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# UHECR composition in source simulations with CRPropa

Leonel Morejon

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SFB-1491 CIM General Assembly

6-9.11.2023

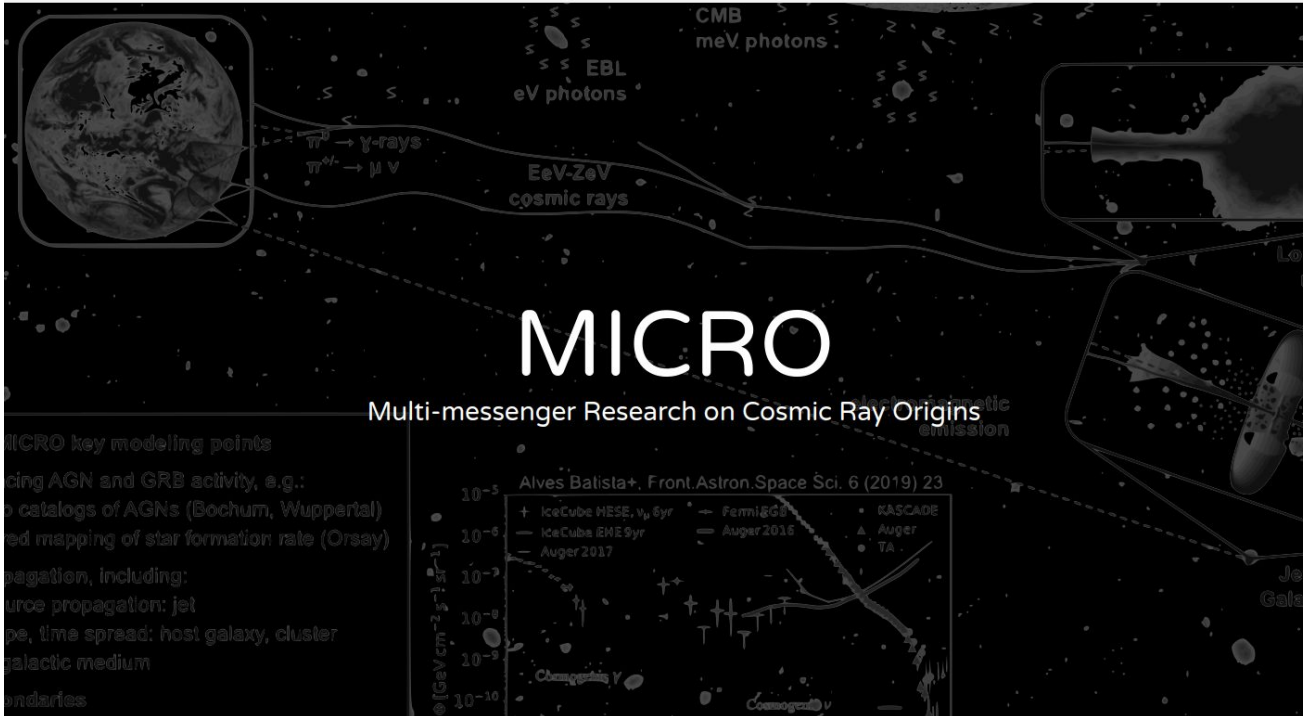


**BERGISCHE  
UNIVERSITÄT  
WUPPERTAL**

# Multi-messenger probe of Cosmic Ray Origins

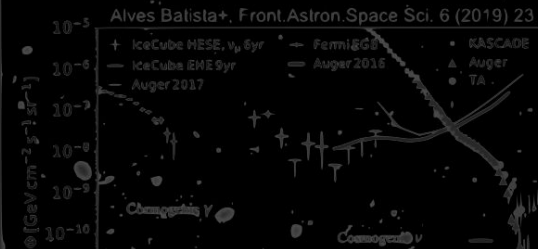


Updates Research About Members



MICRO key modeling points

- AGN and GRB activity, e.g.:
- AGN catalogs (Bochum, Wuppertal)
- Galactic mapping of star formation rate (Orsay)
- Propagation, including:
- Source propagation: jet
- Time spread: host galaxy, cluster
- Galactic medium
- Boundaries



