UHECRs and the Galactic magnetic field

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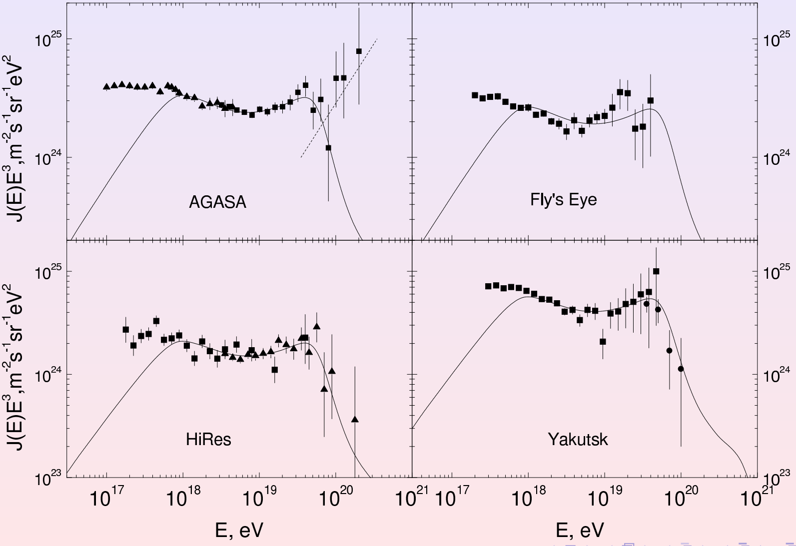
Two outstanding questions:

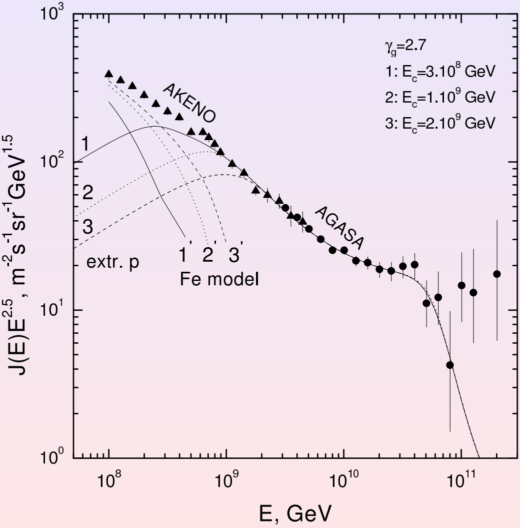
- Is astronomy with UHECRs possible?
  - protons vs nuclei as primaries
  - role of magnetic fields
- Is physics beyond the SM needed to explain UHECR events?
  - energy spectrum consistent with GZK suppression?
    - suppression depends on number of sources, their minimal distances, magnetic fields, . . .
  - correlations with sources at cosmological distances?

Cosmic ray spectrum: the dip at 10^{19} eV

[Berezinsky, Grigorieva, Hnatyk '04]



Transition to extragalactic protons



[Berezinsky, Grigorieva, Hnatyk '04]

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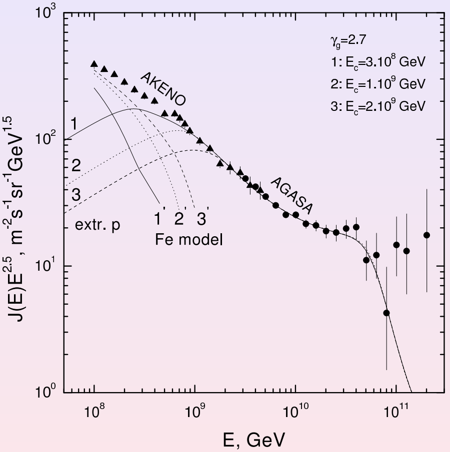
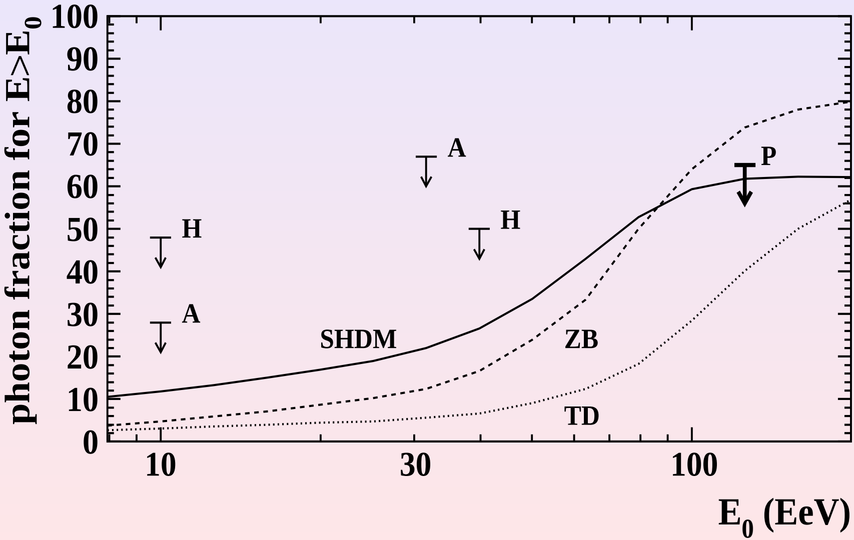


