

computational methods for astroparticle propagation

class 1: introduction

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- ▶ understand the basics of how particles travel in the universe;
- ▶ learn about the computational methods used to model their propagation
- ▶ get a glimpse into some of the codes widely employed by the community
- ▶ understand the difficulties and limitations of model-building
- ▶ learn how to build and run a simulation with the CRPropa code
 - ✦ *install CRPropa on your own before Wednesday afternoon!*

- ▶ **class 1**
 - ◆ introduction to the course
 - ◆ introduction to astroparticle physics
- ▶ **classes 2 and 3**
 - ◆ the theory of astroparticle transport
 - ◆ analytical and numerical methods for modelling astroparticle propagation
- ▶ **class 4**
 - ◆ a primer on the CRPropa framework
- ▶ **class 5**
 - ◆ hands-on class on how to simulate the propagation of astroparticles
- ▶ **class 6**
 - ◆ current challenges in astroparticle physics and connection to modelling
 - ◆ philosophical issues in model-building and interpretation of observations

▶ **material**

- ◆ course website: www.8rafael.com/en/teaching/computational-methods-for-astroparticle-propagation/
- ◆ github: https://github.com/rafaelab/Course_AstroparticlePropagation

▶ **references**

- ◆ lecture notes *(will be released soon)*
- ◆ T. Gaisser et al. "Cosmic Rays and Particle Physics". Cambridge Uni. Press, 2016.
- ◆ M. Longair. "High Energy Astrophysics". Cambridge Uni. Press, 2011.
- ◆ G. Sigl. "Astroparticle Physics: theory and phenomenology". Springer, 2017.
- ◆ A. Shalchi. "Nonlinear Cosmic Ray Diffusion Theories". Springer, 2009.
- ◆ G. Fleishman and I. Toptygin. "Cosmic Electrodynamics". Springer, 2013.

**cosmic
rays**

$E > \text{TeV}$

**gamma
rays**

electrons

$E > \text{GeV}$

neutrinos

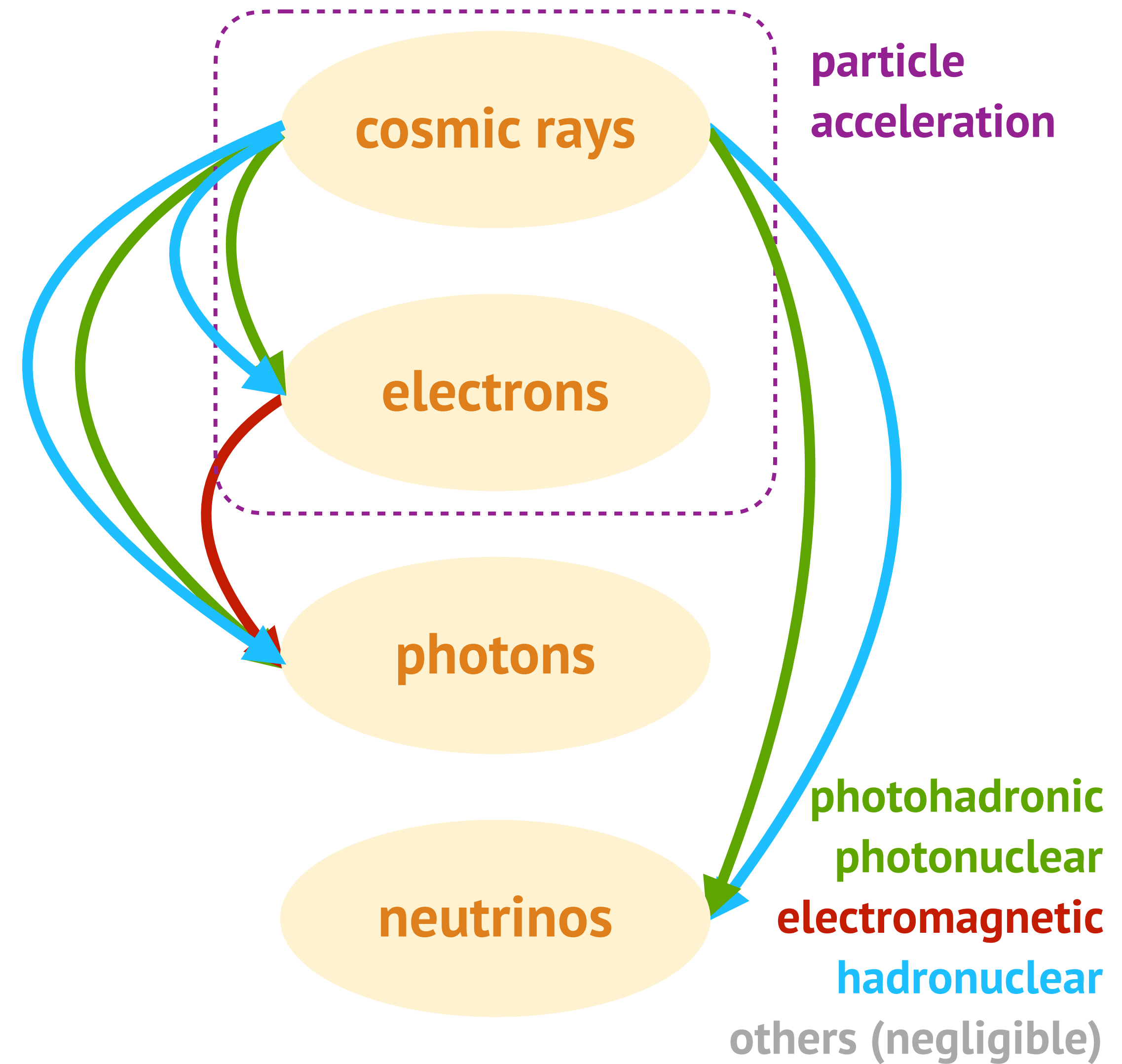
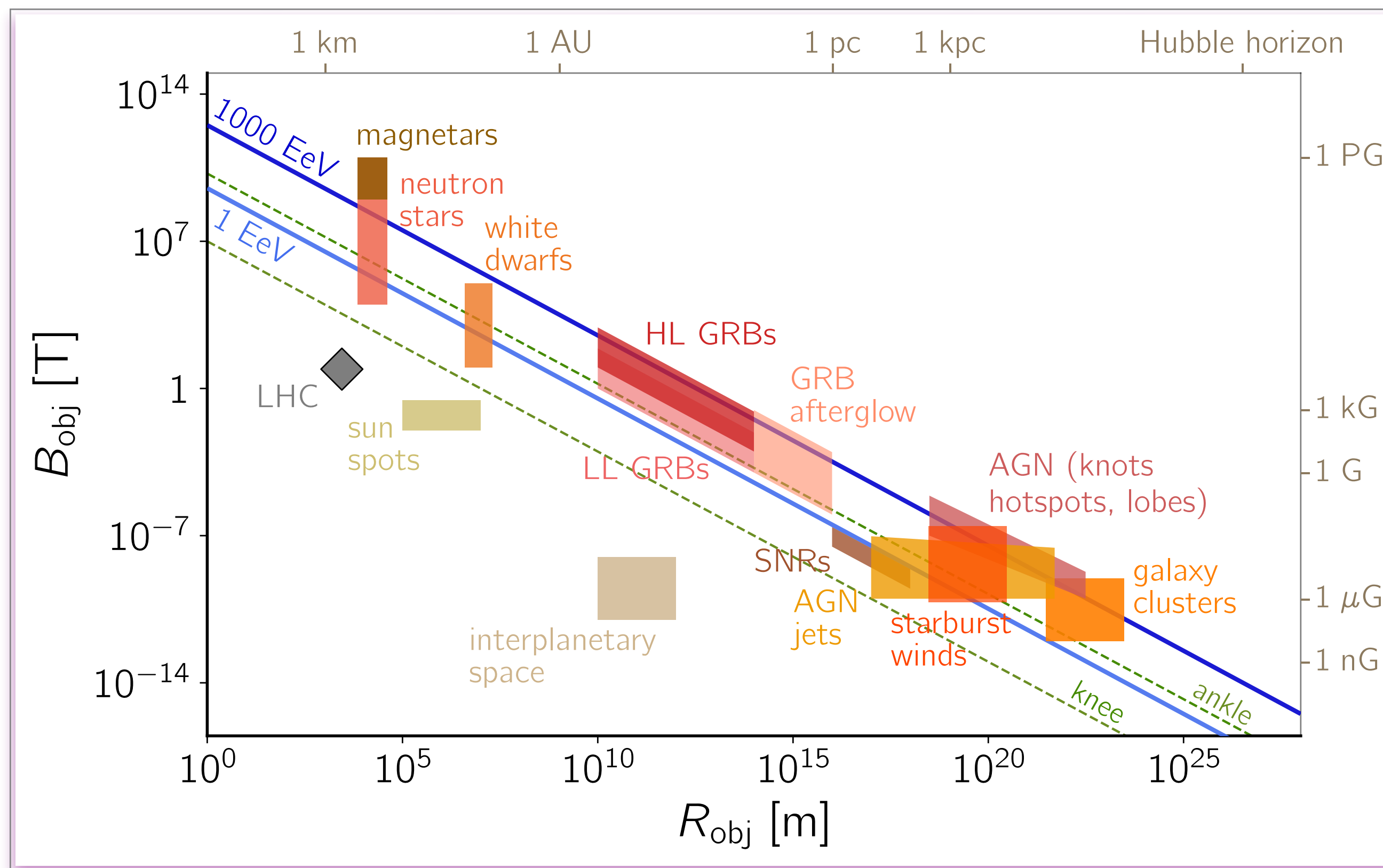
$E > \text{TeV}$

multimessenger

high-energy astroparticles: production mechanisms

high-energy astroparticles: production and synergies

- ▶ how are (ultra-)high-energy particles produced?
 - ◆ *charged particles*: electromagnetic acceleration
 - ◆ *neutral particles*: particle interactions

