Fast and Accurate AMS-02 Antiproton Likelihoods for Global Dark Matter Fits


Sowmiya Balan


Kathrin Nippel


Michael Korsmeier

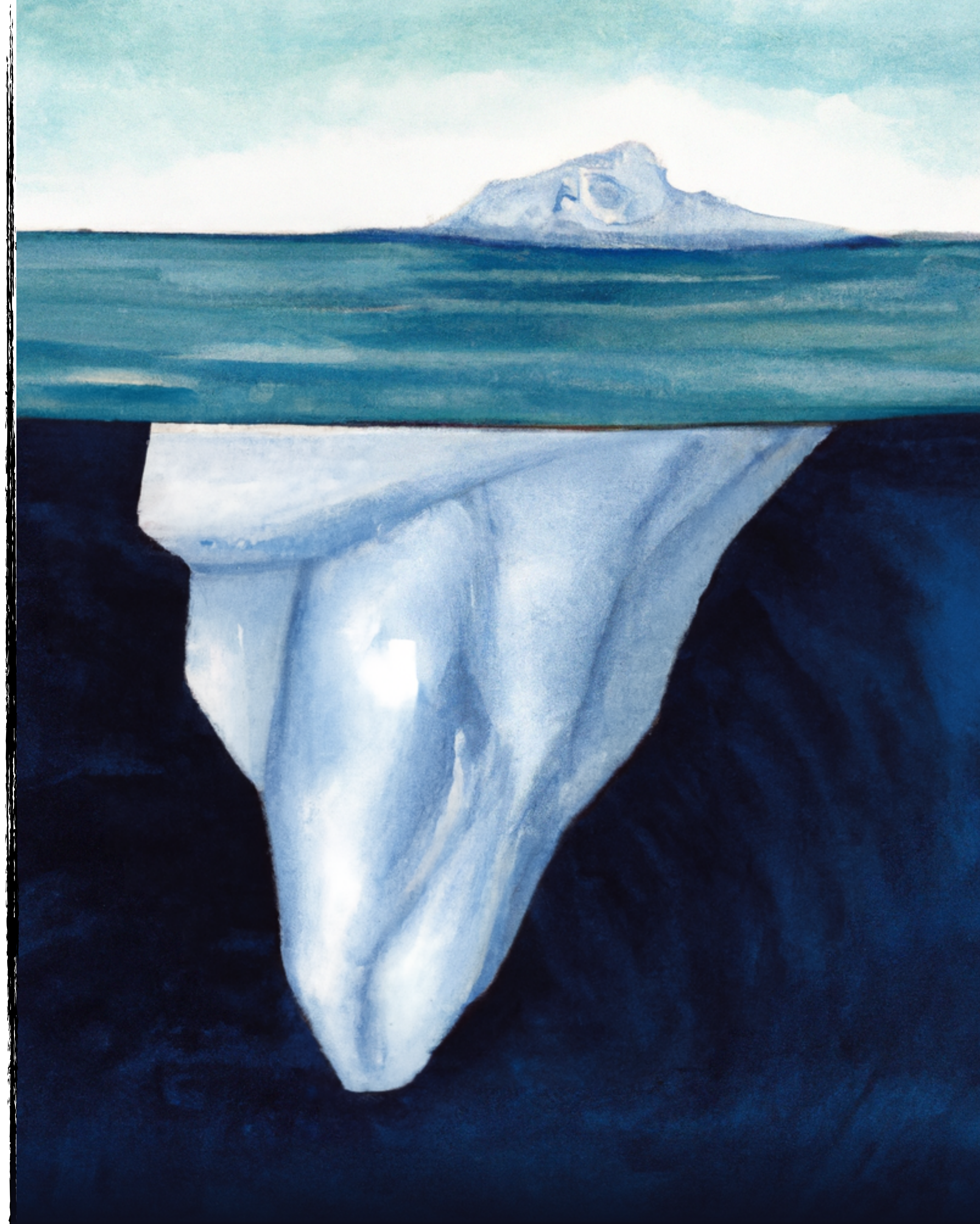

Silvia Manconi


Felix Kahlhoefer

Oskar Klein centre

Stockholm University

TeVPA 2023

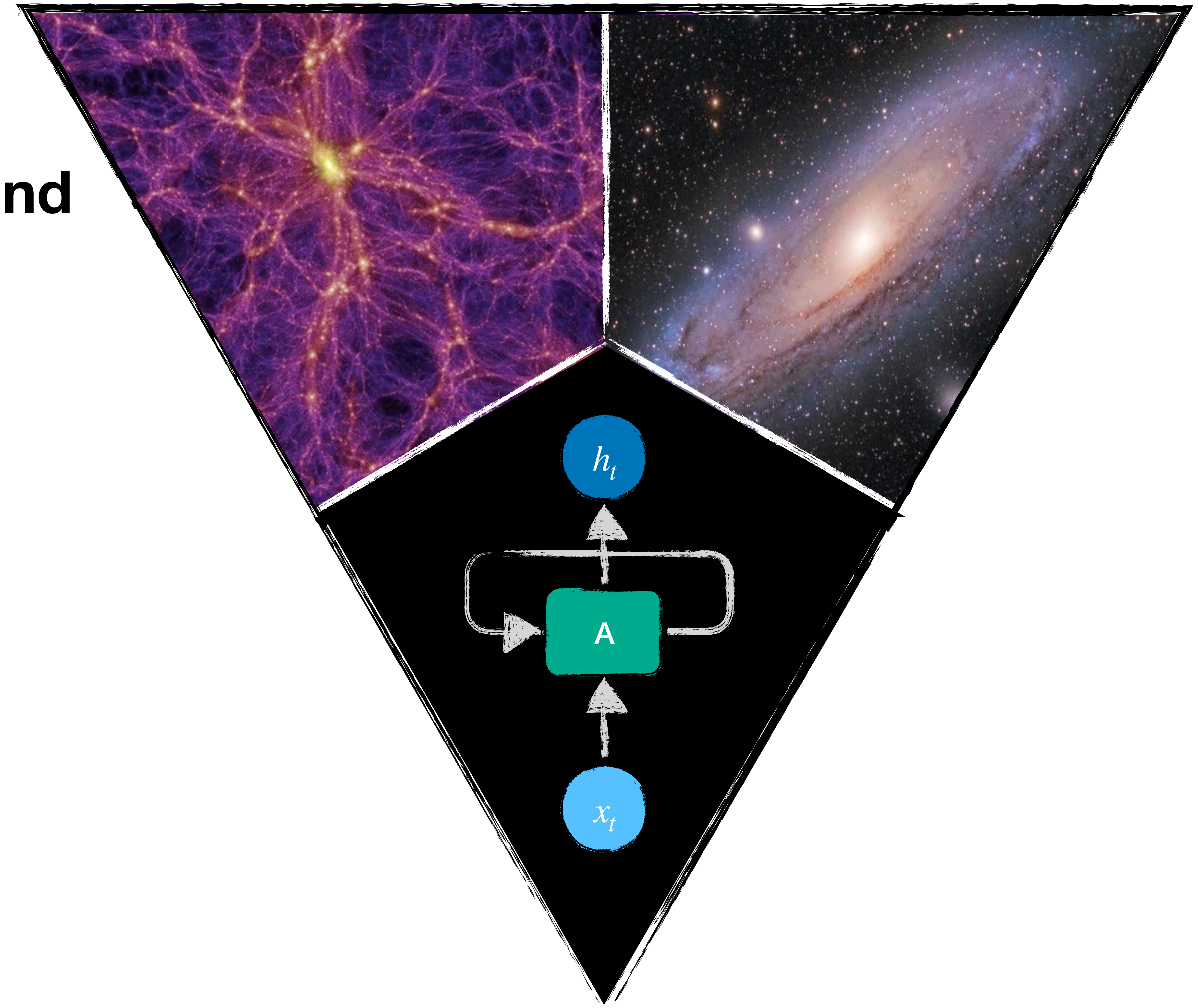


Balan, Sowmiya et al., JCAP 08 (2023) 052

Kahlhoefer, Felix et al., JCAP 12 (2021) 037

Motivation:
Dark Matter Limits and Indirect Detection

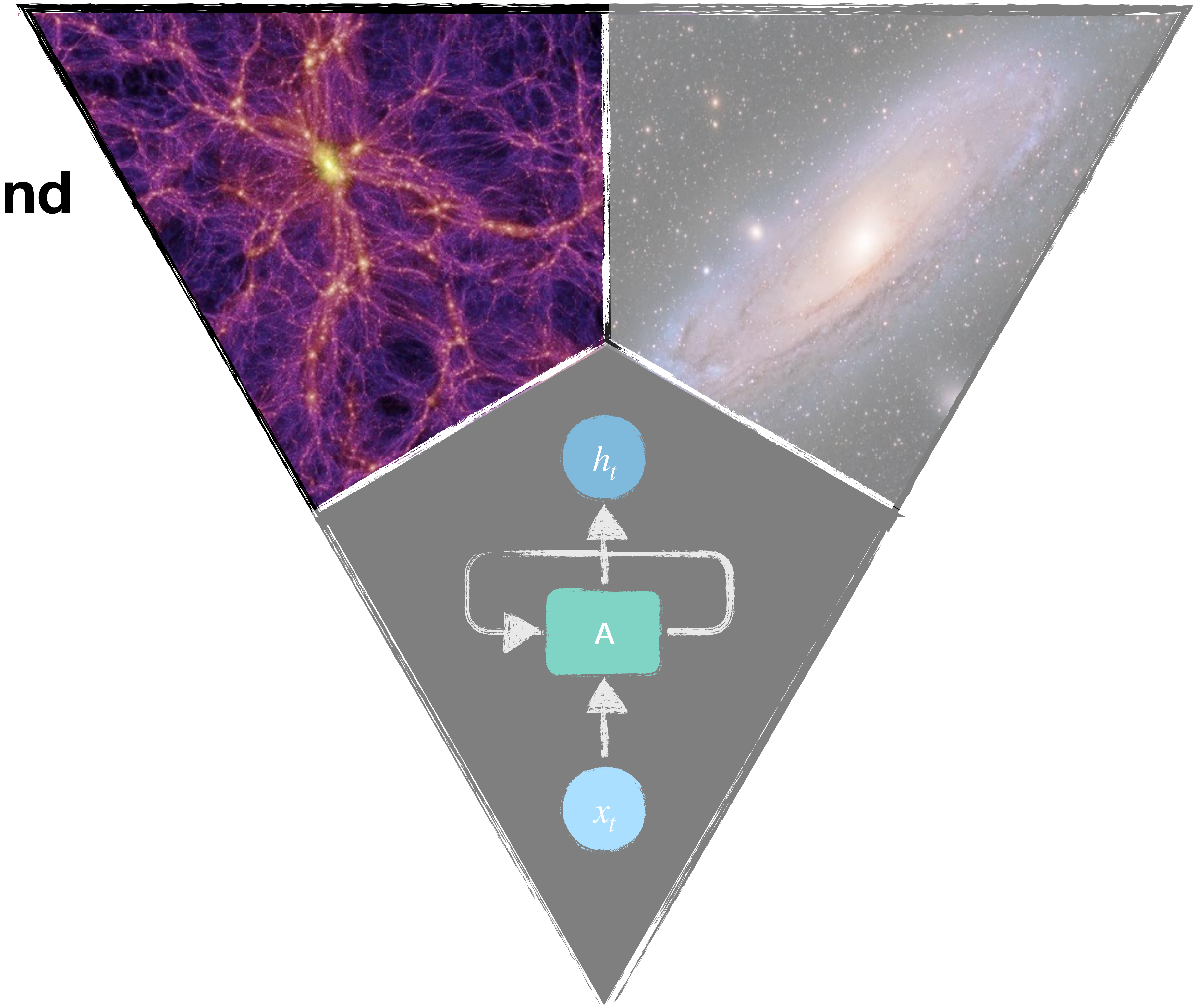
Cosmic Rays:
Propagation and the Role of Antiprotons



Speed-up: Neural Networks and Importance Sampling

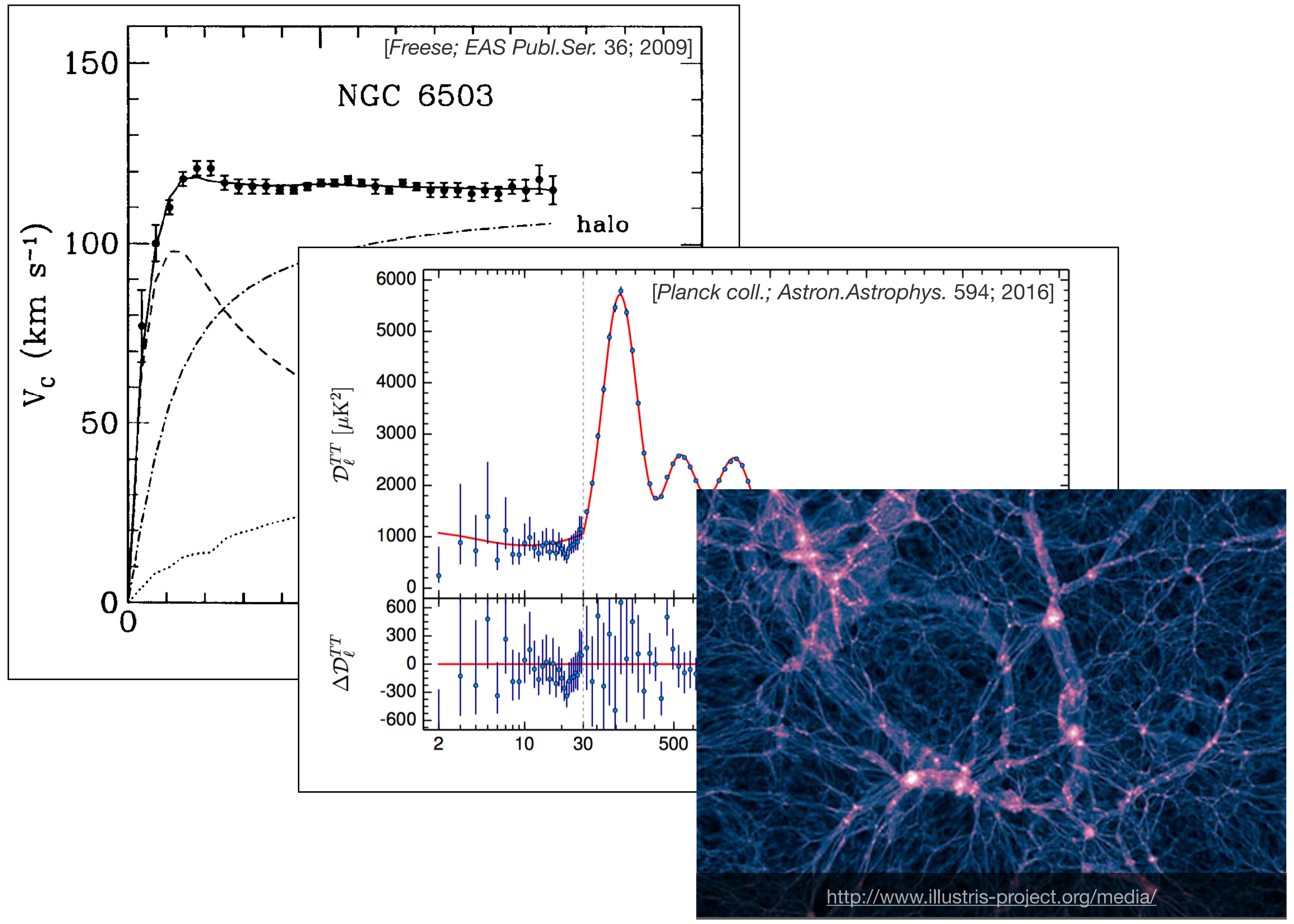
Motivation:
Dark Matter Limits and Indirect Detection

Cosmic Rays:
Propagation and the Role of Antiprotons



Speed-up: Neural Networks and Importance Sampling

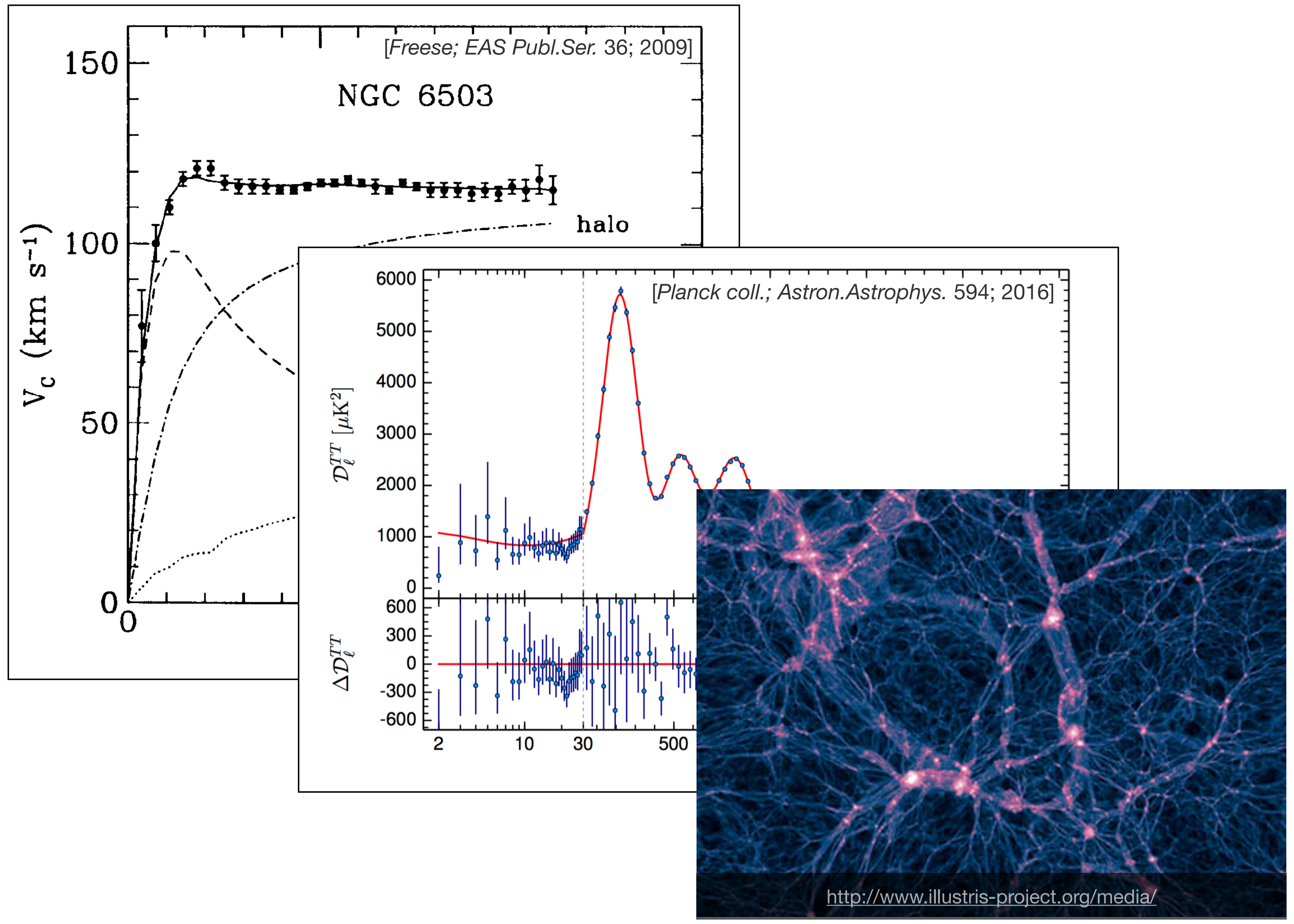
Motivation



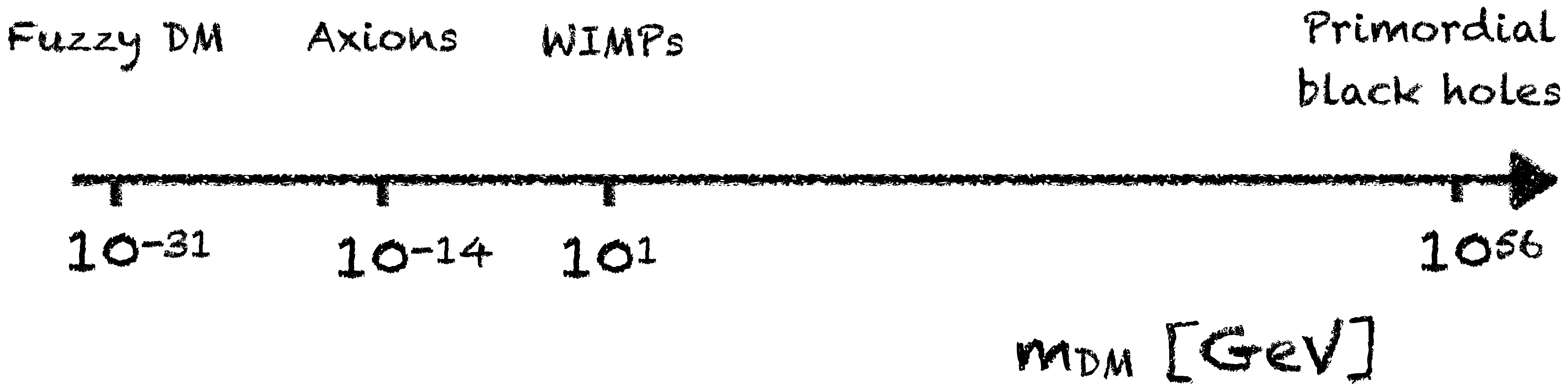
Gravitational evidence at various scales is overwhelming.

More details:
Kenny CY Ng
Tuesday, 9:00 am

Motivation



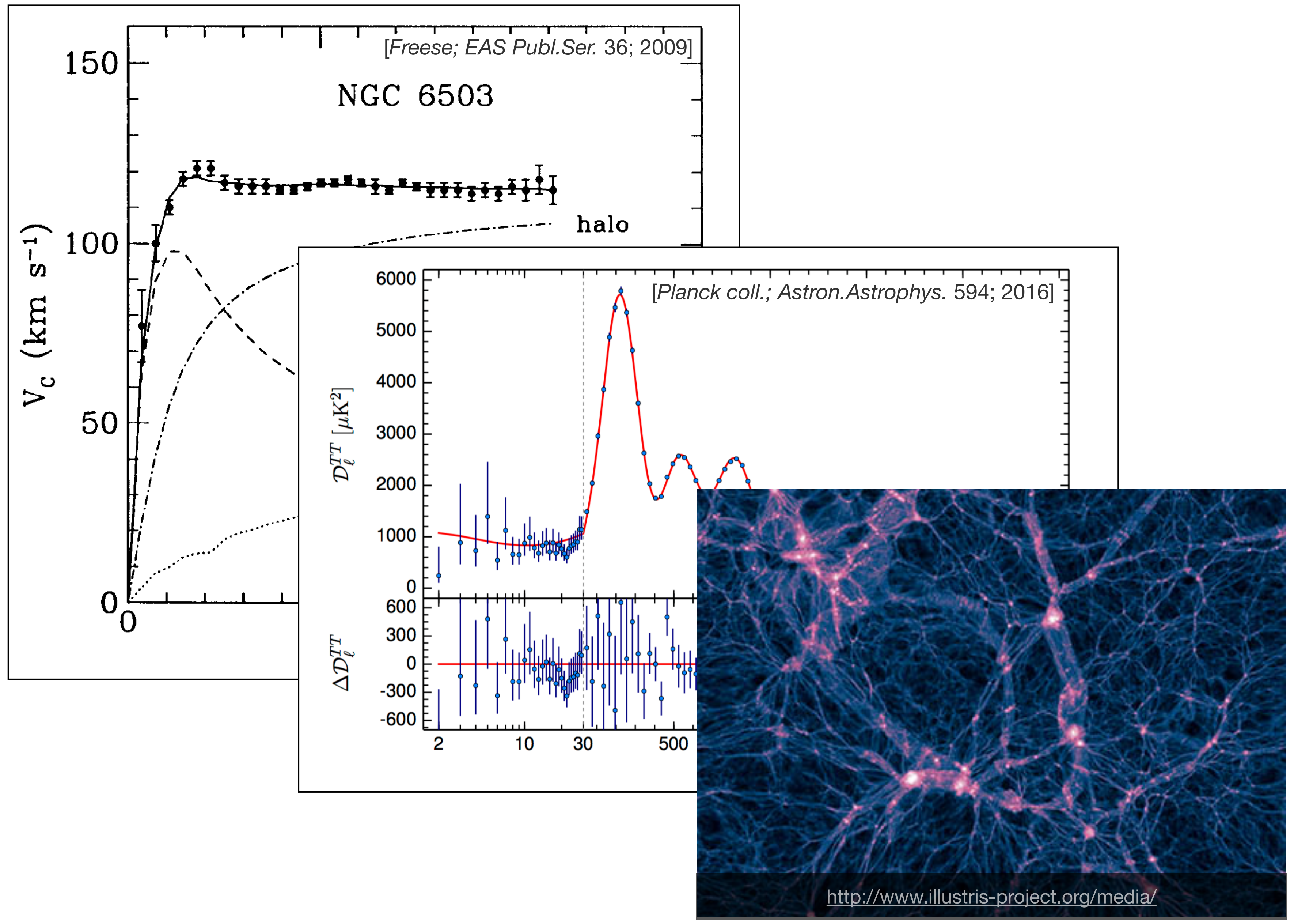
Gravitational evidence at various scales is overwhelming.



