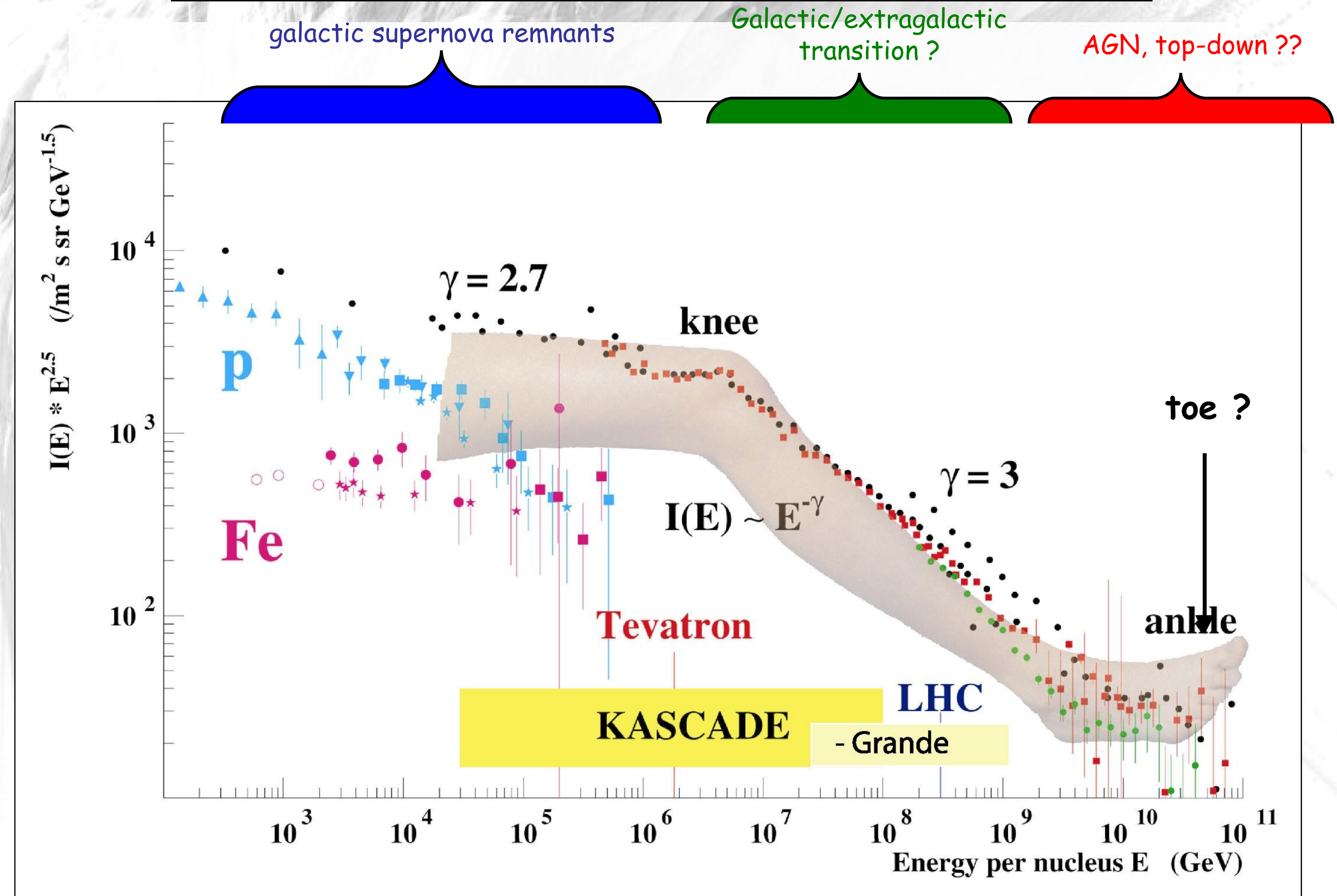
Ultra-High Energy Cosmic Rays

- (Very short) reminder on Cosmic Ray experimental situation and current understanding
- Interpretations of Correlation with Large Scale Structure
- Composition and propagation in cosmic magnetic fields
- Multi-messenger signatures of potential sources
- Physics with Secondary gamma-rays and neutrinos

Günter Sigl
II. Institut theoretische Physik, Universität Hamburg
http://www2.iap.fr/users/sigl/homepage.html

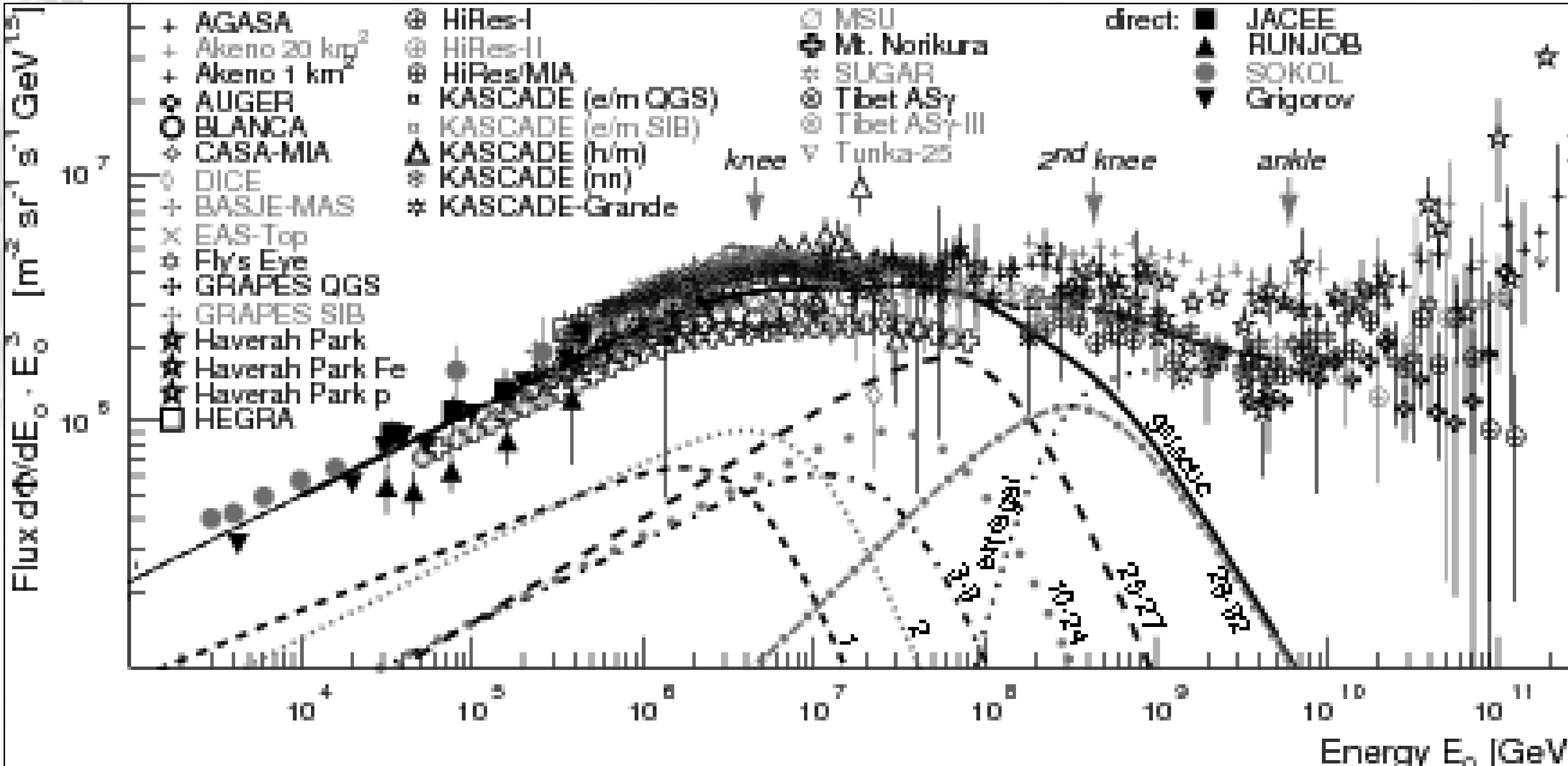
The structure of the spectrum and scenarios of its origin



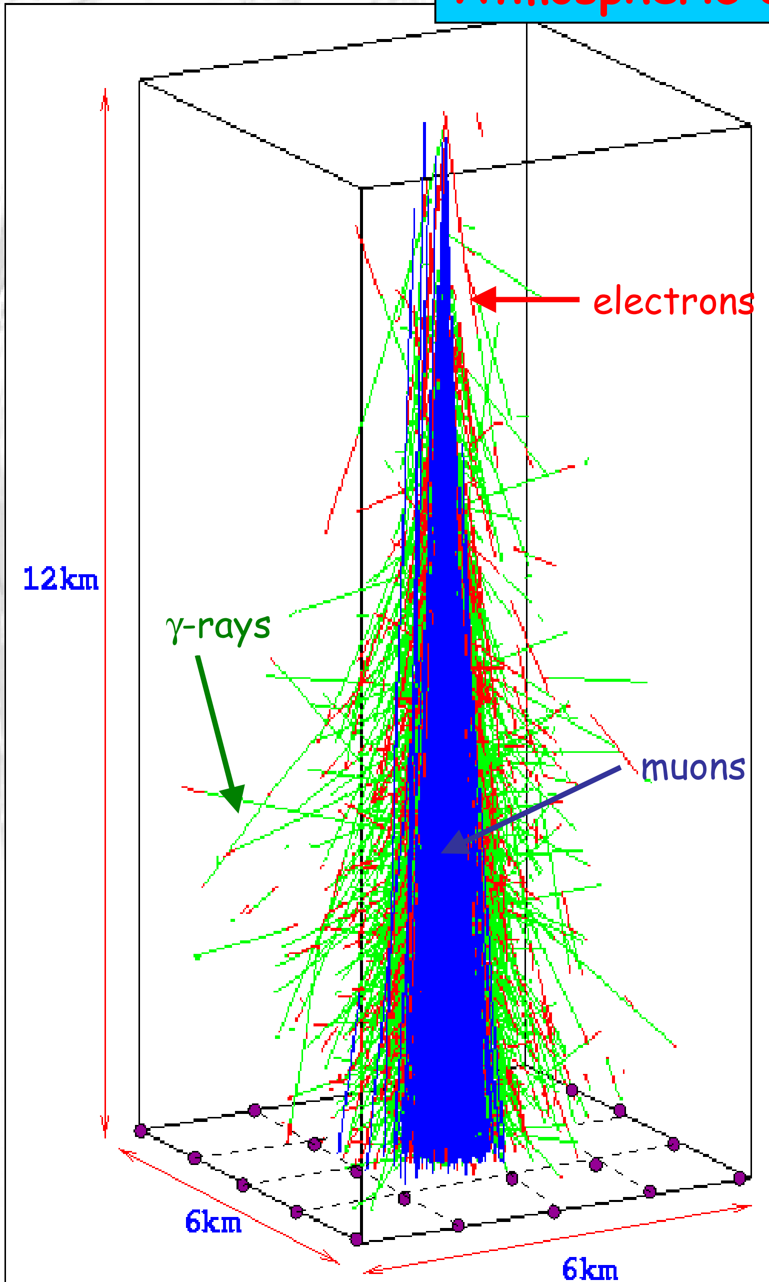
All Particle Spectrum and chemical Composition

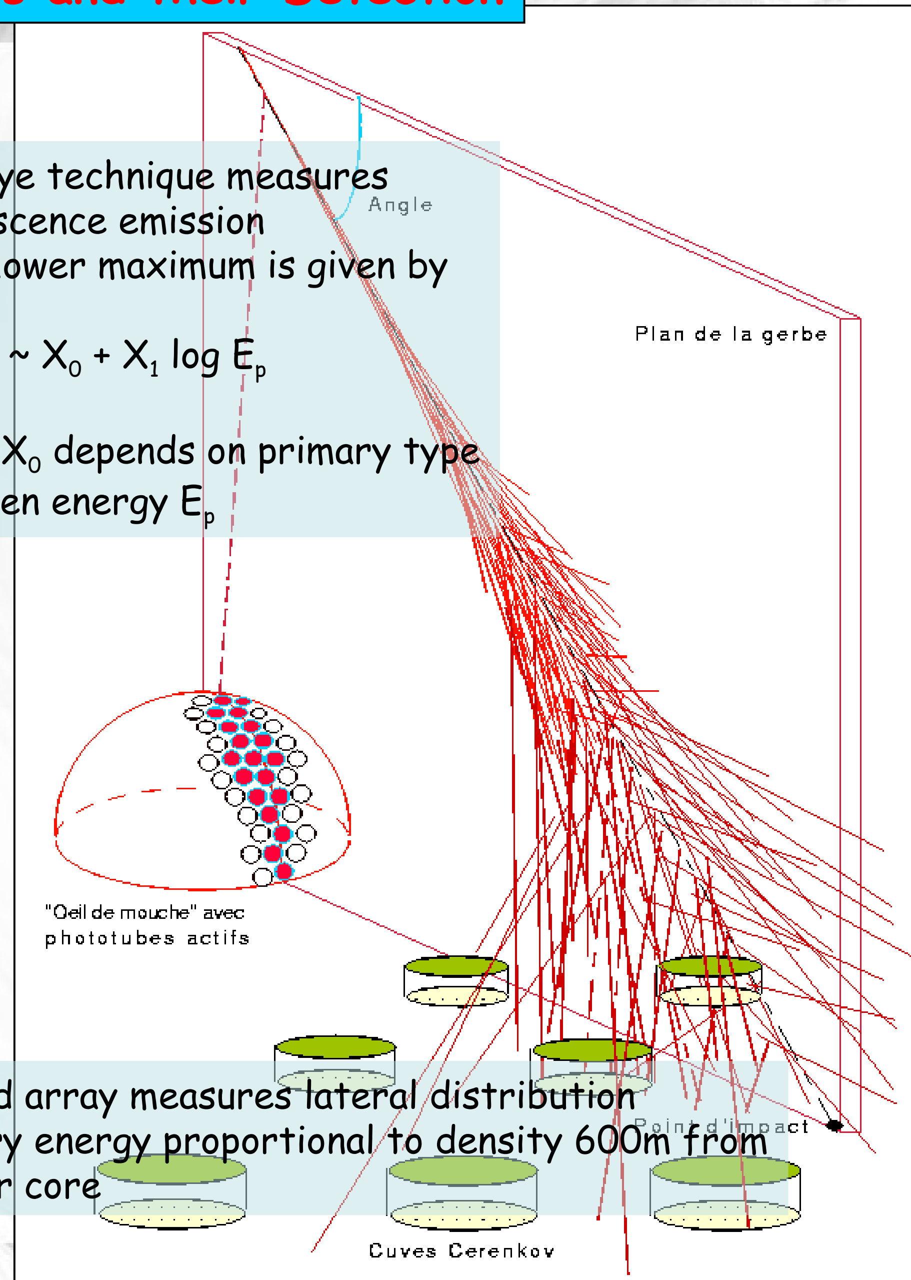
Heavy elements start to dominate above knee
Rigidity (E/Z) effect: combination of deconfinement and maximum energy

Hoerandel, astro-ph/0702370



Atmospheric Showers and their Detection





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

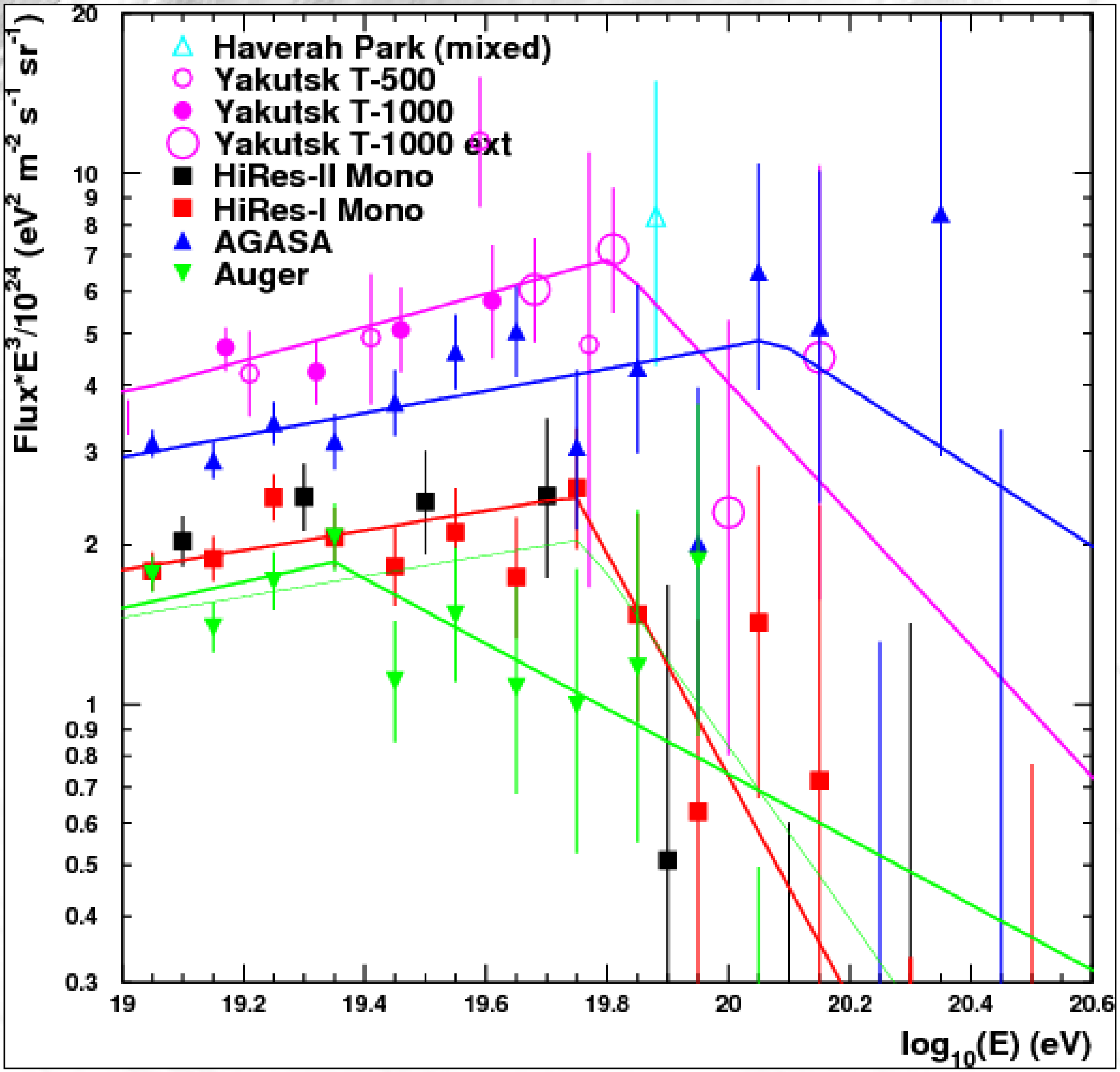
$$X_{max} \sim X_0 + X_1 \log E_p$$

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

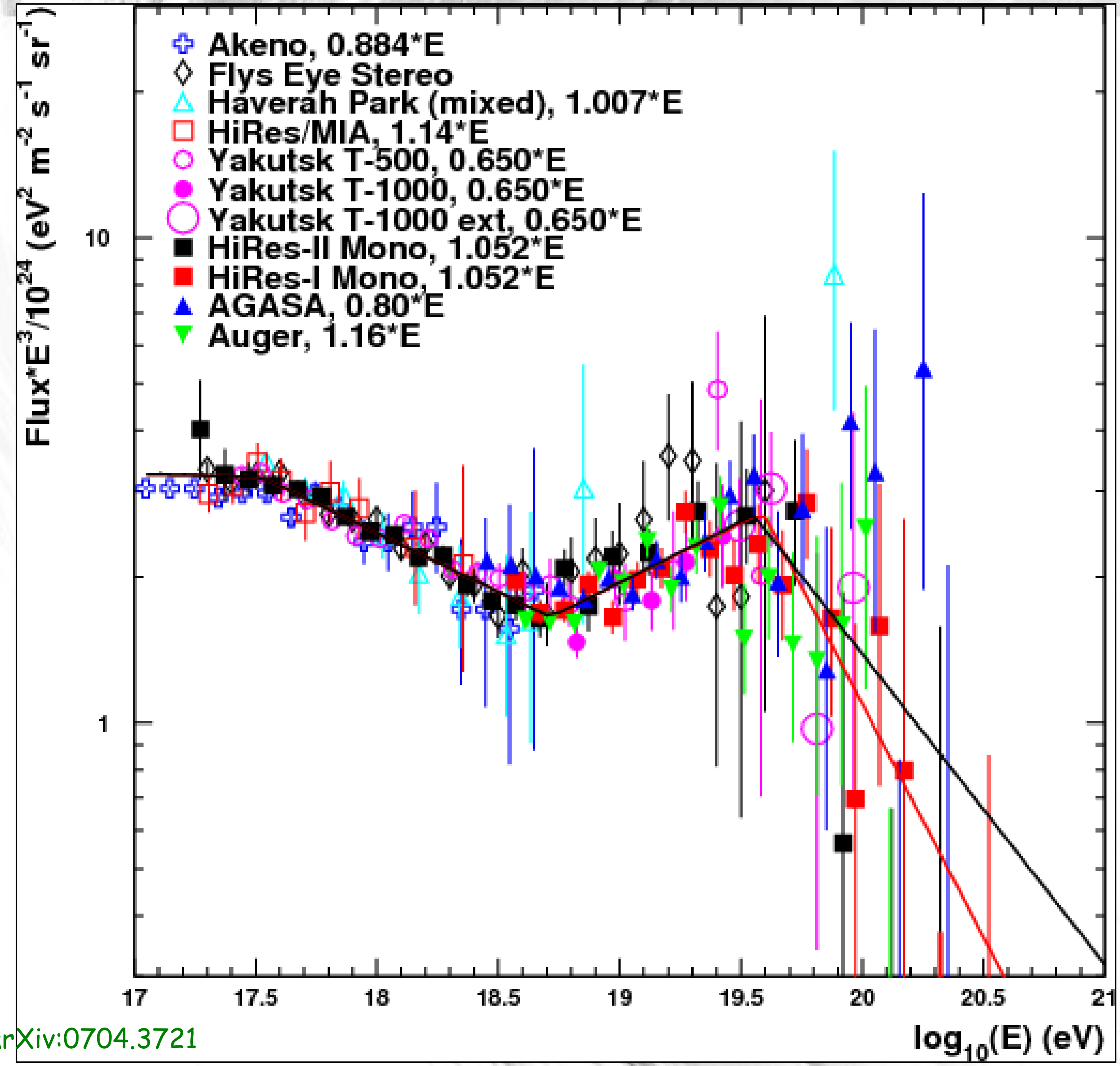
Lowering AGASA energy scale by about 20% brings it in accordance with HiRes up to the GZK cut-off, but maybe not beyond ?

Bergmann, Belz, J.Phys.G34 (2007) R359



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

Comparison with earlier Experimental Spectra

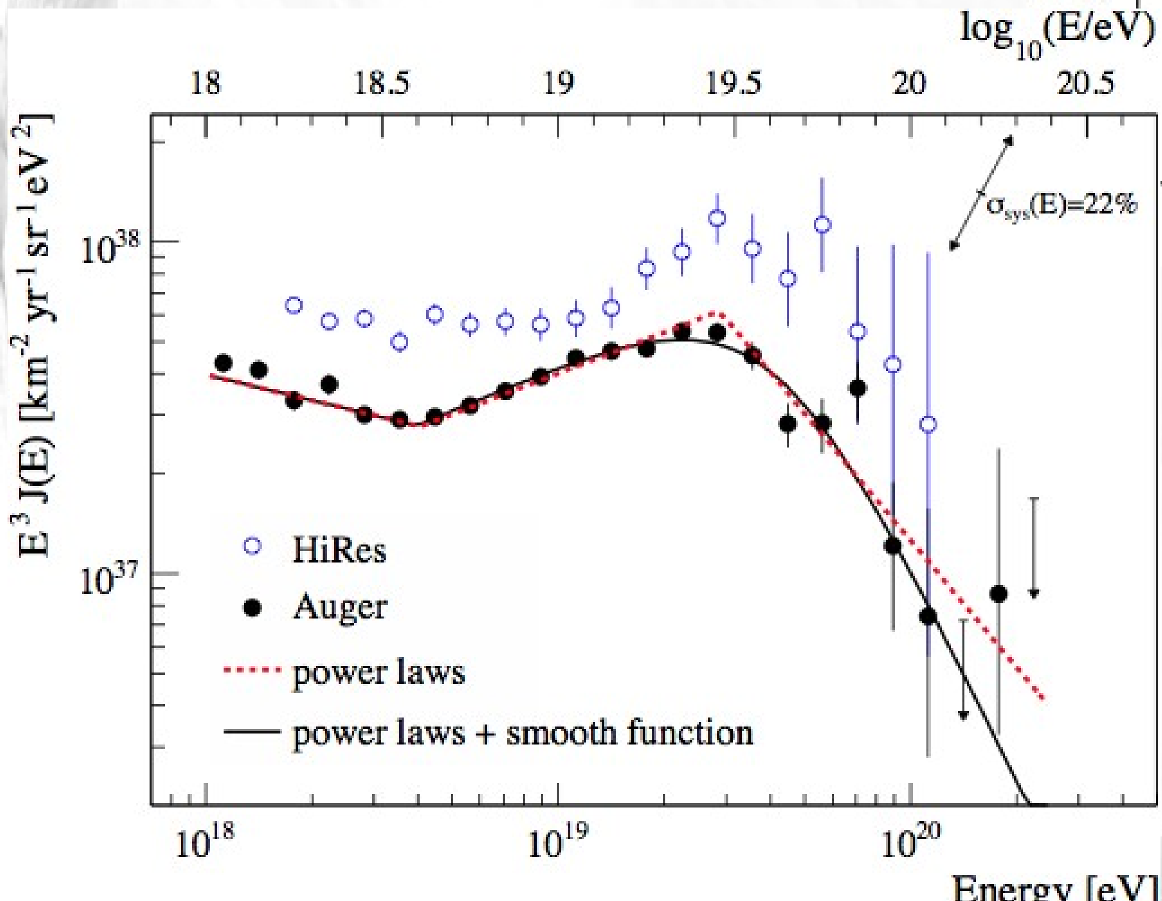


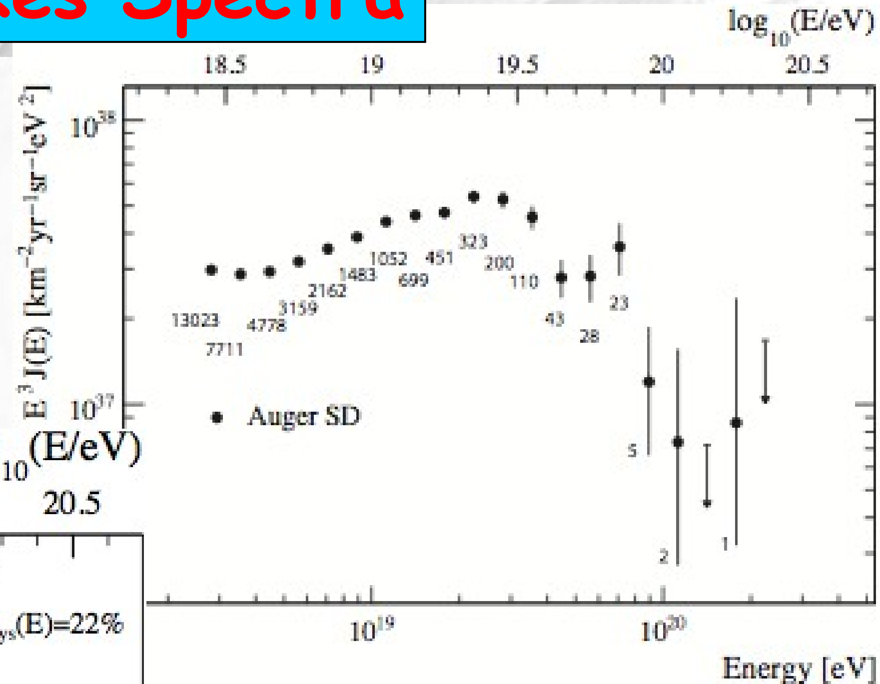
Bergmann, Belz, arXiv:0704.3721

Auger and HiRes Spectra

Auger exposure = 12,790 km^2 sr yr up to December 2008

Pierre Auger Collaboration, PRL 101, 061101 (2008)
and Phys.Lett.B 2010, to appear





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

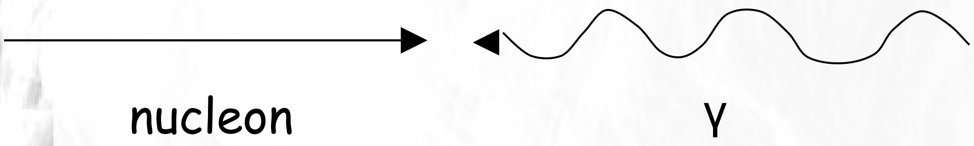
1.) electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 50 Mpc.

