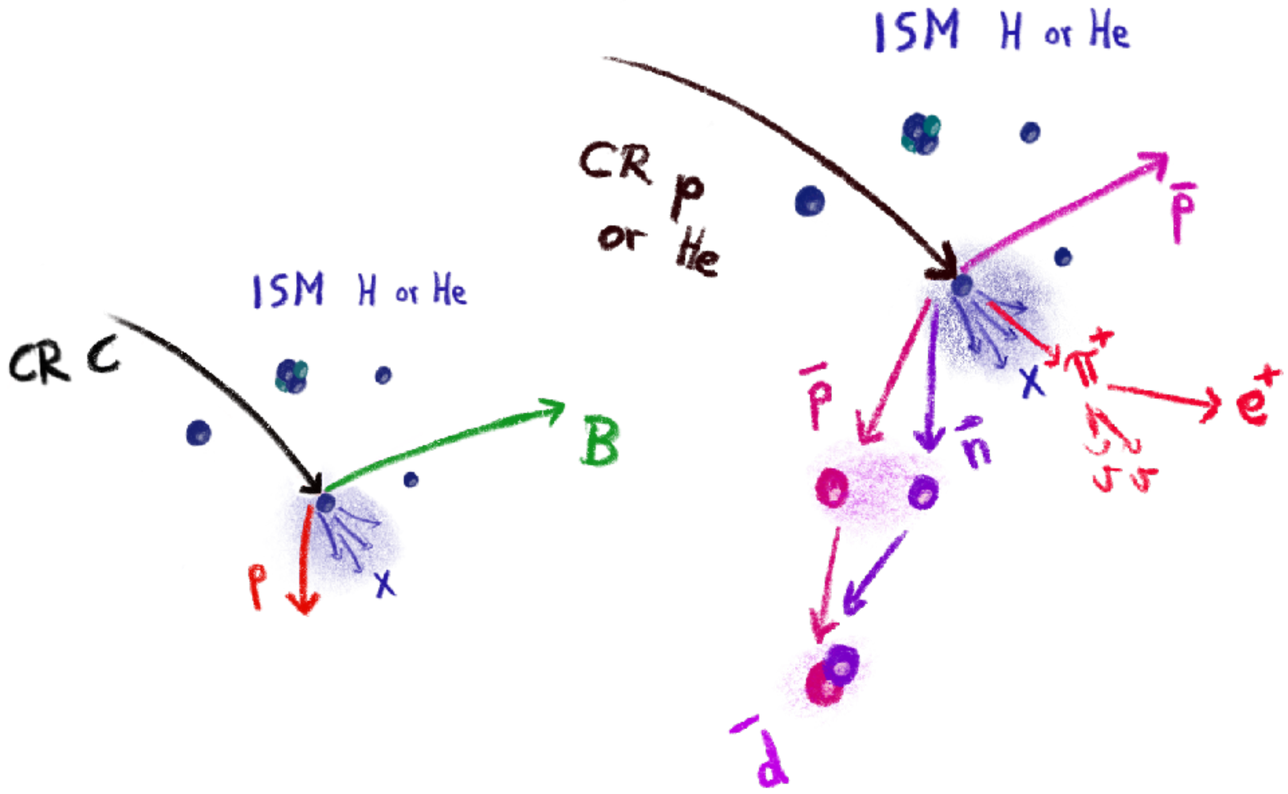
Michael Korsmeier
2023/05/22

In collaboration with Mattia di Mauro, Fiorenza Donato, and Luca Orusa

How can LHC data contribute to cosmic-rays studies?



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How can LHC data contribute to cosmic-rays studies?

Outline

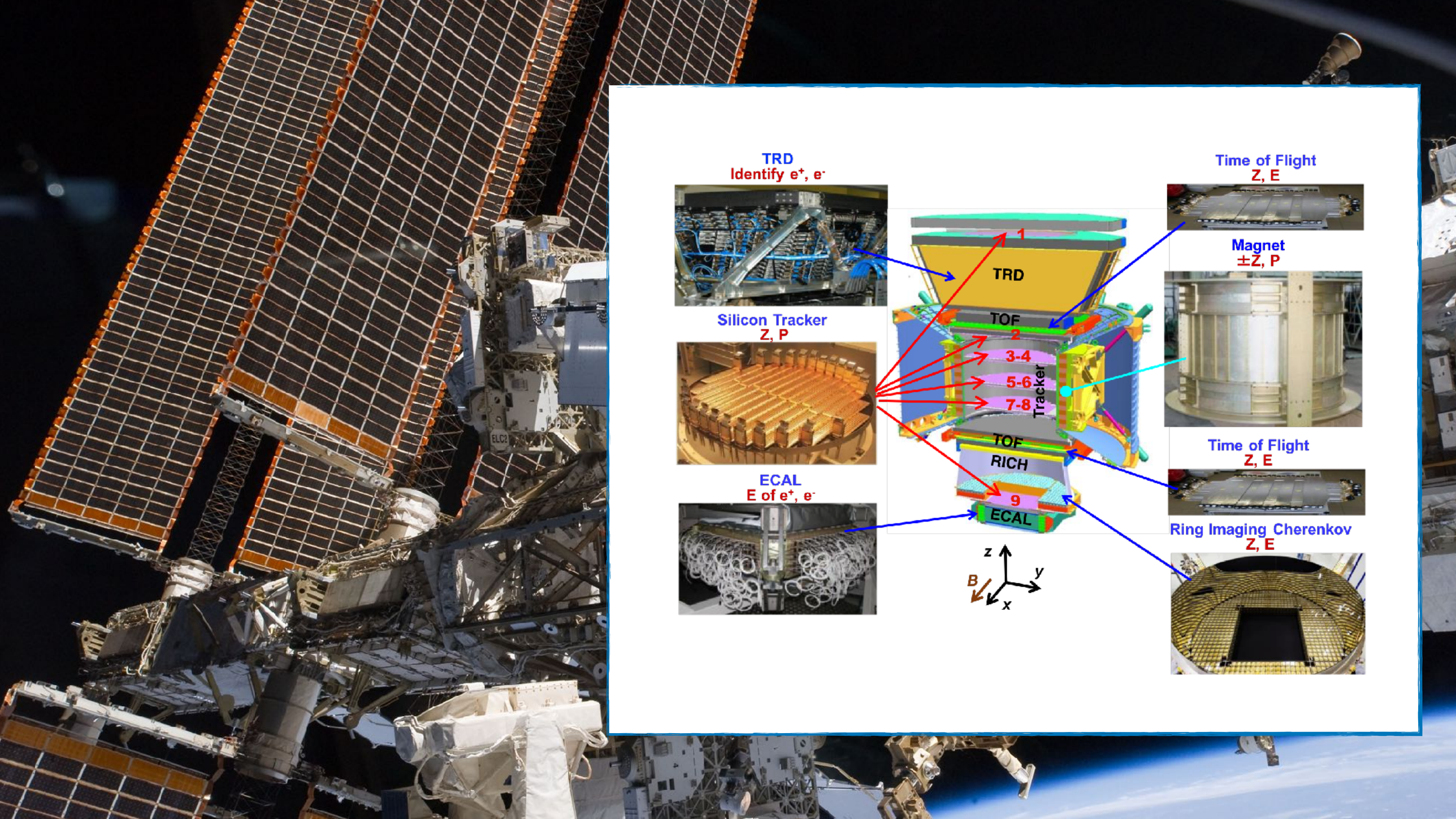
Brief introduction to Galactic cosmic rays

Cross sections for secondary antiprotons

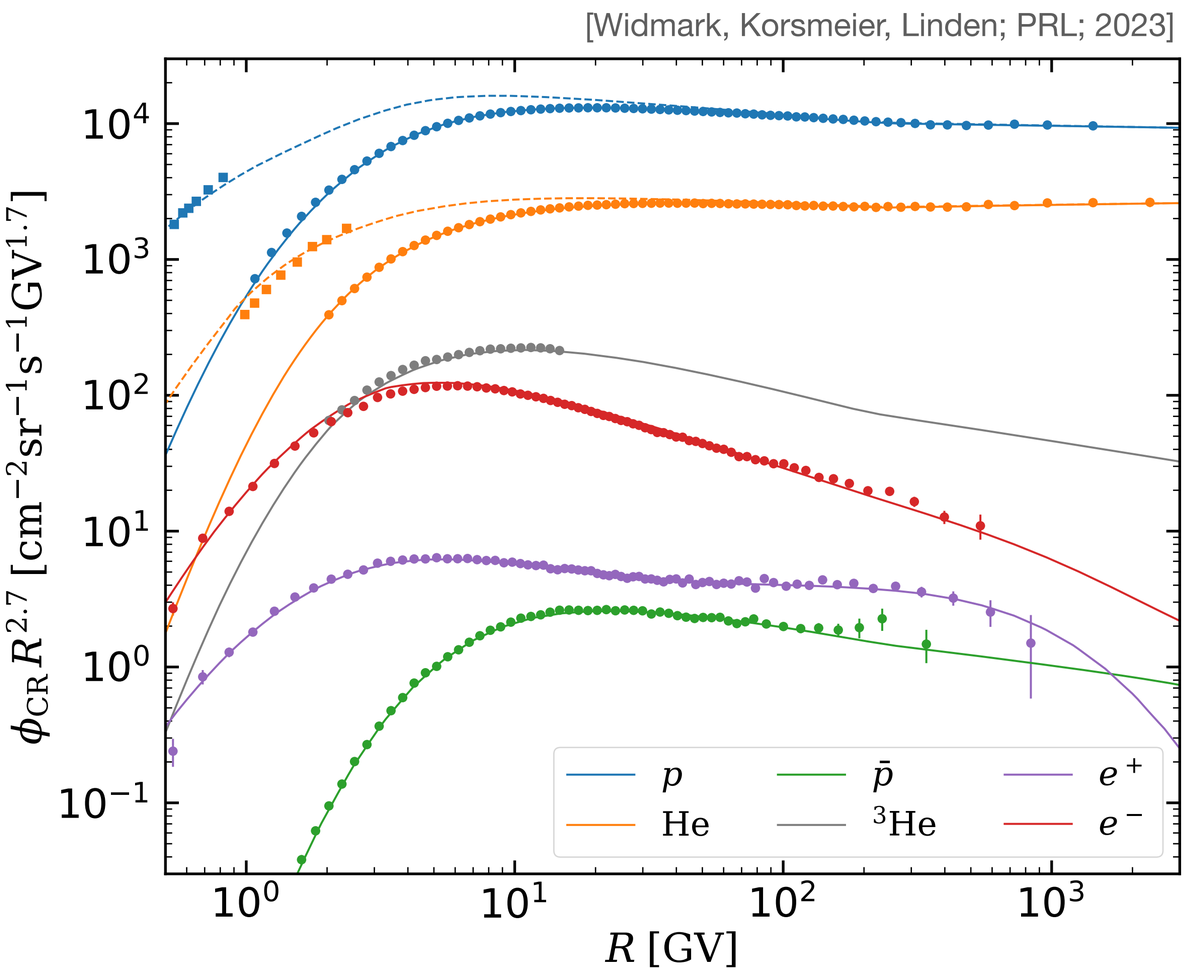
Cross sections for positrons and gamma rays

Summary and conclusions

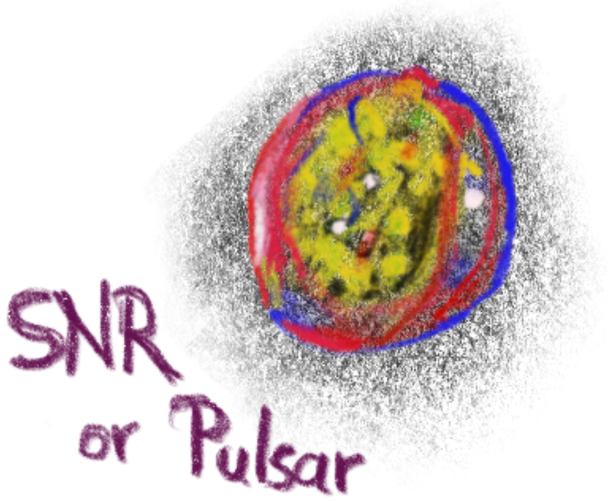

ELC2
P6TE

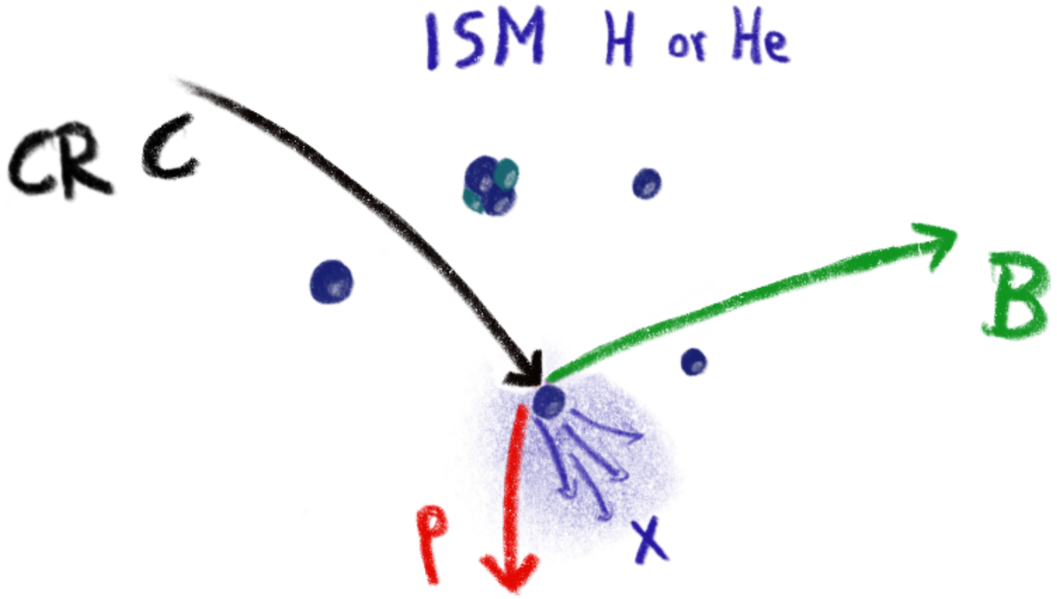

TRD
Identify e+, e-
Silicon Tracker
Z, P
ECAL
E of e+, e-
1
TRD
TOF
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
z
y
x
B
Time of Flight
Z, E
Magnet
±Z, P
Time of Flight
Z, E
Ring Imaging Cherenkov
Z, E

[Widmark, Korsmeier, Linden; PRL; 2023]



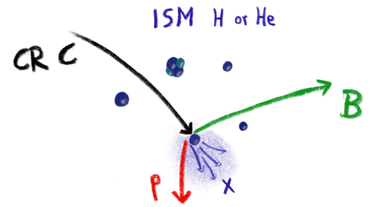
Primaries and secondaries

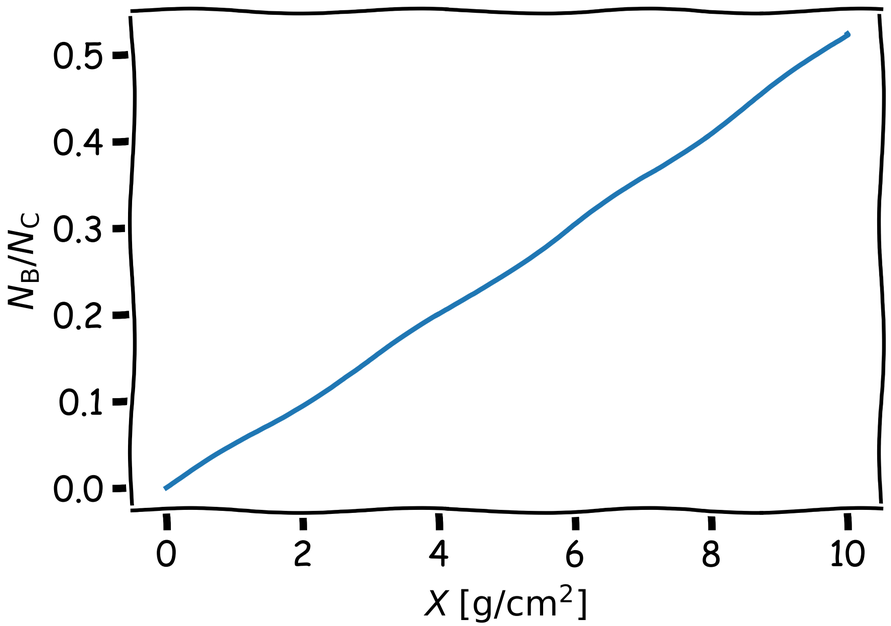




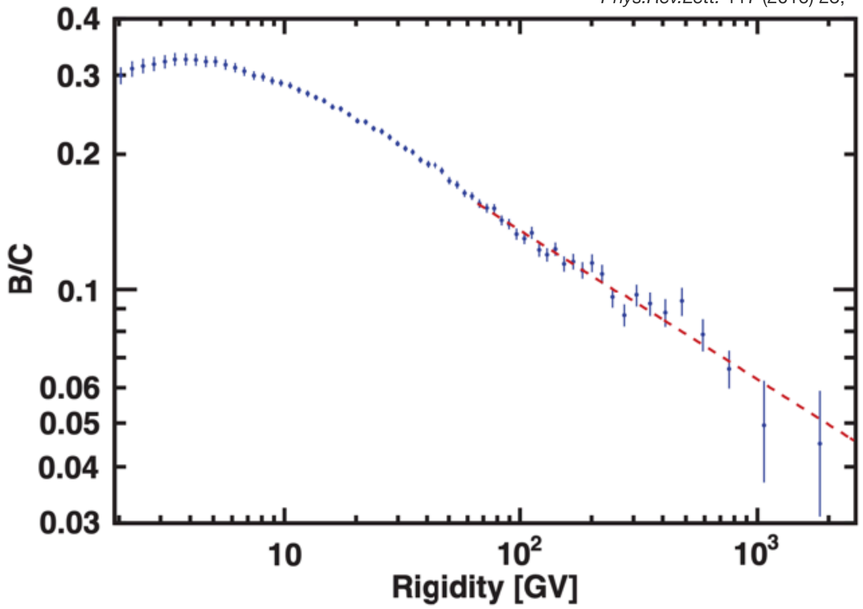
For more information on fragmentation cross section of CR nuclei:
[Korsmeier, Cuoco; PRD; 2021] [Genolini, Maurin, Moskalenko, Unger; PRC 20218]

Primaries and secondaries





Phys.Rev.Lett. 117 (2016) 23,



$$\mathrm{B/C} \sim 0.3 \qquad \text{(at 10 GV)}$$

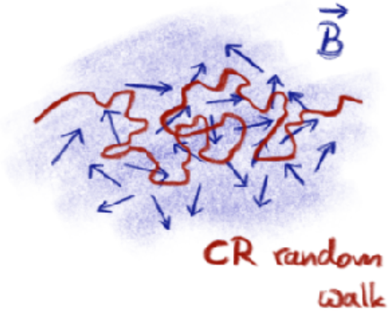
$$X_{10\,\mathrm{GeV}} \sim 6\ \mathrm{g/cm^2}$$

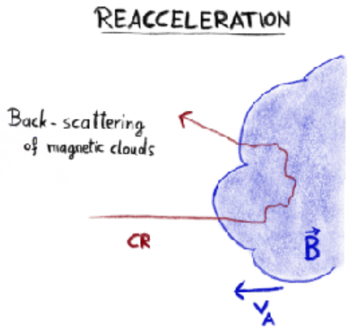
$$X_{\text{Galactic disc}} \sim 2 \times 10^{-3}\ \mathrm{g/cm^2}$$

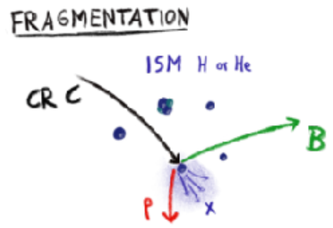
CRs traverse the Galactic disc for a few thousand times!

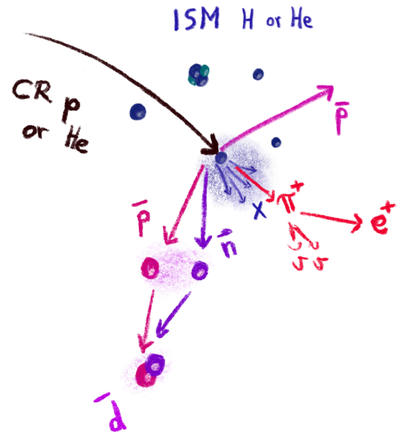
For more information on fragmentation cross section of CR nuclei:
[Korsmeier, Cuoco; PRD; 2021] [Genolini, Maurin, Moskalenko, Unger; PRC 20218]

