Ultra-High Energy Cosmic Radiation

and what it teaches us about astro- and fundamental physics

- General facts and the experimental situation
- Acceleration (“bottom-up” scenario)
- Cosmic magnetic fields and their role in cosmic ray physics
- The connection with gamma rays and neutrinos
- New interactions and new particles -> Luis

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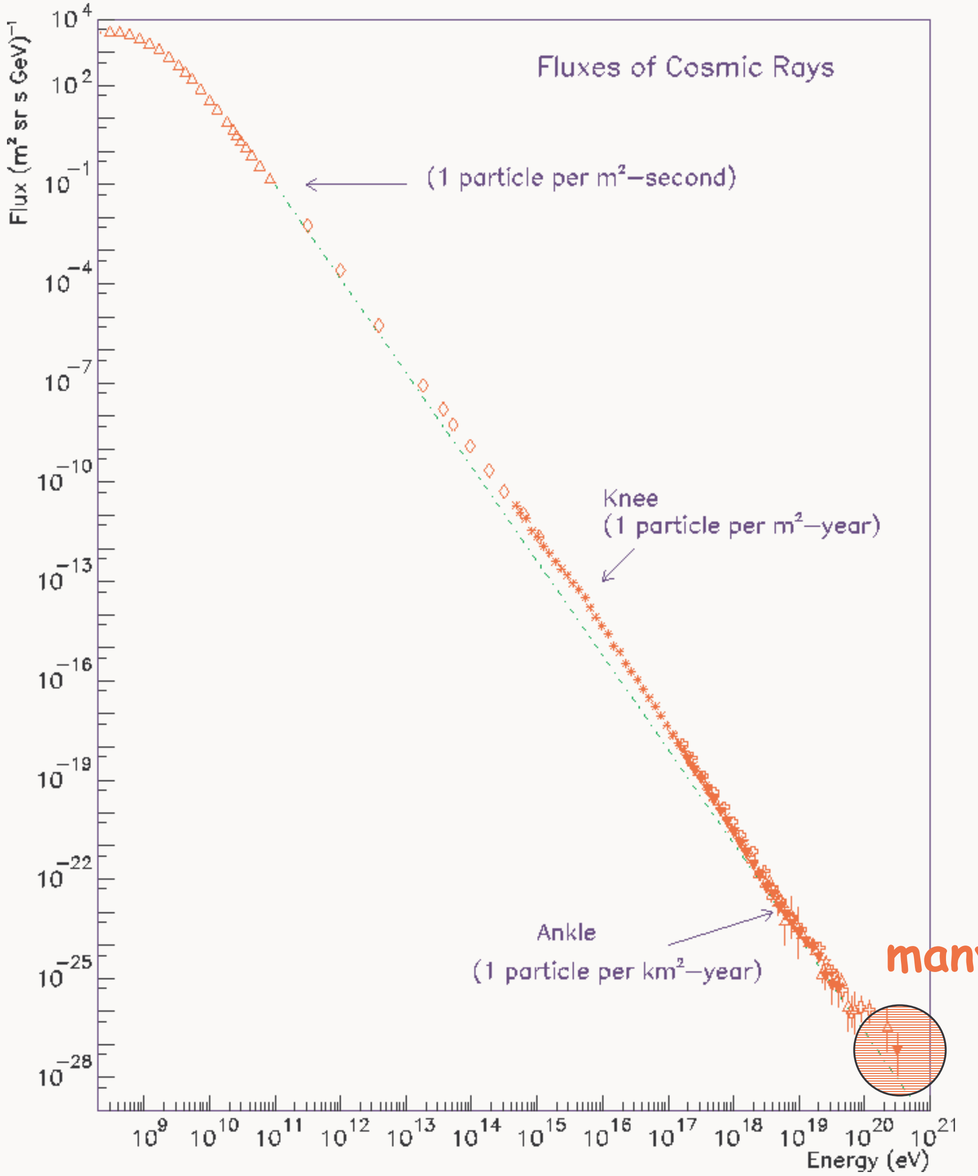
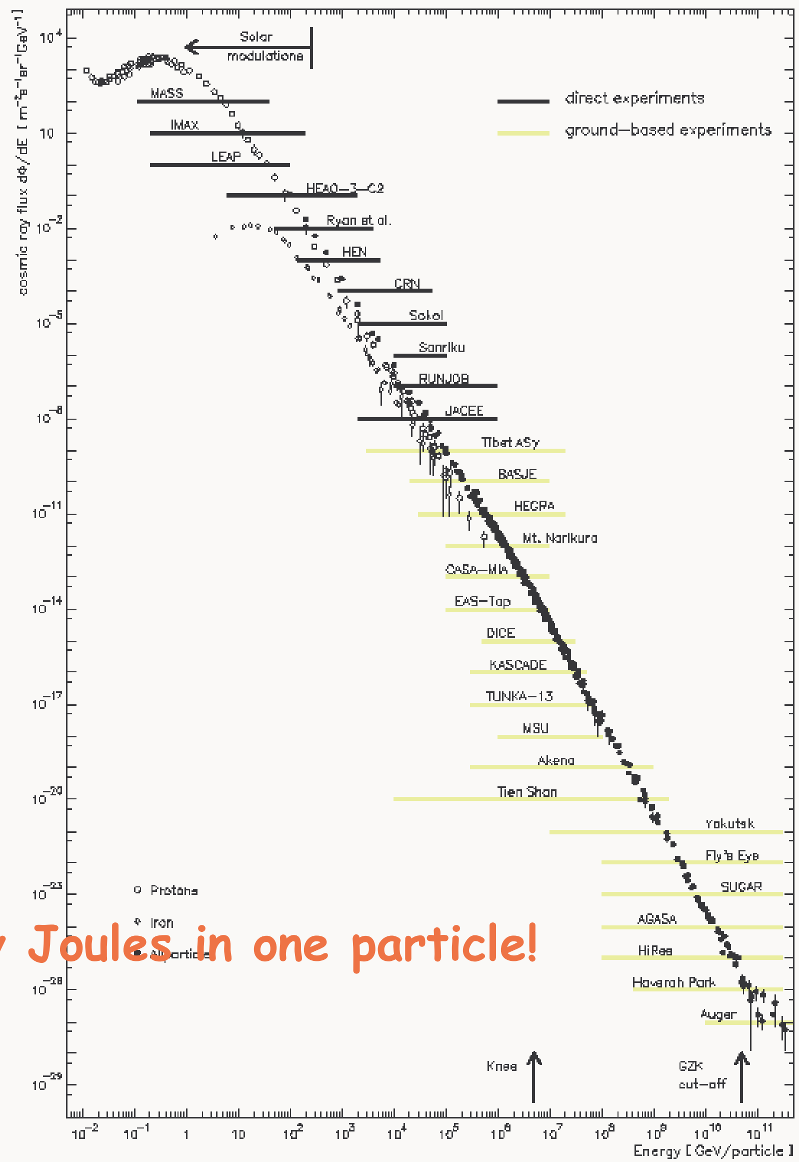
Further reading:
short review: Science **291** (2001) 73
long review: Physics Reports **327** (2000) 109
review collection: Lecture Notes in Physics **576** (2001) (eds.: M.Lemoine, G.Sigl)

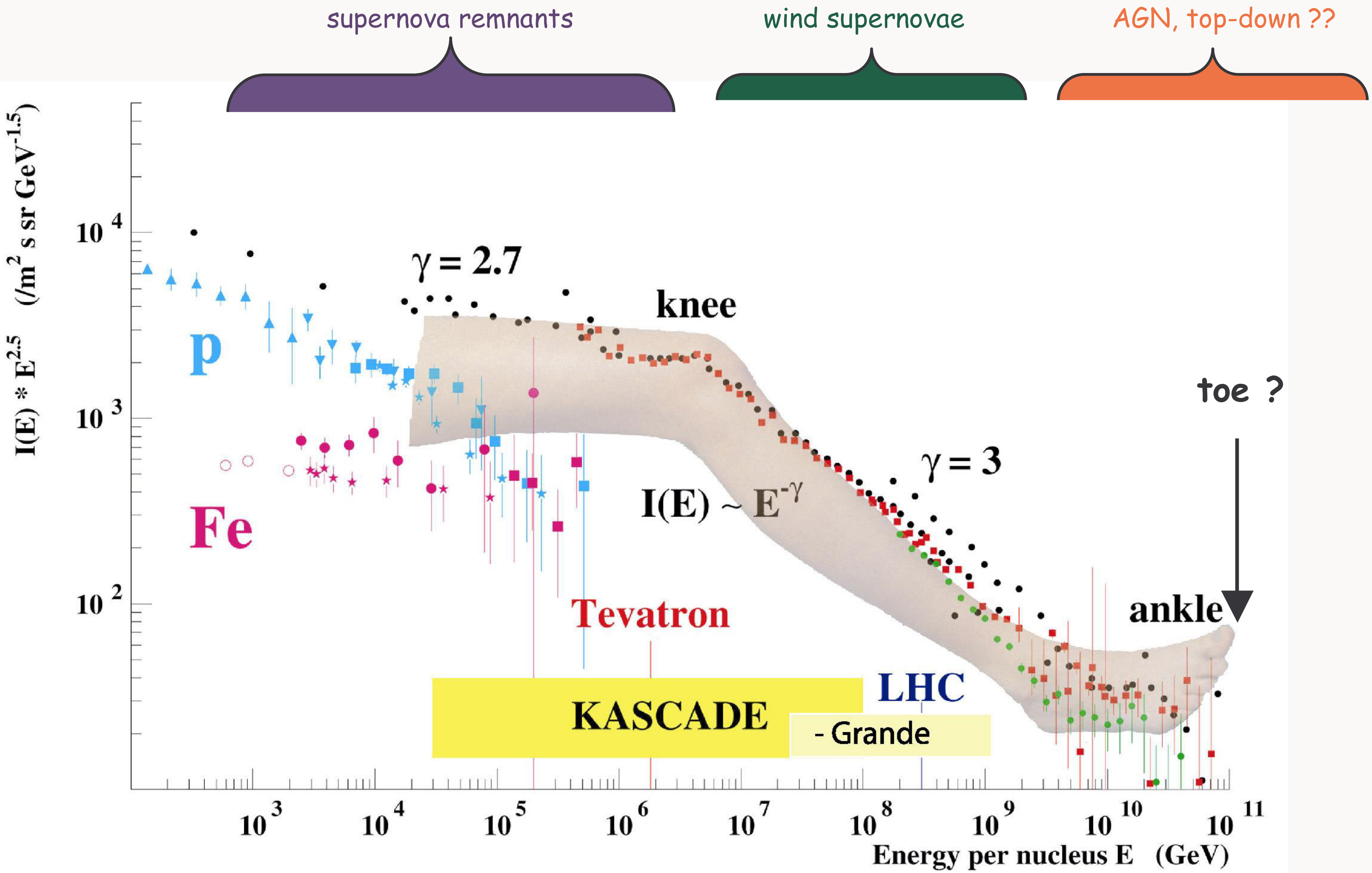
The cosmic ray spectrum stretches over some 12 orders of magnitude in energy and some 30 orders of magnitude in differential flux:



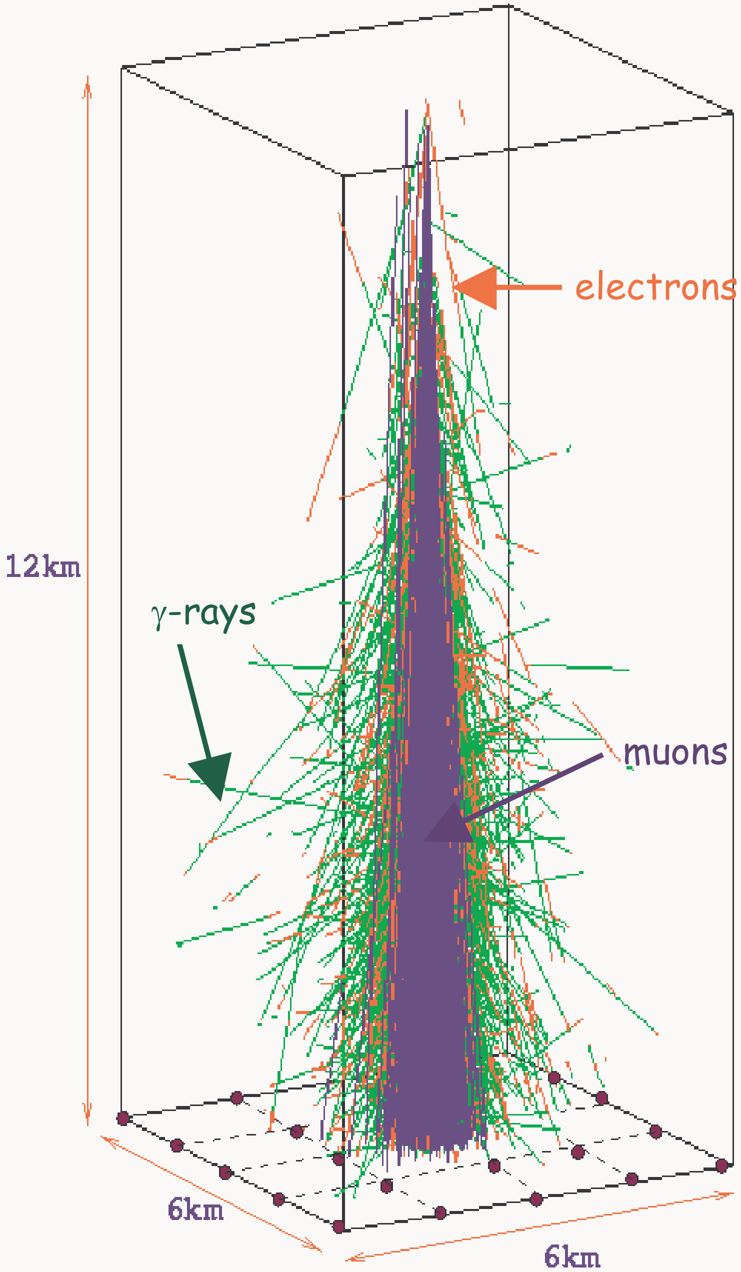


many Joules in one particle!

The structure of the spectrum and scenarios of its origin



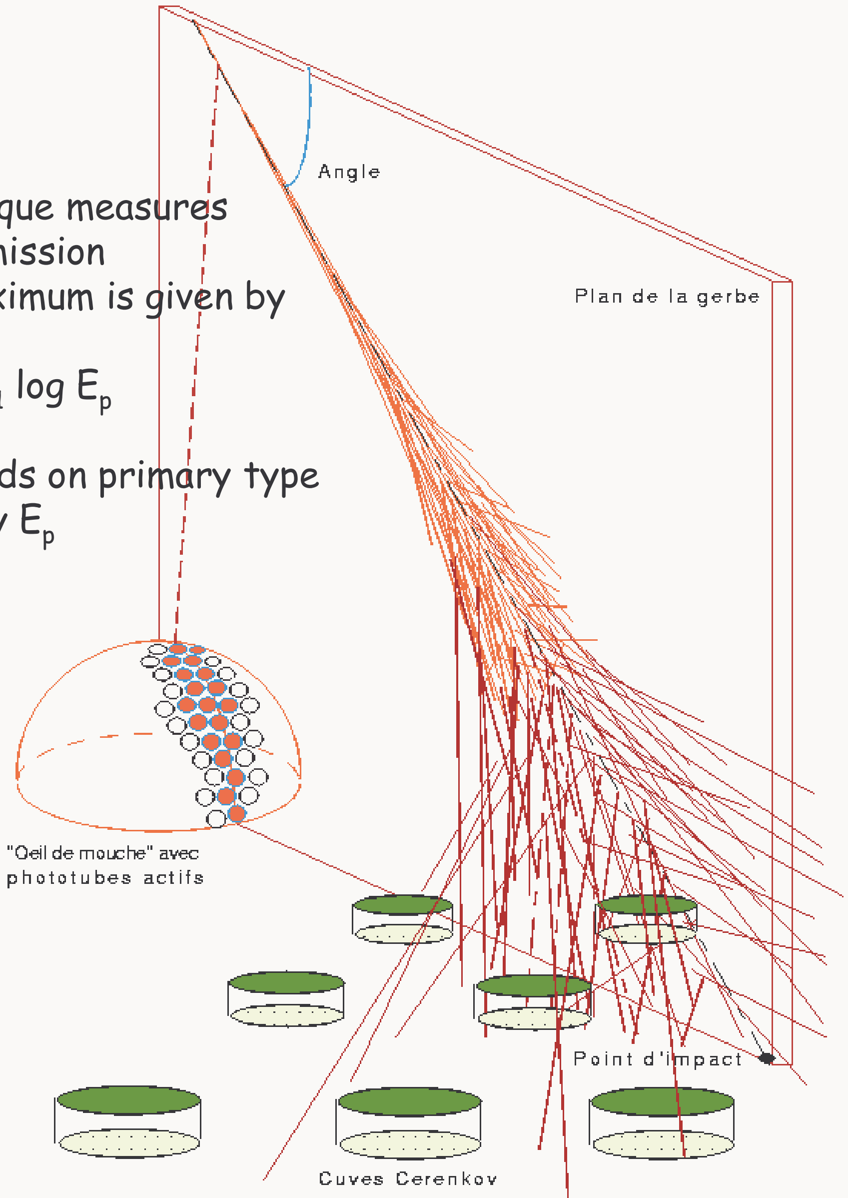
Atmospheric Showers and their Detection



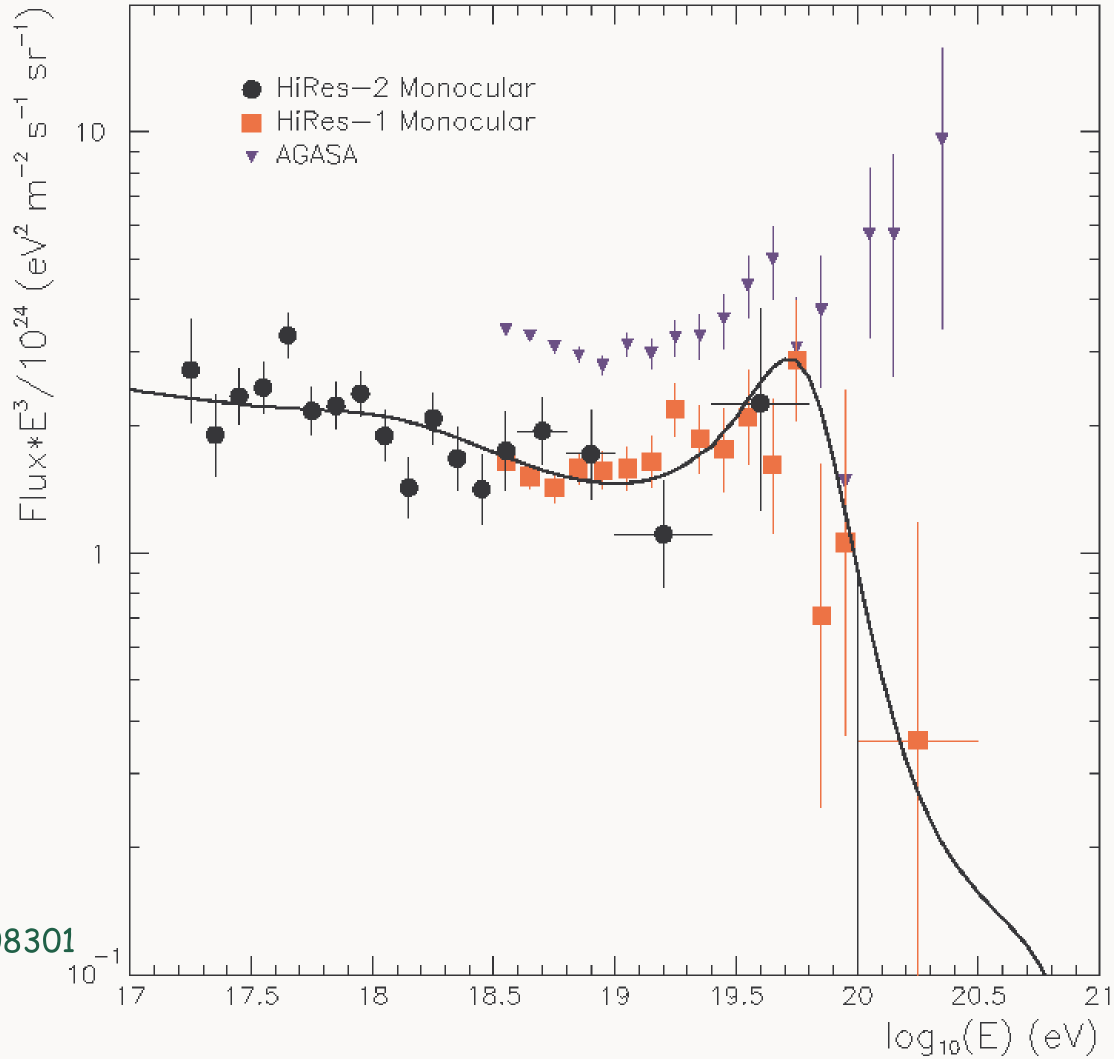
Fly's Eye technique measures fluorescence emission
The shower maximum is given by