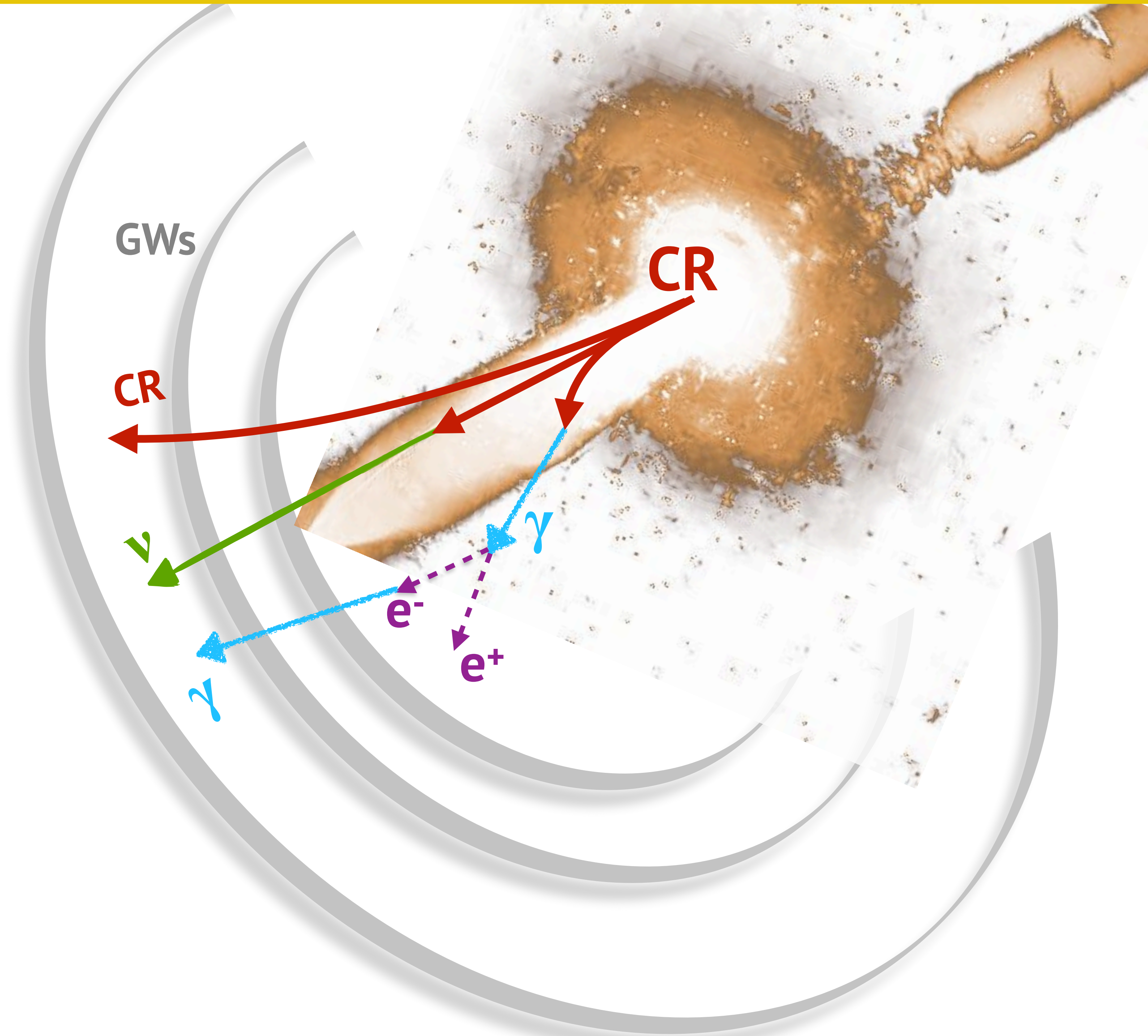


Hillas criterion $E_{\text{max}} \sim 2qv_{\text{sh}}BR_L \sim 10^{18}Z \left(\frac{B}{\mu\text{G}}\right) \left(\frac{R}{\text{kpc}}\right) \text{eV}$

ultra-high-energy (particle) astrophysics:
messengers above ~ 1 EeV and their by-products

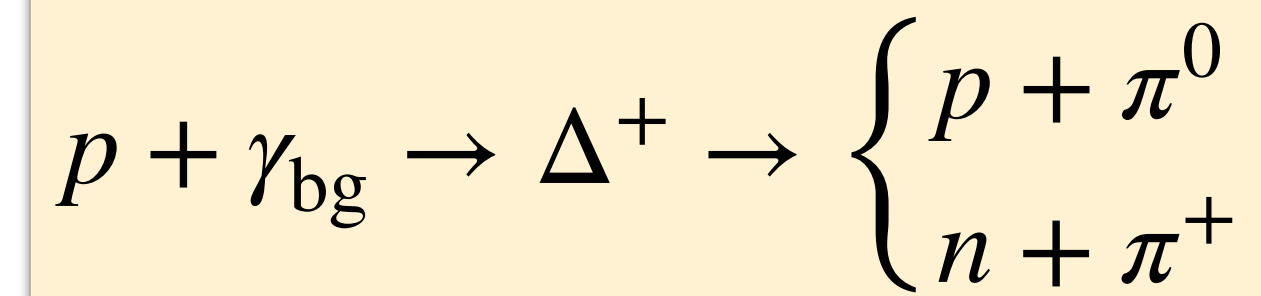
high-energy astroparticles: propagation mechanisms

multimessenger picture: **sources**



multimessenger propagation picture: **cosmic rays**

photopion production



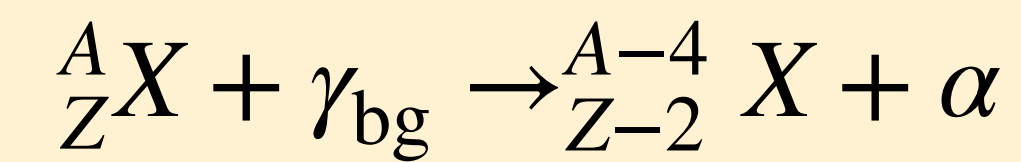
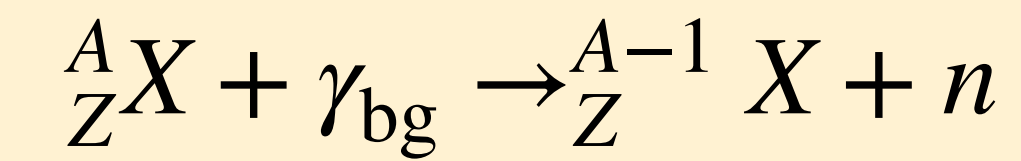
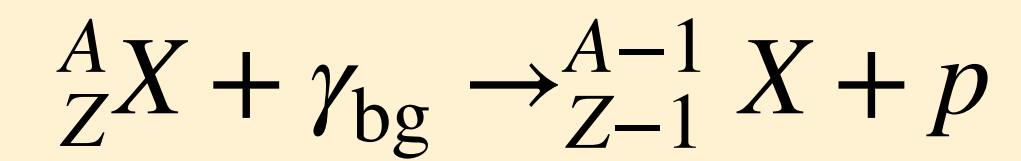
(secondary)
CR

cosmogenic ν

cosmogenic γ

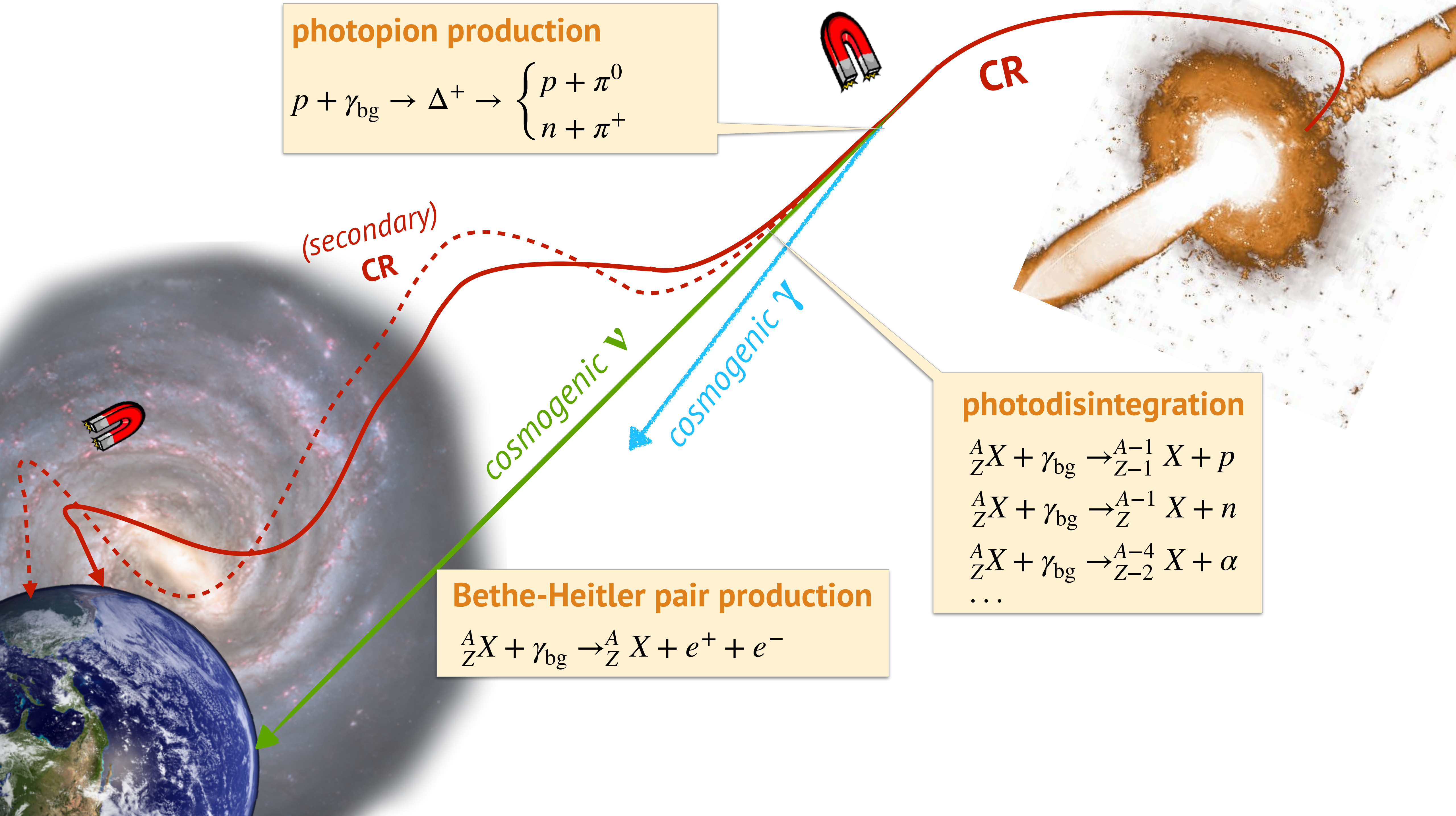
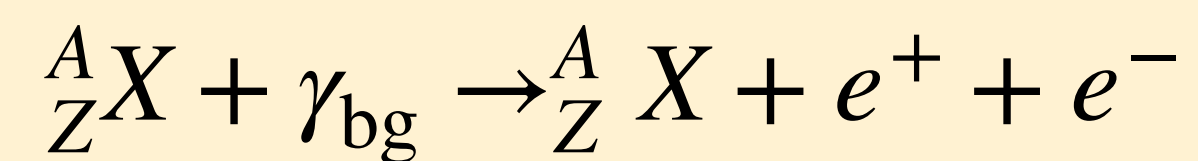
CR

