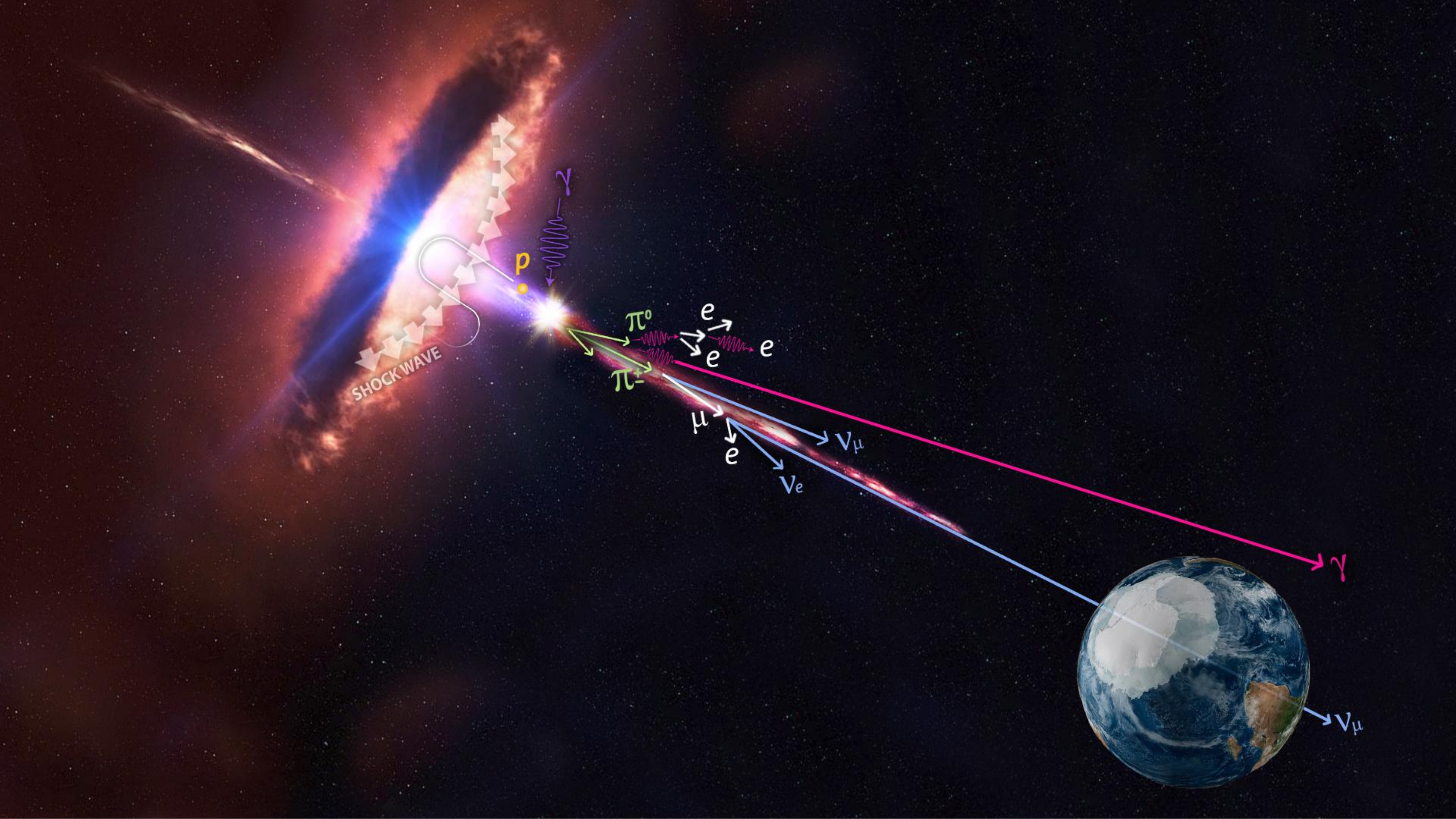
Photonuclear cross sections and UHECR transport: towards more transparency

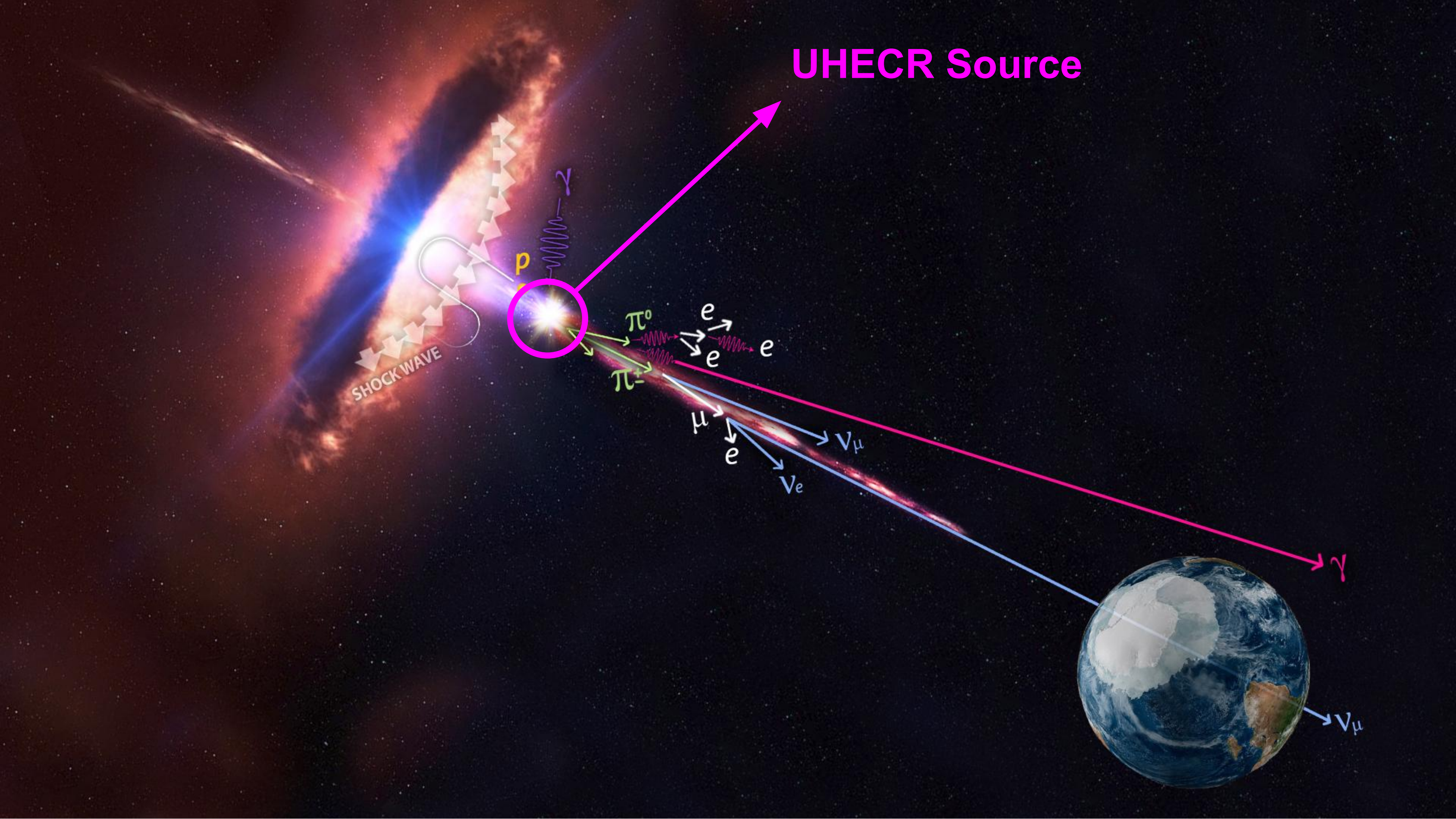
Leonel Morejon

XSCRC 2024 @ CERN

16-18.10.2024



SHOCK WAVE
p
γ
π⁰
π±
e
e
e
e
μ
e
ν_μ
ν_e
γ
ν_μ


UHECR Source
γ
p
SHOCK WAVE
π⁰
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e
e
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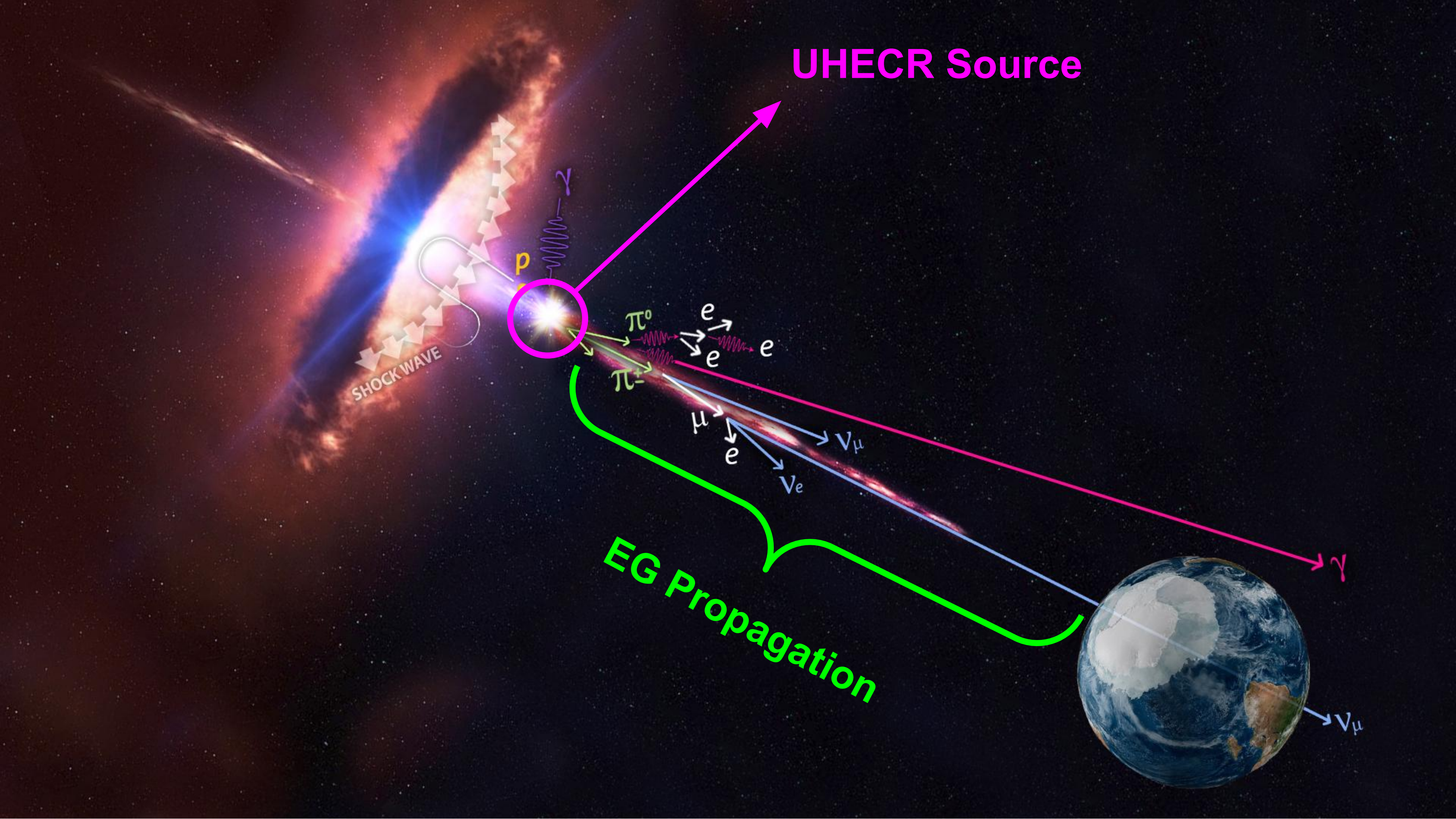
ν_μ


UHECR Source
SHOCK WAVE
γ
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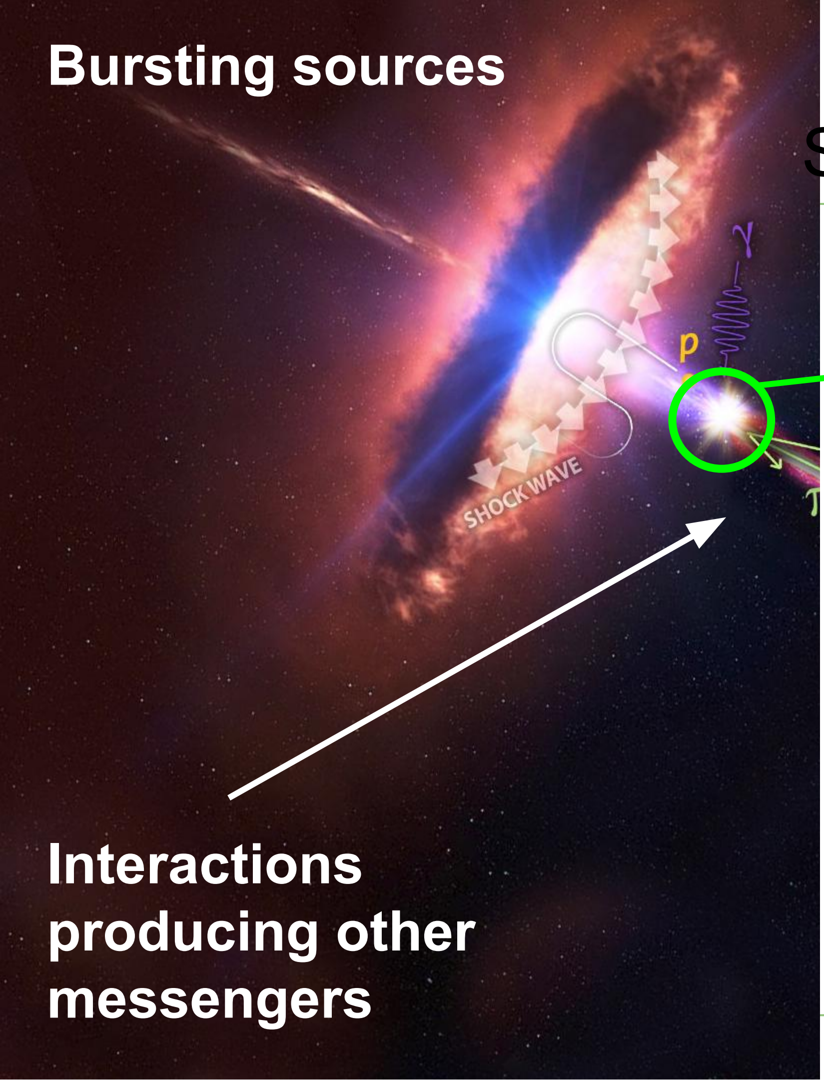
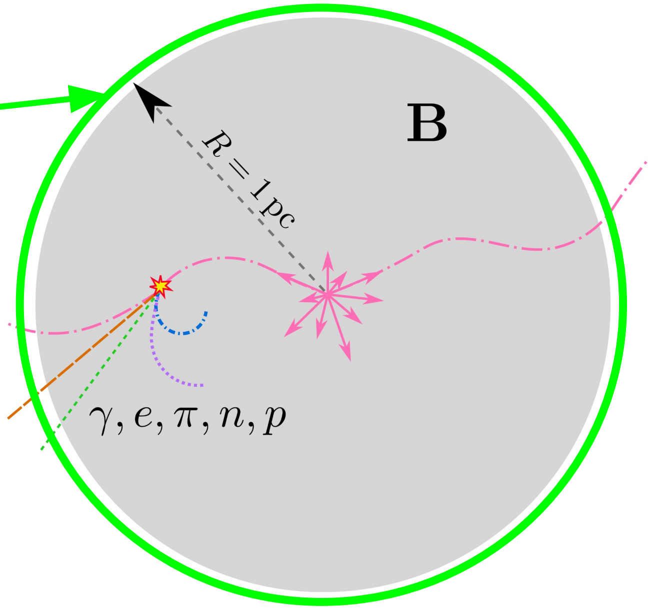
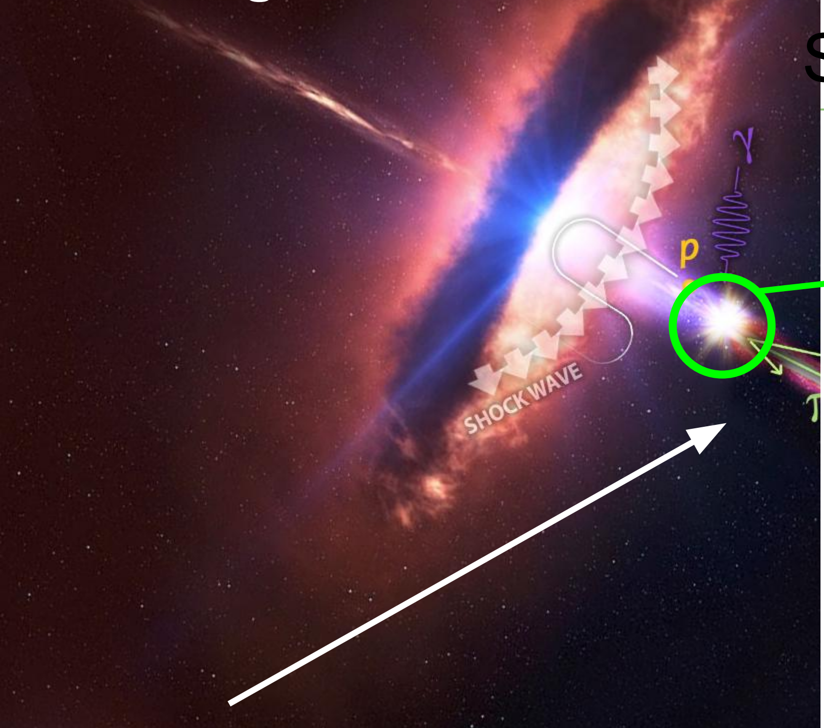
e
νμ
νe
γ
νμ
EG Propagation



