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Propagation of UHECRs through the Large Scale Structure of the Universe

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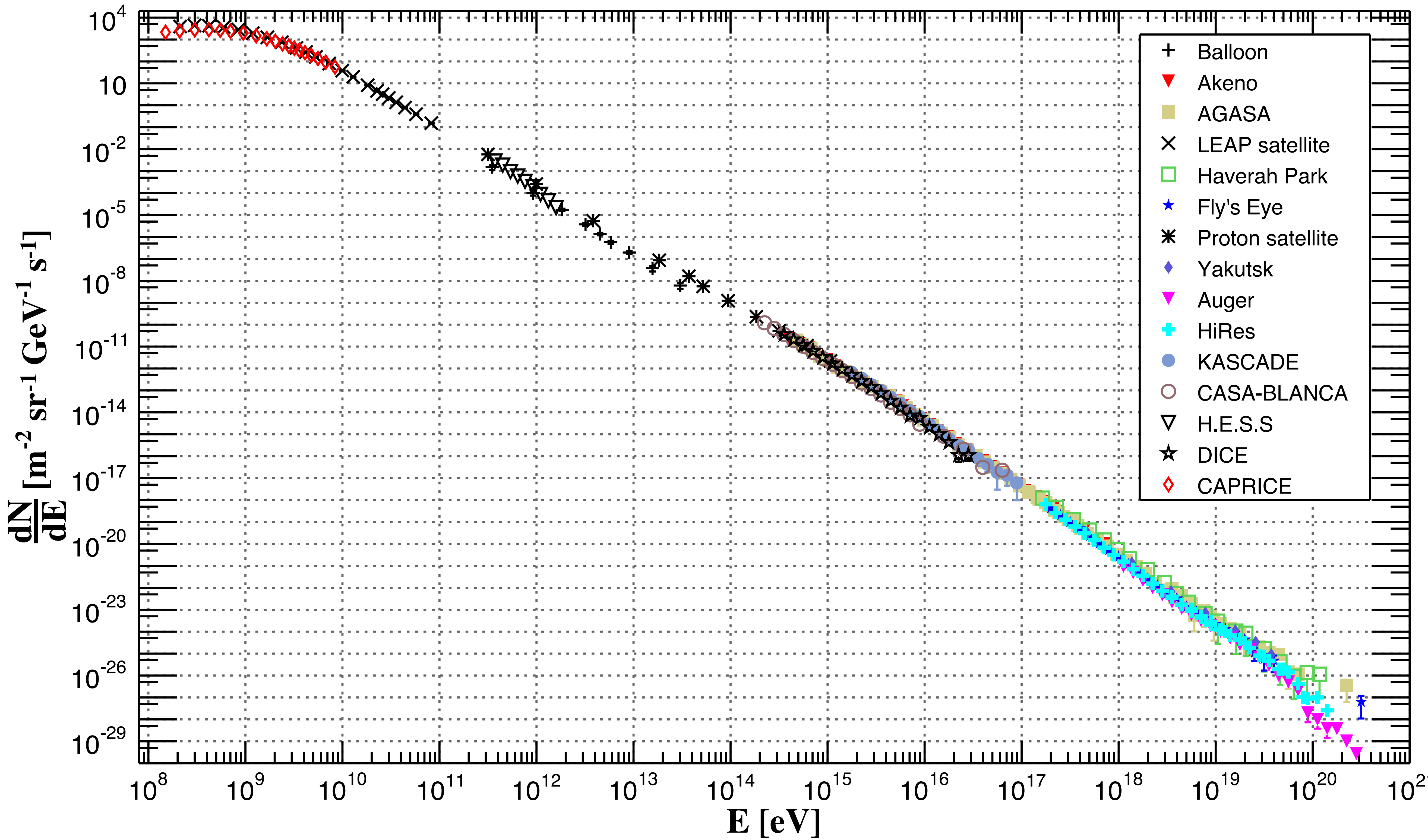
the cosmic ray spectrum



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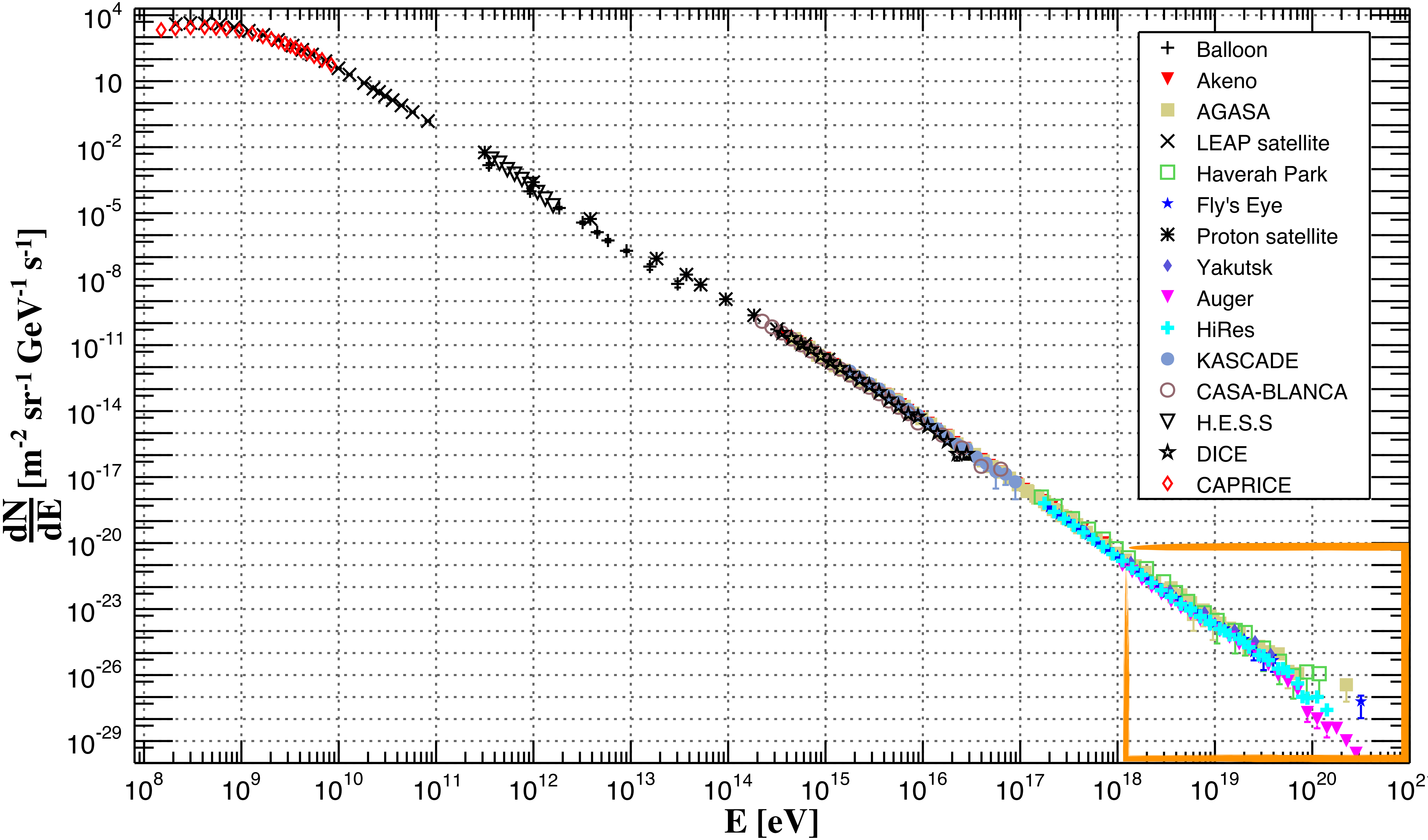
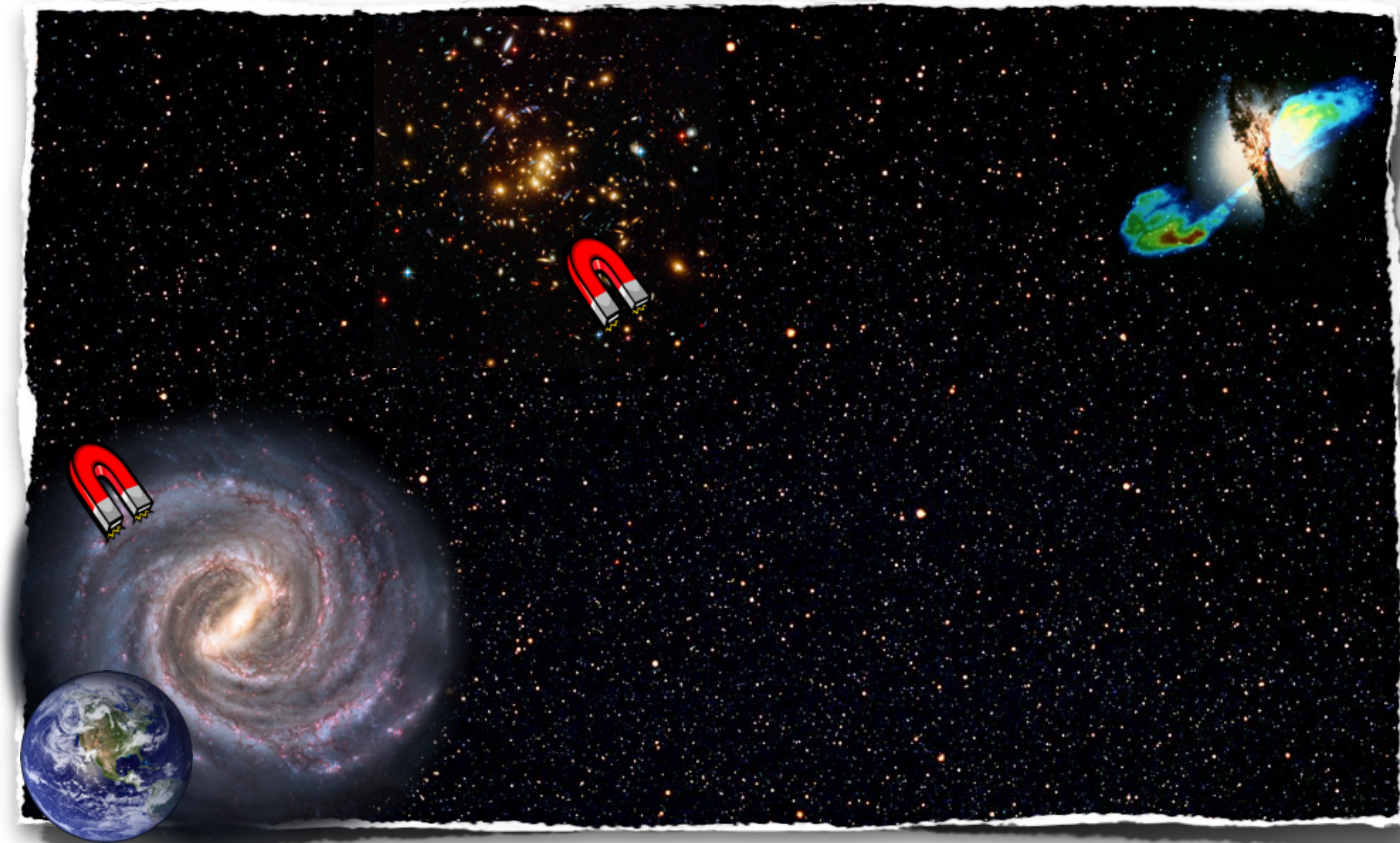
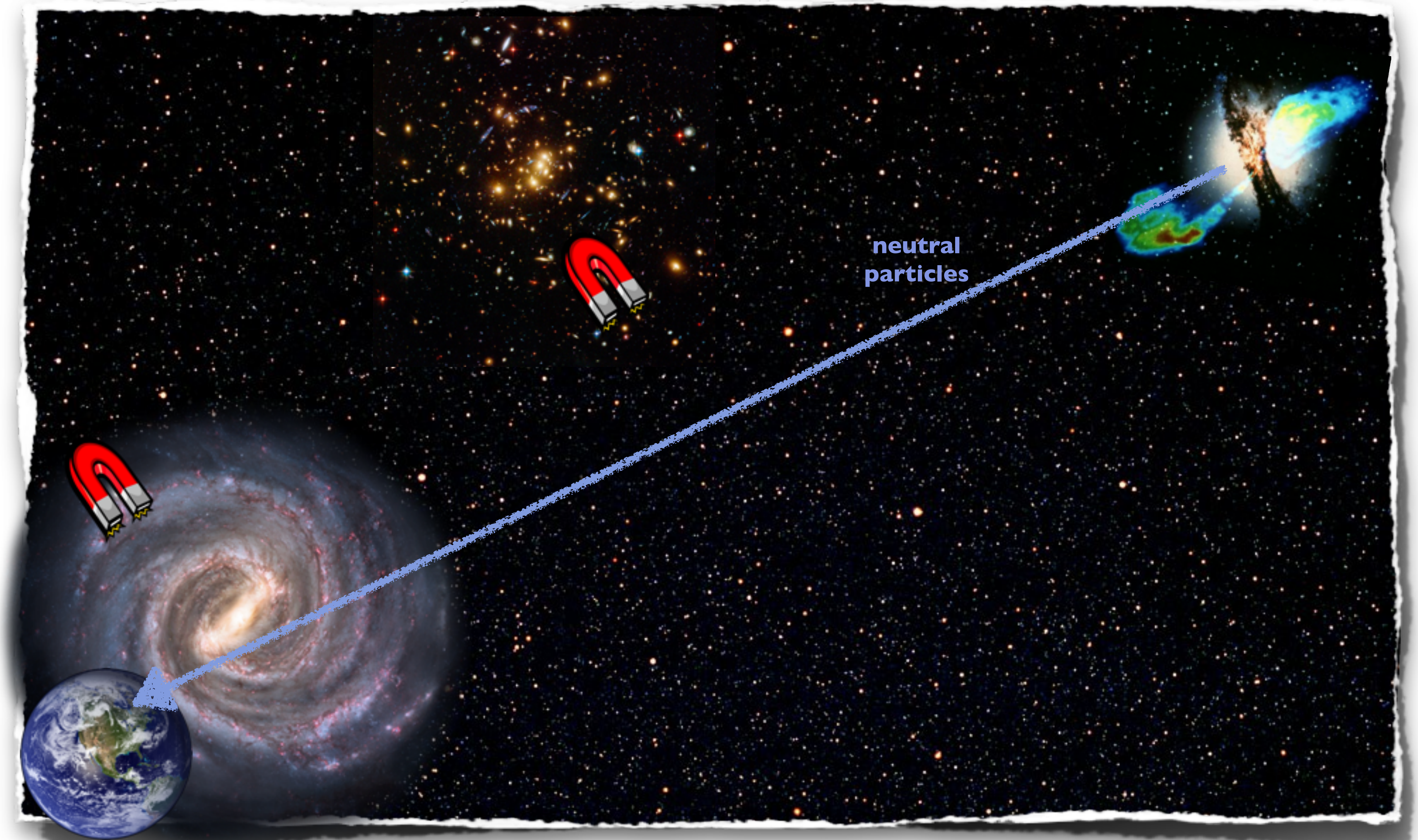


