ultra-high energy cosmic rays: present and future

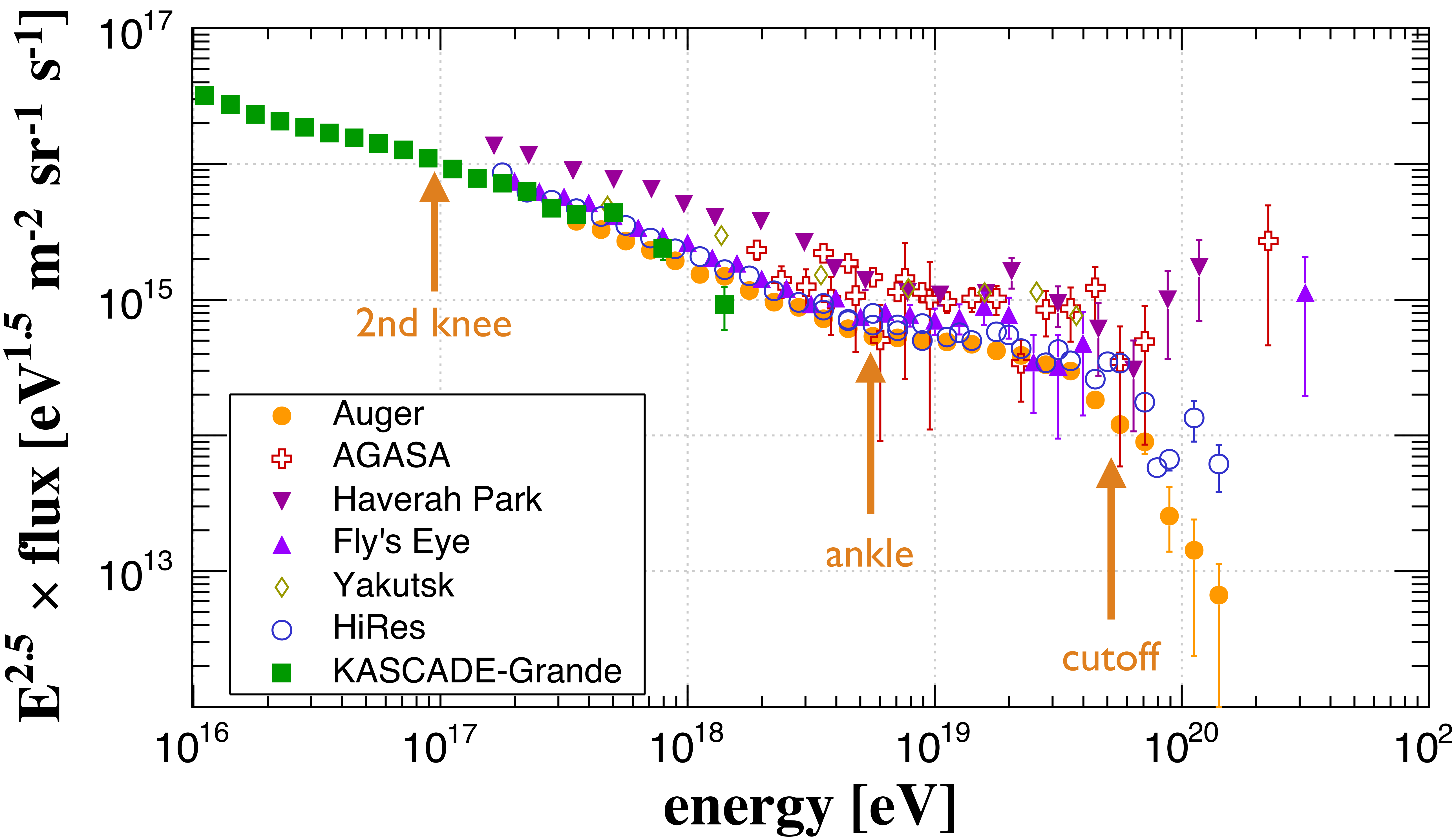
Rafael Alves Batista

University of Oxford

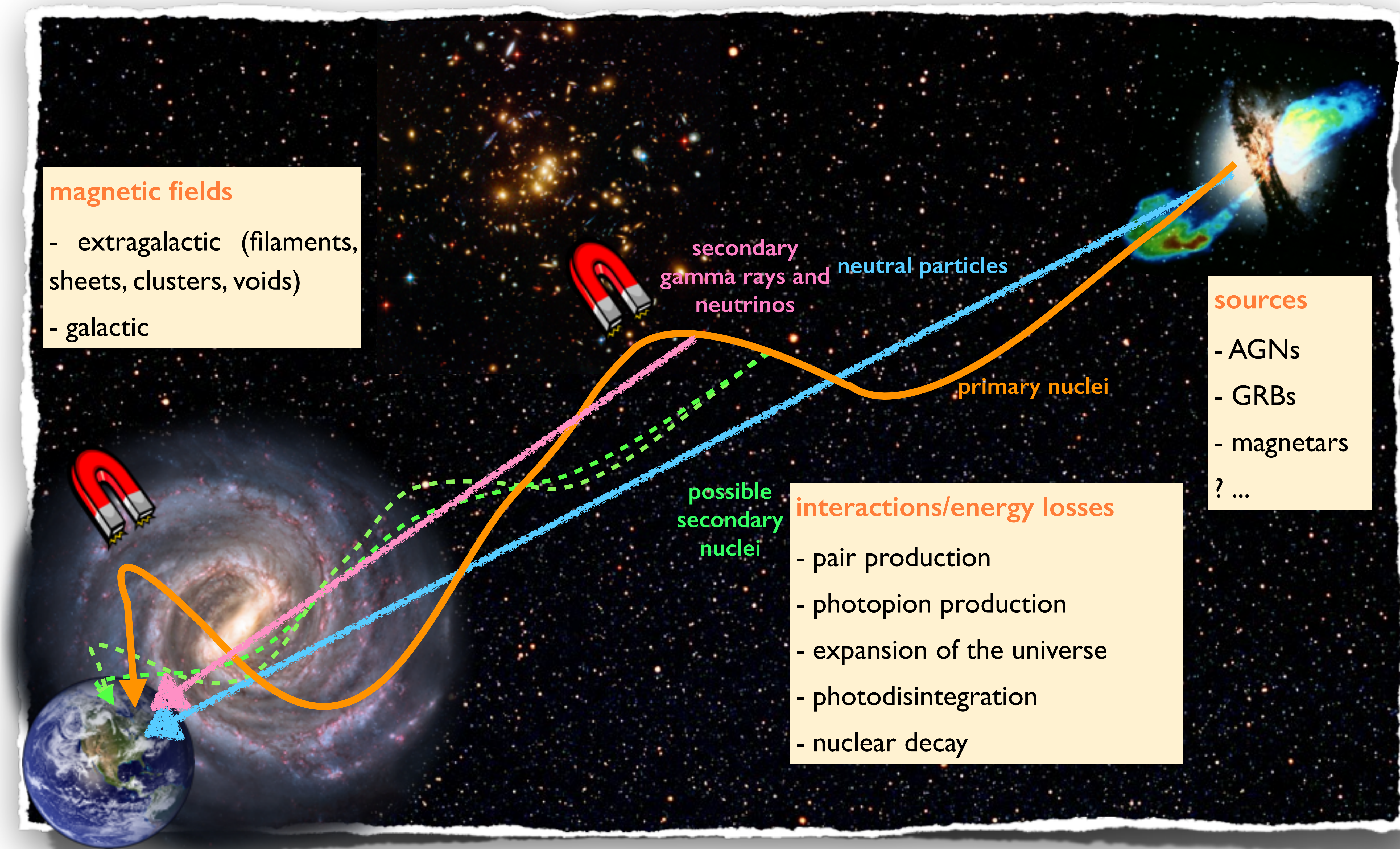
rafael.alvesbatista@physics.ox.ac.uk

Oxford
25/11/2015

the cosmic ray spectrum



propagation picture



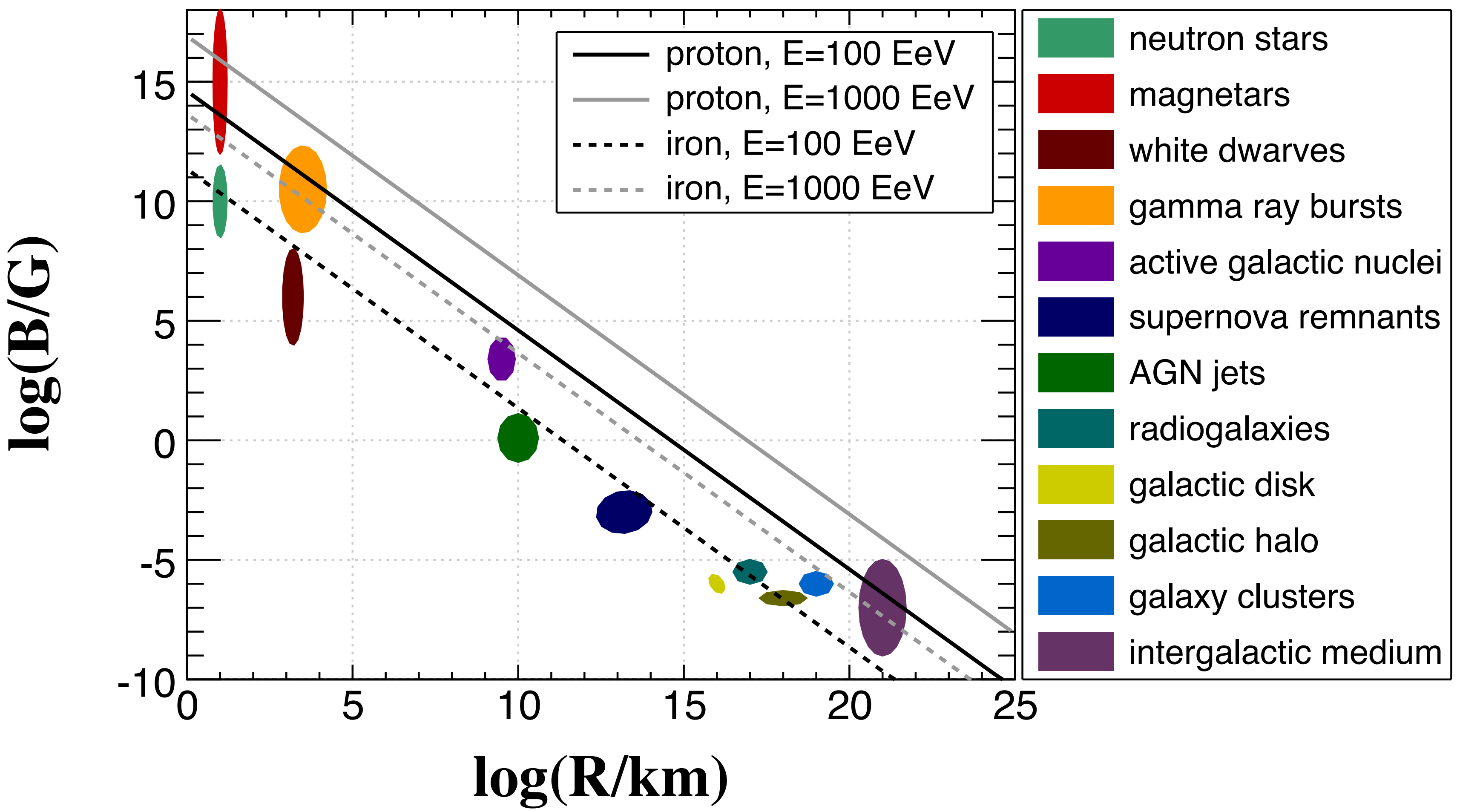
modelling the propagation of UHECRs: photon backgrounds

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

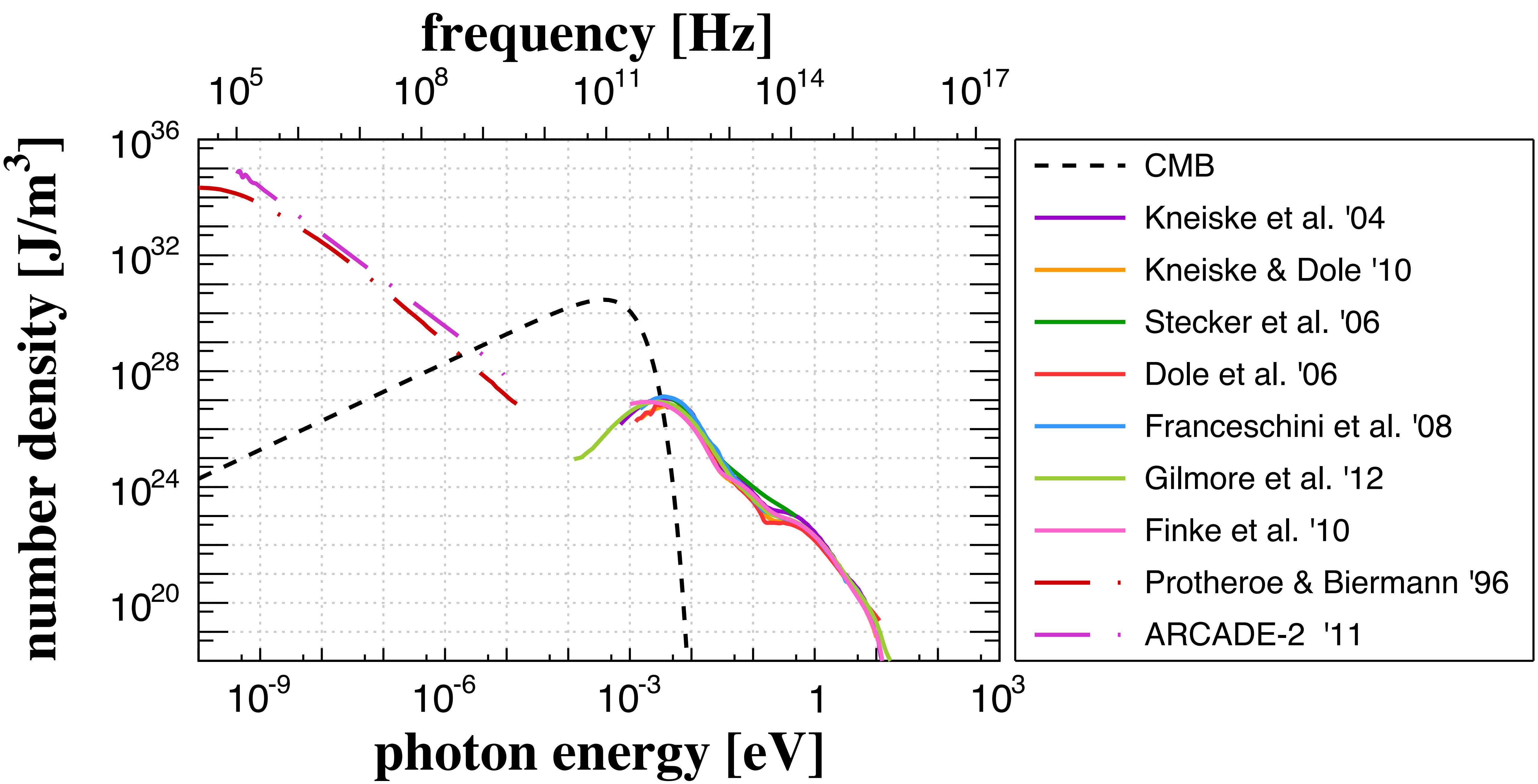
- Hillas criterion: Larmor radius should be smaller than accelerator size

$$E_{max} \approx 2\beta c Z e B R_L$$

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



modelling the propagation of UHECRs: photon backgrounds



modelling the propagation of UHECRs: energy losses

photopion production

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

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

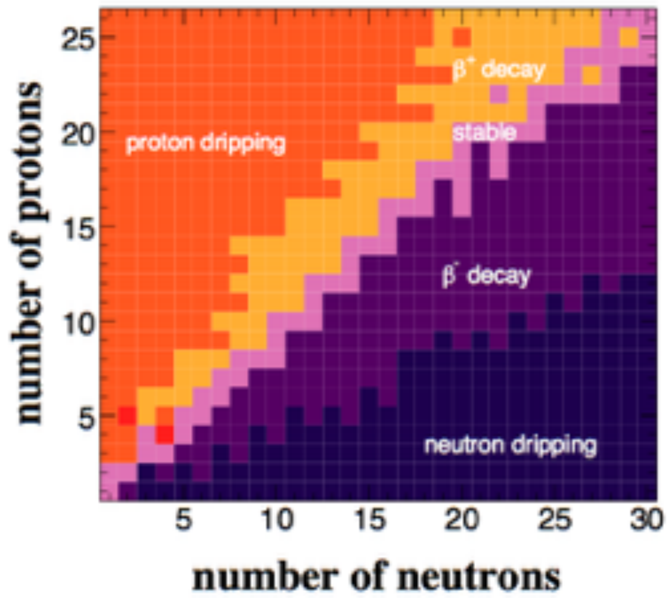
pair production

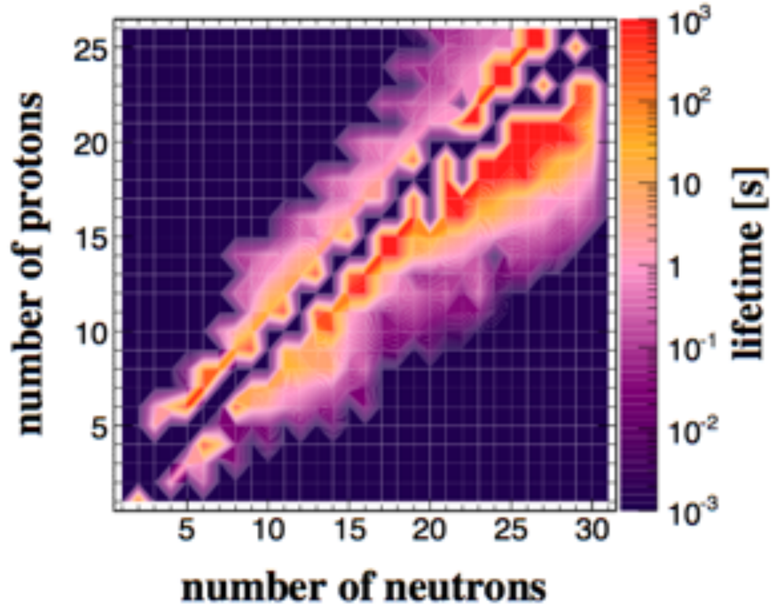
$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 k_B T f(\Gamma)$$