Simulating the source environment

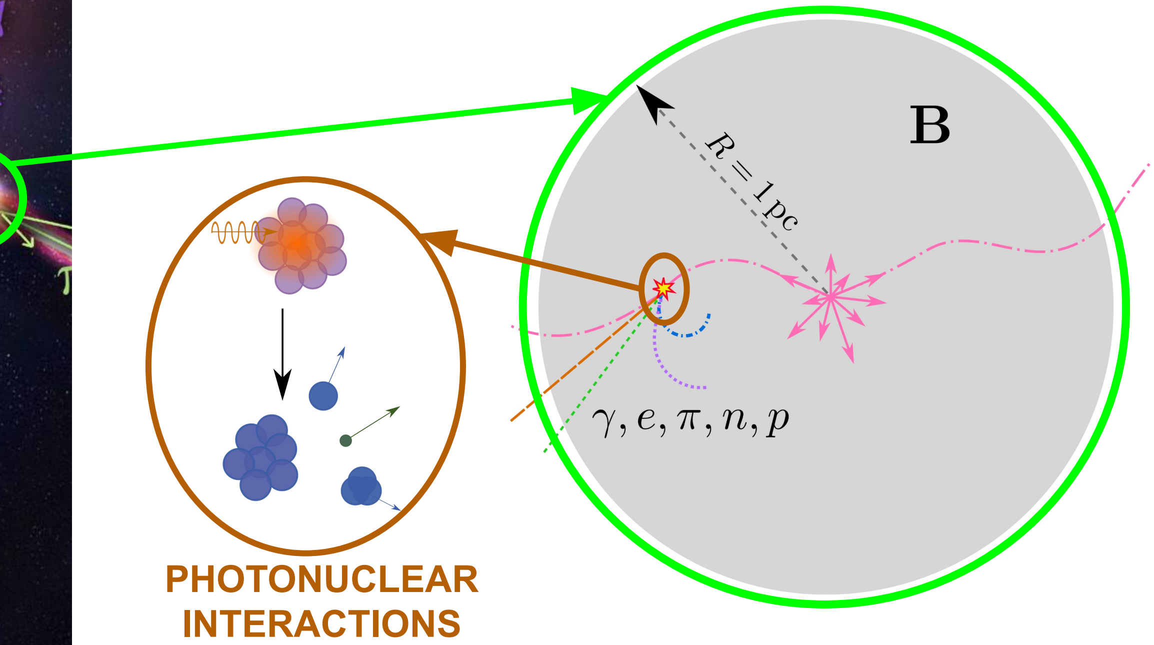


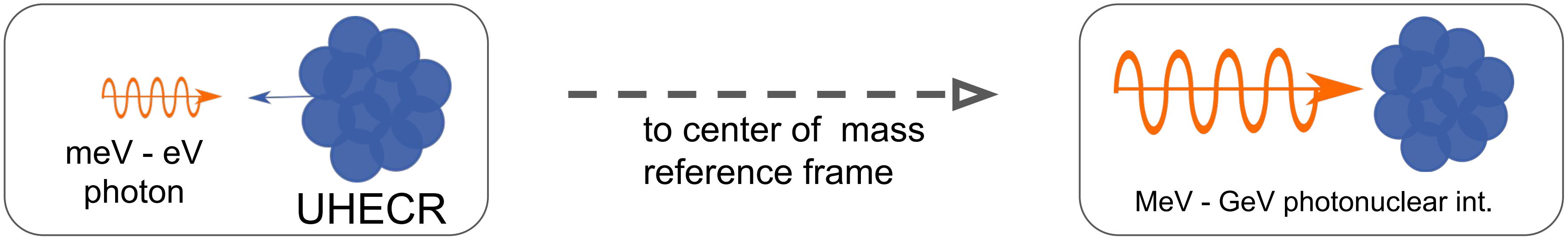
Bursting sources

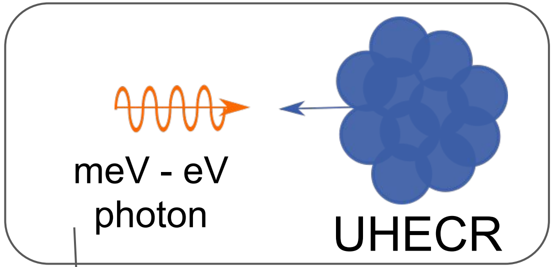


Interactions producing other messengers

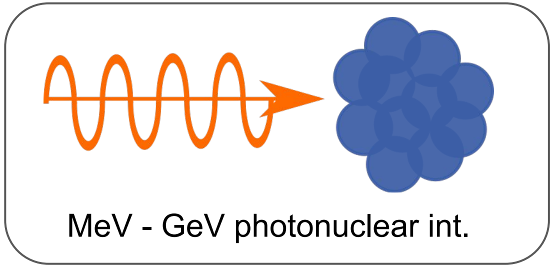
Simulating the source environment



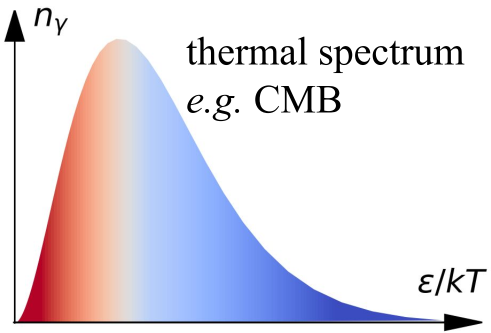

meV - eV
photon
UHECR
to center of mass
reference frame
MeV - GeV photonuclear int.

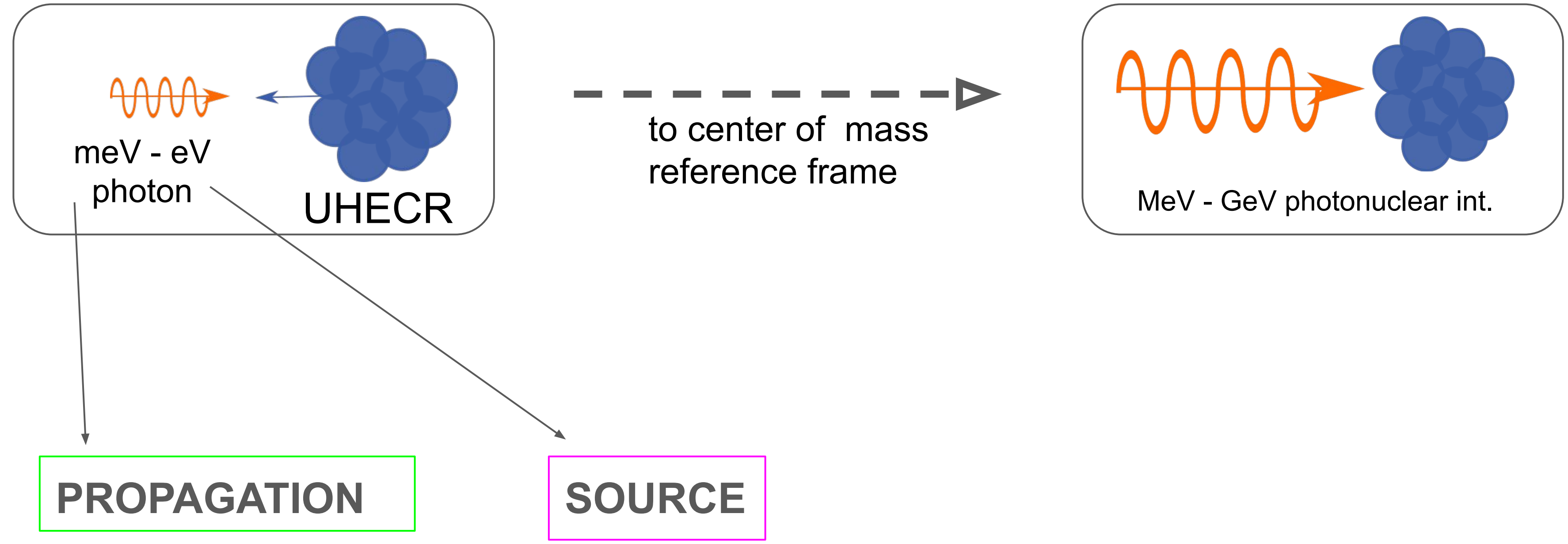


to center of mass reference frame



PROPAGATION

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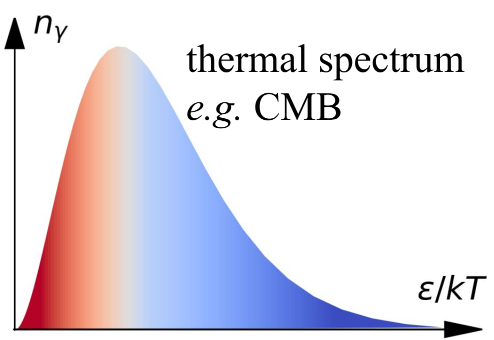
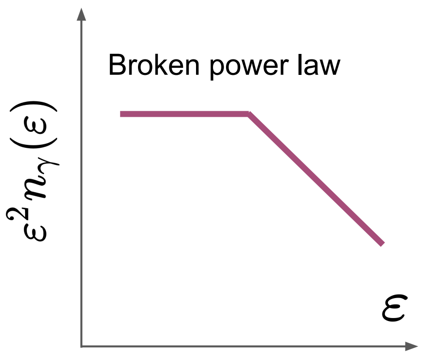
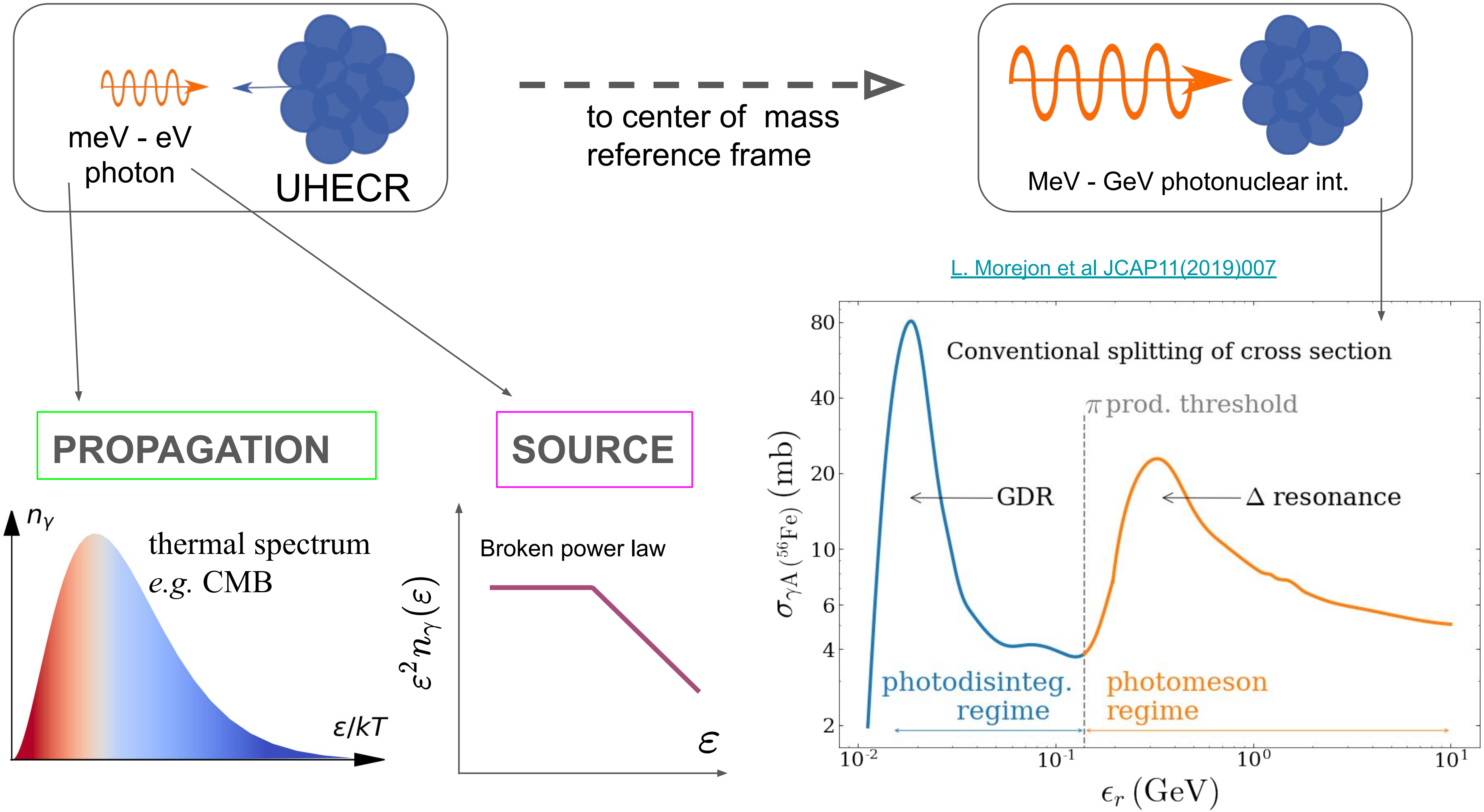
PROPAGATION
SOURCE


n_γ
thermal spectrum
e.g. CMB
ε/kT


Broken power law
$\varepsilon^2 n_\gamma(\varepsilon)$
ε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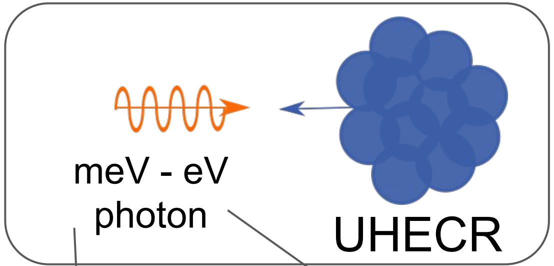
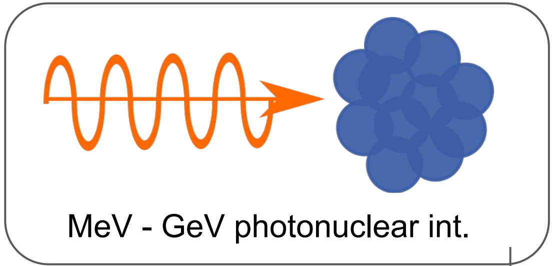
L. Morejon et al JCAP11(2019)007
PROPAGATION
SOURCE
n_γ
thermal spectrum
e.g. CMB
ε/kT
Broken power law
$\varepsilon^2 n_\gamma(\varepsilon)$
ε
Conventional splitting of cross section
π prod. threshold
GDR
Δ resonance
$\sigma_{\gamma A}(^{56}\mathrm{Fe})$ (mb)
photodisinteg.
regime
photomeson
regime
ϵ_r (GeV)
80
40
20
10
6
4
2
10^{-2}
10^{-1}
10^{0}
10^{1}



to center of mass
reference frame

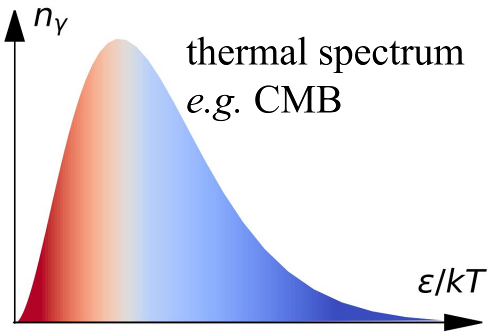


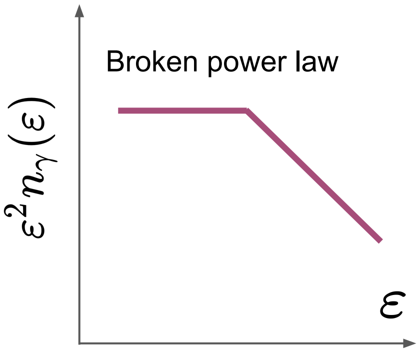
$$\lambda(\gamma) = \frac{1}{2\gamma^2} \int_0^{\infty} \frac{n(\epsilon)}{\epsilon^2} d\epsilon \int_0^{2\epsilon\gamma} \varepsilon\sigma(\varepsilon) d\varepsilon$$

