

# **do magnetic fields frustrate CR astronomy?**

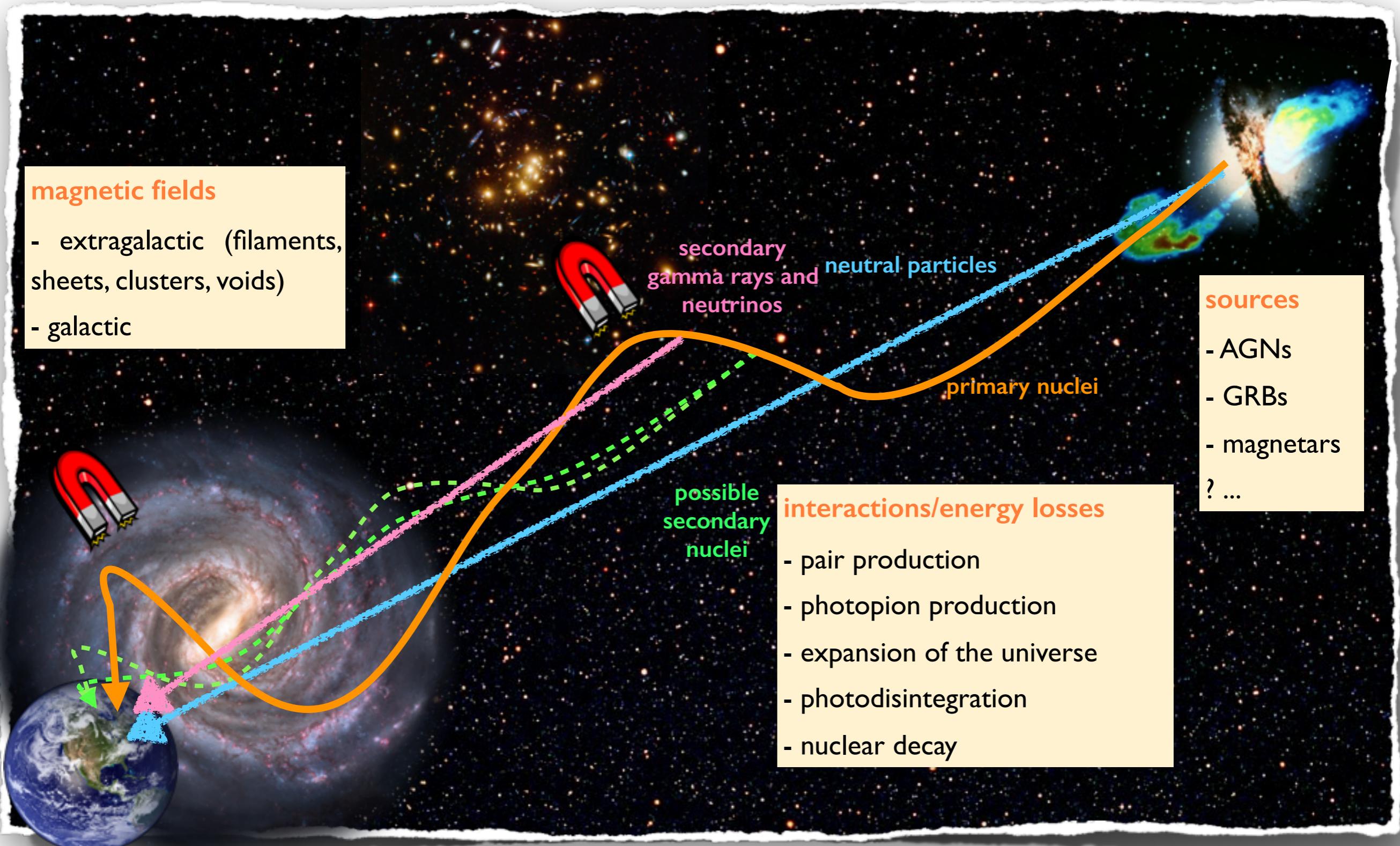
**Rafael Alves Batista**

**University of Oxford**

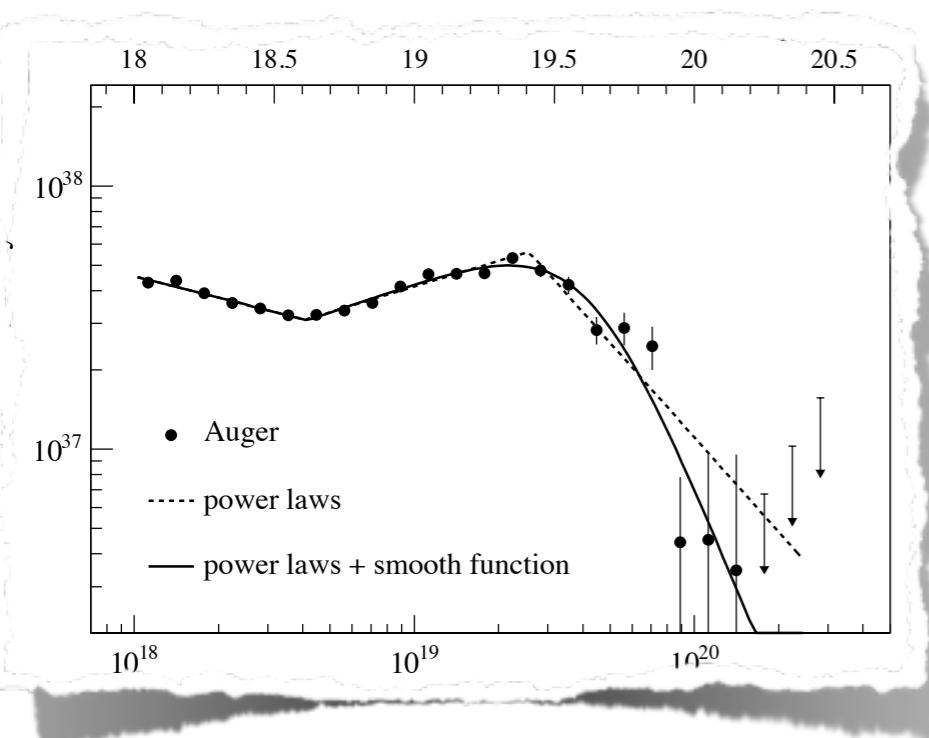
**[rafael.alvesbatista@physics.ox.ac.uk](mailto:rafael.alvesbatista@physics.ox.ac.uk)**

Dublin  
12/04/2016

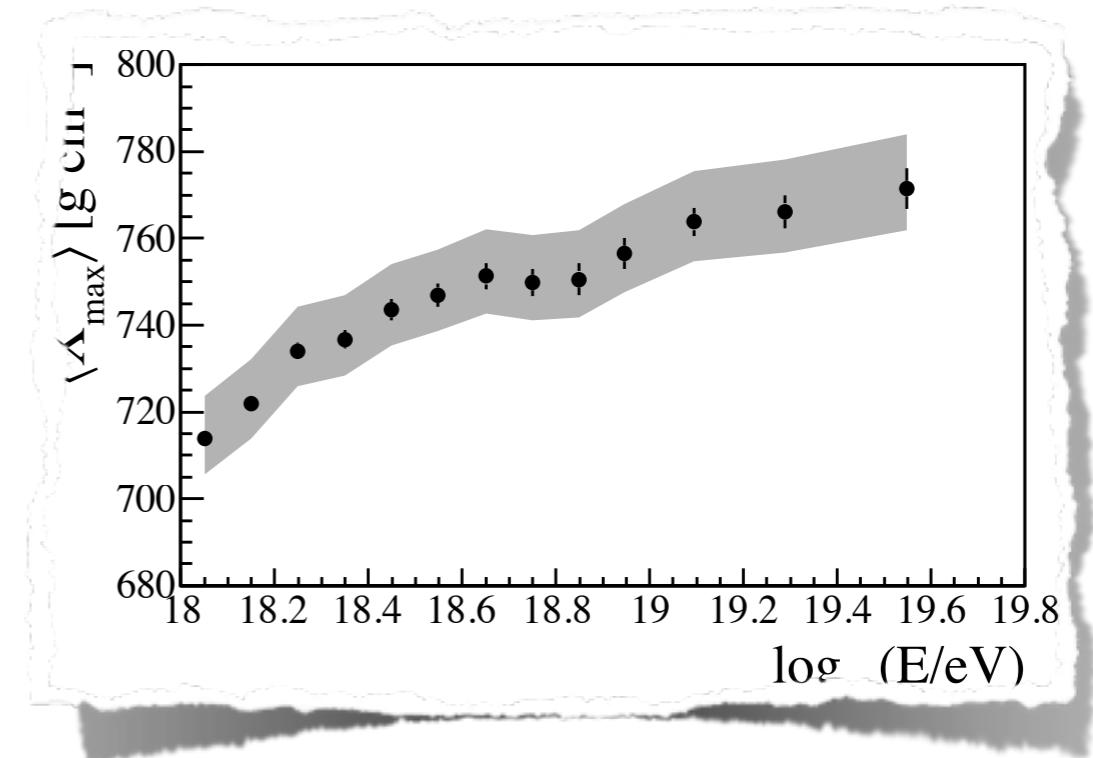
# propagation picture



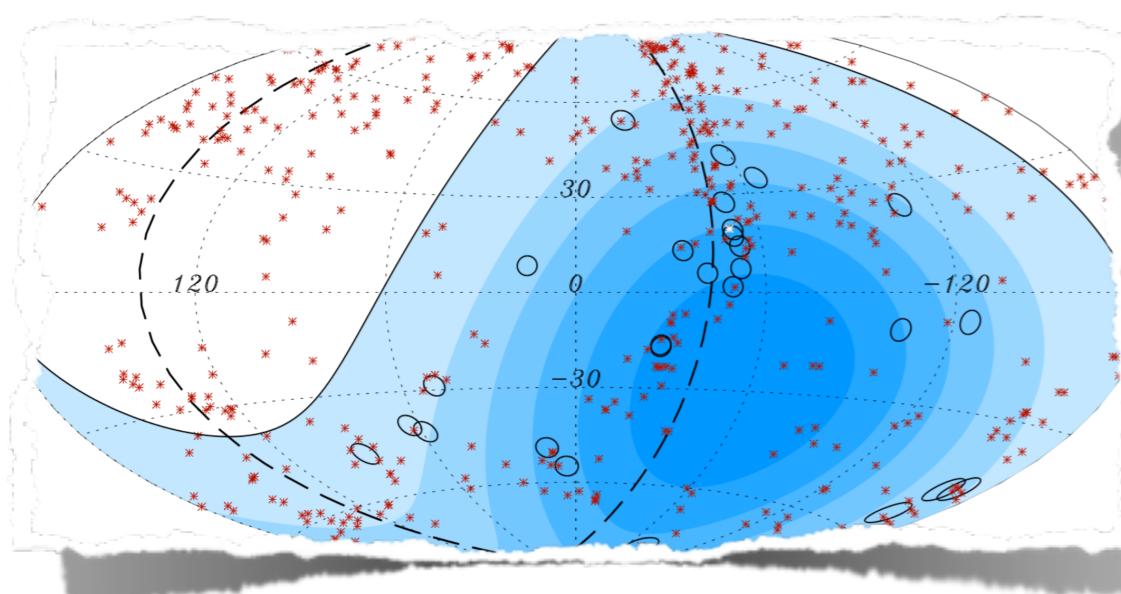
# modelling the propagation of UHECRs



Pierre Auger Collaboration. ICRC 2011.



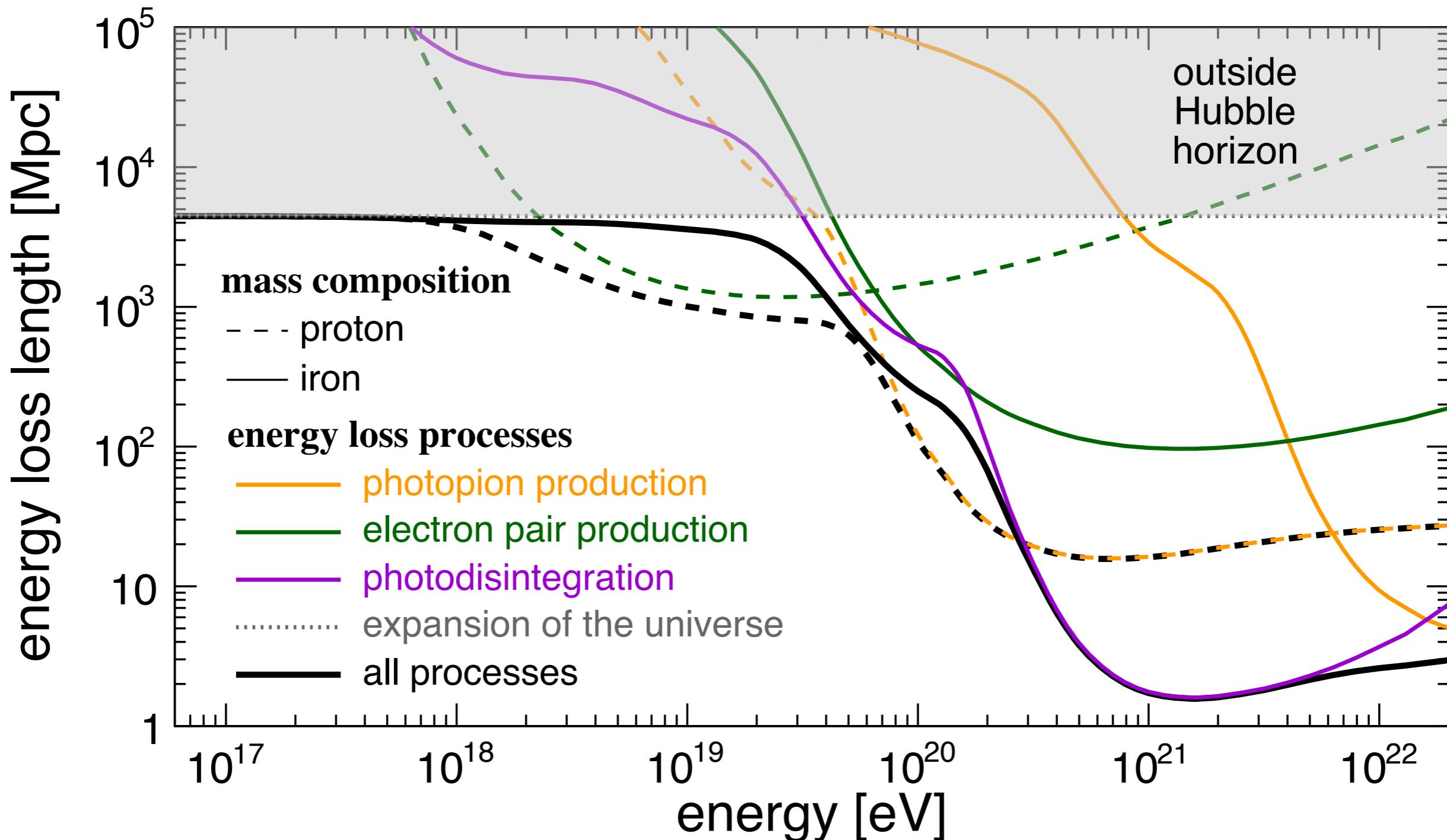
Pierre Auger Collaboration. ICAP 02 (2013) 026.



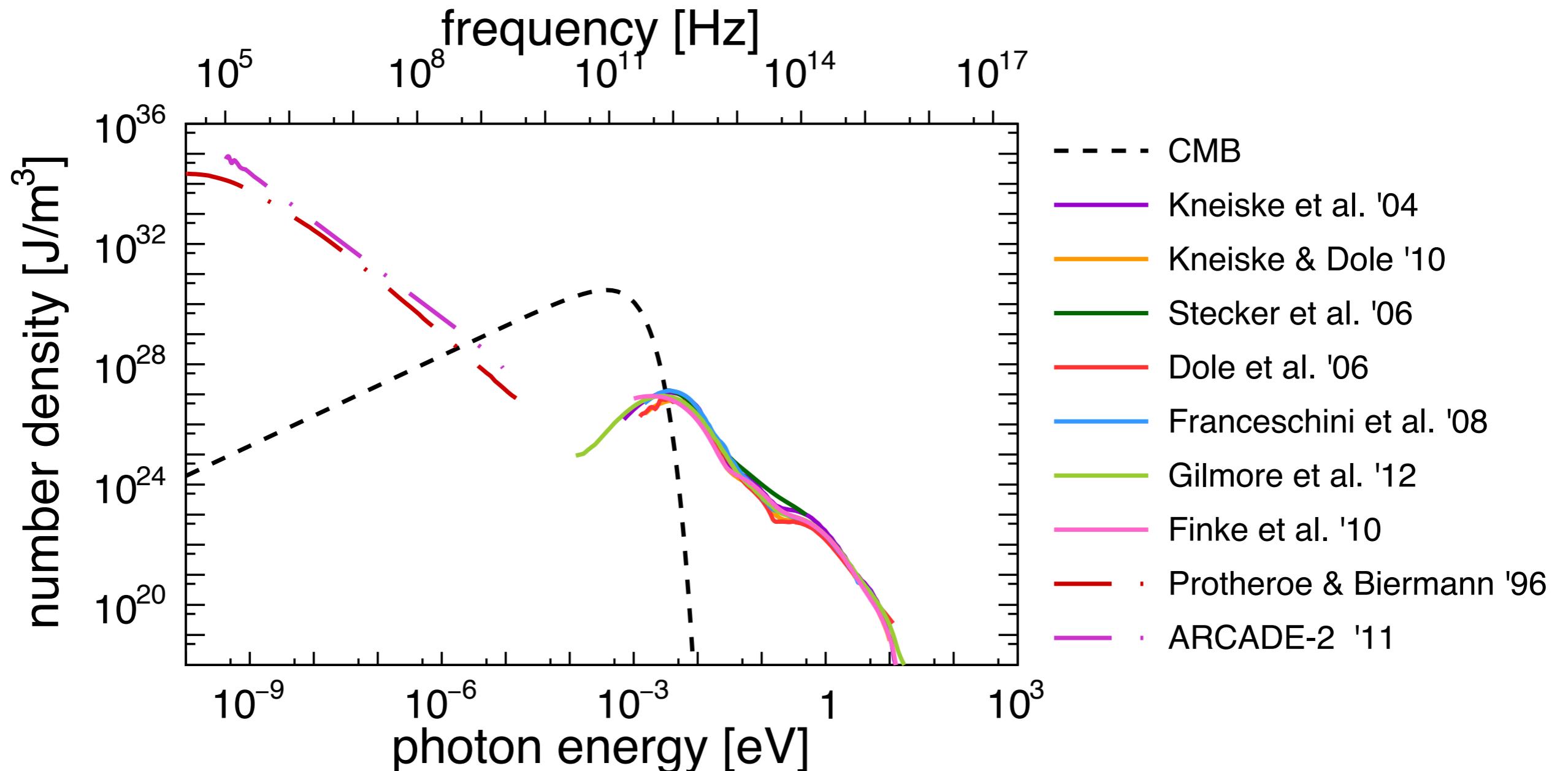
Pierre Auger Collaboration. Science 318 (2007) 938.

