extragalactic cosmic-ray propagation

Rafael Alves Batista

Instituto de Astronomia, Geofísica e Ciências Atmosféricas
Universidade de São Paulo

rafael.ab@usp.br

www.8rafael.com

TeVPA
Berlin
27/Aug/2018

ultra-high energy cosmic rays (UHECRs)

fundamental questions

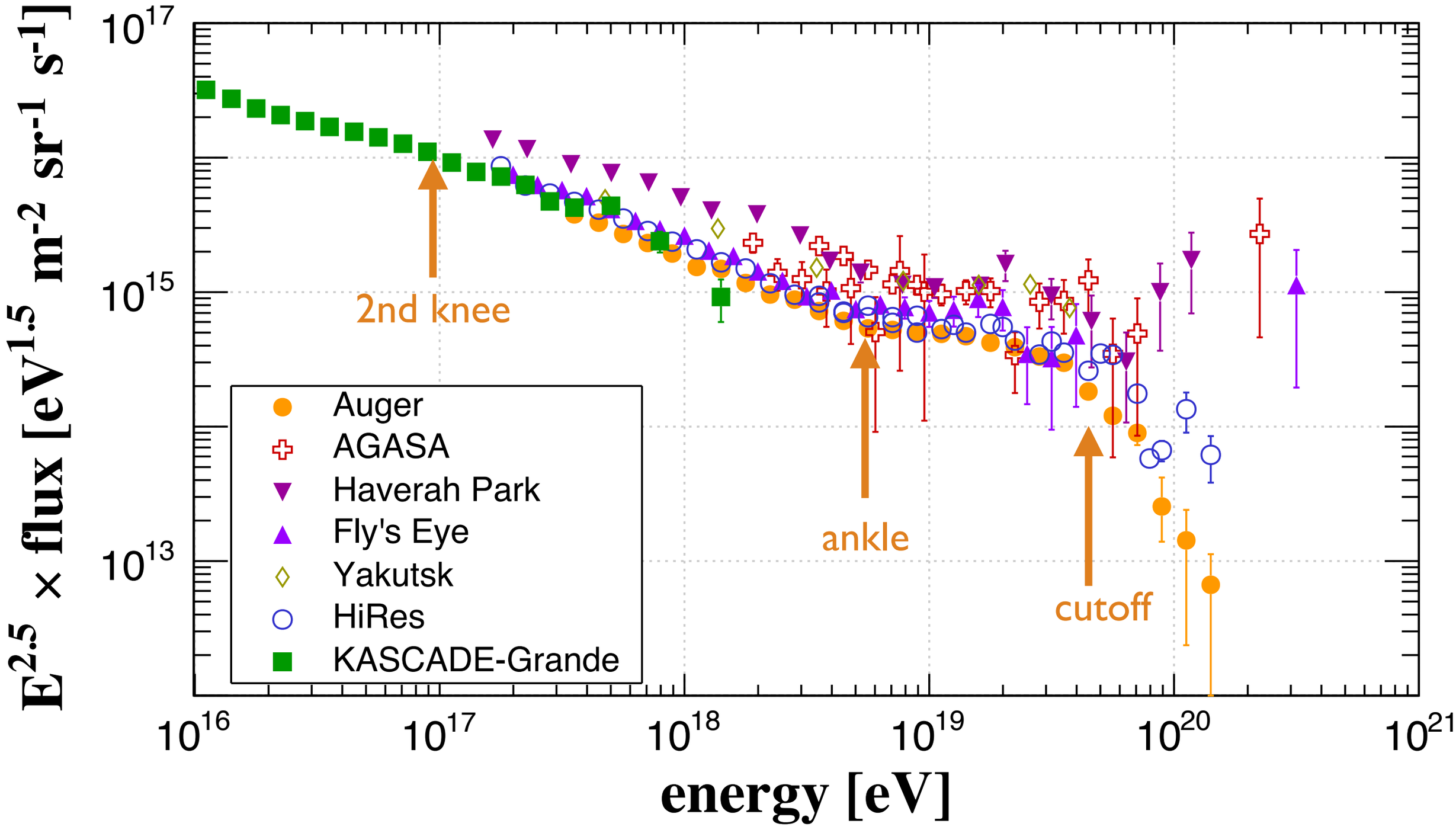
- where do they come from?
- what are they made of?
- how are they accelerated?

some problems

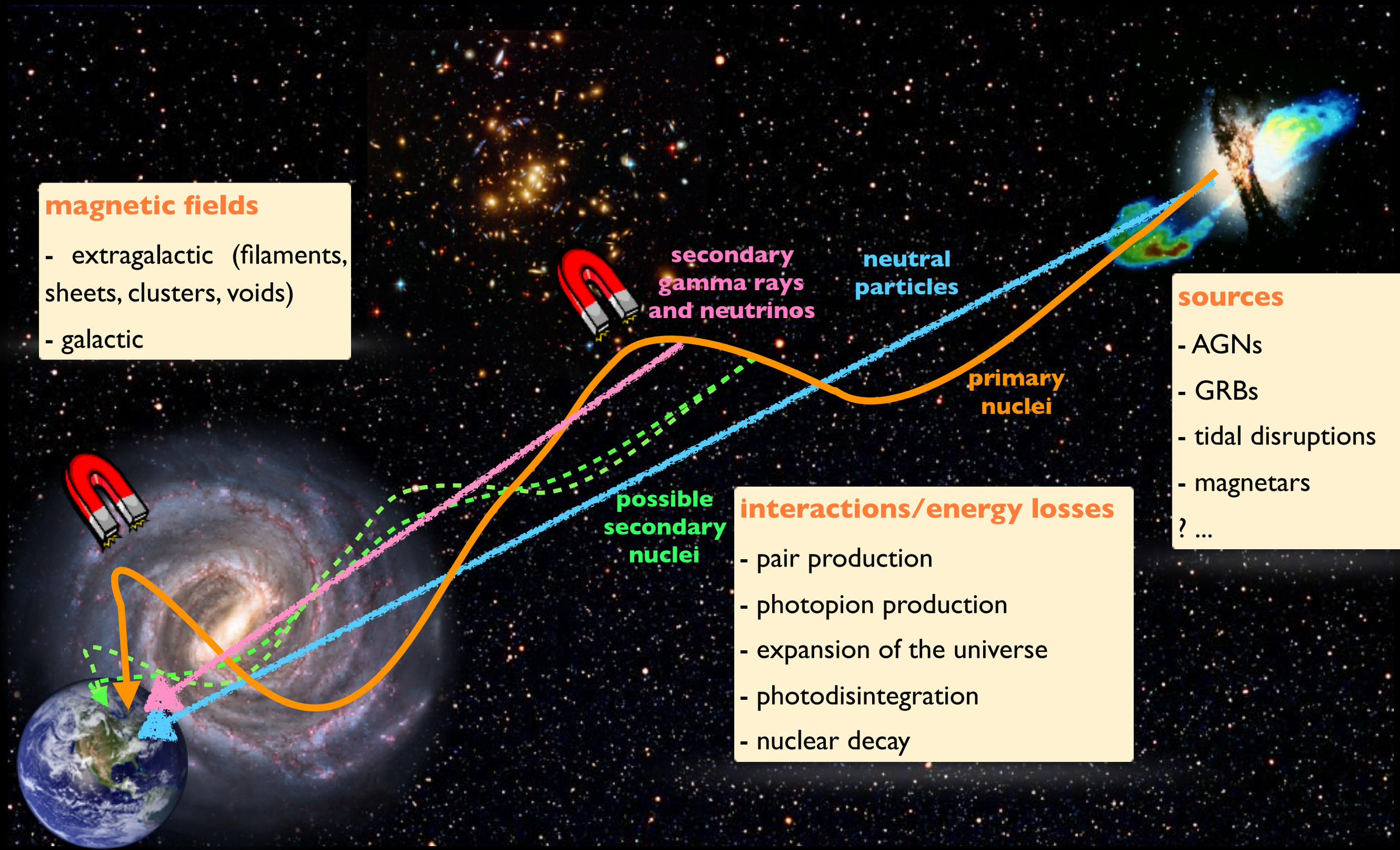
- what is the maximal energy they can reach?
- do we see a GZK cutoff?
- where does the transition between galactic and extragalactic cosmic rays take place?

- cosmic-ray propagation: astrophysics/cosmology + particle/nuclear physics
- observables from CR experiments: spectrum, composition, anisotropy
- neutrinos and photons provide complementary information
- test new physics scenarios using UHECRs (?)

the cosmic-ray spectrum



propagation picture



modelling the propagation of UHECRs: interactions

photopion production

$$p + \gamma_{\rm bg} \to \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

$$\pi^0 \to 2\gamma$$ **photons**

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$ **neutrinos**

$$n \to p + e^- + \bar{\nu}_e$$ **neutrinos**

pair production (Bethe-Heitler)

$${}^A_Z X + \gamma_{\rm bg} \to {}^A_Z X + e^+ + e^-$$ **electrons**

electromagnetic cascades

$$e^\pm + \gamma_{\rm bg} \to \gamma + e^\pm$$

$$\gamma + \gamma_{\rm bg} \to e^+ + e^- + (e^+ + e^-) + \ldots$$

photodisintegration

$${}^A_Z X + \gamma_{\rm bg} \to {}^{A-1}_{Z} X + n$$

$${}^A_Z X + \gamma_{\rm bg} \to {}^{A-1}_{Z-1} X + p$$

$${}^A_Z X + \gamma_{\rm bg} \to {}^{A-4}_{Z-2} X + {}^4_2\,{\rm He}$$

others

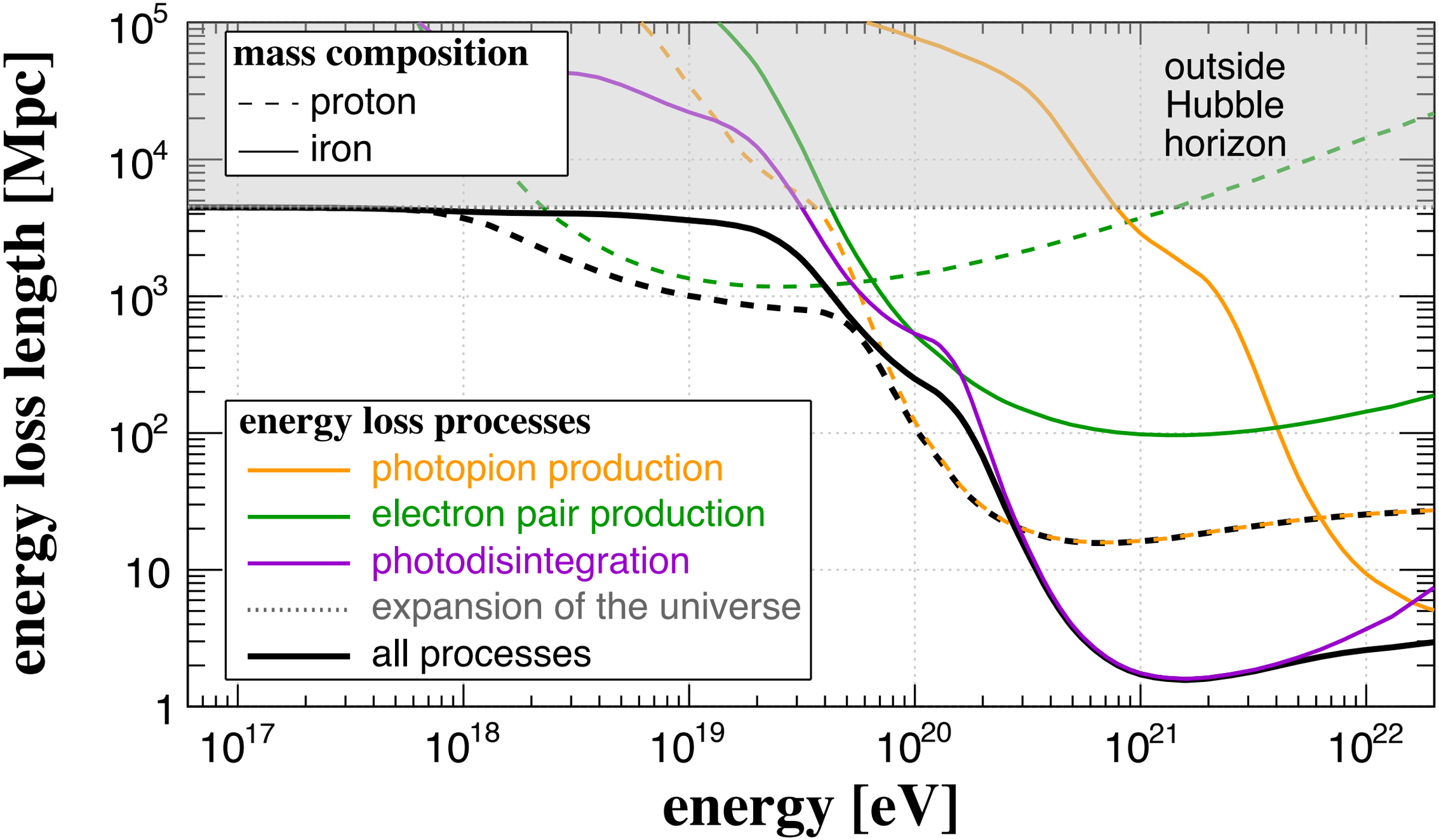
synchrotron emission

adiabatic losses (expansion of the universe)

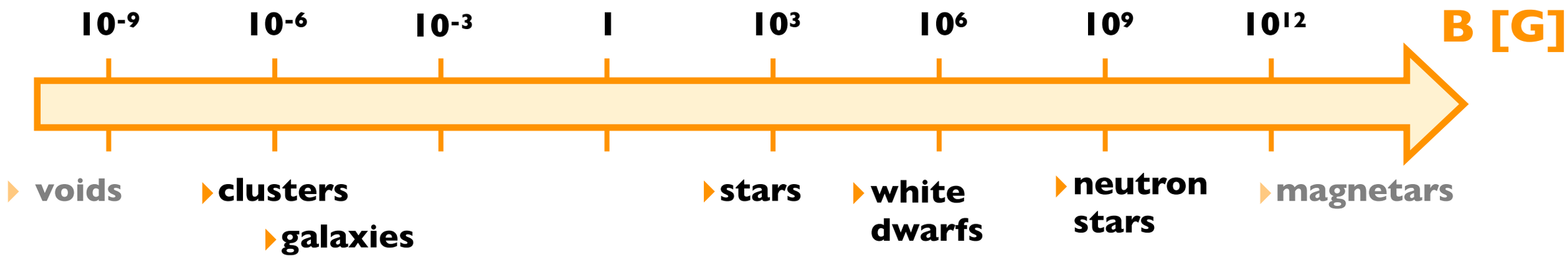
nuclear decay of unstable nuclei

- there are more processes than the ones shown
- hadronuclear interactions (nucleus-nucleus) should be accounted for in dense environments

