CRPropa

CRPropa 3.2: a framework for high-energy astroparticle propagation

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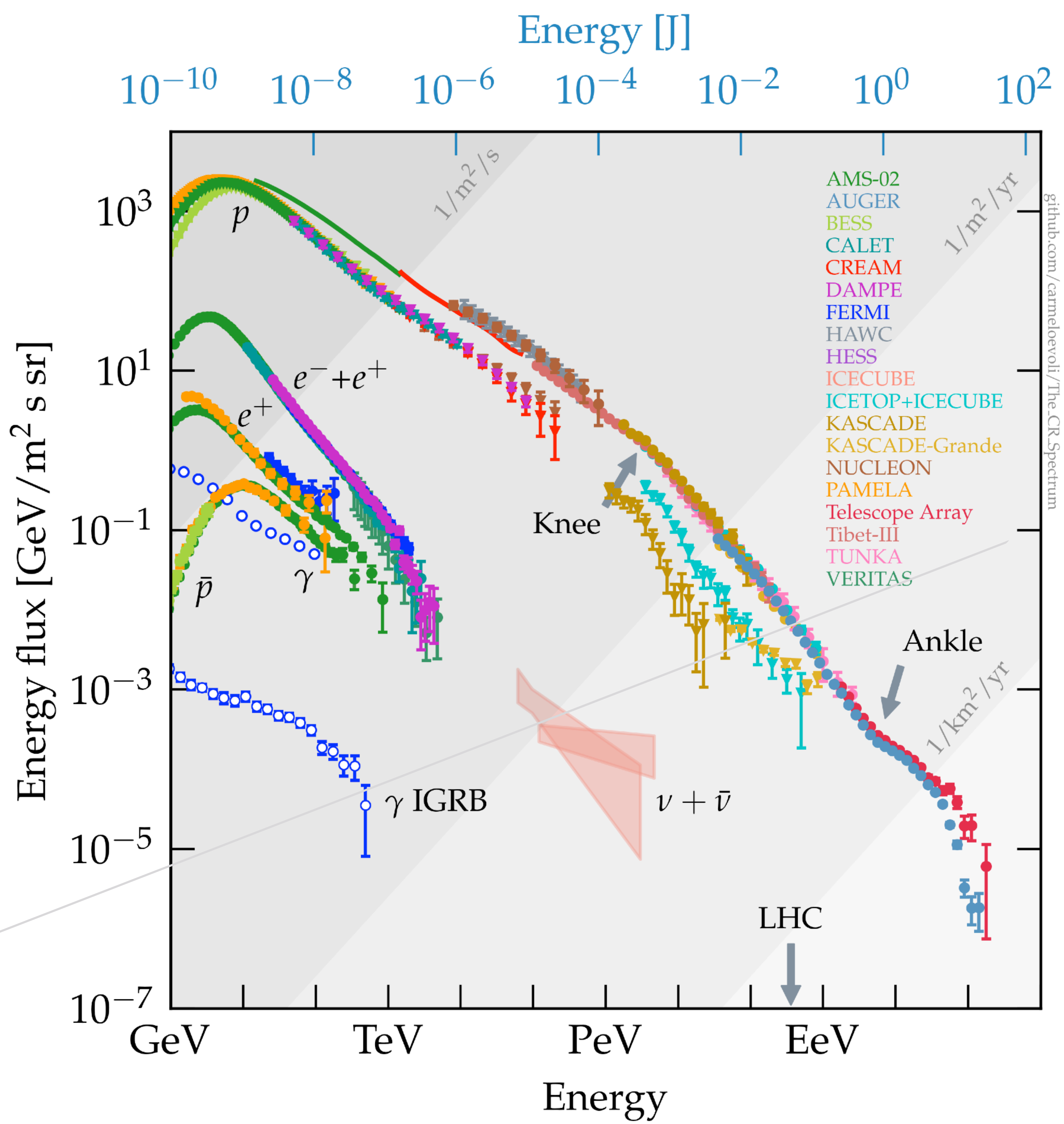
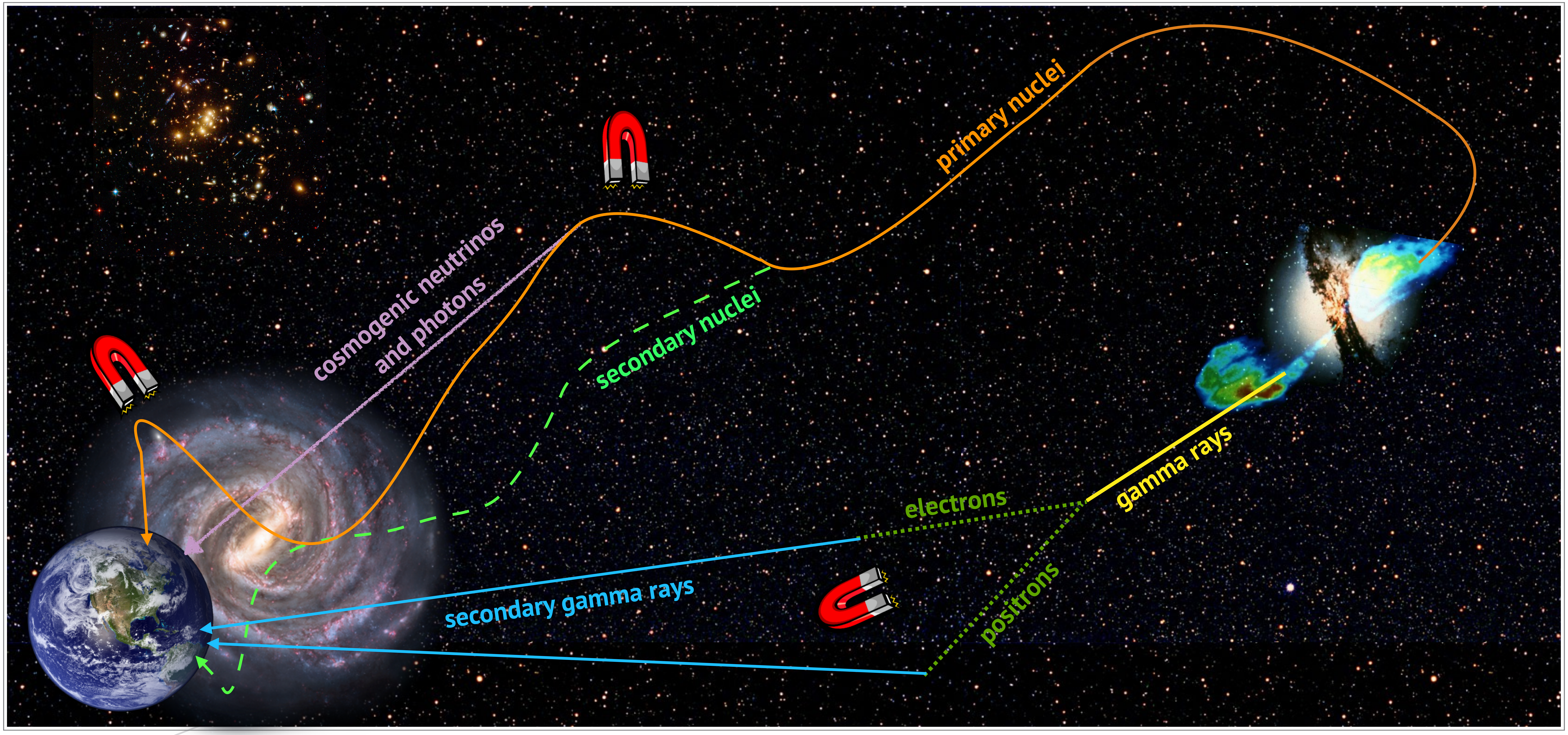
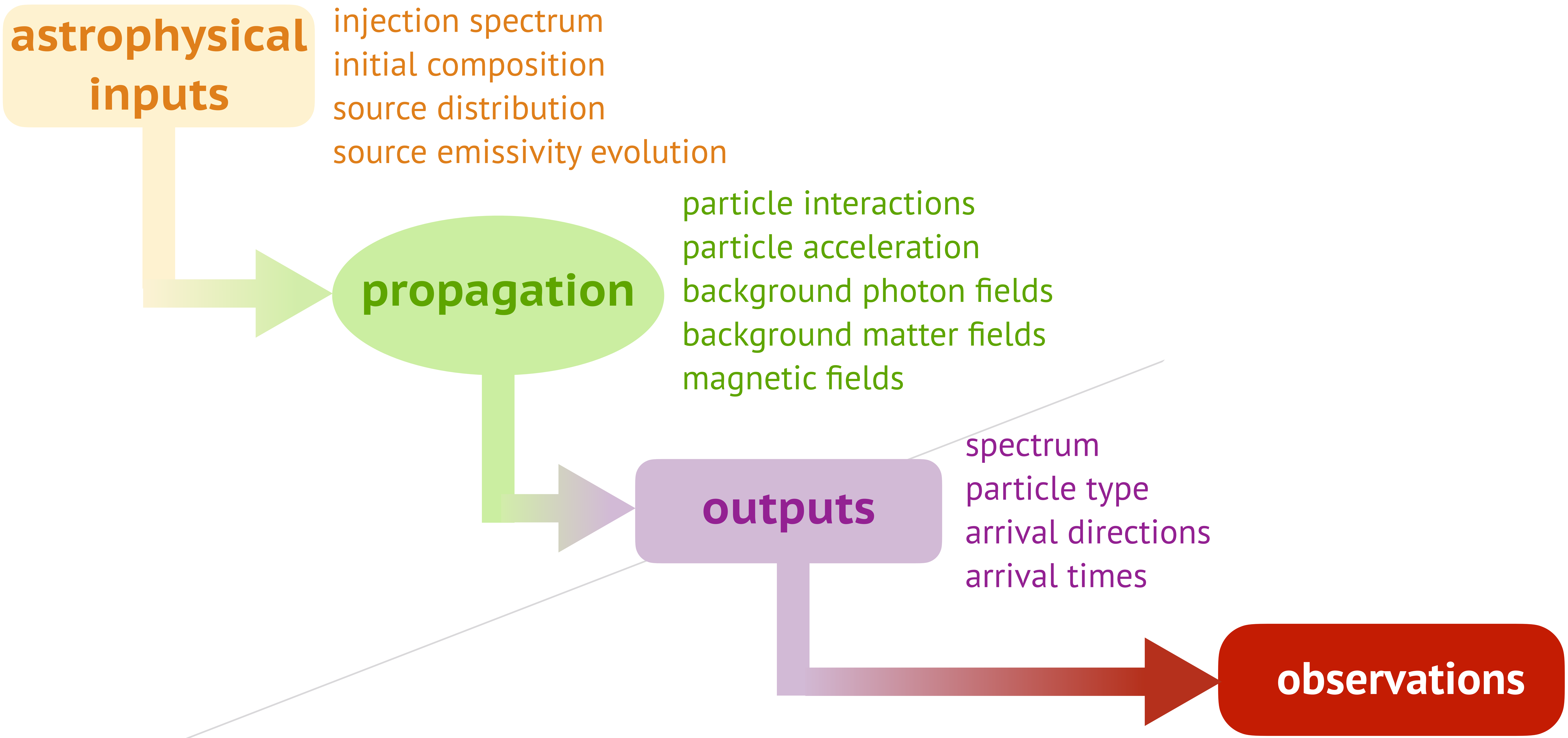
ICRC 2021