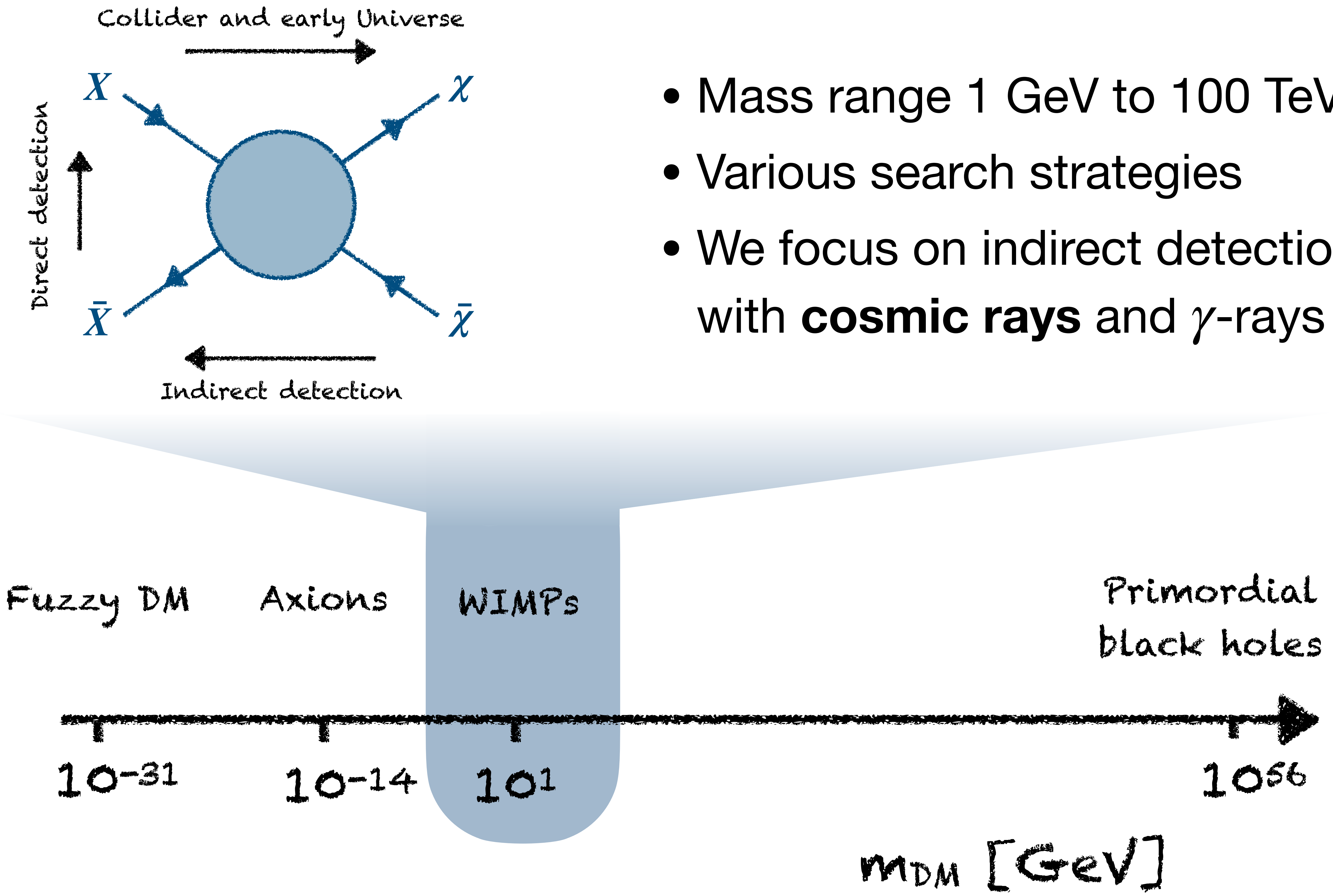
More details:
Kenny CY Ng
Tuesday, 9:00 am

Nature of dark matter remains unknown!

Motivation



Gravitational evidence at various scales is overwhelming.

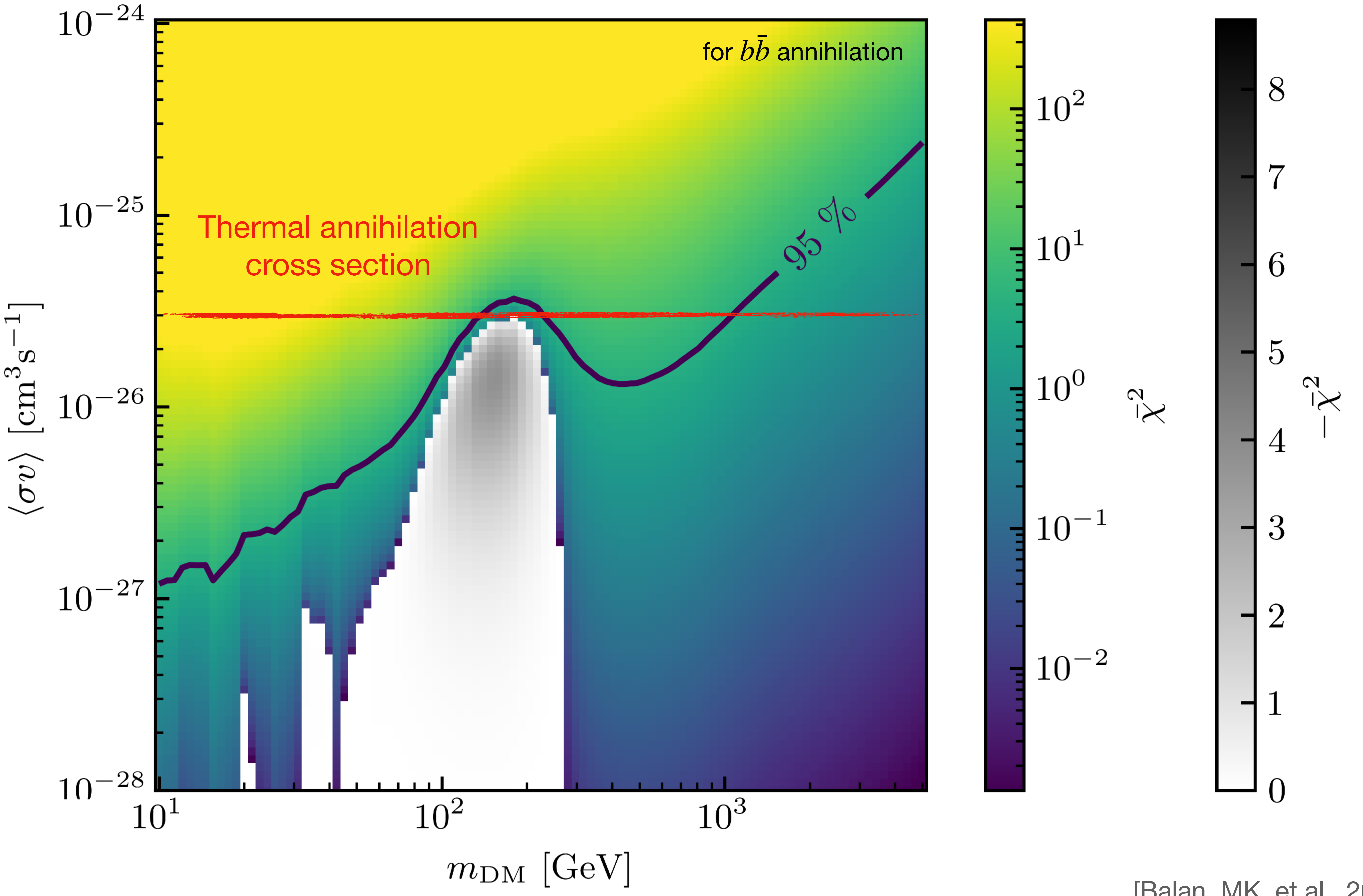


- Mass range 1 GeV to 100 TeV
- Various search strategies
- We focus on indirect detection with **cosmic rays** and γ-rays

More details:
Kenny CY Ng
Tuesday, 9:00 am

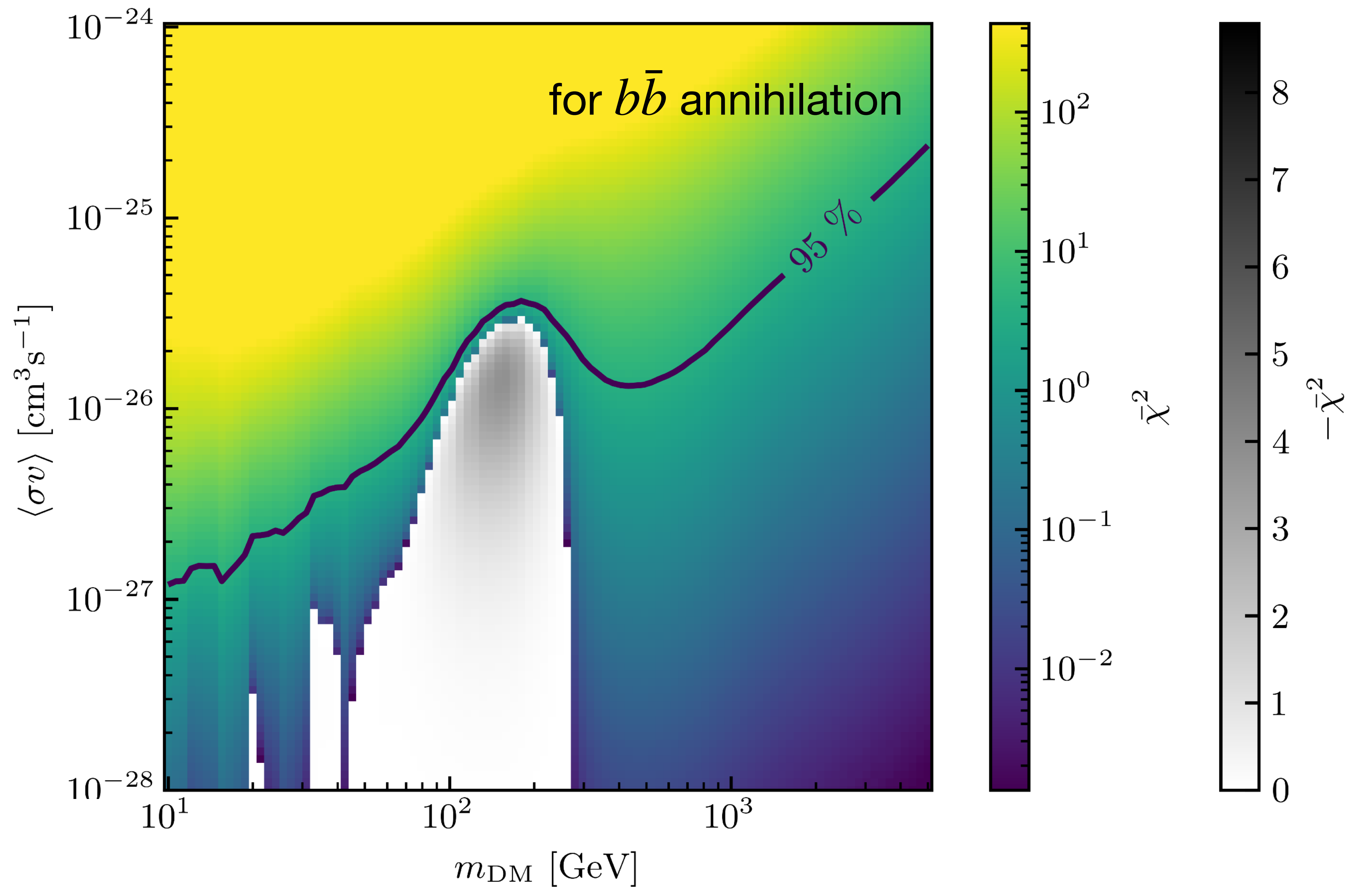
Nature of dark matter remains unknown!

Limits for DM Annihilation



[Balan, MK, et al. 2023]

Limits for DM Annihilation



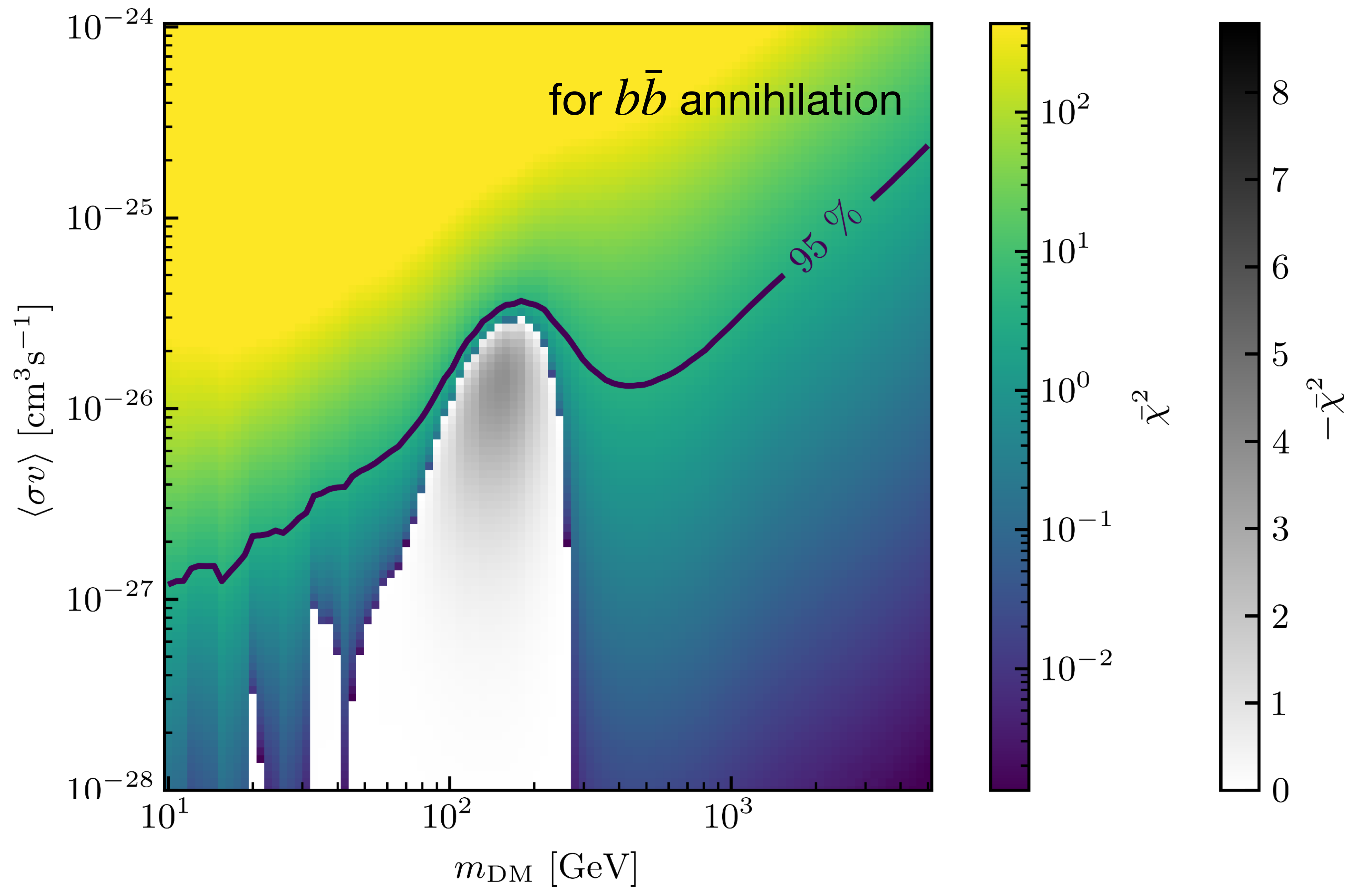
DARK RAY NET

pbarlike

GAMBIT

[Balan, MK, et al. 2023]

Limits for DM Annihilation



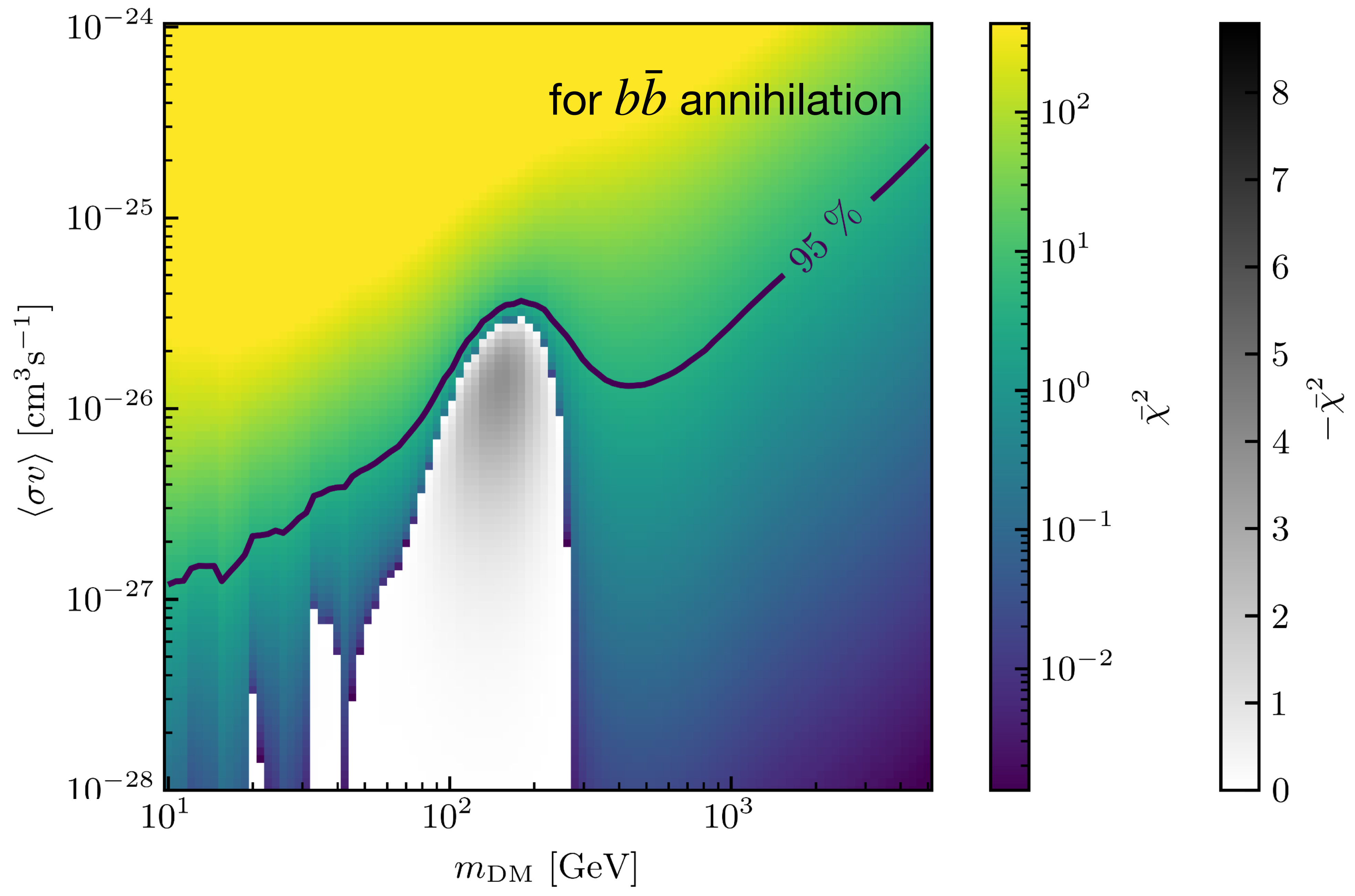
DARK RAY NET

pbarlike

GAMBIT

- Neural Network predicting CR signals
- Wide range of propagation parameters/models
- Likelihood of AMS-02 data
- Correlation, $\bar{p}$ cross section uncertainties, marginalization over propagation
- Global fits of DM models including `pbarlike`

