Simulations of ultra-high Energy Cosmic Rays in the local Universe and the origin of Cosmic Magnetic Fields

Stefan Hackstein

1st year PhD student @

shackste@physnet.uni-hamburg.de

Supervisors: Marcus Brüggen, Franco Vazza

Collaborators: Günter Sigl, Andrej Dundovic, Jenny G. Sorce, Stefan Gottlöber

2017-10-17

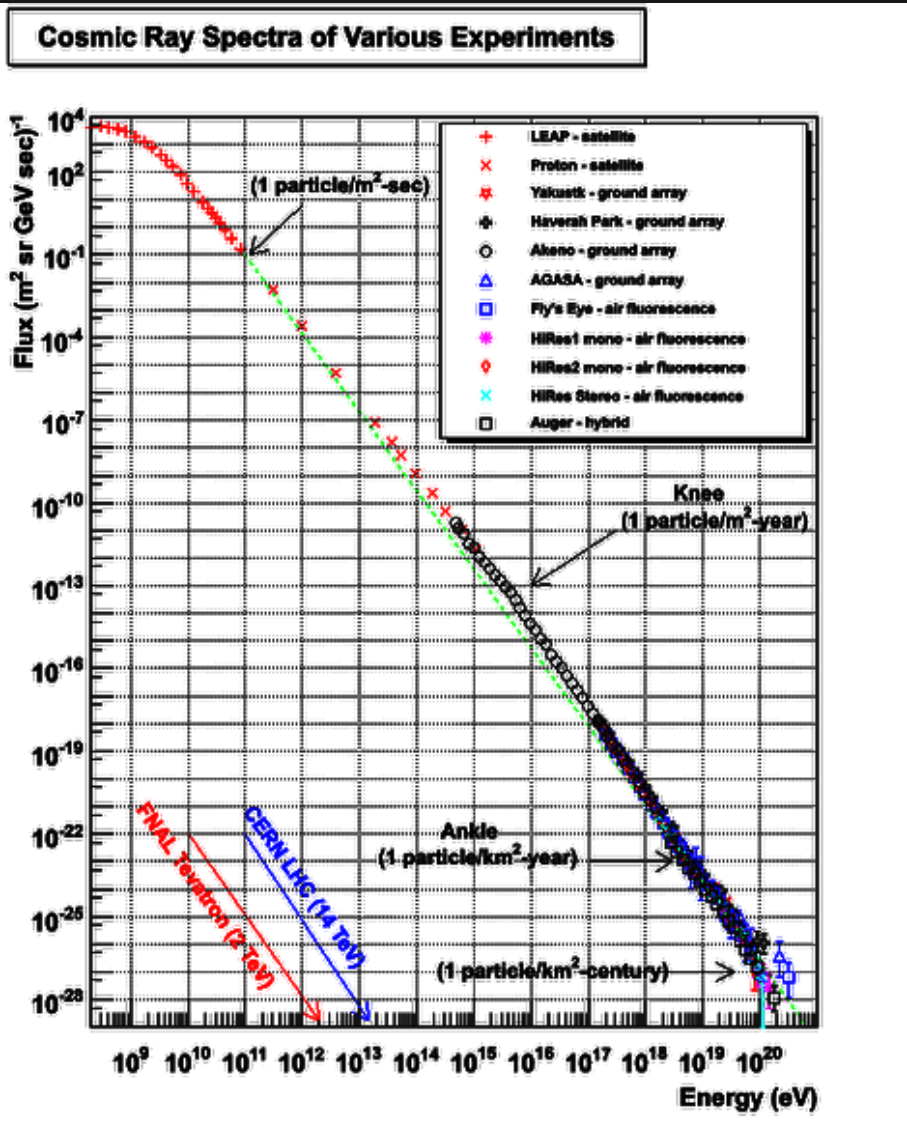
Overview

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: most likely remnants of SNe

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: most likely remnants of SNe
- *Blasi 2013*

