

# **modelling the propagation of ultra-high-energy cosmic rays**

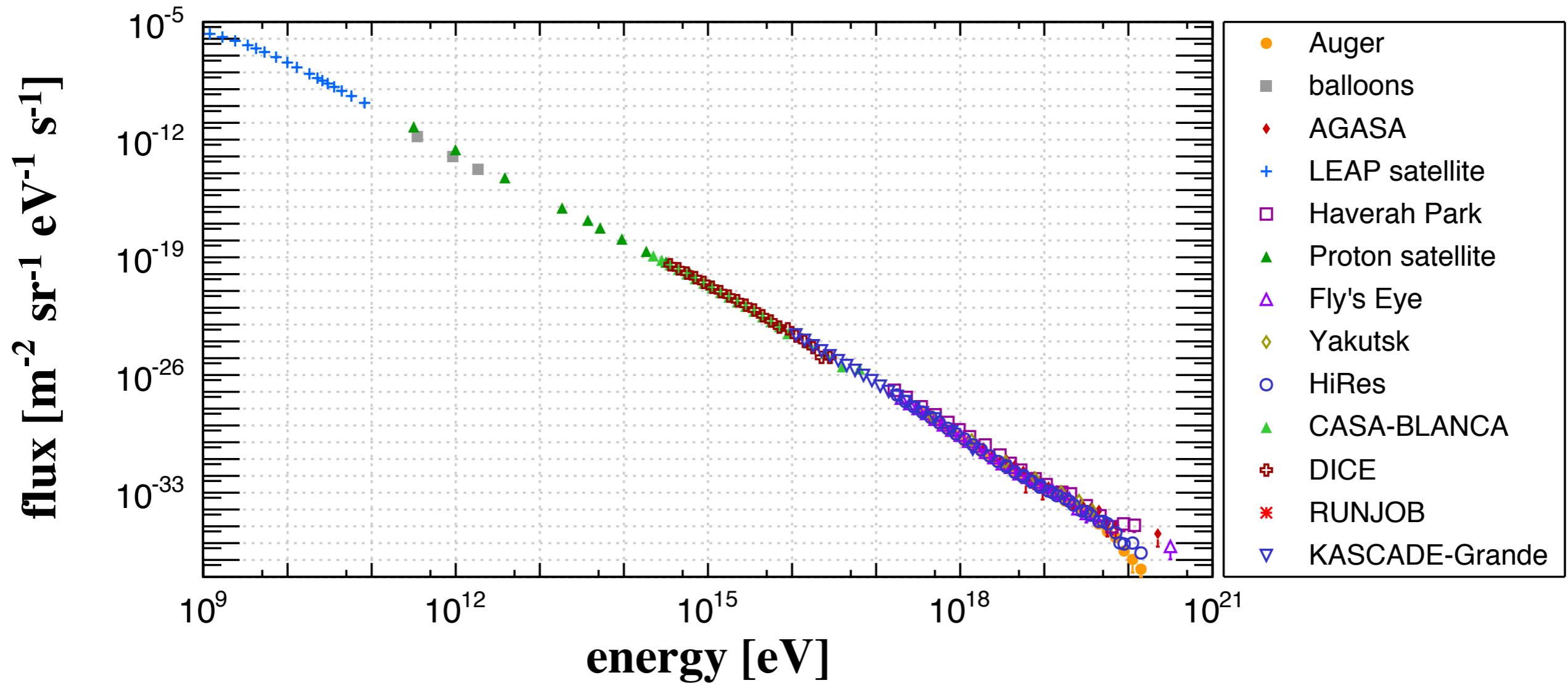
**Rafael Alves Batista**

**University of Oxford**

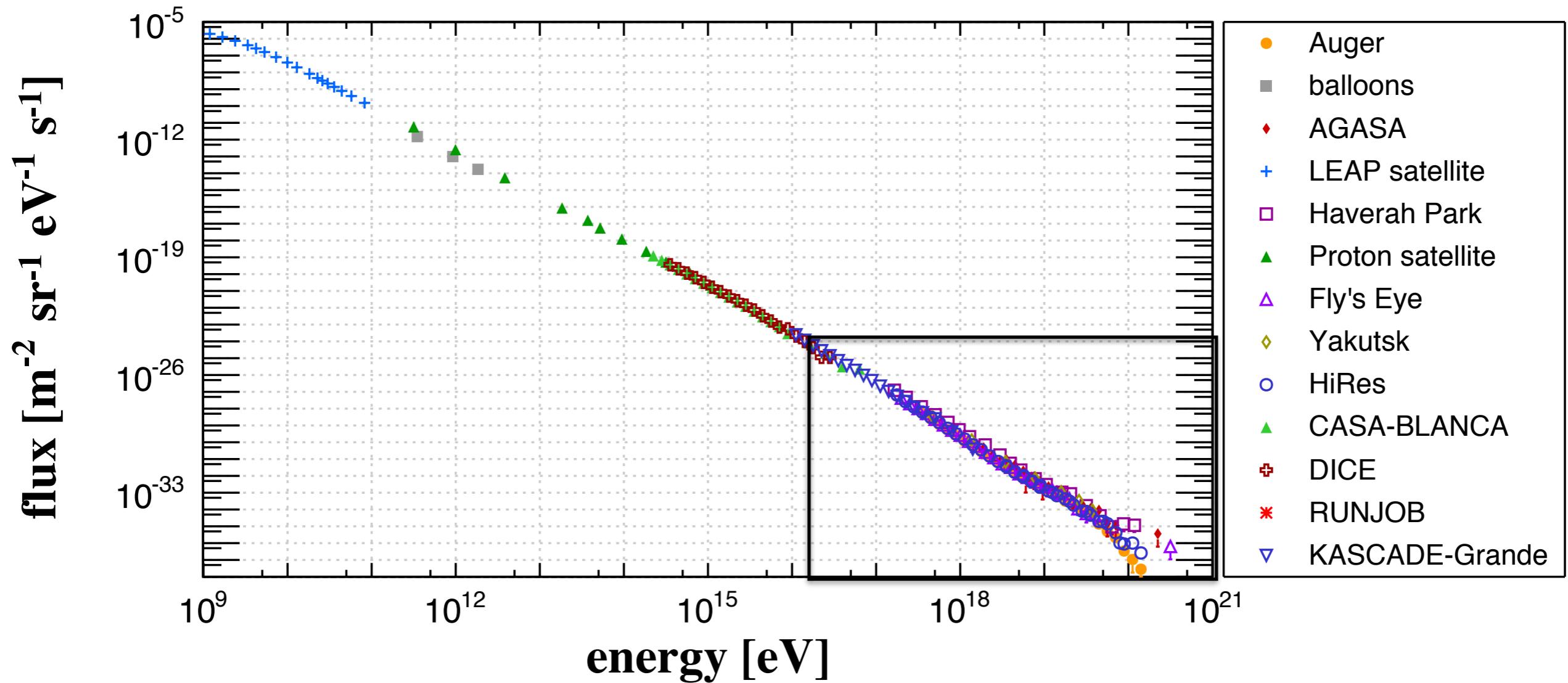
**[rafael.alvesbatista@physics.ox.ac.uk](mailto:rafael.alvesbatista@physics.ox.ac.uk)**

Columbus  
30/Sep/2016

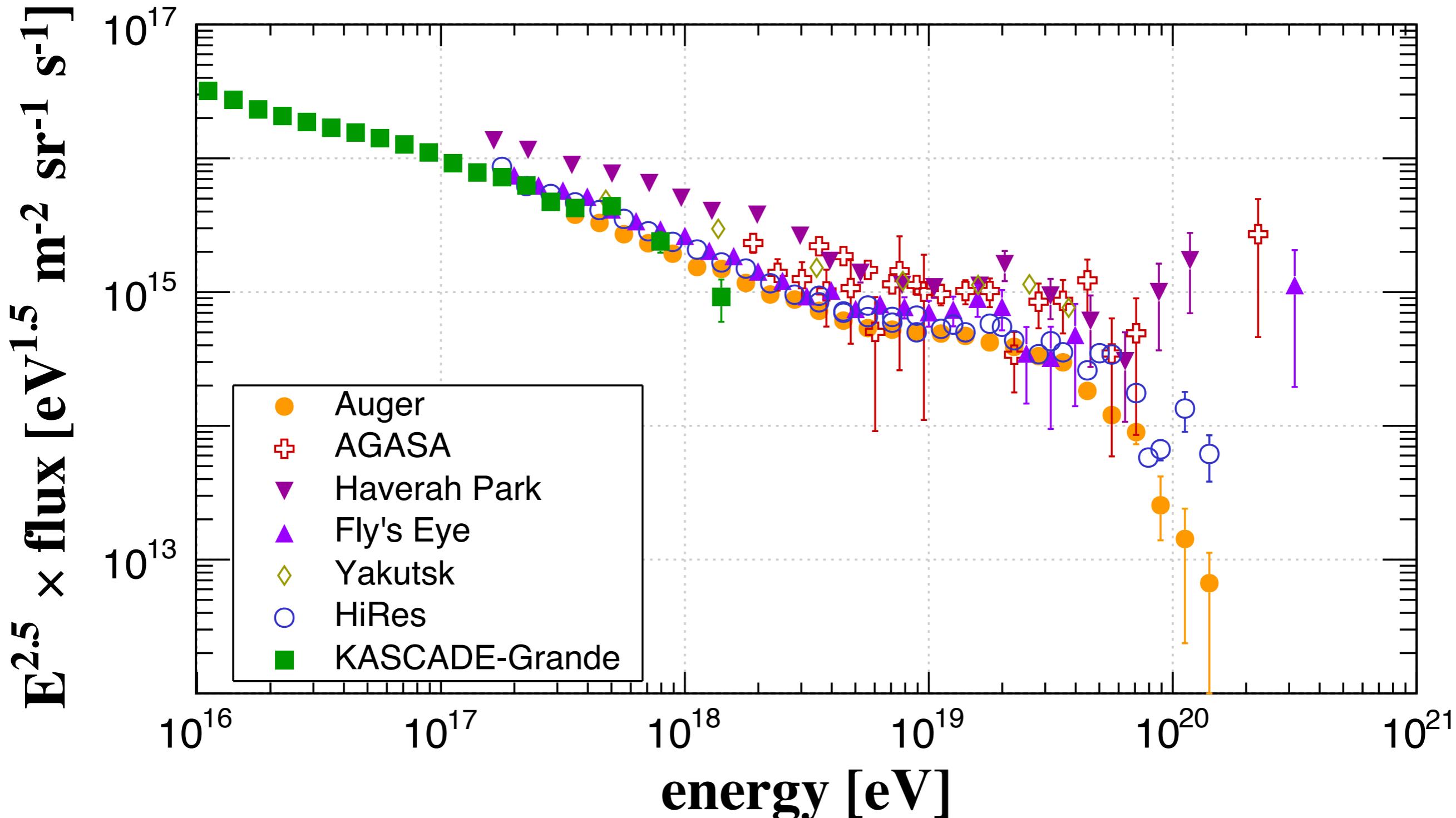
# the cosmic ray spectrum at high energies



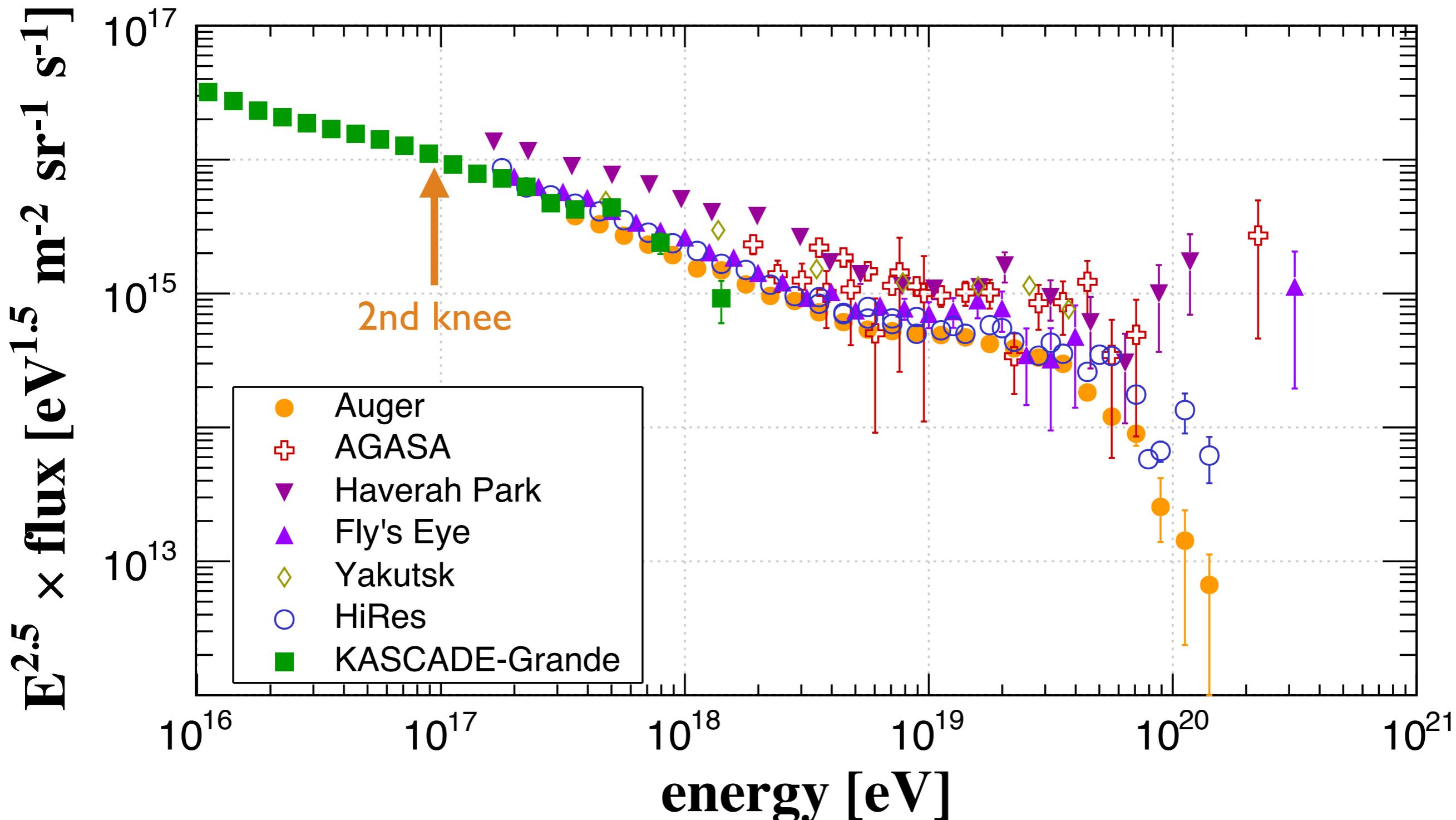
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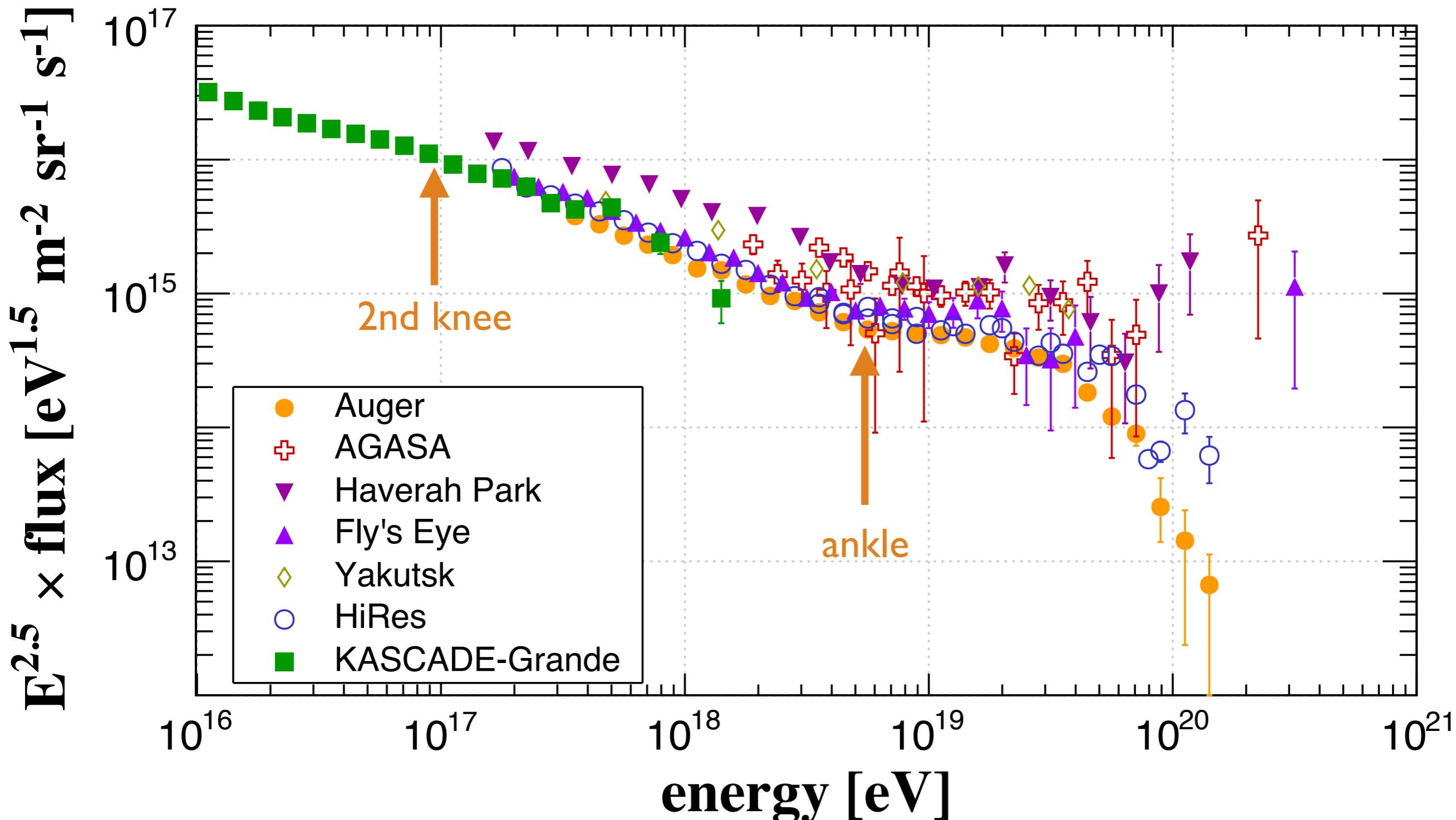
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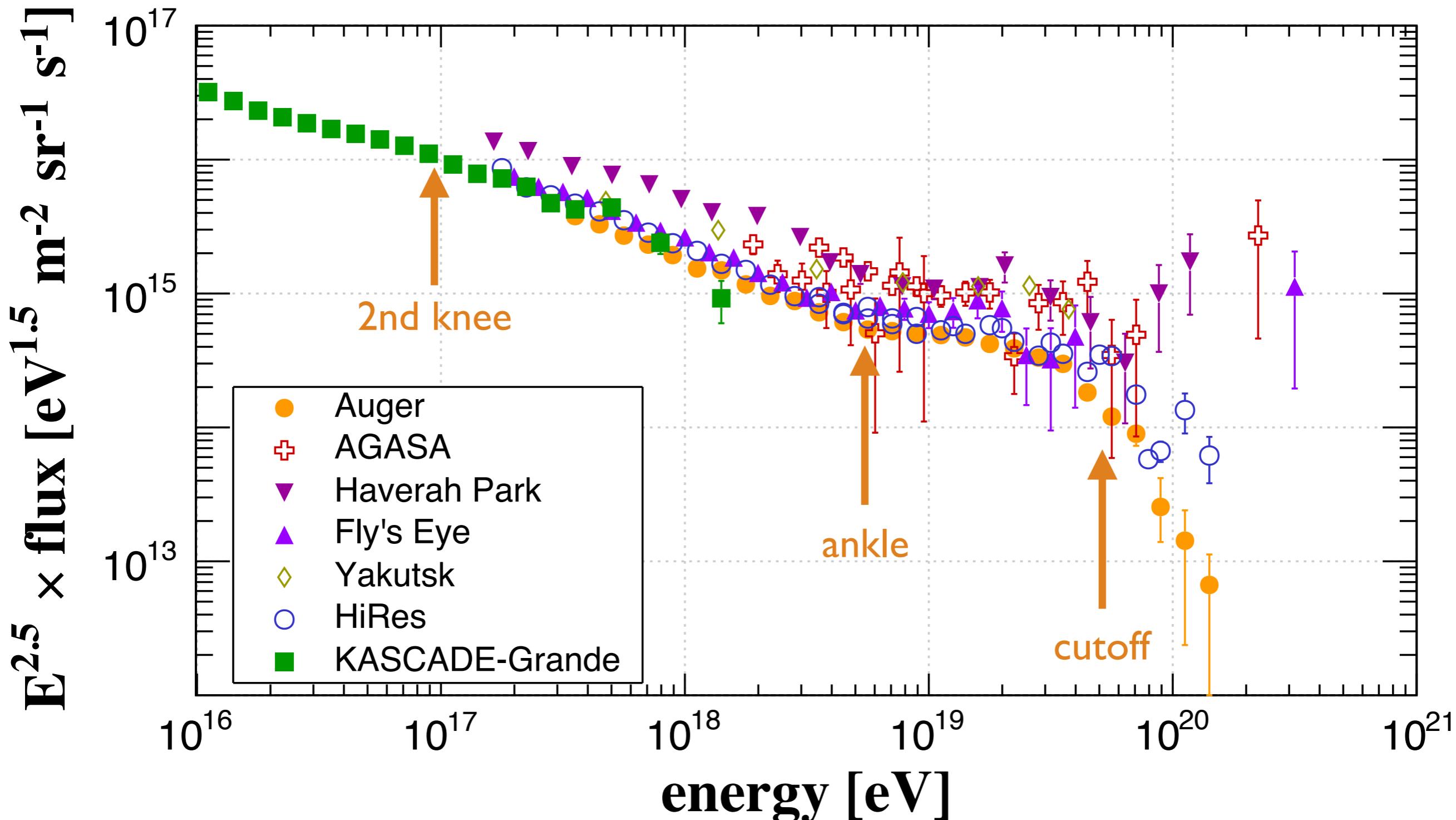
# the cosmic ray spectrum at high energies



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# the cosmic ray spectrum at high energies



# ultra-high energy cosmic rays

## fundamental questions

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

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- ▶ 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?

