ultra-high energy cosmic rays and the magnetized universe

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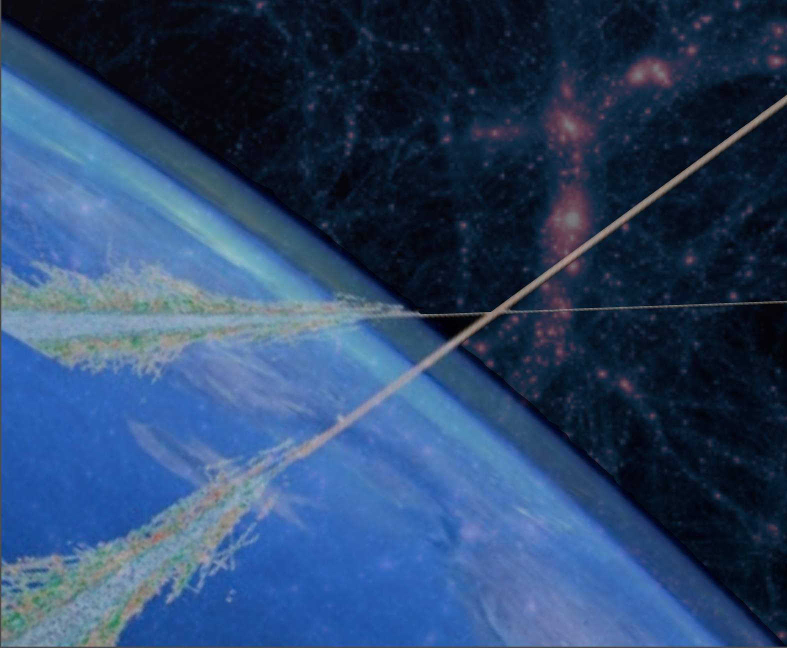
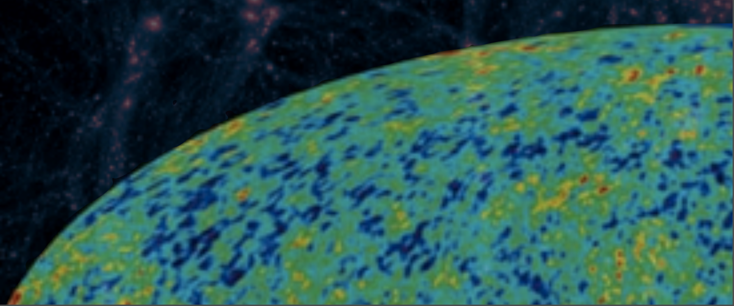




ultra-high energy cosmic rays (UHECRs)

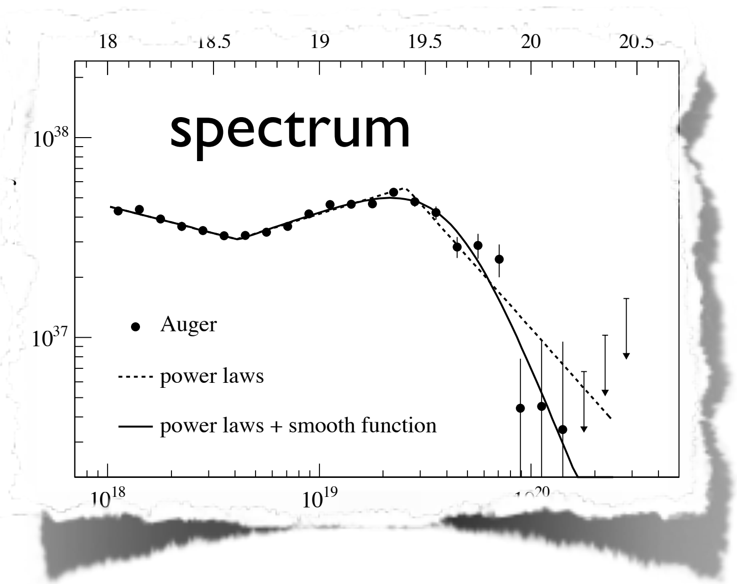
fundamental questions

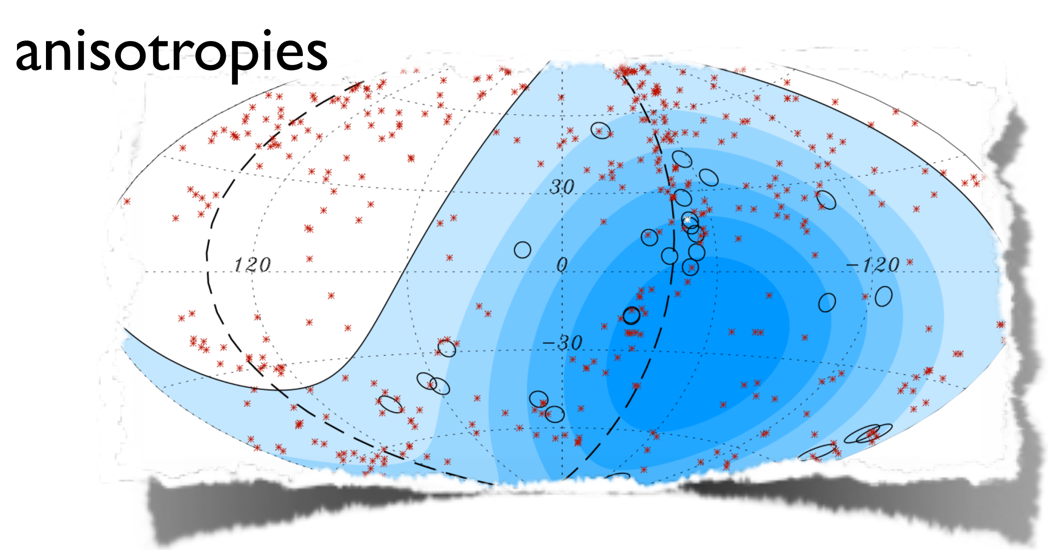
- where do they come from?
- what are they made of?
- how are they accelerated?

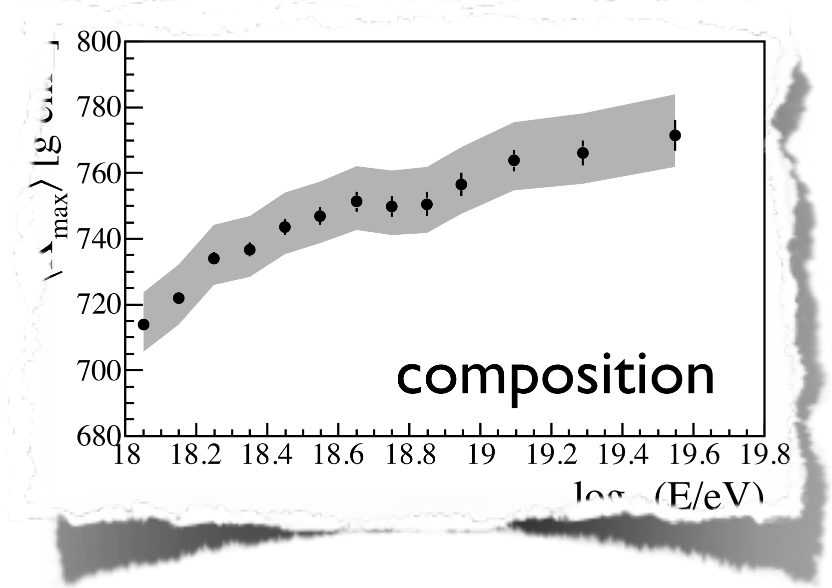
some problems

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

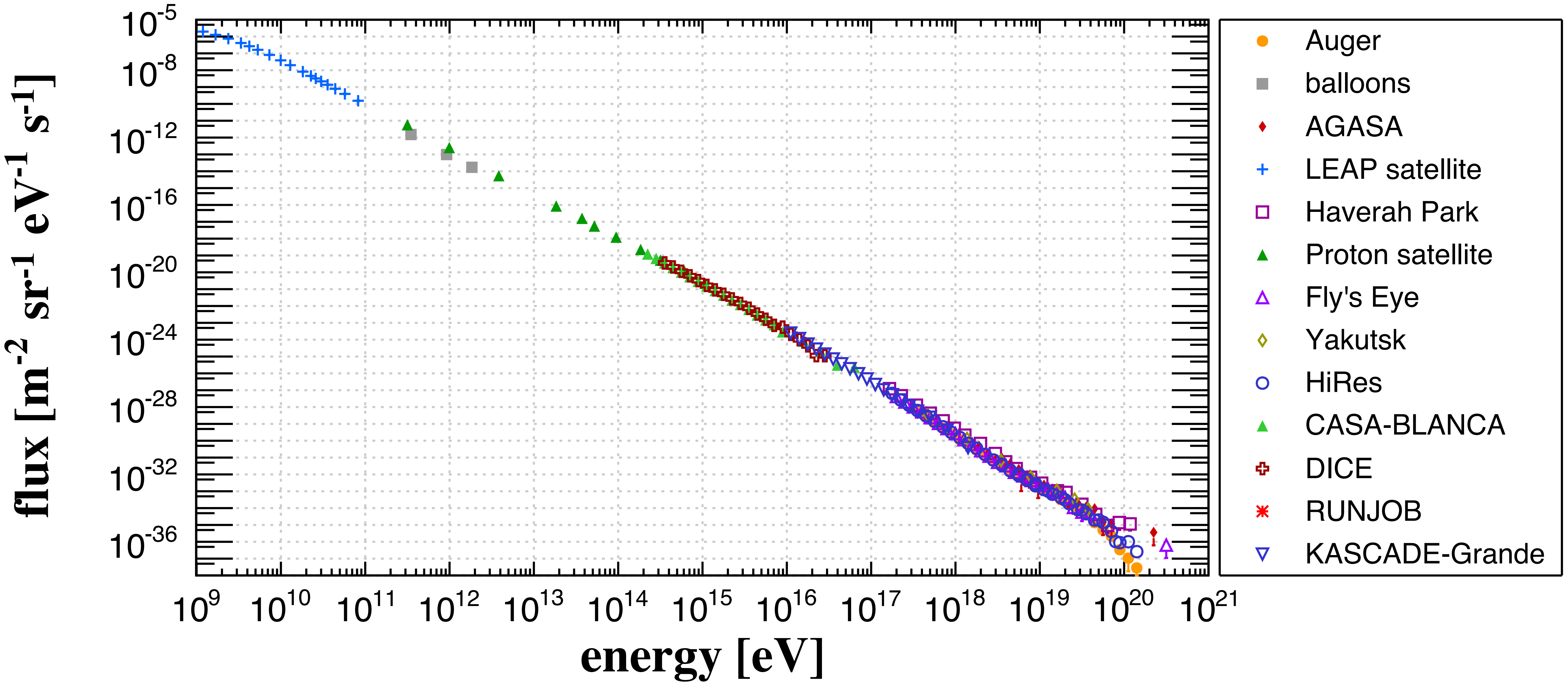
- some observables from CR experiments: spectrum, composition, anisotropy
- cosmic magnetic fields (galactic and extragalactic) are important







the cosmic ray spectrum



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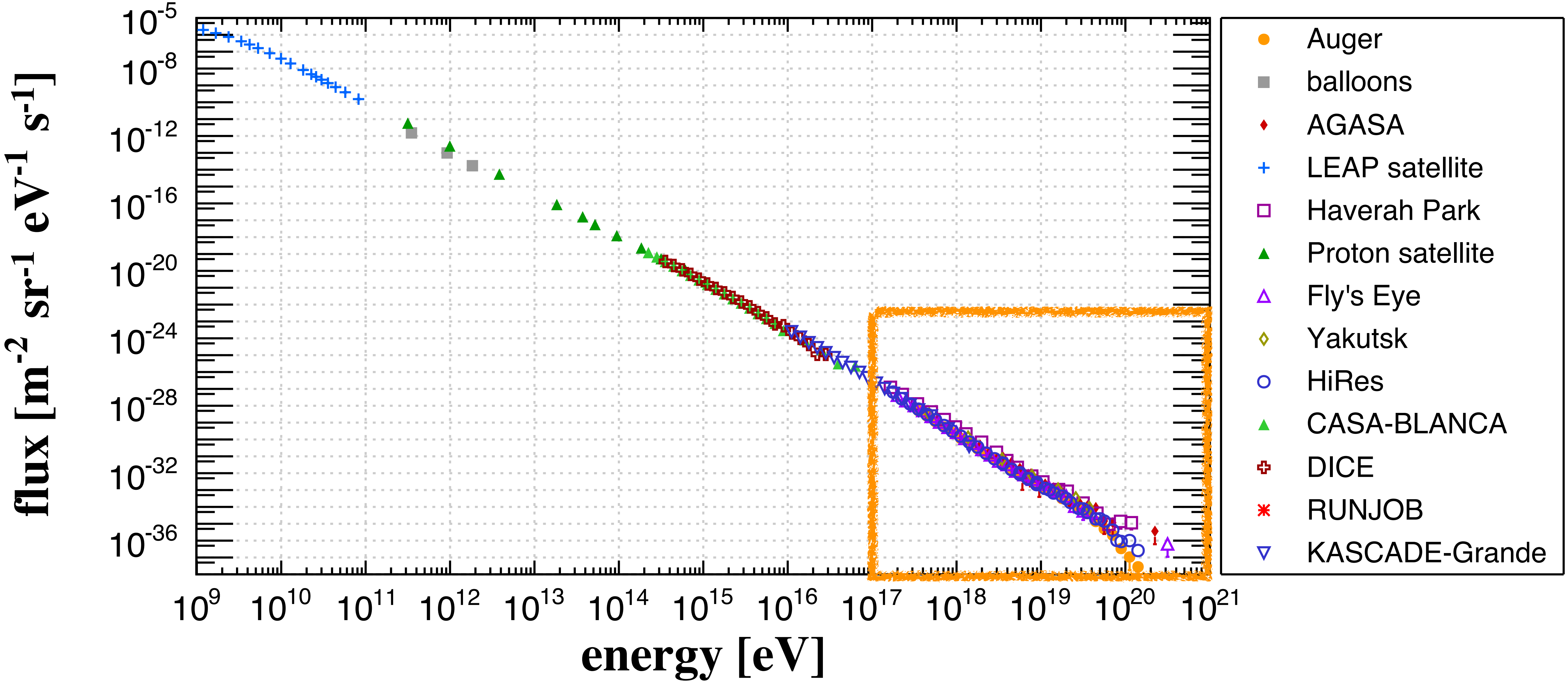