## Participating institutions



## Funded by:

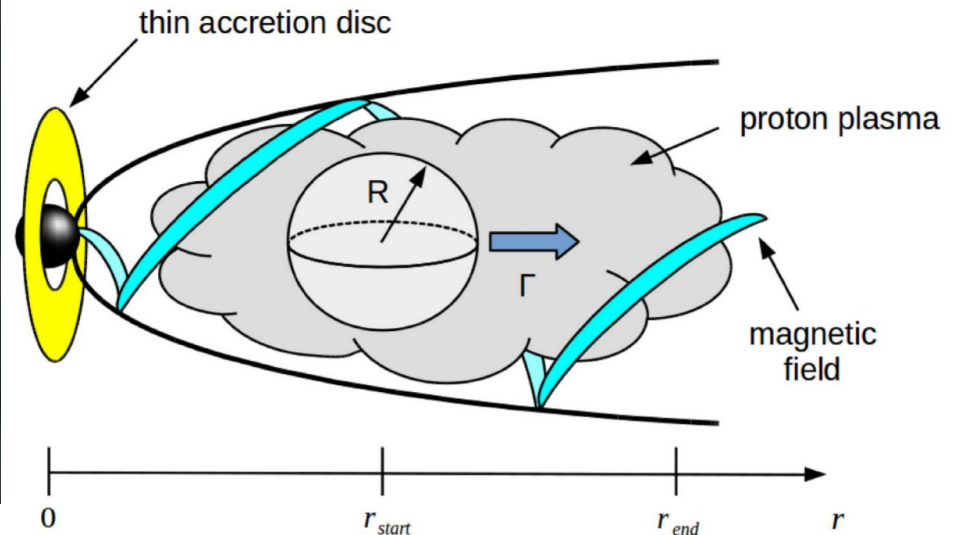


# Bursting Sources of UHECRs: AGNs

Ongoing work by Leander and Marcel



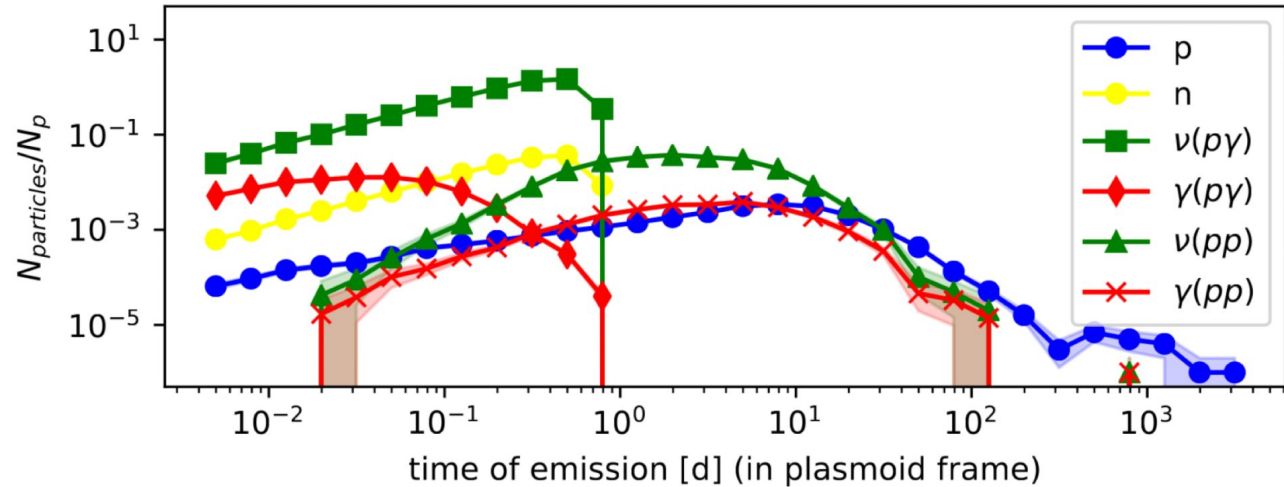
Source: DESY



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

# Bursting Sources of UHECRs: AGNs

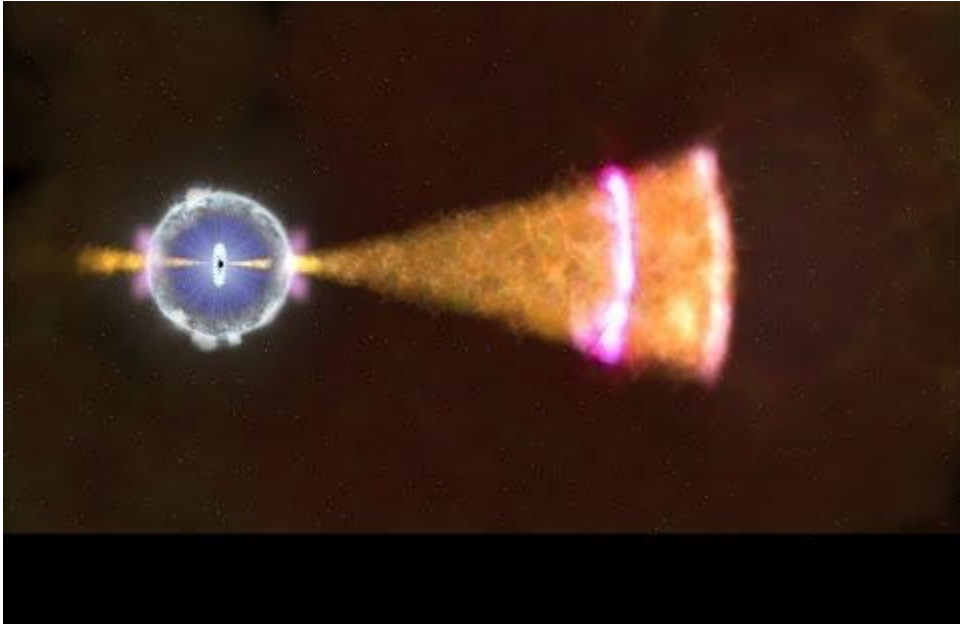
Ongoing work by Leander and Marcel



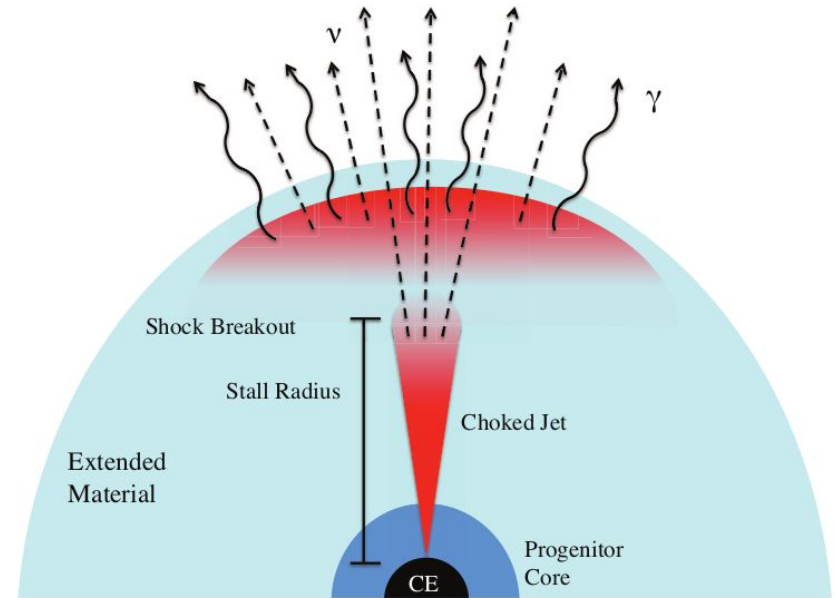
Source: DESY

# Bursting Sources of UHECRs: Choked GRBs

Scenarios I am currently working on



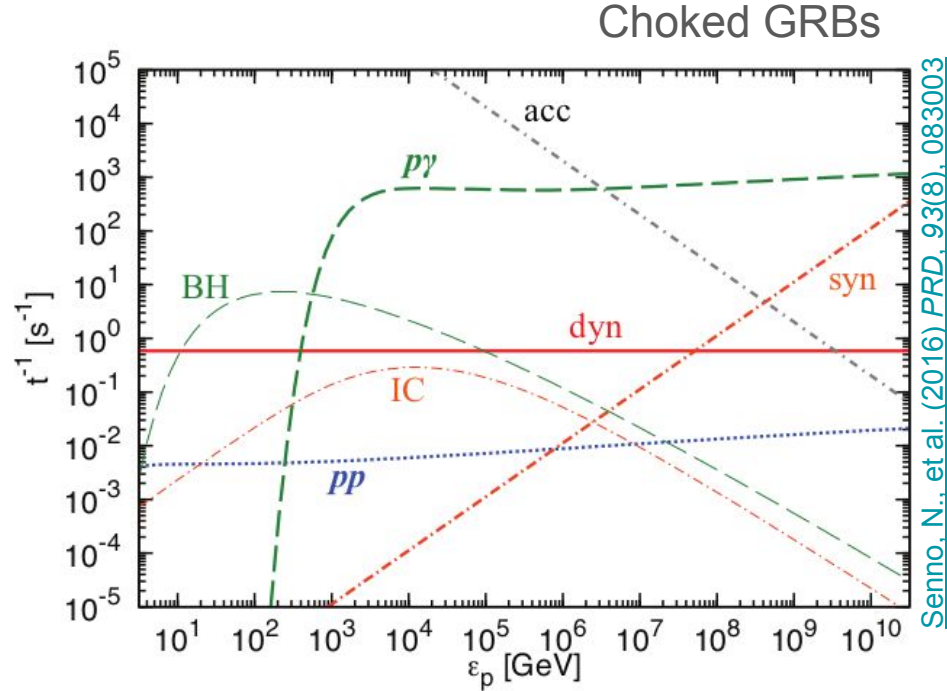
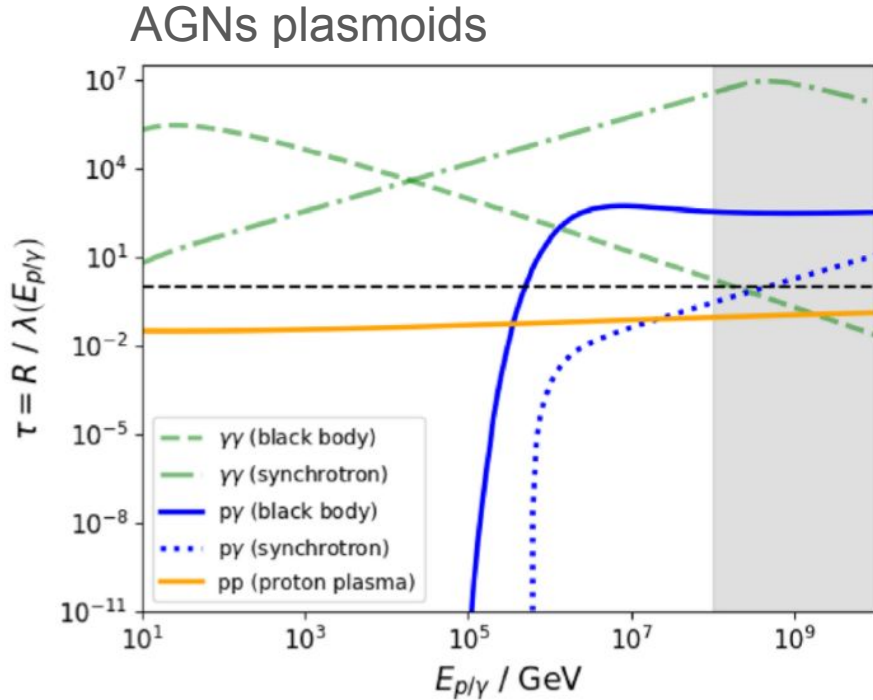
[Source: NASA](#)



[Senno, N., et al. \(2016\) PRD, 93\(8\), 083003](#)

# Bursting Sources of UHECRs: Relevant Interactions

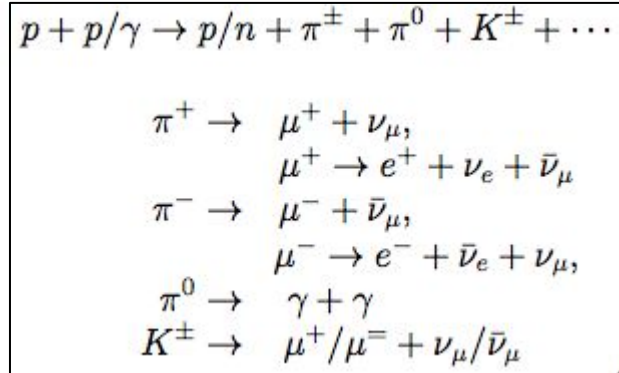
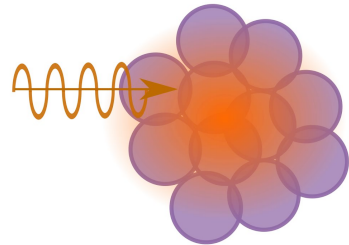
Necessity of simulating both **p-p** and **p- $\gamma$**  interactions consistently!



# Modeling interactions and secondaries' spectra

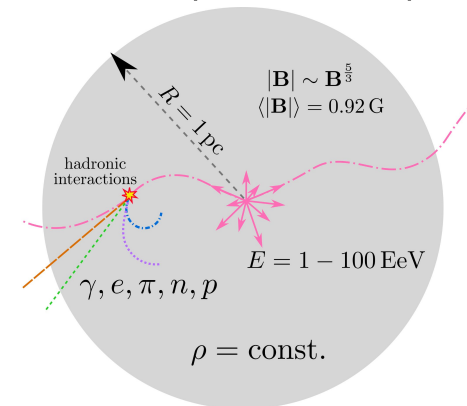
## Interactions discussed

Photohadronic  
(photomeson)



[L. Morejon, et al, JCAP 11 \(2019\) 007](#)

Hadronic (p+p, p+A)

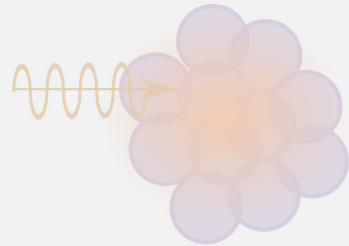


[L. Morejon, K.H.Kampert PoS ICRC2023 \(2023\) 285](#)

# Modeling interactions and secondaries' spectra

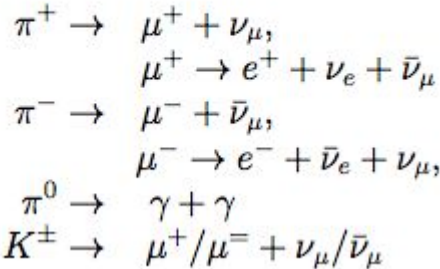
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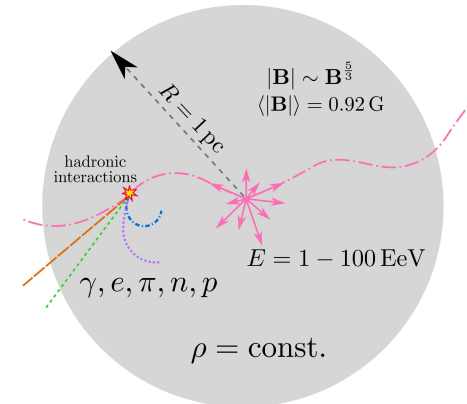


[L. Morejon, et al, JCAP 11 \(2019\) 007](#)

$$p + p/\gamma \rightarrow p/n + \pi^\pm + \pi^0 + K^\pm + \dots$$



Hadronic (p+p, p+A)



[L. Morejon, K.H.Kampert PoS ICRC2023 \(2023\) 285](#)