# ultra-high energy cosmic rays

## fundamental questions

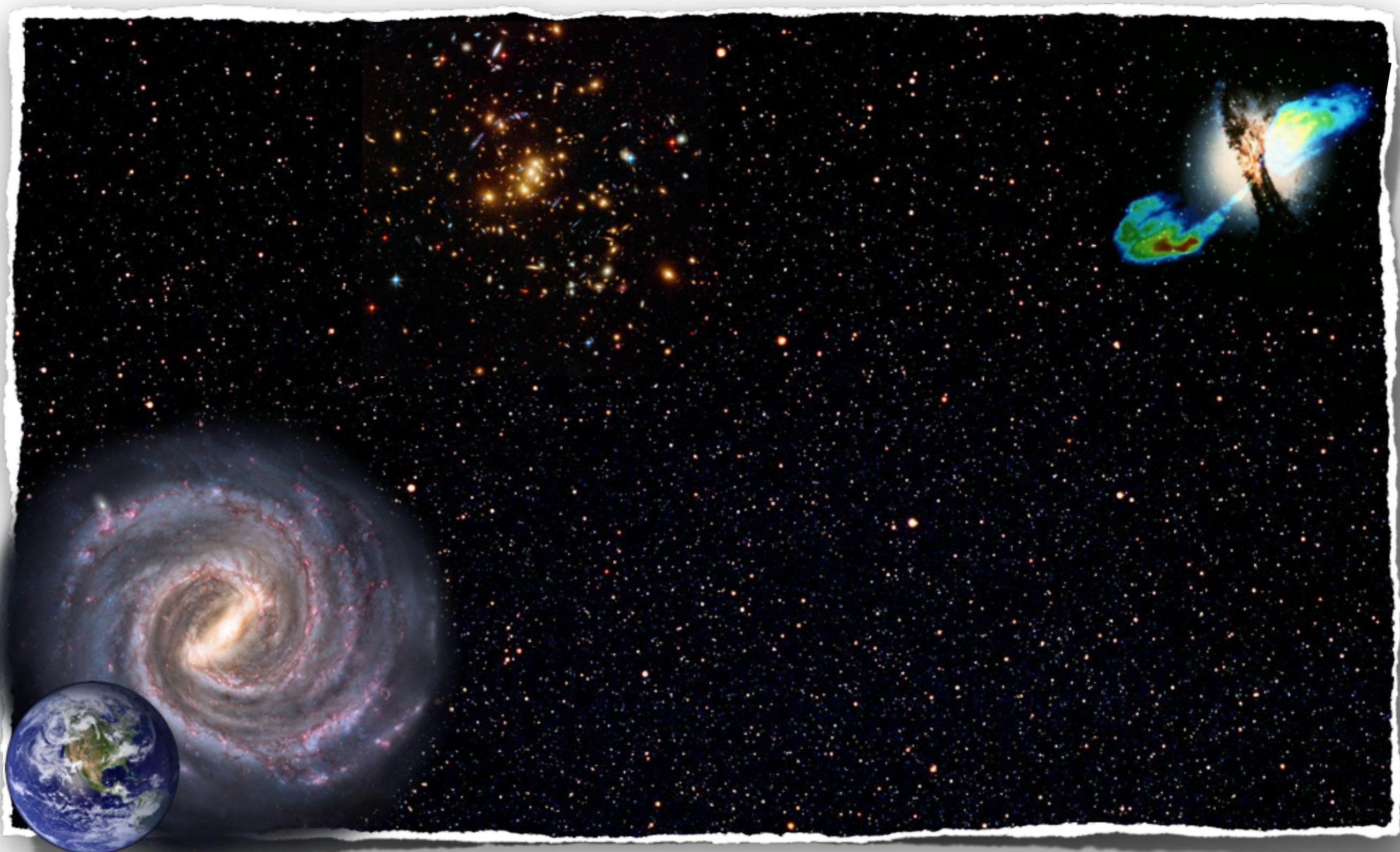
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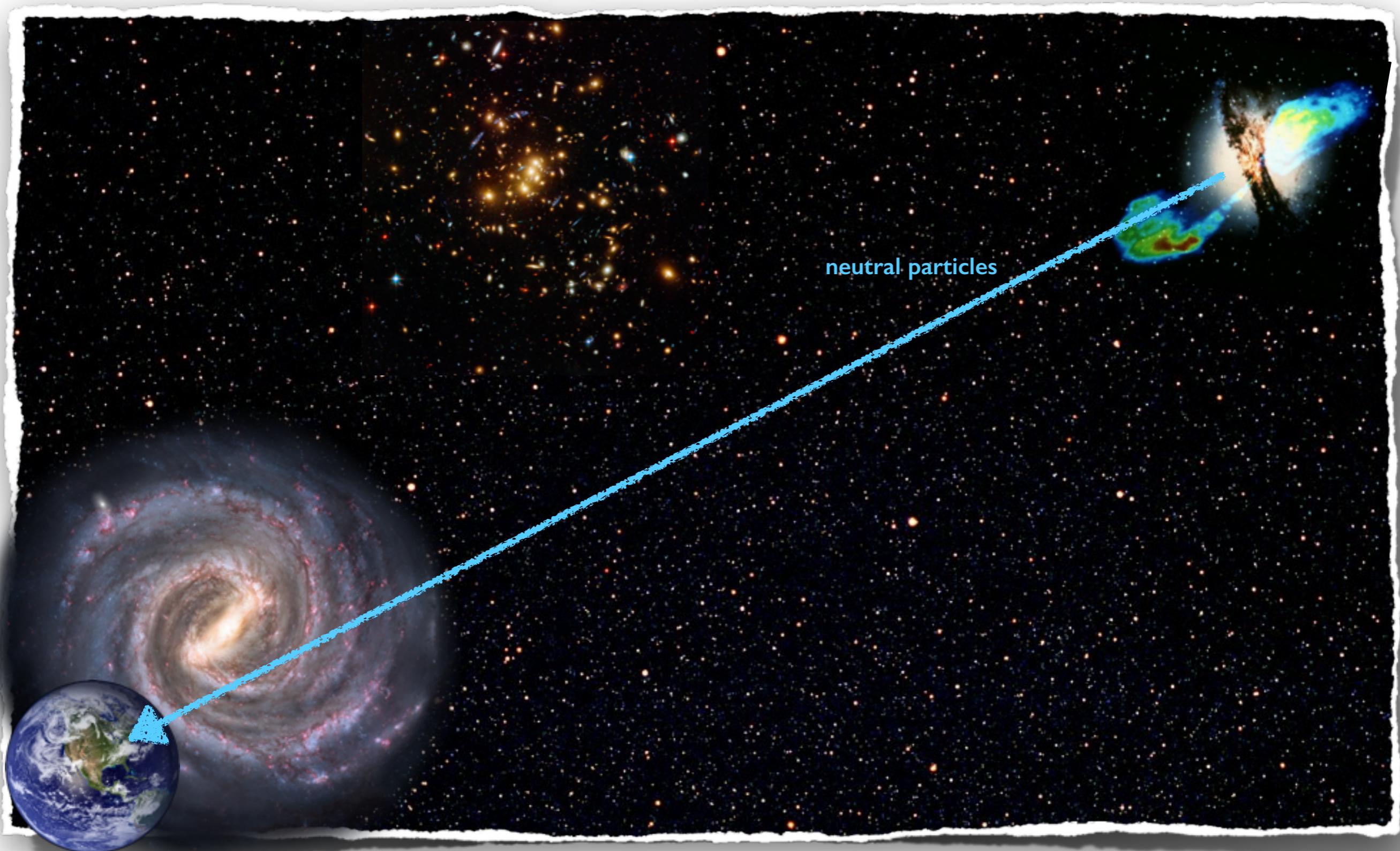
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- ▶ observables from CR experiments: spectrum, composition, anisotropy
- ▶ cosmic magnetic fields (galactic and extragalactic) are important
- ▶ test new physics scenarios using UHECRs (?)

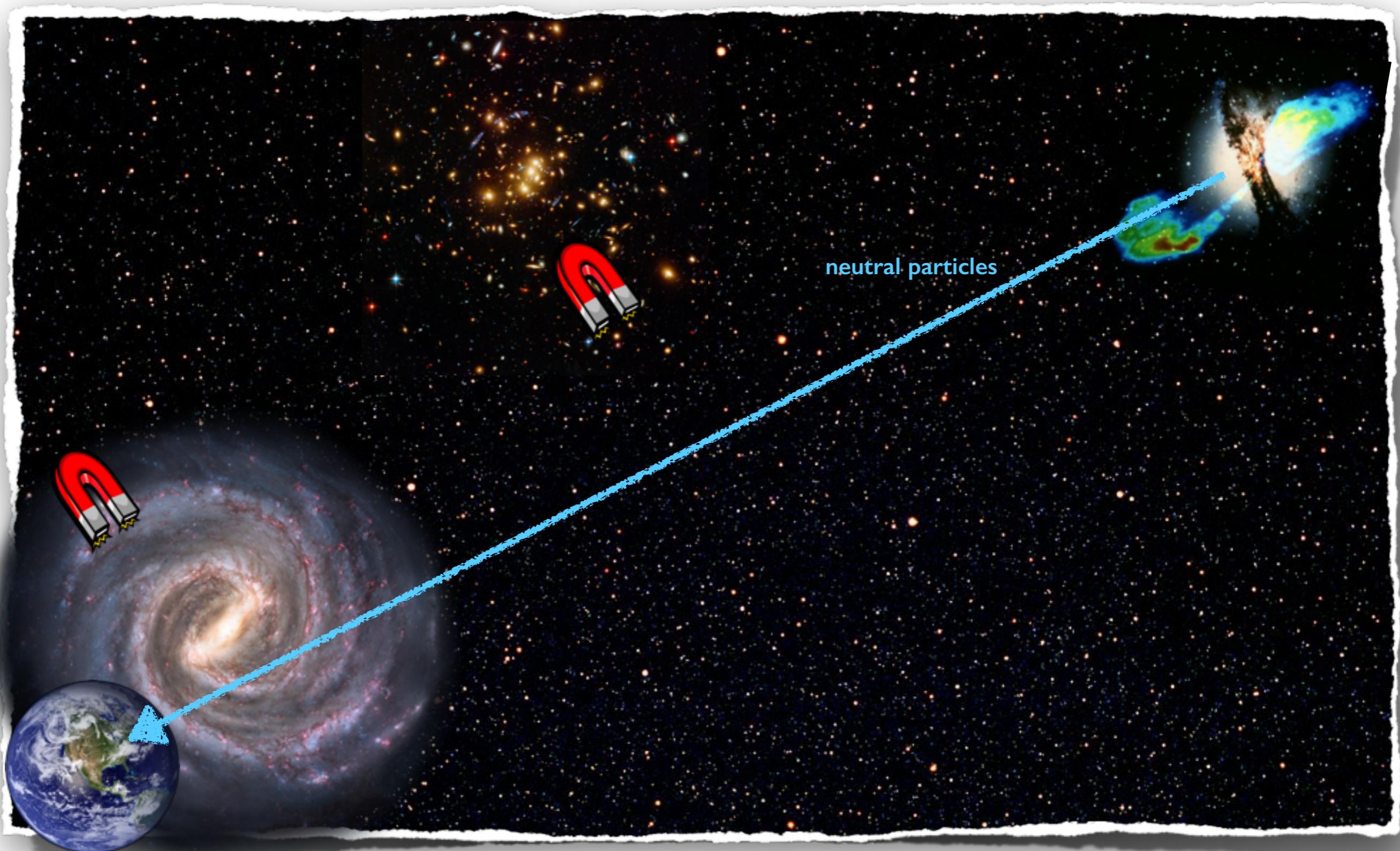
# propagation picture



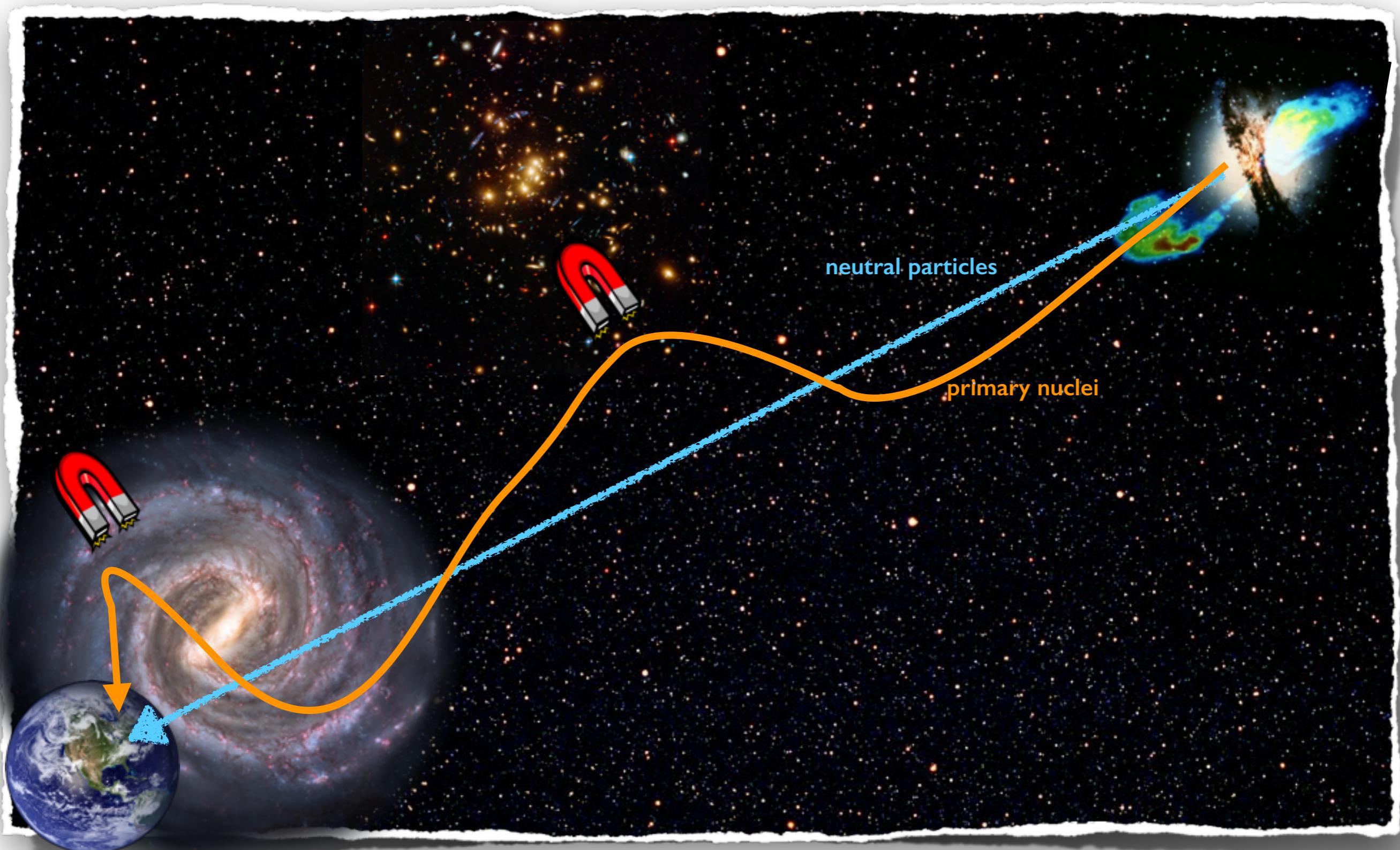
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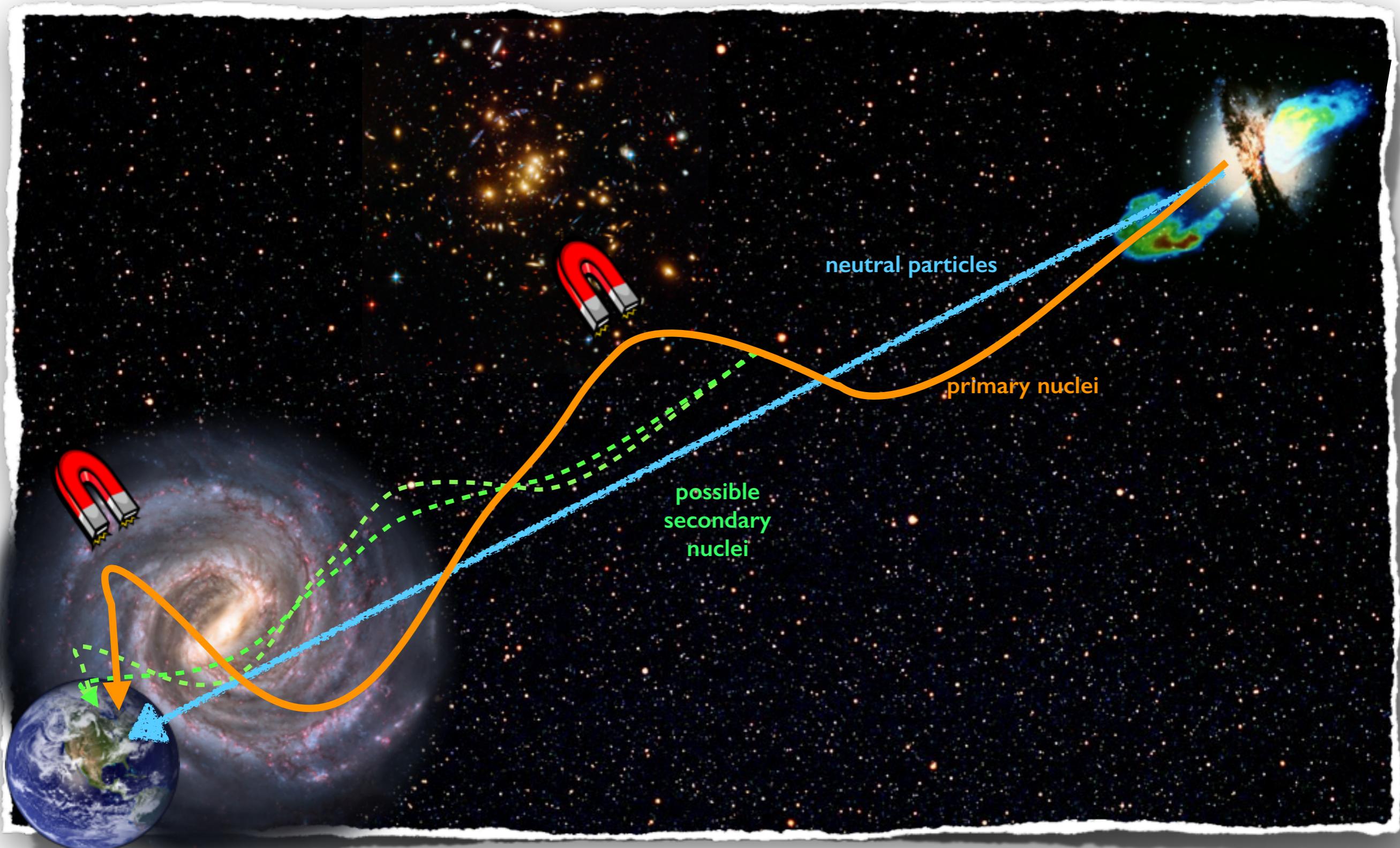
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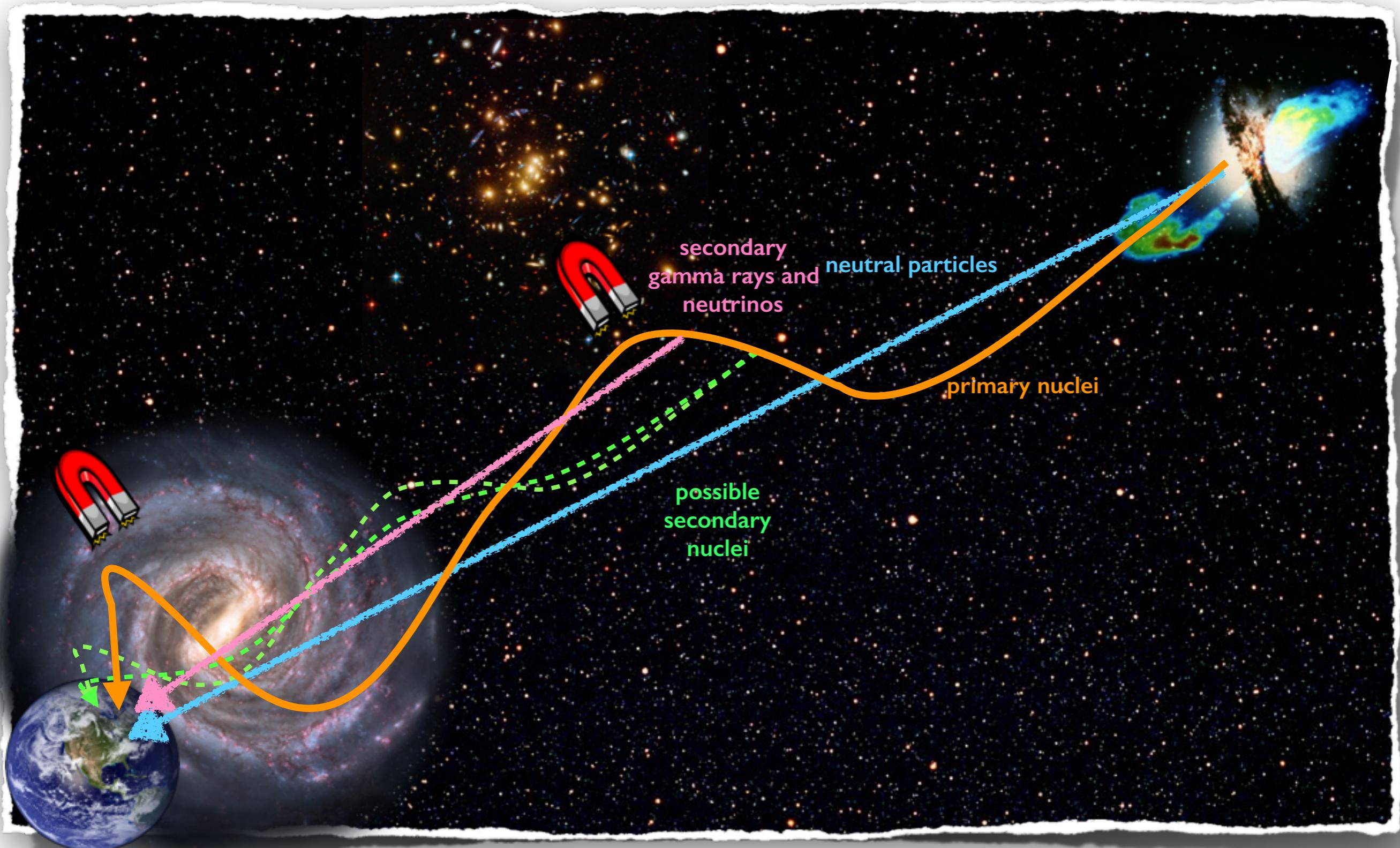
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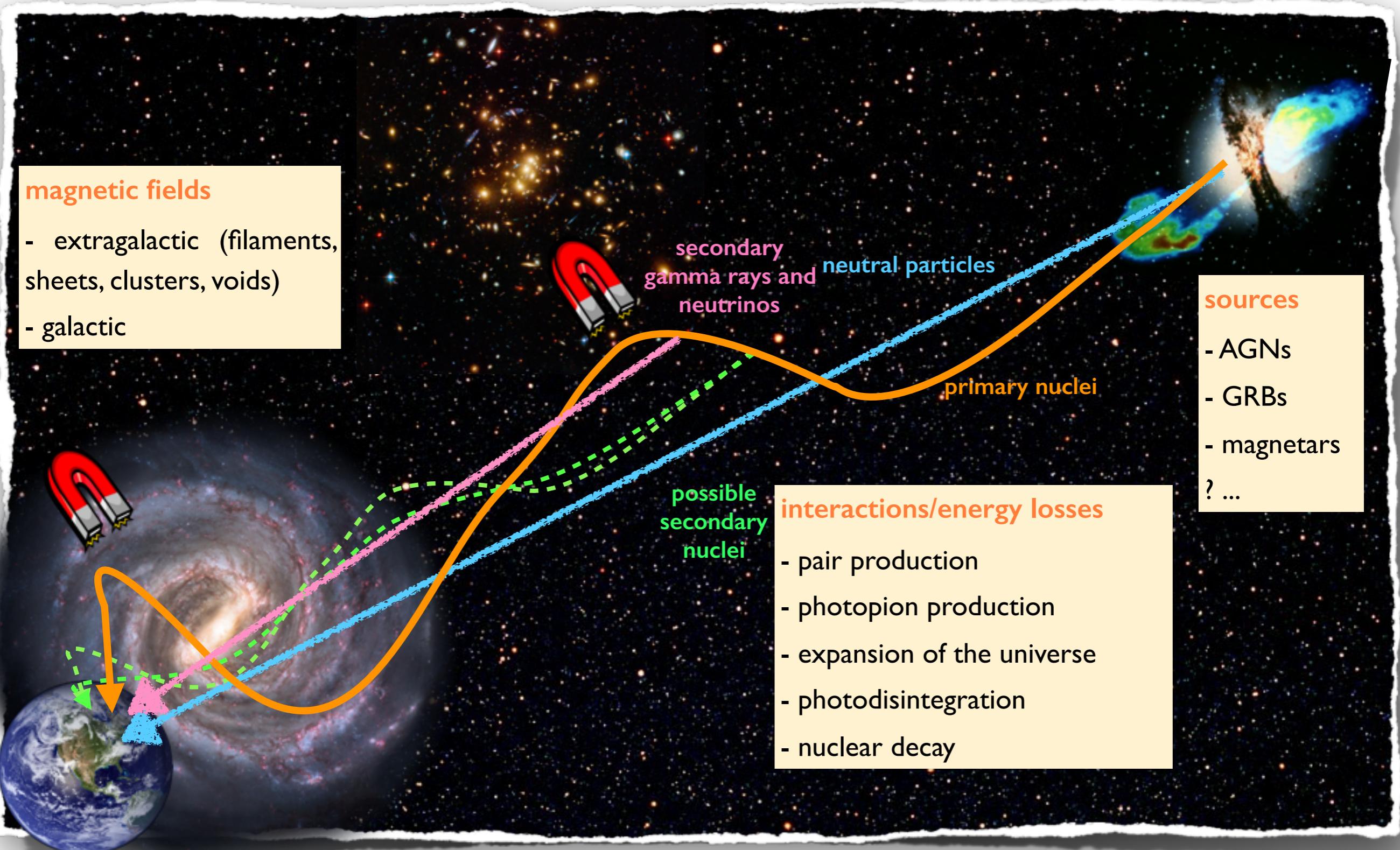
# propagation picture



