Propagation of UHECRs over cosmological distances

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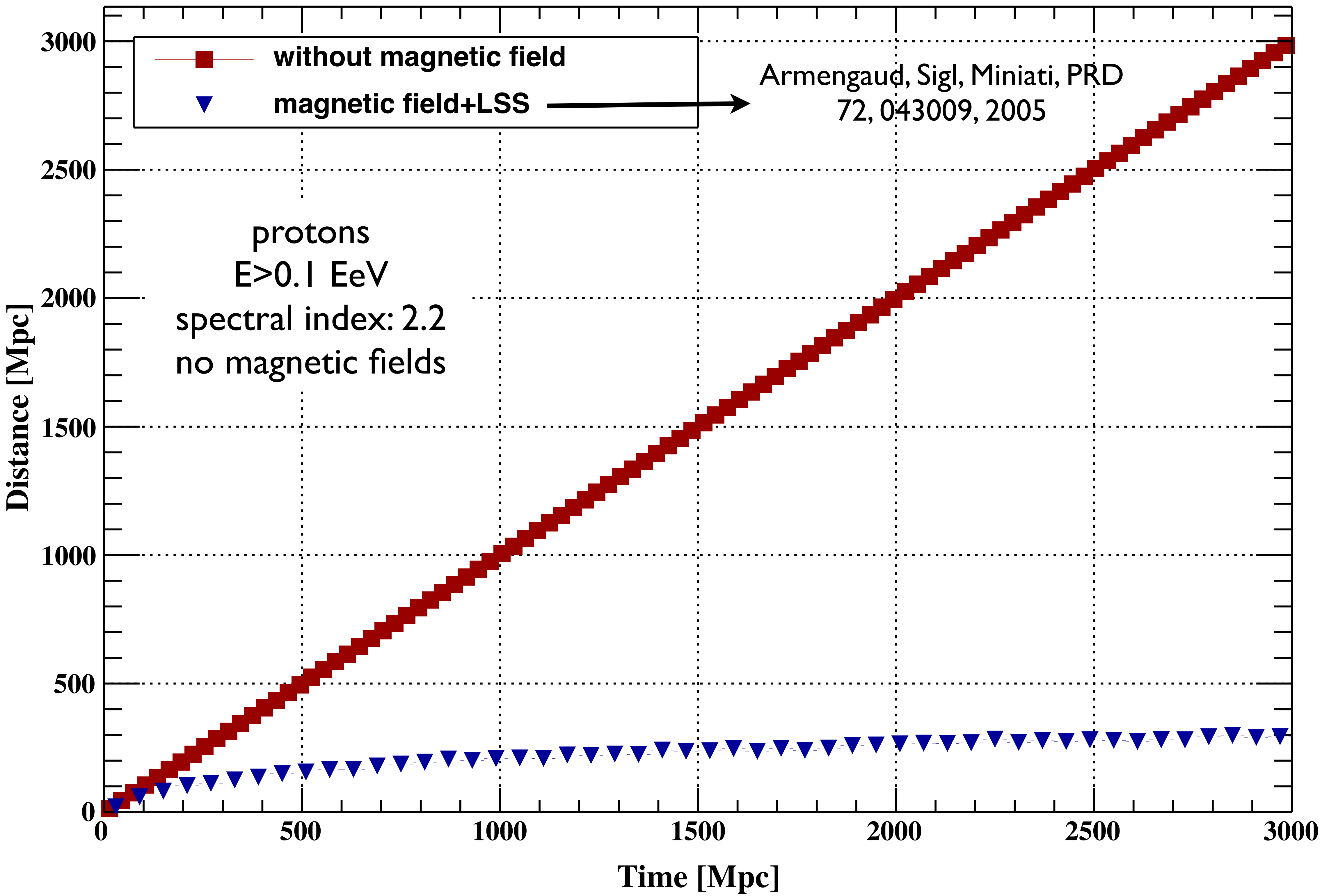
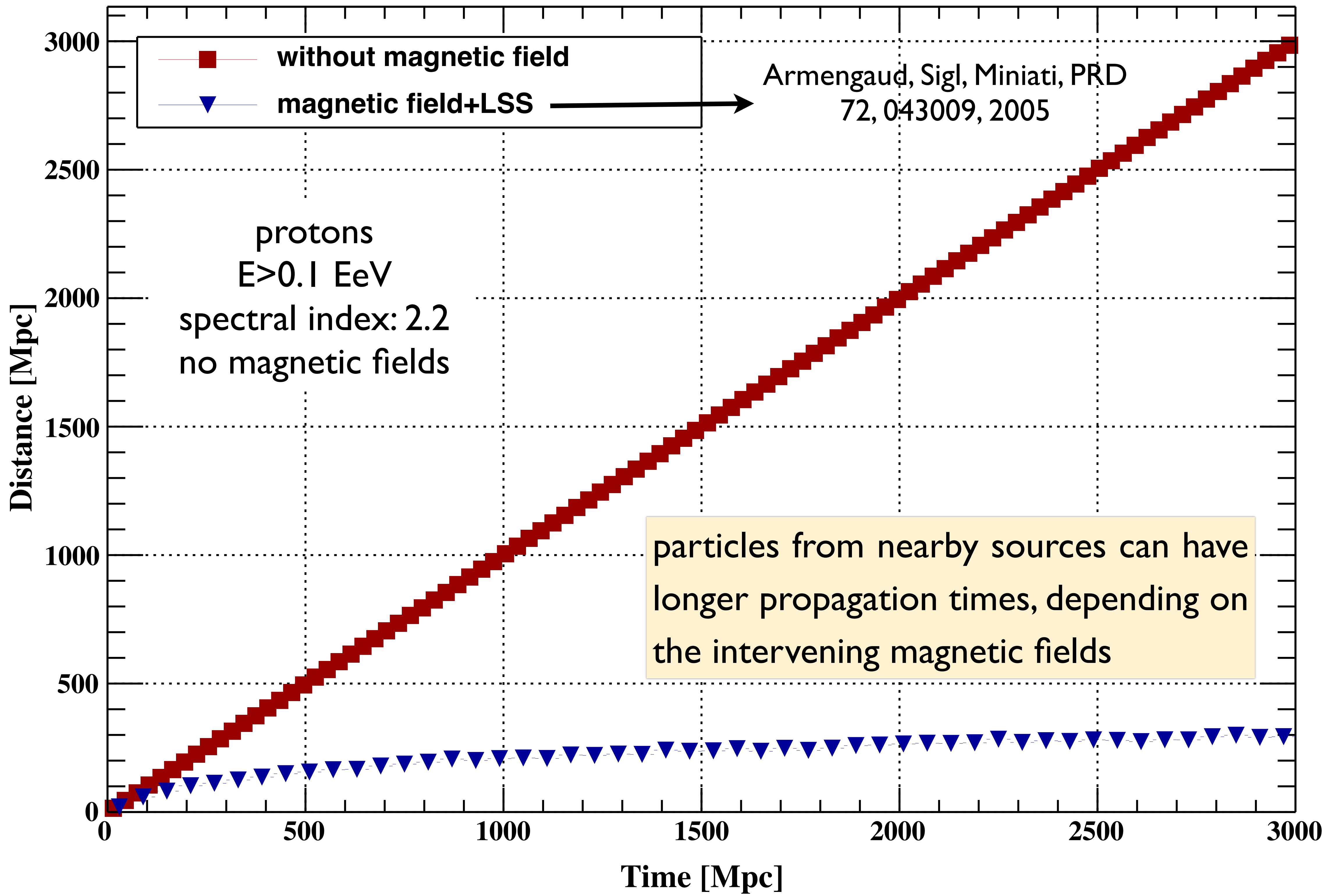
motivation: magnetic fields