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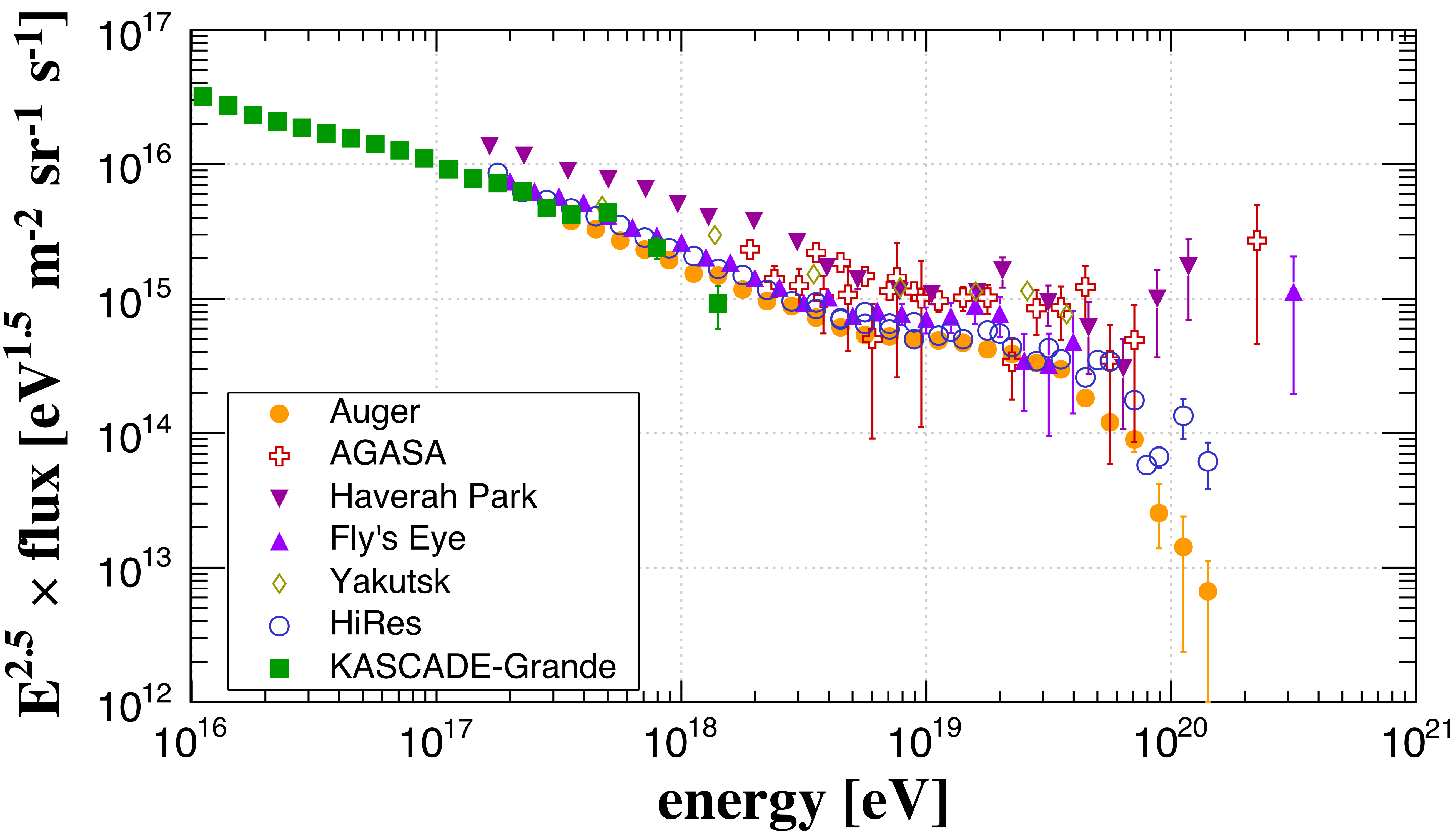
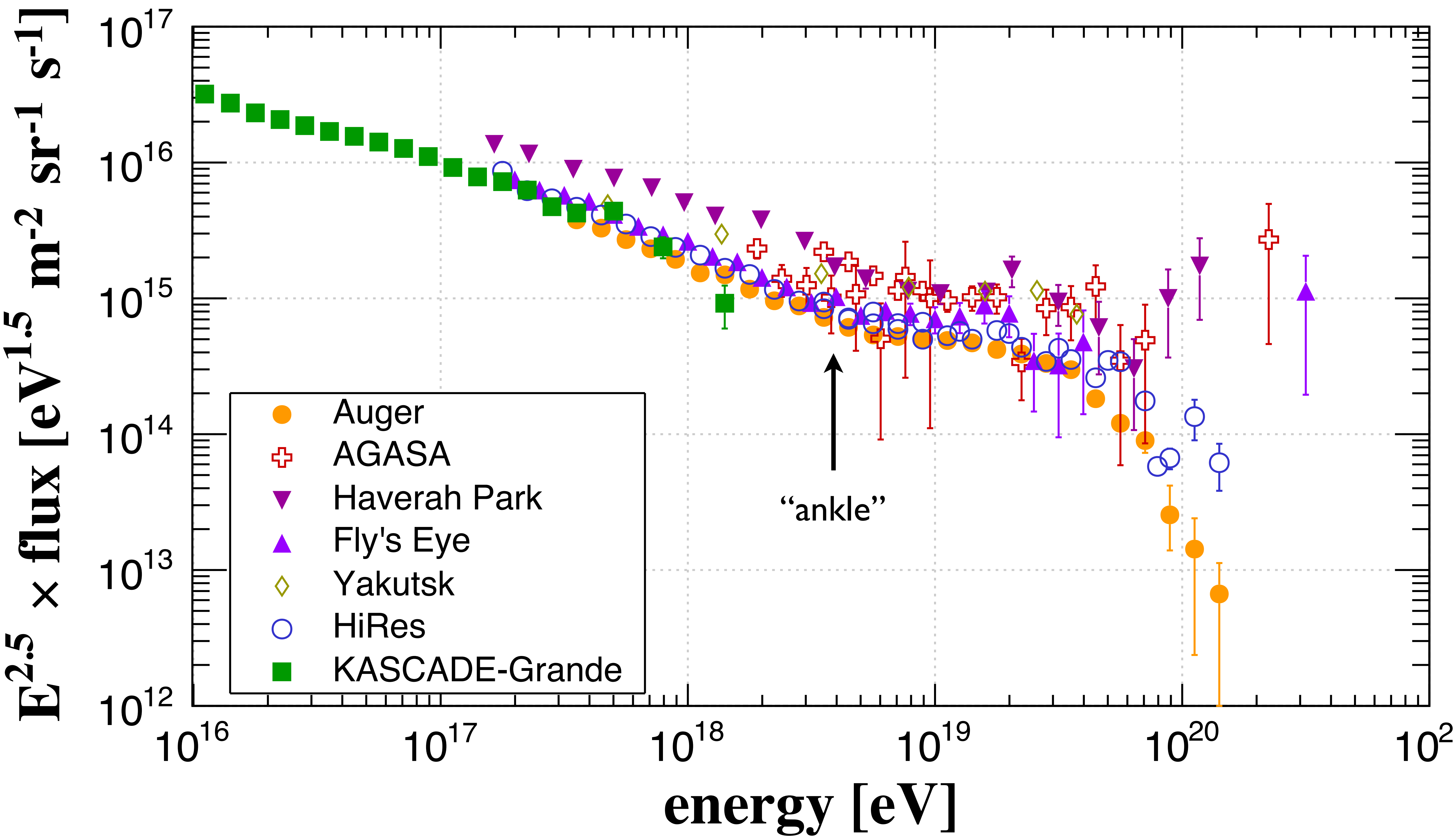
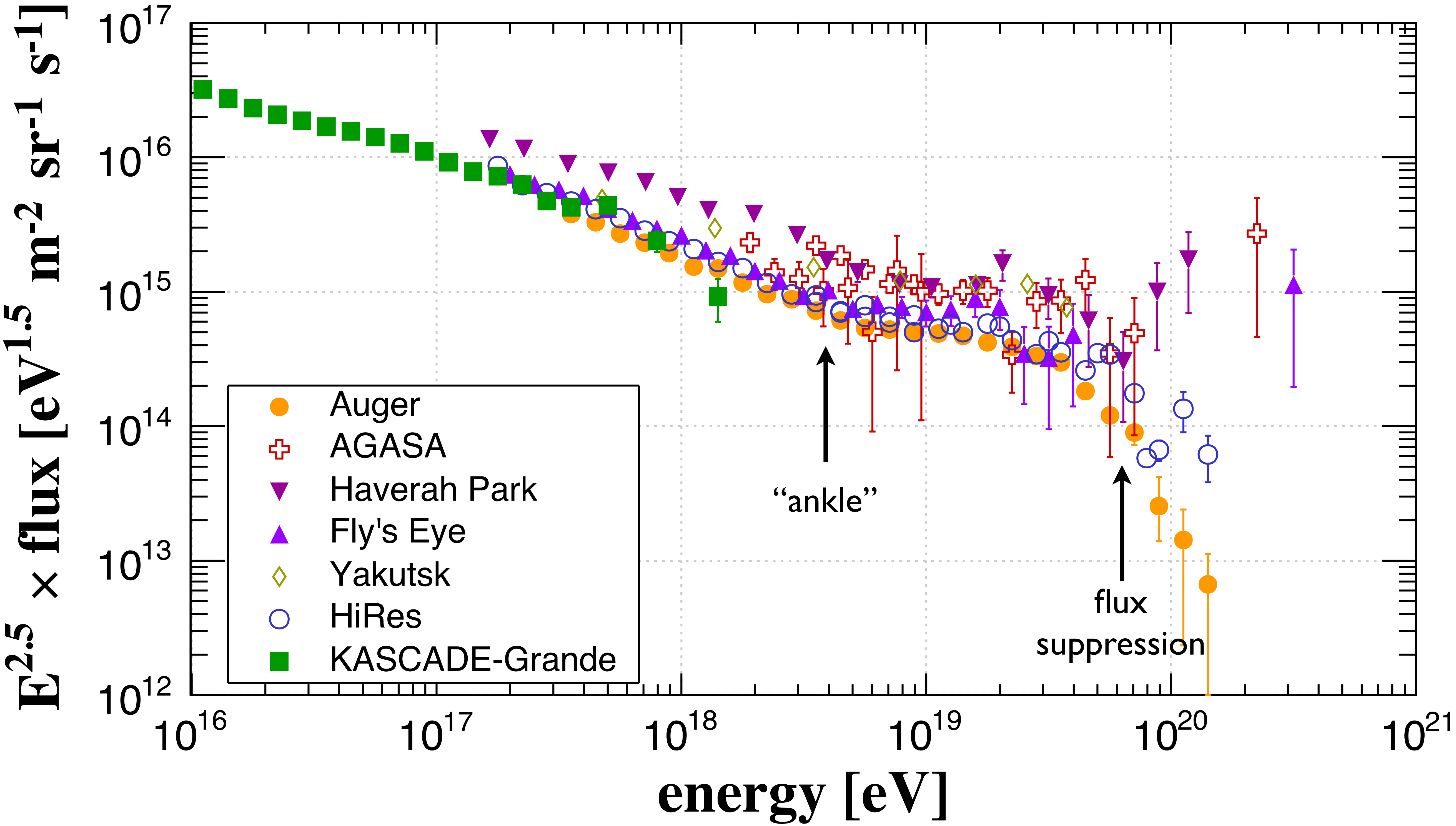
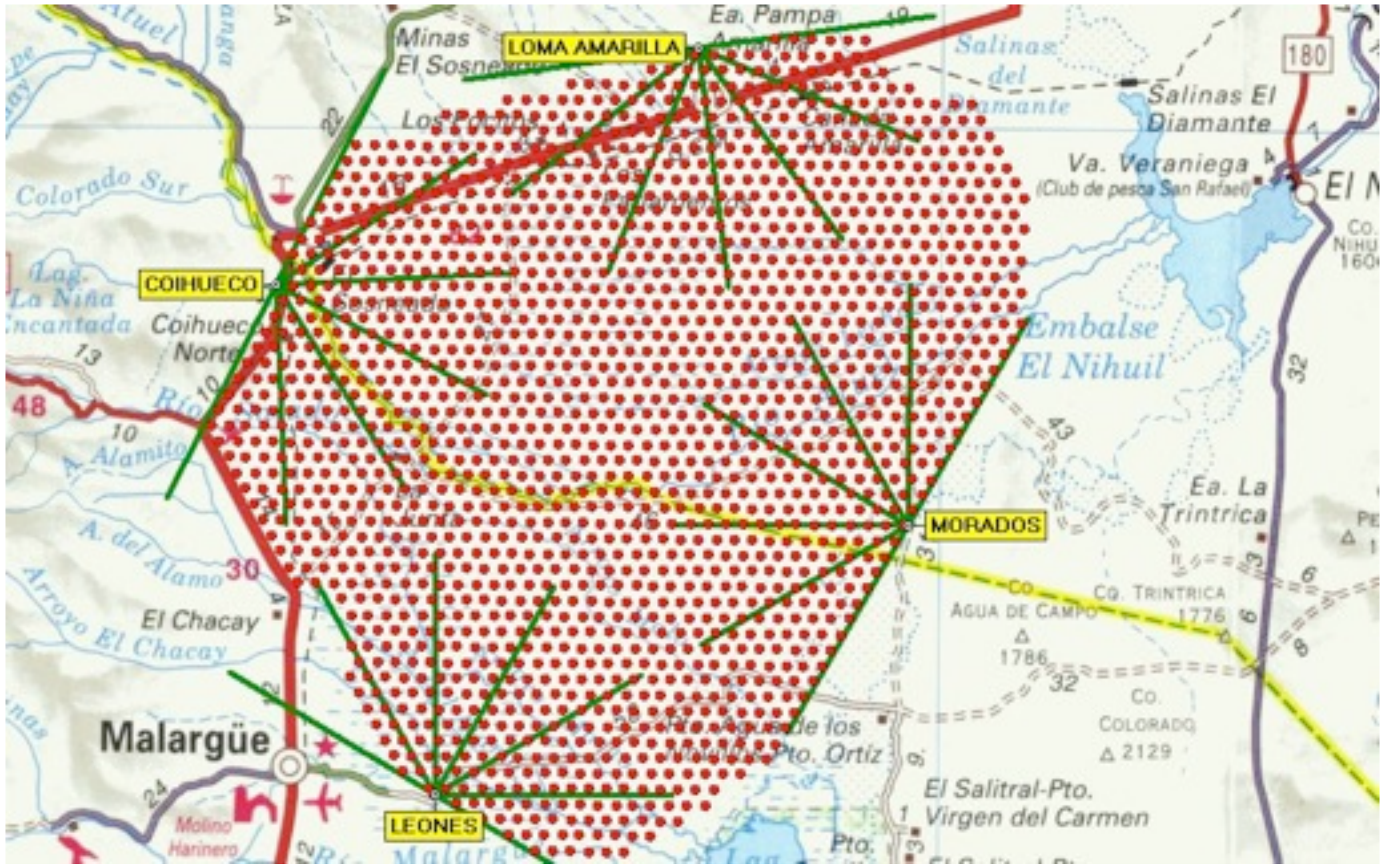



$E^{2.5} \times$ flux [eV$^{1.5}$ m^{-2} sr^{-1} s^{-1}]
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
energy [eV]
"ankle"
Auger
AGASA
Haverah Park
Fly's Eye
Yakutsk
HiRes
KASCADE-Grande

the cosmic ray spectrum



experimental techniques: the Pierre Auger Observatory



- largest UHECR observatory
- ~3000 km^2 in Argentina
- hybrid detection: fluorescence + surface
- enhancements: radio detection (AERA) + lower energy extension (infill array) + ...

propagation: overture

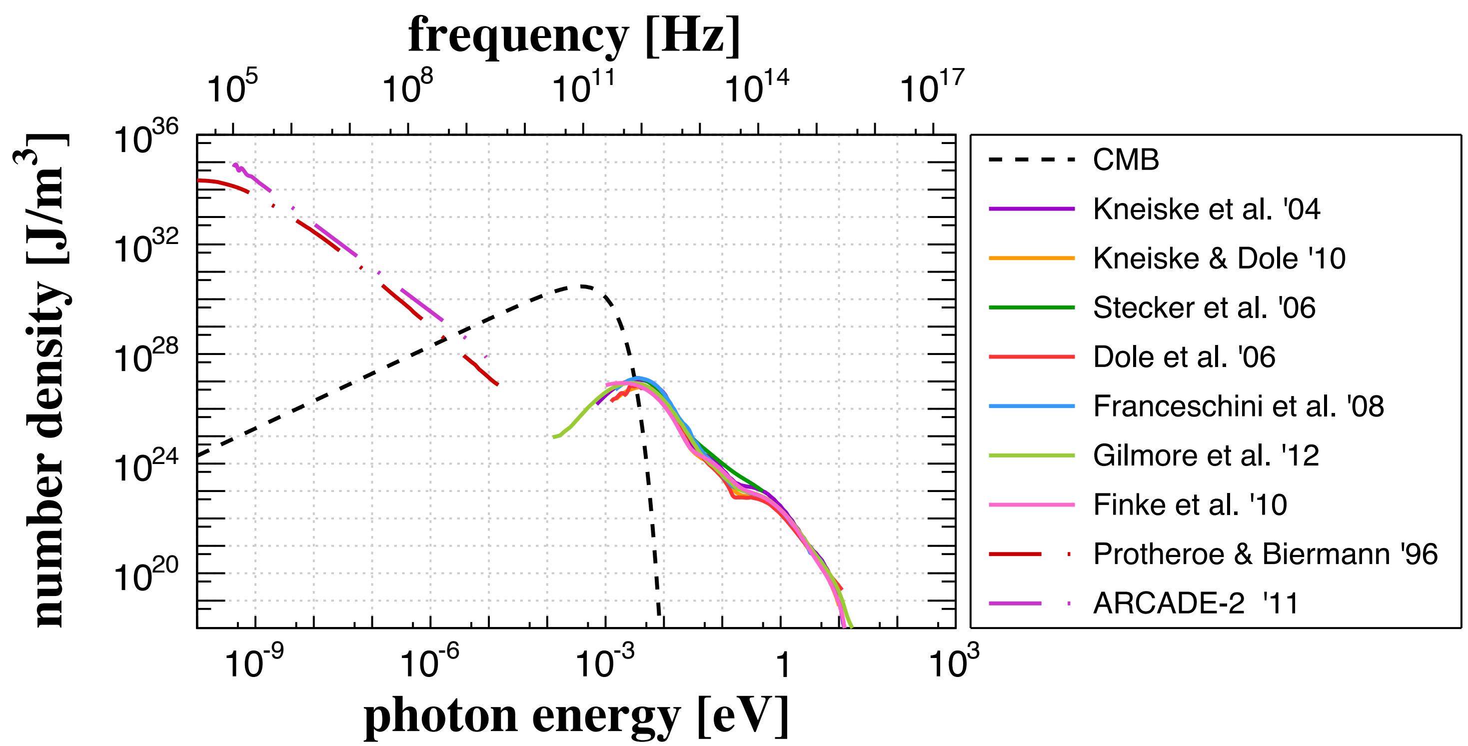
source → - magnetic fields
- photon fields → Earth

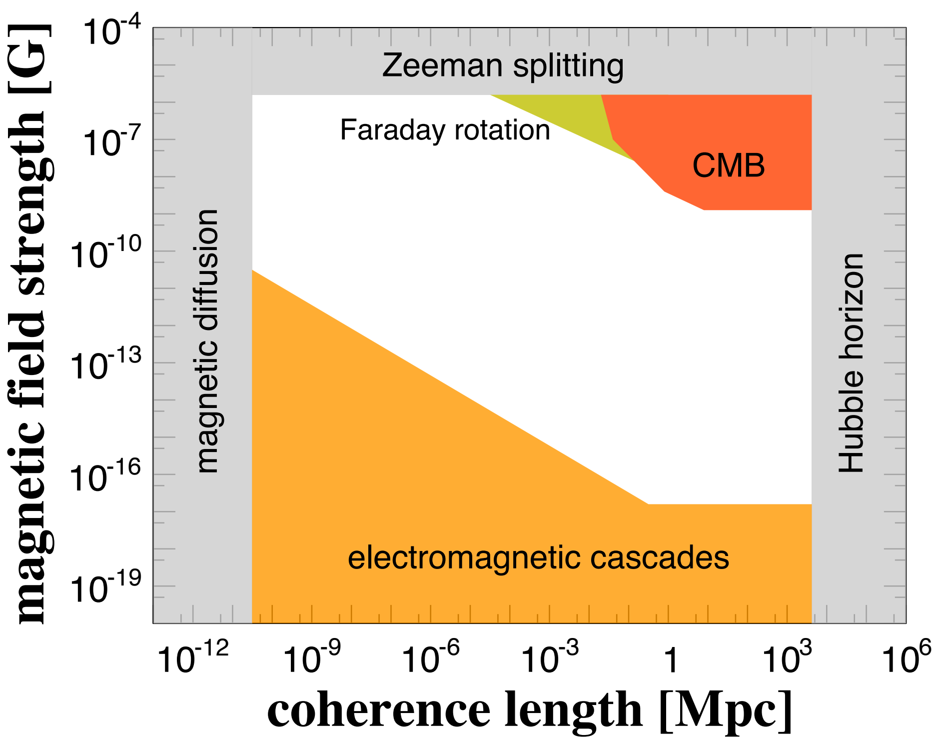
- the presence of photon backgrounds (e.g. CMB, EBL, ...) permeating the universe provide a medium where interactions can take place

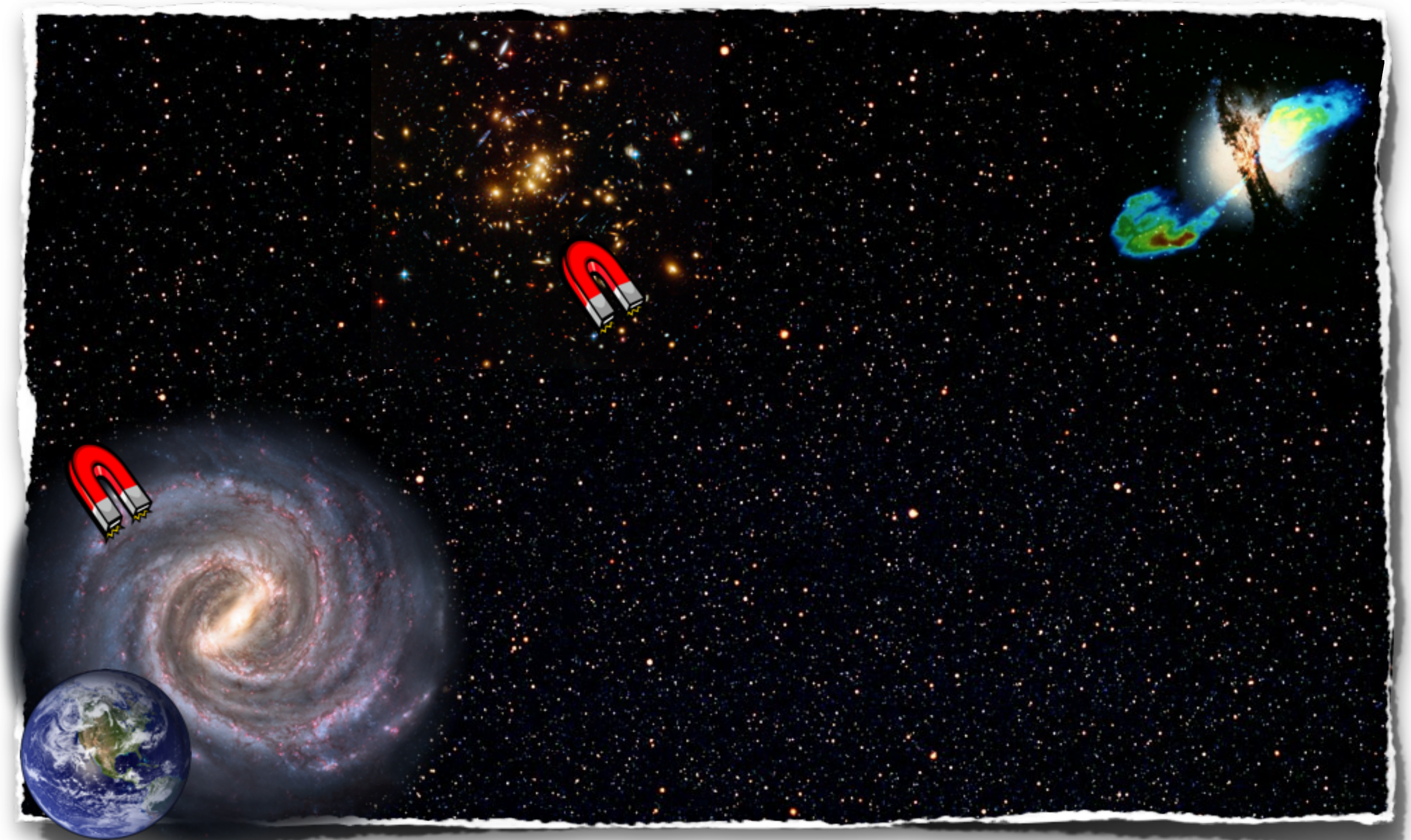
photon backgrounds

- cosmic magnetic fields (galactic and extragalactic) can affect the trajectory of particles