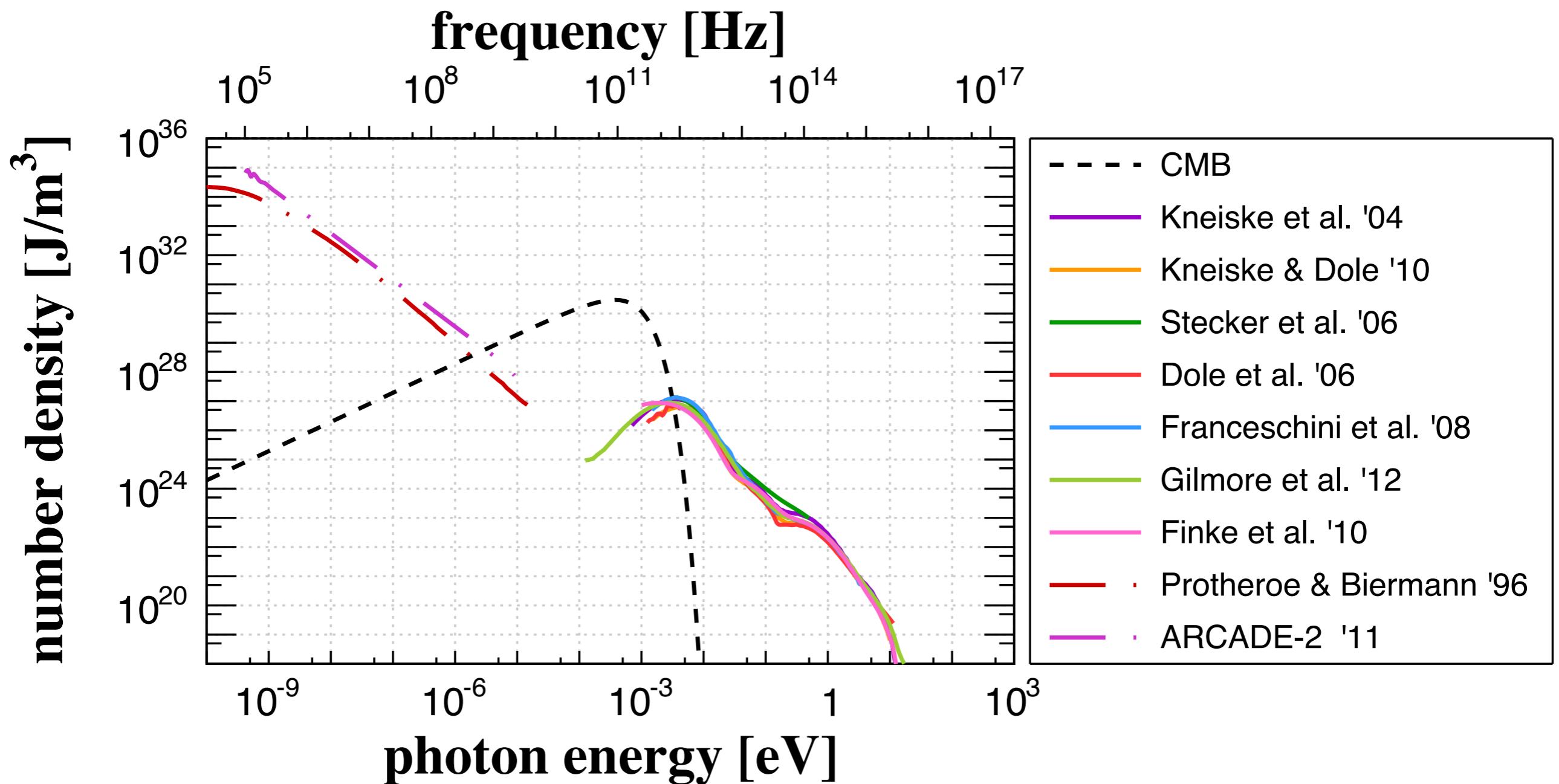
# propagation picture



# propagation picture

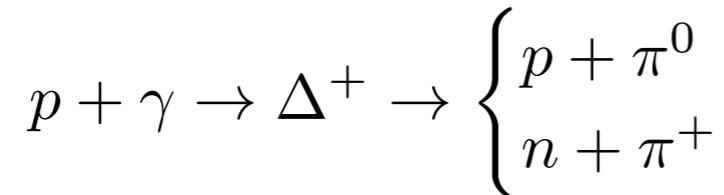


# modelling the propagation of UHECRs: photon backgrounds



# 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

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

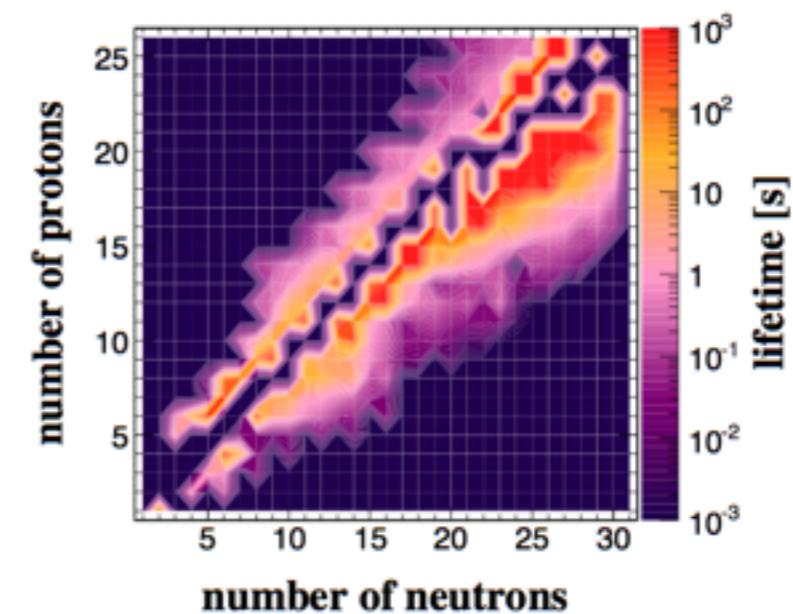
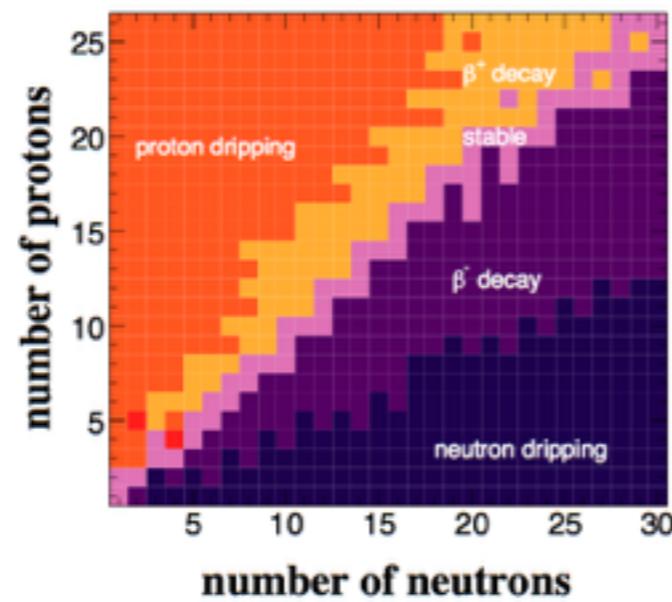
pair production

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

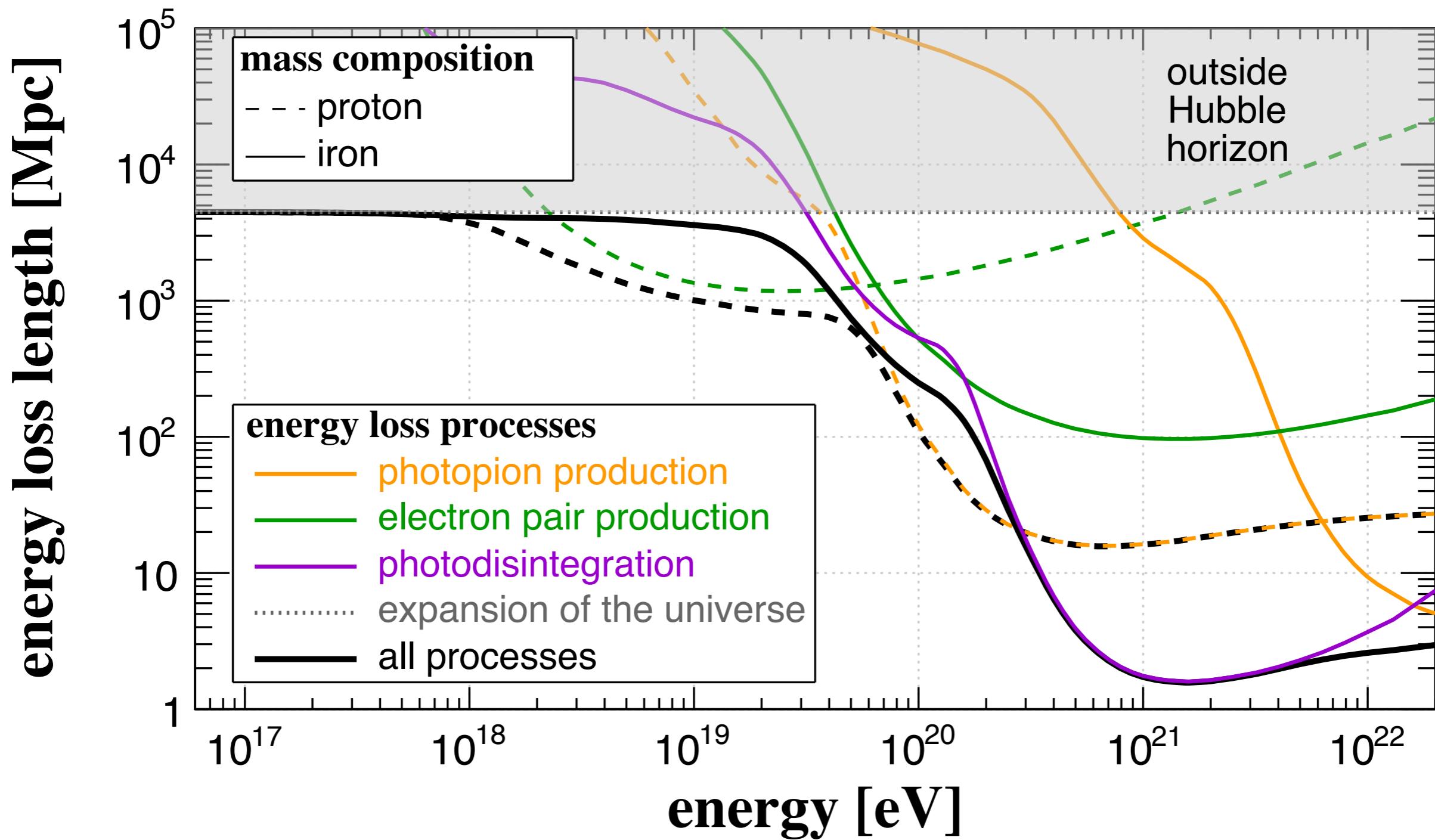
photodisintegration

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

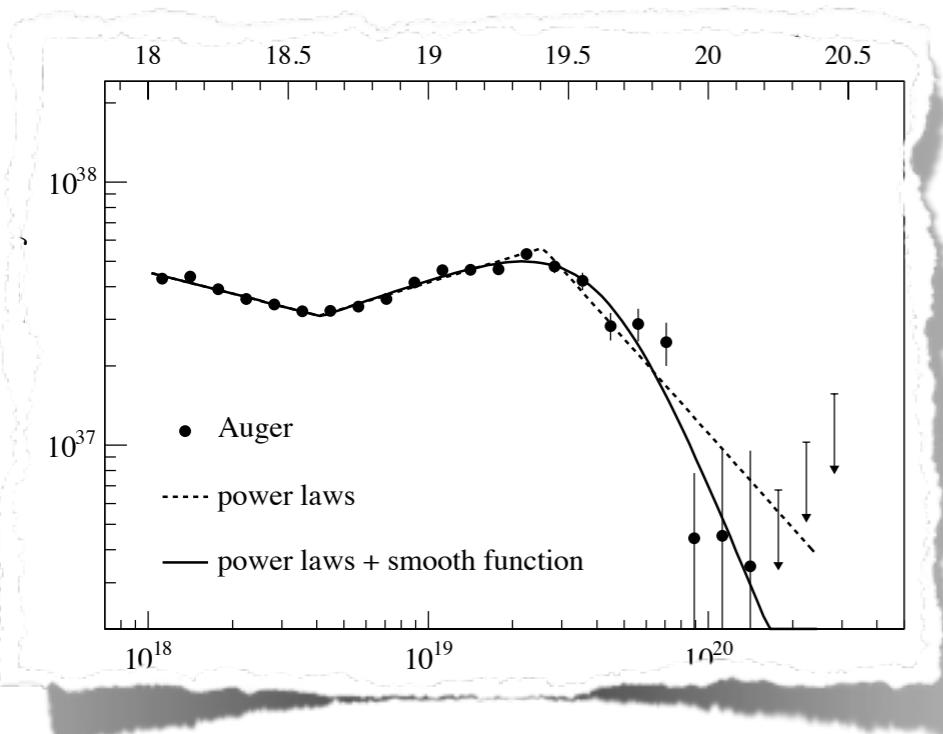
nuclear decay



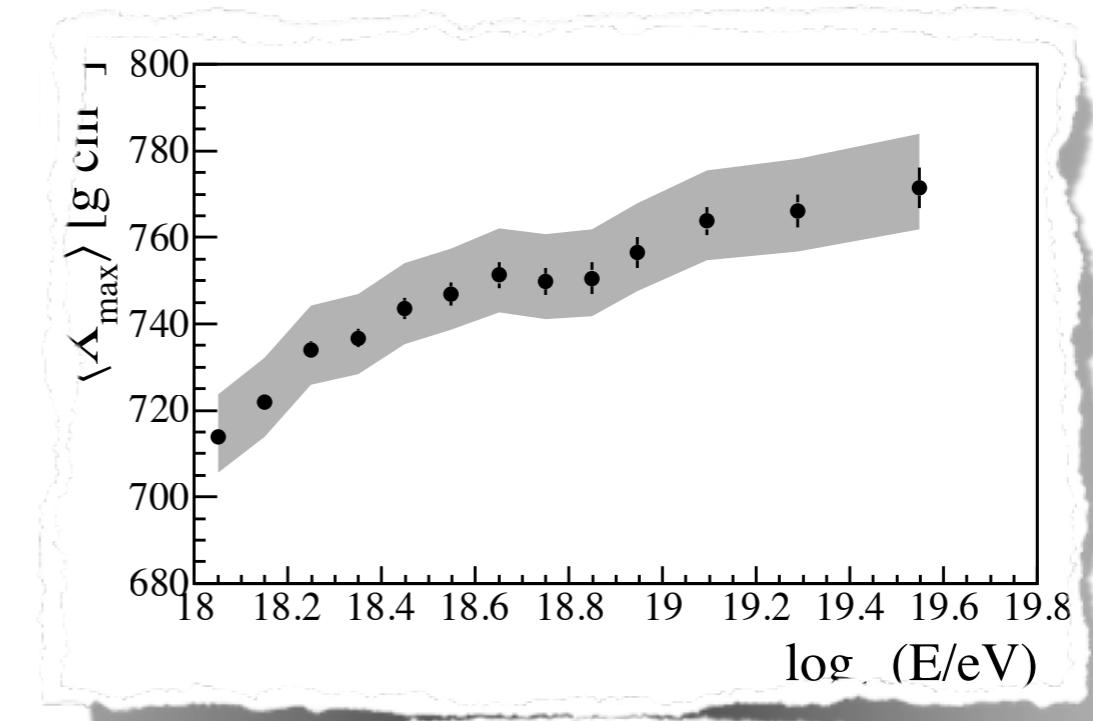
# modelling the propagation of UHECRs: energy losses



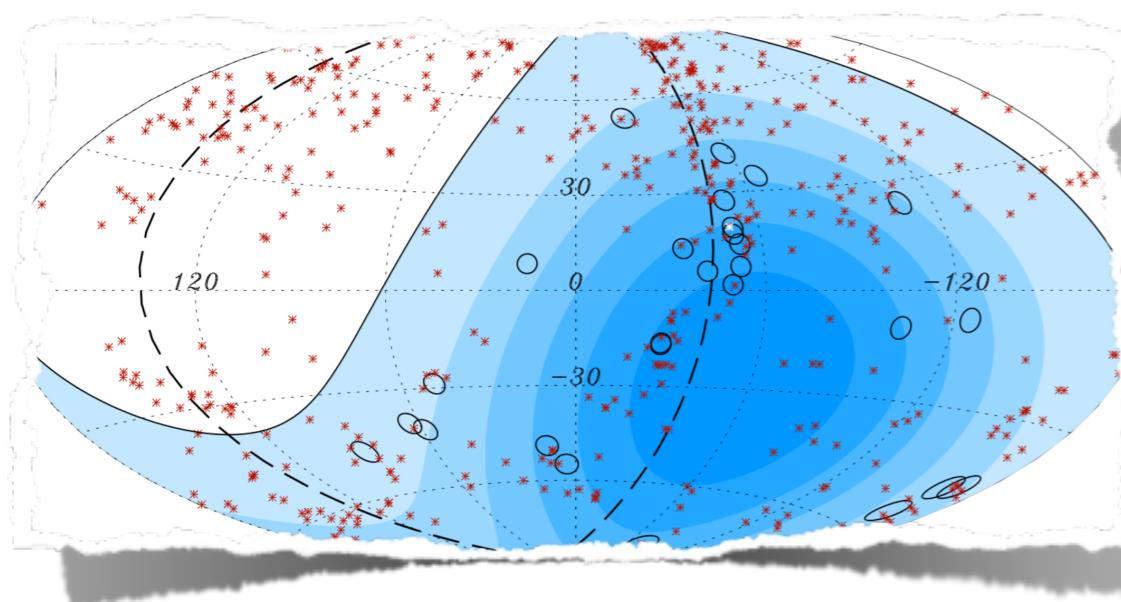
# modelling the propagation of UHECRs



Pierre Auger Collaboration. ICRC 2011.



Pierre Auger Collaboration. JCAP 02 (2013) 026.



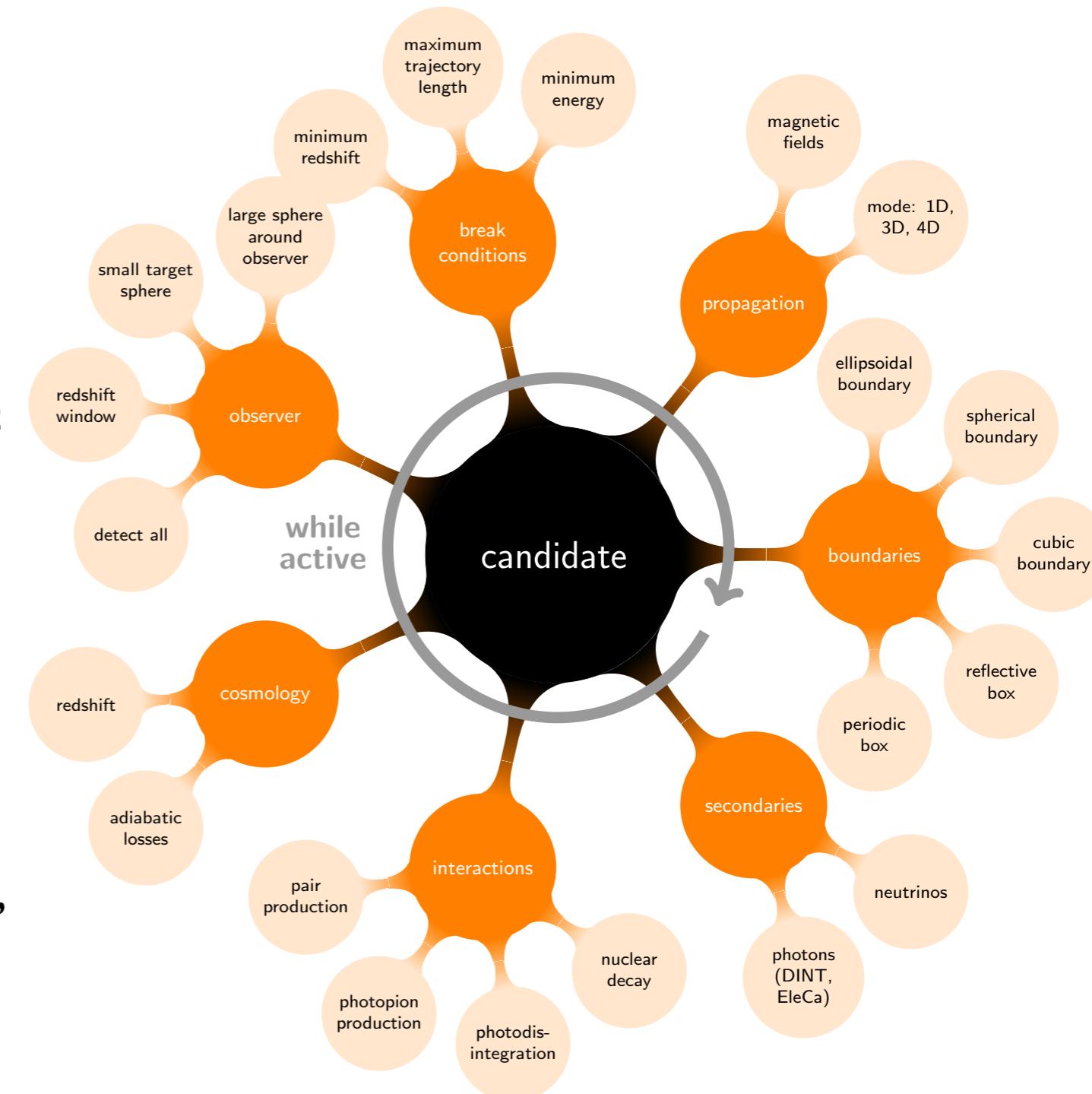
Pierre Auger Collaboration. Science 318 (2007) 938.

- ▶ 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

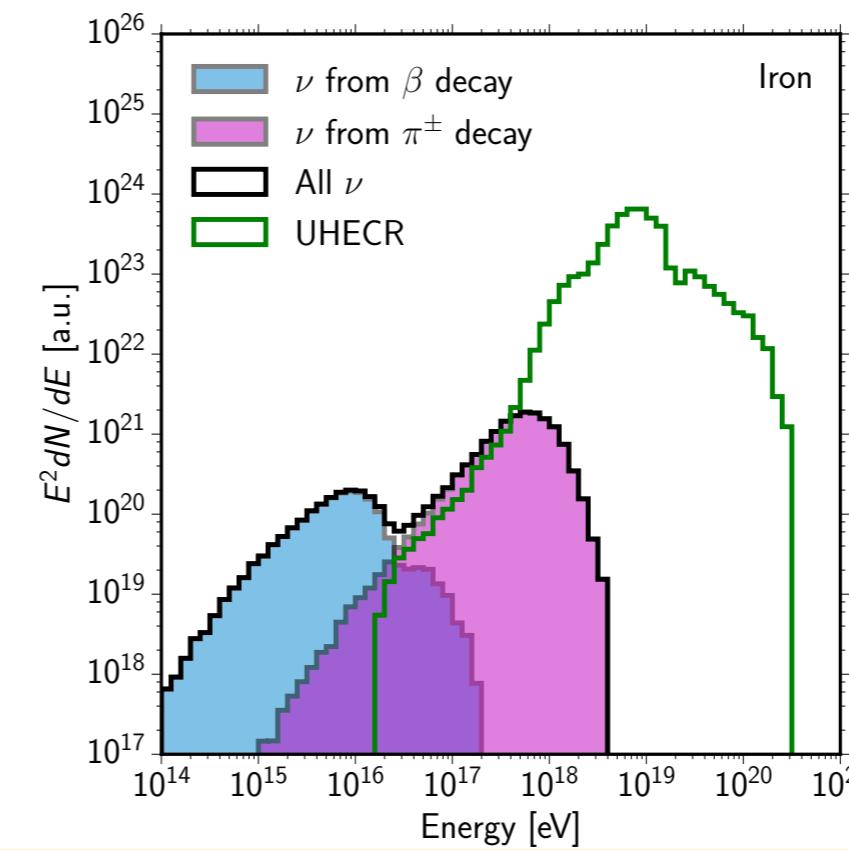
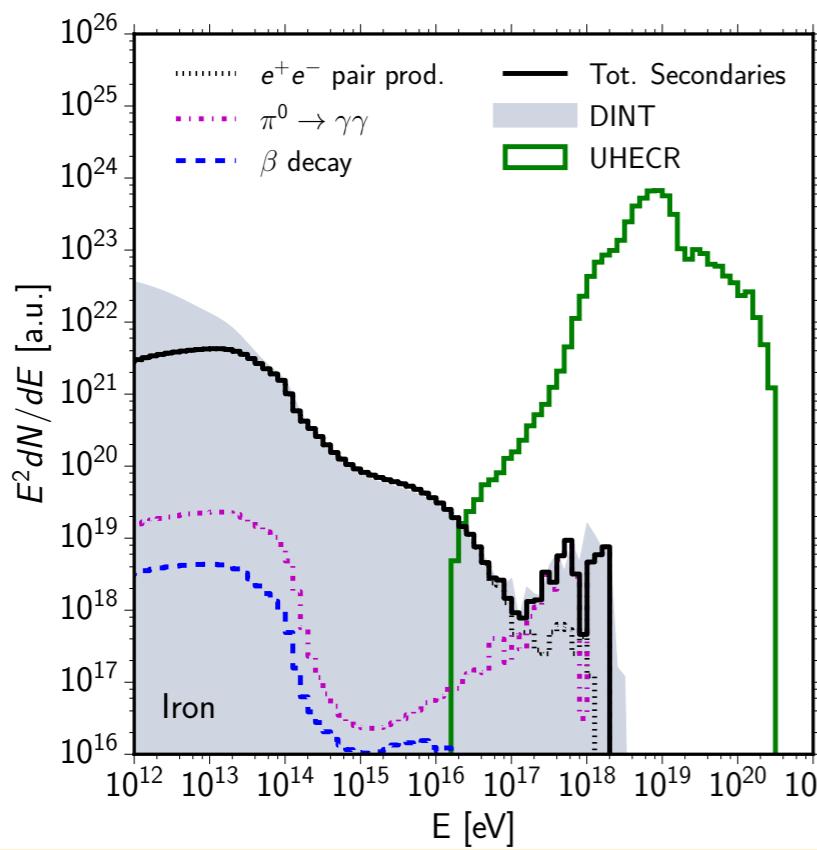
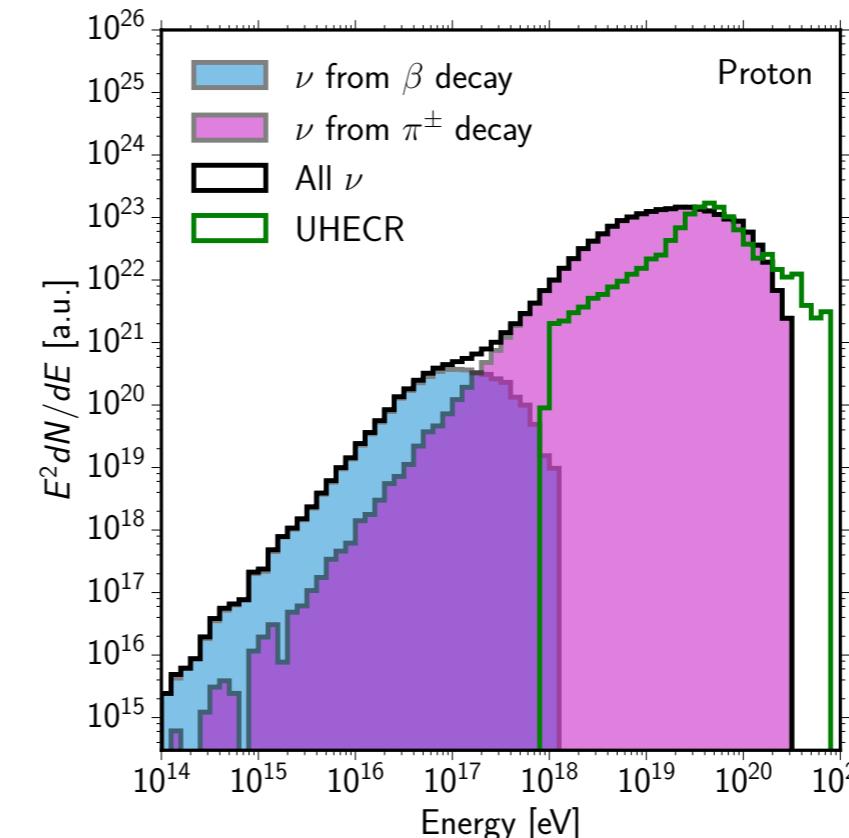
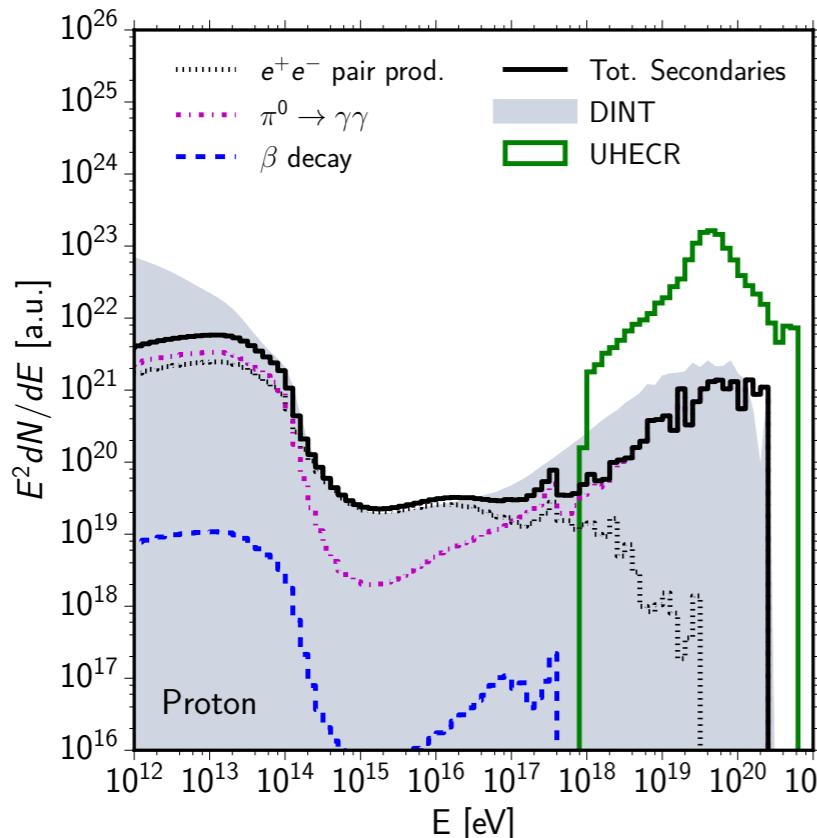
- ▶ publicly available Monte Carlo code for propagating UHECRs and their secondaries in the intergalactic space
- ▶ modular structure
- ▶ parallelisation with OpenMP
- ▶ 1D, 3D and "4D" simulations
- ▶ relevant energy losses implemented
- ▶ variety of tools to handle custom magnetic field models
- ▶ 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)