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

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

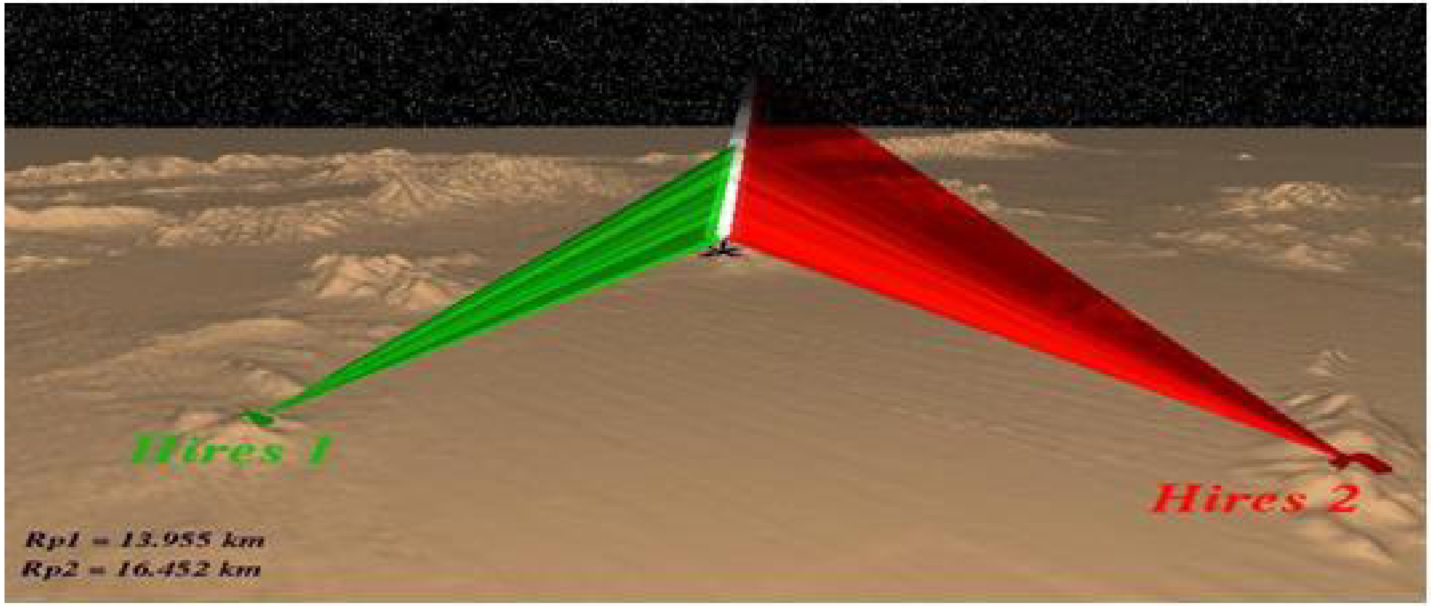


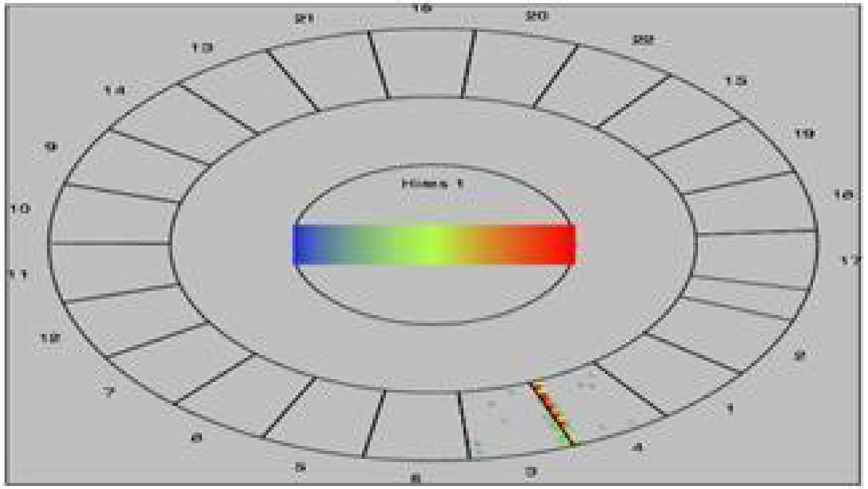
HiRes collaboration, astro-ph/0208301

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

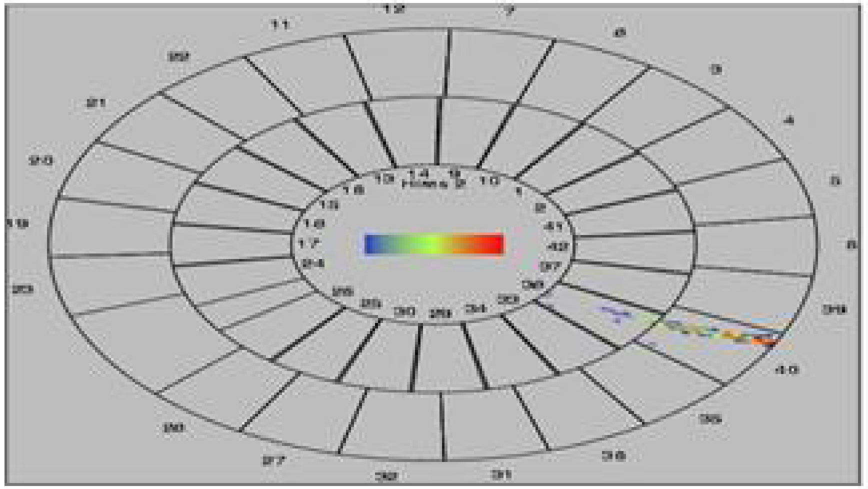
May need an experiment combining ground array with fluorescence such as the Auger project to resolve this issue.

Stereo Event E ~50 EeV



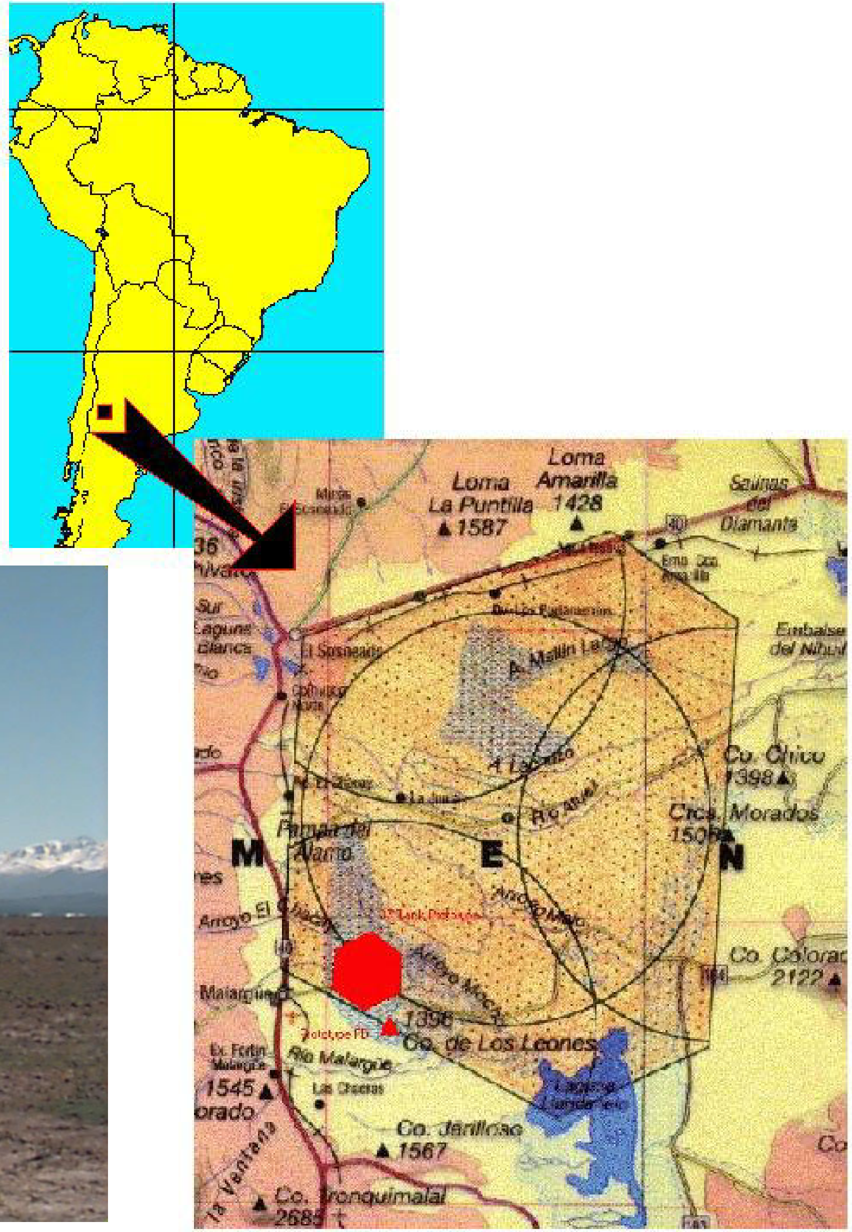


HiRes1



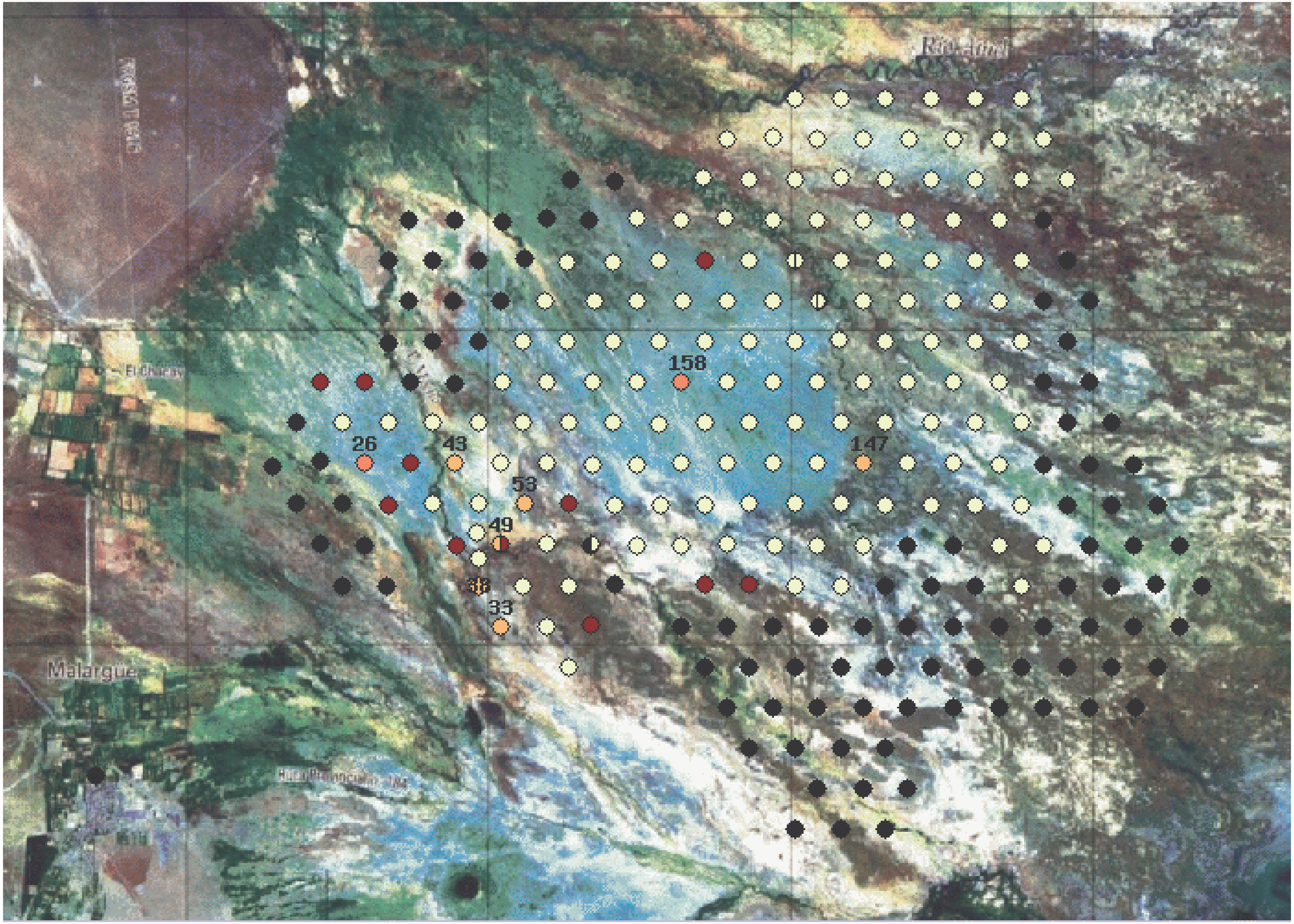
HiRes2

The southern Auger site is under construction.

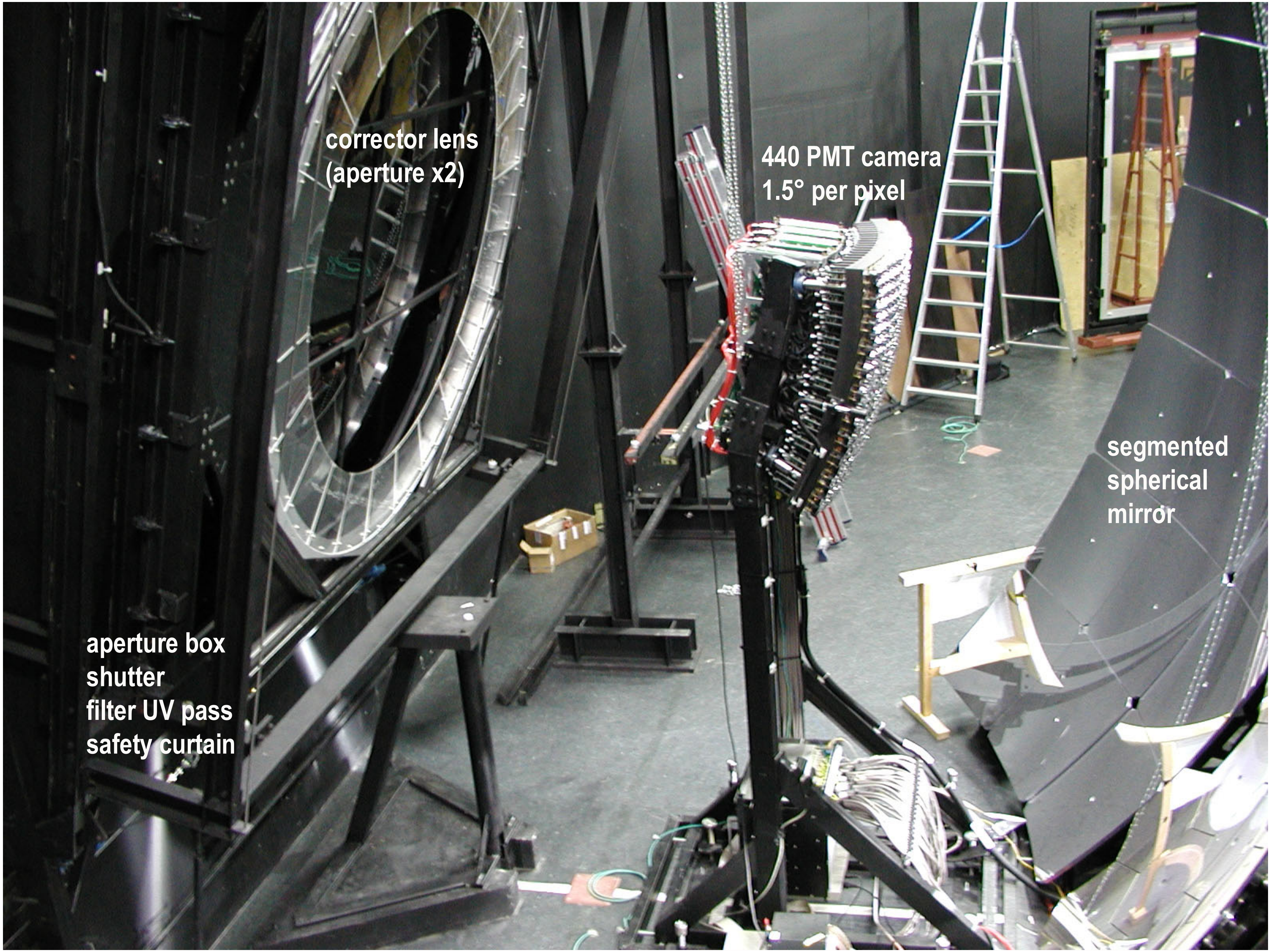


60 km

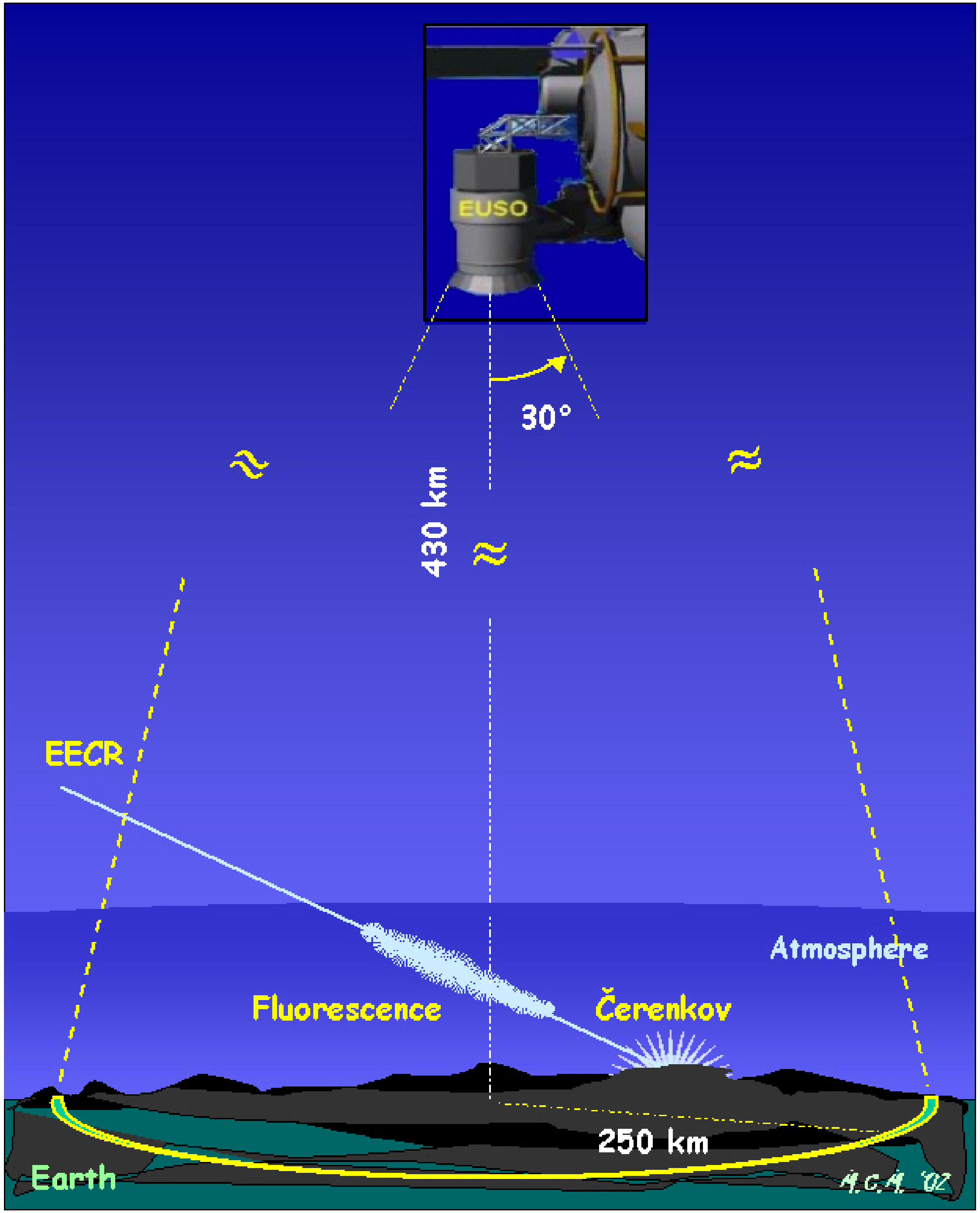
Contour of site (3000 km-sq)
In red: engineering array
Circles: average range of the fluorescence det.
Dots: the 1600 detector stations (tanks)



