CRPropa: Overview and Hadronic Interactions

Leonel Morejon

Workshop on the tuning of Hadronic Interaction Models

22-25.01.2024

SFB1491

BERGISCHE UNIVERSITÄT WUPPERTAL

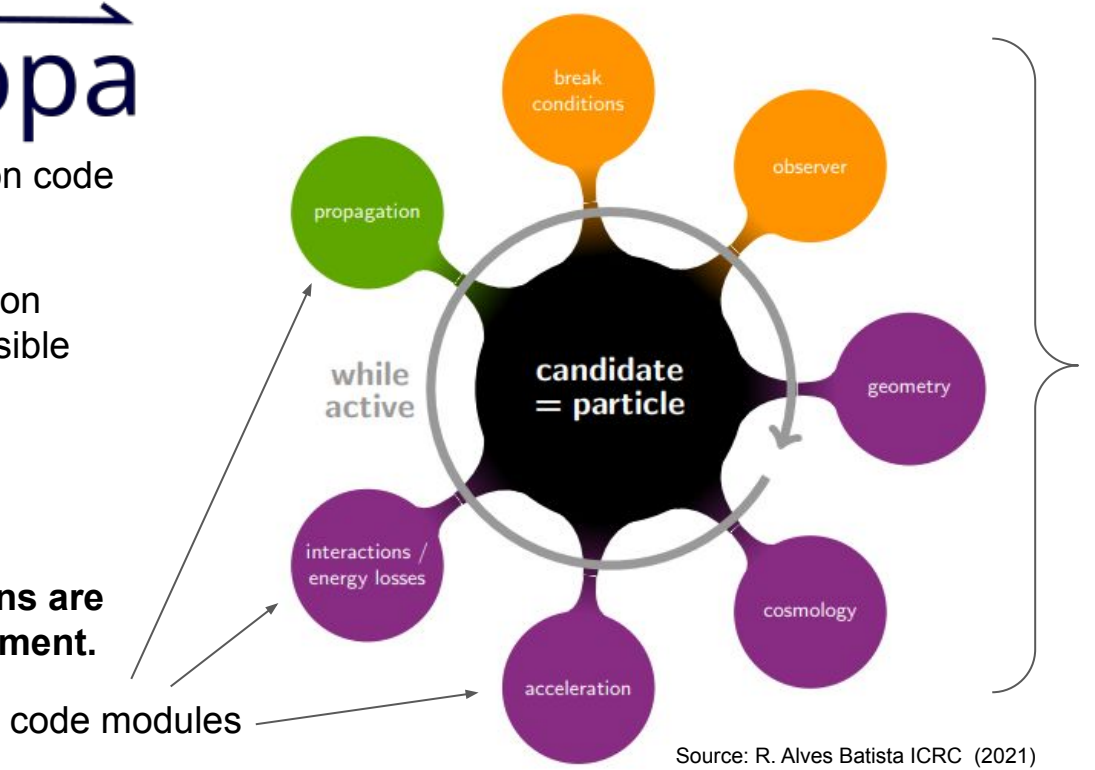
Workflow in CRPropa

CRPropa

Cosmic **R**ay **Propa**gation code

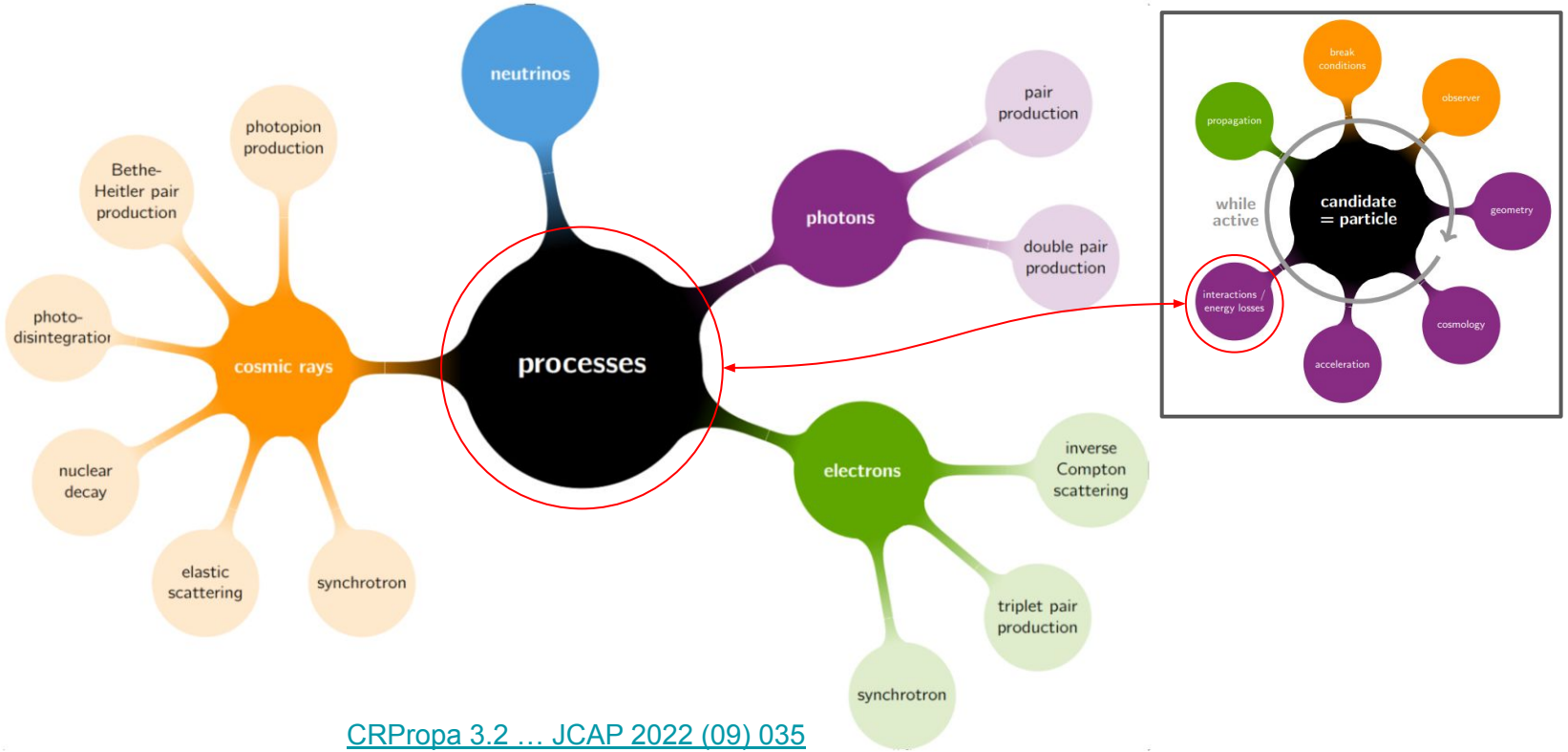
- Modular structure
- Interactive simulation
- Flexible and extensible
- **Python interface**

Extensions and plugins are under active development.



Source: R. Alves Batista ICRC (2021)

Interactions in CRPropa



CRPropa 3.2 … JCAP 2022 (09) 035

Hadronic Interactions Module (HIM)

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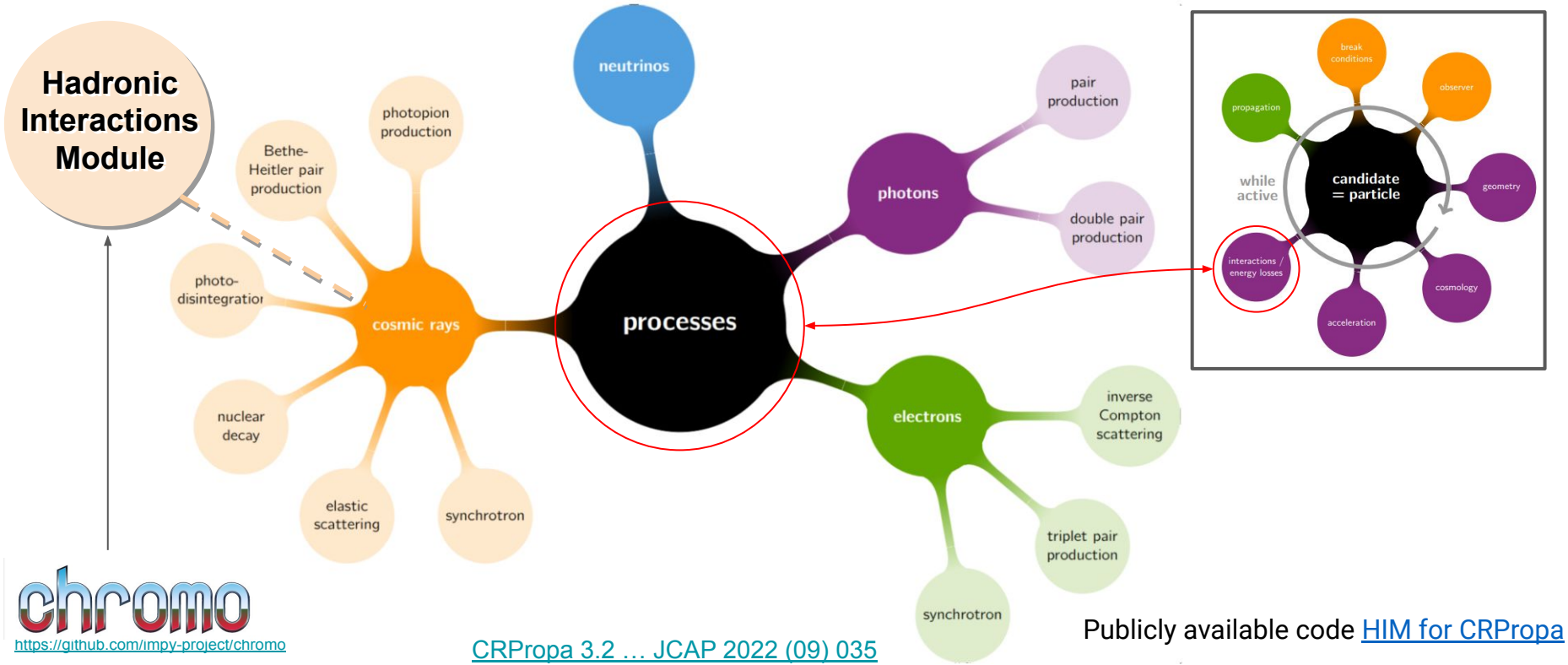