the high-energy astrophysical landscape



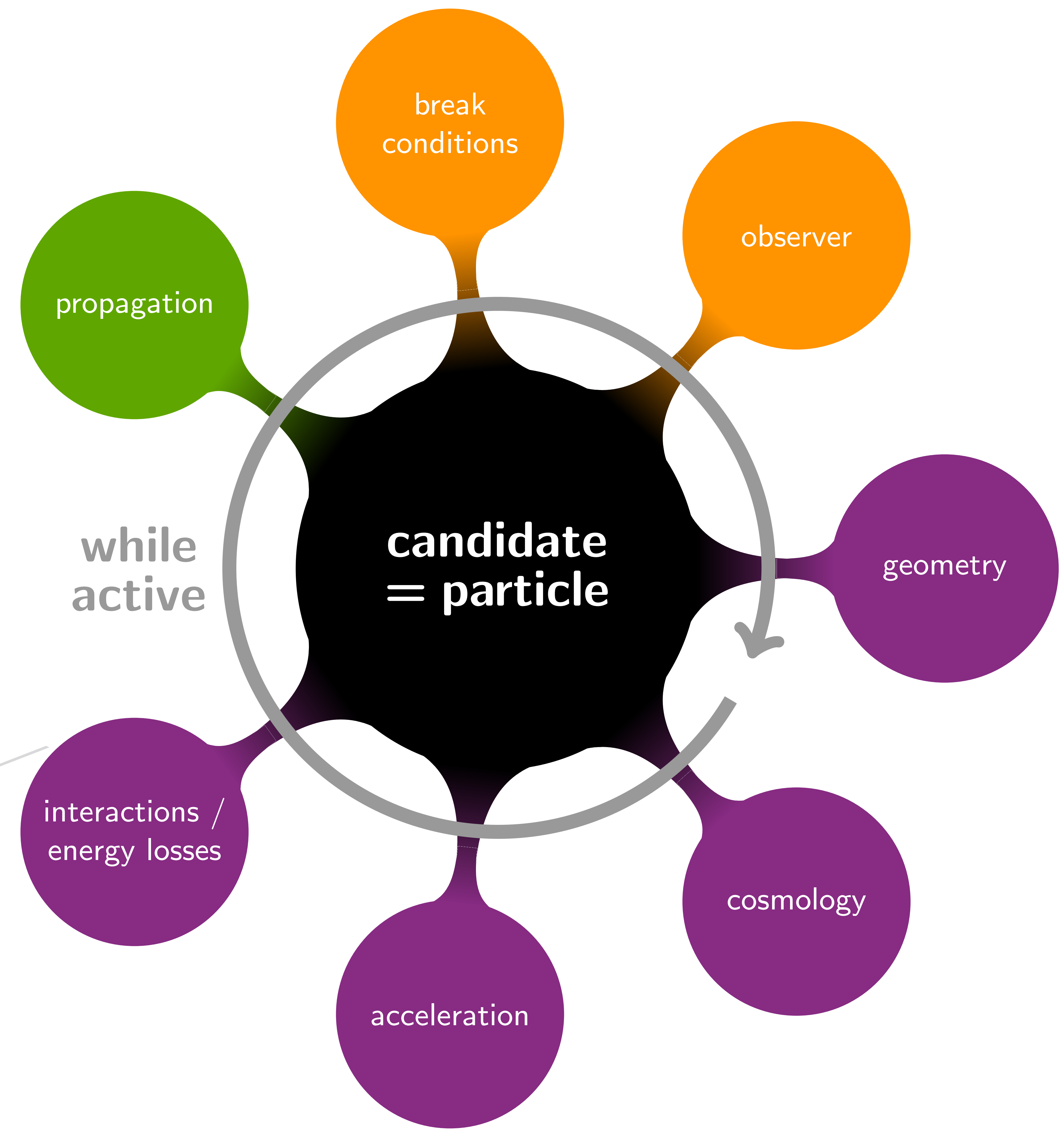

primary nuclei
cosmogenic neutrinos
and photons
secondary nuclei
gamma rays
electrons
positrons
secondary gamma rays