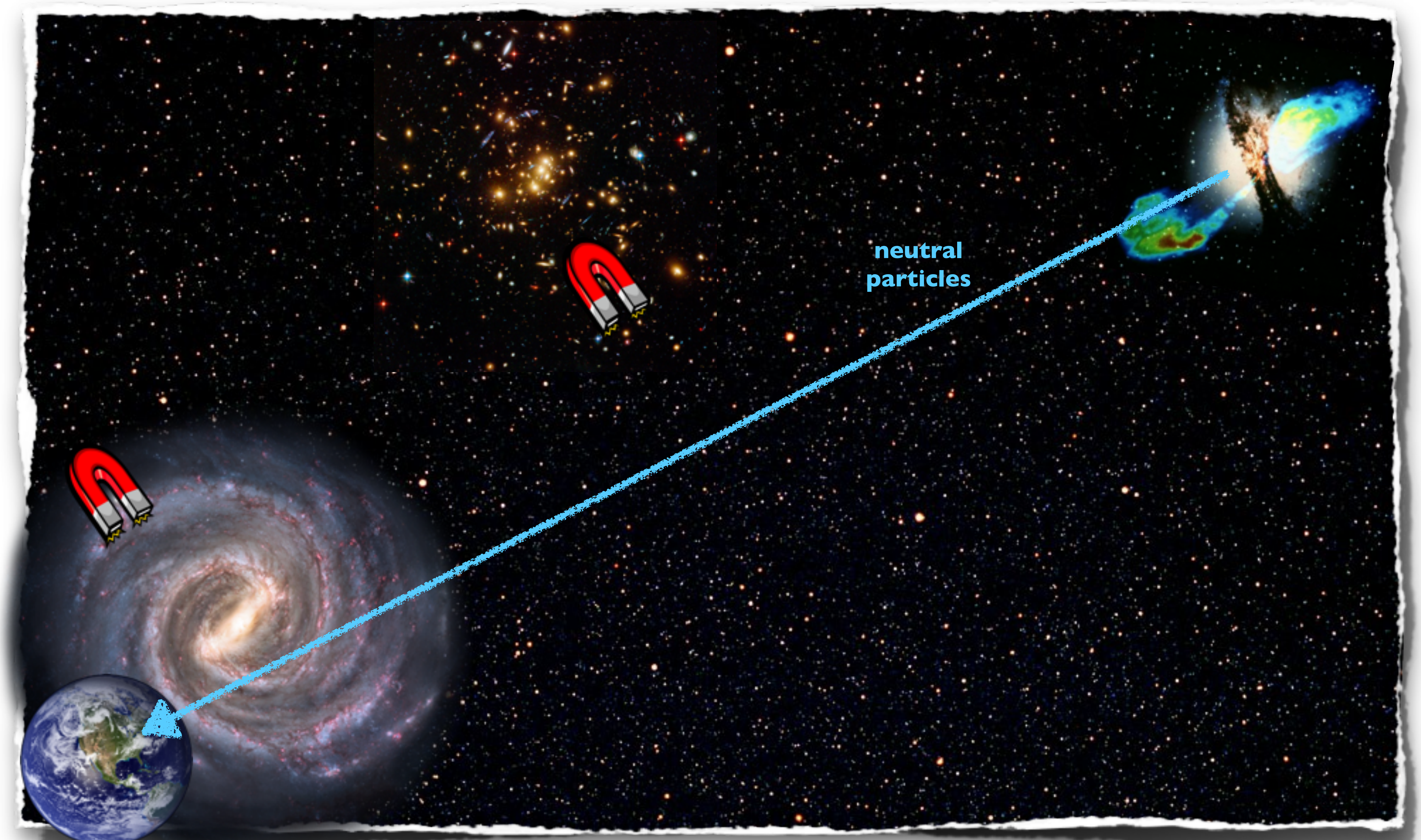
magnetic fields



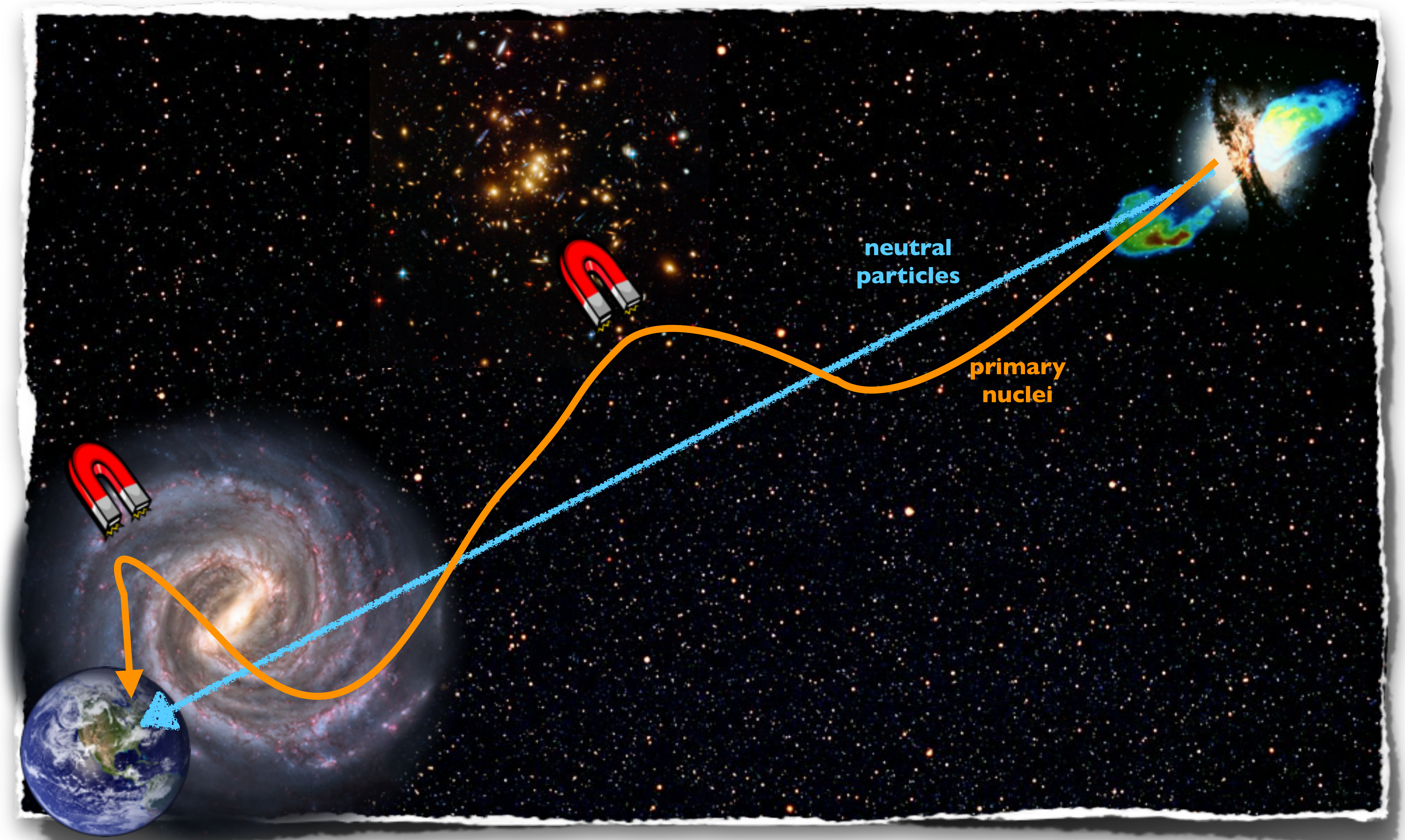




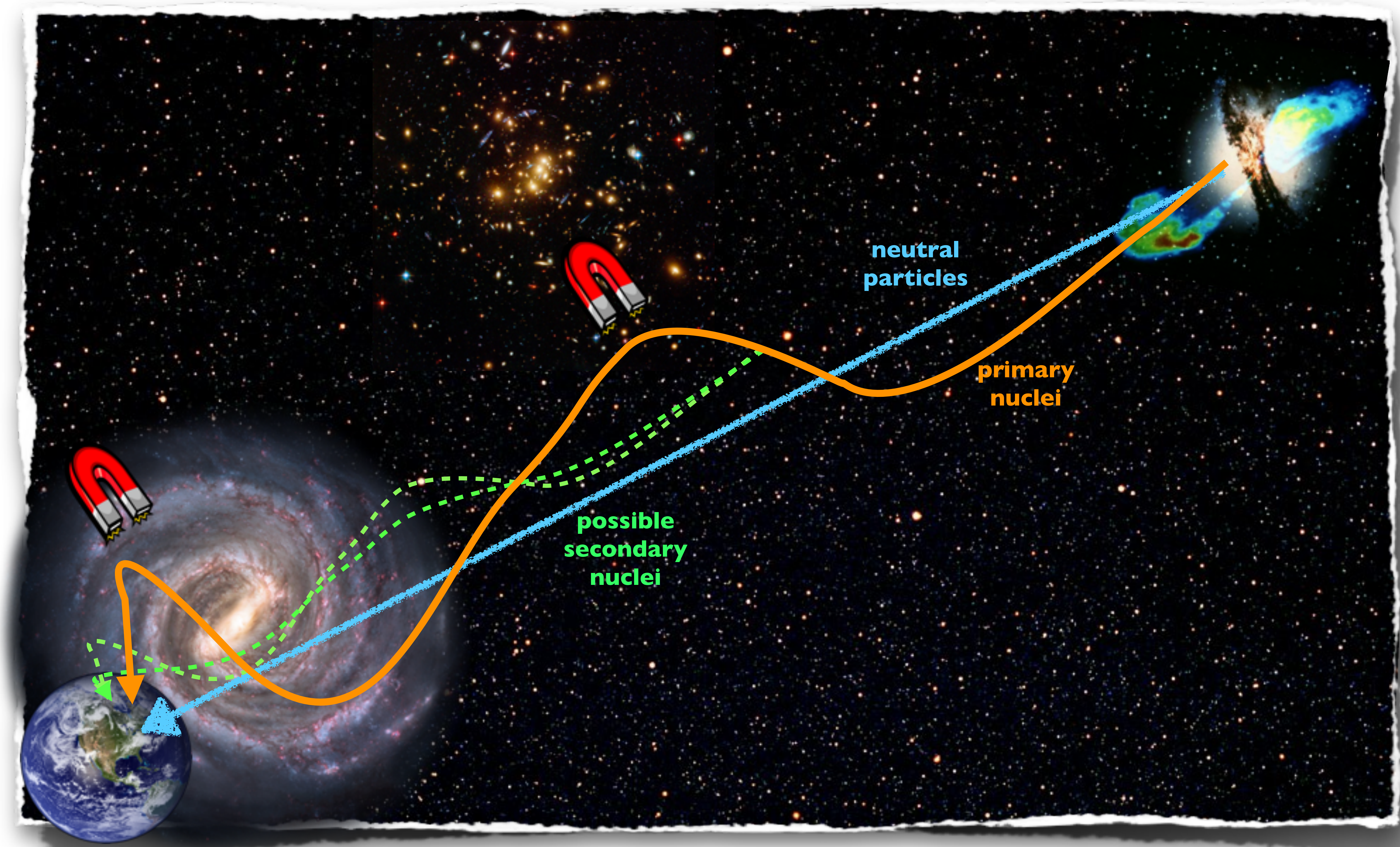
propagation picture



propagation picture



propagation picture



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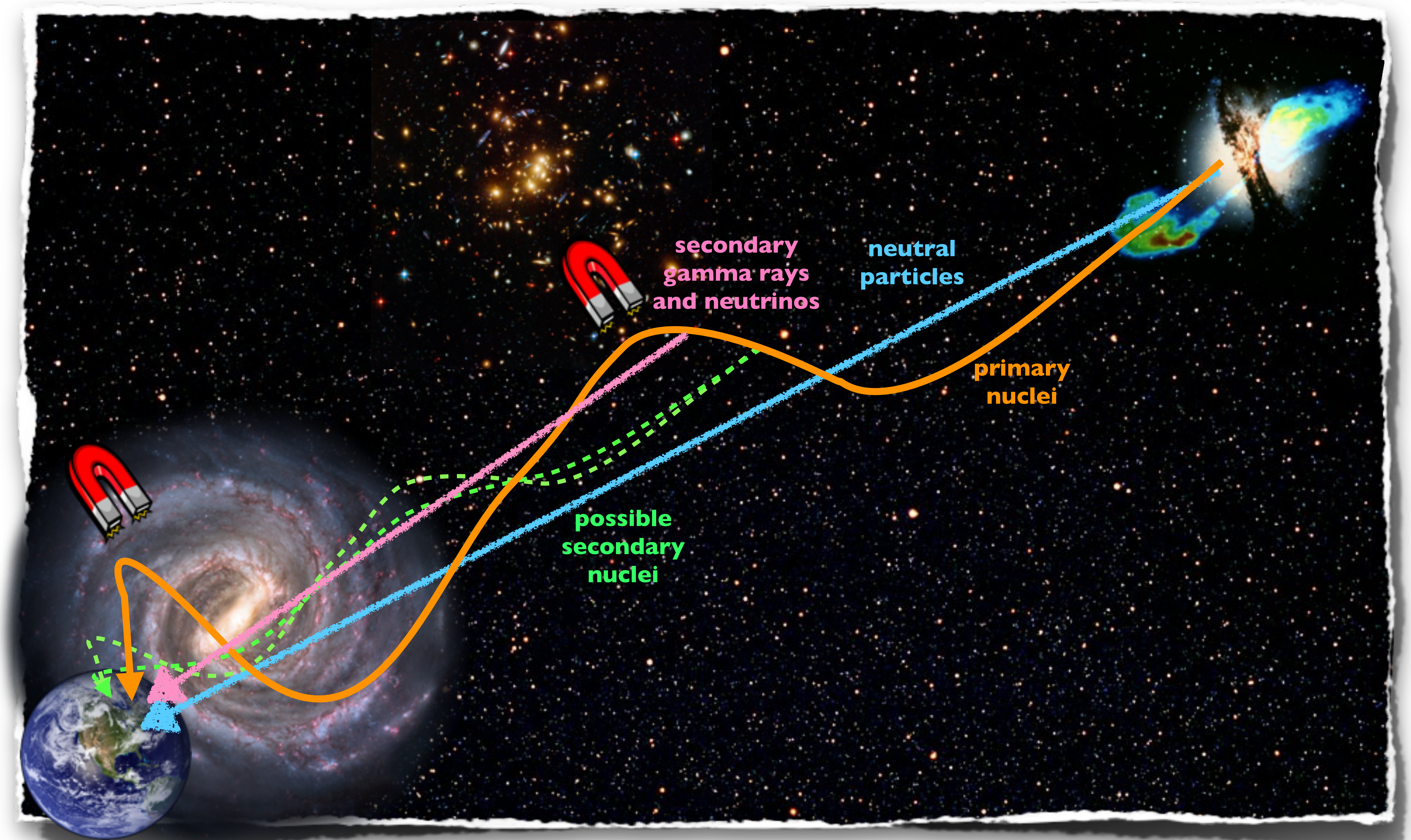

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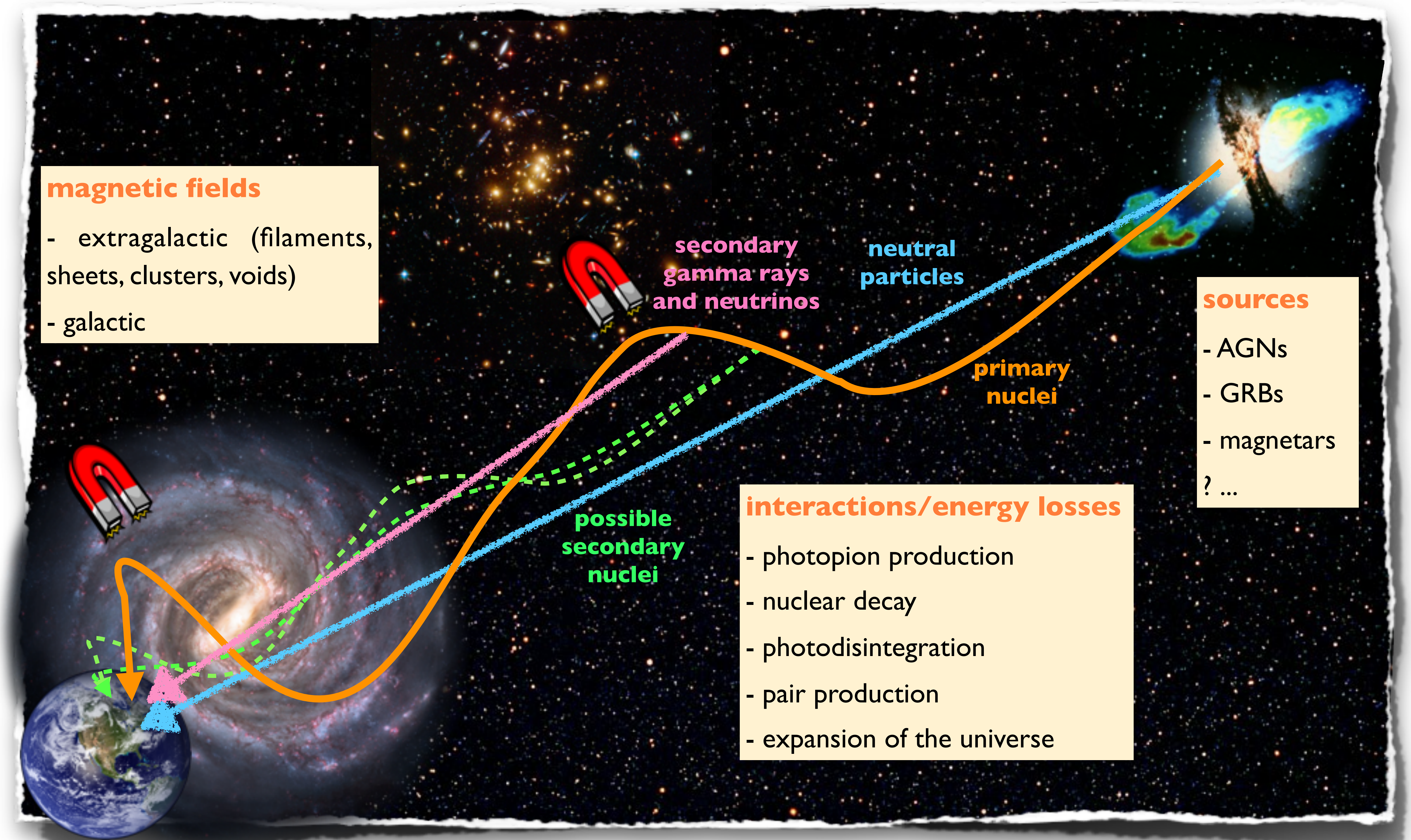


interactions and energy loss processes

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

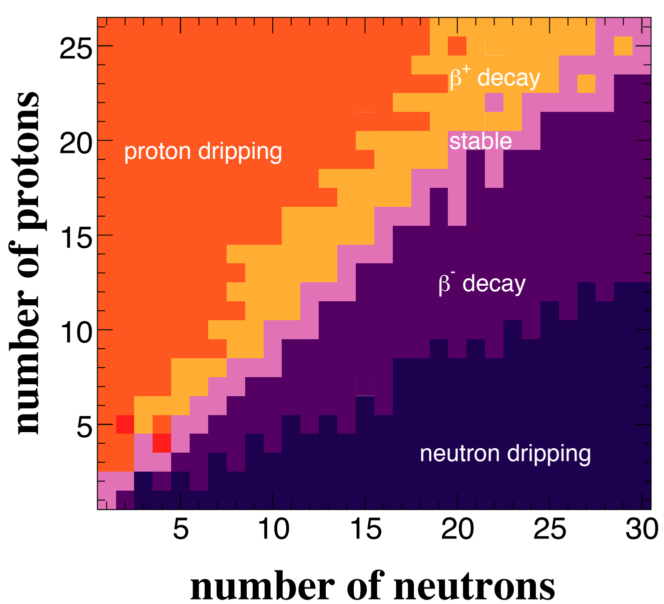
$$-\frac{dE_{A,Z}}{dt} = 3\alpha h^{-3} Z^2 \left(m_e c^2 k_B T\right)^2 f(\Gamma)$$

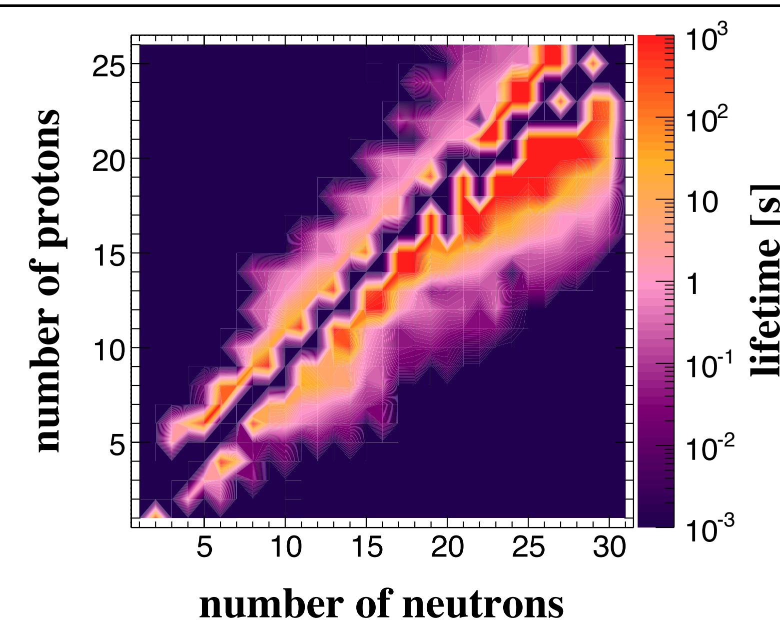
photodisintegration

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

tabulated cross sections from TALYS 1.6

nuclear decay





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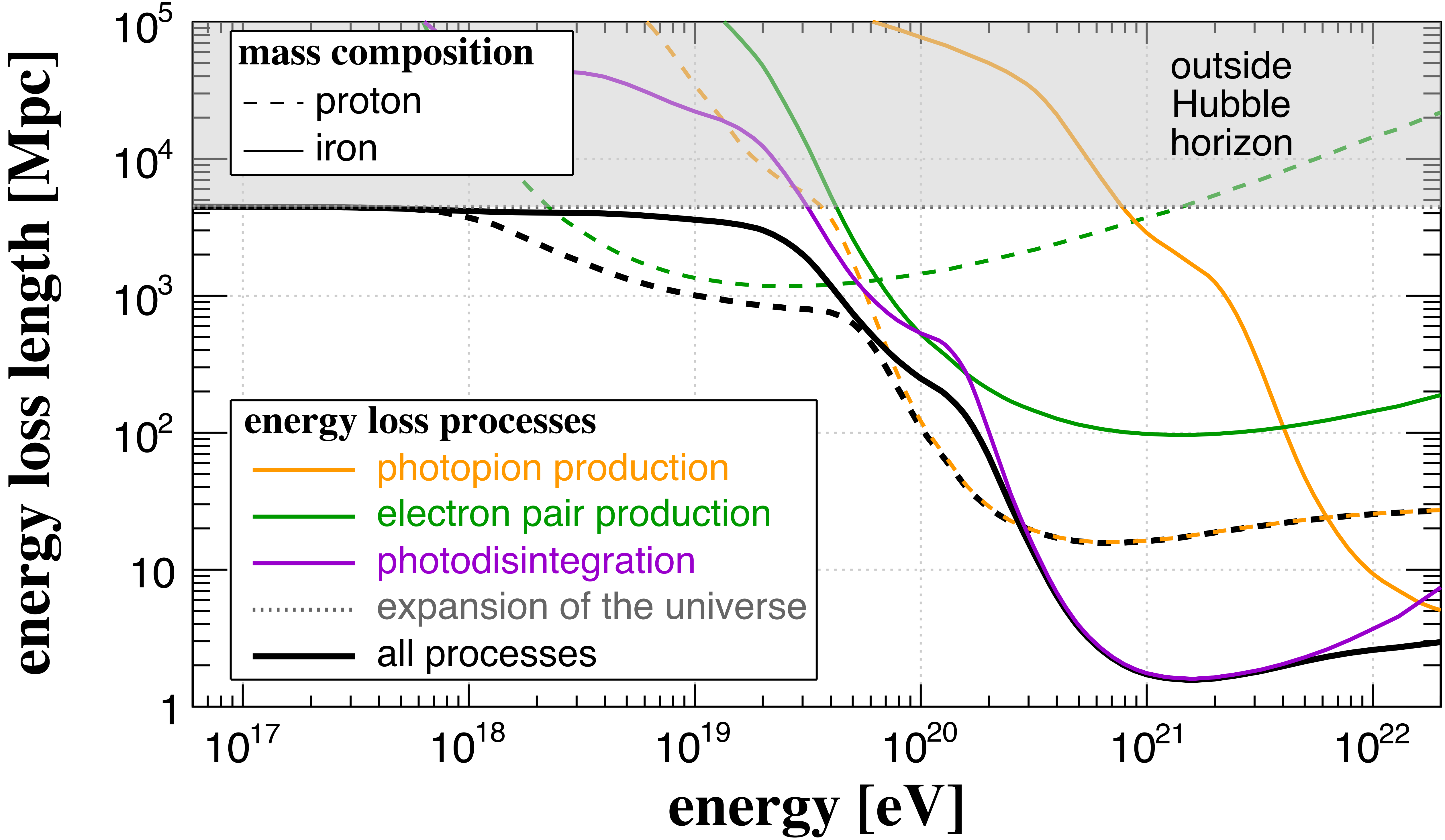