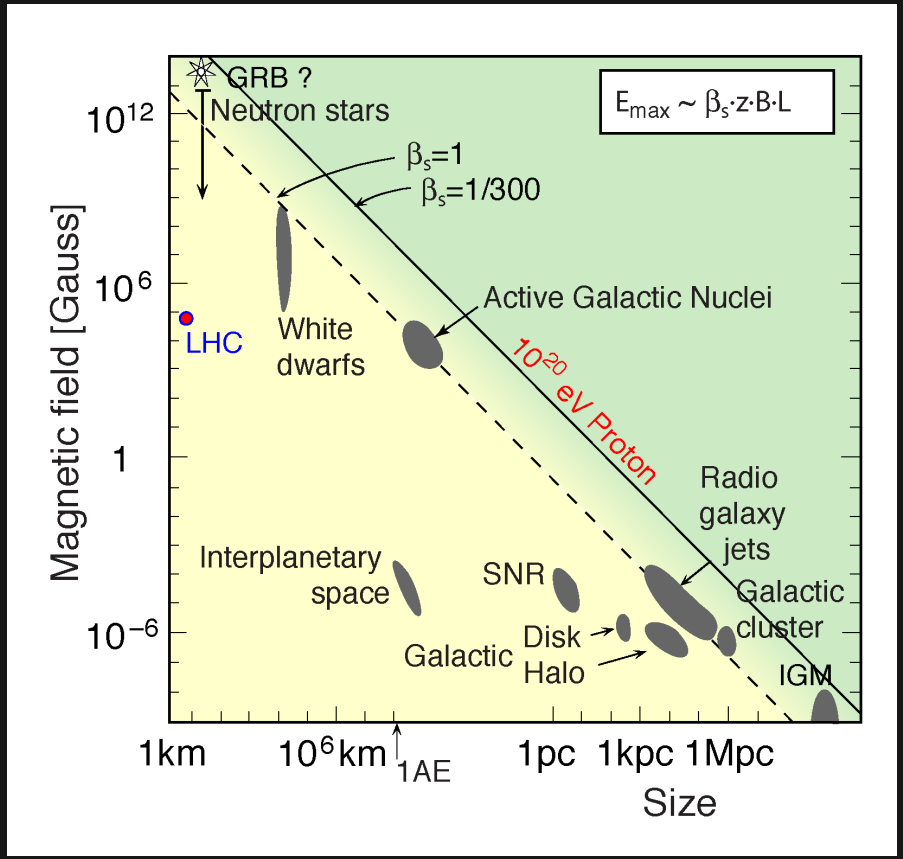
high energy $E > 10^{18}\mathrm{eV}$

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

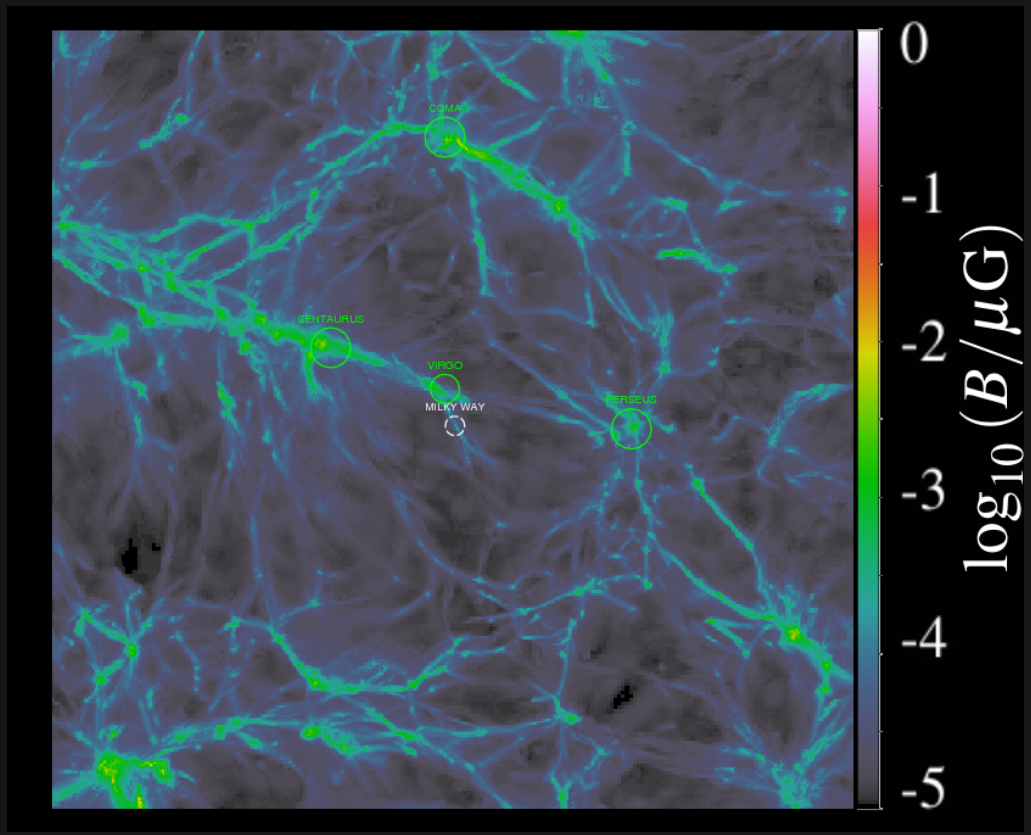
Extragalactic sources

Fermi-Acceleration:
multiple reflections
at MF shock front
$\Rightarrow$ gain energy $\propto \beta_{shock}$

Hillas criterion:
$2 \times r_g < R_{Source}$
$\Rightarrow E_{max} \sim B \cdot R_{Source}$)
Hillas 1984



Extra-Galactic Magnetic Fields



Franco Vazza, Bologna

Voids ($\approx 80\%$ of volume)

$B_0 \leq 0.55 - 5.6\ \mathrm{nG}$

Planck 2015

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

Neronov & Vovk 2010

LSS ($\approx 20\%$ of volume)

galaxies $\sim 5 - 15\ \mu\mathrm{G}$

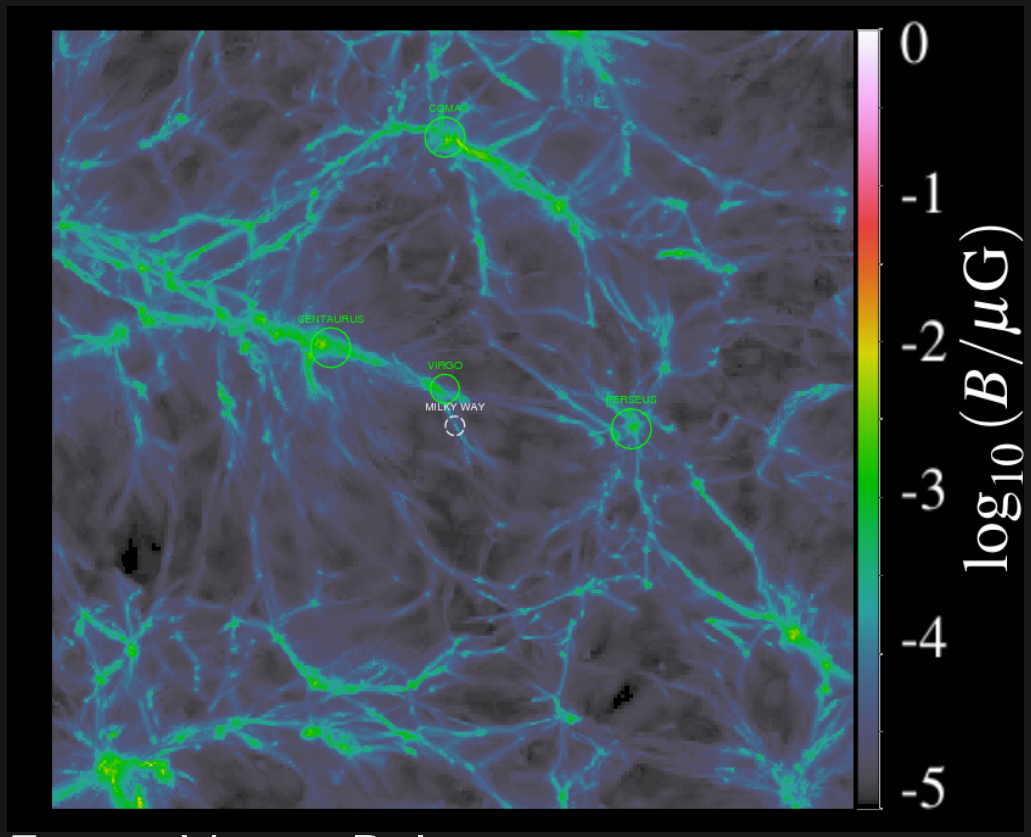
clusters $\sim \mu\mathrm{G}$

filaments $\lesssim 0.1\mu\mathrm{G}$

Beck+ 2016, Feretti+ 2012, Brown+ 2017

Extra-Galactic Magnetic Fields

measure EGMFs with UHECRs?
constrain seeding processes?



Franco Vazza, Bologna

Voids ($\approx 80\%$ of volume)

$B_0 \leq 0.55 - 5.6\ \mathrm{nG}$

Planck 2015

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

Neronov & Vovk 2010

huge range of uncertainty

LSS ($\approx 20\%$ of volume)

galaxies $\sim 5 - 15\ \mu\mathrm{G}$

clusters $\sim \mu\mathrm{G}$

filaments $\lesssim 0.1\mu\mathrm{G}$

cluster outskirts

unknown

Combine

ENZO

(large MHD cosmological simulations with AMR)

CRPropa

(propagation of UHECRs in 3D models of EGMF)

