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# the inhomogeneous universe: matter distribution and magnetic fields

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L'Aquila - 04/06/2014

# introduction

origin

- where do UHECRs come from?
- are the sources uniformly distributed?
- do the sources follow the matter distribution?

what are UHECRs made of? — nature

**how to answer these questions?**

## magnetic field and matter distributions

✦ magnetic fields determine trajectory of particles

✦ sources may follow the matter distribution

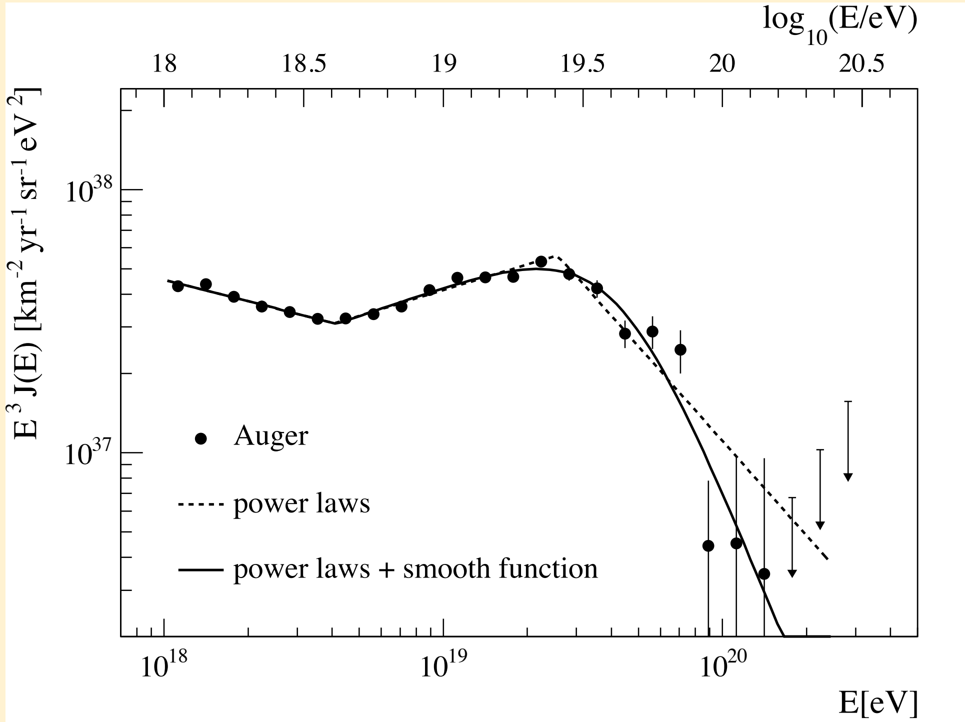
✦ magnetic field and matter distribution may be correlated

✦ to do UHECR astronomy: we need to understand magnetic fields (galactic and extragalactic)

✦ signatures of magnetic field and matter distributions may be imprinted in on experimental data (spectrum, composition and anisotropies)

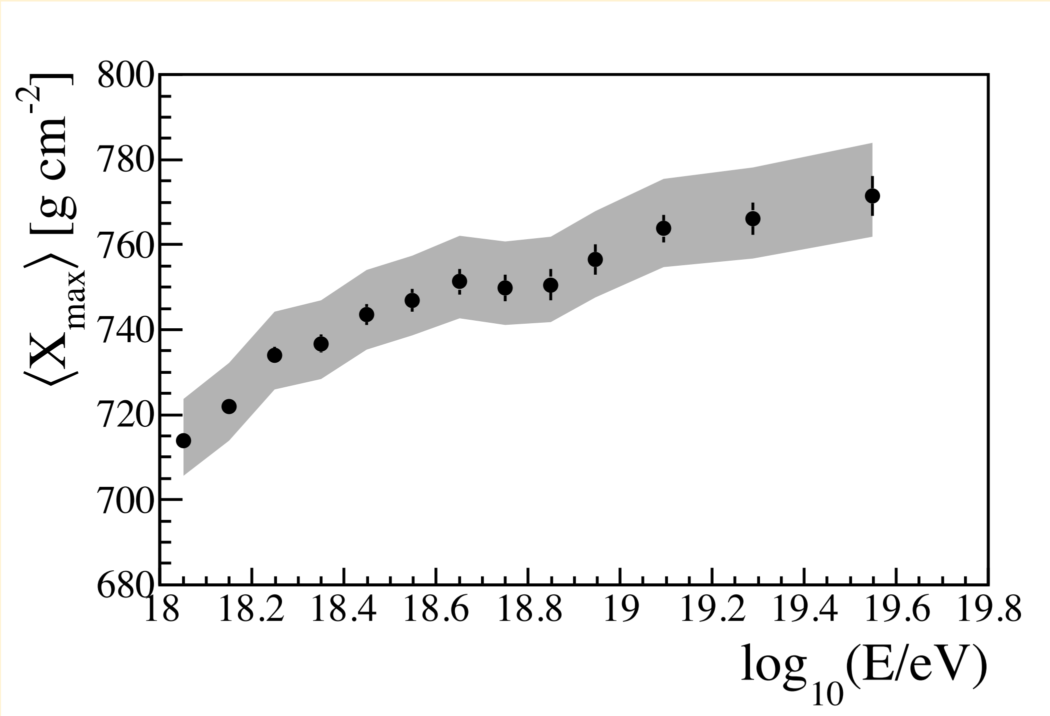
# UHECRs observables

## spectrum



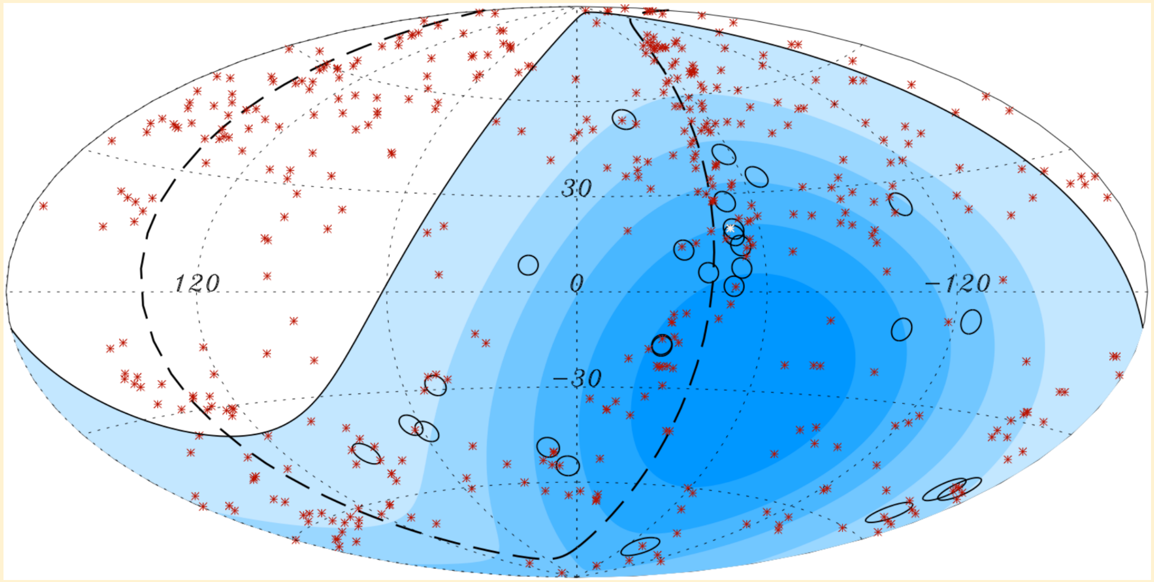

Pierre Auger Collaboration, ICRC 2011.

## composition




Pierre Auger Collaboration, JCAP 02 (2013) 026.

## anisotropy




Pierre Auger Collaboration, Science 318 (2007) 938.

- ✦ magnetic fields and source distribution may affect spectrum and composition, and certainly affect anisotropy
- ✦ explain these observables simultaneously
- ✦ 3D models are needed

# motivation

## overview

✦ magnetic fields and matter distribution can affect the shape of the spectrum

✦ sources may be distributed according to the matter distribution

✦ cosmological effects can be relevant depending on the magnetic fields, even for nearby sources, depending on the properties of the intervening magnetic fields (e.g. diffusion)

✦ fit the spectrum and composition might not be enough to obtain physical scenarios to explain UHECRs => anisotropies can be important

## a few works making predictions about some of these observables

✦ dip model - Berezinsky et al. **S C**

✦ disappointing model - Aloisio et al. **S C**

✦ Allard et al. **S C**

✦ Hooper & Taylor **S C**

✦ Sigl et al. **S C A**

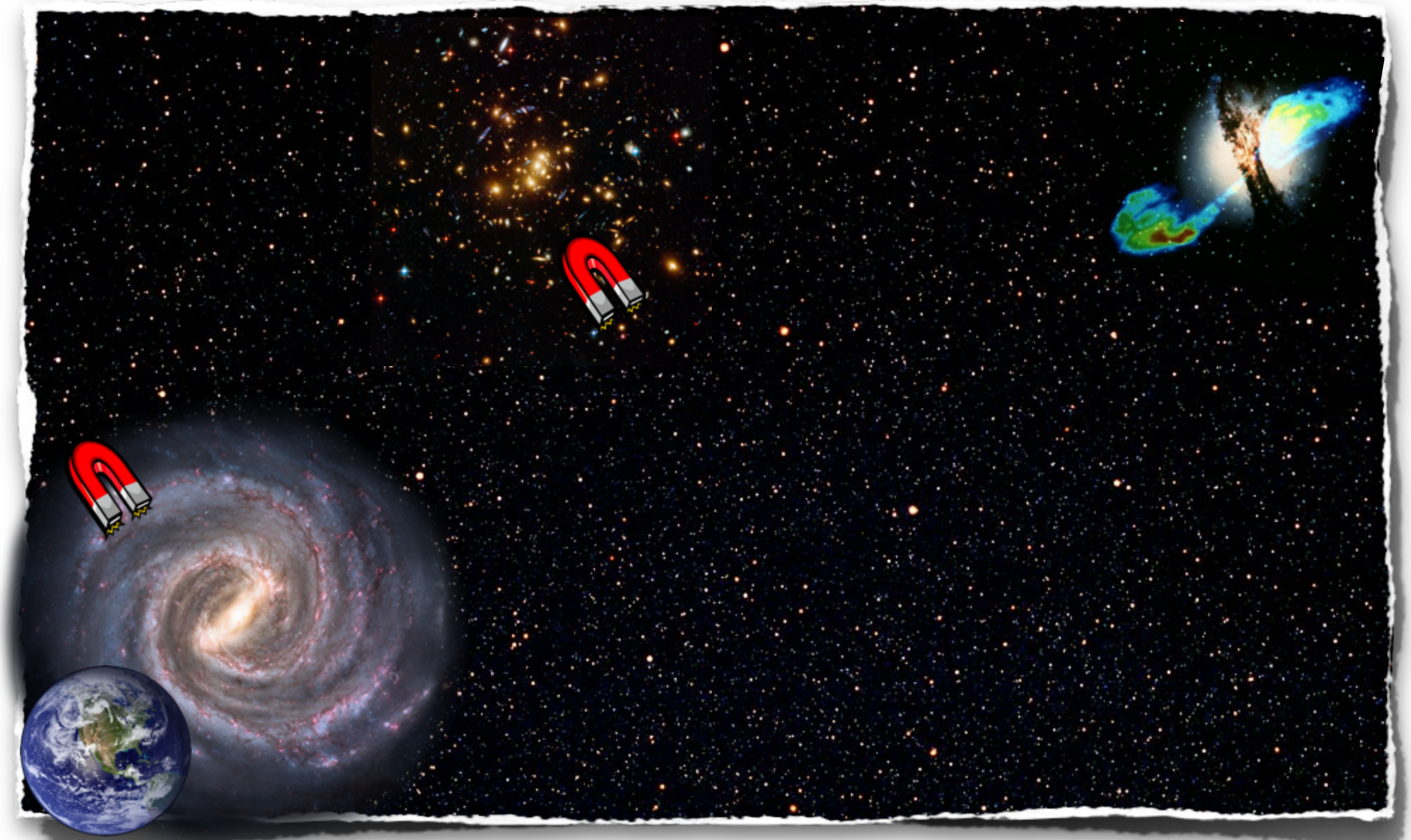
✦ Dolag et al. **A**

✦ many others

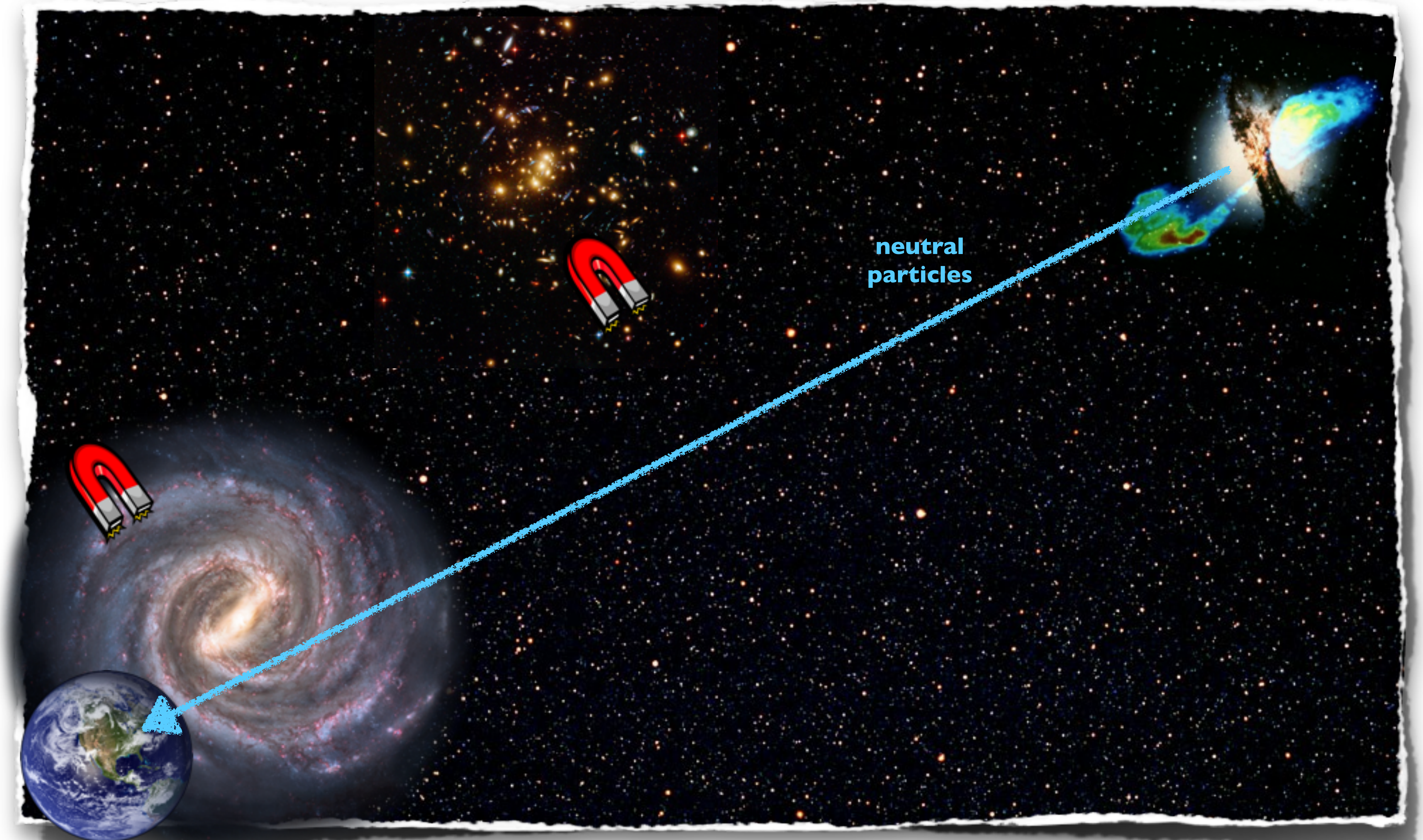
**S**pectrum
**C**omposition
**A**nisotropy


**Berezinsky et al. Phys. Rev. D 74 (2006) 043005**
**Aloisio et al. Astropart. Phys. 34 (2011) 620**
**Allard et al. JCAP 10 (2008) 033**
**Hooper and Taylor, Astropart. Phys. 33 (2010) 151**
**Sigl et al. Phys. Rev. D 68 (2003) 043002**
**Sigl et al. Phys. Rev. D 70 (2004) 043007**
**Dolag et al. JCAP 0501 (2005) 009**

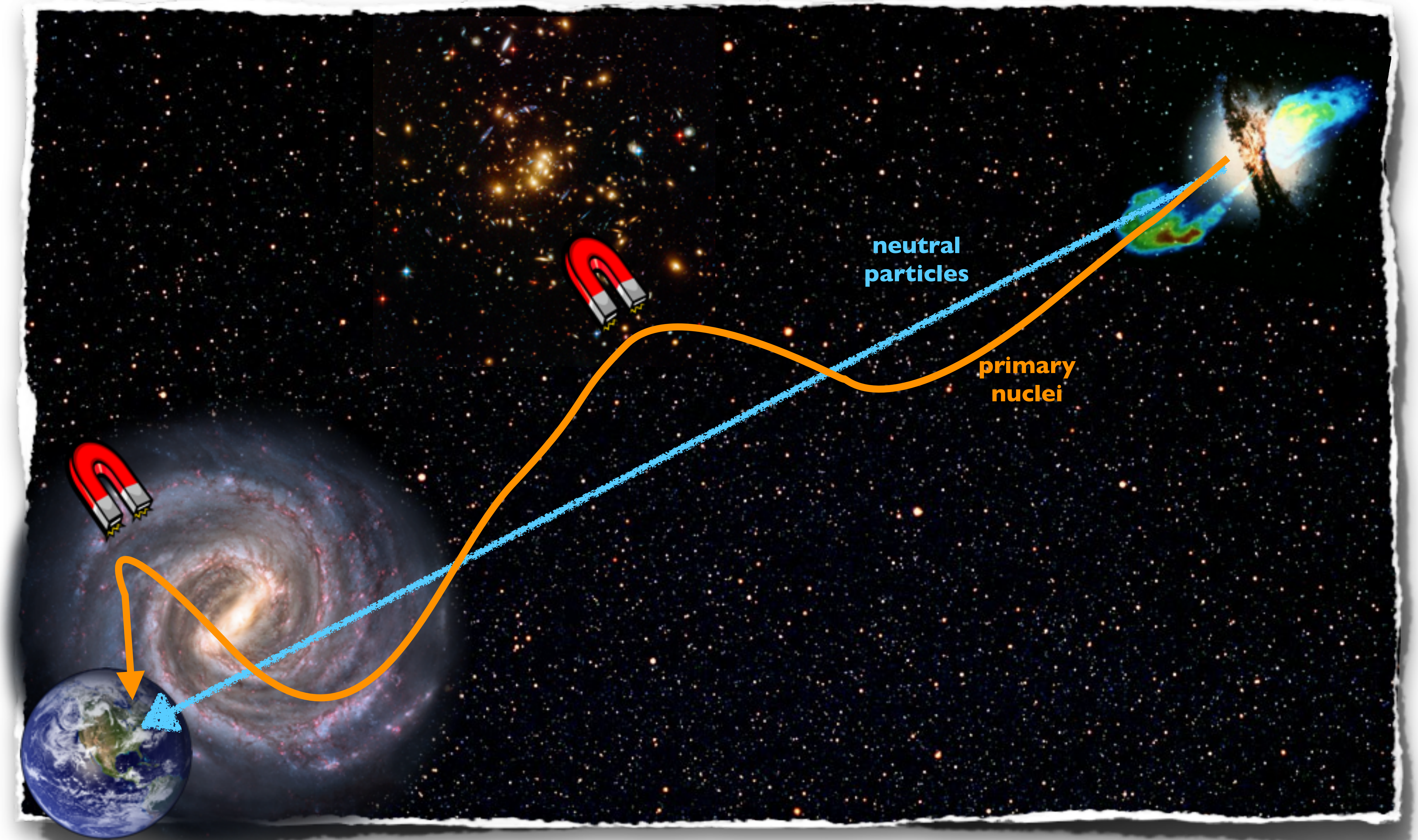
# cosmic ray propagation: general picture