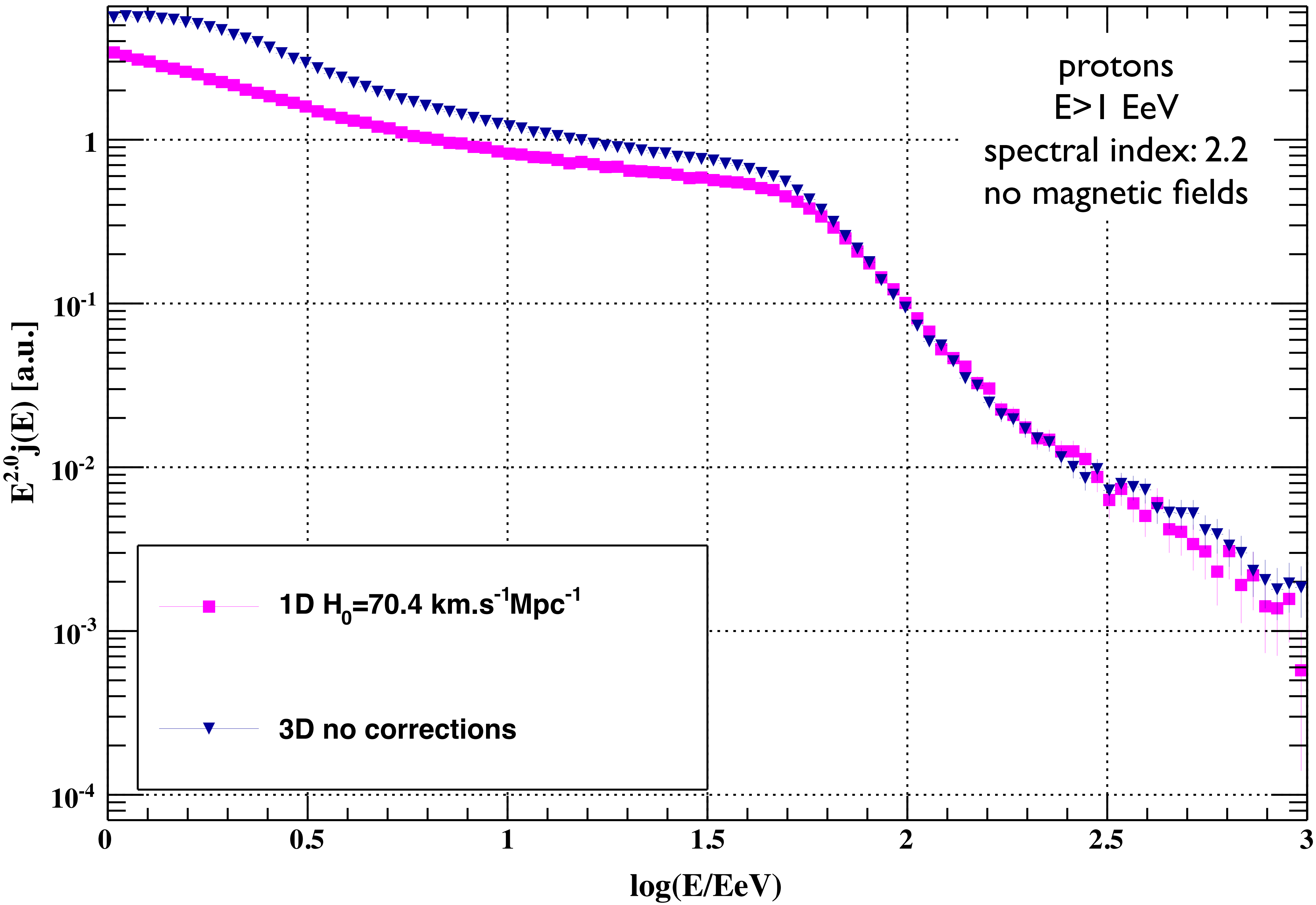


motivation: magnetic fields



particles from nearby sources can have longer propagation times, depending on the intervening magnetic fields

motivation: 1D vs. 3D simulations



CRPropa and 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

✦ Astropart. Phys. 42:41, fev., 2013

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

energy losses of UHE protons

pair production

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

pion production

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + 2\gamma$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu$$

