Studying bursting sources

Leonel Morejon

CRPropa meeting

UAM-CSIC 16.02.2022

BERGISCHE
UNIVERSITÄT
WUPPERTAL

MultI-messenger probe of Cosmic Ray Origins

Goal

Multi-messenger study of bursting sources and their contribution to UHECRs.

Participating institutions

Funded by:

MultI-messenger probe of Cosmic Ray Origins

Goal

Multi-messenger study of bursting sources and their contribution to UHECRs.

Approach

Modelling in-source production, interactions and propagation of UHECRs from bursting sources to compute expected values of observables.

Participating institutions

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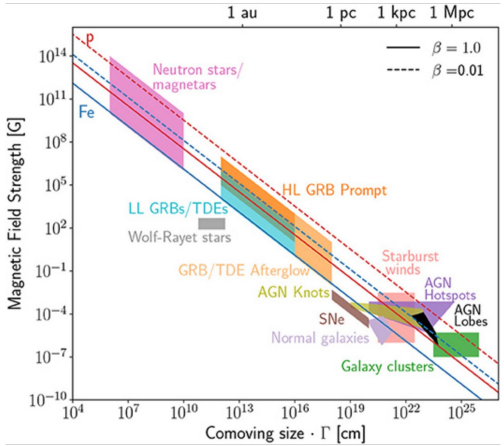
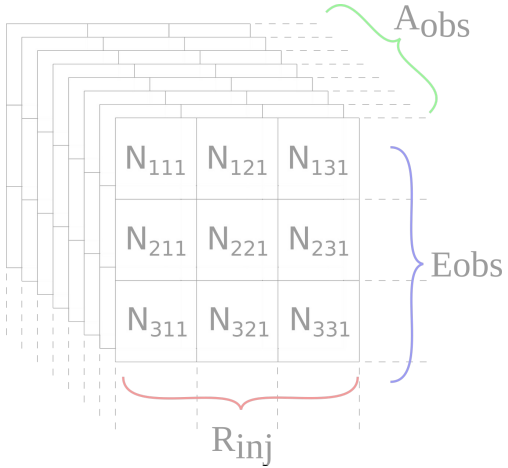
MultI-messenger probe of Cosmic Ray Origins

Frontlines

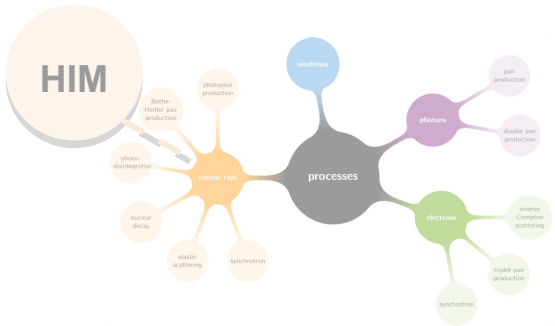
Analysis and experimental data



Propagation



Source Modelling



MultI-messenger probe of Cosmic Ray Origins

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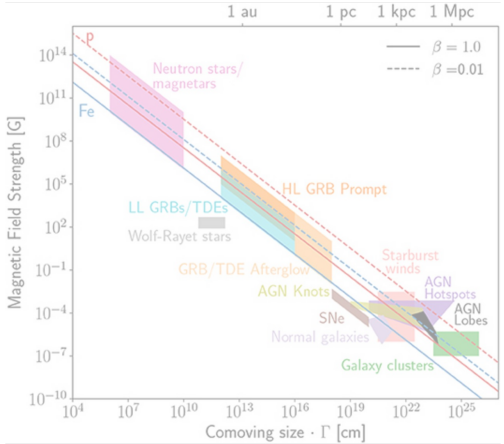

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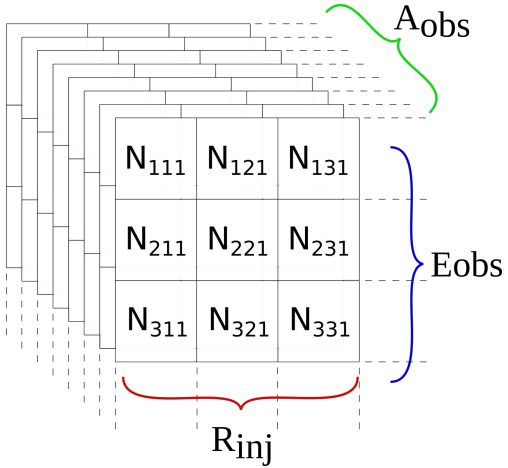

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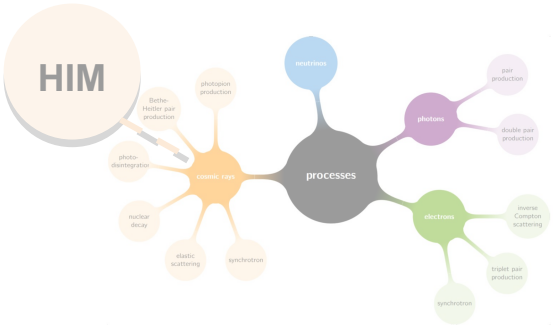
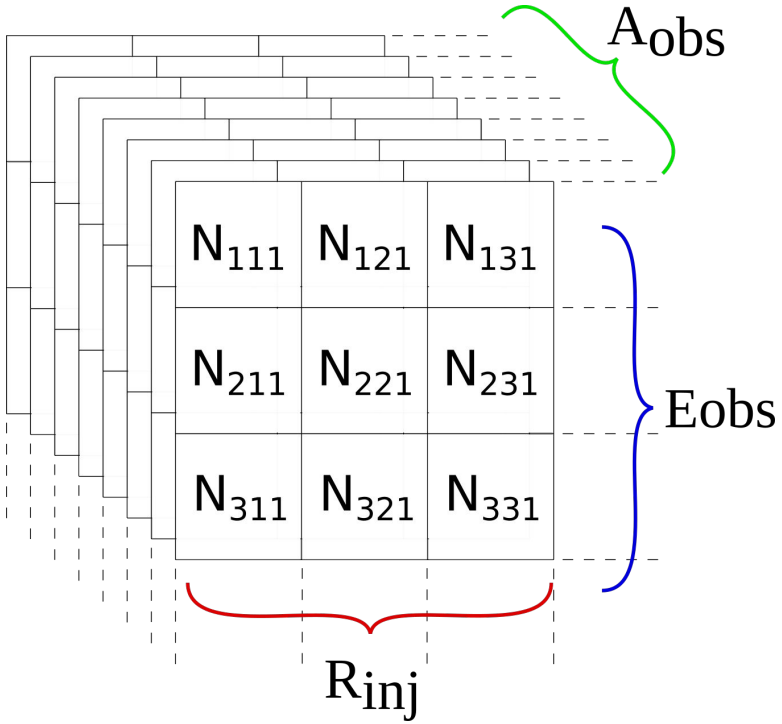


Propagation tensor



Build a tensor for efficient CR propagation

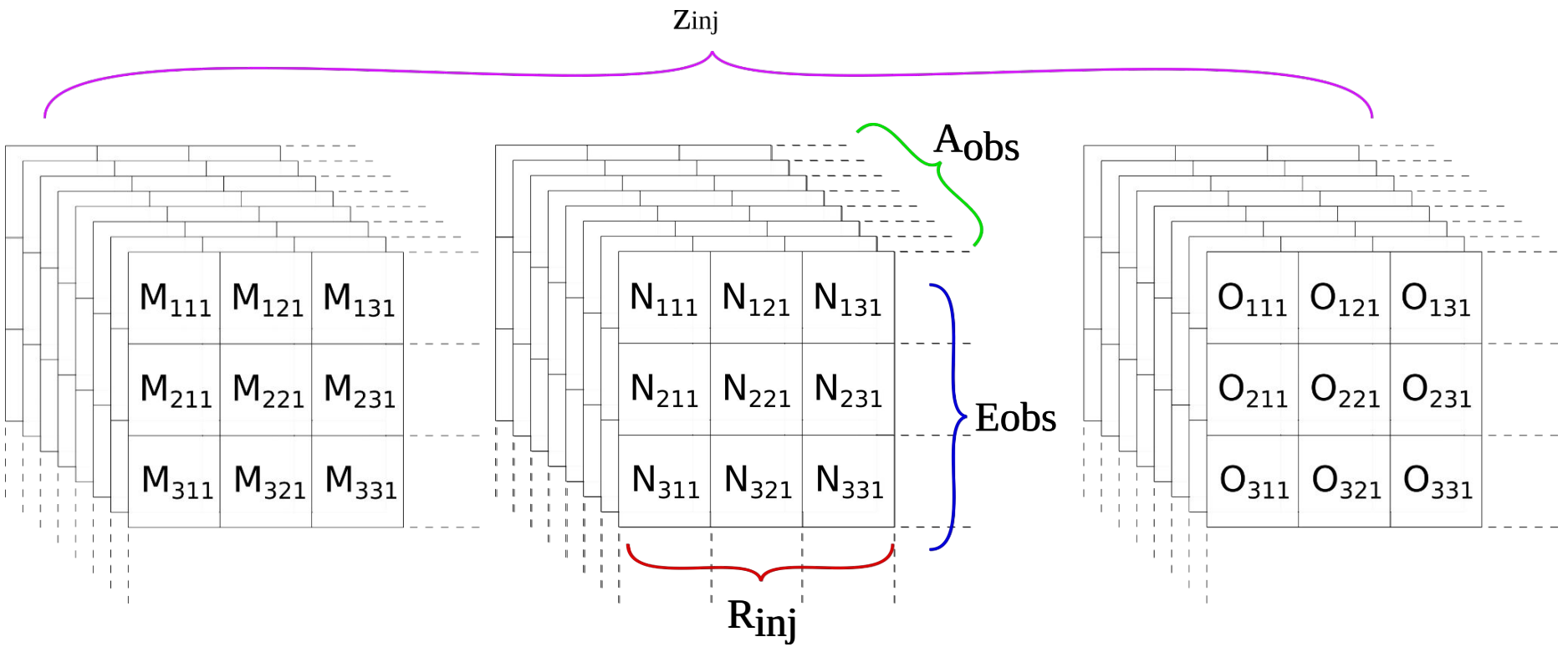
Input quantities:

- Injection rigidity
- Injection redshift
- Injected species

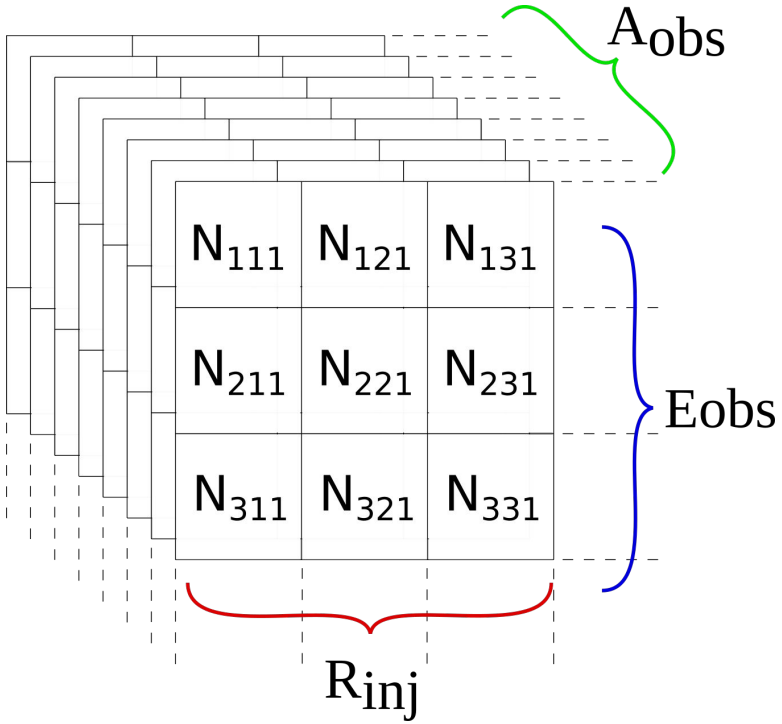
Output parameters:

- Injection rigidity
- Injection redshift

Propagation tensor



Propagation tensor computation



Parameters

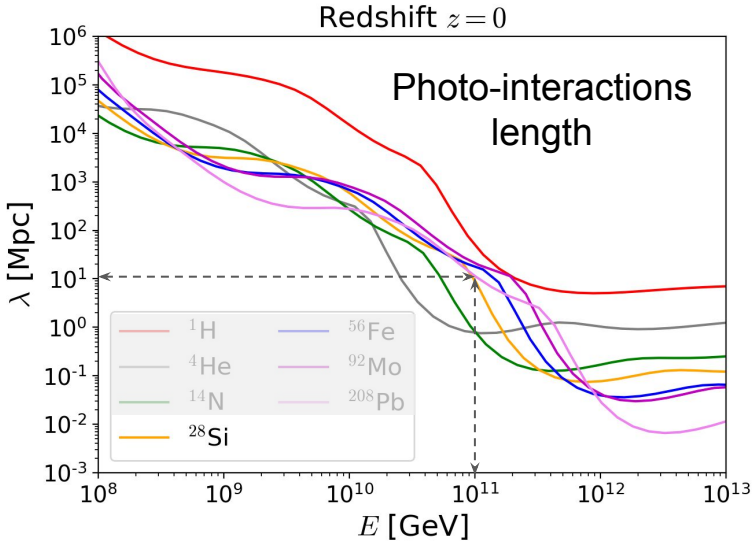
- Injected species: p, He, C, N, O, Ne, Mg, Si, S, Fe
- Rigidity: 1E17 - 1E21 (continuous, flat logR)
- Redshift: 0.0 - 2.5 (zmin -> 1 pc) 47 steps