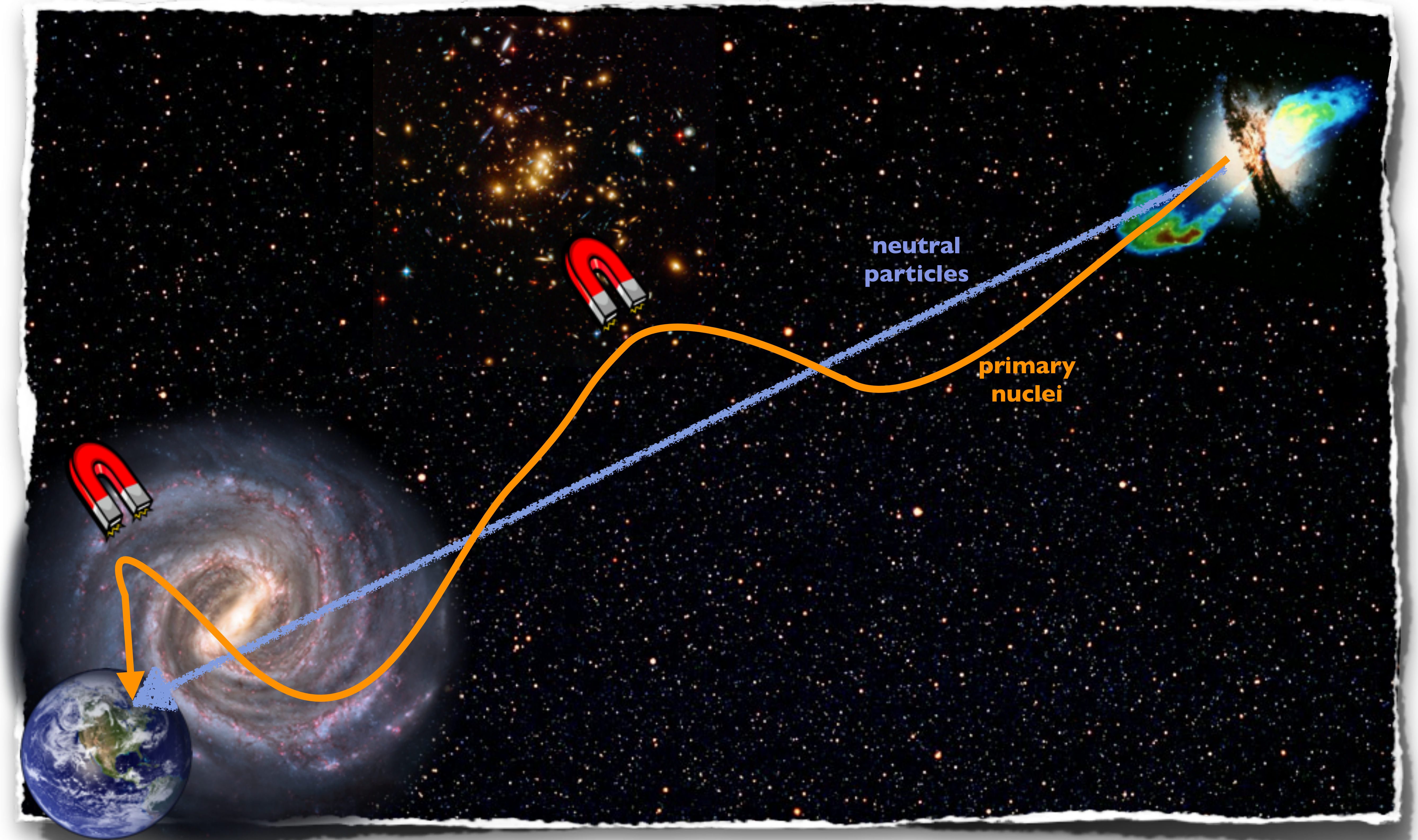
general picture



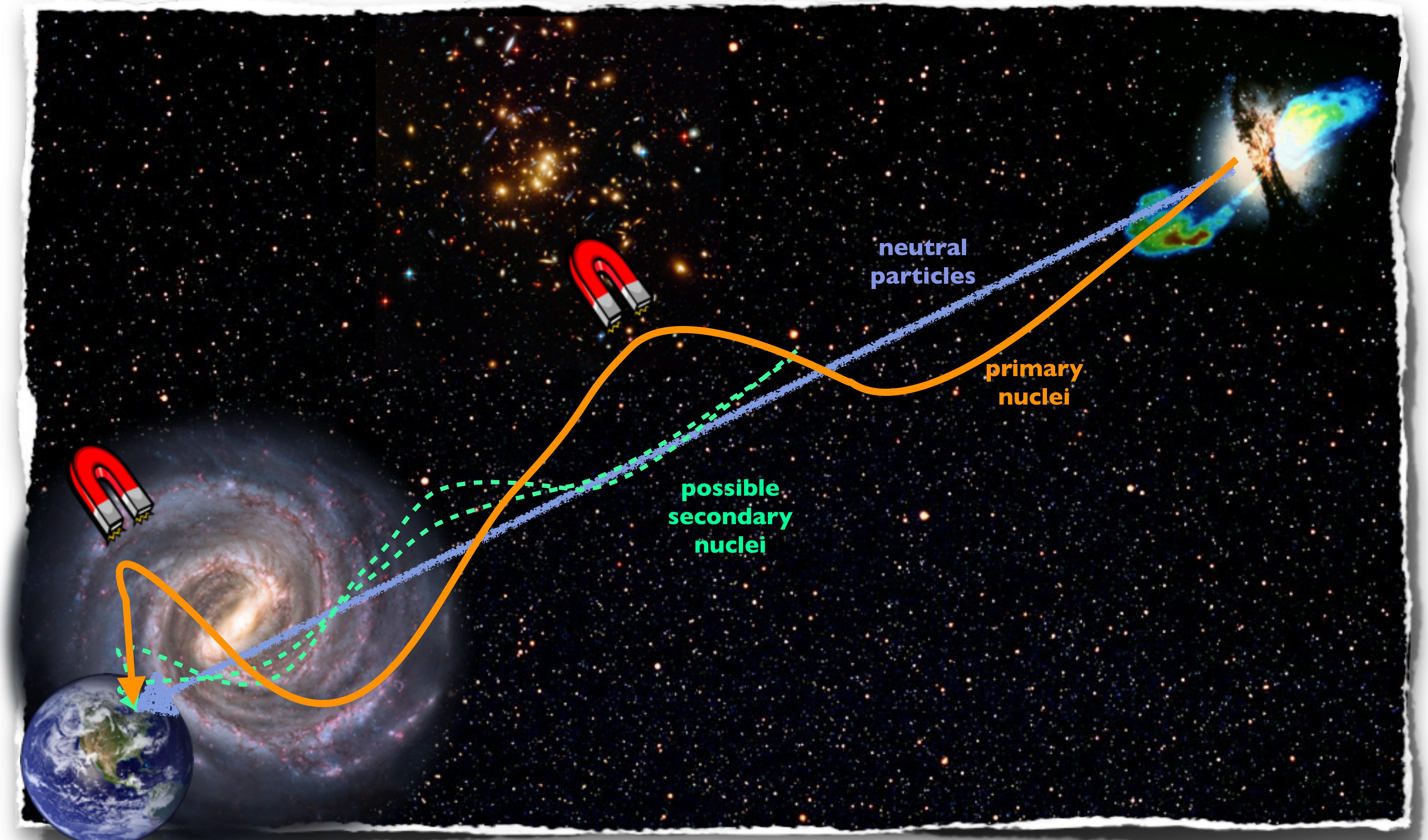
general picture



general picture



general picture



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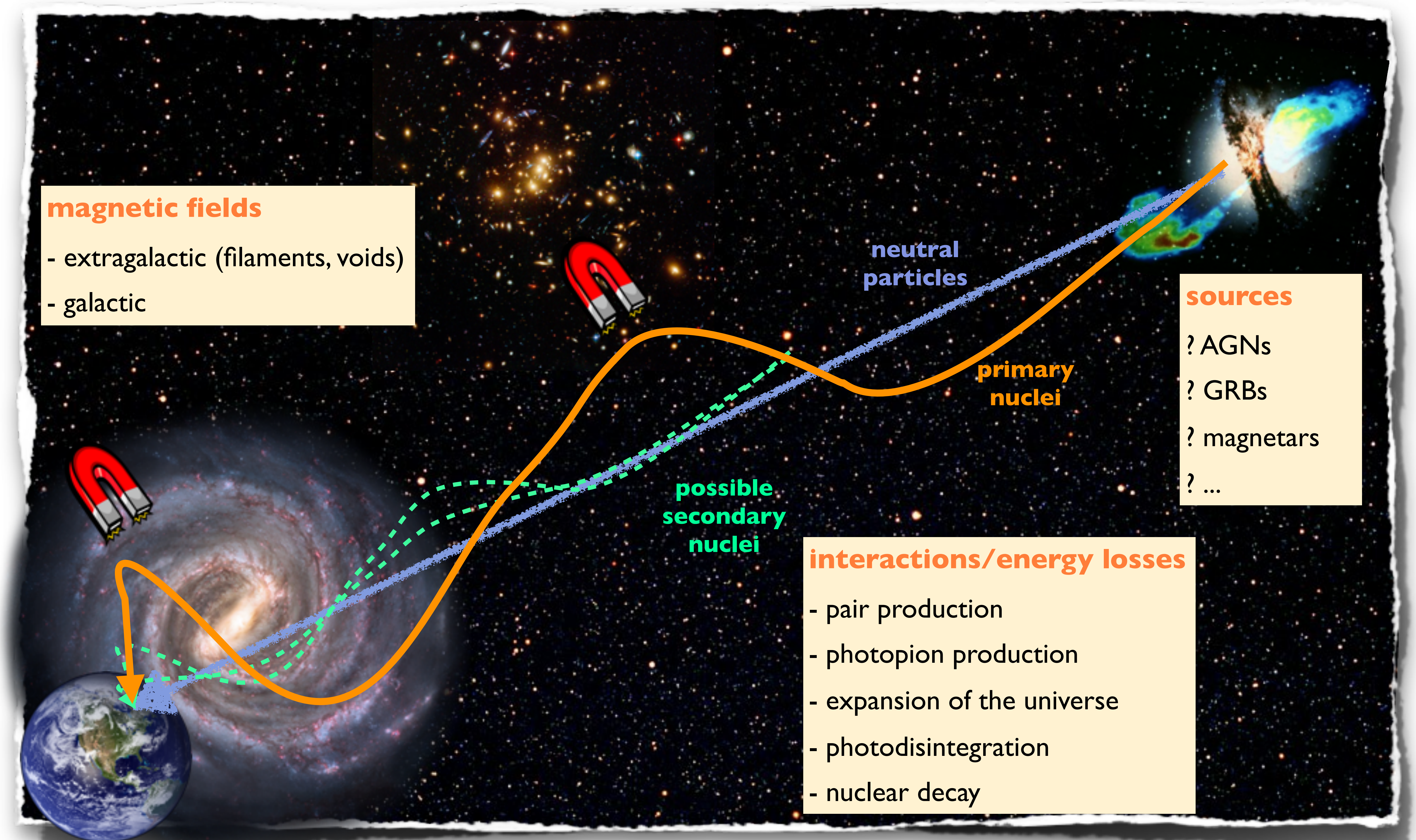


energy loss and interaction processes

photopion production

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

