Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

BERGISCHE UNIVERSITÄT WUPPERTAL

RWTH AACHEN UNIVERSITY

CRPropa: a public framework to propagate UHECRs in the universe

R. Alves Batista[1], M. Erdmann[2], C. Evoli[1], K.-H. Kampert[3], D. Kuempel[2], G. Müller[2], M. Settimo[4], G. Sigl[1], A. van Vliet[1], D. Walz[2], T. Winchen[3]

[1] University of Hamburg
[2] RWTH Aachen University
[3] University of Wuppertal
[4] University of Paris 6

rafael.alves.batista@desy.de

International Symposium on Very High Energy Cosmic Ray Interactions
CERN
22/08/2014

bmb+f Großgeräte der physikalischen Grundlagenforschung

HELMHOLTZ GEMEINSCHAFT
Allianz für Astroteilchenphysik

Forschungs- und Wissenschaftsstiftung Hamburg

contents of this talk

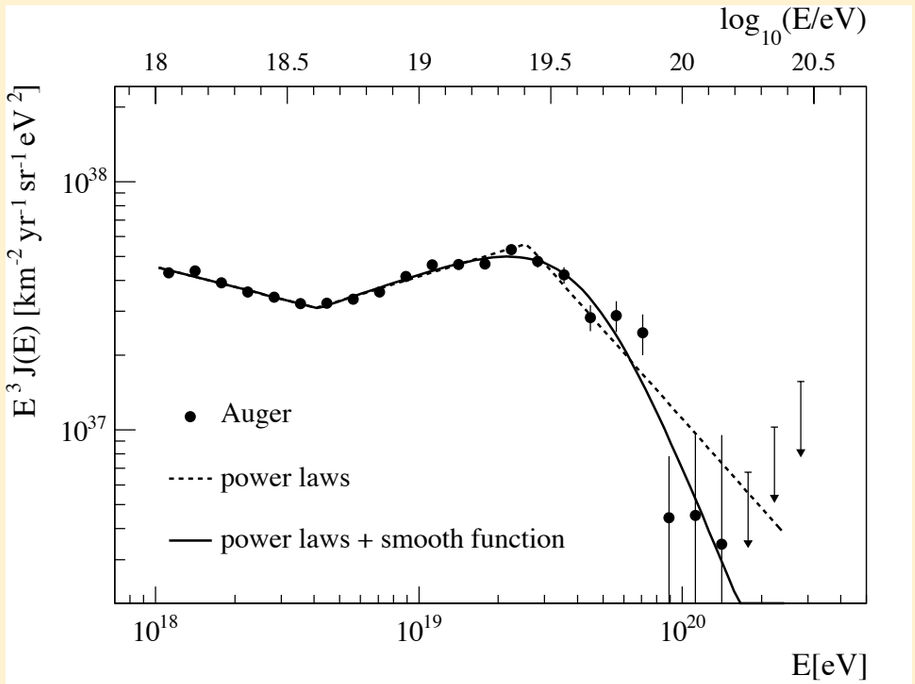
- motivation
- propagation picture + multimessenger approach
- code features
- CR interactions
- code improvements
  - updated photodisintegration cross sections
  - galactic magnetic field
  - UHE photons (EleCa code)
- 1D mode and secondary neutrinos and gamma rays
- 3D and 4D modes
- other applications
- outlook

UHECRs: open questions

- ✦ where do they come from?
- ✦ what is their chemical composition?
- ✦ what are the acceleration processes?
- ✦ is there a maximum energy that they can reach?
- ✦ can we see hint of new physics through their interaction?

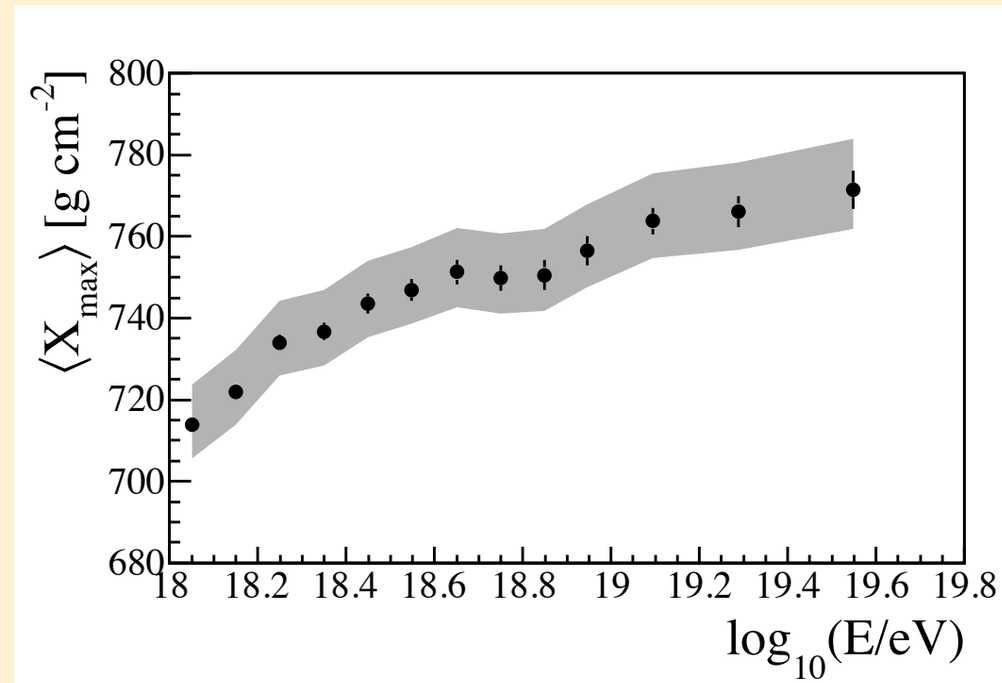
motivation

spectrum



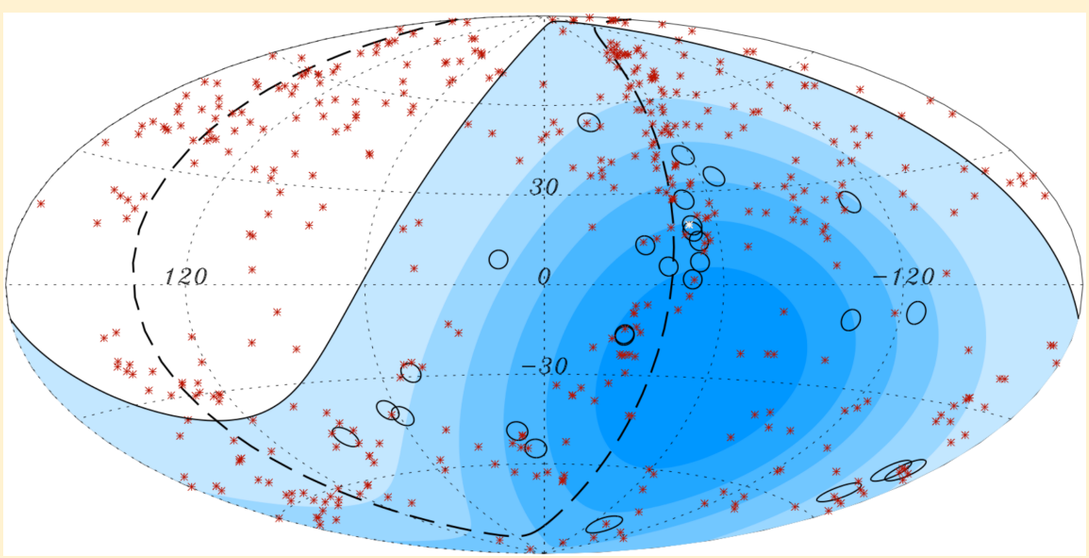
Pierre Auger Collaboration. ICRC 2011.

composition



Pierre Auger Collaboration. JCAP 02 (2013) 026.

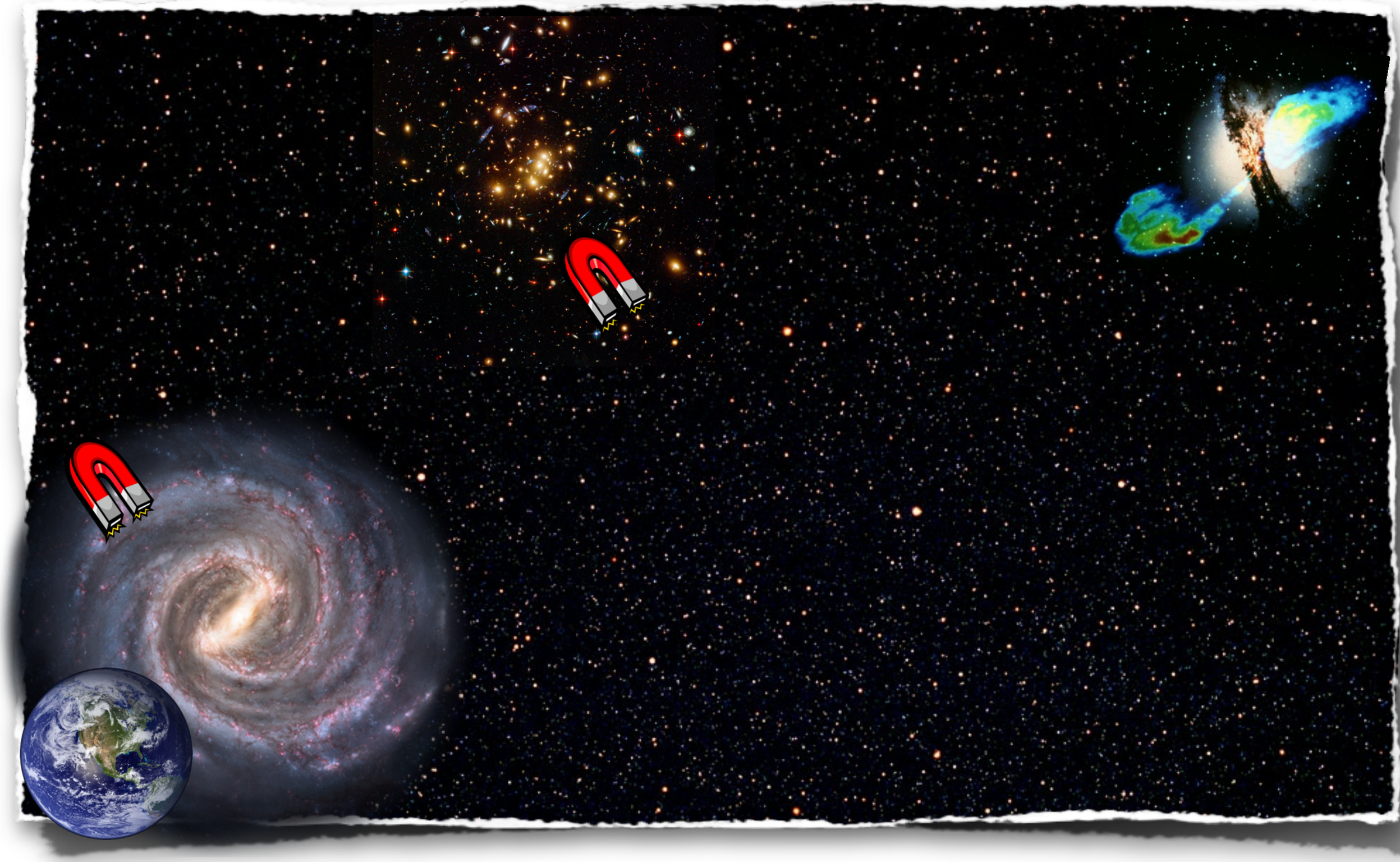
anisotropy



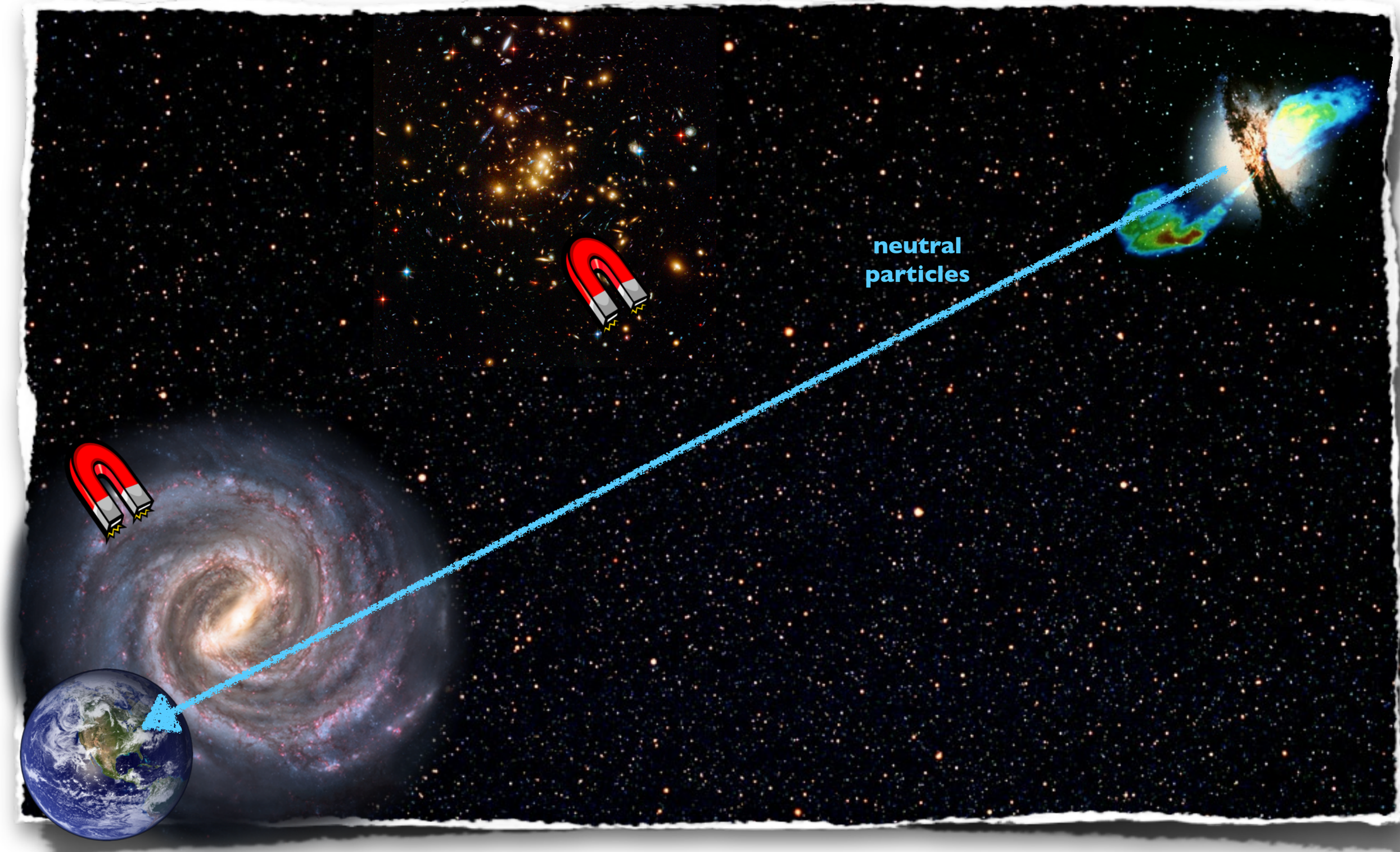
Pierre Auger Collaboration. Science 318 (2007) 938.