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

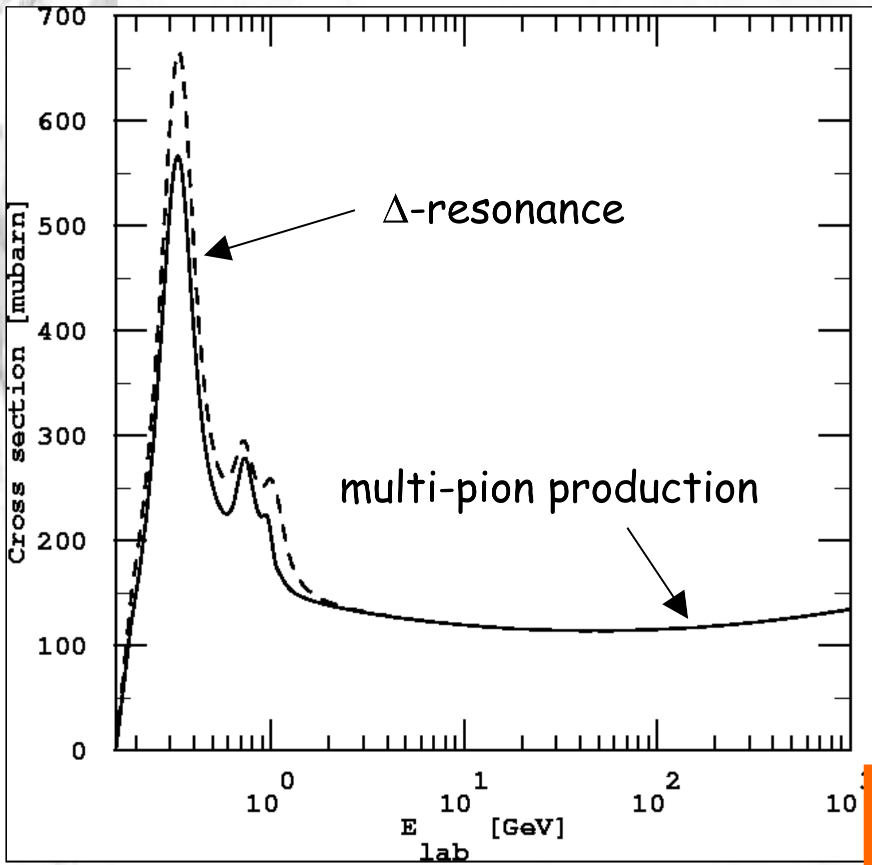
3.) The observed distribution does not yet reveal unambigously the sources, although there is some correlation with local large scale structure

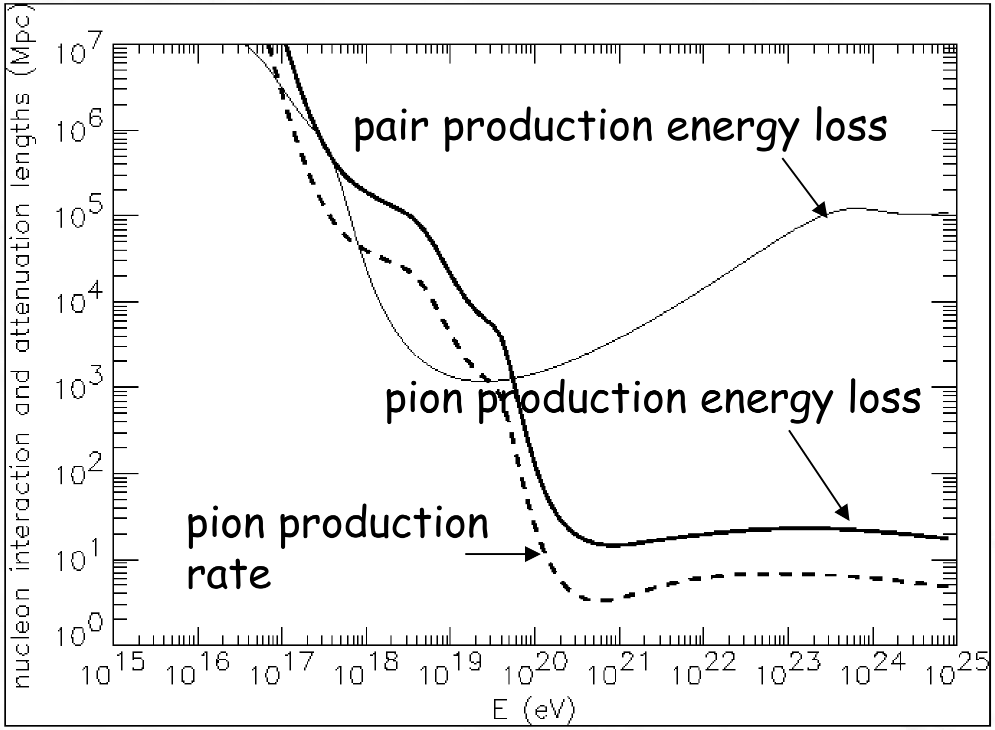
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\epsilon} \approx 4\,x\,10^{19}\,\text{eV}$$

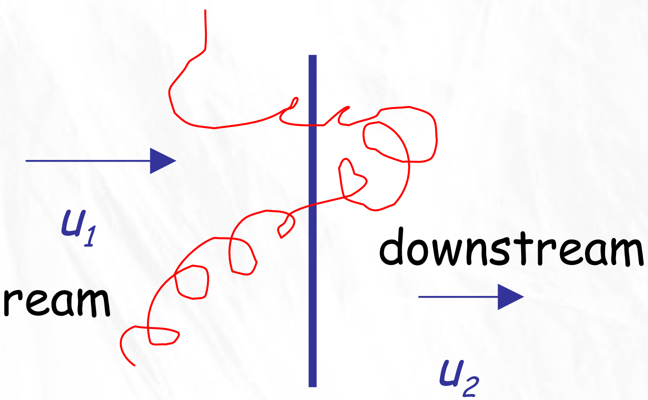




sources must be in cosmological backyard
Only Lorentz symmetry breaking at Γ>10¹¹ could avoid this conclusion.

1st Order Fermi Shock Acceleration

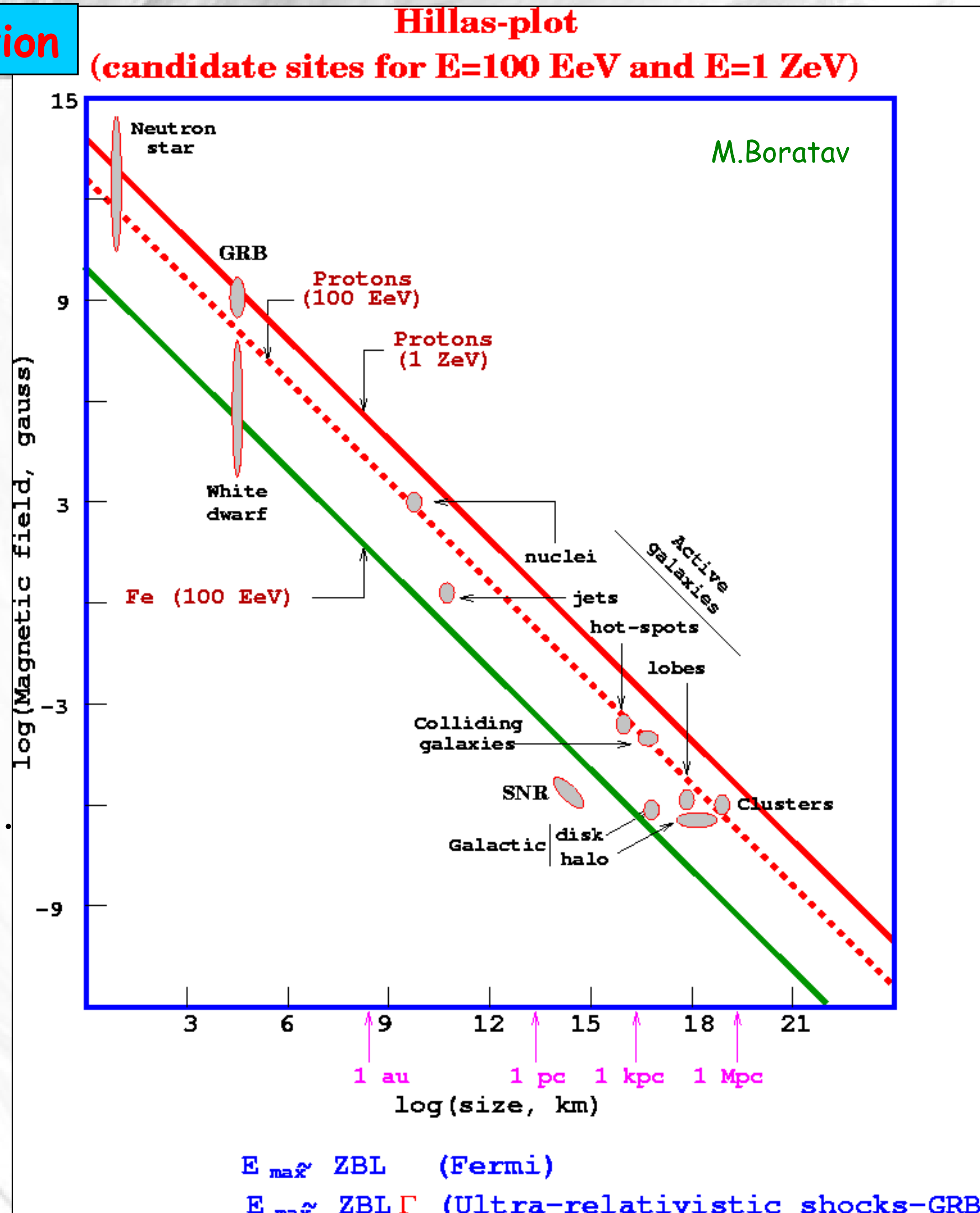
The most widely accepted scenario of cosmic ray acceleration



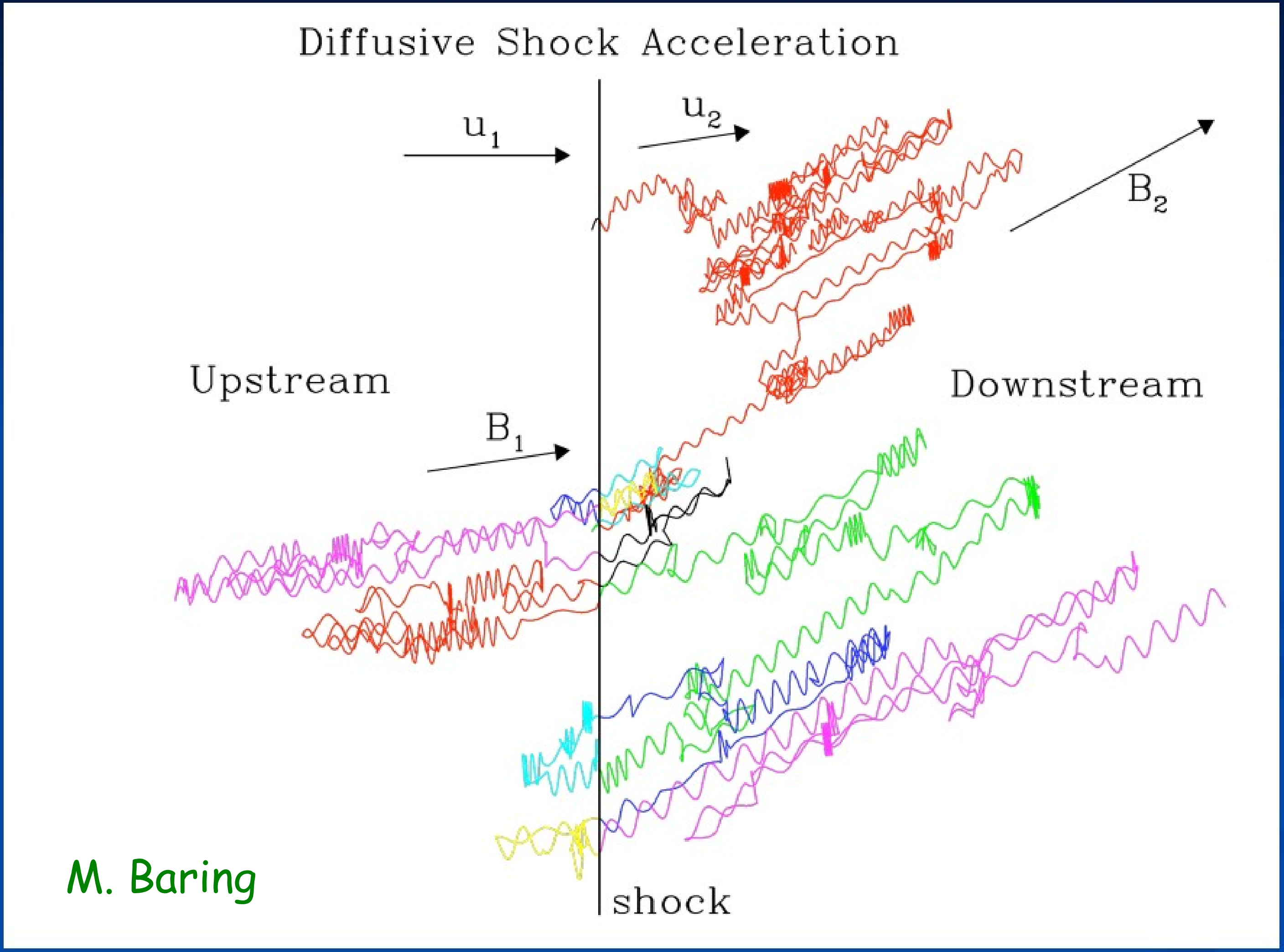
Fractional energy gain per shock crossing ~u_1-u_2 on time scale ~r_L/u_2 .

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.

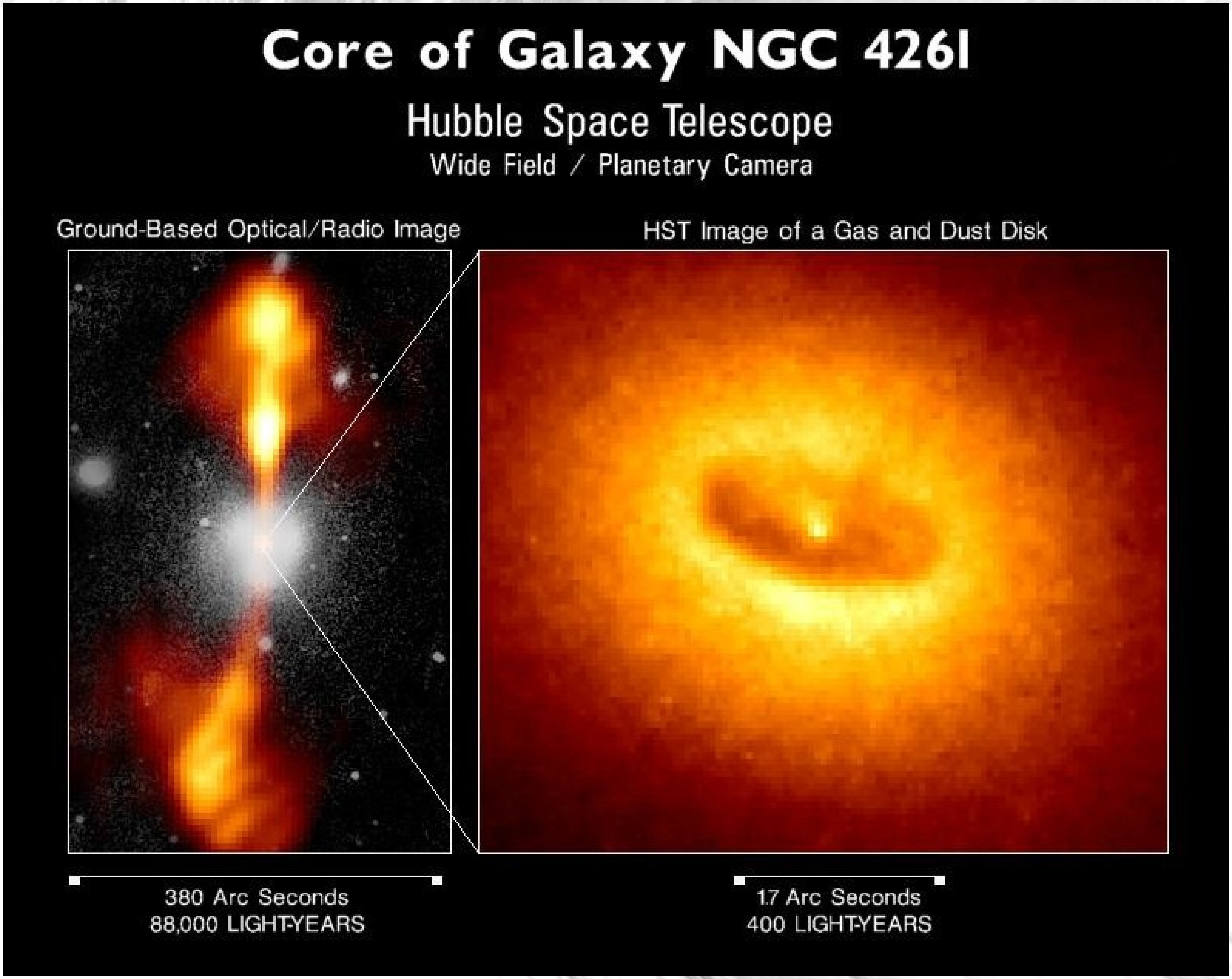


Monte Carlo Simulation Particle Trajectories

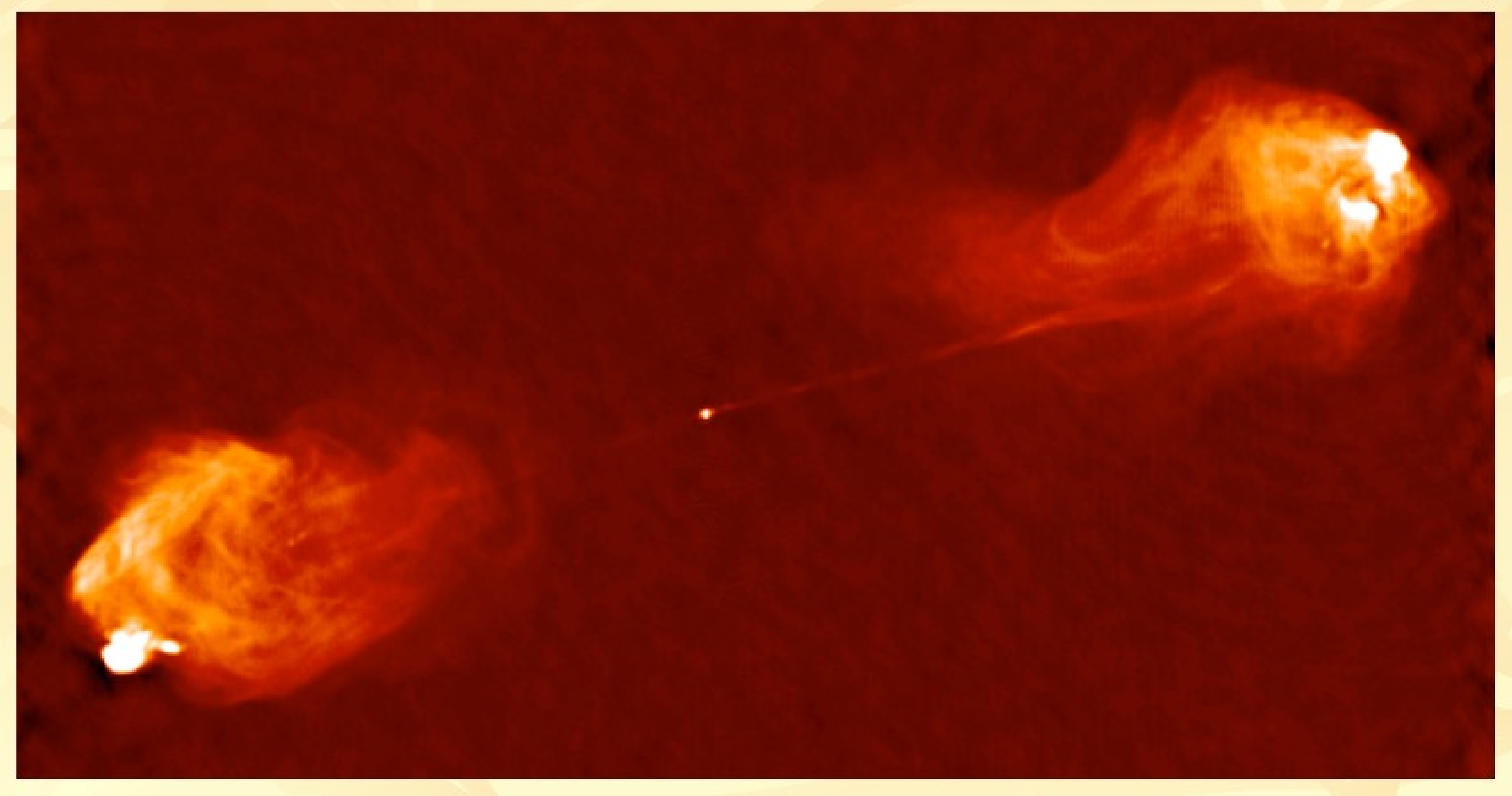


- Gyration in B-fields and diffusive transport modeled by a Monte Carlo technique; color-coded in Figure according to fluid frame energy.
- Shock crossings produce net energy gains (evident in the increase of gyroradii) according to principle of first-order Fermi mechanism.

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

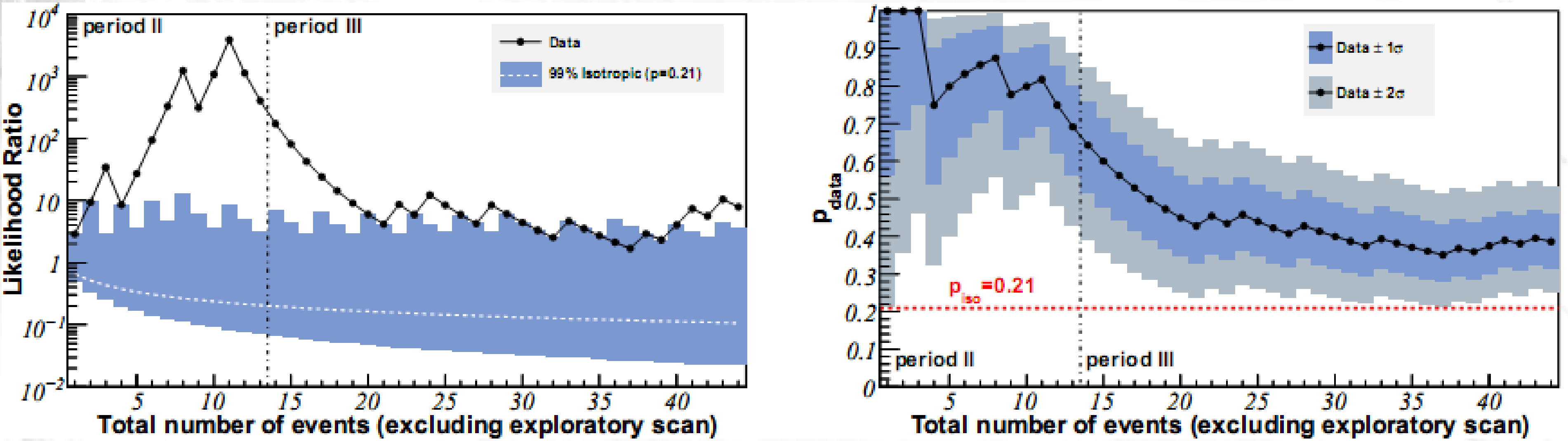


Or Cygnus A



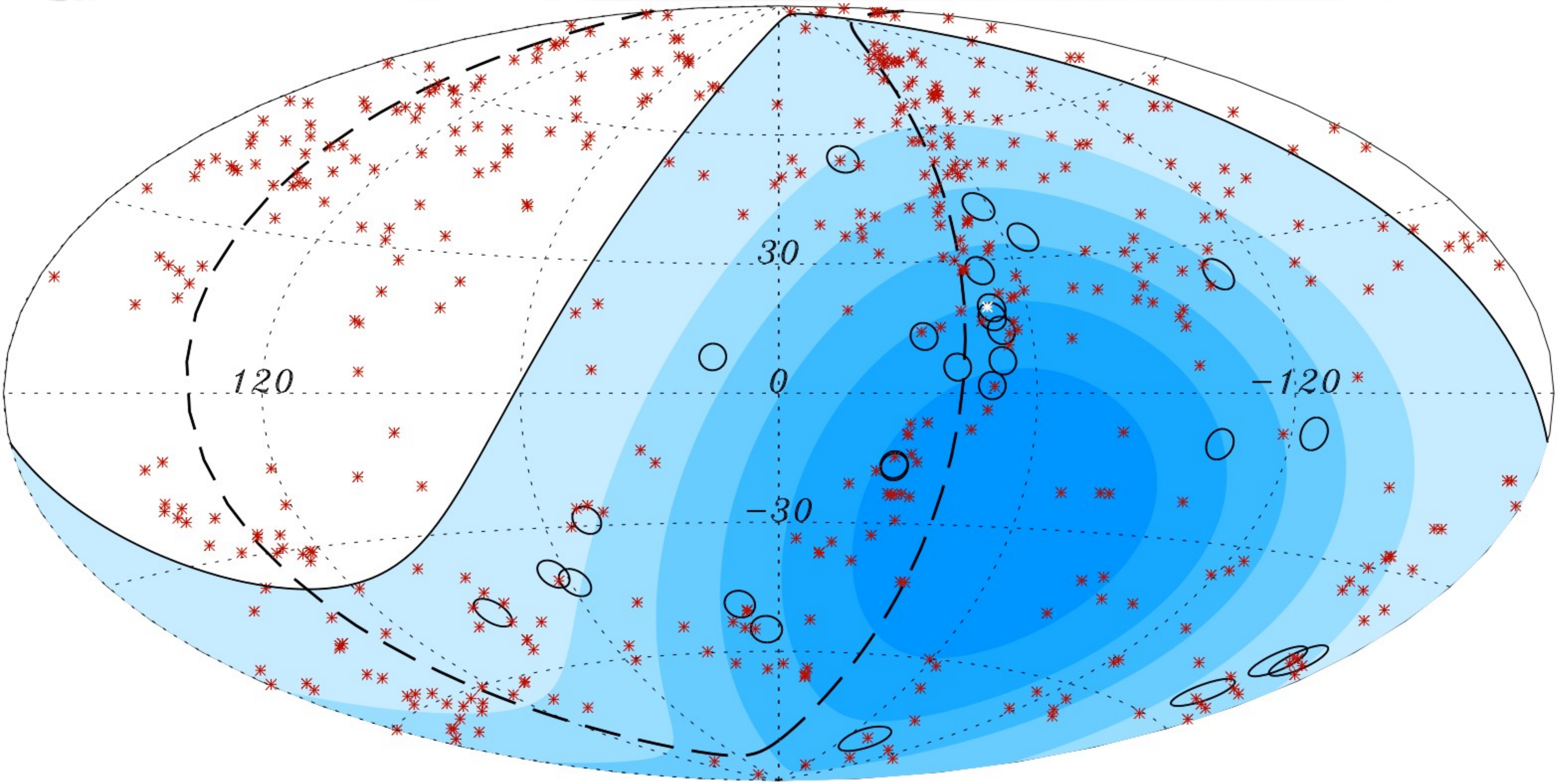
Ultra-High Energy Cosmic Ray Sources and Composition

New results from the Pierre Auger Observatory presented at the International Cosmic Ray Conference 2009 in Krakow, Poland



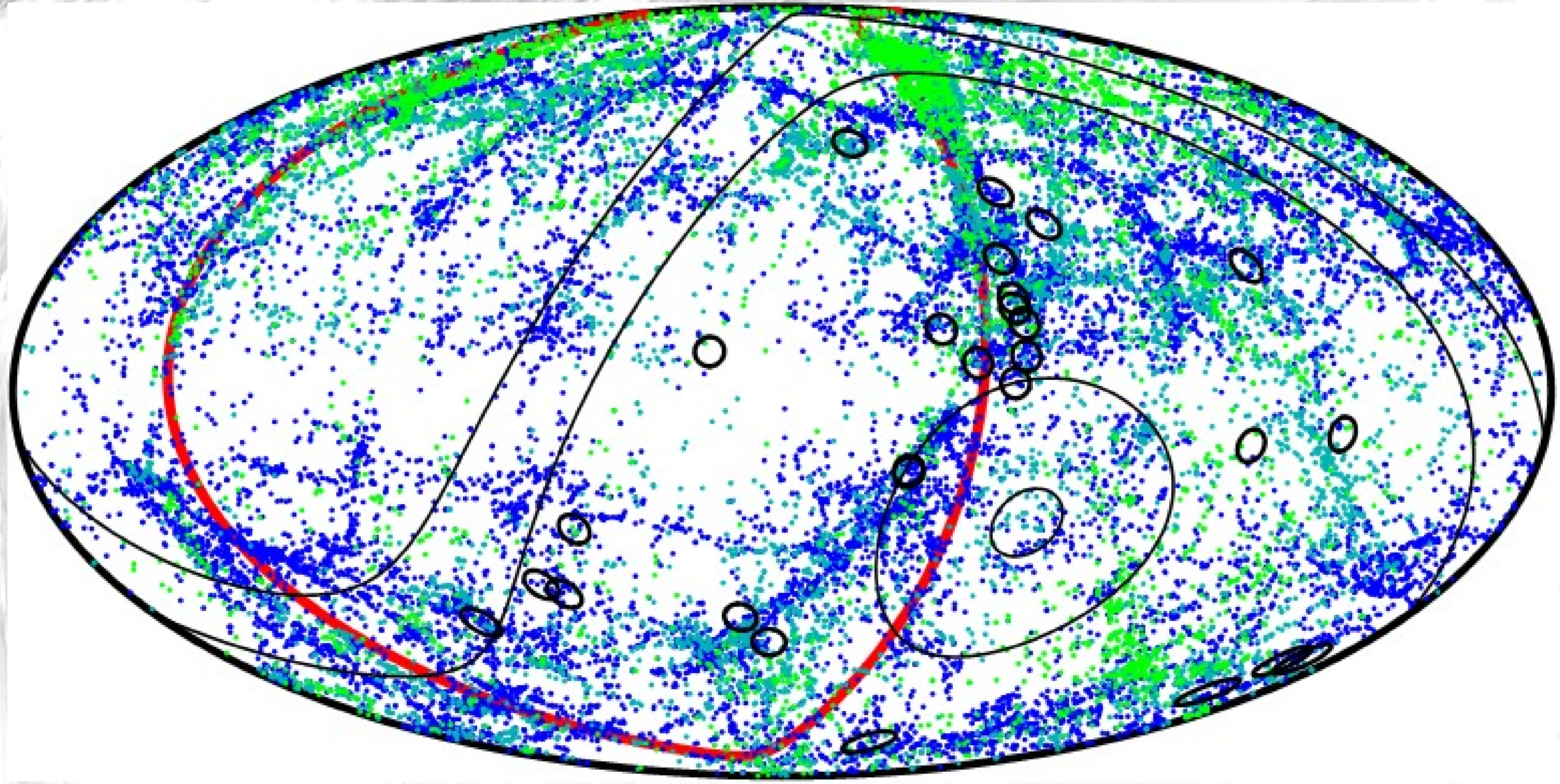
The case for anisotropy does not seem to have strengthened with more data

Auger sees Correlations with AGNs !



