Simulations of UHECRs
in the
local Universe
and the
origin of Cosmic Magnetic Fields

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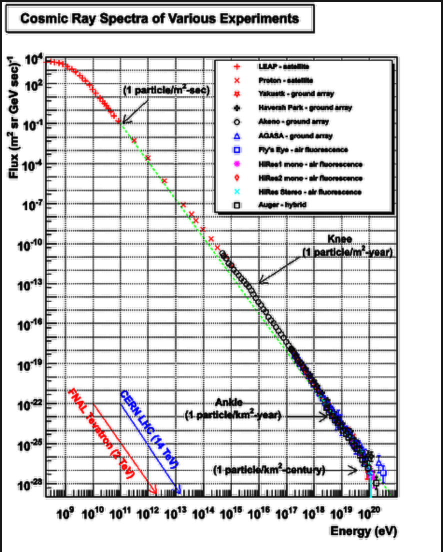
Overview

Ultra-high Energy Cosmic Rays &
Extragalactic Magnetic Fields
Magneto-Genesis
Magnetic Environment

Outline

Ultra-high Energy Cosmic Rays &
Extragalactic Magnetic Fields

Ultra-high Energy Cosmic Rays



W. Hanlon, Utah

charged Nuclei

gyro radius $r_g = E/eZB$

low energy $E < 10^{18}\mathrm{eV}$

- galactic origin
- sources: SN remnants
- *Blasi 2013*

Ultra-high Energy Cosmic Rays

ASPERA/Novapix/L. Bret

charged Nuclei

gyro radius $r_g = E/eZB$

low energy $E < 10^{18}\mathrm{eV}$

- galactic origin
- sources: SN remnants
- *Blasi 2013*

high energy $E > 10^{18}\mathrm{eV}$

- $r_g > R_{MW} \Rightarrow$ extragalactic origin
- sources: *unknown*
- *GRB? AGN? RG? ...*

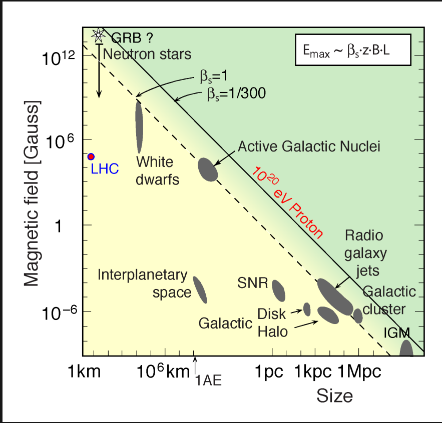
Hillas Criterion

Fermi acceleration

gyro radius $r_g = E/eZB$

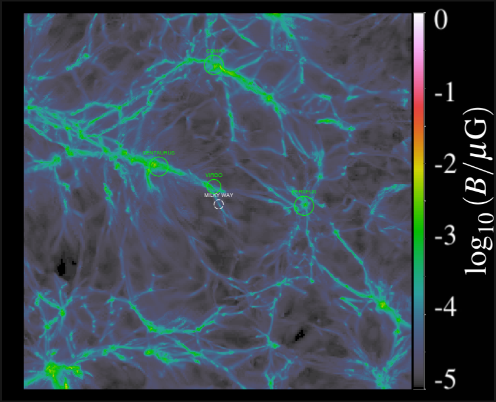
Hillas Criterion:
$R > r_g \Rightarrow E_{max} \propto B \cdot R$

Sources: GRB? AGN? RG? Cluster?