Limits for DM Annihilation



DARK RAY NET

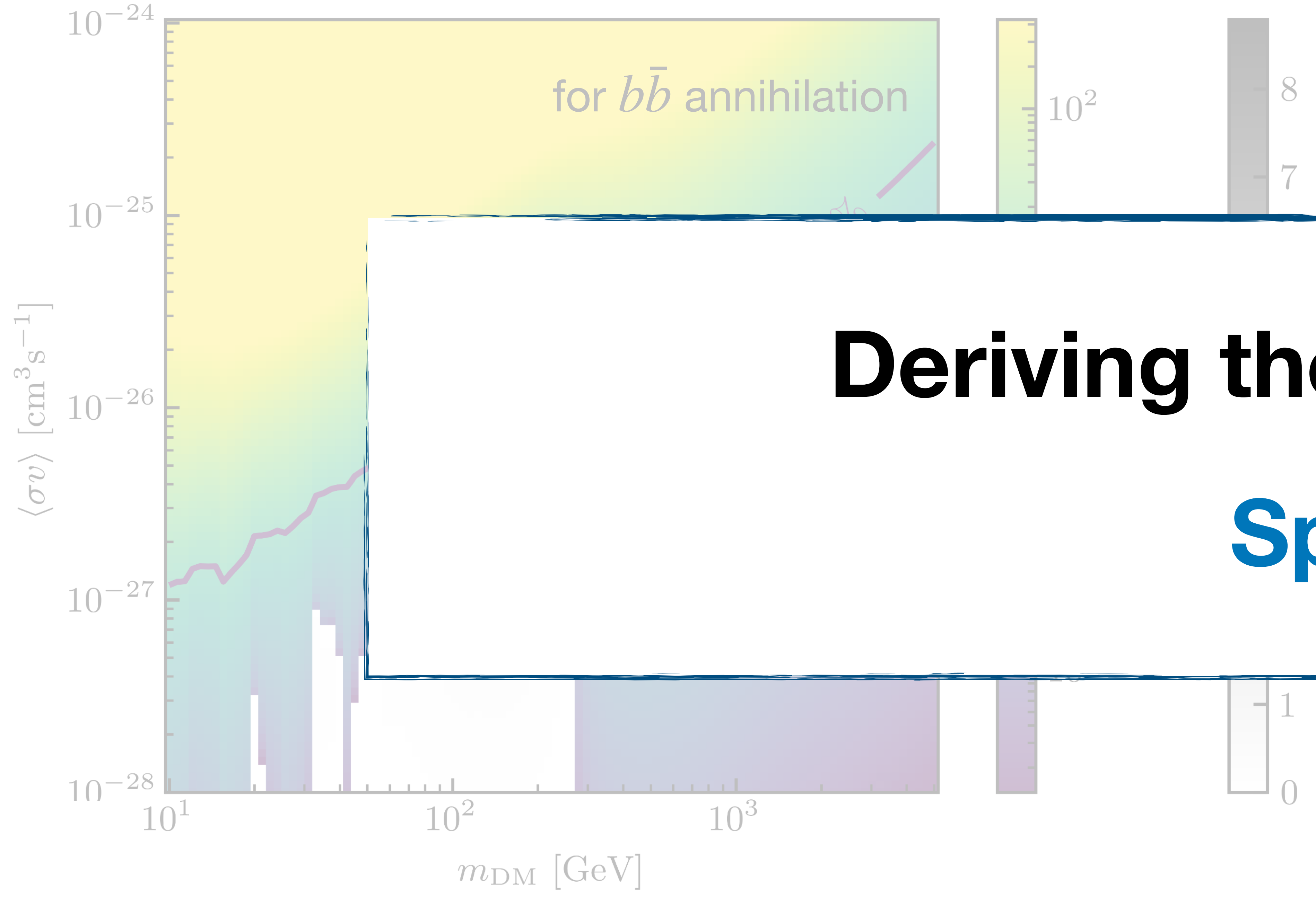
pbarlike

GAMBIT

Expert: Kathrin Nippel

Expert: Sowmiya Balan

Limits for DM Annihilation



n Nippel

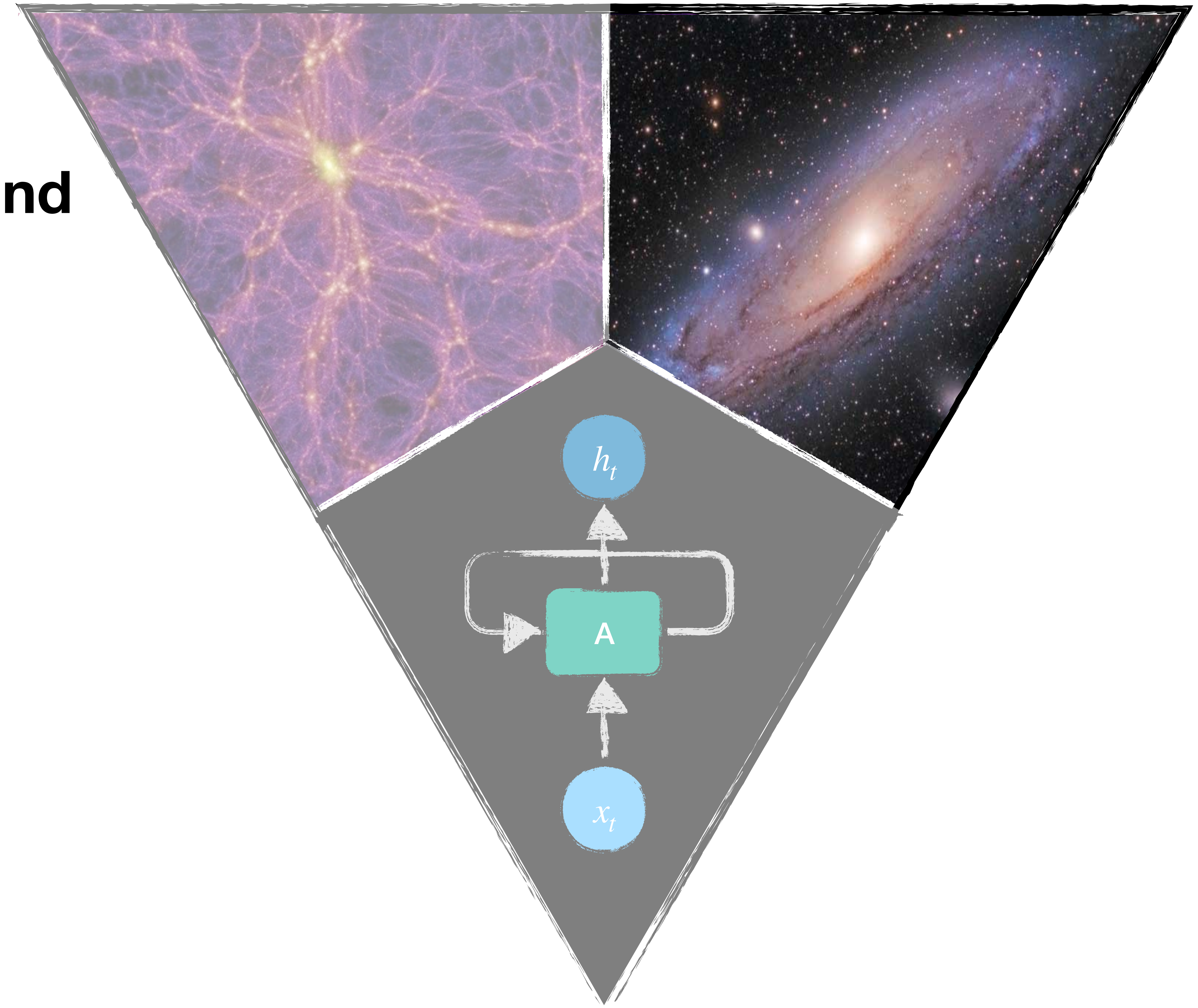
Deriving the limit takes ~ 60 cpu-hours.

Speed-up of $\mathcal{O}(100)$!

Expert: Sowmiya Balan

Motivation:
Dark Matter Limits and Indirect Detection

Cosmic Rays:
Propagation and the Role of Antiprotons



Speed-up: Neural Networks and Importance Sampling

State of the Art CR Modeling

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

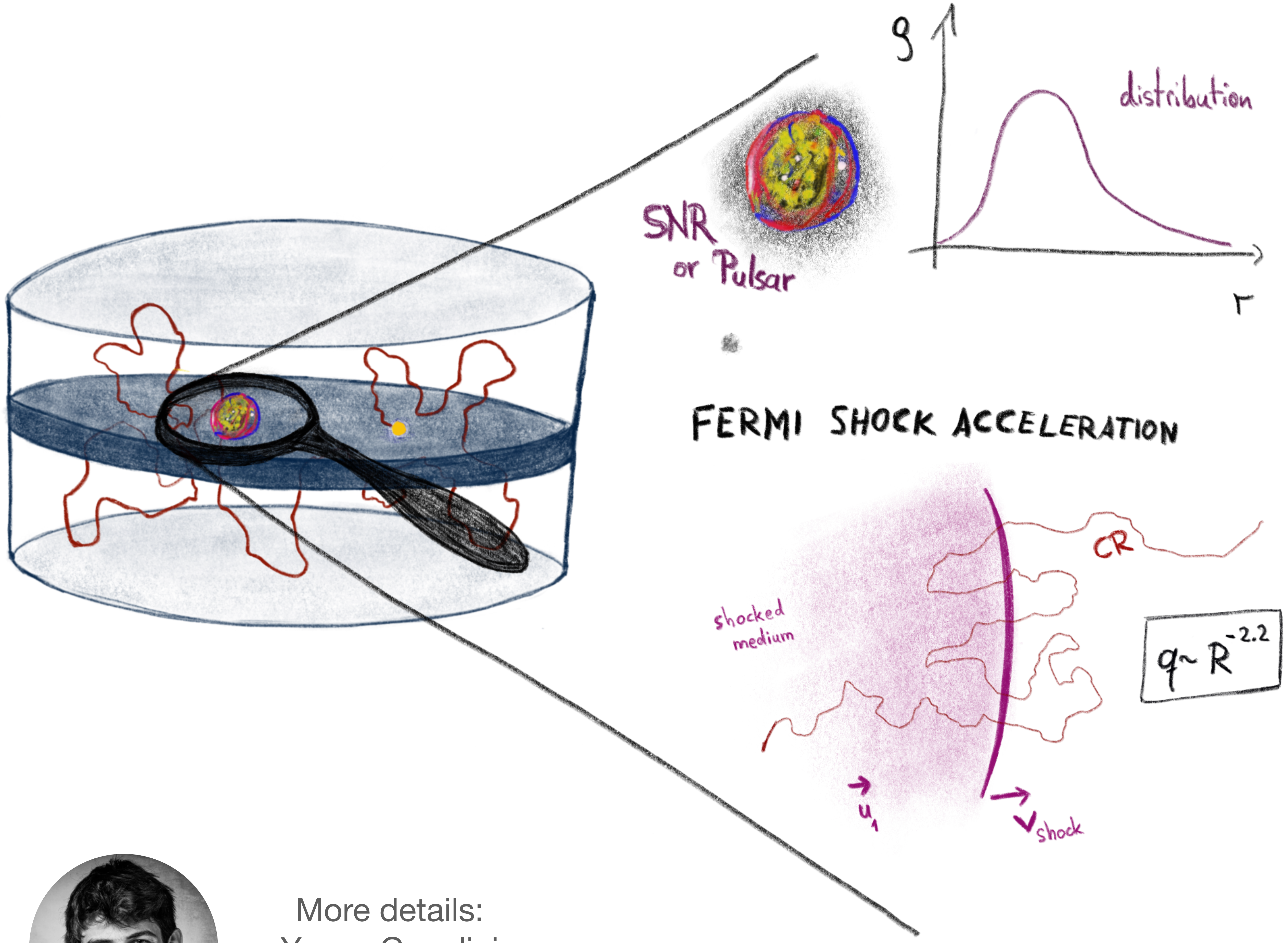
$$-\frac{\partial}{\partial p}\left(\frac{dp}{dt} \psi_i\right)$$
Energy losses

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

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

More details:
Yoann Genolini
Monday, 10:20 am

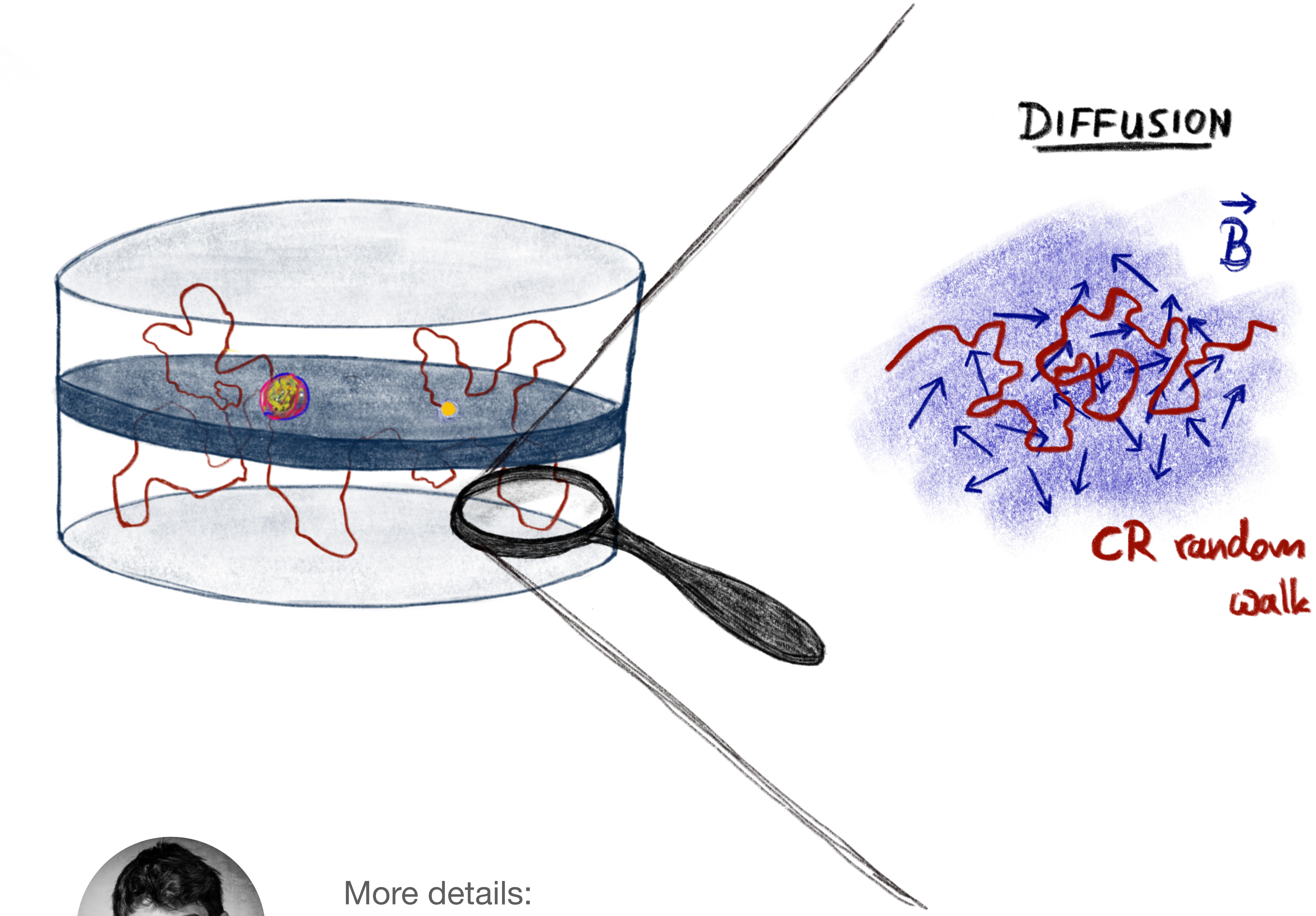
State of the Art CR Modeling



$$
\begin{aligned}
\frac{d\psi_i}{dt} = & \ \boxed{q_i(\boldsymbol{x}, p)} && \text{Source term} \\
& + \nabla D_{xx} \nabla \psi_i && \text{Diffusion} \\
& - \nabla \boldsymbol{V} \psi_i + \frac{\partial}{\partial p}\left(\frac{p}{3} \nabla \cdot \boldsymbol{V} \psi_i\right) && \text{Convection} \\
& - \frac{\partial}{\partial p}\left(\frac{dp}{dt} \psi_i\right) && \text{Energy losses} \\
& - \frac{\psi_i}{\tau_f} - \frac{\psi_i}{\tau_r} && \text{Fragmentation and decay} \\
& + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i && \text{Reacceleration}
\end{aligned}
$$

More details:
Yoann Genolini
Monday, 10:20 am

State of the Art CR Modeling



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

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

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

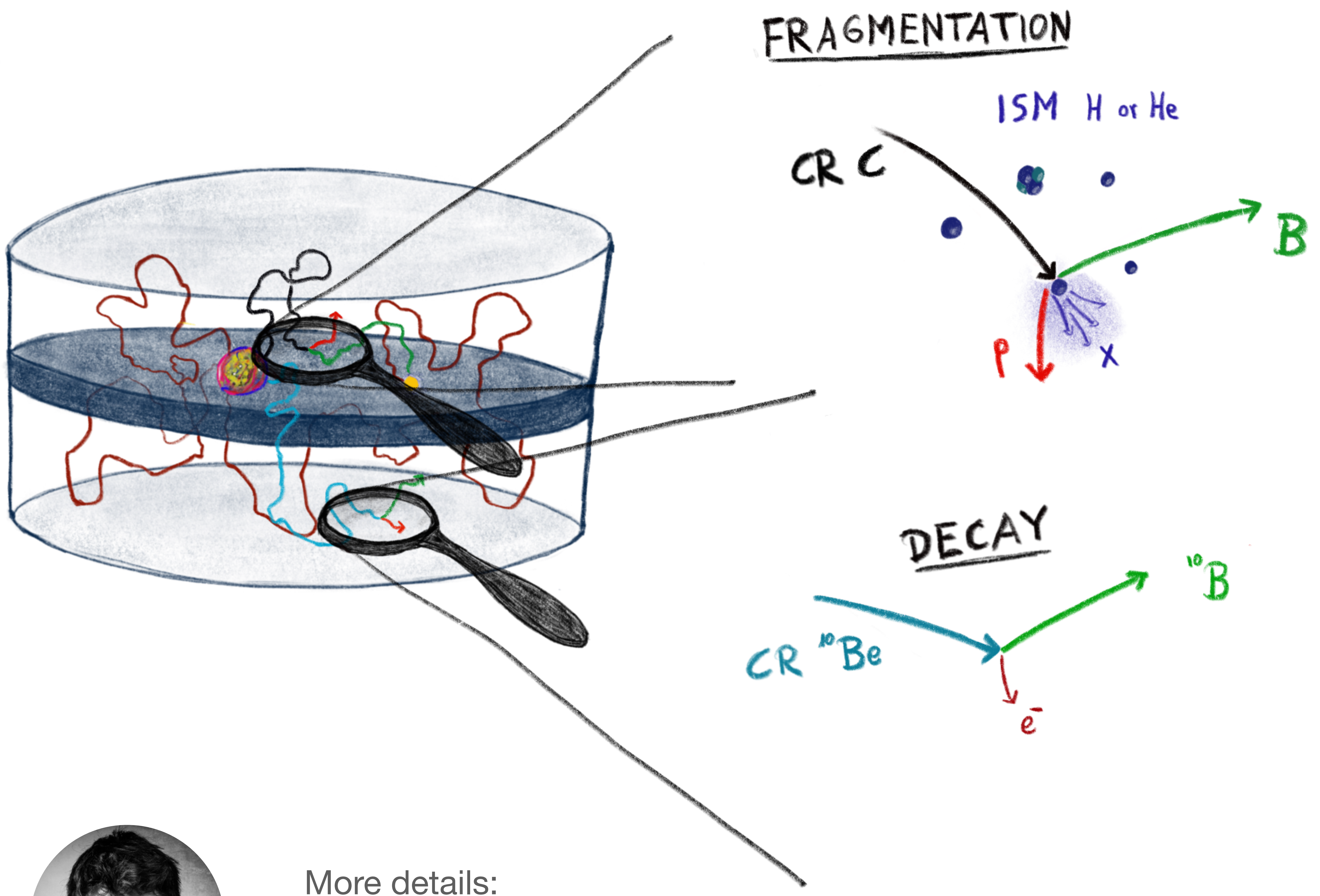
$$-\frac{\partial}{\partial p}\left(\frac{dp}{dt}\psi_i\right)$$ Energy losses

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

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

More details:
Yoann Genolini
Monday, 10:20 am

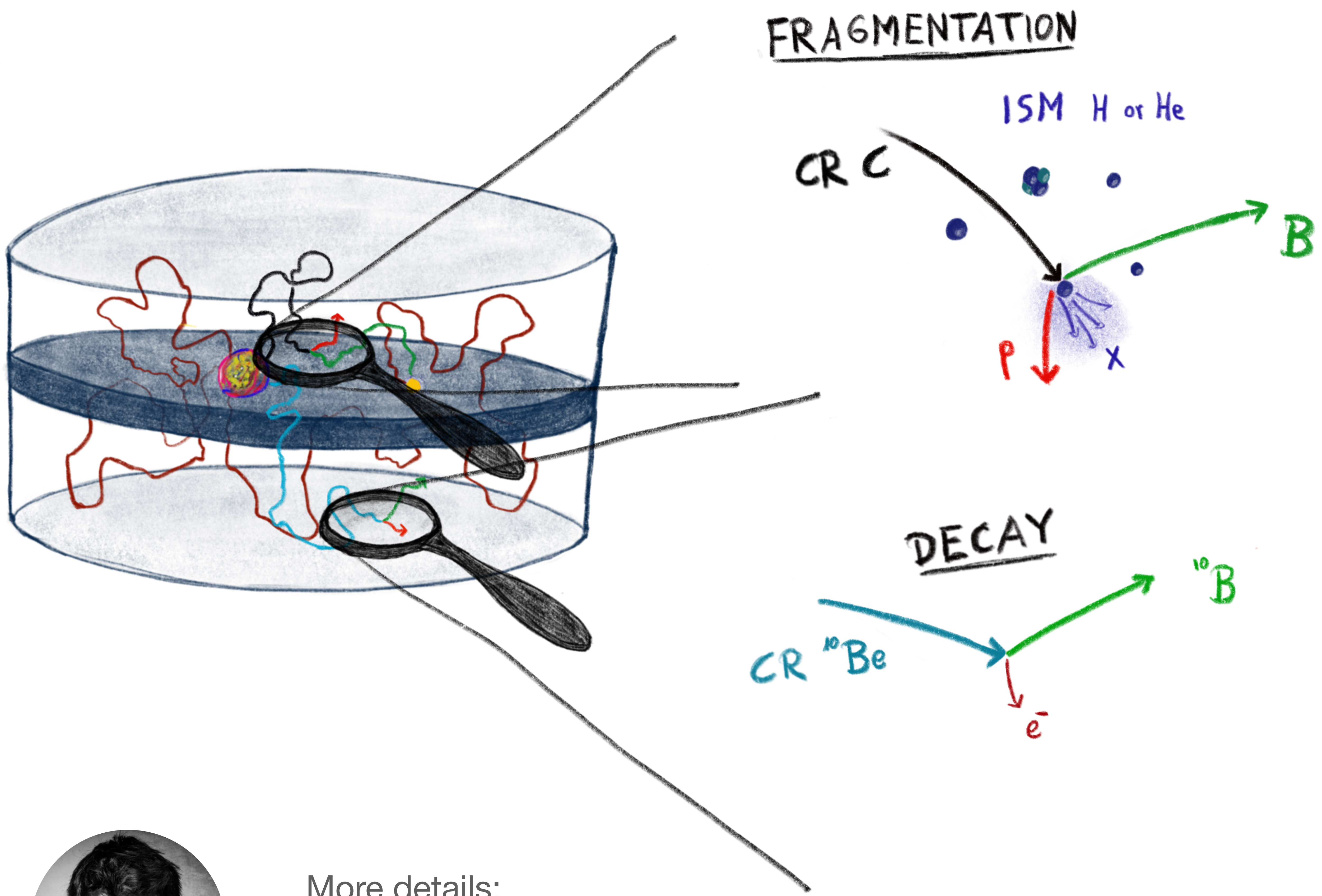
State of the Art CR Modeling



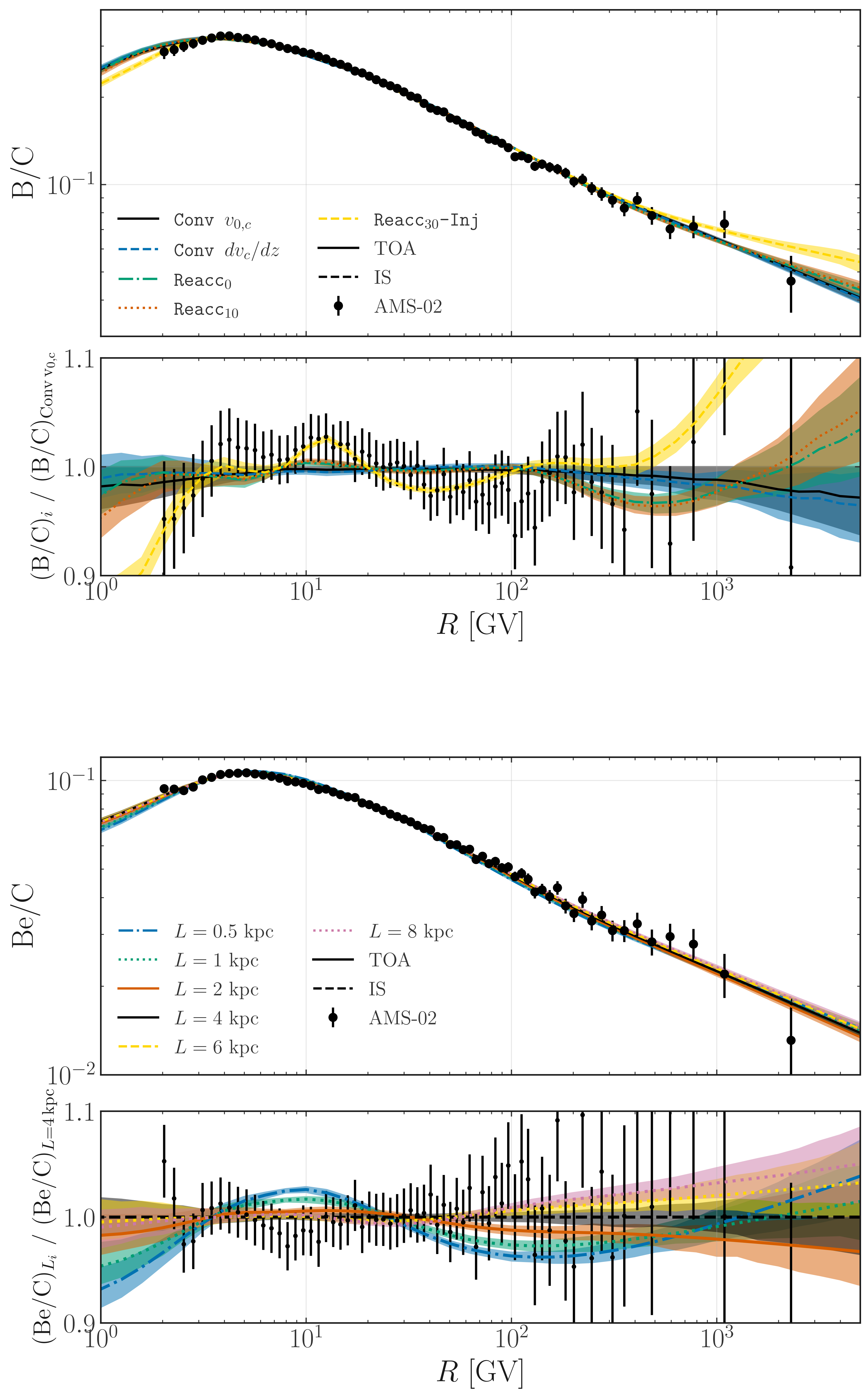
$$
\begin{aligned}
\frac{d\psi_i}{dt} &= q_i(\boldsymbol{x}, p) && \text{Source term}\\
&+ \nabla D_{xx} \nabla \psi_i && \text{Diffusion}\\
&- \nabla \boldsymbol{V} \psi_i + \frac{\partial}{\partial p}\left(\frac{p}{3}\nabla \cdot \boldsymbol{V}\psi_i\right) && \text{Convection}\\
&- \frac{\partial}{\partial p}\left(\frac{dp}{dt}\psi_i\right) && \text{Energy losses}\\
&\boxed{- \frac{\psi_i}{\tau_f} - \frac{\psi_i}{\tau_r} \qquad \text{Fragmentation and decay}}\\
&+ \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i && \text{Reacceleration}
\end{aligned}
$$