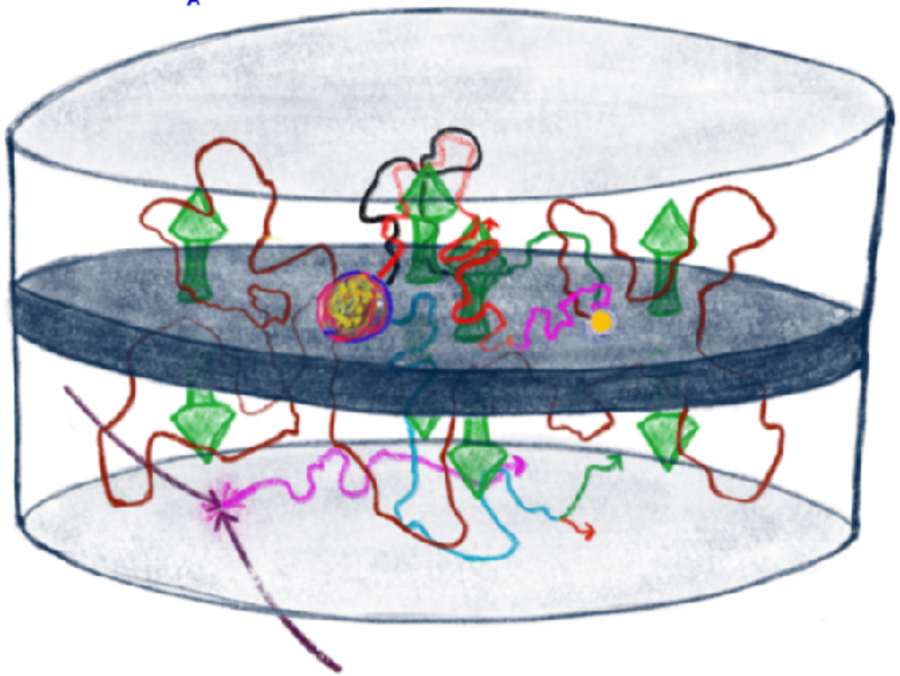
Modeling Cosmic-Ray Propagation

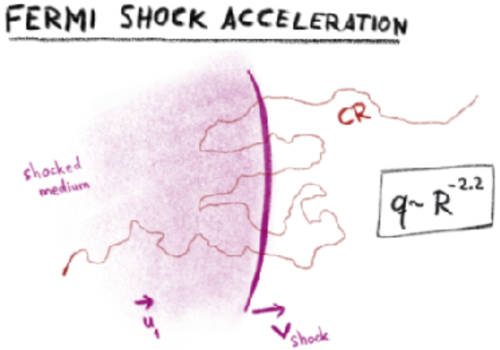


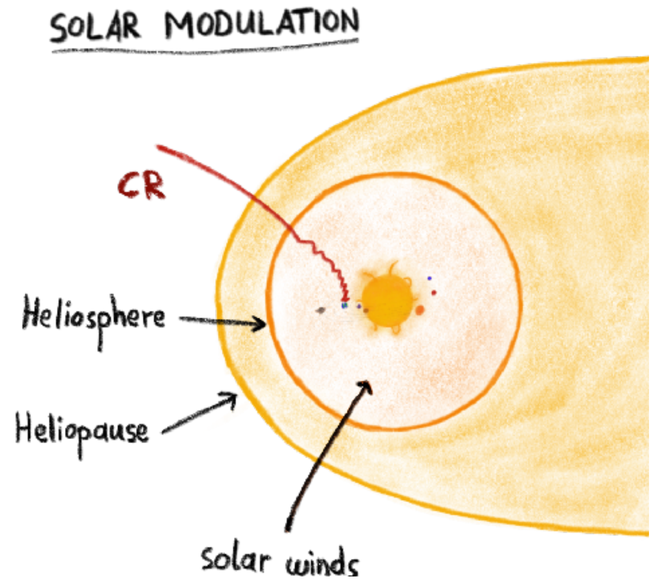




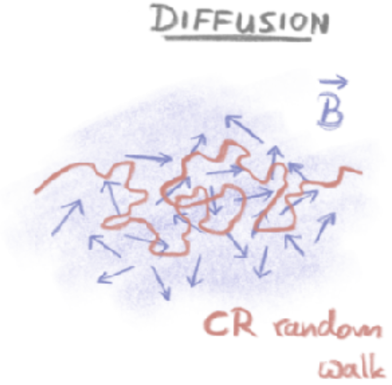


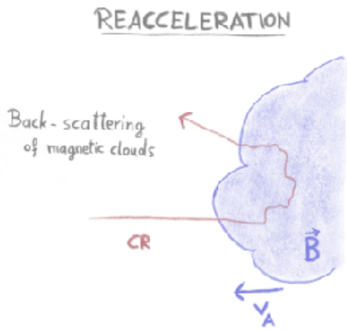


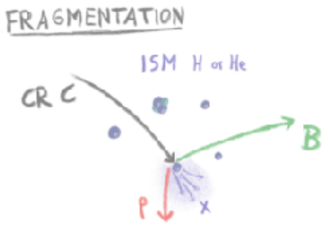


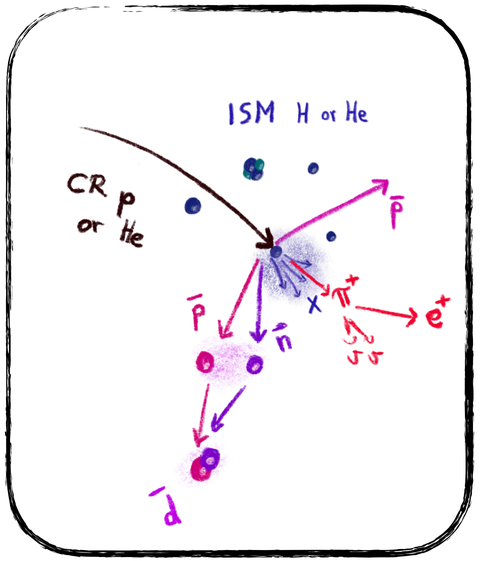


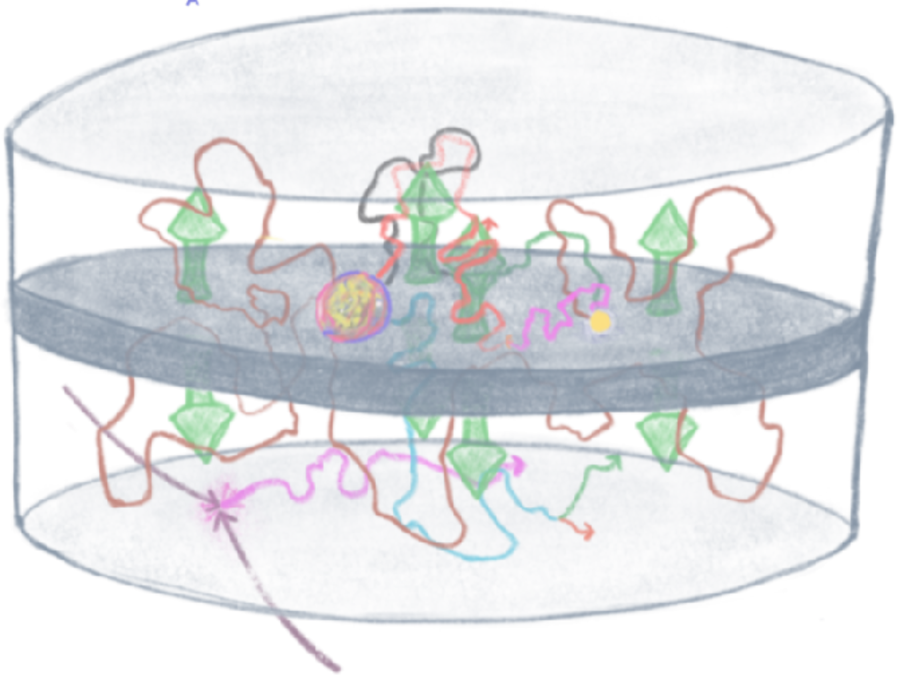
Modeling Cosmic-Ray Propagation

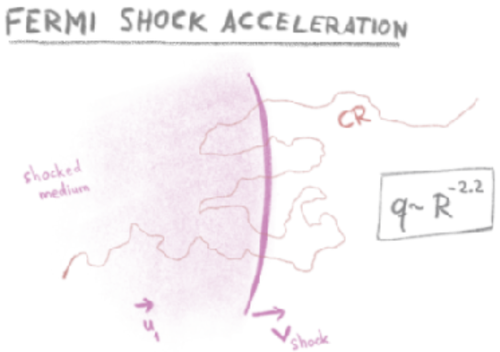


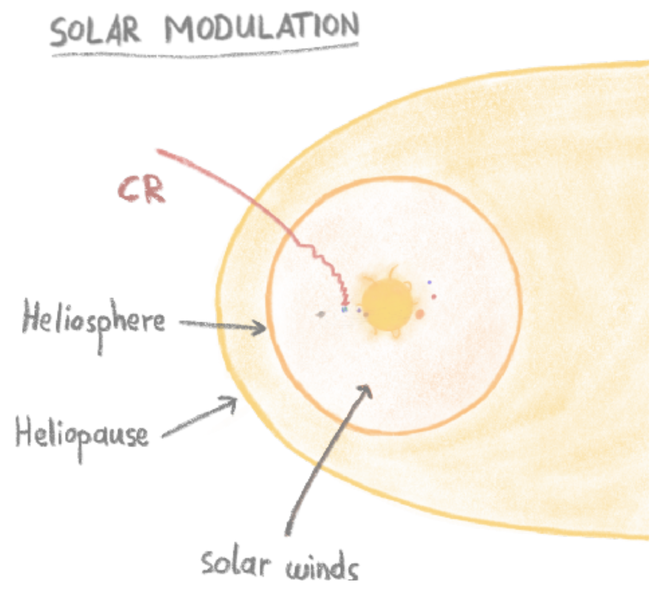






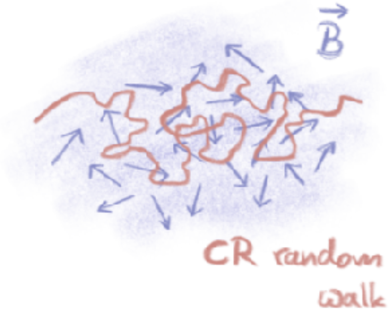


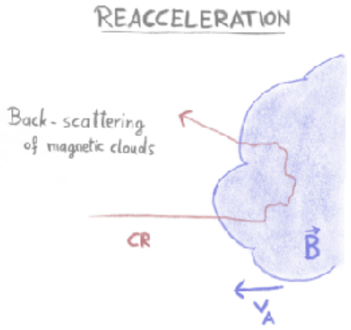


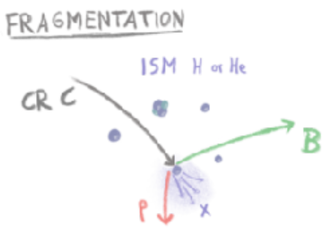


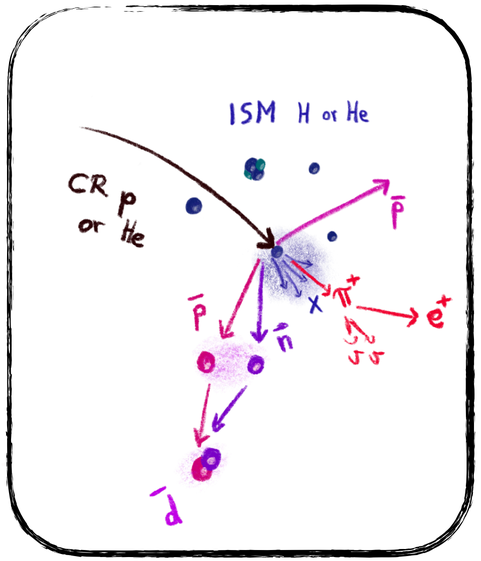
Modeling Cosmic-Ray Propagation

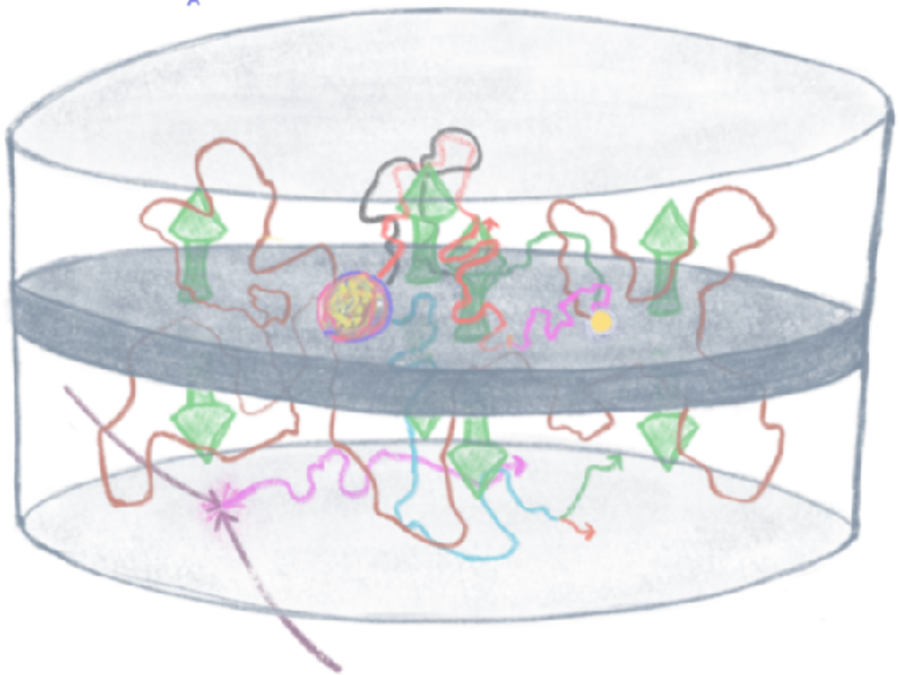
For more information on $\bar{d}$ see talk by Pavel Larionov (Monday 16:12)

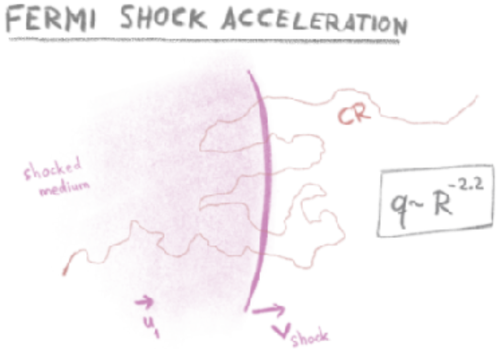


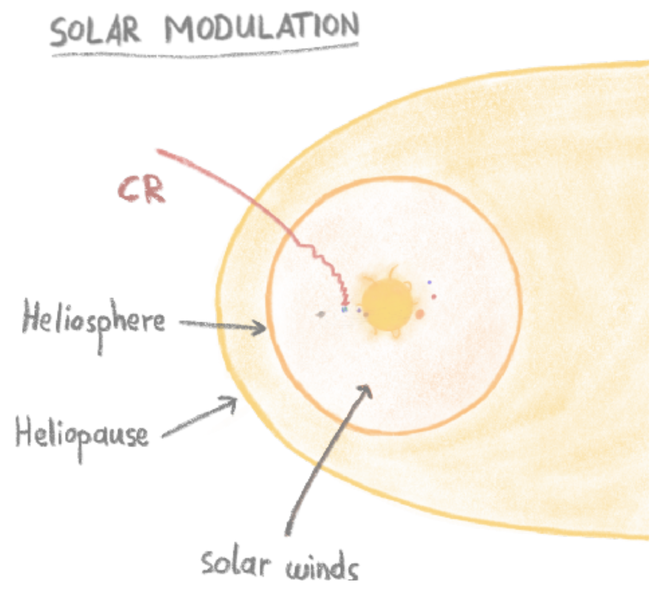












General Strategies

$$q(T_{e^\pm}, \boldsymbol{x}) = \sum_{i,j} 4\pi \, n_{\mathrm{ISM},j}(\boldsymbol{x}) \times \int dT_i \, \phi_i(T_i, \boldsymbol{x}) \frac{d\sigma_{ij}}{dT_{e^\pm}}(T_i, T_{e^\pm})$$

Source Term of $e^\pm$ in the Galaxy

Gas in the Galaxy

Flux of primary cosmic rays (p, He)

Secondary production cross section

General Strategies

$$q(T_{e^\pm}, \boldsymbol{x}) = \sum_{i,j} 4\pi \, n_{\mathrm{ISM},j}(\boldsymbol{x}) \times \int dT_i \, \phi_i(T_i, \boldsymbol{x}) \frac{d\sigma_{ij}}{dT_{e^\pm}}(T_i, T_{e^\pm})$$

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	Analytic Parametrization	Monte Carlo Event Generator
Procedure	• Parametrization of the (Lorentz invariant) cross section • Fit to experimental data • Integration over production angle	• Tuning of the MC event generator to the relevant experimental data • Generation of data • Extraction of the final cross section
Examples	• Antiprotons: [Tan&Ng ’83; Winkler ’17; Korsmeier ‘18] • Positrons: [Dermer ’86, Orusa ’22] • Nuclei: [GALPROP; DRAGON]	• Antiprotons: [AAfrag/QGS-Jet (Kachelriss ’17)] • Positrons: [Kamae ’05] • Nuclei: [FLUKA (della Torre Luque ’22)]

General Strategies

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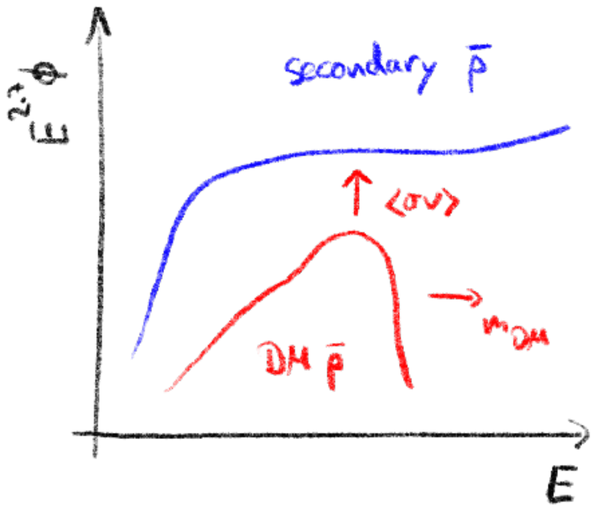
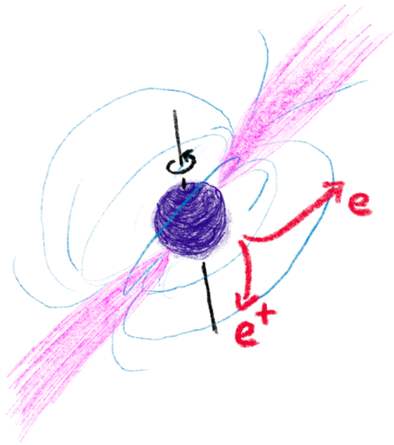
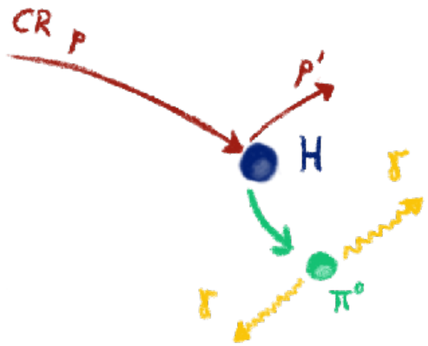
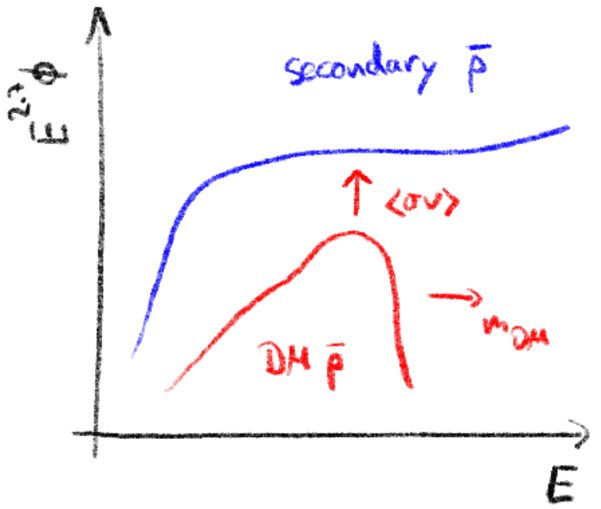
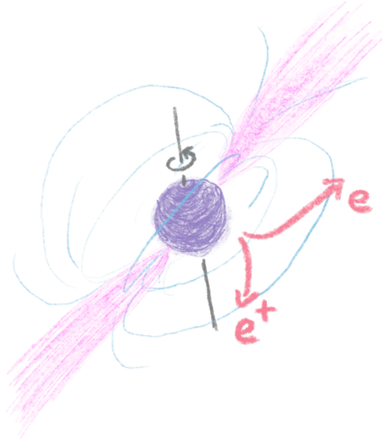
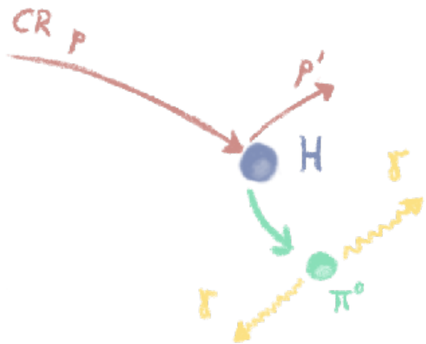
Motivation to study secondary …

antiprotons	positrons	gamma rays
		
• DM searches and constraints • Cosmic-ray propagation • …	• Quantifying/explaining the excess in the positron fraction • Cosmic-ray propagation • …	• Understanding galactic diffuse emission • Foreground/Background) for many gamma-ray targets (GCE, point sources, …)

Motivation to study secondary …

antiprotons	positrons	gamma rays
		
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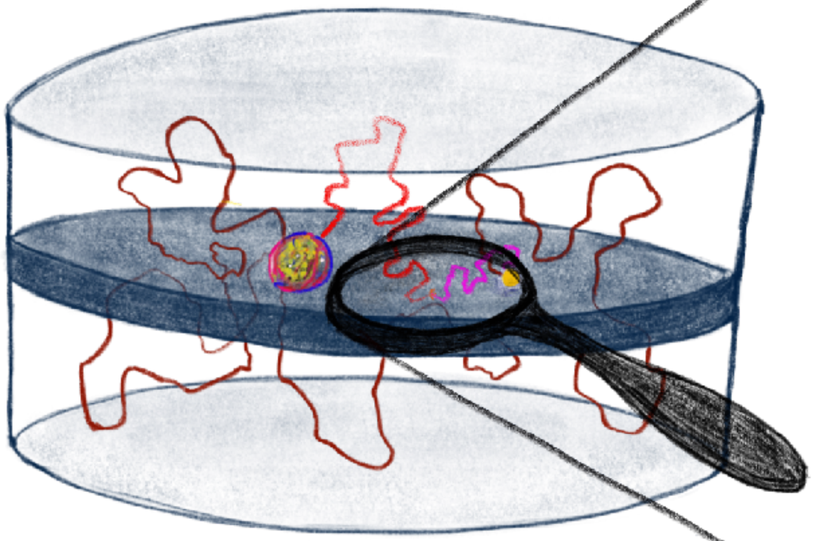
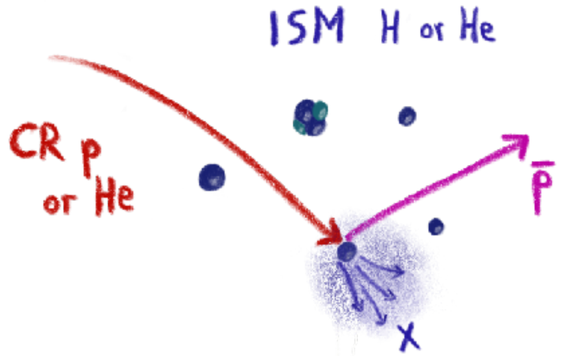
Secondary antiprotons



ANTIPROTONS



$$CR + ISM \rightarrow \bar{p} + X$$

$$q^{\bar{p}}(T_{\bar{p}}) = \int dT\, 4\pi\, n_{ISM}\, \phi_{CR}(T)\, \frac{d\sigma(T, T_{\bar{p}})}{dT_{\bar{p}}}$$

Antiproton production $p + p \rightarrow \bar{p} + X$

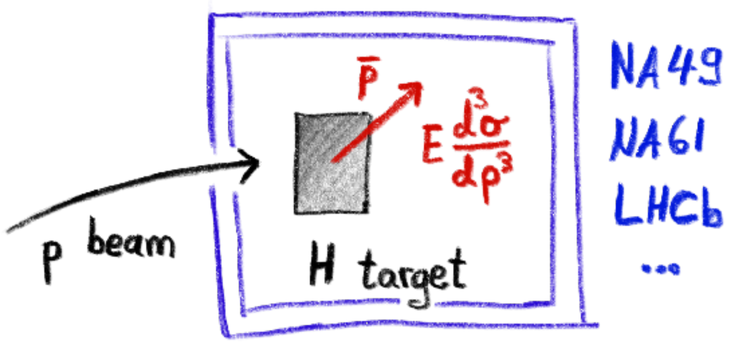
$$E\frac{d^3\sigma}{dp^3} \sim R(s, x_R)\,(1 - x_R)^{c_1}\, e^{-c_2 p_T}$$

scaling violation — Feynman scaling invariance — p_T suppression

Lorentz transformation + angular integration

$$\frac{d\sigma(T, T_{\bar{p}})}{dT_{\bar{p}}}$$

Modeling the antiproton production cross section



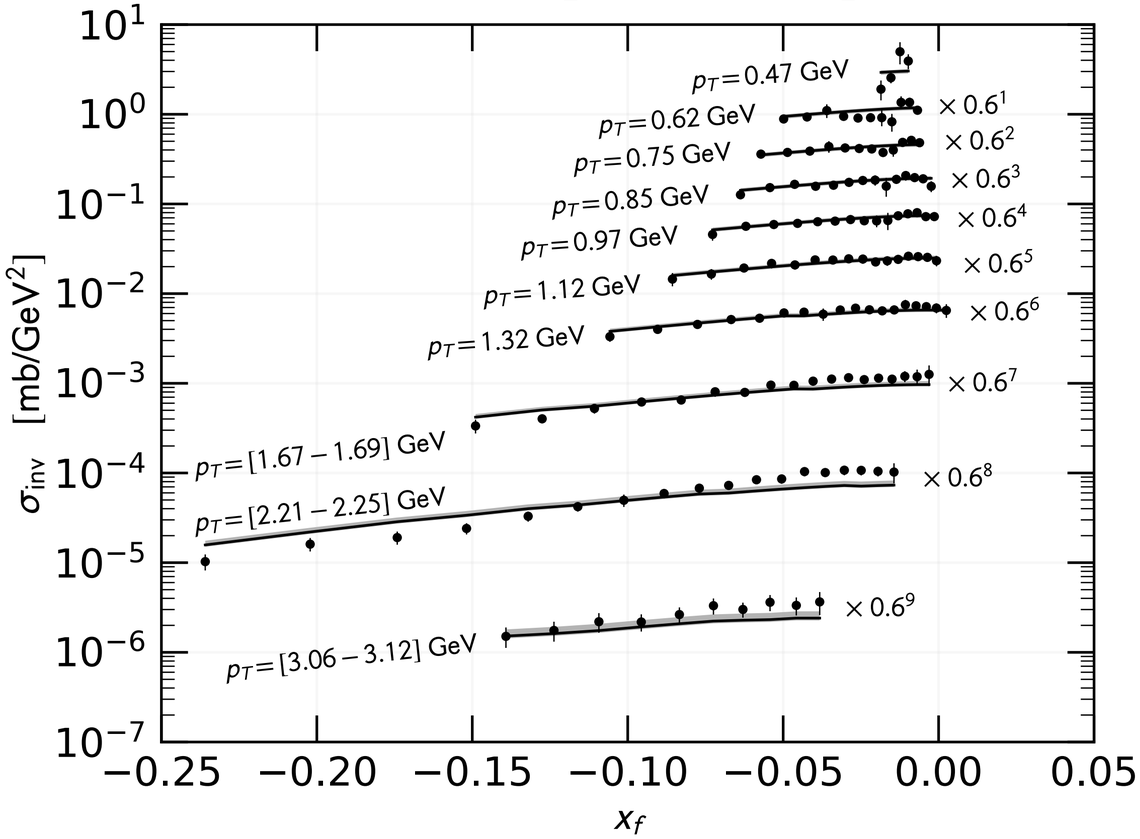
Parametrization of the Lorentz invariant cross section:

$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp}(\sqrt{s}, x_R, p_T) = \sigma_{\text{in}} R(\sqrt{s}, x_R, p_T)\, C_1 (1 - x_R)^{C_2} \left[1 + \frac{X}{\text{GeV}}(m_T - m_p)\right]^{-\frac{1}{C_3 X}}$$

$$R = \begin{cases} 1 & , \sqrt{s}\,10\,\text{GeV} \\ \left[1 + C_5\left(10 - \frac{\sqrt{s}}{\text{GeV}}\right)^5\right] \exp\left[C_6\left(10 - \frac{\sqrt{s}}{\text{GeV}}\right)^2 (x_R - x_{R,\min})\right] & , \text{elsewhere} \end{cases}$$

$$X = C_4 \log^2\left(\frac{\sqrt{s}}{4m_p}\right) \quad \text{and} \quad x_R = E^*_{\bar{p}} / E^*_{\bar{p},\max}$$

LHCb data for $p + \text{He} \to \bar{p} + X$

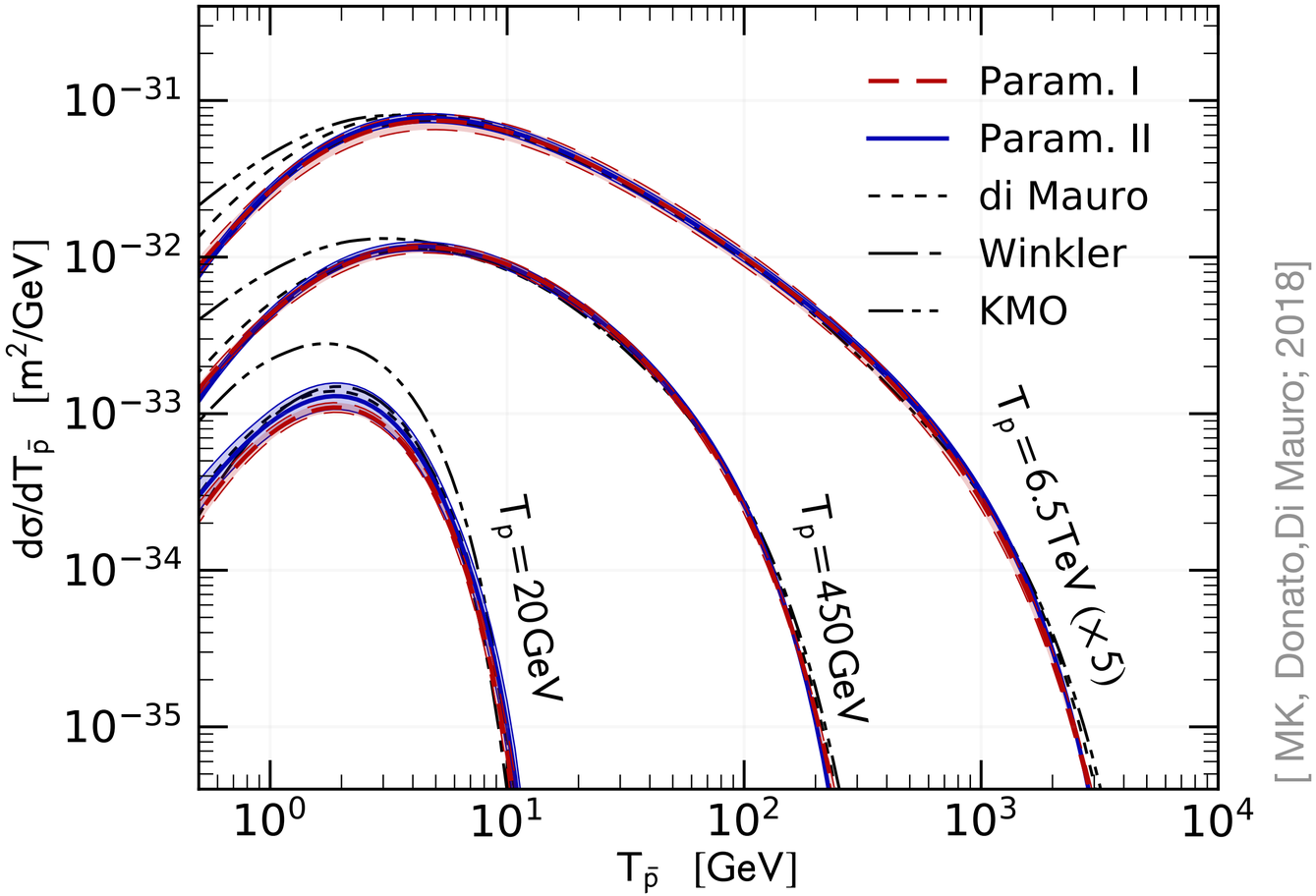


[MK, Donato,Di Mauro; 2018]

For more information see talk
by Giacomo Graziani (Monday 15:55)

Modeling the antiproton production cross section

$$\frac{d\sigma}{dT_{\bar{p}}}(T_p, T_{\bar{p}}) = p_{\bar{p}} \int d\Omega \left(E \frac{d^3\sigma}{dp^3} \right)(T_p, T_{\bar{p}}, \theta)$$



[MK, Donato,Di Mauro; 2018]

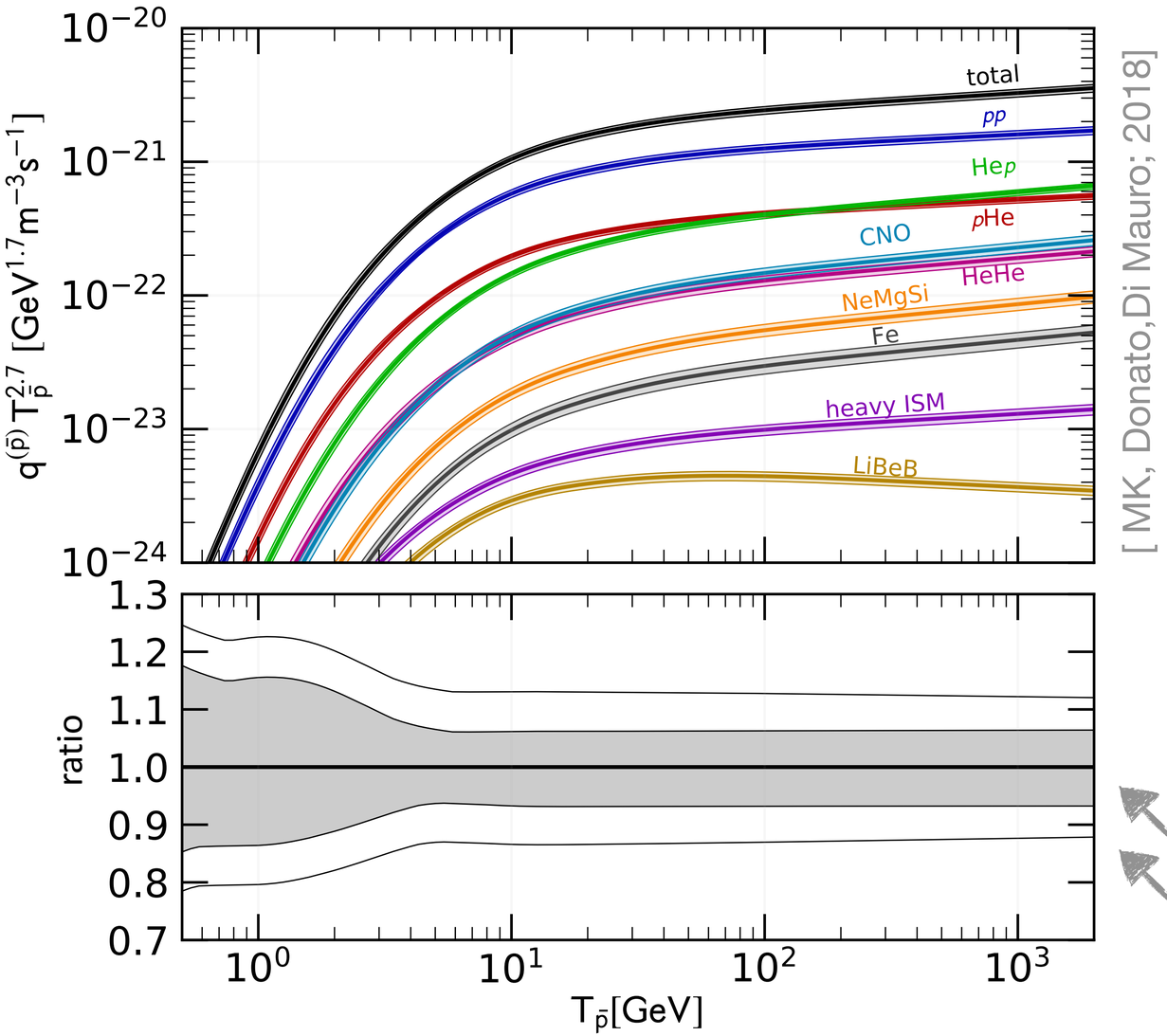
Data for $p + p \to \bar{p} + X$:

Experiment	$\sqrt{s}$ [GeV]	σ_{scale}	I	II
NA49	17.3	6.5%	×	×
NA61	7.7, 8.8, 12.3, 17.3	5%	×	×
Dekkers *et al.*	6.1, 6.7	10%	×	×
BRAHMS	200	10%	×	

Data for $p + \mathrm{He}$ and $p + \mathrm{C}$:

	$\sqrt{s}$ [GeV]	σ_{scale}	I-A	I-B	II-A	II-B
NA49	17.3	6.5%	×	×	×	×
LHCb	110	6.0%		×		×

Antiproton source term



[MK, Donato,Di Mauro; 2018]

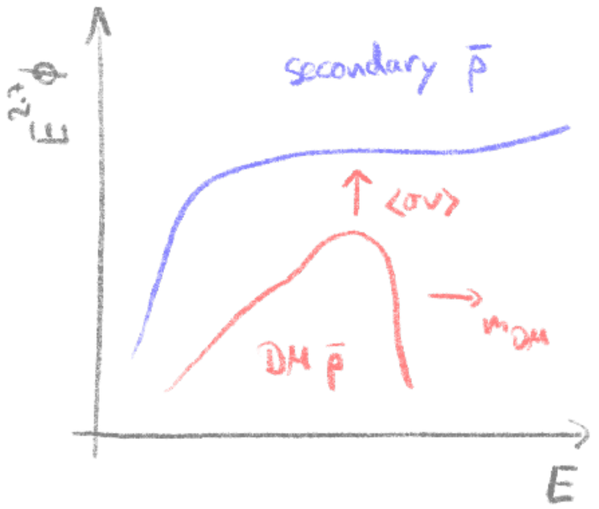
- Updated parametrization of pp and pA cross sections based on measurements by NA49, NA61 and LHCb experiments
- LHCb $p\mathrm{He}$ data constrains high-energy cross section shape
- The total source term uncertainties are up to $\pm 20\,\%$ (at 2σ level)
- Future data may help to improve constraints on secondary antiprotons in cosmic rays

Prompt antiprotons

Isospin and hyperons

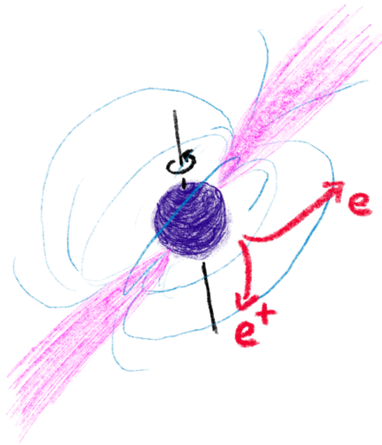
Motivation to study secondary …

antiprotons



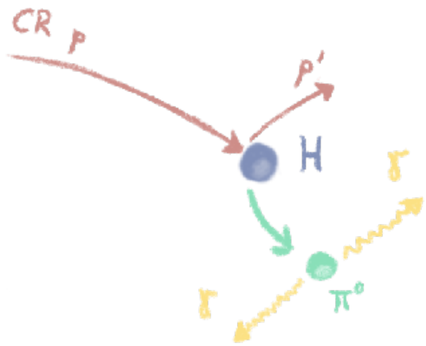
- DM searches and constraints
- Cosmic-ray propagation
- …

positrons



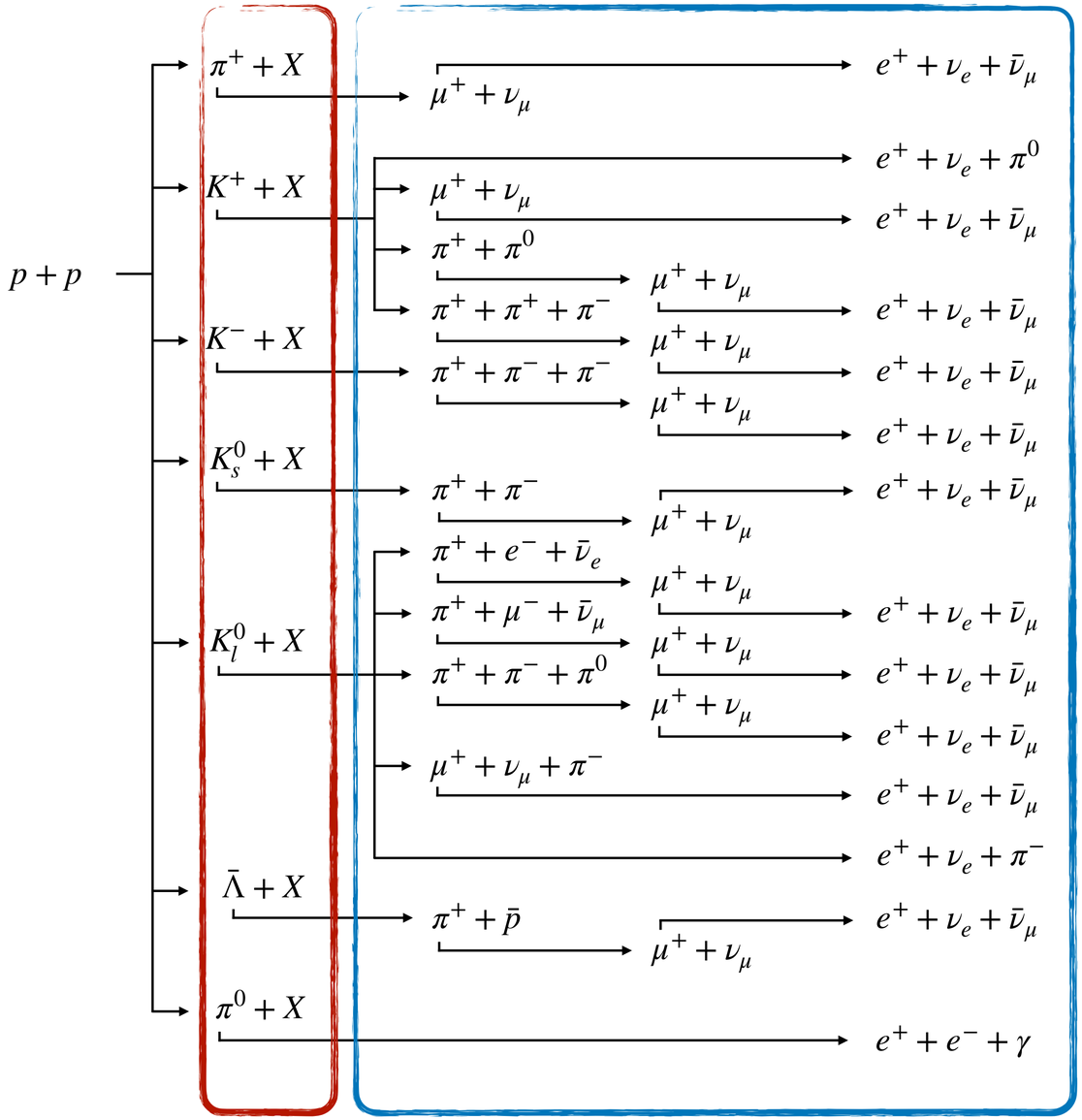
- Quantifying/explaining the excess in the positron fraction
- Cosmic-ray propagation
- …

gamma rays



- Understanding galactic diffuse emission
- Foreground/Background) for many gamma-ray targets (GCE, point sources, …)

Positrons



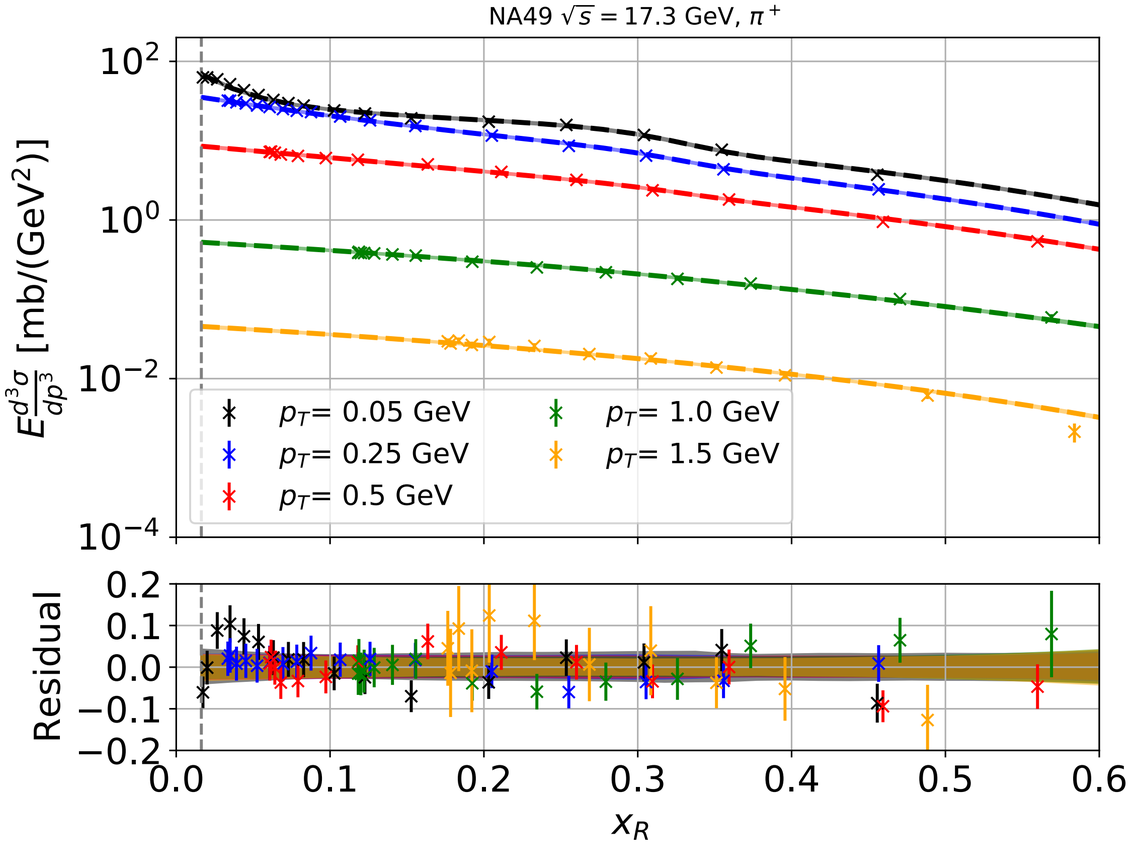
Parametrized from data:

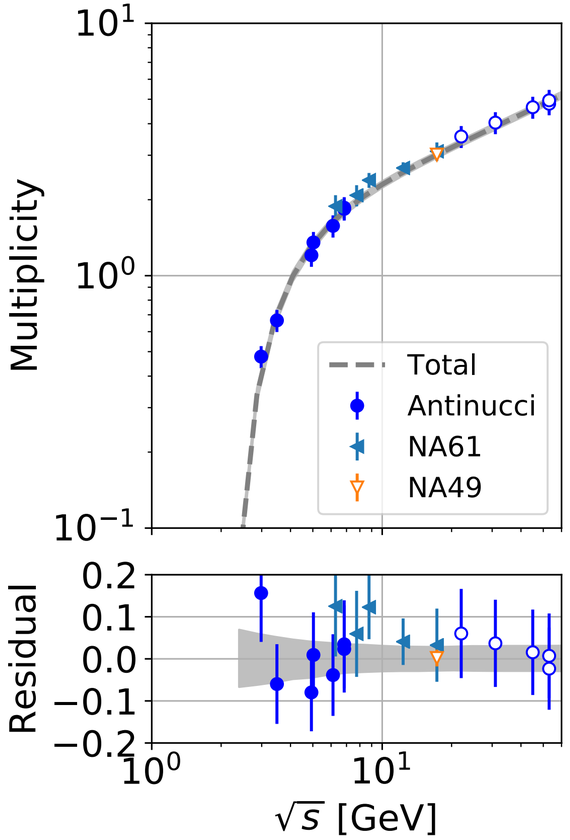
Experiment	$\sqrt{s}$ [GeV]		σ_{inv}	n	Ref.
NA49	17.3	$(\pi^\pm, K^\pm)$	$\surd$	-	[67, 76]
ALICE	900	$(\pi^+, K^\pm)$	$\surd$	-	[77]
CMS	900, 2760, 7000, 13000	$(\pi^\pm, K^\pm)$	$\surd$	-	[72, 78]
Antinucci	3.0, 3.5, 4.9, 5.0, 6.1, 6.8	$(\pi^\pm)$	-	$\surd$	[79]
	2.8, 3.0,3.2, 5.3, 6.1, 6.8	(K^+)	-	$\surd$	[79]
	4.9, 5.0, 6.1, 6.8	(K^-)	-	$\surd$	[79]
NA61/SHINE	6.3, 7.7, 8.8, 12.3, 17.3	$(\pi^\pm, K^\pm)$	-	$\surd$	[68]

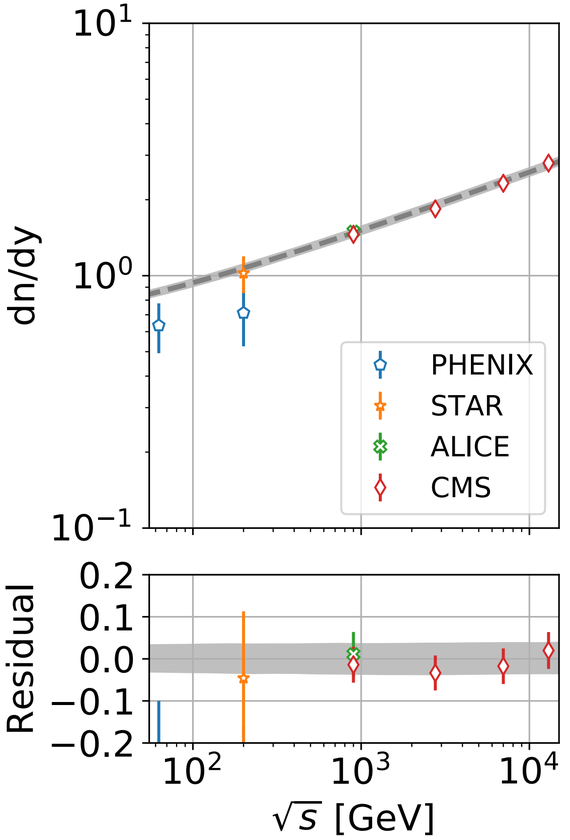
Calculated:

Polarized μ^+ decay is considered at NLO

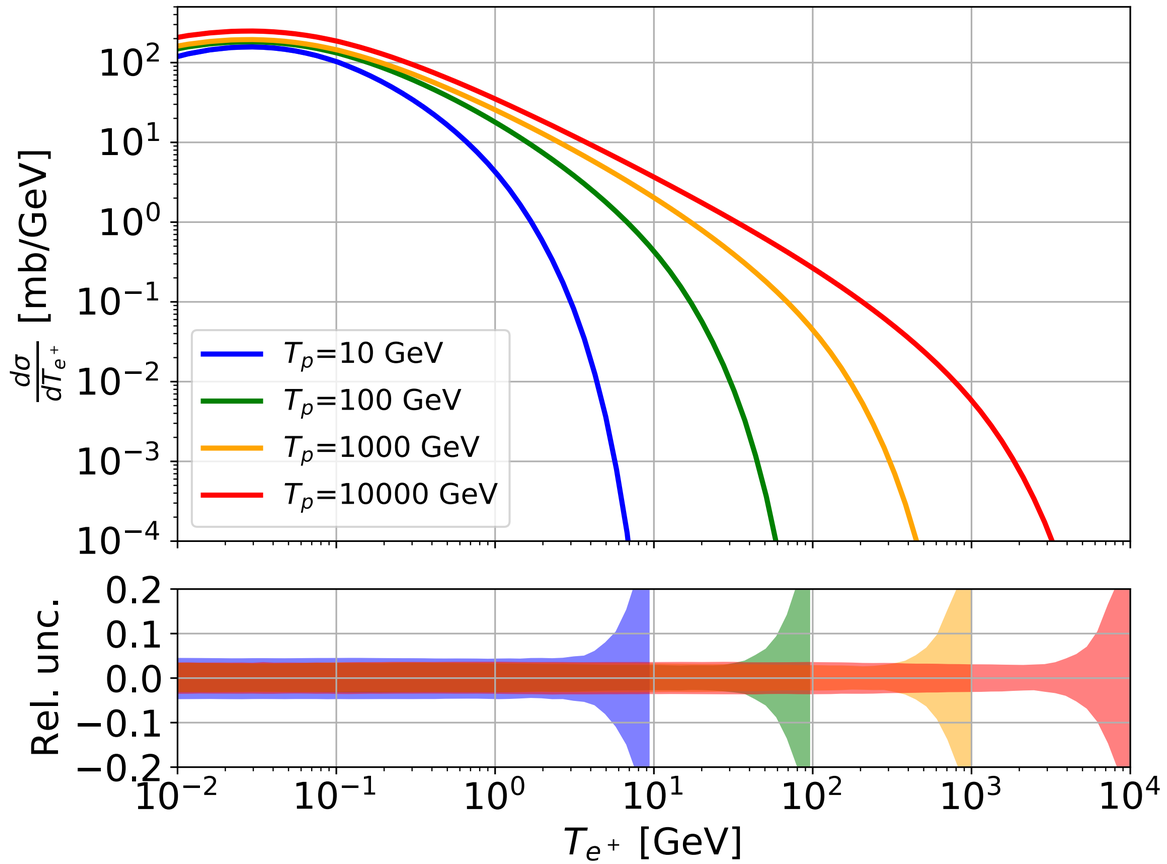
From Cross Sections to the Cosmic-Ray Source Term







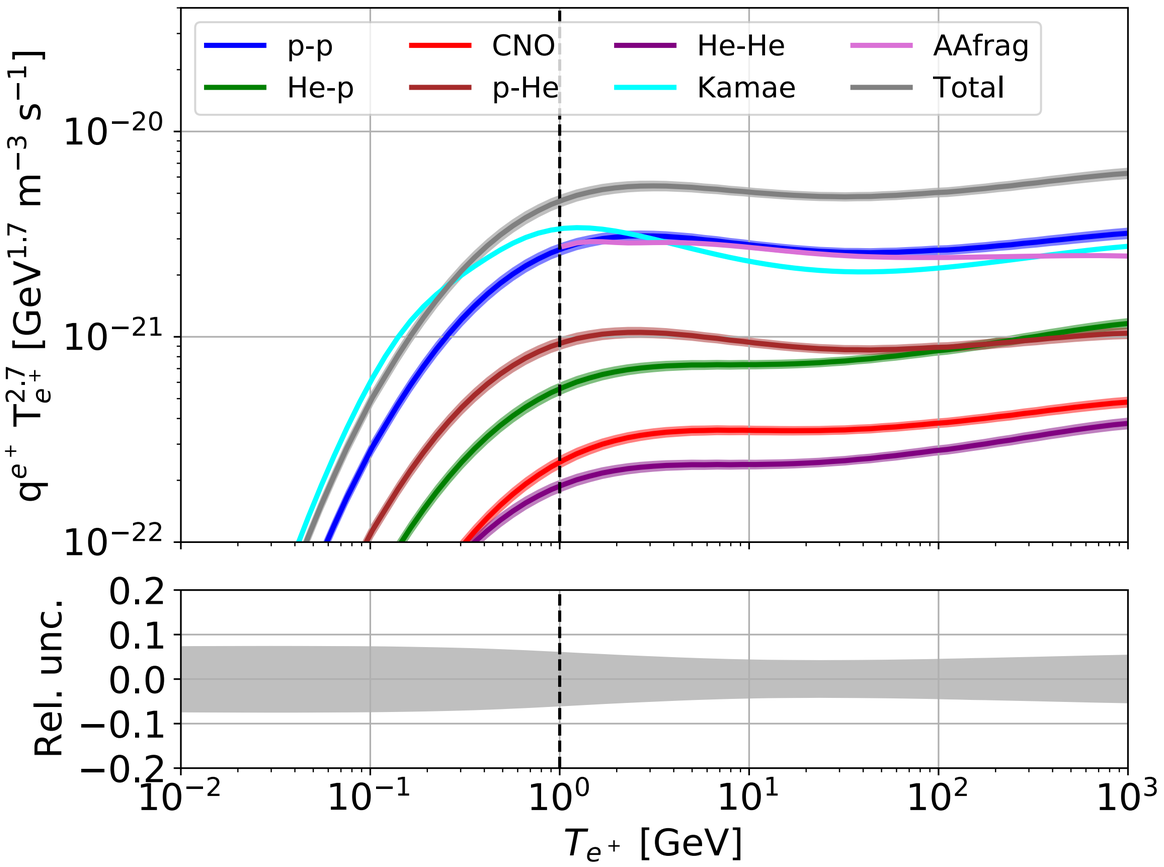
From Cross Sections to the Cosmic-Ray Source Term



$$\frac{d\sigma_{ij}}{dT_{\pi^\pm}}(T_i, T_{\pi^\pm}) = p_{\pi^\pm} \int d\Omega \; \sigma_{\mathrm{inv}}^{(ij)}(T_i, T_{\pi^\pm}, \theta)$$

$$\frac{d\sigma_{ij}}{dT_{e^\pm}}(T_i, T_{e^\pm}) = \int dT_{\pi^\pm} \; \frac{d\sigma_{ij}}{dT_{\pi^\pm}}(T_i, T_{\pi^\pm}) \; P(T_{\pi^\pm}, T_{e^\pm})$$

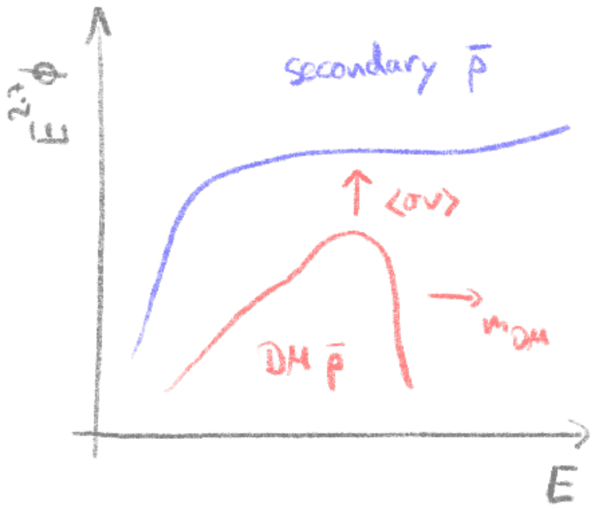
From Cross Sections to the Cosmic-Ray Source Term



- AMS-02 measures cosmic-ray e^+ (and e^-) with high precision
- Accurate description of the secondary component produced in proton and helium interaction is necessary
- New analytical functions for the Lorentz invariant cross section of $\pi^{\pm}$ and $K^{\pm}$ production are determined by fitting collider experiment data
- Cross section is predicted from 10 MeV to 10 TeV with an uncertainty of about 5-7% at the energies relevant for AMS-02 positron flux

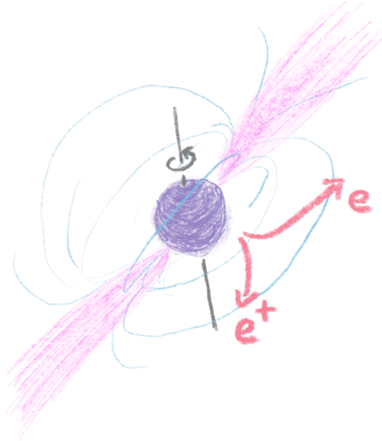
Motivation to study secondary …

antiprotons



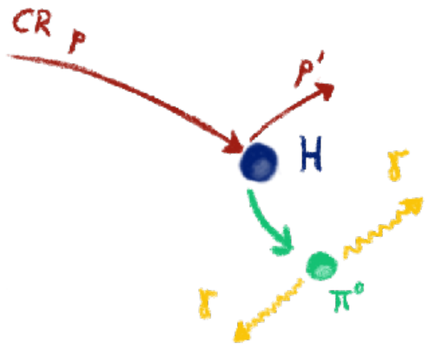
- DM searches and constraints
- Cosmic-ray propagation
- …

positrons



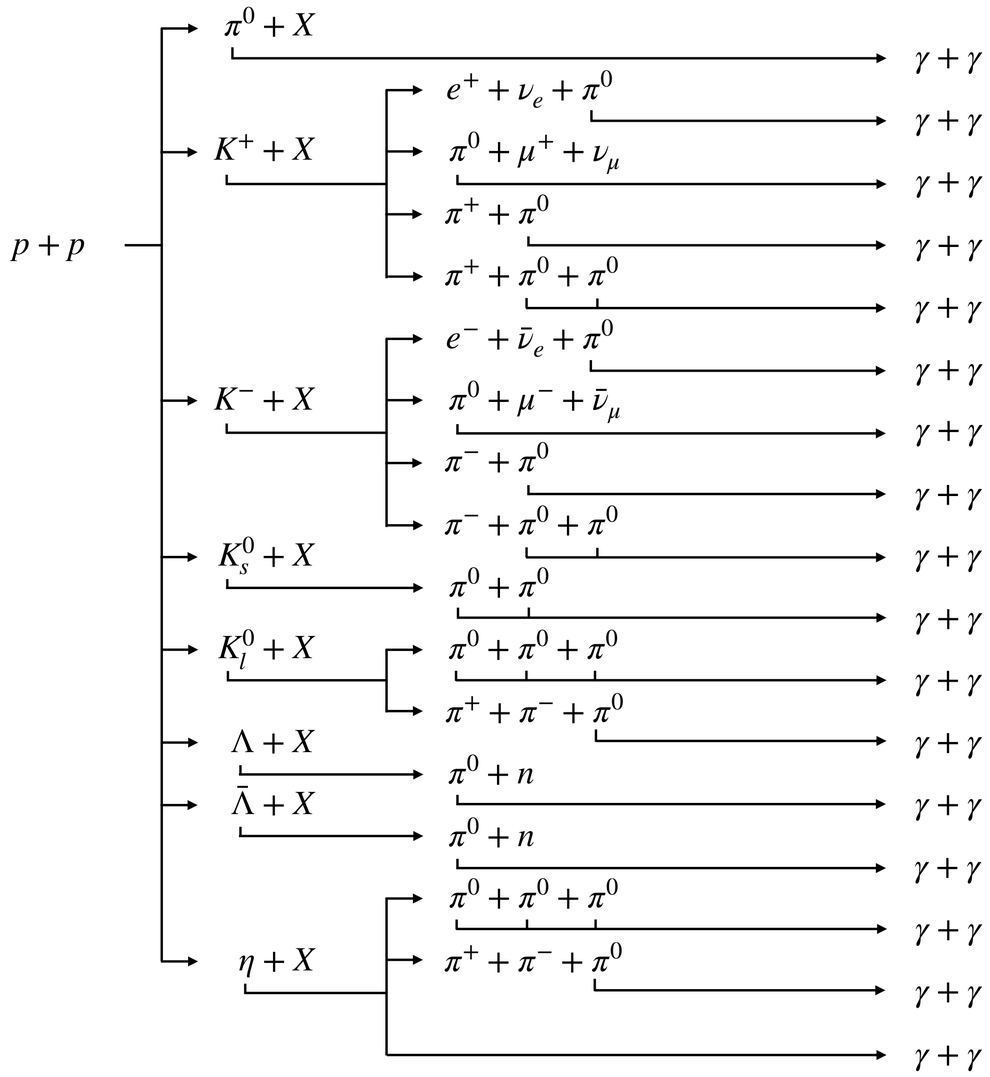
- Quantifying/explaining the excess in the positron fraction
- Cosmic-ray propagation
- …

gamma rays



- Understanding galactic diffuse emission
- Foreground/Background) for many gamma-ray targets (GCE, point sources, …)

Gamma Rays



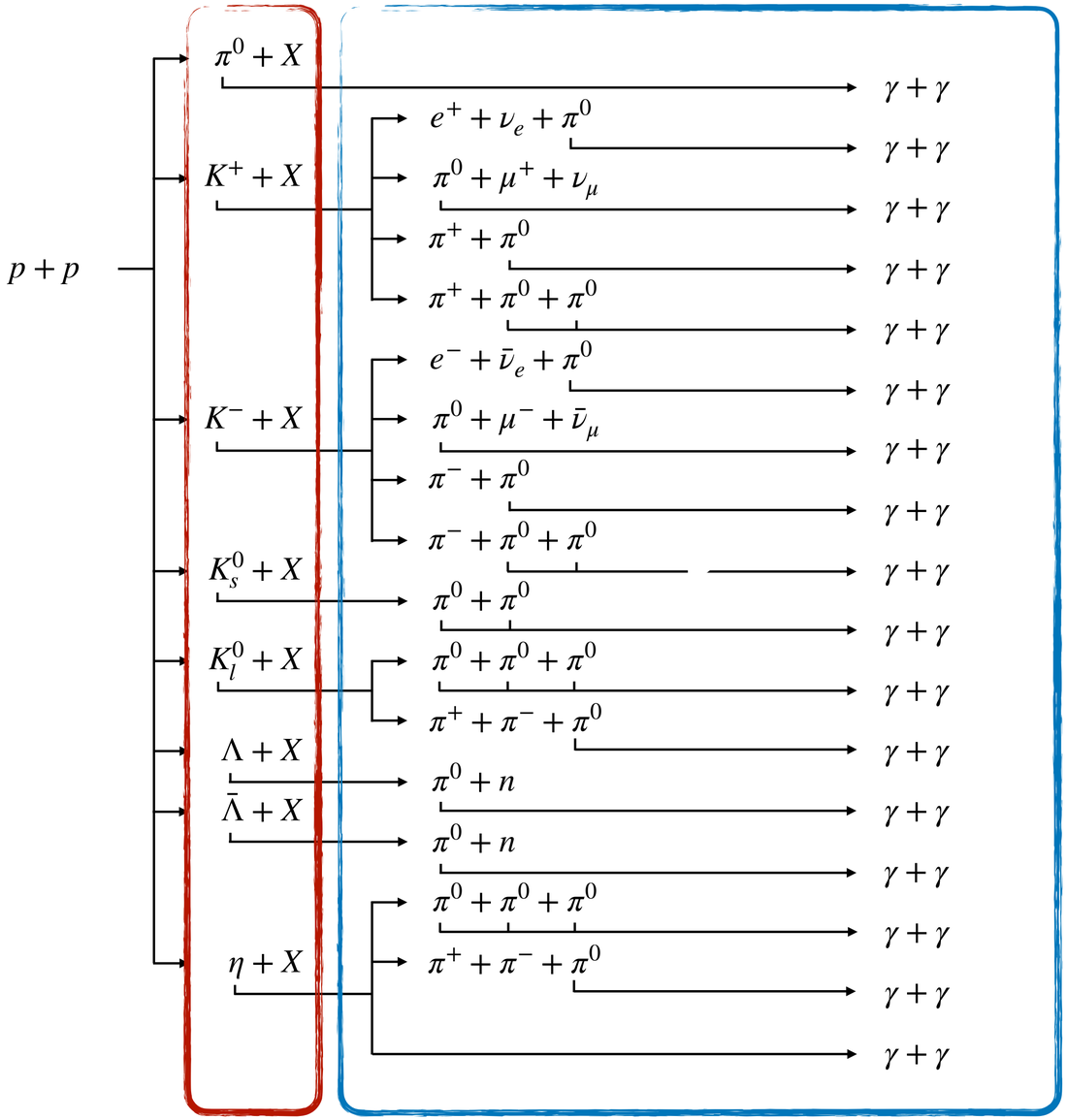
Parametrization:

- Low-energy multiplicity of π^0 from [Dermer 1986]
- High-energy dn/dx_F from LHCf
- Kinematic shape form π^+ and π^-

Calculated:

π^0 decays (and decay of all other mesons)

Gamma Rays



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- Kinematic shape form π^+ and π^-

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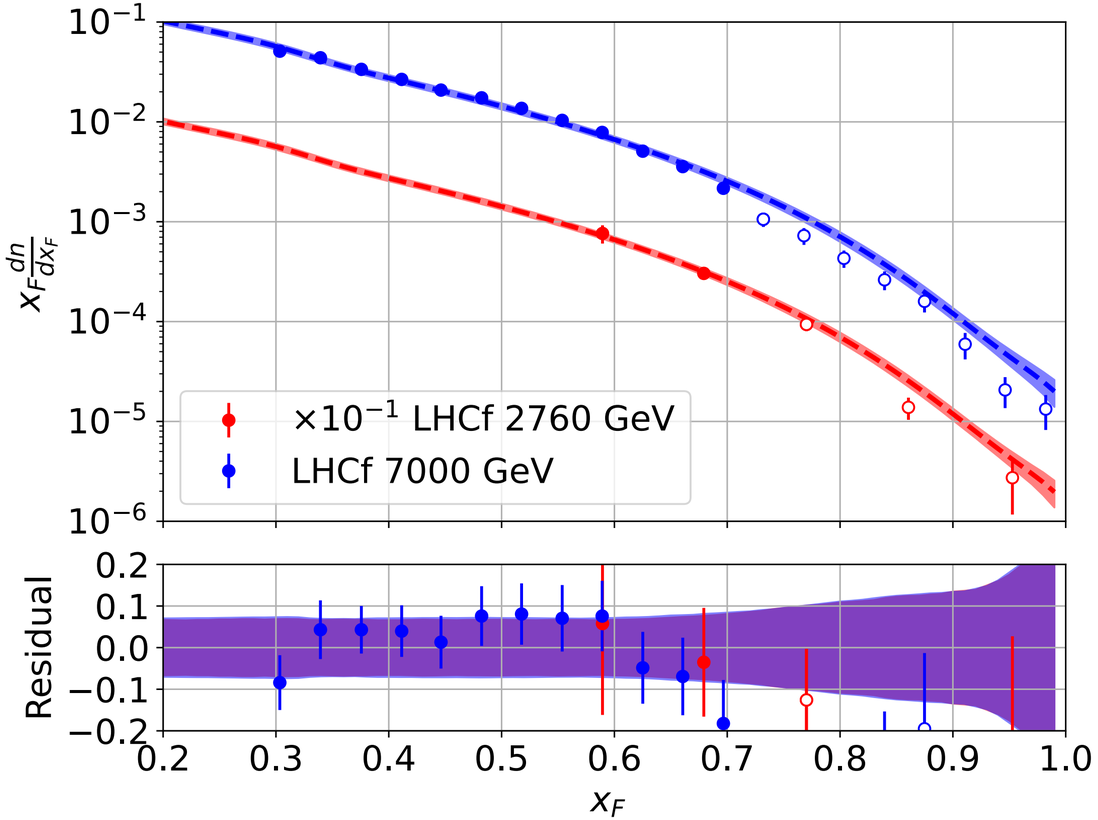
Gamma Rays



Parametrization:

- Low-energy multiplicity of π^0 from [Dermer 1986]
- High-energy dn/dx_F from LHCf
- Kinematic shape form π^+ and π^-

Calculated:

π^0 decays (and decay of all other mesons)

Summary

Cosmic rays are provided with unprecedented precision by AMS-02

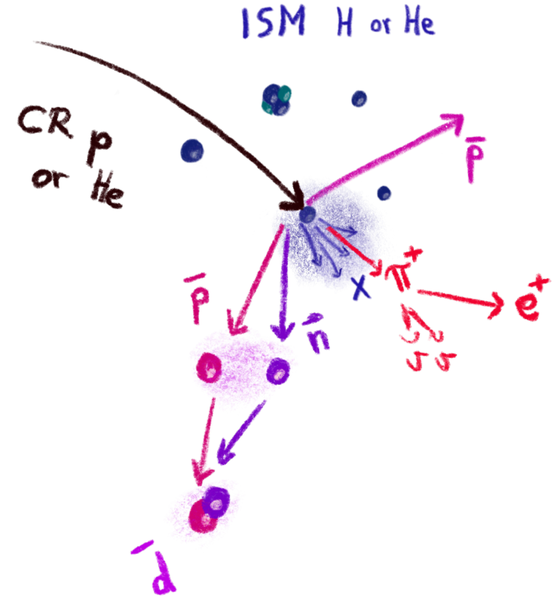
In order to model and interpret the data more accurate models/parametrizations of cross sections are required

We are interested in many reactions:

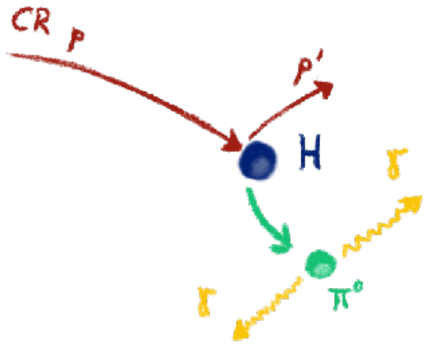
- $\bar{p}$, $\pi^{\pm}$ & $K^{\pm}$ (for $e^{\pm}$), π^{0} (for γ-rays) production in pp and $p\mathrm{He}$ collisions
- Fragmentation of nuclei (e.g. $\mathrm{C} \rightarrow \mathrm{B}$)

Please reach out if you can perform measurements!

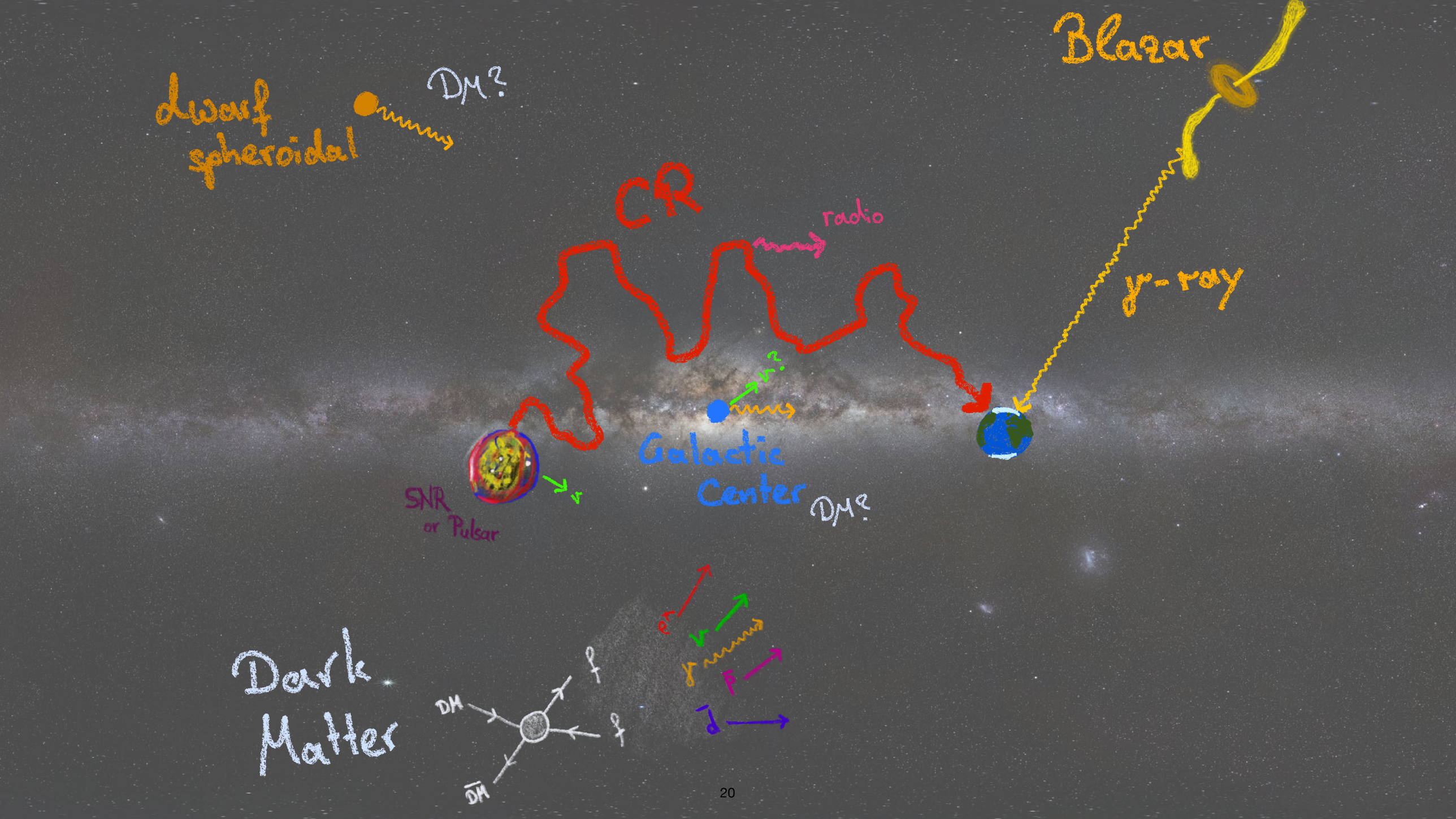
Collider experiments provide important important measurements



Thank you for your attention!



