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Forschungs- und Wissenschaftsstiftung Hamburg

Propagation of UHECRs in the Universe

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in collaboration with
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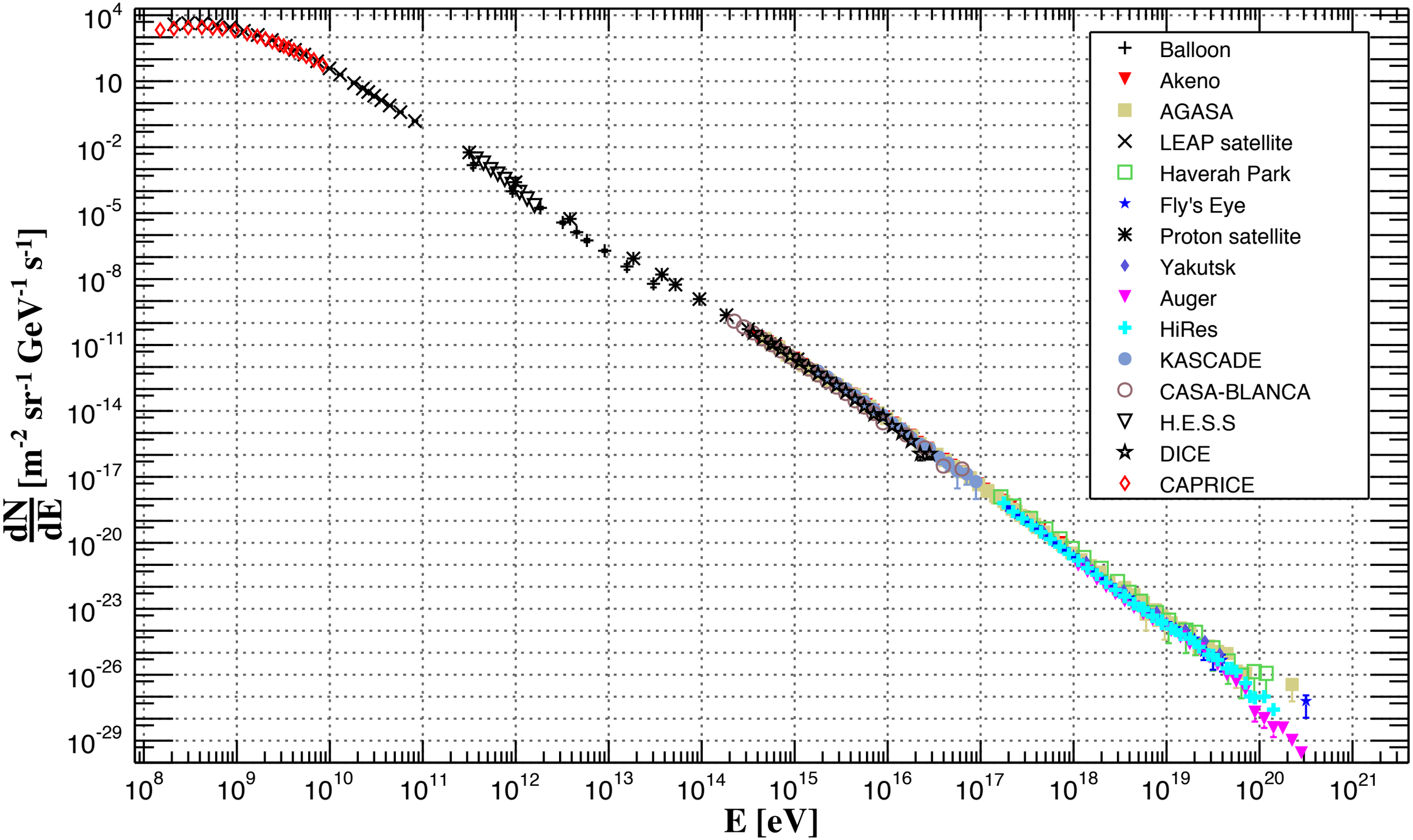
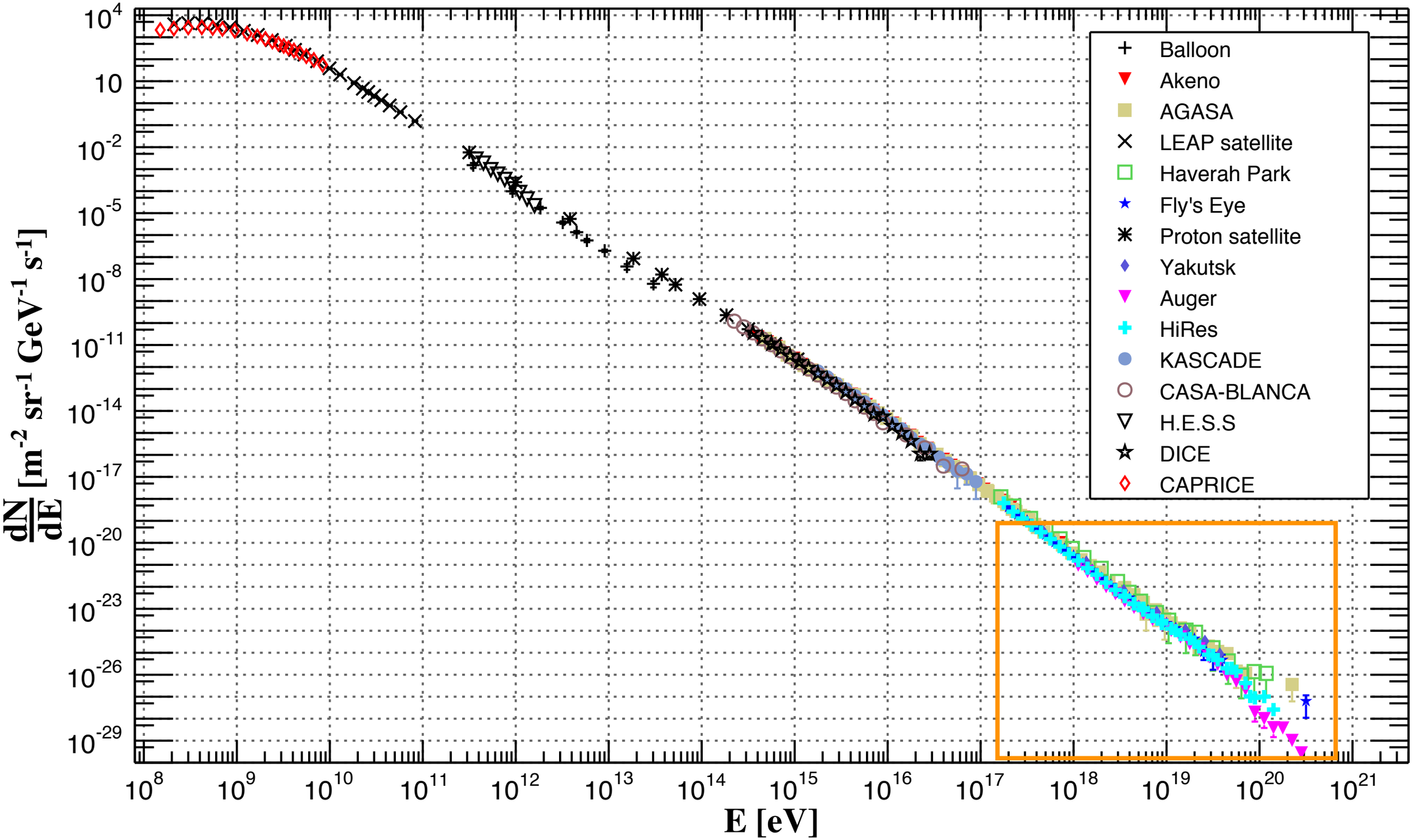
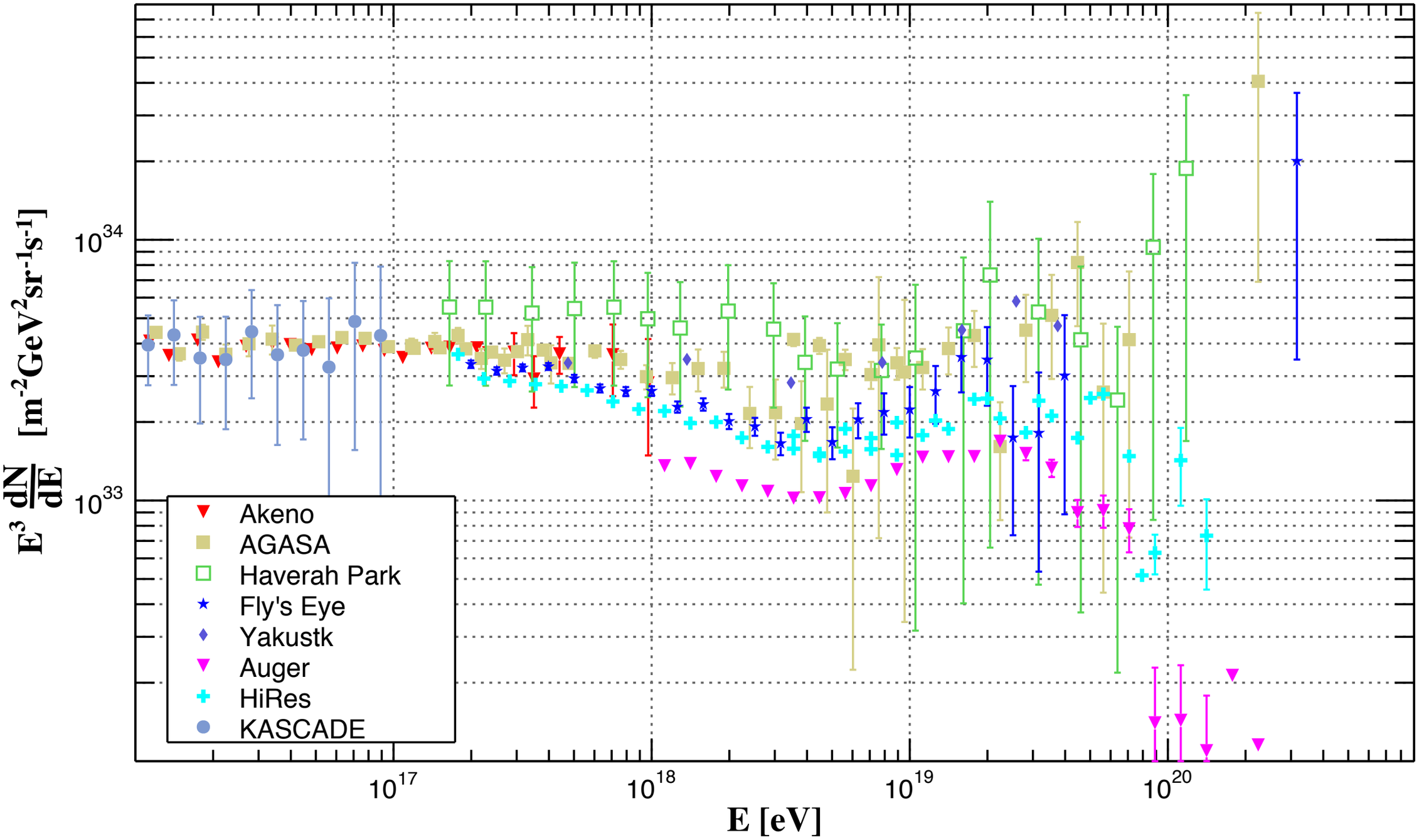
cosmic ray spectrum