Outline

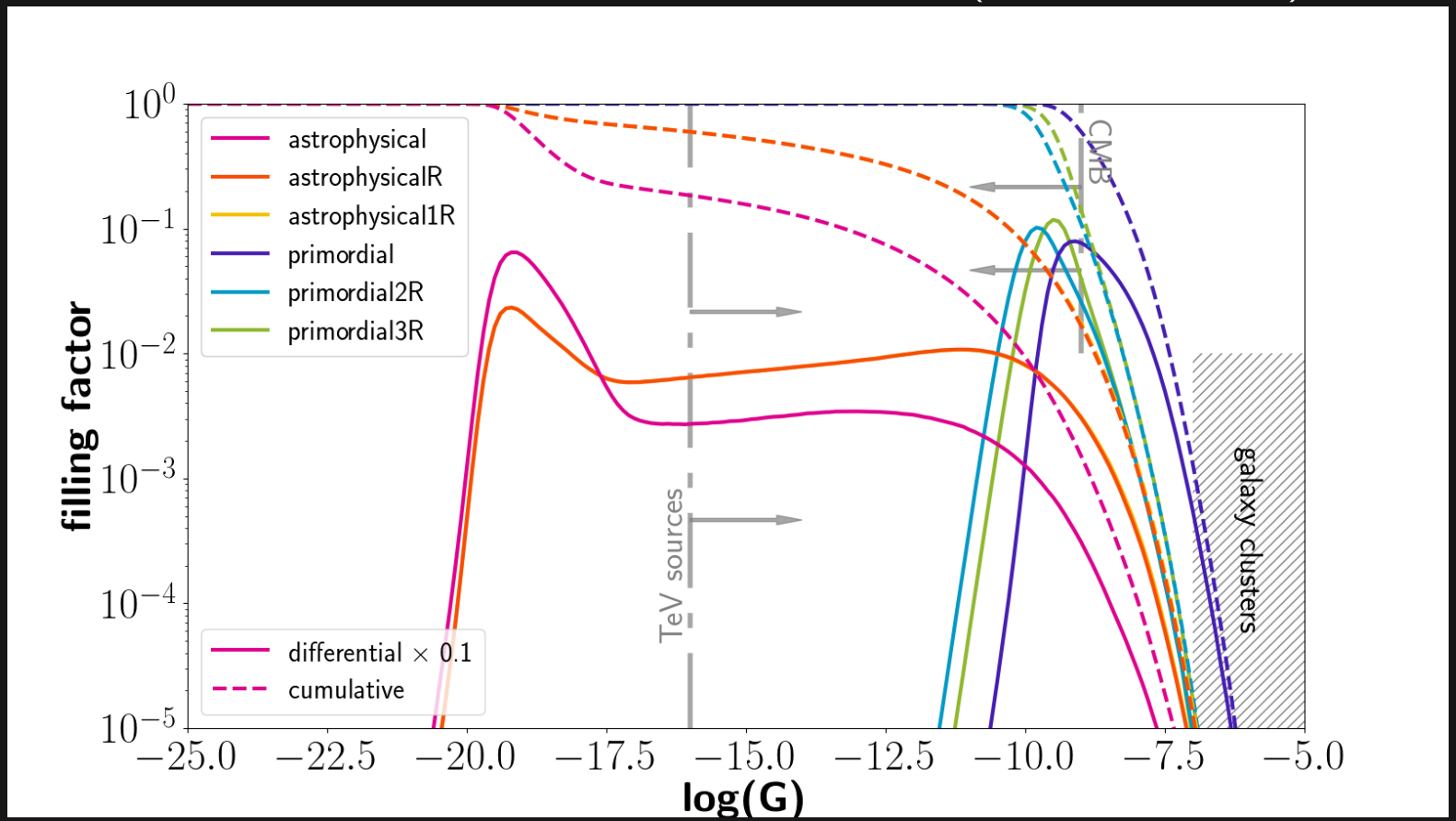
MHD models

density perturbations: **constrained** ICs (*Sorce+ 2015*)
seed magnetic field:

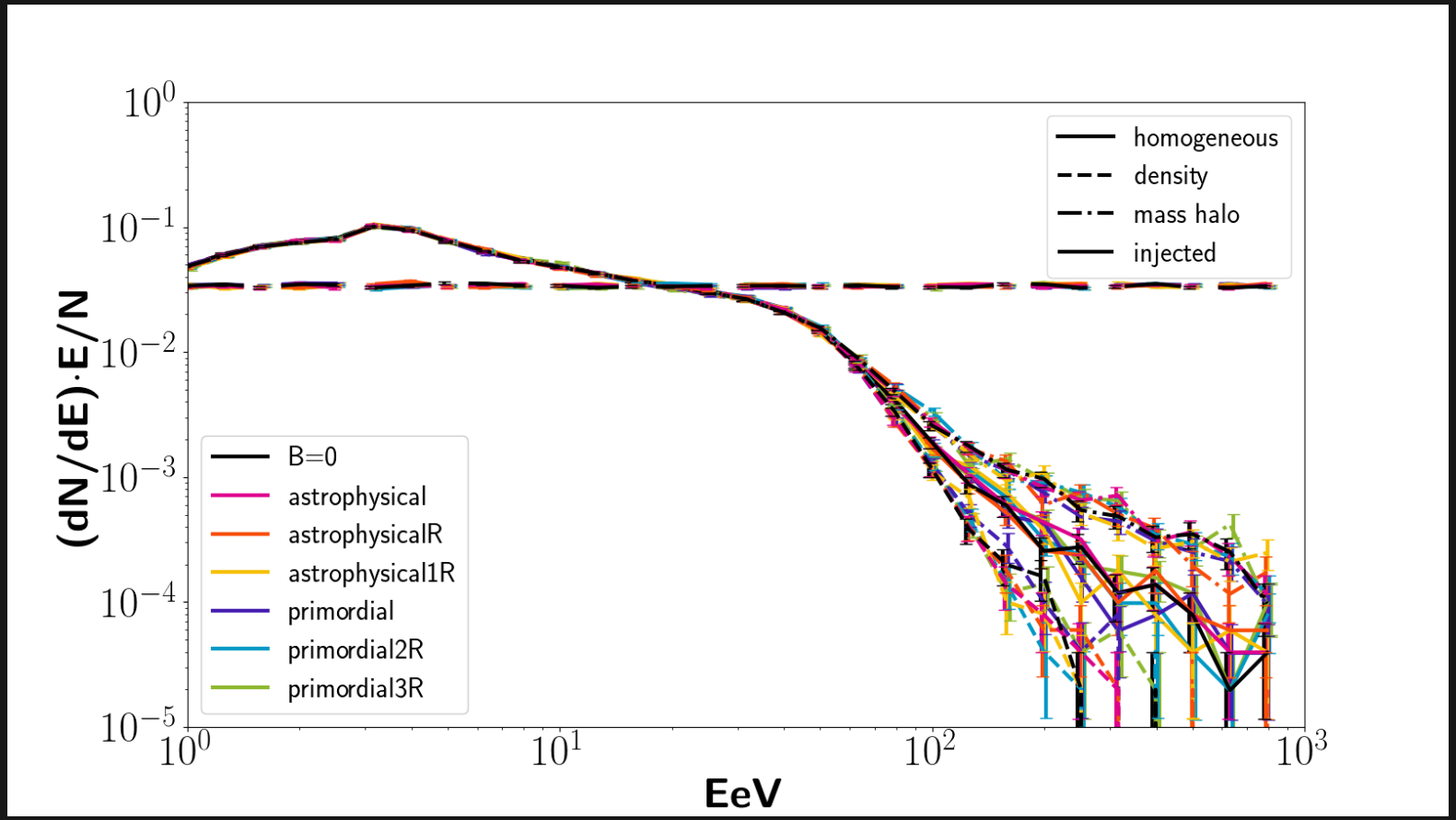
primordial: $B_0 = 10^{-9}$ G, $z = 60$

astrophysical:

magnetic feedback from AGN, $z < 4$ ($B_0 = 10^{-20}$ G)