[Berezinsky, Grigorieva, Hnatyk '04]

dip suggests: primaries above 10^{18} eV are extragalactic protons

Chemical composition studies–photon limits



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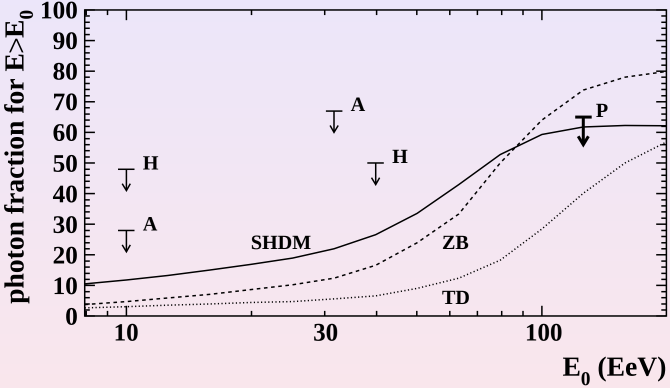
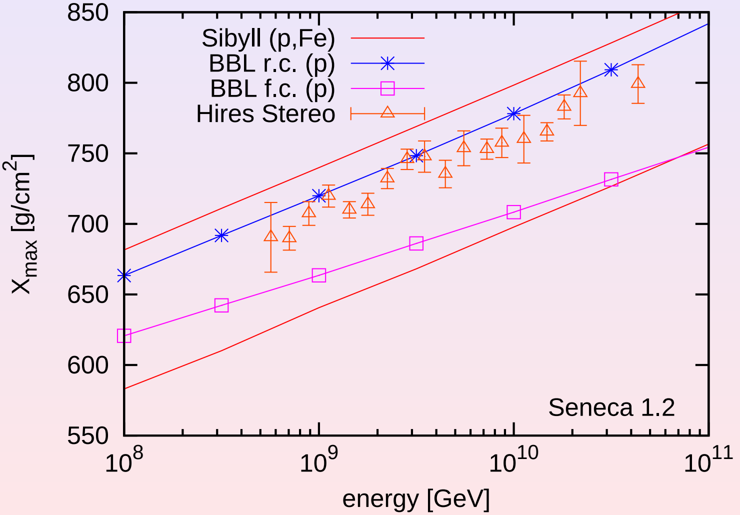