photodisintegration

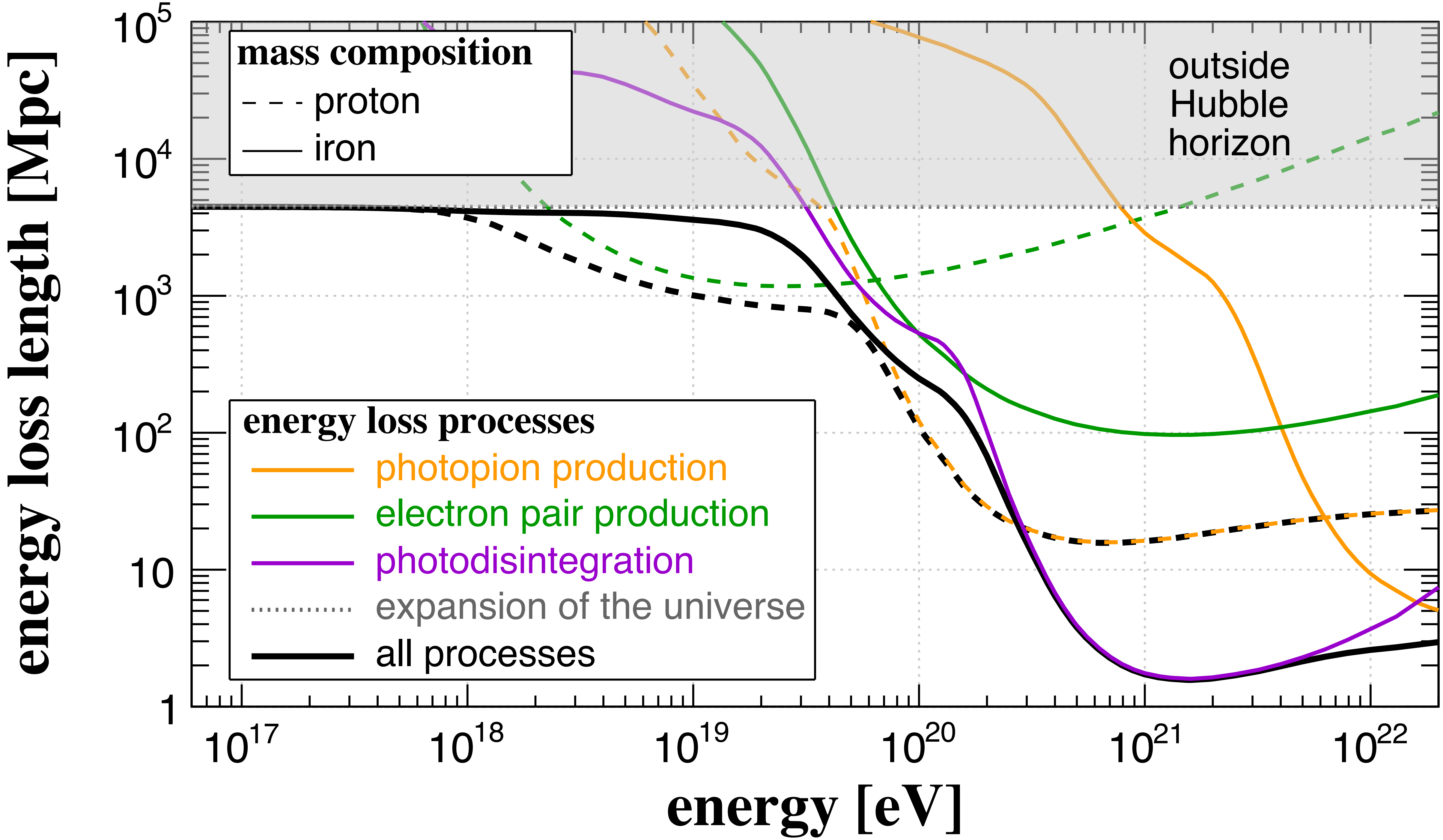
$$\frac{1}{\lambda(\Gamma)} = \int_{E_{min}}^{E_{max}} n(\epsilon, z)\bar{\sigma}(\epsilon'_{max} = 2\Gamma\epsilon)d\epsilon$$

nuclear decay

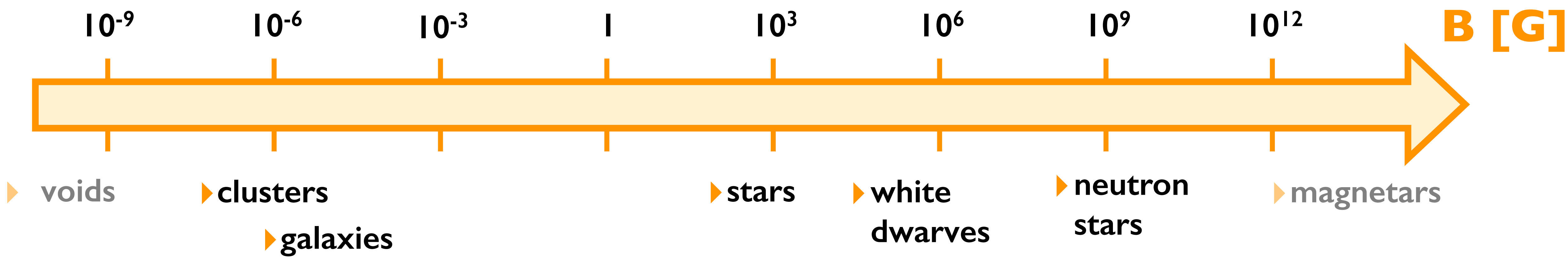




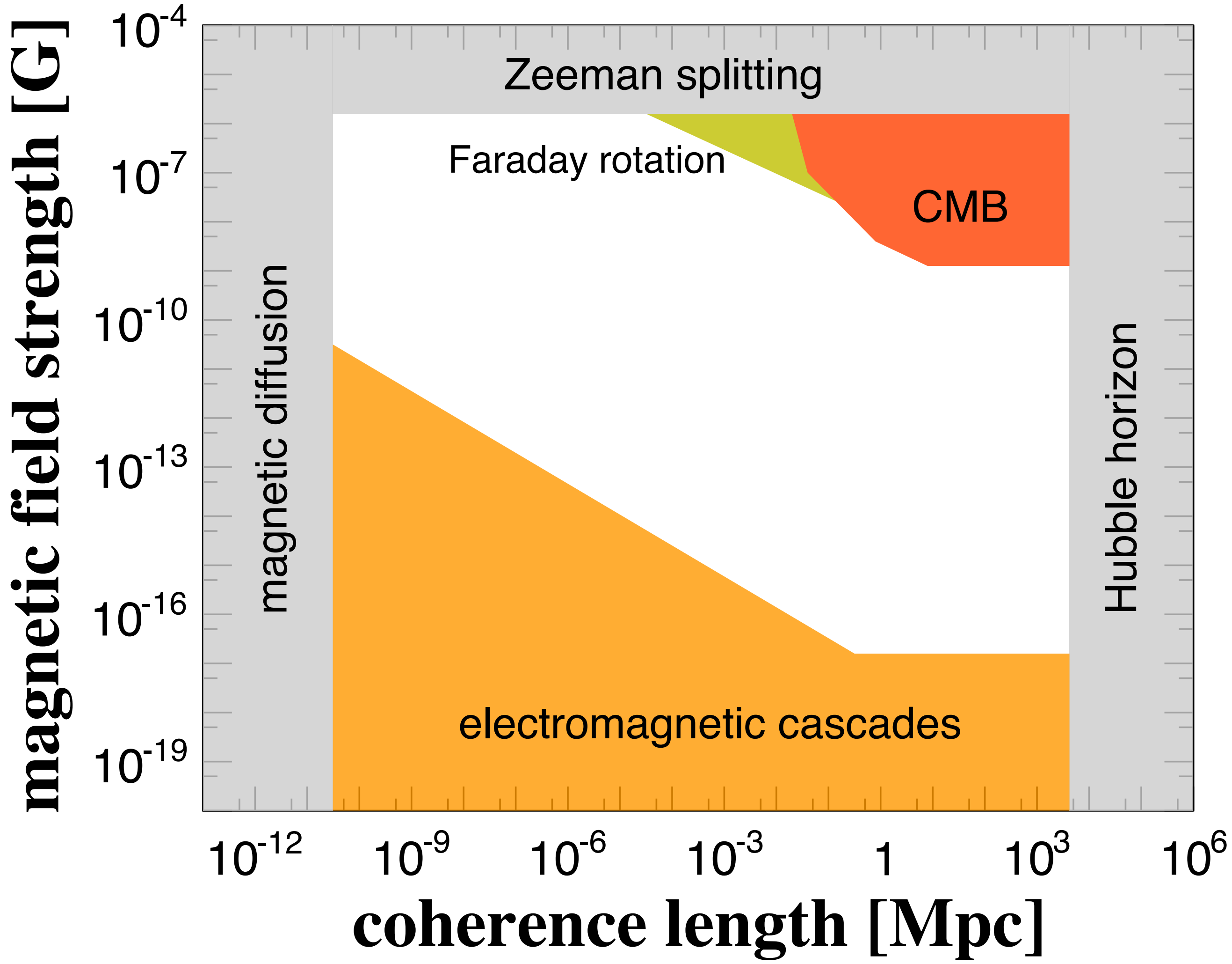
modelling the propagation of UHECRs: energy losses



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



ultra-high energy cosmic rays

fundamental questions

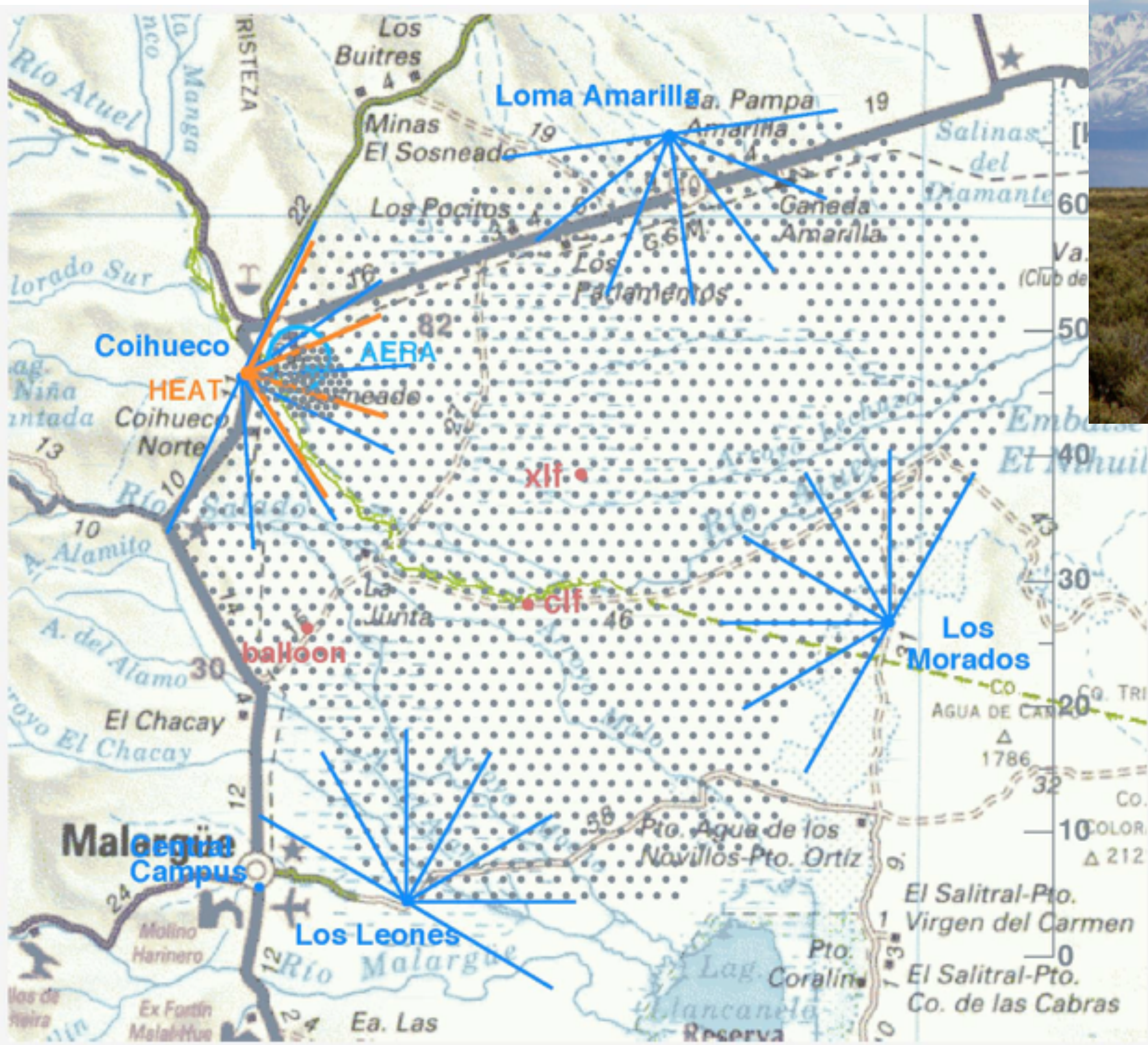
- where do they come from?
- what are they made of?
- how are they accelerated?

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?
- where does the transition between diffusive and ballistic regimes happen?

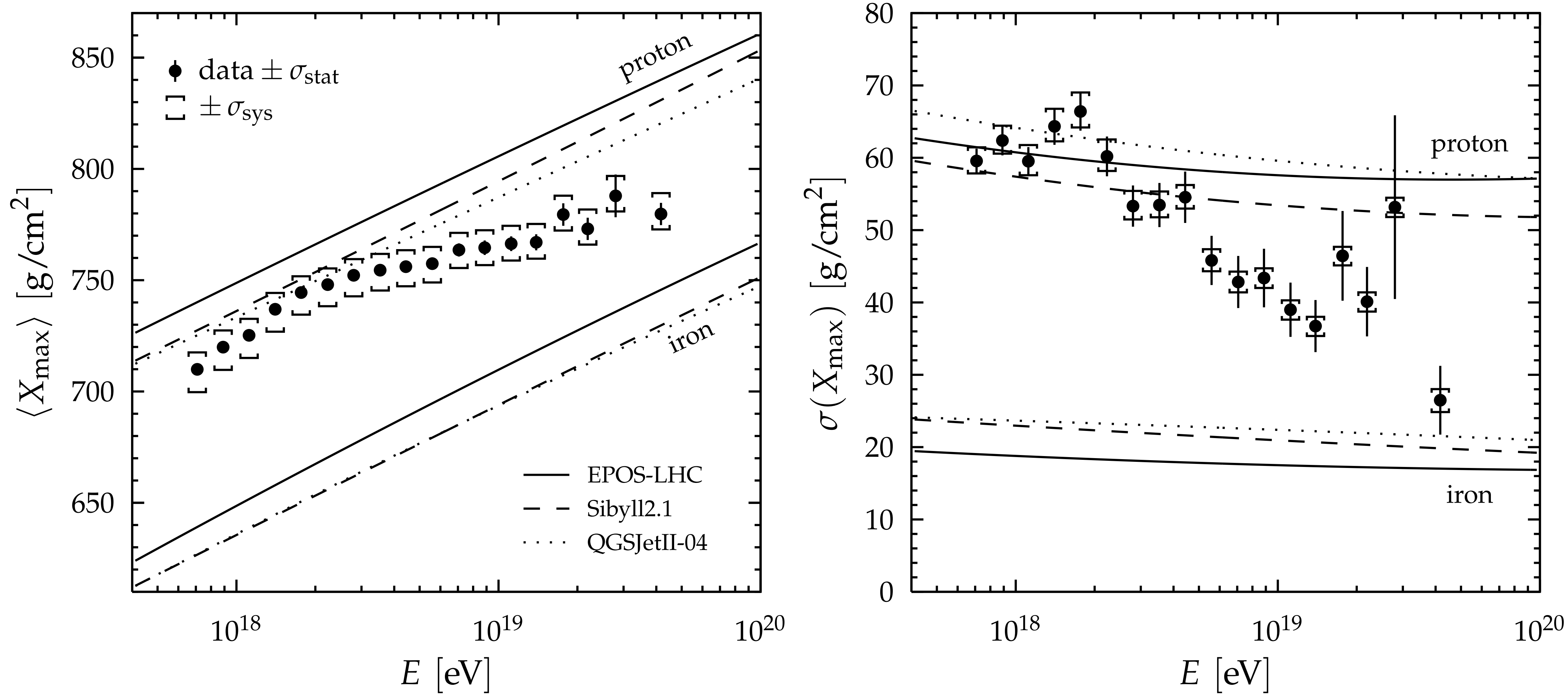
- observables from CR experiments: spectrum, composition, anisotropy
- cosmic magnetic fields (galactic and extragalactic) are important
- test new physics scenarios using UHECRs (?)

state of the art: Pierre Auger Observatory



what are UHECRs made of?