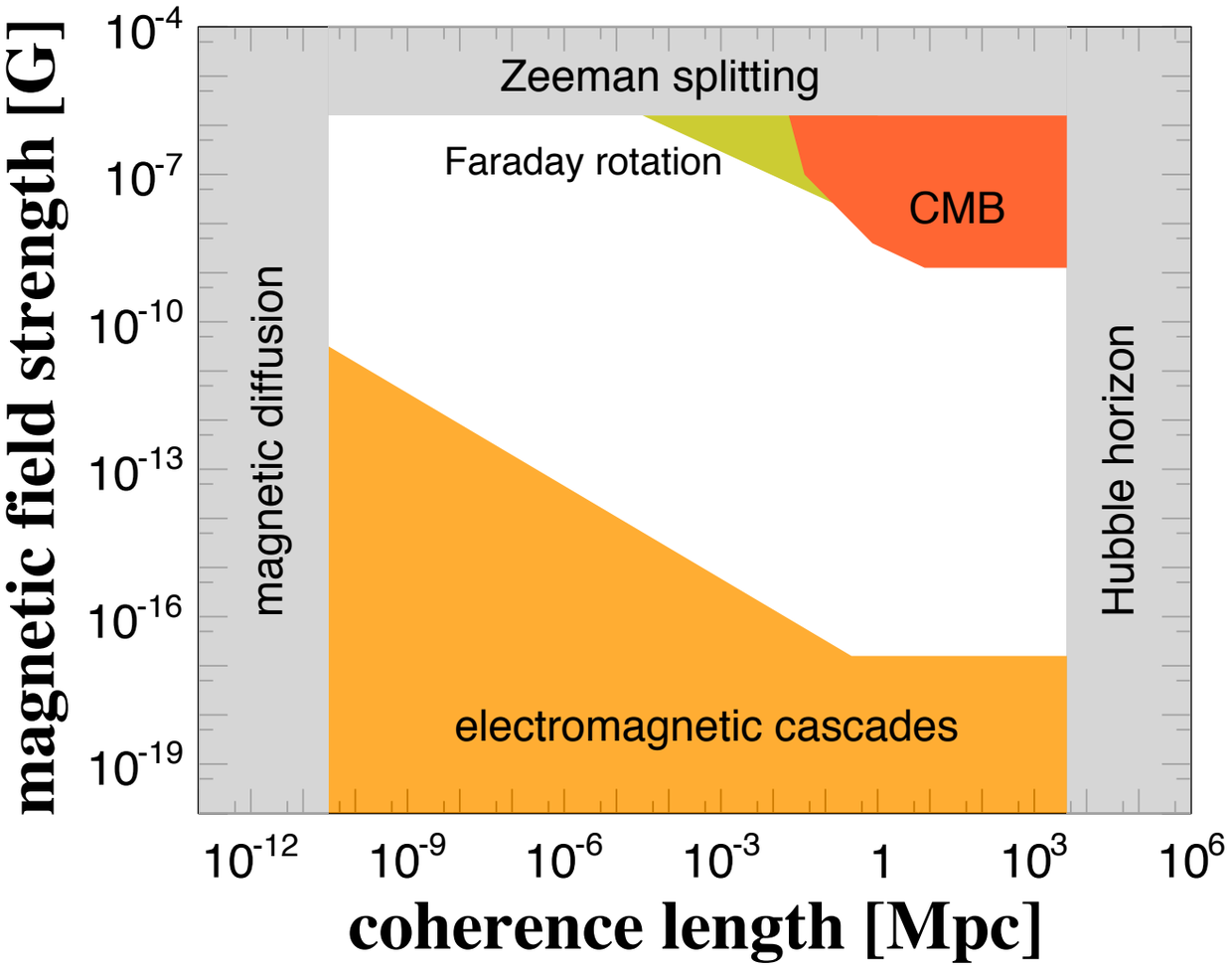
modelling the propagation of UHECRs: energy losses



modelling the propagation of UHECRs: magnetic fields



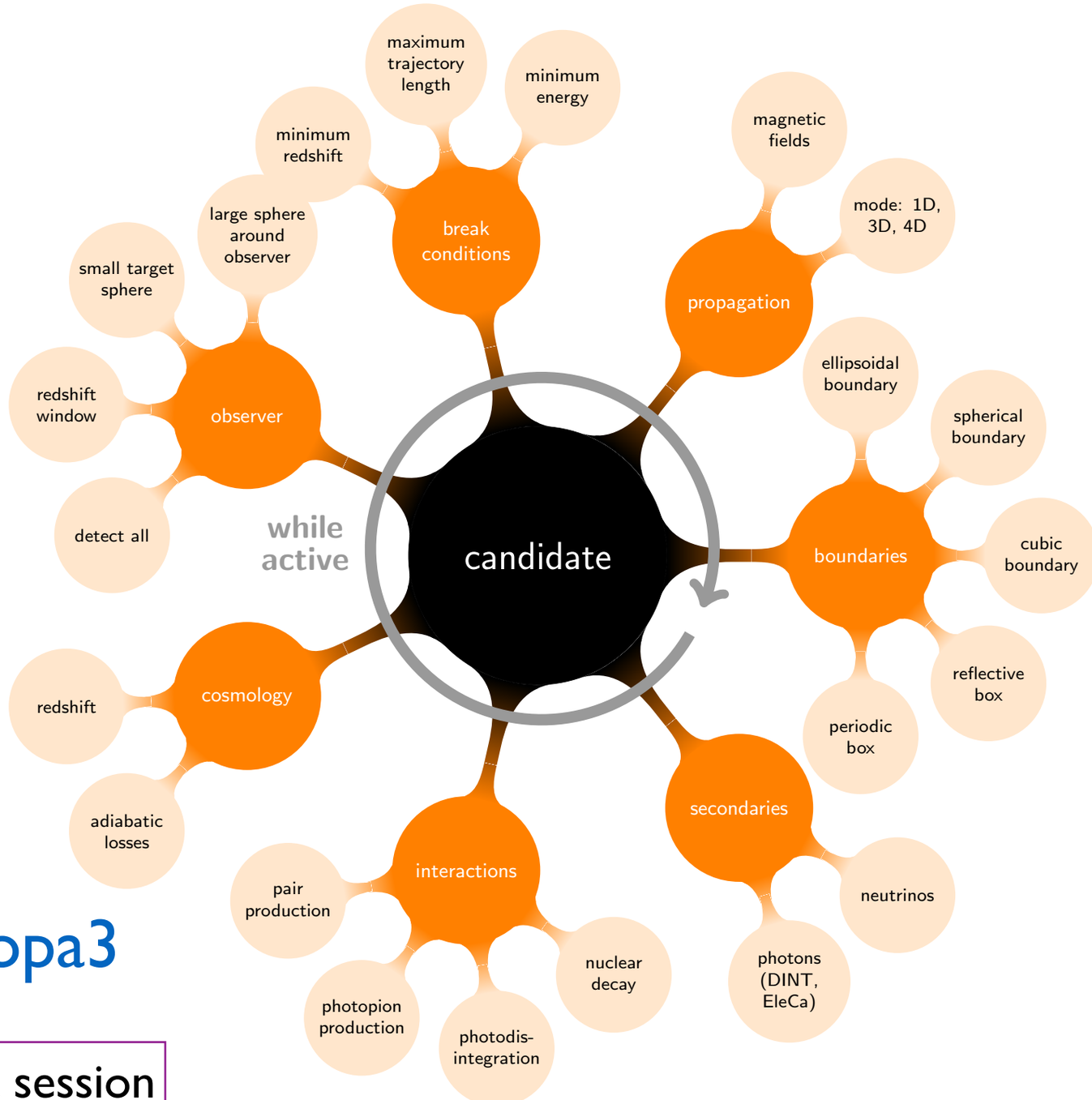
- are there cosmological magnetic fields?
- how did the magnetic fields in the universe come to be? astrophysical vs cosmological origin
- we have upper and lower bounds, but parameter space is still large



modelling the propagation of UHECRs: CRPropa

- publicly available Monte Carlo code for propagating UHECRs and their secondaries in the intergalactic space
- modular structure
- parallelisation with OpenMP
- 1D, 3D and "4D" simulations
- relevant energy losses implemented
- variety of tools to handle custom magnetic field models
- predict spectrum, composition, and anisotropies simultaneously
- several models of EBL available
- possible to compute secondary **gamma** and **neutrino** fluxes

RAB et al. JCAP 05 (2016) 038. arXiv:1603.07142



https://github.com/CRPropa/CRPropa3

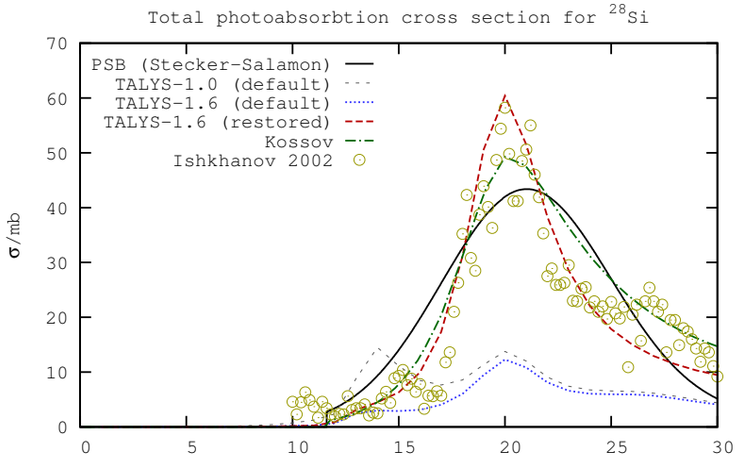
see talk by L. Merten on Wednesday, 15:05, CR session

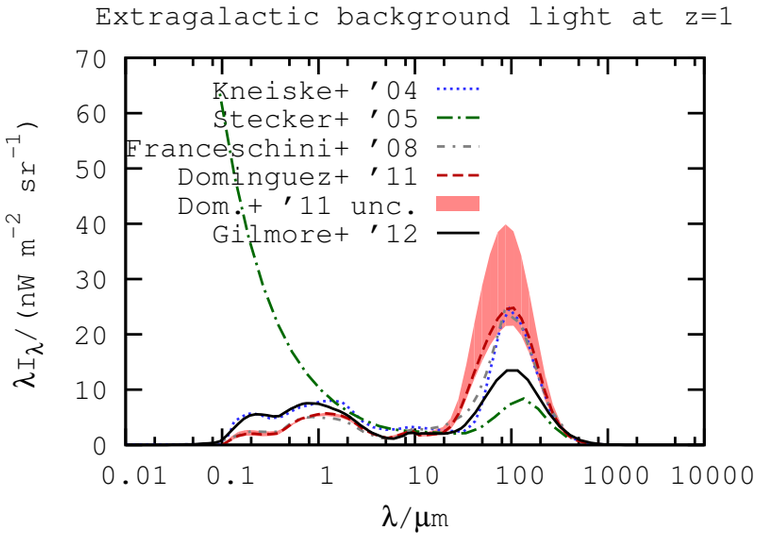
theoretical uncertainties in the modelling

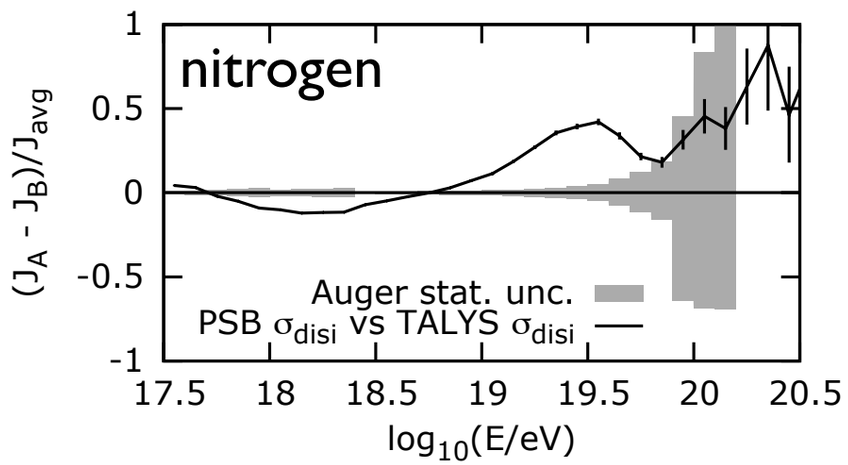
main sources of uncertainties

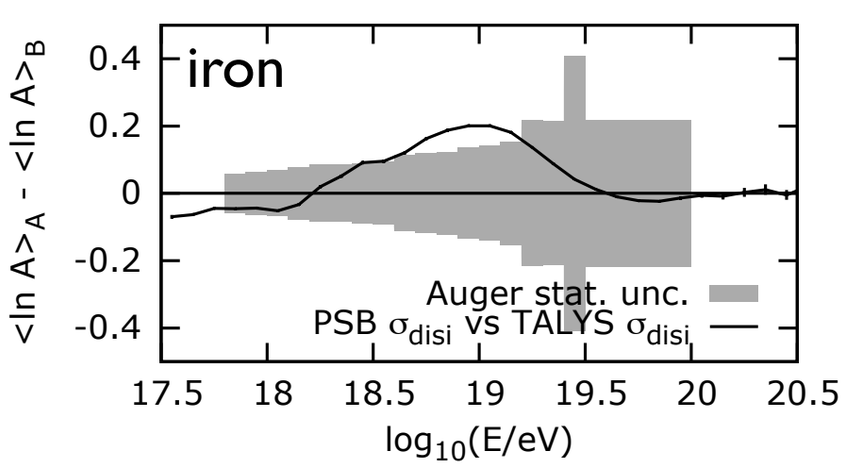
RAB, Boncioli, di Matteo, van Vliet, Walz. JCAP 1510 (2015) 063. arXiv:1508.01824

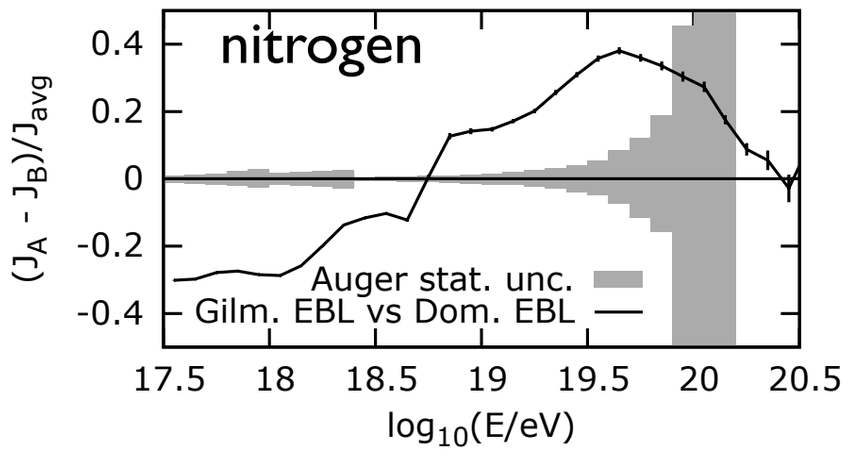
- photodisintegration cross sections
- EBL model
- propagation codes (e.g. CPropa, SimProp, ...)

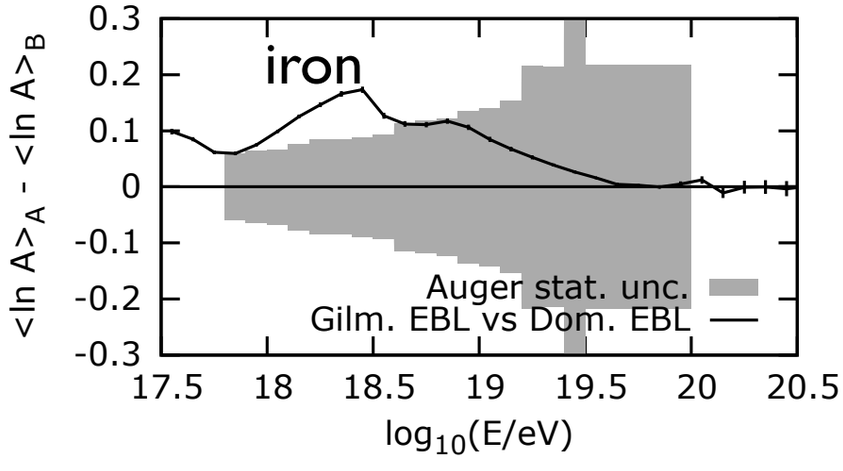




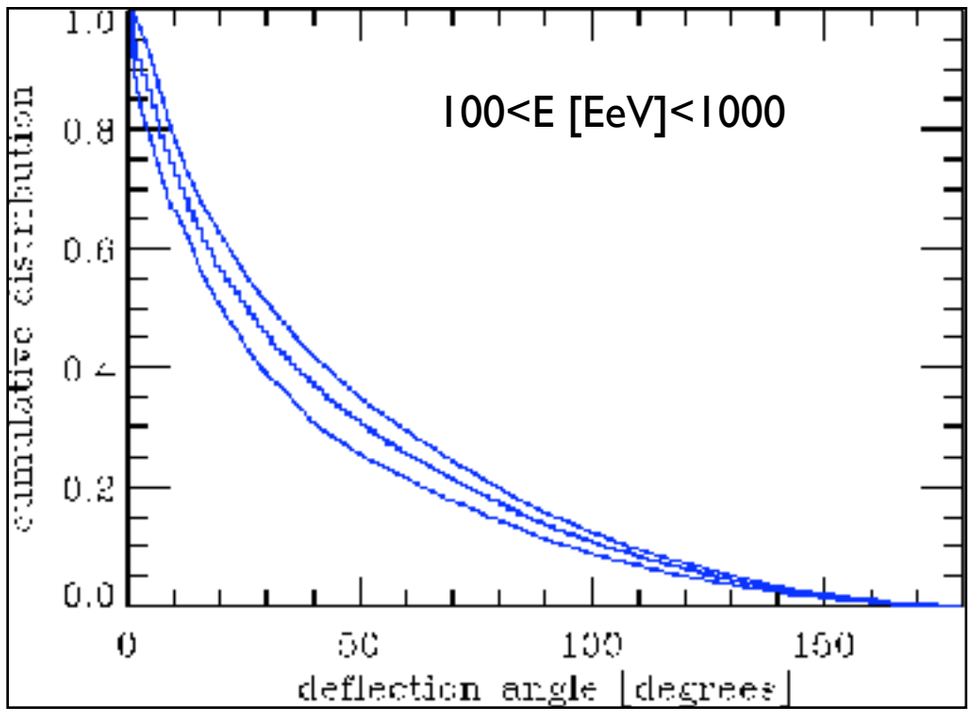






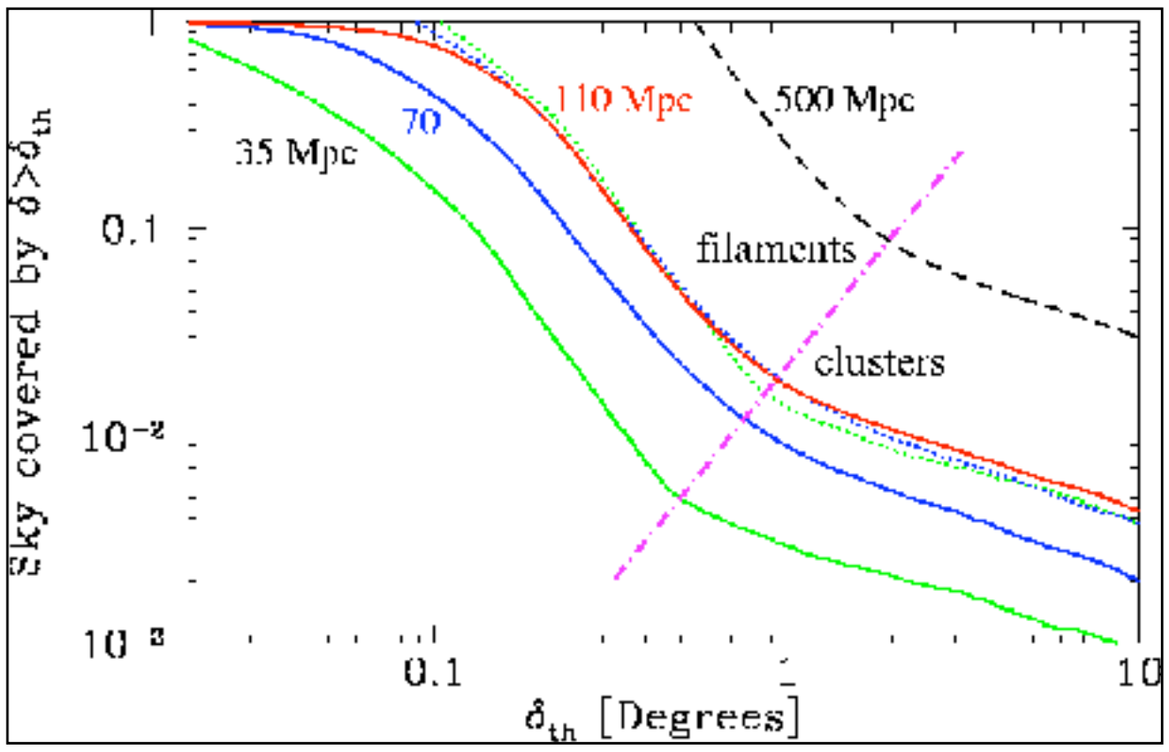


UHECR astronomy?