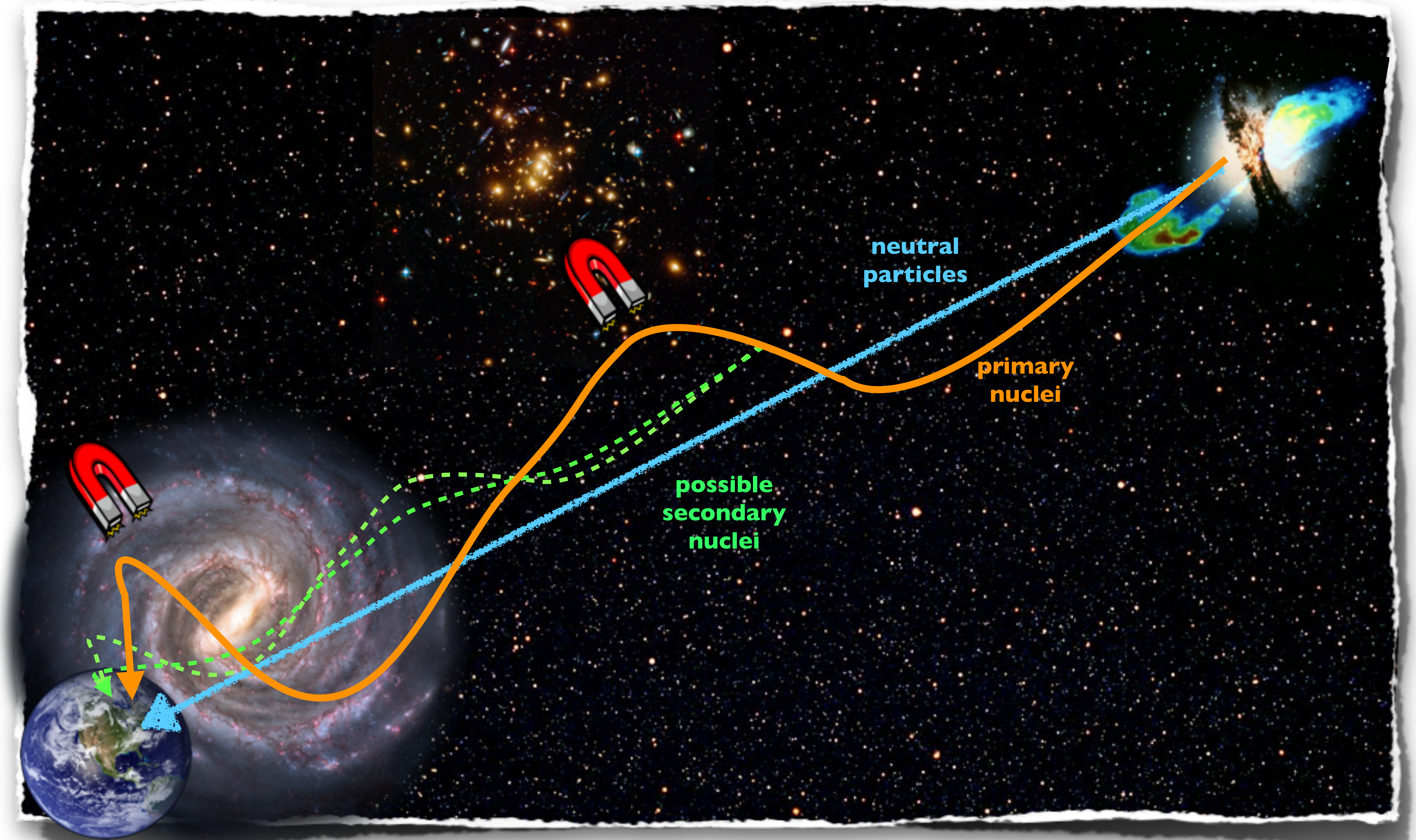
# cosmic ray propagation: general picture



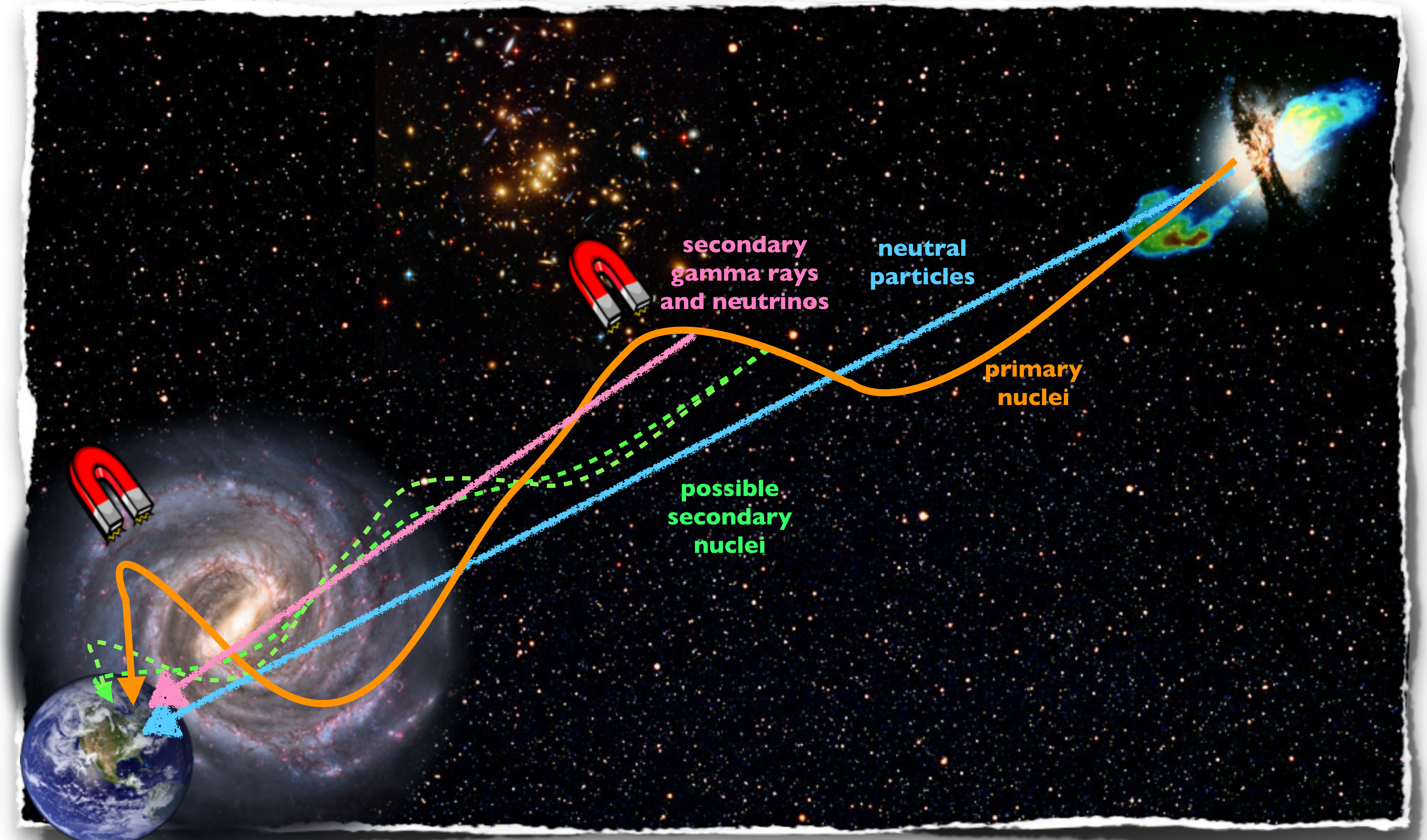
# cosmic ray propagation: general picture



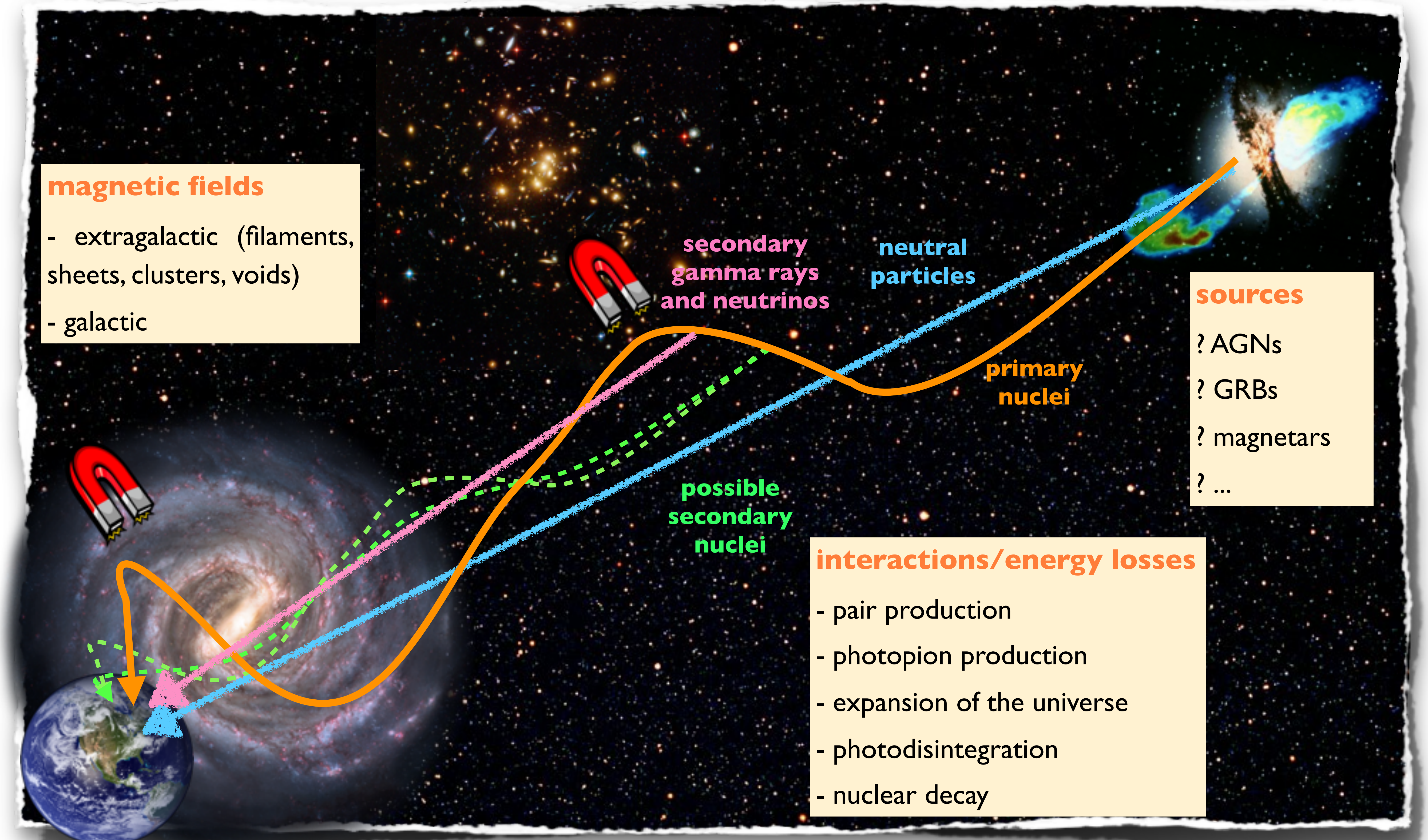
# cosmic ray propagation: general picture



# cosmic ray propagation: general picture



# cosmic ray propagation: general picture



# simulating the propagation of UHECRs

## propagation codes

✦ CRPropa 3

- code available in crpropa.desy.de **RAB et al. Proceedings 33rd ICRC. arXiv:1307.2643**
- based on CRPropa 2 **Kampert et al. Astropart. Phys. 42 (2013) 41**
- modular structure
- parallel code → faster simulations → wide range of parameters

✦ other public codes:

- SimProp **Aloisio et al. JCAP 1210 (2012) 007**
- HERMES **Domenico. EPJ Plus 128 (2013) 99**
- transport code **Kalashev, Kuzmin, Semikoz. arXiv:astro-ph/9911035**