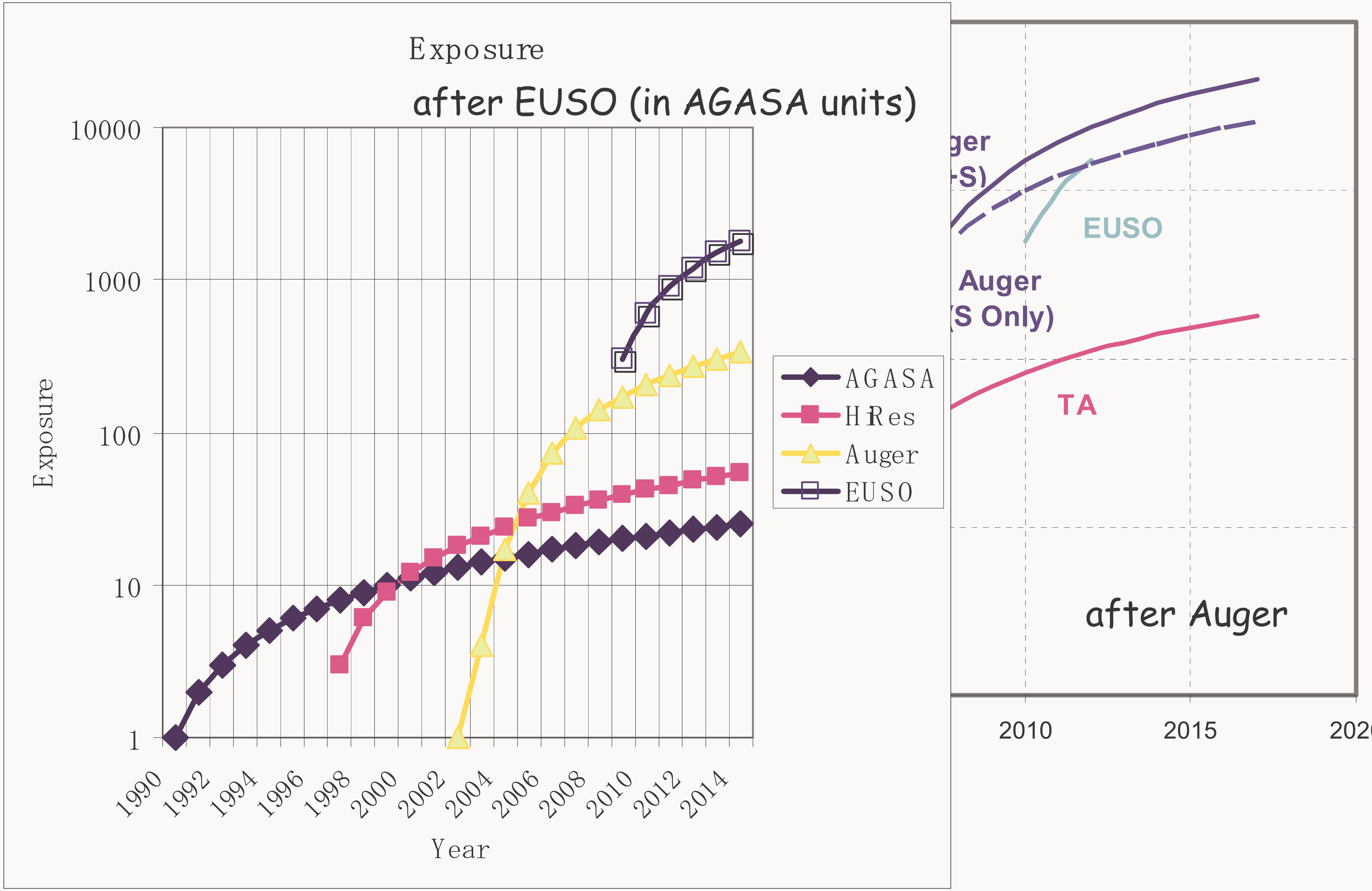
Malargüe
158
26
43
147
53
49
33


corrector lens
(aperture x2)
440 PMT camera
1.5° per pixel
segmented
spherical
mirror
aperture box
shutter
filter UV pass
safety curtain

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

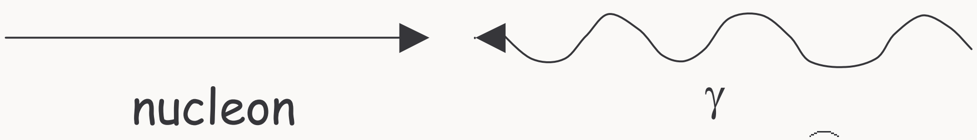
1.) electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 50 Mpc.

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

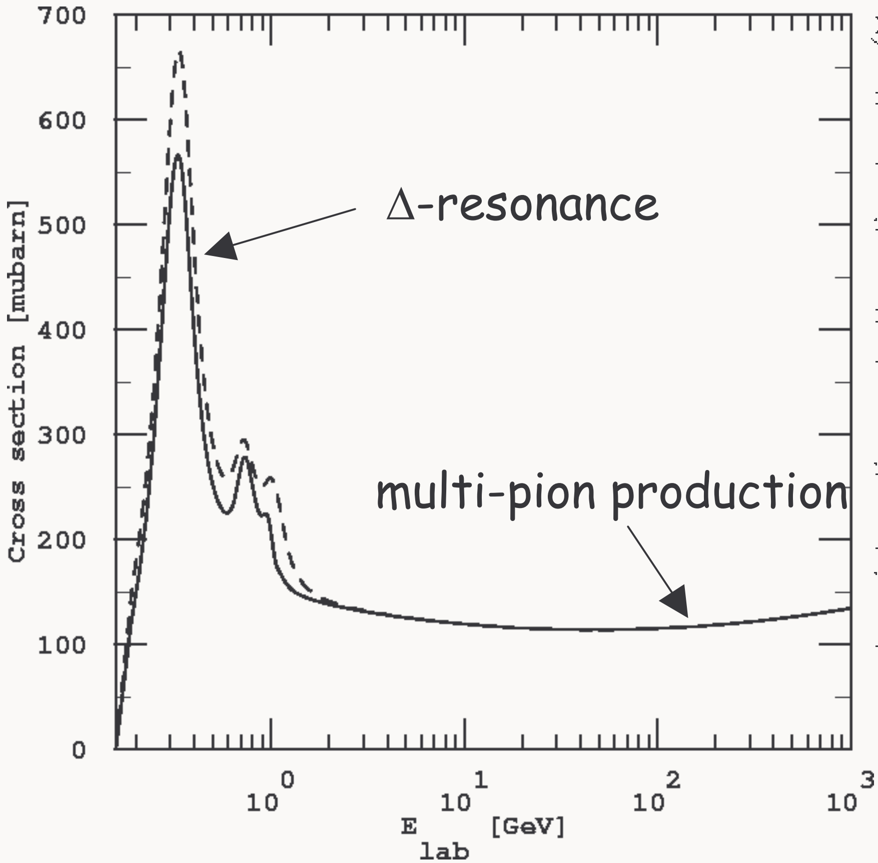
3.) The observed distribution seems to be very isotropic (except for a possible interesting small scale clustering)

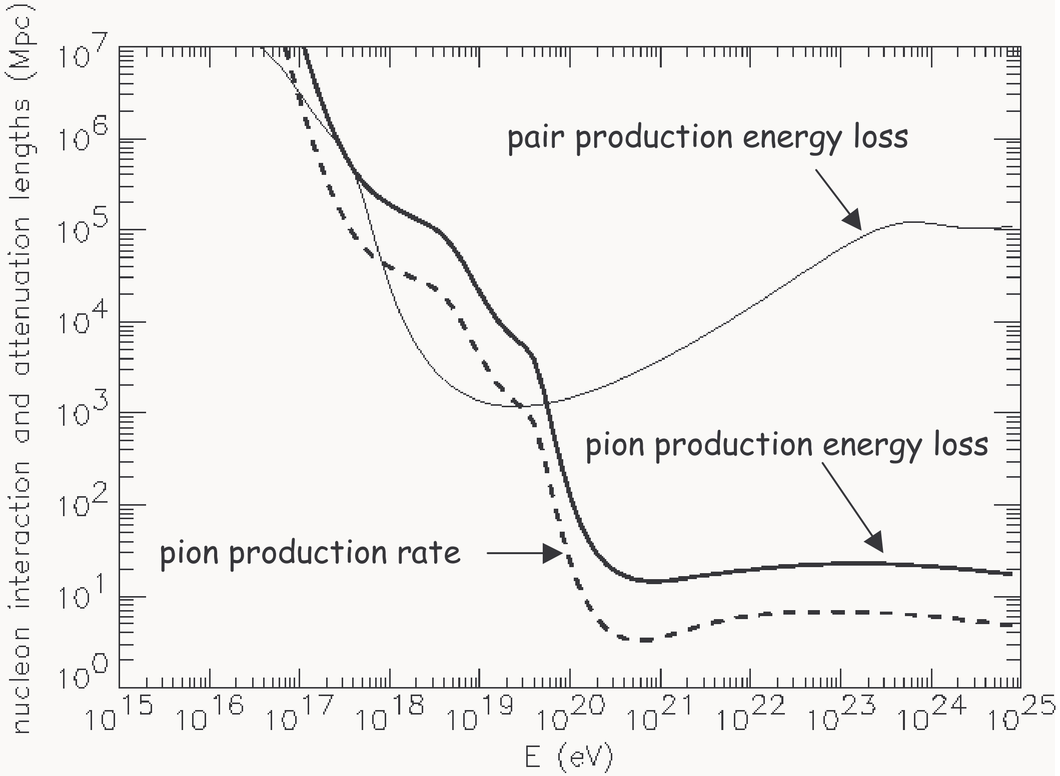
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



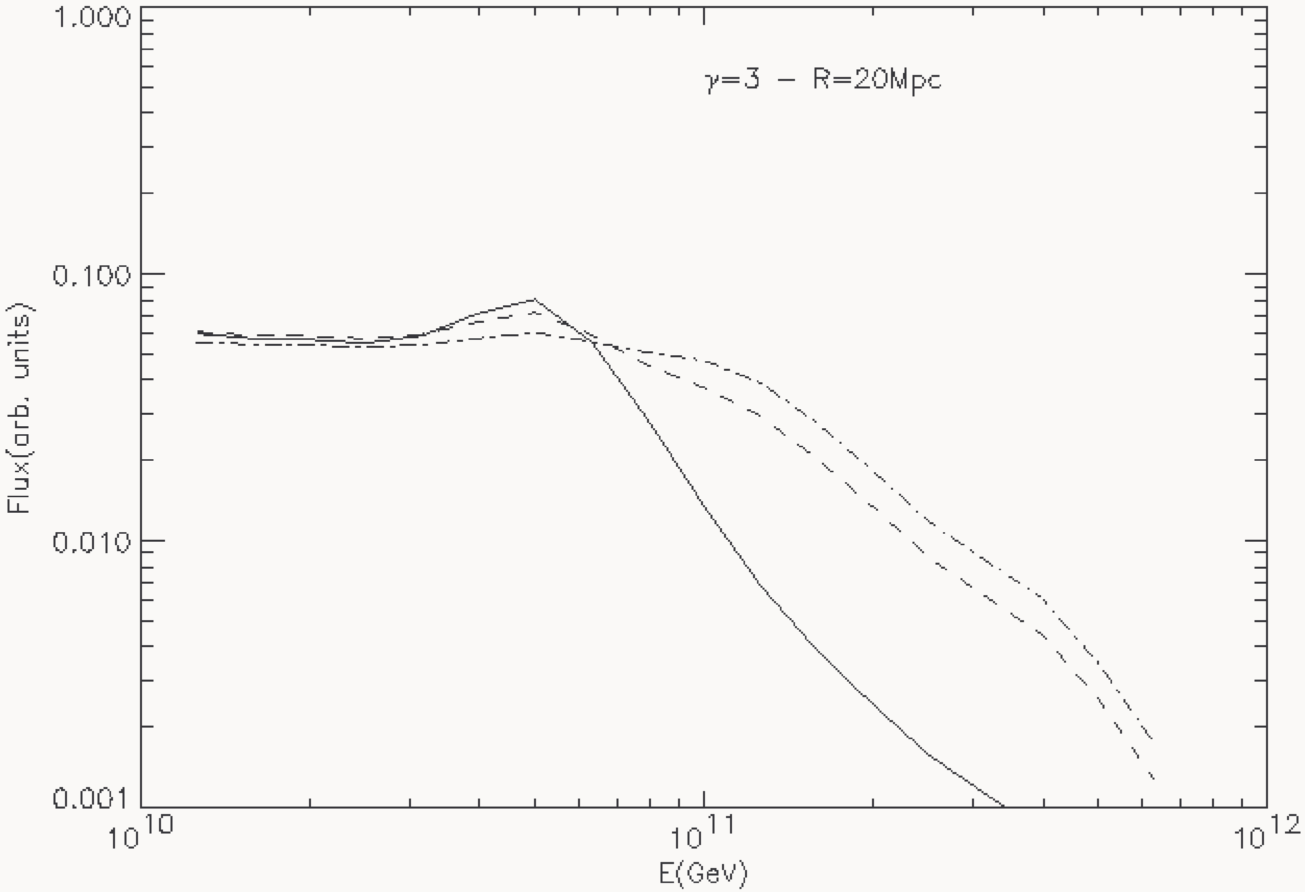
$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4 \cdot 10^{19}\,\mathrm{eV}$$





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

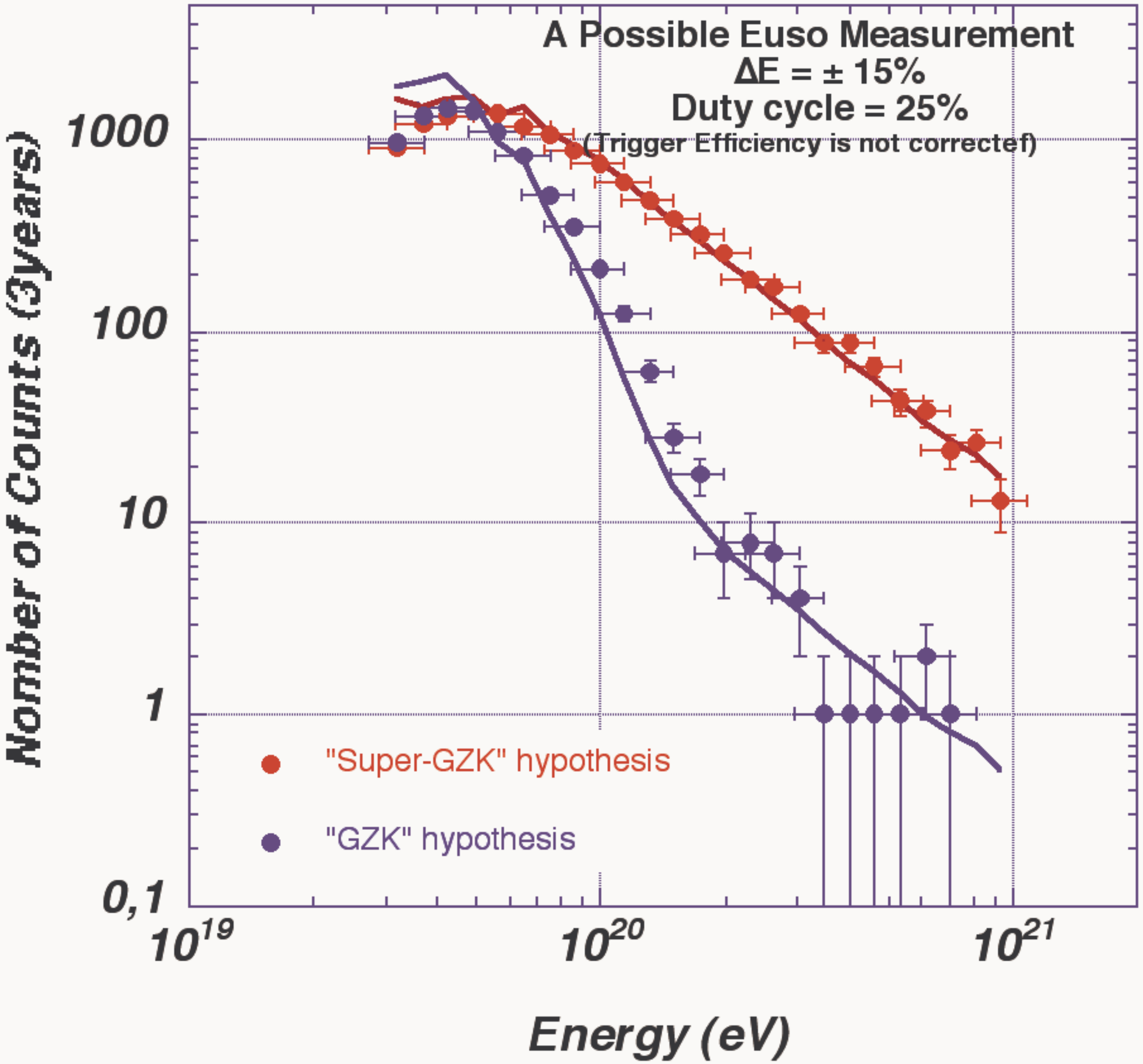
What the GZK effect tells us about the source distribution (in the absence of strong magnetic deflection)



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.