- ✦ 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

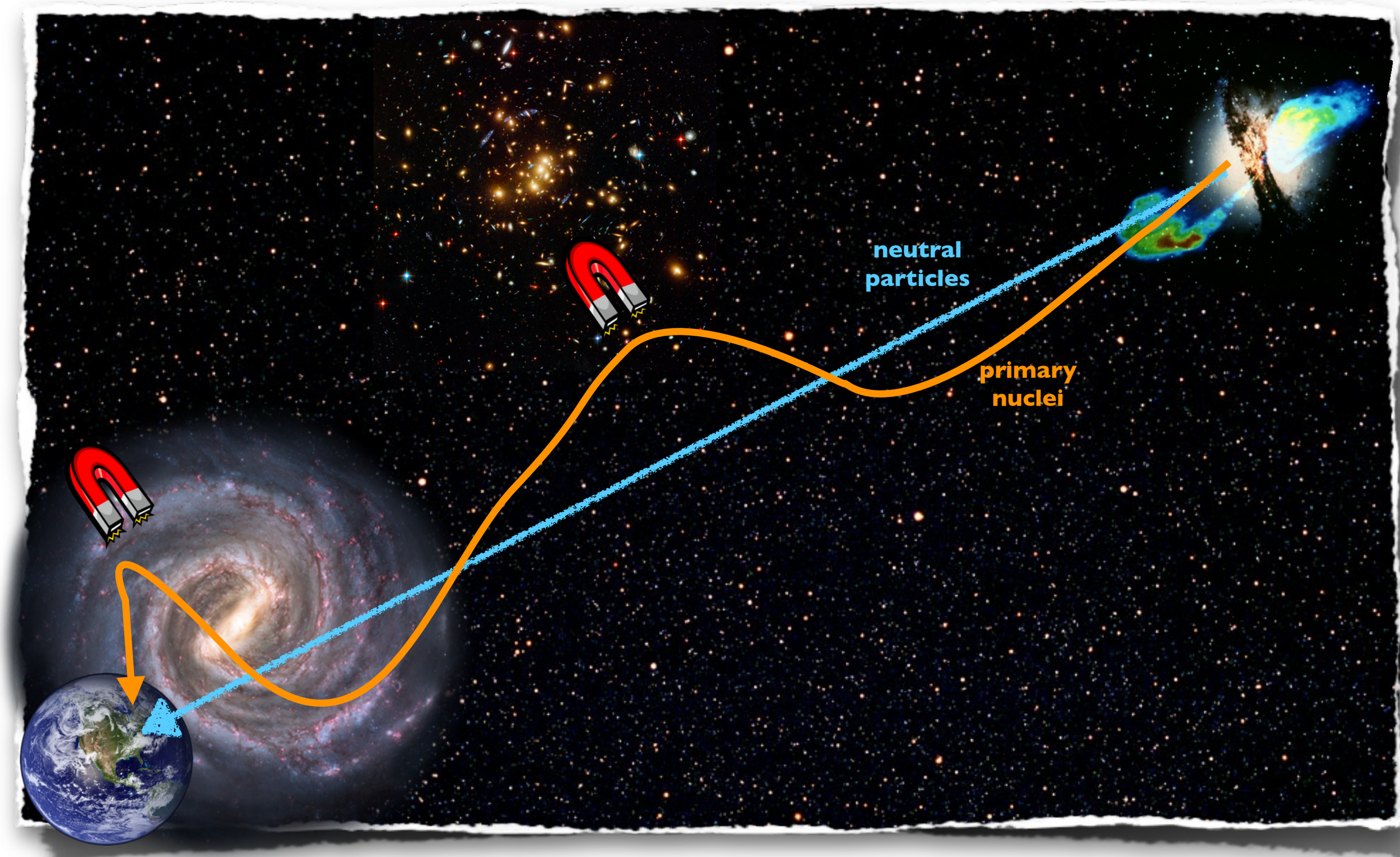
general picture



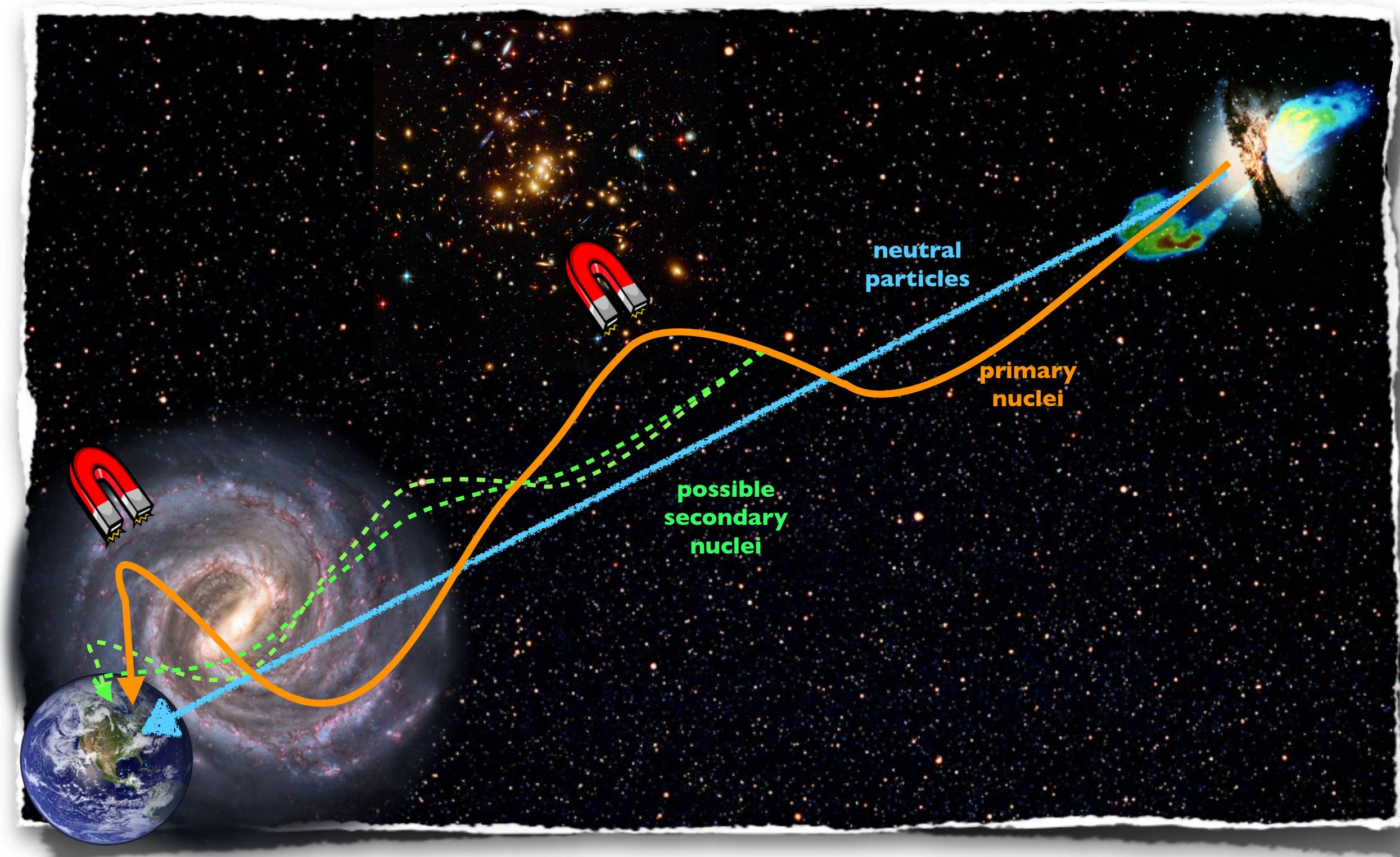
general picture



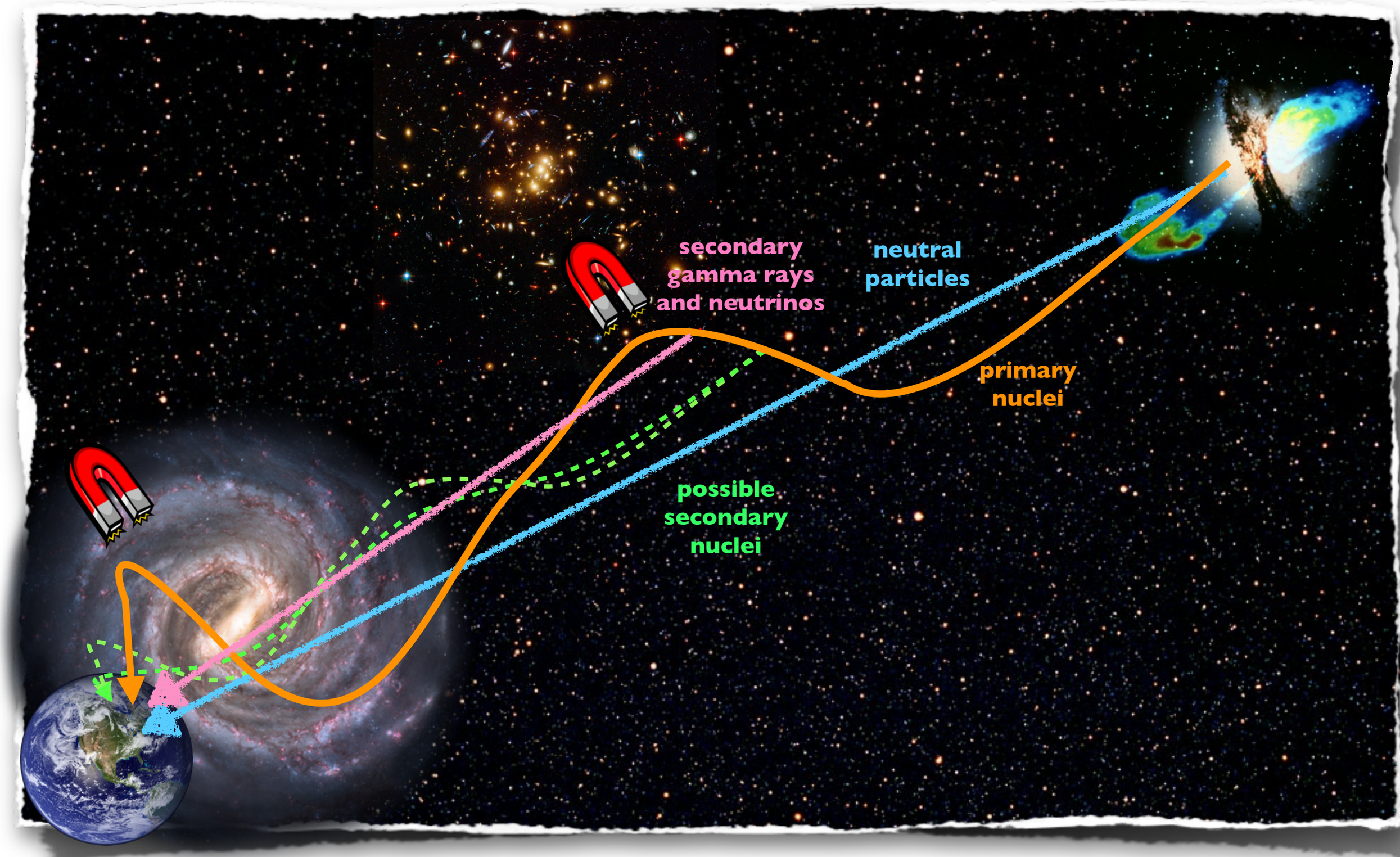
general picture



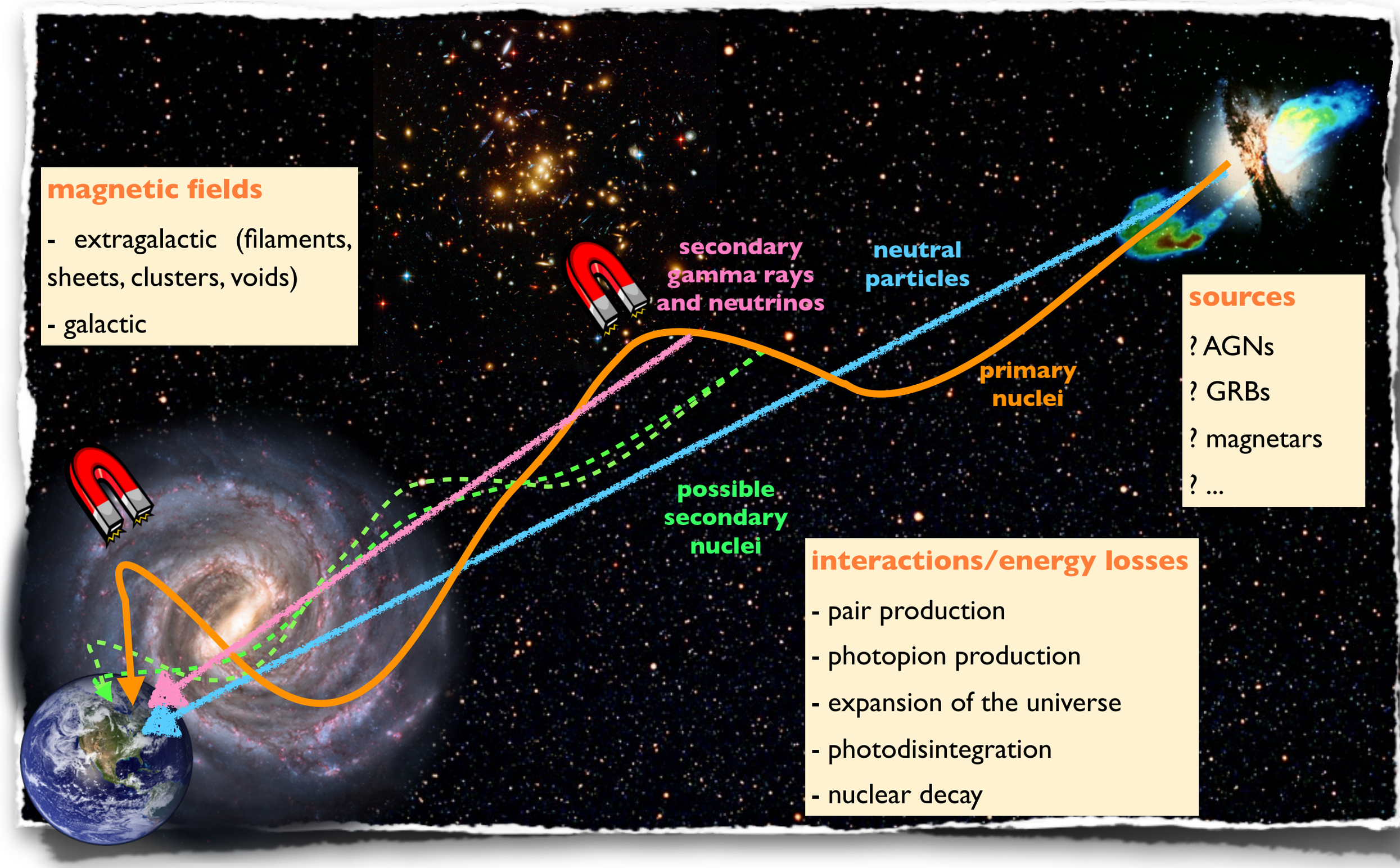
general picture



general picture



general picture



code features

CRPropa 2.0

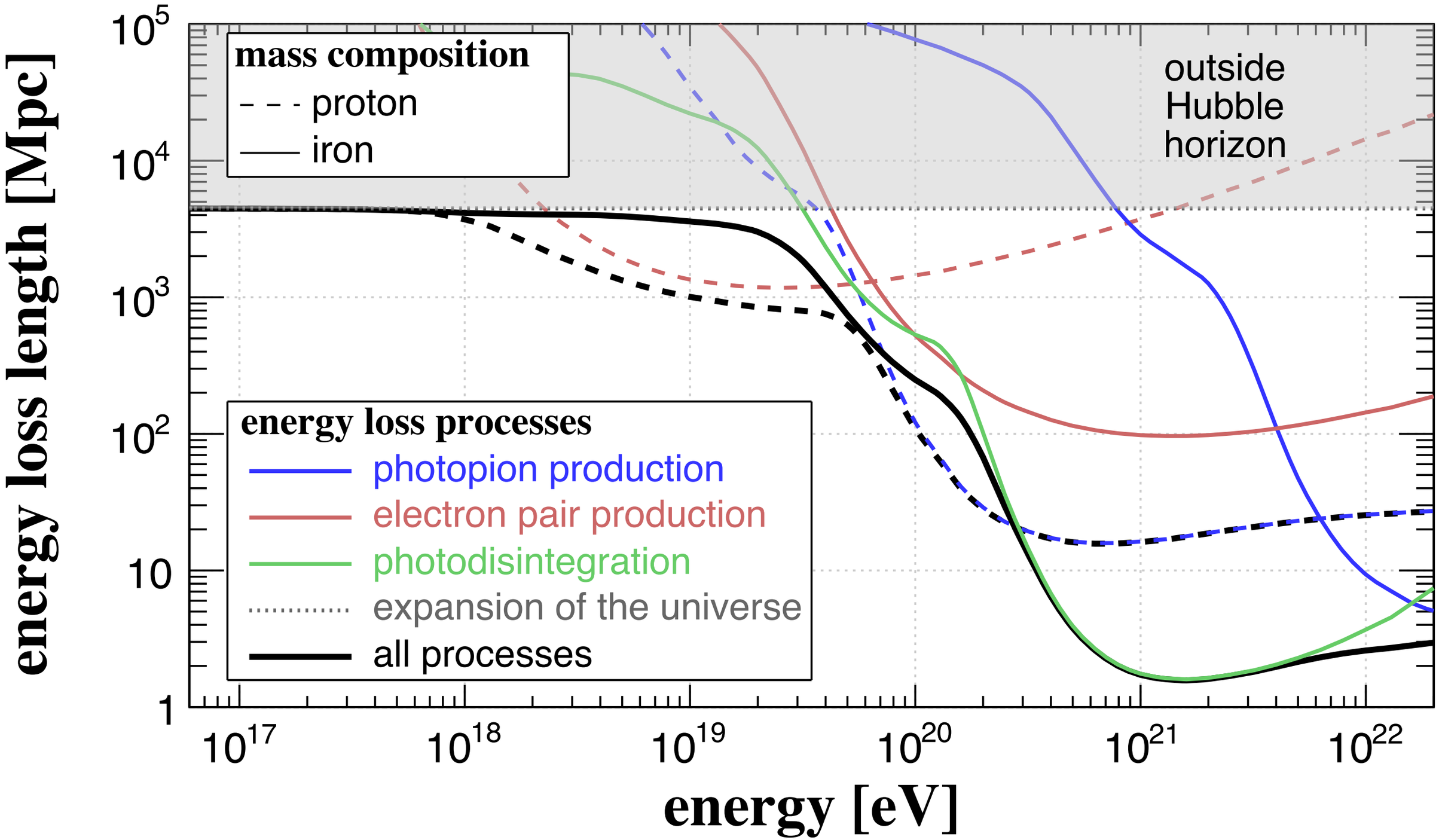
- ✦ "official" release
- ✦ Kampert et al. Astropart. Phys. 42 (2013) 41
- ✦ 1D simulations with cosmology (e.g. source evolution, adiabatic losses, etc)
- ✦ 3D simulations in cosmic magnetic fields (uniform B, turbulent B, uniform grid)
- ✦ source (point sources, uniform distribution, density grid)
- ✦ interaction of particles with background photons (CMB, IRB)
- ✦ secondary gamma rays (kinetic equations - DINT package)
- ✦ secondary neutrinos
- ✦ some improvements suggested by Kalashev & Kido (arXiv:1406.0735)

CRPropa 3.0