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



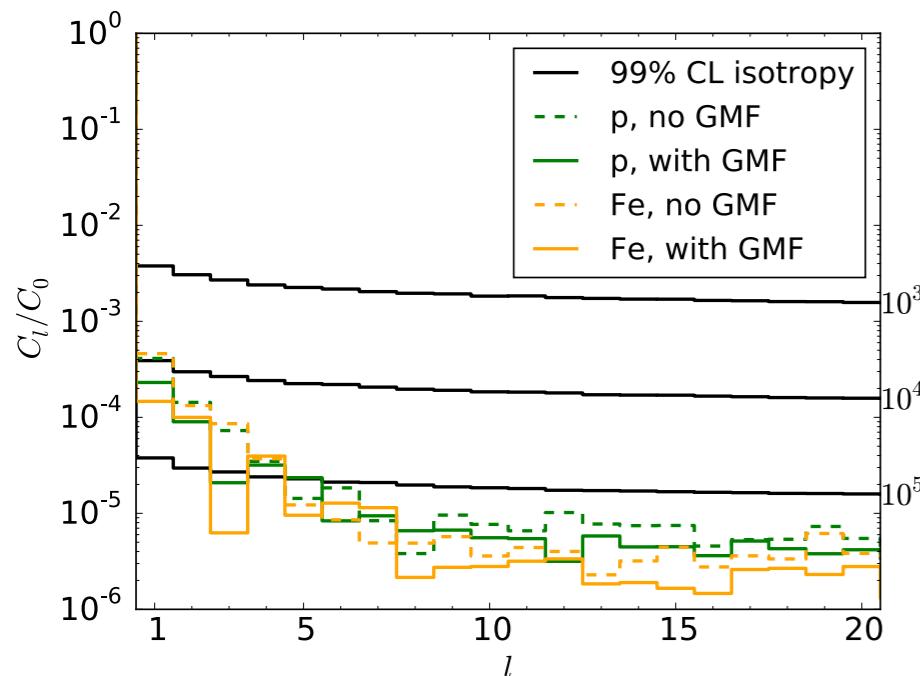
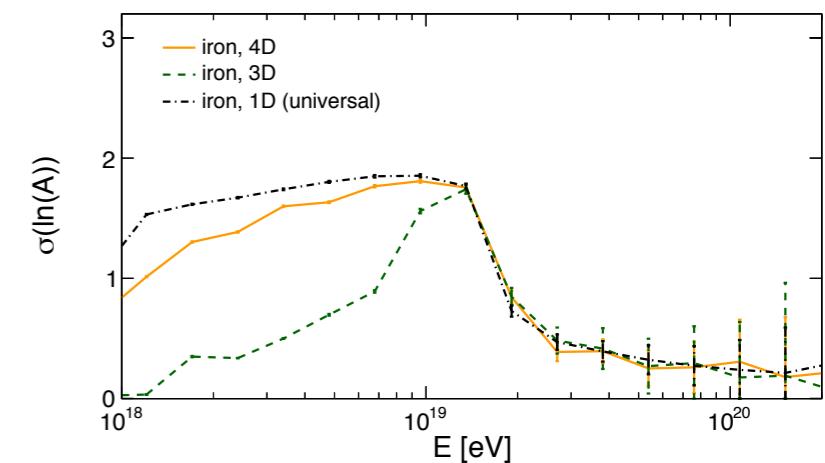
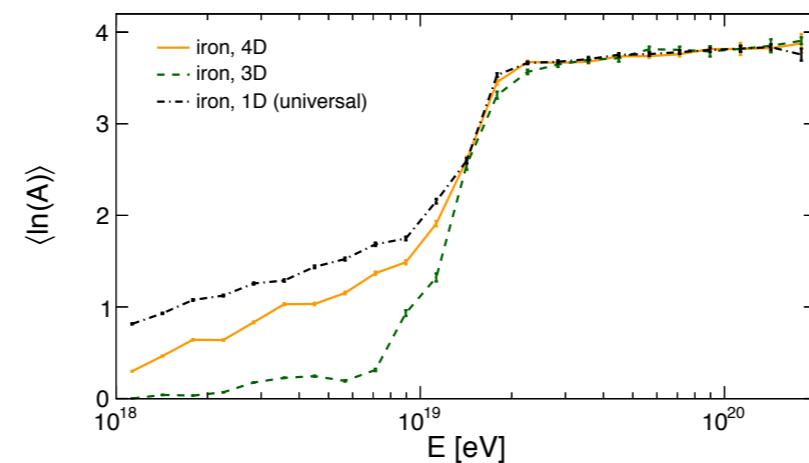
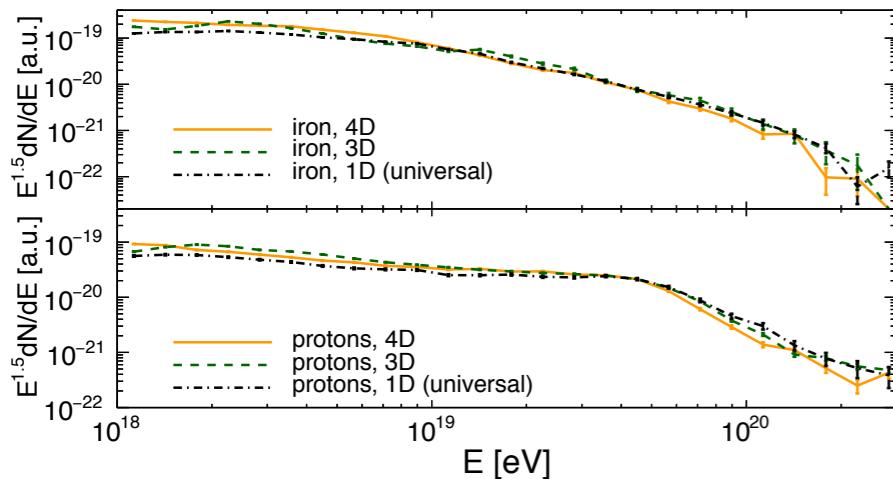
[crpropa.desy.de](http://crpropa.desy.de)

# ID example: gamma rays and neutrinos

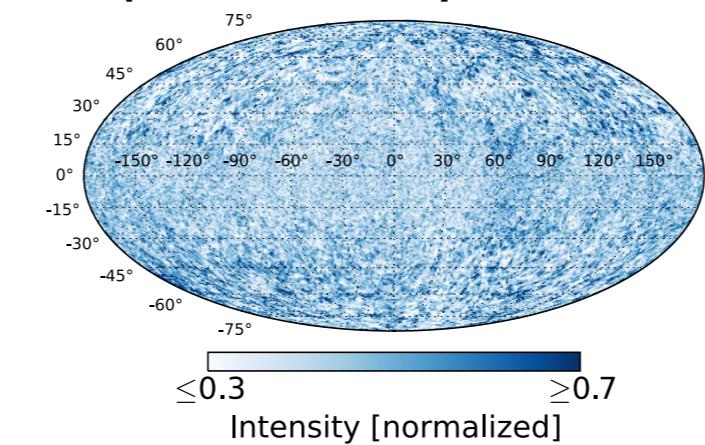


RAB et al. JCAP 05 (2016) 038.  
arXiv:1603.07142

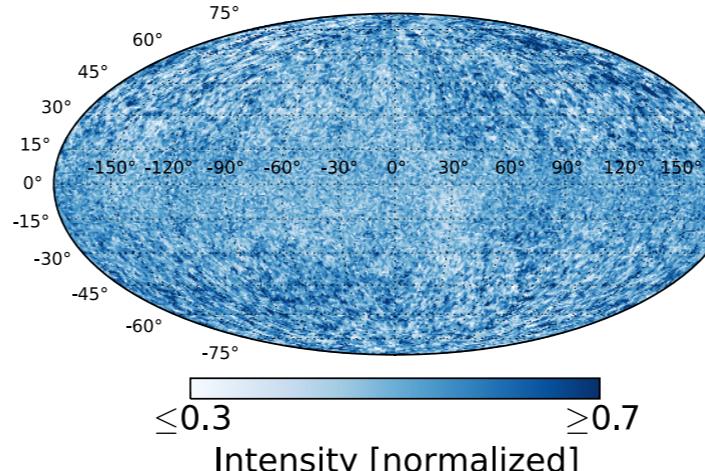
# 3D/4D examples: including galactic lensing



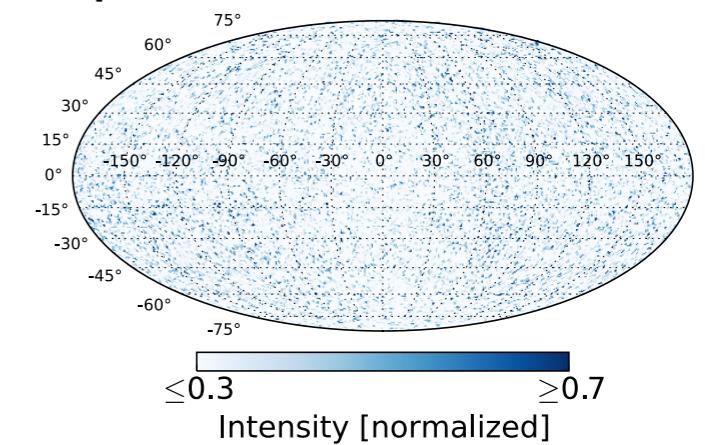
proton - only EGMF



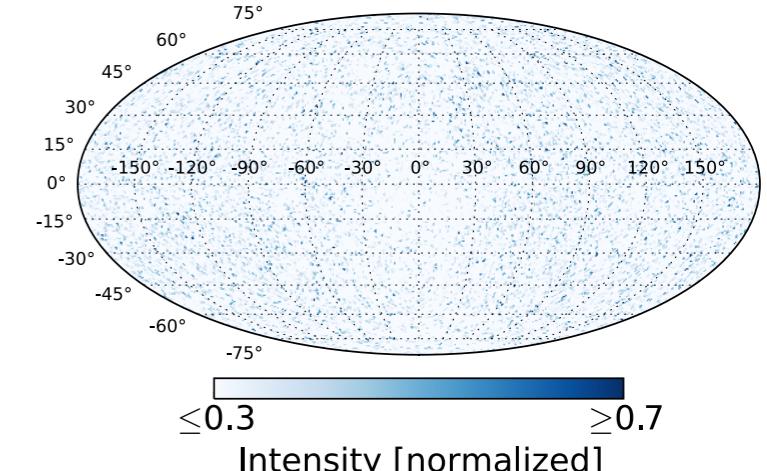
iron - only EGMF



proton - EGMF+GMF



iron - EGMF+GMF



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

# theoretical uncertainties in the modelling

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

## main sources of uncertainties

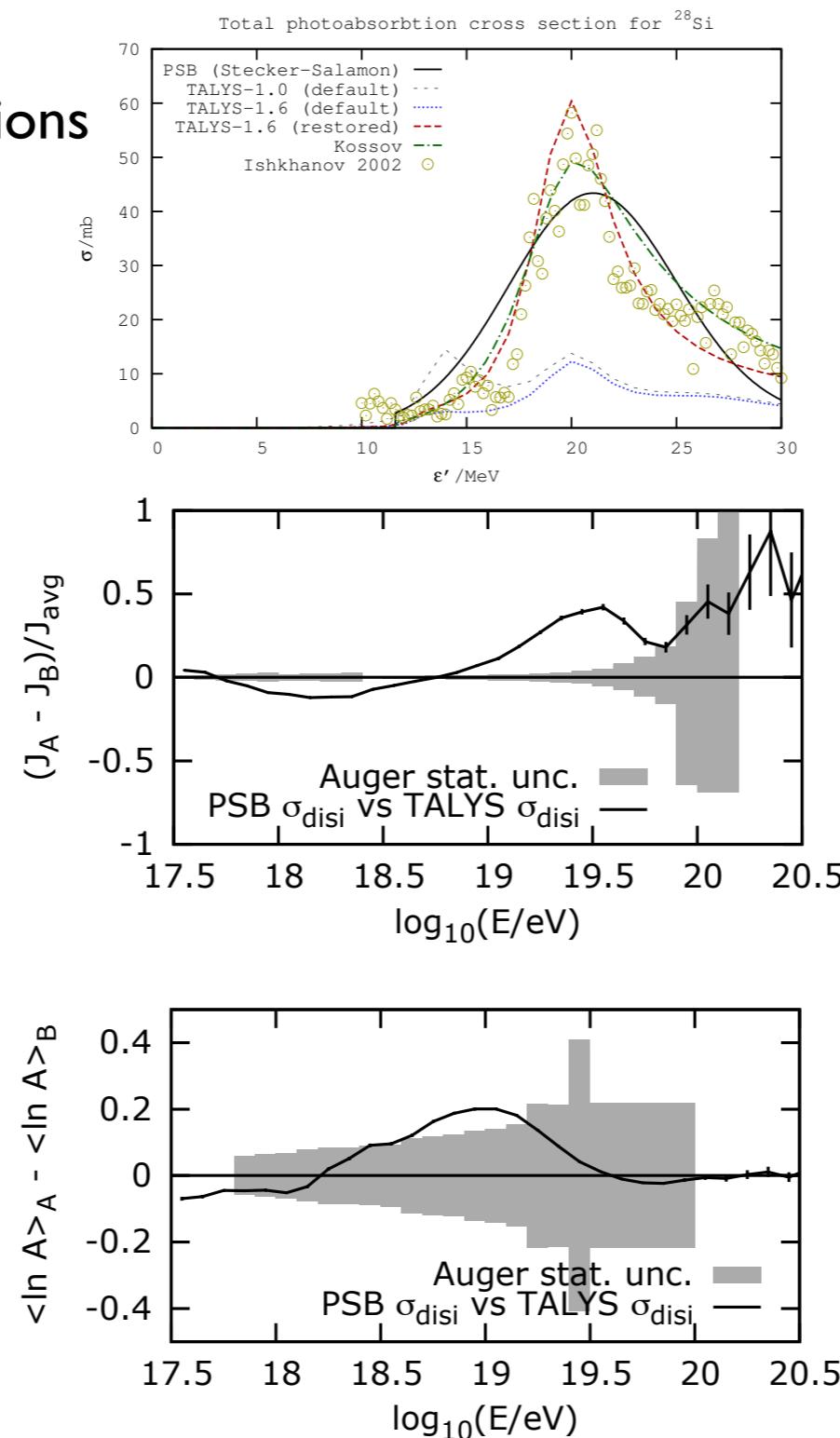
- ▶ photodisintegration cross sections
- ▶ EBL model
- ▶ scaling of alpha-channels
- ▶ propagation codes

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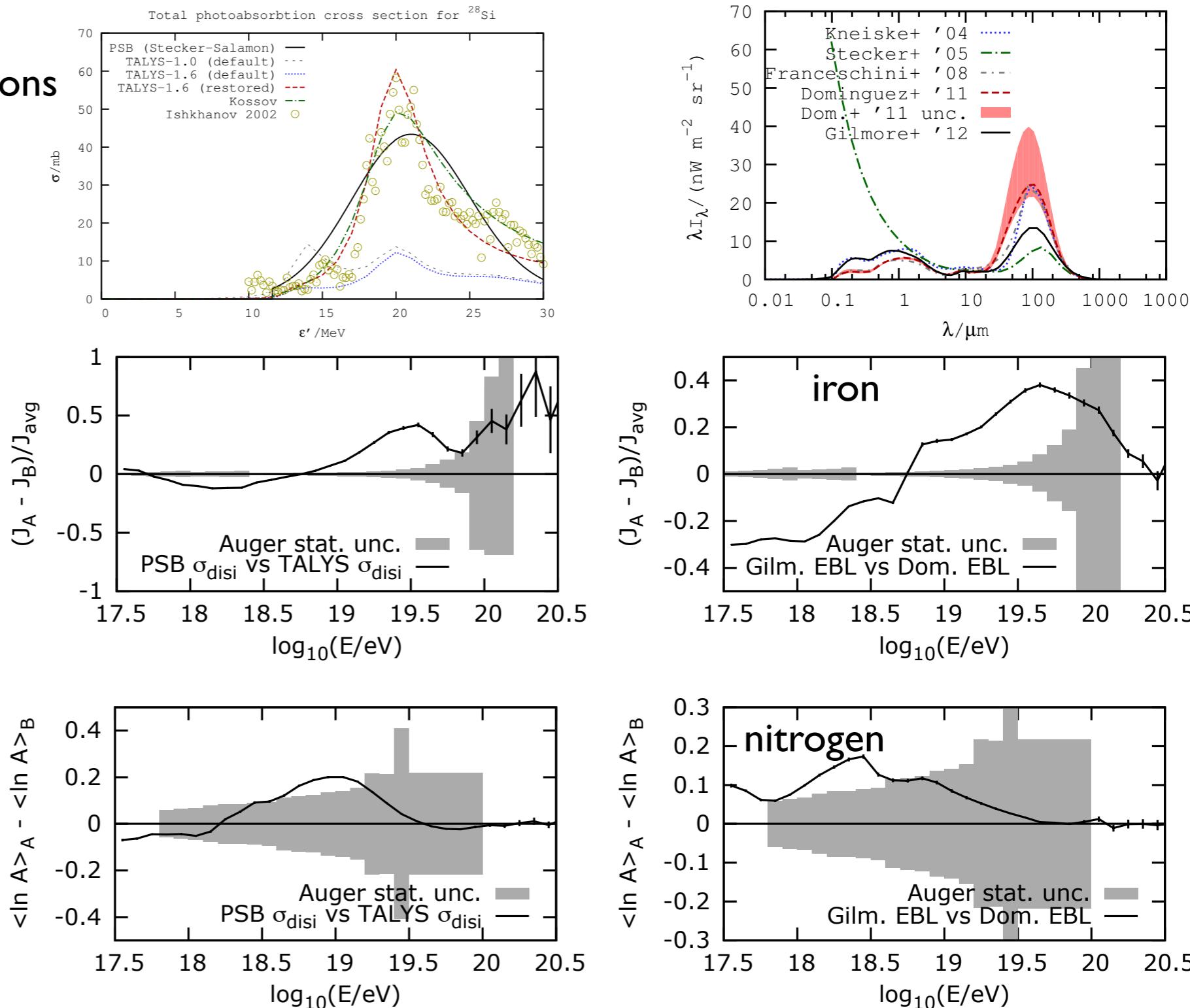


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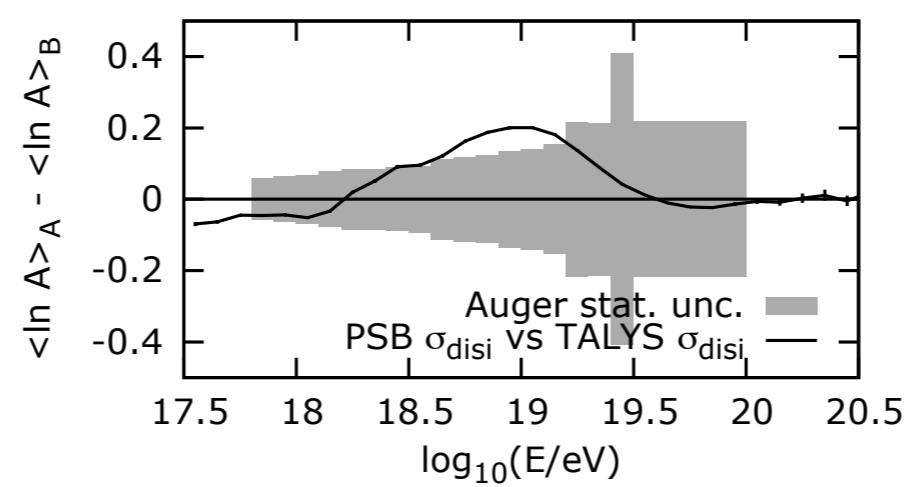
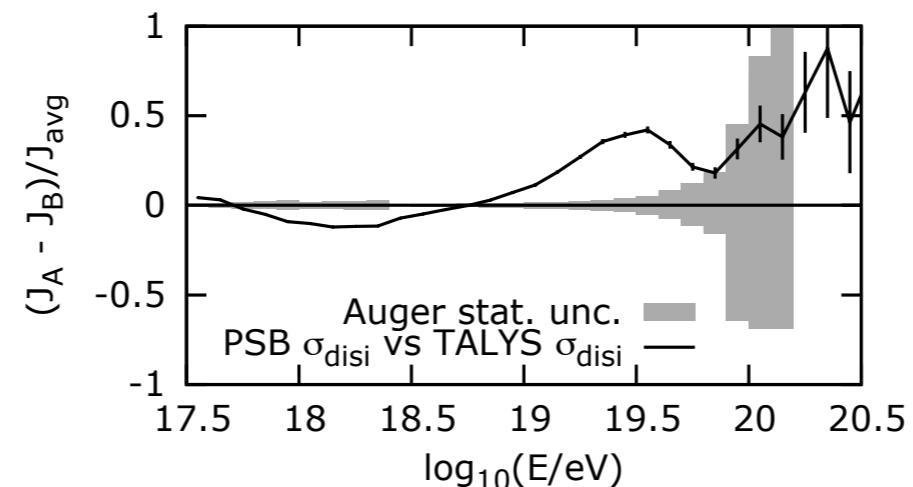
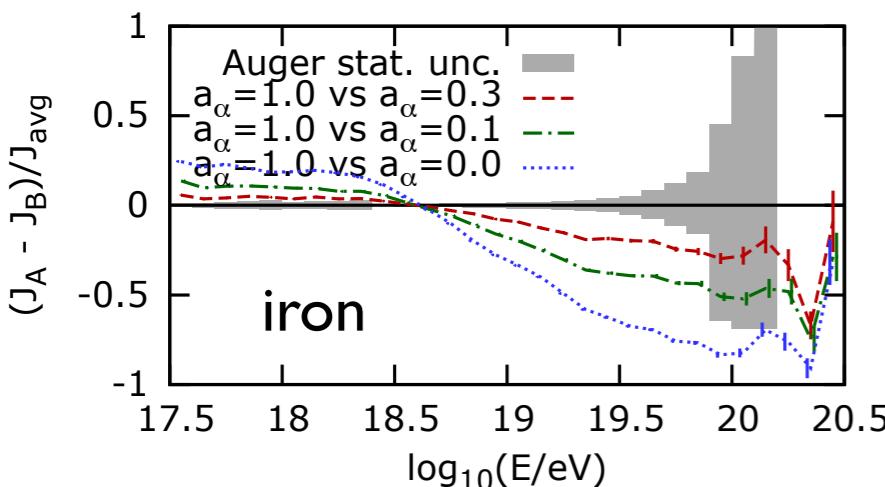
RAB, Boncioli, di Matteo, van Vliet, Walz. JCAP 1510 (2015) 063. arXiv:1508.01824  
Extragalactic background light at z=1