expansion of the universe

$$\frac{dt}{dz} = \frac{1}{H_0}\frac{1}{1+z}\frac{1}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

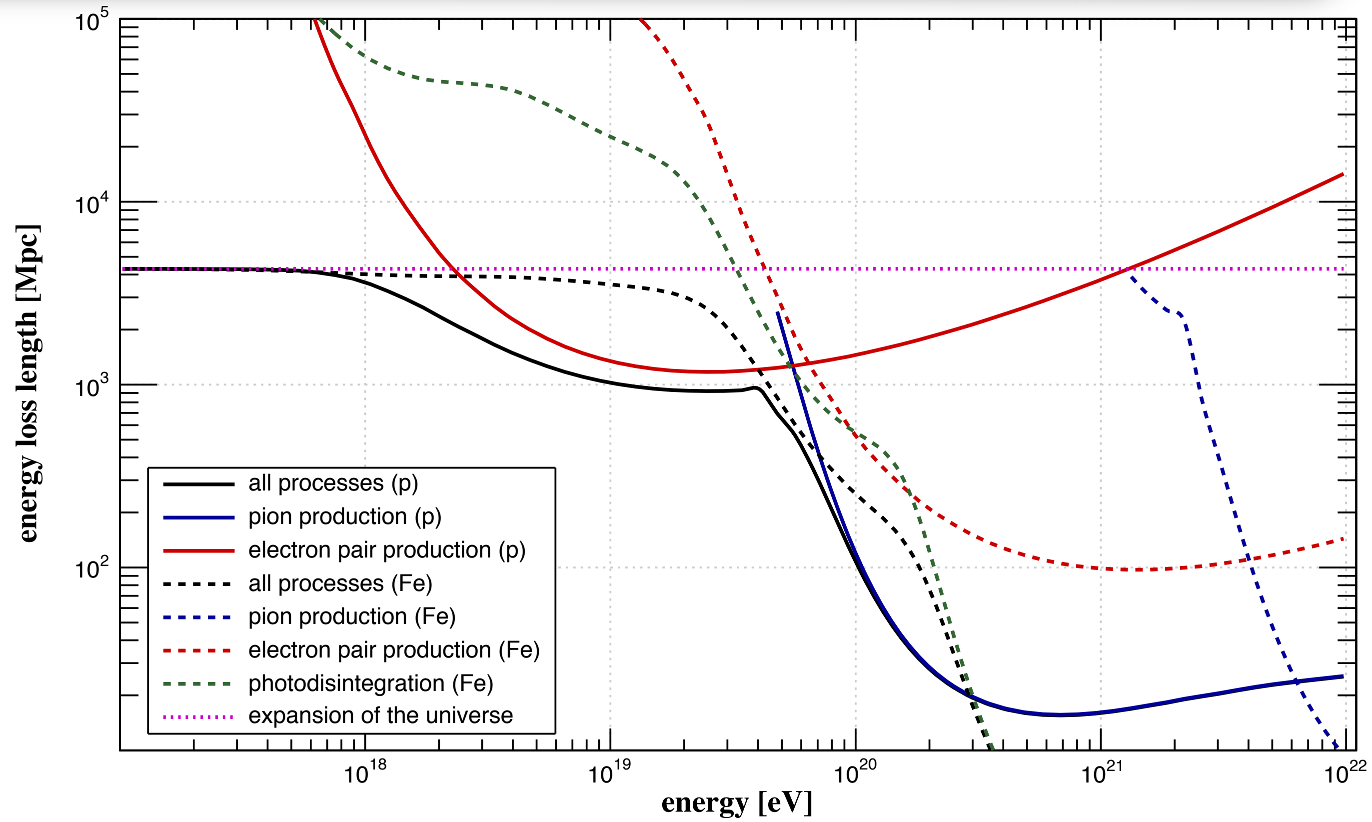
$$E = \frac{E_0}{1+z}$$

pair production

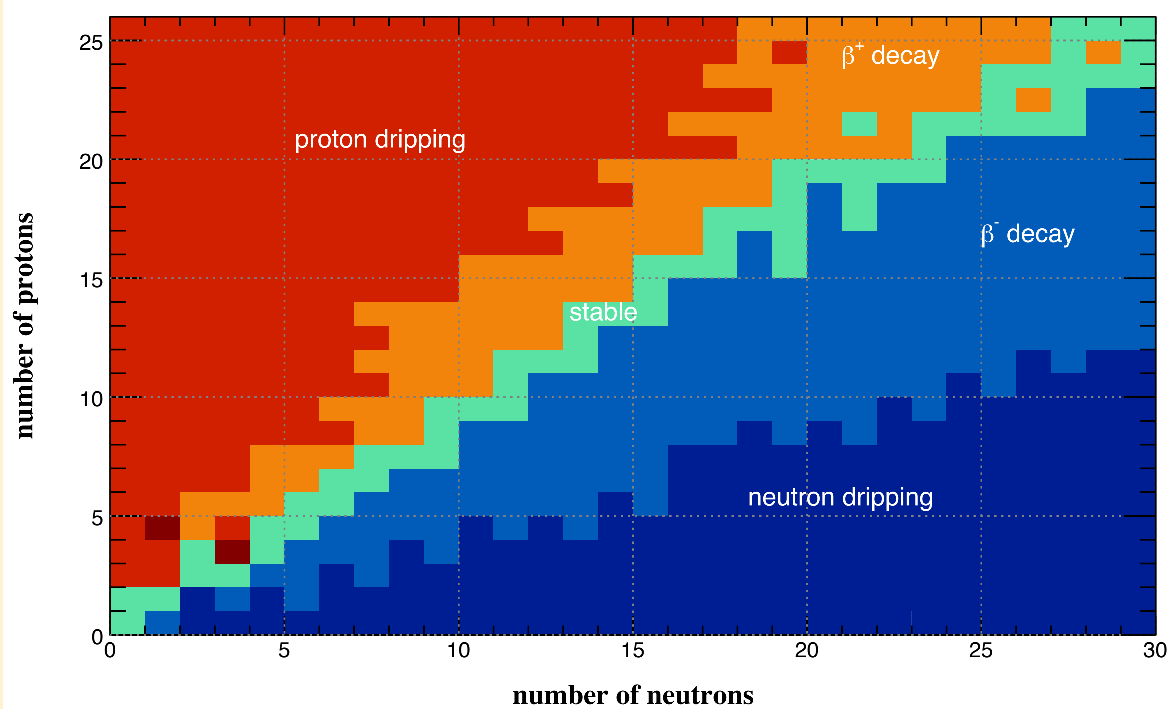
$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 k_B T f(\Gamma)$$