- ✦ development version
- ✦ see RAB et al. [arXiv:1307.2643]
- ✦ 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 (EleCa code)
- ✦ large scale magnetic fields through smooth particle formalism
- ✦ updated photodisintegration cross sections
- ✦ more IRB models
- ✦ improved interaction rate tables

http://crpropa.desy.de

energy loss processes



energy loss and interaction 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

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

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

pair production

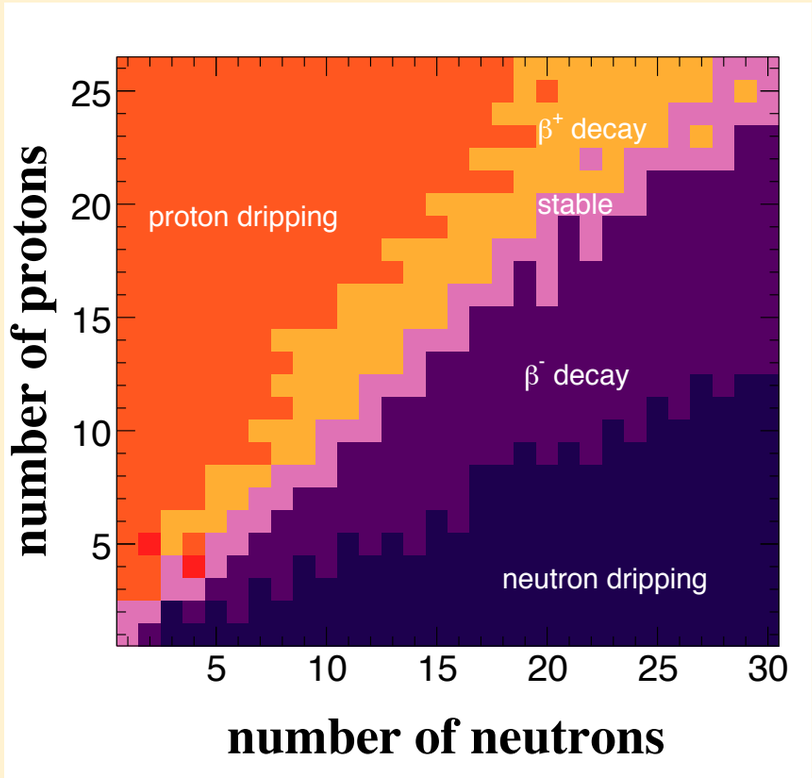
$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 k_B T f(\Gamma)$$

photodisintegration

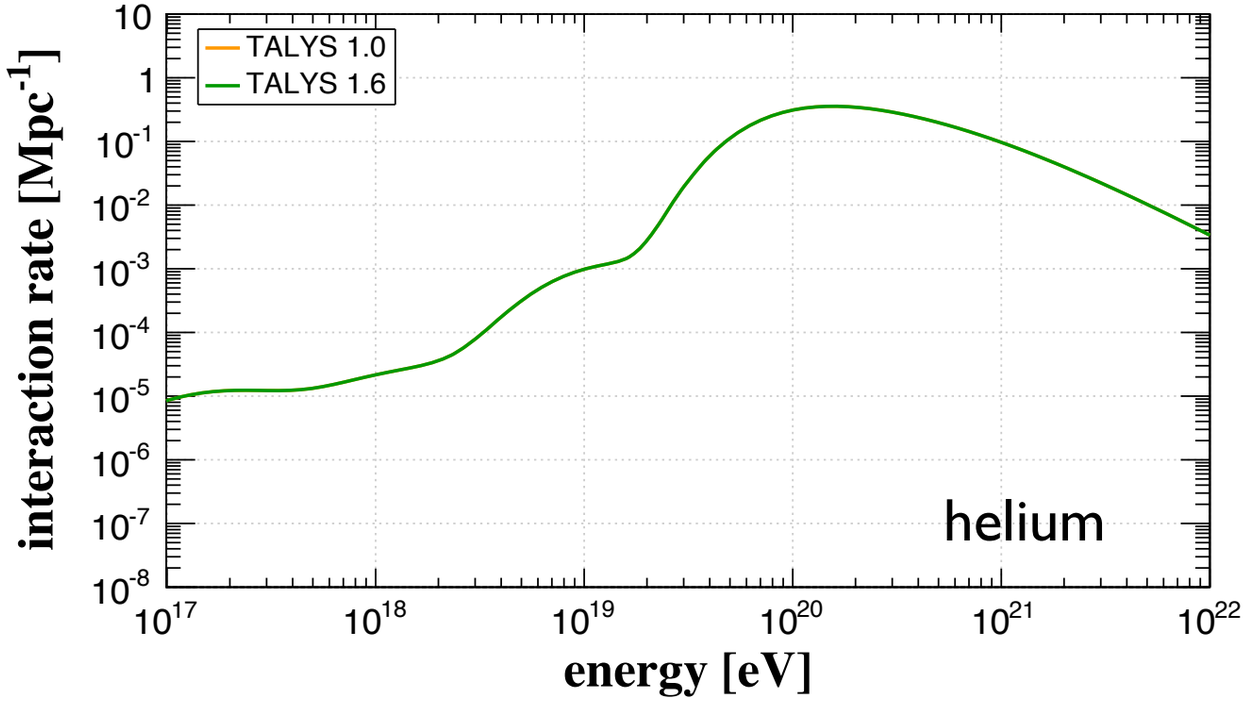
- tabulated cross sections from TALYS

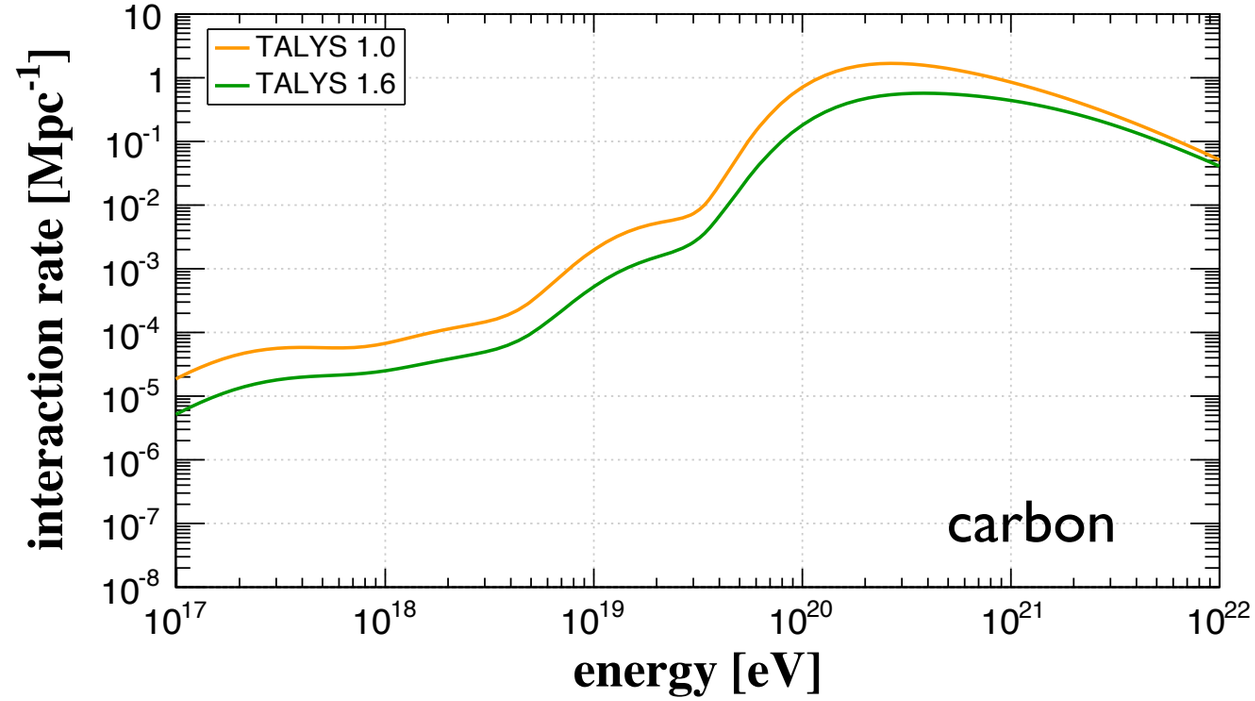
$$\frac{1}{\lambda(\Gamma)} = \int_{E_{min}}^{E_{max}} n(\epsilon, z)\bar{\sigma}(\epsilon'_{max} = 2\Gamma\epsilon) d\epsilon$$