recipes for astroparticle propagation



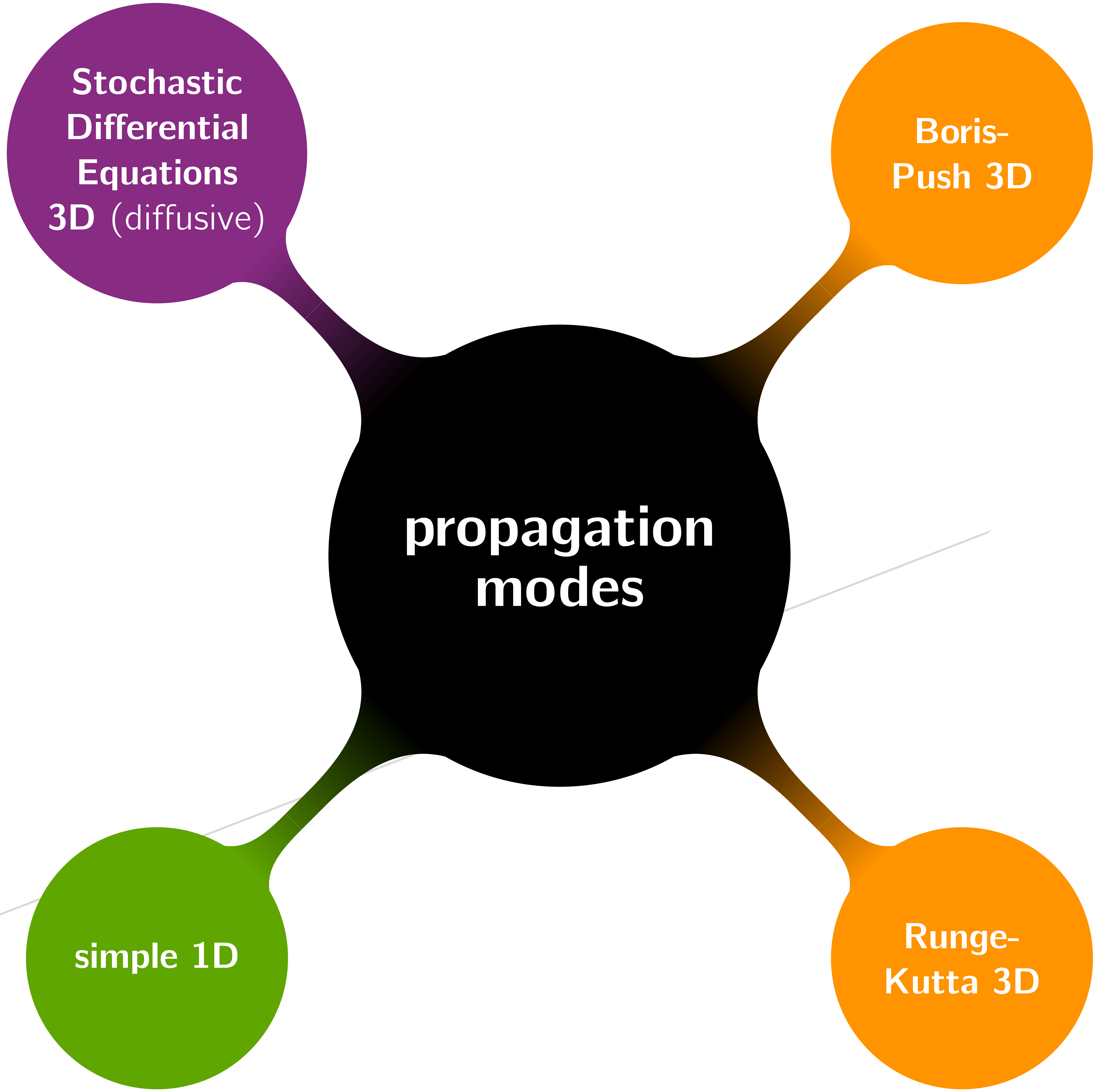
the CRPropa framework

- publicly available Monte Carlo code
- modular structure
- propagation of cosmic rays, gamma rays, neutrinos
- galactic and extragalactic propagation
- parallelisation with OpenMP
- development on Github:
  https://github.com/CRPropa/CRPropa3
- **CRPropa 3.2 coming out very soon!**