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

- cumulative deflections displayed are for protons
- Sigl+: deflections are high
- Dolag+: deflections are small
- for heavy nuclei deflections can be even higher



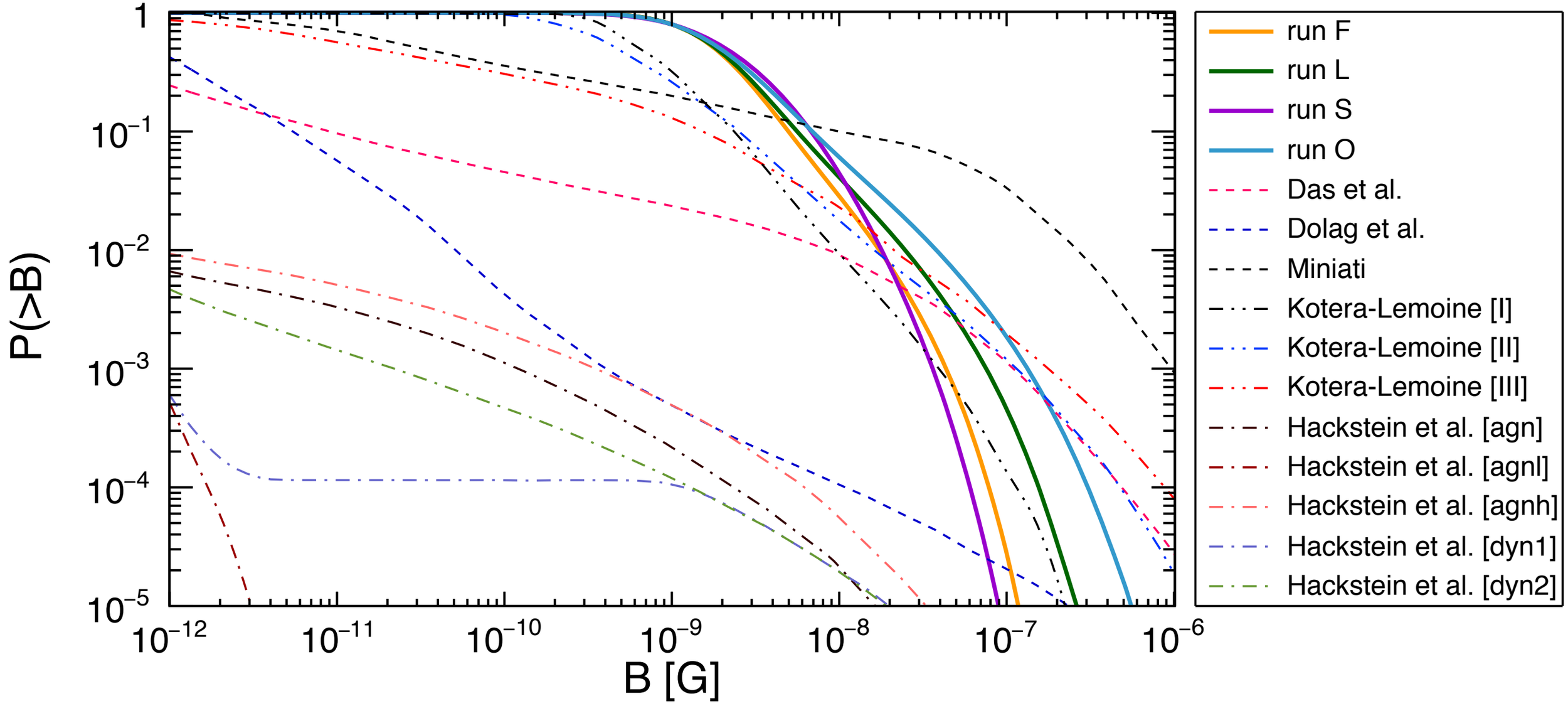
Dolag et al. JETP 79(2004) 583

- UHECR astronomy may be possible in the later but not in the former scenario
- how to solve this controversy?

what would happen in the extreme case in which voids are highly magnetised?

UHECR astronomy?

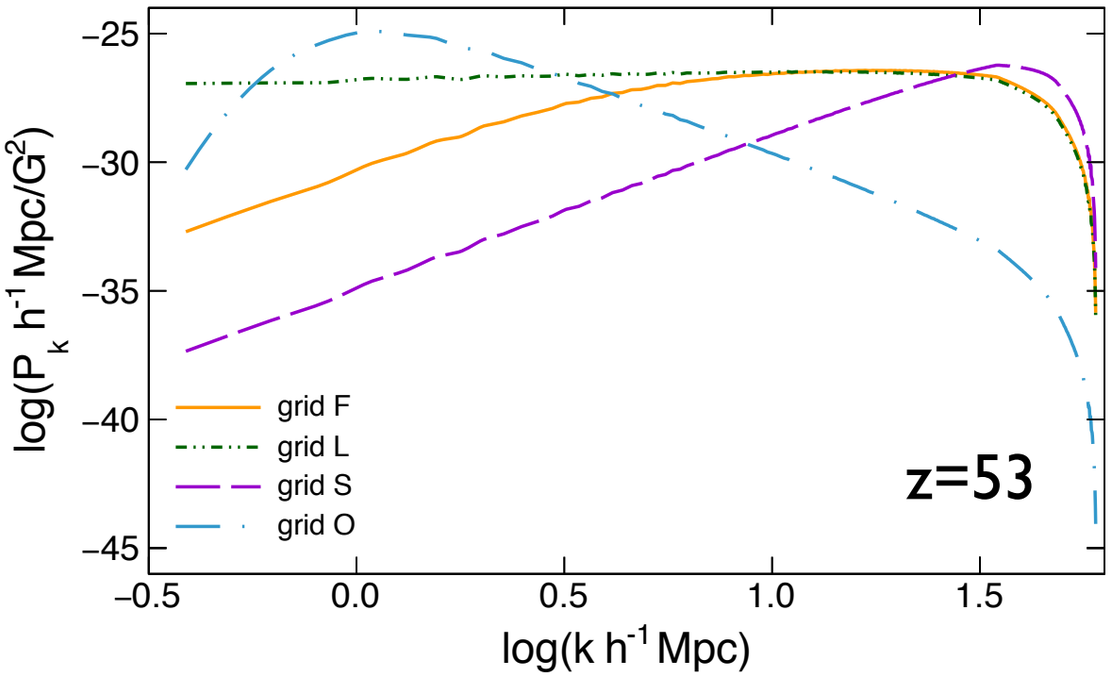
RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869

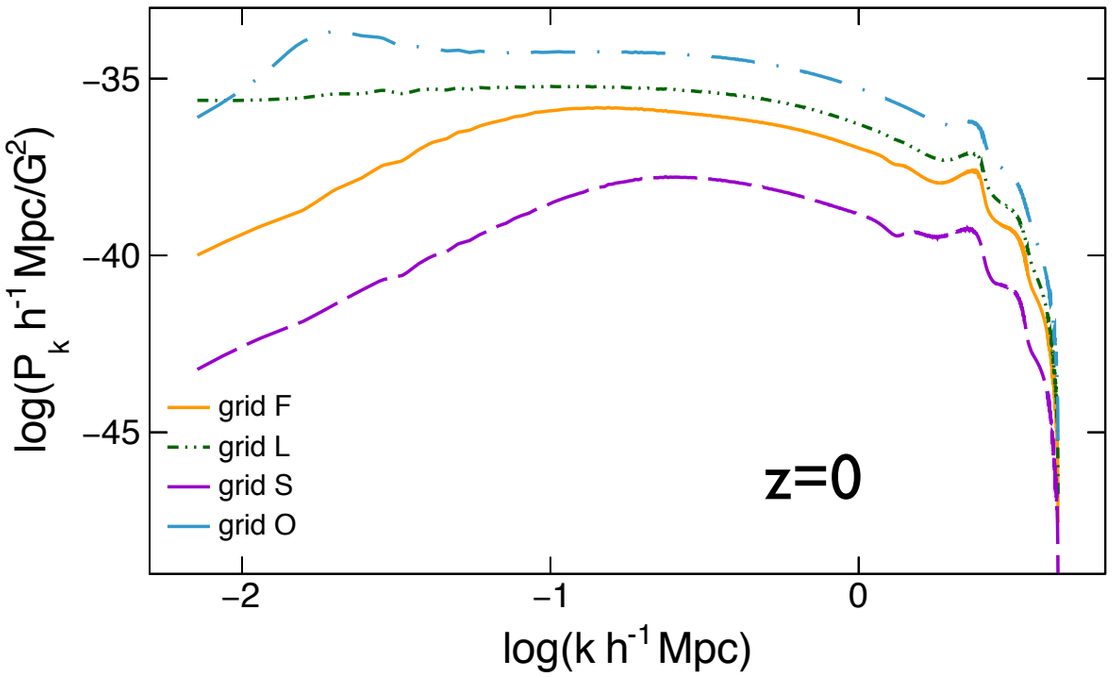


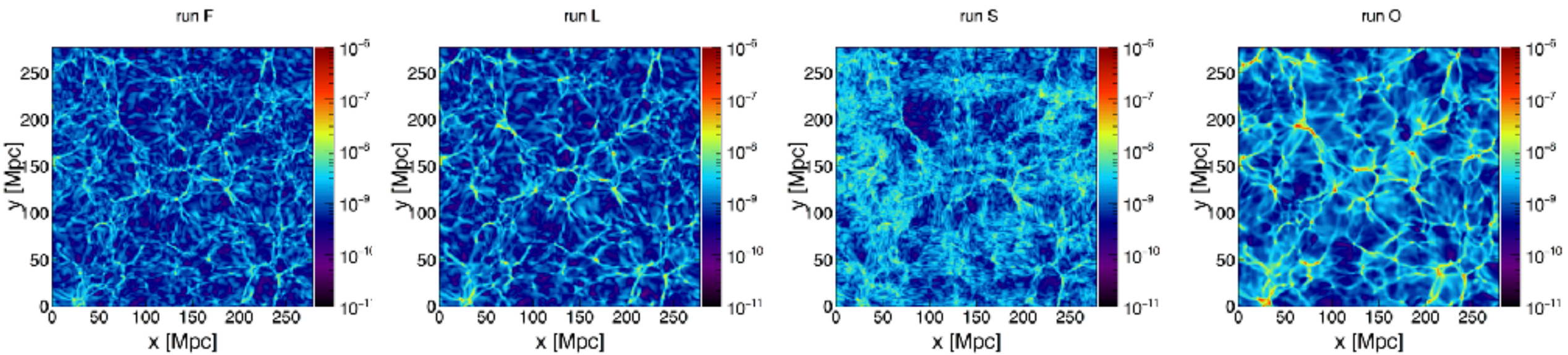
- MHD simulations of the cosmic web give VERY different results
- power spectrum of magnetic fields affects UHECR astronomy
- **we know nothing about extragalactic magnetic fields**
- **...but we can set limits**

deflections in extragalactic magnetic fields

RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869

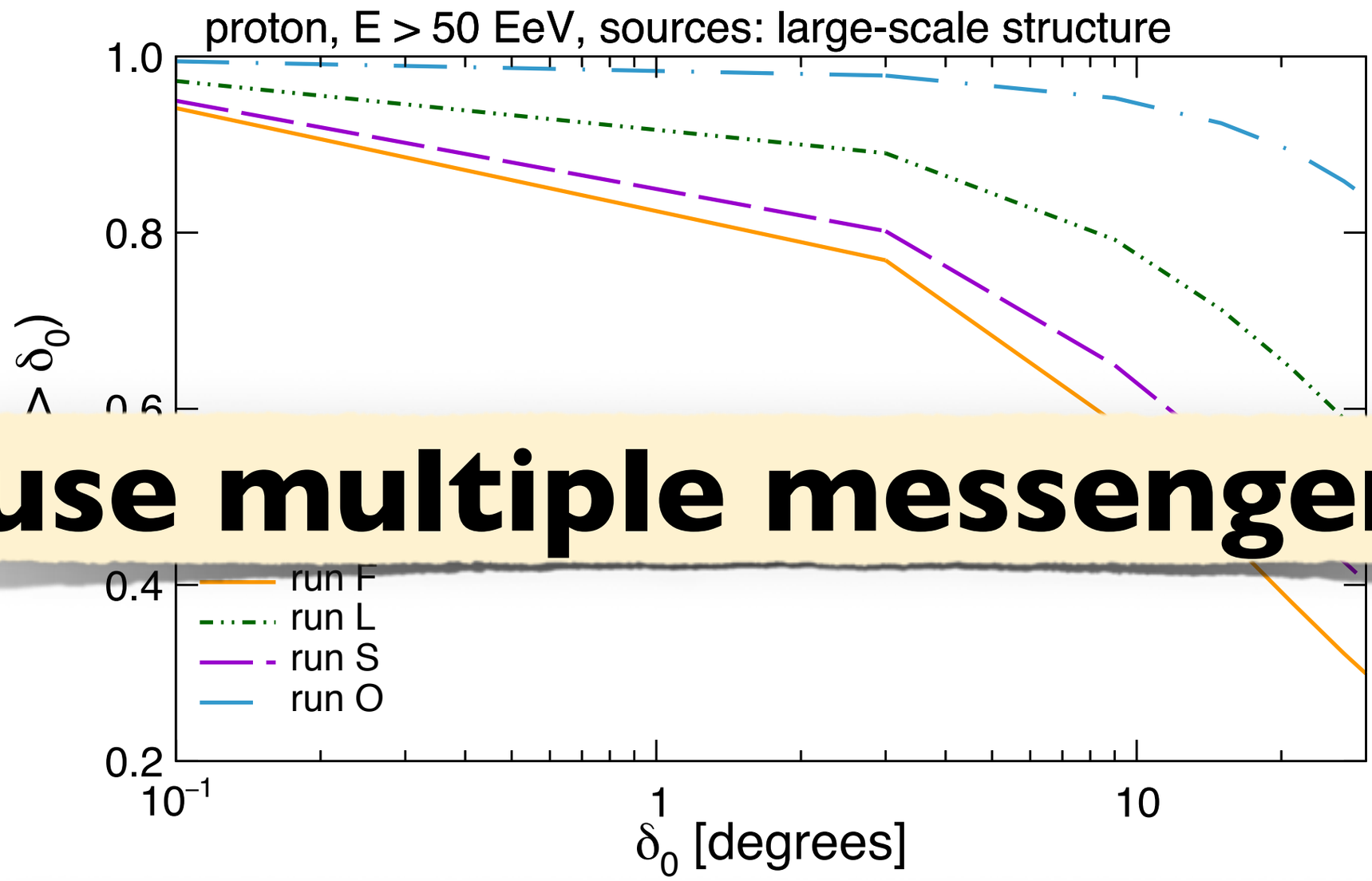






prospects for UHECR astronomy

RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869



use multiple messengers!!!

