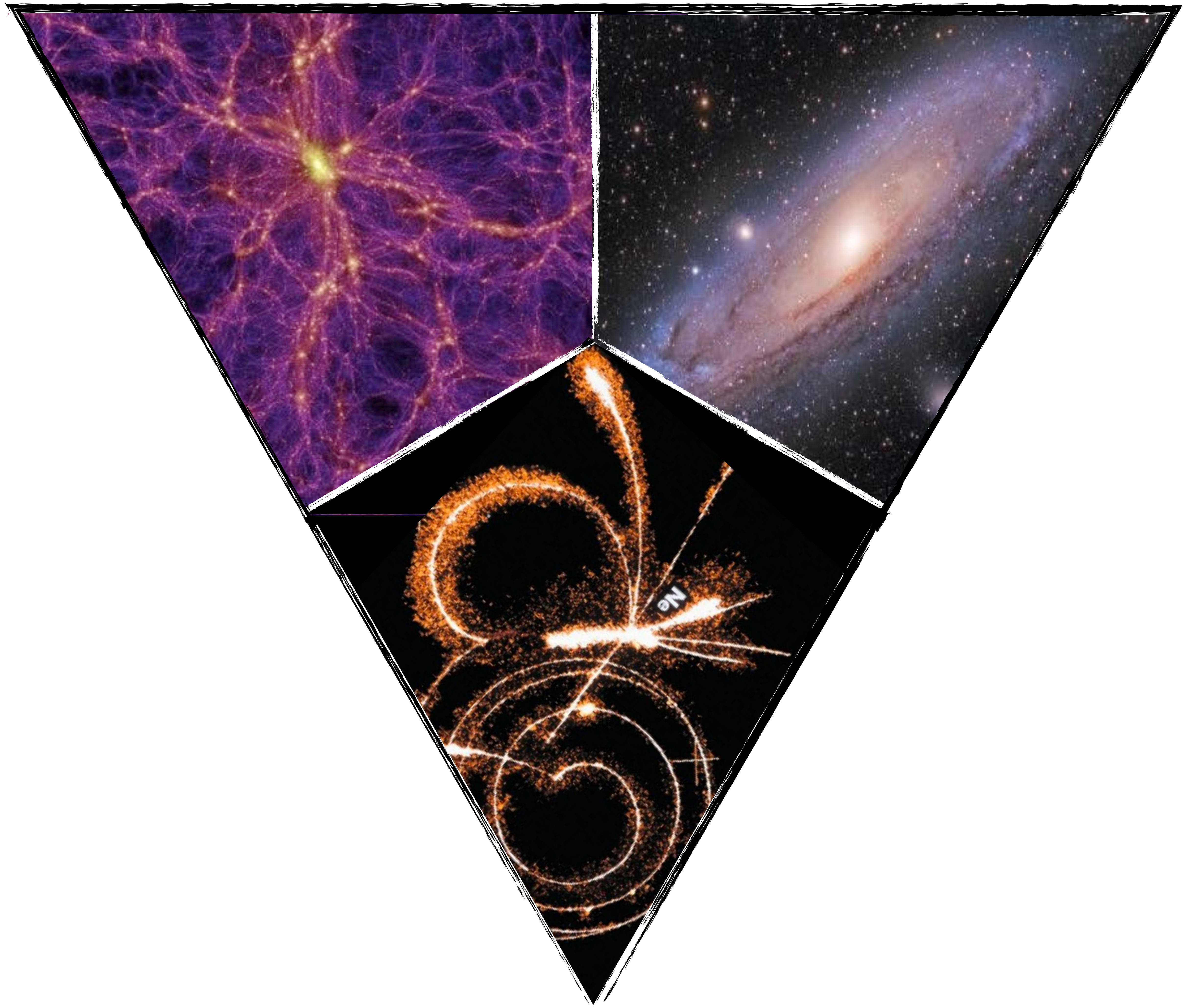
Please sign up so we get more fika!

Michael Korsmeier
2023/05/12

Why we are looking at Antimatter to learn more about Dark Matter

Dark Matter

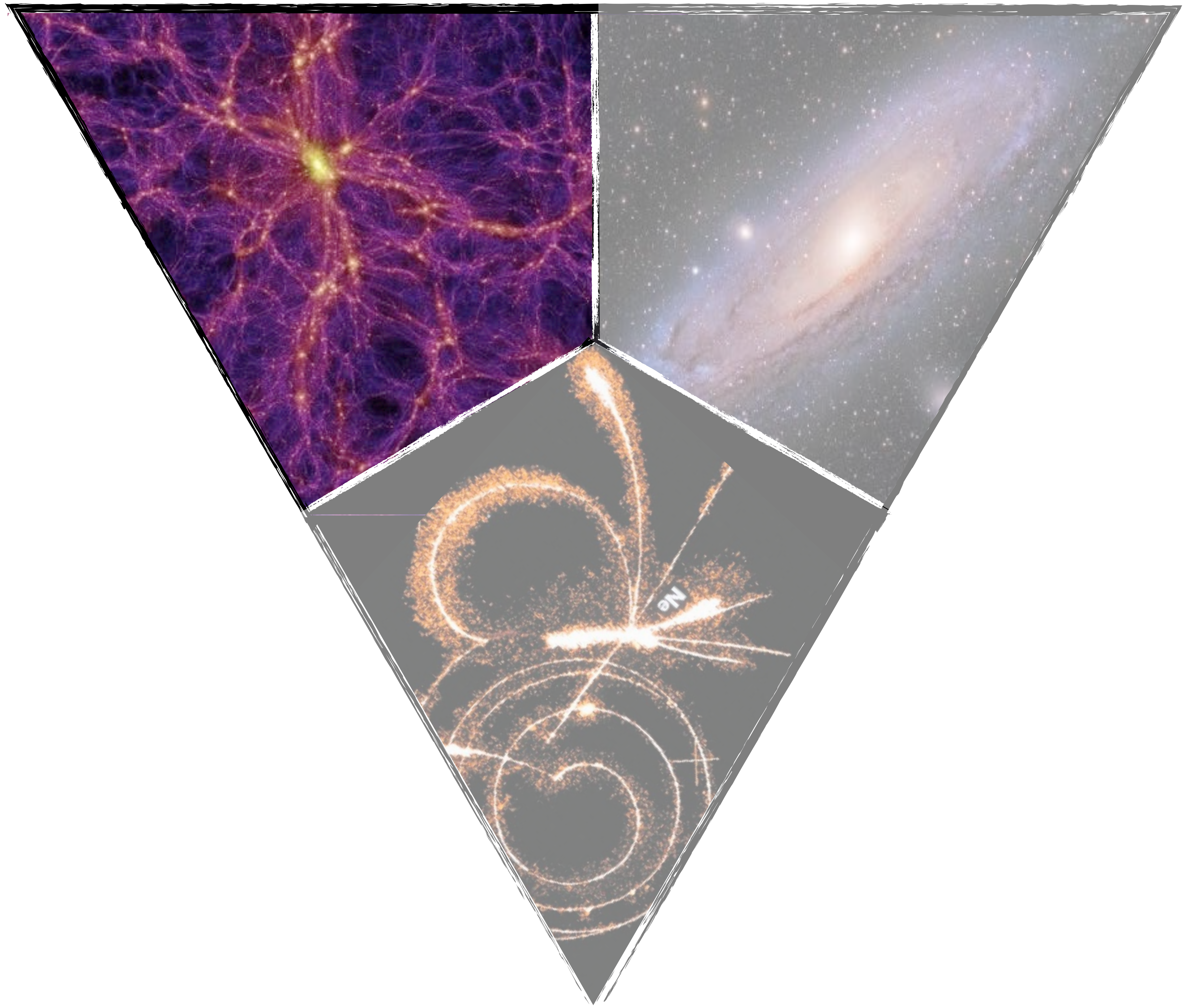
Cosmic Rays



Antimatter

Dark Matter

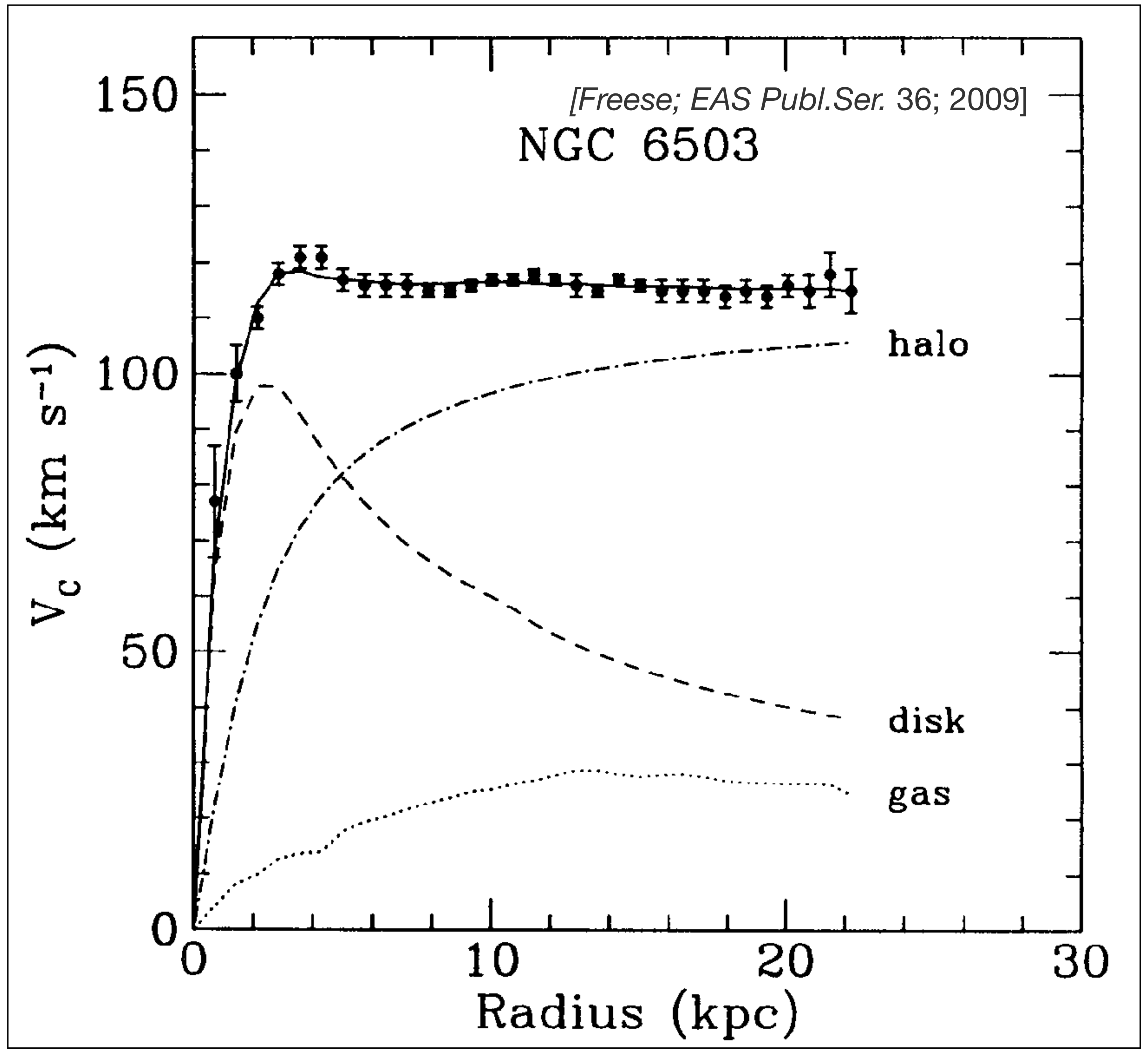
Cosmic Rays



Antimatter

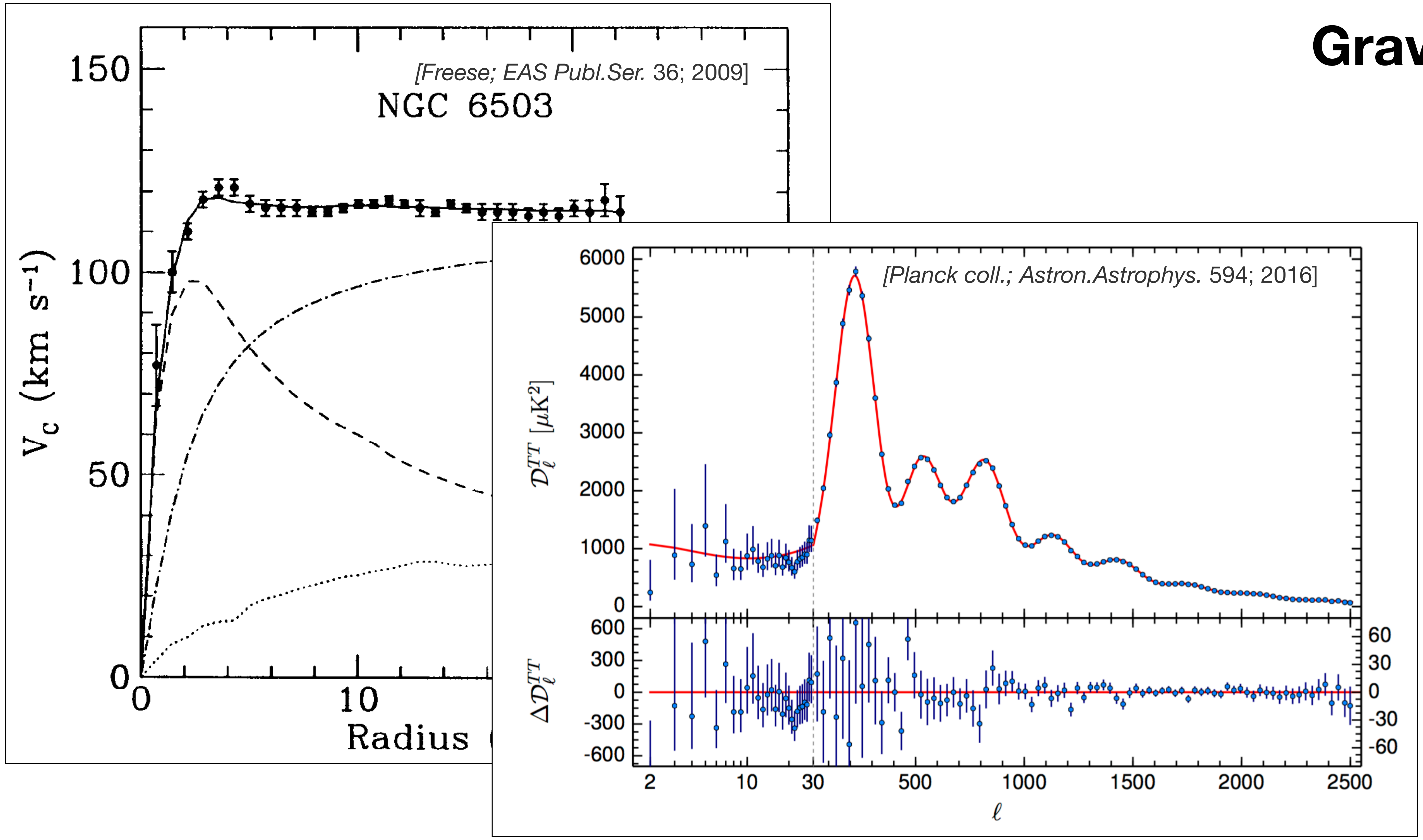
Dark Matter Evidence

Dark Matter Evidence



Gravitational evidence at various scales is overwhelming.

Dark Matter Evidence



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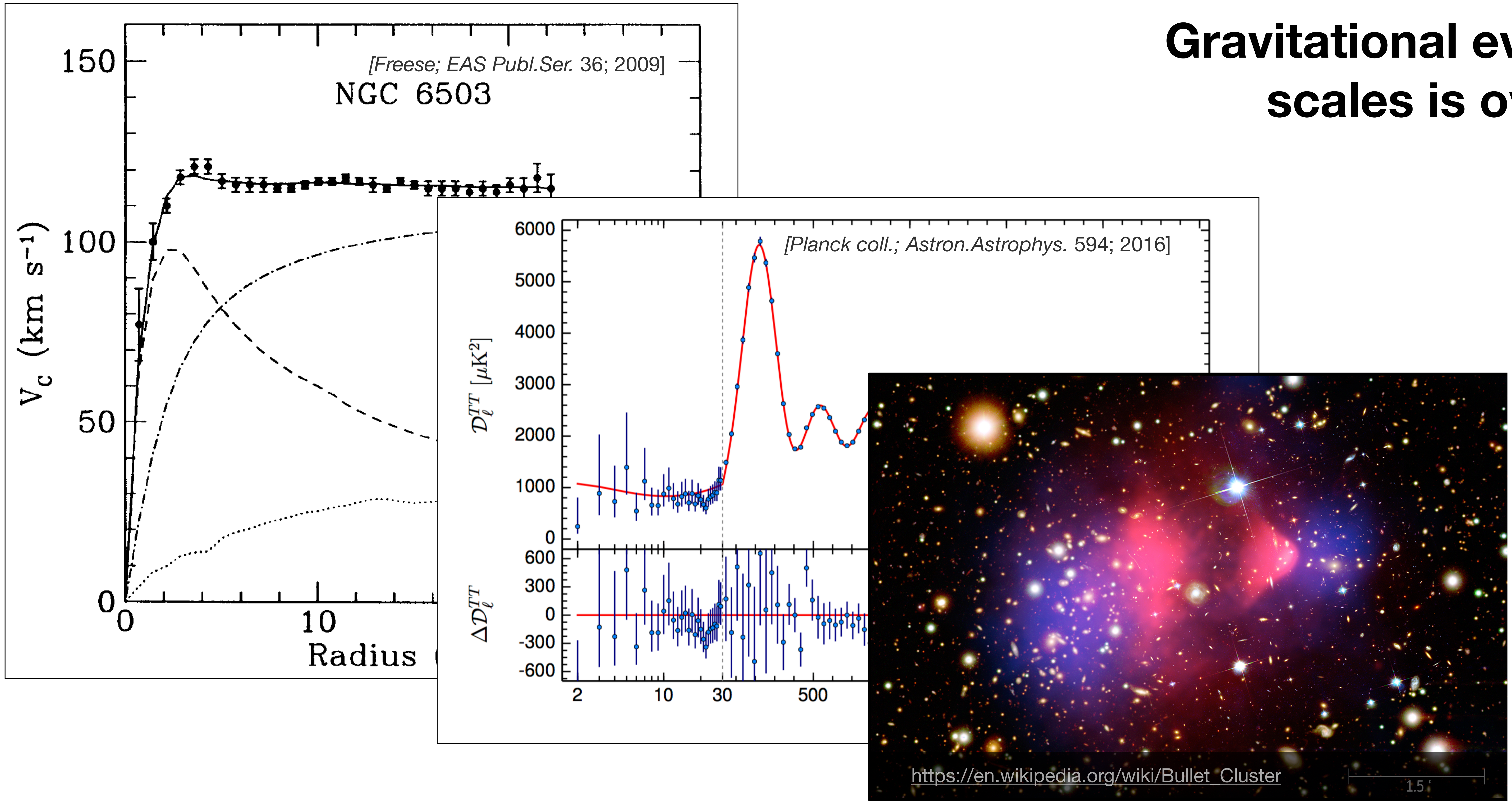

Gravitational evidence at various scales is overwhelming.

Dark Matter Evidence

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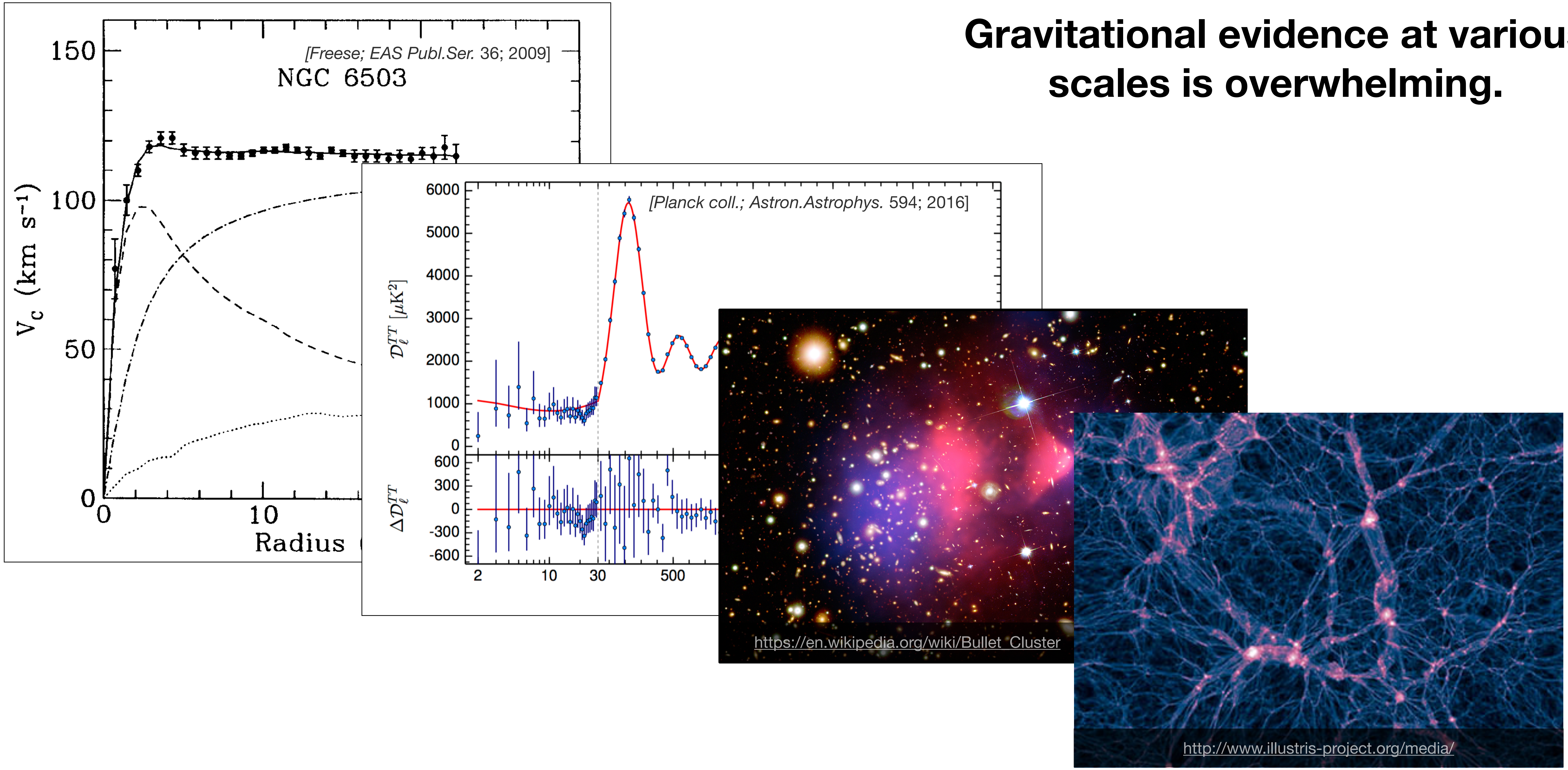
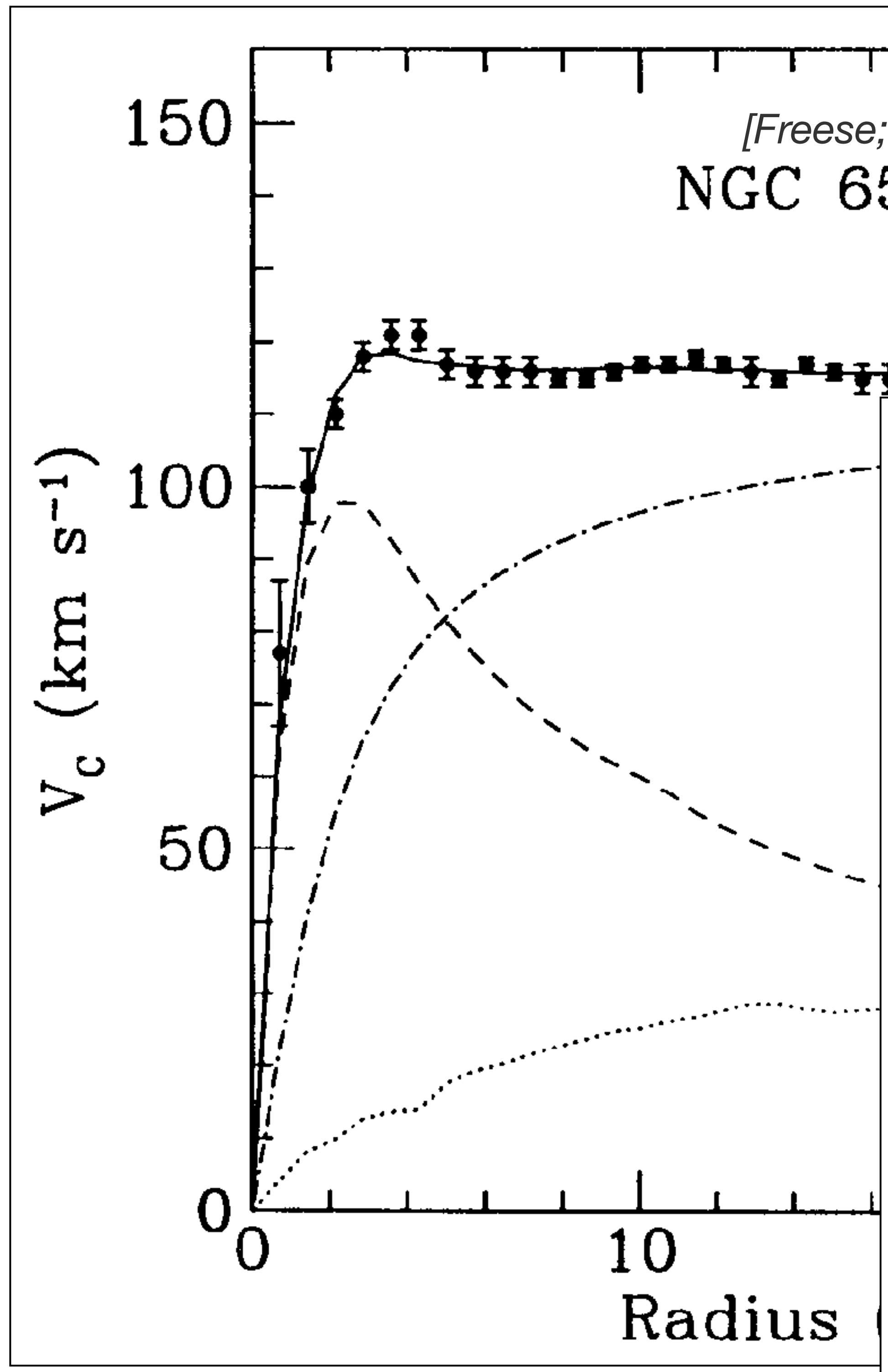
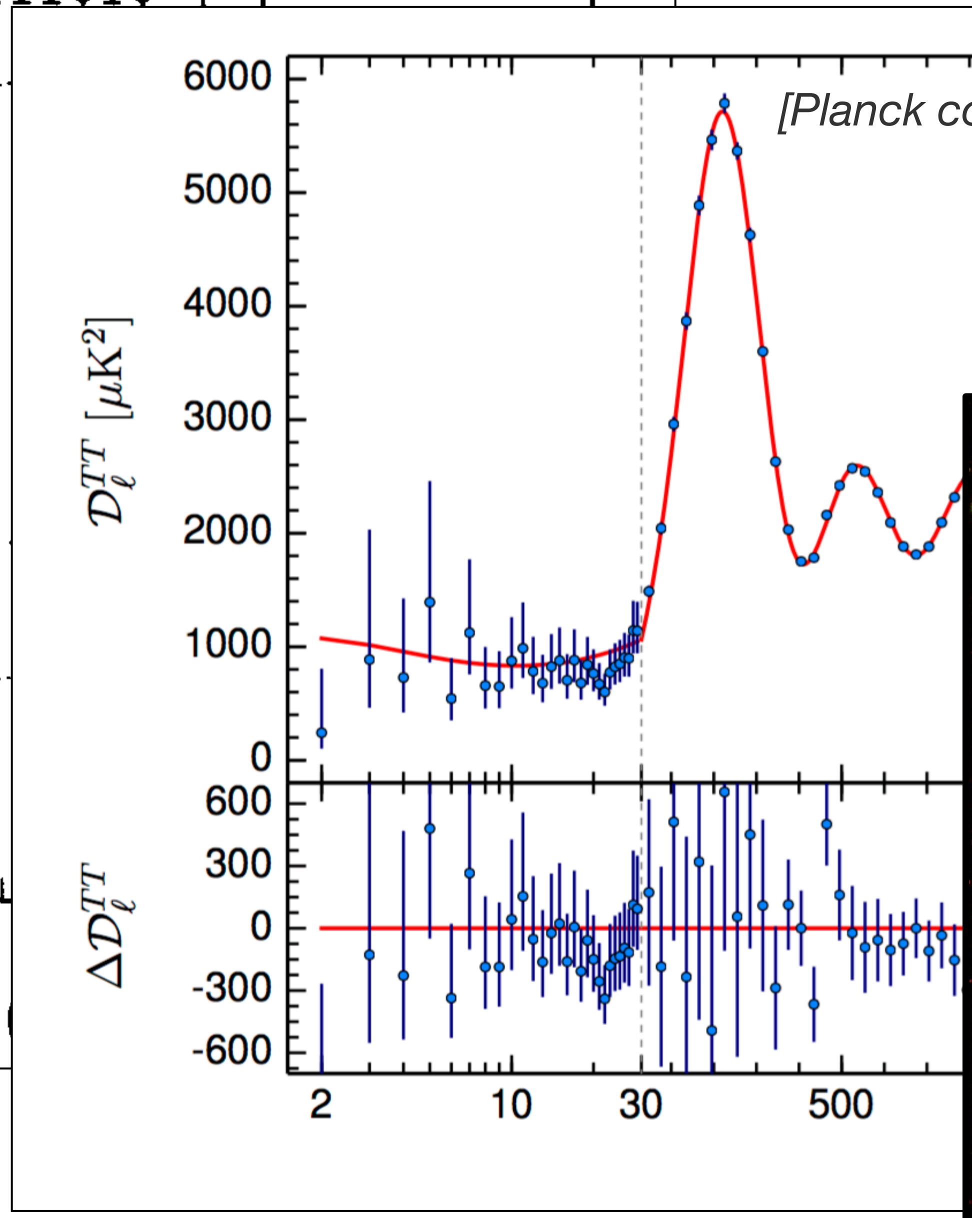
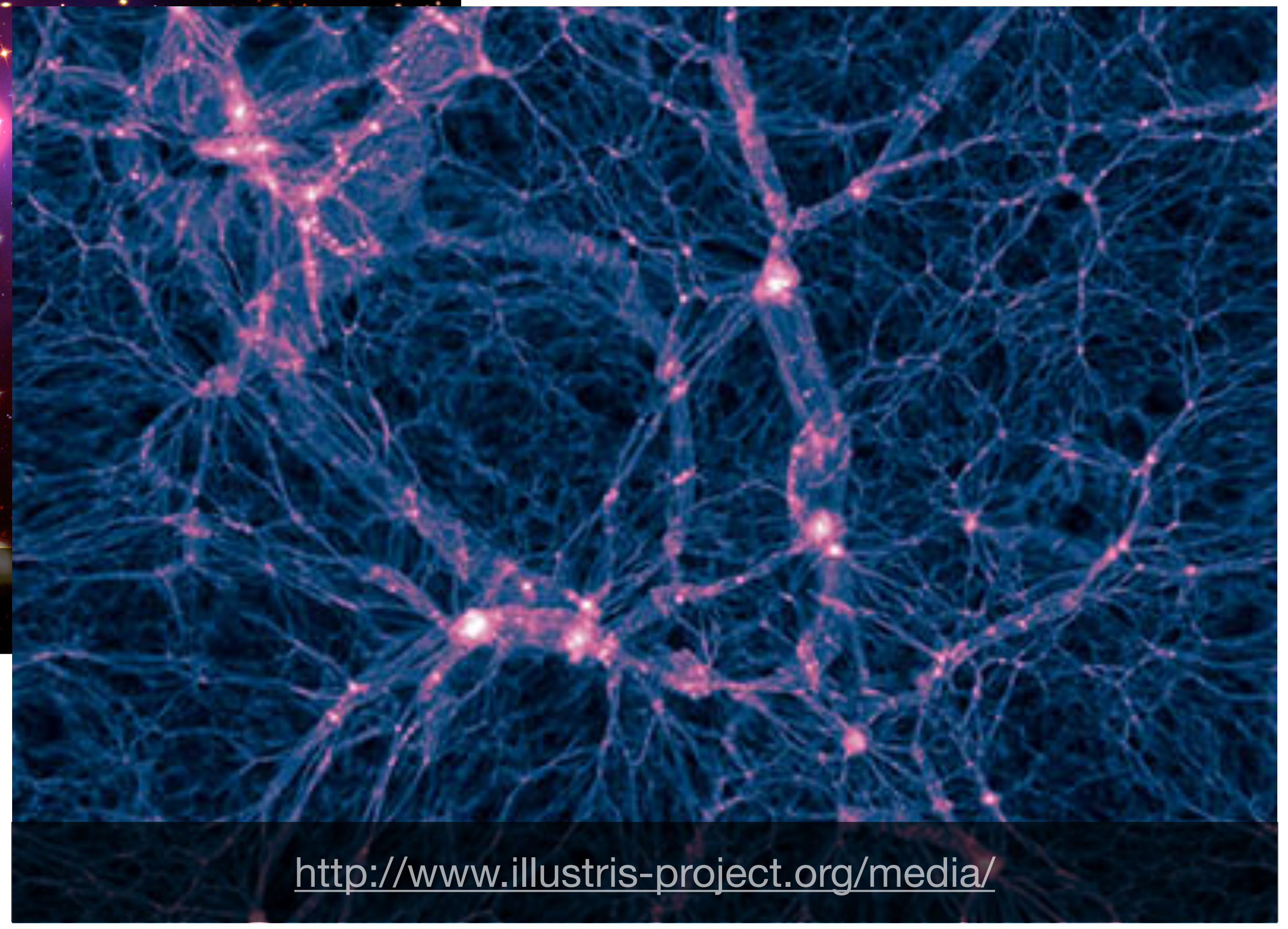


Dark Matter Evidence



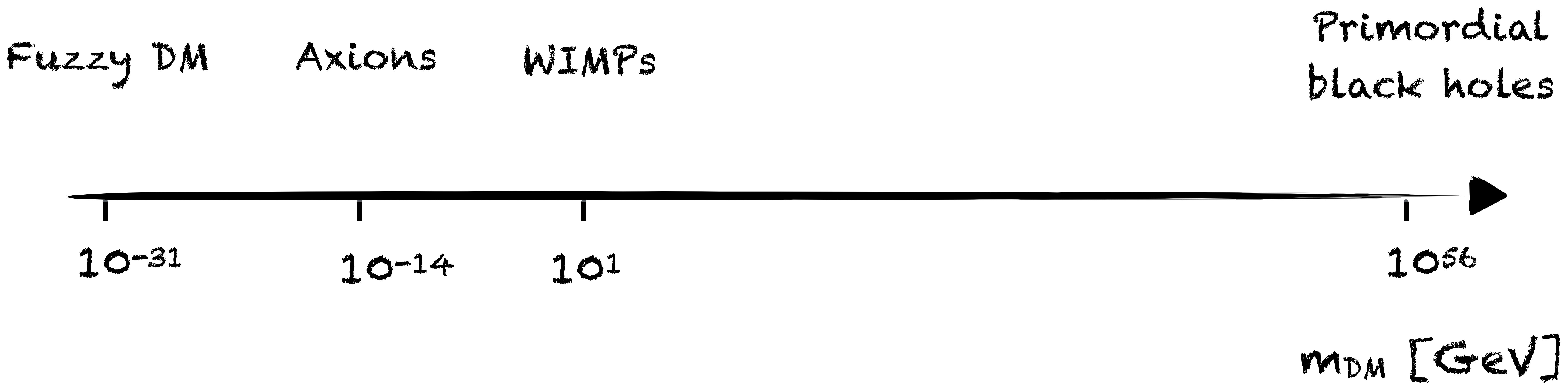




Gravitational evidence at various scales is overwhelming.

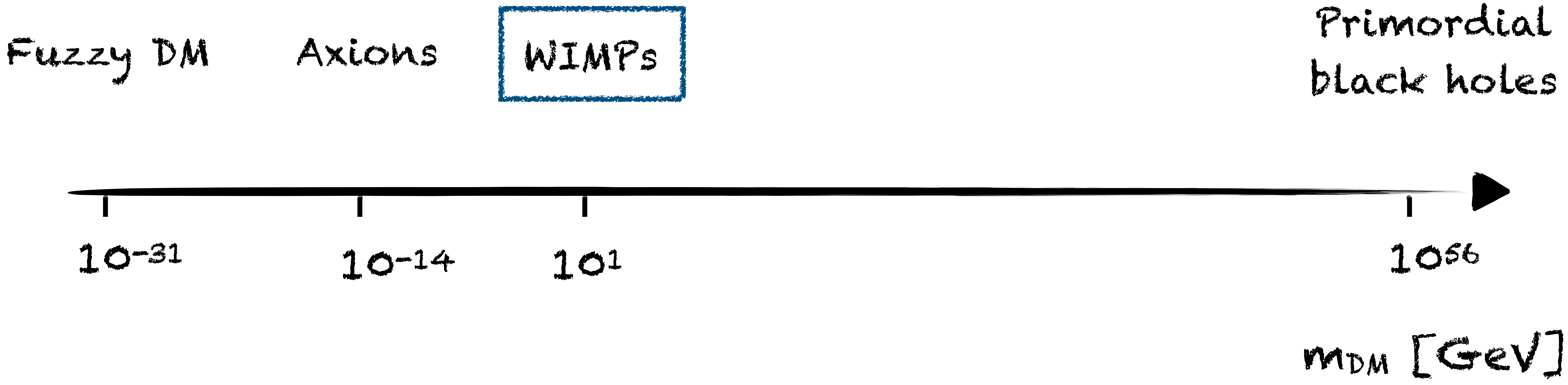
The nature of dark matter remains unknown!

