Hadronic Interactions in CRPropa with state-of-the-art generators

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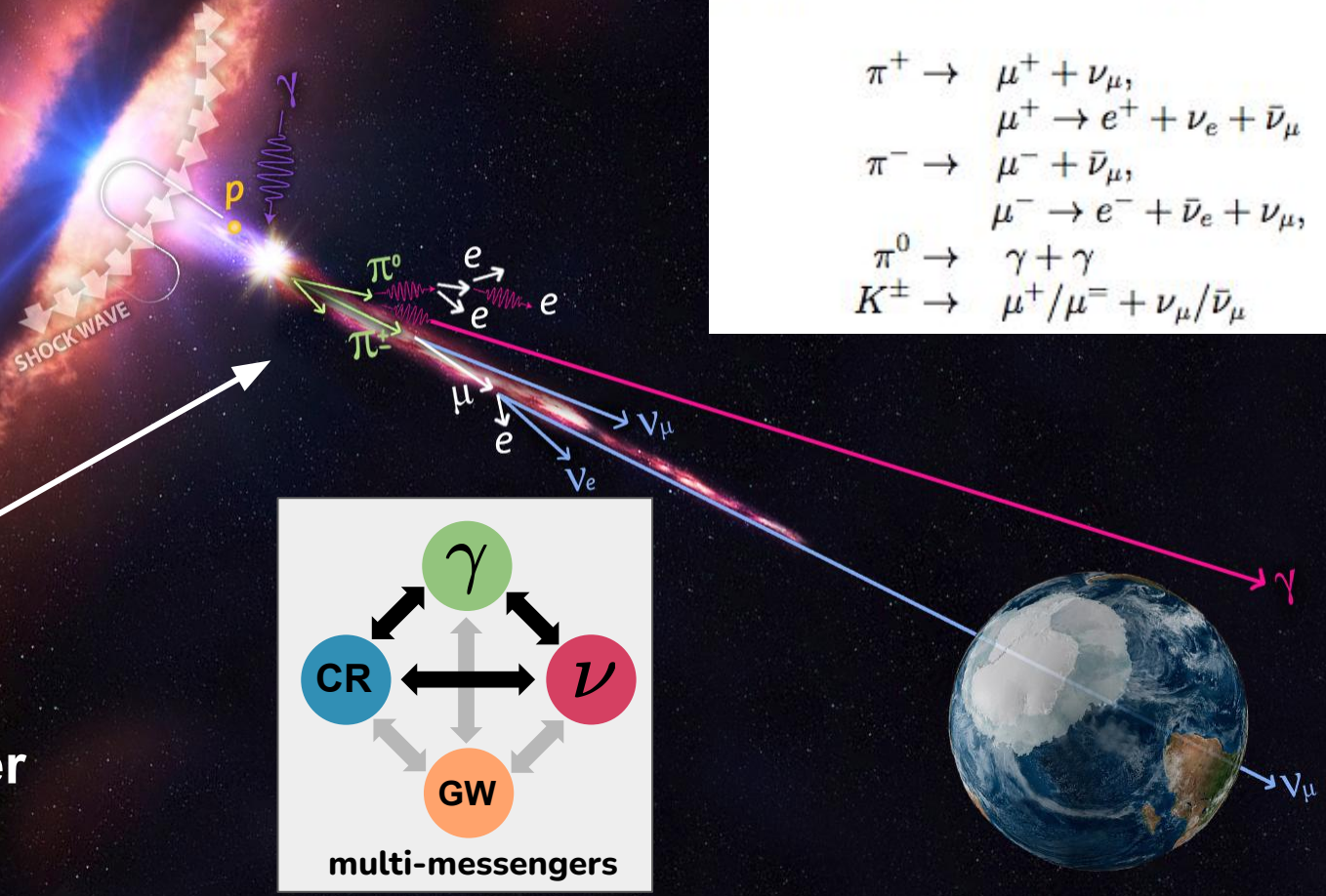
BERGISCHE
UNIVERSITÄT
WUPPERTAL

Cosmic Ray Interactions

Credit: NASA

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

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

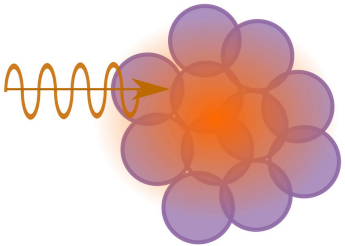


Interactions producing other messengers

Modeling interactions and secondaries' spectra

Interactions discussed

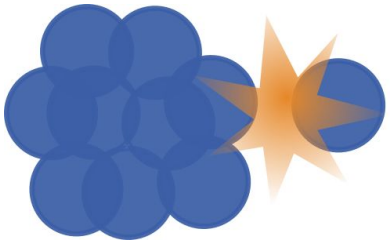
Photohadronic (photomeson)



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

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

Hadronic (p+p, p+A)



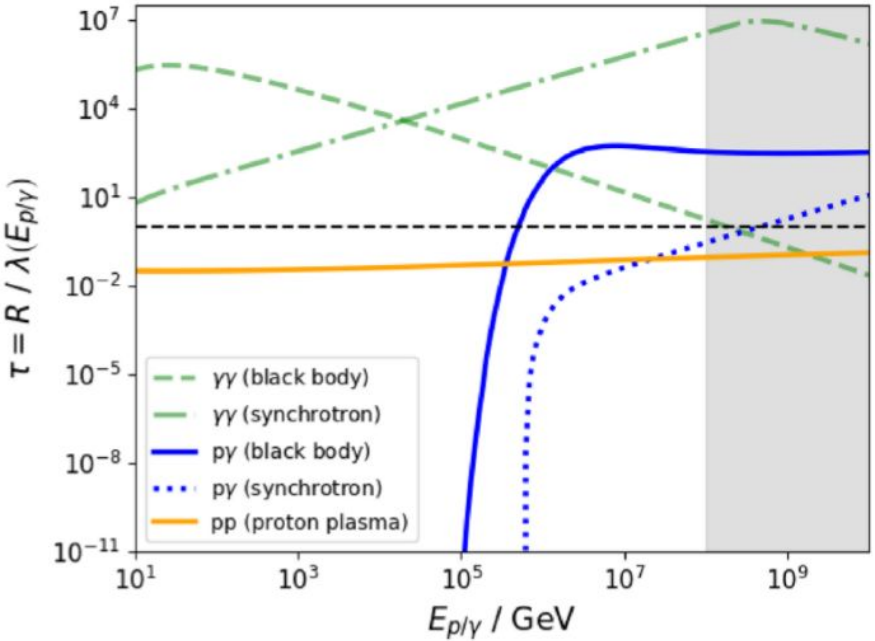
L. Morejon, et al, *JCAP* 11 (2019) 007

L. Morejon, K.H.Kampert *PoS* ICRC2023 (2023) 285

Bursting Sources of UHECRs

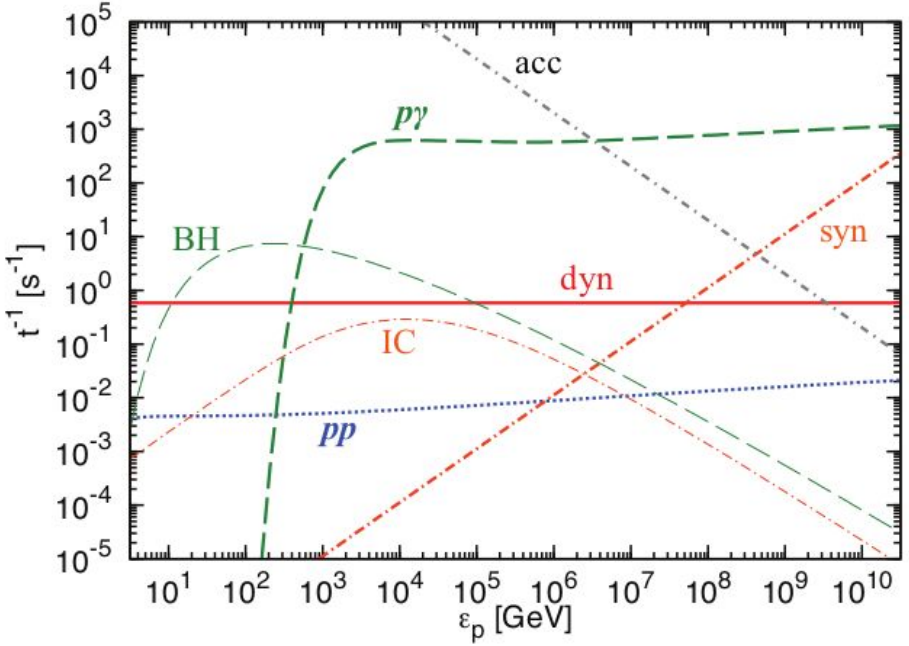
Necessity of simulating both **p-p** and **p-γ** interactions consistently!

AGNs plasmoids



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

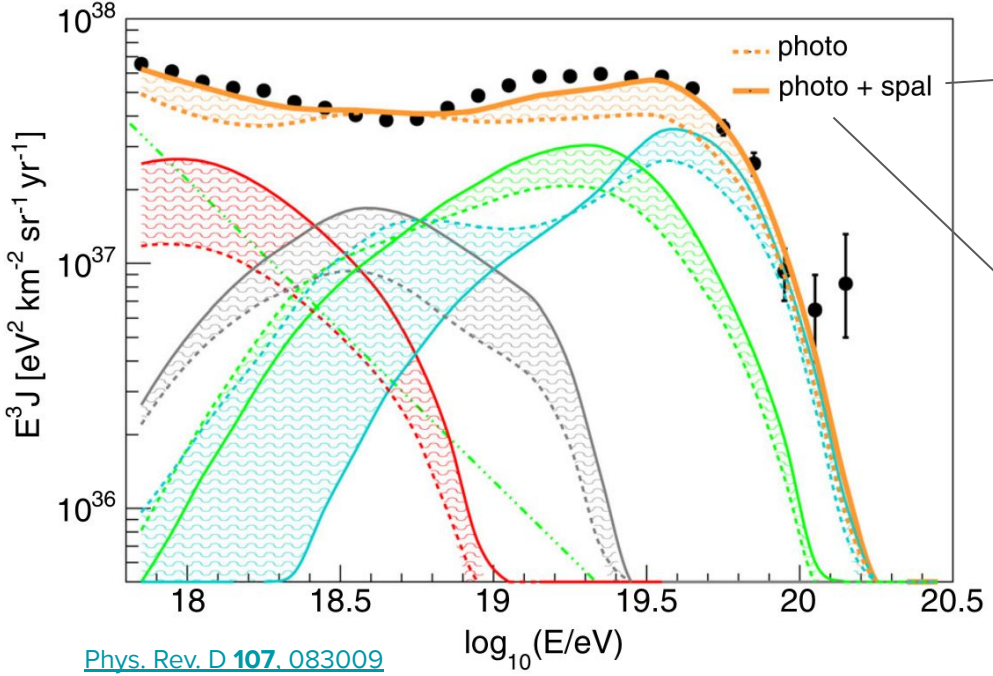
Choked GRBs



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

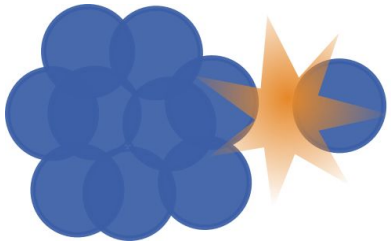
Relevance in UHECRs and VHE neutrinos

UHECRs from Starburst Galaxies

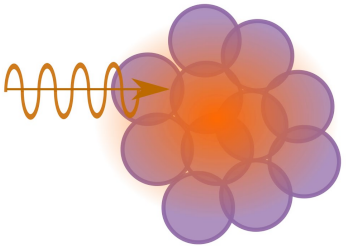


Phys. Rev. D **107**, 083009

Hadronic

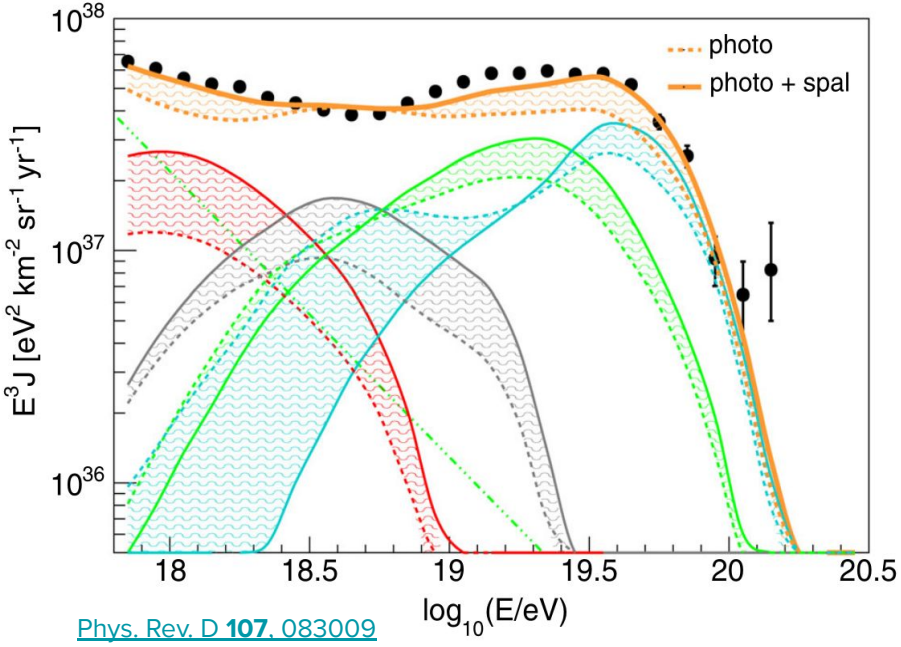


Photohadronic

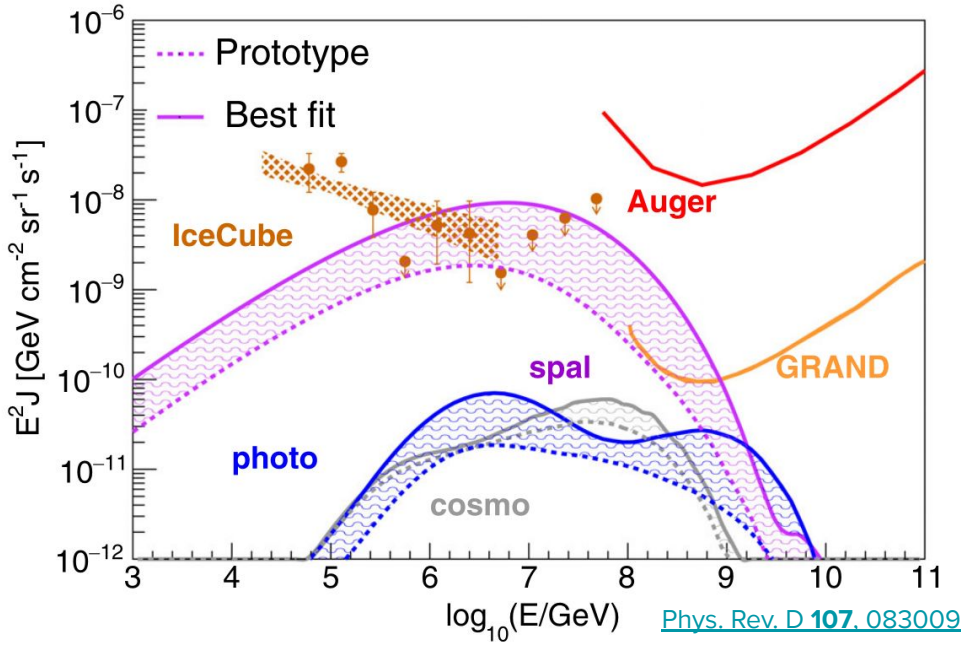


Relevance in UHECRs and VHE neutrinos

UHECRs from Starburst Galaxies -> Hadr. interactions enhance neutrinos!