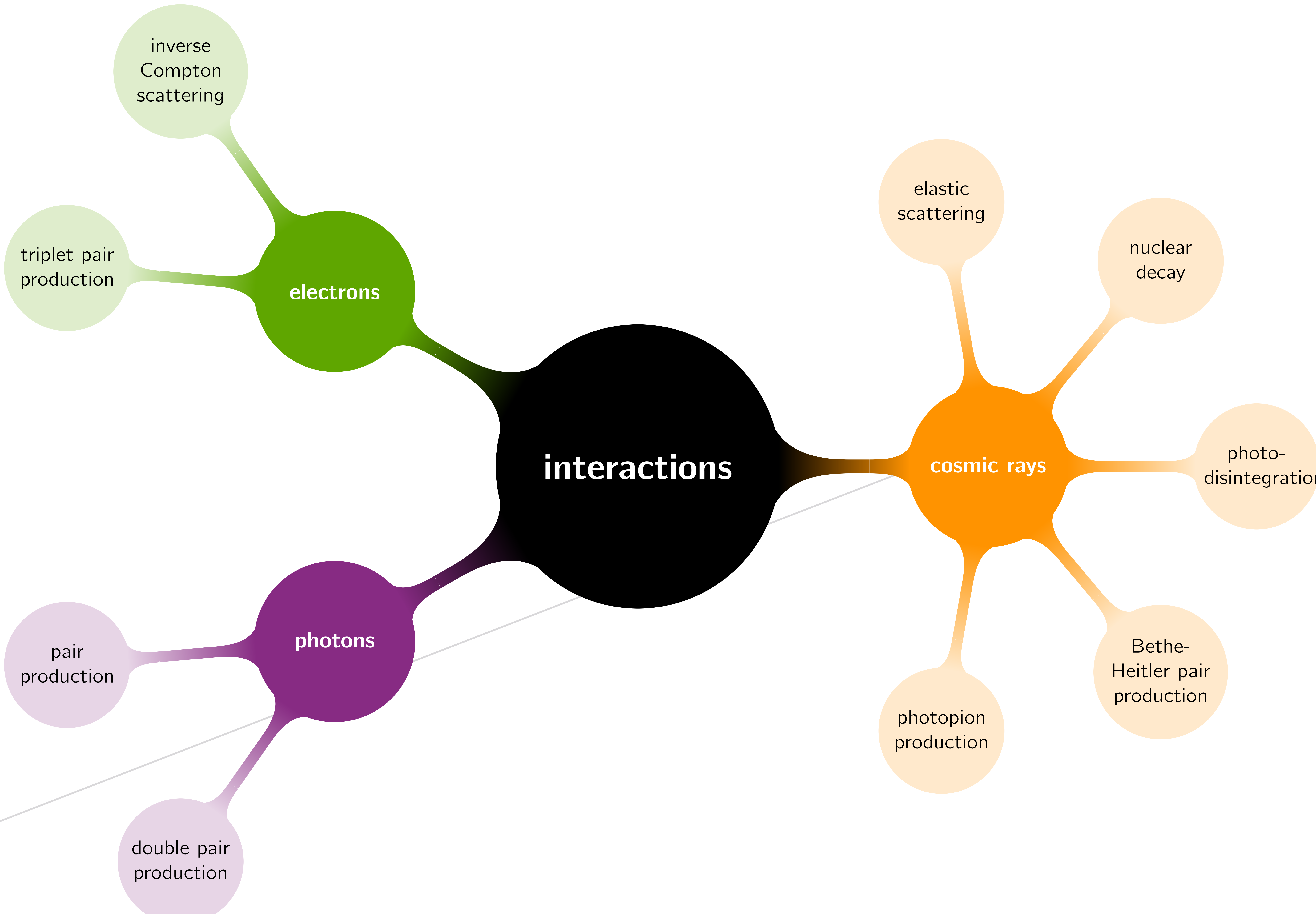


Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142

CRPropa: propagation modes

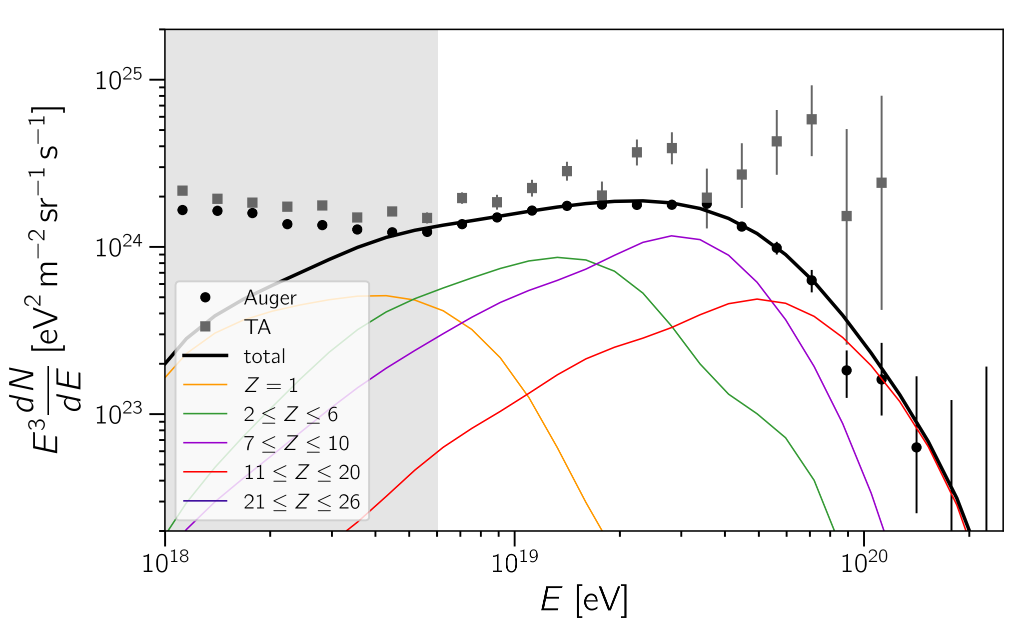


CRPropa: interactions with photon backgrounds



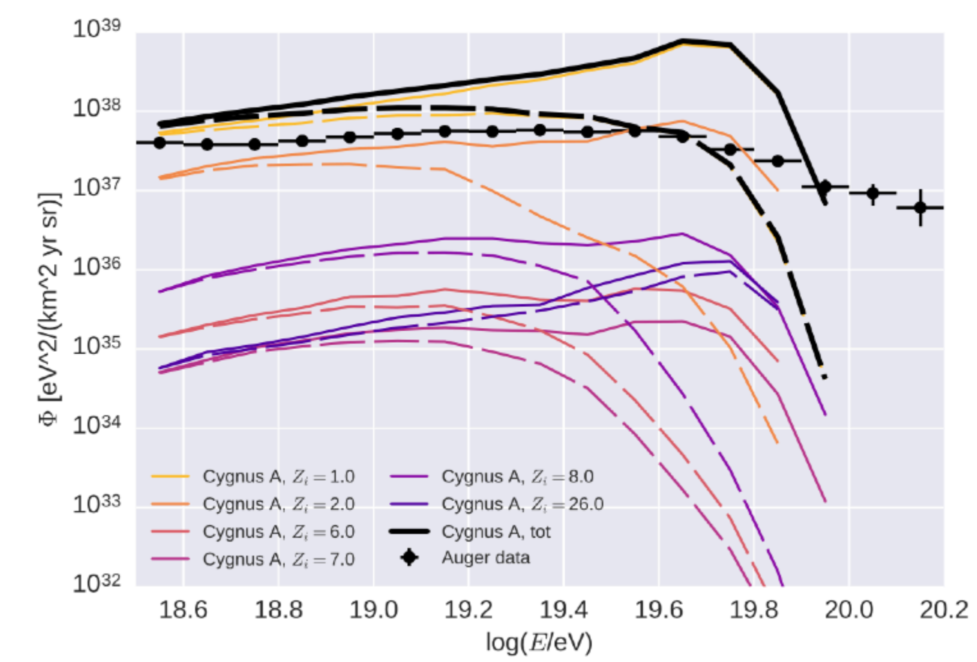
applications at a glance

fit UHECR measurements



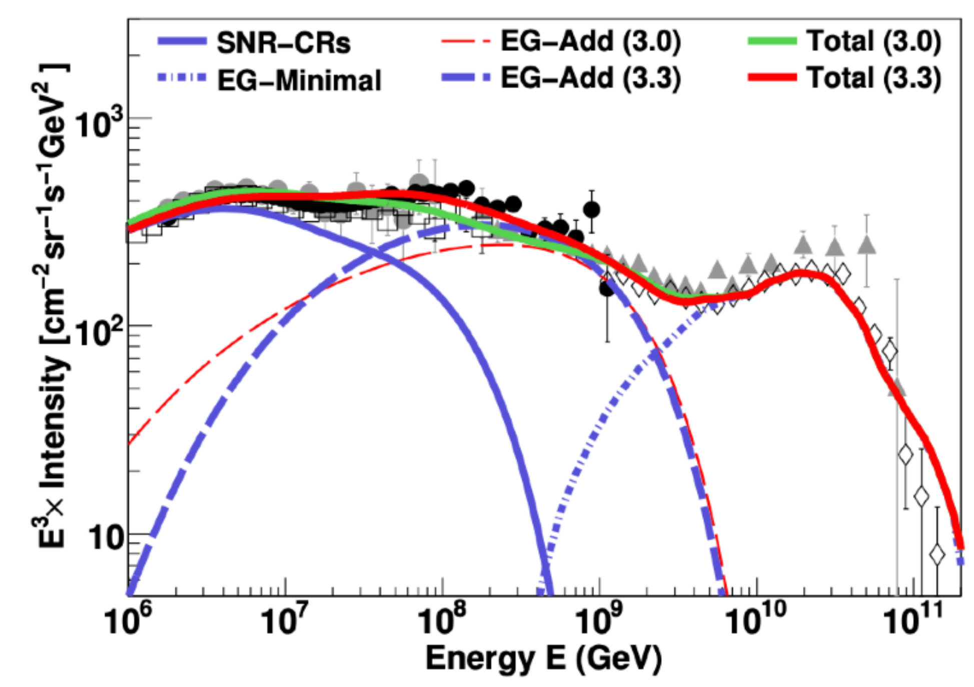
Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

test UHECR source models



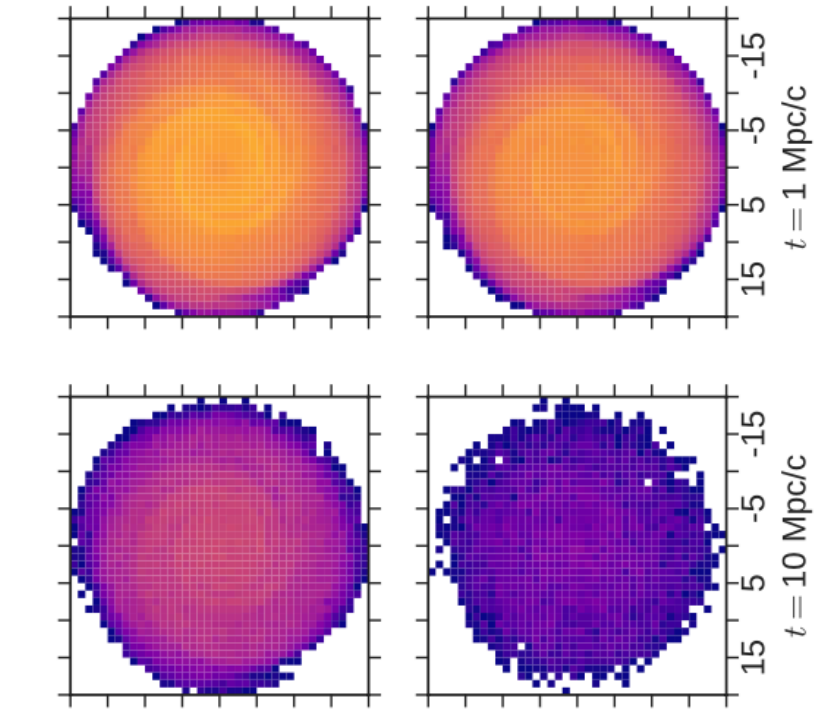
Eichmann et al. JCAP 02 (2018) 036. arXiv:1701.06792

transition G-EG CRs



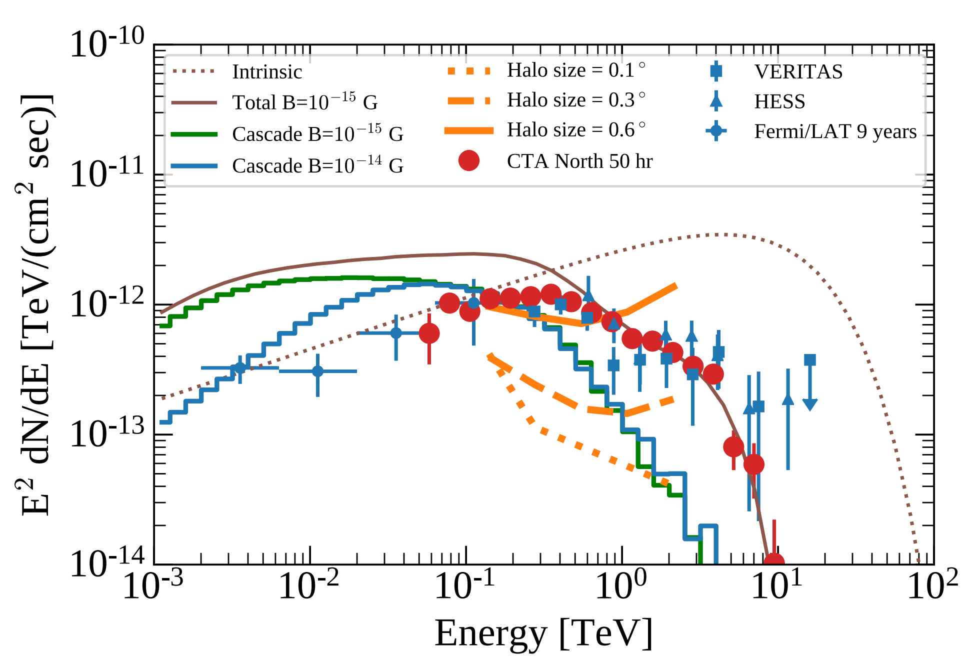
Thoudam et al. Astron. Astrophys. 595 (2016) A33. arXiv:1605.03111

diffusion of Galactic CRs



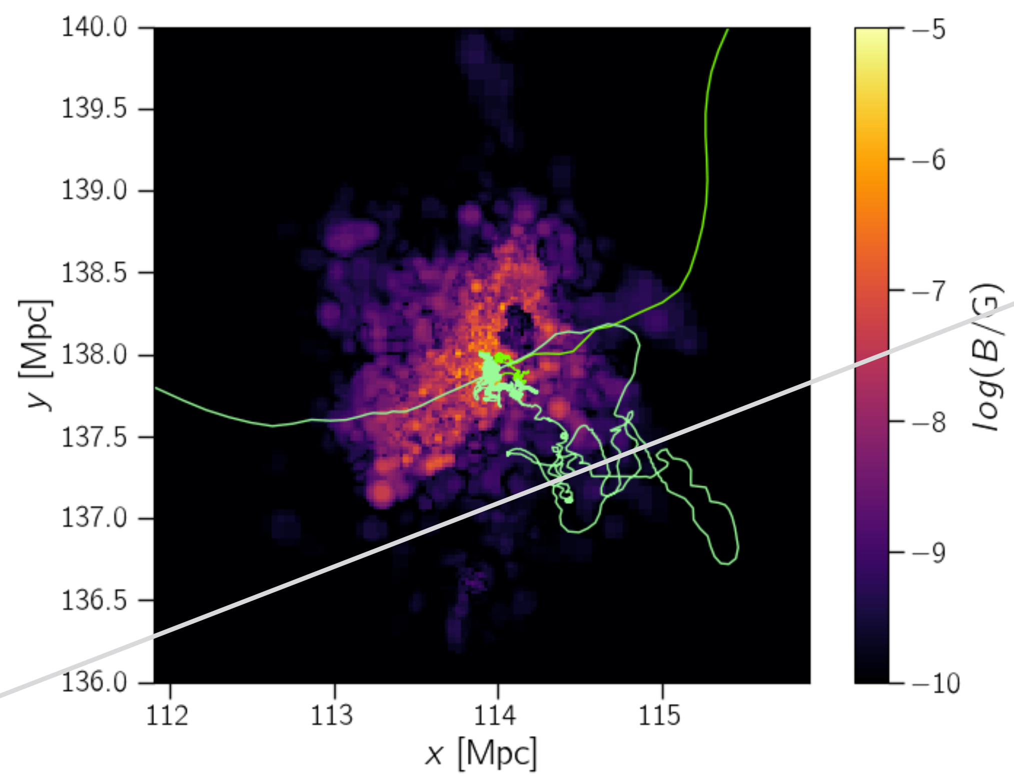
Merten et al. JCAP 06 (2016) 046. arXiv:1704.07484