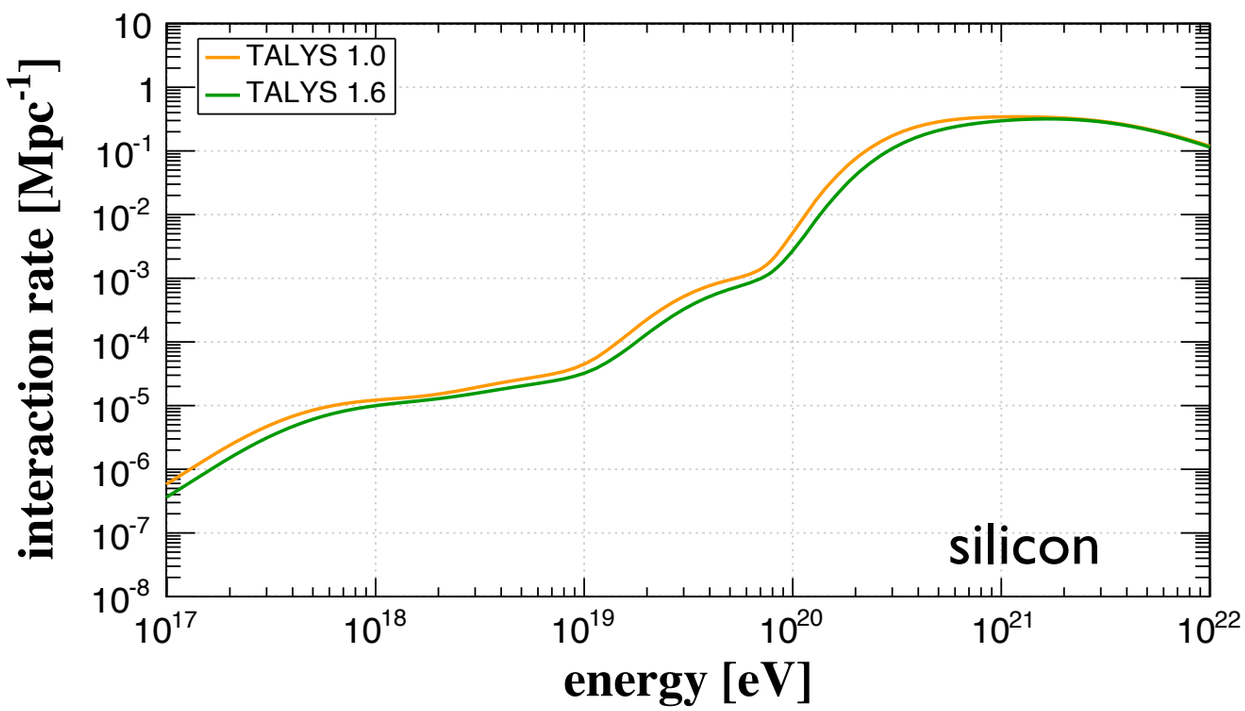
nuclear decay

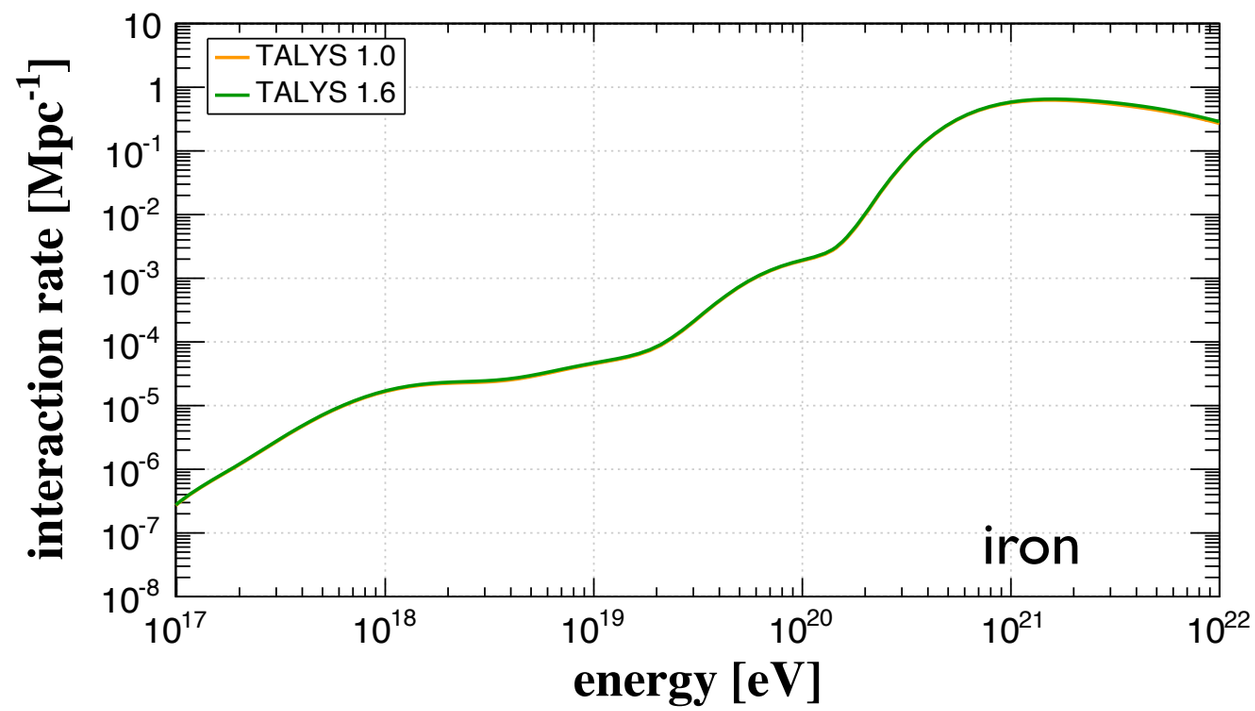


updated photodisintegration cross sections

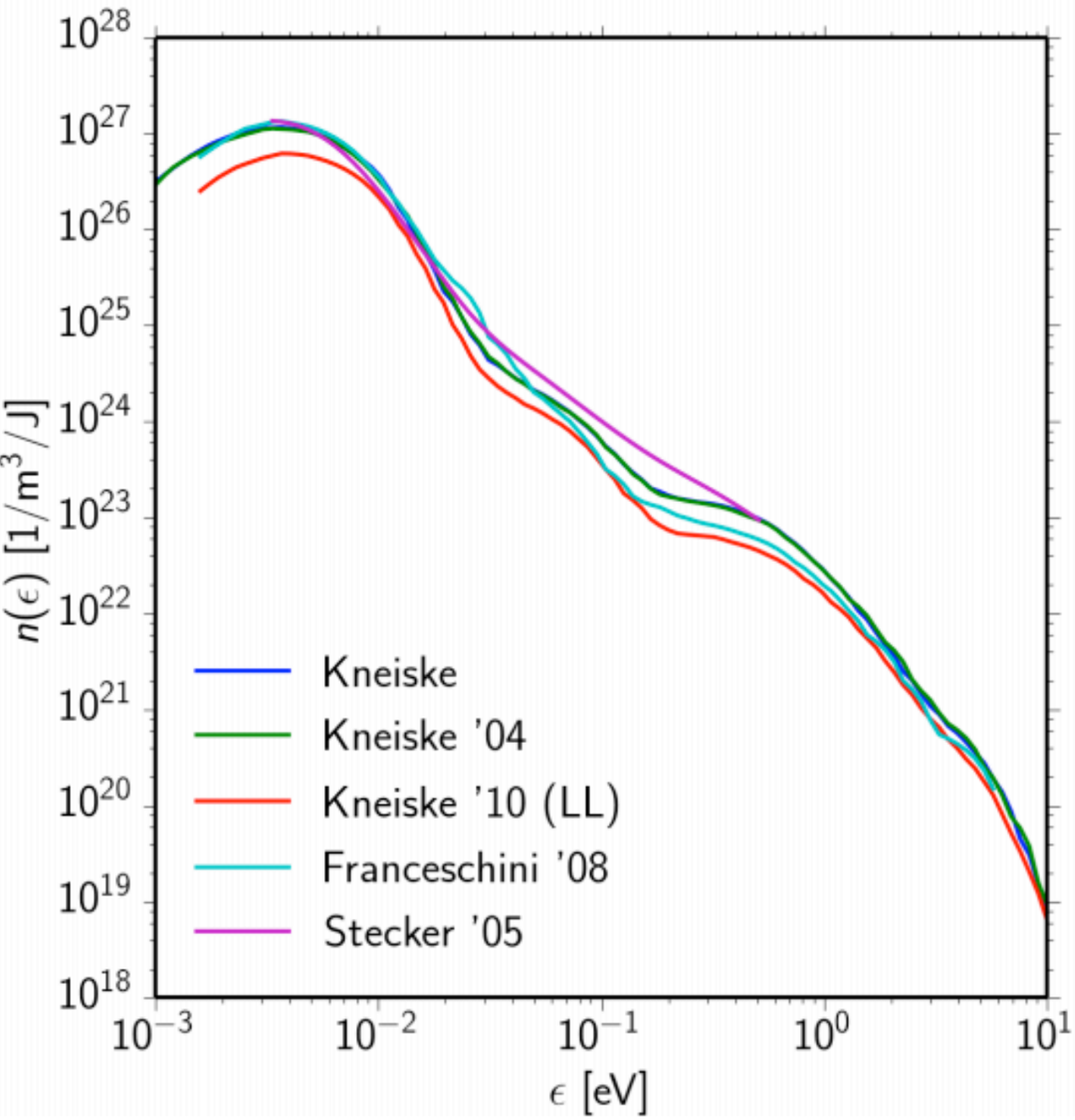


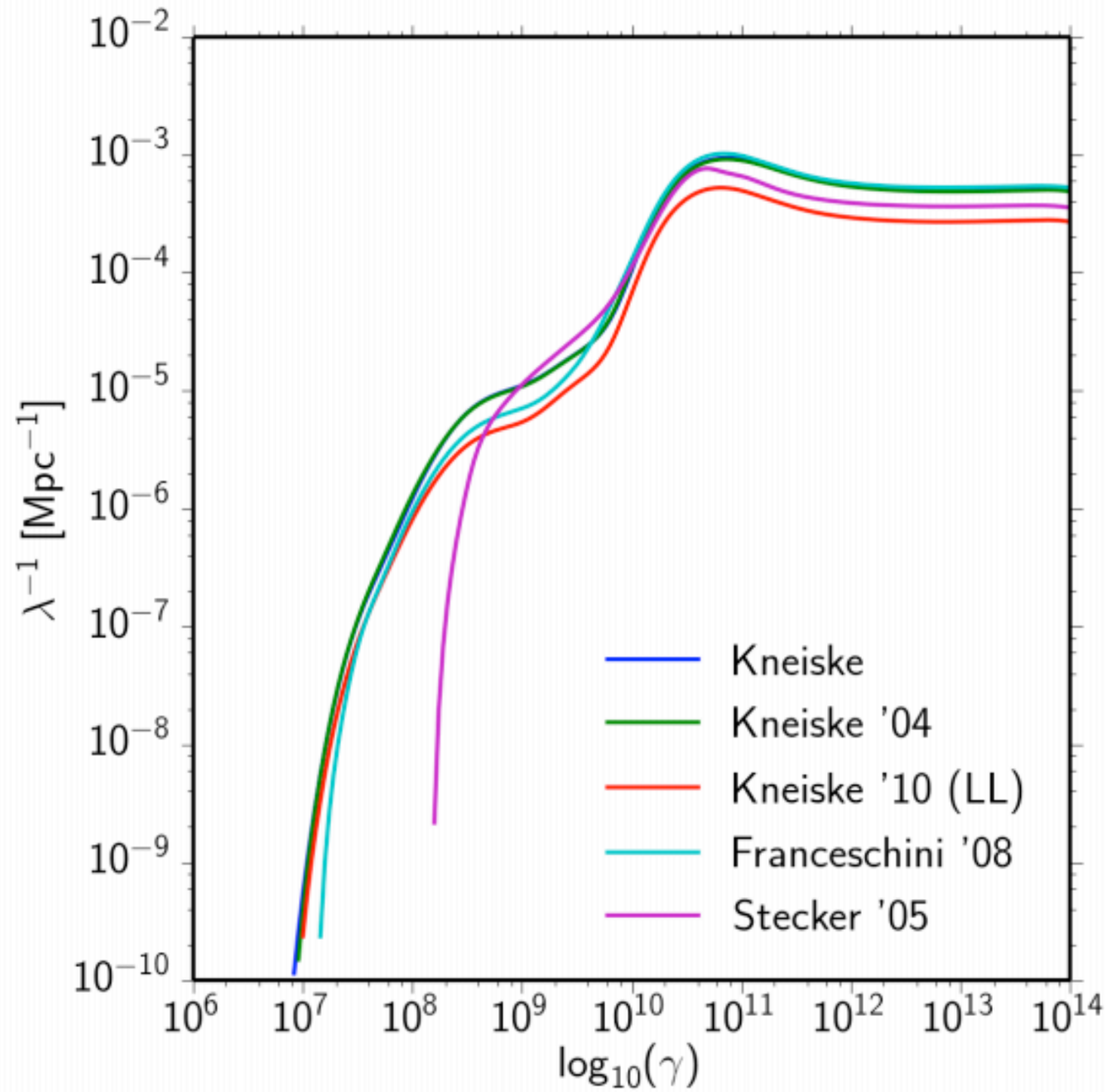






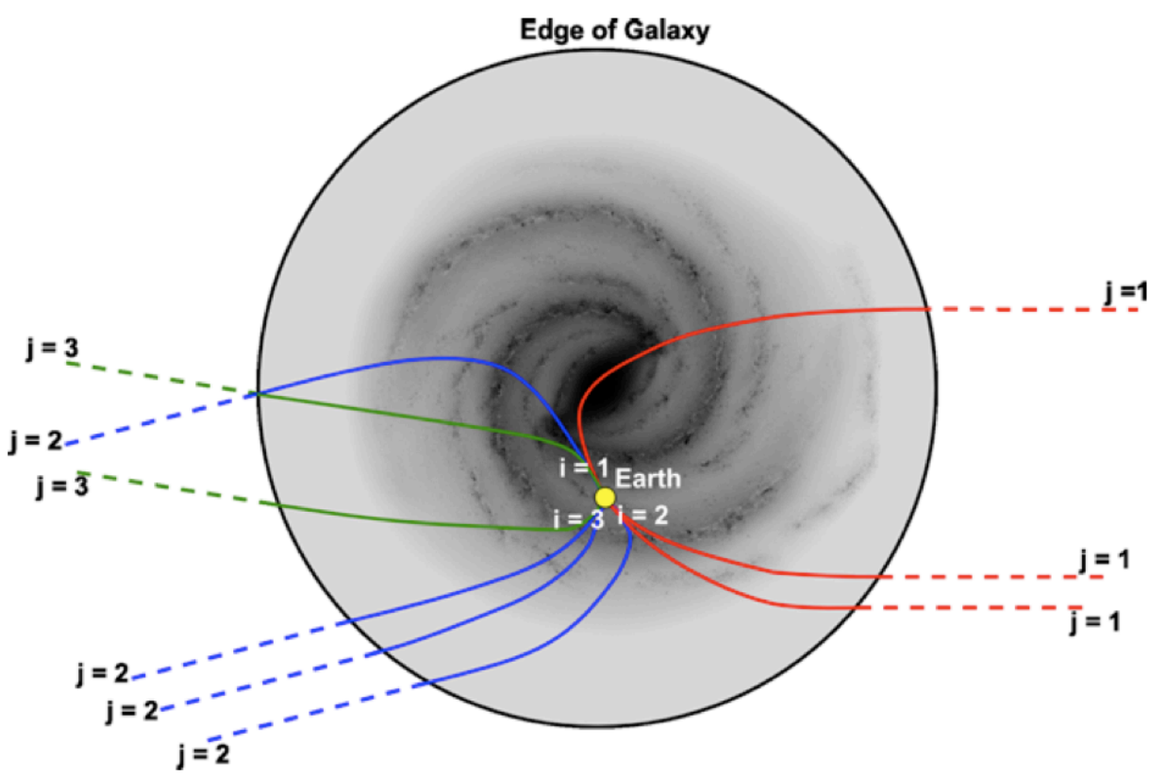
infrared background models

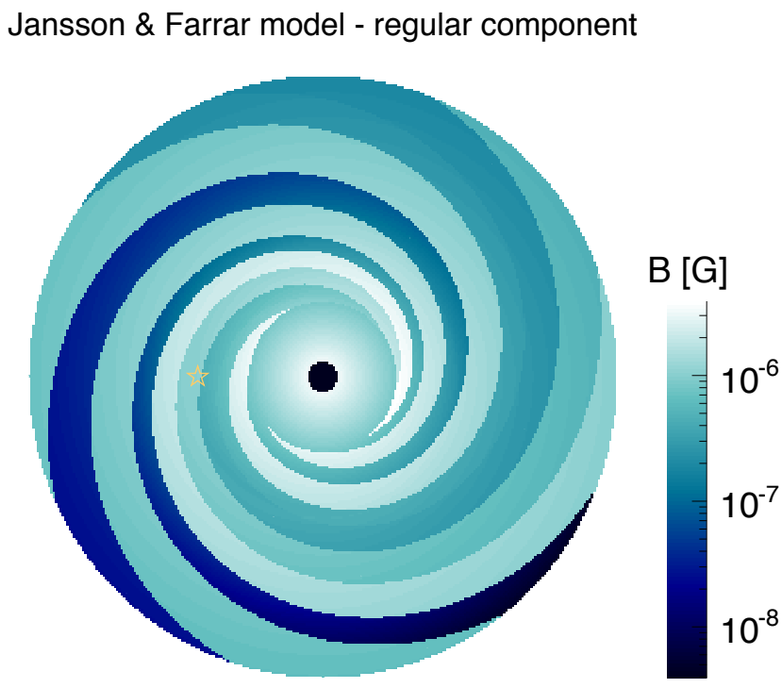


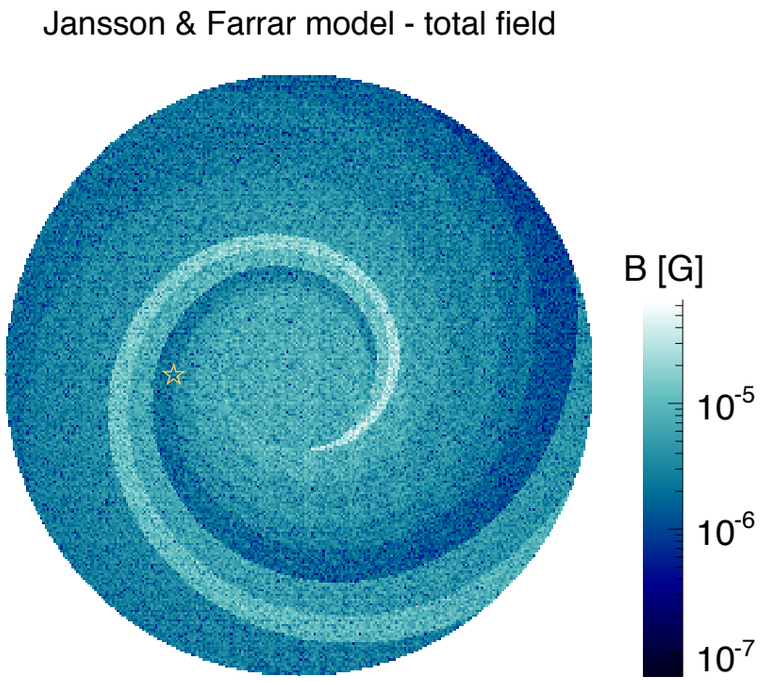


lensing technique: galactic magnetic field