Simulation definition

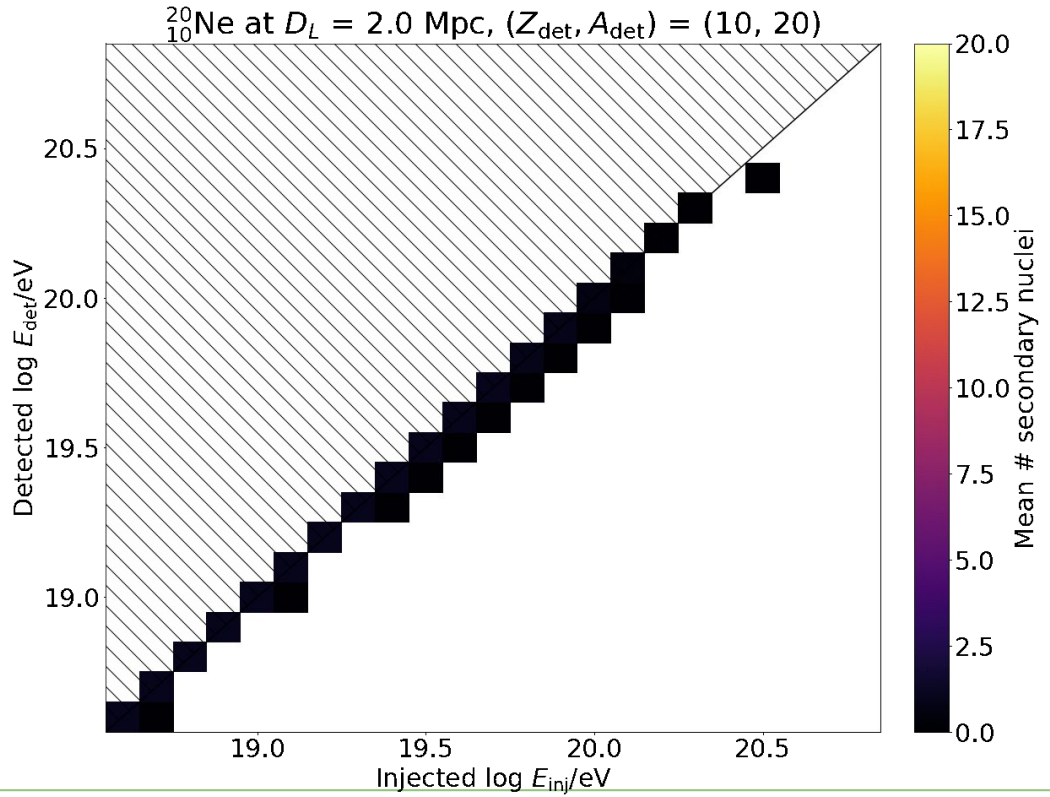
- Simulations 1D
- Source distribution: homogeneous & continuous
- 470 separate simulations

Computational resources used: ~600 cpu*hours

Tensor representation



Roughly consistent with interaction length of ~10 Mpc at 100 EeV



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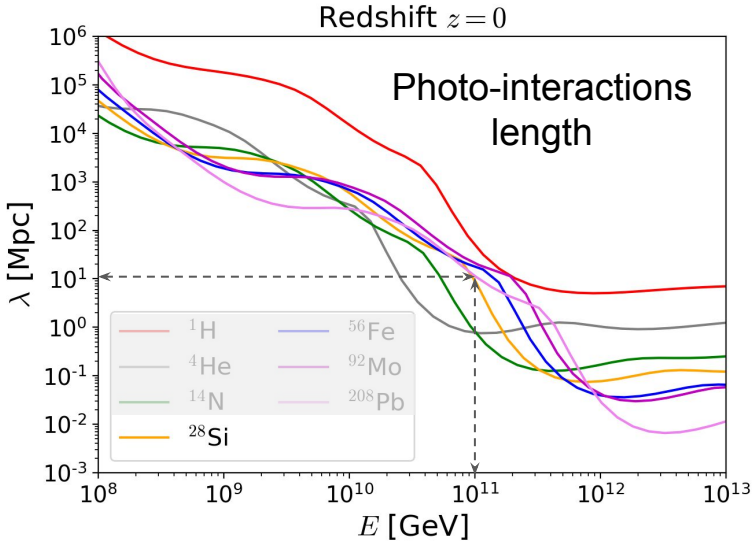

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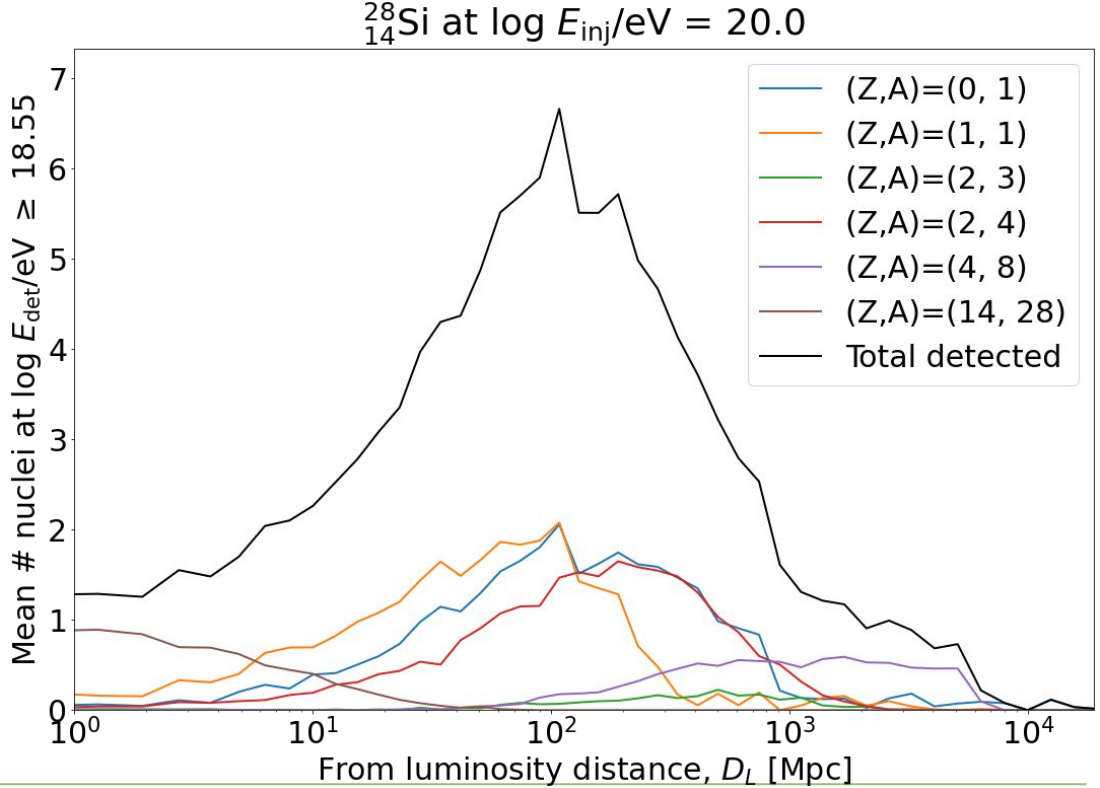


Propagation matrix vs Propagation Tensor

Propagation Tensor

- Differential in redshifts
- One tensor per injected species
- Differential produced species
- Differential rigidity
- Suitable for approximate computations

Propagation Matrix

- Implicit assumption of a redshift distribution
- Aggregation of propagation tensor of all species
- Species grouped into 5 groups
- Suitable for detailed computations

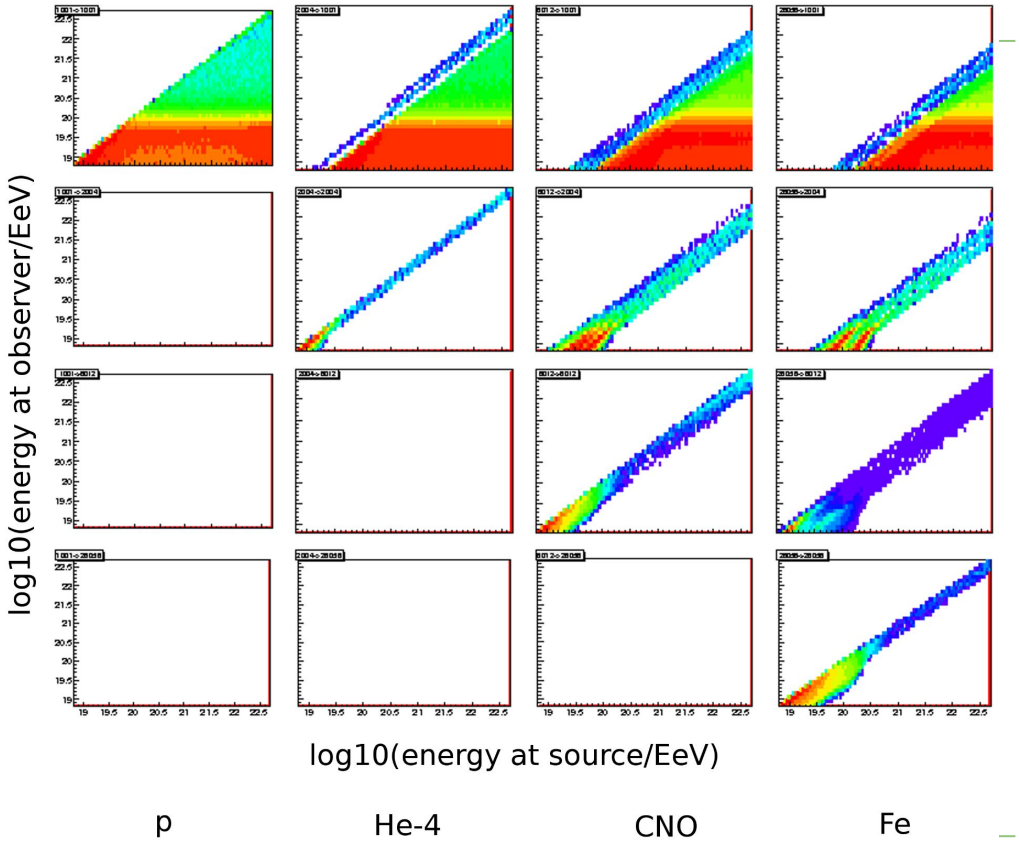
Complementary functionality

Propagation matrix

Matrix after redshift integration

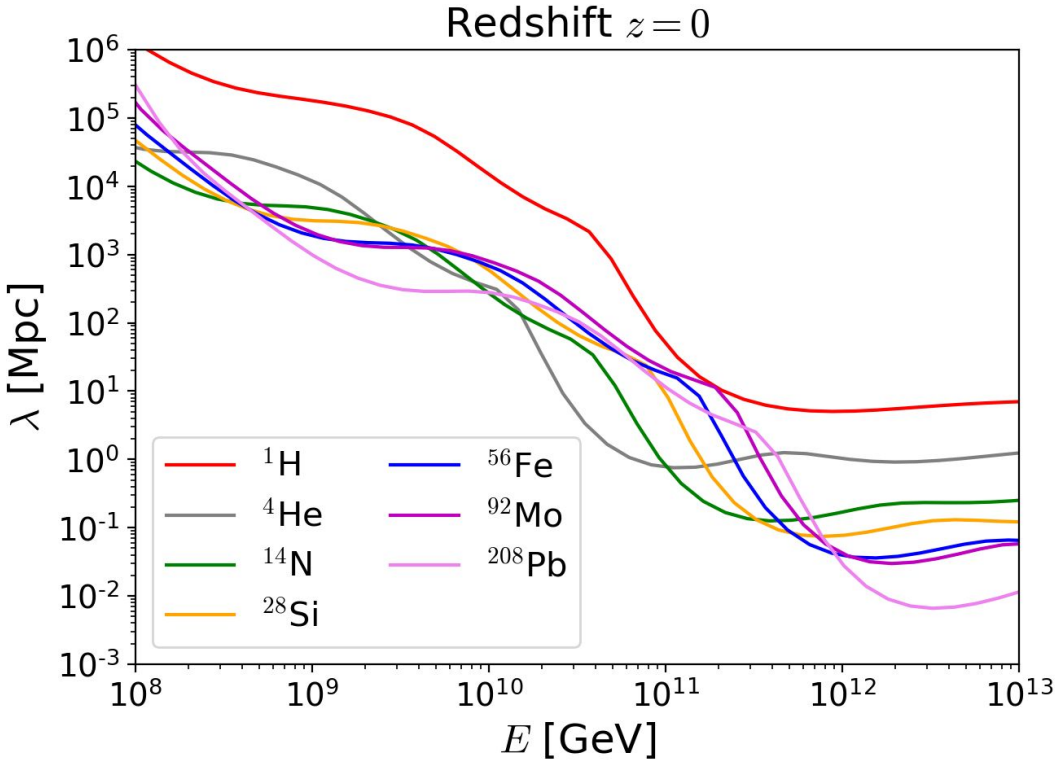
- Implicit assumption of a redshift distribution
- Aggregation of propagation tensor of all species
- Species grouped into 4 groups
- **Restricted prediction possibilities, less free parameters.**

Figure from Tobias Wichen



Reading the propagation matrix

The vertical spread is produced by continuous losses like pair production. The highest y is due to the largest energy of the secondary species, that is ratio of the nuclear mass.