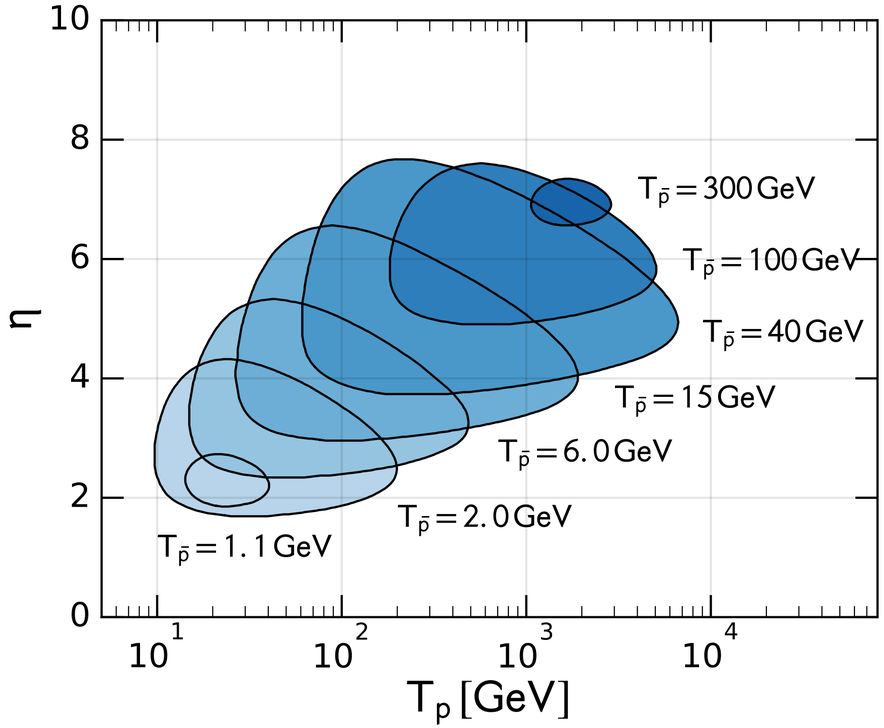
Backup


dwarf spheroidal
DM?
Blazar
CR
radio
γ-ray
γ?
Galactic Center
DM?
SNR or Pulsar
Dark Matter
DM
DM
f
f
e⁻
ν
γ
F
d

Required cross section data for antiprotons

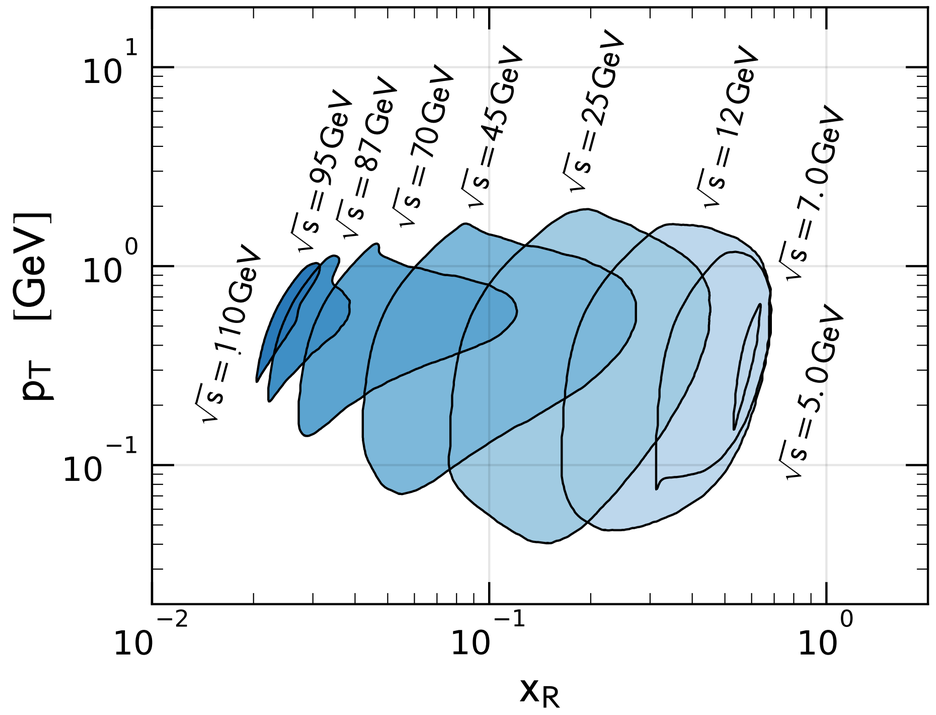
Fix target experiment

$$\left(E\frac{d^3\sigma}{dp^3}\right)\left(T_p, T_{\bar{p}}, \eta\right)$$



Collider experiment

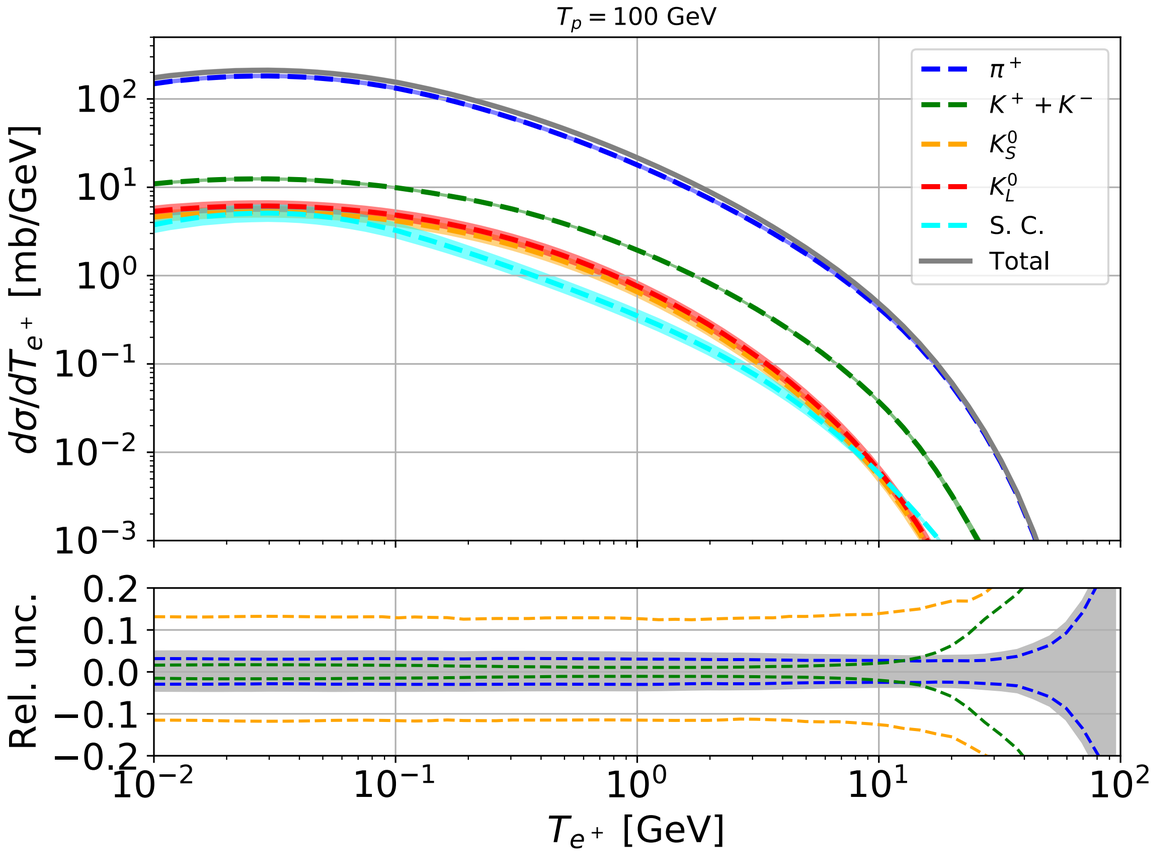
$$\left(E\frac{d^3\sigma}{dp^3}\right)\left(\sqrt{s}, x_R, p_T\right)$$

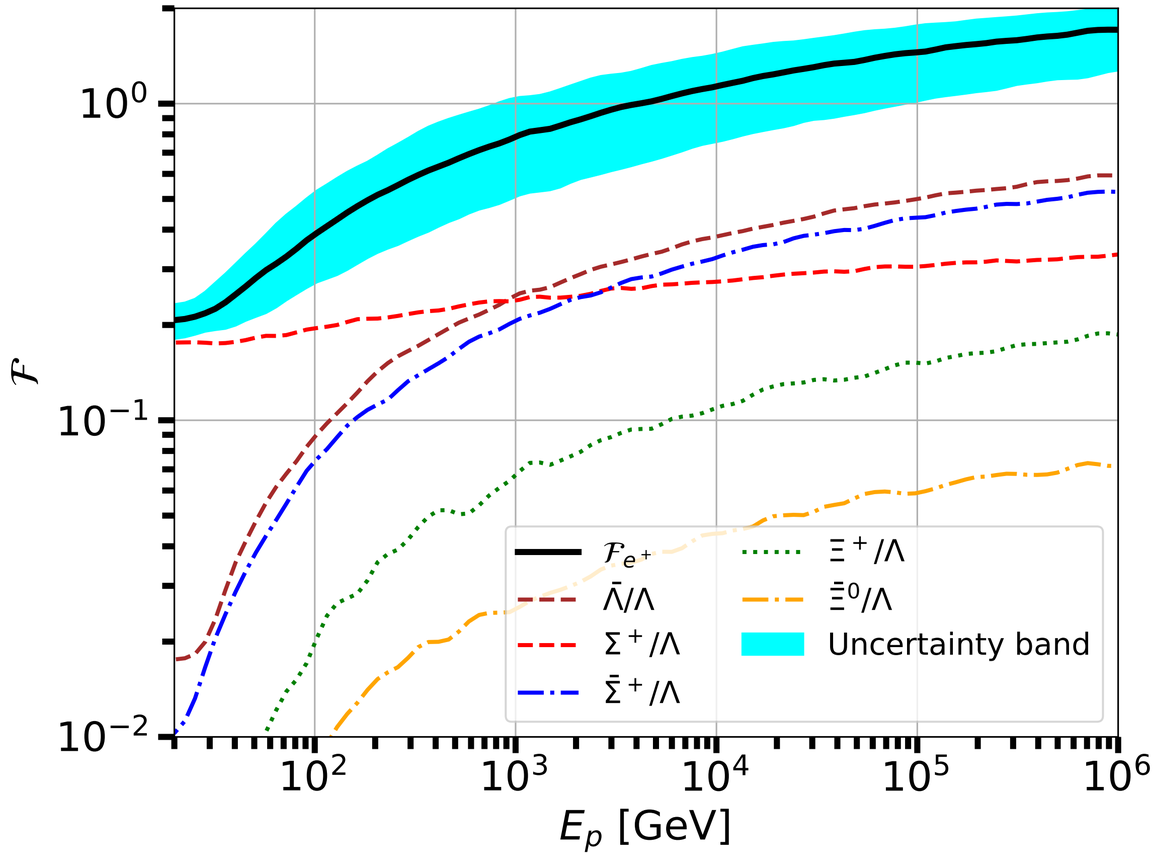


[Donato, MK, Di Mauro; 2017]

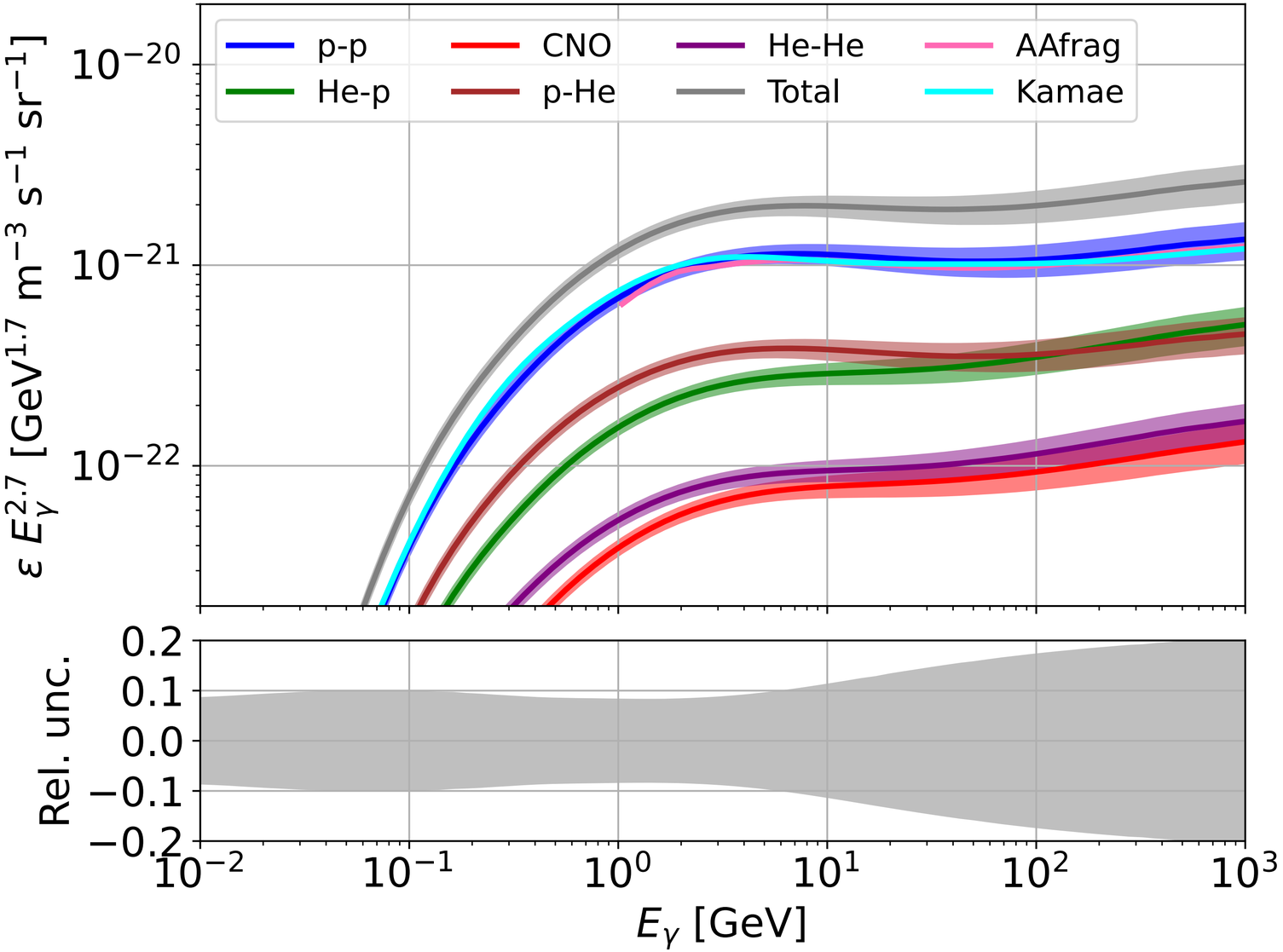
If the cross section is measured with 3% accuracy inside the blue contours and with 30% outside the contours we can reach the measurement uncertainties of the AMS-02 antiproton flux.

Mesons and hadrons contributing to the e^+ production

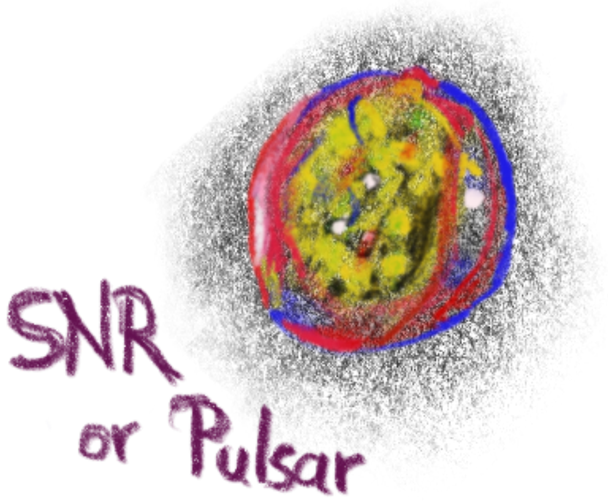


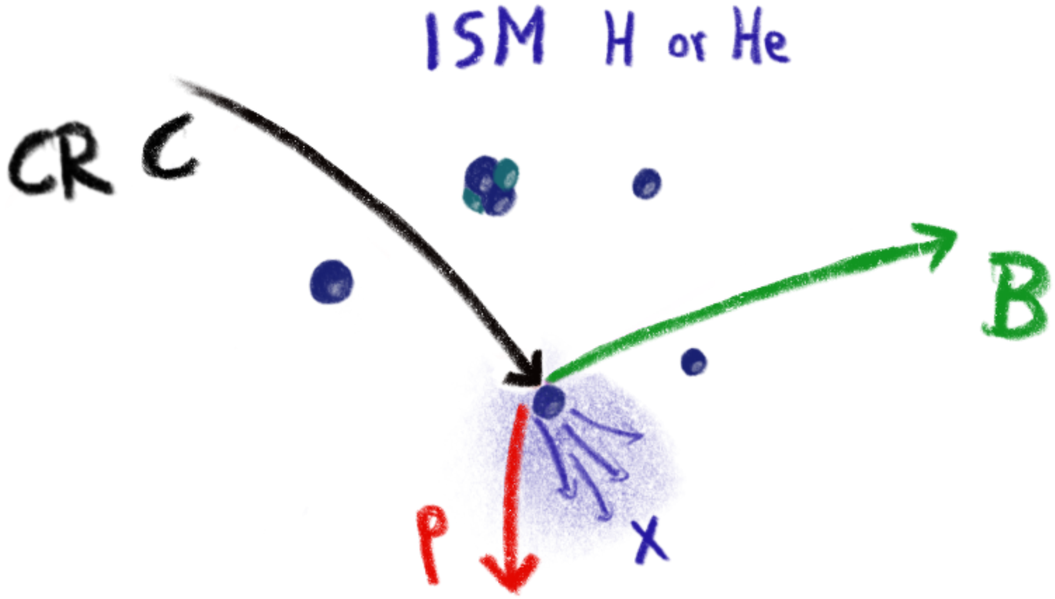


Gamma Ray source term



Gramage





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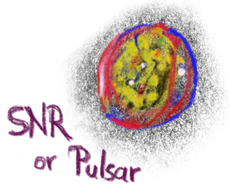
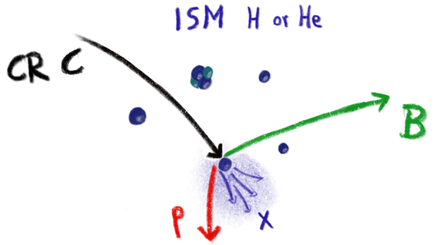
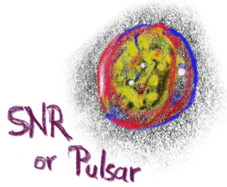


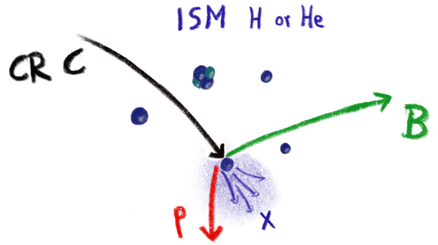


$$\frac{dN_{\mathrm{C}}}{d\ell} = -\frac{N_{\mathrm{C}}}{\lambda_{\mathrm{int}}}$$

$$\frac{dN_{\mathrm{B}}}{d\ell} = -\frac{N_{\mathrm{B}}}{\lambda_{\mathrm{int}}} + \frac{N_{\mathrm{C}}}{\lambda_{\mathrm{C}\to\mathrm{B}}}$$

Gramage



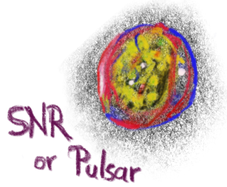


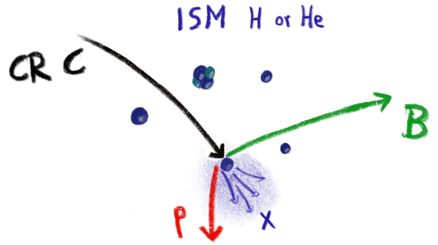
$$X = \ell \cdot \rho$$

$$\frac{dN_{\mathrm{C}}}{dX} = -\frac{\sigma_{\mathrm{inel,C}}}{m_p} N_{\mathrm{C}}$$

$$\frac{dN_{\mathrm{B}}}{dX} = -\frac{\sigma_{\mathrm{inel,B}}}{m_p} N_{\mathrm{B}} + \frac{\sigma_{\mathrm{C}\to\mathrm{B}}}{m_p} N_{\mathrm{C}}$$

Gramage



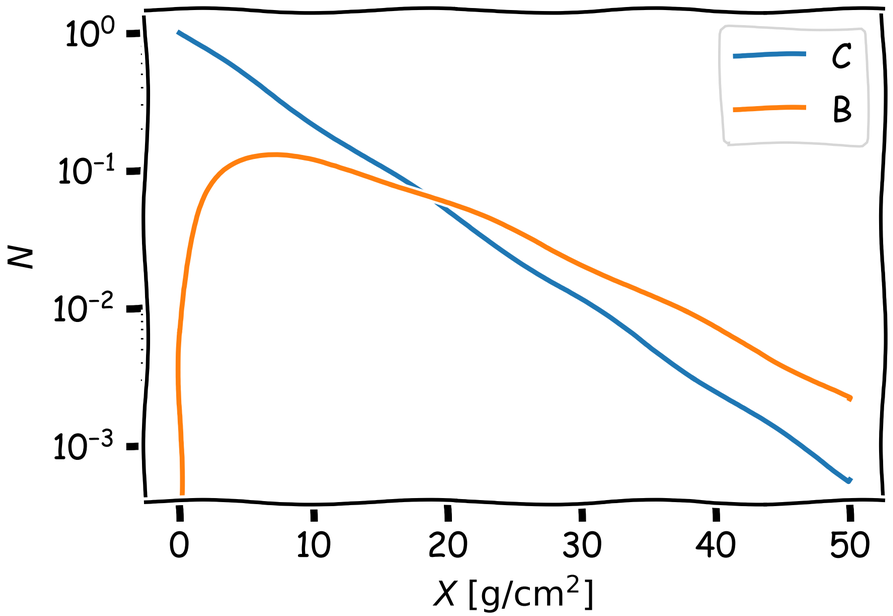


$$X = \ell \cdot \rho$$

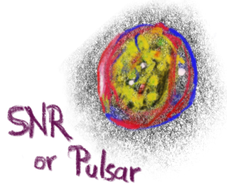
$$N_{\mathrm{C}} = N_0 \exp\left(-\frac{\sigma_{\mathrm{inel,C}}}{m_p} X \right)$$

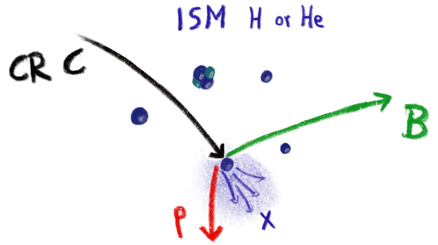
$$\frac{N_{\mathrm{B}}}{N_{\mathrm{C}}} = \frac{\sigma_{\mathrm{C}\to\mathrm{B}}}{\sigma_{\mathrm{inel,C}} - \sigma_{\mathrm{inel,B}}} \left[\exp\left(\frac{\sigma_{\mathrm{inel,C}} - \sigma_{\mathrm{inel,B}}}{m_p} X \right) - 1 \right]$$