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

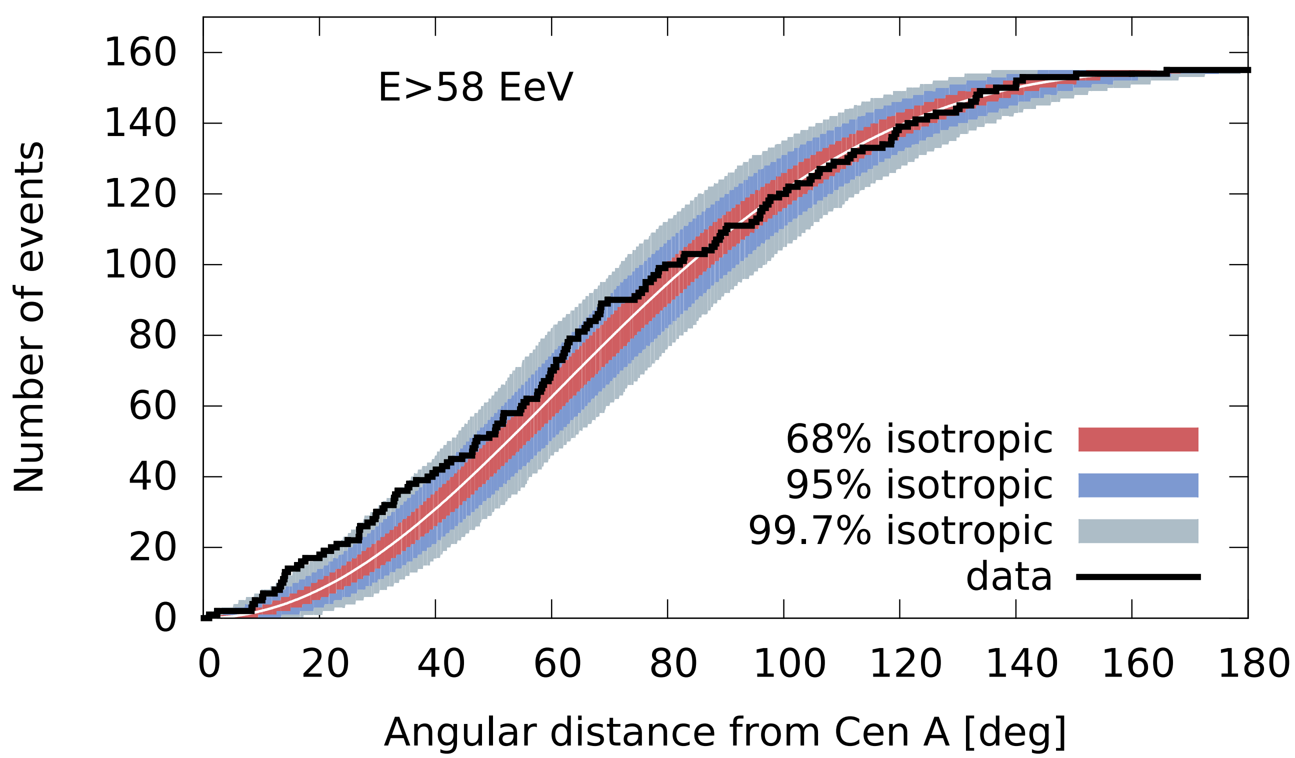


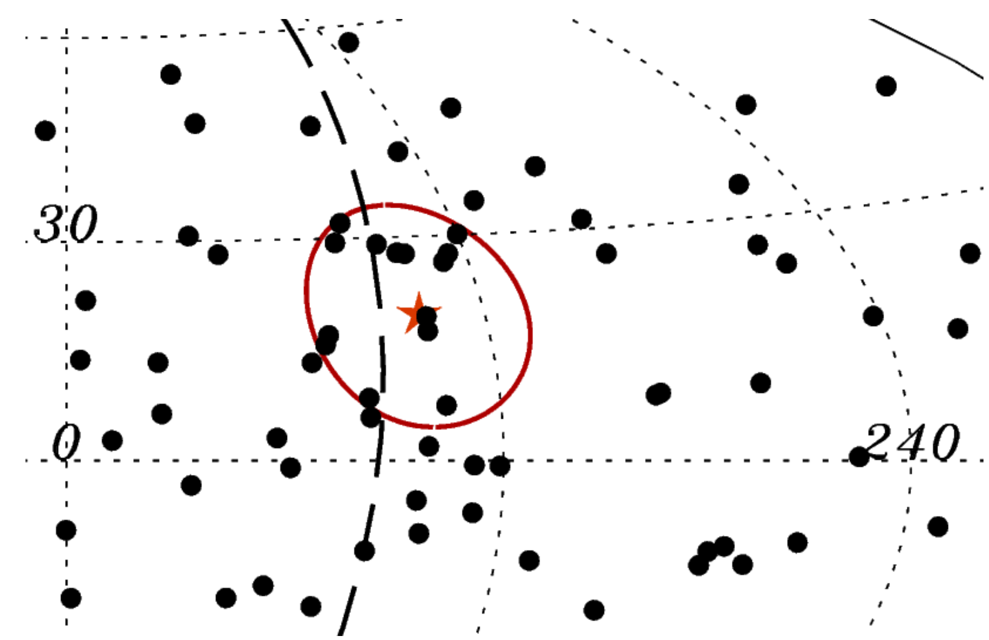
- UHECRs are very likely atomic nuclei
- showers are reconstructed assuming hadronic interaction models, which are based on extrapolation of accelerator data
- New Physics in air showers?
- direct implication: high energy cutoff probably not GZK

what are the sources of UHECRs?

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

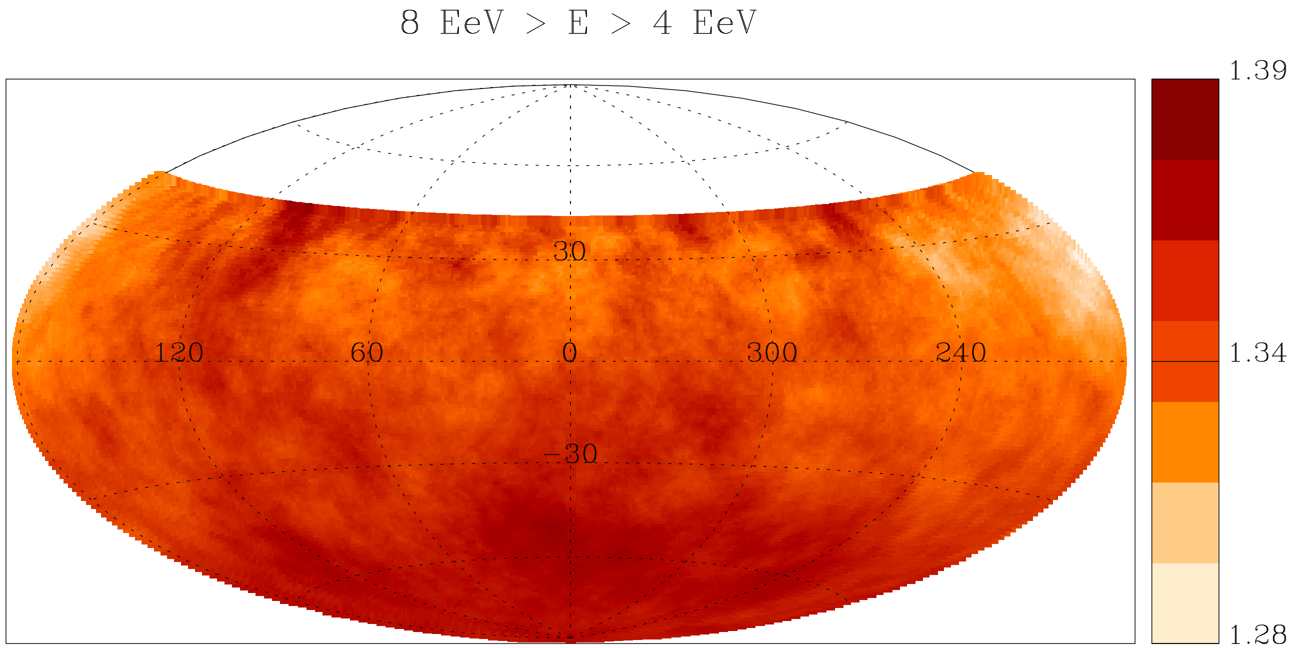
Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	$\mathscr{L}_{min}$ [erg/s]	f_{min}	$\mathscr{P}$
2MRS Galaxies	52	9	90	-	1.5×10^{-3}	24%
Swift AGNs	58	1	80	-	6×10^{-5}	6%
Radio galaxies	72	4.75	90	-	2×10^{-4}	8%
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	72	4.75	90	$10^{39.33}$	5.1×10^{-5}	11%
Centaurus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

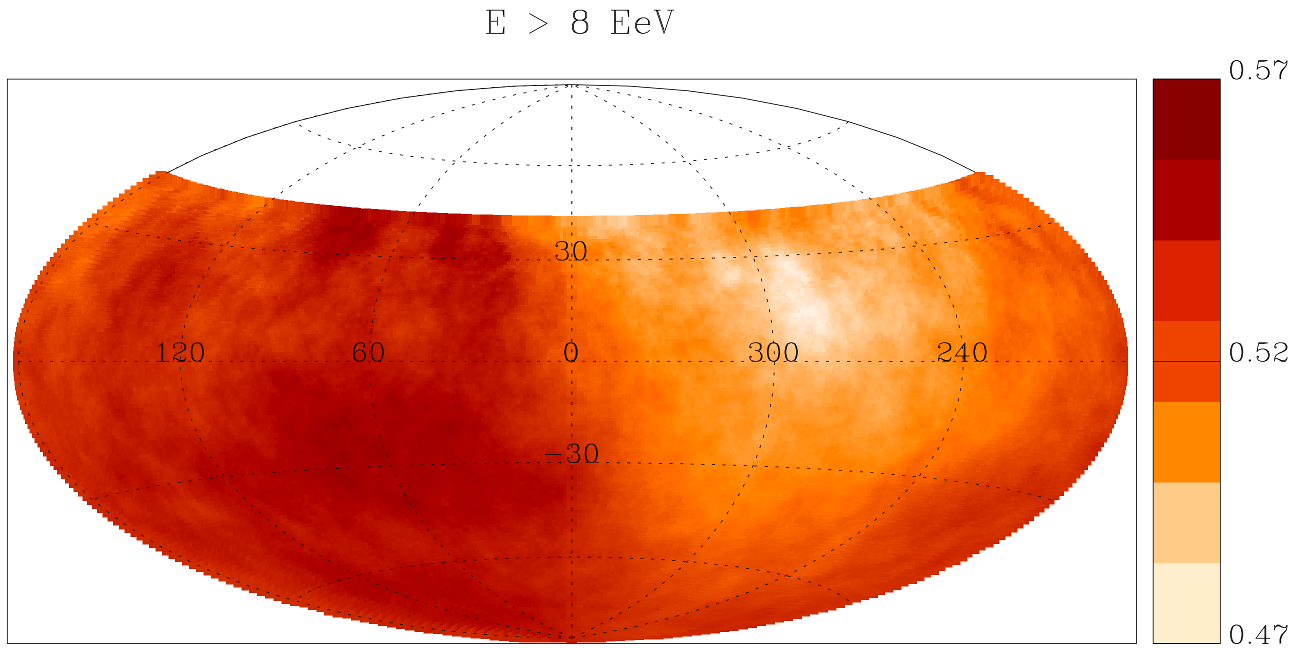




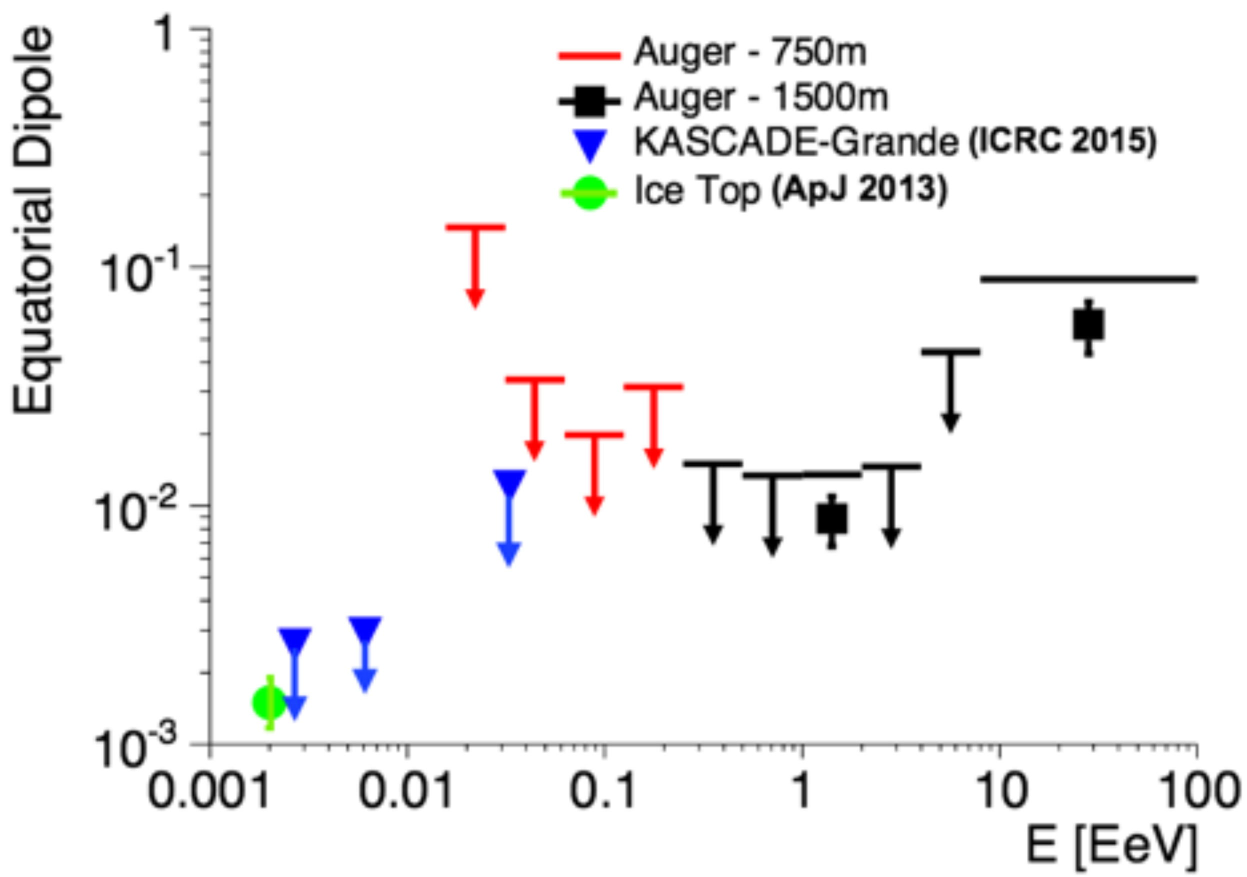
what are the sources of UHECRs?