Dark Matter Search



Dark Matter Search

- Mass range 1 GeV to 100 TeV
- Various search strategies
- We focus on indirect detection with **cosmic rays** and ***γ*-rays**



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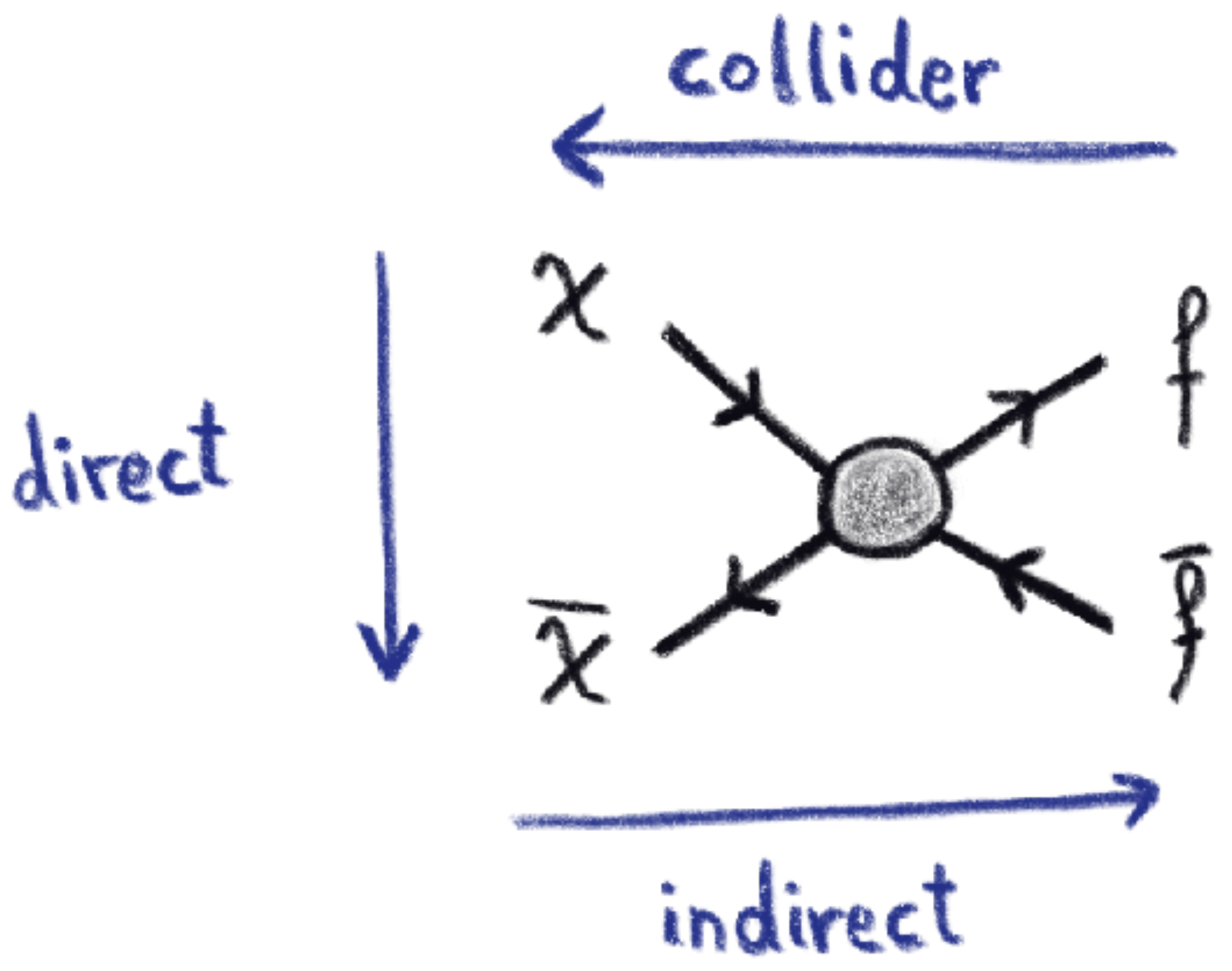
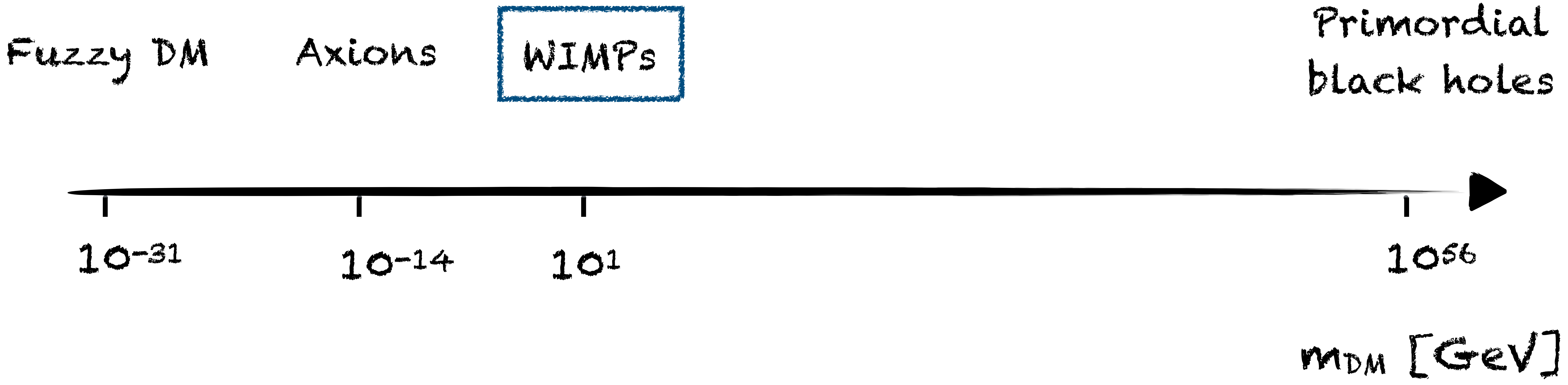
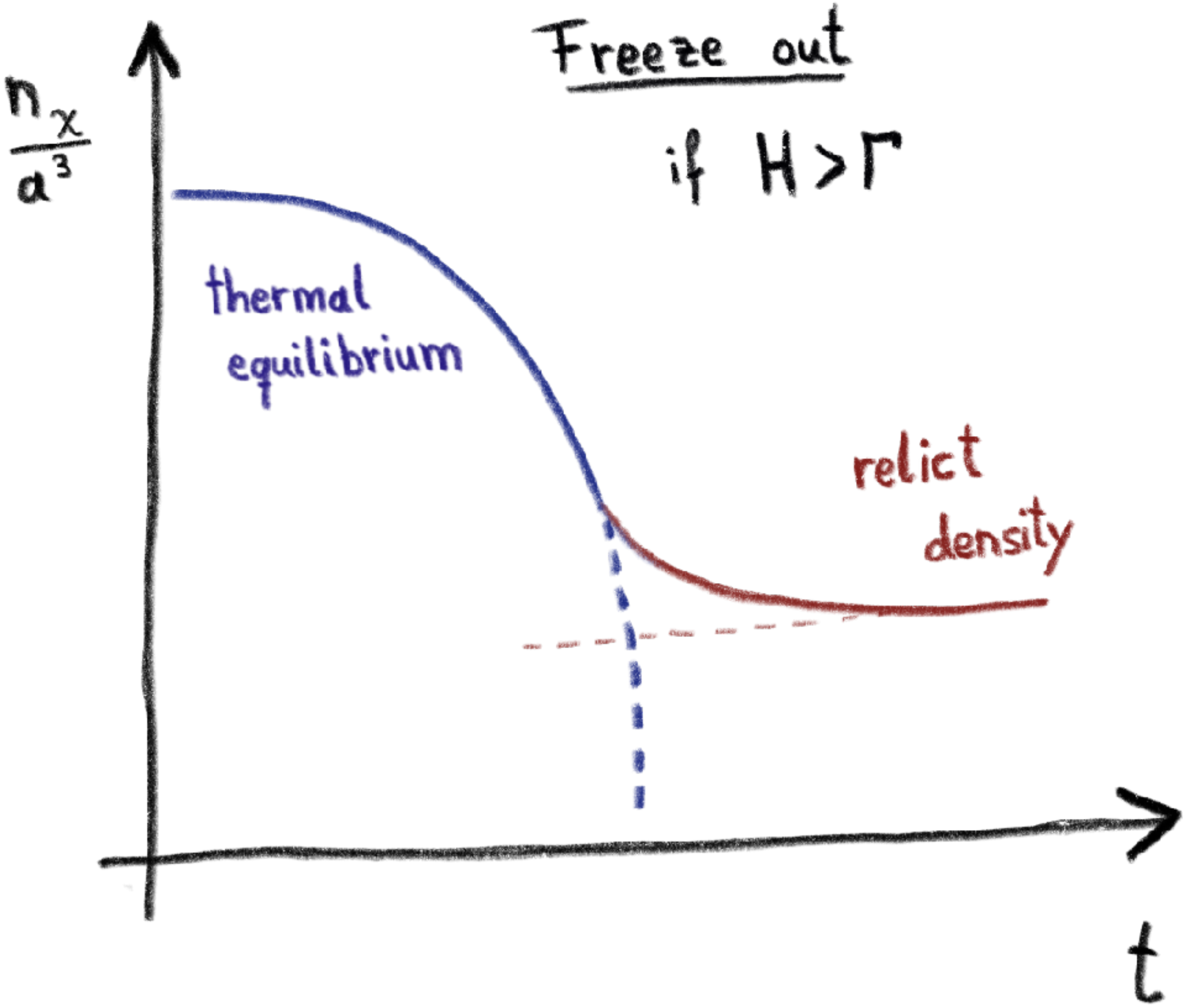


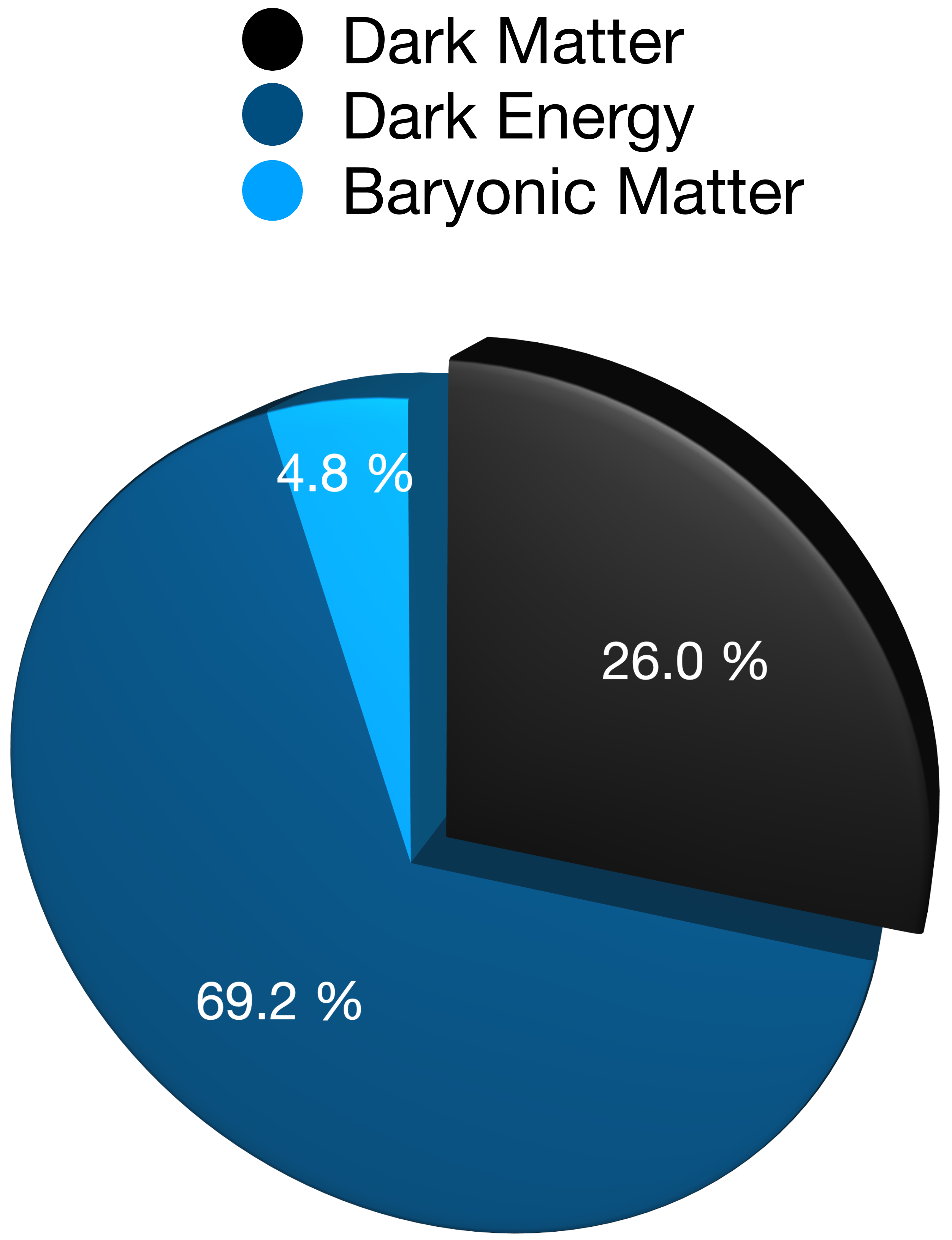


What’s special about WIMPs?



Properties of Dark Matter

- Cold
- Neutral
- Stable
- Small self-interaction
- Match relic density
- Compatible with bounds from:
  - collider searches
  - direct detection
  - astrophysics/cosmology

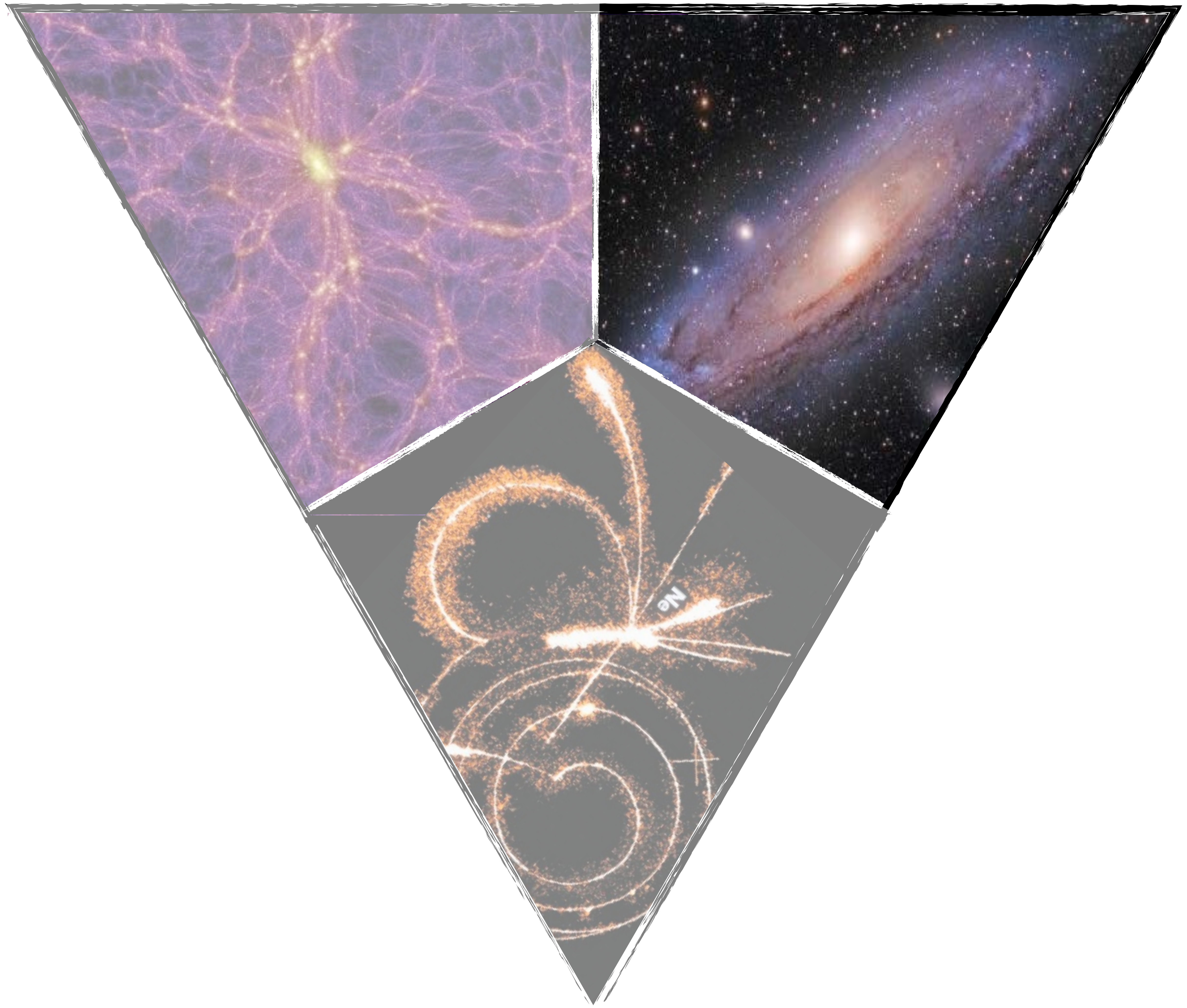


Numbers from: [Planck coll.; Astron.Astrophys. 594; 2016]

Energy content of the Universe <u>today</u>

Dark Matter

Cosmic Rays



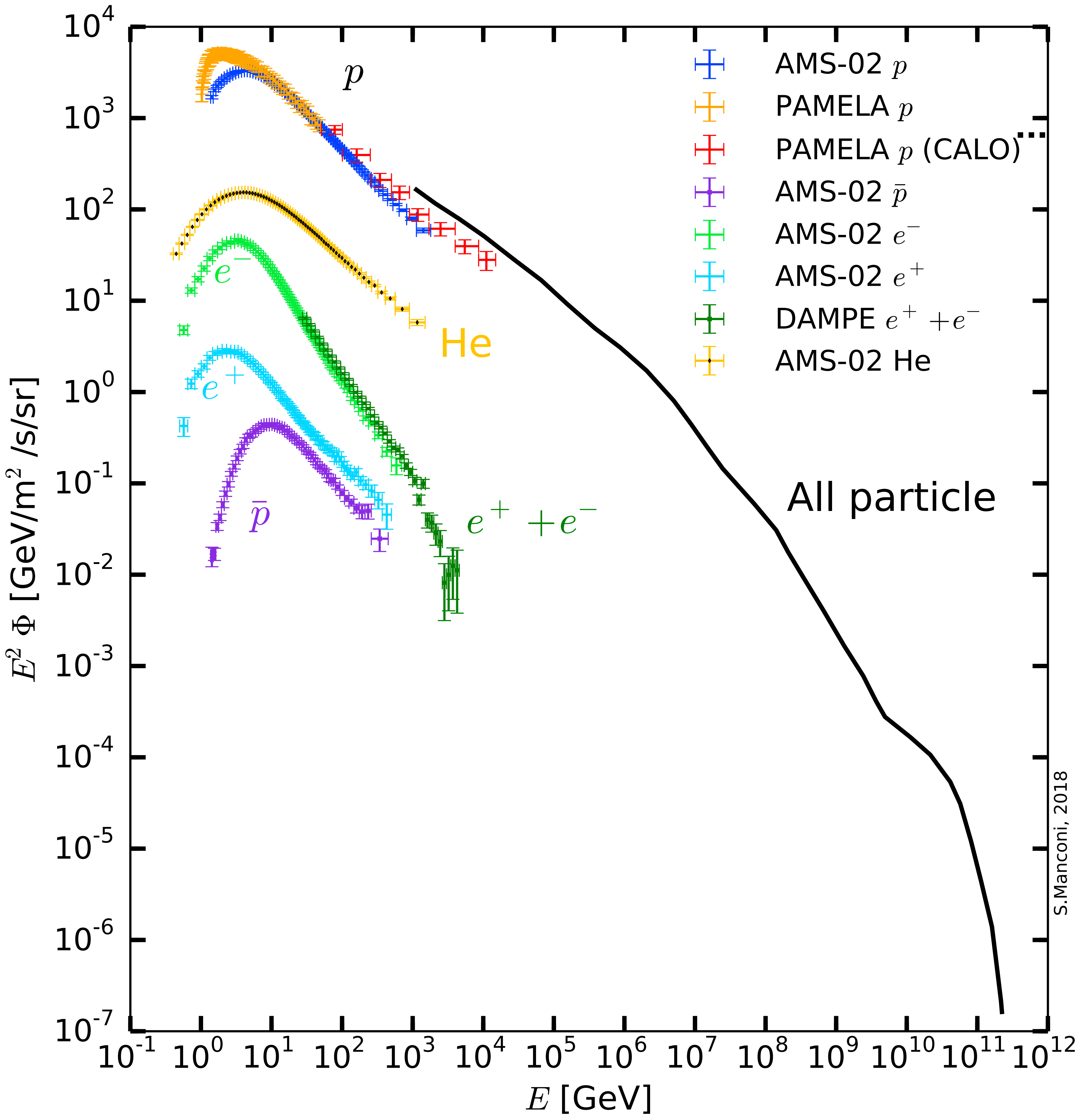
Antimatter

A brief History of Cosmic-Ray Physics

1909	Theodor Wulff	**Radiation increase** - Eiffel Tower
1911	Domenico Pacini	Radiation **decreases under water**
1912	Victor Hess	**Ionization rate increases** with altitude Balloon flights up to 5 km — Nobel Prize in 1936
1932	Arthur Compton	**Latitude dependence** of cosmic rays
1932	Carl Anderson	Discovery of the **positron**
1937	Anderson & Neddermeyer	Discovery of the **muon**
1947	Lattes, Occhialini, Moorhead & Powell	Discovery of the **charge pions**


[Wikipedia]

The Cosmic-Ray Spectrum



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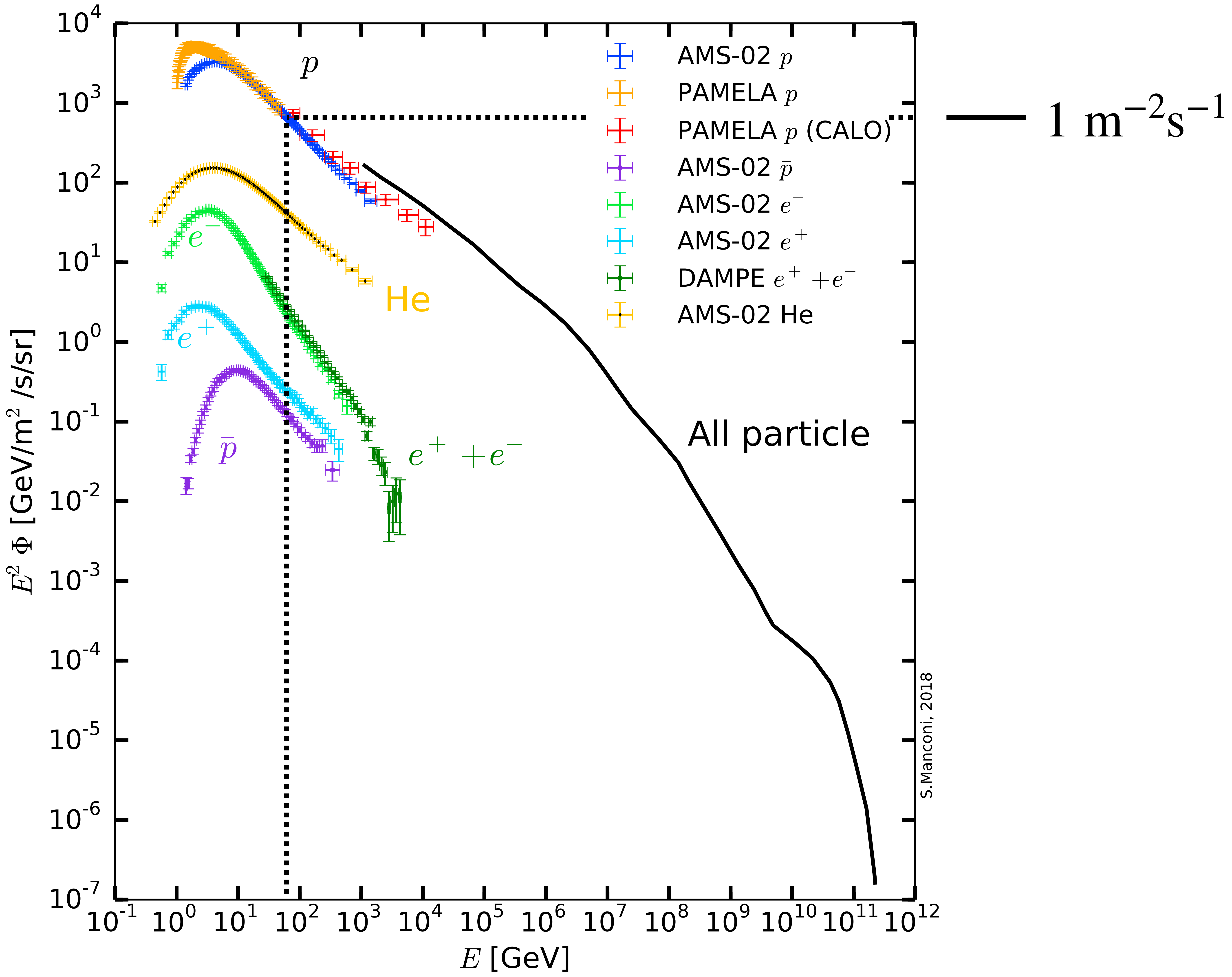

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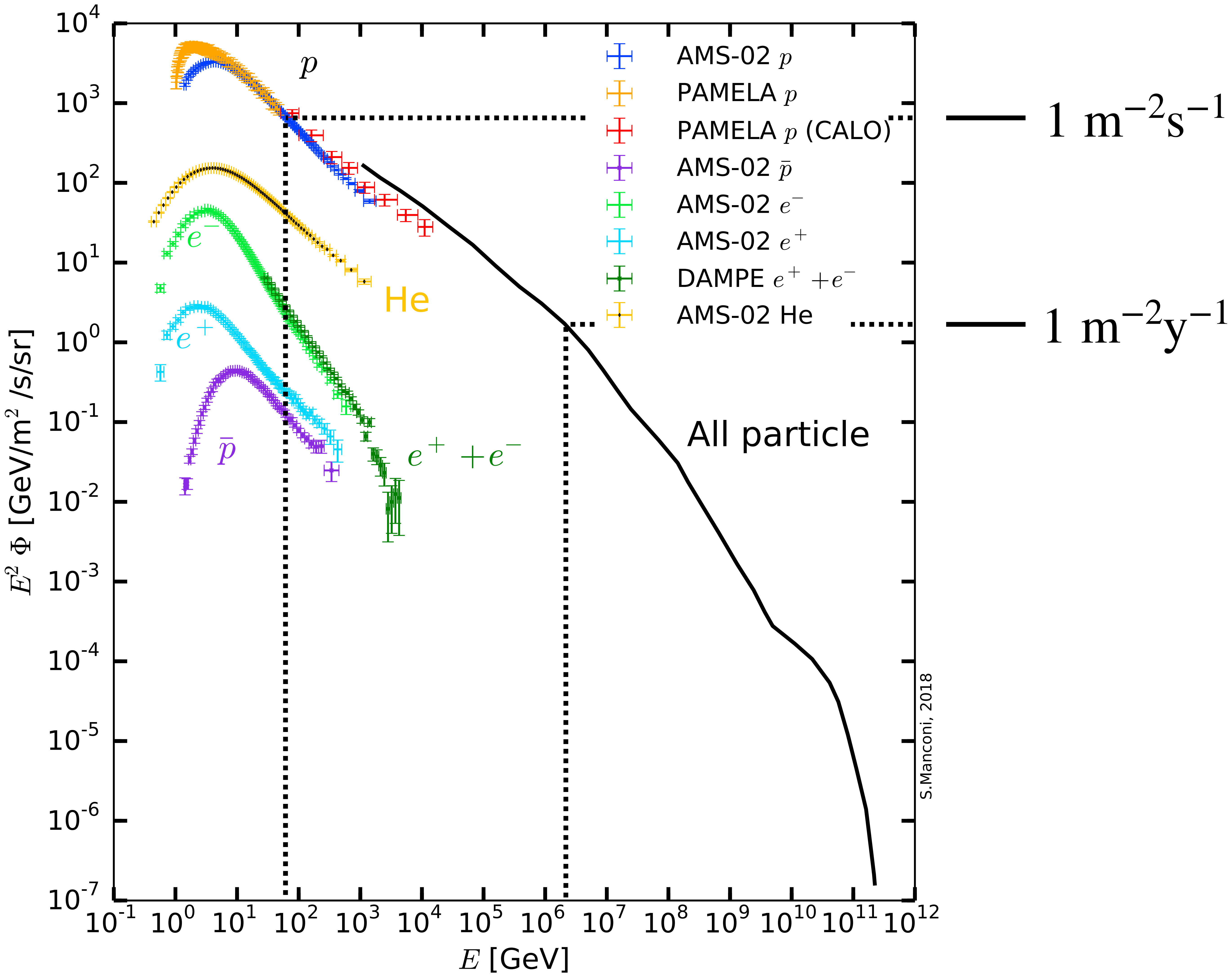

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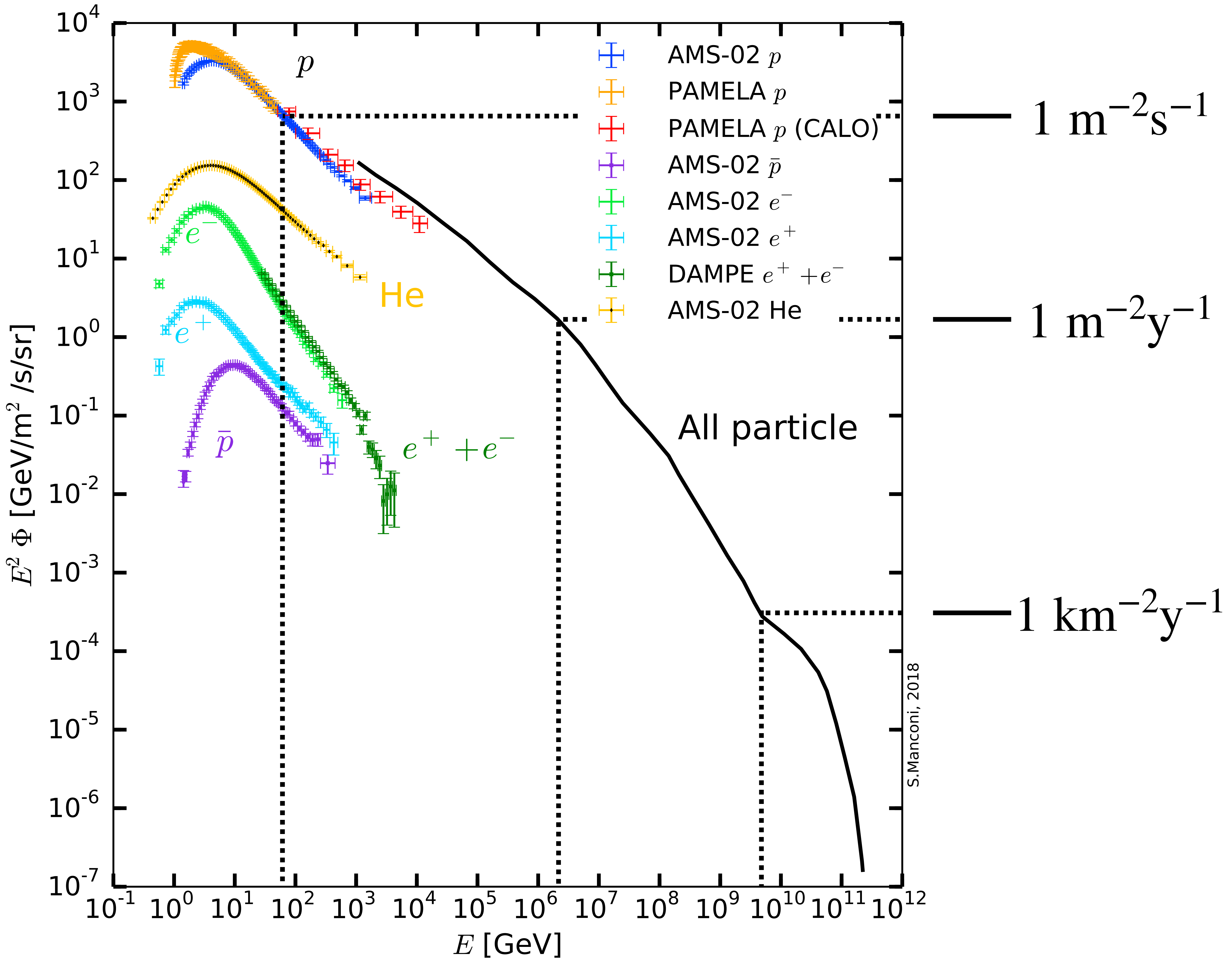



AMS-02
ELC2
ELC4

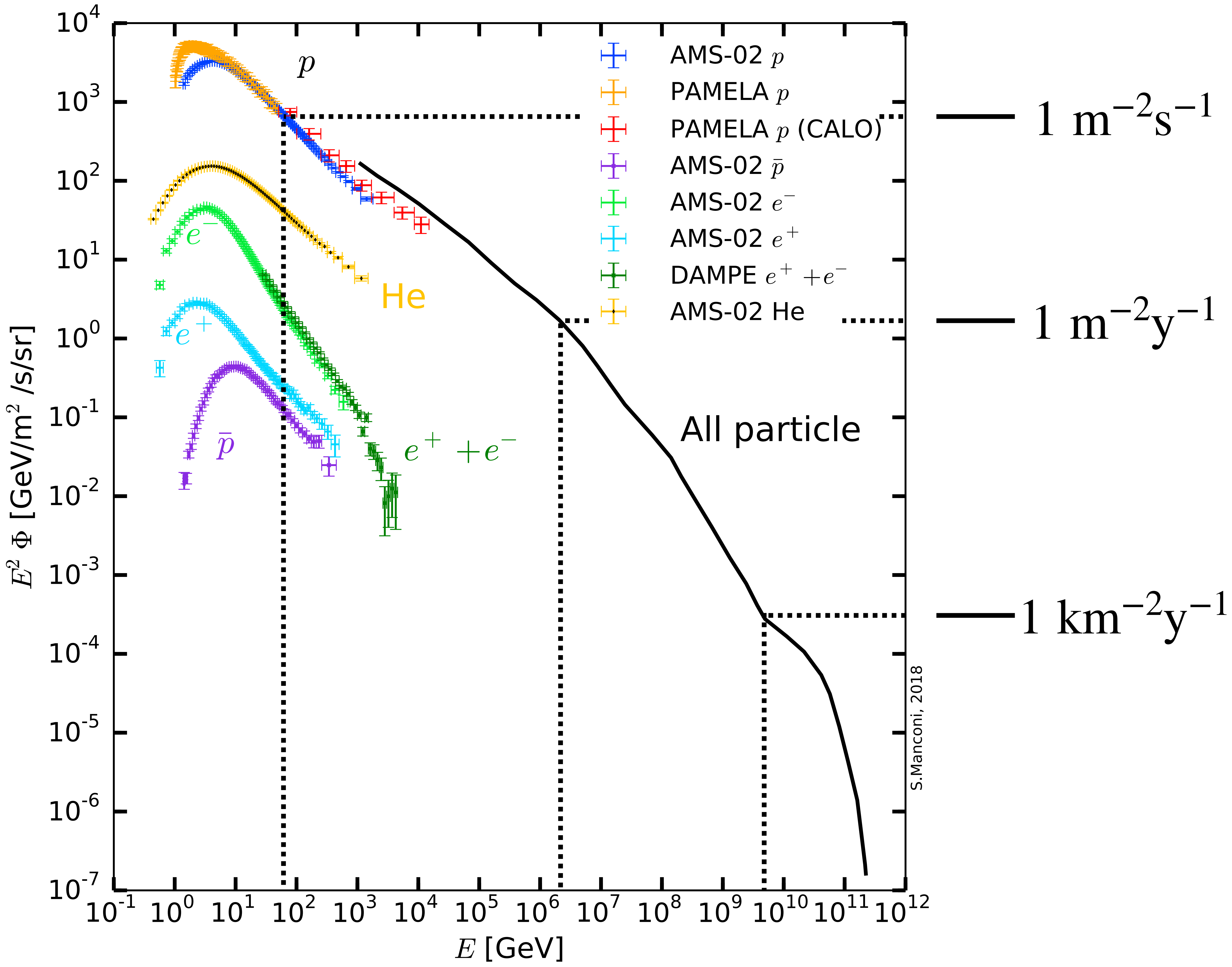

AMS-02
ELC2
ELC4
TRD
Identify e+, e-
Silicon Tracker
Z, P
ECAL
E of e+, e-
Time of Flight
Z, E
Magnet
±Z, P
Time of Flight
Z, E
Ring Imaging Cherenkov
Z, E
1
TRD
TOF
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
z
y
x
B


IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
50 m
2010: 79 strings in operation
2011: Project completion, 86 strings
IceCube Array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors
1450 m
AMANDA
DeepCore
6 strings-spacing optimized for lower energies
360 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock


ALAIDE


ALAIDE

The Cosmic-Ray Spectrum



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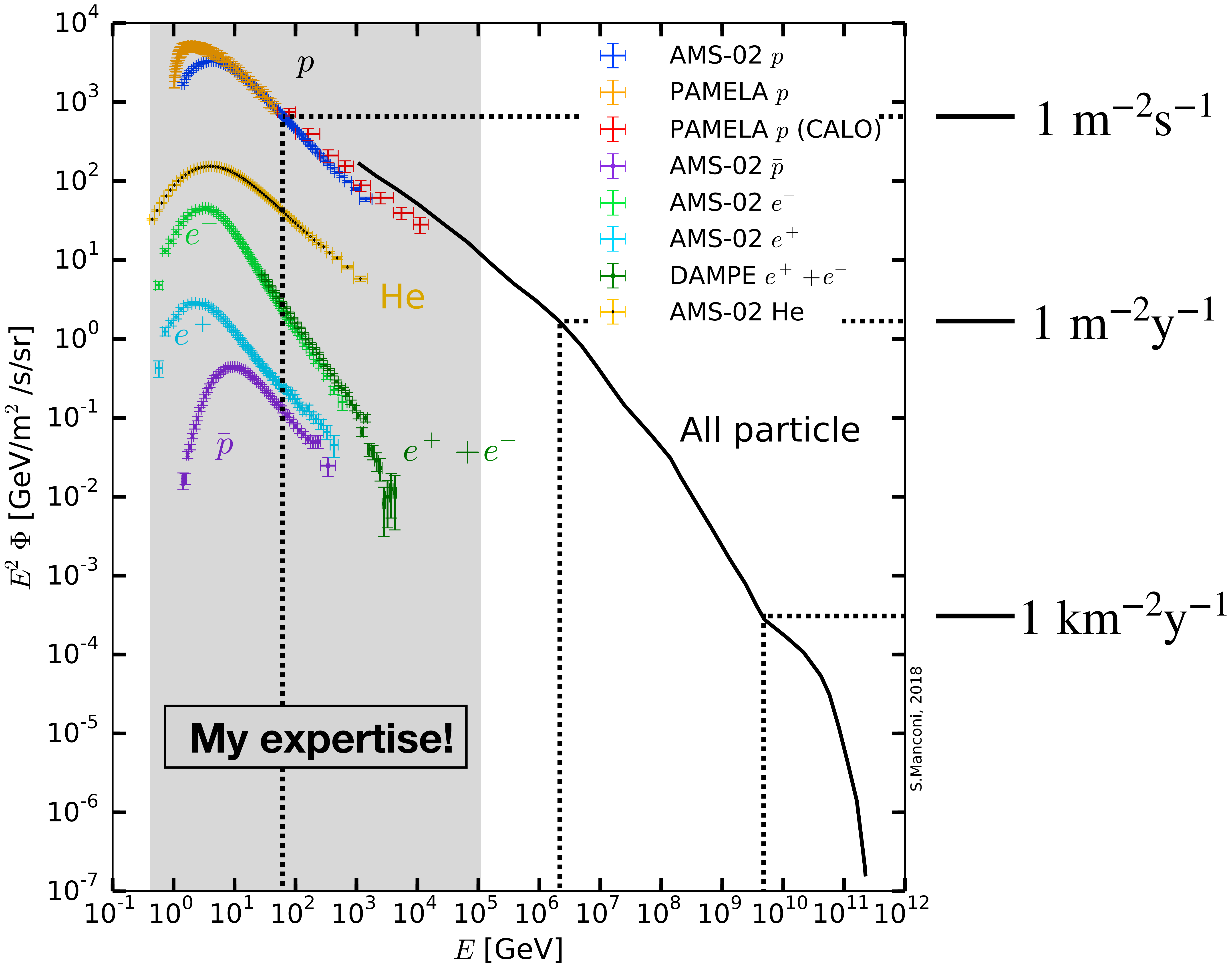
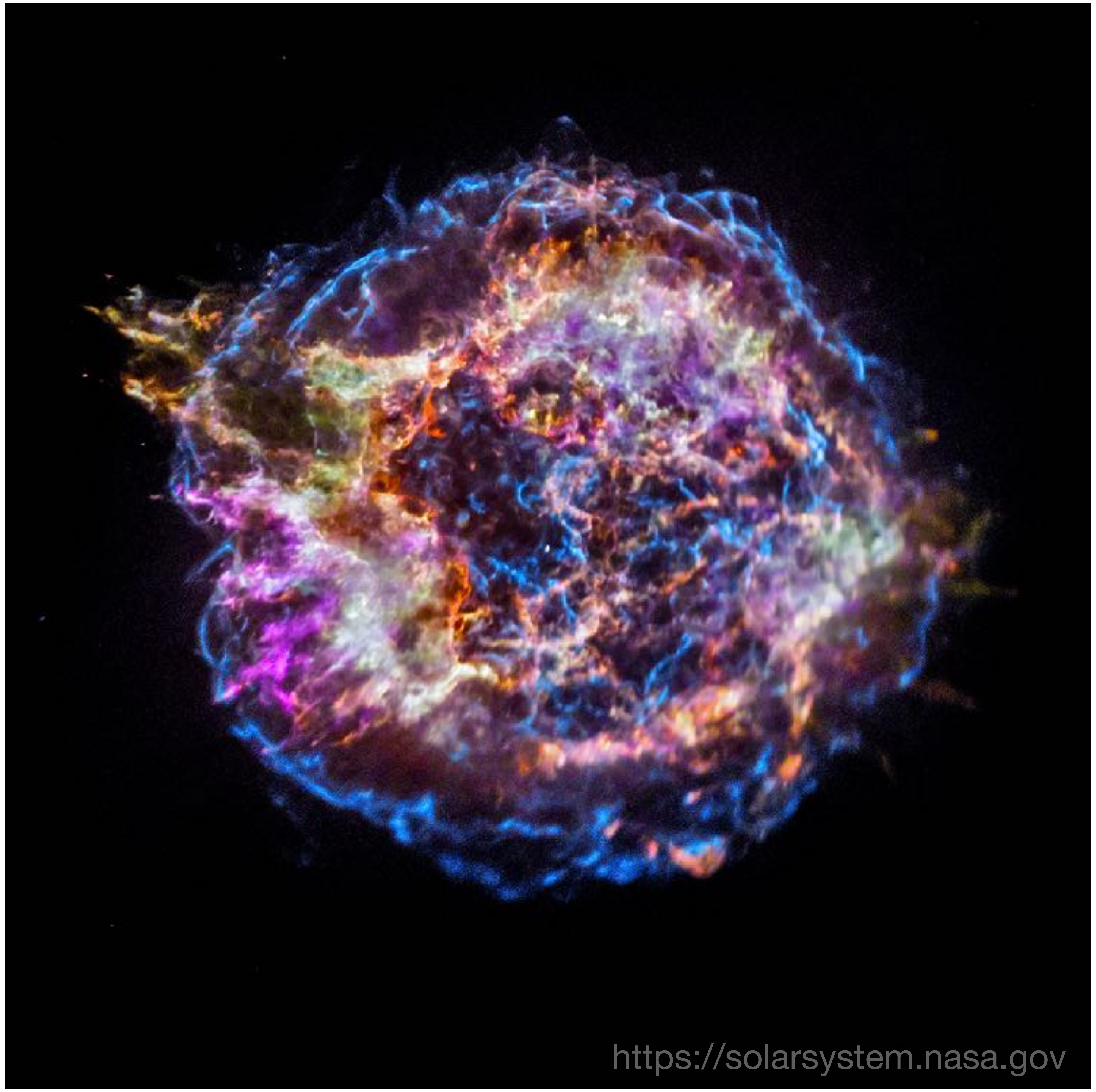


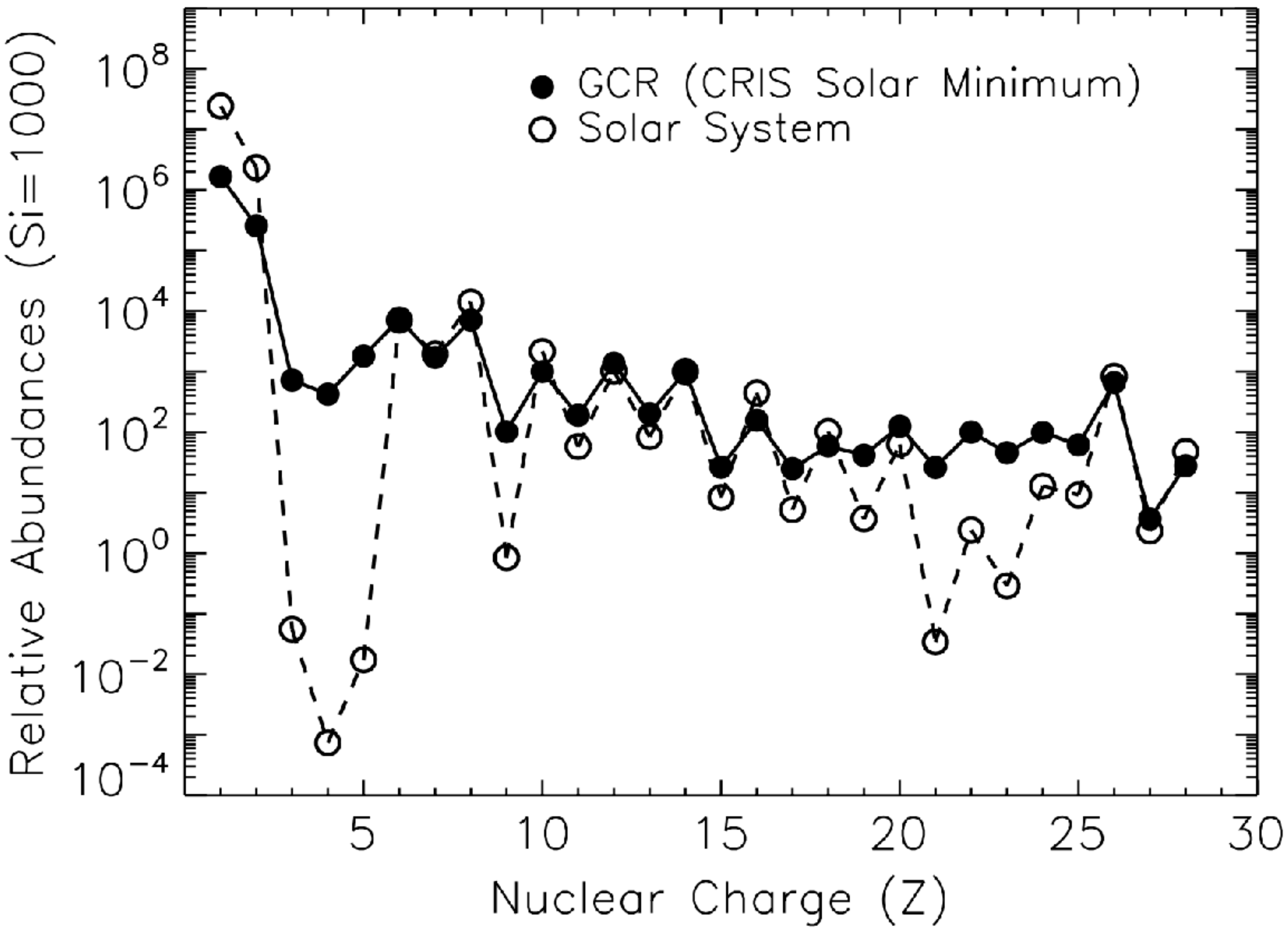
Acceleration Mechanism

Acceleration Mechanism



- Shock fronts are observed at SNRs
- CRs accelerated by SNRs are called **primaries**
- Dominat CRs: p, He, CNO