photodisintegration

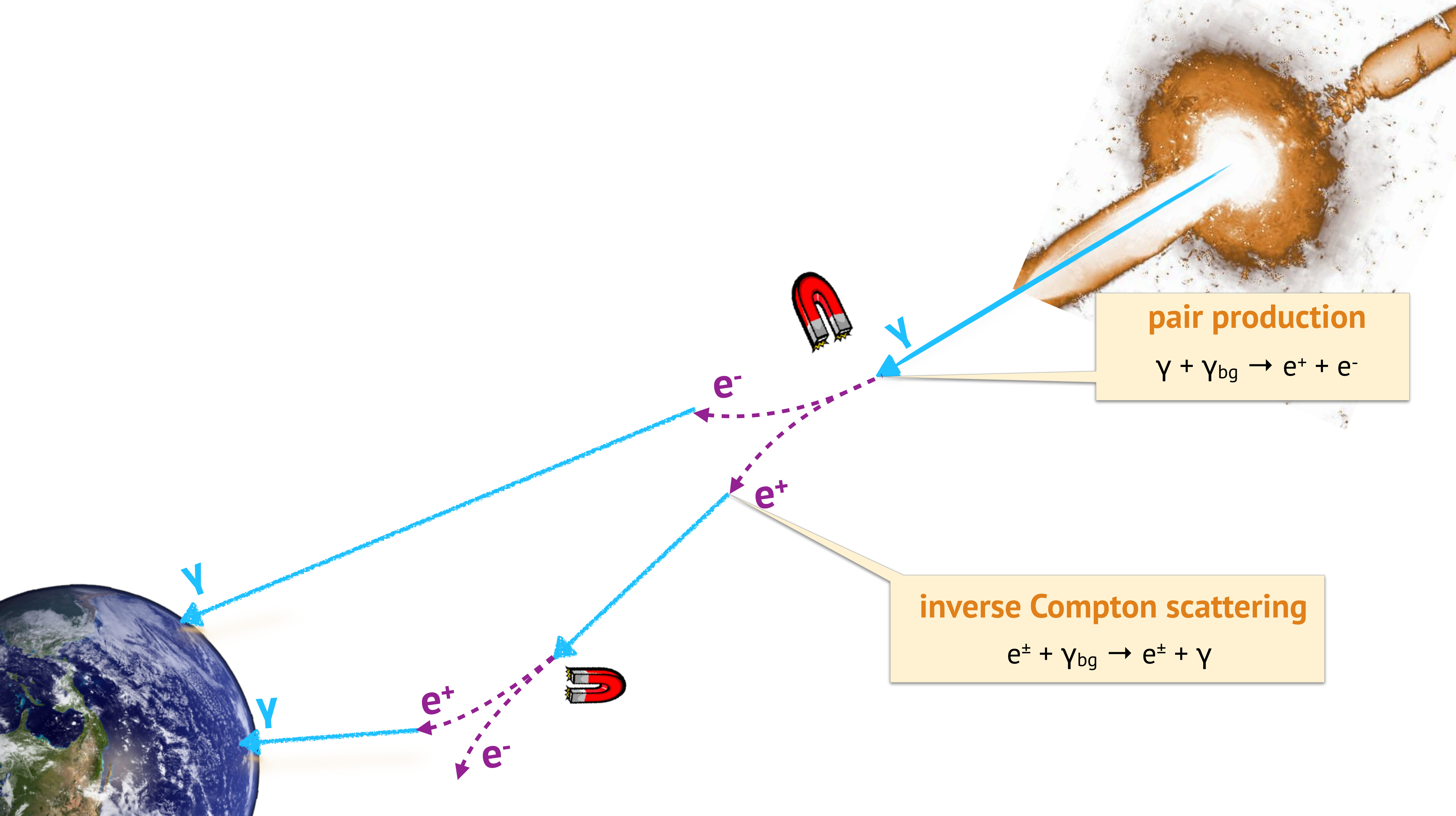


...

Bethe-Heitler pair production



multimessenger propagation picture: **gamma rays and electrons**



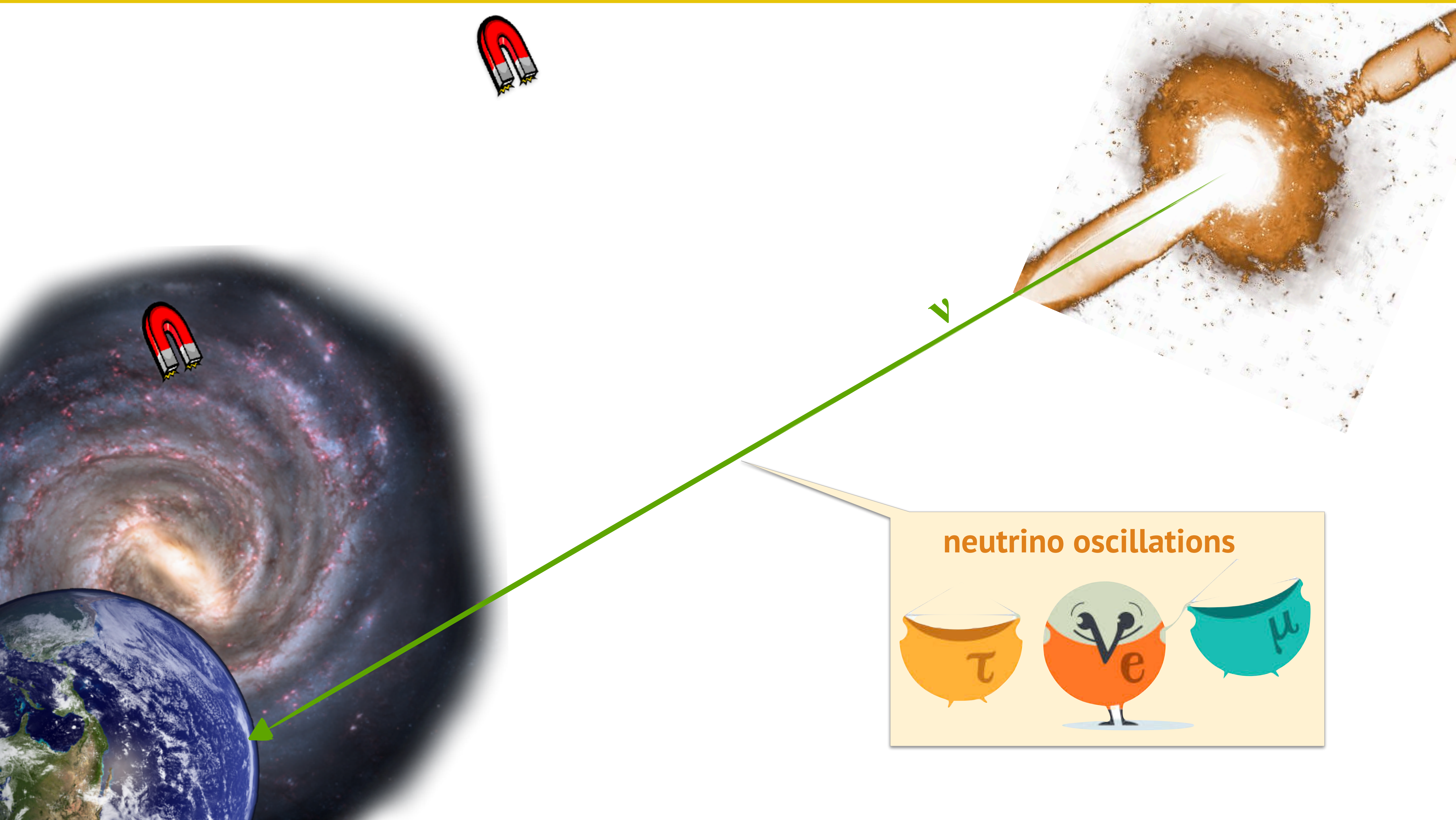
pair production

$$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$$

inverse Compton scattering

$$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$$

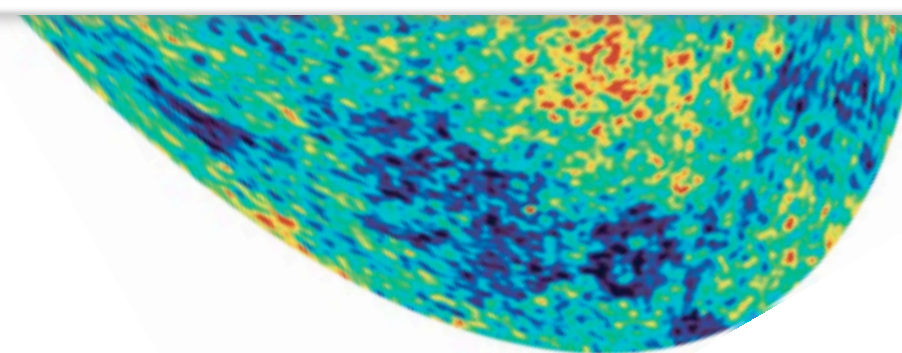
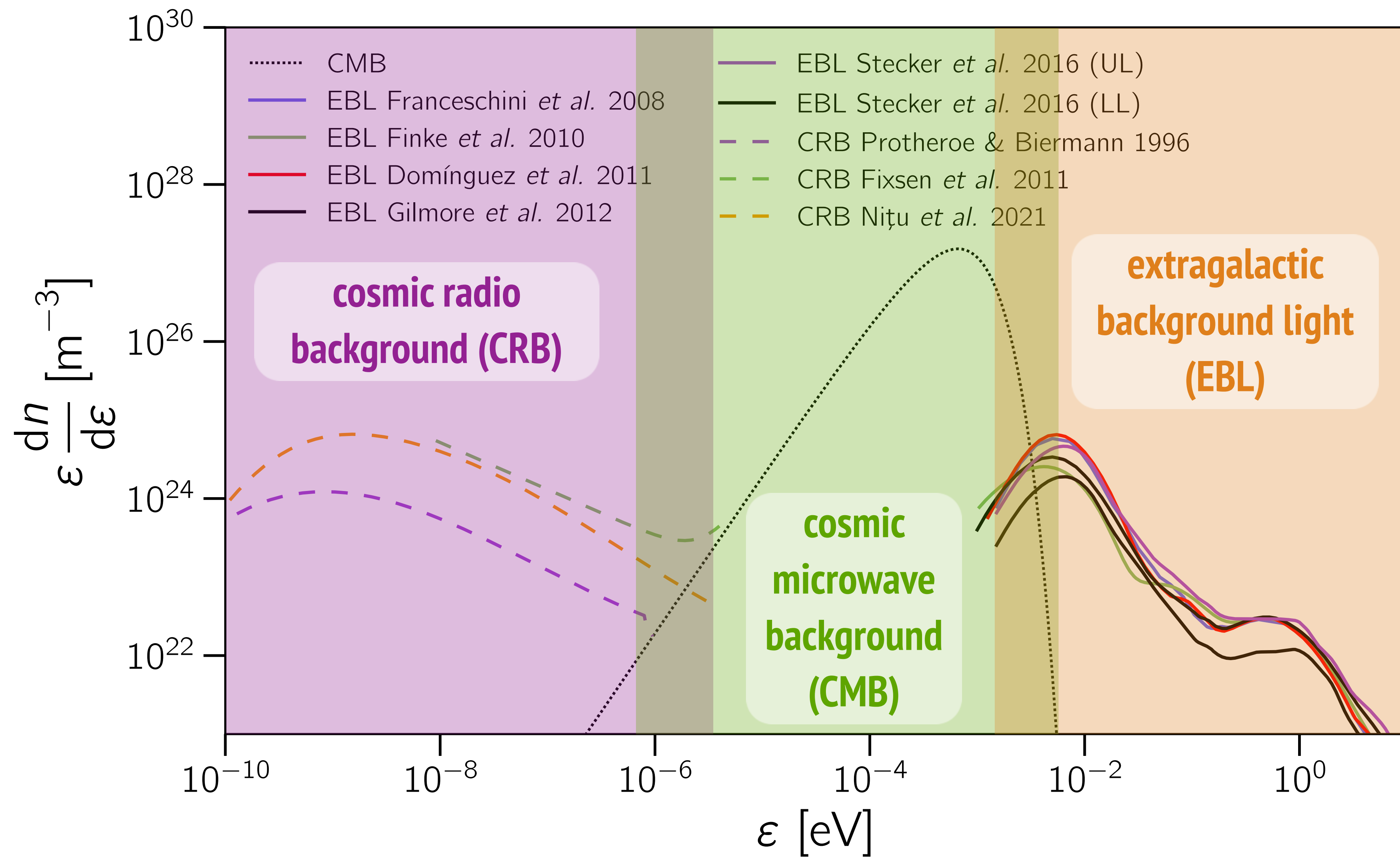
multimessenger propagation picture: **neutrinos**