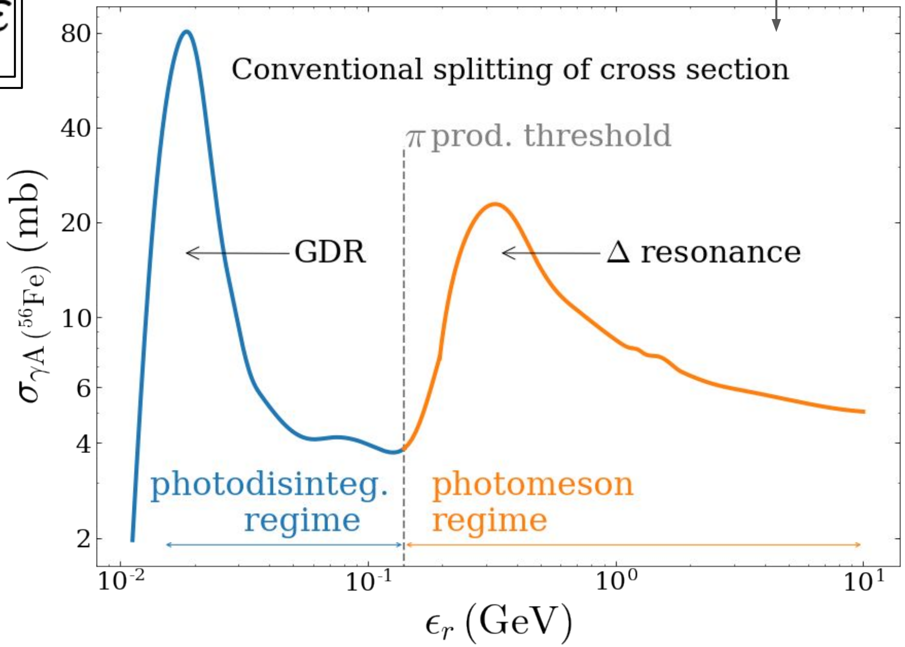
L. Morejon et al JCAP11(2019)007

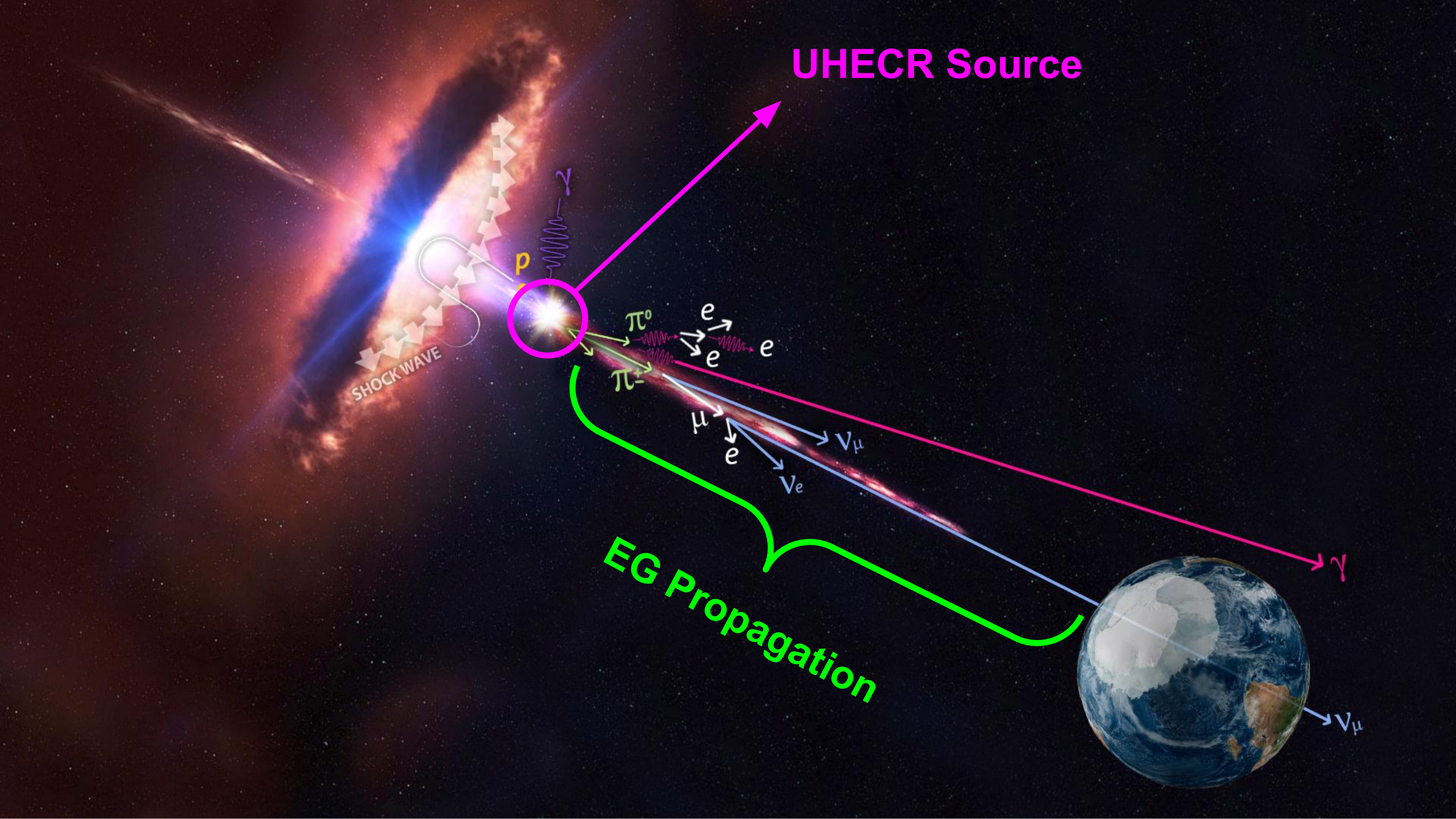
PROPAGATION

SOURCE





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EG Propagation
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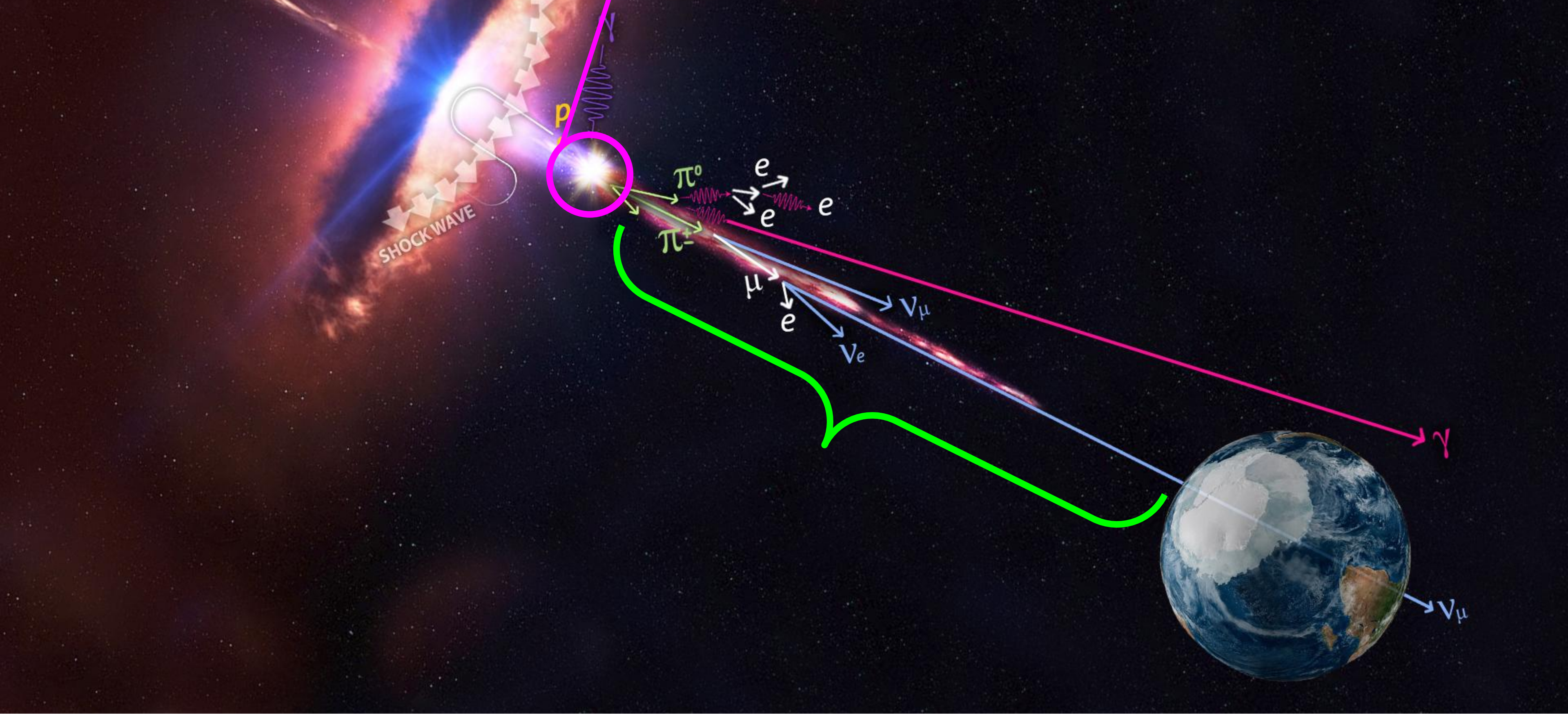
ν_μ

UHECR Source codes

- NeuCosmA Hümmer *et al.* Astrop. Phys. Vol. 34 Issue 4, 2010, 205-224
- AM3 (no nuclear cascades) Klinger et al. 2023 (arXiv:2312.13371



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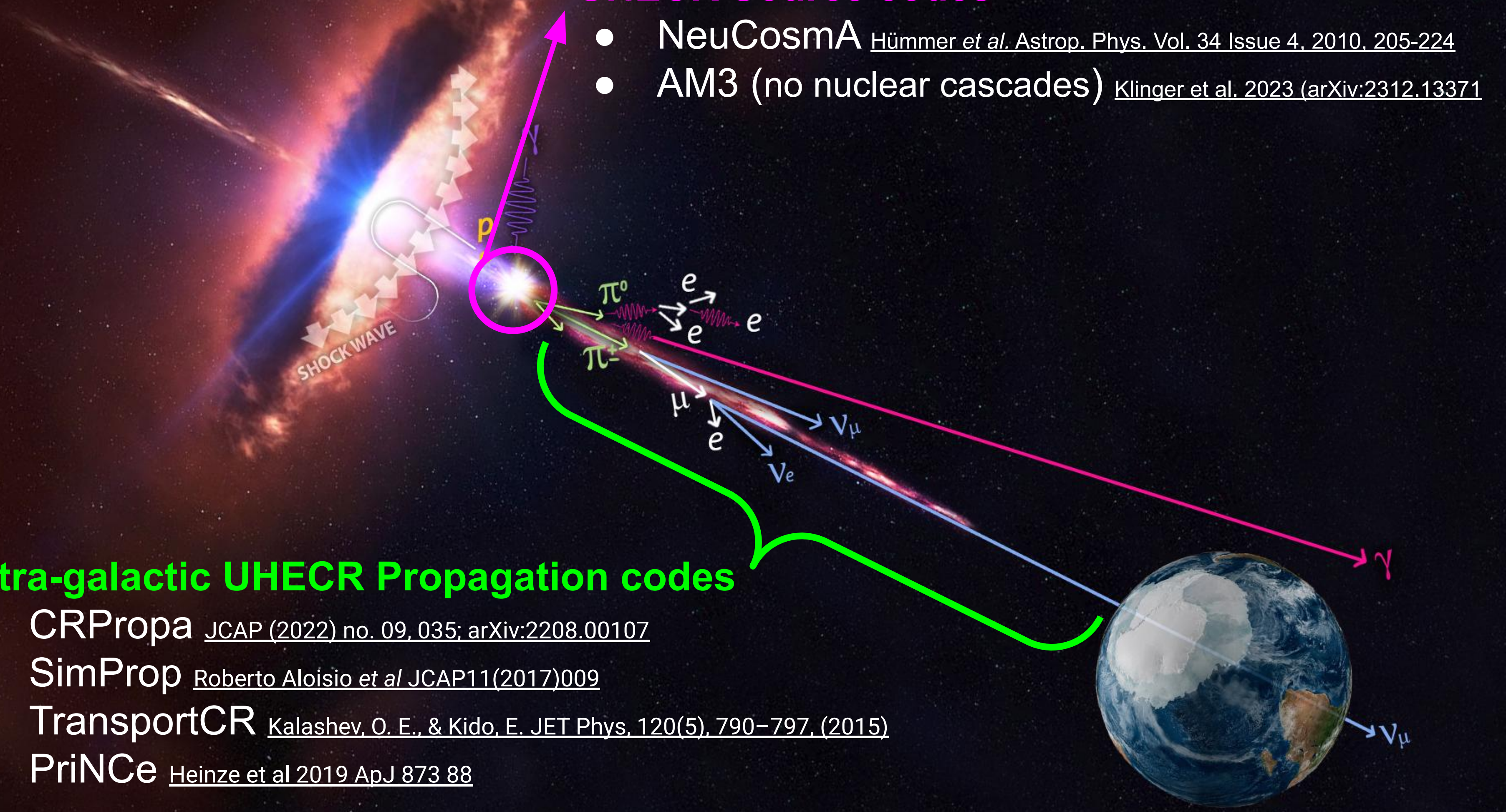

Extra-galactic UHECR Propagation codes

- CRPropa JCAP (2022) no. 09, 035; arXiv:2208.00107
- SimProp Roberto Aloisio *et al* JCAP11(2017)009
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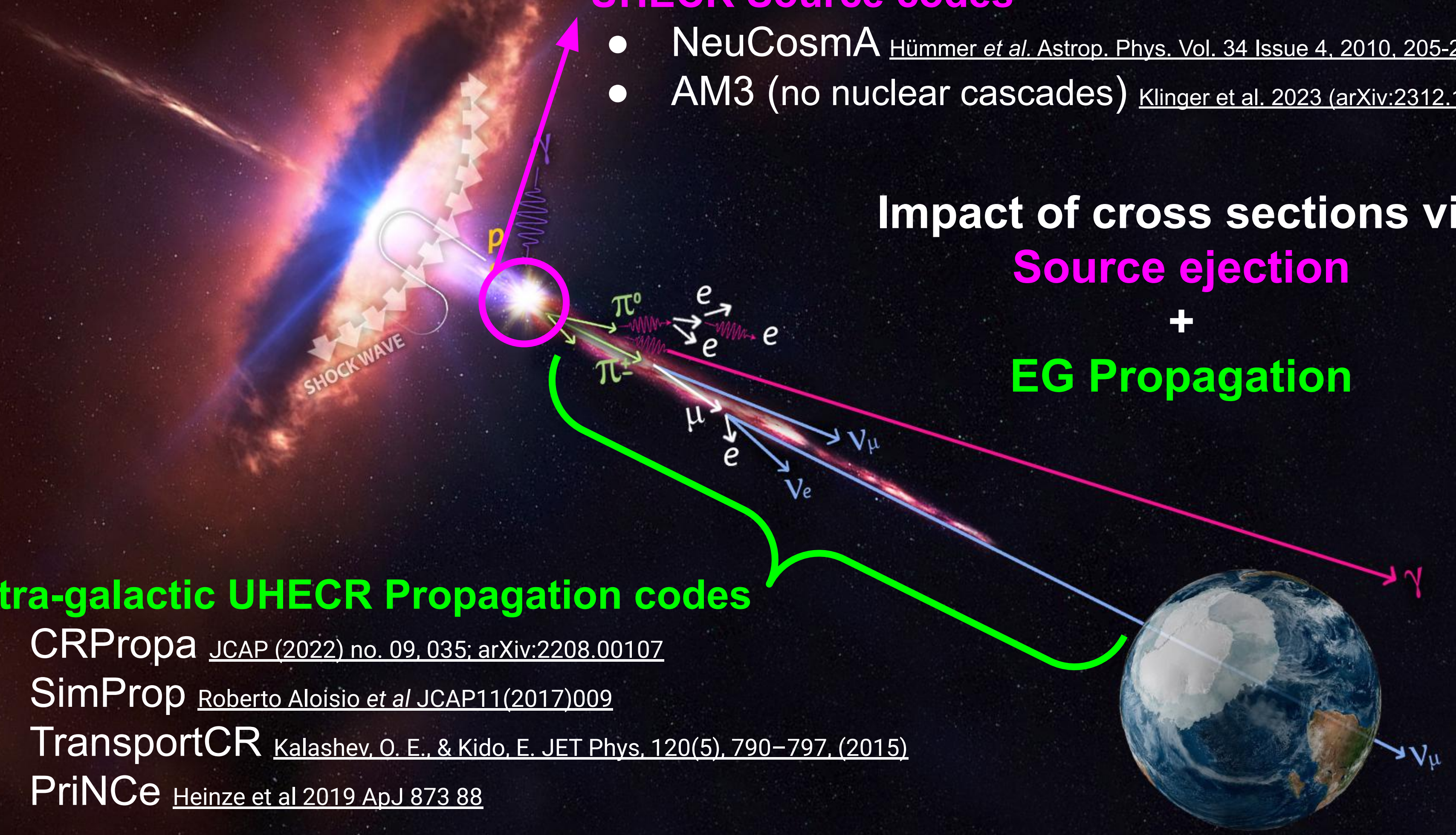
Impact of cross sections via
Source ejection
+
EG Propagation



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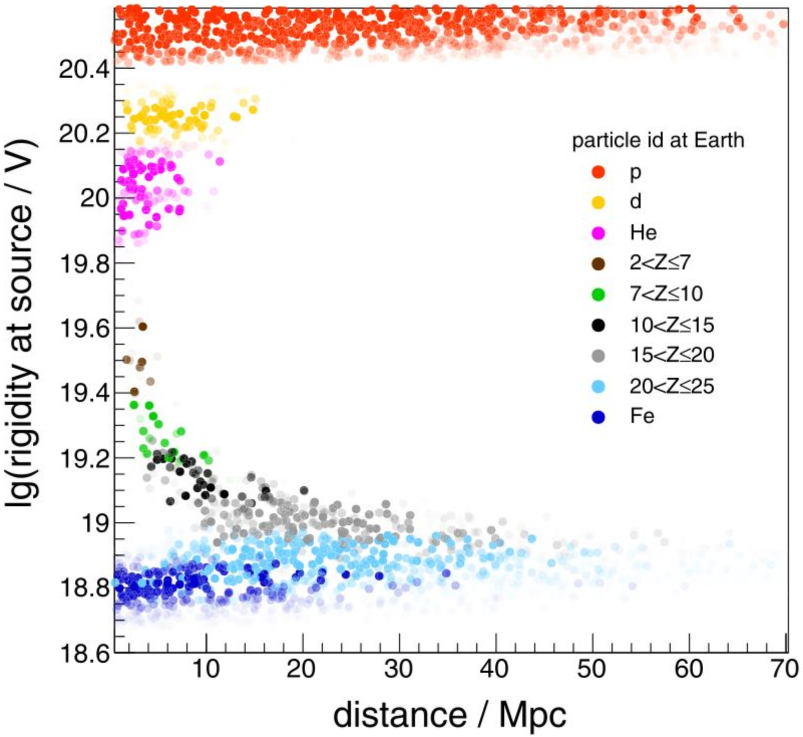
Probabilistic description with analytic expressions

Computed with CRPropa



Michael Unger and Glennys R. Farrar 2024 *ApJL* 962 L5

Morejon, Cent. Eur. Astrophys. Bull. (2024) (*in preparation*)

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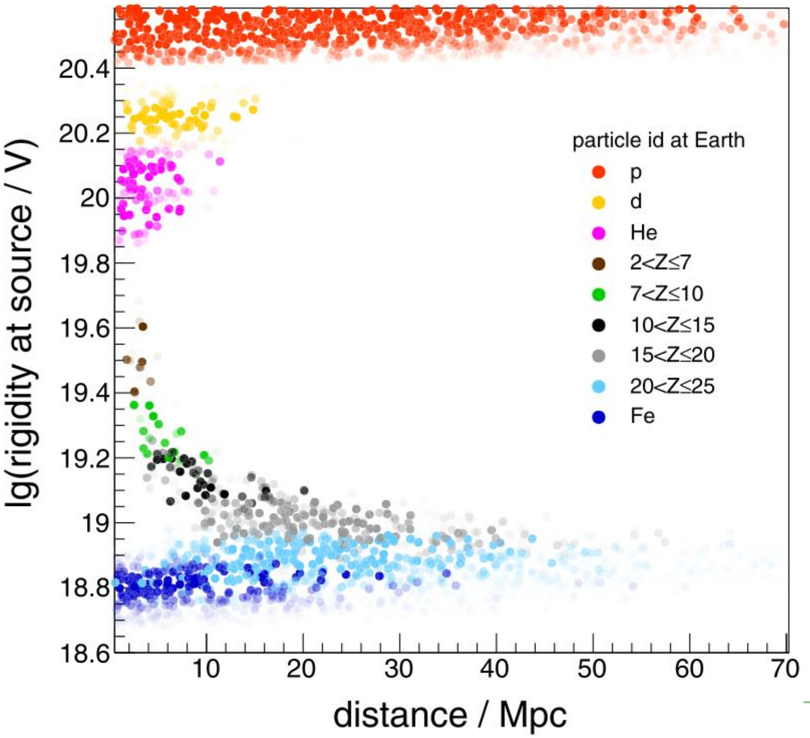
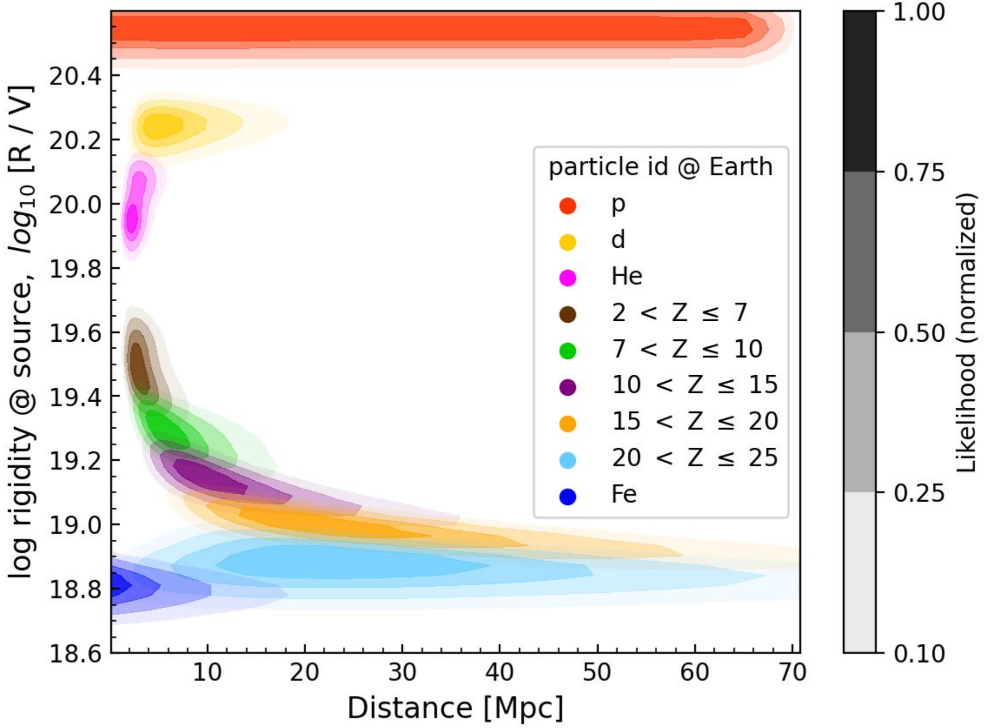