Red crosses = 472 AGNs from the Veron Cetty catalogue for z < 0.018
circles = 27 highest enery events above 57 EeV.
20 events correlated within 3.1°, 7 uncorrelated of which most in galactic plane

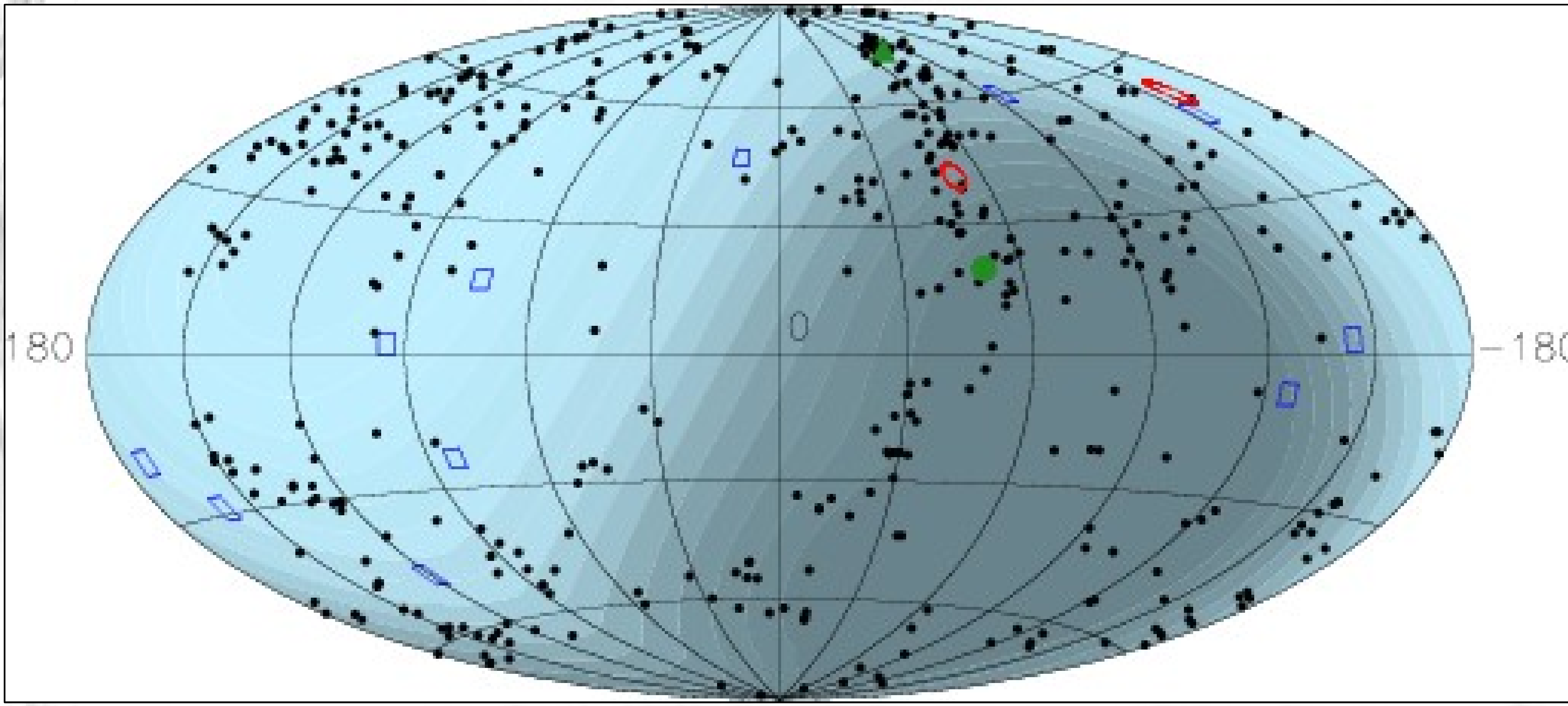
Pierre Auger Collaboration, Science 318 (2007) 938



Points = galaxies with z < 0.015
Black circles = Auger events above 60 EeV.
Black lines = equal exposure contours test
red line= supergalactic plane

Lipari, arXiv:0808.0417

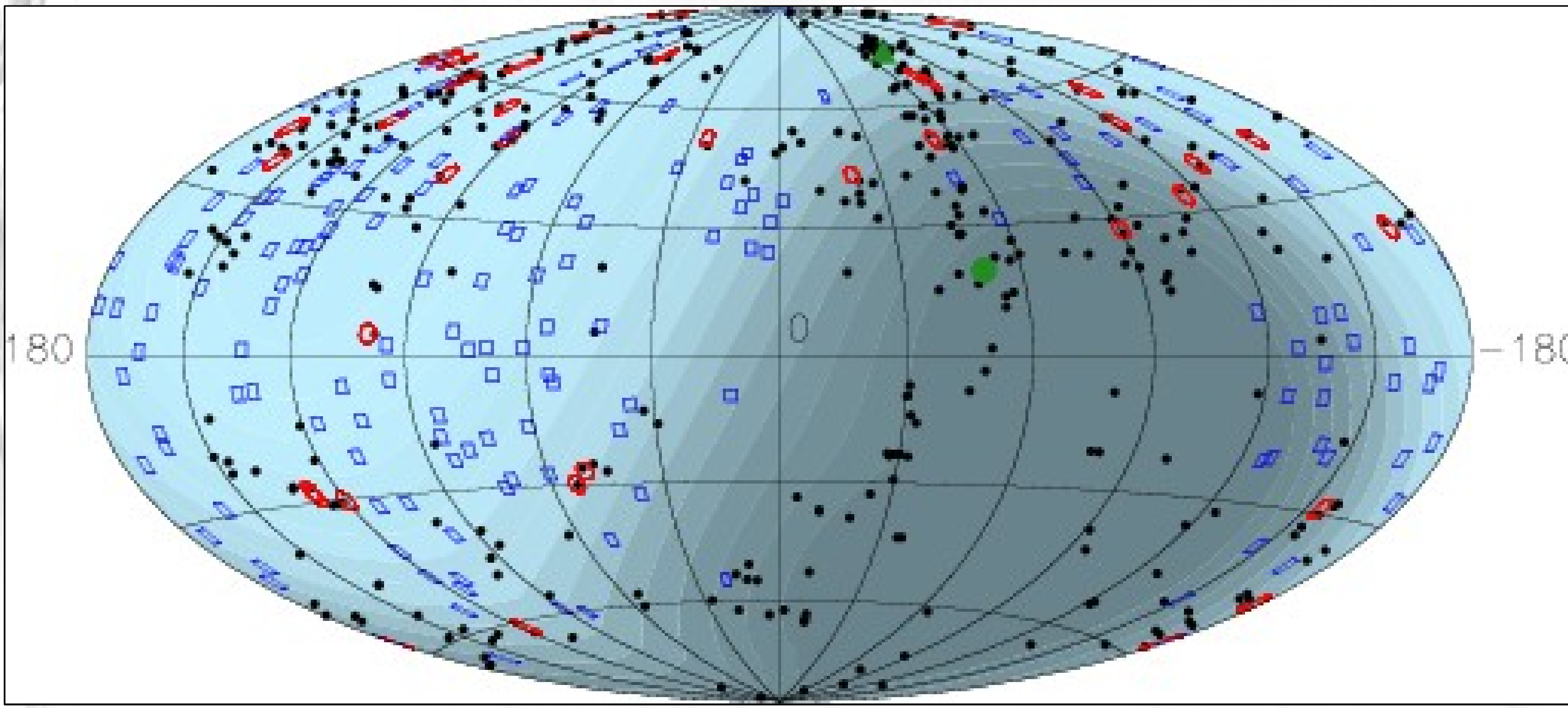
But HiRes sees no Correlations !



Black dots = 457 AGNs + 14 QSOs from the Veron Cetty catalogue for z < 0.018
red circles = 2 correlated events above 56 EeV within 3.1°,
blue squares = 11 uncorrelated events

HiRes Collaboration, arXiv:0804.0382

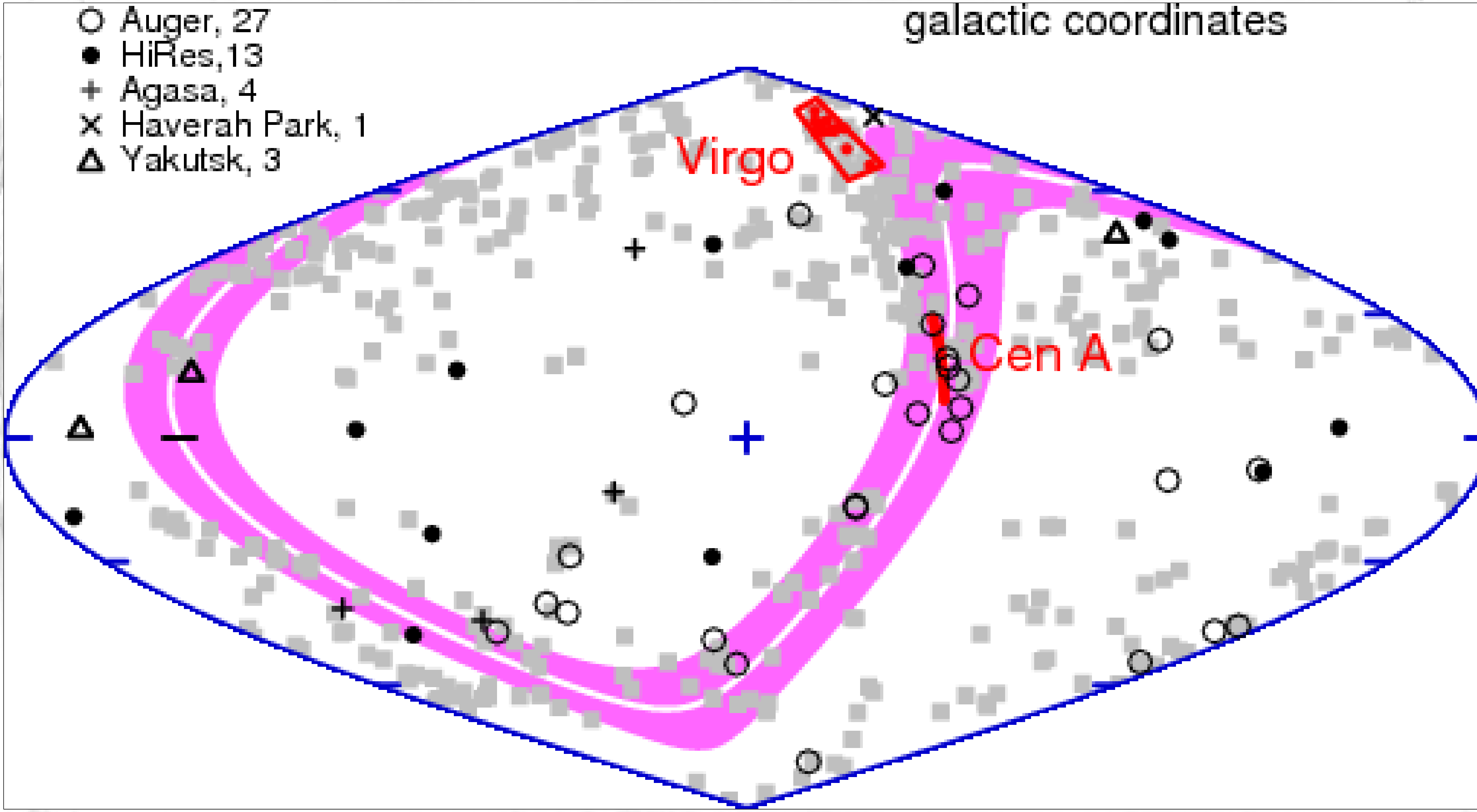
But HiRes sees no Correlations !



Black dots = 389 AGNs + 14 QSOs from the Veron Cetty catalogue for z < 0.016
red circles = 36 correlated events above 15.8 EeV within 2.0°,
blue squares = 162 uncorrelated events

HiRes Collaboration, arXiv:0804.0382

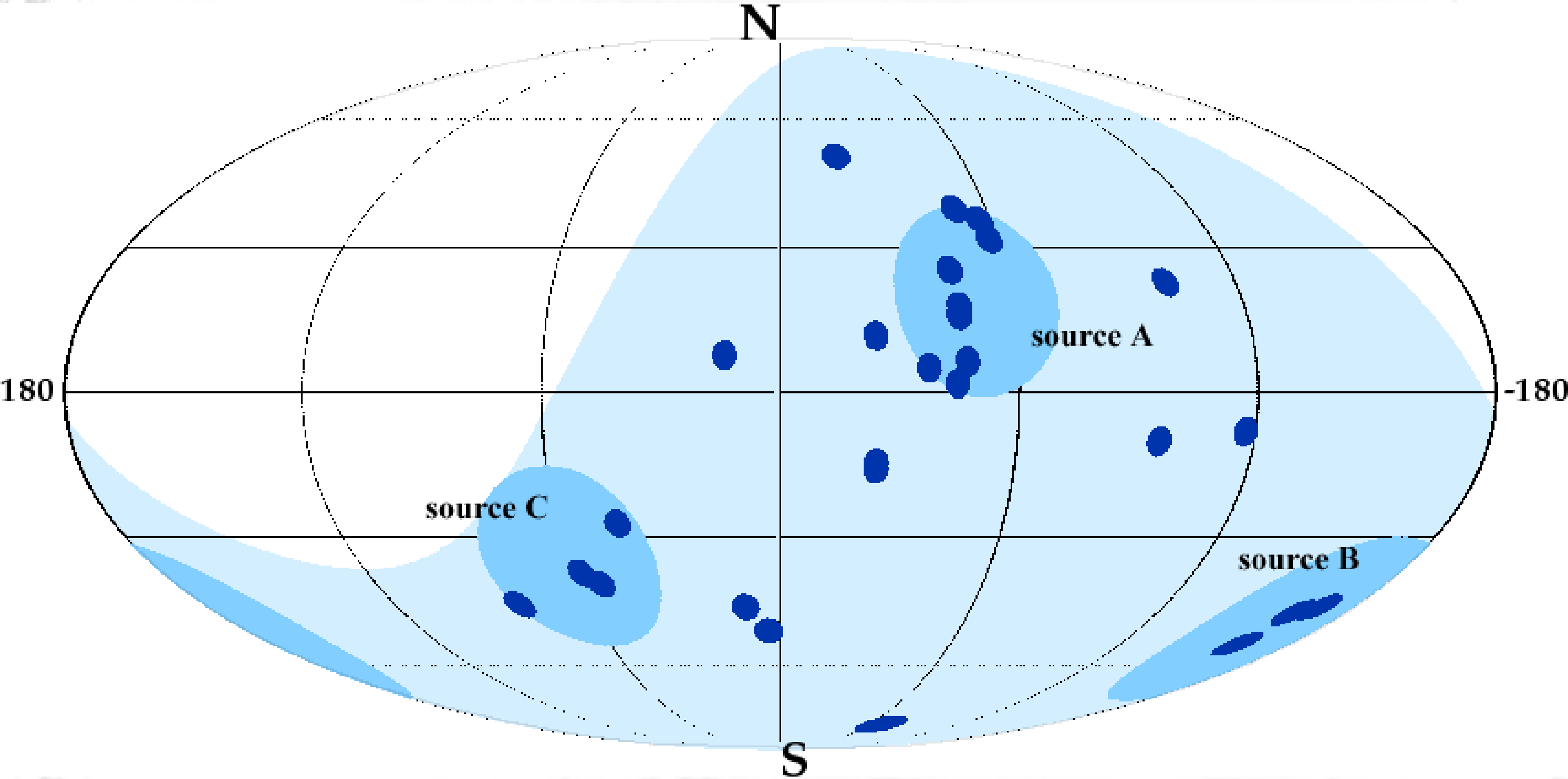
Correlation with supergalactic plane



Correlation with supergalactic plane within 10° (15°) is improved from 2.0 (2.4) sigma to 3.6 (3.2) sigma when definition relates to structure within 70 Mpc.

Stanev, arXiv:0805.1746

Are there only three sources ?



Wibig and Wolfendale, arXiv:0712.3403

Some general estimates for sources

Accelerating particles of charge eZ to energy E_{max} requires induction $\varepsilon > E_{max}/eZ$. With $Z_0 \sim 100\Omega$ the vacuum impedance, this requires dissipation of minimum bolometric power of (Lovelace, Blandford, ..)

$$L_{\min} \approx \epsilon^2 / Z_0 \approx 10^{45} Z^{-2} \left(\frac{E_{\max}}{10^{20}\,\mathrm{eV}} \right)^2 \mathrm{erg\,s^{-1}}$$

This „Poynting" luminosity can also be obtained from $L_{min} \sim (BR)^2$ where BR is given by the „Hillas criterium":

$$BR \; > \; 3 \times 10^{17}\, \Gamma^{-1} \left(\frac{E_{\max}}{10^{20}\,\mathrm{eV}} \right) \mathrm{Gauss\,cm}$$

Where Γ is a possible beaming factor.
If most of this goes into electromagnetic channel, only AGNs and maybe gamma-ray bursts could be consistent with this.

In arXiv:1003.2500 Hardcastle estimates a corresponding lower limit on the radio luminosity:

$$L_{408\,\mathrm{Hz}} > 2\times10^{24}\,\epsilon\left(\frac{E/Z}{10^{20}\,\mathrm{eV}}\right)^{7/2}\left(\frac{r_{\mathrm{lobe}}}{100\,\mathrm{kpc}}\right)^{-1/2}\mathrm{W\,Hz}^{-1}$$

For an E^{-2} electron spectrum
with ε = energy in electrons / energy in magnetic field

He concludes: if protons, then very few sources which should be known and spectrum should cut off steeply at observed highest energies

If heavier nuclei then there are many radio galaxy sources but only Cen A may be identifiable

Further Curiosities in the Sky Distributions

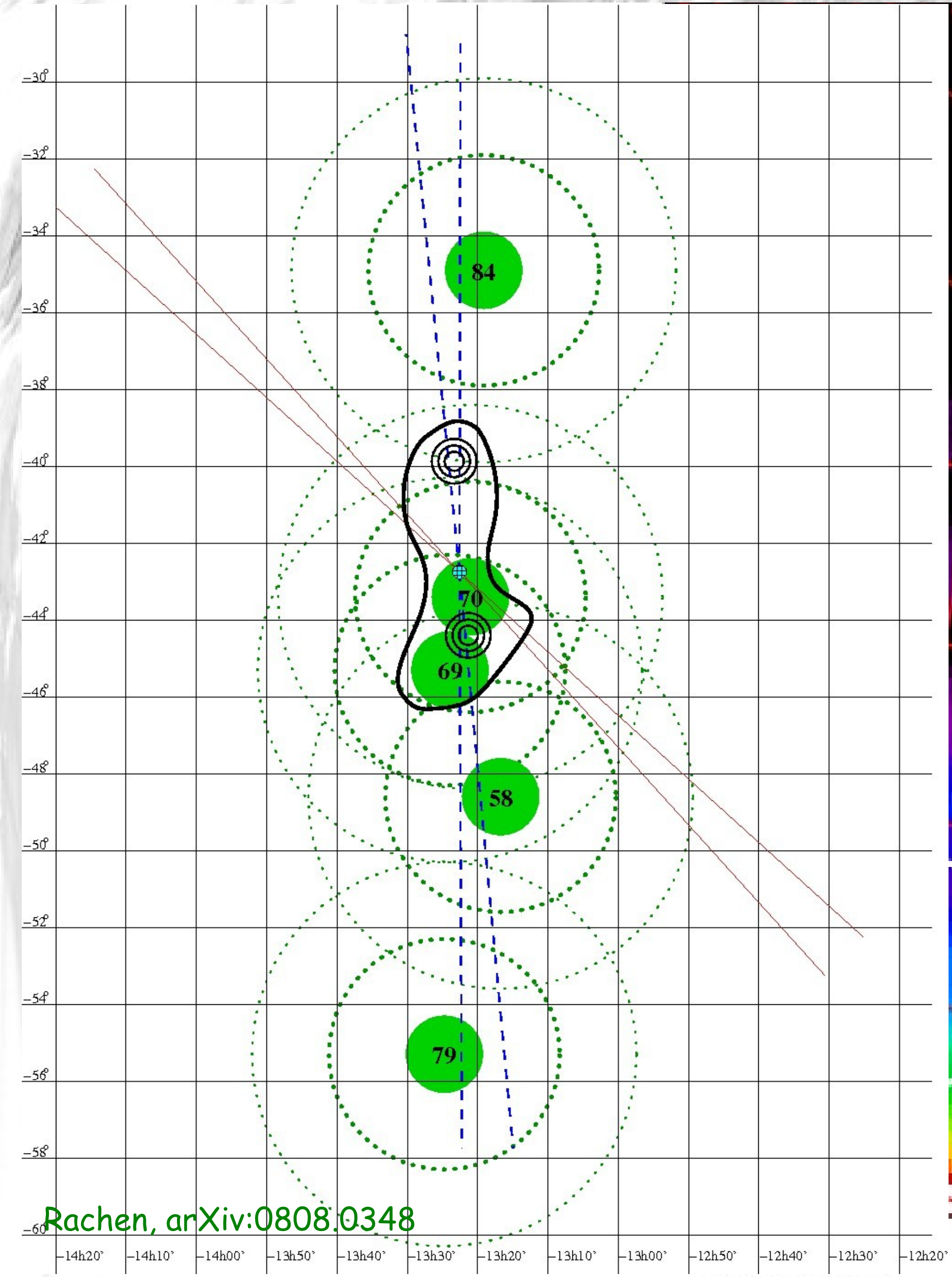
too few events from Virgo cluster, see
Gorbunov et al., JETP Lett. 87 (2007) 461

too many events from Centaurus A, e.g. Moskalenko et al., arXiv:0805.1260; Rachen, arXiv:0808.0348.

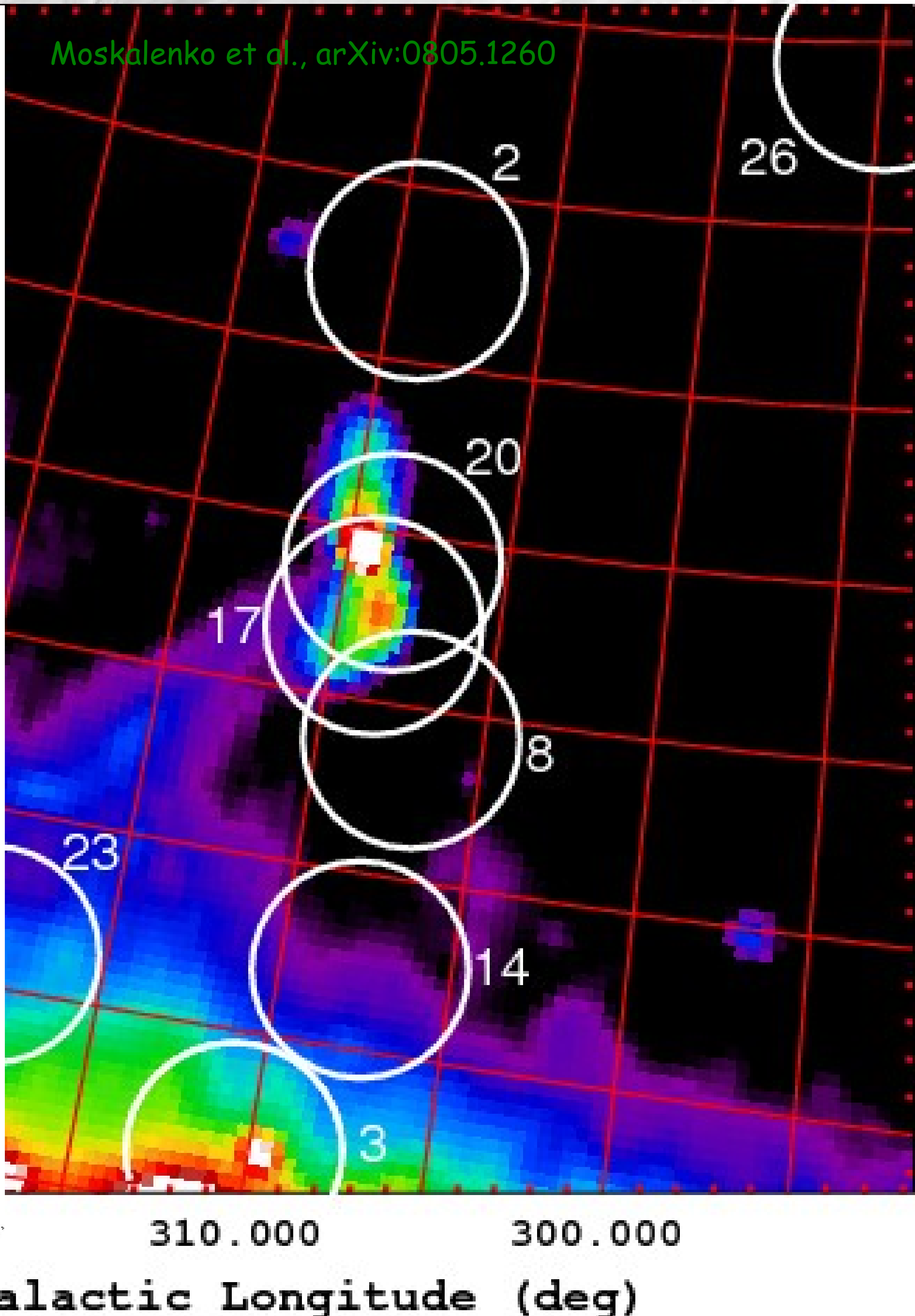
The AGNs with which Auger events correlate are not thought to be strong enough, see Moskalenko et al., arXiv:0805.1260; Zaw, Farrar, Greene, arXiv:0806.3470 (the latter arguing for flares)

According to Gureev and Troitsky, arXiv:0808.0481, the correlation of Auger events with AGNs is stronger when nearest neighbor sources only are counted, than when all AGN within given off-set are counted. According to them, this reveals individual sources rather than the population.

