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 power of

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

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

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

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:

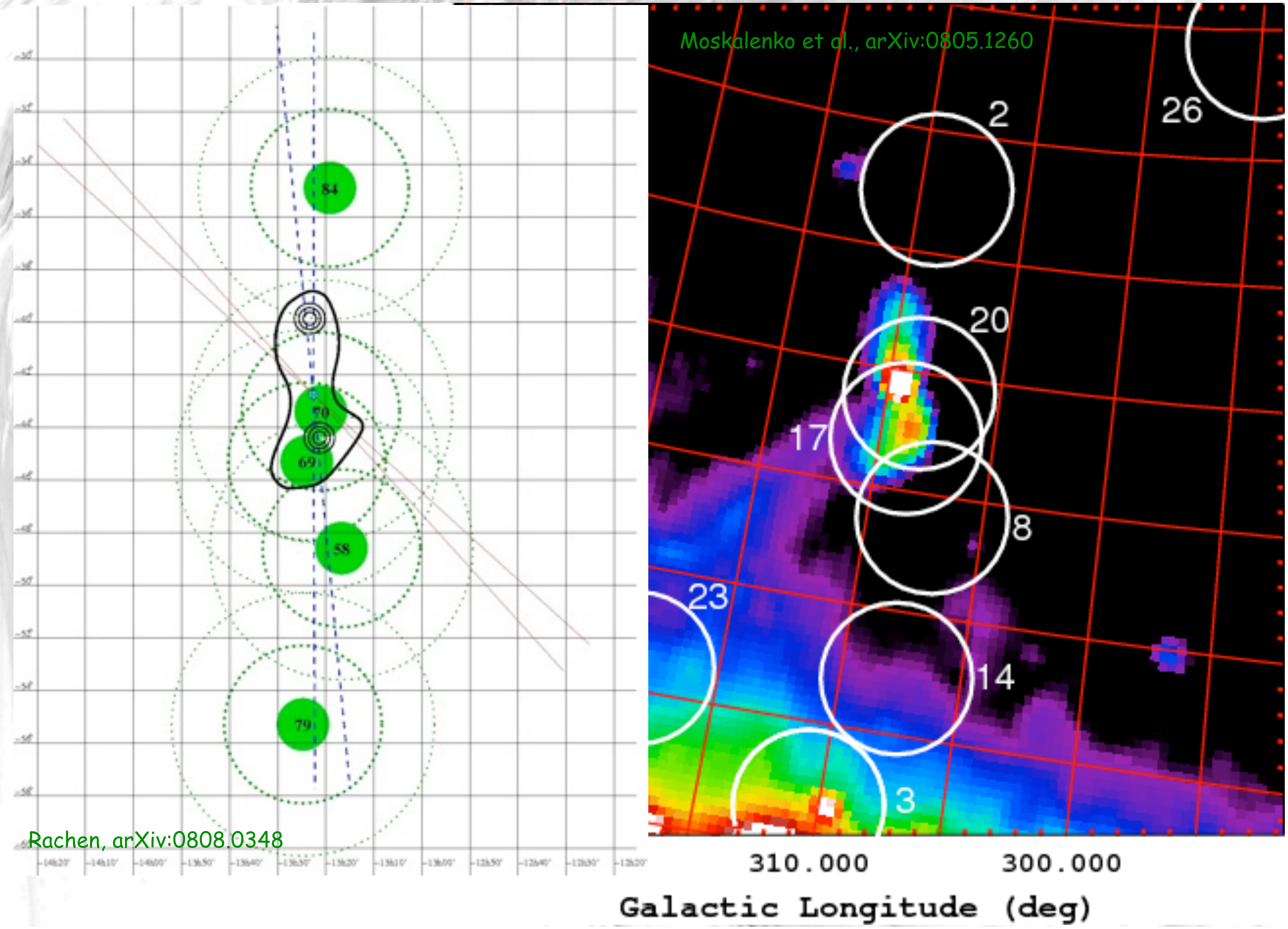
$$L_{108\,\mathrm{MHz}} > 2 \times 10^{24}\,\epsilon \left(\frac{E/Z}{10^{20}\,\mathrm{eV}}\right)^{7/2} \left(\frac{r_{\mathrm{lobe}}}{100\,\mathrm{kpc}}\right)^{-1/2} \mathrm{W\,Hz^{-1}}$$

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

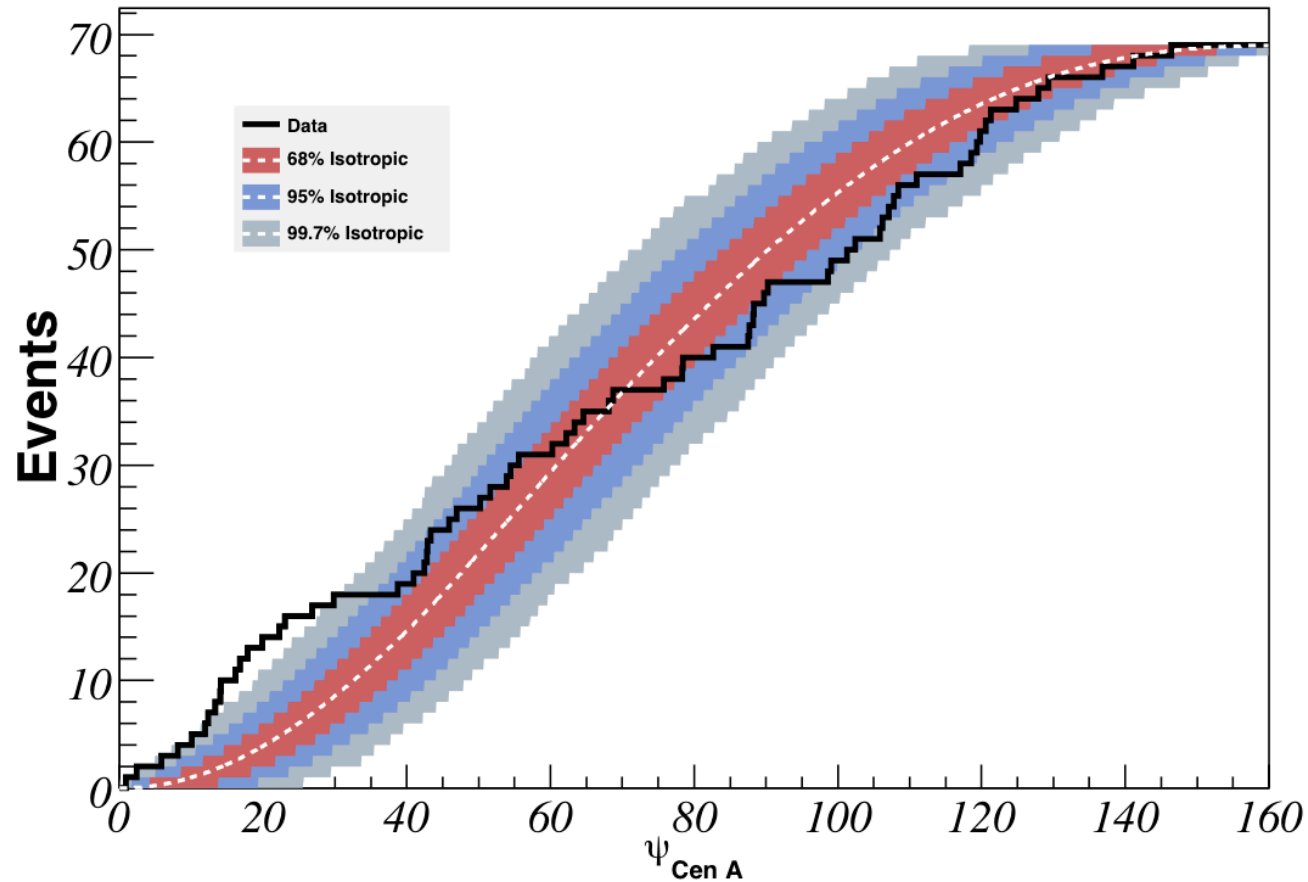
He concludes: if protons, then very few sources which should be known and spectrum should cut off steeply at observed highest energies

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

Centaurus A



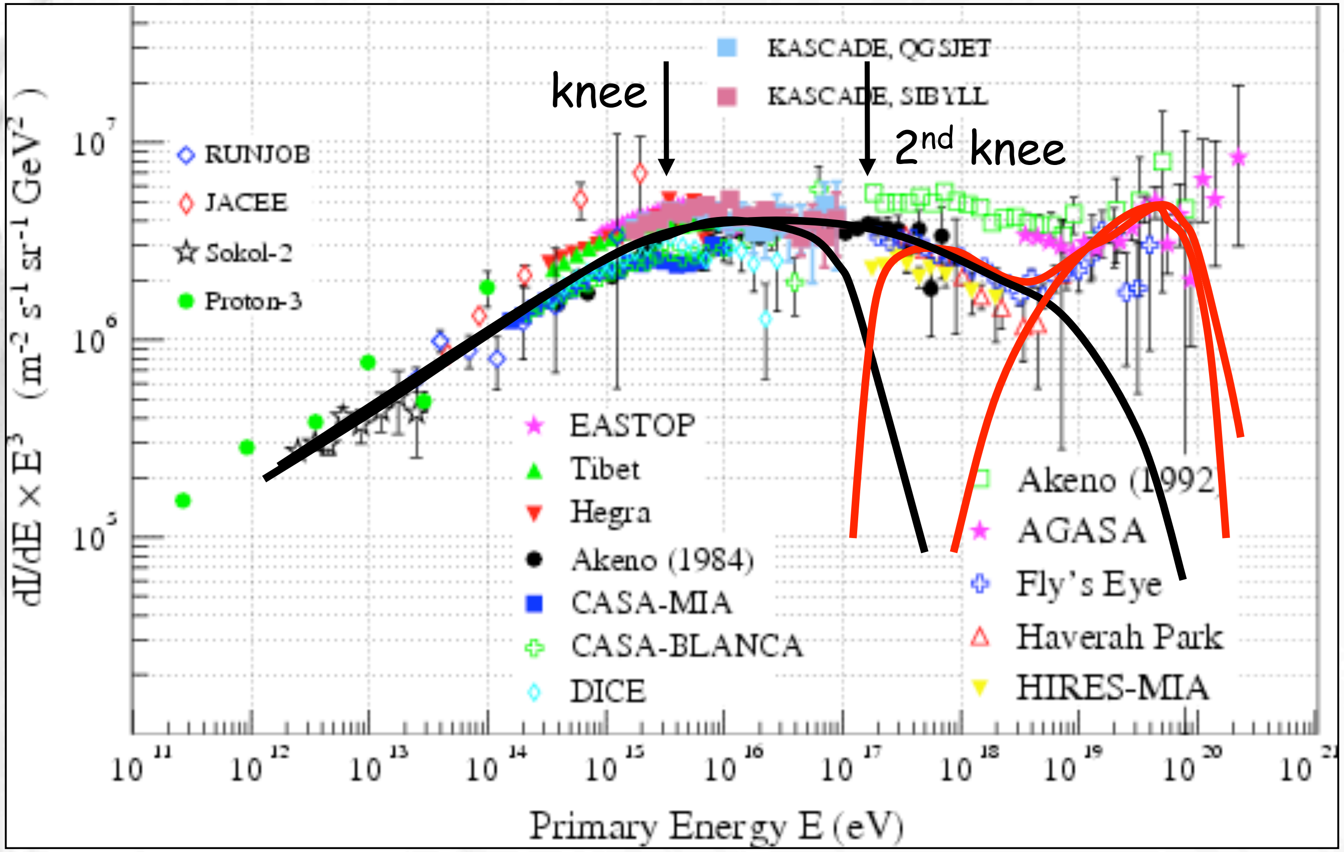
Moskalenko et al., arXiv:0805.1260
2
26
20
17
8
23
14
3
84
70
69
58
79
Rachen, arXiv:0808.0348
310.000
300.000
Galactic Longitude (deg)



Pierre Auger sees a clear excess in the direction of Centaurus A.