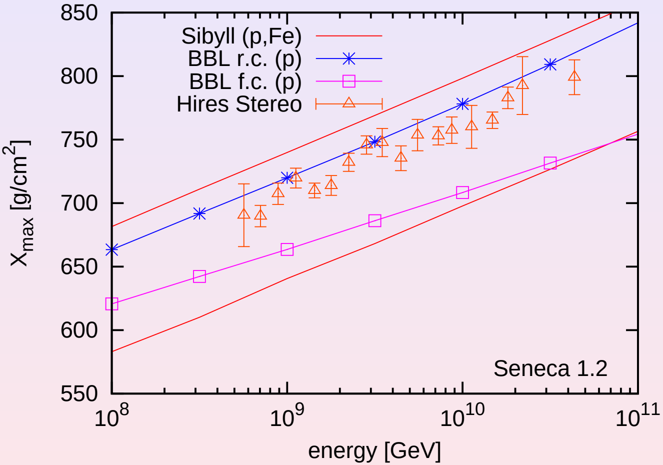
protons or nuclei are main primaries

Chemical composition studies



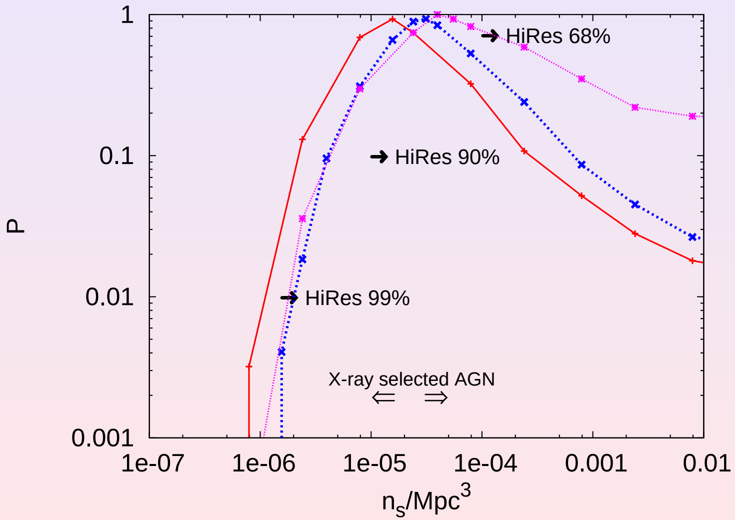
[Drescher, Dumitru,Strikman '04]

Chemical composition studies

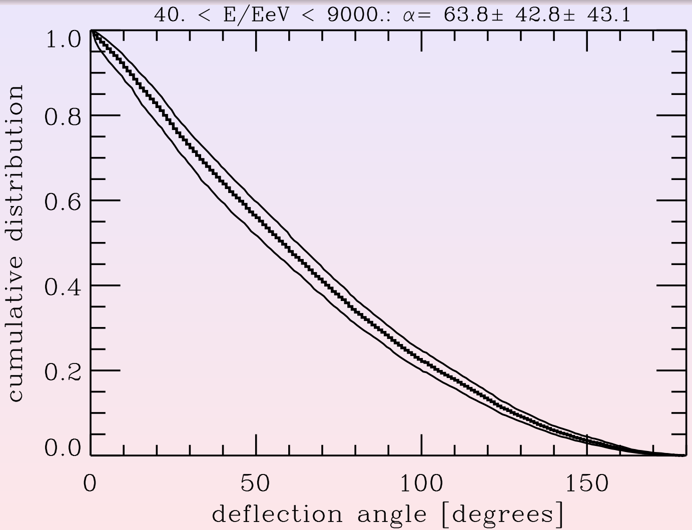


QCD uncertainties prevent even after LHC clear distinction p $\leftrightarrow$ Fe

Small-scale clusters and density of sources:



Extragalactic magnetic field – simulation by SME:



[Sigl, Miniato, Ensslin '03]

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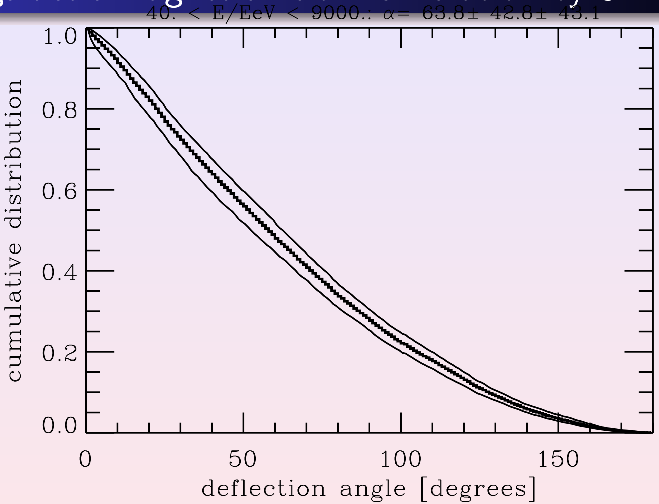
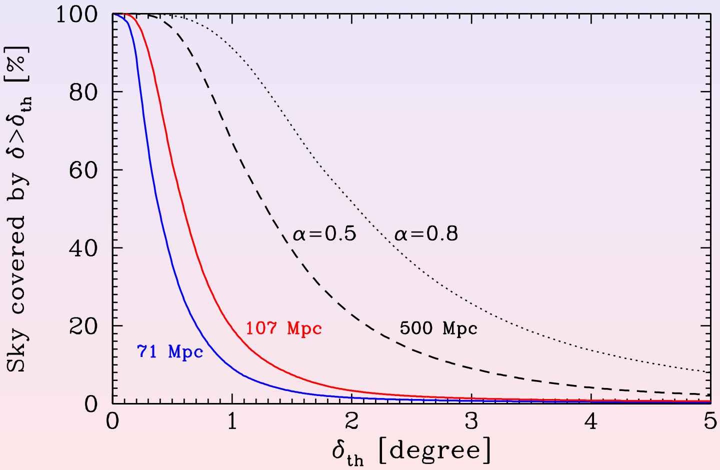