- ▶ 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

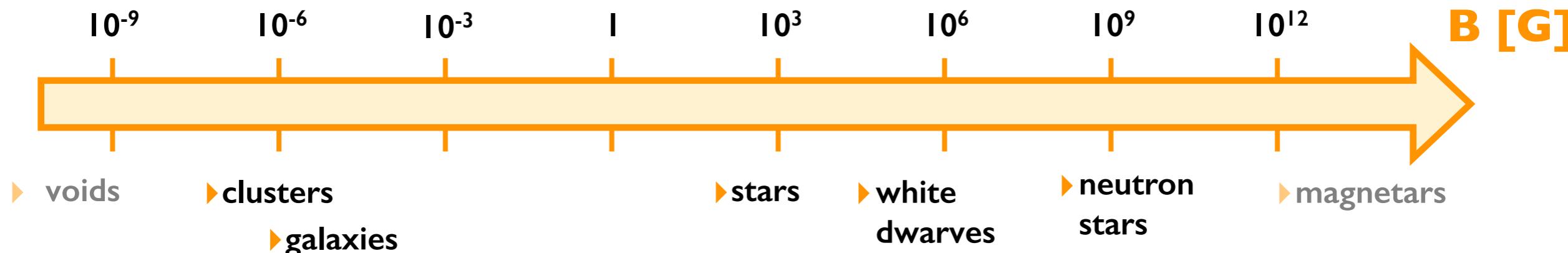
# modelling the propagation of UHECRs: energy losses



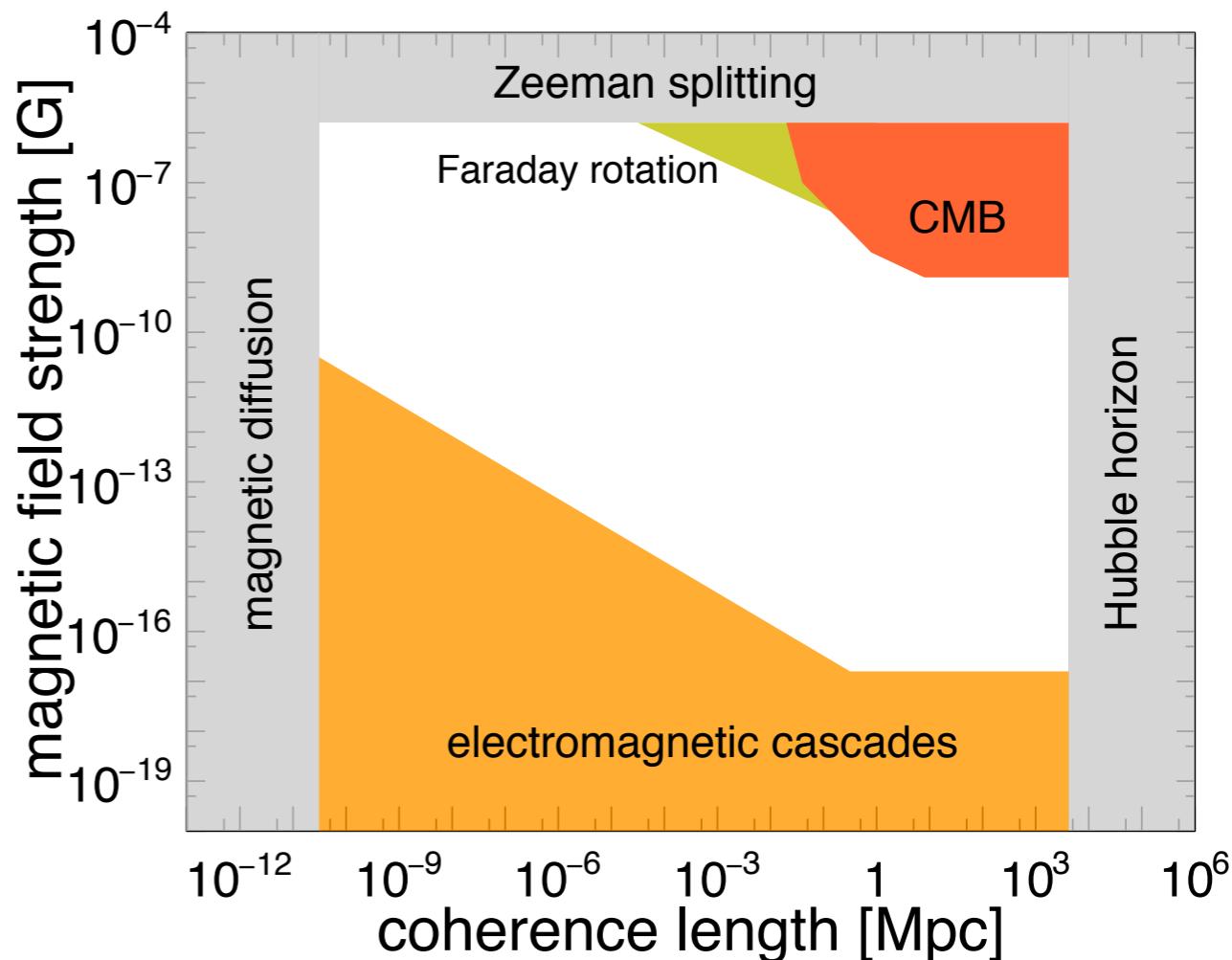
# modelling the propagation of UHECRs: photon backgrounds



# modelling the propagation of UHECRs: magnetic fields

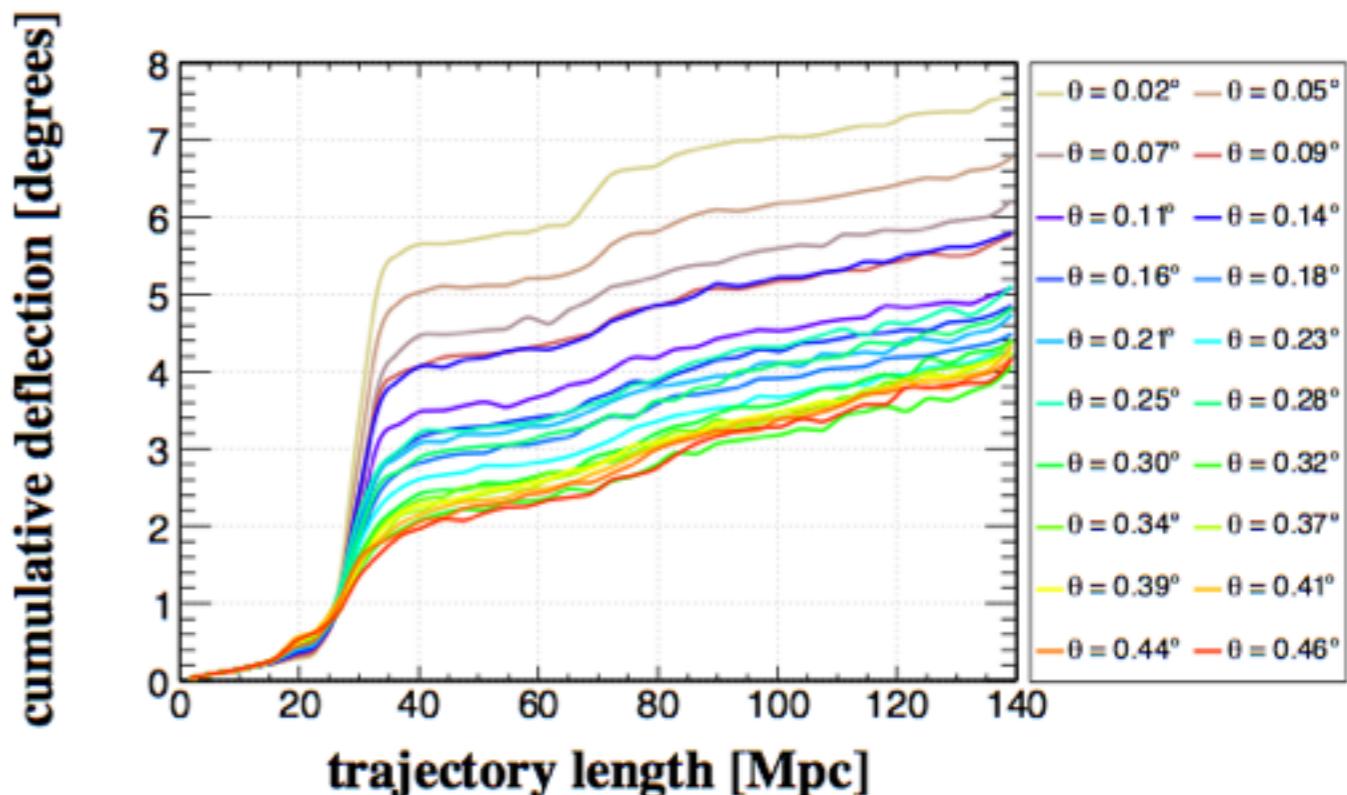
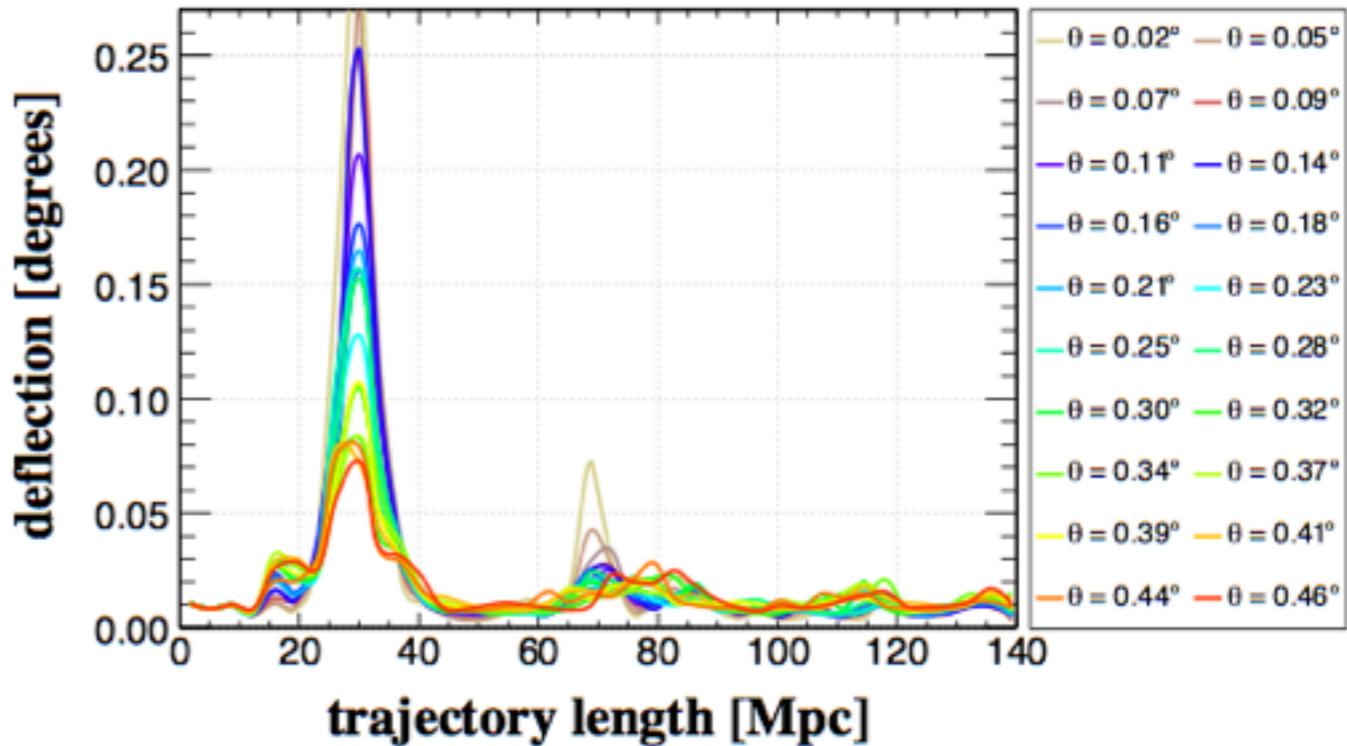


- are there cosmological magnetic fields?
- how did the magnetic fields in the universe come to be? astrophysical vs cosmological origin
- we have upper and lower bounds, but parameter space is still large

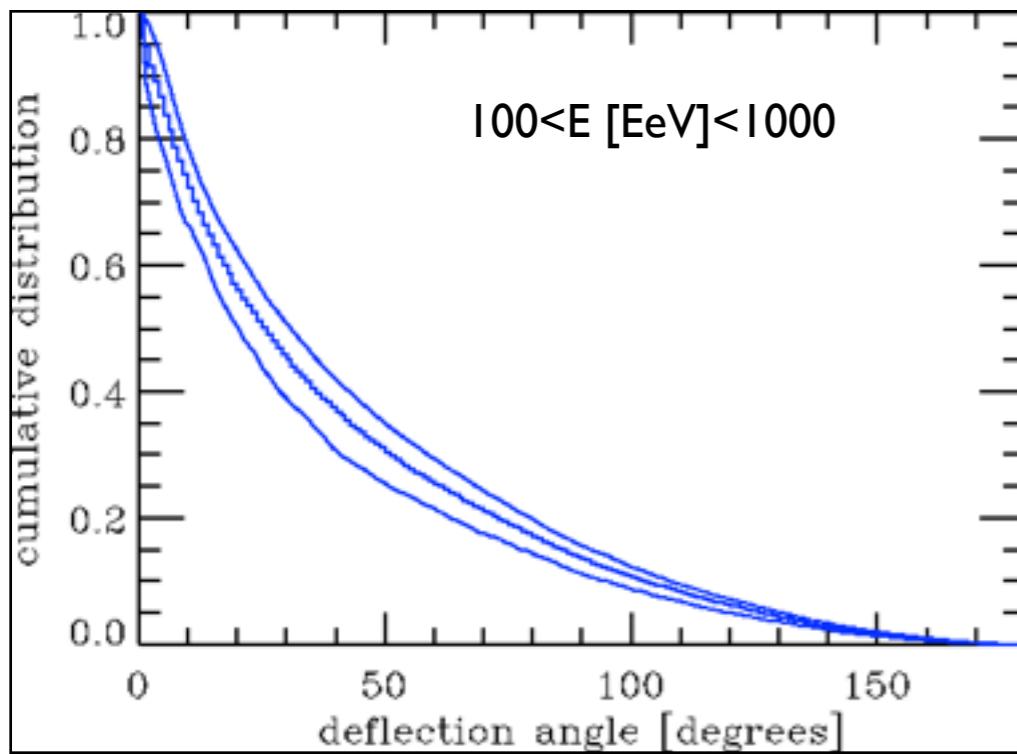


# deflections in extragalactic magnetic fields

- ▶ correlation between magnetic field and matter density
- ▶ structure of the magnetic field
- ▶ essentially what matters (on average) are the filling factors
- ▶ exceptions are possible “local” sources