gamma rays + IGMFs



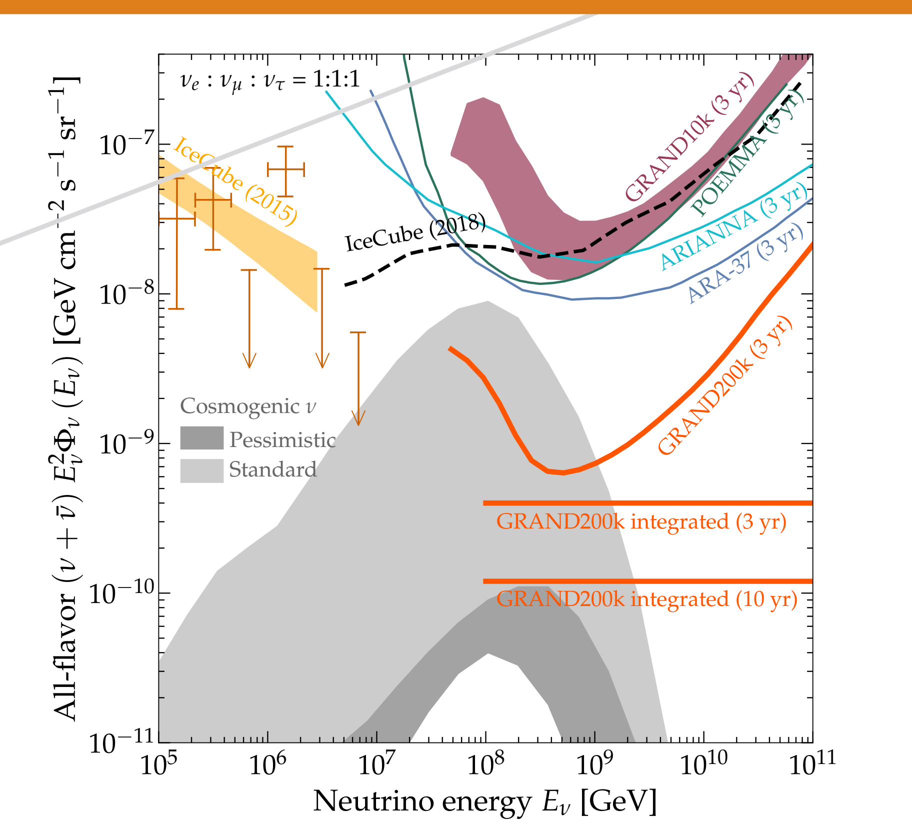
CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349

neutrinos from galaxy clusters



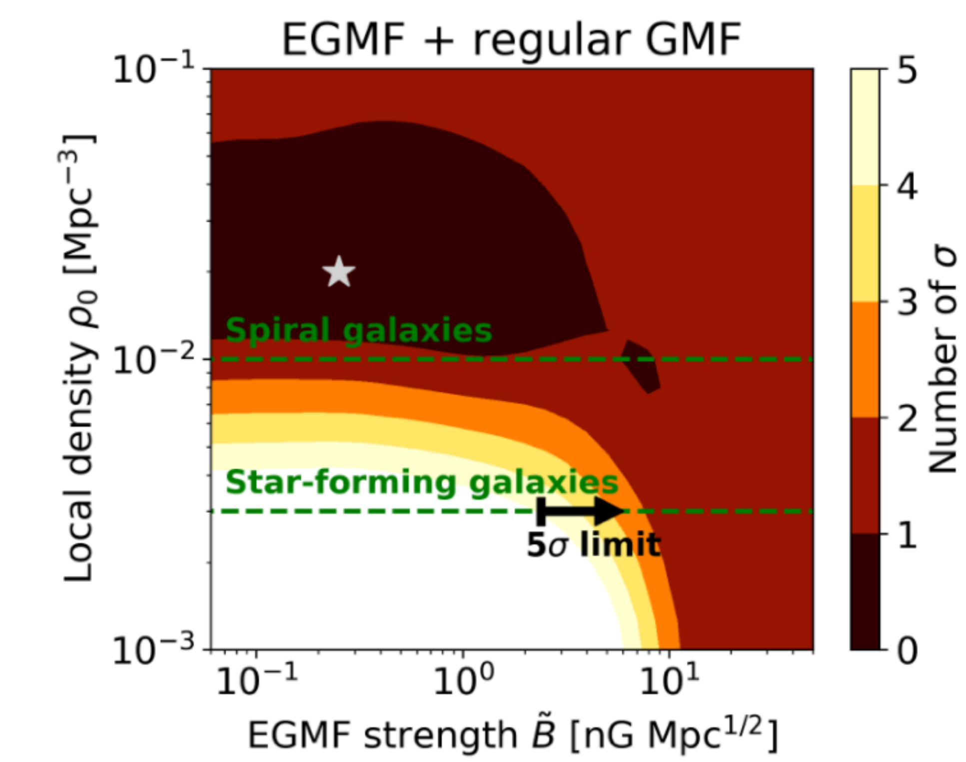
Hussain, Alves Batista, de Gouveia Dal Pino. arXiv:2101.07702

cosmogenic neutrinos



GRAND Collaboration. Science China Phys 63 (2020) 219501. arXiv:1810.09994

EGMF constraints



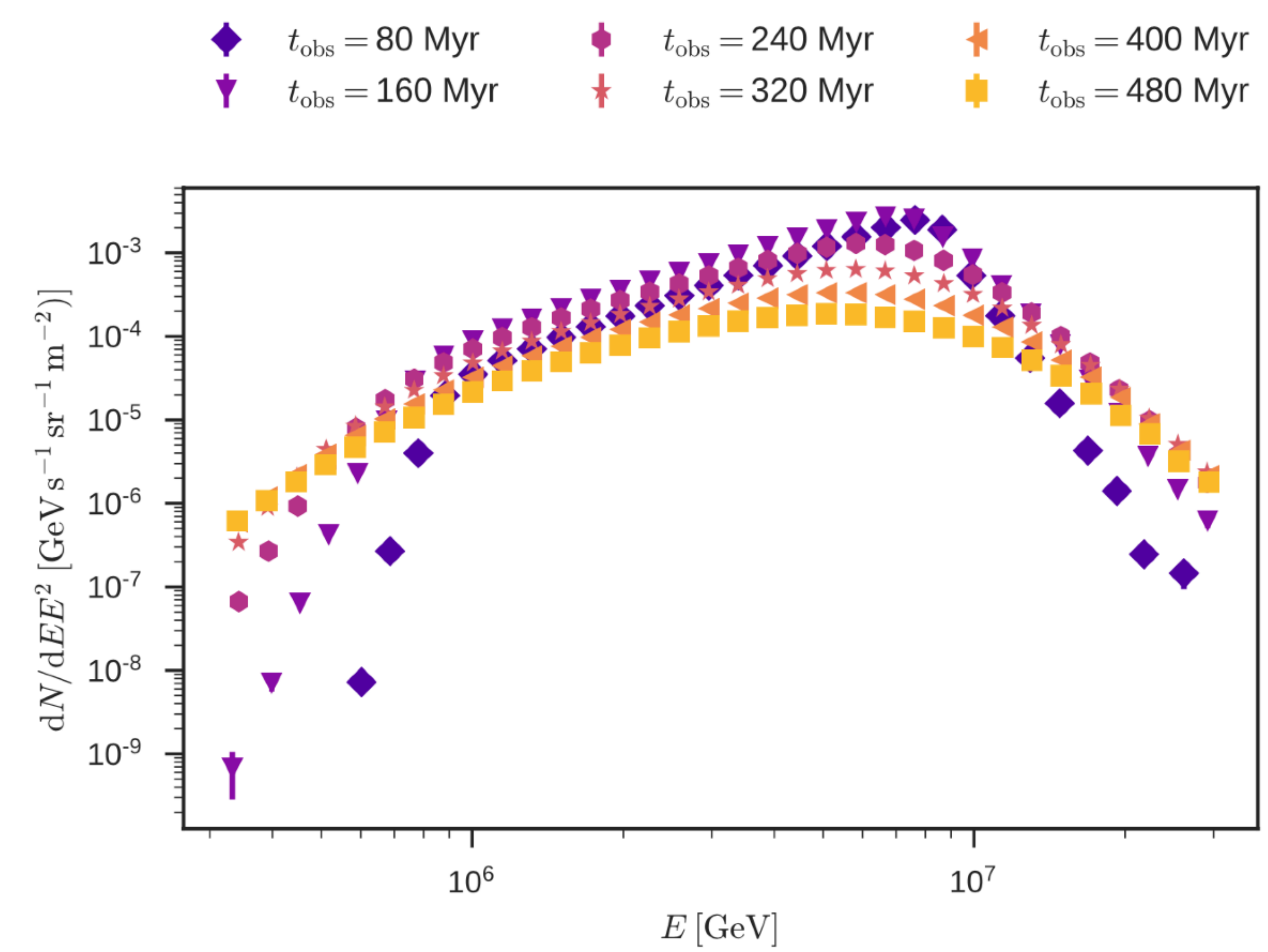
van Vliet, Palladino, Taylor, Winter. arXiv:2104.05732

and much more!

what is new?