cosmic ray spectrum



cosmic ray spectrum



energy losses at ultra-high energies

pair production

$$p + \gamma \rightarrow p + e^+ + e^-$$

expansion of the universe

redshift evolution:

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

energy loss:

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

photodisintegration

$$N(A,Z) \rightarrow \sum_i N_i(A_i, Z_i)$$

pion production

$$p + \gamma \rightarrow p + \pi^0$$

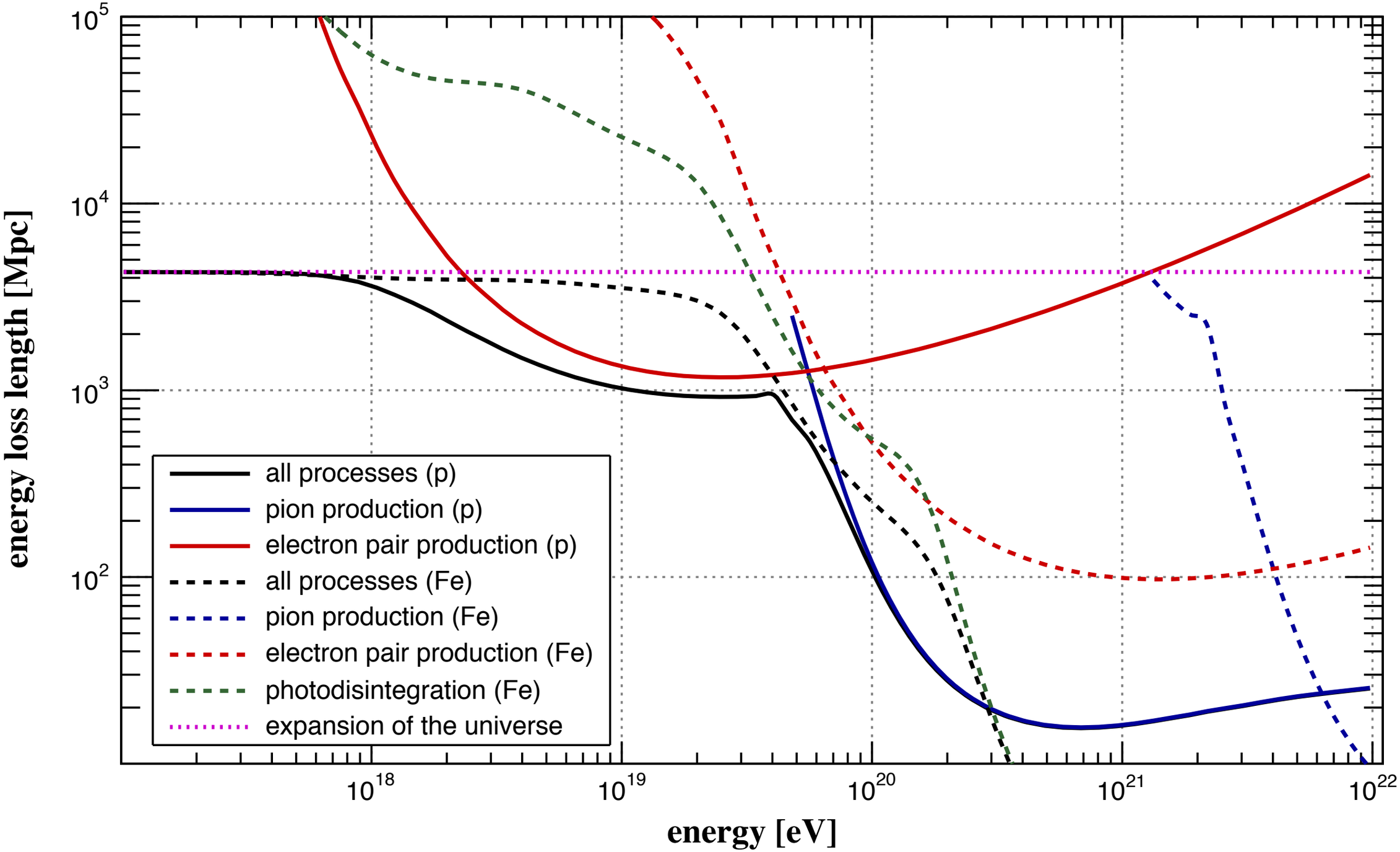
$$p + \gamma \rightarrow n + \pi^+$$

photon backgrounds

cosmic microwave background (CMB)

cosmic infrared background (IRB)

energy losses at UHE



simulating the propagation of UHECRs

sources
- continuous
- discrete

injection
- monochromatic
- power law

propagation
- interactions
- neutral secondaries
- deflections in 3D
- redshifts in 1D

observers
- origin of coordinates
- spheres around the sources
- small spheres in the box

code

- ✦ CRPropa
- ✦ available in: crpropa.desy.de
- ✦ paper: Kampert et al. Astropart. Phys. 42 (2013) 41.

1D simulations

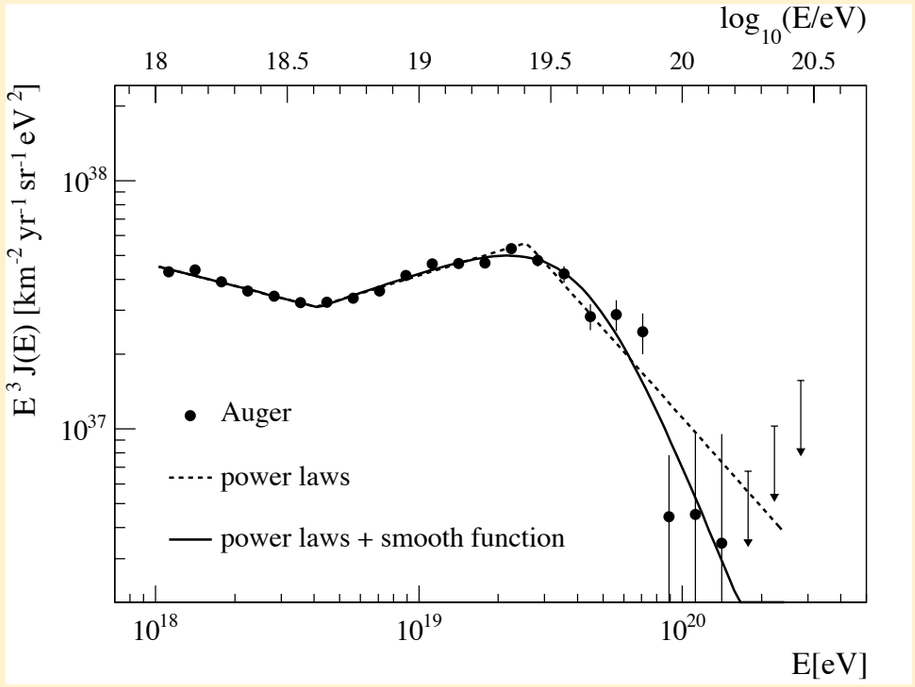
- ✦ redshift losses
- ✦ source evolution
- ✦ no deflection by magnetic fields