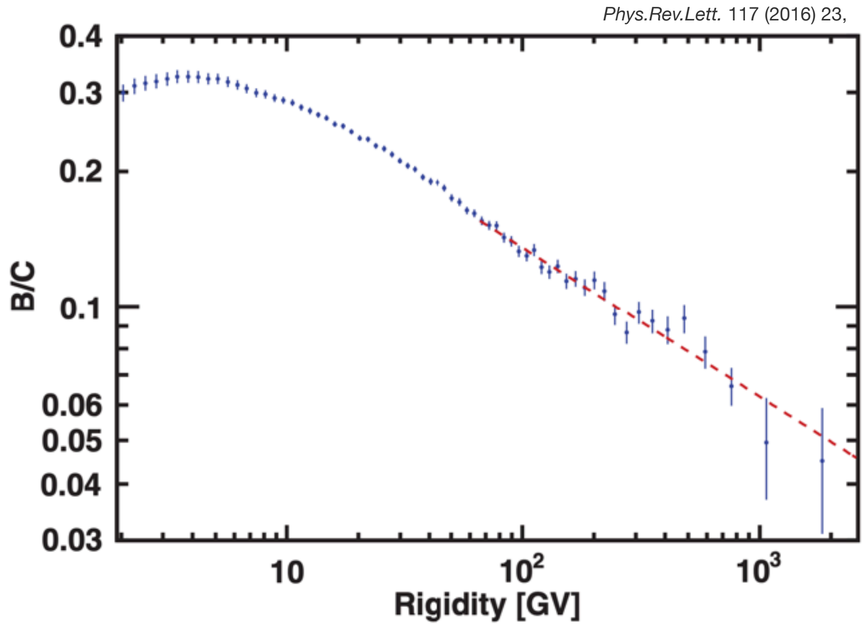
$$\sigma_{\mathrm{C,inel}} \sim 250 \text{ mb}$$
$$\sigma_{\mathrm{B,inel}} \sim 220 \text{ mb}$$
$$\sigma_{\mathrm{C}\to\mathrm{B}} \sim 80 \text{ mb}$$

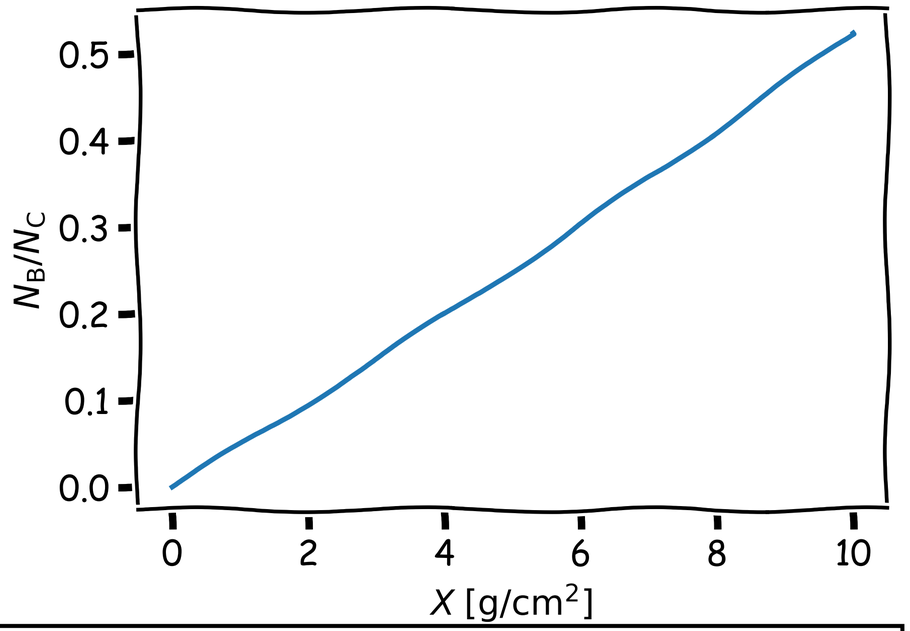


Gramage









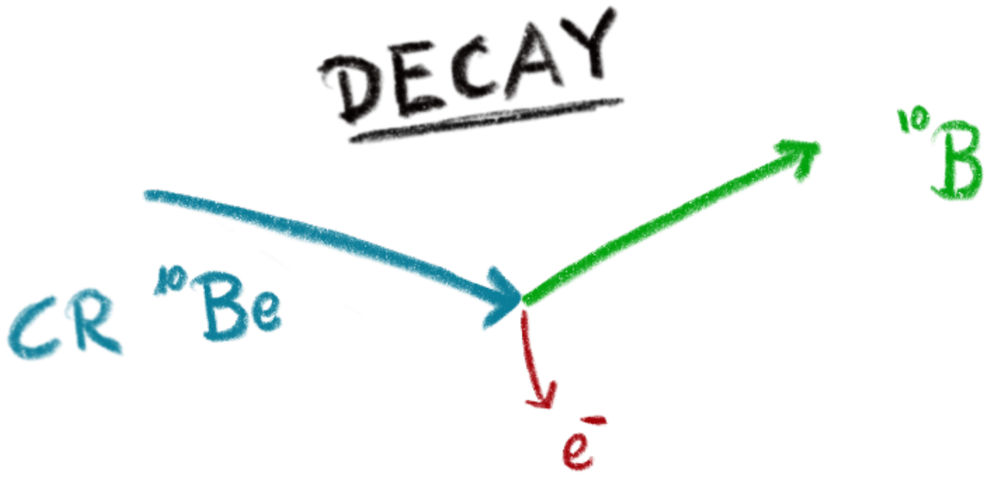
$$\mathrm{B/C} \sim 0.3 \qquad \text{(at 10 GV)}$$

$$X_{10\,\mathrm{GeV}} \sim 6\ \mathrm{g/cm^2}$$

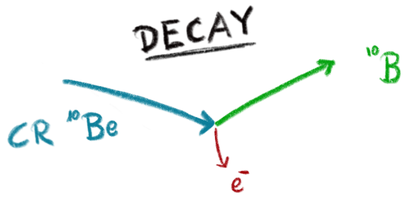
$$X_{\text{Galactic disc}} \sim 2 \times 10^{-3}\ \mathrm{g/cm^2}$$

CRs traverse the Galactic disc for a few thousand times → diffusion!

Cosmic-Ray Clocks



Cosmic-Ray Clocks

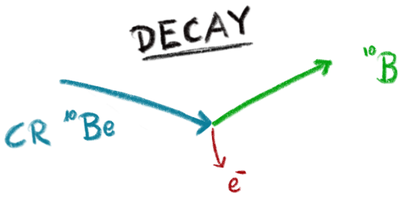


The Leaky Box Model

$$\frac{dN_{^9\mathrm{Be}}}{dt} = -\frac{N_{^9\mathrm{Be}}}{t_{\mathrm{esc}}} - \frac{N_{^9\mathrm{Be}}}{t_{\mathrm{int},9}} + Q_9$$

$$\frac{dN_{^{10}\mathrm{Be}}}{dt} = -\frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{esc}}} - \frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{int},10}} - \frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{dec},10}} + Q_{10}$$

Cosmic-Ray Clocks

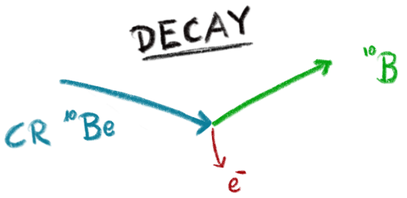


The Leaky Box Model

$$0 = -\frac{N_{^9\mathrm{Be}}}{t_{\mathrm{esc}}} - \frac{N_{^9\mathrm{Be}}}{t_{\mathrm{int},9}} + \frac{N_{\mathrm{CNO}}}{t_{\mathrm{CNO}\rightarrow{}^9\mathrm{Be}}}$$

$$0 = -\frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{esc}}} - \frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{int},10}} - \frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{dec},10}} + \frac{N_{\mathrm{CNO}}}{t_{\mathrm{CNO}\rightarrow{}^{10}\mathrm{Be}}}$$

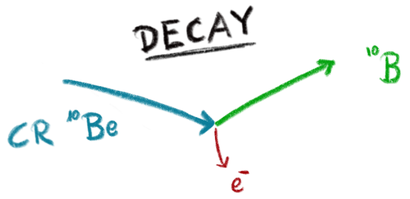
Cosmic-Ray Clocks



The Leaky Box Model

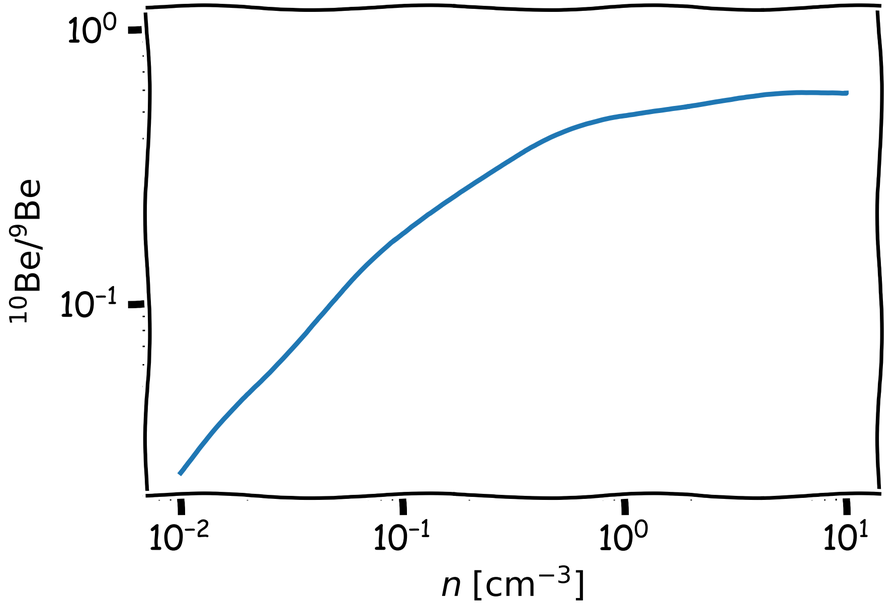
$$\frac{N_{^{10}\mathrm{Be}}}{N_{^{9}\mathrm{Be}}} = \frac{\sigma_{\mathrm{CNO}\rightarrow{}^{10}\mathrm{Be}}}{\sigma_{\mathrm{CNO}\rightarrow{}^{9}\mathrm{Be}}} \frac{\frac{1}{t_{\mathrm{esc}}} + \frac{1}{t_{\mathrm{int},9}}}{\frac{1}{t_{\mathrm{esc}}} + \frac{1}{t_{\mathrm{int},10}} + \frac{1}{t_{\mathrm{dec},10}}}$$

Cosmic-Ray Clocks

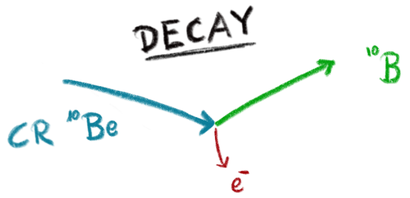


The Leaky Box Model

$$\frac{N_{^{10}\mathrm{Be}}}{N_{^{9}\mathrm{Be}}} = \frac{\sigma_{\mathrm{CNO}\rightarrow{}^{10}\mathrm{Be}}}{\sigma_{\mathrm{CNO}\rightarrow{}^{9}\mathrm{Be}}} \frac{\frac{v\, m_p\, n}{X} + v\, n\, \sigma_9}{\frac{v\, m_p\, n}{X} + v\, n\, \sigma_{10} + \frac{1}{\gamma \tau_{\mathrm{dec},10}}}$$



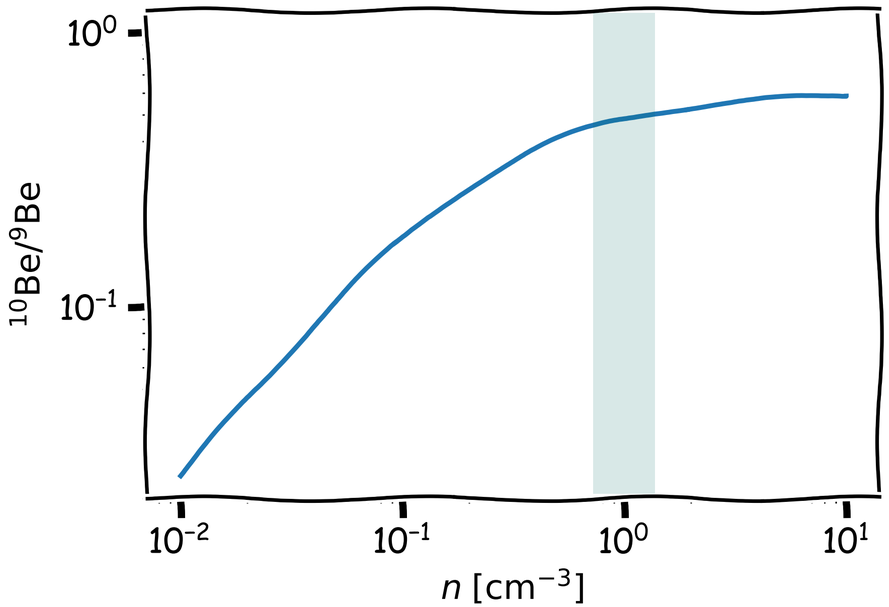
Cosmic-Ray Clocks



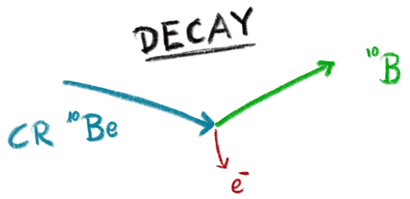
The Leaky Box Model

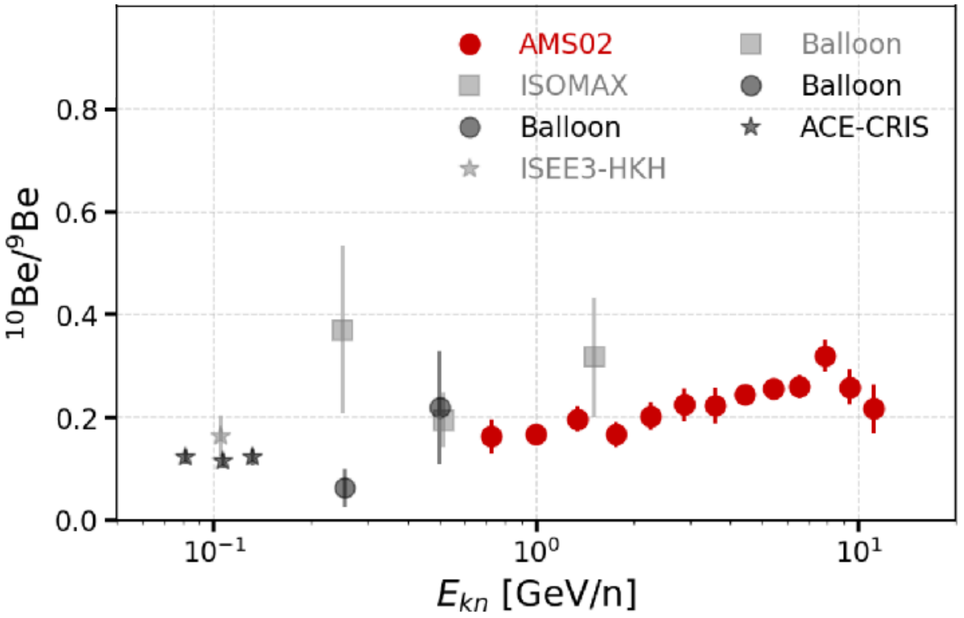
$$\frac{N_{^{10}\mathrm{Be}}}{N_{^{9}\mathrm{Be}}} = \frac{\sigma_{\mathrm{CNO}\rightarrow{}^{10}\mathrm{Be}}}{\sigma_{\mathrm{CNO}\rightarrow{}^{9}\mathrm{Be}}} \frac{\frac{v\, m_p\, n}{X} + v\, n\, \sigma_9}{\frac{v\, m_p\, n}{X} + v\, n\, \sigma_{10} + \frac{1}{\gamma \tau_{\mathrm{dec},10}}}$$

Galactic disc

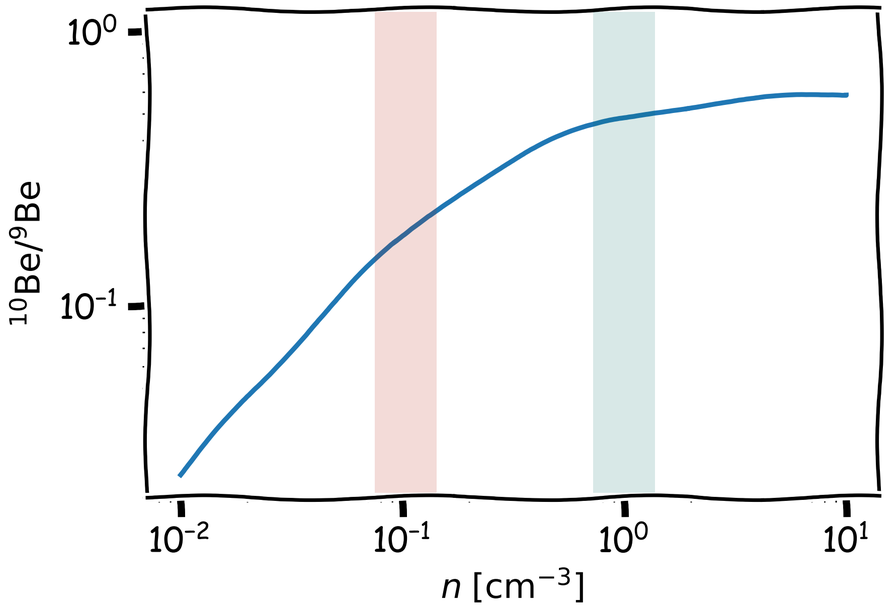


Cosmic-Ray Clocks

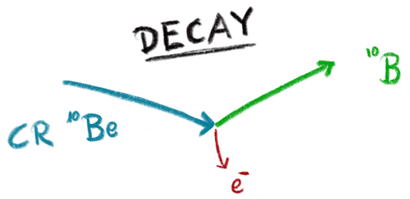


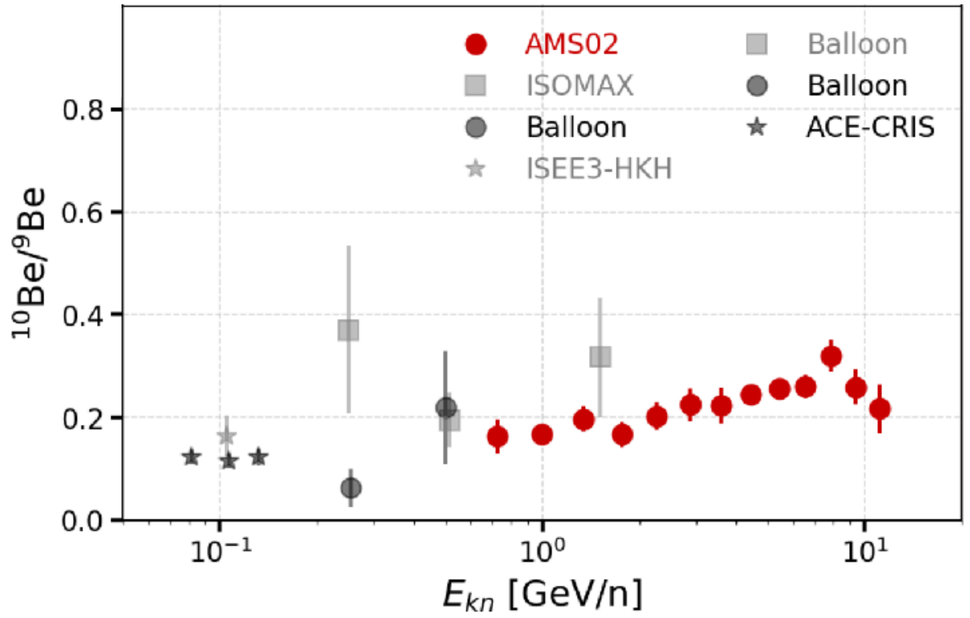


^{10}Be/^{9}Be Galactic disc

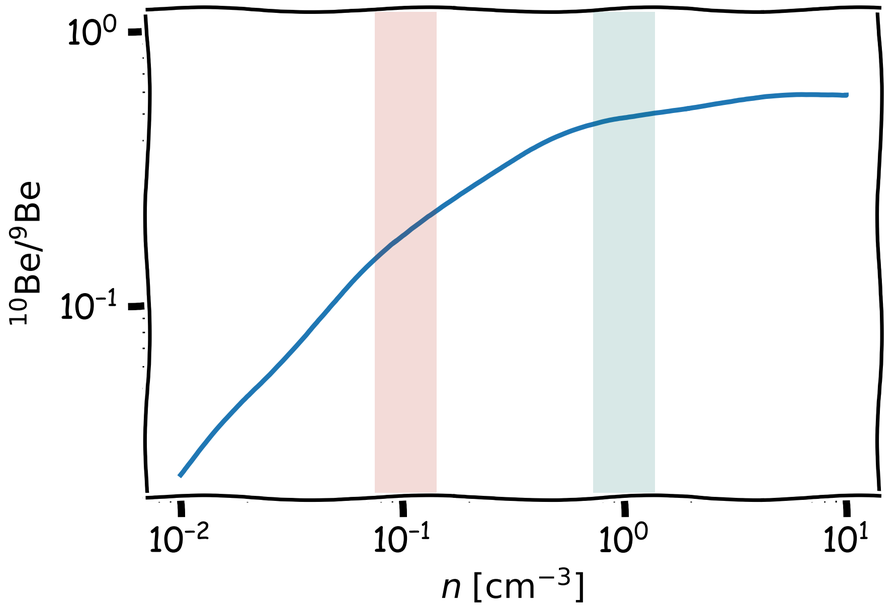


Cosmic-Ray Clocks



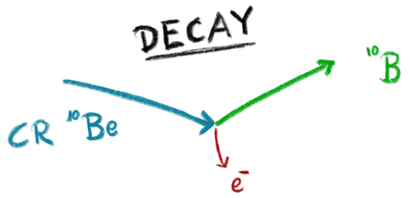


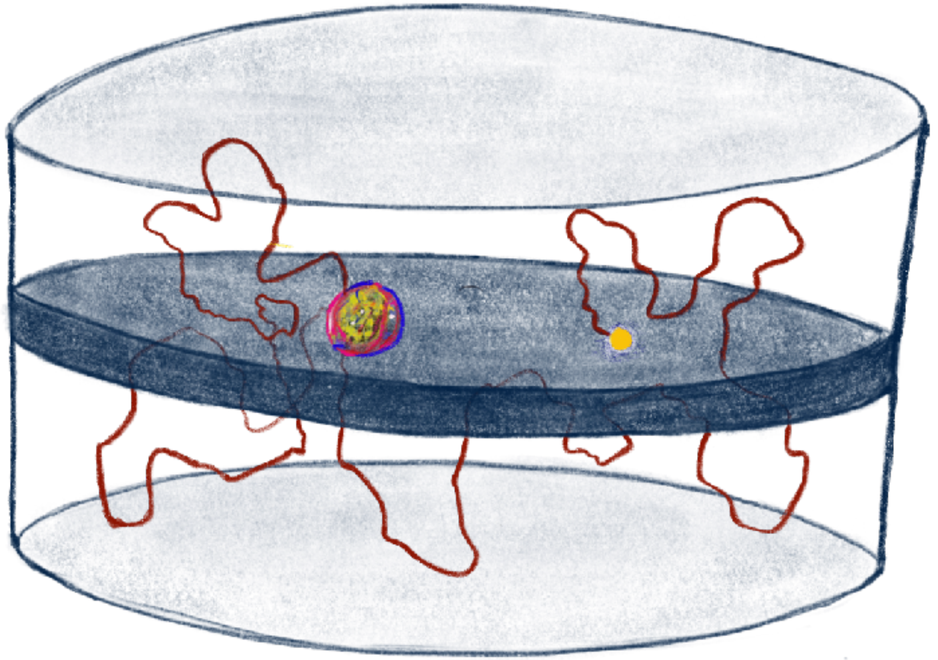
^{10}Be/^{9}Be Galactic disc



CRs spend a significant time outside the Galactic disc!