Analytic expressions



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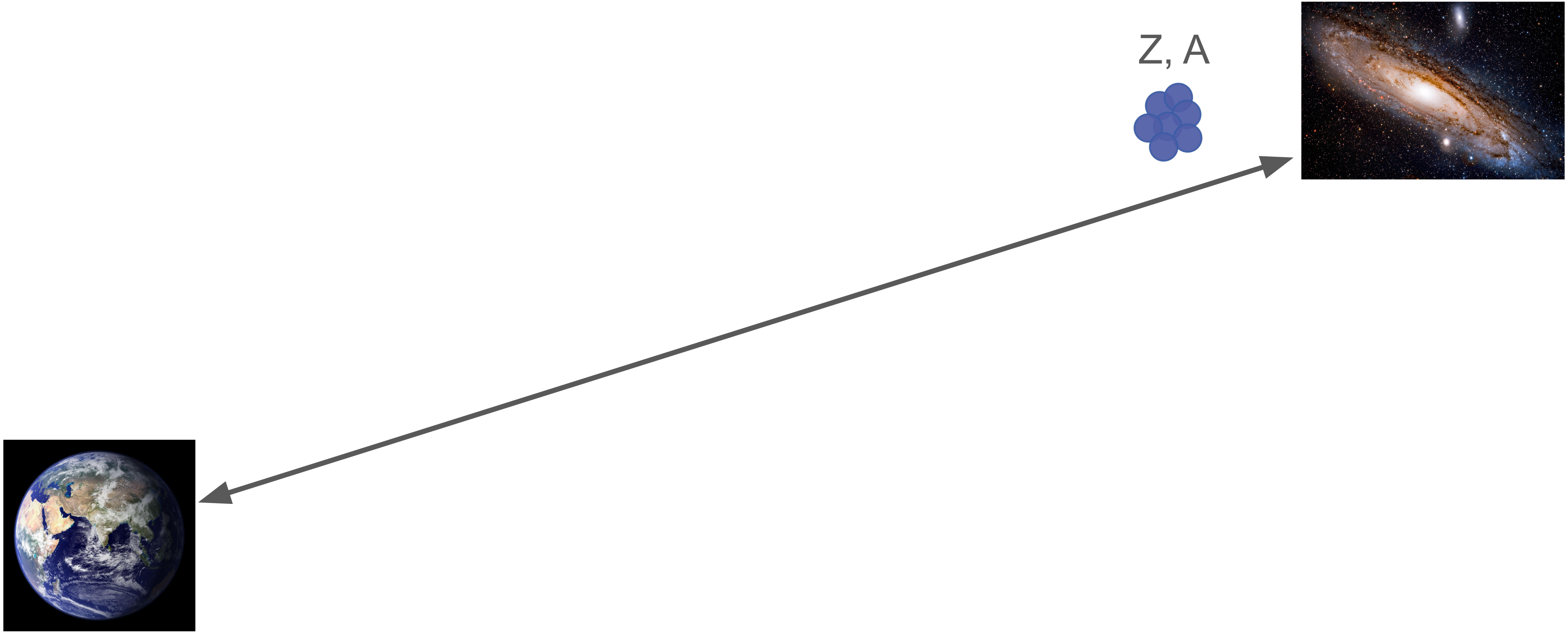
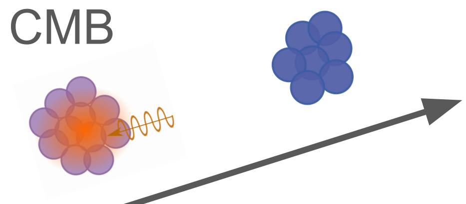
Nuclear interactions over cosmic distances



Nuclear interactions over cosmic distances

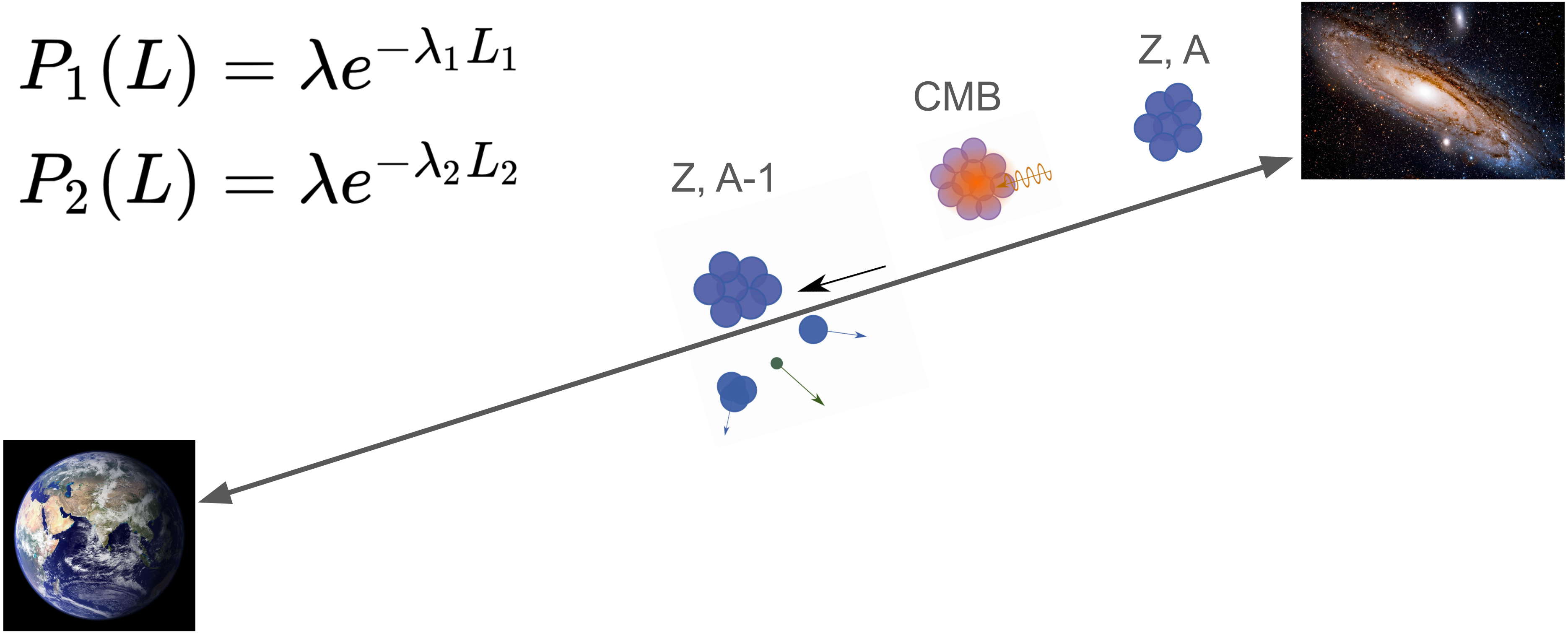
$$P_1(L) = \lambda e^{-\lambda_1 L_1}$$



Nuclear interactions over cosmic distances

$$P_1(L) = \lambda e^{-\lambda_1 L_1}$$

$$P_2(L) = \lambda e^{-\lambda_2 L_2}$$



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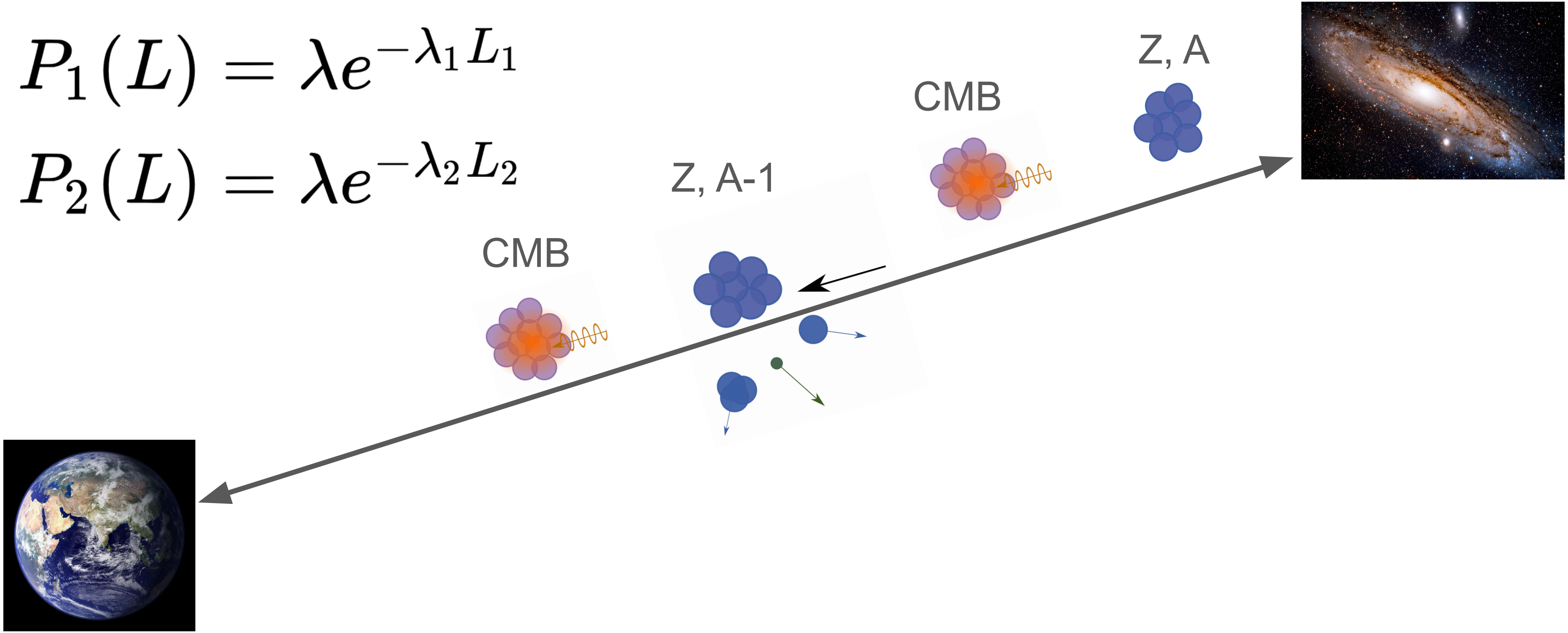

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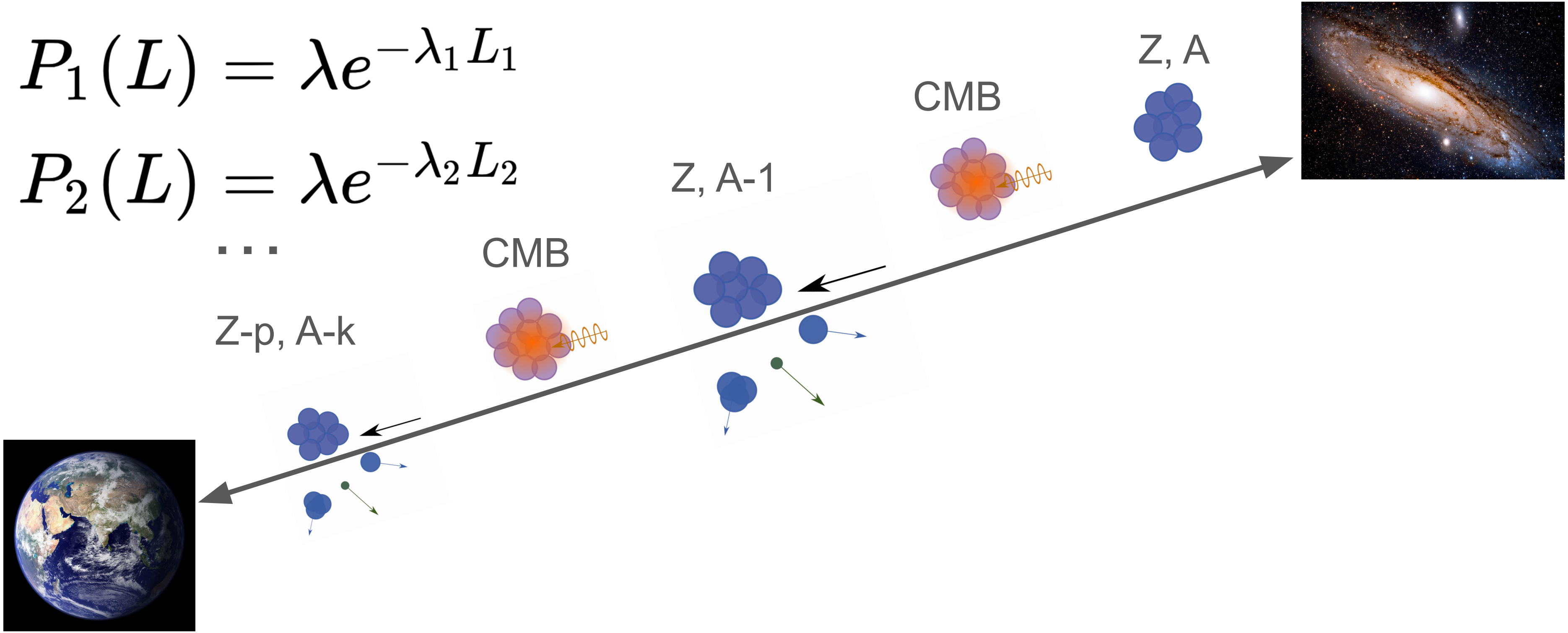

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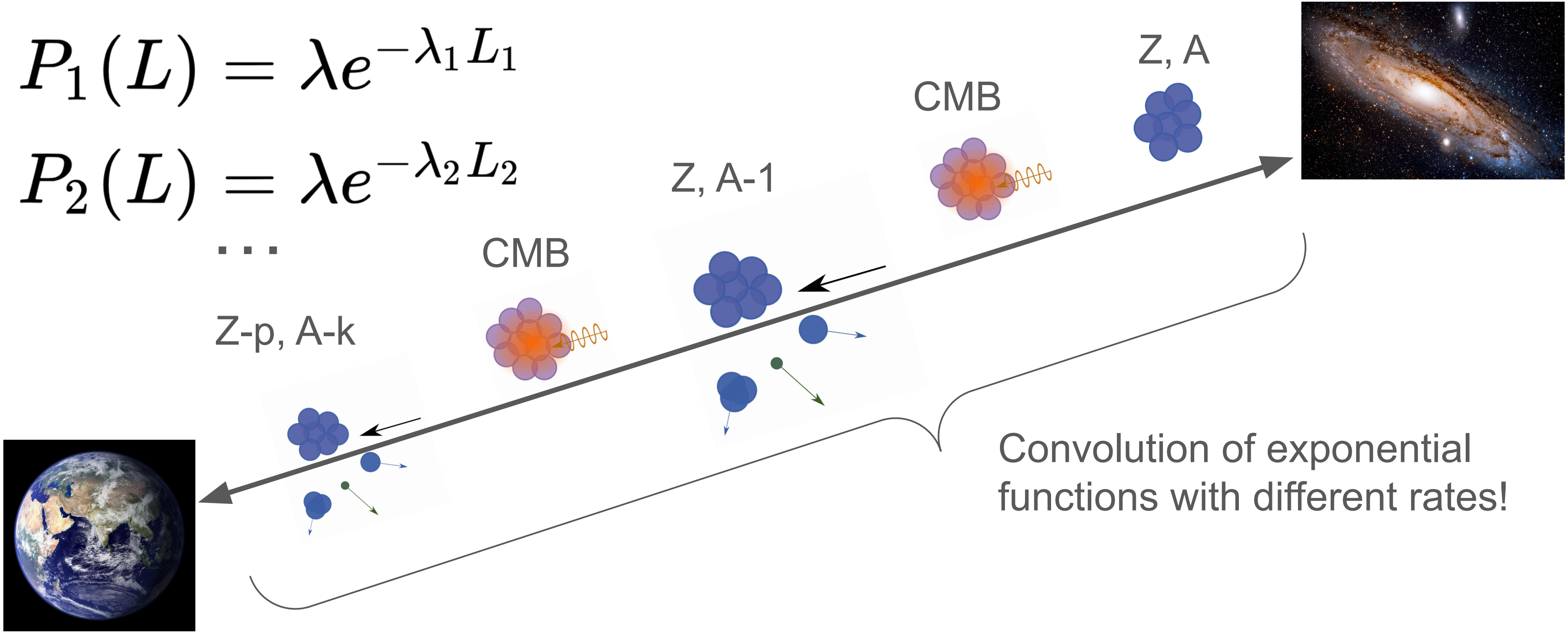


Convolution of exponential functions with different rates!