3D simulations

- ✦ effects of large scale structure
- ✦ magnetic deflections
- ✦ no redshift losses
- ✦ no source evolution

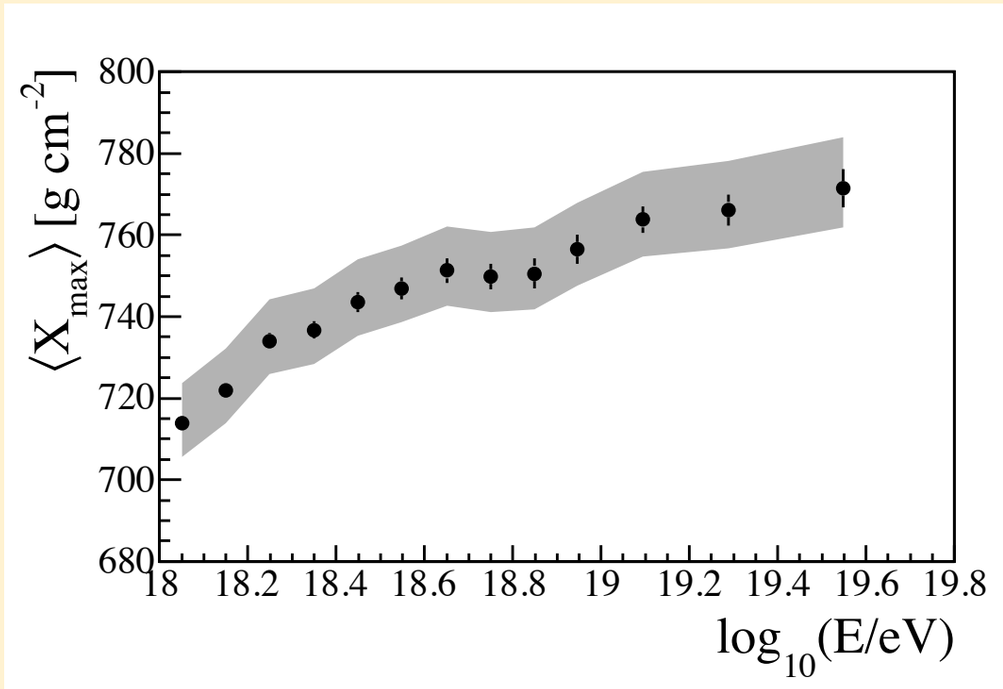
motivation

spectrum



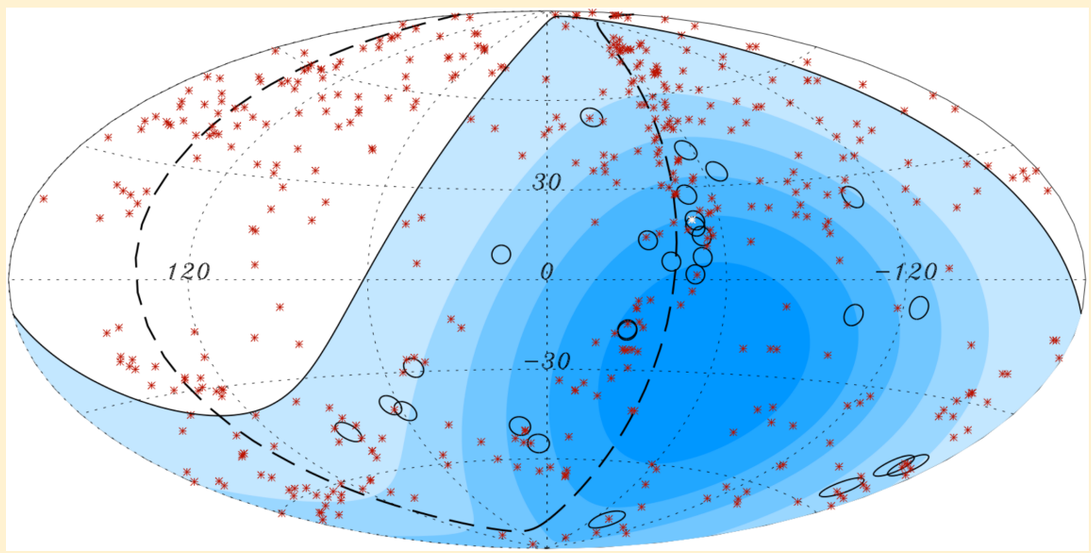
Pierre Auger Collaboration. ICRC 2011.

composition



Pierre Auger Collaboration. JCAP 02 (2013) 026.