In the worst-case scenario UHECR astronomy is not impossible, but it is not very easy either.
How to unveil the sources of UHECRs then?

multi-messenger constraints on sources

$$p + \gamma \to p + e^+ + e^-$$

$$p + \gamma \to p + \pi^0$$

$$p + \gamma \to n + \pi^+$$

$${}^{A}_{Z}X + \gamma \to {}^{A-1}_{Z} X + n$$

$${}^{A}_{Z}X + \gamma \to {}^{A}_{Z} X + e^+ + e^-$$

$${}^{A}_{Z}X + \gamma \to {}^{A-1}_{Z-1} X + p$$

$$\pi^0 \to 2\gamma$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$n \to p + e^- + \bar{\nu}_e$$

$$e^+ + e^- \to \gamma$$

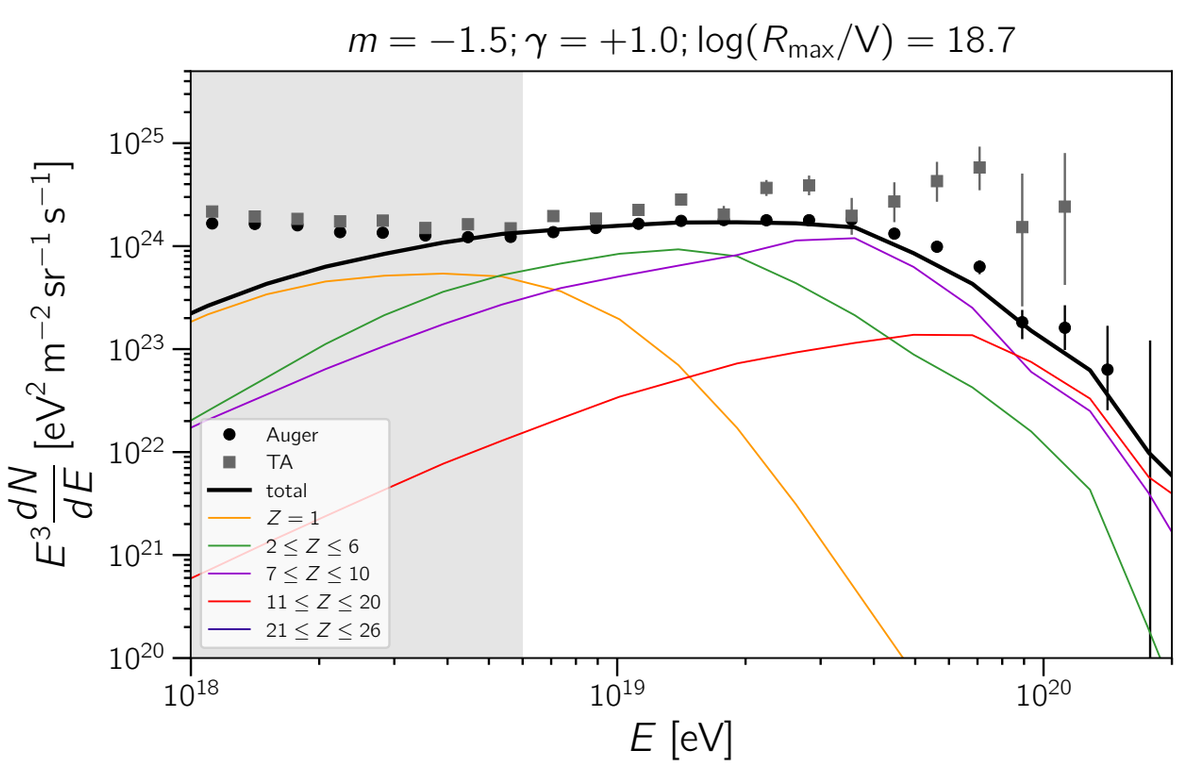
neutrinos

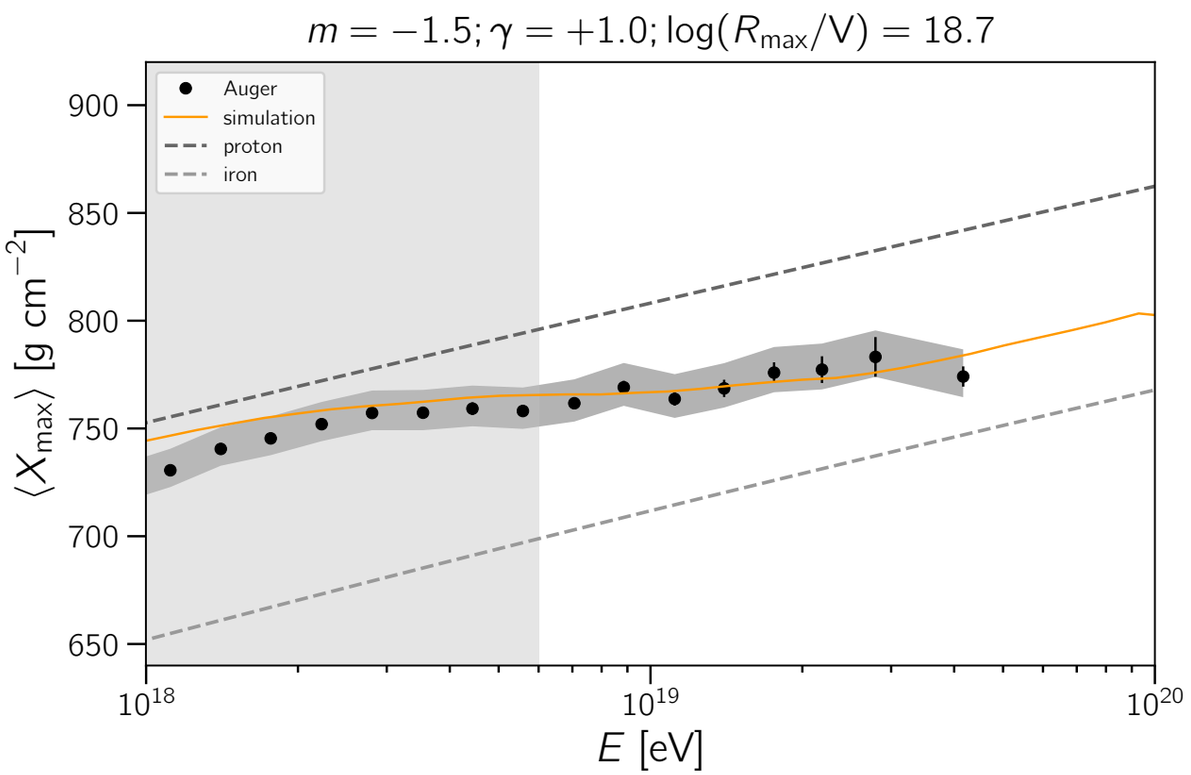
photons

	UHECRs	gamma rays	neutrinos
how far can we see with it	100 Mpc at 50 EeV 👎	10 Mpc at 1 EeV 👎	observable universe 👍
suitability for astronomy	👎	👍	👍
how hard it is to be detected	👍	👍	👎

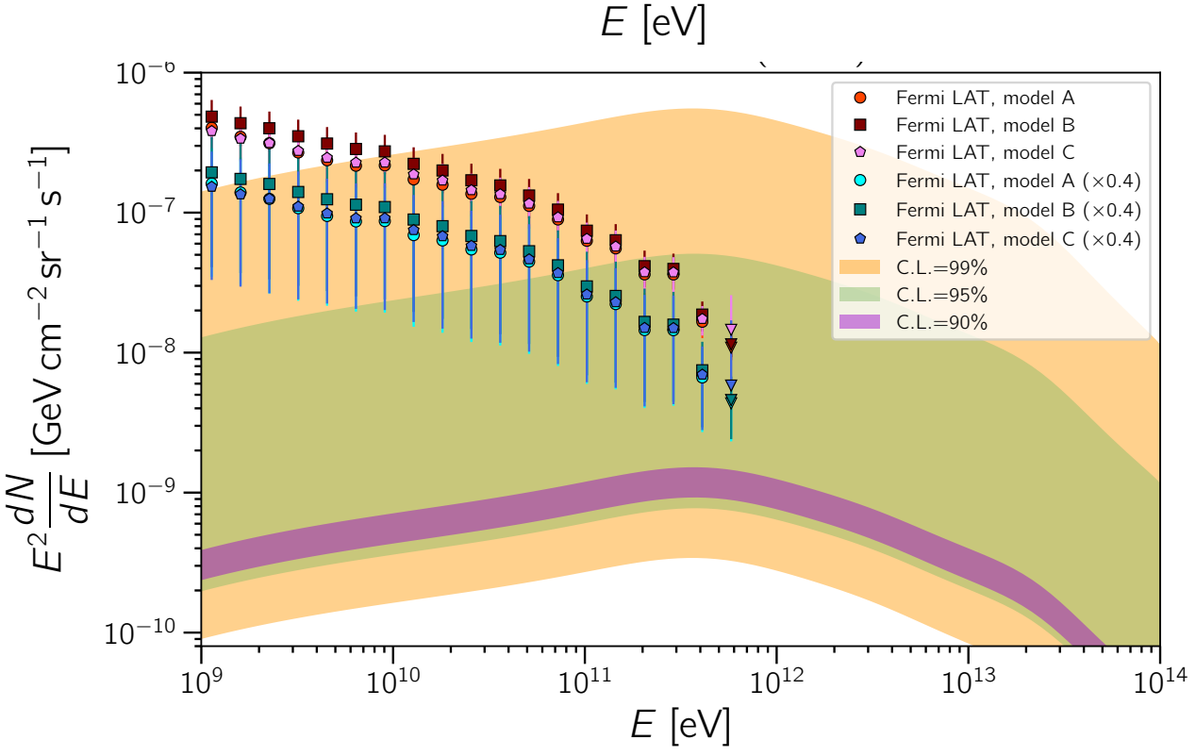
cosmogenic photons and the DGRB

RAB, R. M. de Almeida. B. Lago, K. Kotera. arXiv:1806.10879



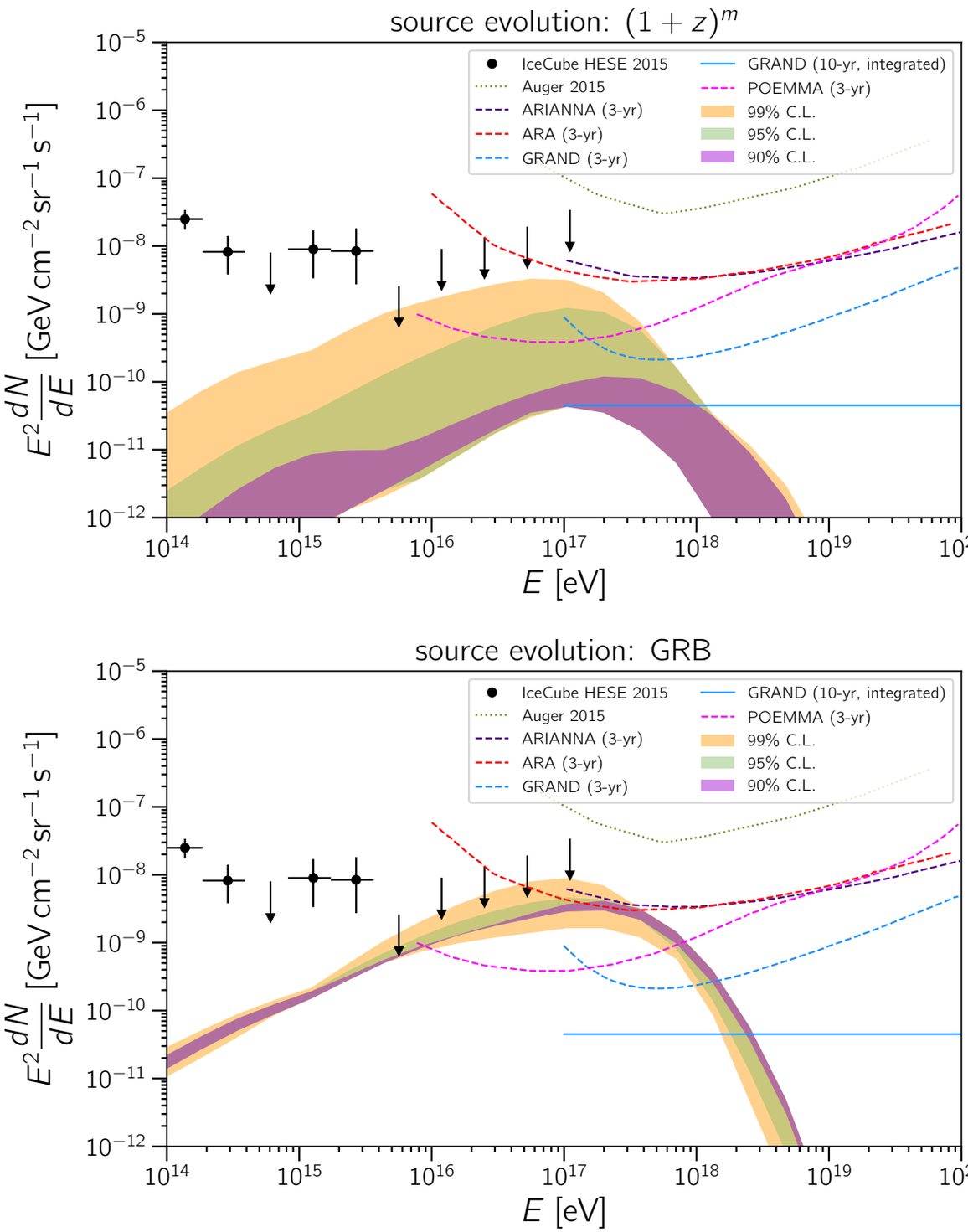


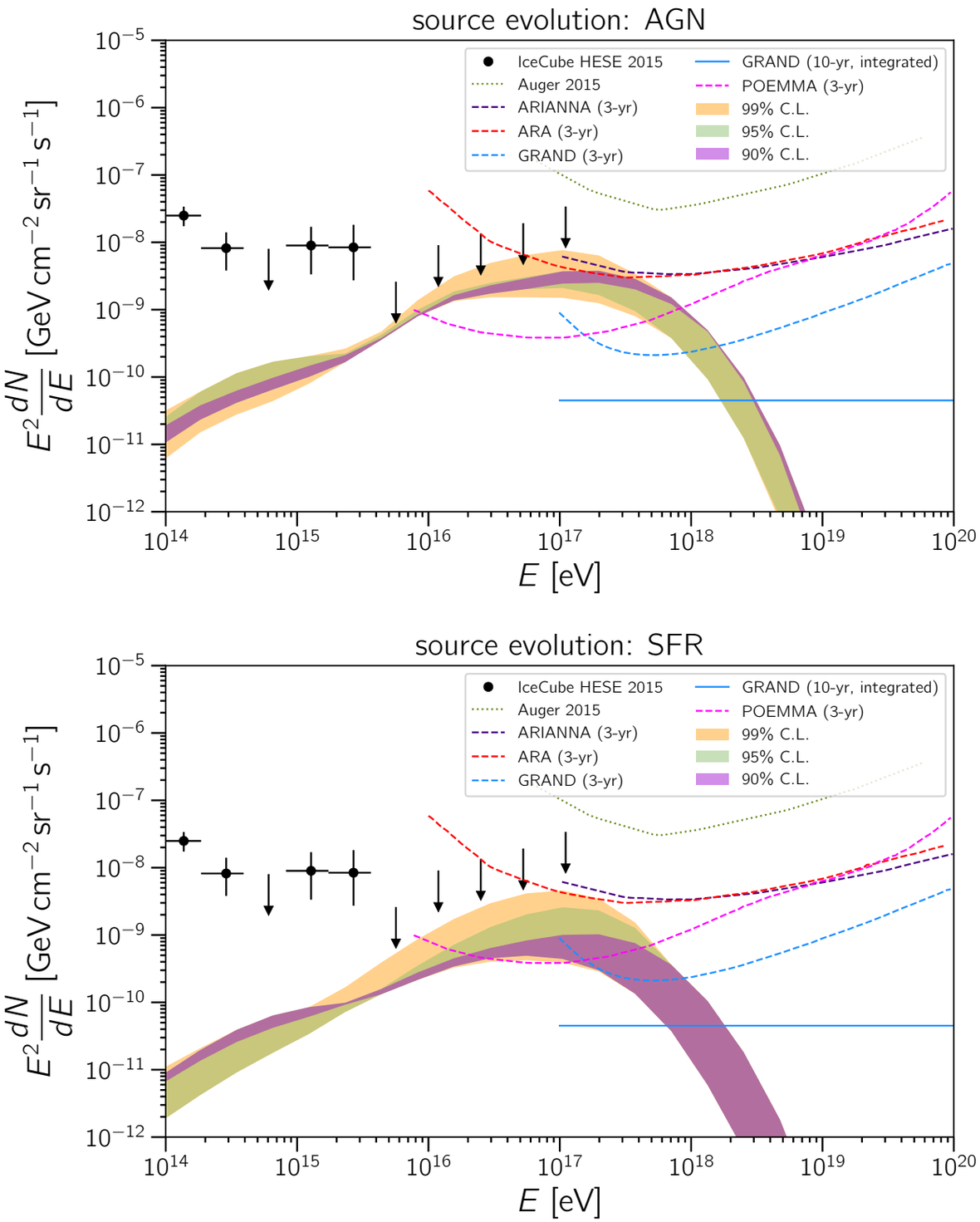
- fit Auger data assuming spectrum with spectral index α, with an exponential cutoff at R_{max}
- source evolution is $(1+z)^m$
- five CR species: p, He, N, Si, Fe
- DGRB can be used to constrain UHECR models