photodisintegration

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

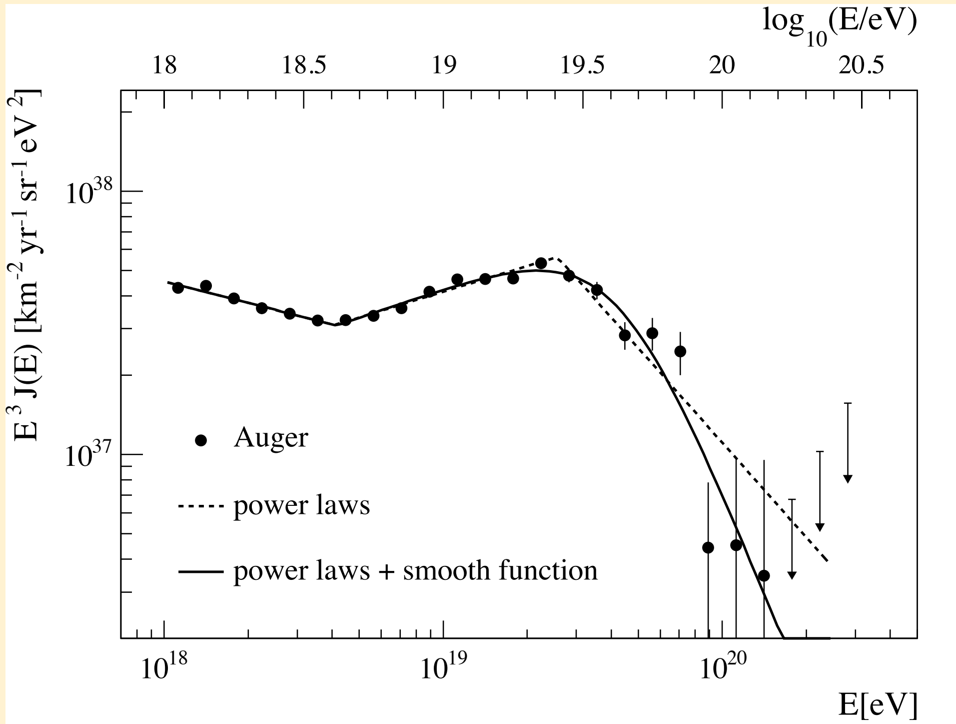


nuclear decay



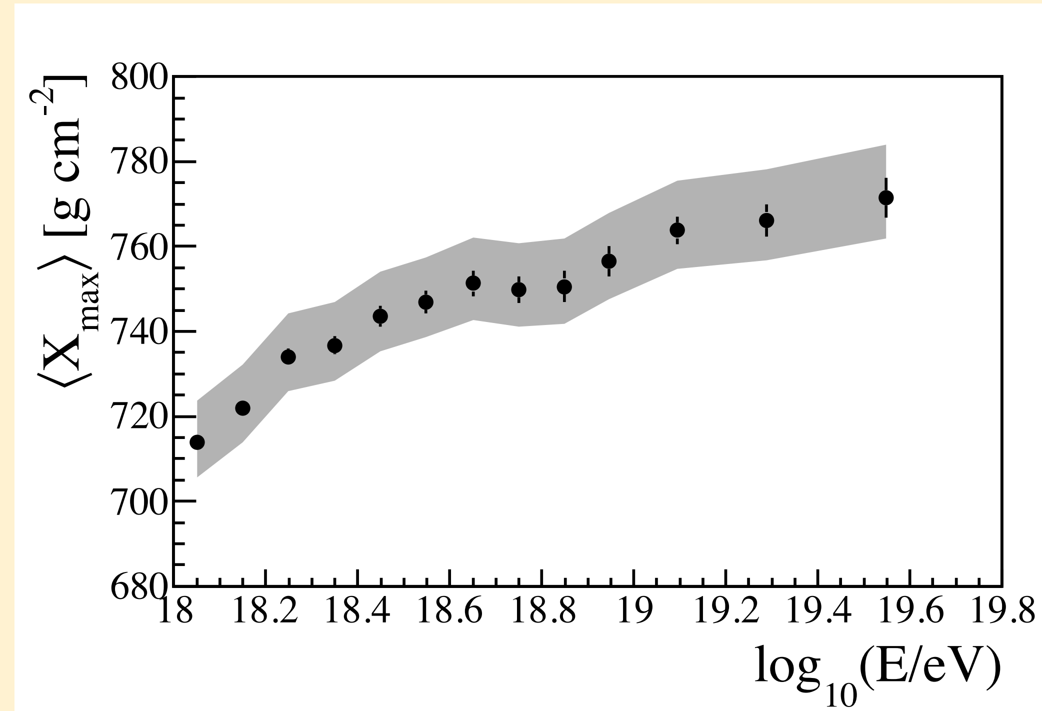
motivation

spectrum



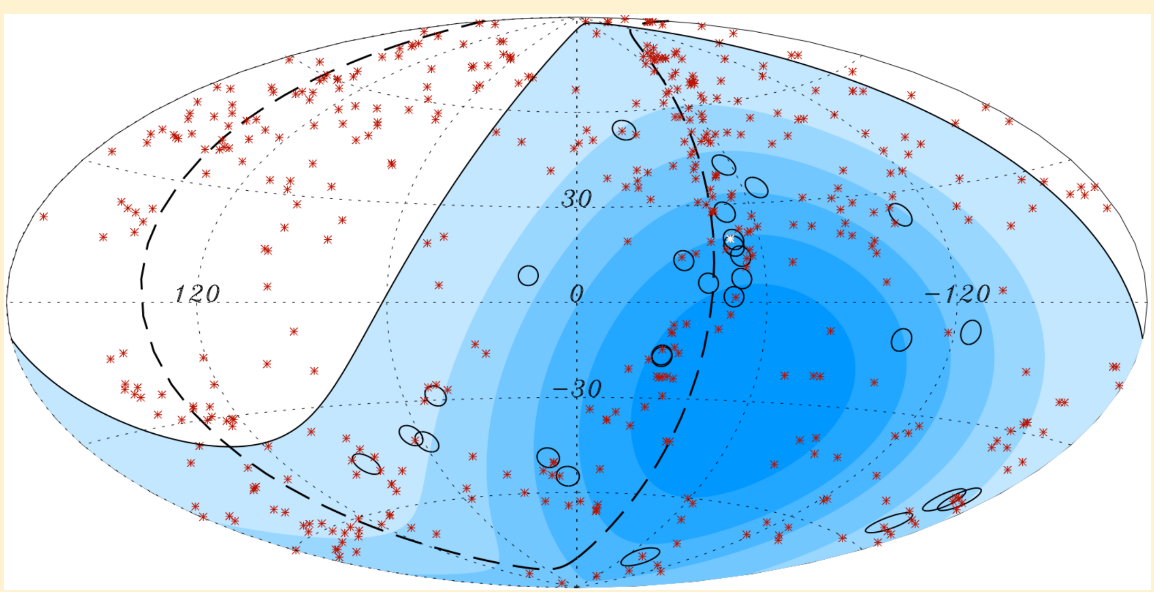
Pierre Auger Collaboration, ICRC 2011.

composition



Pierre Auger Collaboration, JCAP 02 (2013) 026.

anisotropy



Pierre Auger Collaboration, Science 318 (2007) 938.

- ✦ explain these three observables
- ✦ magnetic fields and source distribution may affect spectrum and composition, and certainly affect anisotropy
- ✦ 3D simulations are needed
- ✦ large parameter space => fast simulations

motivation

overview

✦ magnetic fields affect the shape of the spectrum

✦ cosmological effects can be relevant depending on the magnetic fields, even for nearby sources

✦ fit the spectrum and composition might not be enough to obtain physical scenarios to explain UHECRs => anisotropies can be important

a few works making predictions about some of these observables

✦ dip model - Berezinsky et al. **S C**

✦ disappointing model - Aloisio et al. **S C**

✦ Allard et al. **S C**

✦ Hooper & Taylor **S C**

✦ Sigl et al. **S C A**

✦ Dolag et al. **C A**

✦ many others

Spectrum
Composition
Anisotropy

- Berezinsky et al. Phys. Rev. D 74 (2006) 043005
- Aloisio et al. Astropart. Phys. 34 (2011) 620
- Allard et al. JCAP 10 (2008) 033
- Hooper and Taylor, Astropart. Phys. 33 (2010) 151
- Sigl et al. Phys. Rev. D 68 (2003) 043002
- Sigl et al. Phys. Rev. D 70 (2004) 043007
- Dolag et al. JCAP 0501 (2005) 009

simulating the propagation of UHECRS

CRPropa3

- ✦ see arXiv:1307.2643 [RAB et al. Proceedings 33rd ICRC]
- ✦ based on CRPropa 2 [Kampert et al. Astropart. Phys. 42 (2013) 41]
- ✦ modular structure
- ✦ parallel code → faster simulations → wide range of parameters