## 1D simulations

✦ redshift losses

✦ source evolution

✦ no deflection by magnetic fields

## 3D simulations

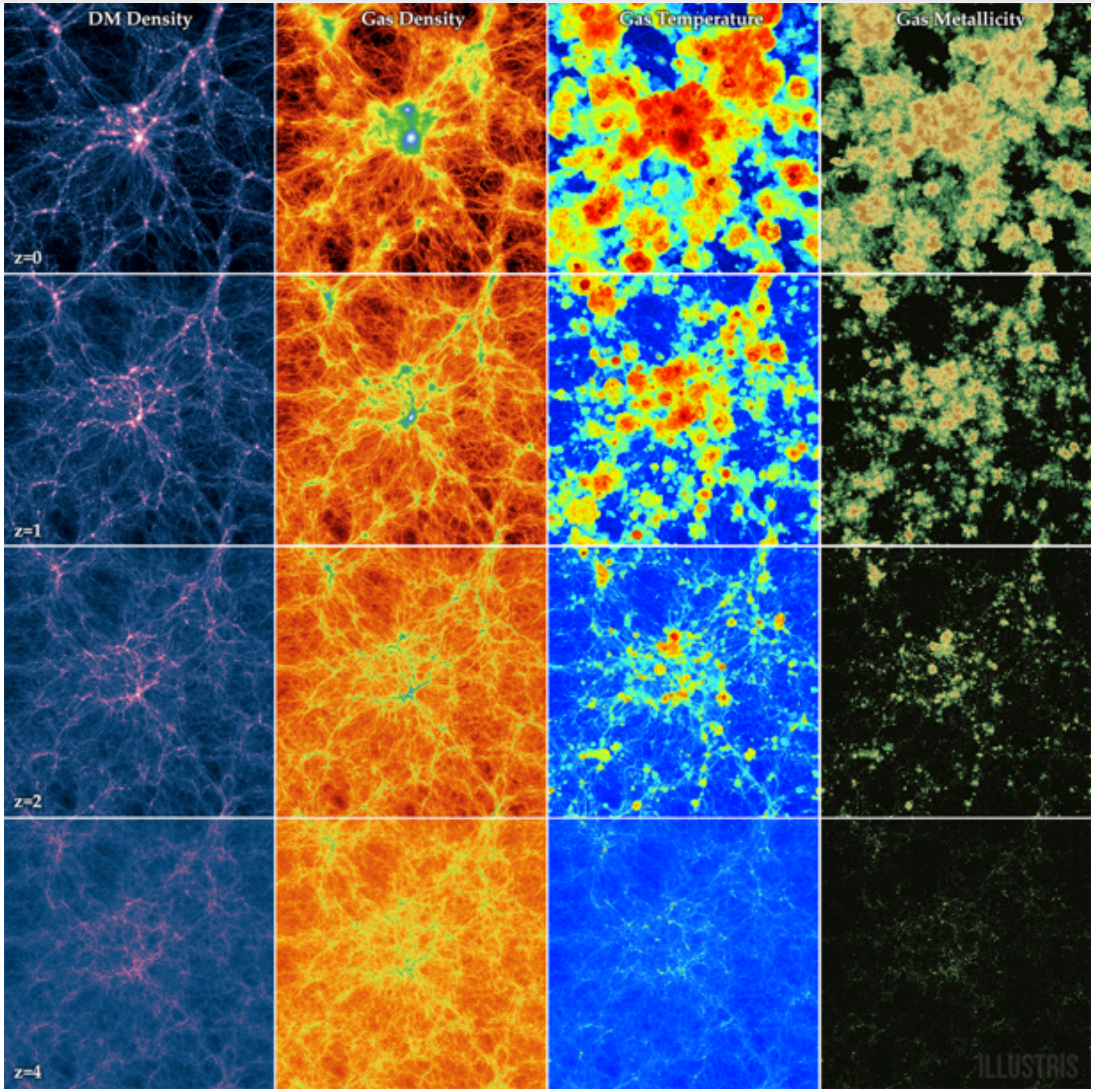
✦ effects of large scale structure

✦ magnetic deflections

✦ galactic lensing

# matter distribution and magnetic fields

# matter distribution



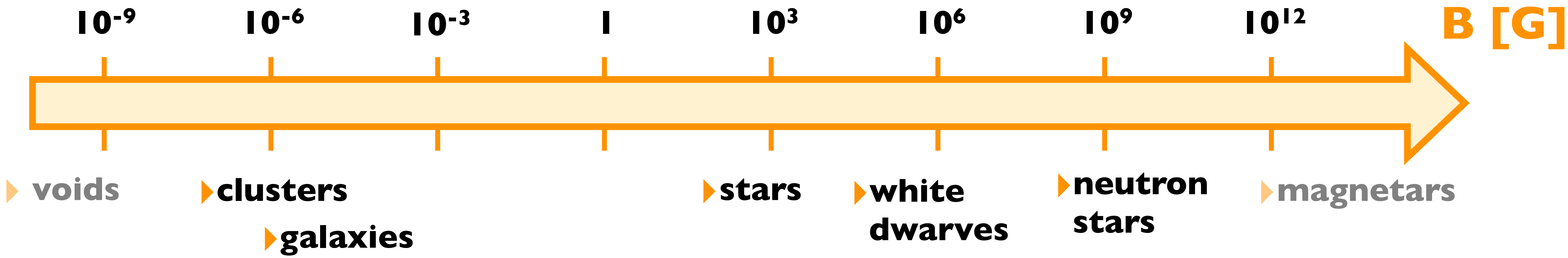

Credits: Illustris Collaboration

# matter distribution

M. Vogelsberger et al. Nature 509 (2014).

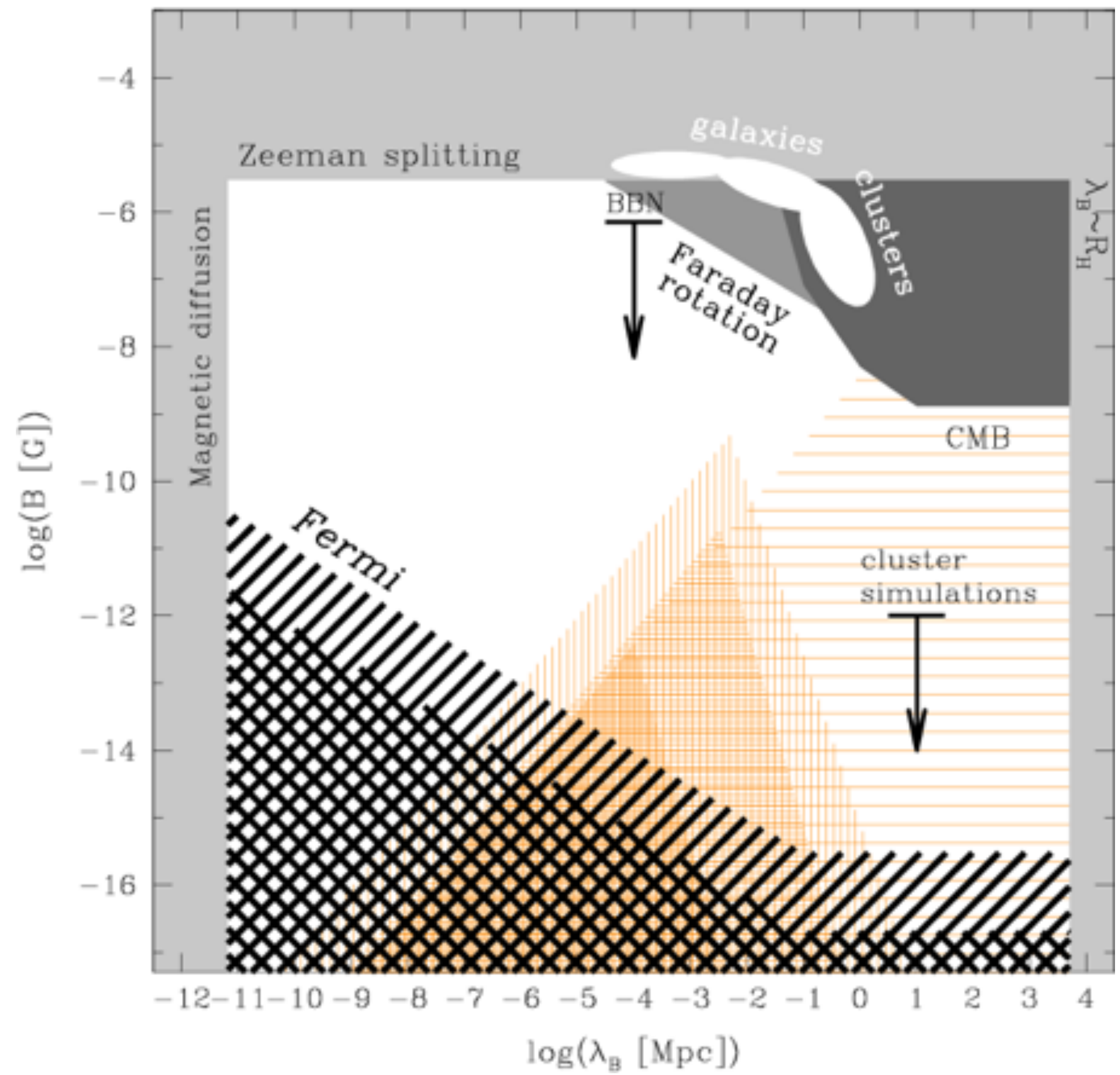
Credits: Illustris Collaboration

# cosmic magnetic fields



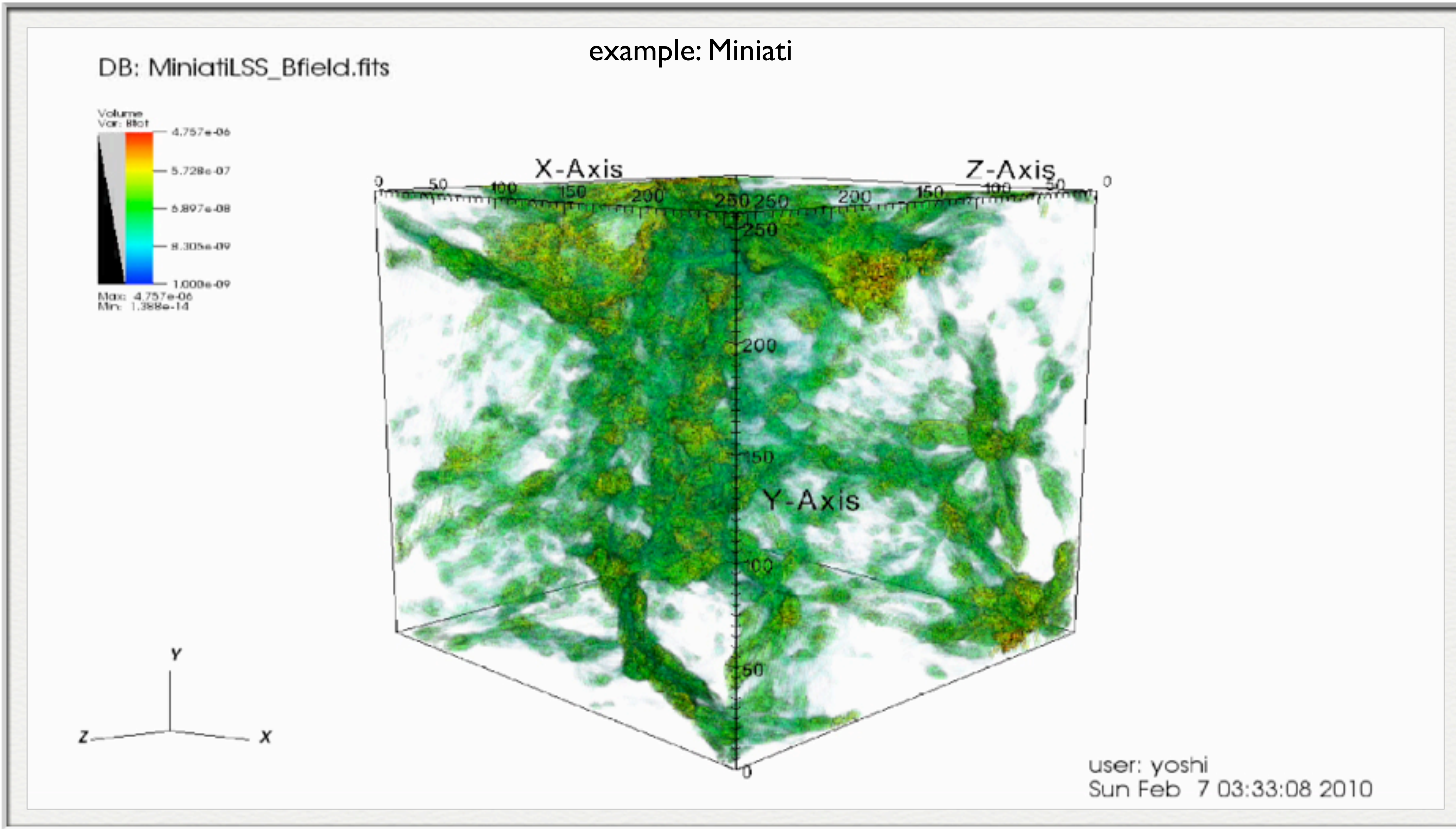

## overview

- ✦ are there cosmological magnetic fields?
- ✦ how are magnetic fields created?
  - astrophysical (Biermann battery)
  - cosmological (inflation, phase transitions, etc)
- ✦ lower limit: electromagnetic cascades (?)

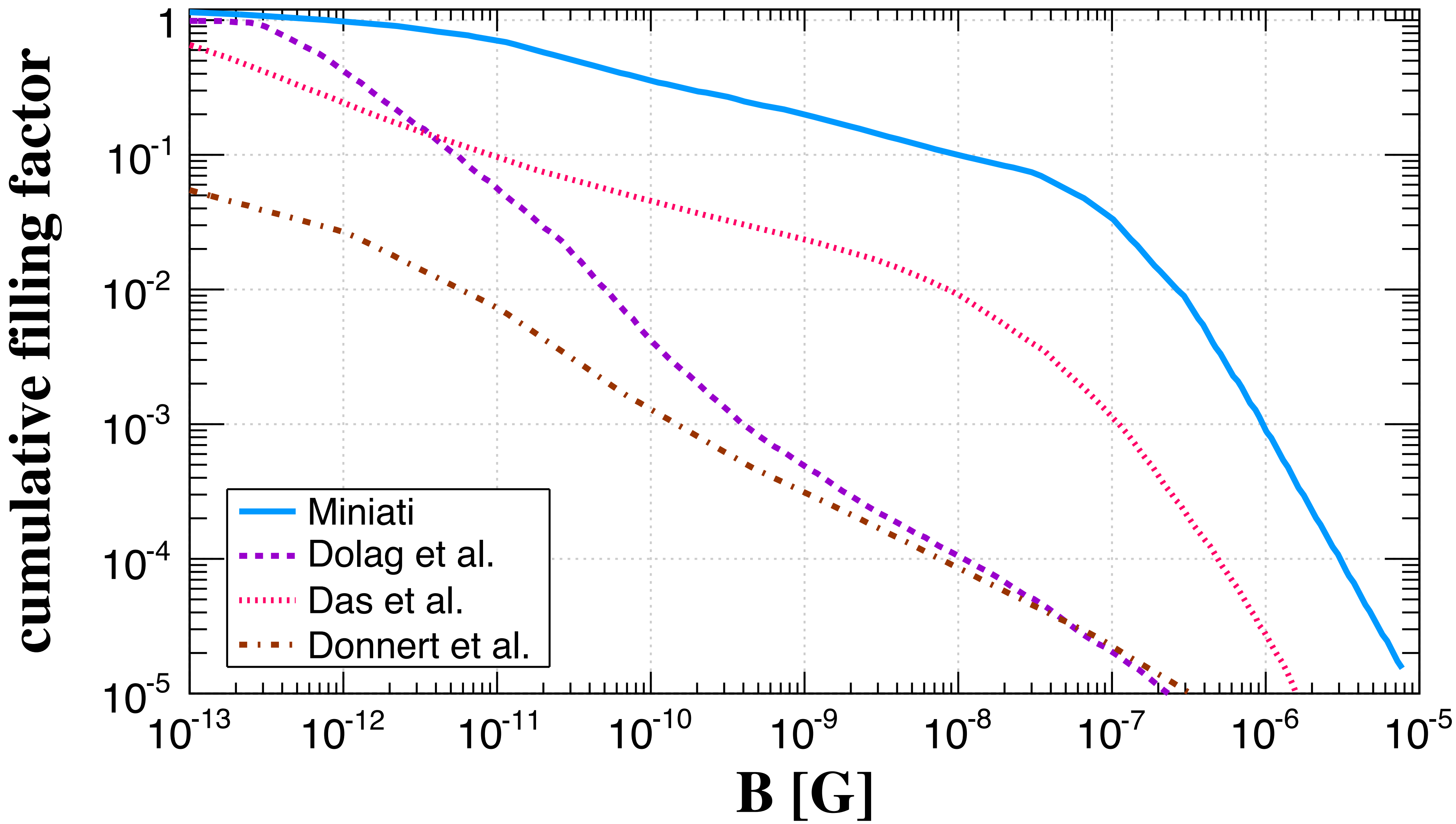



Neronov, Vovk. Science 328 (2010) 73

# structured magnetic fields

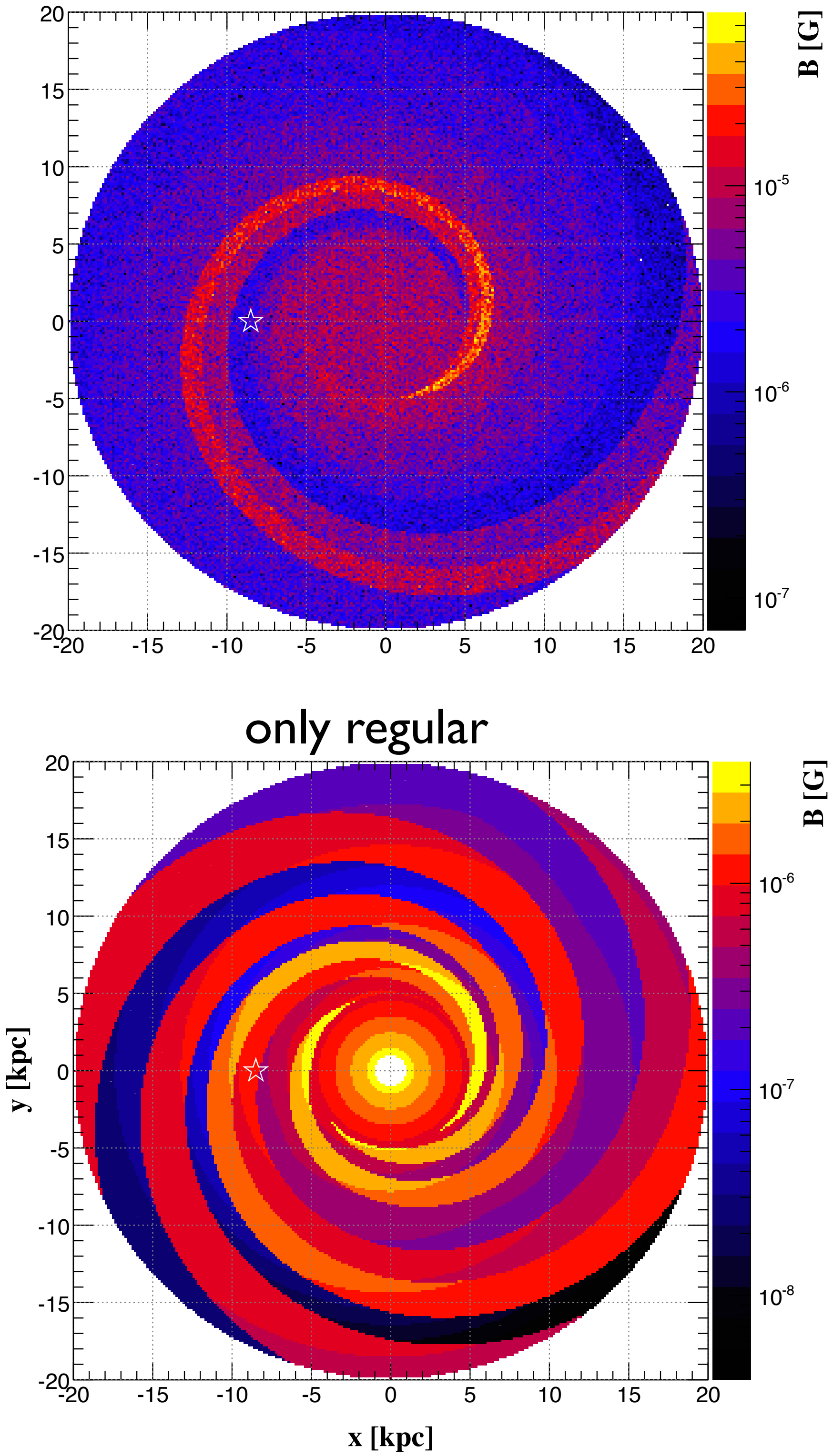


# structured magnetic fields

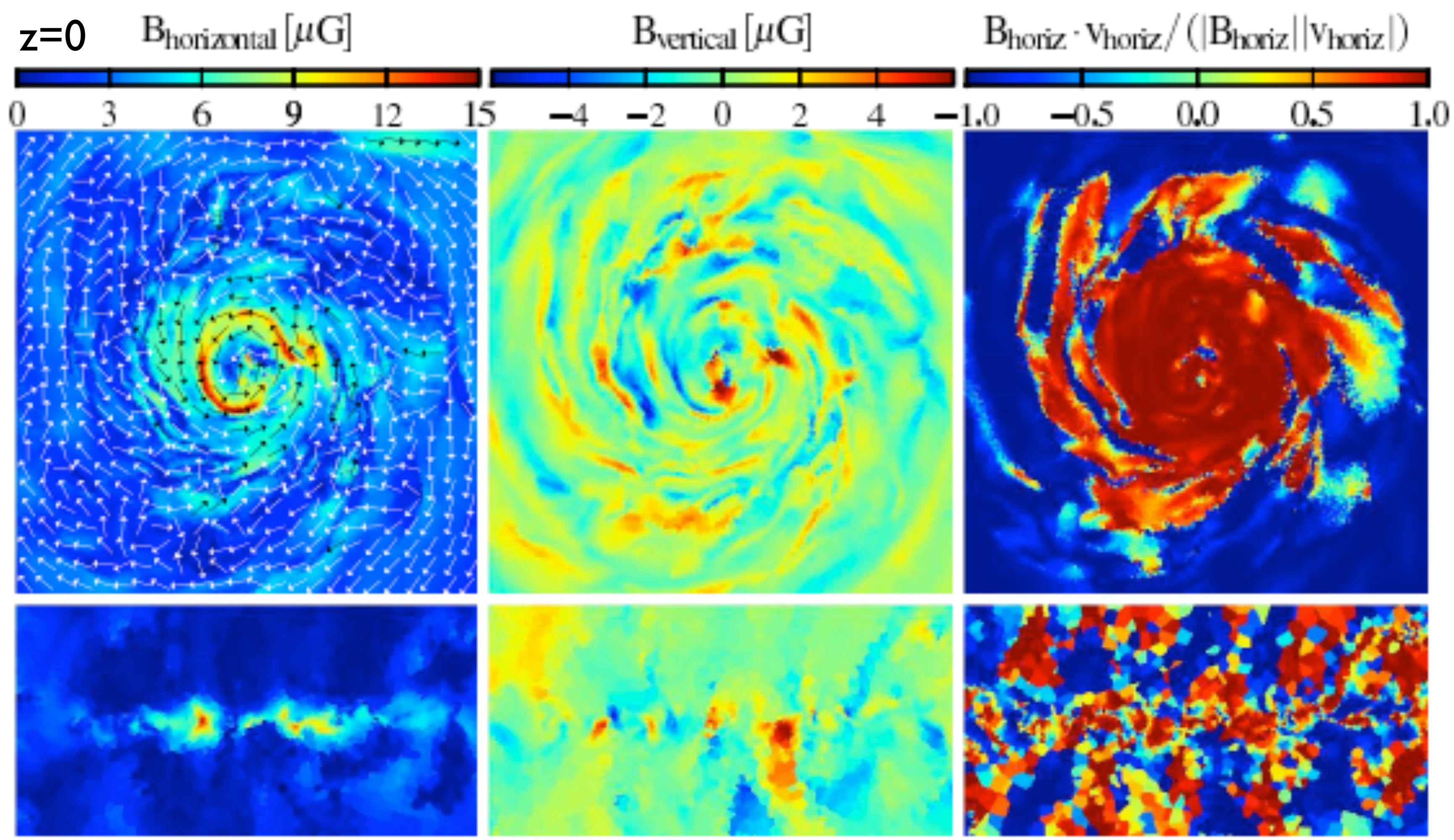



- ✦ filling factors are not well known
- ✦ they depend on how the cosmological simulation was done
- ✦ choice of normalization can result on different filling factors
- ✦ we show only four cosmological simulations, but there are many others