redshift losses

- ✦ scale parameter and redshift

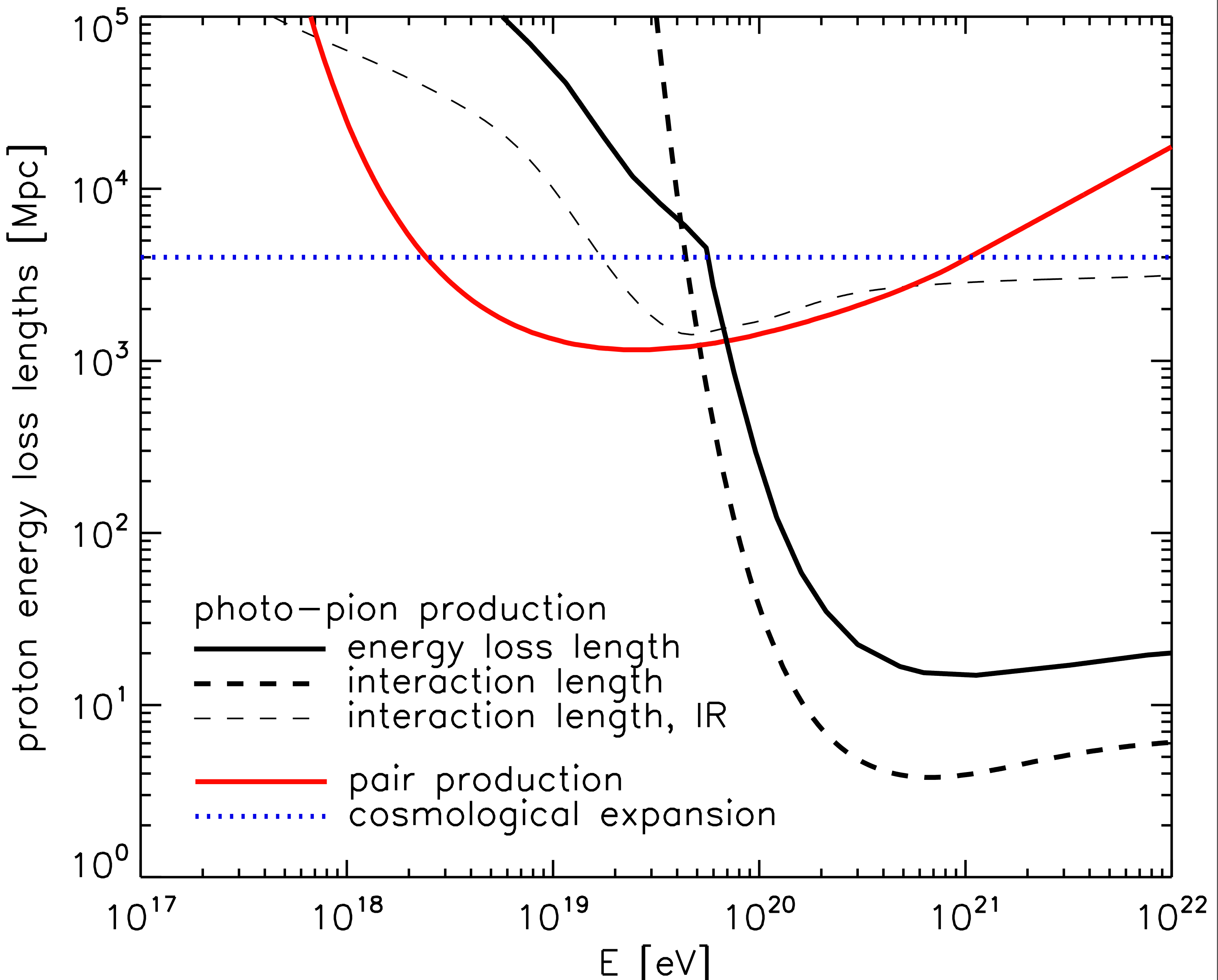
$$a(t) = \frac{1}{1+z}$$

- ✦ redshift evolution

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

- ✦ energy losses

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



from Kotera, Olinto. Annu. Rev. Astron. Astrophys., 49, 2010.

