searching for the sources of ultra-high-energy cosmic rays

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structure of this talk

introduction &
open questions

(UHECR acceleration by
IMBHs + WDs)

sources &
propagation

experiments &
state of the art

UHECR astronomy &
cosmic magnetic fields

source constraints with
neutrinos and photons

numerical
modelling

ultra-high energy cosmic rays

fundamental questions

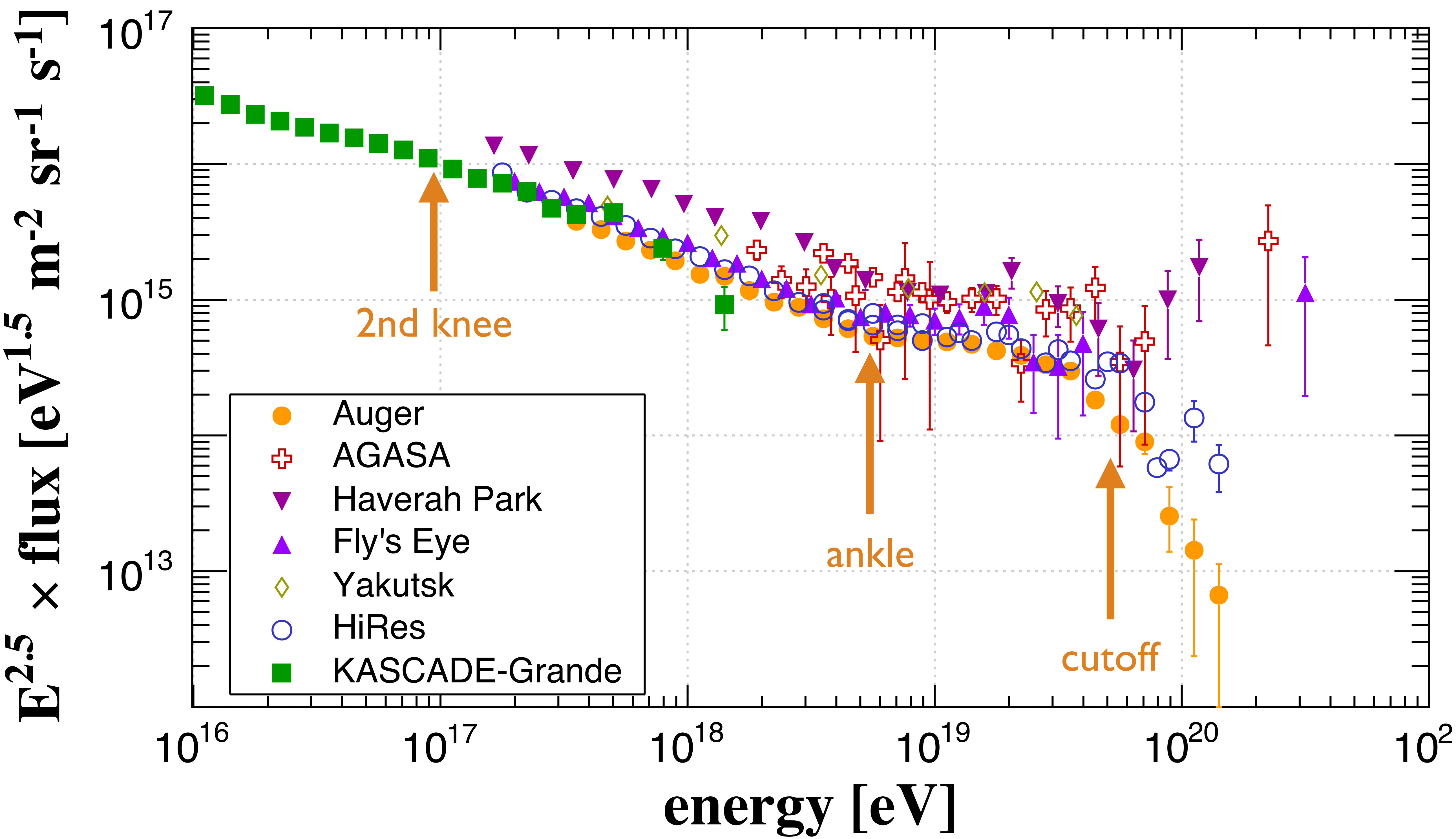
- where do they come from?
- what are they made of?
- how are they accelerated?

some problems

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

- observables from CR experiments: spectrum, composition, anisotropy
- cosmic magnetic fields (galactic and extragalactic) are important
- test new physics scenarios using UHECRs (?)

the cosmic ray spectrum



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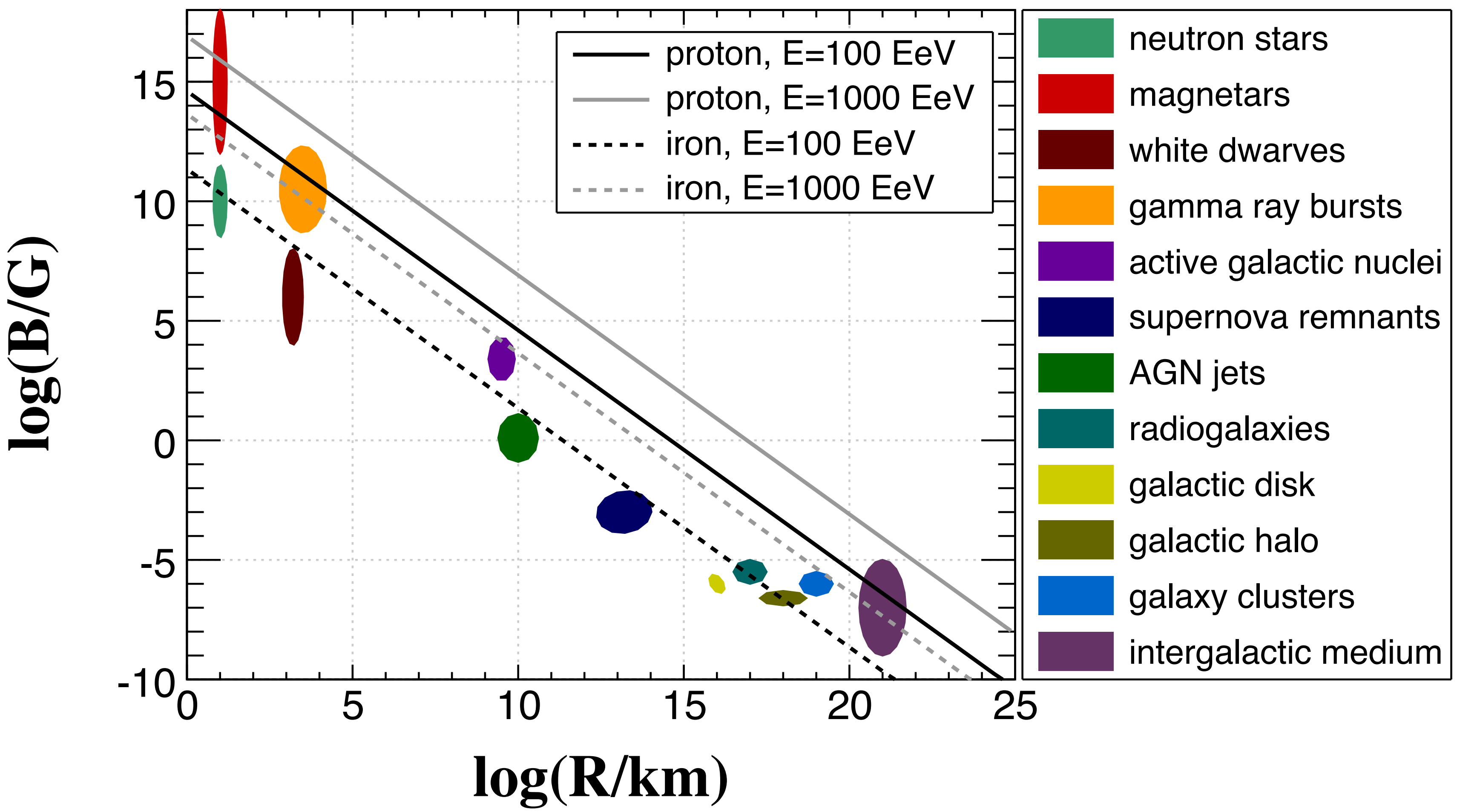
UHECR sources

- UHECR acceleration models: bottom-up and top-down
- the vast majority of **top-down** models were excluded by Auger measurements of the photon fraction
- **bottom-up**: educated guess for accelerator sites: Hillas condition

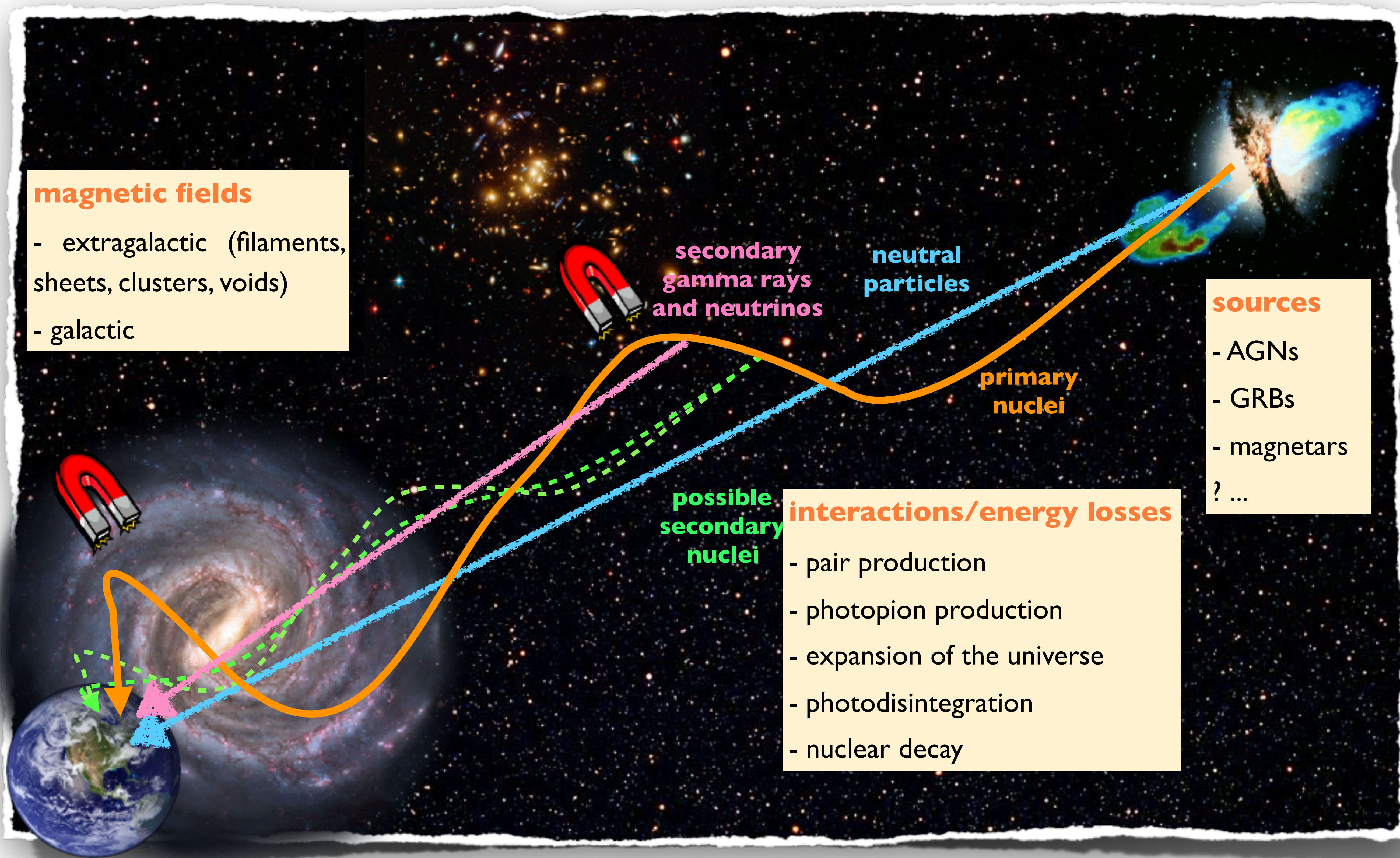
- Hillas criterion: Larmor radius should be smaller than accelerator size

$$E_{max} \approx 2\beta cZeBR_L$$

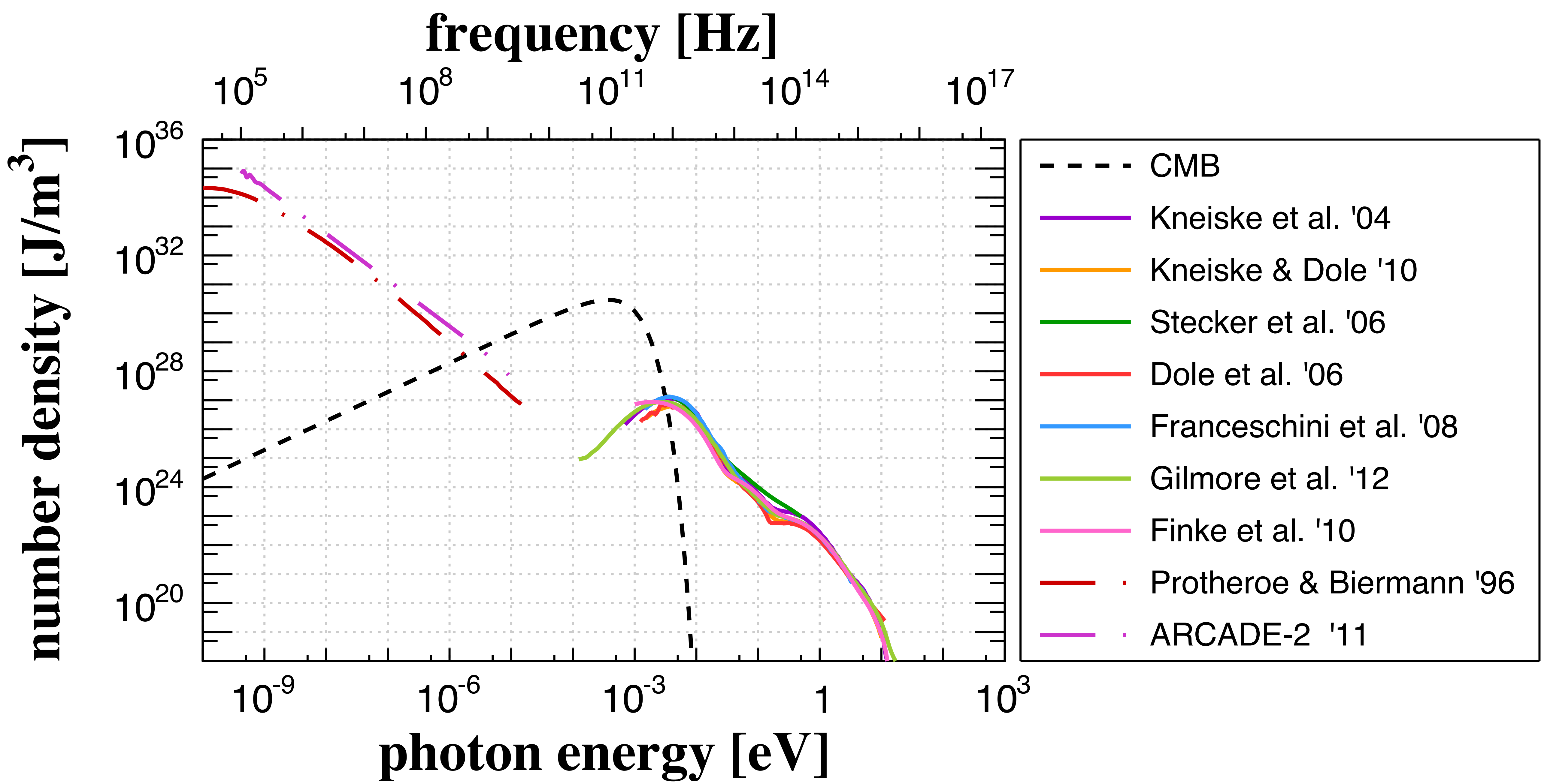
- acceleration mechanism affects energy spectrum
- "popular" candidates: AGNs, young pulsars, magnetars, TDEs



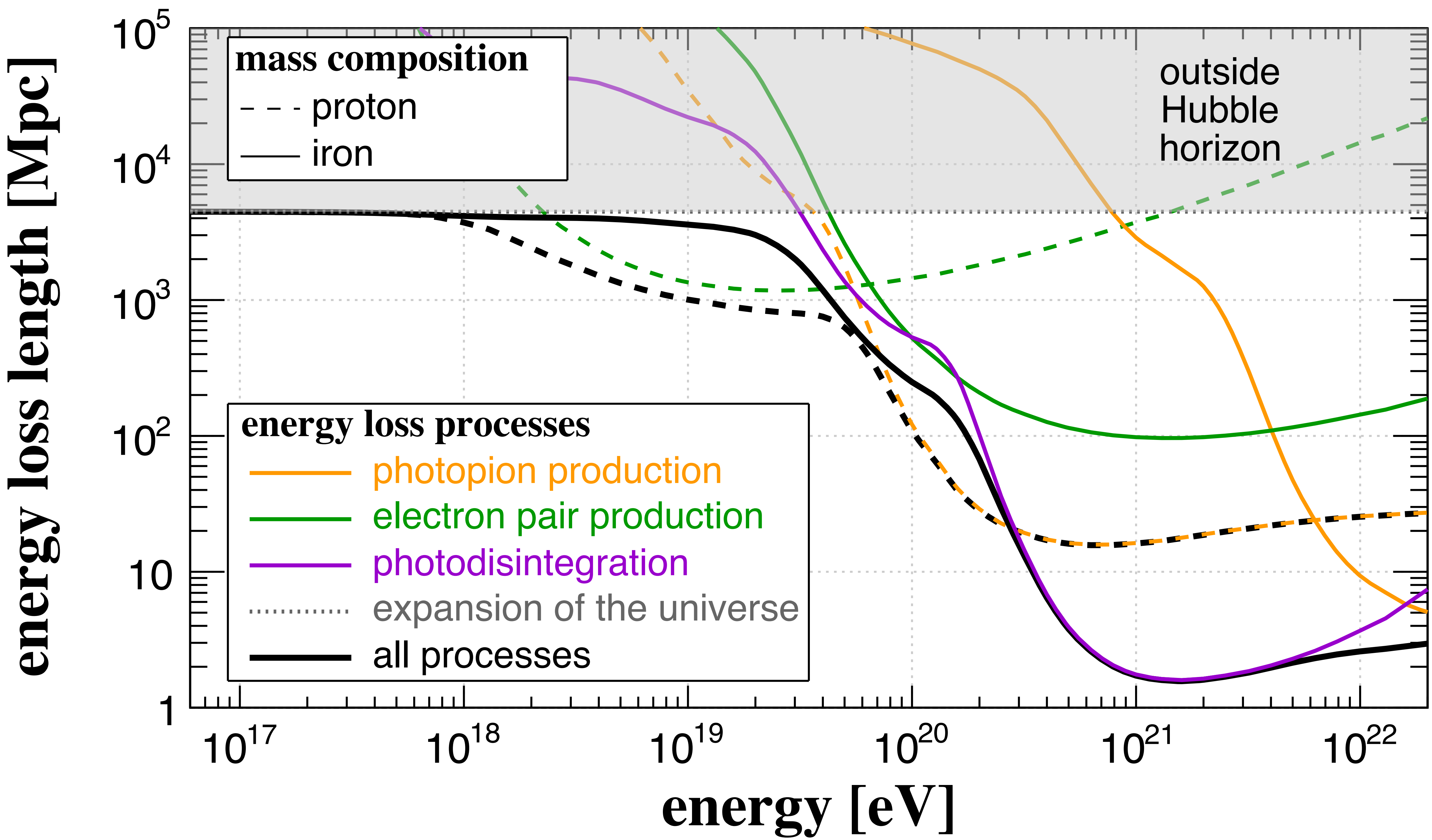
propagation picture



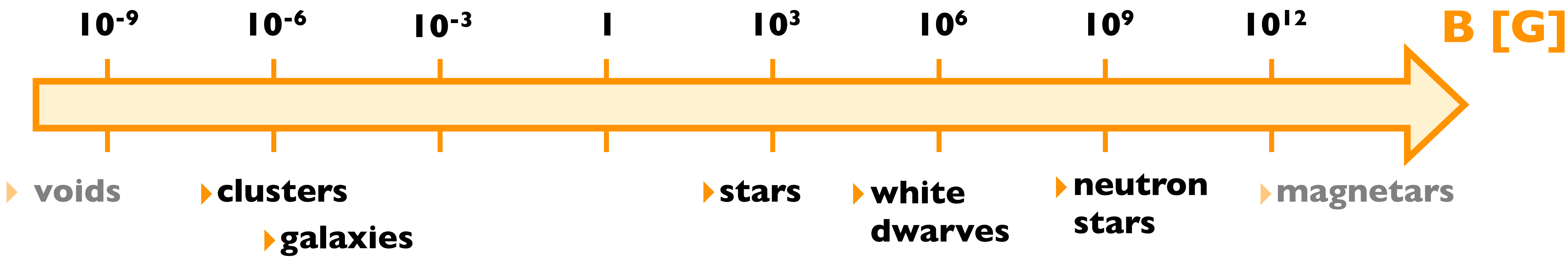
modelling the propagation of UHECRs: photon backgrounds