Phys. Rev. D **107**, 083009



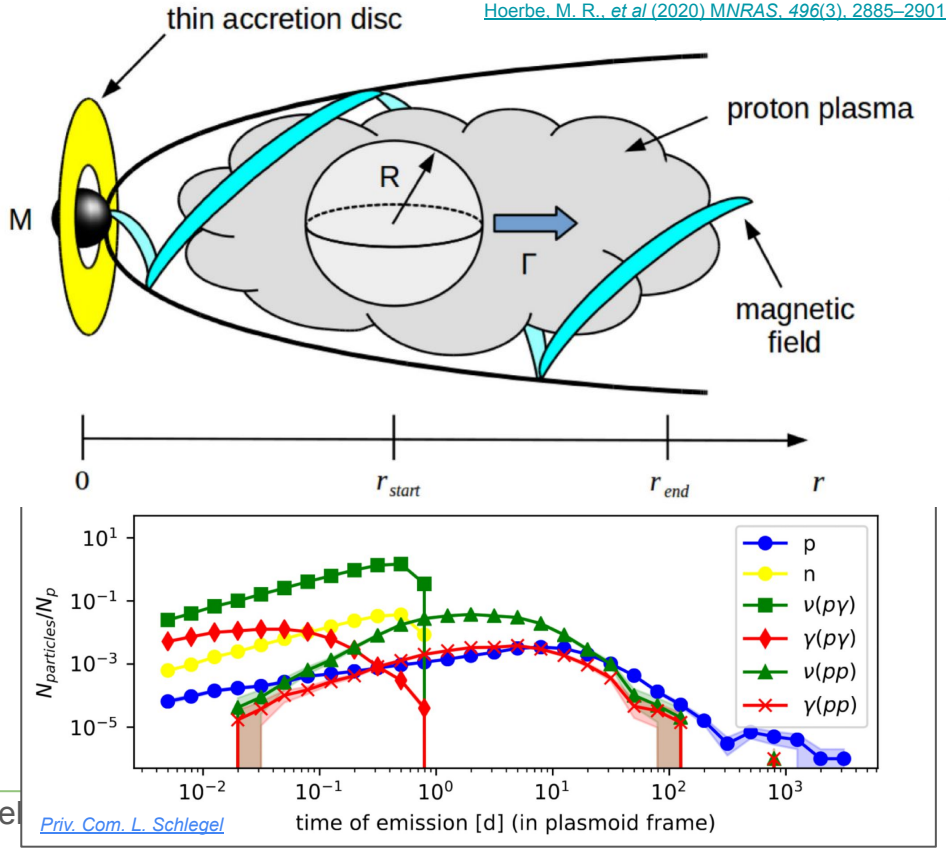
Phys. Rev. D **107**, 083009

Previous works

Example in AGNs

- Plasmoid emission as it moves
- Variable target photon fields
- Photomeson interactions
- **Hadronic Interactions**

Time dependent spectra of secondaries



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

Priv. Com. L. Schlegel

Brief words about CRPropa

CRPropa 3.2 … JCAP 2022 (09) 035

CRPropa

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

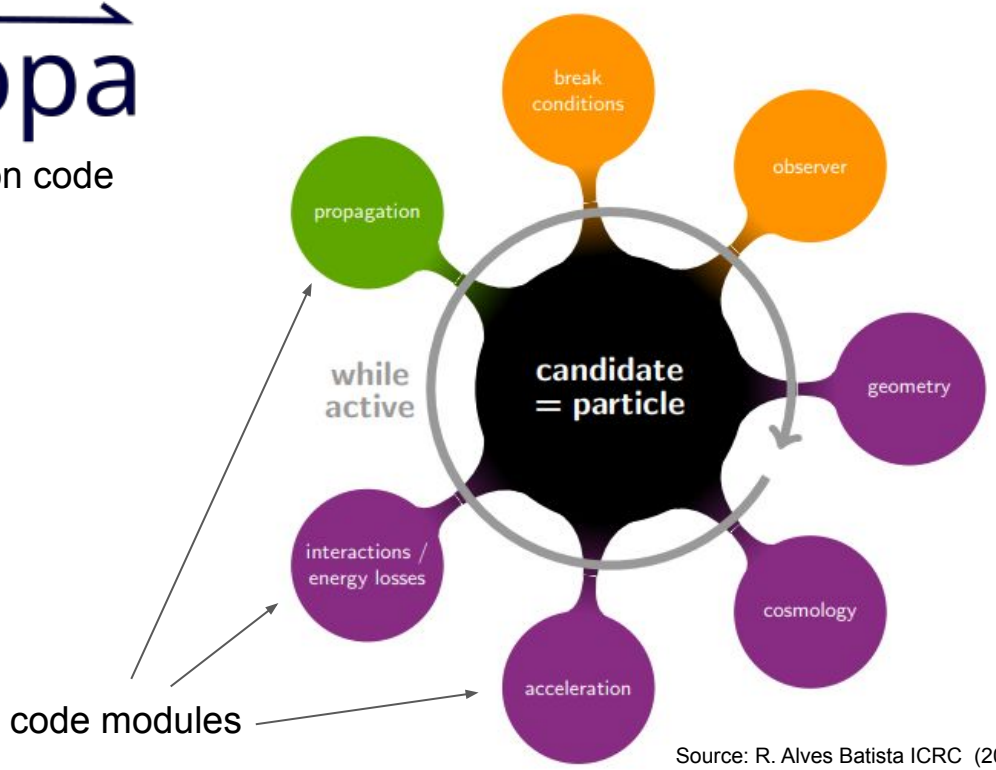
Brief words about CRPropa

CRPropa 3.2 … JCAP 2022 (09) 035

CRPropa

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

- Modular structure



Source: R. Alves Batista ICRC (2021)

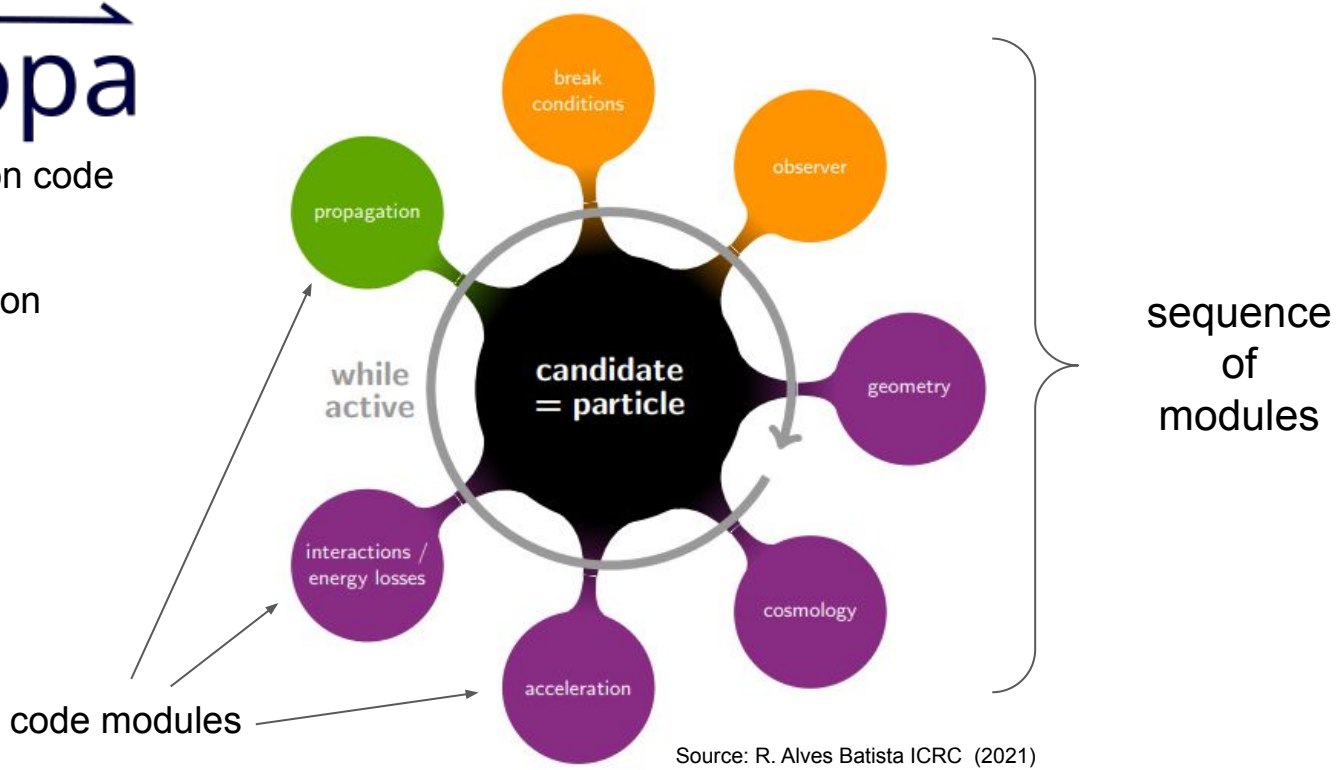
Brief words about CRPropa

CRPropa 3.2 … JCAP 2022 (09) 035

CRPropa

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

- Modular structure
- Interactive simulation



Source: R. Alves Batista ICRC (2021)

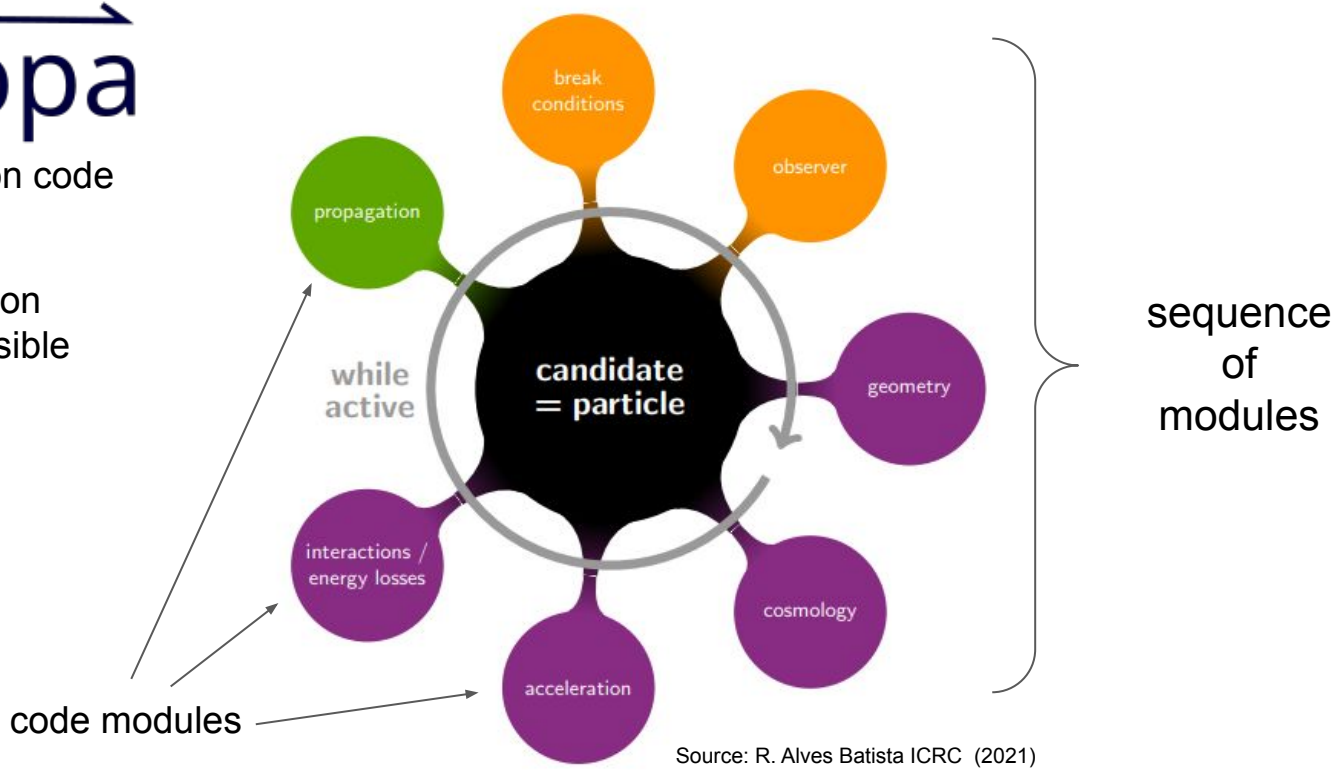
Brief words about CRPropa

CRPropa 3.2 … JCAP 2022 (09) 035

CRPropa

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

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



Source: R. Alves Batista ICRC (2021)