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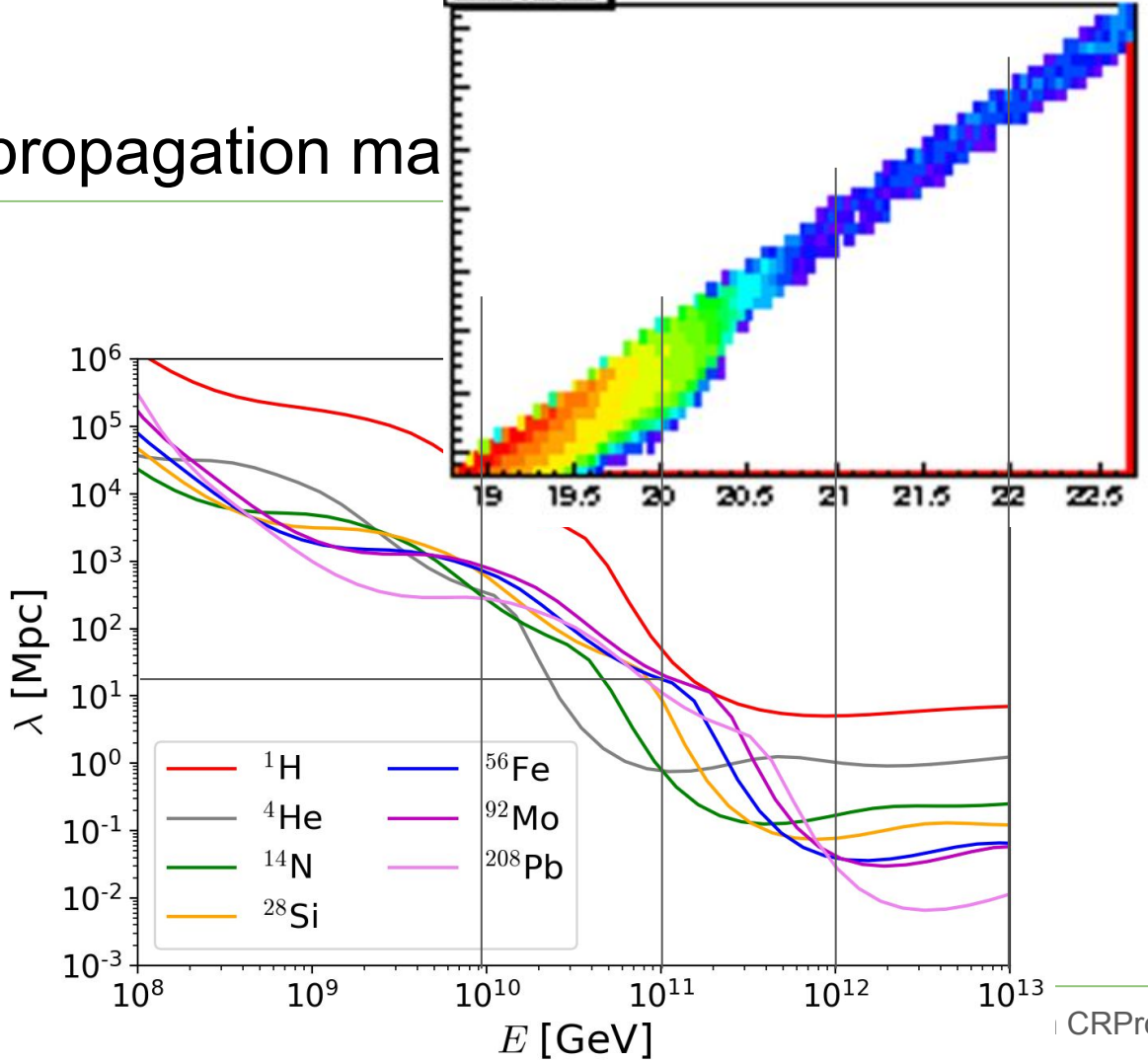

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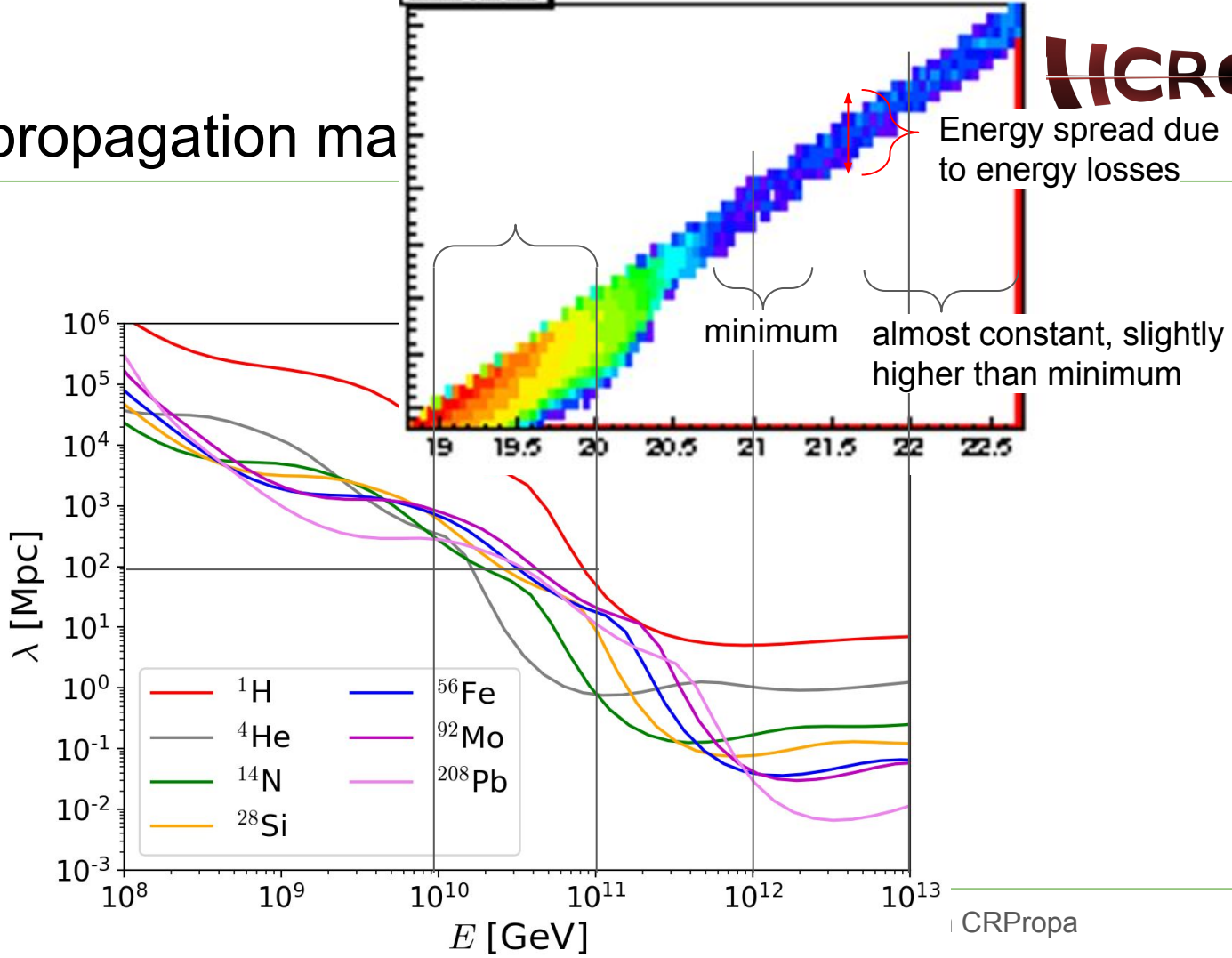
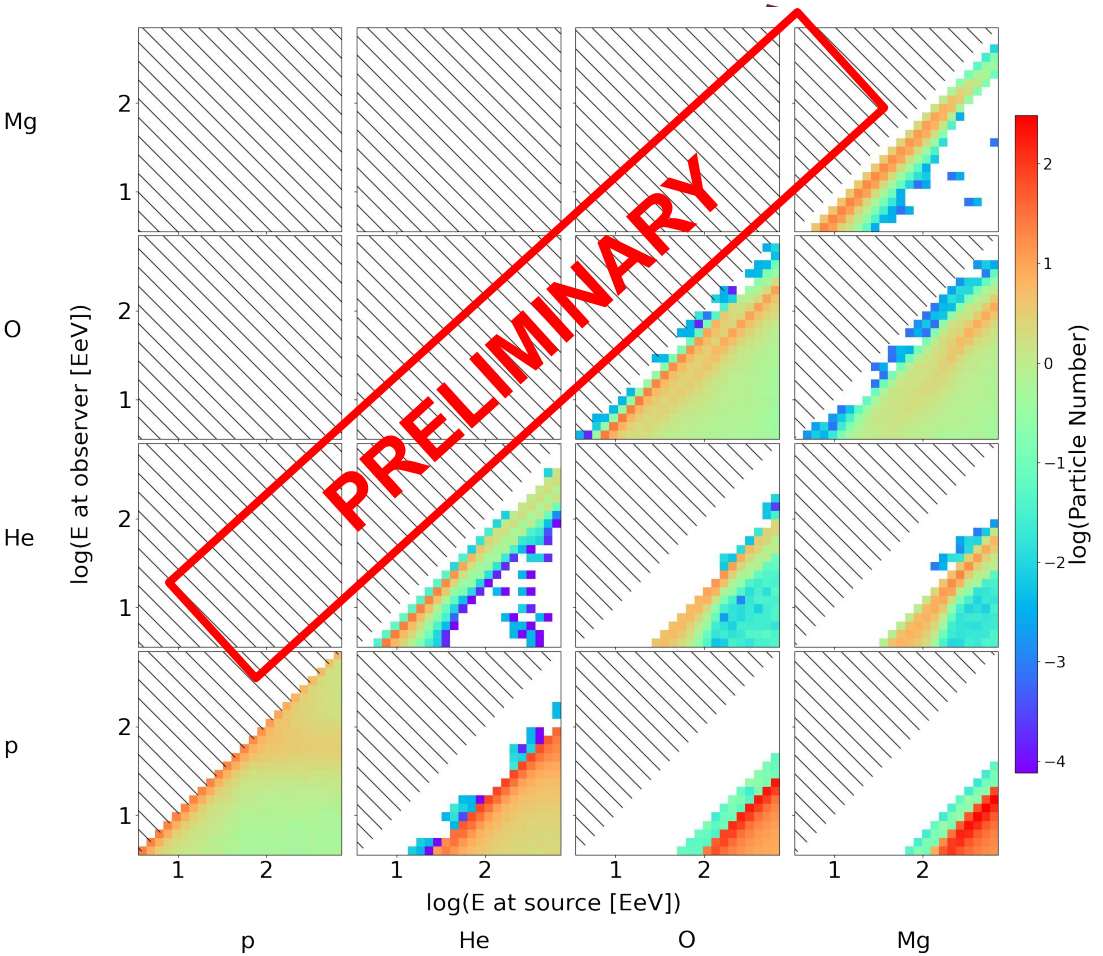


CRPropa matrix

Quantifies CR spectral redistribution between groups of nuclear species.

