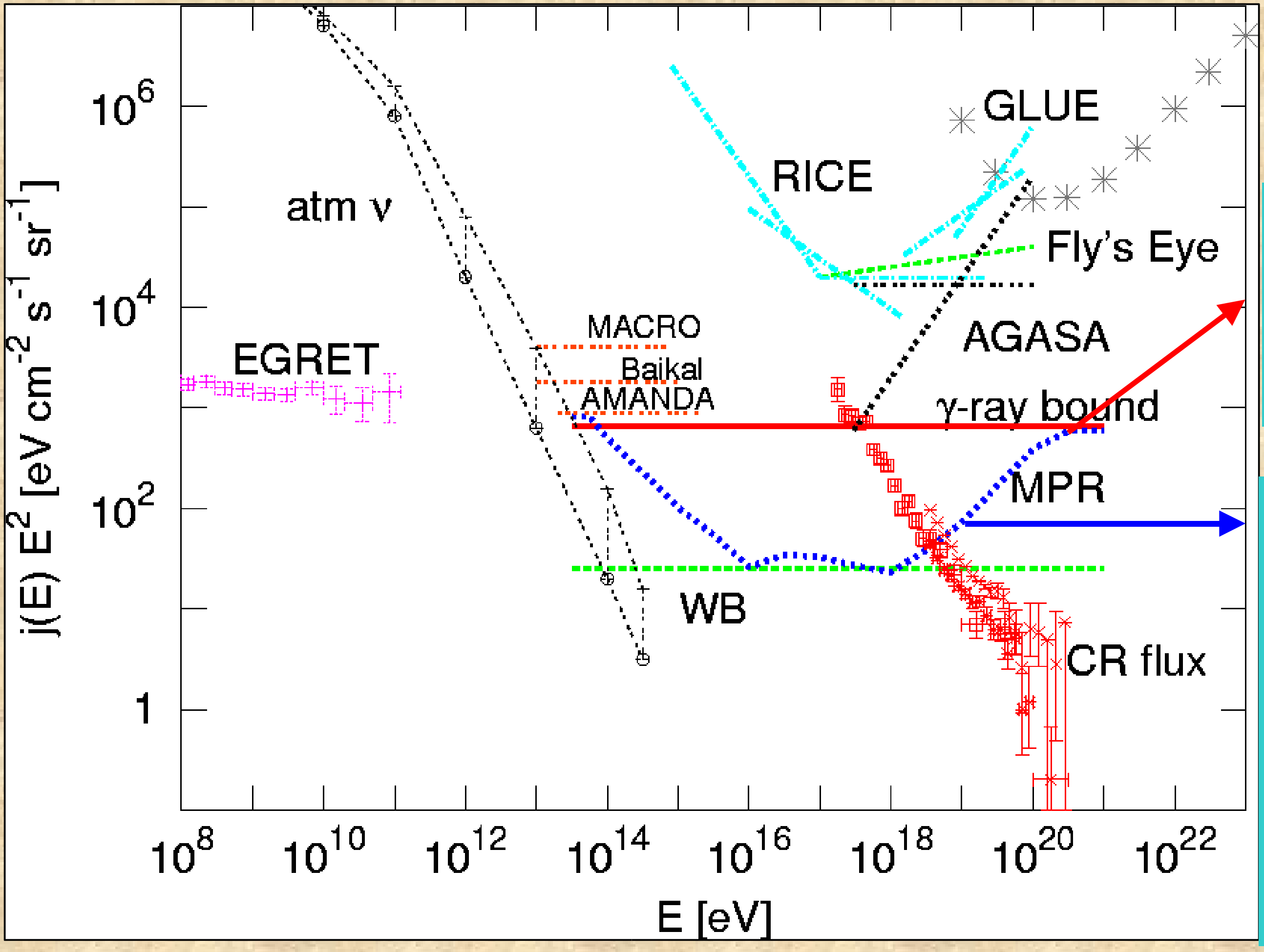
Gammas: pair-production through IR, CMB, and radio backgrounds

Protons: Bethe-Heitler pair production, pion photoproduction

The EGRET background



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)

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

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

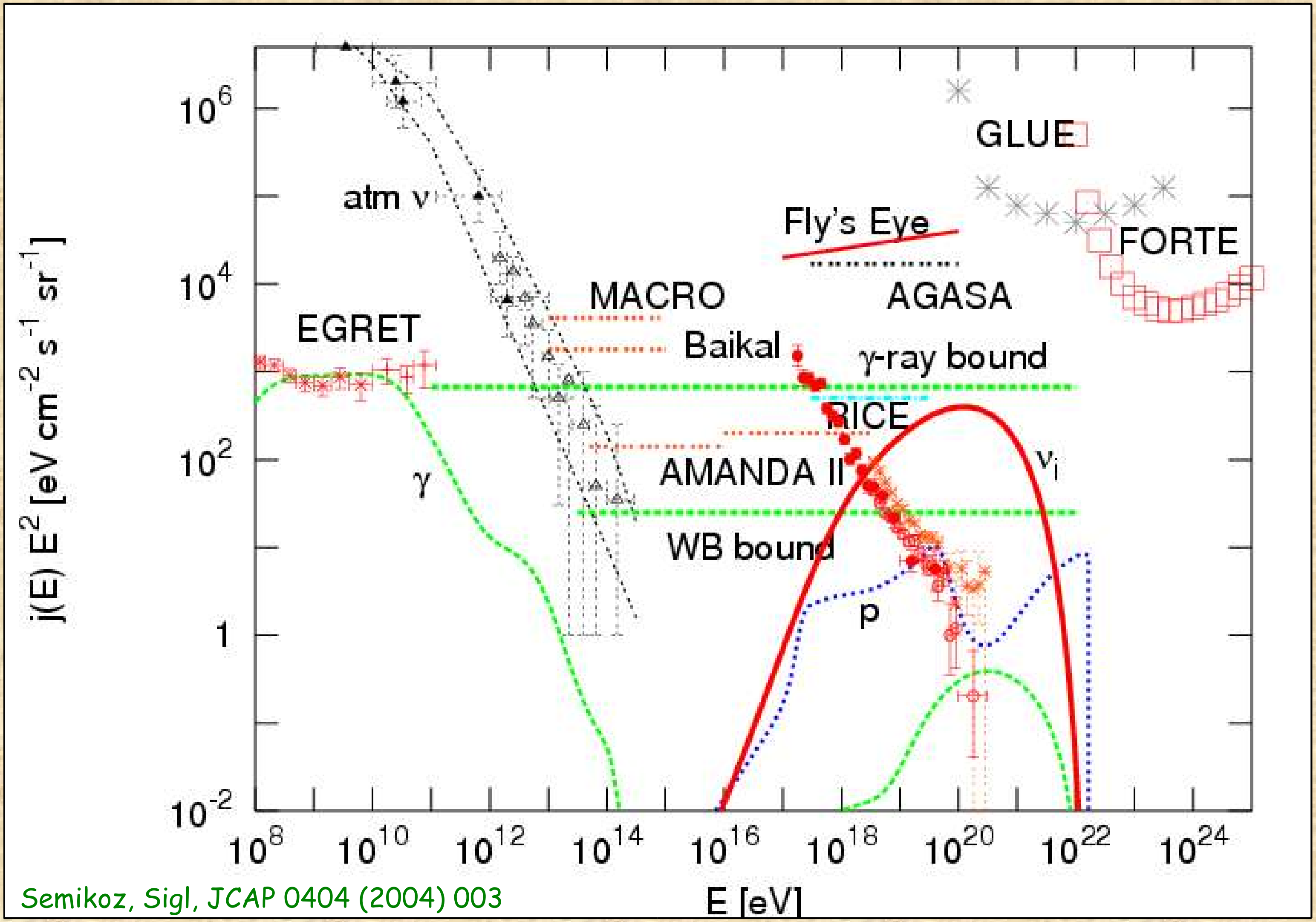
  with fractional energy loss η of leading e

