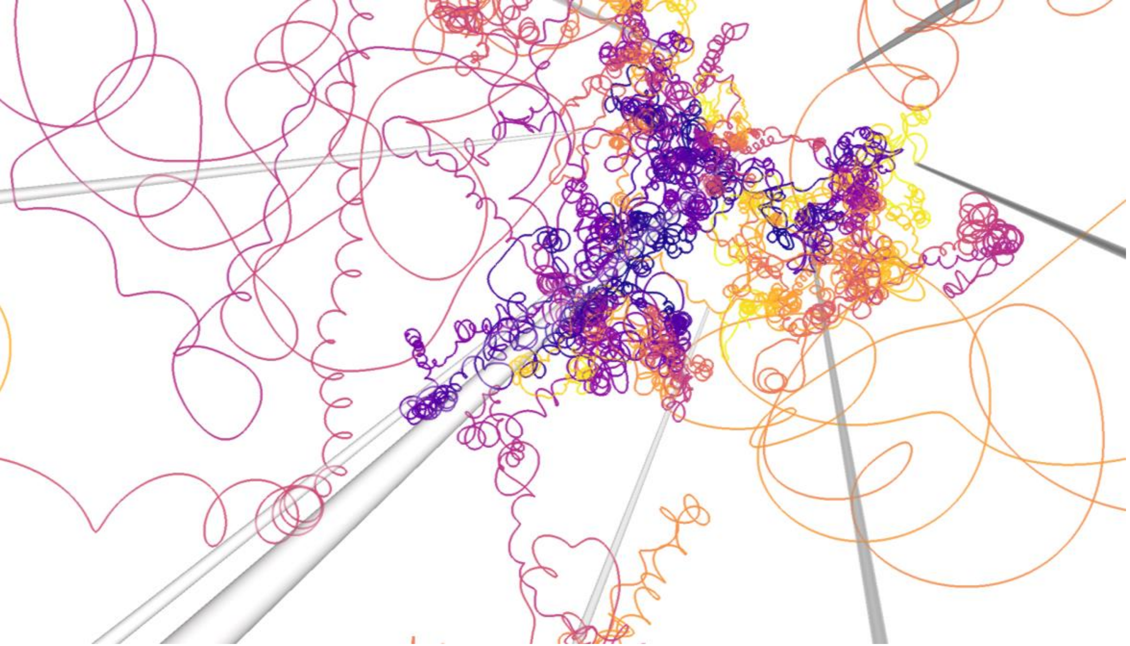

RUHR-UNIVERSITÄT BOCHUM

News from CRPropa

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Version 3.2: JCAP 09 (2022) 035