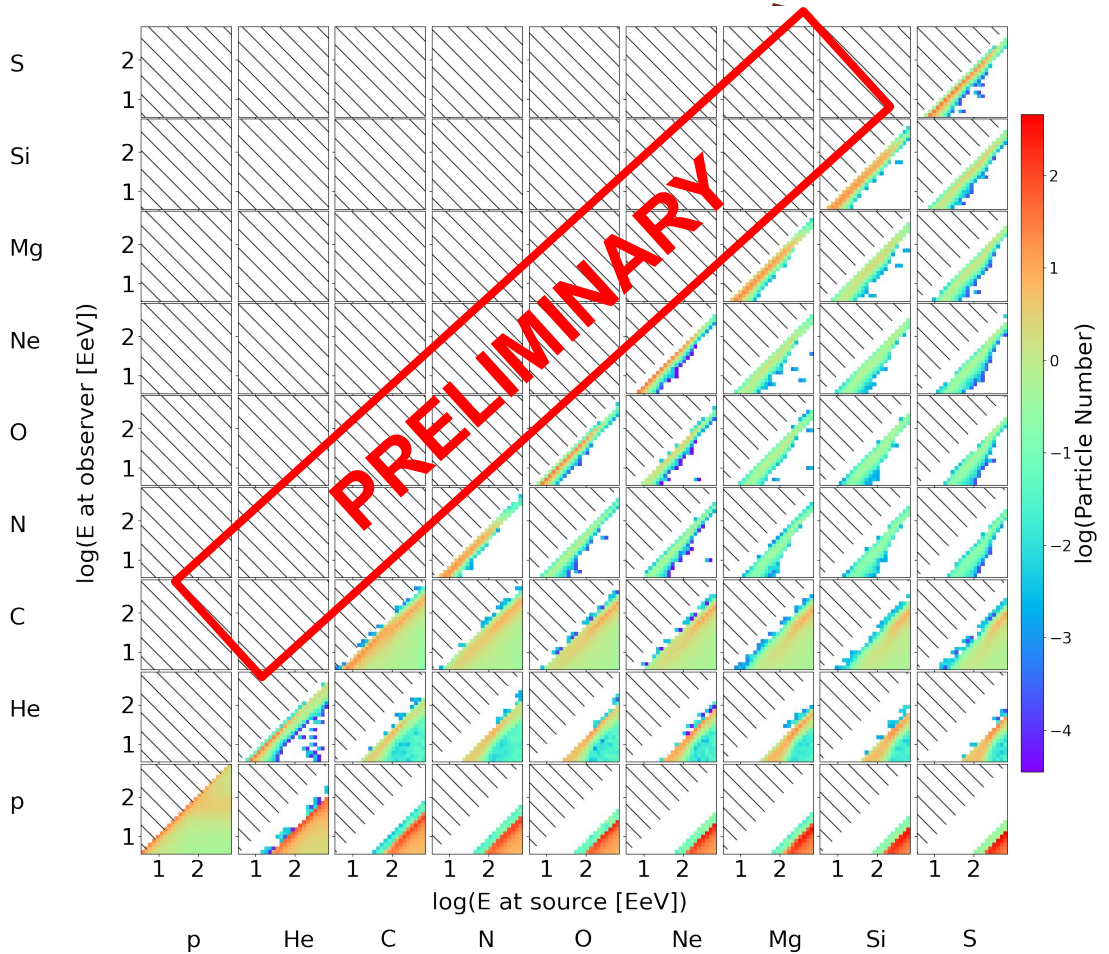
- Flat injection over redshift
- Observed vs Injected fraction by group
- Species grouped into 5 groups
- Variable composition allowed



CRPropa matrix

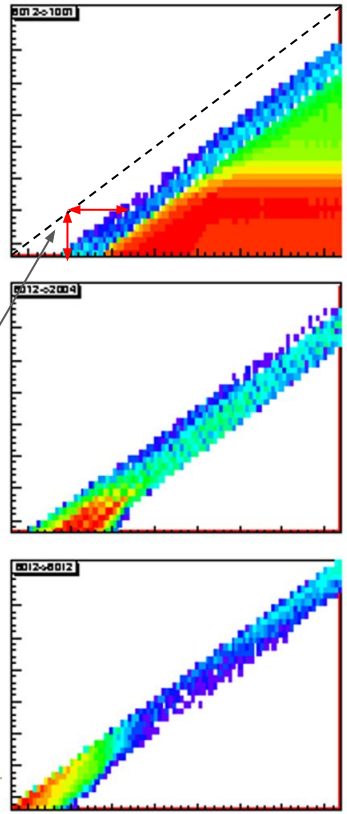
Quantifies CR spectral redistribution between groups of nuclear species.

- Flat injection over redshift
- Observed vs Injected fraction by group
- **Species grouped into 9 groups**
- Variable composition allowed



Reading the propagation matrix

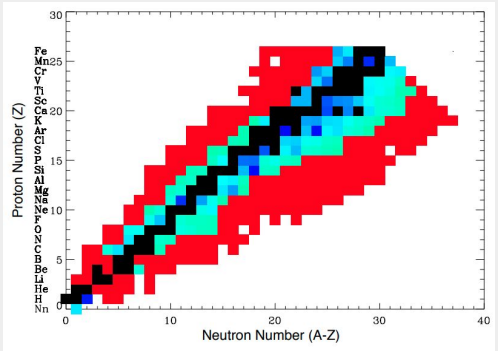
Ak/A energy loss due to nucleon loss. Vertical displacement due to injection on given energy, and horizontal displacement due to vertical fall of diagonal line which the injected nuclei fall into.



protons

next mass group

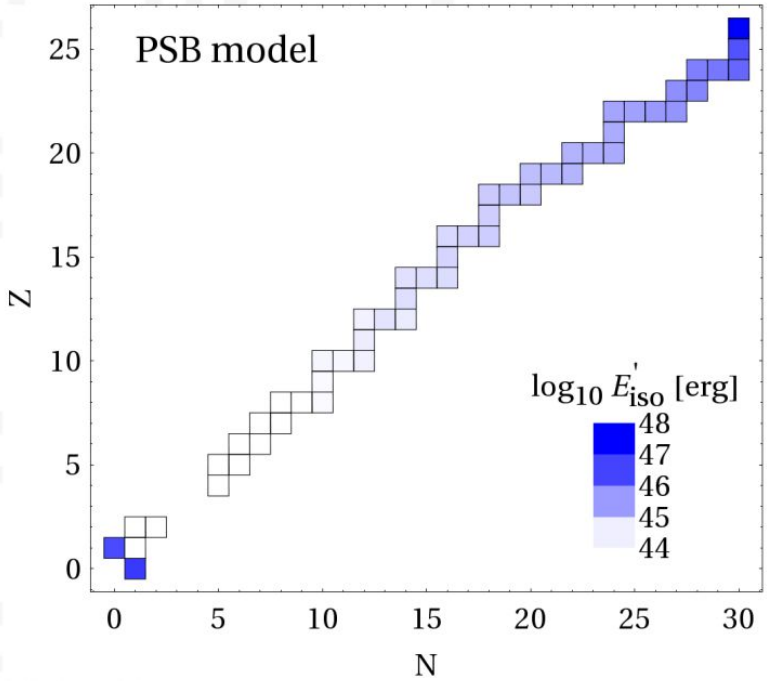
injected mass group



CRPropa nuclei

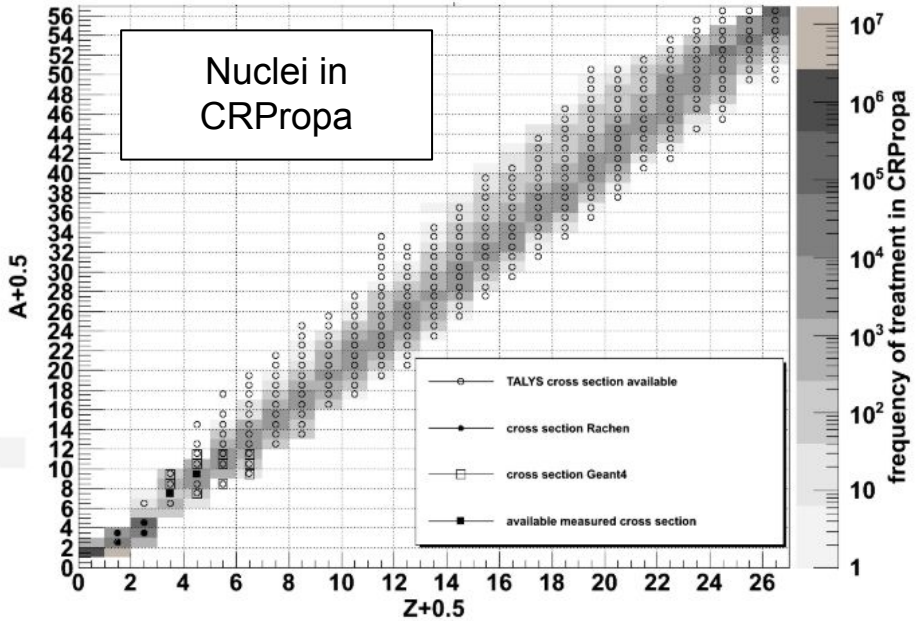
Photodisintegration cascade impact

DB, Fedynitch & Winter, Sci. Reports 2017



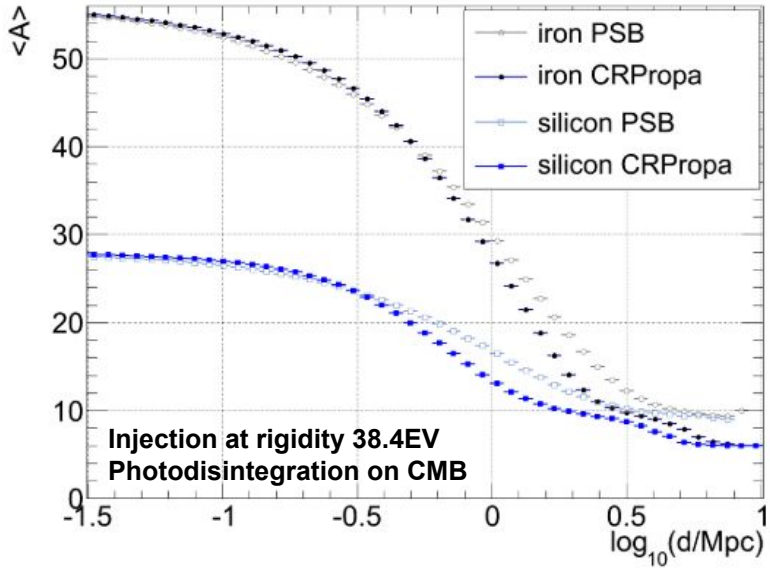
VS

Kampert, *et al* (2013) *Astroparticle Physics*, *42*, 41–51

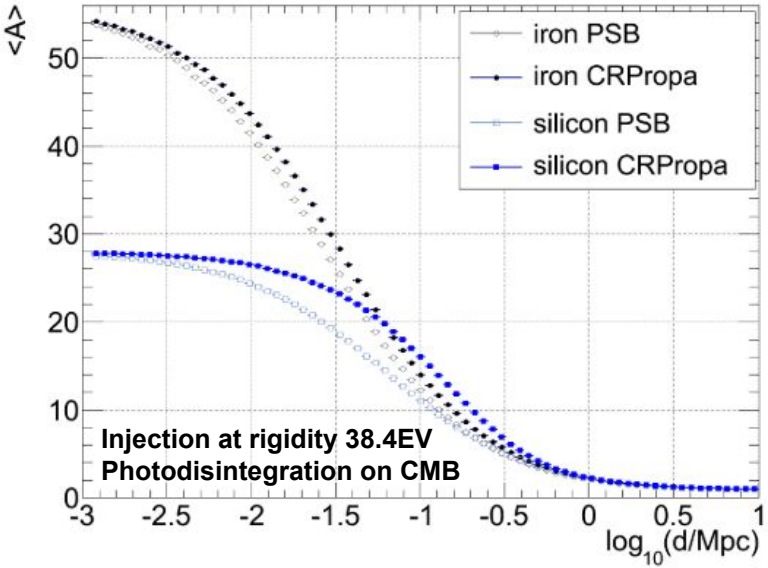


Photodisintegration cascade impact

Notable differences in mean mass (3-7 nucleons)