A. M. Hillas

Extra-Galactic Magnetic Fields



Franco Vazza, Bologna

Voids ($\approx$ 80% of volume)

$B_0 \leq 0.55 - 5.6$ nG

Planck 2015

$B_{\text{void}} \geq 10^{-16}$G

Neronov & Vovk 2010

LSS ($\approx$ 20% of volume)

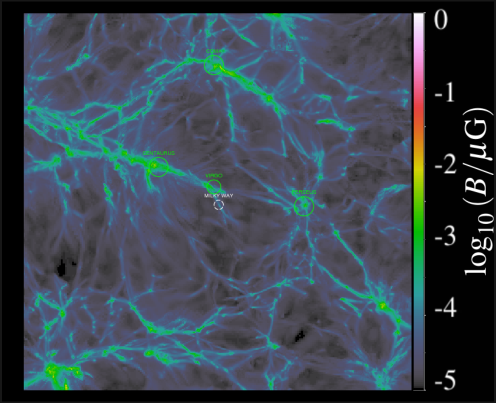
galaxies $\sim 5 - 15\ \mu$G

clusters $\sim \mu$G

filaments $\lesssim 0.1\mu$G

Beck+ 2016, Feretti+ 2012, Brown+ 2017

measure EGMFs with UHECRs?
constrain seeding processes?



Franco Vazza, Bologna

Voids ($\approx$ 80% of volume)

$B_0 \leq 0.55 - 5.6$ nG
Planck 2015

$B_{\rm void} \geq 10^{-16}$G
Neronov & Vovk 2010

huge range of uncertainty

LSS ($\approx$ 20% of volume)

galaxies $\sim 5 - 15\ \mu$G

clusters $\sim \mu$G

filaments $\lesssim 0.1\mu$G

cluster outskirts
unknown

Combine

ENZO

(large cosmological MHD simulations with AMR)

CRPropa

(propagation of UHECRs in 3D models of EGMF)

Outline

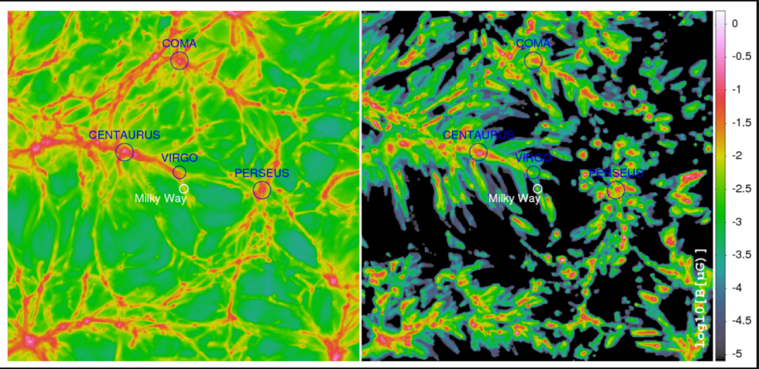
Magneto-Genesis

MHD models

density perturbations: **constrained** ICs (*Sorce+ 2015*)

seed magnetic field:

- **primordial**: $B_0 = 10^{-9}$ G, $z = 60$
- **astrophysical**:
  magnetic feedback from AGN, $z < 4$ ($B_0 = 10^{-20}$ G)



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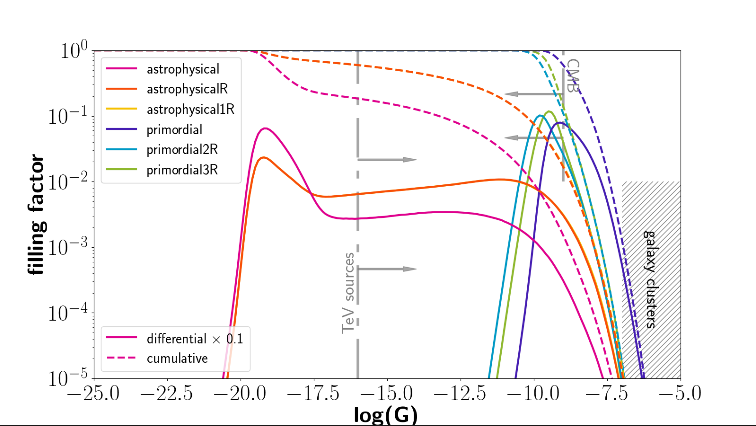
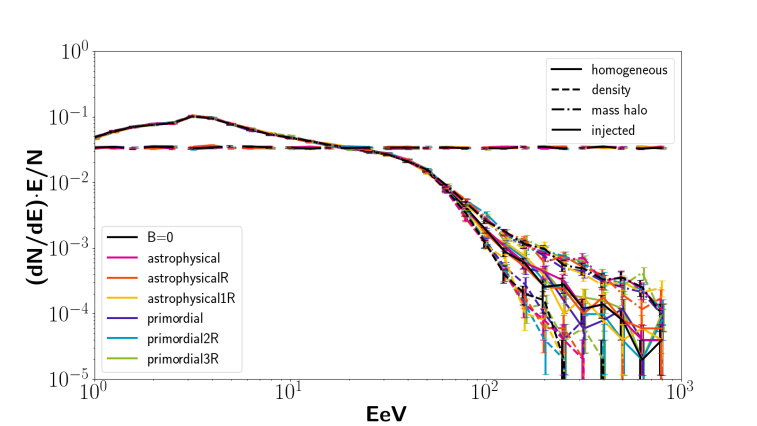