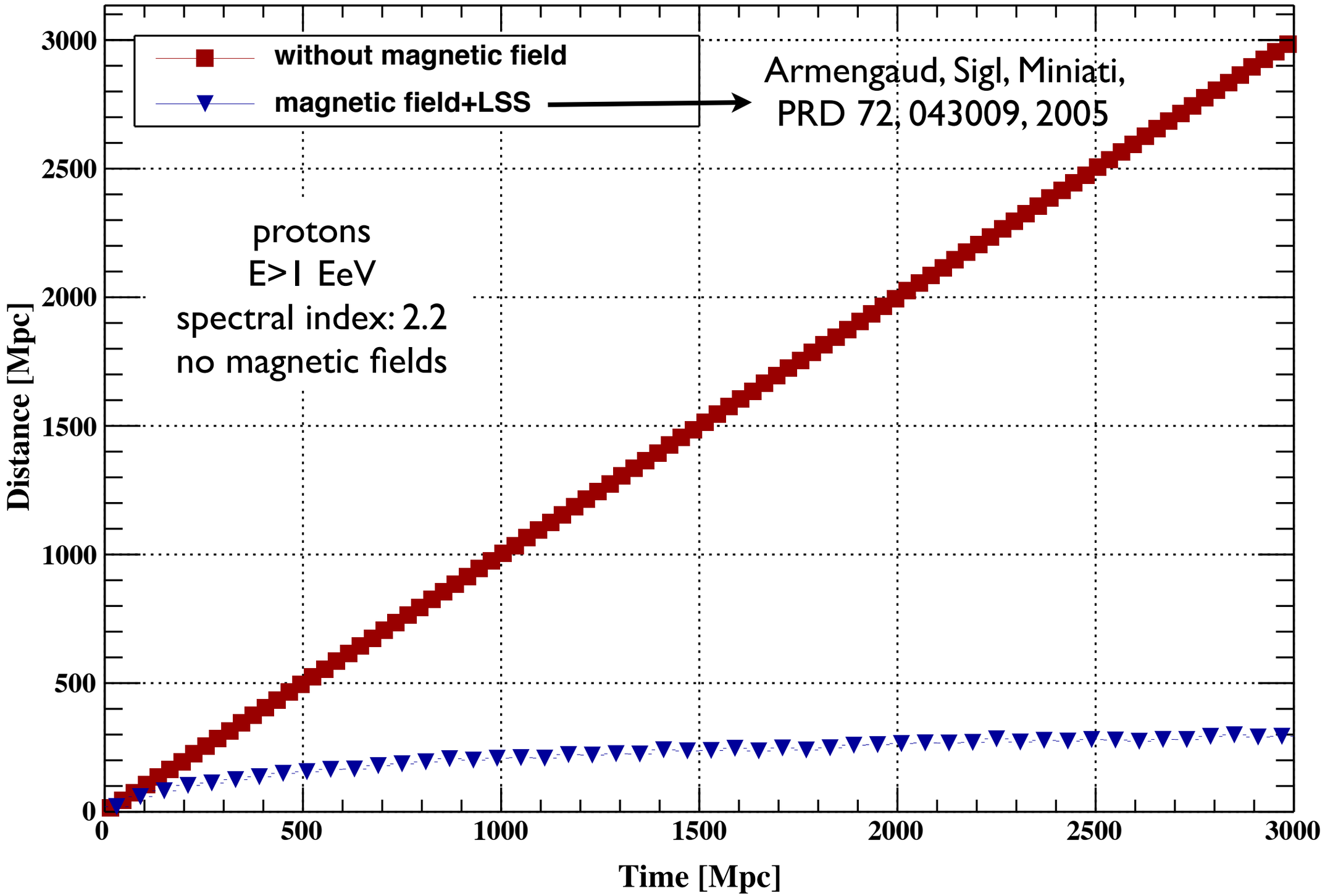
anisotropy



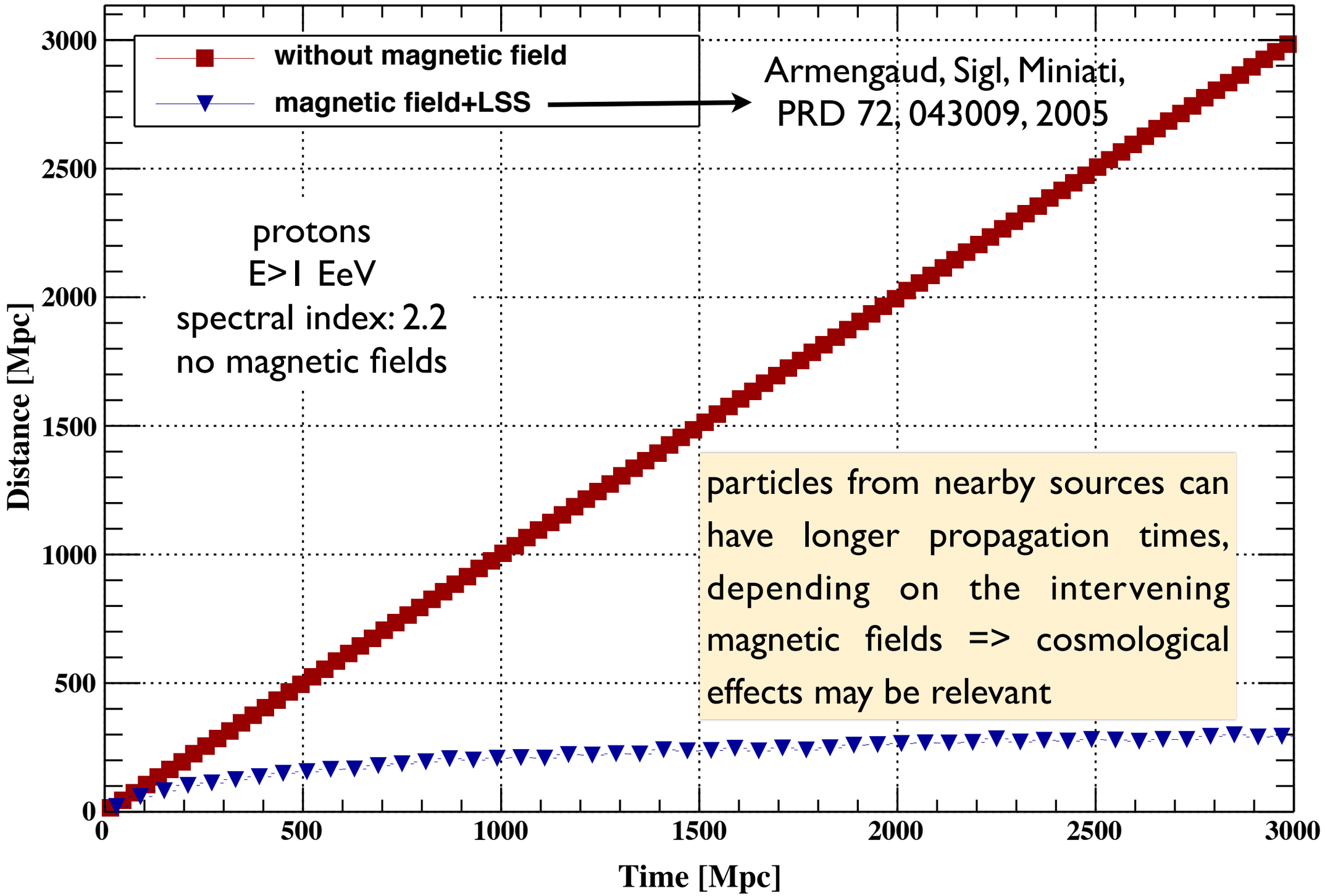
Pierre Auger Collaboration. Science 318 (2007) 938.

- ✦ fit the three observables simultaneously
- ✦ 3D simulations needed for anisotropies
- ✦ cosmology needed to fit the composition and spectrum, specially at energies ~ EeV

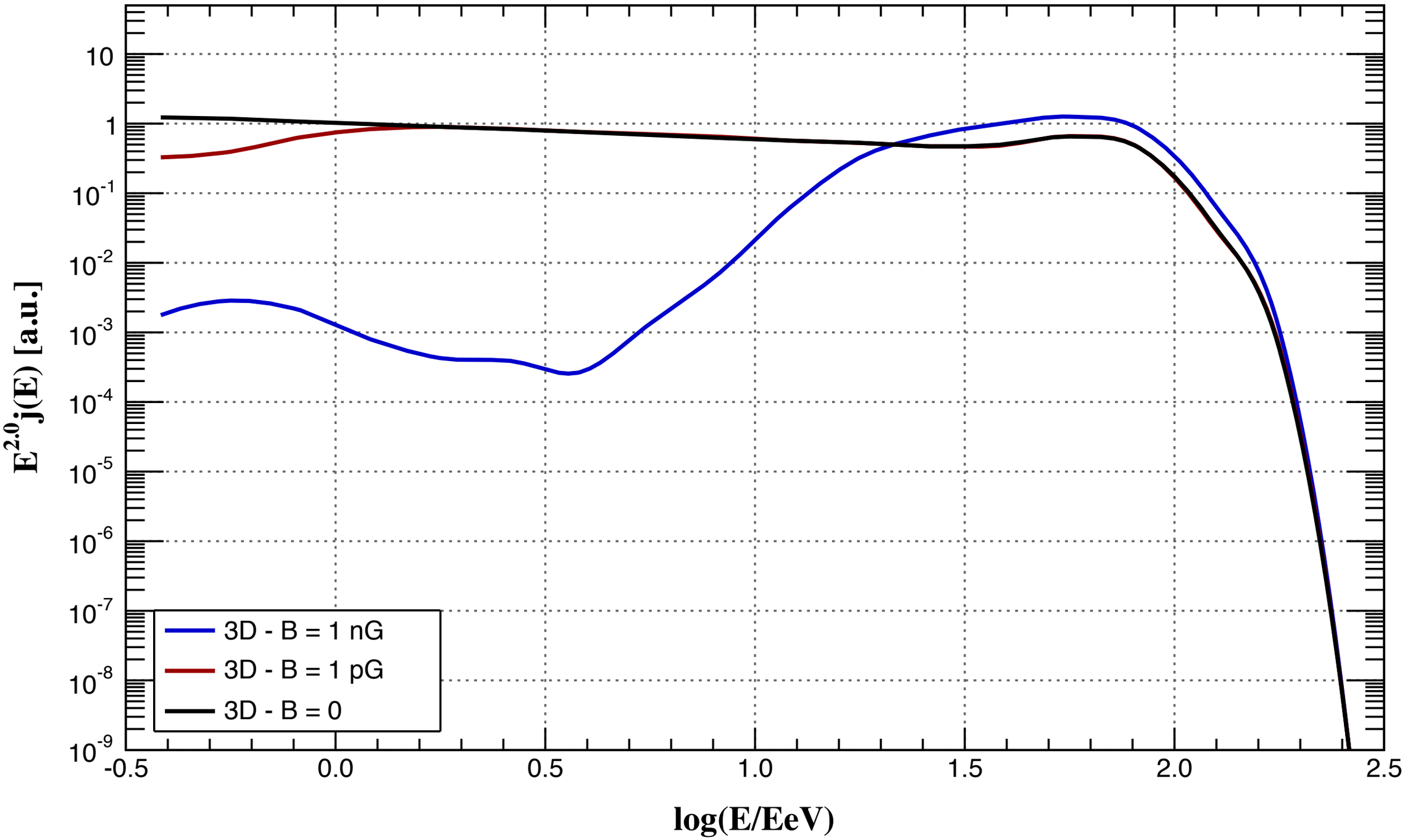
motivation


without magnetic field
magnetic field+LSS
Armengaud, Sigl, Miniati,
PRD 72, 043009, 2005
protons
E>1 EeV
spectral index: 2.2
no magnetic fields
Distance [Mpc]
Time [Mpc]
0
500
1000
1500
2000
2500
3000

motivation


without magnetic field
magnetic field+LSS
Armengaud, Sigl, Miniati,
PRD 72, 043009, 2005
protons
E>1 EeV
spectral index: 2.2
no magnetic fields
particles from nearby sources can have longer propagation times, depending on the intervening magnetic fields => cosmological effects may be relevant
Distance [Mpc]
Time [Mpc]
0
500
1000
1500
2000
2500
3000

effects of magnetic fields on the spectrum



- source alocated 50 Mpc from the observer
- injection spectrum $E^{-2.2}$
- only protons
- Kolmogorov magnetic field
- L_{min} = 150 kpc
- L_{max} = 2 Mpc

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

some works making predictions about some 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**