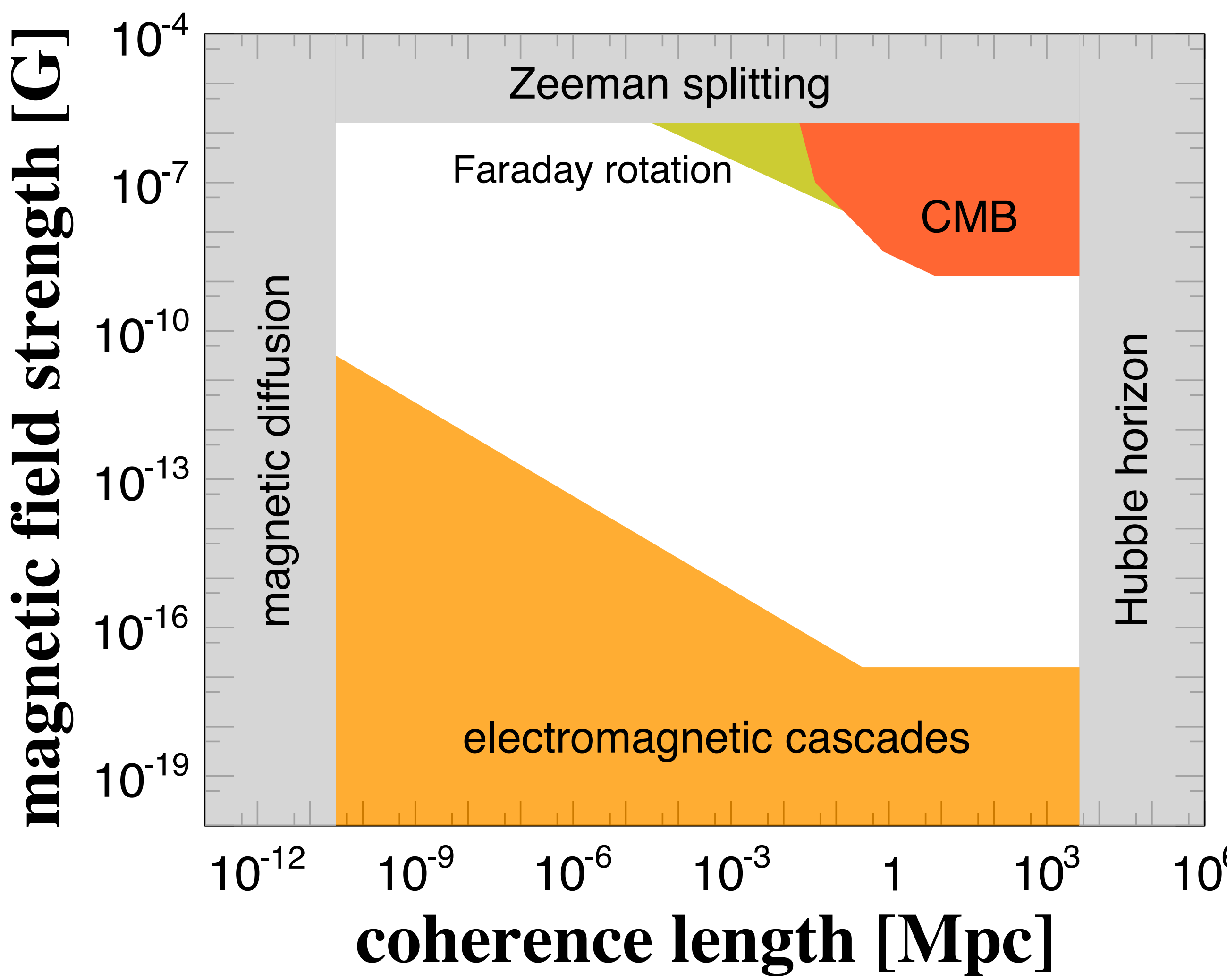
modelling the propagation of UHECRs: energy losses



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



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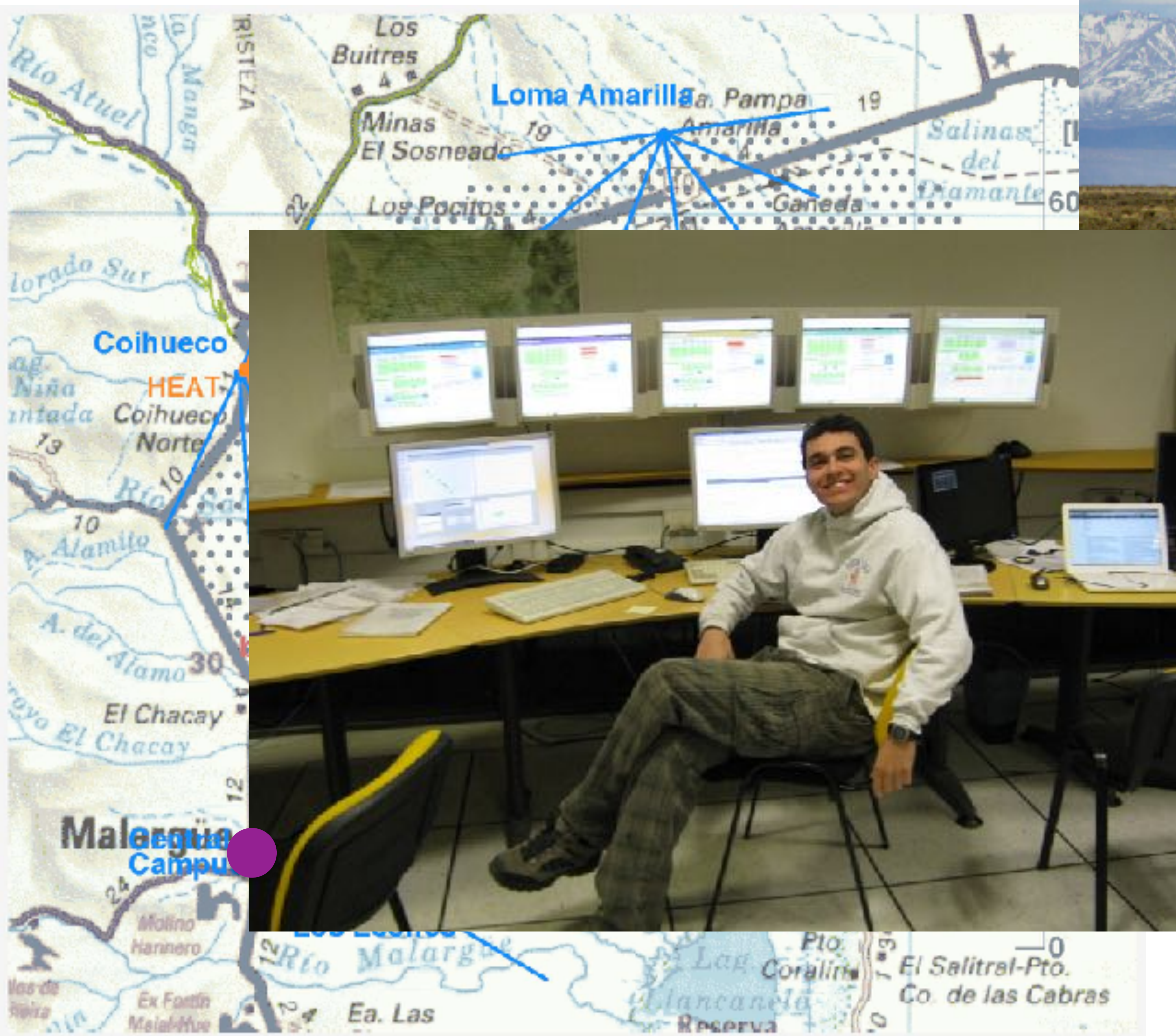
state of the art: Pierre Auger Observatory



surface detector

vatory in

fluorescence detector

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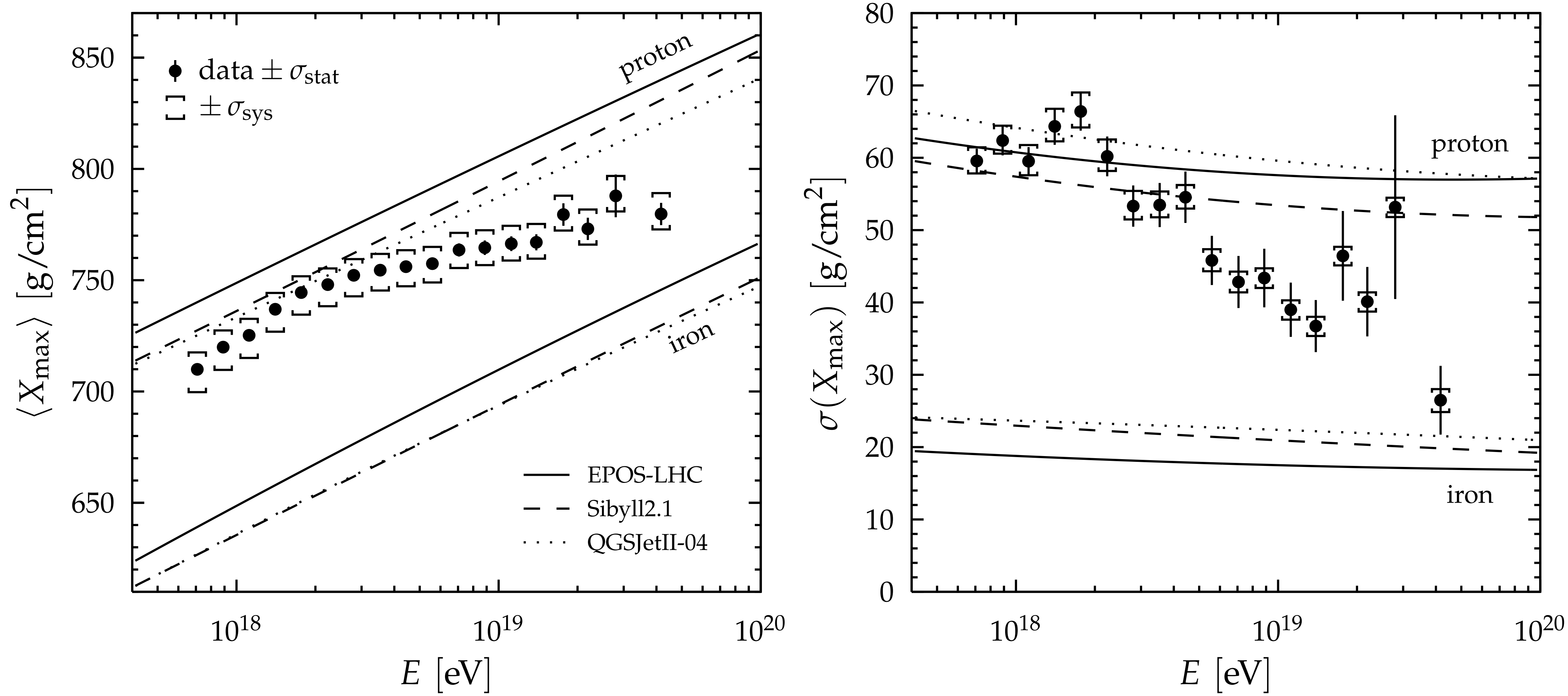
e)

ue

radio detector

what are UHECRs made of?

Pierre Auger Collaboration. PRD 90 (2014) 122005.
arXiv:1409.4809

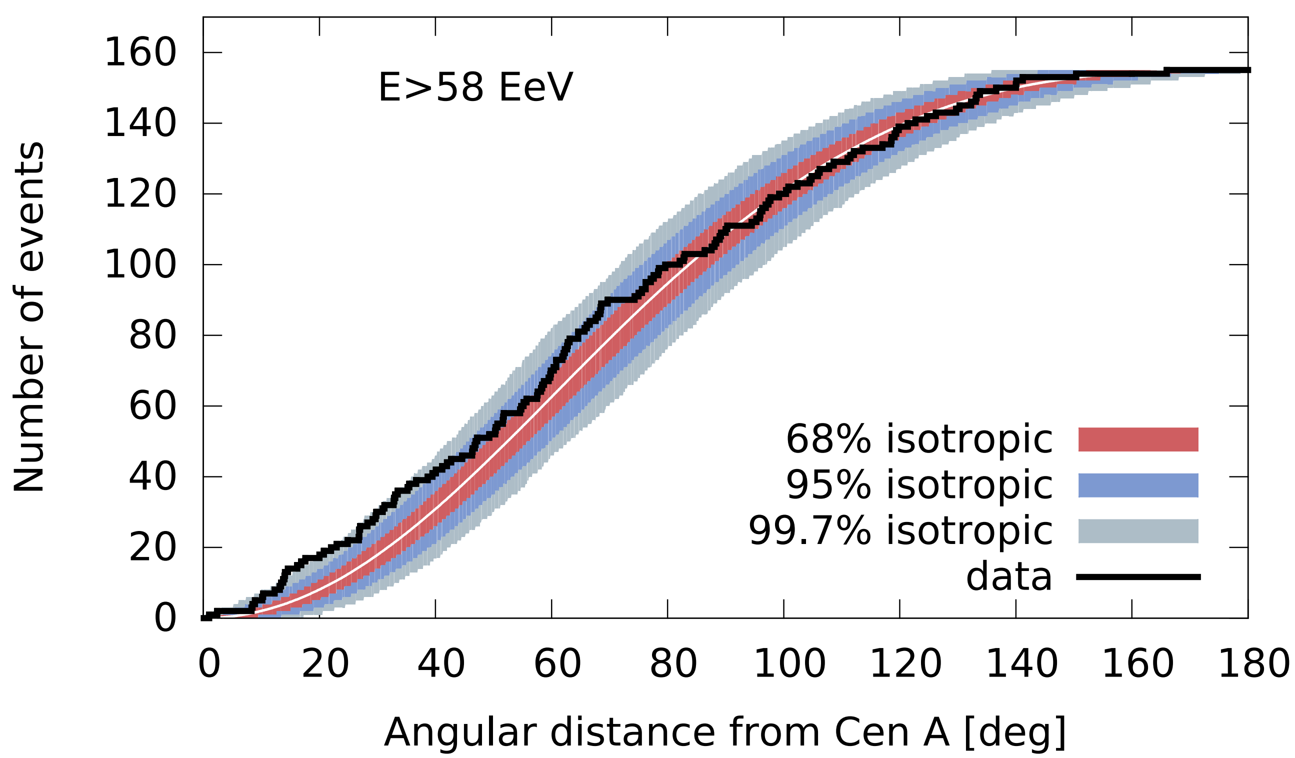


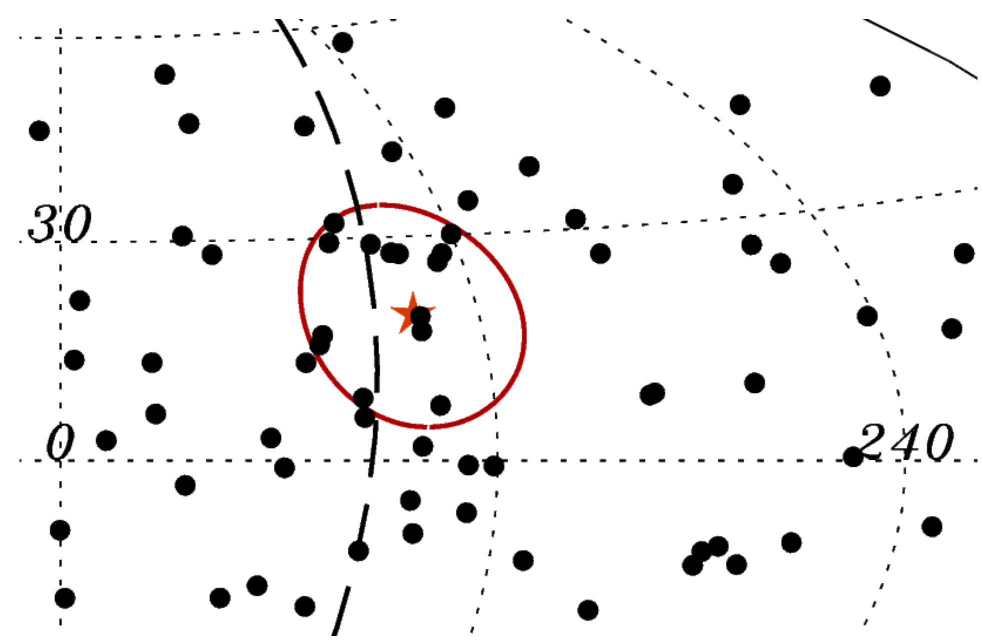
- UHECRs are very likely atomic nuclei
- showers are reconstructed assuming hadronic interaction models, which are based on extrapolation of accelerator data
- New Physics in air showers?
- direct implication: high-energy cutoff implies probably no or small GZK effect

what are the sources of UHECRs?