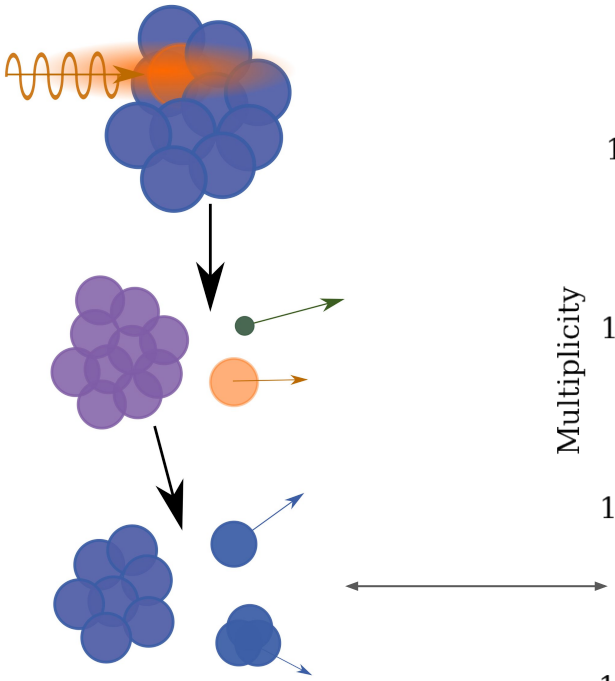
(a) primary cosmic rays

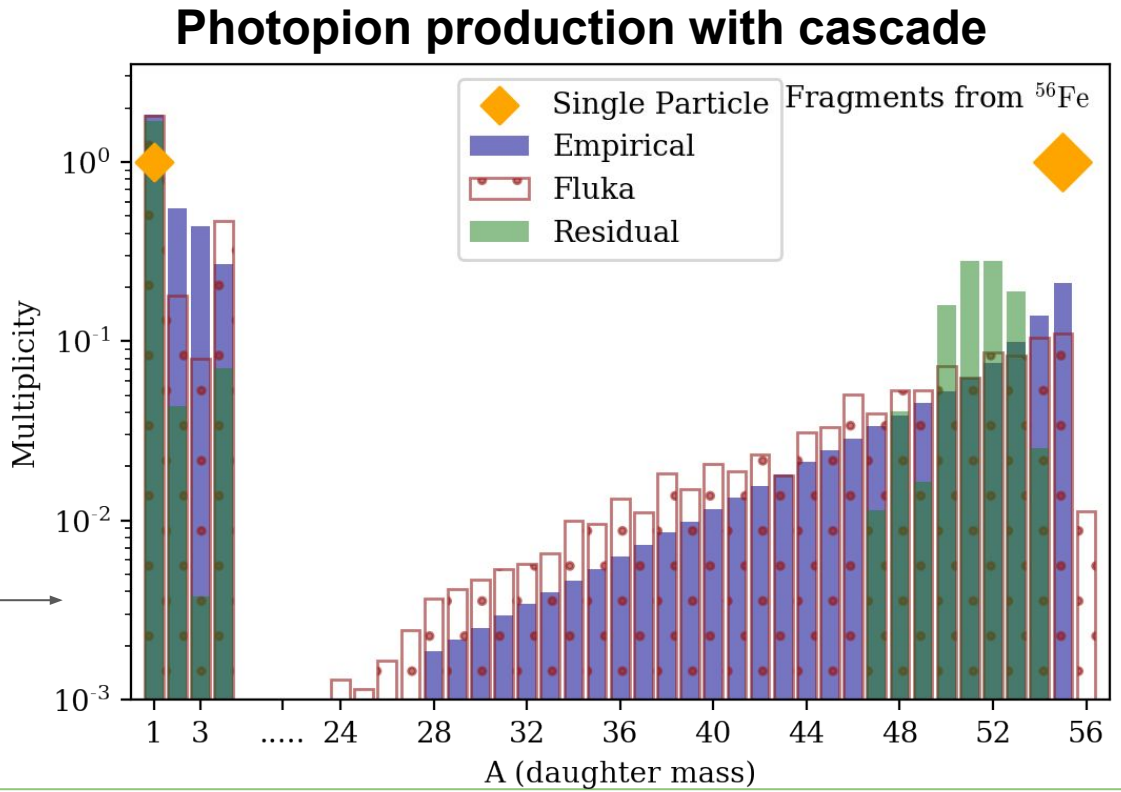


(b) cosmic rays including secondaries

Kampert, *et al* (2013) *Astroparticle Physics*, *42*, 41–51

Possible effects on secondaries: cascade broadening

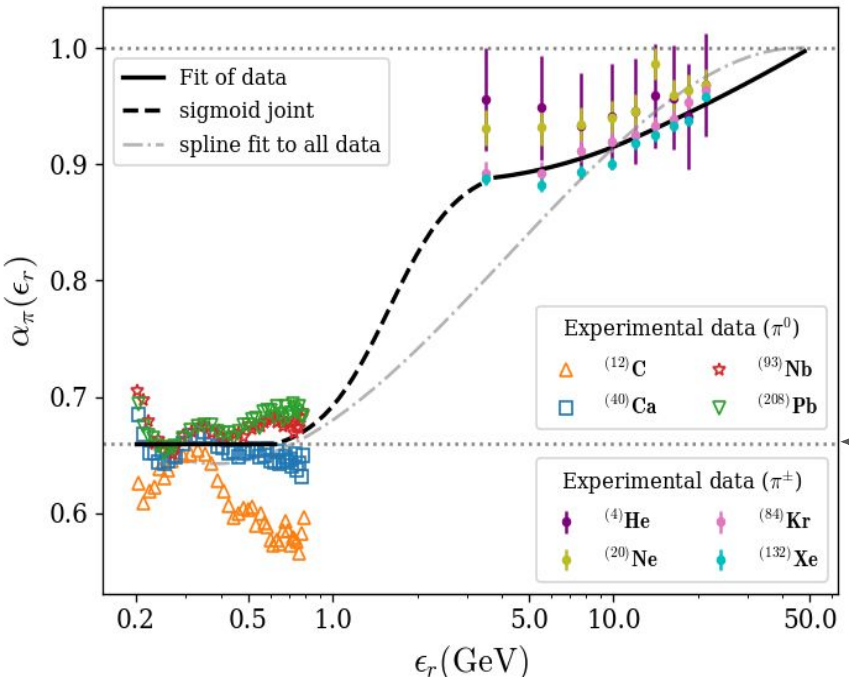




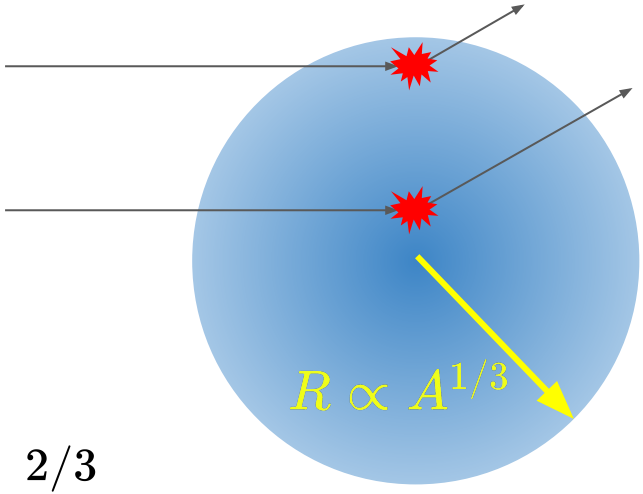
Ref: **L. Morejon**, et al, *JCAP* 11 (2019) 007

Possible effects on secondaries: nuclear pion suppression

Energy dependent escape, increase of production



$2/3$



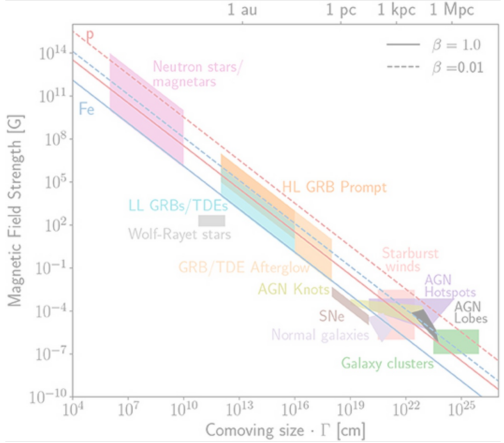
$$\sigma \propto A^{\alpha}$$

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

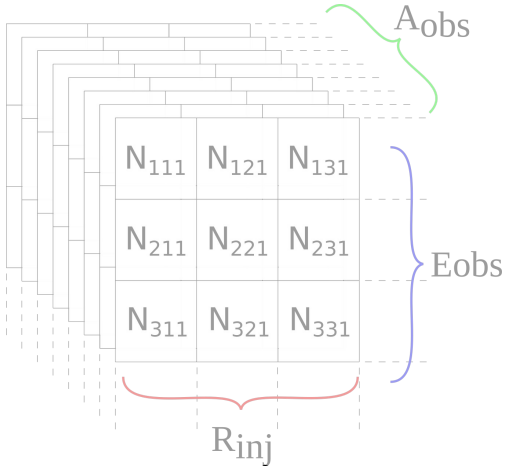
MultI-messenger probe of Cosmic Ray Origins