Pierre Auger Collaboration, arXiv:1009.1855

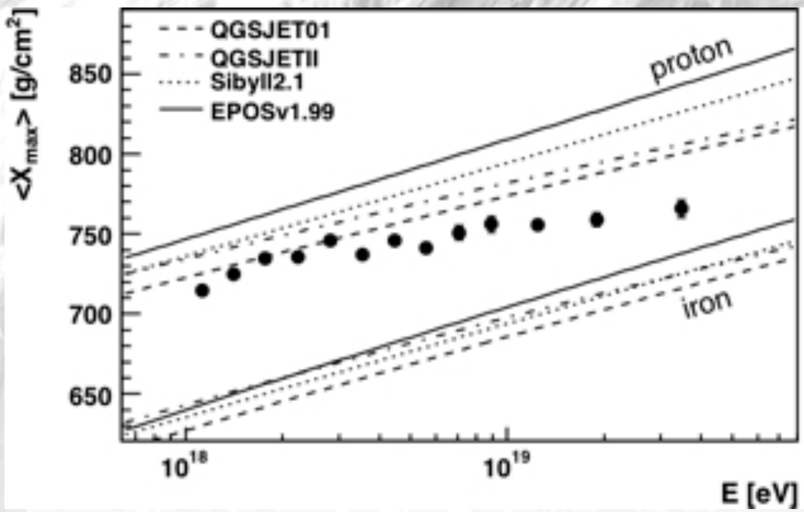
Chemical Composition, Nature of the Ankle

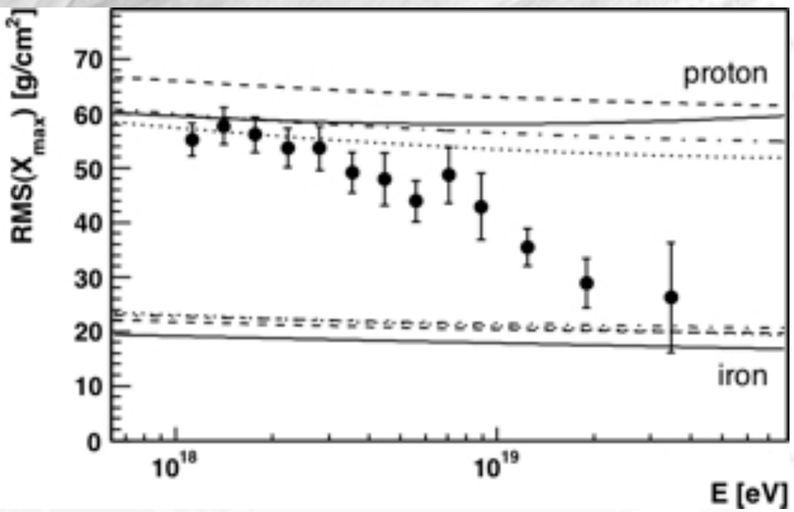


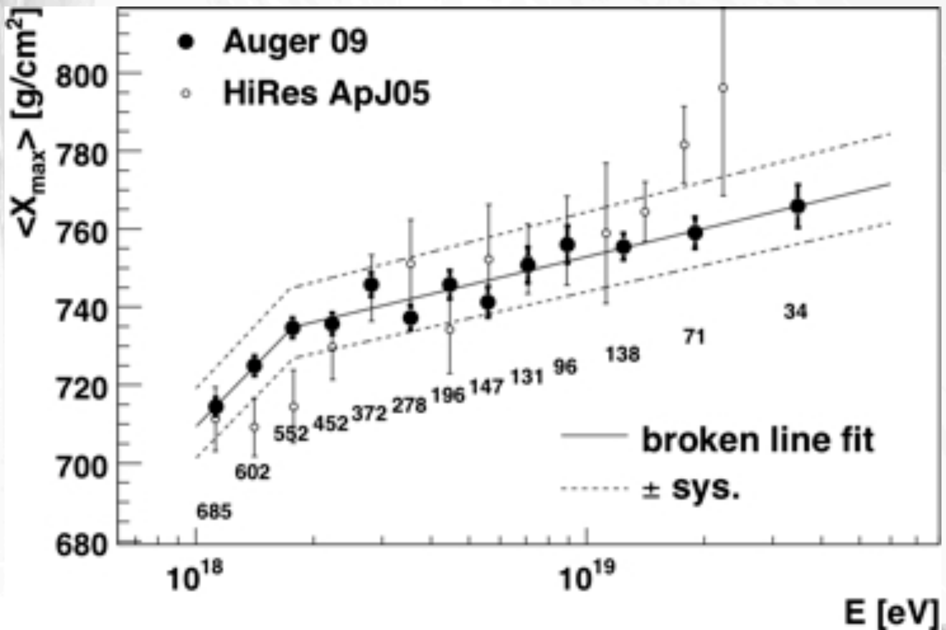
"Conventional Scenario":
The ankle at ~5×10^{18} eV is a crossover from a heavy Galactic to a light extragalactic component.

Scenario of Berezinsky et al.:
Galactic cosmic rays level out at the 2[nd] knee at ~4×10^{17} eV where dominated by heavy nuclei.
The ankle at ~5×10^{18} eV is due to pair production of extragalactic protons on the CMB. Requires >85% protons at the ankle.

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



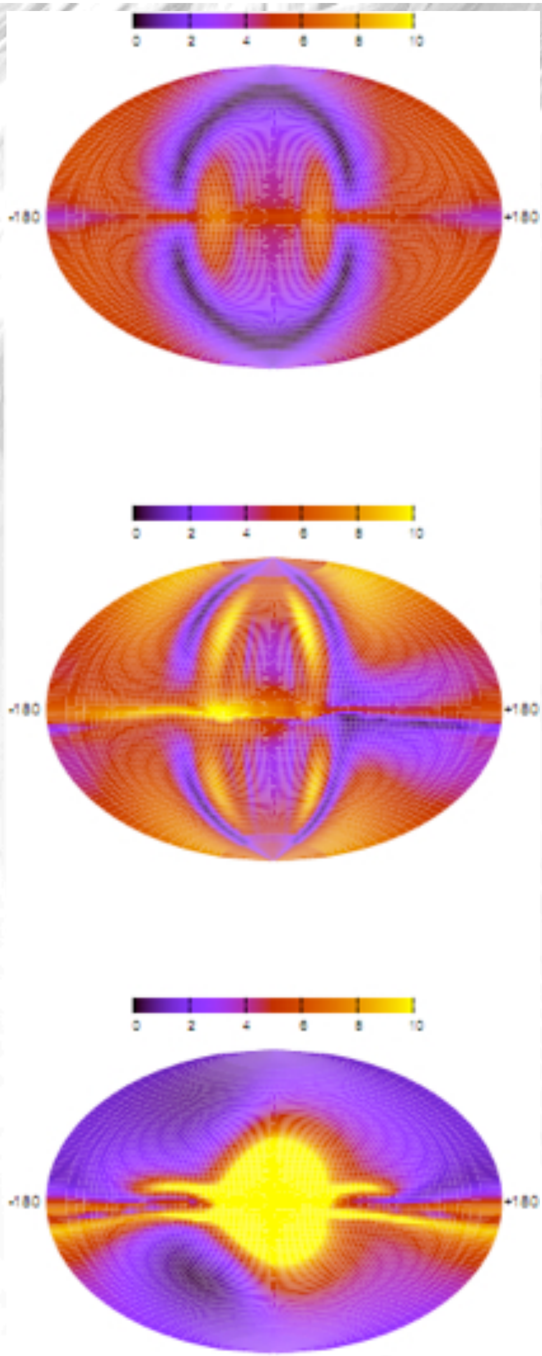




Auger data on composition seem to point to a quite heavy composition at the highest energies, whereas HiRes data seem consistent with a light composition.

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

HiRes Collaboration,
Phys.Rev.Lett. 104 (2010) 161101



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)

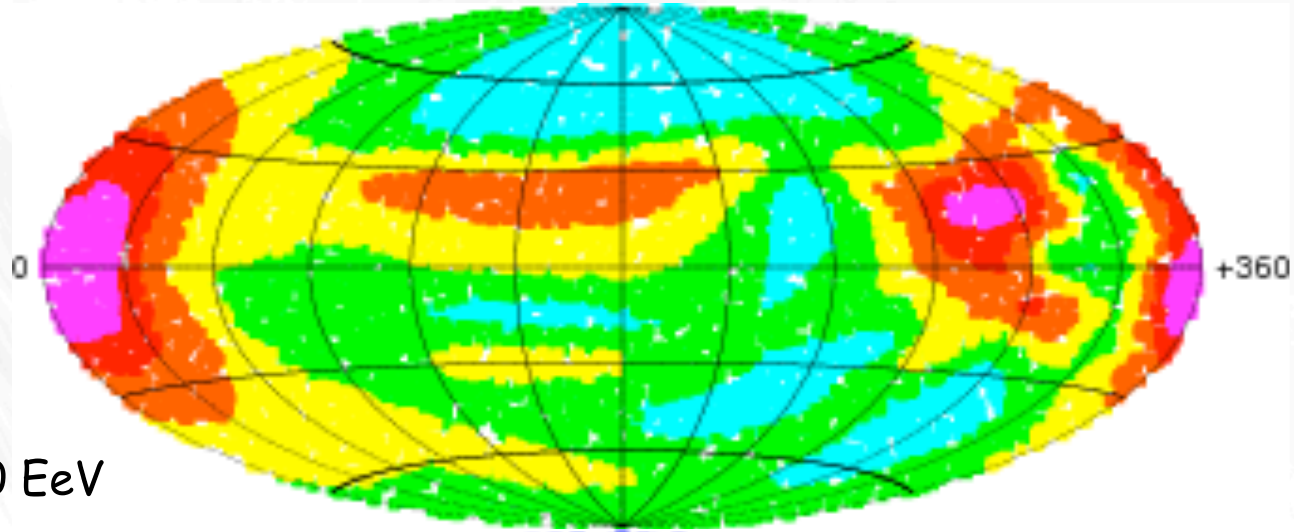
Prouza, Smida (bottom)

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

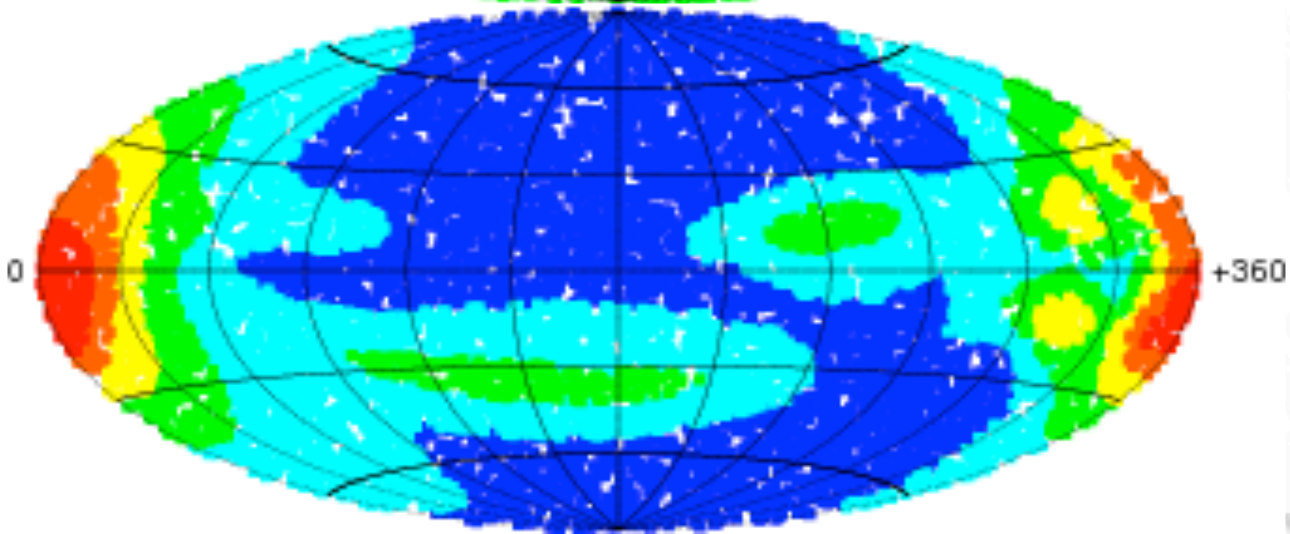
Kachelriess, Serpico, Teshima, Astropart. Phys. 26 (2006) 378