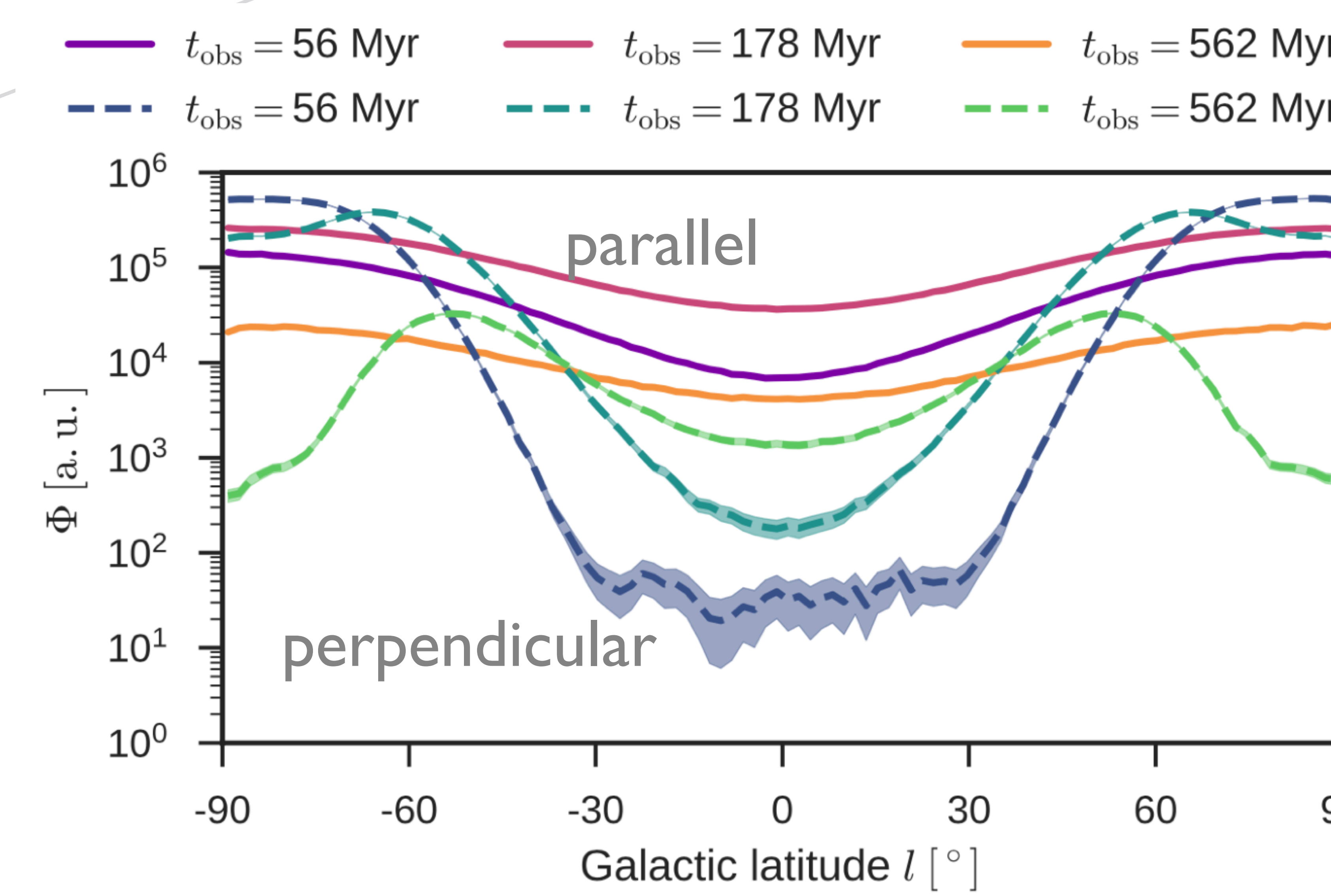
- ensemble-averaged propagation using transport equations
- ideal for diffusive propagation of charged particles, e.g., in the Galaxy
- employs stochastic differential equations

$$\frac{\partial n}{\partial t} + \vec{u} \cdot \vec{\nabla} n = \vec{\nabla} \cdot \left(\hat{\kappa} \vec{\nabla} n \right) + \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 \kappa_{pp} \frac{\partial n}{\partial p} \right) + \frac{p}{3} \frac{\partial n}{\partial p} \vec{\nabla} \cdot \vec{u} + S$$



example

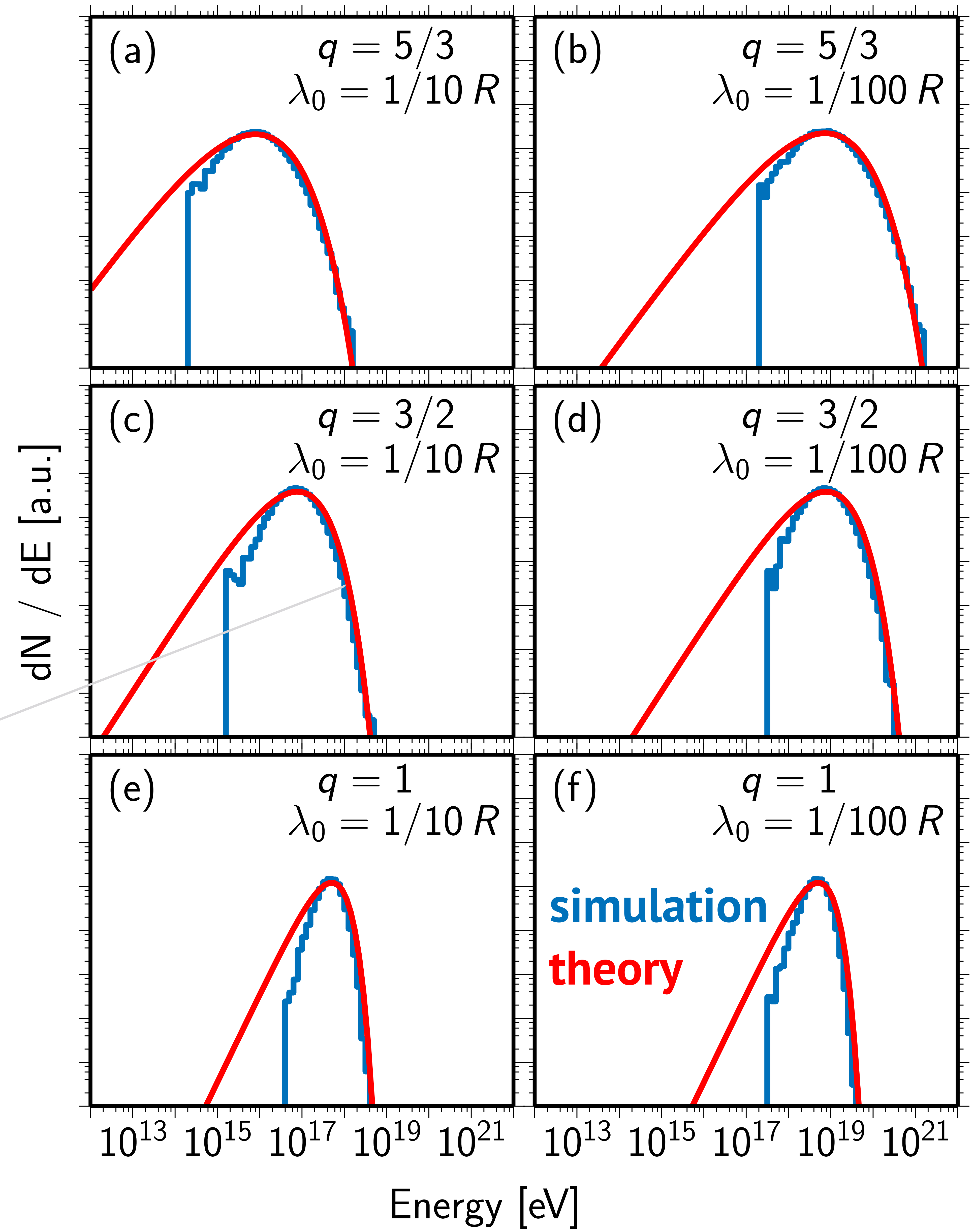
- Galactic wind termination shock
- anisotropic diffusion + advection + adiabatic cooling
- Archimedean spiral background field
- CRs from the termination shocks might account for part of the flux at PeV-EeV