Frontlines

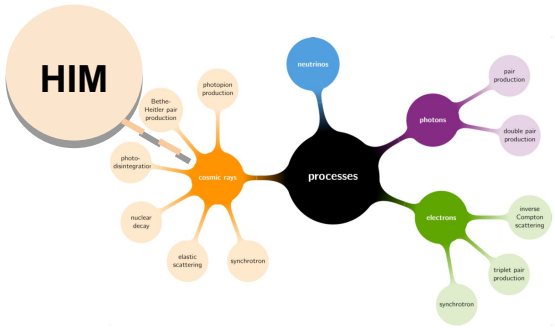
Analysis and experimental data



Propagation



Source Modelling

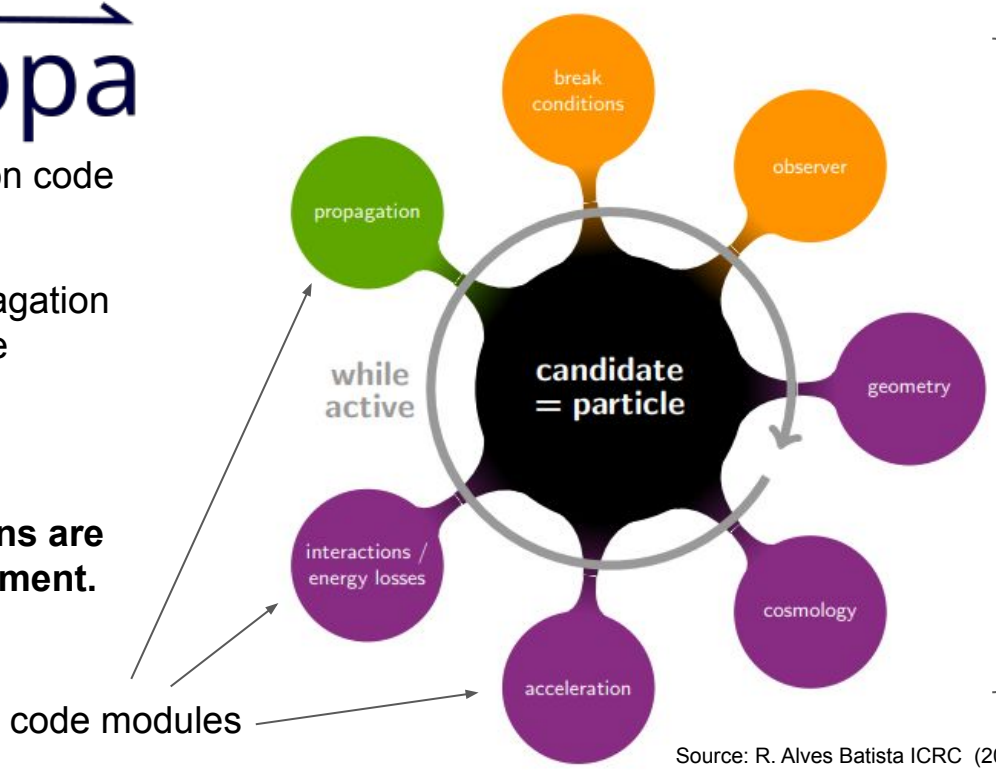


Workflow in CRPropa

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

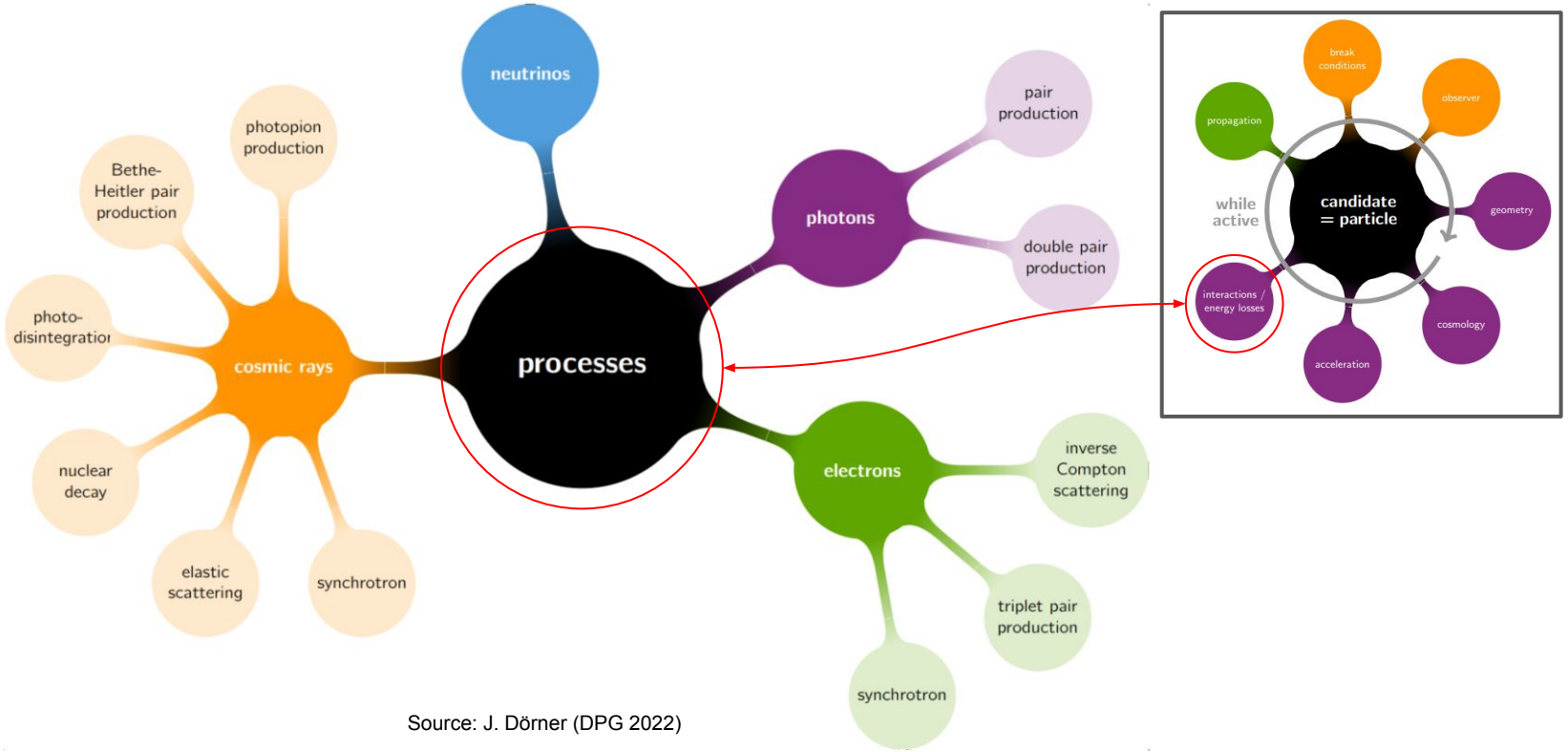
- Modular code
- Multi-particle propagation
- Flexible, extensible

Extensions and plugins are under active development.



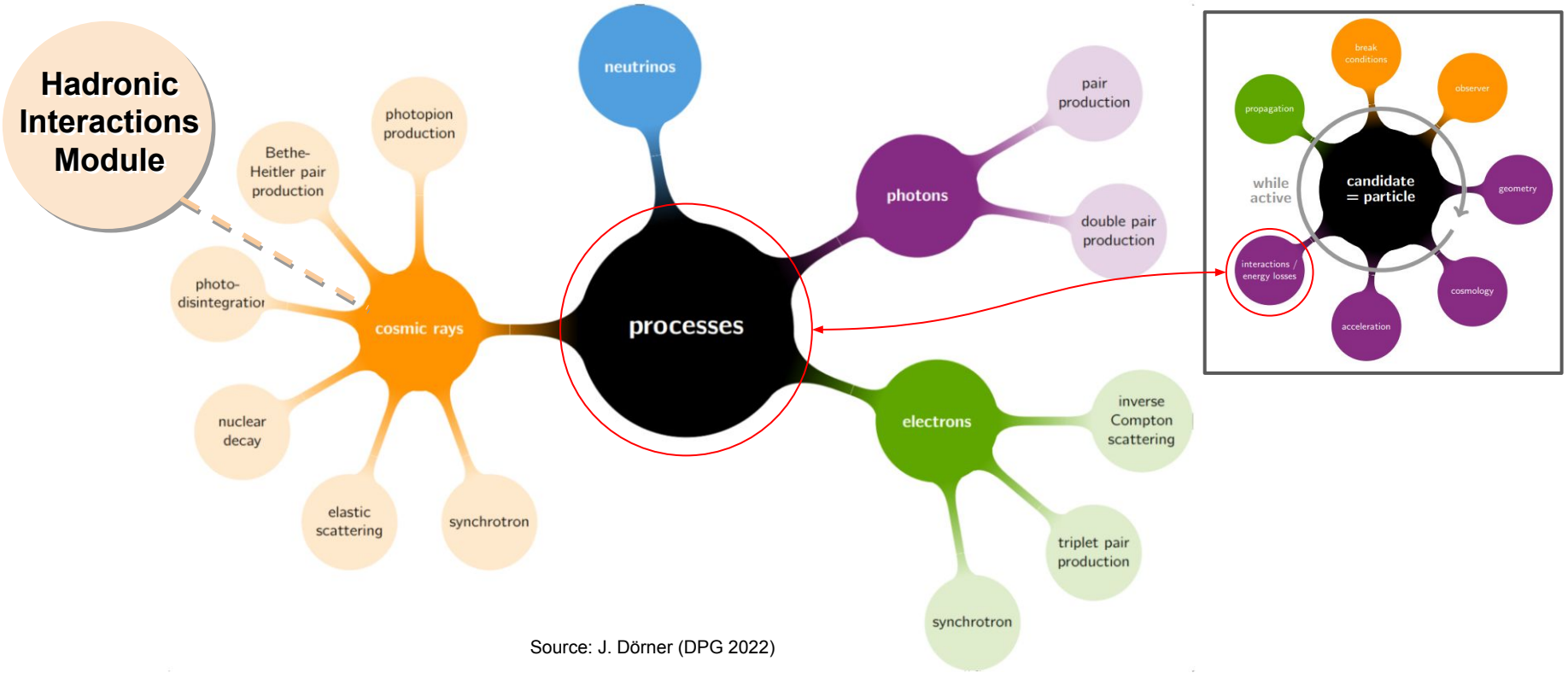
Source: R. Alves Batista ICRC (2021)

Interactions in CRPropa



Source: J. Dörner (DPG 2022)

Hadronic Interactions Module (HIM)



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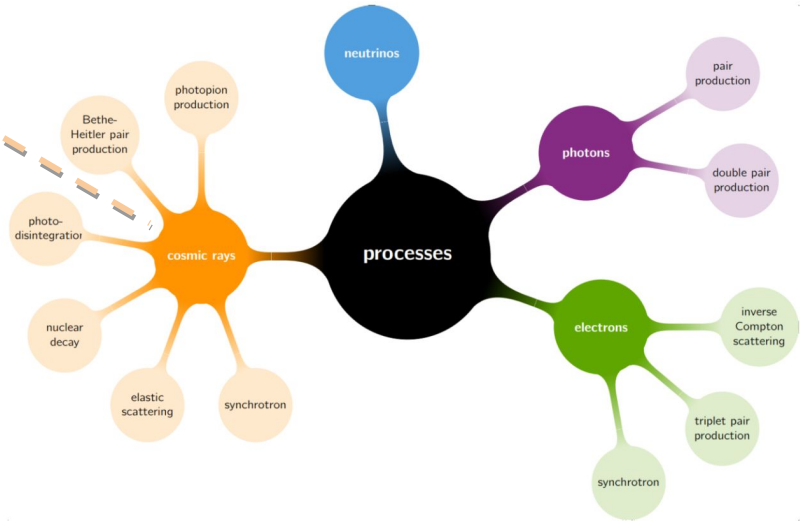
Elements of the HIM

- 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 (soon downloadable with CRPropa)



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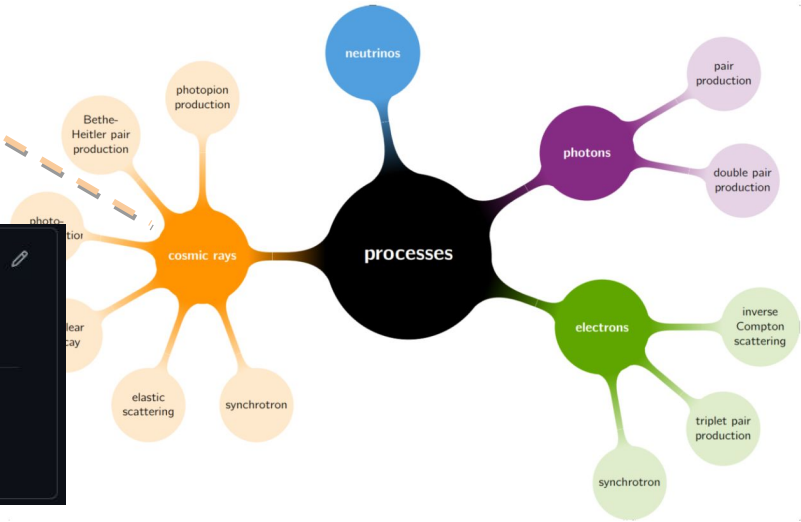

https://github.com/mohller/prototype_him_crpropa

Hadronic Interactions Module (HIM) for CRPropa

A (prototype) implementation of hadronic interactions in crpropa based on impy.

Still under testing, but a release version will be issued by December 2022.

Elements of the HIM

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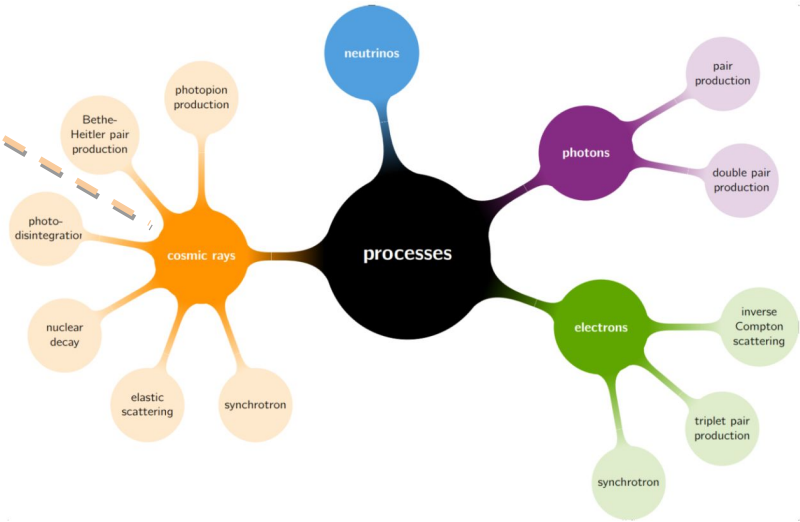


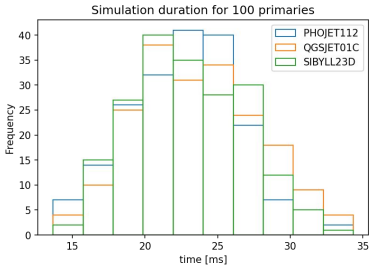
github.com/impy-project

impy - (hadronic) interaction models in python

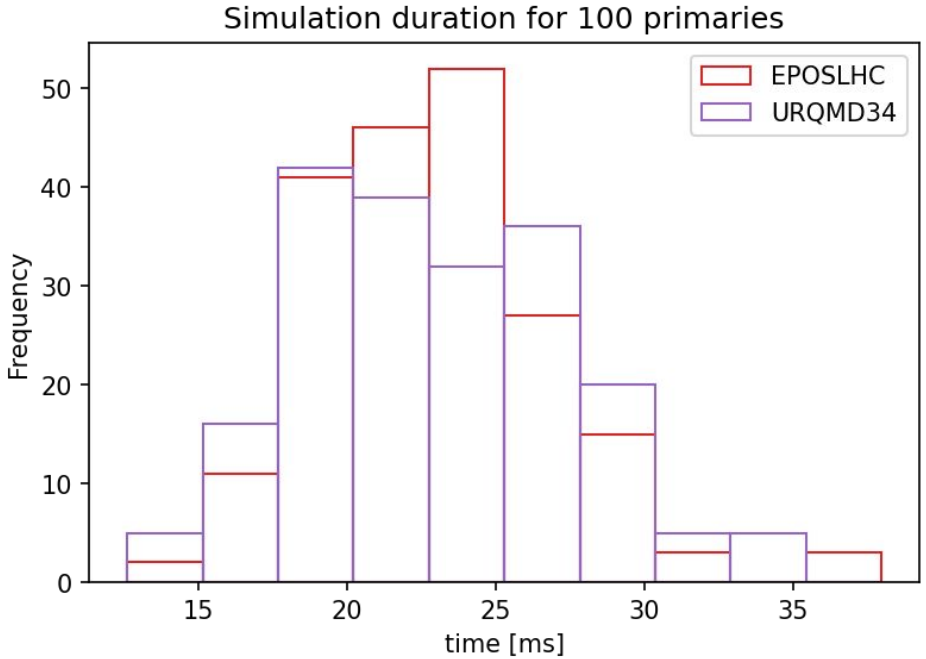
This package implements are generic user interface to popular event generators used in cosmic ray and high-
particle physics. The purpose of the package is to simplify working with simulations of particle interactions with
need to use Fortran style interfaces to event generators, 'ASCII input cards' and files or C++ dependencies.