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

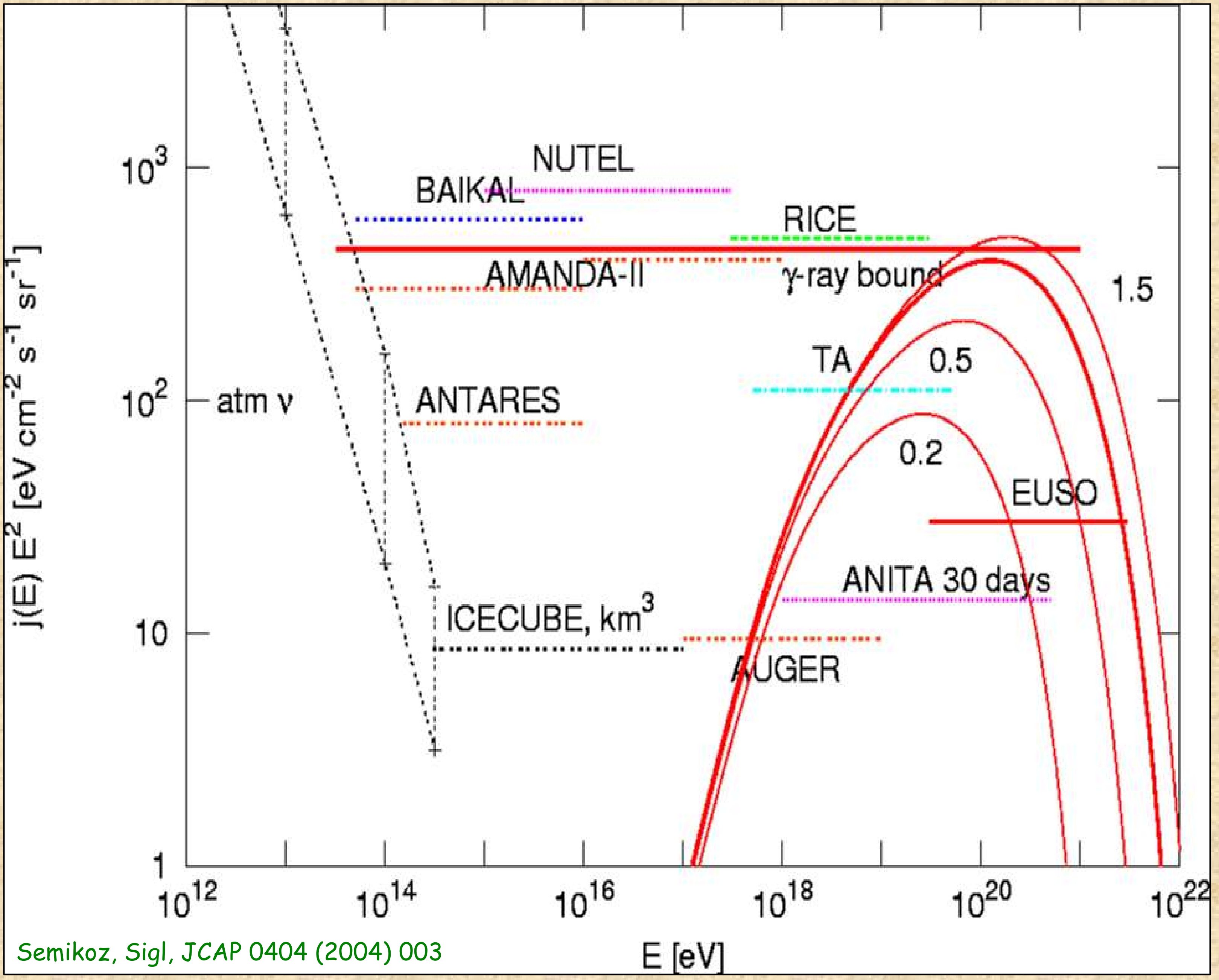
- synchrotron loss of electrons and positrons in cosmic magnetic fields: $eB \to e\gamma$. Energy loss given by