the method

✦ “force” the spectrum to be equal for 1D and 3D

✦ use injected energy, propagation time and observed energy

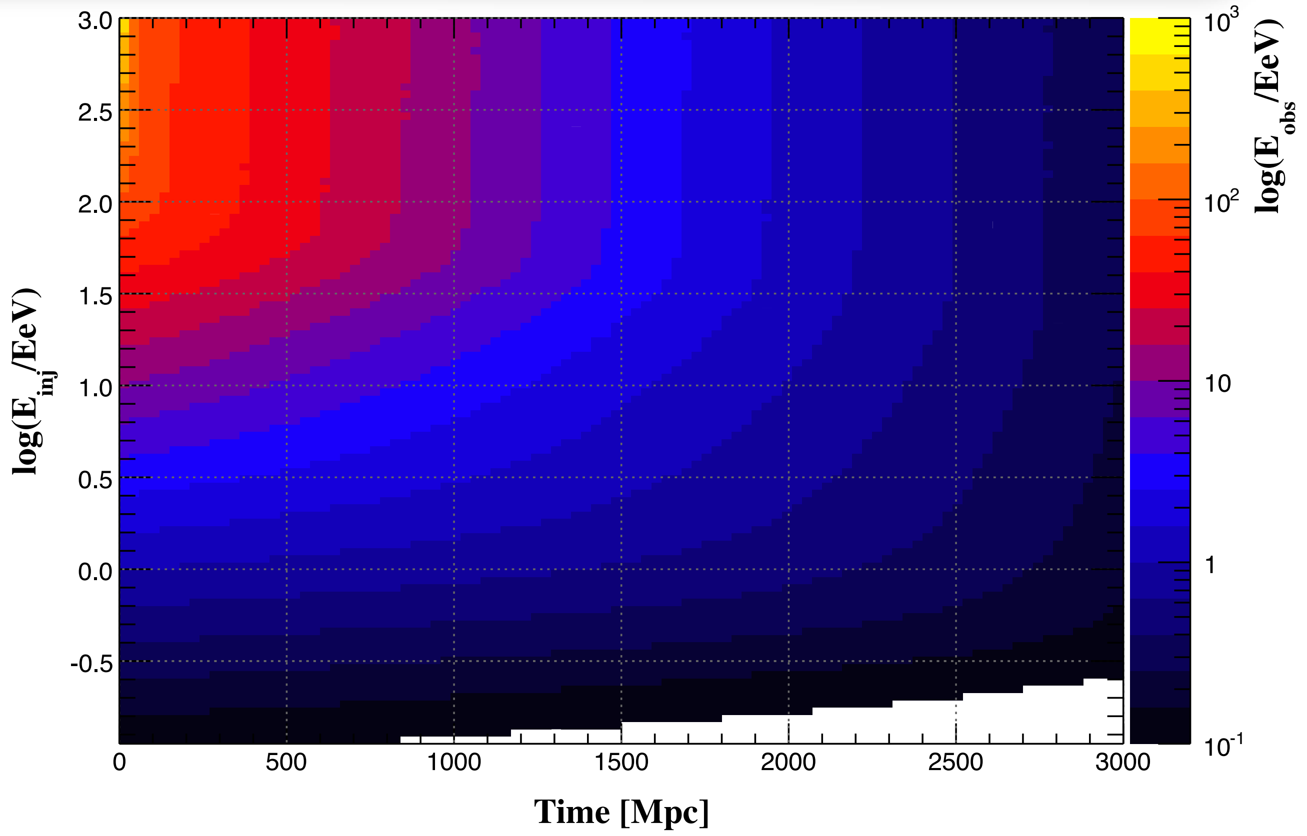
✦ obtain a (binned) correction table

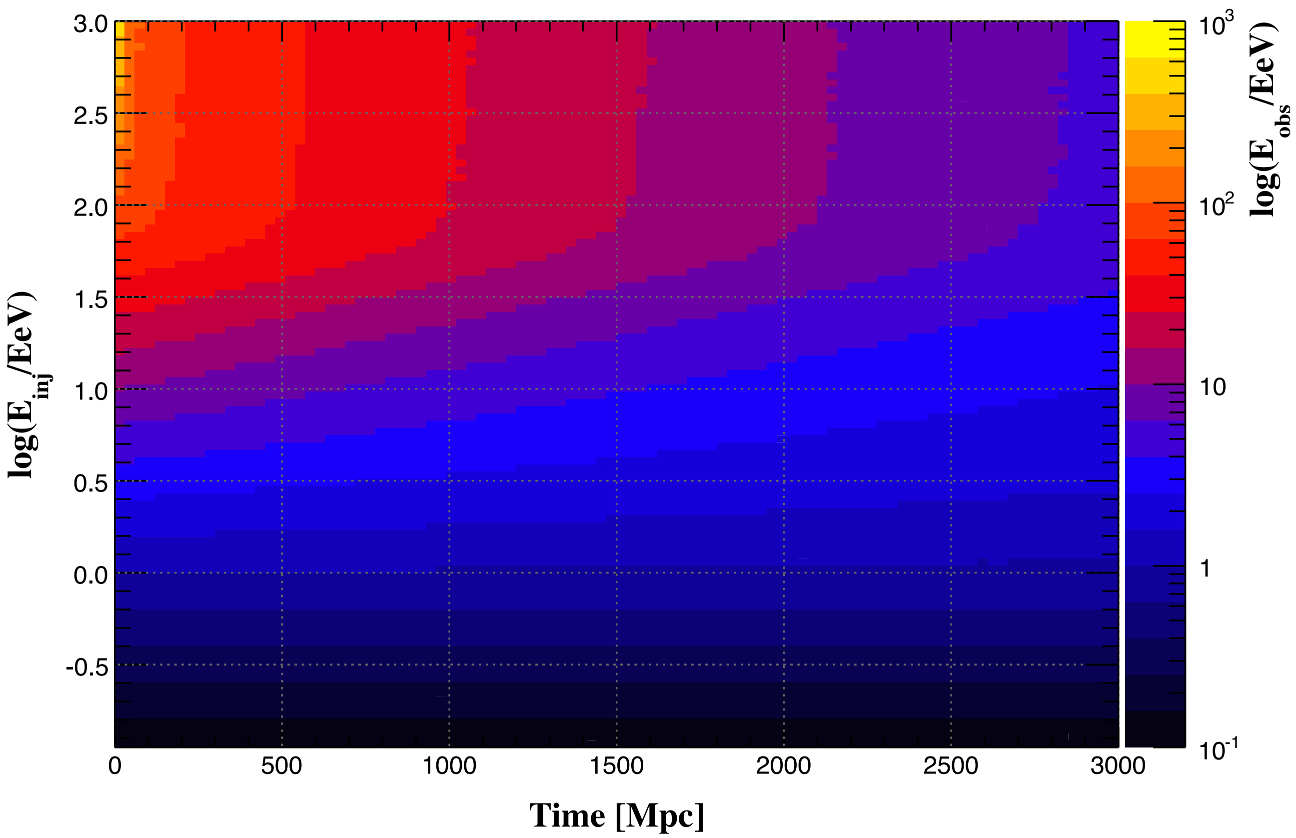
✦ analysis only for **protons** (so far)

✦ extract a correction factor from the table

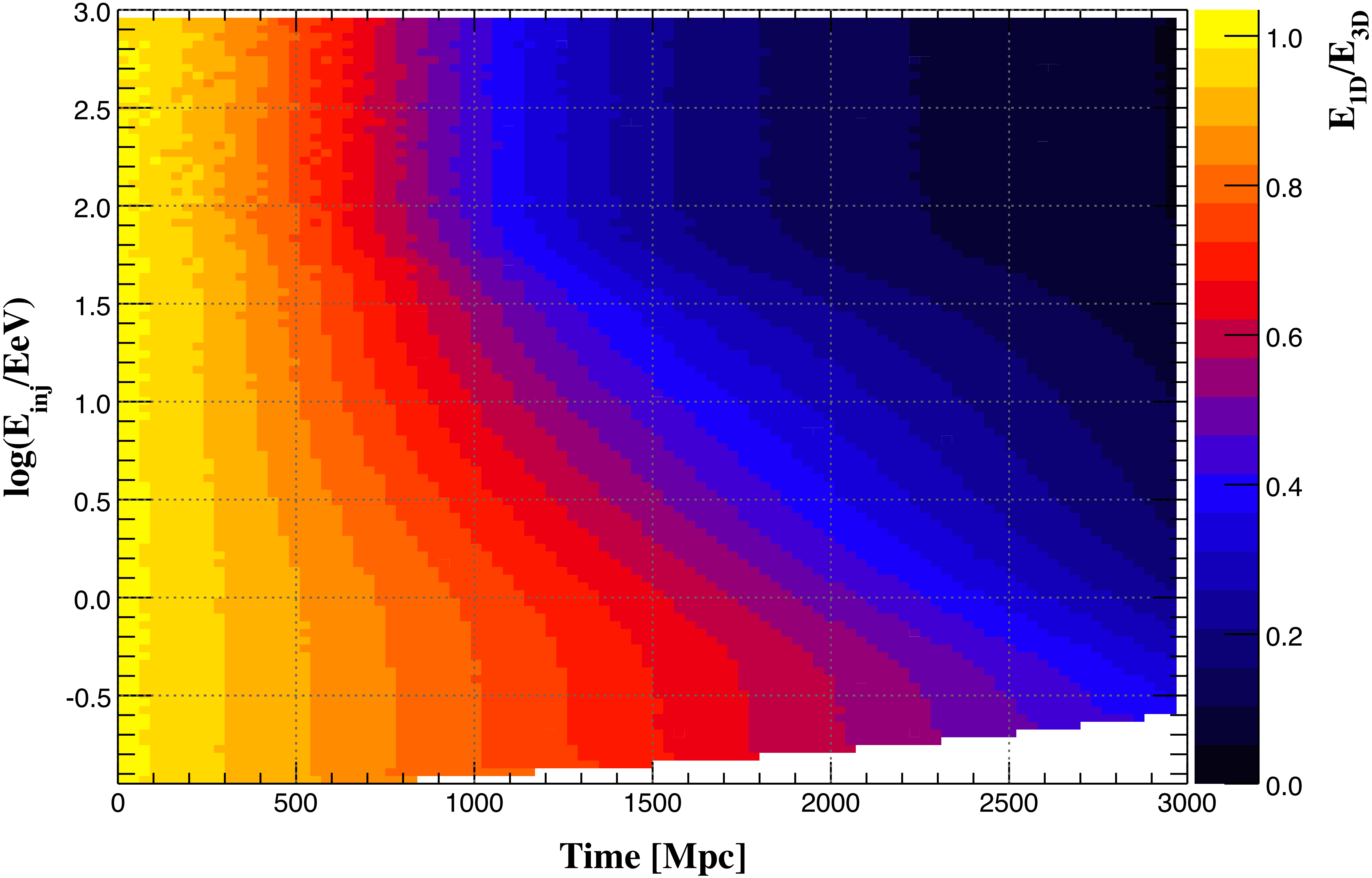
✦ use this factor to correct the spectrum (a posteriori)