UHECR results

Full Sky Energy Spectrum



GZK $\Rightarrow \gtrsim 100\mathrm{EeV}$ determined by nearby sources

independent of Magnetic Fields
(Propagation Theorem, *Aloisio & Berezinsky 2004*)

Full Sky Composition

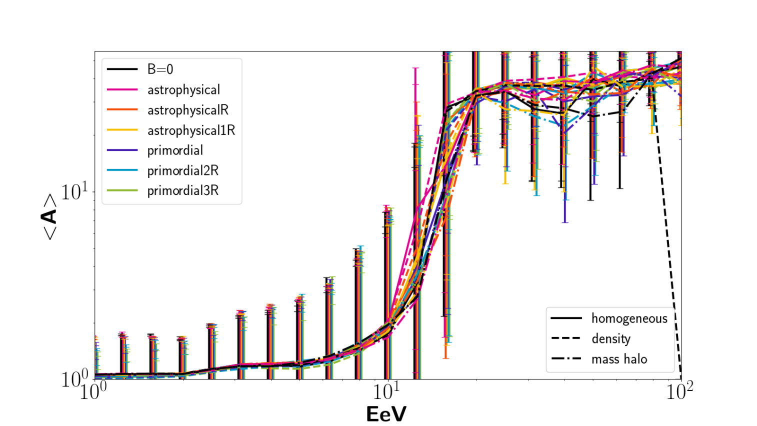


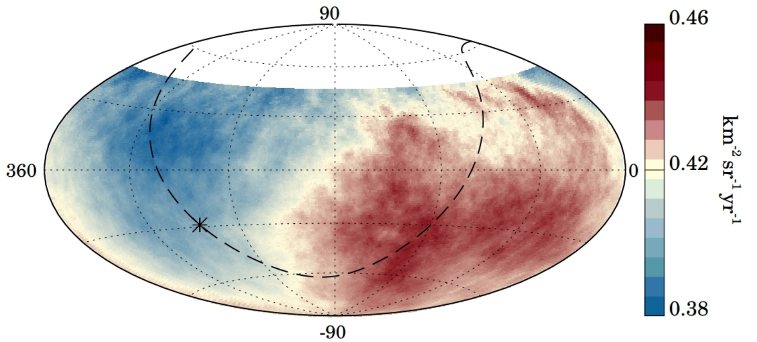
Photo-disintegration $\Rightarrow$ $\lesssim 10\mathrm{EeV}$ dominated by secondary nuclei

$$N_Z^A + \gamma \rightarrow N_{Z-1}^{A-1} + p^+ \qquad \frac{\Delta E}{E} = \frac{\Delta A}{A} \ \textit{(Epele \& Roulet 1998)}$$

independent of Magnetic Fields

Search for anisotropy

Anisotropy observed!