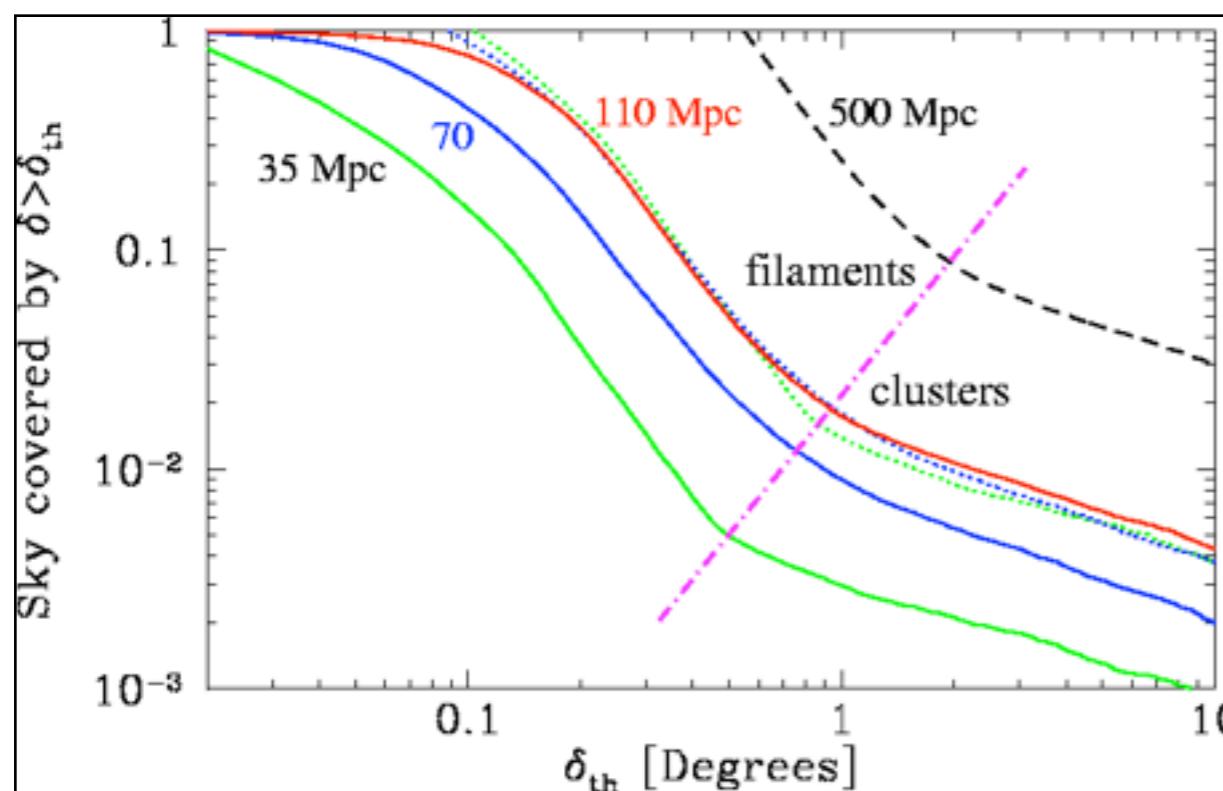


# UHECR astronomy?



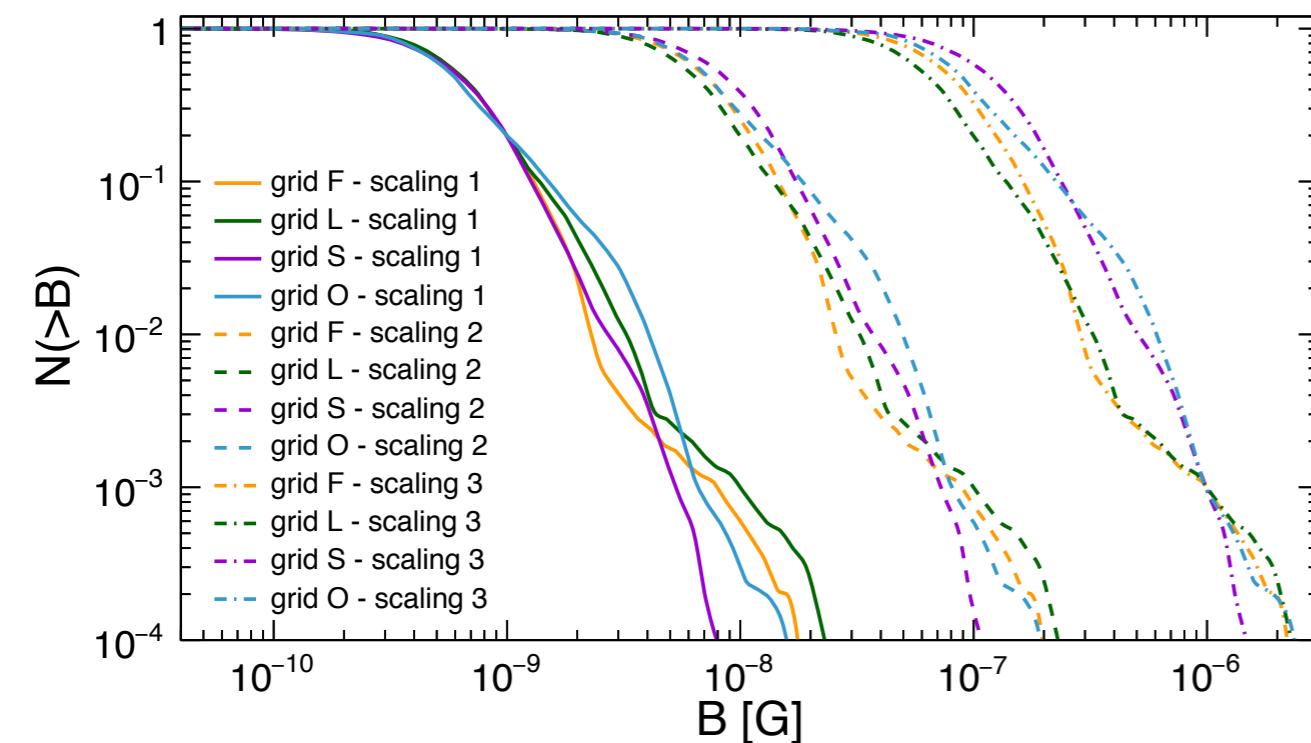
Sigl, Miniati, Ensslin. PRD 70  
(2004) 043007

- ▶ 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 latter but not in the former scenario

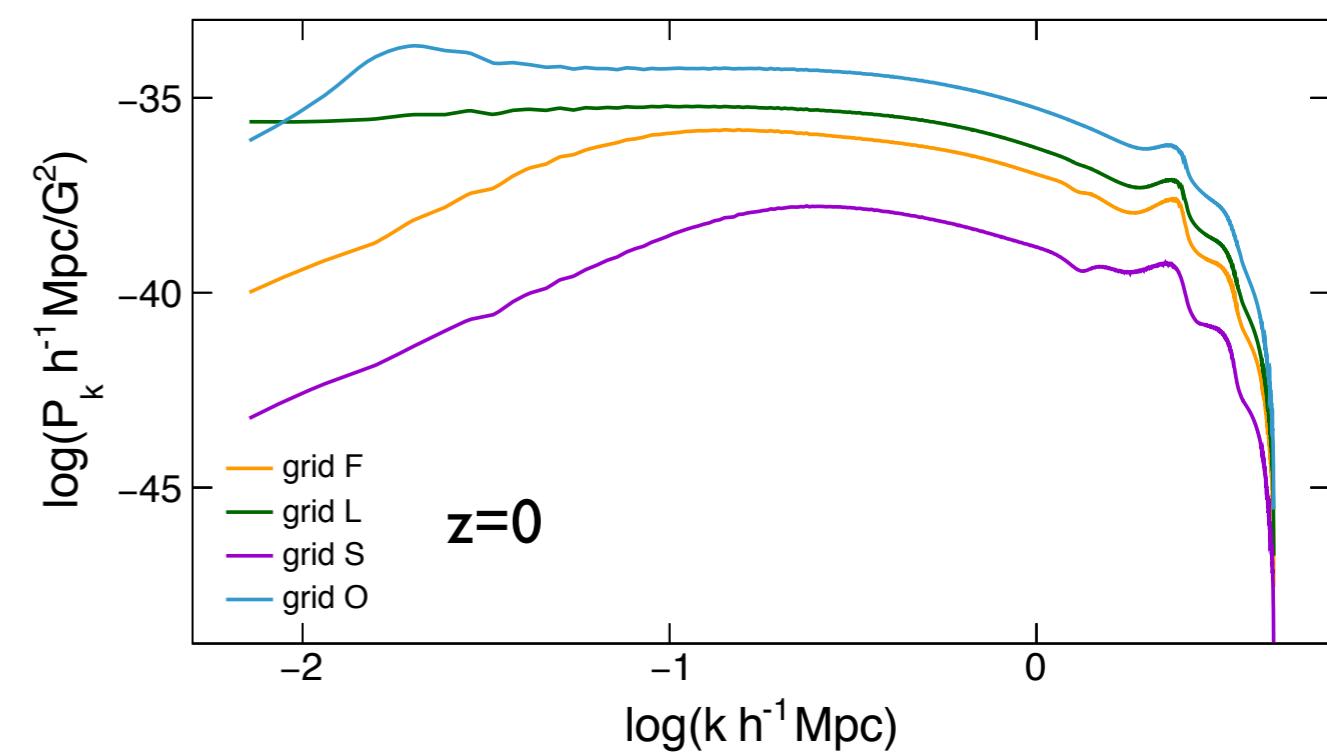
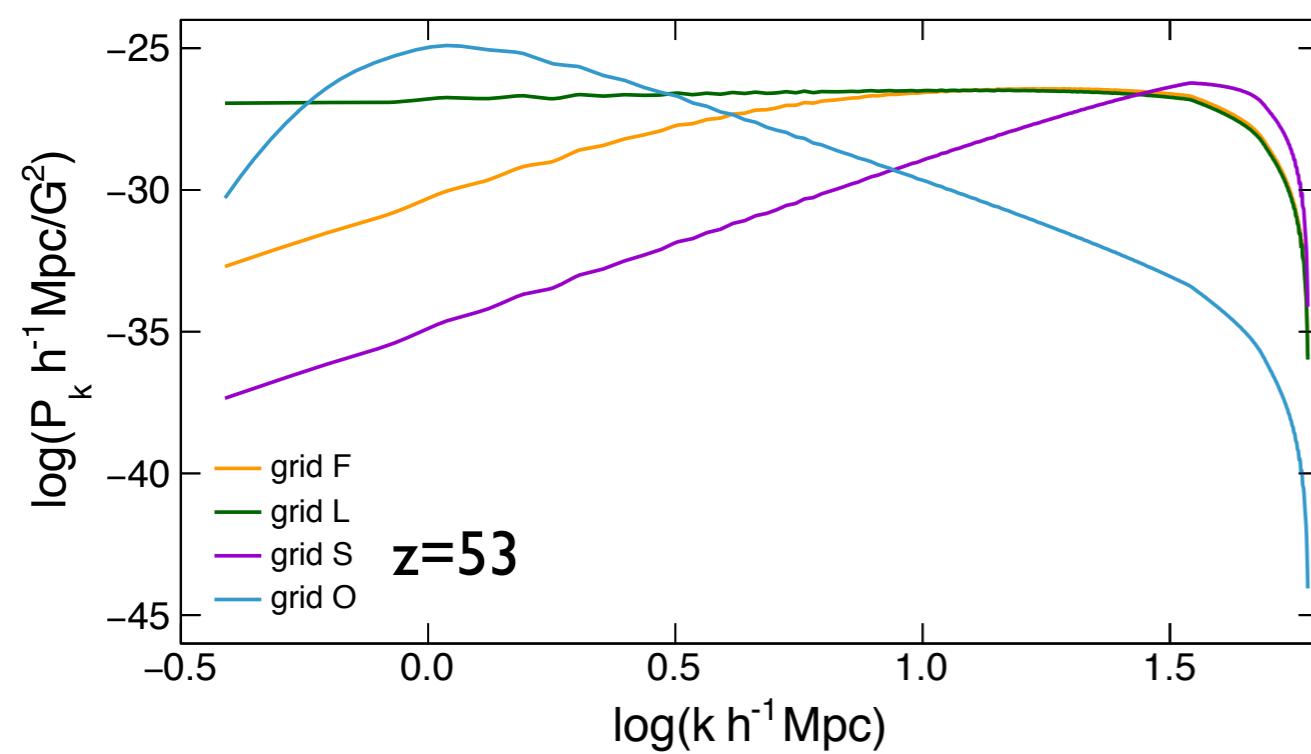