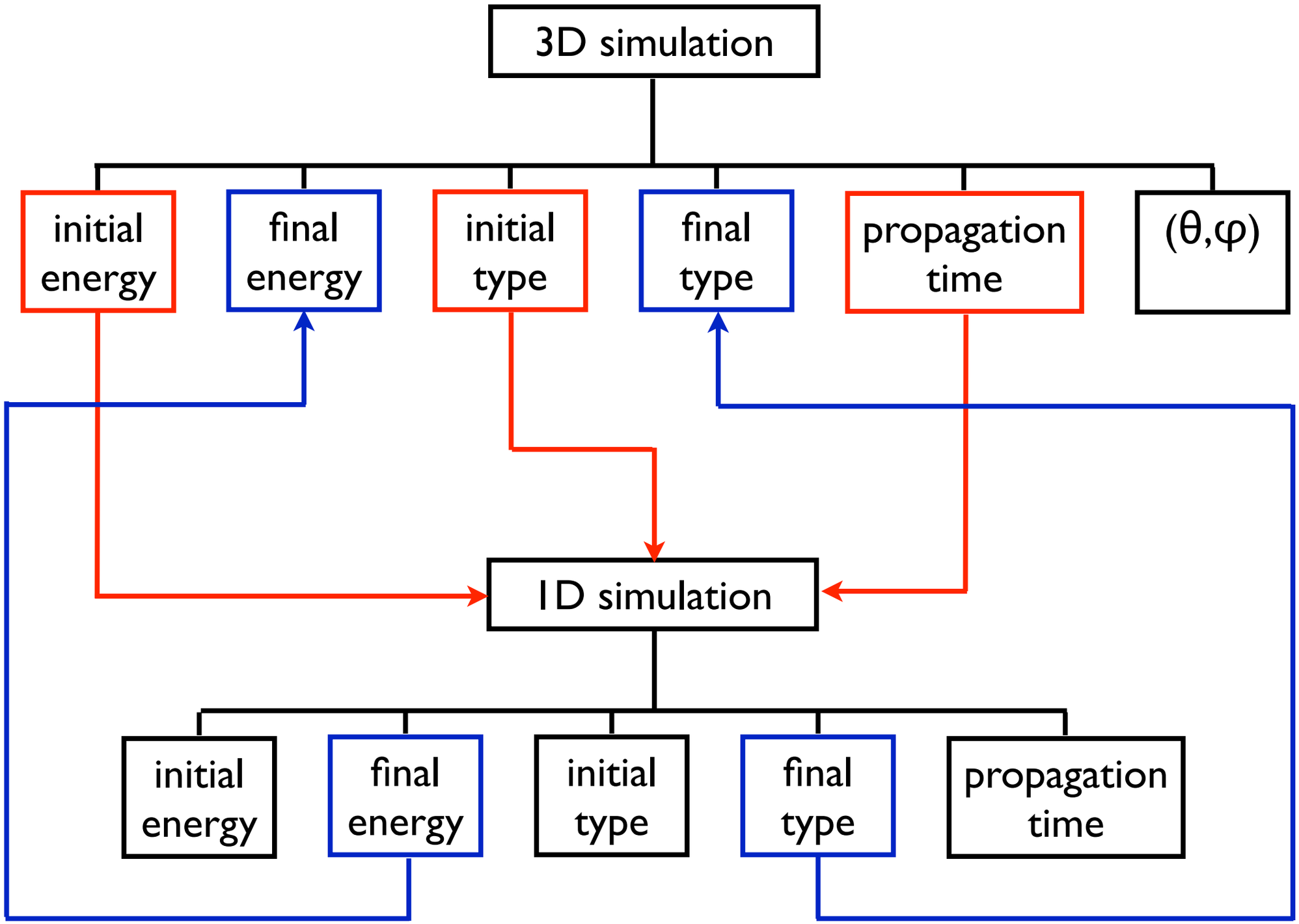
✦ Dolag et al. **C A**

✦ many others

Spectrum
Composition
Anisotropy

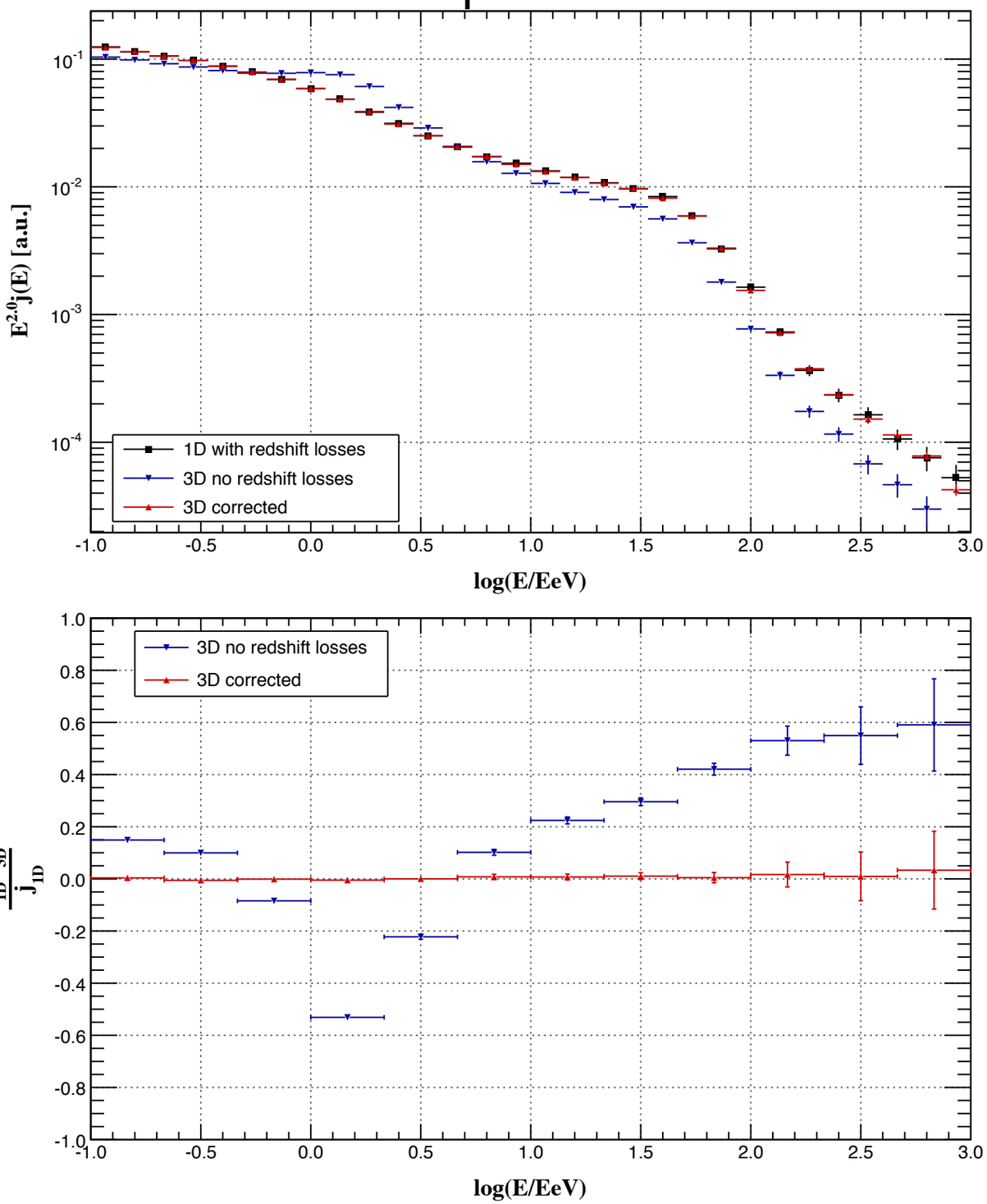
- Berezinsky et al. Phys. Rev. D 74 (2006) 043005
- Aloisio et al. Astropart. Phys. 34 (2011) 620
- Allard et al. JCAP 10 (2008) 033
- Hooper and Taylor, Astropart. Phys. 33 (2010) 151
- Sigl et al. Phys. Rev. D 68 (2003) 043002
- Dolag et al. JCAP 0501 (2005) 009