# galactic magnetic field (GMF)




Jansson & Farrar, ApJ 761 (2012) L11




Pakmor, Marinacci, Springel. arXiv:1312.2620

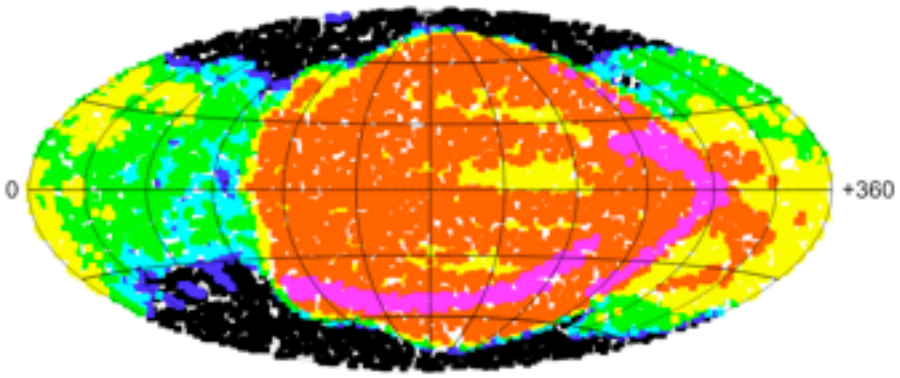
- ✦ fit of observations: e.g. Jansson-Farrar model
- ✦ MHD simulations: e.g. Pakmor et al.

# UHECRs and the galactic magnetic field

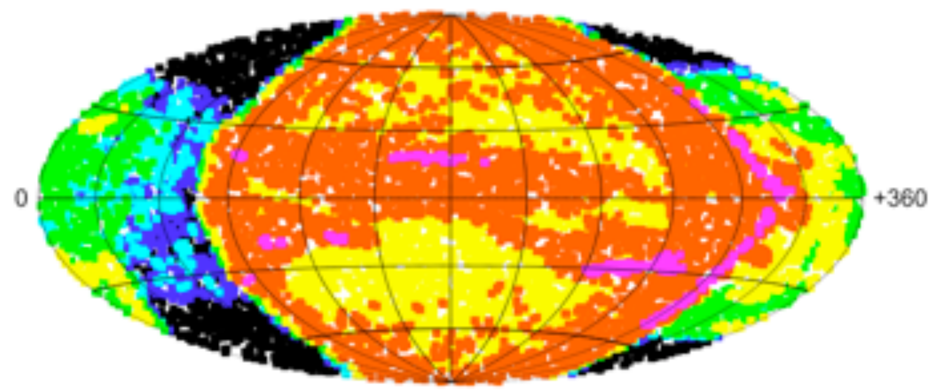
# galactic magnetic field: UHECR lensing

density

E=60 EeV




E=140 EeV




black: $\delta < 10°$

gray: $10° < \delta < 25°$

dark blue: $25° < \delta < 40°$

light blue: $40° < \delta < 55°$

green: $55° < \delta < 70°$

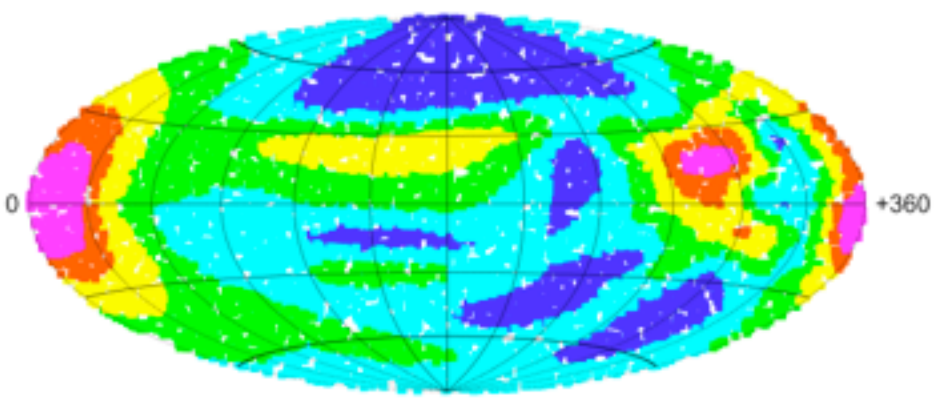
yellow: $70° < \delta < 85°$

orange: $85° < \delta < 100°$

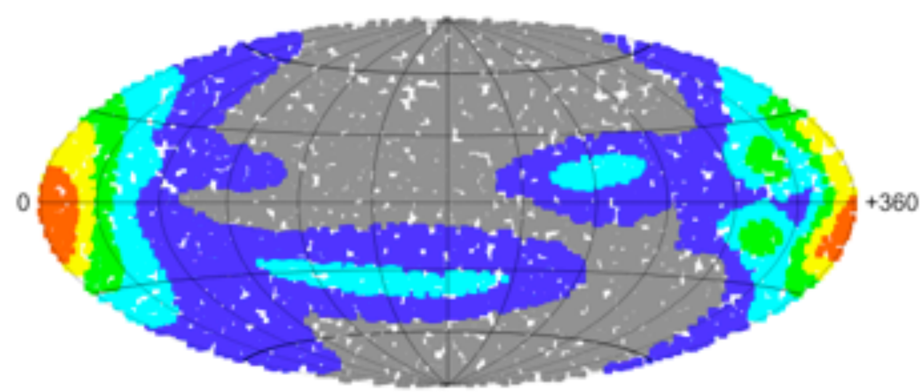
magenta: $100° < \delta$

deflections

E=60 EeV




E=140 EeV




dark blue: $-2.0 < \log(\rho/\langle\rho\rangle) < -1.5$

light blue: $-1.5 < \log(\rho/\langle\rho\rangle) < -1.0$

green: $-1.0 < \log(\rho/\langle\rho\rangle) < -0.5$

yellow: $-0.5 < \log(\rho/\langle\rho\rangle) < 0.0$

orange: $0.0 < \log(\rho/\langle\rho\rangle) < 0.5$

magenta: $0.5 < \log(\rho/\langle\rho\rangle)$

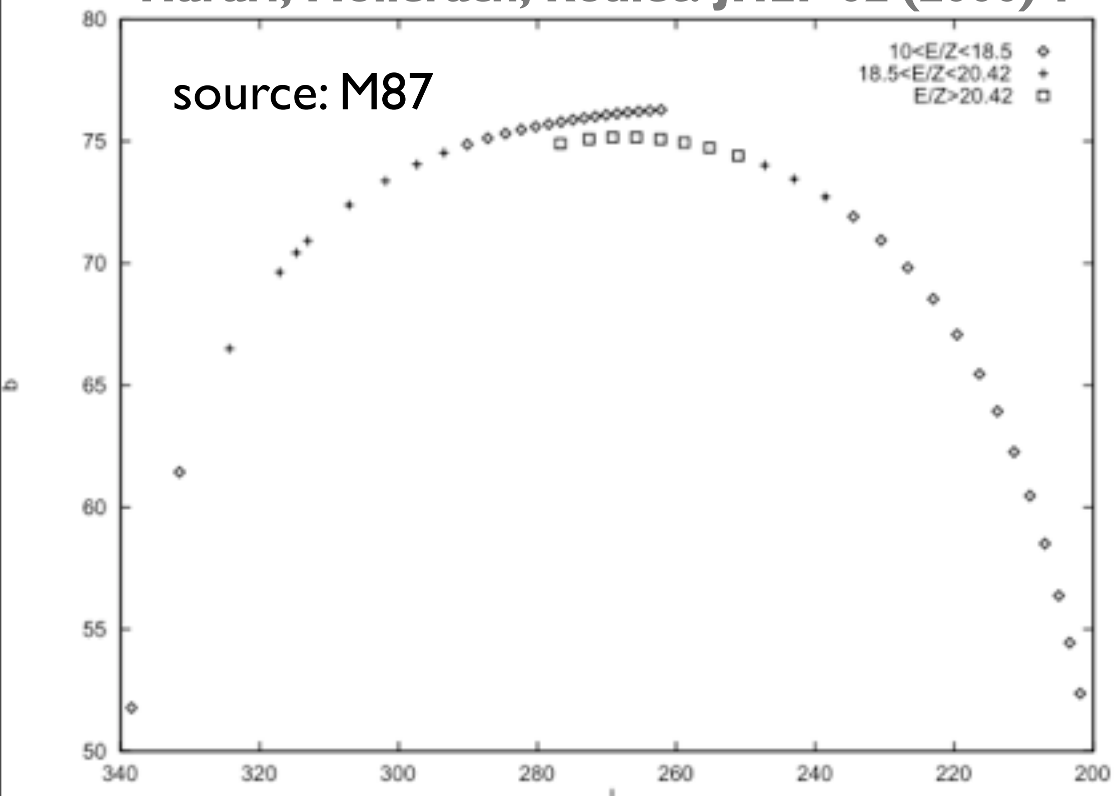
Giacinti, Kachelriess, Semikoz, Sigl. JCAP 1008 (2010) 036.

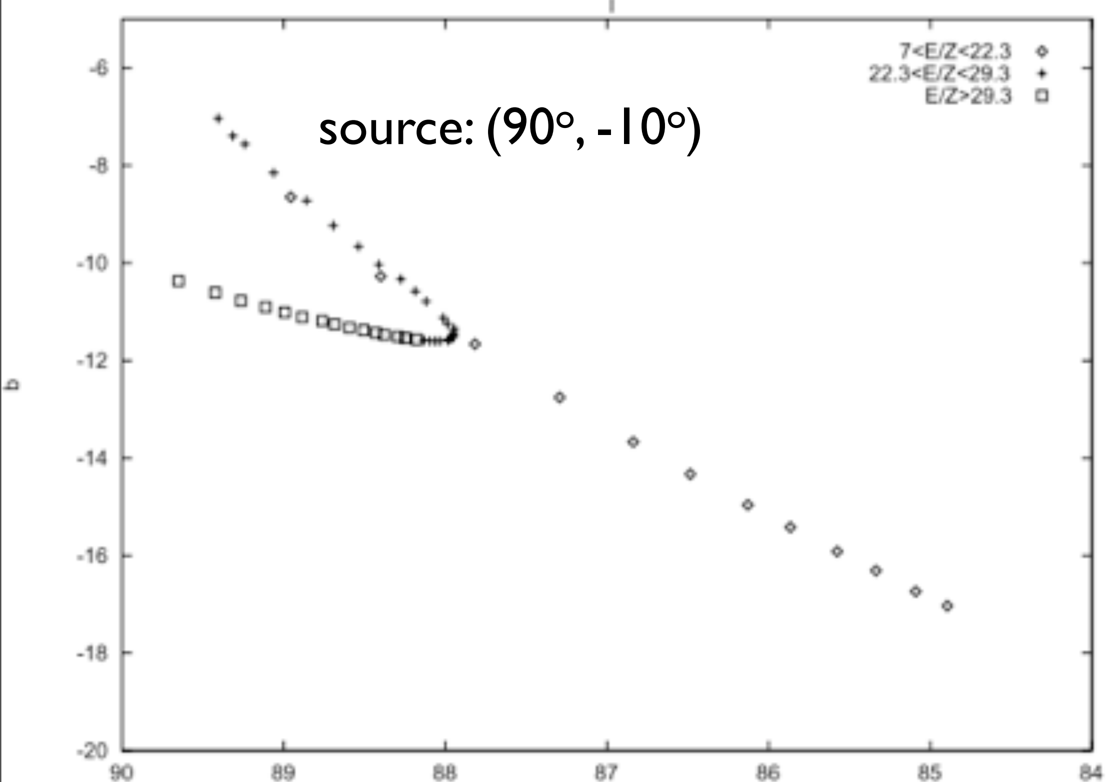
- ✦ injected iron isotropically (from Earth)
- ✦ particles backtracked to the edge of the galaxy
- ✦ GMF model used: Prouza-Smida

- ✦ “blind” spots
- ✦ strong deflections
- ✦ deflections depend on the GMF model

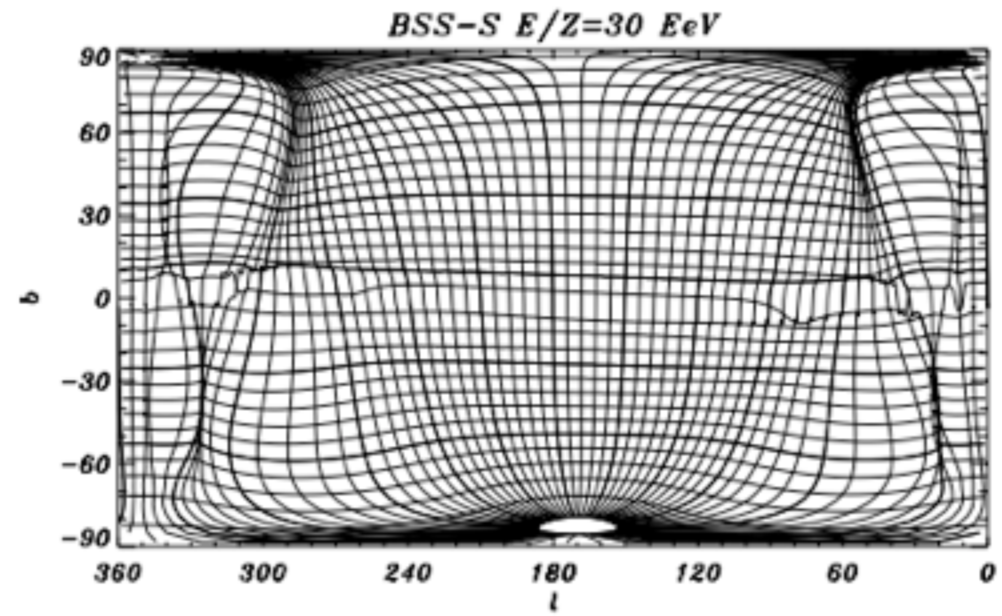
# galactic magnetic field: UHECR lensing

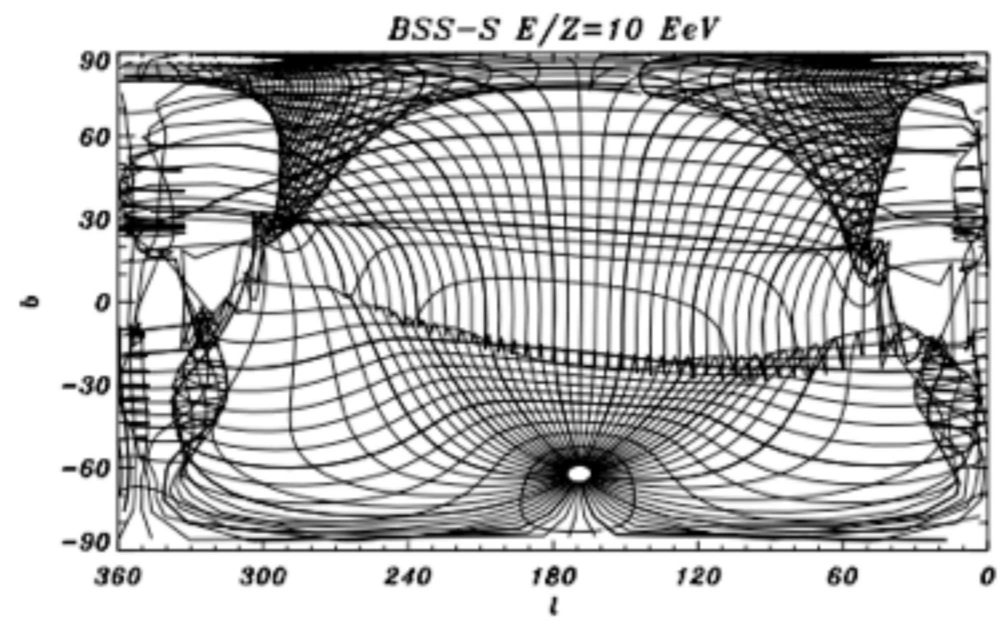
Harari, Mollerach, Roulet. JHEP 02 (2000) 1