Dolag et al. JETP 79(2004) 583

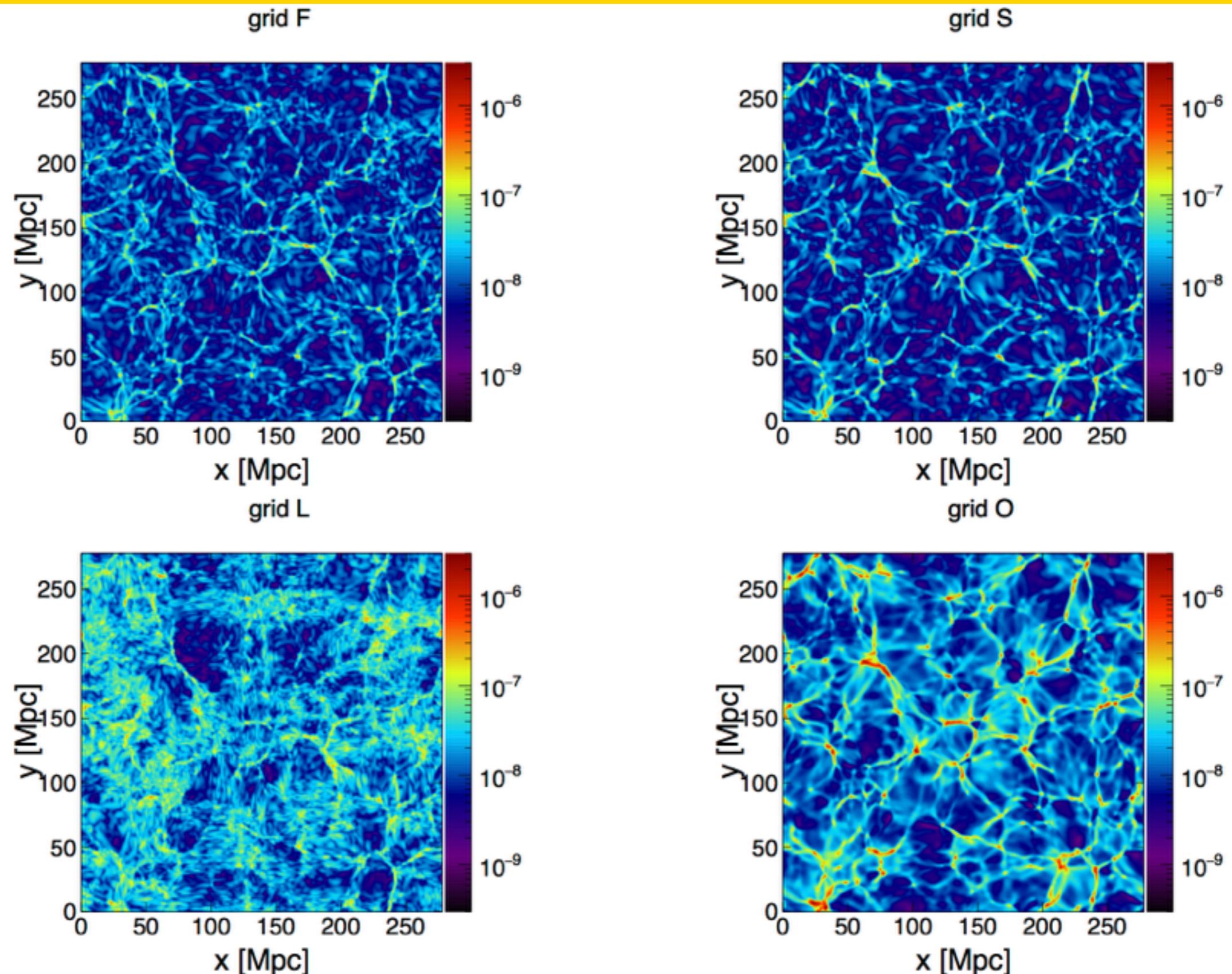
# MHD simulations



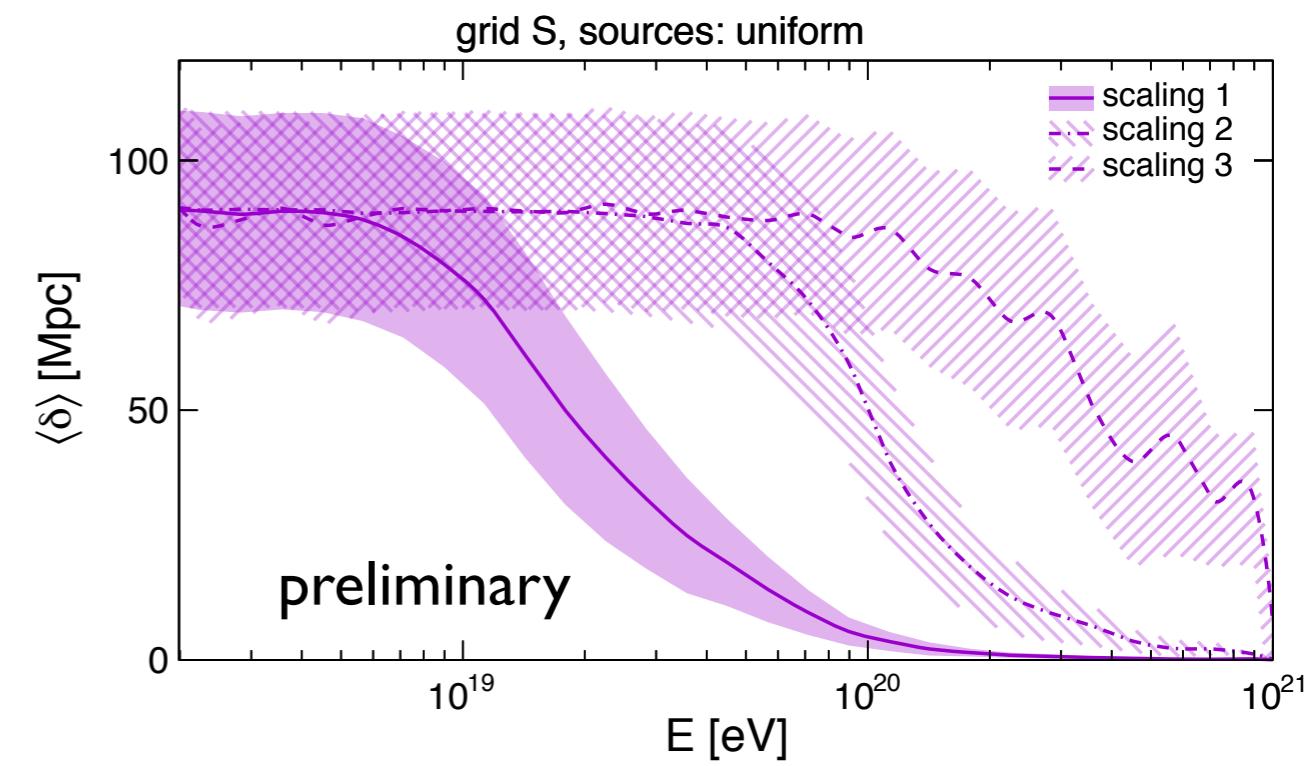
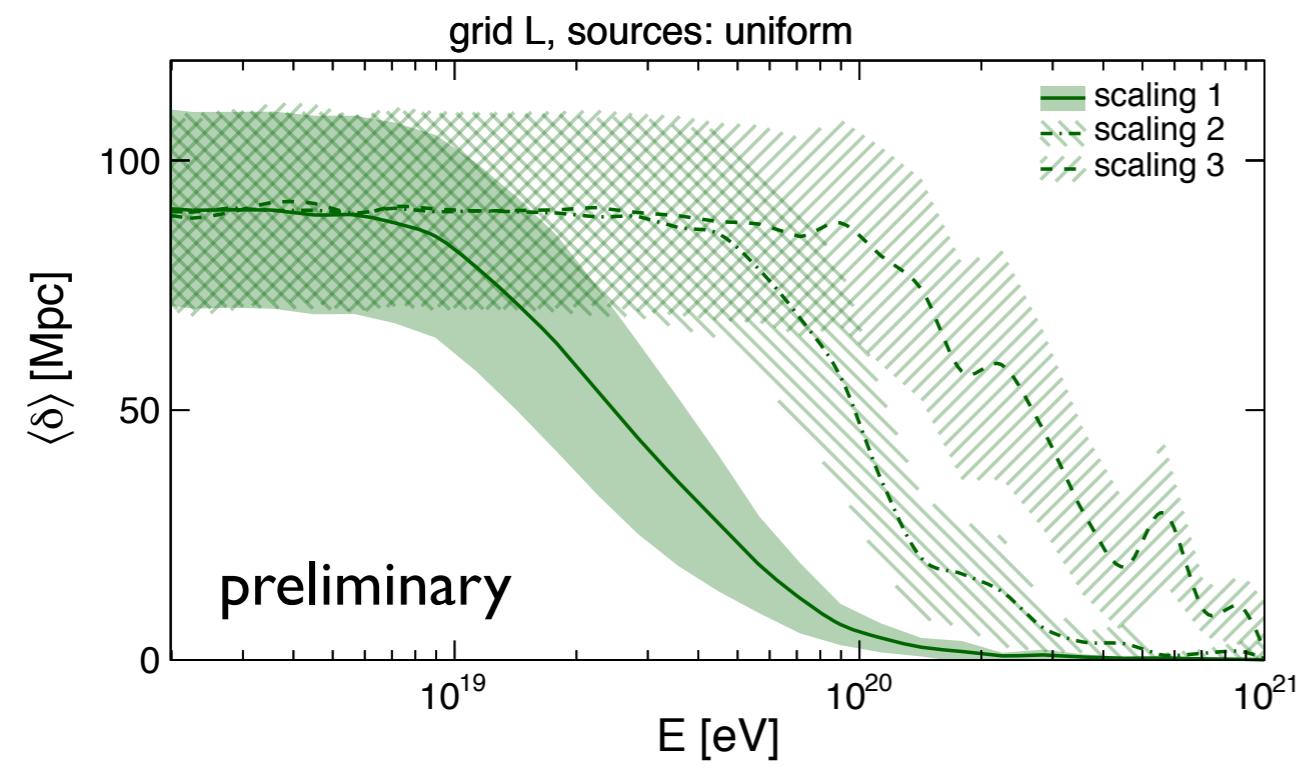
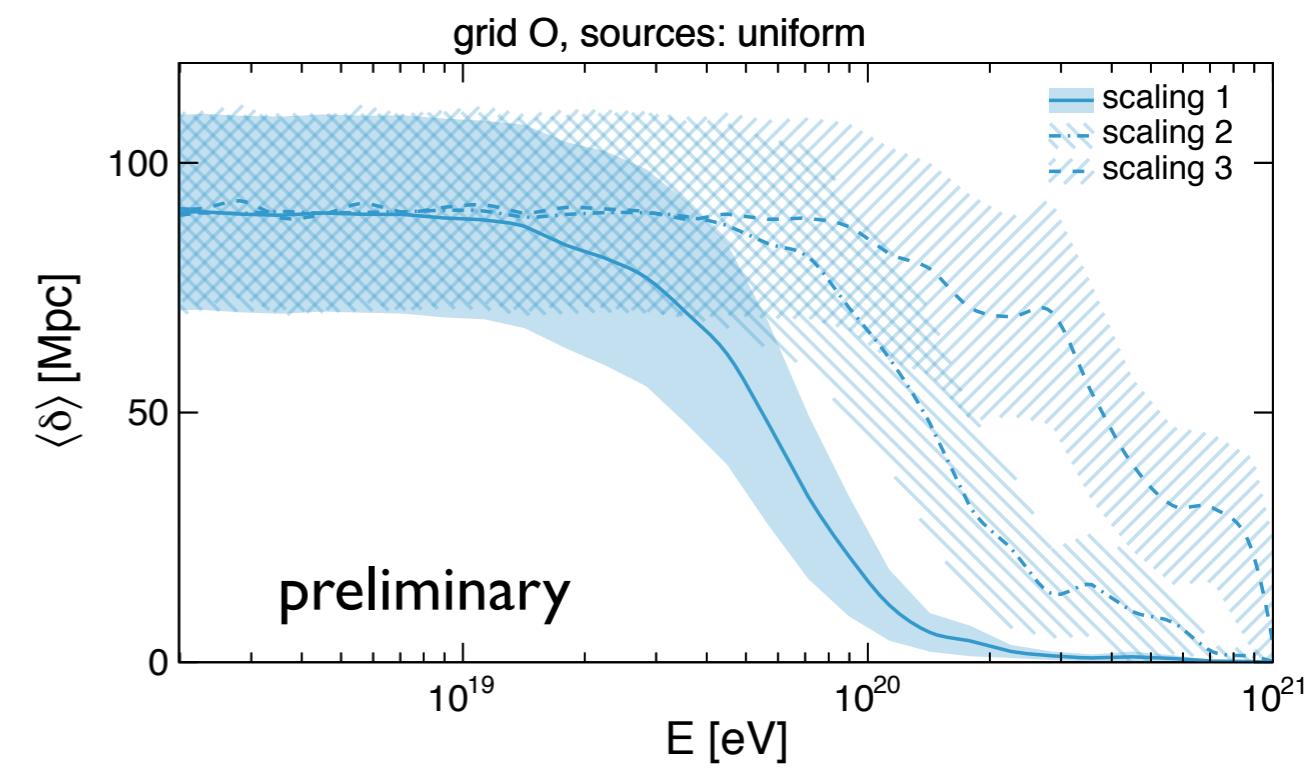
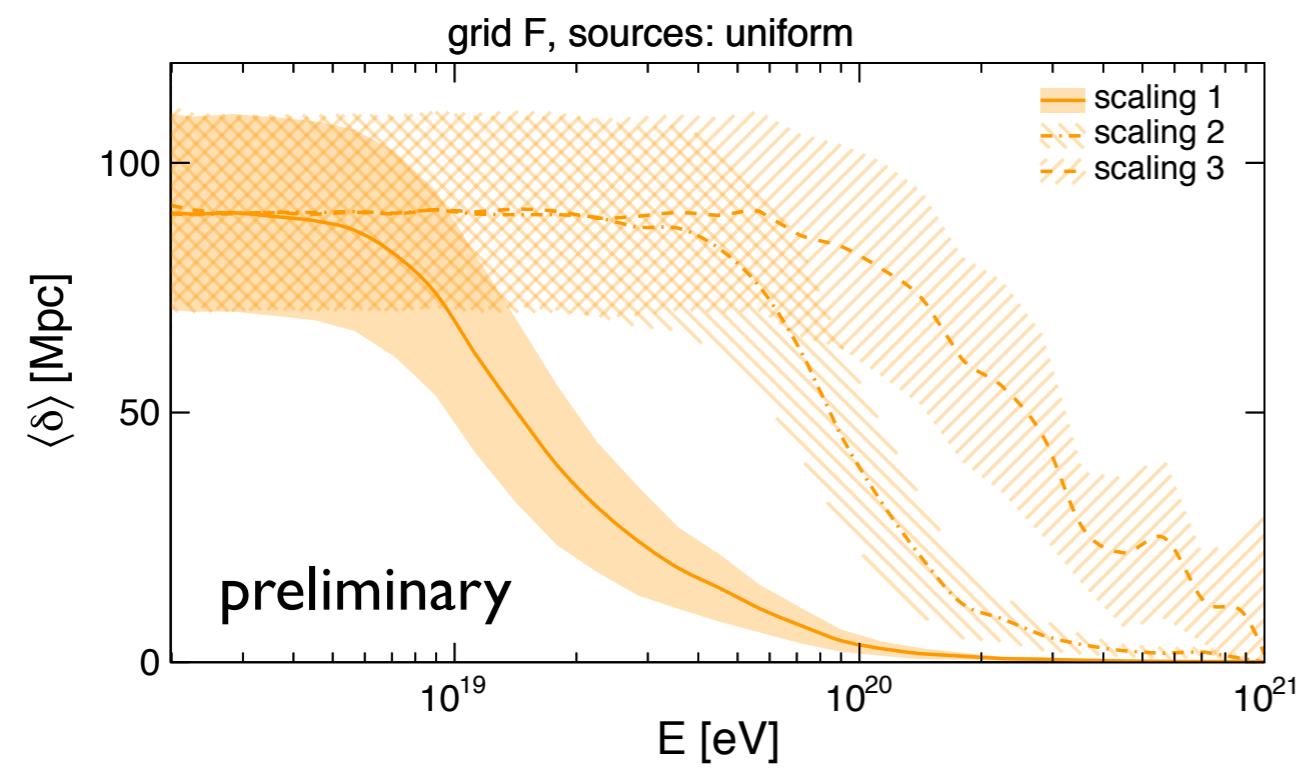
- MHD simulations of  $(200h^{-1} \text{ Mpc})^3$
- different magnetic field seeds
- scaling 1:  $B=1 \text{ nG}, f=0.2$
- scaling 3:  $B=1 \mu\text{G}, f=0.001$
- scaling 2:  $(\log(\text{scaling 1}) + \log(\text{scaling 2})) / 2$