Pierre Auger Collaboration. ApJ 804 (2015) 15.
arXiv:1411.6111

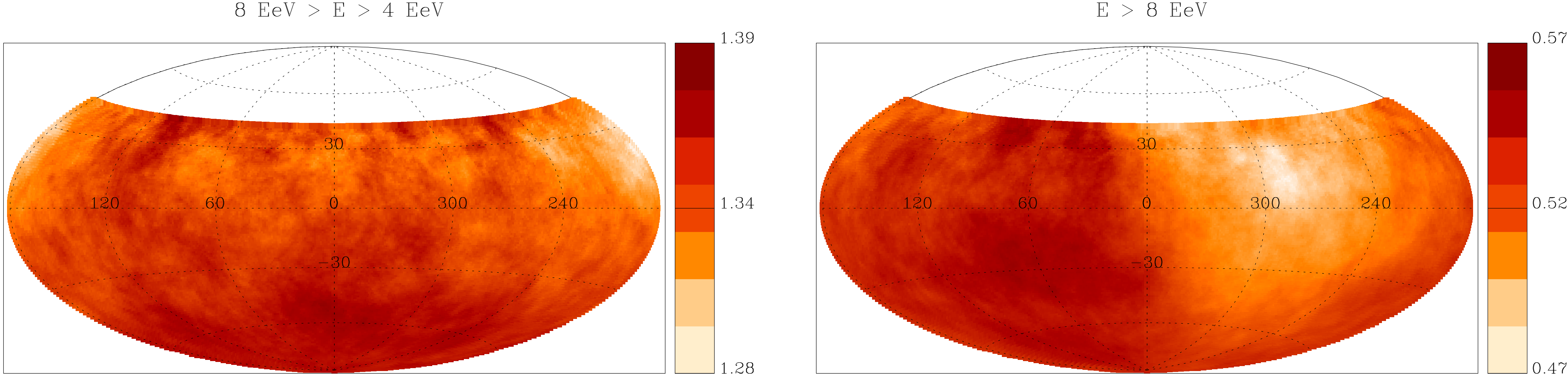
Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	$\mathscr{L}_{min}$ [erg/s]	f_{min}	$\mathscr{P}$
2MRS Galaxies	52	9	90	-	1.5×10^{-3}	24%
Swift AGNs	58	1	80	-	6×10^{-5}	6%
Radio galaxies	72	4.75	90	-	2×10^{-4}	8%
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	72	4.75	90	$10^{39.33}$	5.1×10^{-5}	11%
Centaurus A	58	15	-	-	2×10^{-4}	1.4%



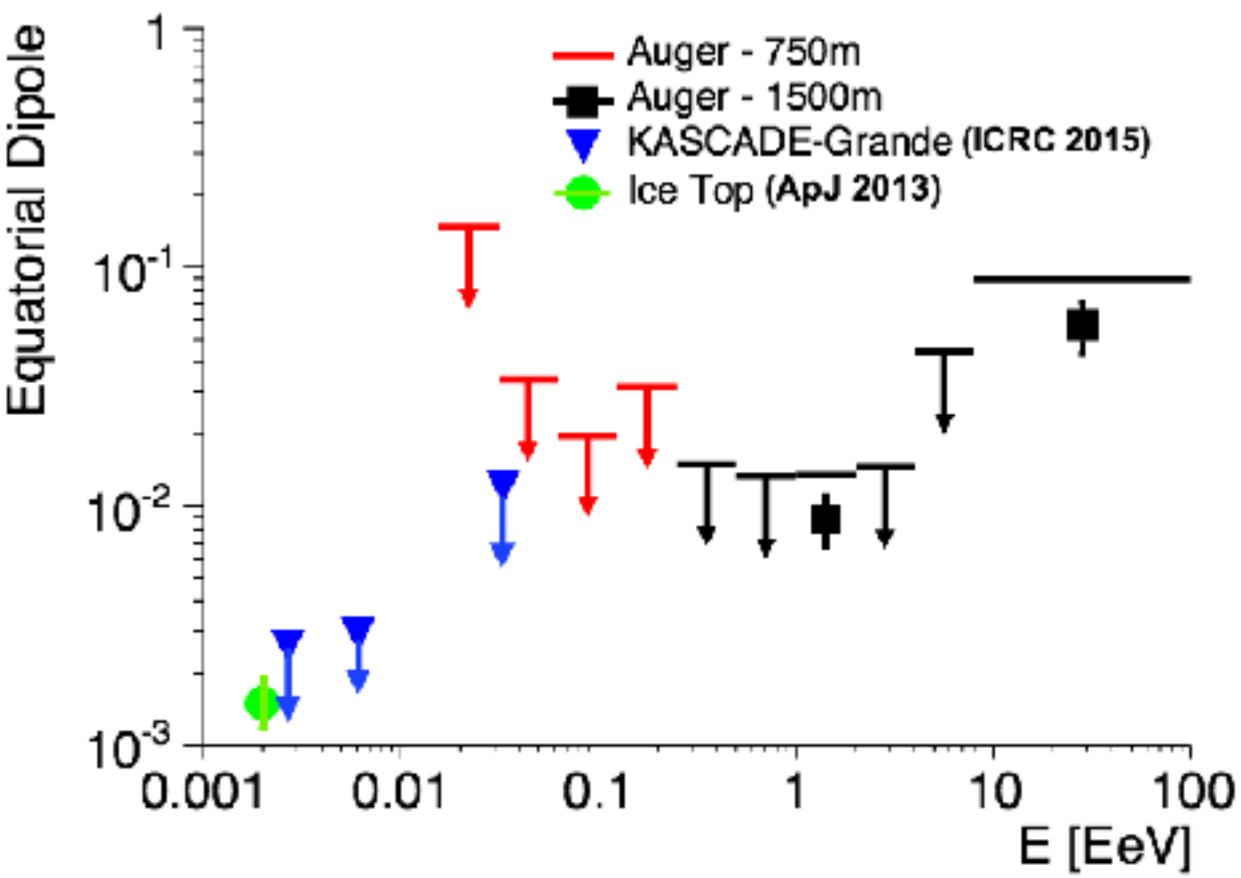


what are the sources of UHECRs?

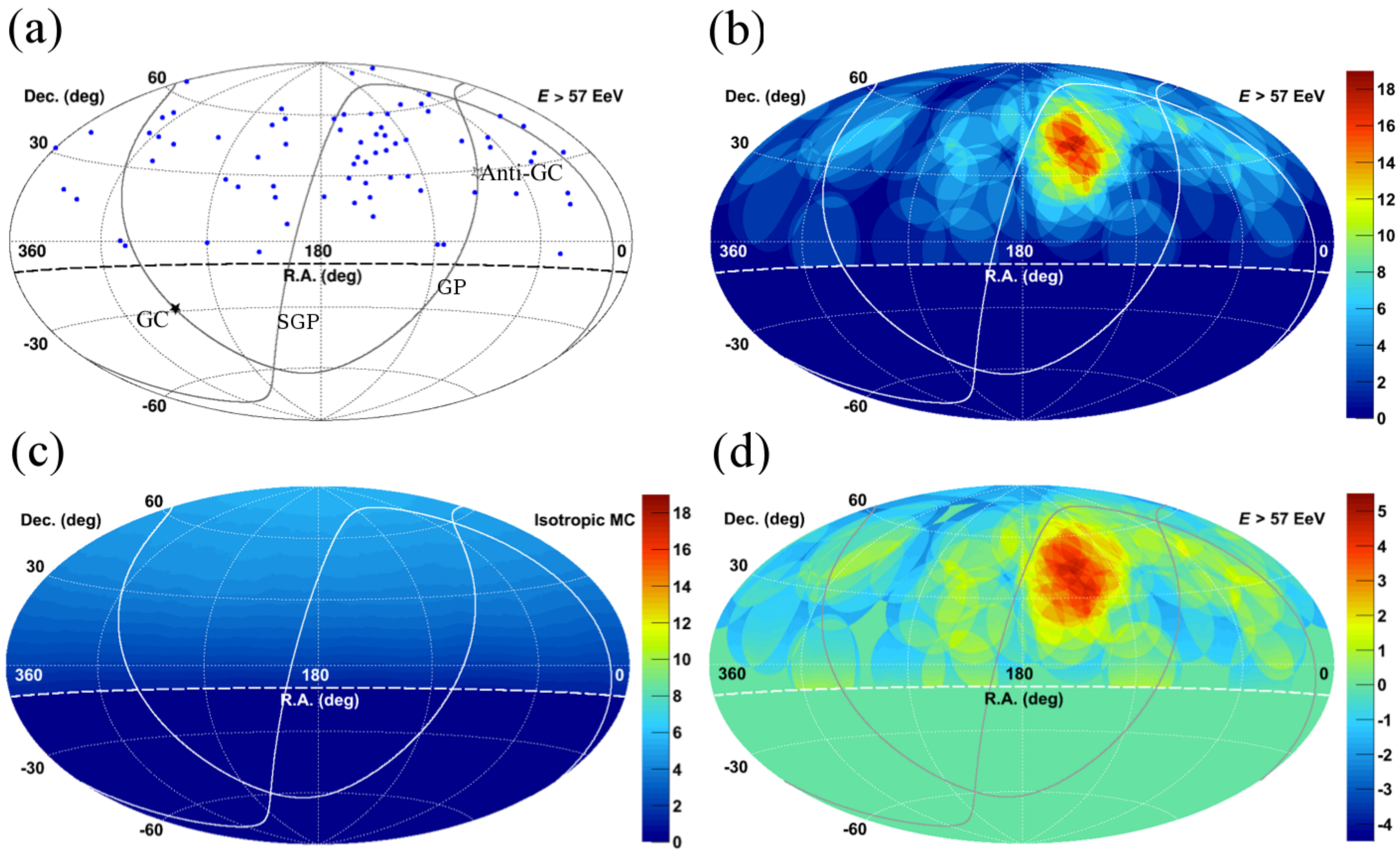
Pierre Auger Collaboration. ApJ 802 (2015) 111. arXiv:1411.6953



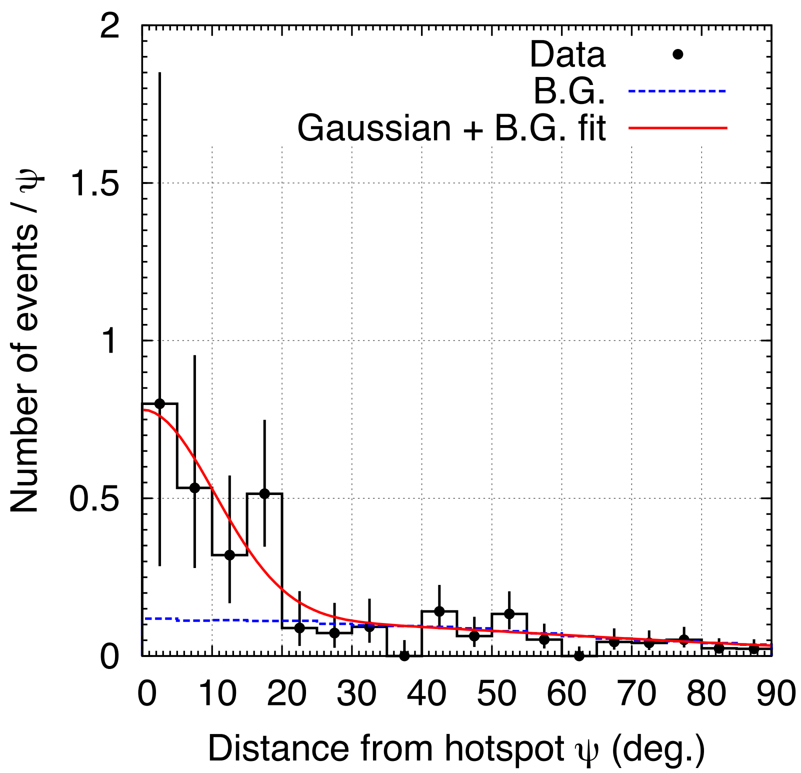
- dipolar anisotropy ~a few percent
- dipolar anisotropy could be a result of diffusive propagation of UHECRs in turbulent magnetic fields
- source distribution may also cause similar pattern



what are the sources of UHECRs?



Telescope Array Collaboration. ApJL 790 (2014) L21.
arXiv:1404.5890



- hotspot detected with significance 3.4σ
- no sources nearby
- excess near supergalactic plane, which contains e.g. Ursa Major, Virgo and Coma cluster
- distance to Ursa Major cluster ~ 19 degrees

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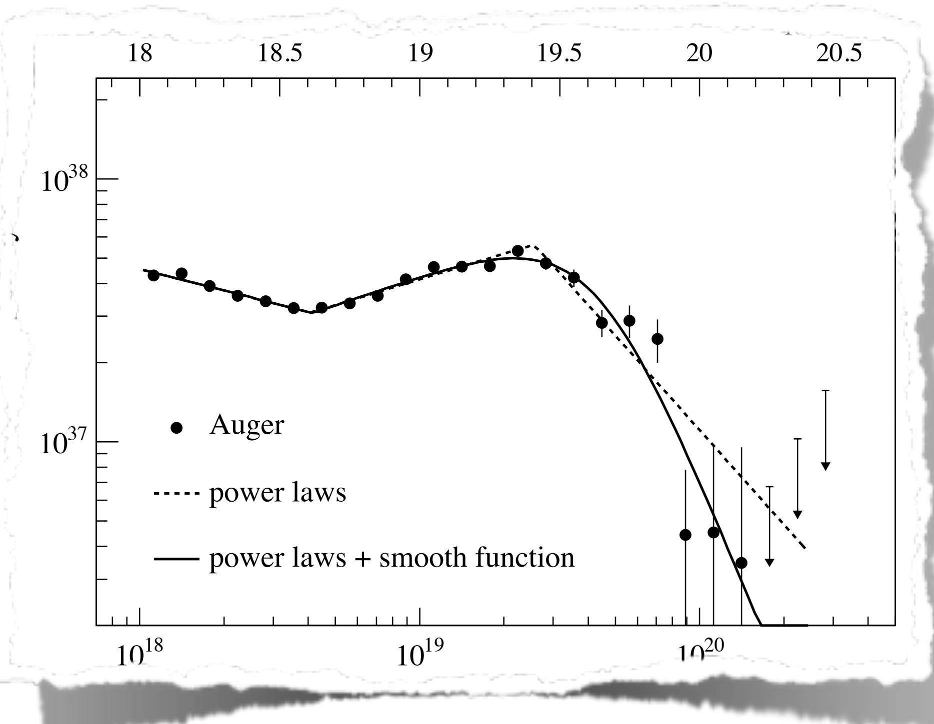
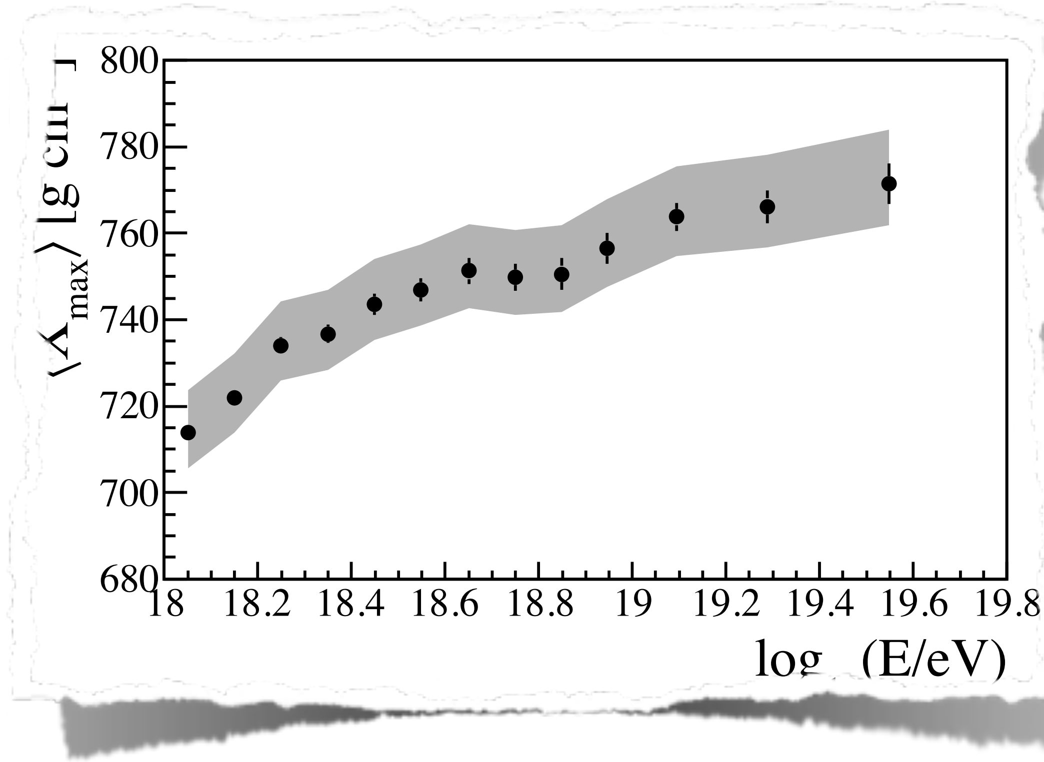
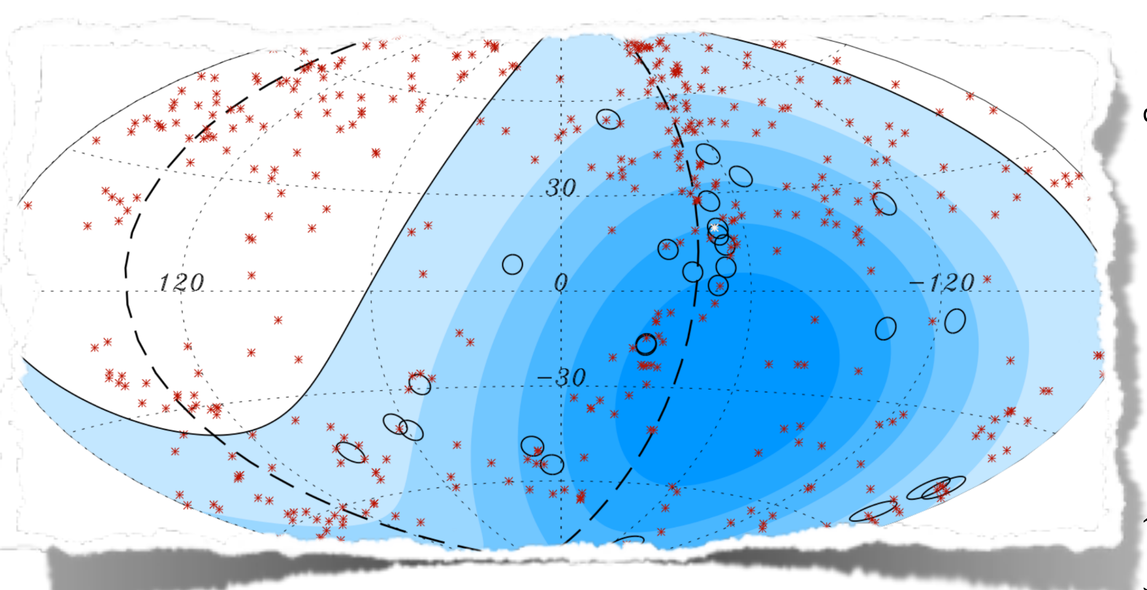
modelling the propagation of UHECRs



Pierre Auger Collaboration. ICRC 2011.