Primary and Secondary Cosmic Rays



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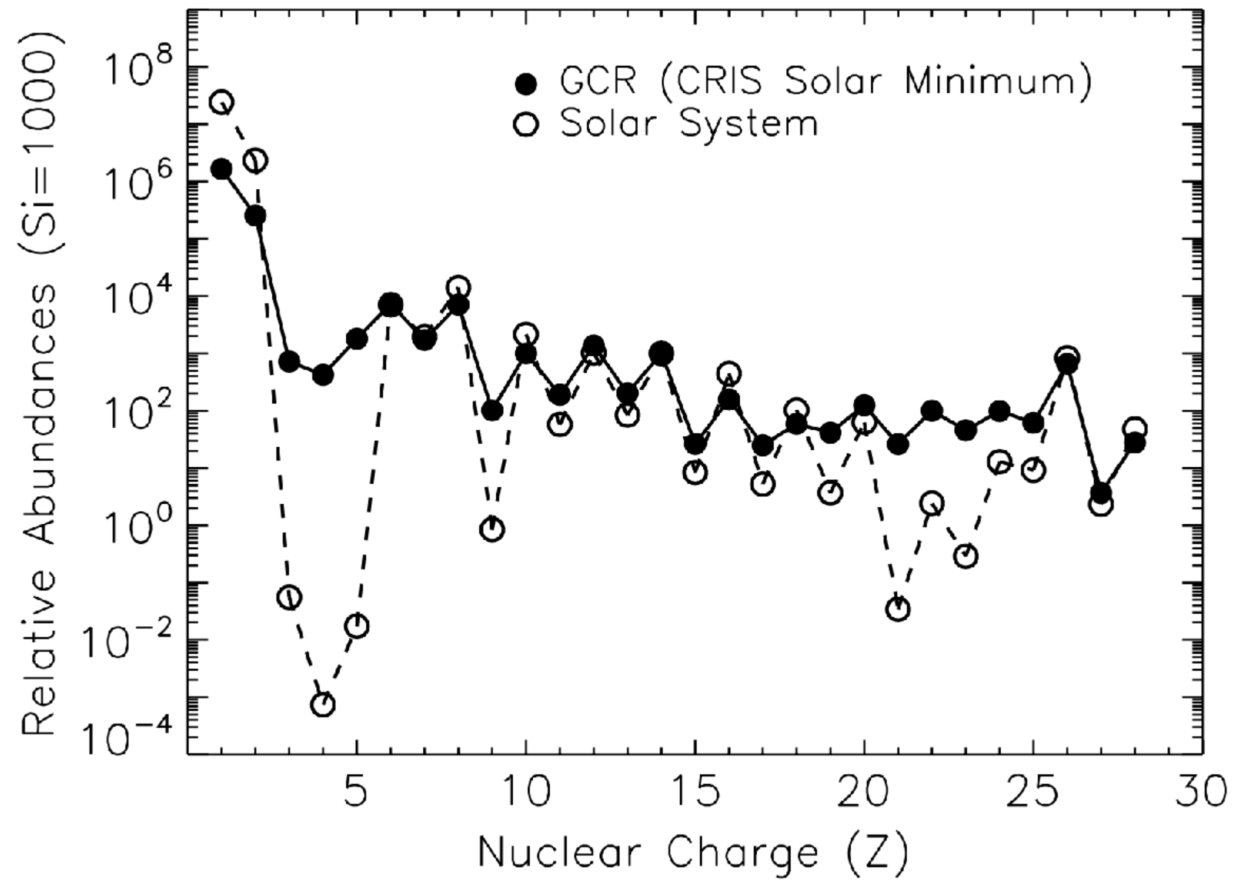
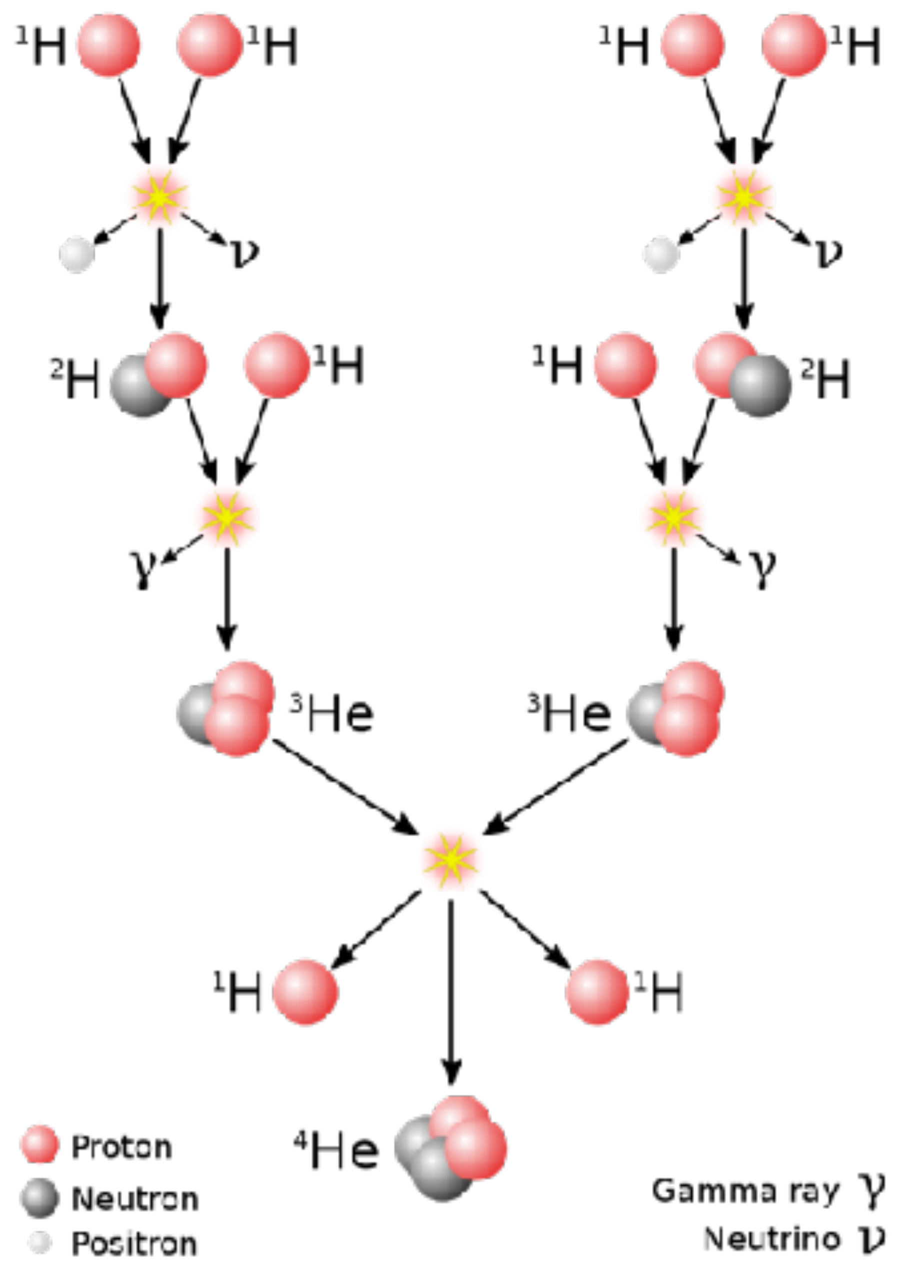
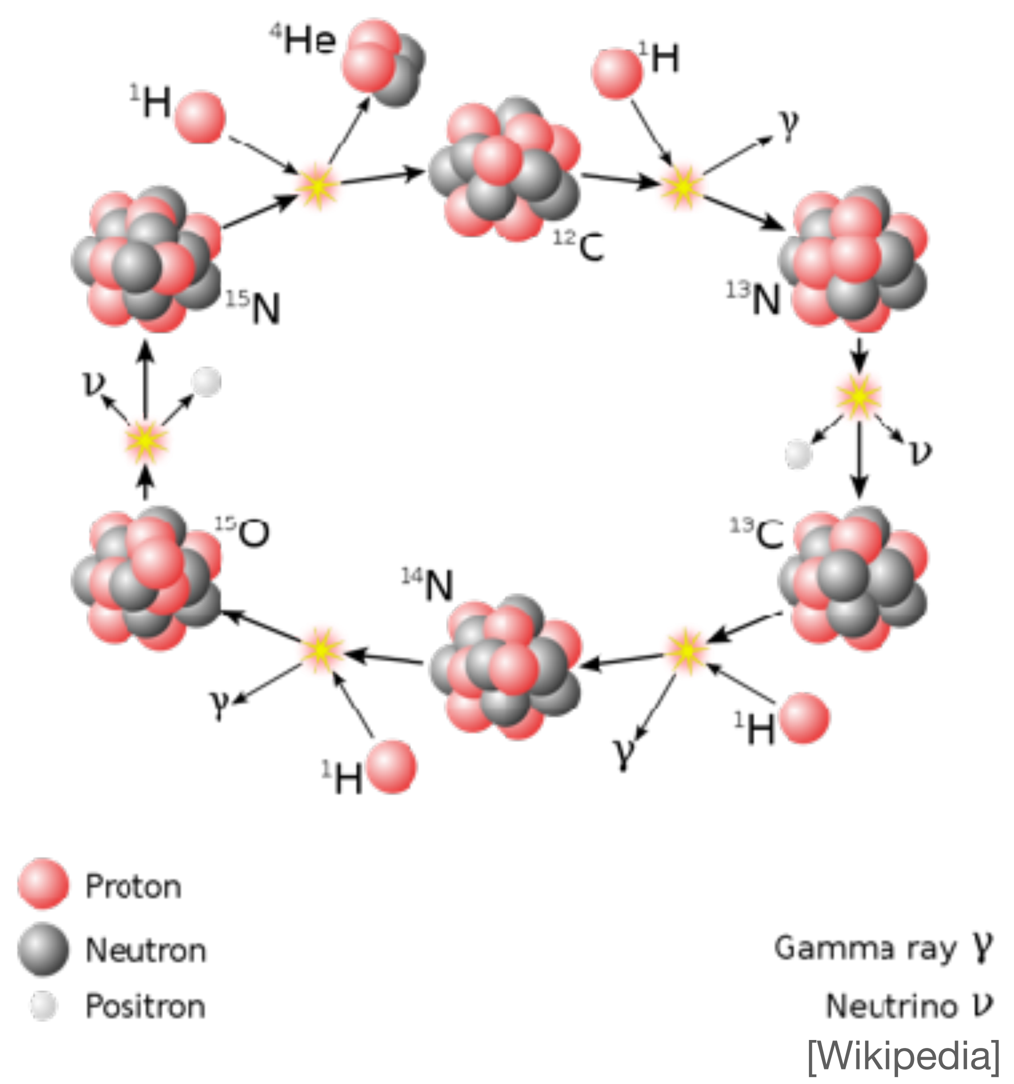


Sun-like Stars

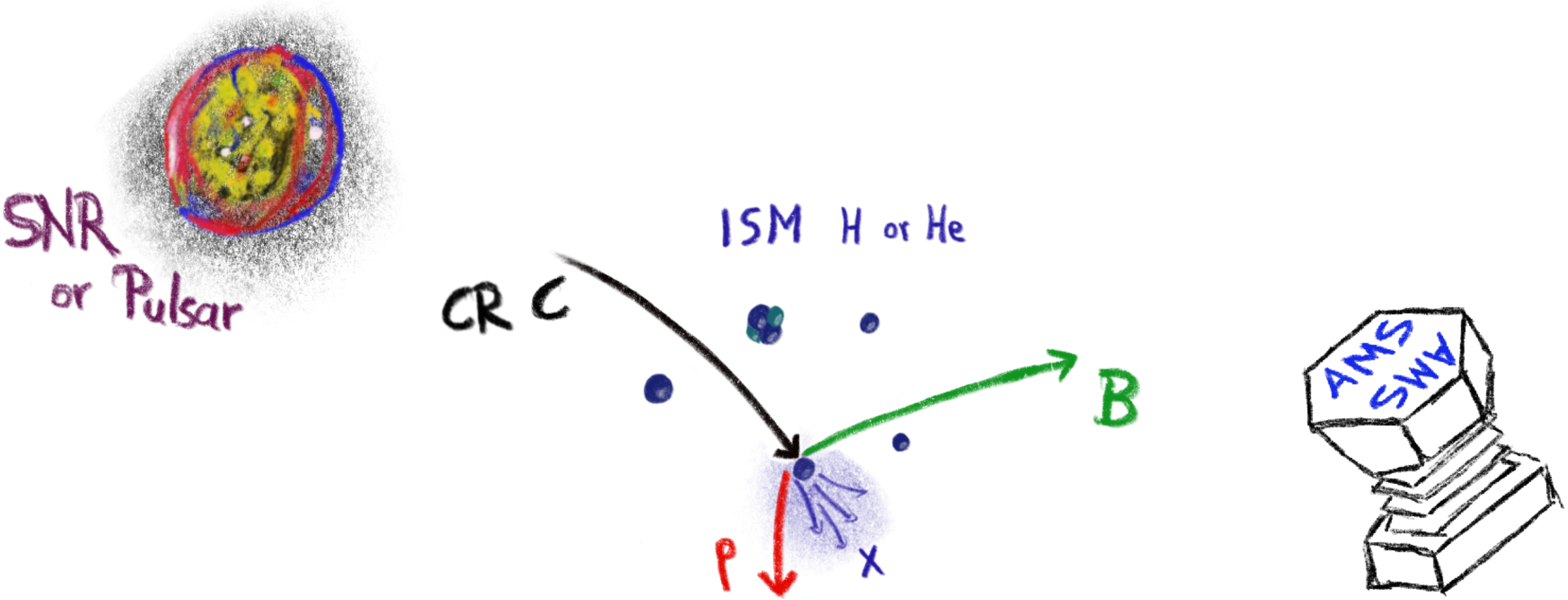


Heavier Stars



- The **secondaries** (like Li, Be, and B) are not produced by nuclear fusion in stars
- **Secondaries** are produced during CR propagation

Gramage



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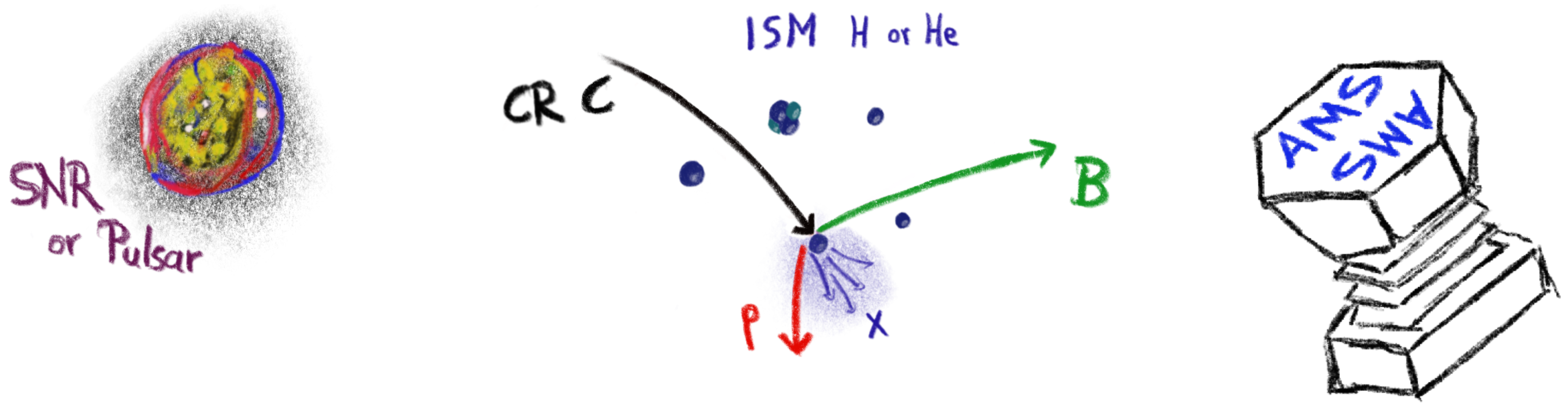
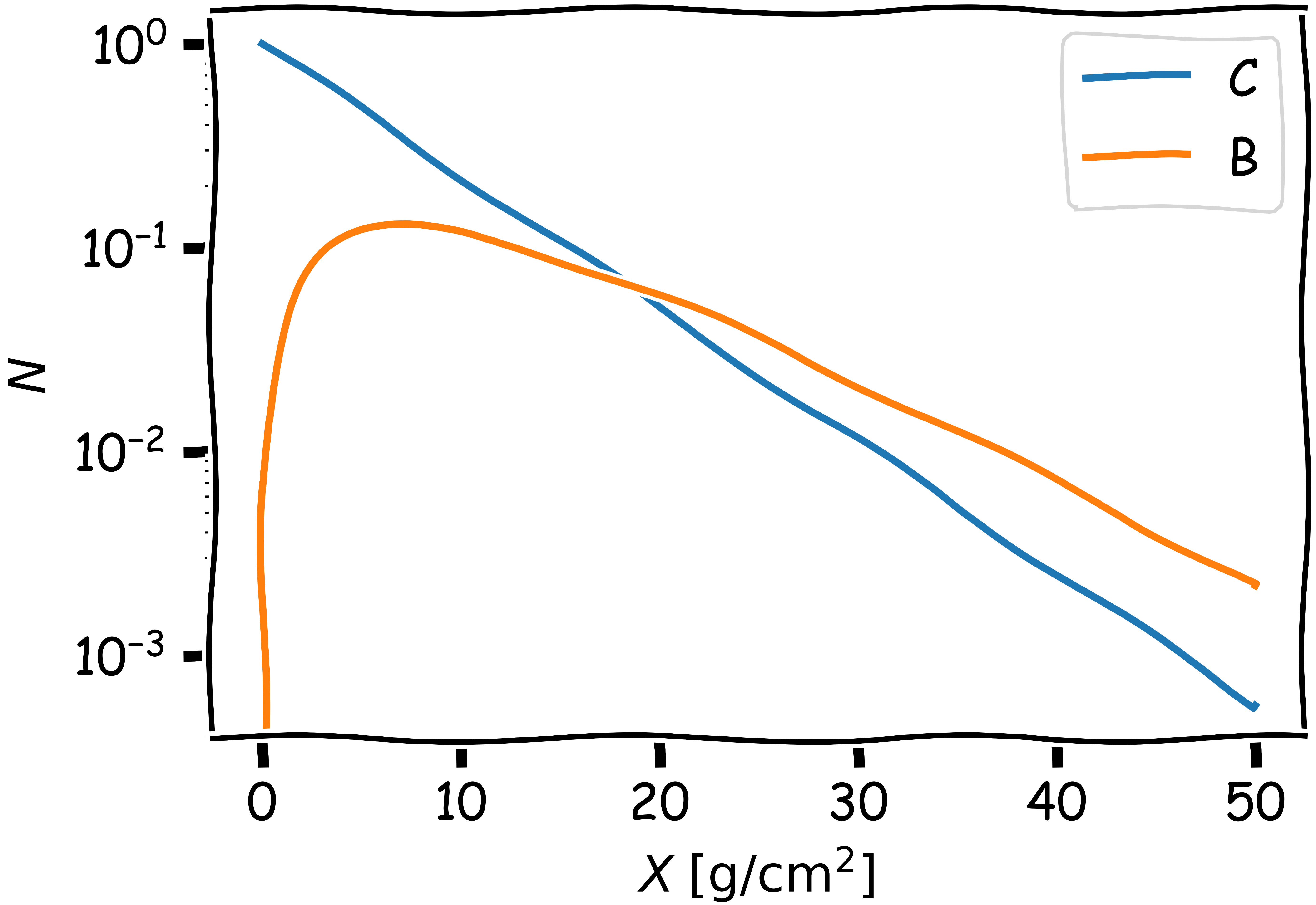
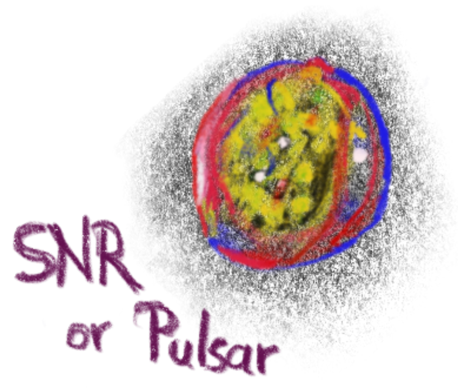
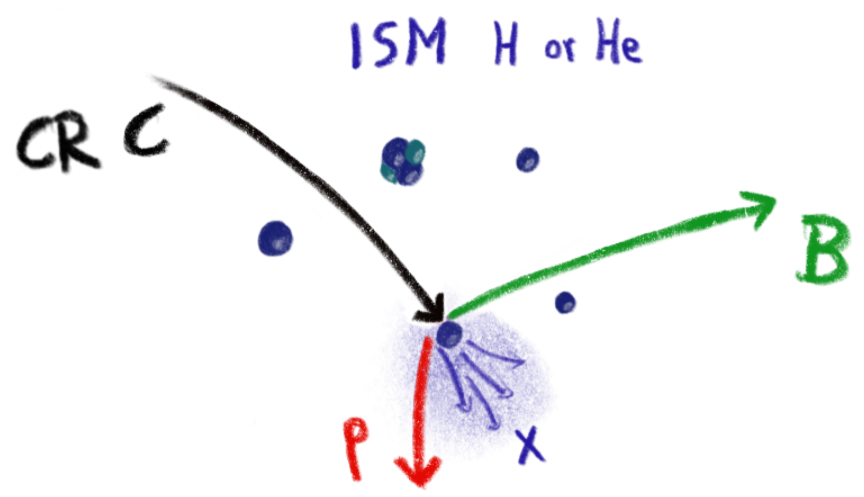
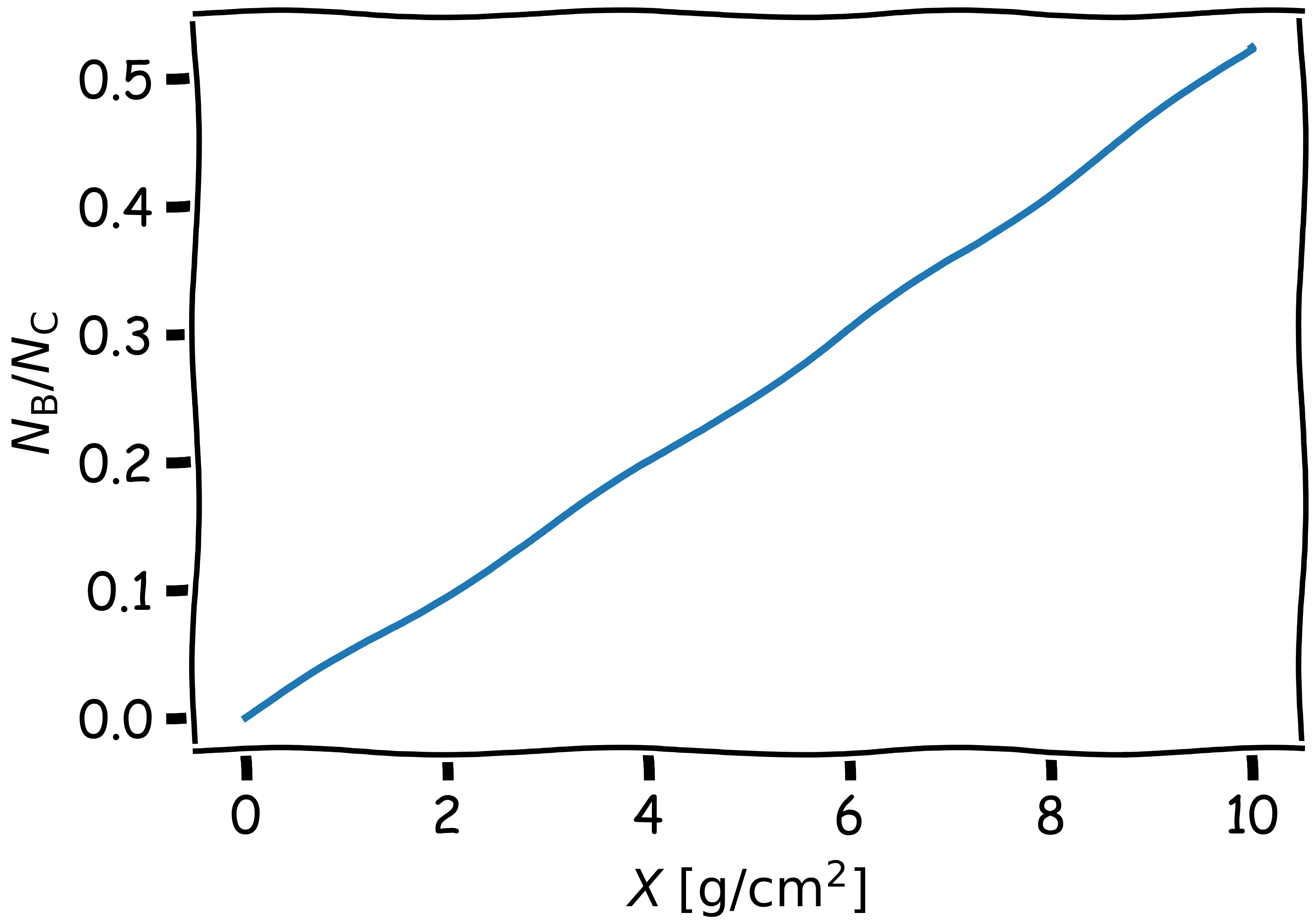

SNR
or Pulsar
CR C
ISM H or He
B
P
X
AMS
AMS


10^0
10^{-1}
10^{-2}
10^{-3}
N
0
10
20
30
40
50
X [g/cm^2]
C
B

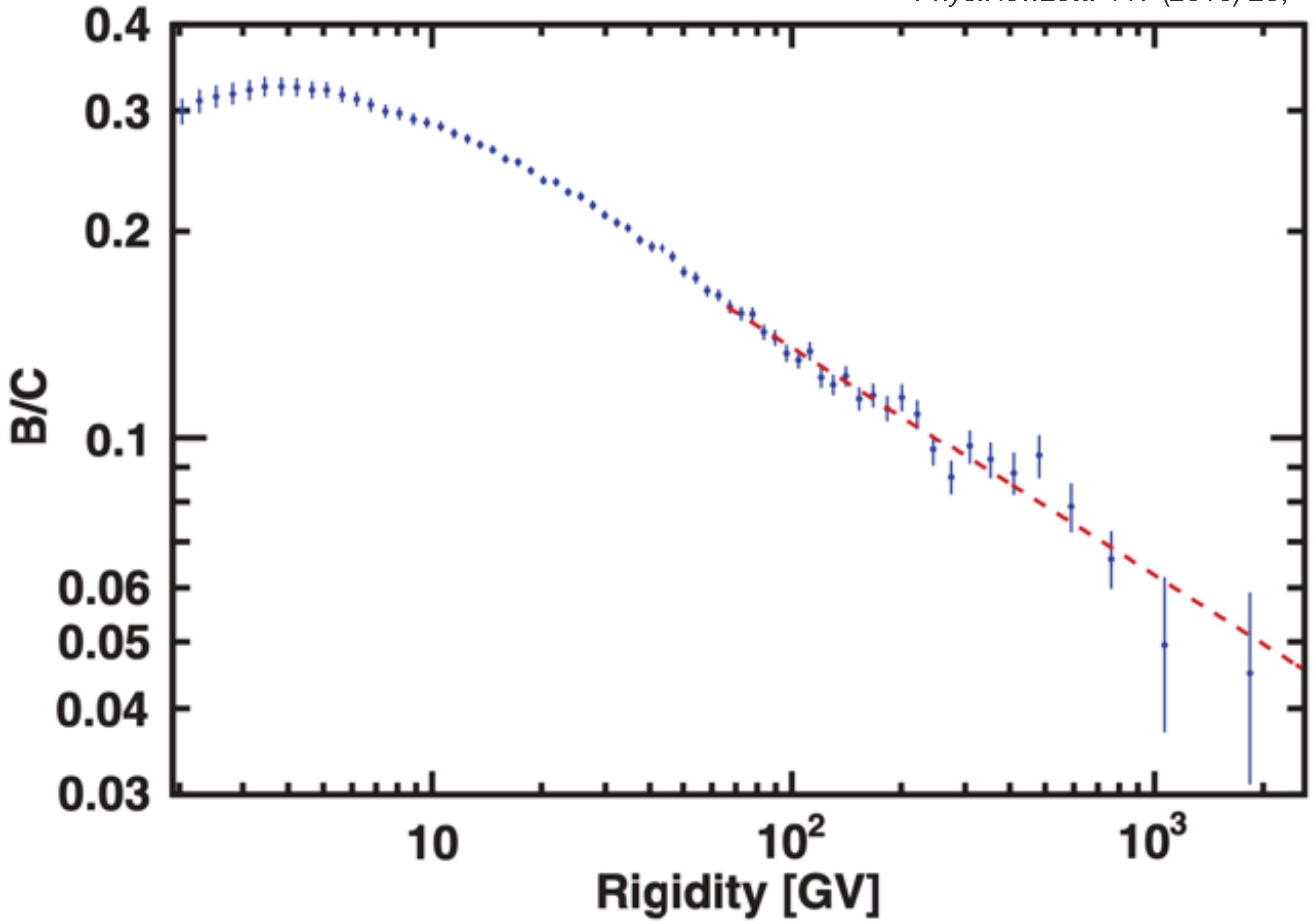
Gramage







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



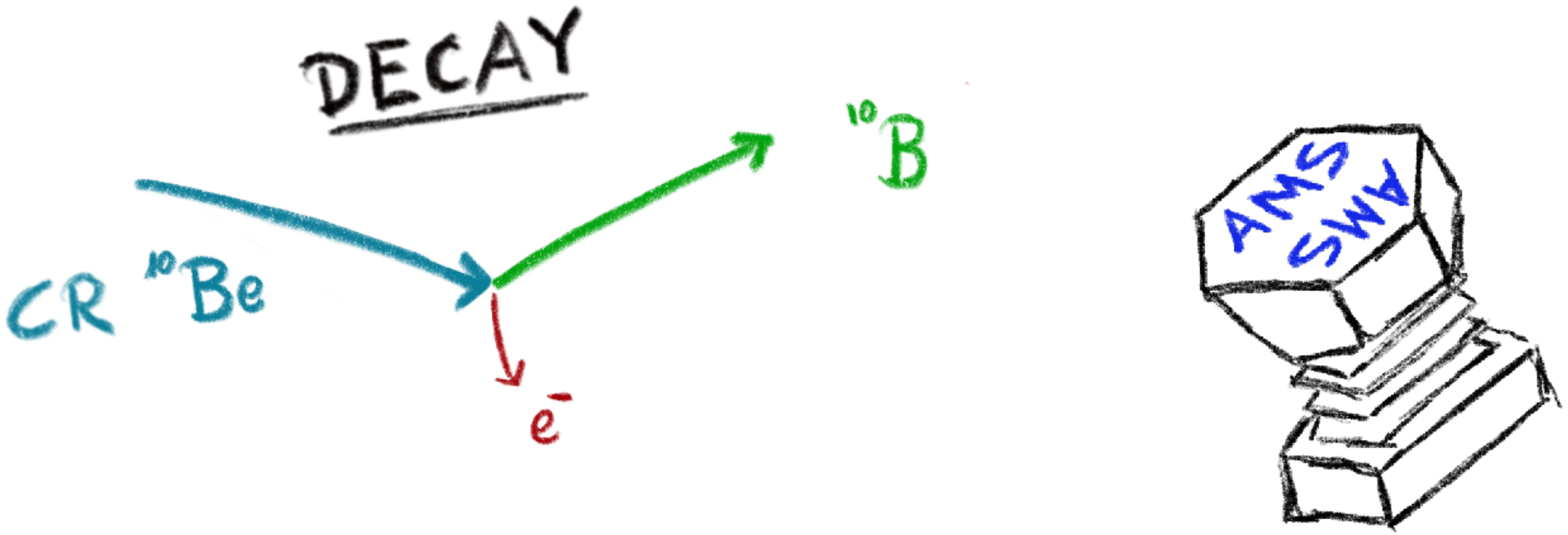
$$\mathrm{B/C} \sim 0.3 \qquad \text{(at 10 GV)}$$

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

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

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

Cosmic-Ray Clocks



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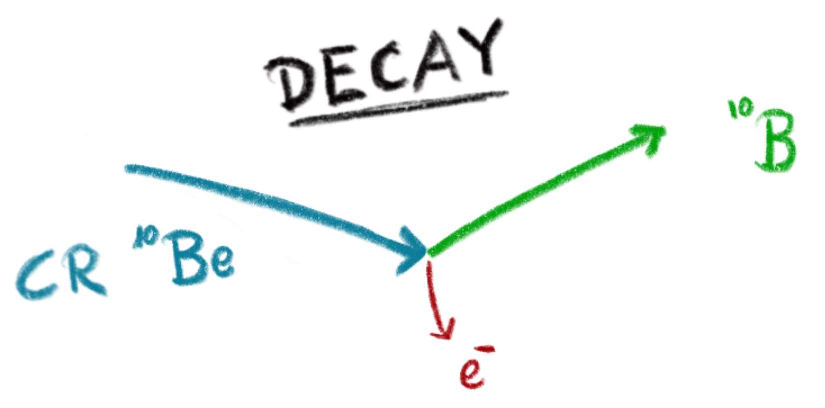
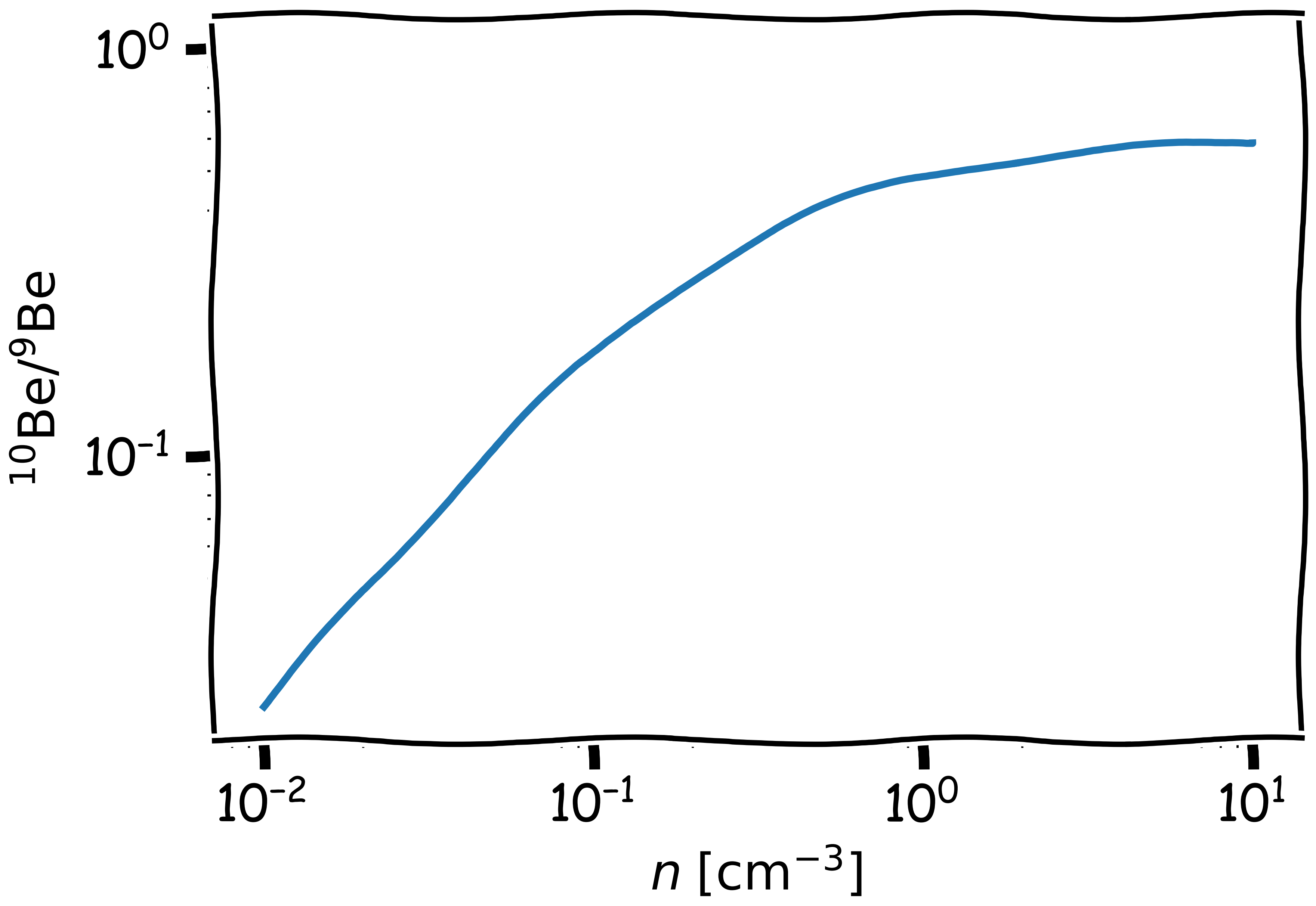


The Leaky Box Model

	Production	Loss by Escape	Loss by Interaction	Loss by Decay
^{9}Be	✅	✅	✅	❌
^{10}Be	✅	✅	✅	✅



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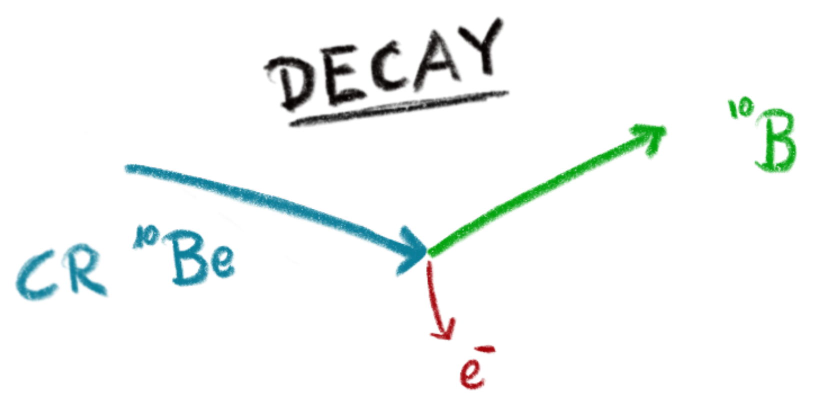

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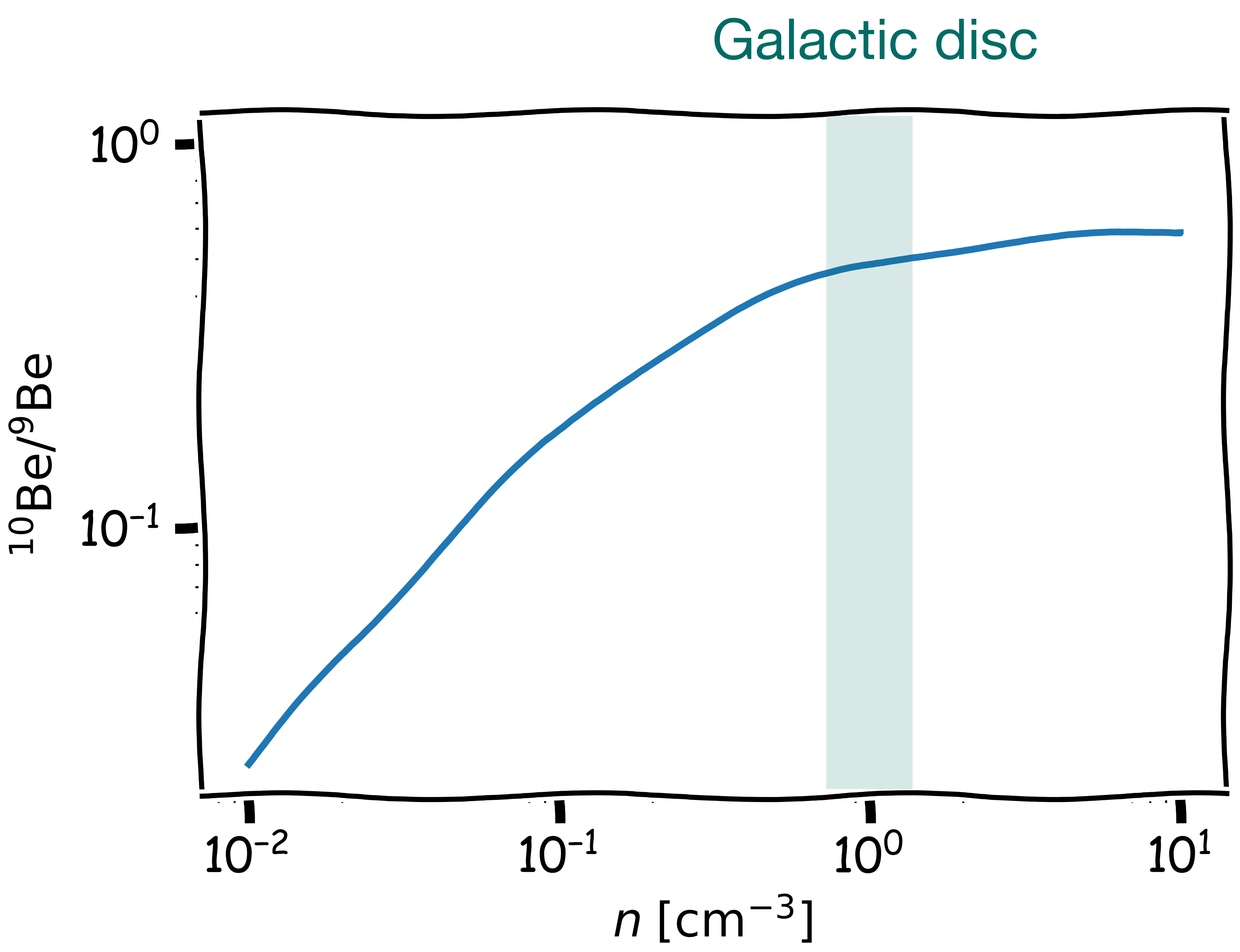

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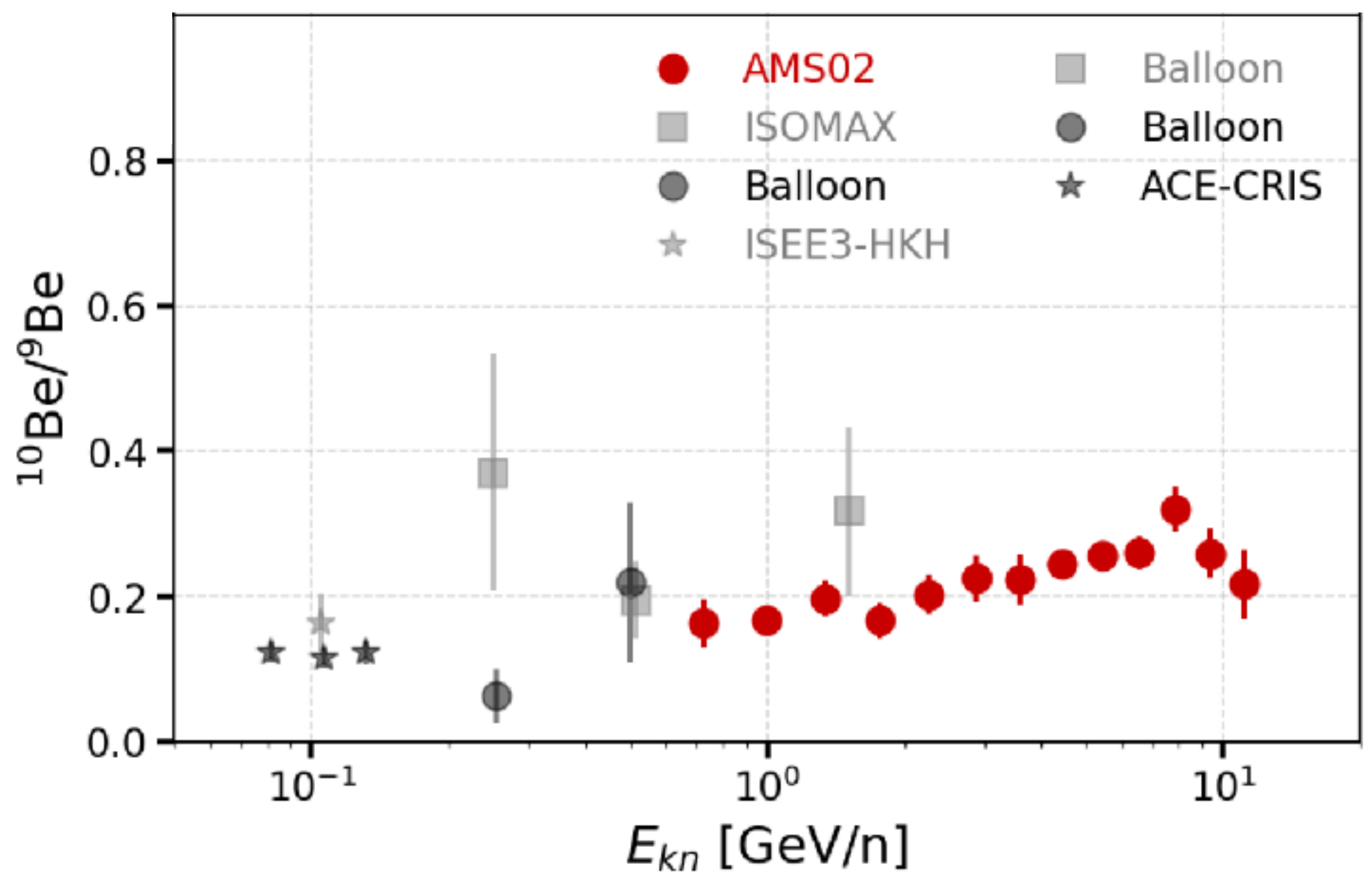