✦ correction applied to the propagation time and not the distance



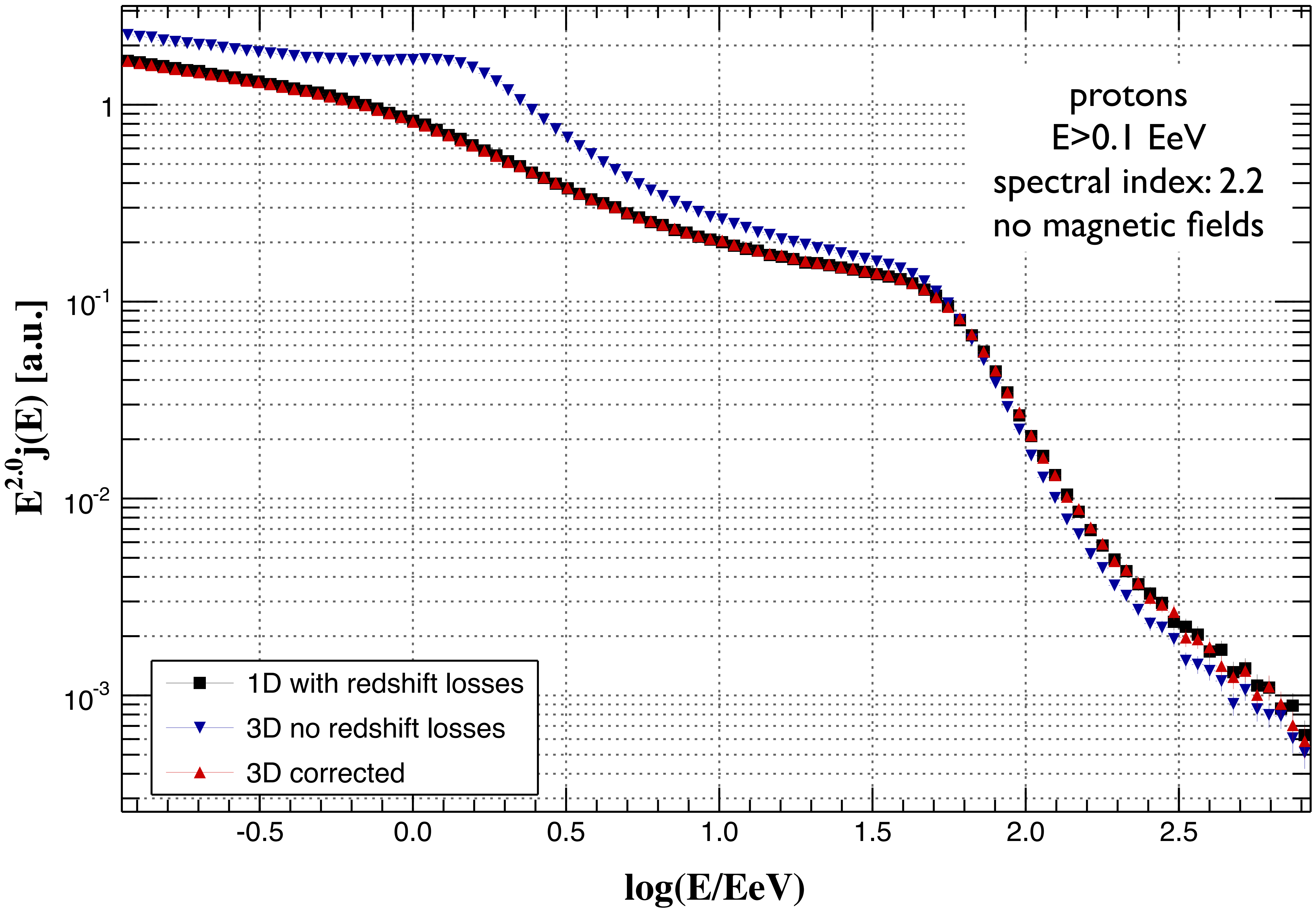


the method

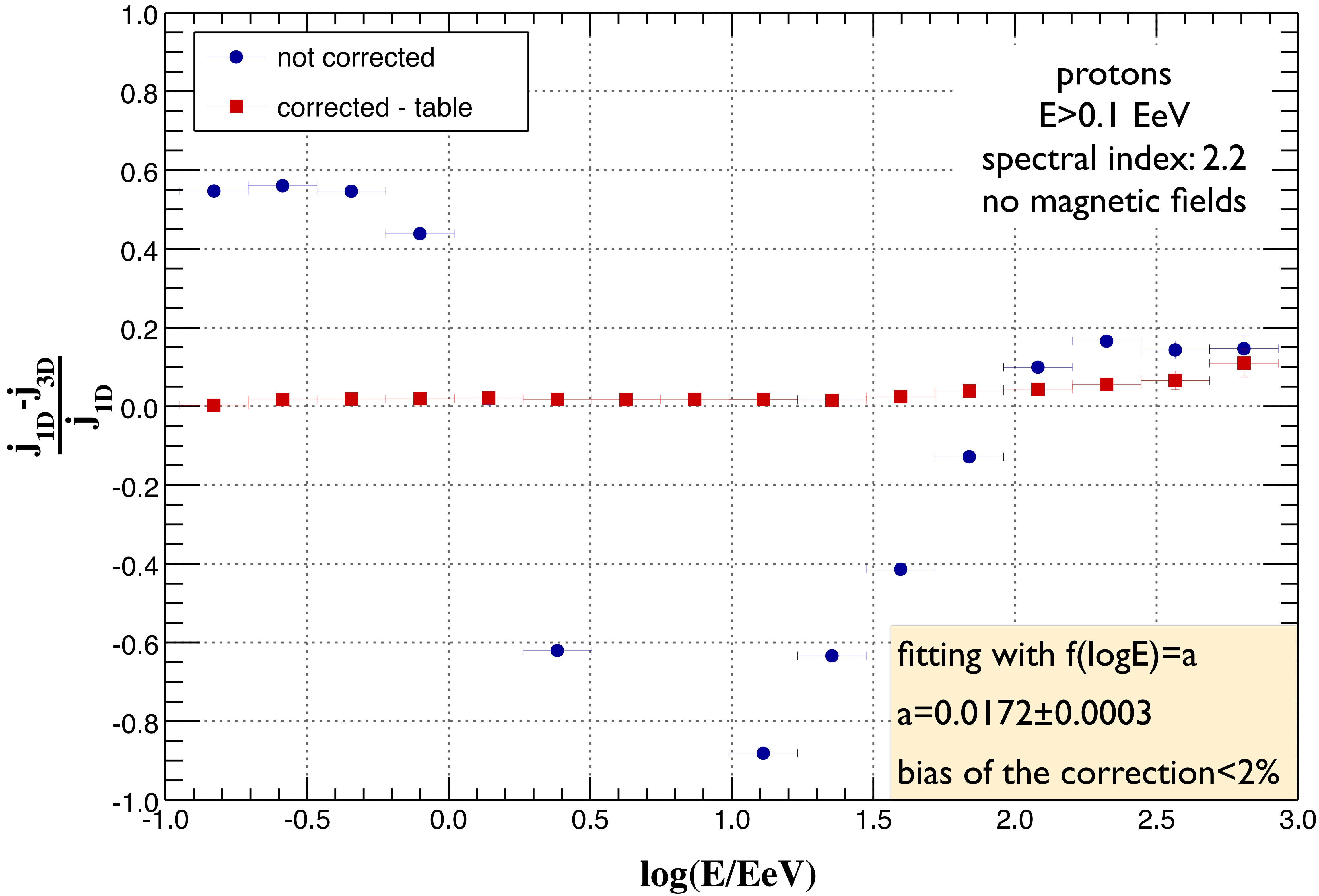


3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
$\log(E_{inj}/EeV)$
0
500
1000
1500
2000
2500
3000
Time [Mpc]
1.0