More details:
Yoann Genolini
Monday, 10:20 am

State of the Art CR Modeling

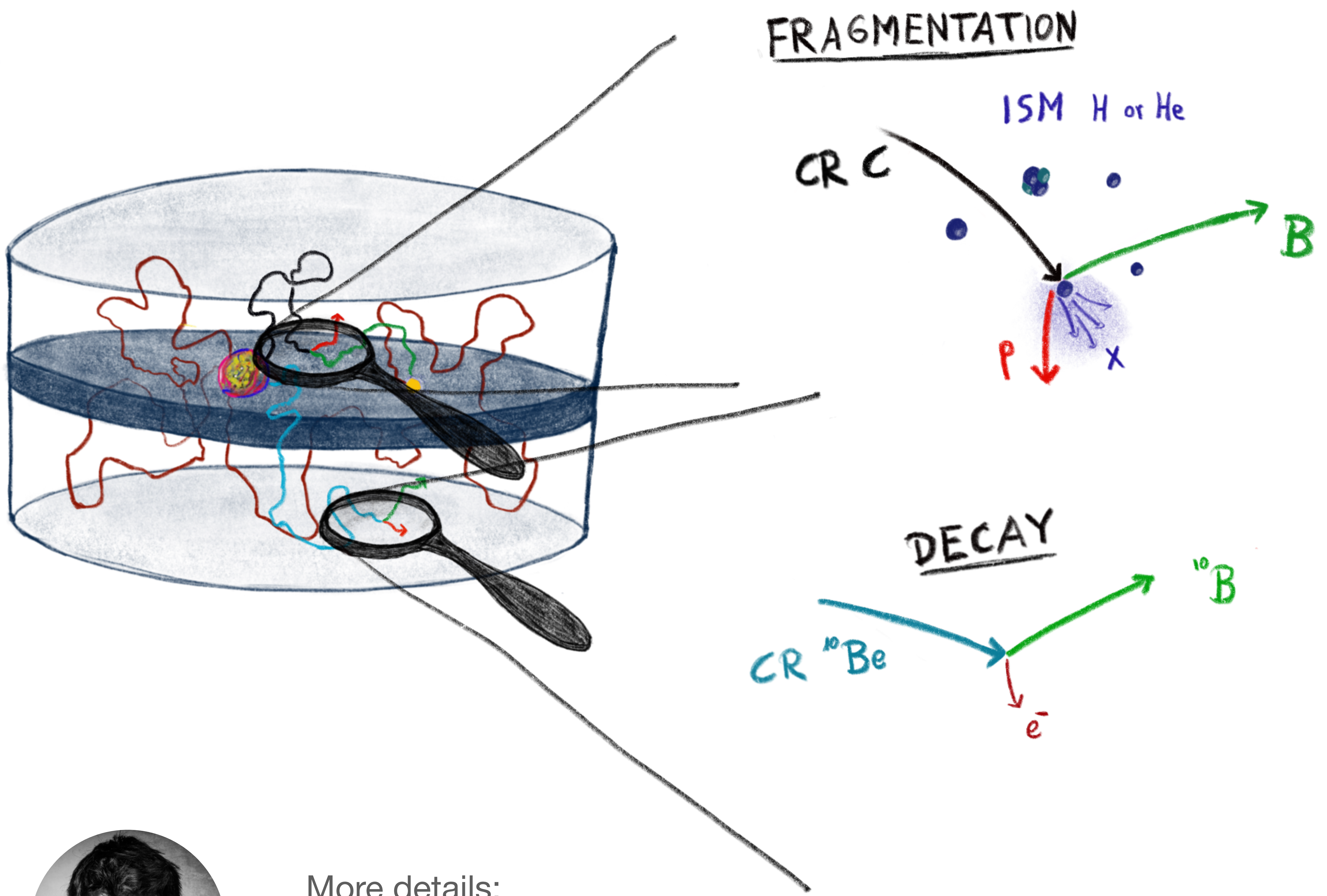


More details:
Yoann Genolini
Monday, 10:20 am

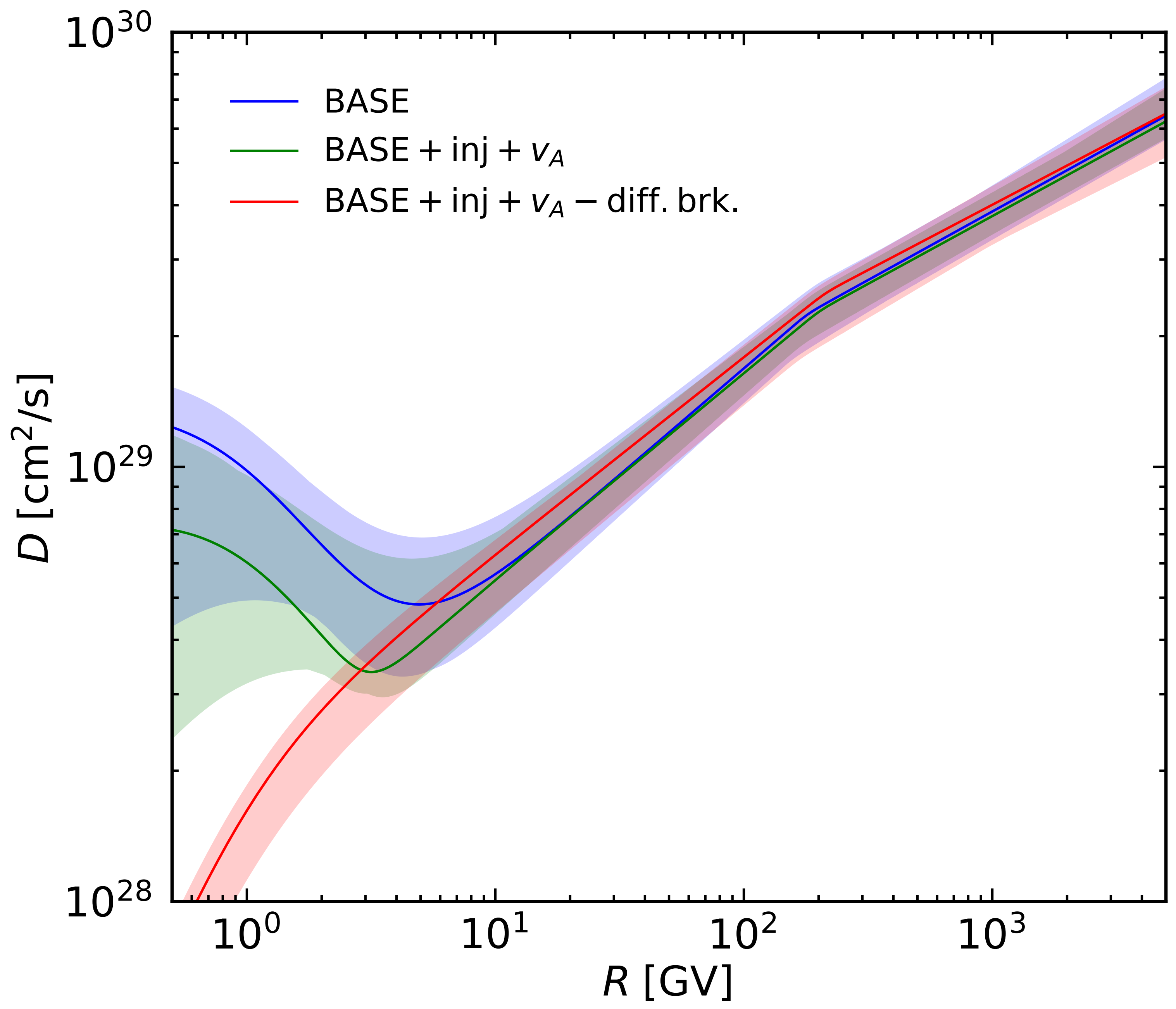


[Di Mauro, MK, et al. 2023]

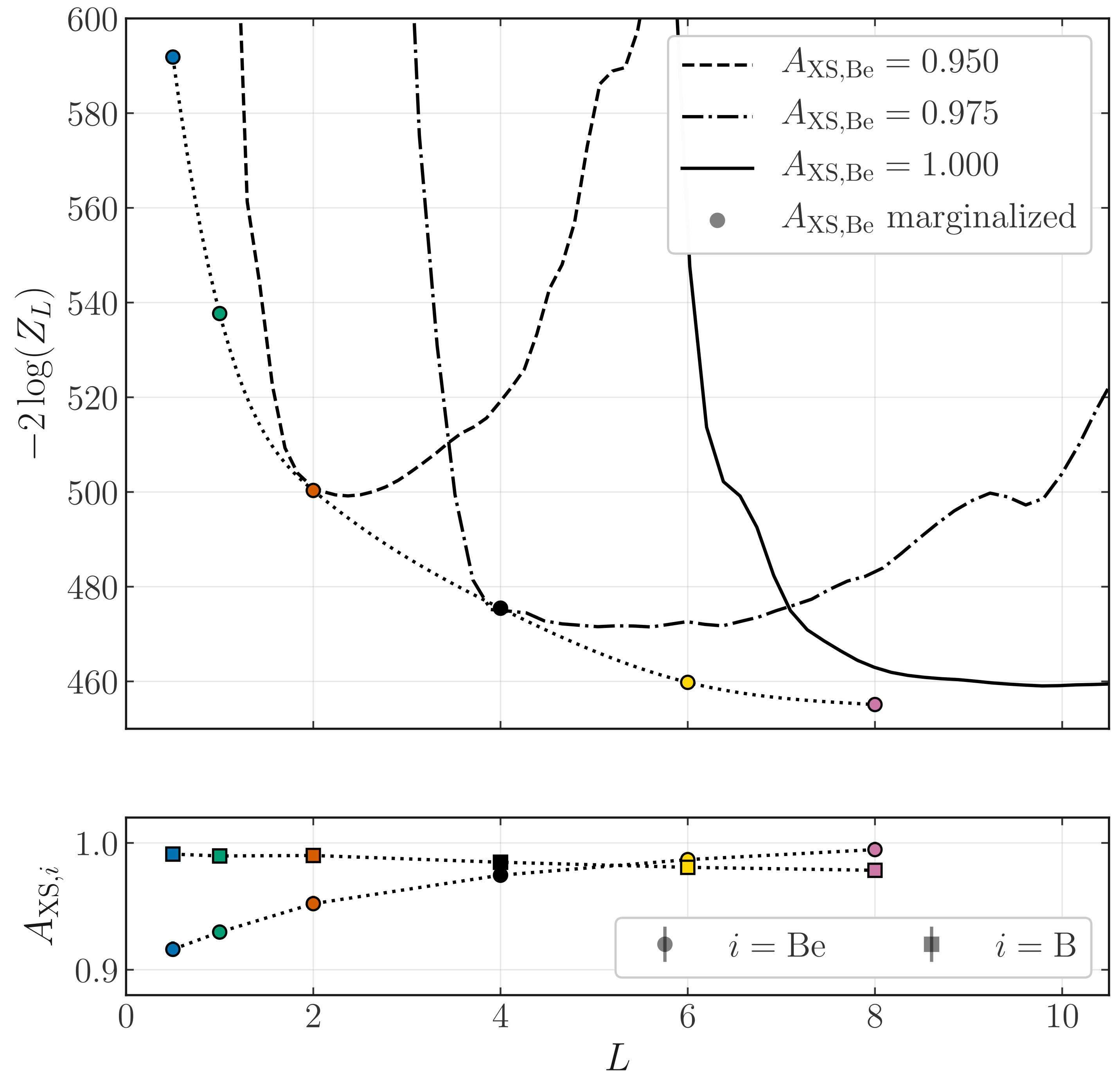
State of the Art CR Modeling



More details:
Yoann Genolini
Monday, 10:20 am



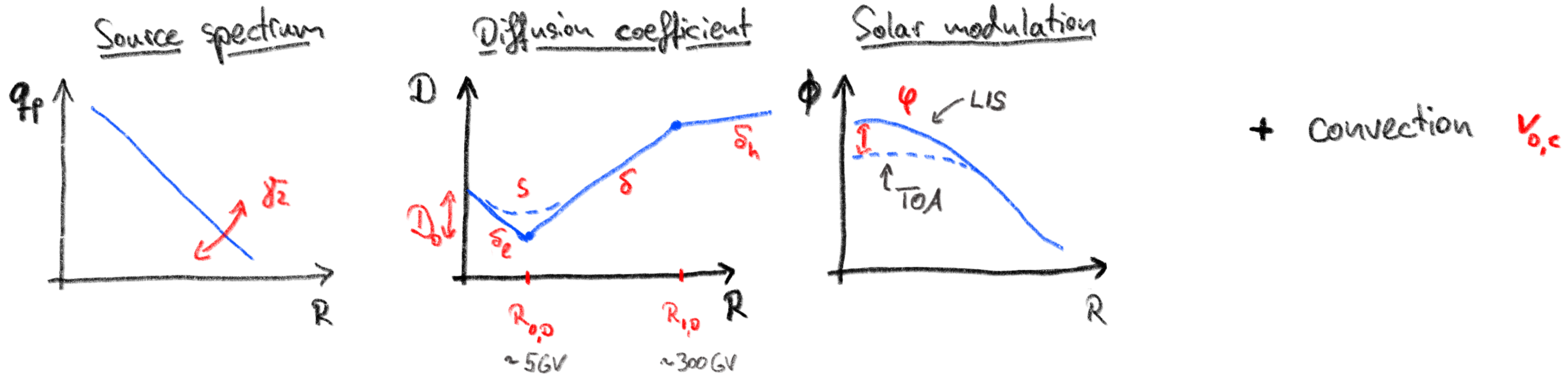
[MK, Cuoco, 2021]



[Di Mauro, MK, et al. 2023]