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

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

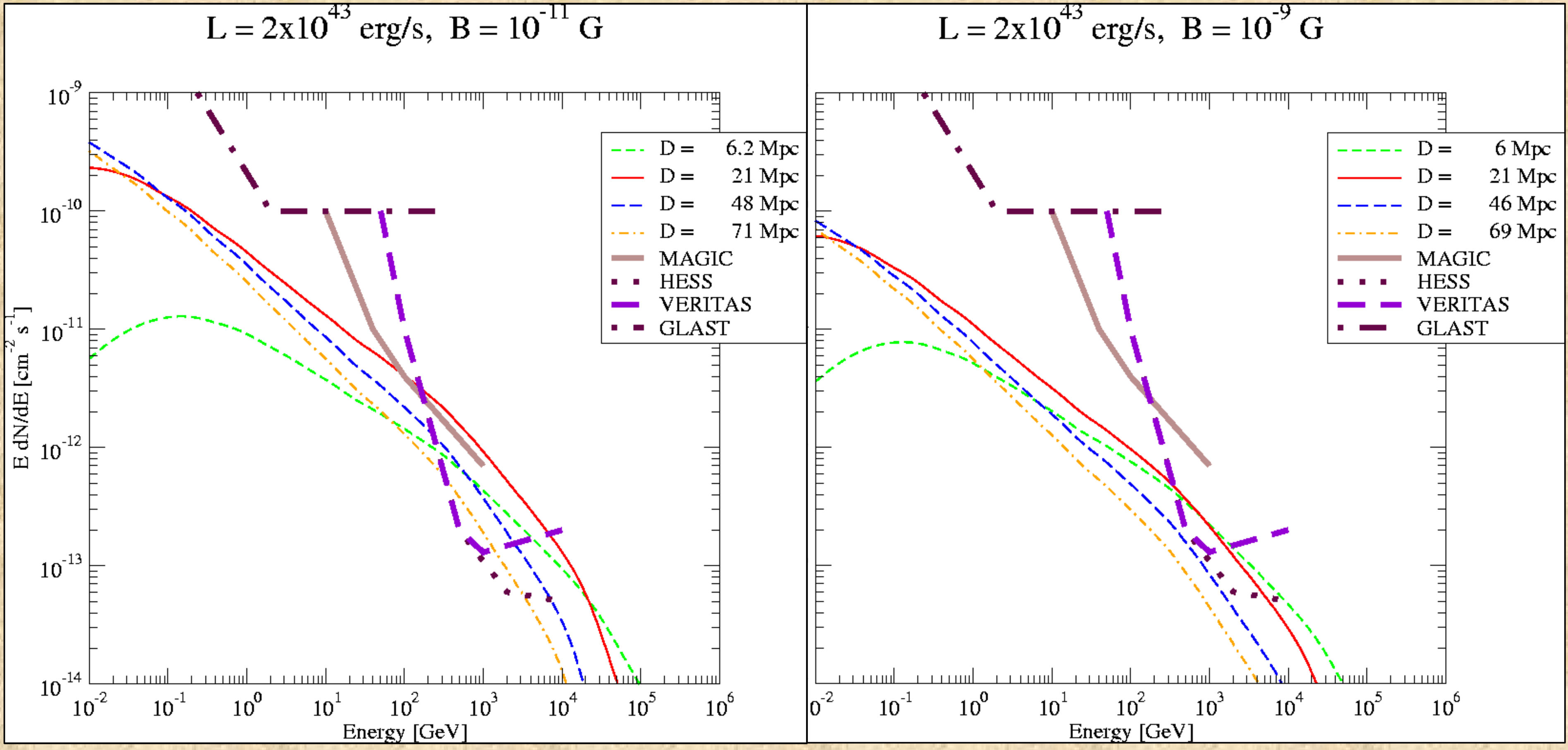


Future neutrino flux sensitivities



Semikoz, Sigl, JCAP 0404 (2004) 003

Secondary γ-rays from discrete sources

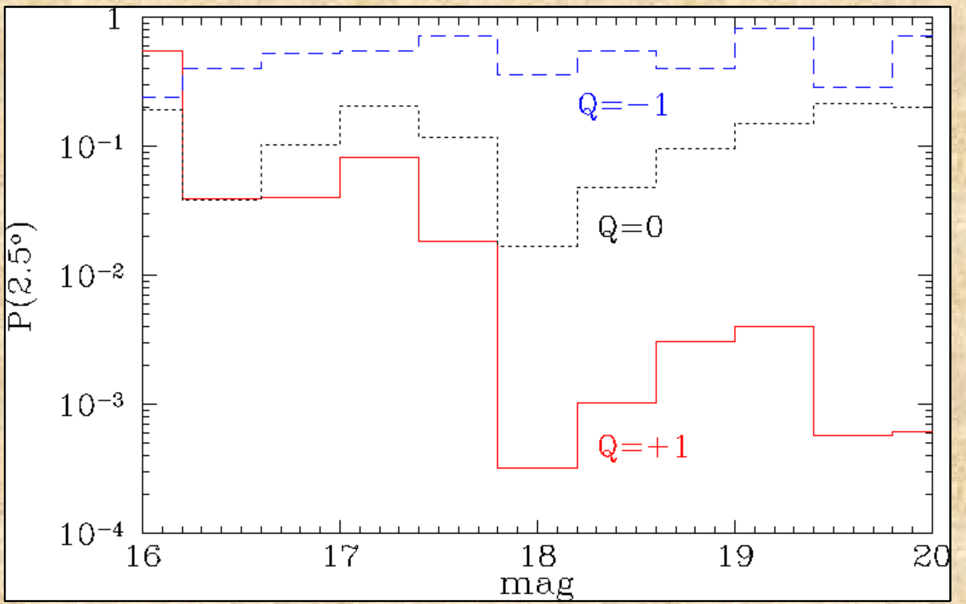


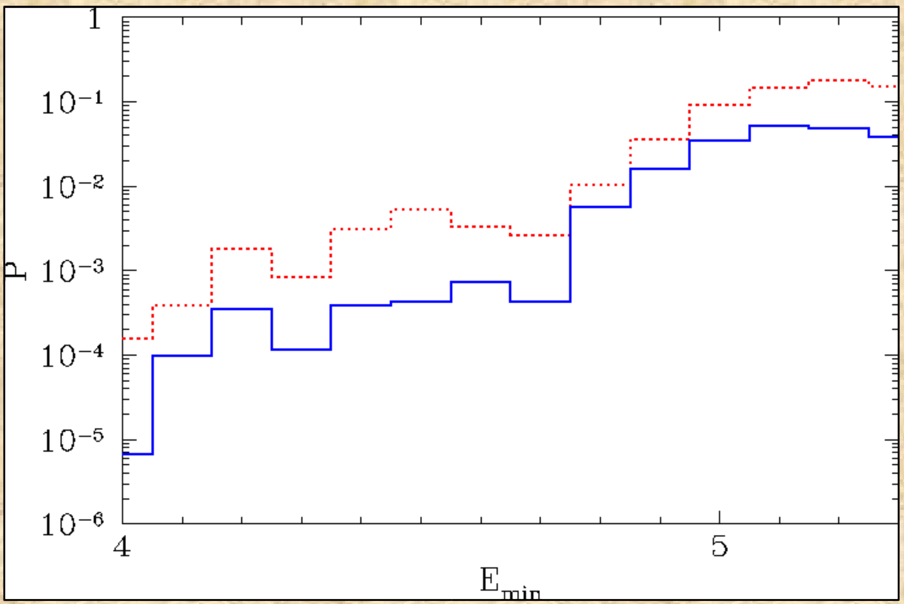
Fluxes depend significantly on extra-galactic magnetic fields.

Ferrigno, Blasi, DeMarco, astro-ph/0404352.