Version 3.2.1: PoS (ICRC2023) 1471

RAPP Center

RUB

SFB1491

Cosmic Interacting Matters
from source to signal

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

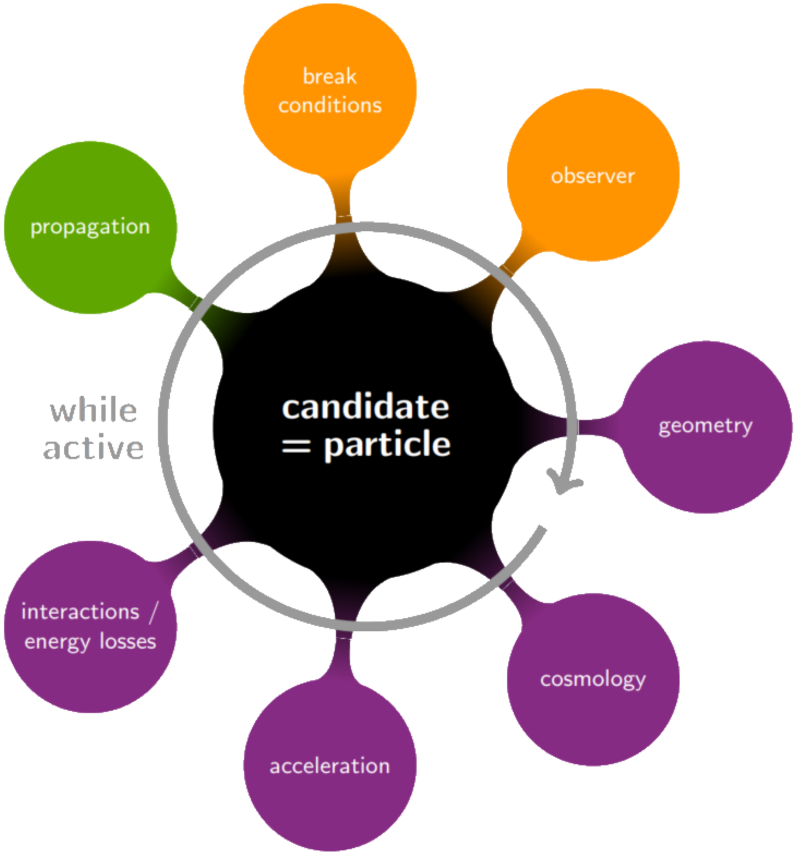
CRPropa

CRPropa overview

overview of CRPropa

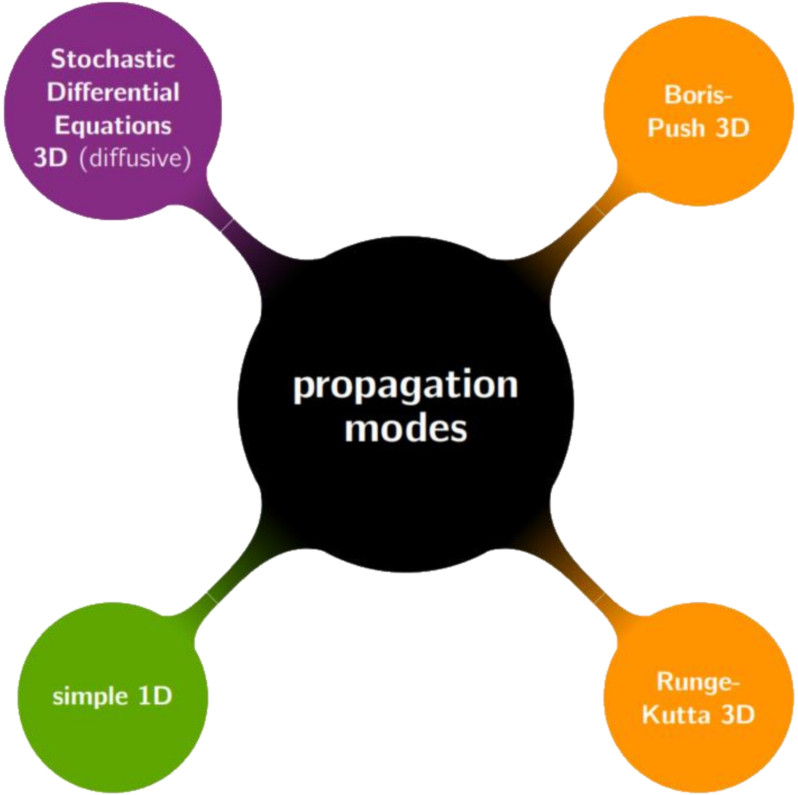
- publicly available Monte Carlo code
- modular structure
- propagation of cosmic rays, gamma rays, neutrinos
- Galactic and extragalactic propagation
- parallelisation with OpenMP
- development on GitHub: https://github.com/CRPropa/CRPropa3

➢ **CRPropa 3.2 published in 2022**
JCAP 09 (2022) 035



propagation modes

- **ballistic propagation**
  (EoM) $\ddot{\vec{r}} = \frac{q}{m^2}\,(\vec{p} \times \vec{B})$
- **diffusiv propagation**
  transport equation
- **simple 1D propagation**
  (without magnetic field)
- all ways possible with backtracking
- Lensing interface for arrival direction



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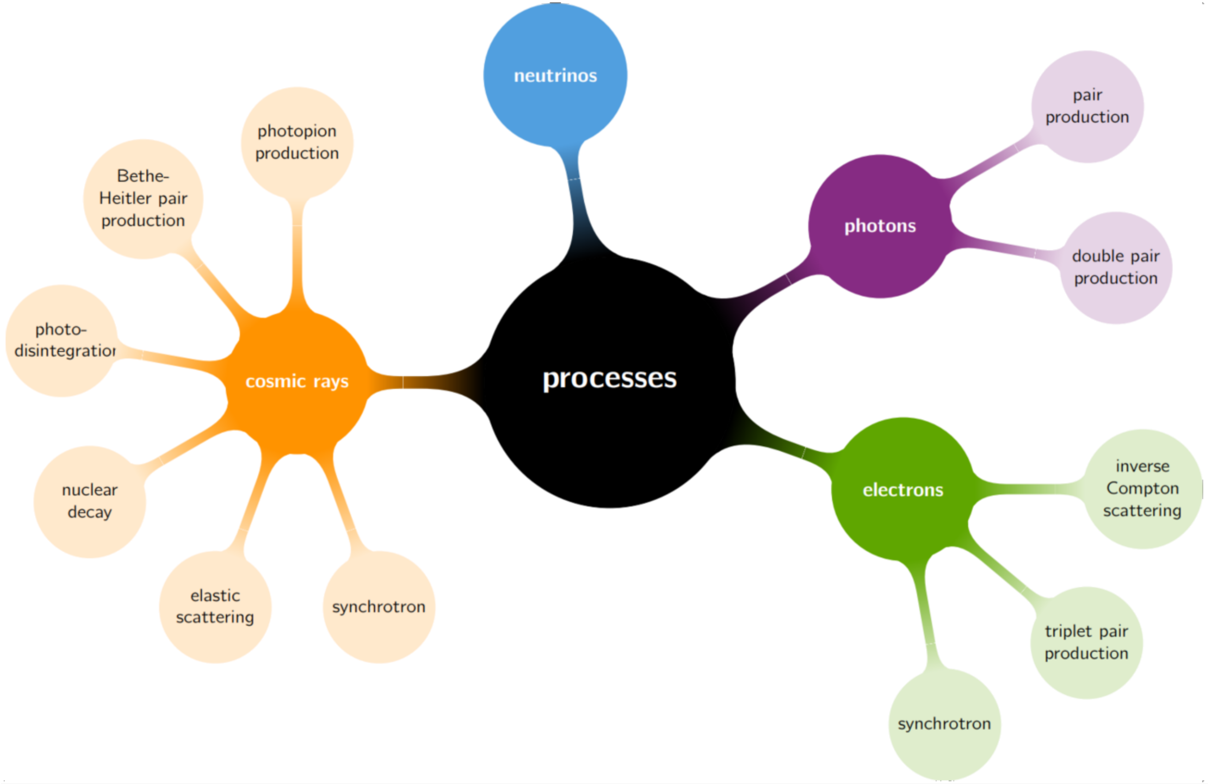
Multi-messenger Particles and Interactions



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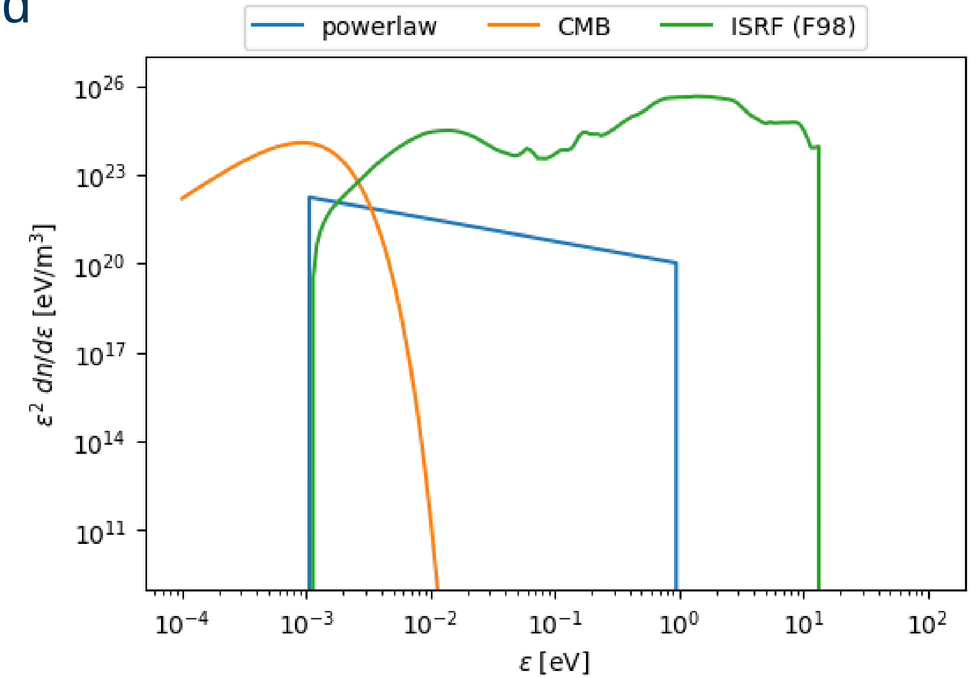
New features for CRPropa 3.2.1