Centaurus A

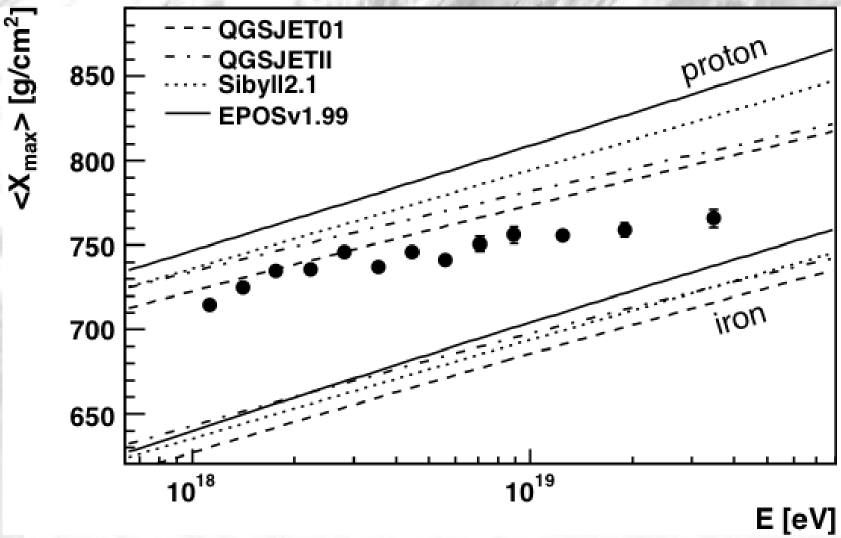


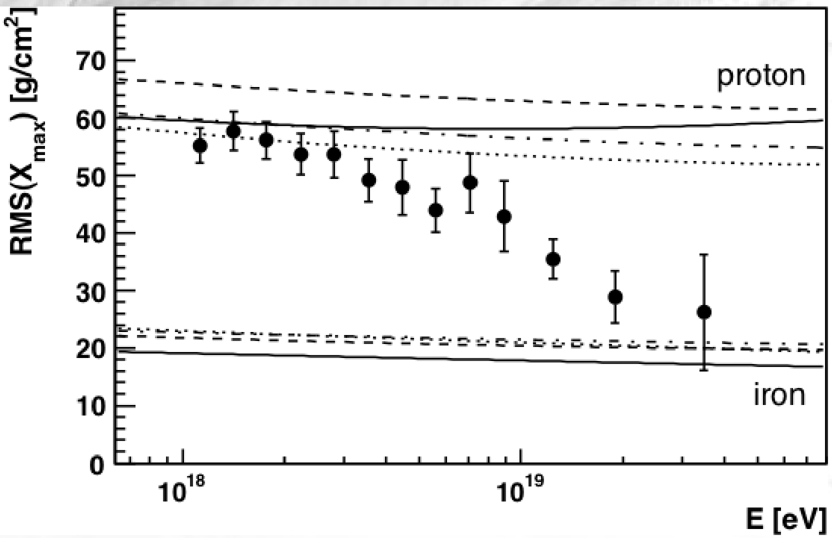
Rachen, arXiv:0808.0348
84
70
69
58
79
−30°
−32°
−34°
−36°
−38°
−40°
−42°
−44°
−46°
−48°
−50°
−52°
−54°
−56°
−58°
−60°
14h20'
14h10'
14h00'
13h50'
13h40'
13h30'
13h20'
13h10'
13h00'
12h50'
12h40'
12h30'
12h20'

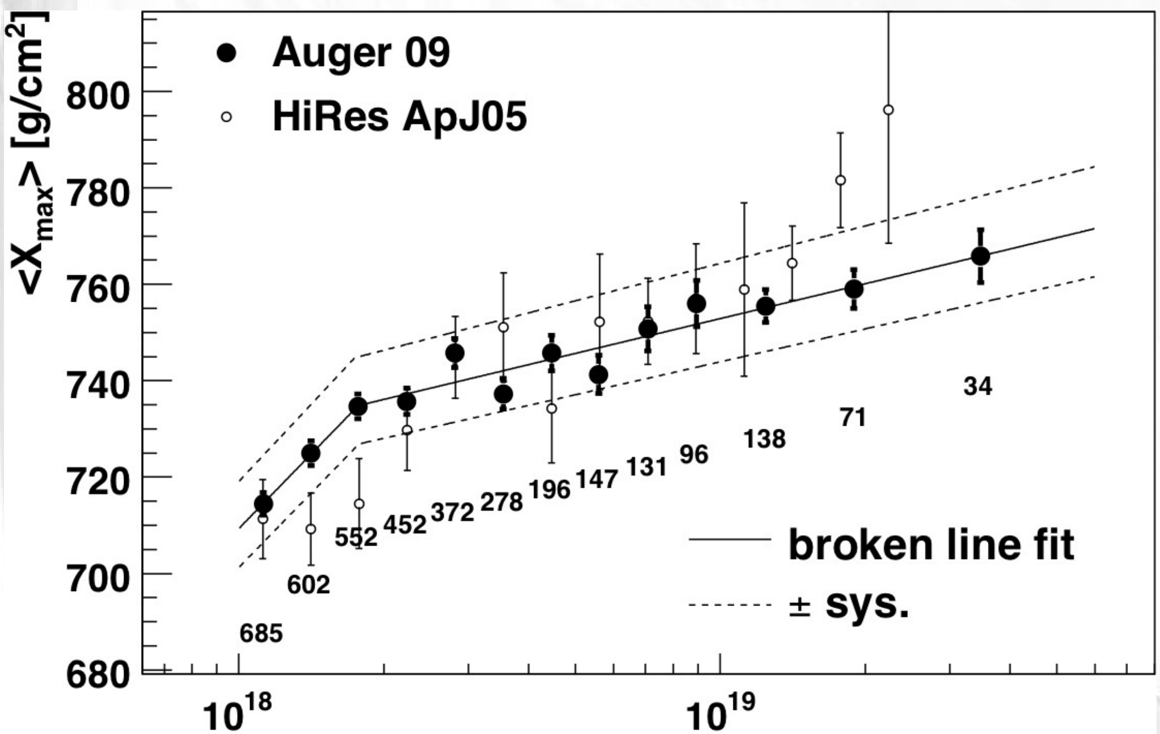


Moskalenko et al., arXiv:0805.1260
2
26
20
17
8
23
14
3
310.000
300.000
Galactic Longitude (deg)

There may be a significant heavy component at the highest energies:

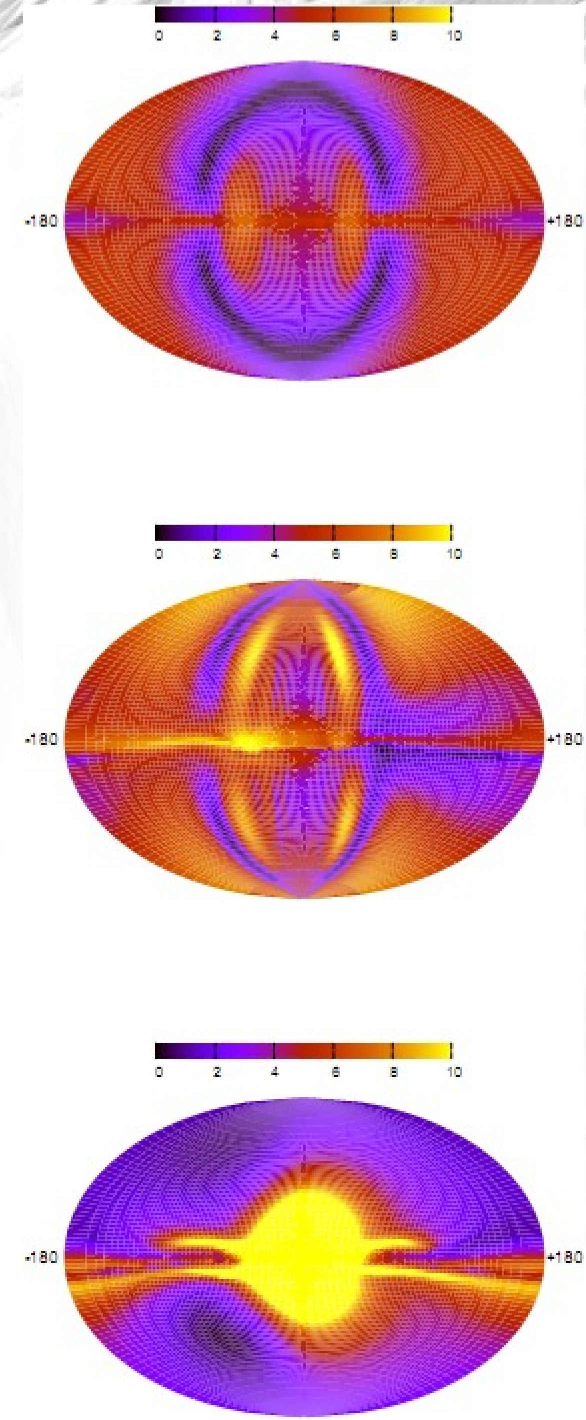






Auger data on composition seem to point to a quite heavy composition at the highest energies, whereas HiRes data seem consistent with a light composition.

Pierre Auher Collaboration, Phys.Rev.Lett., 104 (2010) 091101



Consequences for Galactic Deflection

Deflection in **galactic magnetic field** is rather model dependent, here for $E/Z=4\ 10^{19}$ eV for Models of

Tinyakov, Tkachev (top)

Harrari, Mollerach, Roulet (middle)

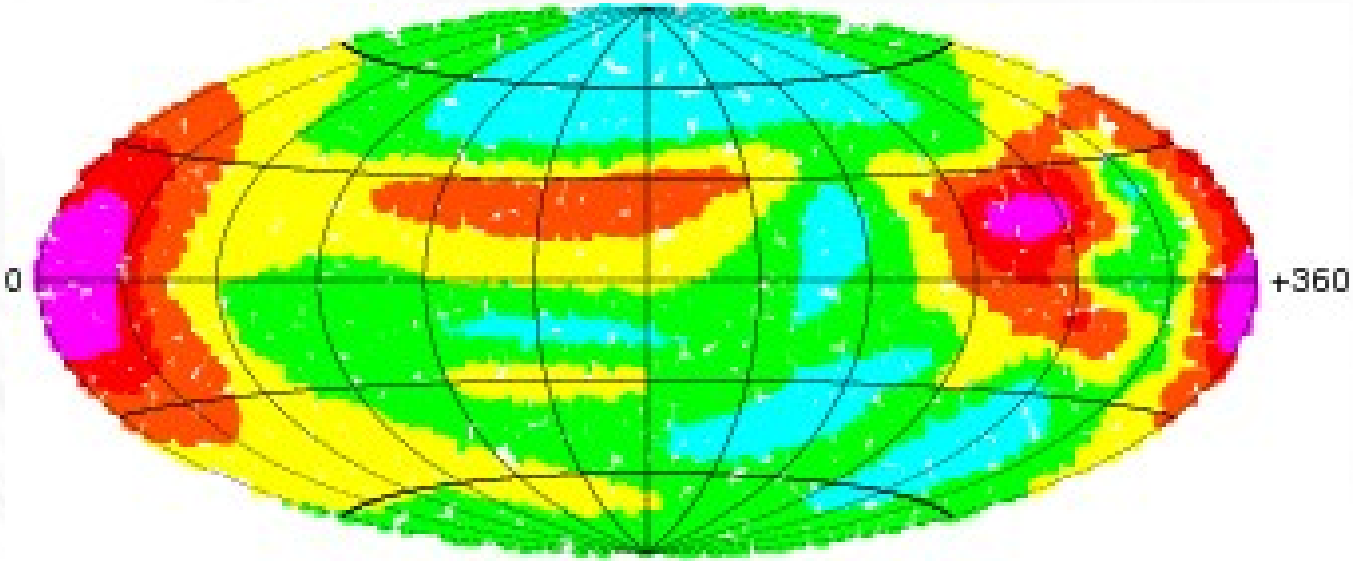
Prouza, Smida (bottom)

Deflection in **extragalactic fields** is even more uncertain

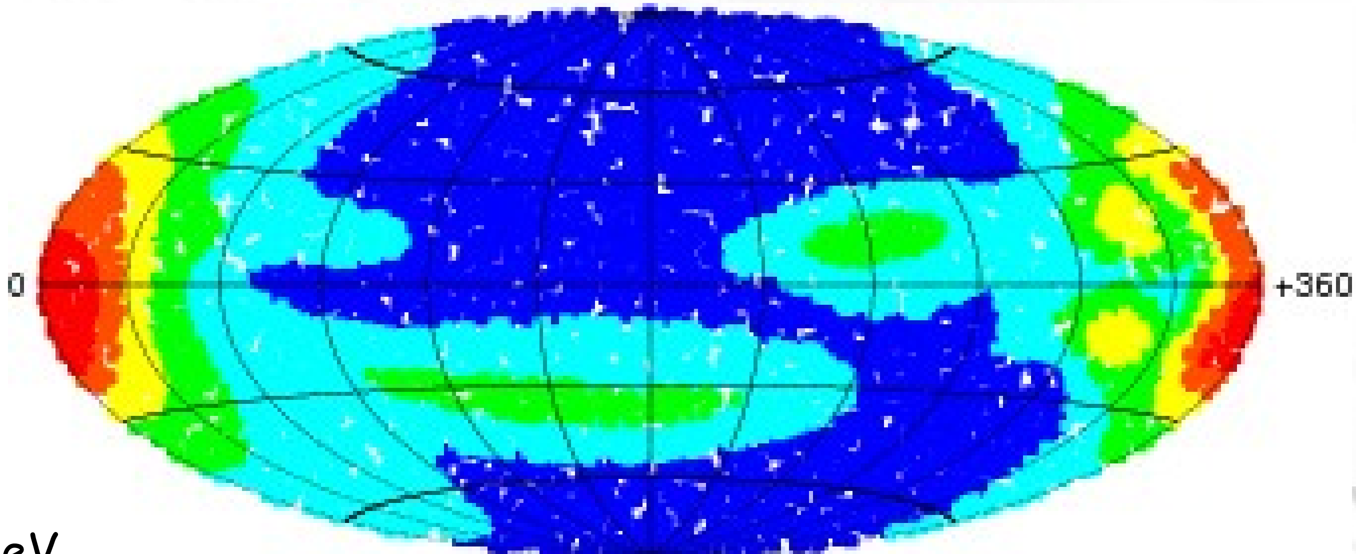
Kachelriess, Serpico, Teshima Astropart. Phys. 26 (2006) 378

Deflection of iron in galactic magnetic field model of Prouza&Smida

Angular range between 0 and 100 degrees, galactic coordinates



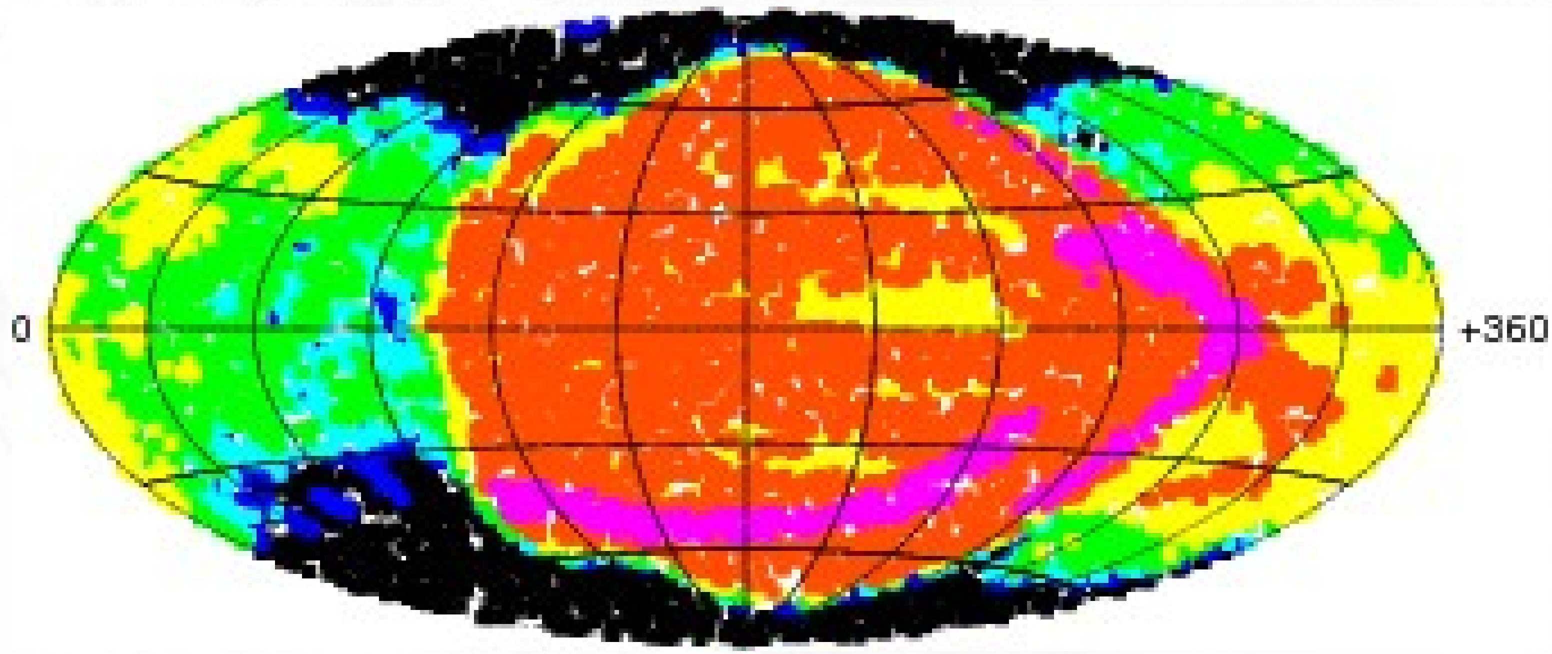
E=60 EeV



E=140 EeV

Giacinti, Kachelriess, Semikoz, Sigl, arXiv:1006.5416

Bachtracking of iron in galactic magnetic field model of Prouza&Smida



E=60 EeV

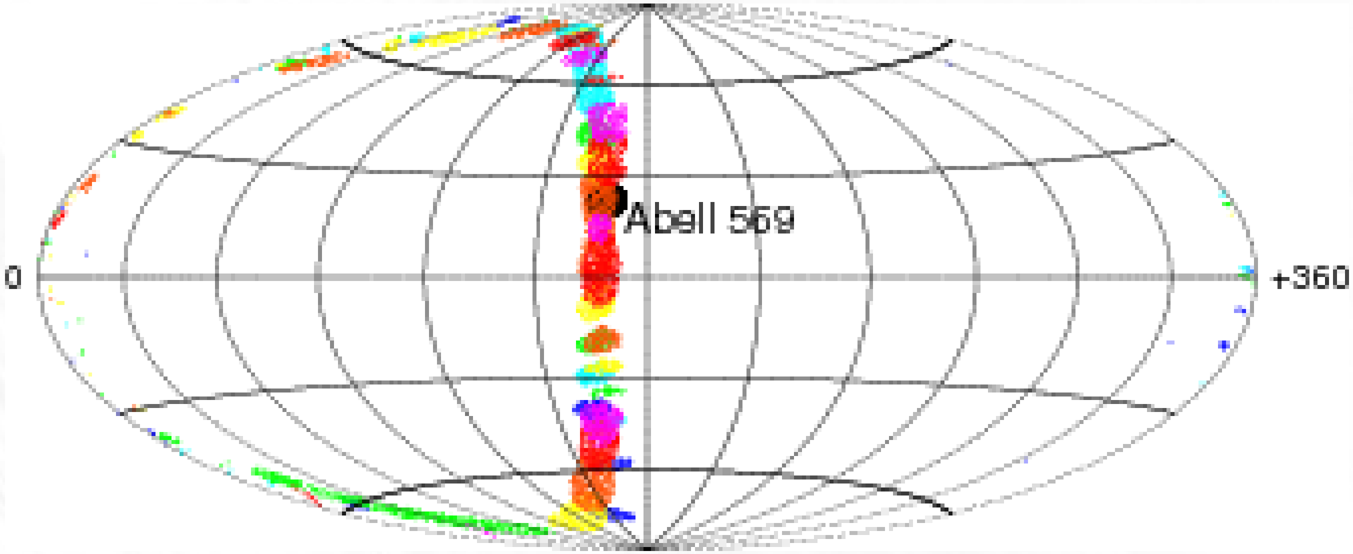
Giacinti, Kachelriess, Semikoz, Sigl, arXiv:1006.5416

Density range between 10^{-3} and $10^{0.5}$, galactic coordinates

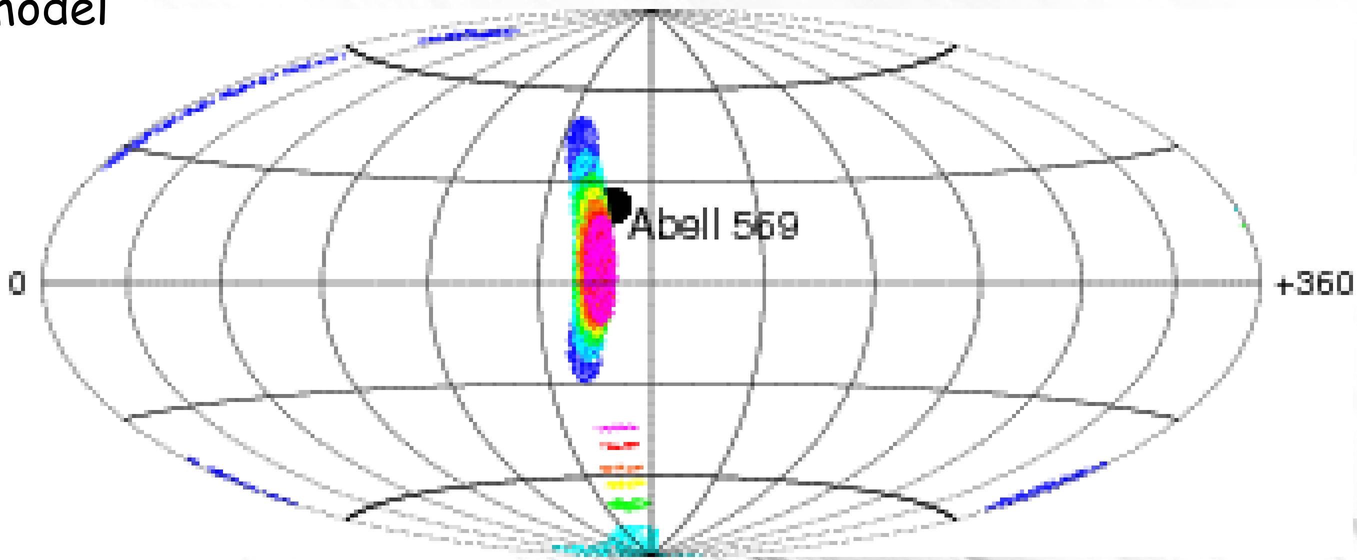
Highly anisotropic picture
Empty backtracked regions are invisible from within the Galaxy !

“Iron Image” of galaxy cluster Abell0569 in two galactic field models

Energy range from 60 to 140 EeV



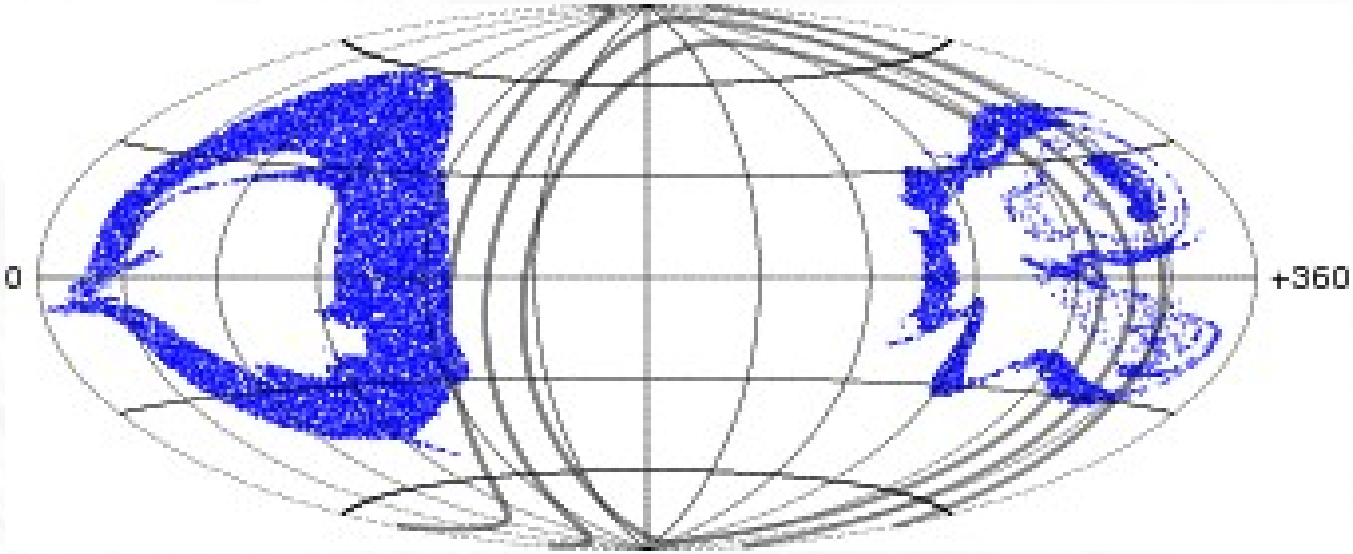
Sun08 model



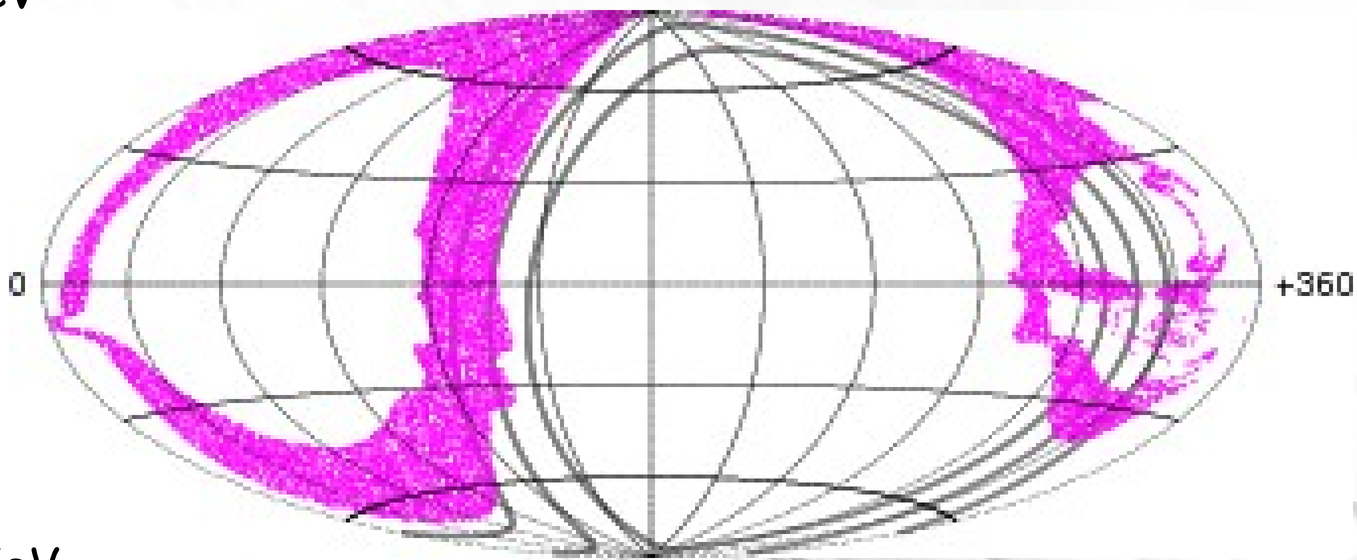
Sun08 modified halo model

Giacinti, Kachelriess, Semikoz, Sigl, arXiv:1006.5416

"Iron image" of supergalactic plane in galactic magnetic field model of Prouza&Smida



E=60 EeV



E=140 EeV

Giacinti, Kachelriess, Semikoz, Sigl, arXiv:1006.5416

“Conundrum”:

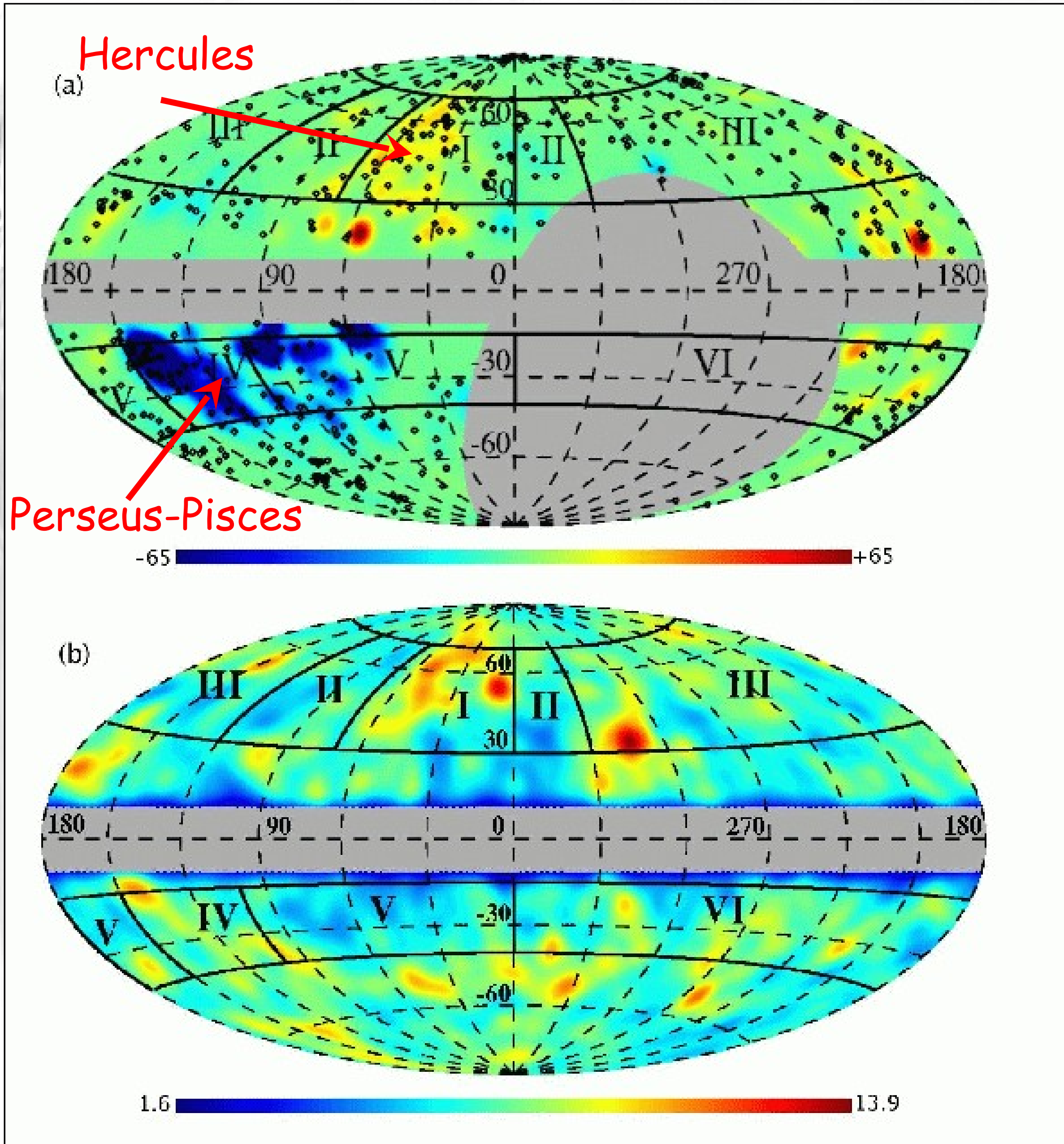
If deflection is small and sources follow the local large scale structure then

a) primaries should be protons to avoid too much deflection in galactic field

b) but air shower measurements by Pierre Auger (but not HiRes) indicate mixed or heavy composition

c) Theory of AGN acceleration seem to necessitate heavier nuclei to reach observed energy

Propagation in structured extragalactic magnetic fields



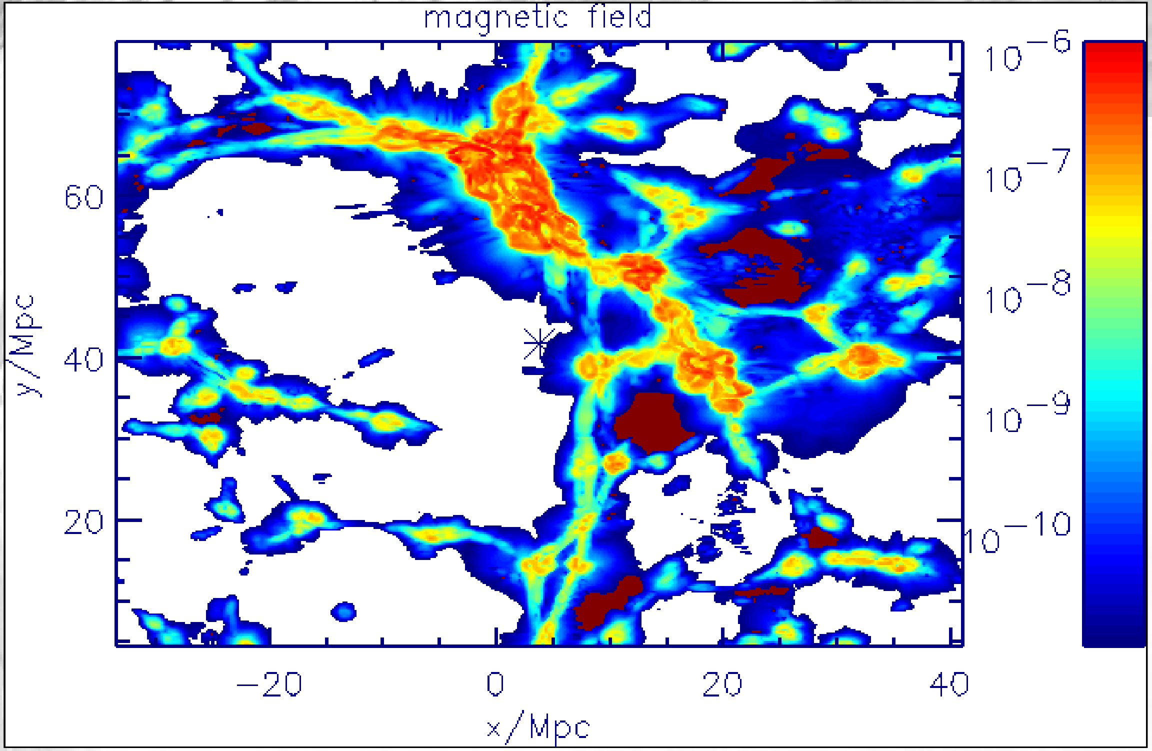
Smoothed rotation measure:
Possible signatures of ~0.1μG level on super-cluster scales!

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

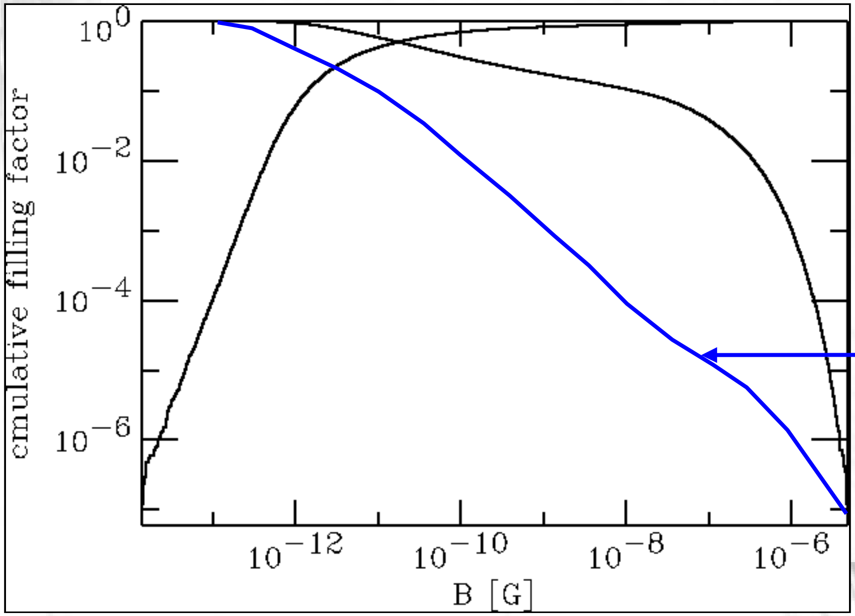
But need much more data from radio astronomy, e.g. Lofar, SKA

2MASS galaxy column density

Xu et al., astro-ph/0509826



Observer immersed in fields of ~10^{-11} Gauss:
Cut thru local magnetic field strength

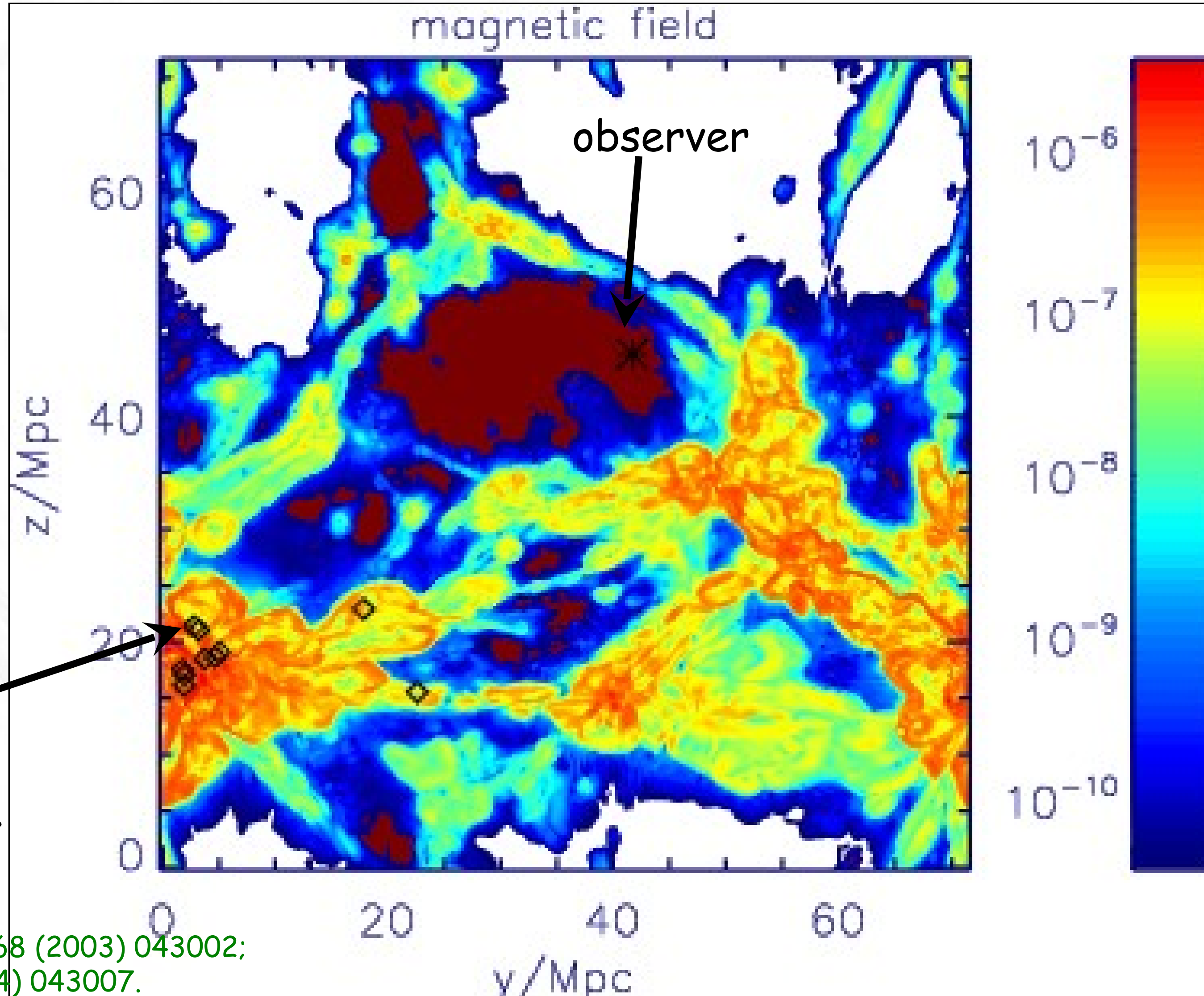


Filling factors of magnetic fields from the large scale structure simulation.

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

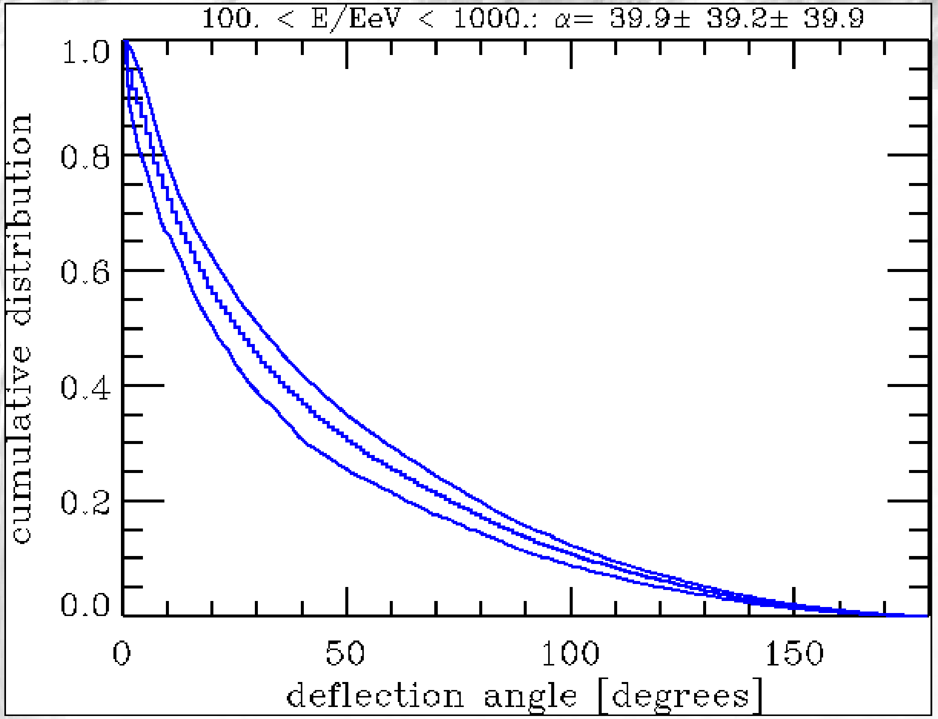
Sigl, Miniati, Ensslin, Phys.Rev.D 68 (2003) 043002; astro-ph/0309695; PRD 70 (2004) 043007.

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



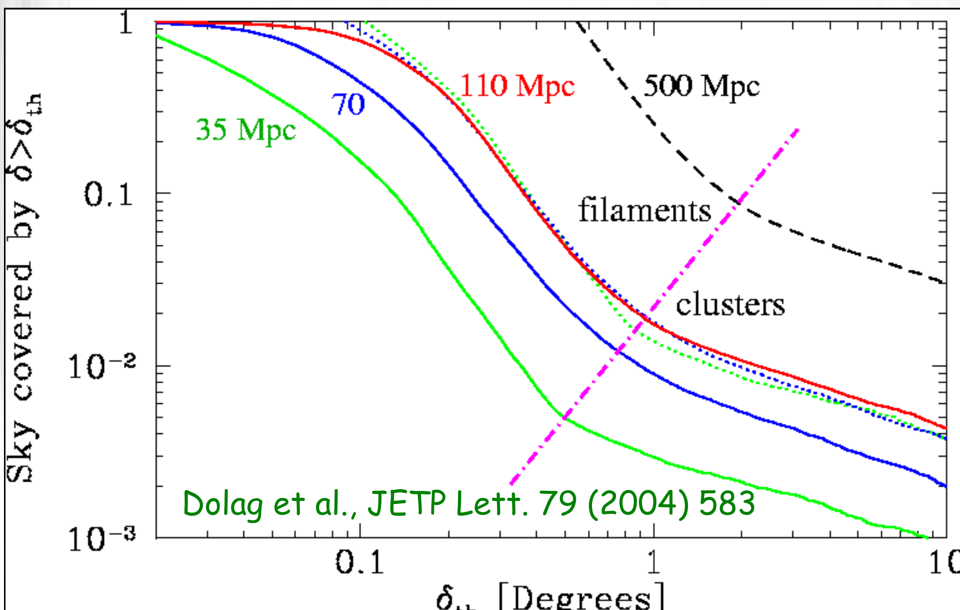
Discrete sources of density ~10^{-5} Mpc^{-3} follow baryon density, field at Earth ~10^{-11} G.

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

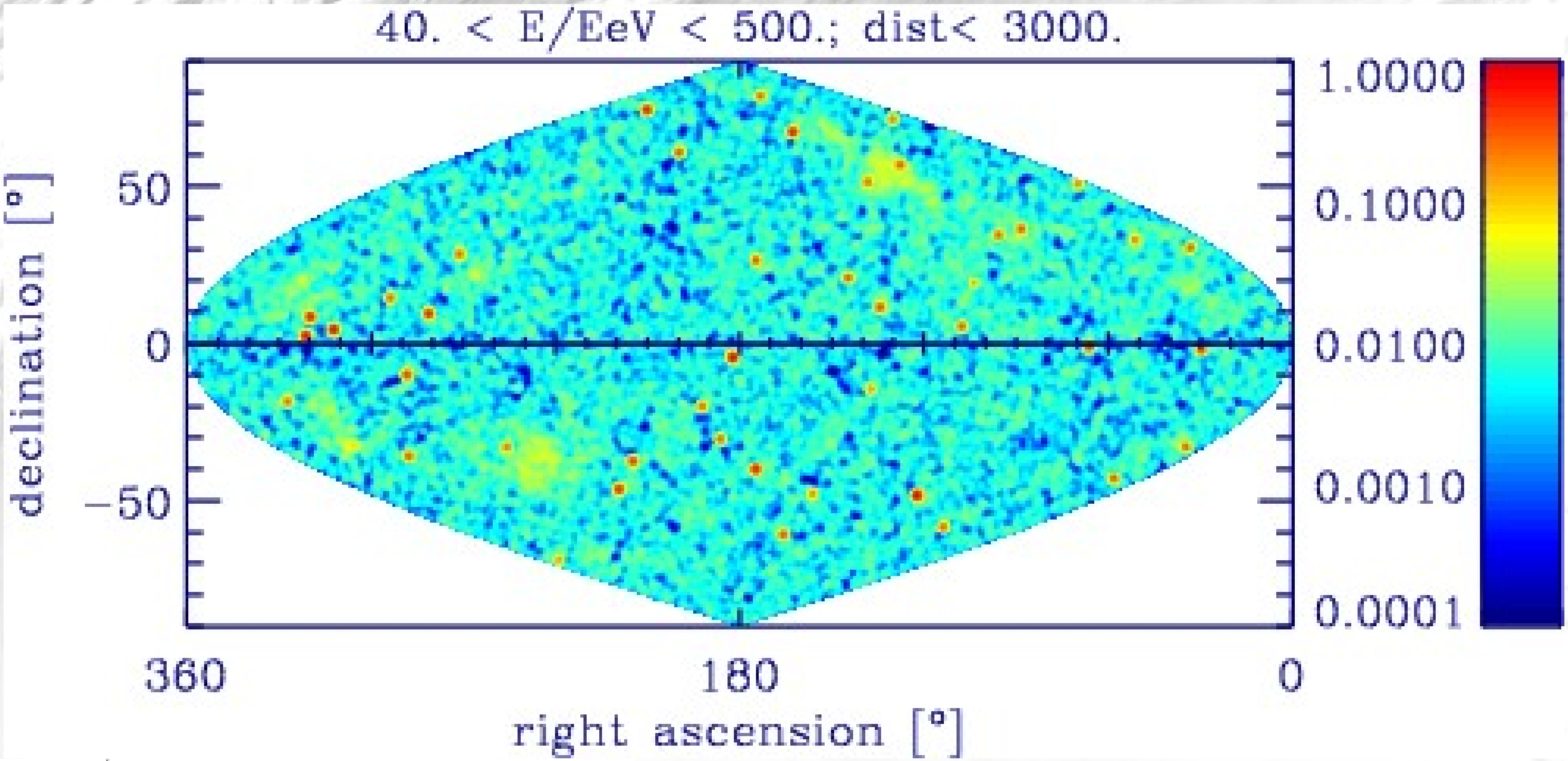


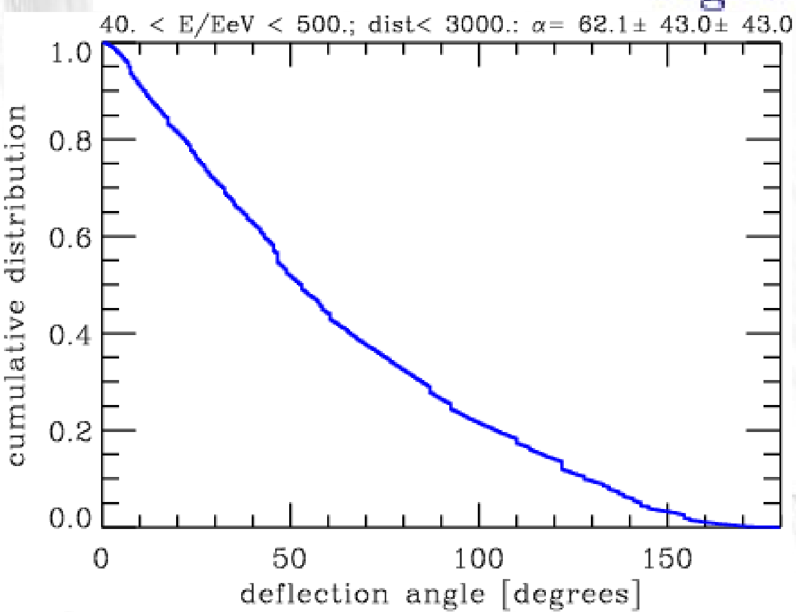
Deflection in magnetized structures surrounding the sources lead to off-sets of arrival direction from source direction up to >10 degrees up to 10^{20} eV in our simulations. This is contrast to Dolag et al., JETP Lett. 79 (2004) 583.

Particle astronomy not necessarily possible, especially for nuclei !

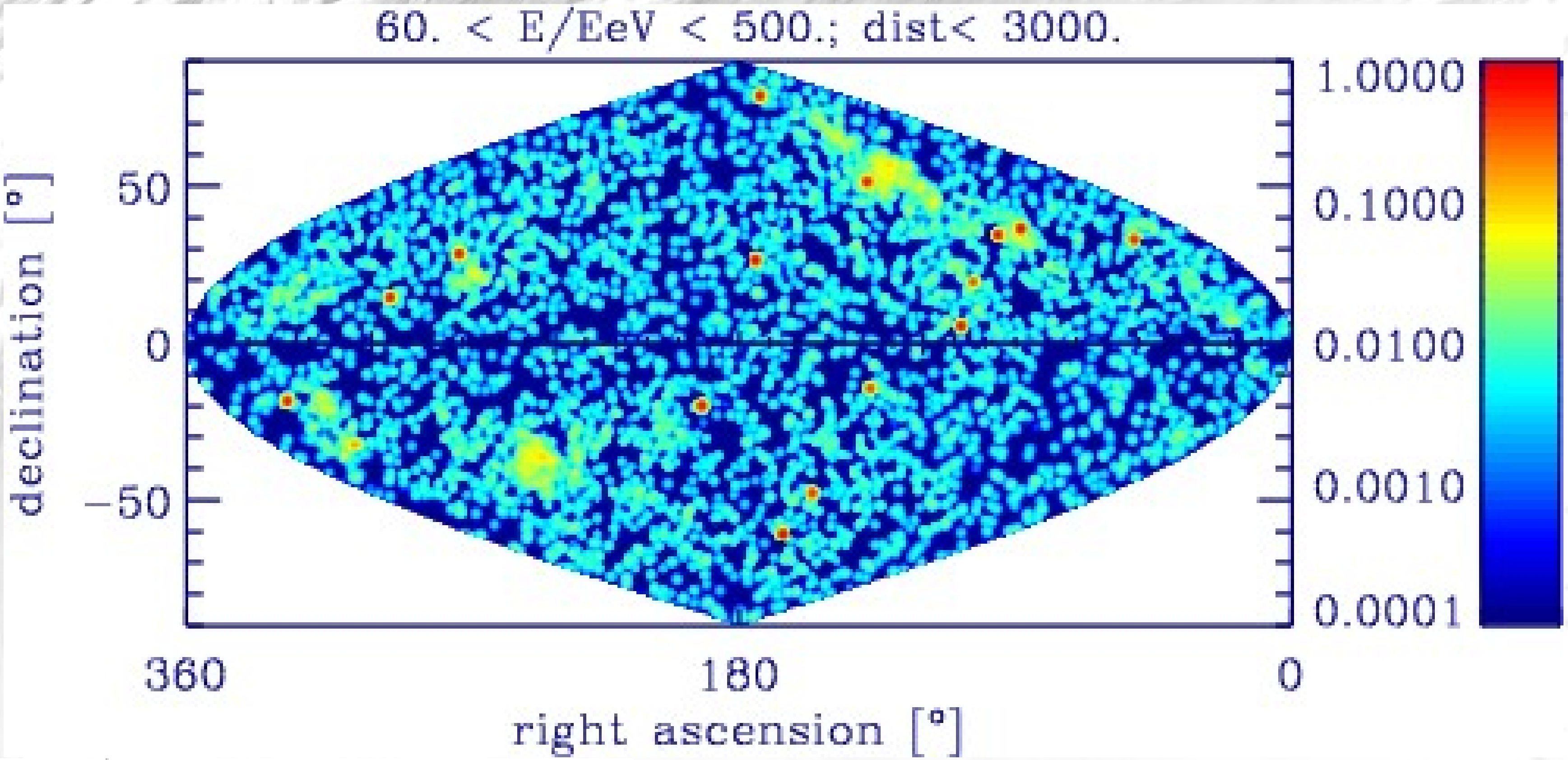


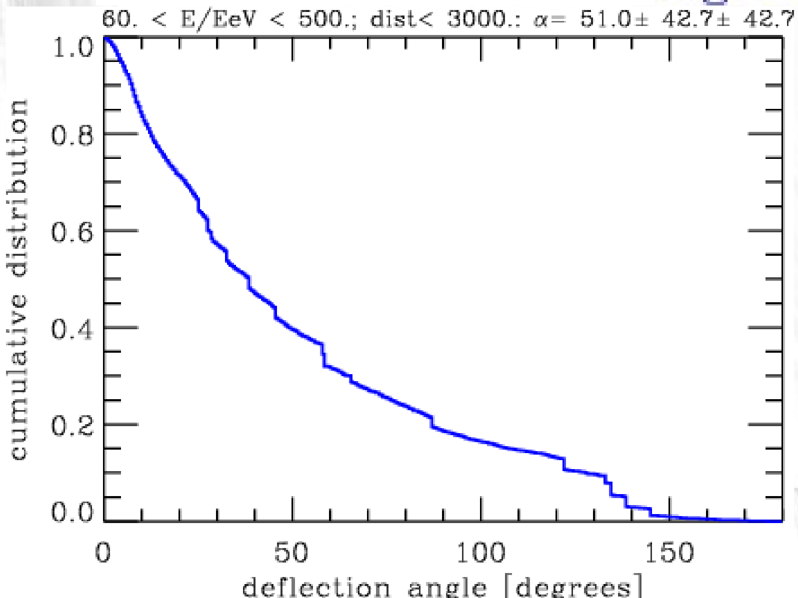
Cumulative deflection angle distributions for proton primaries