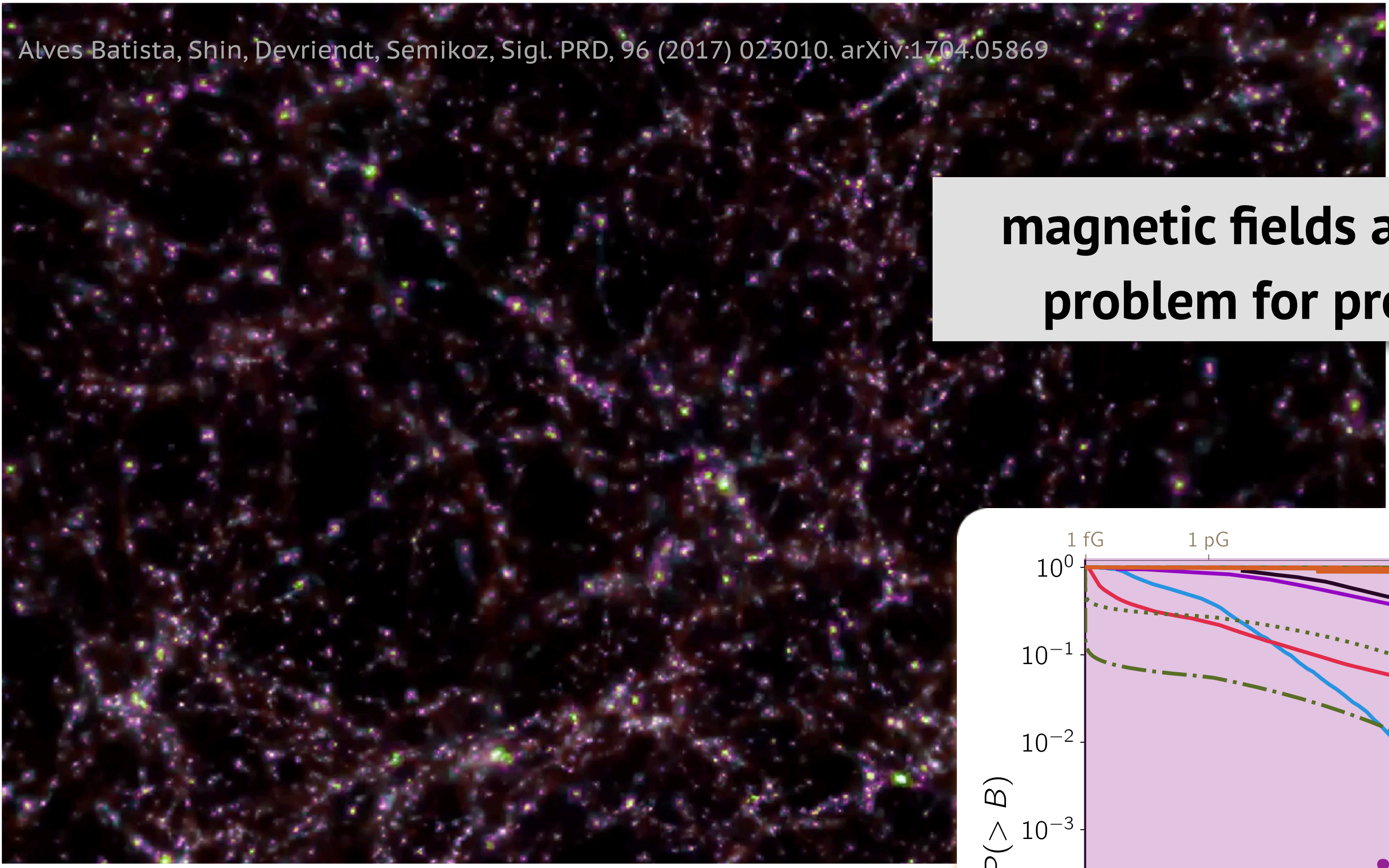
neutrino oscillations



propagation picture: photon backgrounds

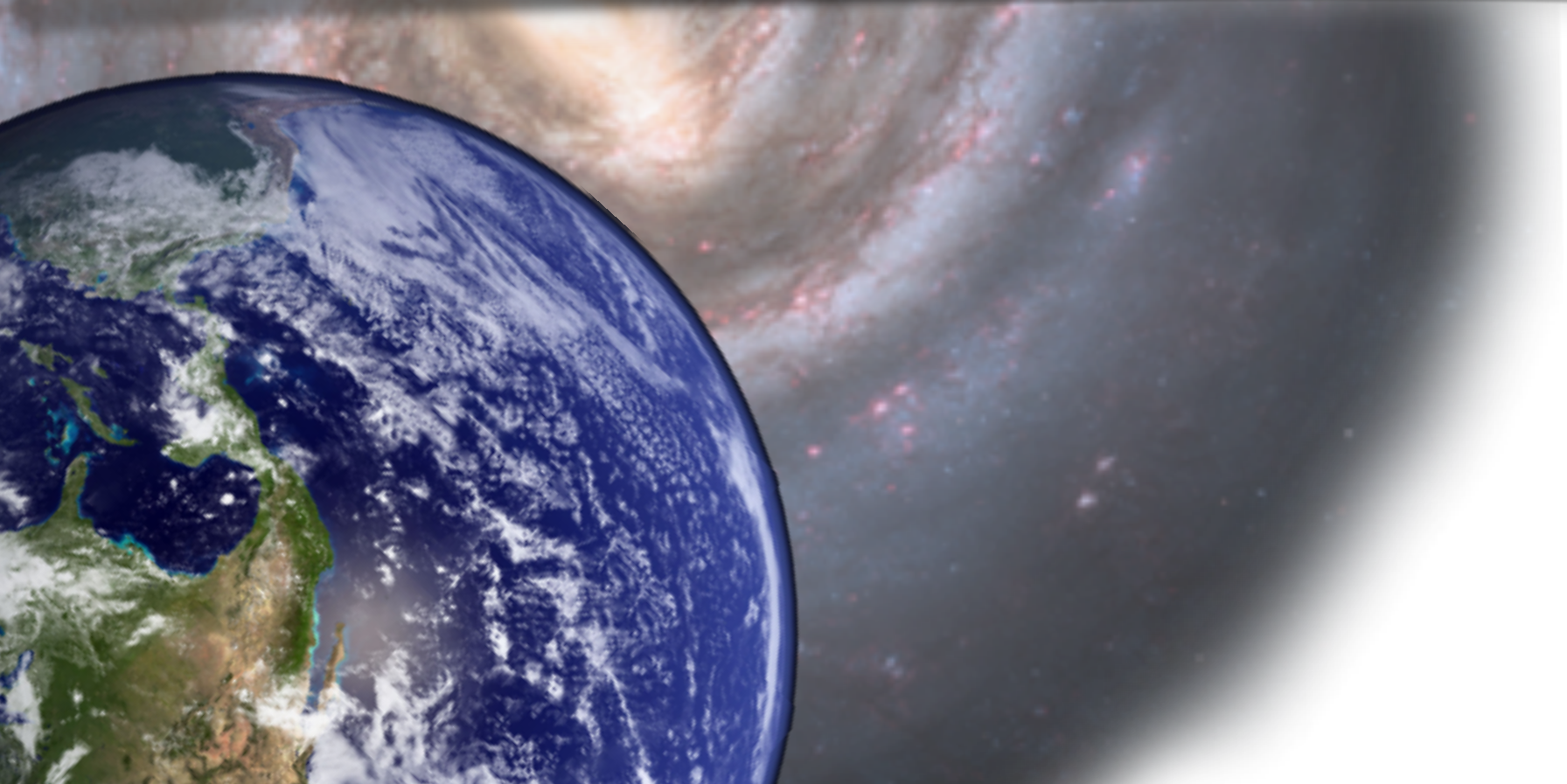
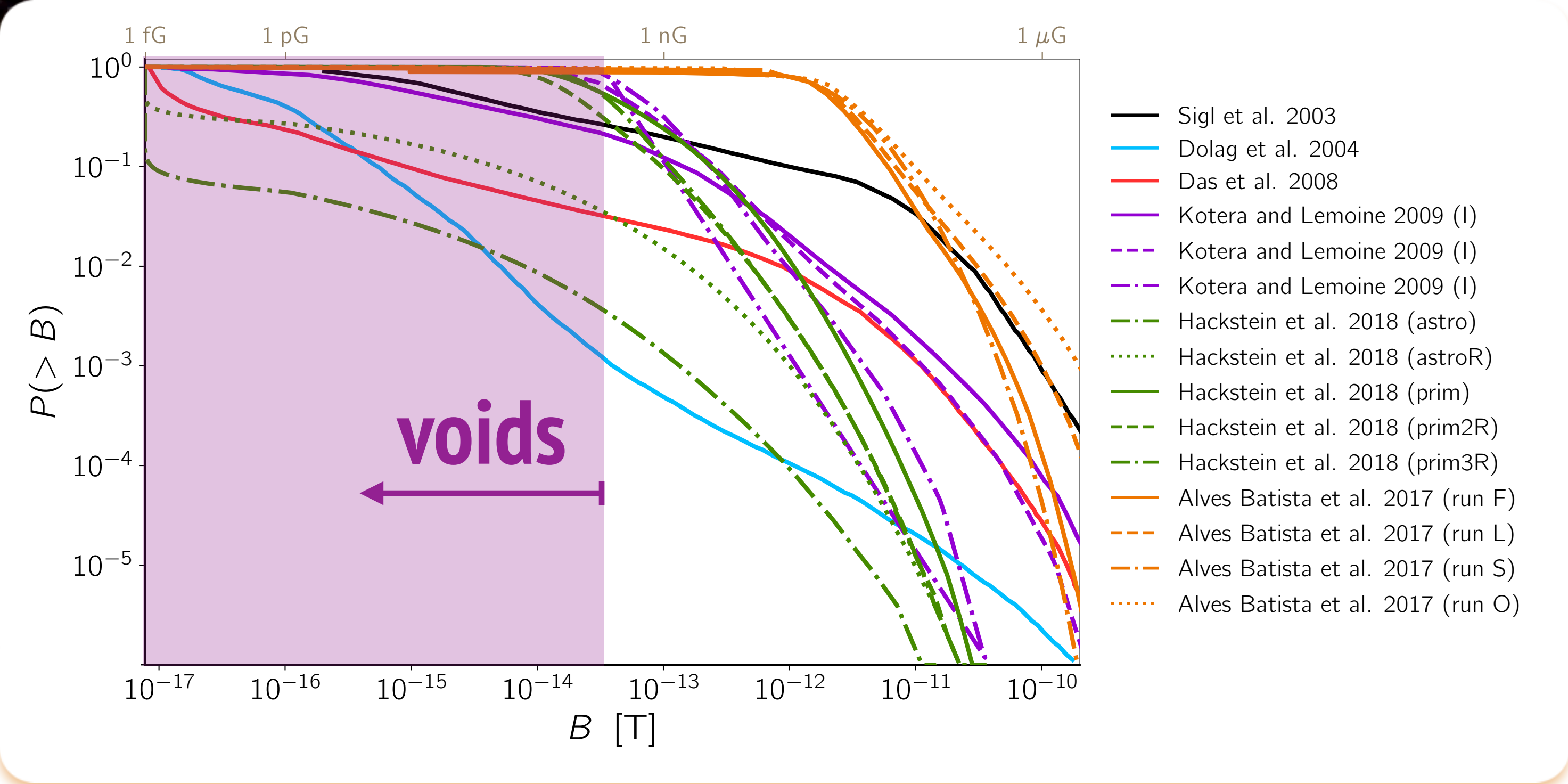
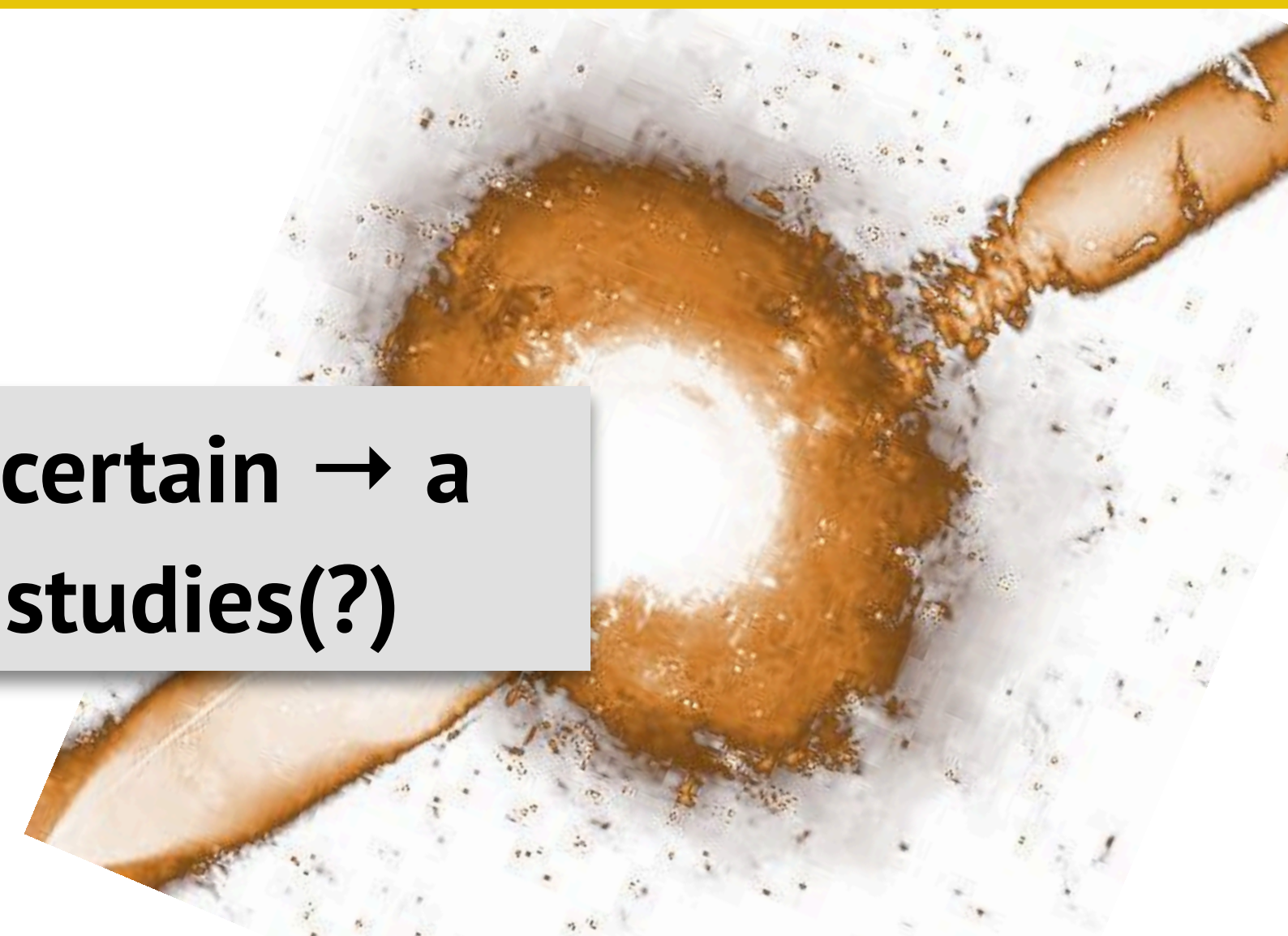


