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Propagation of UHECRs in the Universe and CRPropa

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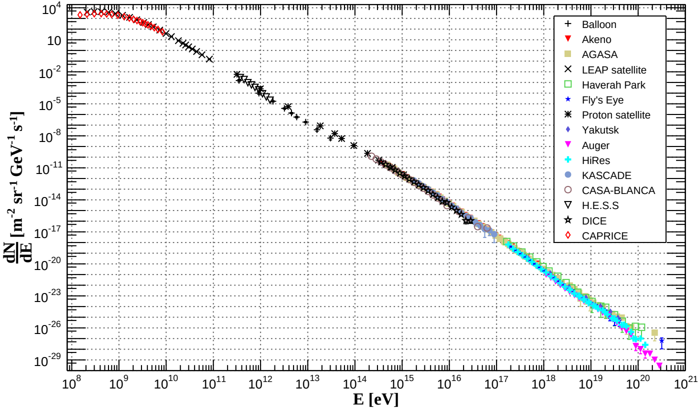
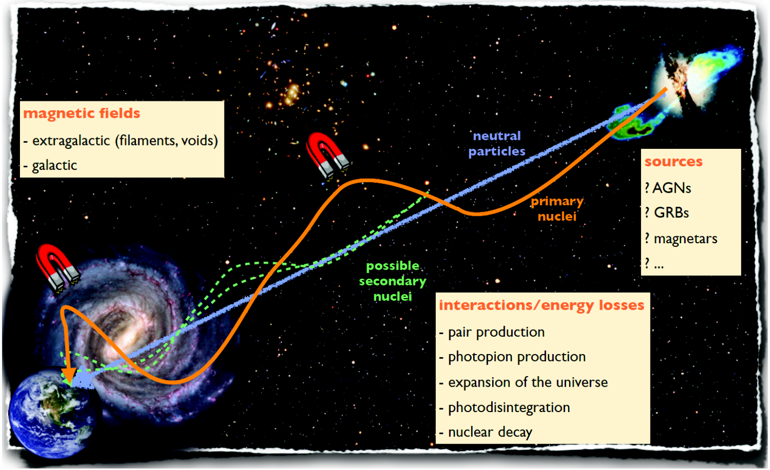
the UHECR spectrum



propagation: general picture



interaction processes and energy losses

pion production

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

pair production

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

expansion of the universe

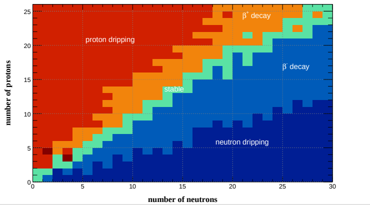
$$\frac{dt}{dz} = \frac{1}{H_0}\frac{1}{1+z}\frac{1}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

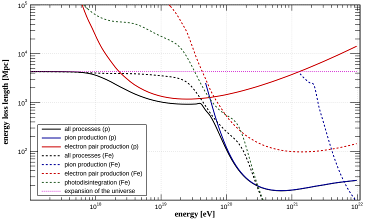
$$E = E/(1+z)$$

photodisintegration

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

nuclear decay





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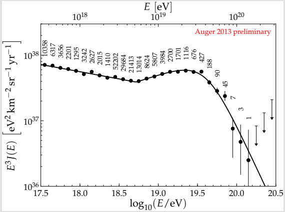
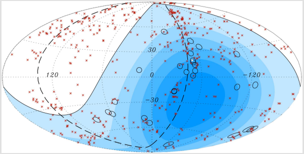
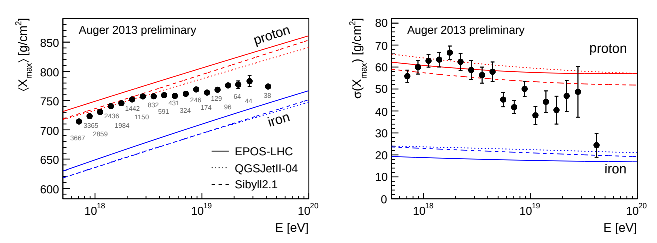
spectrum



anisotropy



composition



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- explain these observables (spectrum, composition and anisotropy)
- fit the spectrum and composition might not be enough to determine astrophysical scenarios to explain UHECRS anisotropies can play an important role
- role of galactic and extragalactic magnetic fields are not fully understood $\longrightarrow$ 3D simulations
- need to span a wide range of parameters $\longrightarrow$ fast simulations