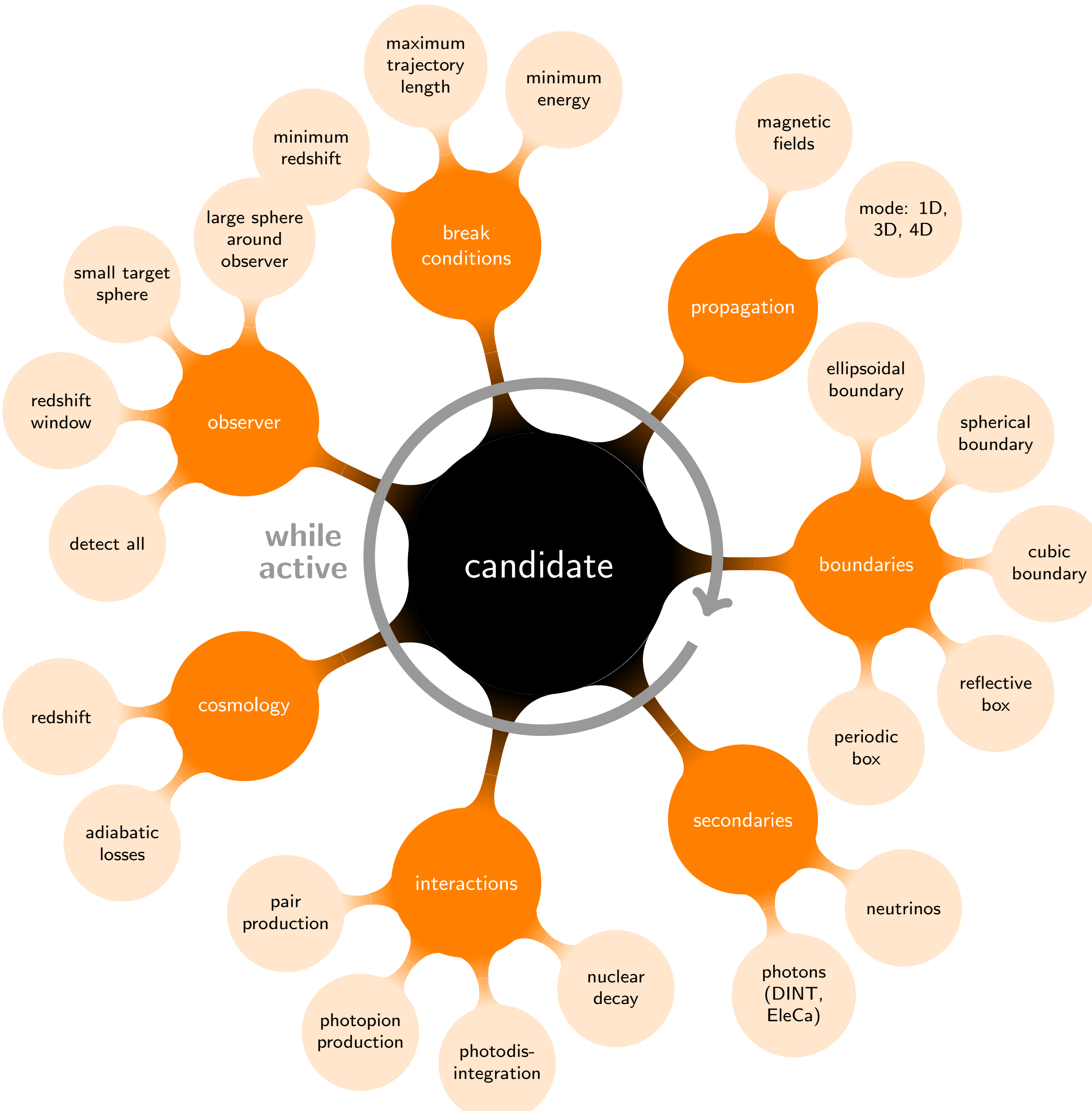
CRPropa 3

RAB+ '13, arXiv:1307.2643

RAB+ '13, arXiv:1411.2259

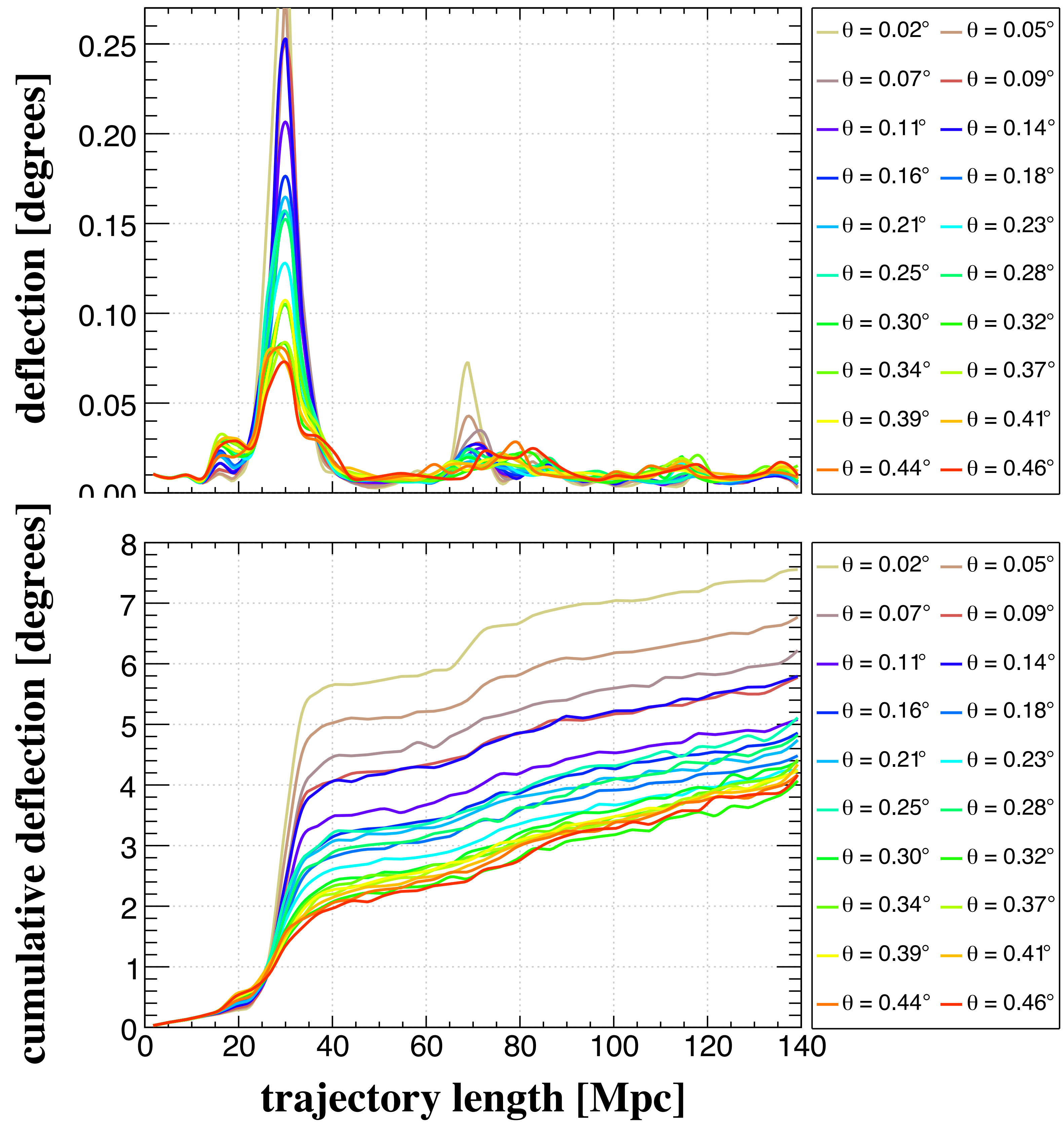
RAB+. J. Phys: Conf. Ser. 608 (2015) 012076

- development version
- complete redesign of the code
- modular structure and python steering
- parallel processing
- 3D simulations with cosmology ("4D mode")
- galactic magnetic field through lenses
- MC photon propagation
- large scale magnetic fields through SPH
- AMR grids
- updated photodisintegration cross sections
- more EBL models
- improved interaction rate tables

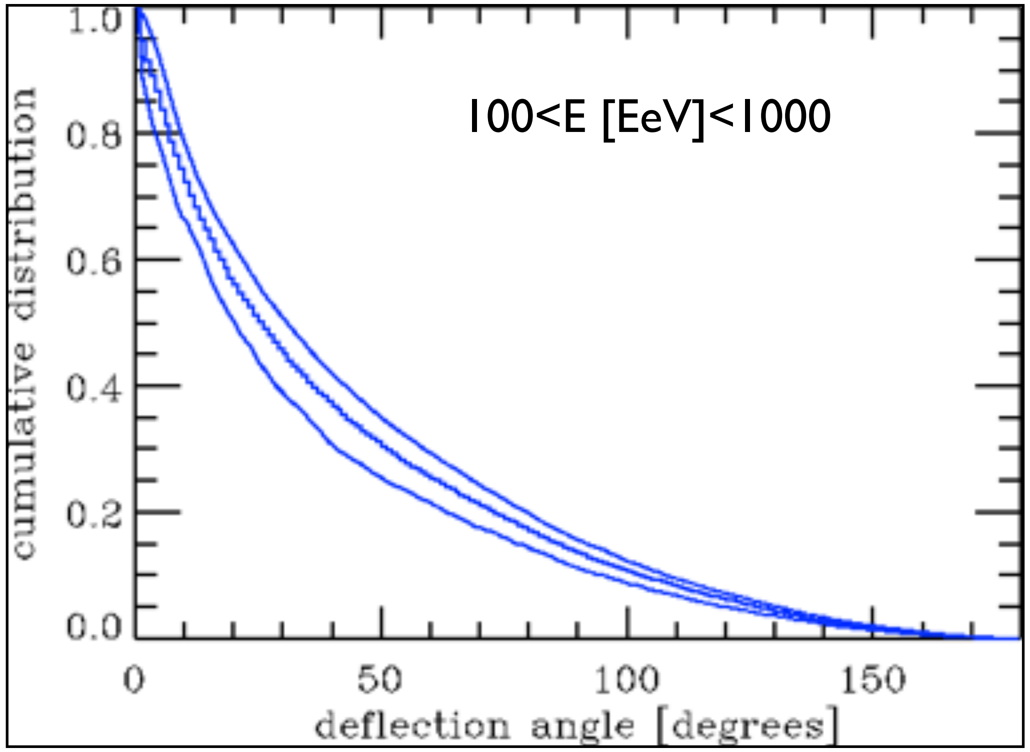


http://crpropa.desy.de

UHECR tomography of the cosmic web

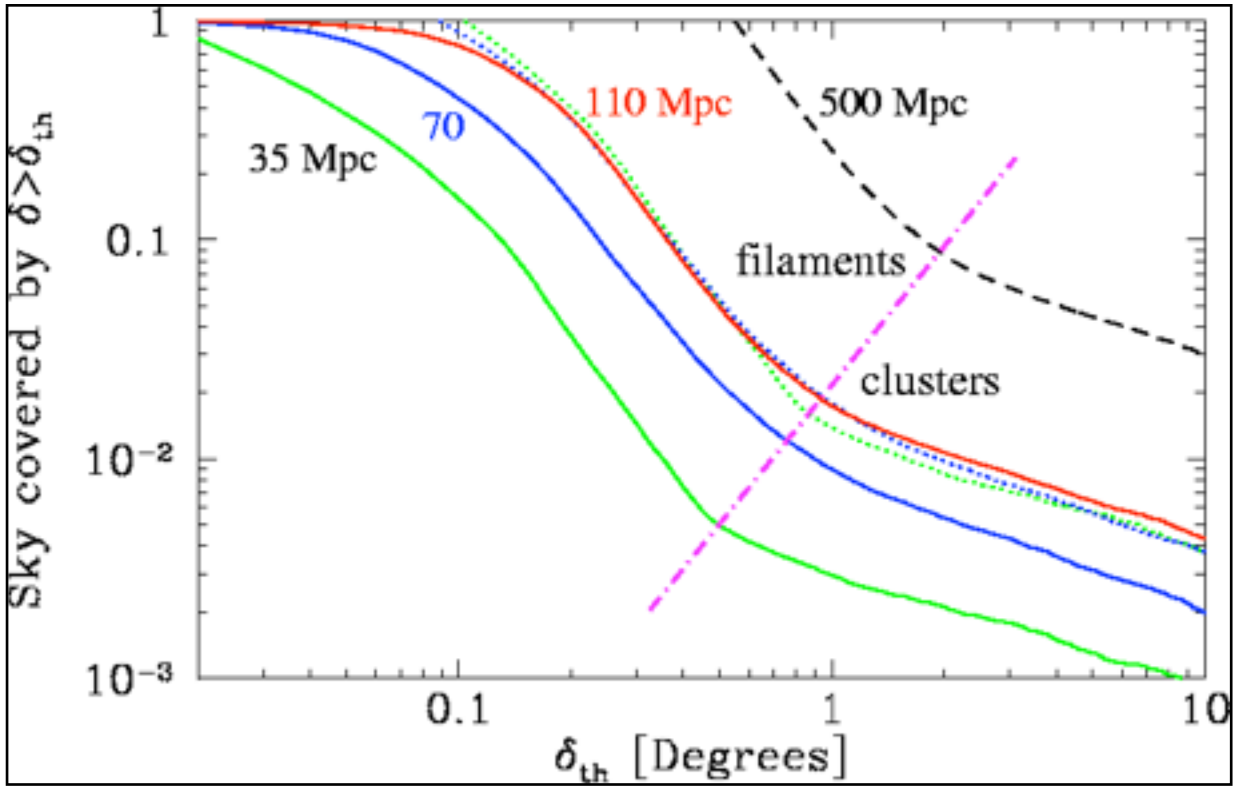


UHECR astronomy?



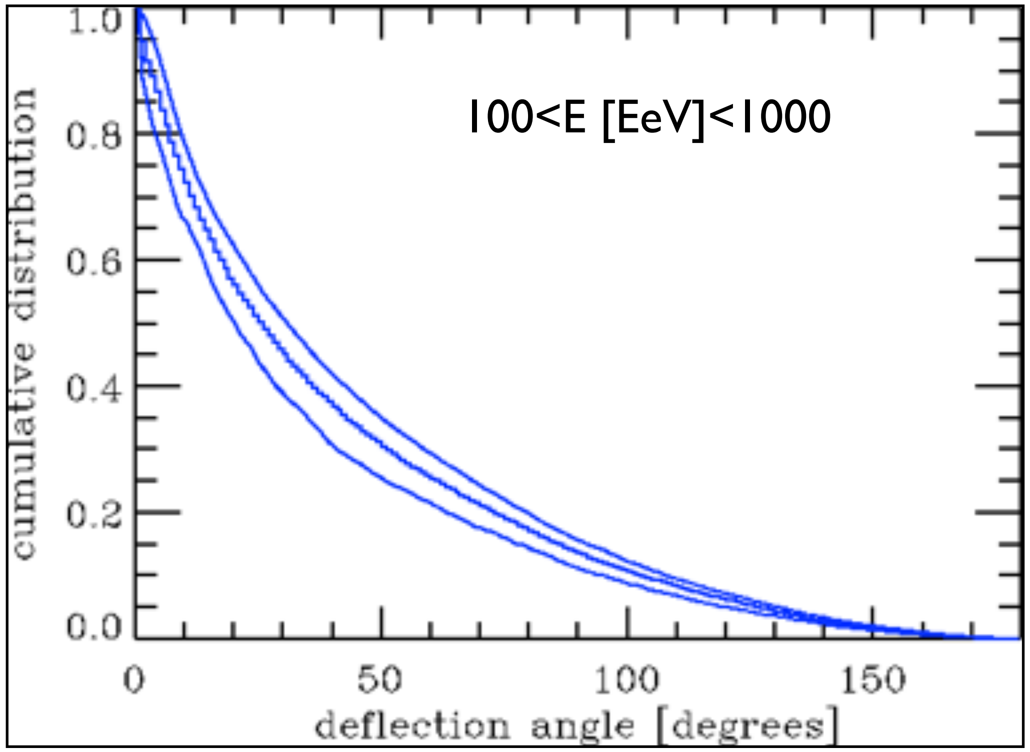
Sigl, Miniati, Ensslin. PRD 70 (2004) 043007

- cumulative deflections displayed are for protons
- Sigl+ '04: deflections are high
- Dolag+ '04: 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

UHECR astronomy?



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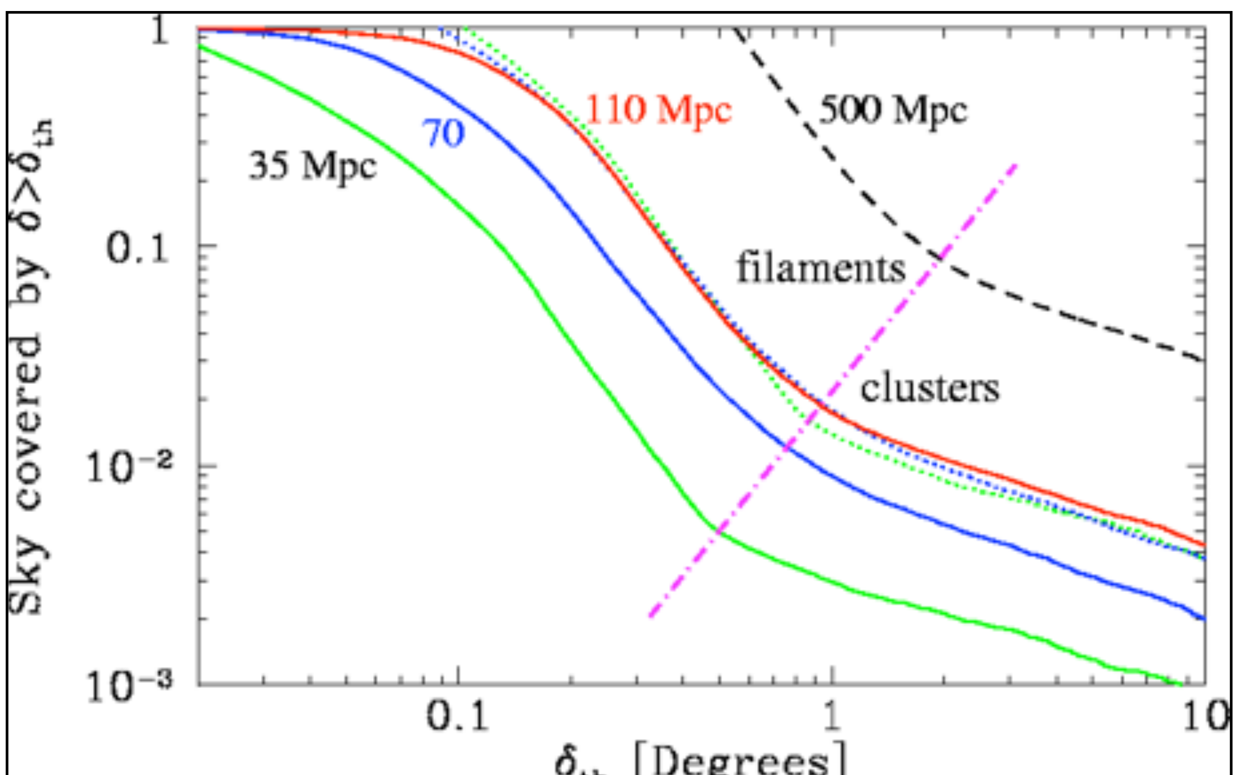
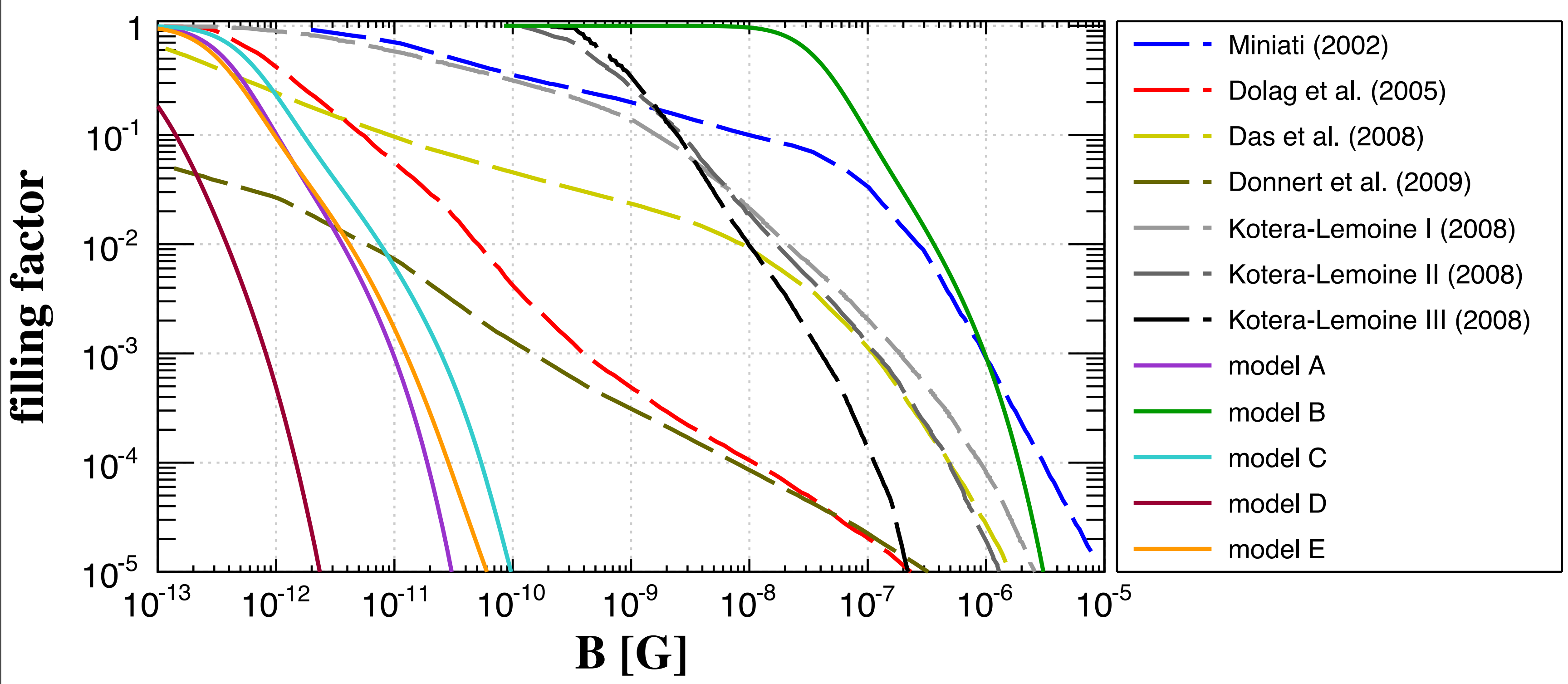


Dolag et al. JETP 79(2004) 583

Is UHECR astronomy really possible?