Harari, Mollerach, Roulet. JHEP 08 (1999) 022



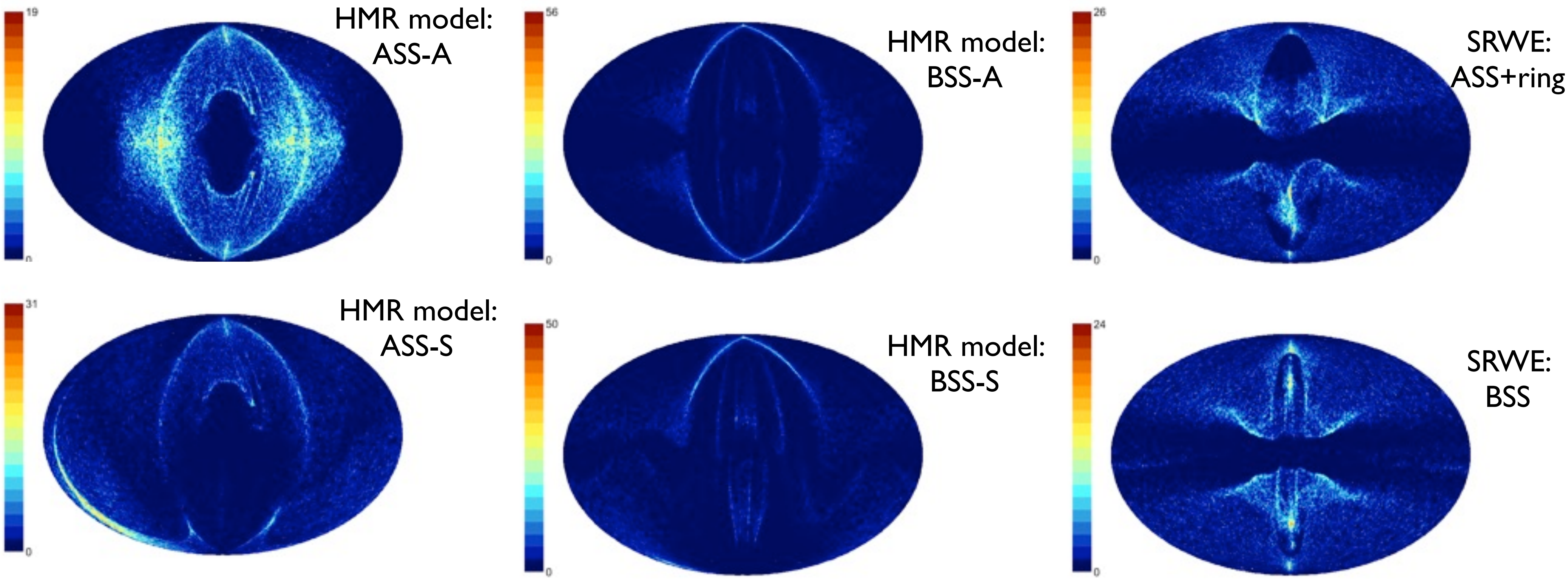




✦ sources may have multiple images due to the GMF

✦ sky sheets: no lensing → regular grid; if the sheets are folded sources have multiple images

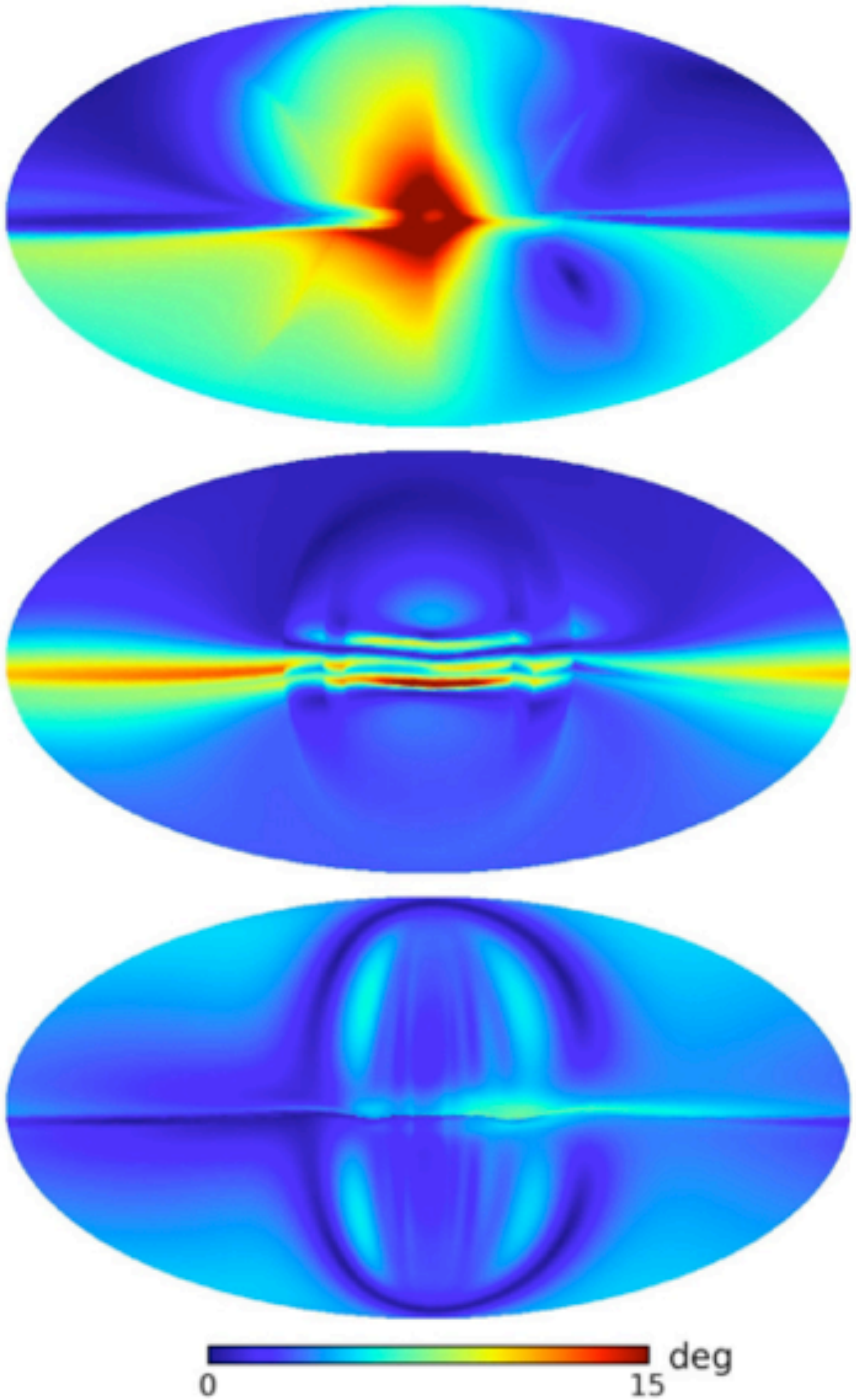
# GMF: model dependence

RAB & E. Kemp. 2012




- ✦ 3000 protons events above 20 EeV (spec index = -2)
- ✦ isotropic events injected at Earth and backtracked to the edge of the galaxy
- ✦ HMR model: **Harari, Mollerach, Roulet. JHEP 08 (1999) 022**
- ✦ SRWE model: **Sun et al. A&A 592 (2008) 573**

# GMF: model dependence




Jansson & Farrar - best fit model

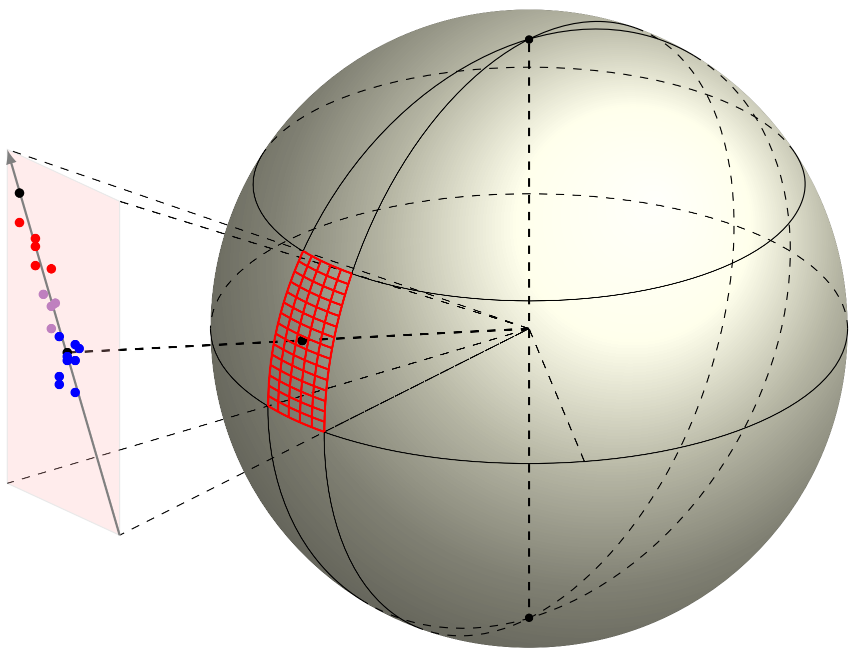
Sun et al. - best fit model

Stanev - bissymmetric spiral

Jansson & Farrar, ApJ 757 (2012)

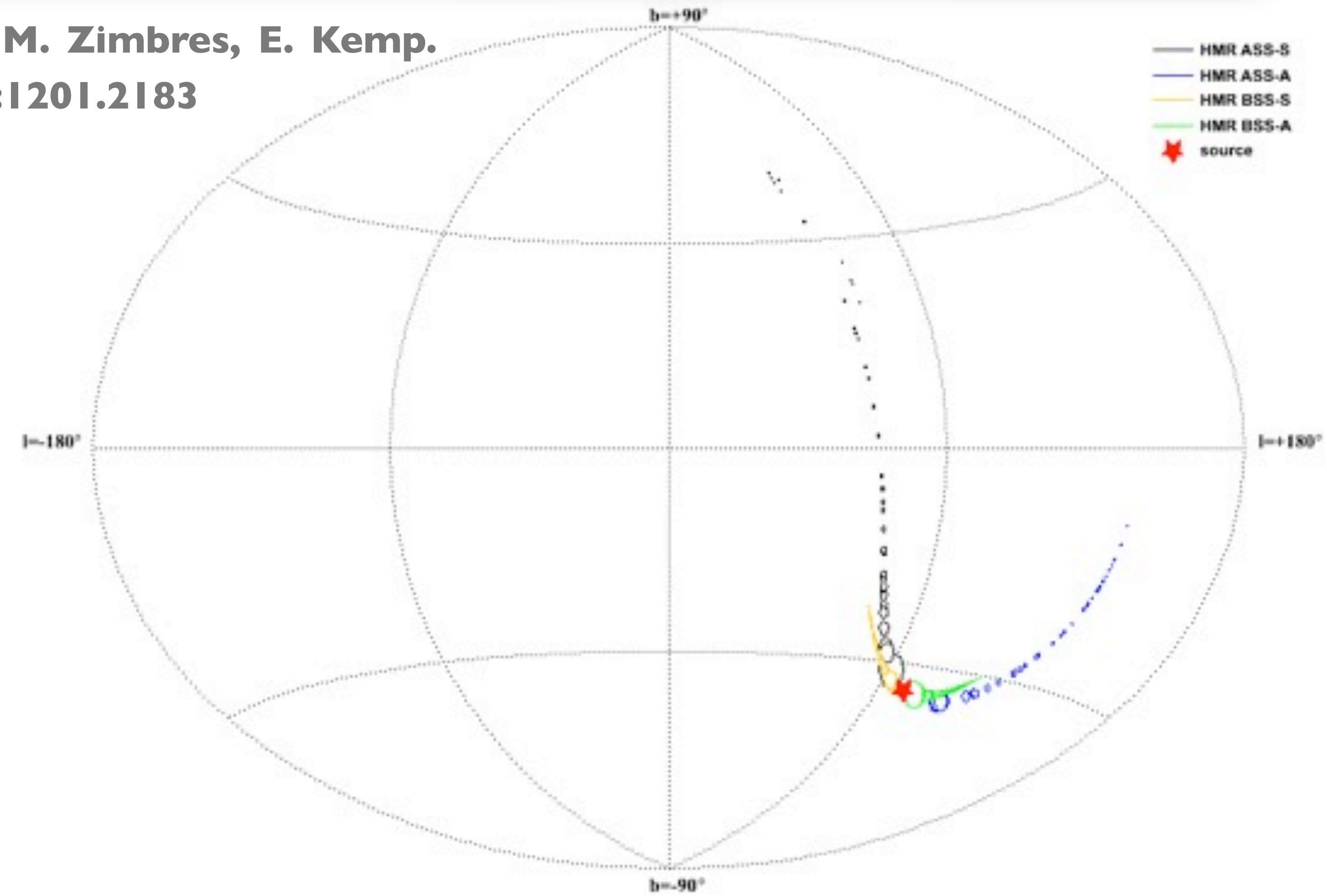
- ✦ GMF is model dependent
- ✦ most recent GMF model: Jansson & Farrar
  - \- obtained from the fit of the most recent RM and synchrotron data
  - \- null divergence condition satisfied
- ✦ pictures shows deflection angles for 60 EeV protons backtracked from Earth to the edge of the galaxy
- ✦ GMF strongly affects the propagation of UHECRs → finding sources of UHECRs require a deep understanding of the GMF

# GMF: UHECR multiplets



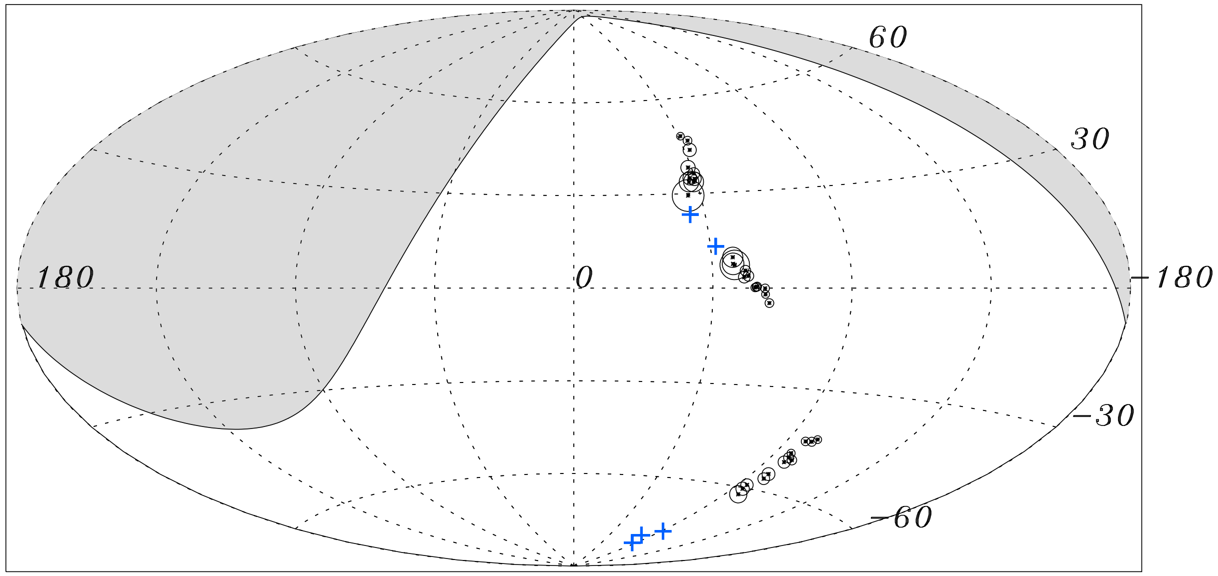
M. Zimbres, RAB, E. Kemp. Astropart. Phys. 54 (2014) 54.

RAB, M. Zimbres, E. Kemp. arXiv:1201.2183



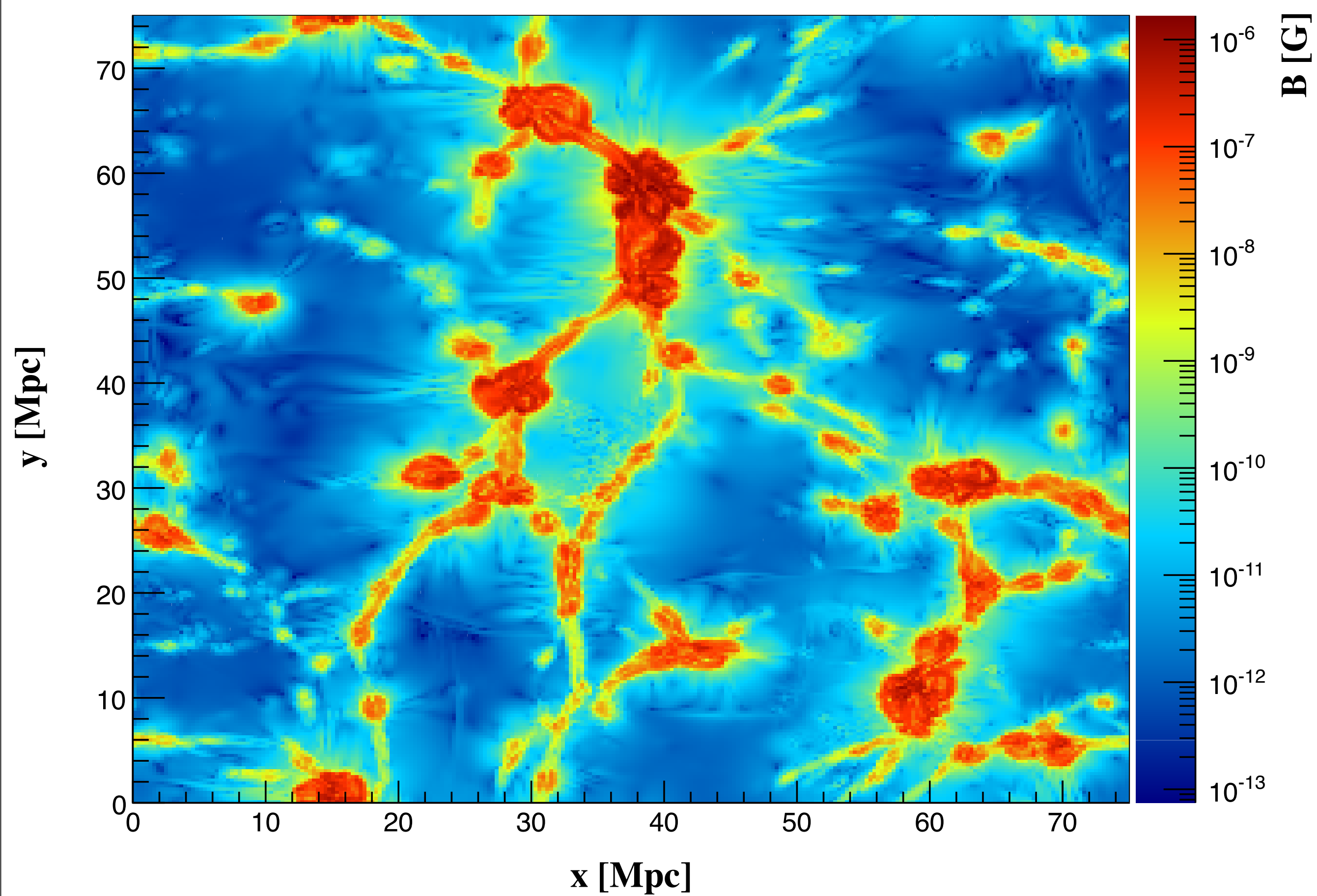

- ✦ events from a single source with different energies → energy ordered structures
- ✦ analysis of the orientation of multiplets can constrain GMF models
- ✦ multiplets allow the reconstruction of the position of the source