# Workflow in CRPropa

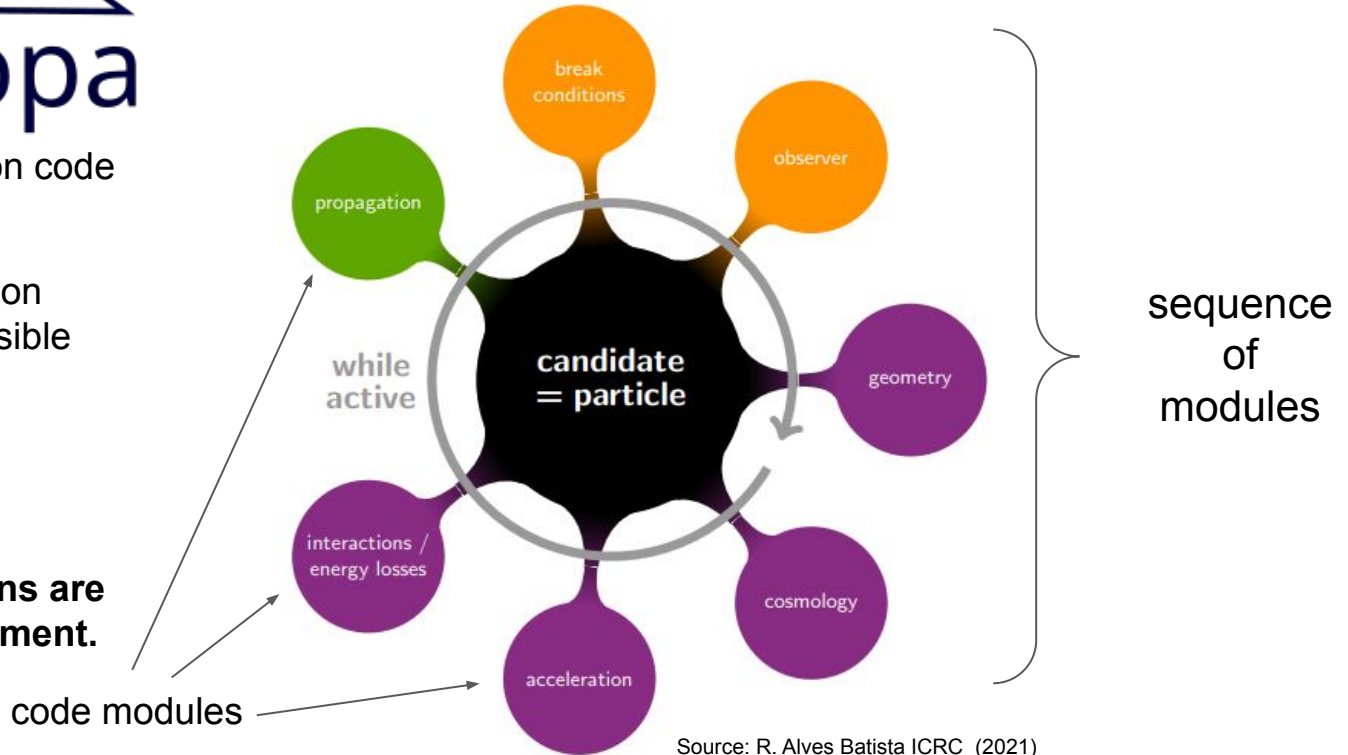
# CRPropa

Cosmic Ray Propagation code

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

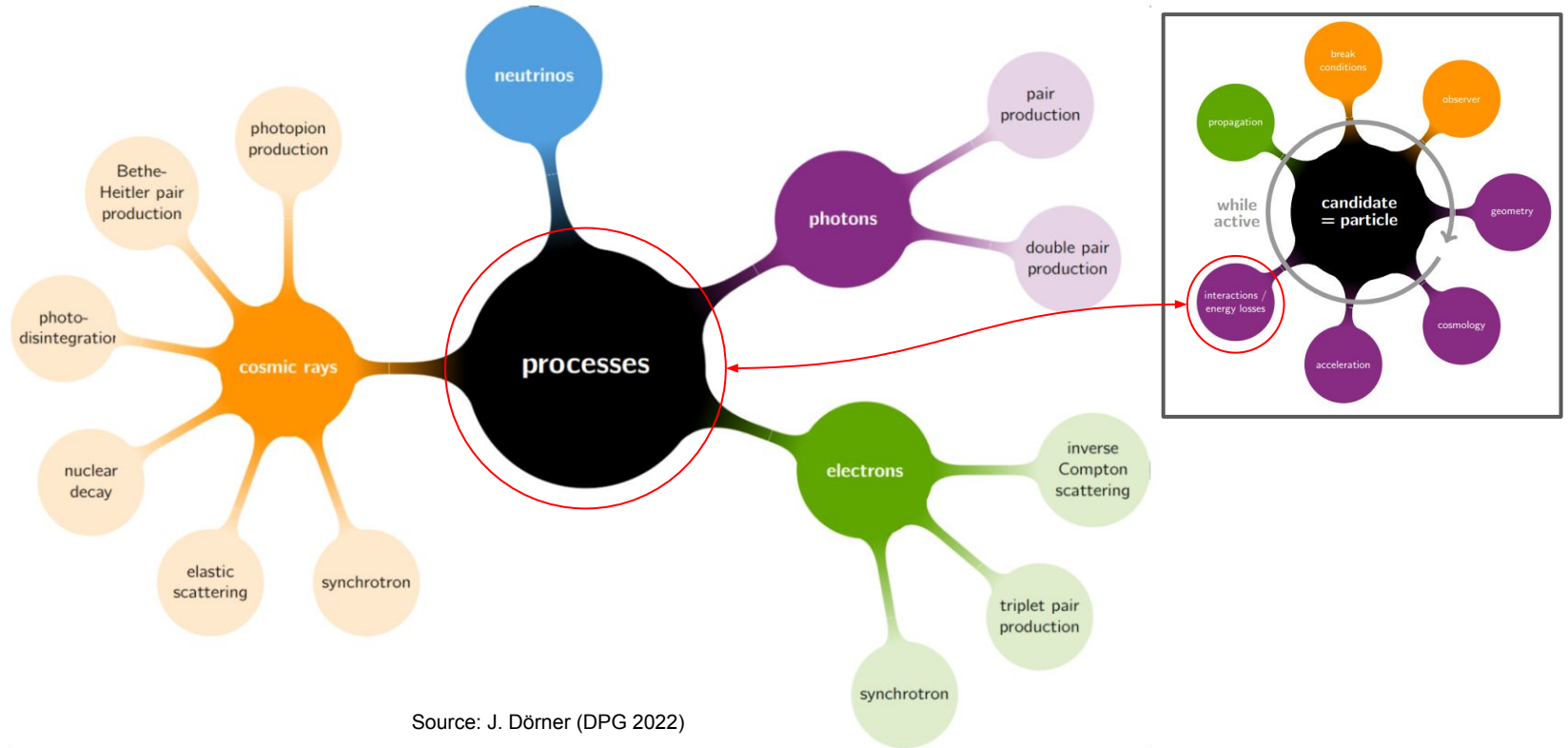


**Extensions and plugins are under active development.**



Source: R. Alves Batista ICRC (2021)

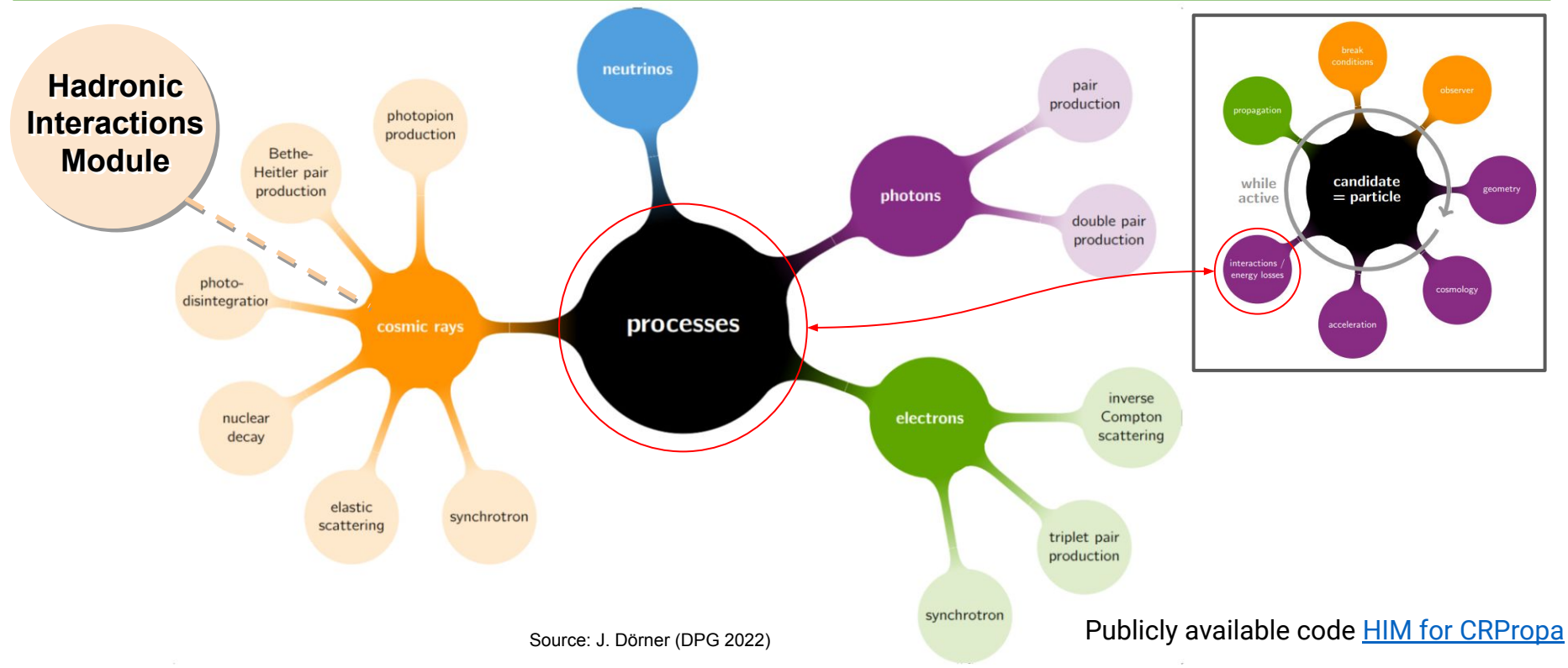
# Interactions in CRPropa



Source: J. Dörner (DPG 2022)