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

Angular range between 0 and 100 degrees, galactic coordinates



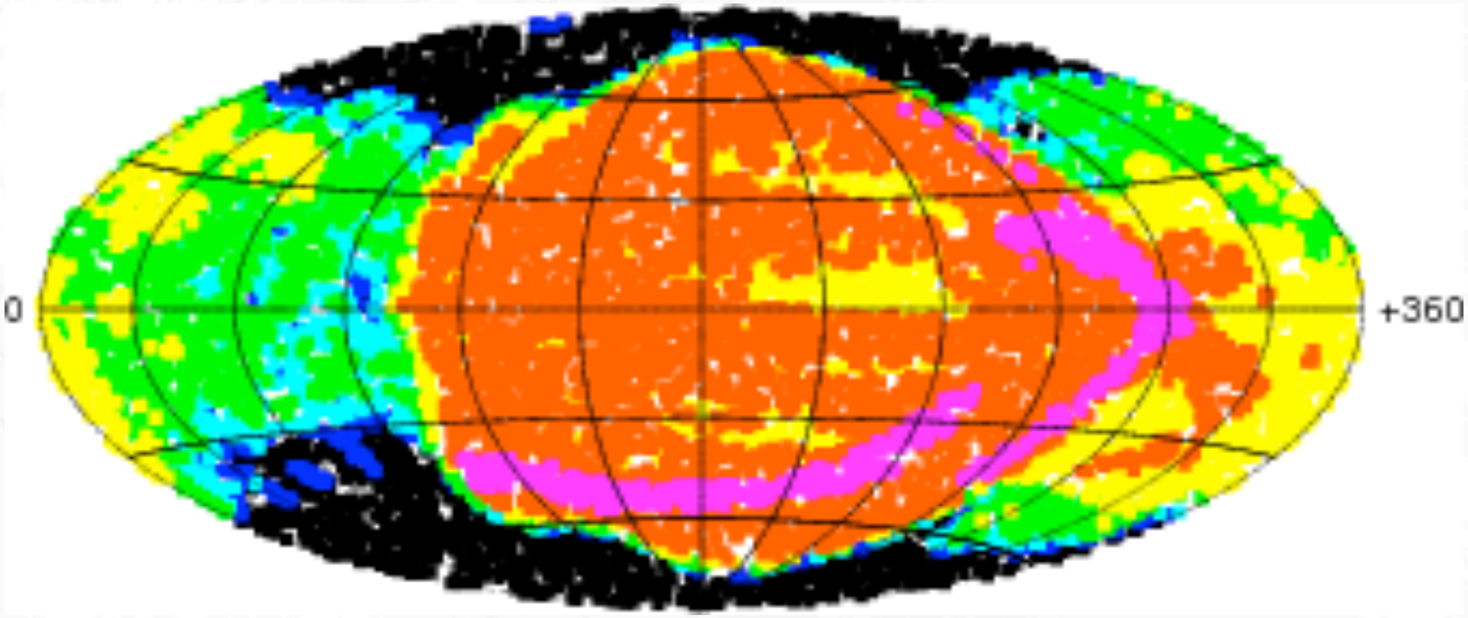
E=60 EeV



E=140 EeV

Giacinti, Kachelriess, Semikoz, Sigl, JCAP 1008 (2010) 036

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



E=60 EeV

Giacinti, Kachelriess, Semikoz, Sigl, JCAP 1008 (2010) 036

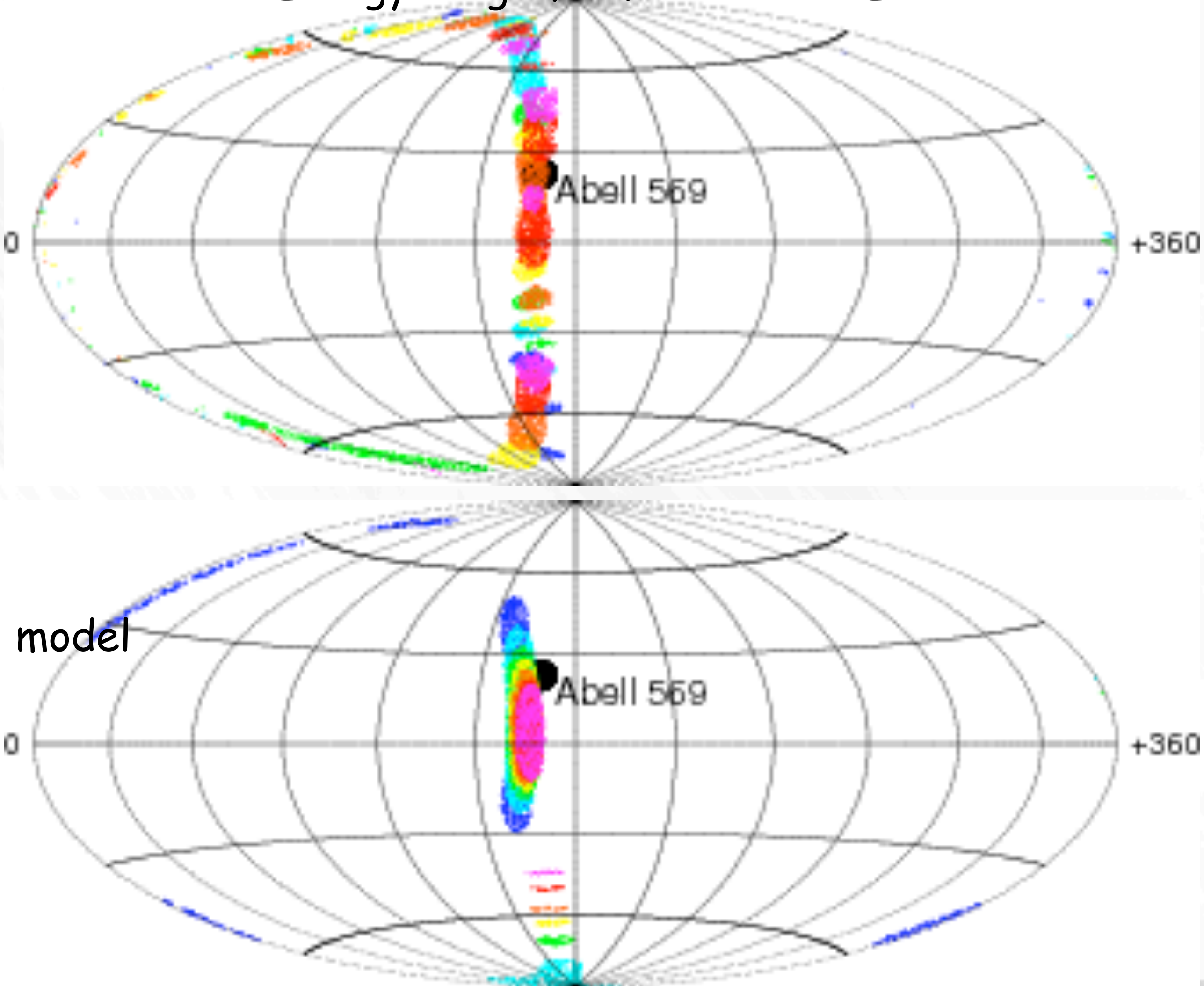
Density range between 10^{-3} and $10^{0.5}$, galactic coordinates

Highly anisotropic picture

Empty backtracked regions are invisible from within the Galaxy !

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

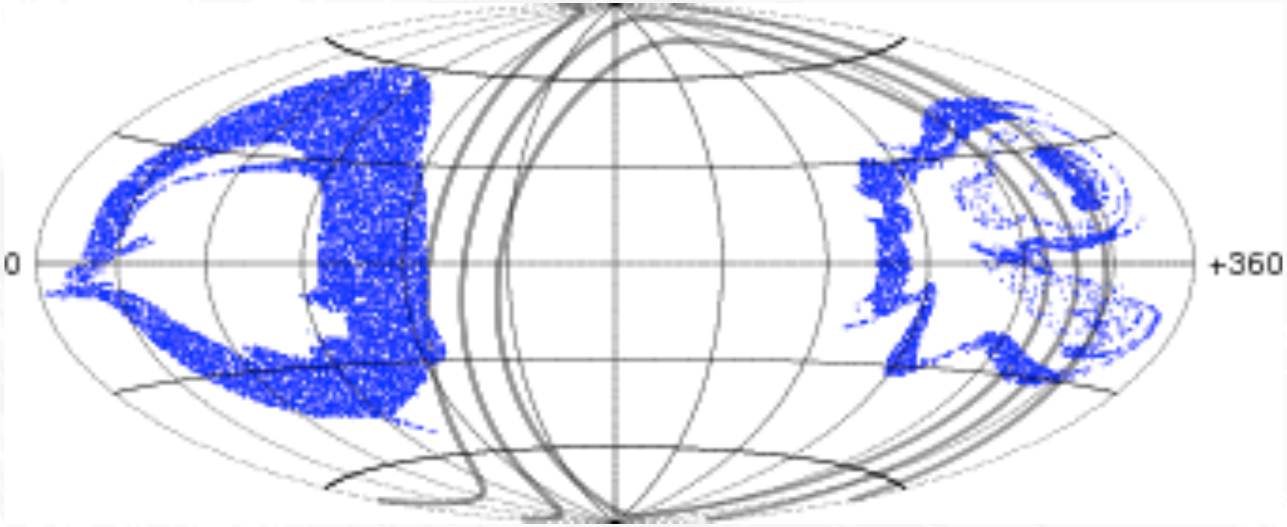
Energy range from 60 to 140 EeV

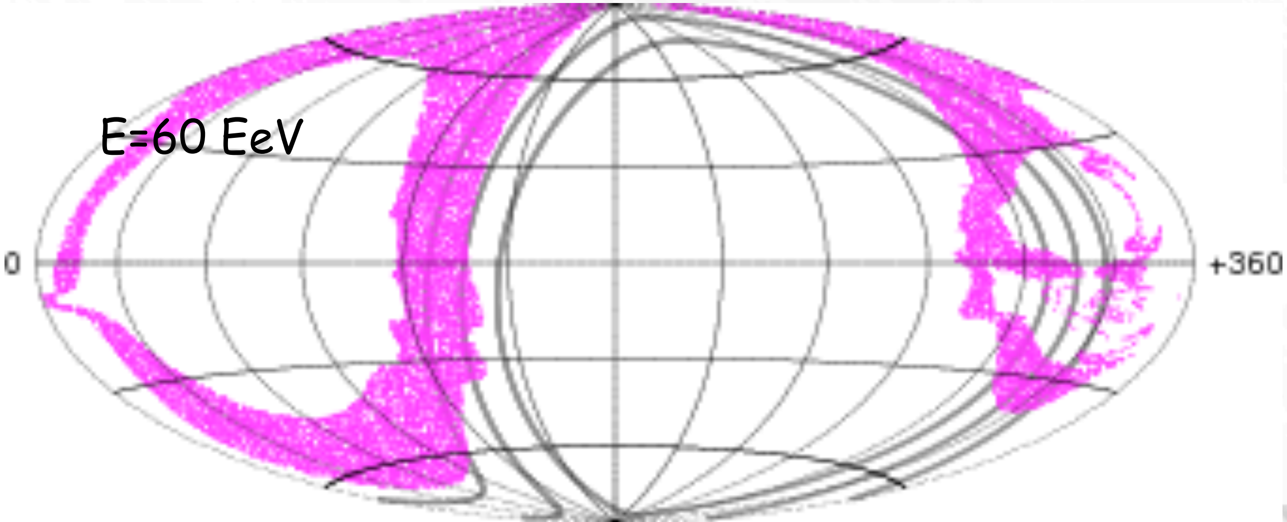


Sun08 model

Giacinti, Kachelriess, Semikoz, Sigl, JCAP 1008 (2010) 036

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





Giacinti, Kachelriess, Semikoz, Sigl, JCAP 1008 (2010) 036

“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

Extragalactic Ultra-High Energy Cosmic Ray Propagation and Magnetic Fields

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

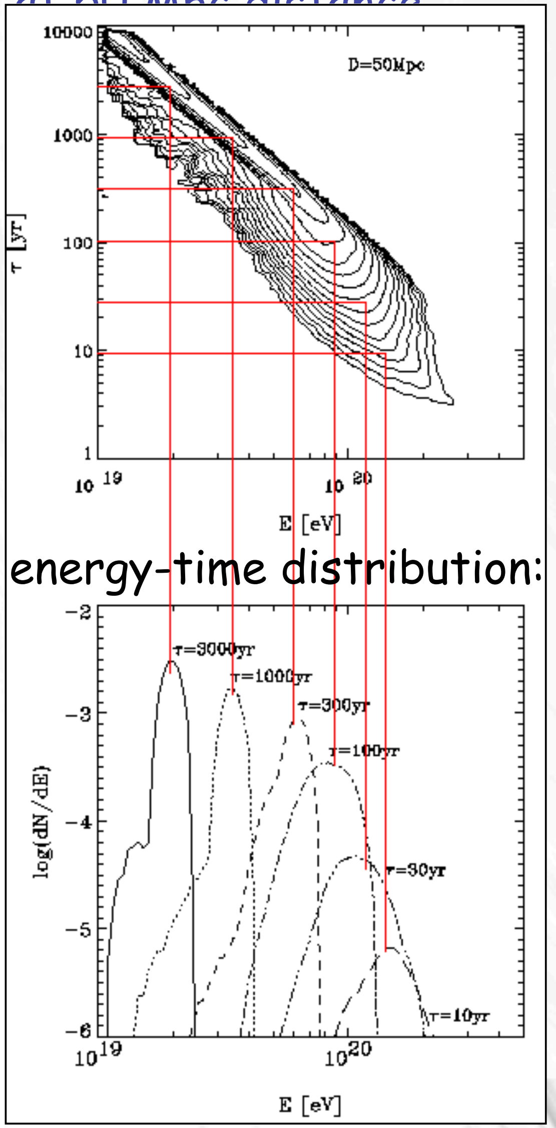
However, very little is known about about B_{XG}: It could be as small as 10^{-20} G (primordial seeds, Biermann battery) or up to fractions of micro Gauss if concentrated in clusters and filaments (equipartition with plasma).