New treatement of custom photon fields

- Interactions on photon-background need pre-tabulated data
- New generalized generation of data for all photon field:
- Input: energy denstity $\frac{dn}{d\epsilon}(\epsilon)$
- No spatial dependence



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SDE - approach

Spatial Diffusion | Adiabatic Effects

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

Advection | Momentum diffusion | Sources

Equivalence

$$\mathrm{d}\vec{x} = \vec{u}dt + \hat{D}\mathrm{d}\vec{w}$$

$$\mathrm{d}p = -{}^{p}/_{3}(\nabla\cdot\vec{u})\mathrm{d}t + D_{pp}\mathrm{d}w_p$$

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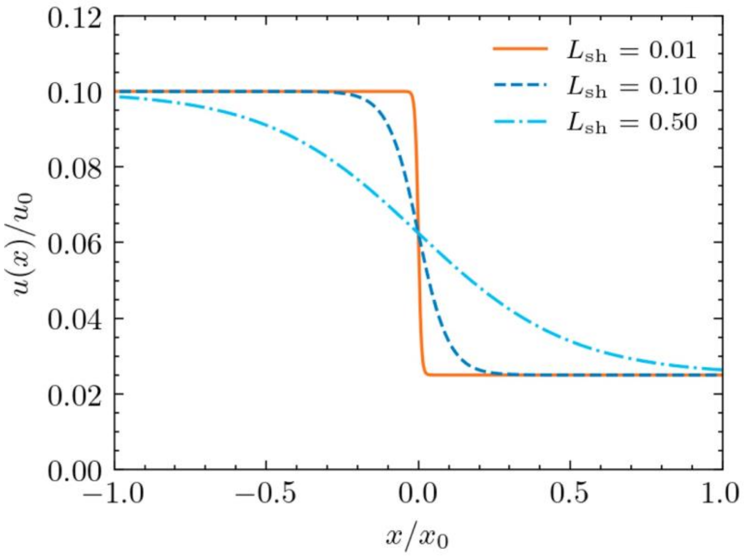
Advection and Diffusion

Diffusion description as SDEs allows to include advection

- Advective propagation
- Adiabatic energy change
- Pre-described advection profile for 1D / 3D planar and spherical shock



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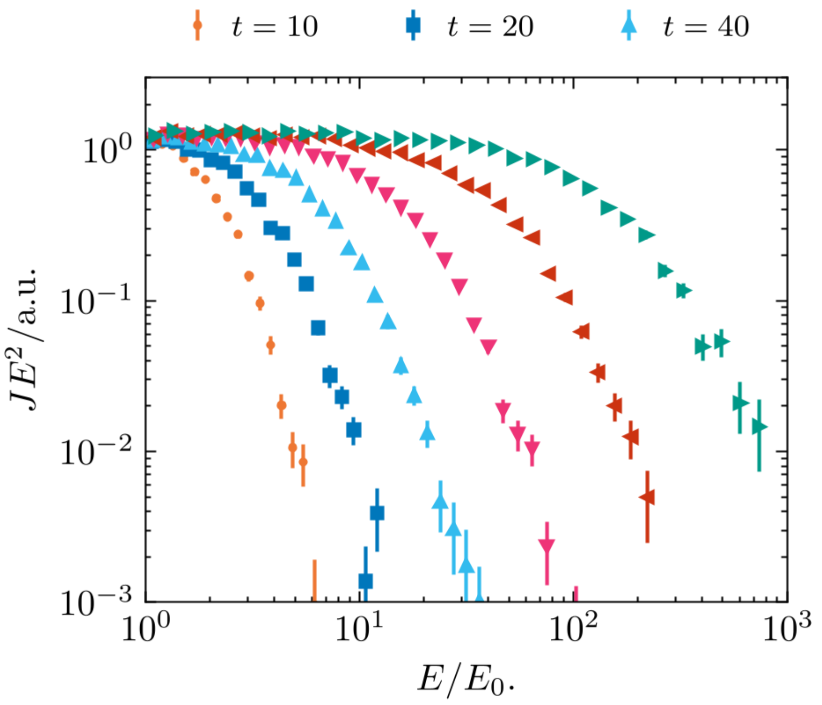
First order FERMI acceleration