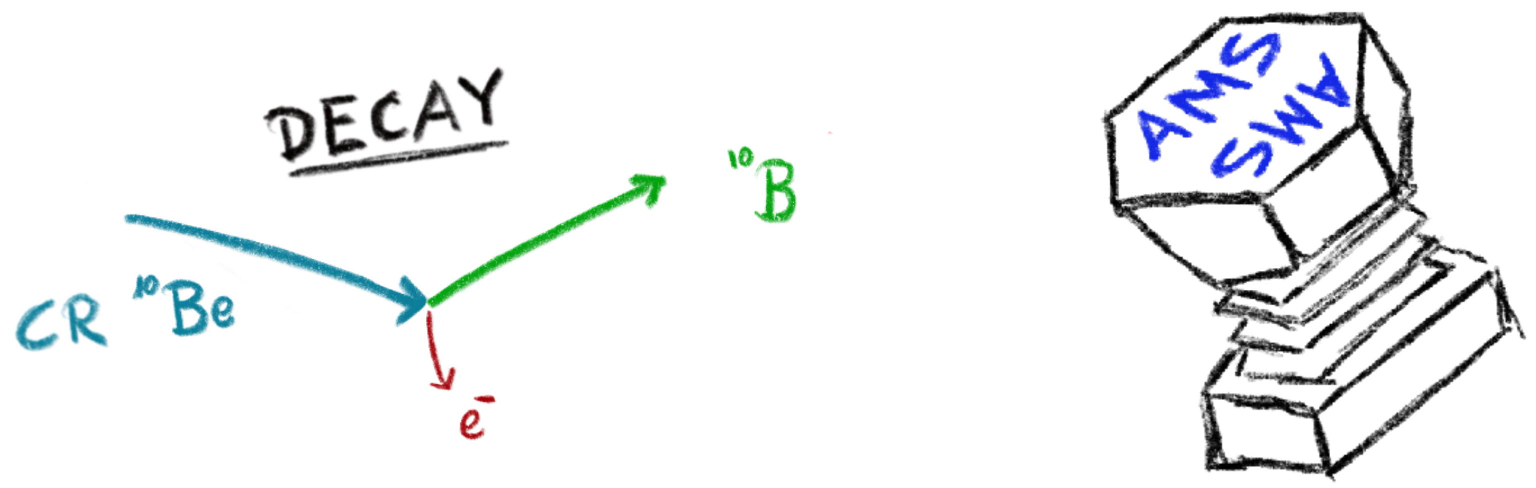

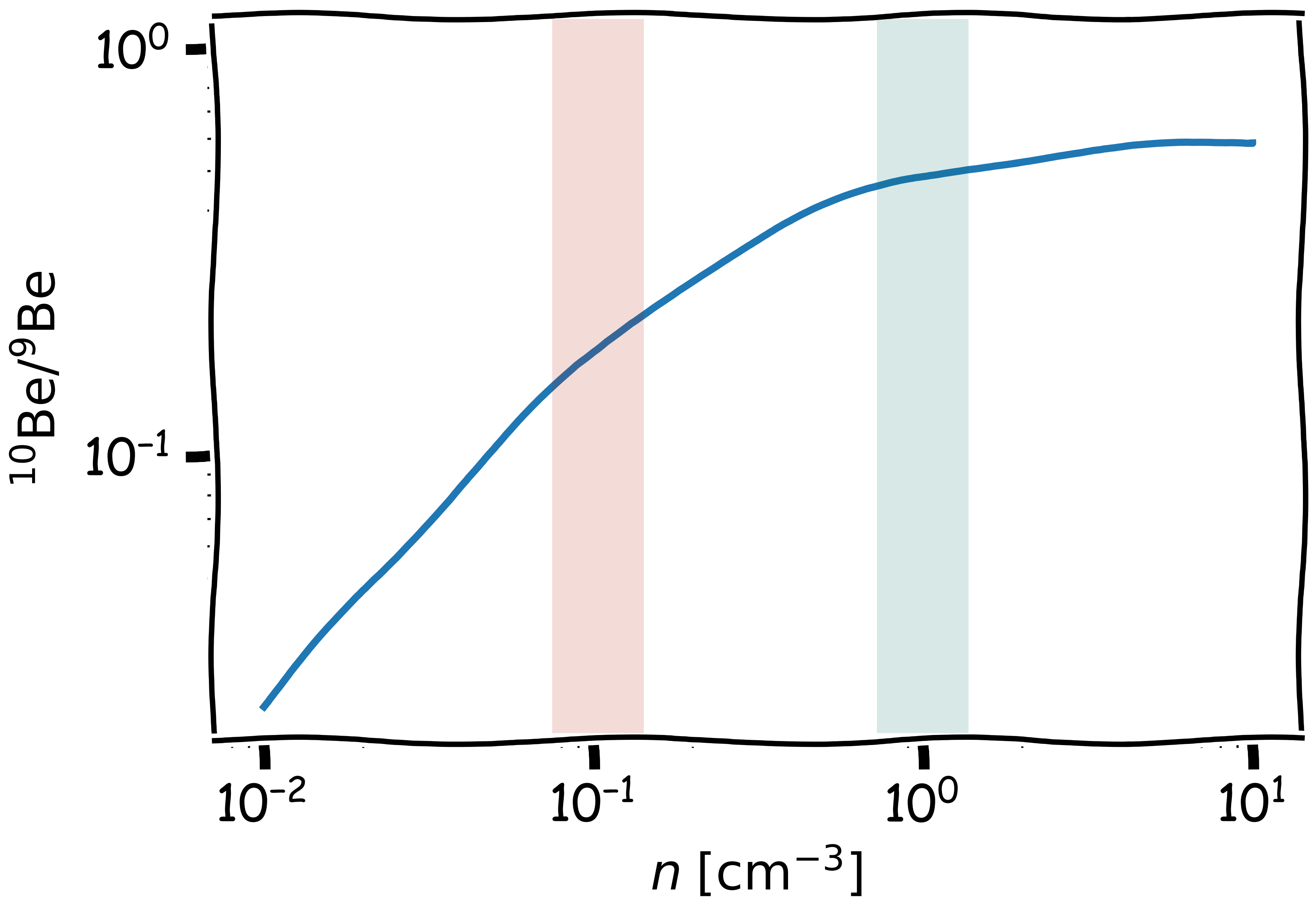

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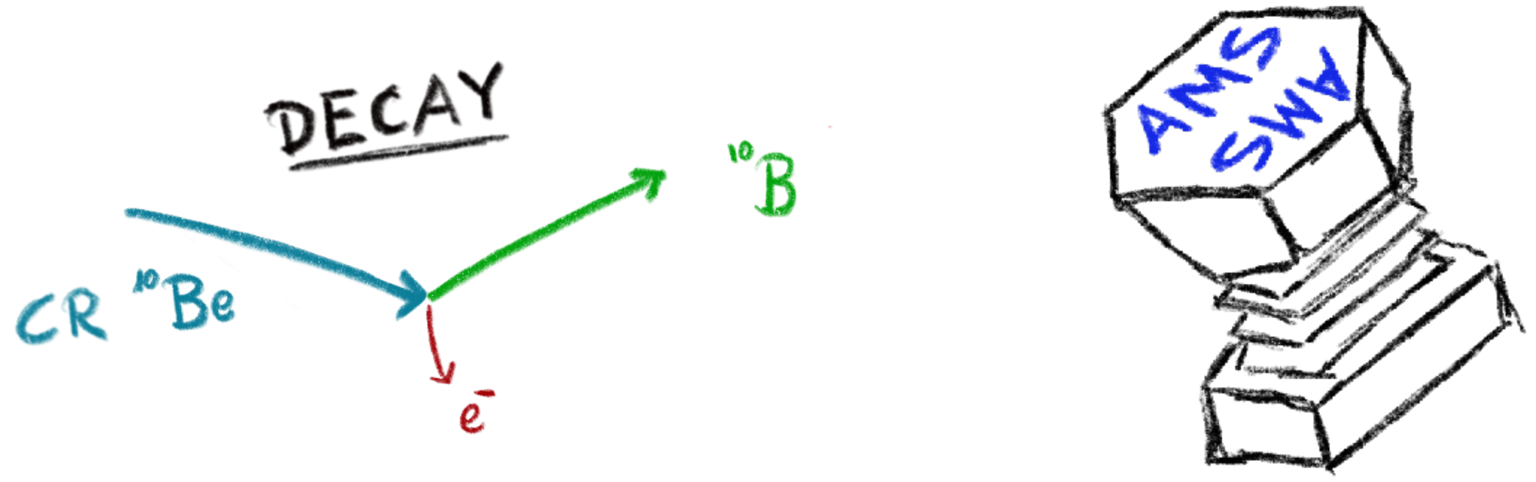
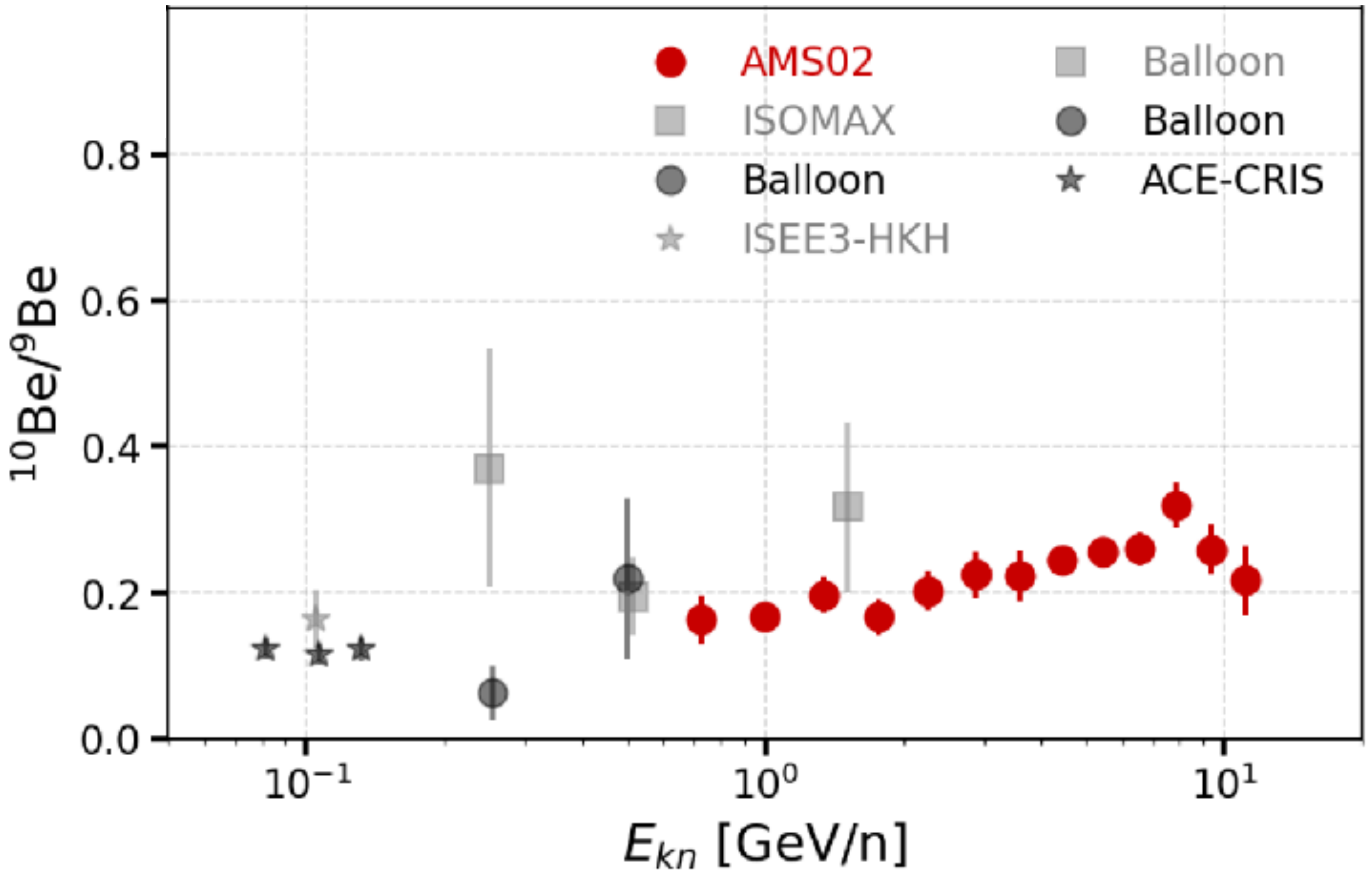
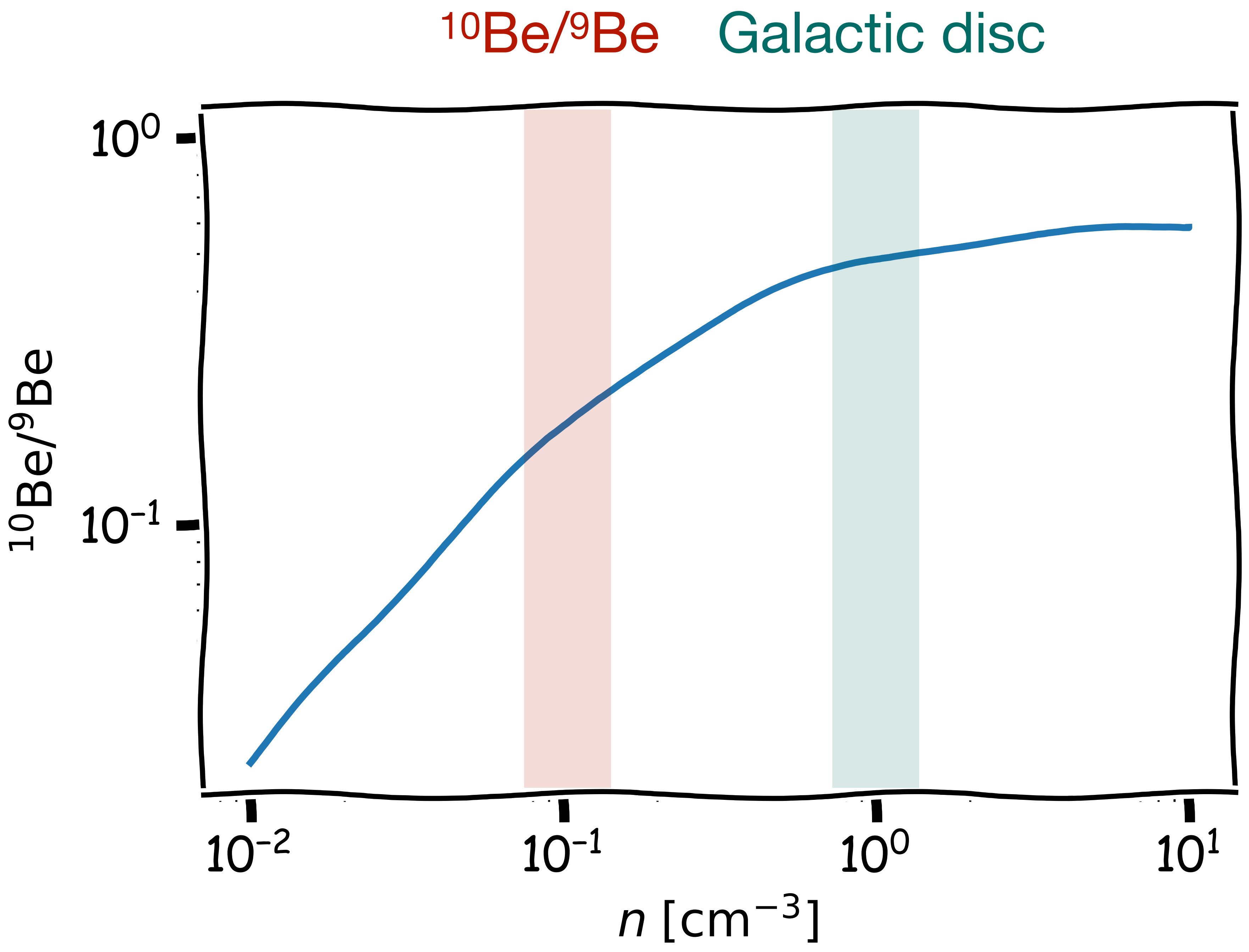
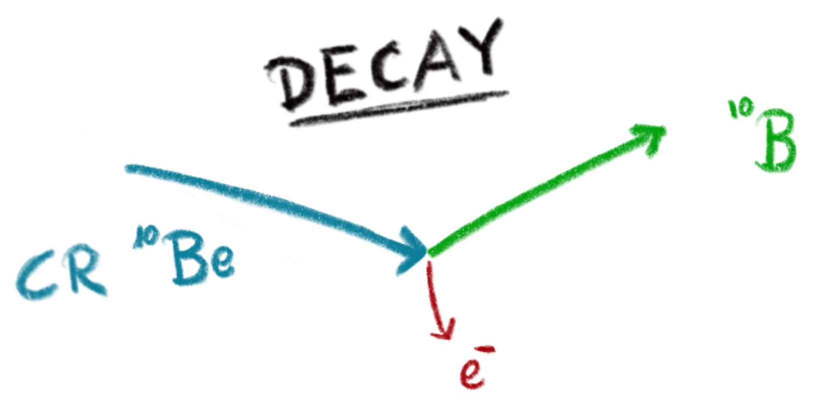


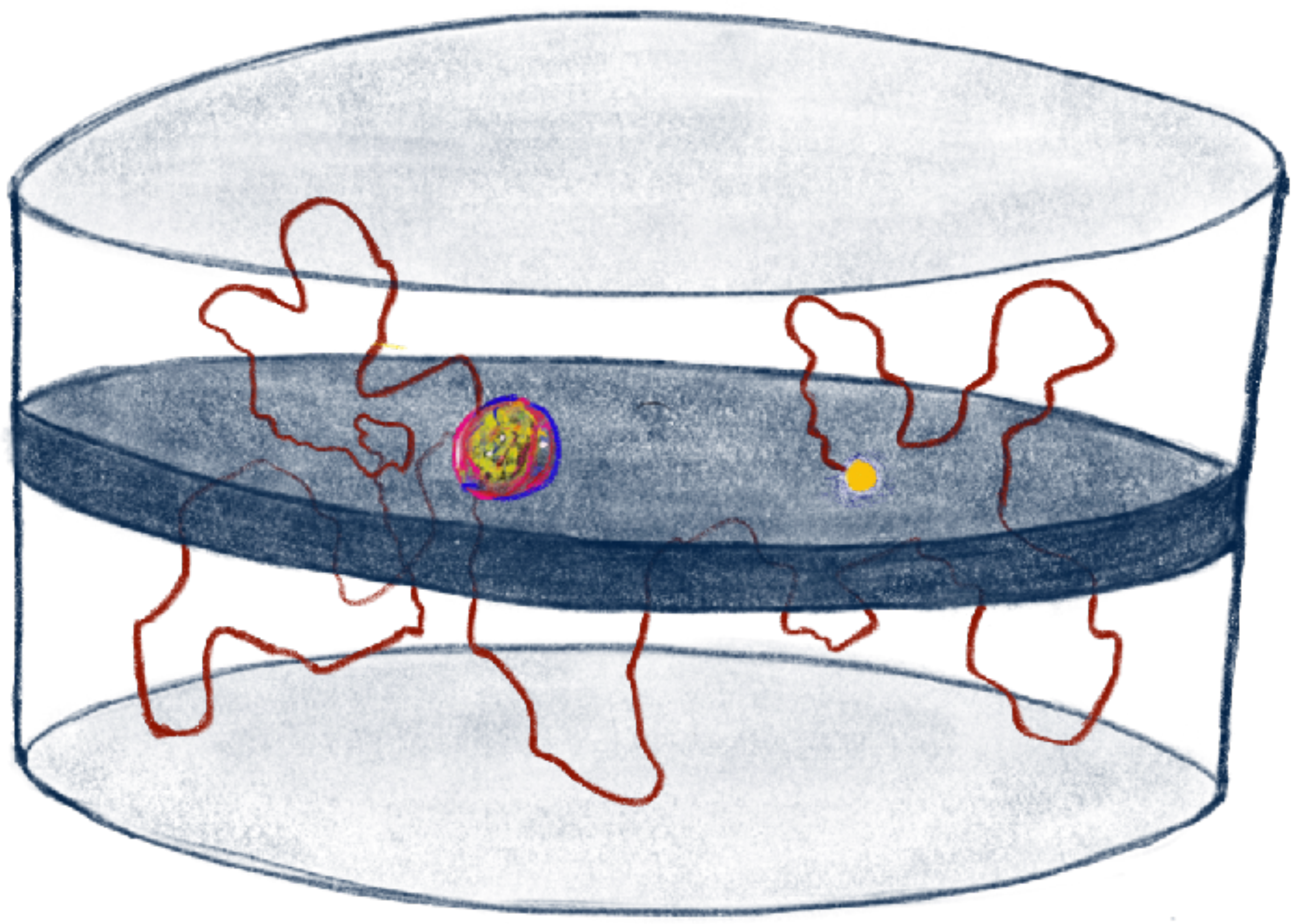




CRs spend a significant time outside the Galactic disc!

Cosmic-Ray Clocks





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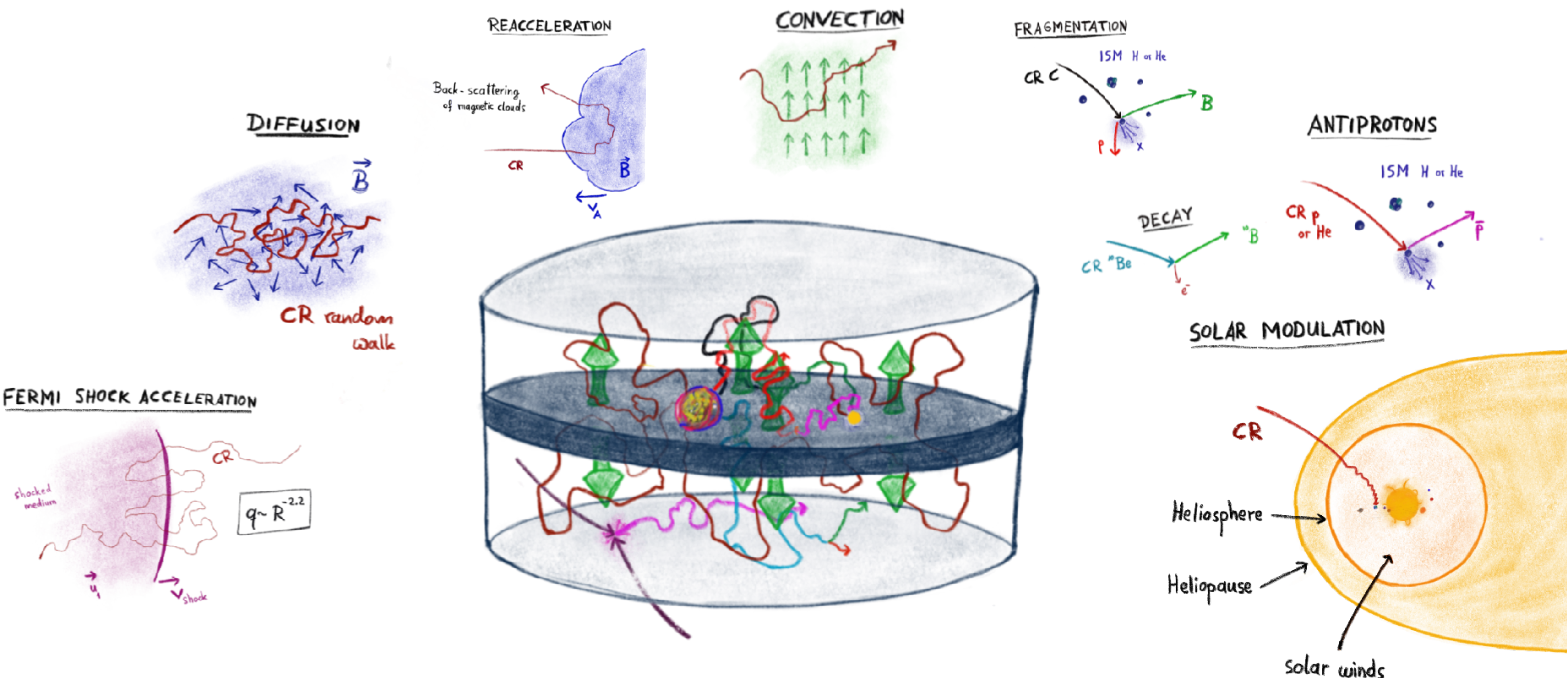
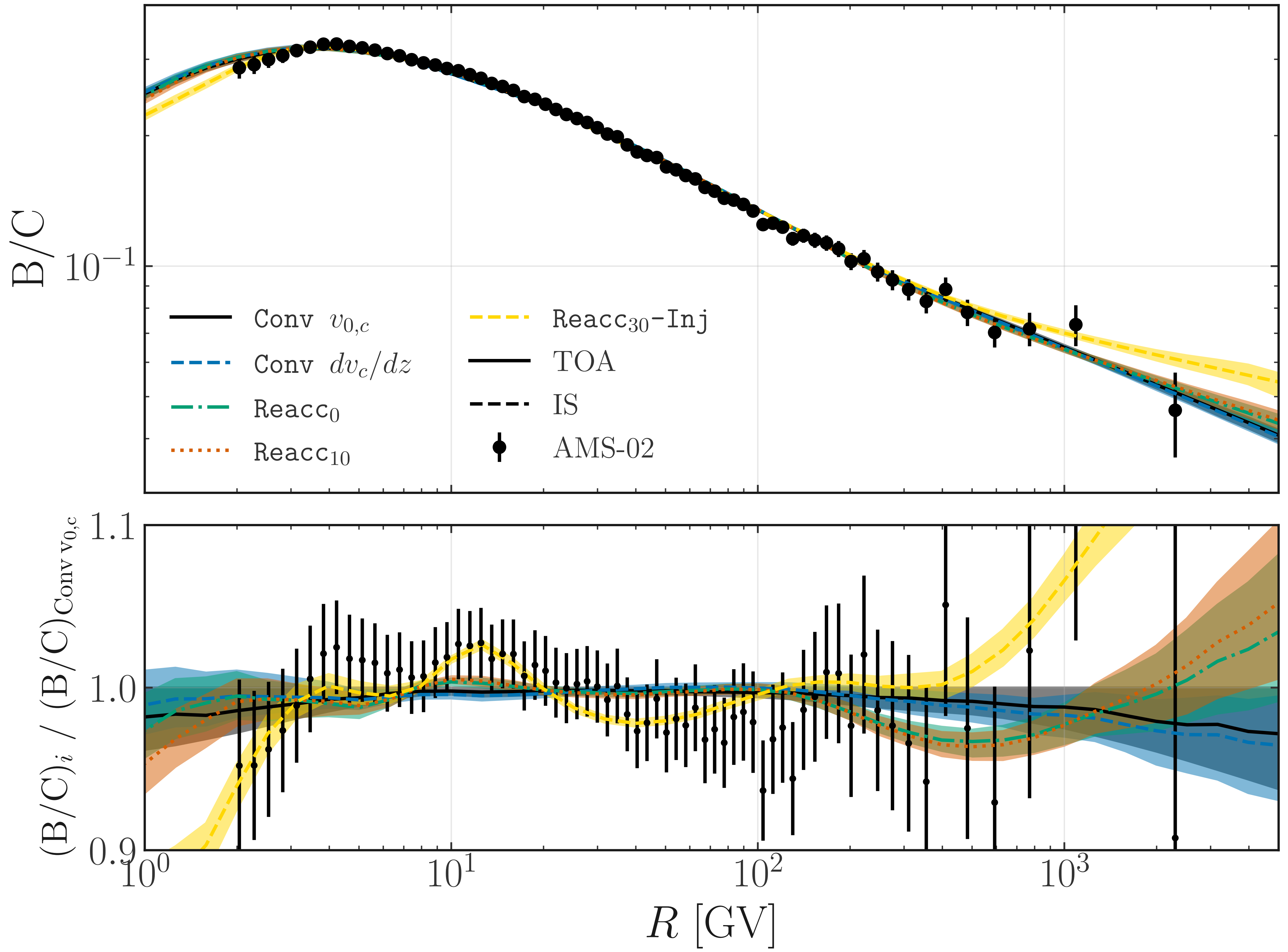
Modeling Cosmic-Ray Propagation



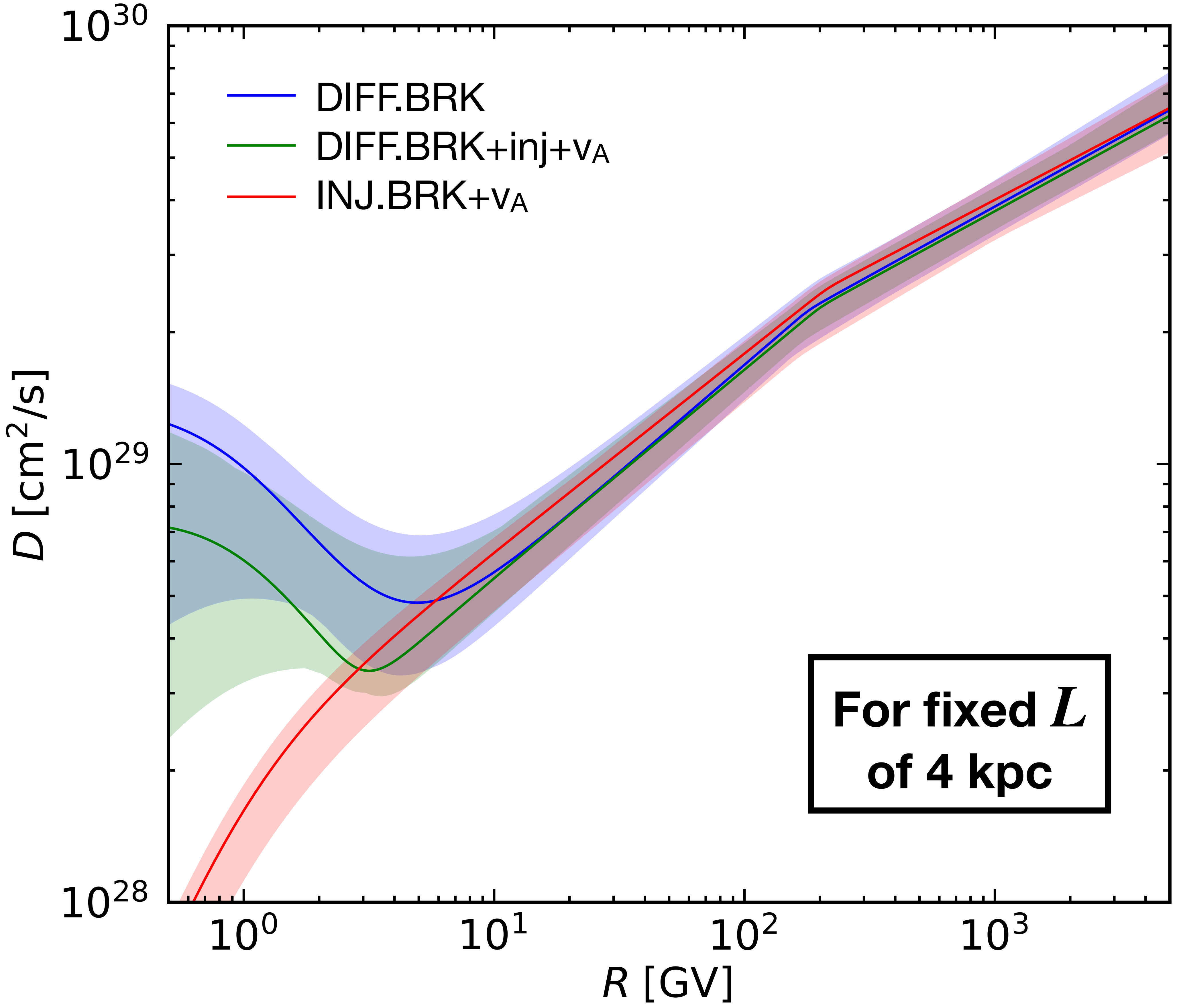
Diffusion Equation of Cosmic Rays

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

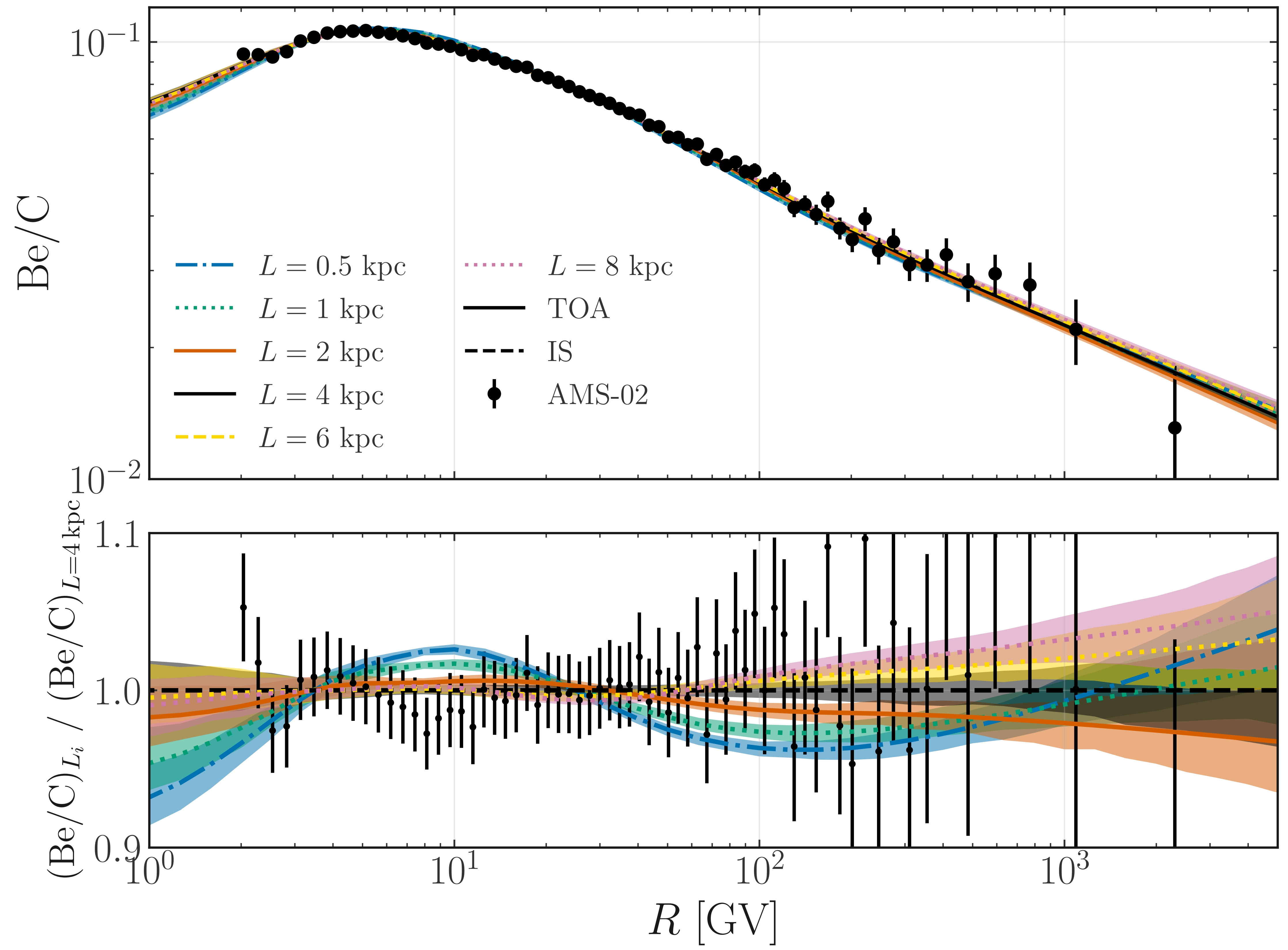


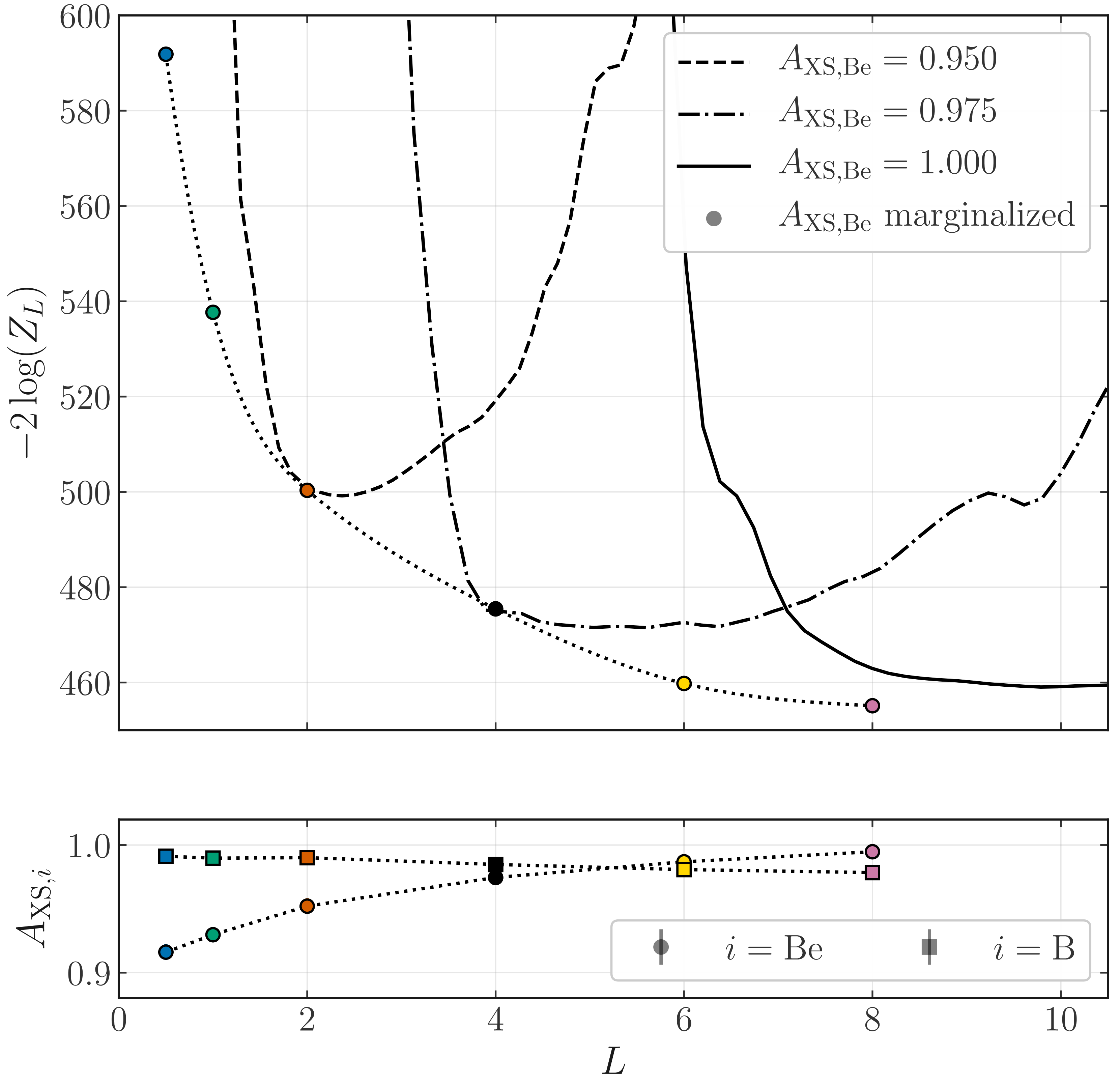
[Di Mauro, MK, et al. 2023]



[MK, Cuoco, 2021]

Cosmic-Ray Clocks constrain the Halo Size

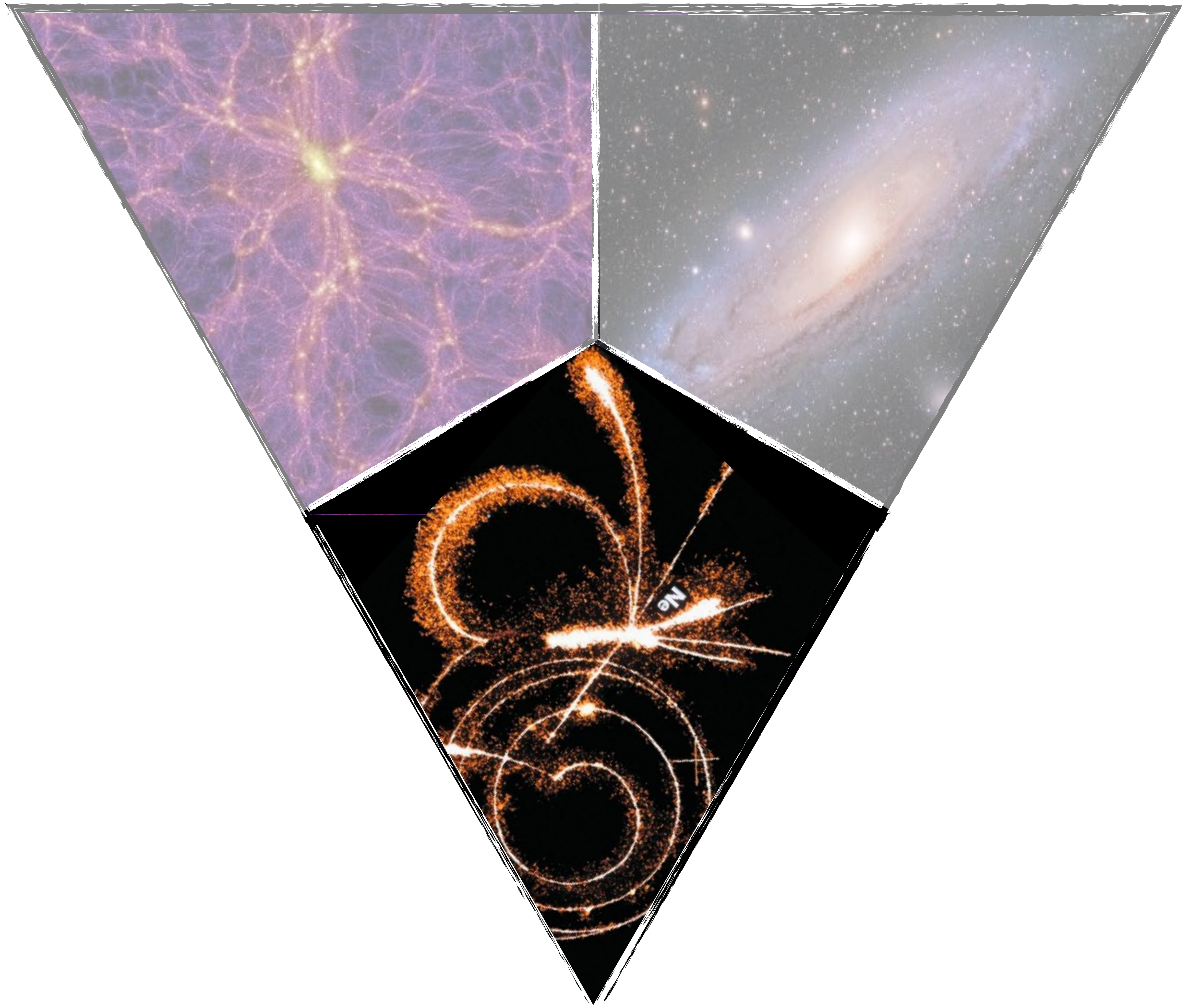




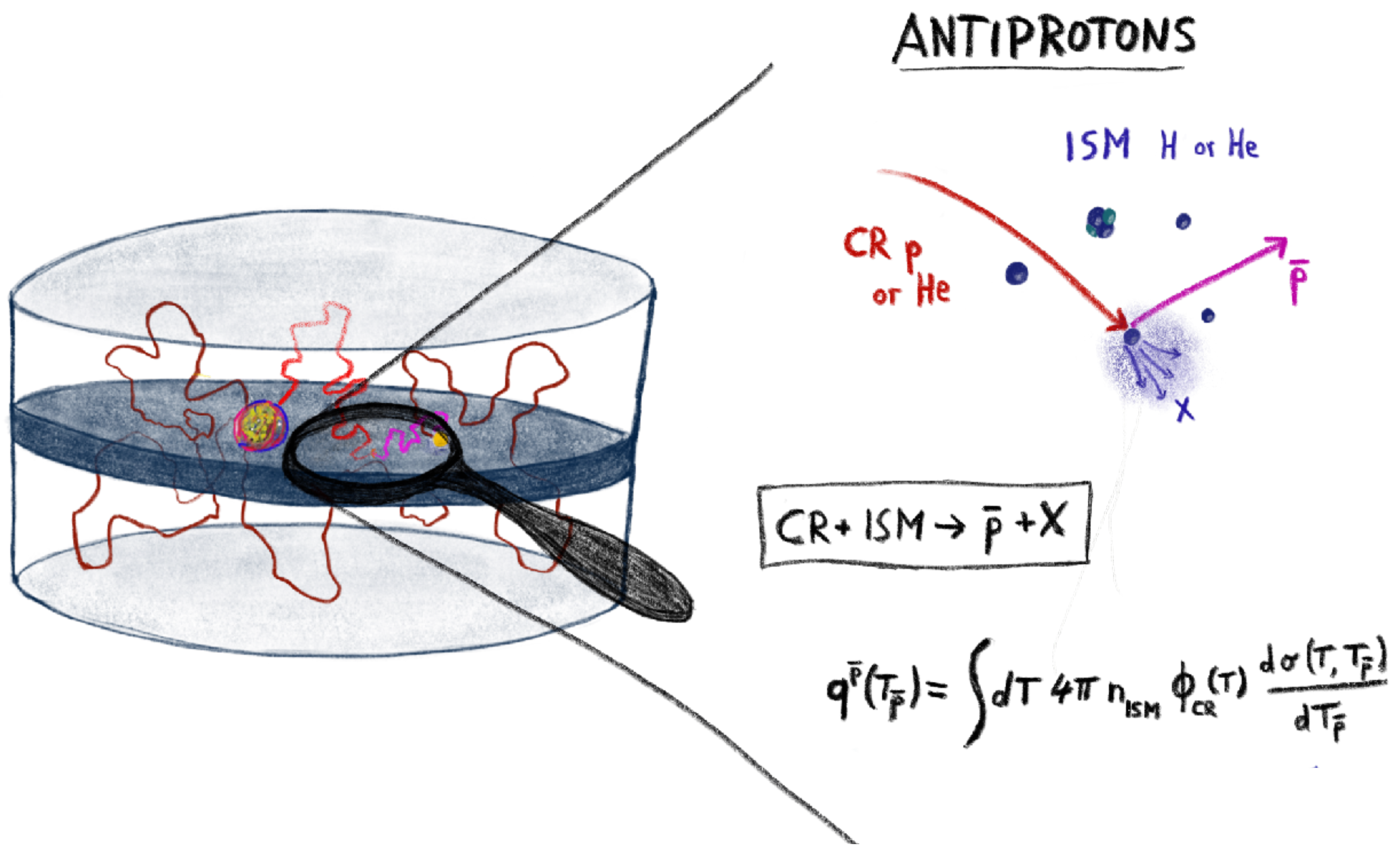
[Di Mauro, MK, et al. 2023]