Merten et al. ApJ 859 (2018) 63. arXiv:1803.08376

Winchen and Buitnik. Astropart. Phys. 102 (2018) 25. arXiv:1612.0.675

- implementation of 1st- and 2nd-order Fermi acceleration
- performance improvements through particle splitting
- quasi-linear theory predicts scattering of charged particle in magnetic fields with typical length scale λ
- prediction: $$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{3-q} \exp\left(-\left(\frac{E}{E_0}\right)^{2-q}\right)$$



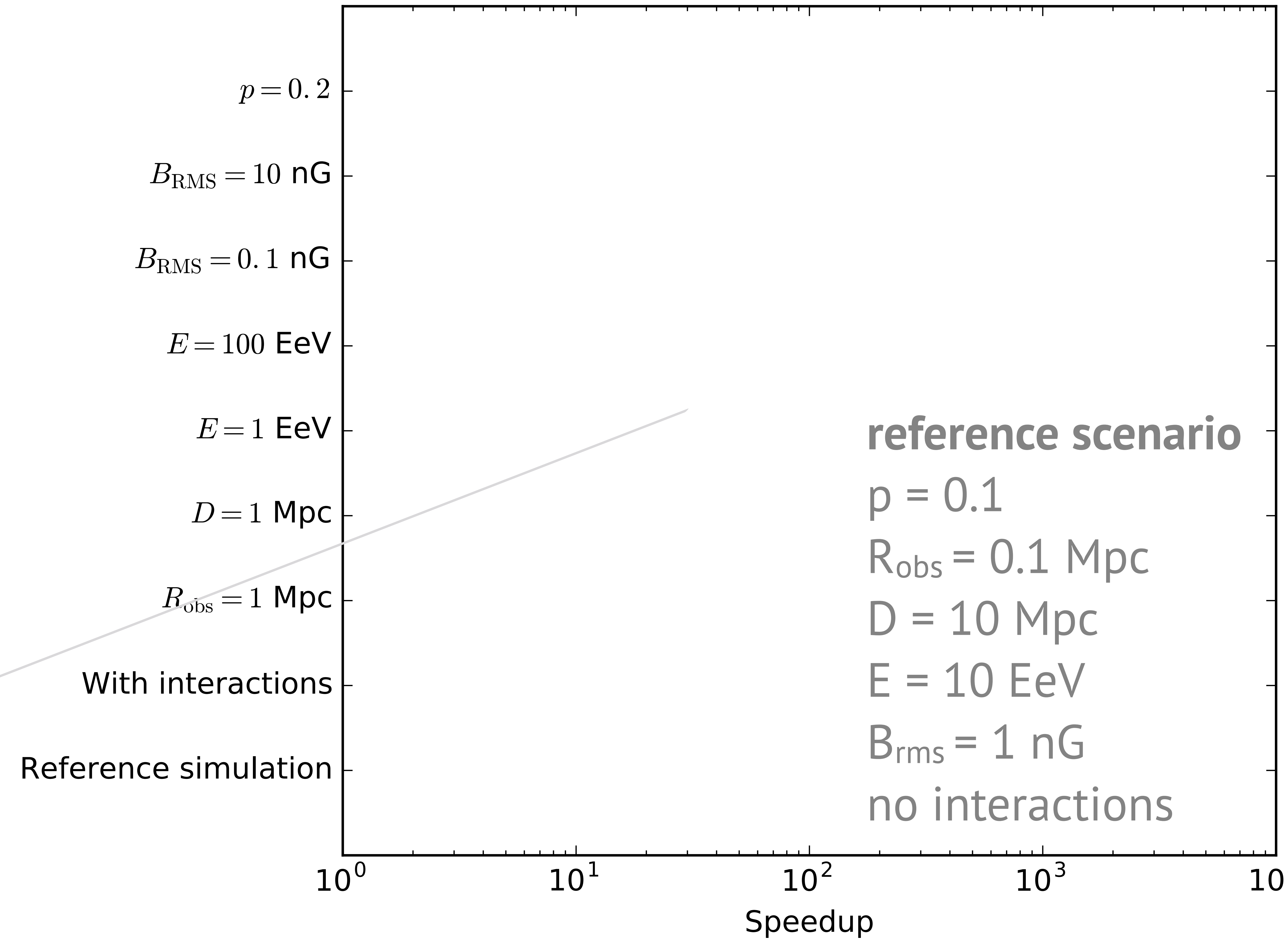
example

- 2nd-order Fermi acceleration of protons
- sub-relativistic case: β=0.5

new features: targetting

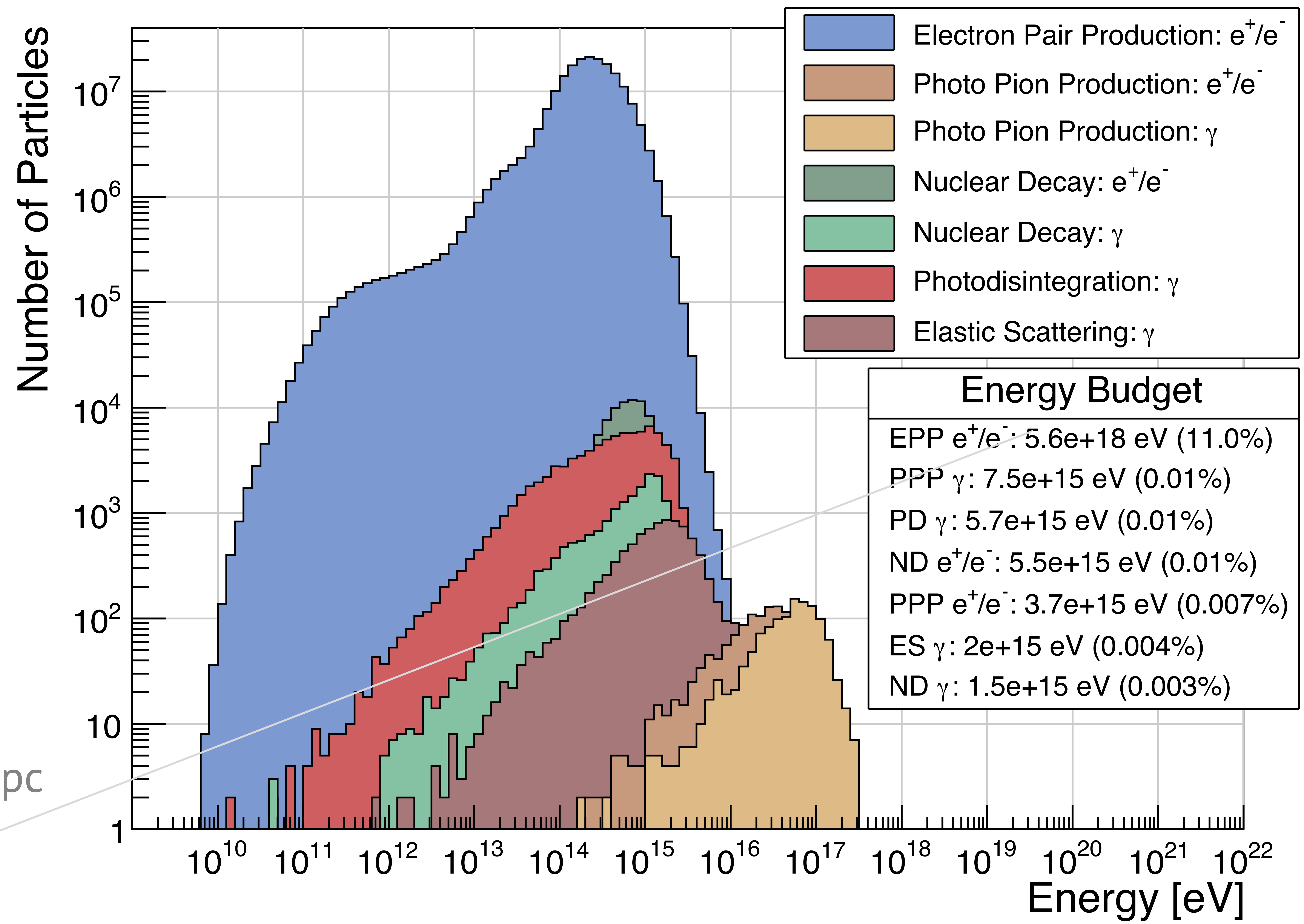
Jasche, van Vliet, Rachen. PoS (ICRC2019) 447.