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

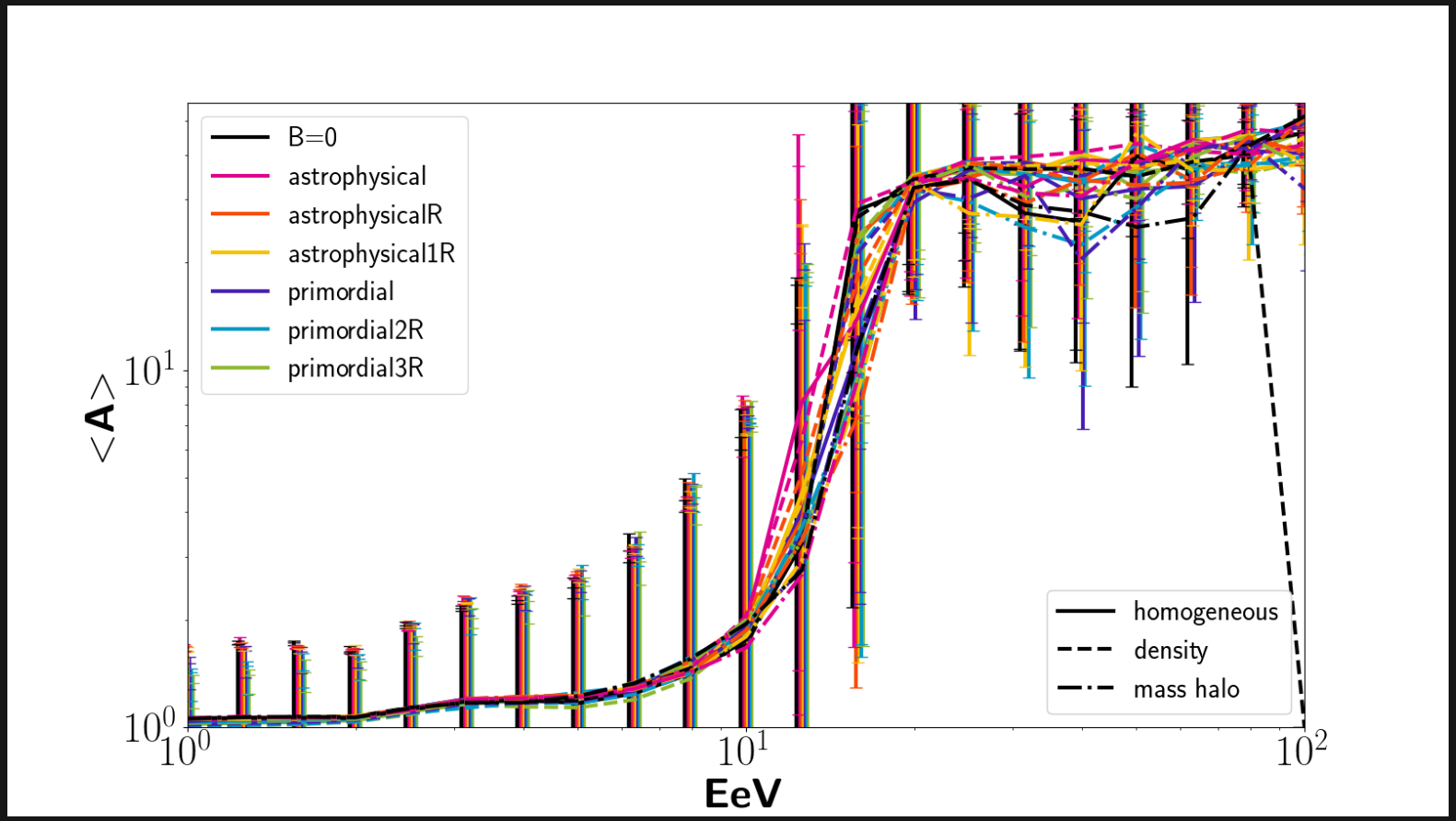


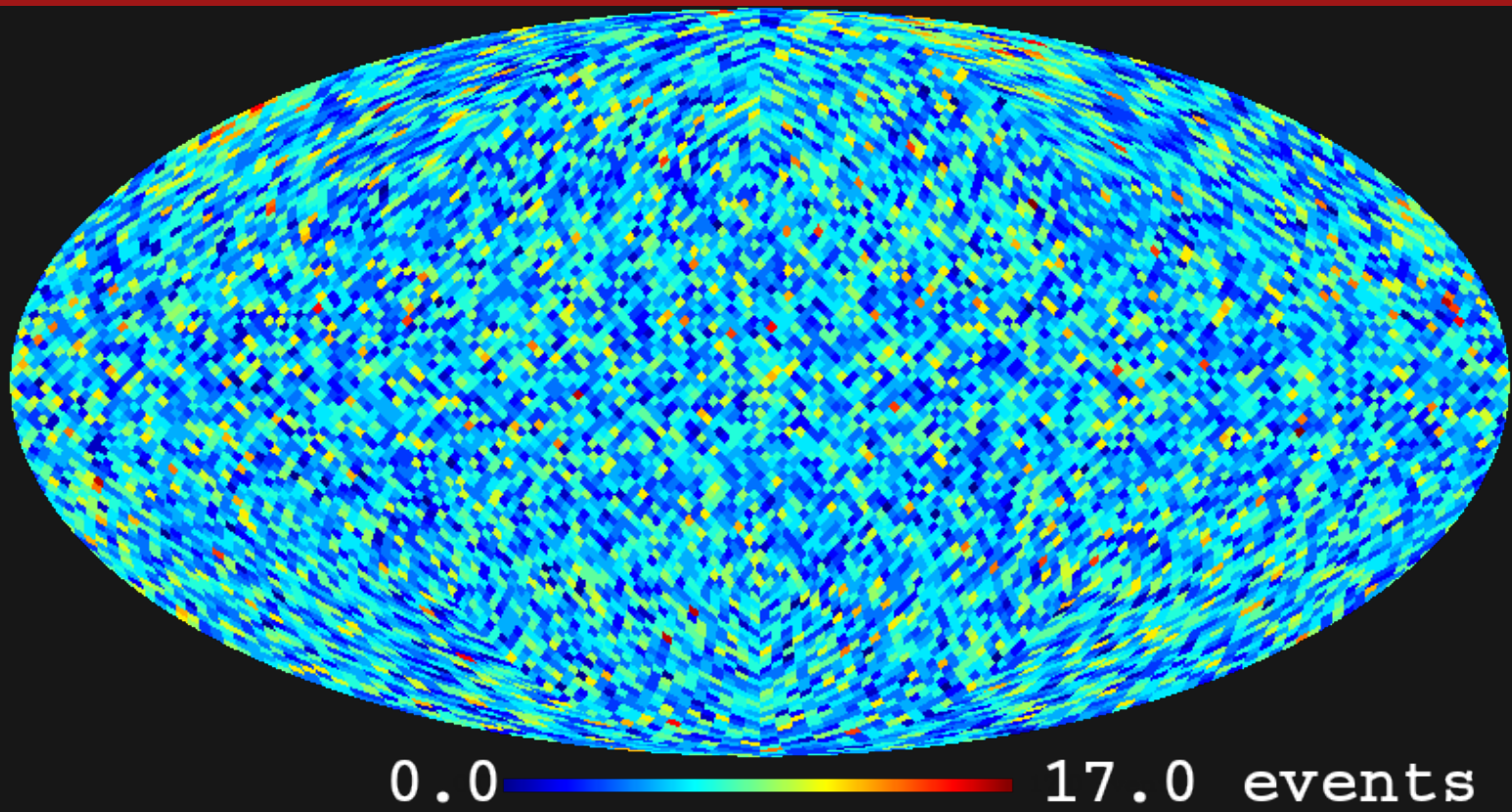
Photo-disintegration $\Rightarrow$ $\lesssim 10\mathrm{EeV}$ dominated by remnants