- ✦ 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 [arXiv:1302.3761]
- ✦ these lenses are applied to the simulated data a posteriori



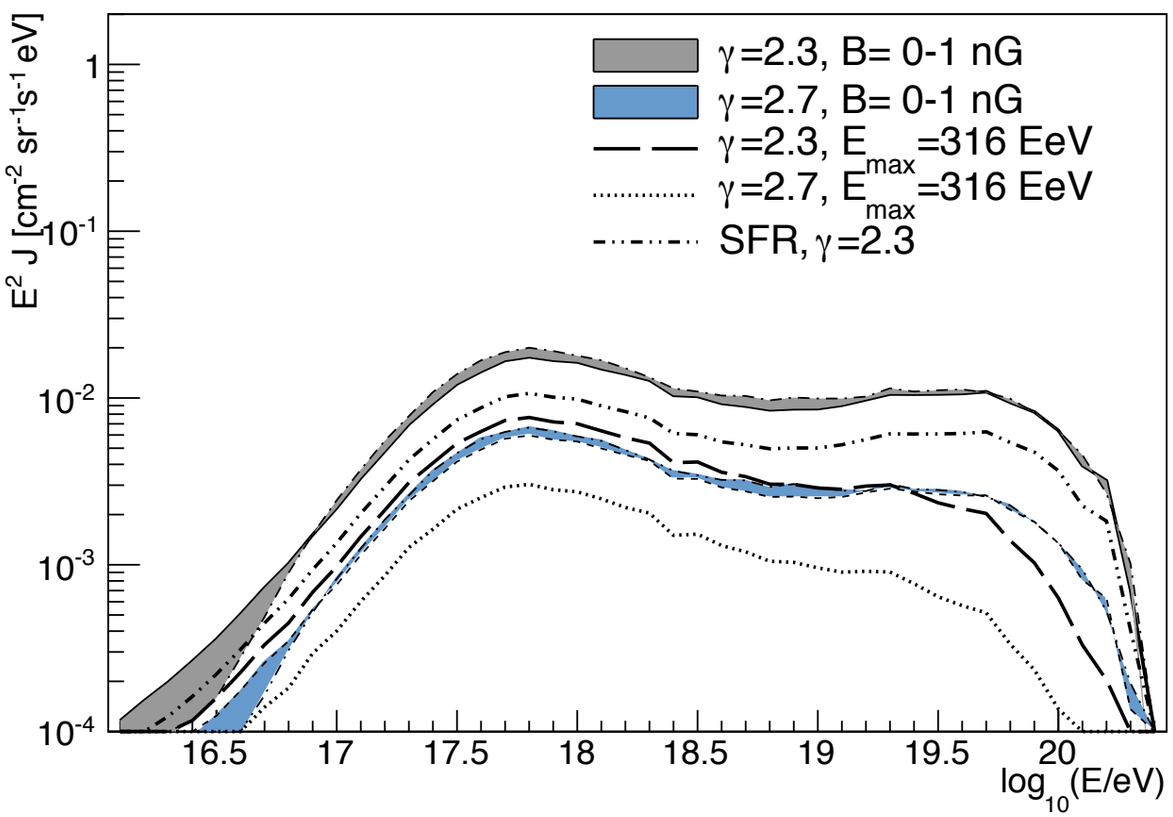




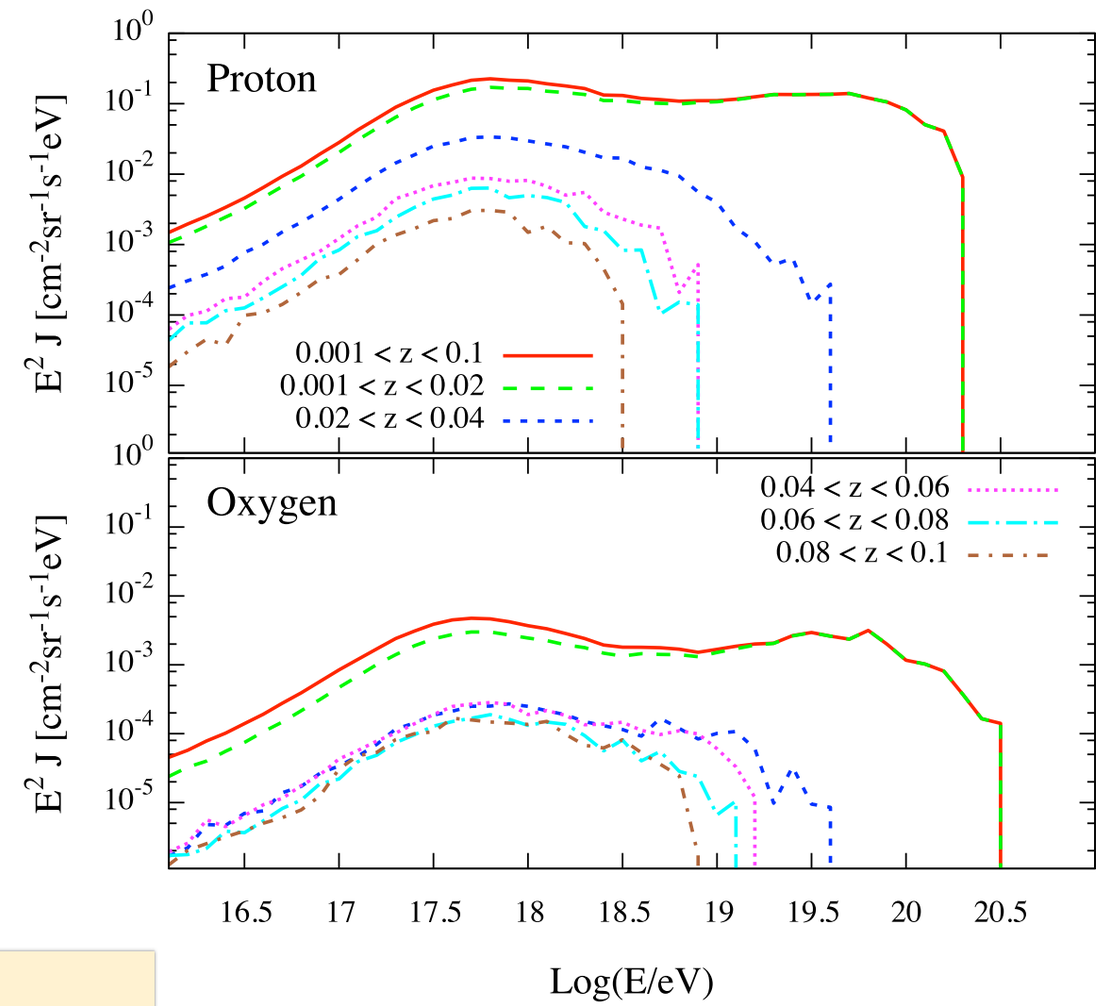
Jansson & Farrar, ApJ 761 (2012) L11

UHE photons (EleCa code)

effects of source evolution and magnetic fields



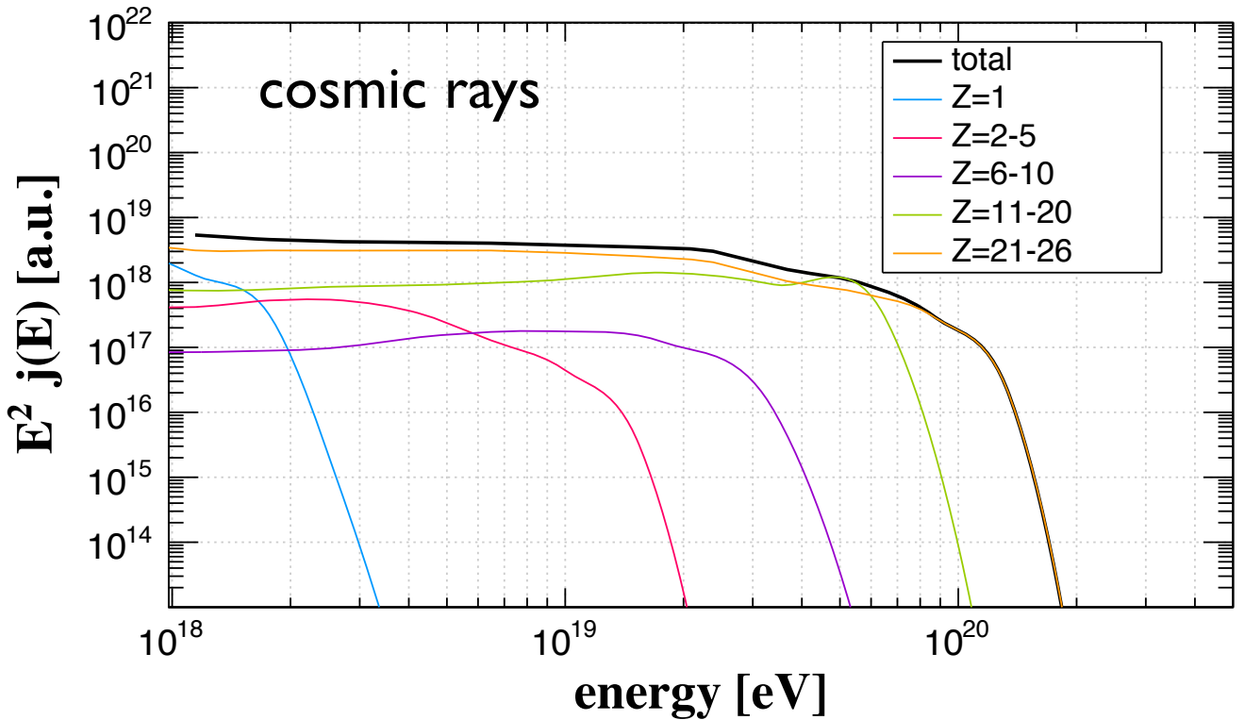
contribution of sources at different distances