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

$$E_c \sim 1.2 \times 10^{19} \left(\frac{Z}{26}\right) \left(\frac{d}{\mathrm{Mpc}}\right)^{1/2} \left(\frac{B_{\mathrm{rms}}}{\mathrm{nG}}\right) \left(\frac{\lambda_c}{\mathrm{Mpc}}\right)^{1/2} \mathrm{eV}$$

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

time delay

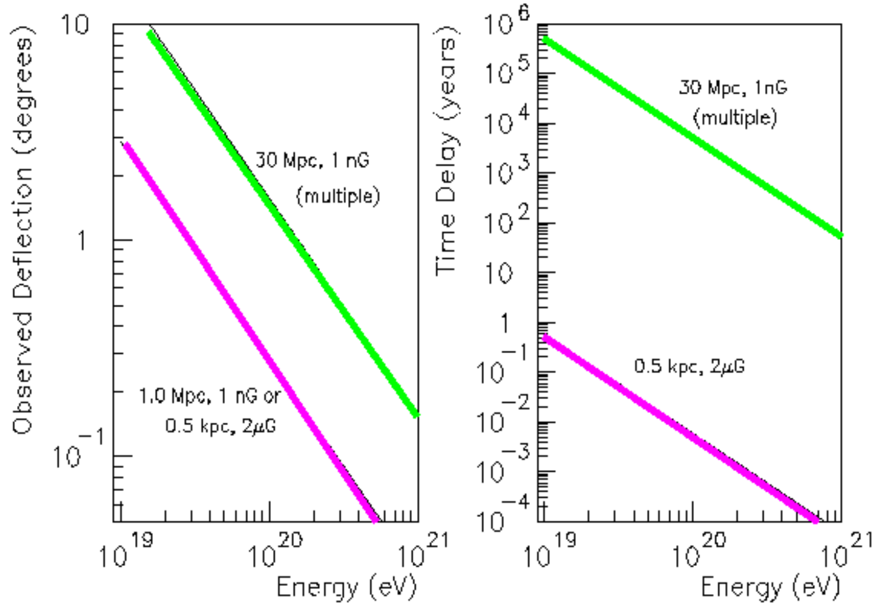


cuts through energy-time distribution:

differential spectrum

Lemoine, Sigl

Typical numbers:



Δθ for a vertical shower:

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

Transition rectilinear-diffusive regime

Neglect energy losses for simplicity.

Time delay over distance d in a field B_{rms} of coherence length λ_c for small deflection:

$$\tau(E,d) \simeq \frac{d\theta(E,d)^2}{4} \simeq 1.5\times10^3\,Z^2\left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-2}\left(\frac{d}{10\,\mathrm{Mpc}}\right)^2\left(\frac{B_{\rm rms}}{10^{-9}\,\mathrm{G}}\right)^2\left(\frac{\lambda_c}{\mathrm{Mpc}}\right)\,\mathrm{yr}$$

This becomes comparable to distance d at energy E_c:

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

In the rectilinear regime for total differential power Q(E) injected inside d, the differential flux reads

$$j(E) = \frac{Q(E)}{(4\pi d)^2}$$

In the diffusive regime characterized by a diffusion constant D(E), particles are confined during a time scale

$$\tau(E,d) \simeq \frac{d^2}{D(E)}$$

which leads to the flux

$$j(E) \simeq \frac{Q(E)\tau(E)}{(4\pi)^2 d^3} = \frac{Q(E)}{(4\pi)^2 d D(E)}$$

For a given power spectrum B(k) of the magnetic field an often used (very approximate) estimate of the diffusion coefficient is

$$D(E) \simeq \frac{r_g(E)}{3} \frac{B_{\rm rms}}{\int_{1/r_g(E)}^{\infty} dk k^2 \langle B^2(k) \rangle},$$

where $B_{rms}^2 = \int_0^\infty dk k^2 \langle B^2(k) \rangle$, and the gyroradius is

$$r_g(E) \simeq \frac{E}{ZeB_{\rm rms}} \simeq 110\, Z^{-1} \left(\frac{E}{10^{20}\,{\rm eV}}\right) \left(\frac{B_{\rm rms}}{10^{-6}\,{\rm G}}\right)^{-1} {\rm kpc}$$

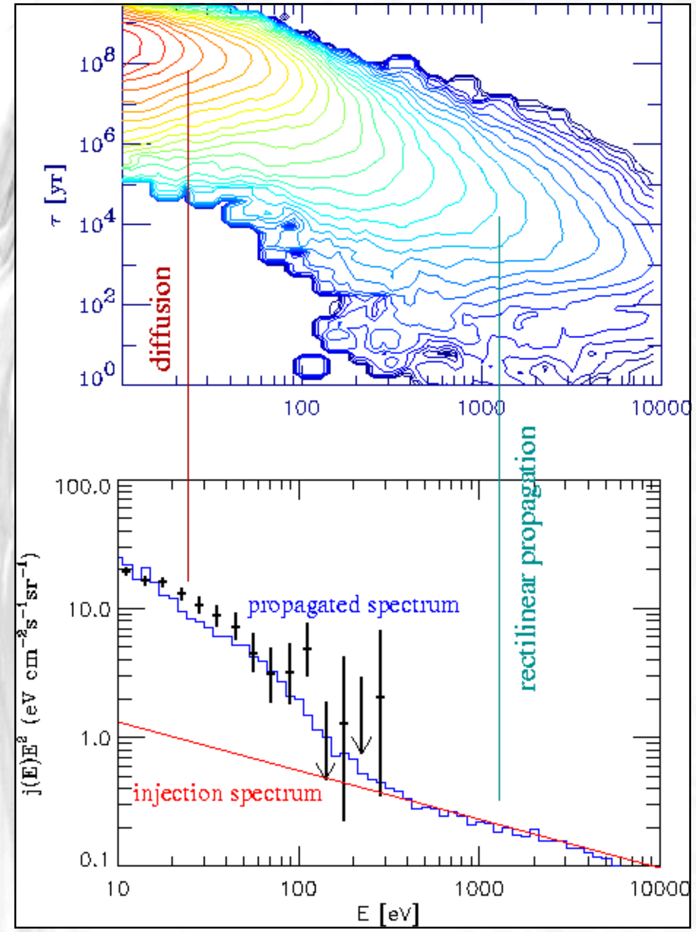
IF $E \ll E_c$ and IF energy losses can be approximated as continuous, $dE/dt=-b(E)$ (this is not the case for pion production), the local cosmic ray density $n(E,\mathbf{r})$ obeys the diffusion equation

$$\partial_t n(E,\mathbf{r}) + \partial_E \left[b(E)n(E,\mathbf{r})\right] - \nabla \cdot \left[D(E,\mathbf{r})\nabla n(E,\mathbf{r})\right] = q(E,\mathbf{r})$$

Where now $q(E,\mathbf{r})$ is the differential injection rate per volume, $Q(E)=\int d^3\mathbf{r}\, q(E,\mathbf{r})$. Analytical solutions exist (Syrovatskii), but the necessary assumptions are in general too restrictive for ultra-high energy cosmic rays.

Monte Carlo codes are therefore in general indispensable.

Transition rectilinear-diffusive regime: Summary



$$\tau(E) \propto d\theta^2 \propto \frac{d^2}{E^2}$$ in rectilinear regime

$$\tau(E,d) \simeq \frac{d^2}{D(E)}$$ in diffusive regime

$$j(E) \propto \frac{Q(E)}{d^2}$$ in rectilinear regime

$$j(E) \propto \frac{Q(E)\tau(E)}{d^3} \propto \frac{Q(E)}{dD(E)}$$ in diffusive regime

Simulated example: Continuous source distribution following Gaussian profile; $B=3\times10^{-7}$ G, d=10 Mpc, λ_c=1 Mpc.

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

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

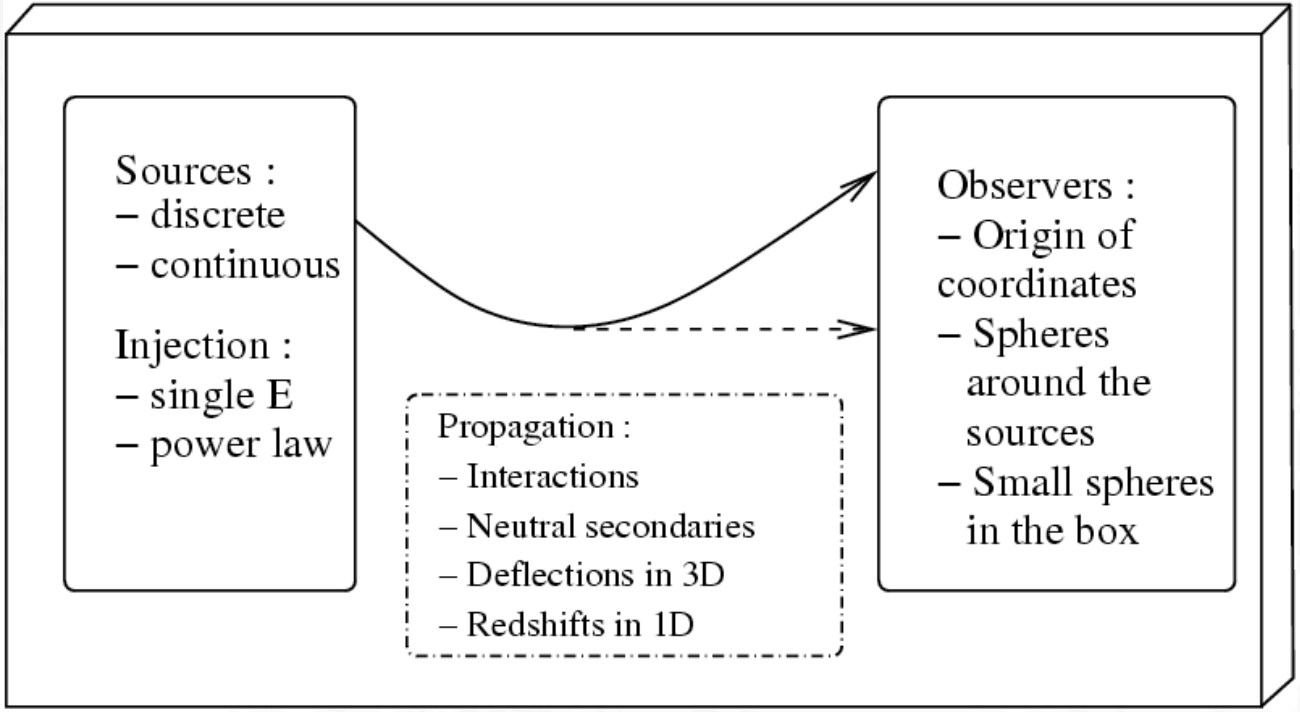
Principle of deflection Monte Carlo code

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 environments without symmetries.

Simulating Propagation of Ultrahigh Energy Cosmic Rays, Gamma-Rays and Neutrinos with CRPropa

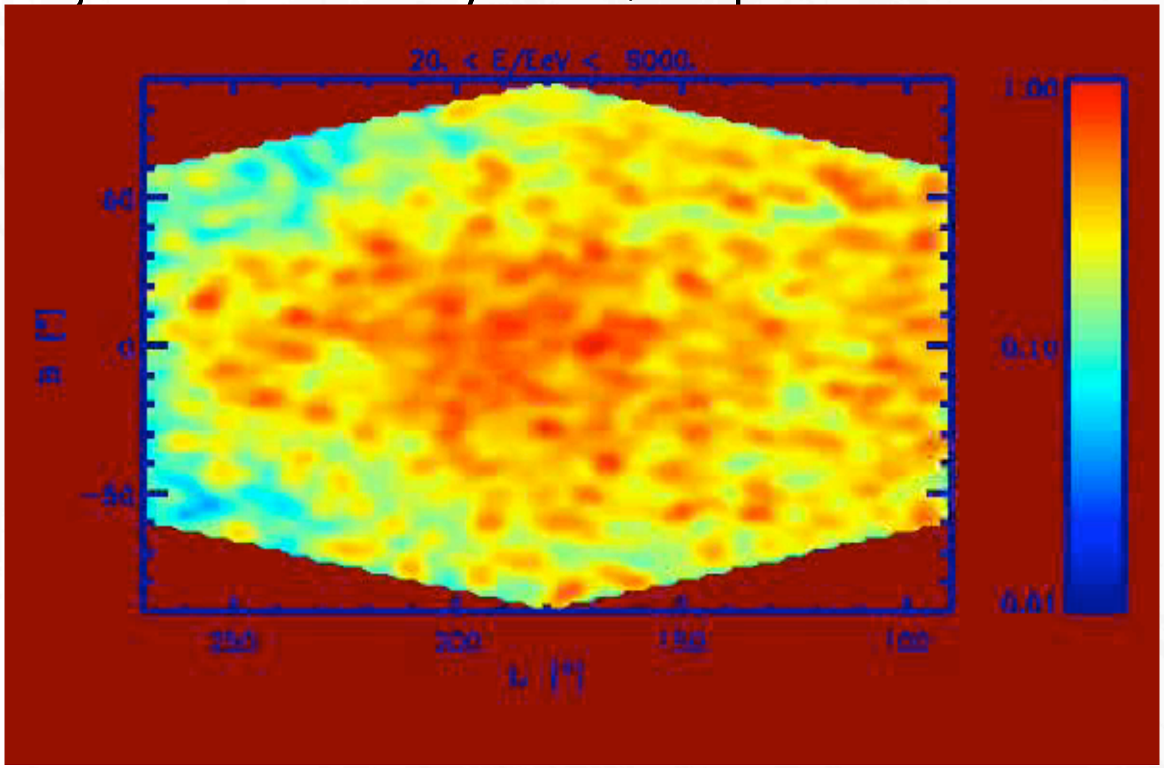
CRPropa is a public code for UHE cosmic rays, neutrinos and γ-rays being extended to heavy nuclei and hadronic interactions



Eric Armengaud, Tristan Beau, Günter Sigl, Francesco Miniati,
Astropart.Phys.28 (2007) 463.
http://apcauger.in2p3.fr/CRPropa/index.php
Now including: Jörg Kulbartz, Luca Maccione, Ricard Tomas, Mariam Tortola,
Nils Nierstenhoefer, Karl-Heinz Kampert, ...