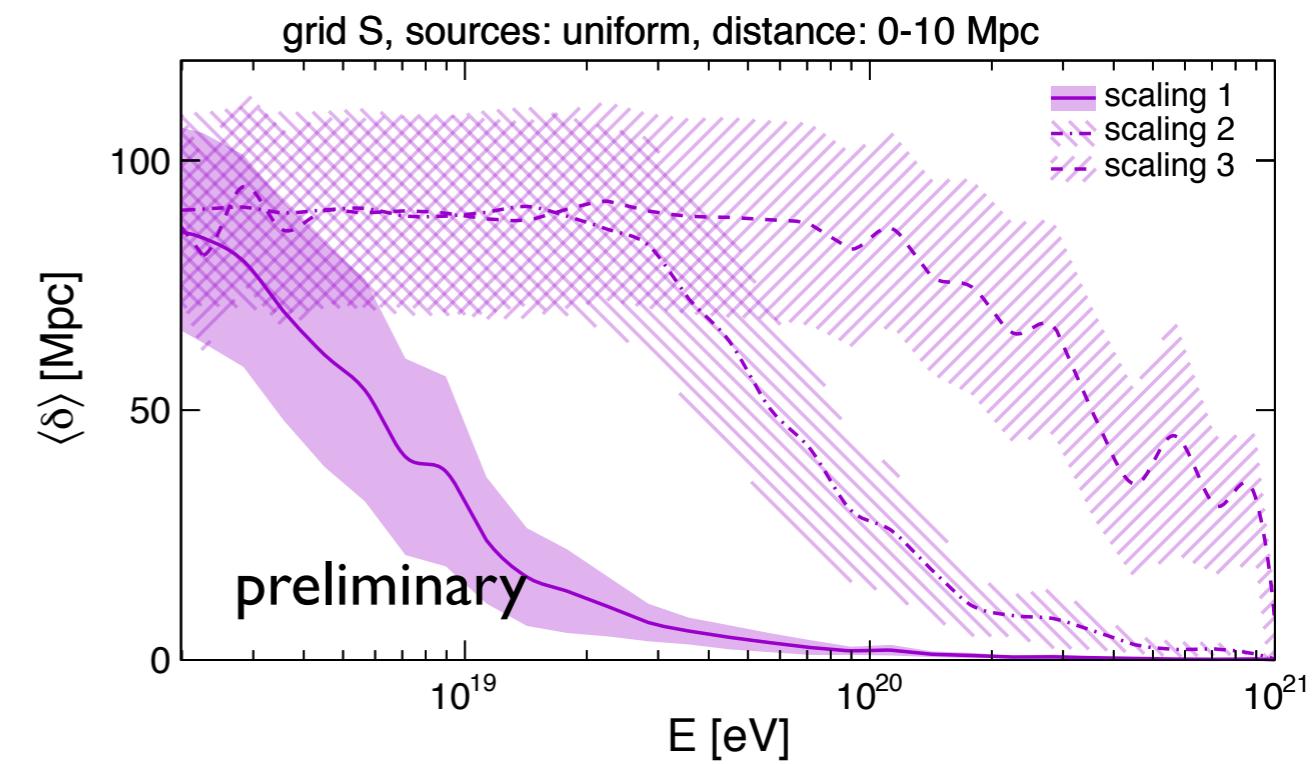
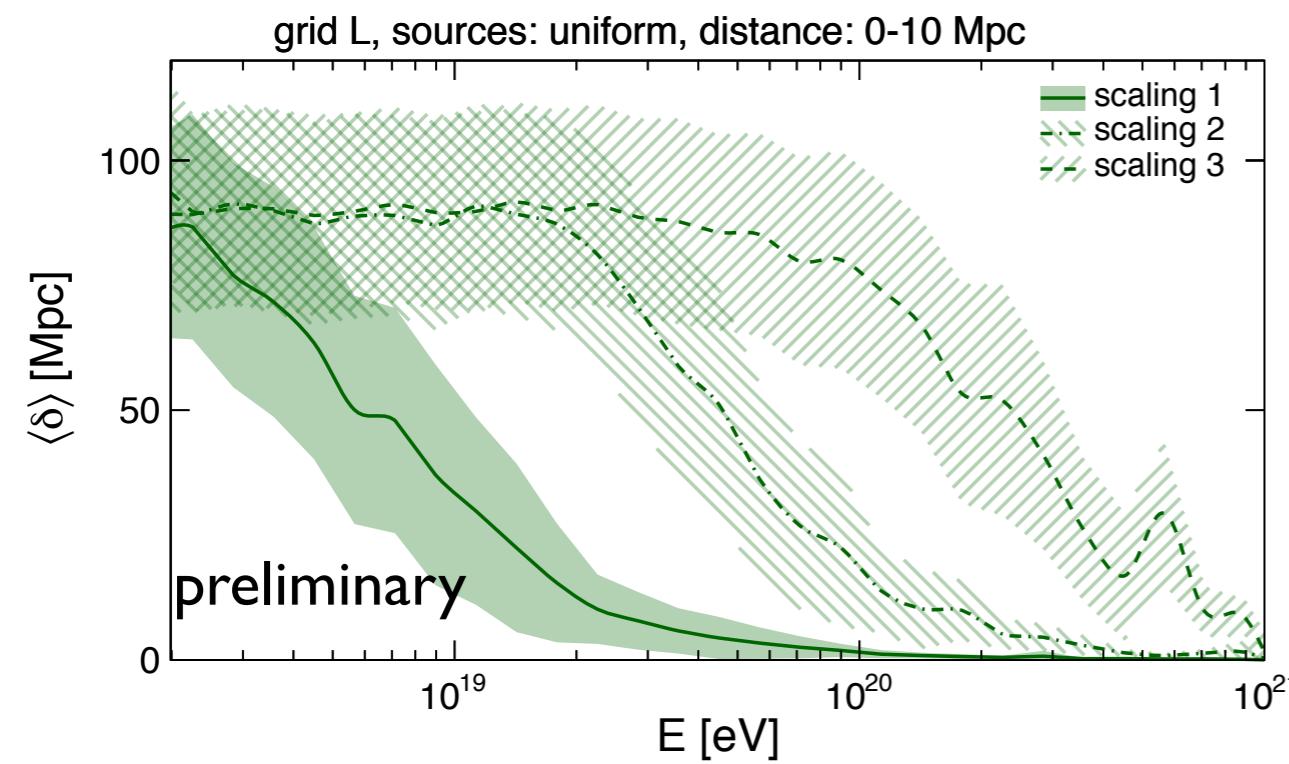
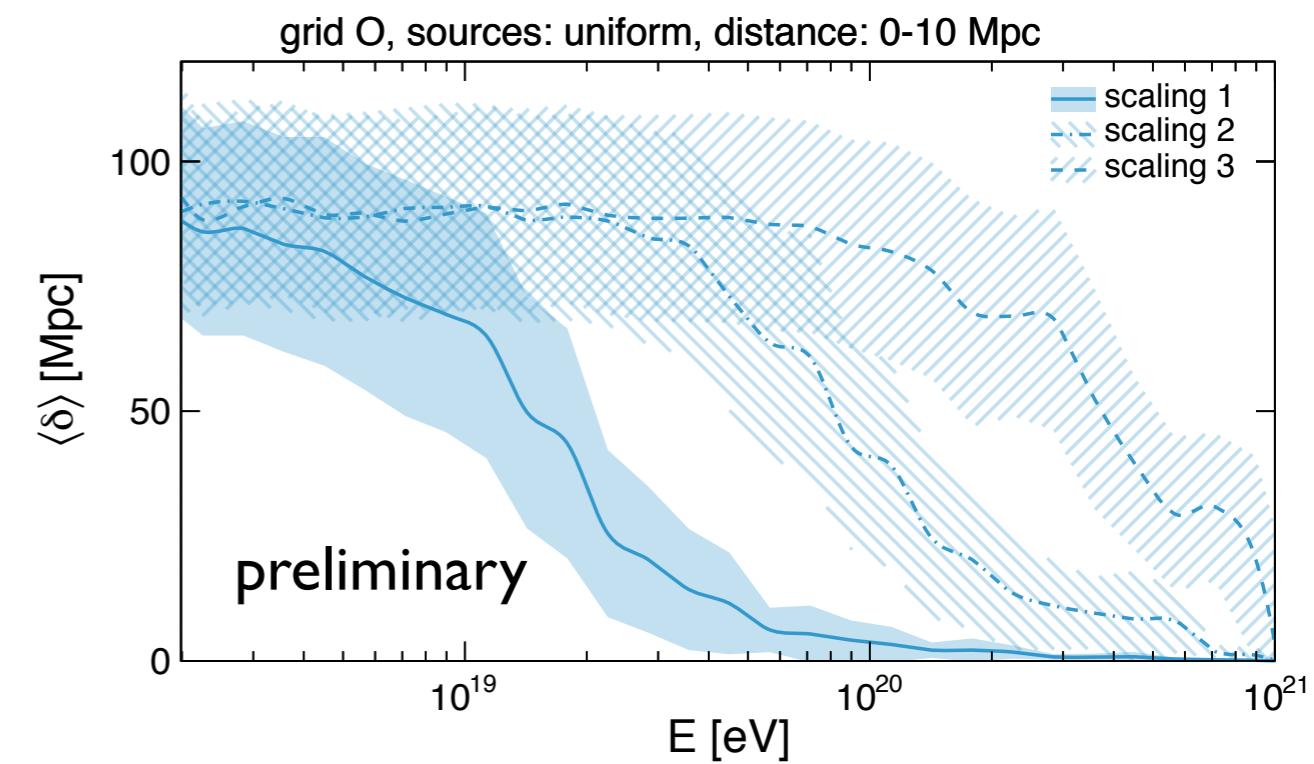
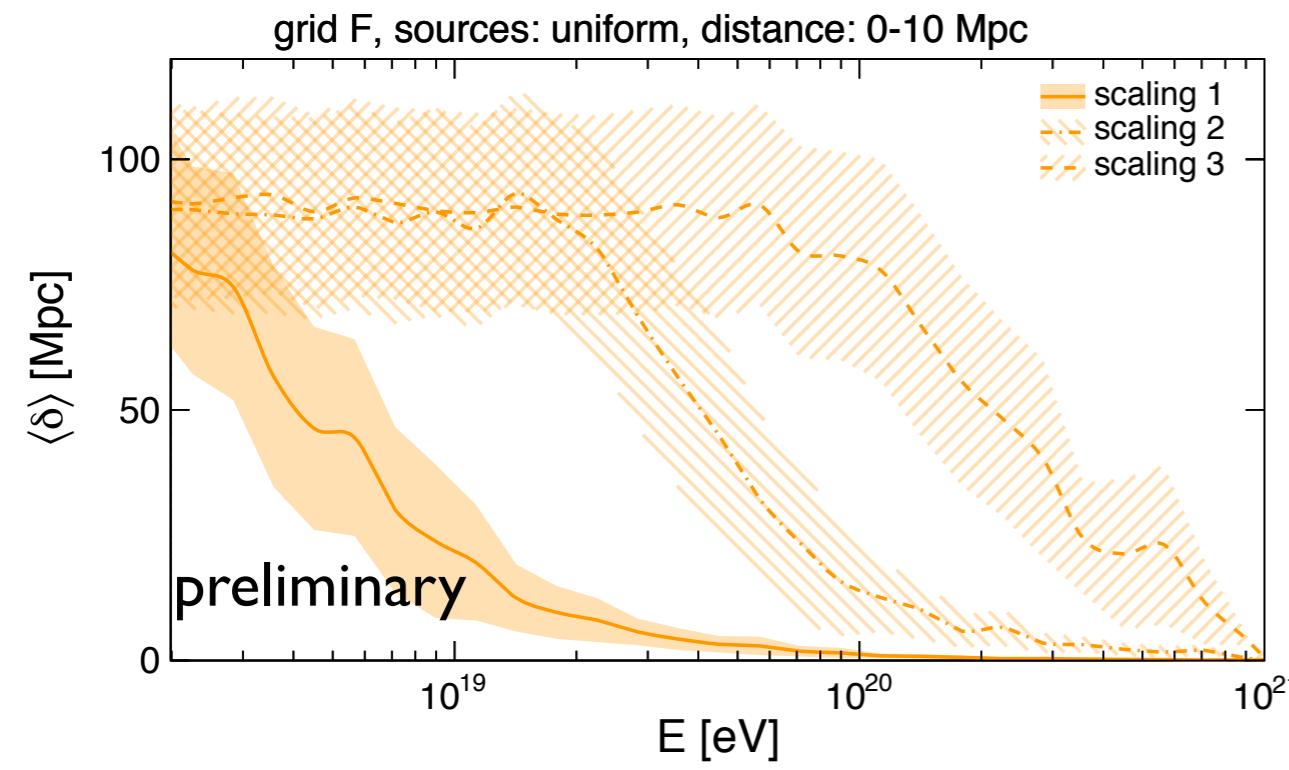
# MHD simulations



# deflections

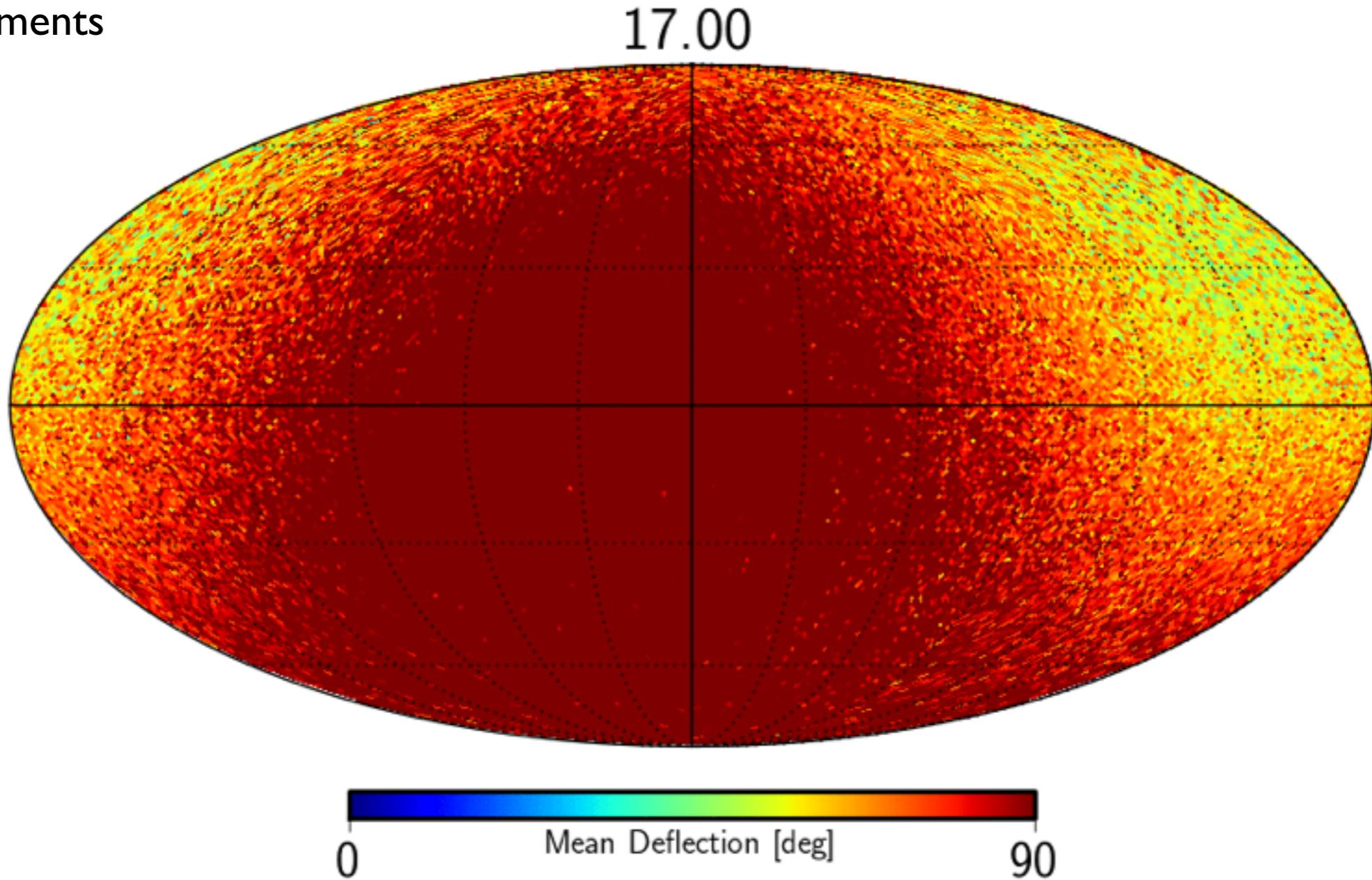


# deflections: $D < 10$ Mpc



# 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

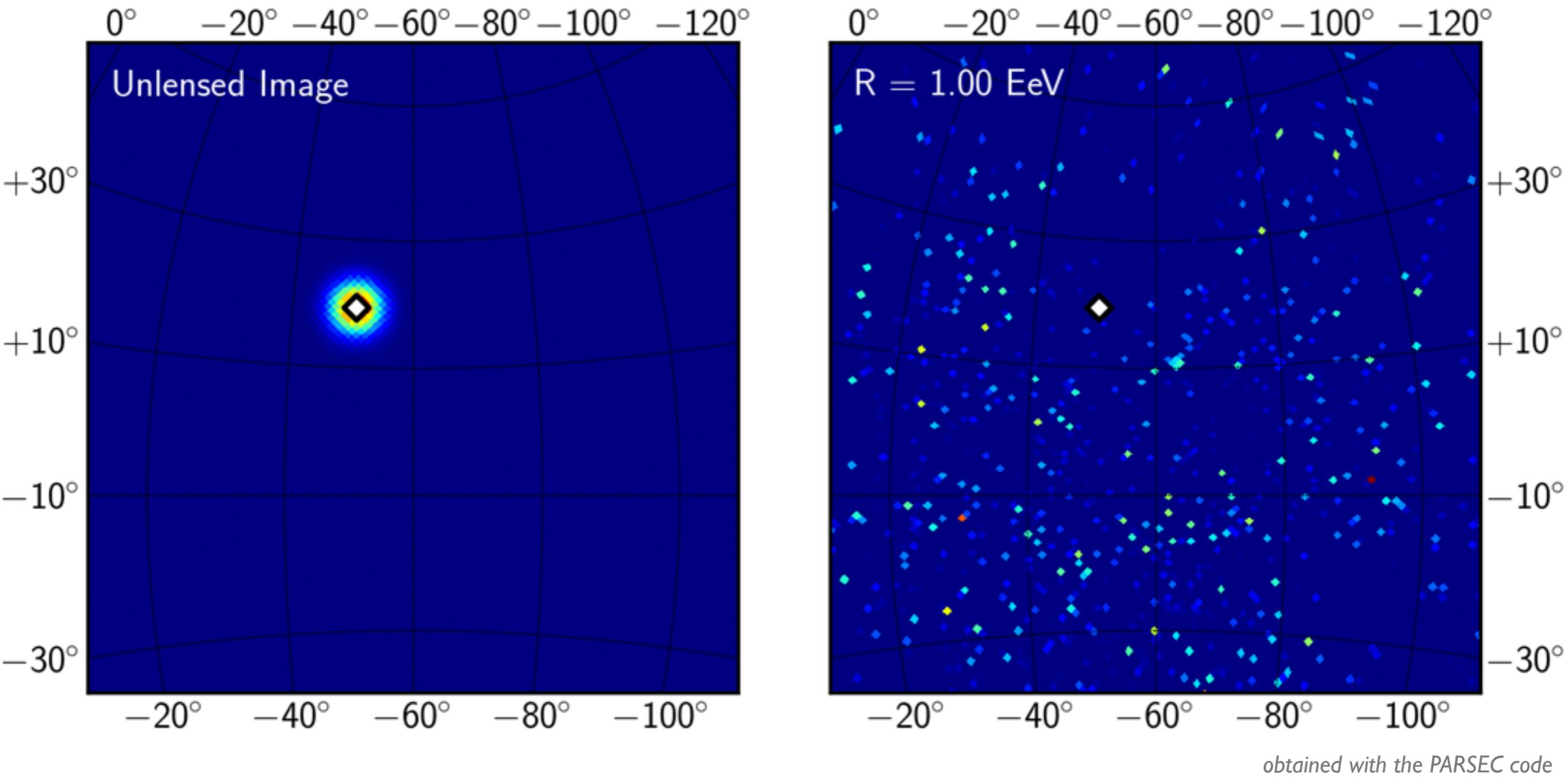


obtained with the PARSEC code:

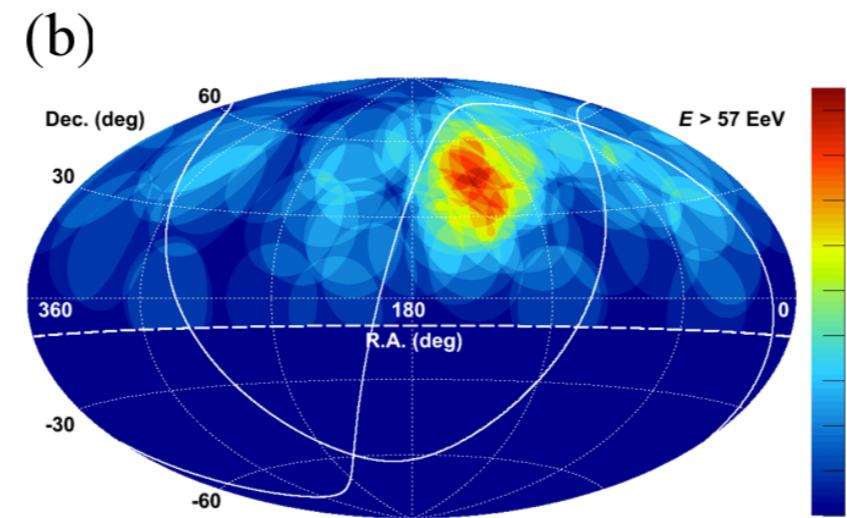
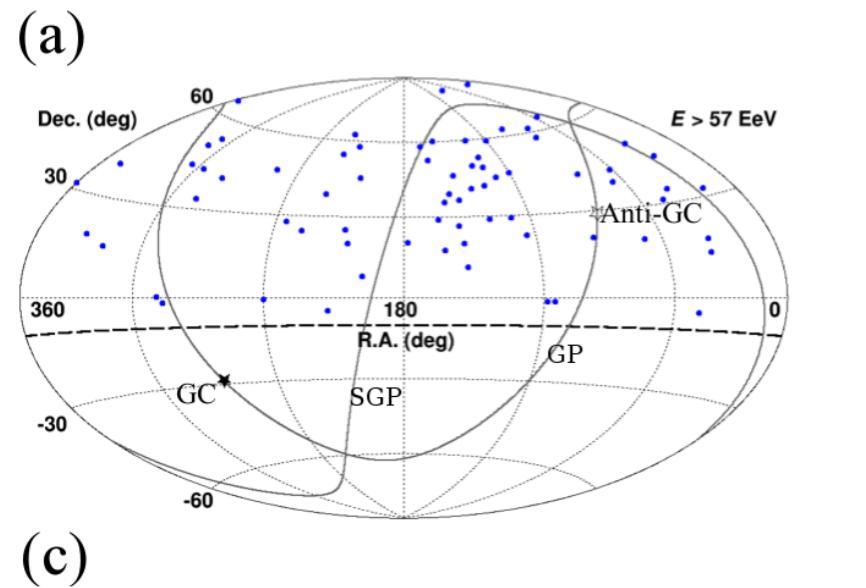
[http://web.physik.rwth-aachen.de/Auger\\_MagneticFields/PARSEC](http://web.physik.rwth-aachen.de/Auger_MagneticFields/PARSEC)