Pierre Auger Collaboration. JCAP 02 (2013) 026.



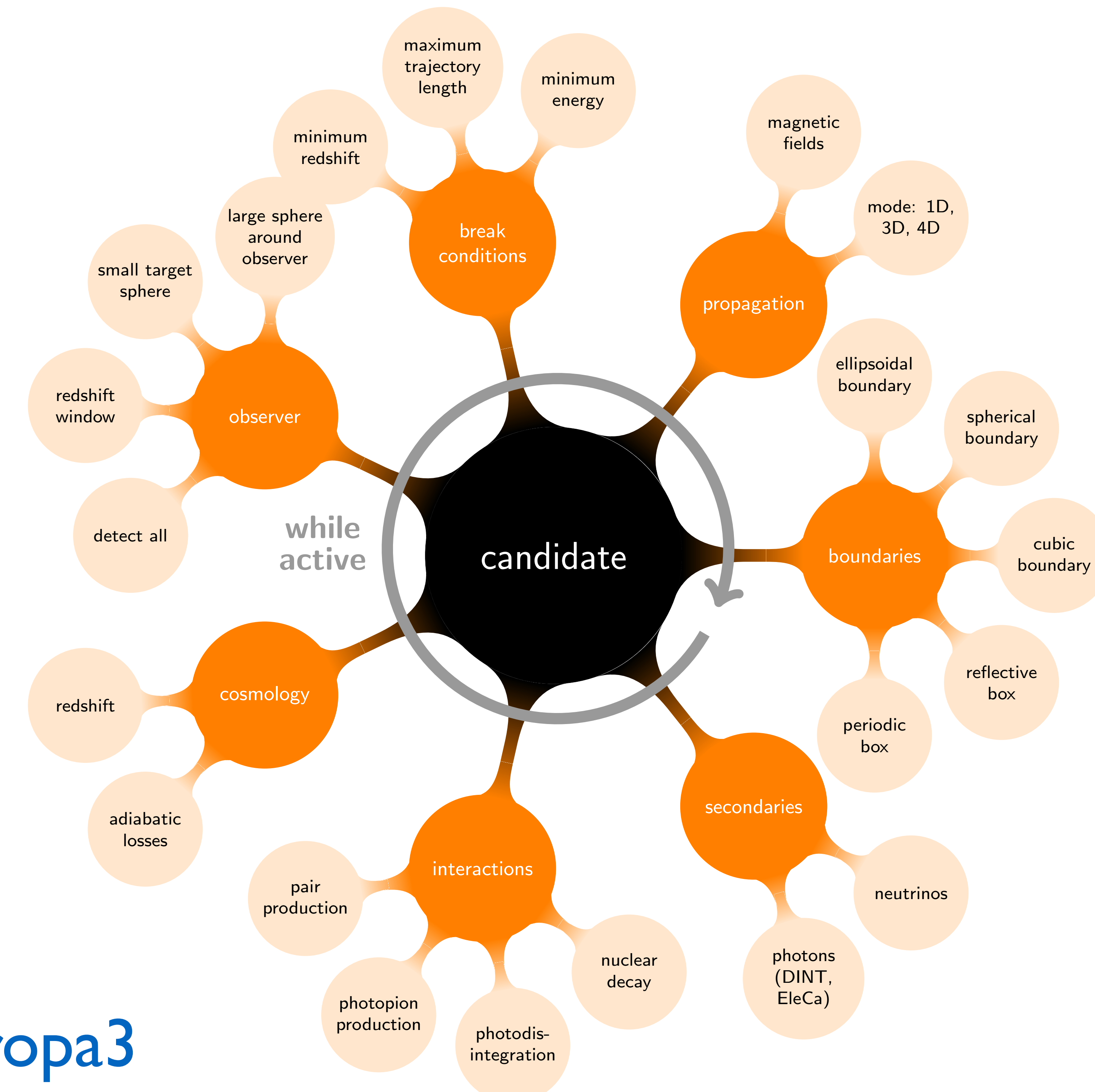
Pierre Auger Collaboration. Science 318 (2007) 938.

- explain these three observables
- explain also gamma ray and neutrino counterparts
- magnetic fields and source distribution may affect spectrum and composition, and certainly affect anisotropy
- 3D simulations are needed
- large parameter space → fast simulations

modelling the propagation of UHECRs: CRPropa

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

- 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 neutrinos fluxes



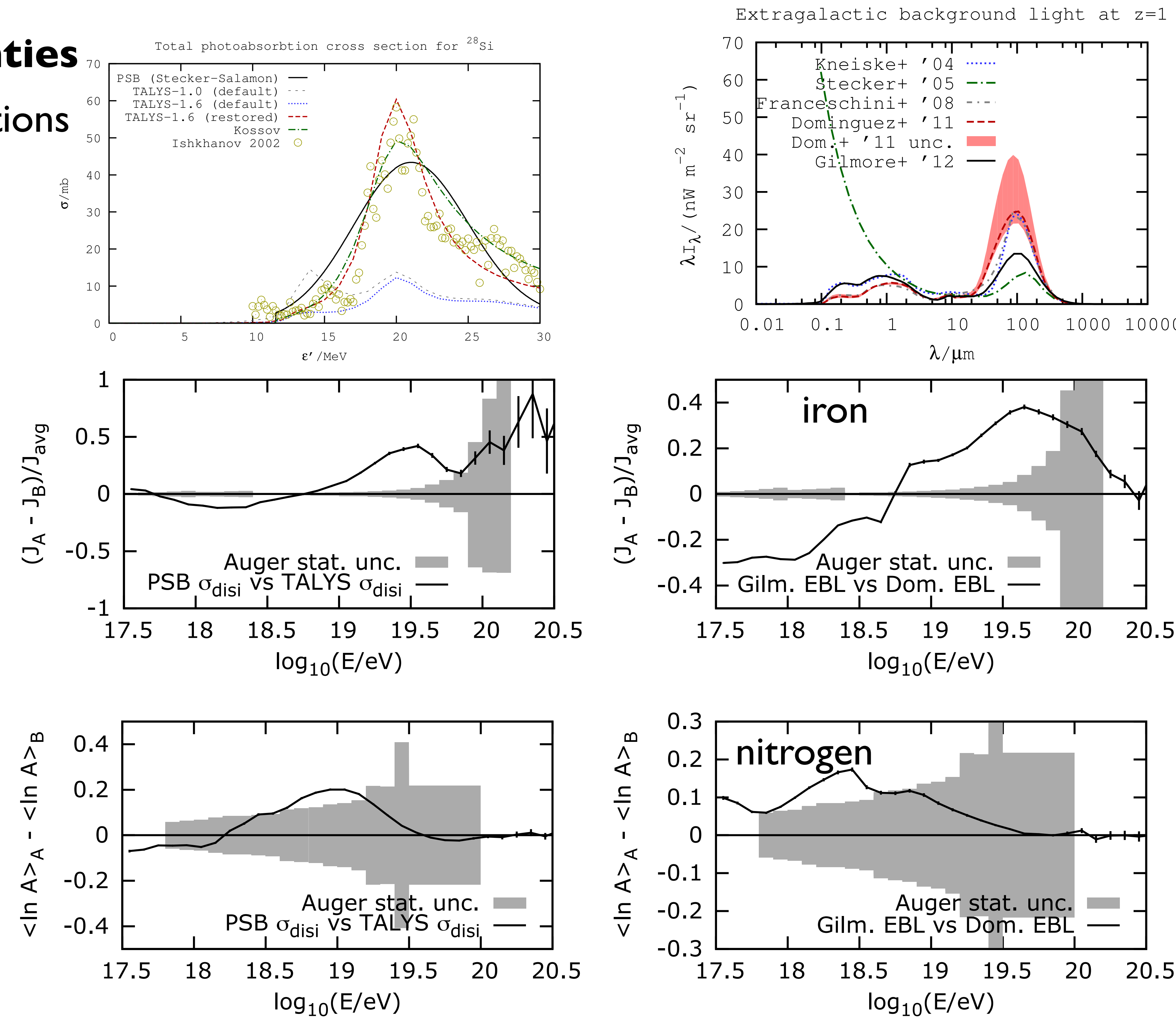
https://github.com/CRPropa/CRPropa3

theoretical uncertainties in the modelling

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

main sources of uncertainties

- photodisintegration cross sections
- EBL model
- propagation codes



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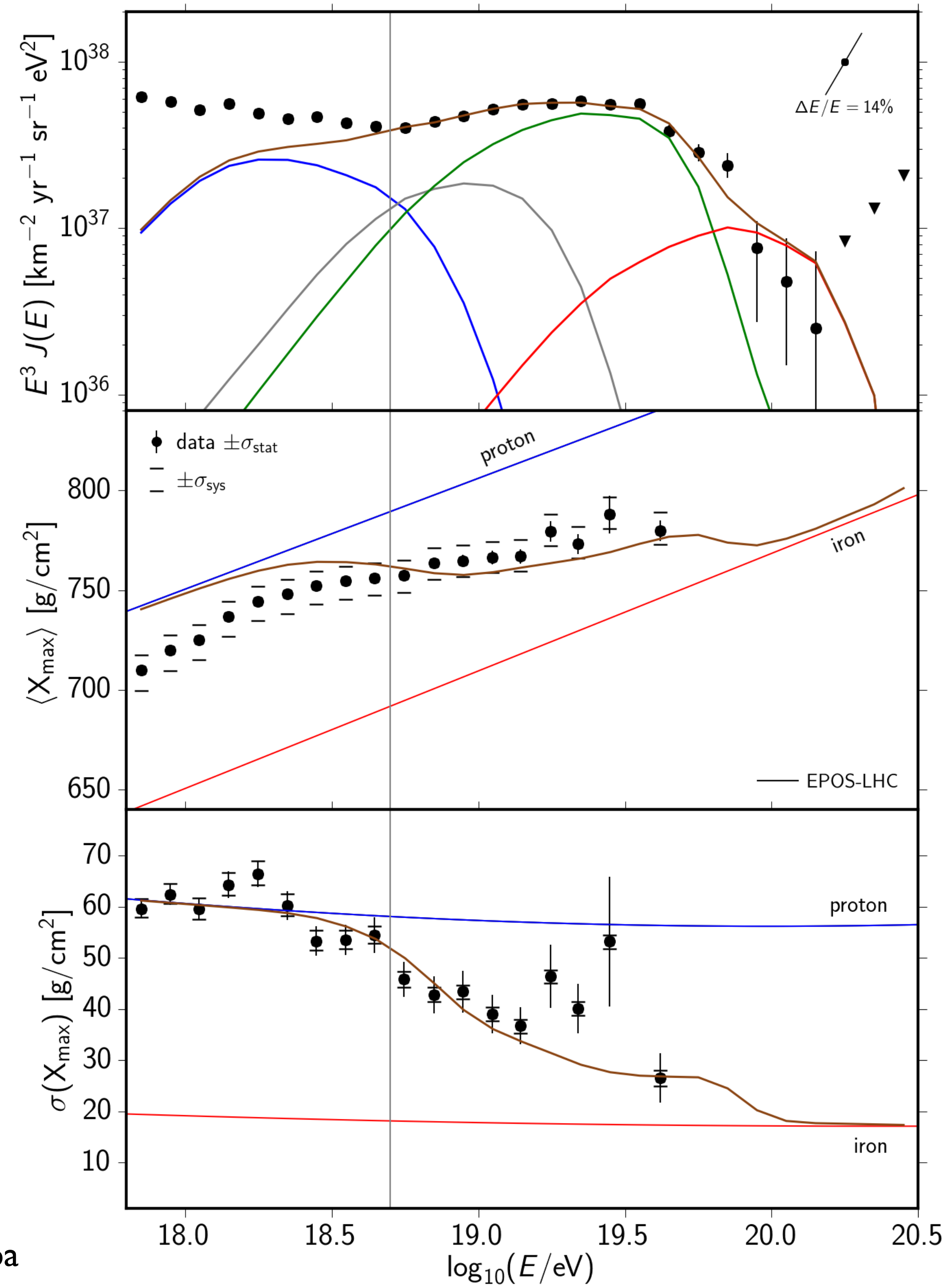
combined spectrum-composition fits

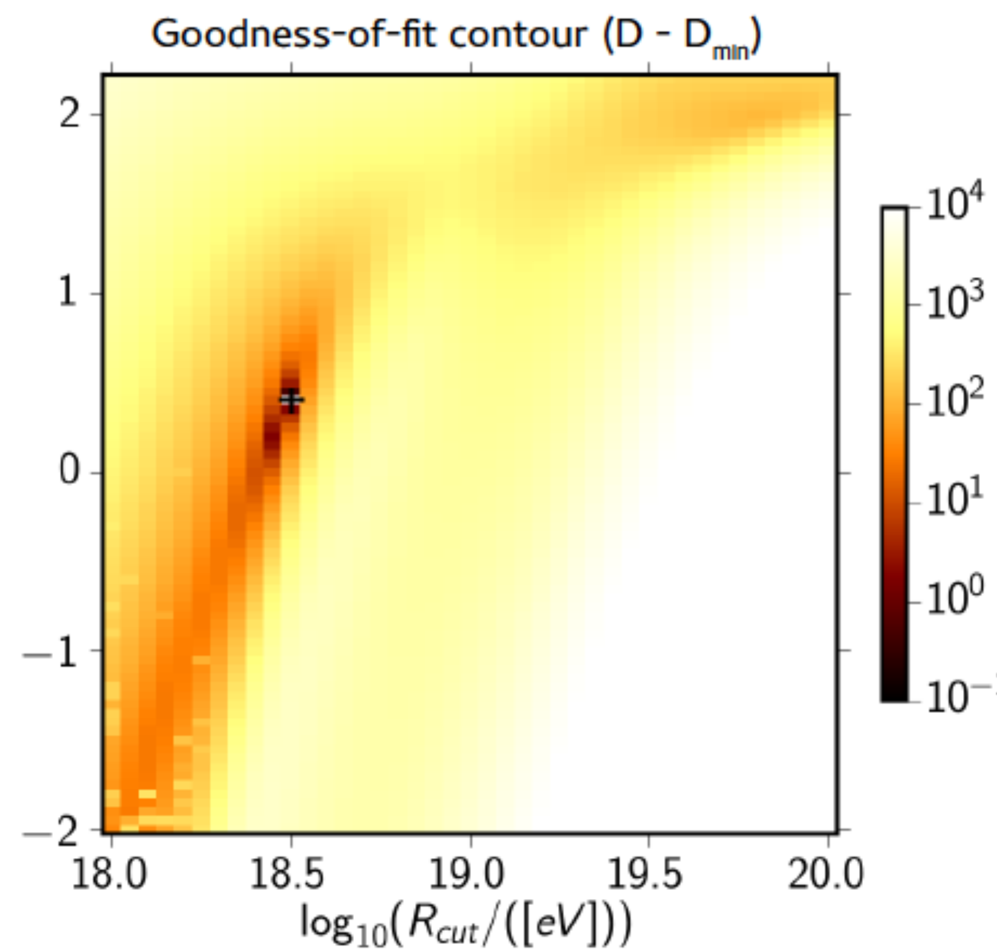


CRPropa

Kneiske '04 EBL model

TALYS cross sections for PD

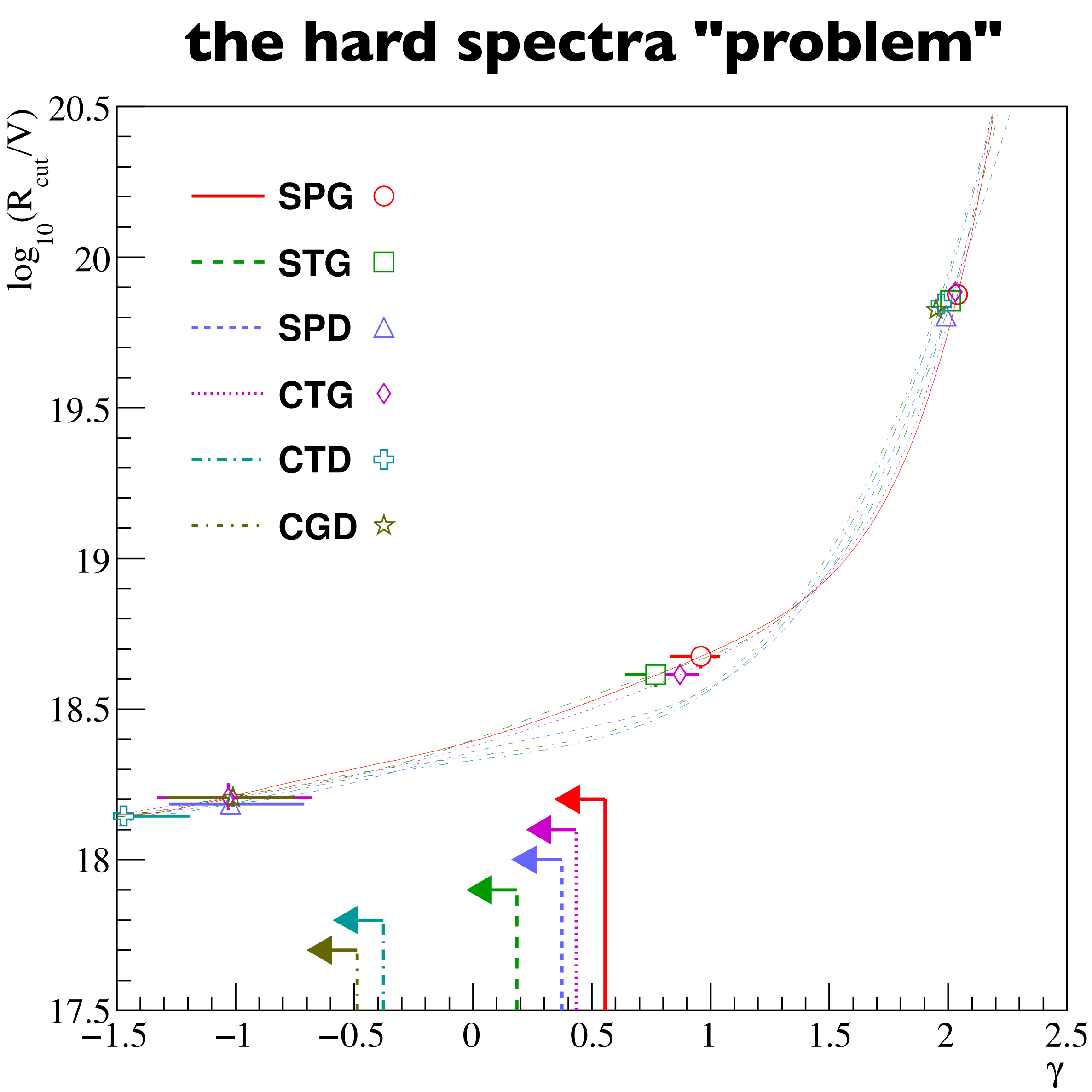
A. di Matteo+ (Pierre Auger Collaboration). ICRC 2015 Proceedings. arXiv:1509.03732