detection of cosmogenic neutrinos

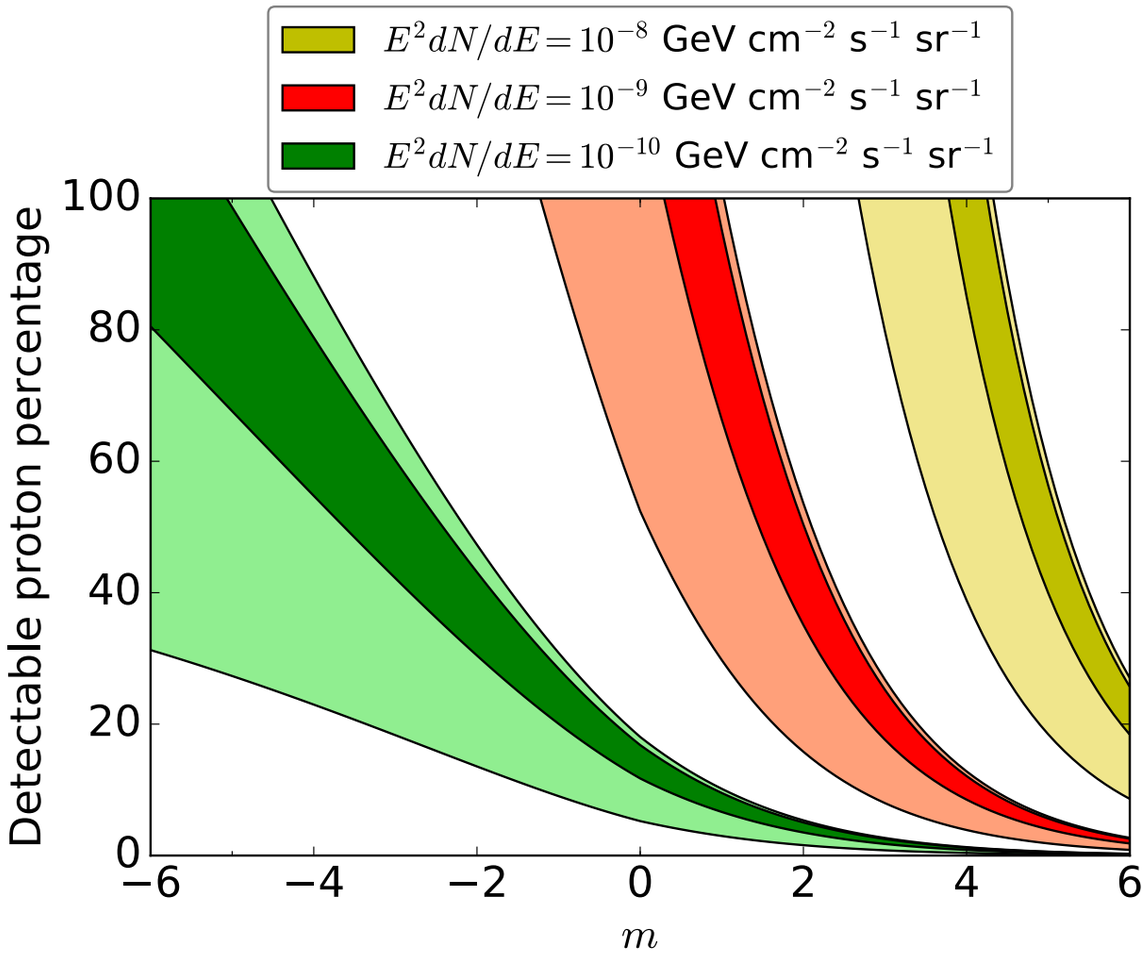
RAB, R. M. de Almeida. B. Lago, K. Kotera. arXiv:1806.10879





proton fraction at ultra-high energies

A. van Vliet, RAB, J. Hörandel. In preparation. 2018.



sources evolve as $(1+z)^m$

bands encompass upper and lower limits:

- spectral indices: 2-3 (darker); 1-3 (lighter)
- log(Emax/eV): 20-23 (darker); 19.6-23 (lighter)

- the production of cosmogenic neutrinos due to cosmic-ray interactions with extragalactic photon fields may help us solving the riddle of the UHECRs
- fraction of protons and evolution of sources can be excluded with neutrino experiments
- IceCube does not have the required sensitivity, but next-generation detectors such as the Giant Radio Antenna for Neutrino Detection (GRAND) can reach the sensitivity to probe part of the parameter space

see talk by A. van Vliet, CR session, Friday 14:45

where do we stand?

- it is difficult to build detailed models for UHECR propagation in the extragalactic space
- EBL spectrum, photonuclear cross sections, magnetic field power spectrum are all sources of uncertainty in the modelling of UHECR propagation
- if extragalactic magnetic fields (and hopefully galactic) are tiny, then we don't need very detailed models; if they are not, it is crucial to understand them for UHECR astronomy
- **magnetic fields may spoil UHECR astronomy**
- MHD simulations suggest that even if voids are highly magnetised, UHECR astronomy may be possible in a fraction of the sky for typical magnetic power spectra
- if extragalactic deflections are low, it might be possible to **constrain the galactic magnetic field** using UHECRs other messengers are also useful to constrain UHECR sources
- **multimessenger astronomy** with neutrinos + photons + cosmic rays (+ gravitational waves?) may be needed to unveil the sources of UHECRs

thanks!

back-up slides

modelling the propagation of UHECRs: energy losses

photopion production

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

Greisen-Zatsepin-Kuz'min (GZK) cutoff

expansion of the universe

$$\frac{dt}{dz} = \frac{1}{H_0} \frac{1}{1+z} \frac{1}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \qquad E = \frac{E_0}{1+z}$$

ΛCDM cosmology

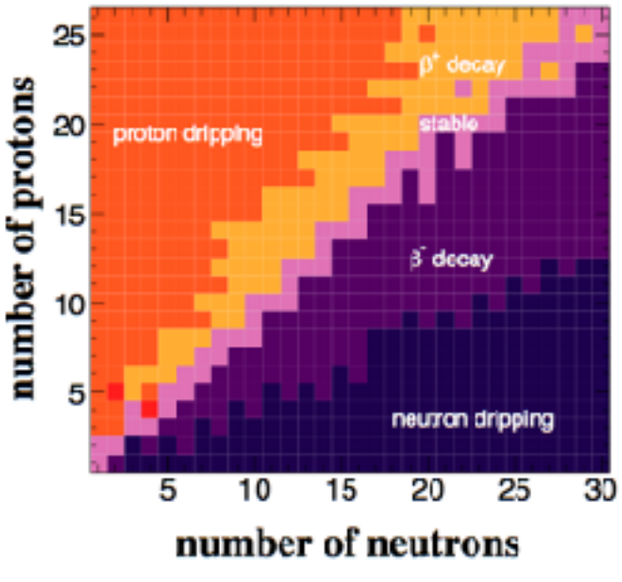
pair production

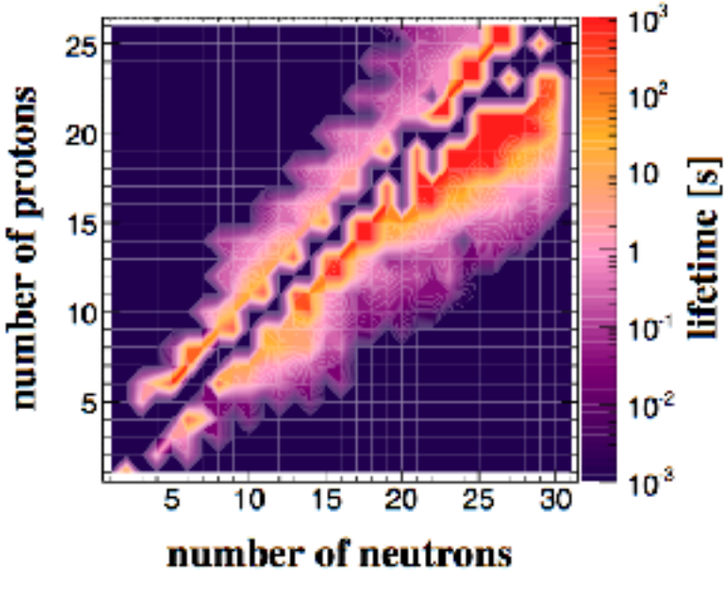
$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 k_B T f(\Gamma)$$

photodisintegration

$$\frac{1}{\lambda(\Gamma)} = \int_{E_{min}}^{E_{max}} n(\epsilon, z) \bar{\sigma}(\epsilon'_{max} = 2\Gamma\epsilon) d\epsilon$$

nuclear decay

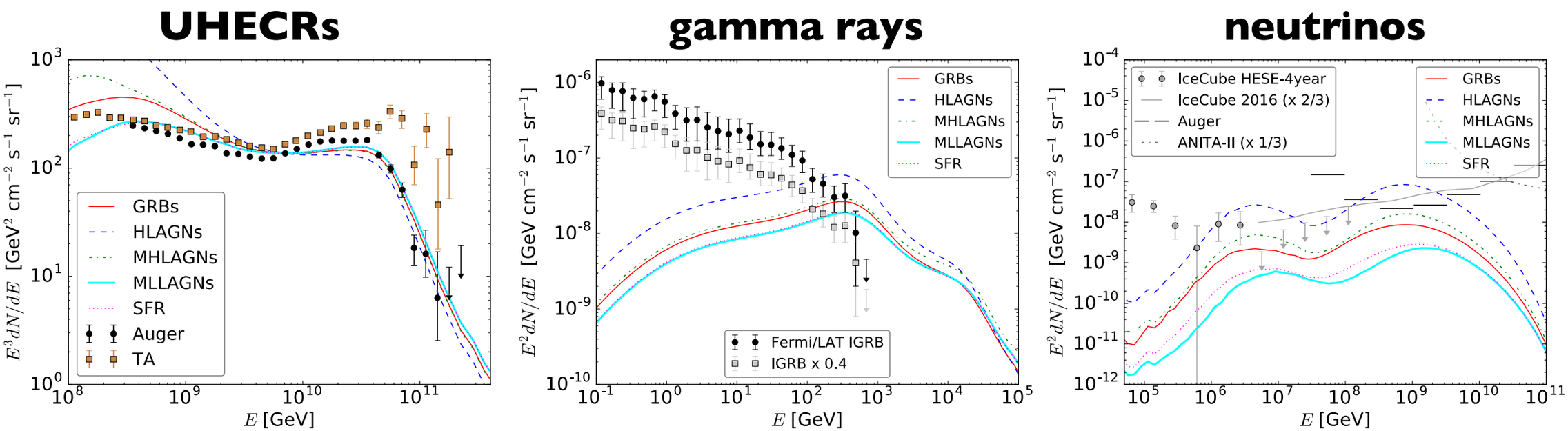




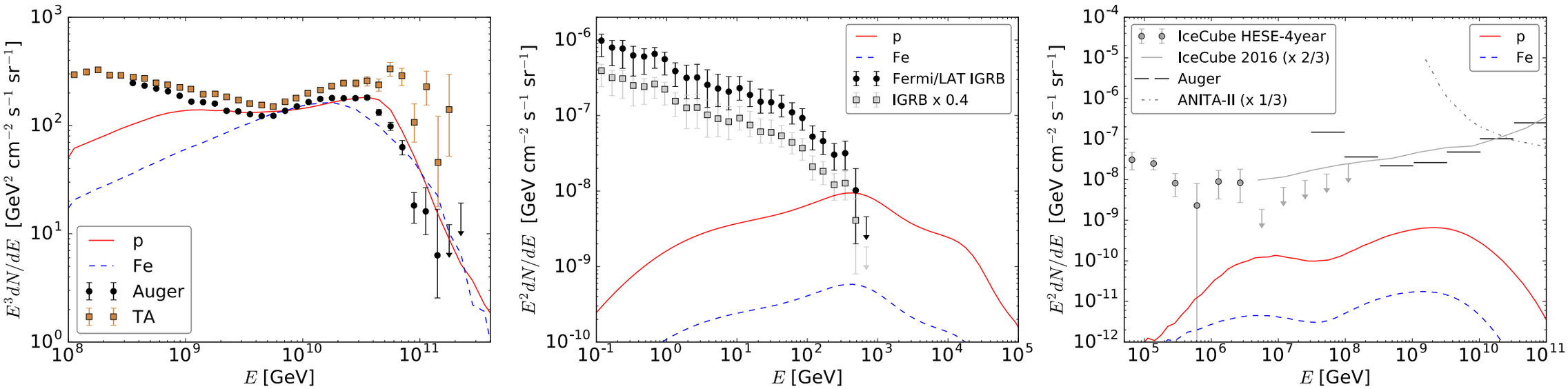
UHECR constraints with UHECR astronomy

A. van Vliet, J. Hörandel, RAB. Proc. of Science (ICRC2017) 562. arXiv: 17017.04511

constraining sources



constraining composition



first row: pure proton, spectral index = 2.5, source evolutions indicated, maximal rigidity = 200 EV
second row: pure proton/iron, spectral index = 2.5, no source evolution, maximal rigidity = 200 EV

MHD simulations

RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869

- simulation volume: $(200h^{-1}\ \mathrm{Mpc})3$
- AMR grid obtained using RAMSES, with 18 levels of refinement
- simulation:

  part 1: solve ideal MHD ensuring precise conservation of momentum, energy, and mass

  guarantee that there are no magnetic monopoles in the simulation

  part II: physical parametrisation

  cooling, heating, and other relevant energy terms

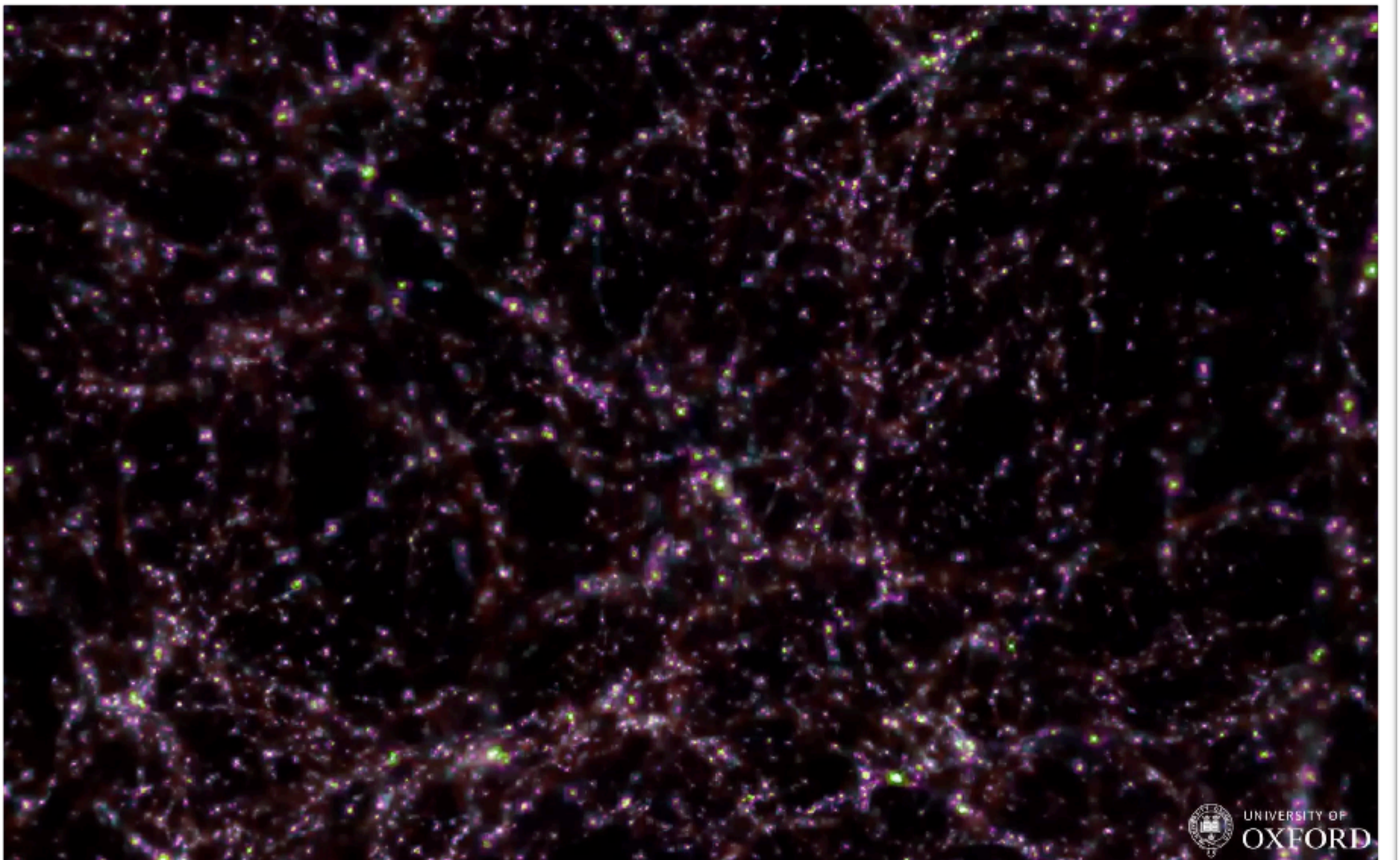
  subgrid models including formation and death of objects, feedback, turbulence, ...

  properly model source and sink terms
- feedback ignored, but could be very important