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

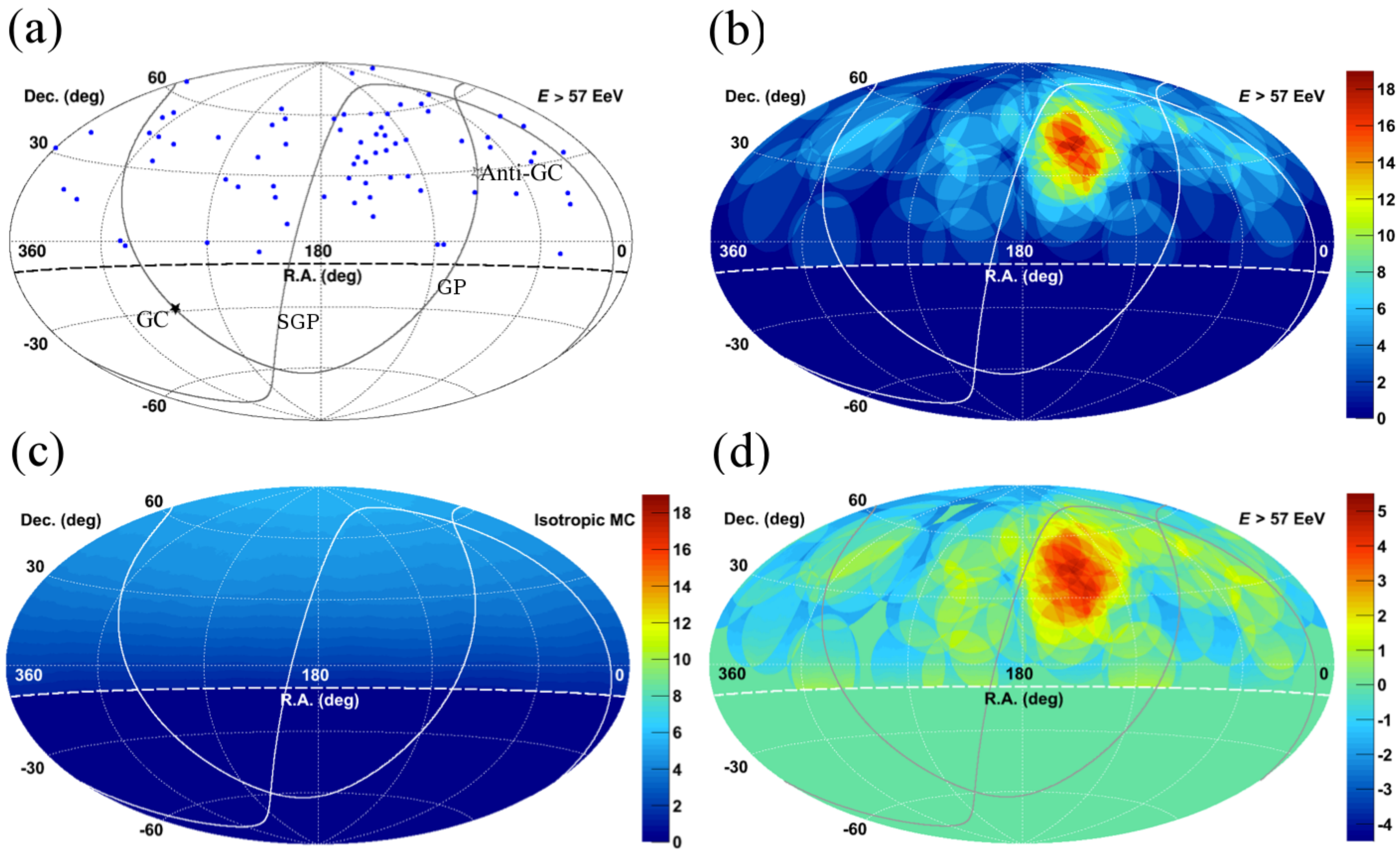




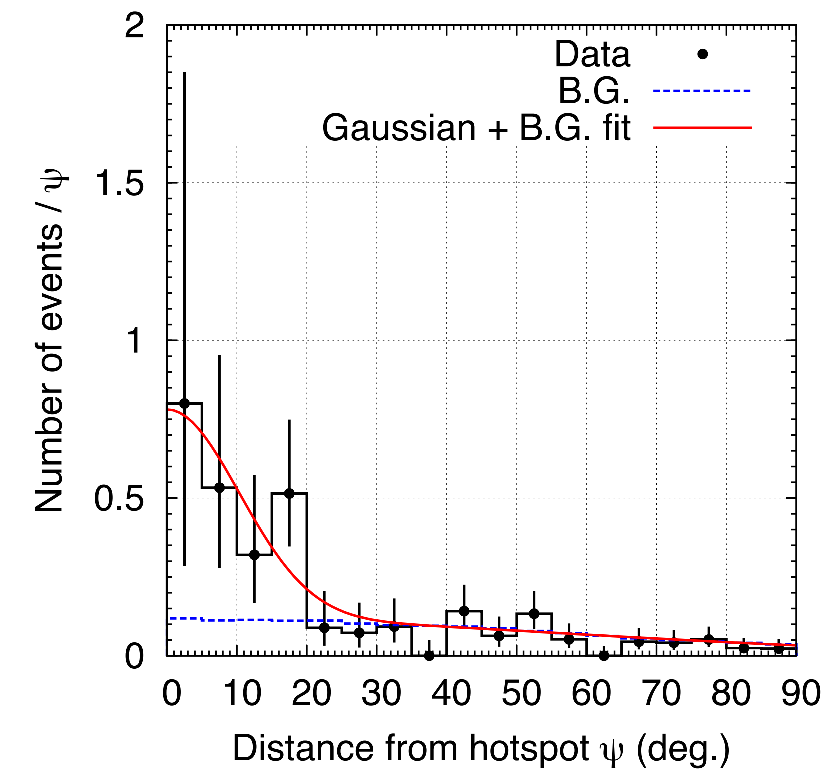
- dipolar anisotropy ~a few percent
- dipolar anisotropy could be a result of diffusive propagation of UHECRs in turbulent magnetic fields
- source distribution may also cause similar pattern



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

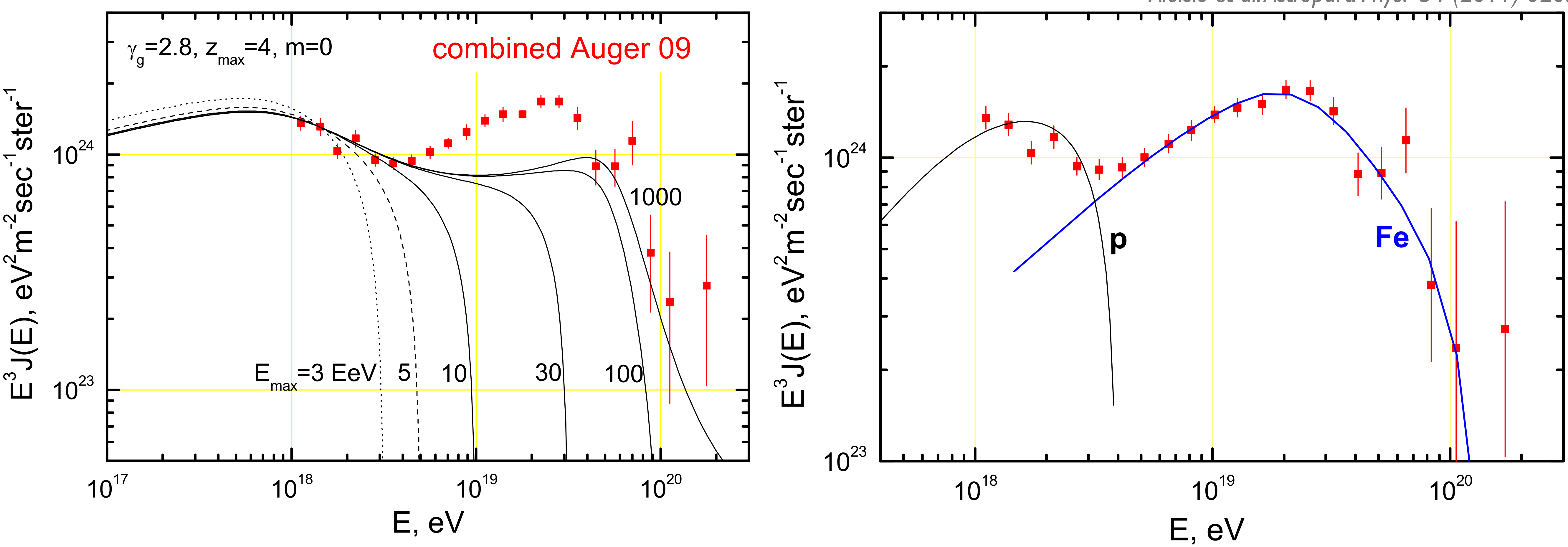
the end of the cosmic ray spectrum

- Greisen-Zatsepin-Kuzmin (GZK) cutoff?

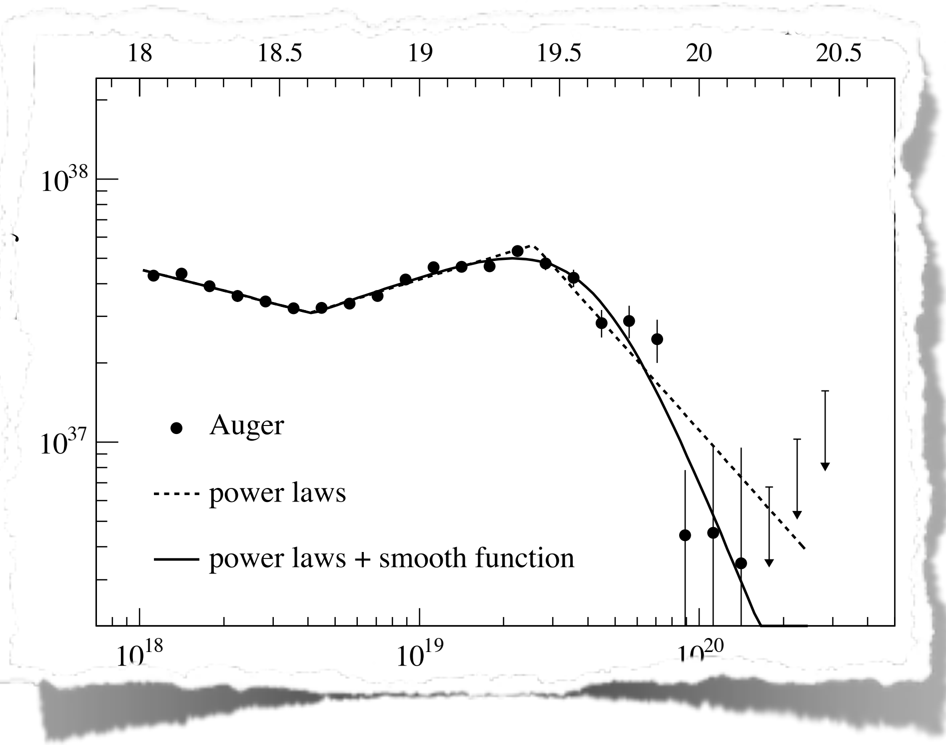
$$p + \gamma \to \Delta^+ \to \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

- energy of the GZK cutoff: ~ 50 EeV
- GZK cutoff requires → proton-dominated composition at the highest energies
- alternative: the "disappointing" model (Aloisio, Berezinsky, Gazizov 2011)
- rigidity-dependent acceleration and maximum rigidity around the 5 EeV

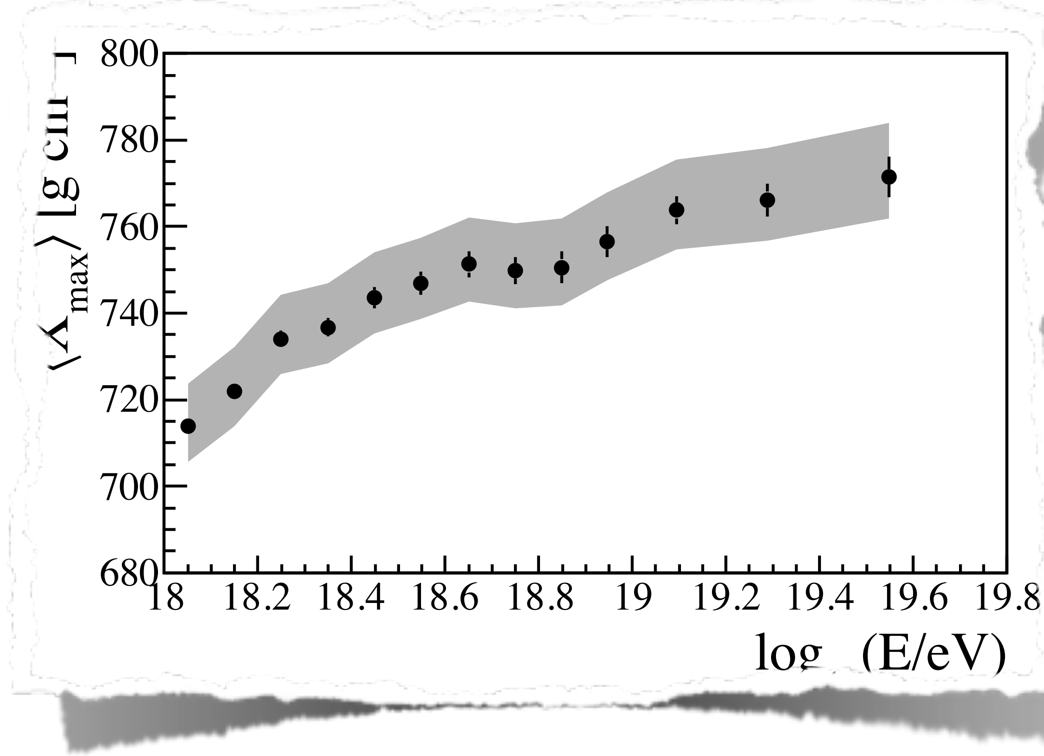
Aloisio et al. Astropart. Phys. 34 (2011) 620.



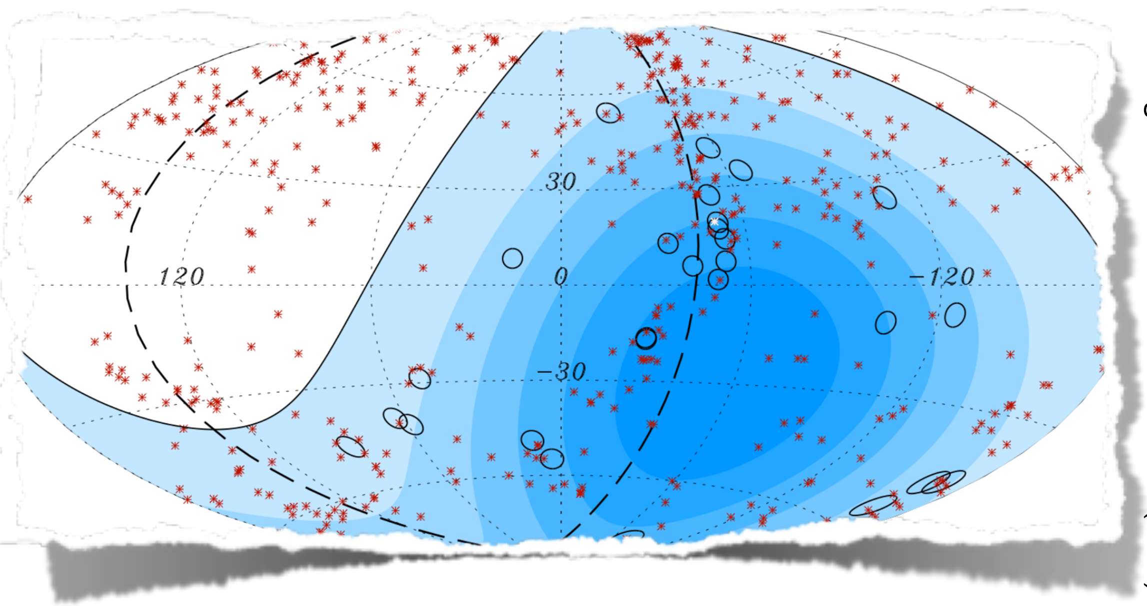
modelling the propagation of UHECRs



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

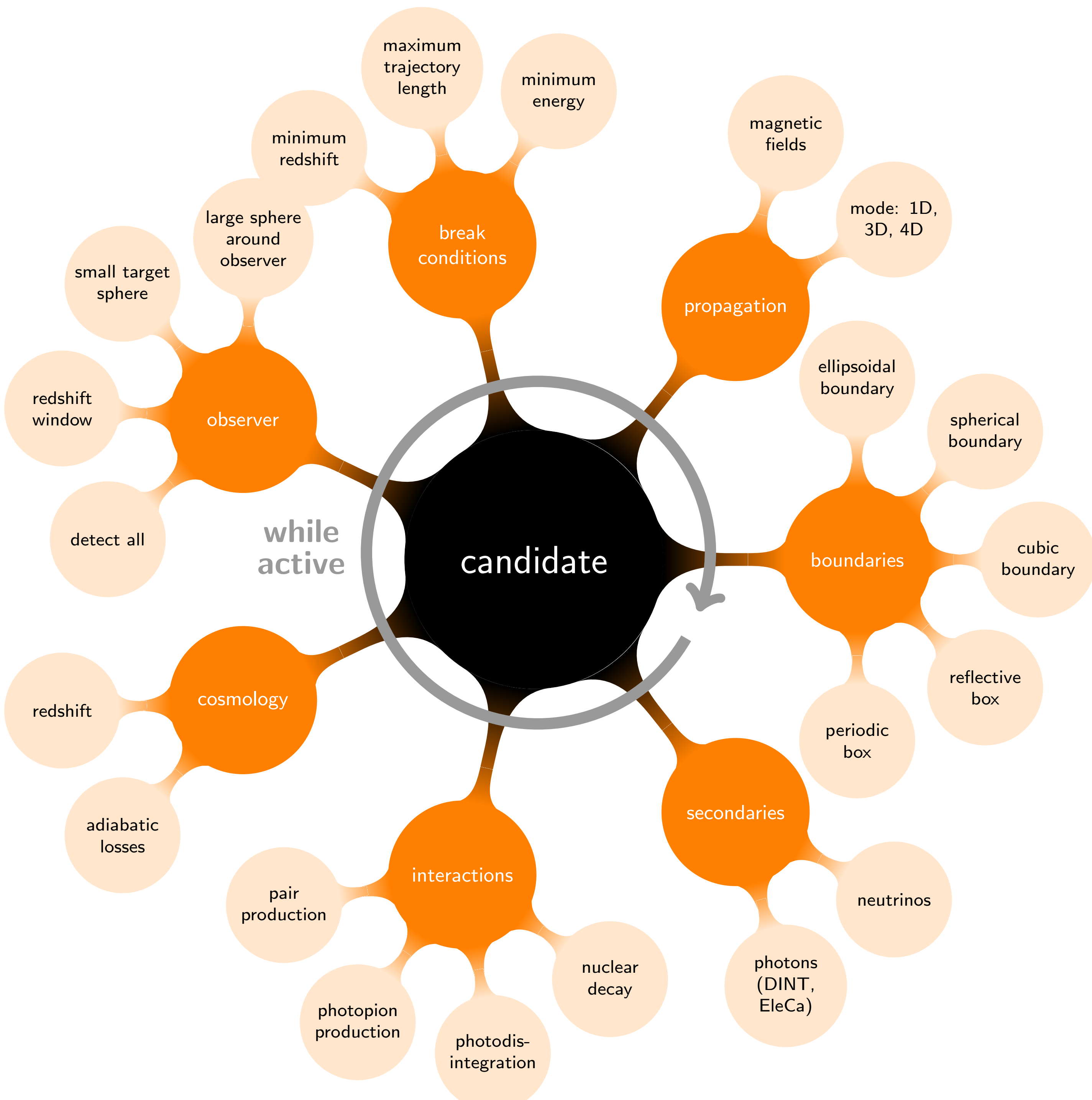
modelling the propagation of UHECRs: CRPropa