chromo
https://github.com/impy-project/chromo

CRPropa 3.2 … JCAP 2022 (09) 035

Publicly available code HIM for CRPropa

Ballistic propagation with **magnetic fields**

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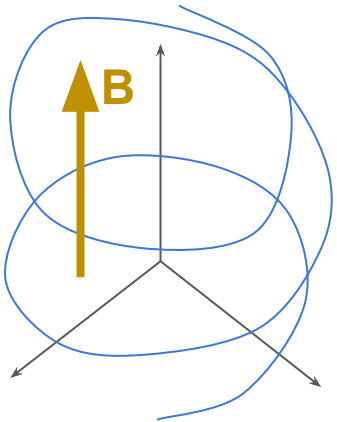
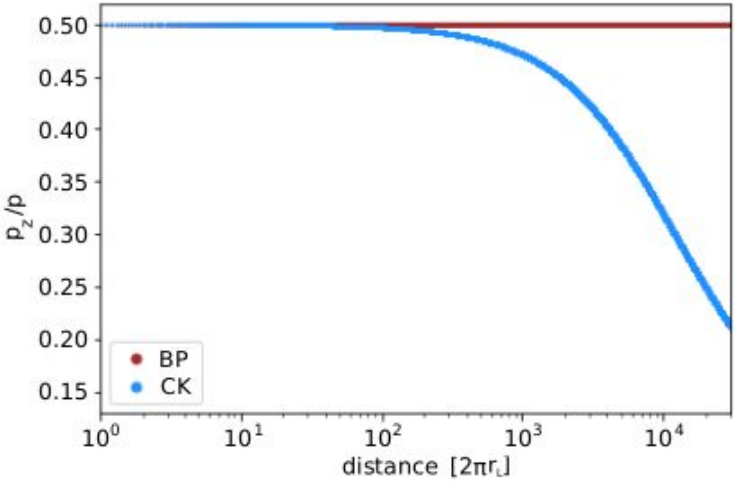
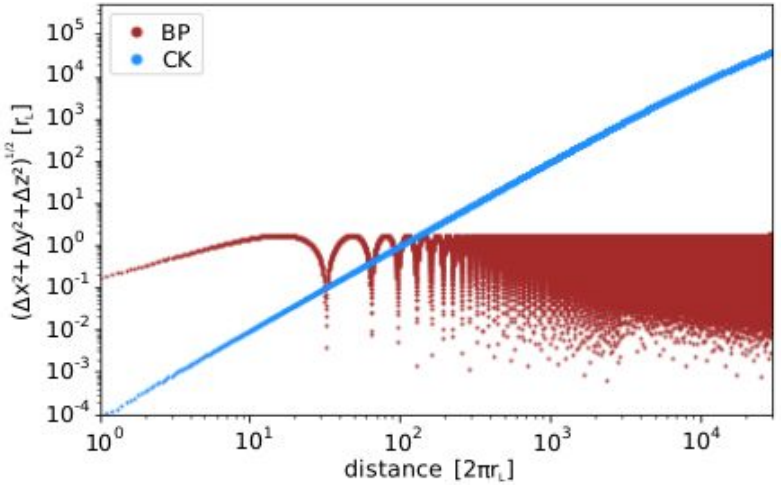
Trajectory integration using well known optimized algorithms

- Boris push (BP): energy conserved as default / phases not preserved
- Cash-Karp (CK): energy conserving enforced / phases preserved







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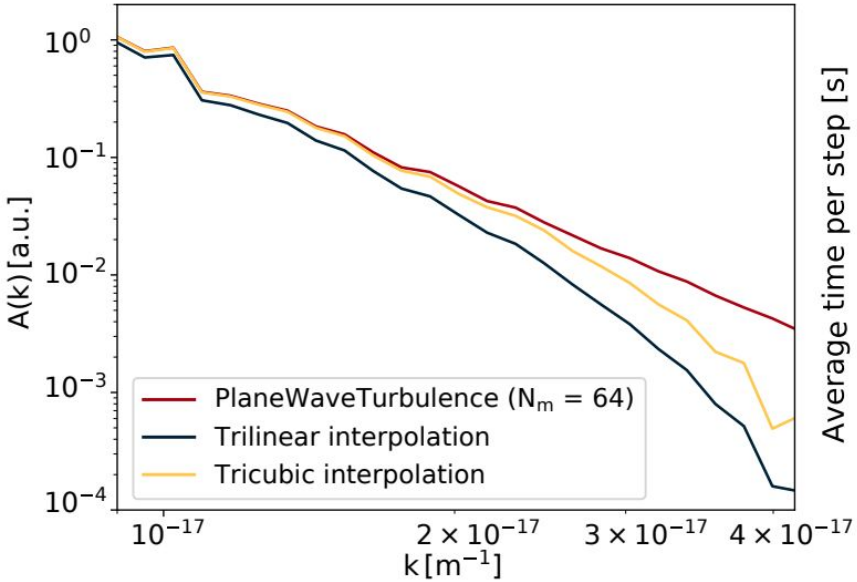
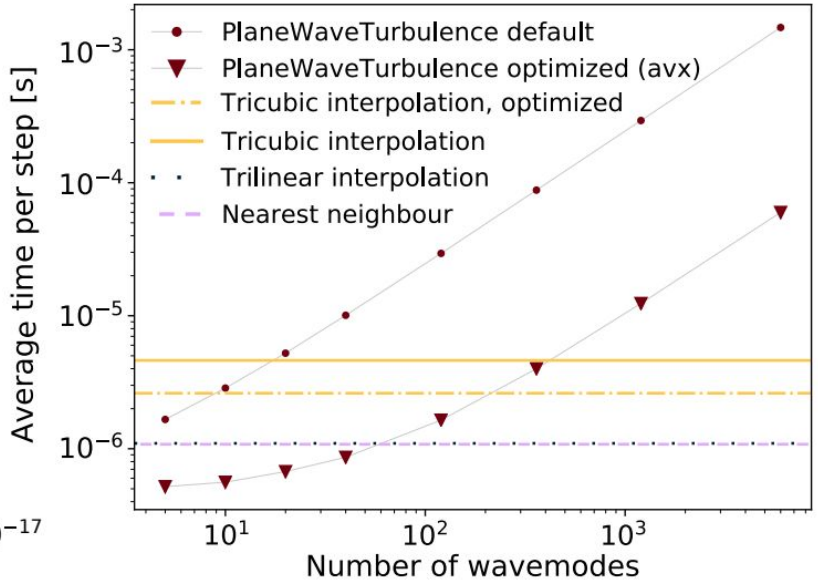
Enhanced interpolation of magnetic fields (grids)

Magnetic Field interpolation (different methods available)

- **Nearest Neighbor**: No correlation. Fast but yields discontinuities.
- **Trilinear**: 8-neighbours correlation. Default, good compromise. Thin grid needed.
- **Tricubic**: 64-neighbours correlation. Smoother. Thinner grid needed.





Diffusion simulation of CRs in the galaxy

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Diffusion simulated by solving the diffusion equation

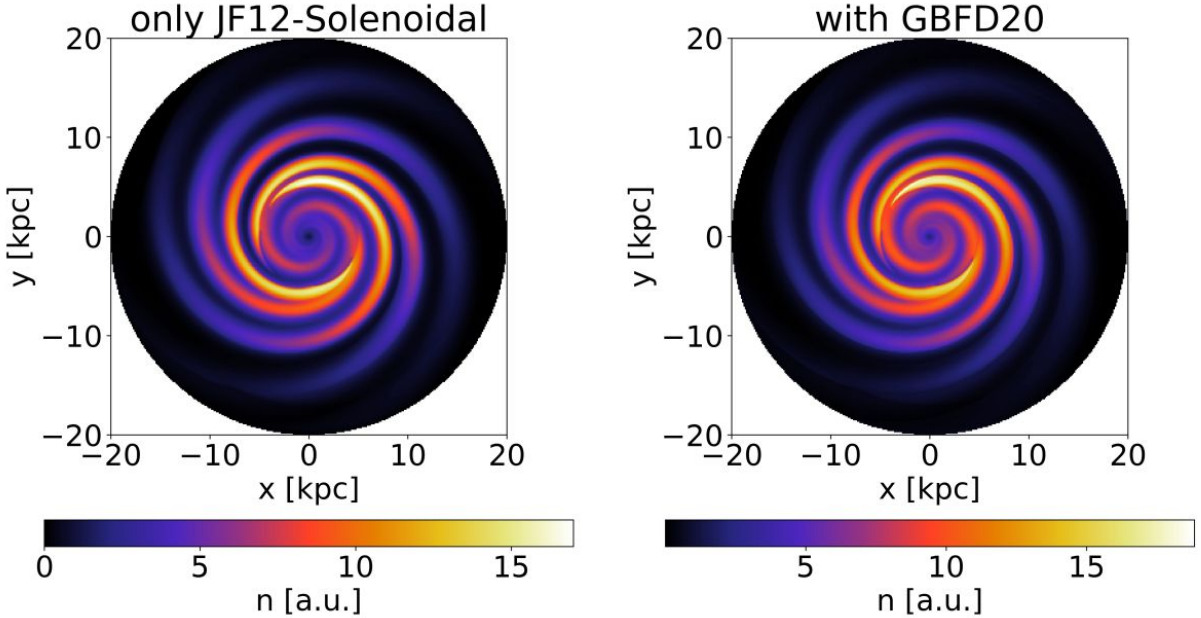
Matter densities

- 3D distribution as grid
- Separate components (H-I, H-II, H2)
- Source emission can be connected to density

Gal. Magn. Fields

- Multiple options available
  Astrophys. J. 877 (2019) 76
  Astron. Astrophys. 644 (2020) A71
  (…)
- Simulation sensitive to GMF central features

Cosmic ray density in the galactic plane



EM cascade simulation

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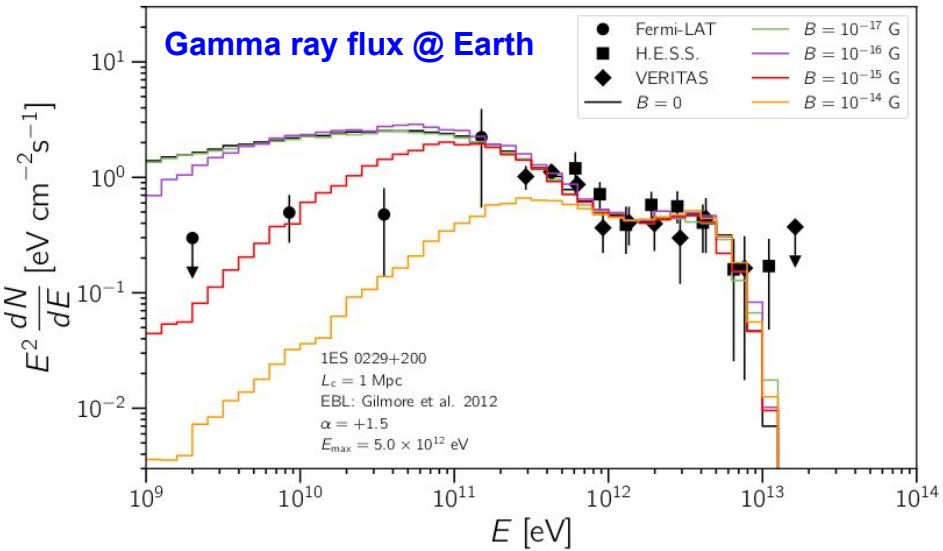
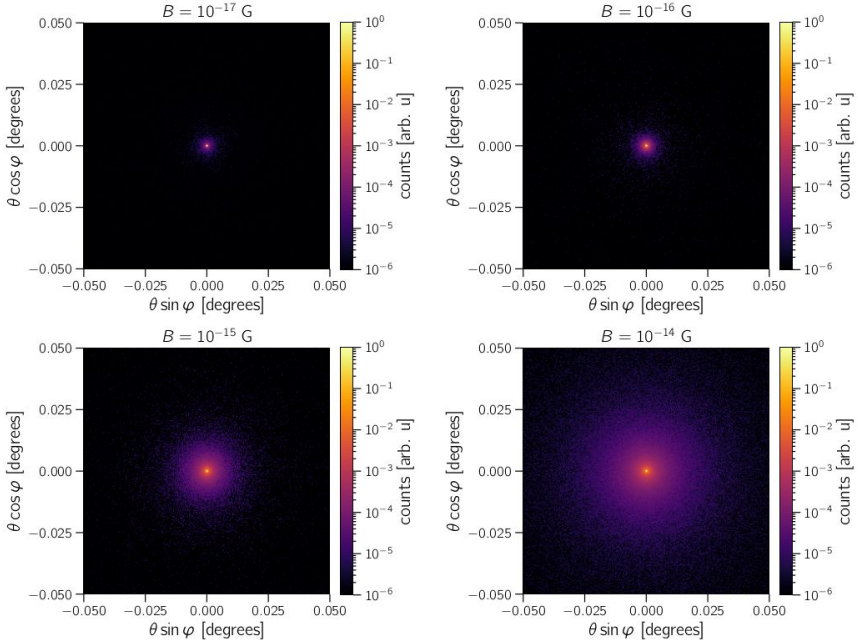
EM cascades in strong magnetic fields