# Hadronic interactions

## Hadronic Interactions Module (HIM)



# Hadronic interactions

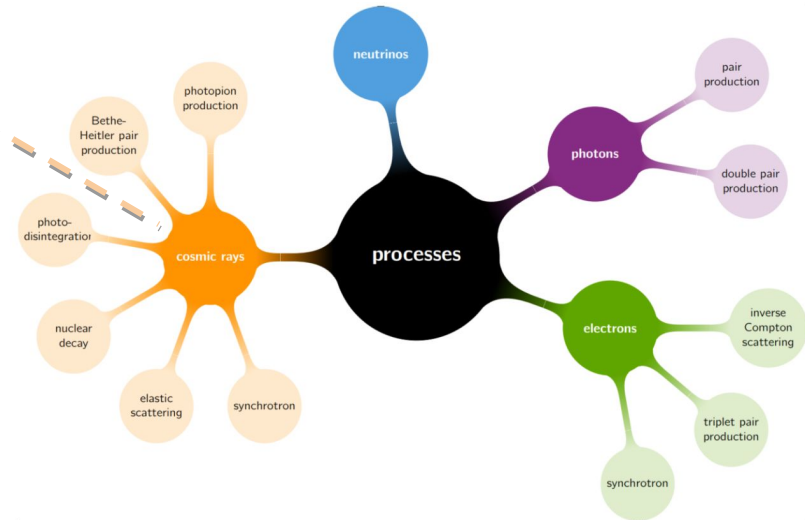
## Elements of the HIM

- 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 (installation separate from CRPropa)

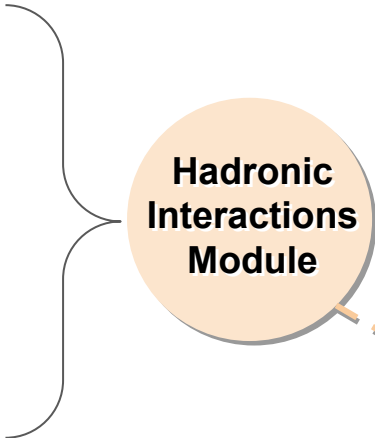
Publicly available code [HIM for CRPropa](#)



# Hadronic interactions

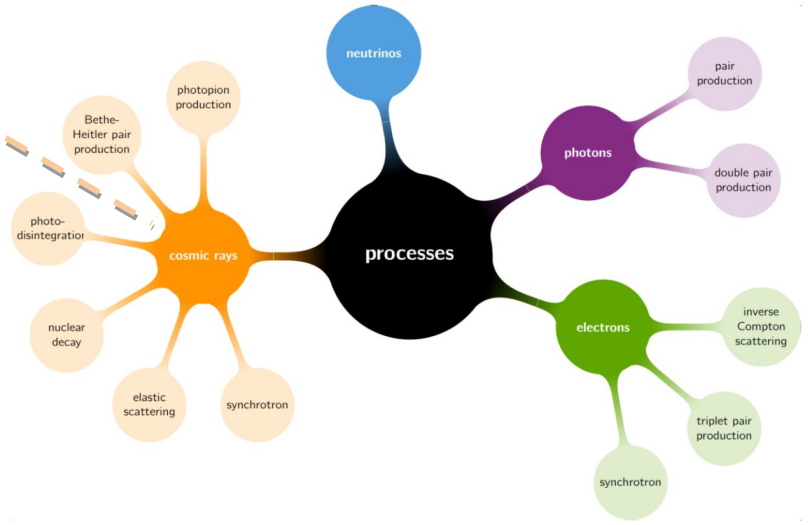
## New interface: CHROMO

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



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

Publicly available code [HIM for CRPropa](#)



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

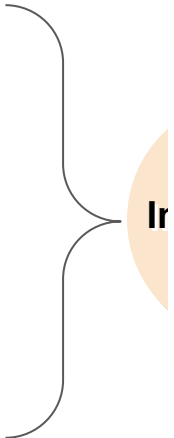


Cosmic ray and HadRONic interactiOn MONte-carlo frontend

# Hadronic interactions

## CHROMO

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



Interaction model	Supported proj/targ
DPMJET-III 3.0.6 & PHOJET 1.12-35	<i>hN, <math>\gamma\gamma, \gamma N, hA, \gamma A, AA</math></i>
DPMJET-III & PHOJET 19.1 and 19.3 (repo on GitHub)	<i>hN, <math>\gamma\gamma, \gamma N, hA, \gamma A, AA</math></i>
EPOS-LHC	<i>hN, hA, AA</i>
PYTHIA 6.4	<i>hN, <math>ee, \gamma\gamma, \gamma N</math></i>
PYTHIA 8.3 ( <a href="https://pythia.org/">https://pythia.org/</a> )	<i>hN, <math>ee, \gamma\gamma, \gamma N</math> &amp; <math>hA, AA</math> (Argantyr)</i>
QGSJet-01	<i>hN, hA, AA</i>
QGSJet-II-03	<i>hN, hA, AA</i>
QGSJet-II-04	<i>hN, hA, AA</i>
SIBYLL-2.1	<i>hN, hA (A&lt;=20)</i>
SIBYLL-2.3d	<i>hN, hA (A&lt;=20)</i>
SOPHIA 2.0	<i><math>\gamma N</math></i>
UrQMD 3.4 + second citation	<i>hN, hA, AA*</i>

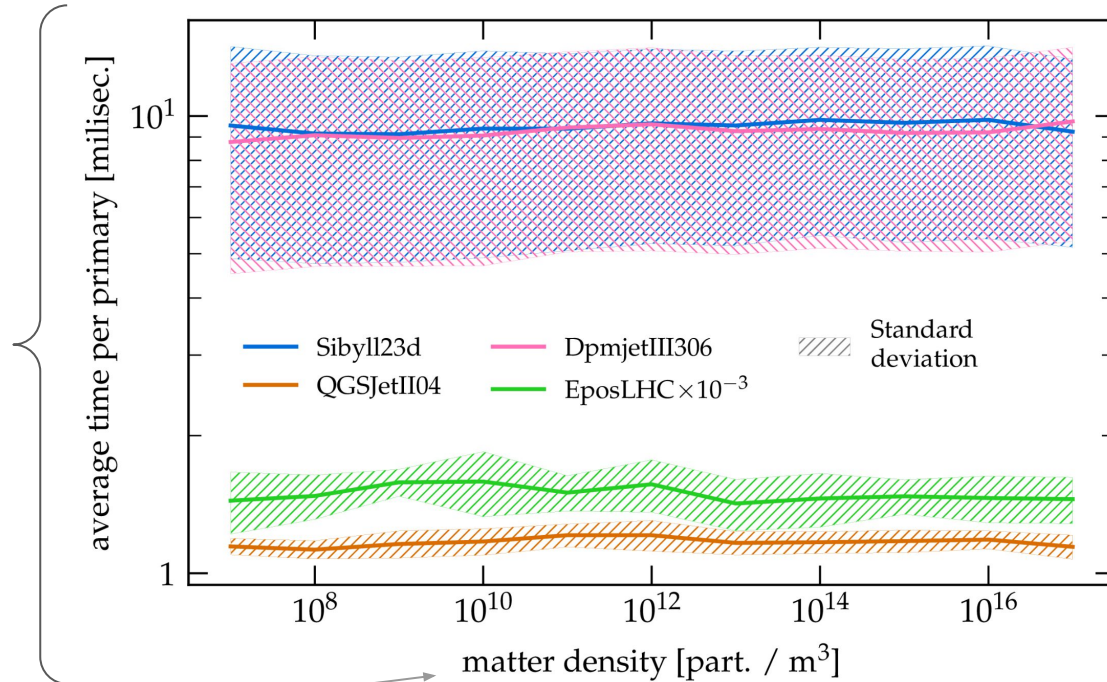
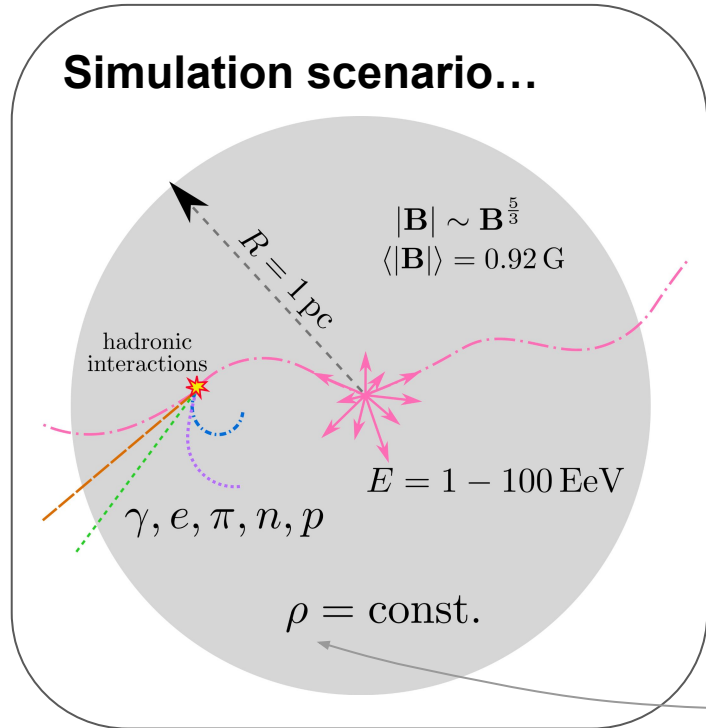
<https://github.com/impj-proje>