0.8
0.6
0.4
0.2
0.0
E_{1D}/E_{3D}

results

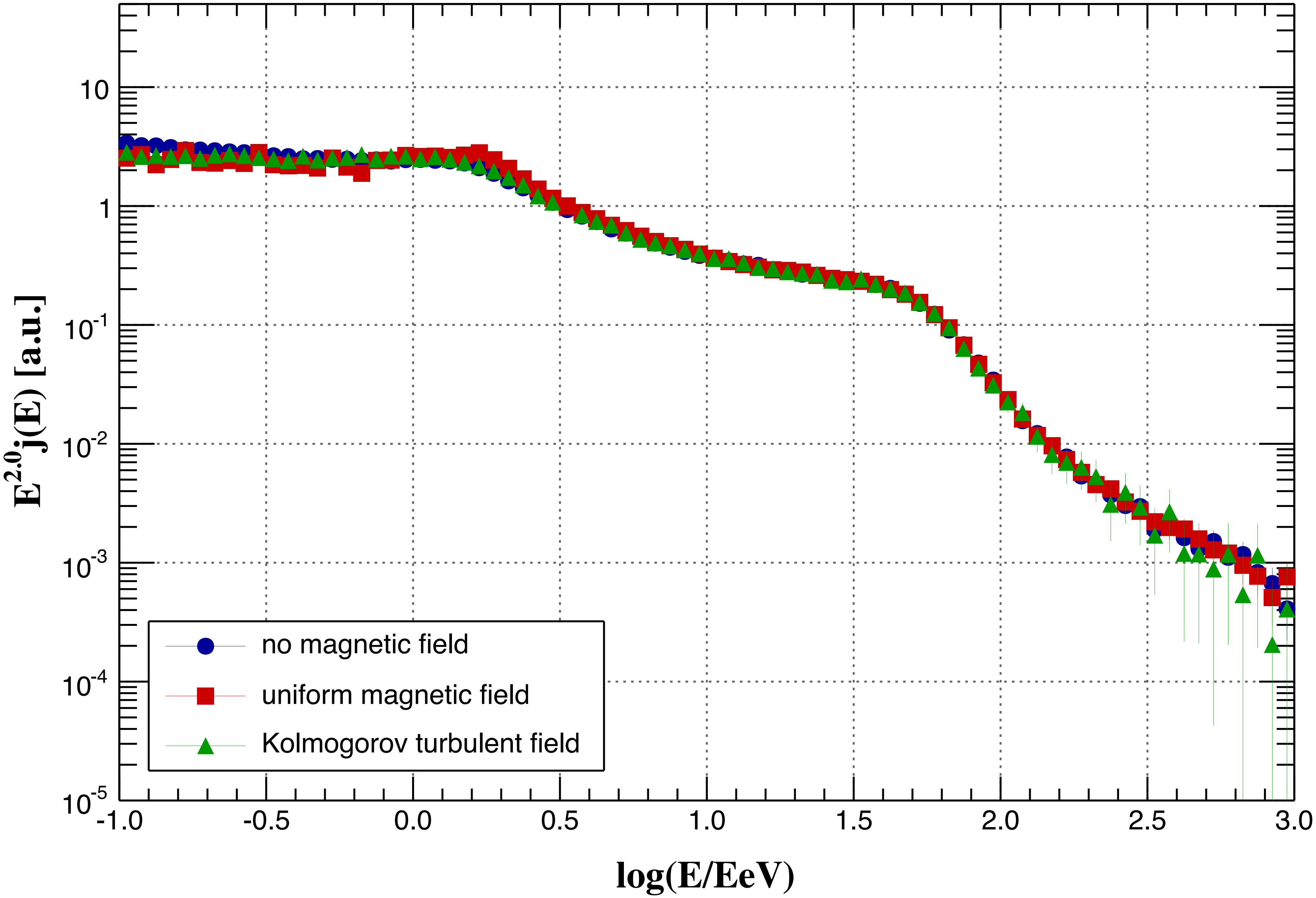

protons
E>0.1 EeV
spectral index: 2.2
no magnetic fields
1D with redshift losses
3D no redshift losses
3D corrected
$E^{2.0}j(E)$ [a.u.]
log(E/EeV)
1
10^{-1}
10^{-2}
10^{-3}
-0.5
0.0
0.5
1.0
1.5
2.0
2.5