- problem with 3D/4D Monte Carlo simulations → low detection efficiency
- start with isotropic emission and learn from detections and non-detections
- correct source emission according to detection probability using a von Mises-Fischer distribution
- performance enhancement depends on scenario → weaker magnetic fields lead to greater speedup, in general



new features: new photon production channels

Heiter, Kuempel, Walz, Erdmann. Astropart. Phys. 102 (2018) 102. arXiv:1710.11406



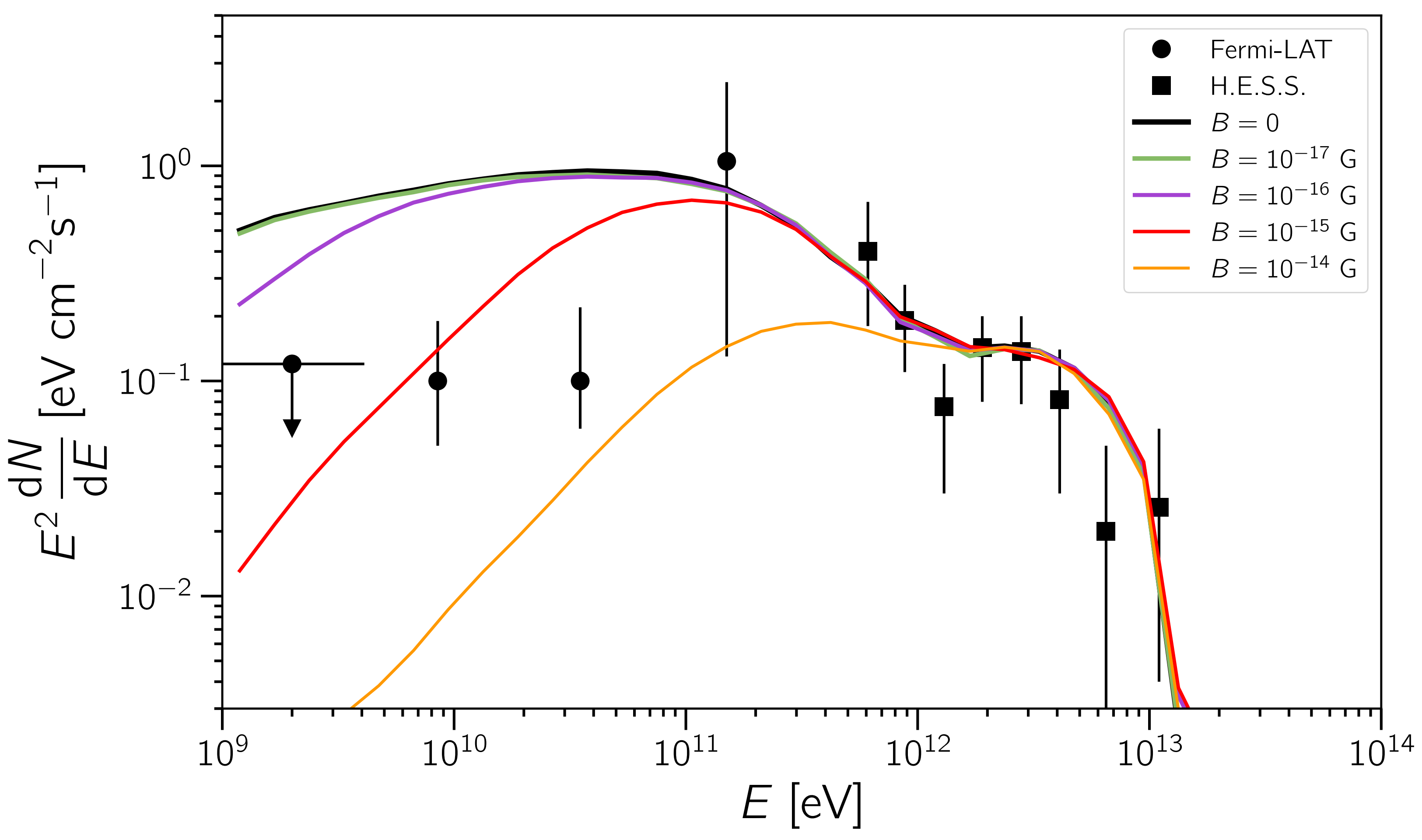
D = 3-1000 Mpc
E = 50 EeV
iron

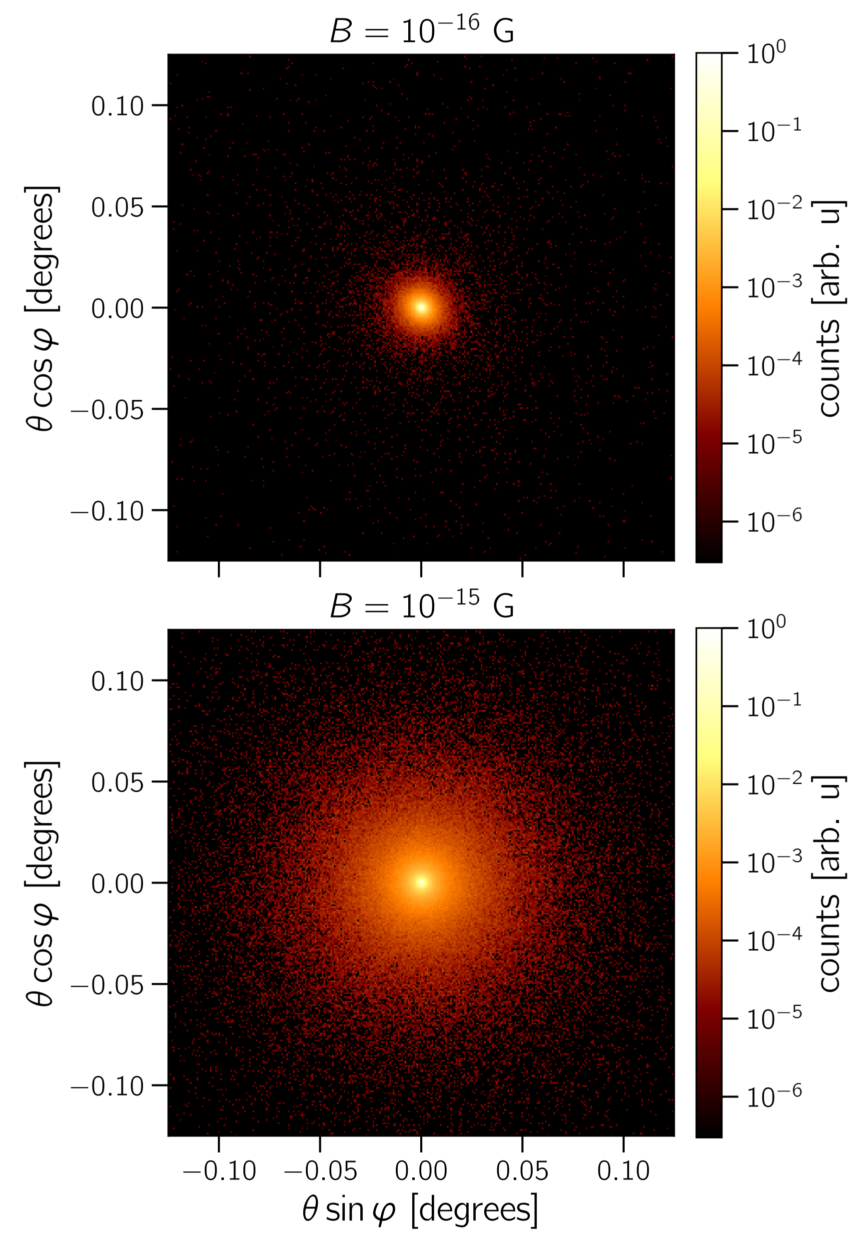
new feature: electromagnetic interactions

- CRPropa-native implementation of electromagnetic interactions
- replaces the external codes DINT and EleCa used in previous versions
- new interactions: pair production, inverse Compton scattering, double and triplet pair production
- thinning procedure to speed up simulations → performance gains
- applications to gamma-ray astronomy: EBL & IGMF studies, UHECR-induced cascades, etc

example

- gamma rays from blazar 1ES 0229+200
- 3D simulations
- models for IGMF constraints, searches for pair haloes





Alves Batista and Saveliev. arXiv: 2105.12020

summary & outlook

summary & outlook

- CRPropa: public framework for the propagation of high-energy particles
- treatment of CRs, neutrinos, gamma rays, electrons
- 1D, 3D, and "4D" simulations possible
- many photon background and magnetic-field models
- **modular design** enables easy customisation for various applications in astroparticle physics
- enables a self-consistent interpretation of observations with **multiple messengers**

more information:

crpropa.desy.de

version 3.2

- improved algorithm for Galactic CR propagation
- new Galactic magnetic field models
- targeting algorithm to speed up 3D/4D simulations
- native treatment of electromagnetic interactions
- new channels for photon production
- and much more