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

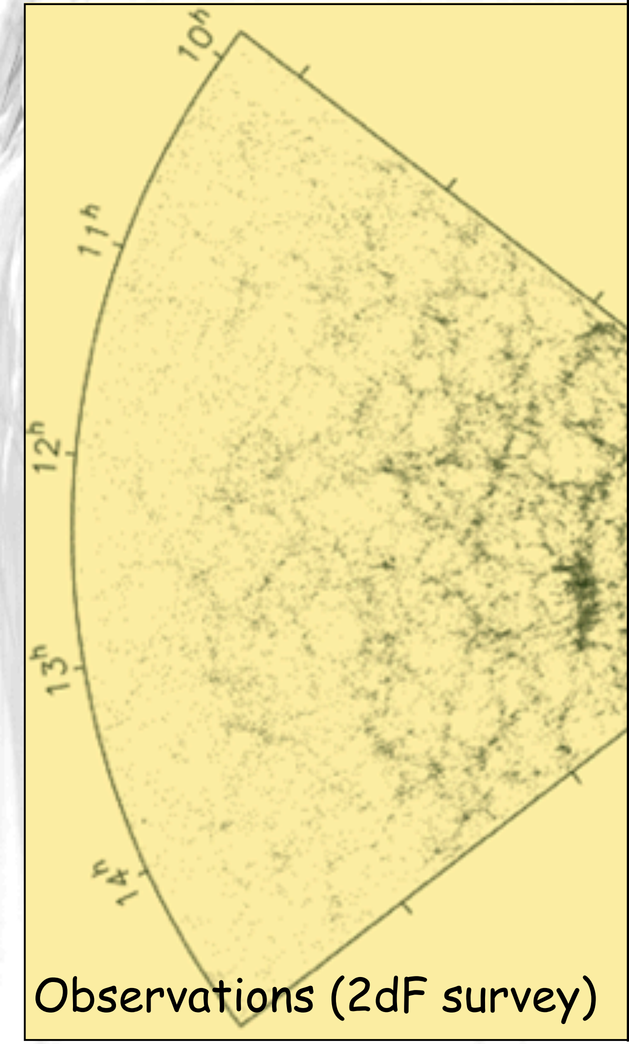
Isola, Lemoine, Sigl

Conclusions:

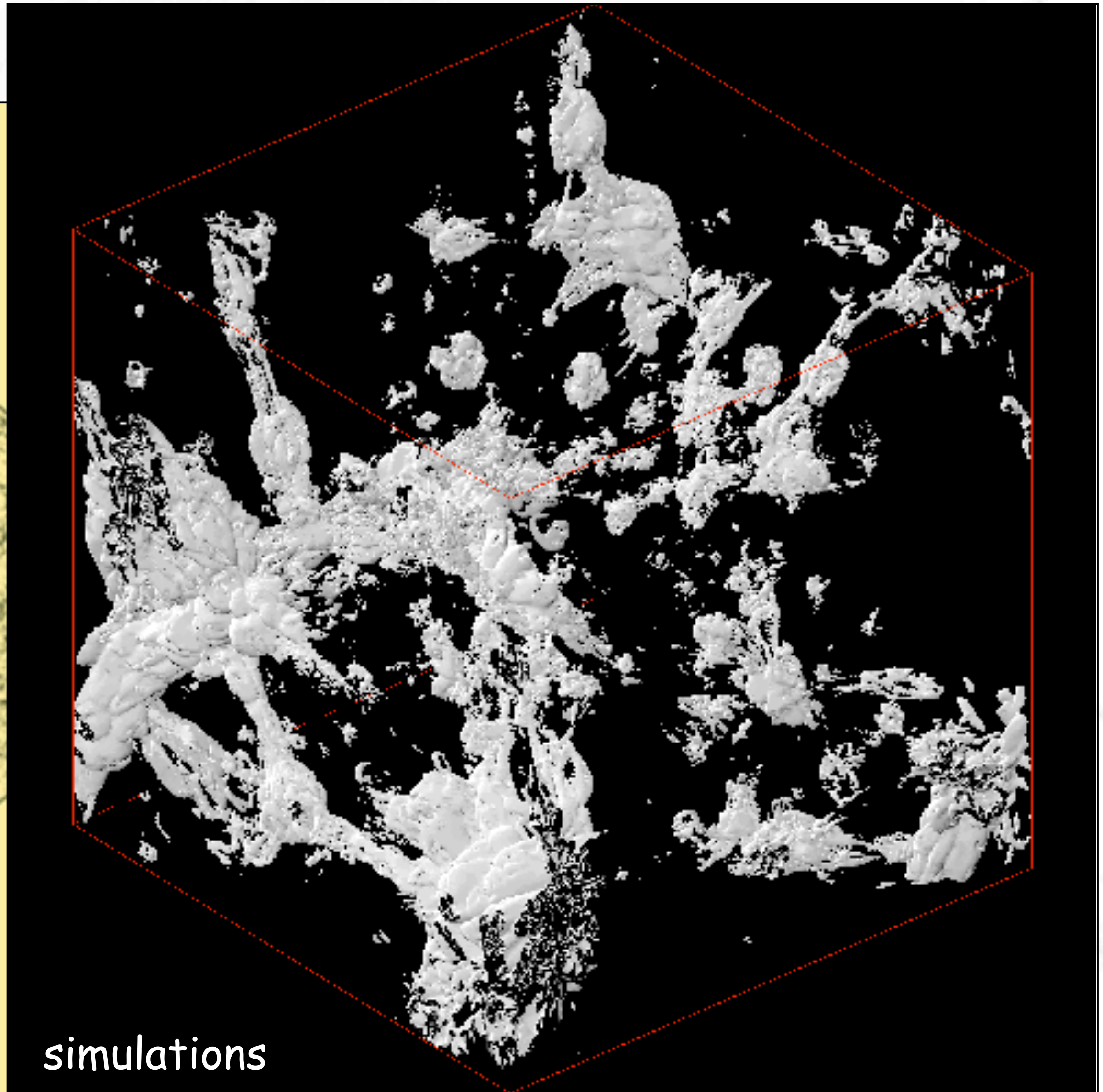
1.) Isotropy is inconsistent with only one source.

2.) Strong fields produce interesting lensing (clustering) effects.

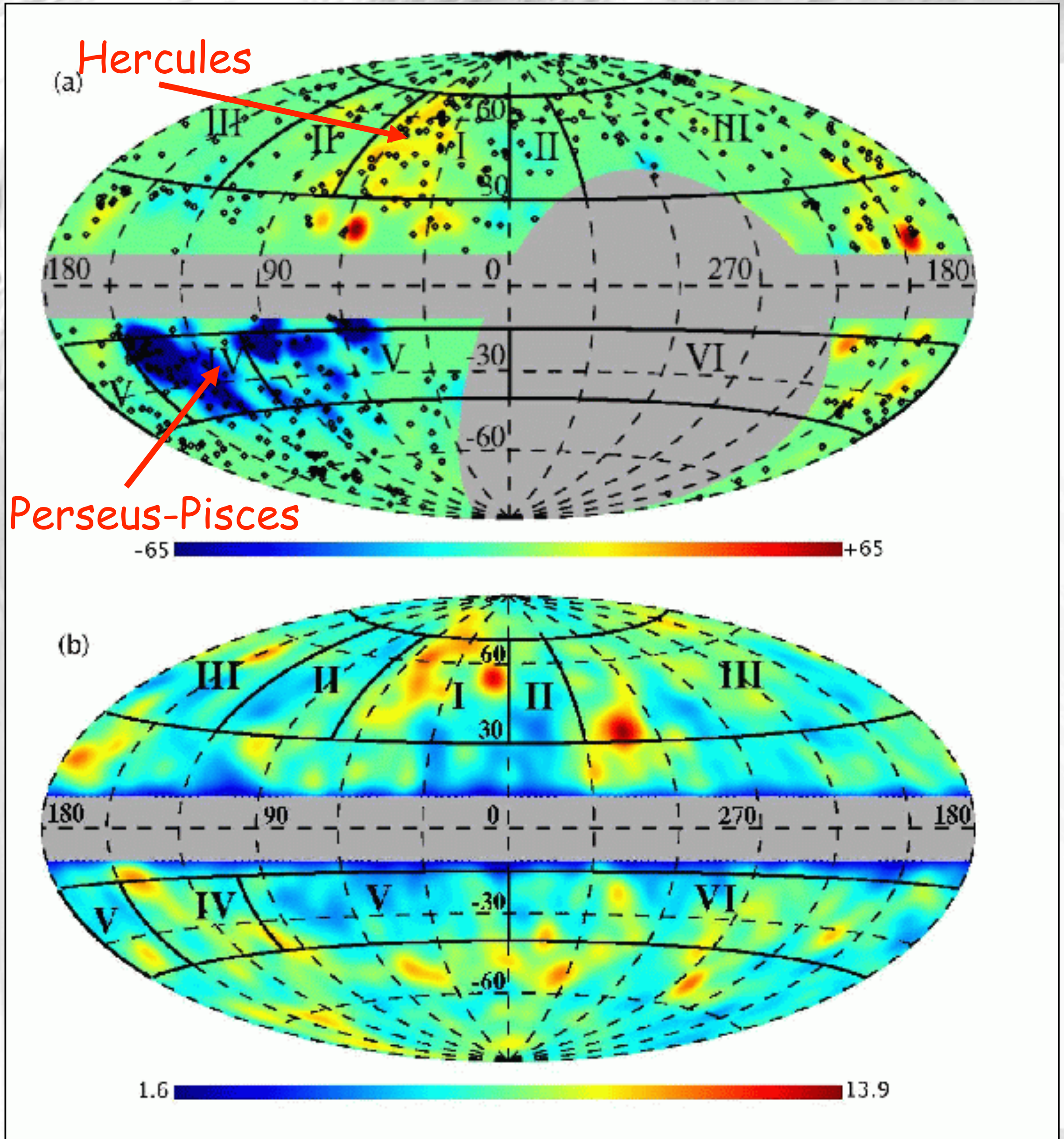
The Universe is structured



Observations (2dF survey)



simulations



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

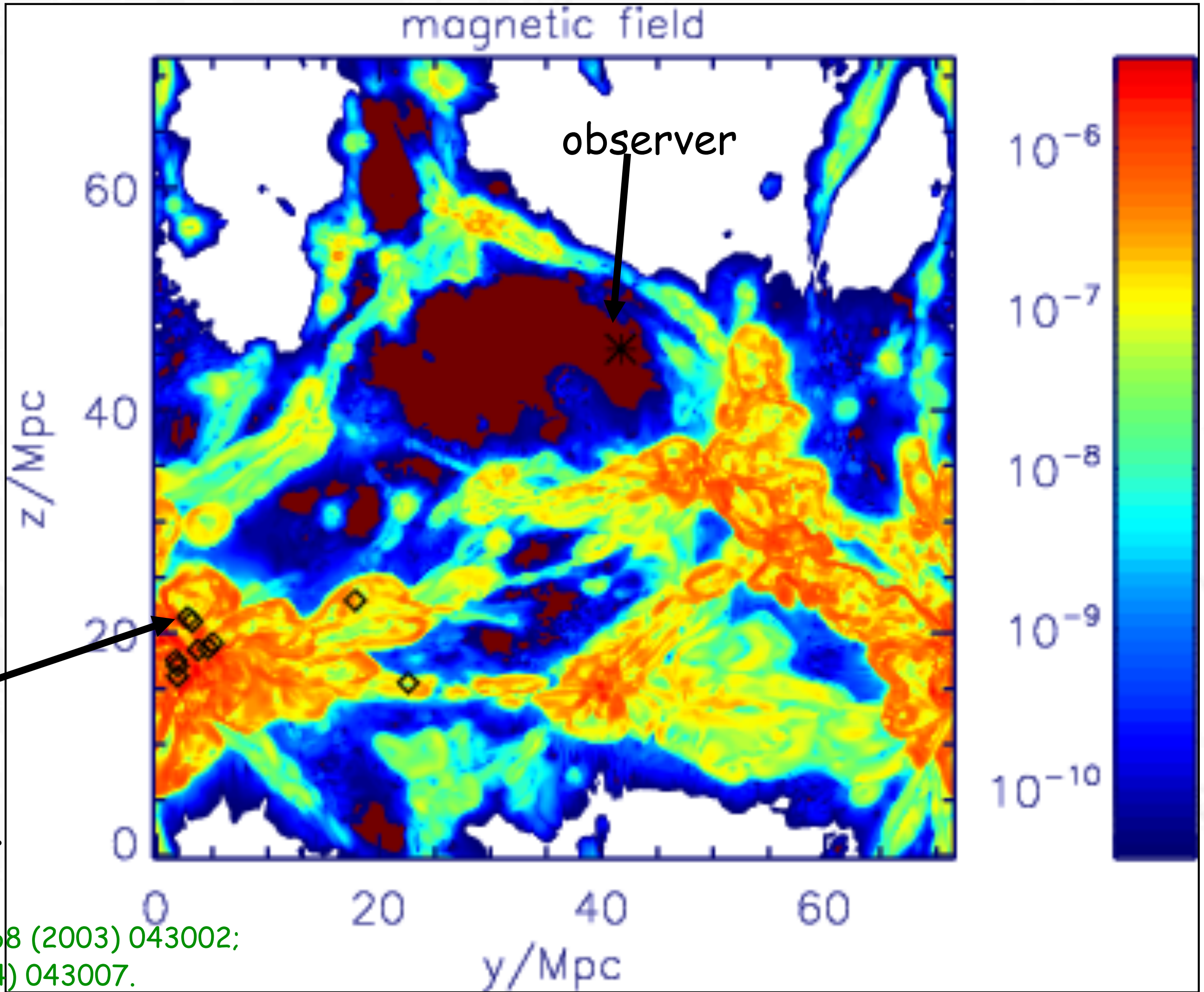
But need much more data from radio astronomy, e.g. Lofar, SKA