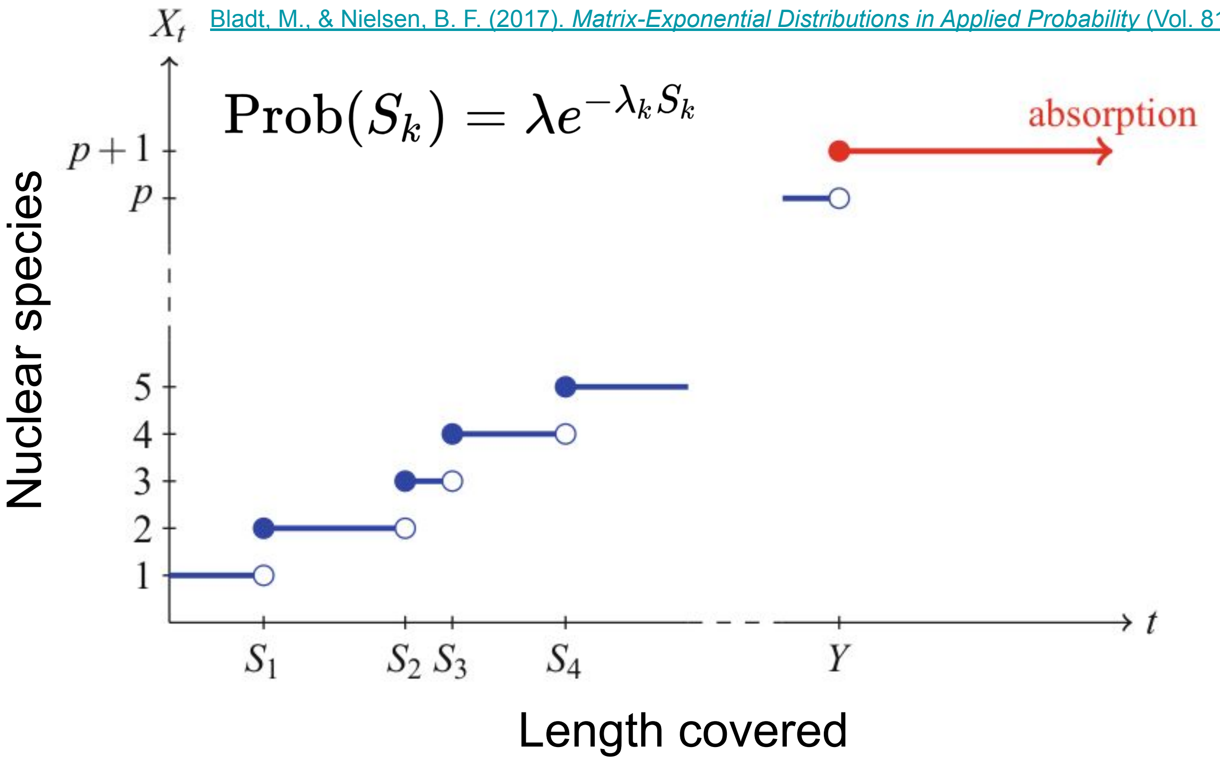
UHECR disintegration as a Markov Process

The successive disintegrations are Poisson distributed.

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

Jumps are transitions between nuclear species.

Bladt, M., & Nielsen, B. F. (2017). *Matrix-Exponential Distributions in Applied Probability* (Vol. 81)

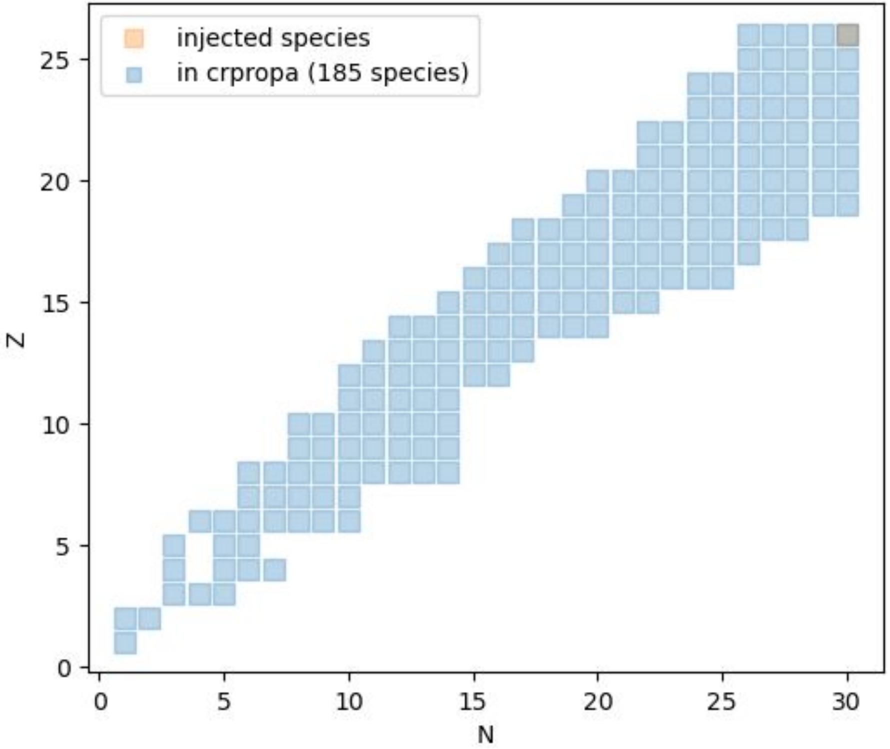


L. Morejon PoS ICRC2023 (2023) 284

Matrix Exponential Distributions: Construction

Theoretical expressions for distributions

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



L. Morejon PoS ICRC2023 (2023) 284

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

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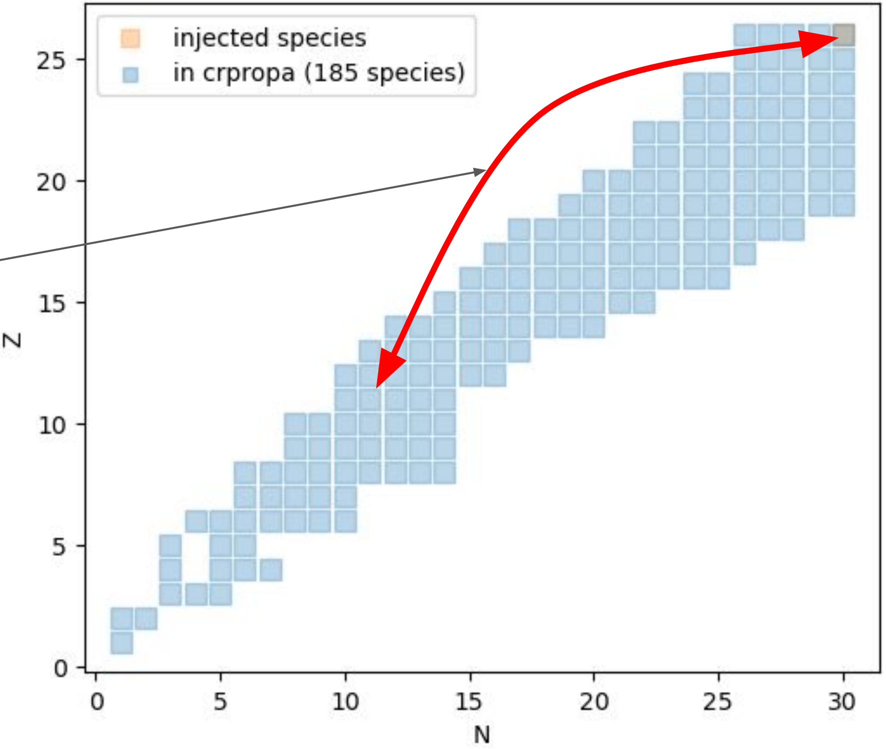

L. Morejon PoS ICRC2023 (2023) 284

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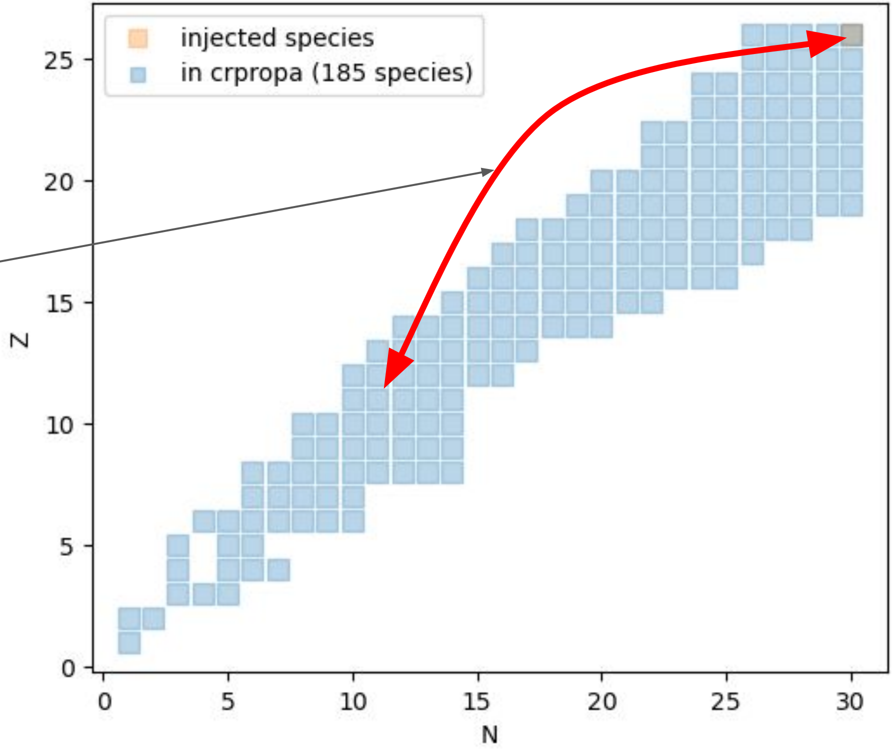
Total interaction rate



[L. Morejon PoS ICRC2023 (2023) 284]

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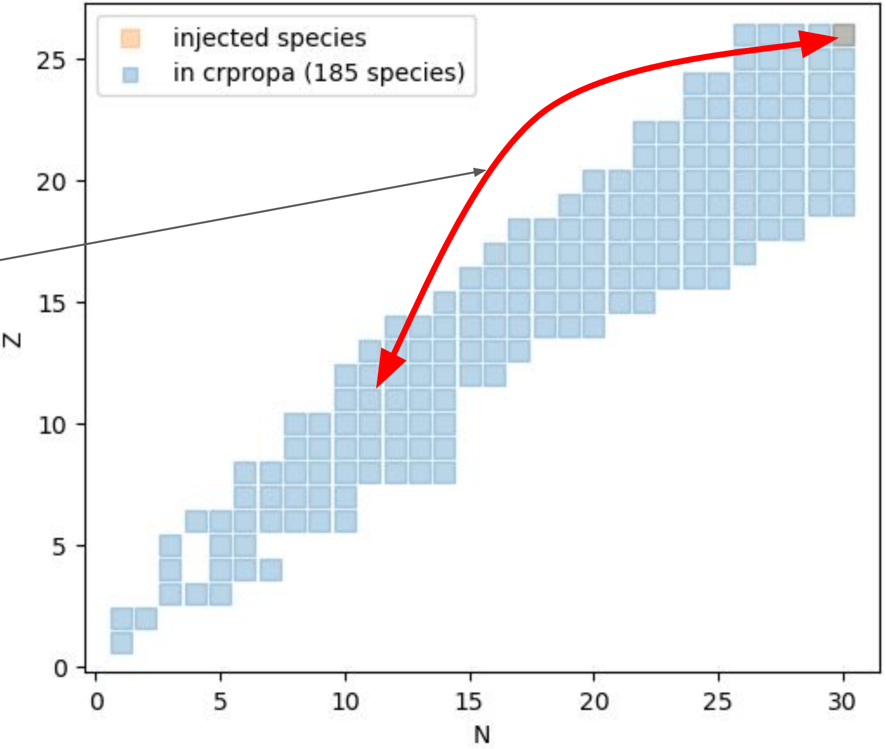
Total interaction rate

Lower triangular is null (mass increase not possible)



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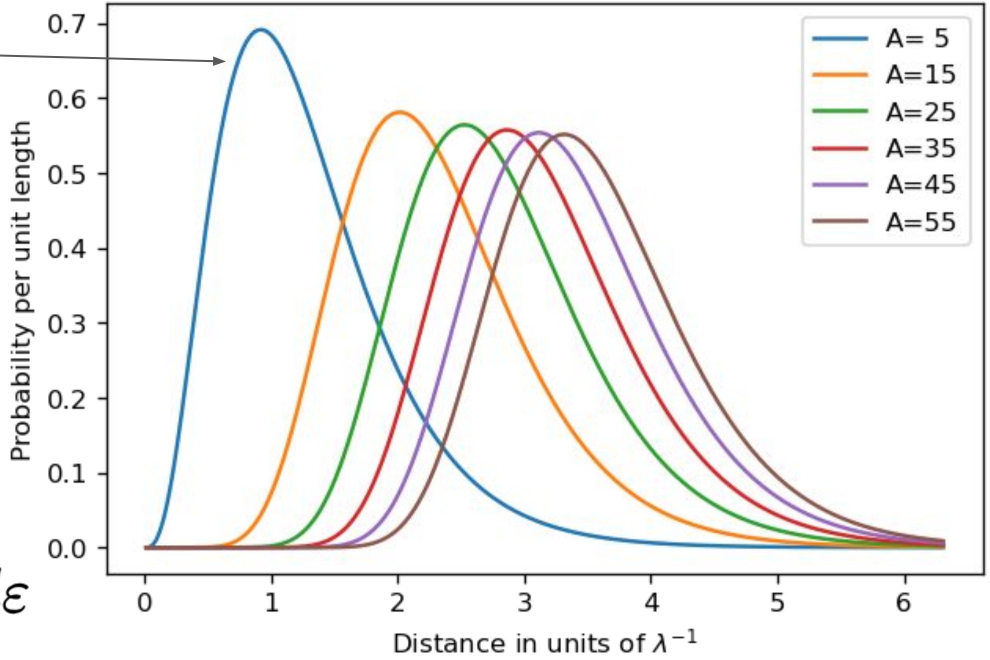
Distance until full disintegration

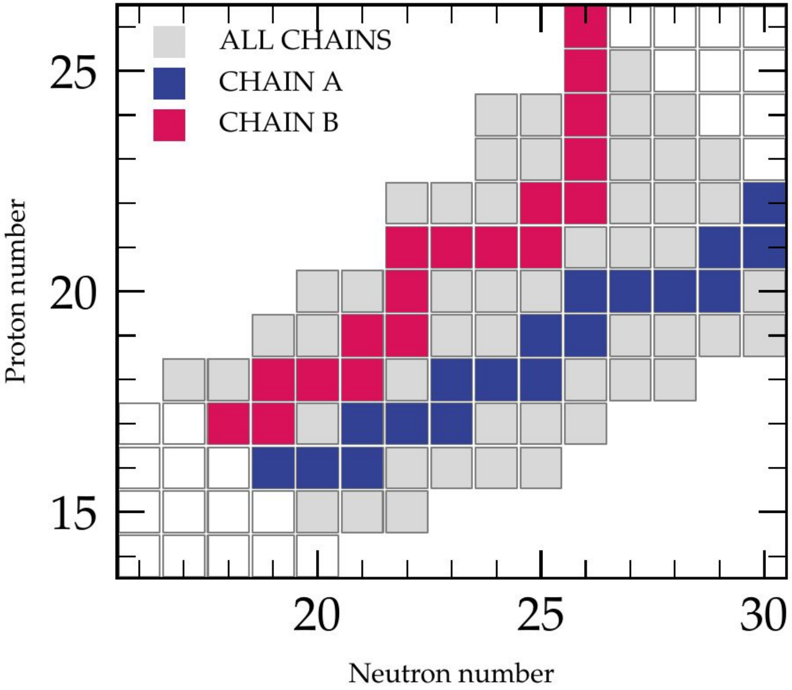


Example distribution chains

The sum of rows is equal to zero!

$$\boldsymbol{\Lambda}(\gamma) = \begin{pmatrix} -\lambda^{\text{tot}}_{S_1} & \lambda^{\text{tot}}_{S_1} & 0 & 0 & 0 & \dots & 0 \\ 0 & -\lambda^{\text{tot}}_{S_2} & \lambda^{\text{tot}}_{S_2} & 0 & 0 & \dots & 0 \\ 0 & 0 & -\lambda^{\text{tot}}_{S_3} & \lambda^{\text{tot}}_{S_3} & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & 0 & \dots & -\lambda^{\text{tot}}_{S_N} \end{pmatrix}$$

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



Example distribution chains

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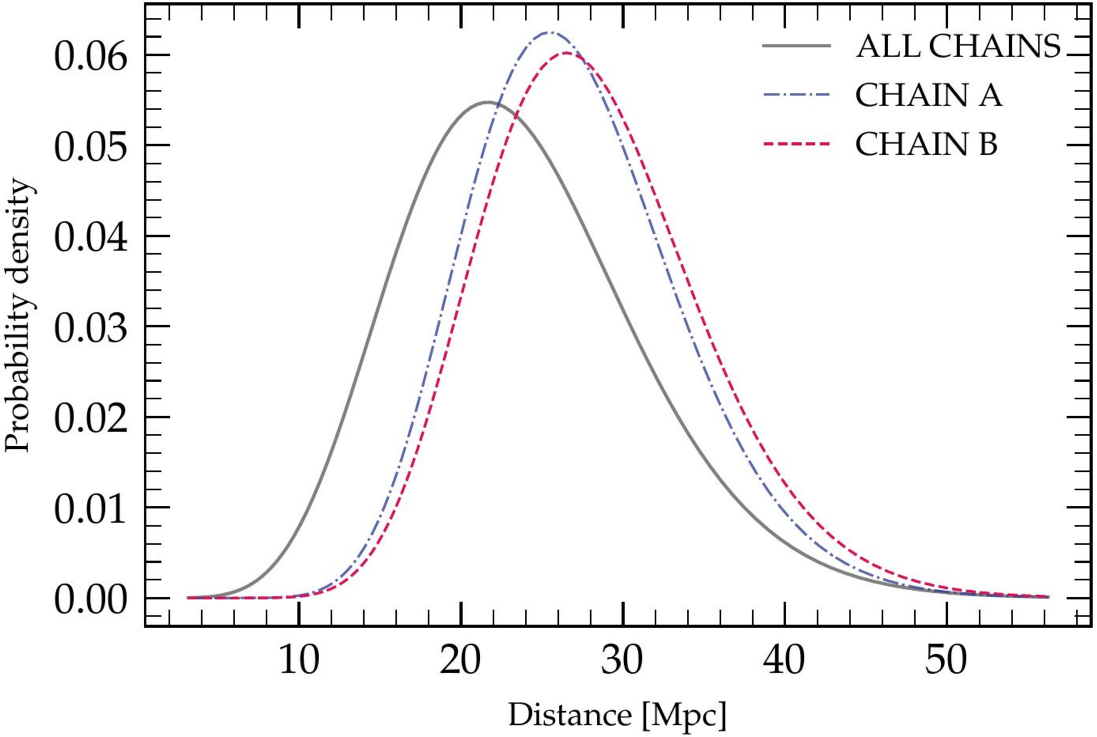