propagation picture: intergalactic magnetic fields



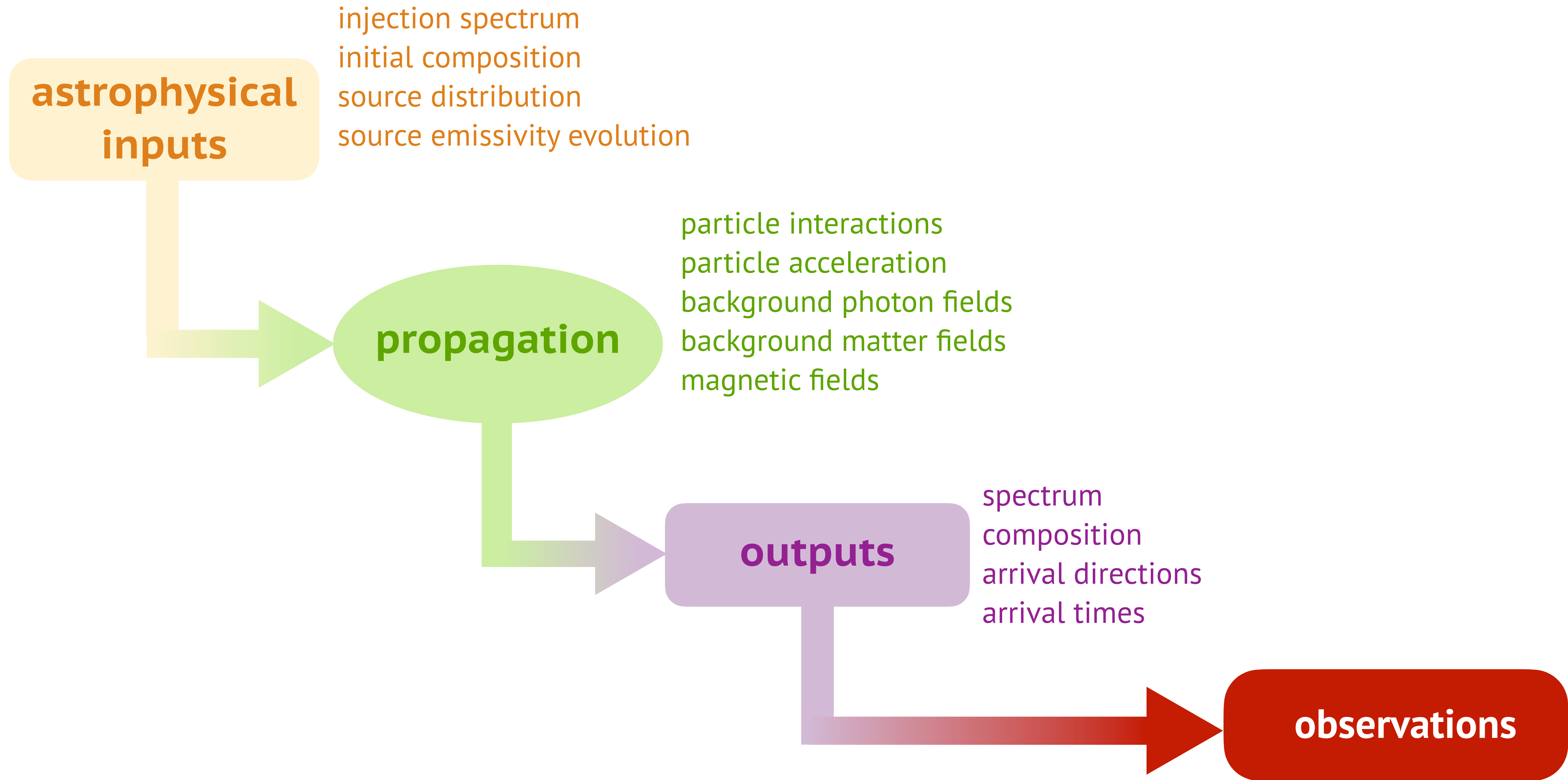
Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869

magnetic fields are very uncertain → a problem for propagation studies(?)

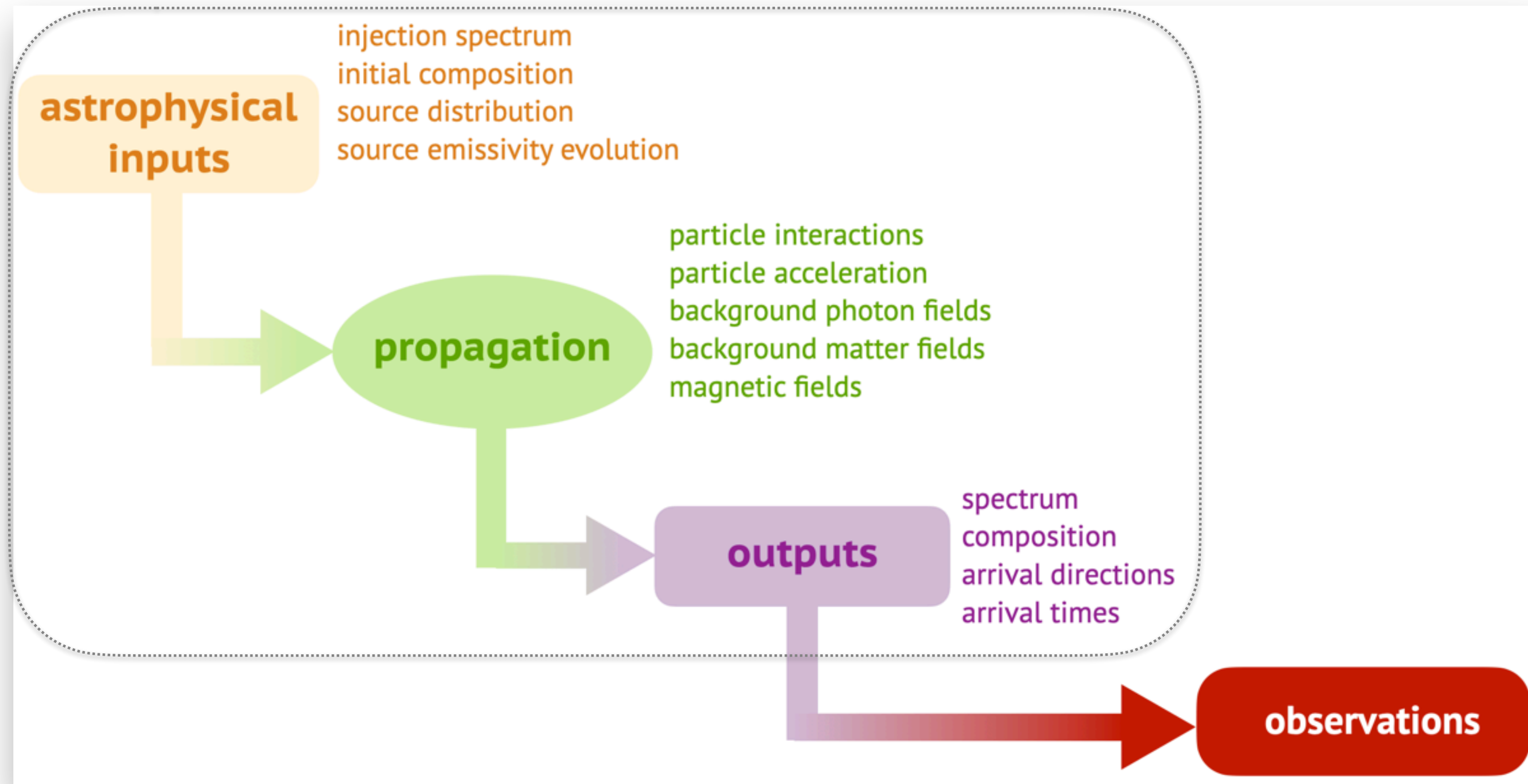


building propagation models

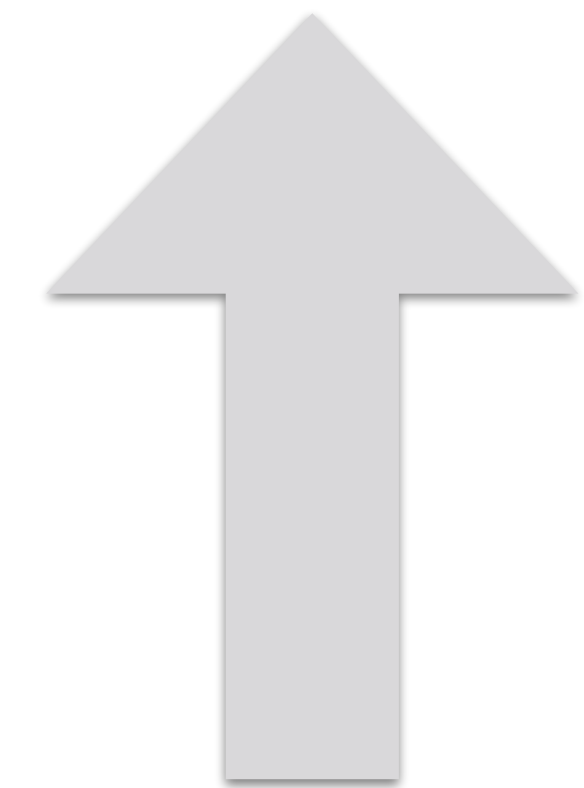
modelling the propagation of astroparticles