1D simulations

- ✦ redshift losses
- ✦ source evolution
- ✦ no deflection by magnetic fields

3D simulations

- ✦ effects of large scale structure
- ✦ magnetic deflections
- ✦ cosmology correction
- ✦ galactic lensing

code available in:
crpropa.desy.de

correcting for cosmology in 3D simulations

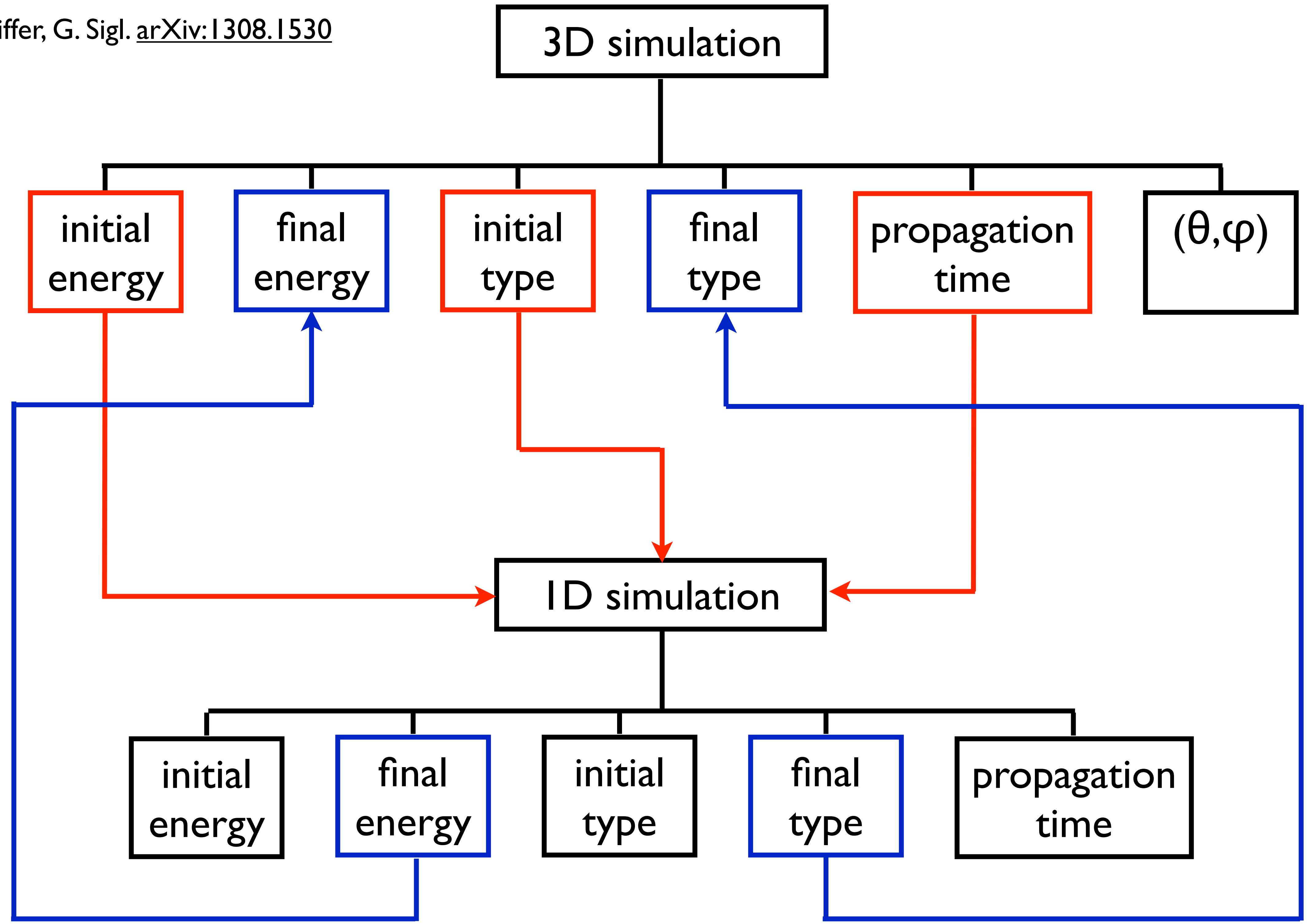
cosmology in 3D: what is the problem?

✦ not possible to know beforehand the position (therefore redshift) of the particle due to magnetic deflections

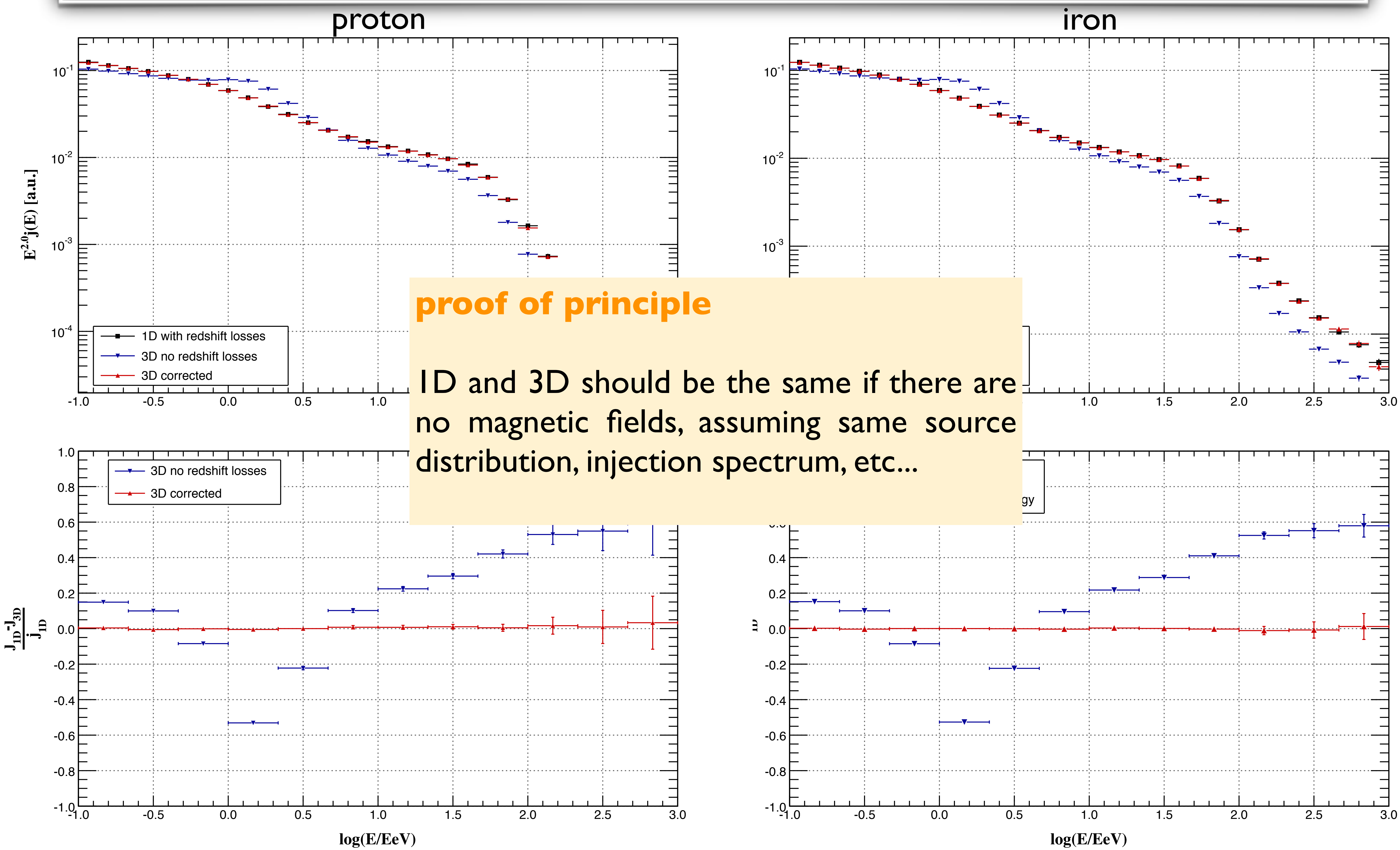
✦ direct solution would be to perform a 4D simulation => time consuming

correcting for cosmology in 3D simulations

RAB, P. Schiffer, G. Sigl. arXiv:1308.1530



testing the cosmology correction

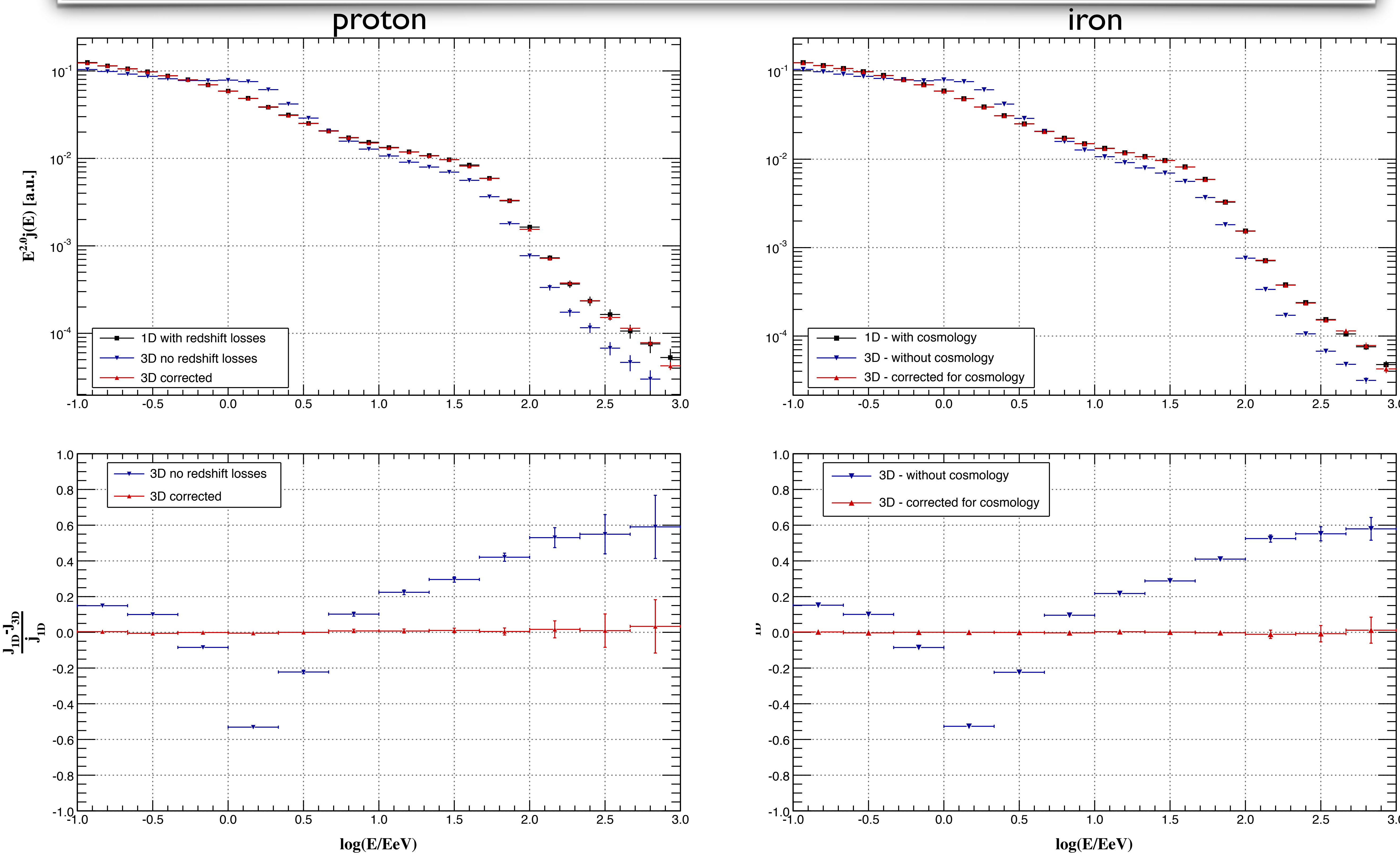


proof of principle

1D and 3D should be the same if there are no magnetic fields, assuming same source distribution, injection spectrum, etc...