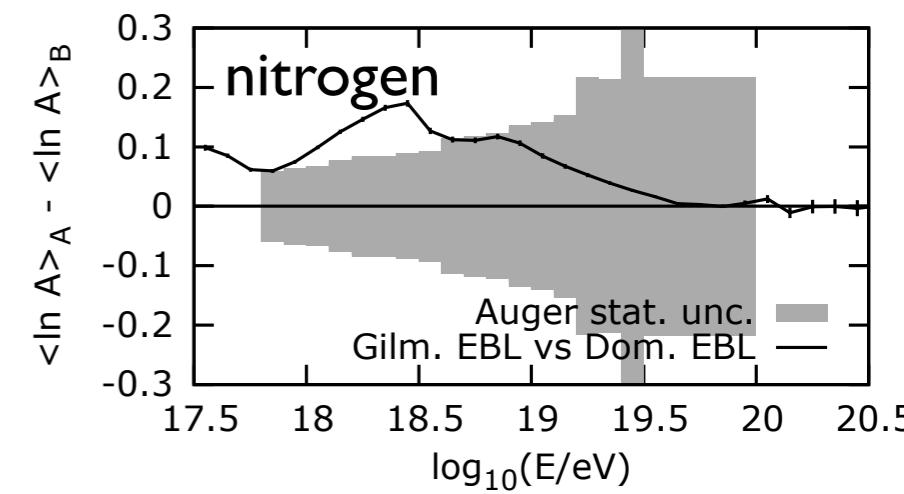
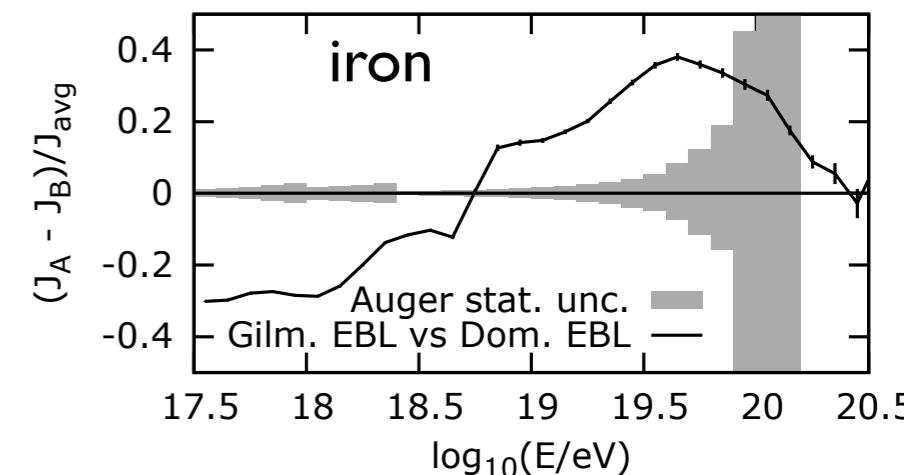
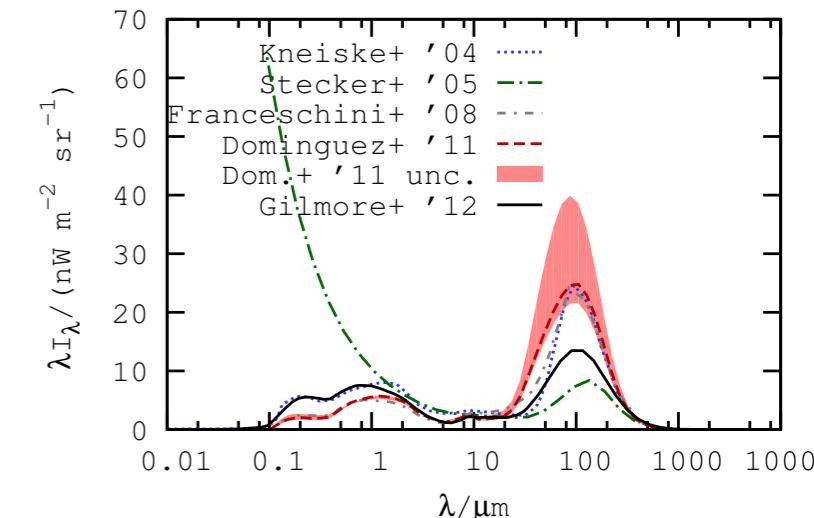
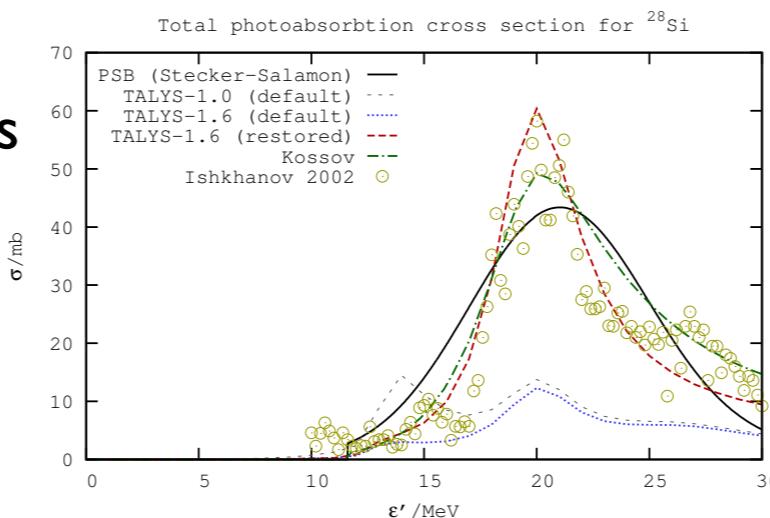
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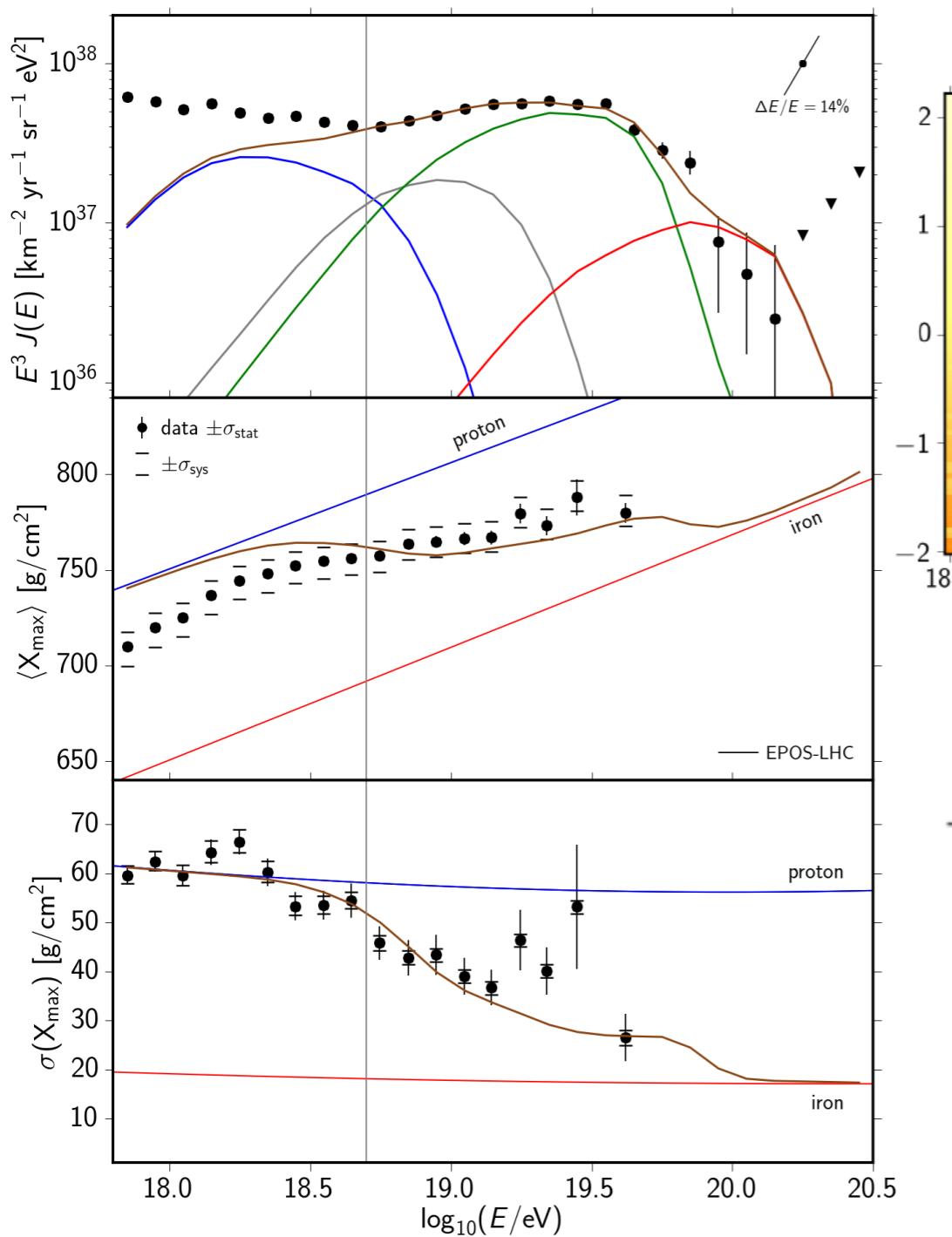
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RAB, Boncioli, di Matteo, van Vliet, Walz. *JCAP 1510 (2015) 063. arXiv:1508.01824*  
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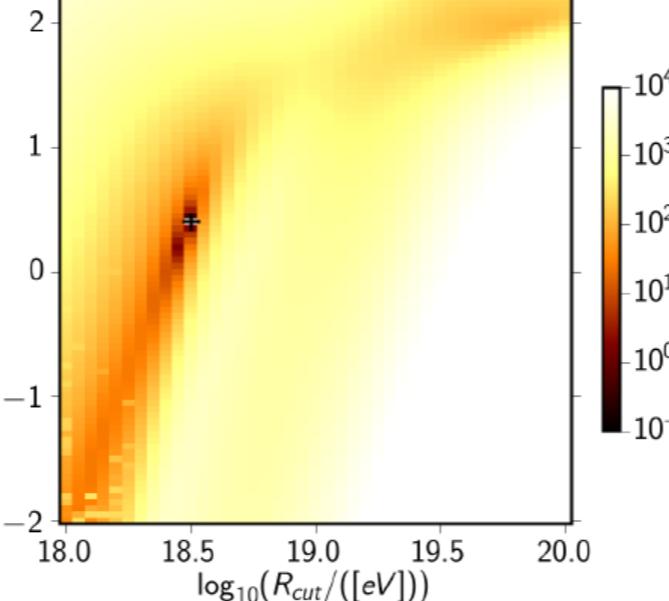
# combined spectrum-composition fits



CRPropa  
Kneiske '04 EBL model

TALYS cross sections for PD

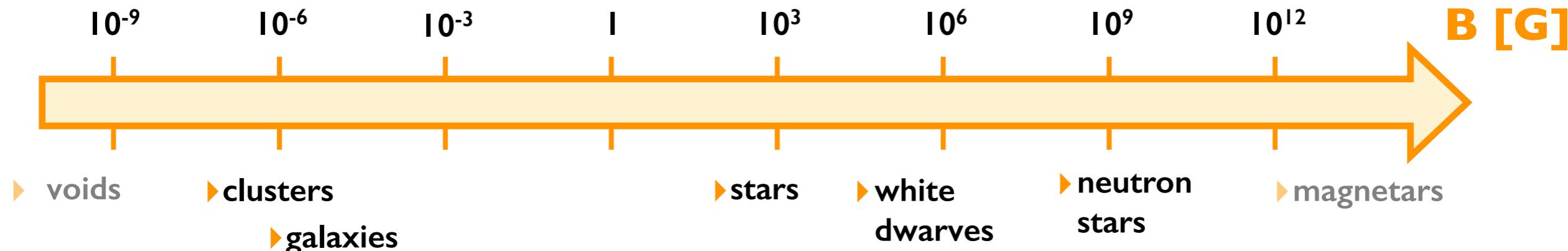
A. di Matteo+ (Pierre Auger Collaboration). ICRC 2015 Proceedings.  
arXiv:1509.03732



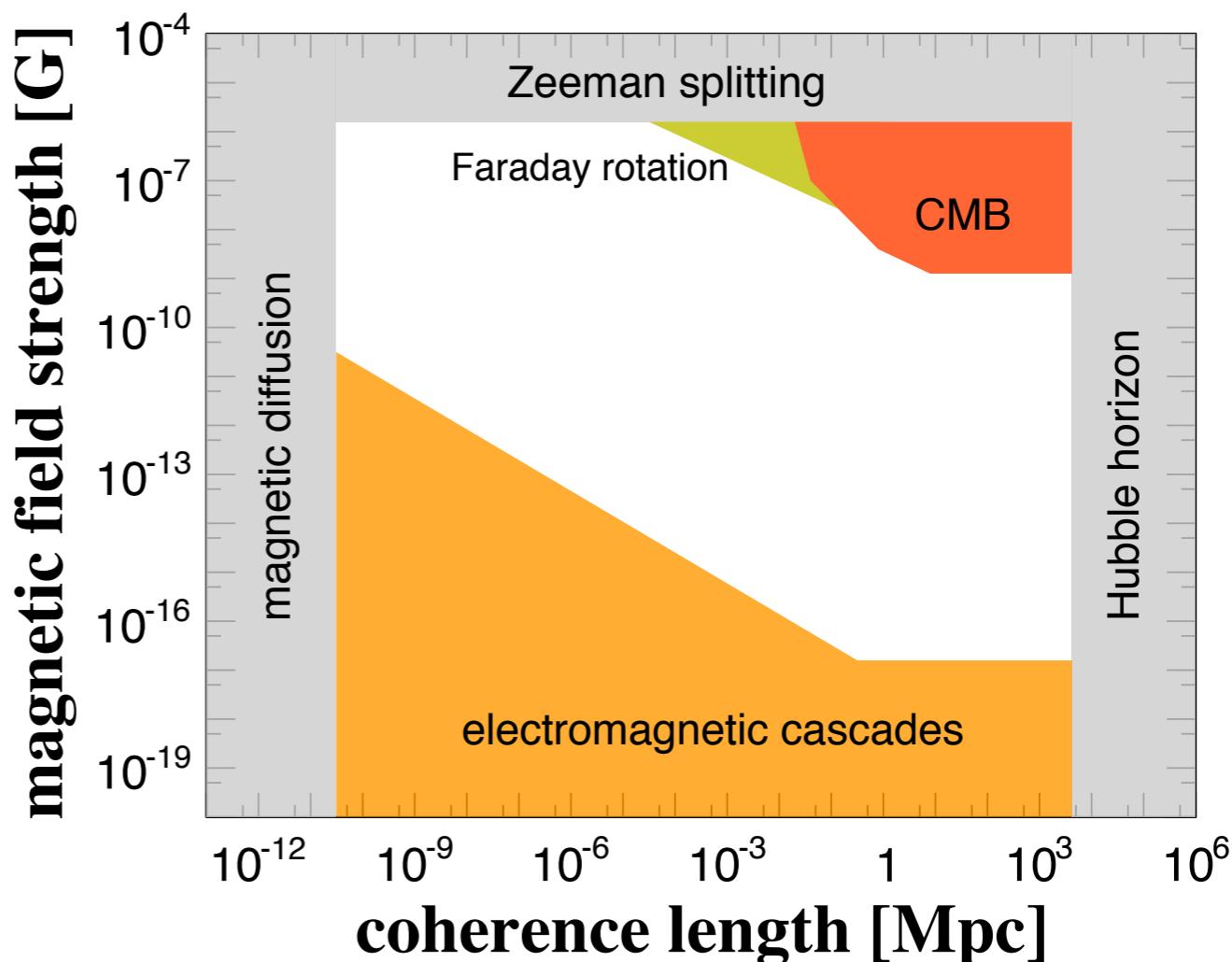
- $\log(R_{\text{cut}}/V) = 18.48$
- $\gamma = 0.29 (+0.08 | -0.07)$
- fraction of H: 14.3% (+4.2 | -14.2)
- fraction of He: 10.0% (+2.2 | -10.0)
- fraction of N: 75.3% (+15.5 | -9.4)
- fraction of Fe: 0.5% (+0.1 | -0.1)

	$\gamma$ (1st min)	$\log_{10}(R_{\text{cut}}/V)$	$D \frac{D(J)}{D(X_{\text{max}})}$
SPG	$+0.94^{+0.09}_{-0.10}$	$18.67 \pm 0.03$	$178.5^{18.8}_{159.8}$
SPD	$-0.45 \pm 0.41$	$18.27^{+0.07}_{-0.06}$	$193.4^{21.1}_{172.3}$
STG	$+0.69^{+0.07}_{-0.06}$	$18.60 \pm 0.01$	$176.9^{19.5}_{157.4}$
CTG	$+0.73^{+0.07}_{-0.06}$	$18.58 \pm 0.01$	$195.3^{33.6}_{161.7}$
CTD	$-1.06^{+0.29}_{-0.22}$	$18.19^{+0.04}_{-0.02}$	$192.3^{21.2}_{171.1}$
CGD	$-1.29^{+0.38}_{*}$	$18.18^{+0.06}_{-0.04}$	$192.5^{19.2}_{173.3}$

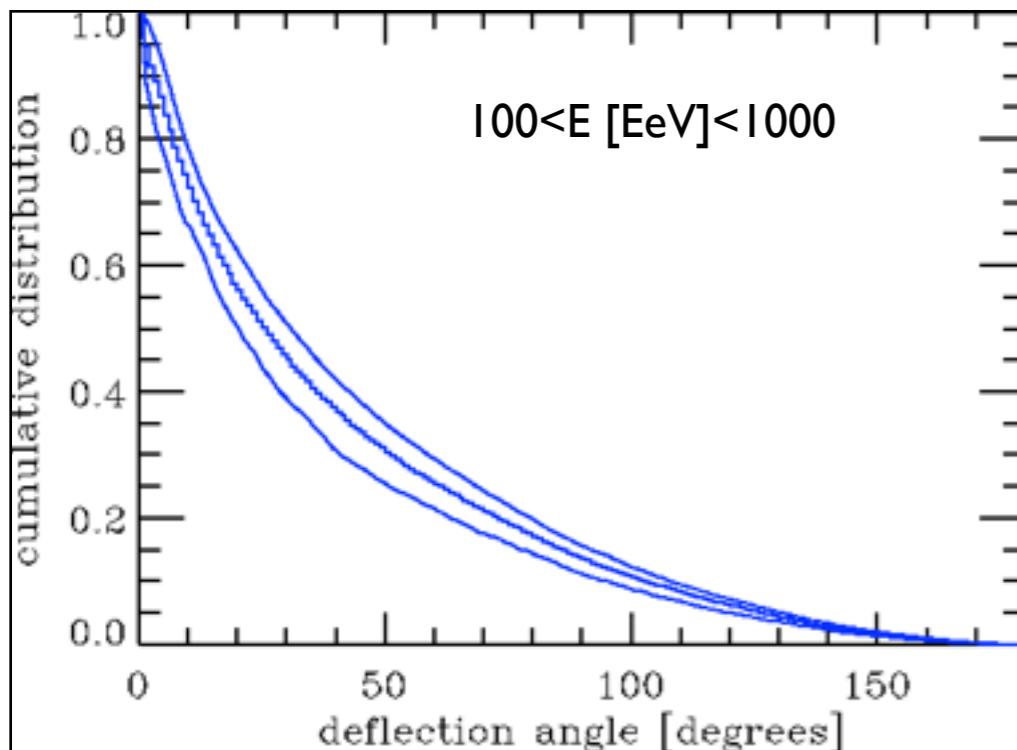
# modelling the propagation of UHECRs: magnetic fields



- 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

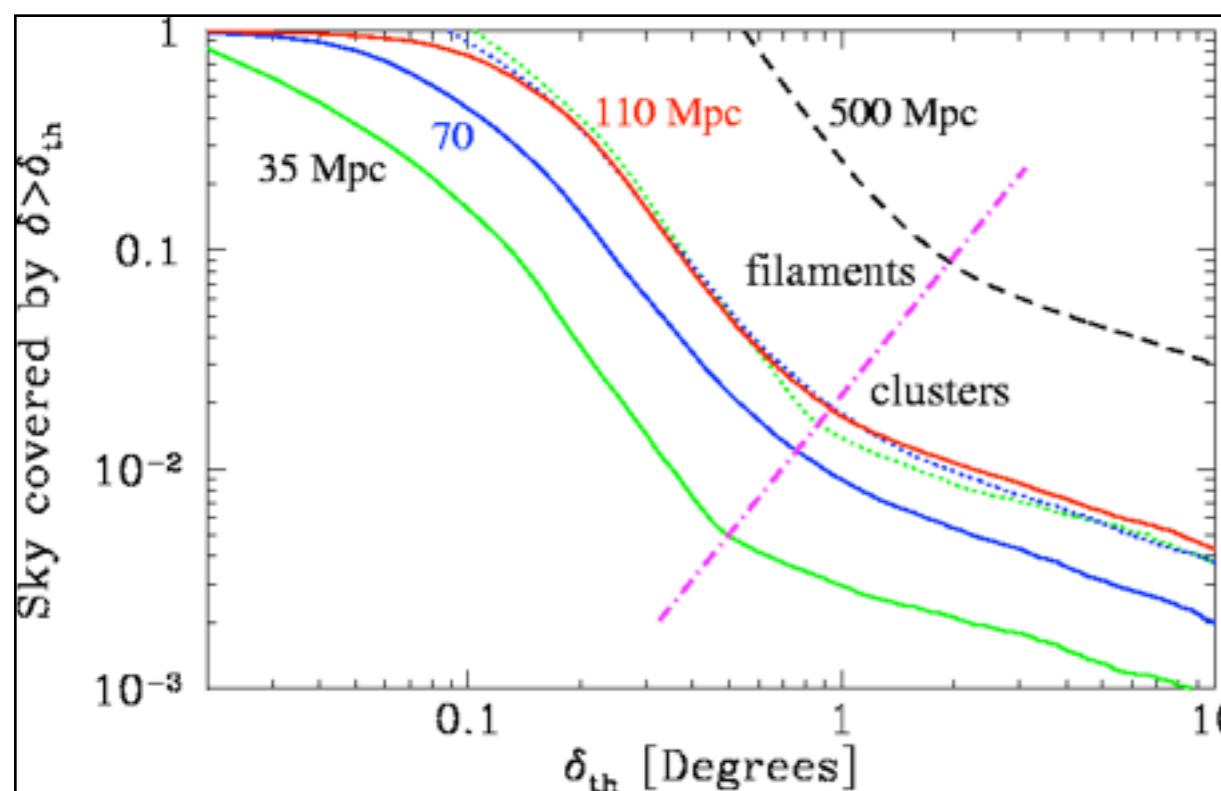


# UHECR astronomy?



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

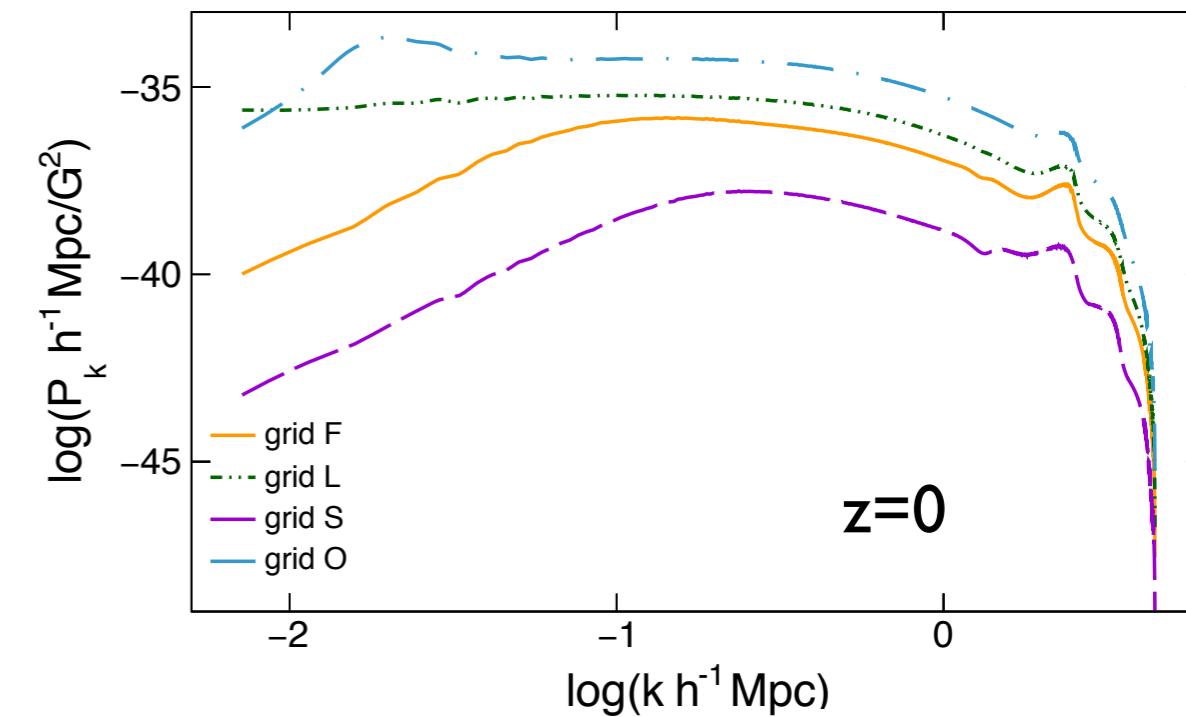
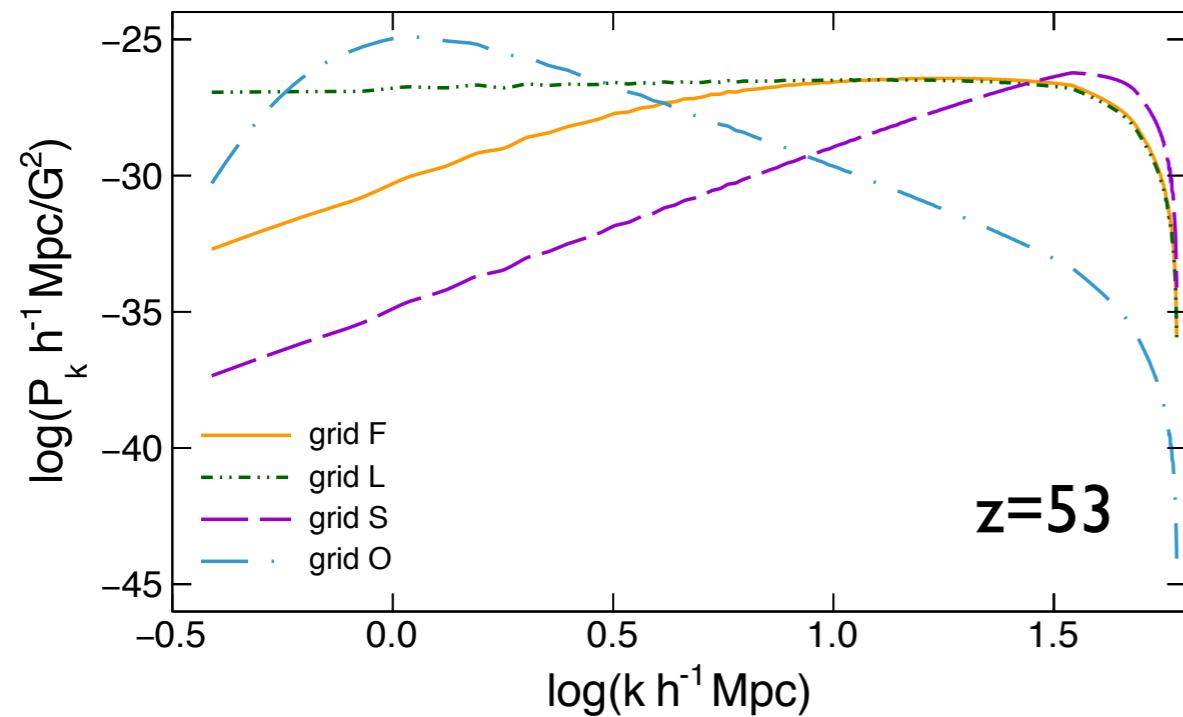
- ▶ cumulative deflections displayed are for protons
- ▶ Sigl+: deflections are high
- ▶ Dolag+: deflections are small
- ▶ for heavy nuclei deflections can be even higher
- ▶ UHECR astronomy may be possible in the later but not in the former scenario