- **Electron pair production** simulated per primary gamma
- **Thinning**: Needed for efficiency. Energy dependent



Arrival directions of Gamma rays @ Earth



Hadronic Interactions Module (HIM)

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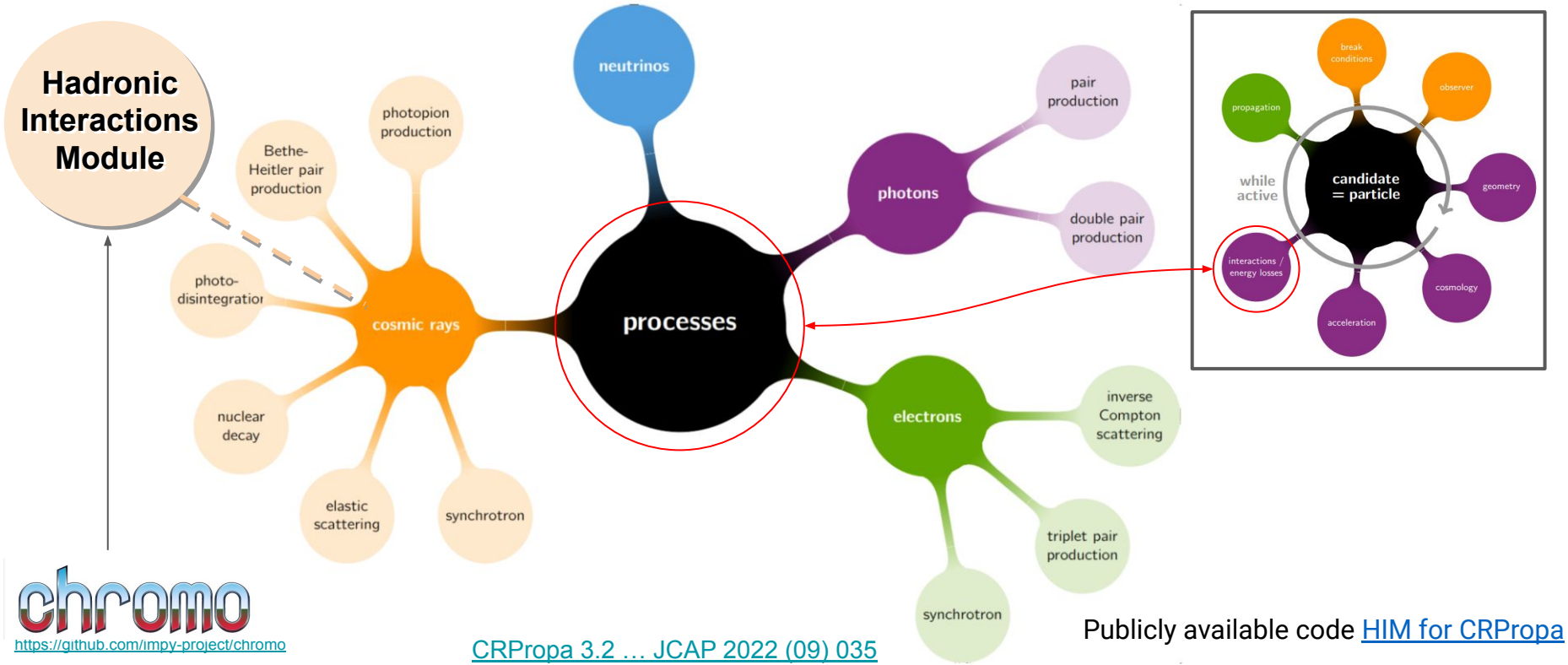

chromo
https://github.com/impy-project/chromo

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Publicly available code HIM for CRPropa

Modeling interactions and secondaries' spectra

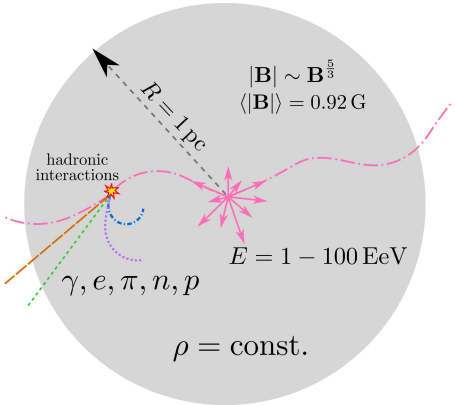
Interactions discussed

Photohadronic (photomeson)

$$p + p/\gamma \rightarrow p/n + \pi^{\pm} + \pi^{0} + K^{\pm} + \cdots$$

$$\begin{aligned}
\pi^{+} &\rightarrow \mu^{+} + \nu_{\mu}, \\
&\quad \mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} \\
\pi^{-} &\rightarrow \mu^{-} + \bar{\nu}_{\mu}, \\
&\quad \mu^{-} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu}, \\
\pi^{0} &\rightarrow \gamma + \gamma \\
K^{\pm} &\rightarrow \mu^{+}/\mu^{=} + \nu_{\mu}/\bar{\nu}_{\mu}
\end{aligned}$$

Hadronic (p+p, p+A)



L. Morejon, et al, *JCAP* 11 (2019) 007

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Elements of the HIM

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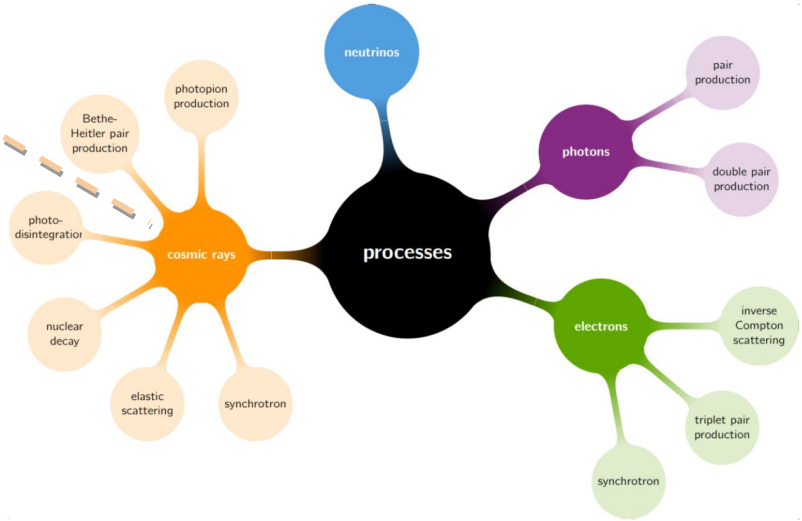
- Sample hadr. interaction
- Produce input params.
- Call to external codes:
  - EPOS-LHC, SIBYLL, QGSJet, DPMJET, etc.
- Collect secondaries
- Transform btw. frames

Hadronic Interactions Module

Module written in python. Available on Github (installation separate from CRPropa)

Publicly available code HIM for CRPropa



Interface: CHROMO

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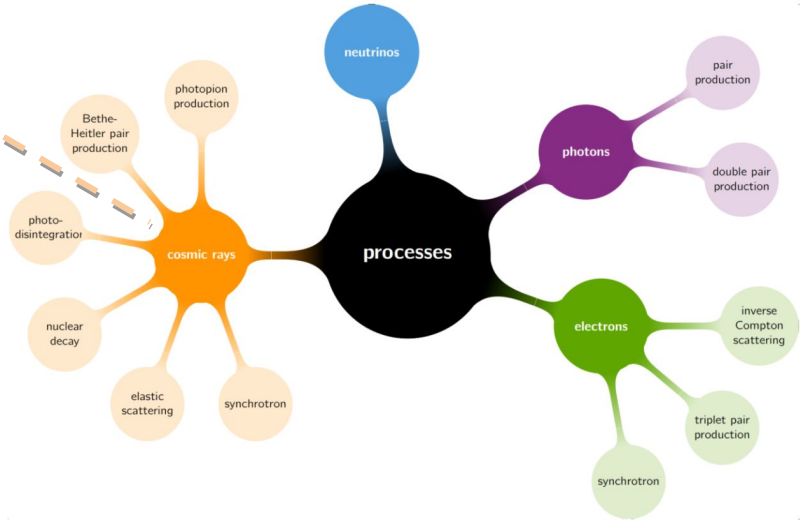

https://github.com/impy-project/chromo

chromo

Cosmic ray and HadROnic interactiOn MOnte-carlo frontend

Hadronic interactions

Interface: CHROMO

- Sample hadr. interaction
- Produce input params.
- Call to external codes:
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- Transform btw. frames

https://github.com/impy-proje

chromo

Cosmic ray and HadROnic interactiOn MOnte-ca frontend

Interaction model	Supported proj/targ
DPMJET-III 3.0.6 & PHOJET 1.12-35	*hN, γγ, γN, hA, γA, AA*
DPMJET-III & PHOJET 19.1 and 19.3 (repo on GitHub)	*hN, γγ, γN, hA, γA, AA*
EPOS-LHC	*hN, hA, AA*
PYTHIA 6.4	*hN, ee, γγ, γN*
PYTHIA 8.3 (https://pythia.org/)	*hN, ee, γγ, γN & hA, AA* (Argantyr)
QGSJet-01	*hN, hA, AA*
QGSJet-II-03	*hN, hA, AA*
QGSJet-II-04	*hN, hA, AA*
SIBYLL-2.1	*hN, hA (A<=20)*
SIBYLL-2.3d	*hN, hA (A<=20)*
SOPHIA 2.0	*γN*
UrQMD 3.4 + second citation	hN, hA, AA*

h = hadron, *N* = nucleon (p or n), *A* = nucleus, *γ* = photon, *e* = electron/positron

Interaction rate and step sampling

The interaction step is sampled as

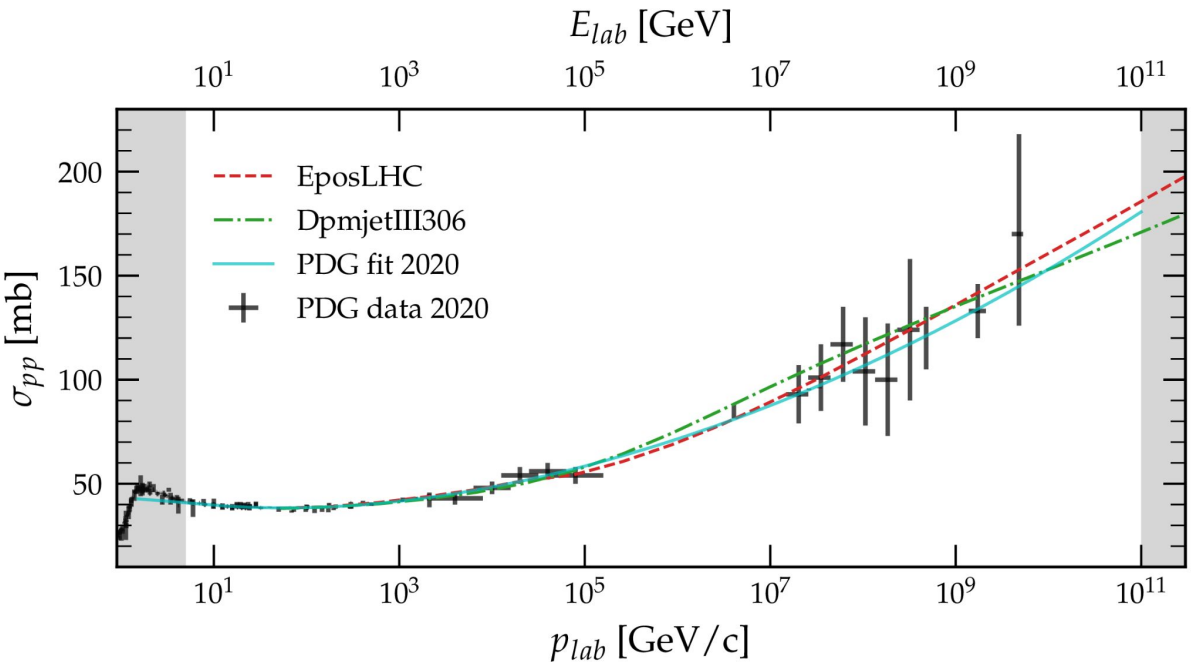
$$d = -\frac{\log p}{\sigma \rho}$$

where **p** is a random number sampled using CRPropa functions.