- uniform source distribution
- sources up to 4000 Mpc
- injection spectrum source = -2.2
- maximum propagation length = 4000 Mpc

testing the cosmology correction



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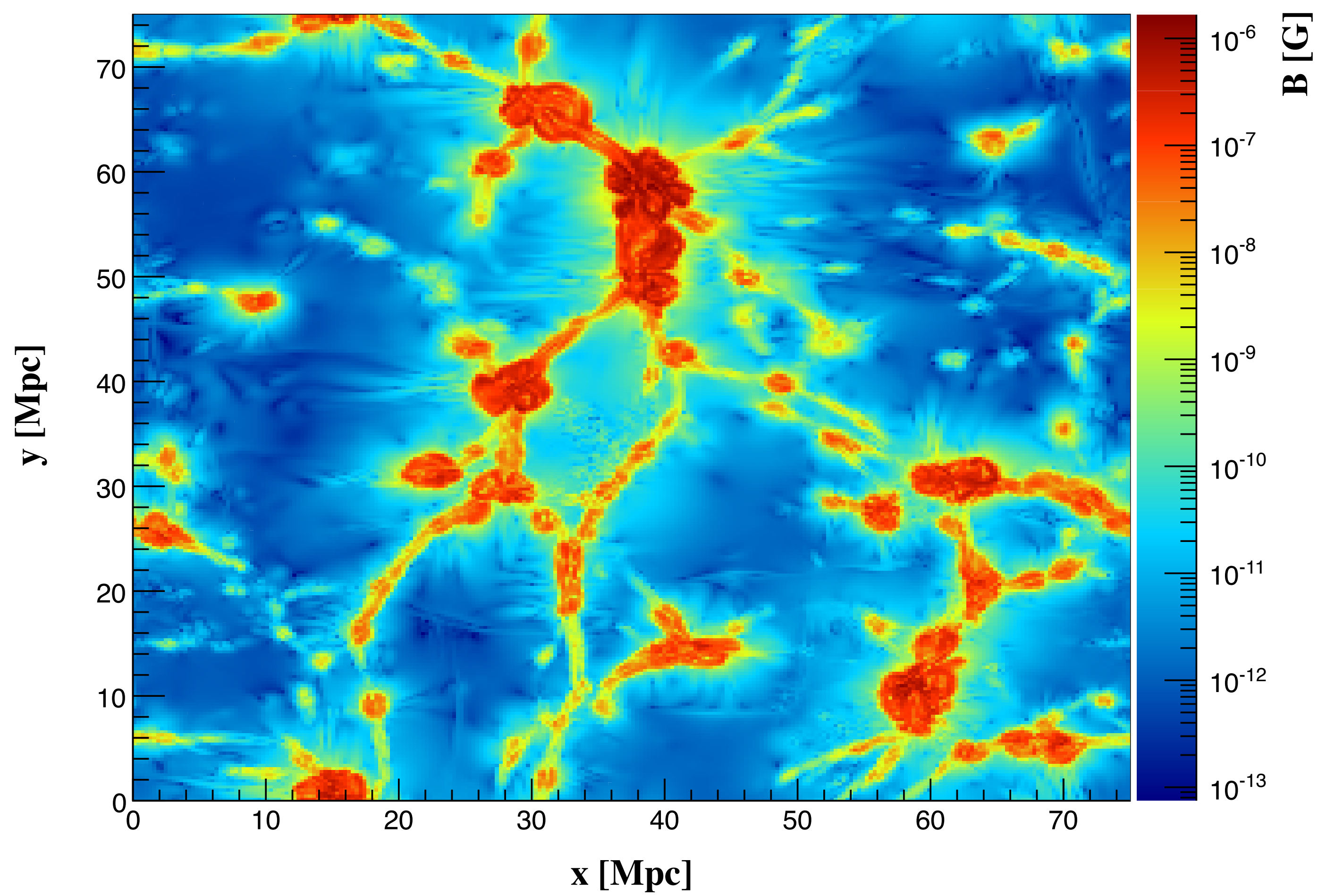
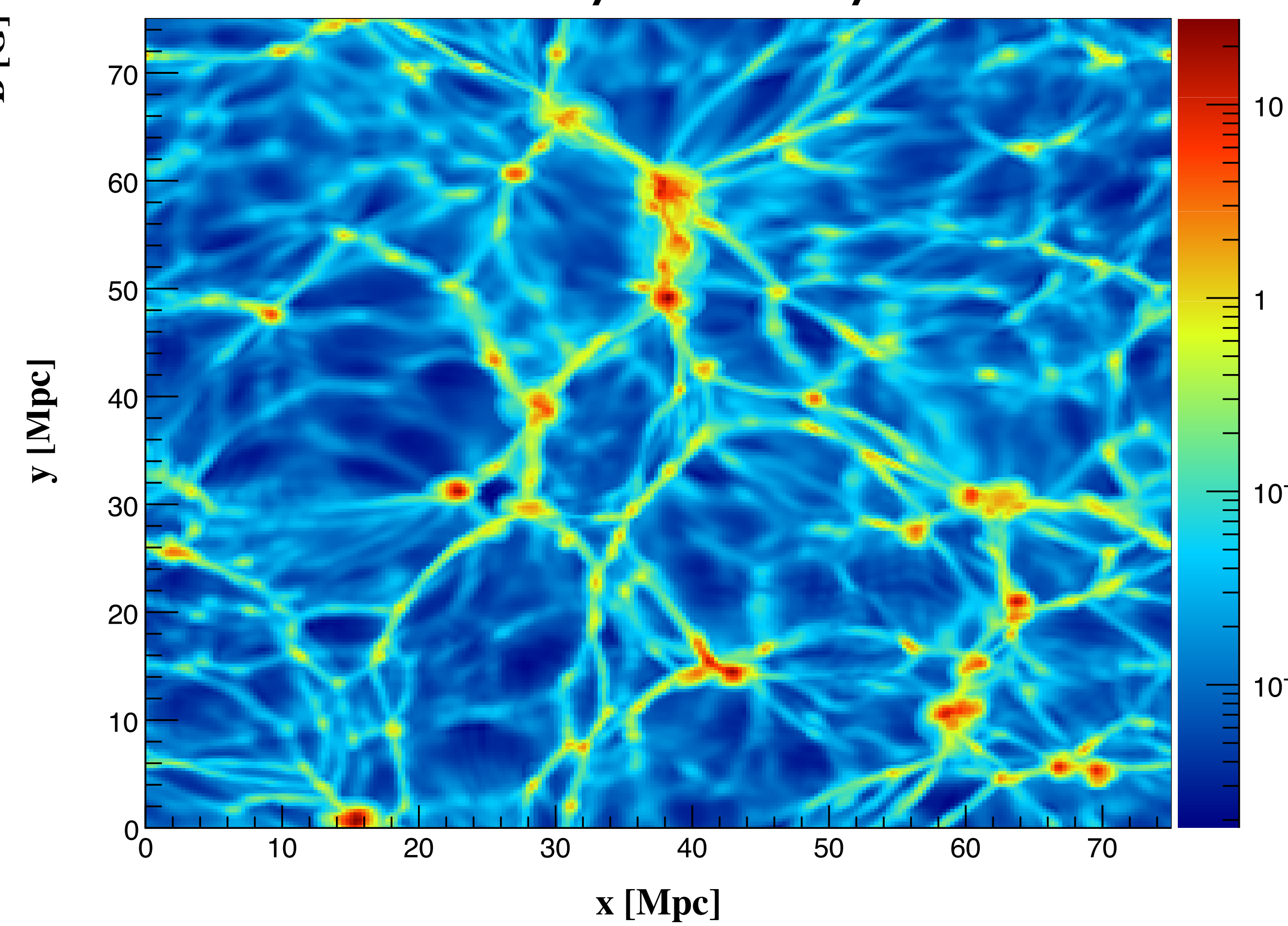
application: simulation setup