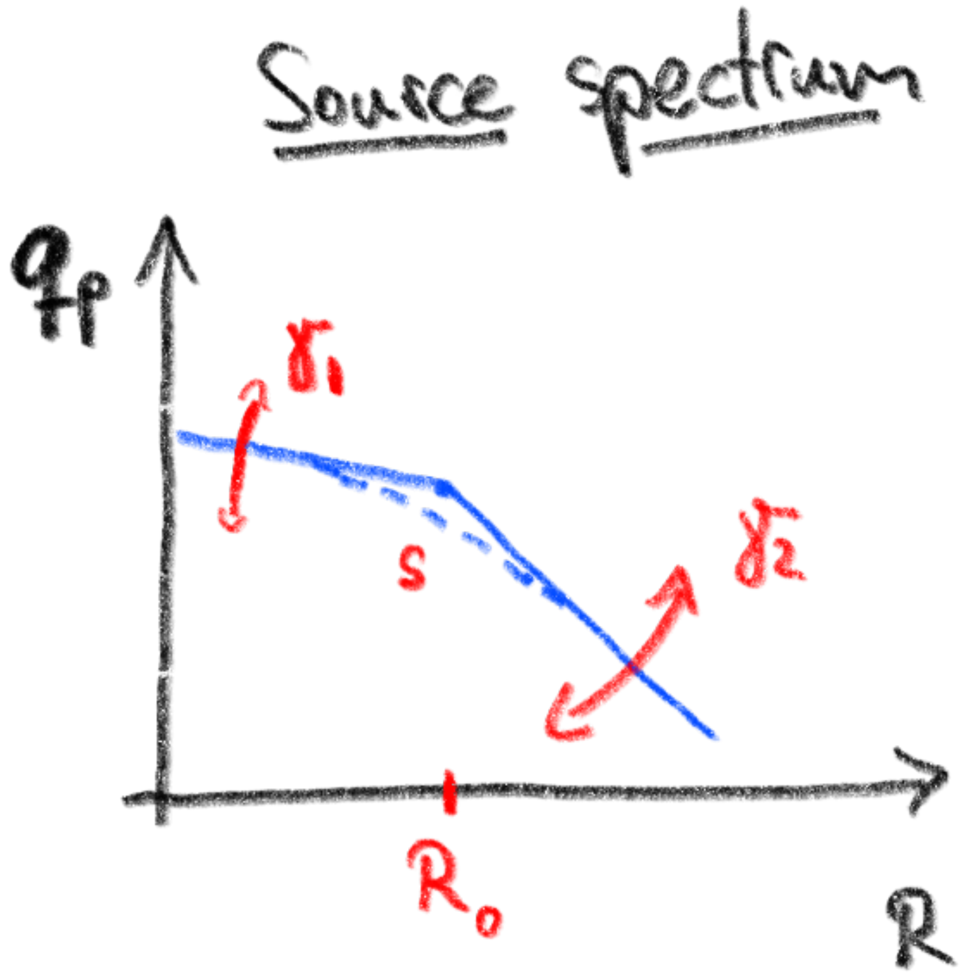
Two Distinct CR Propagation Models

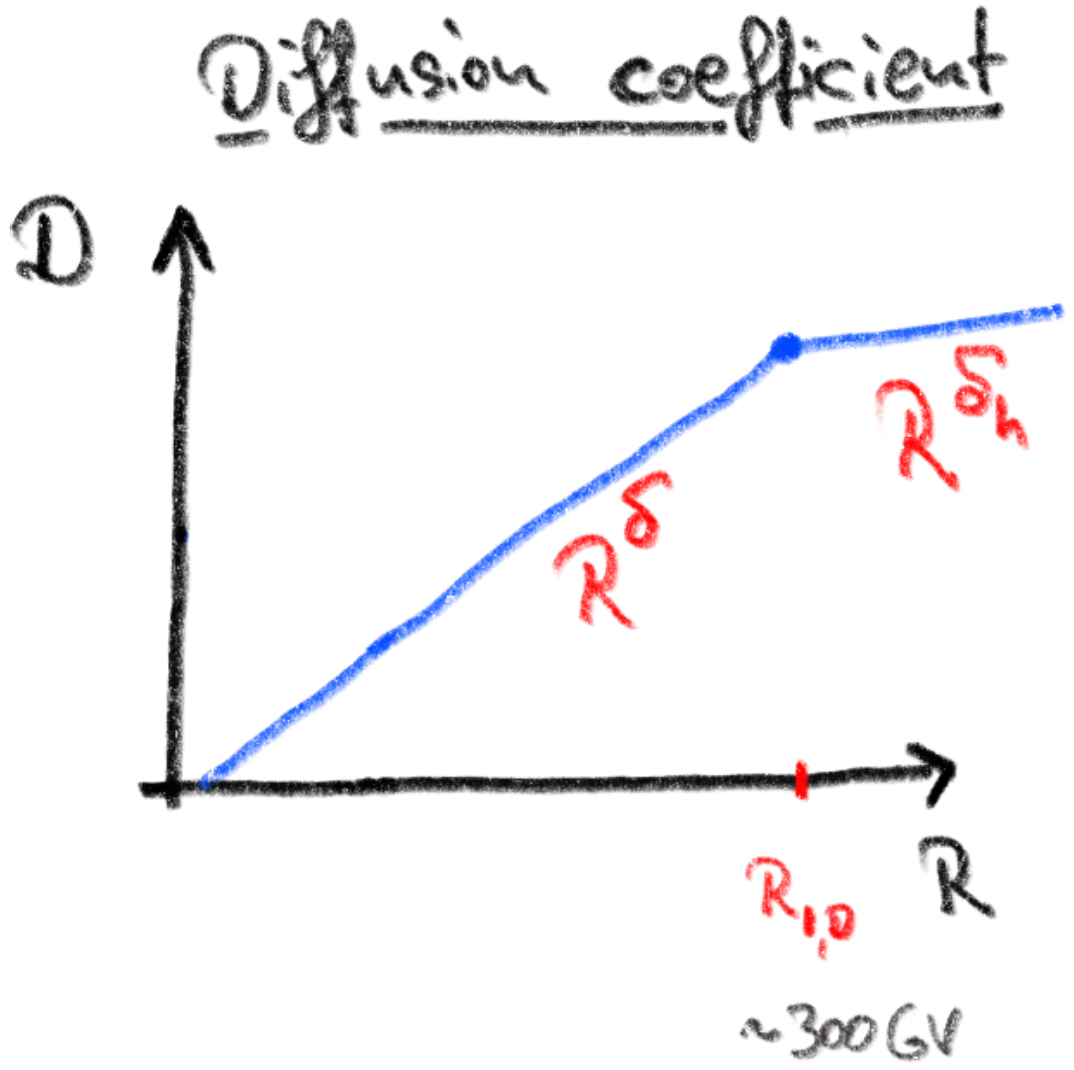
DIFF.BRK **INJ.BRK**

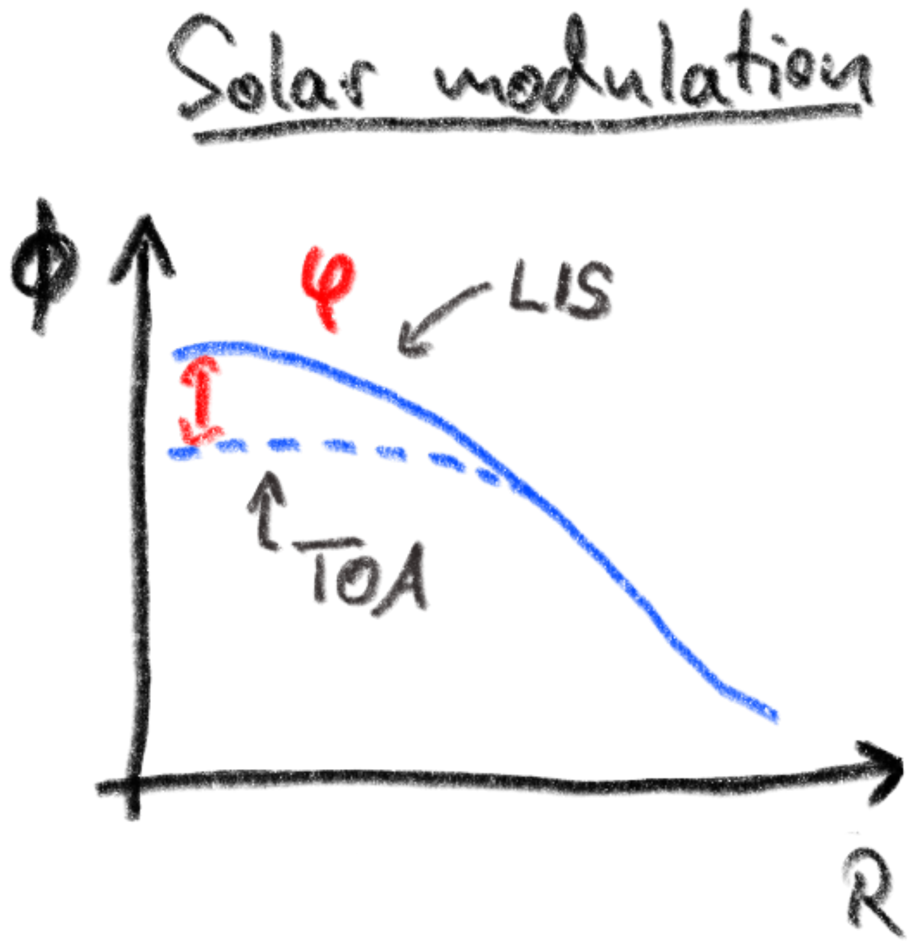


Two Distinct CR Propagation Models

DIFF.BRK **INJ.BRK**





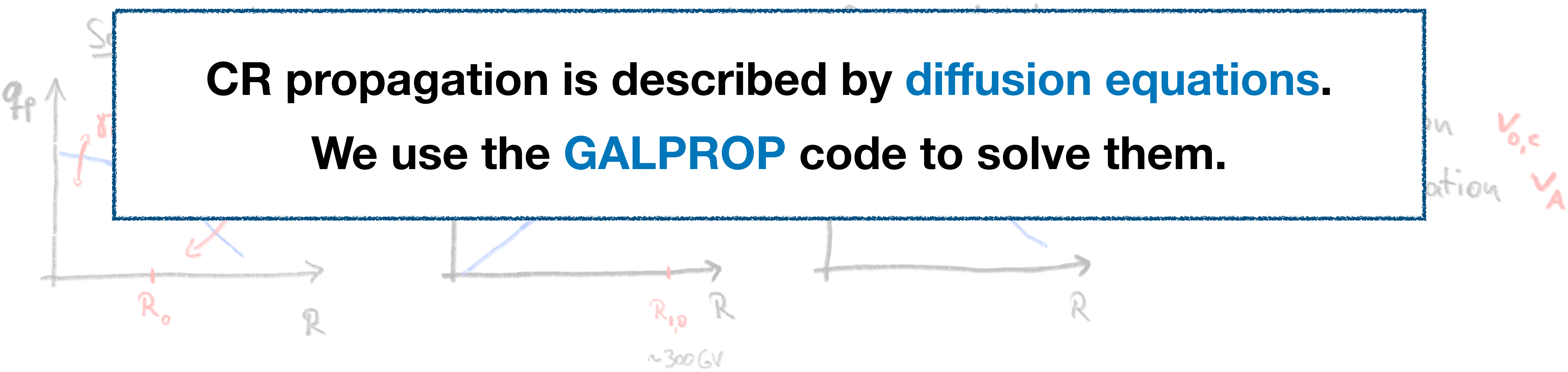


+ convection $v_{0,c}$
+ reacceleration v_A

Two Distinct CR Propagation Models

DIFF.BRK

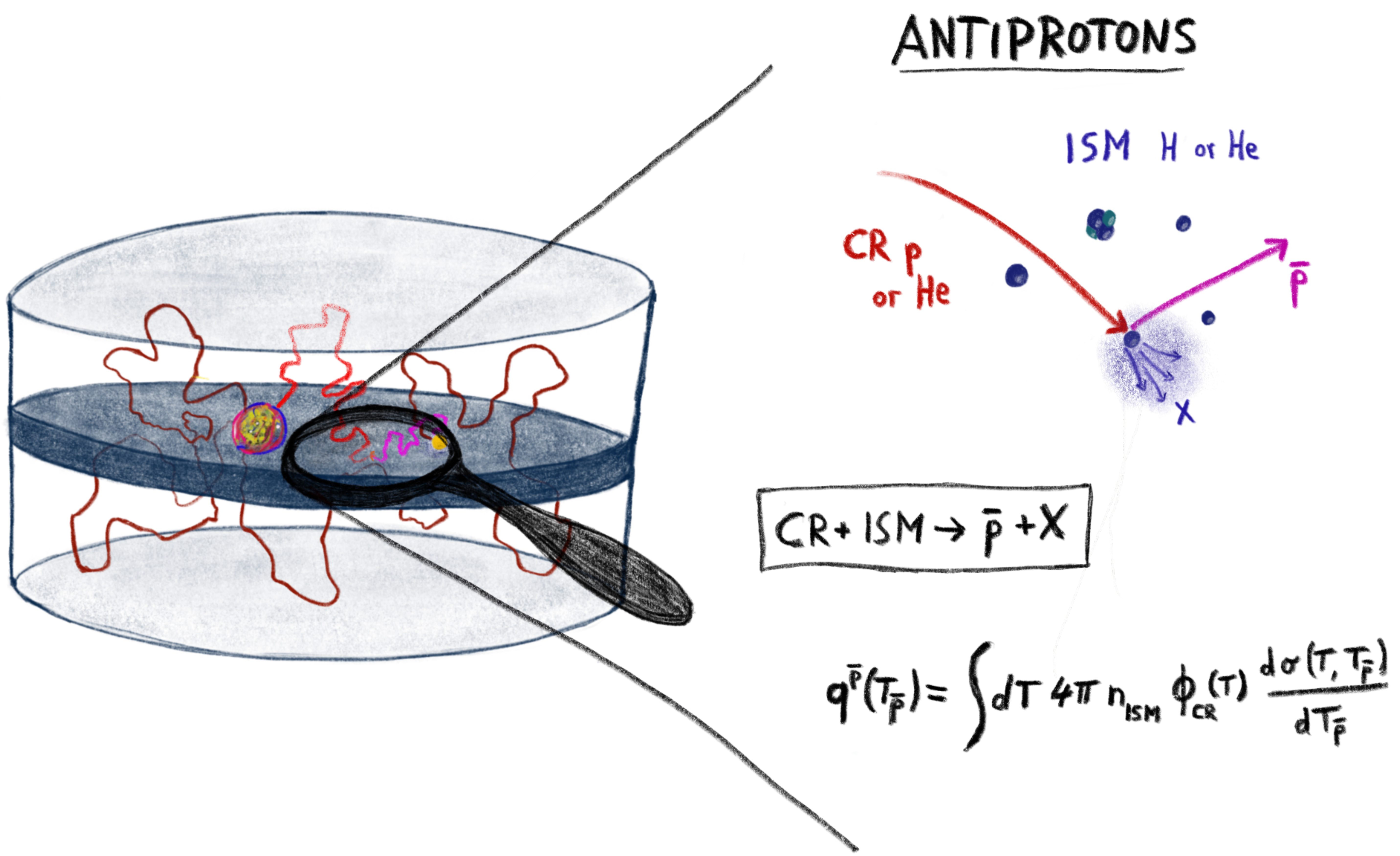
INJ.BRK



CR propagation is described by diffusion equations.

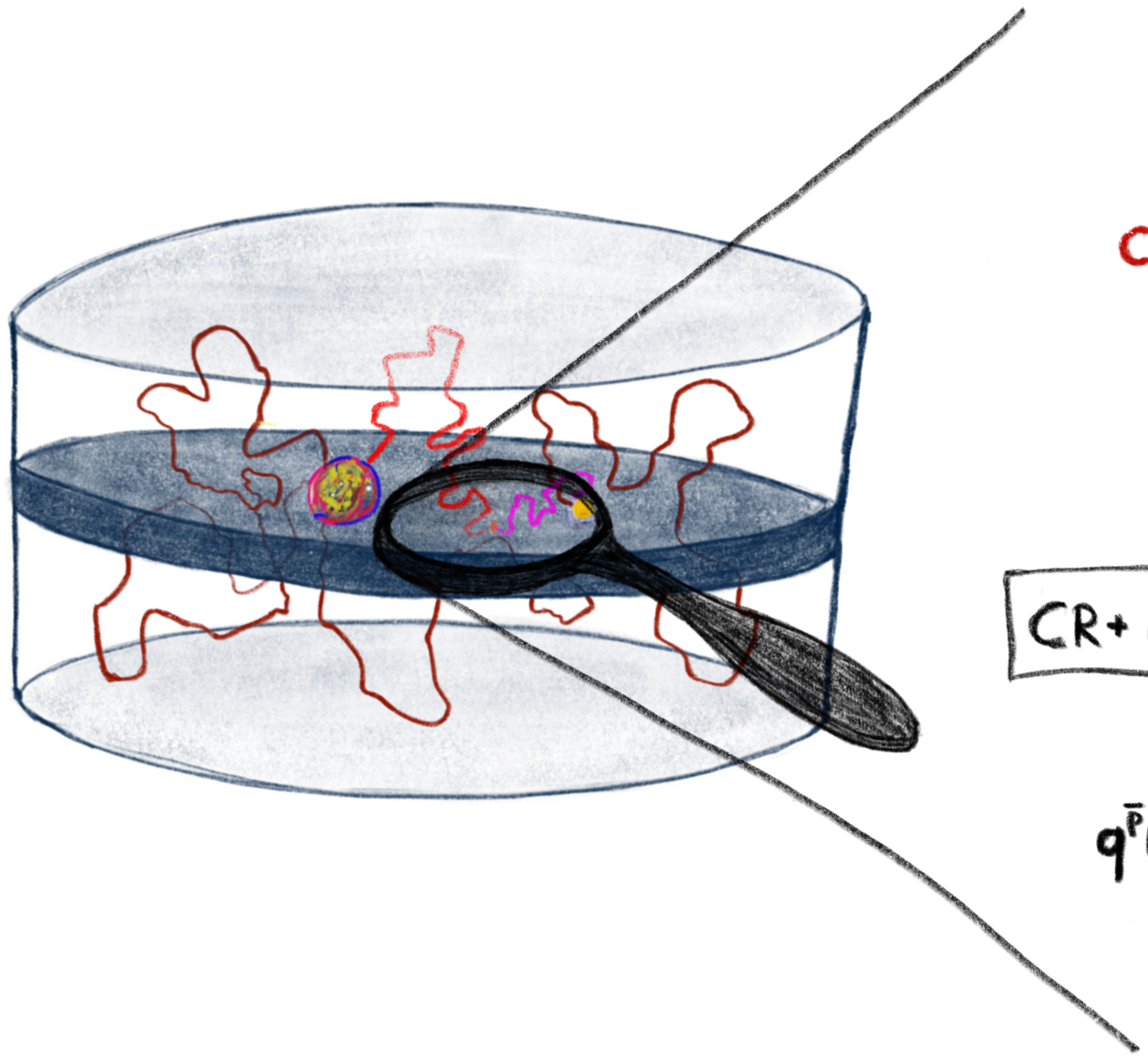
We use the GALPROP code to solve them.

Secondary CR Antiprotons

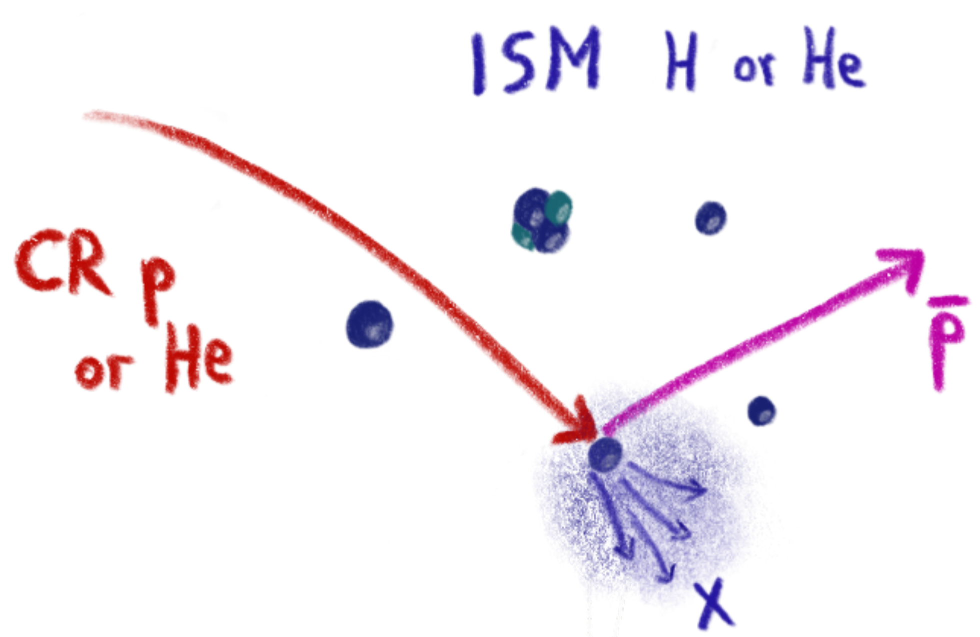


More details:
Zhicheng Tang
Monday, 15:10 am

Secondary CR Antiprotons

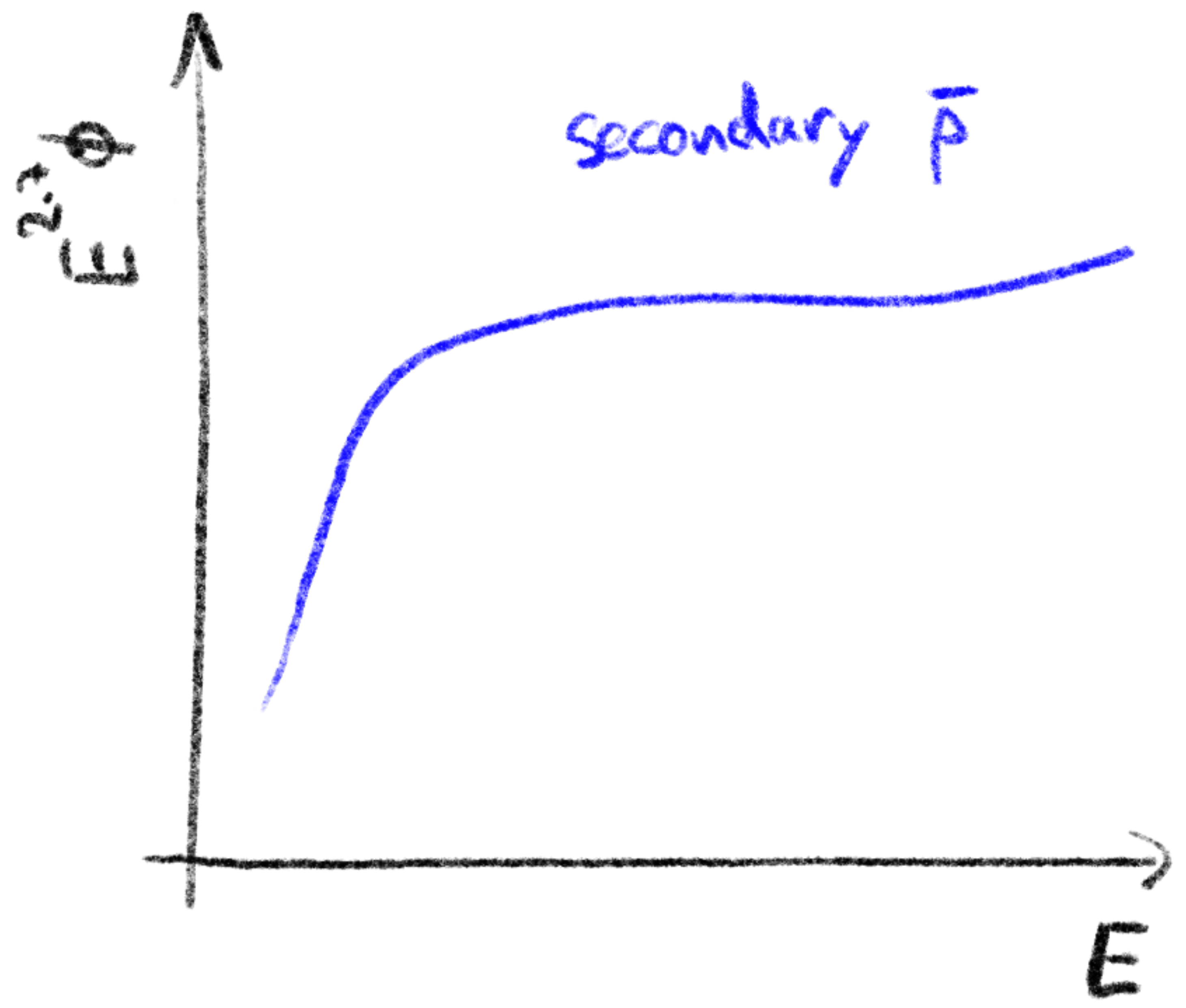


ANTIPROTONS



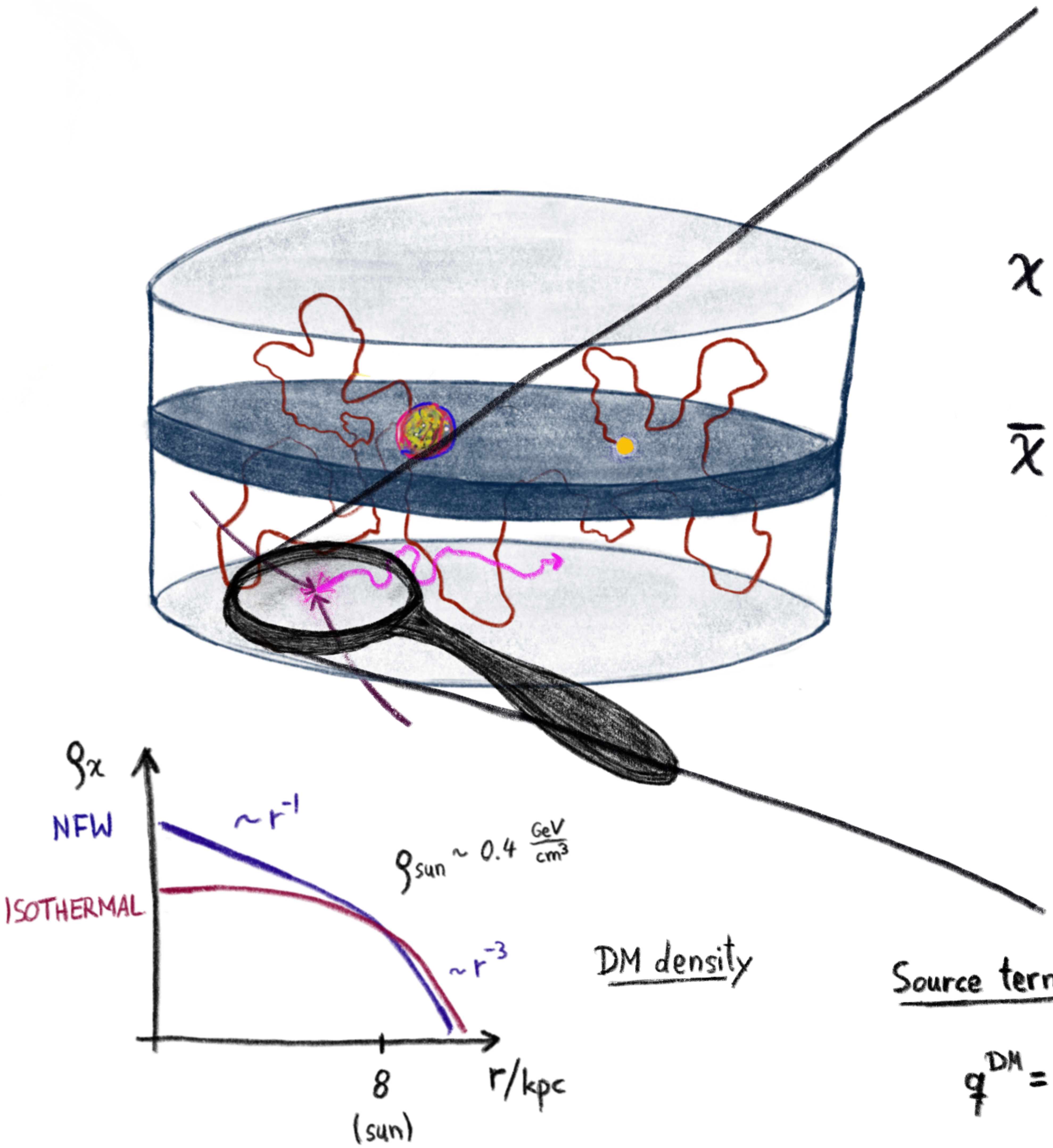
$\boxed{CR + ISM \rightarrow \bar{p} + X}$