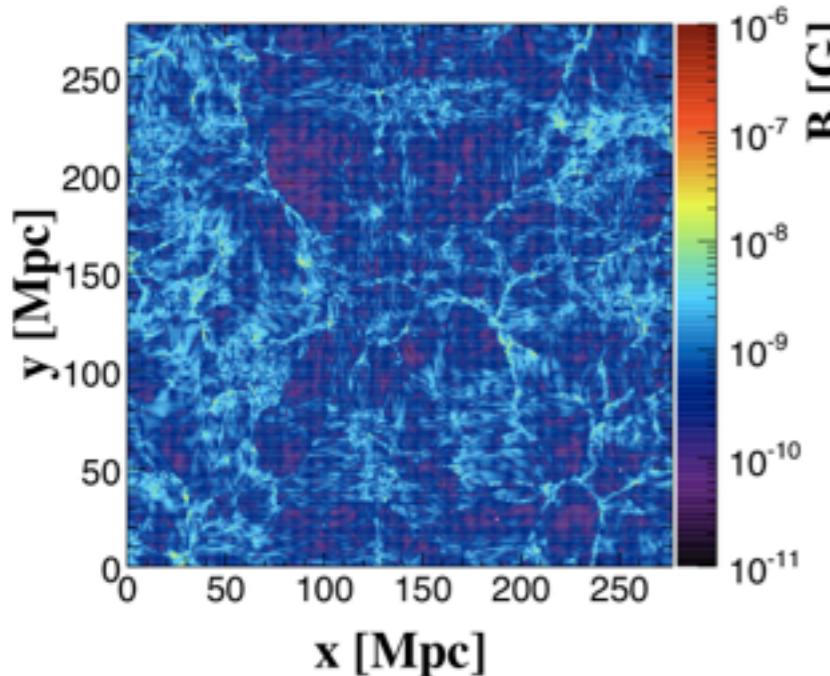
Dolag et al. JETP 79(2004) 583

# power spectrum of seed fields

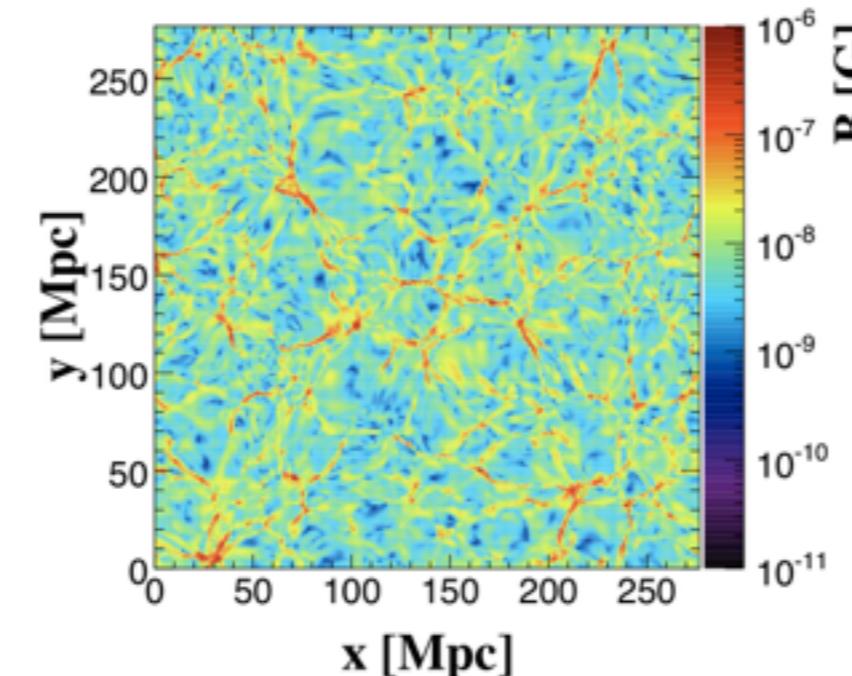
RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. In preparation. arXiv:1610.XXXXX



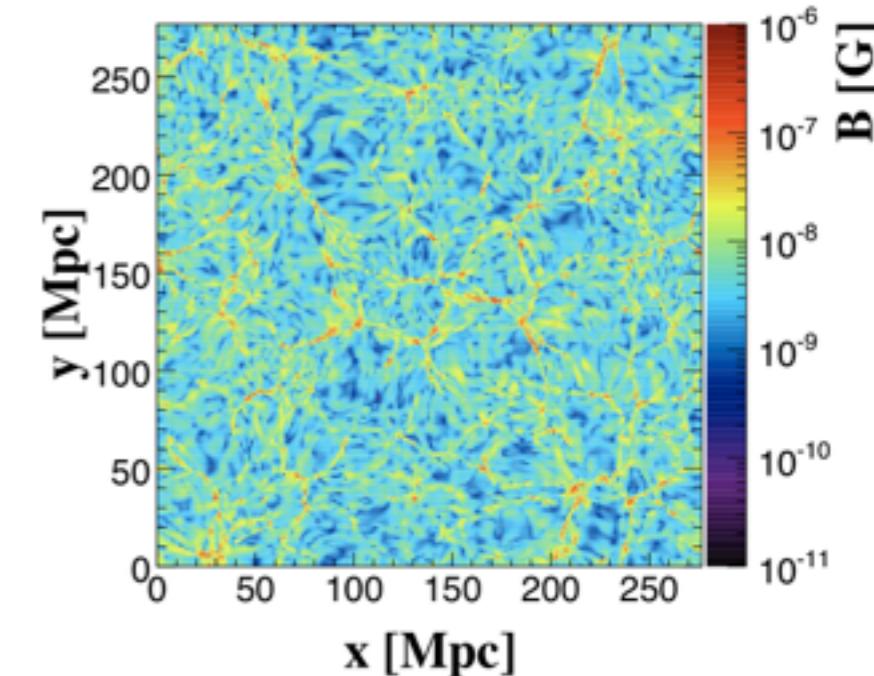
grid S



grid L

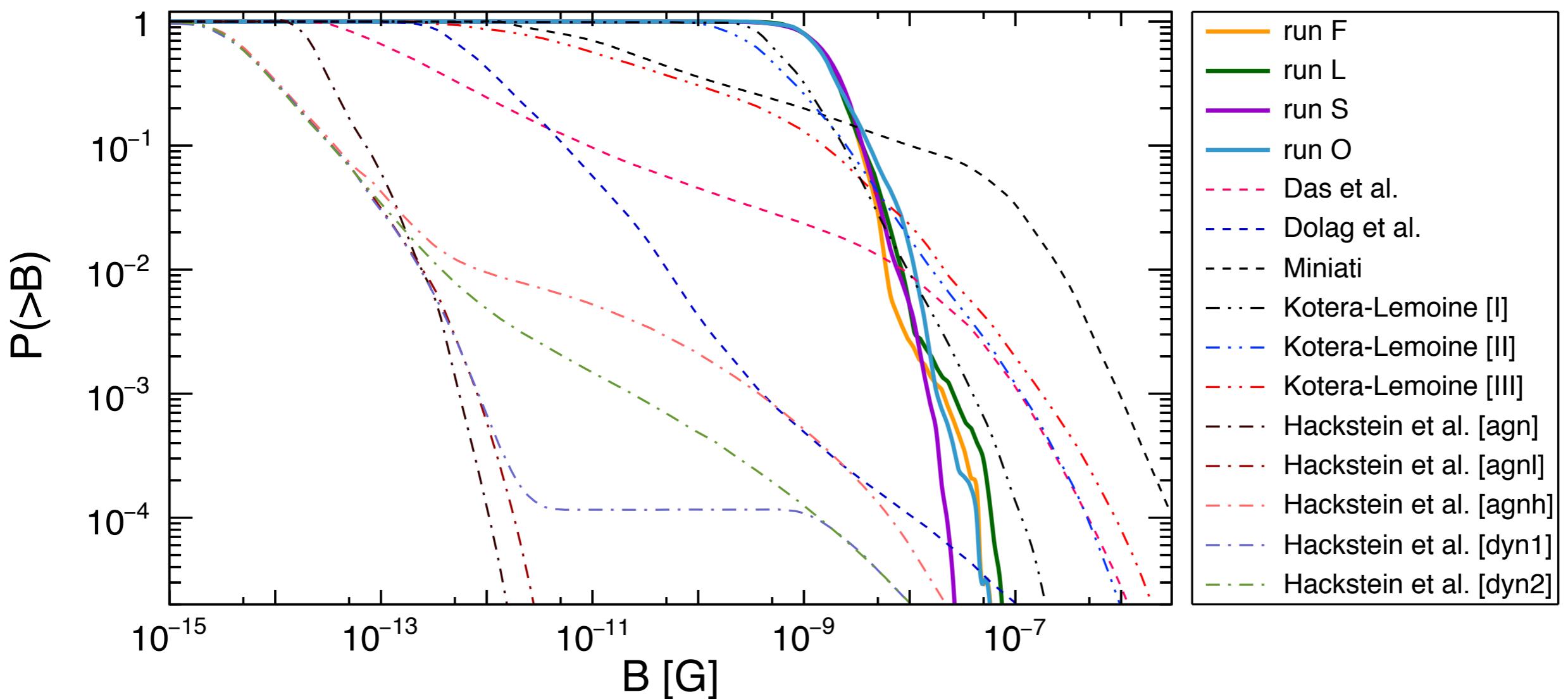


grid F



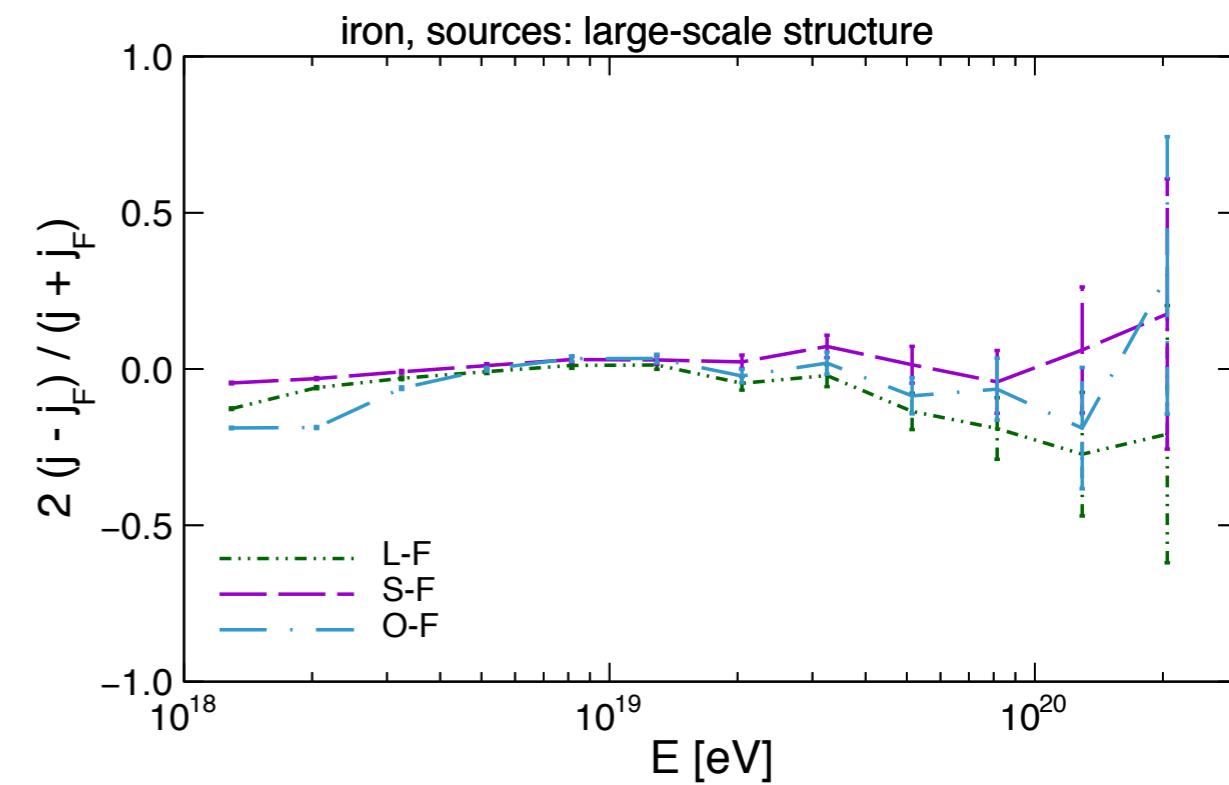
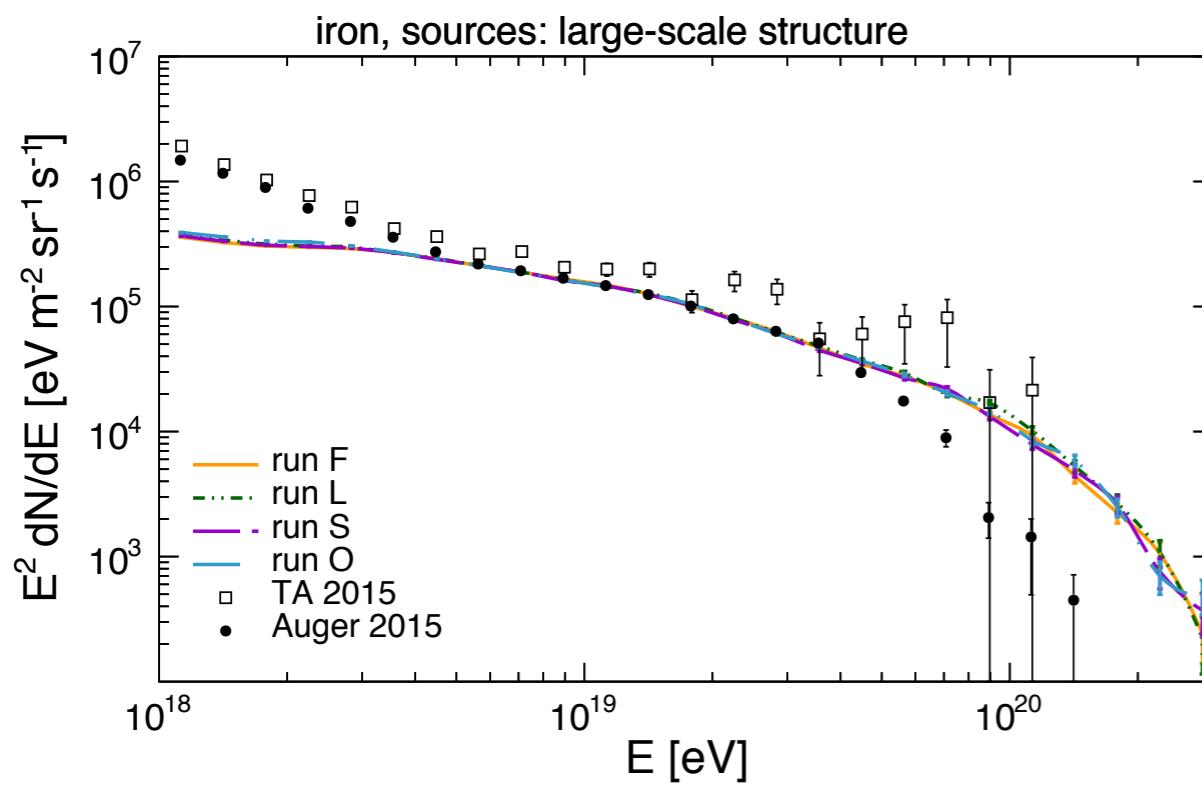
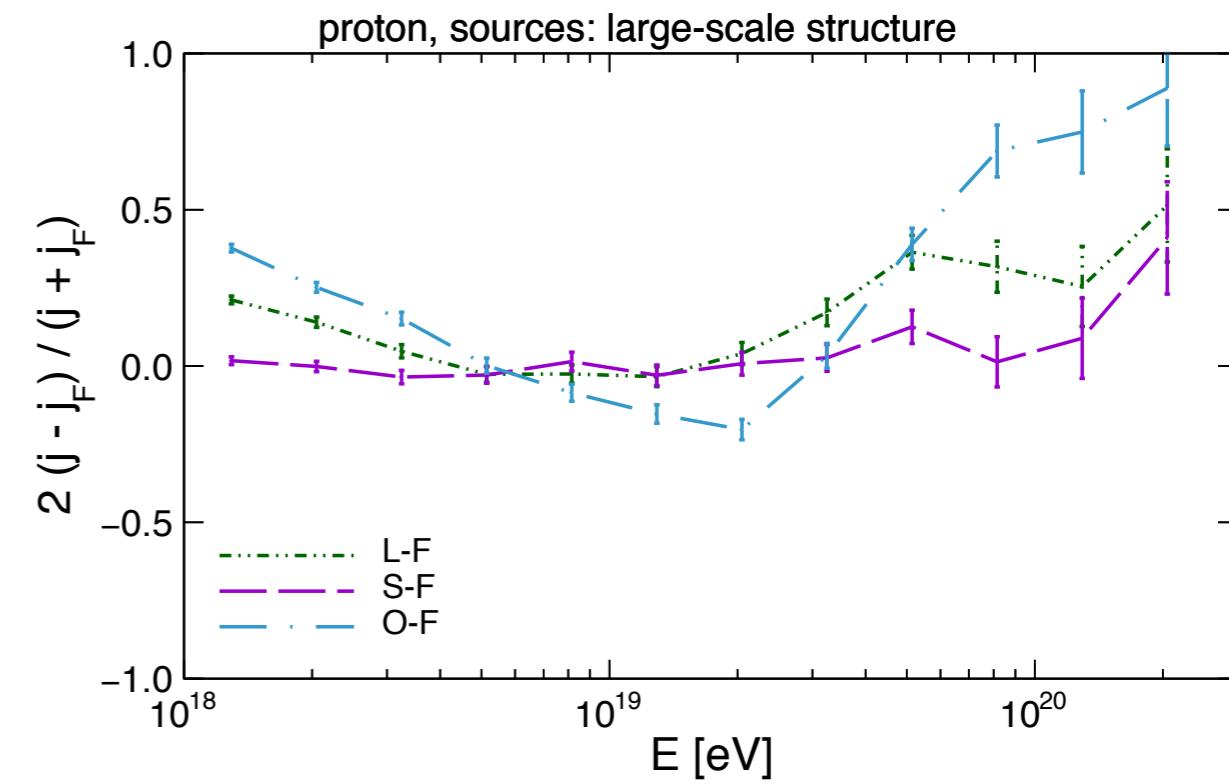
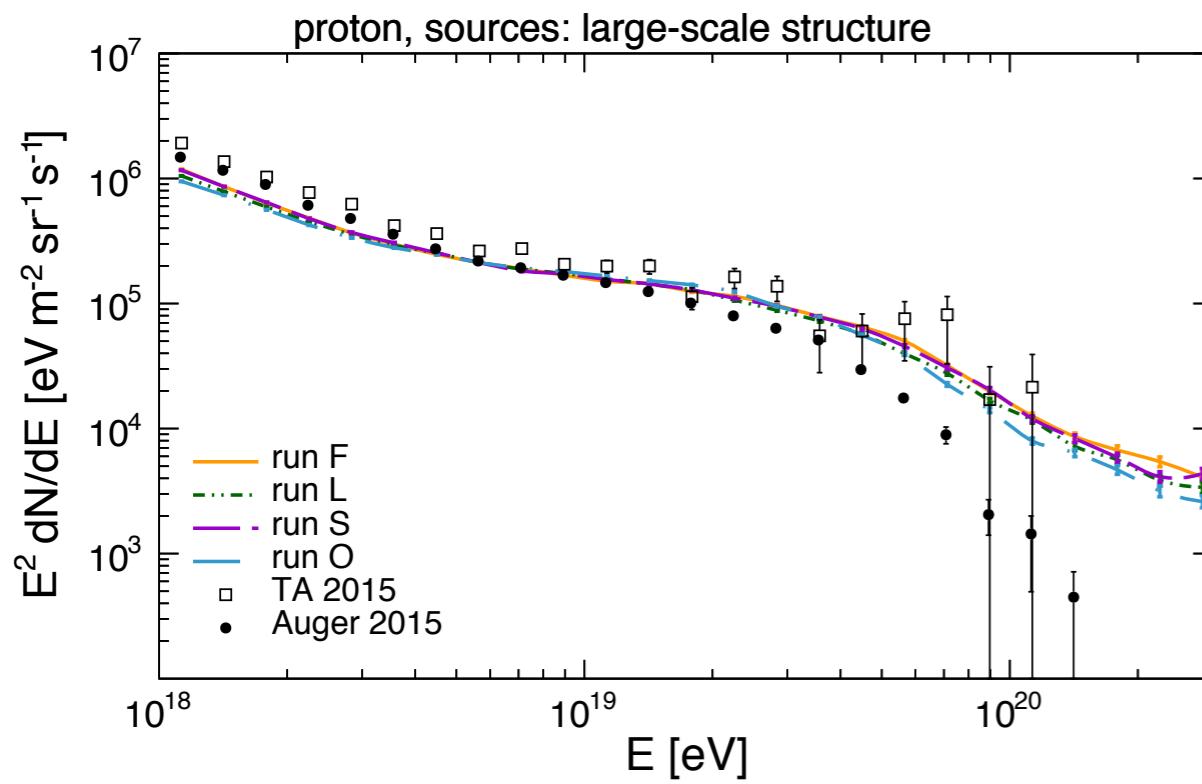
# the magnetised cosmic web

- ▶ we use Planck's upper limit to normalise the magnetic field in voids
- ▶ upper limit on (extragalactic) UHECR deflection