magnetic field



baryon density



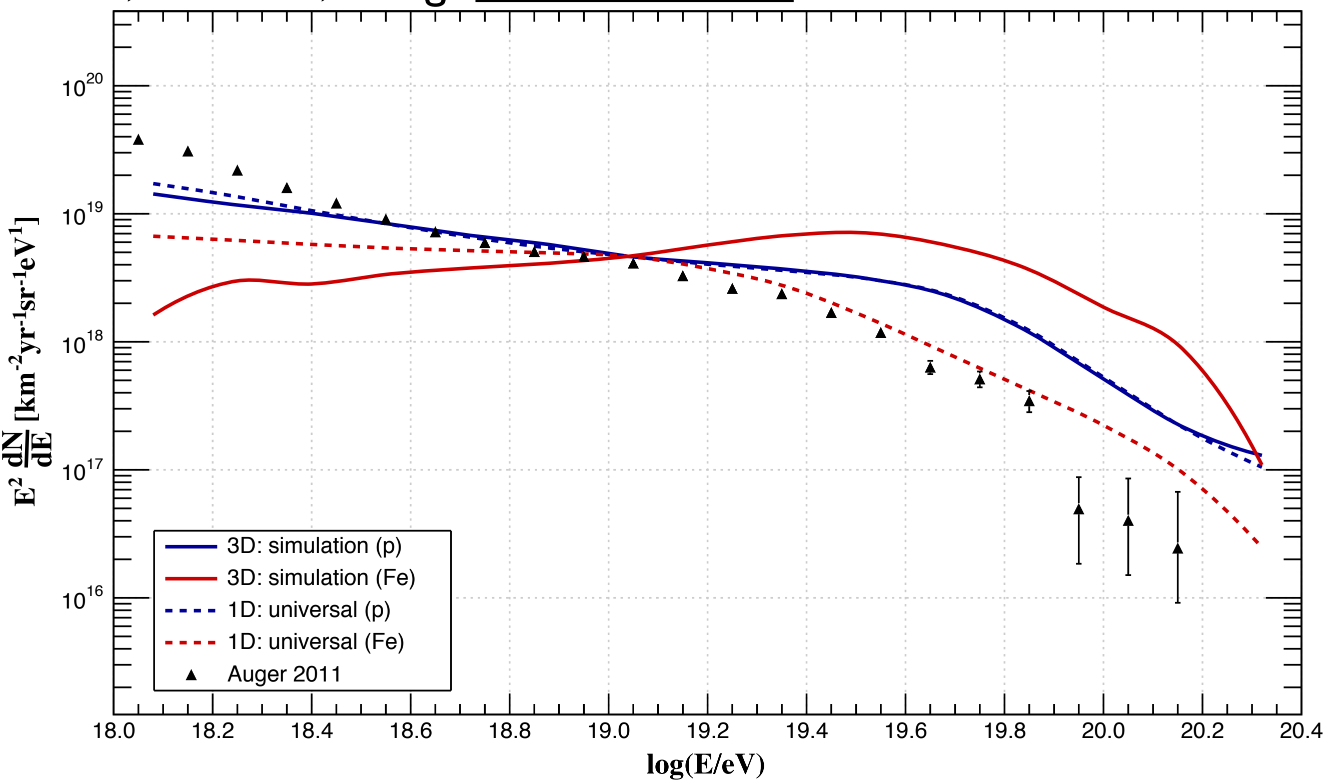
- ✦ MHD simulation from G. Sigl, F. Miniatti, T. Ensslin
- ✦ maximum rigidity = 1000 EeV
- ✦ maximum source distance = 2 Gpc
- ✦ sources following LSS baryon density

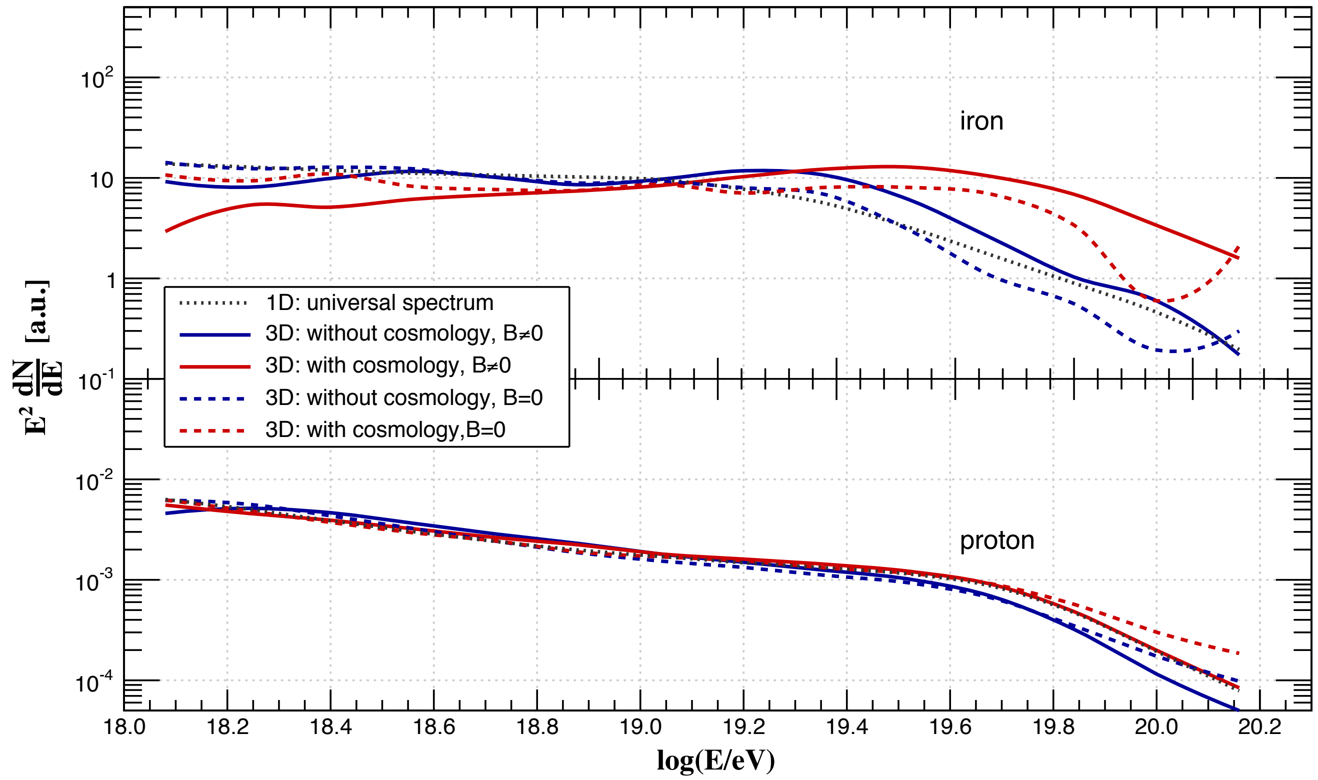
- ✦ composition: proton and iron (two cases)
- ✦ minimum energy = 1 EeV
- ✦ uniform grid
- ✦ magnetic field from the grid

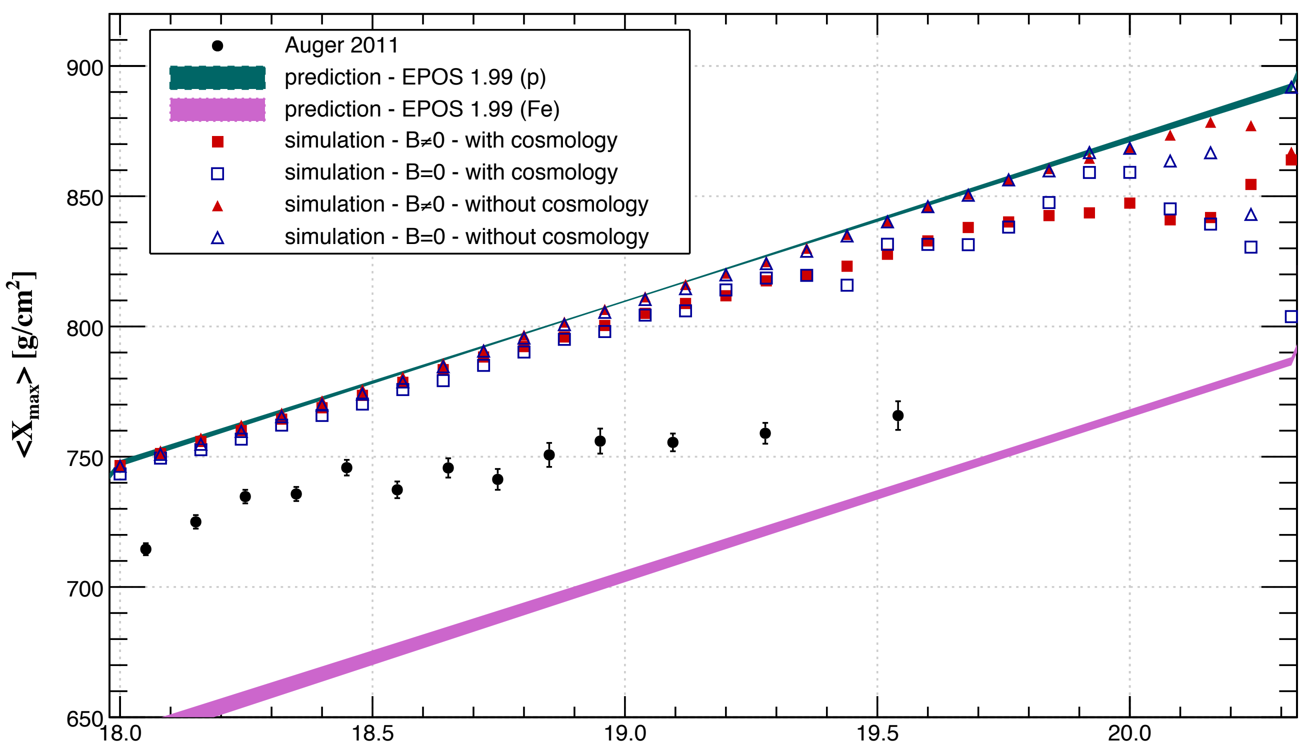
G. Sigl, F. Miniati, T.A. Enßlin, 2004, Nuclear Physics B Proc. Supp. 136, 224.