Dark Matter

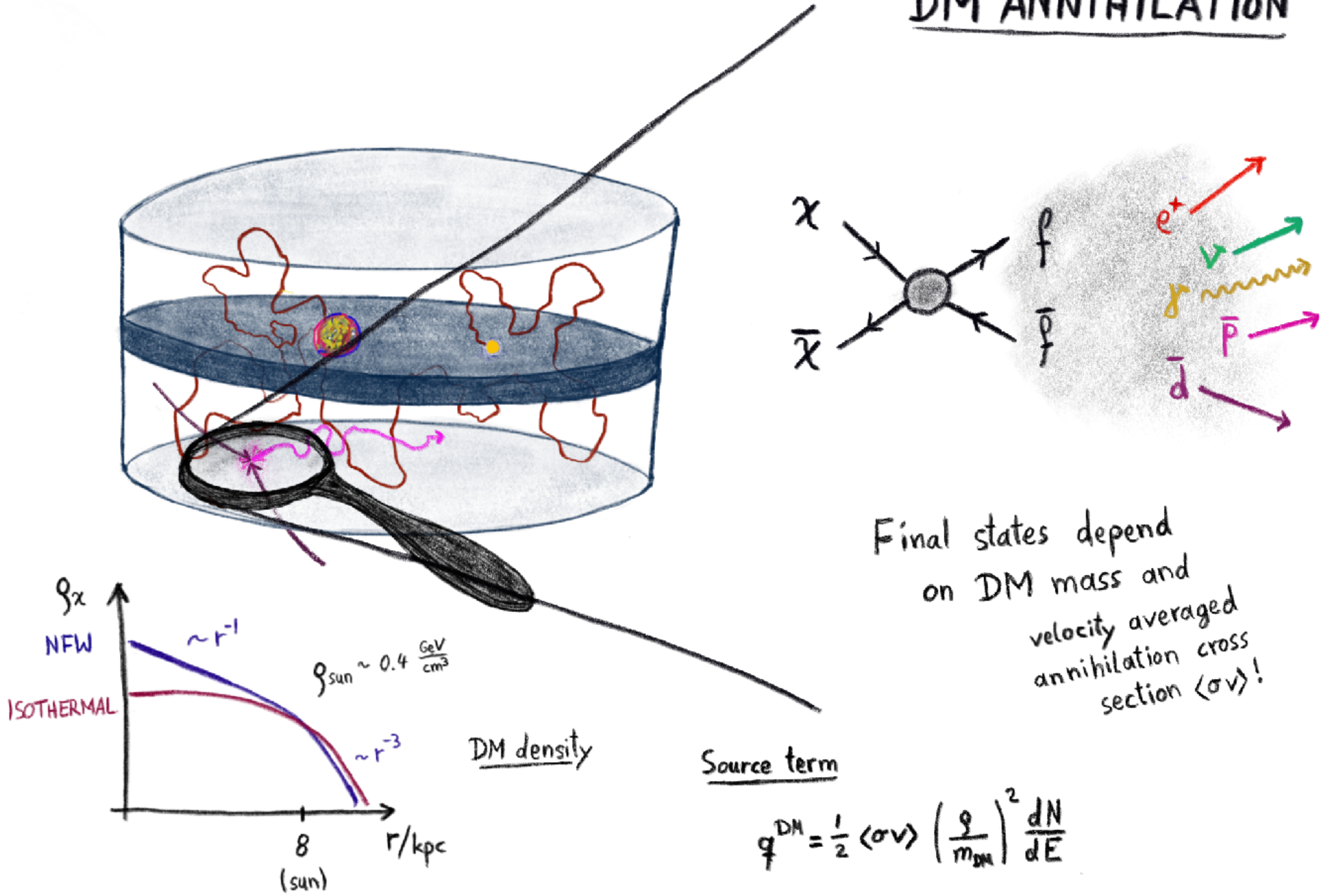
Cosmic Rays



Antimatter


ANTIPROTONS
ISM H or He
CR p or He
$\bar{p}$
X
CR+ ISM → $\bar{p}$ +X
$q^{\bar{p}}(T_{\bar{p}}) = \int dT \, 4\pi \, n_{ISM} \, \phi_{CR}(T) \, \frac{d\sigma(T, T_{\bar{p}})}{dT_{\bar{p}}}$

DM ANNIHILATION

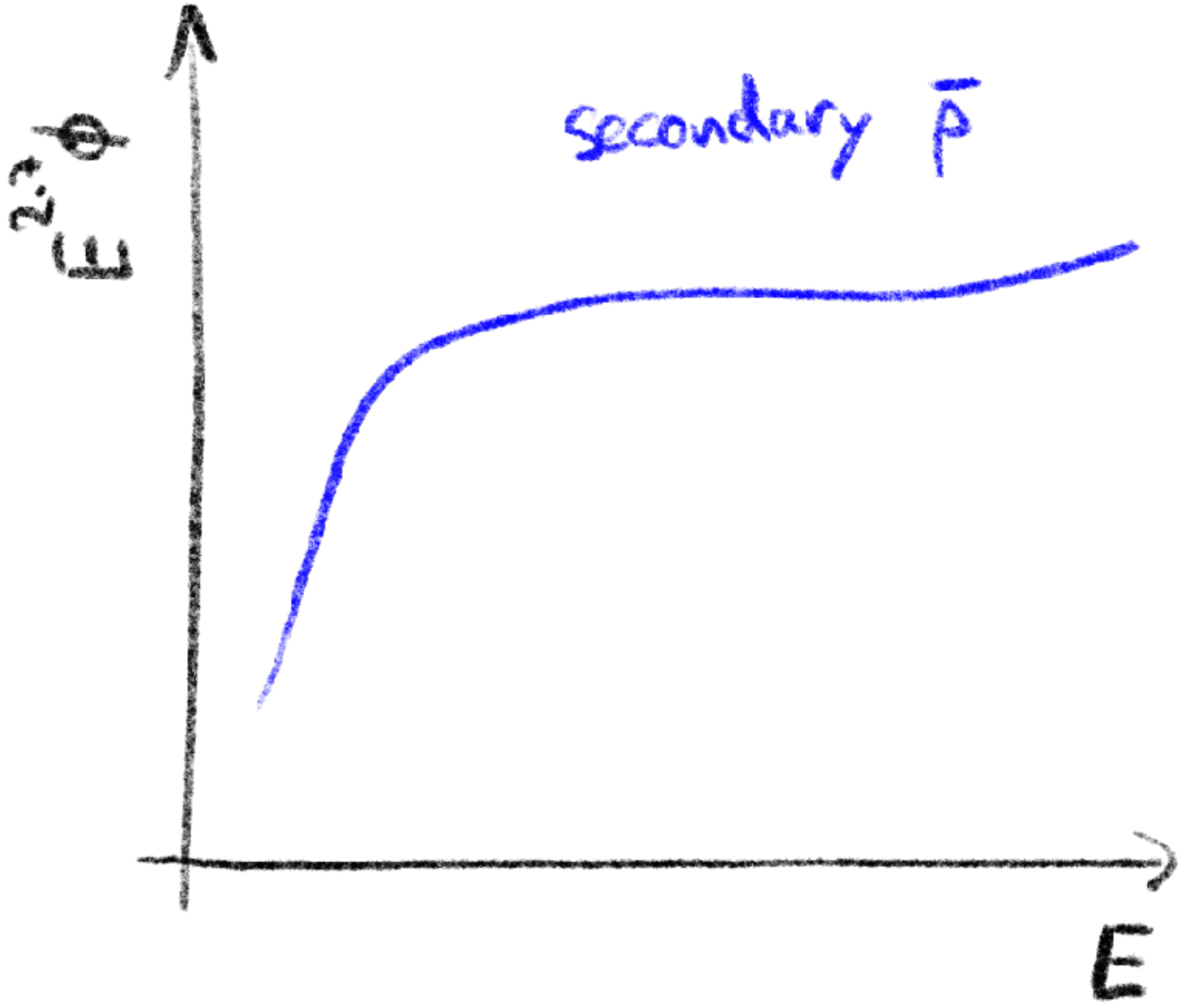


Final states depend on DM mass and velocity averaged annihilation cross section $\langle\sigma v\rangle$!

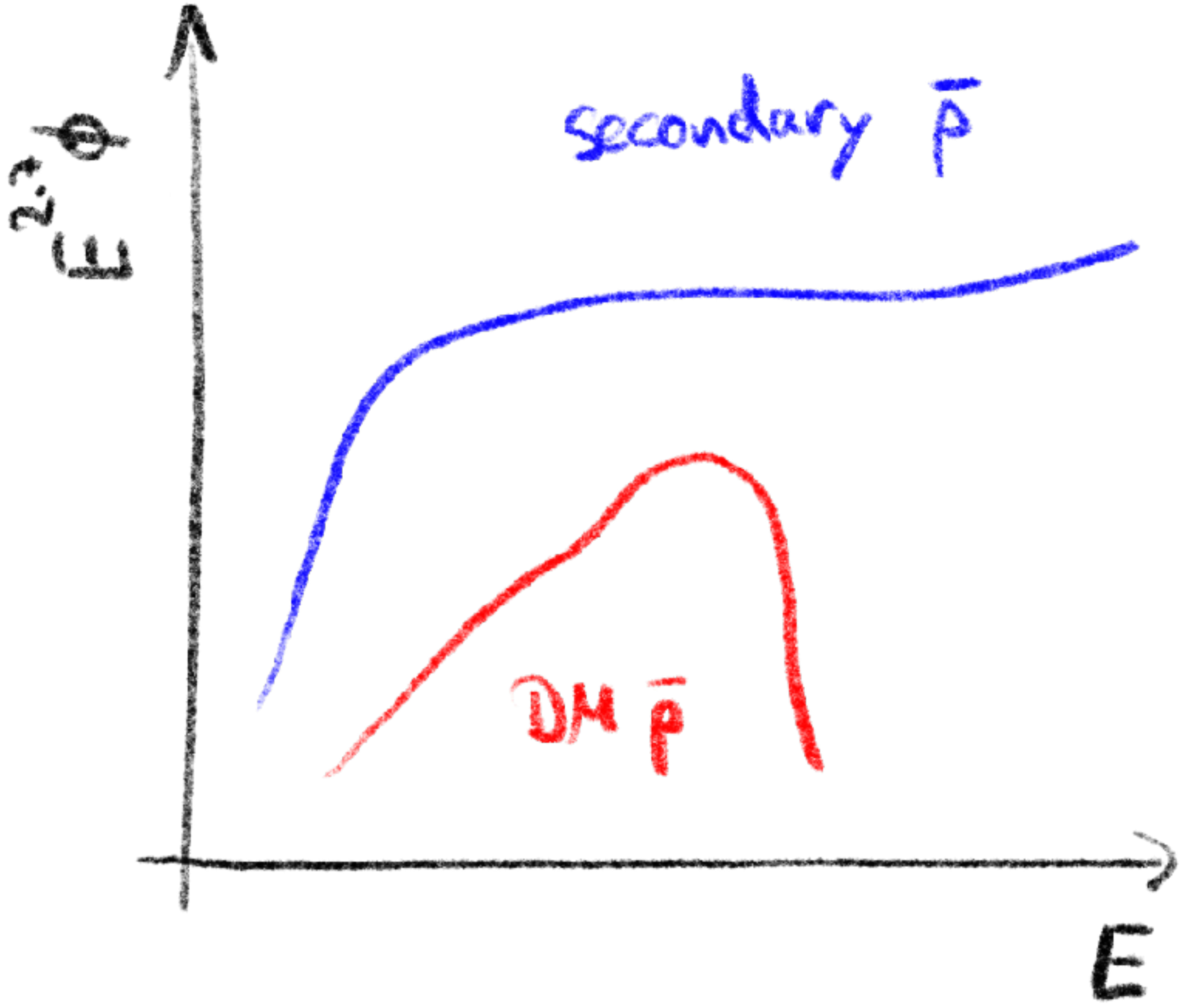
Source term

$$q^{DM} = \frac{1}{2} \langle\sigma v\rangle \left(\frac{\rho}{m_{DM}}\right)^2 \frac{dN}{dE}$$

[Heisig, MK, Winkler, 2000]



[Heisig, MK, Winkler, 2000]



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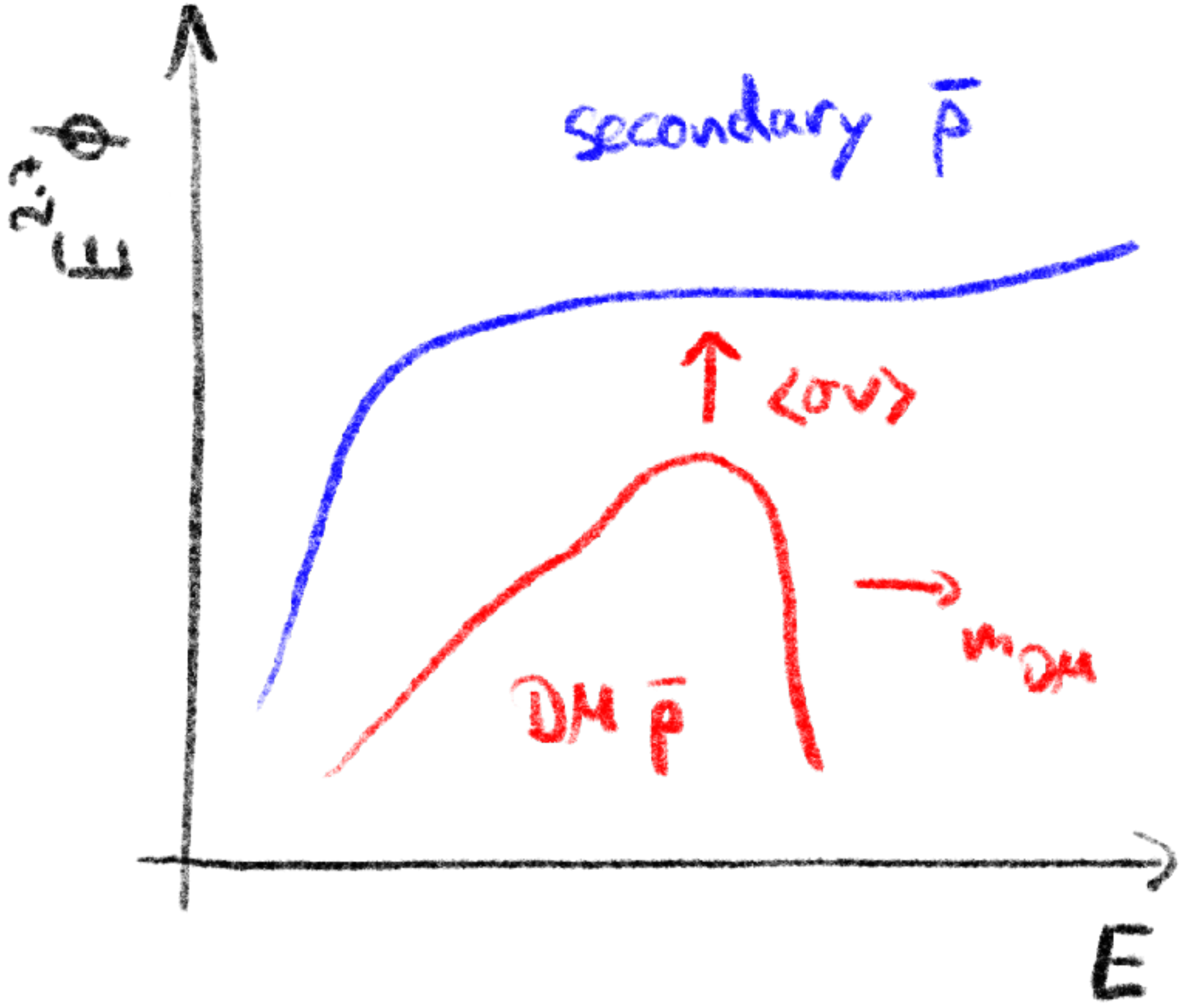

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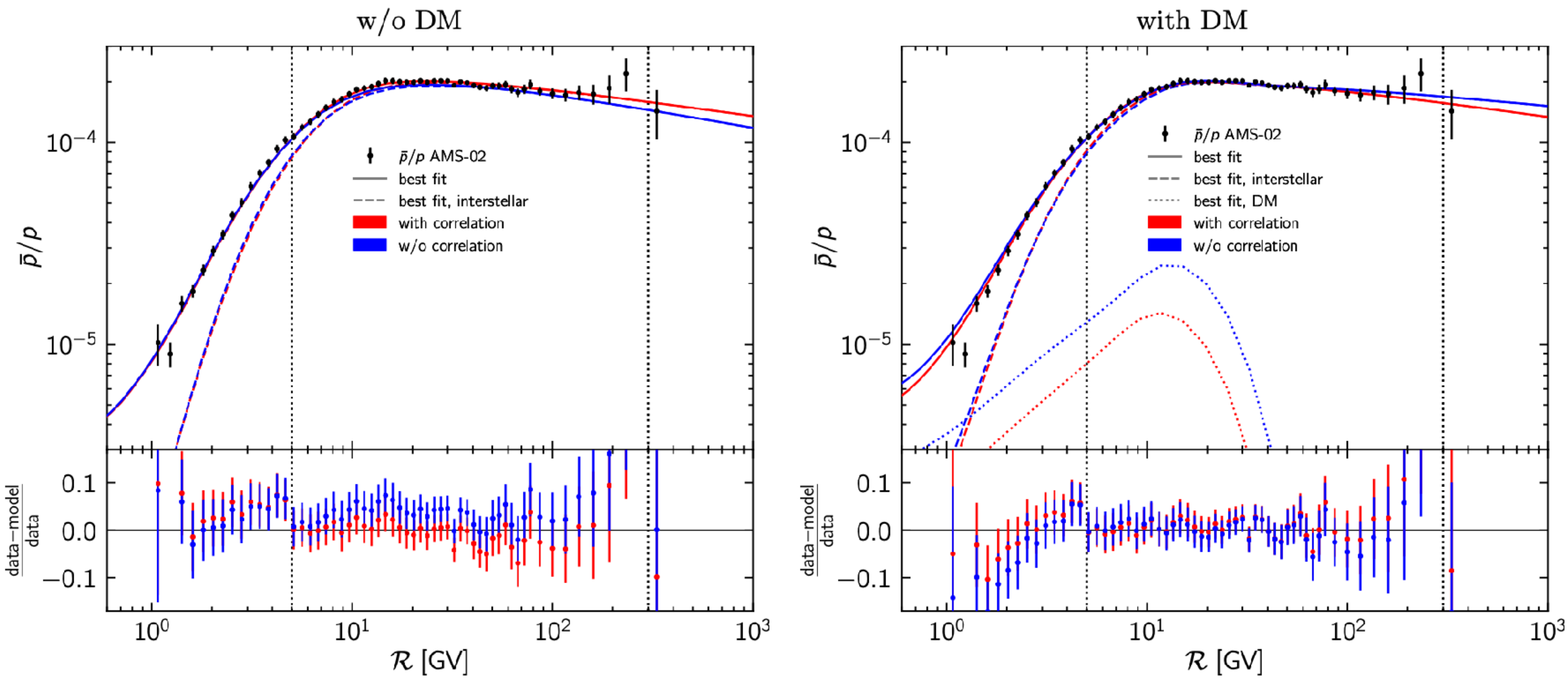
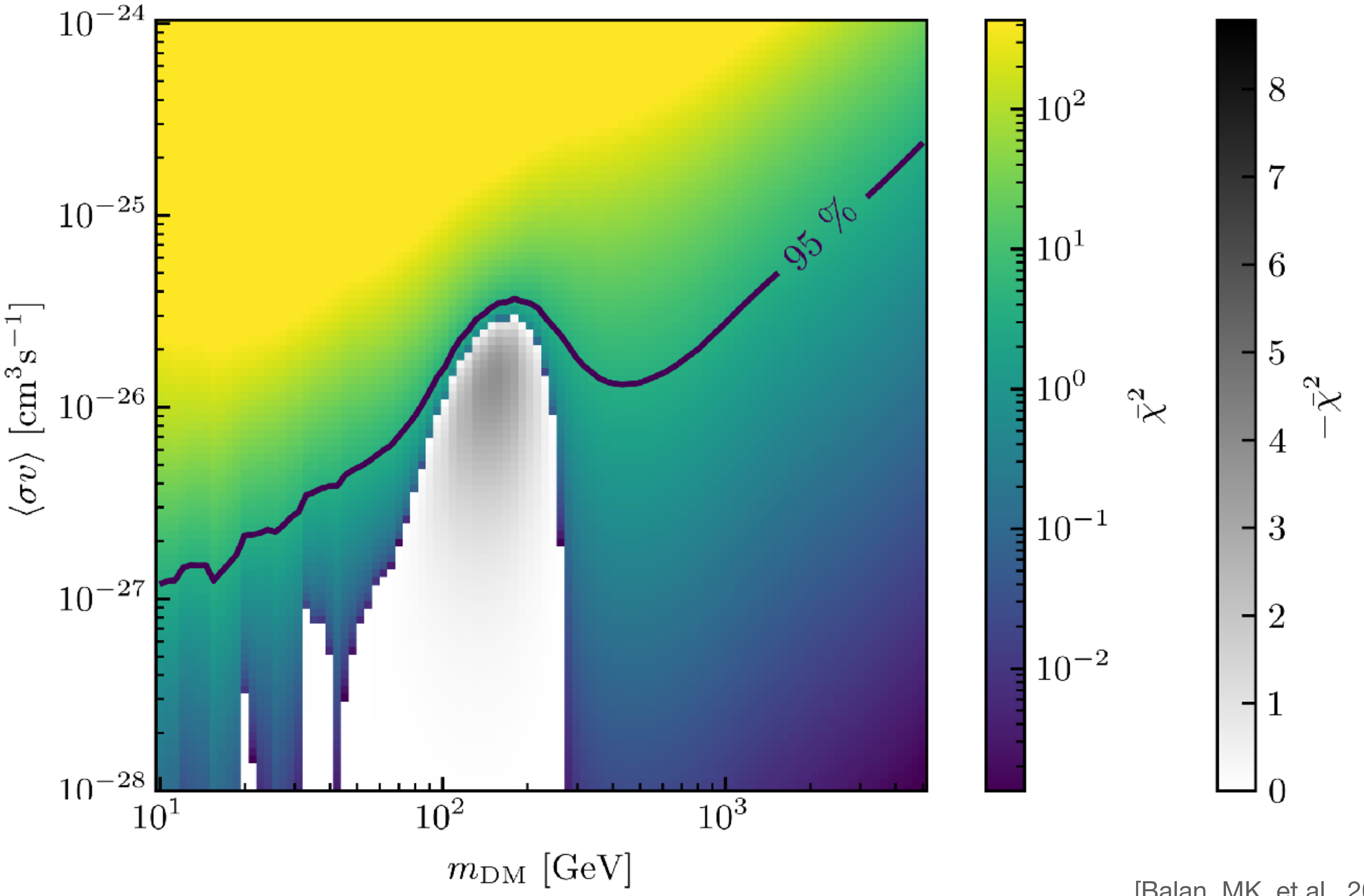


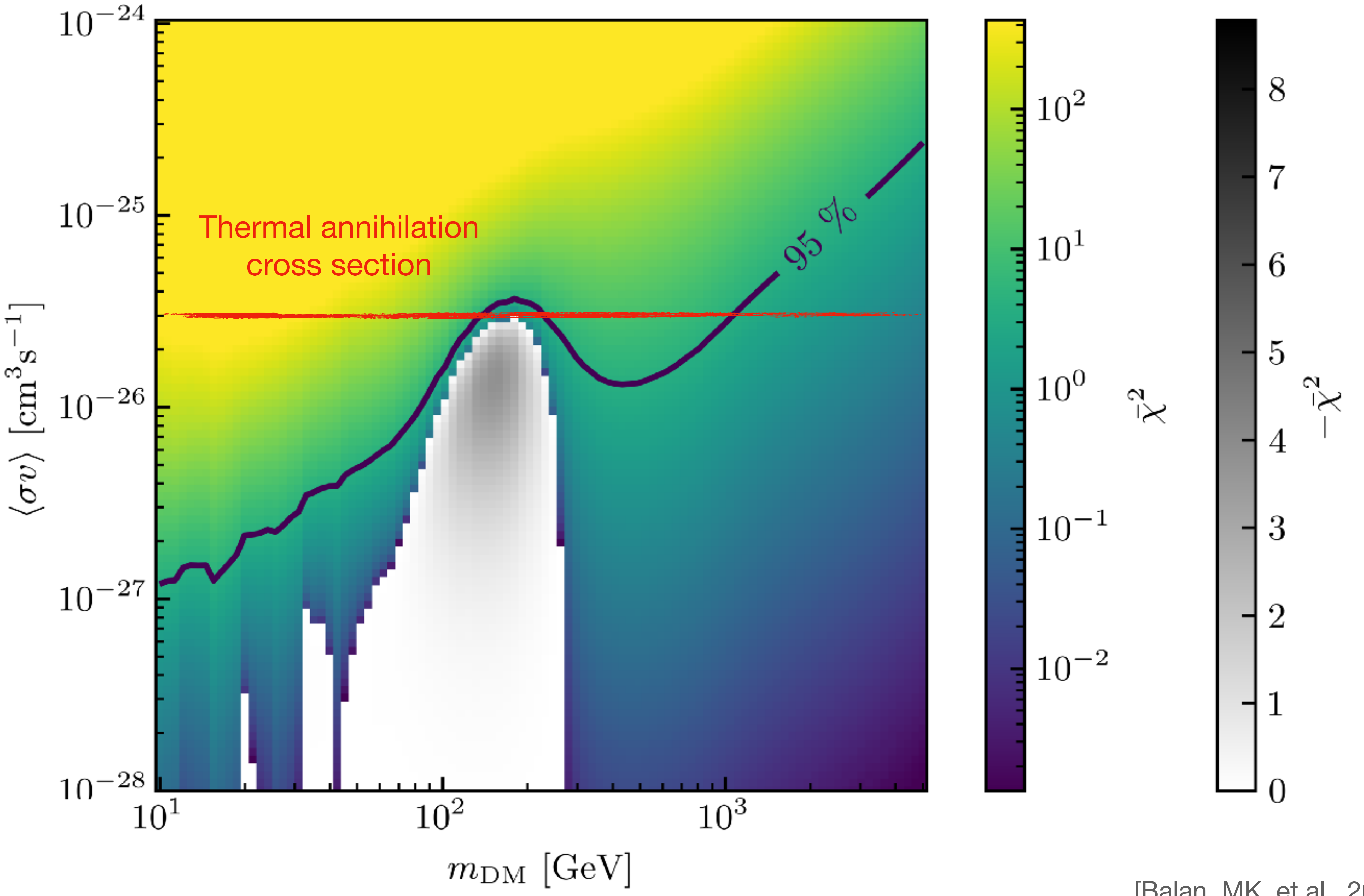
[Heisig, MK, Winkler, 2000]

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



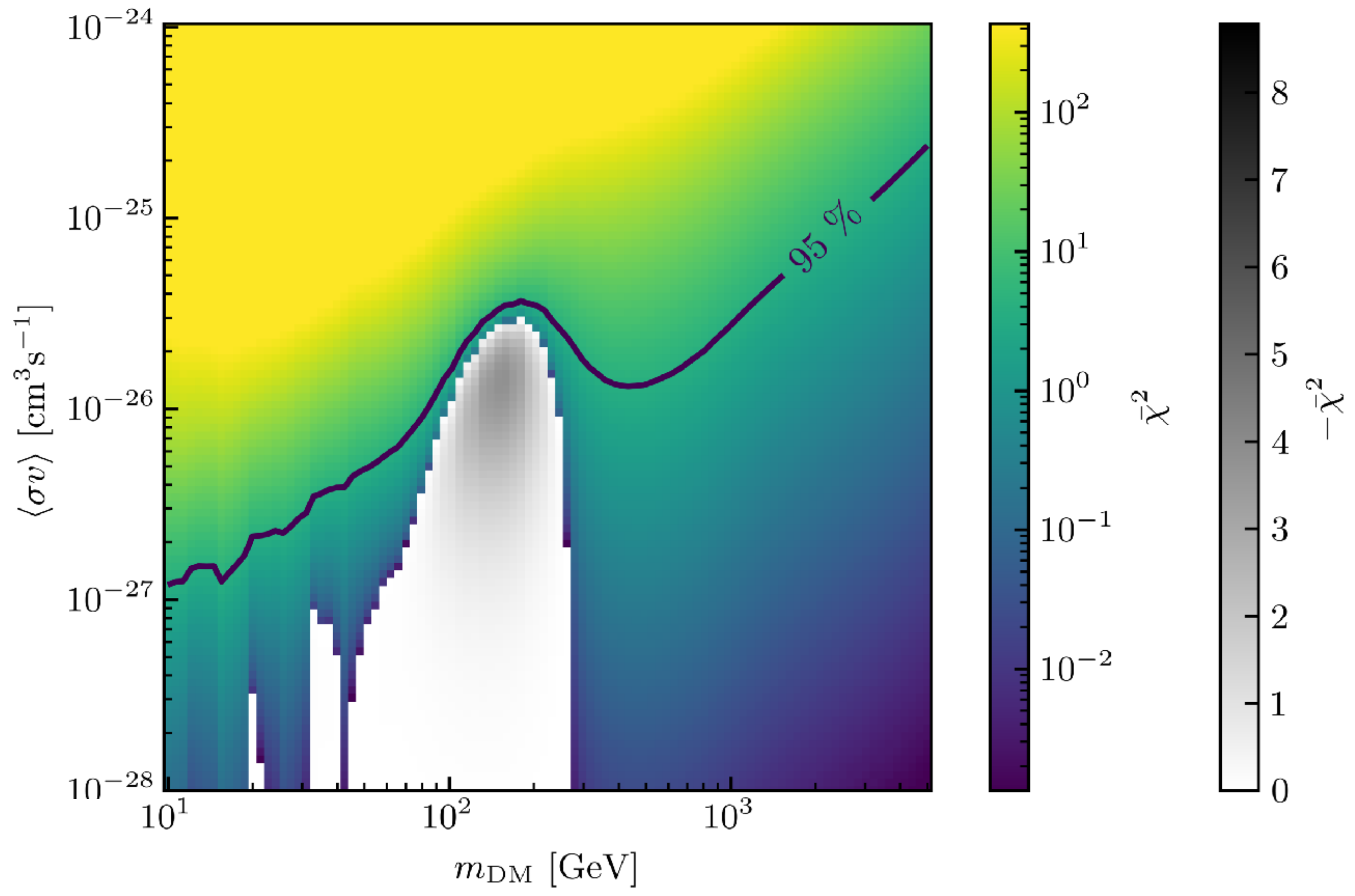
[Balan, MK, et al. 2023]

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



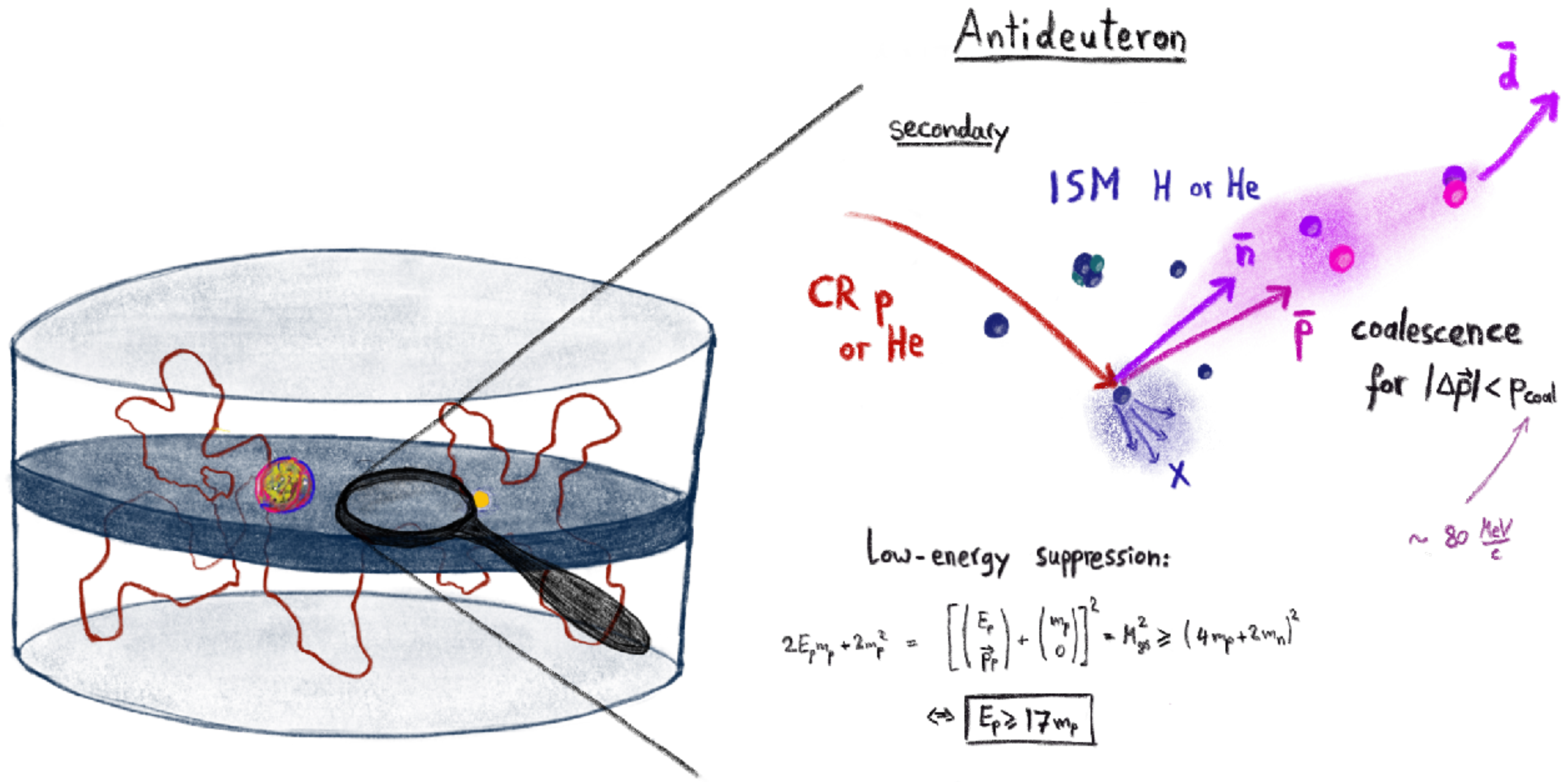
[Balan, MK, et al. 2023]

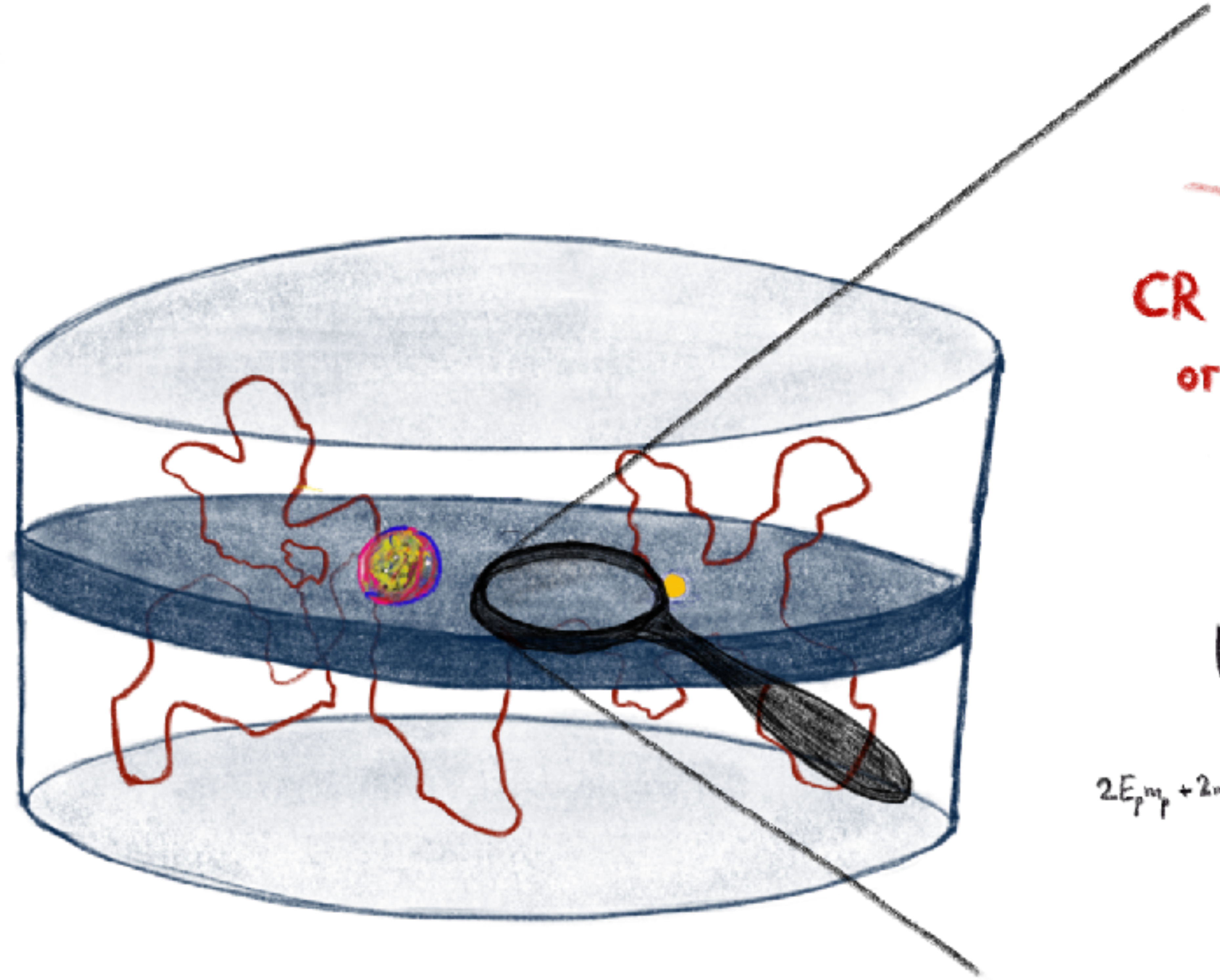
DM limit for DM annihilation into a pair of *b* quarks



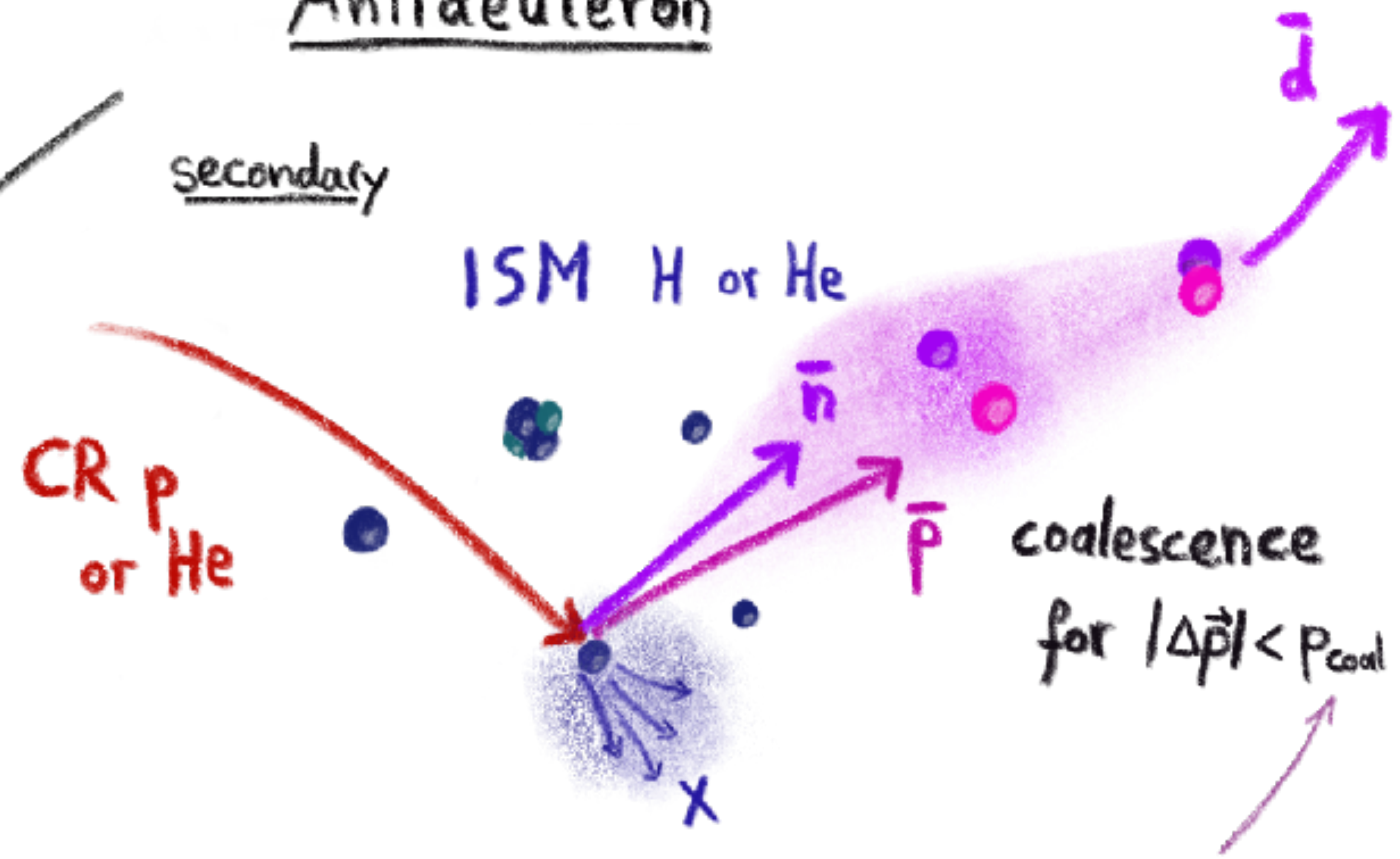
pbarlike

[Balan, MK, et al. 2023]