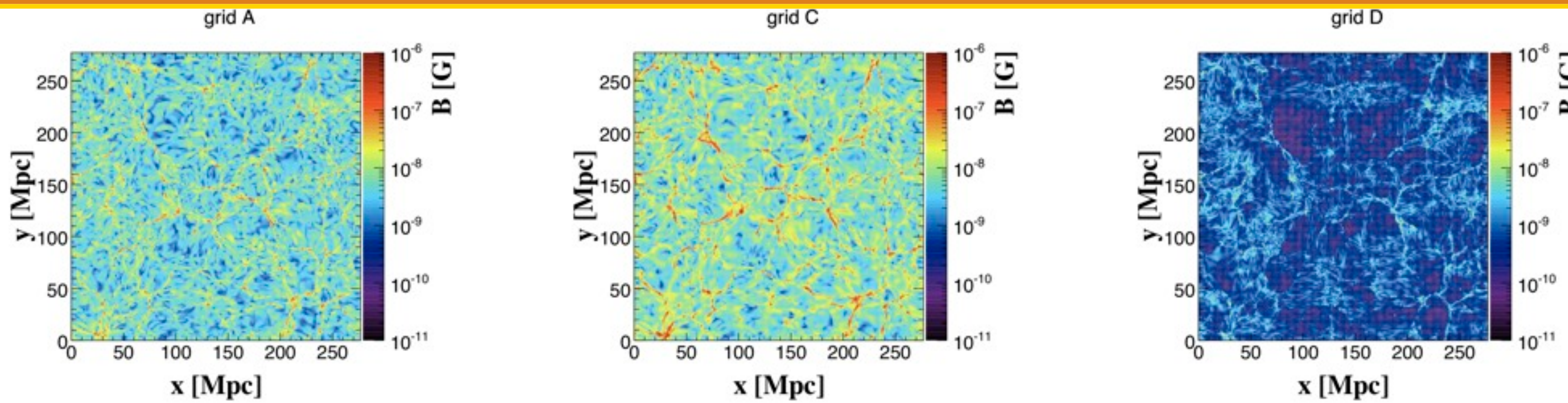
the magnetized cosmic web



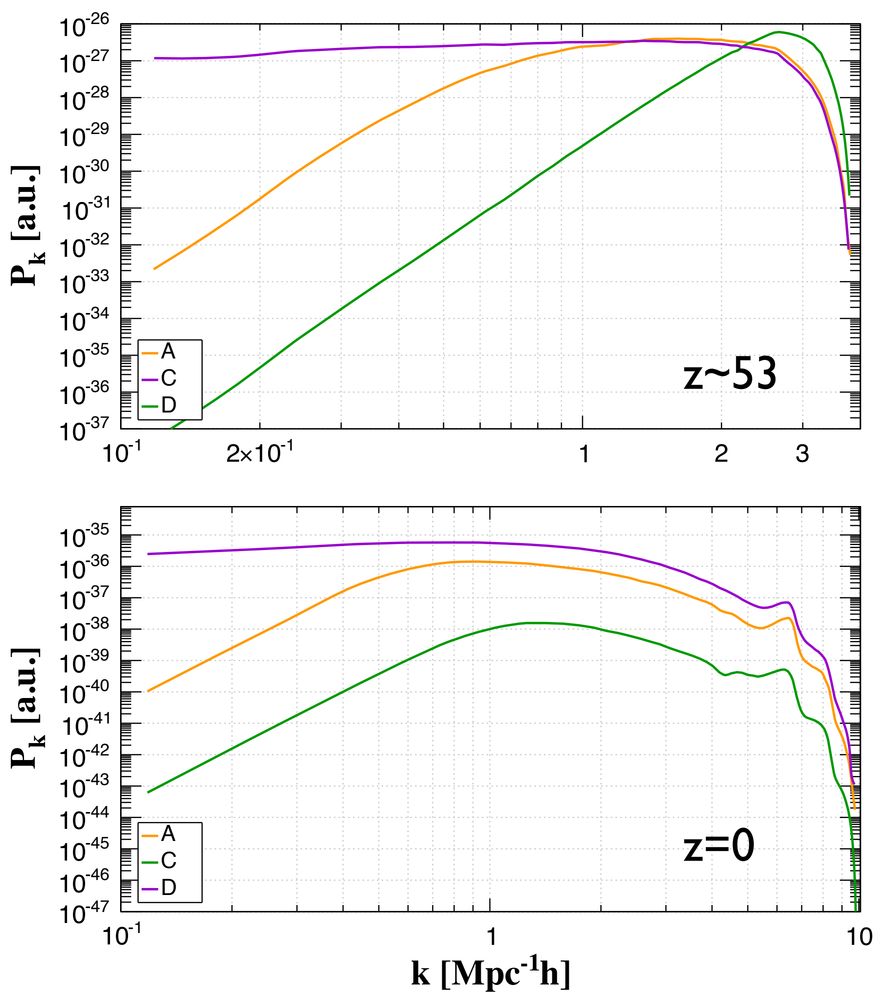
- **model A**: 256^3, fiducial
- **model B**: 256^3, initial B seed 10^5 times stronger
- **model C**: 256^3, power in small and large k range
- **model D**: 256^3, power in small k range
- **model E**: 512^3, fiducial-like

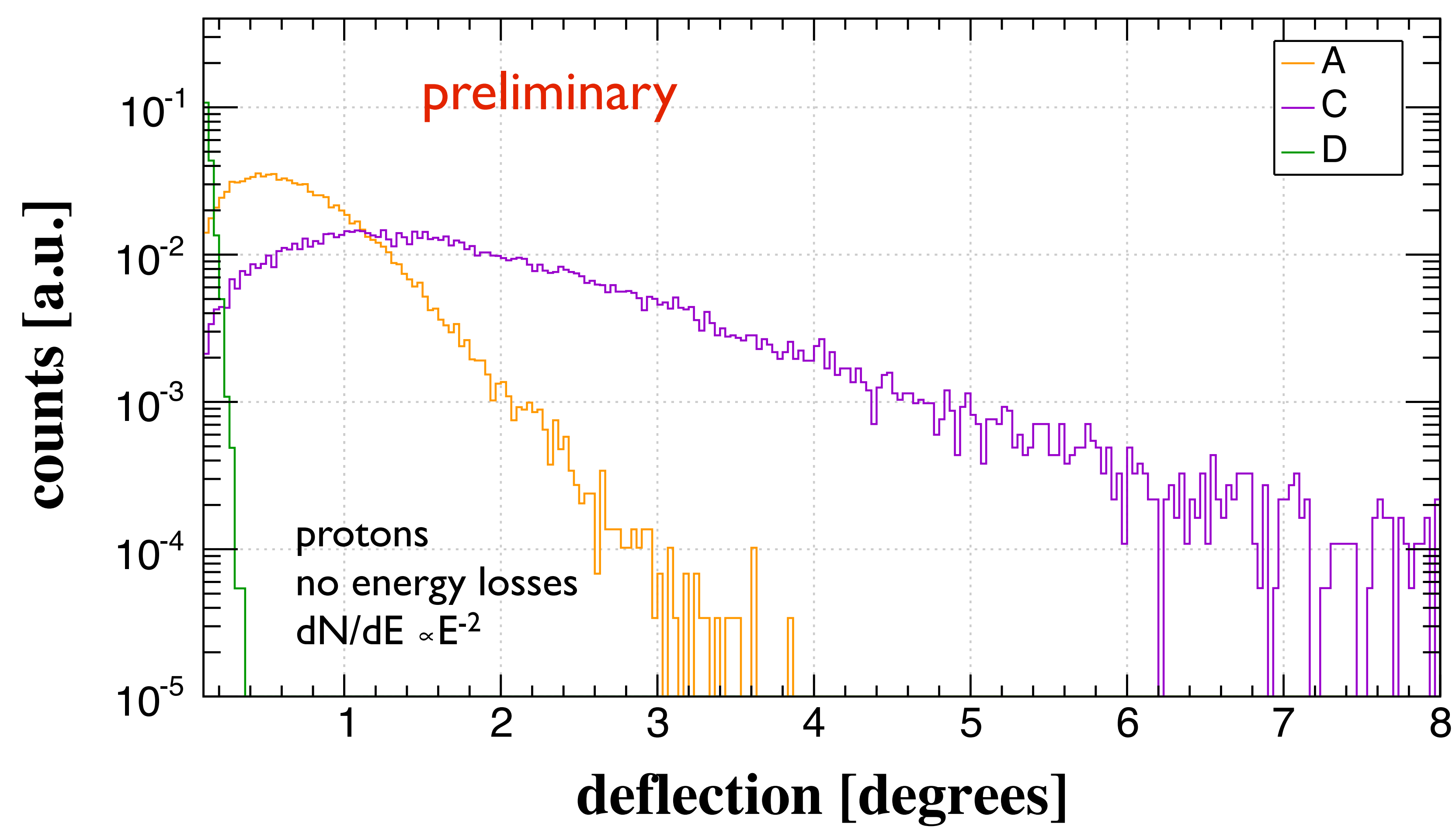
- 200 Mpc/h box
- simulations being done by M.-S. Shin, J. Devriendt
- adaptive mesh refinement (AMR) using the RAMSES code 10 levels of refinement
- comparison of models A and B → can we rescale the magnetic field? YES
- comparison of models A and E → convergence for higher resolution? ROUGHLY
- models C and D → does the initial seed field affect UHECR deflection? A LOT
- how do the results depend on the normalization of the filling factors?

effects of seed fields



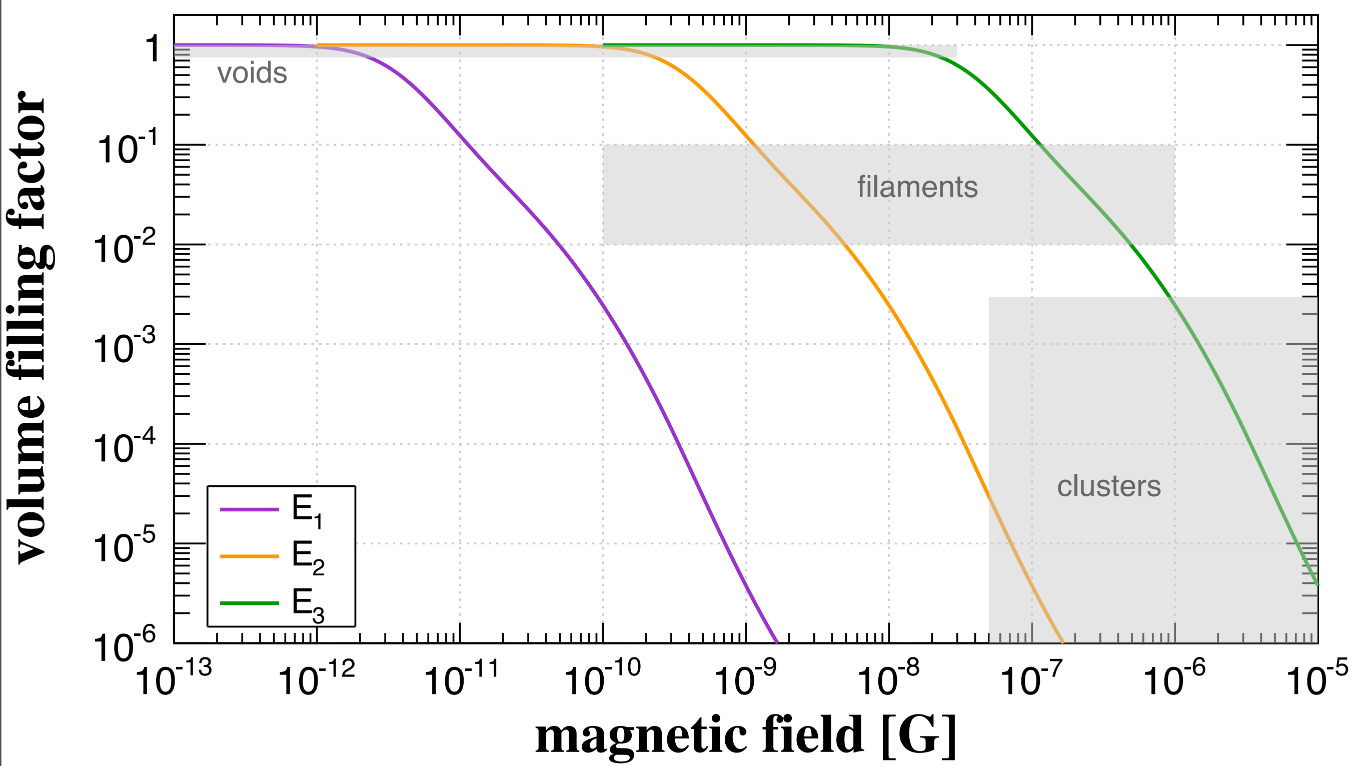
RAB, J. Devriendt, D. Semikoz, M.-S. Shin, G. Sigl. in preparation