The **density** is handled by the Density class available in CRPropa.

The cross section can be chosen:

- from hadronic code (inefficient)
- from DPG recommended fit



* C. Patrignani 2016 Chinese Phys. C 40 100001
* P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

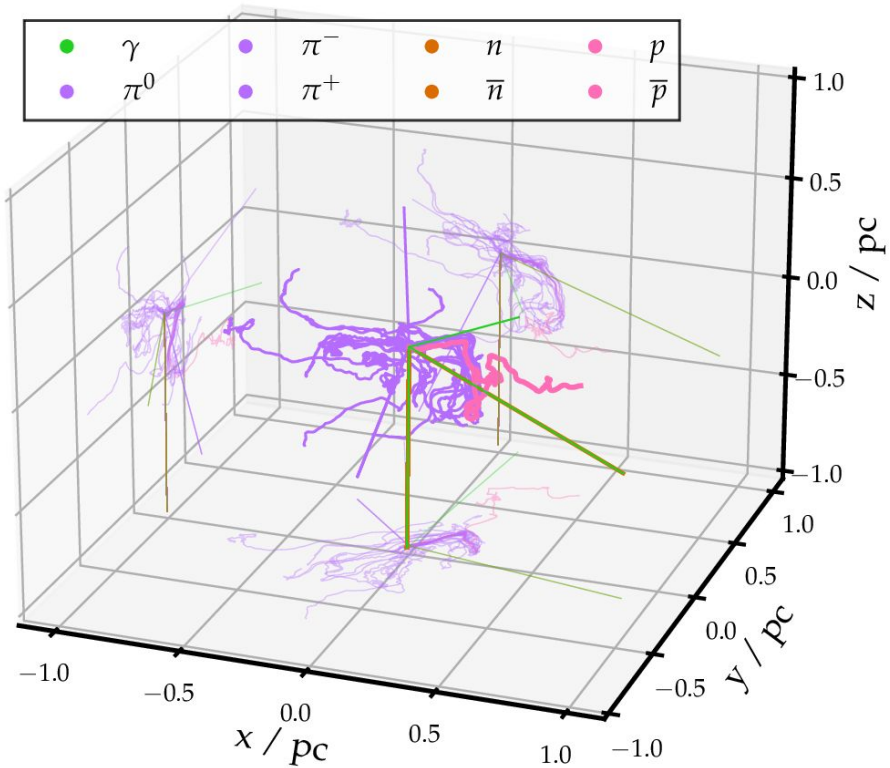
Additional random-seed settings

Seeds available for control:

1. Step-sampling seed
2. Hadronic engine's seed
3. Interaction-plane angle seed

Example figure…

- Injecting a proton 1EeV
- Interaction step controlled by **seed 1**
- Secondaries' species, energy, momenta and distribution controlled by **seed 2**
- Transversal plane momenta controlled by **seed 3**



Simulation time versus matter density

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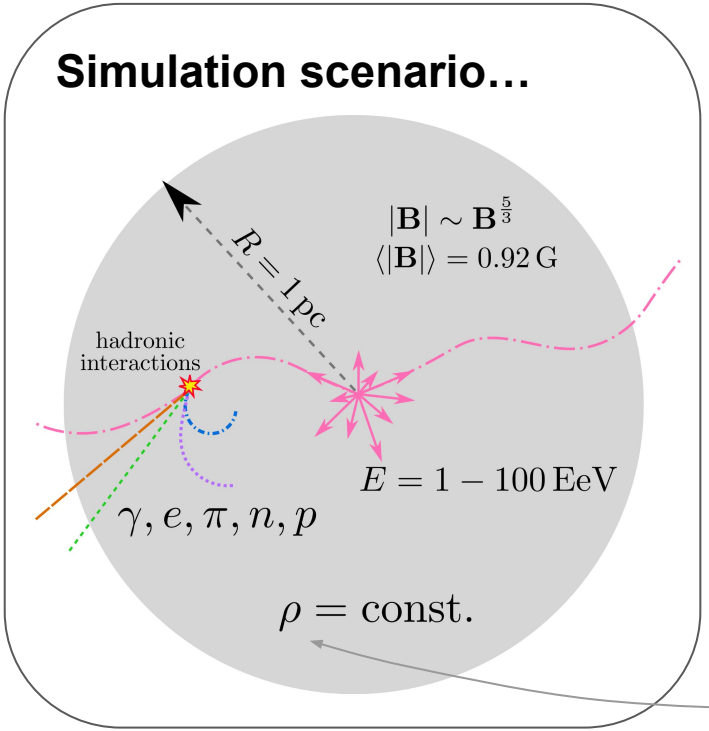

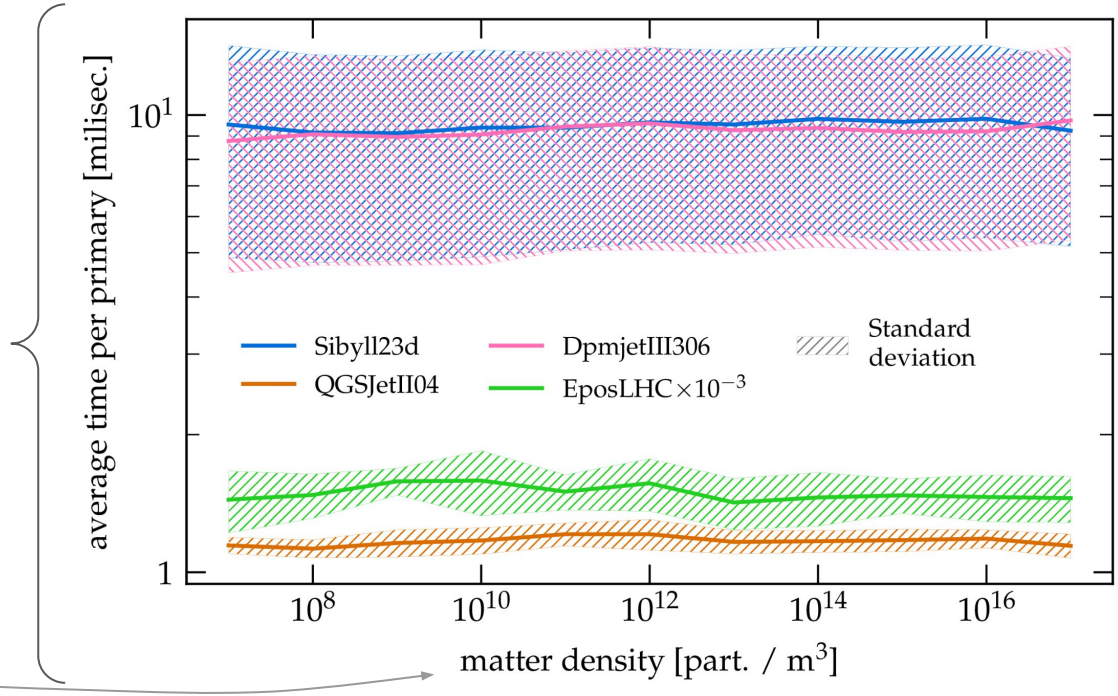

Magnetic Field ON versus OFF

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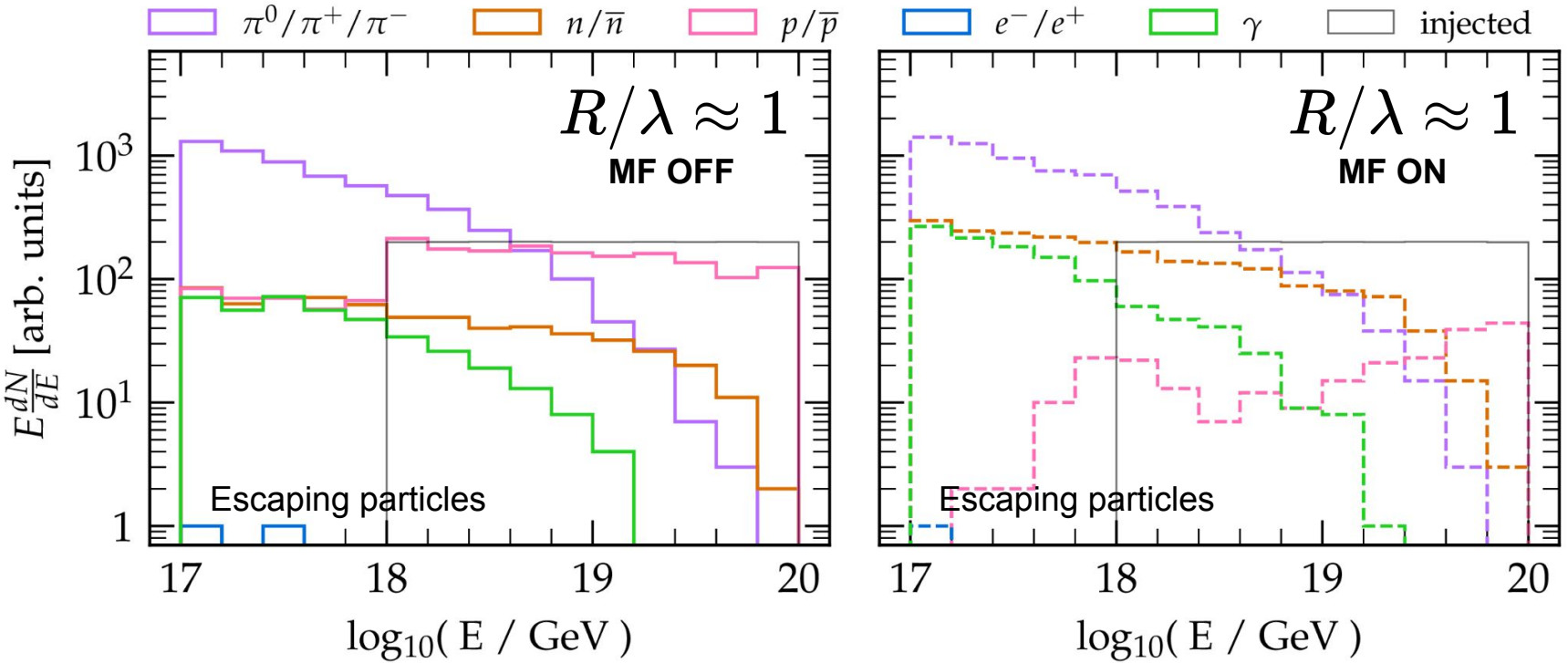