Brief words about CRPropa

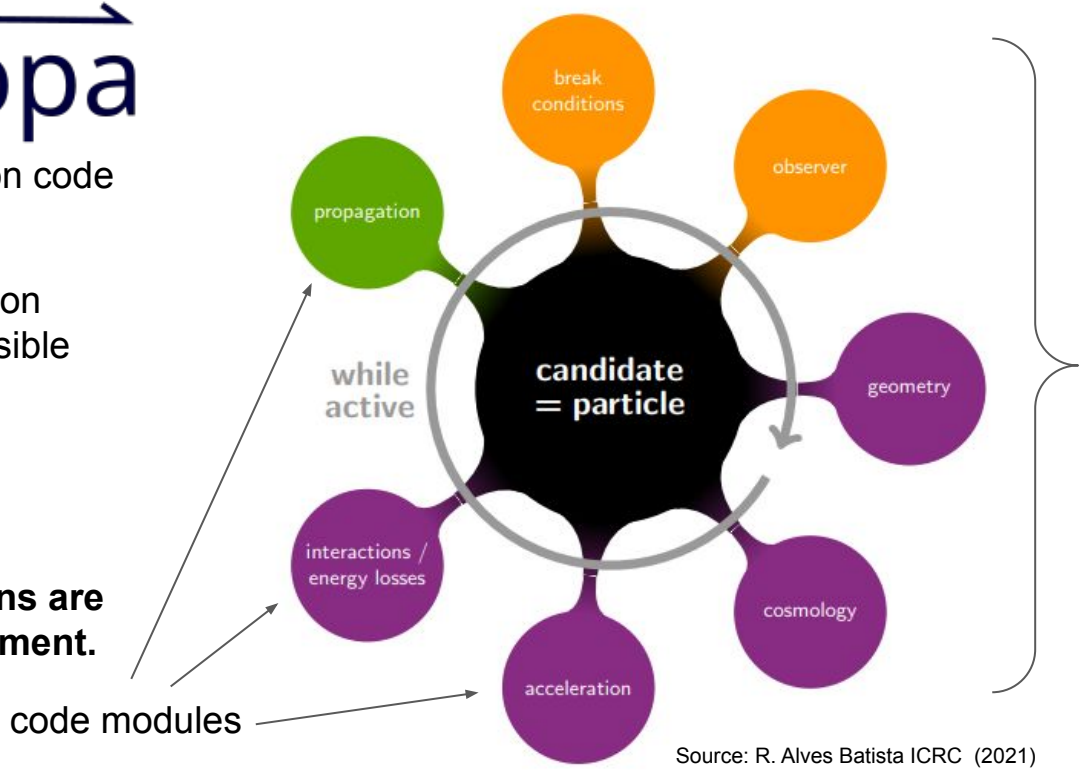
CRPropa 3.2 … JCAP 2022 (09) 035

CRPropa

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

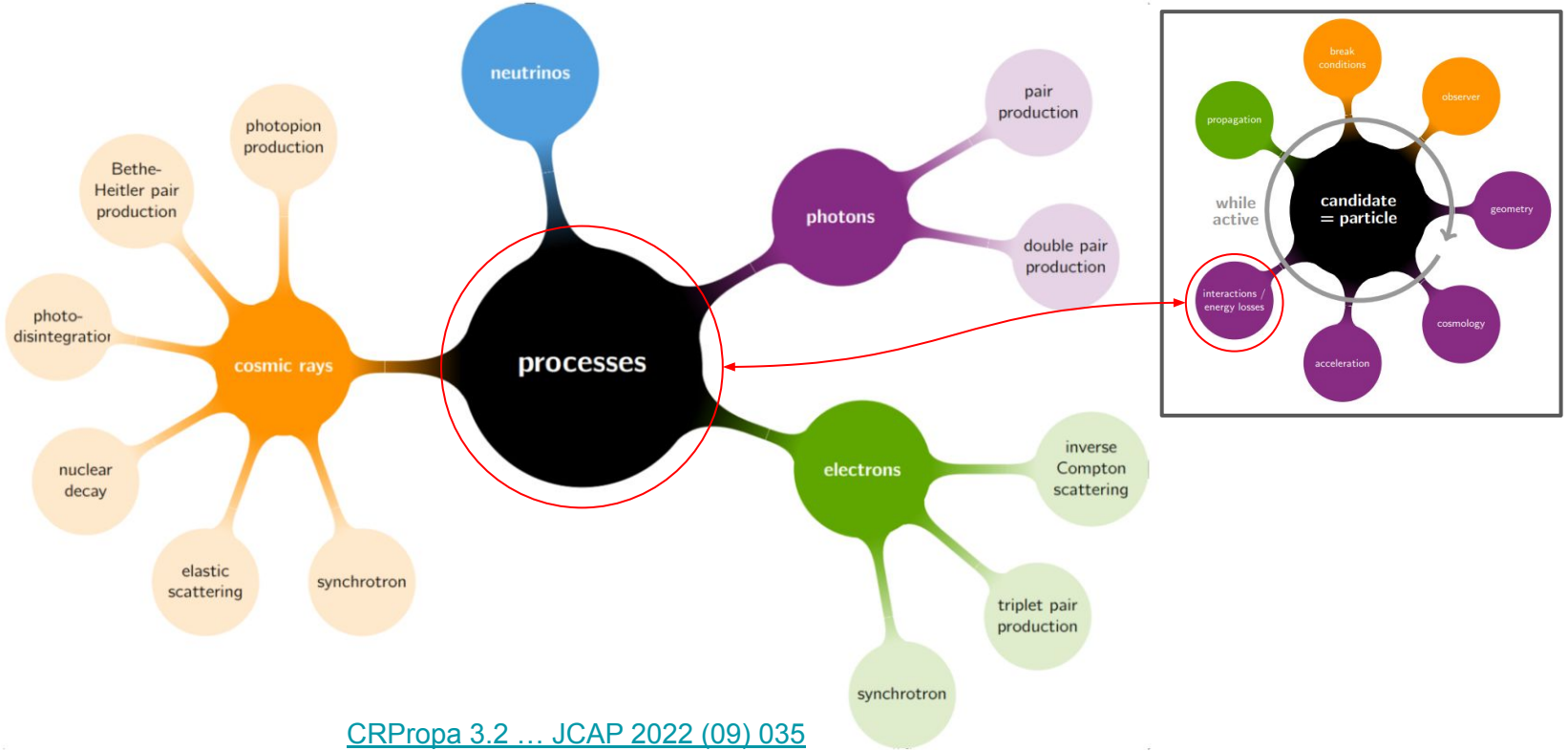
- Modular structure
- Interactive simulation
- Flexible and extensible
- **Python interface**

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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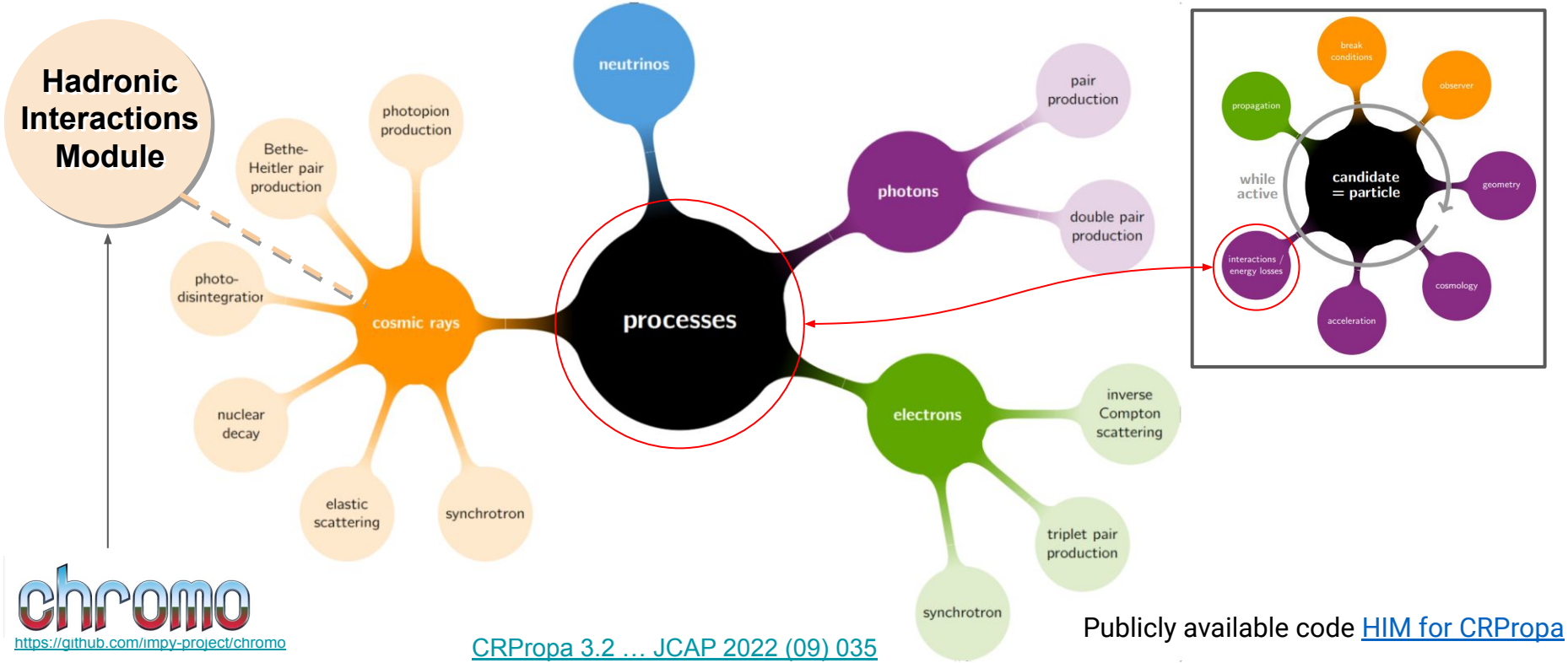

chromo
https://github.com/impy-project/chromo

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Publicly available code HIM for CRPropa

Elements of the HIM

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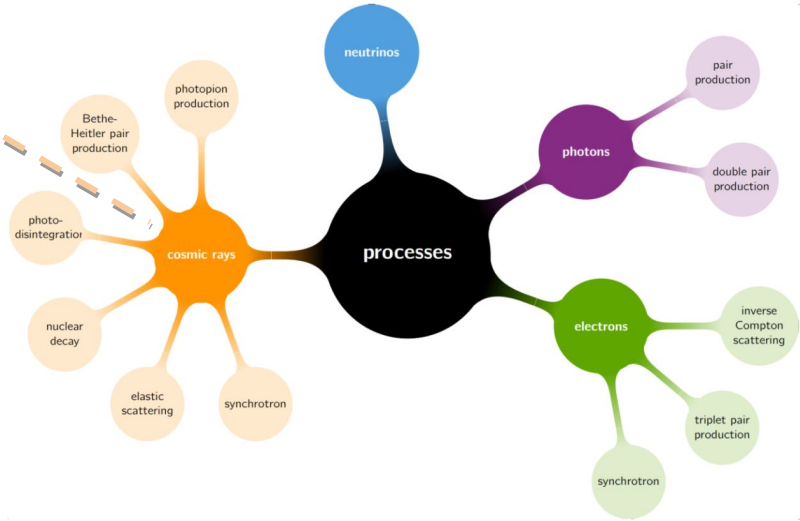
- Sample hadr. interaction
- Produce input params.
- Call to external codes:
  - EPOS-LHC, SIBYLL, QGSJet, DPMJET, etc.
- Collect secondaries
- Transform btw. frames

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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- Sample hadr. interaction
- Produce input params.
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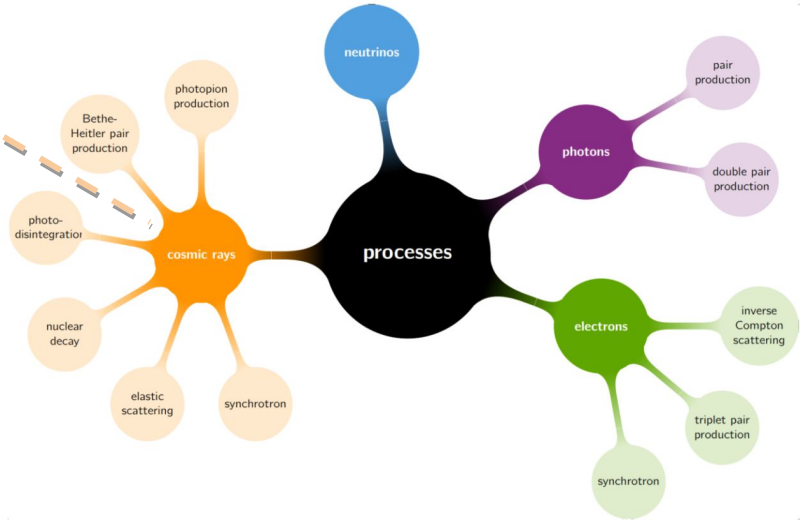


https://github.com/impy-project/chromo

chromo

Cosmic ray and HadROnic interactiOn MOnte-carlo frontend

HIM's inner workings

Interface: CHROMO

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

https://github.com/impy-proje

chromo

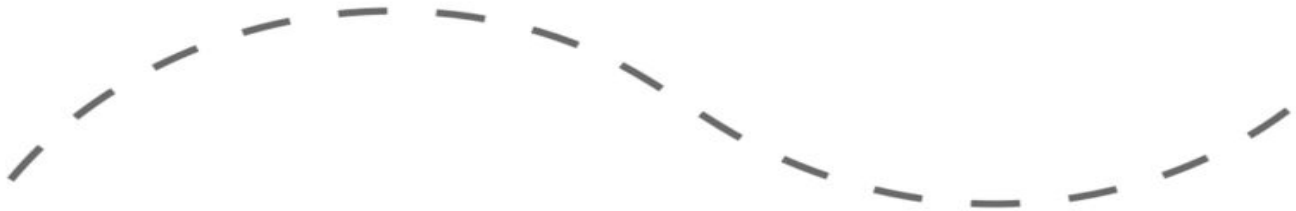
Cosmic ray and HadROnic interactiOn MOnte-ca frontend

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

CRPropa propagation + HIM

- **Propagation module**
  computes trajectory



CRPropa propagation + HIM

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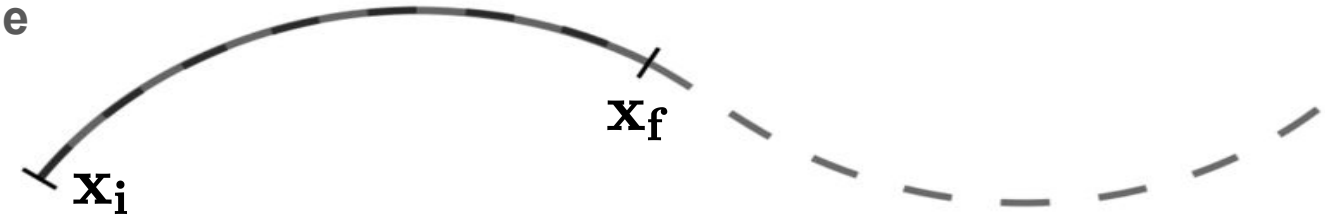
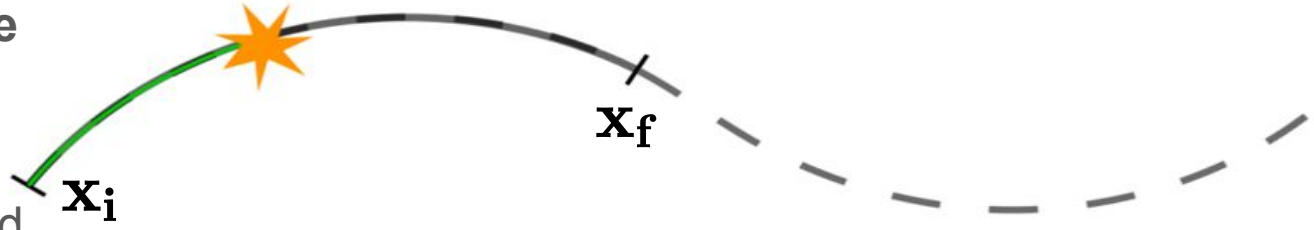