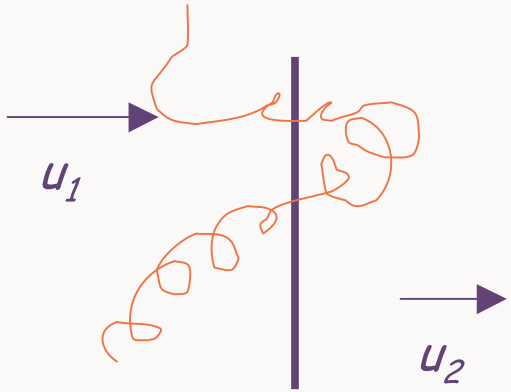
Blanton, Blasi, Olinto, Astropart.Phys. 15 (2001) 275

Possible EUSO measurement



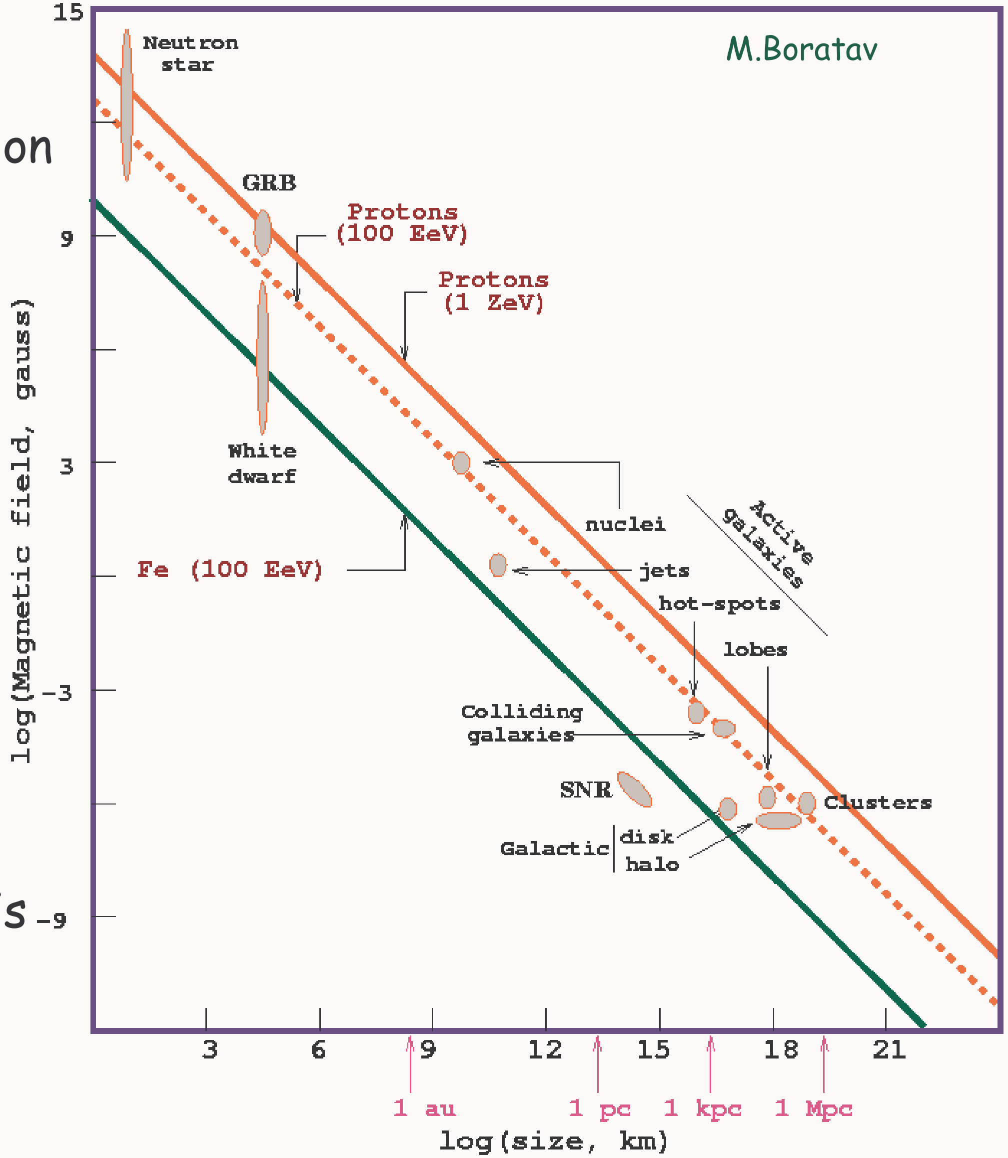
1st Order Fermi Shock Acceleration

This is the most widely accepted scenario of cosmic ray acceleration



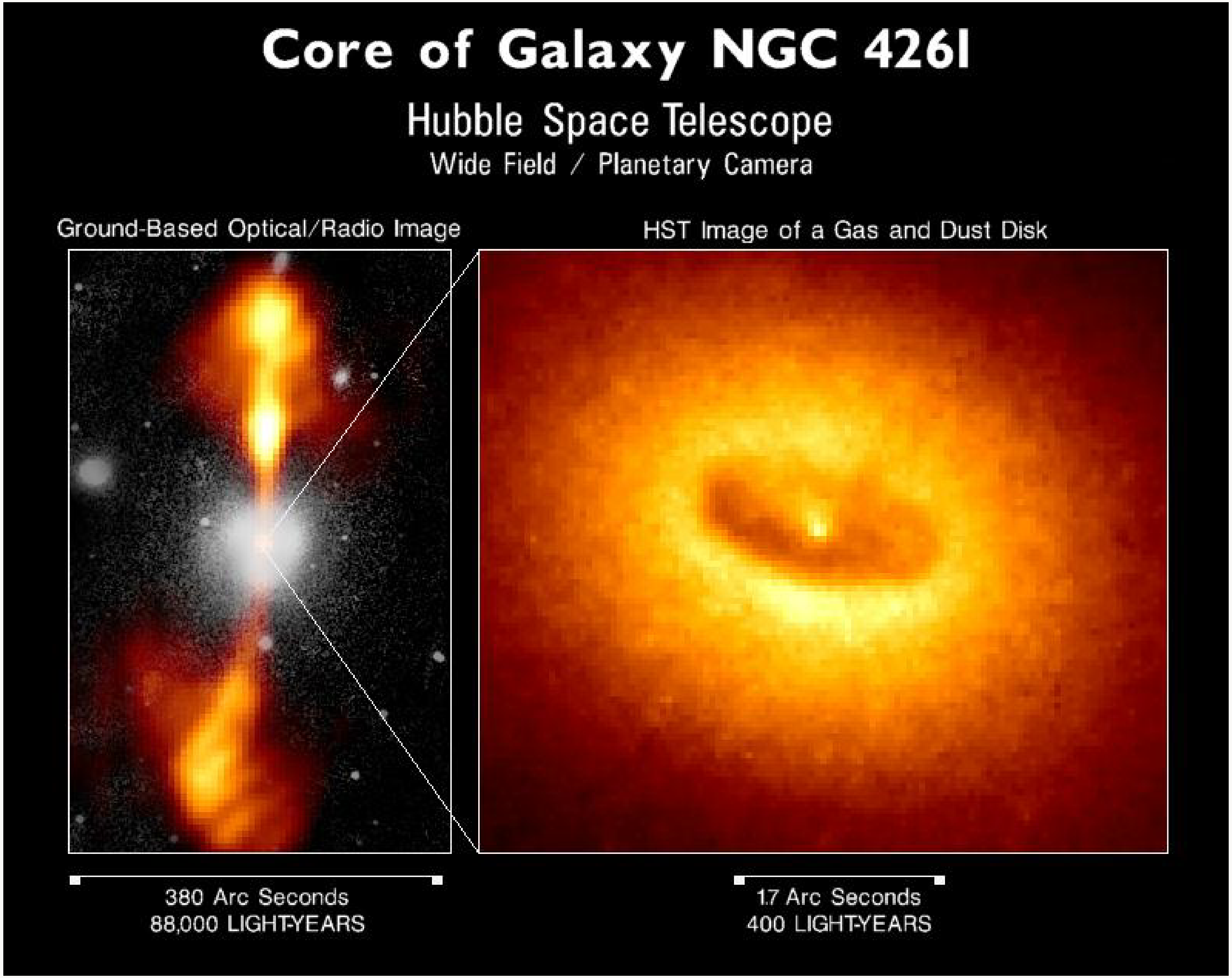
The fractional energy gain per shock crossing depends on the velocity jump at the shock.
Together with loss processes this leads to a spectrum E^{-q} with $q > 2$ typically.
When the gyroradius becomes comparable to the shock size, the spectrum cuts off.

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

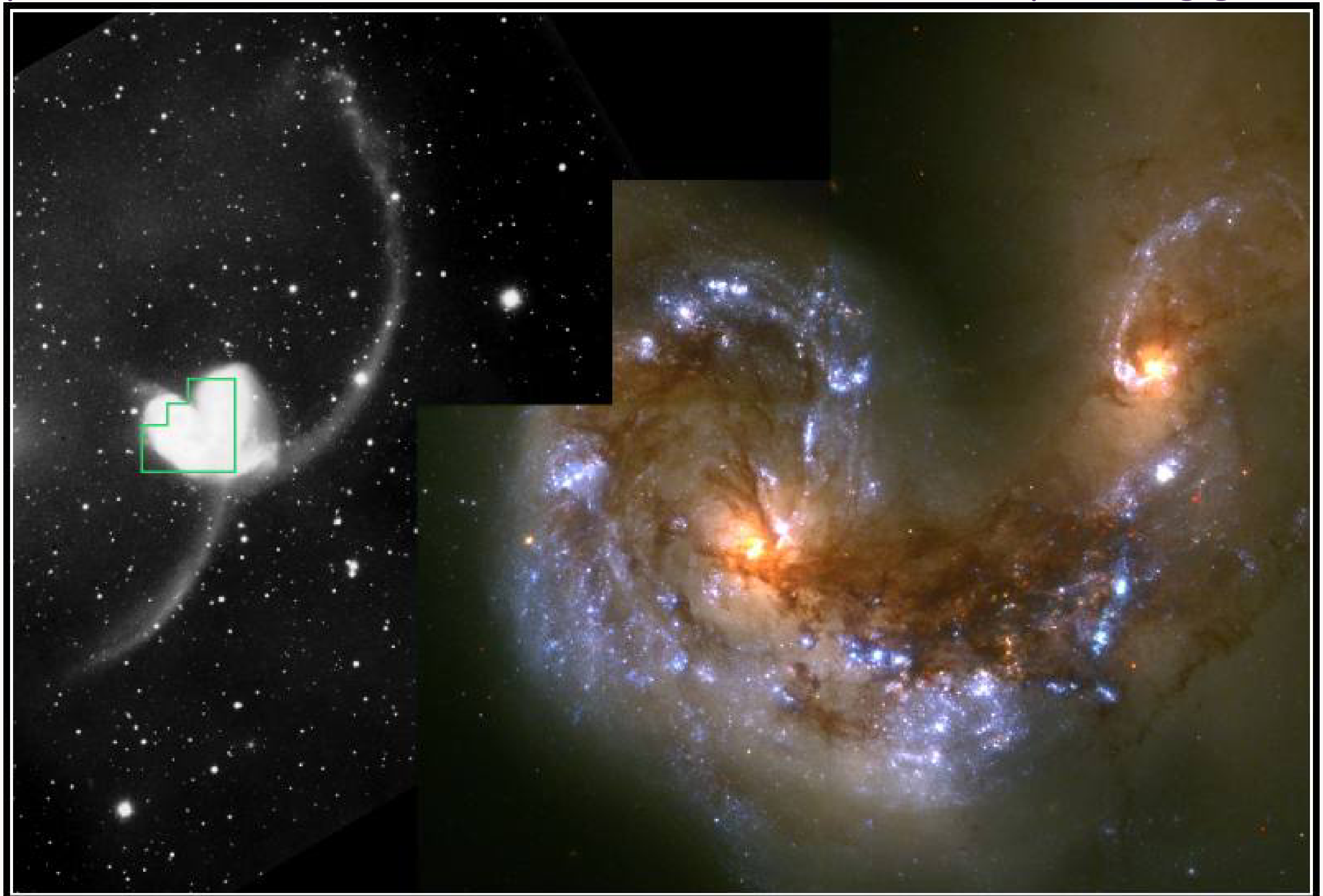


$E_{max} \approx ZBL$ (Fermi)
$E_{max} \approx ZBL\Gamma$ (Ultra-relativistic shocks-GRB)