- $\log(R_{cut}/V)$ = 18.48
- γ = 0.29 (+0.08 | -0.07)
- fraction of H: 14.3% (+4.2 | -14.2)
- fraction of He: 10.0% (+2.2 | -10.0)
- fraction of N: 75.3% (+15.5 | -9.4)
- fraction of Fe: 0.5% (+0.1 | -0.1)

combined spectrum-composition fits

Pierre Auger Collaboration. . JCAP 04 (2017) 038. arXiv:1612.07155



- magnetic horizon effects might soften the hard spectra, making it again compatible with Fermi shock acceleration *[Mollerach & Roulet '13]*
- magnetic horizon effects do not play a role at EeV energies in realistic extragalactic magnetic field models *[RAB & Sigl '14]*
- caveat I: hadronic interaction models can fail to describe interactions at the highest energies (e.g. muon problem *[Auger '14]*)
- caveat II: source distribution, magnetic field model, nearby sources, etc → shape of the spectrum is sensitive to these parameters *[Mollerach & Roulet '13; RAB & Sigl '14; Unger+ '15]*

multi-messenger constraints on sources

some typical processes

$$p + \gamma \rightarrow p + e^{+} + e^{-}$$

$$p + \gamma \rightarrow p + \pi^{0}$$

$$p + \gamma \rightarrow n + \pi^{+}$$

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

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

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

$$\pi^{0} \rightarrow 2\gamma$$

neutrinos

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$n \rightarrow p + e^{-} + \bar{\nu}_{e}$$

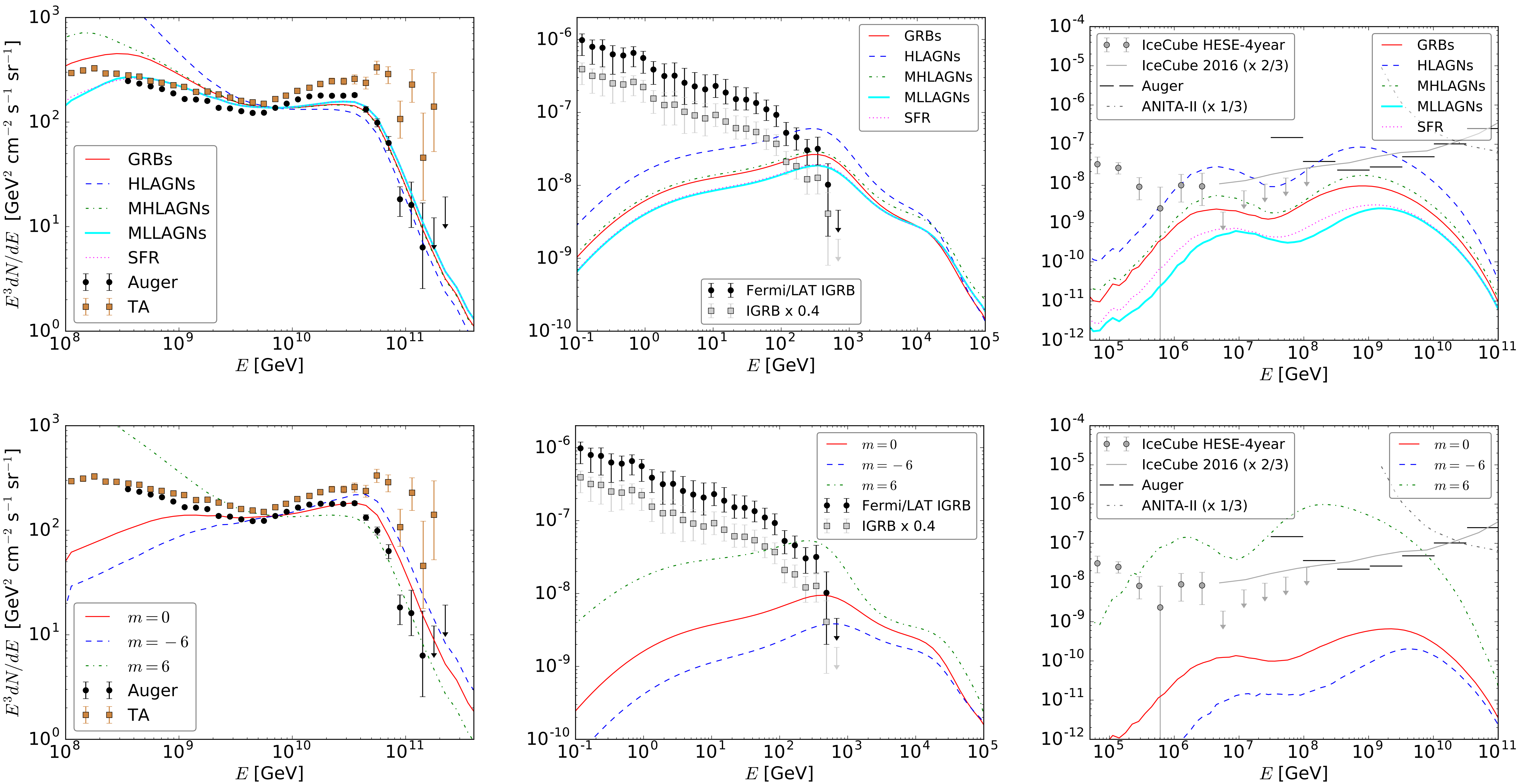
$$e^{+} + e^{-} \rightarrow \gamma$$

photons

UHECR constraints with neutrinos and photons

preliminary

A. van Vliet, J. Hörandel, RAB. Proceedings ICRC2017

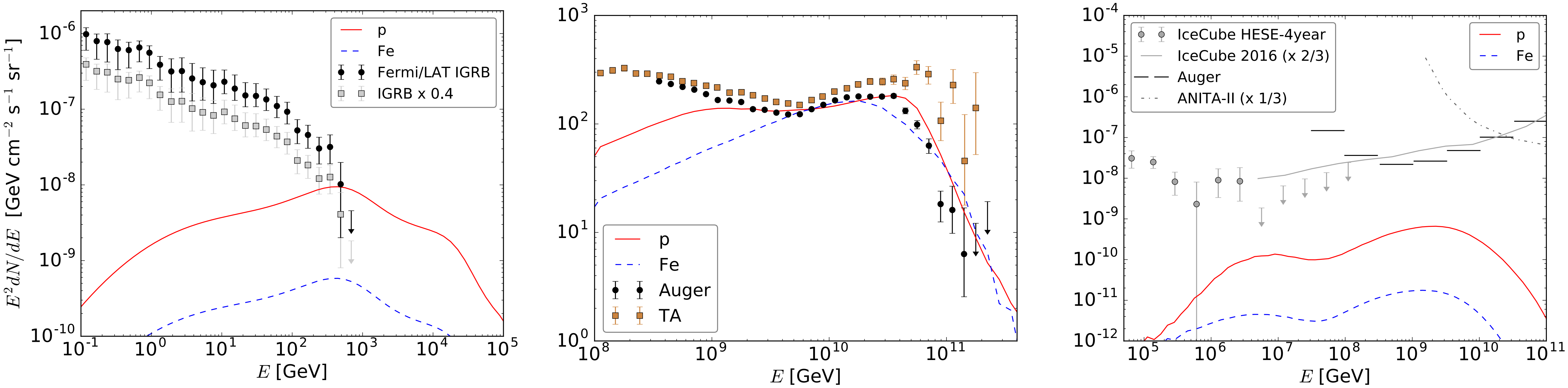


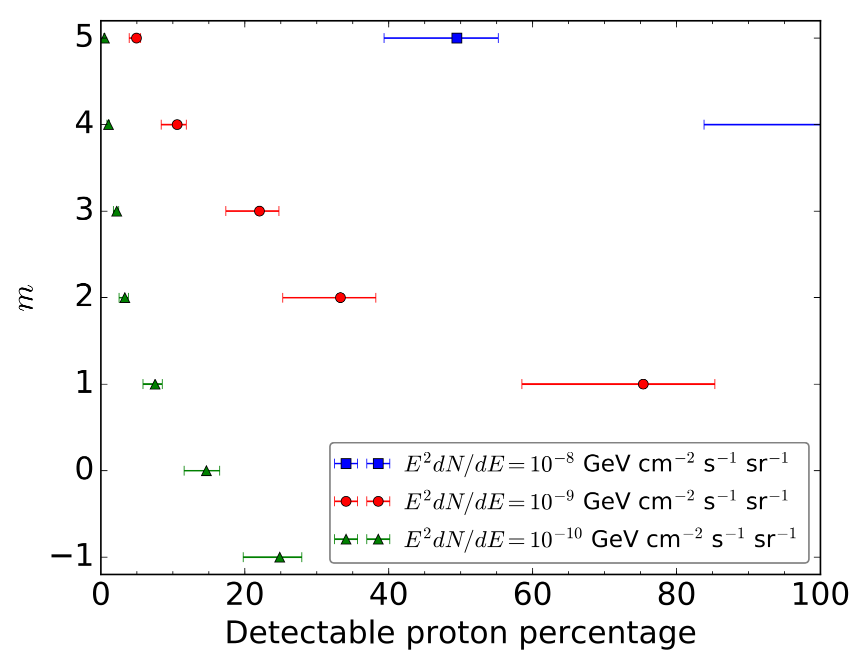
pure proton scenarios

evolution $(1+z)^m$

UHECR constraints with neutrinos and photons

A. van Vliet, J. Hörandel, RAB. Proceedings ICRC2017





- 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

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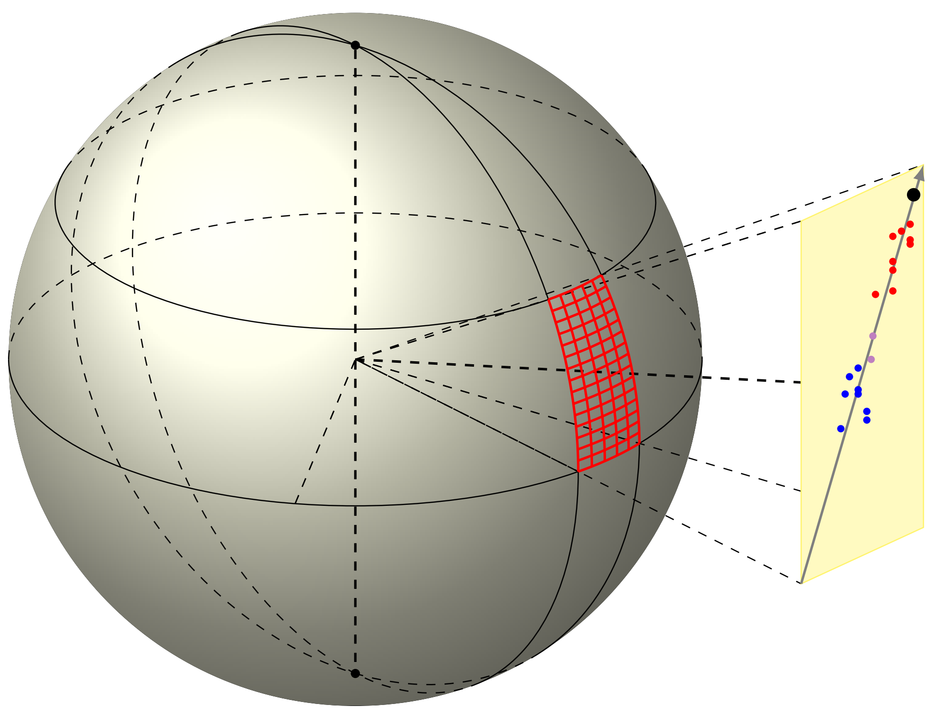
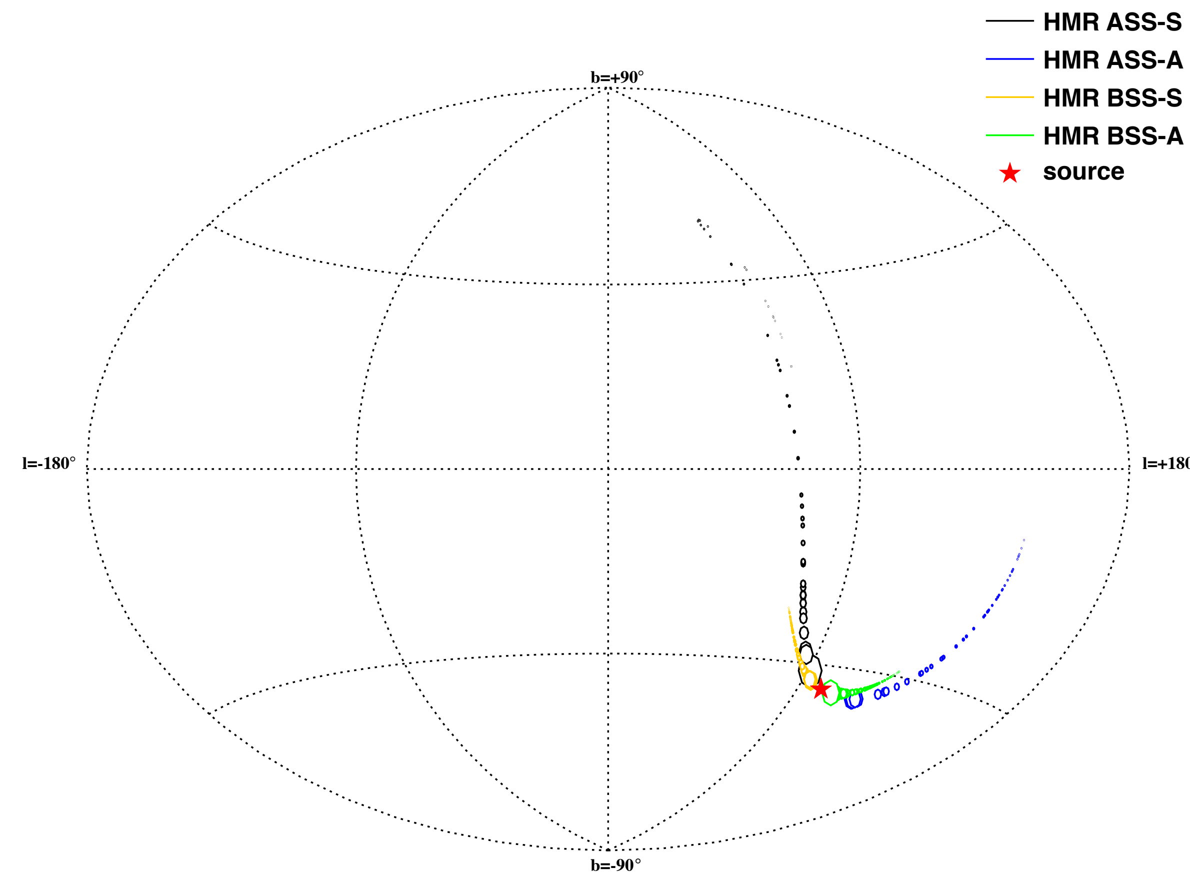
UHECRs and the galactic magnetic field

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?

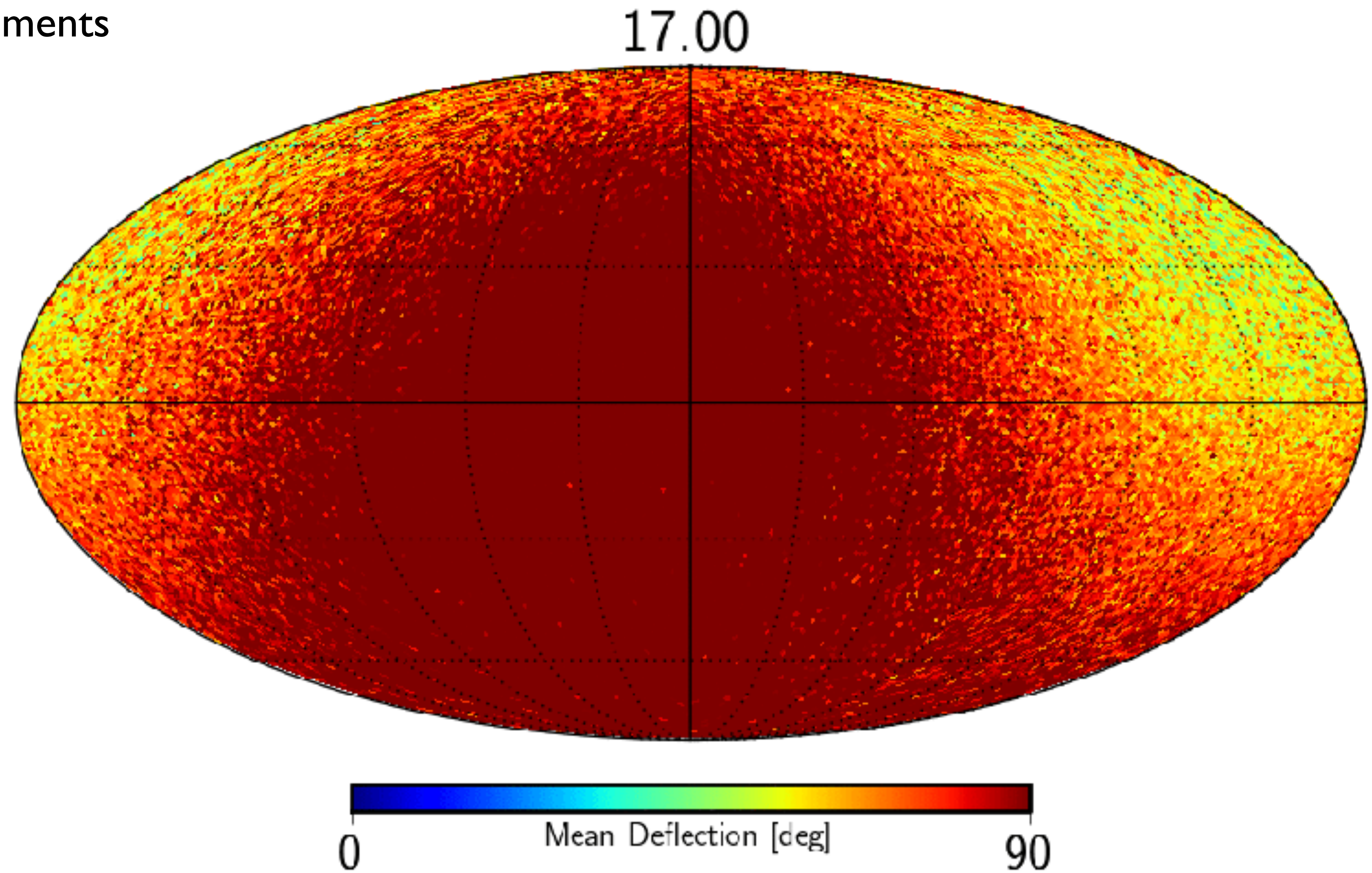




- no multiplets detected in Auger data *[Auger '12]*
- constrain models of GMF with multiplets?
- probably unlikely to be detected, unless source is really close and magnetic fields are "well-behaved"