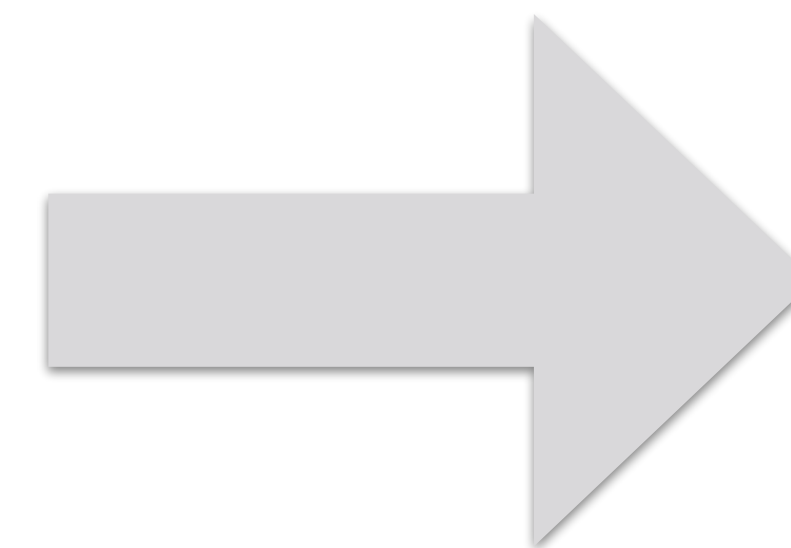
modelling the propagation of astroparticles



CR $\sqrt{\text{Propa}}$



- ▶ mixing all ingredients → interpret (fit) observations based on models
- ▶ this should be done *self-consistently for all messengers*
- ▶ need to *scan full parameter space* of uncertainties



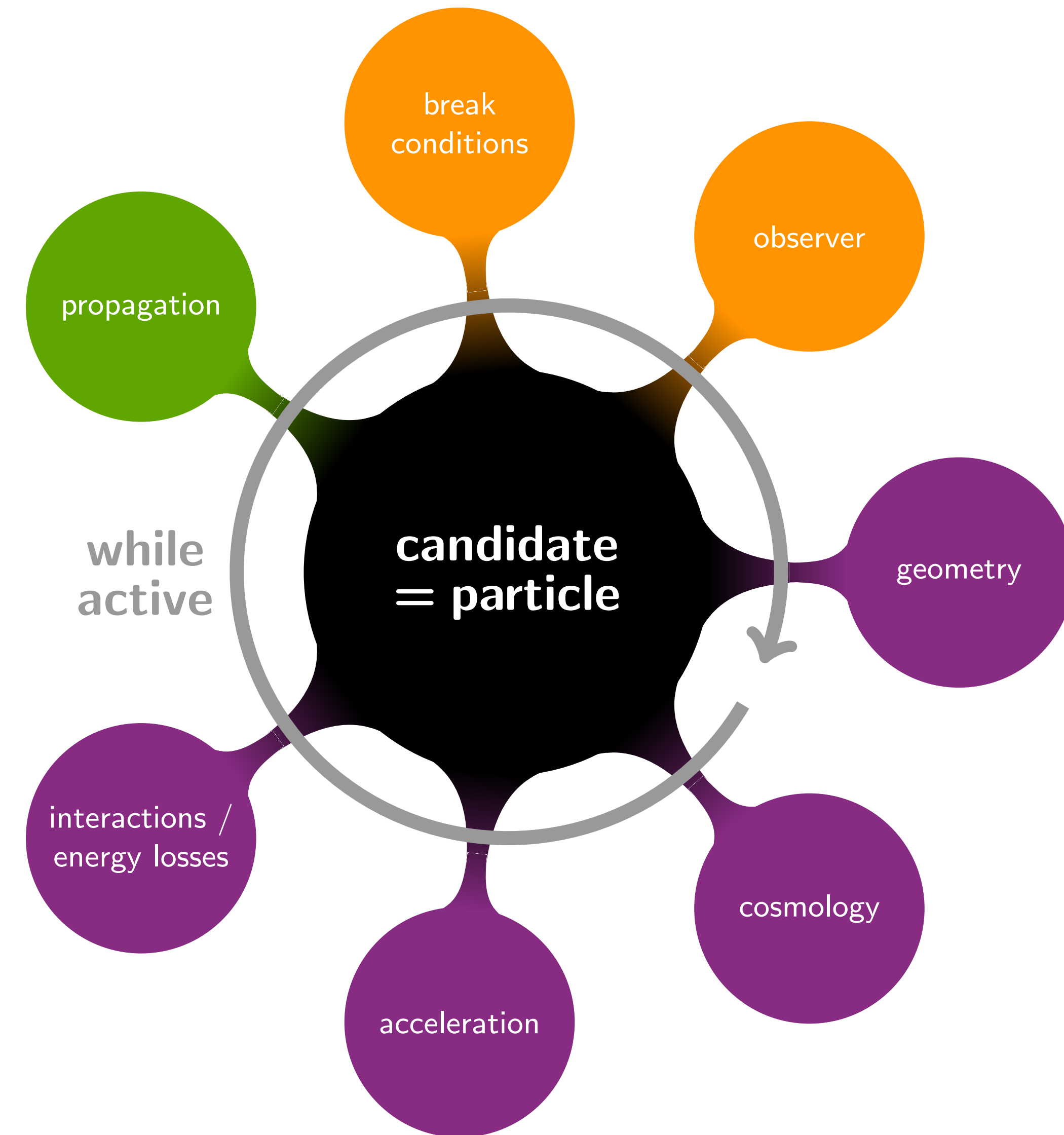
**multimessenger
simulation
framework**

the CRPropa framework

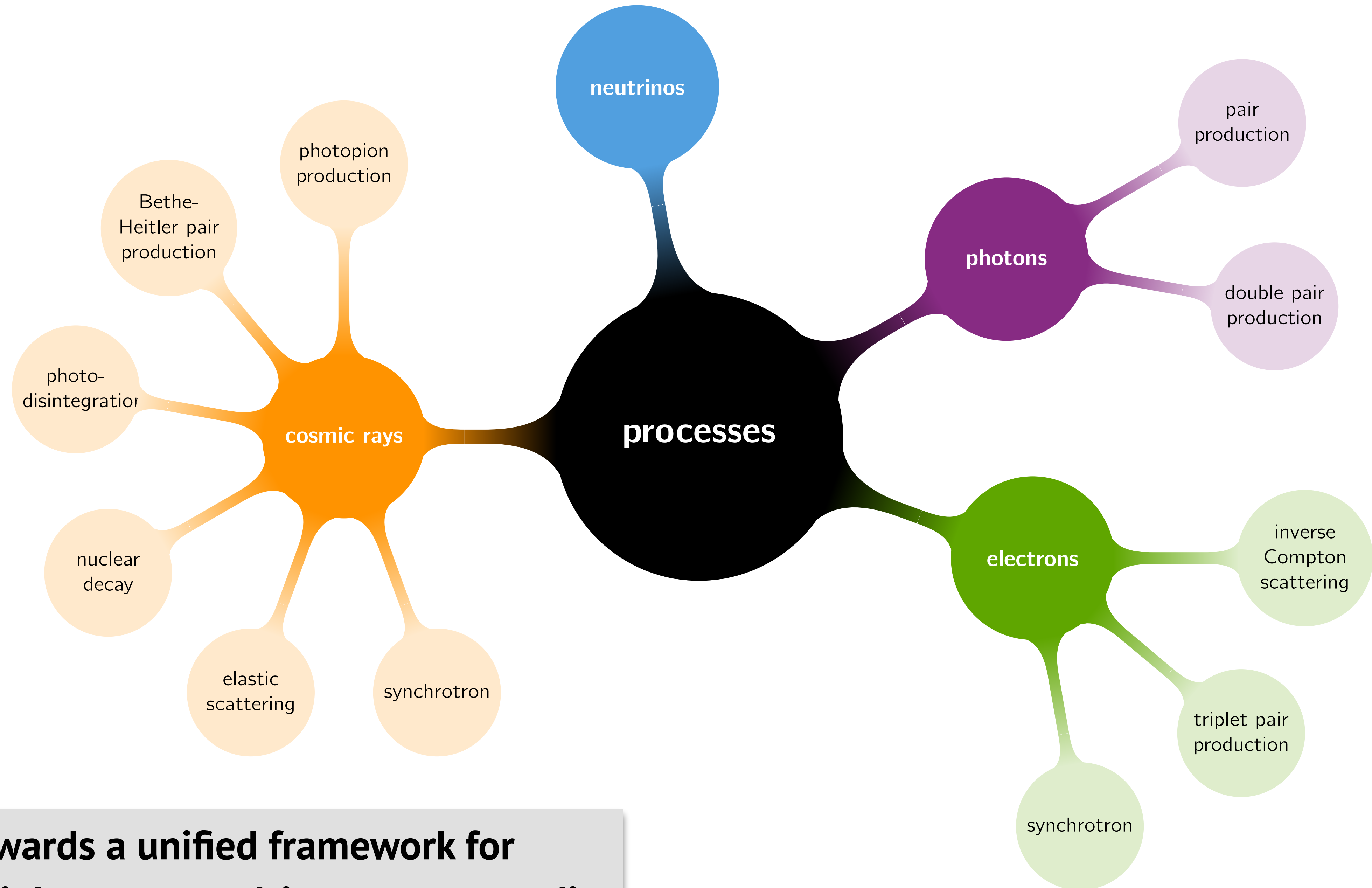
Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142

Alves Batista et al. JCAP 09 (2022) 035. arXiv:2208.00107

- ▶ publicly available Monte Carlo code
- ▶ propagation of high-energy cosmic rays, gamma rays, neutrinos, and electrons
- ▶ propagation in *any* environment (Galactic, extragalactic, around sources)
- ▶ modular structure
- ▶ parallelisation with OpenMP
- ▶ development on Github:
<https://github.com/CRPropa/CRPropa3>