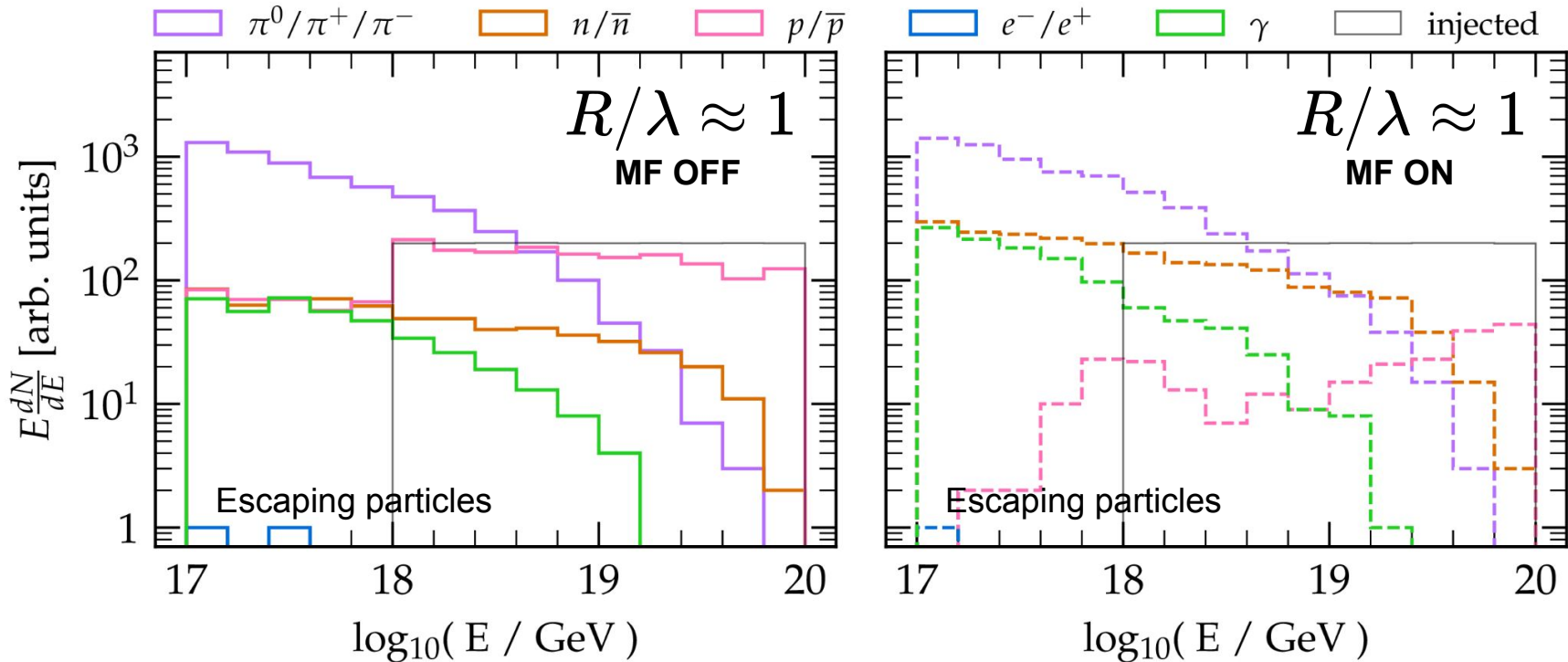
Cosmic ray and HadRONic interactiOn MOnTe-carlo frontend

# Hadronic interactions

## Simulation time versus matter density



## Magnetic Field ON versus OFF

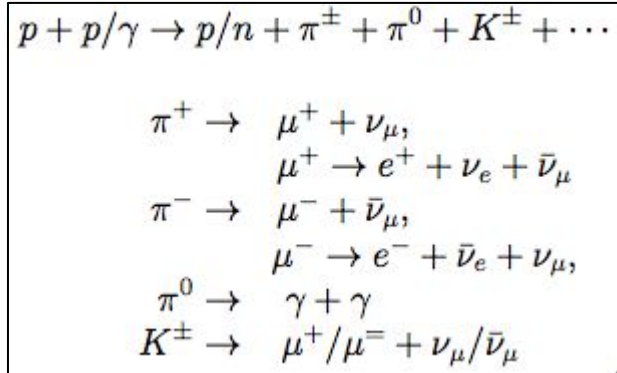
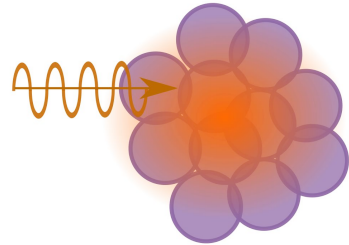




# Which interaction models??

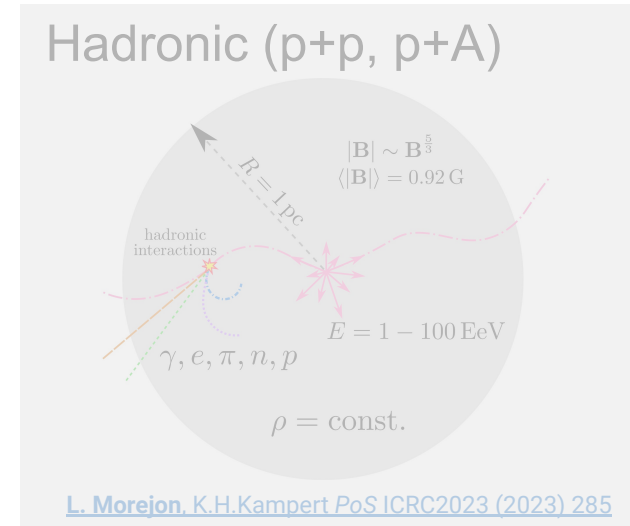
## Interactions discussed

### Photohadronic (photopion)



[L. Morejon, et al, JCAP 11 \(2019\) 007](#)

### Hadronic (p+p, p+A)



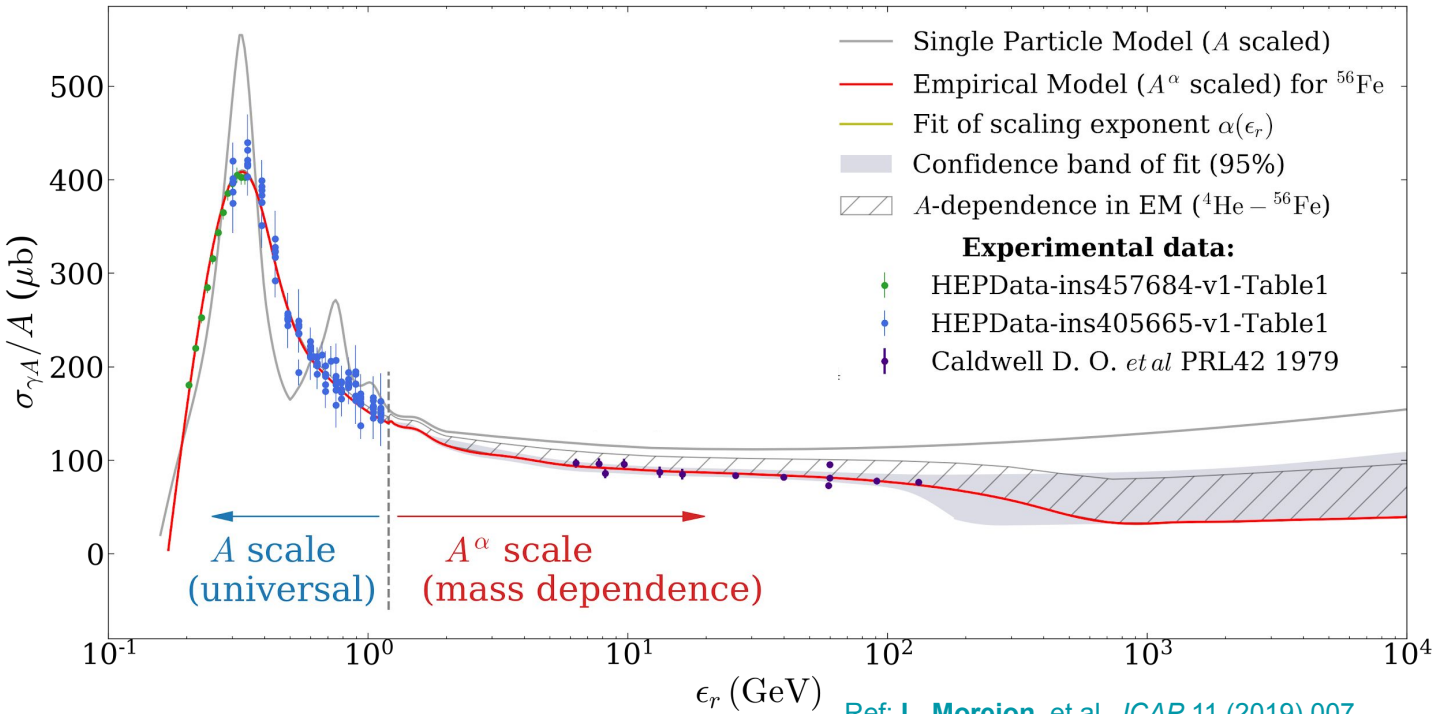
[L. Morejon, K.H.Kampert PoS ICRC2023 \(2023\) 285](#)

# Photohadronic interactions

## Total photonuclear cross section

### Properties:

- Universal curve for all masses
- Smeared resonances
- Mass scaling is energy dependent