Other approaches to hadronic interactions (ongoing)

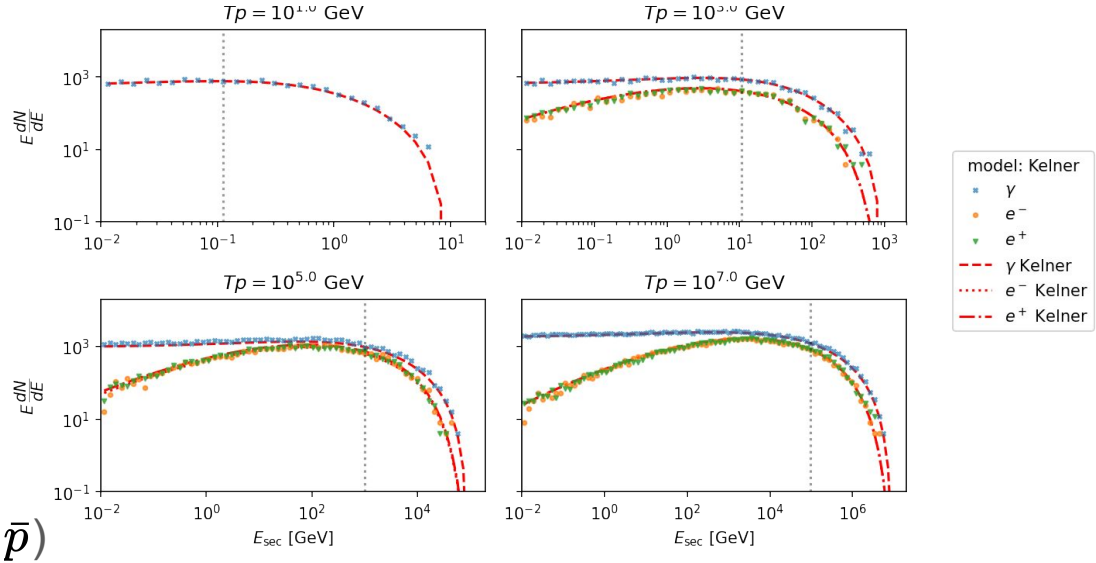
Implementation in source code

- Based on analytic expressions
- Secondaries sampled from pre-computed tables
- References: Kelner, S. *et al.* PRD, 74, 2006
  Orusa, L., *et al.* PRD, 105, 2022
  Orusa, L., *et al.* PRD, 107, 2023
  Kachelrieß, M., *et al.* CPC, 2019

Pros and Cons

+ Very computationally efficient
+ Final products readily available
+ Many secondaries of interest (e.g. $\bar{p}$)
- Production channels non-separable
- Limited interaction partners

PRELIMINARY



J. Dörner *et al.* (in preparation)

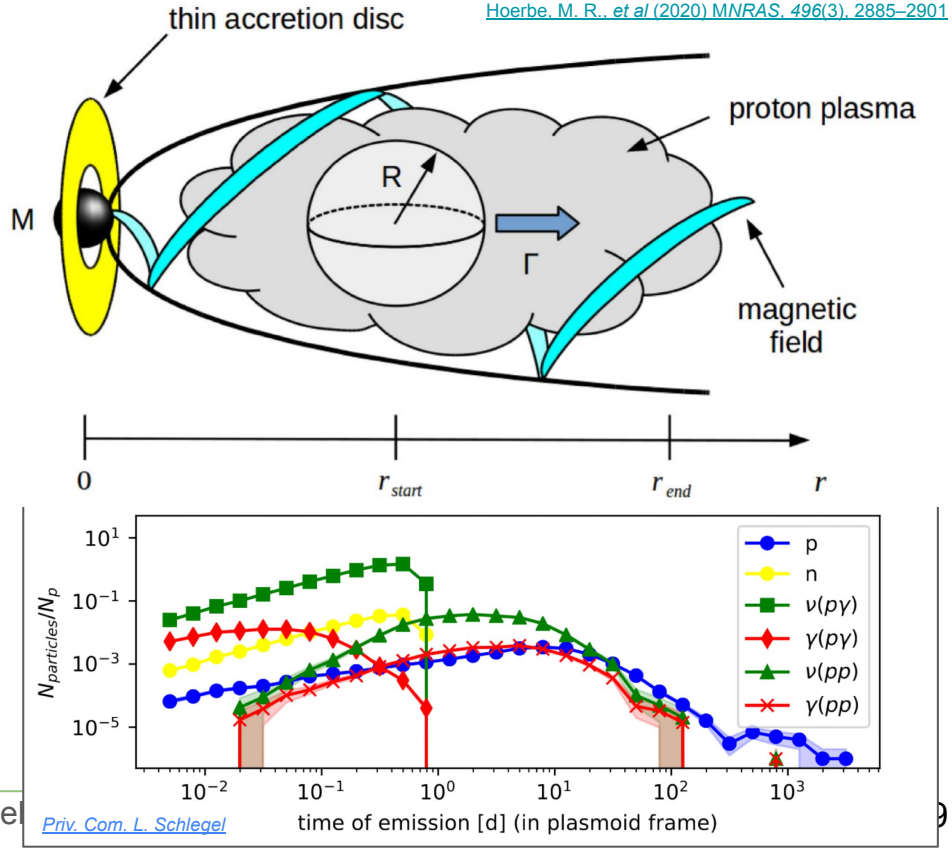
Other approaches to hadronic interactions (ongoing)

Example in AGNs

- Plasmoid emission as it moves
- Variable target photon fields
- Photointeractions in CRPropa

Hadronic Interactions

- Secondaries' spectra computed from resulting proton distributions



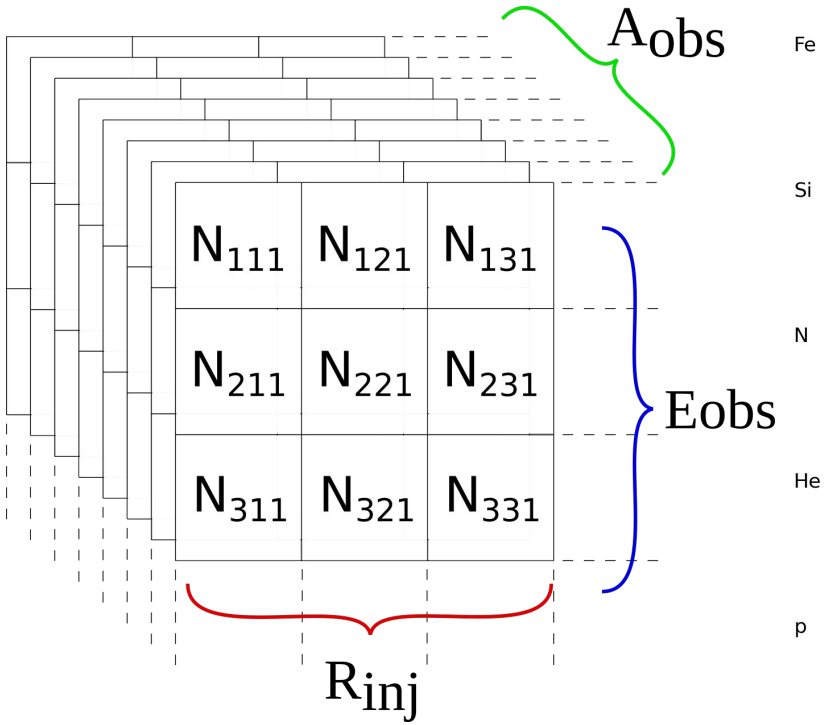
MultI-messenger probe of Cosmic Ray Origins

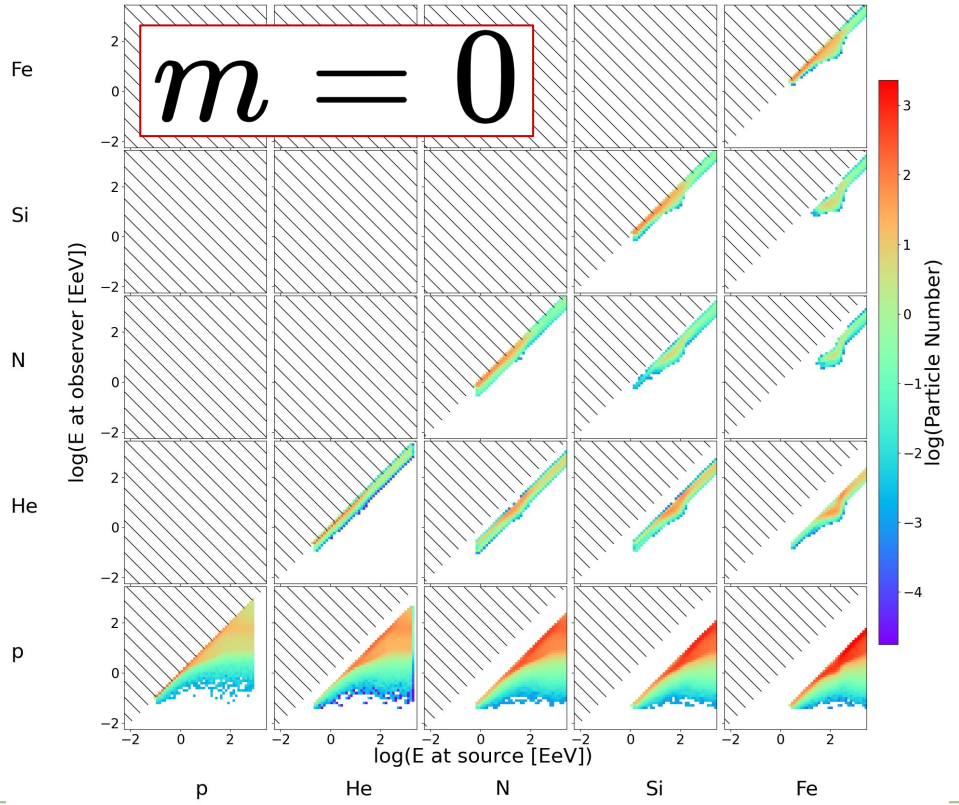
Participating institutions

Funded by:

Propagation tensor & matrix

$$L(z) \propto (1+z)^m$$

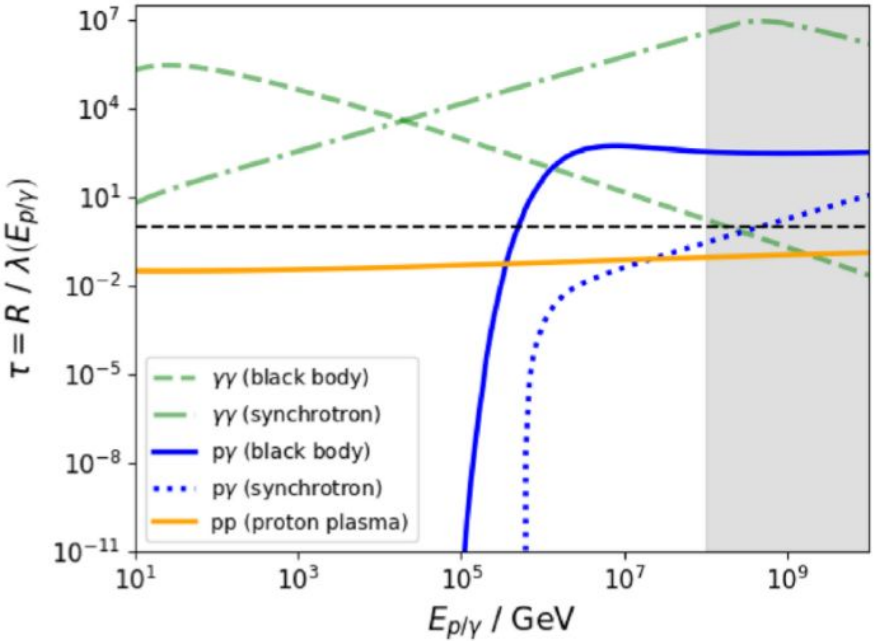




Bursting Sources of UHECRs: Relevant Interactions

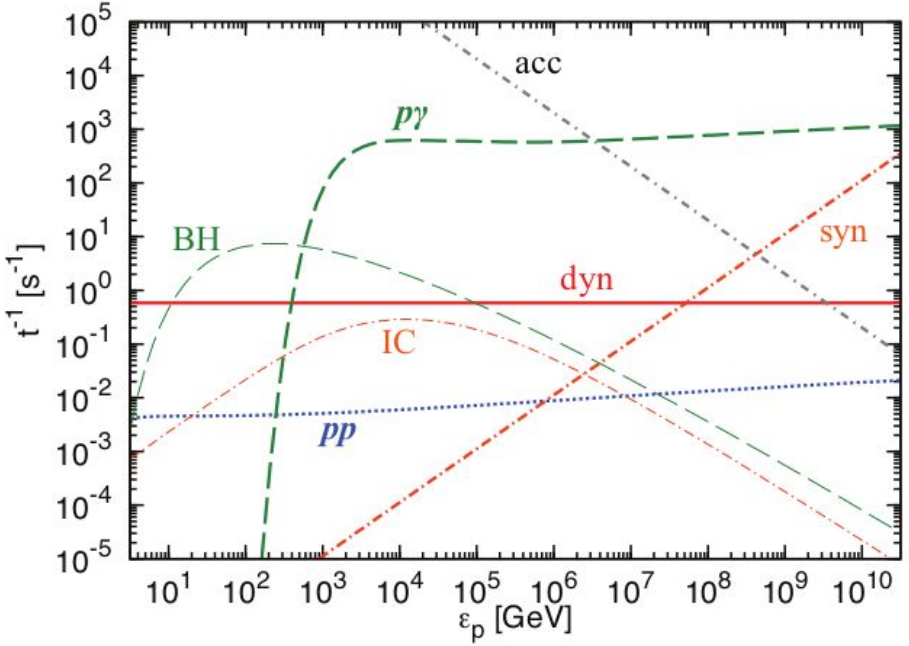
Necessity of simulating both **p-p** and **p-γ** interactions consistently!

AGNs plasmoids



Hoerbe, M. R., *et al* (2020) *MNRAS*, *496*(3), 2885–2901

Choked GRBs

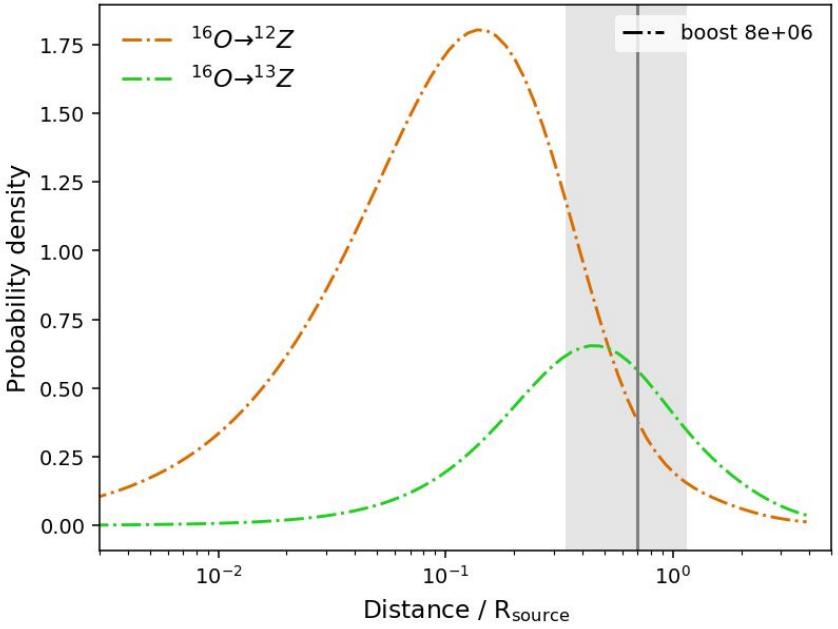


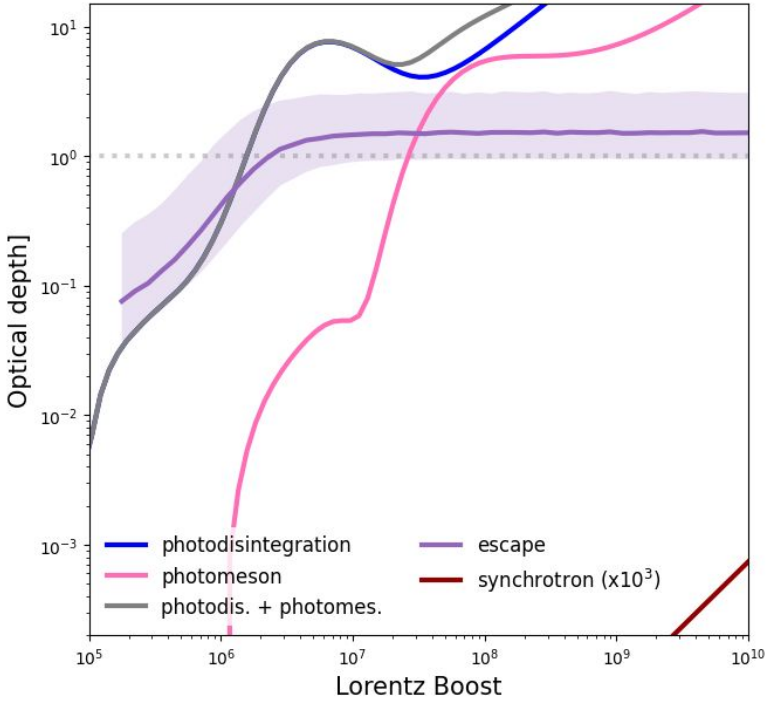
Senno, N., et al. (2016) *PRD*, 93(8), 083003

PRELIMINARY

Example case: AGN with Oxygen injection

1. Computing interaction rates for nuclei (photodisintegration & photopion production)



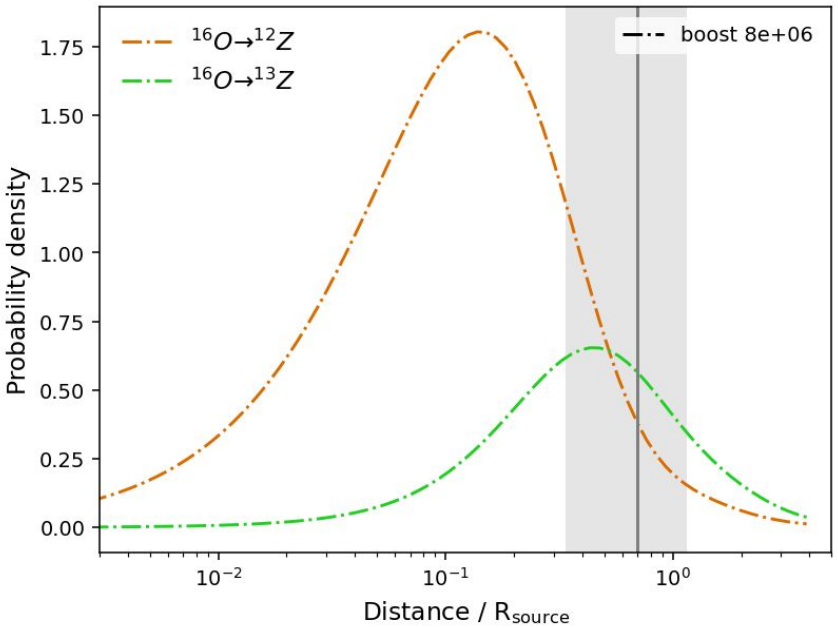


*Source parameters: Hoerbe, M. R., *et al* (2020) M*NRAS*, *496*(3), 2885–2901

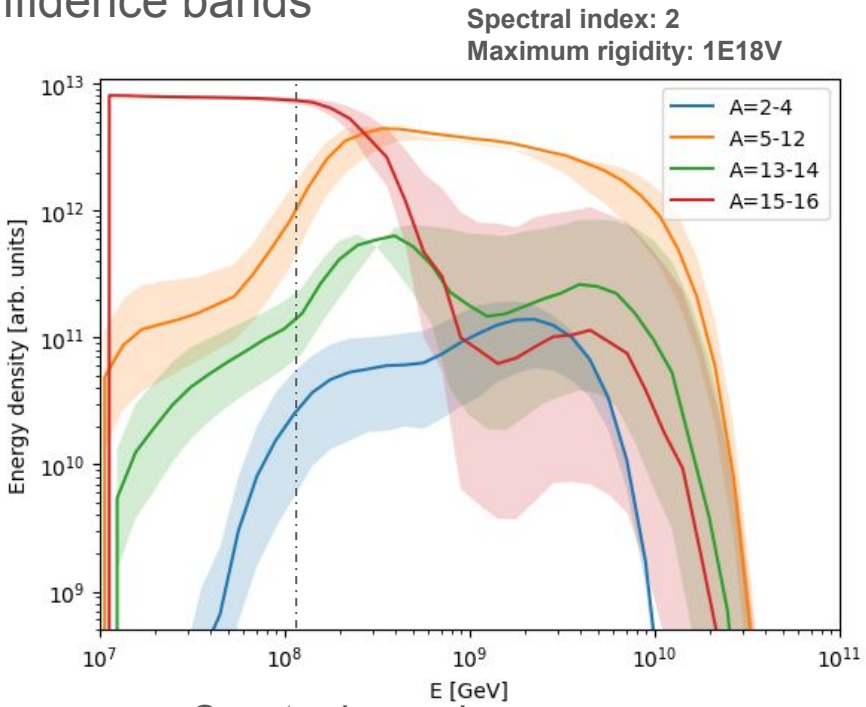
PRELIMINARY

Example case: AGN with Oxygen injection

3. Producing the distributions of nuclei and confidence bands



Convolution with distance distributions



Spectra by nuclear mass group

MICRO website

HIM @ github

Thanks!