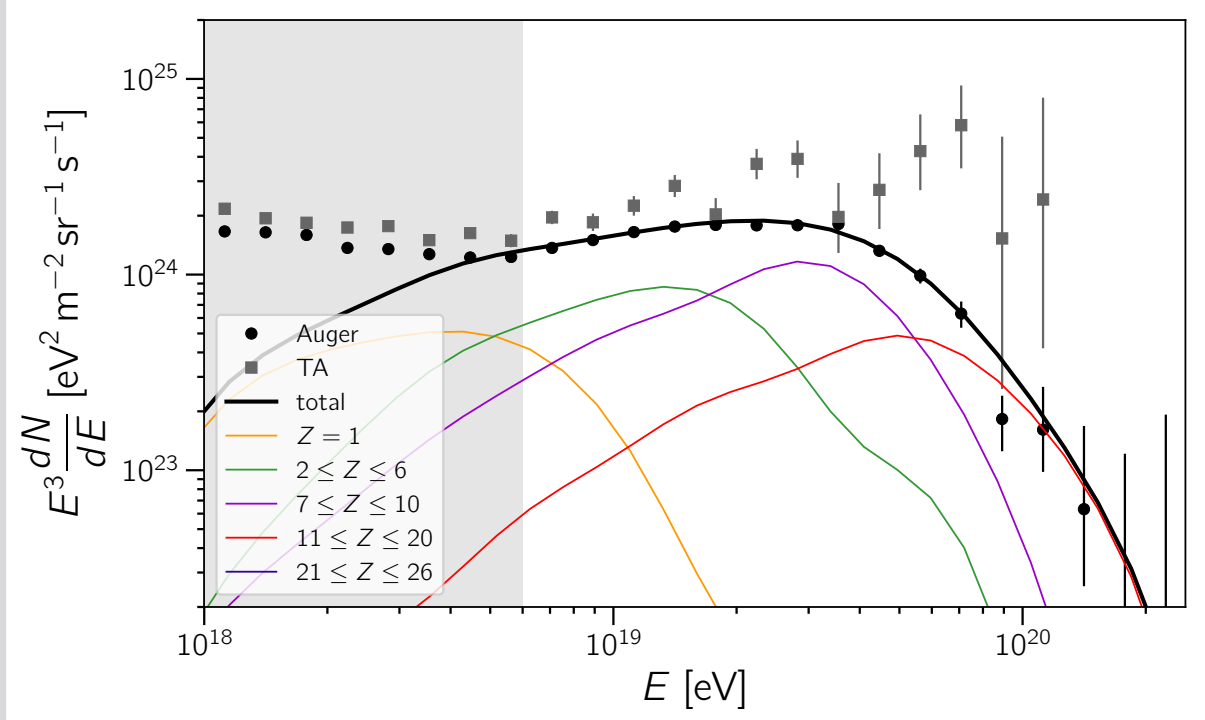


crpropa.desy.de



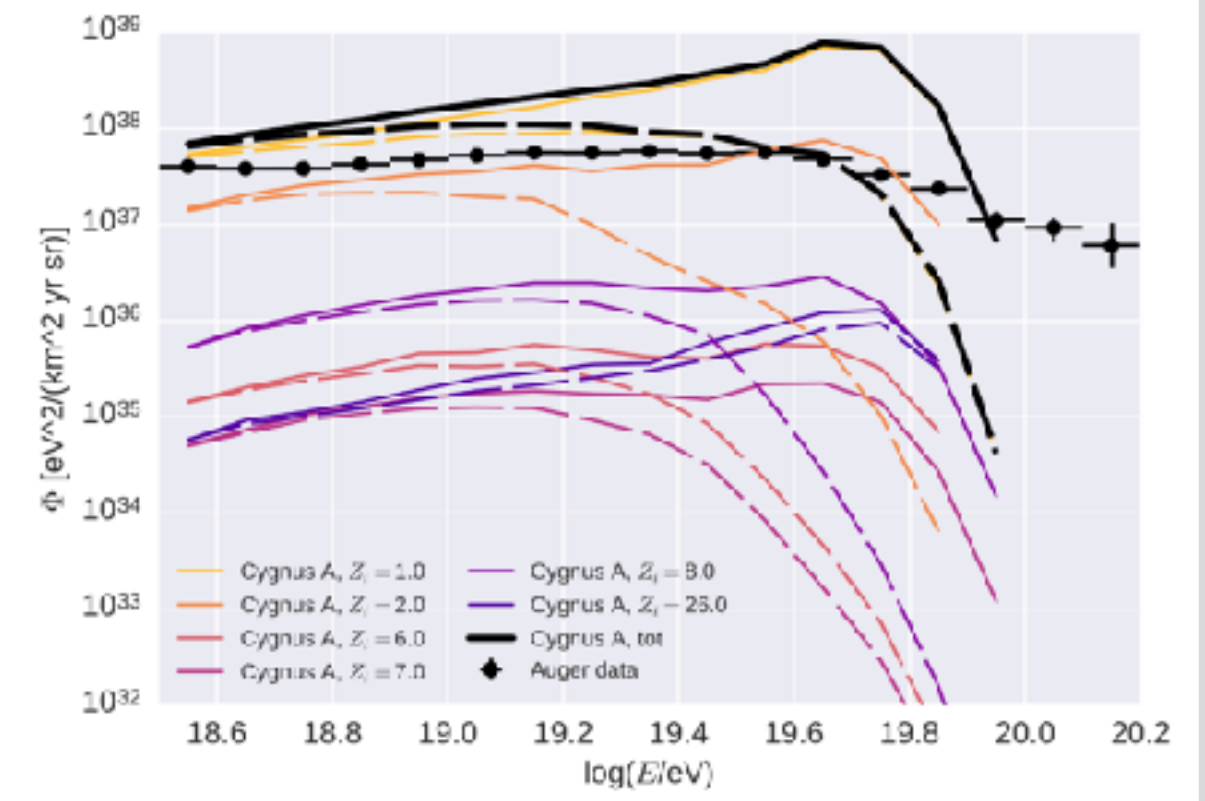
towards a unified framework for (ultra-)high-energy multimessenger studies

fit UHECR measurements



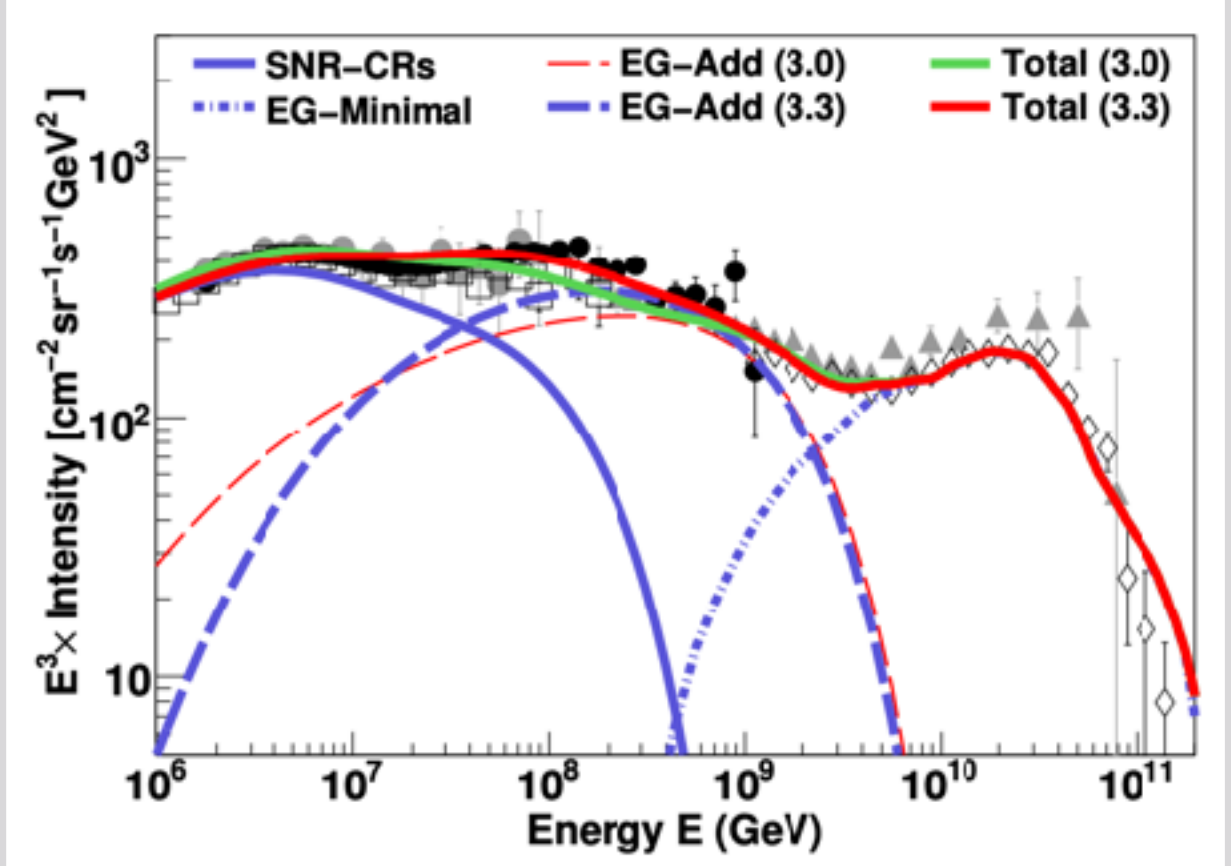
Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

test UHECR source models



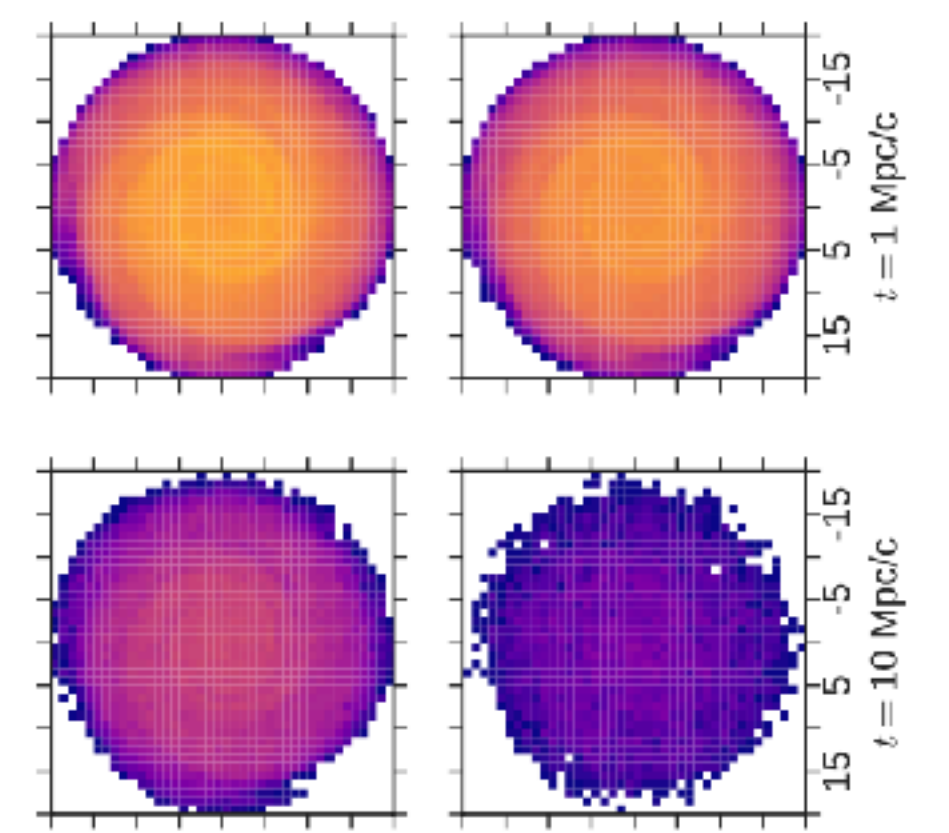
Eichmann et al. JCAP 02 (2018) 036. arXiv:1701.06792