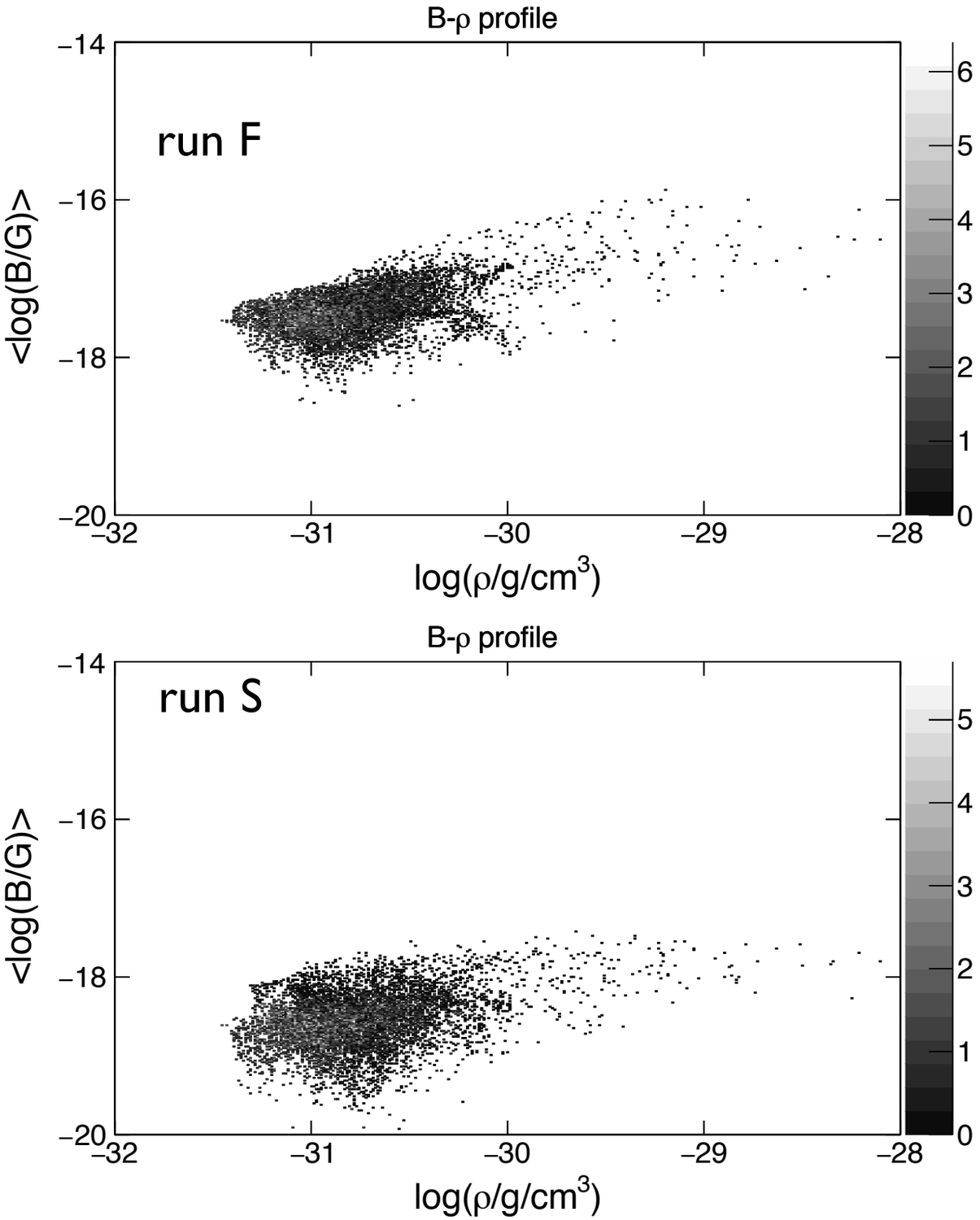
the simulations

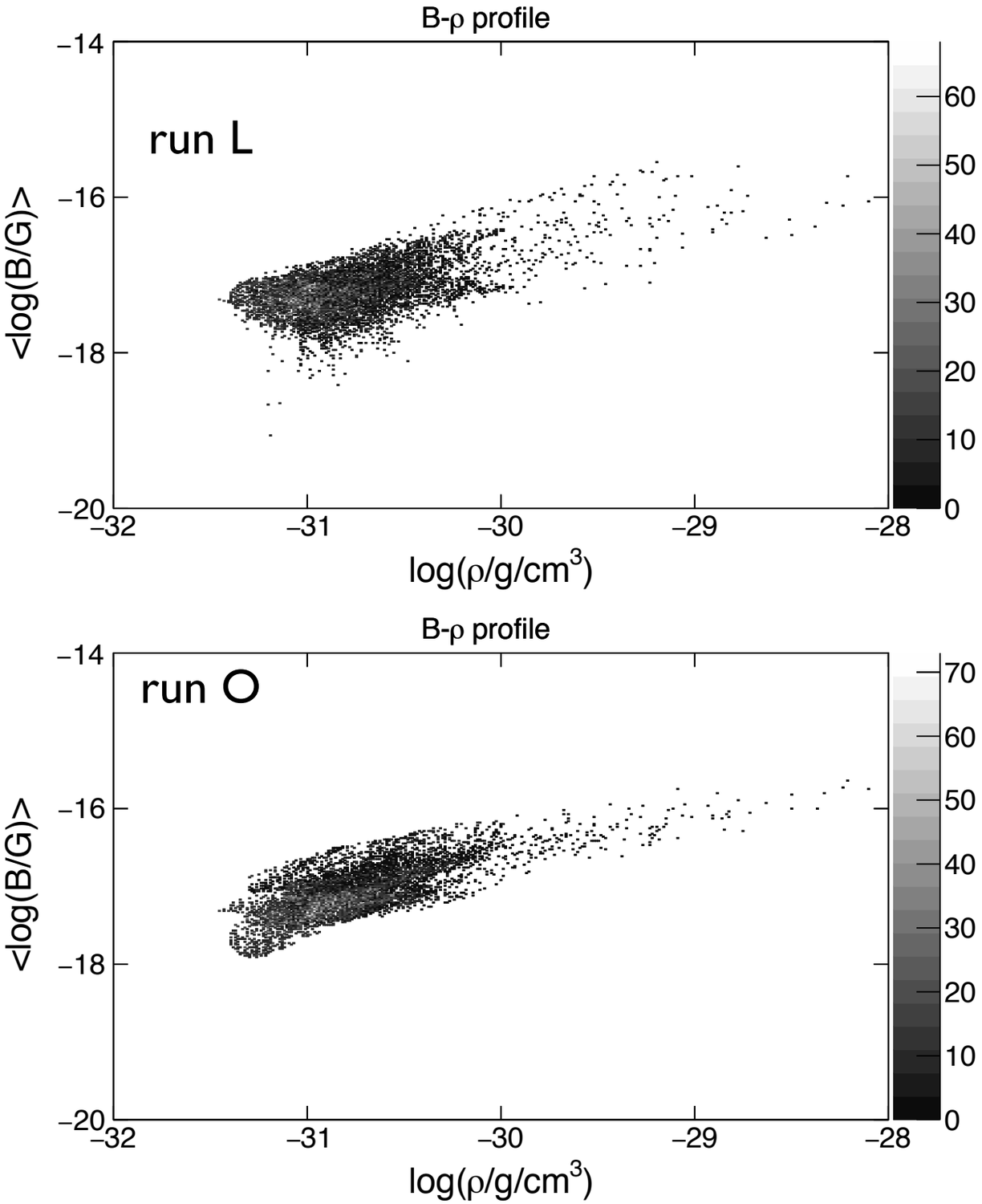
- run F: fiducial run
- run L: less magnetic power over small scales
- run S: less magnetic power over large scales
- run O: power mostly on large scales

MHD simulations



prospects for UHECR astronomy

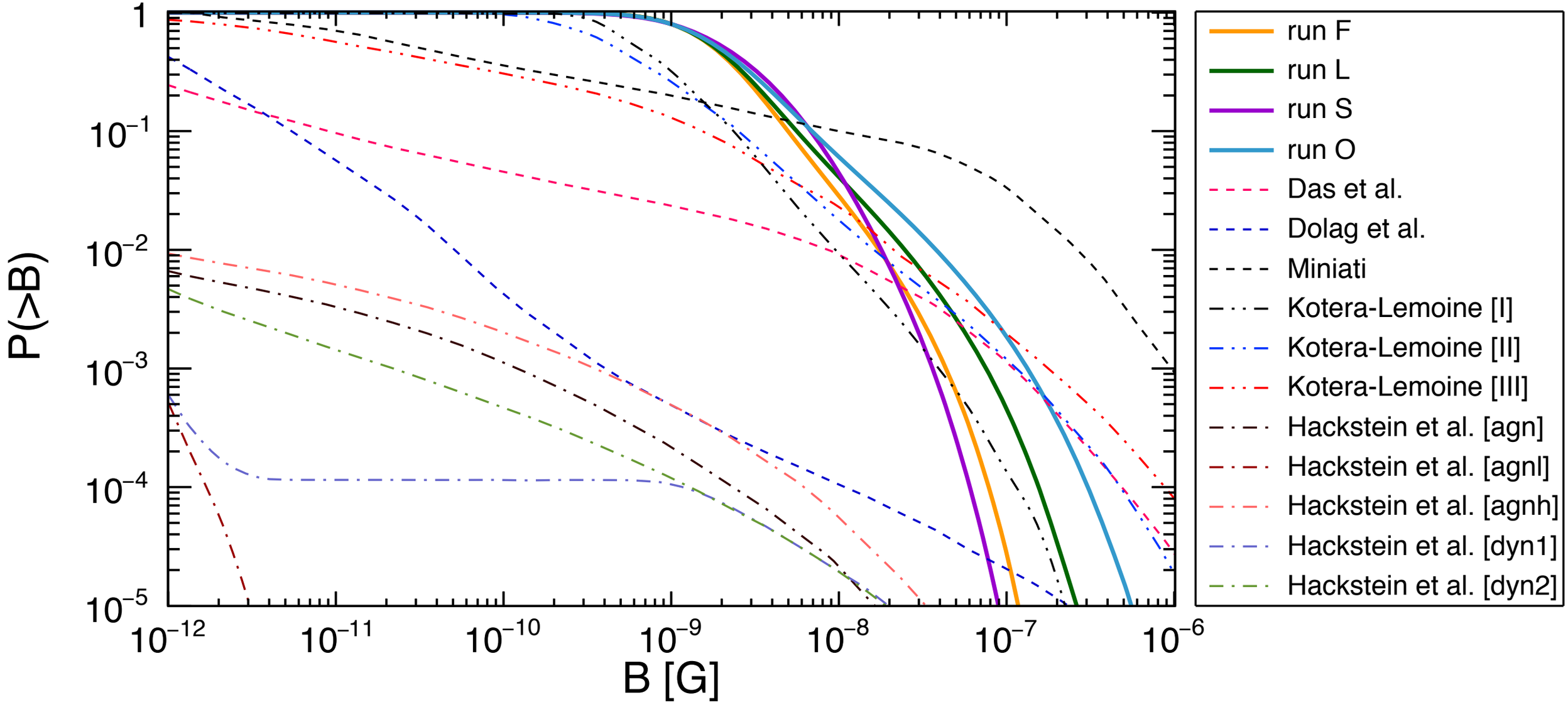




deflections in extragalactic magnetic fields

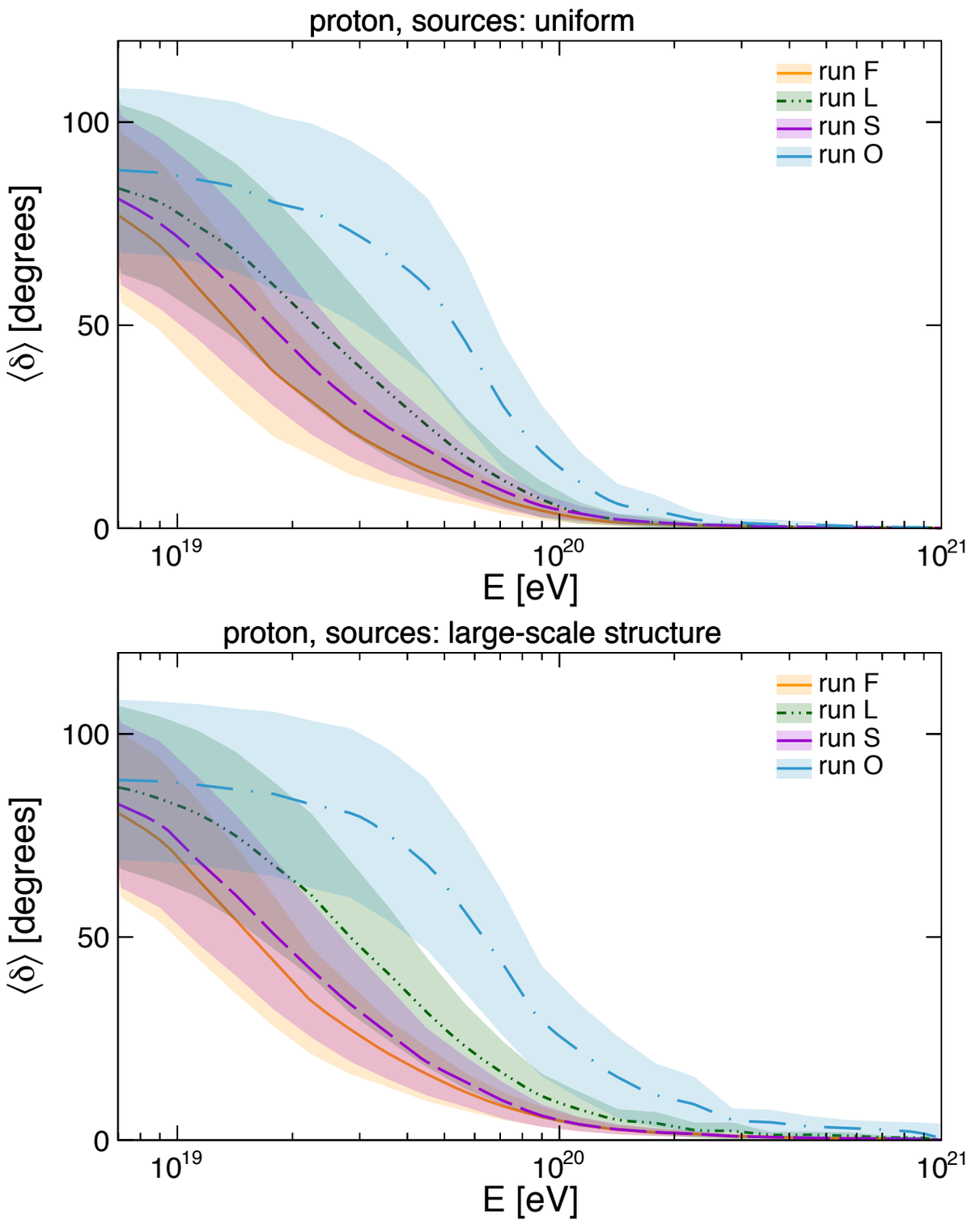
RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869

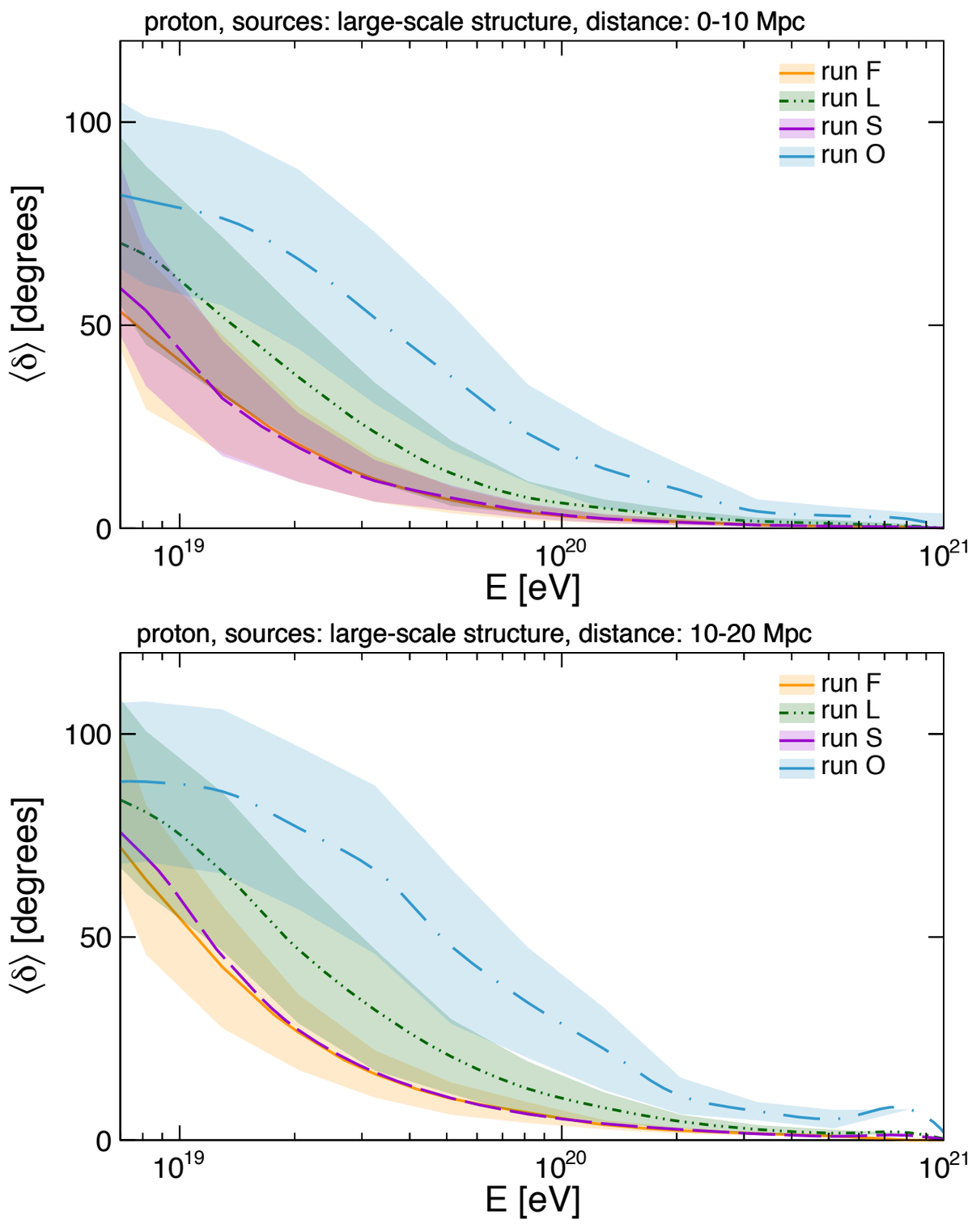
- we use Planck's upper limit to normalise the magnetic field in voids
- this analysis provide an upper limit on (extragalactic) UHECR deflection
- MHD simulations: 512^3 with size $(200h^{-1})^3$; RAMSES code; 18 levels of refinement