SME: astronomy with UHE protons may be impossible

Extragalactic magnetic field – simulation DGST:



[*Dolag, Grasso, Springel, Tkachev '03*]

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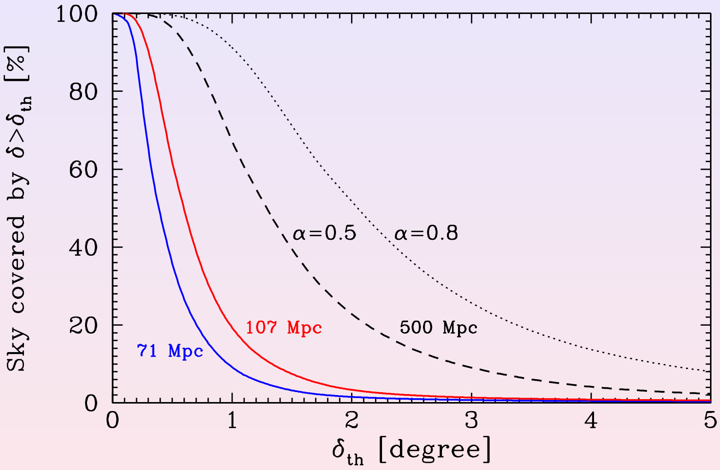
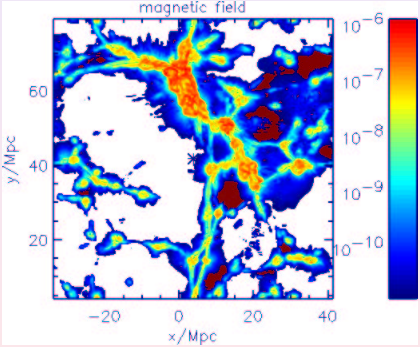


DGST: astronomy with UHE protons possible in large part of sky!

which simulation/conclusion is closer to reality?

- many technical differences between the two simulations; two major conceptional ones:
  - Sigl, Miniato, Ensslin use an unconstrained simulation, putting observer $*$ close to a cluster



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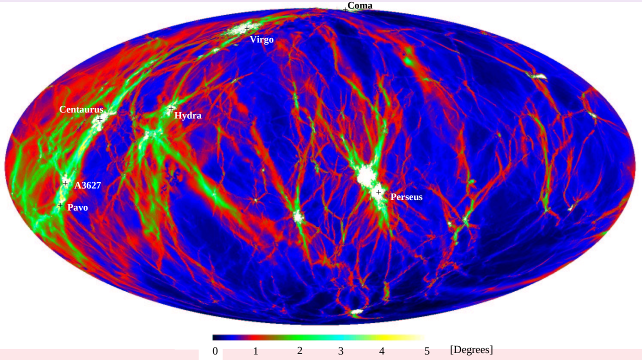

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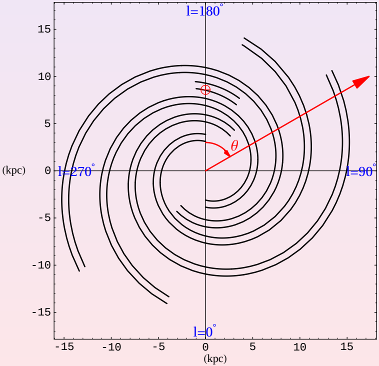
  - Dolag, Grasso, Springel, Tkachev inject protons uniformly on a sphere
  - Sigl, Miniato, Ensslin inject protons following matter distribution