Correlations with extragalactic Sources

Farrar, Biermann	radio-loud quasars	~1%
Virmani et al.	radio-loud quasars	~0.1%
Tinyakov, Tkachev	BL-Lac objects	~10^{-4}
G.S. et al.	radio-loud quasars	~10%





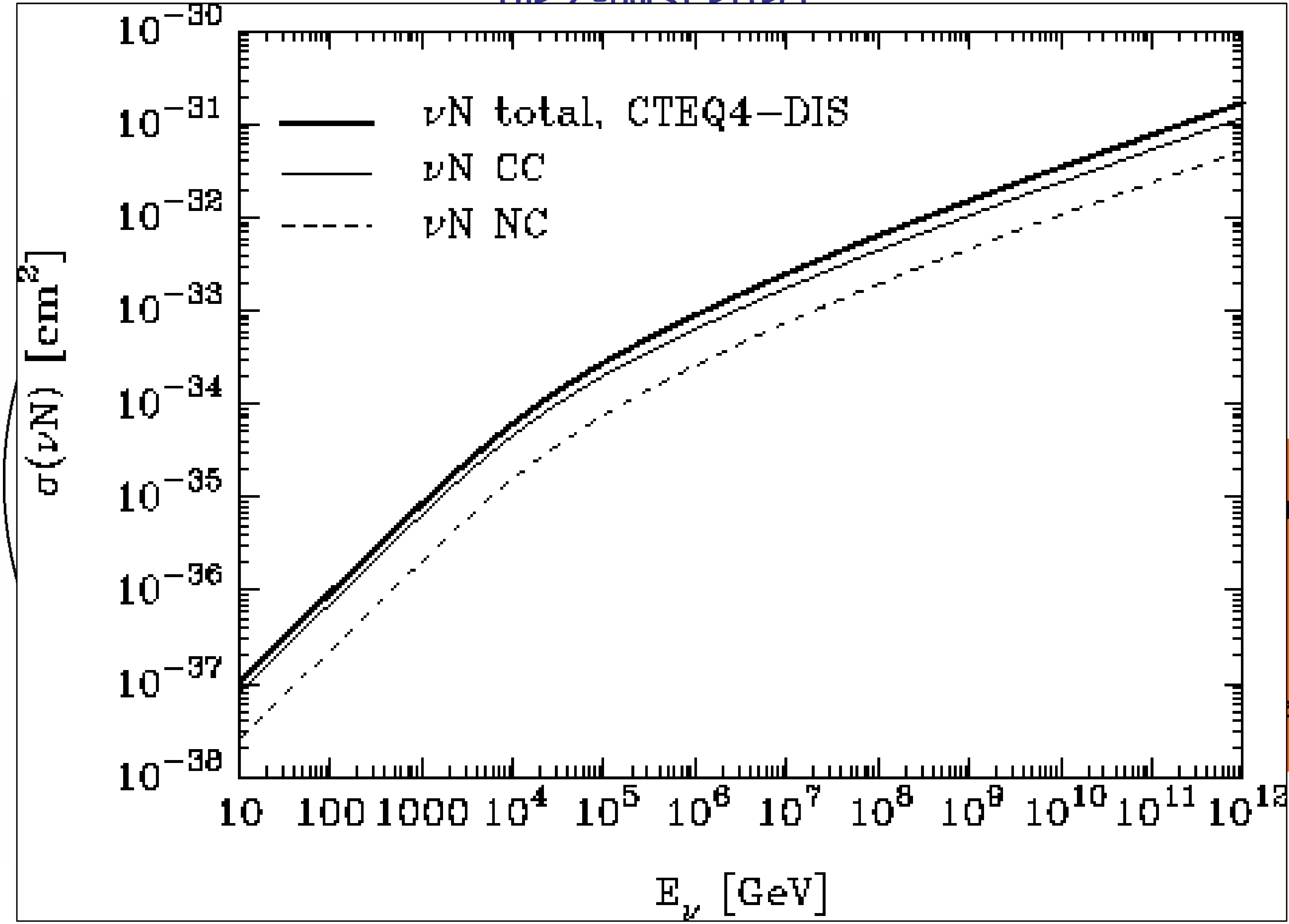
Surprise: Deflection seems dominated by our Galaxy. Sources in direction of voids?

Tinyakov, Tkachev, Astropart.Phys. 18 (2002) 165

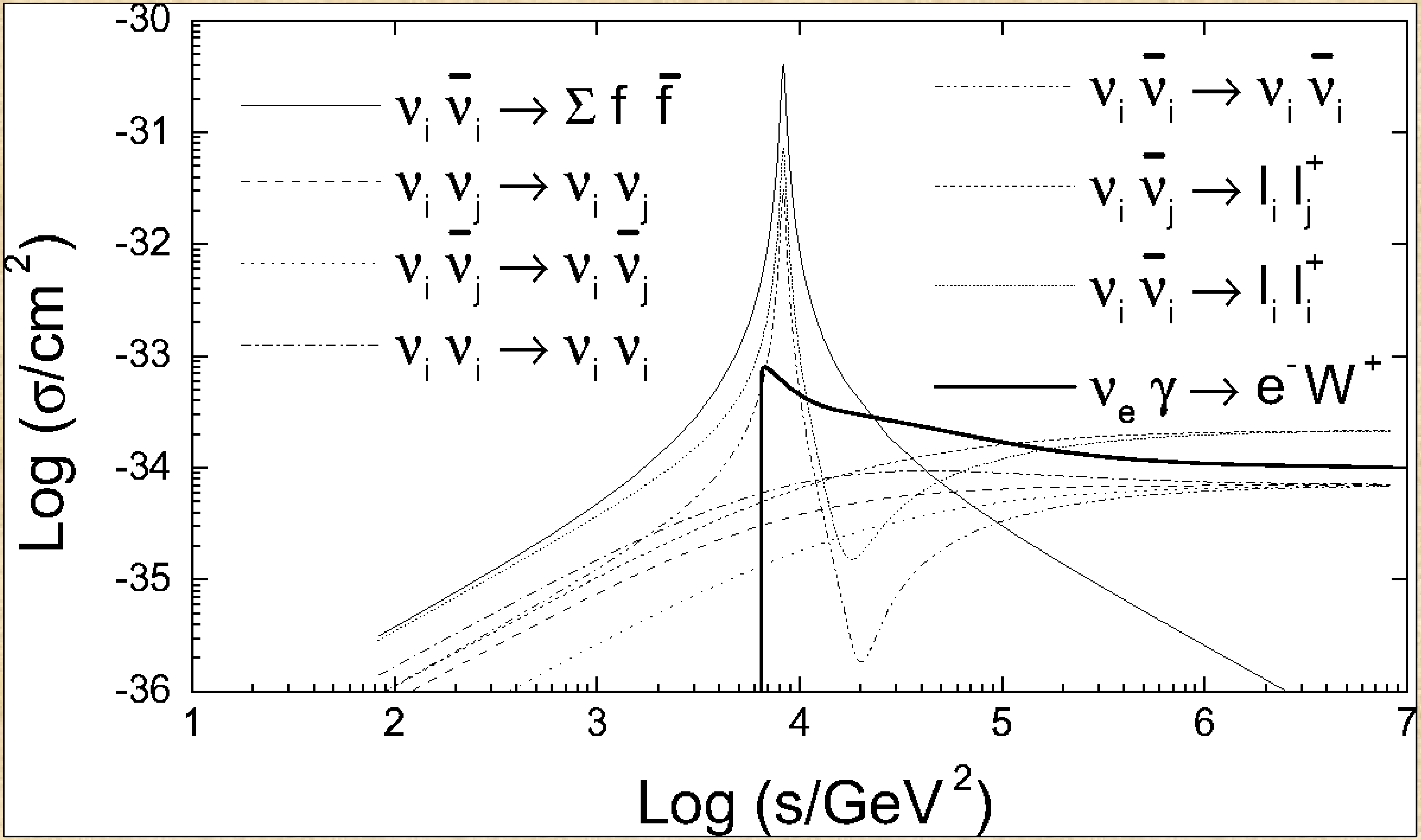
BL-Lac distances poorly known: Are they consistent with UHECR energies ?