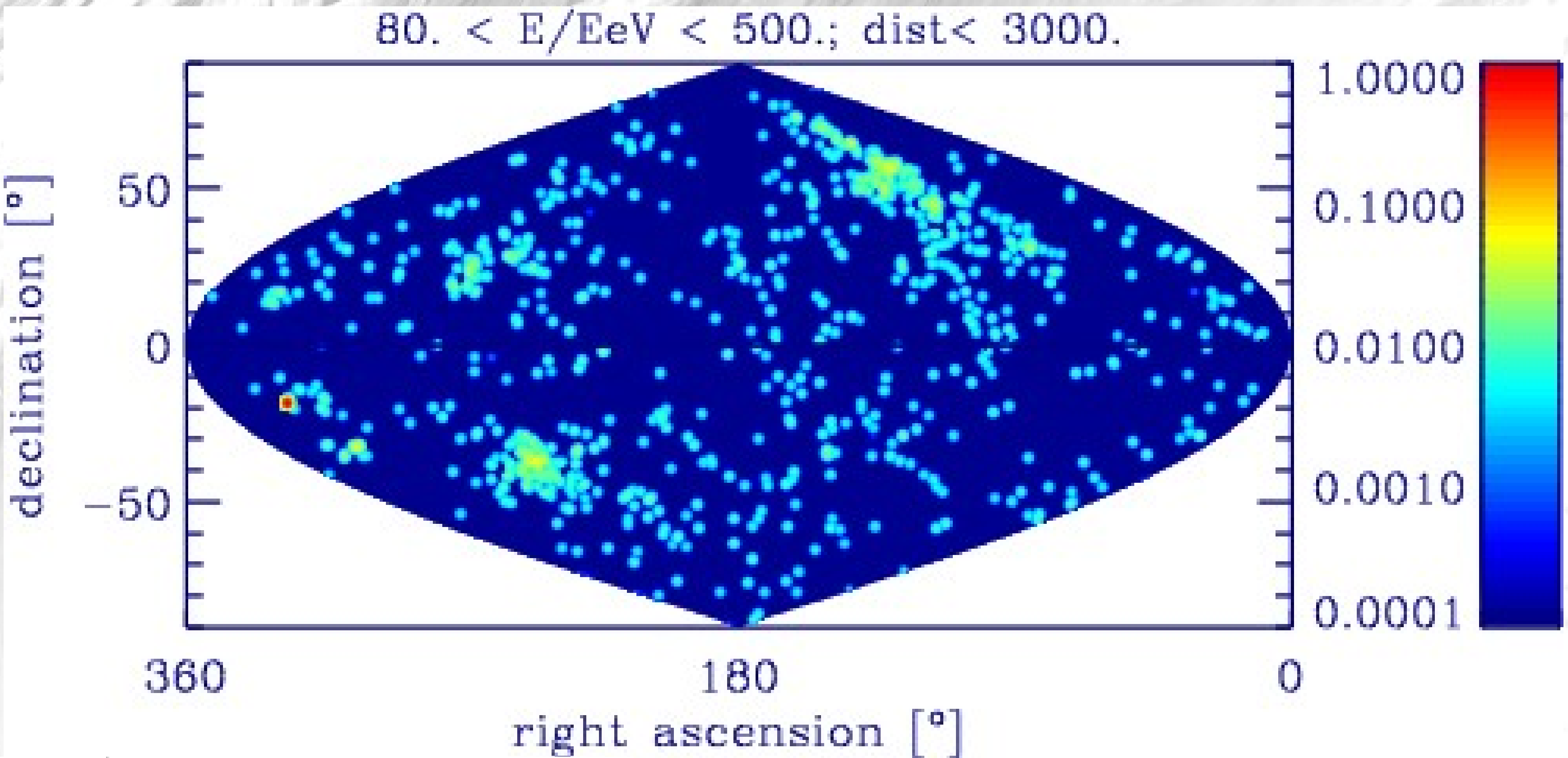


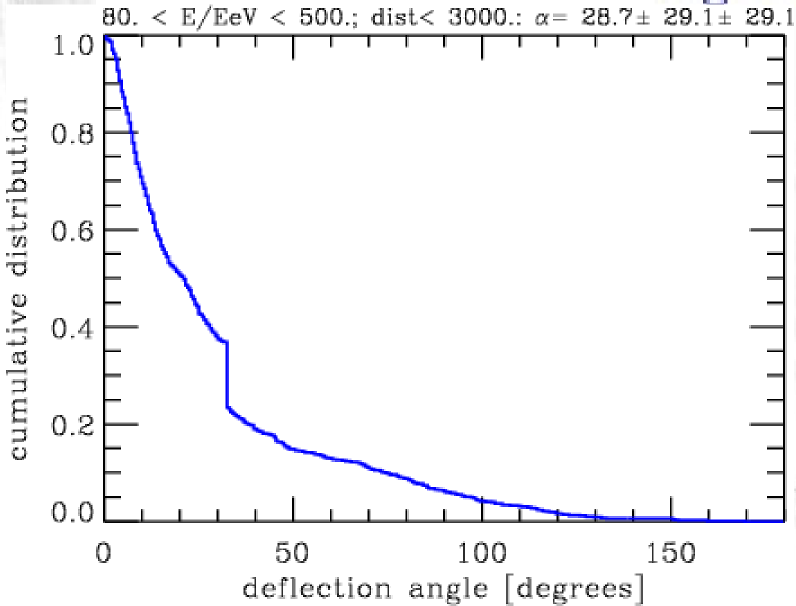
Sky distributions for iron primaries above 40 EeV, $E^{-2.2}$ injection up to 10^{22} eV



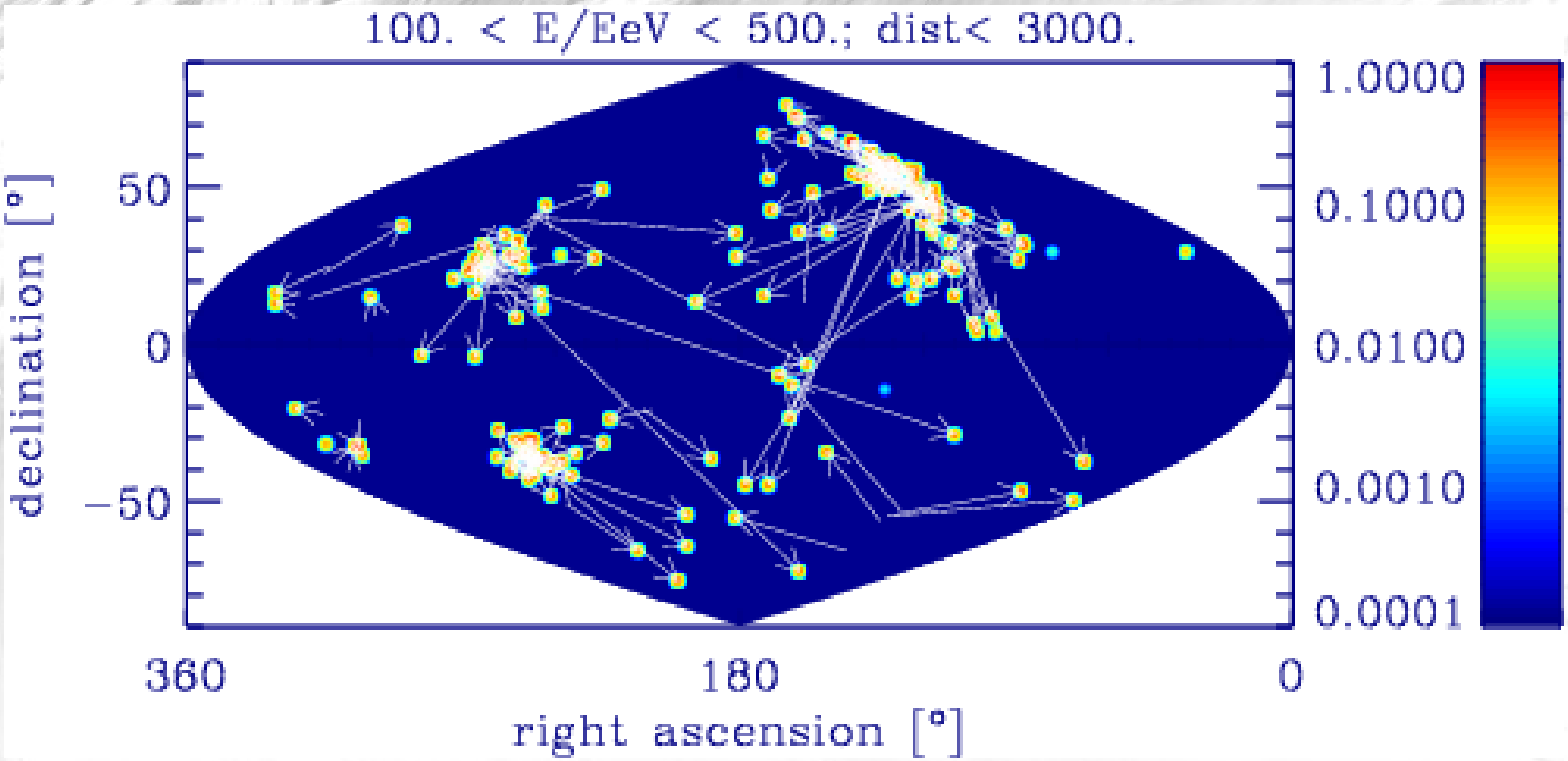


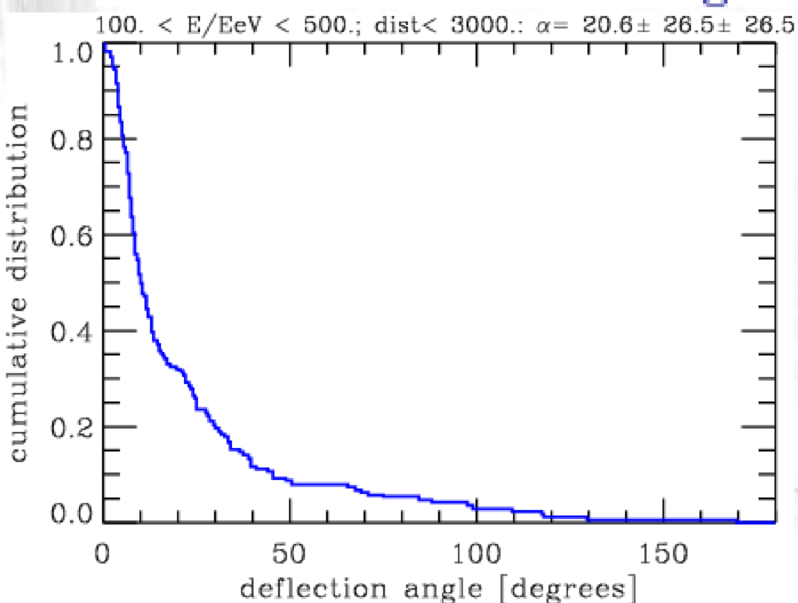
Sky distributions for iron primaries above 60 EeV, $E^{-2.2}$ injection up to 10^{22} eV





Sky distributions for iron primaries above 80 EeV, $E^{-2.2}$ injection up to 10^{22} eV





Sky distributions for iron primaries above 100 EeV, $E^{-2.2}$ injection up to 10^{22} eV

Conclusion:

A correleation with the local large scale structure is not necessarily destroyed by relatively large deflection, not even for iron, provided the field correlates with the large scale structure and deflection is mainly within that structure

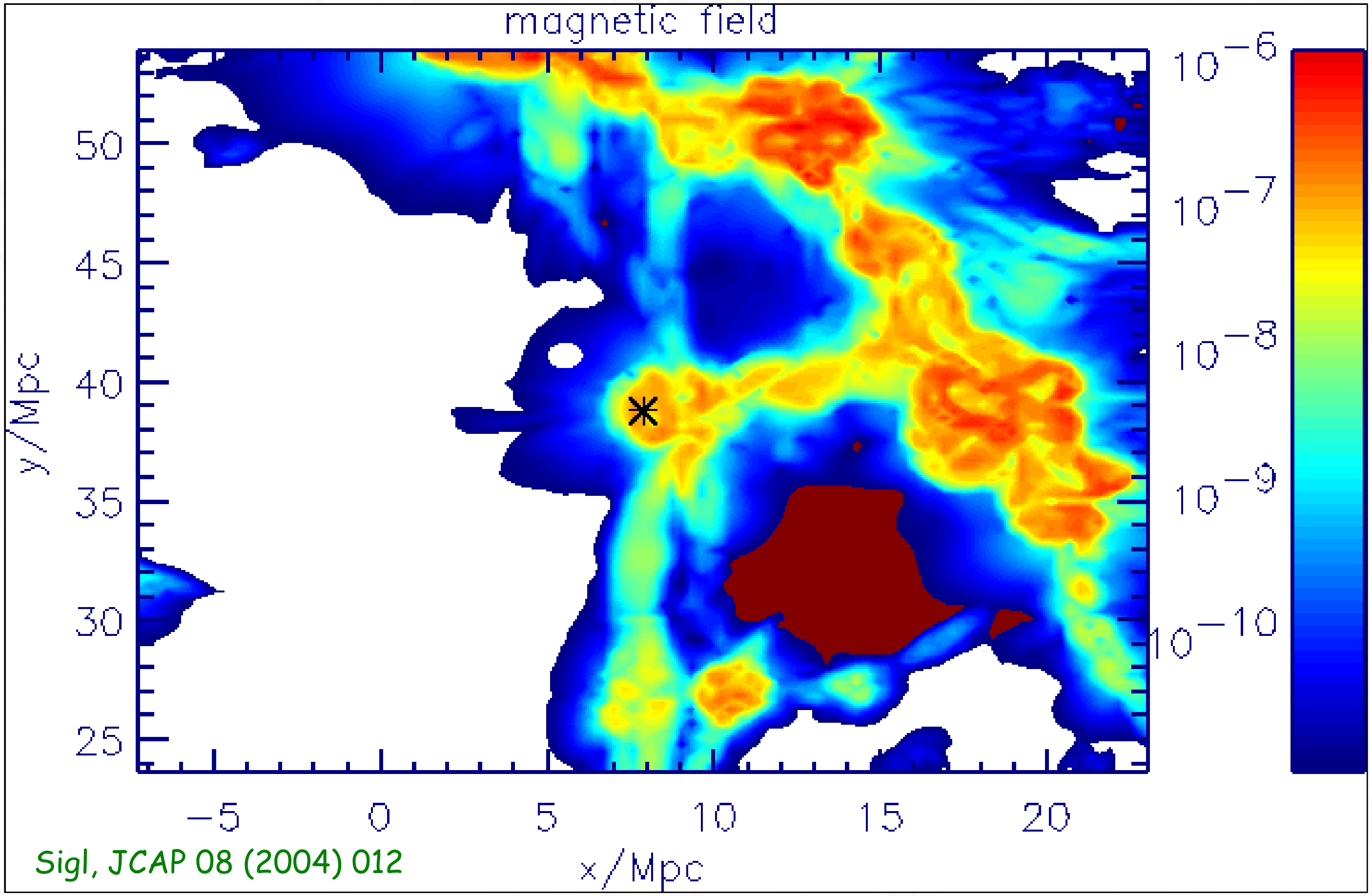
It would mean that any correlation with specific sources does not identify particular sources, but only a source class that is distributed as the large scale structure

Instead of AGN it could be e.g. due to GRBs or magnetars

But galactic deflection is also large and in general does not align with with supergalactic plane

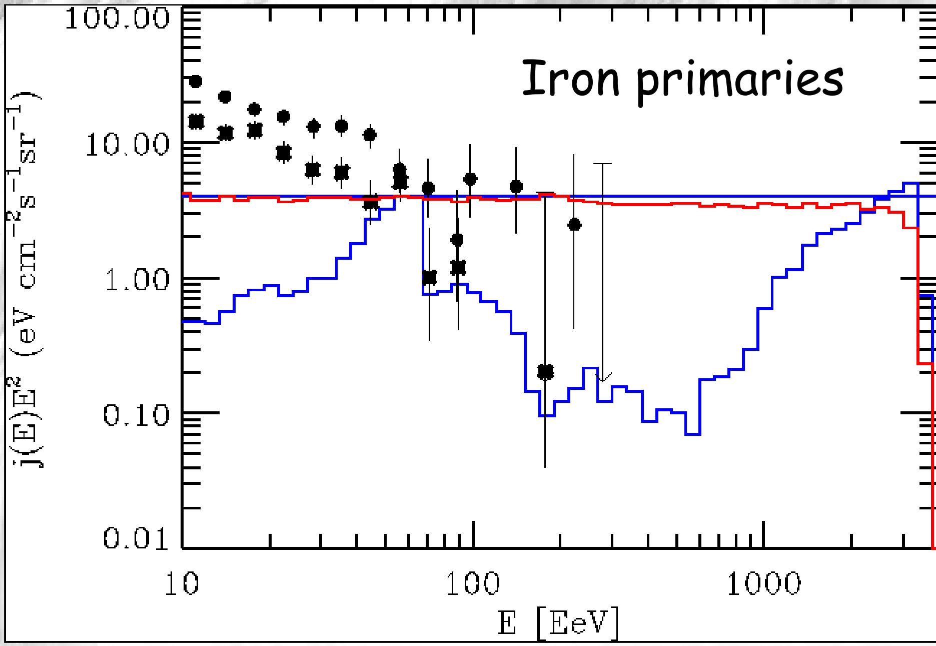
Heavy Nuclei: Structured Fields and Individual Sources

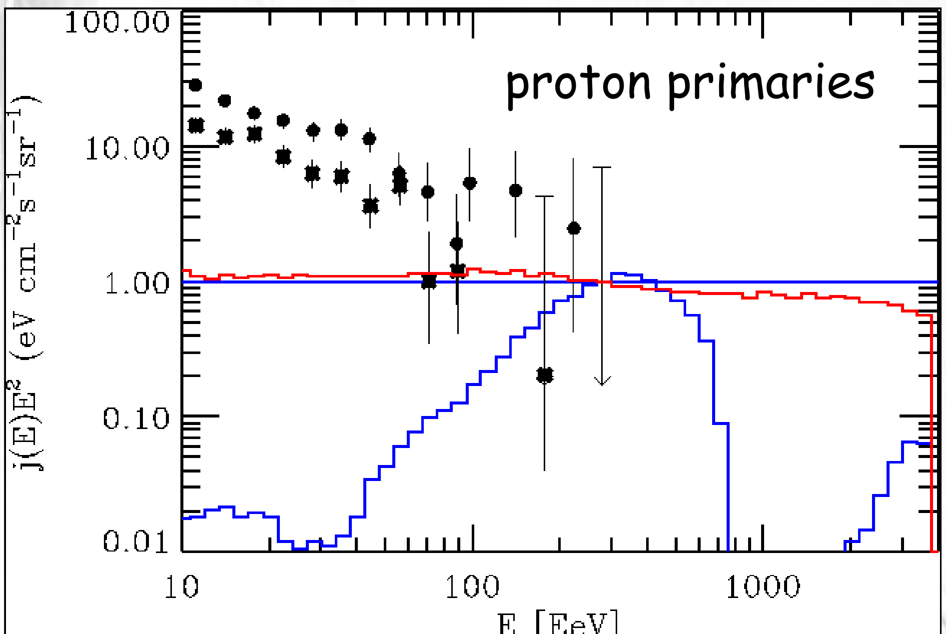
Spectra and Composition of Fluxes from Single Discrete Sources considerably depend on Source Magnetization, especially for Sources within a few Mpc.

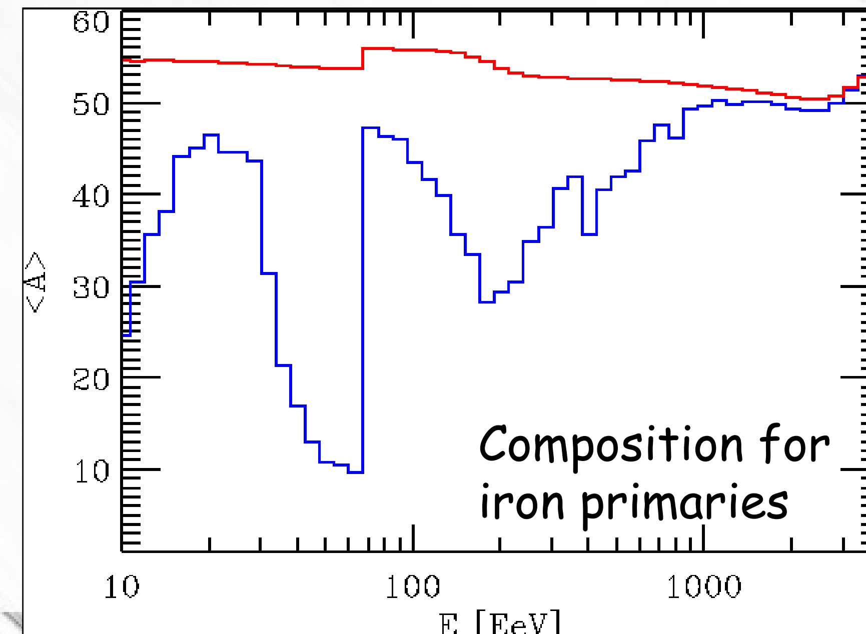


Source in the center; weakly magnetized observer modelled as a sphere shown in white at 3.3 Mpc distance.

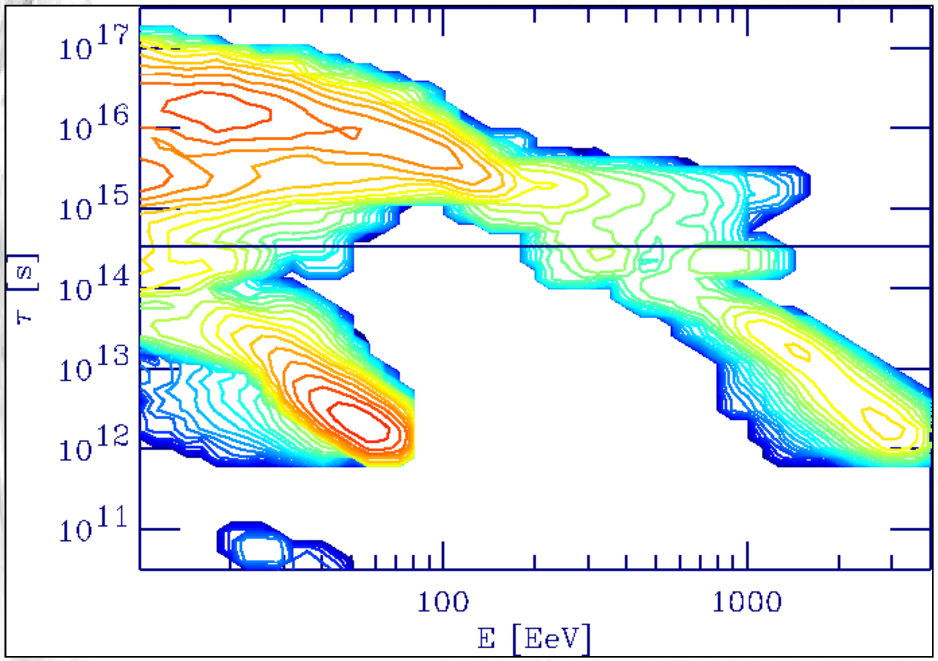
With field = blue
Without field = red
Injection spectrum = horizontal line

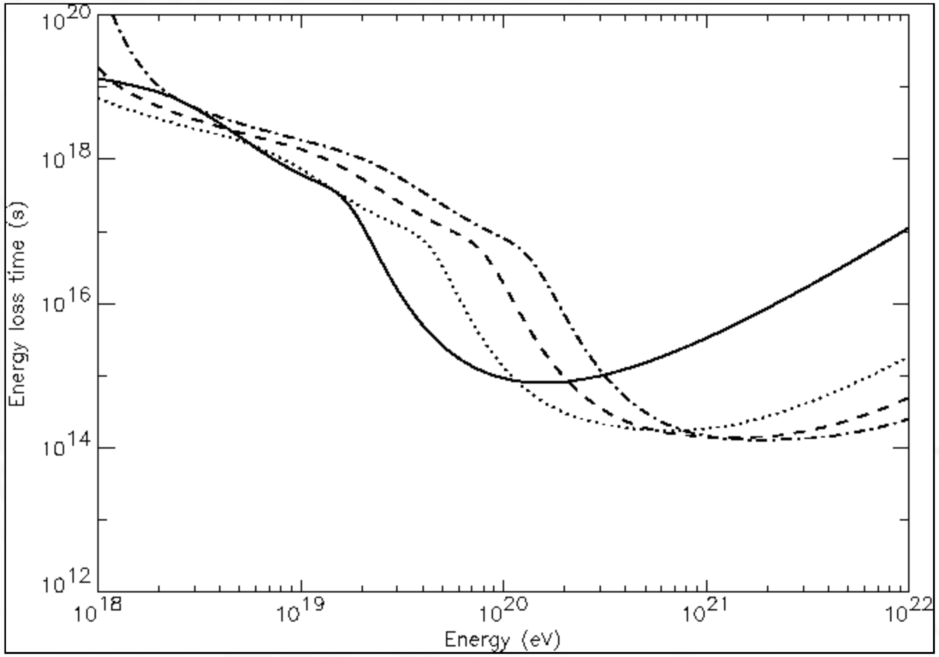






Importance of deflection obvious from comparing energy loss/spallation time scales with delay times



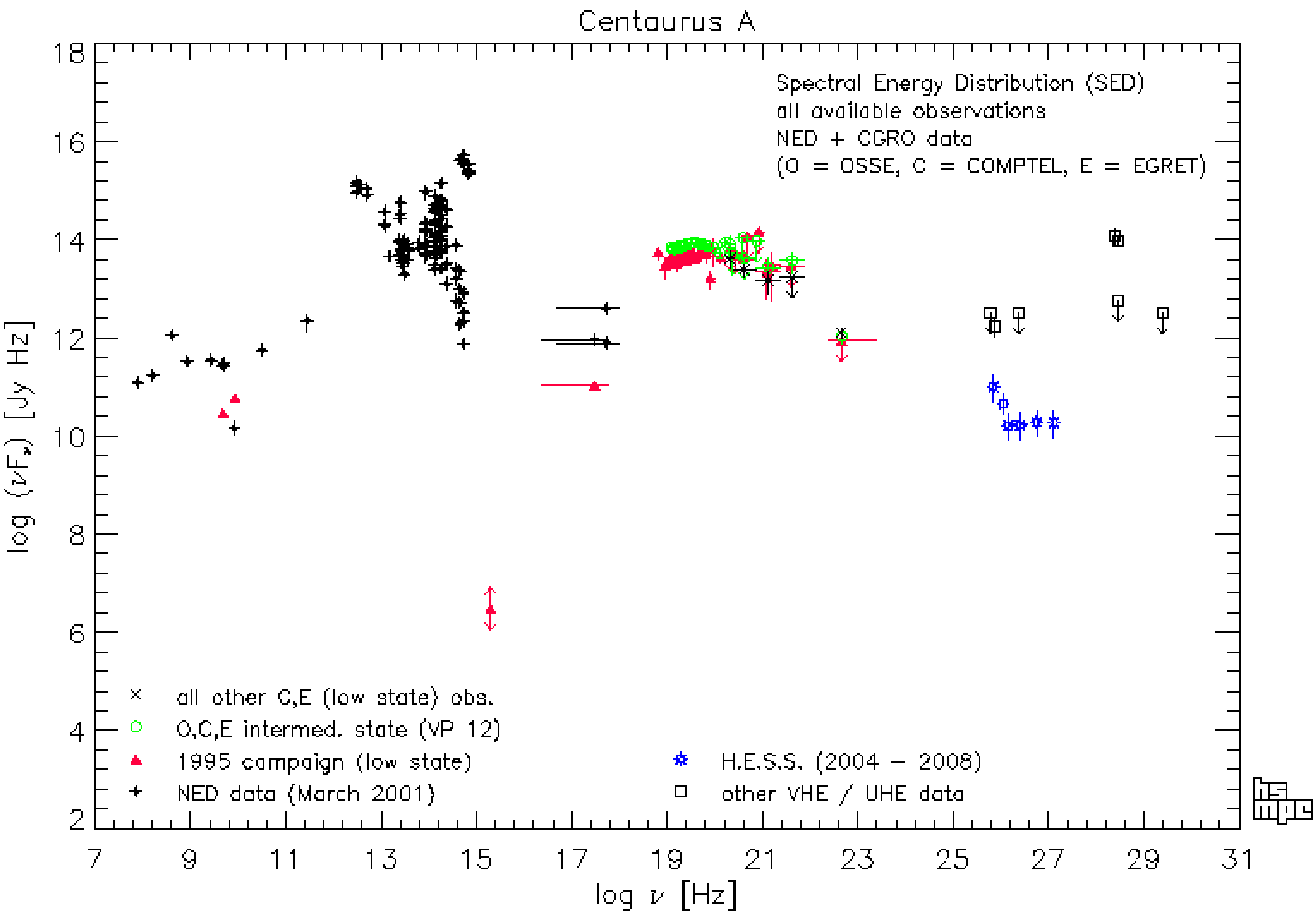


horizontal line=straight line propagation time

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).