CRPropa propagation + HIM

- **Propagation module** computes trajectory
- **HIM** samples an interaction step based on the cross section



$$s_r = -\frac{\log r}{\sigma\rho}$$

Interaction rate and step sampling

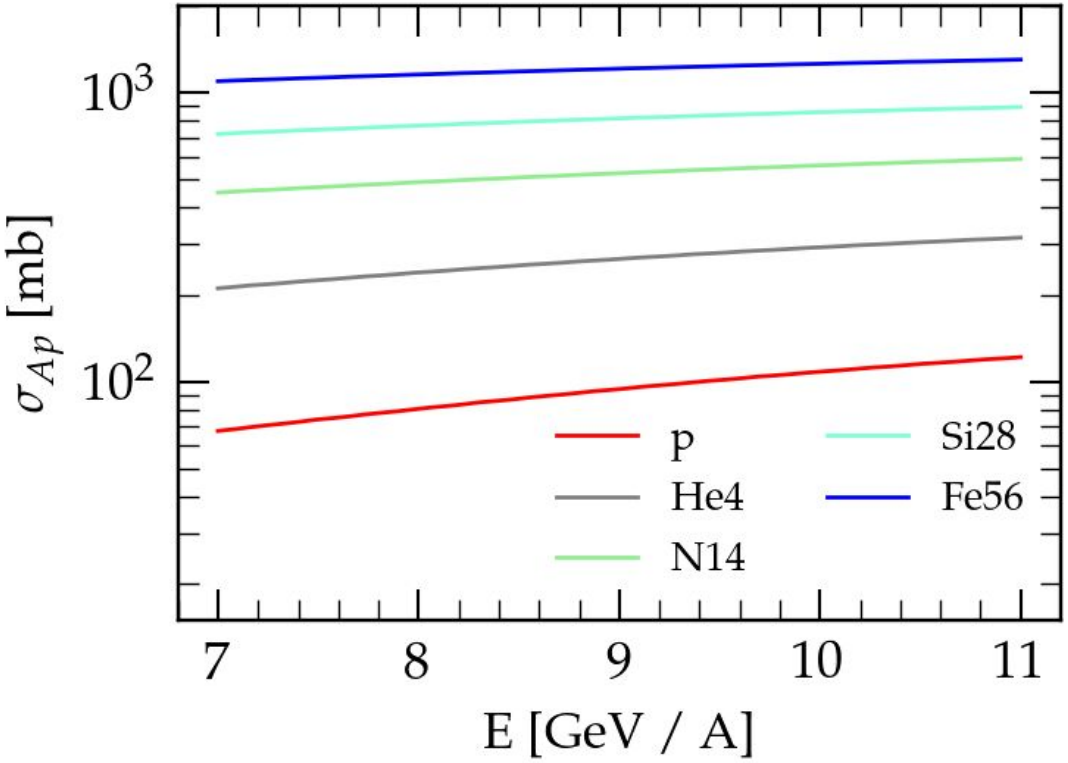
The interaction step is sampled as

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

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

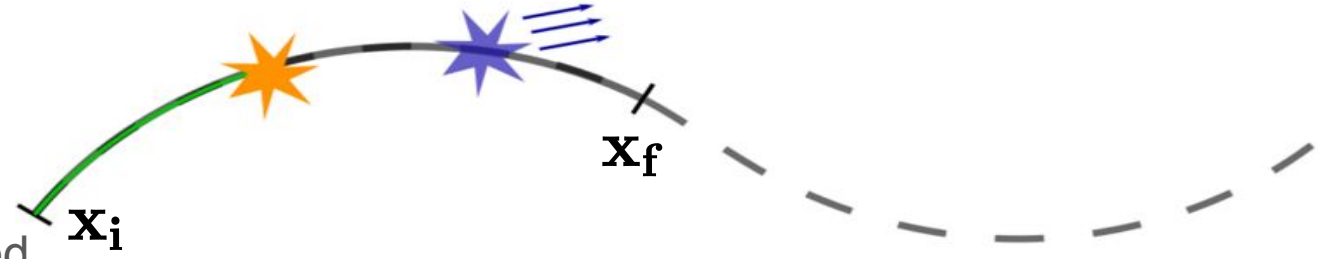
Hadronic Generators are sampled for the cross section.

Alternatively, pretabulated values.

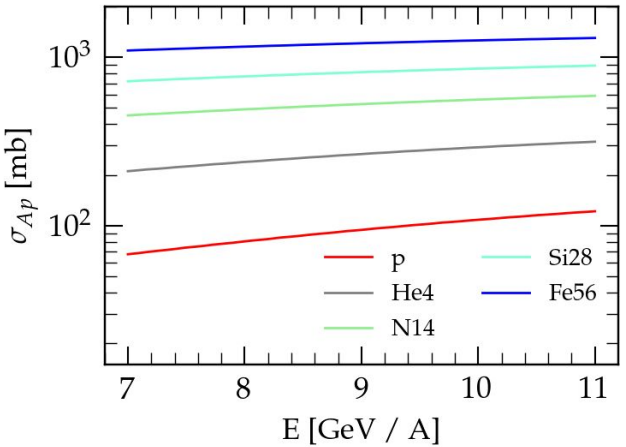


CRPropa propagation + HIM

- Propagation module computes trajectory
- **HIM** samples an interaction step based on the cross section
- Call to HI generator

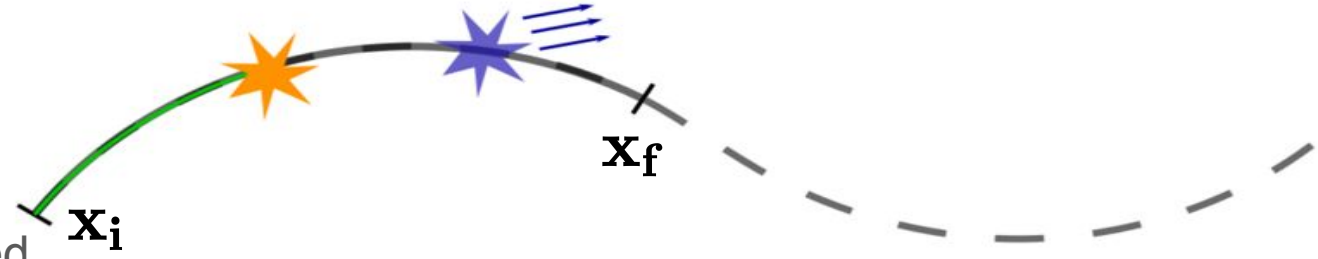


$$s_r = -\frac{\log r}{\sigma\rho}$$

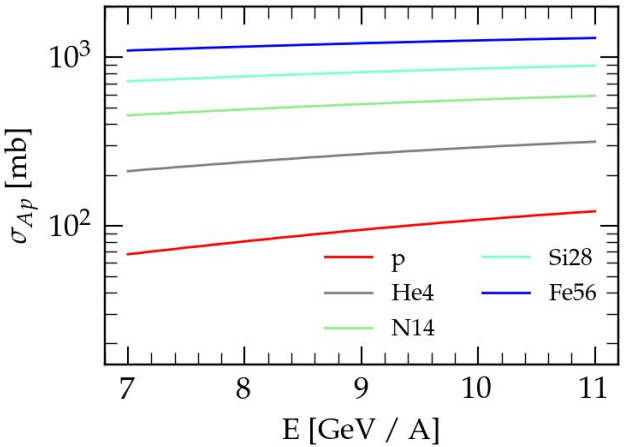


CRPropa propagation + HIM

- Propagation module computes trajectory
- **HIM** samples an interaction step based on the cross section
- Call to HI generator
- Introduce secondaries
- Modify primary particle
- Repeat



$$s_r = -\frac{\log r}{\sigma\rho}$$



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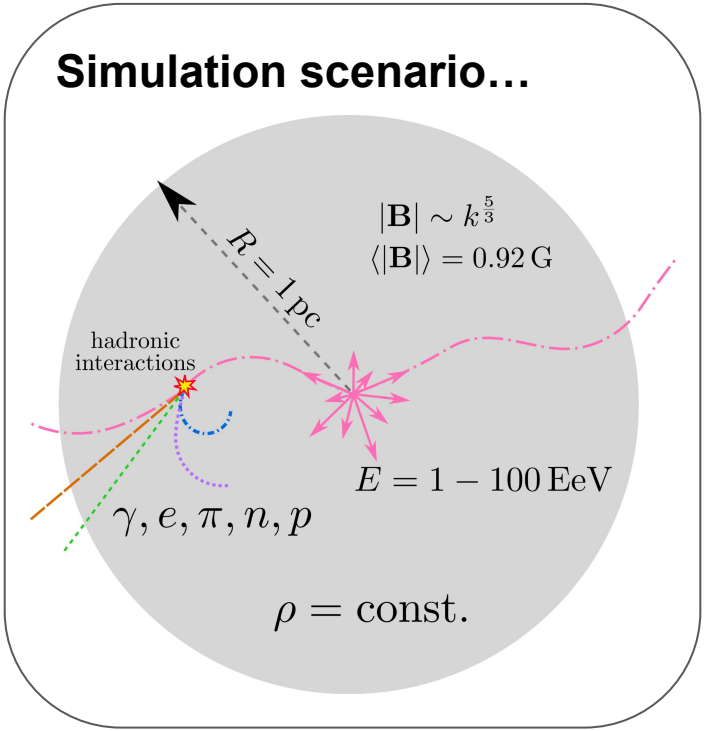
Typical simulation scenario



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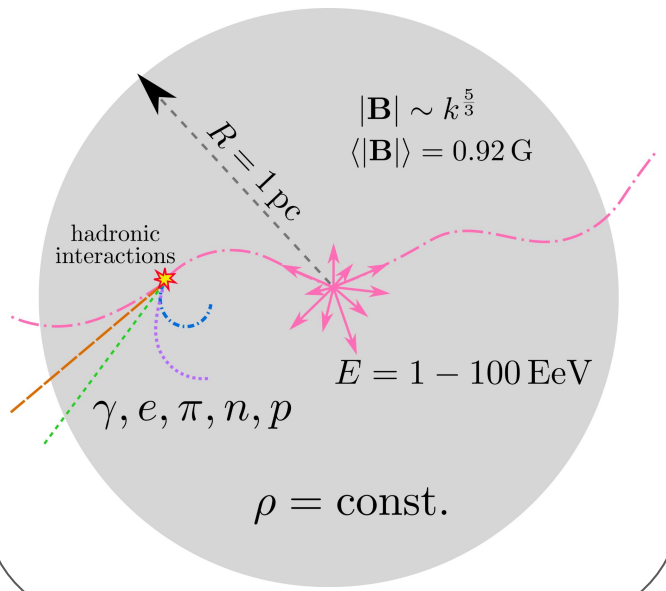
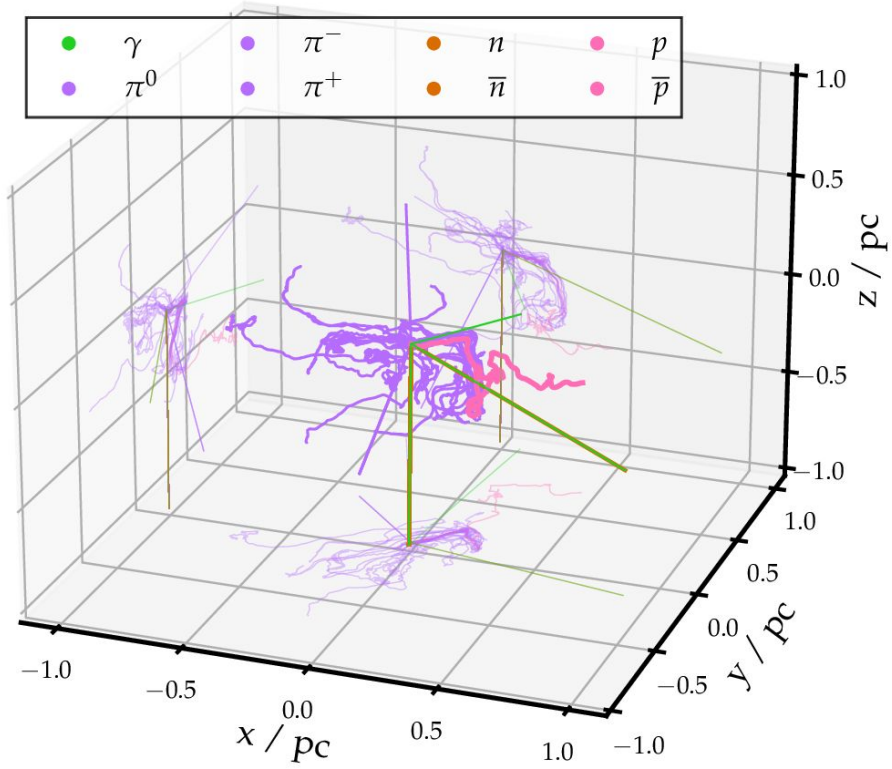
Typical simulation scenario