correcting for cosmology in 3D simulations

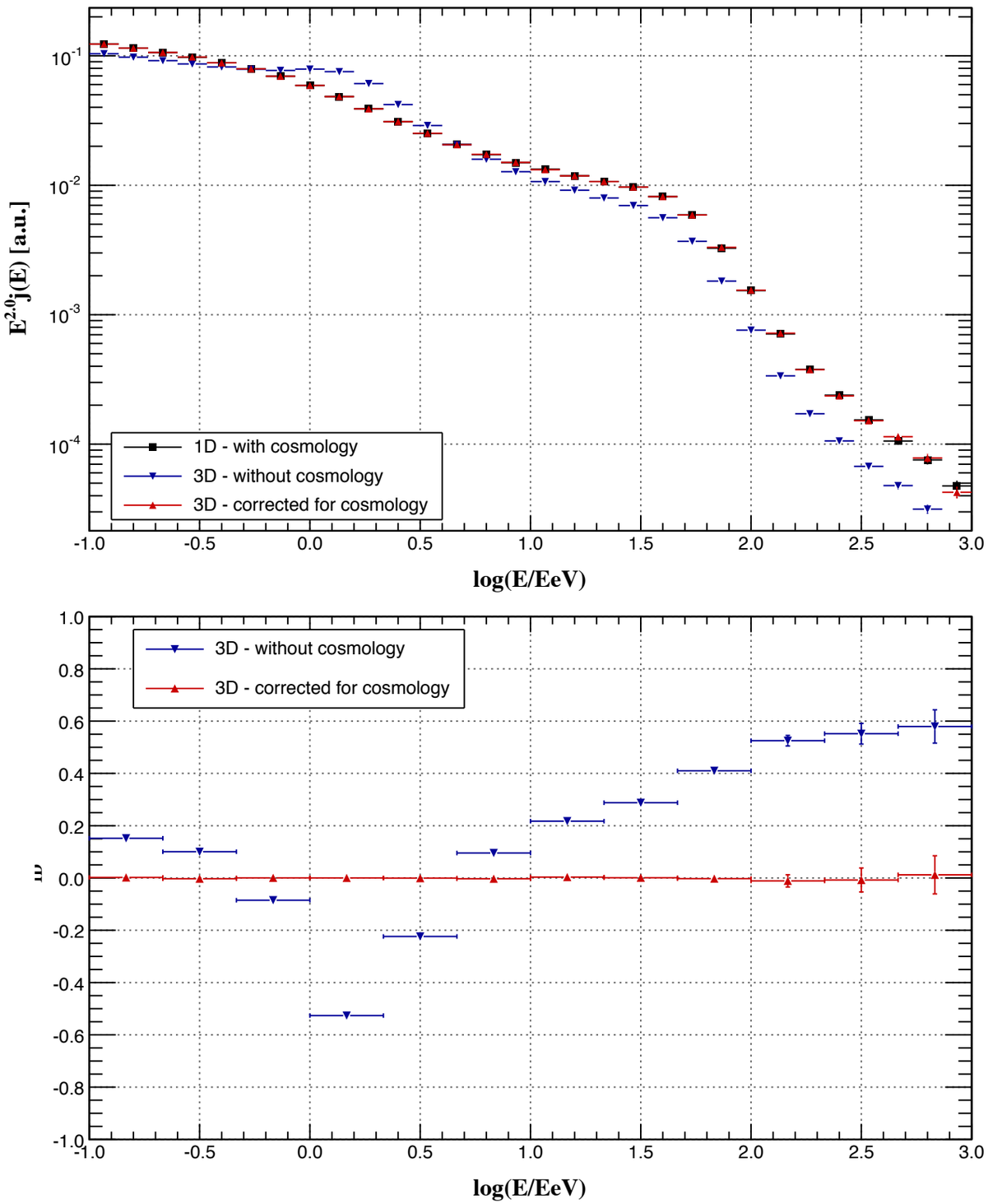


efficiency of the cosmology correction

proton



iron



- uniform source distribution
- sources up to 3000 Mpc
- injection spectrum source = -2.2
- maximum propagation length = 3000 Mpc

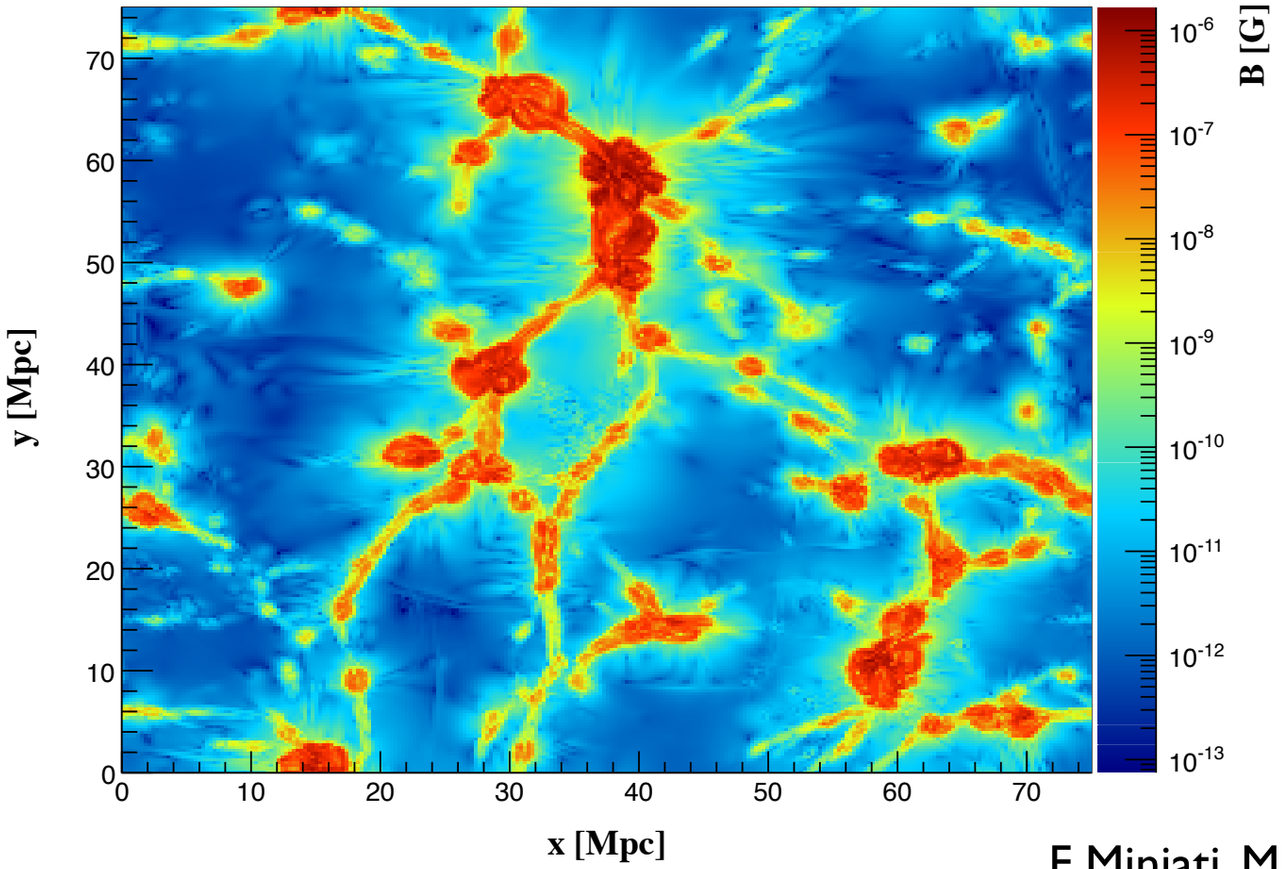
application: LSS and magnetic fields

simulation setup

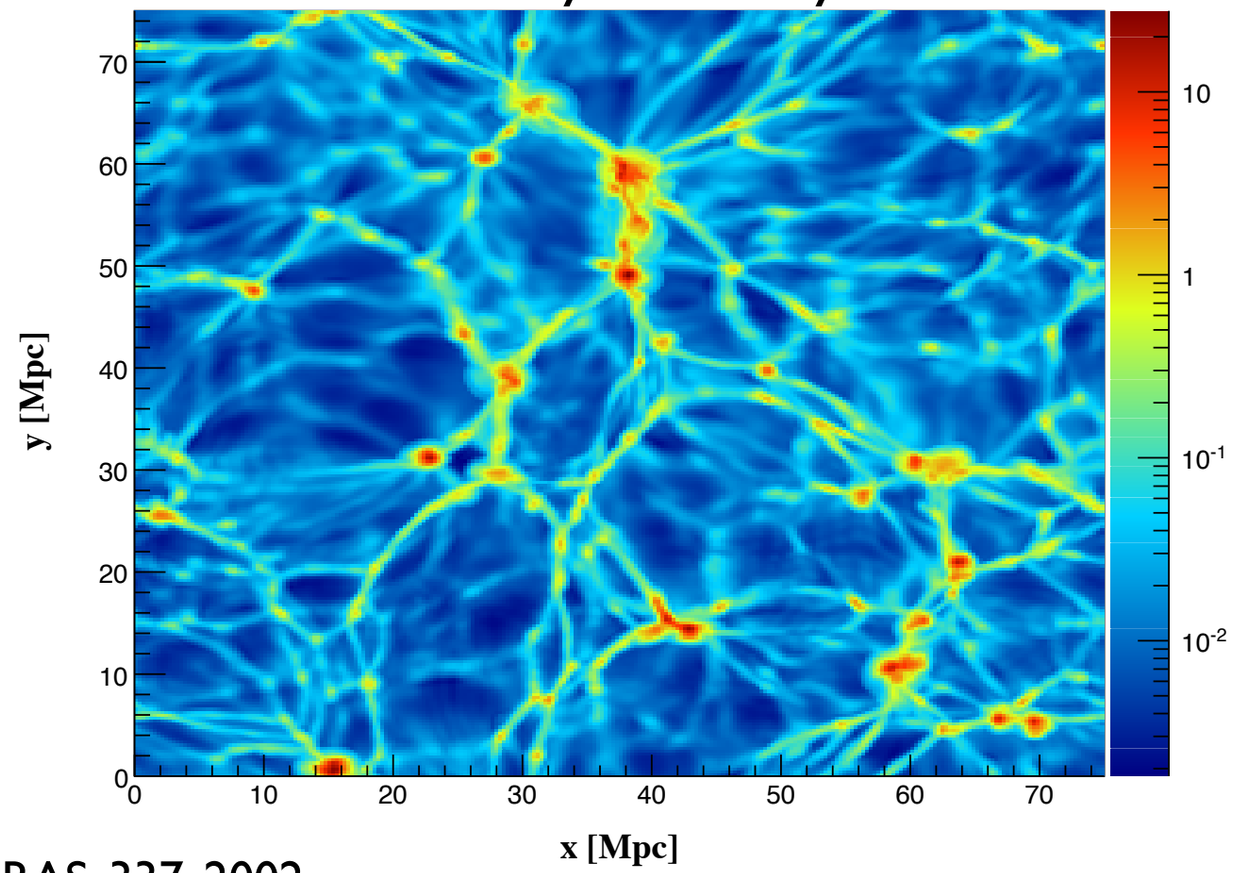
- ✦ source spectral index = -2.2
- ✦ minimum energy = 1 EeV
- ✦ maximum propagation time = 3000 Mpc