Modelling the regular Galactic field:

- thin disc field ressembles matter structure

$$B(\rho,\vartheta) = b(\rho)\cos\left(\vartheta - \frac{1}{\tan p}\ln(\rho/\xi_0)\right)$$



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- even more uncertain: halo or dipole component

GMF Models considered:

- Tinyakov & Tkachev (TT):
  - BSS-A
  - $f(z) = \mathrm{sign}(z)\exp(-|z|/z_0)$ and $z_0 = 1.5$ kpc

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- Prouza & Smida (PS):
  - BSS-S
  - $f(z) = \exp(-|z|/z_0)$ with $z_0 = 0.2$ kpc
  - toroidal thick disc/halo contribution with width 0.3 kpc
  - dipole field

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- should be included in estimates of stat. significance of (auto-) correlations
- technical complications: energy dependence of ω, singular points and lines, backtracing

Comment on Liouville theorem:

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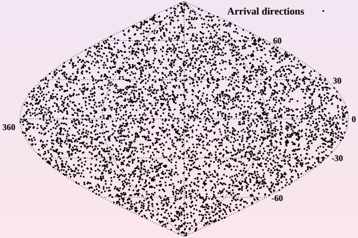
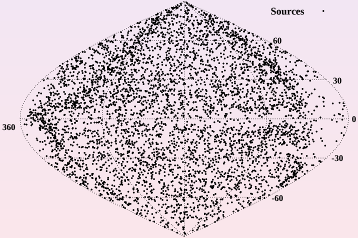
- isotropic flux outside GMF remains isotropic
- GMF does not create, only enhances anisotropies
- but distribution of "effective" sources is anisotropic or $\omega_{\rm mag} \neq 1$



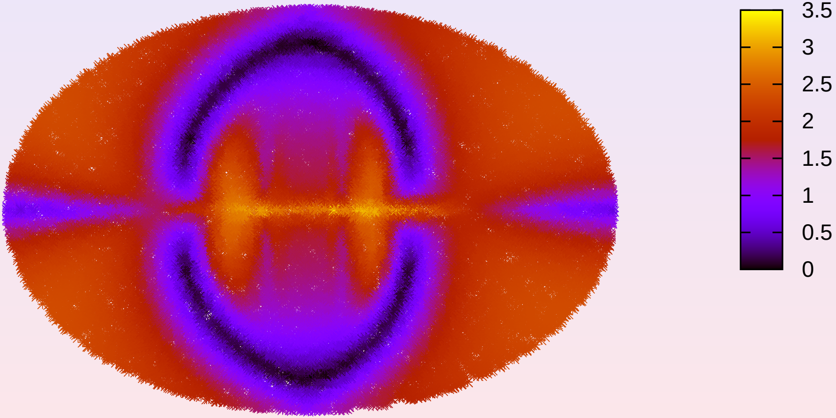
arrival directions on Earth



position of the sources

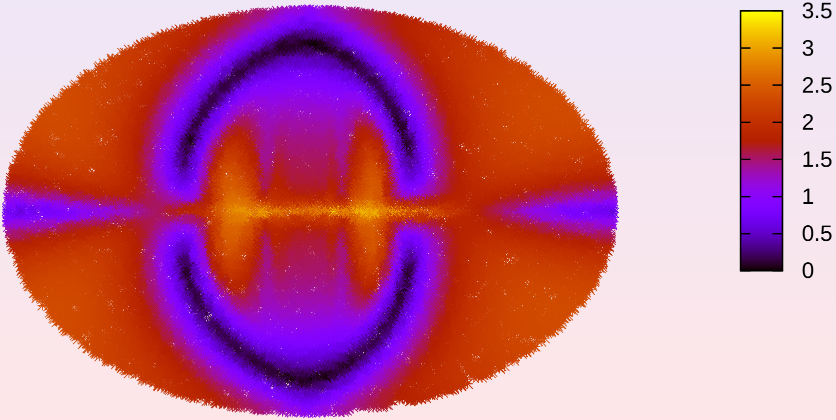
[Alvarez-Muñiz, Engel, Stanev '01]