Simulation scenario…





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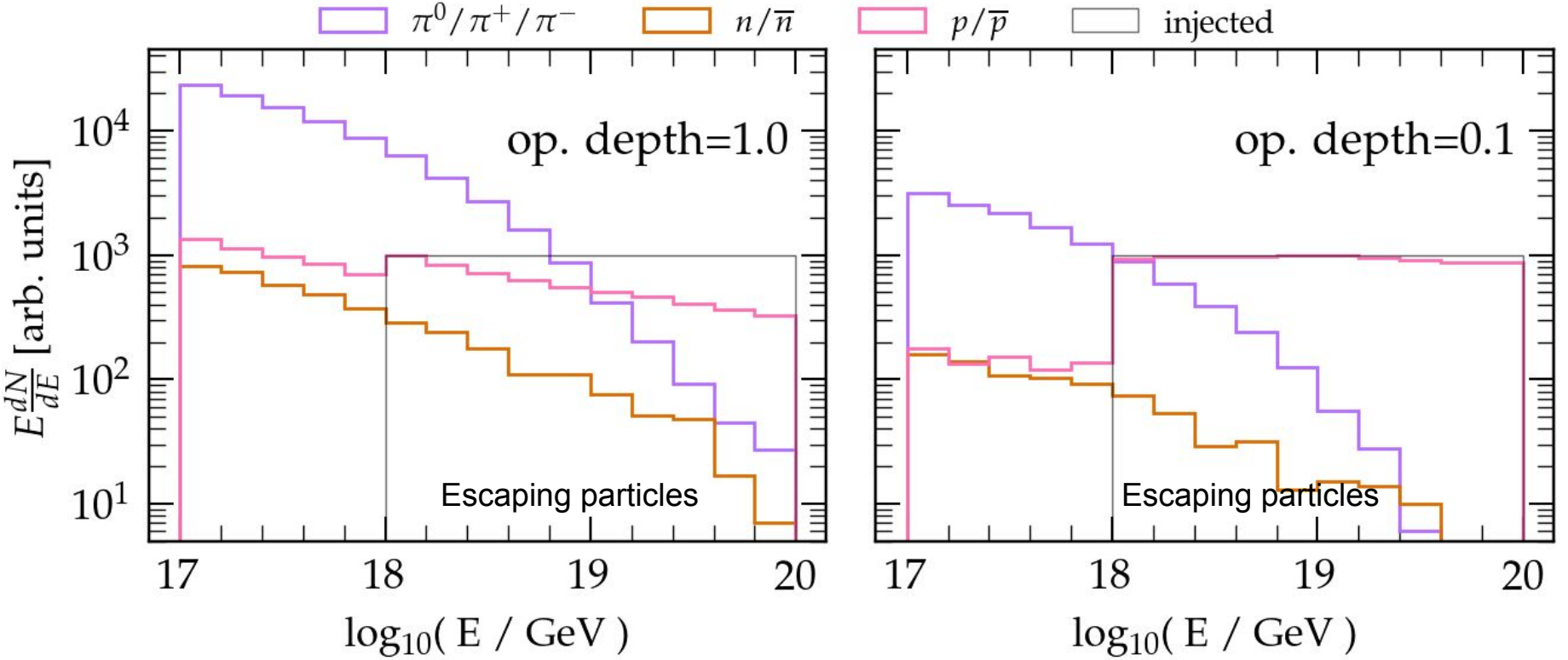
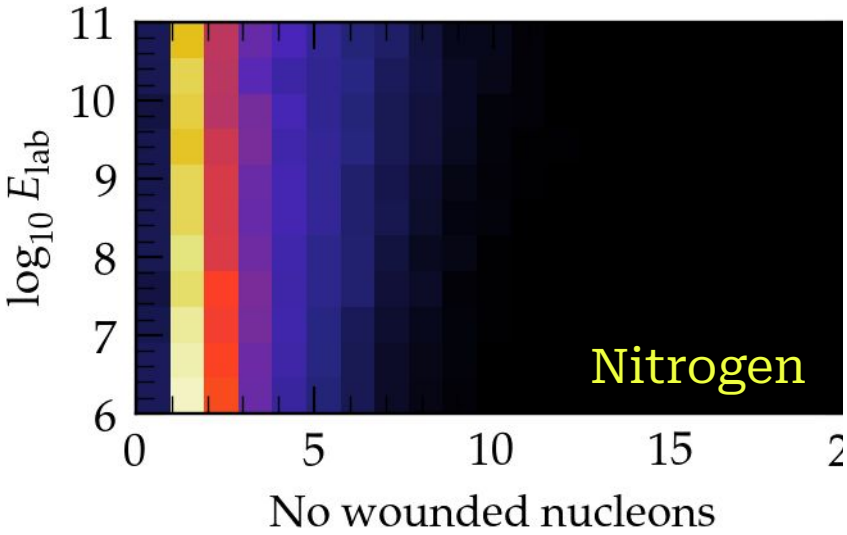
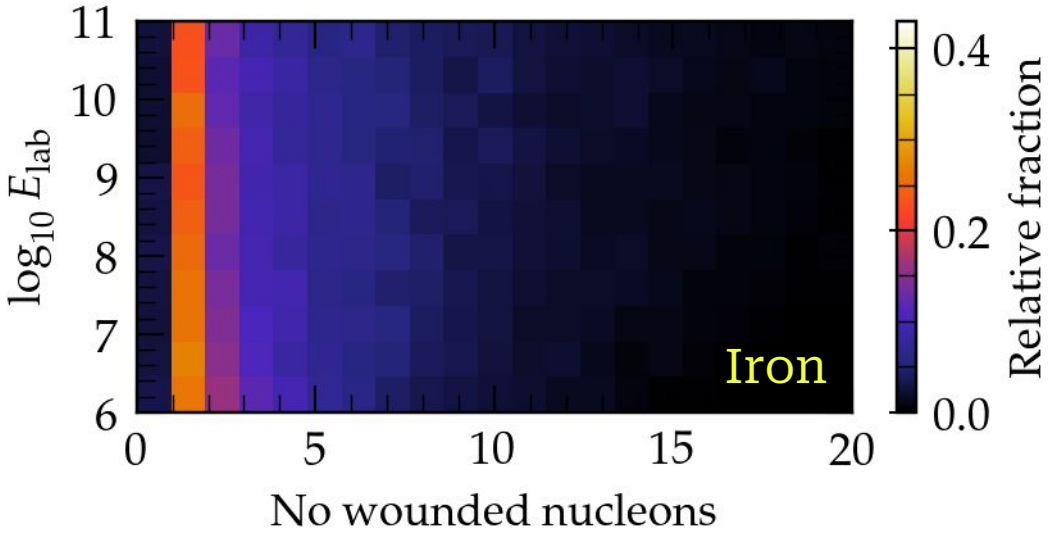
Example: proton propagation (no magnetic fields)



Nuclear fragments production

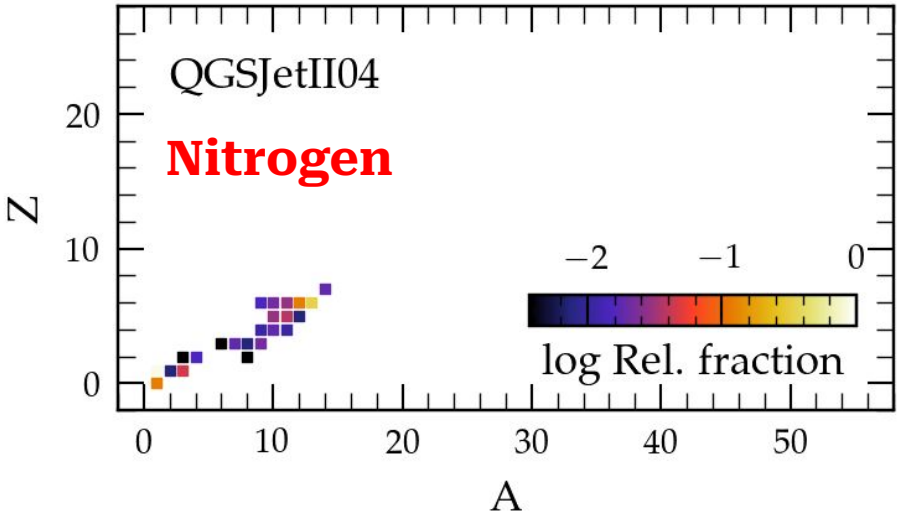
- Fragment choice from wounded nucleons (no fragments in chromo v0.5.1)
- Remnant mass used to choose randomly the nuclear species

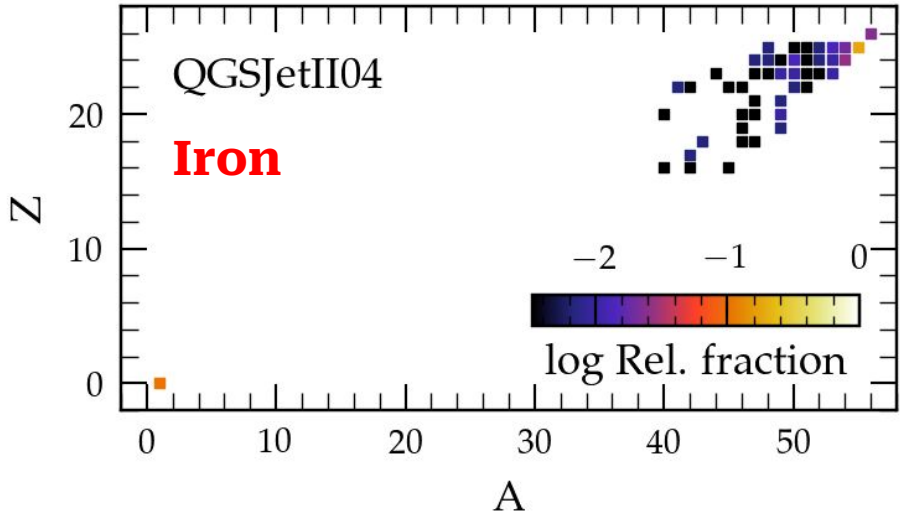




Fragment distributions

- Fragment choice from wounded nucleons (no fragments in chromo-0.5.1)
- Remnant mass used to choose randomly the nuclear species





Example: 4He injection (Magn. Field OFF)

Example: 14N injection (Magn. Field OFF)

J. Dörner, *LM et al.* (in preparation)

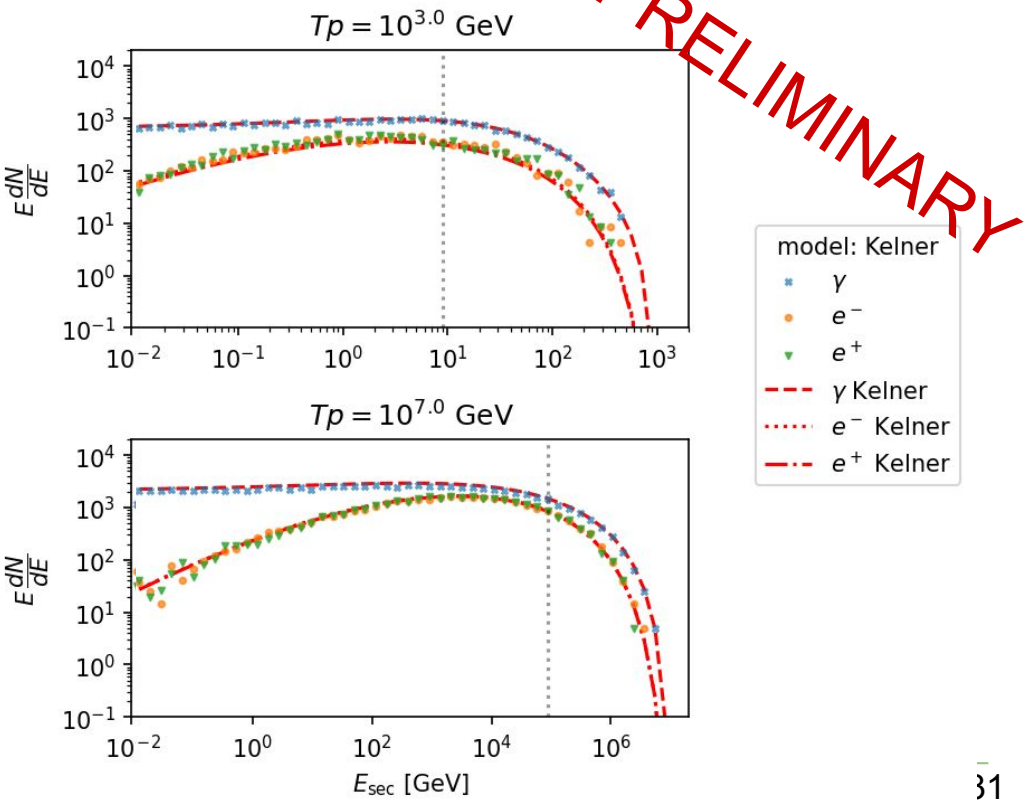
Alternative approach: sampling from precomp. tables / fits

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

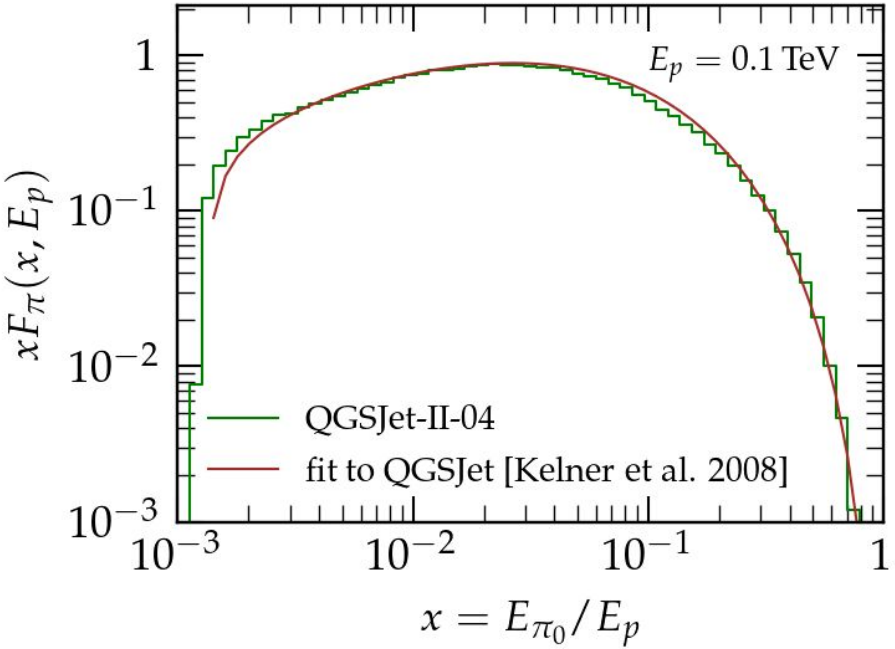
Pros and Cons

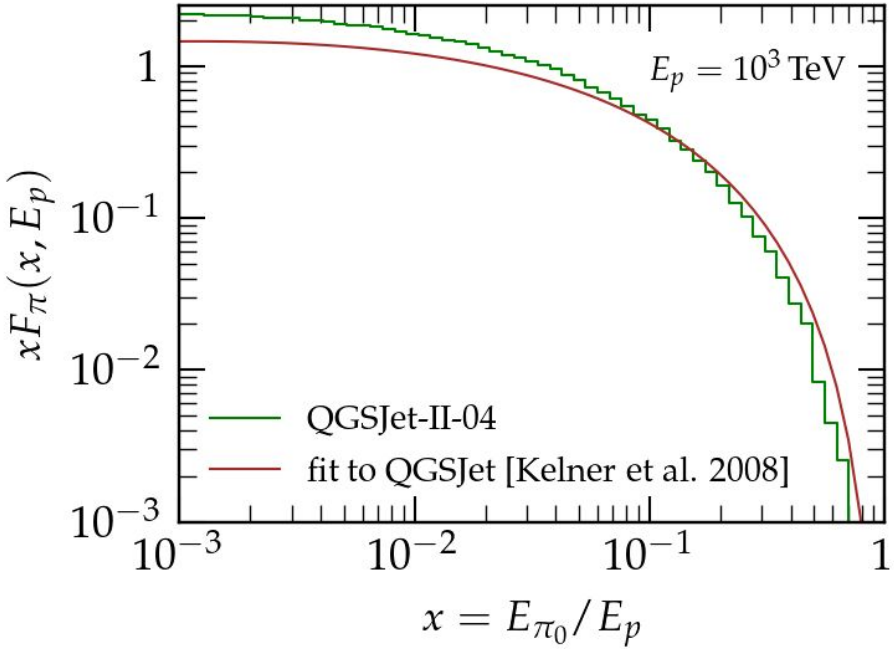
\+ More efficient
\+ Final state products
\+ Many secondaries of interest
\- Production channels non-separable
\- Limited interaction partners