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

independent of Magnetic Fields

Search for anisotropy in nergy spectrum (or composition)

Angular Power spectrum

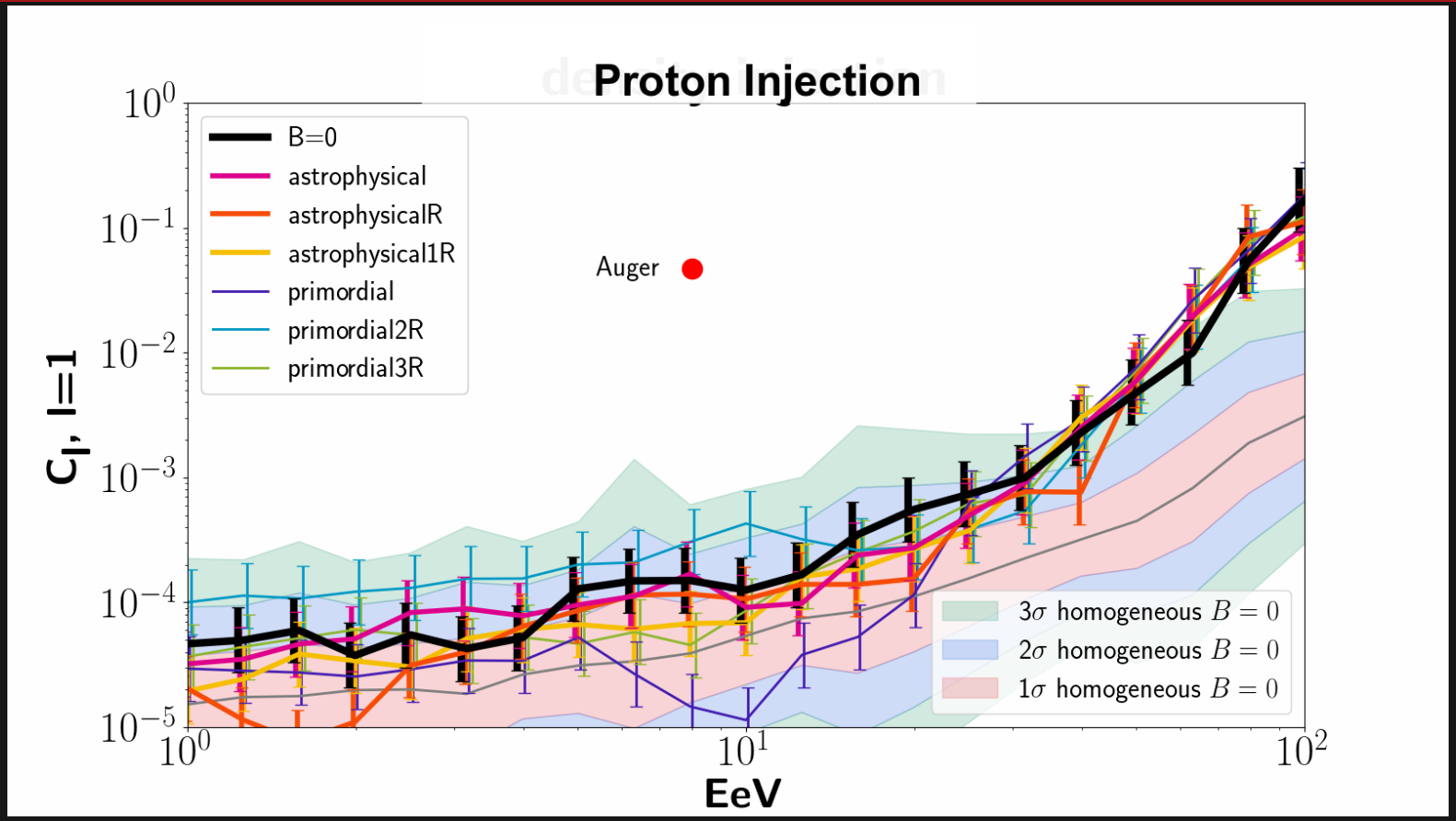


Flux: $\Phi(\vec{n}) = \sum_{lm} a_{lm} Y_{lm}(\vec{n})$

Angular Power Spectrum:

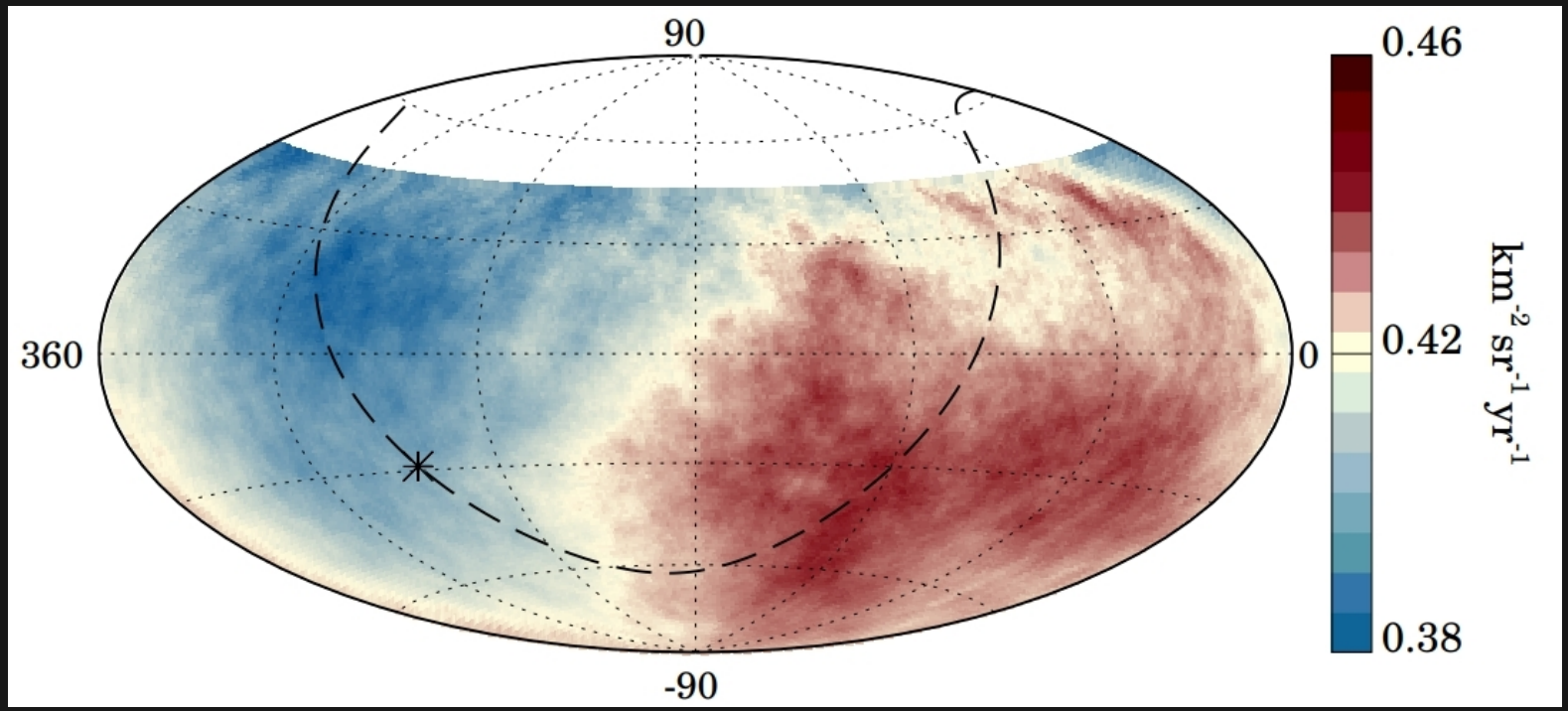
$$C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2$$

Angular Power spectrum



$C_2 \gtrsim 100\mathrm{EeV}$ independent of MF
determined by sources
$\Rightarrow$ **UHECR astronomy possible** *(cf. Dolag+ 2004)*
(Hackstein et al. in sub.)