UHECRs and the galactic magnetic field

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

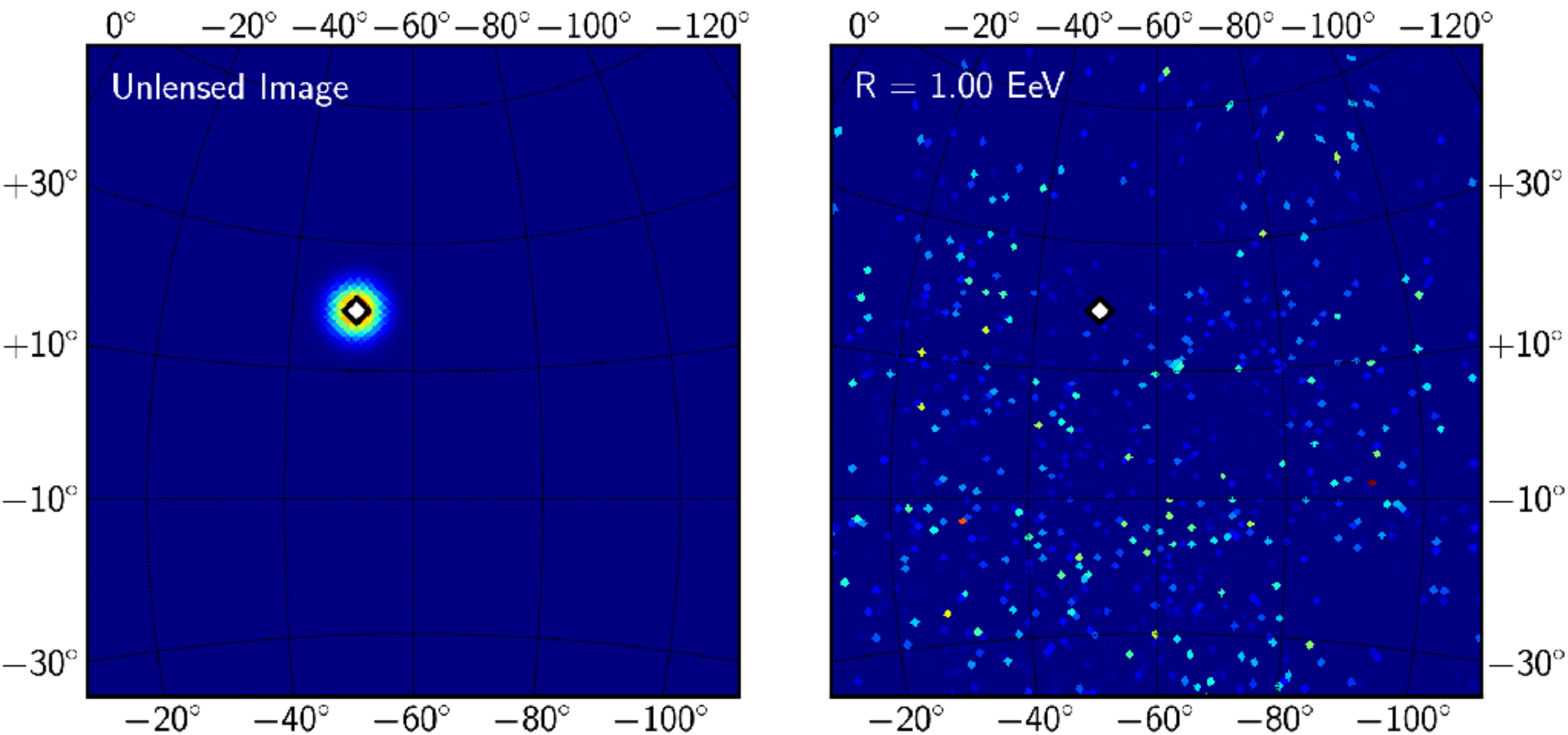


obtained with the PARSEC code:

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

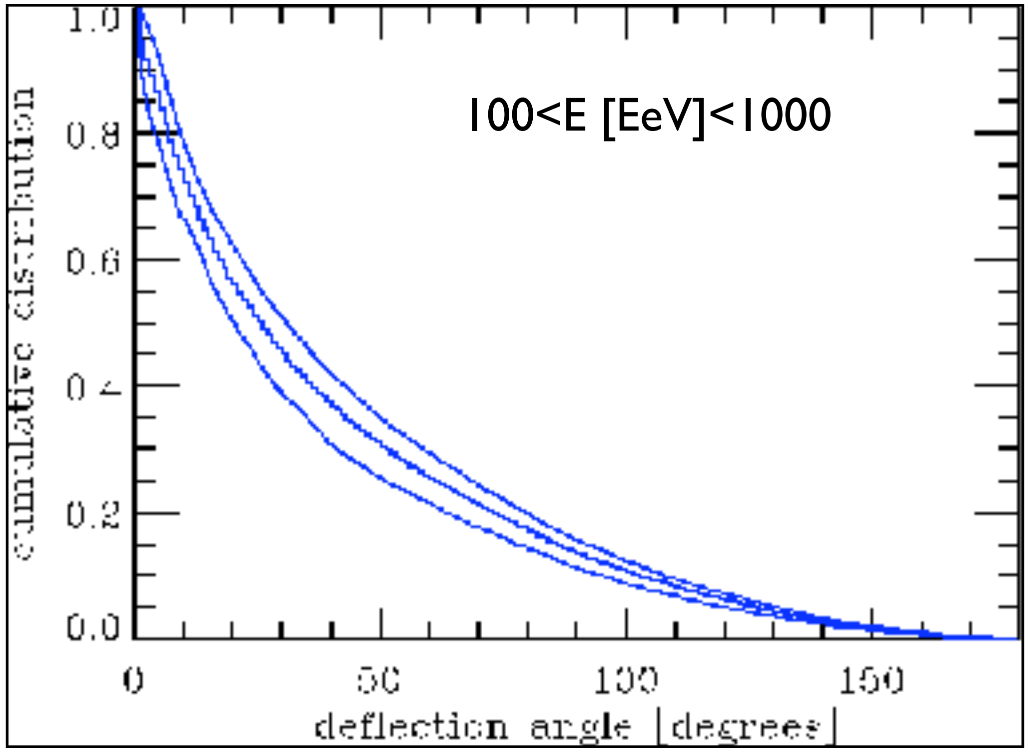
UHECRs and the galactic magnetic field

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



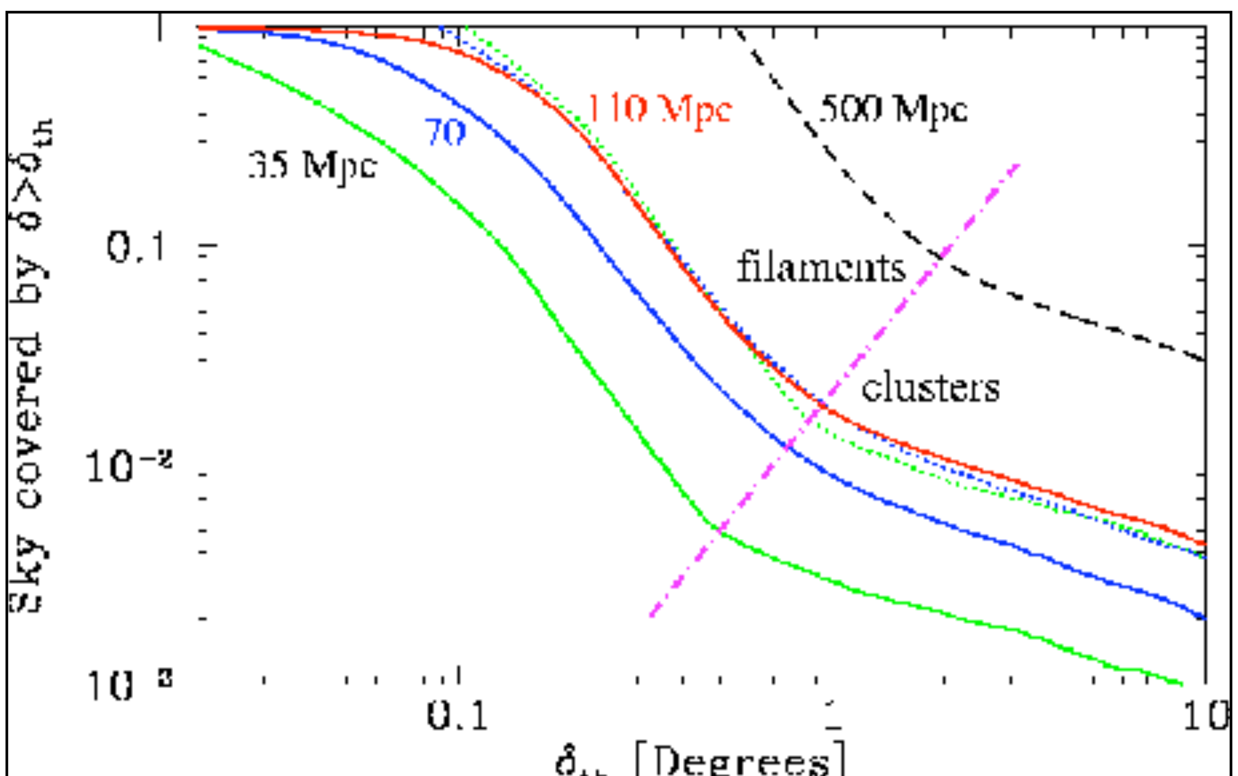
obtained with the PARSEC code

UHECR astronomy?



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

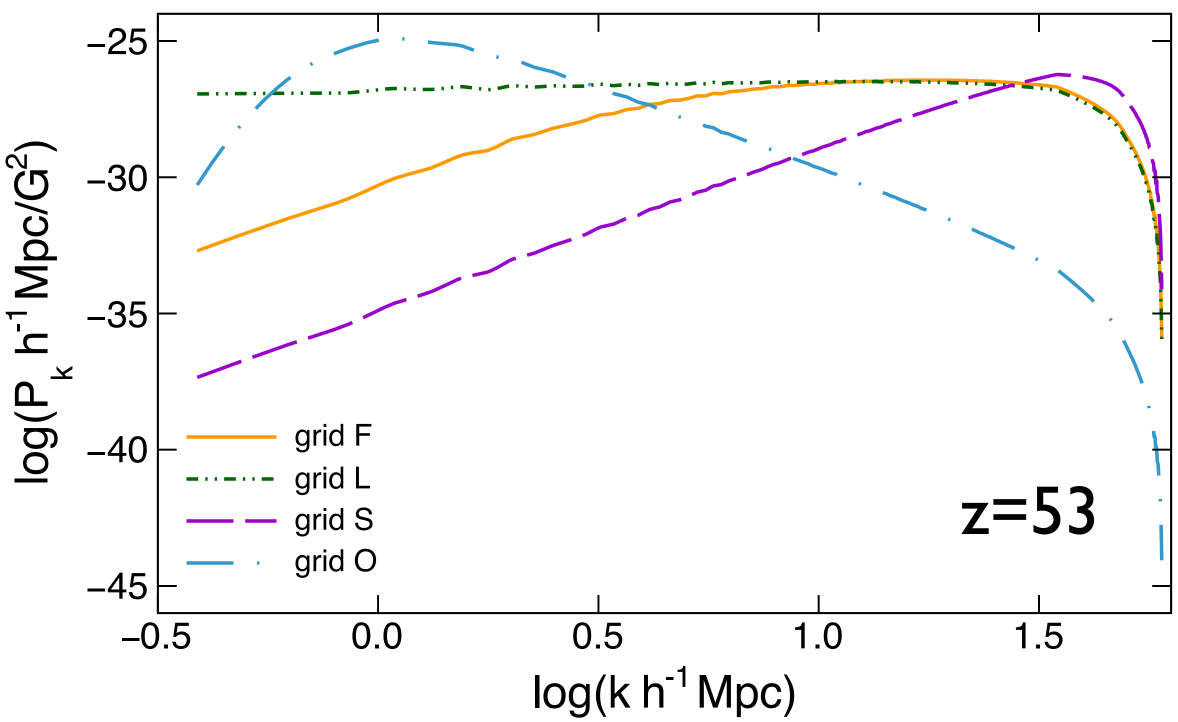
- cumulative deflections displayed are for protons
- Sigl+: deflections are high
- Dolag+: deflections are small
- for heavy nuclei deflections can be even higher
- UHECR astronomy may be possible in the later but not in the former scenario