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



A possible acceleration site associated with shocks formed by colliding galaxies

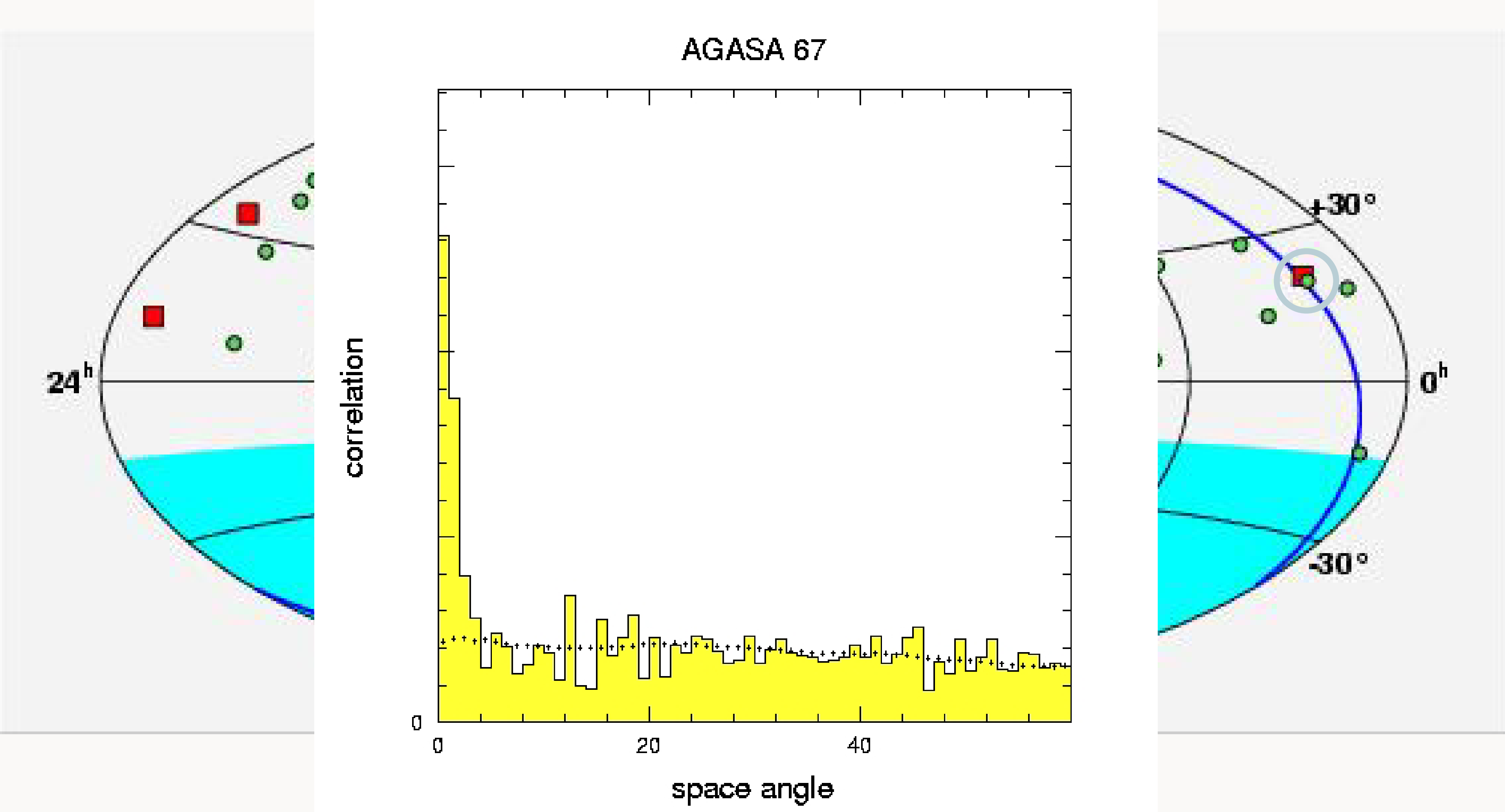


Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

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)
  - Disputed by HiRes

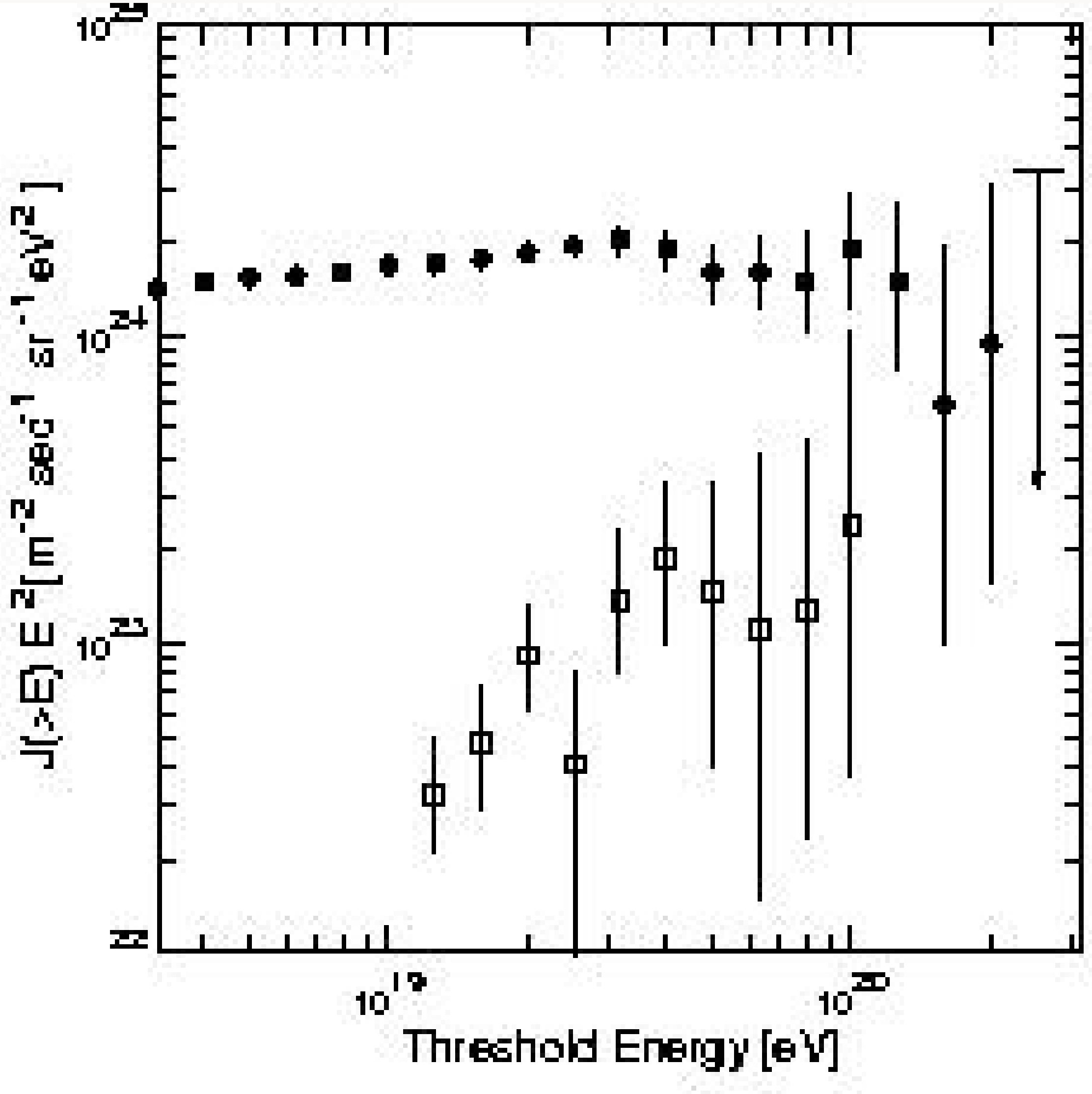


Spectrum of the clustered component in the AGASA data

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



Cosmic Magnetic Fields and their Role in Cosmic Ray Physics

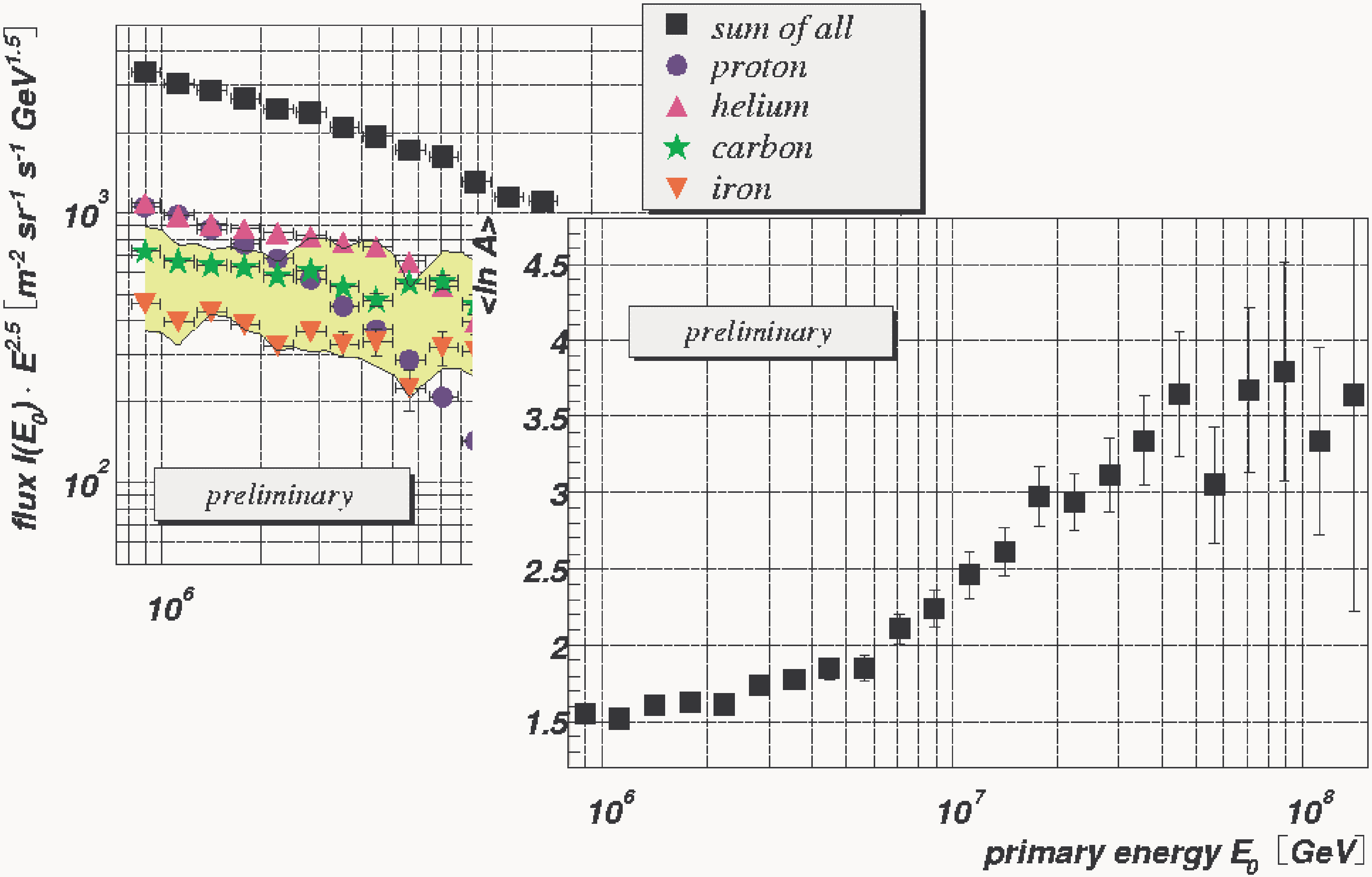
1.) Magnetic fields are main players in cosmic ray acceleration.

2.) Cosmic rays up to ~10^{18} eV are partially confined in the Galaxy.

Energy densities in cosmic rays, in the galactic magnetic field, in the turbulent flow, and gravitational energy are of comparable magnitude.

The galactic cosmic ray luminosity L_{CR} required to maintain its observed density u_{CR}~1eVcm^{-3} in the galactic volume V_{gal} for a confinement time t_{CR}~10^7 yr, $L_{CR} \sim u_{CR} V_{gal} / t_{CR} \sim 10^{41}$ erg/sec, is ~10% of the kinetic energy rate of galactic supernovae.

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



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

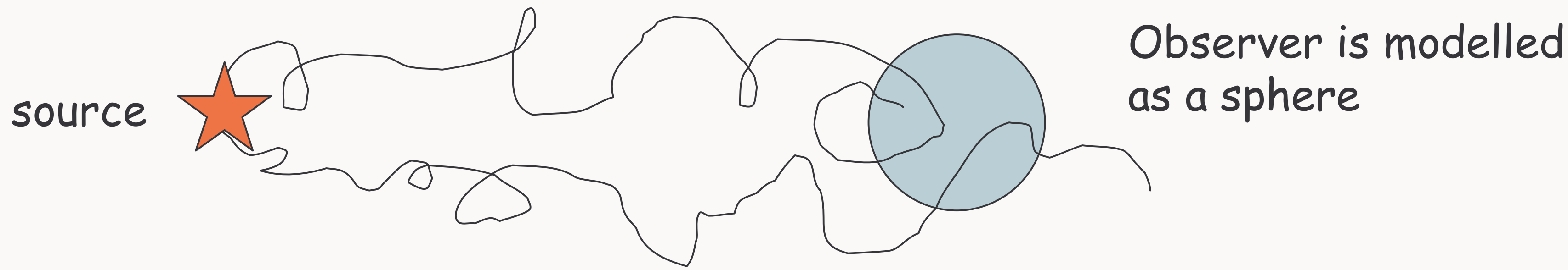
However, very little is known about about B_{XG}: It could be as small as 10^{-20} G (primordial seeds, Biermann battery) or up to fractions of micro Gauss if concentrated in clusters and filaments (equipartition with plasma).

There is a transition from rectilinear to diffusive propagation over distance d in a field of strength B and coherence length Λ_c at an energy roughly given by:

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

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

Principle of deflection Monte Carlo code

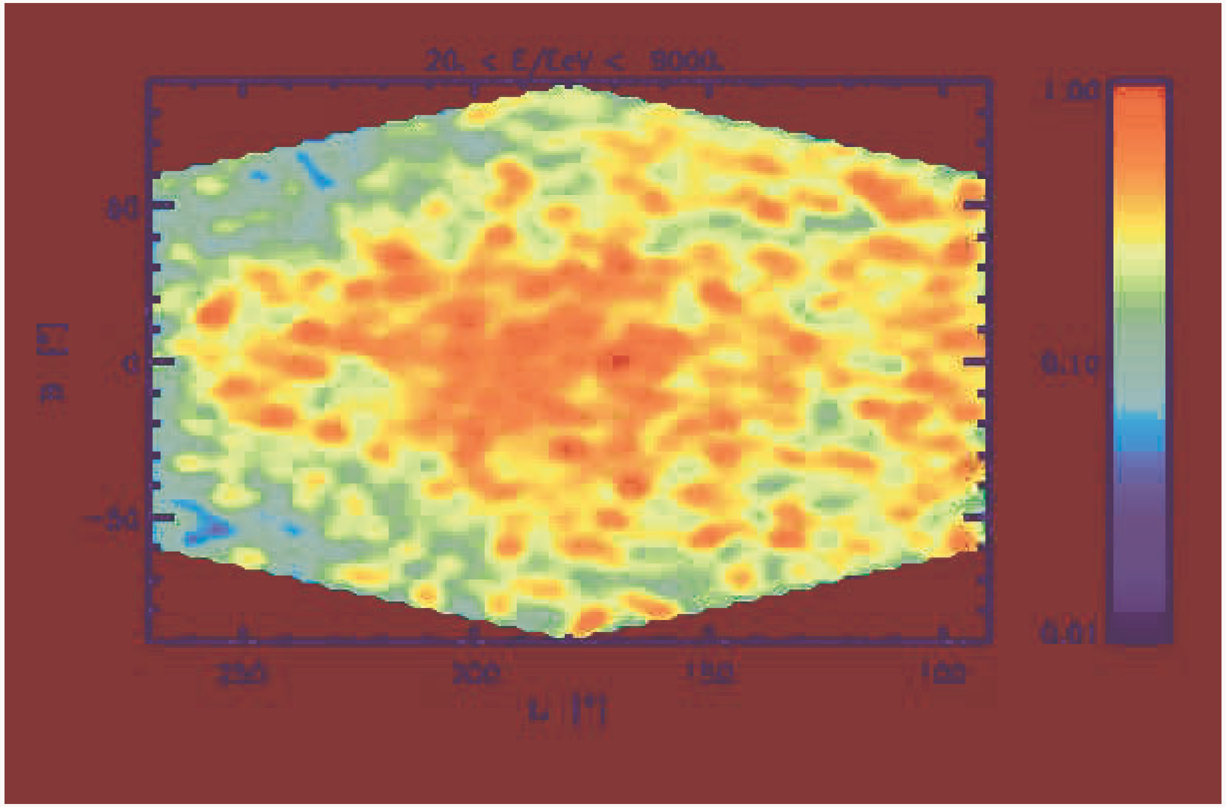


A particle is registered every time a trajectory crosses the sphere around the observer. This version to be applied for individual source/magnetic field realizations and inhomogeneous structures.

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.

More detailed scenarios of large scale magnetic fields use large scale structure simulations with magnetic fields followed passively and normalized to a few micro Gauss in galaxy clusters.
We use an Eulerian, grid-based total-variation-diminishing hydro +N-body code.

It is a $(75\ \mathrm{Mpc})^3$ box, repeated by periodic boundary conditions, to take into account sources at cosmological distances.

We then consider different observer and source positions for structured and unstructured distributions with and without magnetization.

We analyze these scenarios and compare them with data based on large scale multi-poles, auto-correlations, and clustering.

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

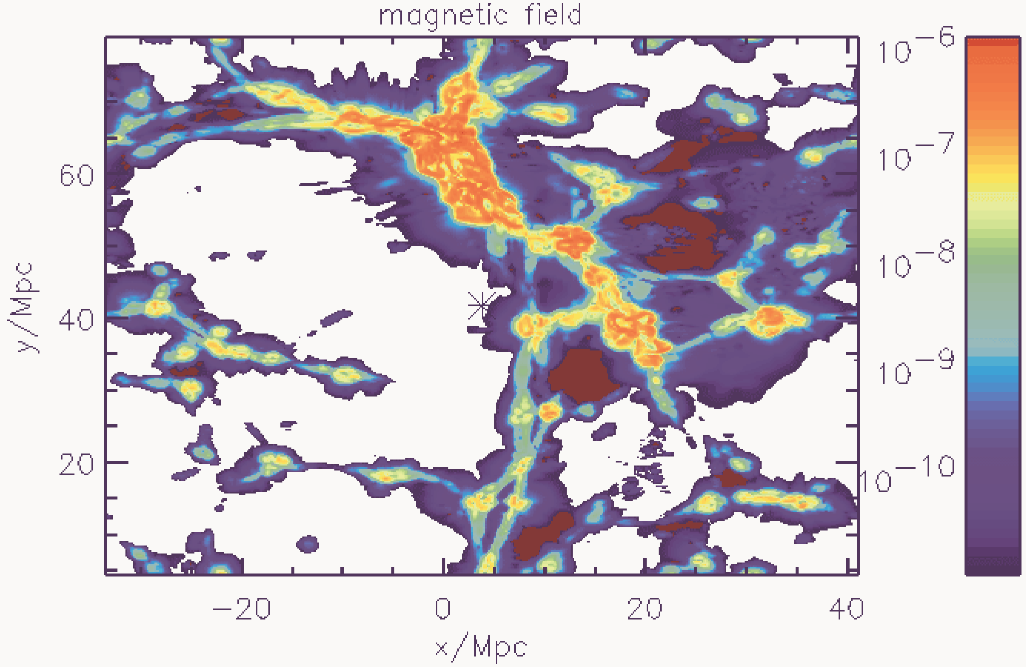
Some results on propagation in structured extragalactic magnetic fields

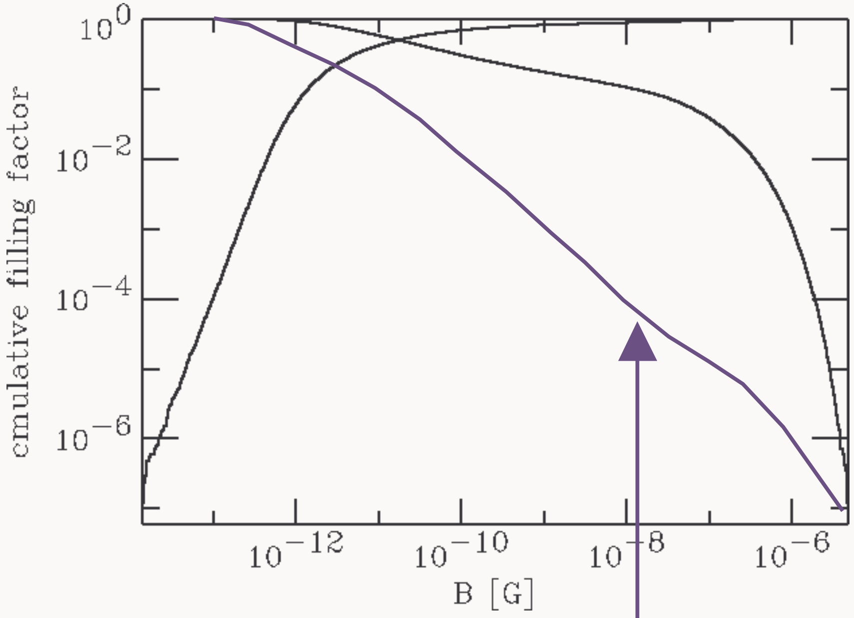
Scenarios of extragalactic magnetic fields using large scale structure simulations with magnetic fields followed passively and normalized to a few micro Gauss in galaxy clusters.

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

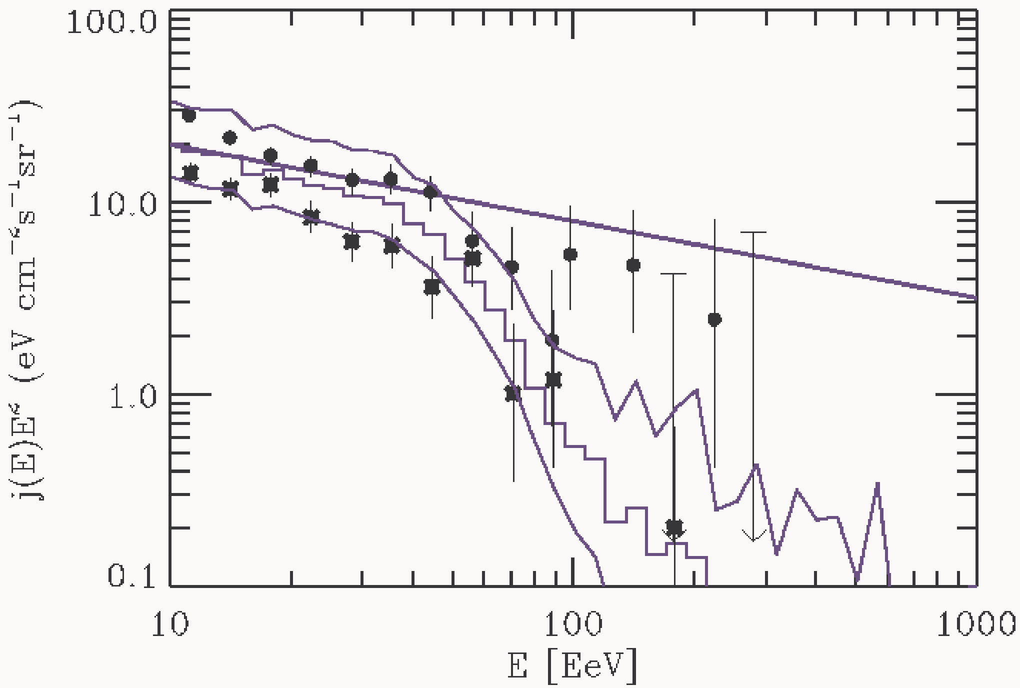
Magnetic field filling factors

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

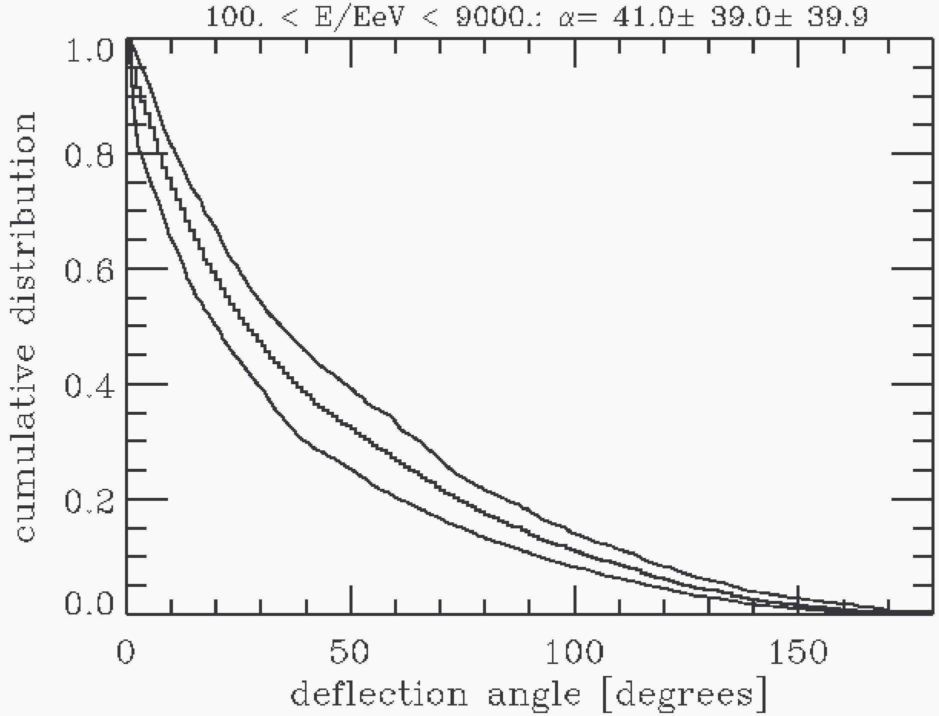




Note: MHD code of Dolag et al., JETP Lett. 79 (2004) 583 gives much smaller filling factors.