Multi-Messenger Astrophysics with Discrete Sources: Centaurus A



Interactions of Hadronic primary cosmic rays

γ-rays can be produced by pp -> ppπ^0 -> ppγγ

$$\sigma_{pp}(s) \approx [35.49 + 0.307 \ln^2(s/28.94\,\mathrm{GeV}^2)]\,\mathrm{mb}$$

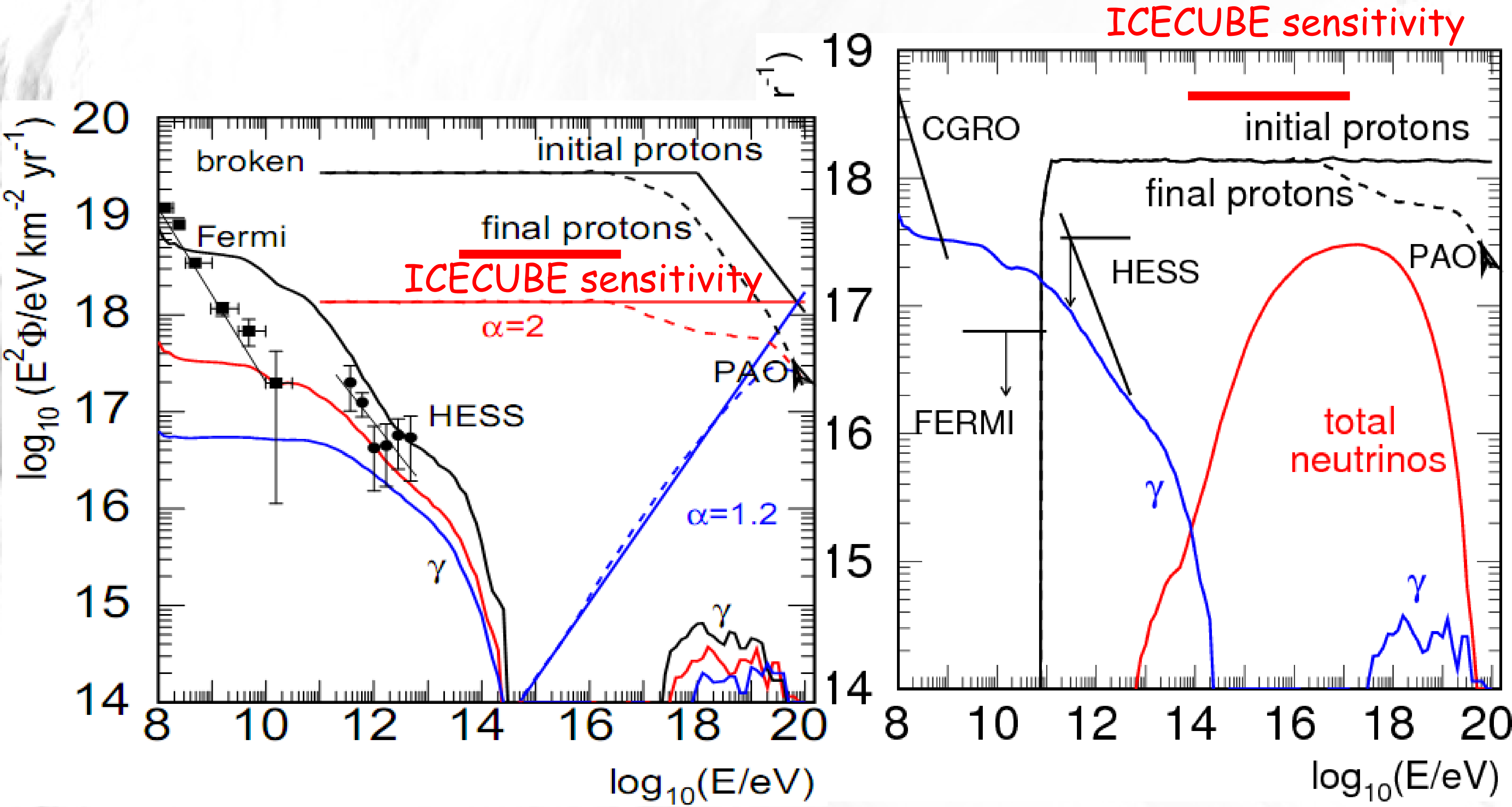
This cross section is almost constant -> secondary spectra roughly the same shape as primary fluxes as long as meson cooling time is much larger than decay time.

γ-rays can also be produced by **pγ interactions:**

For sub-MeV photons the cross section has a threshold and is typically ~ 100 mb and weakly energy dependent at energies much above the threshold

=> Secondary neutrino flux also has a (very high energy) threshold above which it roughly follows the primary spectrum.

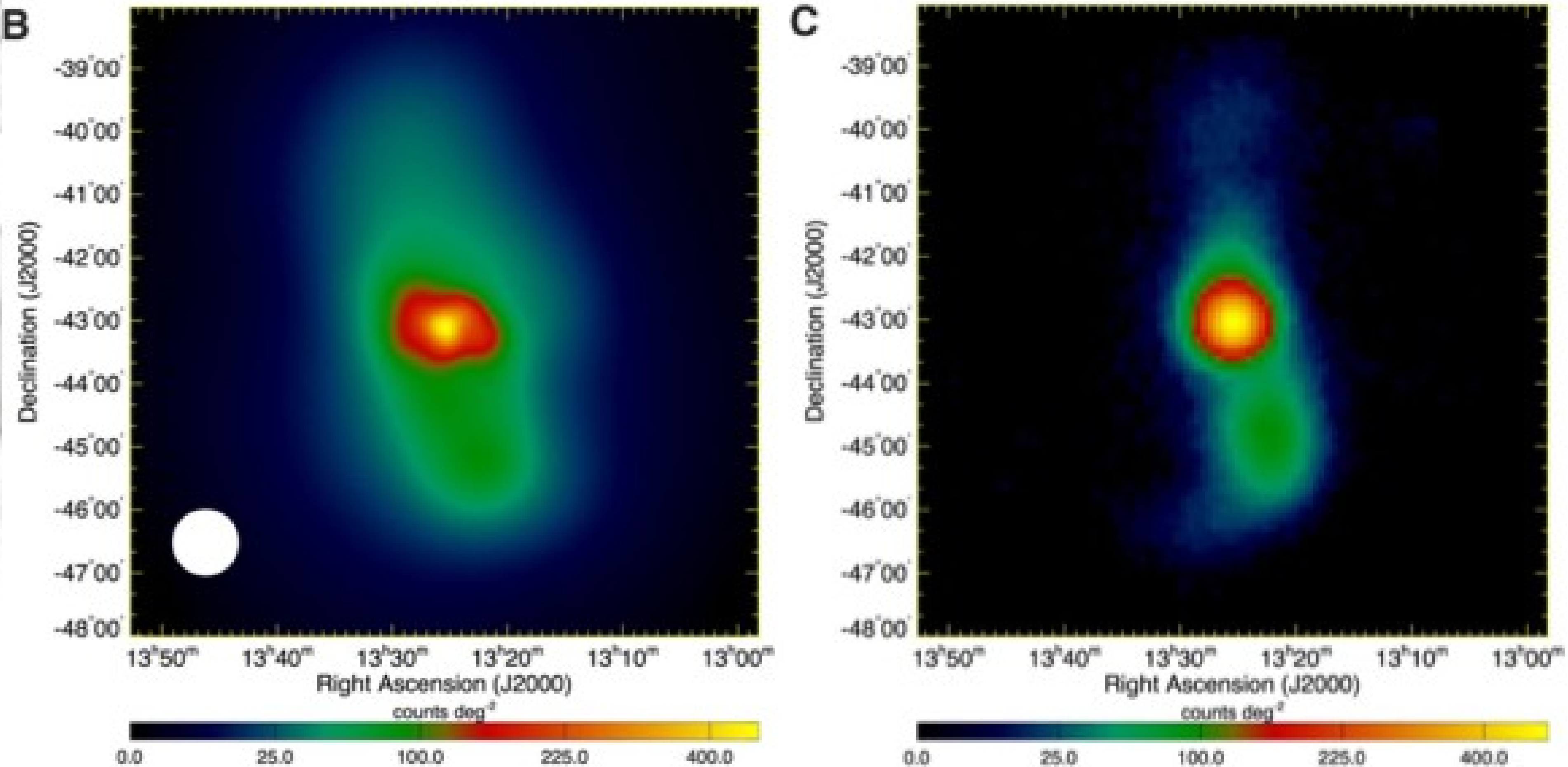
Centaurus A as Multimessenger Source: Hadronic Model



acceleration of protons around the core: pγ dominated
and secondary γ-rays cascade in infrared field of the source

Kachelriess, Ostapchenko, Tomas, NJP 11 (2009) 065017

Lobes of Centaurus A seen by Fermi-LAT

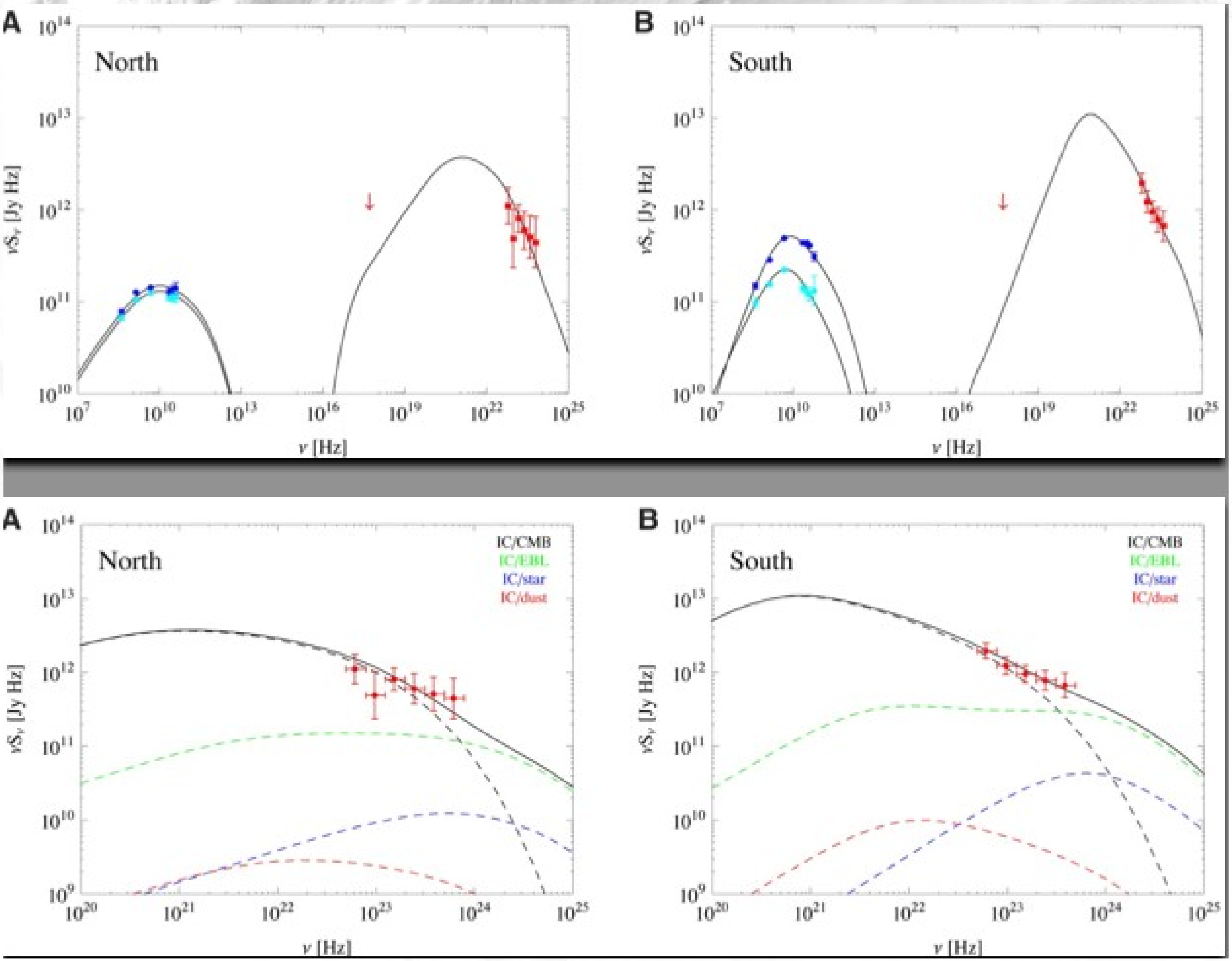


> 200 MeV γ-rays

Radio observations

Abdo et al., Science Express 1184656, April 1, 2010

Can be explained within **electromagnetic scenarios**

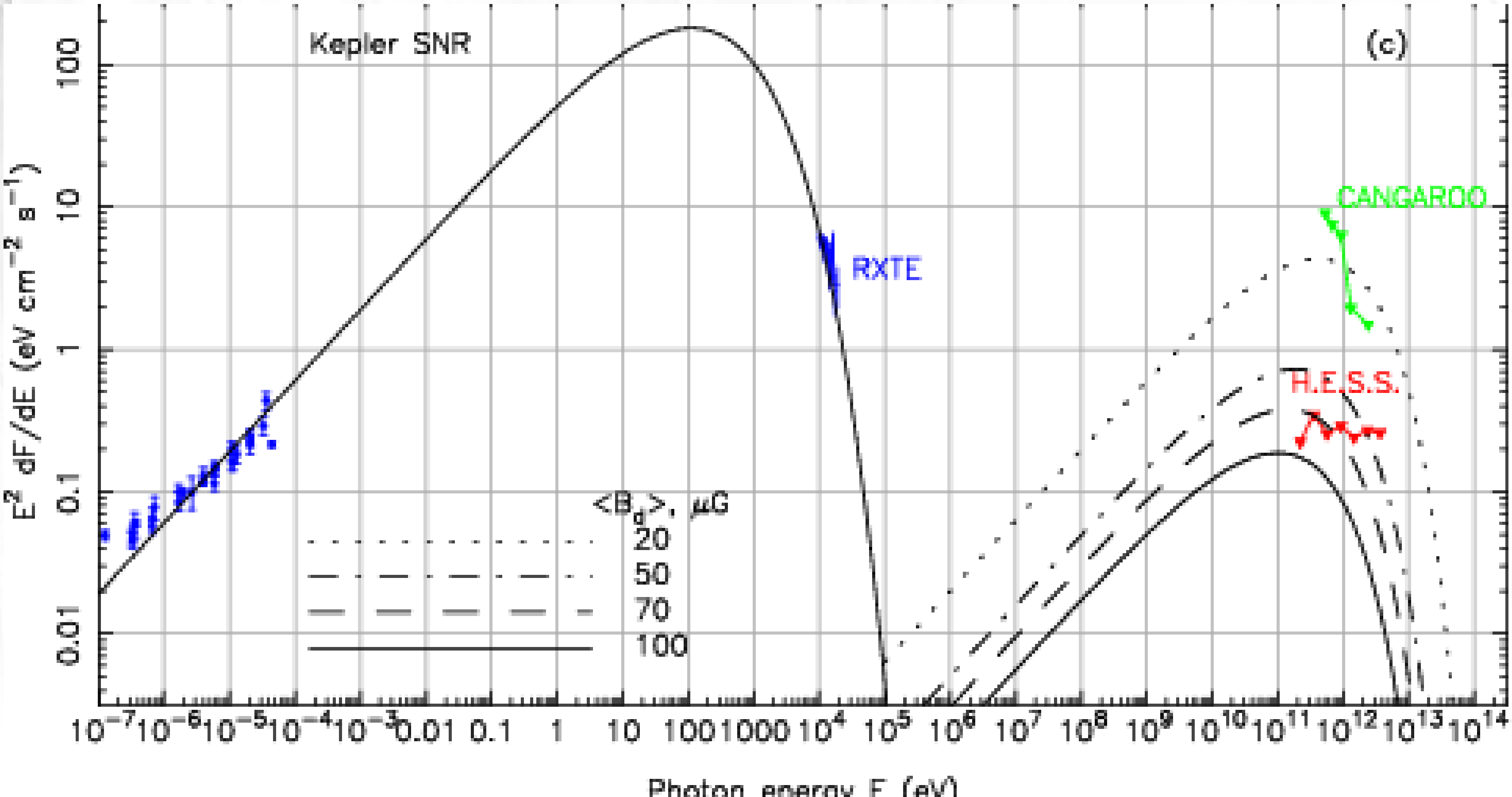


Low energy bump = synchrotron
high energy bump = inverse Compton on CMB in ~0.85μG field

Abdo et al., Science Express 1184656, April 1, 2010

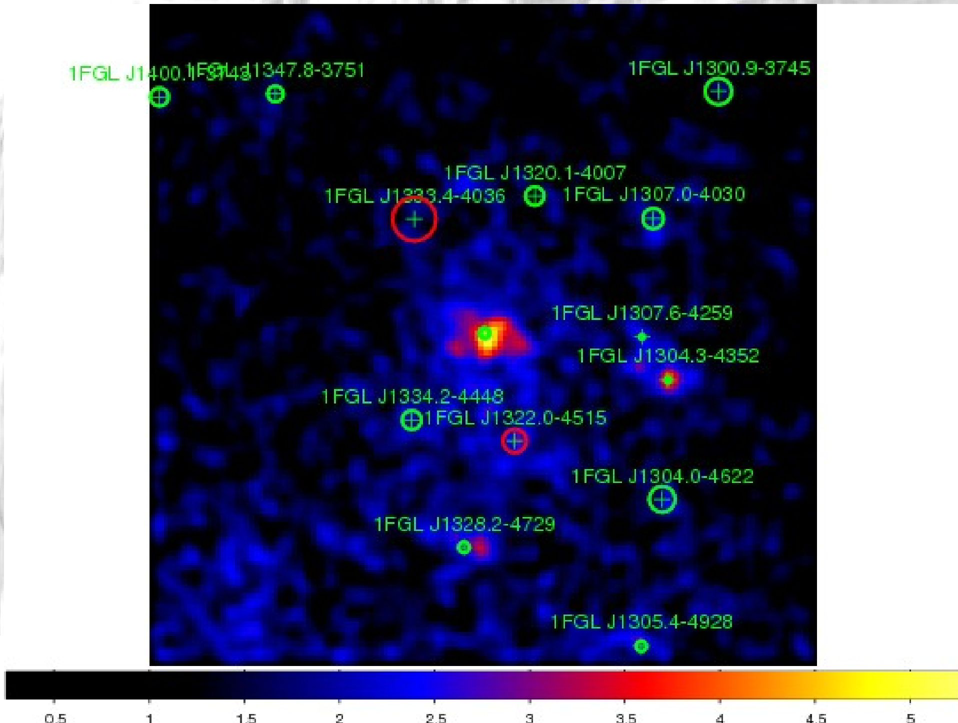
In **electromagnetic scenarios** the magnetic field is given by relative height of synchrotron and inverse Compton peak in the leptonic model would be too high:

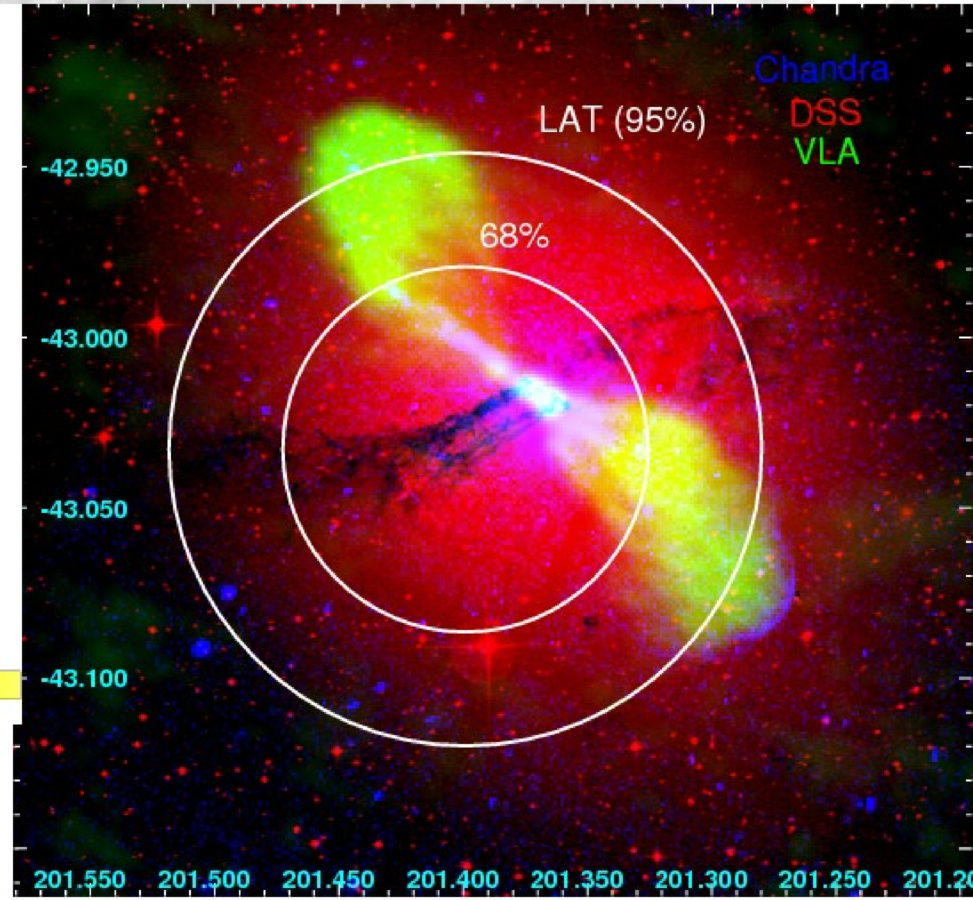
$$\frac{P_{\rm synch}}{P_{\rm IC}} = \frac{u_B}{u_{\rm CMB+IR}}$$

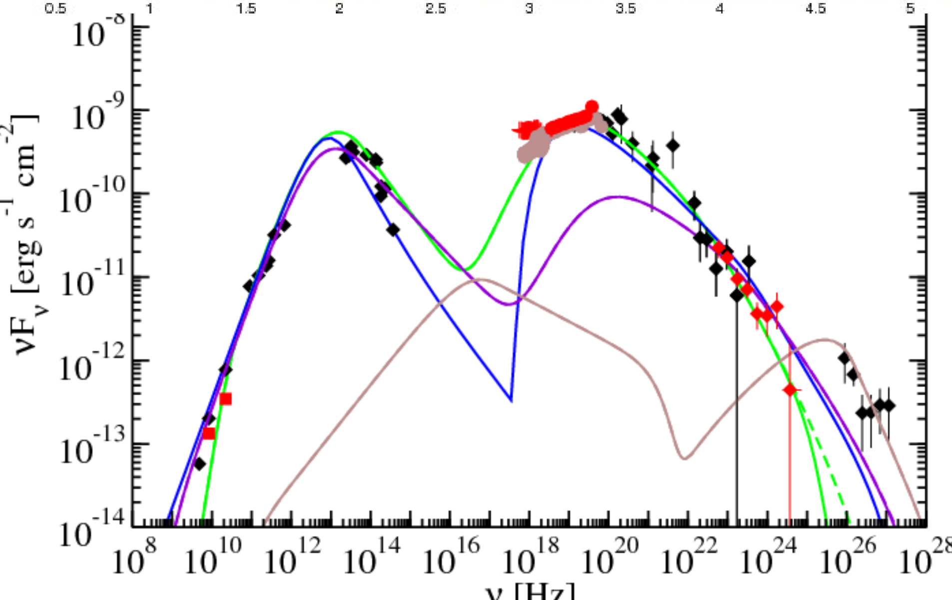


Voelk, Ksenofontov, Berezhko, arXiv:0809.2432

Core of Centaurus A seen by Fermi-LAT

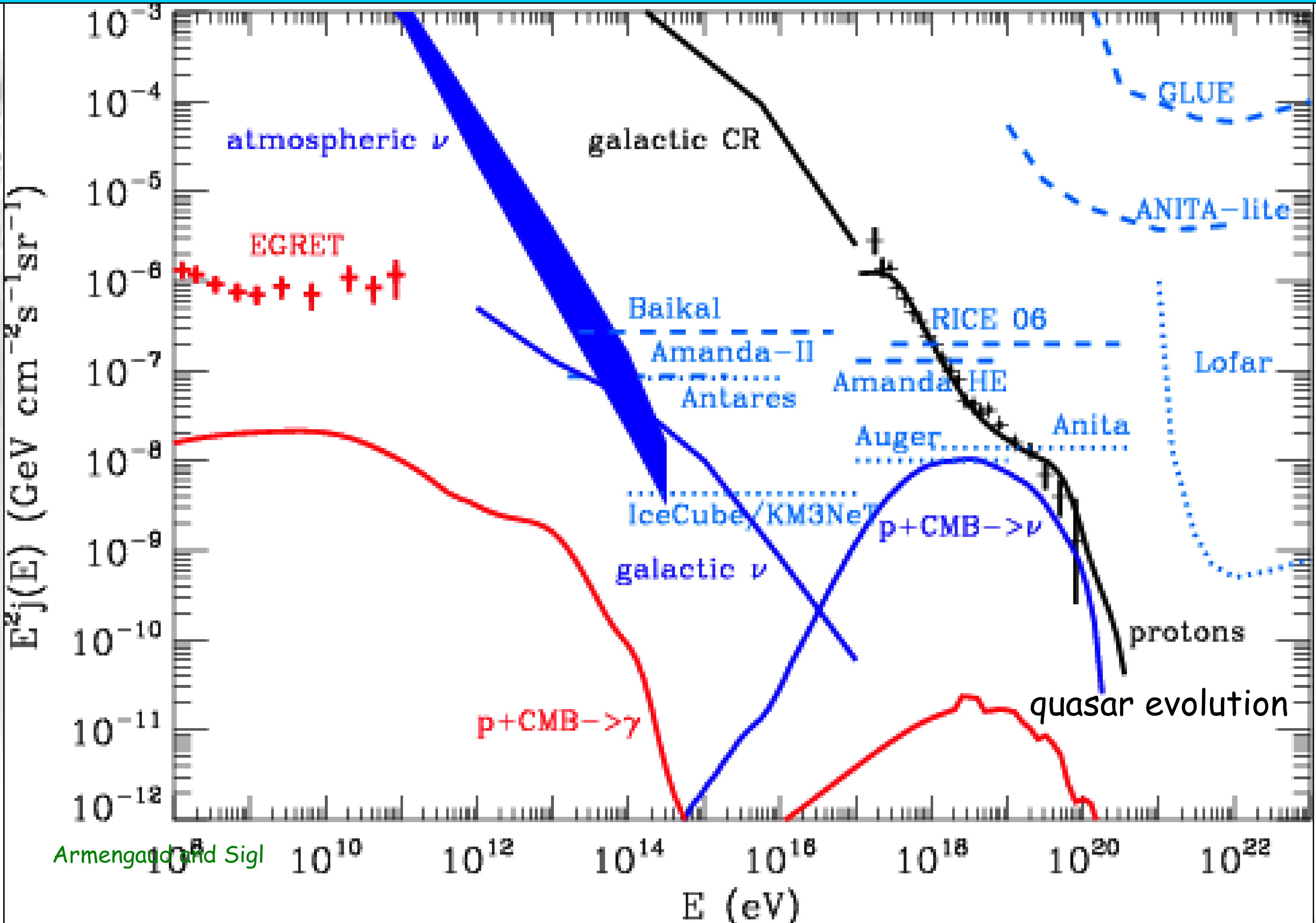




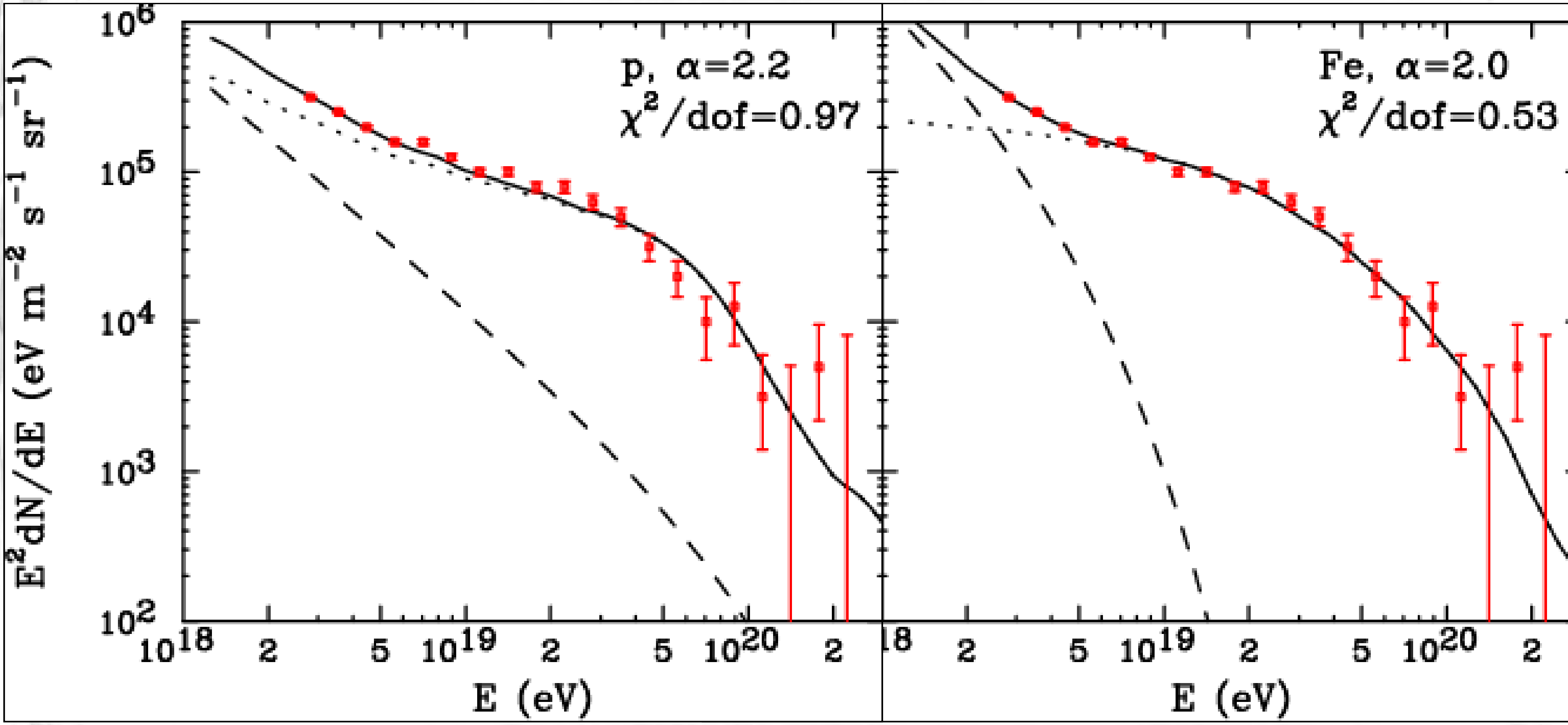


Can be explained by synchrotron self Compton except for HESS observation

Diffuse Secondary Gamma-Ray and Neutrino Fluxes



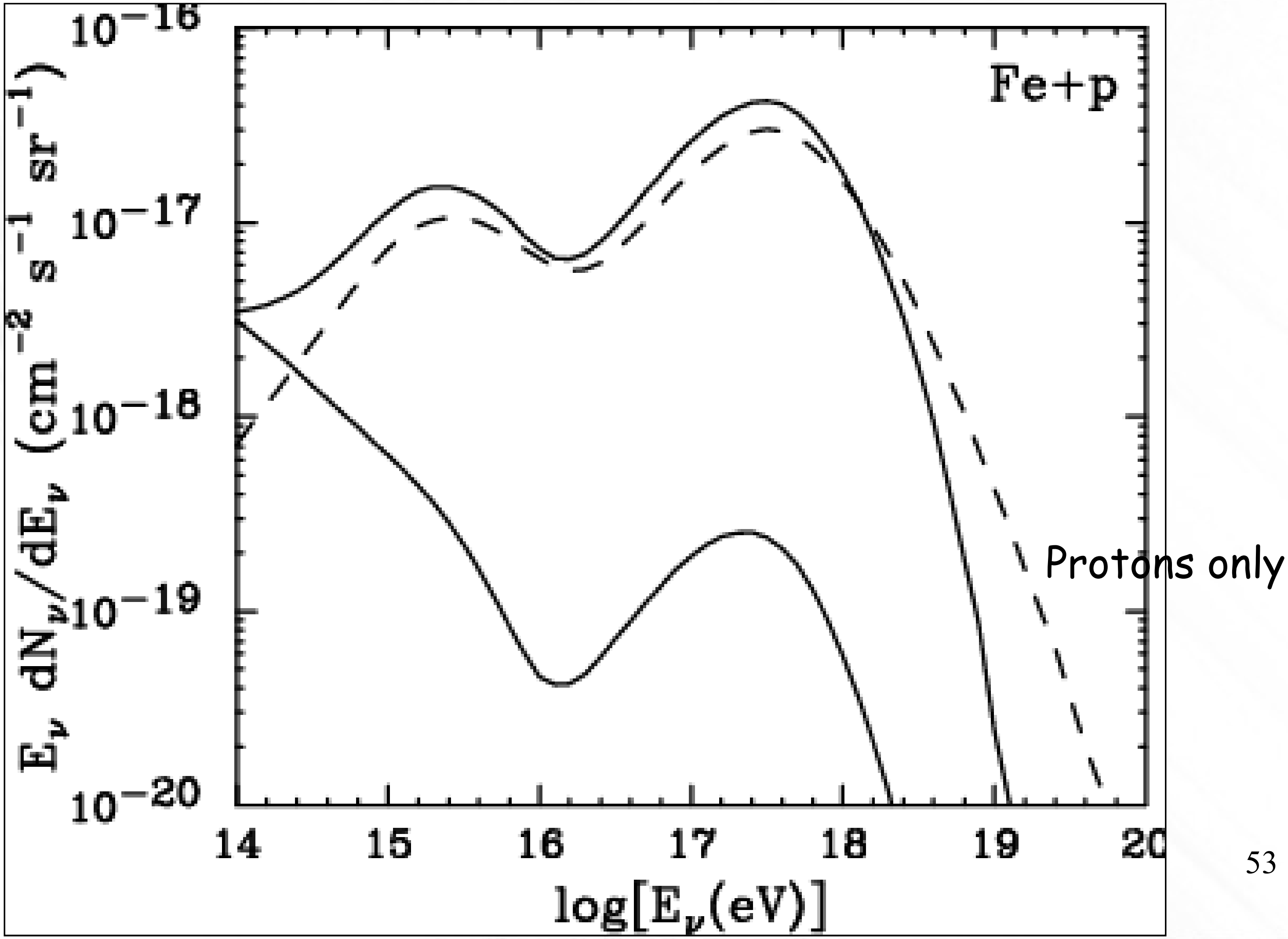
Chemical Composition and Cosmogenic Neutrino Flux