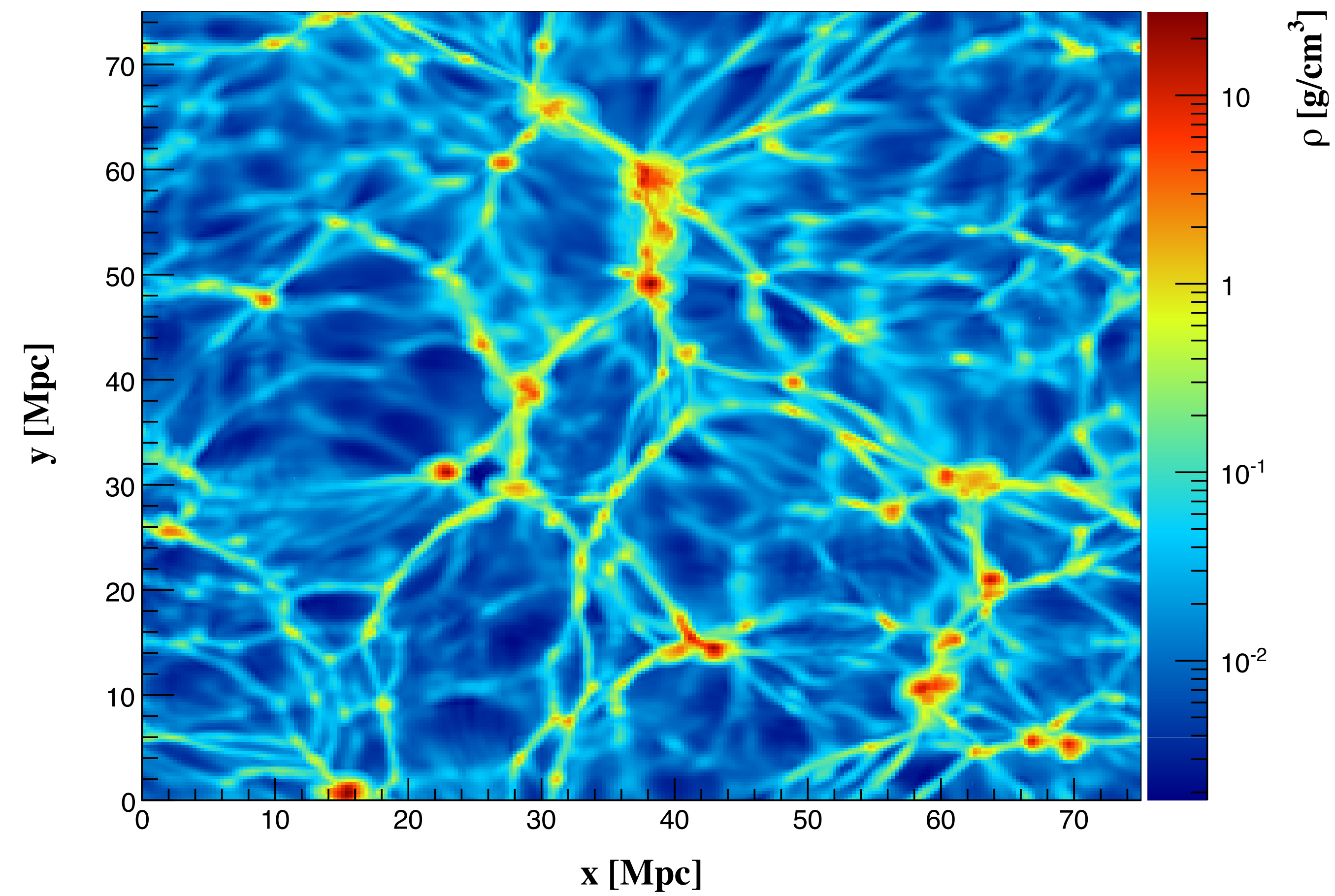
Pierre Auger Collaboration. Astropart. Phys. 35 (2012) 354.



# UHECRs and extragalactic magnetic fields

# structured magnetic fields: an example

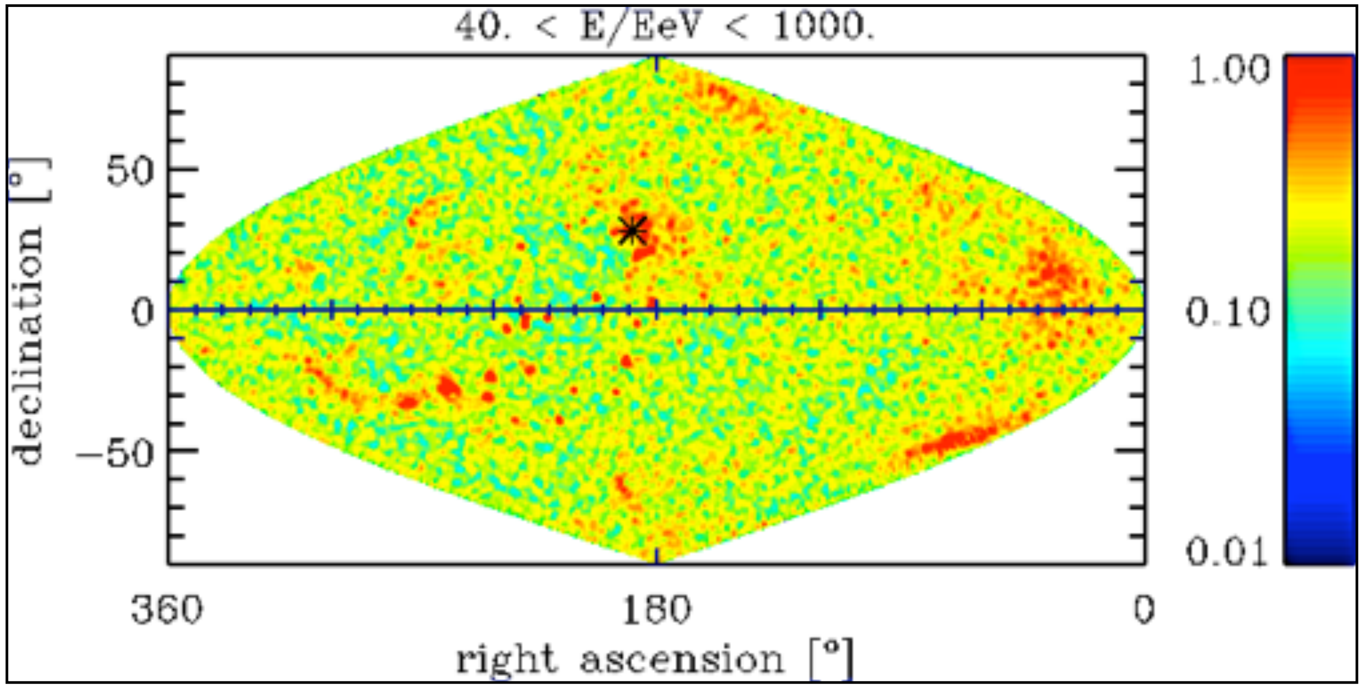


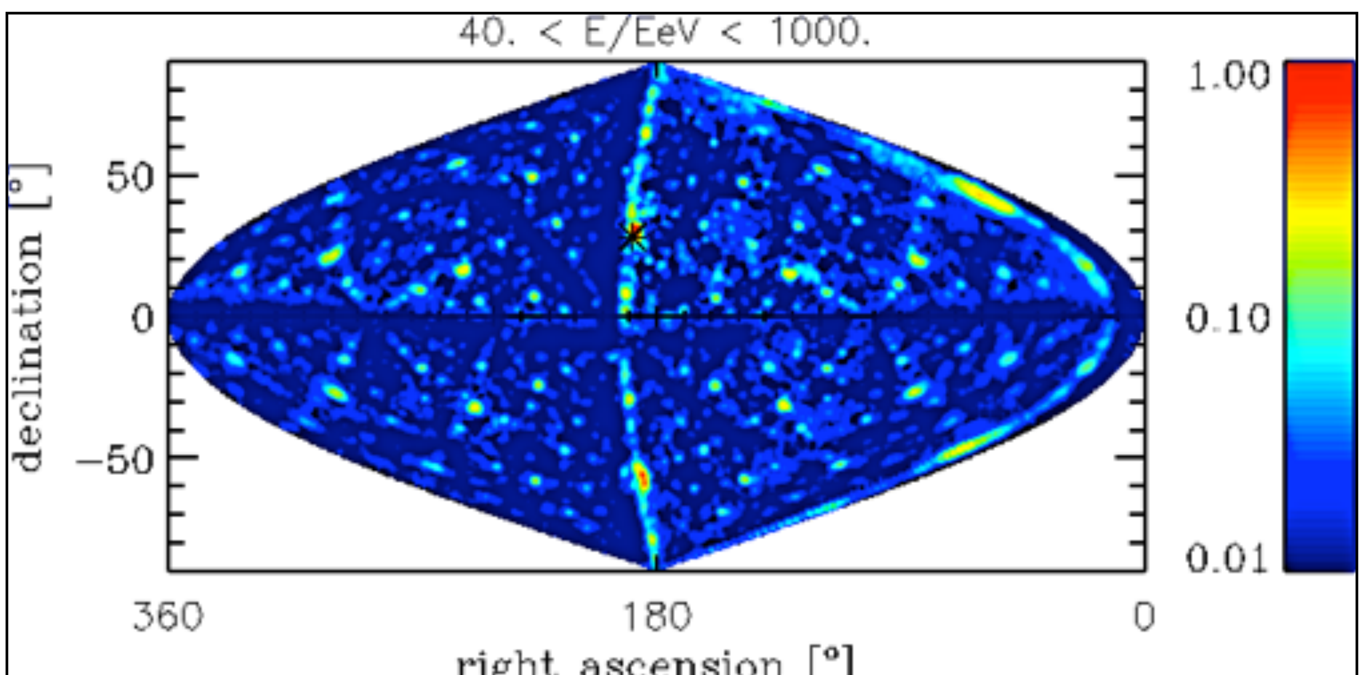

- ✦ MHD simulation from Miniati
- ✦ volume: $(50h^{-1}\ \mathrm{Mpc})^3$
- ✦ EGMF set to zero in the beginning
- ✦ magnetic field seed generated in shocks through the Biermann battery mechanism

# propagation in the large scale structure

with magnetic field




no magnetic field

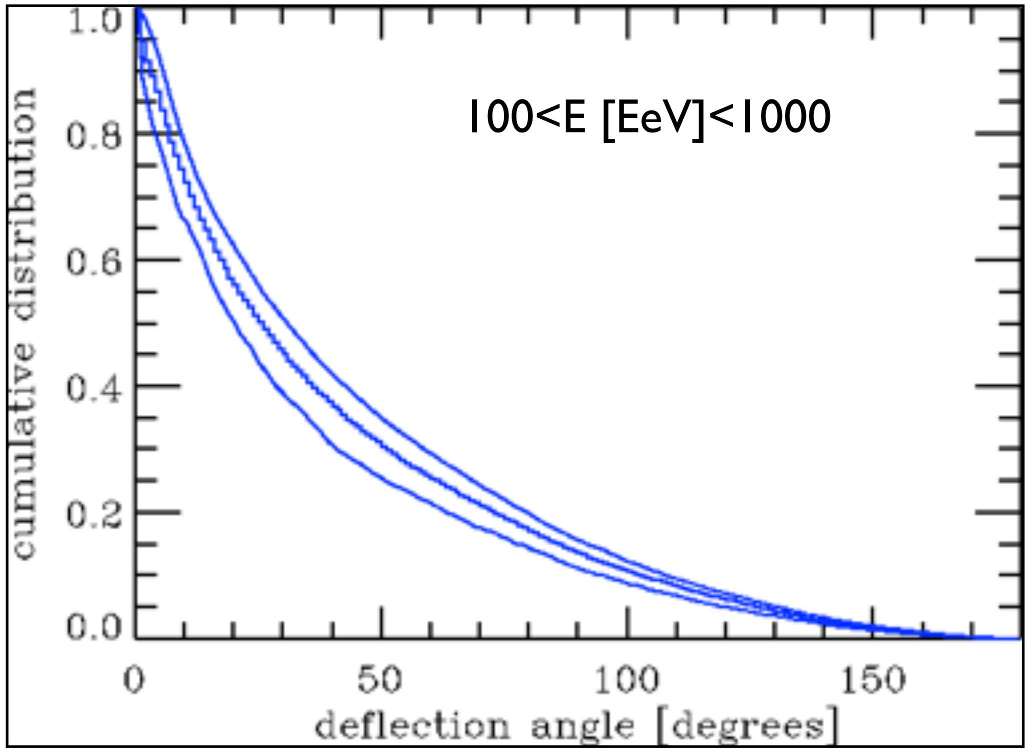



- ✦ matter distribution and magnetic field: Miniati MHD simulation
- ✦ sky above 40 EeV
- ✦ sources following matter distribution
- ✦ source density: $2.4 \times 10^{-5}$ Mpc$^{-3}$
- ✦ ~$2 \times 10^{5}$ events
- ✦ sky highly anisotropic above 40 EeV

Sigl, Miniati, Ensslin. PRD 68 (2003) 043002

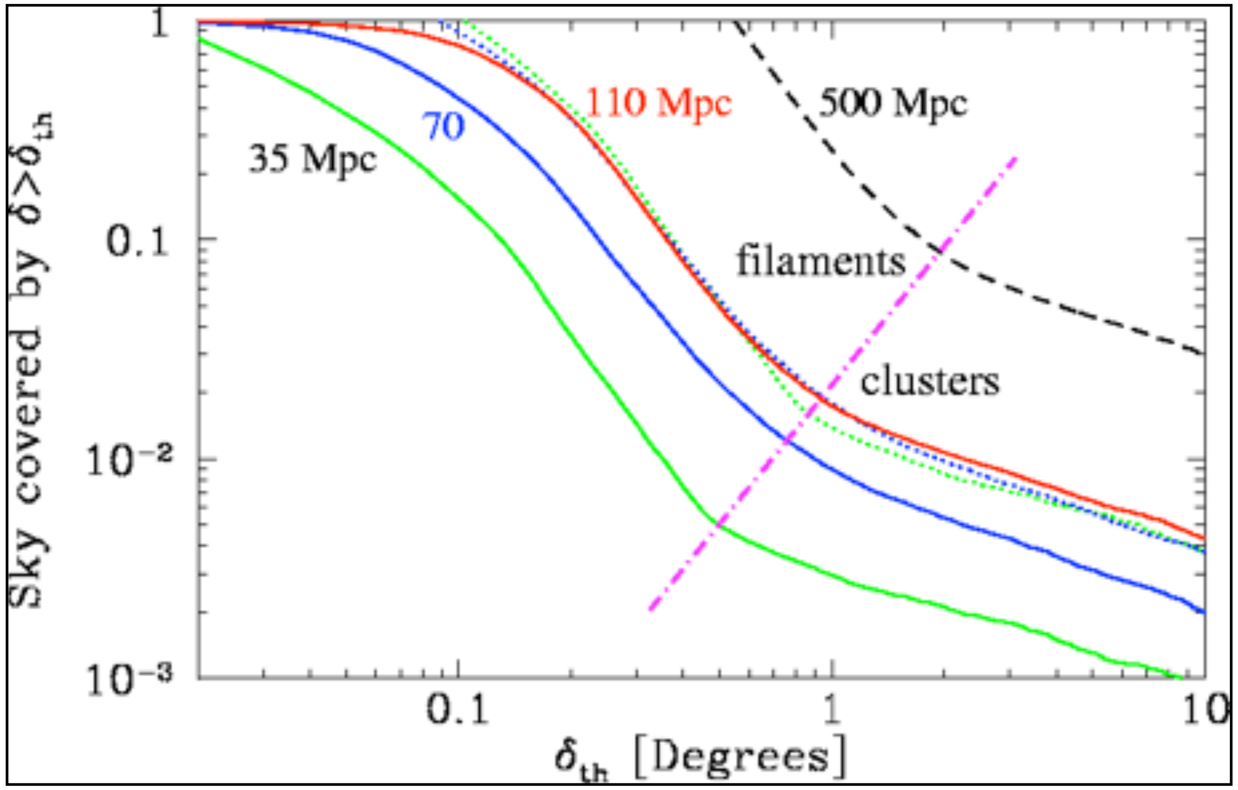
Sigl, Miniati, Ensslin. PRD 70 (2004) 043007

# UHECR astronomy?




Sigl, Miniati, Ensslin.
PRD 70 (2004) 043007

- ✦ cumulative deflections displayed are for protons
- ✦ Sigl et al.: deflections are high
- ✦ Dolag et al.: lower deflections (constrained MHD simulation)
- ✦ for heavy nuclei the deflections can be even higher
- ✦ UHECR astronomy may be possible in the later scenario, but not in the former (in the full sky)




Dolag et al. JETP 79 (2004) 583

# UHECR “tomography”

RAB, J. Devriendt, D. Semikoz, M.-S. Shin, G. Sigl. In preparation.