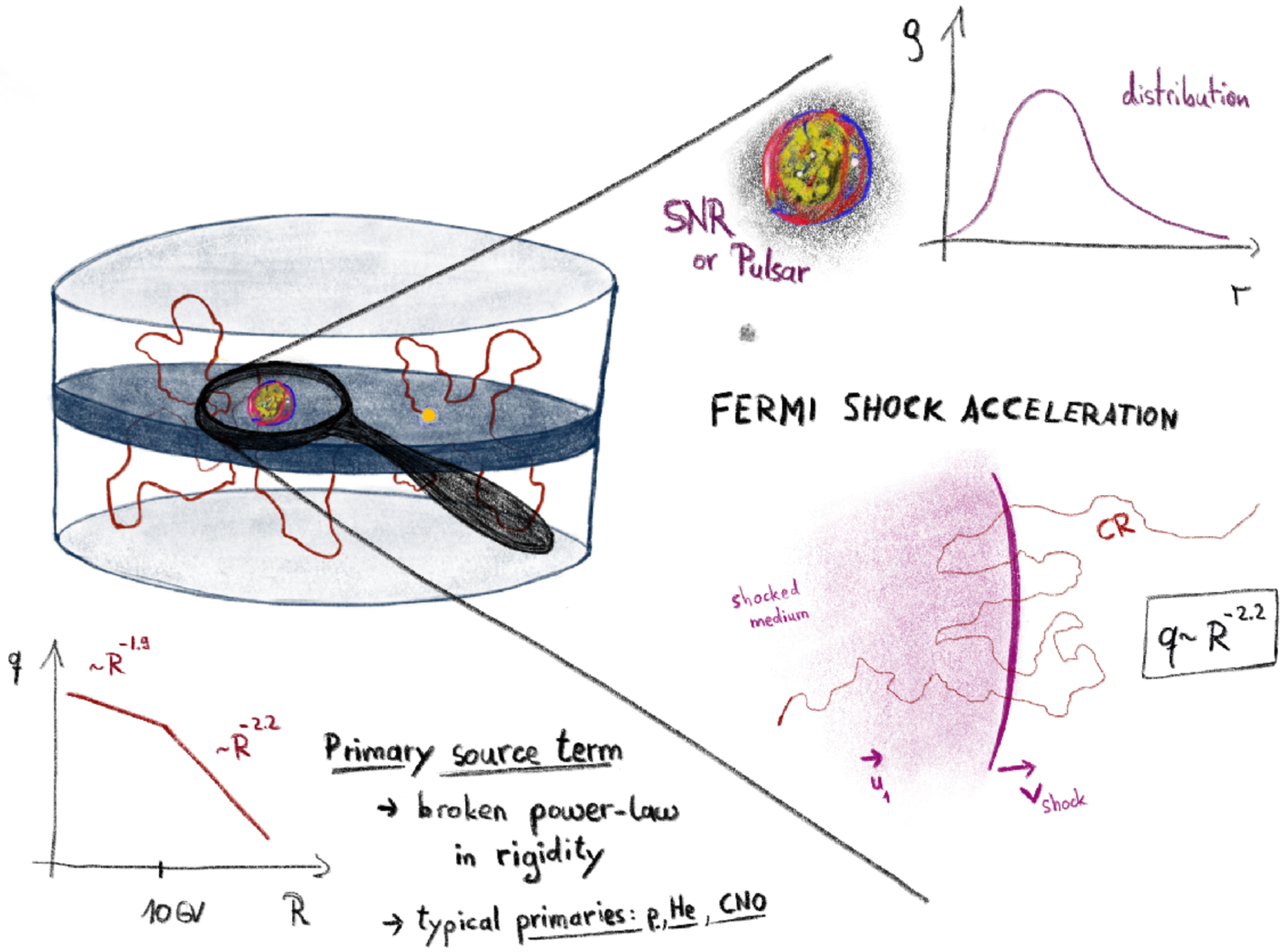
Cosmic-Ray Clocks



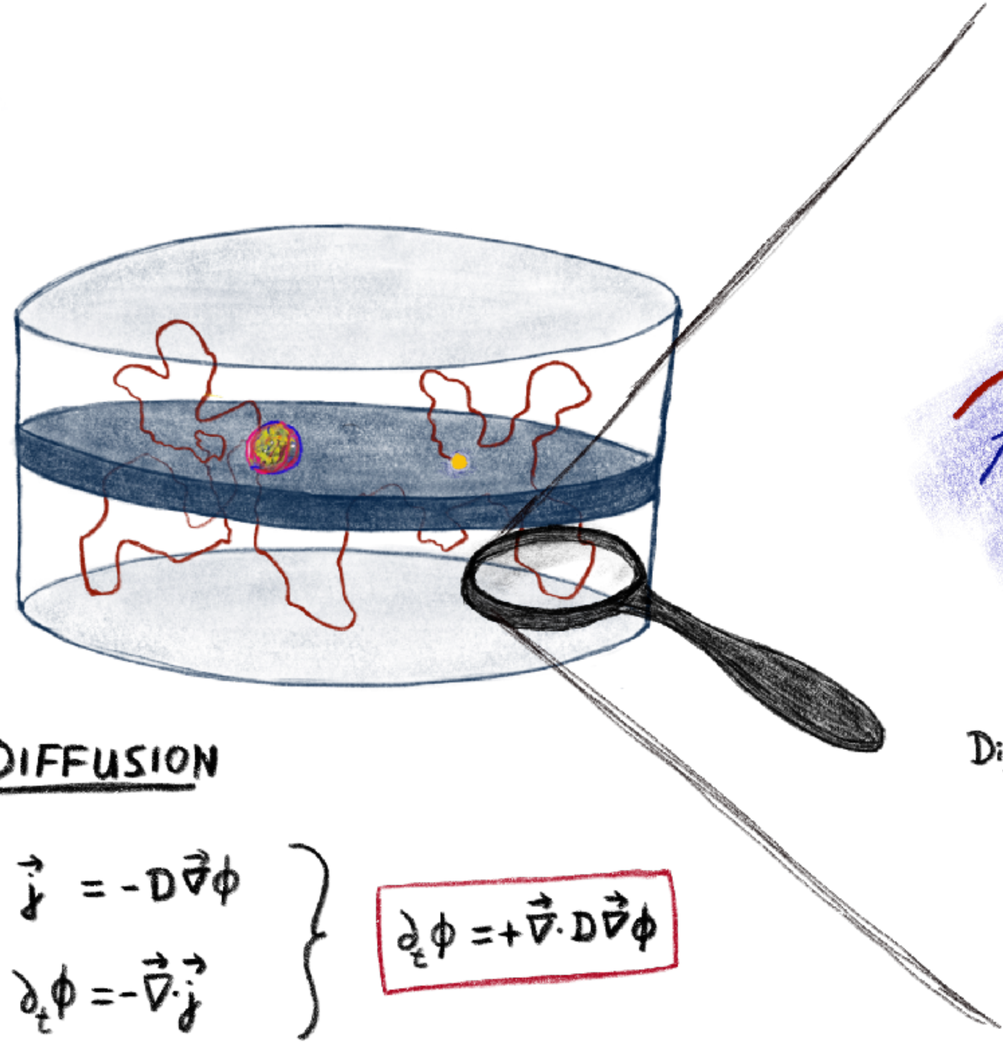


CRs spend a significant time outside the Galactic disc!

Modeling Cosmic-Ray Propagation



Modeling Cosmic-Ray Propagation



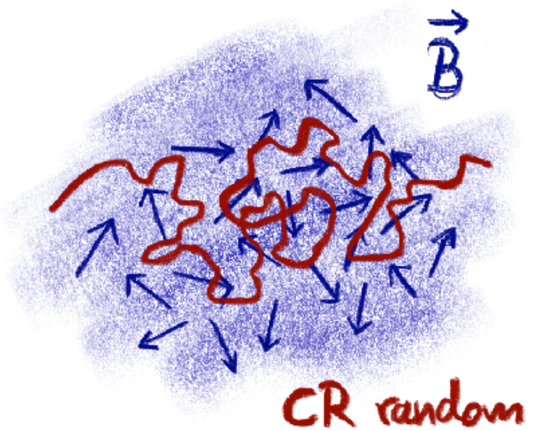
DIFFUSION

$$\vec{j} = -D\vec{\nabla}\phi$$

$$\partial_t\phi = -\vec{\nabla}\cdot\vec{j}$$

$$\partial_t\phi = +\vec{\nabla}\cdot D\vec{\nabla}\phi$$

DIFFUSION

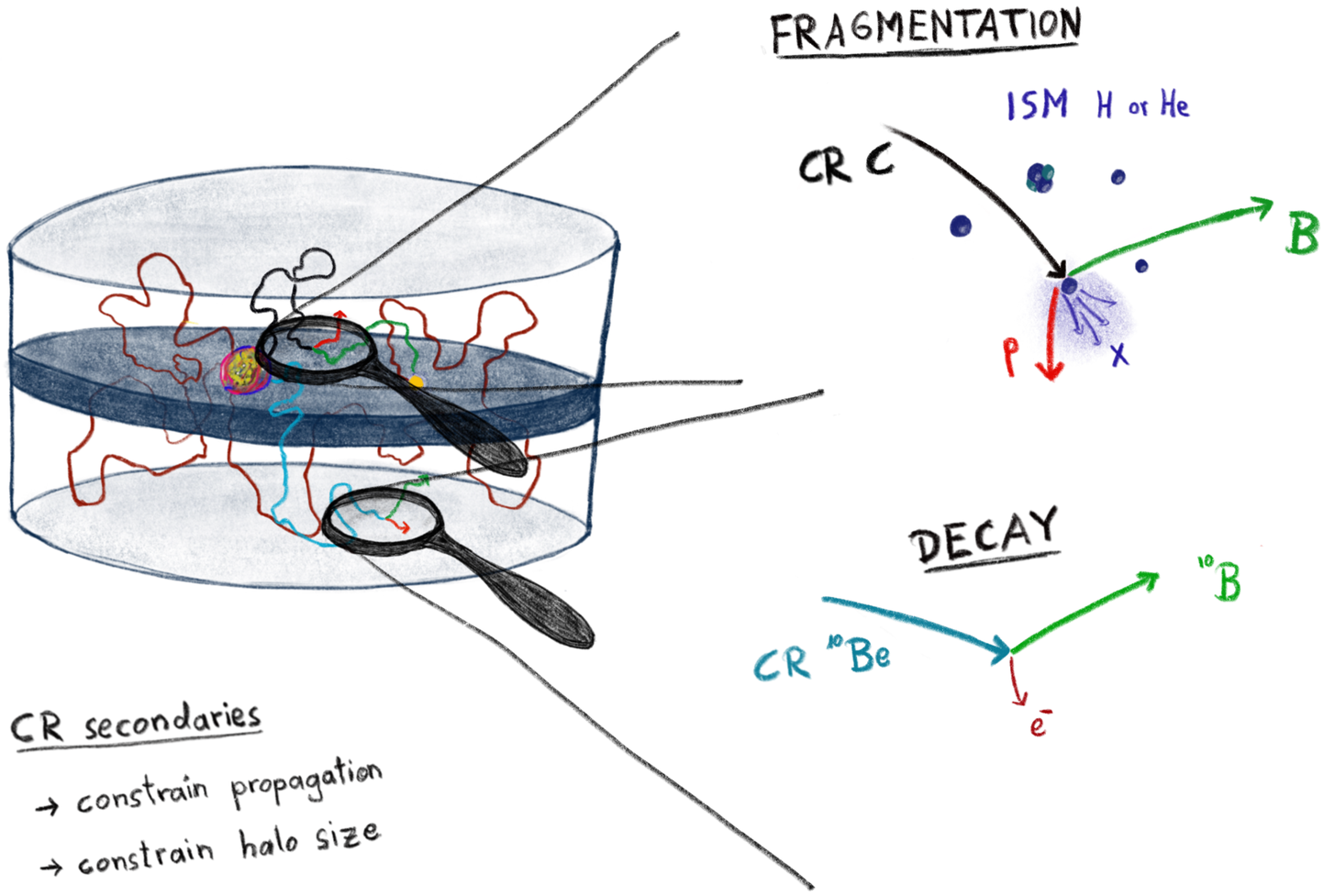


CR random walk

Diffusion constant is energy-dependend

$$D = \beta D_0 R^{+\delta}$$

Modeling Cosmic-Ray Propagation



Diffusion Equation for the Cosmic-Rays Flux

$$\frac{d\psi_i}{dt} = q_i(\boldsymbol{x}, p)$$ **Source term**

$$+\nabla D_{xx} \nabla \psi_i$$ Diffusion

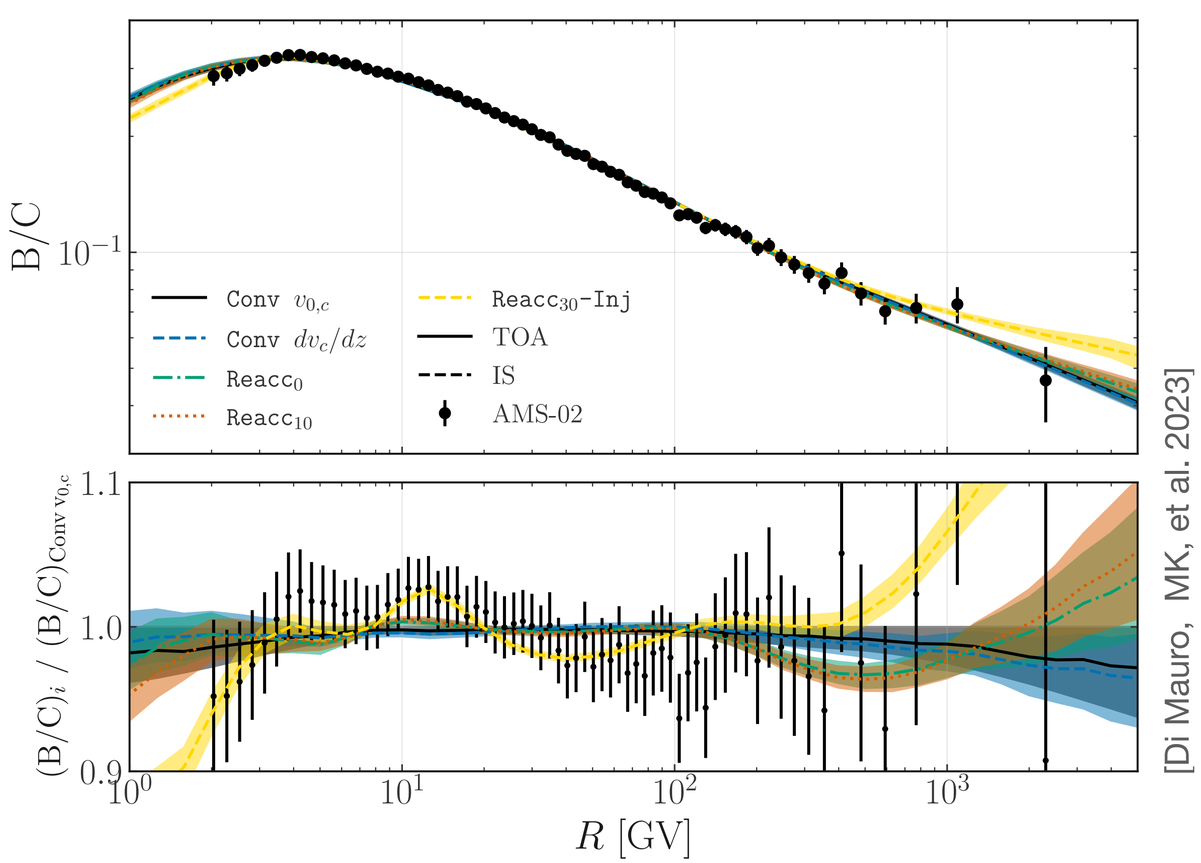
$$-\nabla \boldsymbol{V} \psi_i + \frac{\partial}{\partial p}\left(\frac{p}{3}\nabla \cdot \boldsymbol{V}\psi_i\right)$$ Convection

$$-\frac{\partial}{\partial p}\left(\frac{dp}{dt}\psi_i\right)$$ Energy losses

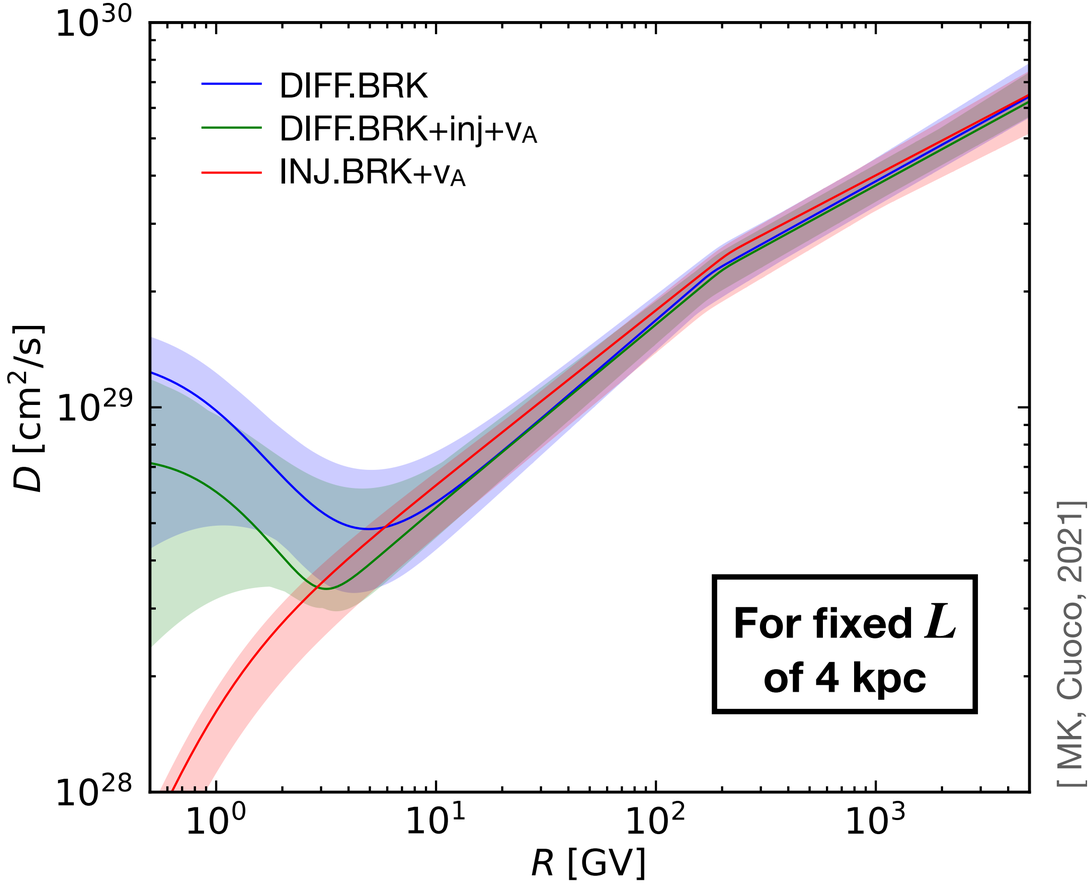
$$-\frac{\psi_i}{\tau_f} - \frac{\psi_i}{\tau_r}$$ **Fragmentation** and decay

$$+\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i$$ Reacceleration

Secondary-to-Primary ratios constrain propagation

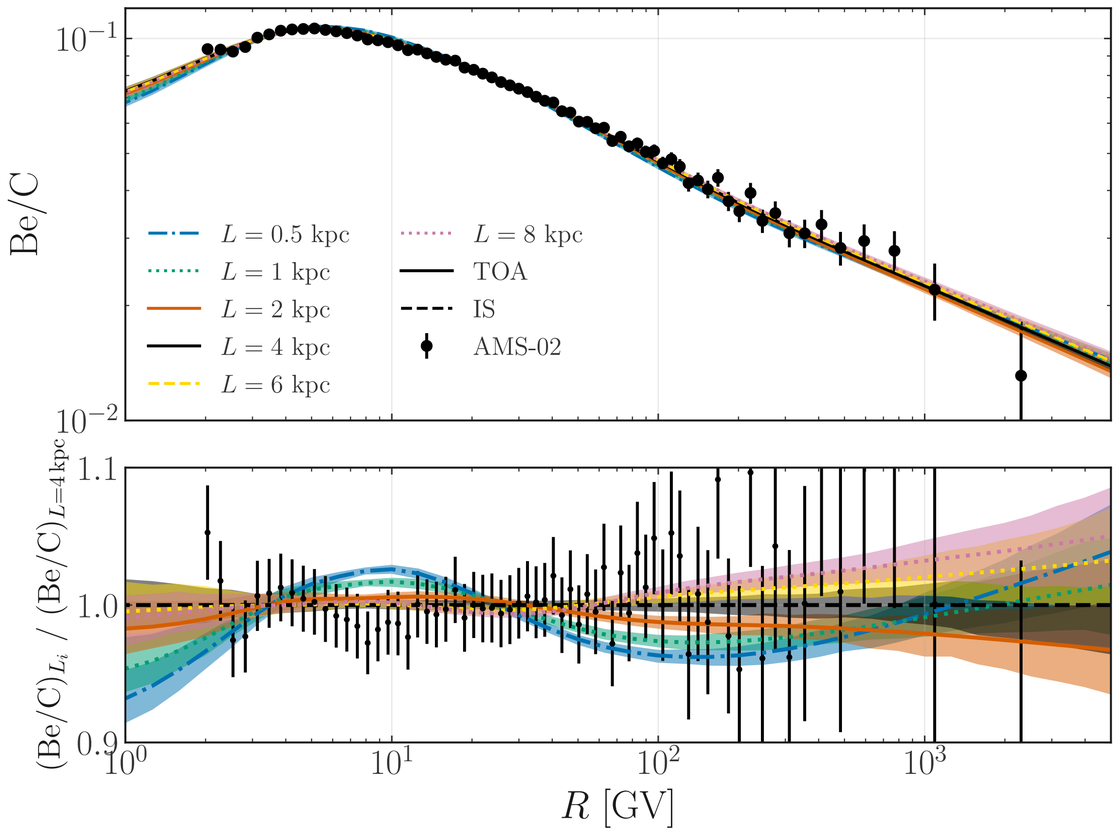


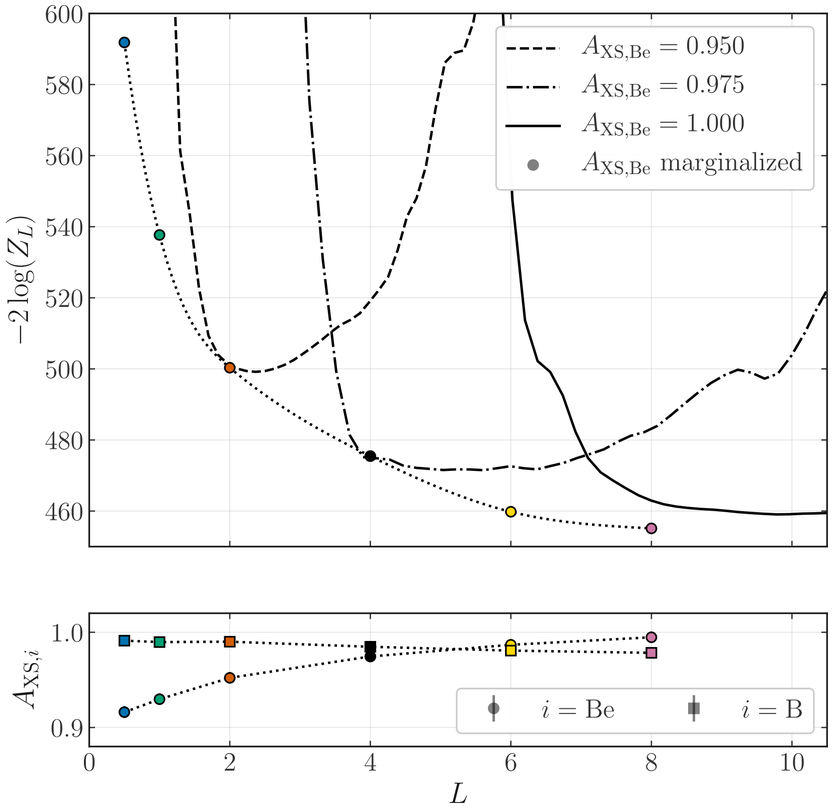
[Di Mauro, MK, et al. 2023]



[MK, Cuoco, 2021]

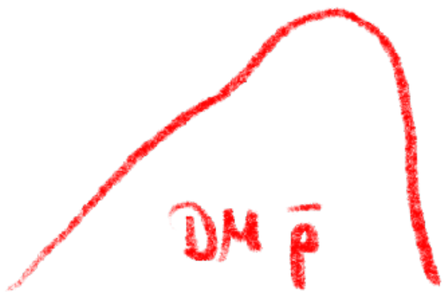
Cosmic-Ray Clocks constrain the Halo Size