Tinyakov, Tkachev, hep-ph/0212223

The Z-burst effect

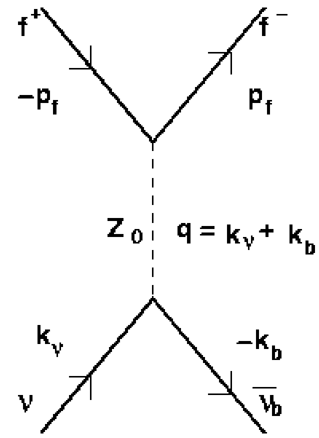


The Z-burst mechanism: Relevant neutrino interactions



Neutrinos:

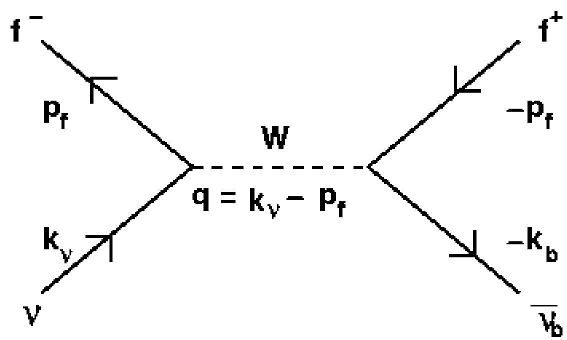
- s−channel Z^0−production: $\nu_i\bar{\nu}_i \to Z^0 \to f\bar{f}$ where f is any fermion (including hadronic fragmentation in case of quarks)



$$\frac{d\sigma_s}{d\mu^*} = \frac{G_F^2 s}{16\pi}\frac{M_Z^4}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\left[g_L^2(1+\mu^*)^2+g_R^2(1-\mu^*)^2\right] ,$$

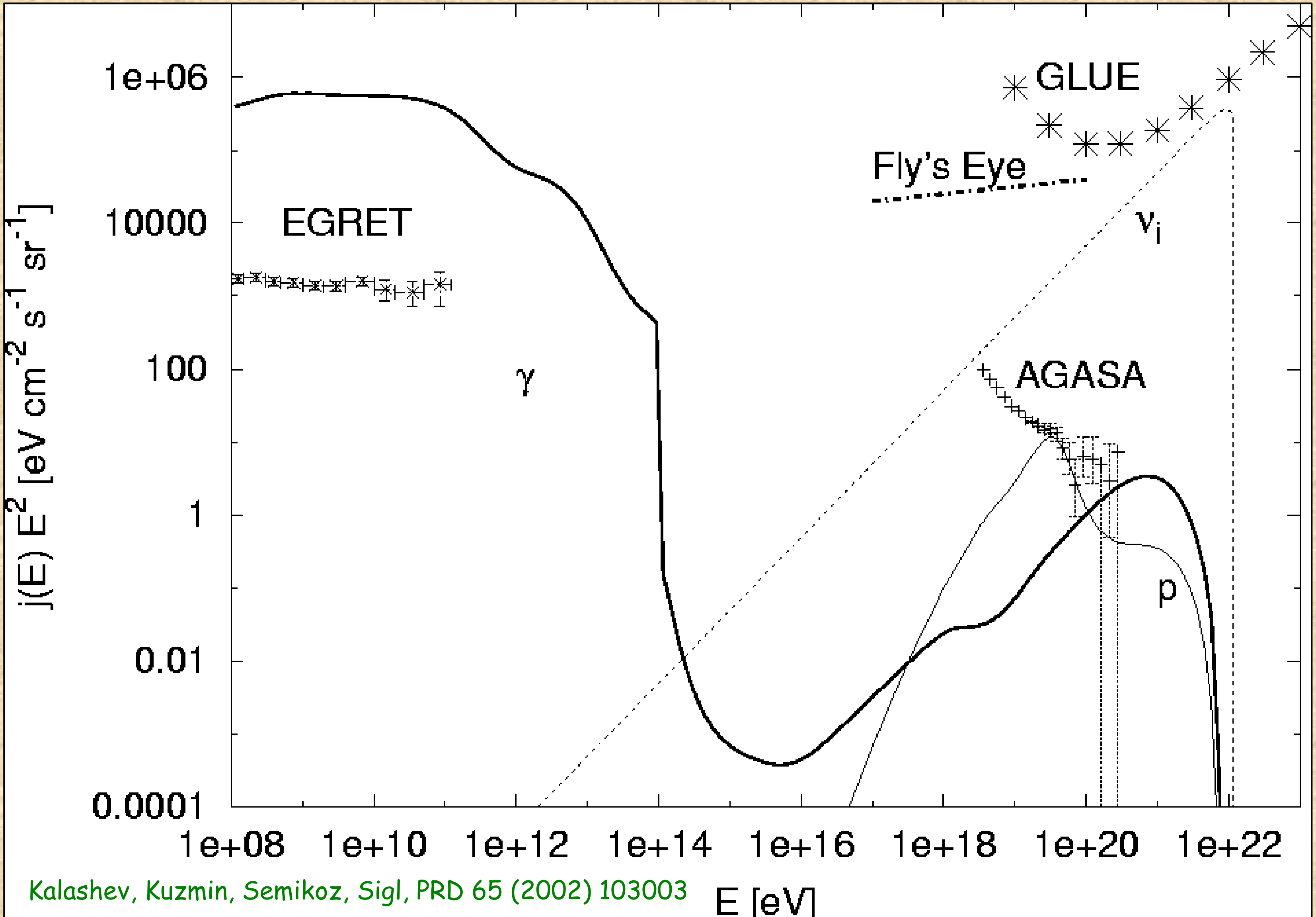
where μ^* = cos(scattering angle in center of mass), Γ_Z =width of Z^0, $g_V = t_3 - q\sin\theta_W^2$ and $g_A = -q\sin\theta_W^2$ with t_3 =weak isospin and q =charge.