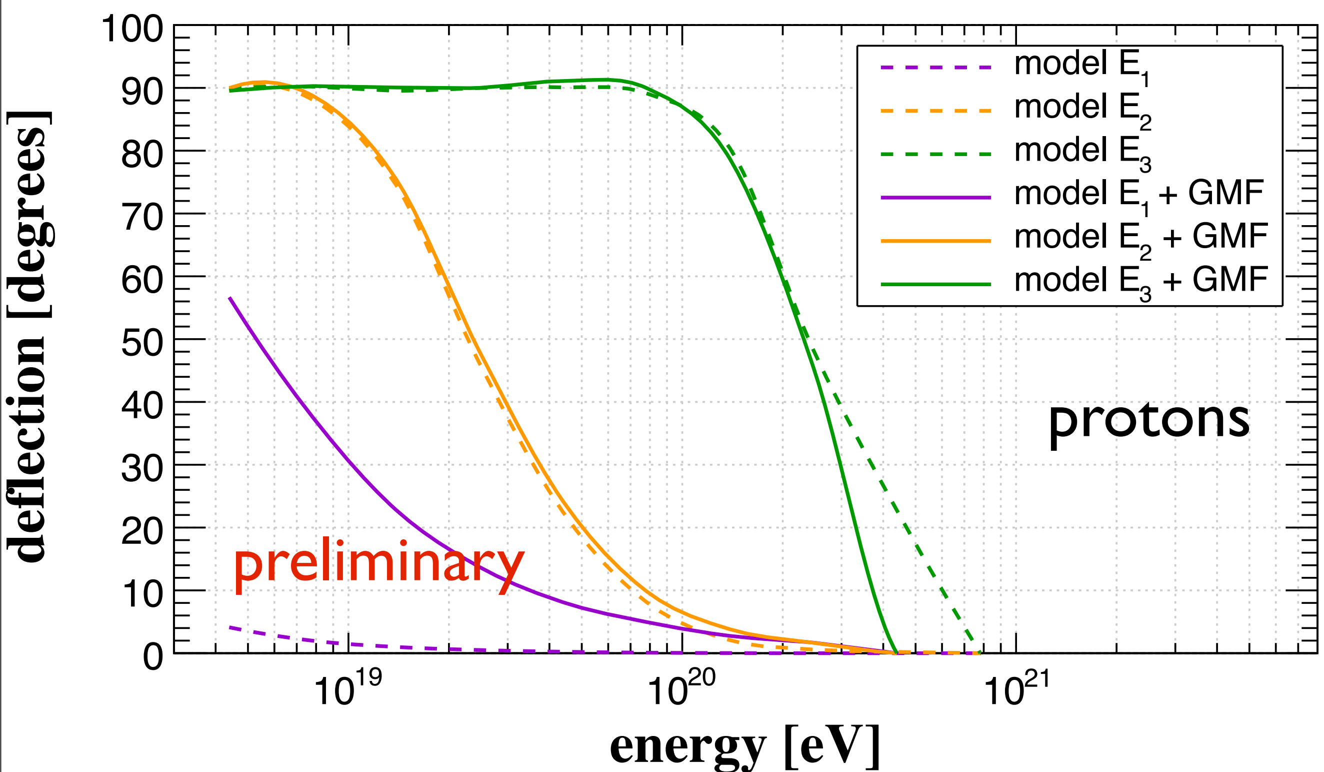


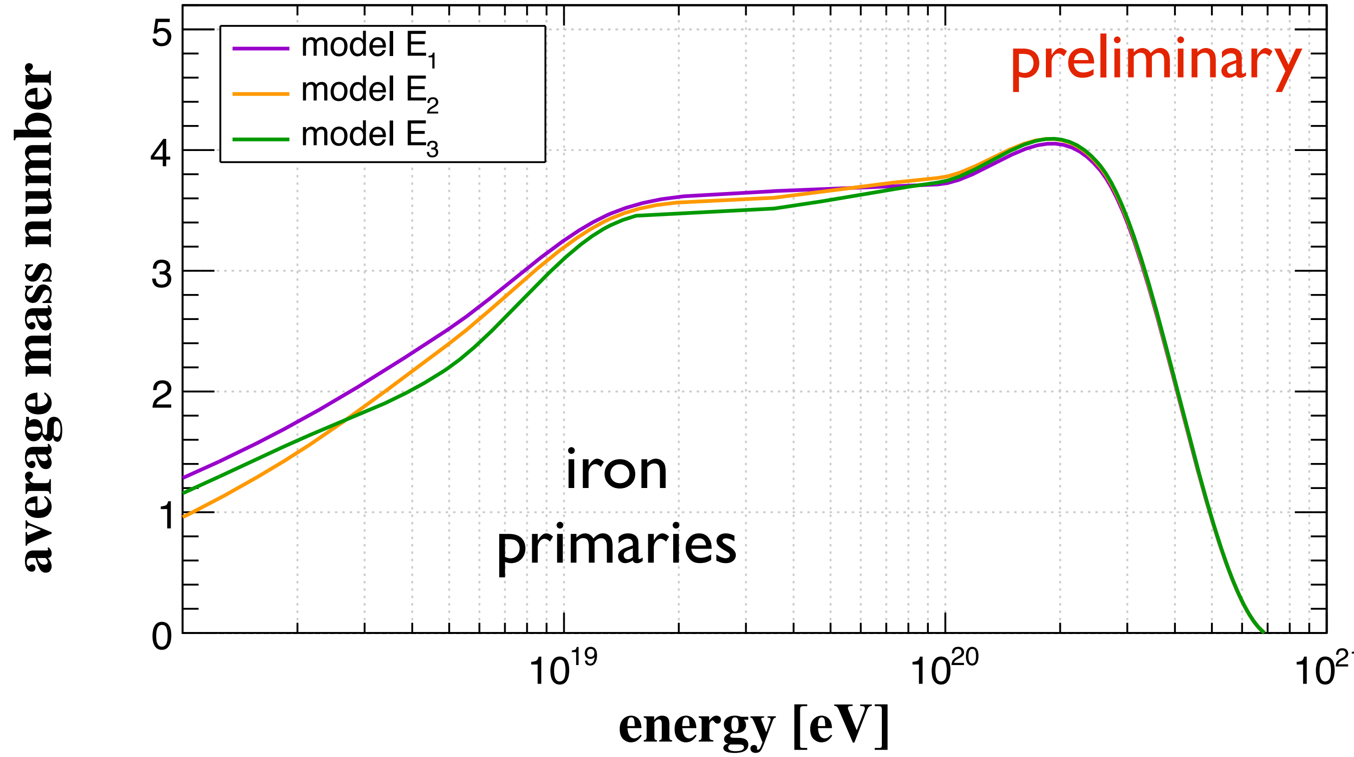
effects of normalization

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



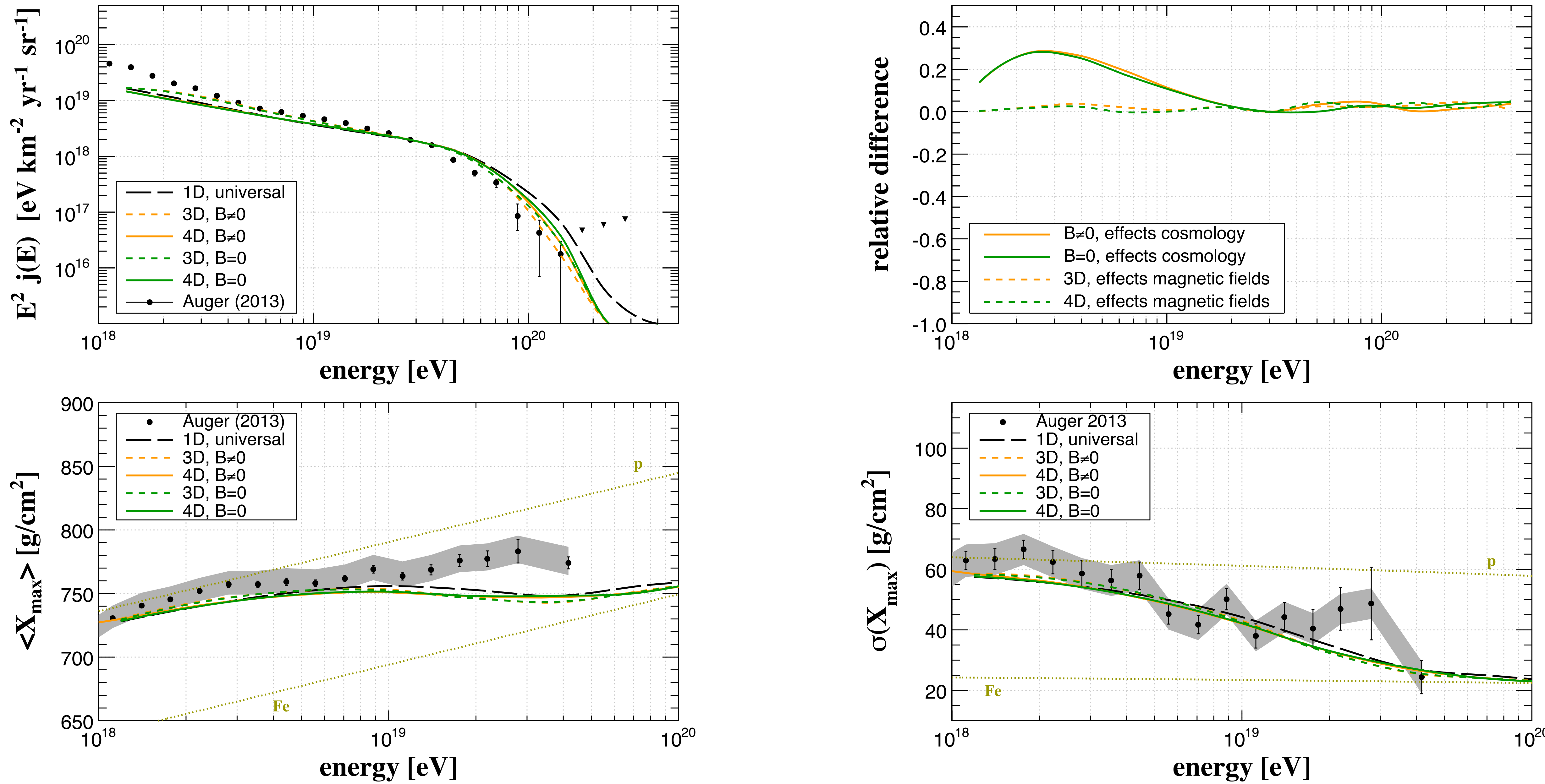
- 3 models derived from model E, with different normalizations were used
- above 10^{19} eV deflections are large, even if the GMF is neglected
- noticeable effects on the composition, specially at lower energies





cosmological effects

RAB, P. Schiffer, G. Sigl. NIM A 742 (2014) 245

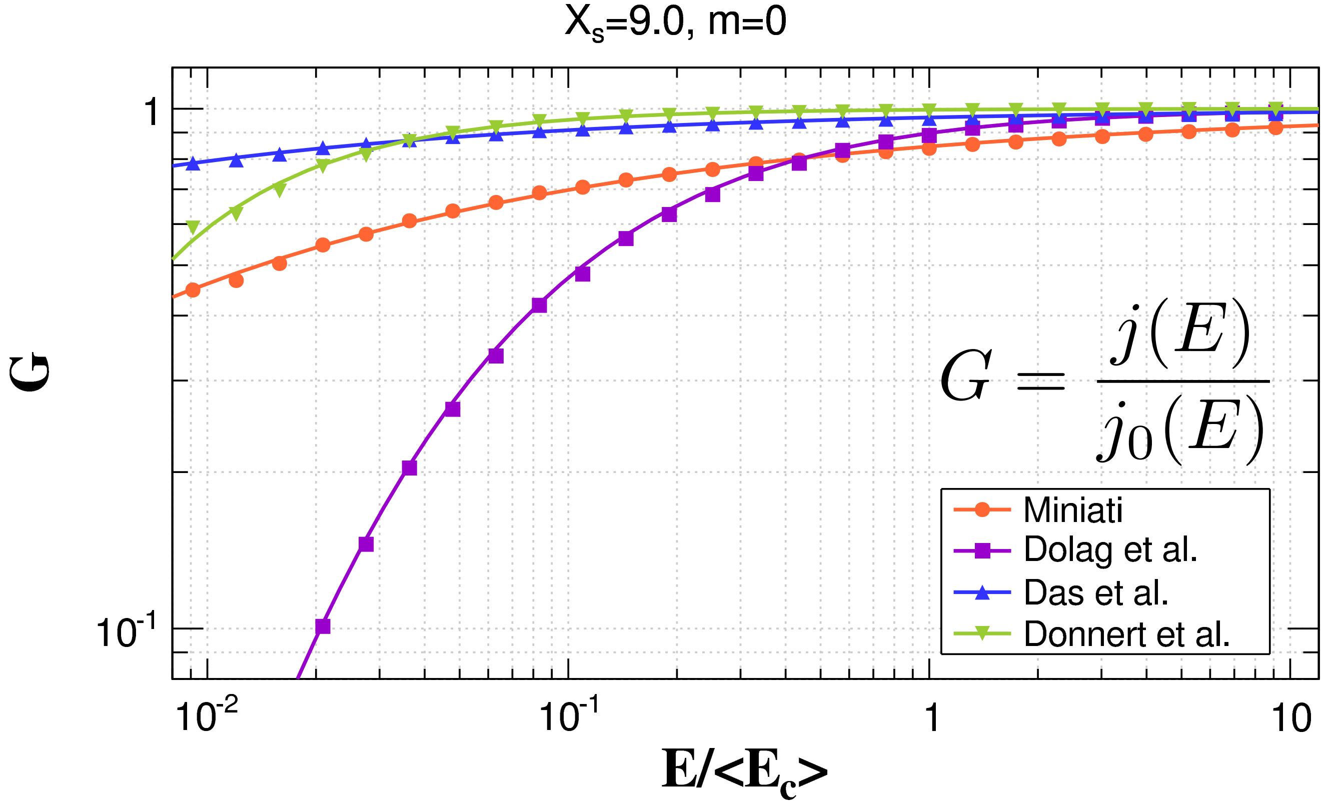


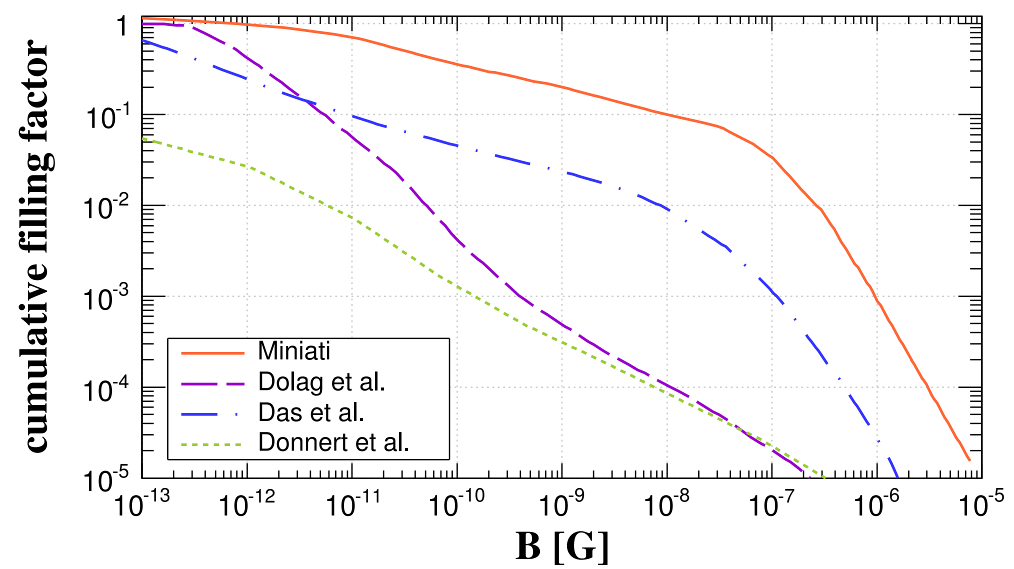
- difficult to account for cosmological effects in 3D → novel method (4D propagation)
- in this particular case cosmological effects are more relevant than magnetic fields
- magnetic field: Dolag+ ’04

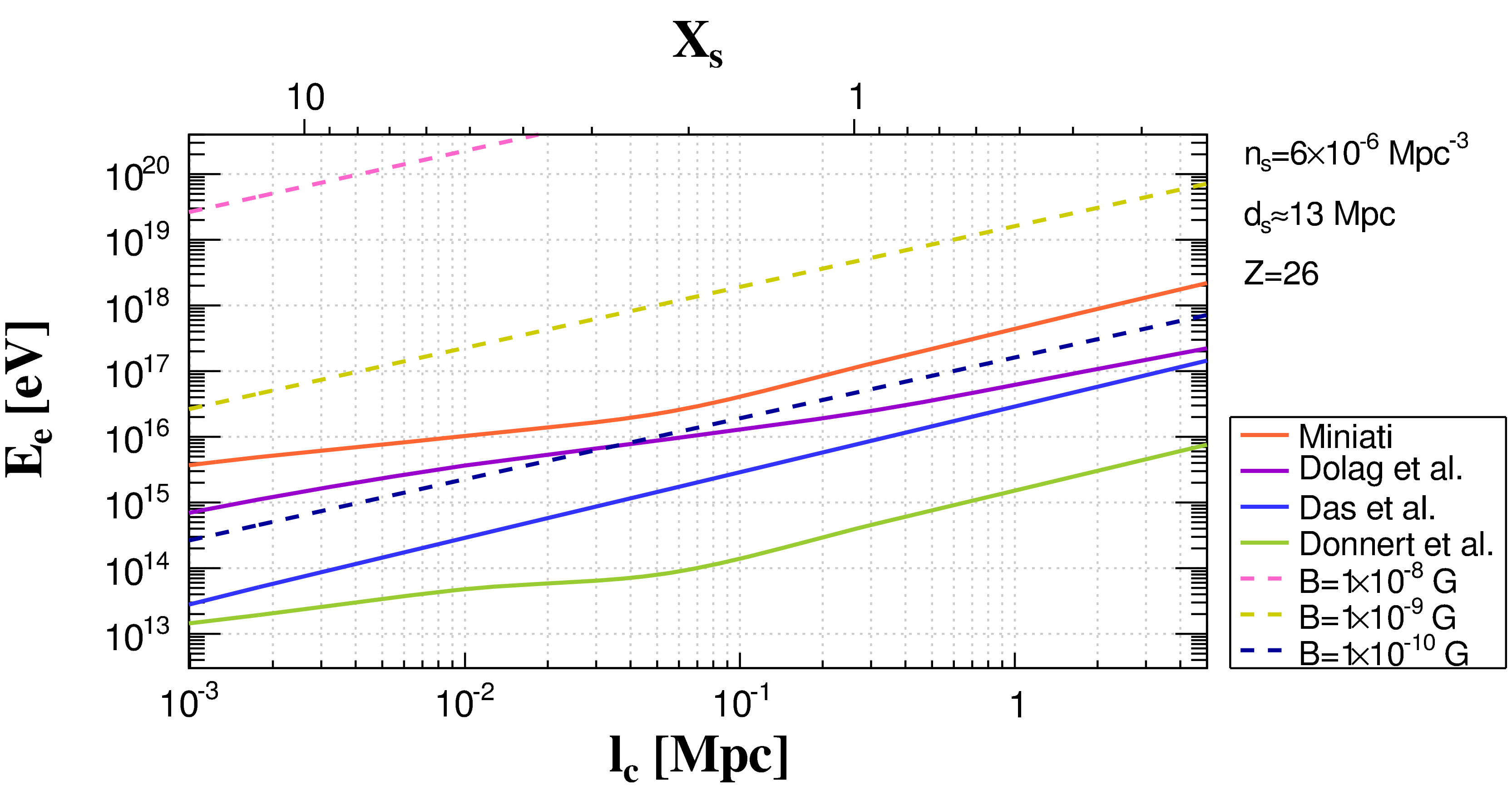
diffusion in extragalactic magnetic fields

RAB & G. Sigl. JCAP 1411 (2014) 031

RAB & G. Sigl. arXiv:1410.7800





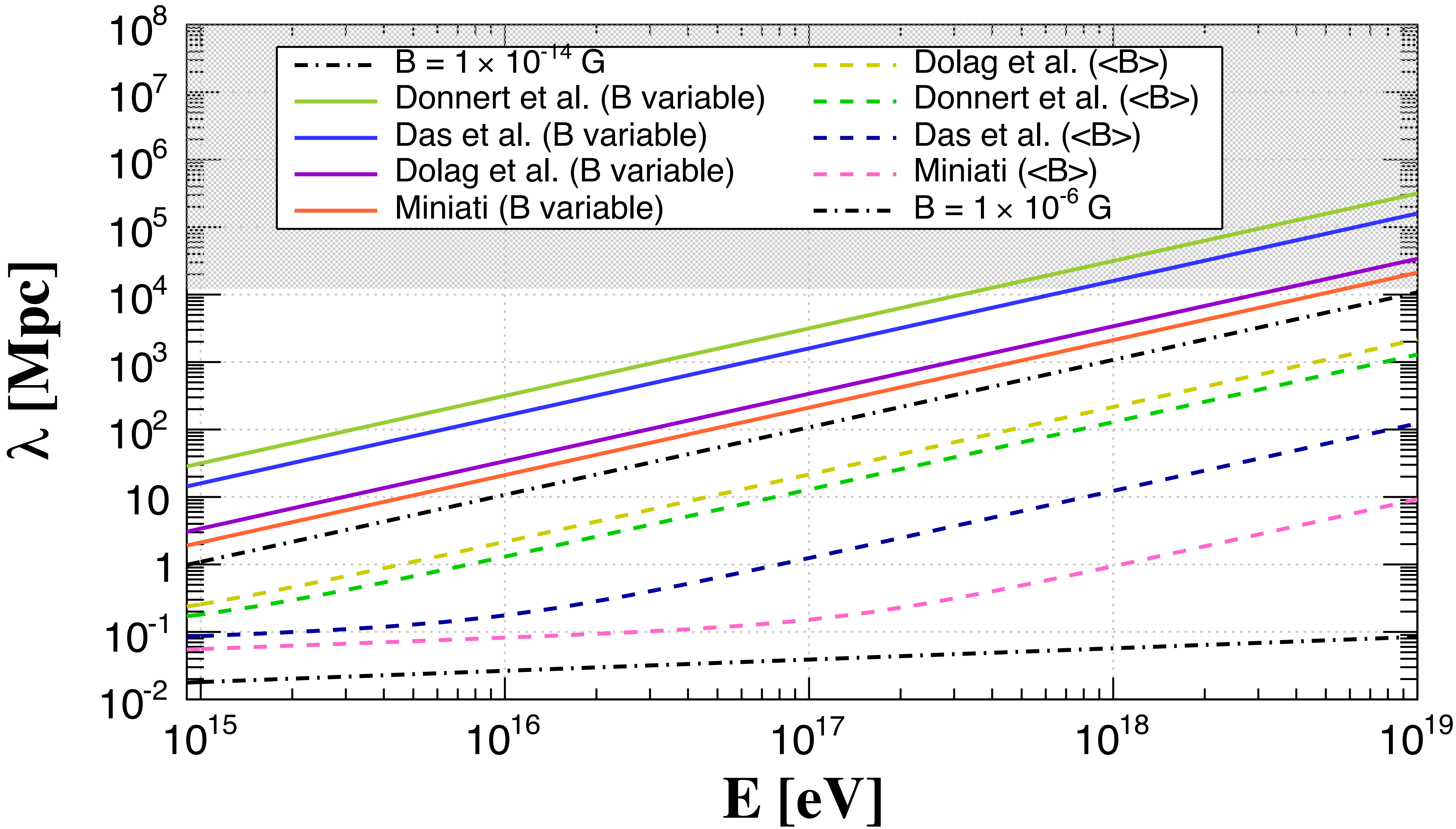


- magnetic horizons were postulated by Mollerach & Roulet '13 to explain the "hard spectra" problem (combined spectrum-composition fits favoring sources with hard spectral indexes below ~ 1.5)
- problem with this: simple turbulent field was assumed
- suppression is small at E ~ 1 EeV in "realistic" EGMF models

diffusion in extragalactic magnetic fields

RAB & G. Sigl. JCAP 1411 (2014) 031

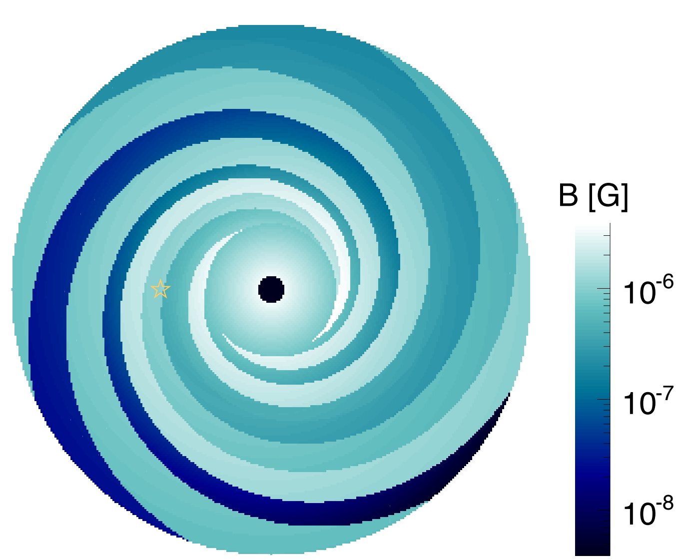
RAB & G. Sigl. arXiv:1410.7800



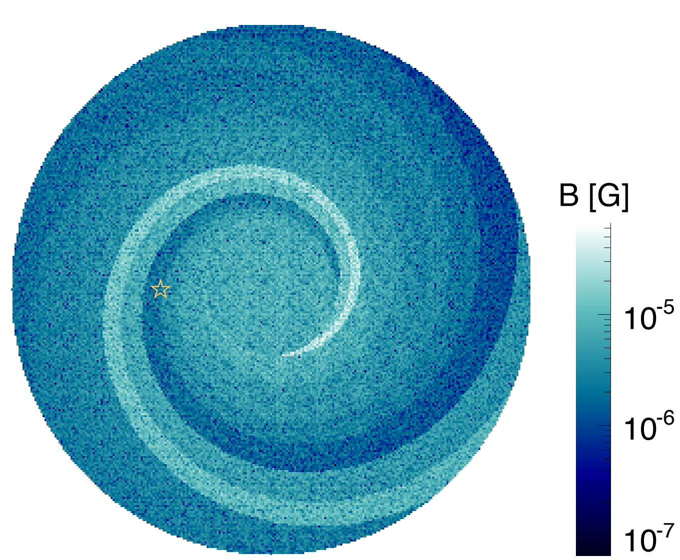
UHECRs and the galactic magnetic field

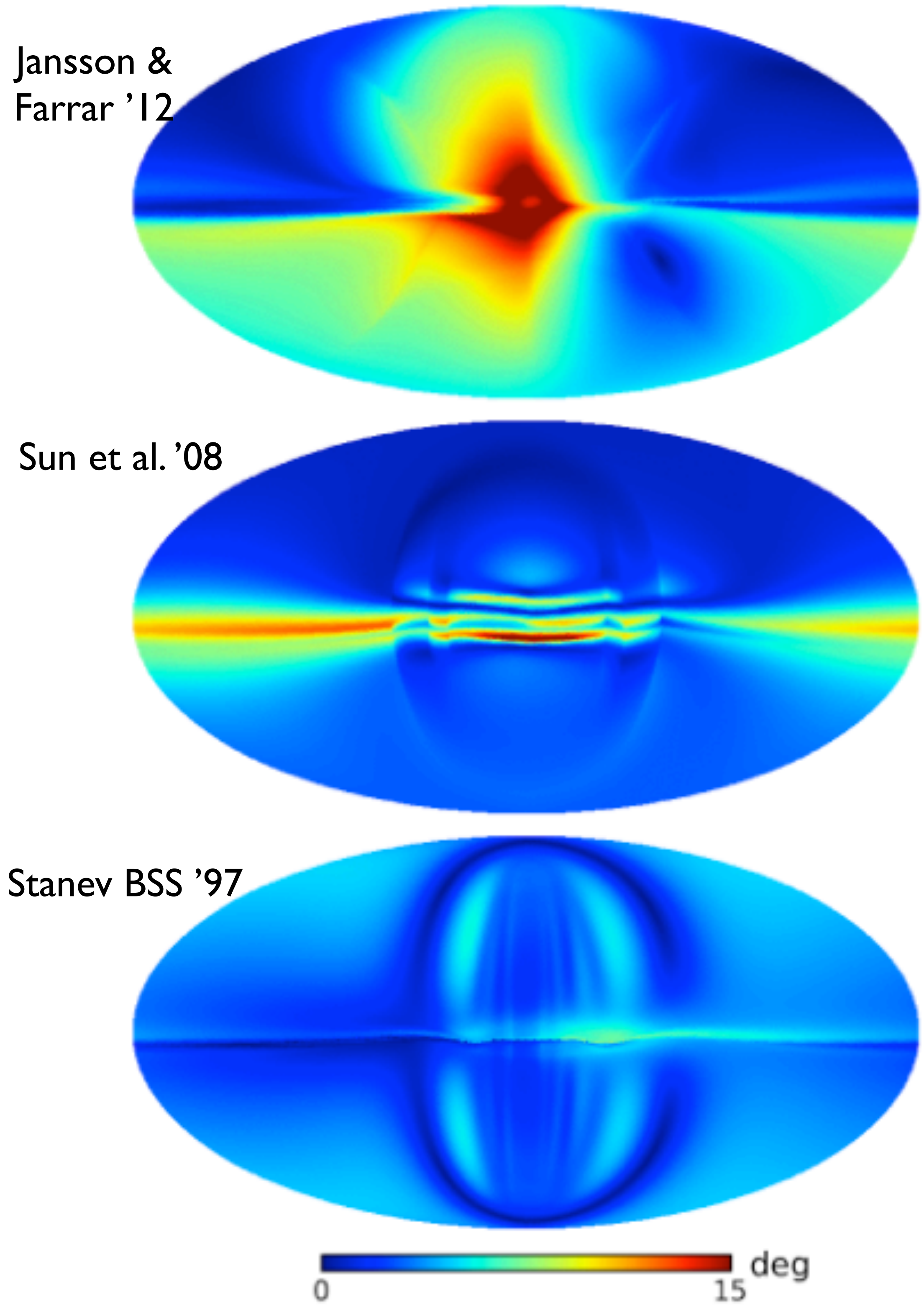
- different models of GMF predict very different distributions of fields
- most recent model: Jansson & Farrar '12
- the GMF strongly affects the propagation of UHECRs (see plot)
- pictures show 60 EeV protons backtracked from Earth to the edge of the galaxy (initially isotropically distributed)
- negligible energy losses → easier treatment :-)