# UHECRs and the galactic magnetic field

- ▶ the case of Centaurus A, assuming only galactic deflections and the complete JFI2 field

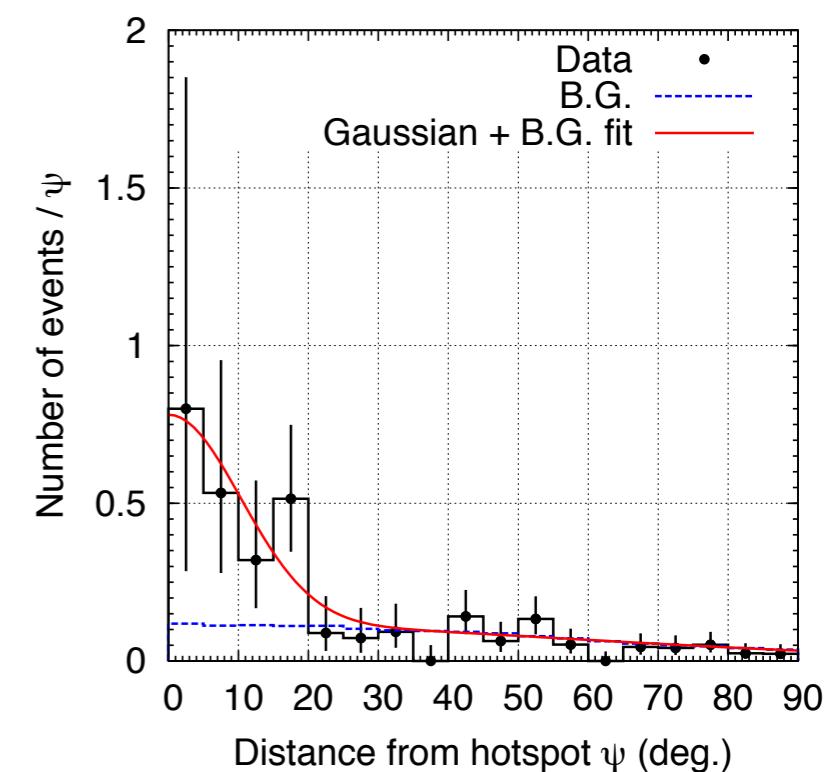
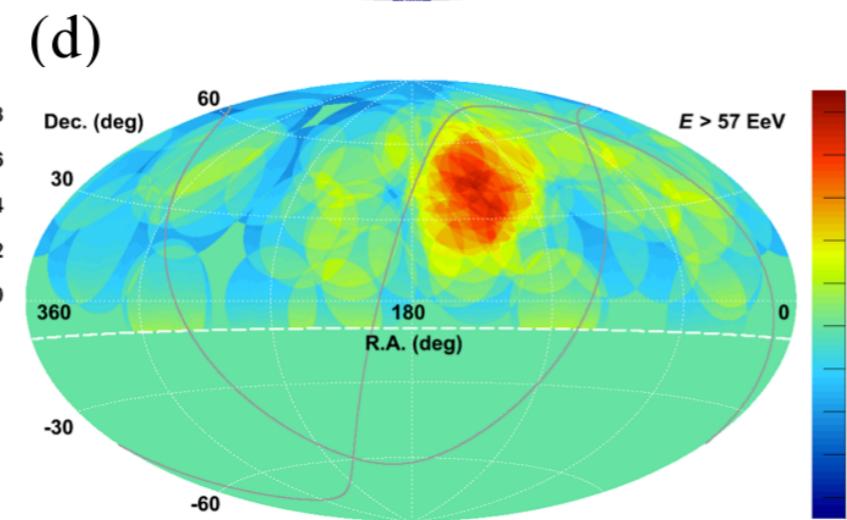
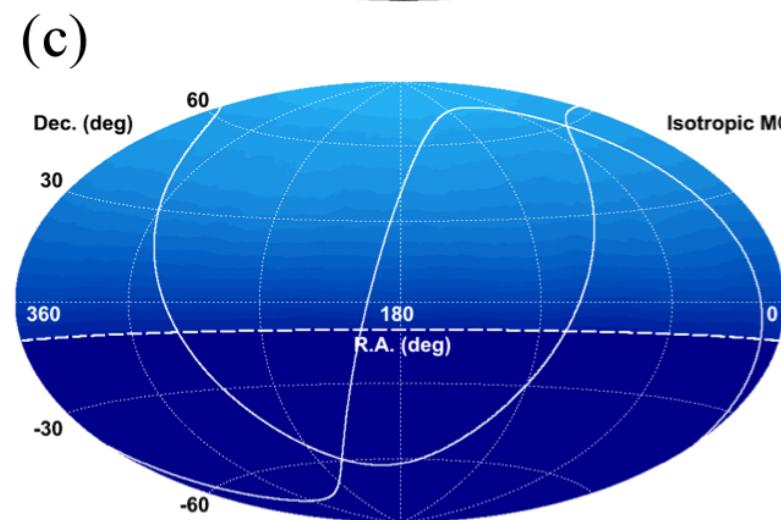


# what are the sources of UHECRs?



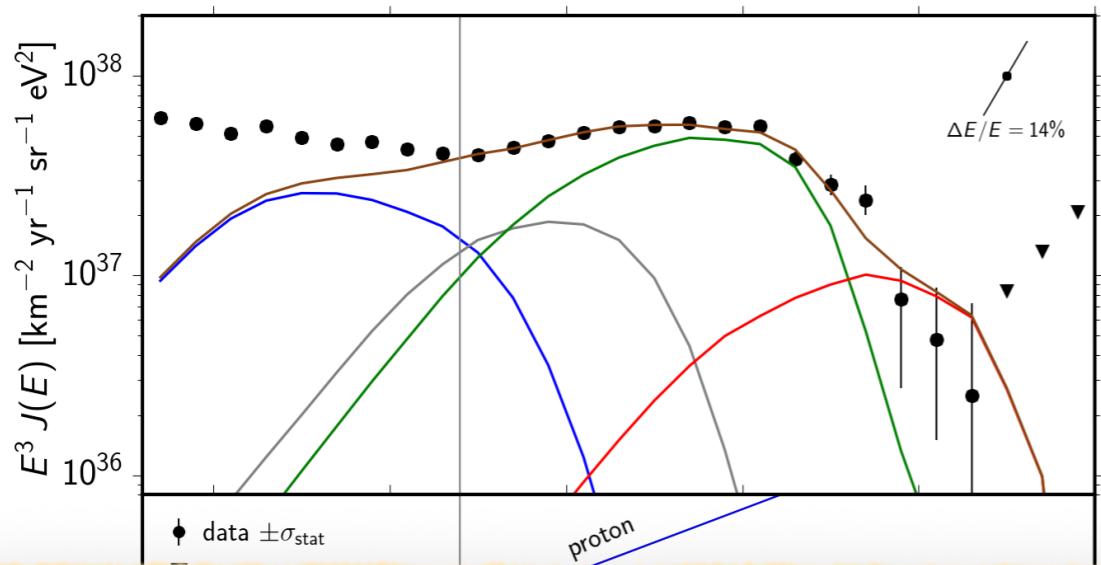
Telescope Array Collaboration. *ApJL* 790 (2014) L21.

arXiv:1404.5890

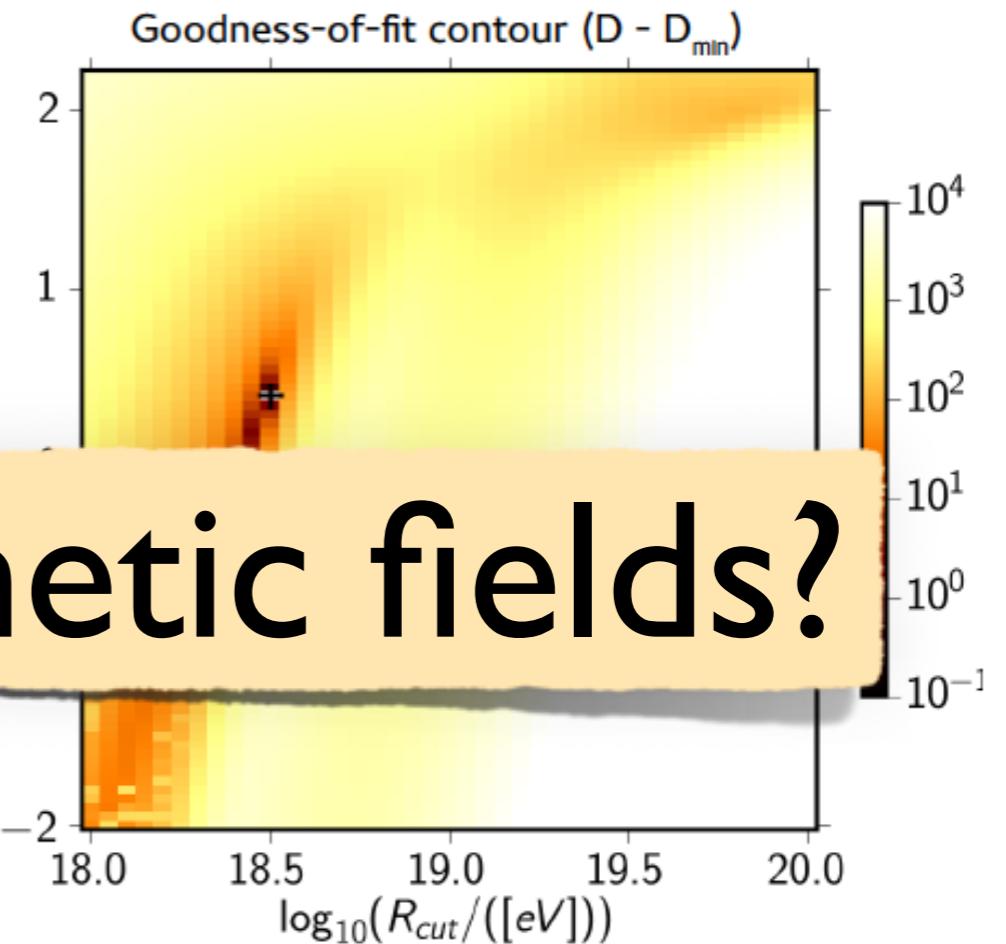


- ▶ hotspot detected with significance  $3.6\sigma$
- ▶ no sources nearby
- ▶ excess near supergalactic plane, which contains e.g. Ursa Major, Virgo and Coma cluster
- ▶ distance to Ursa Major cluster  $\sim 19$  degrees
- ▶ multiple sources? extended source? single source with large deflection?

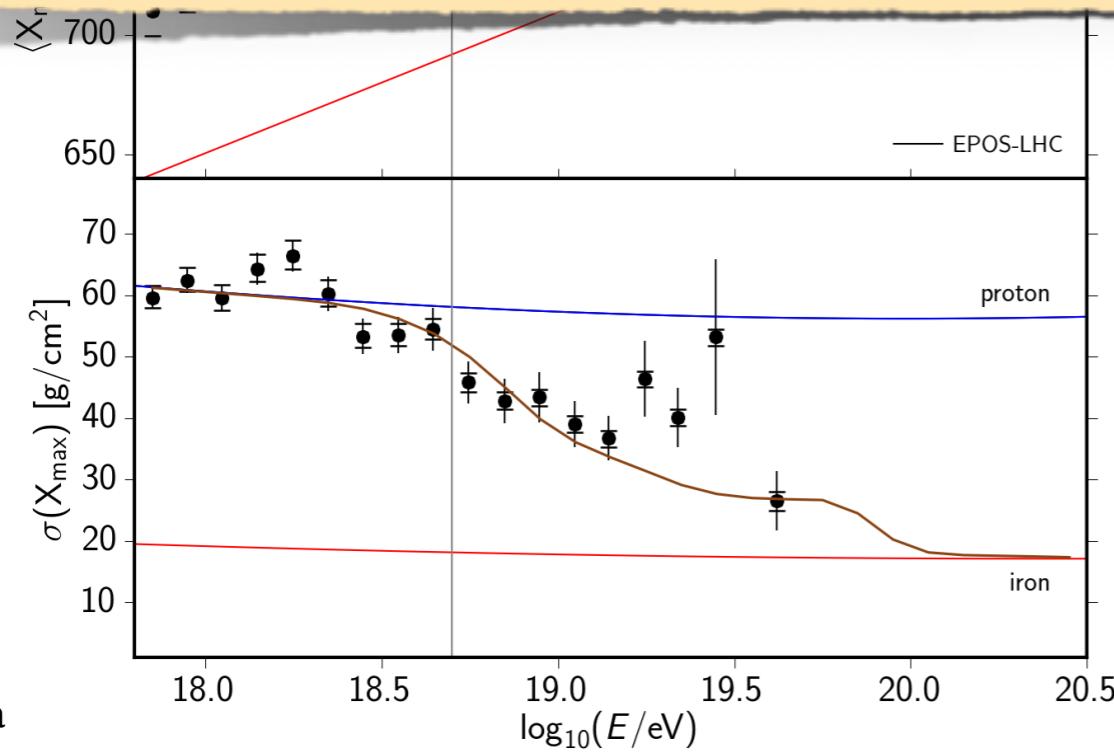
# combined spectrum-composition fits



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



## what about magnetic fields?



CRPropa

Kneiske '04 EBL model

TALYS cross sections for PD

- $\log(R_{\text{cut}} / V) = 18.48$
- $\gamma = 0.29 (+0.08 | -0.07)$
- 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)