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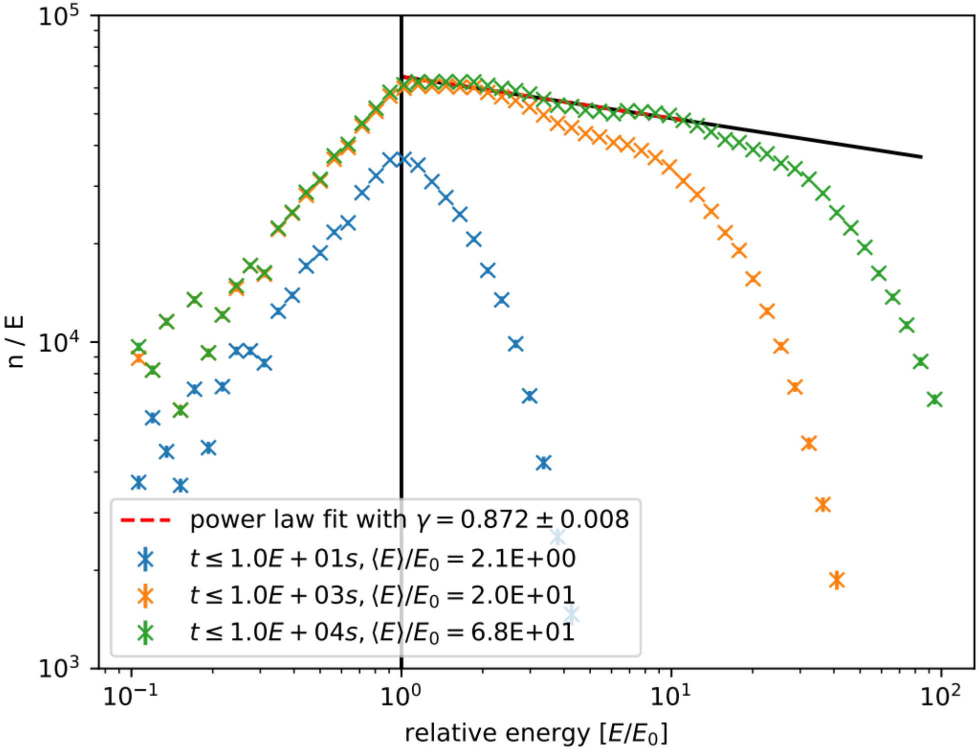
Momentum Diffusion



$$D_{pp} \propto E^{0.1} \Rightarrow \frac{dN}{dE} \propto E^{0.9}$$

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On-going development

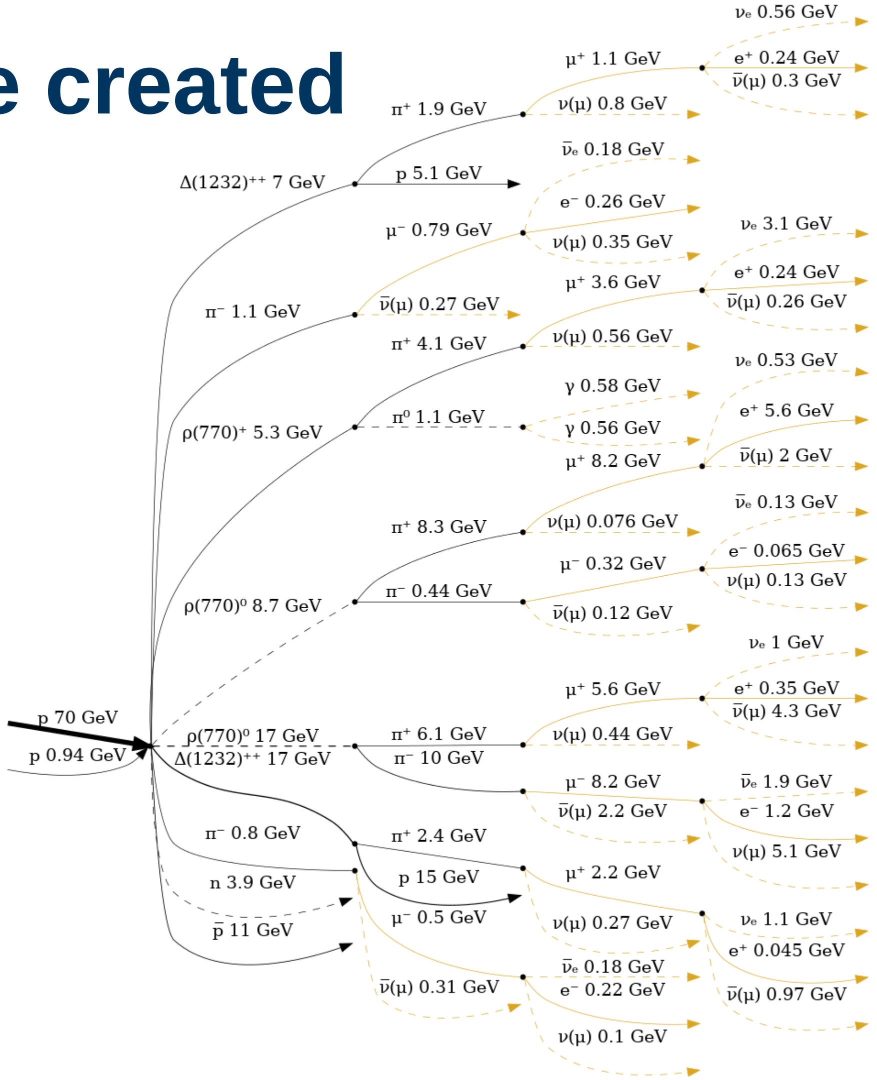
hadronic interactions

bunch of particles can be created

- $p + p \;\rightarrow \pi^0 \rightarrow \gamma\gamma$
  dominant process for diffuse galactic gamma-ray emission

- $p + p \;\rightarrow \pi^{\pm} \;\rightarrow e^{\pm}\, \nu_e\, \nu_\mu$
  production of (Galactic) neutrinos as seen in IceCube