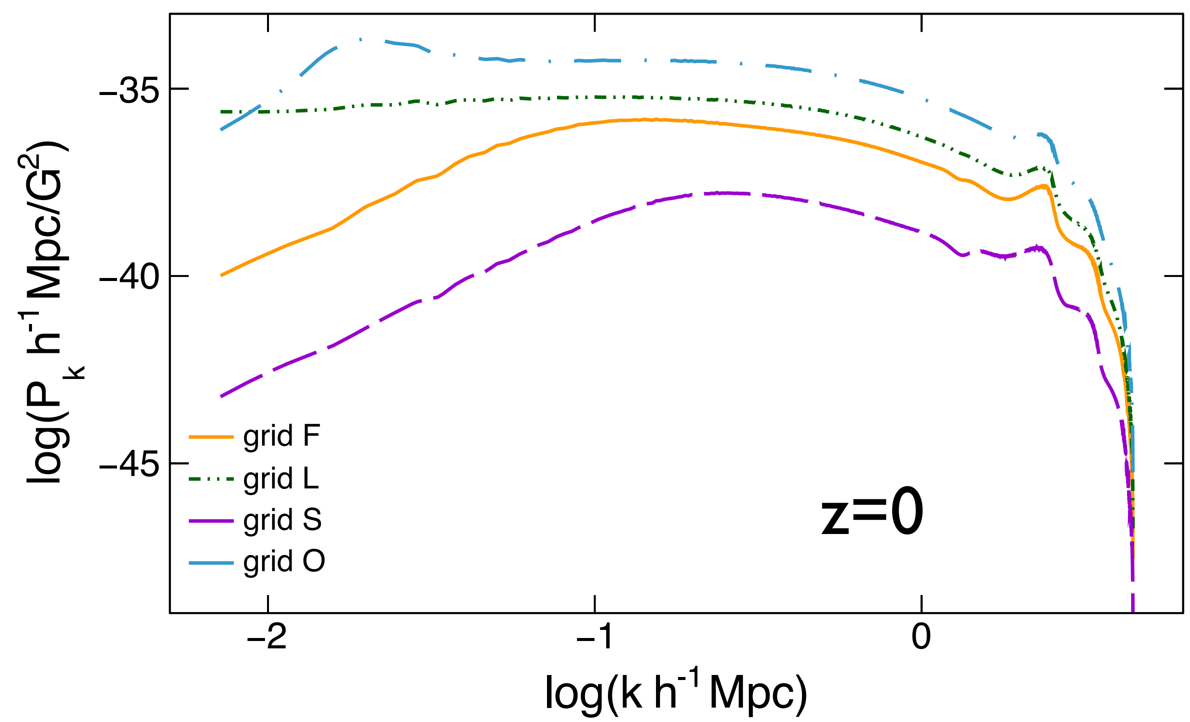


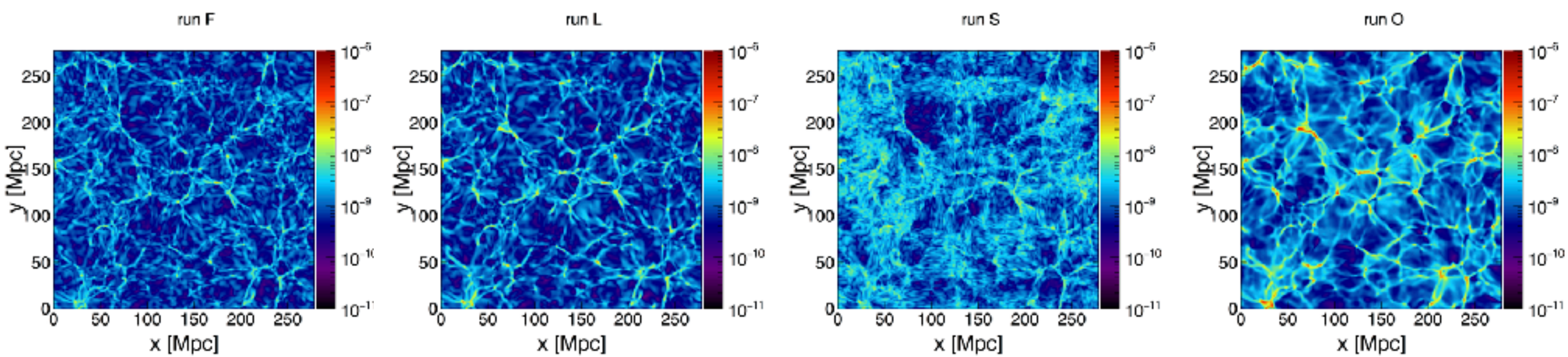
Dolag et al. JETP 79(2004) 583

deflections in extragalactic magnetic fields

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



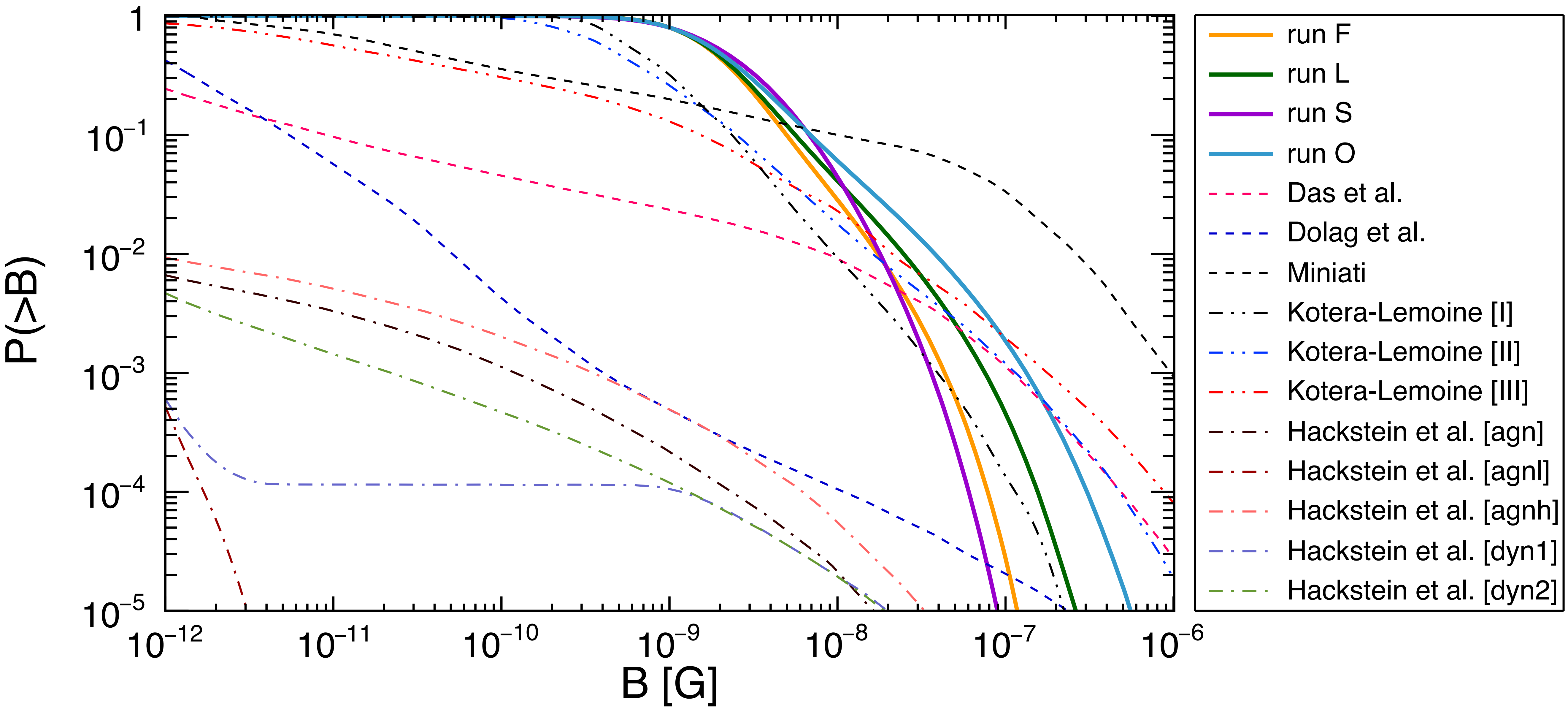




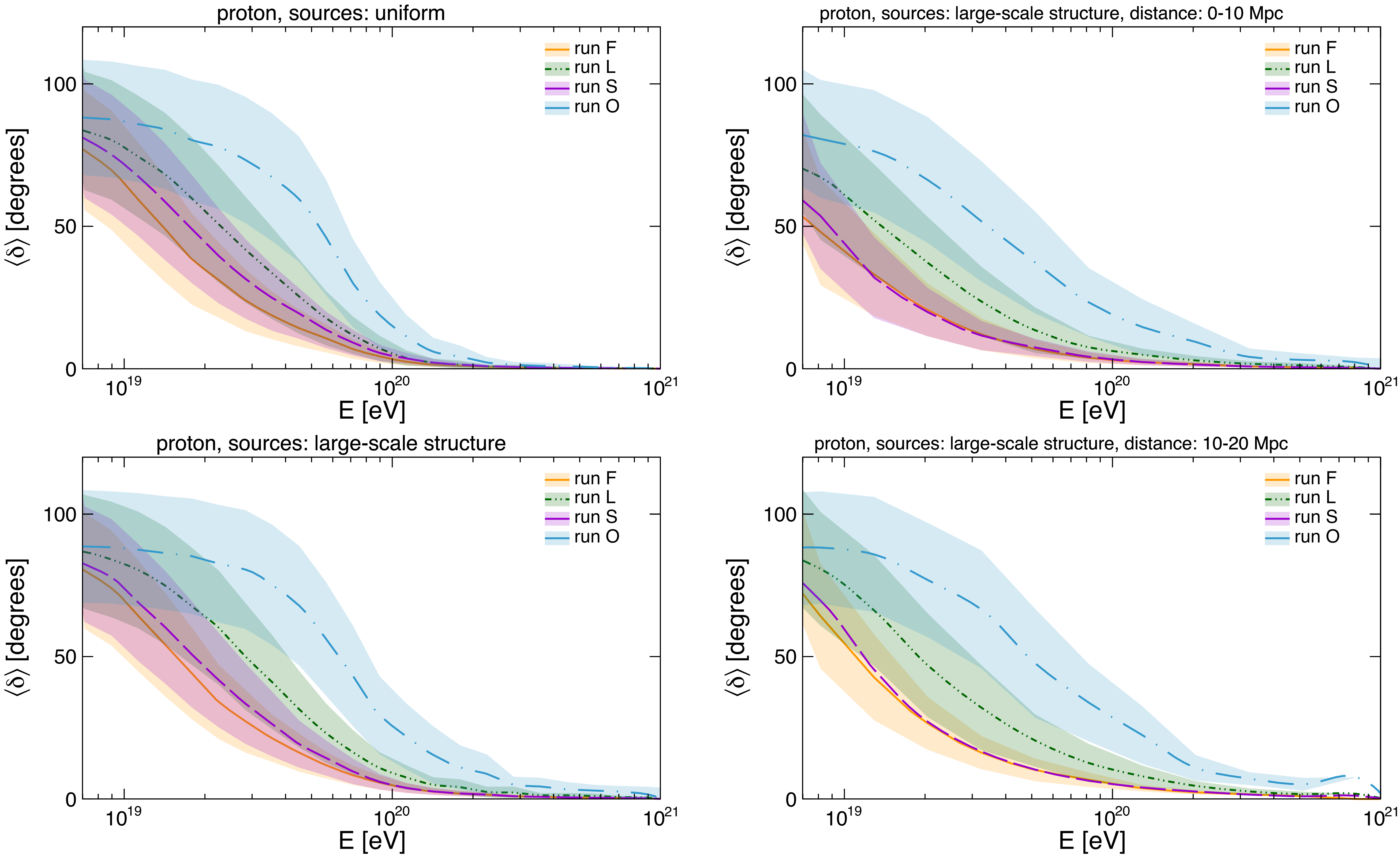
deflections in extragalactic magnetic fields

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

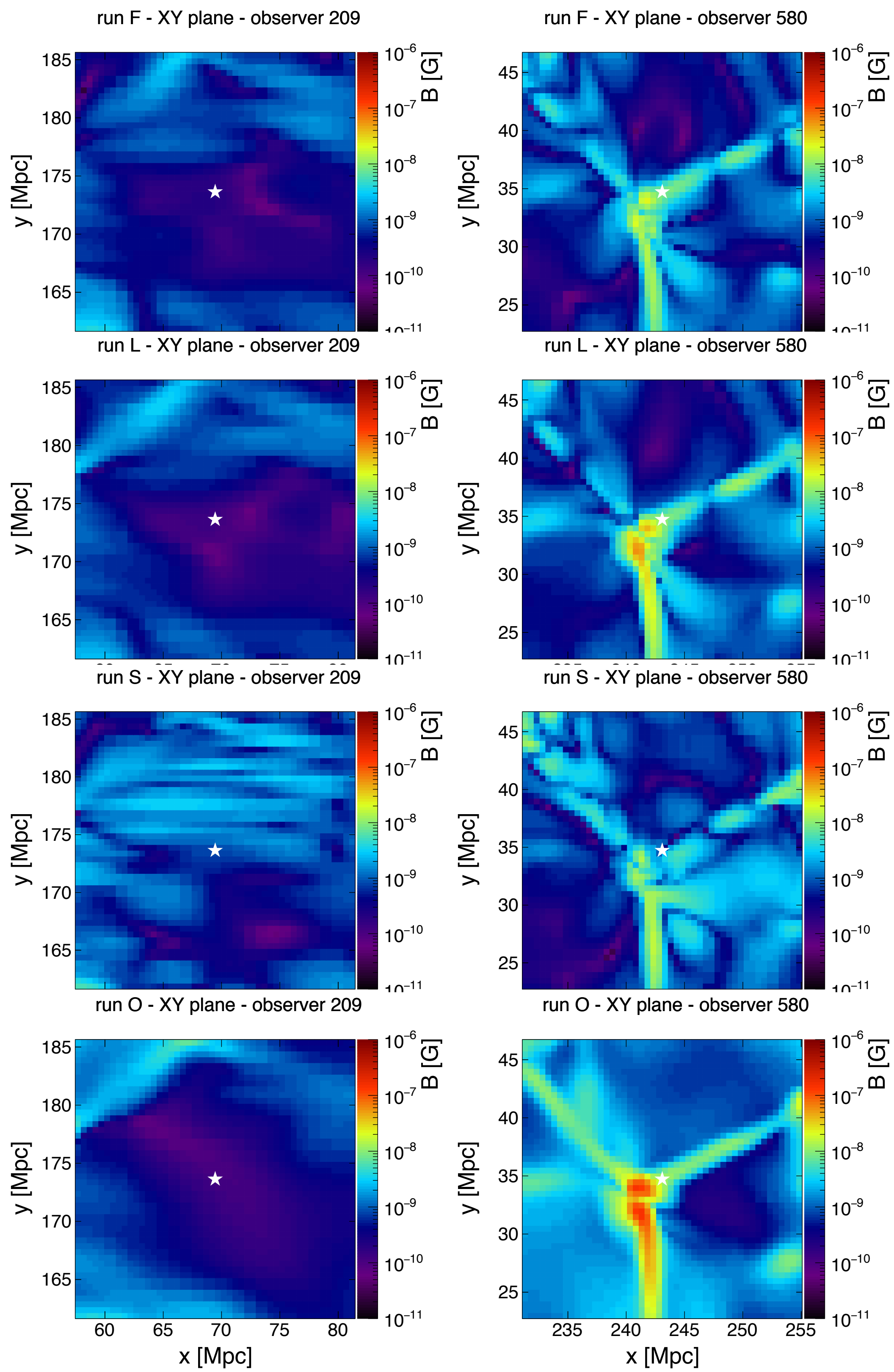
- we use Planck's upper limit to normalise the magnetic field in voids
- upper limit on (extragalactic) UHECR deflection
- 512^3 with size $(200h^{-1})^3$; RAMSES code; 18 levels of refinement

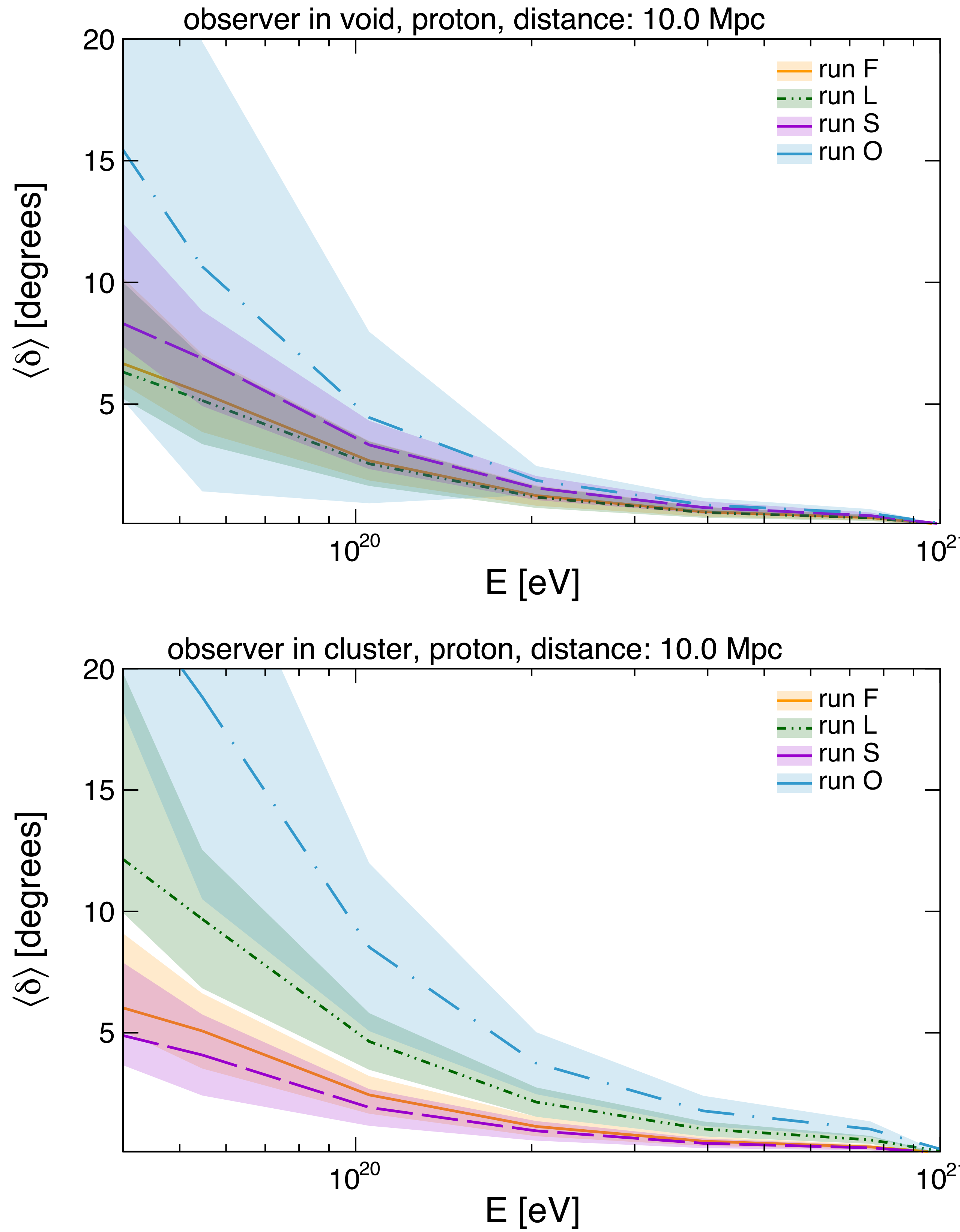


deflections in extragalactic magnetic fields



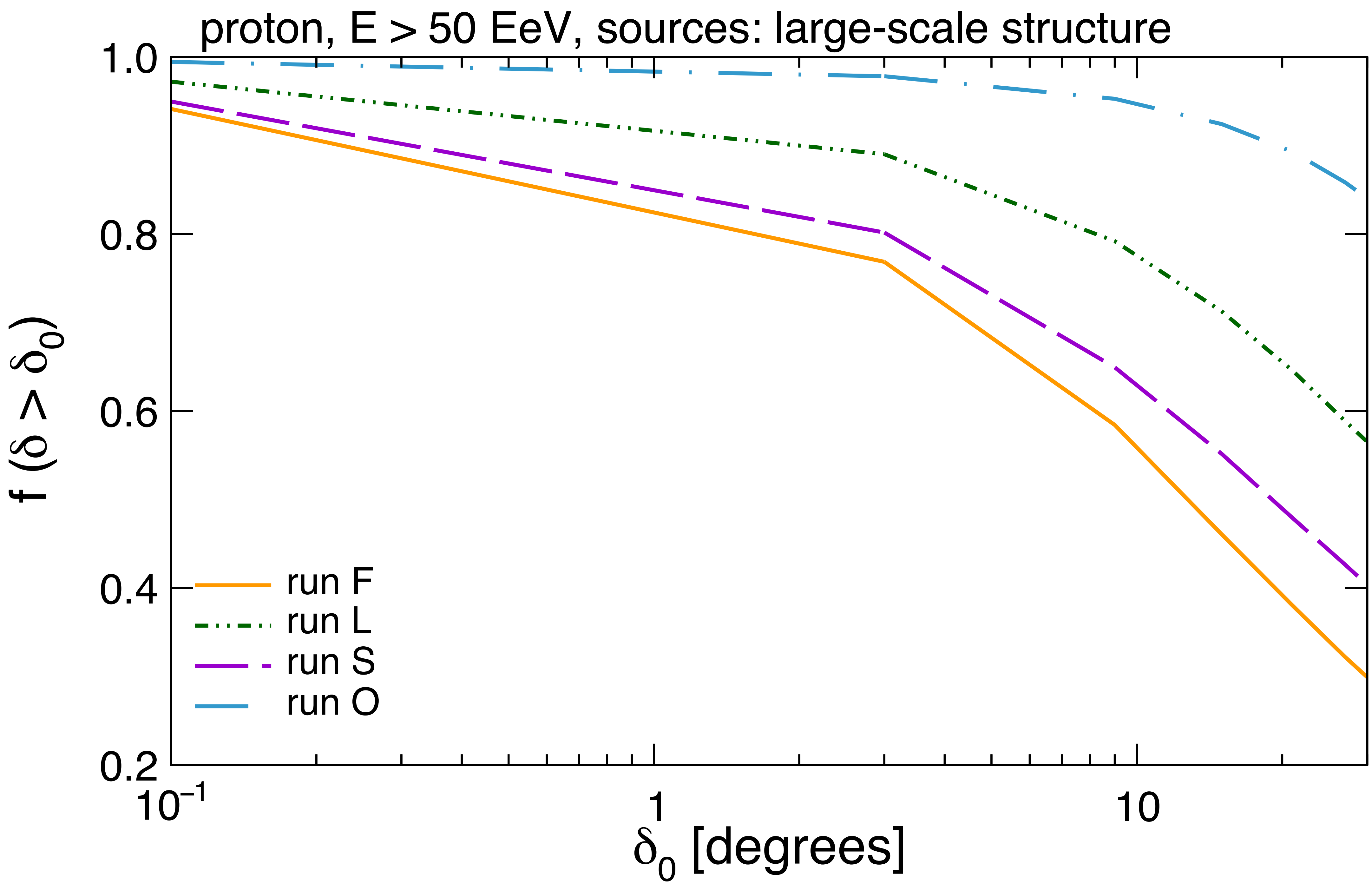
deflections in extragalactic magnetic fields