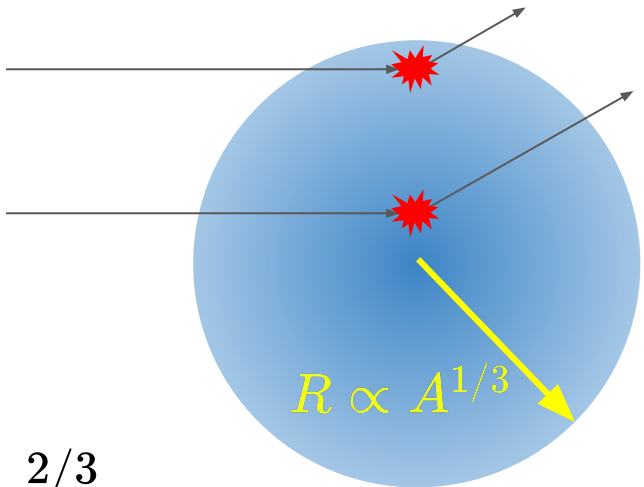
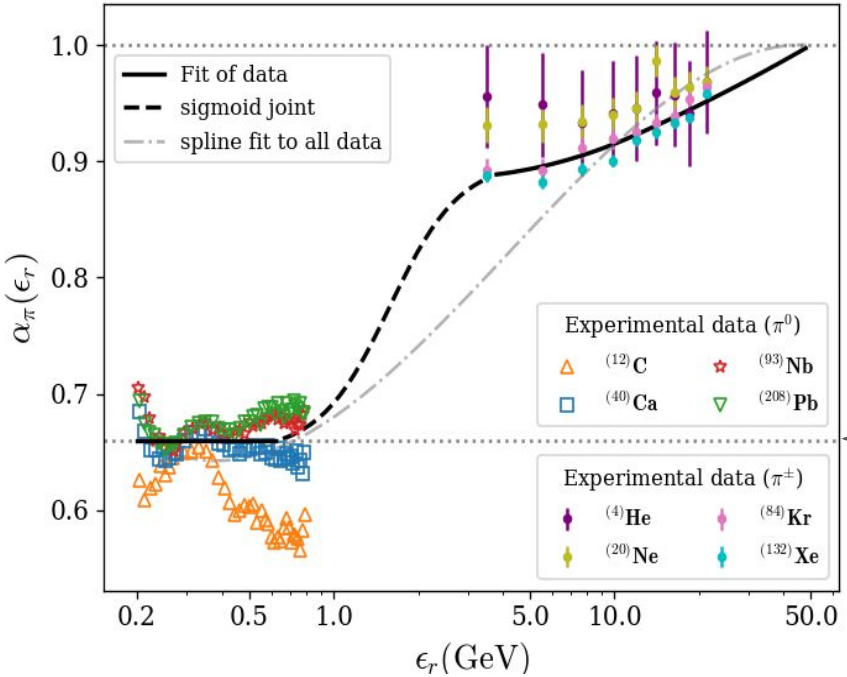


Ref: [L. Morejon, et al. JCAP 11 \(2019\) 007](#)

# Photohadronic interactions

## Photopion suppression

Energy dependent escape, decrease of production

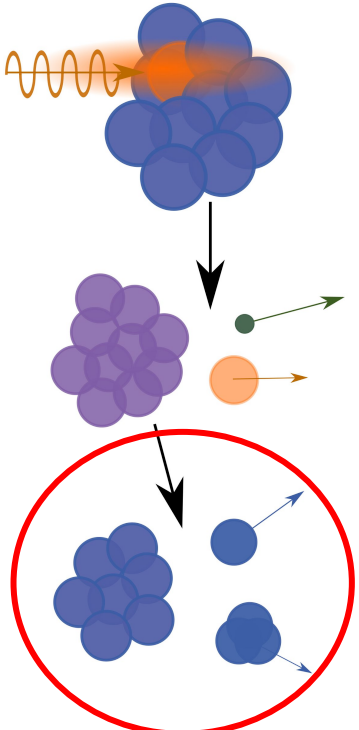


$$\sigma \propto A^\alpha$$

Ref: [L. Morejon, et al, JCAP 11 \(2019\) 007](#)

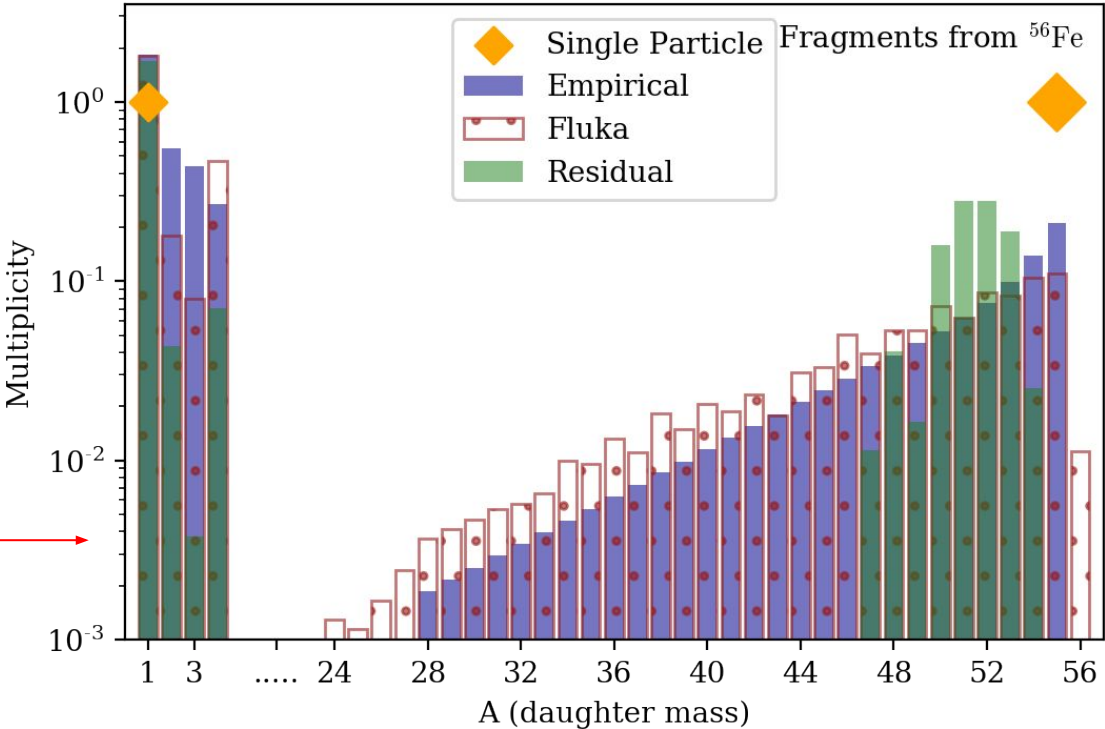
# Photohadronic interactions

## Cascade Enhancement



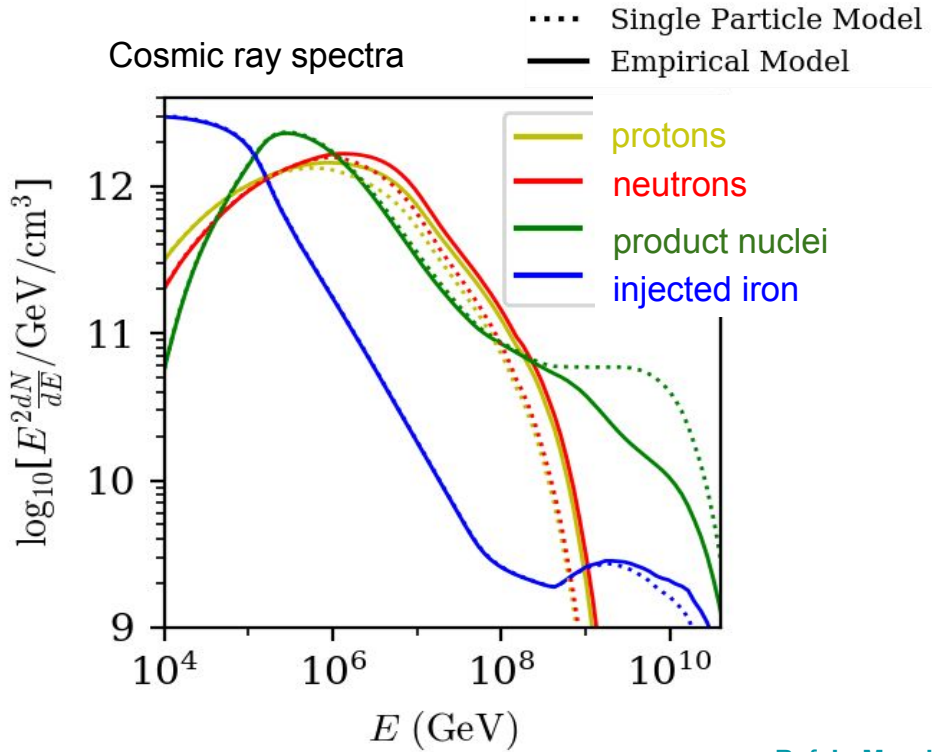
Ref: [L. Morejon, et al, JCAP 11 \(2019\) 007](#)

### Photopion production with cascade

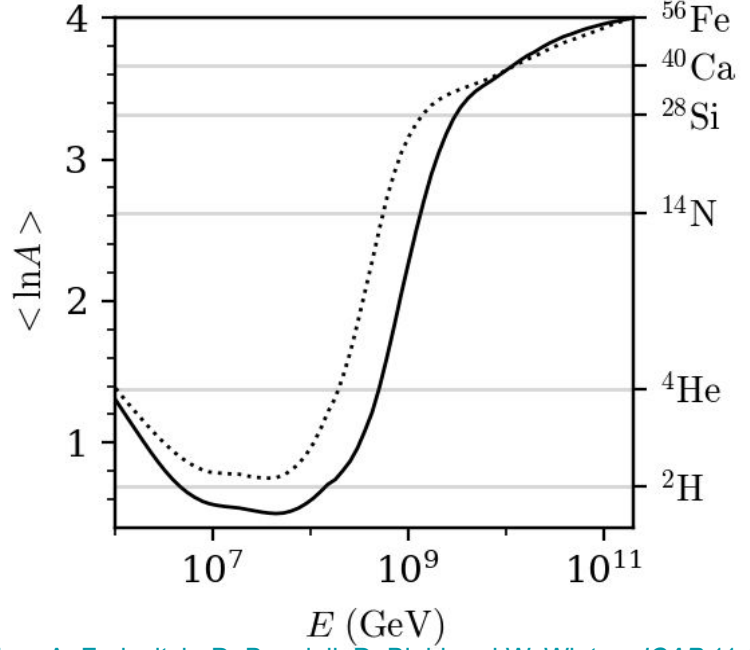


# Photohadronic interactions

## Impact on source simulation: GRB

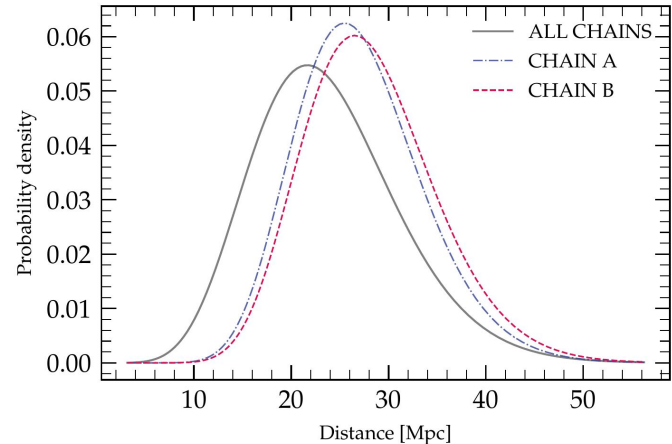
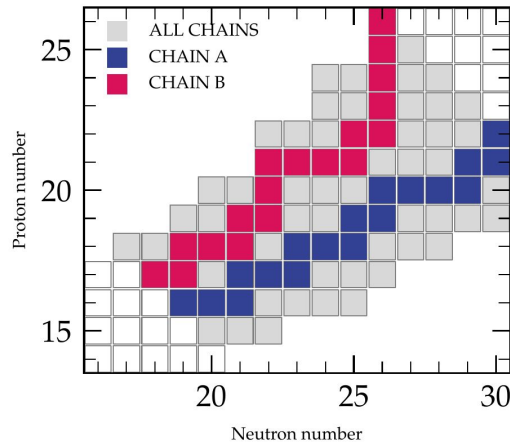