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

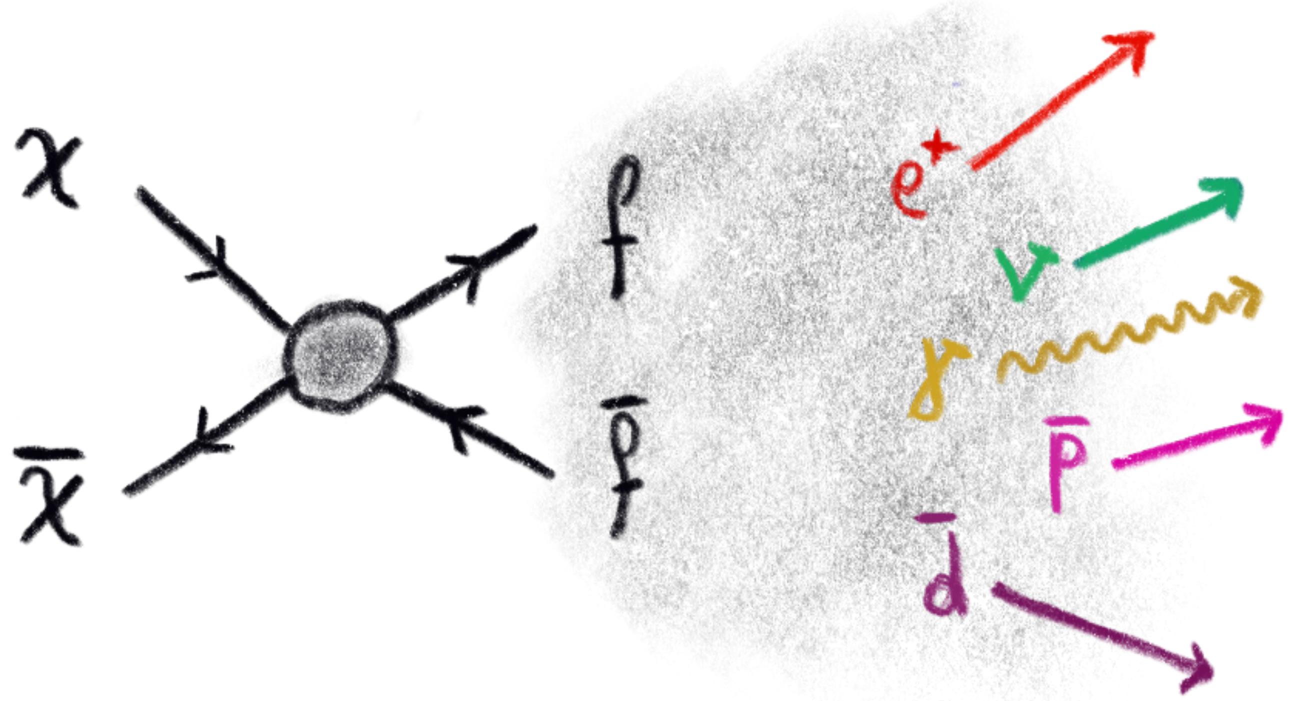


More details:
Zhicheng Tang
Monday, 15:10 am

Antiprotons from Dark Matter



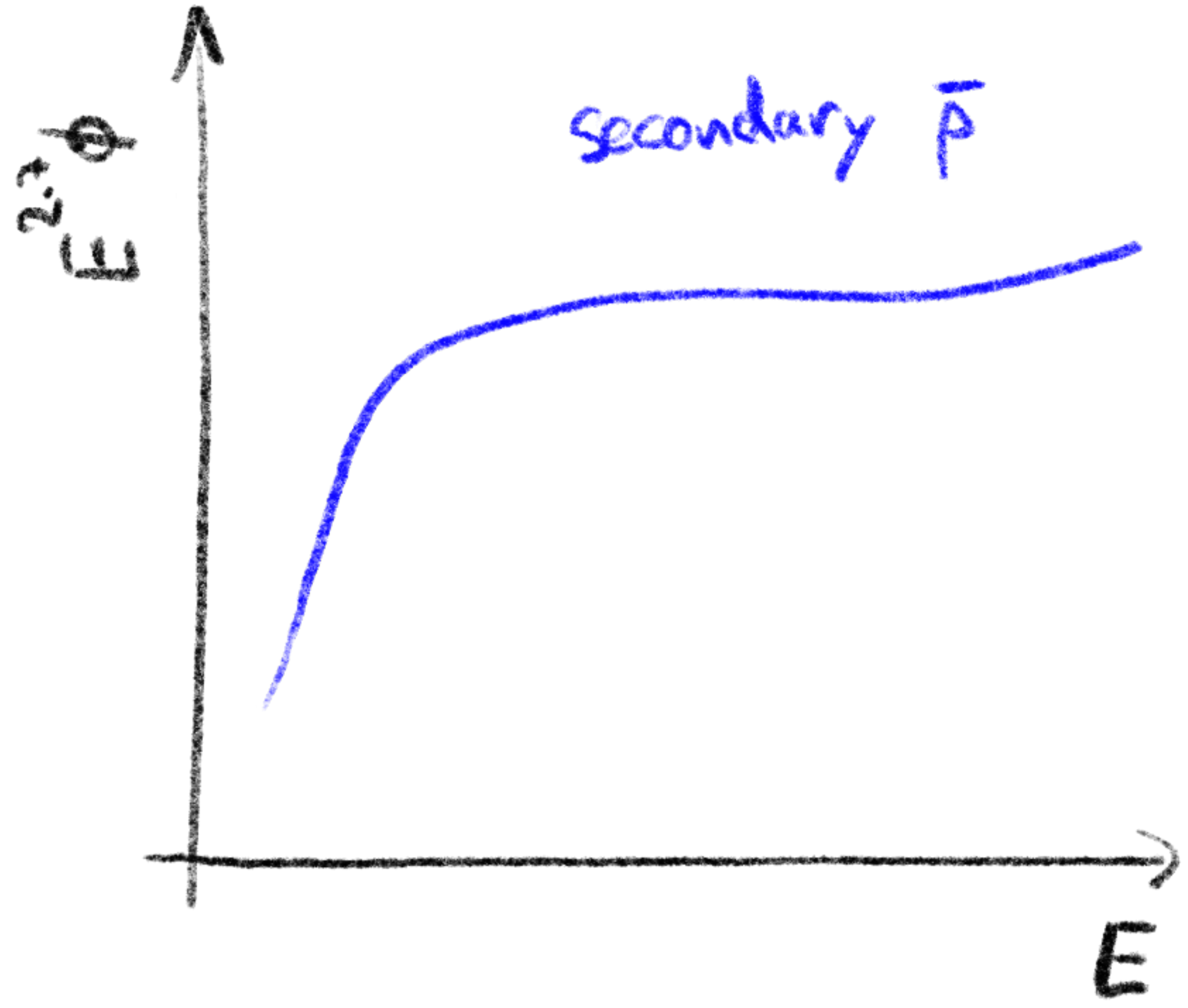
DM ANNIHILATION



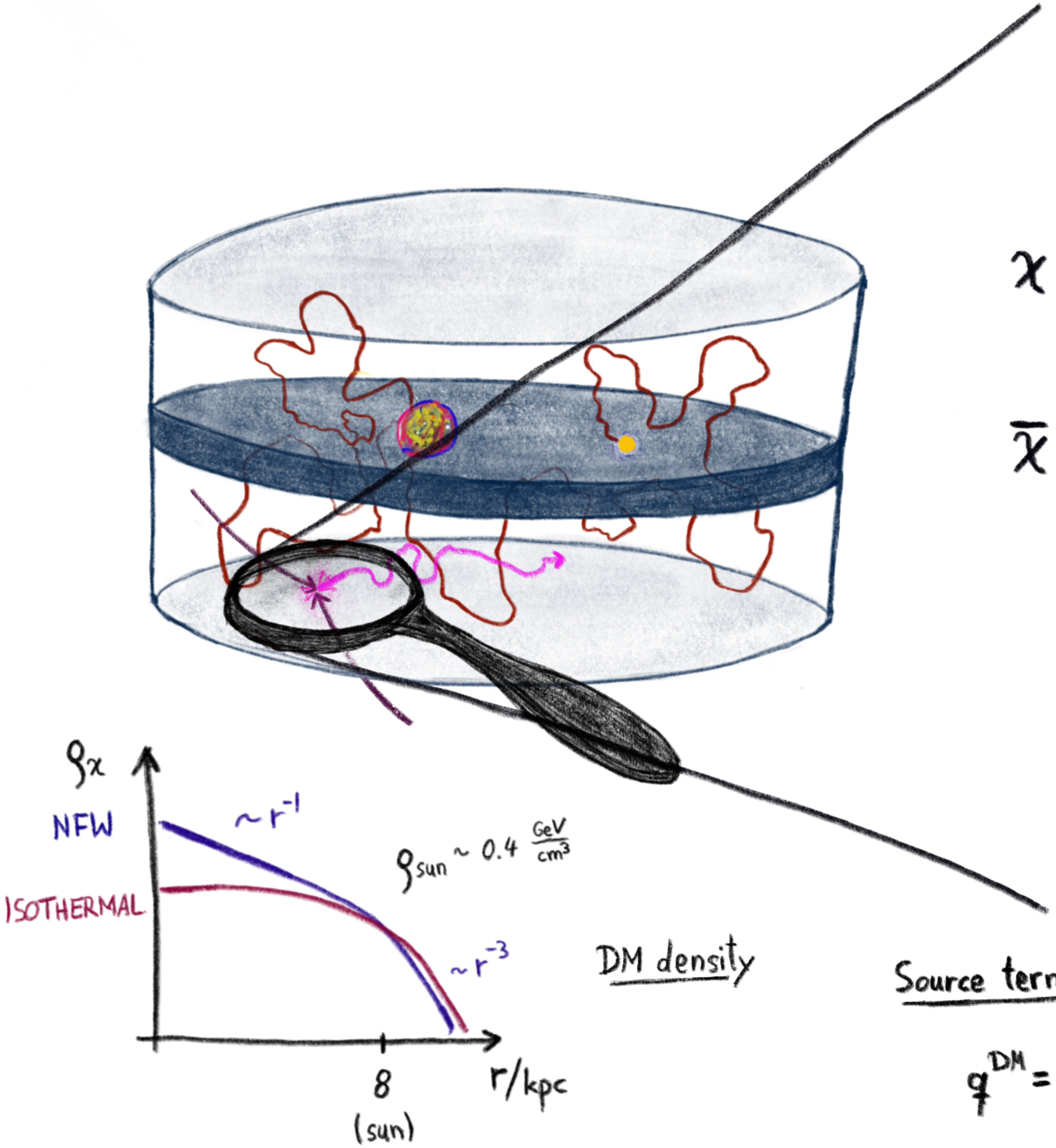
Final states depend on DM mass and velocity averaged annihilation cross section $\langle \sigma v \rangle$!

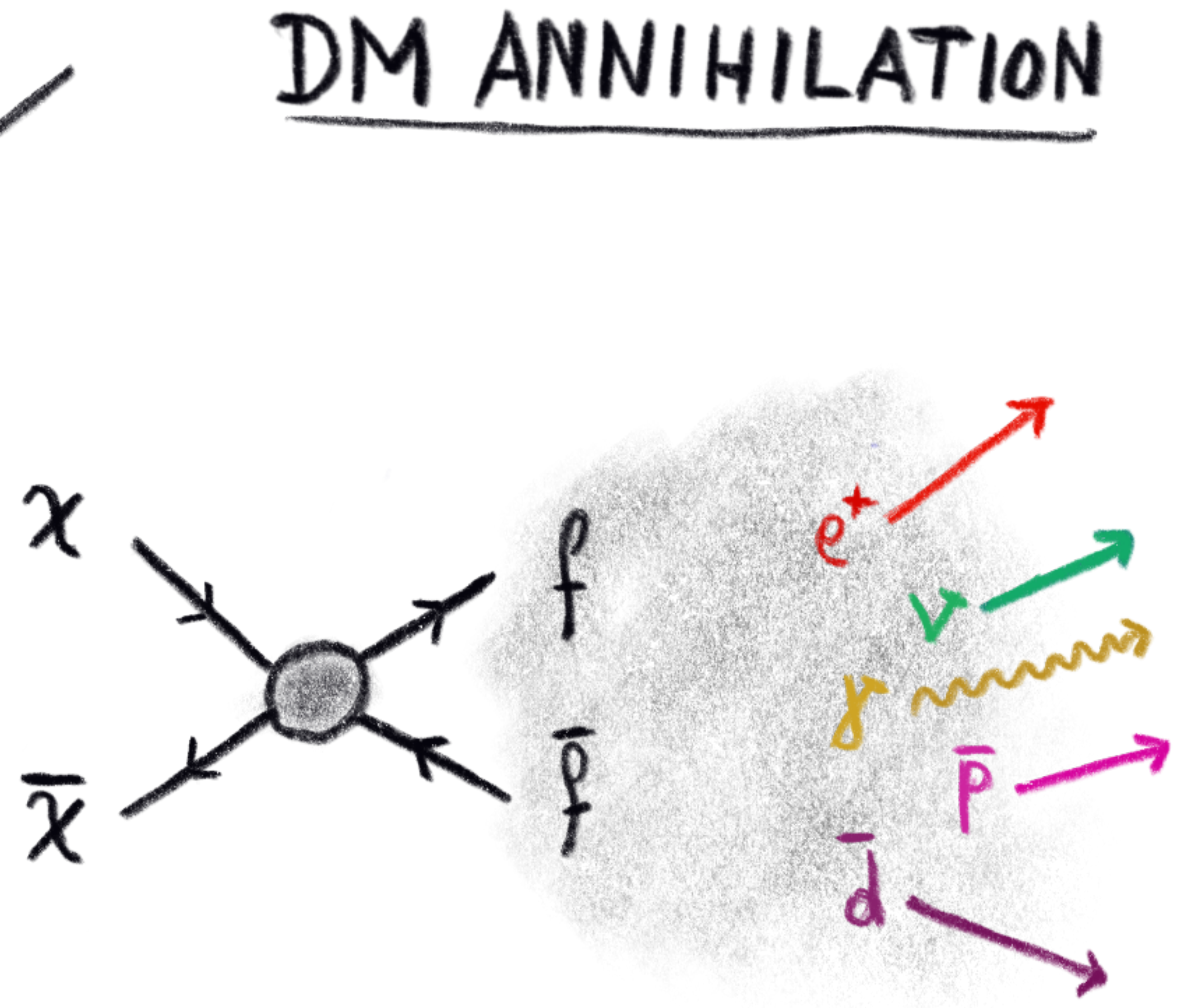
Source term

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



Antiprotons from Dark Matter

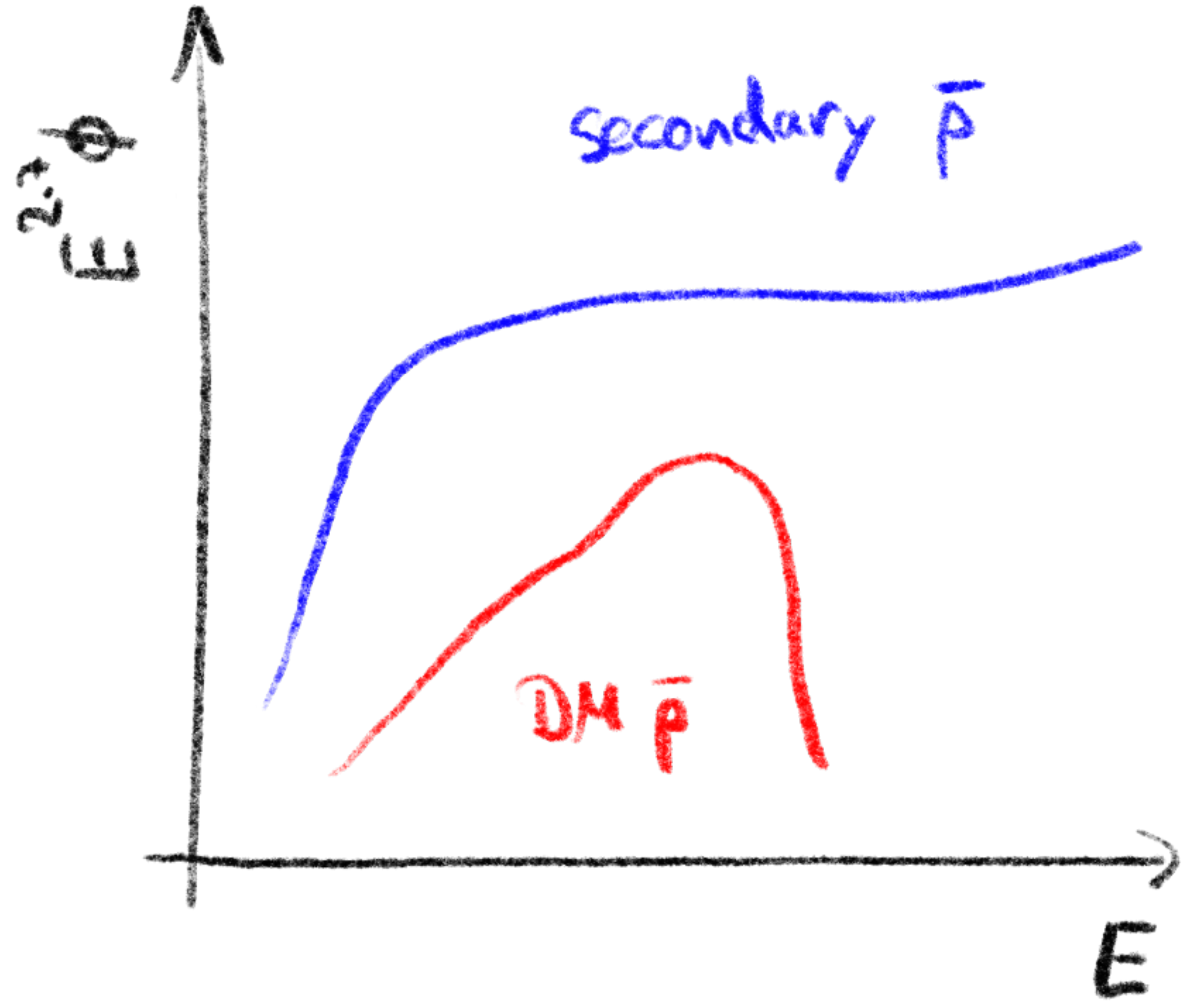




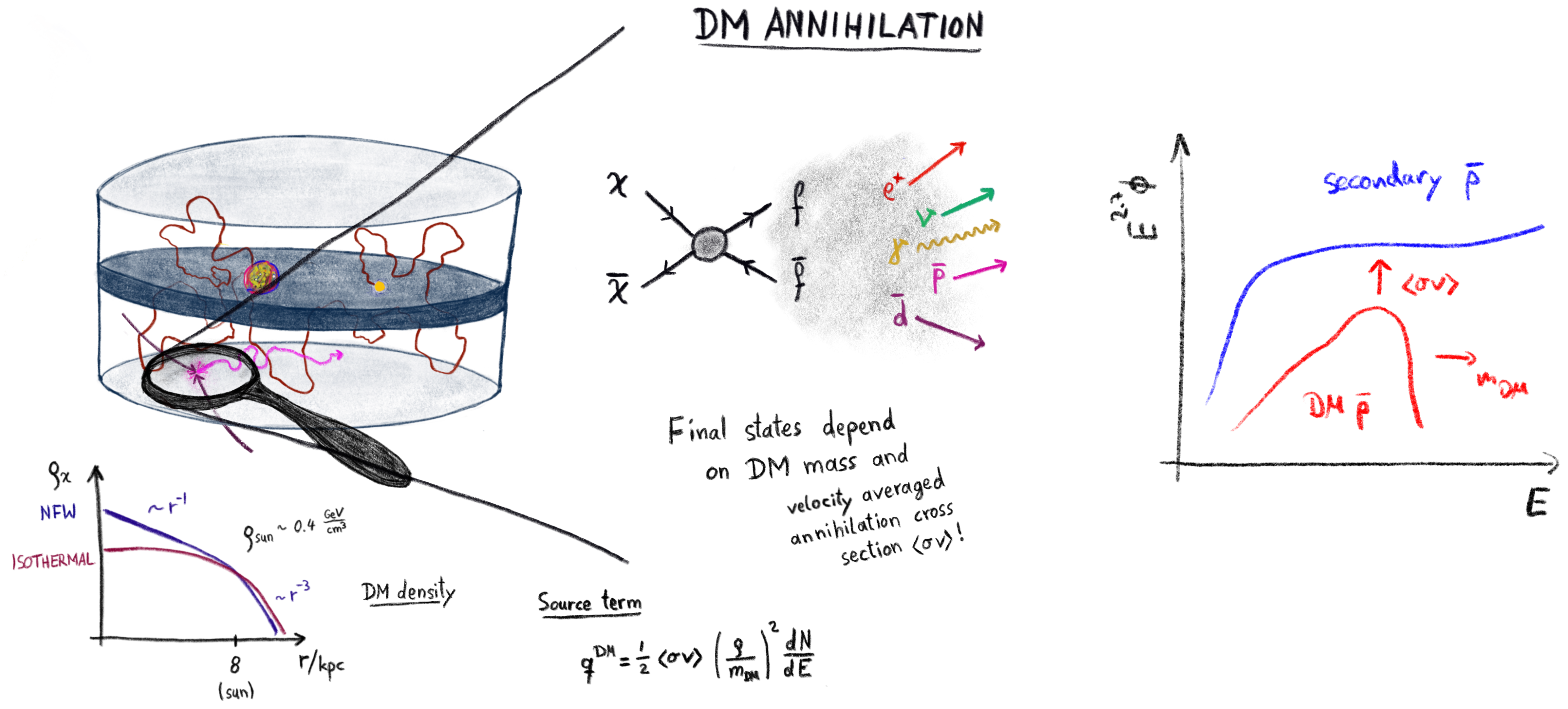
Final states depend on DM mass and velocity averaged annihilation cross section $\langle\sigma v\rangle$!