Comparison between approaches

Neutral pion production: HIM vs sampling from tables





MultI-messenger probe of Cosmic Ray Origins

Participating institutions

Funded by:

MICRO website

HIM @ github

MICRO website

HIM @ github

Additional slides

Interaction rate and step sampling

The interaction step is sampled as

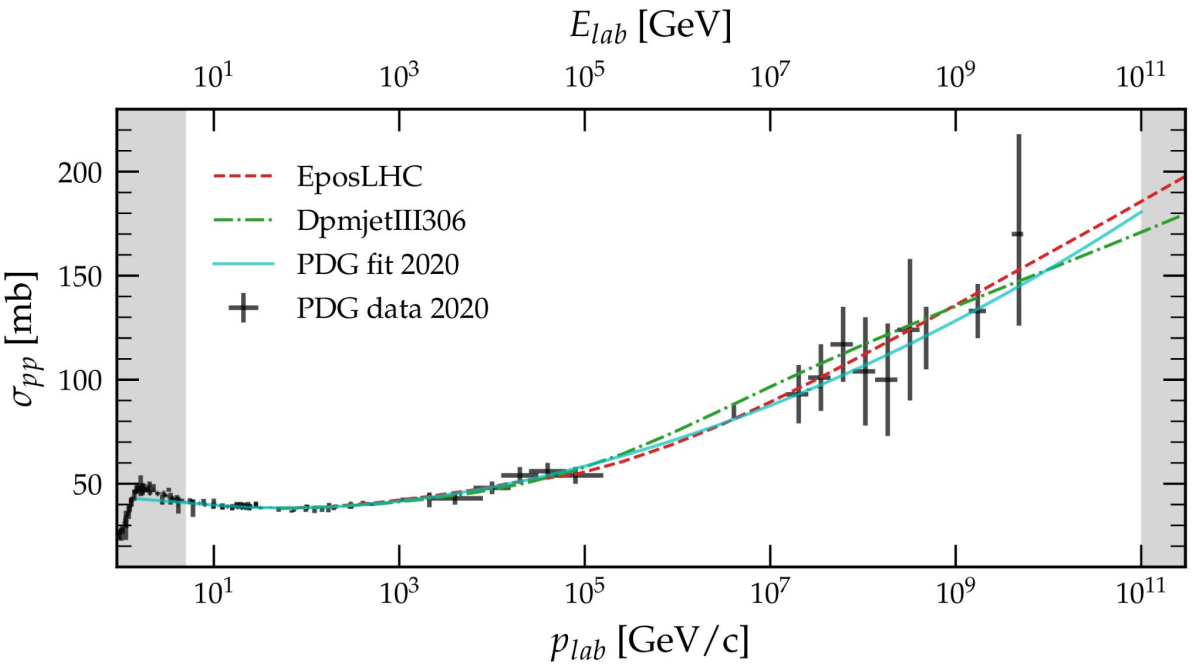
$$d = -\frac{\log p}{\sigma \rho}$$

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



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* 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.

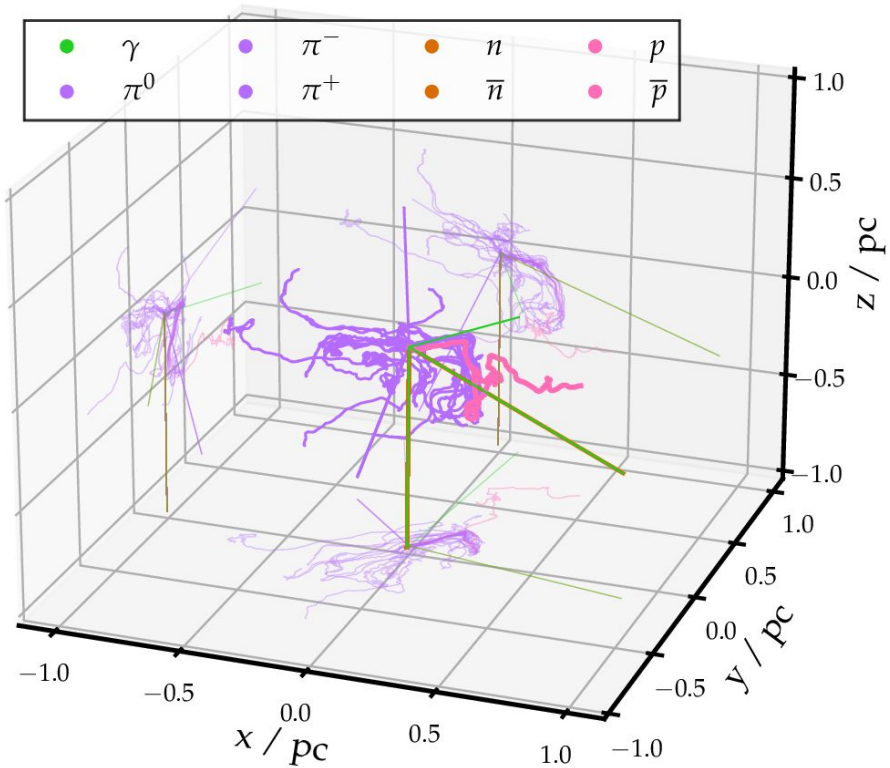
Additional random-seed settings

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**

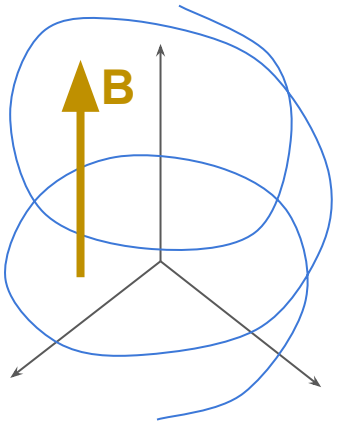


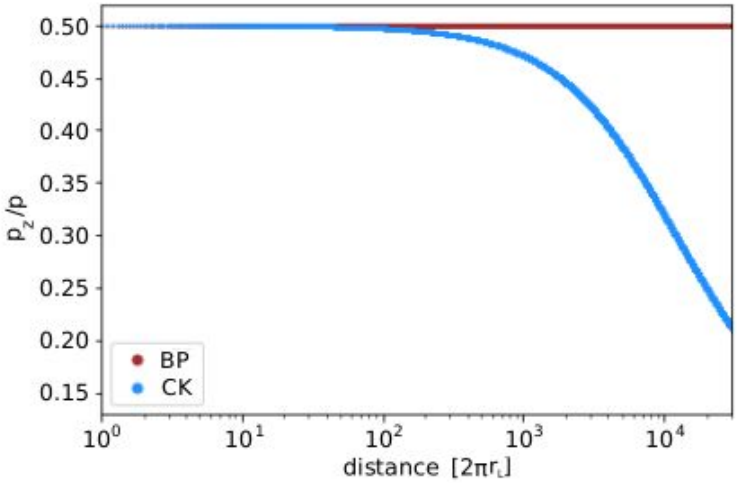
Ballistic propagation with **magnetic fields**

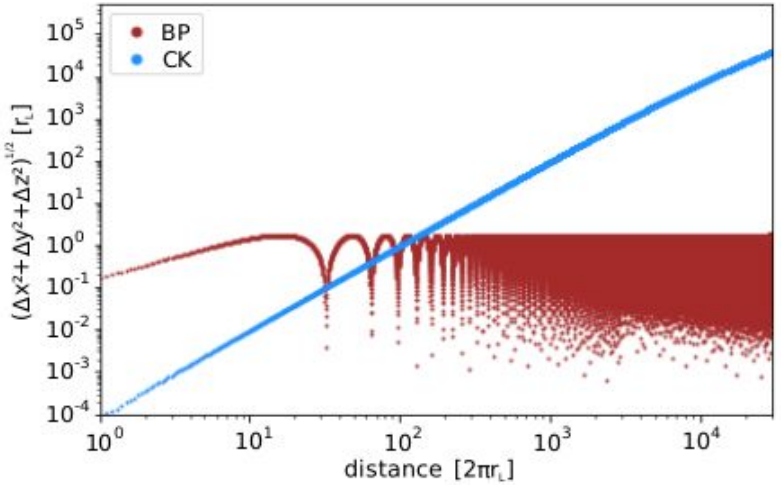
CRPropa 3.2 … JCAP 2022 (09) 035

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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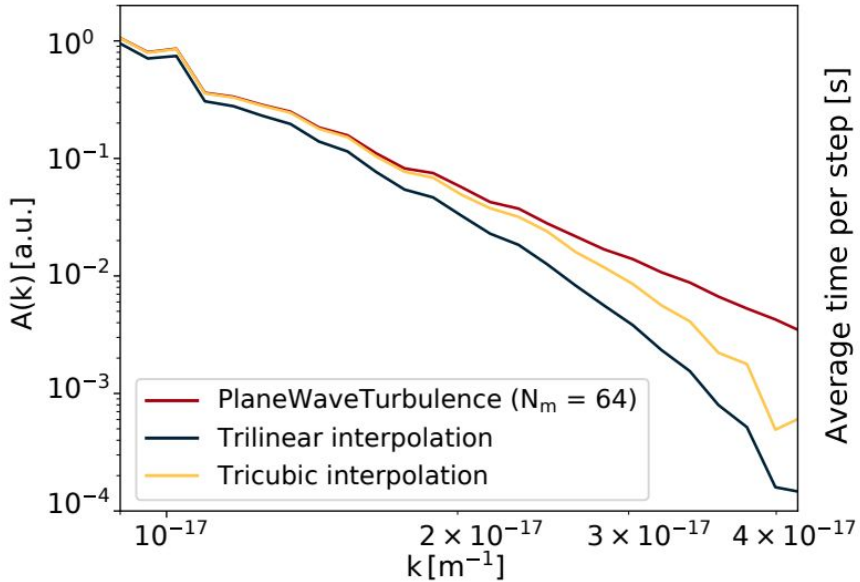
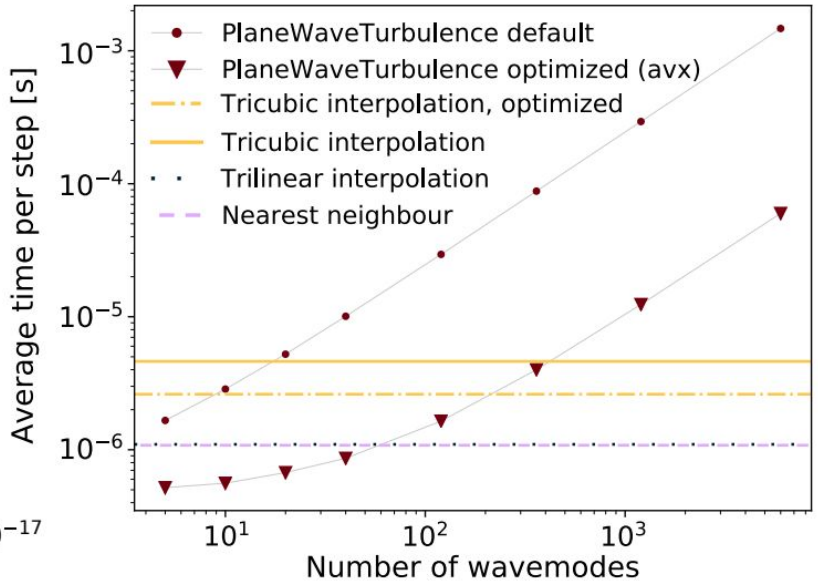
Enhanced interpolation of magnetic fields (grids)