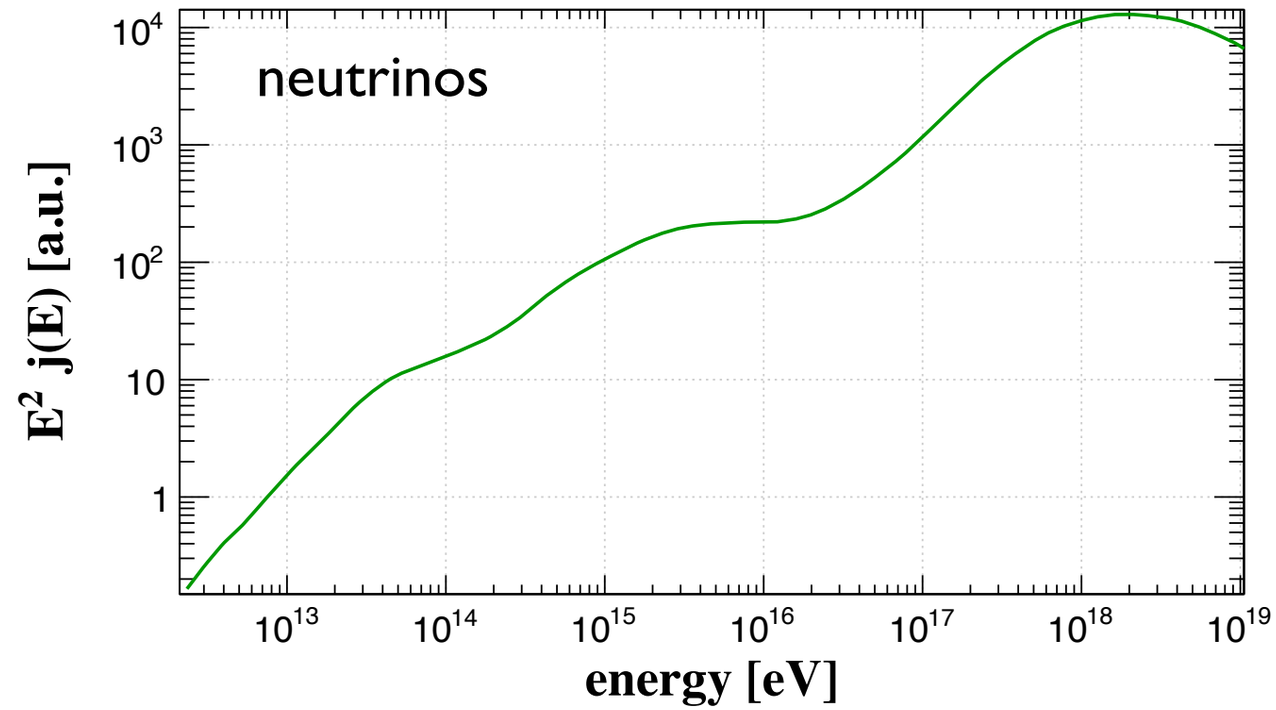


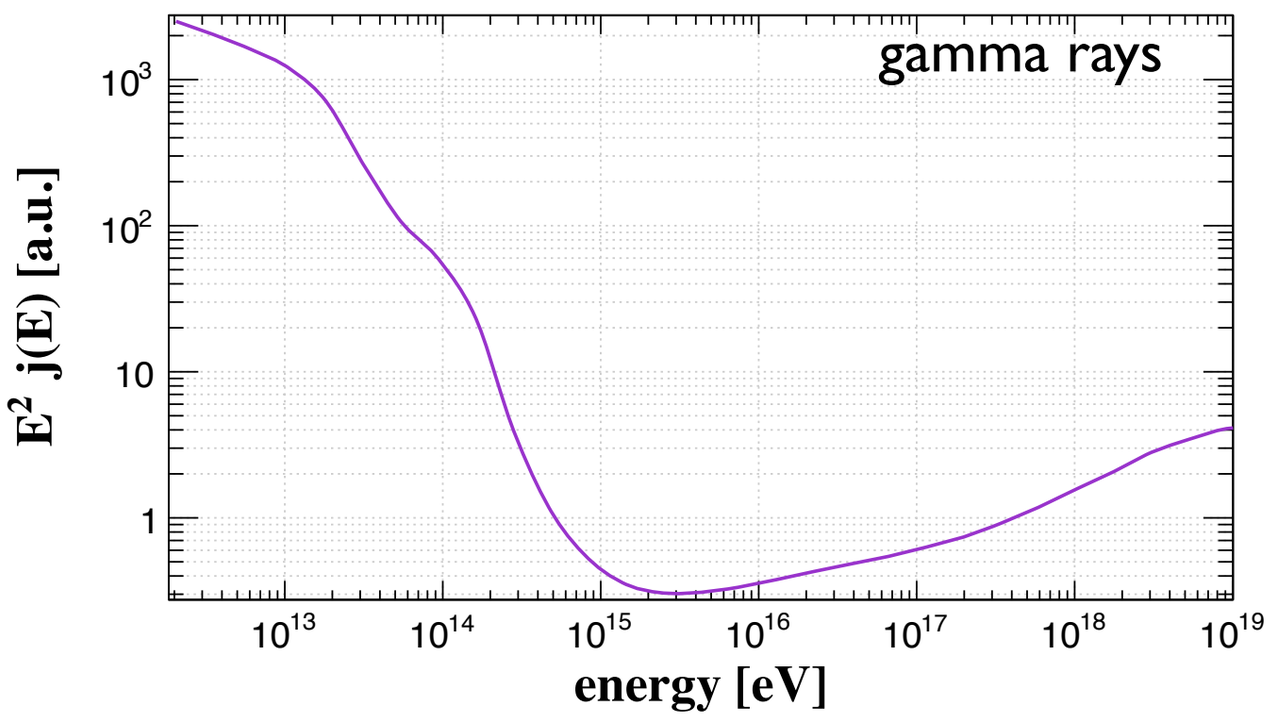
- ✦ EleCa is now included in CRPropa 3
- ✦ UHE photon Monte Carlo propagation
- ✦ 1D propagation
- ✦ magnetic deflections → "small angle" approximation

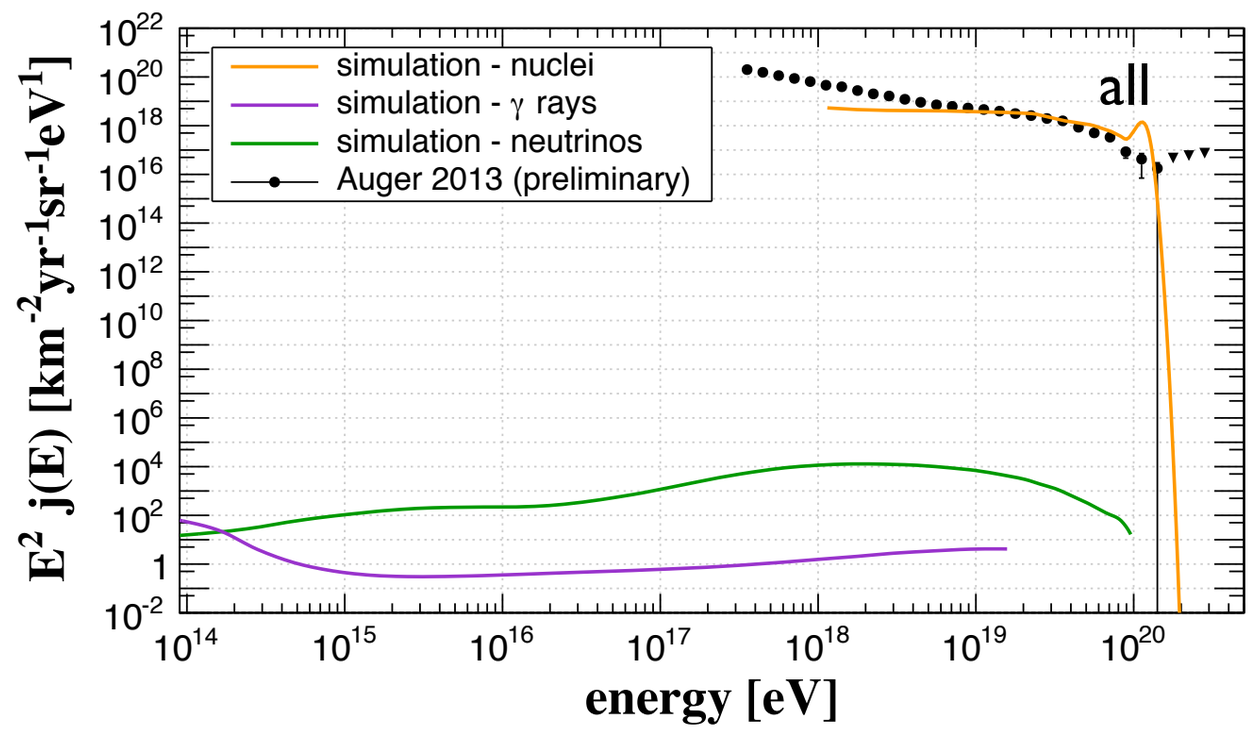
Settimo & De Domenico. arXiv:1311.6140
(accepted Astropart. Phys.)