Antideuteron
secondary
ISM H or He
CR p or He
n̄
p̄
d̄
X
coalescence for |Δp⃗| < p_coal
~ 80 MeV/c
Low-energy suppression:
2E_p m_p + 2m_p² = [(E_p, p⃗_p) + (m_p, 0)]² = M_gs² ≥ (4m_p + 2m_n)²
⇔ E_p ≳ 17 m_p



Antideuteron



~ 80 MeV/c

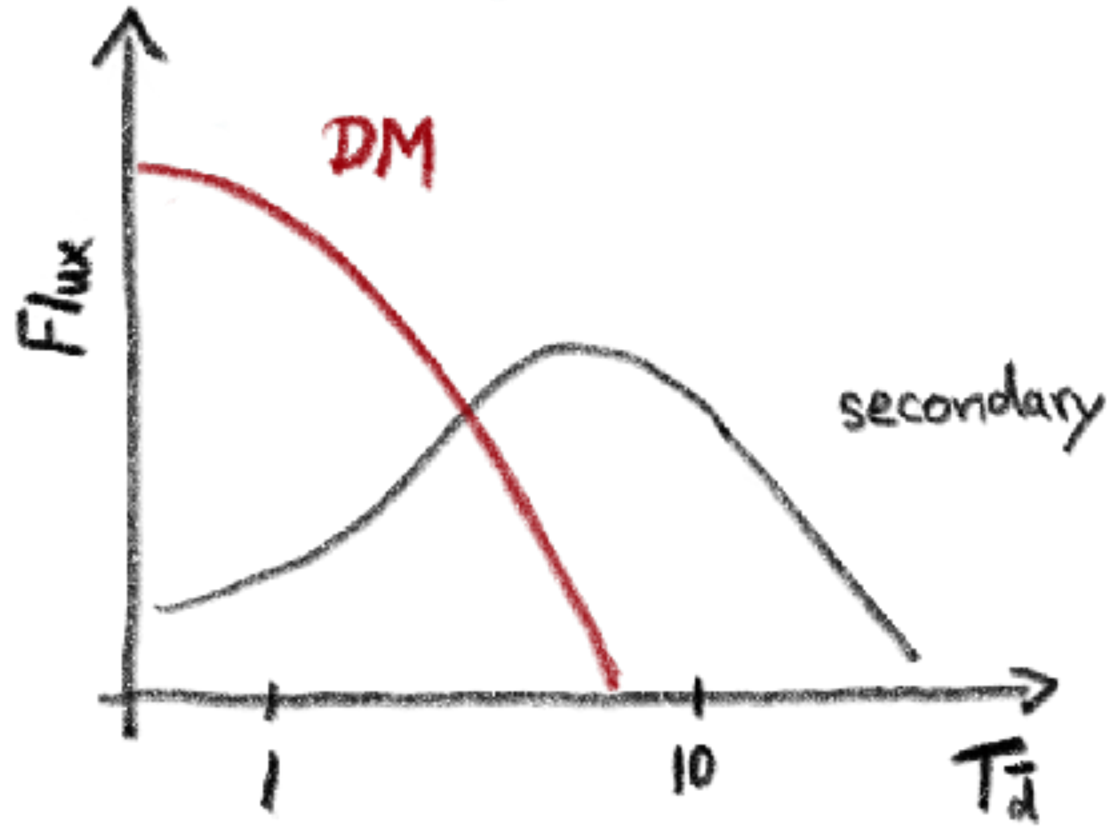
Low-energy suppression:

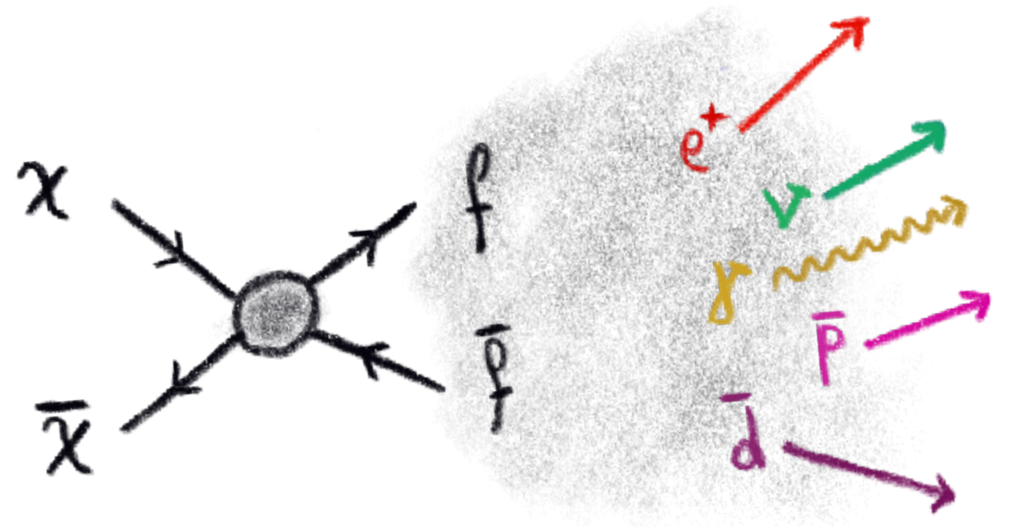
$$2E_p m_p + 2m_p^2 = \left[\begin{pmatrix}E_p\\ \vec{p}_p\end{pmatrix} + \begin{pmatrix}m_p\\ 0\end{pmatrix}\right]^2 = M_{gs}^2 \geq (4m_p + 2m_n)^2$$

$$\Leftrightarrow \boxed{E_p \gtrsim 17\, m_p}$$

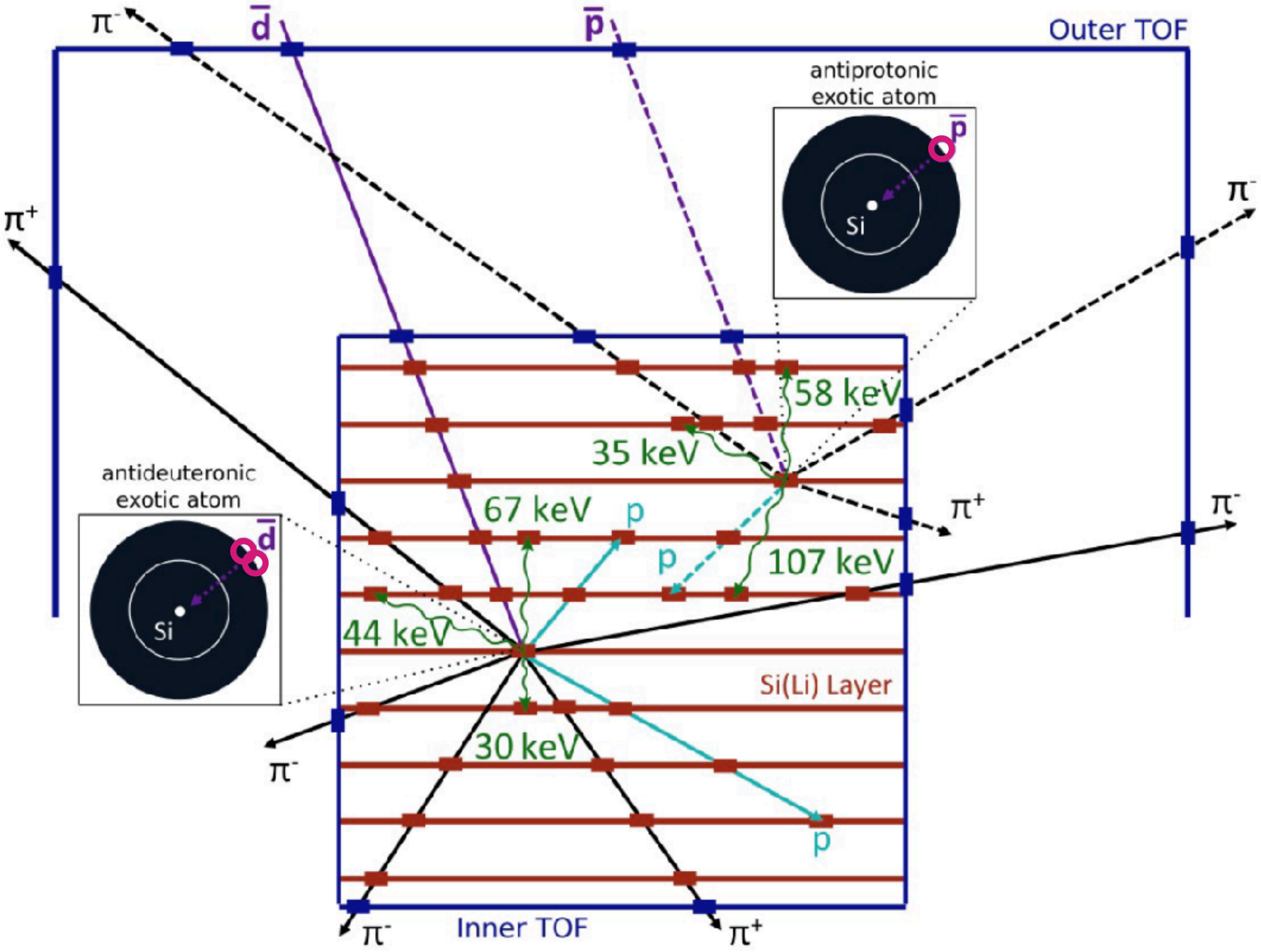
DM

- Production by coalescence
- No low-energy suppression (annihilation at rest)

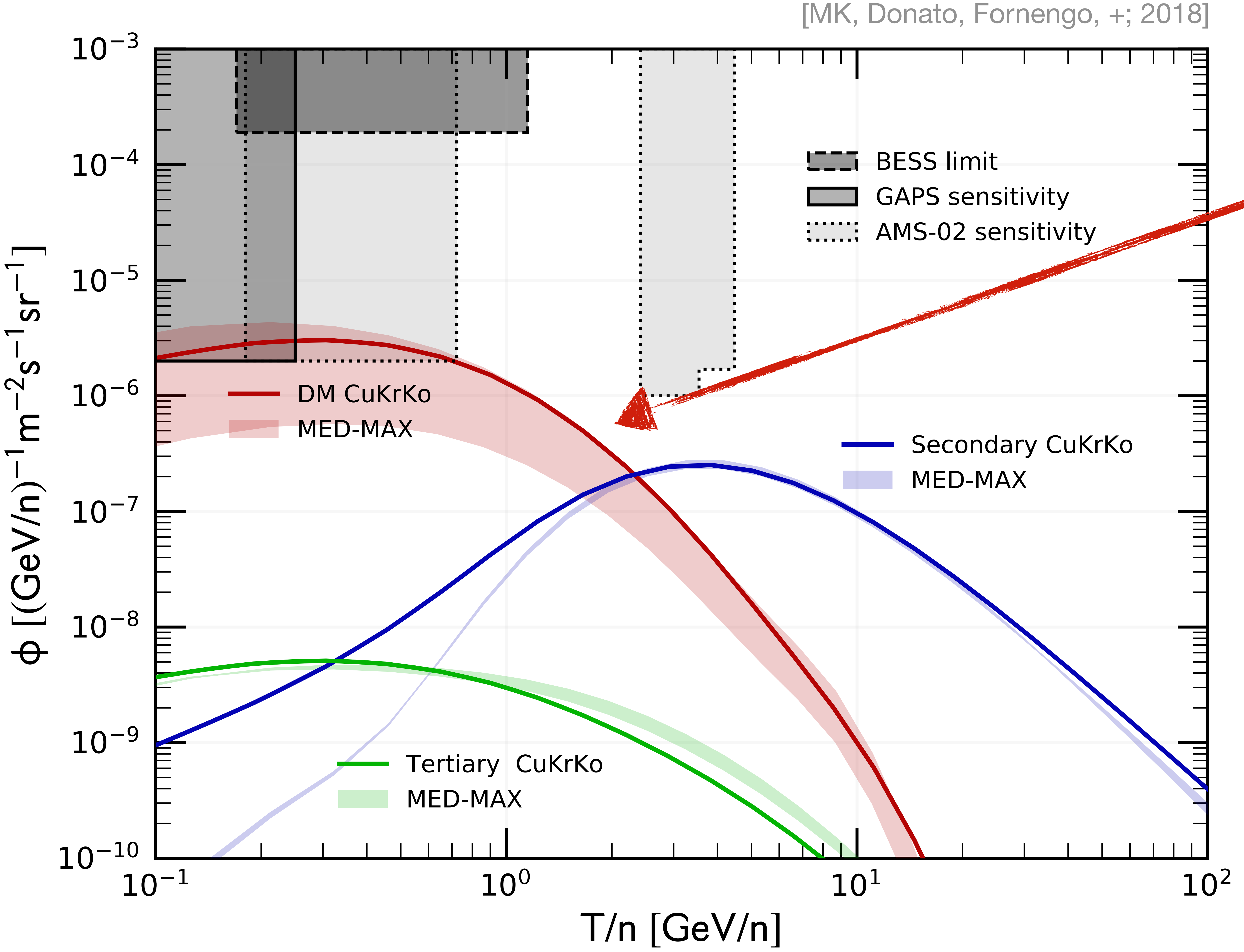


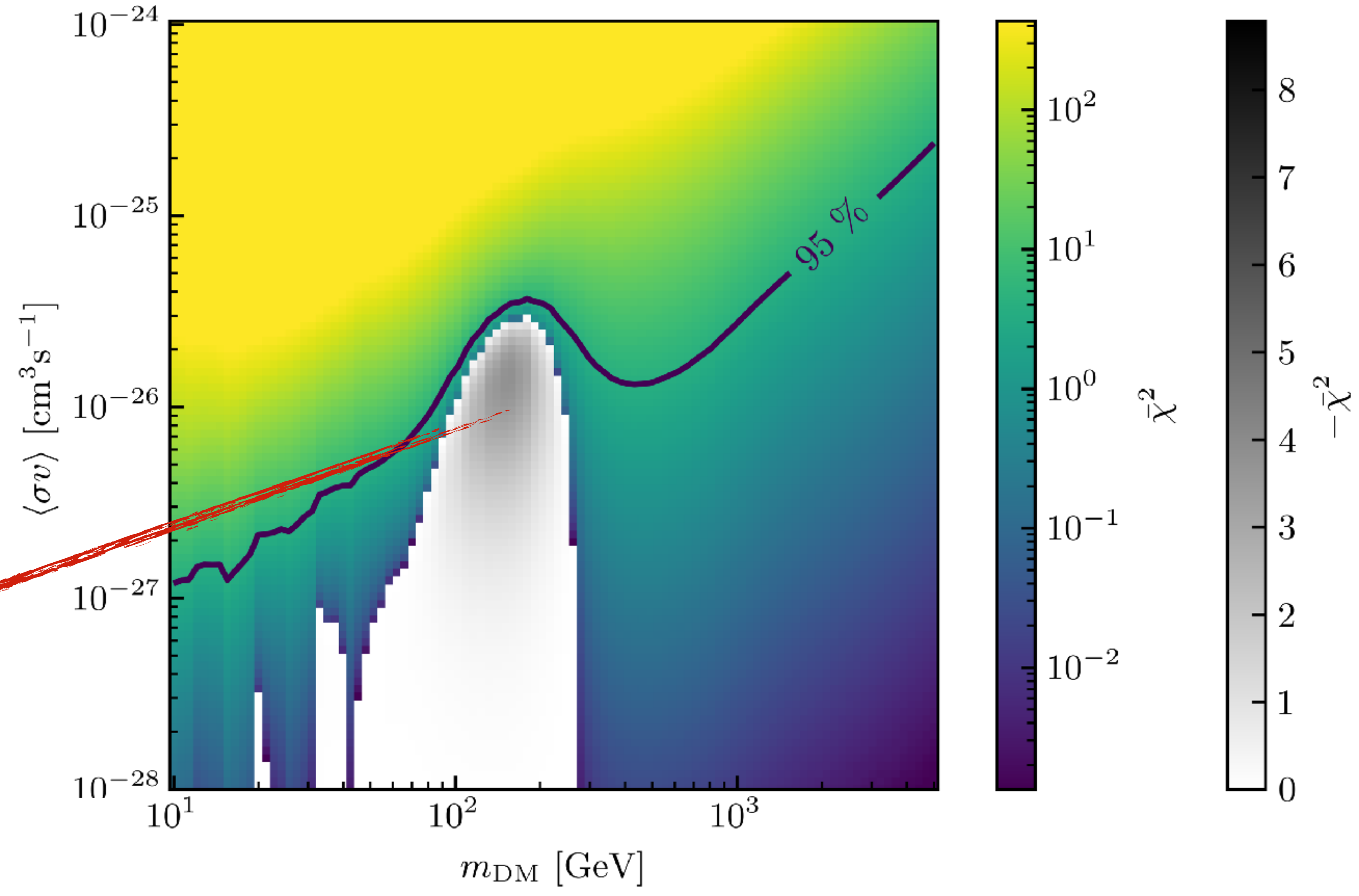


GAPS detector concept



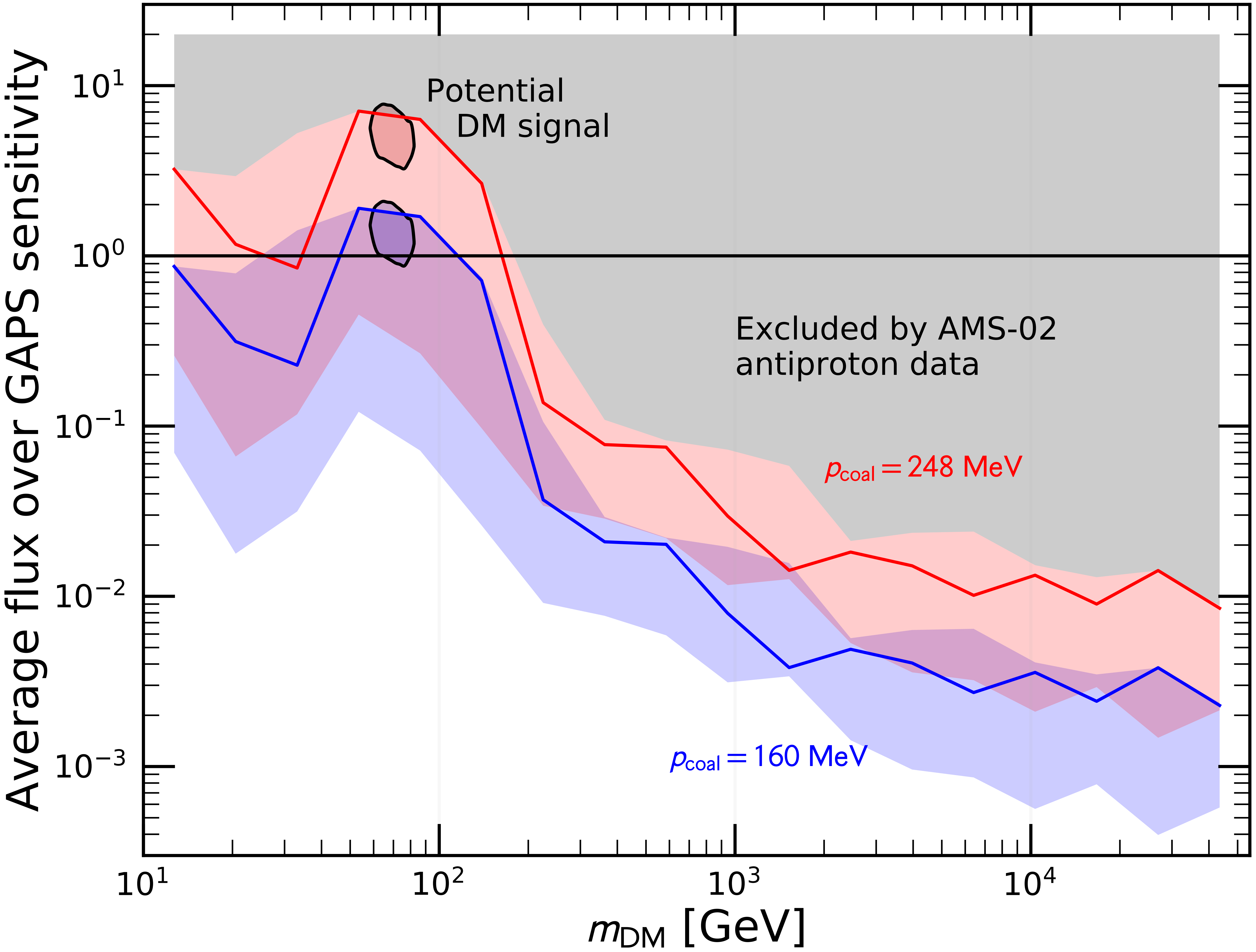
Predicted Antideuteron flux





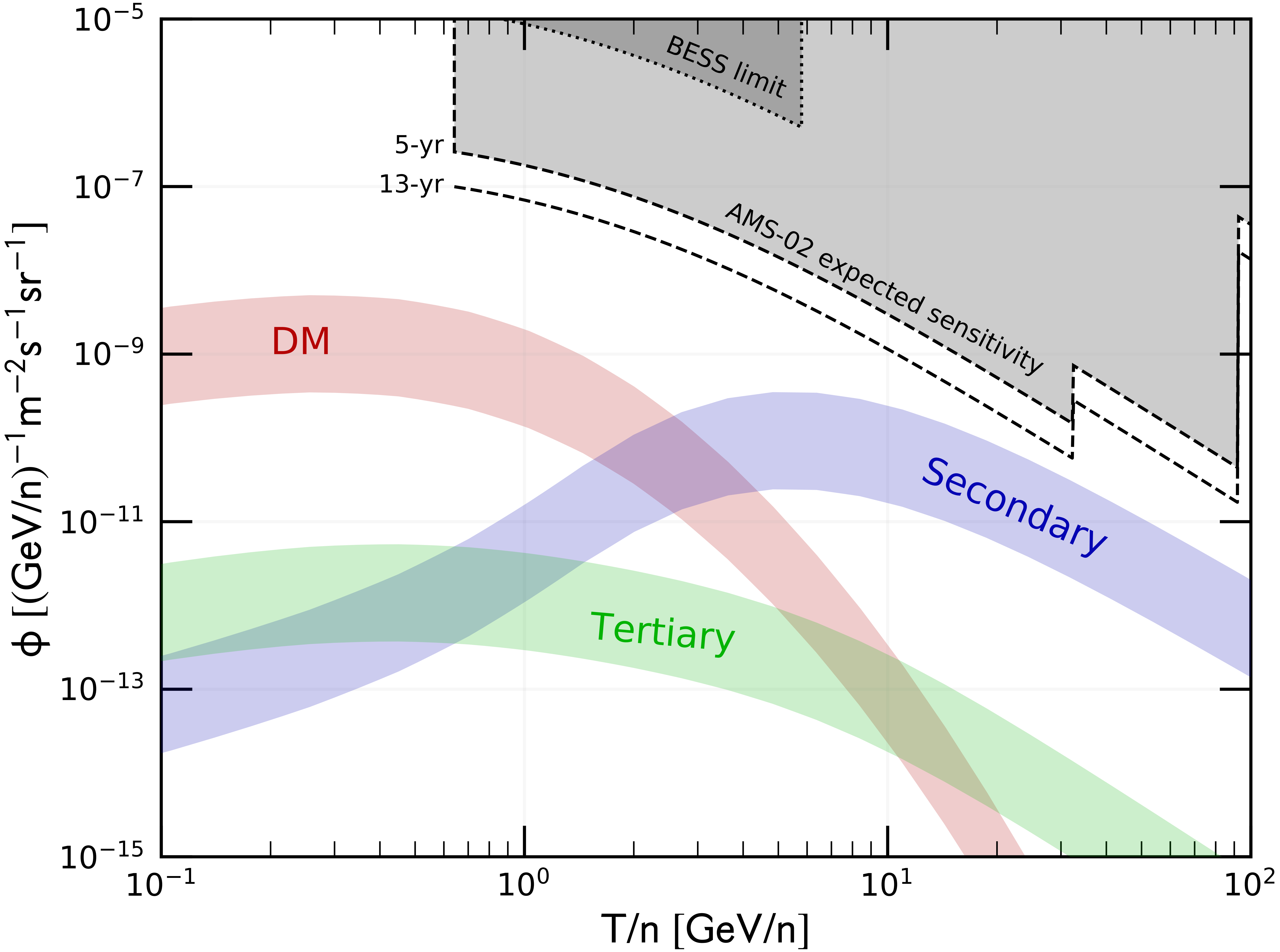
The DM "hint" in antiprotons might be in the sensitivity range of the (future) cosmic-ray experiments AMS-02 and GAPS.

Possible Dark Matter Antideuteron flux for GAPS

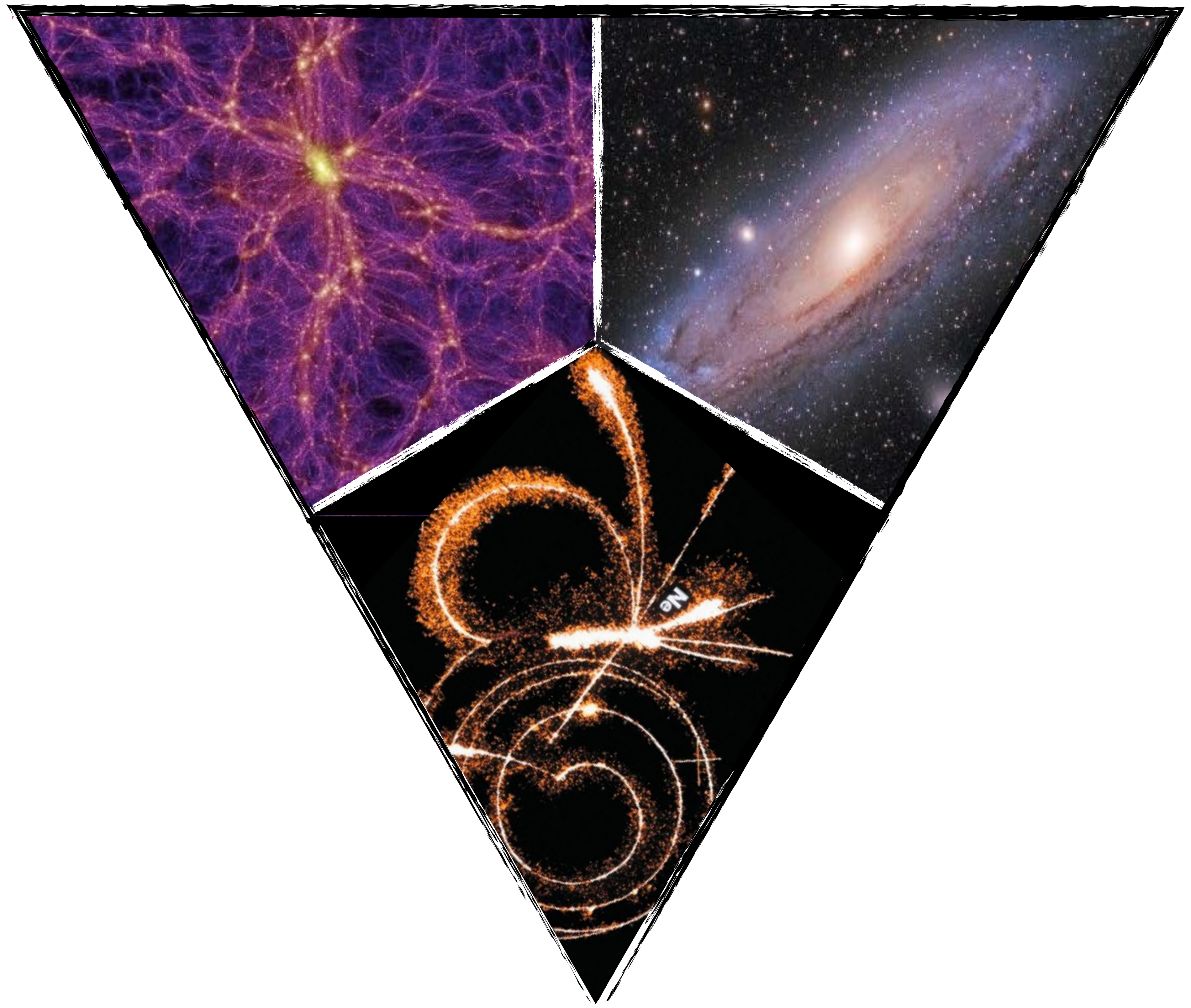


Predicted antihelium flux

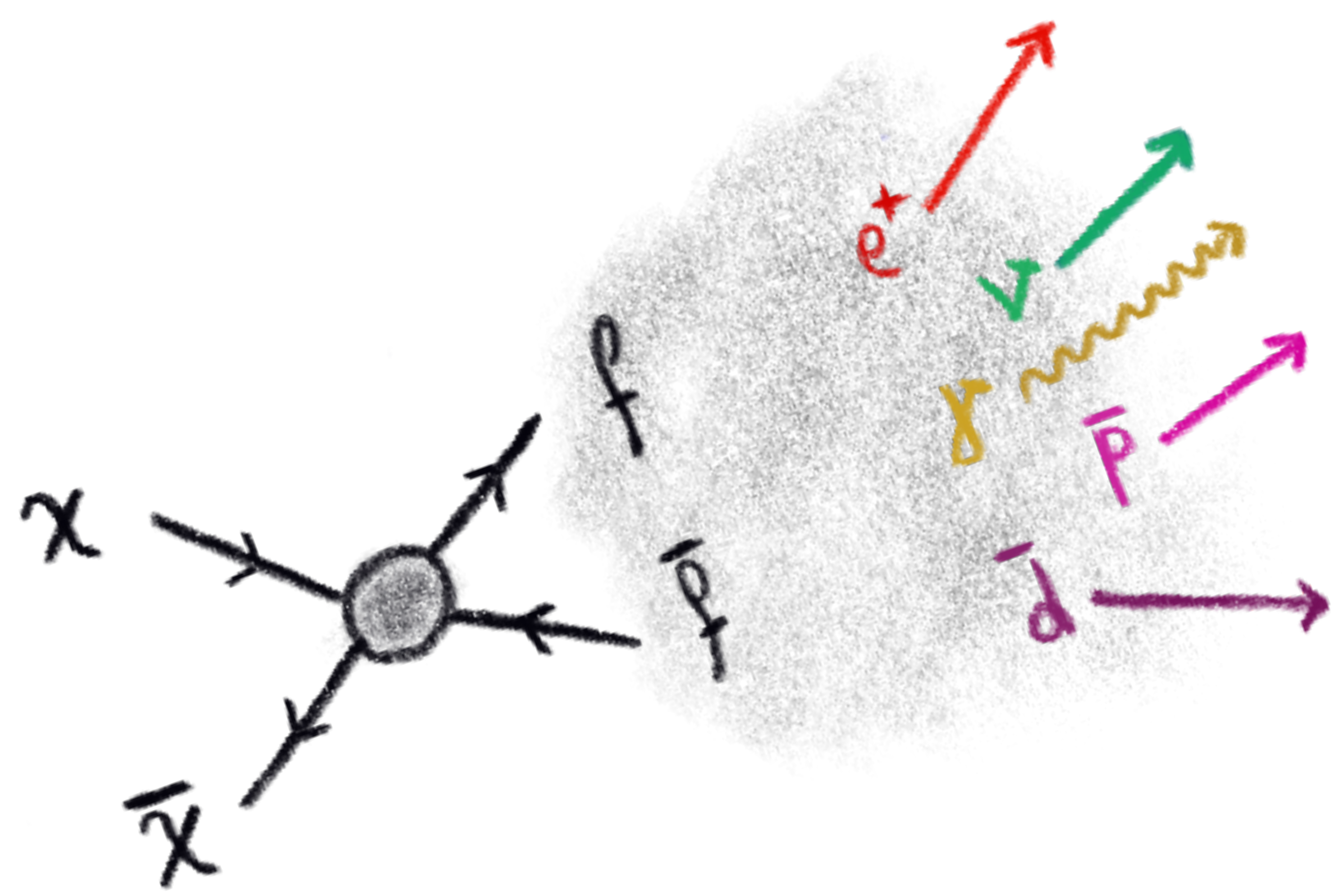
[MK, Donato, Fornengo, +; 2018]