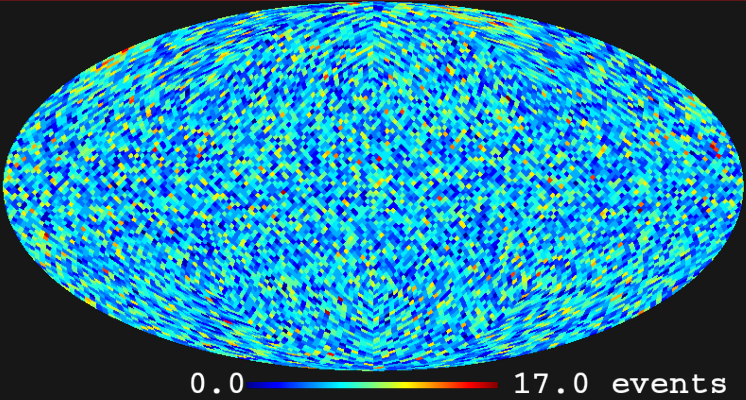


Recent observation of dipole by Pierre Auger Coll. 2017

Amplitude: 0.5%
Significance: $\gtrsim 5\sigma$

Time has come to identify sources?

Angular Power spectrum

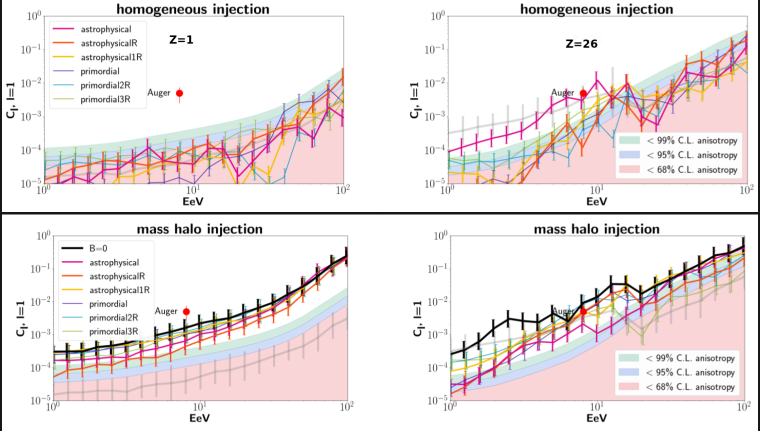


Flux: $\Phi(\vec{n}) = \sum_{lm} a_{lm} Y_{lm}(\vec{n})$

Angular Power Spectrum:

$$C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2$$

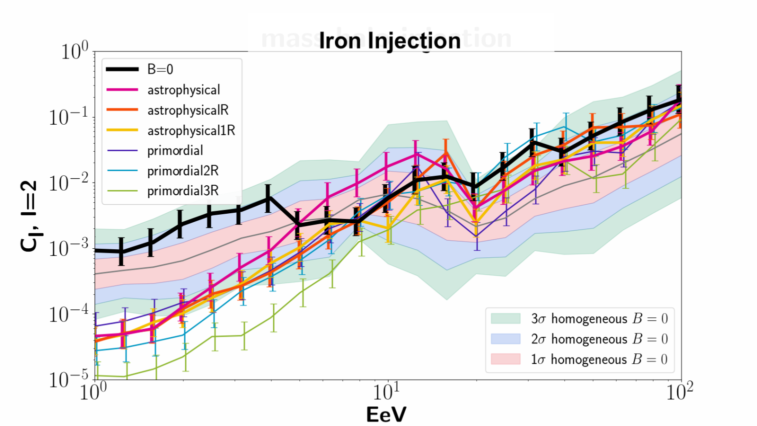
Angular Power spectrum



results for different MHD models well converged
$\Rightarrow$ **no info on magneto-genesis** in global anisotropy

heavy injection composition increases anisotropy $\lesssim E_{\max}/A$
$\Rightarrow$ **reproduce Auger signal** *(Hackstein et al. 2018)*