CRPropa

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- Monte Carlo code for propagating UHECRs, secondary γ rays and neutrinos
- history
  - CRPropa 1 [Armengaud *et al.* Astropart. Phys. 28 (2007) 463.] **old**
  - CRPropa 2 [Kampert *et al.* Astropart. Phys. 42 (2013) 41-51.] **current**
  - CRPropa 3 [Alves Batista *et al.* Proceedings 33rd ICRC.] **development**
- code available in crpropa.desy.de
- modes: 1D, 3D and 4D (not fully tested)

1D mode

- redshift losses
- souce evolution
- no magnetic deflections

3D mode

- effects of large scale distribution of matter (MHD simulations)
  - uniform grids
  - SPH
  - AMR (under development)
- extragalactic magnetic fields (e.g. turbulent, uniform, MHD simulations)
- galactic magnetic field $\longrightarrow$ lensing technique

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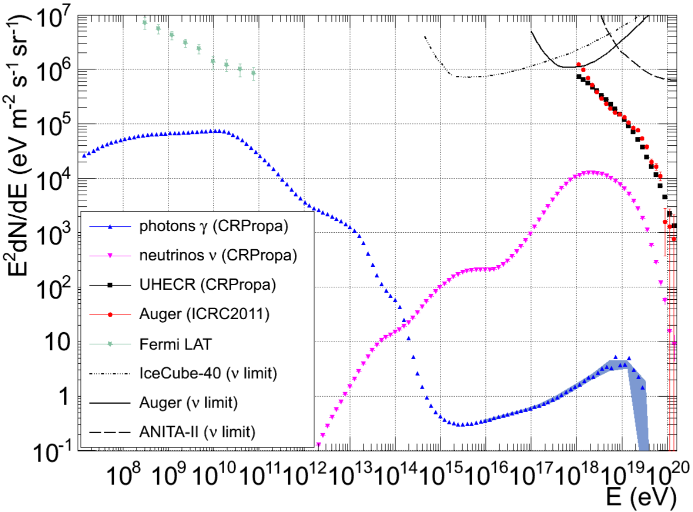

Kampert *et al.* Astropart. Phys. 42 (2013) 41-51.

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cosmology in 3D: what is the problem?

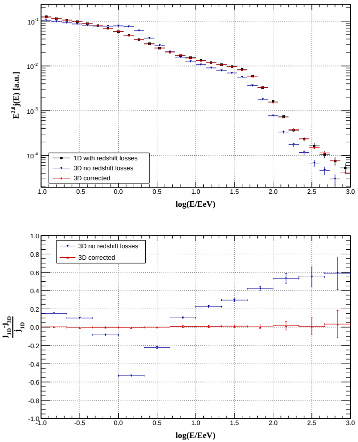
- in 1D we always know the distance between the current position of the particle and the observer
- if there are magnetic fields (3D) we don't know this information $\rightarrow$ it is not possible to know before hand the position (therefore redshift) of a particle due to magnetic deflections
- a trivial solution is a 4D simulation $\rightarrow$ time consuming (not viable)

correcting for cosmology in 3D simulations

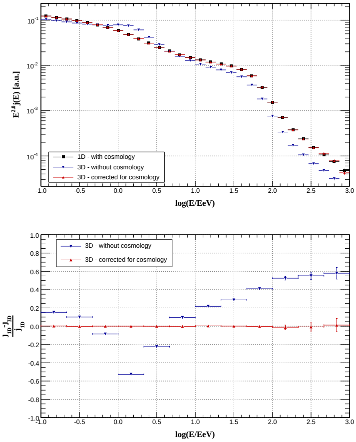
- from a 3D simulation we get: E_i^{3D}, E_f^{3D}, (A_i^{3D}, Z_i^{3D}), (A_f^{3D}, Z_f^{3D}), T^{3D}, (θ, φ)
- resimulate in 1D each particle observed in 3D using $E_i^{1D} = E_i^{3D}$, $(A_i^{1D}, Z_i^{1D}) = (A_i^{3D}, Z_i^{3D})$, $D = T$
- replace in the 3D simulation the observed energy and particle type: $E_f^{3D} = E_f^{1D}$, $(A_f^{3D}, Z_f^{3D}) = (A_f^{1D}, Z_f^{1D})$