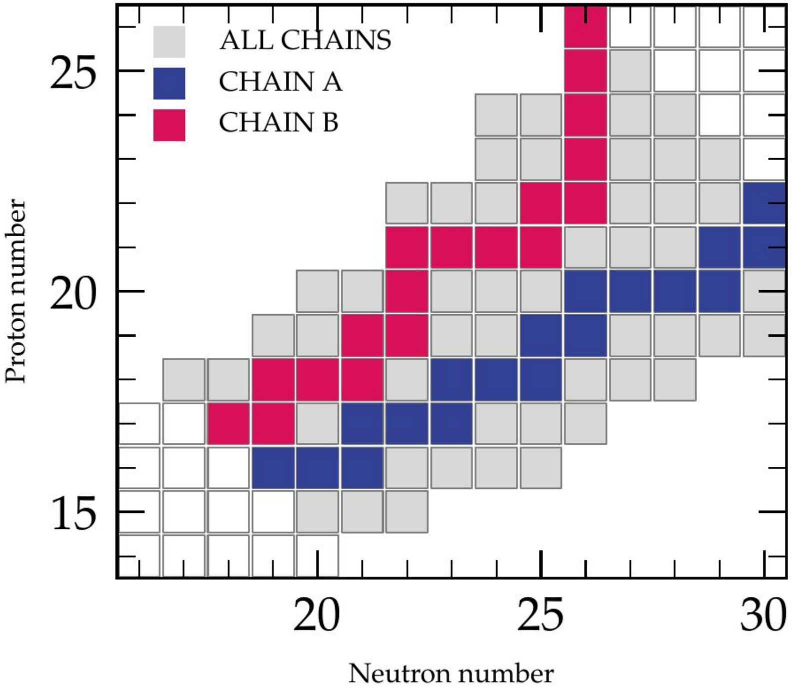

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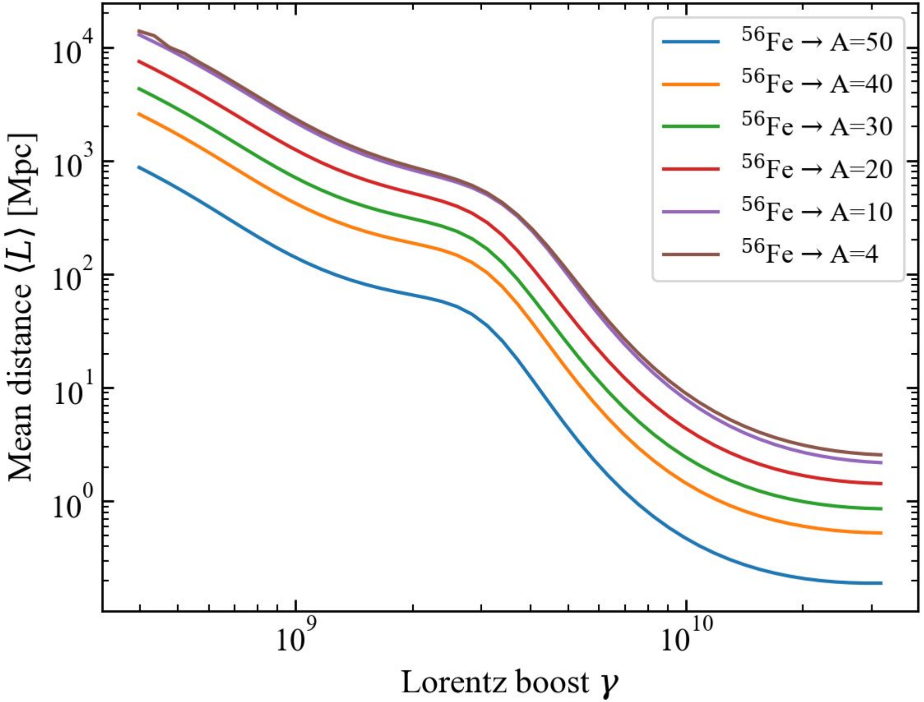
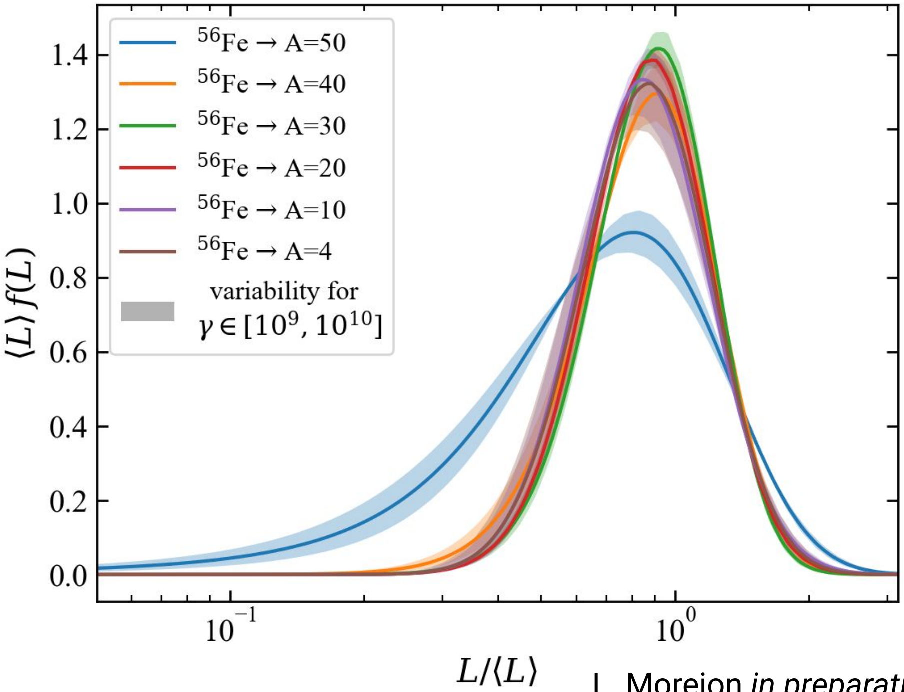
Extragalactic propagation distributions

Rates ranging several orders of magnitude … but very similar distribution shapes

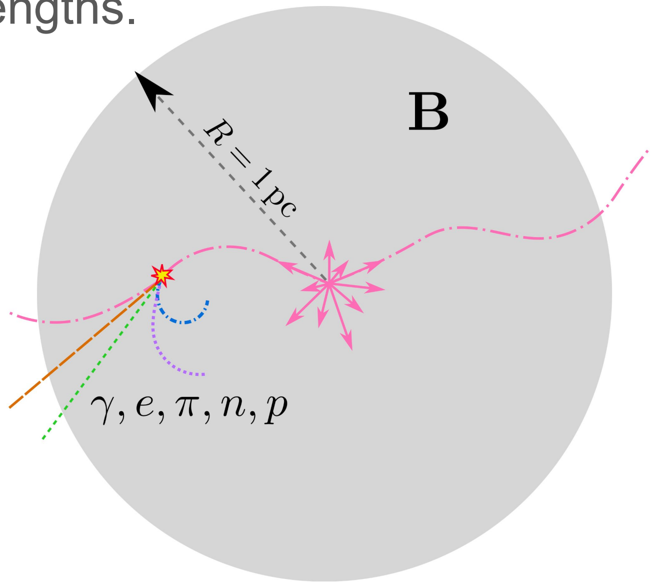




L. Morejon *in preparation*

Example case: AGN with Oxygen injection (homogeneous)

1. Simulation of protons (no interactions) to compute the distributions of trajectory lengths.

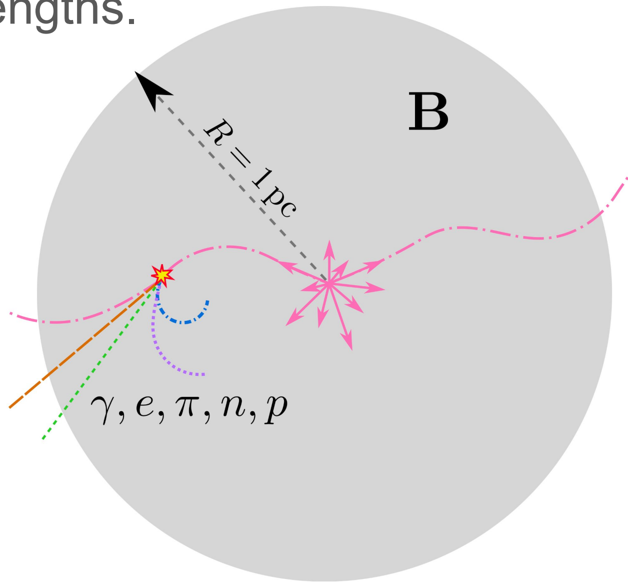


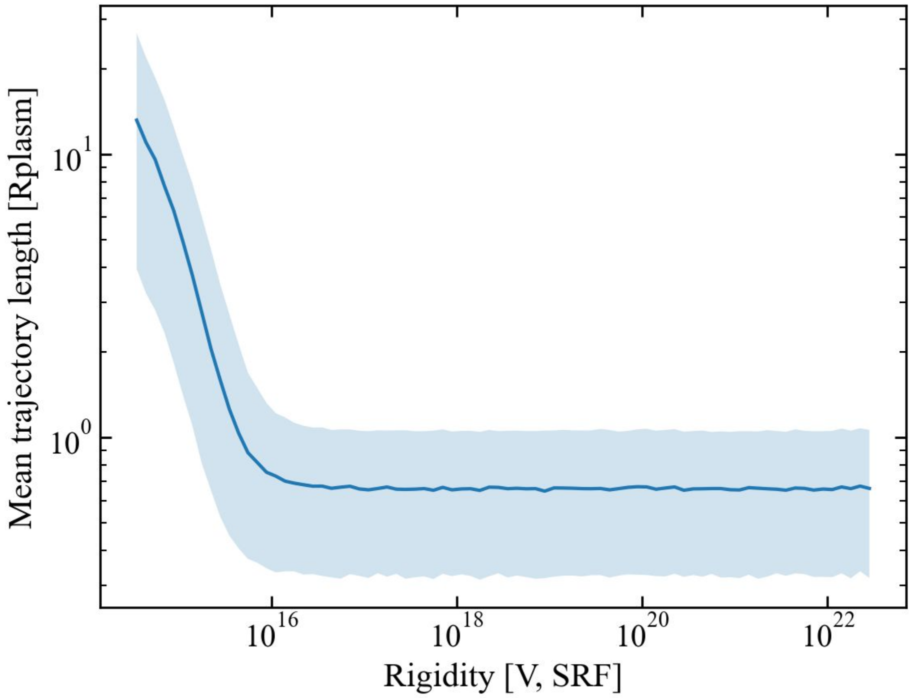
***Provided by L. Schlegel, scaled up by factor 100**

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

Example case: AGN with Oxygen injection (homogeneous)

1. Simulation of protons (no interactions) to compute the distributions of trajectory lengths.



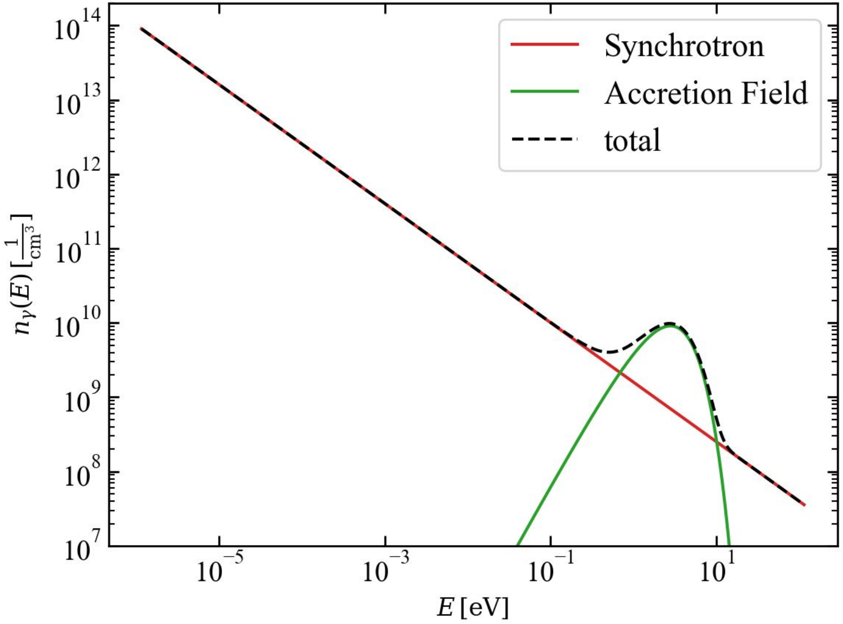


***Provided by L. Schlegel, scaled up by factor 100**

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

Example case: AGN with Oxygen injection

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



***Provided by L. Schlegel, scaled up by factor 100**

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

Example case: AGN with Oxygen injection

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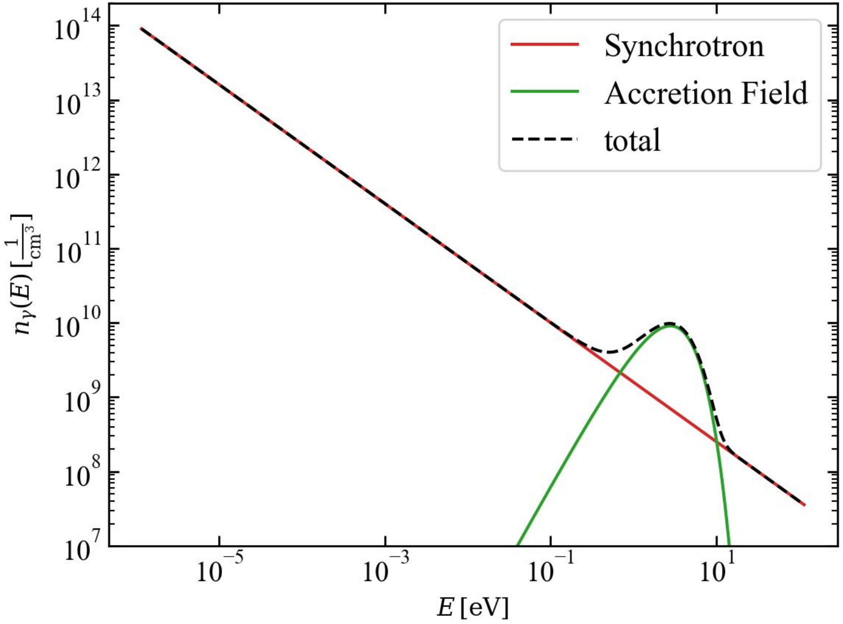
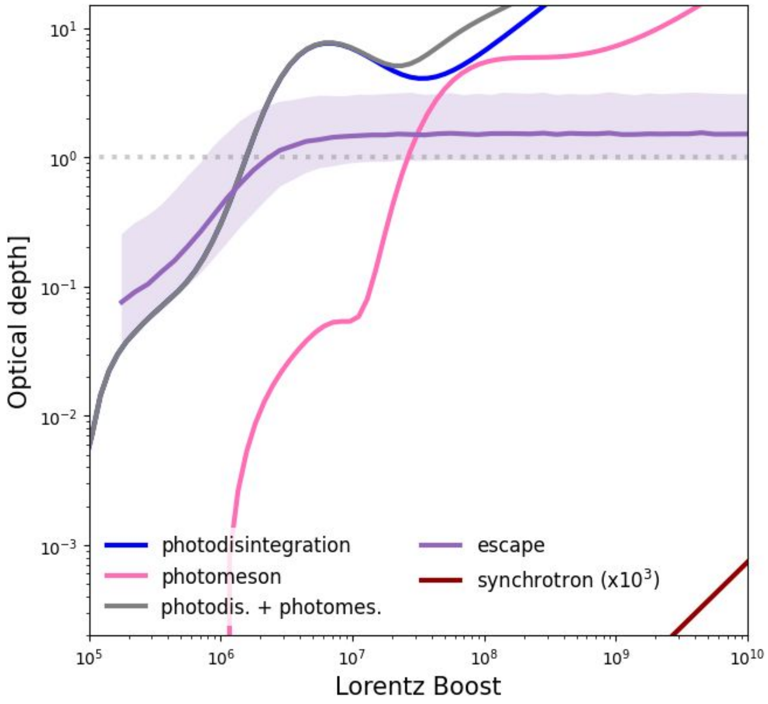


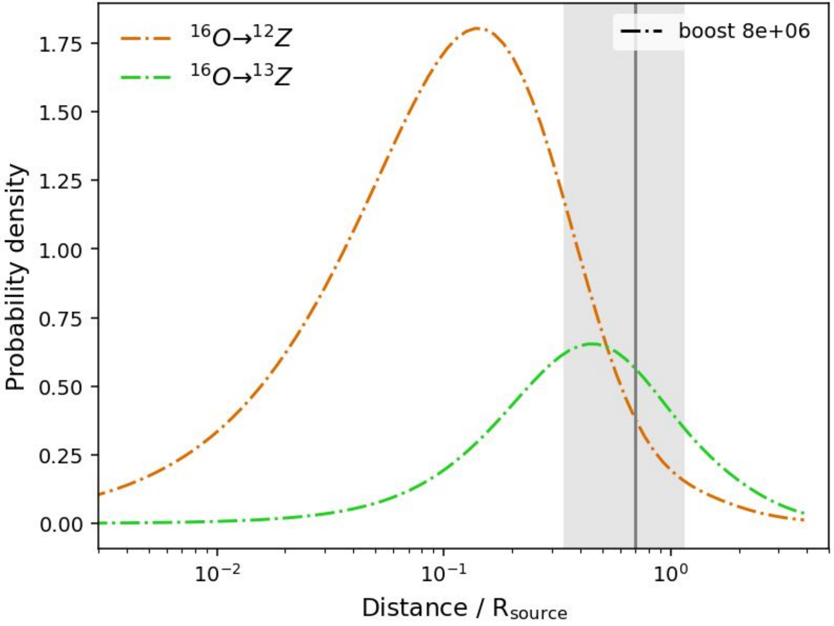


***Provided by L. Schlegel, scaled up by factor 100**

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

Example case: AGN with Oxygen injection

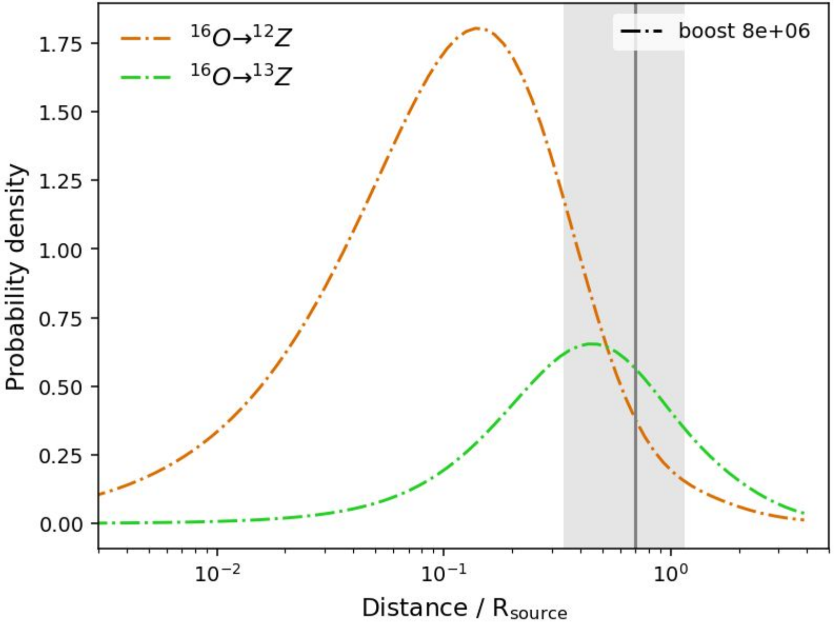
3. Producing the distributions of nuclei and confidence bands