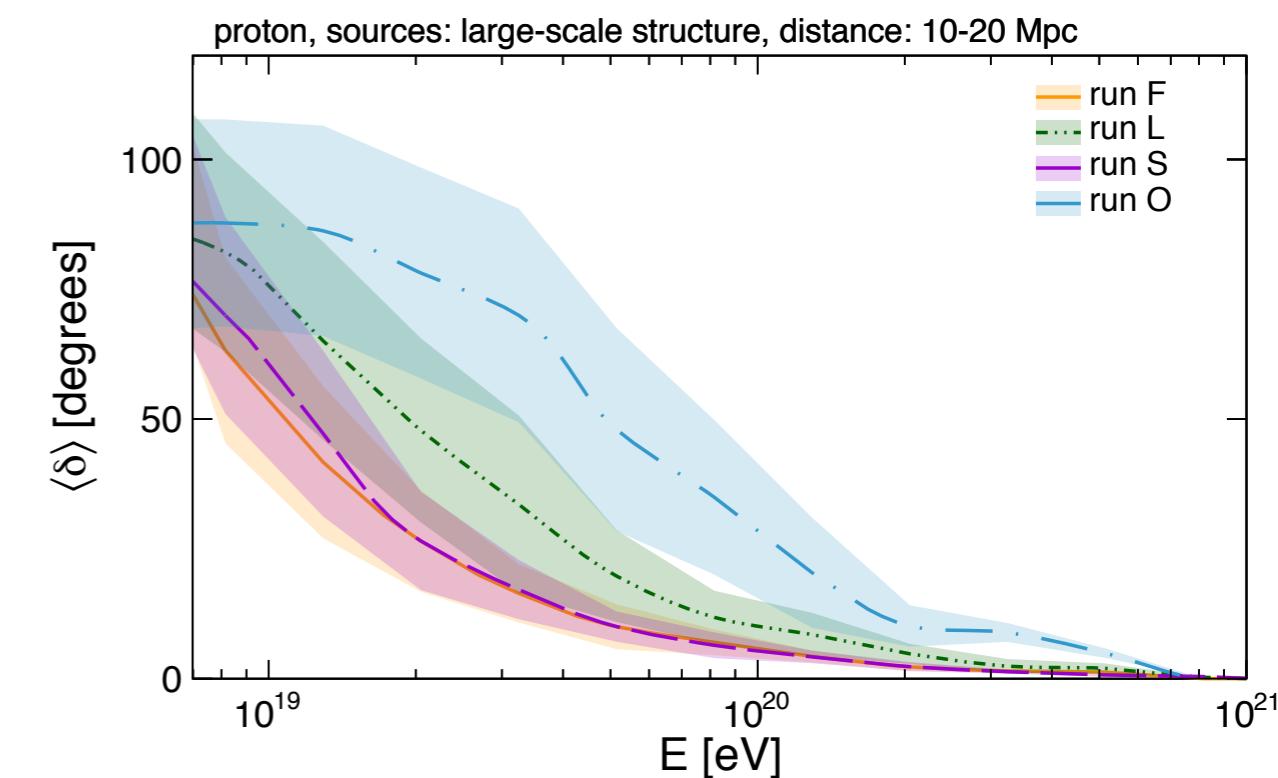
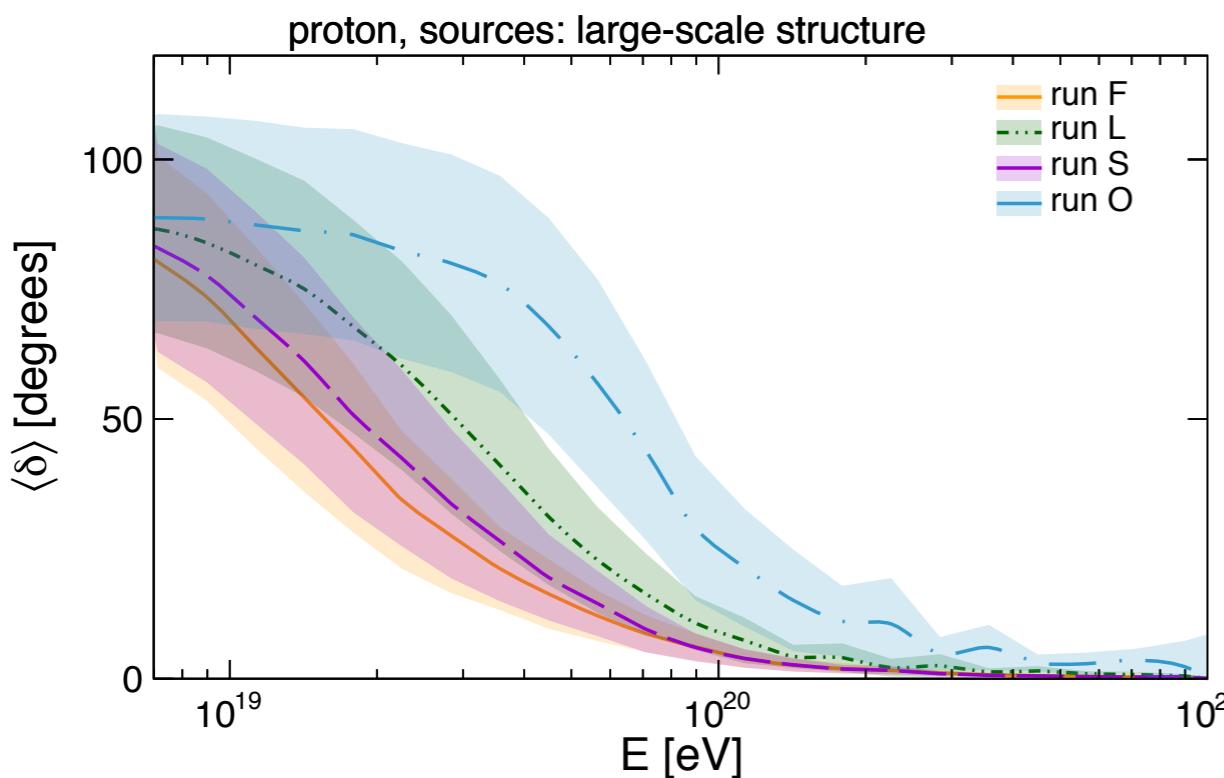
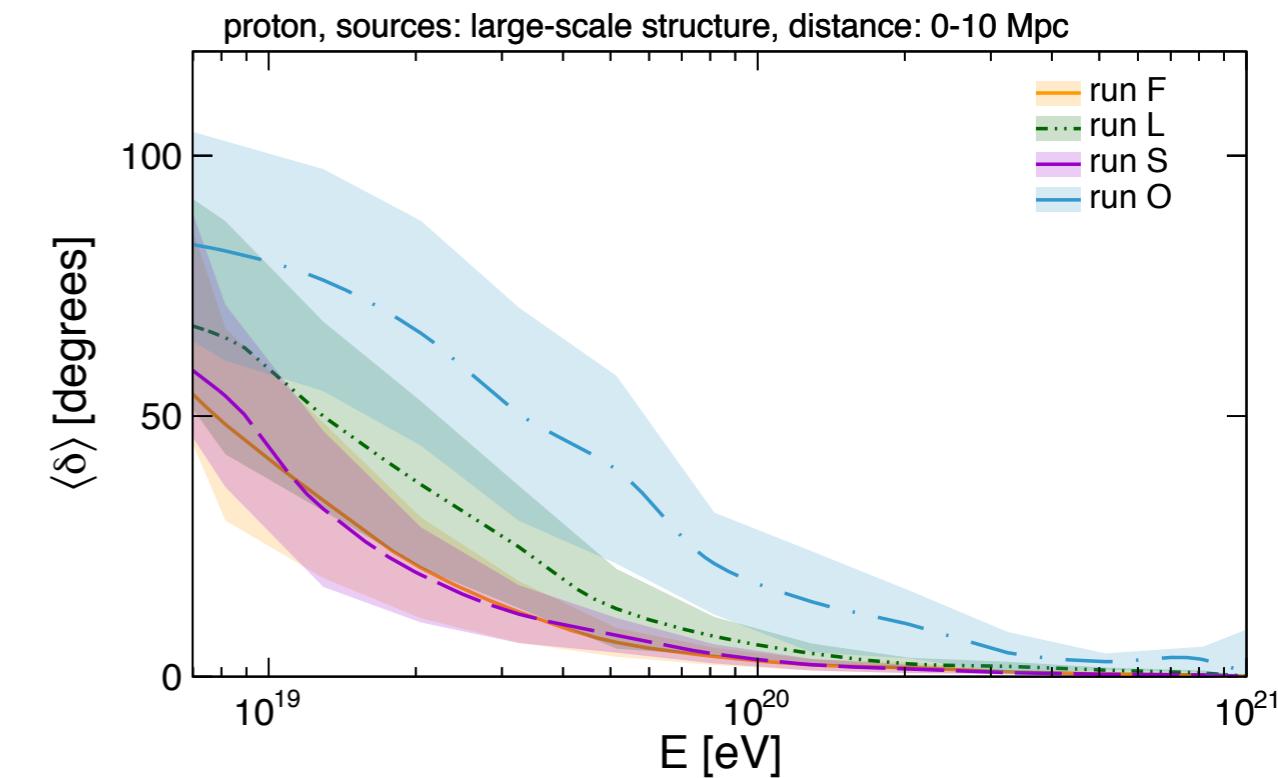
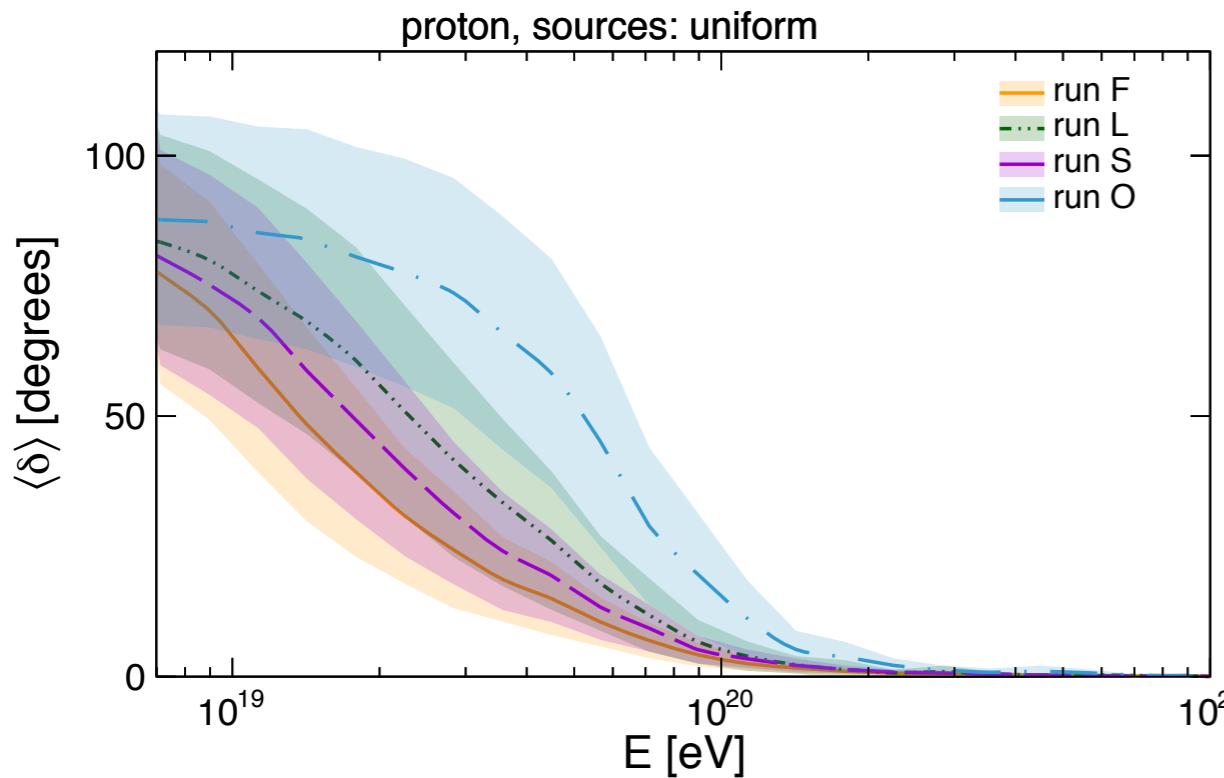
RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. In preparation. arXiv:1610.XXXXXX

# UHECR spectrum: impact of the B power spectrum



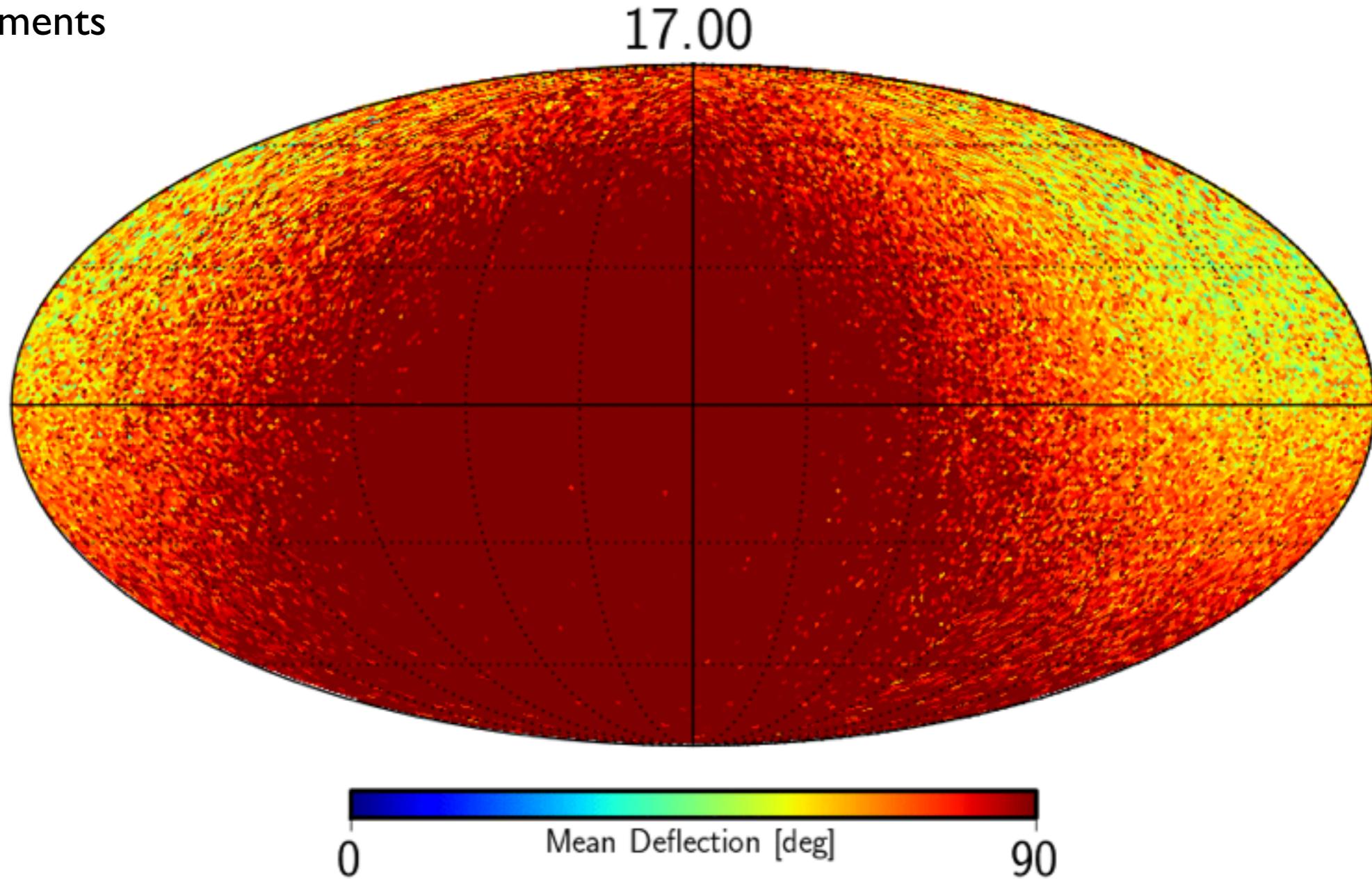
# UHECR deflections: impact of the B power spectrum

RAB, M.-S. Shin, J. Devriendt, D. Semikoz, G. Sigl. In preparation. arXiv:1610.XXXXX



# 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

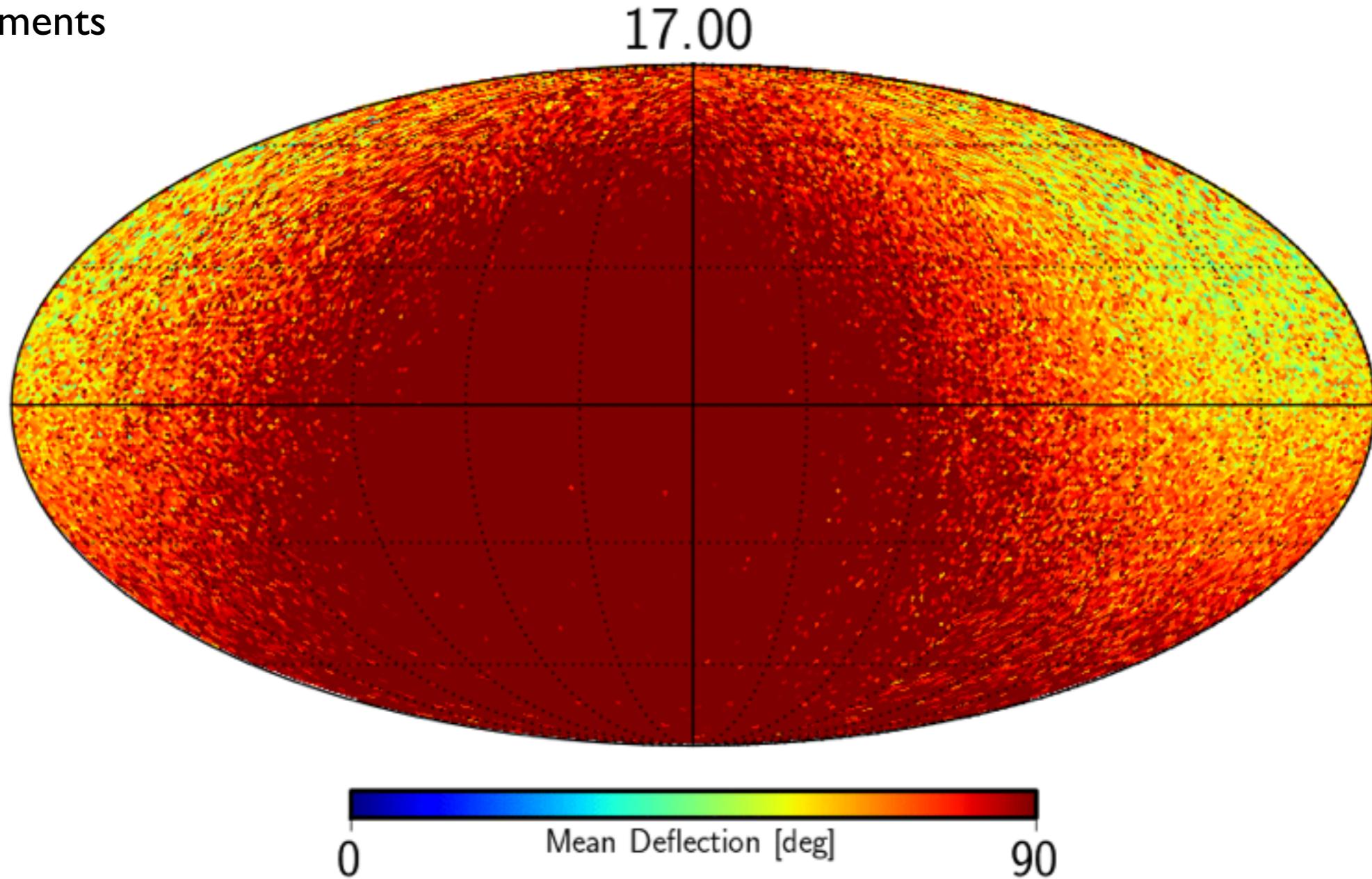


obtained with the PARSEC code:

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

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



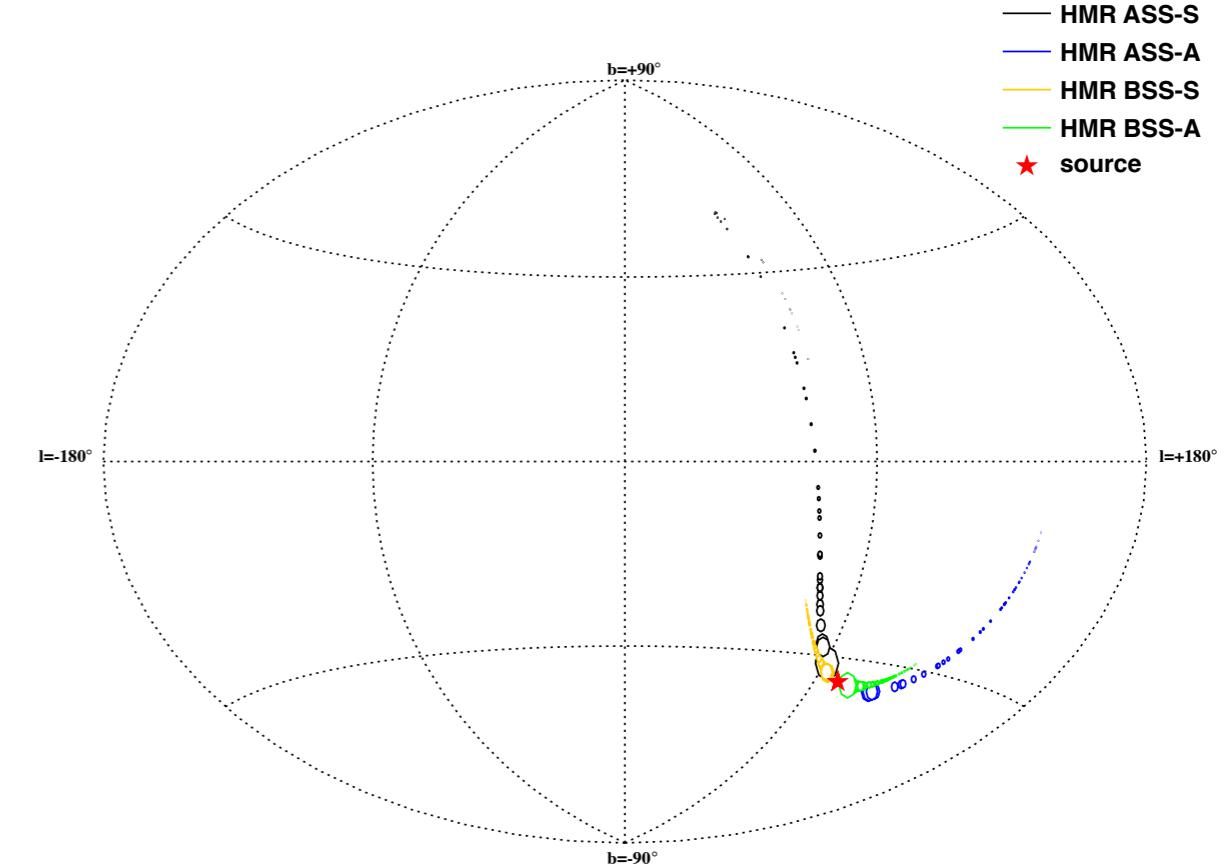
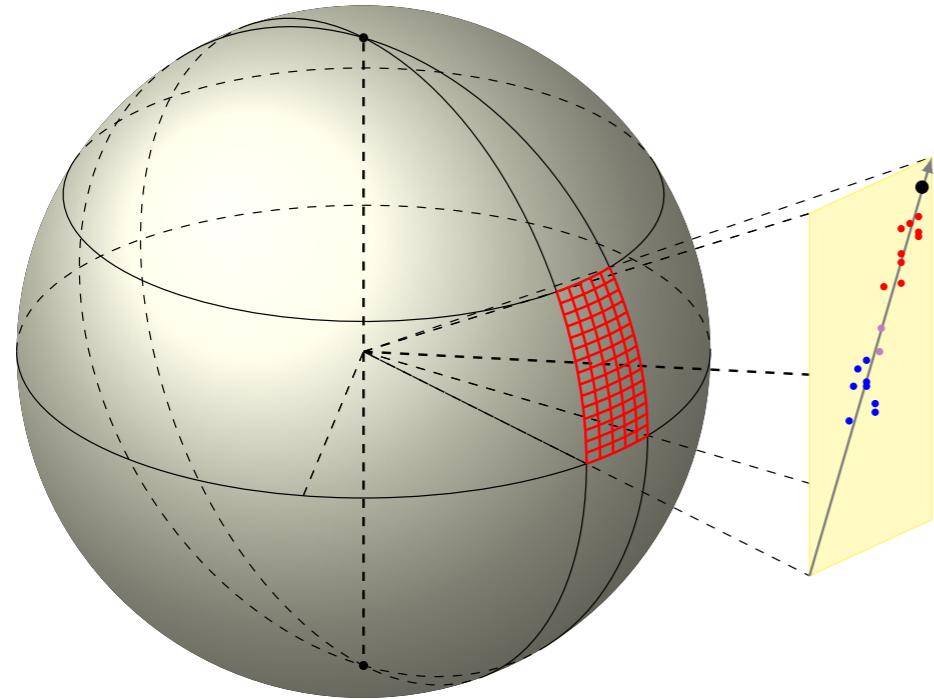
obtained with the PARSEC code:

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

# UHECRs and the galactic magnetic field

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

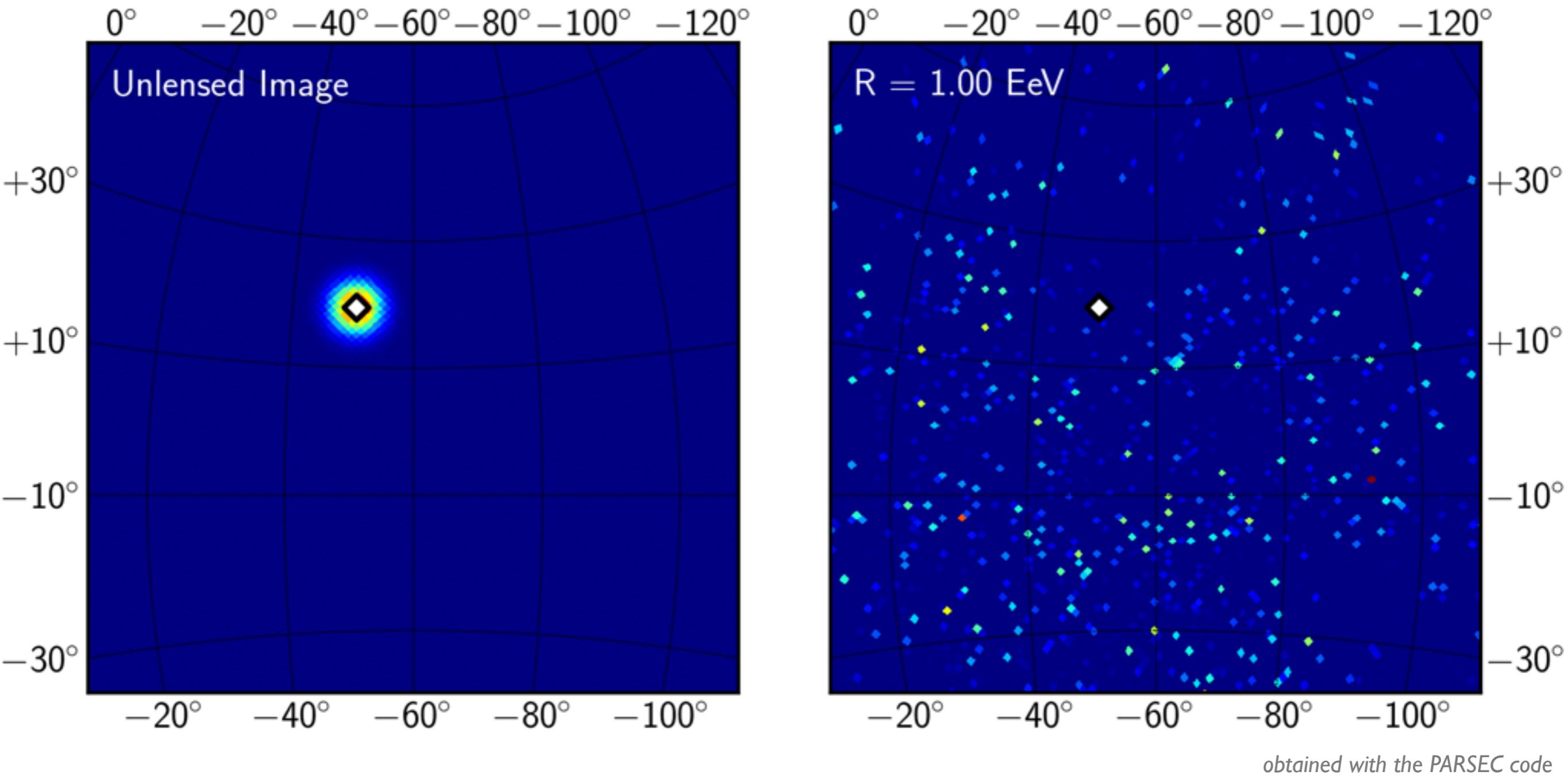
- if galactic deflections dominate over extragalactic, can we reconstruct source position?