Deflections for $eE/Q = 10^{20}$eV: TT model

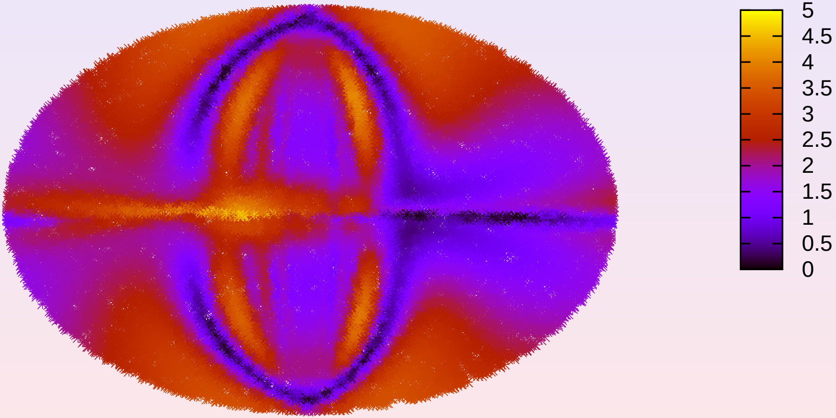


Deflections for $eE/Q = 10^{20}$eV: TT model

deflections $\gtrsim 2.5^\circ$ at 4×10^{19} eV in large fraction of sky



Deflections for $eE/Q = 10^{20}$eV: HMR model



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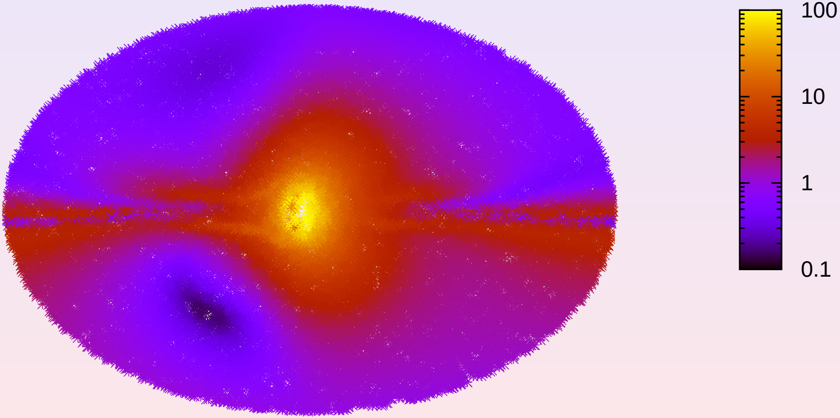
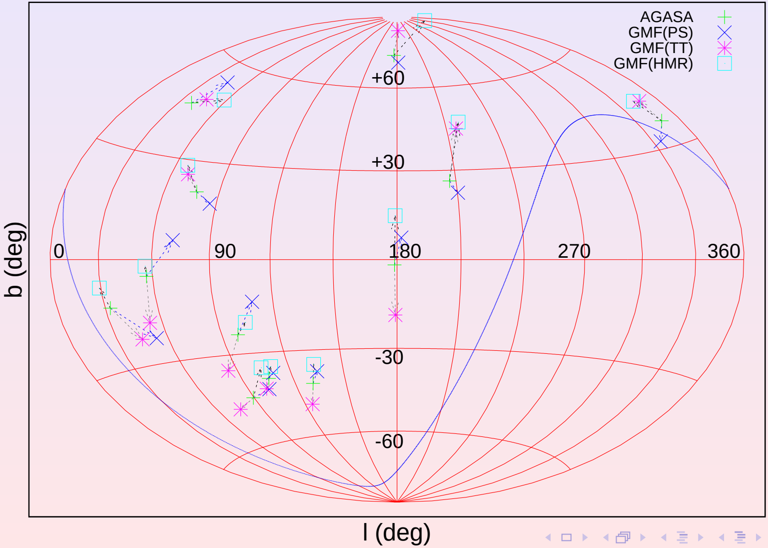
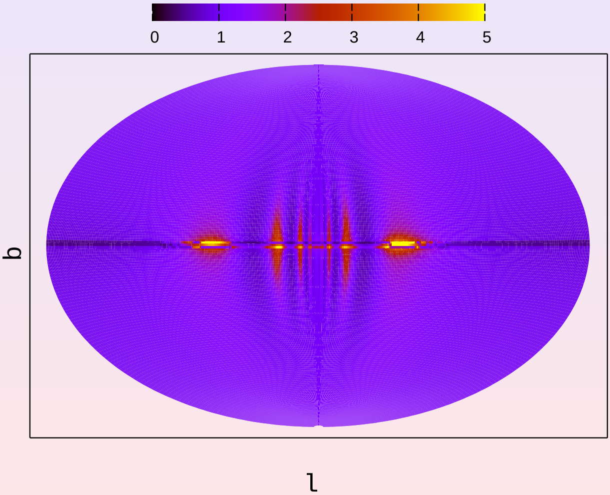