Angular Power spectrum



ordered magnetic fields "wash out" anisotropy

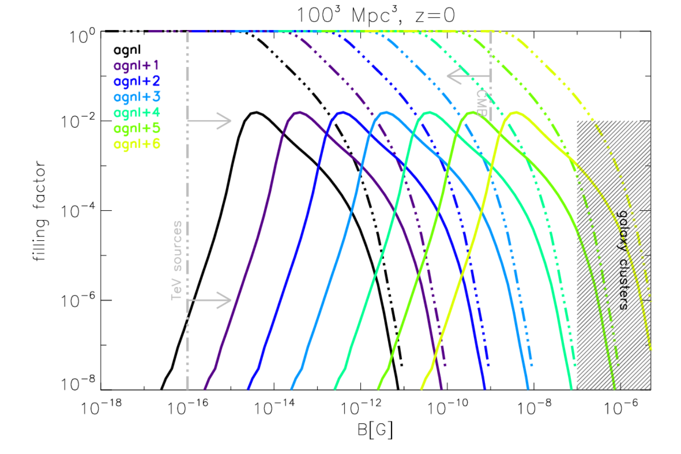
(Hackstein et al. 2018)

Outline

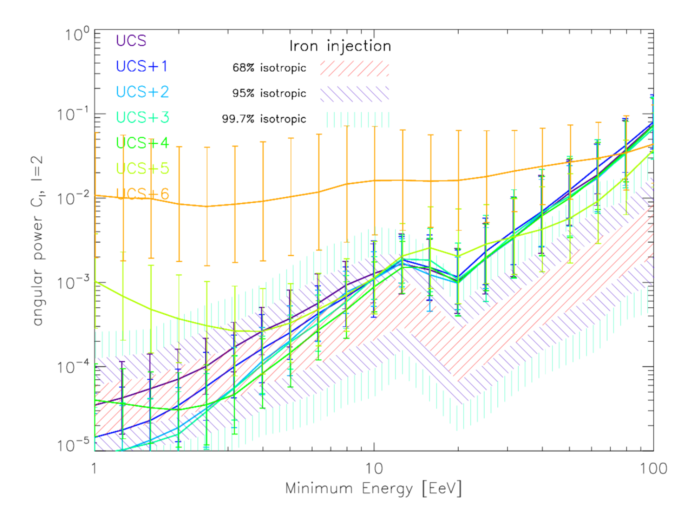
Magnetic Environment

MHD models

unconstrained, 18 MW observers *(Hackstein et al. 2016)*
primordial: $B_0 = 10^{-13} - 10^{-8}$ G, $z = 60$
and astrophysical:
magnetic feedback from AGN, $z < 1$



Angular Power spectrum



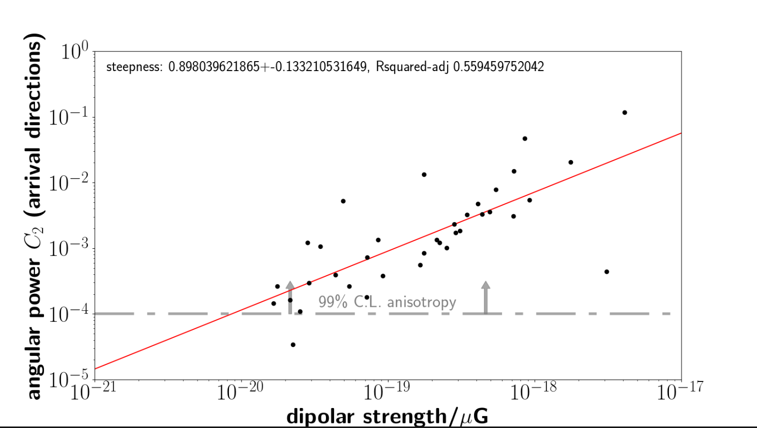
strong $B = const.$ $\Rightarrow$ deflection $\perp$ stronger than $||$

$\Rightarrow$ increased travel time $\Rightarrow$ change in energy spectrum

$\Rightarrow$ **quadrupole anisotropy**

Angular Power spectrum

!!! Preliminary !!!



linear relation quadrupole $C_2 \sim$ magnetic strength within $\lesssim 5\mathrm{Mpc}$

limit strength of magnetic field around MW?