2MASS galaxy column density

Xu et al., astro-ph/0509826

Propagation in structured extragalactic magnetic fields

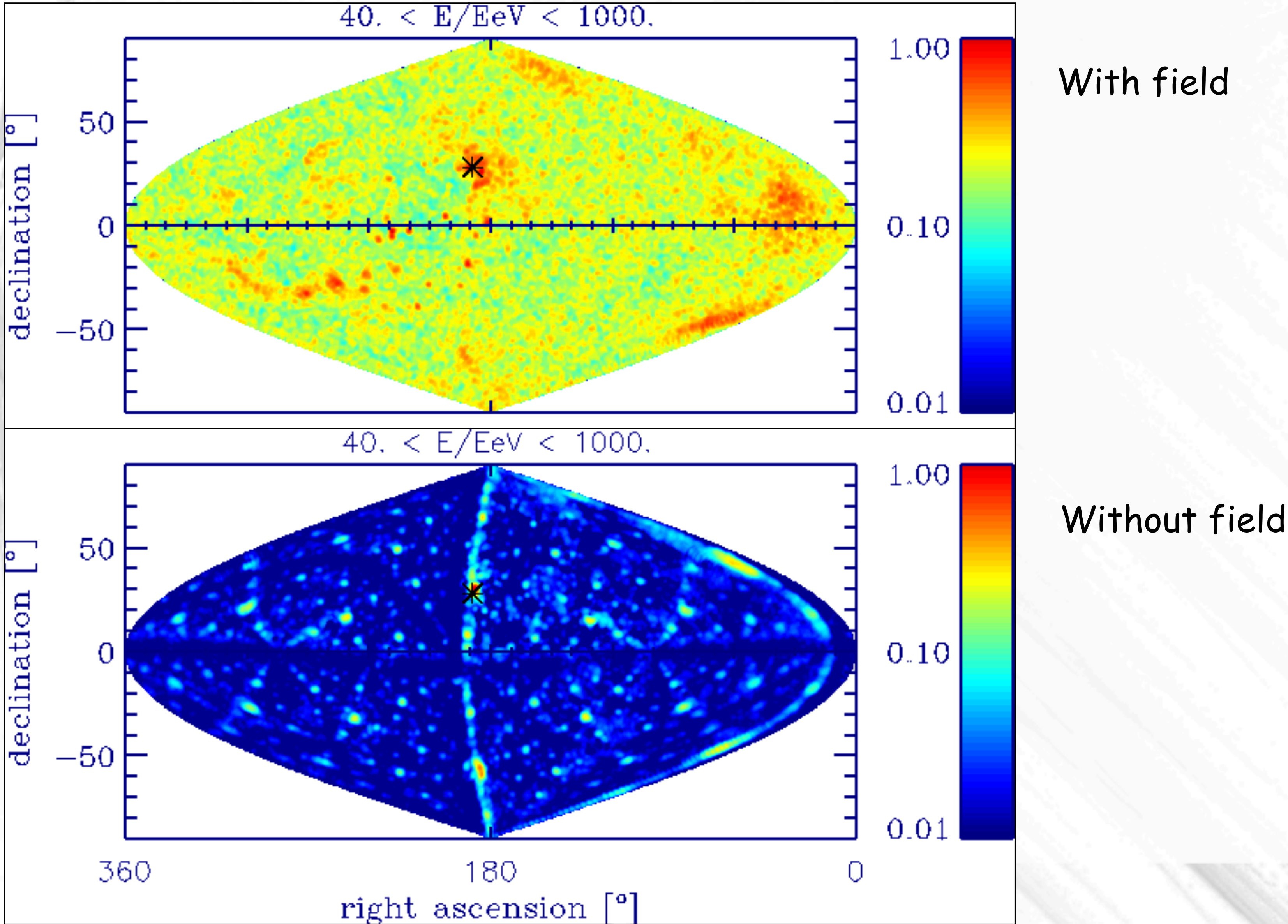
Scenarios of extragalactic magnetic fields using large scale structure simulations with magnetic fields reaching few micro Gauss in galaxy clusters.



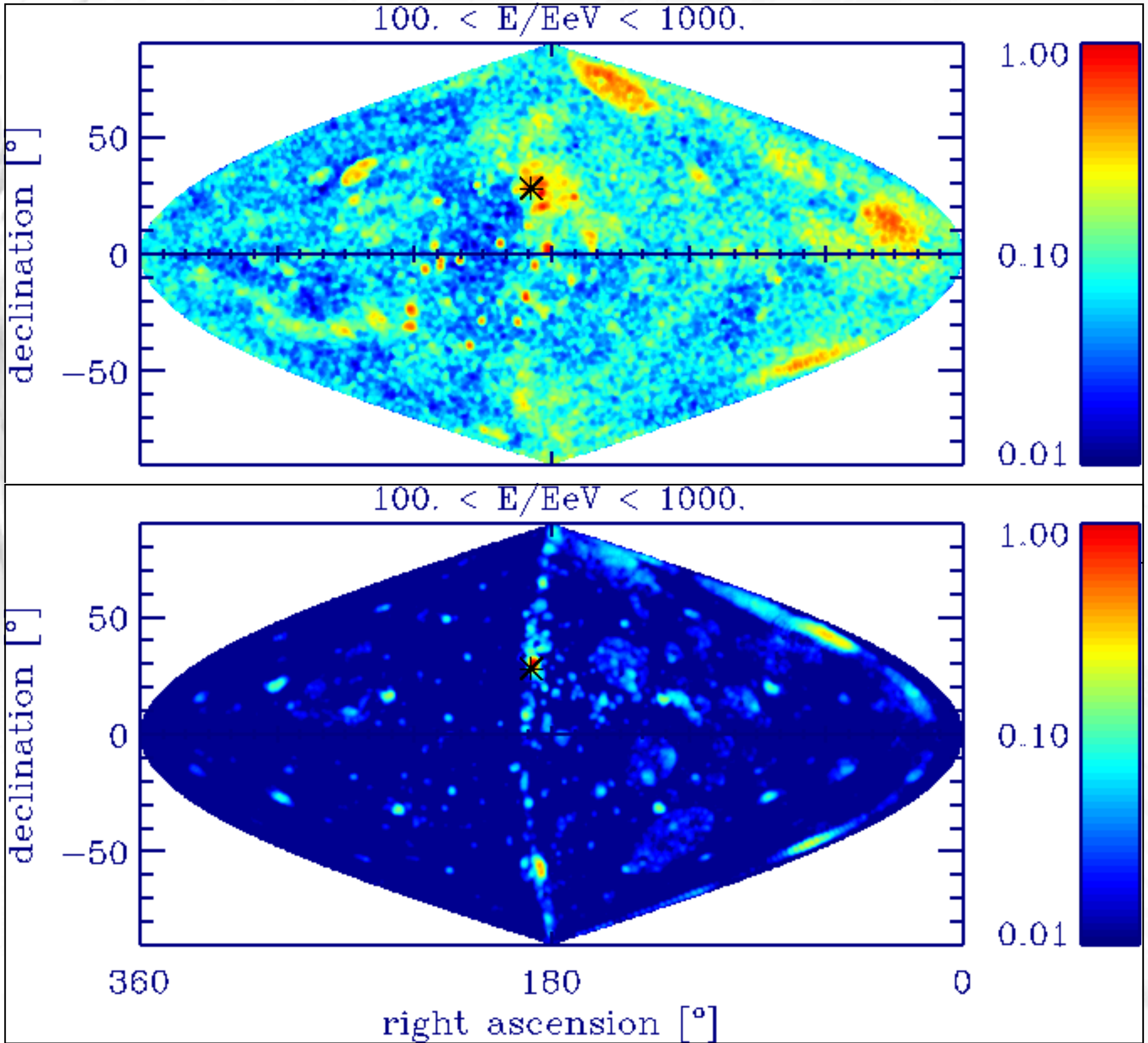
Discrete sources of density ~10^{-5} Mpc^{-3} follow baryon density, field at Earth ~10^{-11} G.

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

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

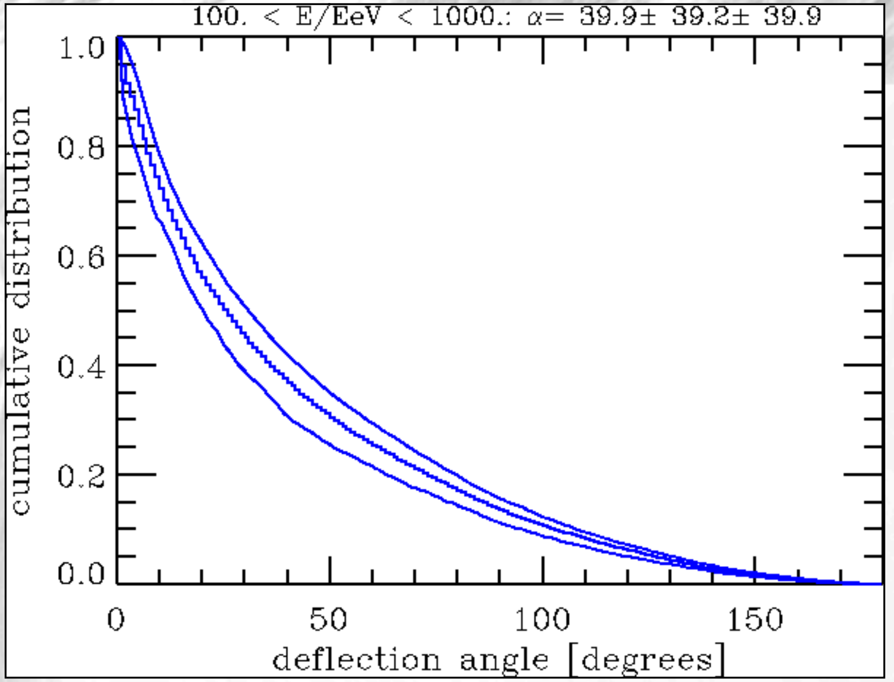


The simulated sky above 10^{20} eV with structured sources of density 2.4×10^{-5} Mpc^{-3} : ~2×10^{5} simulated trajectories above 10^{20} eV.