Best fits to Auger spectrum for proton and iron injection with $E_{max}=(Z/26)\,10^{22}$ eV

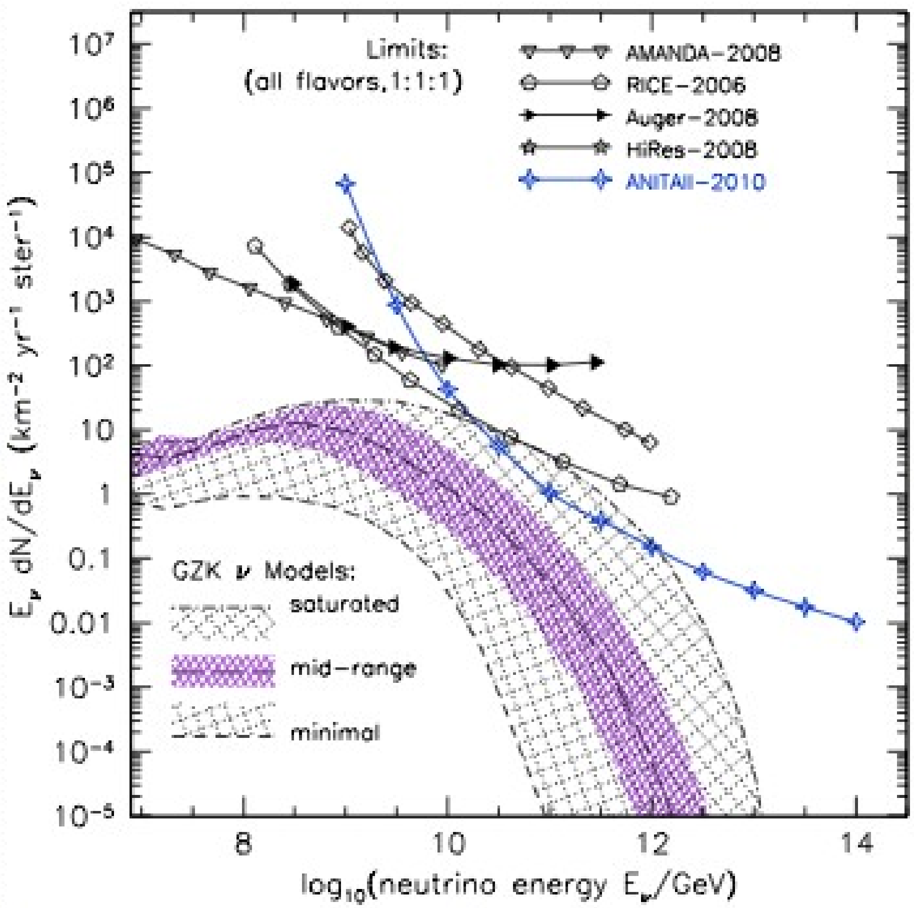
Anchordoqui, Hooper, Sarkar, Taylor, Astropart.Phys. 29 (2008) 1

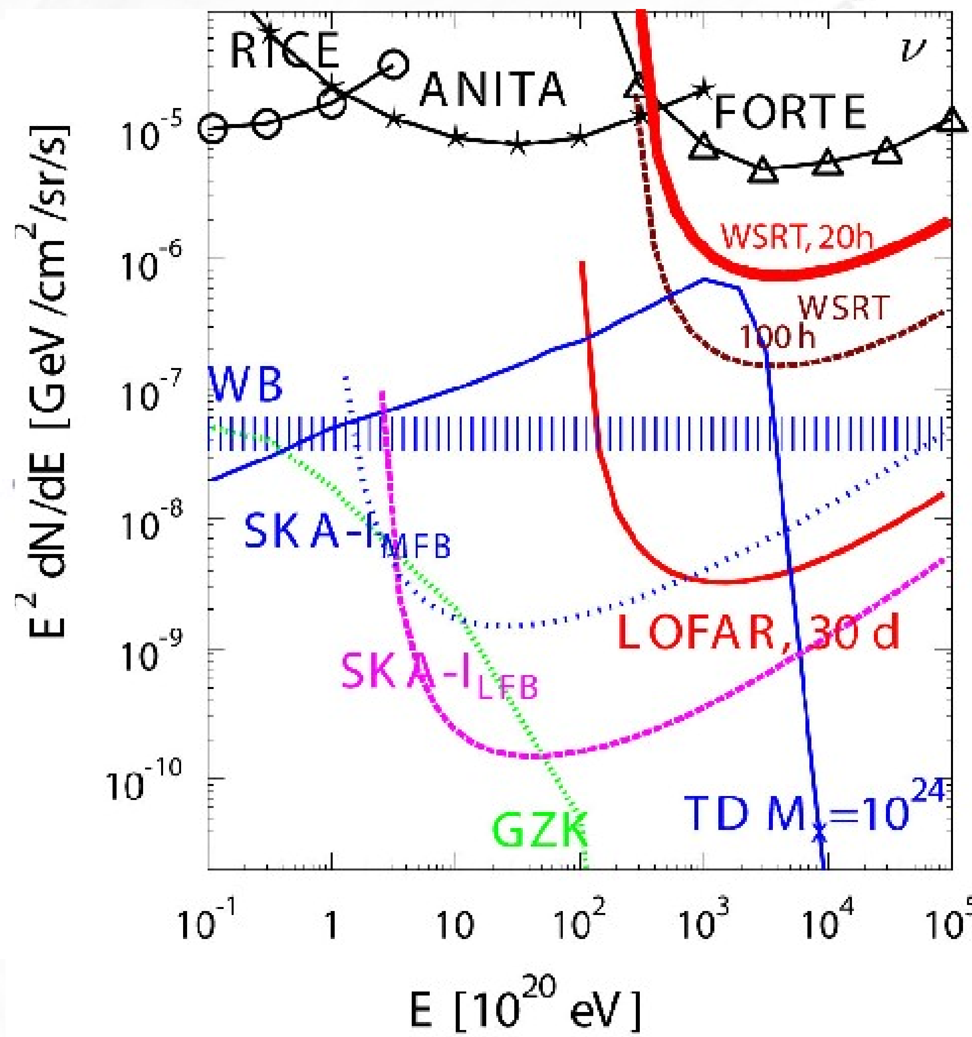
Range of cosmogenic neutrino fluxes consistent with PAO spectrum and composition



Anchordoqui, Hooper, Sarkar, Taylor, Phys.Rev.D 76 (2007) 123008

Limits and future Sensitivities to UHE neutrino fluxes



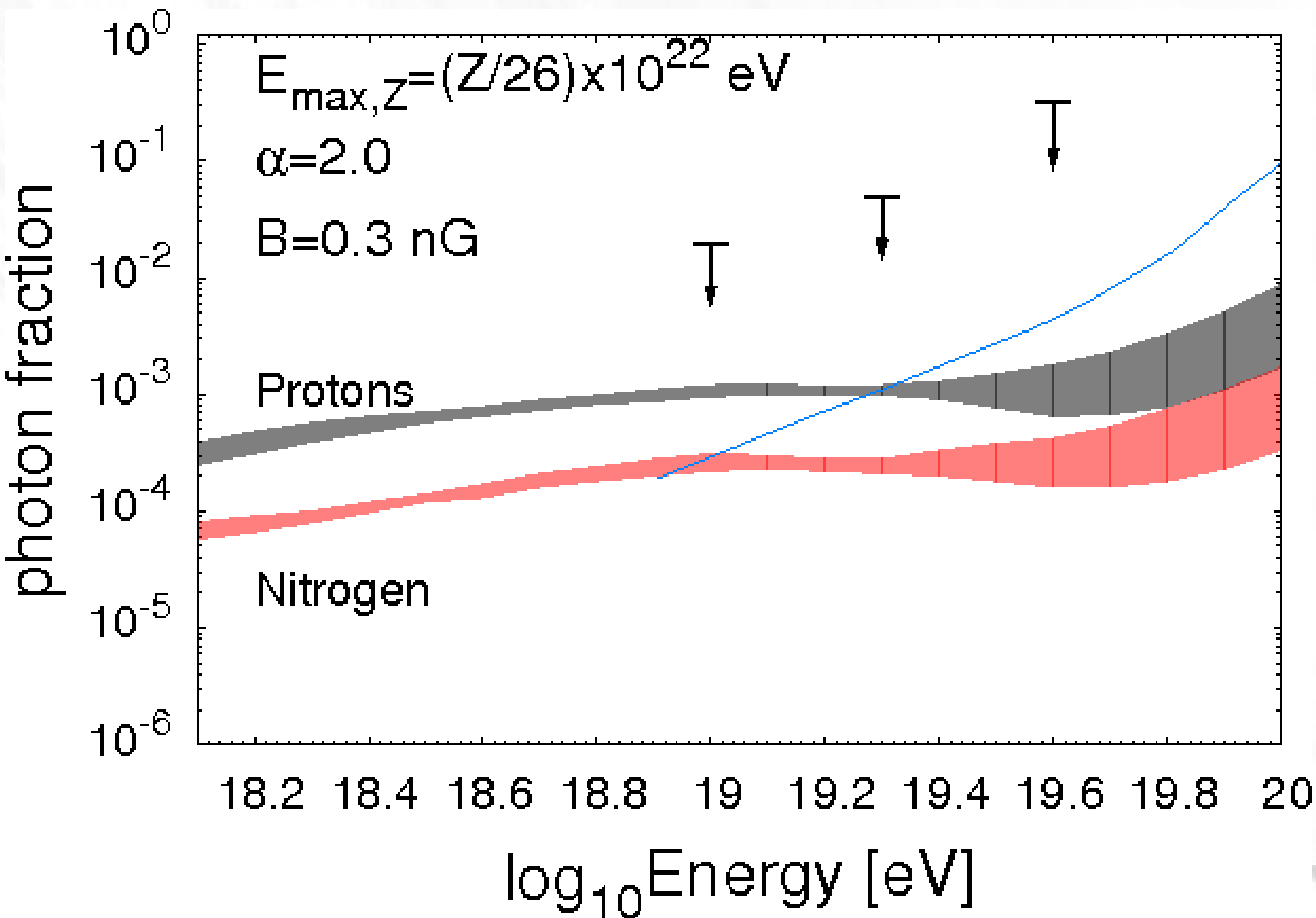


P. Gorham et al, arXiv:1003.2961

A. Haungs, arXiv:0811.2361

Physics with Diffuse Secondary Gamma-Ray Fluxes

Also UHE gamma ray fluxes depend on composition, see e.g. Hooper, Taylor, Sarkar, arXiv:1007.1306



Lorentz Symmetry Violation in the Photon Sector

For photons we assume the dispersion relation

$$\omega_\pm^2 = k^2 + \xi_n^\pm k^2 \left(\frac{k}{M_{Pl}}\right)^n, \quad n \geq 1,$$

and for electrons

$$E_{e,\pm}^2 = p_e^2 + m_e^2 + \eta_n^{e,\pm} p_e^2 \left(\frac{p_e}{M_{\mathrm{Pl}}}\right)^n, \quad n \geq 1,$$

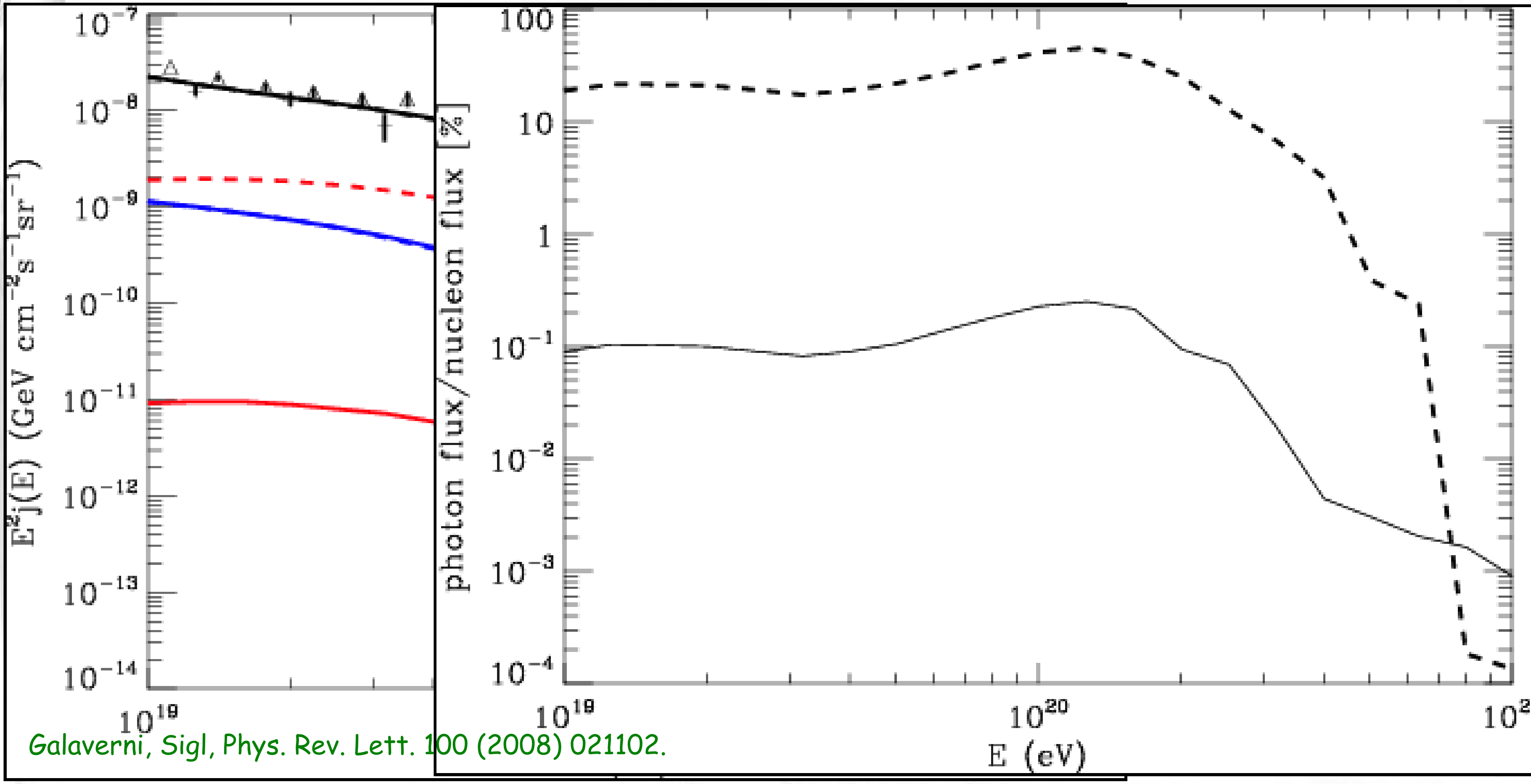
with only one term present. Polarizations denoted with ±. For positrons, effective field theory implies $\eta_n^{p,\pm} = (-1)^n \eta_n^{e,\pm}$. Furthermore, $\xi_n^+ = (-1)^n \xi_n^-$, so that the problem depends on three parameters which in the following we denote by

$$\xi_n, \eta_n^+, \eta_n^-$$

for each *n*.

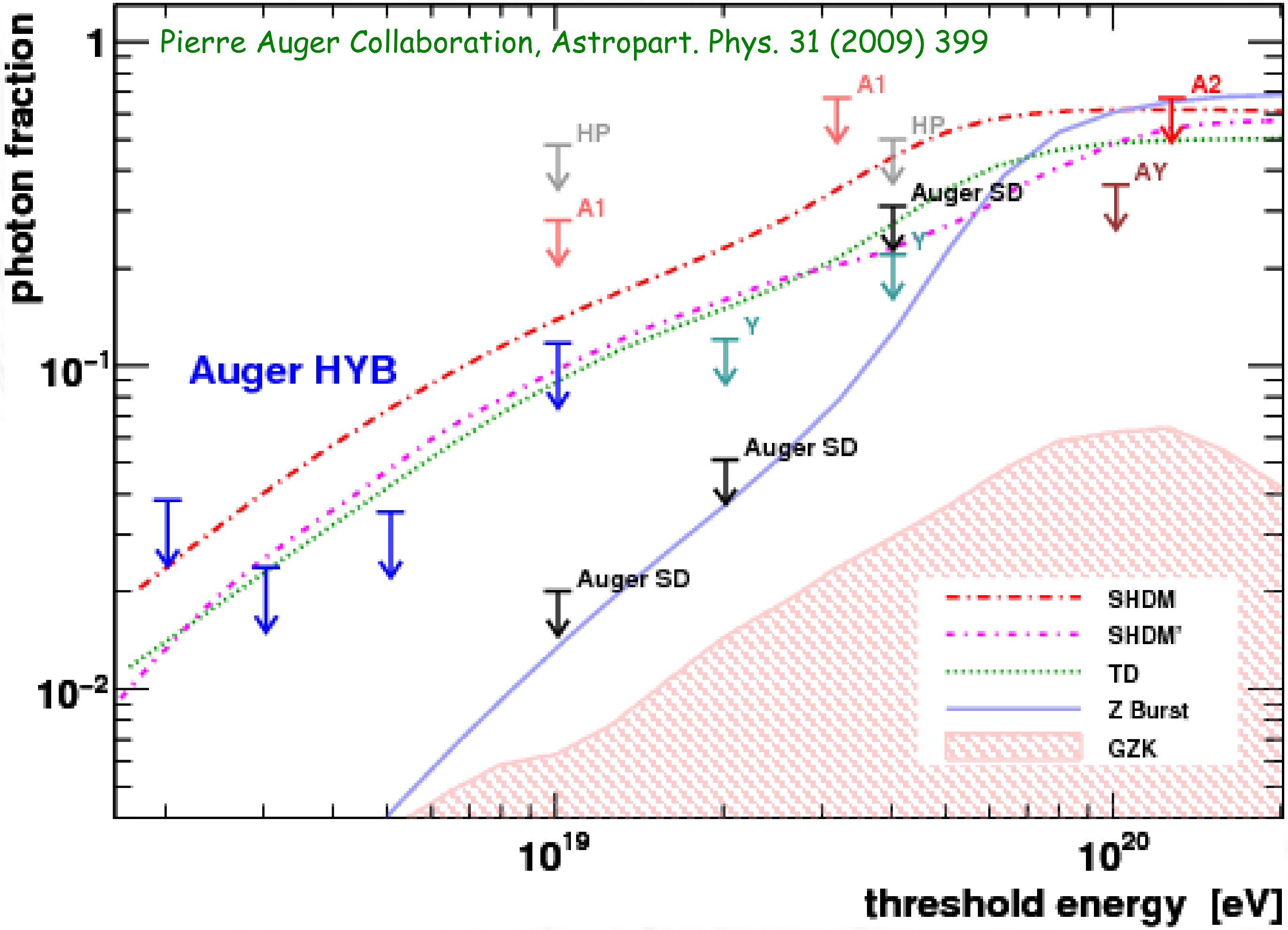
Photon decay becomes possible and/or pair production may become inhibited !

In absence of pair production for 10^{19} eV < ω < 10^{20} eV the photon fraction would be ~20% and would violate experimental bounds:

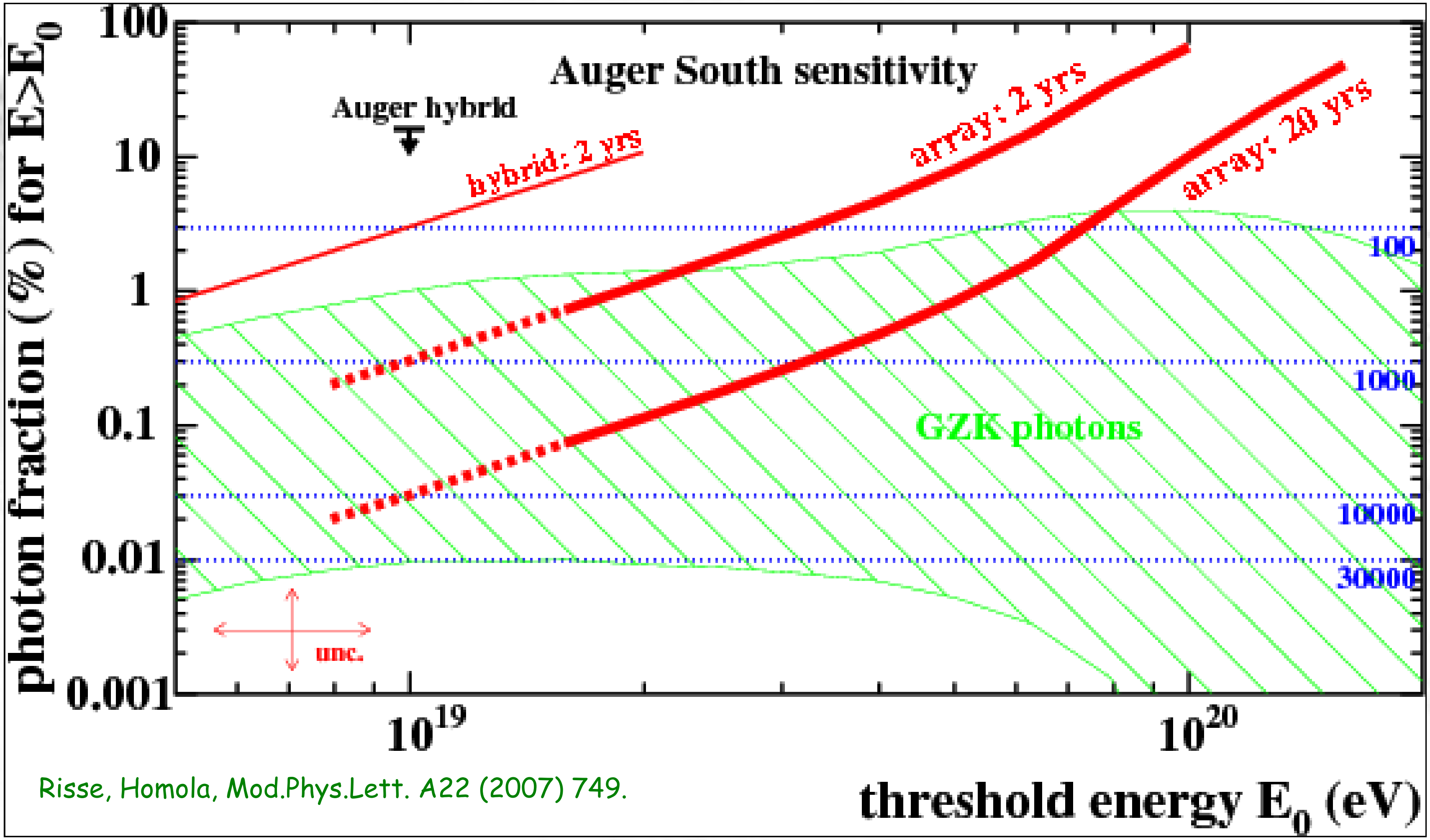


Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

Current upper limits on the photon fraction are of order 2% above 10^{19} eV from latest results of the Pierre Auger experiments (ICRC) and order 30% above 10^{20} eV.



Future data will allow to probe smaller photon fractions and the GZK photons



Risse, Homola, Mod.Phys.Lett. A22 (2007) 749.

A given combination $\xi_n, \eta_n^+, \eta_n^-$ is ruled out if, for 10^{19} eV < ω < 10^{20} eV, at least one photon polarization state is stable against decay and does not pair produce for any helicity configuration of the final pair.

In the absence of LIV in pairs for n=1, this yields:

$$\xi_1 \leq 10^{-12}$$

Such strong limits may indicate that Lorentz invariance violations are completely absent !

These limits are also inconsistent with interpretations of time delays of high energy gamma-rays from GRBs within quantum gravity secanrios based on effective field theory (Maccione, Liberati, Sigl, PRL 105 (2010) 021101

Possible exception in space-time foam models, Ellis, Mavromatos, Nanopoulos, arXiv:1004.4167

Conclusions1

1.) The origin of very high energy cosmic rays is still 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.) Above 60 EeV, arrival directions are anisotropic at 99% CL and seem to correlate with the local cosmic large scale structure.

3.) It is currently not clear what the sources are within these structures. Potential sources closest to the arrival directions require heavier nuclei to attain observed energies. Air shower characteristics also seem to imply a mixed composition.

4.) This is surprising because larger deflections would be expected for nuclei already in the Galactic magnetic field.

5.) A possible solution could be considerable deflection only within the large scale structure; but this would be a coincidence for galactic deflection

Conclusions2

5.) Both diffuse cosmogenic neutrino and photon fluxes depend on chemical composition (and maximal acceleration energy)

6.) The large Lorentz factors involved in cosmic radiation at energies above ~ 10^{19} eV provides a magnifier into possible Lorentz invariance violations (LIV).

7.) Once UHE photons are detected, all LIV parameters in the electromagnetic sector suppressed to first order in the Planck scale can be constrained to be $\leq 10^{-6}$. At second order, one of the parameters can be large.