(Hackstein, Dundovic & Avola in prep.)

Liouville's Theorem

BUT

Theorem (Liouville's theorem on CRs)

isotropy of CR flux is preserved along line of force
i. e. magnetic deflection cannot create anisotropies

Parker 1967

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Parker 1967

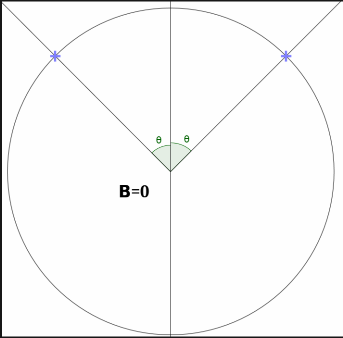
Assumptions: energy, composition & particle number conserved,
infinite trajectories

Uniform field

consider injection from sphere at distance d

no magnetic field:
$B = 0$

number of starting positions on injection sphere depends on Θ & d: N $\propto d \sin\theta$



Hackstein et al. *in proc.*

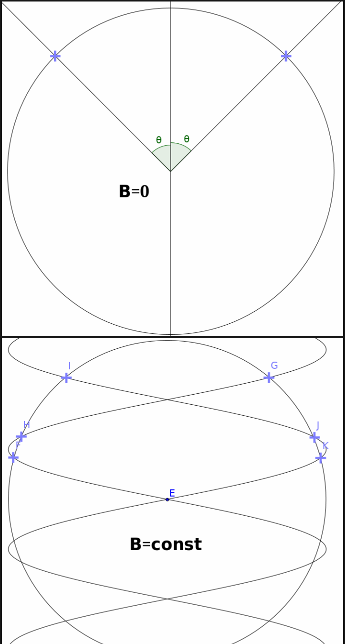
Uniform field

consider injection from sphere at distance *d*

most basic magnetic field: $B = const$

number of starting positions on injection sphere depends on Θ, d & B

Hackstein et al. *in proc.*



Uniform field

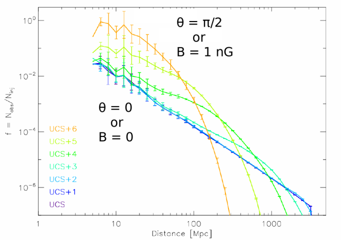
consider injection from sphere at distance d

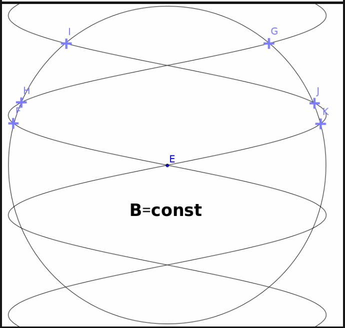
most basic magnetic field: $B = const$

number of starting positions on injection sphere depends on Θ, d & B

$\Rightarrow$ prefer nearby sources
$\Rightarrow$ shorter <trajectory>
$\Rightarrow$ heavier composition

Hackstein et al. *in proc.*





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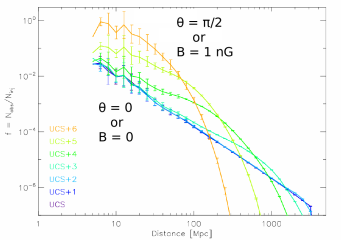
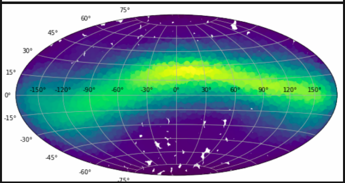
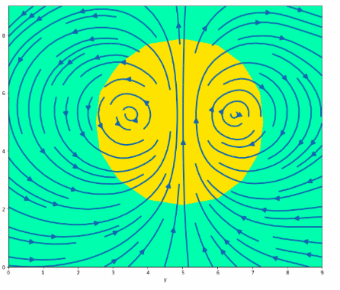
$\Rightarrow$ quadrupole anisotropy