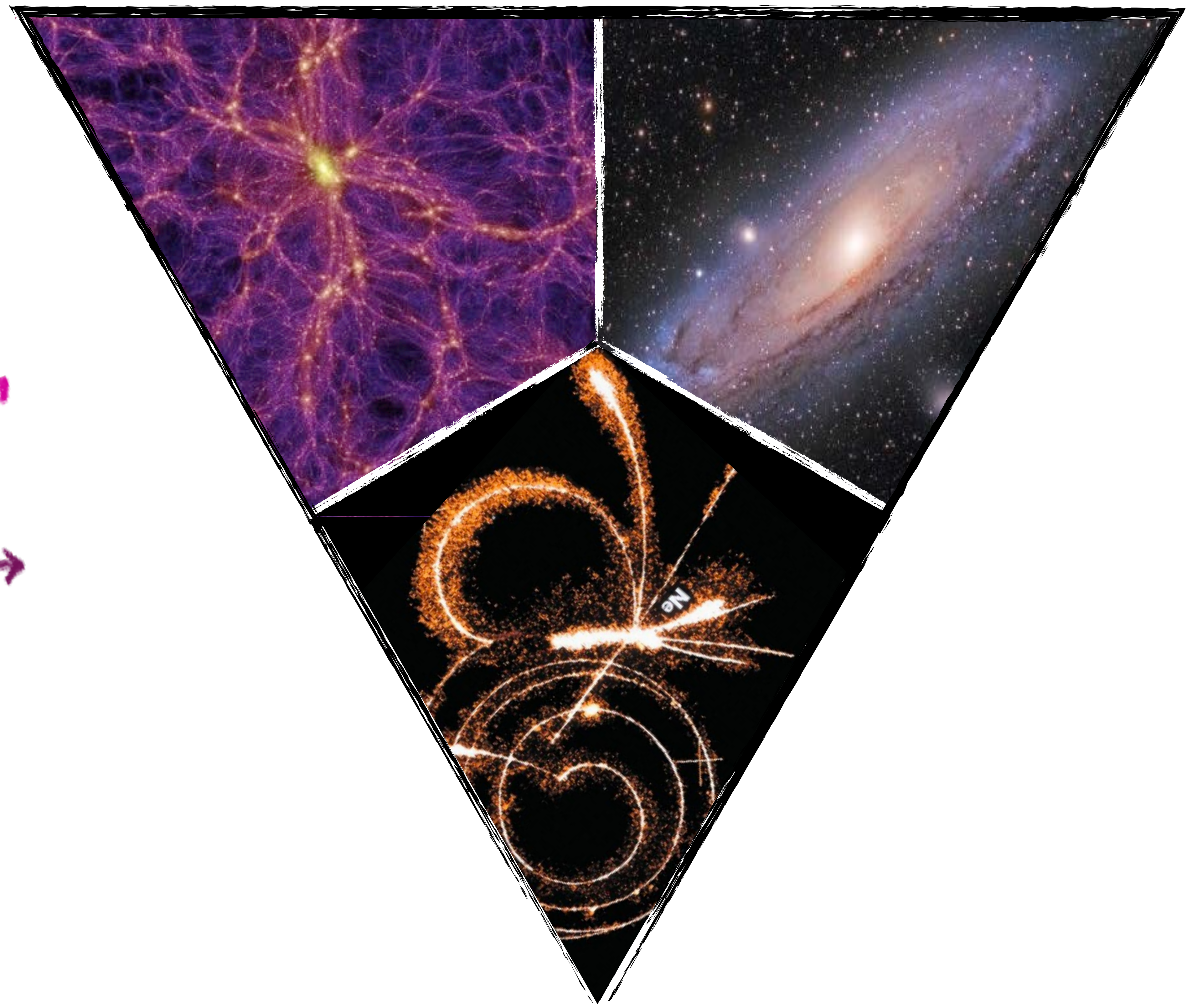


Summary

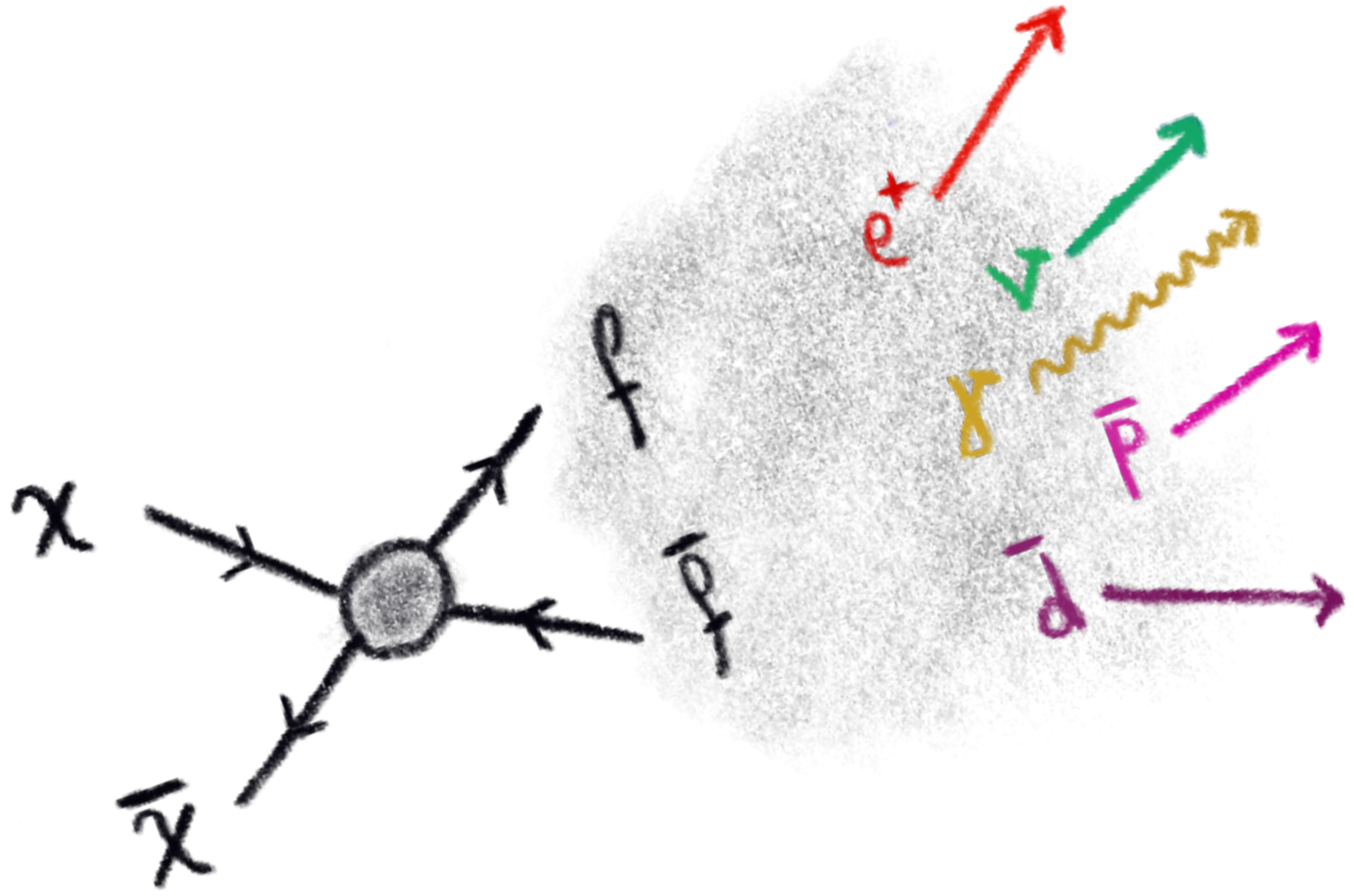


Summary

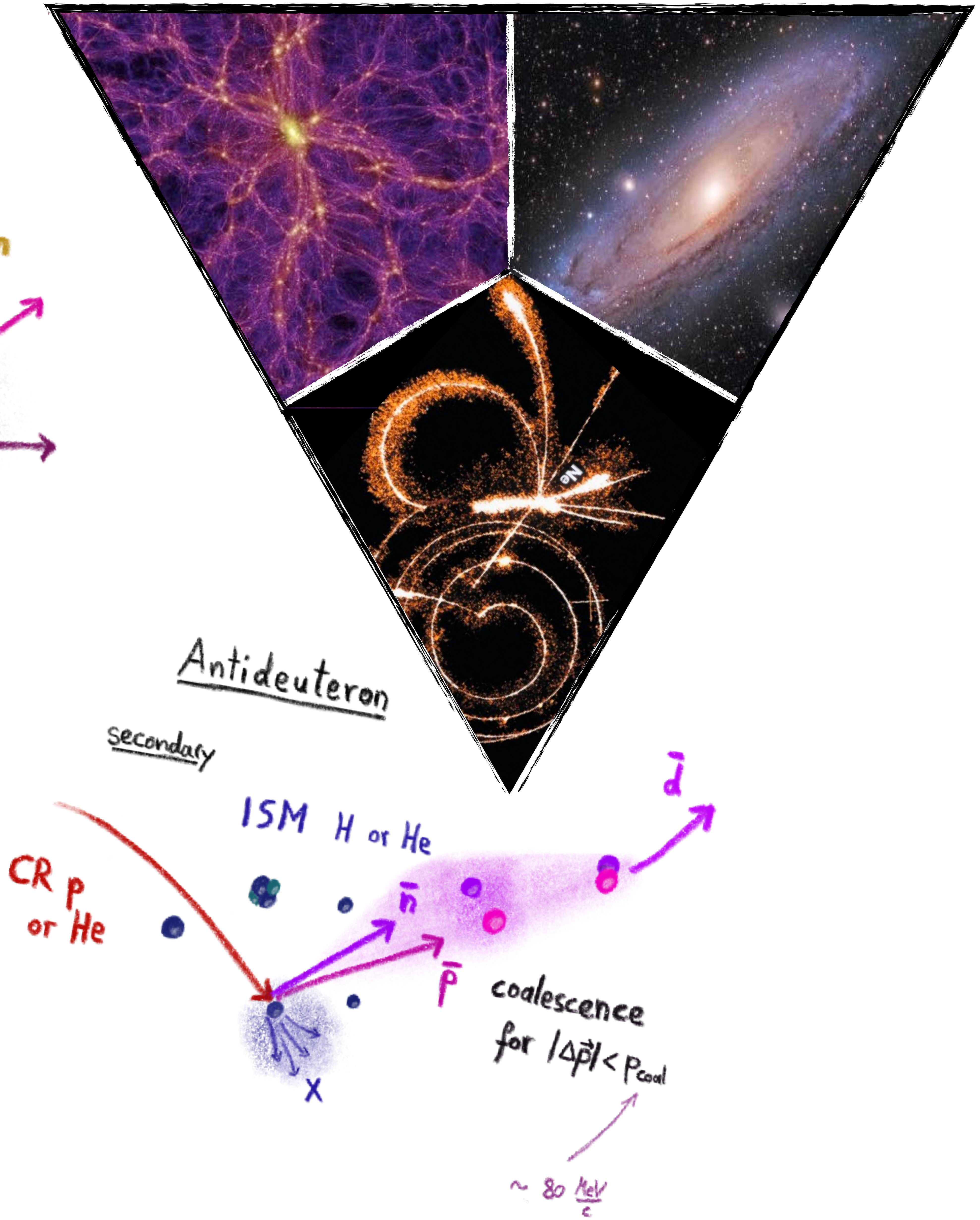




Summary

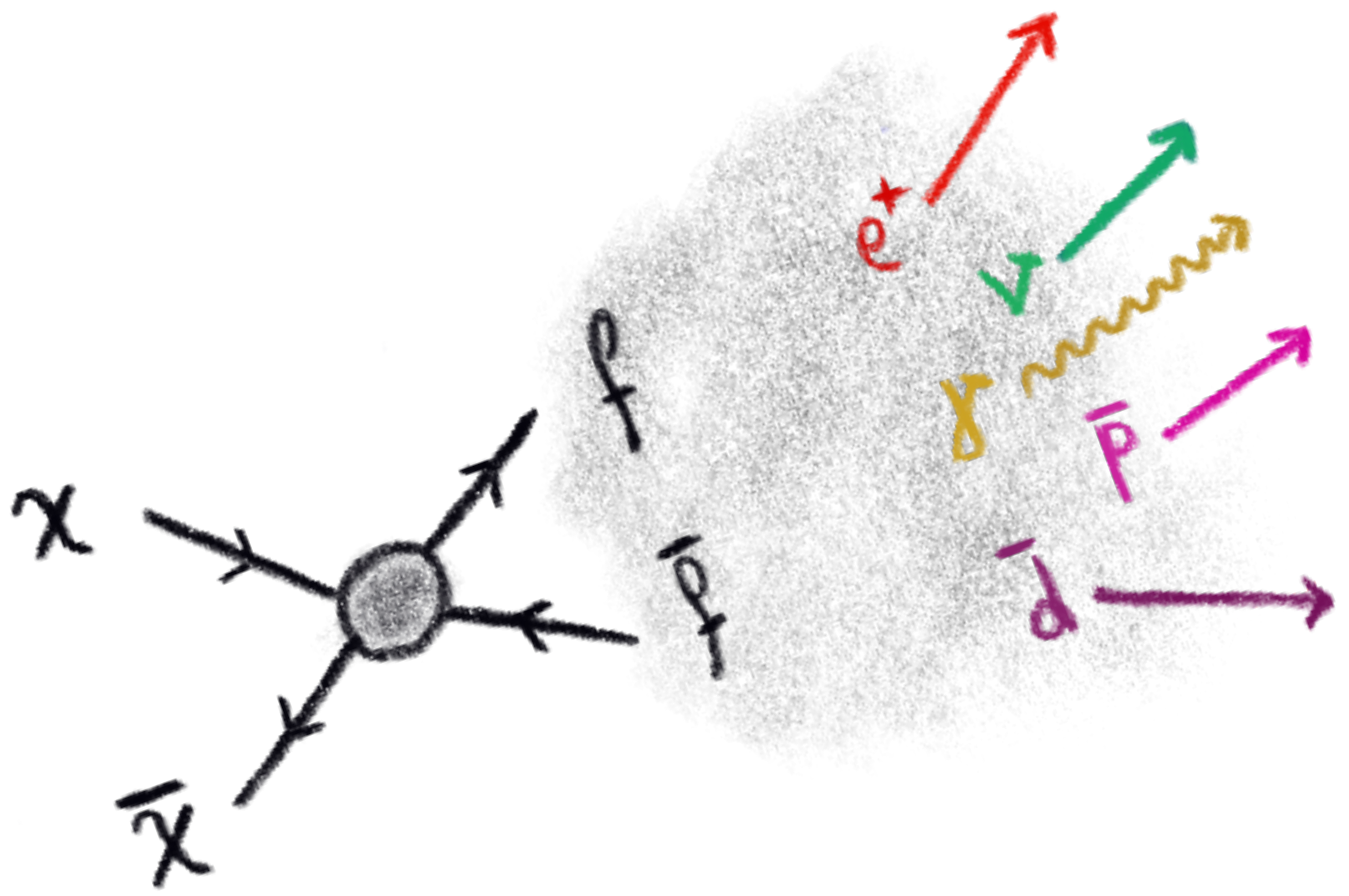


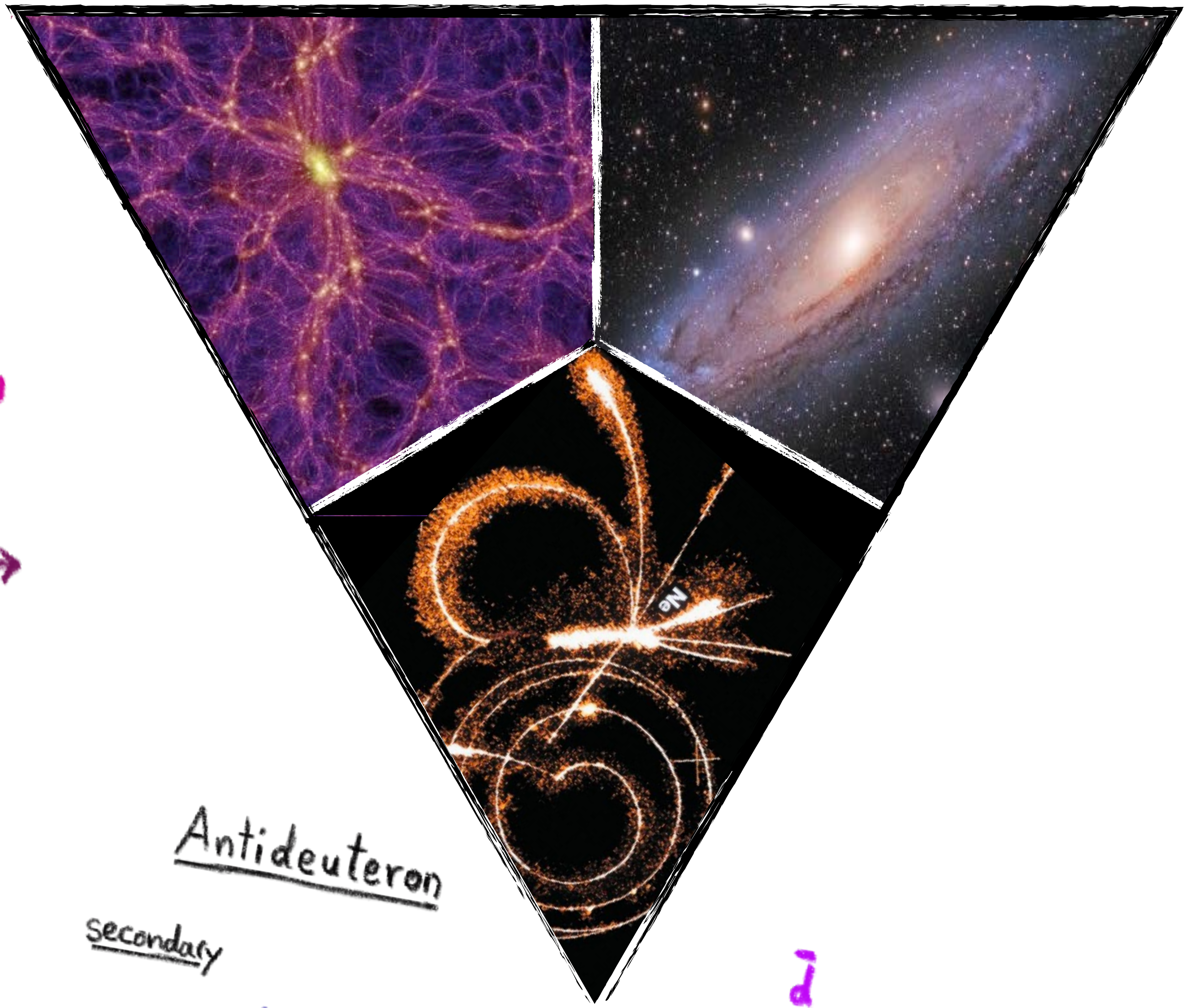
χ
f
f̄
e+
ν
γ
p̄
d̄
χ̄

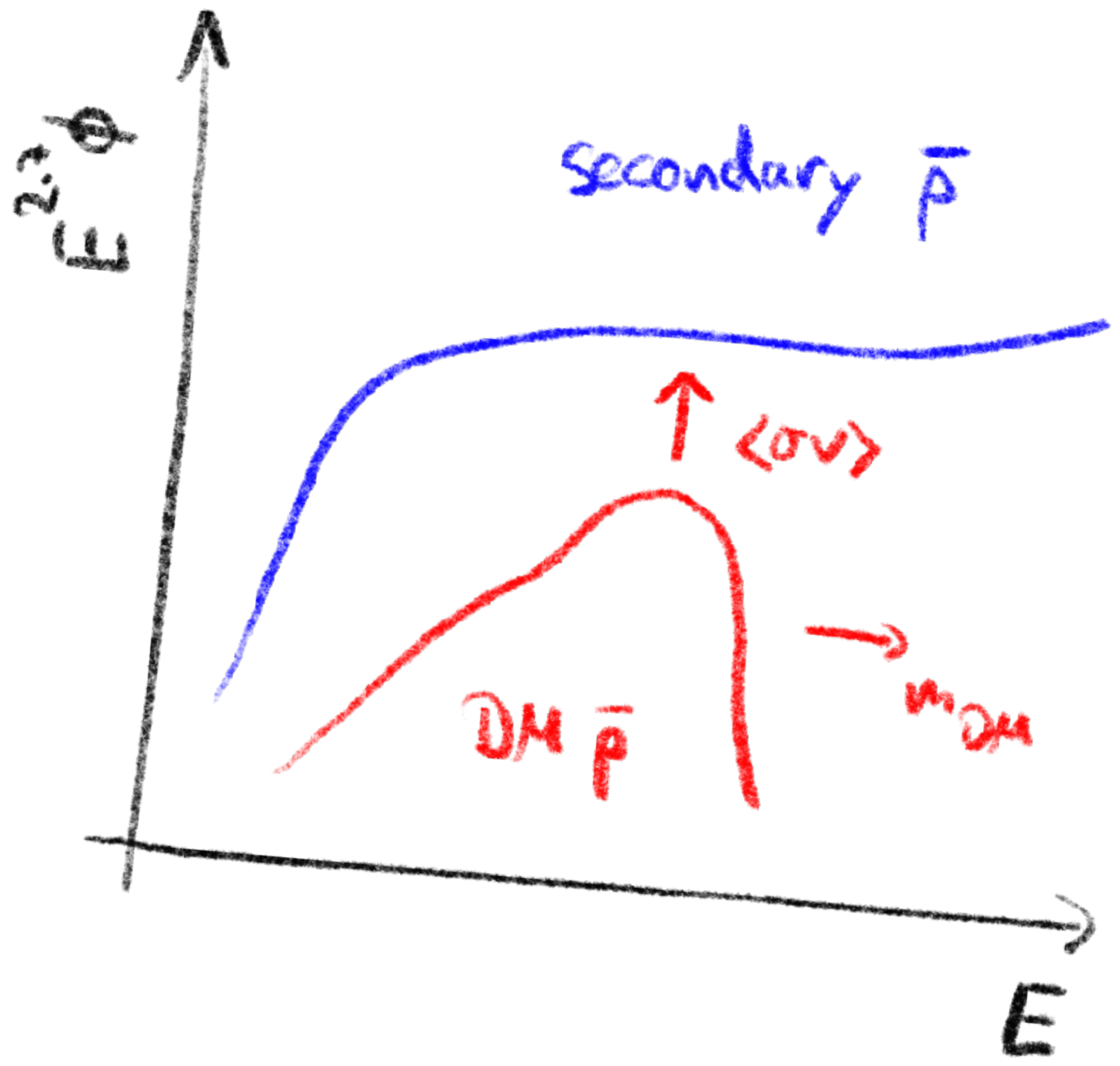


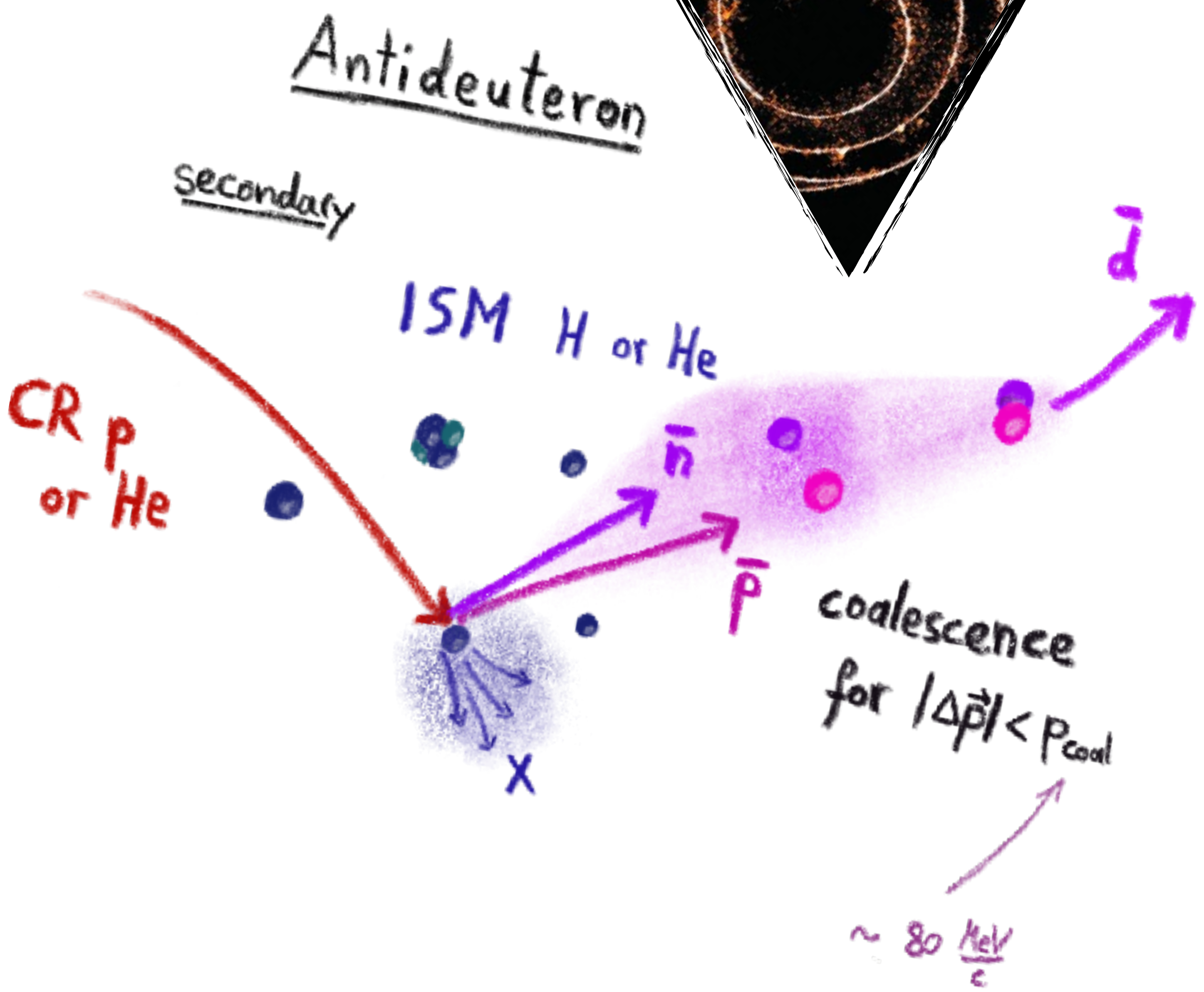
Antideuteron
secondary
ISM H or He
CR p or He
n̄
p̄
d̄
X
coalescence for |Δp⃗| < p_coal
~ 80 MeV/c

Summary


χ
f
f̄
χ̄
e+
ν
γ
p̄
d̄




E^2.7 Φ
secondary p̄
⟨σv⟩
DM p̄
→ m_DM
E


Antideuteron
secondary
ISM H or He
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n̄
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X
coalescence for |Δp⃗| < p_coal
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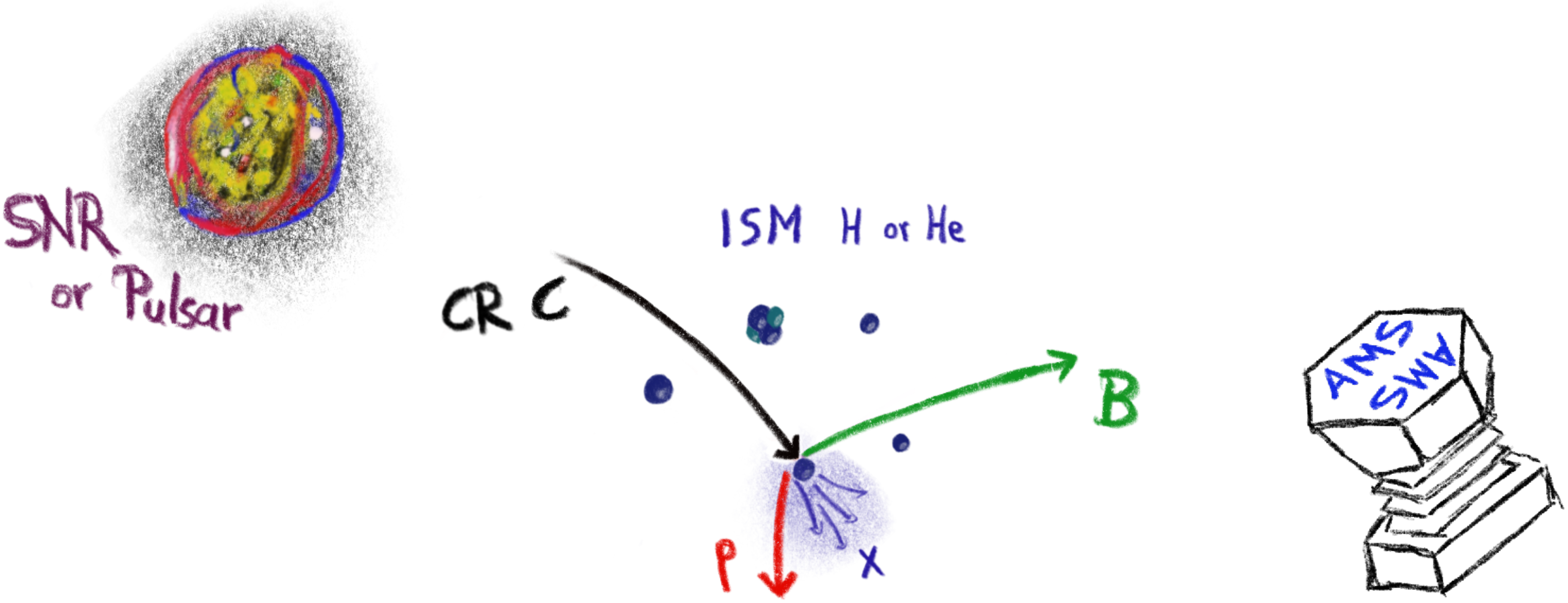
Thank you for your attention!

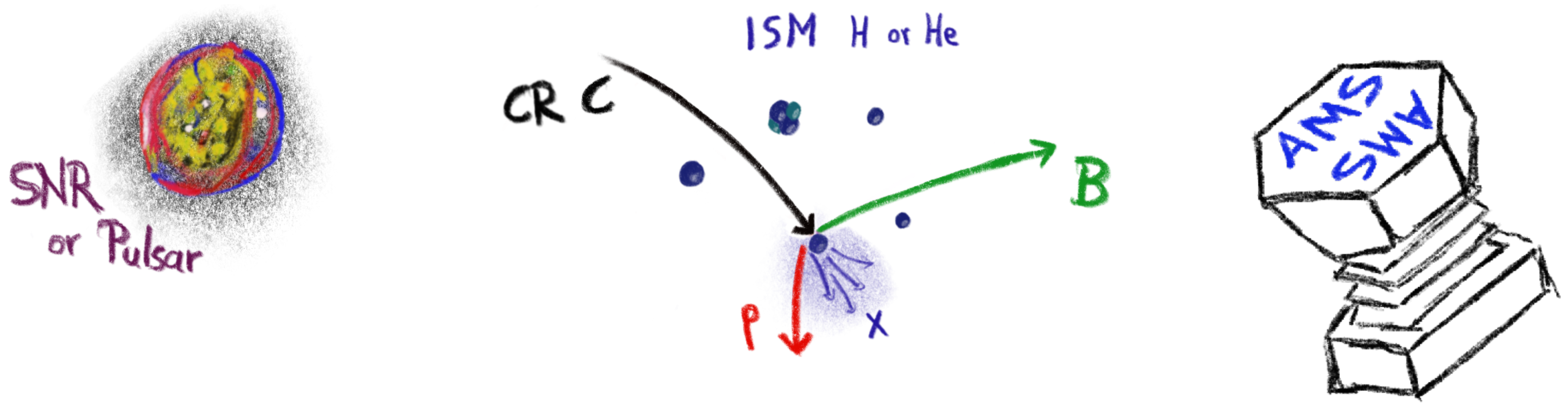
Backup


dwarf spheroidal
DM?
Blazar
CR
radio
γ-ray
ν?
Galactic Center
DM?
SNR or Pulsar
ν
Dark Matter
DM
f
f
$\overline{DM}$
e^+
ν
γ
$\bar{p}$
$\bar{d}$

Gramage



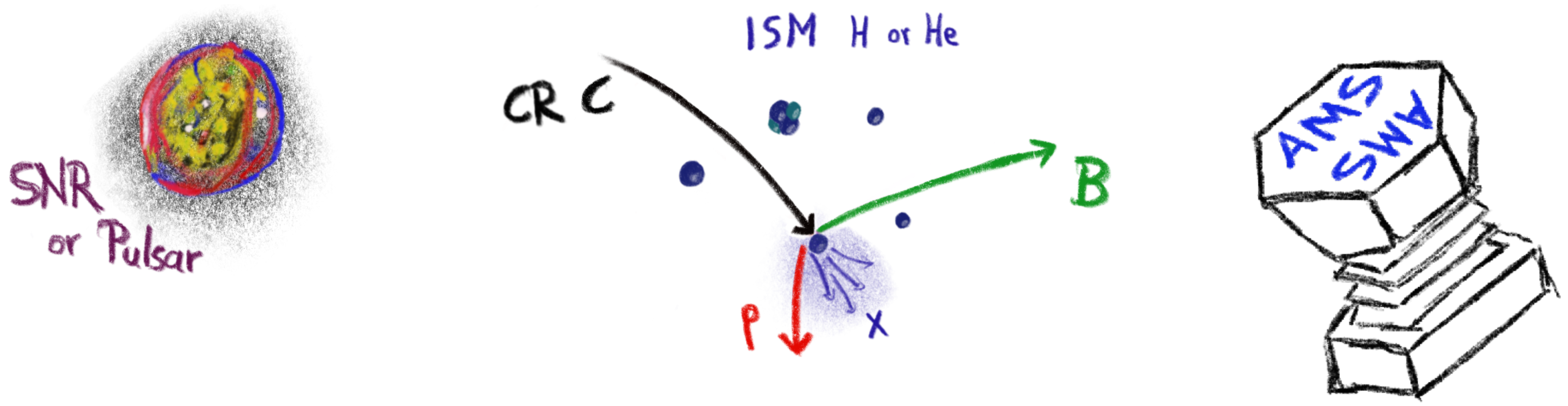
Gramage



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

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

Gramage

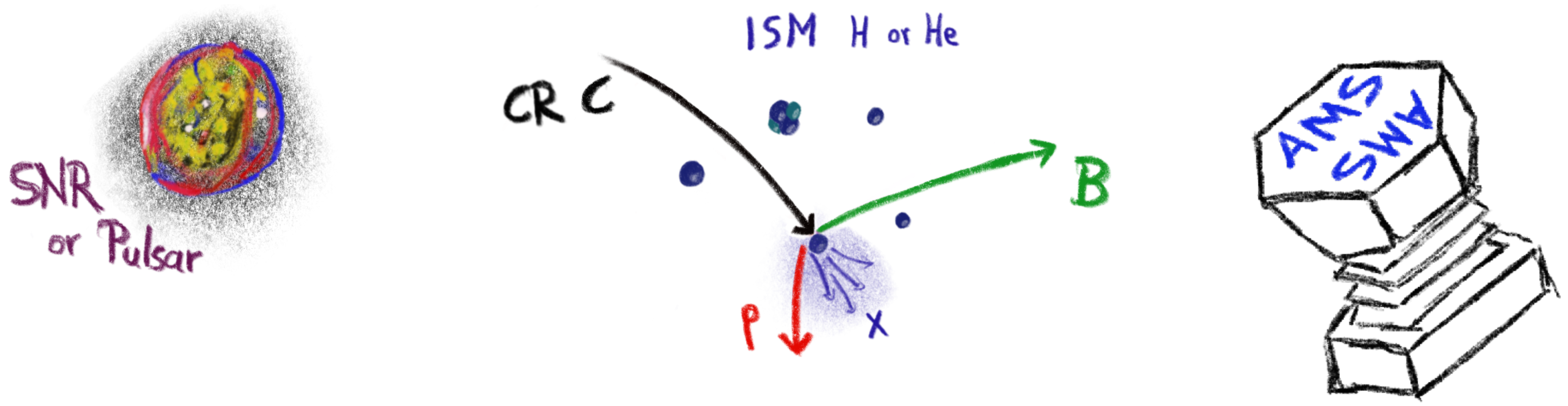


$$X = \ell \cdot \rho$$

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

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

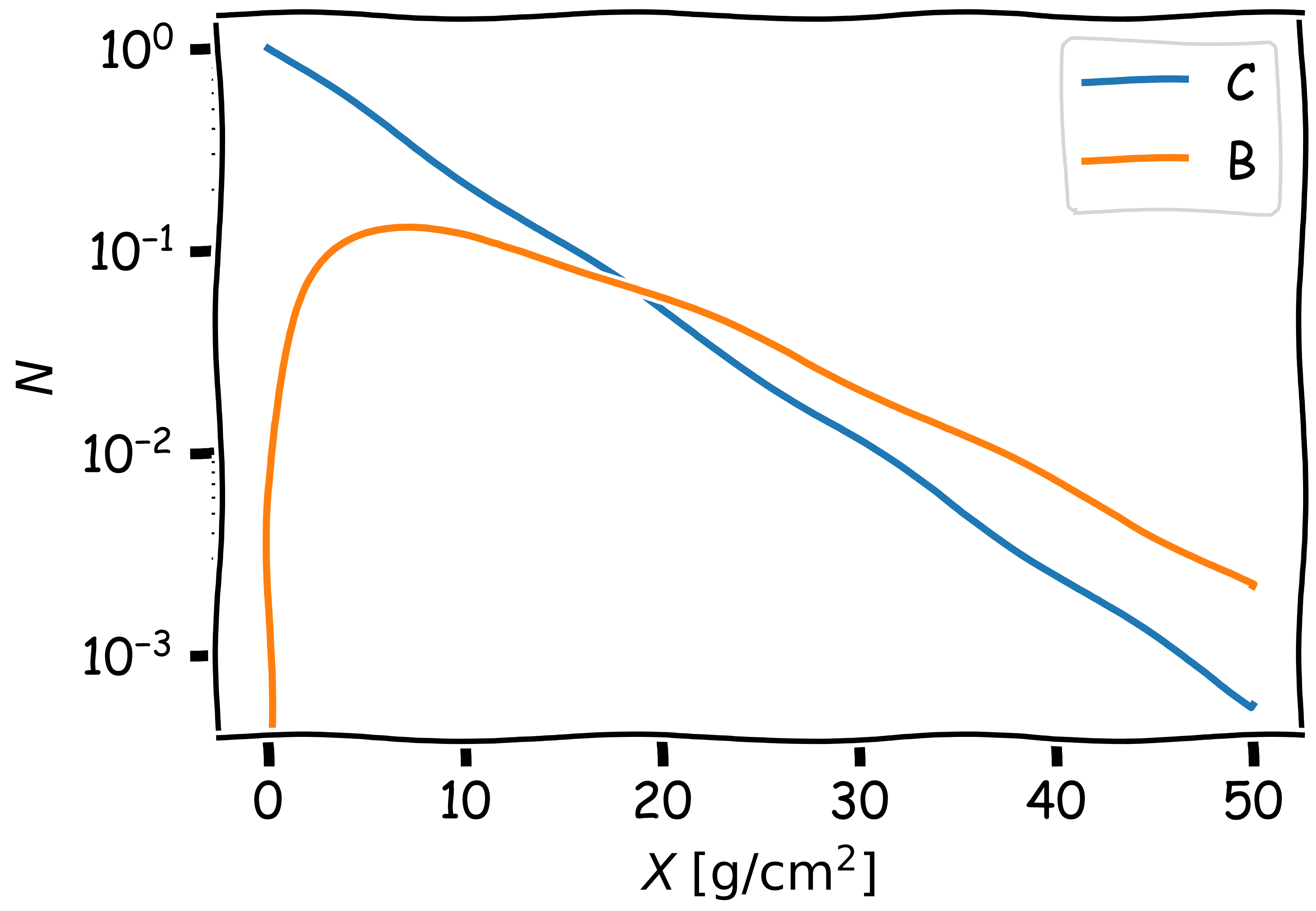
Gramage



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

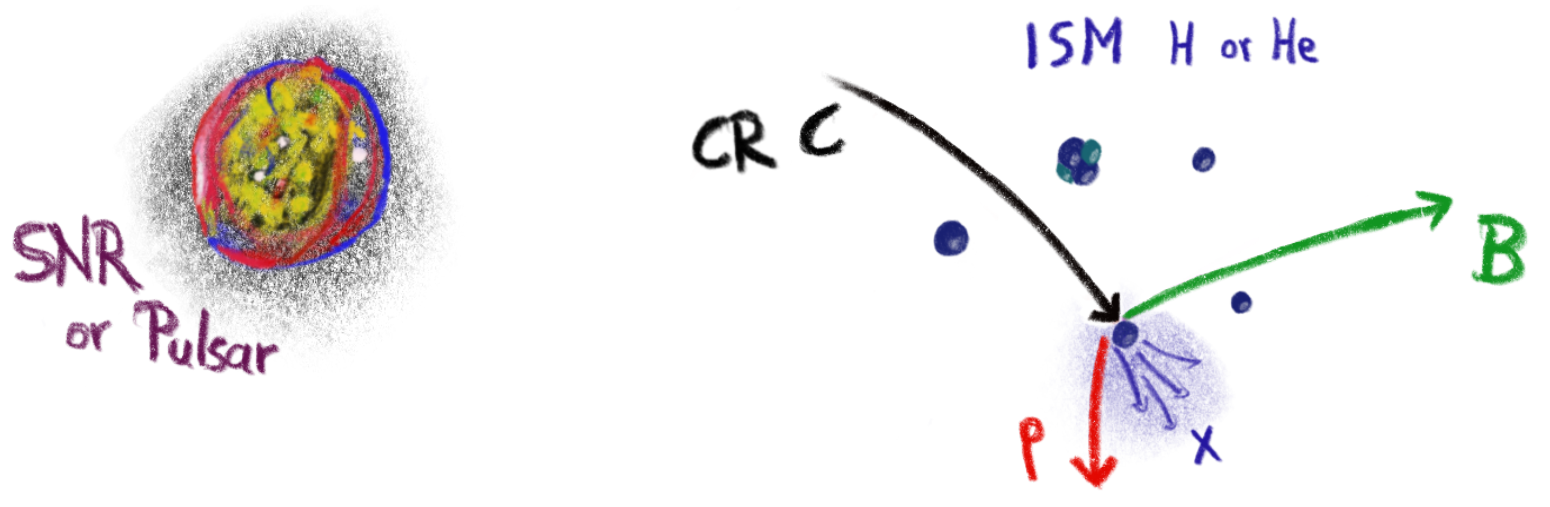
$$N_\mathrm{C} = N_0 \exp\left(-\frac{\sigma_{\mathrm{inel,C}}}{m_p} X\right)$$

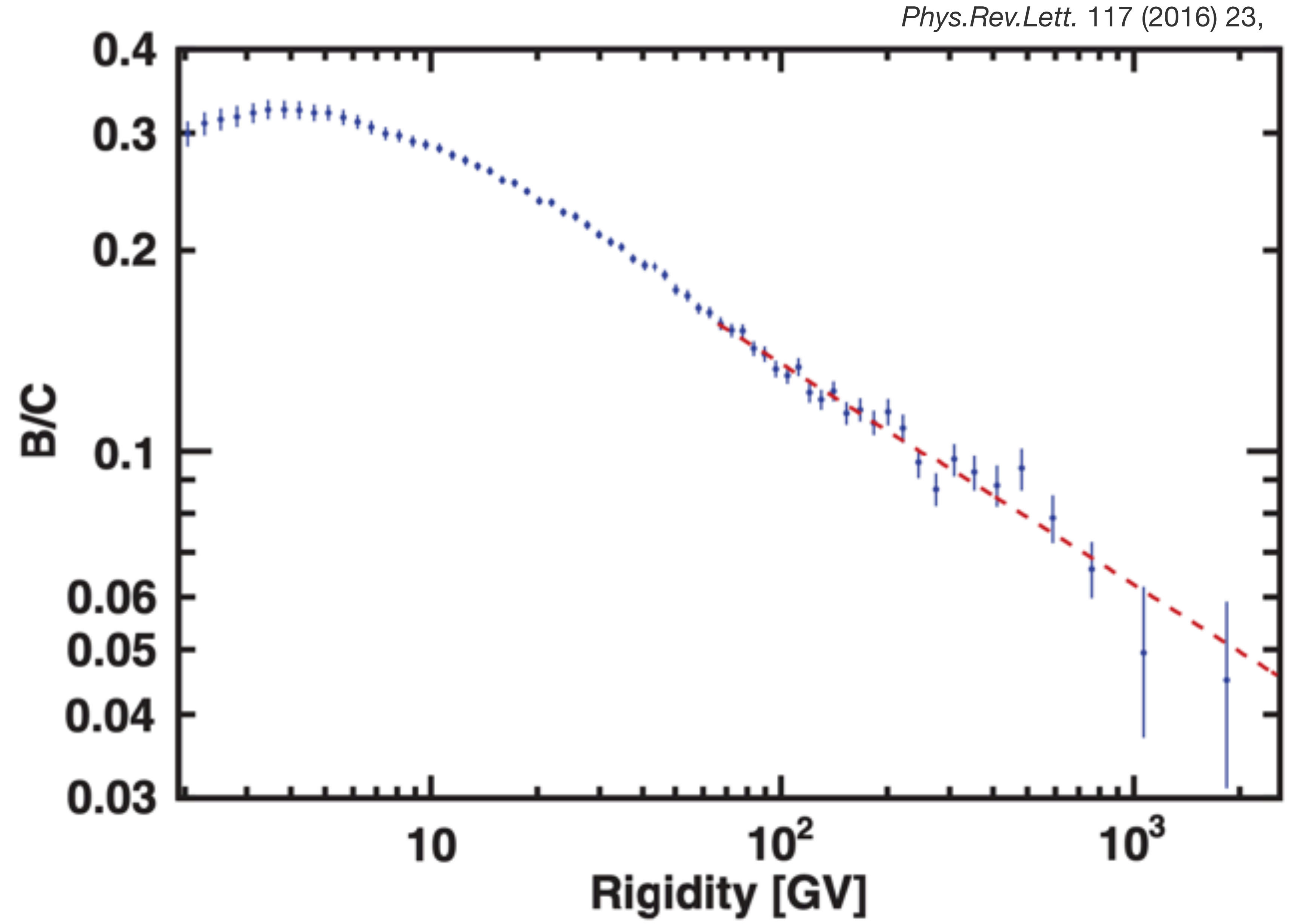
$$\frac{N_\mathrm{B}}{N_\mathrm{C}} = \frac{\sigma_{\mathrm{C}\to\mathrm{B}}}{\sigma_{\mathrm{inel,C}} - \sigma_{\mathrm{inel,B}}} \left[\exp\left(\frac{\sigma_{\mathrm{inel,C}} - \sigma_{\mathrm{inel,B}}}{m_p} X\right) - 1\right]$$

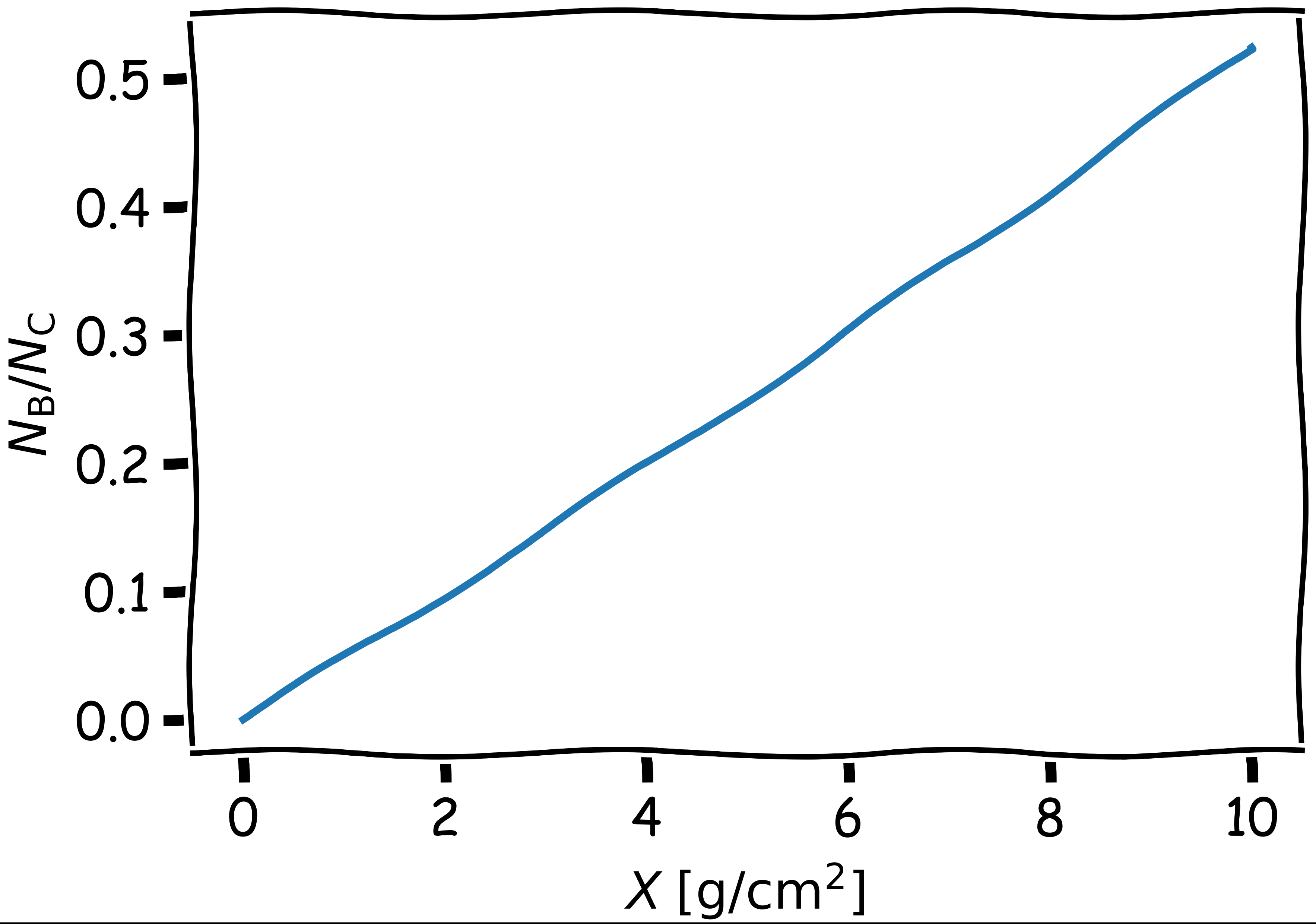


$$\sigma_{\mathrm{C,inel}} \sim 250 \text{ mb}$$
$$\sigma_{\mathrm{B,inel}} \sim 220 \text{ mb}$$
$$\sigma_{\mathrm{C}\to\mathrm{B}} \sim 80 \text{ mb}$$

Gramage







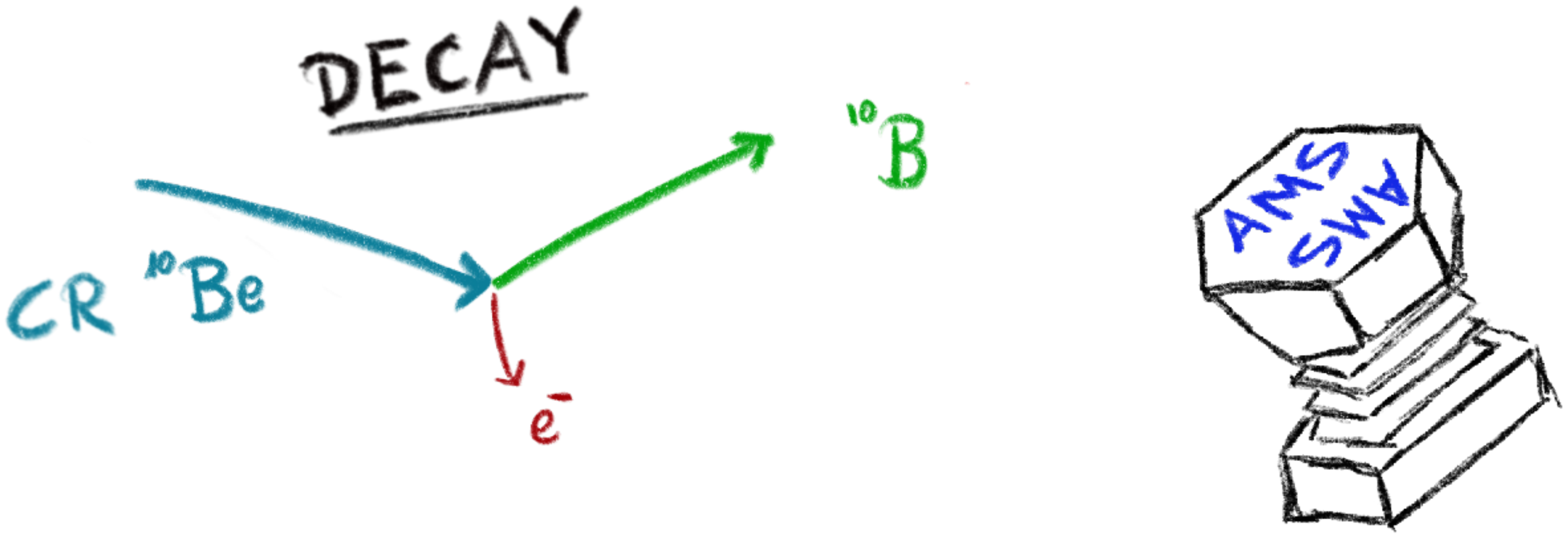
$$\mathrm{B/C} \sim 0.3 \qquad \text{(at 10 GV)}$$