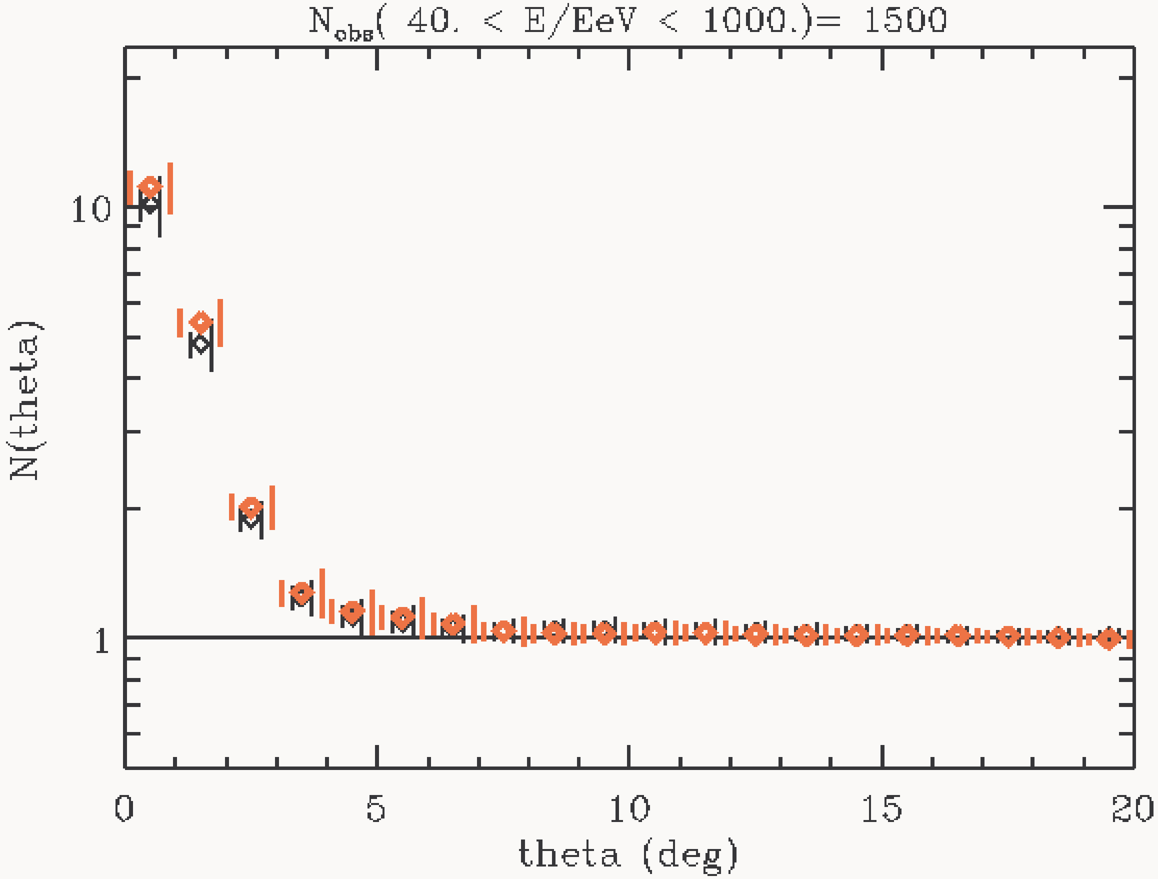
The spectrum in the magnetized source scenario shows a pronounced GZK cut-off (spectrum shown is for AGASA acceptance).



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.

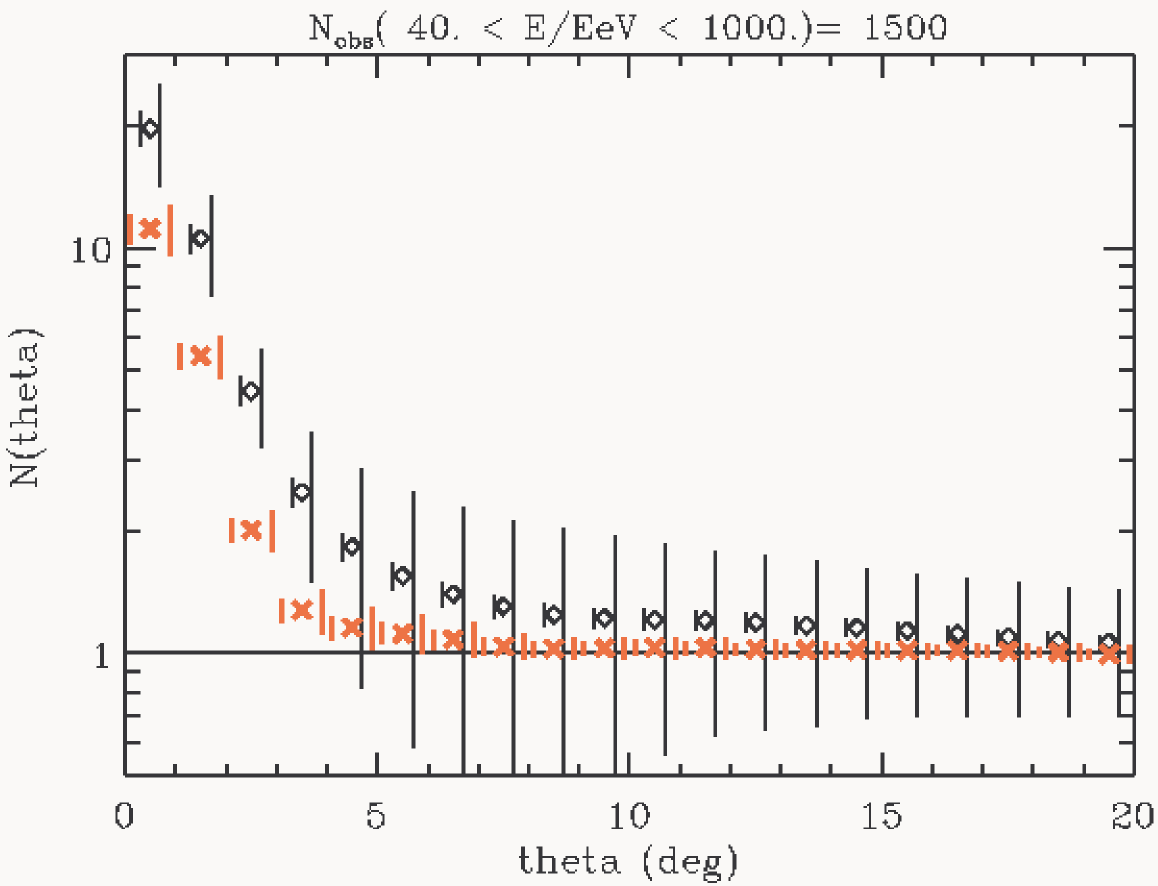
⇒**Particle astronomy not necessarily possible, especially for nuclei !**

Magnetized, Structured Sources



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

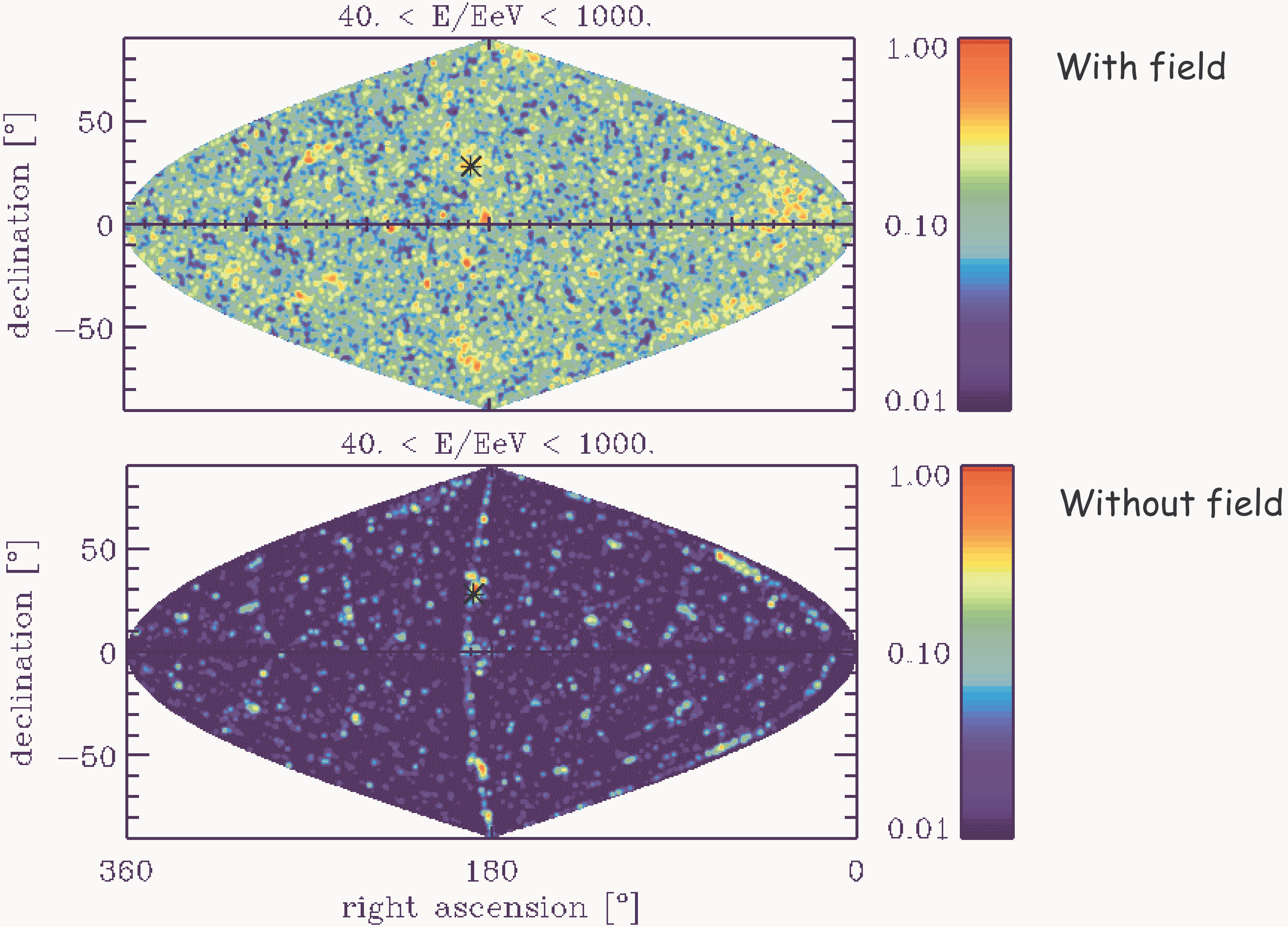
Deflection in magnetic fields makes autocorrelation and power spectrum much less dependent on source density and distribution !



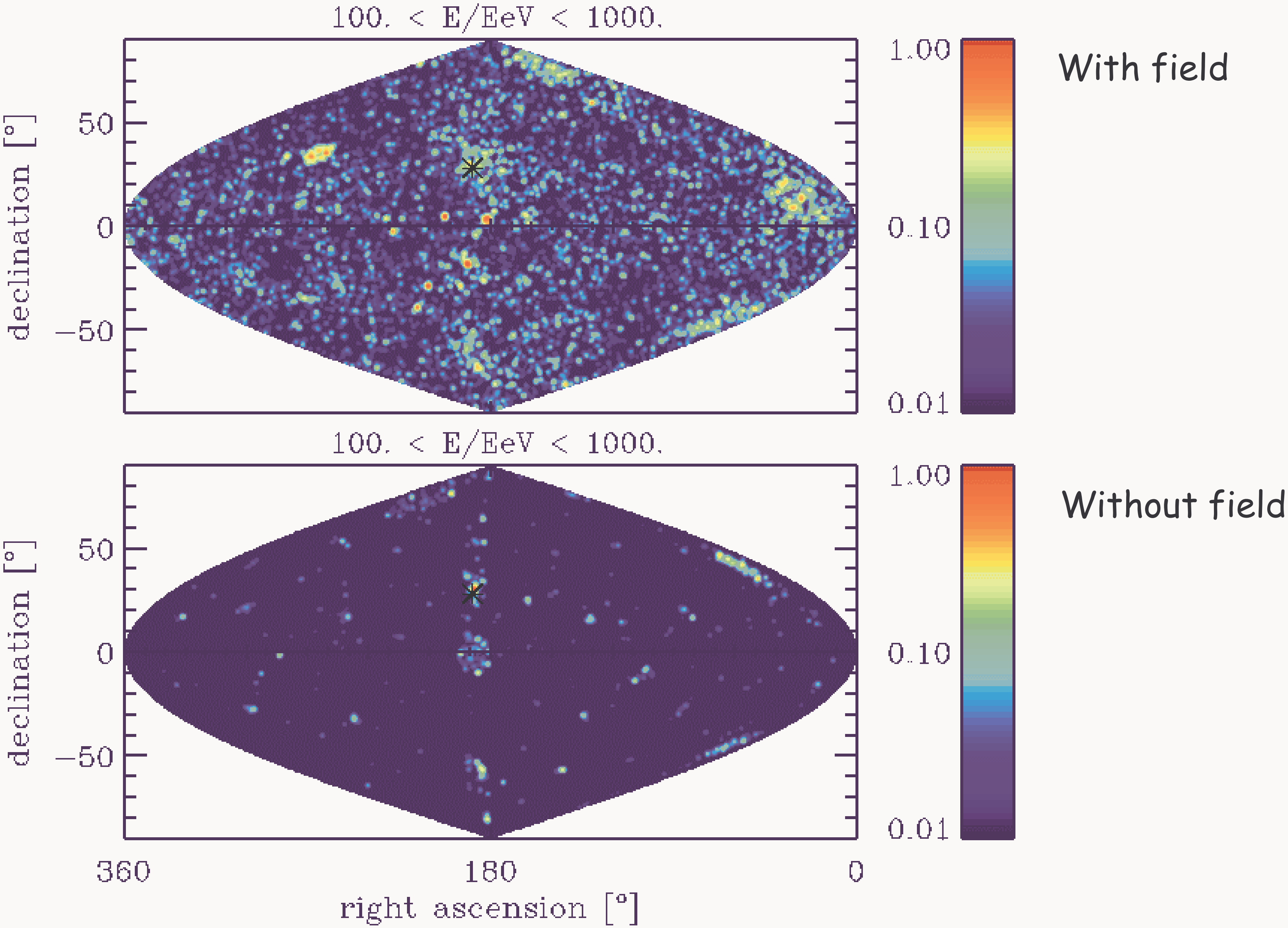
Comparing predicted autocorrelations for source density = 2.4×10^{-5} Mpc^{-3} with (lower set) and without (upper set) magnetization for an Auger-type exposure.

In the future, a suppressed auto-correlation function will be a signature of magnetized sources.

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

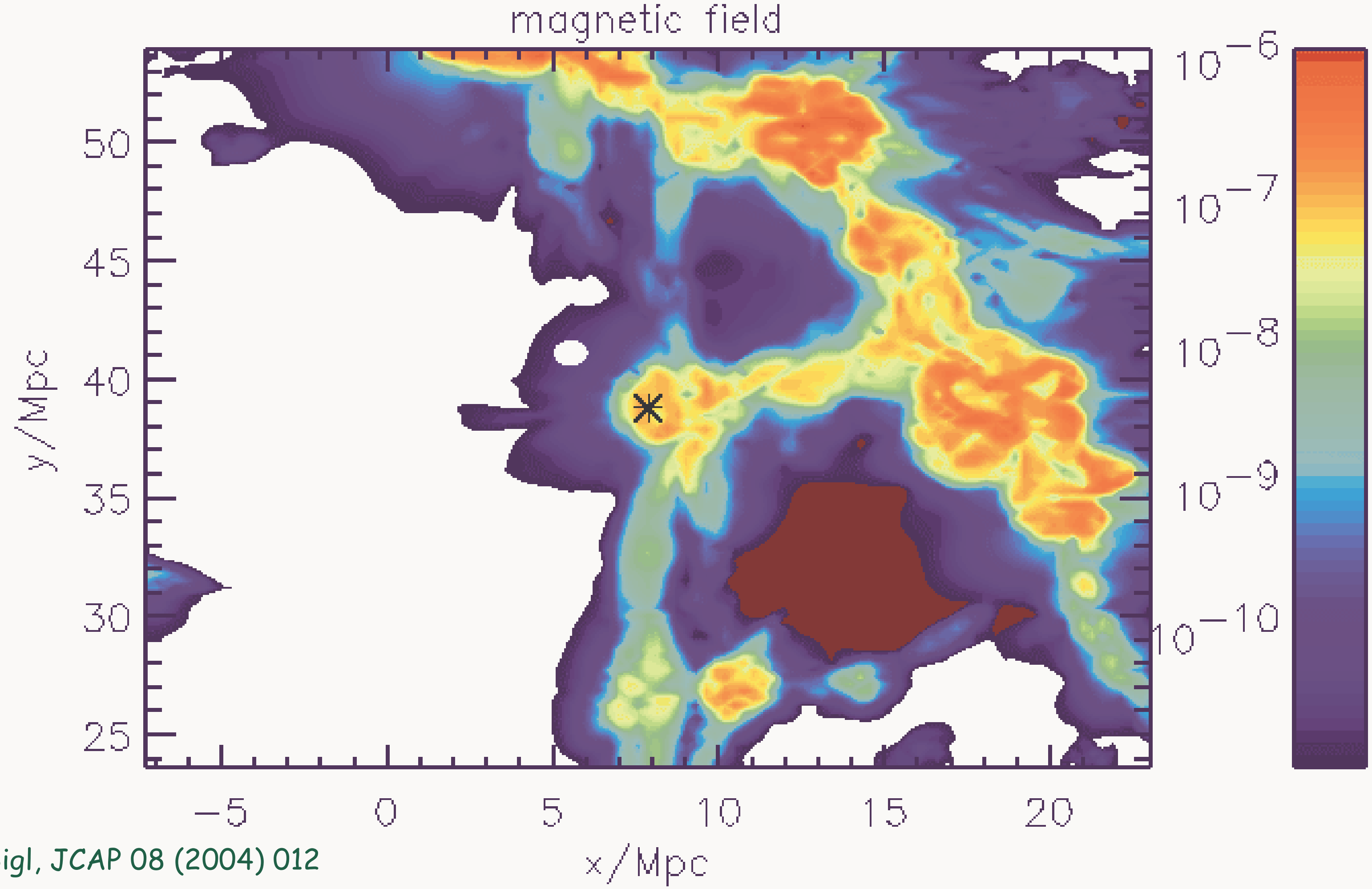


The simulated sky above 10^{20} eV with structured sources of density 2.4×10^{-5} Mpc^{-3} : ~10^5 simulated trajectories above 10^{19} eV.