## Remarkable differences in cascade composition!



Ref: [L. Morejon, A. Fedynitch, D. Boncioli, D. Biehl and W. Winter, JCAP 11 \(2019\) 007](#)

# Probability distributions of disintegration chains of UHECR nuclei

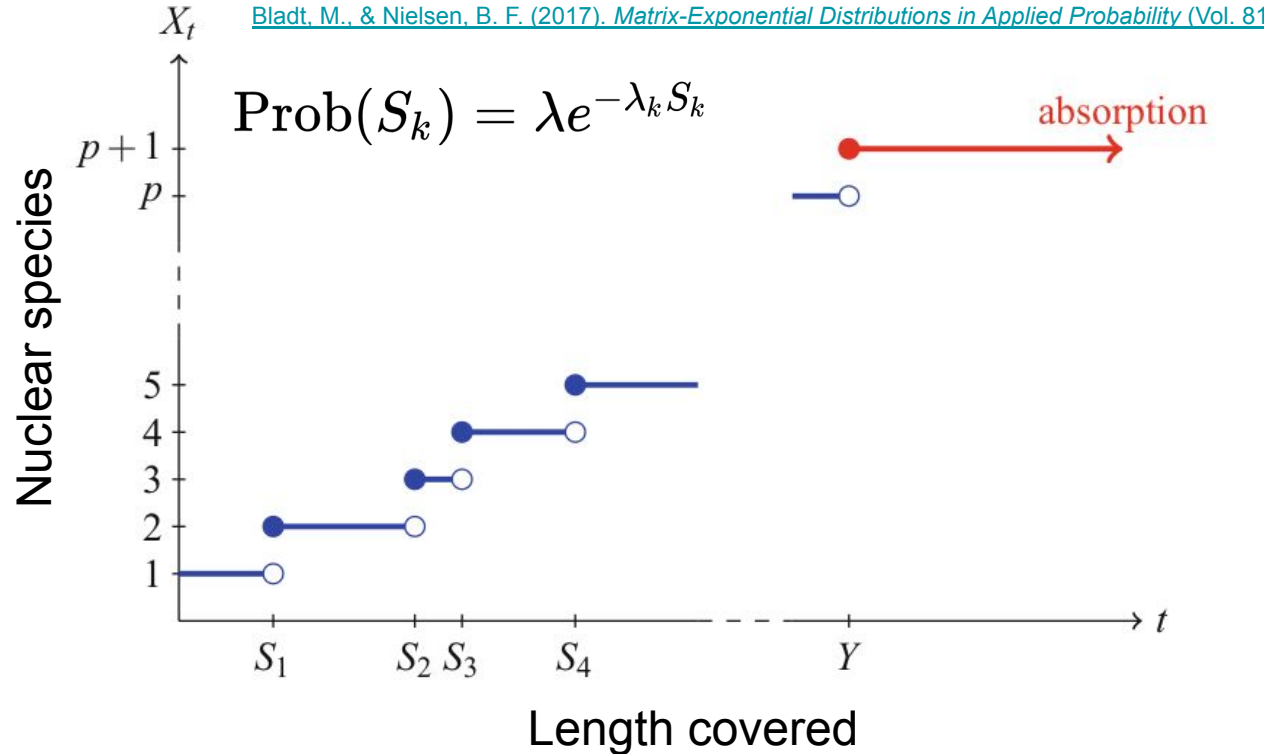


# UHECR disintegration as a Markov Process

The successive disintegrations in UHECR are stochastic.

The propagation is equivalent to a Markov jump process (CTMC).

Jumps are transitions between nuclear species.



# Matrix Exponential Distributions: Construction

Theoretical expressions for distribution

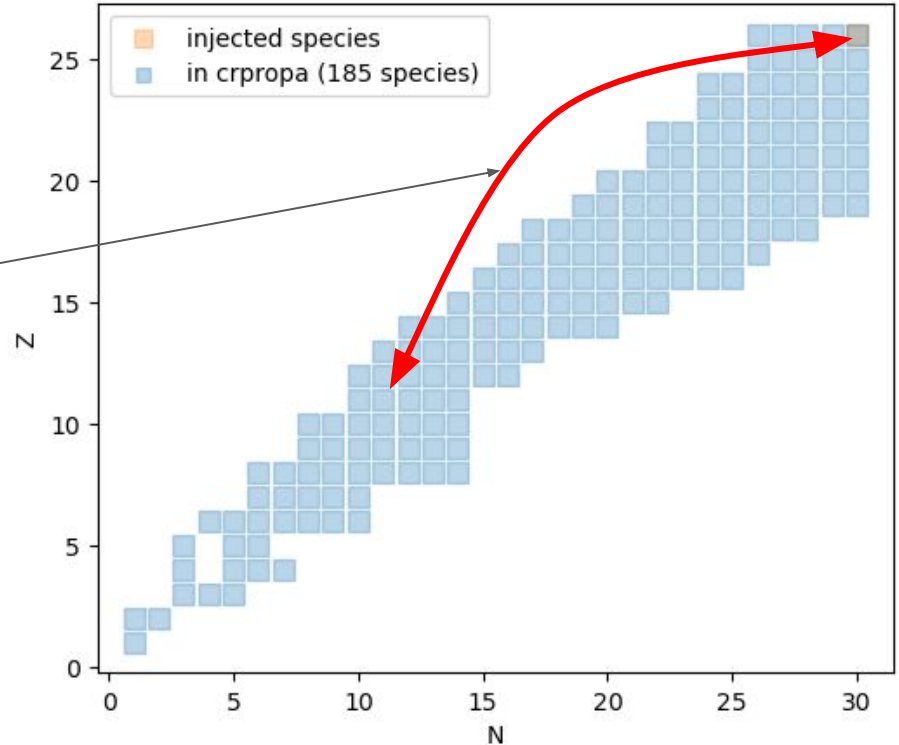
$$f(L) = \boldsymbol{\pi} \exp(\boldsymbol{\Lambda}L) \boldsymbol{\Lambda} \mathbf{e}$$

**Matrix Exponential (ME) distribution**

$$\boldsymbol{\Lambda}(\boldsymbol{\gamma}) = \begin{pmatrix} -\lambda_{S_1}^{\text{tot}} & \lambda_{S_1 \rightarrow S_2} & \lambda_{S_1 \rightarrow S_3} & \lambda_{S_1 \rightarrow S_4} & \lambda_{S_1 \rightarrow S_5} & \dots \\ 0 & -\lambda_{S_2}^{\text{tot}} & \lambda_{S_2 \rightarrow S_2} & \lambda_{S_2 \rightarrow S_3} & \lambda_{S_2 \rightarrow S_4} & \dots \\ 0 & 0 & -\lambda_{S_3}^{\text{tot}} & \lambda_{S_3 \rightarrow S_3} & \lambda_{S_3 \rightarrow S_3} & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & 0 & \dots \end{pmatrix}$$