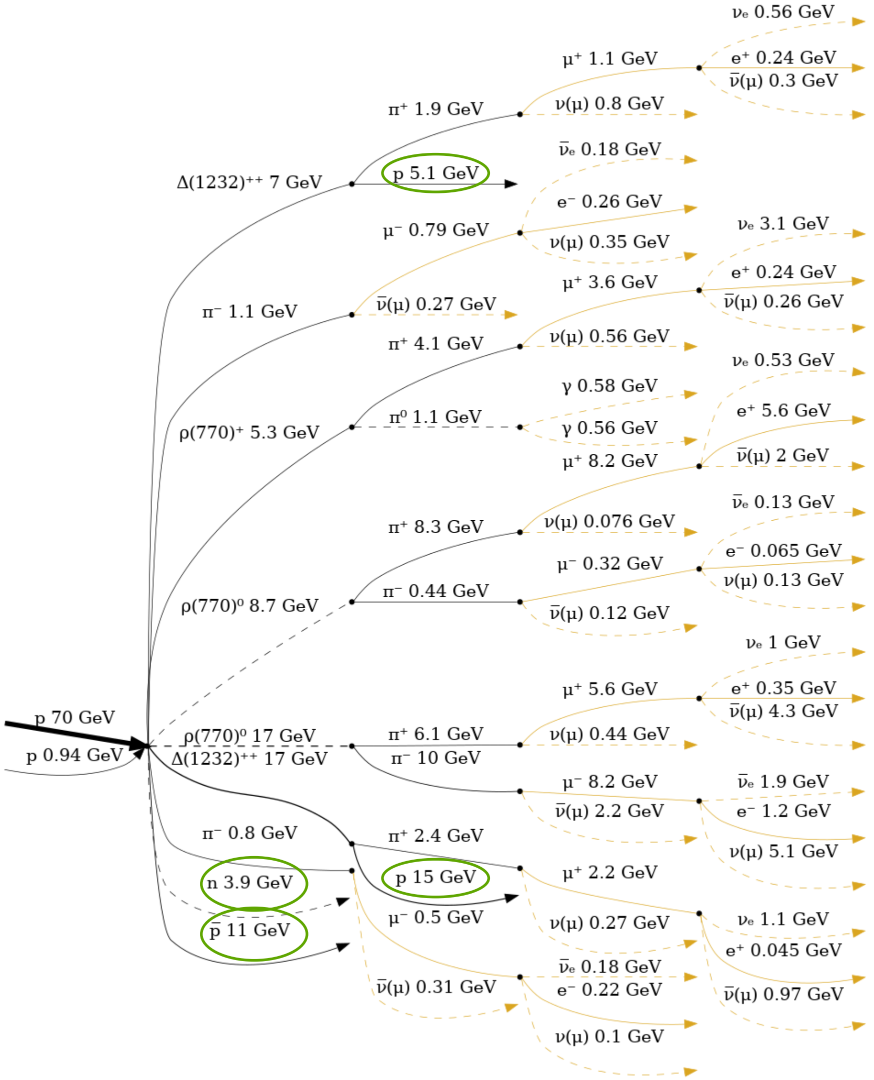
- $p + p\ (A) \rightarrow \bar{p}, \bar{n}, \overline{He}$
  seen by AMS-02



Final state of interaction

- e^-, e^+
- $\nu_e, \bar{\nu}_e$
- $\nu_\mu, \bar{\nu}_\mu$
- $p, \bar{p}, n, \bar{n}$

includes up scattered proton and primary after interaction



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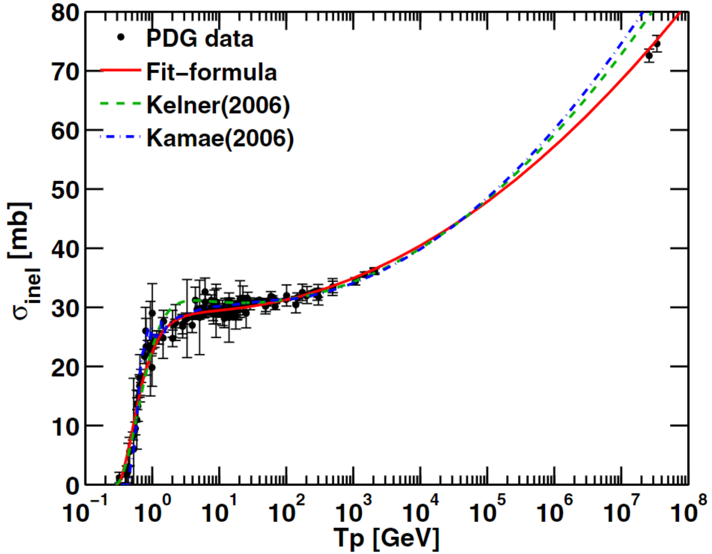
cross-section: inclusive and inelastic

Inelastic cross-section: Kafexhiu+ (2014)

$$\sigma_0(T_p) = [30.7 - 0.96 \log(x) + 0.18 \log^2(x)] \times [1 - x^{1.9}]^3 \text{ mb}$$

$$x = \frac{T_p}{T_p^{th}} \; ; \; T_p^{th} = 2m_\pi + \frac{m_\pi^2}{2\, m_p} \approx 0.2797 \text{ GeV}$$



→ total interaction probability:

$$p = n_{gas} \cdot \sigma \cdot \Delta s$$

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cross-section: inclusive and inelastic

Differential inclusive cross-section:

For each secondary species s

$$\frac{d\sigma^{(s)}}{d\epsilon}\left(T_p, \epsilon\right) = \sigma_0\left(T_p\right) \cdot \frac{dN_s}{d\epsilon}$$

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cross-section: inclusive models

Name	proj	targ.	Incl. secondaries	Primary energy	Secondary energy
Kelner+ (2006)	p	p	$\gamma, e, \nu_e, \nu_\mu$ or π	$0.1 - 10^5$ TeV	$10^{-3} \leq \frac{\epsilon}{T_p} \leq 1$
Kafexhiu+ (2014)	p	p	γ	$T_p < 512$ TeV	As primary
AAfrag Kachelrieß+ (2019)	p, He, C, Al, Fe, $\bar{p}$	p, He	$\gamma, e, \nu_e, \nu_\mu, p, n, \bar{d}, {}^3\overline{He}, {}^3\overline{\mathrm{H}}$	Proton: $5 - 10^{11}$ GeV	As primary
ODDK Orusa+ (2022, 2023)	$p, {}^2_1H, {}^3_2He, {}^4_2He, {}^{12}_6C, {}^{13}_6C, {}^{14}_7N, {}^{15}_7N, {}^{16}_8O$	p, He	$e^\pm, \gamma$	$e^\pm$: $10^{-4} - 10^3$ TeV γ: $10^{-4} - 10^4$ TeV	$10^{-5} - 10$ TeV $10^{-5} - 10^2$ TeV