Source term

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

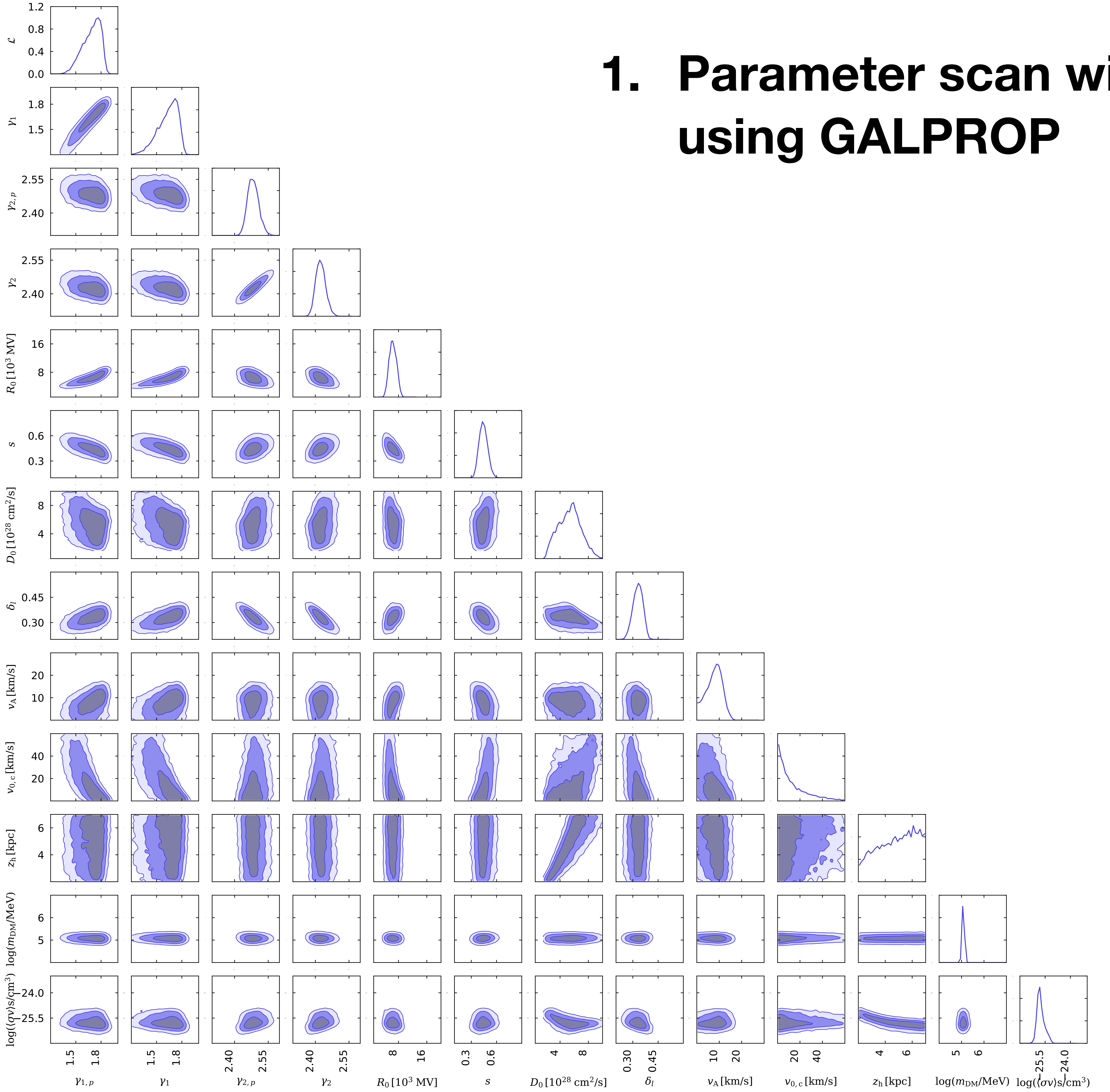


Antiprotons from Dark Matter

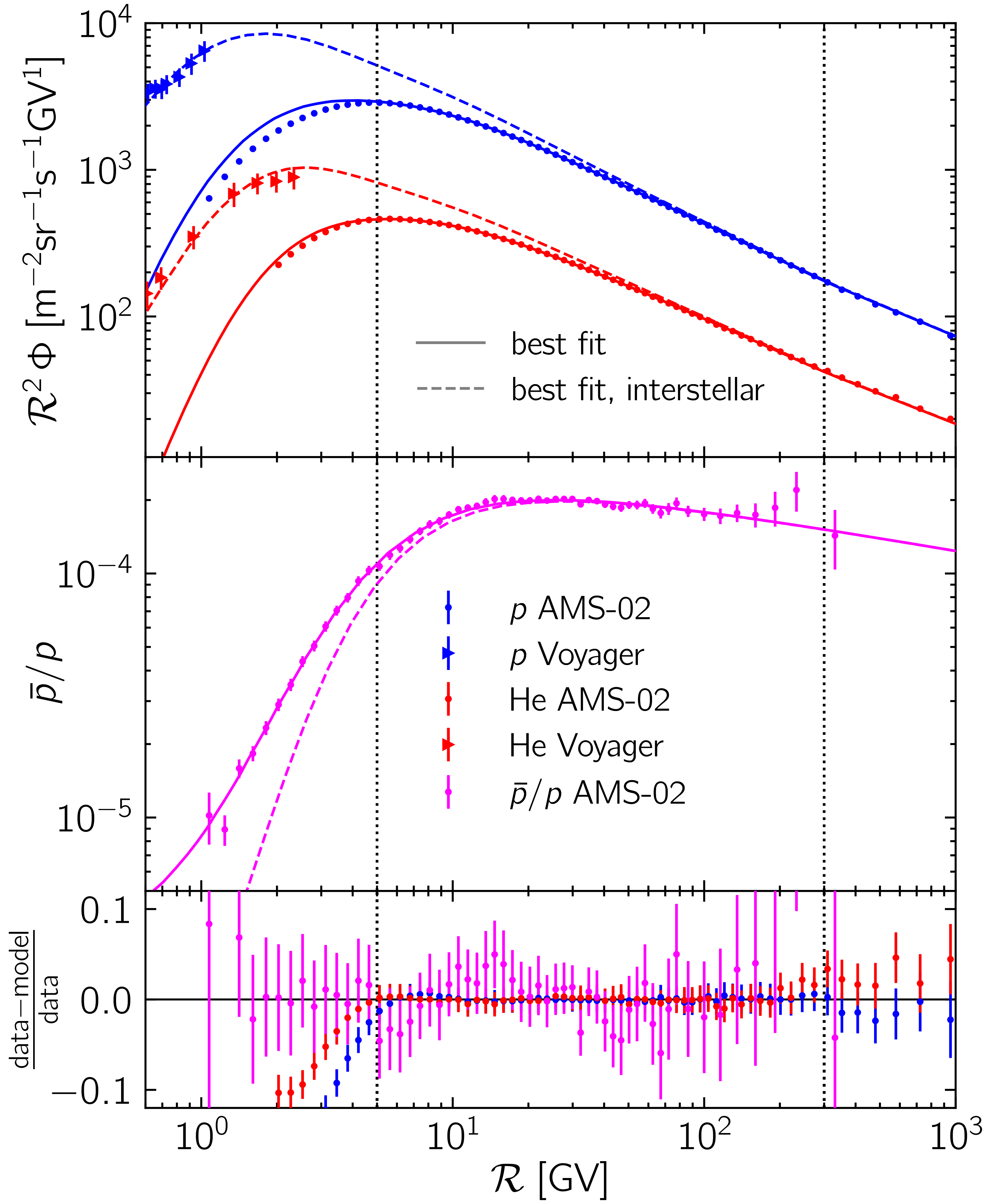


DM Limit — the Traditional Way

DM Limit — the Traditional Way

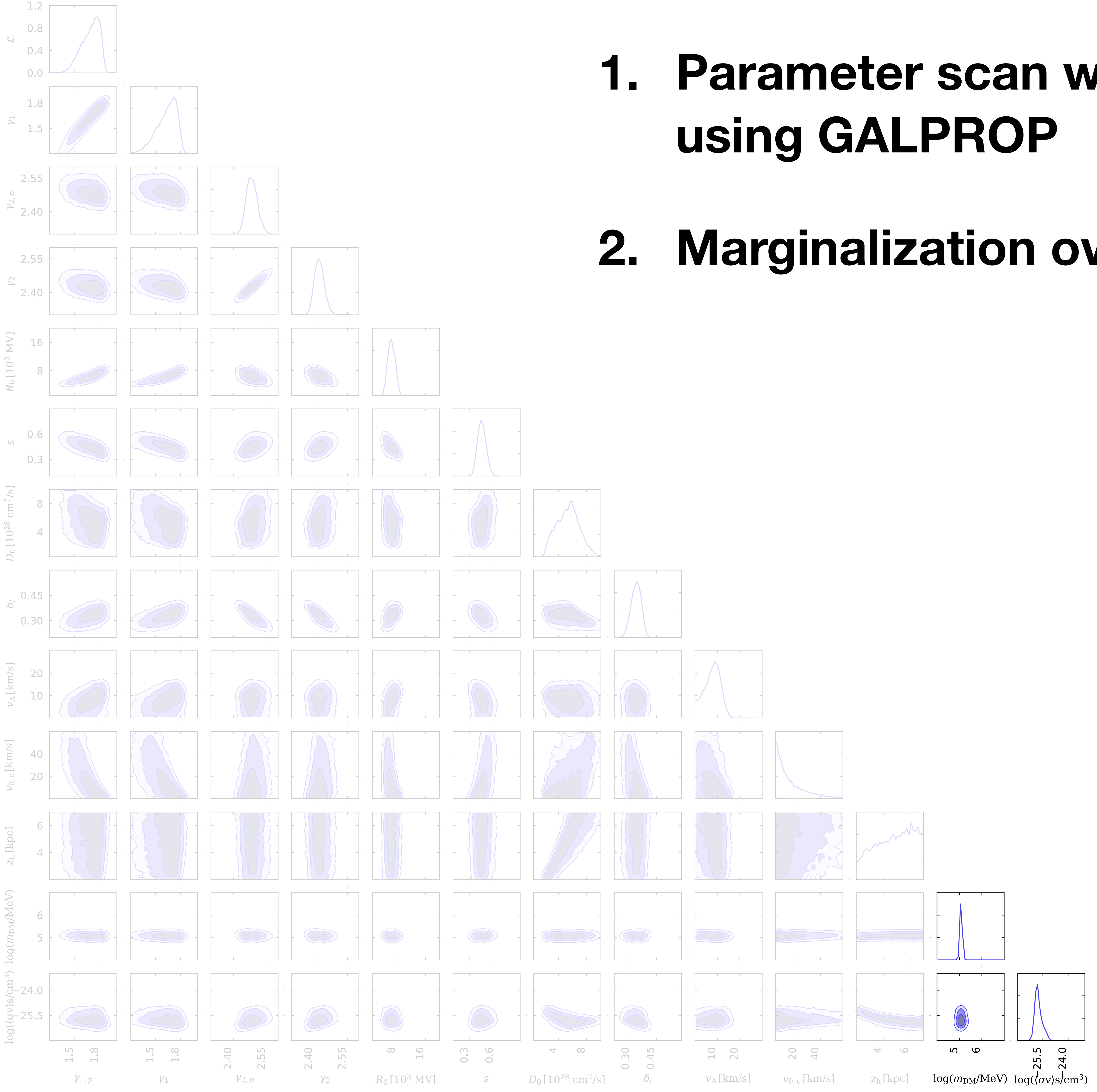


1. **Parameter scan with $\mathcal{O}(10^6)$ likelihood evaluations using GALPROP**



[Cuoco, MK, +; 2019]
(replotted results of the default setup w/o DM)

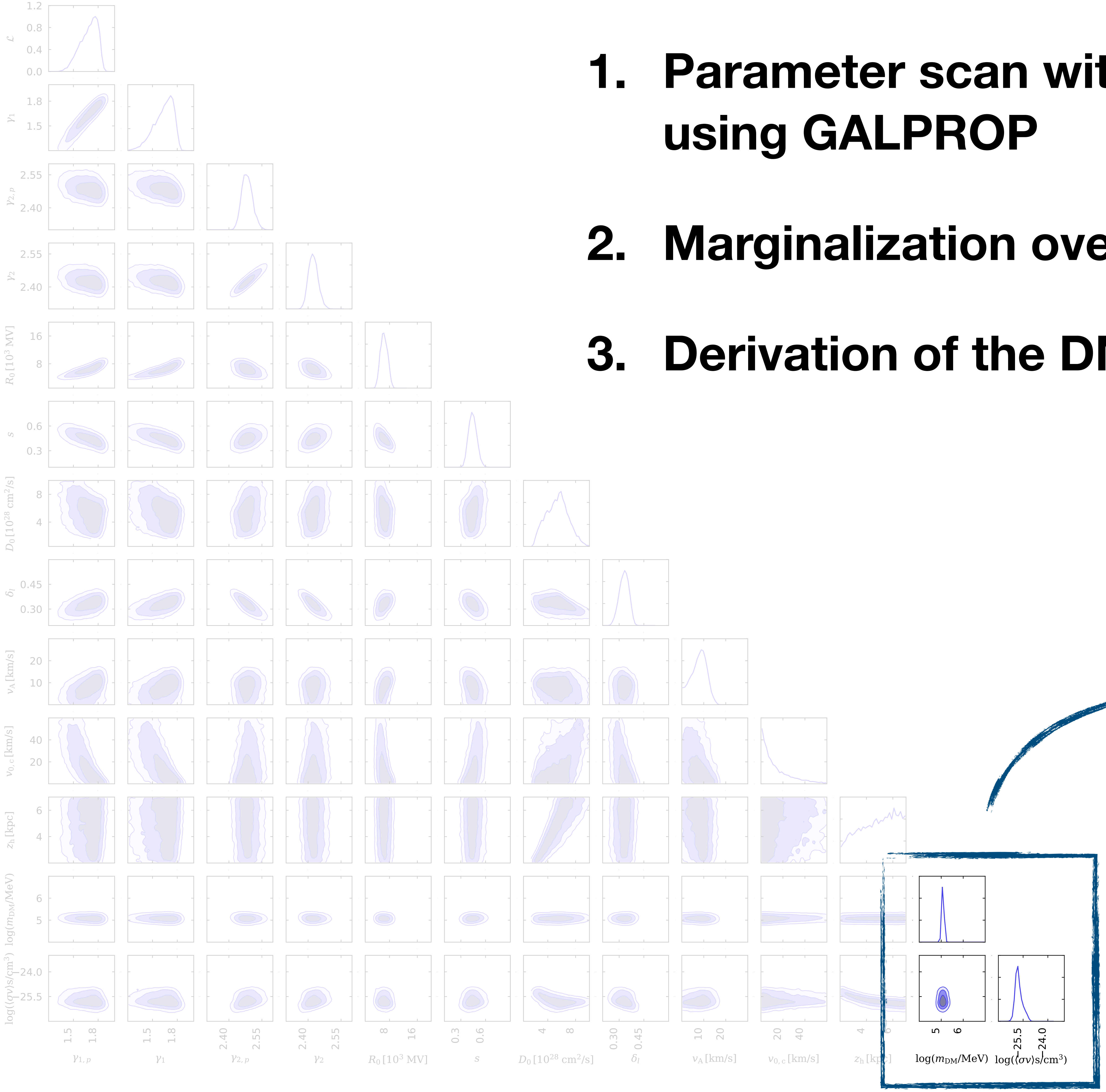
DM Limit — the Traditional Way



1. **Parameter scan with $\mathcal{O}(10^6)$ likelihood evaluations using GALPROP**

2. **Marginalization over CR parameters**

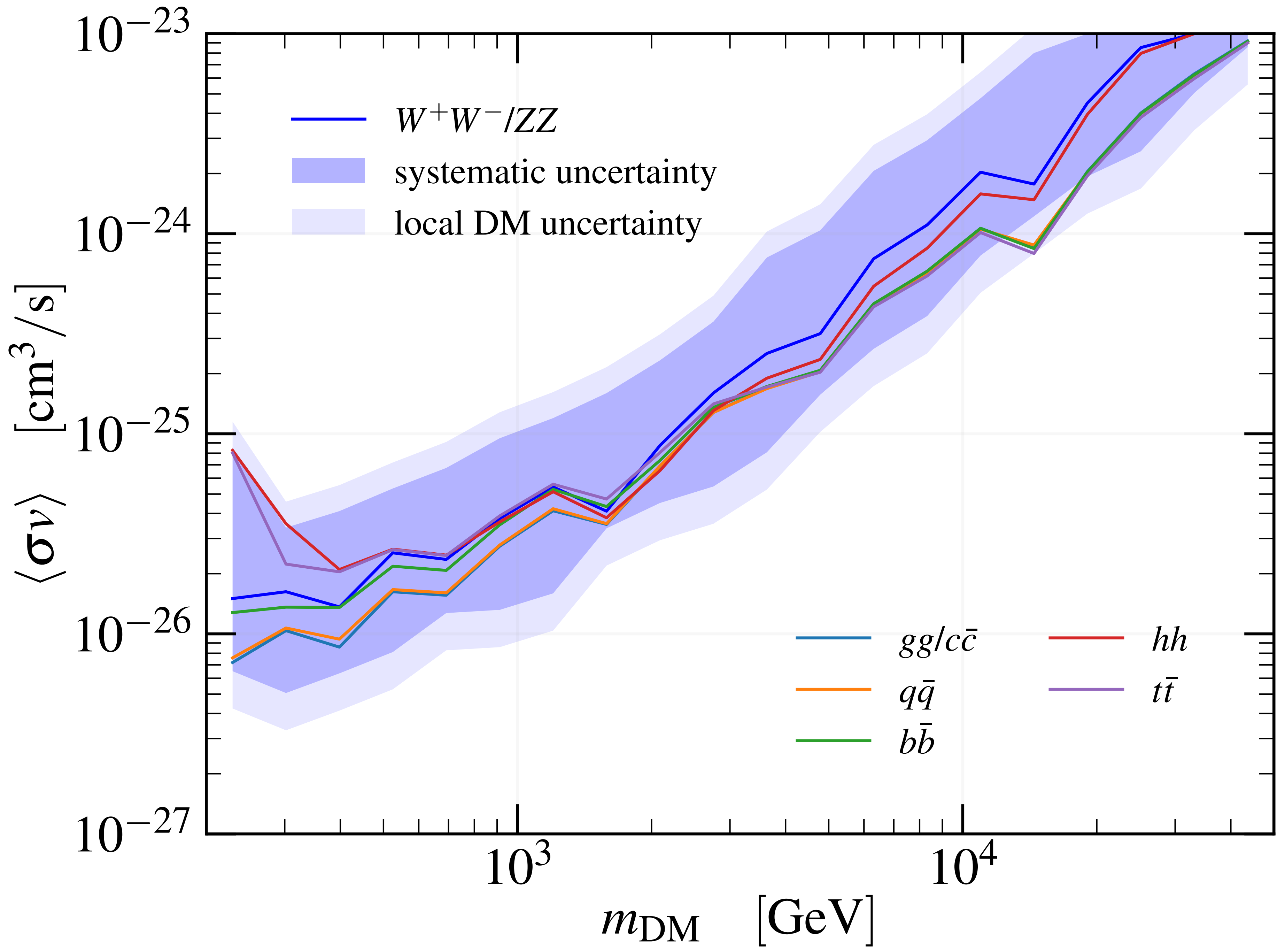
DM Limit — the Traditional Way



1. **Parameter scan with $\mathcal{O}(10^6)$ likelihood evaluations using GALPROP**

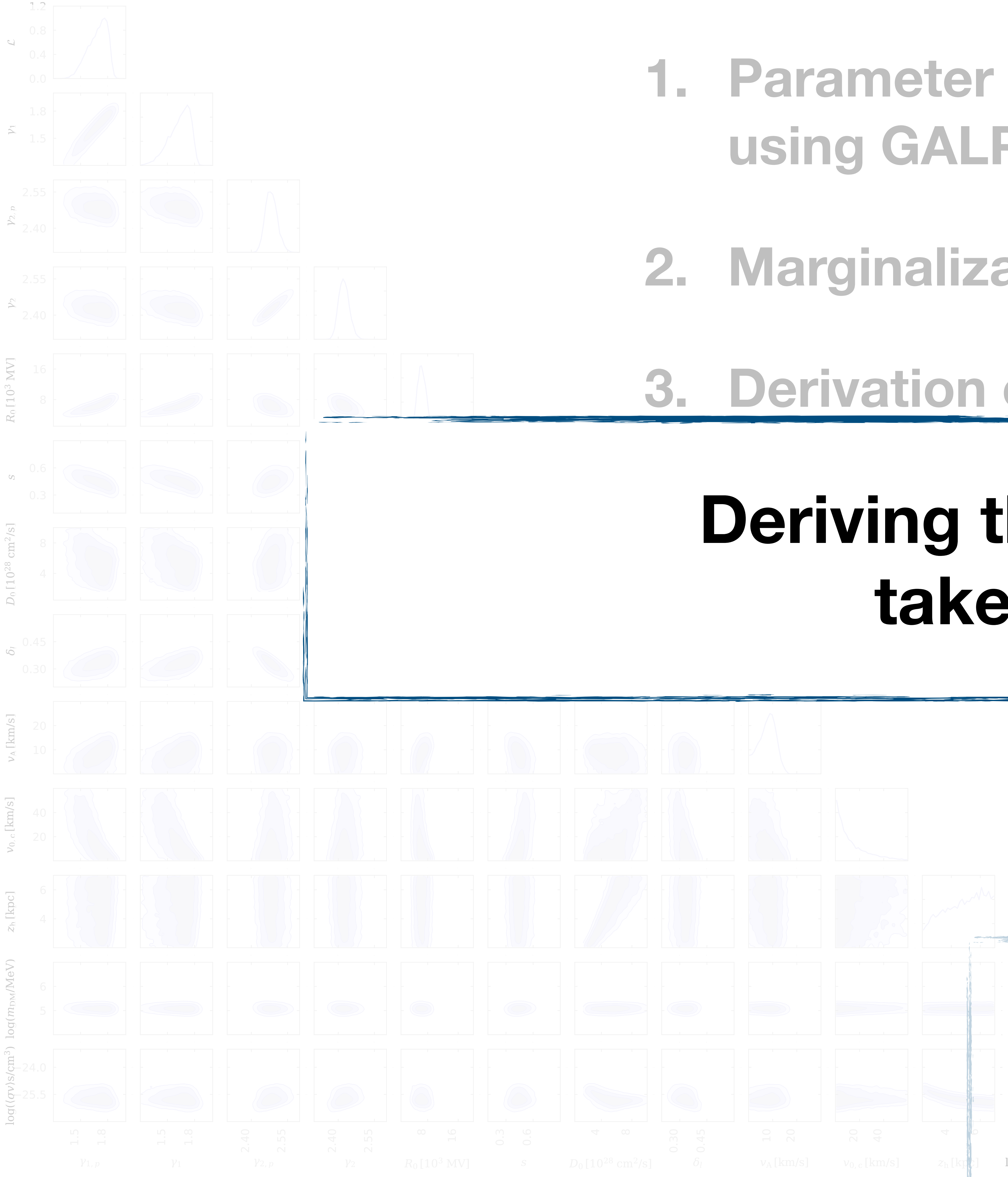
2. **Marginalization over CR parameters**

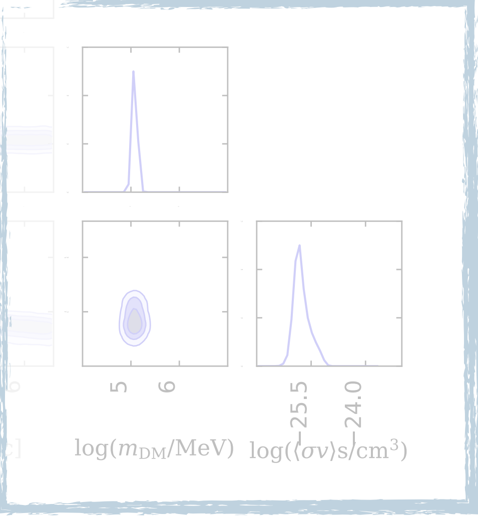
3. **Derivation of the DM limit**



[Cuoco, Heisig, MK, Krämer; 2018]