- 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
- other public codes: SimProp (Aloisio+ 2012), HERMES (de Domenico+ 2013)

crpropa.desy.de

RAB et al. EPJ Web of Conf. 99 (2015) 13004. arXiv:1411.2259

RAB et al. In preparation. arXiv:1512.XXXXX

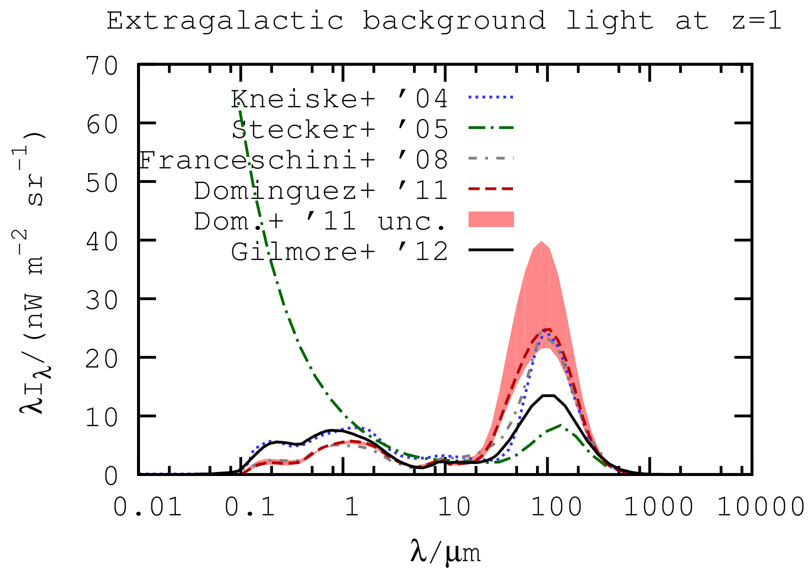


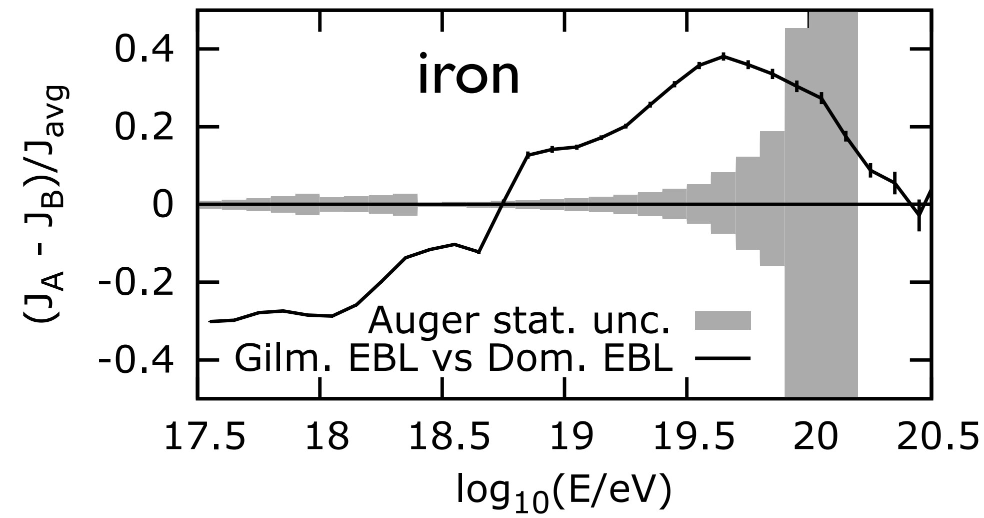
theoretical uncertainties in the modelling

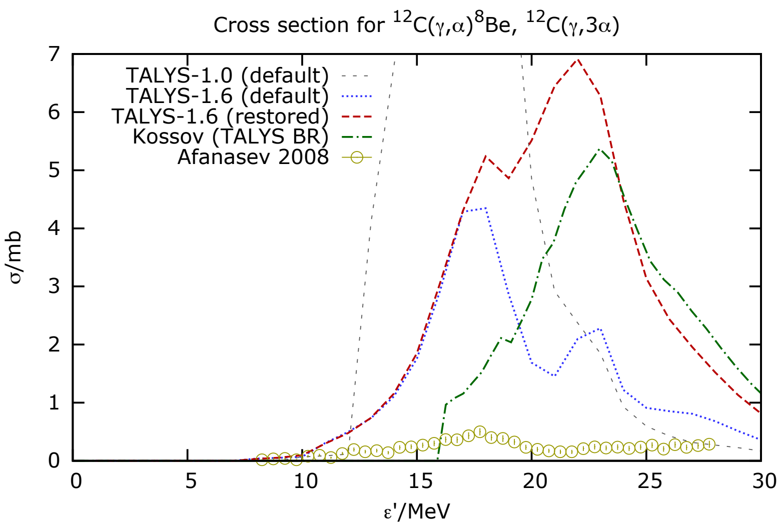
RAB, Boncioli, di Matteo, van Vliet, Walz. JCAP 1510 (2015) 063.
arXiv:1508.01824

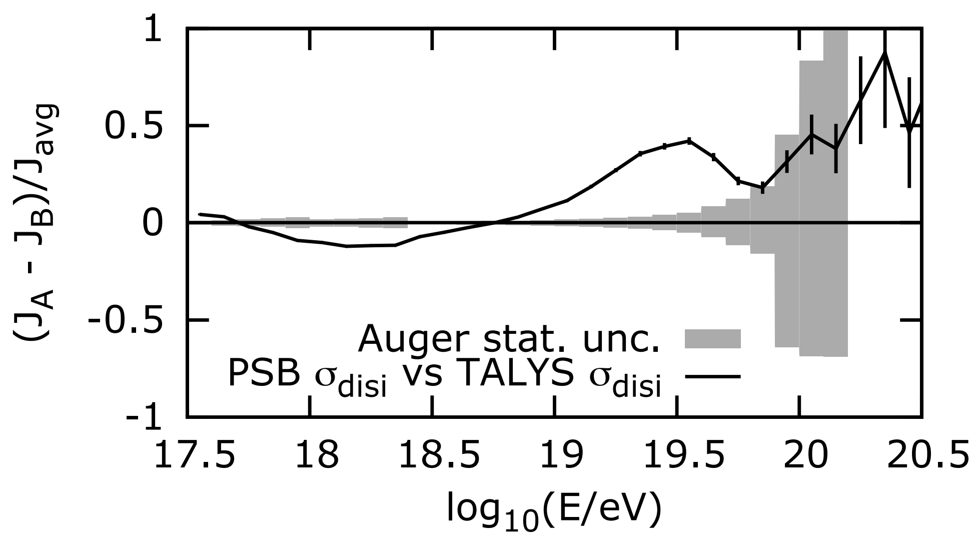
main sources of uncertainties

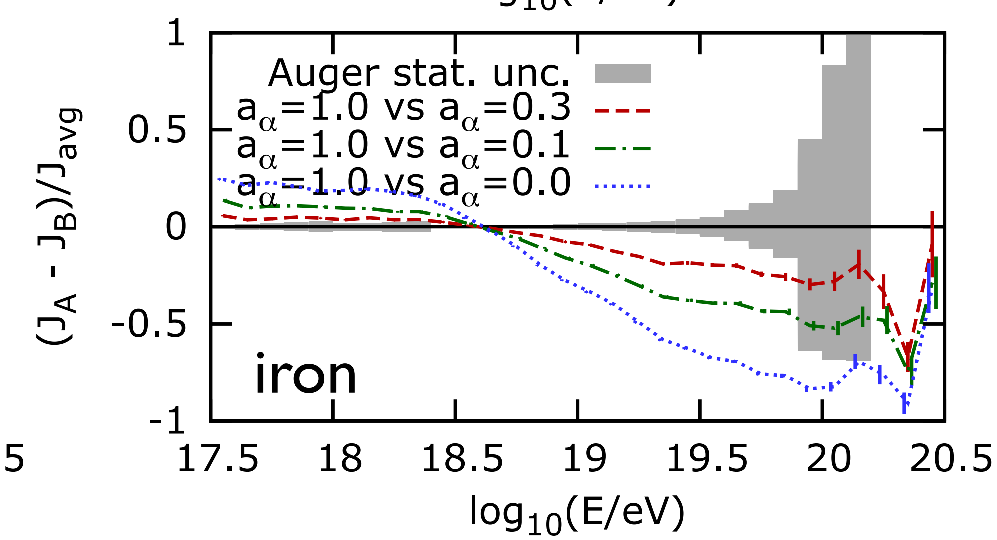
- photodisintegration cross sections
- EBL model
- scaling of alpha-channels
- propagation codes

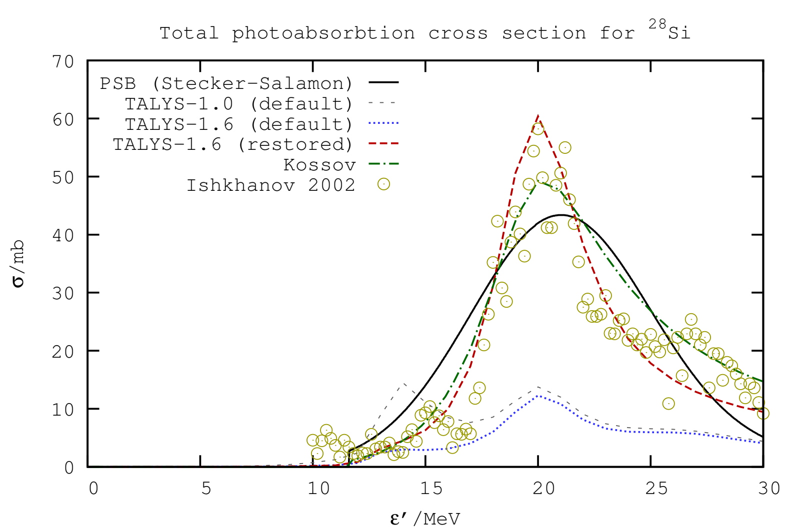


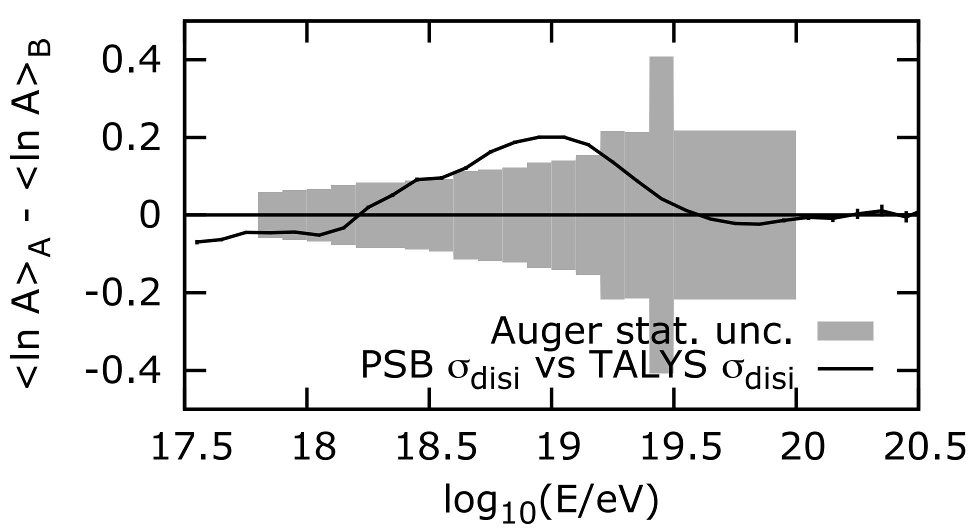


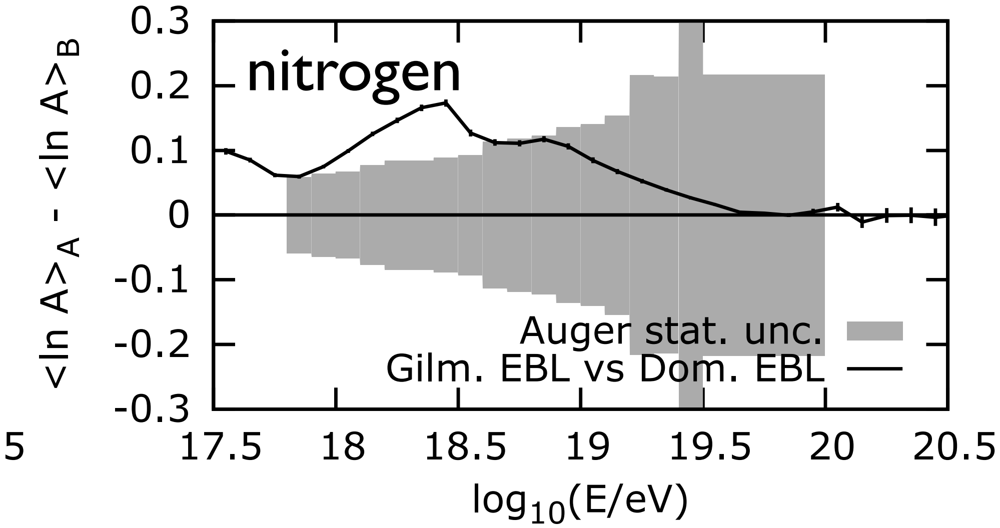












combined spectrum-composition fits

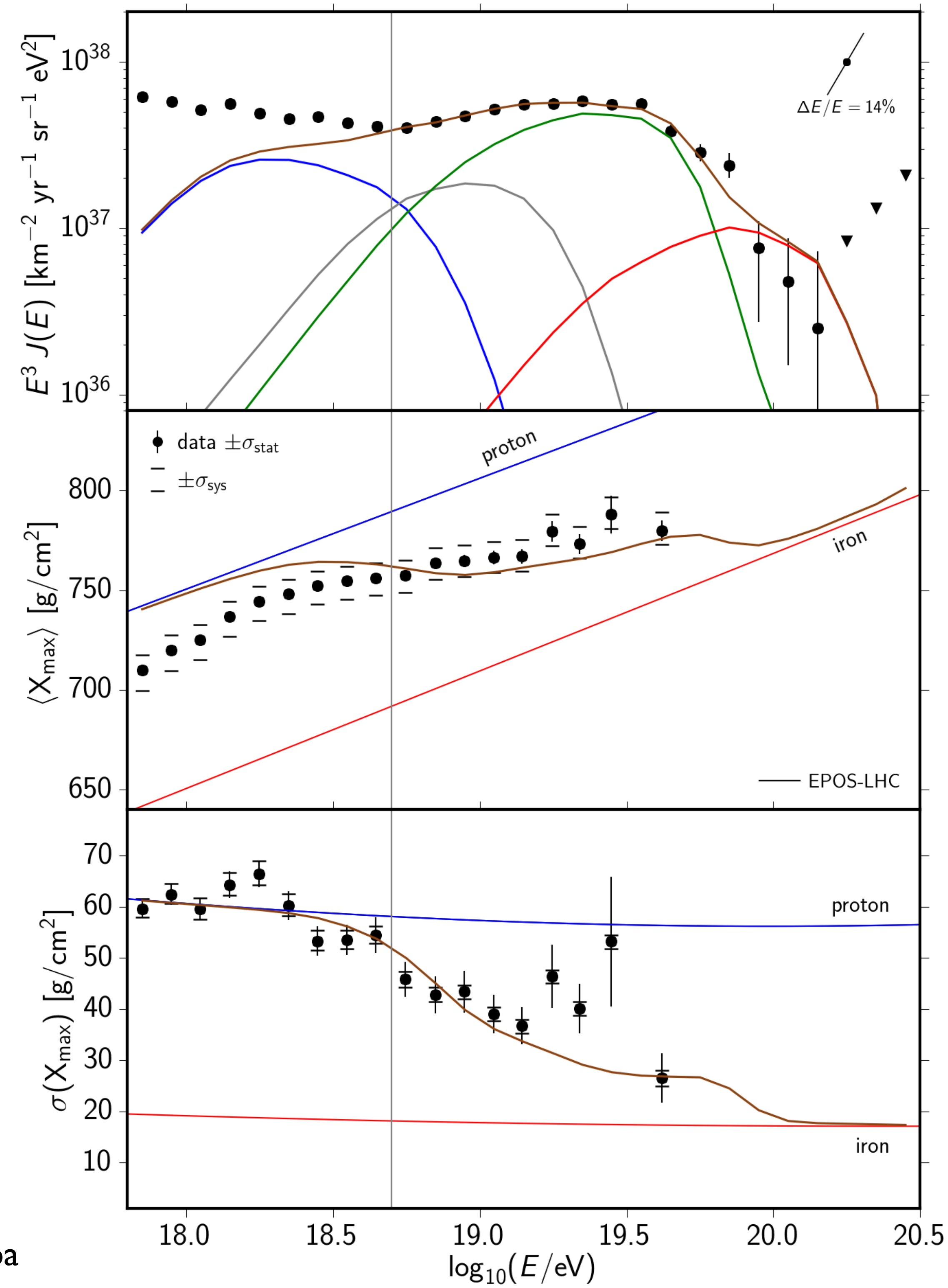
RAB, D. Boncioli, A. di Matteo, A. van Vliet, D. Walz. JCAP 1510 (2015) 063.
arXiv:1508.01824

- attempt to fit the Auger spectrum and composition
- assumption: identical sources uniformly distributed in comoving volume
- nuclear species: ^{1}H, ^{4}He, ^{14}N and ^{56}Fe
- magnetic fields are neglected in this 1st order approximation → 1D propagation
- we fit with the function (above $10^{18.7}$ eV)

$$\frac{dN}{dE} = \sum_i J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1 & \text{if } E < Z_i R_{cut} \\ \exp\left(1 - \frac{E}{Z_i R_{cut}}\right) & \text{if } E > Z_i R_{cut} \end{cases}$$