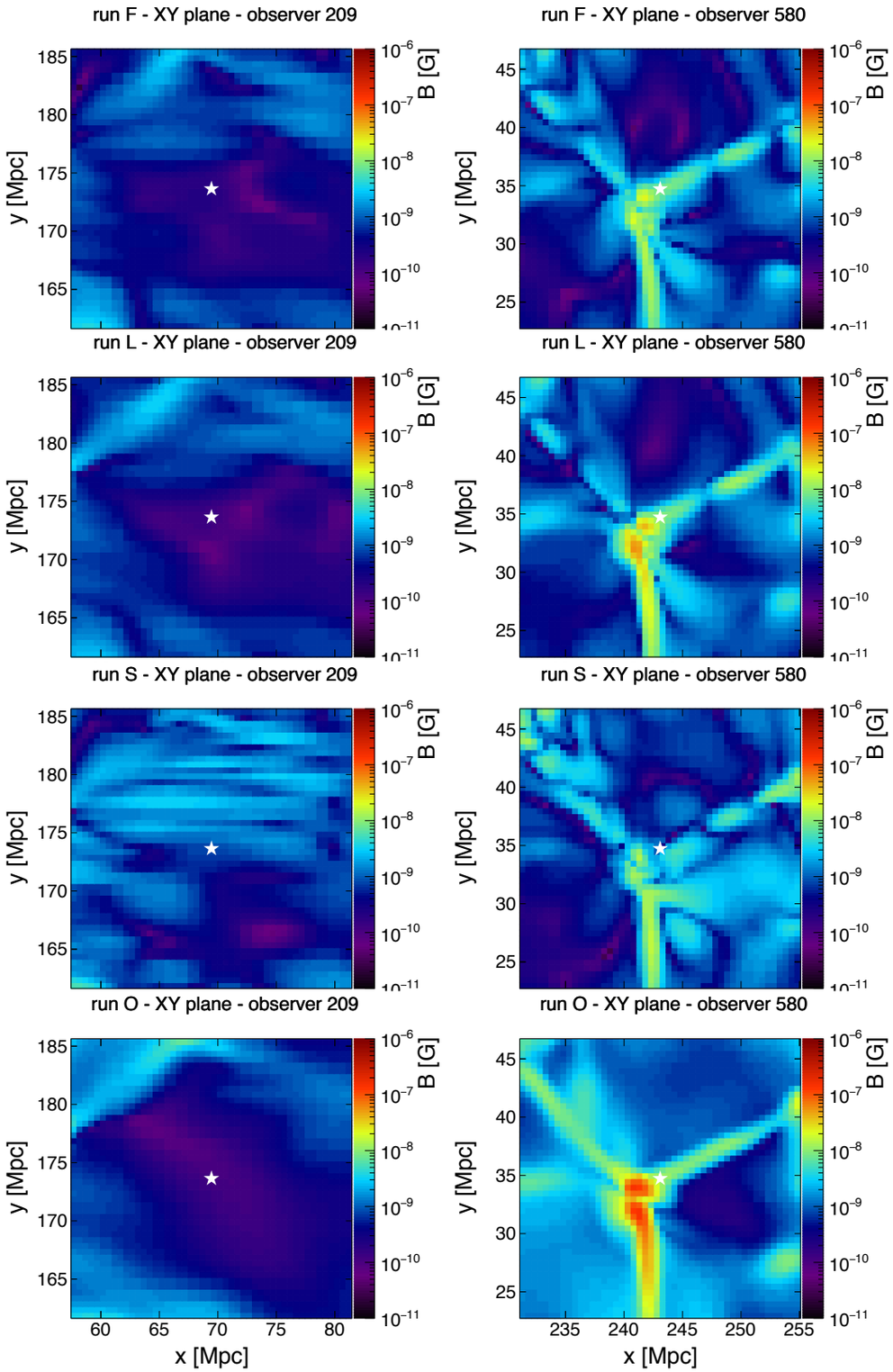
deflections in extragalactic magnetic fields

RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869

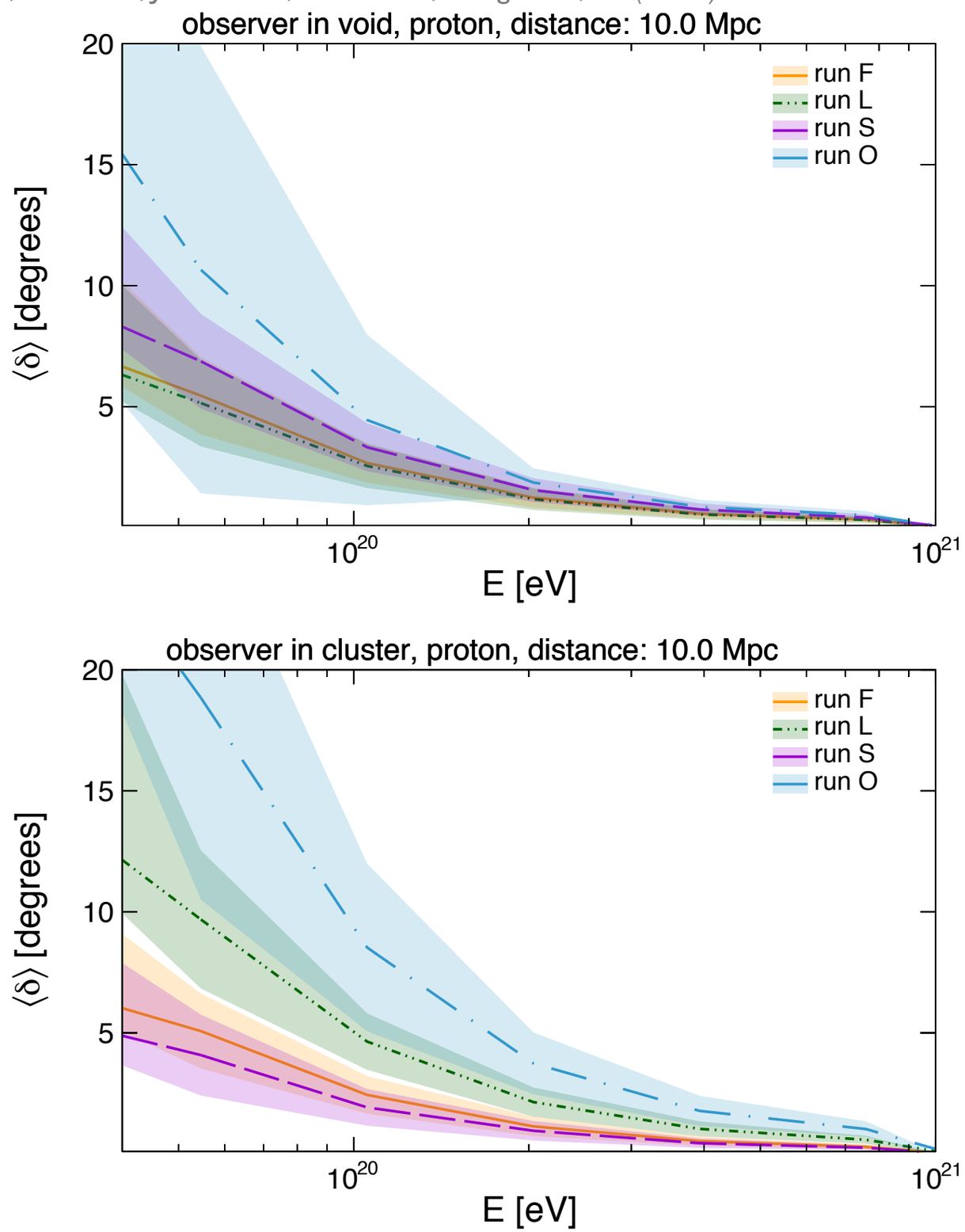




deflections in extragalactic magnetic fields

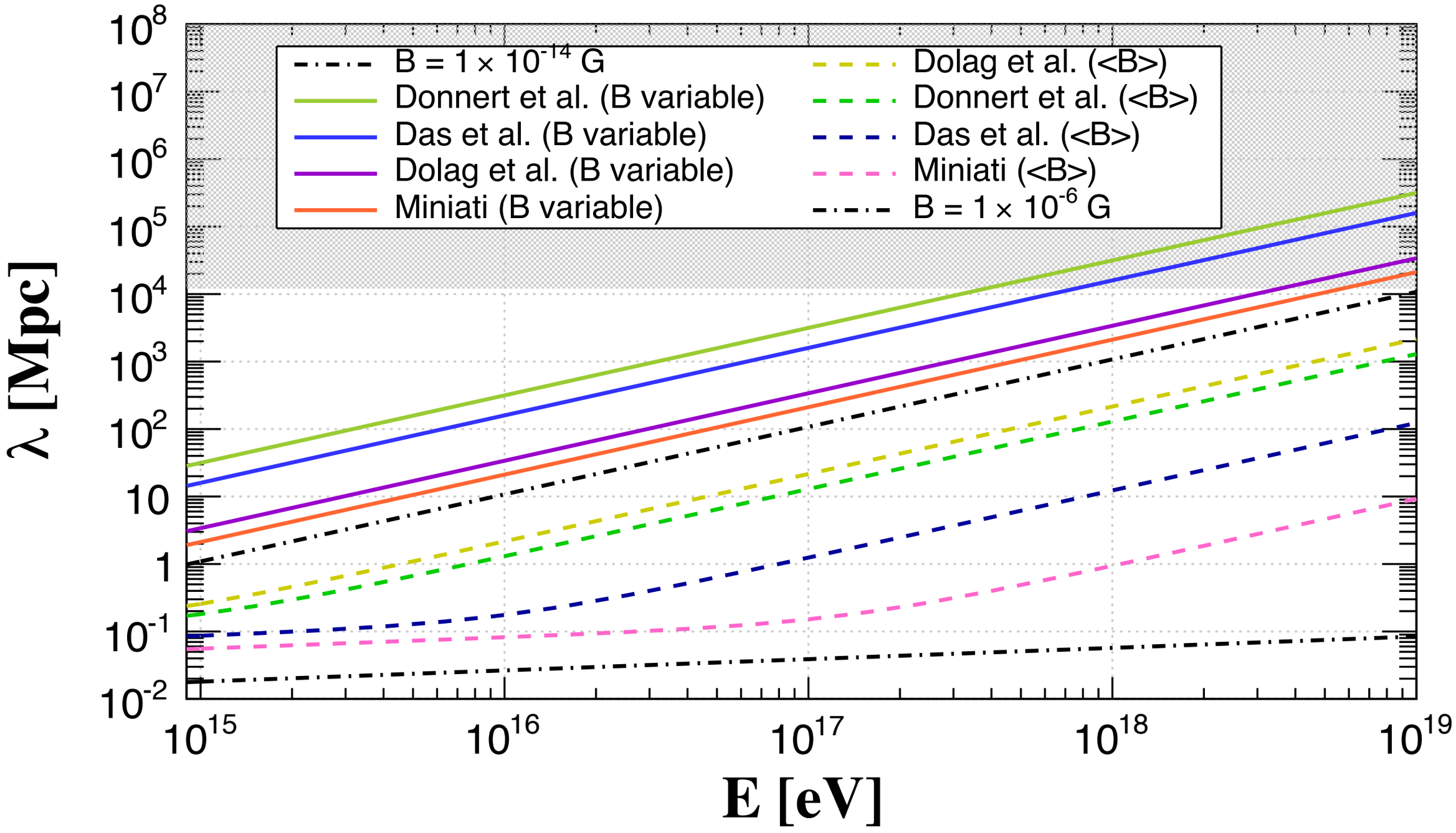


RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869



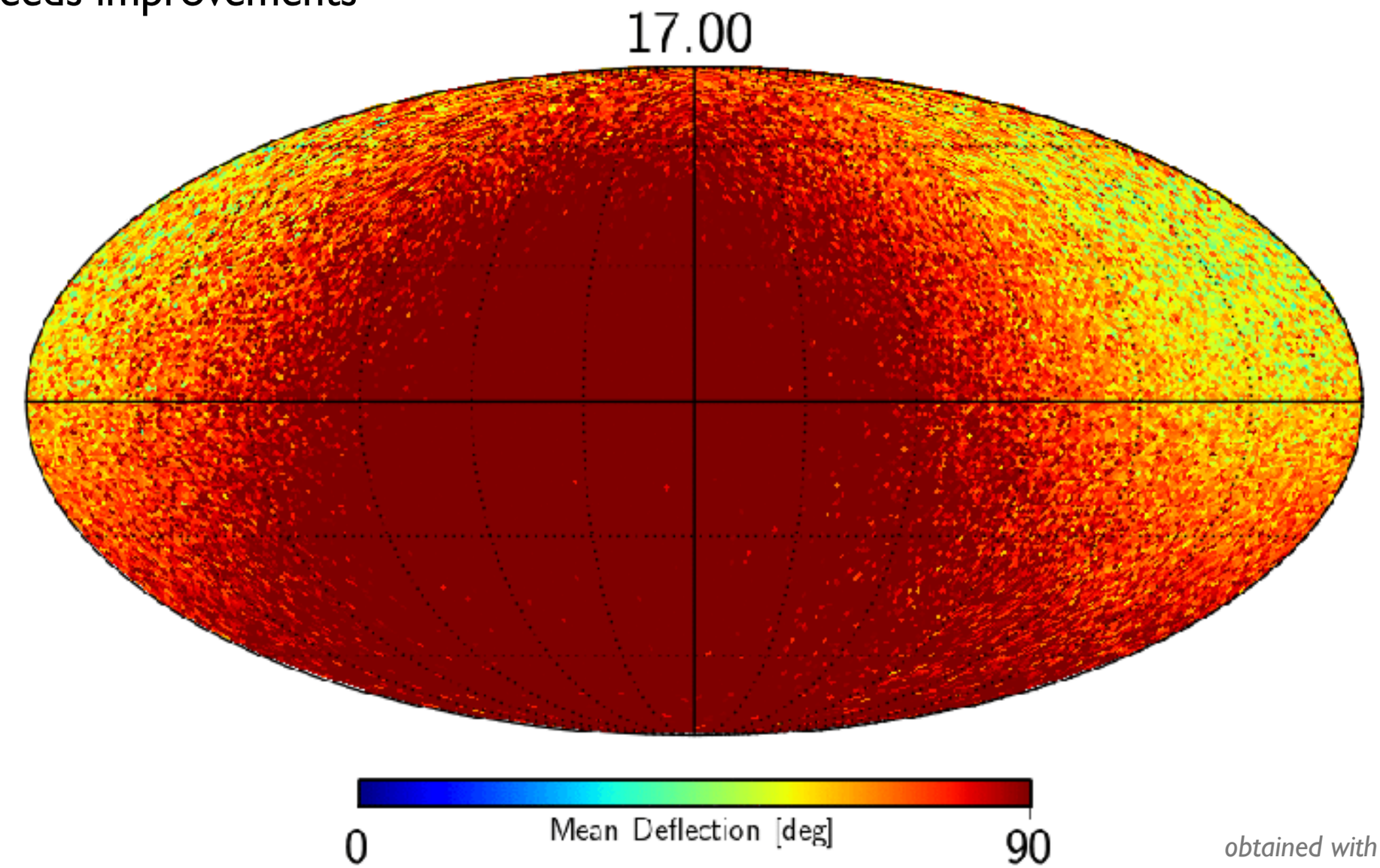
magnetic horizons of UHECRs

RAB & G. Sigl. JCAP 1411 (2014) 031. arXiv:1407.6150



UHECRs and the galactic magnetic field

- state-of-the-art model: Jansson & Farrar '12 (JF12)
- this model is based on fits of synchrotron emission + Faraday rotation + polarisation measurements
- models needs improvements