prospects for UHECR astronomy

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



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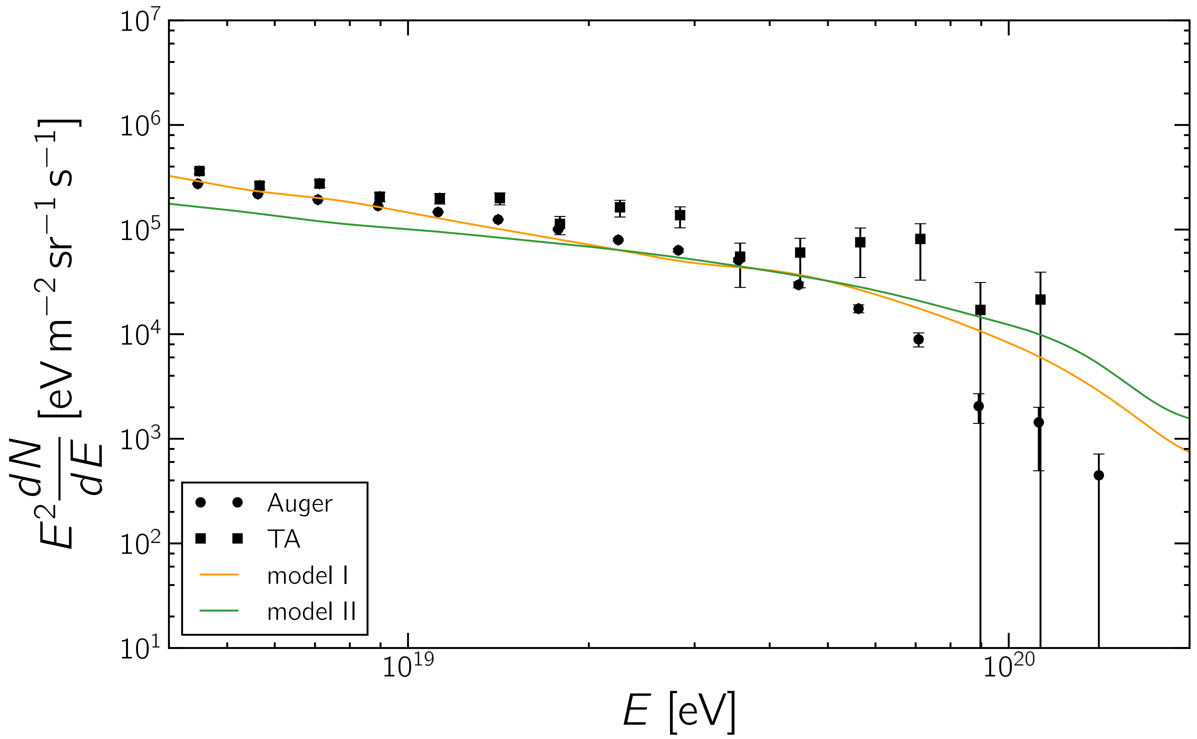
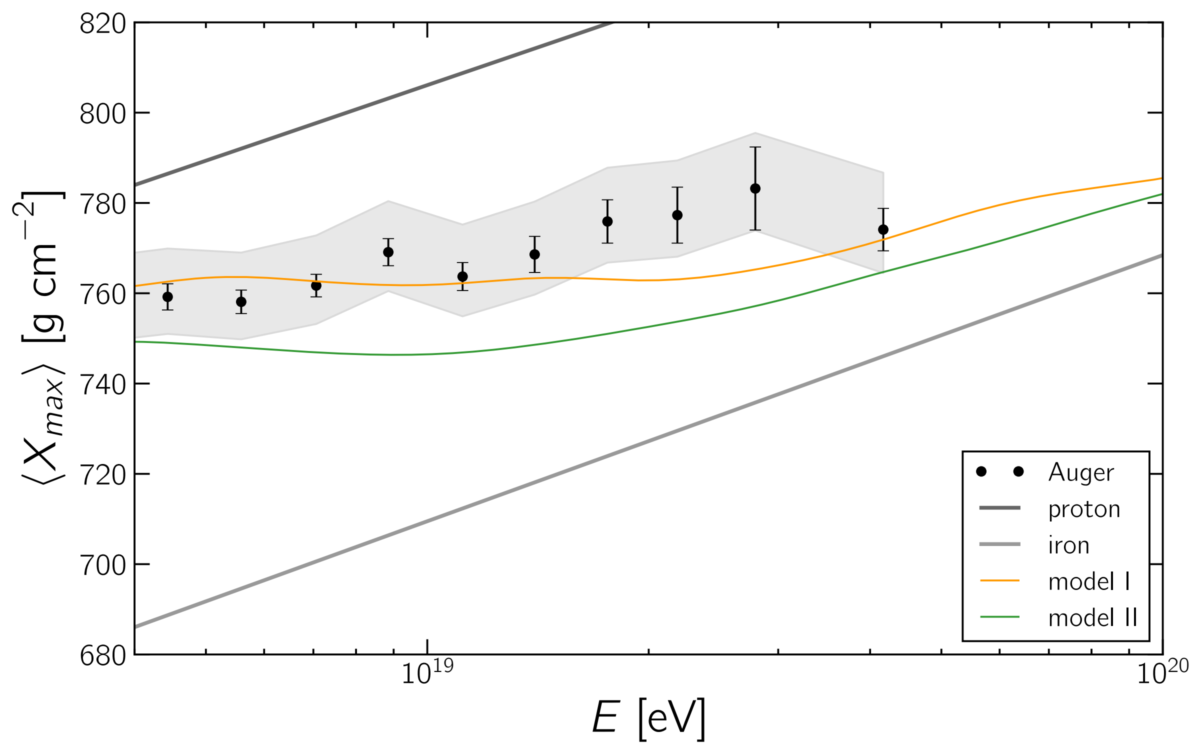
possible sources: IMBH+WD

RAB, J. Silk arXiv:1702.06978

- goal: explain the intermediate composition for the UHECRs measured by Auger
- idea: white dwarfs can be ignited by BHs with mass $10^2\ M_{sun} < M_{BH} < 10^5\ M_{BH}$
- the supernova explosion accelerates CRs via Fermi mechanism
- a jet is launched due to the high accretion rate
- CRs crossing the jet receive an energy boost by a a few orders of magnitude
- model I: CO star; model II: He





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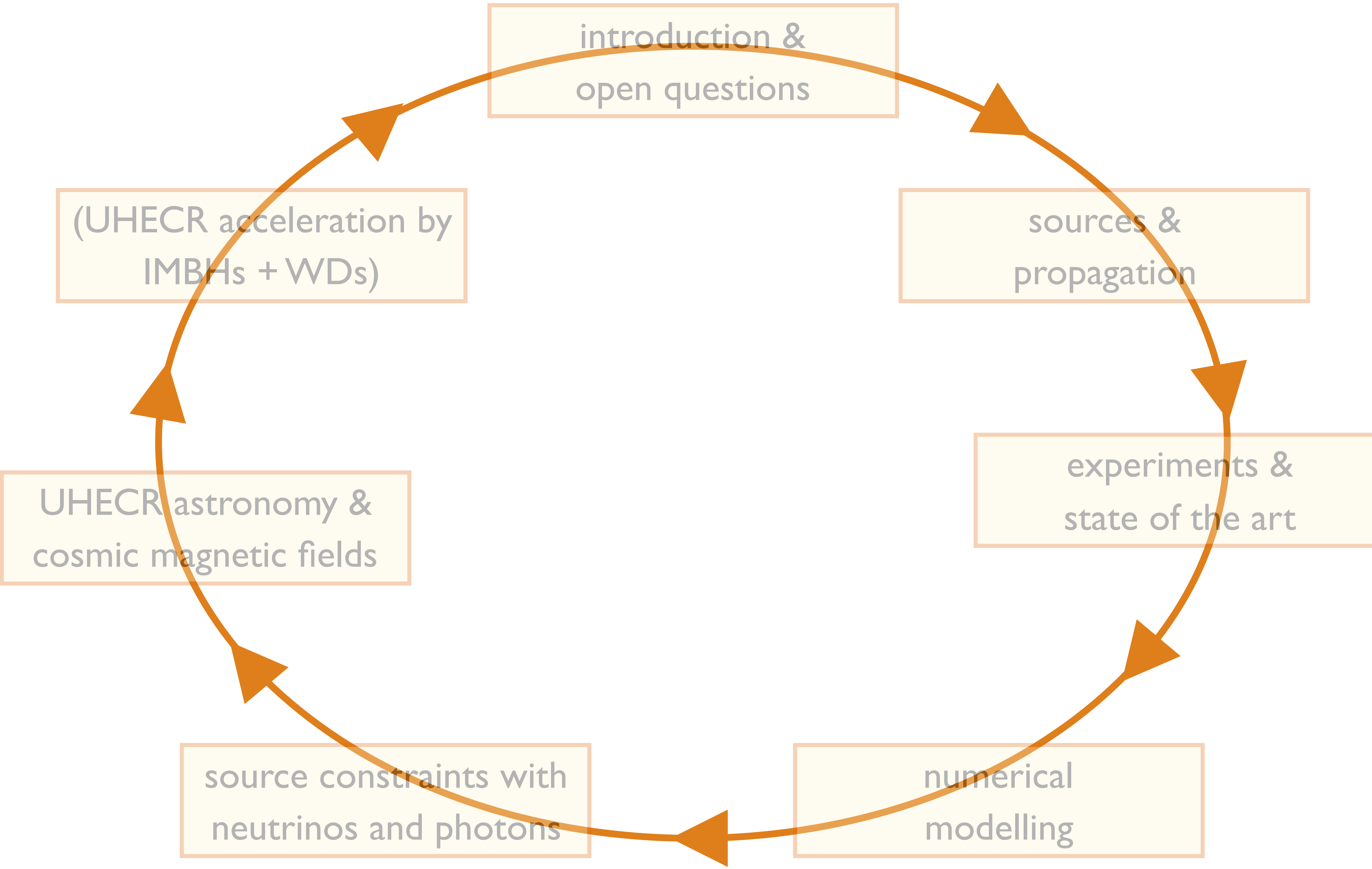


summary and outlook

- difficult to construct models to explain main observables (spectrum, composition and anisotropies)
- understanding cosmic magnetic fields is crucial for particle astronomy
- status:
  - UHECRs can have mixed composition
  - highest energy cutoff may be due to maximum source acceleration instead of GZK
  - "local" sources may be needed to explain measurements
  - after 10 years of operation, Auger has not yet found the sources of UHECRs
  - surprisingly low spectral indices in combined fits
- magnetogenesis process related to UHECR deflections → source of uncertainties
- MHD simulations suggest that even voids are highly magnetised, UHECR astronomy may be possible in a fraction of the sky for typical magnetic power spectra

summary and outlook

- prospects for UHECR astronomy don't look so good; too many uncertainties: EBL, cross sections, magnetic fields
- other messengers are also useful to constrain UHECR sources
- neutrinos allow us to probe the universe at UHE to high redshifts
- future: UHECR astronomy with neutrinos (and photons)?

Thank you!

modelling the propagation of UHECRs: energy losses

photopion production

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

mean free path for nuclei written as a function of the mfp for protons and neutrons

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

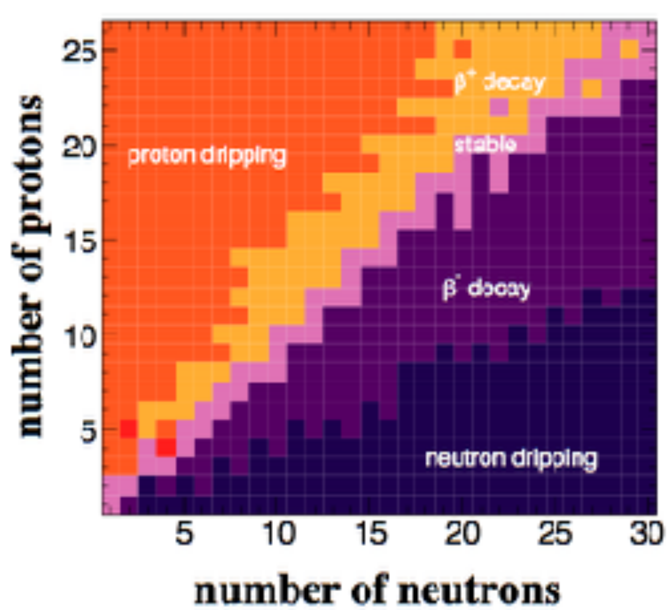
pair production

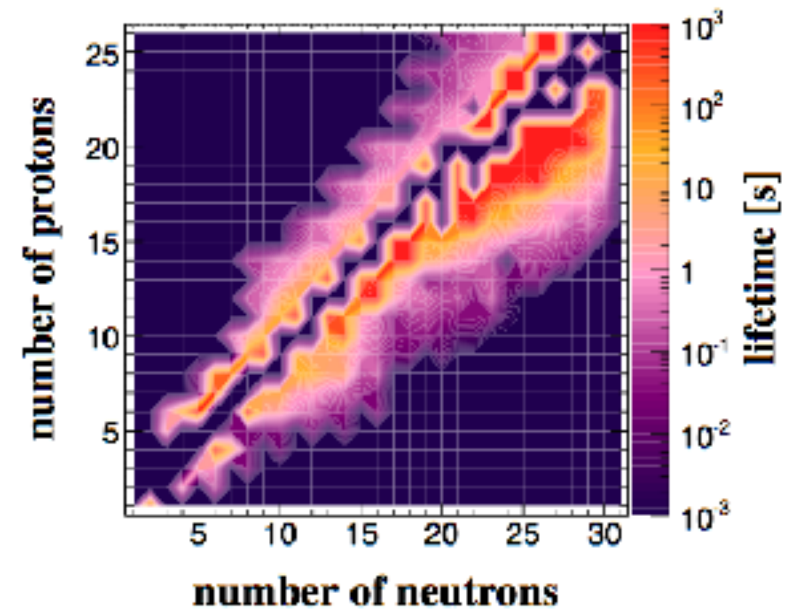
$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 k_B T f(\Gamma)$$

photodisintegration

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

nuclear decay





deflections in extragalactic magnetic fields

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

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

  part I: 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

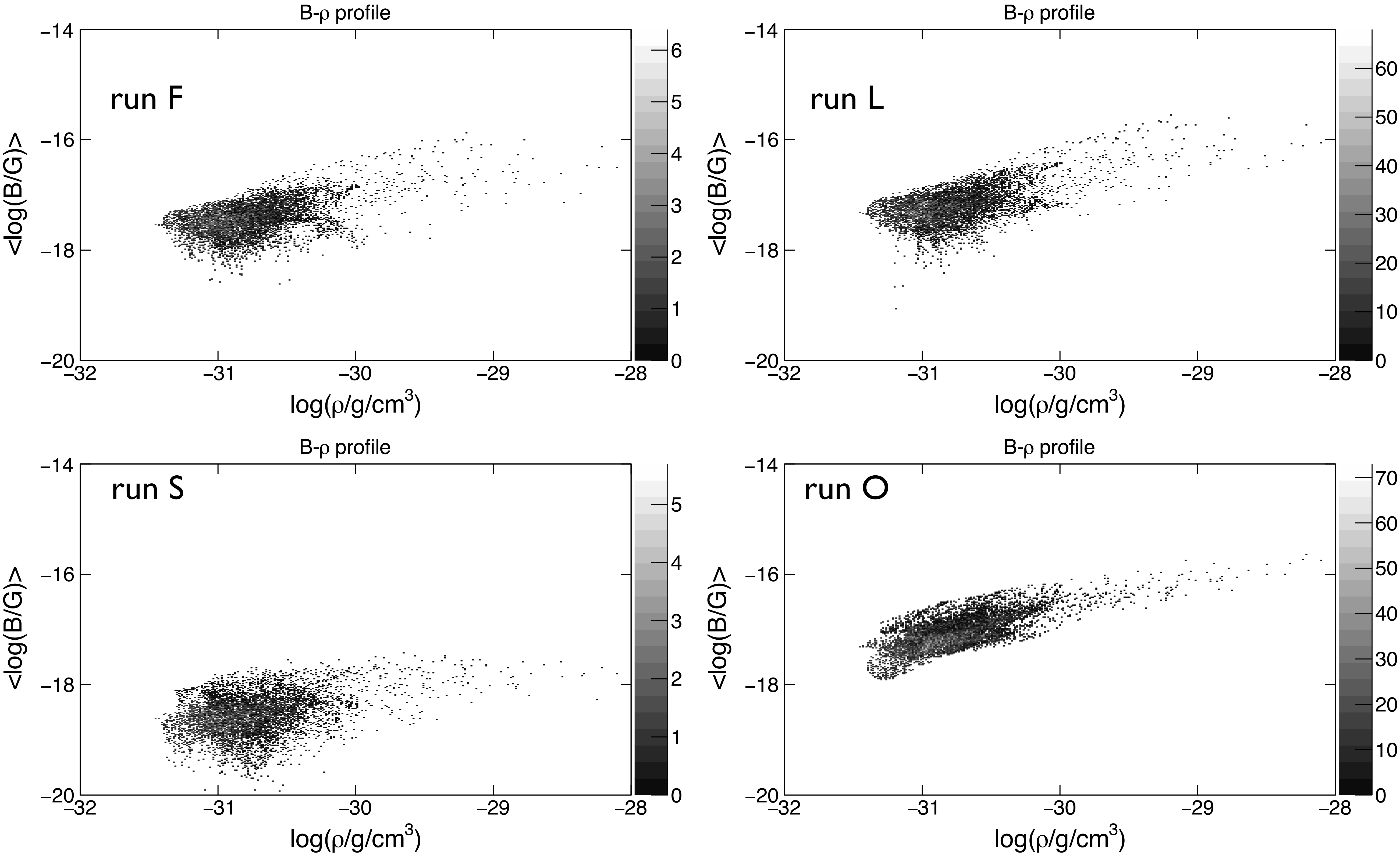
  subgrid models including formation and death of objects, feedback, turbulence, ...

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

the simulations

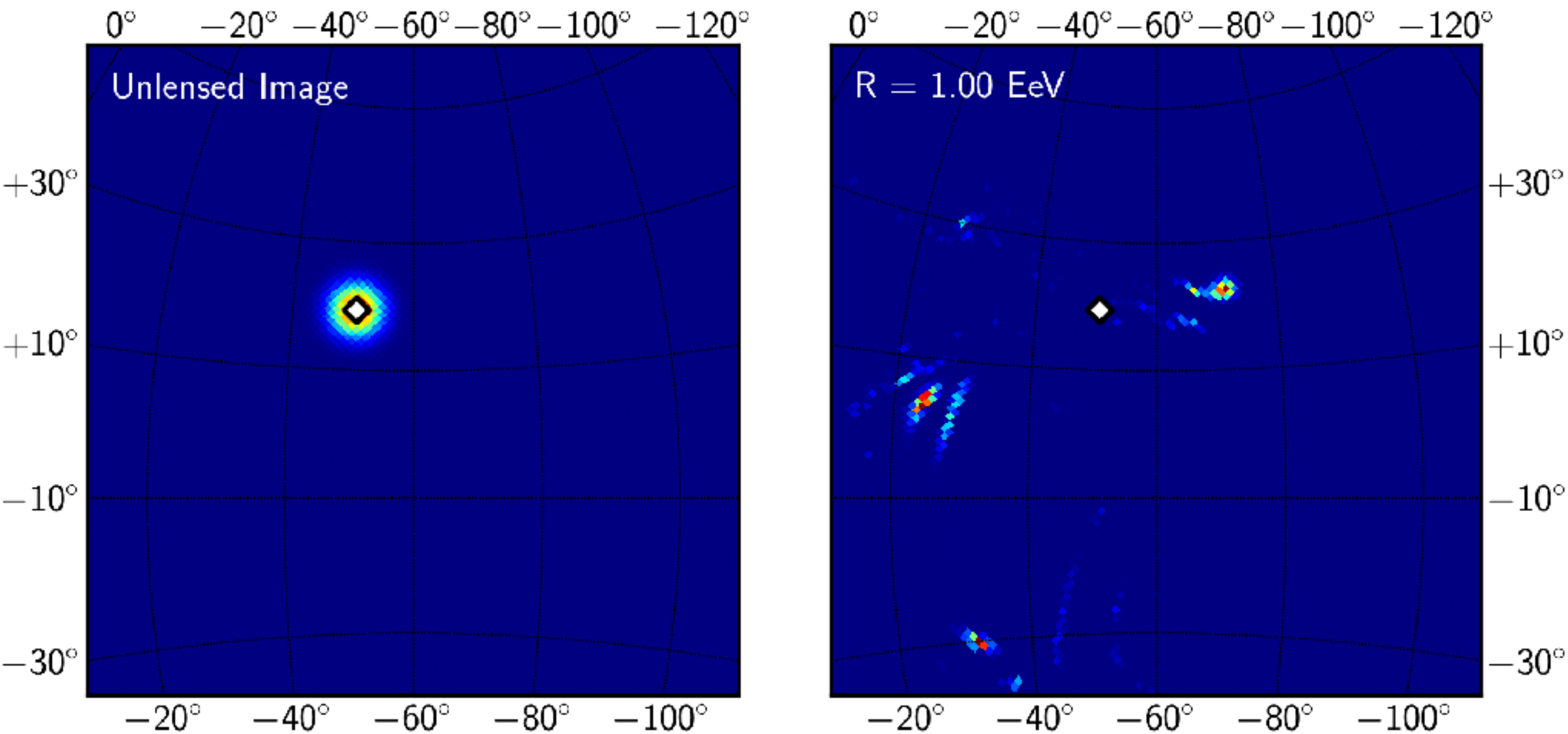
- run F: fiducial run
- run L: less magnetic power over small scales
- run S: less magnetic power over large scales
- run O: power mostly on large scales

prospects for UHECR astronomy



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