Jansson & Farrar model - regular component



Jansson & Farrar model - total field

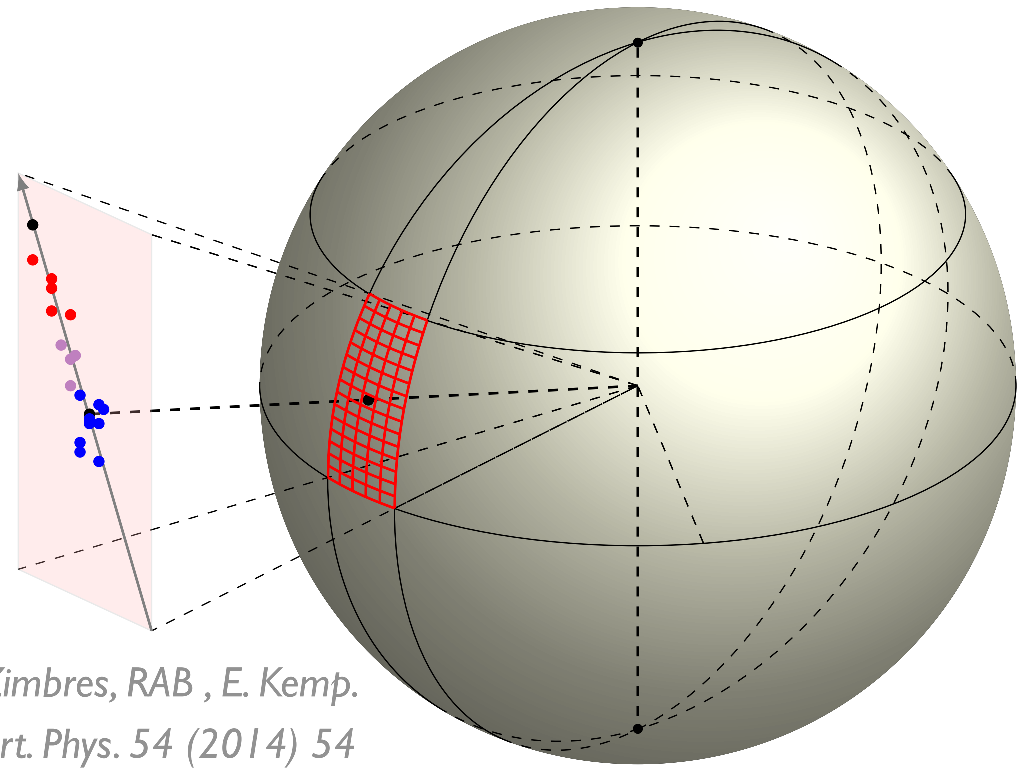




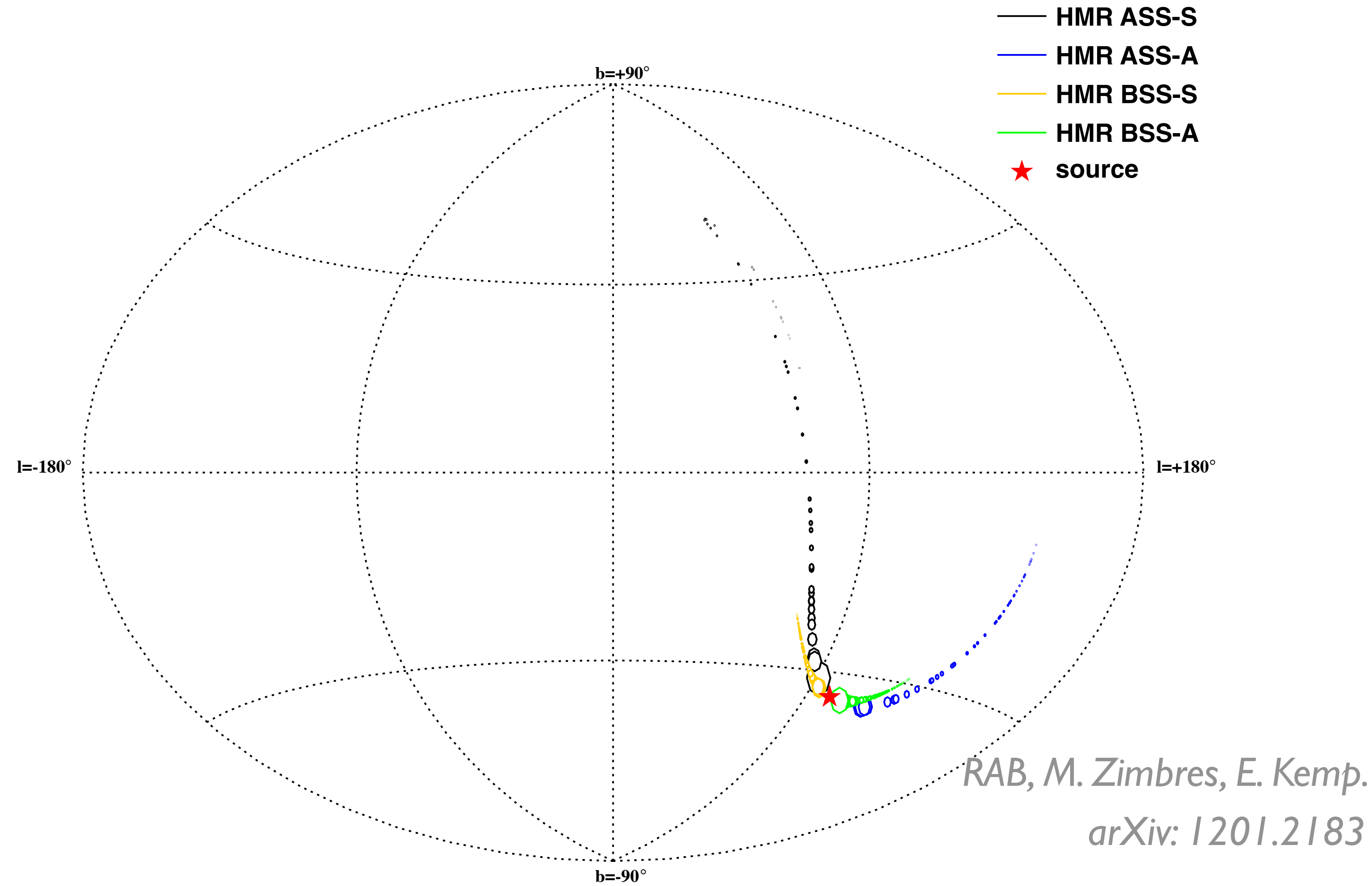
R. Jansson & G. Farrar. ApJ 757 (2012) 14

R. Jansson & G. Farrar. ApJL 761 (2012) L11

UHECRs and the galactic magnetic field

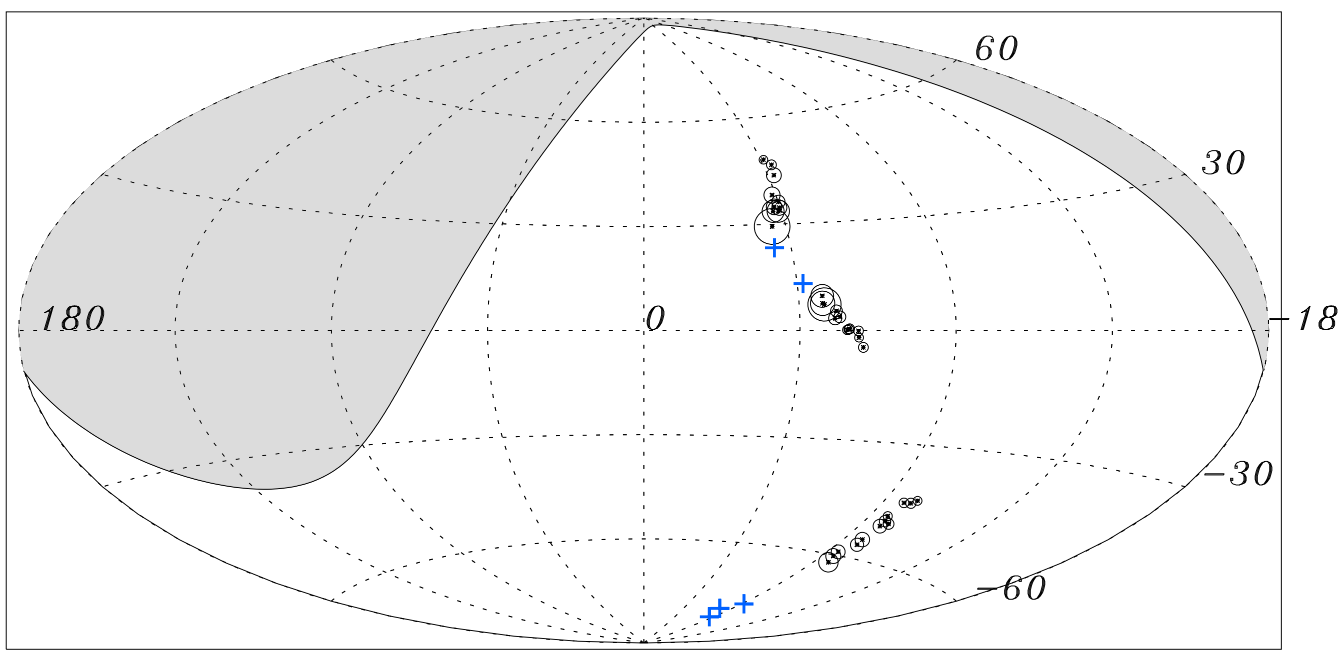


M. Zimbres, RAB , E. Kemp. Astropart. Phys. 54 (2014) 54



RAB, M. Zimbres, E. Kemp. arXiv: 1201.2183

- events from a single source → energy ordered structures
- analysis of the orientation of multiplets → constrain GMF models
- observation of multiplets → reconstruction of source position
- problem: strength of EGMF



Pierre Auger Collaboration. Astropart. Phys. 35 (2012) 354

summary and outlook

- difficult to create models to simultaneously explain main observables (spectrum, composition and anisotropies) → fast simulations including all relevant physical processes → CRPropa
- magnetic horizon effect is globally irrelevant at EeV energies for the studied models → what happens in the new MHD simulations?
- cosmological effects have to be taken into account for studies in the energy range below ~ 1 EeV
- poor knowledge of cosmic magnetic fields is a limiting factor for identifying UHECR sources
- high resolution MHD simulations of the cosmic web → UHECR astronomy might not be possible with current facilities such as Auger (maybe never!?)
- imprint of primordial magnetic fields on the arrival directions of UHECRs → is it possible to constrain these fields using UHECRs?
- uncertainties on normalization of magnetic field → uncertainty in UHECR propagation

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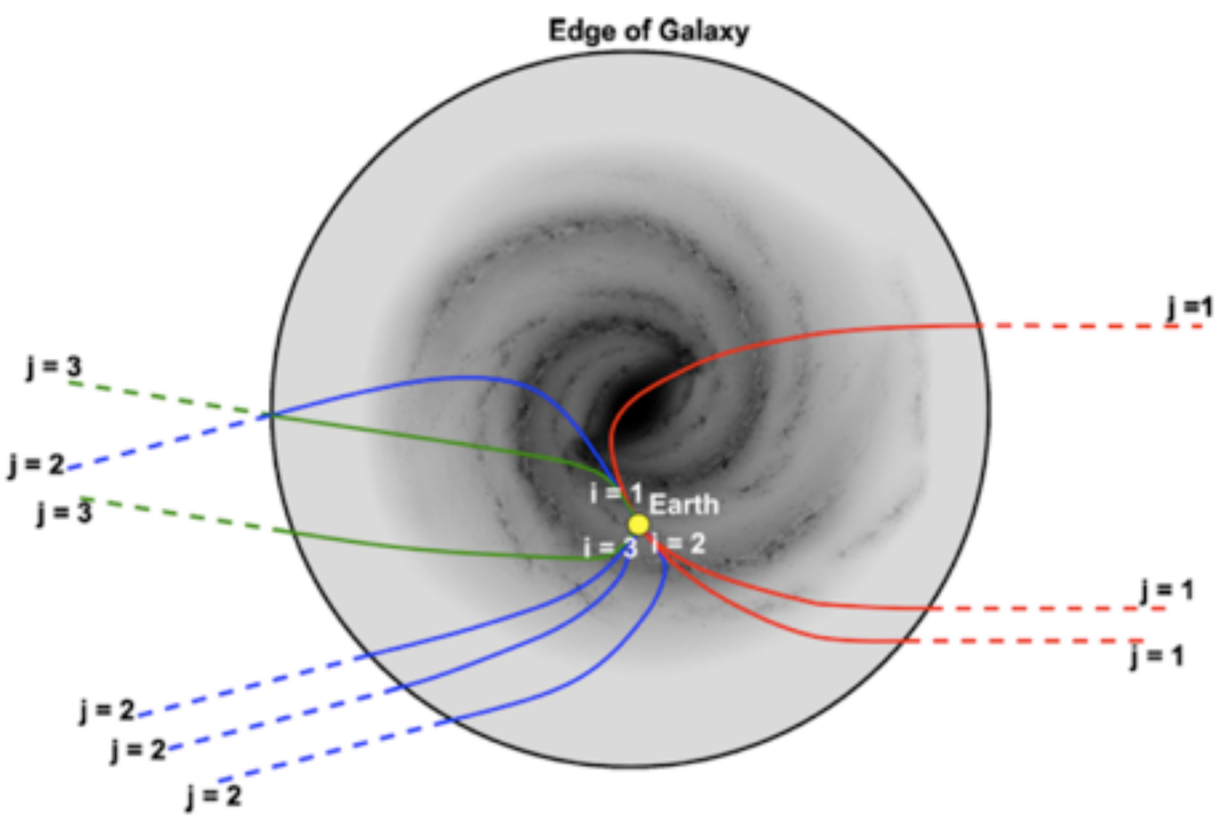
Thank you!

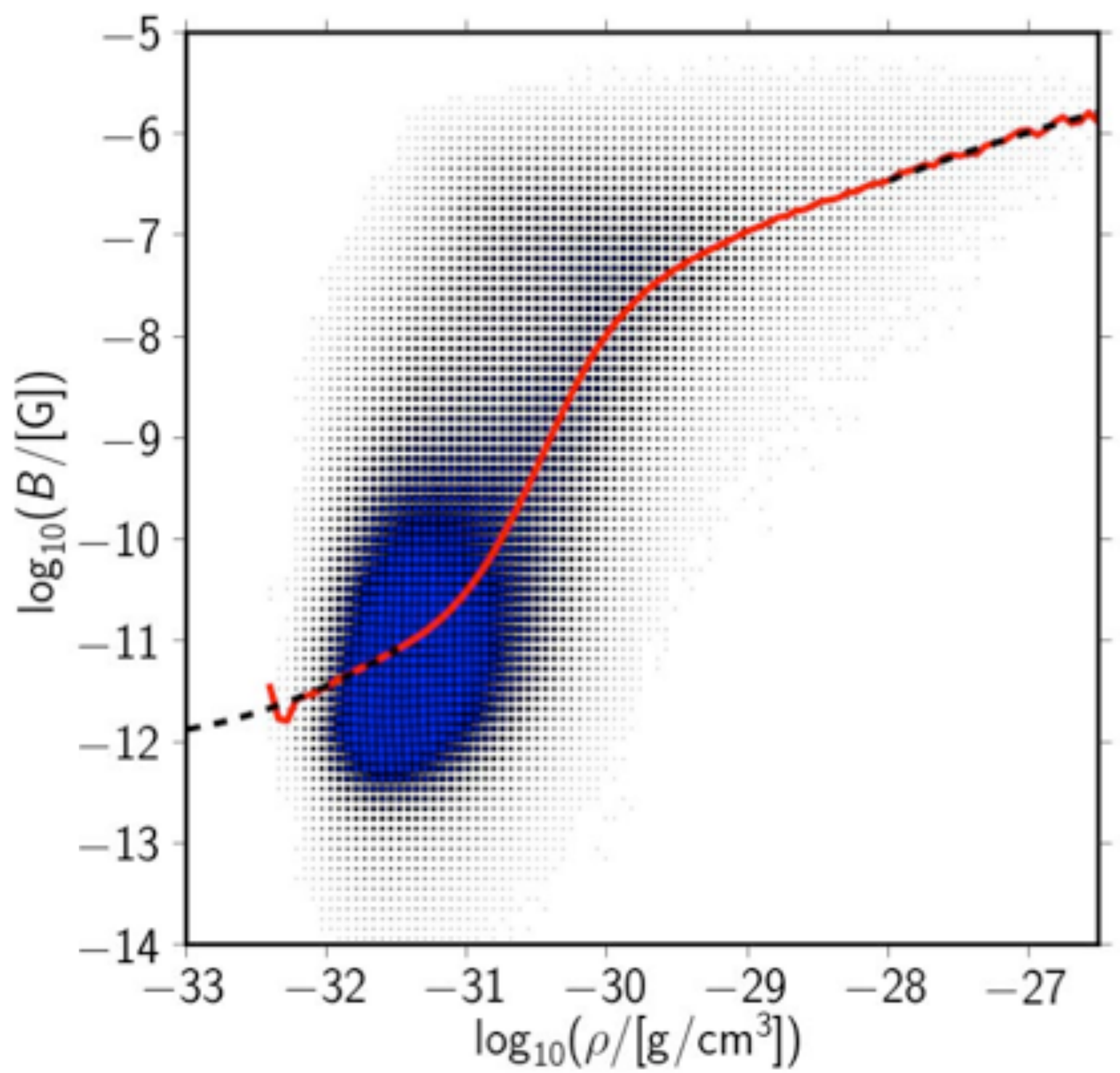
galactic lensing

- assumes no energy losses
- each "lens" corresponds to a different energy bin
- lenses generated by backtracking protons to the galactic border
- nuclei have deflection of Z times the deflection for protons
- technique based on the PARSEC code *[Bretz '14]*
- these lenses are applied to simulated data a posteriori