Total interaction rate

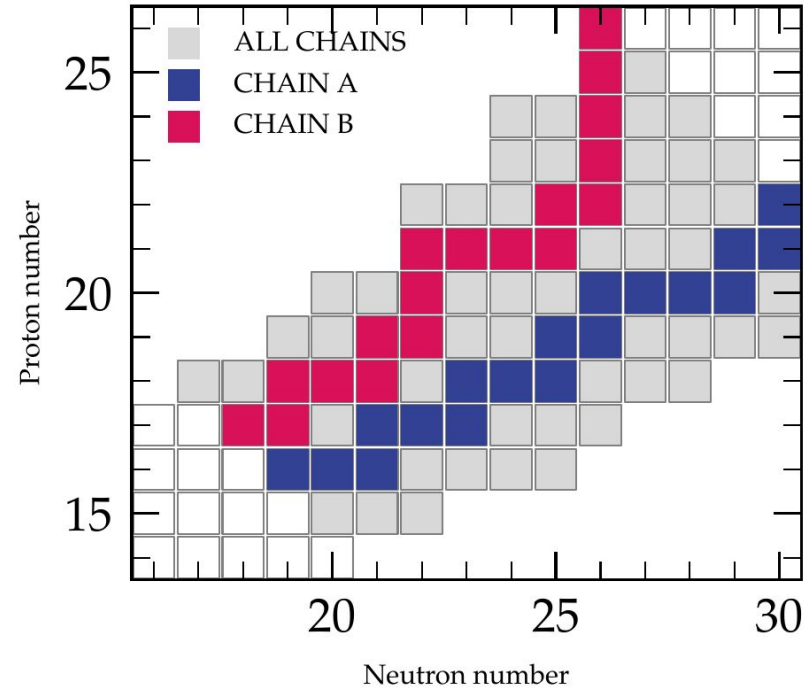
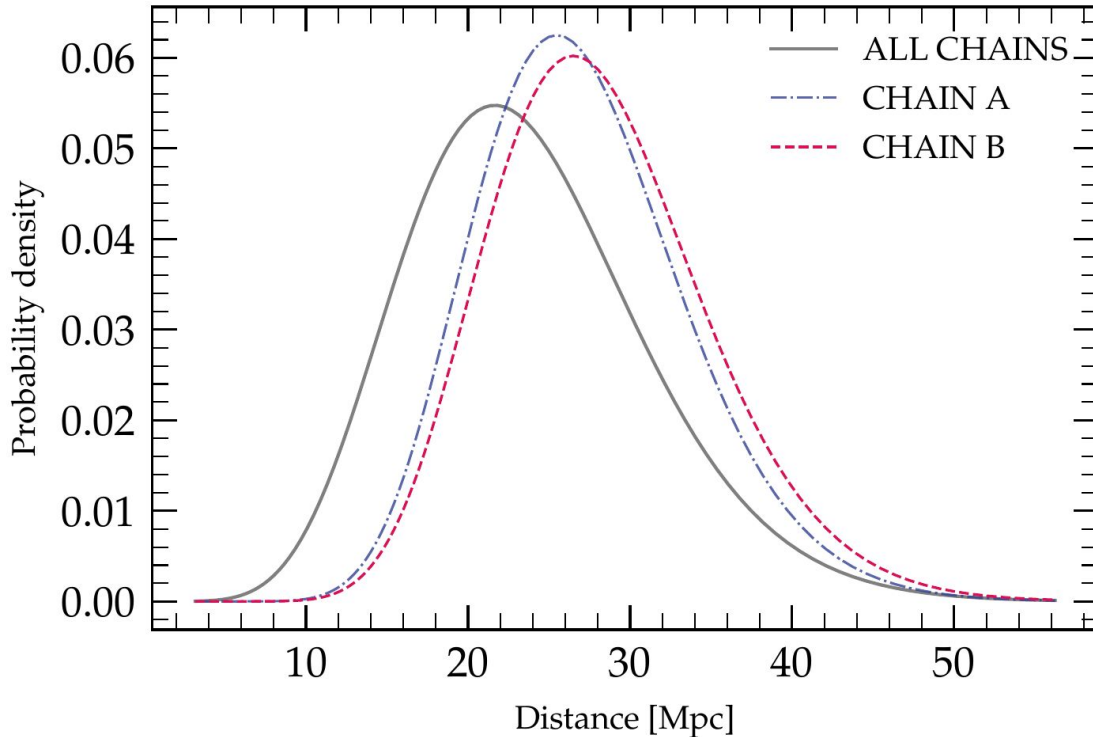
Lower triangular is null (mass increase not possible)





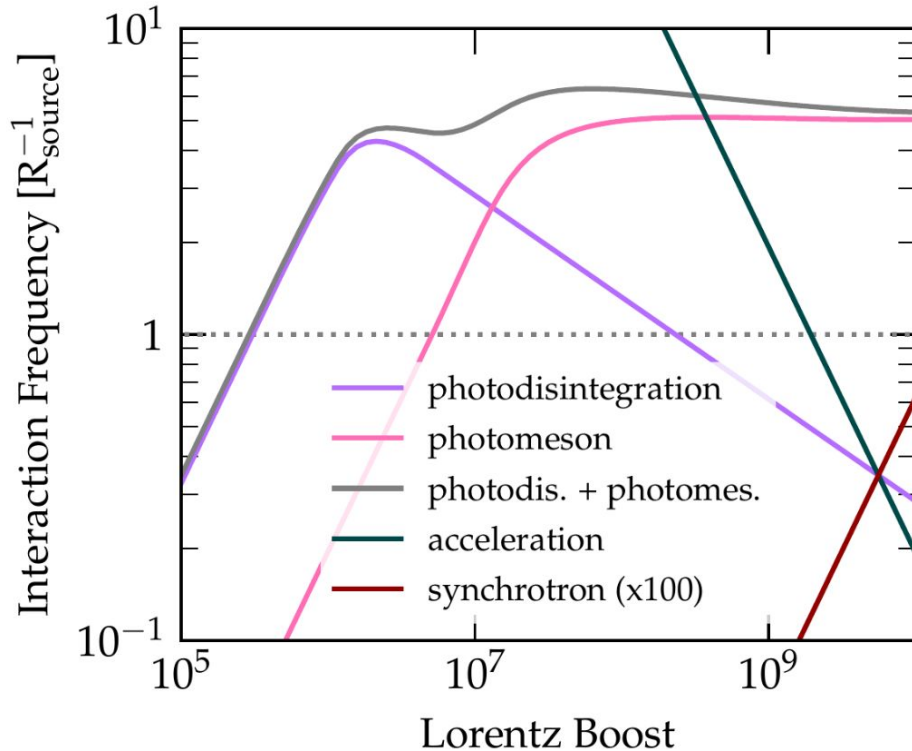
# Example distribution chains

$$f(L) = \pi \exp(\Lambda L) \Lambda e$$



# Example: In-Source propagation

[L. Morejon PoS ICRC2023 \(2023\) 284](#)



## Tidal Disruption Event

SED: Broken power law

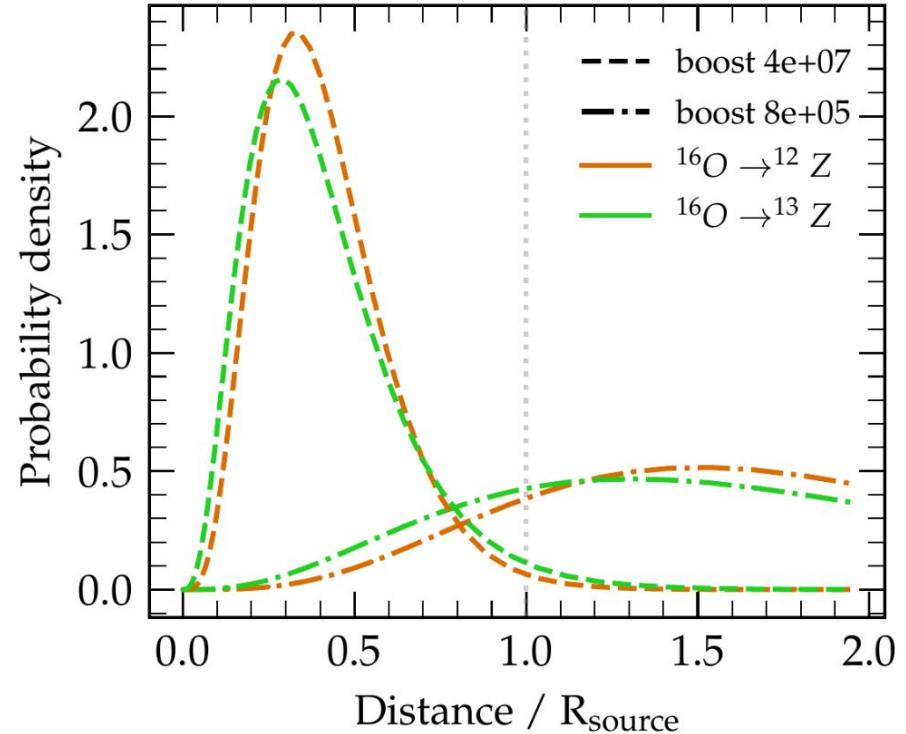
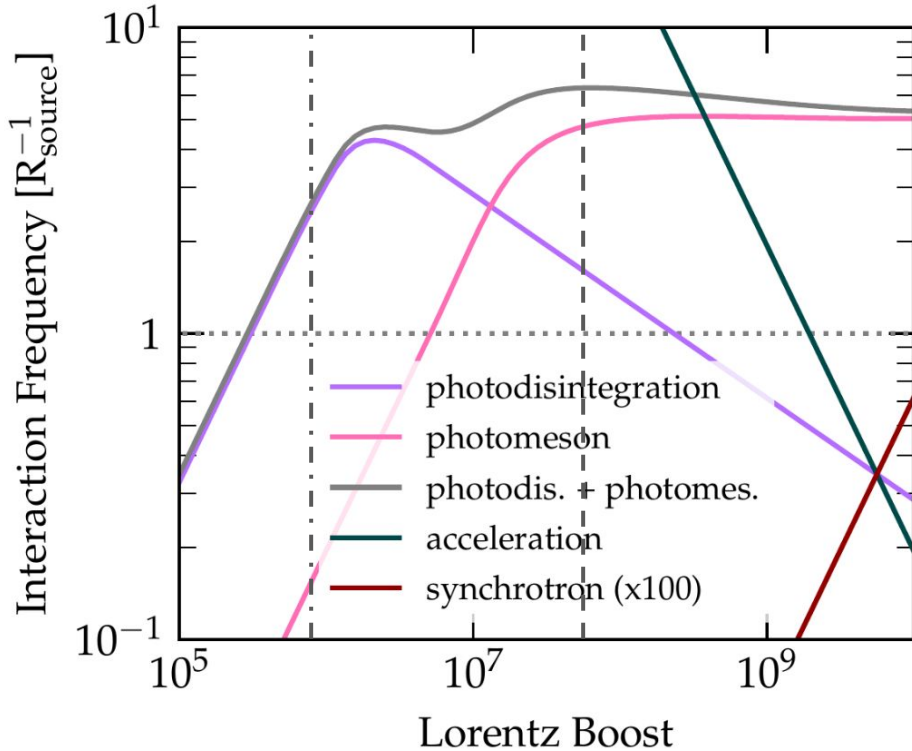
Radius:  $\sim 4E6$  km

Injected species: CNO

**Dominant nuclear interactions are  
boost conserving!**

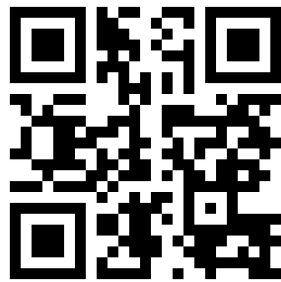
# Example: In-Source propagation

[L. Morejon PoS ICRC2023 \(2023\) 284](#)





MICRO website



MICRO @ github



Photopion @ github



HIM @ github

# Thanks!