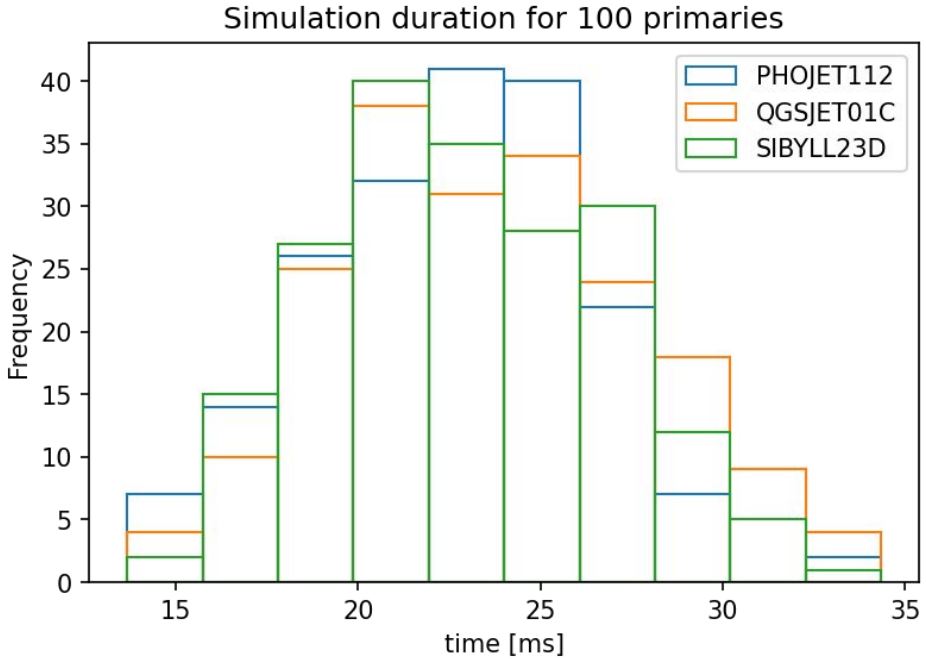
Features of the HIM

- Multiple interaction engines (various versions of EPOS-LHC, SIBYLL, QGSJet, DPMJET, and others)



Multiple interaction engines

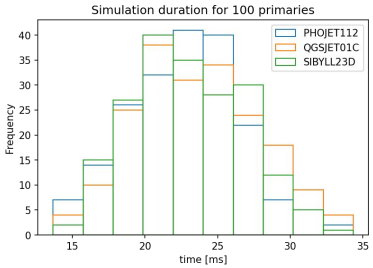


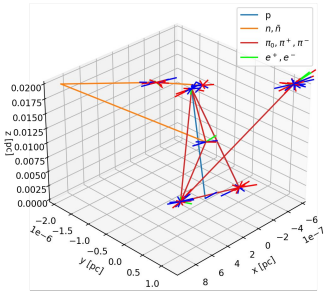


Similar duration of a CRPopa simulation using with different interaction engines.

Features of the HIM

- Multiple interaction engines (various versions of EPOS-LHC, SIBYLL, QGSJet, DPMJET, and others)
- Additional random-seed settings (allows testing and repeatability)





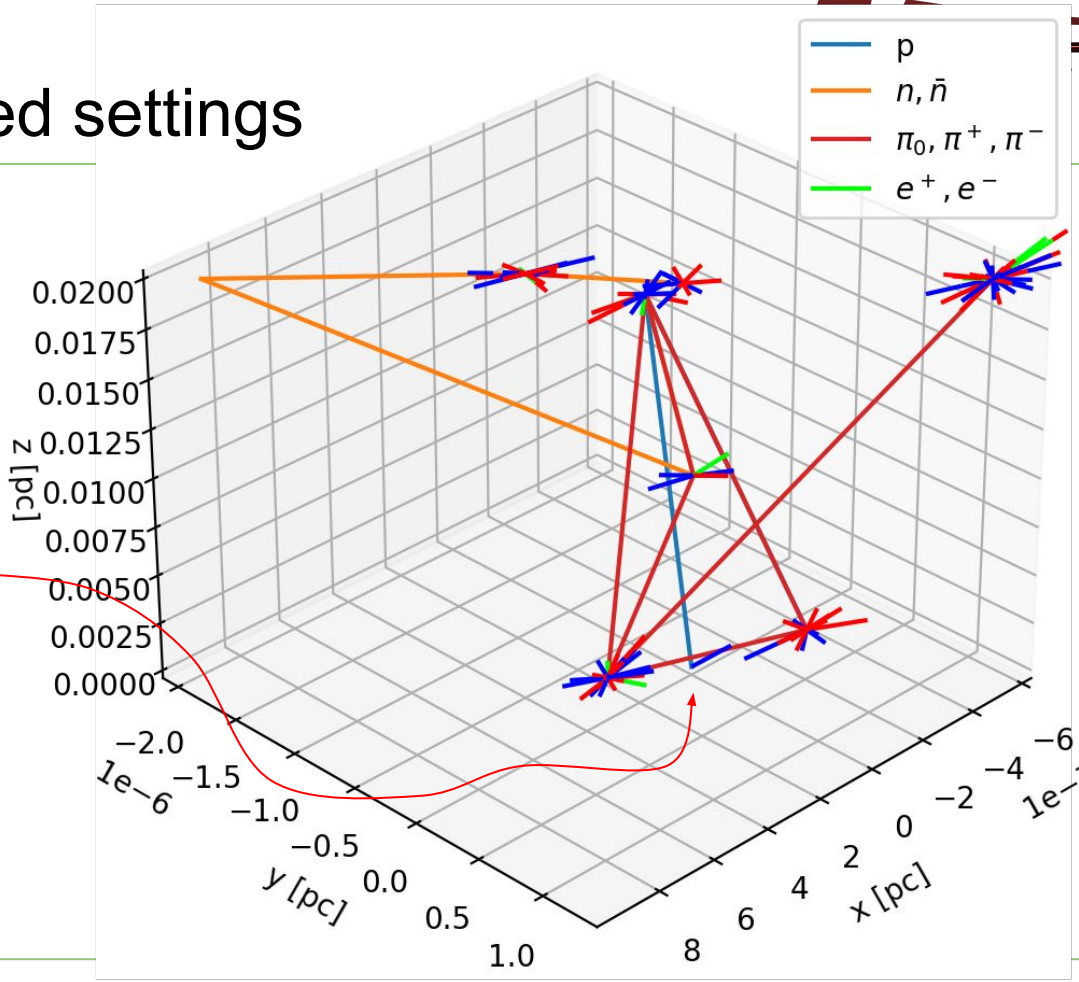
Additional random-seed settings

Seeds added:

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

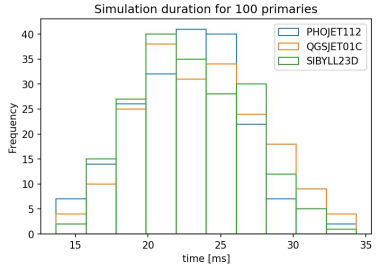
Example figure…

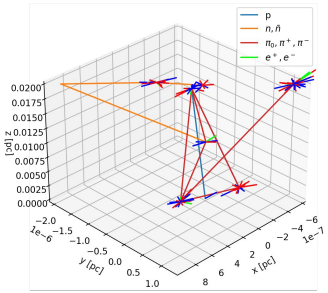
- Injecting a proton 1EeV (0, 0, 0)
- Interaction step controlled by **seed 1**
- Secondaries' species, energy, momenta and distribution controlled by **seed 2**
- Transversal plane momenta controlled by **seed 3**

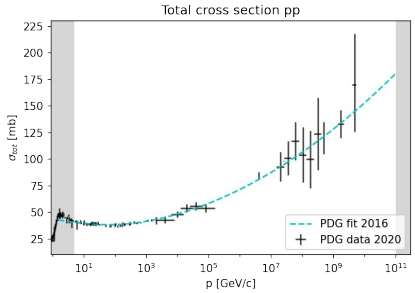


Features of the HIM

- Multiple interaction engines (various versions of EPOS-LHC, SIBYLL, QGSJet, DPMJET, and others)
- Additional random-seed settings (allows testing and repeatability)
- PDG-recommended interaction cross section





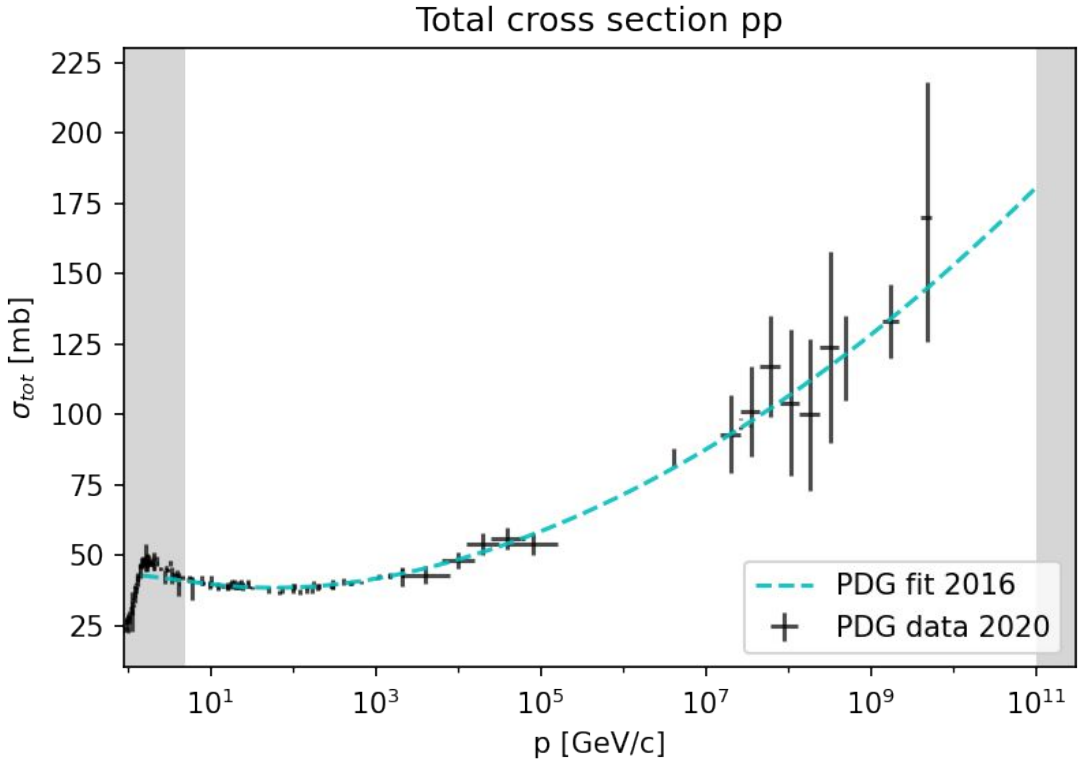


PDG-recommended cross section

The fitted in dashed blue is reported in the references* along with the data. The module employs the fitted function to sample the primary's interaction step.

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

where **p** is a random number sampled using CRPropa functions, and the density is a user input.

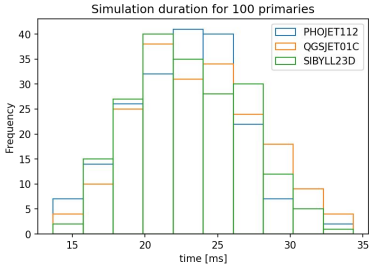


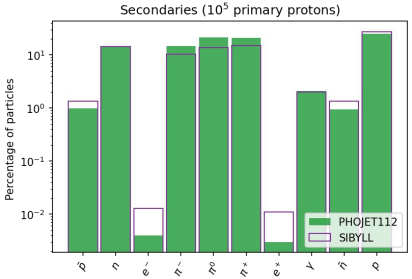
* C. Patrignani 2016 Chinese Phys. C 40 100001

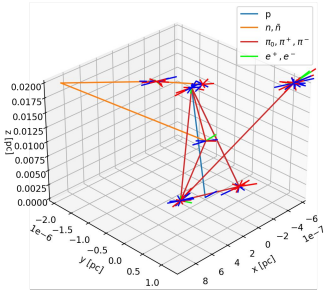
* P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

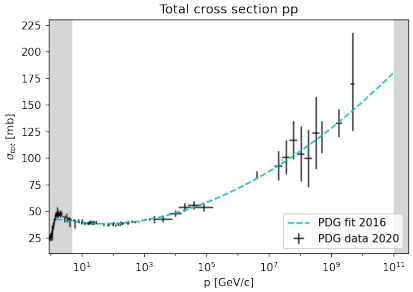
Features of the HIM

- Multiple interaction engines (various versions of EPOS-LHC, SIBYLL, QGSJet, DPMJET, and others)
- Additional random-seed settings (allows testing and repeatability)
- PDG-recommended interaction cross section
- Multiple secondaries (p/pbar, n/nbar, muons, e/e+, gammas, pions, etc.)