Comparison of models



(De-) Magnification for $eE/Q = 4 \times 10^{19}$eV: TT model



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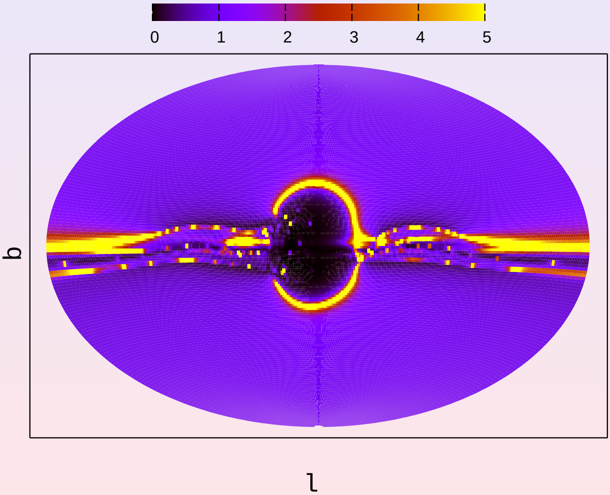

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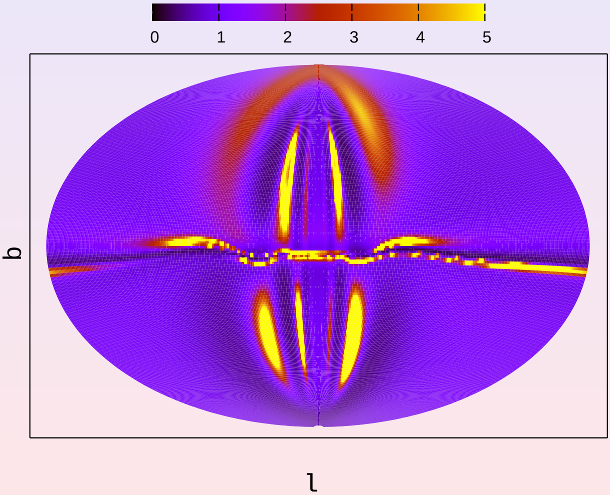
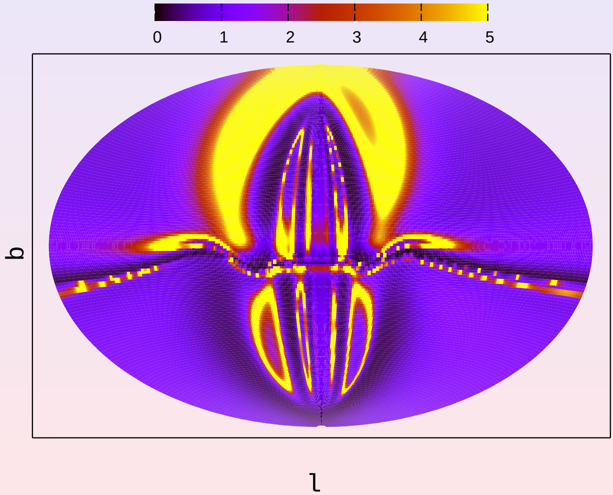
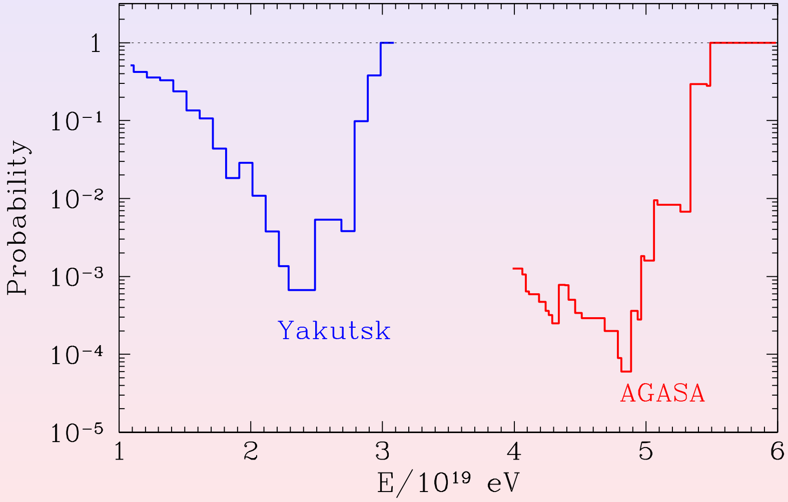