- interactions with the atmosphere modelled with: EPOS-LHC, QGSJET II-04, Sybill 2.1
- sources of uncertainties: EBL model, photodisintegration cross sections [RAB+' 15]
- two codes used for cross-checking: CRPropa, SimProp
- EBL models studied: Kneiske '04, Domínguez+ '11, Gilmore+ '12
- photodisintegration cross sections: TALYS, Geant 4, Puget-Stecker-Bredekamp
- upcoming paper by Auger Collaboration

combined spectrum-composition fits

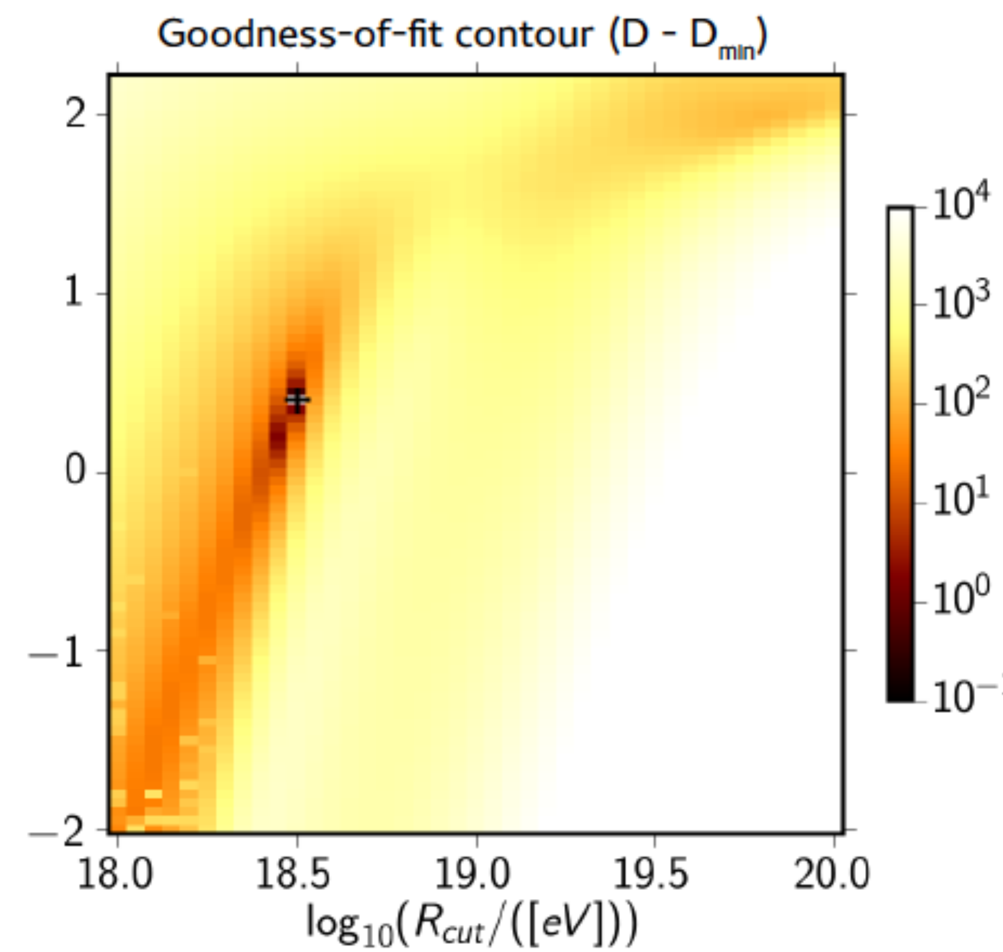


CRPropa

Kneiske '04 EBL model

TALYS cross sections for PD

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



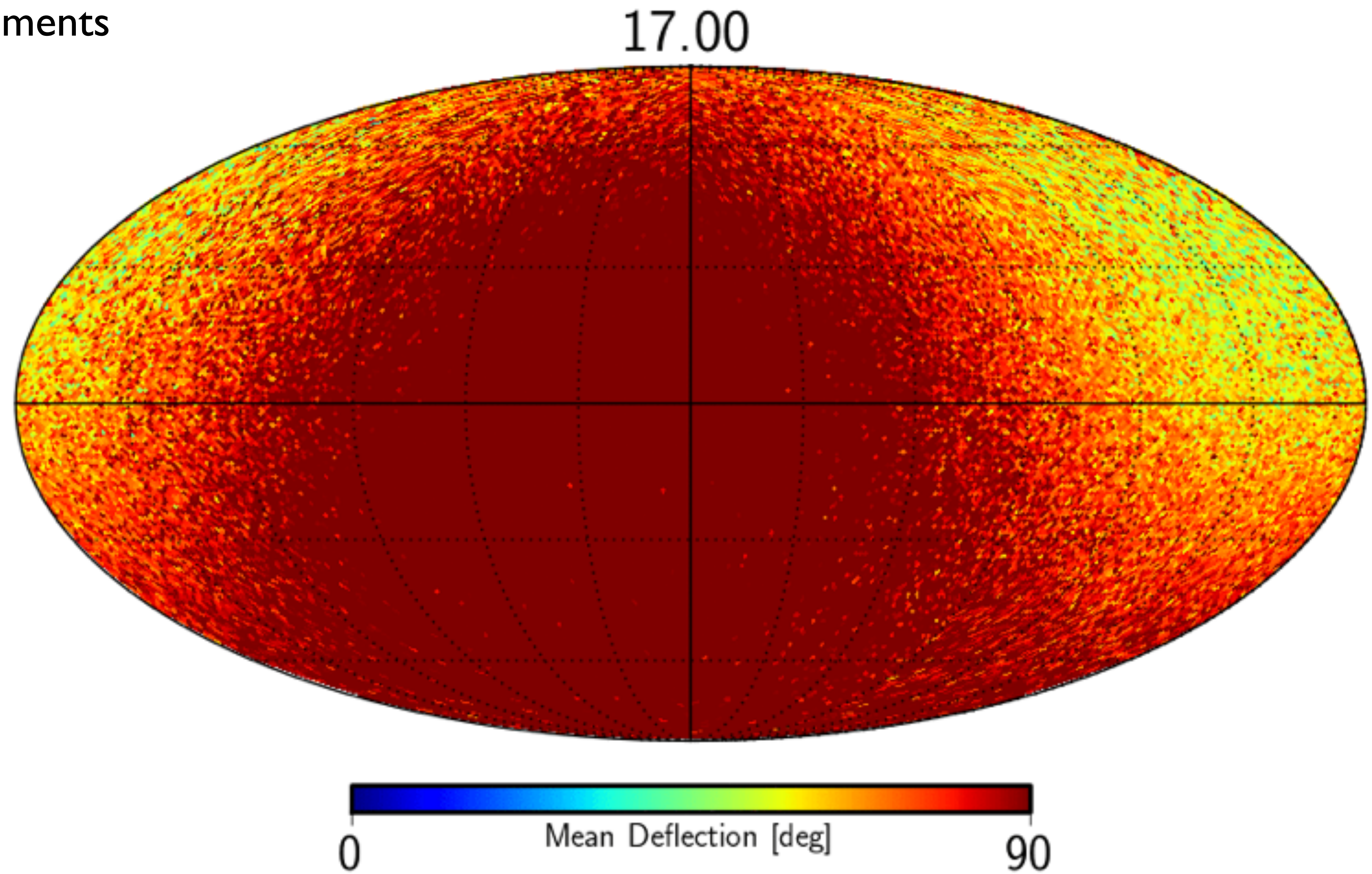
- log(Rcut / V) = 18.48
- γ = 0.29 (+0.08 | -0.07)
- fraction of H: 14.3% (+4.2 | -14.2)
- fraction of He: 10.0% (+2.2 | -10.0)
- fraction of N: 75.3% (+15.5 | -9.4)
- fraction of Fe: 0.5% (+0.1 | -0.1)

combined spectrum-composition fits

- combined spectrum-composition (1D) fits of the Auger spectrum/composition *[Aloisio+ '13, Taylor '13]*
- mixed composition; maximum source acceleration cutoff (no GZK)
- results suggest an extra (light) class of sources below the ankle might be needed → Auger + KASCADE-Grande data
- hard spectra "problem" *[Taylor '13]*: these fits seem to suggest that the sources have spectral indexes harder than expected ($\gamma \approx 1.0$-1.6); expected $\gamma \approx 2.0$-2.2 for Fermi acceleration
- 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]*

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

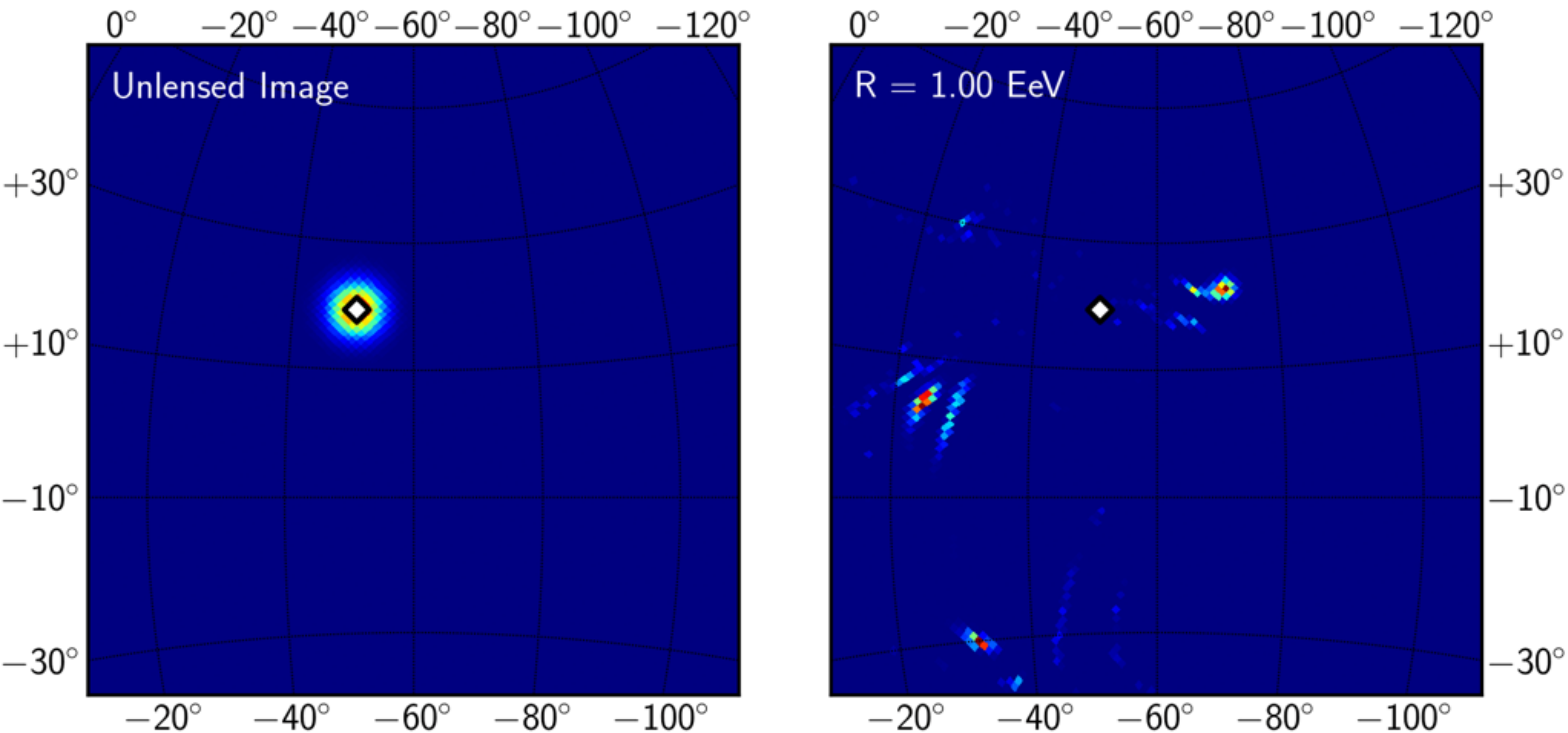


obtained with the PARSEC code:

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

UHECRs and the galactic magnetic field

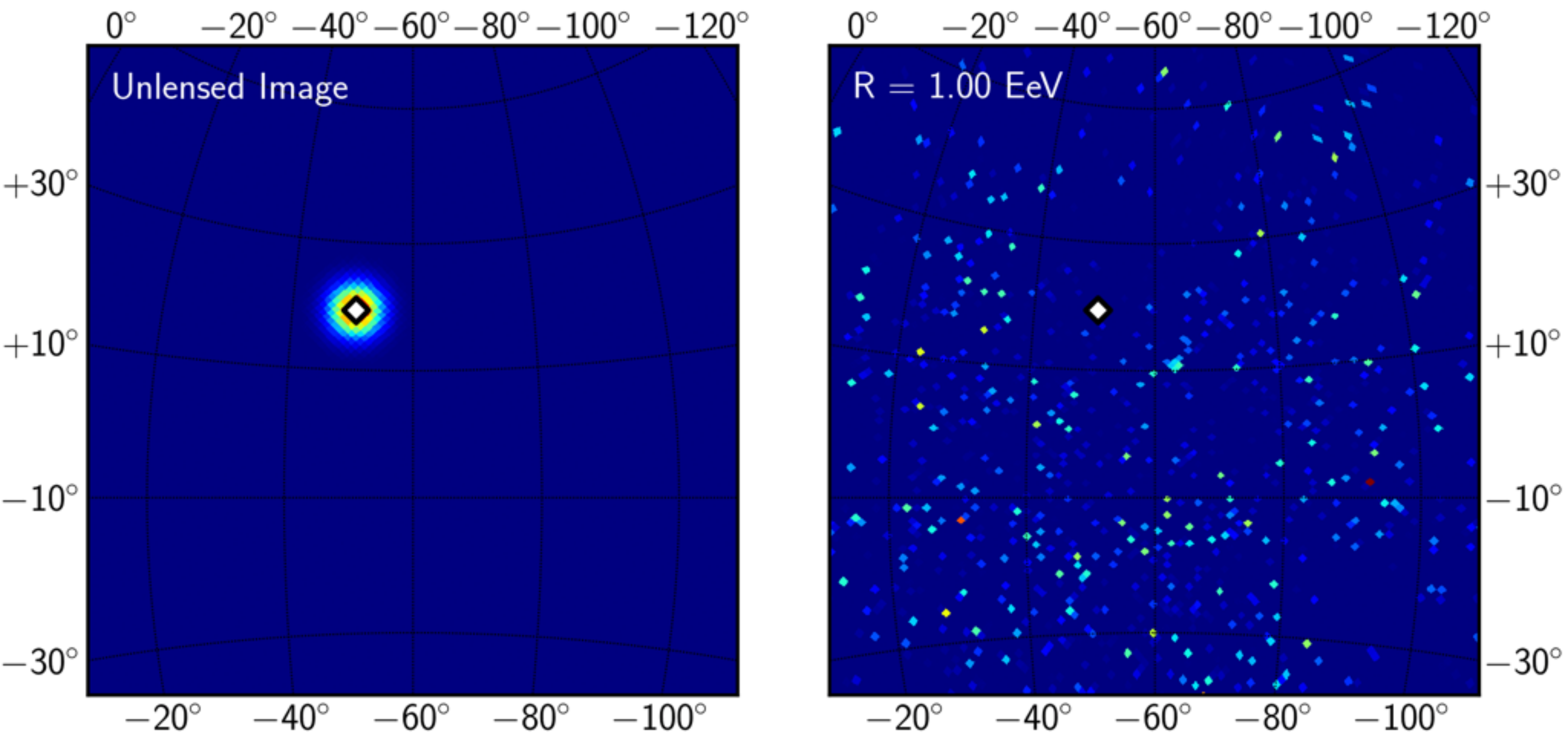
- the case of Centaurus A, assuming only galactic deflections and only the regular component of the field