- ✦ cosmological parameters: H_0=67.04 km/s/Mpc, Ω_Λ=0.6817, Ω_m=0.3183
- ✦ "galactic" composition (Duvernois & Thayer, ApJ 465 (1996) 982.
- ✦ baryon density and magnetic fields shown below
- ✦ box size = 75 Mpc^3

magnetic field strength



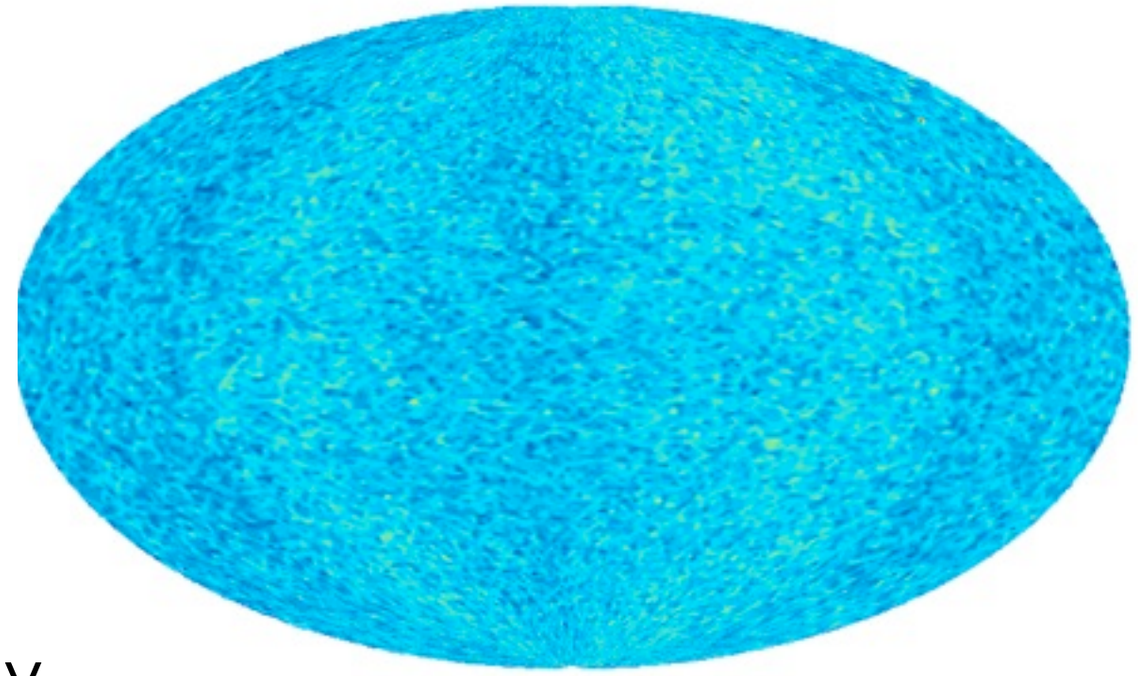
baryon density



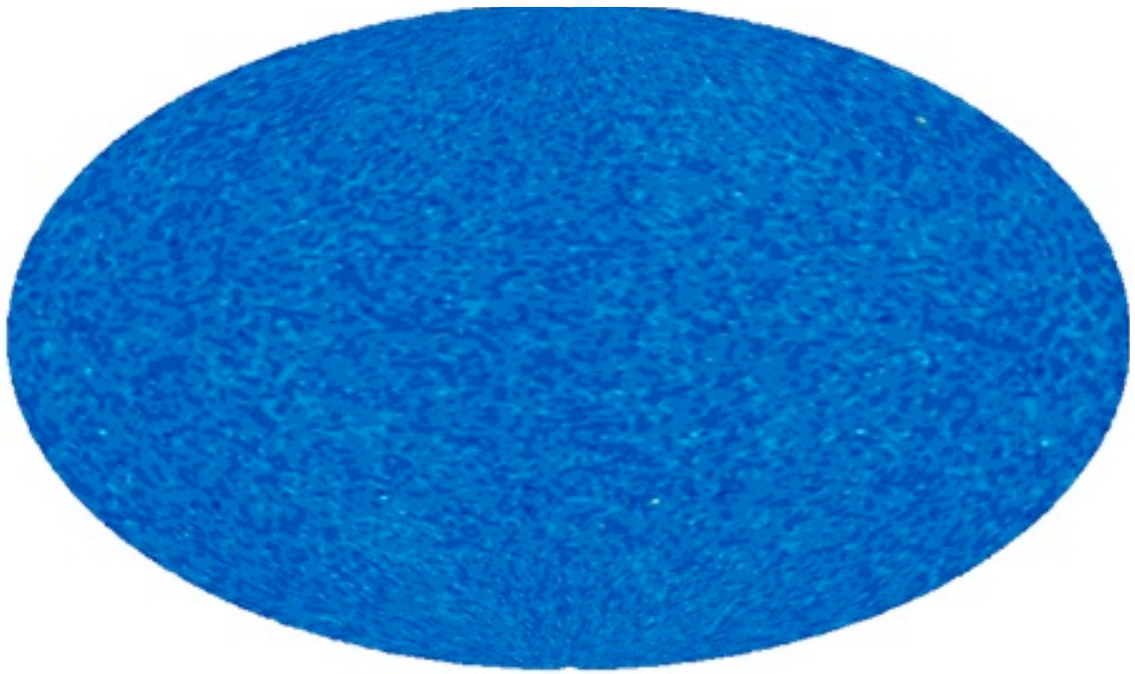
F. Miniati, MNRAS, 337, 2002.
Armengaud, Sigl, Miniati, PRD 72, 043009, 2005