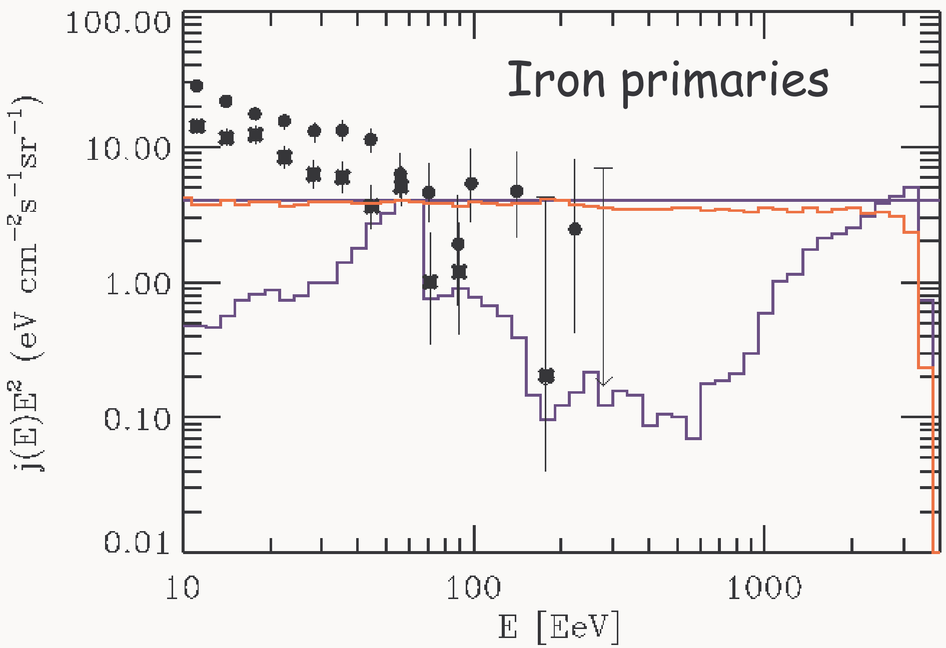
Generalization to Heavy Nuclei: Structured Fields and Individual Sources

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

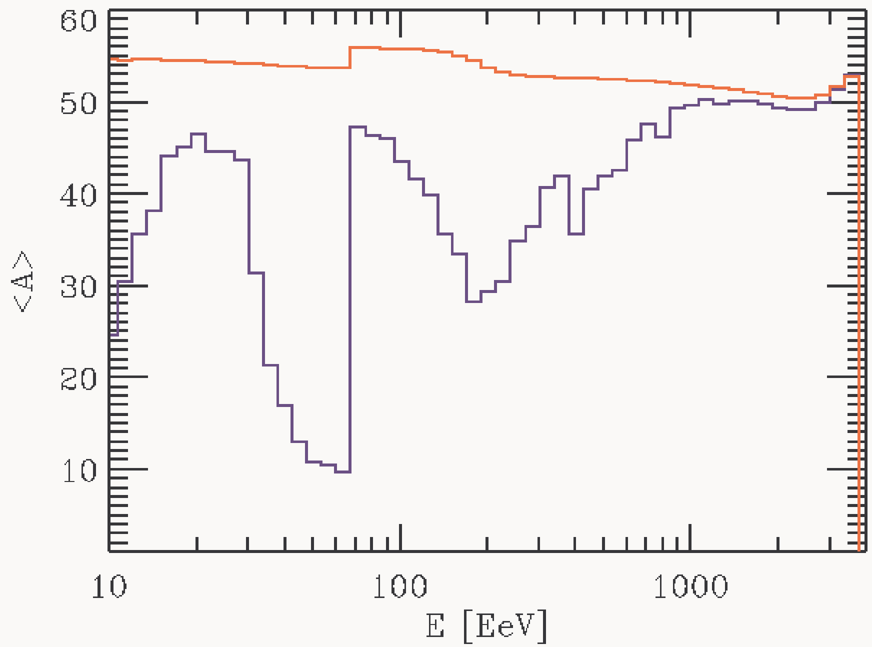


Sigl, JCAP 08 (2004) 012

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



Composition for iron primaries

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

accelerated protons interact:

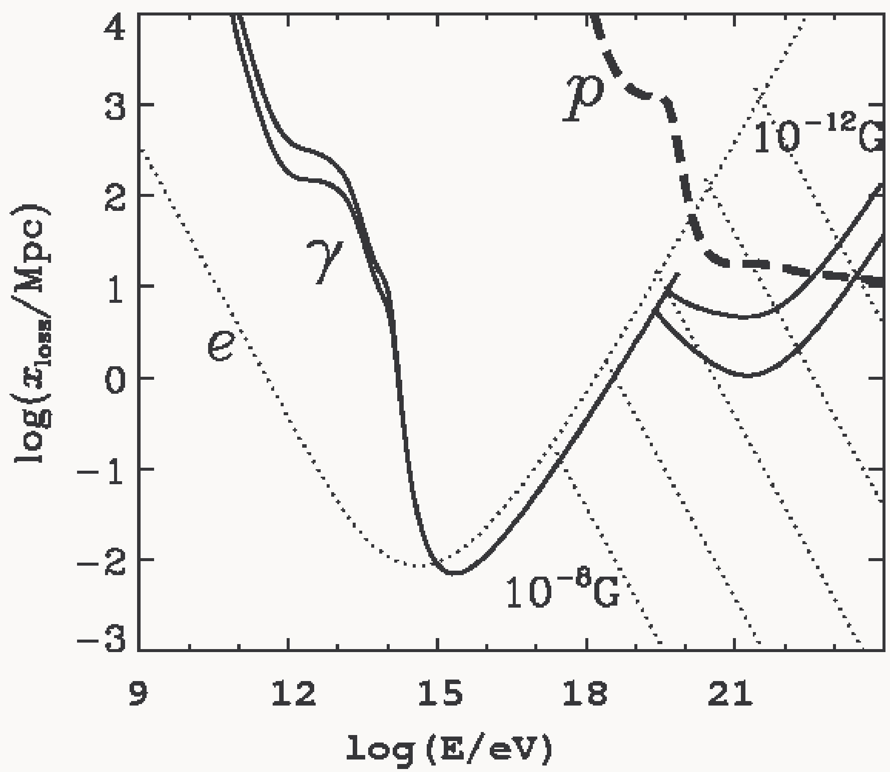
$$p + \begin{matrix} N \\ \gamma \end{matrix} \rightarrow X + \left. \begin{matrix} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{0} \rightarrow \gamma - \text{rays} \end{matrix} \right\}$$

=> energy fluences in γ-rays and neutrinos are comparable due to isospin symmetry.

The neutrino spectrum is unmodified, whereas γ-rays pile up below the pair production threshold on the CMB at a few 10^{14} eV.

The Universe acts as a calorimeter for the total injected electromagnetic energy above the pair threshold. This constrains the neutrino fluxes.

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



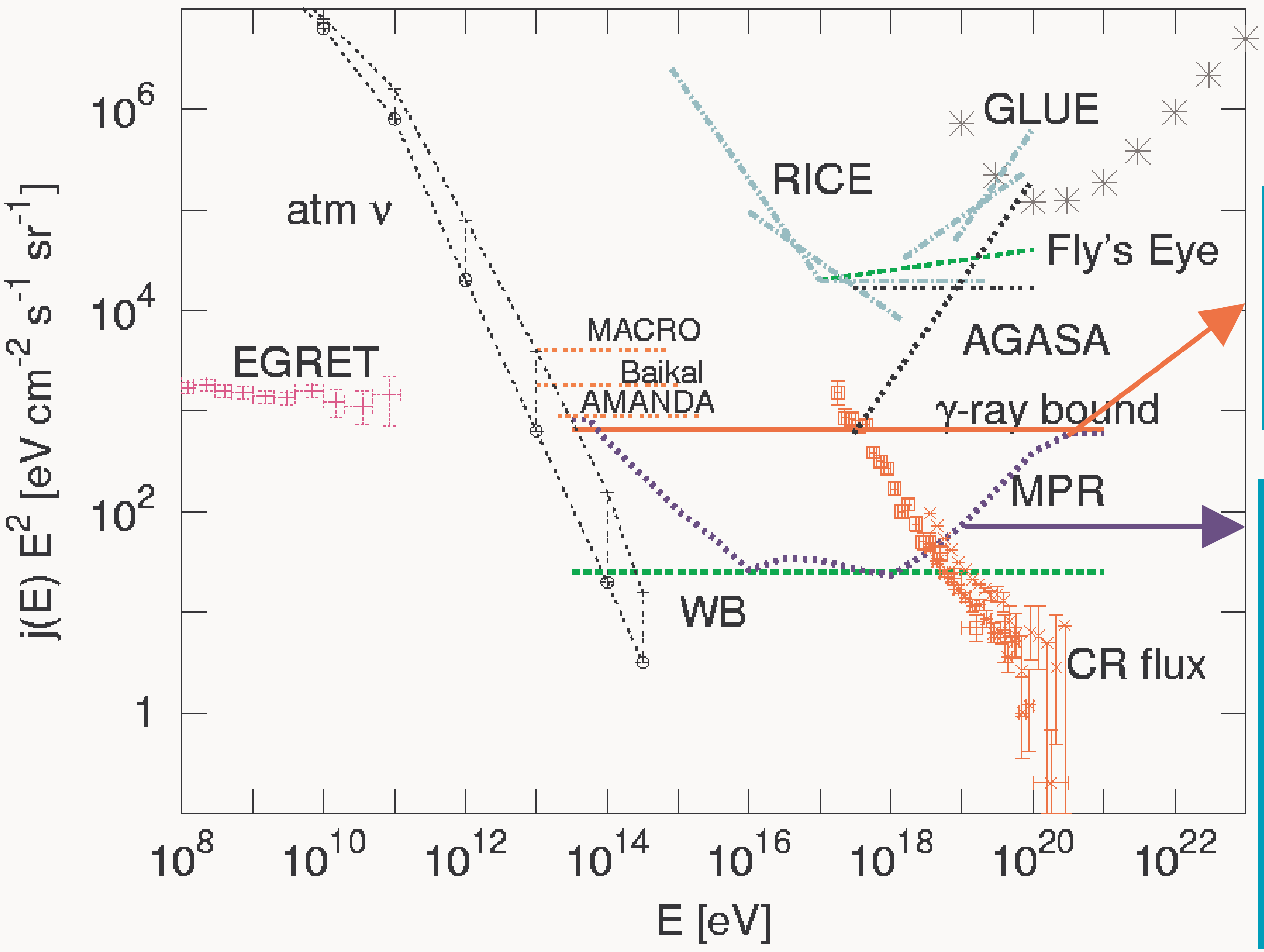
Included processes:

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

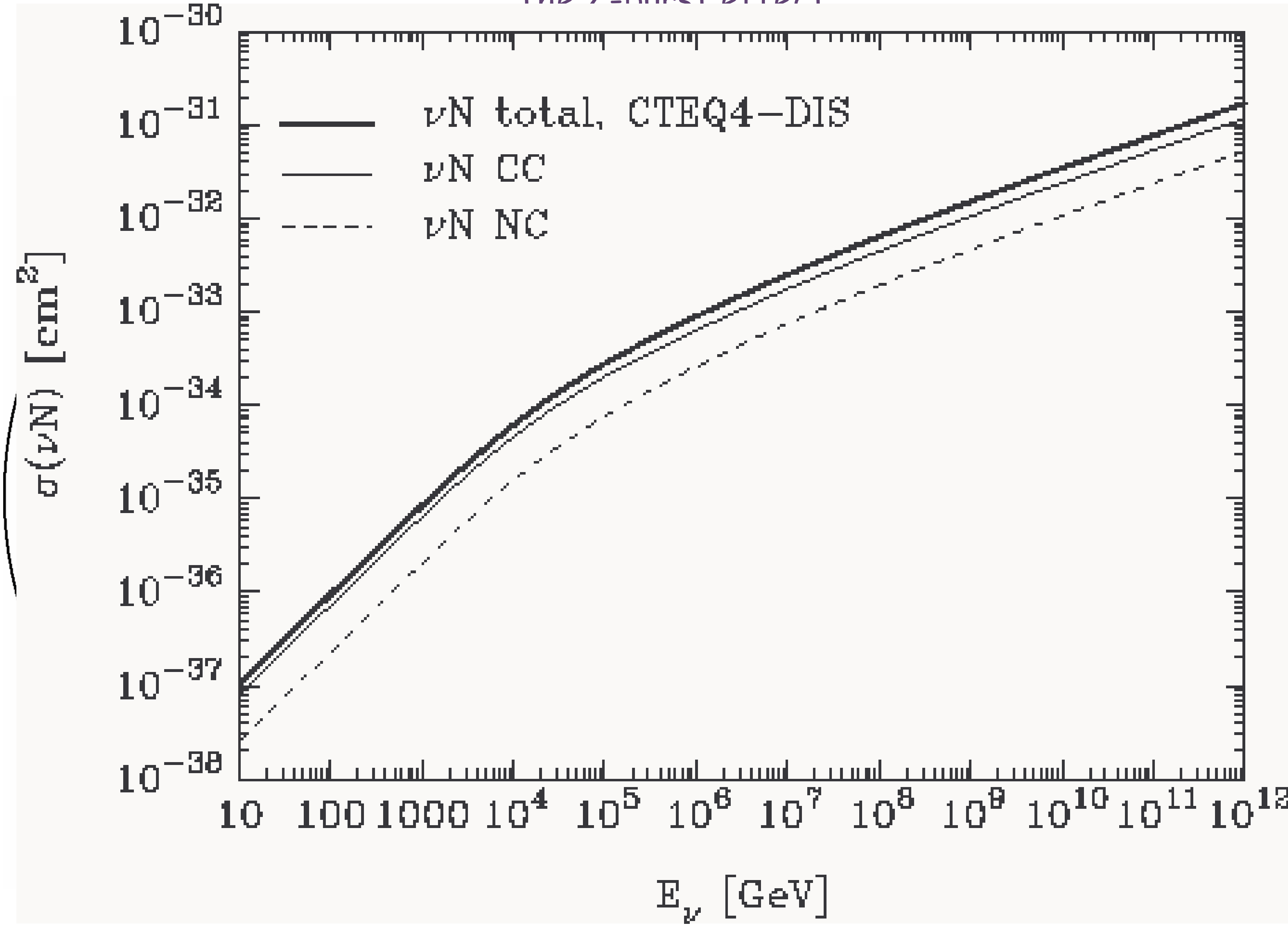
The total injected electromagnetic energy is constrained by the diffuse γ-ray flux measured by EGRET in the MeV – 100 GeV regime



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)

The Z-burst effect



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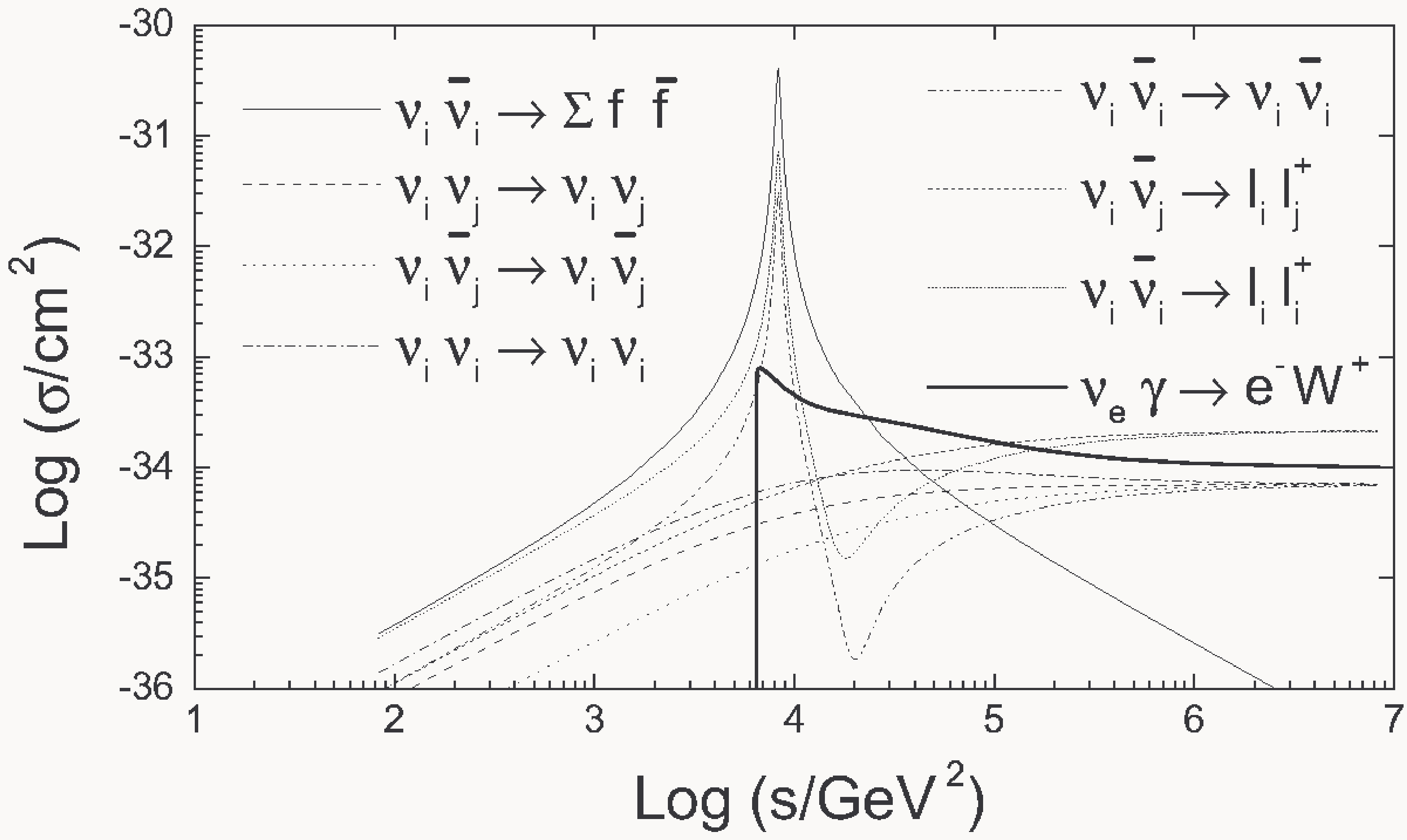
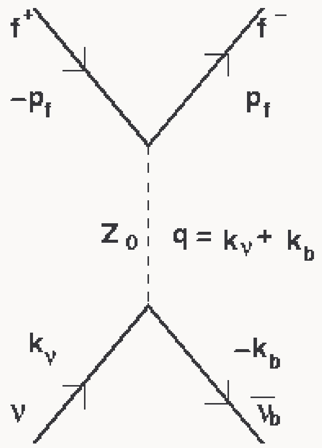
The Z-burst mechanism: Relevant neutrino interactions



Neutrinos:

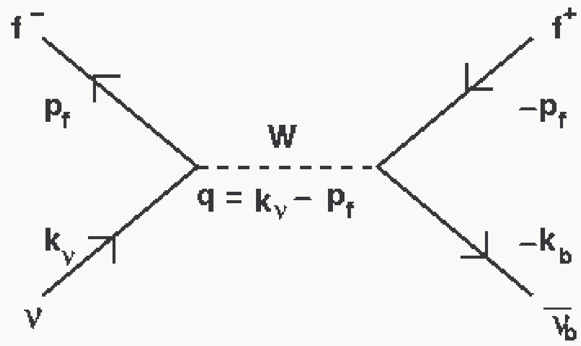
- s−channel Z^0−production: $\nu_i\bar{\nu}_i \to Z^0 \to f\bar{f}$ where f is any fermion (including hadronic fragmentation in case of quarks)



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

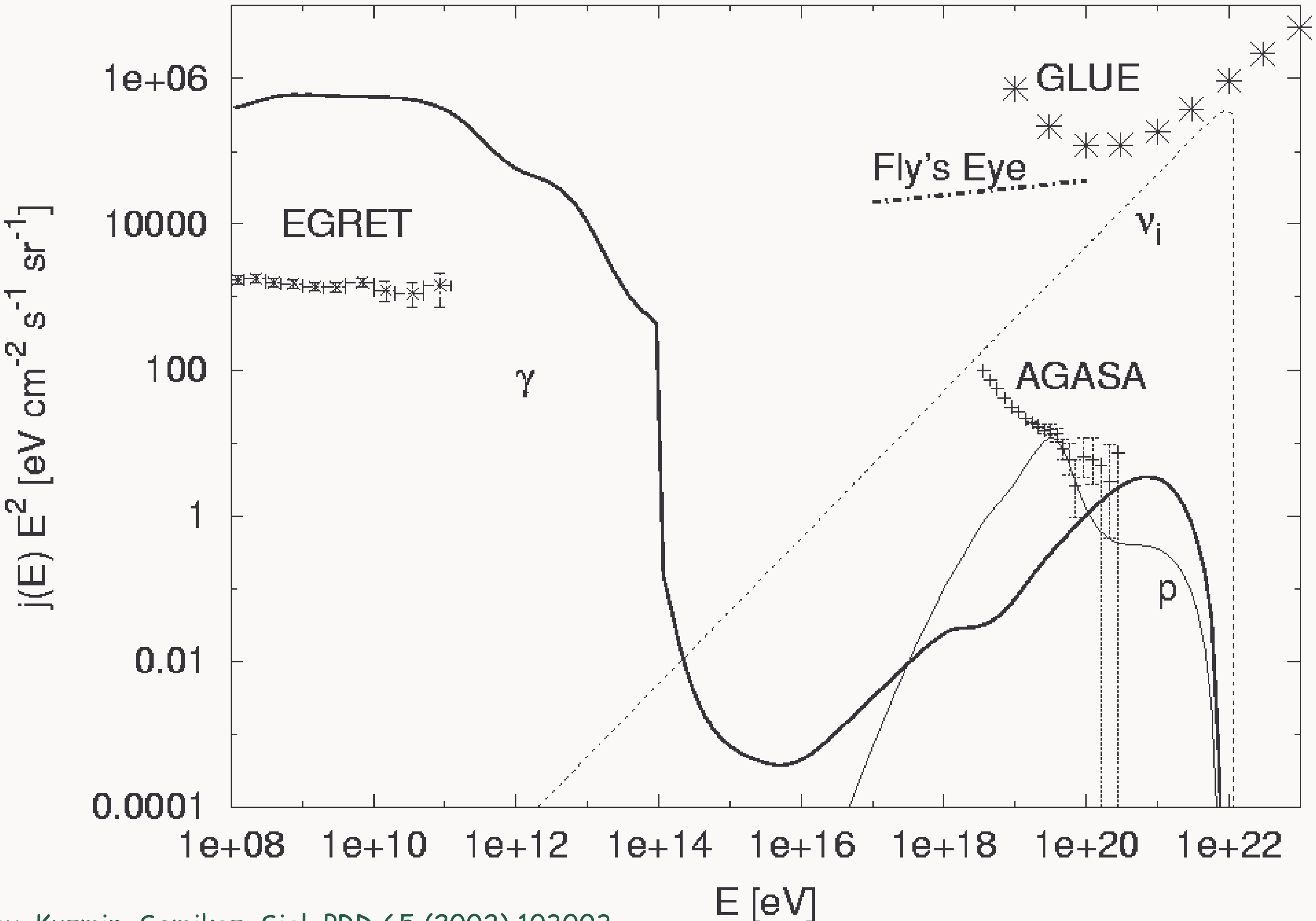
where μ^* = cos(scattering angle in center of mass), Γ_Z =width of Z^0, $g_V = t_3 - q\sin\theta_W^2$ and $g_A = -q\sin\theta_W^2$ with t_3 =weak isospin and q =charge.