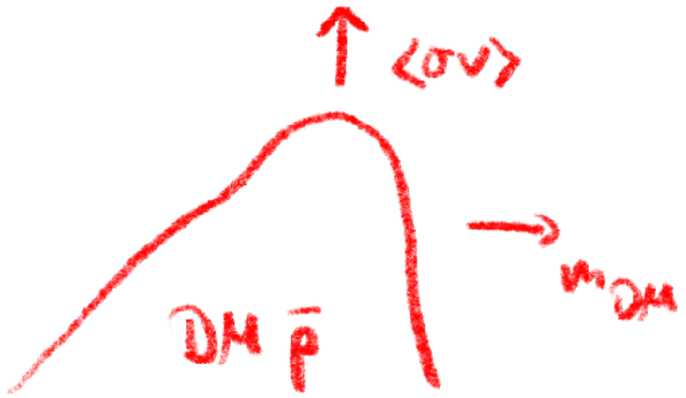


[Di Mauro, MK, et al. 2023]

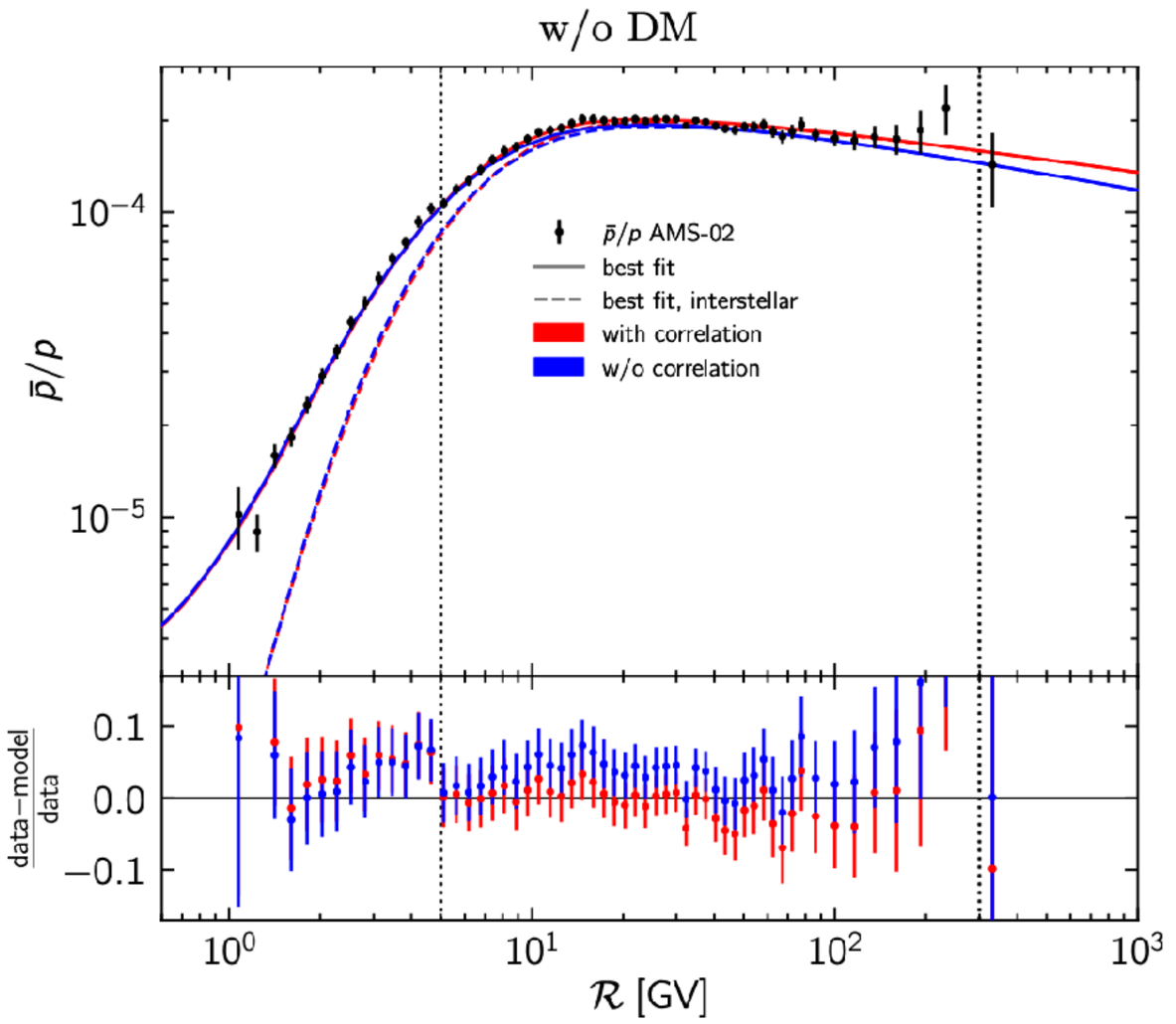
[Heisig, MK, Winkler, 2000]

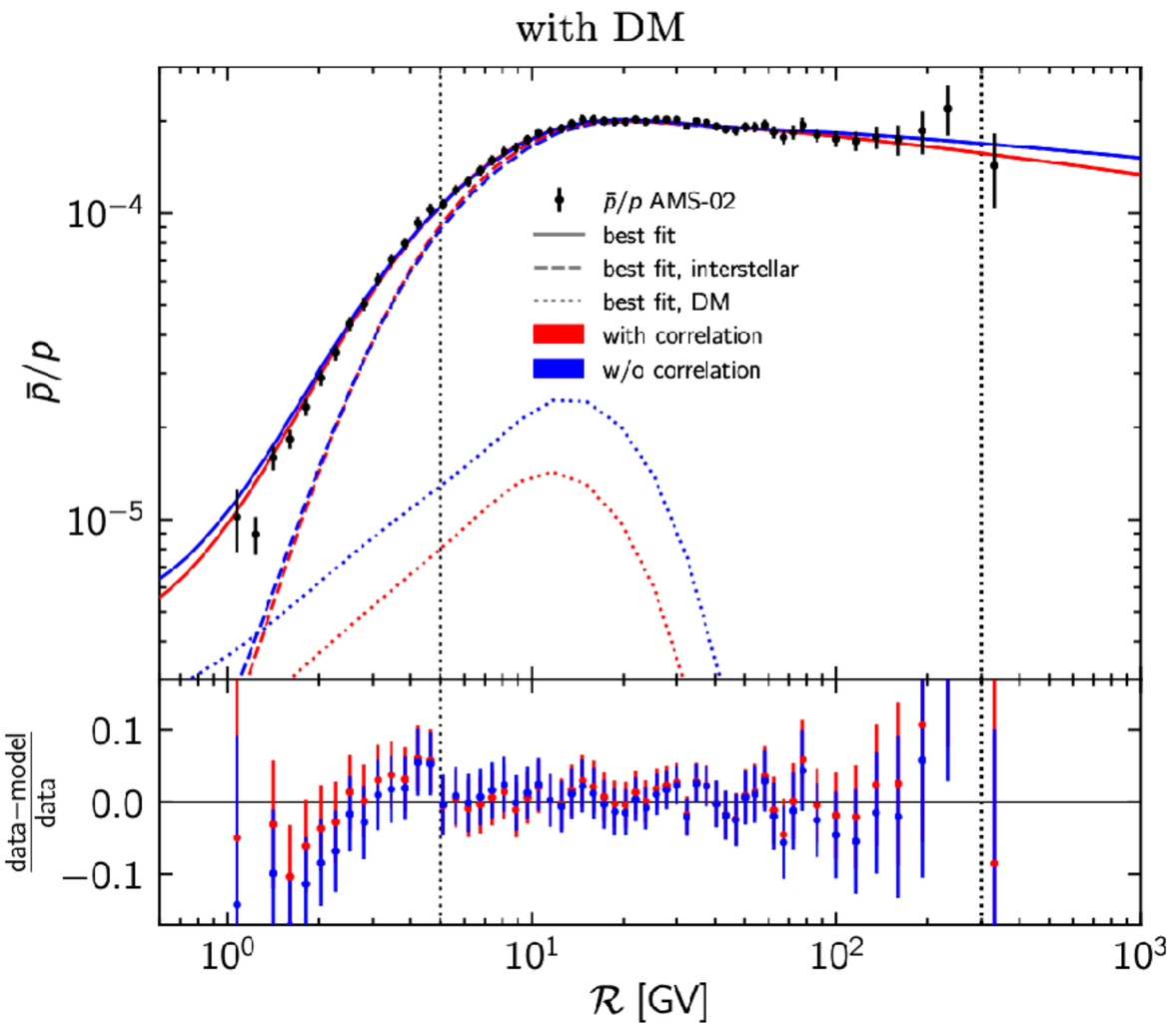


[Heisig, MK, Winkler, 2000]



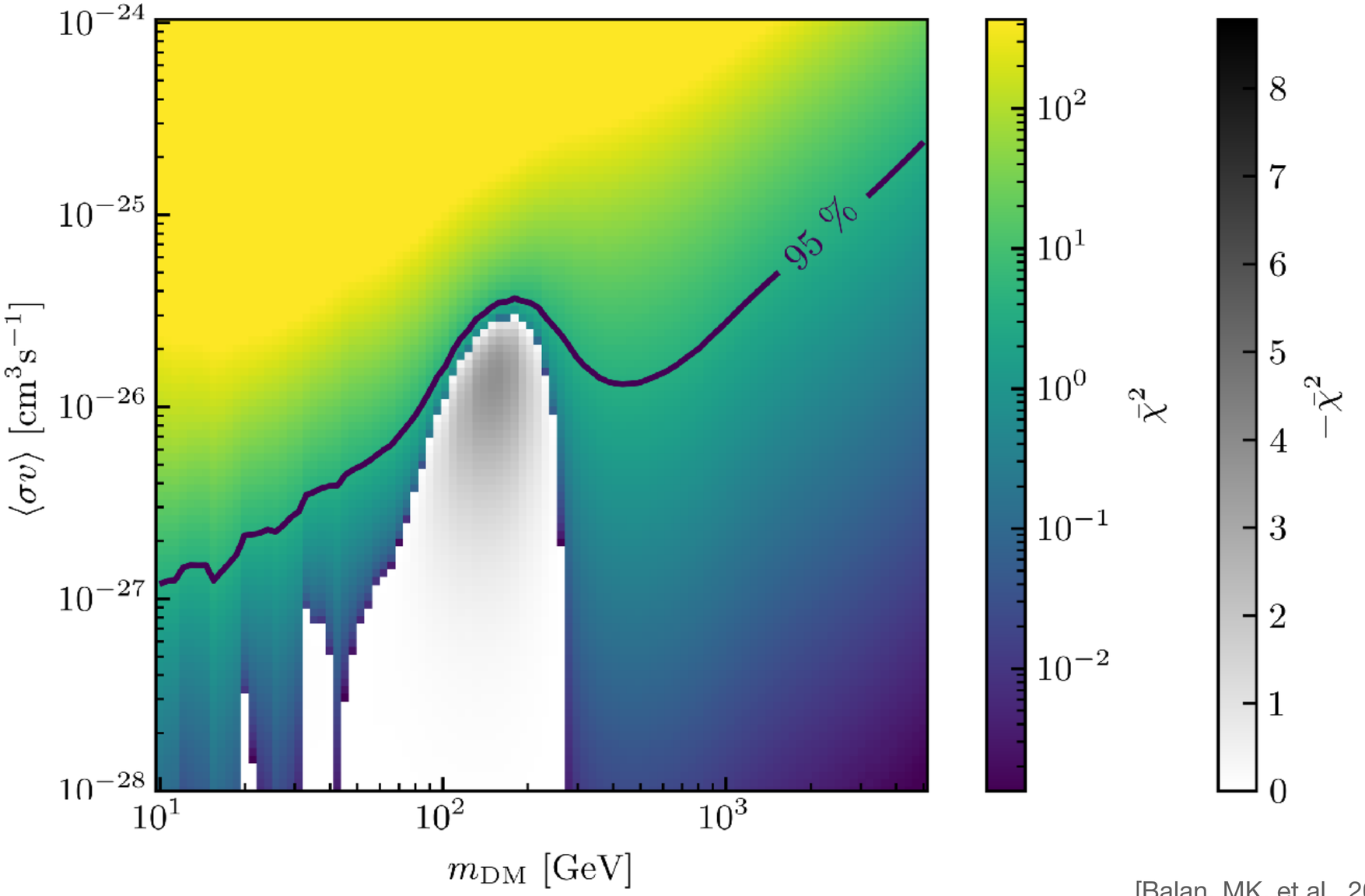
[Heisig, MK, Winkler, 2000]





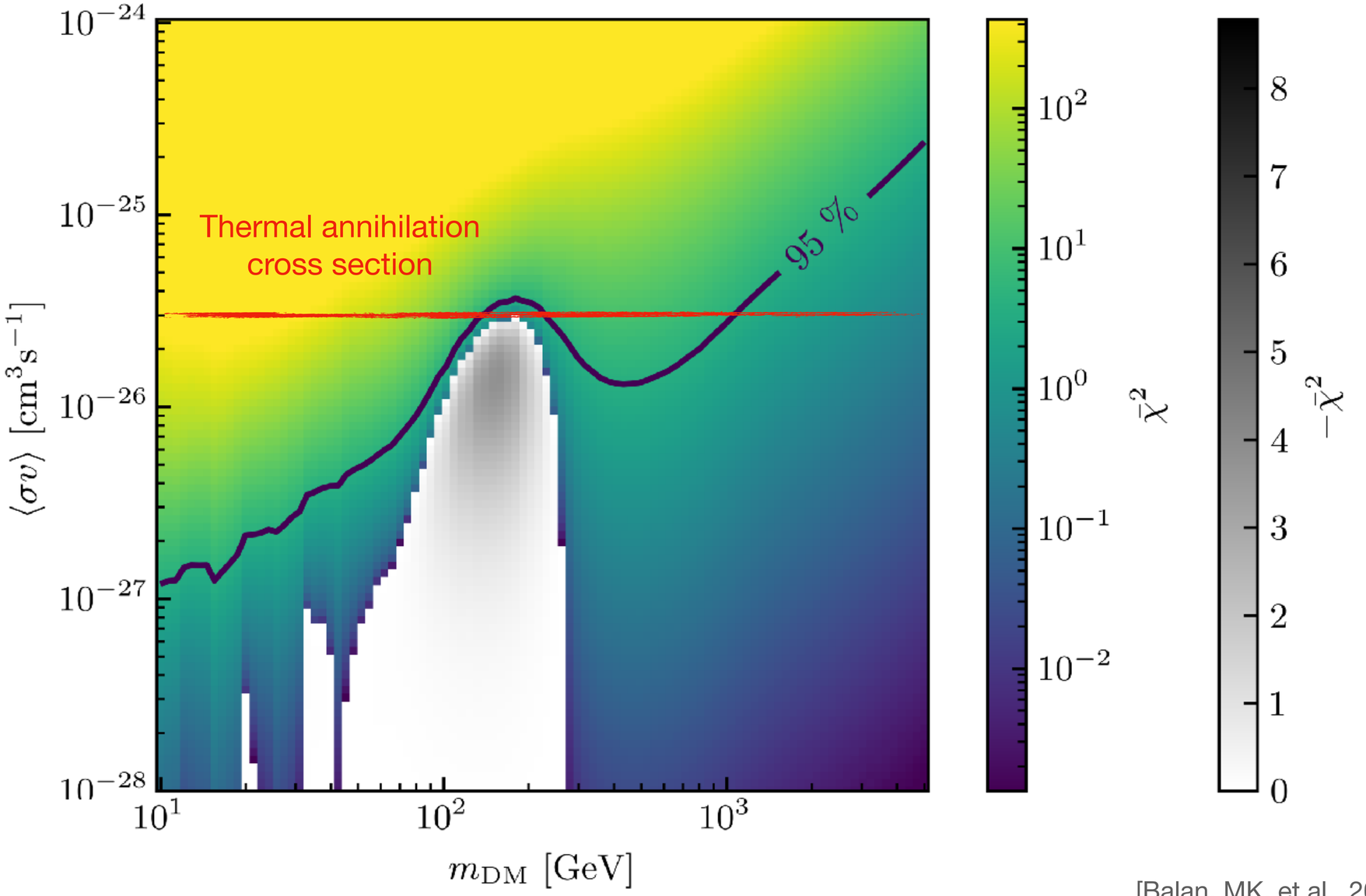
[Heisig, MK, Winkler, 2000]

DM limit for DM annihilation into a pair of *b* quarks



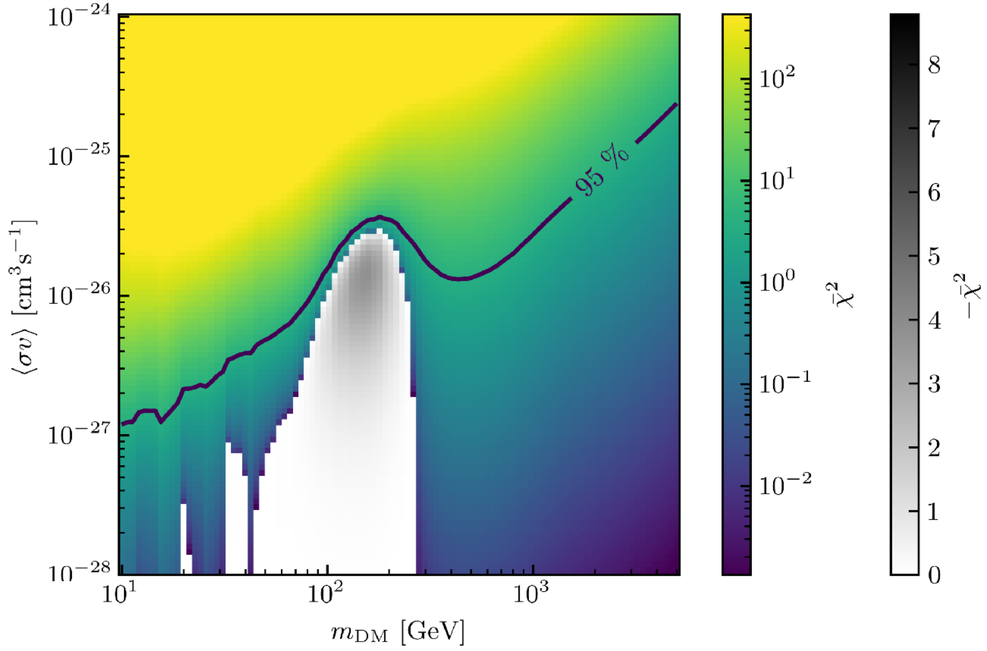
[Balan, MK, et al. 2023]

DM limit for DM annihilation into a pair of *b* quarks



[Balan, MK, et al. 2023]

DM limit for DM annihilation into a pair of *b* quarks



DARK RAY NET

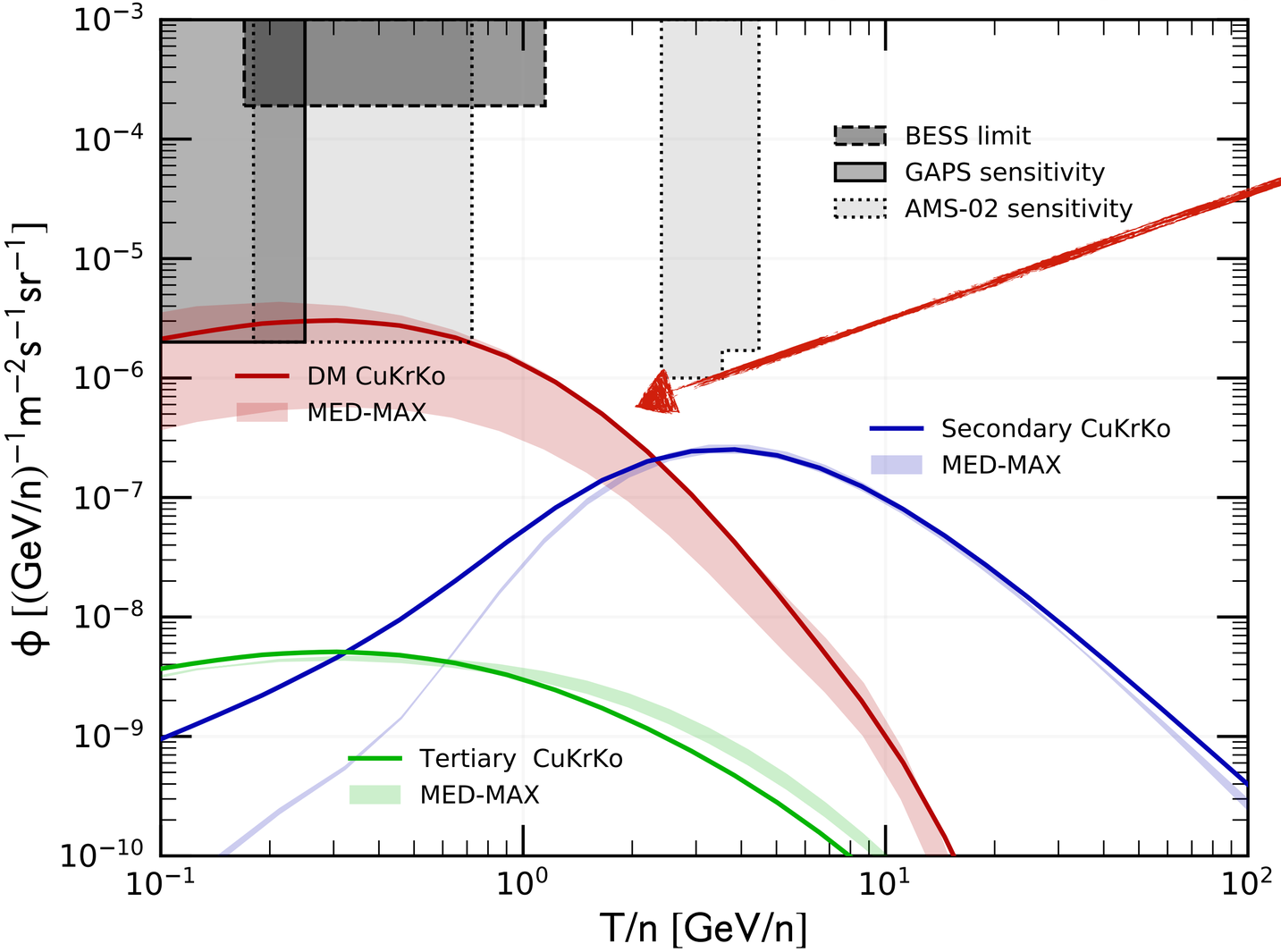
pbarlike

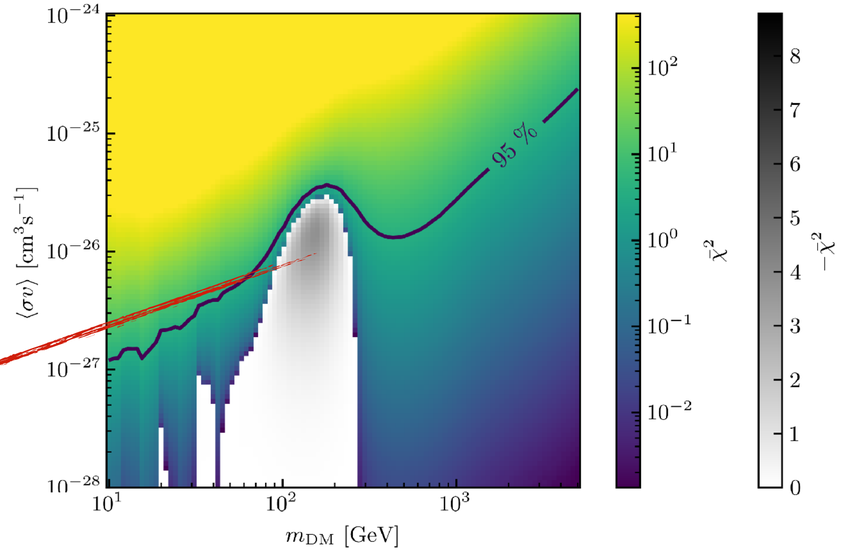
GAMBIT

[Balan, MK, et al. 2023]

Predicted Antideuteron flux

[MK, Donato, Fornengo, +; 2018]





The DM "hint" in antiprotons might be in the sensitivity range of the (future) cosmic-ray experiments AMS-02 and GAPS.