Convolution with distance distributions

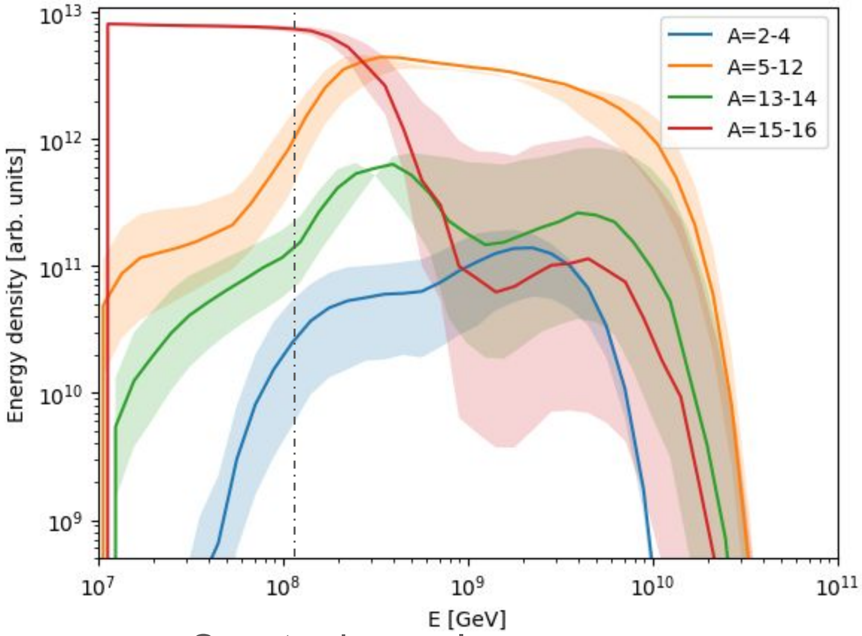
Example case: AGN with Oxygen injection

3. Producing the distributions of nuclei and confidence bands



Convolution with distance distributions

Spectral index: 2
Maximum rigidity: 1E18V



Spectra by nuclear mass group

MICRO website

MICRO@github

CRISP

Cosmic Ray Stochastic Interactions for Propagation

On Github soon!

Thanks!

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MICRO website

MICRO@github

CRISP

Cosmic Ray Stochastic Interactions for Propagation

On Github soon!

Additional slides

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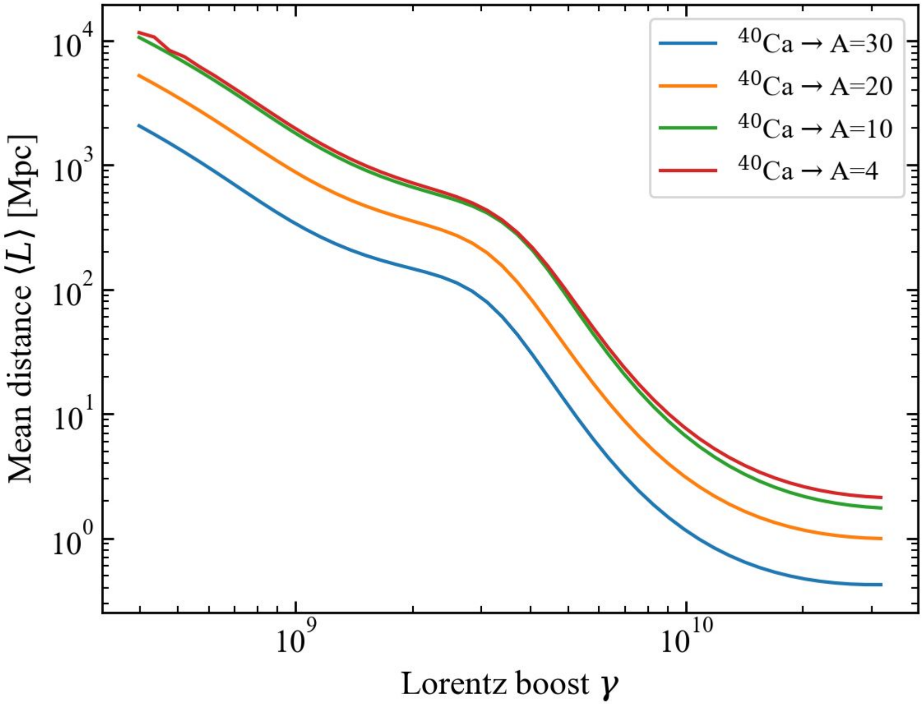
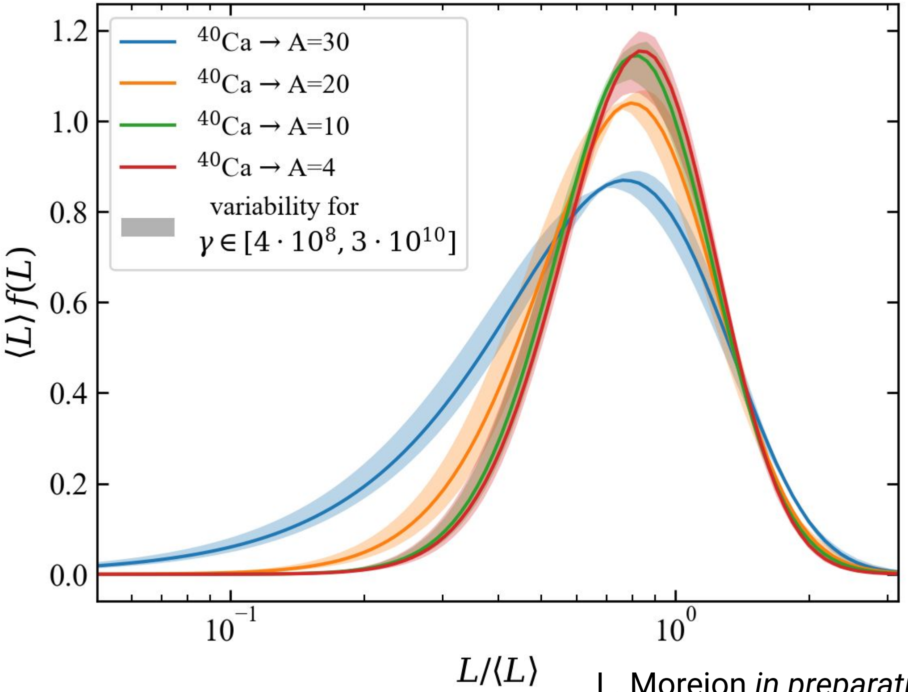
Similarity of distributions

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





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Similarity of distributions

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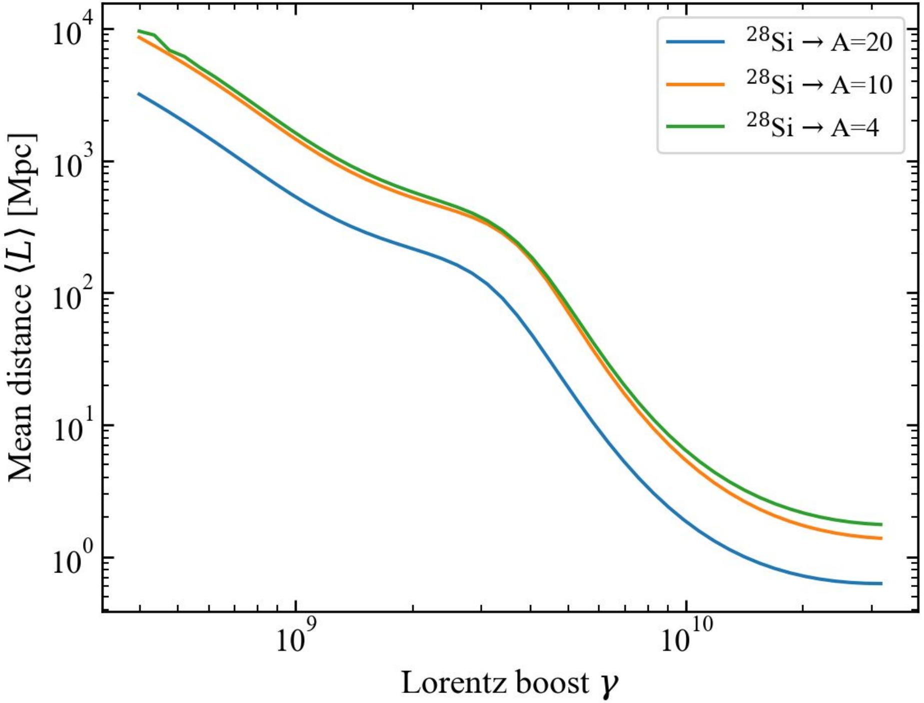

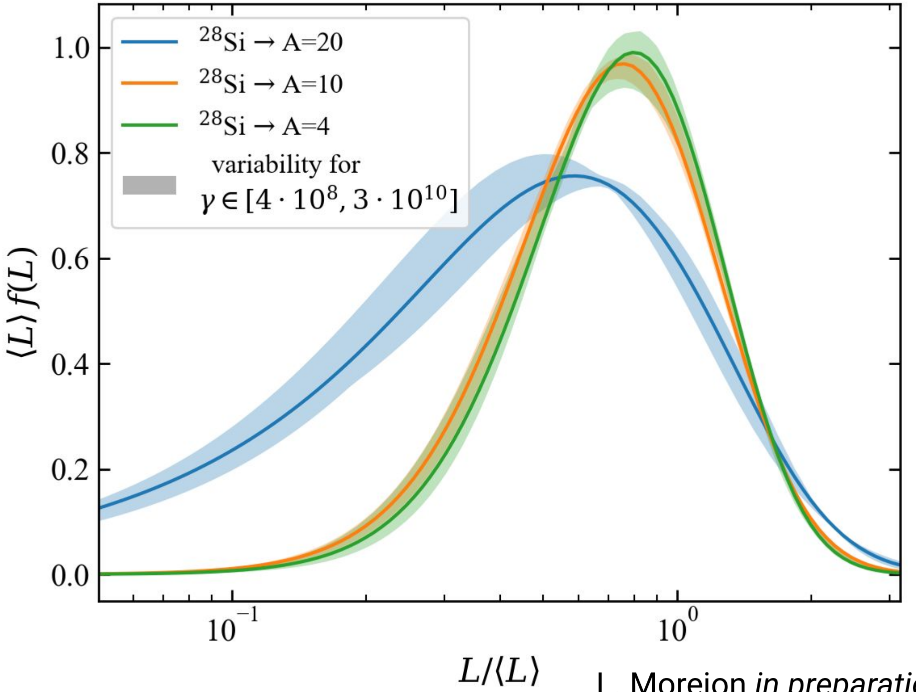

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Extreme-Energy events

Why these events?
- Nearby origin
- Very few events
- Less deflections

Example: Amaterasu

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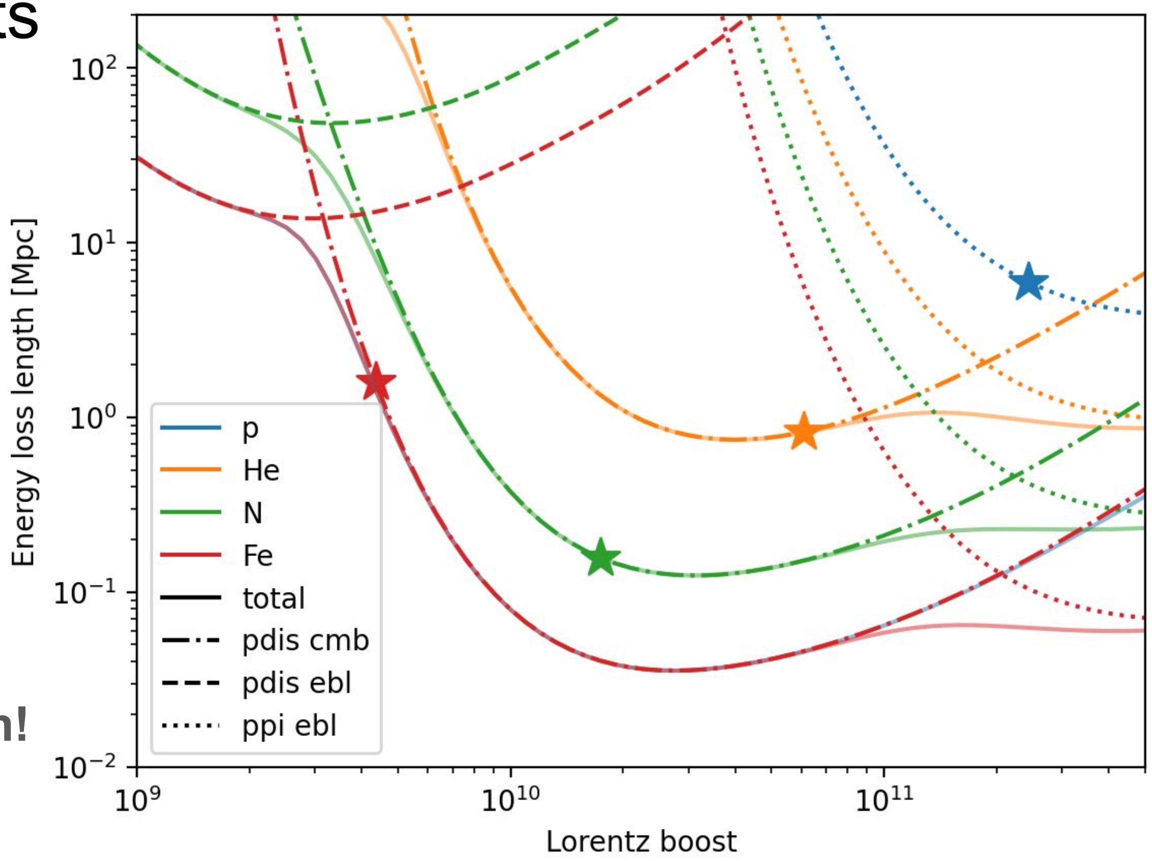
- E0 ~ 244 EeV
- D0 ~ few Mpc
- Large rigidities

Expected to point back to origin!



Combined distance vs rigidity distribution

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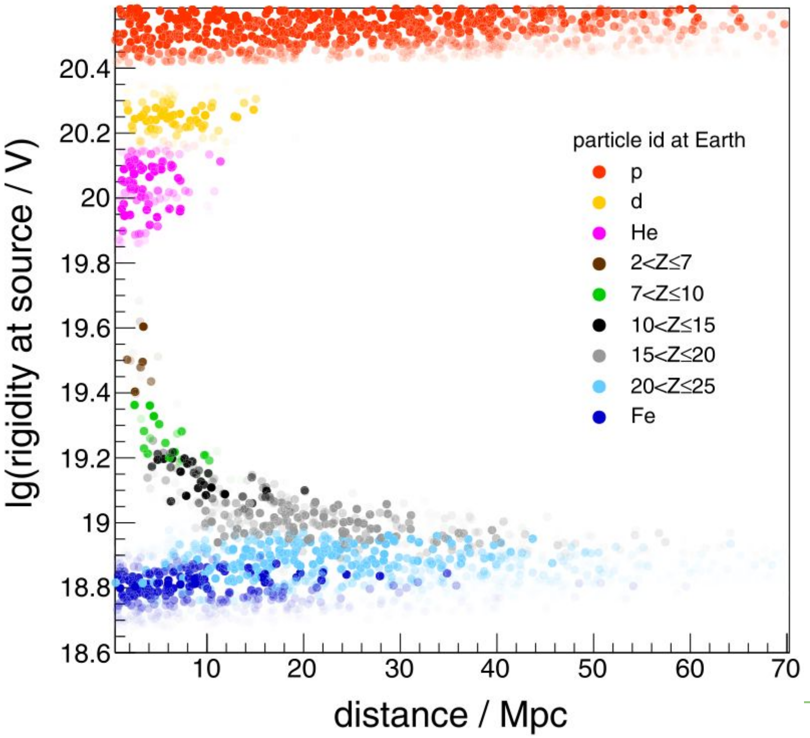

Telescope Array detected extreme UHECR

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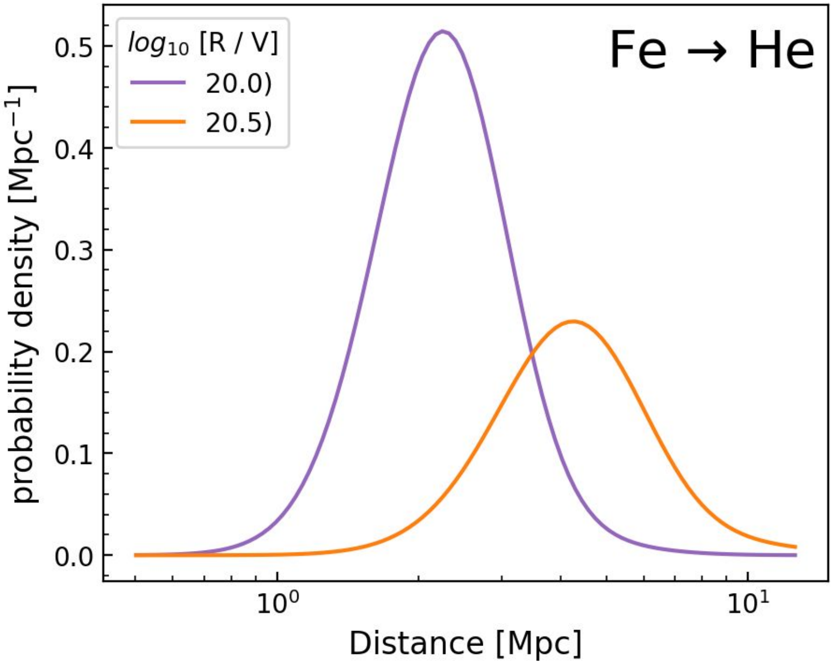
- E = 244 EeV
- Composition @Earth unknown
- No clear source candidate
- Energy @ source unknown
- Composition @ source unknown

Monte Carlo analysis has limitations!