PLUG-IN : Precalculated data

- 2D – table with a CDF

$$\sigma^{(s)}_{\mathrm{CDF}}(T_p, \epsilon) = \int_{E_{th}}^{\epsilon} \mathrm{d}\epsilon' \, \frac{\mathrm{d}\sigma^{(s)}}{\mathrm{d}\epsilon'}$$

- Correction factor for missing energy loss $f^{(s)}_{loss}$

- Data are precalculated and collected with a config file
- Individual cross-section can be loaded and added to the module

PLUG-IN : workflow design

process - function

Decide on Interaction ?
- particle ID
- crosssection
- mass density

yes → perform interaction

no ↓

Limit next step
$0.1\ \lambda_{\mathrm{MFP}}$

perform interaction

Number of secondaries per species

$$N^{(s)} = \frac{\sigma_{CDF}(T_p, T_p)}{\sigma_0(T_p)}$$

Sample secondary energy
- Random bin from CDF
- Random position in bin

Total energy loss

$$\sum_{s} \sum_{i=0}^{N^{(s)}} \epsilon_i \cdot f_{loss}^{(s)}$$

Add secondary if allowed

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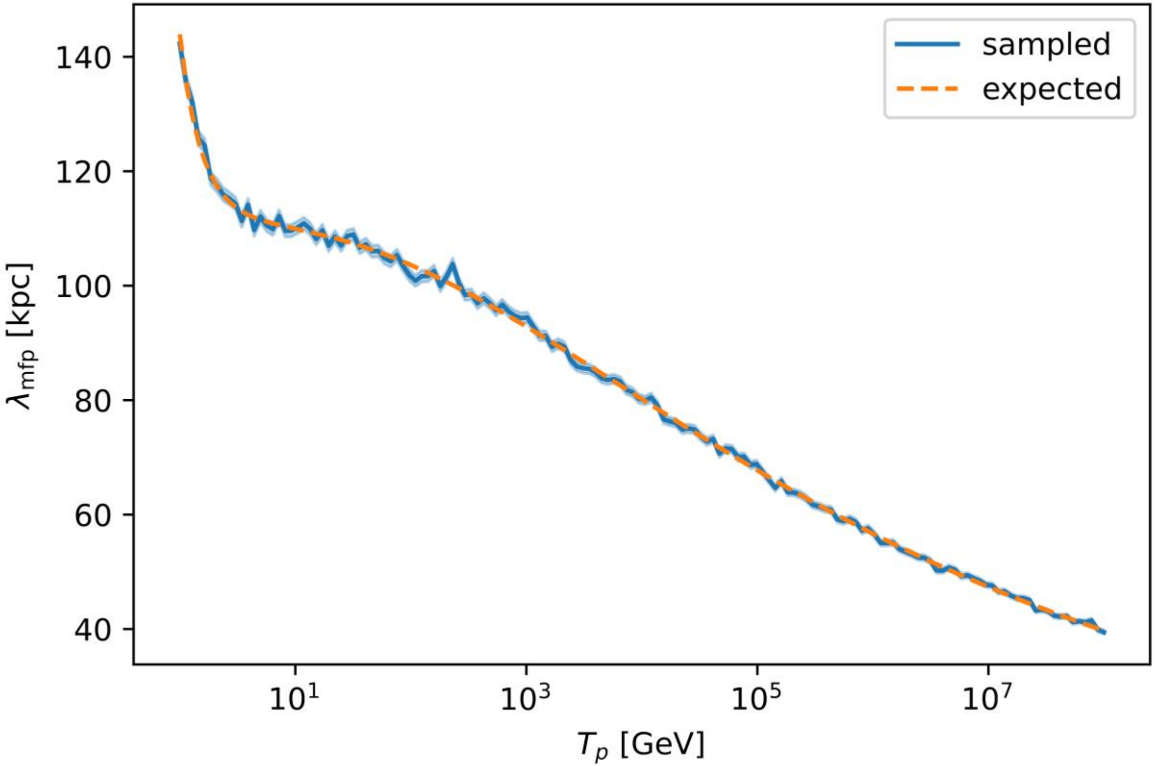
TEST: Mean free path

- 10^4 primary protons per energy
- Constant target density
  $n_H = 10^8\ \mathrm{m}^{-3}$
- Fixed propagation step
  $\Delta s = 100$ pc
- Detect length for first interaction



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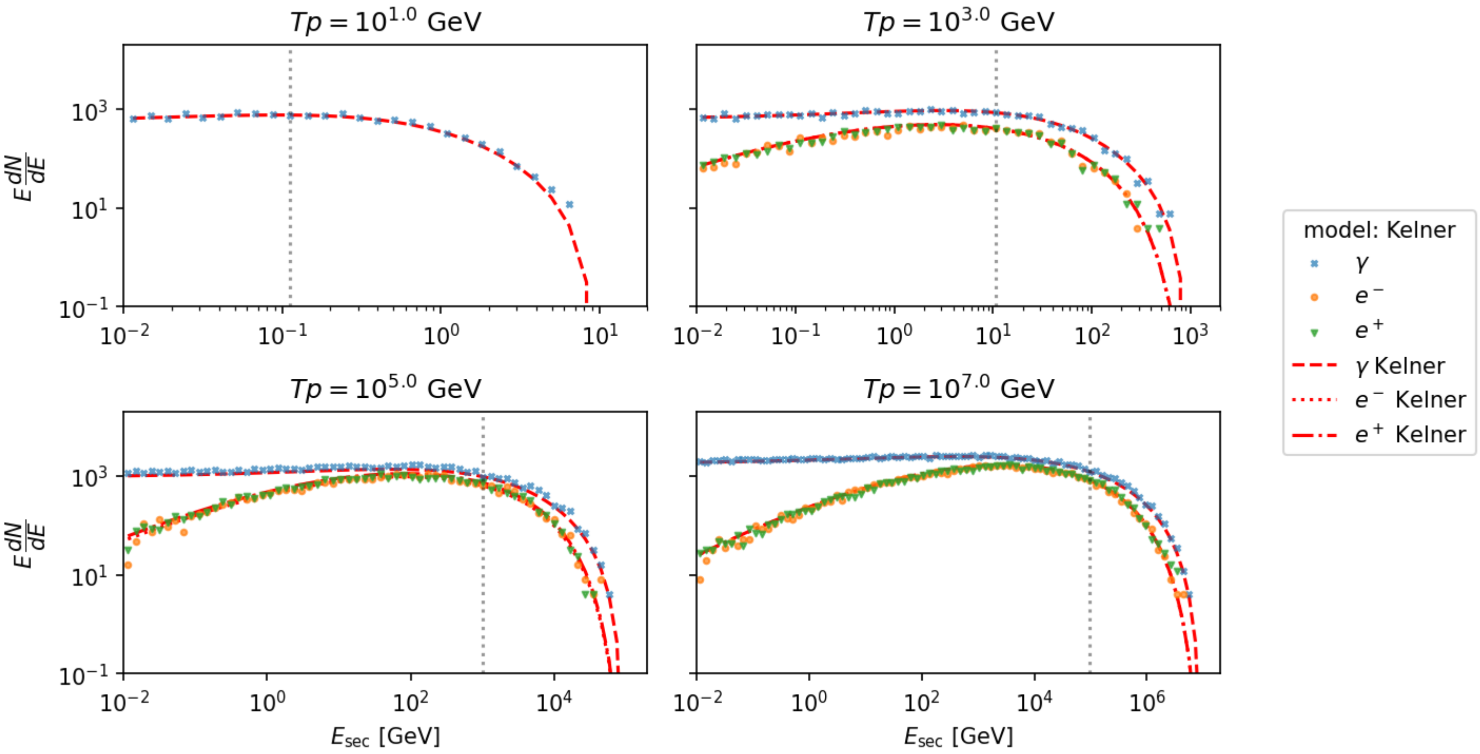
TEST: yields