- 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:



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

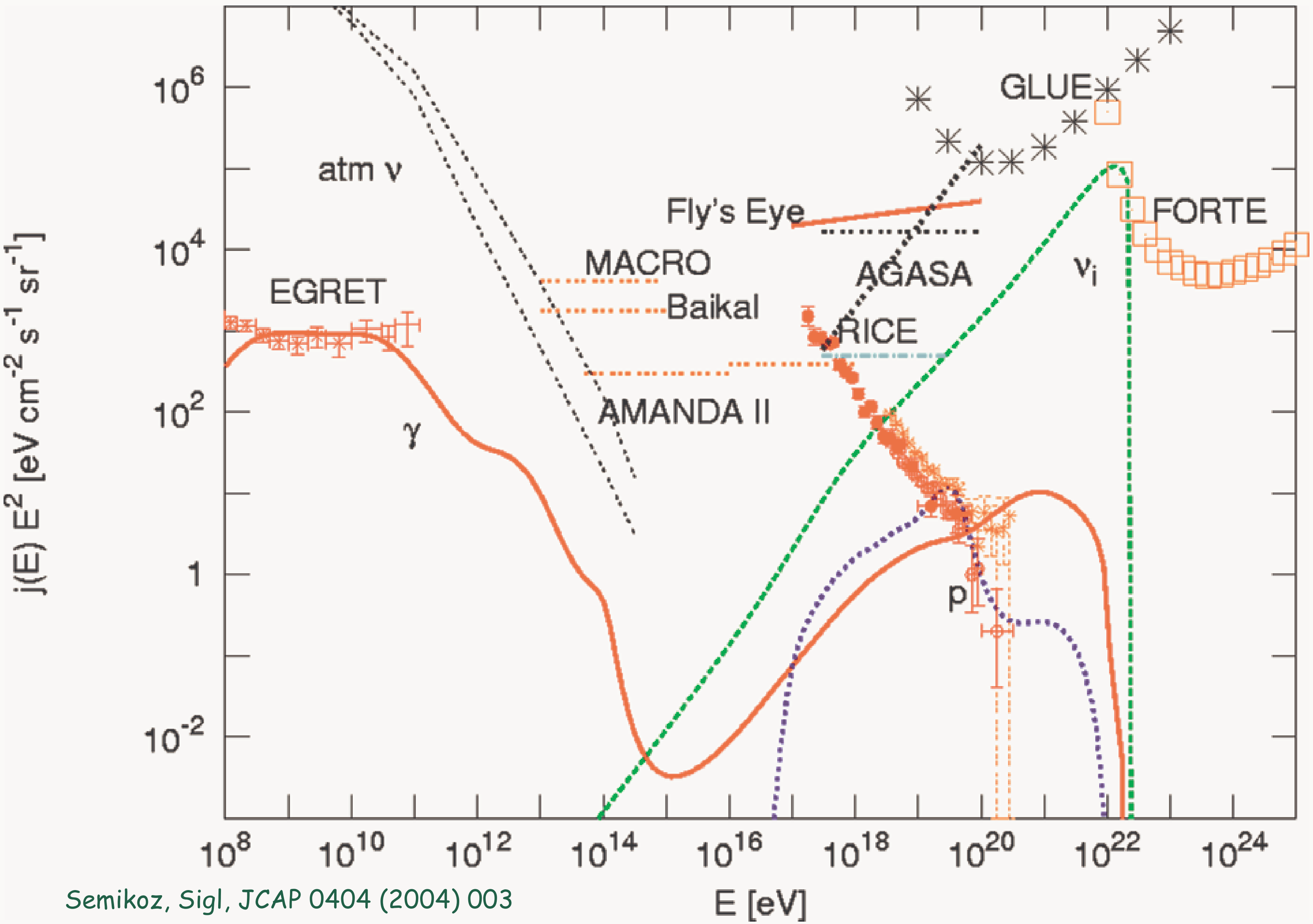
The Z-burst mechanism: Sources emitting neutrinos and γ-rays



Kalashev, Kuzmin, Semikoz, Sigl, PRD 65 (2002) 103003

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 comoving luminosity proportional to $(1+z)^0$ 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).

$$\sum m_{\upsilon_i} \geq 0.3\,\mathrm{eV}$$

Cosmological data including WMAP imply

$$\sum m_{\upsilon_i} \leq 0.6\,\mathrm{eV}$$

Solar and atmospheric neutrino oscillations indicate near degeneracy at this scale

$$\Rightarrow \sum m_{\upsilon_i} \leq 0.2\,\mathrm{eV}$$

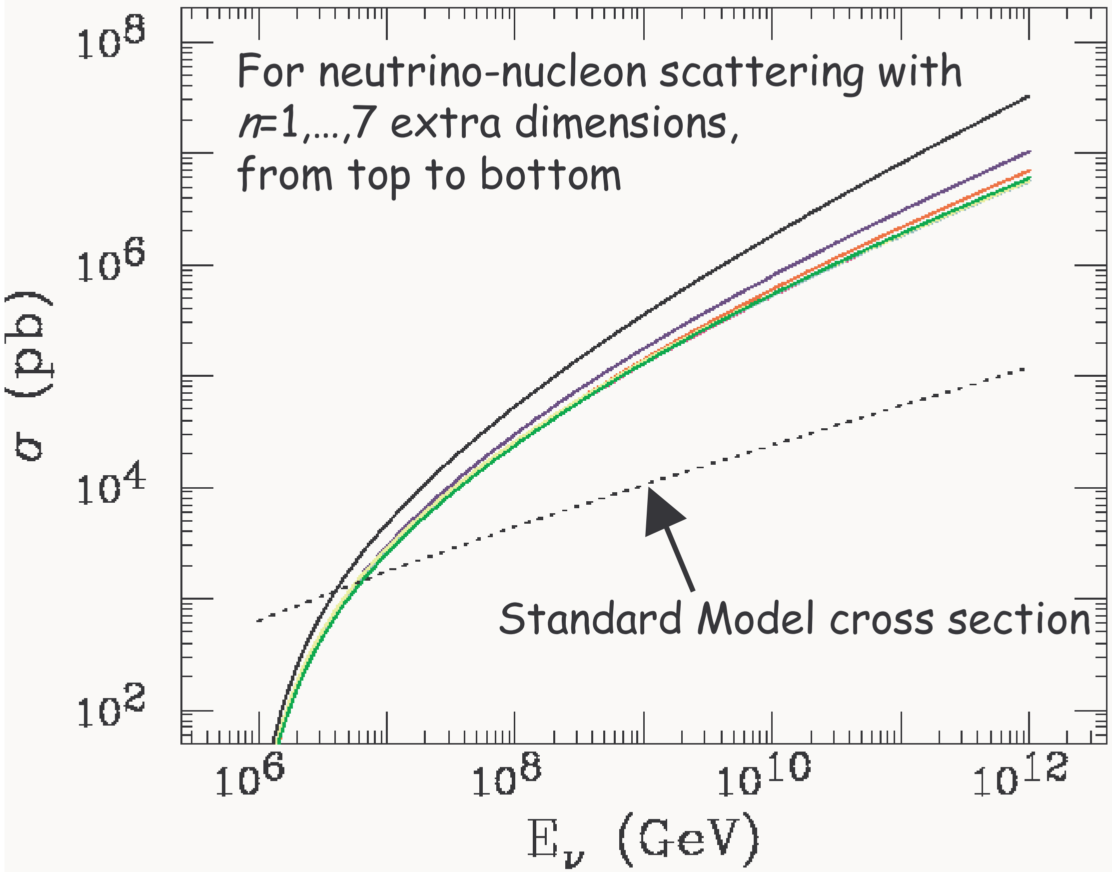
For such masses local relic neutrino overdensities are < 10 on Mpc scales. This is considerably smaller than UHECR loss lengths => required UHE Neutrino flux not significantly reduced by clustering.

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

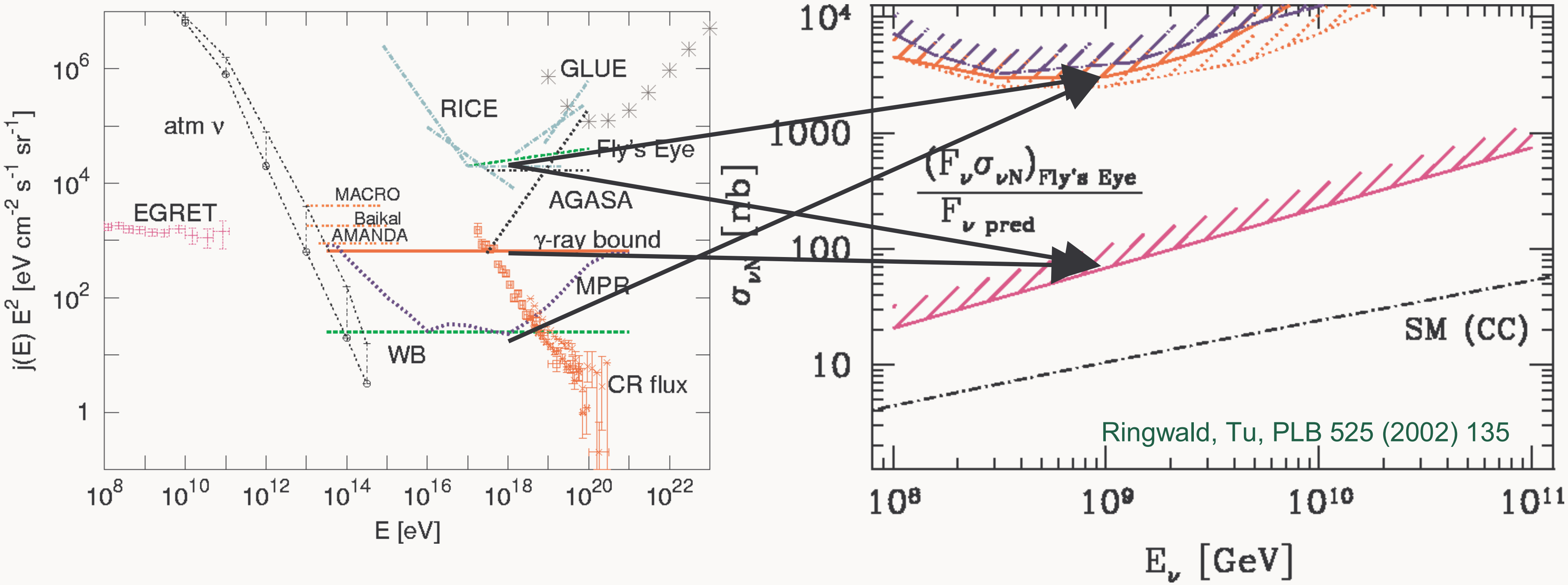
Example: microscopic black hole production in scenarios with a TeV string scale:



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

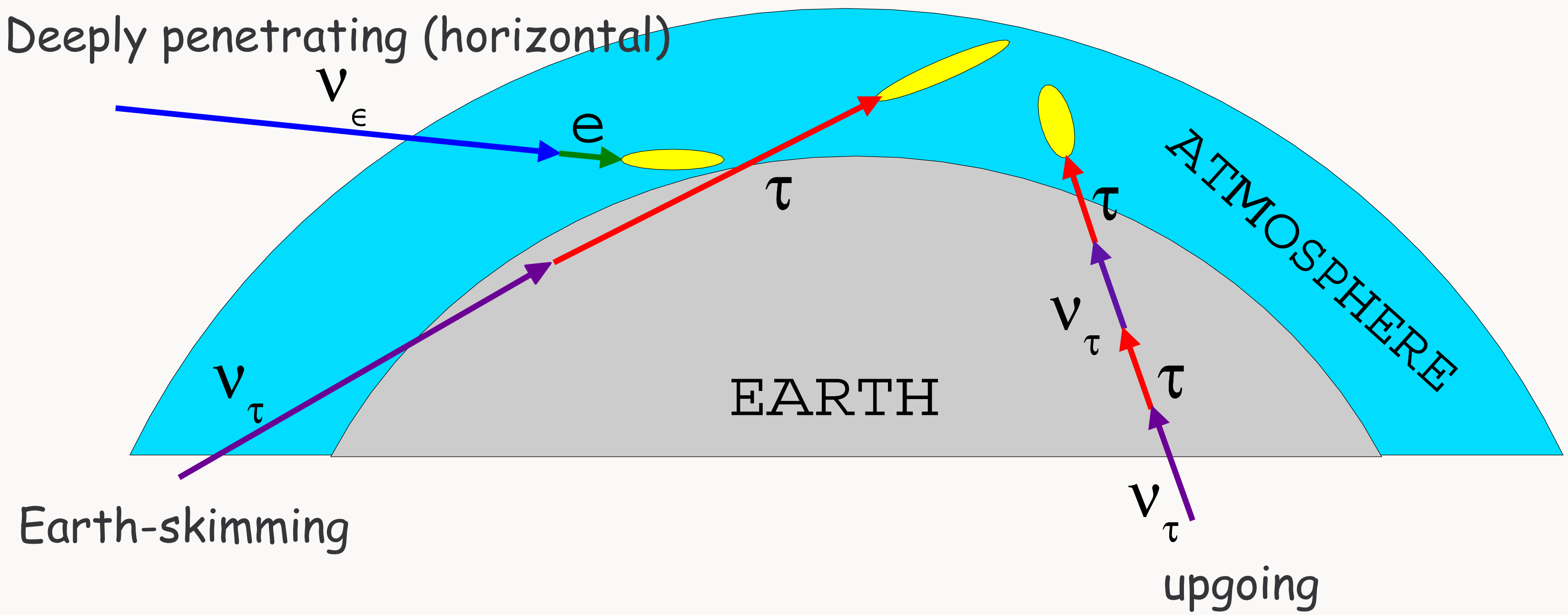
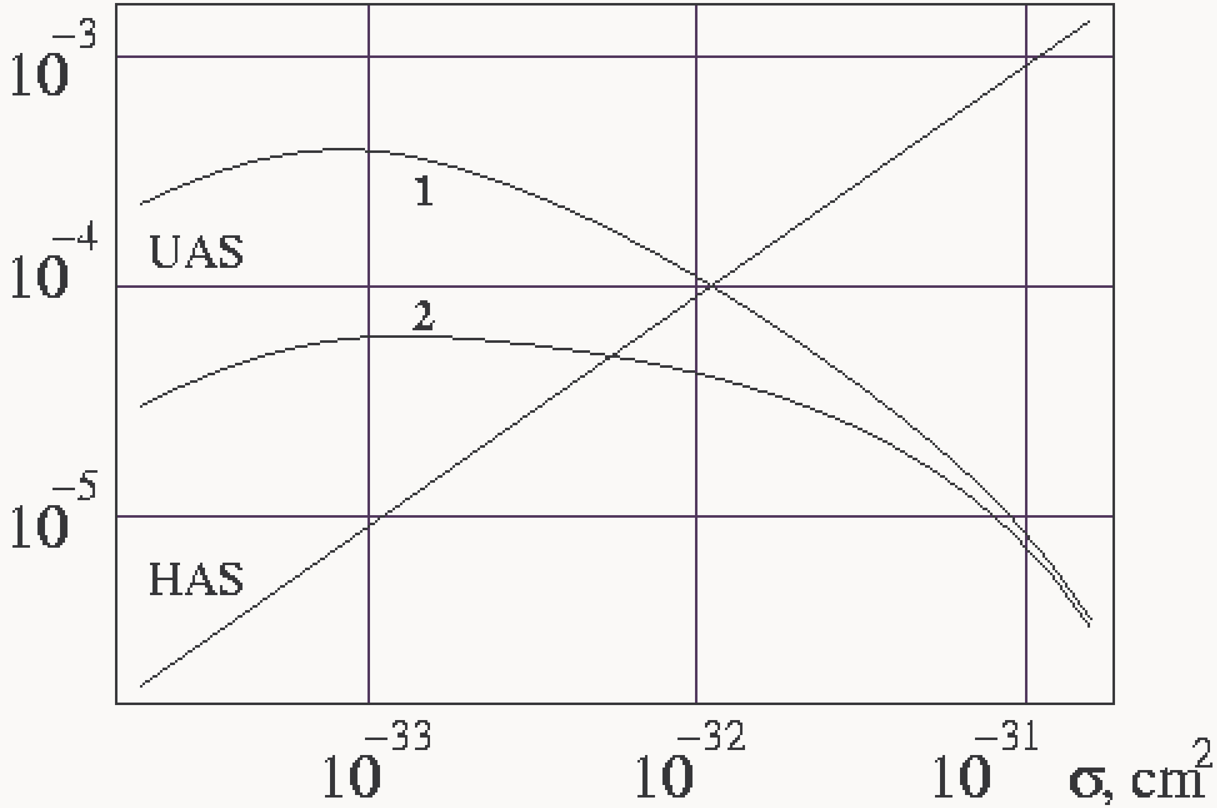


Figure from Cusumano

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.) Acceleration and sky distribution of cosmic rays are strongly linked to the in part poorly known strength and distribution of cosmic magnetic fields.

3.) Deflection angles are currently hard to quantify.

4.) 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.

Conclusions2

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.

6.) There are many potential high energy neutrino sources including speculative ones. But the only guaranteed ones are due to pion production of primary cosmic rays known to exist: Galactic neutrinos from hadronic interactions up to ~10^{16} eV and "cosmogenic" neutrinos around 10^{19} eV from photopion production. Flux uncertainties stem from uncertainties in cosmic ray source distribution and evolution.

7.) The highest neutrino fluxes above 10^{19} eV are predicted by top-down models, the Z-burst, and cosmic ray sources with power increasing with redshift. However, extragalactic top-down models and the Z-burst are unlikely to considerably contribute to ultra-high energy cosmic rays.