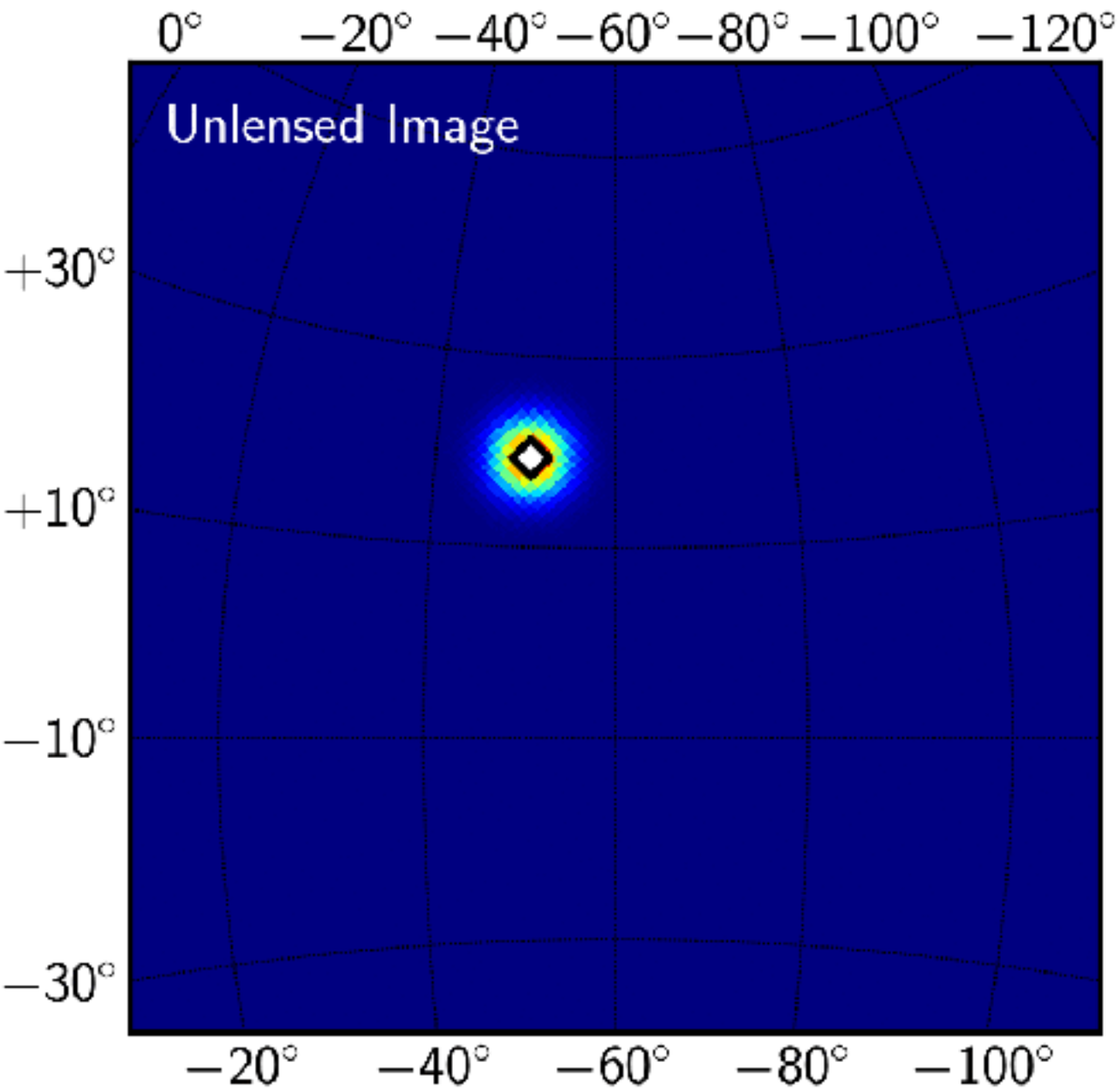


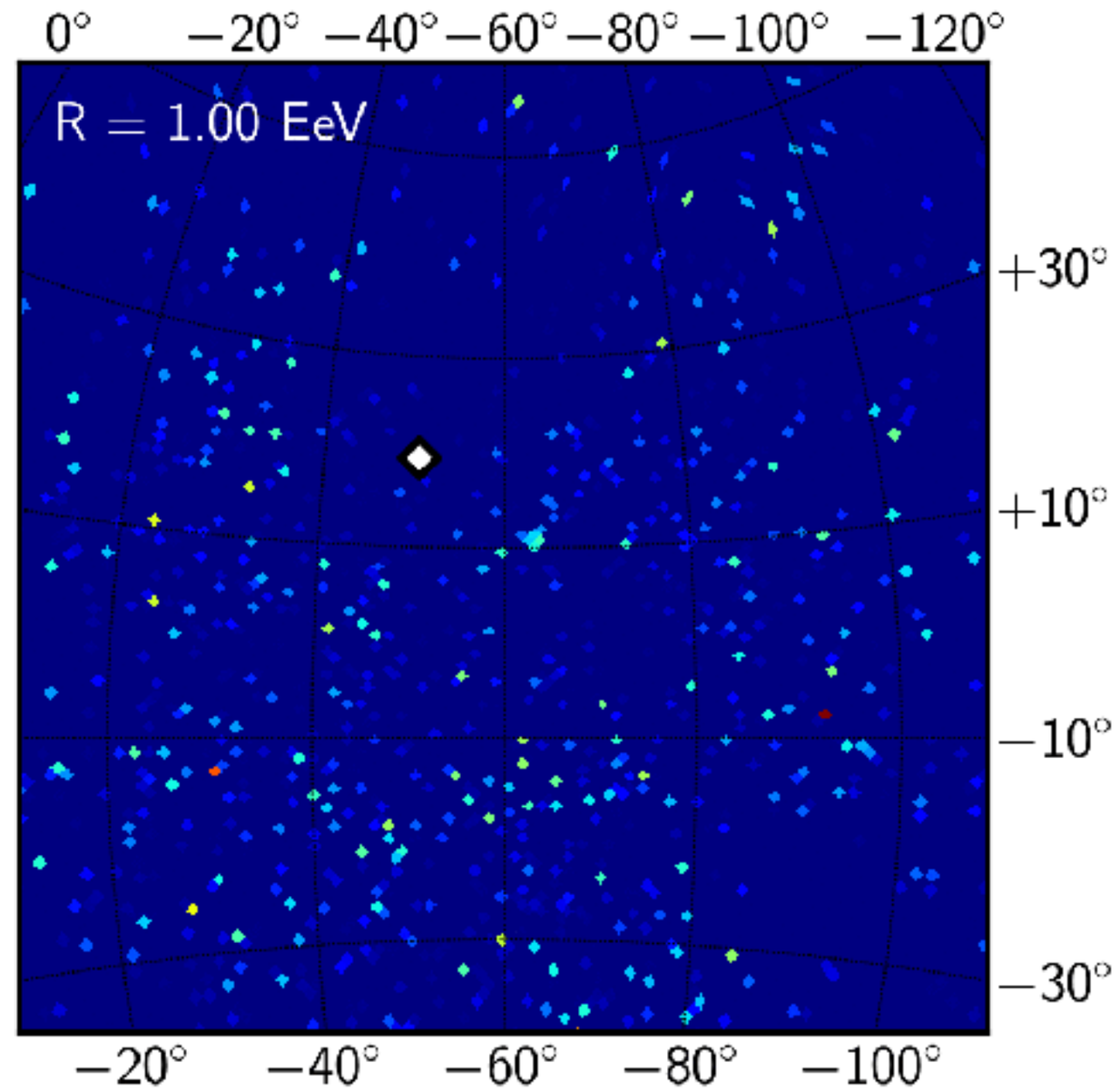
obtained with the PARSEC code:

http://web.physik.rwth-aachen.de/Auger_MagneticFields/PARSEC

UHECRs and the galactic magnetic field

- the case of Centaurus A, assuming only galactic deflections and the complete JF12 field

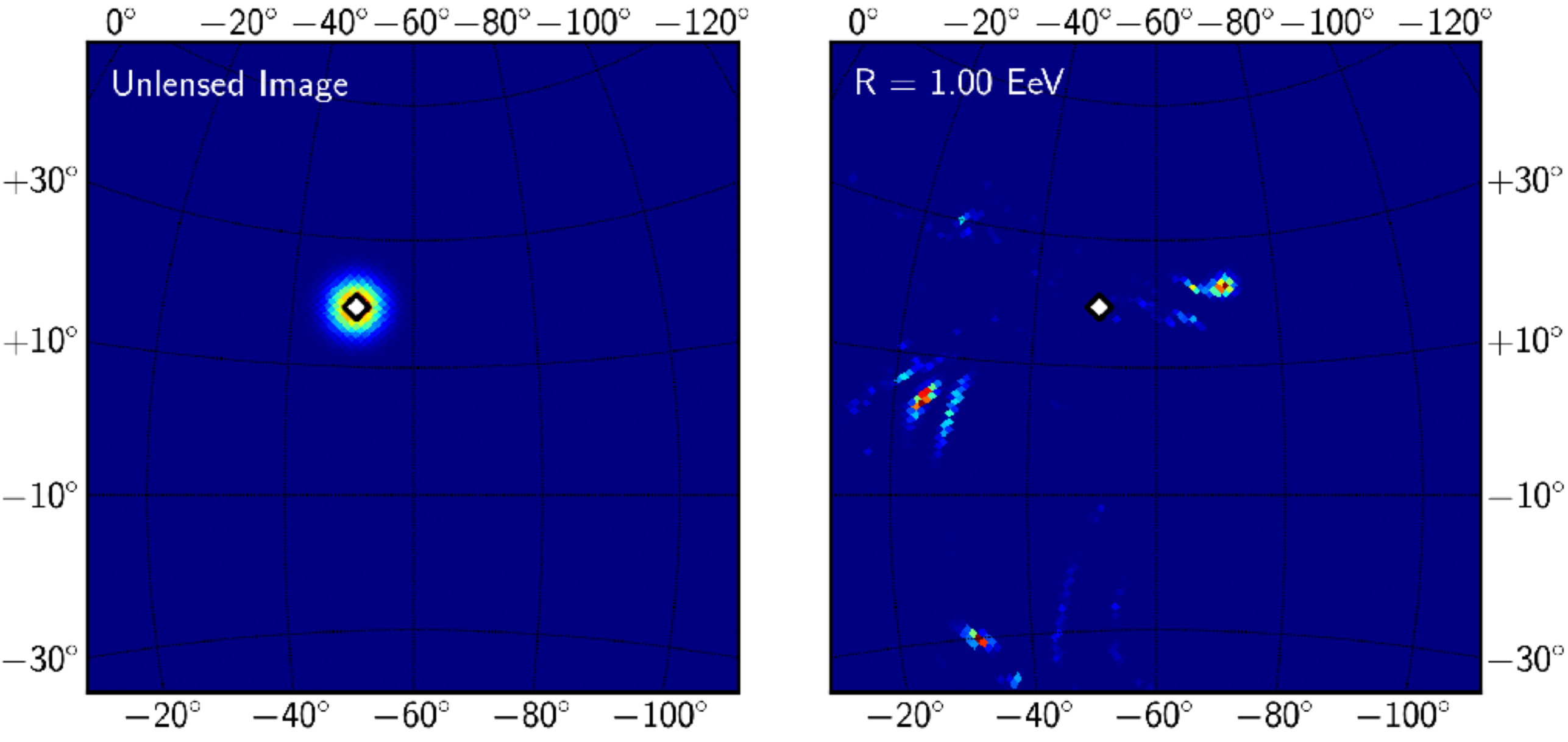




obtained with the PARSEC code

UHECRs and the galactic magnetic field

- the case of Centaurus A, assuming only galactic deflections and only the regular component of the field



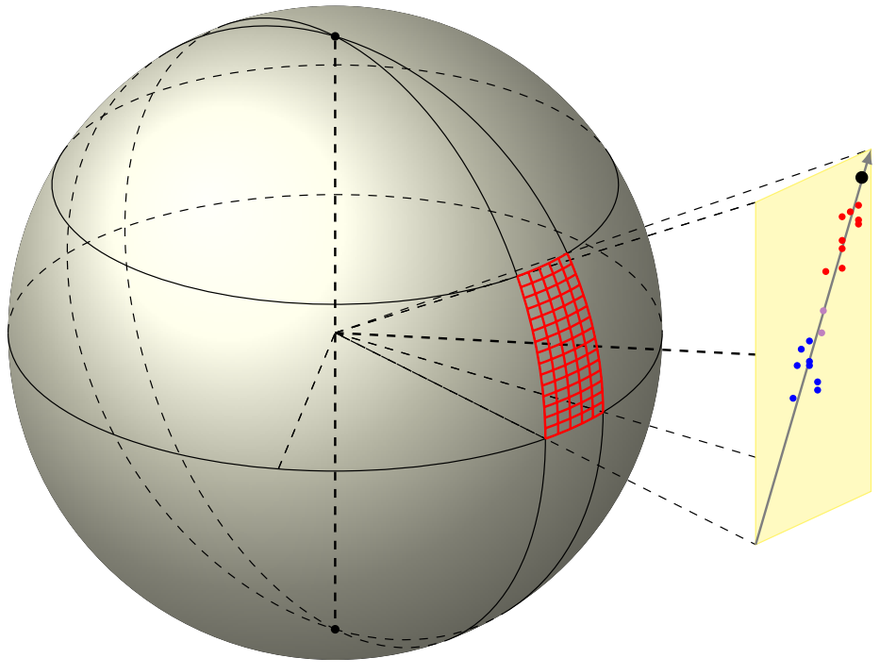
obtained with the PARSEC code

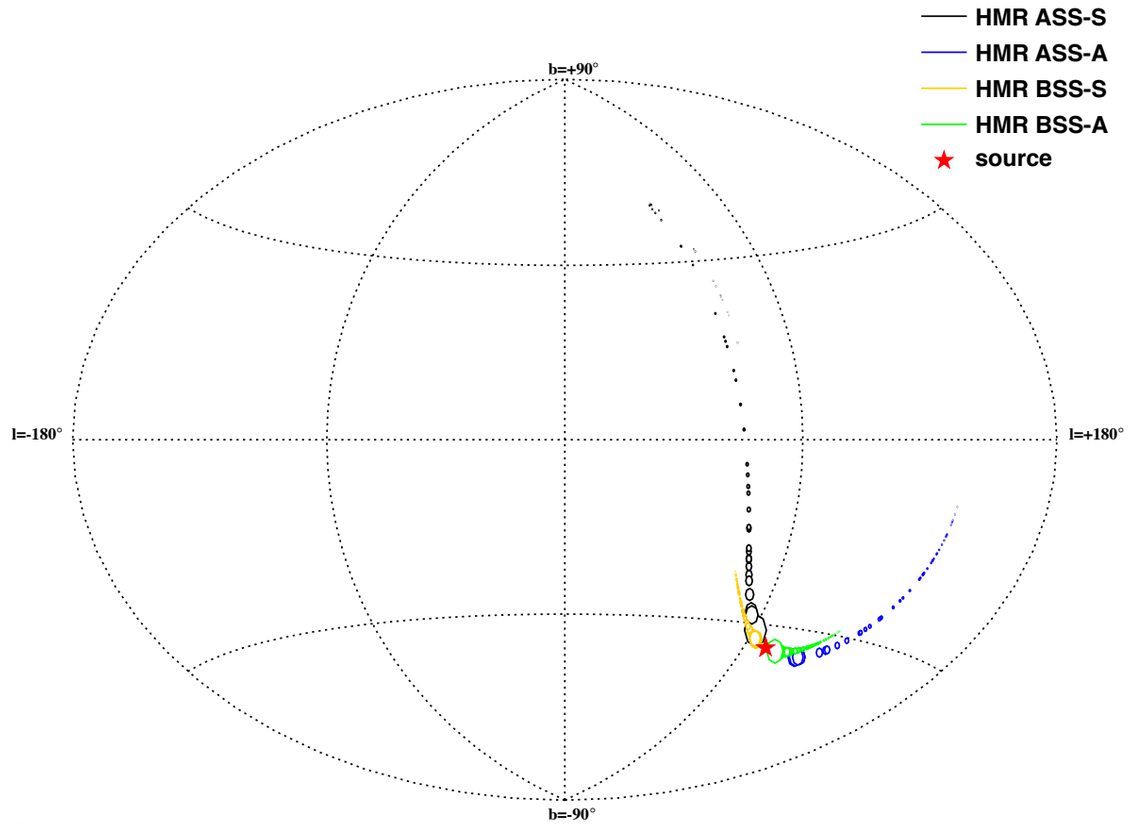
UHECRs and the galactic magnetic field

M. Zimbres, RAB, E. Kemp. Astropart. Phys. 54 (2014) 54. arXiv:1305.0523

RAB, M. Zimbres, E. Kemp. Physicae Proc. 1 (2012) 23. arXiv:1201.2183

- if galactic deflection dominate over extragalactic, can we reconstruct source position?





- no multiplets detected in Auger data *[Auger '12]*
- constrain models of GMF with multiplets?
- unlikely to be detected, unless source is really close and magnetic fields are "well-behaved"
- **cool idea: to use UHECR to measure/constrain cosmic magnetic fields**