- Fixed primary energy T_p
- 10^5 calls of **`performInteraction`**
- Calculate spectra of secondary particles
- Compare to shape of differential cross section (normed at $10^{-2}\,T_p$)

TEST: yields (Kelner 2006)



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TEST: Energy loss from crossection

Total energy loss per unit time:

$$-\frac{dE}{dt}(T_p) = \int_{E_{th}}^{T_p} d\epsilon \;\; v\, \epsilon\, n(\vec{r}) \sum_s \frac{d\sigma^{(s)}}{d\epsilon}(T_p, \epsilon)$$

Approximation by Krakau & Schlickeiser (2015)

$$\frac{dE}{dt}(T_p) \approx 3.85 \cdot 10^{-16} \cdot \left(\frac{n}{10^6\ \mathrm{m}^{-3}}\right) \cdot T_p^{1.28} \cdot \left(T_p + 200\ \mathrm{GeV}\right)^{-0.2}\ \mathrm{GeV/s}$$

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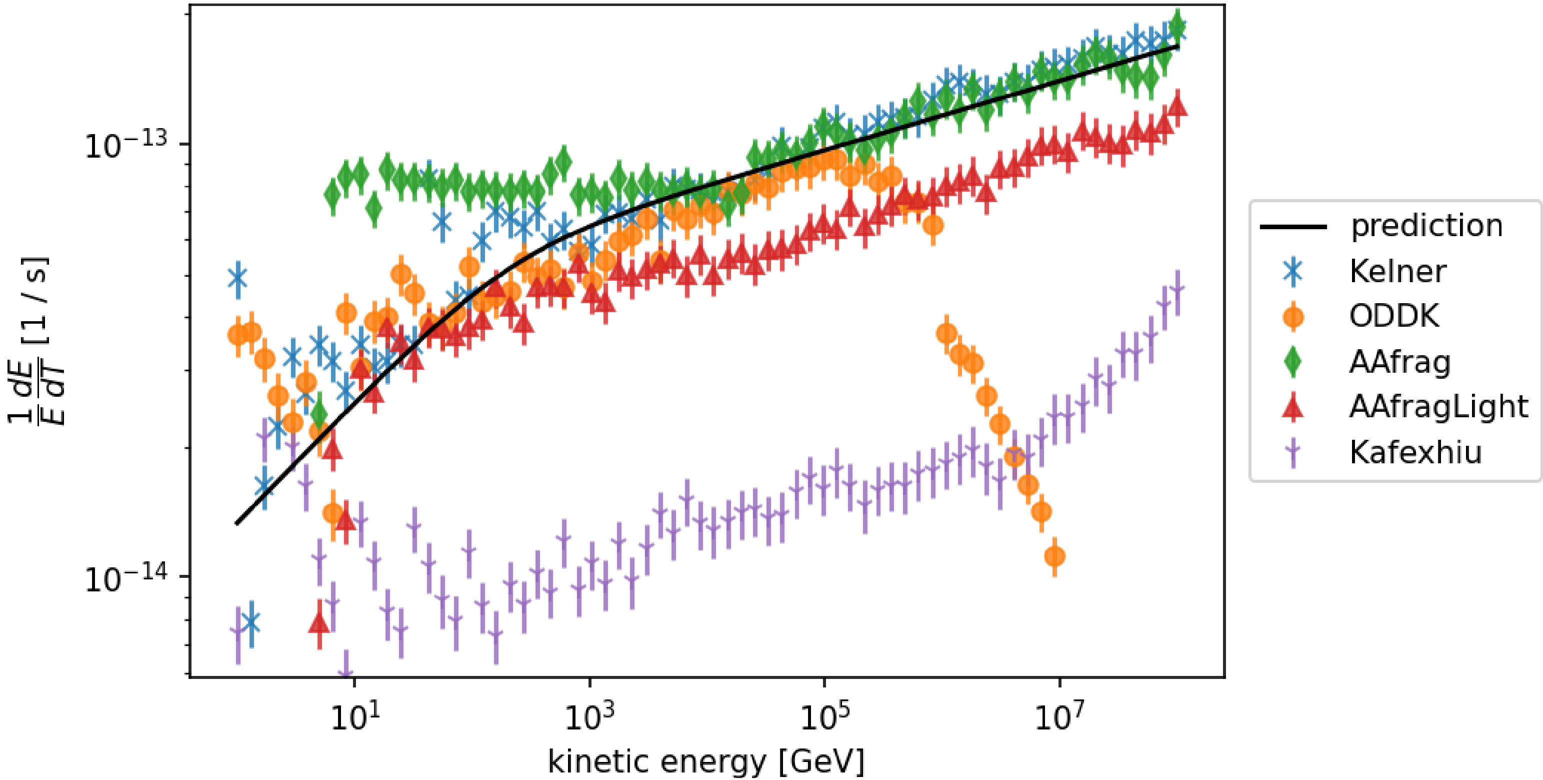
TEST: Energy loss sampling