MICRO website

HIM @ github

Additional slides

Example simulation (Magn. Field OFF)

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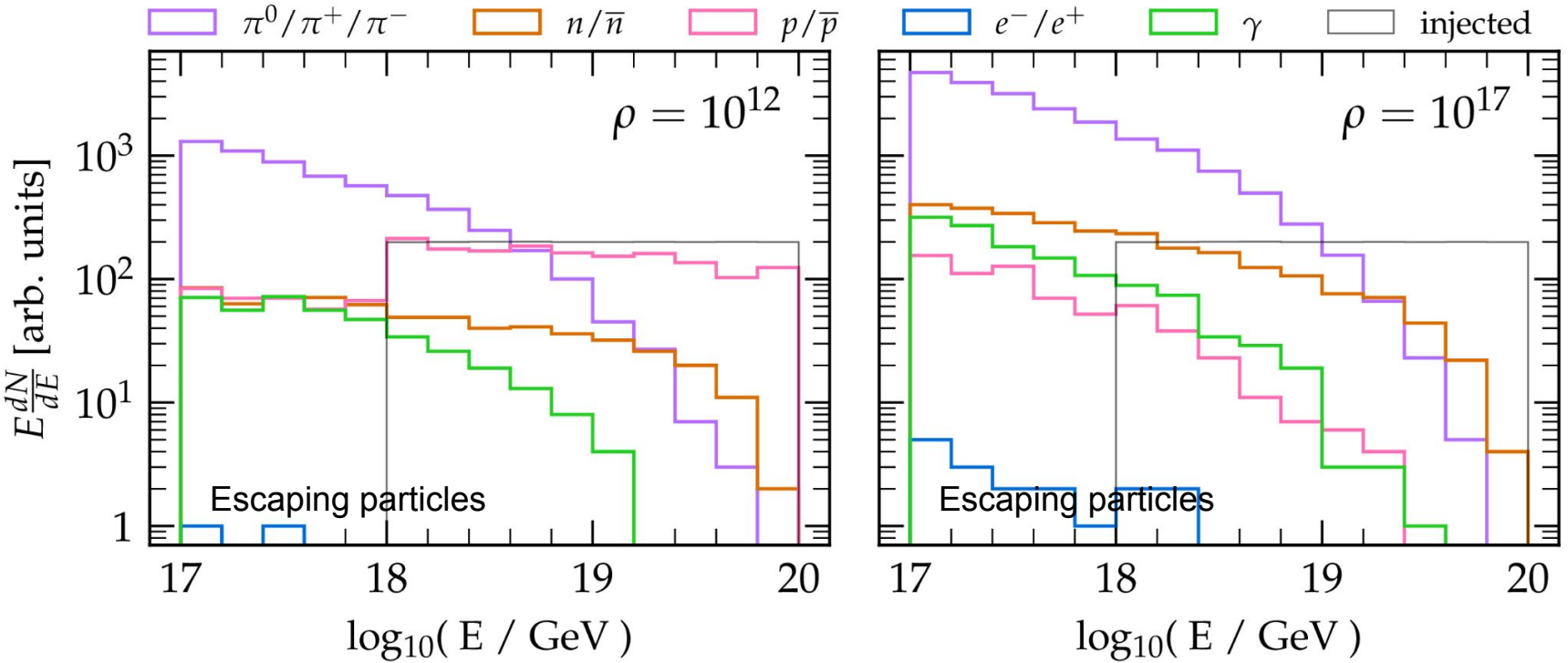

Example simulation (Magn. Field OFF)

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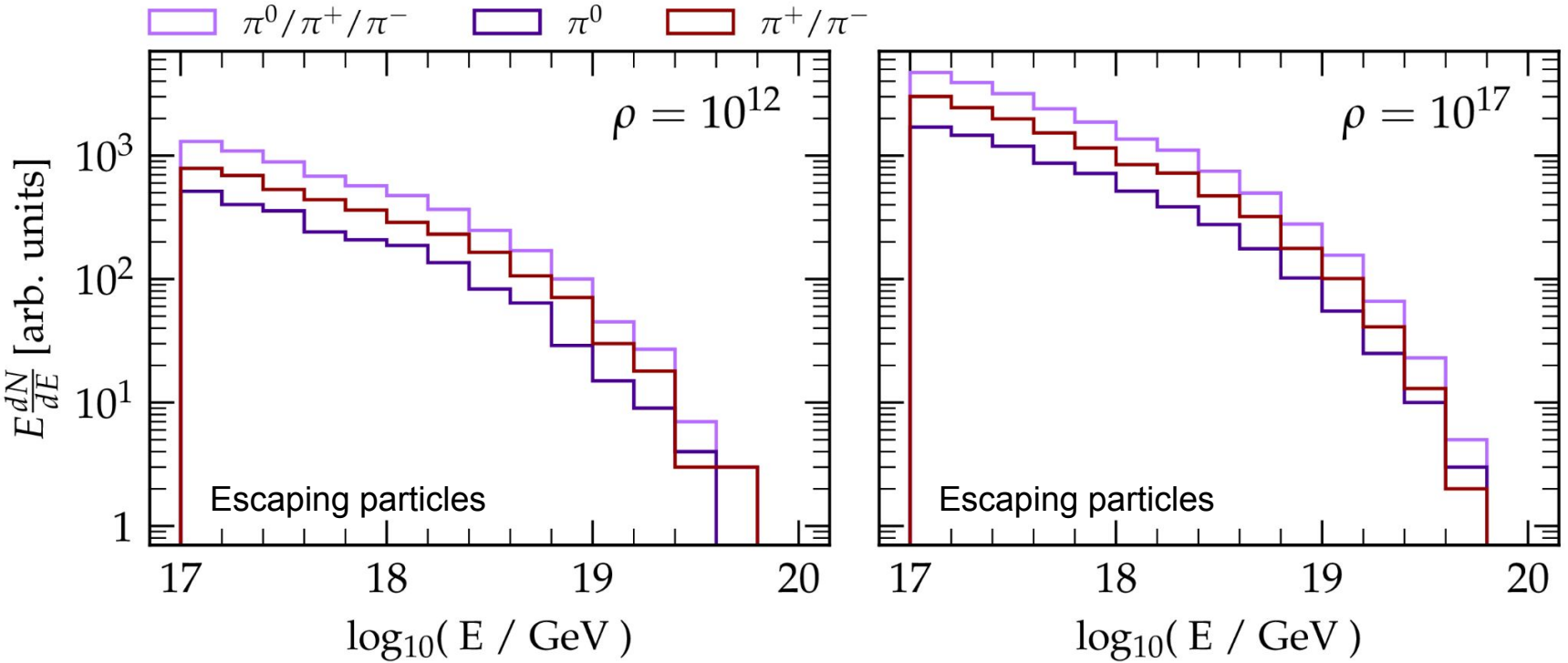

Example simulation (Magn. Field ON)

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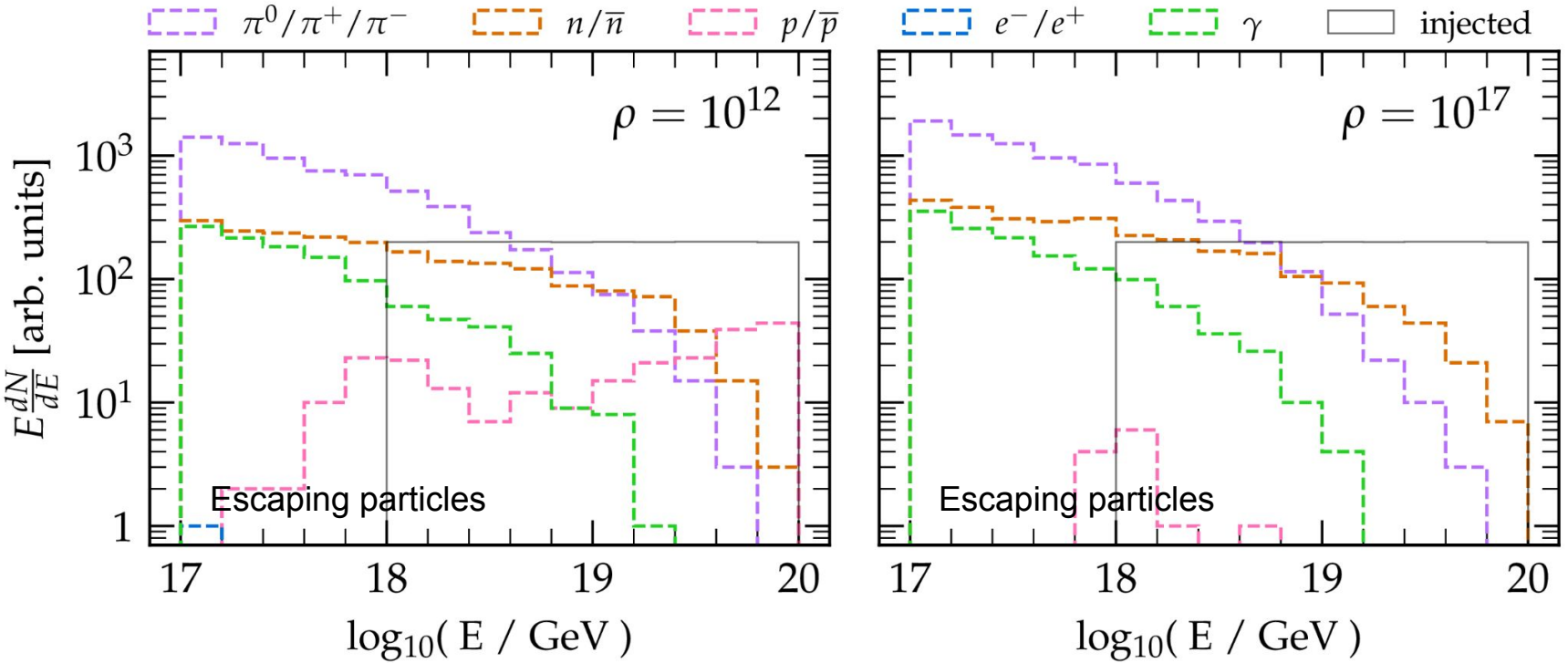

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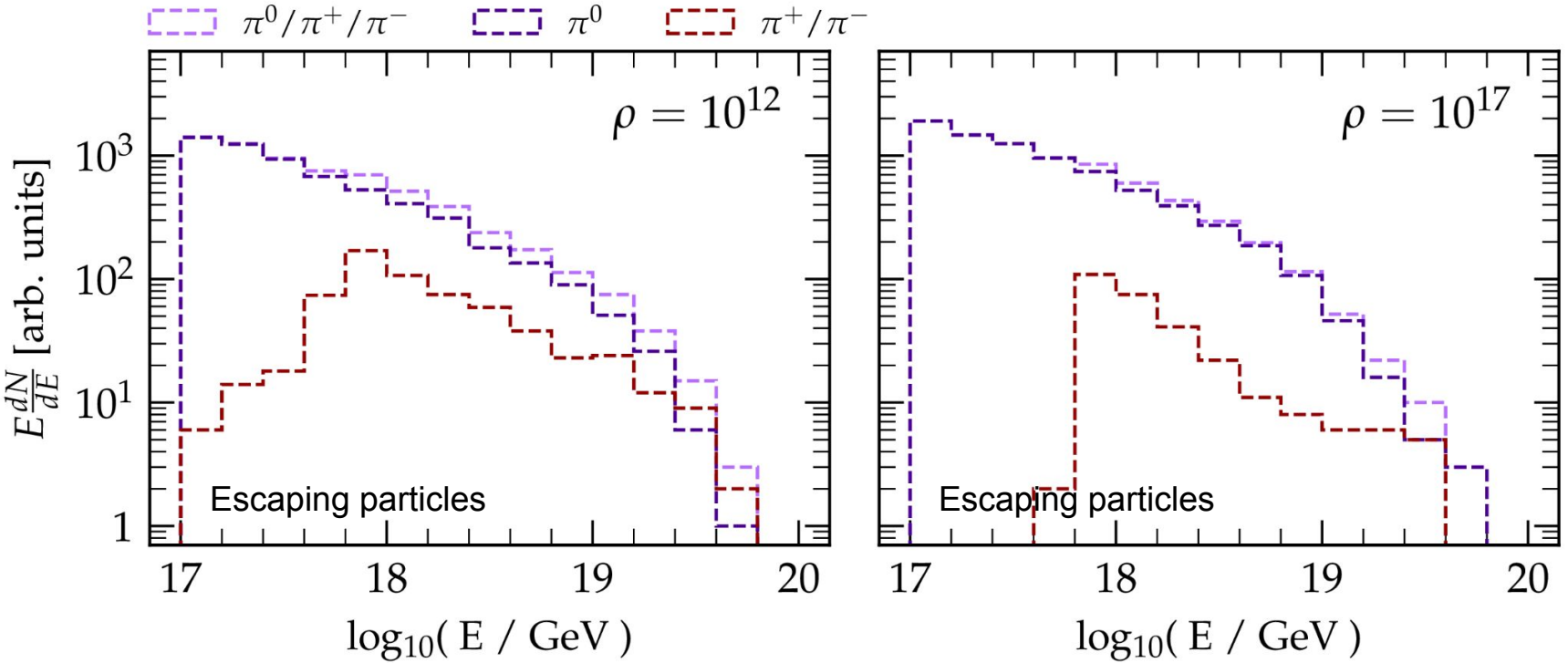