- t−channel $W^\pm$−exchange, e.g. $\nu_i\bar{\nu}_j \to l_i\bar{l}_j$, where l_i is leptonic partner of ν_i:



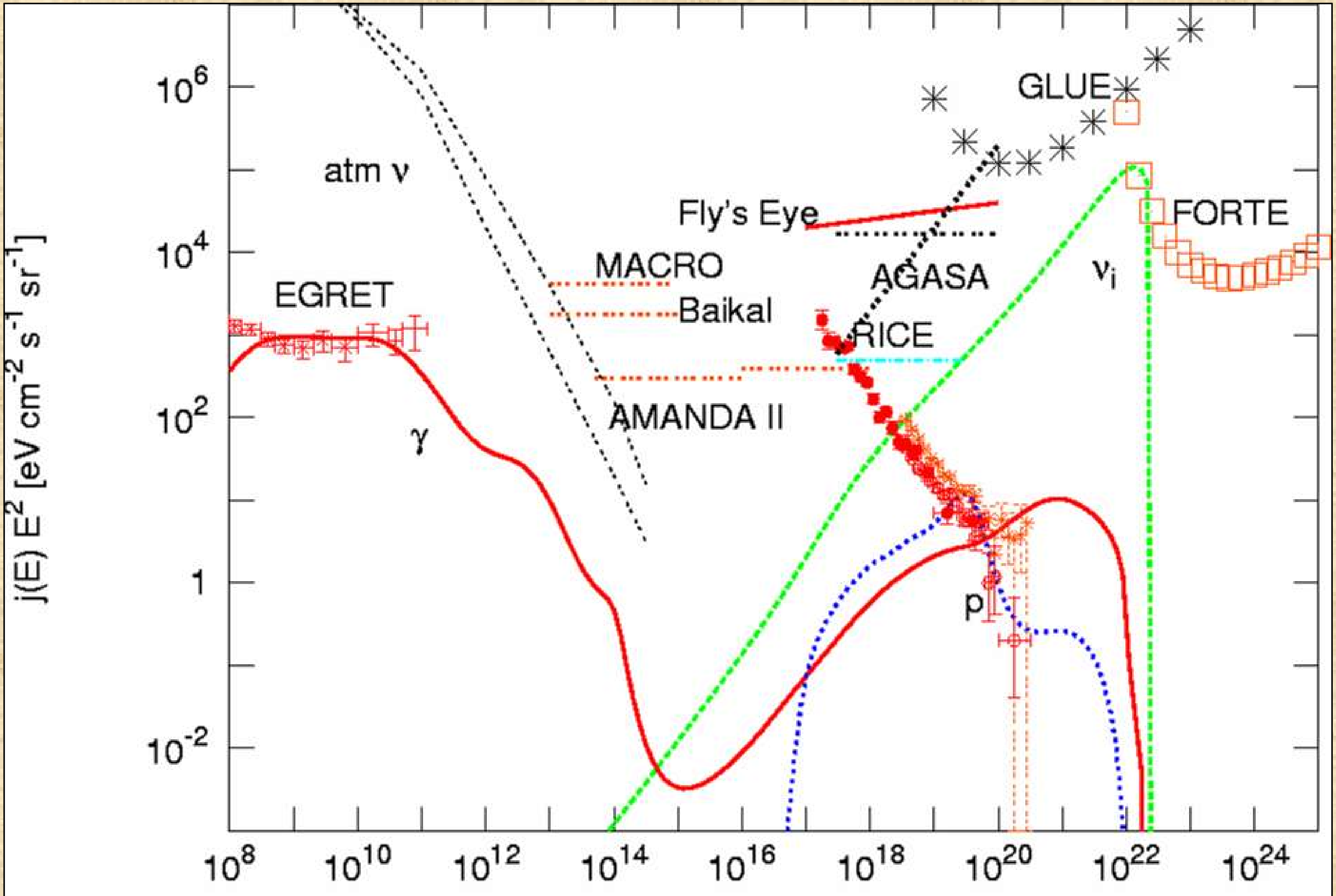
$$\frac{d\sigma_t}{d\mu^*} = \frac{G_F^2 s}{4\pi}\frac{M_W^2(1+\mu^*)^2}{(s(1-\mu^*)/2+M_W^2)}$$

The Z-burst mechanism: Sources emitting neutrinos and γ-rays



Sources with constant comoving luminosity density up to z=3, with E^{-2} γ-ray injection up to 100 TeV of energy fluence equal to neutrinos, m_ν=0.5eV, B=10^{-9} G.

The Z-burst mechanism: Exclusive neutrino emitters



Semikoz, Sigl, JCAP 0404 (2004) 003

Sources with constant comoving luminosity up to z=3, m_ν=0.33eV, B=10^{-9} G.

Even for pure neutrino emitters it is now excluded that the Z-burst contributes significantly to UHECRs

For homogeneous relic neutrinos GLUE+FORTE2003 upper limits on neutrino flux above 10^{20} eV imply (see figure).

$$\sum m_{\nu_i} \geq 0.3\,\text{eV}$$

Cosmological data including WMAP imply

$$\sum m_{\nu_i} \leq 0.6\,\text{eV}$$

Solar and atmospheric neutrino oscillations indicate near degeneracy at this scale

$$\Rightarrow m_{\nu_i} \leq 0.2\,\text{eV}$$

For such masses local relic neutrino overdensities are < 10 on Mpc scales. This is considerably smaller than UHECR loss lengths => required UHE neutrino flux not significantly reduced by clustering.