obtained with the PARSEC code

UHECRs and the galactic magnetic field

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



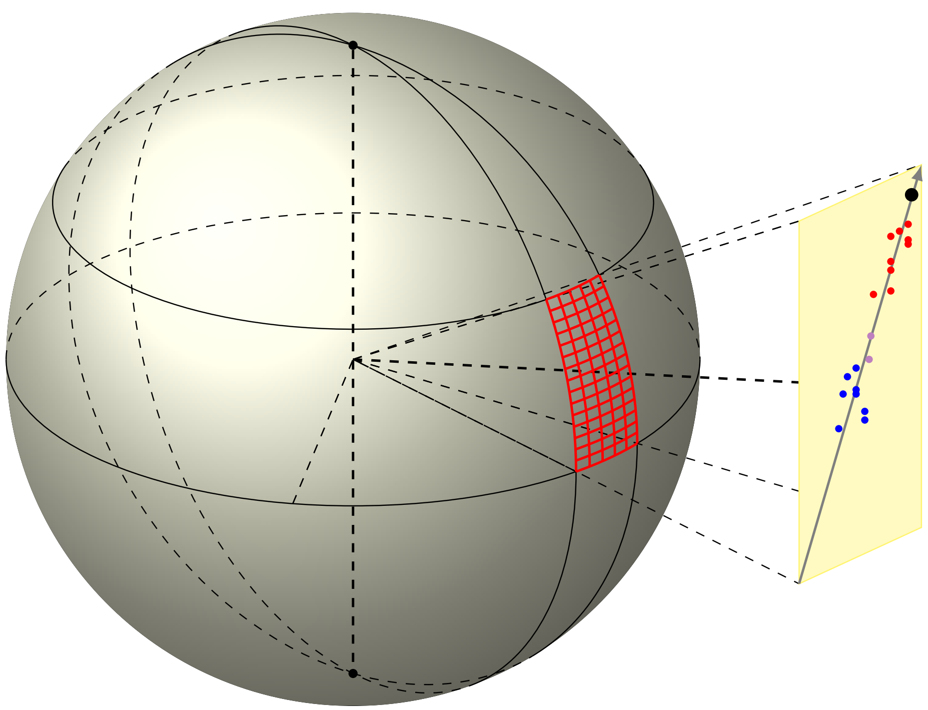
obtained with the PARSEC code

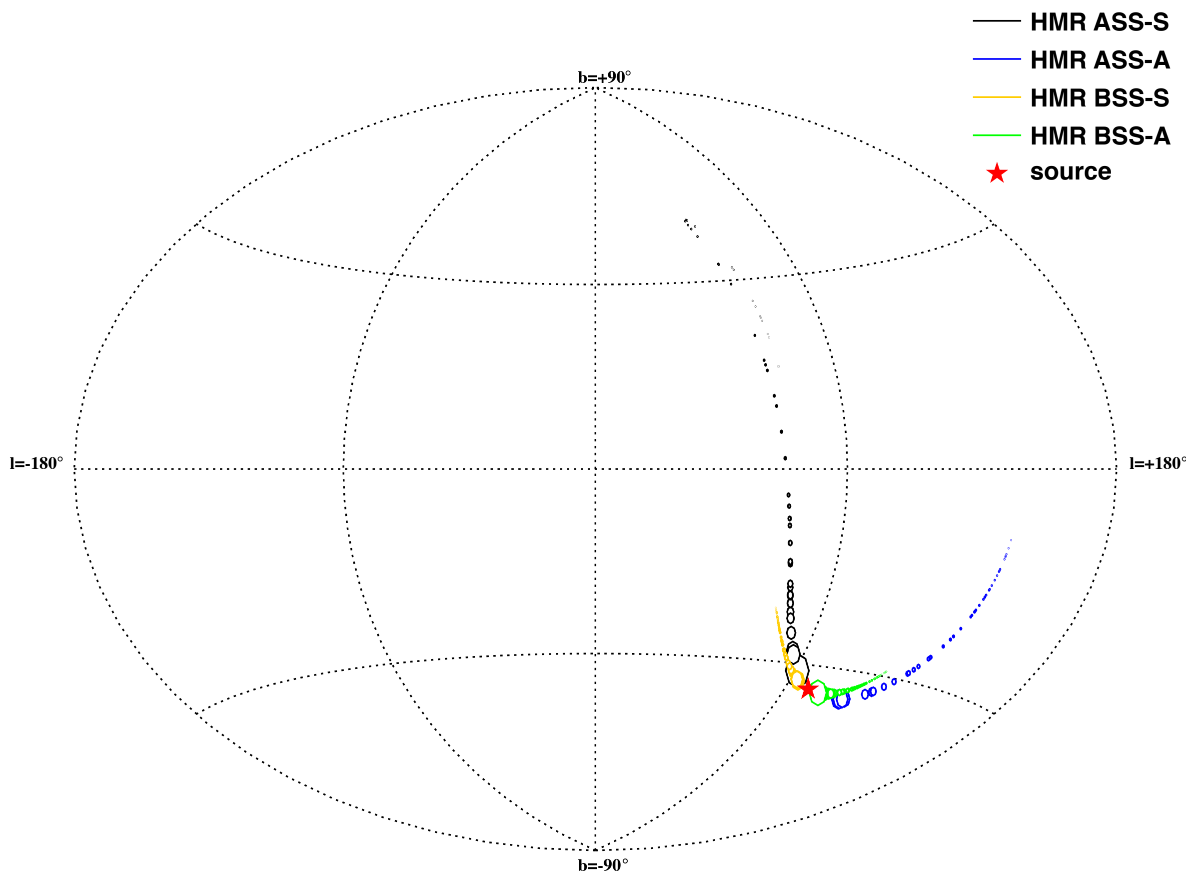
UHECRs and the galactic magnetic field

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?

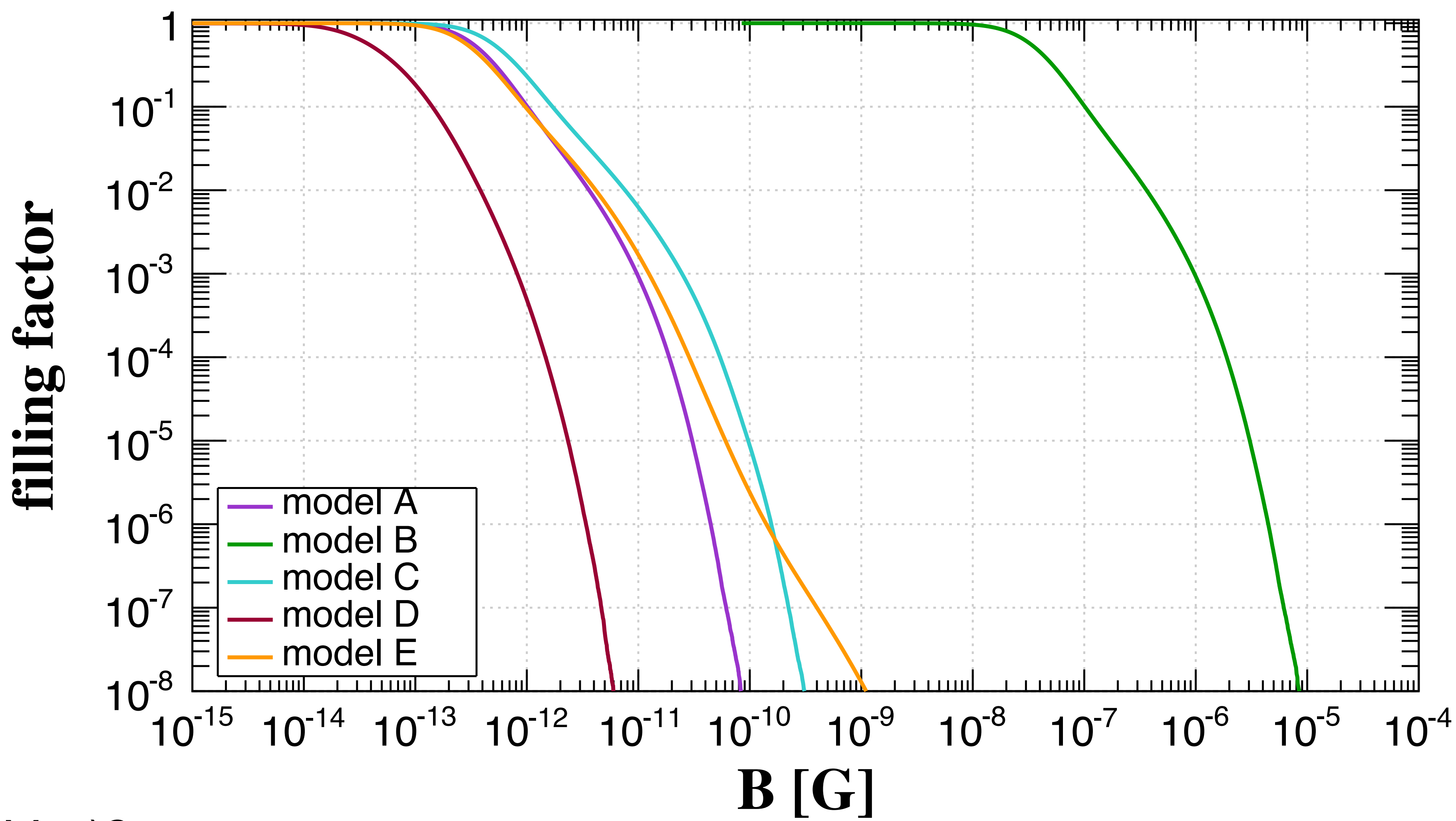




- no multiplets detected in Auger data *[Auger '12]*
- constrain models of GMF with multiplets?
- probably unlikely to be detected, unless source is really close and magnetic fields are "well-behaved"

deflections in extragalactic magnetic fields

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

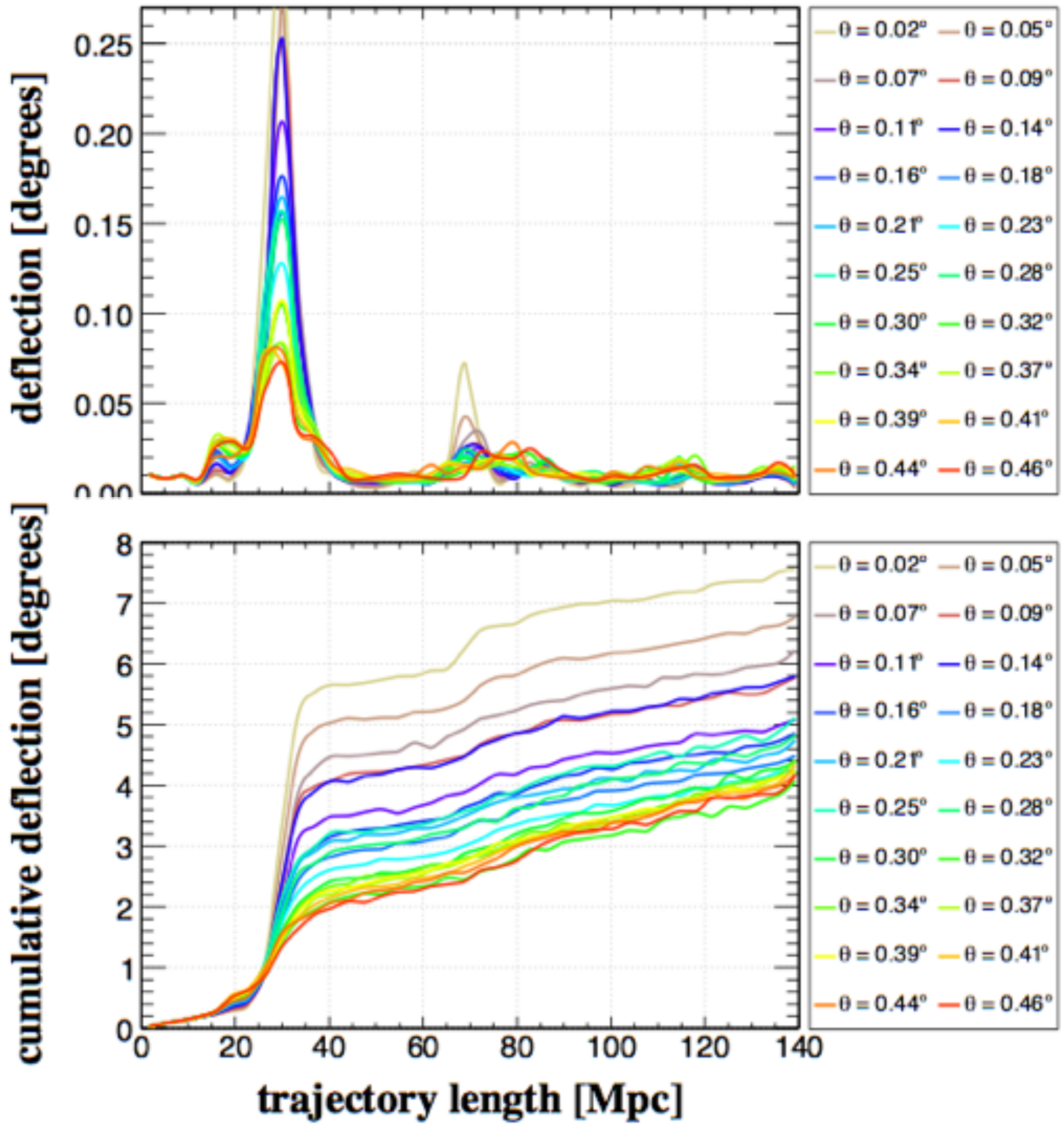


- ($200h^{-1}$ Mpc)3
- AMR grid
- 10 levels of refinement
- RAMSES code
- ideal MHD

- model A: 256^3, fiducial
- model B: 256^3, fiducial, B_0 10^5 x stronger
- model C: 256^3, B_0 small scales
- model D: 256^3, B_0 large scales
- model E: 512^3, fiducial-like

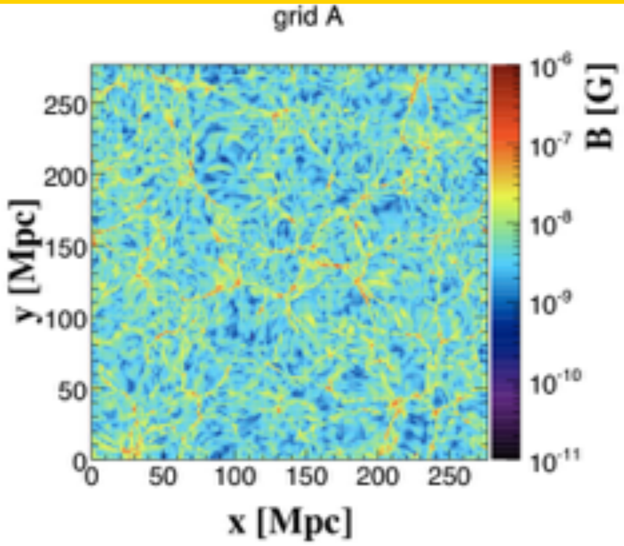
deflections in extragalactic magnetic fields

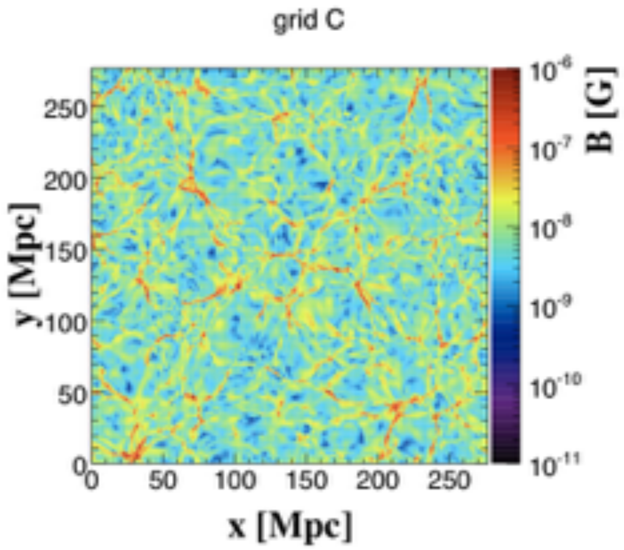
RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. In preparation.

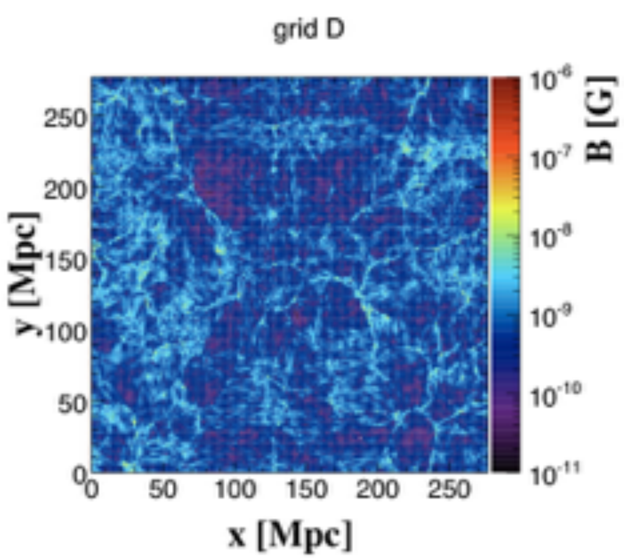


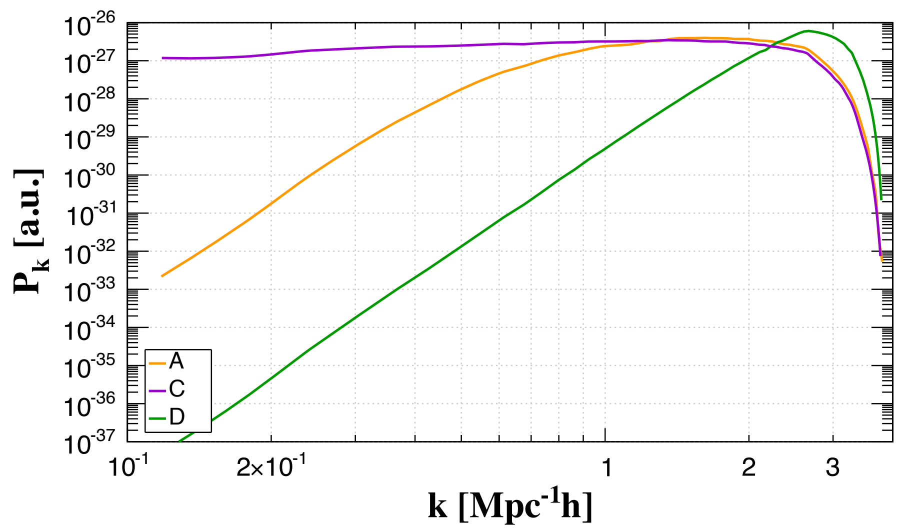
effects of B_0

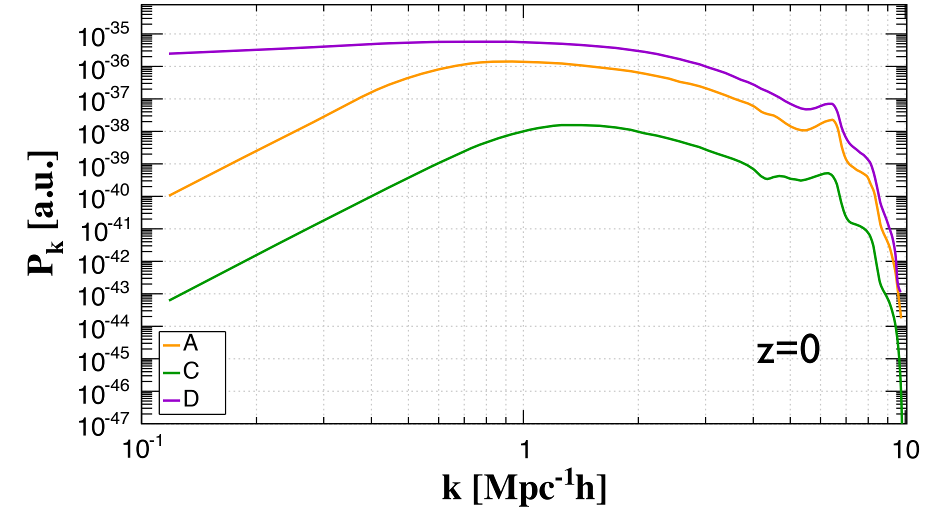
RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. In preparation.