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

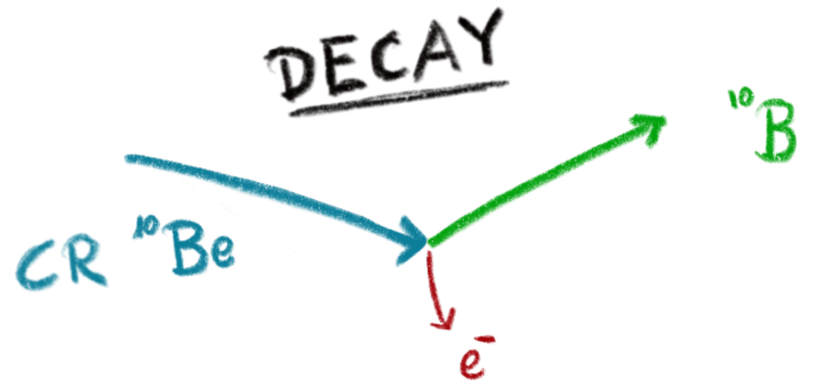
$$X_{\text{Galactic disc}} \sim 2 \times 10^{-3}\ \mathrm{g/cm^2}$$

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

Cosmic-Ray Clocks



Cosmic-Ray Clocks

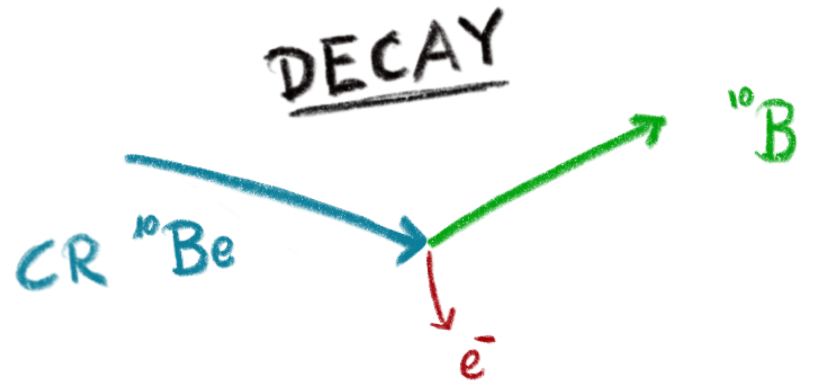


The Leaky Box Model

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

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

Cosmic-Ray Clocks

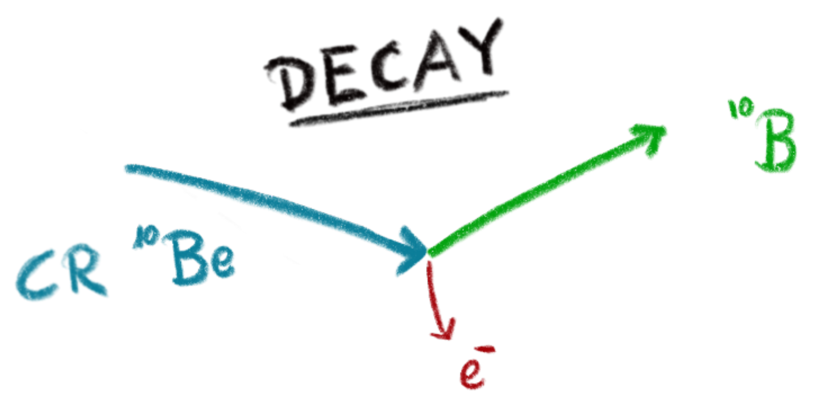


The Leaky Box Model

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

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

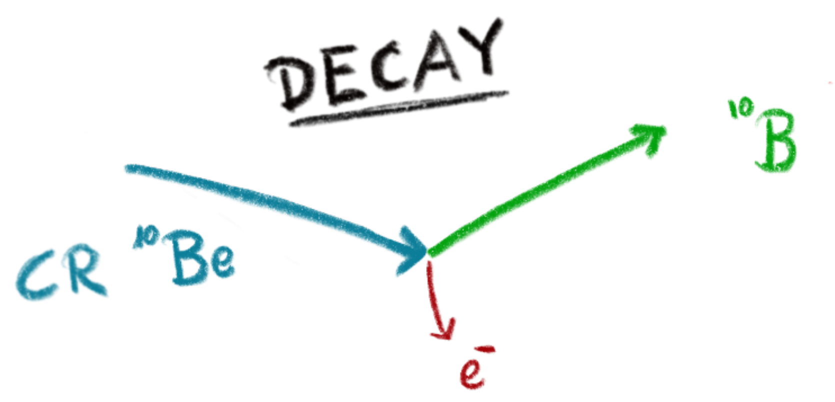
Cosmic-Ray Clocks



The Leaky Box Model

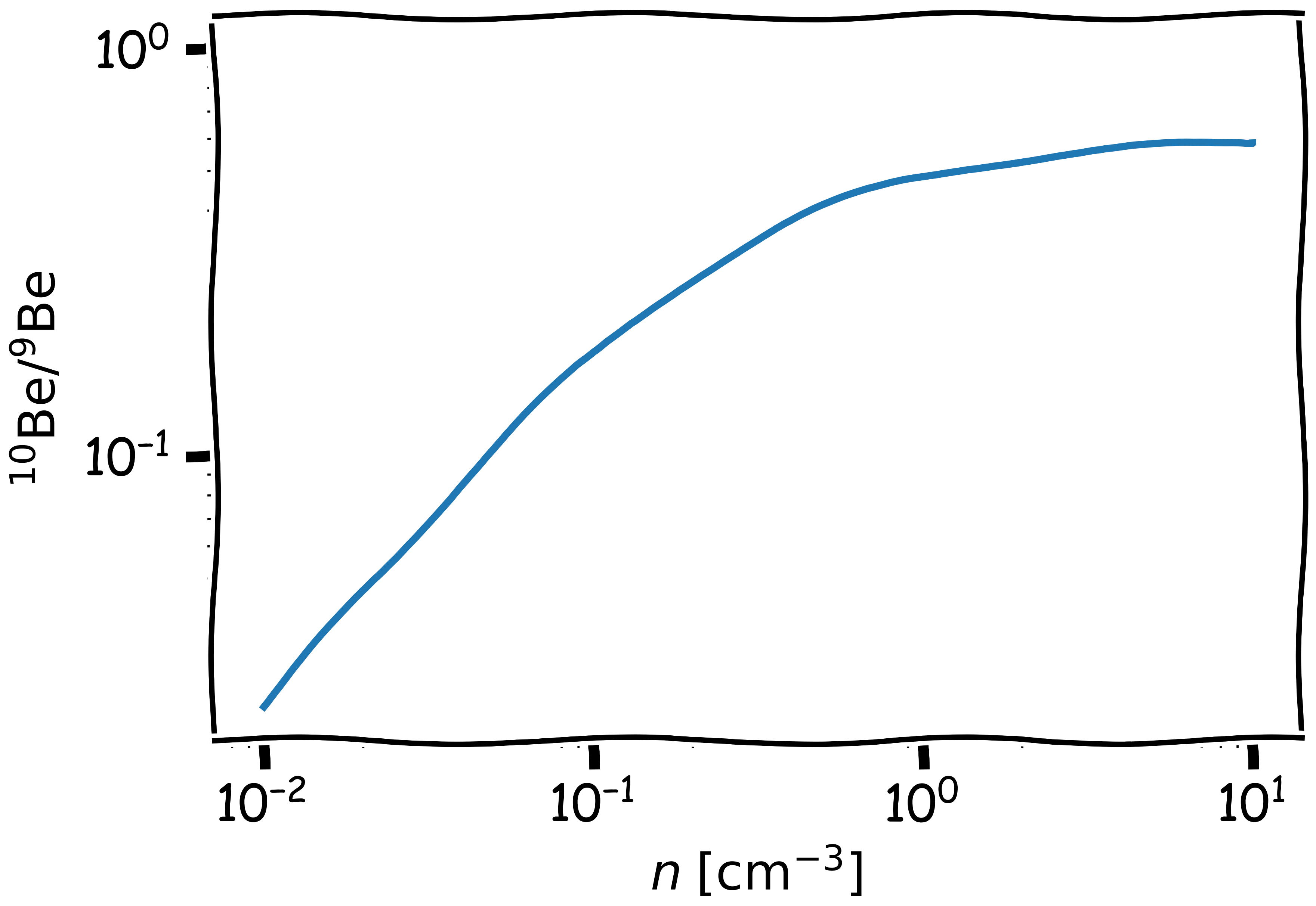
$$\frac{N_{^{10}\mathrm{Be}}}{N_{^{9}\mathrm{Be}}} = \frac{\sigma_{\mathrm{CNO}\to{}^{10}\mathrm{Be}}}{\sigma_{\mathrm{CNO}\to{}^{9}\mathrm{Be}}} \frac{\frac{1}{t_{\mathrm{esc}}} + \frac{1}{t_{\mathrm{int},9}}}{\frac{1}{t_{\mathrm{esc}}} + \frac{1}{t_{\mathrm{int},10}} + \frac{1}{t_{\mathrm{dec},10}}}$$

Cosmic-Ray Clocks

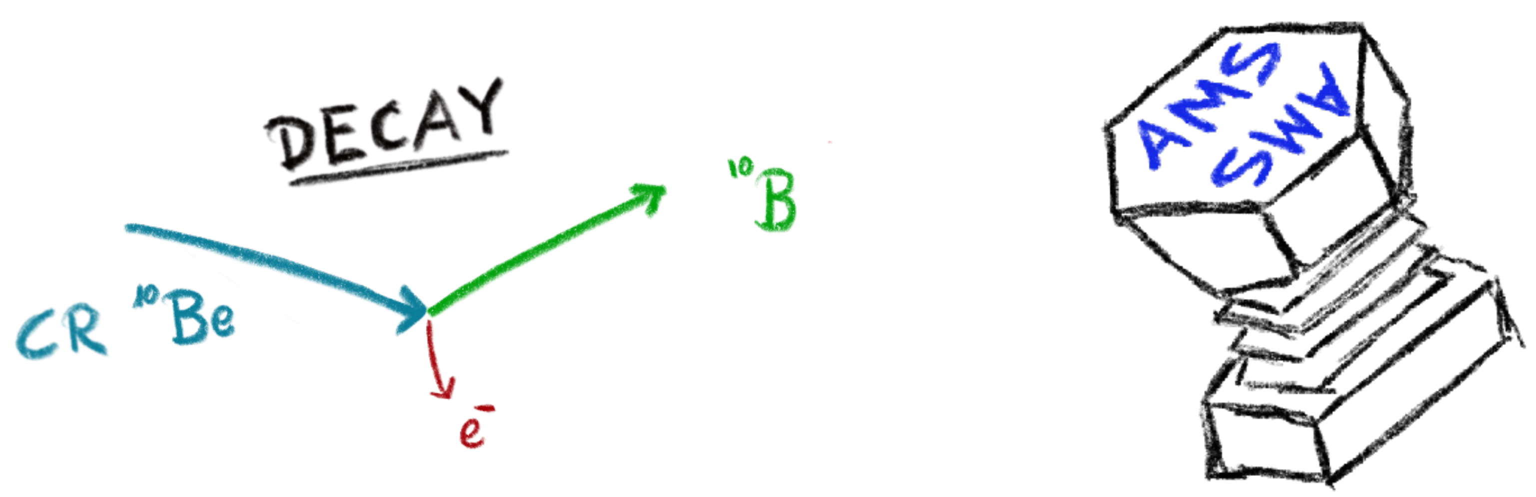


The Leaky Box Model

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



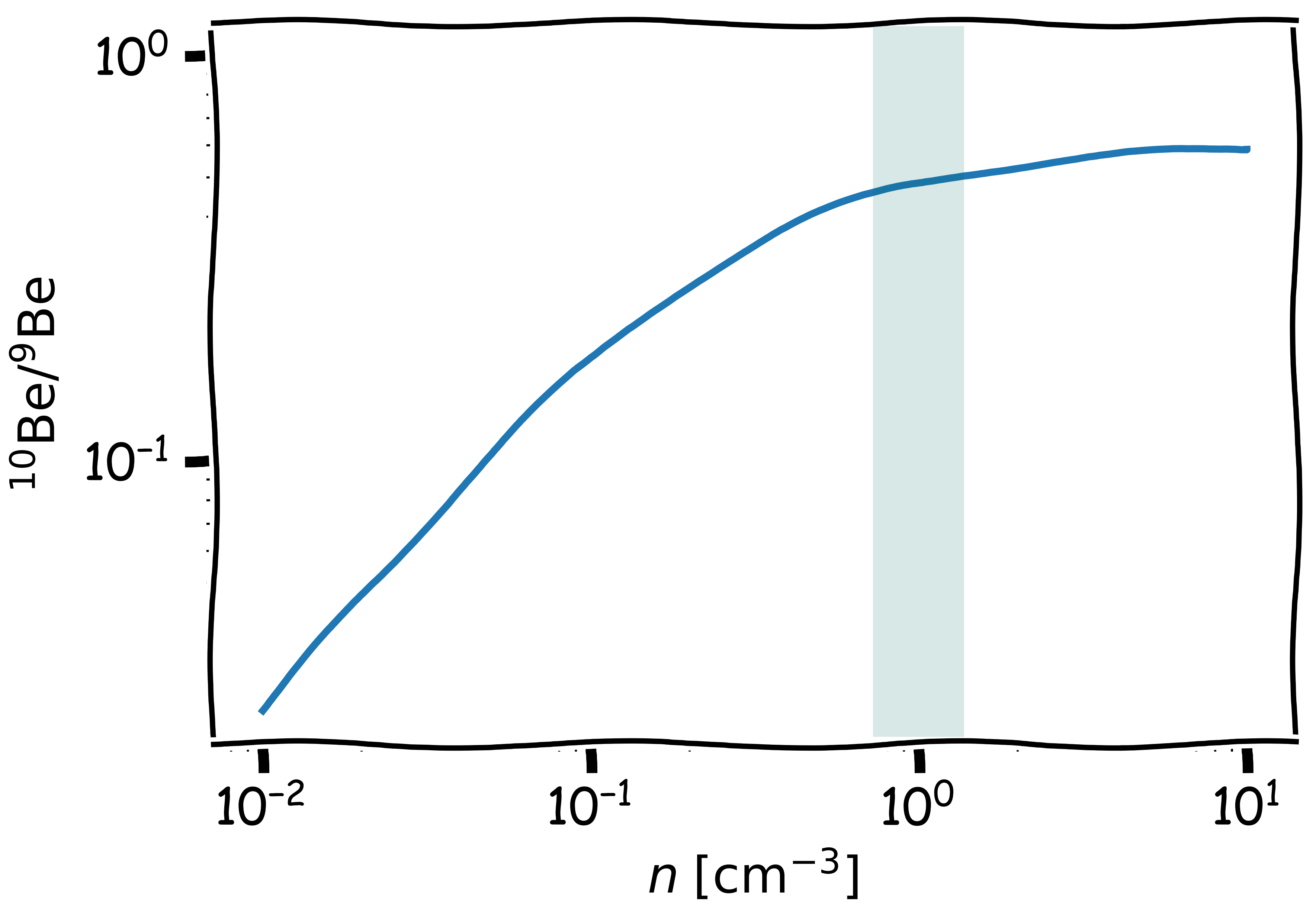
Cosmic-Ray Clocks



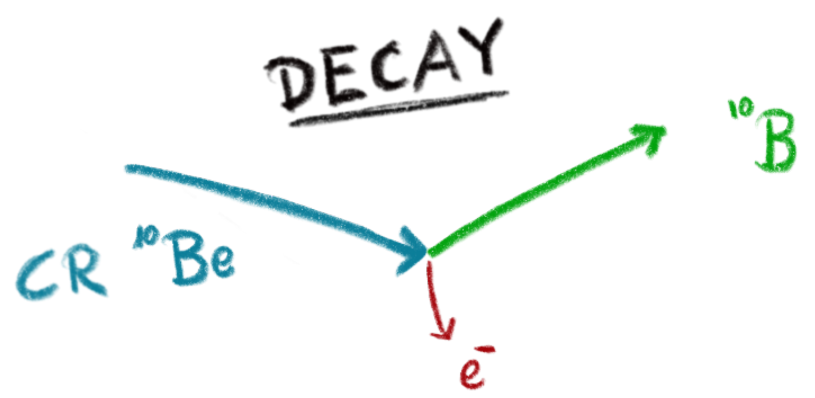
The Leaky Box Model

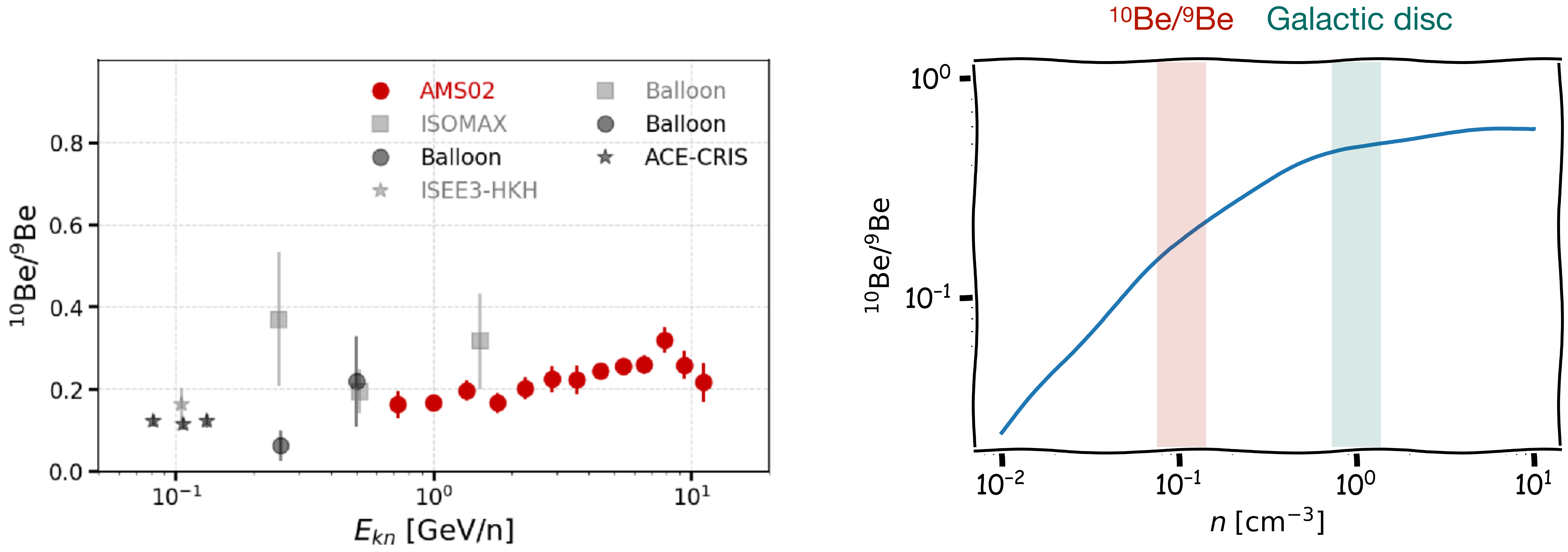
$$\frac{N_{^{10}\mathrm{Be}}}{N_{^{9}\mathrm{Be}}} = \frac{\sigma_{\mathrm{CNO}\to{}^{10}\mathrm{Be}}}{\sigma_{\mathrm{CNO}\to{}^{9}\mathrm{Be}}} \frac{\frac{v\,m_p\,n}{X} + v\,n\,\sigma_9}{\frac{v\,m_p\,n}{X} + v\,n\,\sigma_{10} + \frac{1}{\gamma\tau_{\mathrm{dec},10}}}$$

Galactic disc

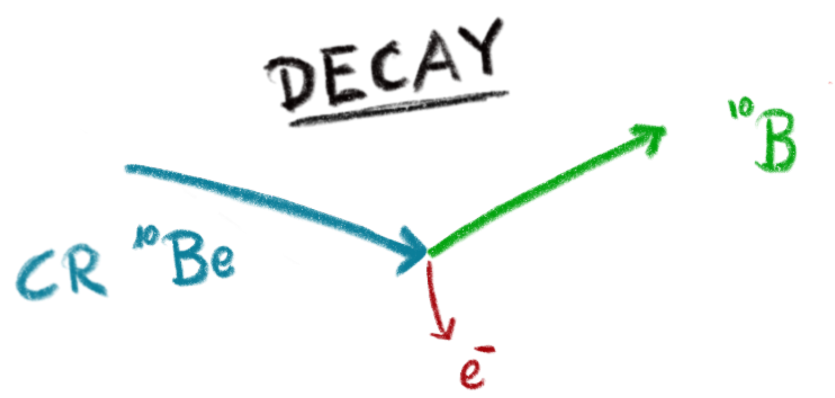


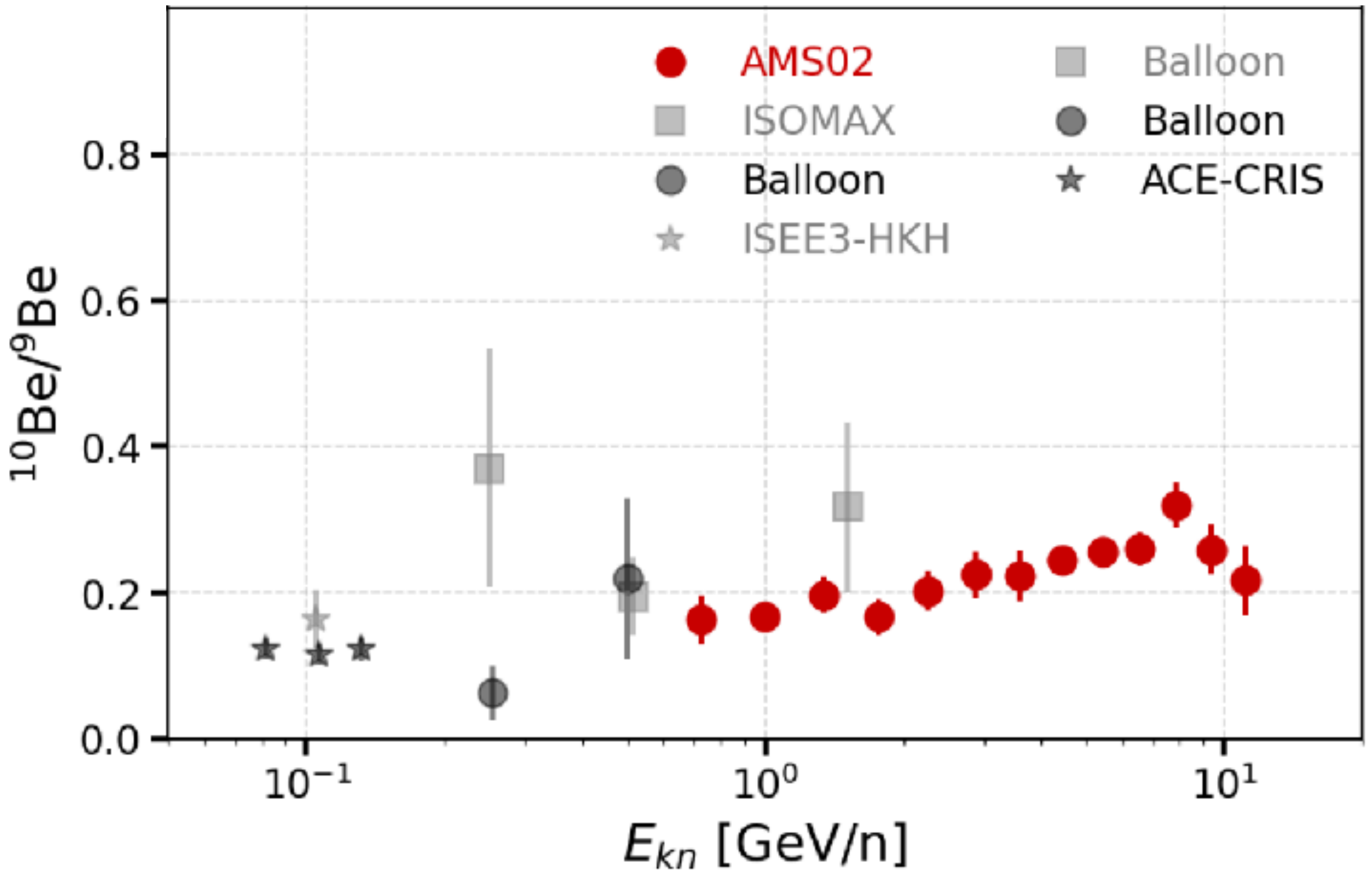
Cosmic-Ray Clocks

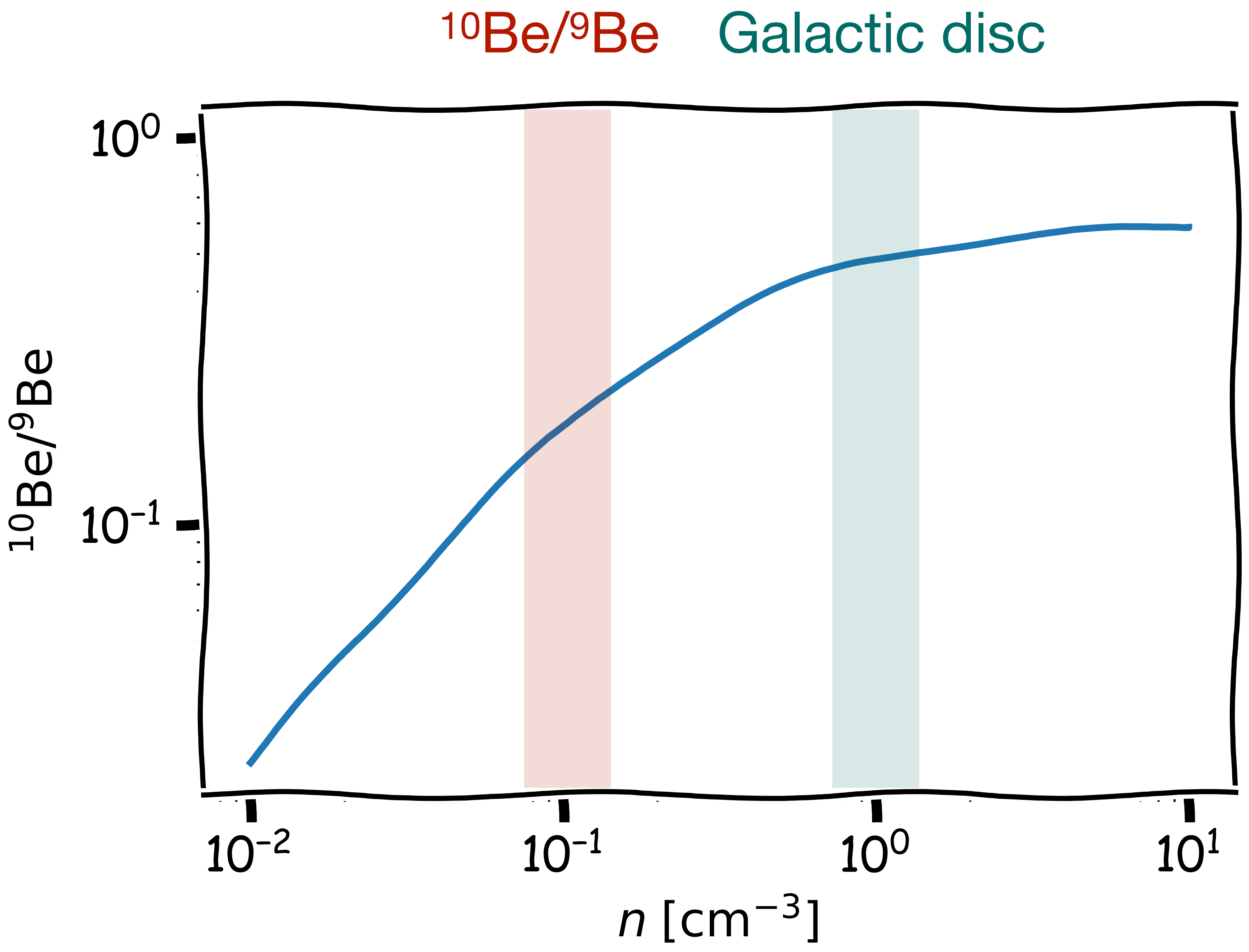




Cosmic-Ray Clocks

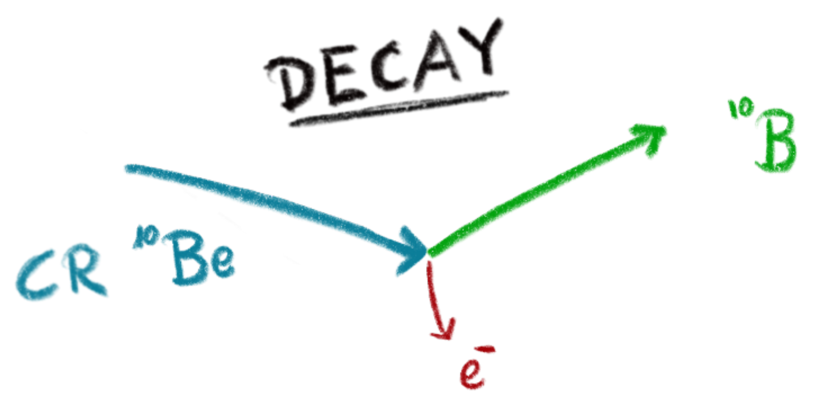


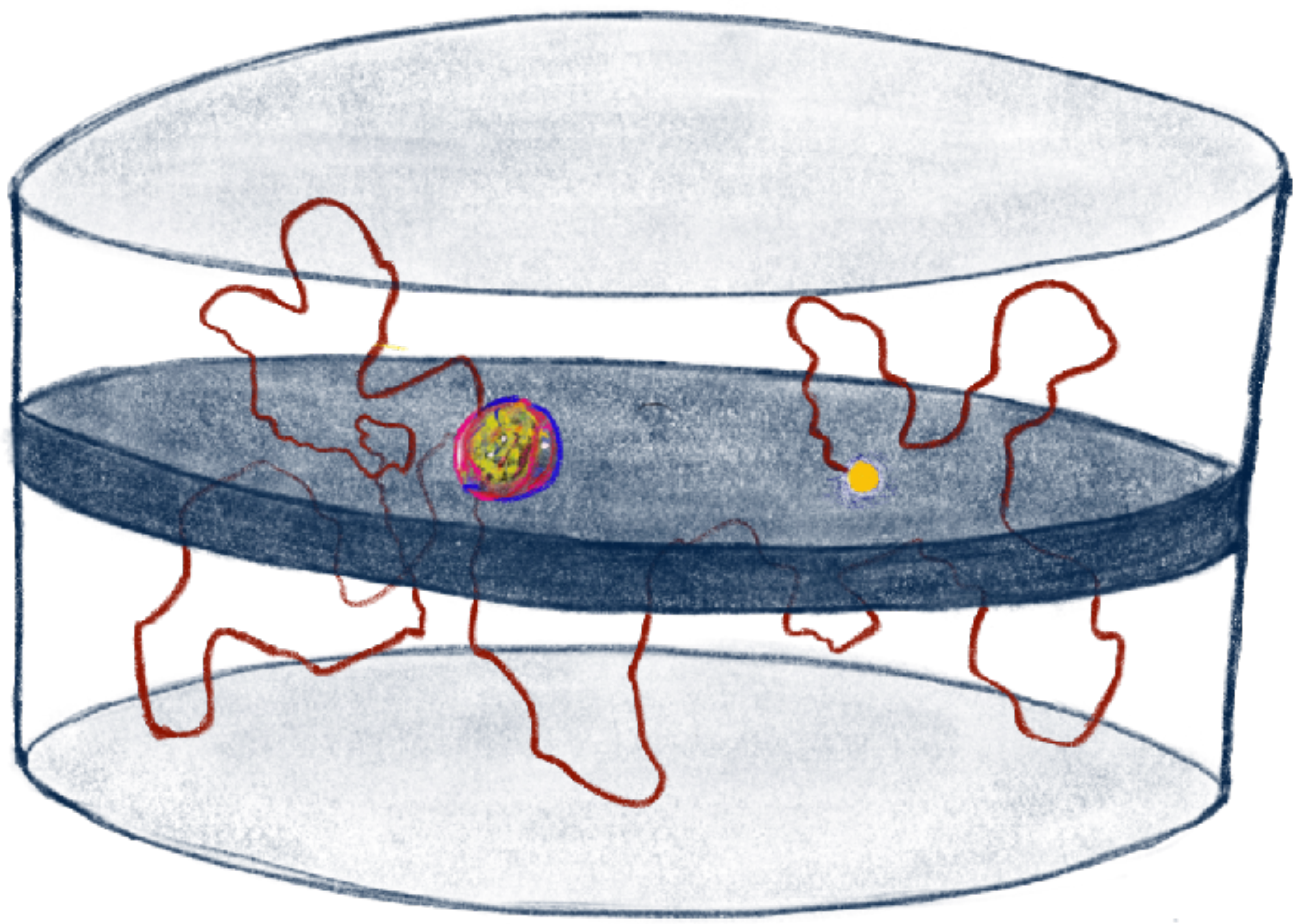




CRs spend a significant time outside the Galactic disc!

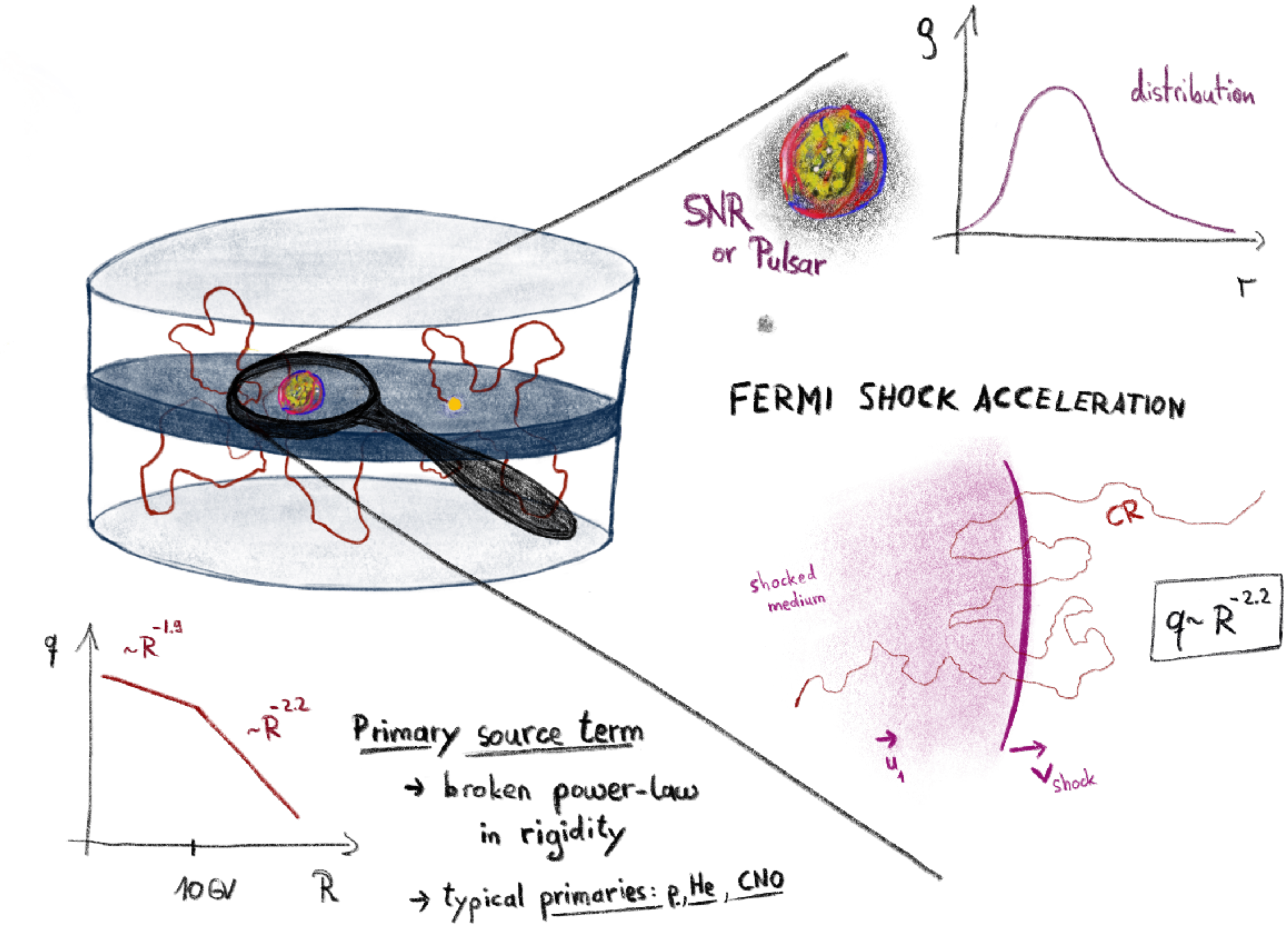
Cosmic-Ray Clocks



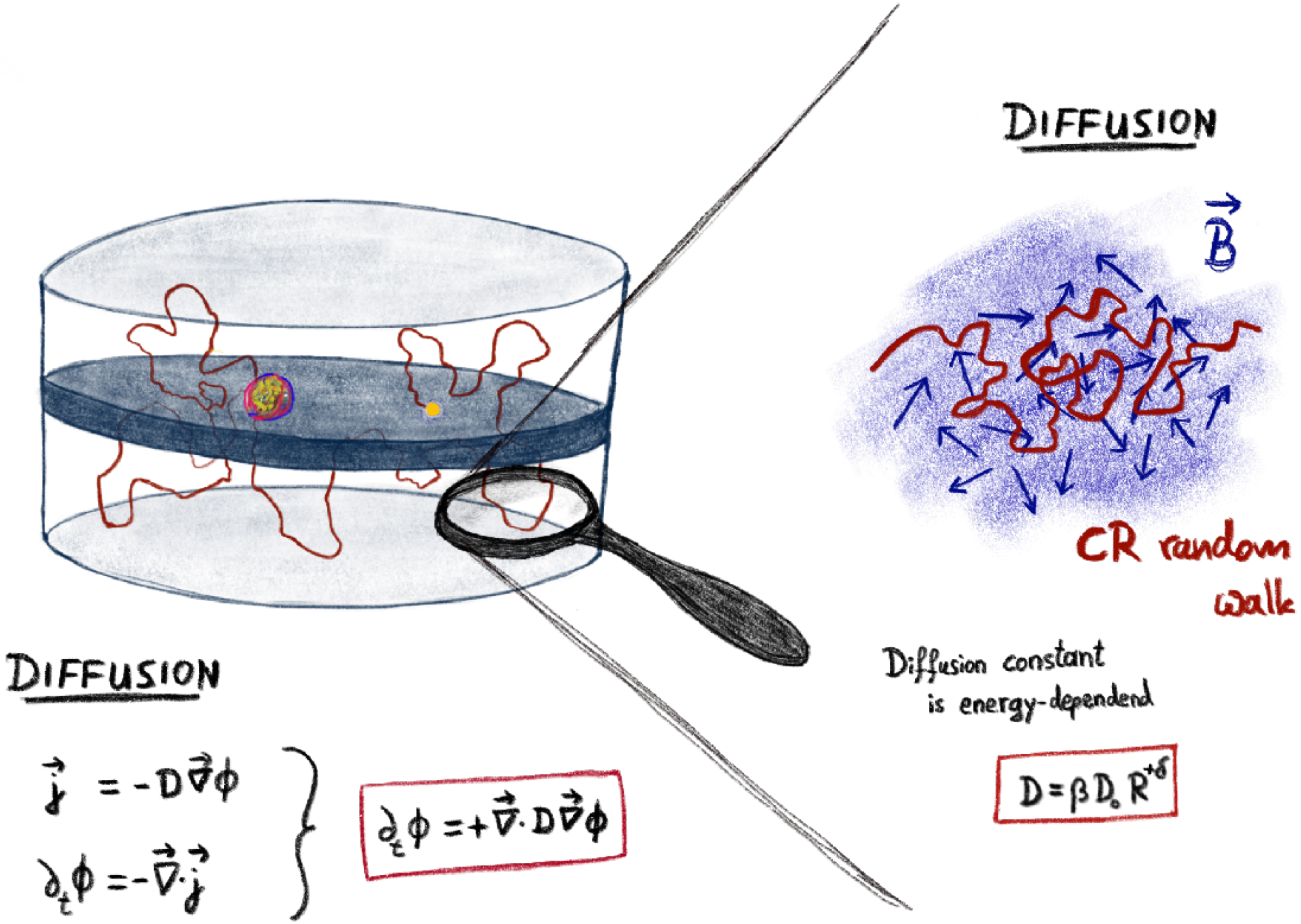


CRs spend a significant time outside the Galactic disc!

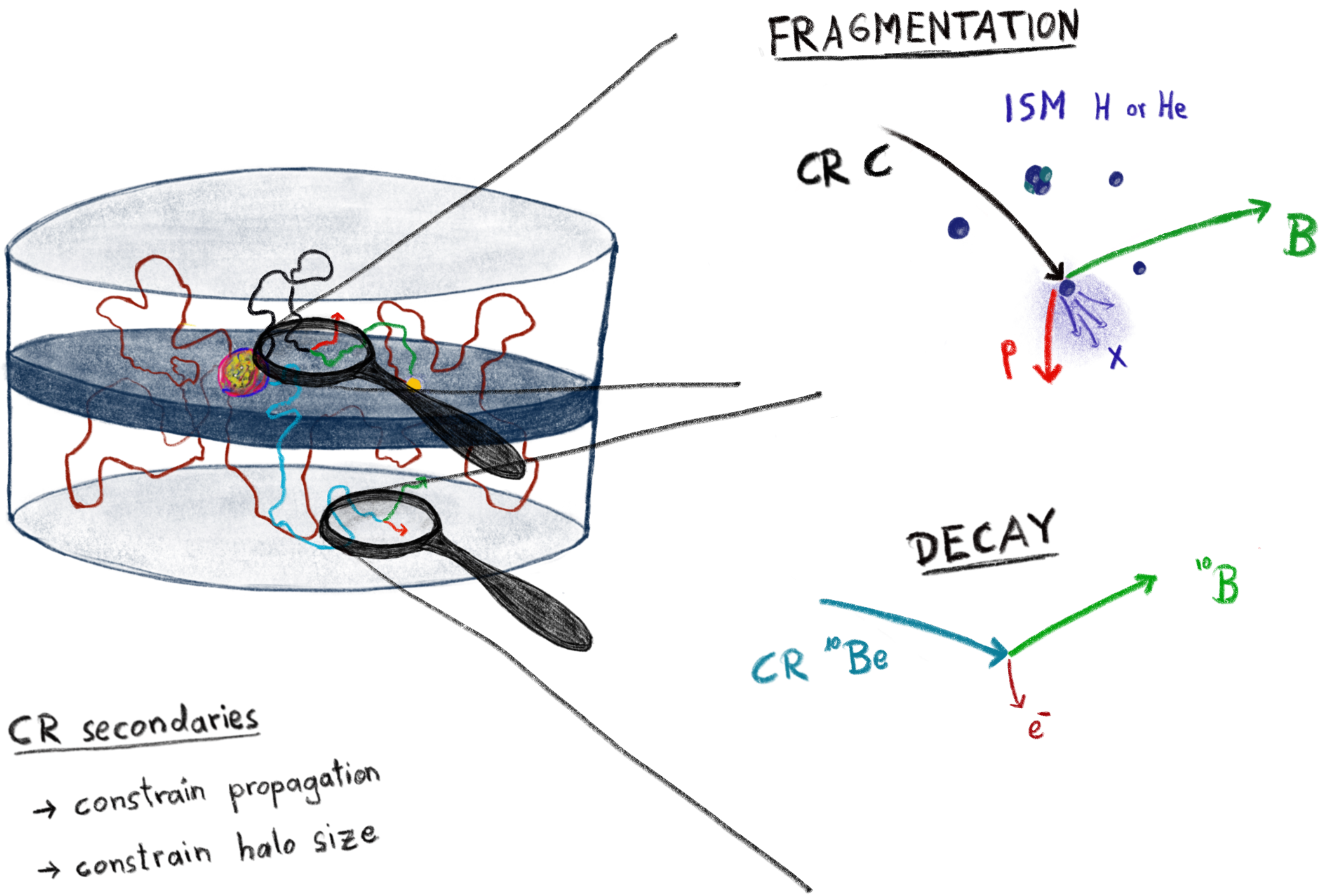
Modeling Cosmic-Ray Propagation



Modeling Cosmic-Ray Propagation



Modeling Cosmic-Ray Propagation



DM limit for DM annihilation — Wino