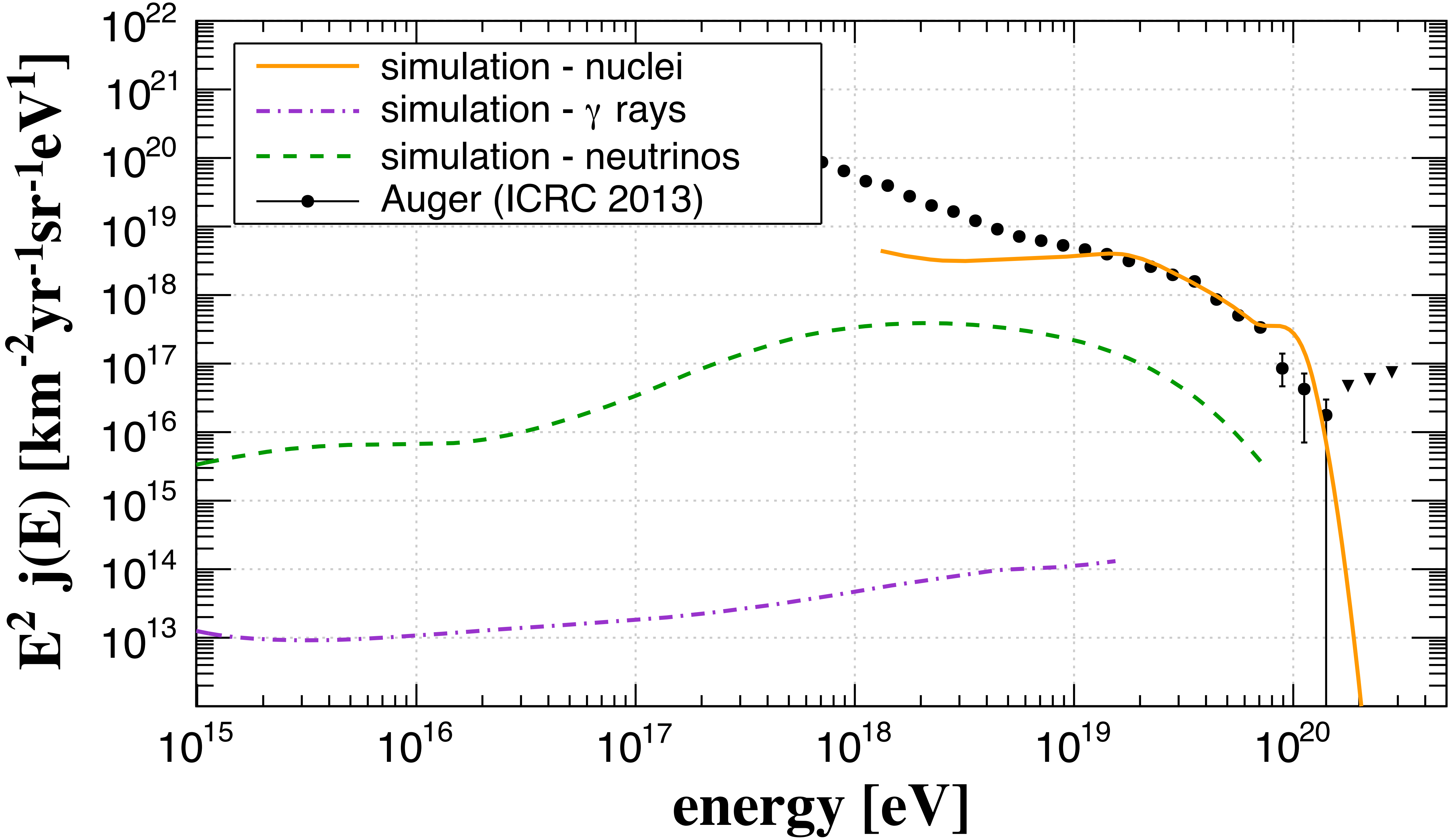
the “benchmark” scenario

- sources randomly distributed according to LSS (down to 3 Mpc)
- “galactic composition” *[DuVernois+ ’96]*
- source density: 10^{-4} Mpc^{-3}
- field strength obtained from B-ρ profile from the Miniati simulation *[Miniati ’02]*
- simulation volume: $(132\ Mpc)^3$ with a spacing of ~300 kpc from Dolag simulation *[Dolag+ ’02]*
- turbulent subgrid with 256^3 cells covering a volume of $(13.2\ Mpc)^3$ periodically repeated to cover the simulation volume



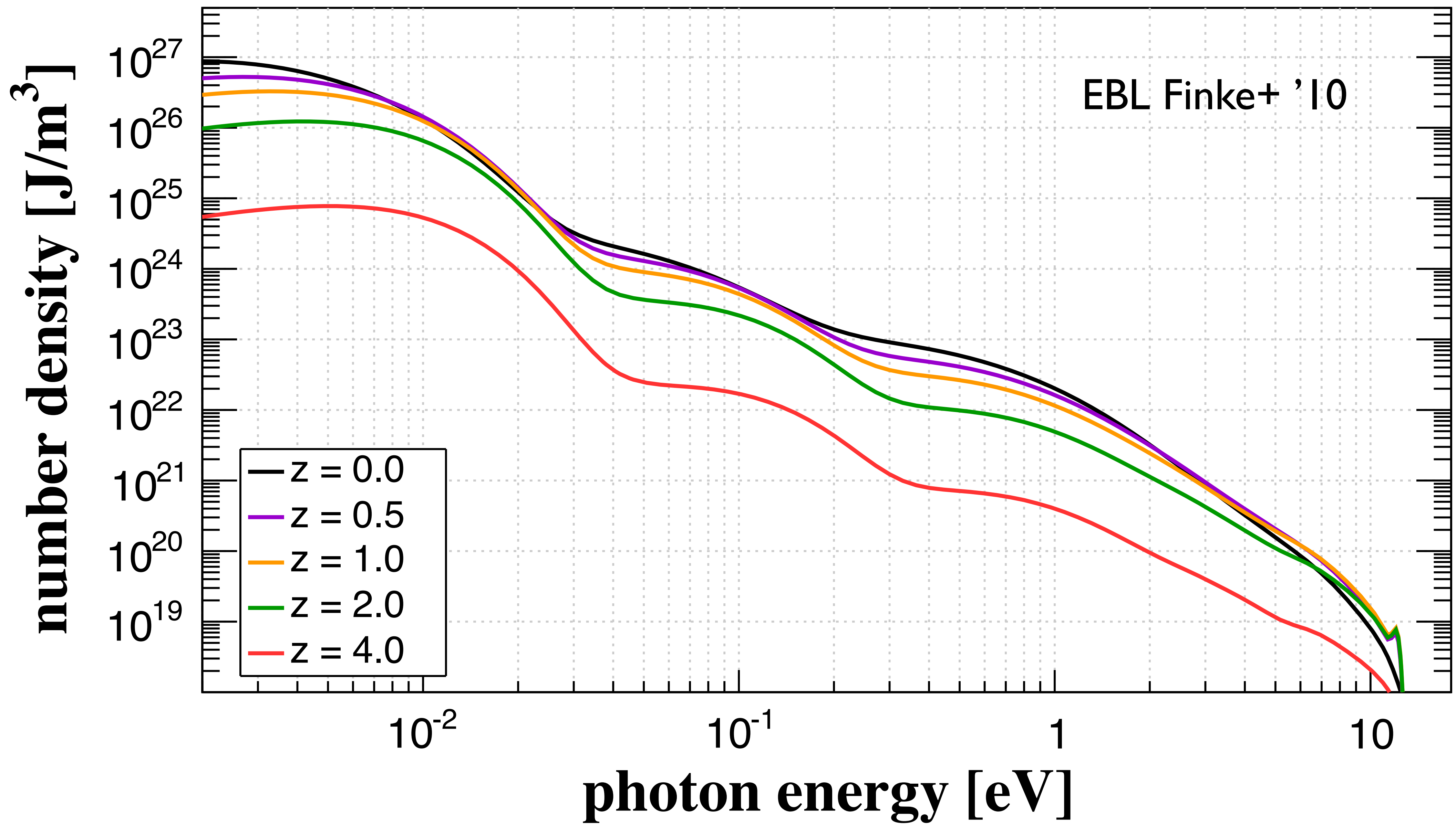
CRPropa: example 1D + secondaries

RAB et al. arXiv:1411.2259



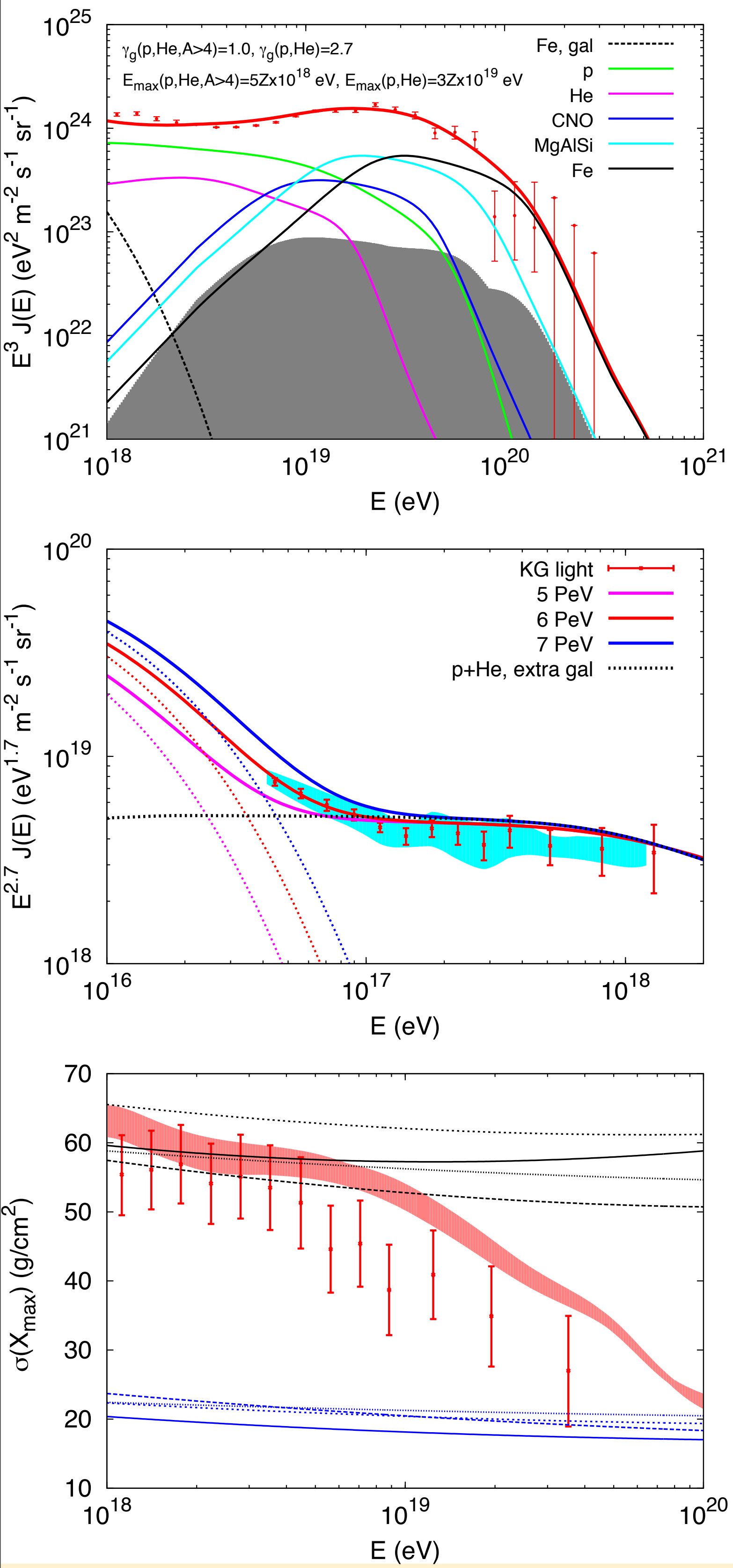
EBL Kneiske '04, injected iron, uniform sources, E^{-2}

redshift dependence CIB



spectrum-composition fits

Aloisio+ '14



- combined spectrum-composition (1D) fits of the Auger spectrum/composition *[Aloisio+ '14, Taylor '14]*
- 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 '14]*: 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

diffusion in extragalactic magnetic fields

diffusive spectrum

$$j_t(E,B) = \sum_{i=1}^{N_s} j_s(E) = \frac{c}{4\pi} \int_0^{z_{max}} dz \left|\frac{dt}{dz}\right| Q(E_g(E,z),z) \frac{dE_g}{dE} \sum_{i=1}^{N_s} \frac{\exp\left(-\frac{r_i^2}{4\lambda^2}\right)}{(4\pi\lambda^2)^{\frac{3}{2}}}$$

- $\left|\frac{dt}{dz}\right|$: redshift evolution
- $Q(E_g(E,z),z)$: source term
- $\frac{dE_g}{dE}$: energy losses
- $\sum_{i=1}^{N_s} \frac{\exp\left(-\frac{r_i^2}{4\lambda^2}\right)}{(4\pi\lambda^2)^{\frac{3}{2}}}$: F factor: magnetic field and source distributions

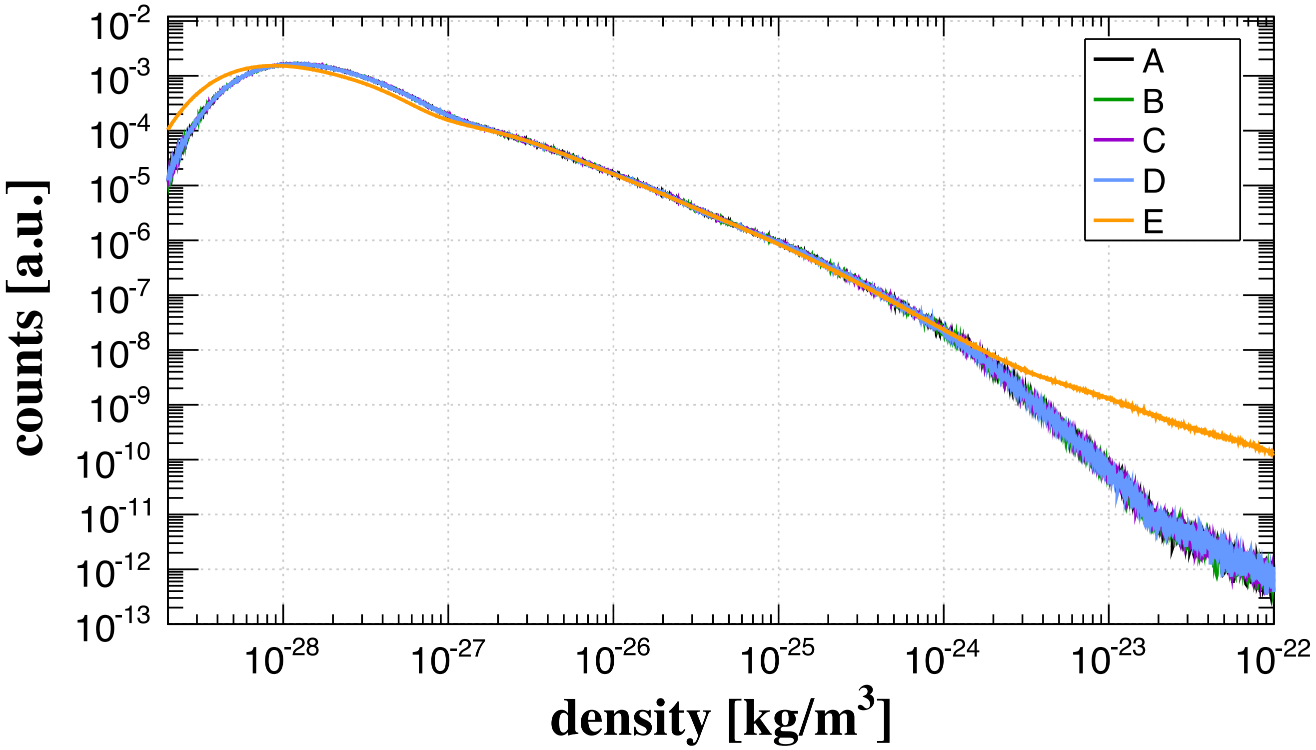
Syrovatskii variable

$$\lambda(E,z,B) = \sqrt{\int_0^{z} dz' \left|\frac{dt}{dz'}\right| \frac{D(E_g,z',B)}{a^2(z')}}$$

diffusion coefficient

$$D(E,z,B) = \frac{cl_c}{3}\left[a_L\left(\frac{E}{E_c}\right)^{\frac{1}{3}} + a_H\left(\frac{E}{E_c}\right)^2\right]$$

- turbulent magnetic field
- coherence length = l_c
- critical energy (Ec): $R_L = l_c$
- uniform source distribution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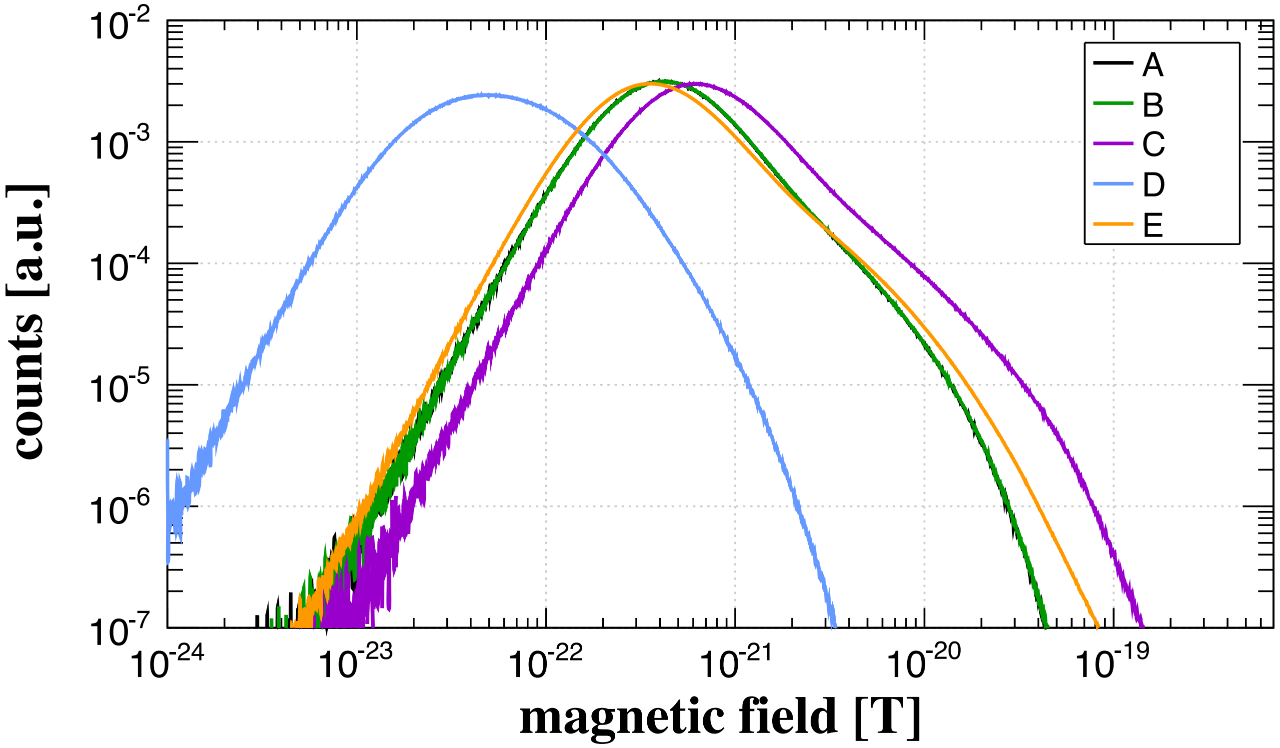
density [kg/m3]
A
B
C
D
E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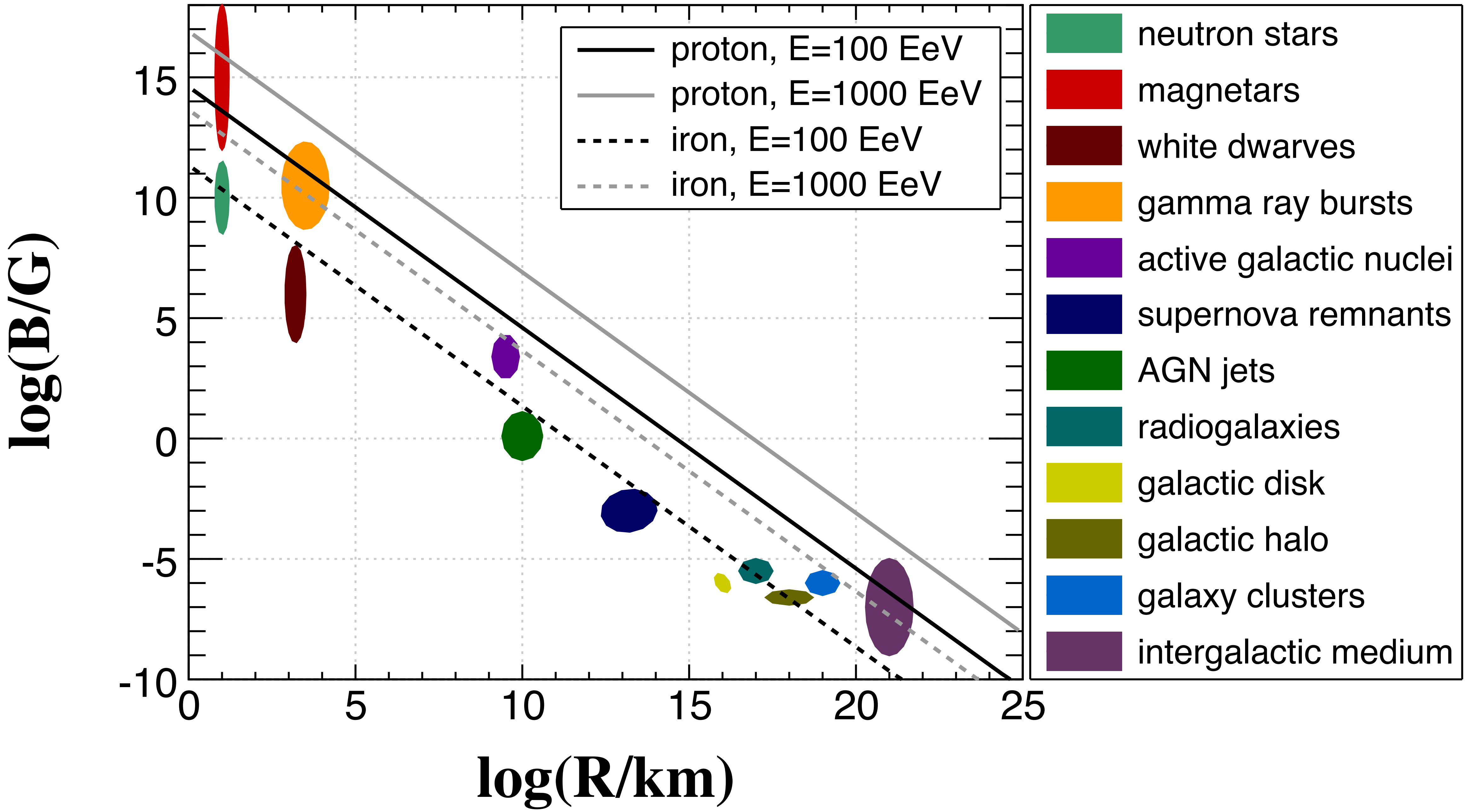
magnetic field [T]
A
B
C
D
E

UHECRs: possible sources



Oxford MHD simulations: convergence and scaling