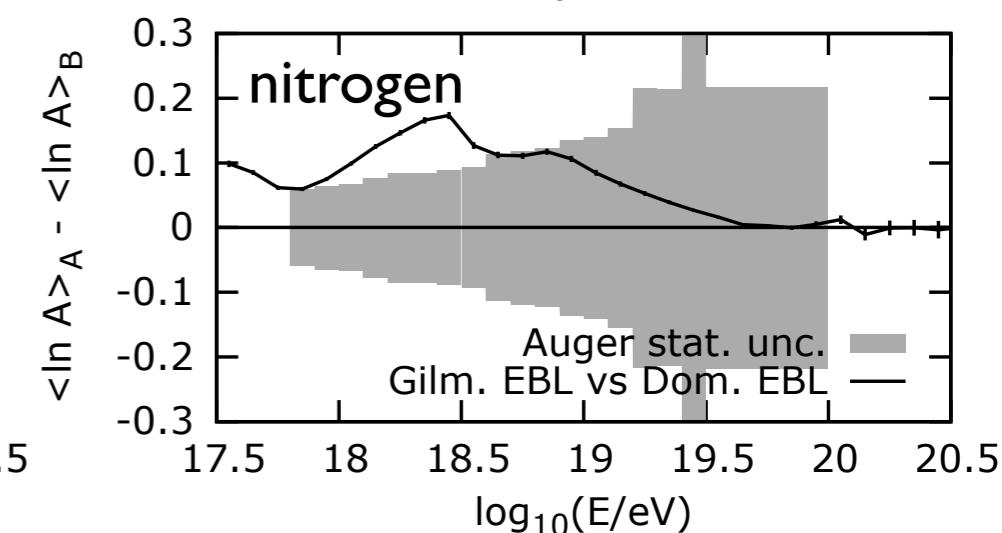
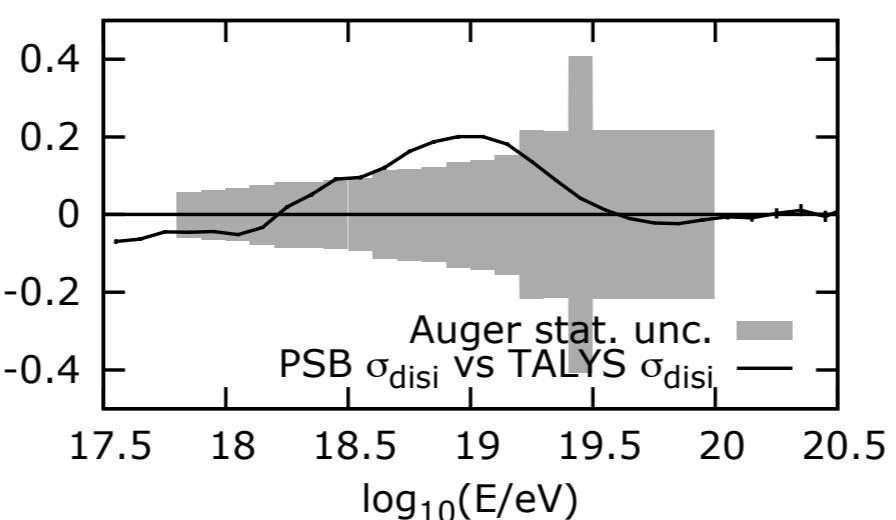
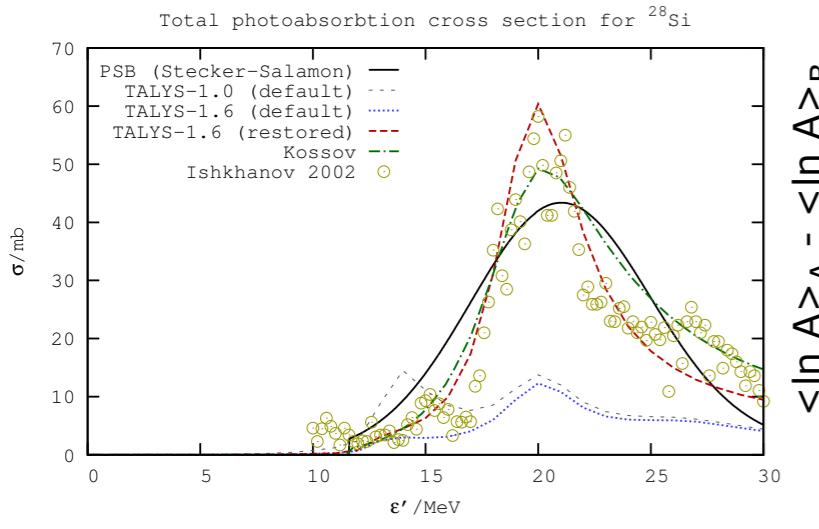
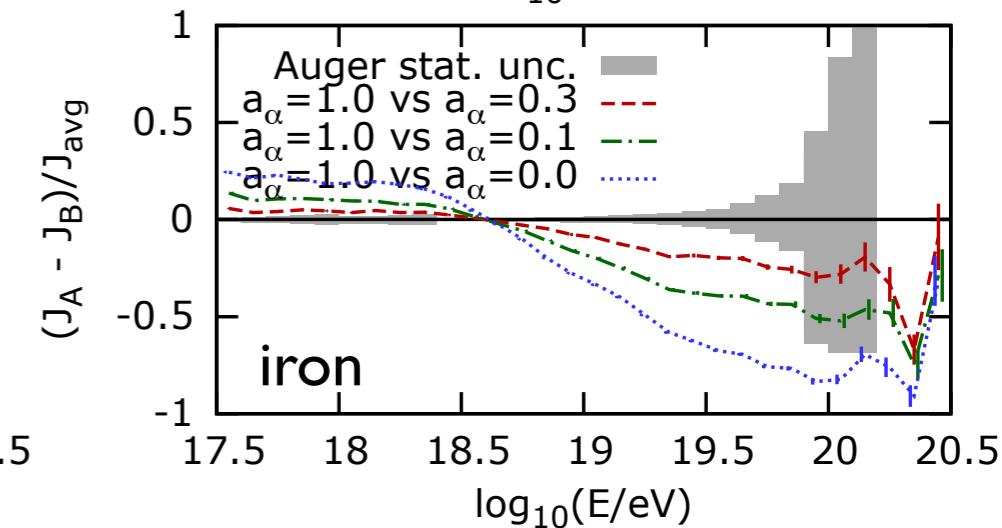
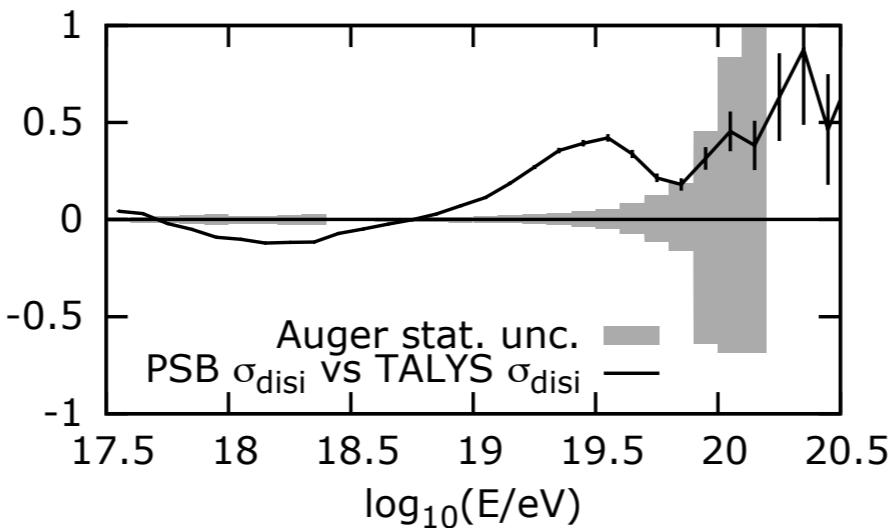
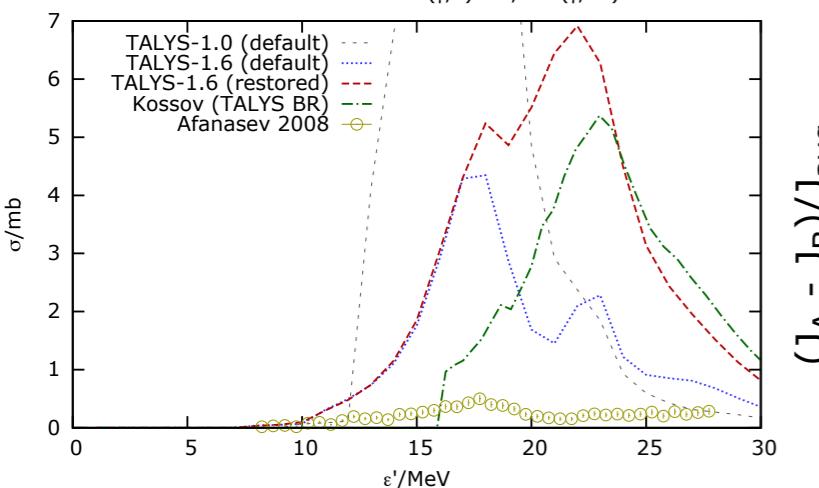
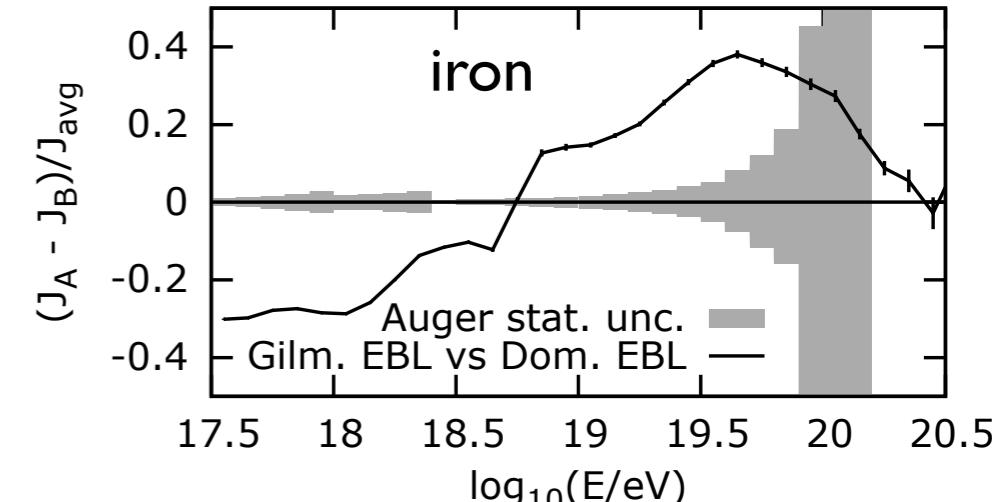
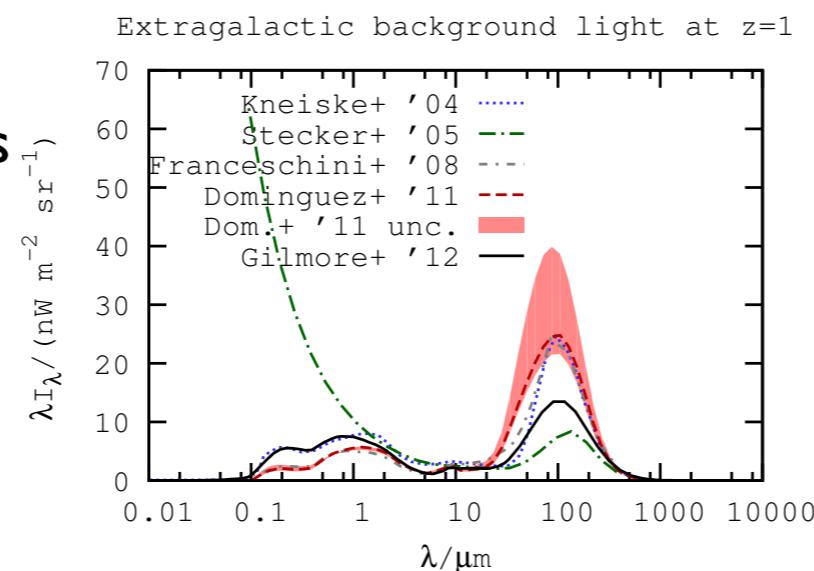
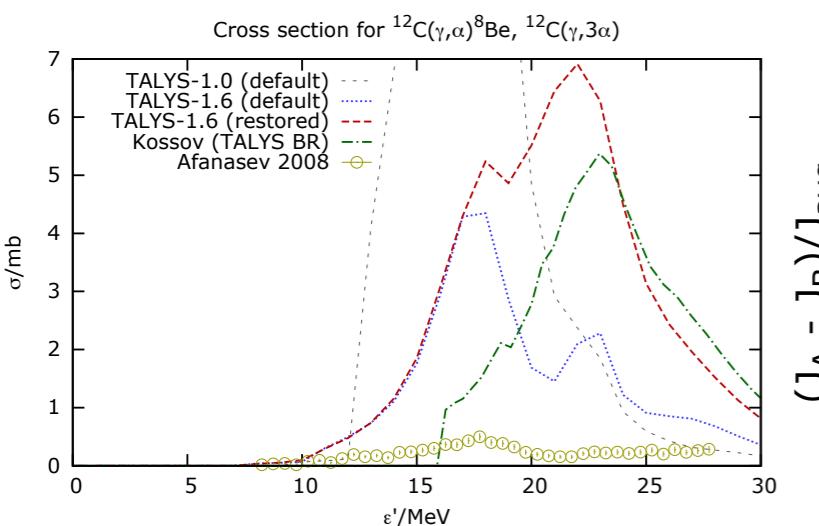
# theoretical uncertainties in the modelling

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

arXiv:1508.01824

## sources of uncertainties

- ▶ photodisintegration cross sections
- ▶ EBL model
- ▶ scaling of alpha-channels



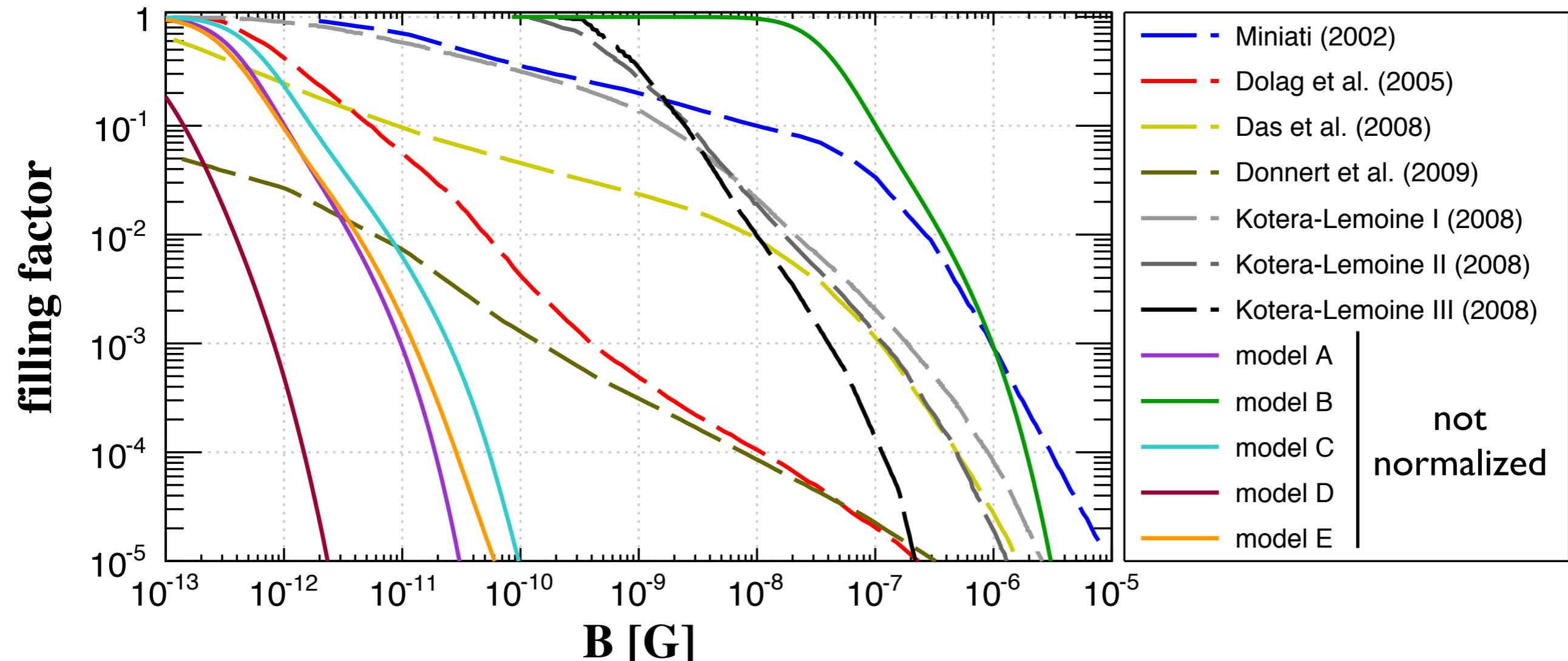
# status of UHECR astronomy

- ▶ 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 (unless we have local sources)

- ▶ deflections of UHECRs may be large (or not); how relevant are extragalactic deflections?
- ▶ magnetic fields are one of the main source of uncertainties in the modelling
- ▶ understanding cosmic magnetic fields is crucial for CR astronomy
- ▶ there are many other sources of uncertainties: source distribution, extragalactic background fields (EBL, probably not CMB), hadronic interaction models, photodisintegration cross sections...
- ▶ natural question: will we ever be able to detect the sources of UHECRs? if not, how do we know when to give up? if yes, when?

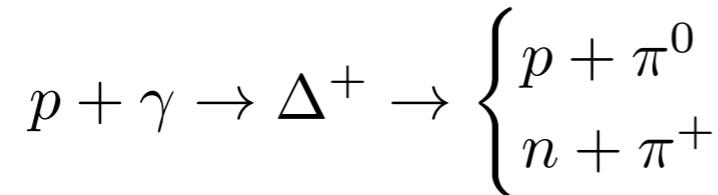
# Backup slides

# uncertainties on EGMFs



# modelling the propagation of UHECRs: energy losses

**photopion  
production**



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

**expansion of the  
universe**

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

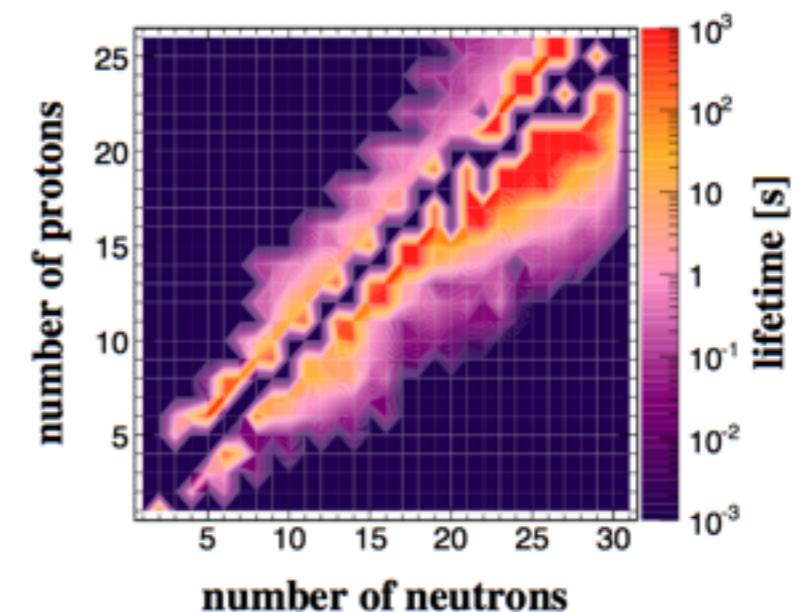
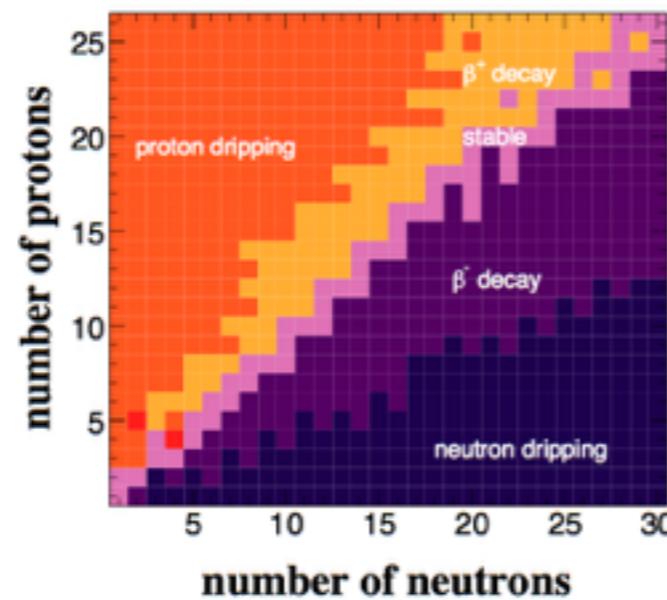
**pair production**