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

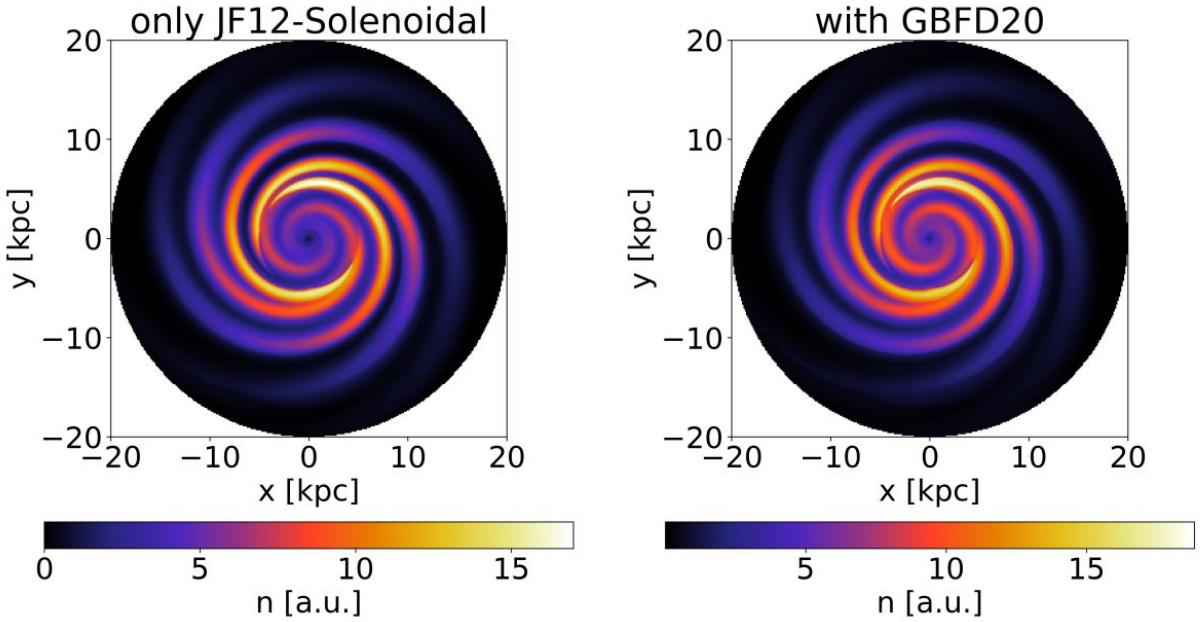
Matter densities

- 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



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EM cascade simulation

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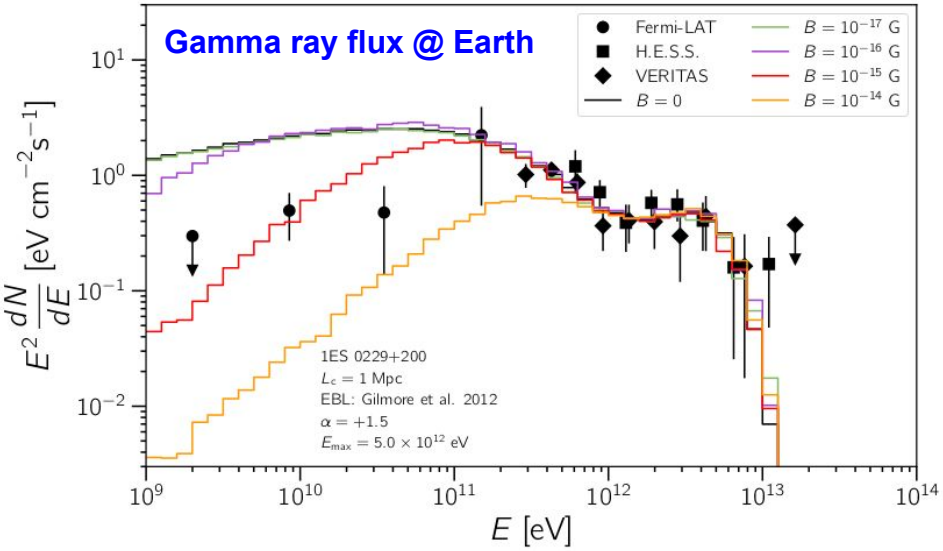
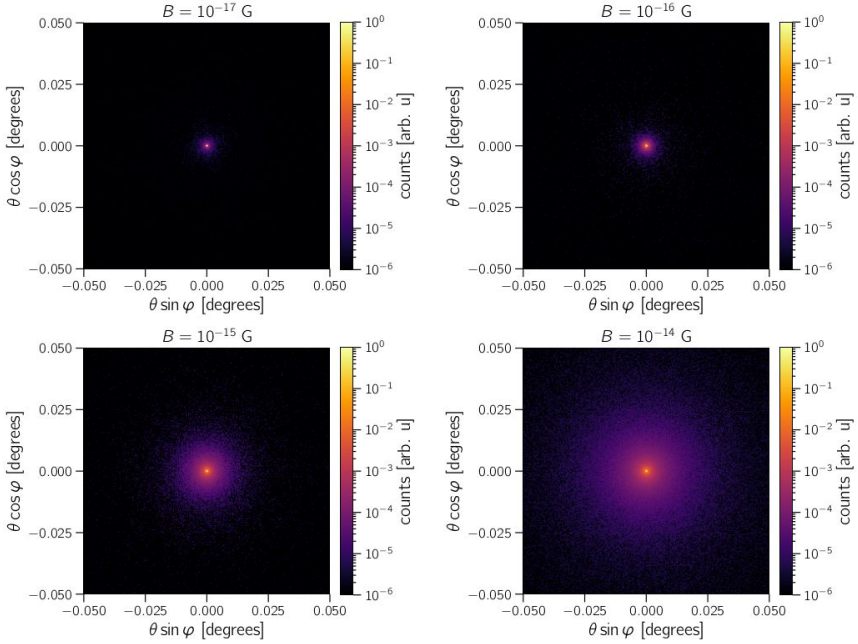
EM cascades in strong magnetic fields

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



Arrival directions of Gamma rays @ Earth



Example simulation (Magn. Field OFF)

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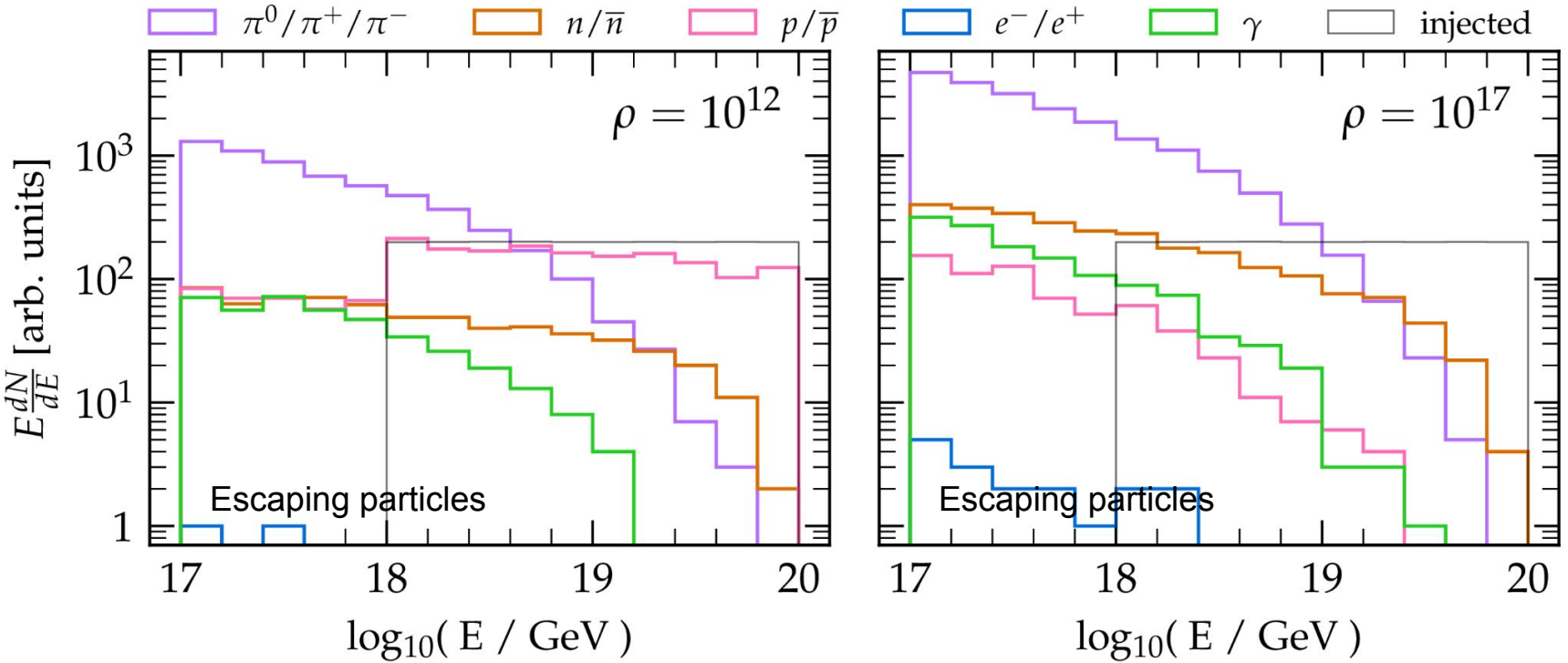
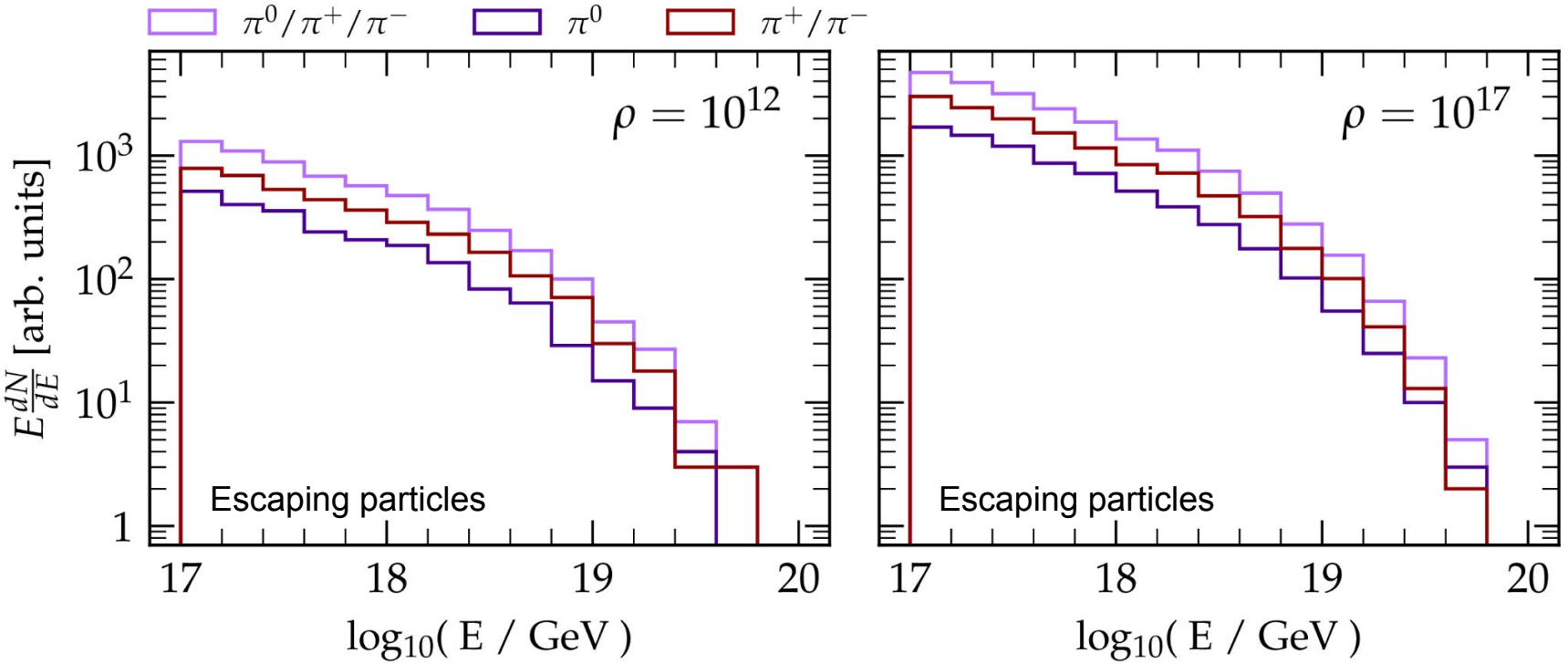


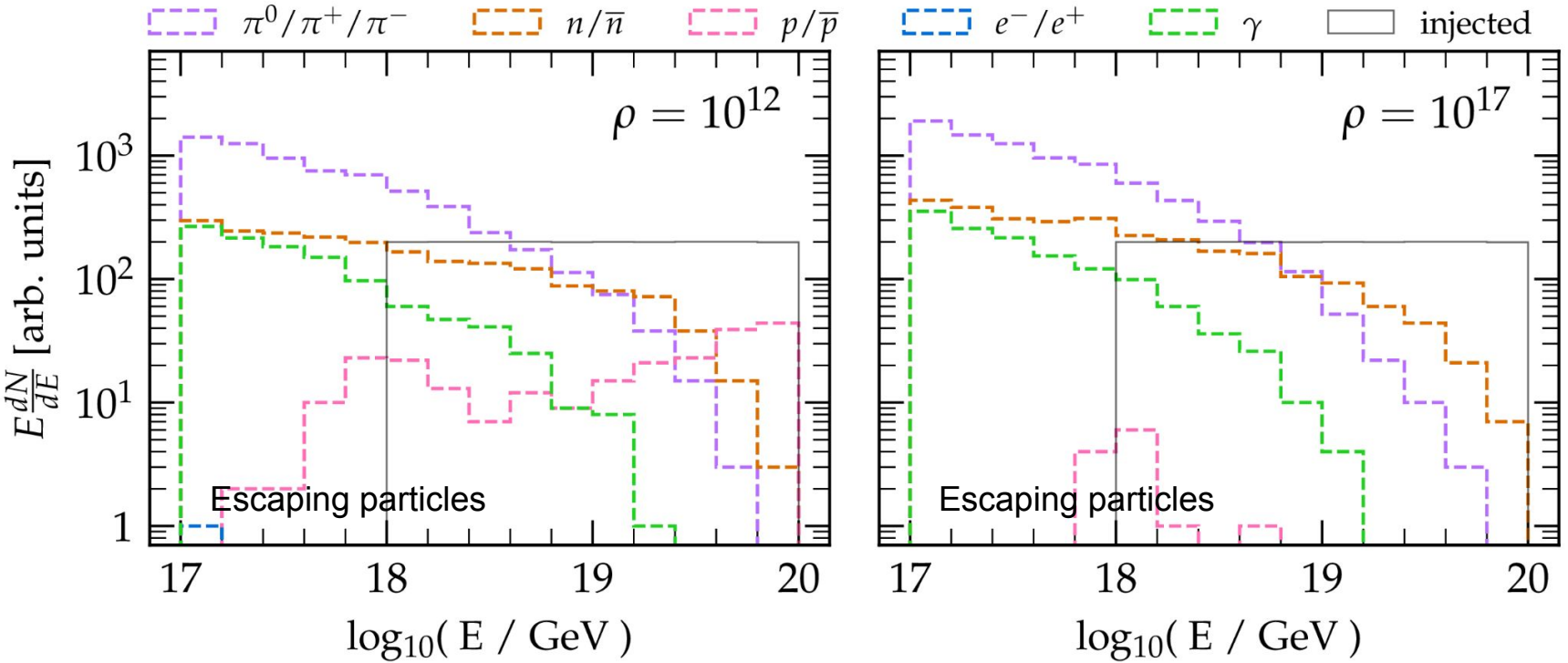
Example simulation (Magn. Field OFF)

L. Morejon, K.H.Kampert *PoS* ICRC2023 (2023) 285



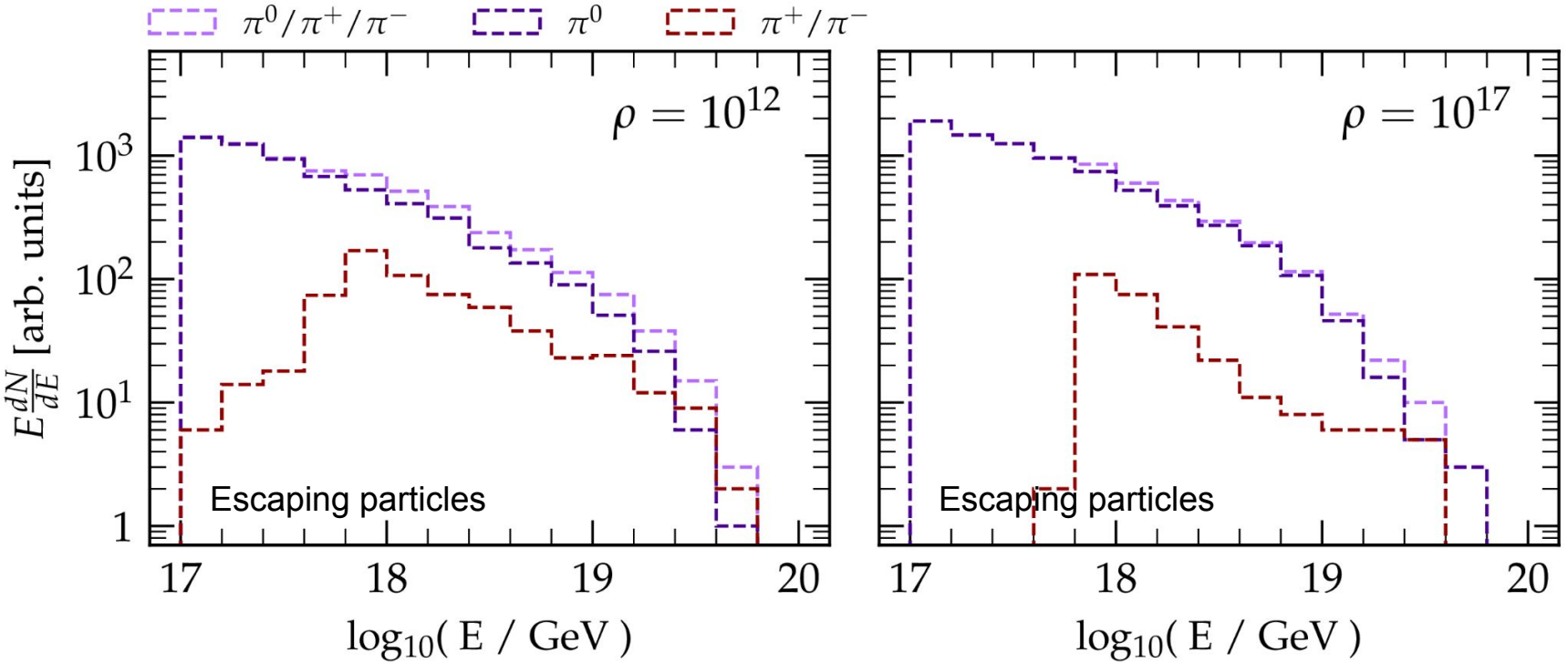
Example simulation (Magn. Field ON)