- 10^5 particles per primary energy
- Primary (kinetic energy) $1 \leq \frac{T_p}{\mathrm{GeV}} \leq 10^8$ with 70 points in logspace
- Density $n_H = 10^8\ \mathrm{m}^{-3}$
- Propagate only one step with $\Delta s = 0.01\,\lambda_{\mathrm{mfp}}$

$$\frac{dE}{dT} \approx \frac{\Delta E}{\Delta s/c}$$

TEST: Energy loss



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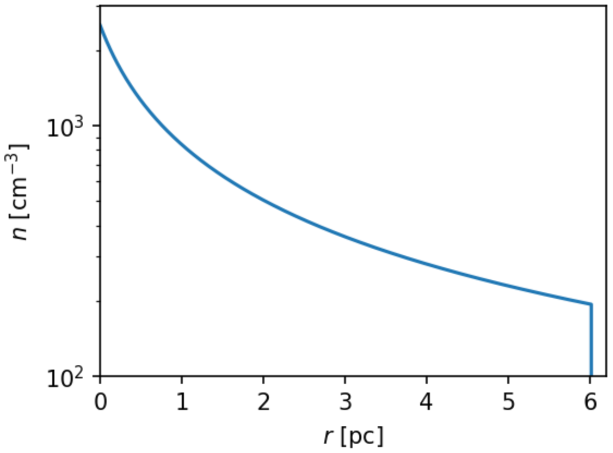
Giant Molecular Cloud – Rho Oph

- Spherical dens cloud $n(r) = \frac{n_0}{1+\frac{r}{R_0}}$
- Injection on a sphere around the cloud
- 10^8 particles with $1\,\mathrm{GeV} \leq T_p \leq 10^7\,\mathrm{GeV}$
- Direct detection of created γ-rays
- Injection spectrum reweighted to LIS

$$j_p(E) = 2.3\ E^{1.12}\ \beta^{-2} \left(\frac{E+0.67\ \mathrm{GeV}}{1.67\ \mathrm{GeV}}\right)^{-3.93} \quad \frac{\mathrm{particle}}{\mathrm{GeV\ m^2\ s\ sr}}$$



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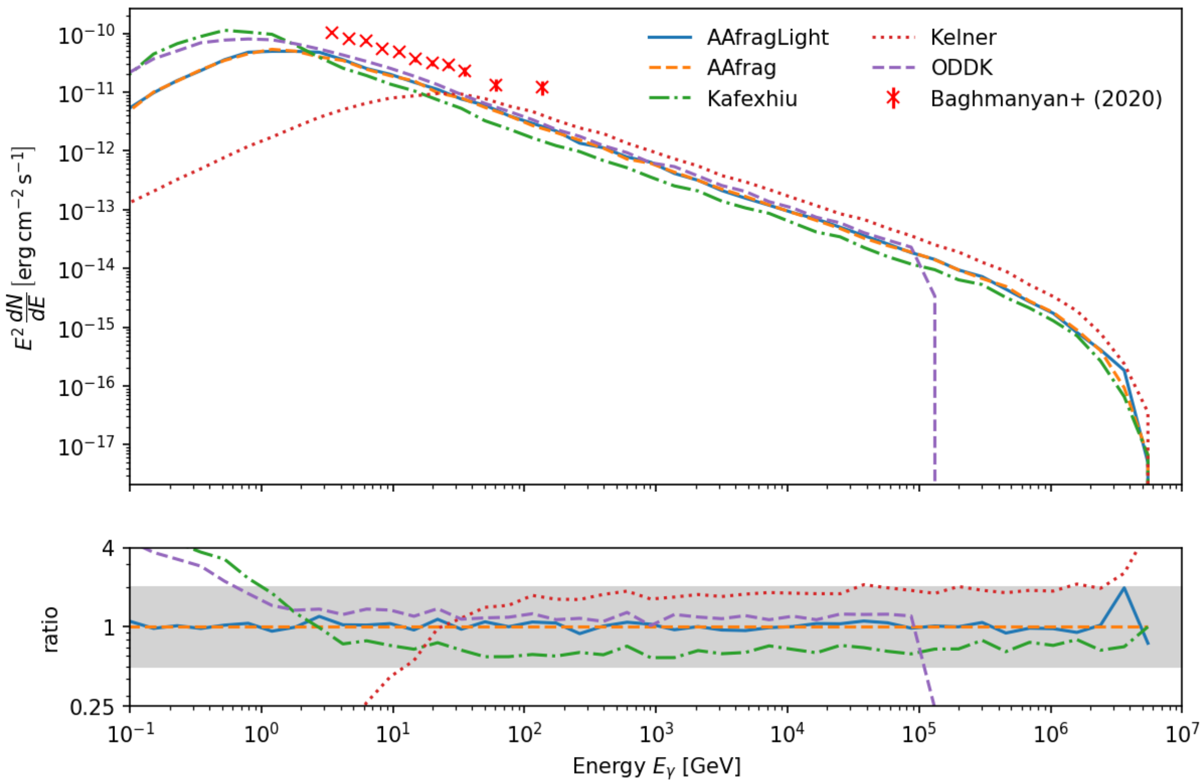
Resulting gamma-ray flux



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summary & conclusion

summary and conclusion

New CRPropa features:

- custom photon fields
- Momentum diffusion
- Shock acceleration

Ongoing development (hadronic interactions)

- Custom description of the differential crosssection
- Trace all possible secondaries
  (including upscattered protons and full cascade)

CRPropa Repository
(GitHub)

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