Angular Power spectrum

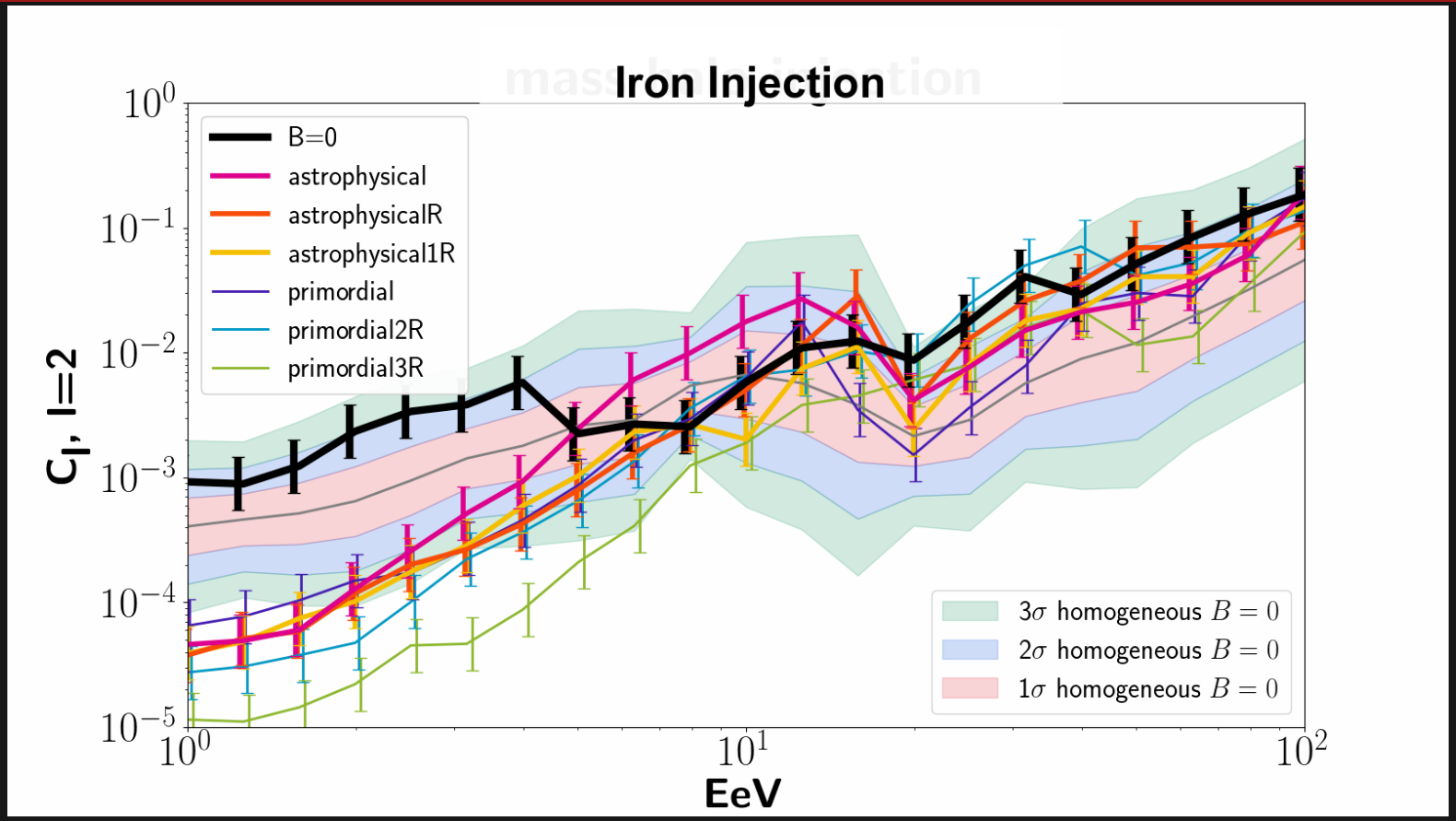


Recent observation of dipole by Pierre Auger Coll. 2017

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

Time has come to identify sources?

Angular Power spectrum



magnetic fields "wash out" anisotropy

different models of EGMF $\rightarrow$ similar result

$\Rightarrow$ **no info on magneto-genesis**

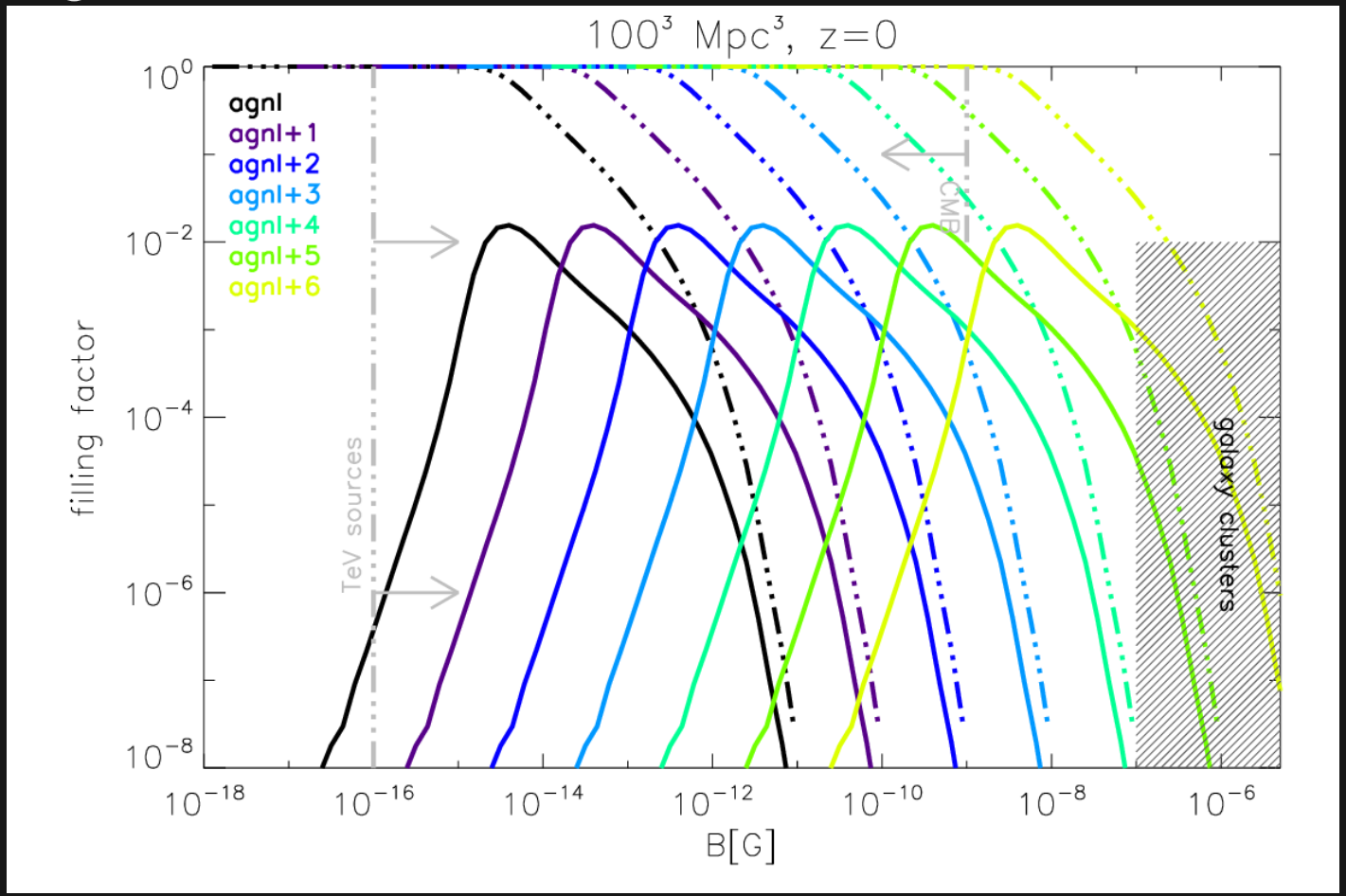
(Hackstein et al. in sub.)