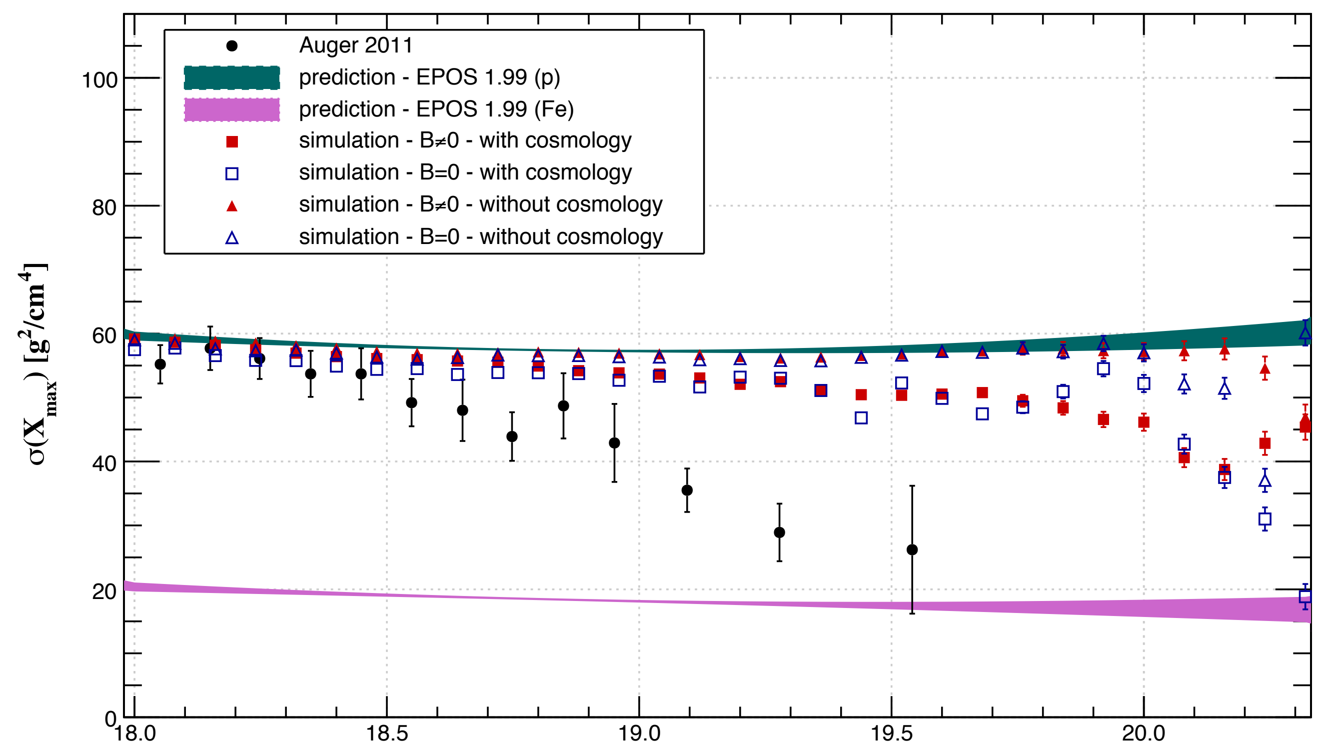
results

RAB, P. Schiffer, G. Sigl. arXiv:1308.1530









log(E/eV) Parametrization from: Pierre Auger Collaboration, JCAP 1302 (2013) 026 log(E/eV)

summary

✦ new method to account for cosmological effects in 3D simulations

✦ simulations of propagation of UHECRs in the large scale structure of the universe

✦ magnetic fields can affect the shape of the spectrum, so they should be taken into account when performing simulations

✦ deviations from universal spectrum for pure iron composition

✦ large scale structures (magnetic field) + cosmological effects + energy losses => realistic simulations

✦ in the future: fit spectrum+composition+anisotropies?

in the future...

✦ propagate UHECRs in the large scale structure of the universe using new MHD simulations, taking into account magnetic fields, cosmology, energy losses and effects of the galactic magnetic field

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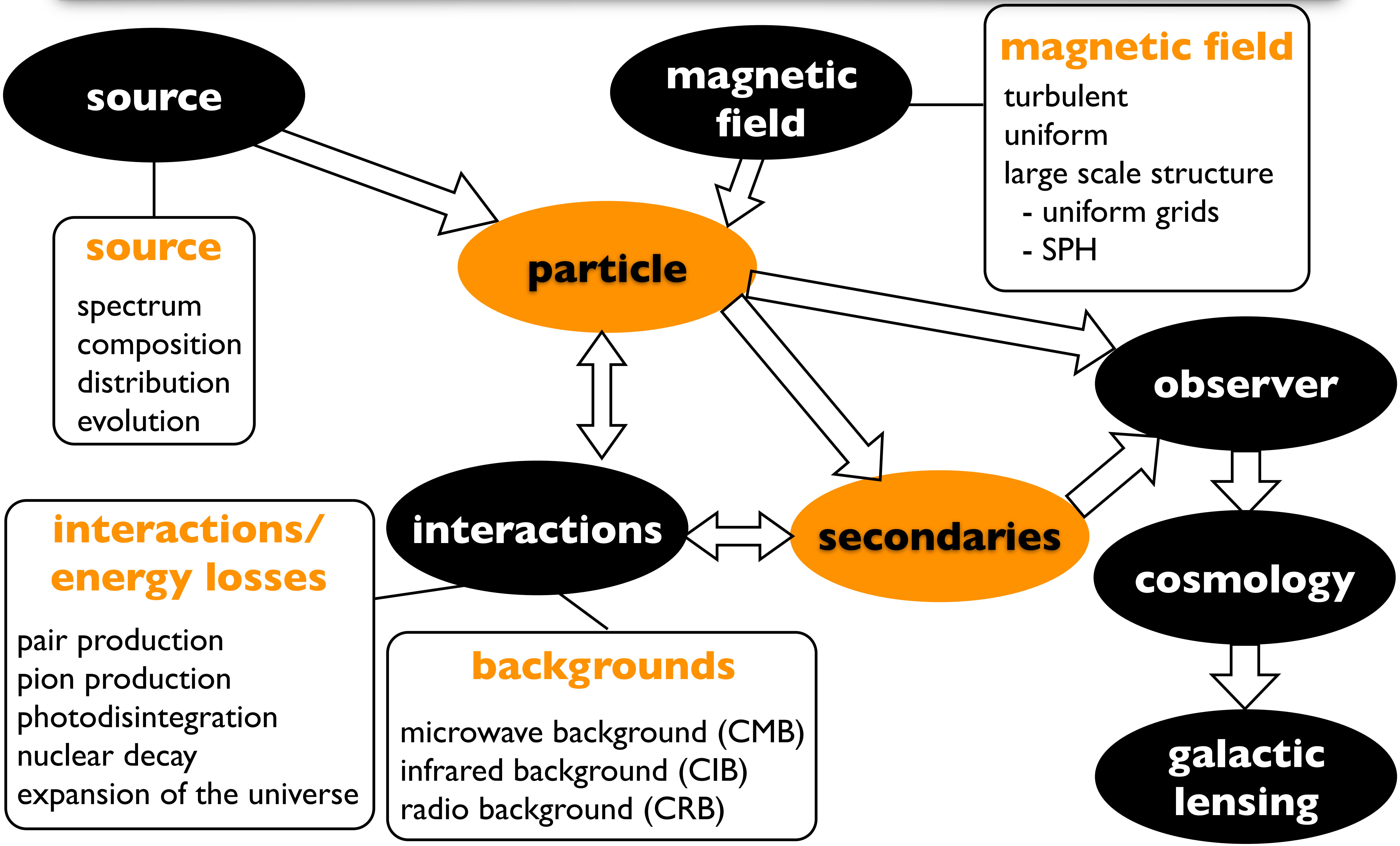
Thank you!

Backup Slides

CRPropa: how does it work



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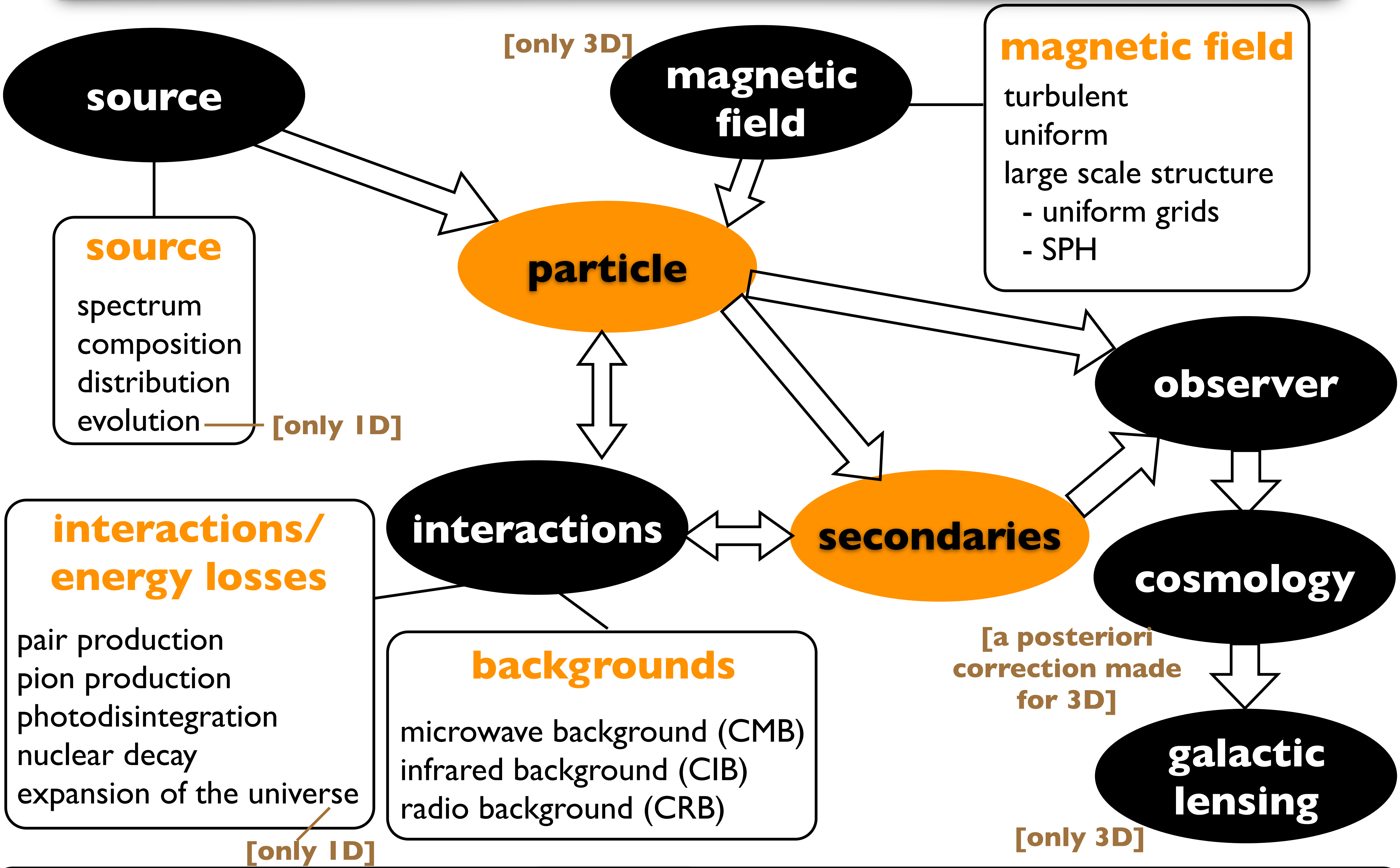

lensing technique: galactic magnetic field

Jansson & Farrar, ApJ 761 (2012) L11

- ✦ assumes no energy losses
- ✦ each "lens" corresponds to a different energy bin
- ✦ backtrack protons to the galactic border
- ✦ nuclei will have deflection of Z times the deflection for protons