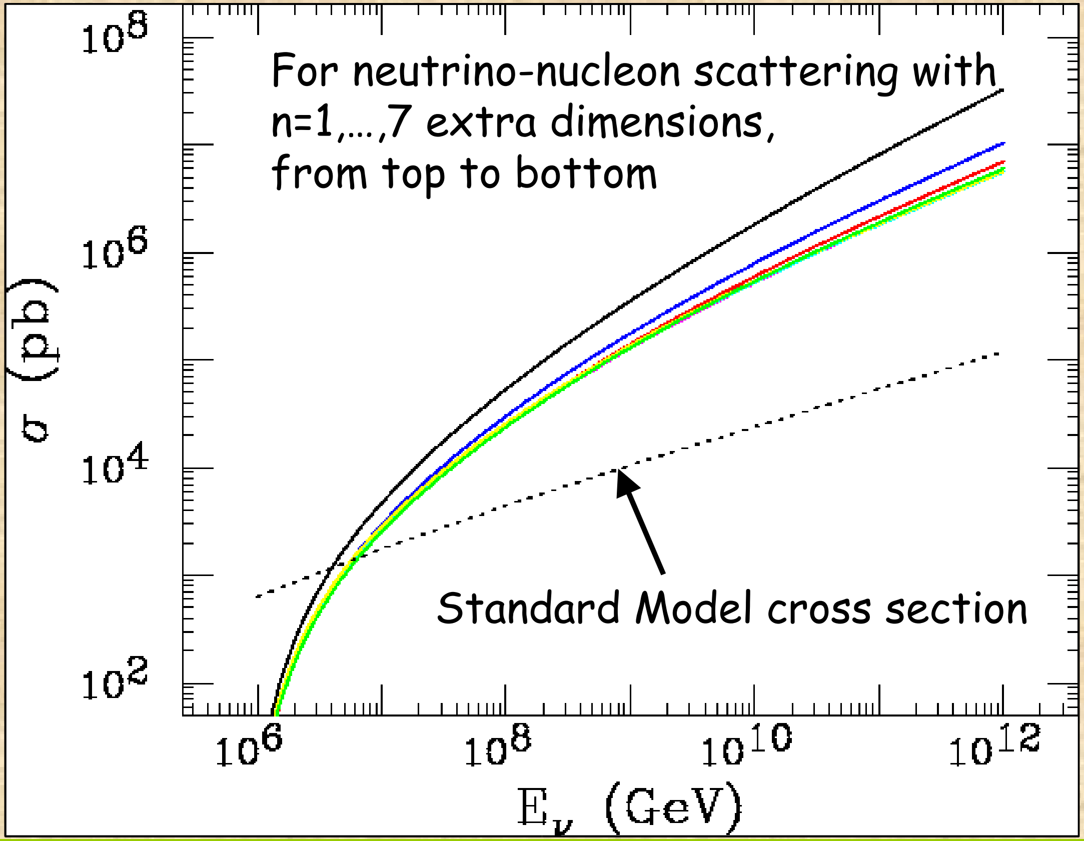
Probes of Neutrino Interactions beyond the Standard Model

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

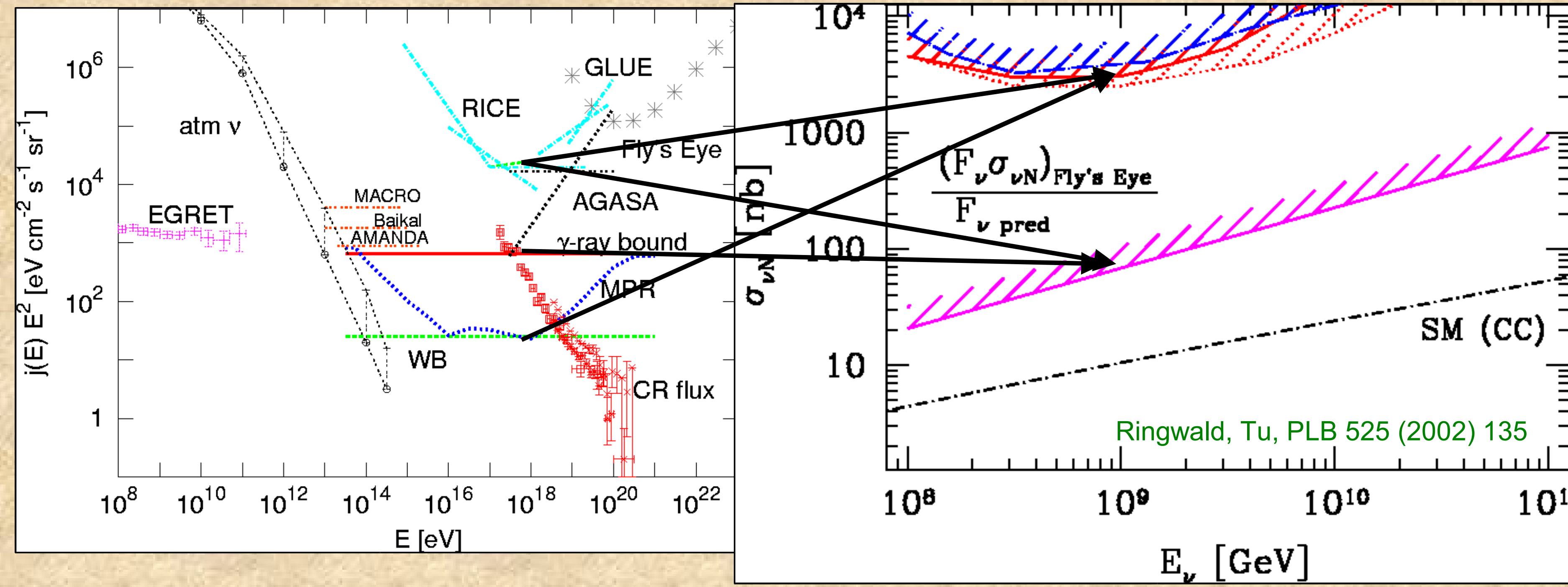
Example: microscopic black hole production in scenarios with a TeV string scale:



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.

However, the neutrino flux from pion-production of extra-galactic trans-GZK cosmic rays allows to put limits on the neutrino-nucleon cross section:



Comparison of this Nγ- ("cosmogenic") flux with the non-observation of horizontal air showers results in the present upper limit about 10^3 above the Standard Model cross section.

Future experiments will either close the window down to the Standard Model cross section, discover higher cross sections, or find sources beyond the cosmogenic flux. How to disentangle new sources and new cross sections?