Outline

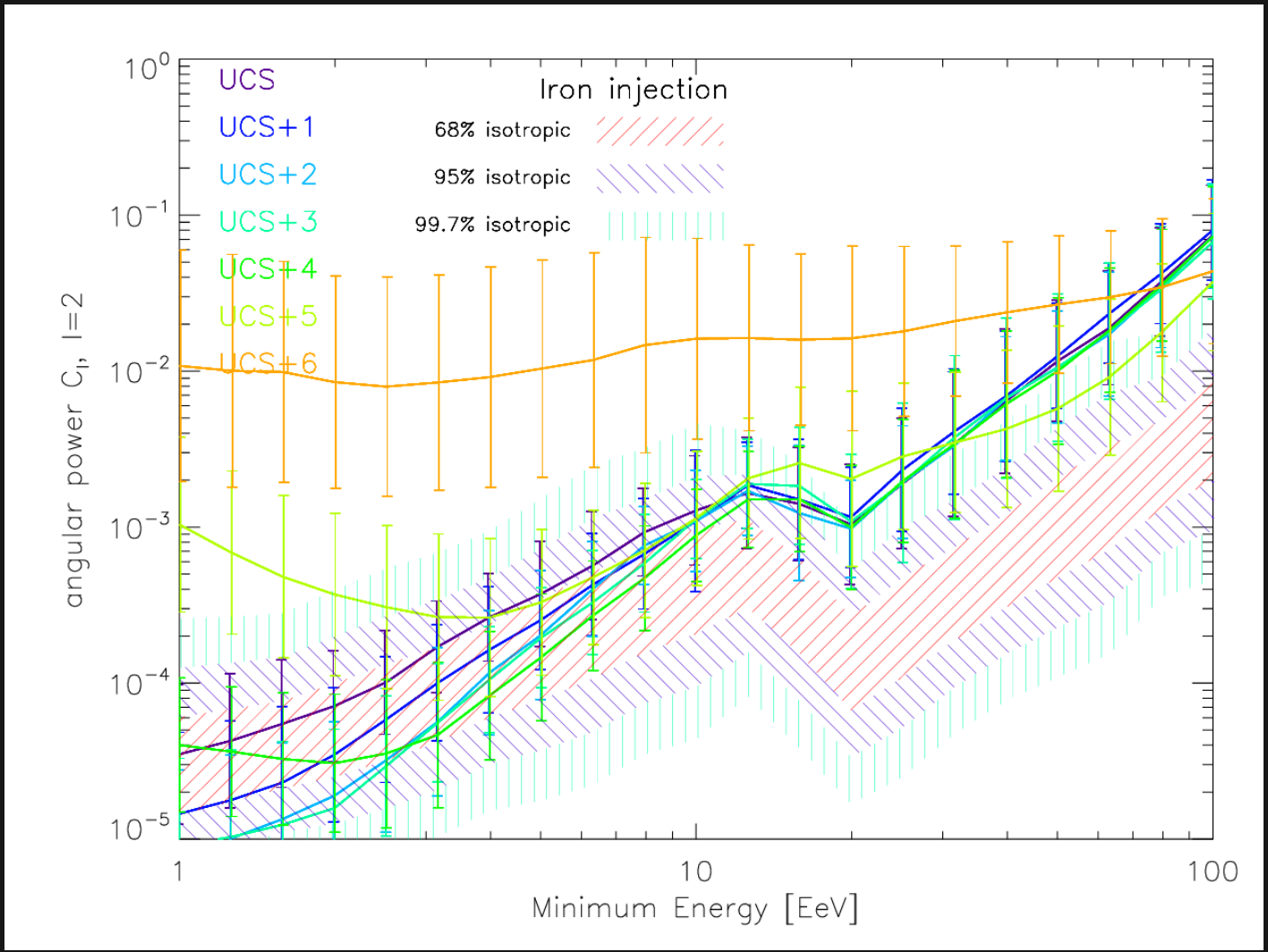
Magnetic Environment

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



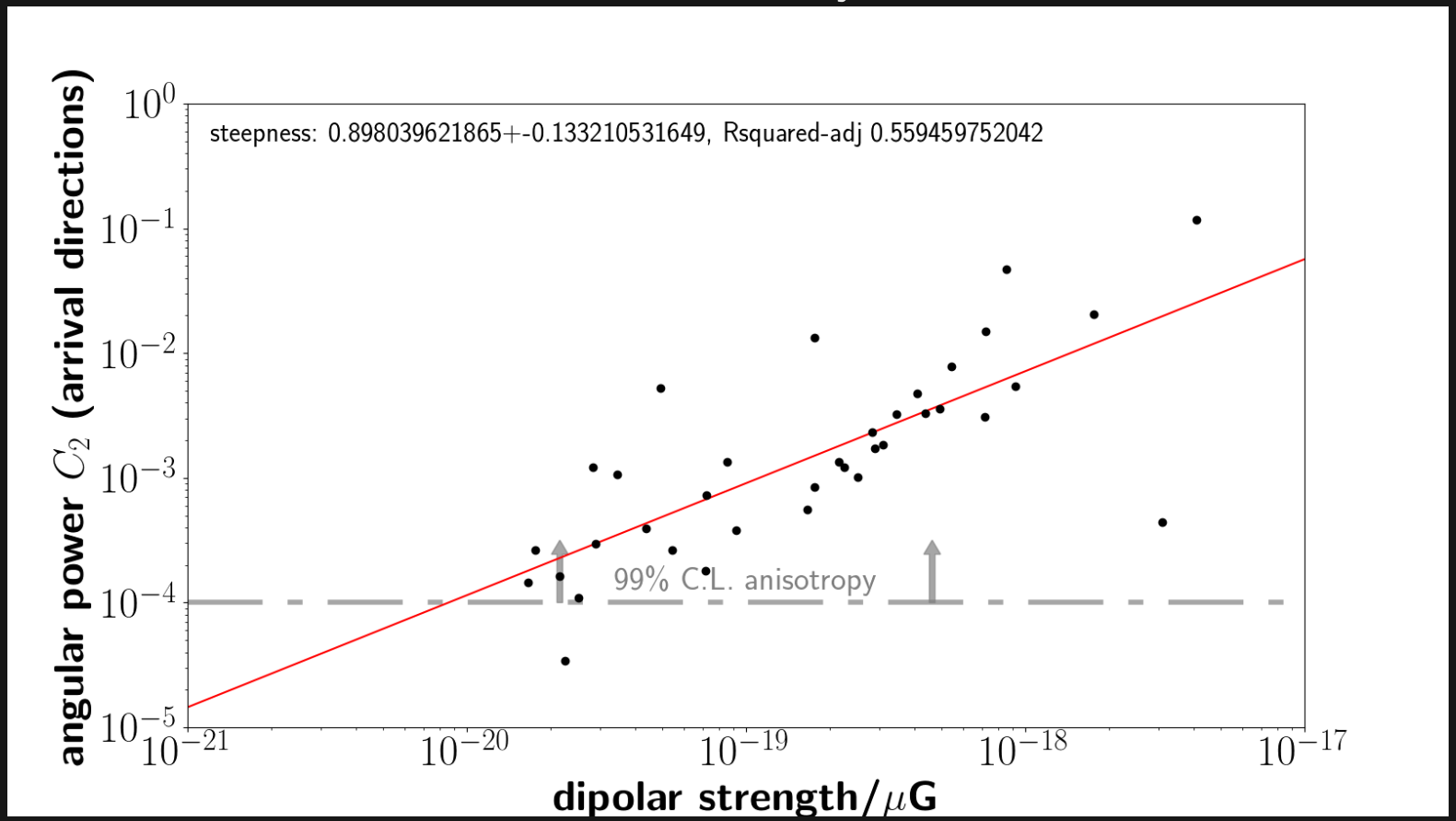
strong magnetic dipole $\Rightarrow$ deflection $\perp$ stronger than $\parallel$