(De-) Magnification for $E/Q = 2 \times 10^{19}$eV: HMR model



Autocorrelation – without GMF correction:

[Tinyakov, Tkachev '01]



Autocorrelation – with GMF correction:

hypothesis: proton primaries, weak EGMF and correct GMF model

- if correct, then w_1 should increase
- $P_{\min}$ using $\omega_{\text{GMF}} = 1$ should decrease
- but $P_{\min}$ with $\omega_{\text{GMF}} \neq 1$ should stay constant

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Model	w_1	$P(w > w_1)[\%]$	$P(w > w_1)$ for $\omega_{\rm GMF} = 1$ [%]
-	11	1.1	1.1
TT	11	1.1	1.1
PS	10	5.0	2.9
HRM	9	8.7	5.7
HRM2	6	63	35

Summary

- deflections $> 2.5^\circ$ at 4×10^{19} eV in large fraction of sky
- deflections very model-dependent

$\Rightarrow$ makes correlation analysis more dubious

- magnification in GMF might enhance small-scale clusters

HMR model:

- BSS-S model with cosh profiles for both the disk and the halo field ($\Rightarrow$ spiral-like geometrical pattern for halo field)
- with scale heights respectively of $z_1 = 0.3$ kpc and $z_2 = 4$ kpc $f(z) = \frac{1}{2\cosh(z/z_1)} + \frac{1}{2\cosh(z/z_2)}$.
- $b(r) = \frac{3R_0}{r} \tanh^3(r/r_1)\,\mu$G, with $r_1 = 2$ kpc, thus reducing to $b(r) \propto r^{-1}$ for $r > r_1$, while vanishing at the galactic center.
- pitch angle $p = -10^\circ$, and $\xi_0 = 10.55$ kpc.

$\Rightarrow$

TT model:

- $b(r) \propto r^{-1}$ for $r > r_{\min} \equiv 4$ kpc, and constant for $r \leq r_{\min}$
- local field intensity of 1.4 μG, pitch angle $p = -8^{\circ}$ and the parameter d fixed to -0.5 kpc.
- BSS-A with $f(z) = \text{sign}(z) \exp(-z/z_0)$ with scale z_0=1.5

$\Rightarrow$

PS model:

- BSS-S configuration with $z_0 = 0.2$ kpc, $p = -8^\circ$, $d = -0.5$ kpc, normalized to local field to 2 μG
- $$B_{Tx} = -B_T \, \mathrm{sign}(z) \cos\vartheta \qquad B_{Ty} = B_T \, \mathrm{sign}(z) \sin\vartheta$$

  where

  $$B_T = \frac{B_{T,\max}(r)}{1 + \left(\frac{|z| - h_T}{w_T}\right)^2}$$

  h_T=1.5 kpc and w_T=0.3 kpc.

PS model:

- dipolar field:

$$B_x = -3\mu_G \cos\varphi \sin\varphi \sin\vartheta / r_{tot}^3$$

$$B_y = -3\mu_G \cos\varphi \sin\varphi \cos\vartheta / r_{tot}^3$$

$$B_z = \mu_G (1 - 3\cos^2\varphi) / r_{tot}^3$$

  where $\mu_G = 123\mu\text{G kpc}^3$ is the magnetic moment of the Galactic dipole, assumed $B_z \simeq +0.2\mu$G near the Solar System.
- replaced by a constant field $B_z = -1m$G in a sphere of 500 pc around GC

$\Rightarrow$