Magn. Field ON versus OFF

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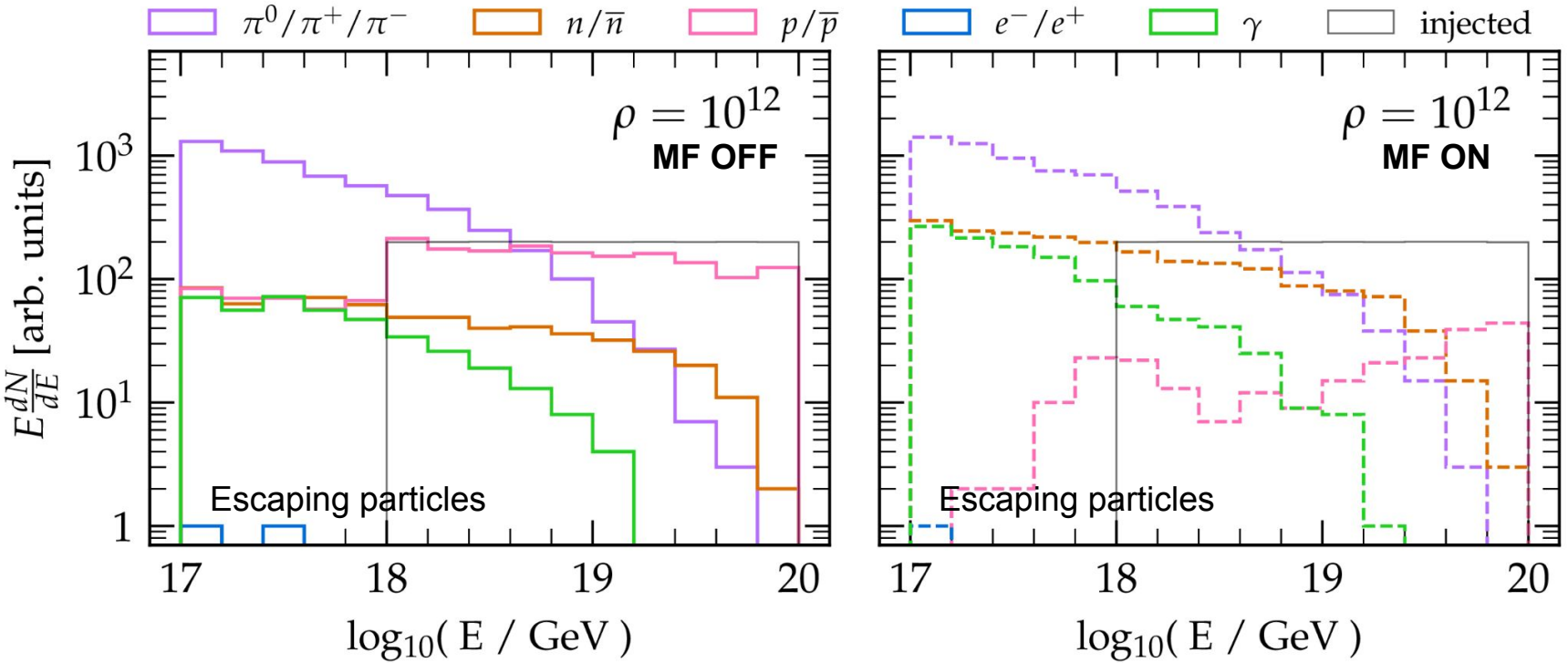

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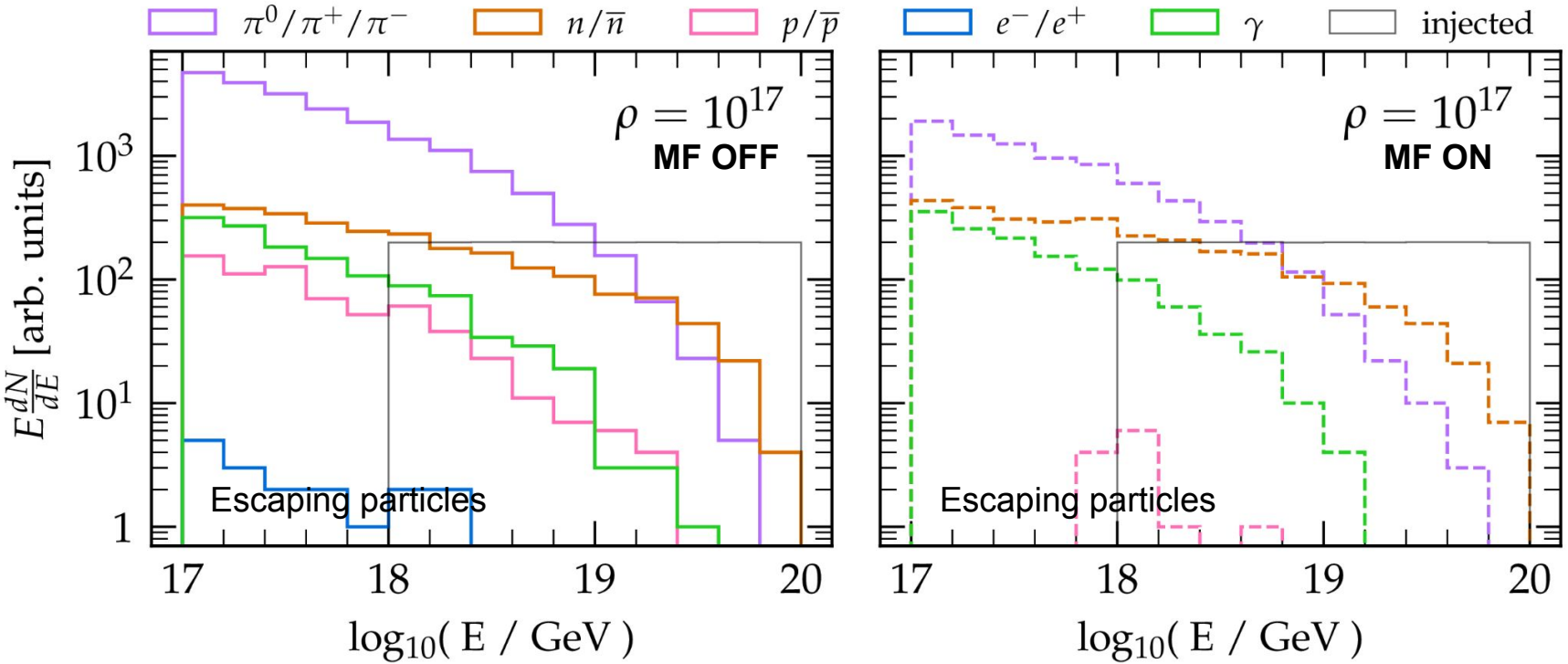

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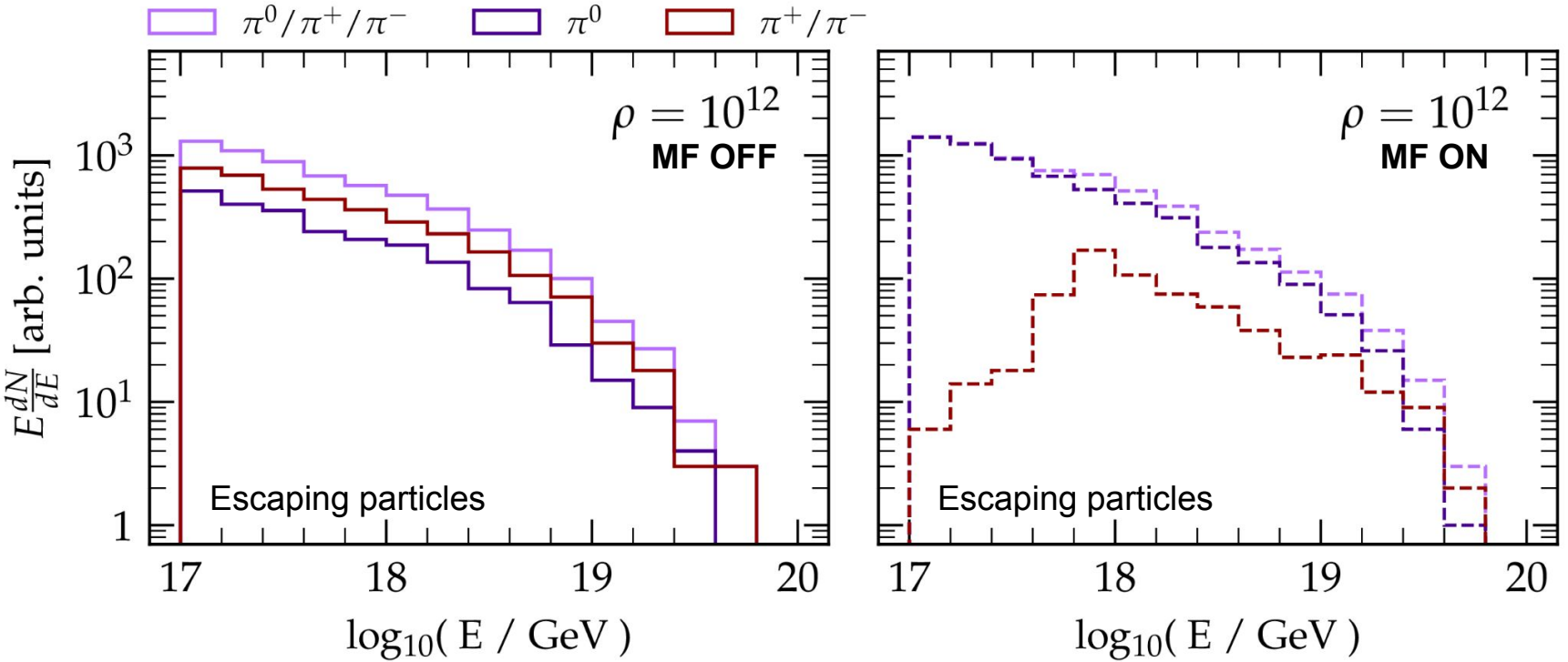

Magn. Field ON versus OFF

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