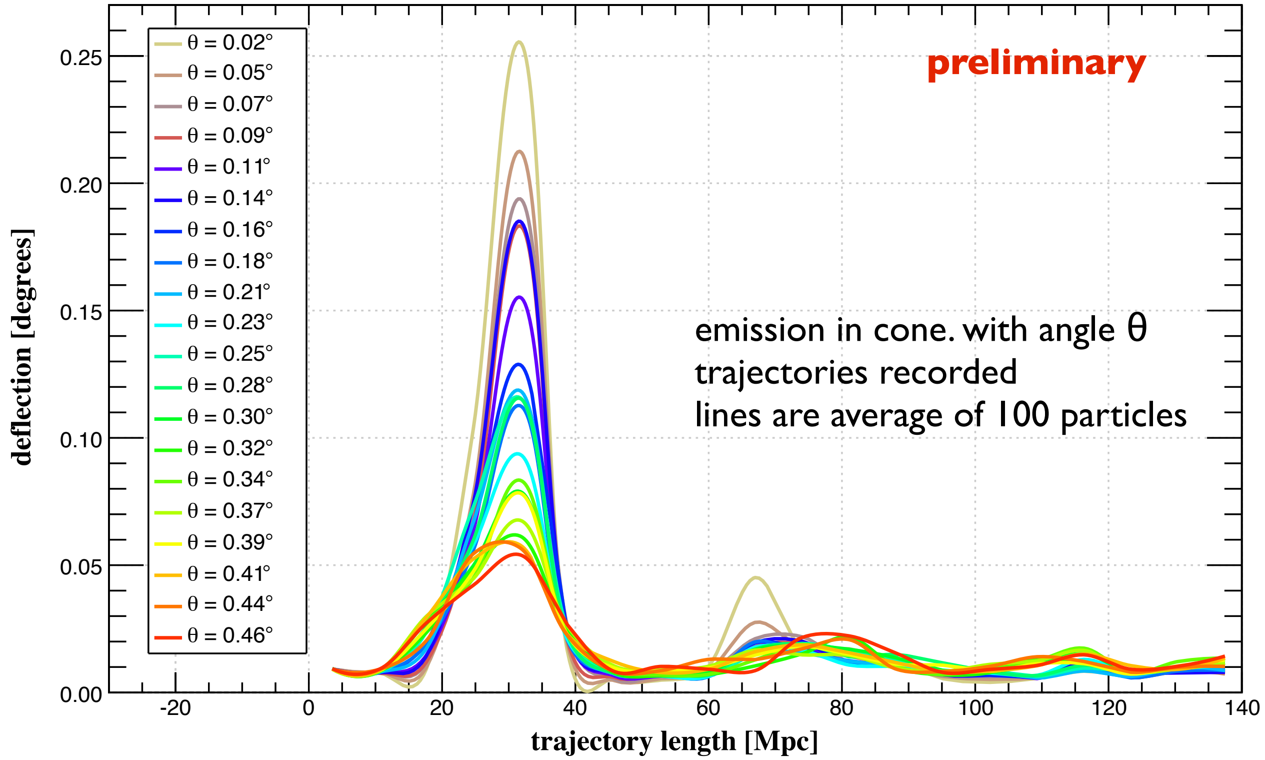
✦ new MHD simulations with kpc scale resolution being done by M.-S. Shin & J. Devriendt

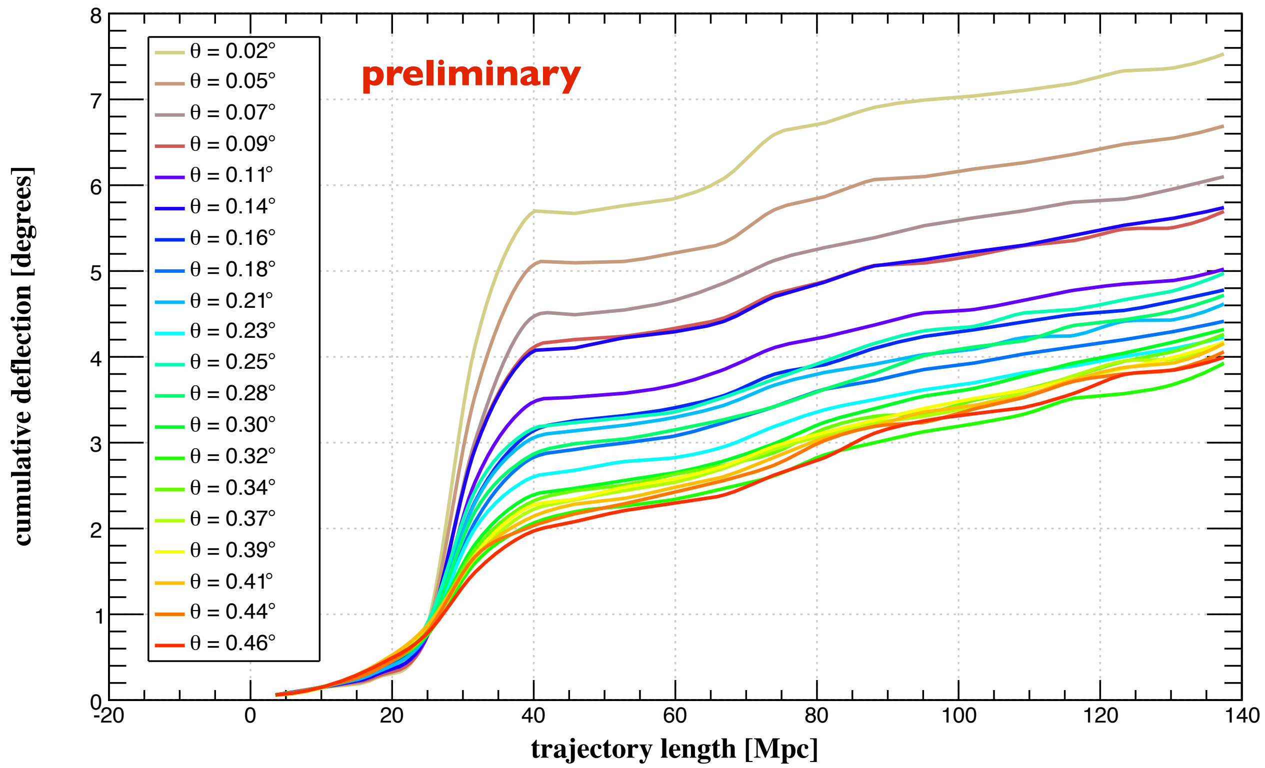
✦ simulation volume: ~(200$h^{-1}$ Mpc)$^3$

✦ deflections of the order of 10 degrees for protons? → if magnetic field in clusters of galaxies is ~0.1 μG

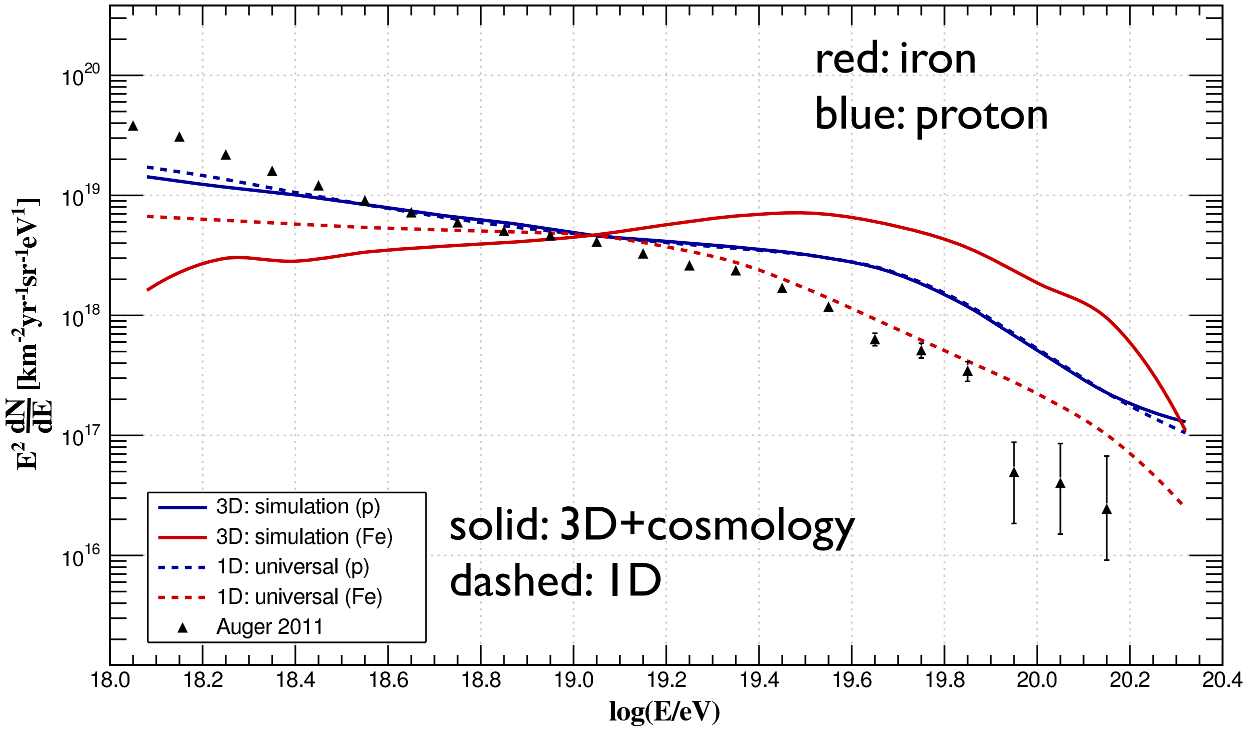
✦ overall normalization of the magnetic field is extremely relevant for UHECR propagation

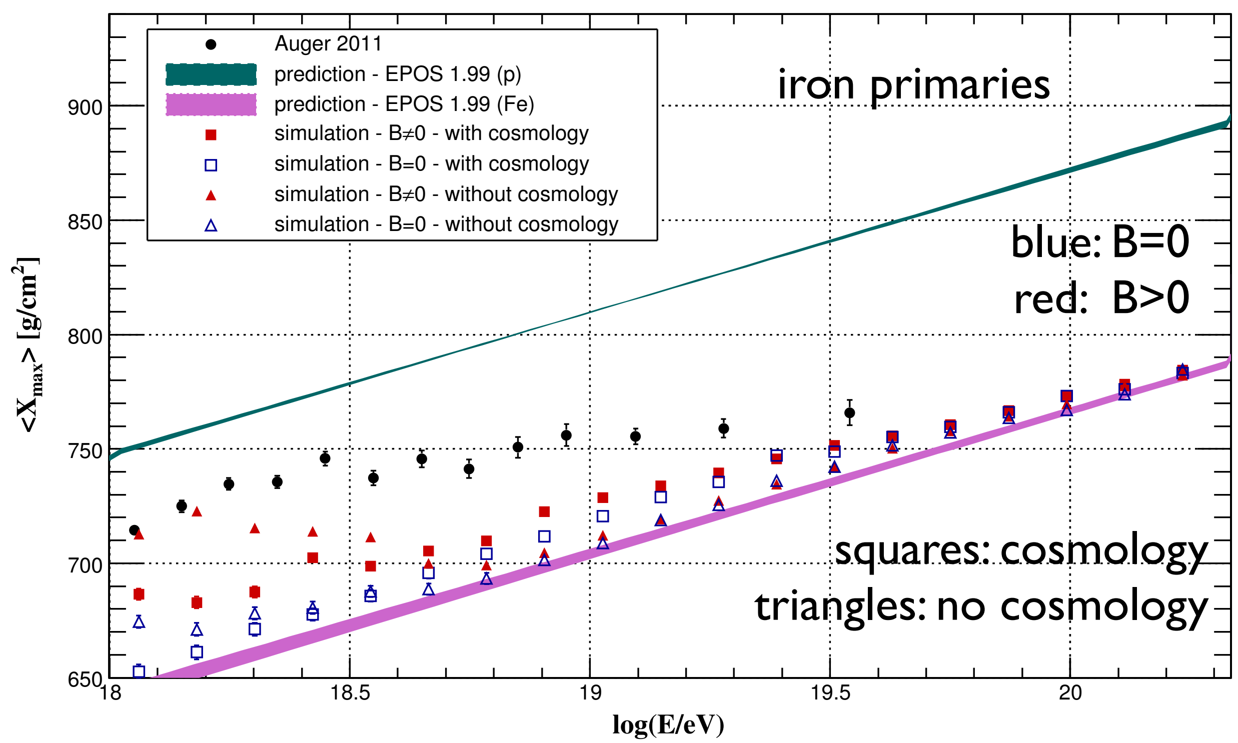
✦ goal: is UHECR astronomy really possible?



# accounting for cosmological effects in 3D




RAB, Schiffer, Sigl. NIM A 742 (2014) 245

- ✦ magnetic fields can affect the shape of the spectrum, so they should be taken into account when performing simulations
- ✦ universal spectrum → expected for a uniform source distribution (separation << propagation lengths) → no magnetic field effects
- ✦ deviations from universal spectrum for pure iron composition
- ✦ large scale structures (magnetic field) + cosmological effects + energy losses → realistic simulations
- ✦ cosmological effects may be relevant, mainly at energies ~ EeV
- ✦ need to include cosmological effects in 3D simulations → 4D simulations

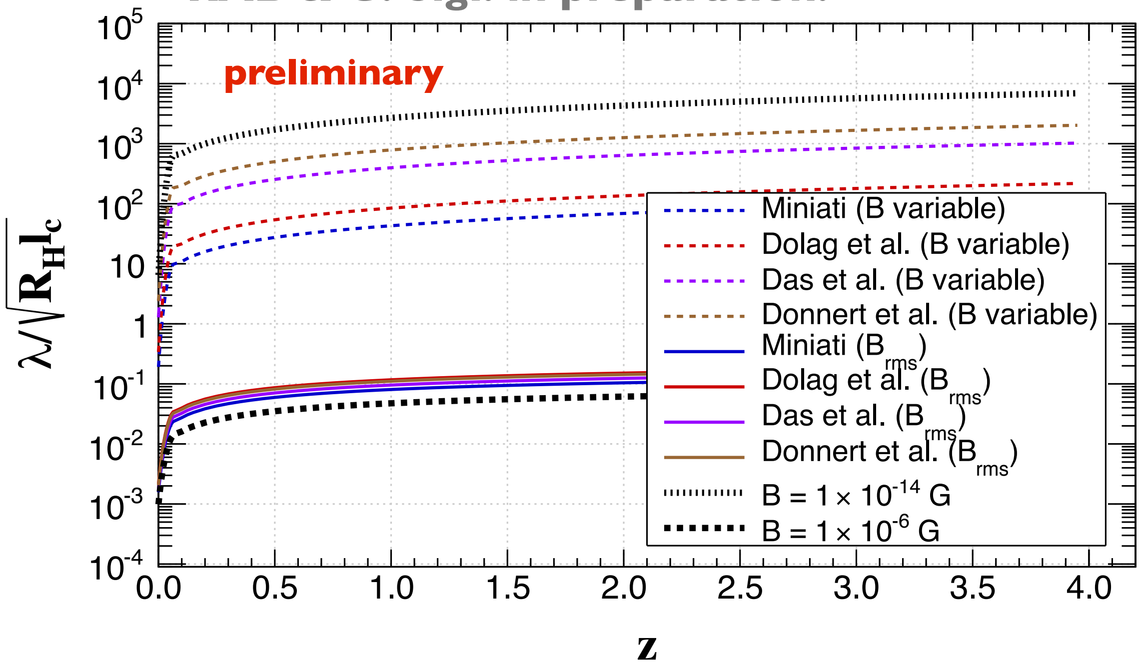
# magnetic diffusion at EeV energies

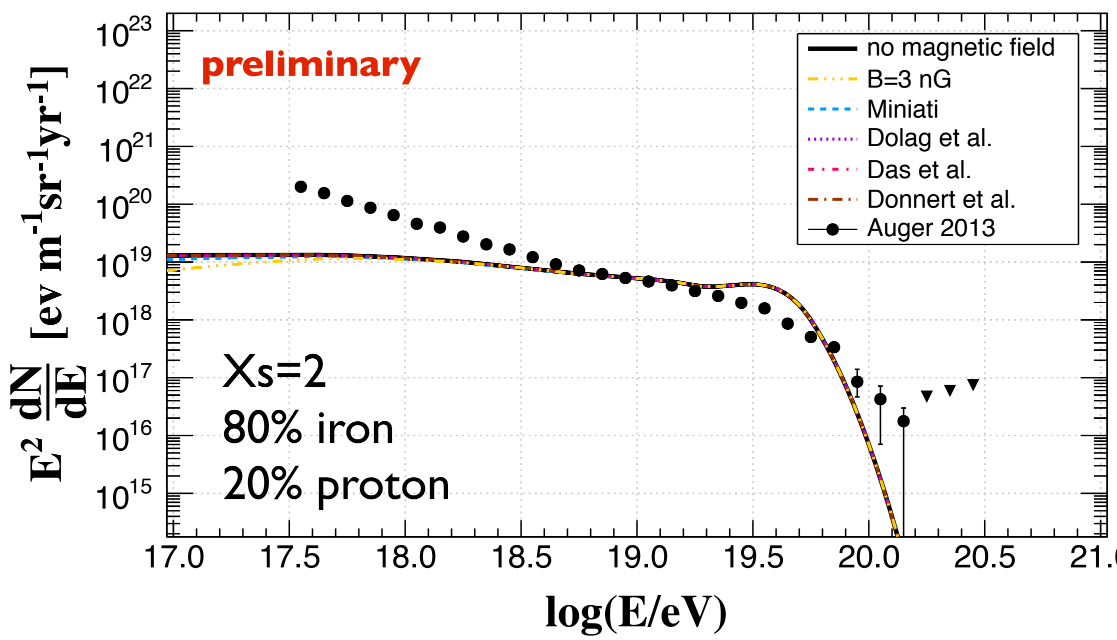
$$J_s(E) = \frac{c}{4\pi} \int_0^{z_{max}} dz \left|\frac{dt}{dz}\right| Q(E_g(E,z),z) \frac{\exp\left(-\frac{r_s^2}{4\lambda^2}\right)}{(4\pi\lambda^2)^{\frac{3}{2}}} \frac{dE_g}{dE}$$

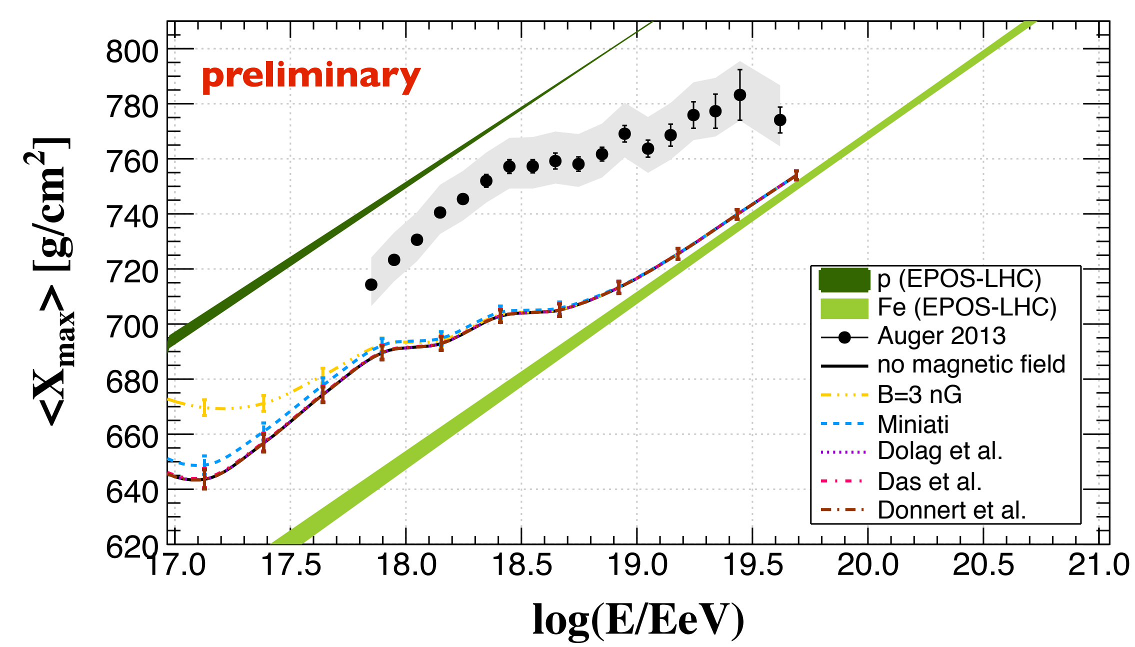
Syrovatskii variable

$$\lambda^2(E,z) = \int^{z} dz' \left|\frac{dt}{dz'}\right| \frac{D(E_g,z')}{a^2(z')}$$