results

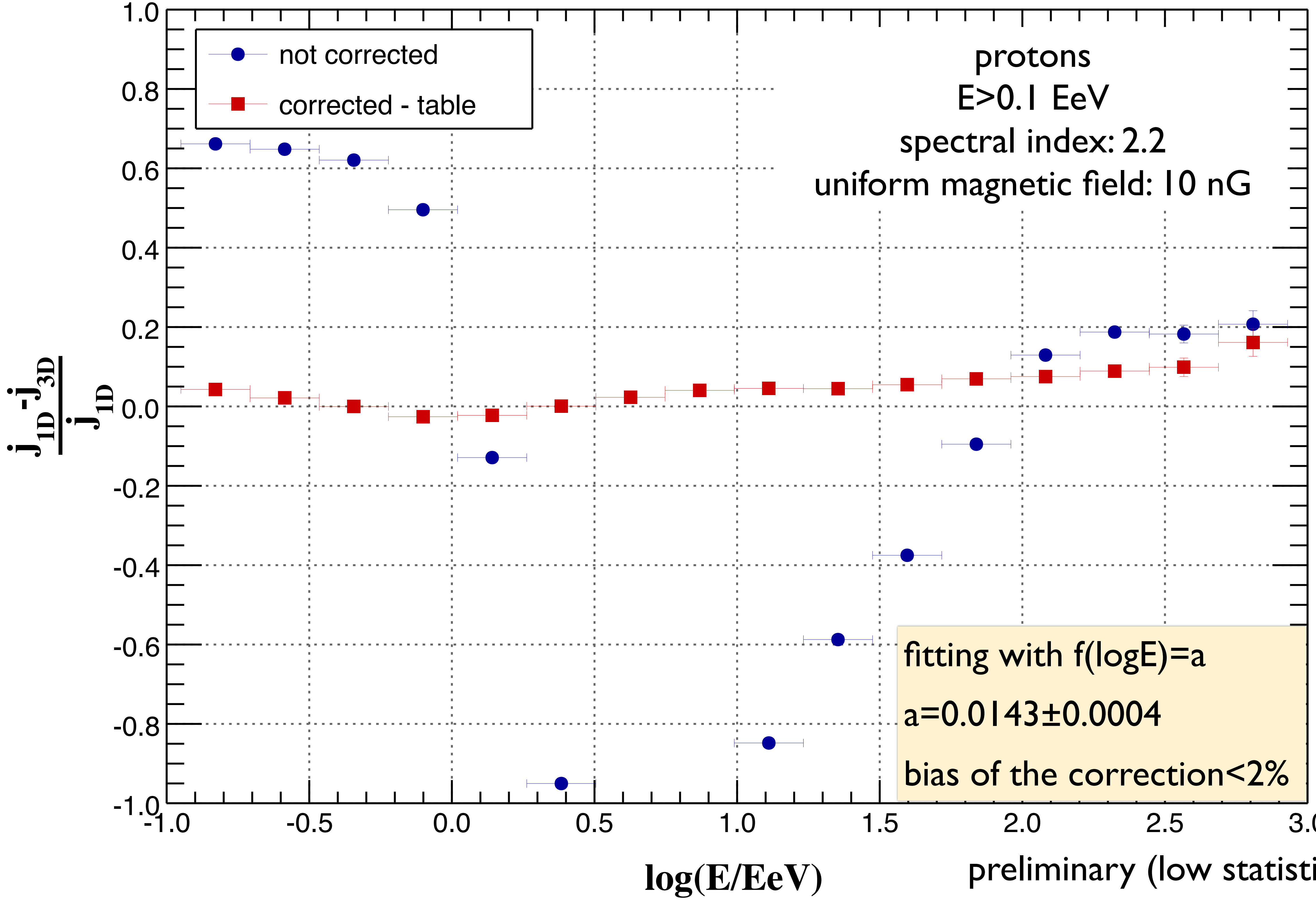

not corrected
corrected - table
protons
E>0.1 EeV
spectral index: 2.2
no magnetic fields
fitting with f(logE)=a
a=0.0172±0.0003
bias of the correction<2%
$\frac{j_{1D} - j_{3D}}{j_{1D}}$
log(E/EeV)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0

the propagation theorem

"for a uniform distribution of identical sources with separation much less than the characteristic propagation lengths, the diffuse spectrum of UHECRs has a universal (standard) form, independent of the mode of propagation" Aloisio, Berezinsky. ApJ., 612, 2004.

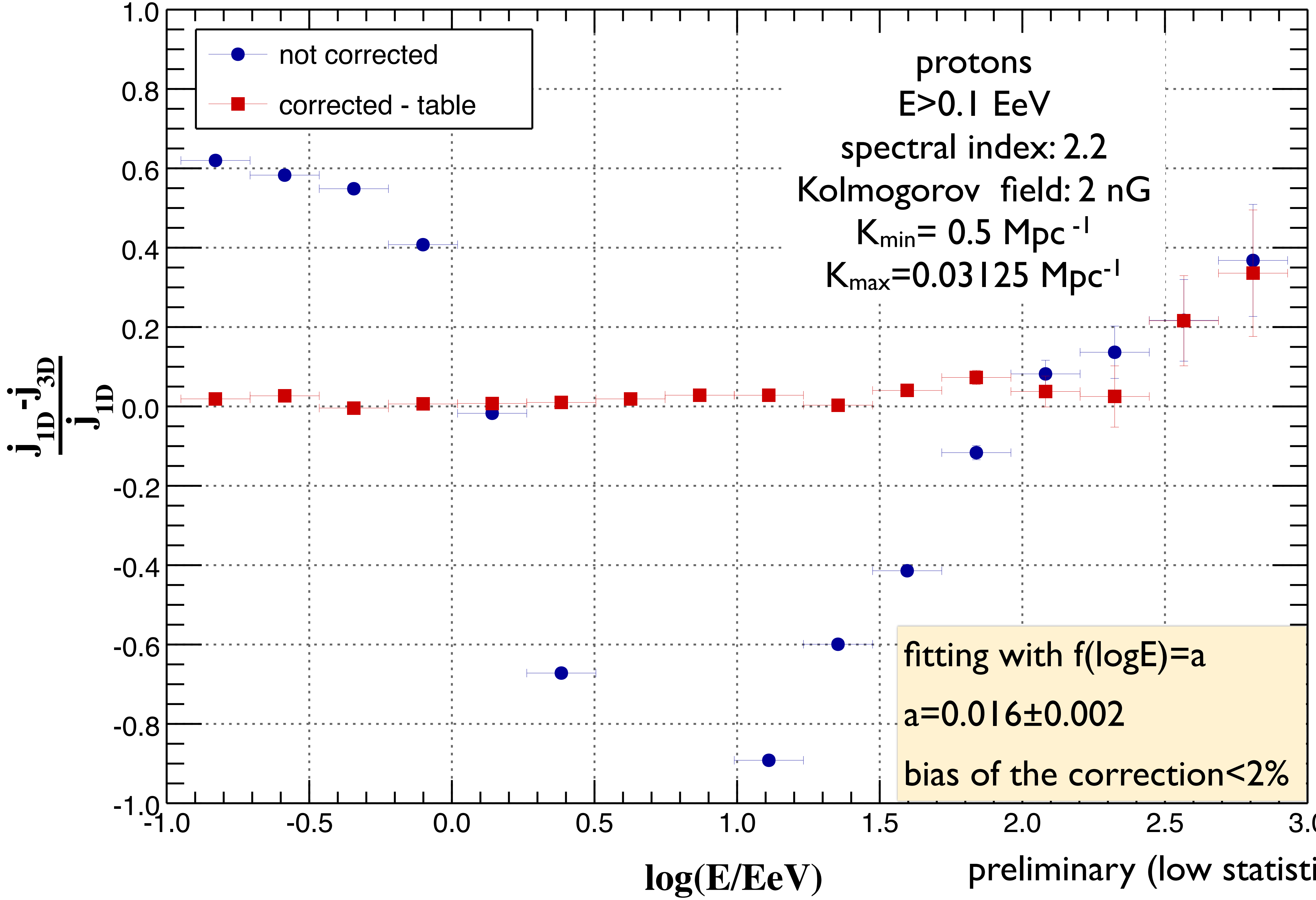


results: uniform magnetic field



preliminary (low statistics)

results: Kolmogorov magnetic field



preliminary (low statistics)

conclusions and perspectives

conclusions

✦ an a posteriori correction to the spectrum can account for energy losses of UHE protons due to the expansion of the universe