testing the cosmology correction

proton



iron



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

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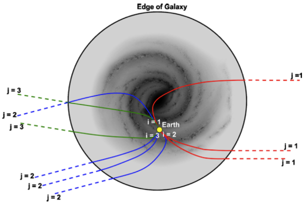
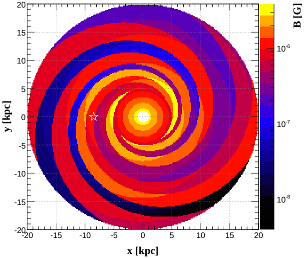
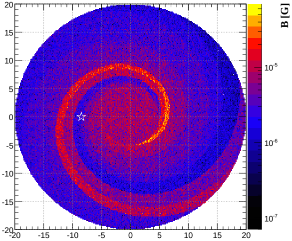
- backtrack antiprotons in the galaxy
- no energy losses (galactic propagation)
- construct transformation matrix (lens)
- deflection for nuclei is Z times deflection for protons
- error is also estimated
- technique used in the PARSEC software [Bretz *et al.* arXiv:1302.3761]







Jansson & Farrar ApJ 757,1 (2012) 14
Jansson & Farrar ApJ 761 (2012) L11

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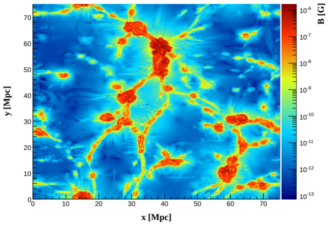
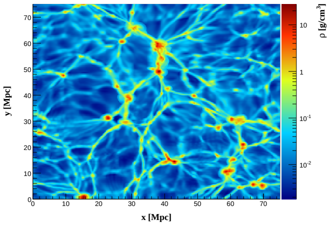
magnetic field



density



- MHD simulation from F. Miniati; uniform grid
- maximum rigidity = 1000 EeV; minimum energy = 1 EeV
- maximum propagation distance = 2 Gpc
- sources following LSS density
- compostion: proton and iron (two cases)
- magnetic field from MHD simulation

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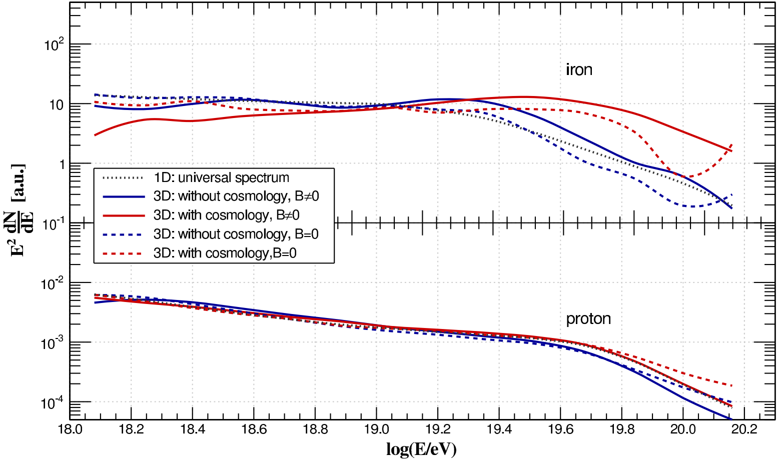
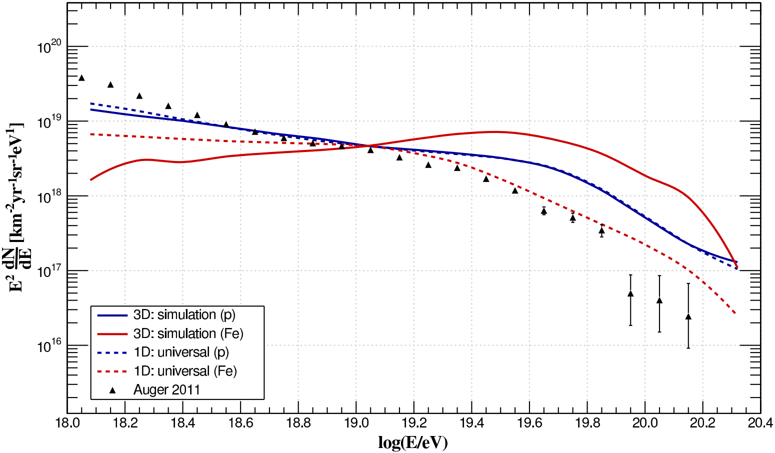