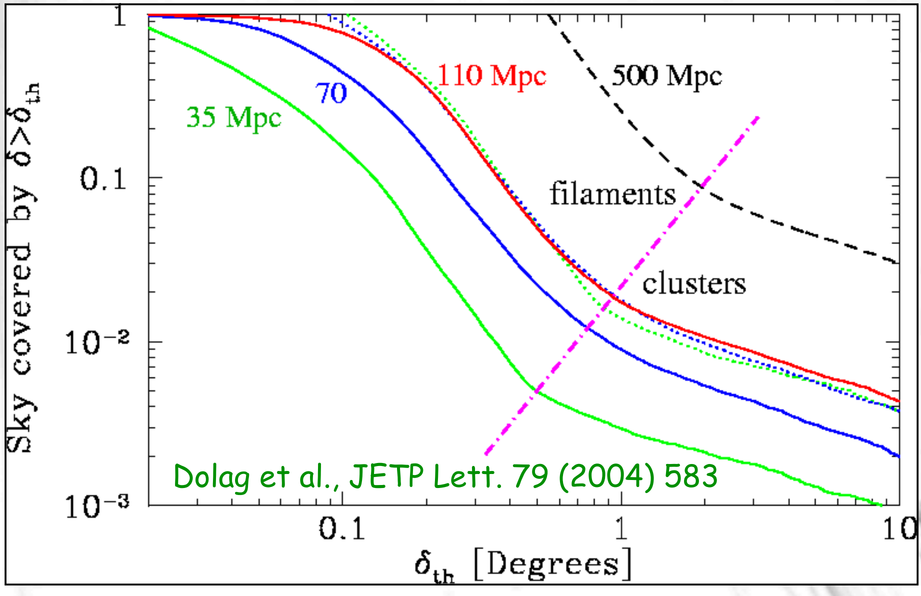
With field

Without field



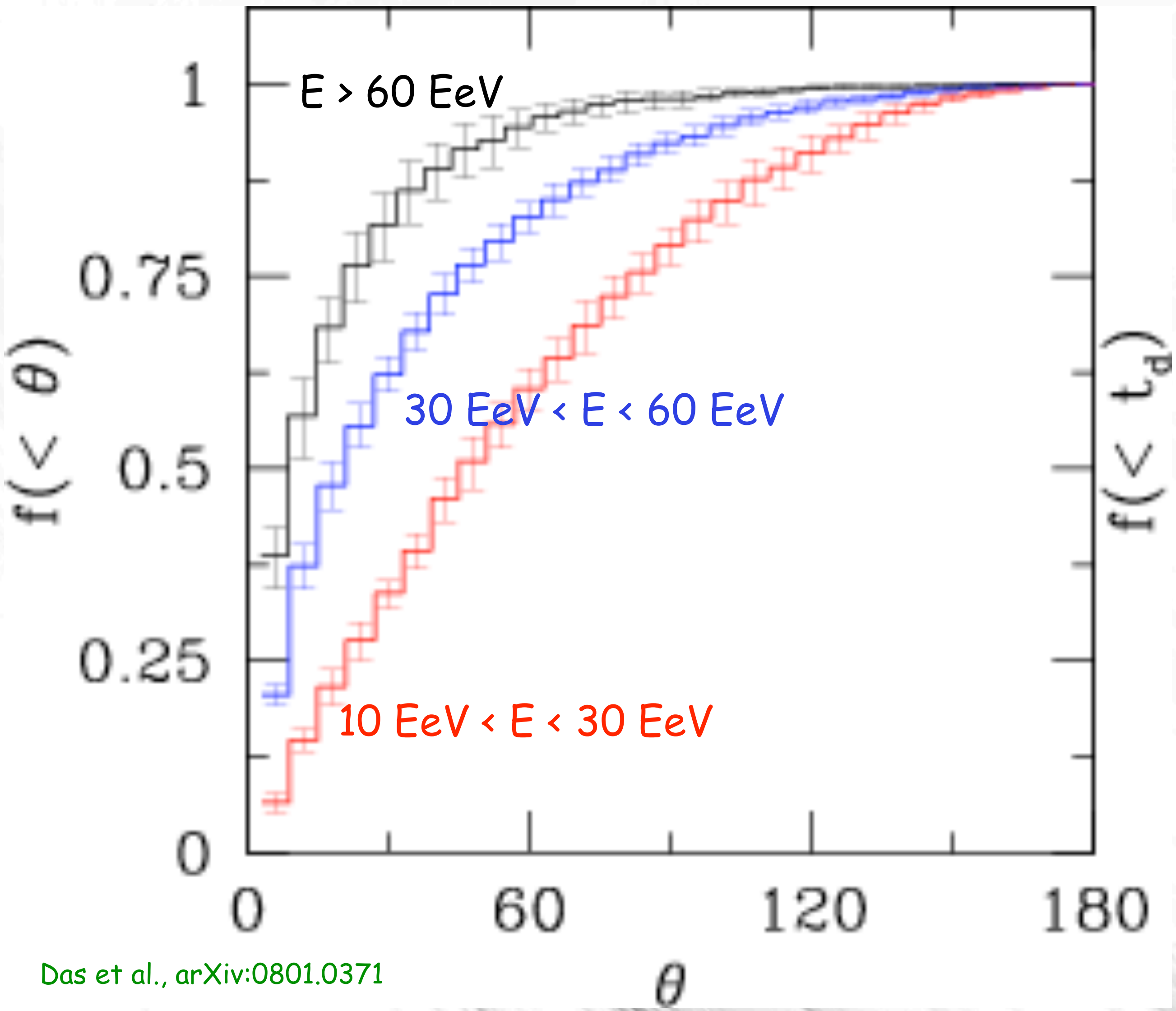
Deflection in magnetized structures surrounding the sources lead to off-sets of arrival direction from source direction up to >10 degrees up to 10^{20} eV in our simulations. This is contrast to Dolag et al., JETP Lett. 79 (2004) 583.

Particle astronomy not necessarily possible, especially for nuclei !

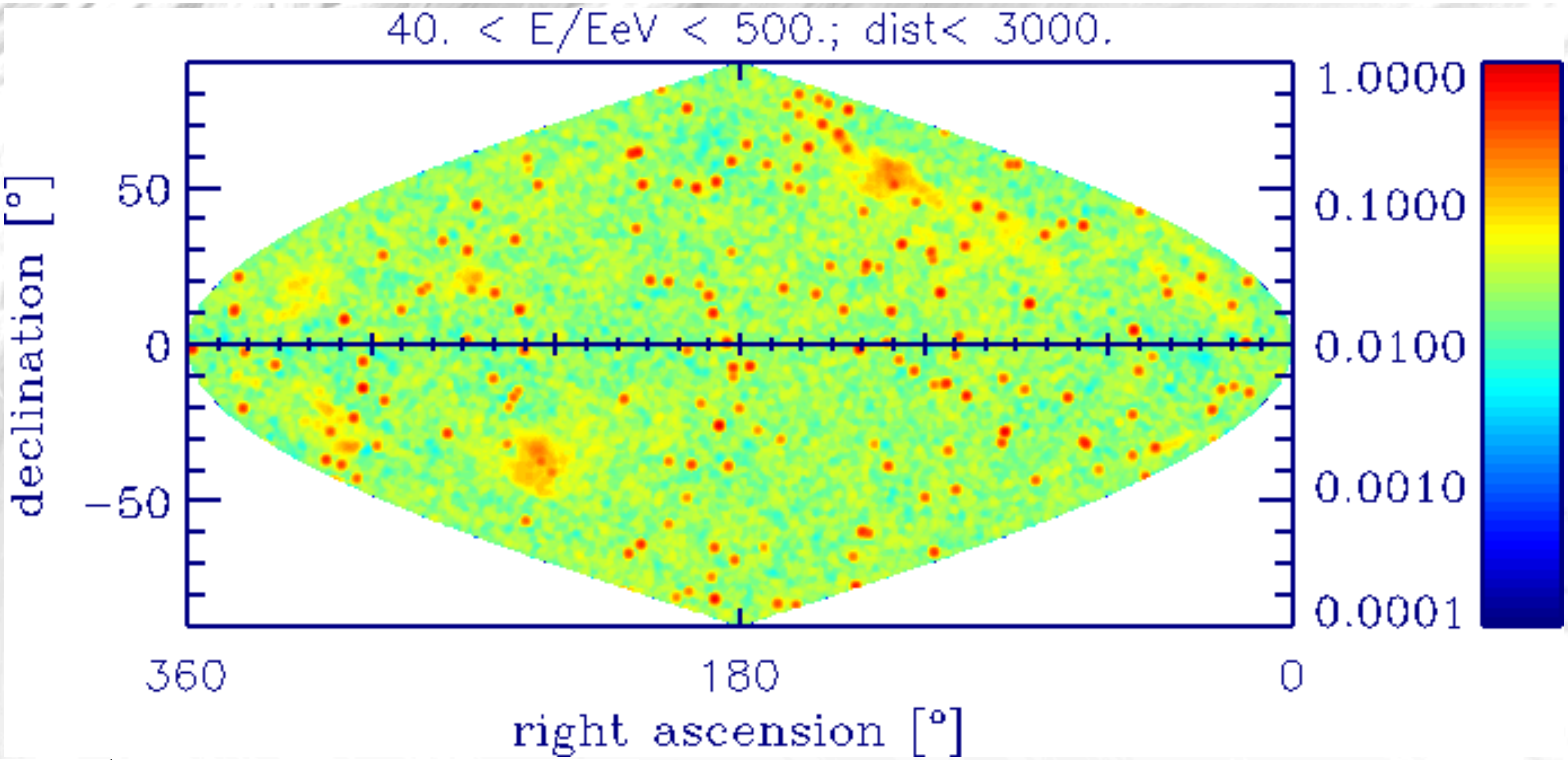


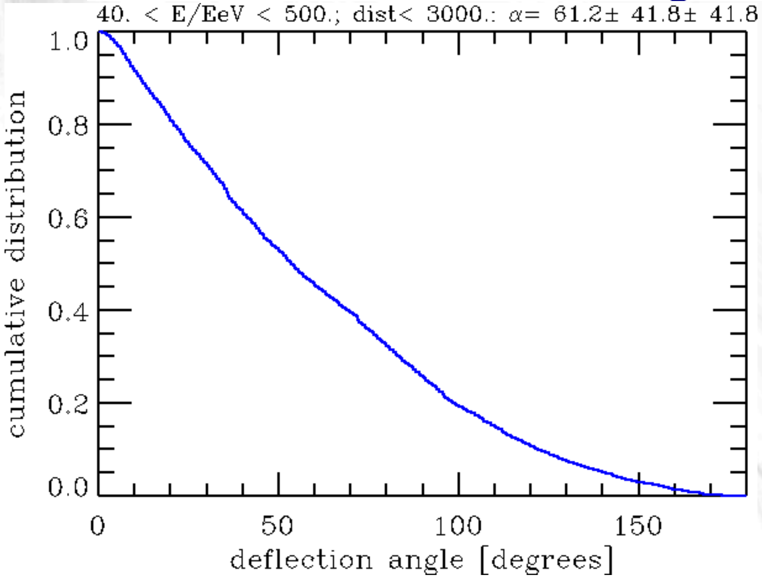
Cumulative deflection angle distributions for proton primaries

Recent results give intermediate and still significant deflections for proton primaries:

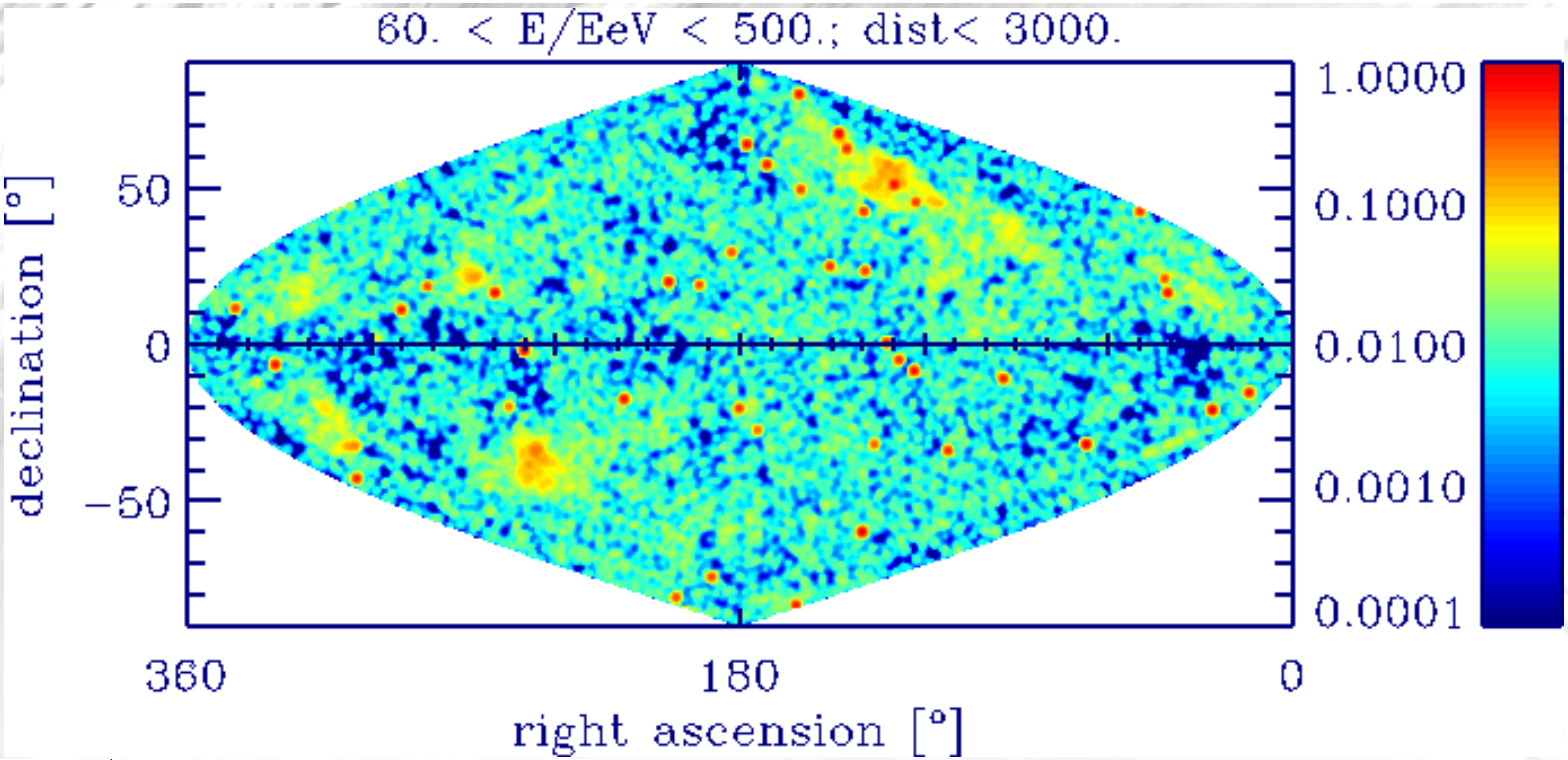


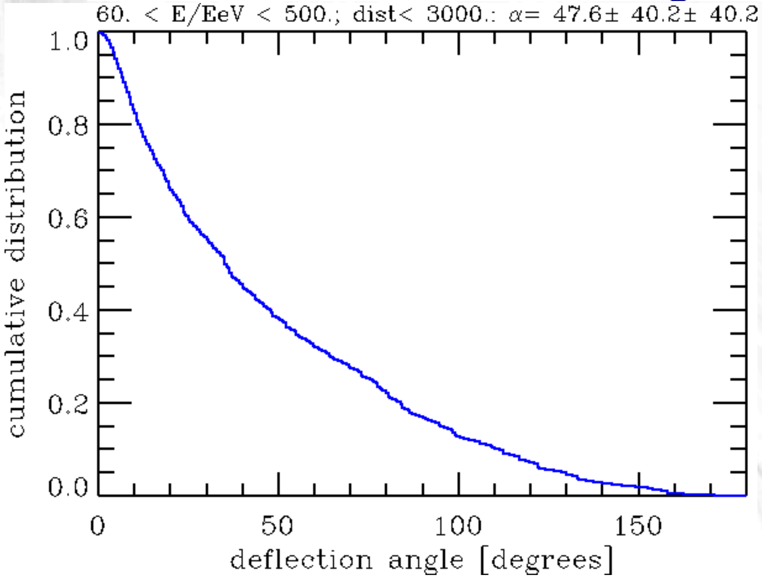
Das et al., arXiv:0801.0371



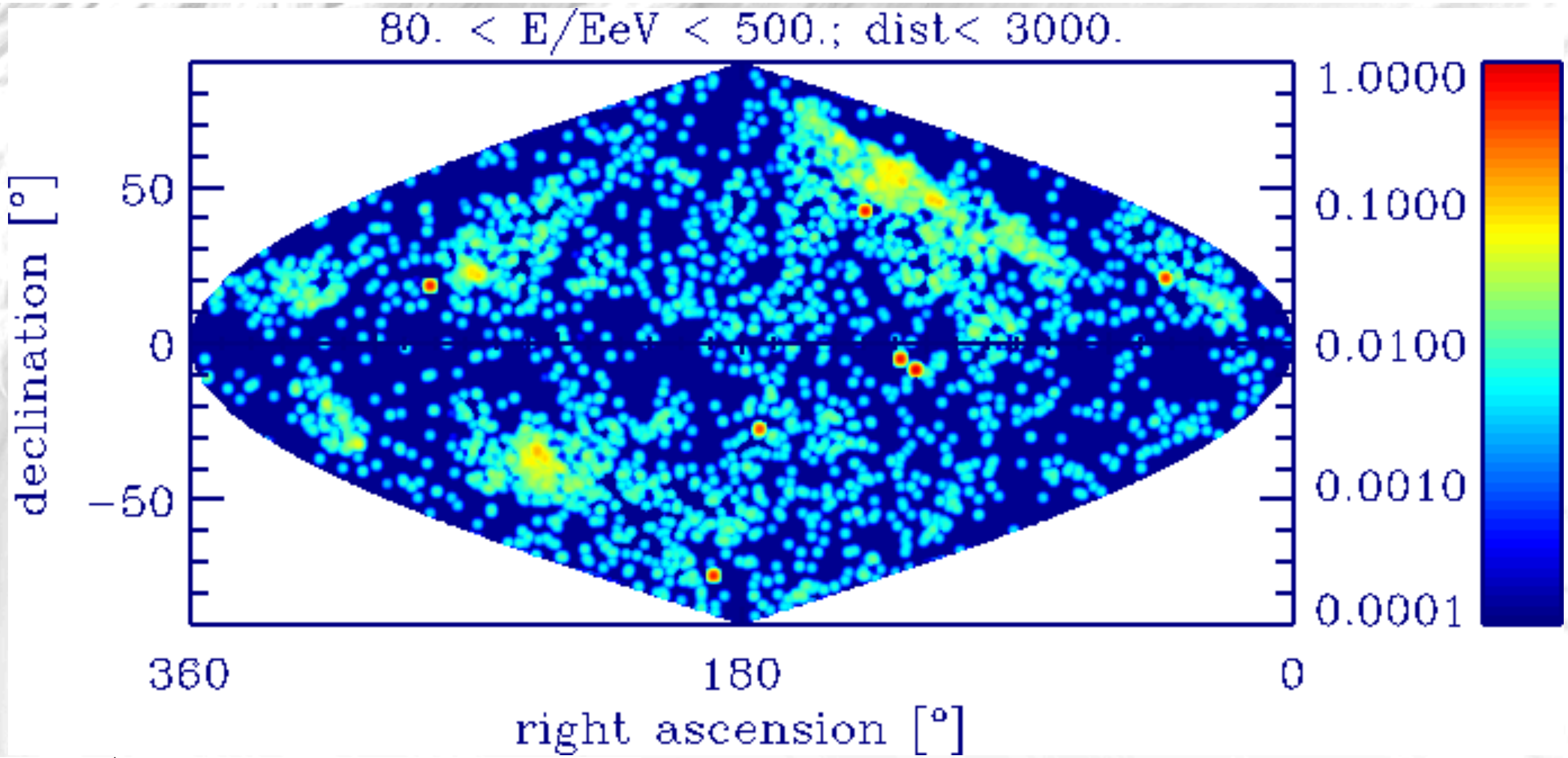


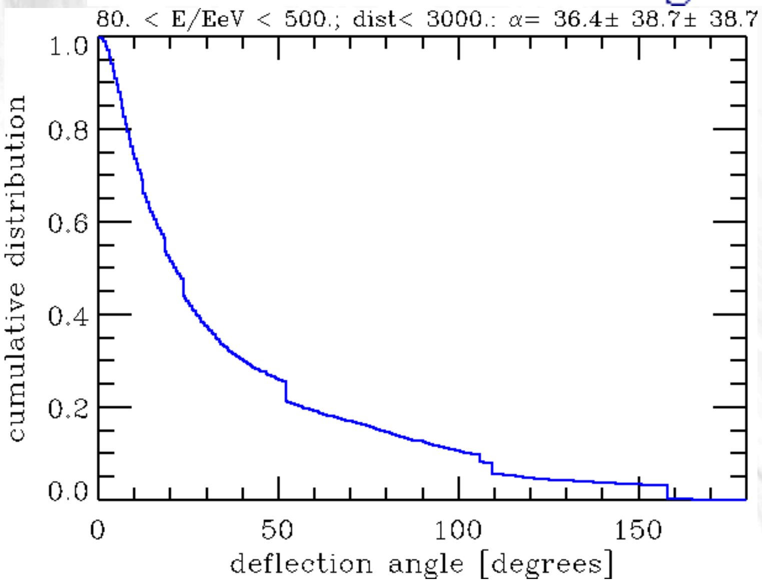
Sky distributions for iron primaries above 40 EeV, $E^{-2.2}$ injection up to 10^{22} eV



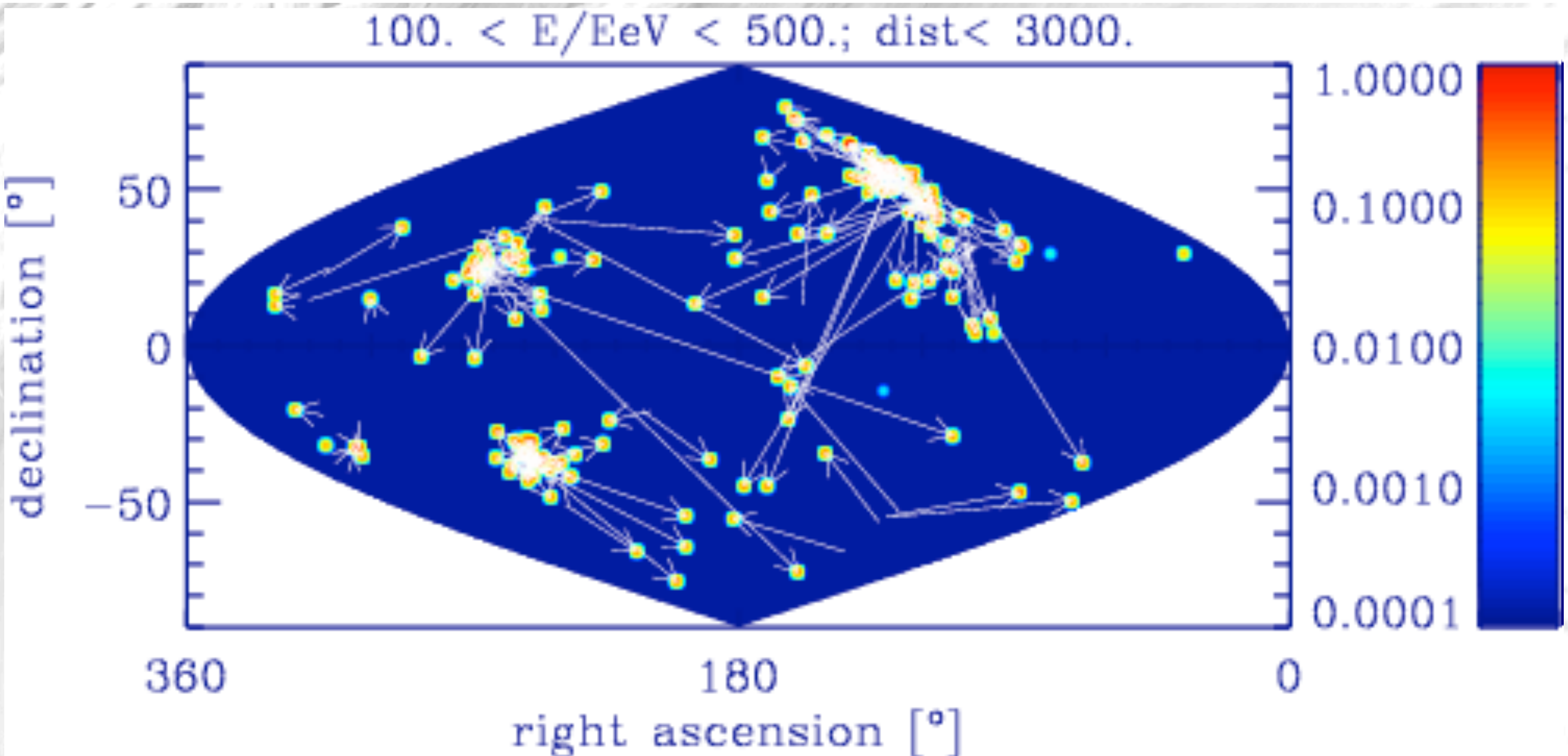


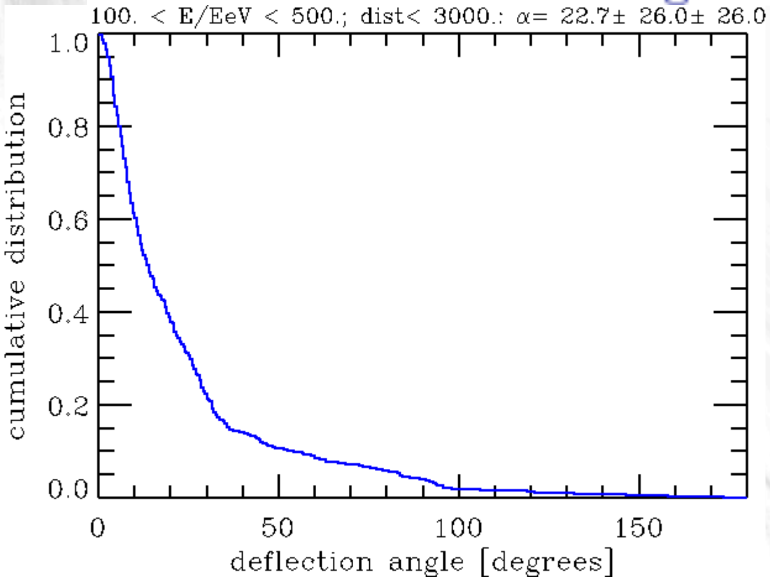
Sky distributions for iron primaries above 60 EeV, $E^{-2.2}$ injection up to 10^{22} eV





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