✦ this correction is applied to the propagation time and not the distance, and thus is applicable to simulations with magnetic fields

✦ it is possible to take into account magnetic fields and large scale structures when propagating these particles

perspectives

✦ attempt to correct the spectrum for nuclei

✦ incorporate these developments into the existing CRPropa code

Backup Slides

parameters

simulation parameters 1D

- ✦ comoving source evolution: $(1+z)^4$, $z_{max}=2$
- ✦ ΛCDM
- ✦ $\Omega_\Lambda=0.734$, $\Omega_m=0.266$, $H_0=70.4$ km/s/Mpc
- ✦ maximum rigidity: 1000 EeV
- ✦ minimum energy: 0.1 EeV
- ✦ injection spectrum $\propto E^{-2.2}$
- ✦ normalization: > 70 EeV

parameters

simulation parameters 3D (no mag. fields)

- ✦ homogeneous source distribution
- ✦ maximum time: 4000 Mpc
- ✦ maximum rigidity: 1000 EeV
- ✦ minimum energy: 0.1 EeV
- ✦ injection spectrum $\propto E^{-2.2}$
- ✦ normalization: > 70 EeV
- ✦ detection: sphere (radius=0.5 Mpc) around observer

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✦ homogeneous source distribution

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✦ Kolmogorov field: coherence length

$$L_c = \frac{L_{max}}{2} \frac{\alpha - 1}{\alpha} \frac{1 - \left(\frac{L_{min}}{L_{max}}\right)^{\alpha}}{1 - \left(\frac{L_{min}}{L_{max}}\right)^{\alpha - 1}}$$

redshift losses

redshift losses

- ✦ scale parameter and redshift

$$a(t) = \frac{1}{1+z}$$

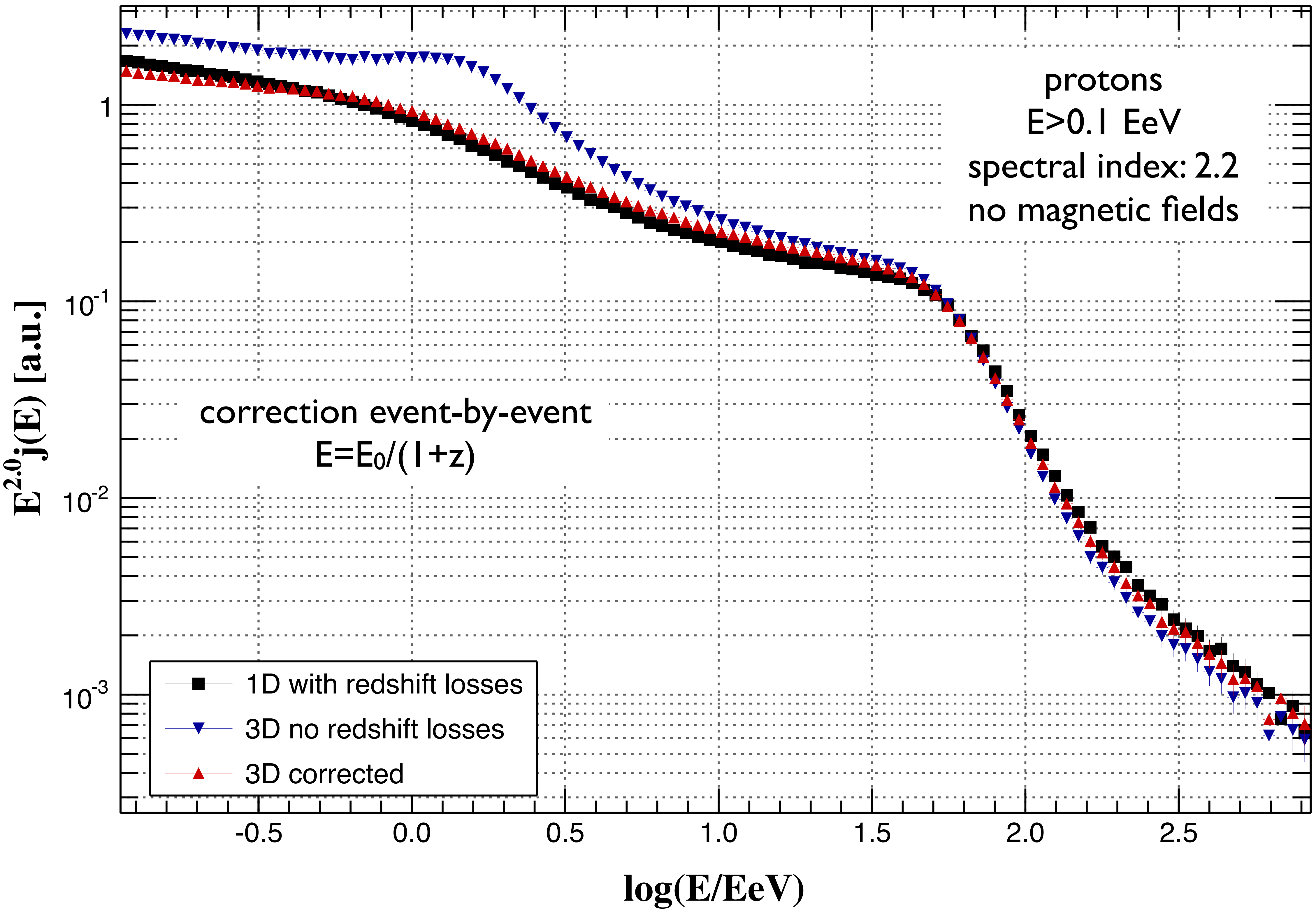
- ✦ redshift evolution

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

- ✦ energy losses

$$\frac{dE}{dt} = -H_0 E$$

correction using the formula



correction using the formula