1D example: UHECRs + secondaries



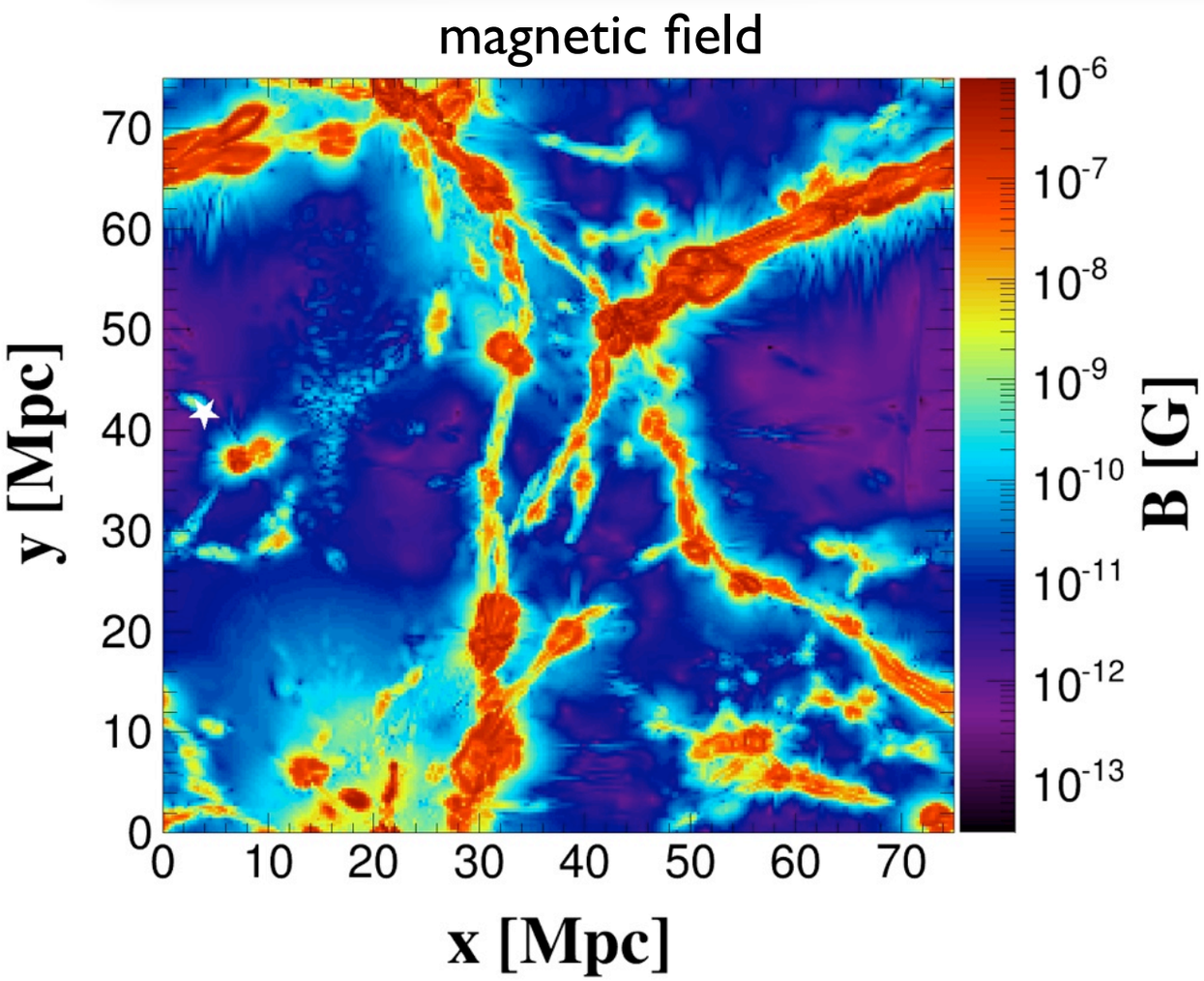


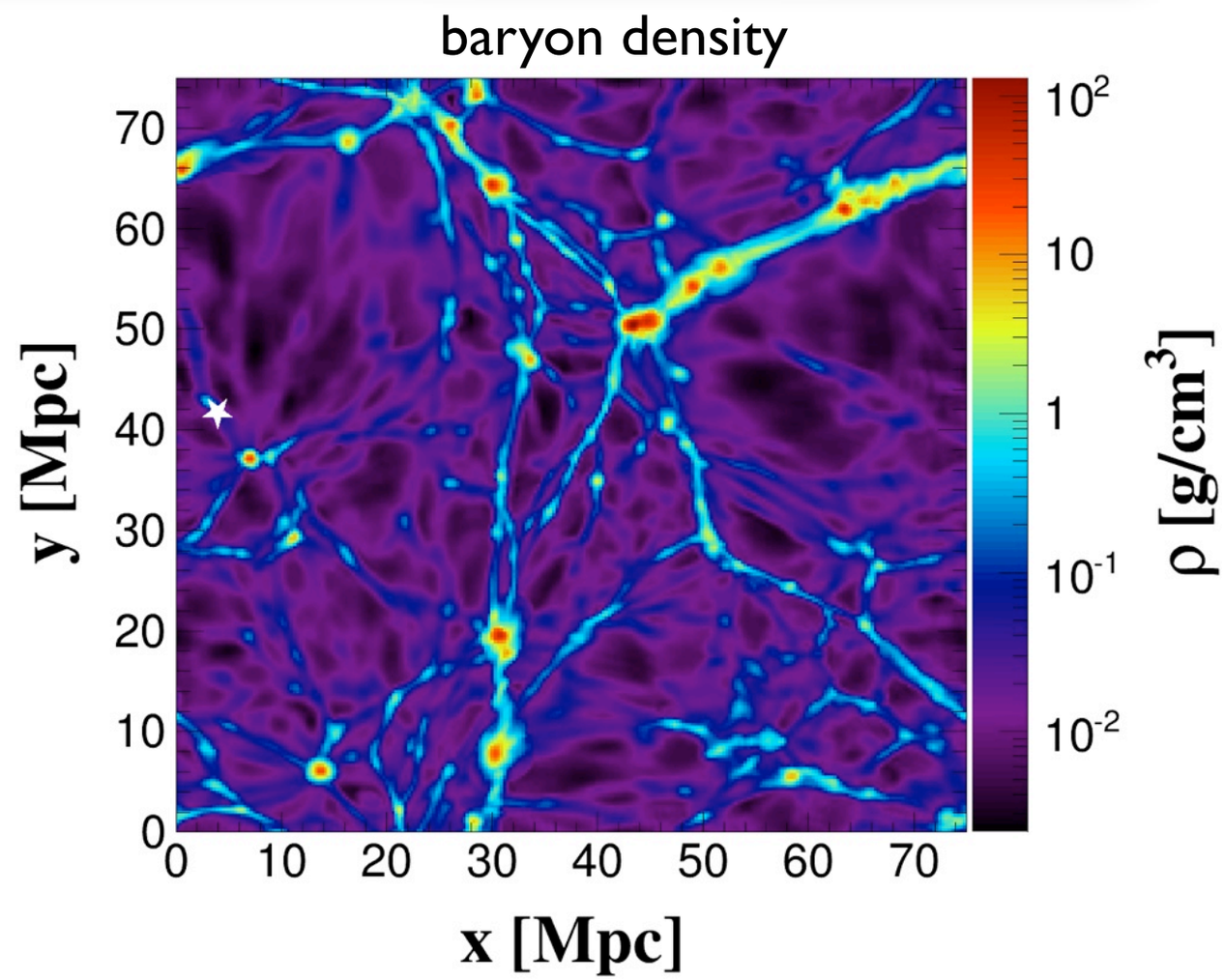




injected iron, uniform sources, E^{-2}

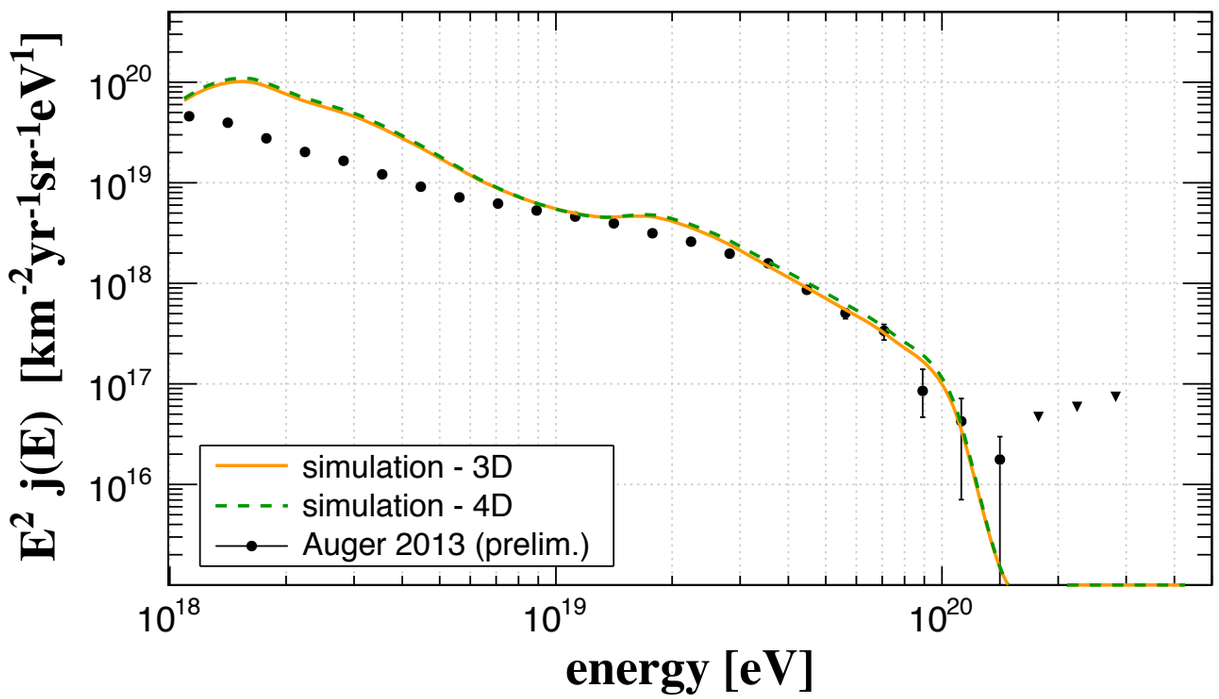
3D example: structured magnetic fields



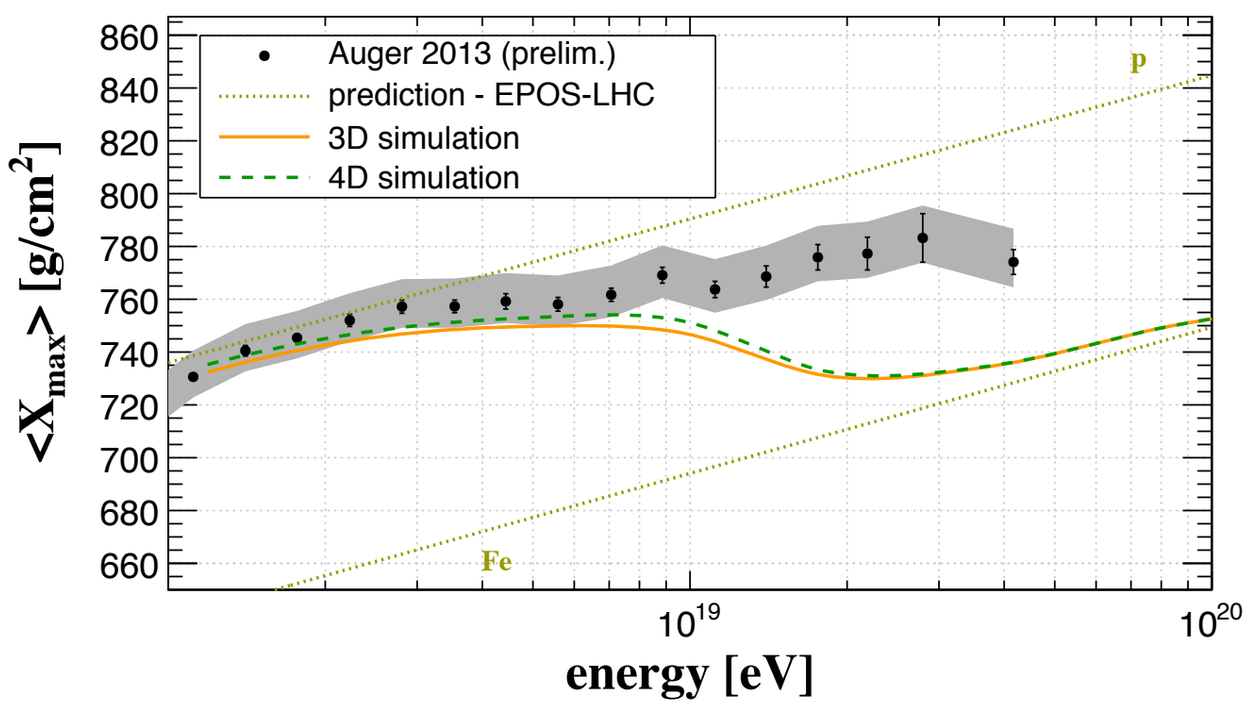


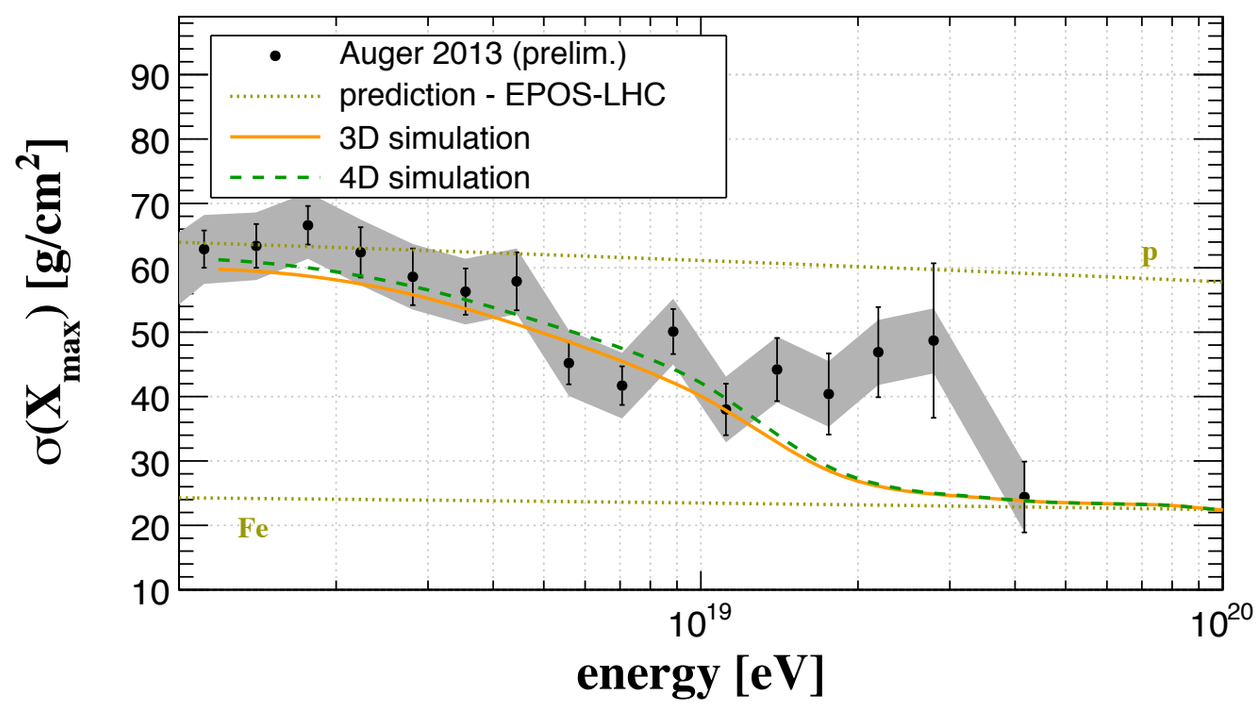
- ✦ MHD simulation from F. Miniati
- ✦ maximum rigidity = 1000 EeV
- ✦ maximum source distance = 4 Gpc
- ✦ sources following LSS baryon density
- ✦ magnetic field from the grid
- ✦ composition: proton (52%), helium (27%), nitrogen (13%), iron (8%)
- ✦ minimum energy = 1 EeV

3D+4D example: spectrum and composition



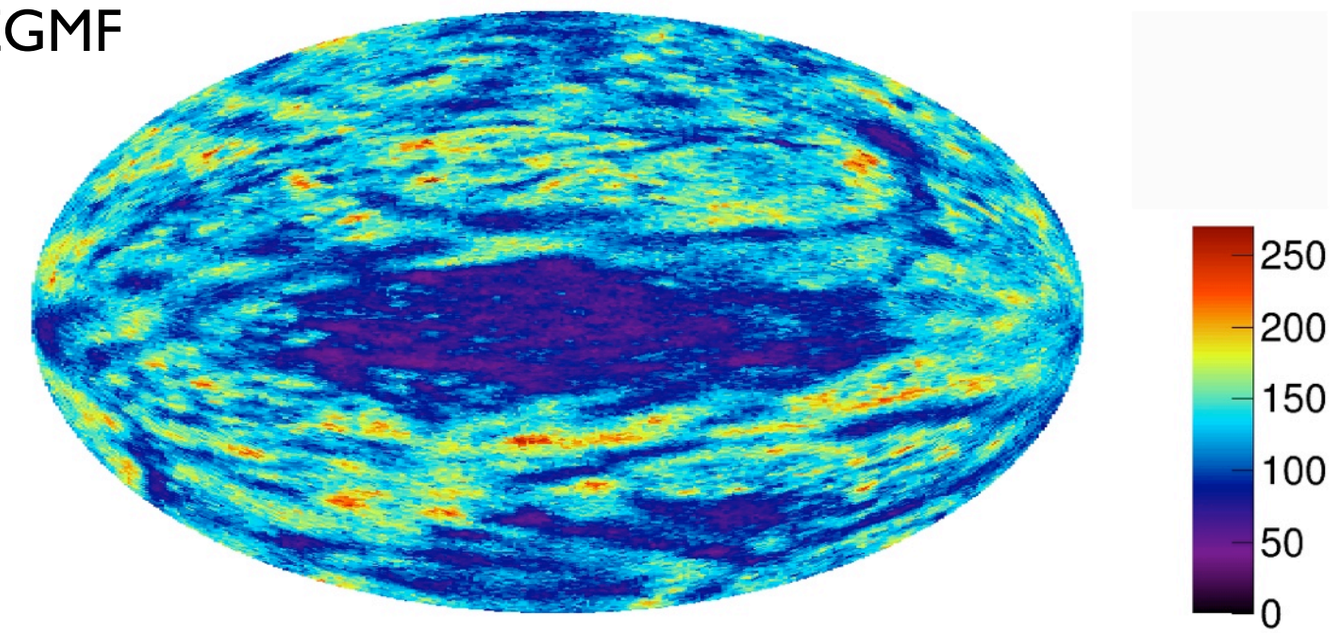
- ✦ adiabatic losses + source evolution + magnetic fields → realistic description
- ✦ 4D drawback: slow compared to the 3D mode
- ✦ particles are detected when its coordinates are within a hypersphere (3 spatial coordinates + time) around the observer