Production of secondaries

Particles included currently:

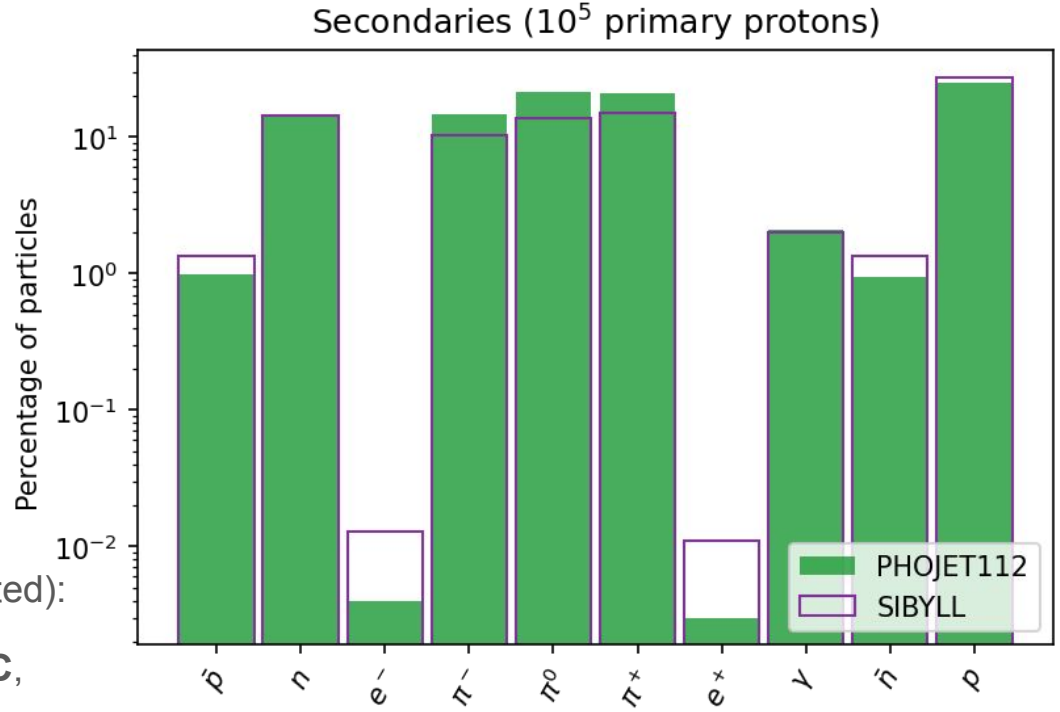
- **protons**: interaction and production
- **γ, e/e+, p/p-, n, pions**: production

Current limitations (on expansion currently):

- Only proton-proton interactions
- Monoenergetic targets

Multiple hadronic codes available (in **bold** tested):

- **SIBYLL**, **QGSJET**, **PHOJET**, **EPOSLHC**, **URQMD**, PYTHIA, DPMJET



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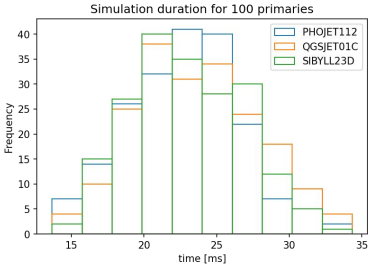

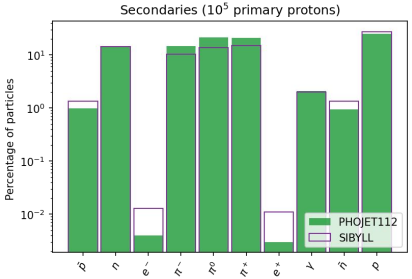

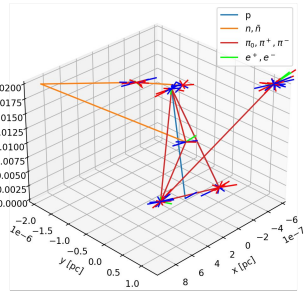

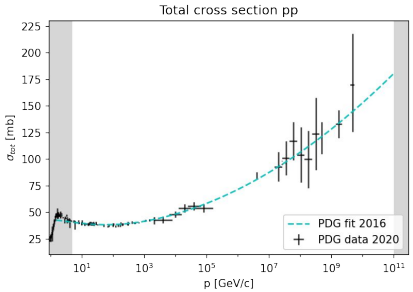

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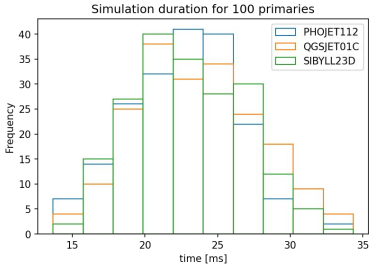
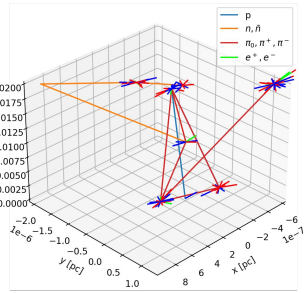
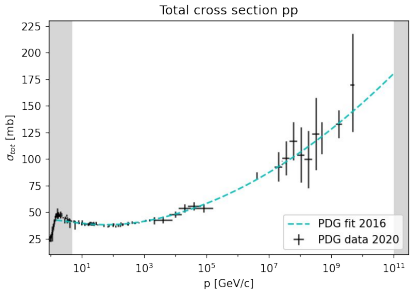
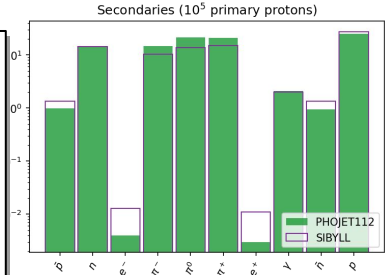




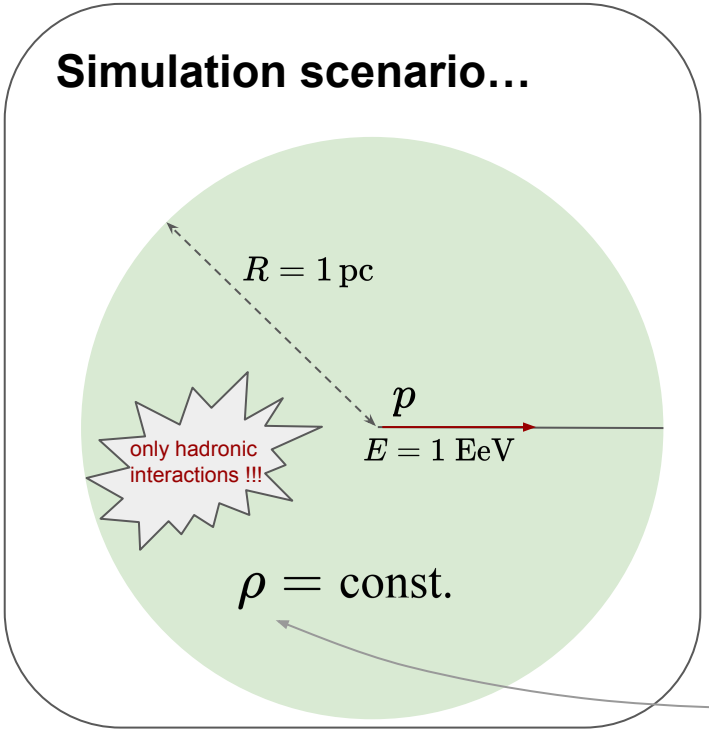


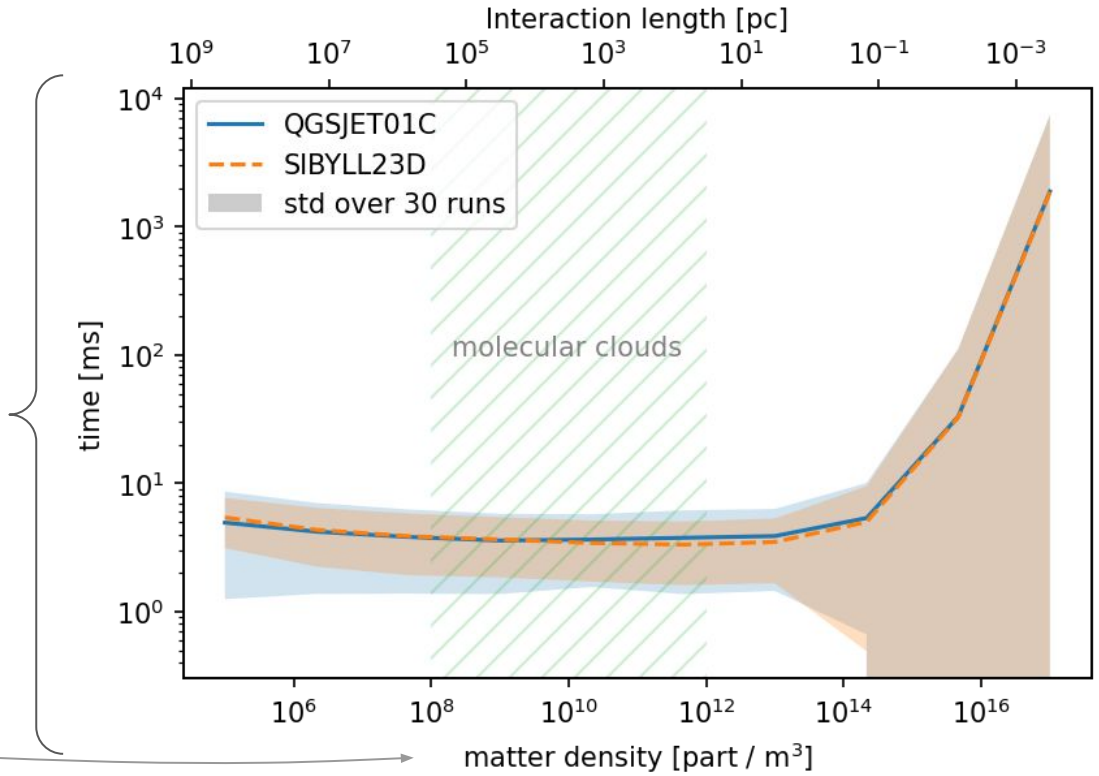


Currently under development…

- Multiple species of targets (p, He, Fe, etc.)
- Input of spectral density of targets
- Decays of secondaries (those not in CRPropa)

Density/luminosity variable with time

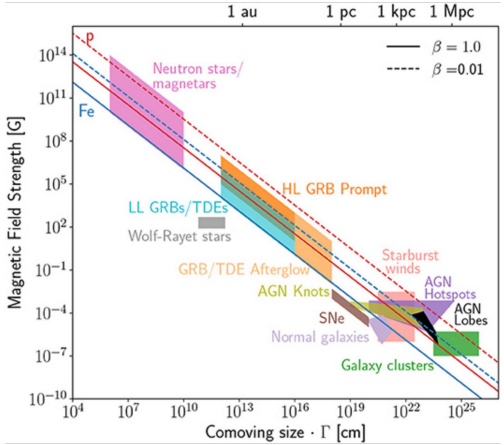




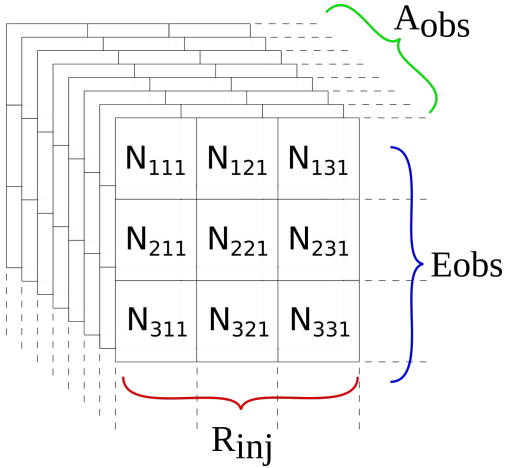
MultI-messenger probe of Cosmic Ray Origins

Frontlines

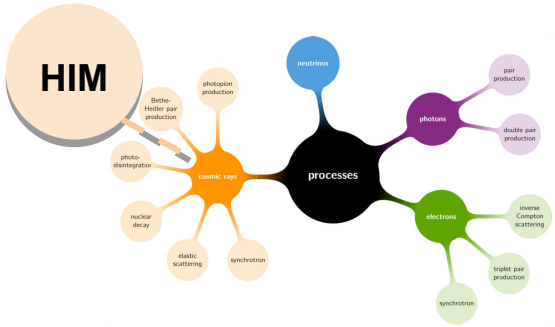
Analysis and experimental data



Propagation



Source Modelling



Check the website for updates

https://micro-uhecr.github.io/

https://github.com/micro-uhecr