Alves Batista *et al.* arXiv:1308.1530

results: spectrum



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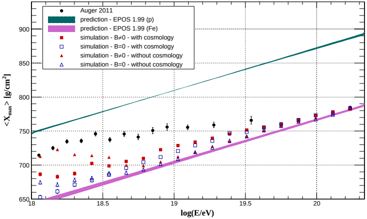
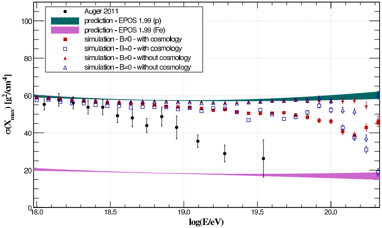
$\langle X_{max} \rangle$



$\sigma(X_{max})$



$\langle X_{max} \rangle$ and $\sigma(X_{max})$ obtained from parametrization from Pierre Auger Collaboration JCAP 1302 (2013) 026

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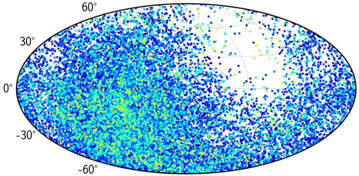
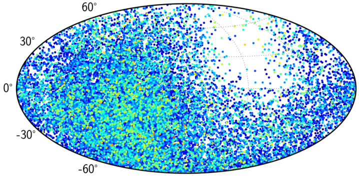
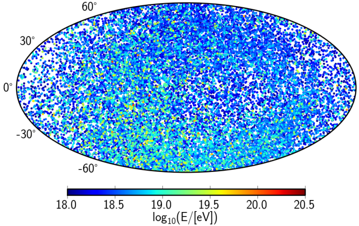
proton - galactic border



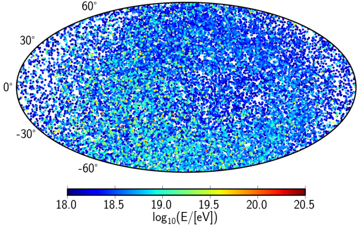
iron - galactic border



proton - Earth



iron - Earth



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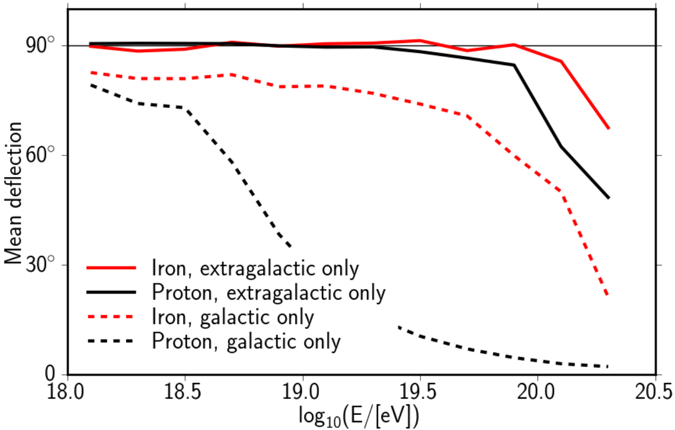

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summary I

- CRPropa: public code that allows the simulation of propagation of UHECRs, secondary protons and neutrinos
- version 3 under development
- new features: cosmology in 3D, magnetic lensing
- parallelization allows fast simulations → span a wide range of parameters
- comparison of simulations with observations
- multimessenger studies

summary II

- magnetic fields can affect the shape of the spectrum, so they should be taken into account when performing simulations
- large scale structure + cosmological effects + energy losses → realistic simulations

the future...

- performance tests with the 4D mode (**current activity**)
- propagation of UHE photons with EleCa code Settimo *et al.* 1311.6140 $\longrightarrow$ interface between codes (**being tested**)
- support for AMR grids for high resolution MHD simulations (**under development**)
- further test of CRPropa 3 (**currect activity**)
- suggestions are welcome