- 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"

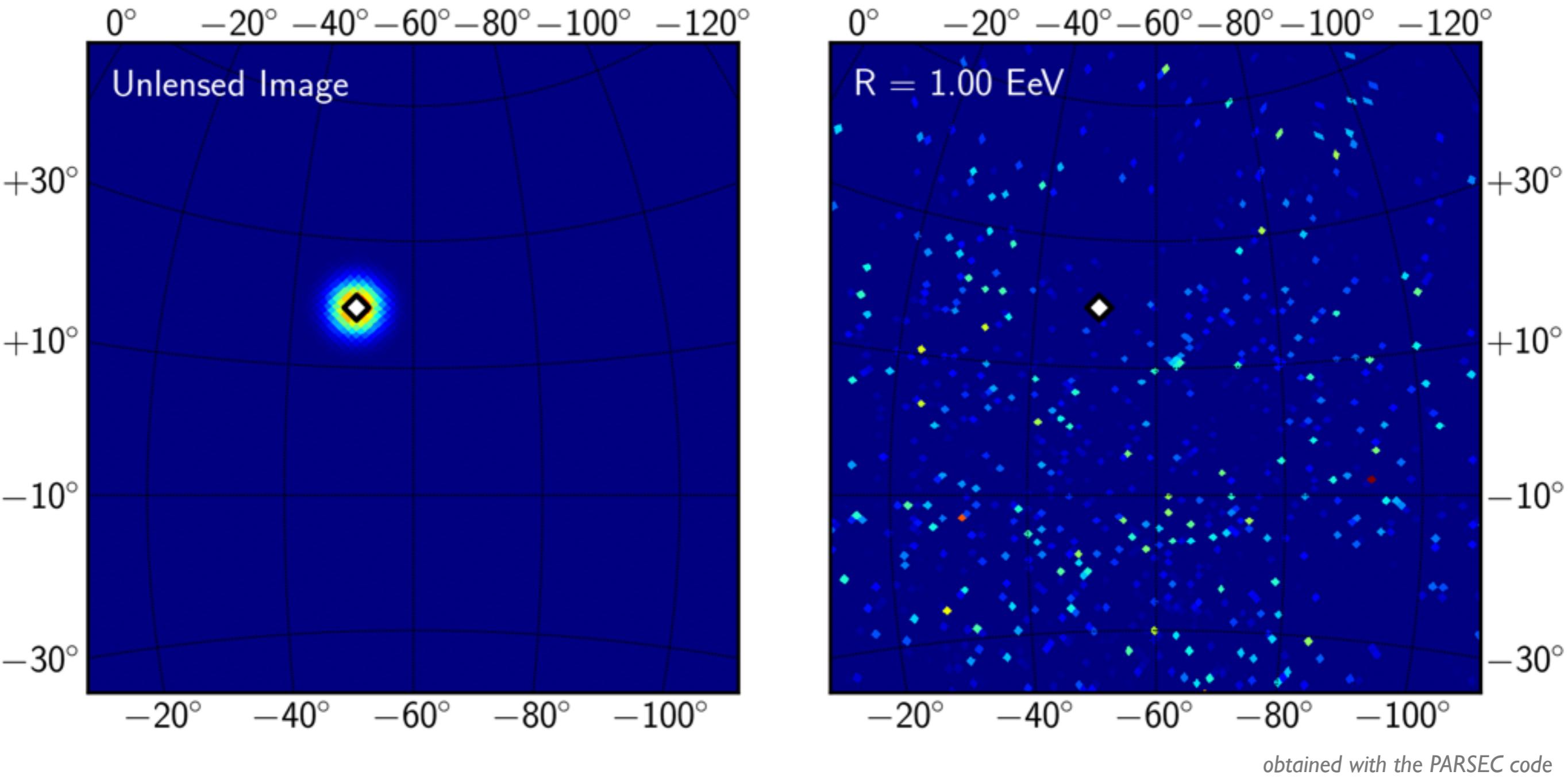
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- ▶ the case of Centaurus A, assuming only galactic deflections and the complete JFI2 field



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Thank you!

# Backup

# combined spectrum-composition fits

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

- ▶ 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

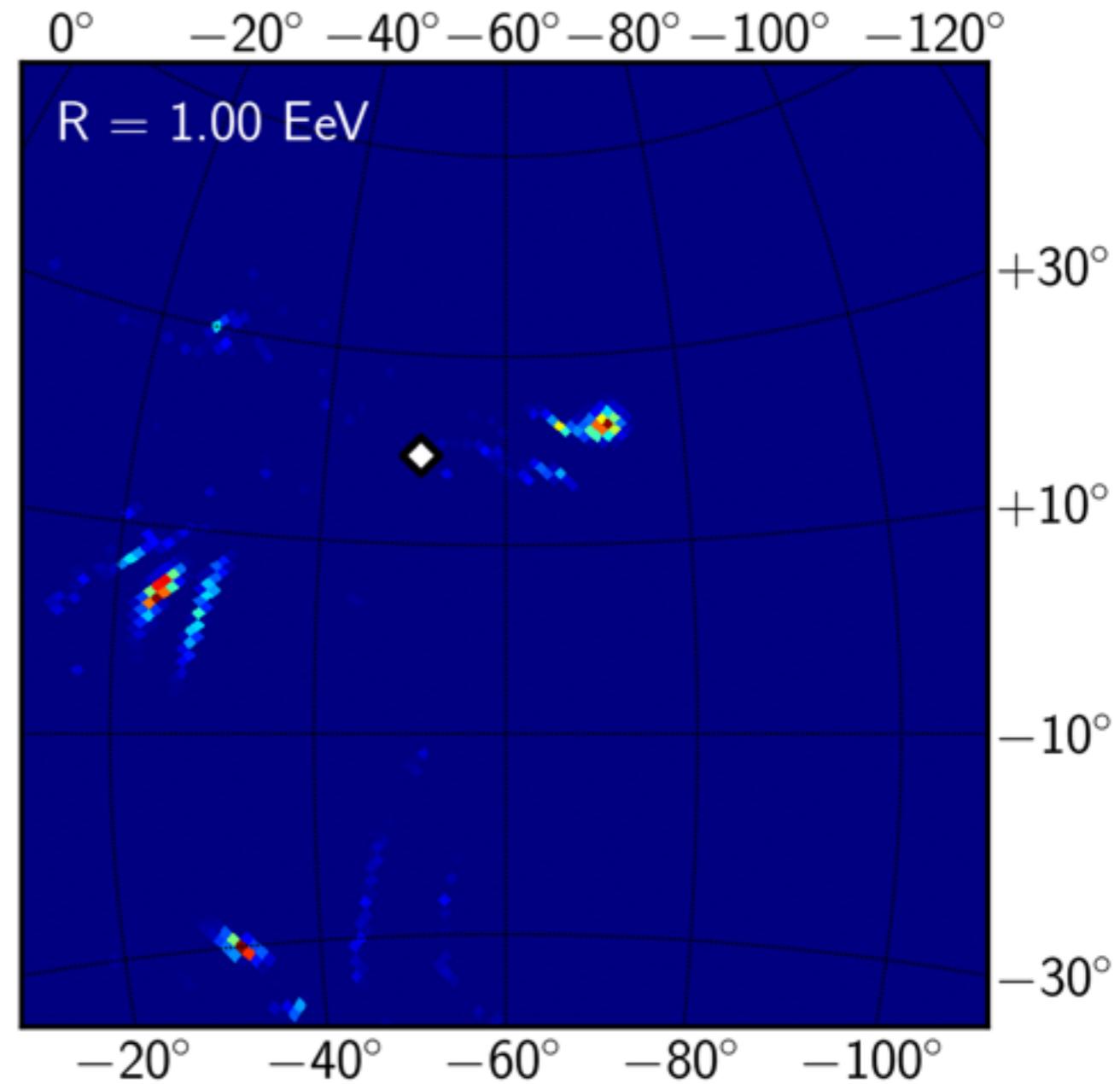
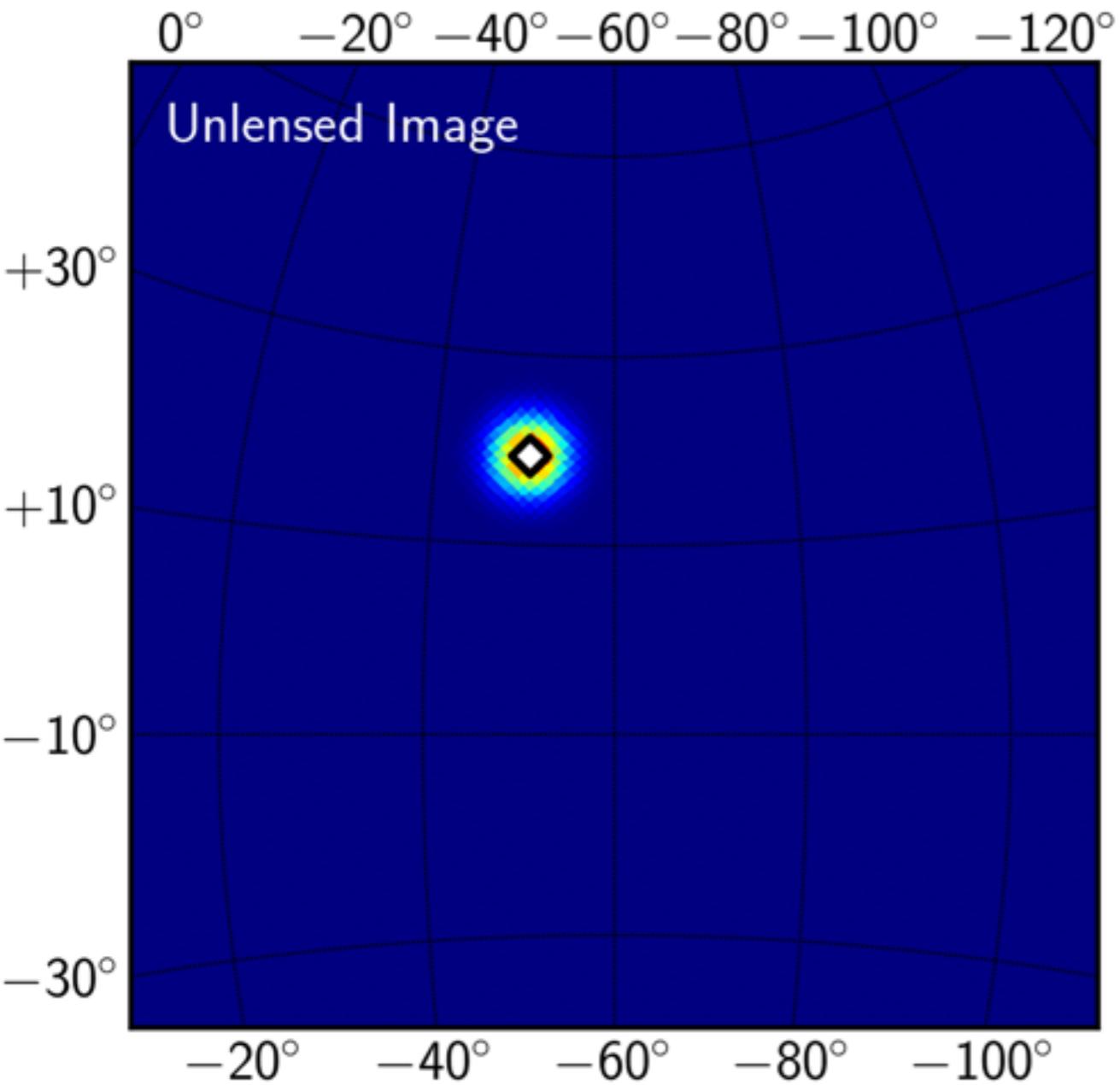
# UHECR deflections: impact of the B power spectrum

TABLE I. Average deflections and corresponding  $1\sigma$  standard deviations of UHECRs from nearby sources in runs F, L, S, and O. Results are presented for the case of sources uniformly distributed ('uni'), and following the large scale structure ('lss'), both for proton (p) and iron (Fe) primaries.

nucleus	E [EeV]	D [Mpc]	sources	run F	run L	run S	run O
p	10	0-10	uni	$21.4^\circ \pm 11.5^\circ$	$31.7^\circ \pm 19.6^\circ$	$30.5^\circ \pm 16.5^\circ$	$67.6^\circ \pm 24.6^\circ$
p	10	0-10	lss	$41.3^\circ \pm 16.2^\circ$	$60.0^\circ \pm 21.1^\circ$	$42.9^\circ \pm 17.4^\circ$	$81.6^\circ \pm 21.0^\circ$
p	60	0-5	uni	$1.5^\circ \pm 1.1^\circ$	$1.7^\circ \pm 1.5^\circ$	$2.3^\circ \pm 1.3^\circ$	$4.0^\circ \pm 2.8^\circ$
p	60	0-5	lss	$4.3^\circ \pm 2.0^\circ$	$8.8^\circ \pm 6.1^\circ$	$4.7^\circ \pm 2.4^\circ$	$27.1^\circ \pm 16.0^\circ$
p	60	0-10	uni	$2.5^\circ \pm 1.4^\circ$	$3.0^\circ \pm 3.2^\circ$	$3.1^\circ \pm 1.6^\circ$	$6.9^\circ \pm 4.0^\circ$
p	60	0-10	lss	$4.9^\circ \pm 2.4^\circ$	$9.8^\circ \pm 6.3^\circ$	$5.5^\circ \pm 2.7^\circ$	$27.3^\circ \pm 15.6^\circ$
p	60	0-10	uni	$2.5^\circ \pm 1.4^\circ$	$3.0^\circ \pm 3.2^\circ$	$3.1^\circ \pm 1.6^\circ$	$6.9^\circ \pm 4.0^\circ$
p	60	0-10	lss	$4.9^\circ \pm 2.4^\circ$	$9.8^\circ \pm 6.3^\circ$	$5.5^\circ \pm 2.7^\circ$	$27.3^\circ \pm 15.6^\circ$
p	60	10-20	uni	$5.1^\circ \pm 2.3^\circ$	$7.4^\circ \pm 3.1^\circ$	$6.4^\circ \pm 3.3^\circ$	$21.7^\circ \pm 13.0^\circ$
p	60	10-20	lss	$7.4^\circ \pm 2.8^\circ$	$13.8^\circ \pm 7.9^\circ$	$7.2^\circ \pm 2.8^\circ$	$35.7^\circ \pm 15.3^\circ$
p	60	20-30	uni	$6.8^\circ \pm 2.2^\circ$	$10.8^\circ \pm 4.2^\circ$	$8.5^\circ \pm 3.7^\circ$	$34.7^\circ \pm 16.6^\circ$
p	60	20-30	lss	$8.4^\circ \pm 3.3^\circ$	$15.3^\circ \pm 7.0^\circ$	$9.0^\circ \pm 3.5^\circ$	$44.0^\circ \pm 16.8^\circ$
p	100	0-5	uni	$0.9^\circ \pm 0.5^\circ$	$1.0^\circ \pm 1.1^\circ$	$1.3^\circ \pm 0.8^\circ$	$2.1^\circ \pm 2.7^\circ$
p	100	0-5	lss	$2.3^\circ \pm 1.1^\circ$	$5.0^\circ \pm 3.2^\circ$	$2.7^\circ \pm 1.4^\circ$	$14.7^\circ \pm 11.5^\circ$
p	100	0-10	uni	$1.3^\circ \pm 0.8^\circ$	$1.8^\circ \pm 1.5^\circ$	$2.0^\circ \pm 1.3^\circ$	$3.9^\circ \pm 4.8^\circ$
p	100	0-10	lss	$2.8^\circ \pm 1.3^\circ$	$5.6^\circ \pm 3.4^\circ$	$2.9^\circ \pm 1.5^\circ$	$16.0^\circ \pm 10.9^\circ$
p	100	10-20	uni	$2.9^\circ \pm 1.2^\circ$	$4.5^\circ \pm 2.0^\circ$	$3.8^\circ \pm 1.7^\circ$	$10.6^\circ \pm 7.5^\circ$
p	100	10-20	lss	$4.1^\circ \pm 1.7^\circ$	$8.5^\circ \pm 4.9^\circ$	$4.3^\circ \pm 1.8^\circ$	$23.9^\circ \pm 12.3^\circ$
p	100	20-30	uni	$4.0^\circ \pm 1.4^\circ$	$6.0^\circ \pm 3.0^\circ$	$5.2^\circ \pm 2.1^\circ$	$19.3^\circ \pm 11.3^\circ$
p	100	20-30	lss	$4.8^\circ \pm 1.7^\circ$	$8.9^\circ \pm 3.2^\circ$	$5.0^\circ \pm 1.6^\circ$	$26.6^\circ \pm 12.4^\circ$
Fe	60	0-5	uni	$44.3^\circ \pm 20.9^\circ$	$43.6^\circ \pm 20.0^\circ$	$60.9^\circ \pm 22.5^\circ$	$64.6^\circ \pm 23.1^\circ$
Fe	60	0-5	lss	$76.6^\circ \pm 23.5^\circ$	$82.0^\circ \pm 20.6^\circ$	$70.0^\circ \pm 21.8^\circ$	$77.0^\circ \pm 19.5^\circ$
Fe	60	0-10	uni	$58.4^\circ \pm 22.4^\circ$	$67.3^\circ \pm 23.3^\circ$	$73.2^\circ \pm 21.7^\circ$	$77.6^\circ \pm 22.6^\circ$
Fe	60	0-10	lss	$78.6^\circ \pm 22.4^\circ$	$83.0^\circ \pm 20.2^\circ$	$78.9^\circ \pm 21.5^\circ$	$81.2^\circ \pm 19.4^\circ$
Fe	60	20-30	uni	$84.4^\circ \pm 18.6^\circ$	$87.7^\circ \pm 19.5^\circ$	$84.3^\circ \pm 19.5^\circ$	$90.2^\circ \pm 20.3^\circ$
Fe	60	20-30	lss	$84.0^\circ \pm 19.7^\circ$	$89.7^\circ \pm 21.2^\circ$	$90.7^\circ \pm 19.6^\circ$	$89.9^\circ \pm 19.0^\circ$
Fe	100	0-5	uni	$16.4^\circ \pm 9.5^\circ$	$32.0^\circ \pm 21.2^\circ$	$45.9^\circ \pm 23.5^\circ$	$51.8^\circ \pm 23.7^\circ$
Fe	100	0-5	lss	$56.0^\circ \pm 20.6^\circ$	$68.1^\circ \pm 21.1^\circ$	$60.9^\circ \pm 21.5^\circ$	$75.5^\circ \pm 24.1^\circ$
Fe	100	0-10	uni	$36.3^\circ \pm 19.8^\circ$	$48.2^\circ \pm 23.1^\circ$	$54.4^\circ \pm 22.9^\circ$	$69.7^\circ \pm 24.0^\circ$
Fe	100	0-10	lss	$64.0^\circ \pm 20.3^\circ$	$71.2^\circ \pm 21.4^\circ$	$64.8^\circ \pm 21.6^\circ$	$73.6^\circ \pm 22.1^\circ$
Fe	100	20-30	uni	$72.5^\circ \pm 17.5^\circ$	$84.3^\circ \pm 20.0^\circ$	$80.3^\circ \pm 23.4^\circ$	$77.4^\circ \pm 17.1^\circ$
Fe	100	20-30	lss	$92.4^\circ \pm 17.7^\circ$	$76.5^\circ \pm 19.0^\circ$	$75.7^\circ \pm 16.5^\circ$	$78.6^\circ \pm 19.3^\circ$

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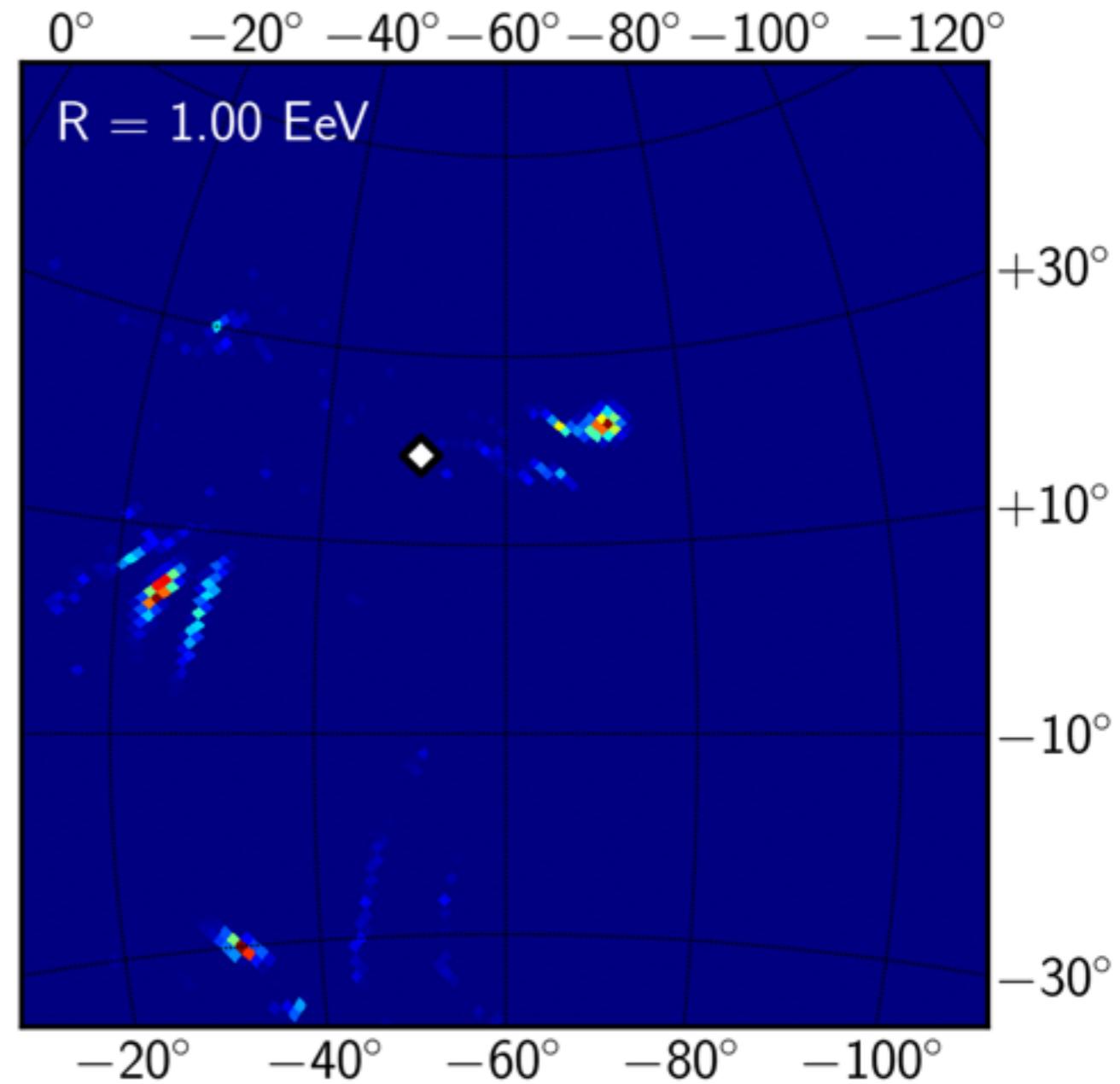
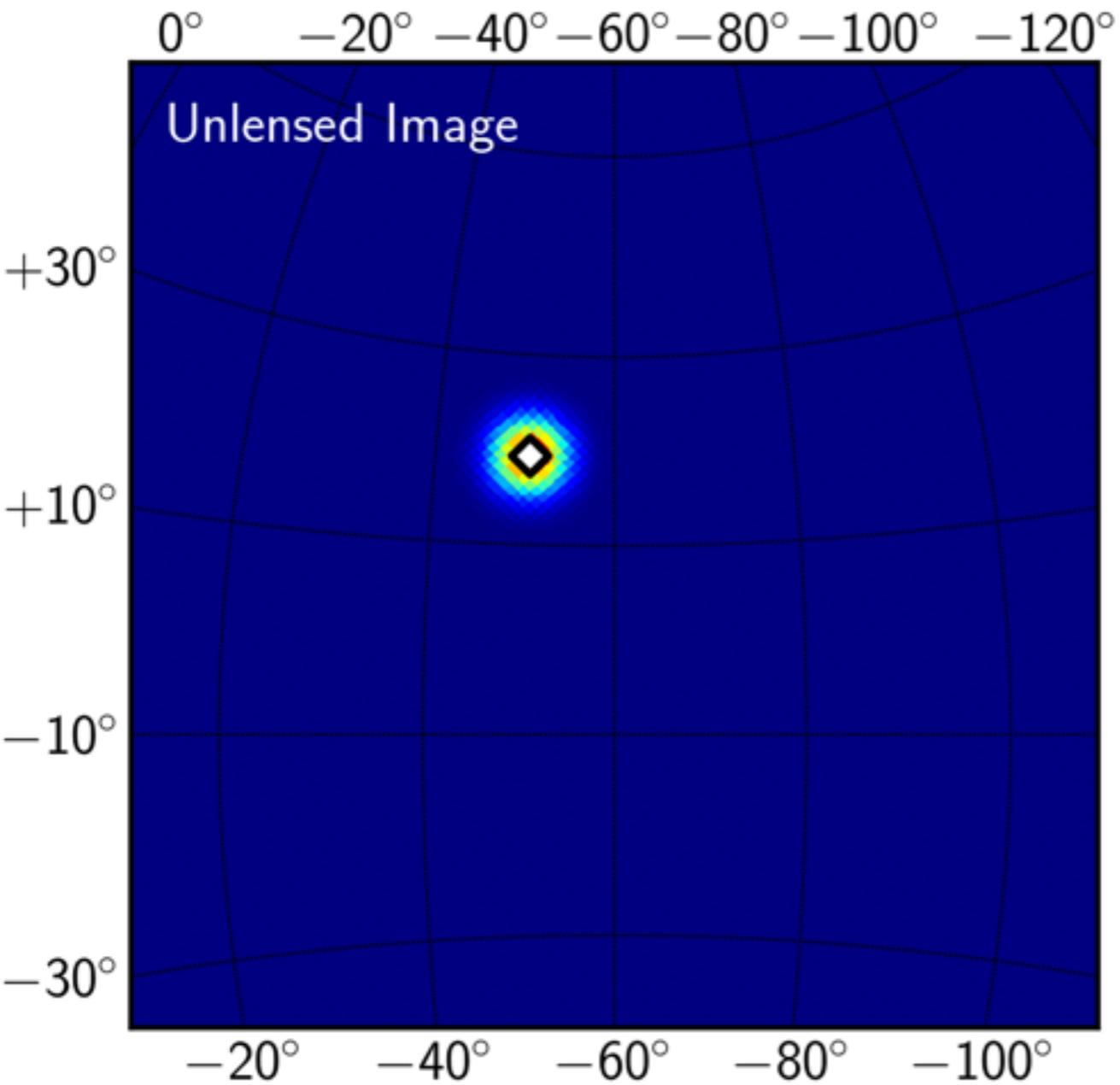
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