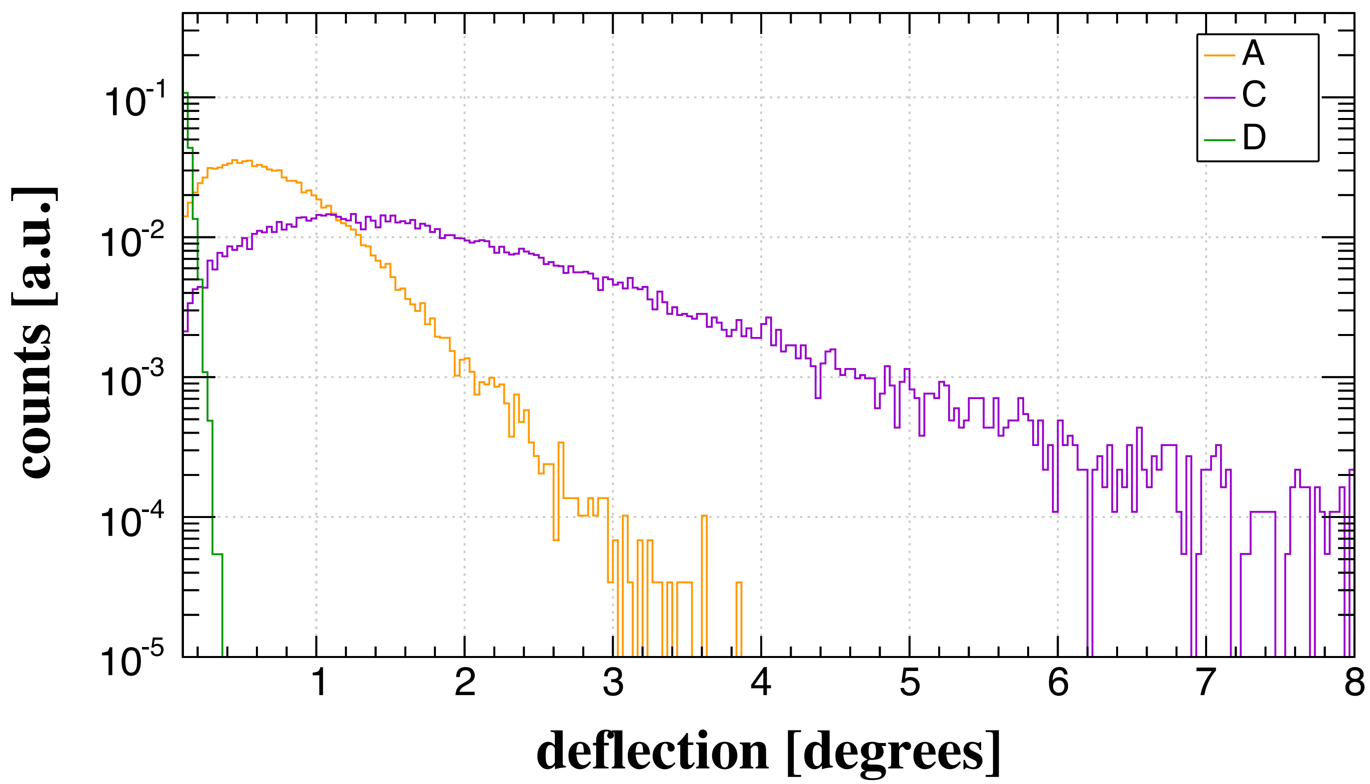






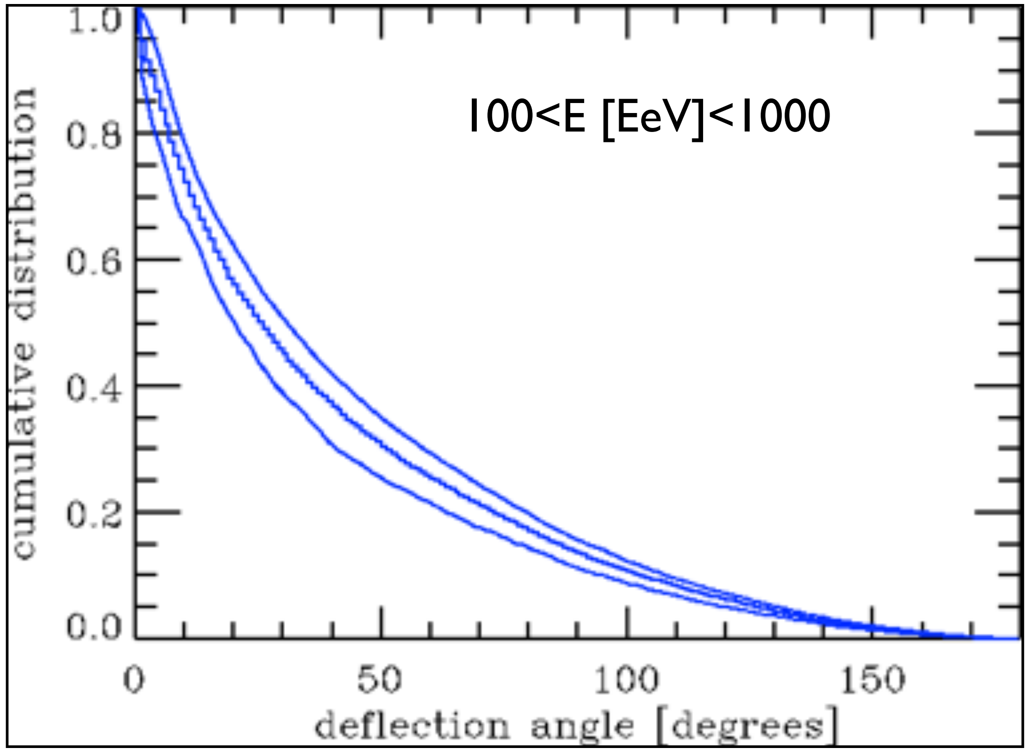






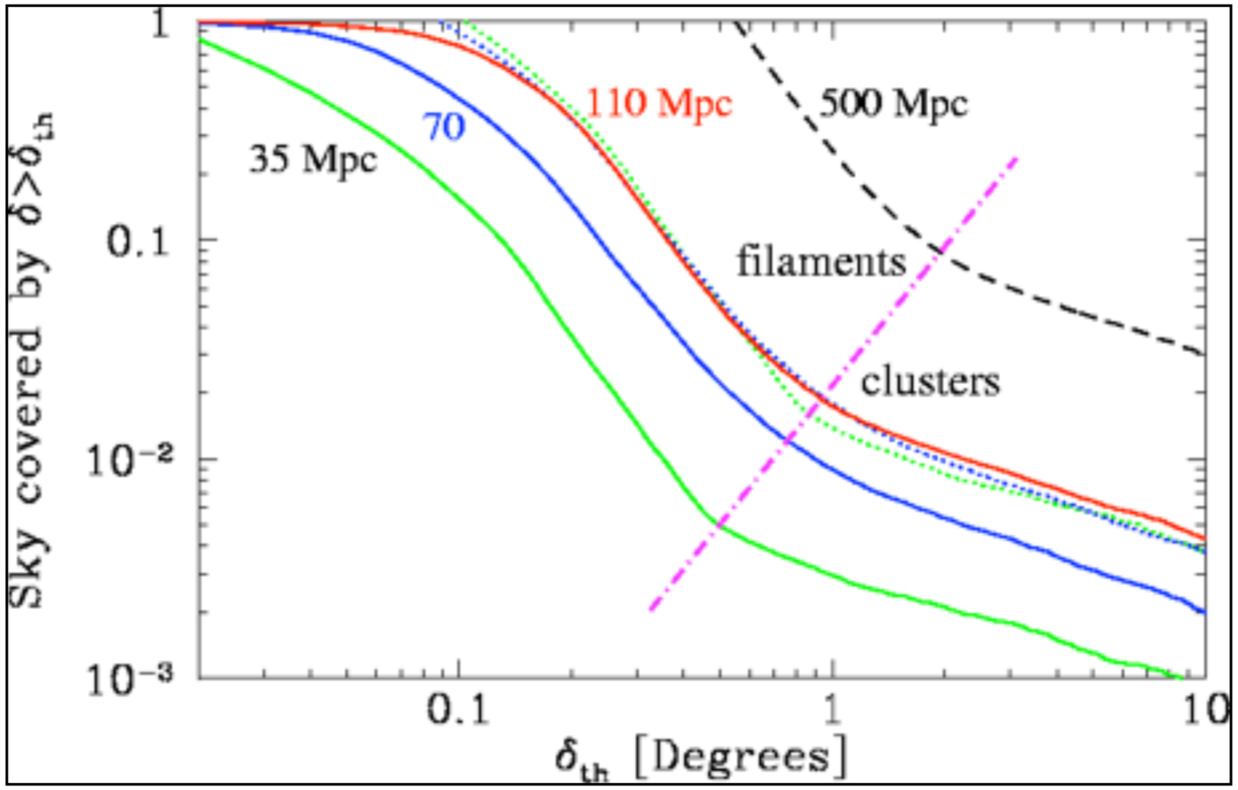
example: protons, only extragalactic magnetic field, same normalisation

UHECR astronomy?



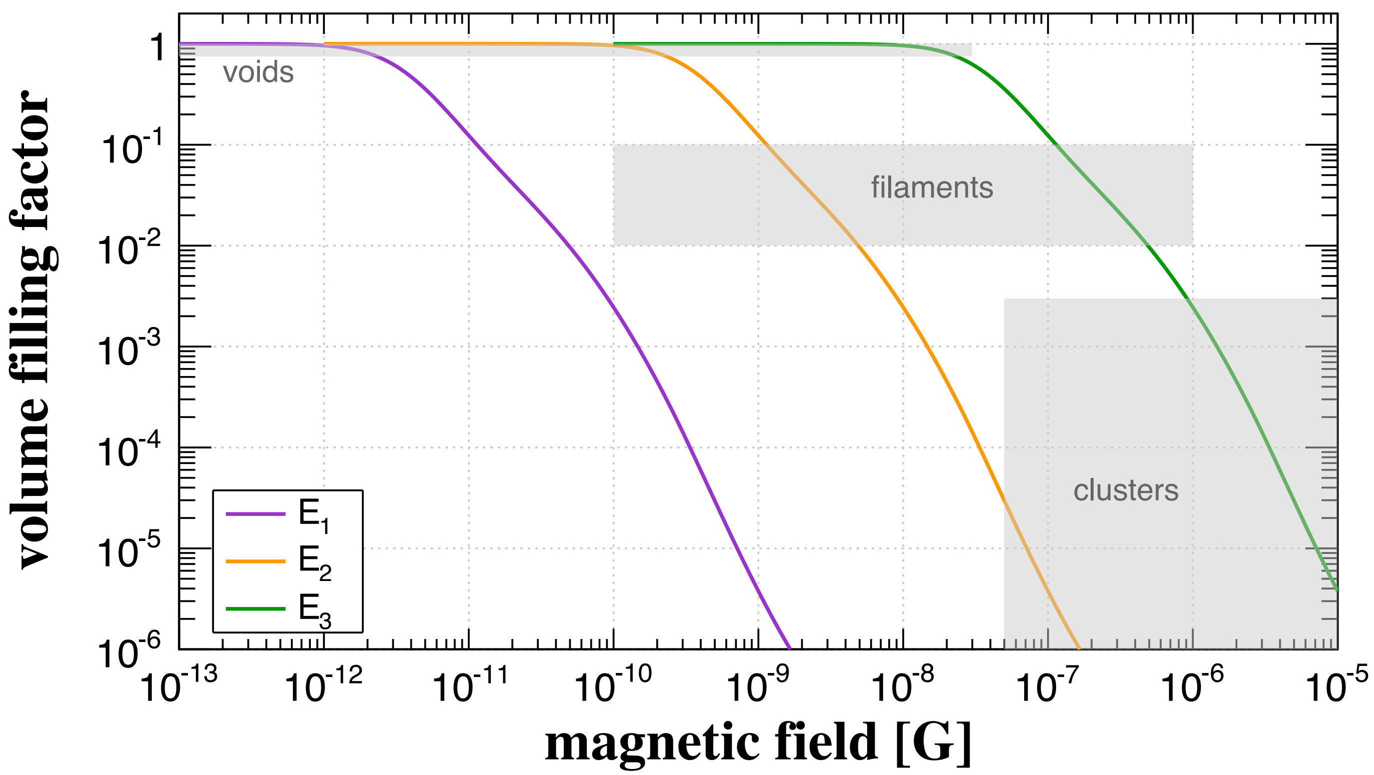
Sigl, Miniati, Ensslin. PRD 70 (2004) 043007

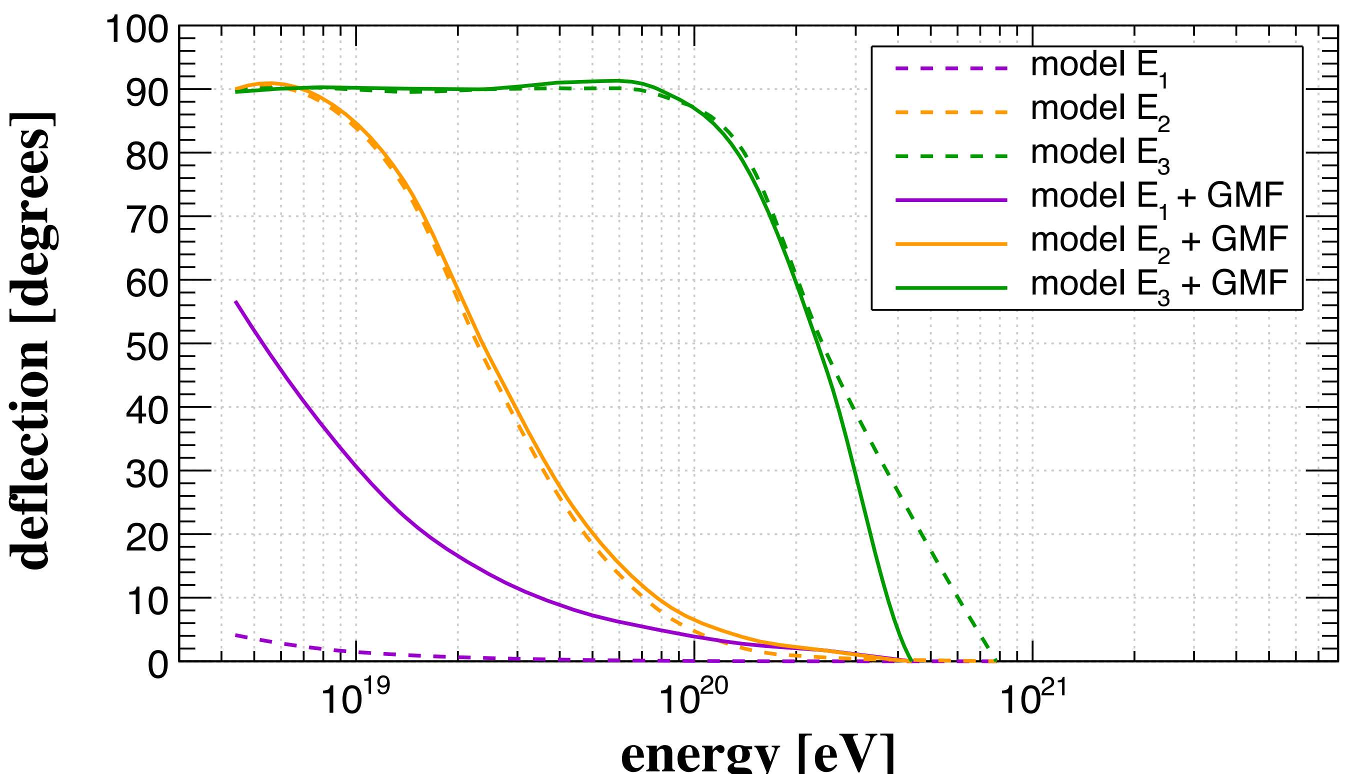
- cumulative deflections displayed are for protons
- Sigl+: deflections are high
- Dolag+: deflections are small
- for heavy nuclei deflections can be even higher
- UHECR astronomy may be possible in the later but not in the former scenario



Dolag et al. JETP 79(2004) 583

UHECR astronomy?





example: protons only

- three scenarios obtained by scaling the filling factors distribution
- "old" debate: Sigl et al. vs Dolag et al.
- Sigl+ '04: deflections are high
- Dolag+ '04: deflections are small
- for heavy nuclei deflections can be even higher
- hard to pinpoint the sources of UHECRs
- UHECR astronomy may still be possible in with 'nearby' (up to ~10 Mpc) sources
- deflection are on average high in most of the sky
- caveat: magnetisation around observer

prospects for UHECR astronomy do not seem so good 😞

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 UHECR may not be possible in the whole sky
- prospects for UHECR astronomy don't look so good; too many uncertainties: EBL, cross sections, magnetic fields, ...

Thank you!