L. Morejon, K.H.Kampert *PoS* ICRC2023 (2023) 285



Example simulation (Magn. Field ON)

L. Morejon, K.H.Kampert *PoS* ICRC2023 (2023) 285



Magn. Field ON versus OFF

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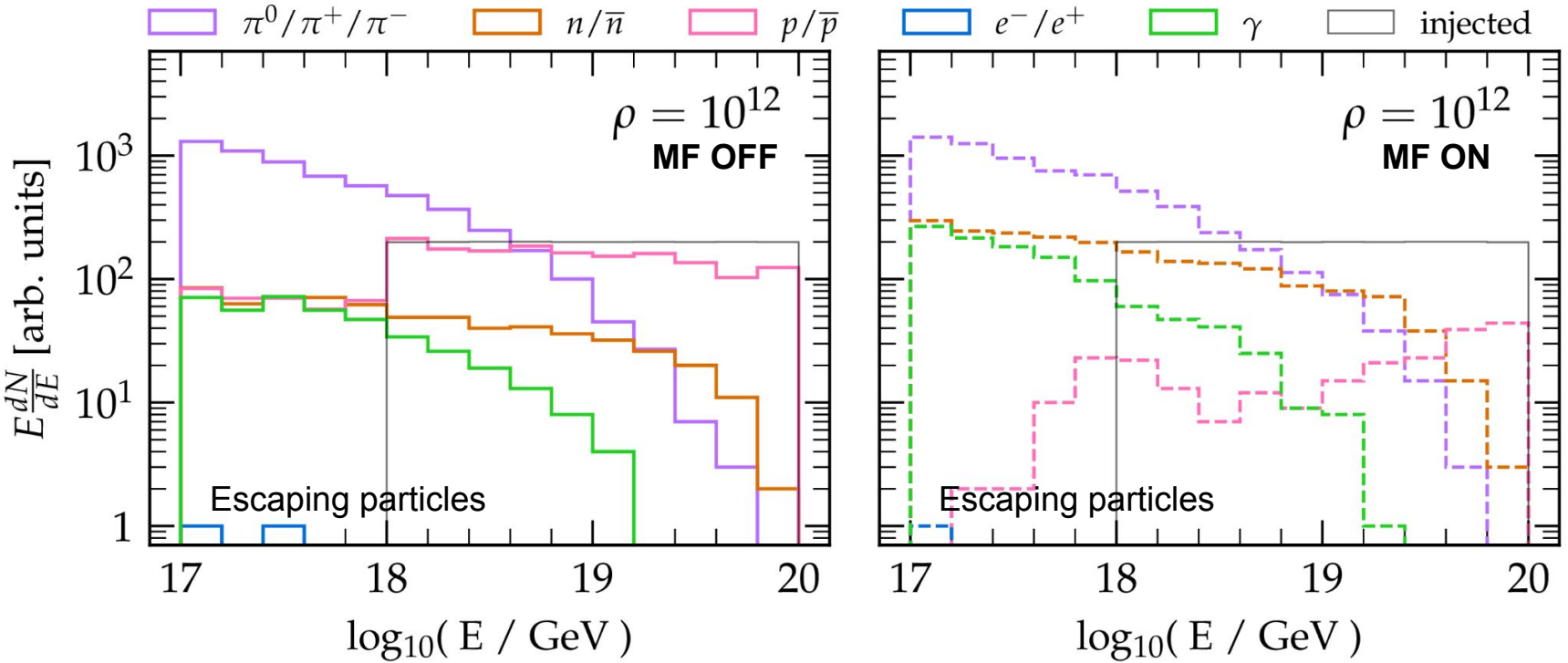

Magn. Field ON versus OFF

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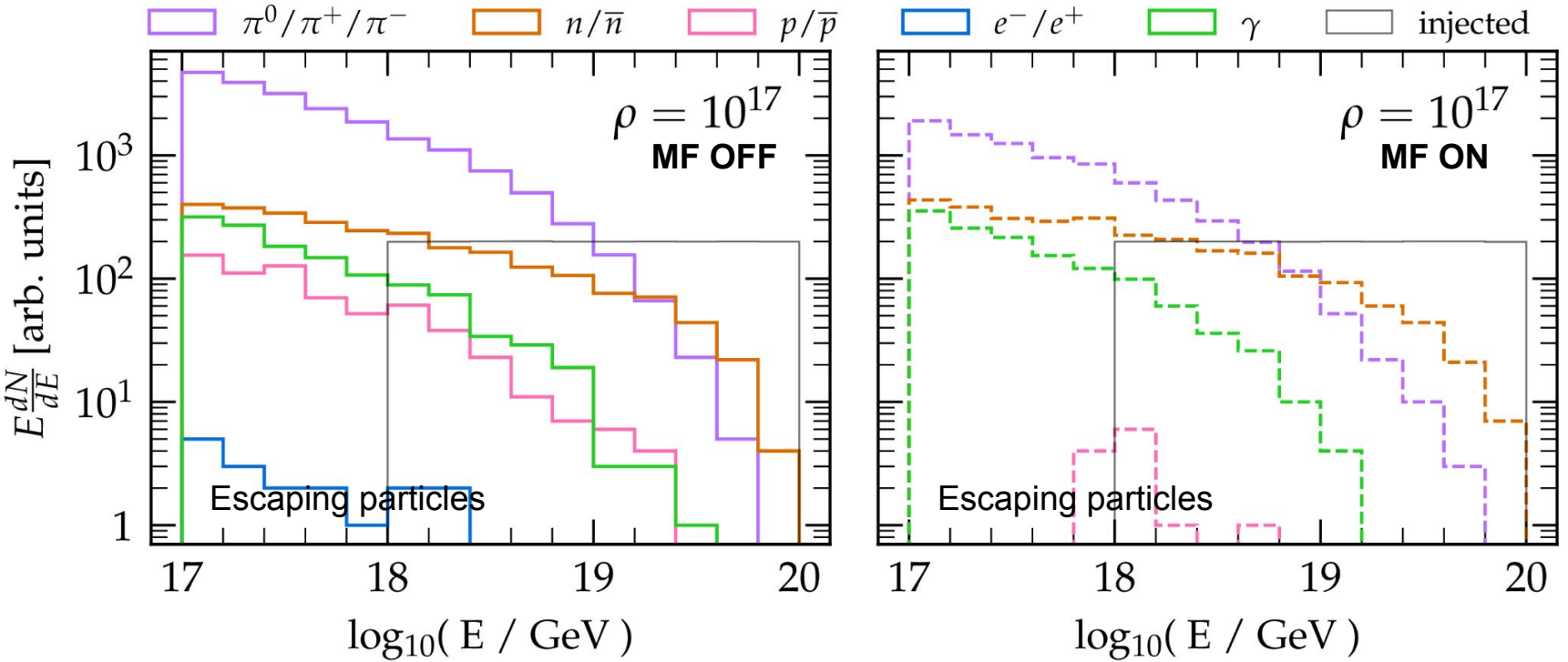

Magn. Field ON versus OFF

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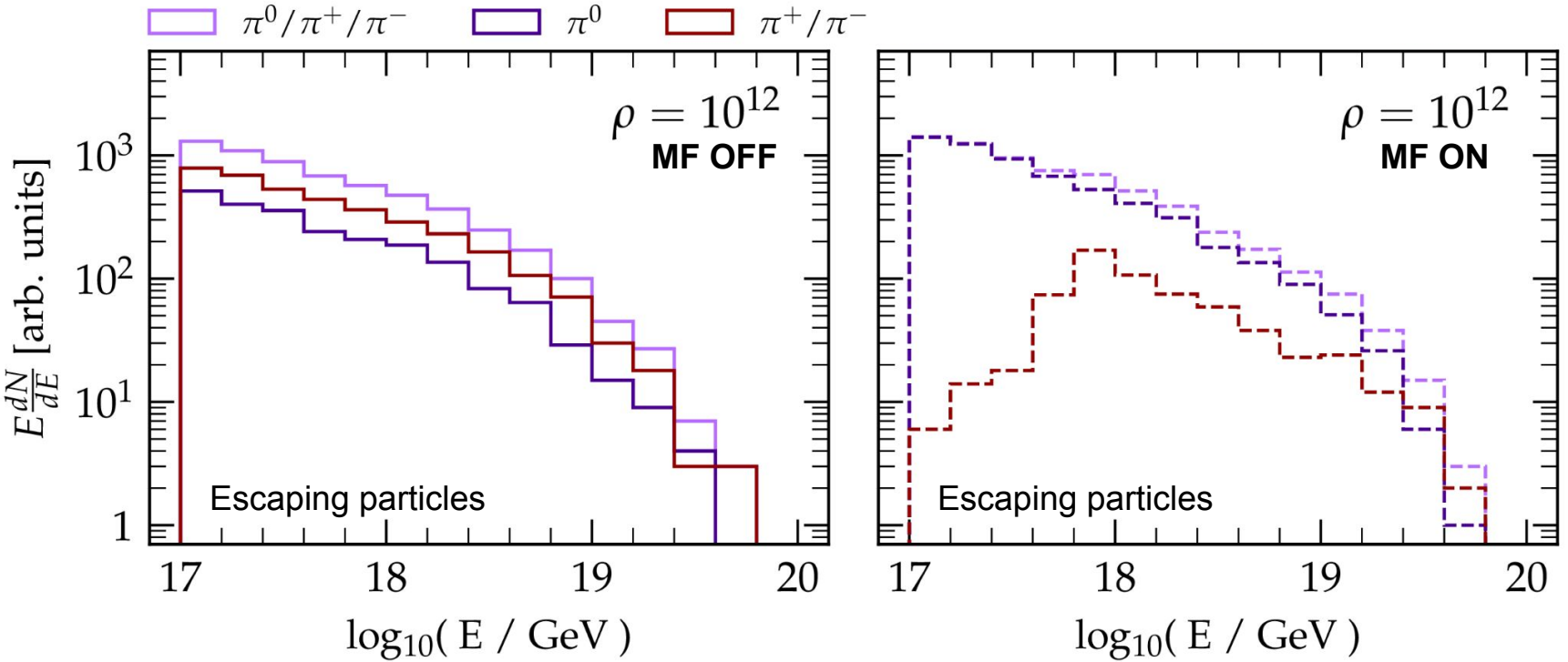

Magn. Field ON versus OFF

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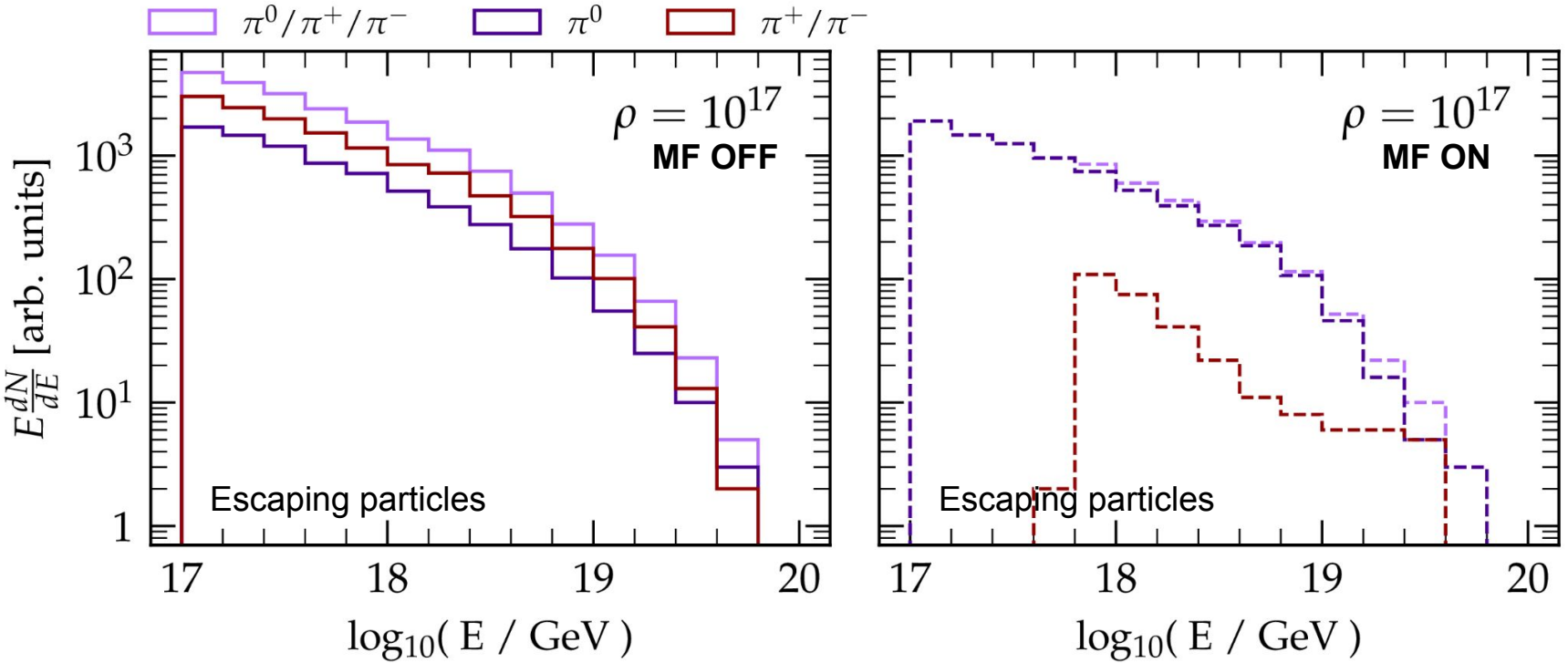

Points to address

- Technical crosschecks

  - energy conservation, kinematics,

- Physical crosschecks

  - cross sections, inelasticity, distribution of secondaries, nuclear masses

- Source scenario showcases
- compare to Antonio's SBG and to Mario's AGN blob