applications: results

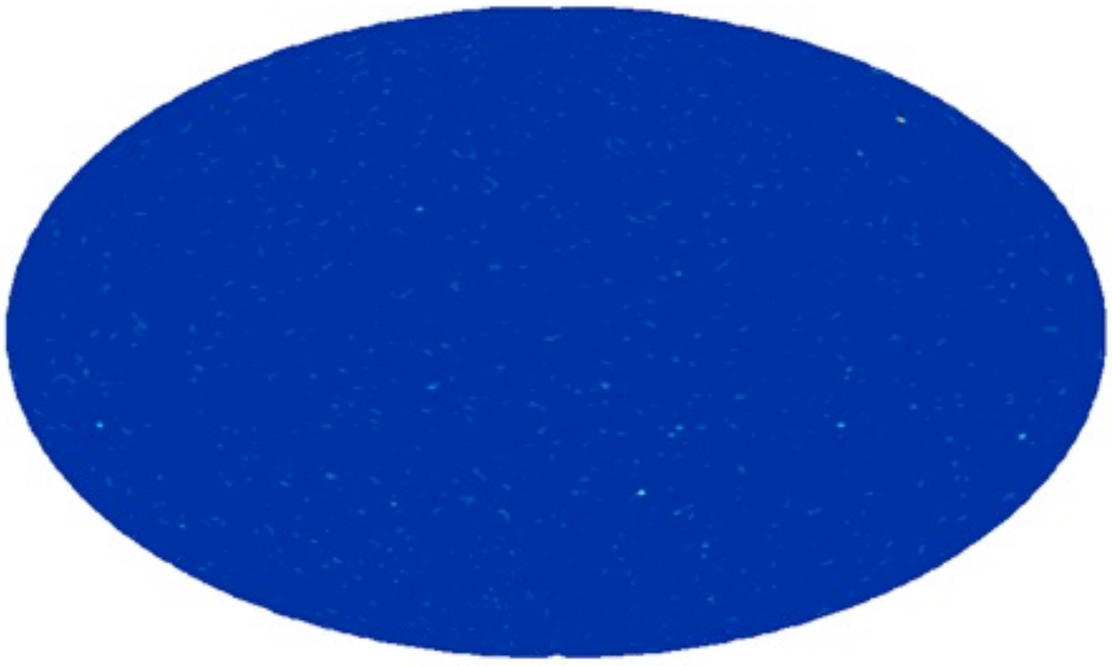
all energies



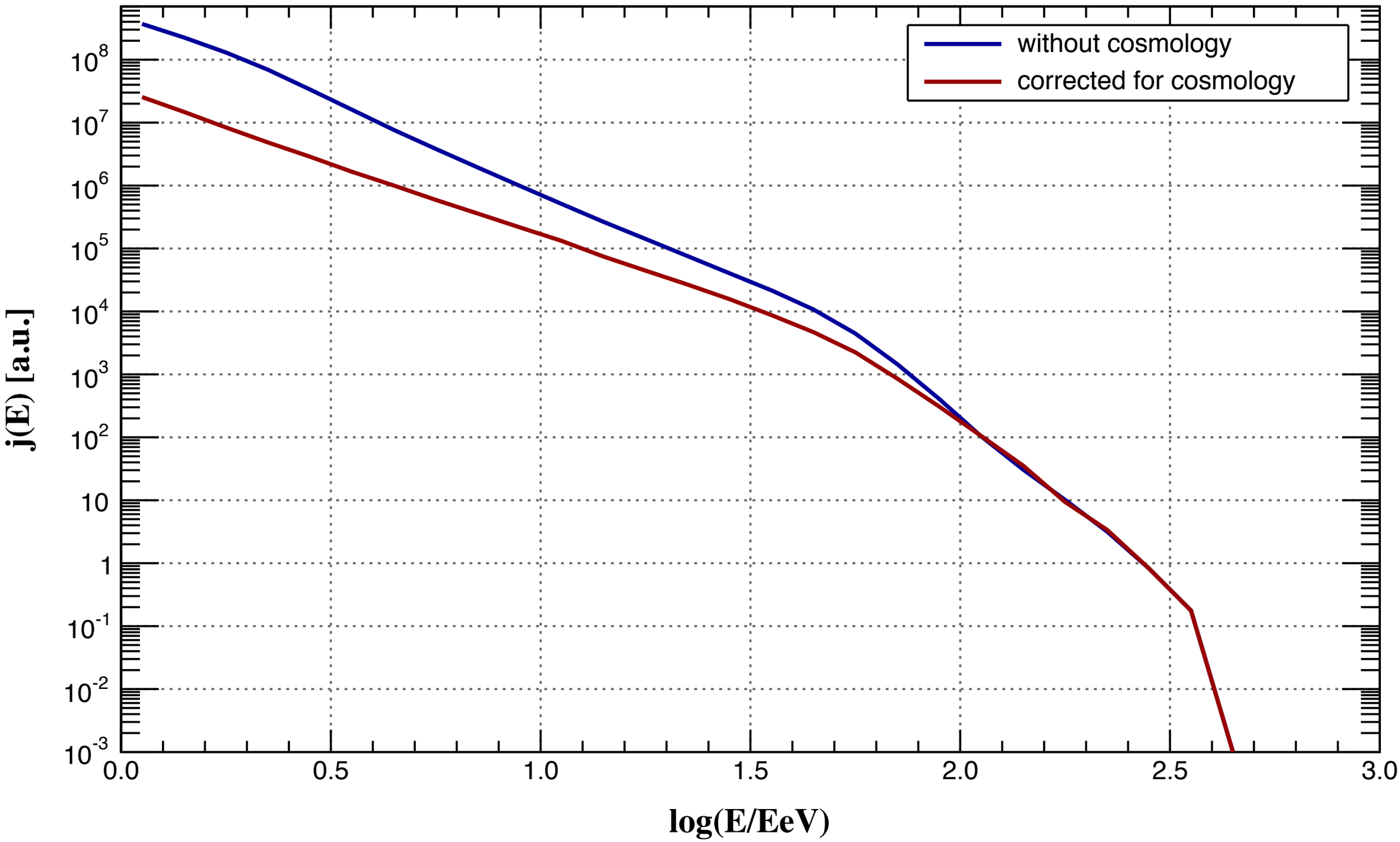
E>20 EeV



E>50 EeV



applications: results



conclusions and perspectives

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

✦ we can propagate UHECRs through the universe considering all relevant sources of energy losses

✦ it was shown that an a posteriori correction to the spectrum can account for energy losses of UHECR due to cosmological effects

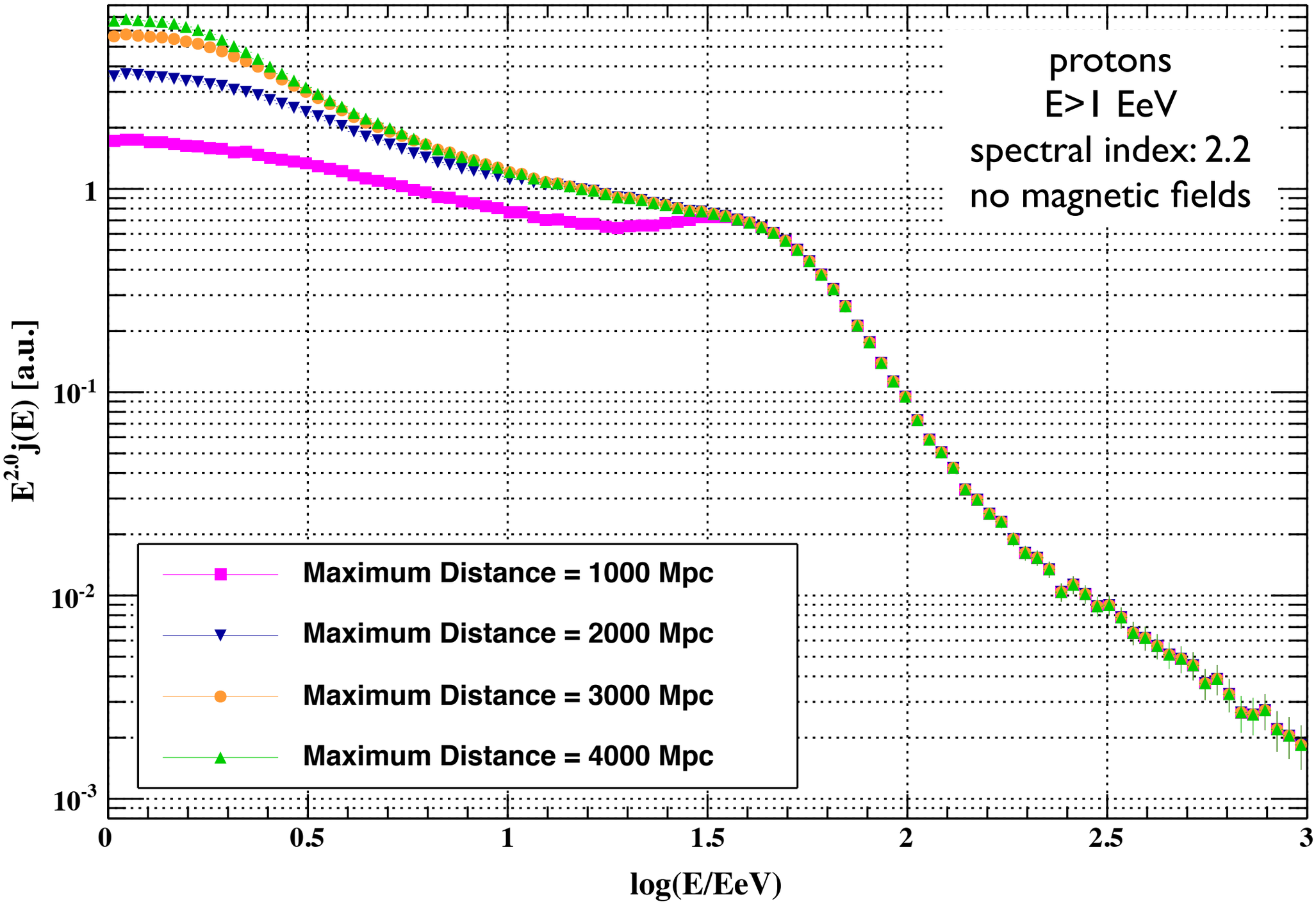
✦ it is possible to take into account magnetic fields and large scale structures, as well as cosmological effects, when propagating these particles => realistic simulations

✦ in the future: fit spectrum, composition and anisotropies?

✦ 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

Backup Slides

effects of source distribution



effects of source distribution