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

**photodisintegration**

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

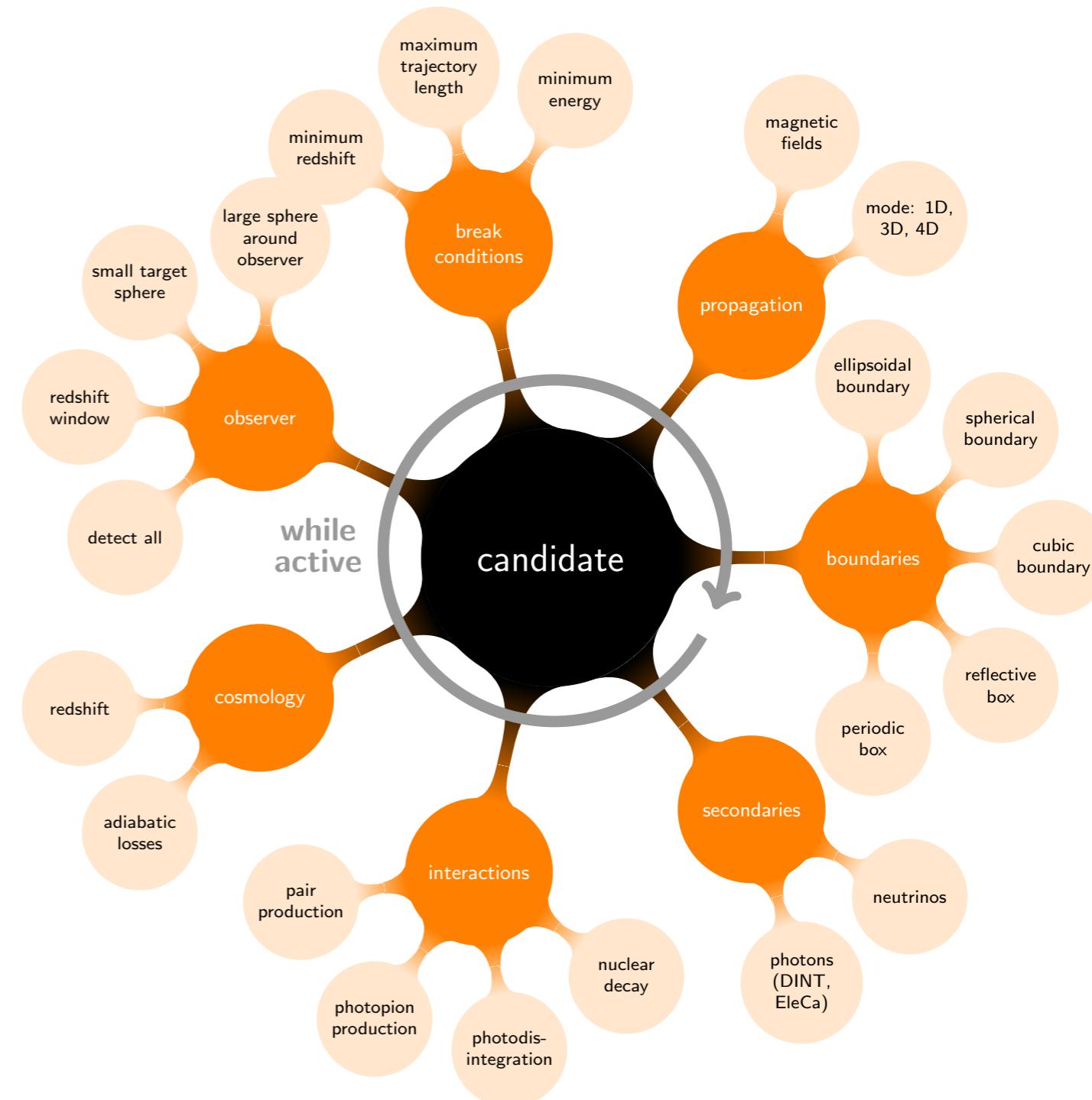
**nuclear decay**



# modelling the propagation of UHECRs: 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)

RAB et al. arXiv:1603.07142



[crpropa.desy.de](http://crpropa.desy.de)

# 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:  $^1\text{H}$ ,  $^4\text{He}$ ,  $^{14}\text{N}$  and  $^{56}\text{Fe}$
- ▶ 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

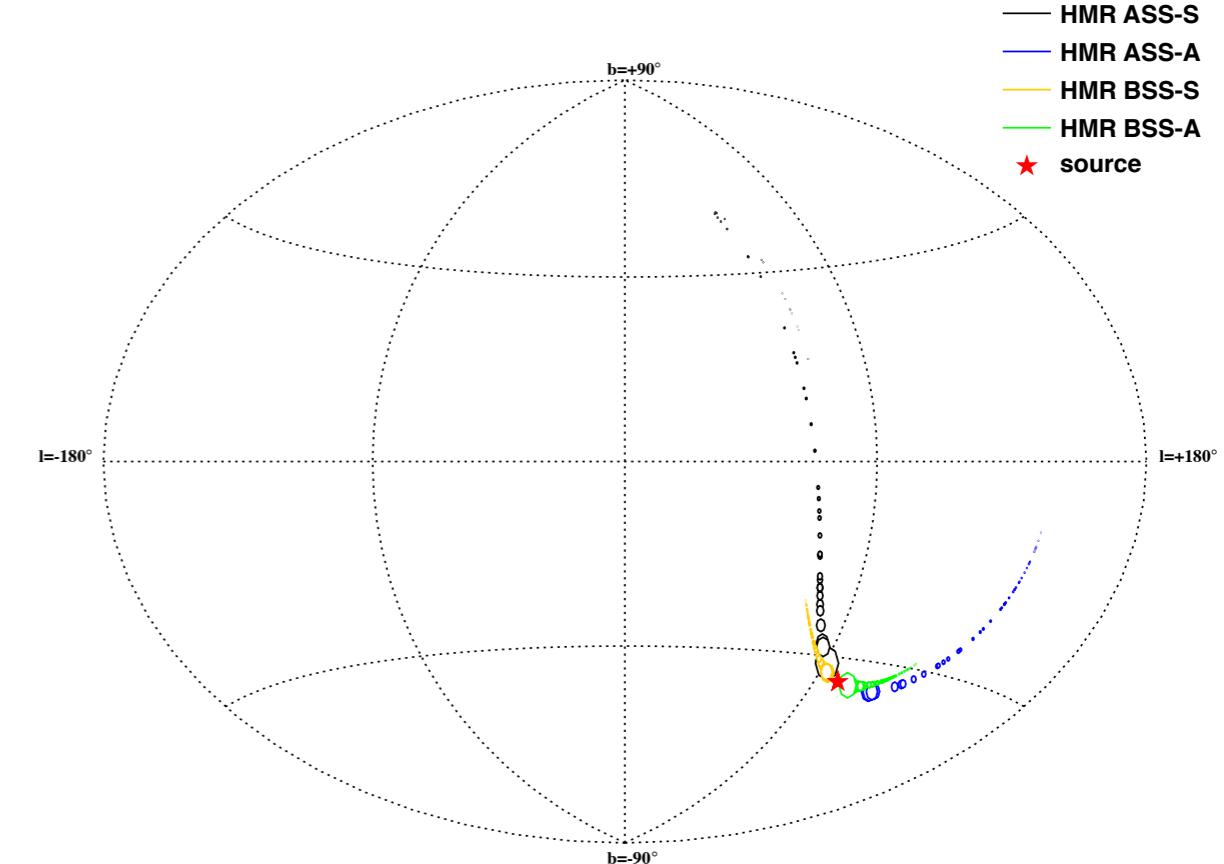
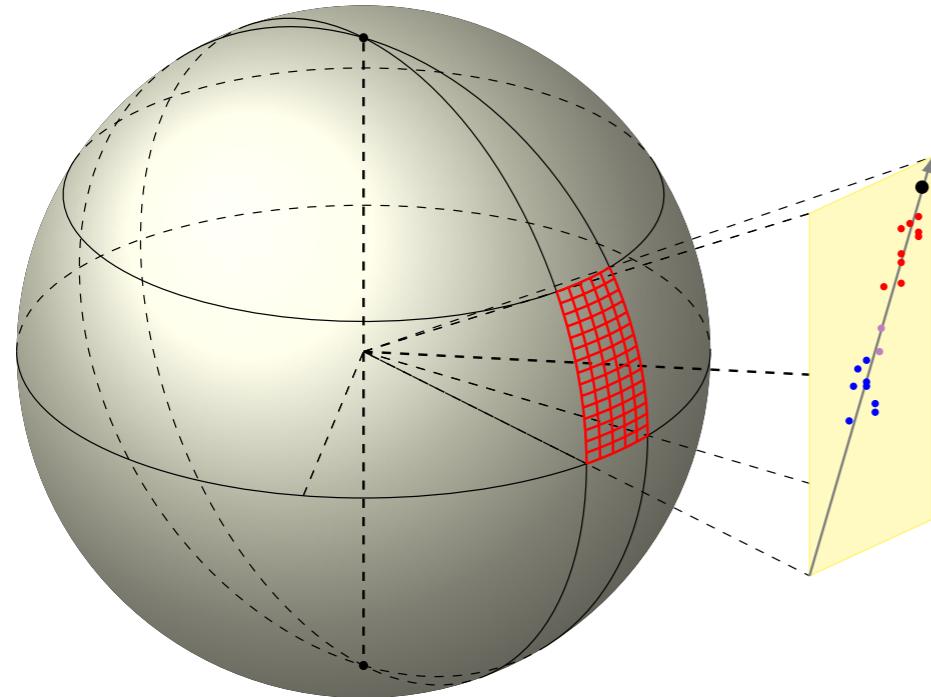
- ▶ combined spectrum-composition (1D) fits of the Auger spectrum/composition [Aloisio+ '13, Taylor '13, ...]
- ▶ mixed composition; maximum source acceleration cutoff (no GZK)
- ▶ results suggest an extra (light) class of sources below the ankle might be needed → Auger + KASCADE-Grande data
- ▶ hard spectra “problem” [Taylor '13]: these fits seem to suggest that the sources have spectral indexes harder than expected ( $\gamma \approx 1.0\text{-}1.6$ ); expected  $\gamma \approx 2.0\text{-}2.2$  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, Taylor+ '15]

# 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. I* (2012) 23. arXiv:1201.2183

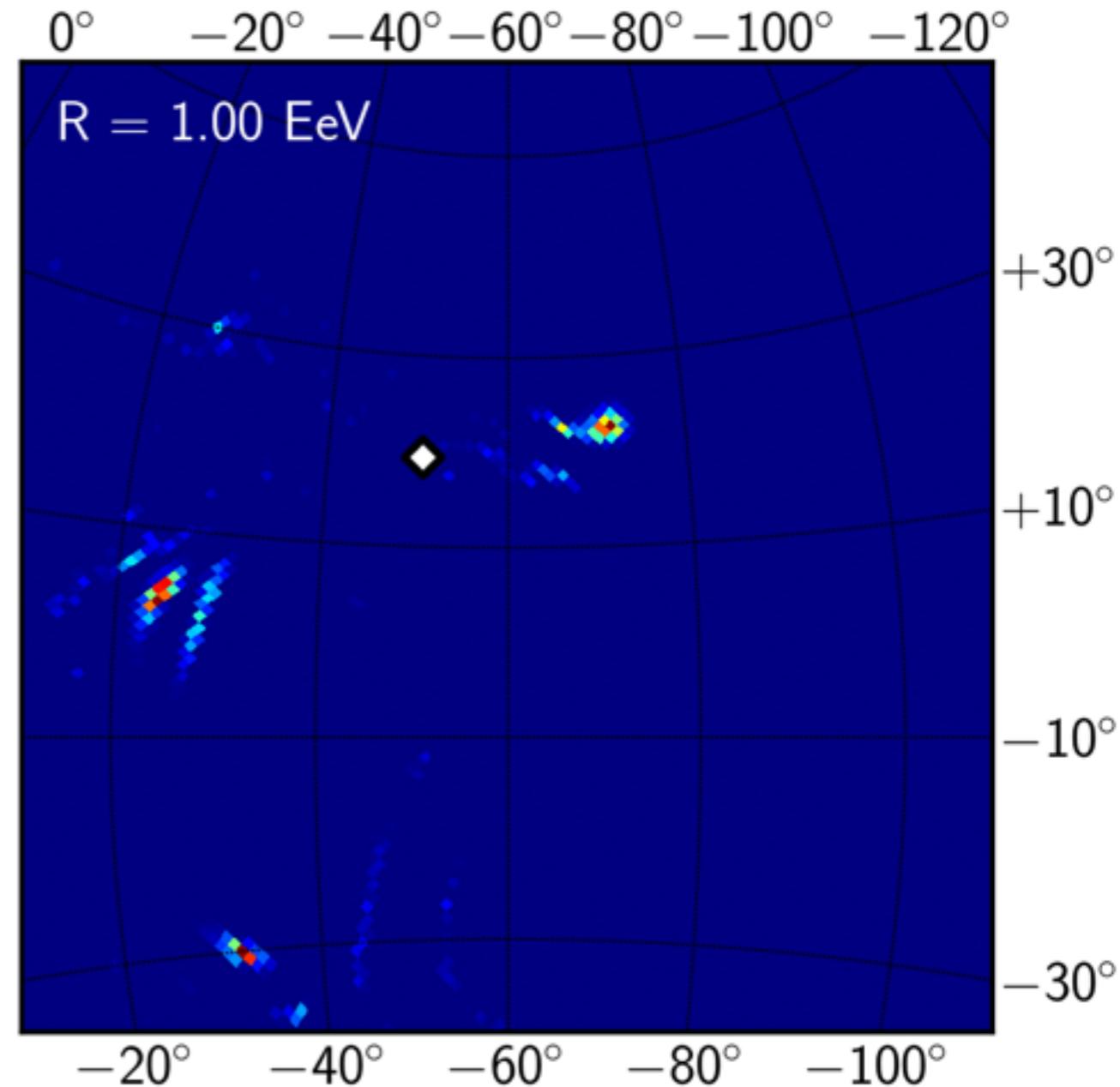
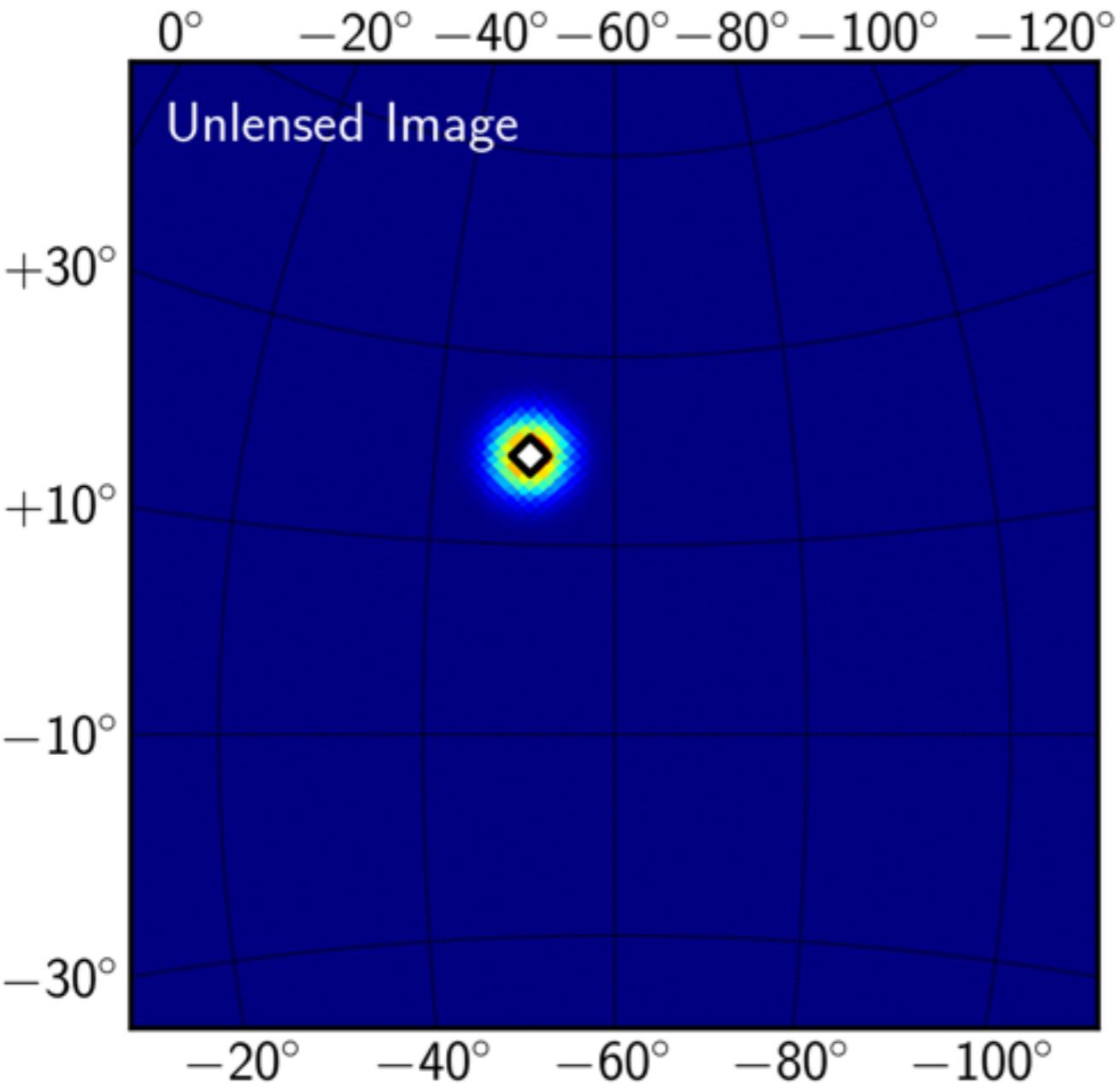
- if galactic deflection dominate over extragalactic, can we reconstruct source position?



- 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

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



obtained with the PARSEC code