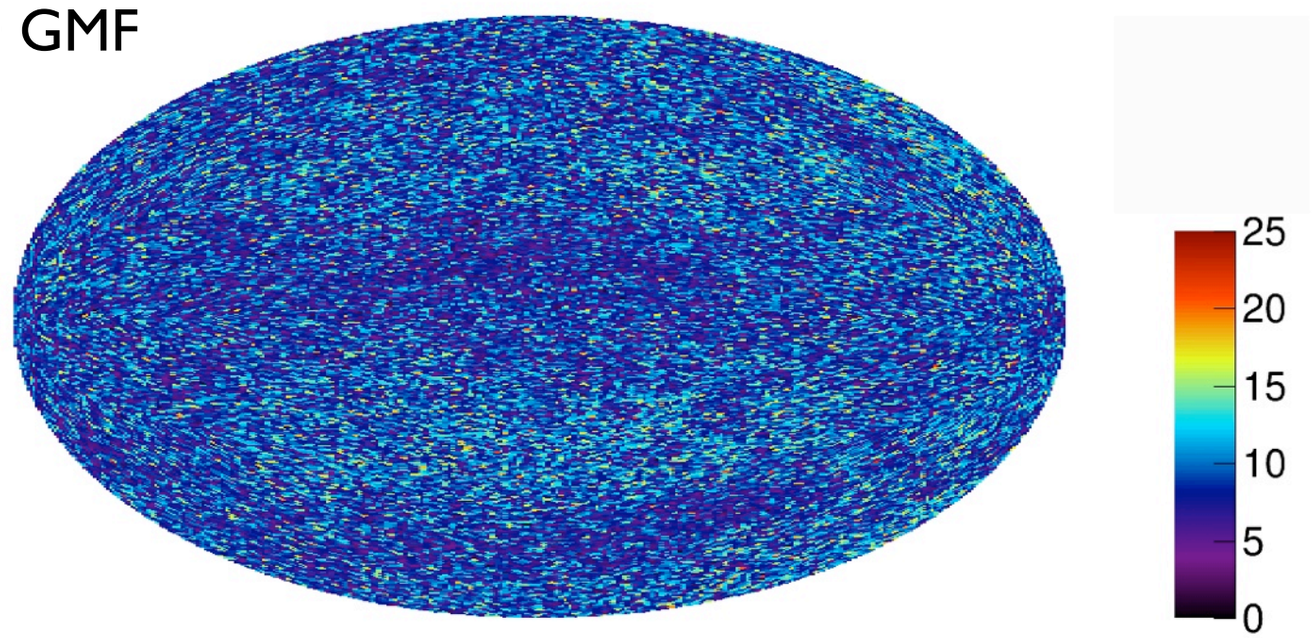


3D example: anisotropies

only EGMF



EGMF + GMF



other examples: TA spectrum fit

slide taken from Masaki Fukushima's talk

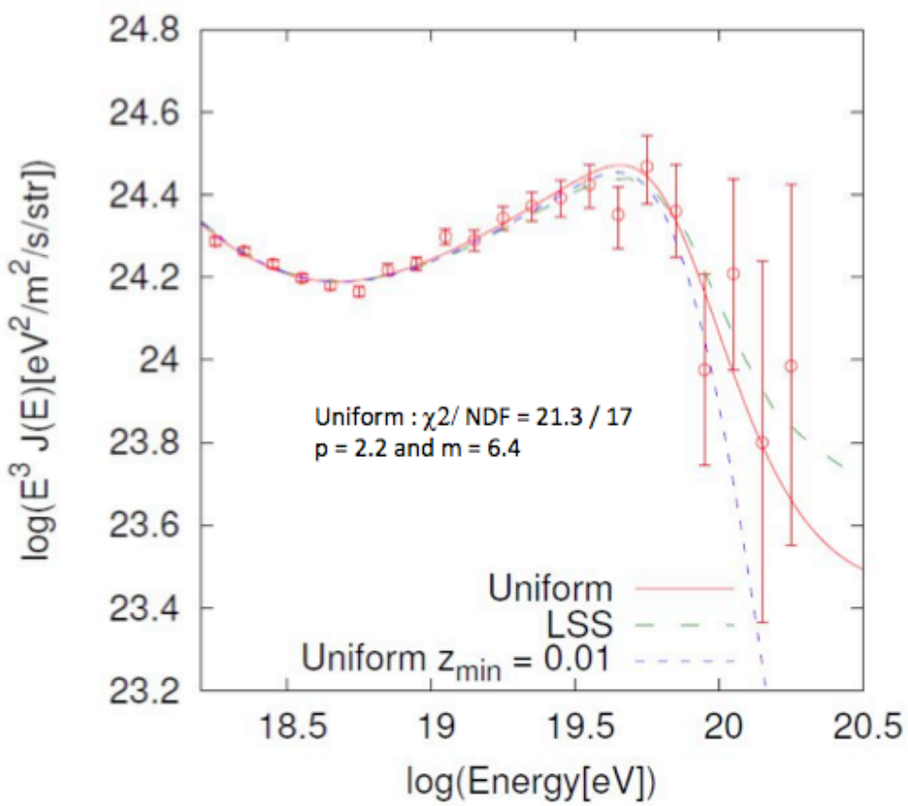
Fitting TA Spectrum with extra-Galactic Proton

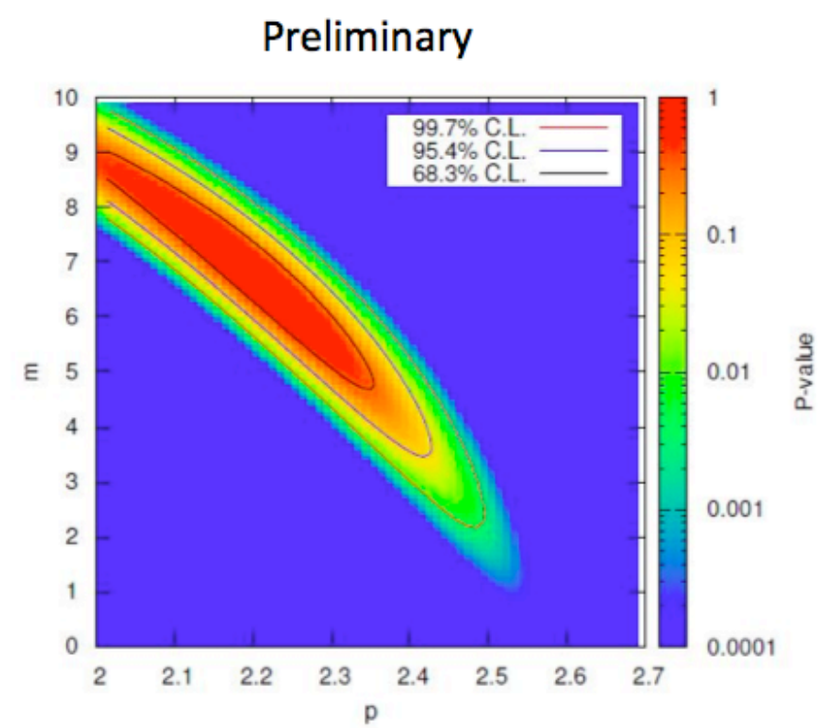
Energy Loss with
- CMB
- Infra-Red

using CRPropa 2.0 checked with transport eq.
(Kalachev+Kido, arXiv:1406.0735)

Source Distribution
- Uniform
- LSS (~2MASS XSCz) up to 250 Mpc
- No magnetic field

4-parameter fit
- Injection spectrum : E^{-p}
  $E_{max} = 10^{21}$ eV
- Evolution : $(1+z)^m$
- Flux normalization
- Energy scale





- ✦ TA spectrum fitted using a modified version of CRPropa 2.0
- ✦ these changes are now partially incorporated in CRPropa

summary

- ✦ CRPropa framework: allows the simulation of the propagation of UHE particles
- ✦ publicly available
- ✦ new features of the development version 3.0:
  - improvements on the photon background handling
  - updated photodisintegration cross sections
  - new IRB models
  - 4D mode
  - galactic magnetic field through lenses
  - Monte Carlo treatment of UHE photons (alternative to kinetic equations)
  - redshift dependent IRB [under development]
- ✦ comparison of simulations with observations in realistic scenarios
- ✦ parallelization allows fast simulations → span a wide range of parameters
- ✦ possibility of multimessenger studies

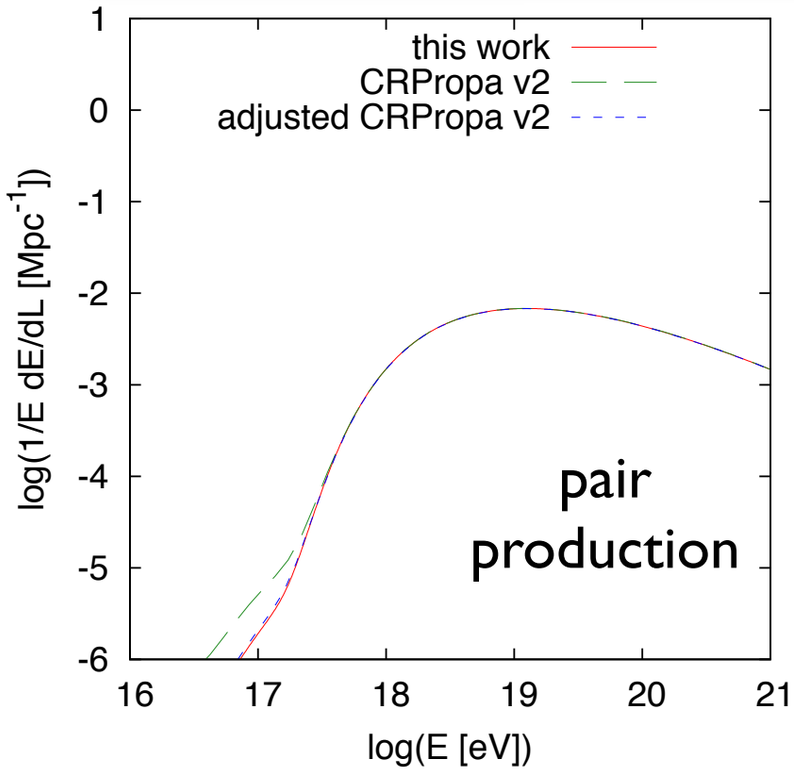
summary

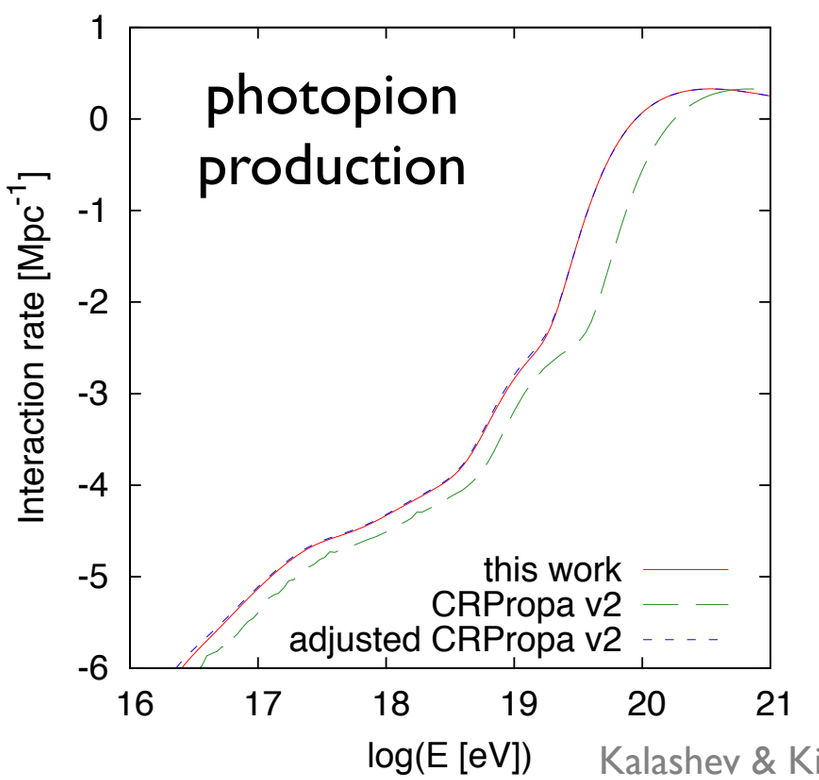
- ✦ CRPropa framework: allows the simulation of the propagation of UHE particles
- ✦ publicly available
- ✦ new features of the development version 3.0:
  - improvements on the photon background handling
  - updated photodisintegration cross sections
  - new IRB models
  - 4D mode
  - galactic magnetic field through lenses
  - Monte Carlo treatment of UHE photons (alternative to kinetic equations)
  - redshift dependent IRB [under development]
- ✦ comparison of simulations with observations in realistic scenarios
- ✦ parallelization allows fast simulations → span a wide range of parameters
- ✦ possibility of multimessenger studies

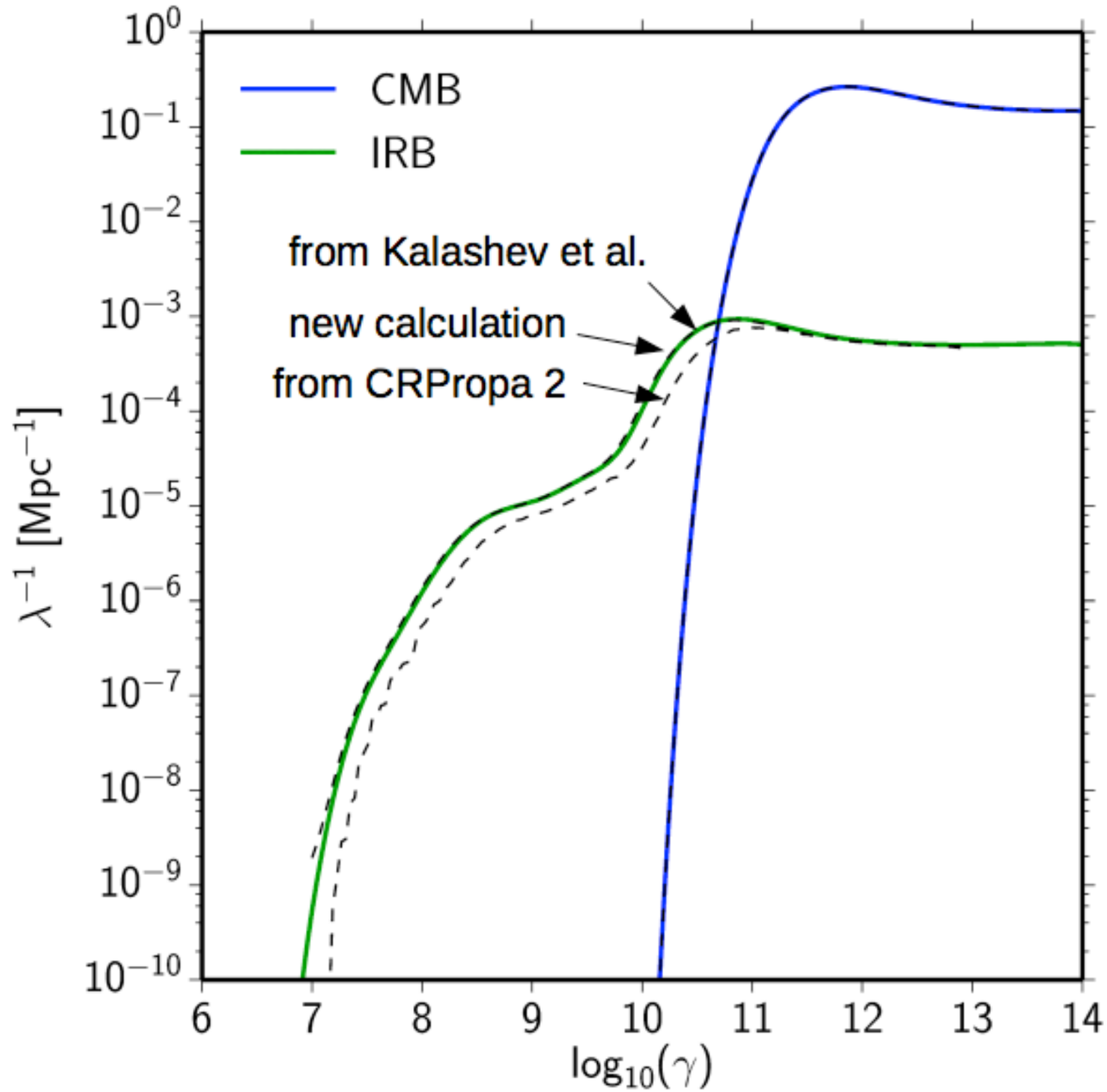
Thank you!

backup slides

improvements by Kalashev & Kido







Kalashev & Kido. arXiv:1406.0735

TALYS1.0 → TALYS 1.6

- ✦ wider energy range
- ✦ better predictions of deuteron reaction cross section
- ✦ improvement treatment of some resonances
- ✦ other (details in http://www.talys.eu)