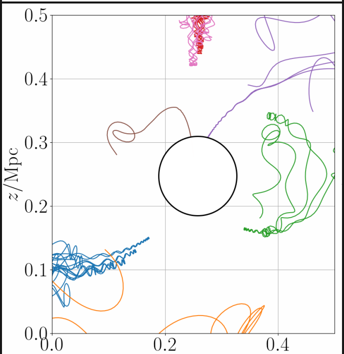
Hackstein et al. *in proc.*





Poloidal field





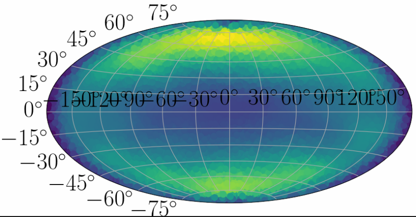
more realistic field: poloidal

shields at equator,
attracts at poles
(cf. earth's magnetosphere)

Parker, van Allen, Alfven, et al. 1960's

$\Rightarrow$ quadrupole anisotropy

Hackstein et al. *in proc.*

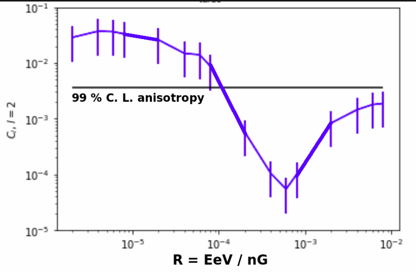


Constrain Magnetosphere of Milky Way

(quadrupole) anisotropy is not observed
$\rightarrow$ infer constraints on poloidal component of MW Magnetosphere

$R \overset{!}{>} 10^{-4} \Rightarrow$
$\underline{B_{\mathrm{Pol}} < \sim 10\ \mu\mathrm{G}}$

predictions for influence of Magntosphere of Milky Way



Hackstein et al. *in proc.*

Conclusions

ballistic propagation $\gtrsim 80\mathrm{EeV}$
$\Rightarrow$ **UHECR astronomy possible**

observed anisotropy suggests **heavy injection composition**

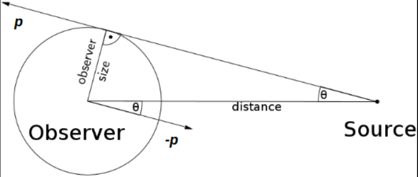
DIfferent seeding models indistinguishable
$\Rightarrow$ **Ordered fields in voids have low impact on anisotropy**
$\Rightarrow$ **No info on magneto-genesis**

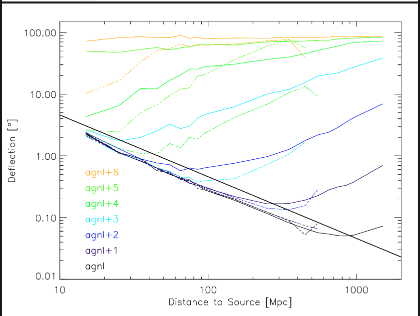
strong vertical magnetic component $\Rightarrow$ stronger $\perp$ deflection
$\Rightarrow$ change in energy spectrum / composition
$\Rightarrow$ **Limit vertical component in close vicinity of MW**

Artefacts

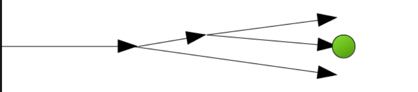
effect of finite observer

artificial deflection

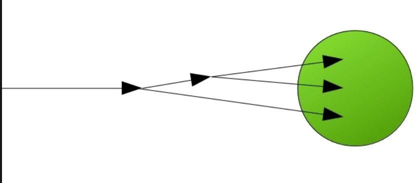




ideal observer



finite observer



magnetized observer