Probability of detection as He

Computed distributions



Starting with one species …

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

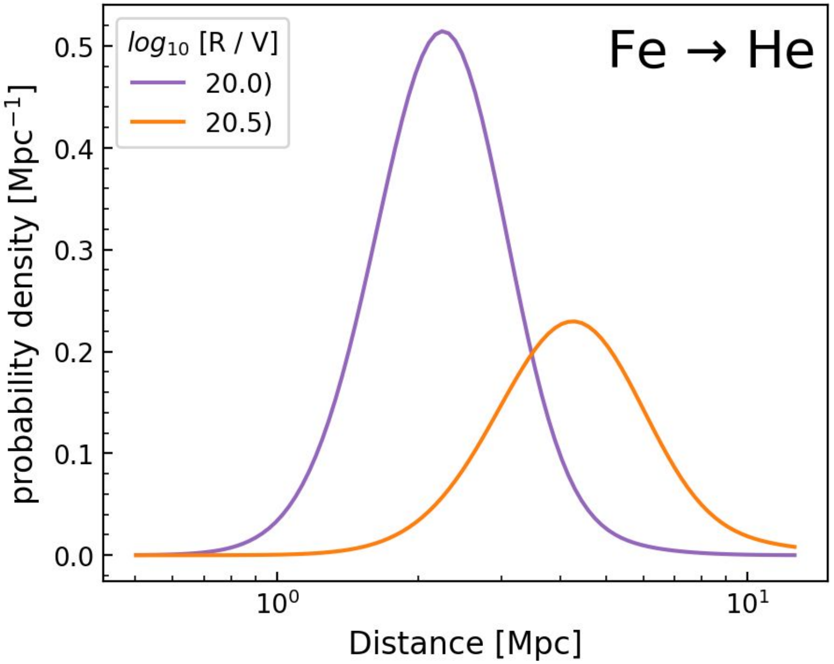
Convolve with emission density for a range of boosts / rigidities

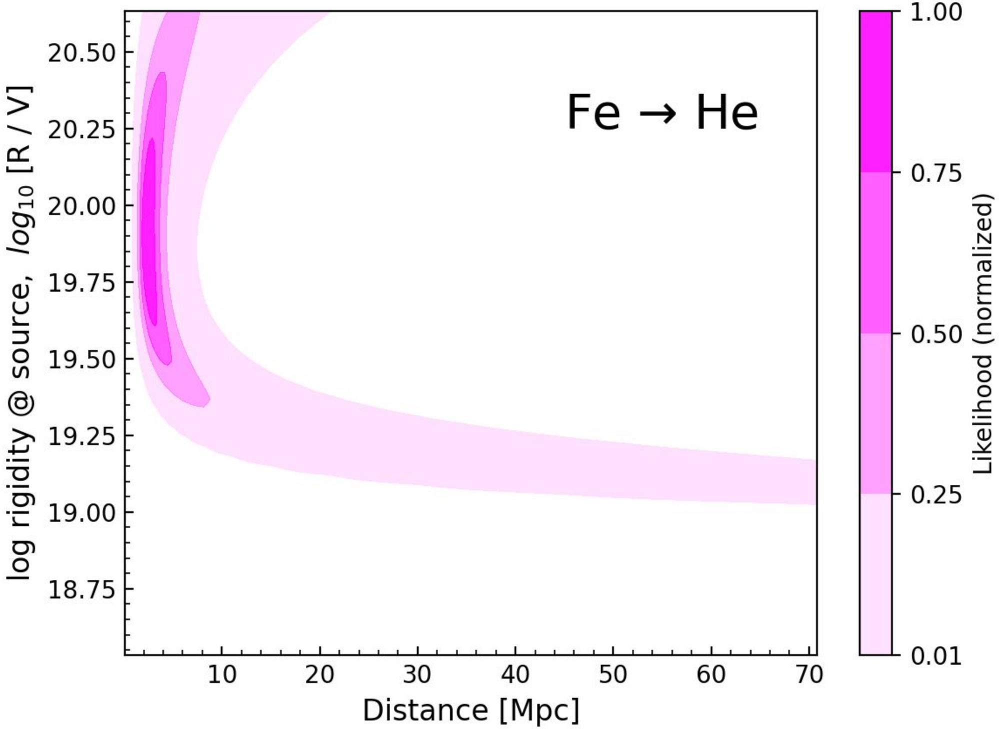
$$\mathcal{L}(D_E) = \int_{\Delta D} f(D_E - D')\rho_E(D_E) dD'$$

Likelihood over range of rigidities @ source

Computed with CRPropa

$$\mathcal{L}(D_E) = \int_{\Delta D} f(D_E - D')\rho_E(D_E)dD'$$





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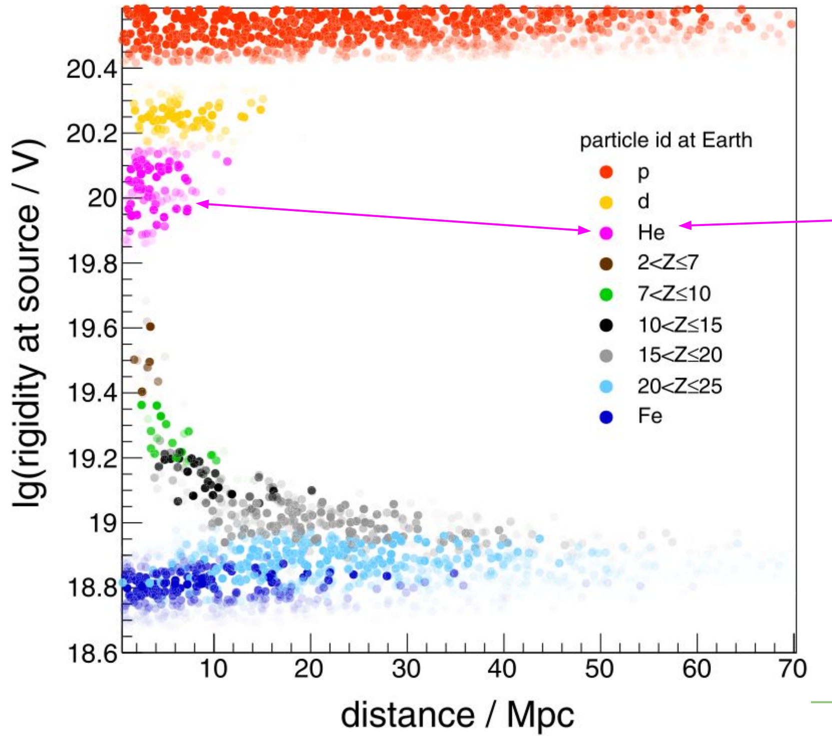
Likelihood over range of rigidities @ source

Computed with CRPropa



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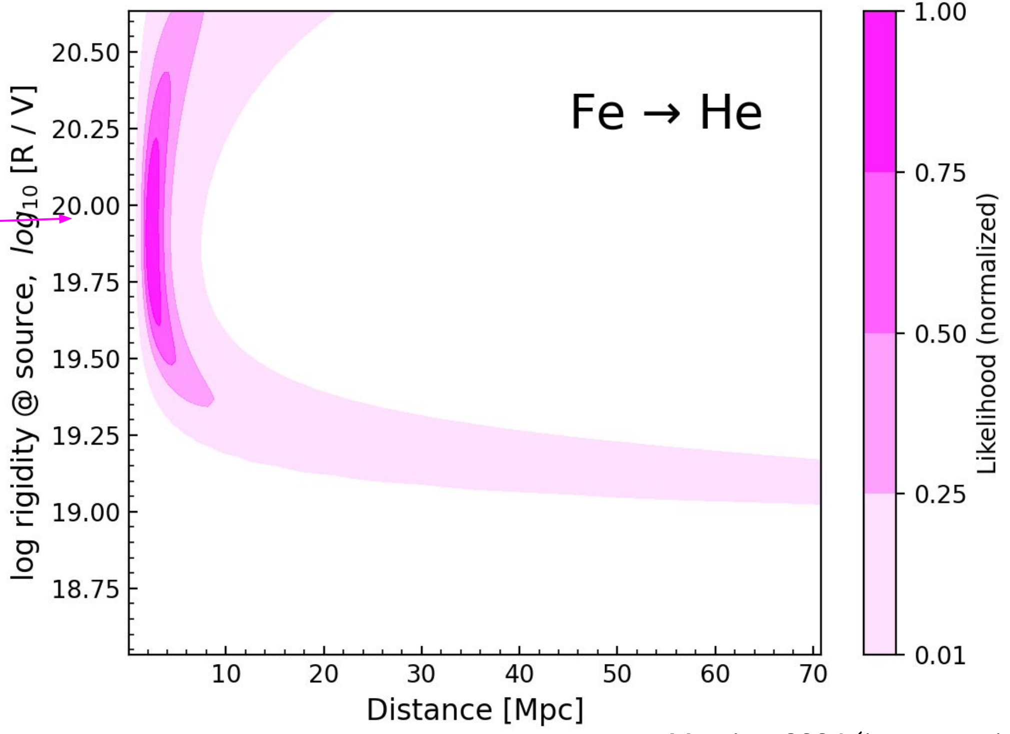
$$\mathcal{L}(D_E) = \int_{\Delta D} f(D_E - D')\rho_E(D_E)dD'$$



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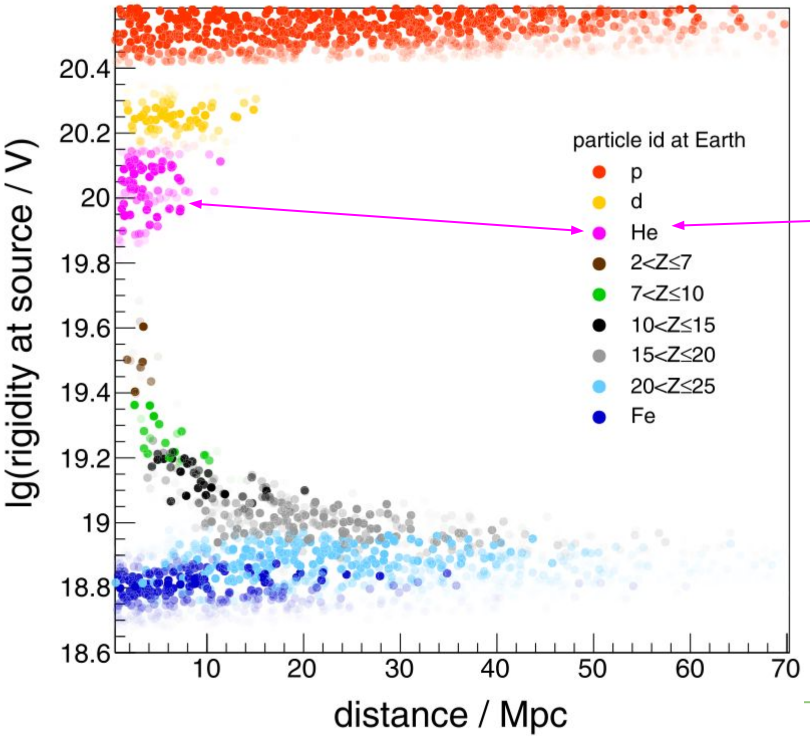
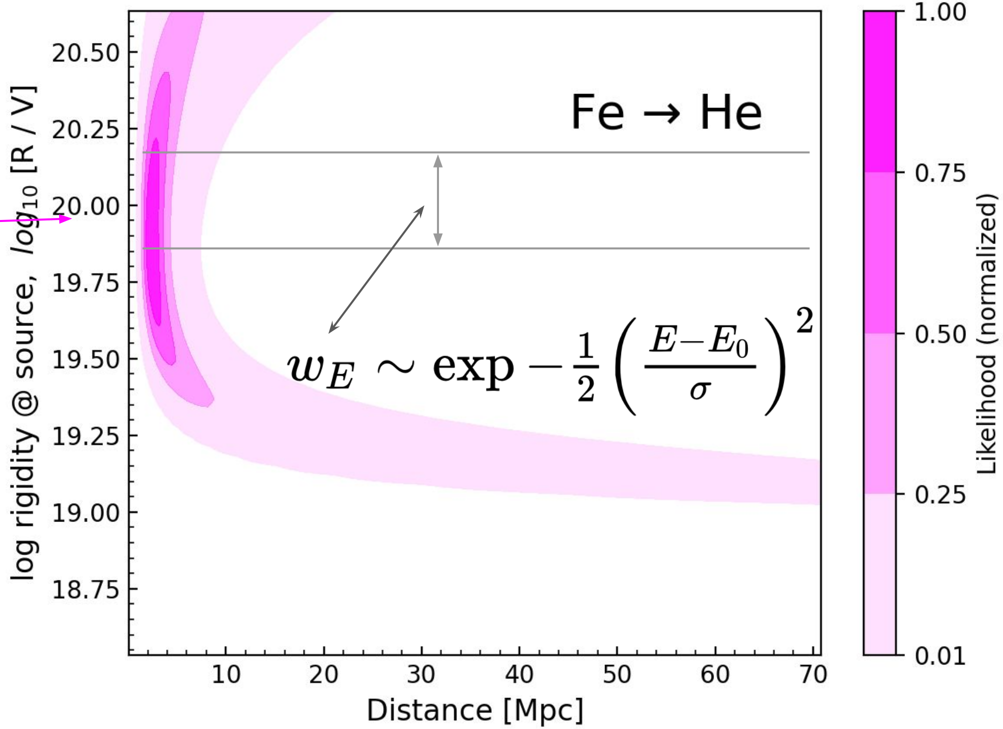
Weight by probability of energy reconstruction

Computed with CRPropa

$$\mathcal{L}(D_E) = \int_{\Delta D} f(D_E - D')\rho_E(D_E)dD'$$





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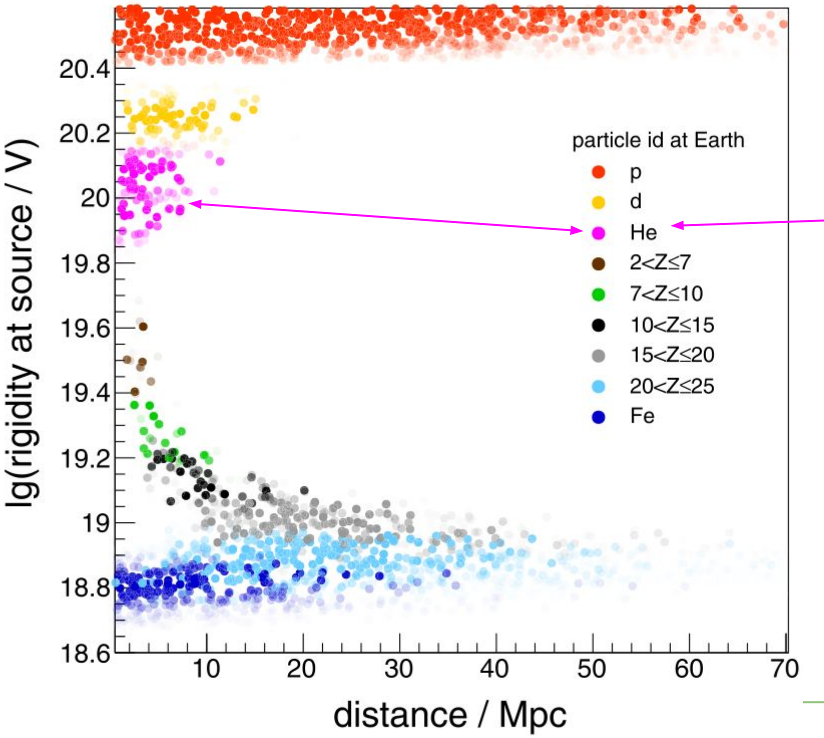
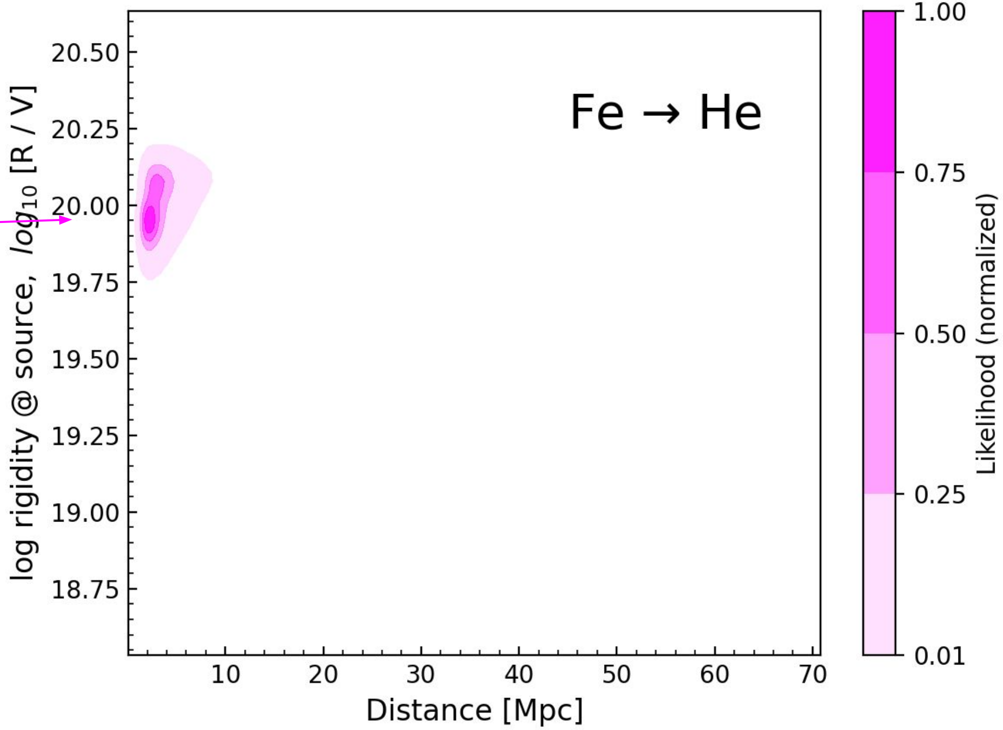
Likelihood distributions

Localized regions in the phase space

Computed with CRPropa



$$\mathcal{L}(D_E) = \int_{\Delta D} f(D_E - D')\rho_E(D_E)dD'$$



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