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

$\Rightarrow$ **quadrupole anisotropy**

Angular Power spectrum

!!! Preliminary !!!



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

limit strength of dipole component around MW?

(Hackstein, Dundovic & Avola in prep.)

Conclusions

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

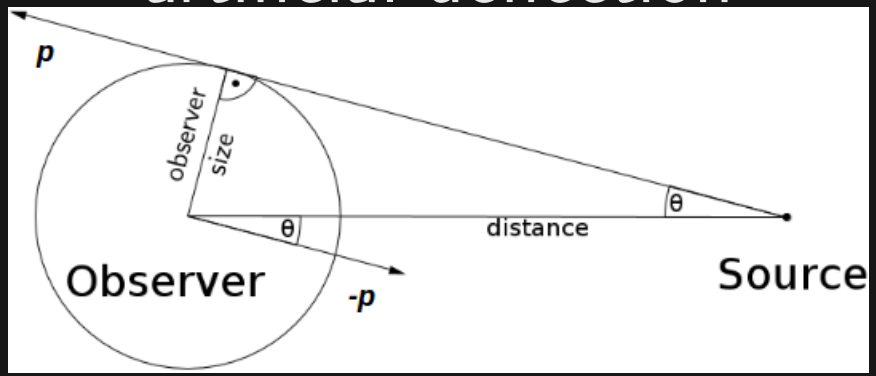
DIfferent seeding models indistinguishable
$\Rightarrow$ **No info on magneto-genesis**

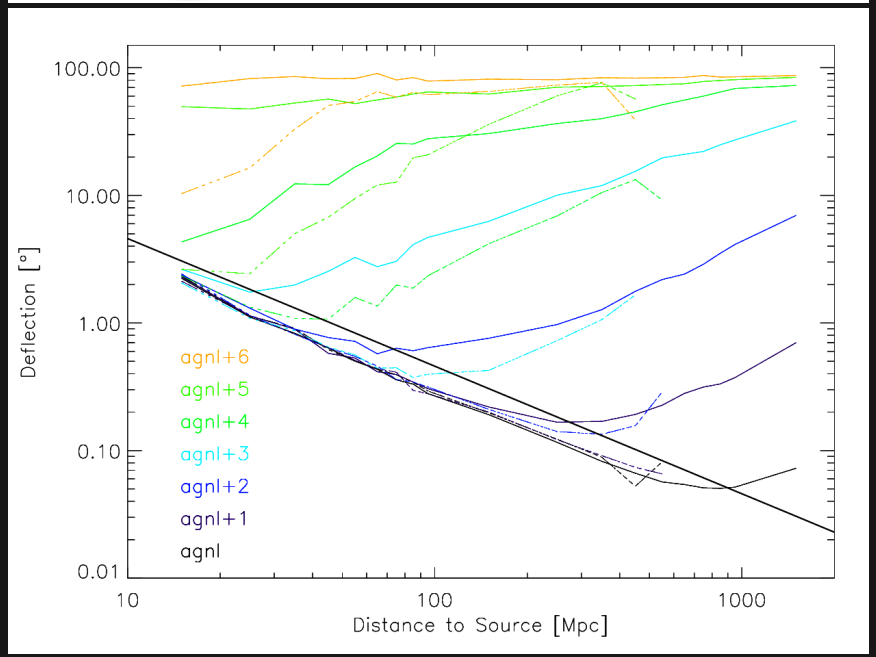
strong magnetic dipole $\Rightarrow$ stronger $\perp$ deflection
$\Rightarrow$ change in energy spectrum / composition
$\Rightarrow$ **Limit dipole component in vicinity of MW**

Artefacts

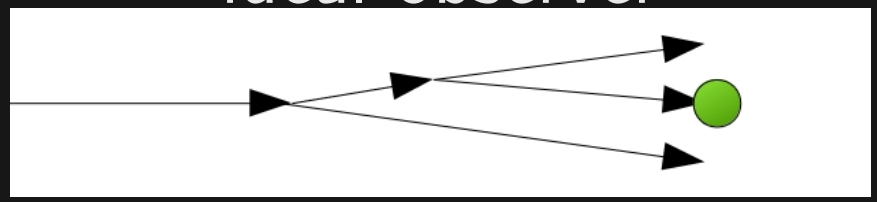
effect of finite observer

artificial deflection

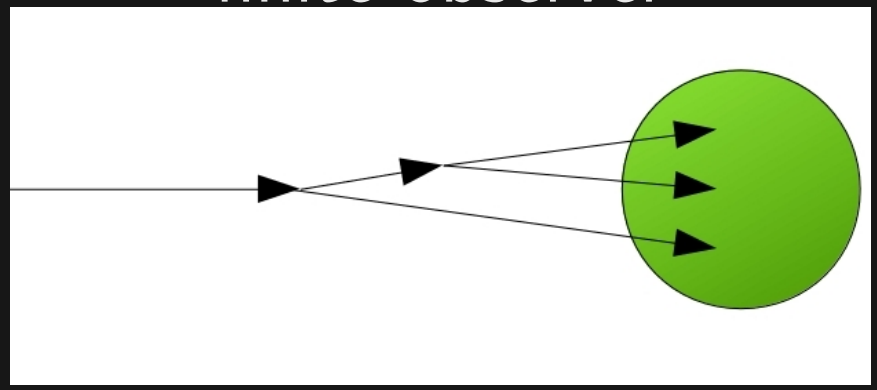




ideal observer



finite observer



magnetized observer