transition G-EG CRs



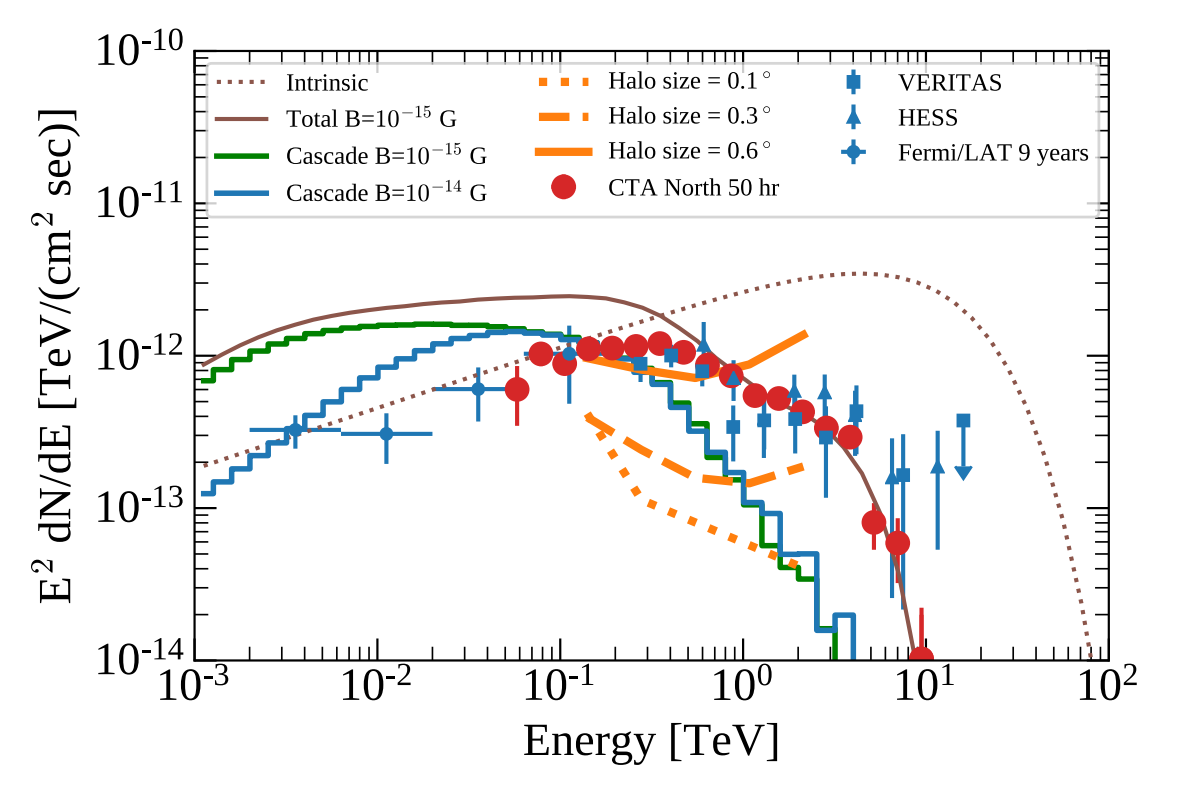
Thoudam et al. Astron. Astrophys. 595 (2016) A33. arXiv:1605.03111

diffusion of Galactic CRs



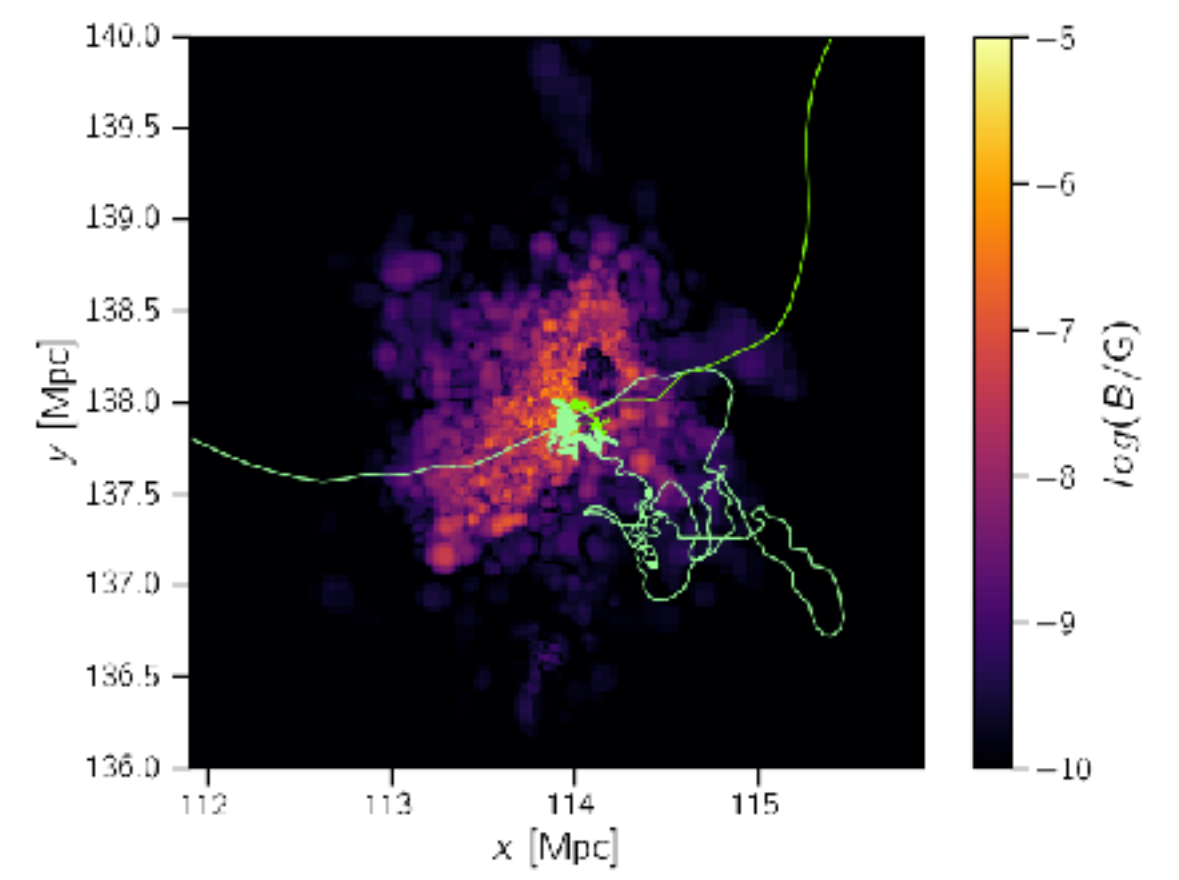
Merten et al. JCAP 06 (2016) 046. arXiv:1704.07484

gamma rays + IGMFs



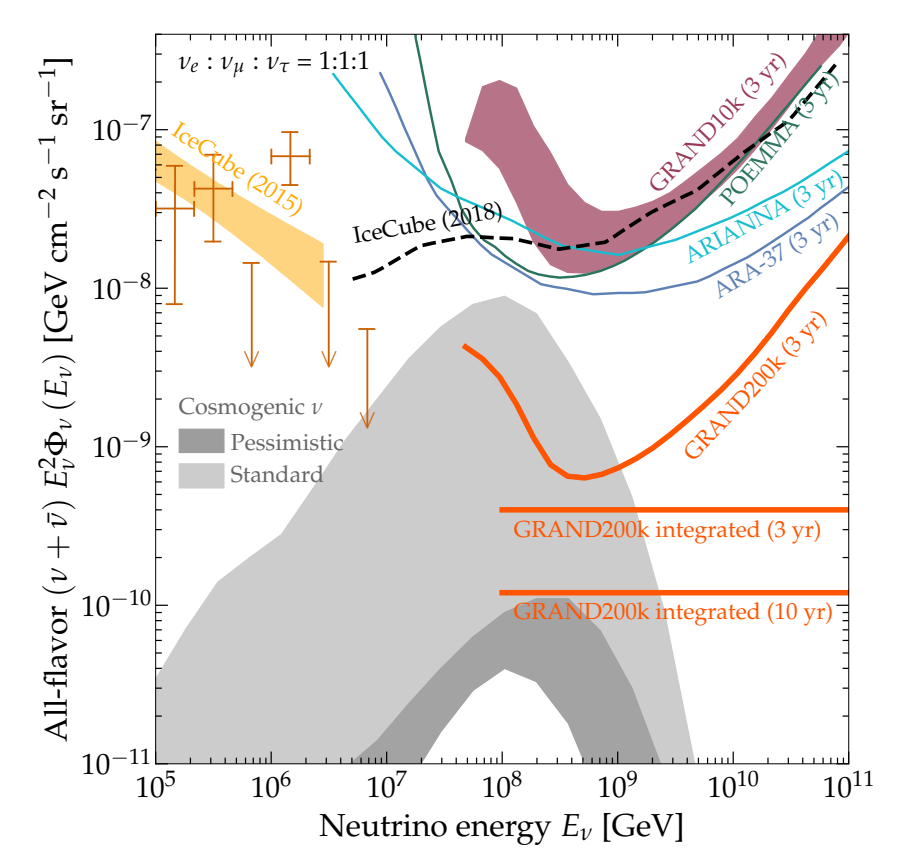
CTA Consortium. JCAP 02 (2021) 048. arXiv:2010.01349

neutrinos from galaxy clusters



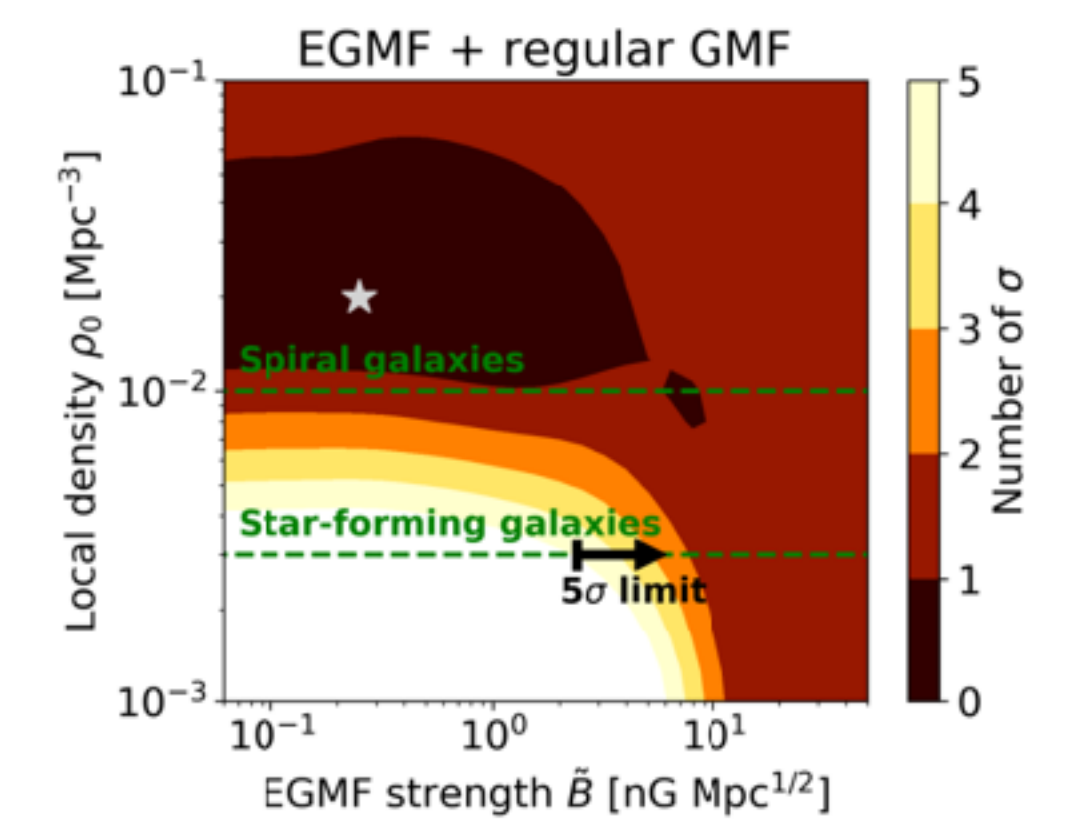
Hussain, Alves Batista, de Gouveia Dal Pino. Nature Comms 14 (2023) 2486. arXiv:2101.07702

cosmogenic neutrinos



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

EGMF constraints



van Vliet, Palladino, Taylor, Winter. MNRAS 510 (2022) 1289. arXiv:2104.05732

... and much more!