**RAB & G. Sigl. in preparation.**



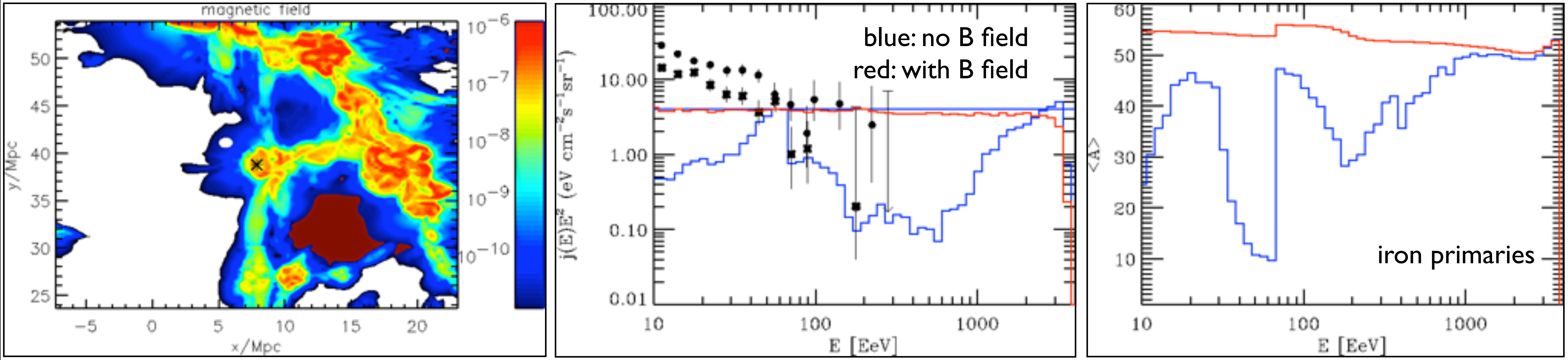



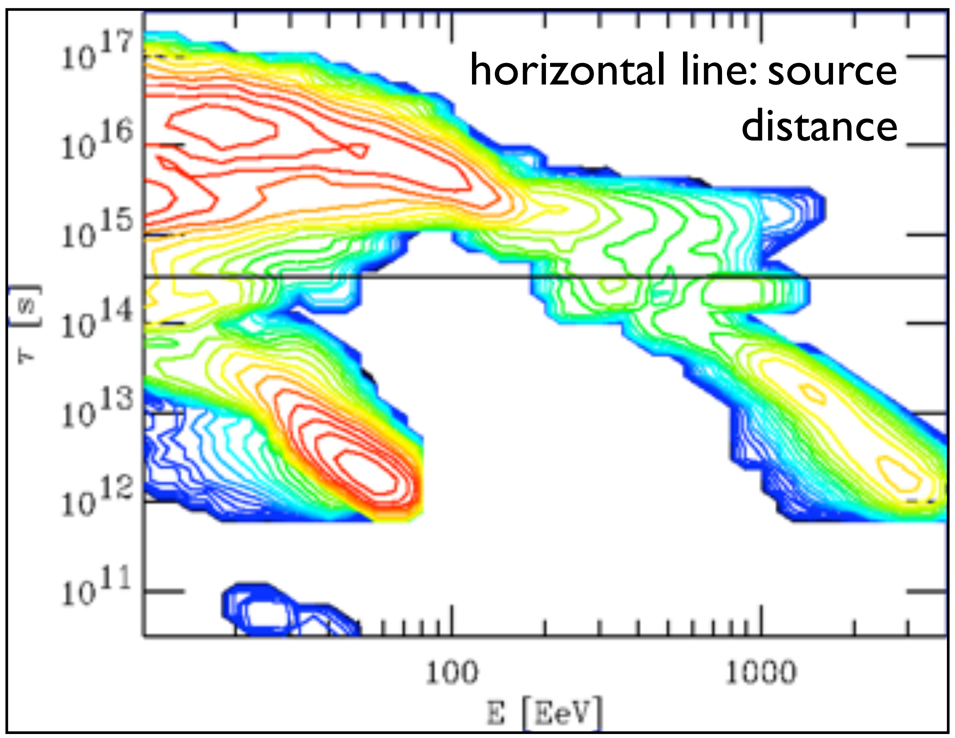




- ✦ constant magnetic field: Mollerach & Roulet 2013
- ✦ our work extends the previous one to inhomogeneous magnetic fields
- ✦ Syrovatskii variable depends on the magnetic field non-linearly

# UHECRs from individual sources

Sigl. JCAP 08 (2004) 012



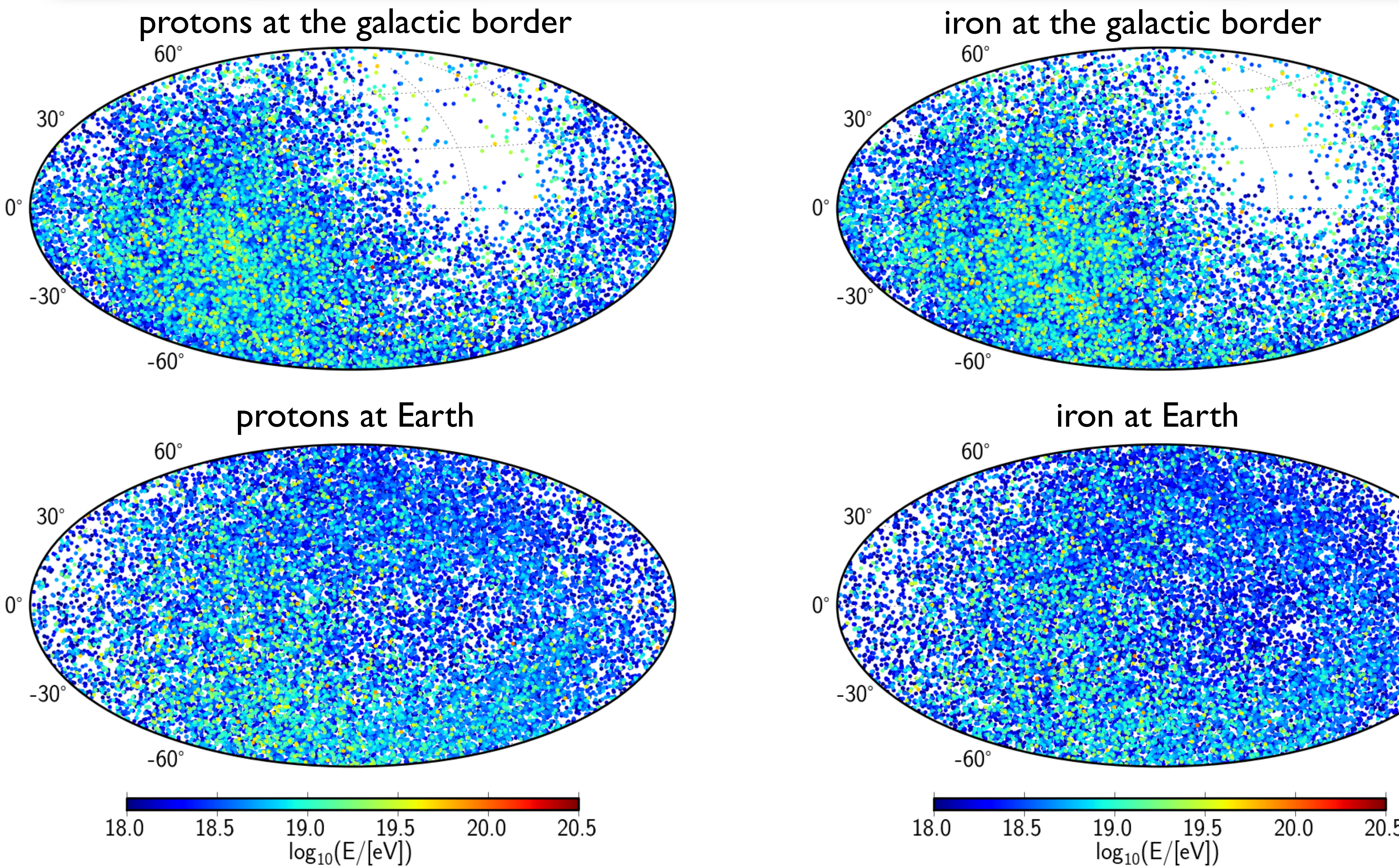




✦ spectra and composition depend considerably on source magnetization, specially for nearby sources

✦ low time delay due to spallation of nucleons far from the source field

✦ deflection is important → compare energy loss/spallation time scales with time delays

# combined extragalactic + galactic deflections

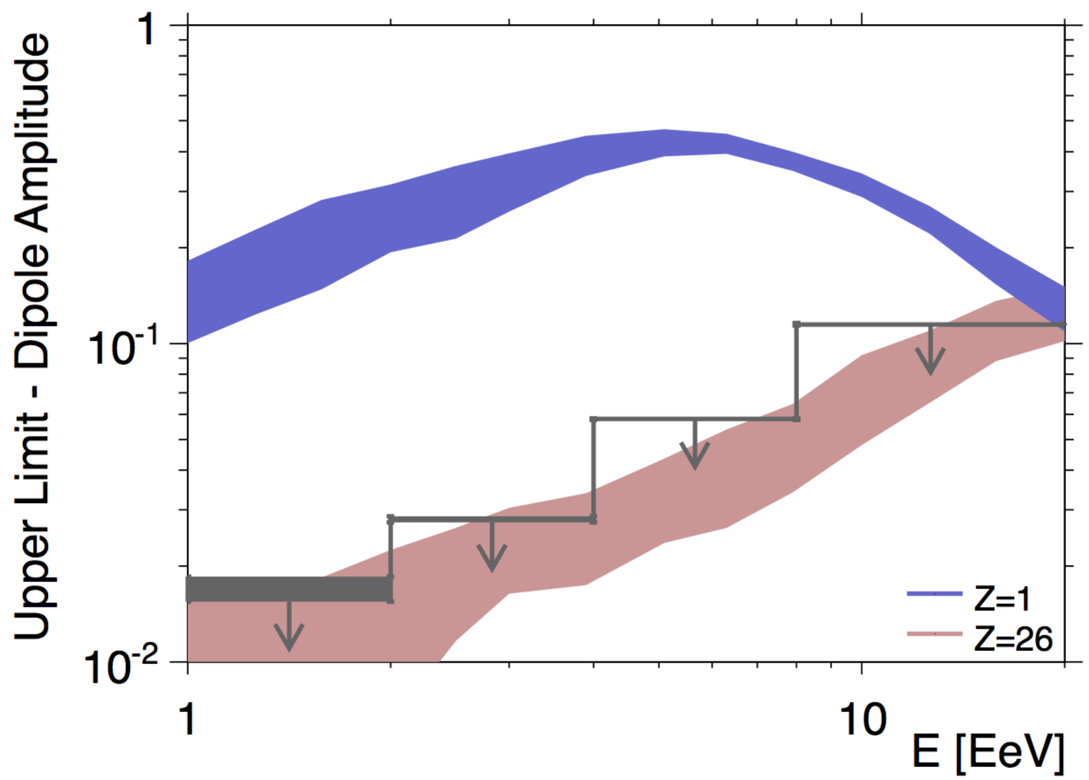



PARSEC code: Bretz et al. Astropart. Phys. 54 (2014) 110

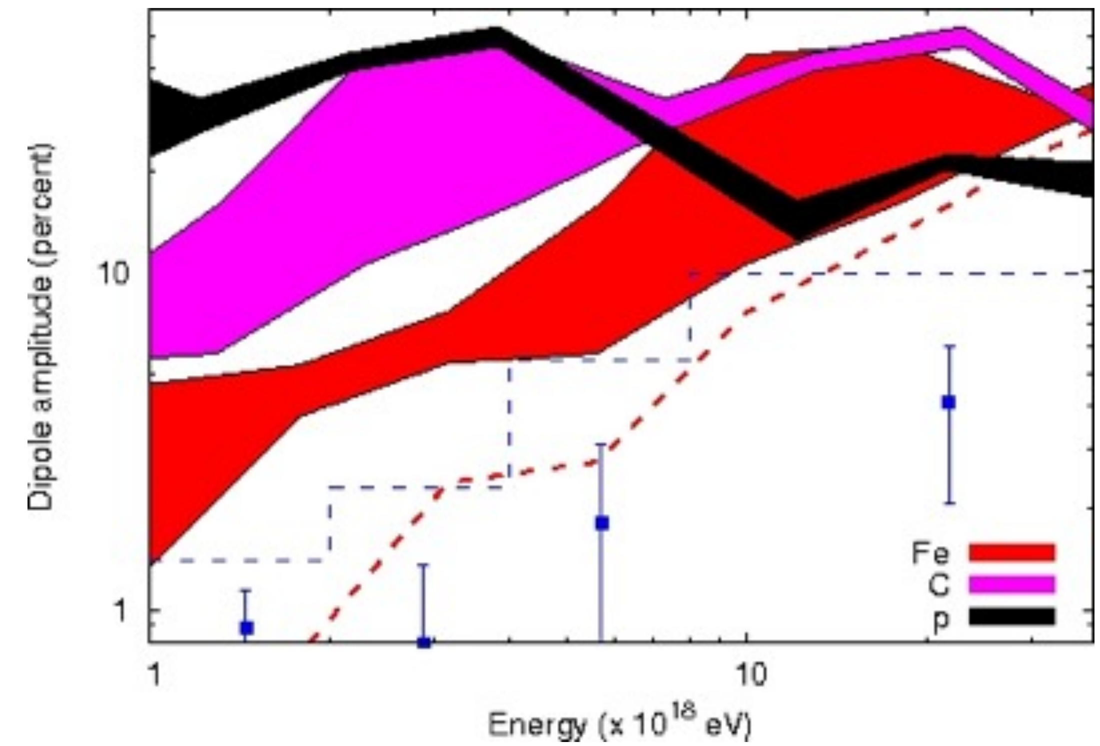
RAB et al. Proceedings 33rd ICRC. arXiv:1307.2643

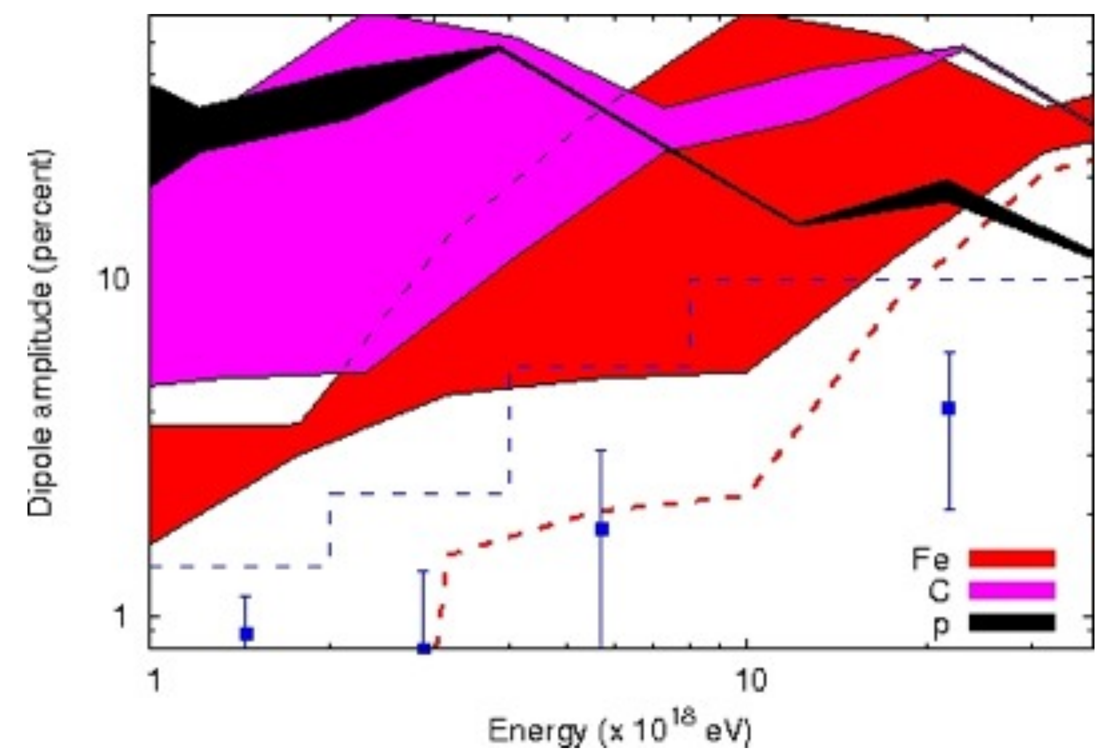
# transition galactic-extragalactic CRs

Pierre Auger Collaboration. ApJ 762 (2013) L13




Giacinti, Kachelriess, Semikoz, Sigl. JCAP 1207 (2012) 031




- ✦ anisotropy due to light galactic nuclei is too high
- ✦ if composition around 1 EeV is light → CRs at this energy probably extragalactic → ankle due to pair production by protons
- ✦ if composition around 1 EeV is heavy → transition could be at the ankle if galactic nuclei are produced by frequent transients

# summary

✦ understanding magnetic fields is important to determine the origin of UHECRs

✦ 3D simulations are needed

✦ matter distribution may be related to magnetic fields and sources of UHECRs

✦ scenarios that fit the observations of only one observable (spectrum or composition or anisotropies) are quite easy to obtain

✦ it is very difficult to construct a scenario that fits these three observables

✦ cosmological effects as well as magnetic fields should be taken into account