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

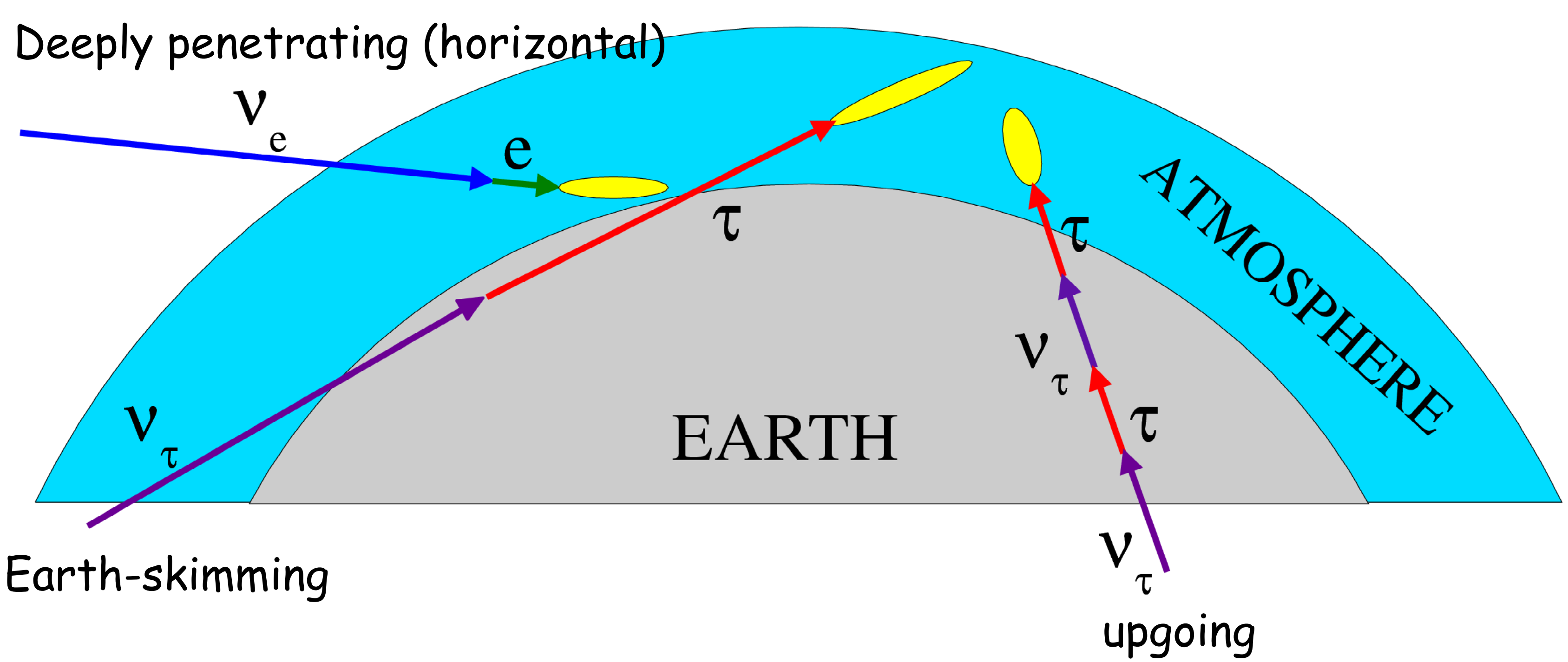
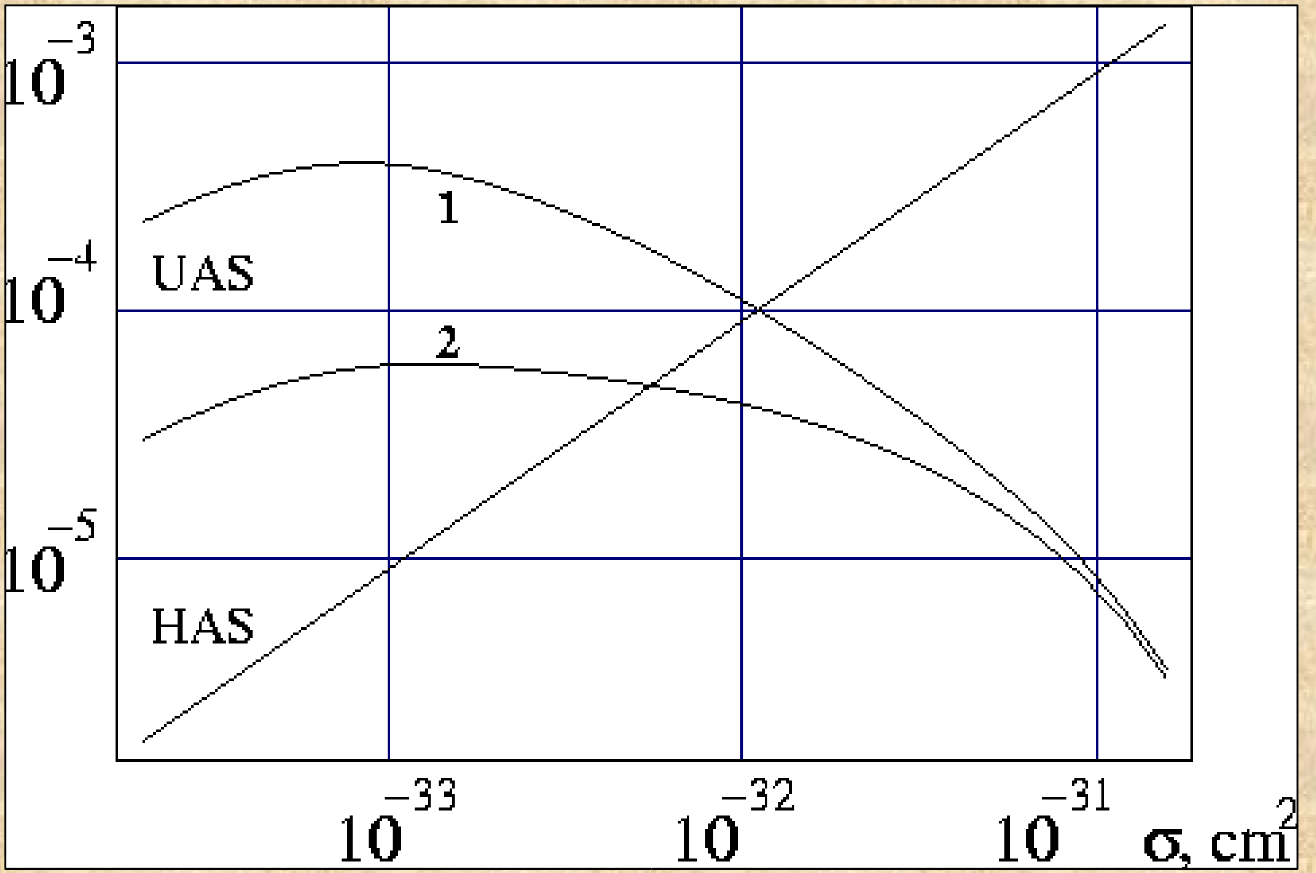


Figure from Cusumano

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

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.) 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.

5.) The only guaranteed high energy neutrino fluxes are due to pion production of primary cosmic rays known to exist: Around 10^{19} eV "cosmogenic" neutrinos from photopion production. Flux uncertainties stem from uncertainties in cosmic ray source distribution and evolution.

Conclusions2

6.) 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. Lorentz symmetry can also be probed to high precision.

7.) 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. Similar in the neutrino and γ-ray sectors.