DM Limit — the Traditional Way



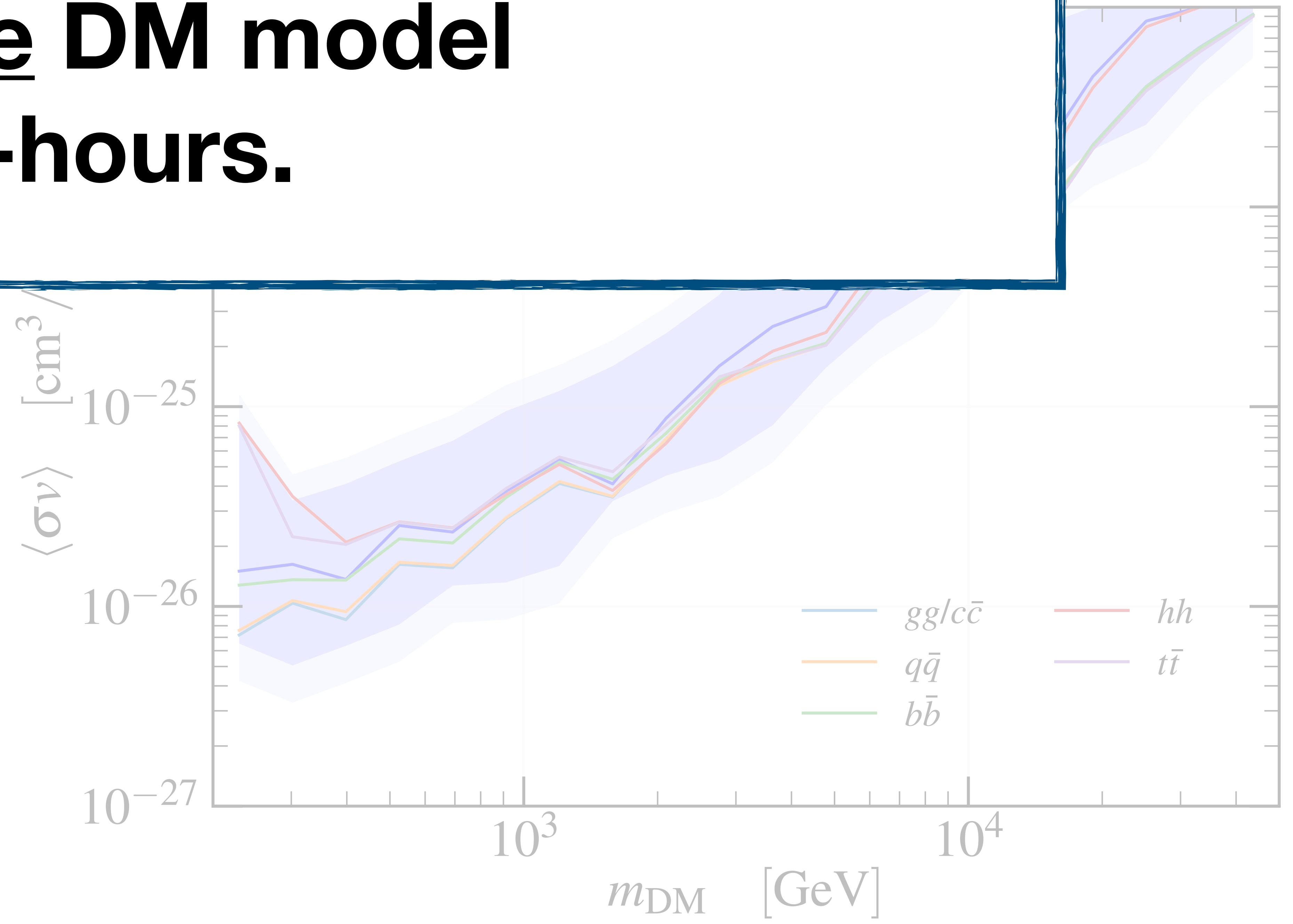


1. Parameter scan with $\mathcal{O}(10^6)$ likelihood evaluations using GALPROP

2. Marginalization over CR parameters

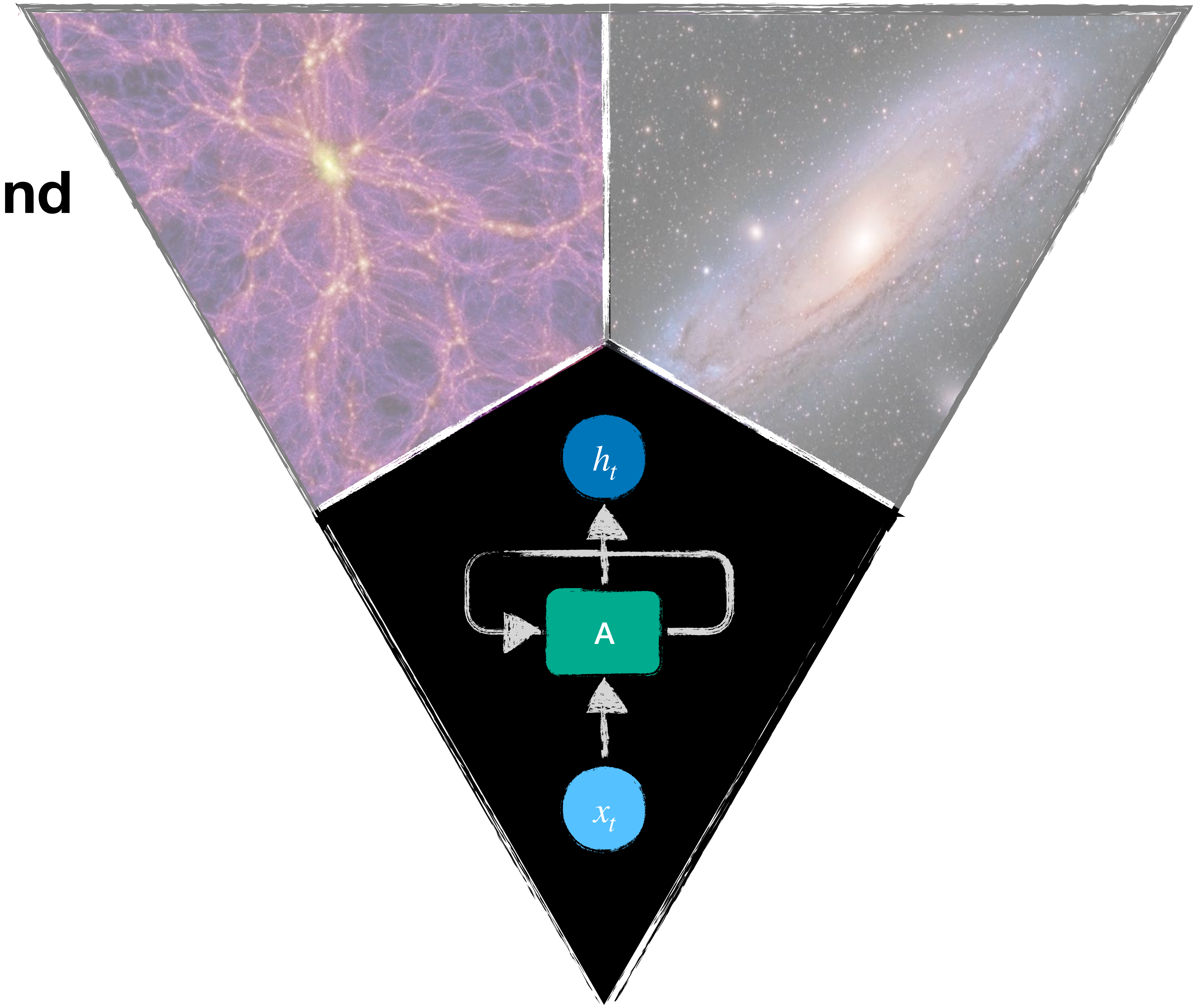
3. Derivation of the DM limit

Deriving the limit for <u>one</u> DM model takes ~50 000 cpu-hours.



[Cuoco, Heisig, MK, Krämer; 2018]

Motivation:
Dark Matter Limits and Indirect Detection



Cosmic Rays:
Propagation and the Role of Antiprotons

Speed-up: Neural Networks and Importance Sampling

Importance Sampling

$\mathscr{L}(\boldsymbol{\theta})$	Likelihood **without DM** signal
$\mathscr{L}(\boldsymbol{\theta}, \boldsymbol{x})$	Likelihood **with DM** signal
$\pi(\boldsymbol{\theta}) = \pi(\boldsymbol{\theta})$	Prior CR propagation

$$\boldsymbol{\theta} = \{\gamma_{1,p}, \gamma_{1,\mathrm{He}}, \gamma_{2,p}, \gamma_{2,\mathrm{He}}, R_0, s, D_0, \delta, v_A, v_{0,c}\,, z_h, \varphi, \varphi_{\bar{p}}\}$$

$$\boldsymbol{x} = \{m_{\mathrm{DM}}, \langle\sigma v\rangle_{gg}, \langle\sigma v\rangle_{q\bar{q}}, \langle\sigma v\rangle_{c\bar{c}}, \langle\sigma v\rangle_{b\bar{b}}, \langle\sigma v\rangle_{t\bar{t}}, \langle\sigma v\rangle_{hh}, \langle\sigma v\rangle_{WW}, \langle\sigma v\rangle_{ZZ}\}$$

$$\{\boldsymbol{\theta}_i\} \sim \mathscr{L}(\boldsymbol{\theta})\pi(\boldsymbol{\theta})$$

$$\overline{\mathscr{L}}(\boldsymbol{x}) = \int \mathrm{d}\theta\, \mathscr{L}(\boldsymbol{\theta}, \boldsymbol{x})\pi(\boldsymbol{\theta})$$

Importance Sampling

$\mathscr{L}(\boldsymbol{\theta})$	Likelihood **without DM** signal
$\mathscr{L}(\boldsymbol{\theta}, \boldsymbol{x})$	Likelihood **with DM** signal
$\pi(\boldsymbol{\theta}) = \pi(\boldsymbol{\theta})$	Prior CR propagation

$$\boldsymbol{\theta} = \{\gamma_{1,p}, \gamma_{1,\mathrm{He}}, \gamma_{2,p}, \gamma_{2,\mathrm{He}}, R_0, s, D_0, \delta, v_A, v_{0,c}\ , z_h, \varphi, \varphi_{\bar{p}}\}$$

$$\boldsymbol{x} = \{m_{\mathrm{DM}}, \langle\sigma v\rangle_{gg}, \langle\sigma v\rangle_{q\bar{q}}, \langle\sigma v\rangle_{c\bar{c}}, \langle\sigma v\rangle_{b\bar{b}}, \langle\sigma v\rangle_{t\bar{t}}, \langle\sigma v\rangle_{hh}, \langle\sigma v\rangle_{WW}, \langle\sigma v\rangle_{ZZ}\}$$

$\{\boldsymbol{\theta}_i\} \sim \mathscr{L}(\boldsymbol{\theta})\pi(\boldsymbol{\theta})$ ⟵ **We have this!**

$$\overline{\mathscr{L}}(\boldsymbol{x}) = \int \mathrm{d}\theta\, \mathscr{L}(\boldsymbol{\theta}, \boldsymbol{x})\pi(\boldsymbol{\theta})$$

Importance Sampling

$\mathcal{L}(\boldsymbol{\theta})$	Likelihood **without DM** signal
$\mathcal{L}(\boldsymbol{\theta}, \boldsymbol{x})$	Likelihood **with DM** signal
$\pi(\boldsymbol{\theta}) = \pi(\boldsymbol{\theta})$	Prior CR propagation

$$\boldsymbol{\theta} = \{\gamma_{1,p}, \gamma_{1,\mathrm{He}}, \gamma_{2,p}, \gamma_{2,\mathrm{He}}, R_0, s, D_0, \delta, v_A, v_{0,c}, z_h, \varphi, \varphi_{\bar{p}}\}$$

$$\boldsymbol{x} = \{m_{\mathrm{DM}}, \langle\sigma v\rangle_{gg}, \langle\sigma v\rangle_{q\bar{q}}, \langle\sigma v\rangle_{c\bar{c}}, \langle\sigma v\rangle_{b\bar{b}}, \langle\sigma v\rangle_{t\bar{t}}, \langle\sigma v\rangle_{hh}, \langle\sigma v\rangle_{WW}, \langle\sigma v\rangle_{ZZ}\}$$

$\{\boldsymbol{\theta}_i\} \sim \mathcal{L}(\boldsymbol{\theta})\pi(\boldsymbol{\theta})$ $\longleftarrow$ **We have this!**

$$\overline{\mathcal{L}}(\boldsymbol{x}) = \int \mathrm{d}\theta\, \mathcal{L}(\boldsymbol{\theta})\pi(\boldsymbol{\theta}) \frac{\mathcal{L}(\boldsymbol{\theta}, \boldsymbol{x})}{\mathcal{L}(\boldsymbol{\theta})} \approx \frac{1}{\tilde{N}} \sum_{i=1}^{N} \frac{\mathcal{L}(\boldsymbol{\theta}_i, \boldsymbol{x})}{\mathcal{L}(\boldsymbol{\theta}_i)}$$

Importance Sampling

$\mathscr{L}(\boldsymbol{\theta})$ Likelihood **without DM** signal

$\mathscr{L}(\boldsymbol{\theta}, \boldsymbol{x})$ Likelihood **with DM** signal

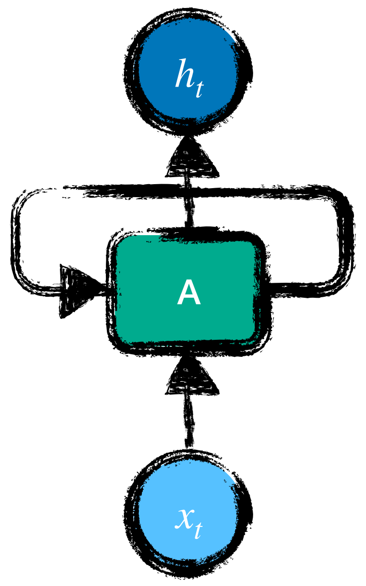
$\pi(\boldsymbol{\theta}) = \pi(\boldsymbol{\theta})$ Prior CR propagation

$$\boldsymbol{\theta} = \{\gamma_{1,p}, \gamma_{1,\mathrm{He}}, \gamma_{2,p}, \gamma_{2,\mathrm{He}}, R_0, s, D_0, \delta, v_A, v_{0,c}, z_h, \varphi, \varphi_{\bar{p}}\}$$

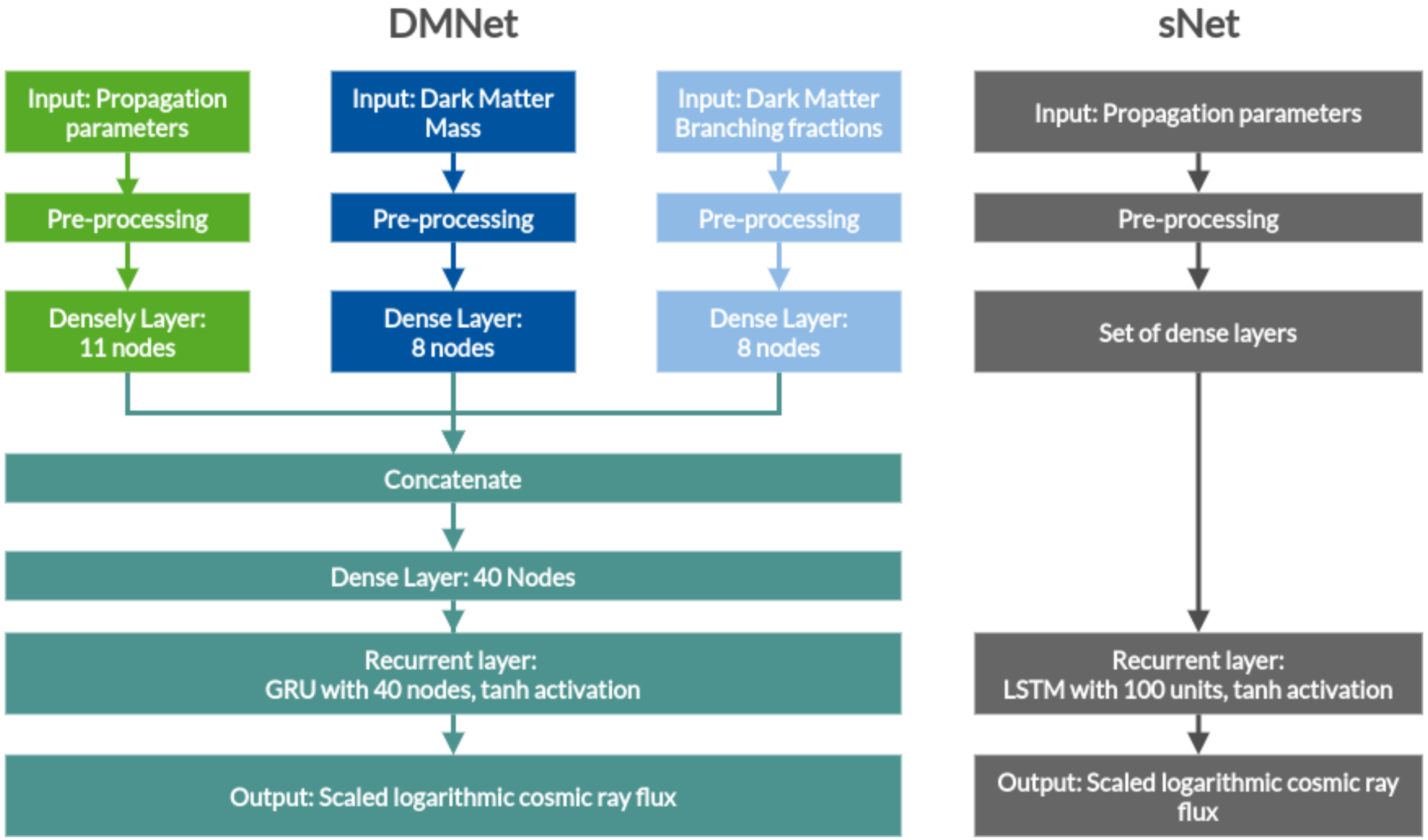
$$\boldsymbol{x} = \{m_{\mathrm{DM}}, \langle\sigma v\rangle_{gg}, \langle\sigma v\rangle_{q\bar{q}}, \langle\sigma v\rangle_{c\bar{c}}, \langle\sigma v\rangle_{b\bar{b}}, \langle\sigma v\rangle_{t\bar{t}}, \langle\sigma v\rangle_{hh}, \langle\sigma v\rangle_{WW}, \langle\sigma v\rangle_{ZZ}\}$$

$$\{\boldsymbol{\theta}_i\} \sim \mathscr{L}(\boldsymbol{\theta})\pi(\boldsymbol{\theta}) \longleftarrow$$ **We have this!**

$$\overline{\mathscr{L}}(\boldsymbol{x}) = \int \mathrm{d}\theta\, \mathscr{L}(\boldsymbol{\theta})\pi(\boldsymbol{\theta}) \frac{\mathscr{L}(\boldsymbol{\theta}, \boldsymbol{x})}{\mathscr{L}(\boldsymbol{\theta})} \approx \frac{1}{\tilde{N}} \sum_{i=1}^{N} \frac{\mathscr{L}(\boldsymbol{\theta}_i, \boldsymbol{x})}{\mathscr{L}(\boldsymbol{\theta}_i)} \longleftarrow$$ **We make it fast!**



Dark Ray Net



[Kahlhoefer, MK, et al. 2021]

$$\tilde{\phi}_s(E) = \log_{10}(E^{2.7}\phi(E)) \qquad \tilde{\phi}_{\mathrm{DM}}(x) = \log_{10}(m_{\mathrm{DM}}^3 x \phi(E))$$

Training Data: Chain of a MultiNest fit

RNNs efficiently learn smooth spectra

Dark Ray Net

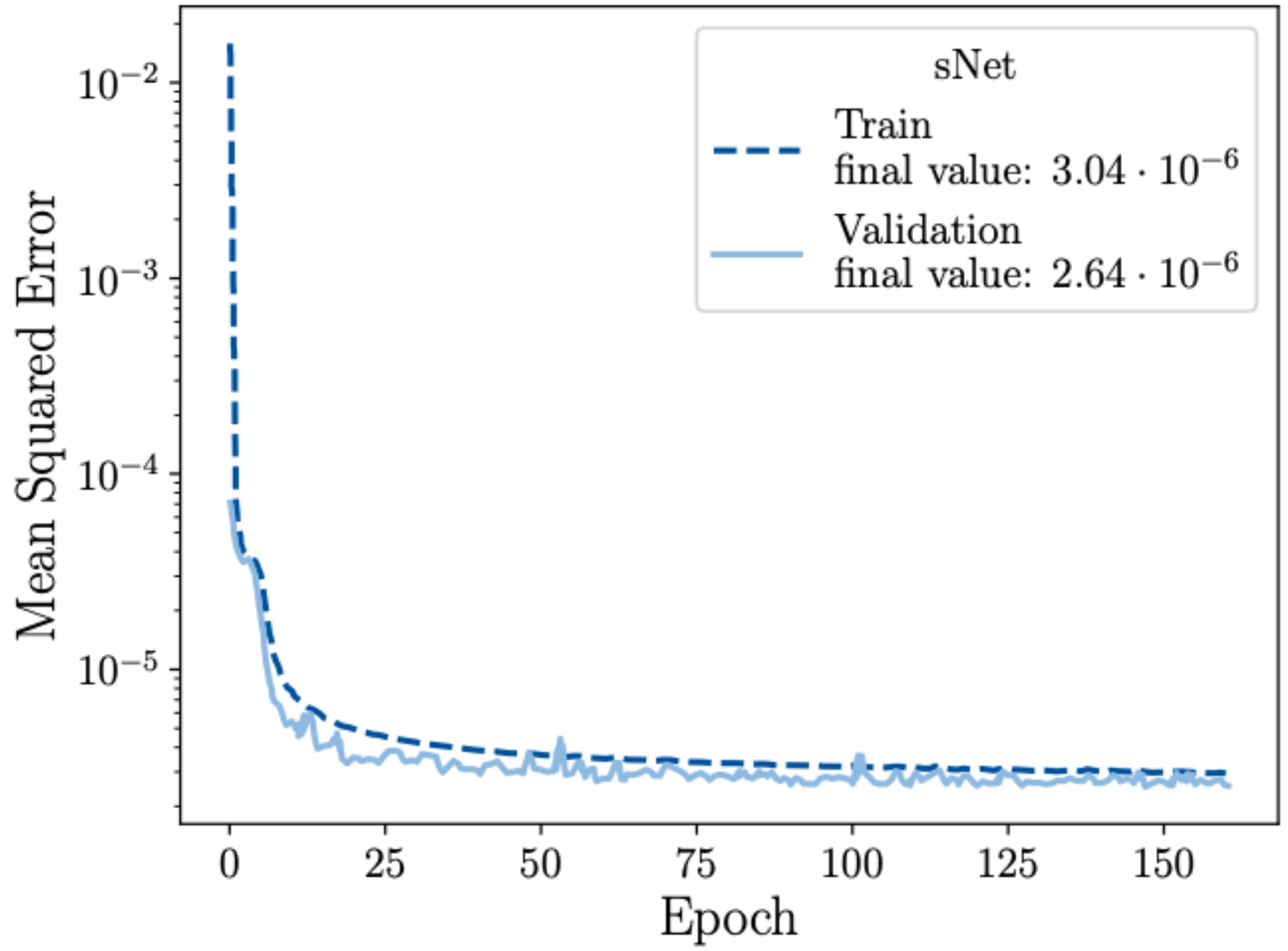
DMNet

sNet

Input: Propagation

Input: Dark Matter

Input: Dark Matter

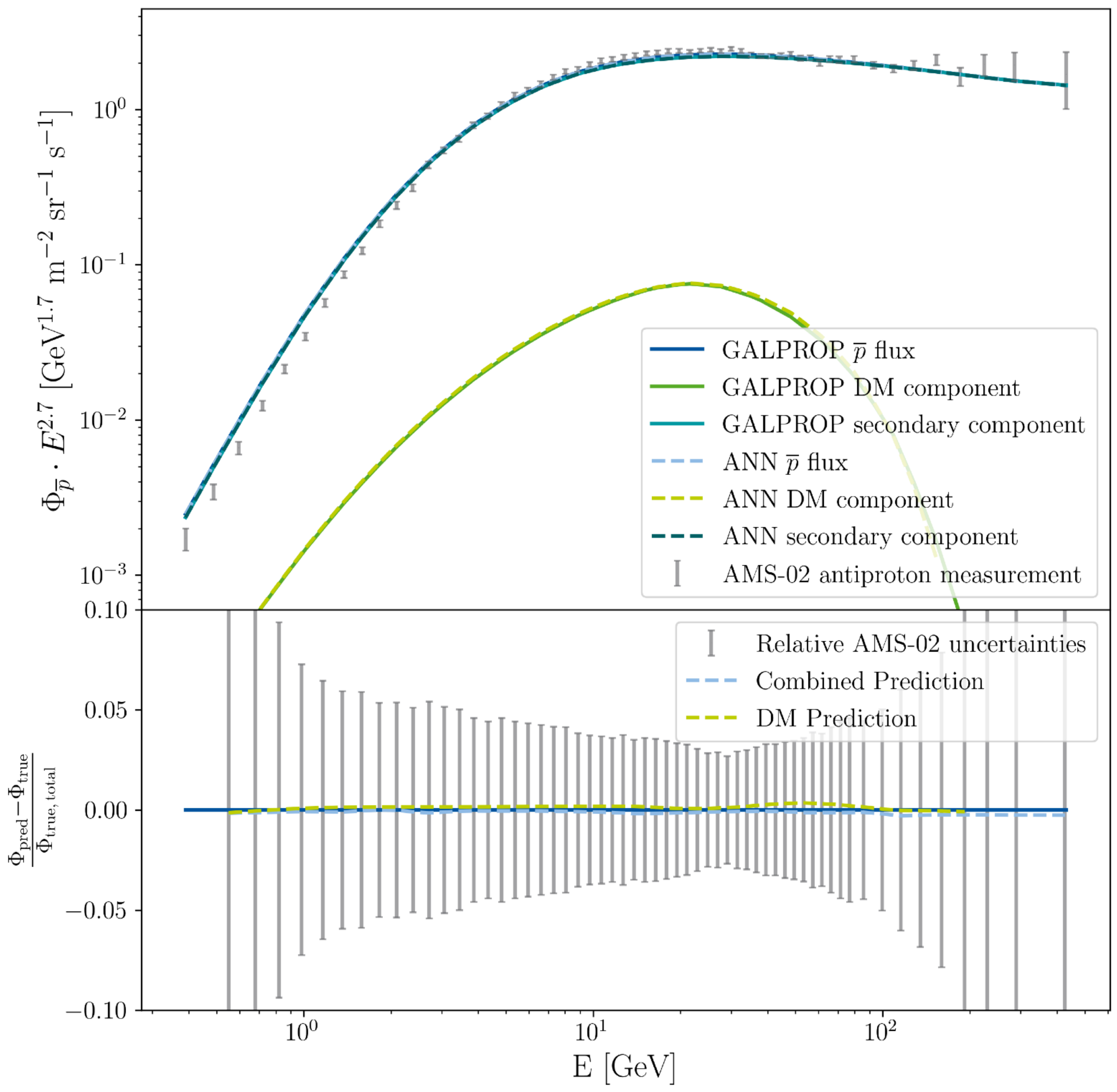


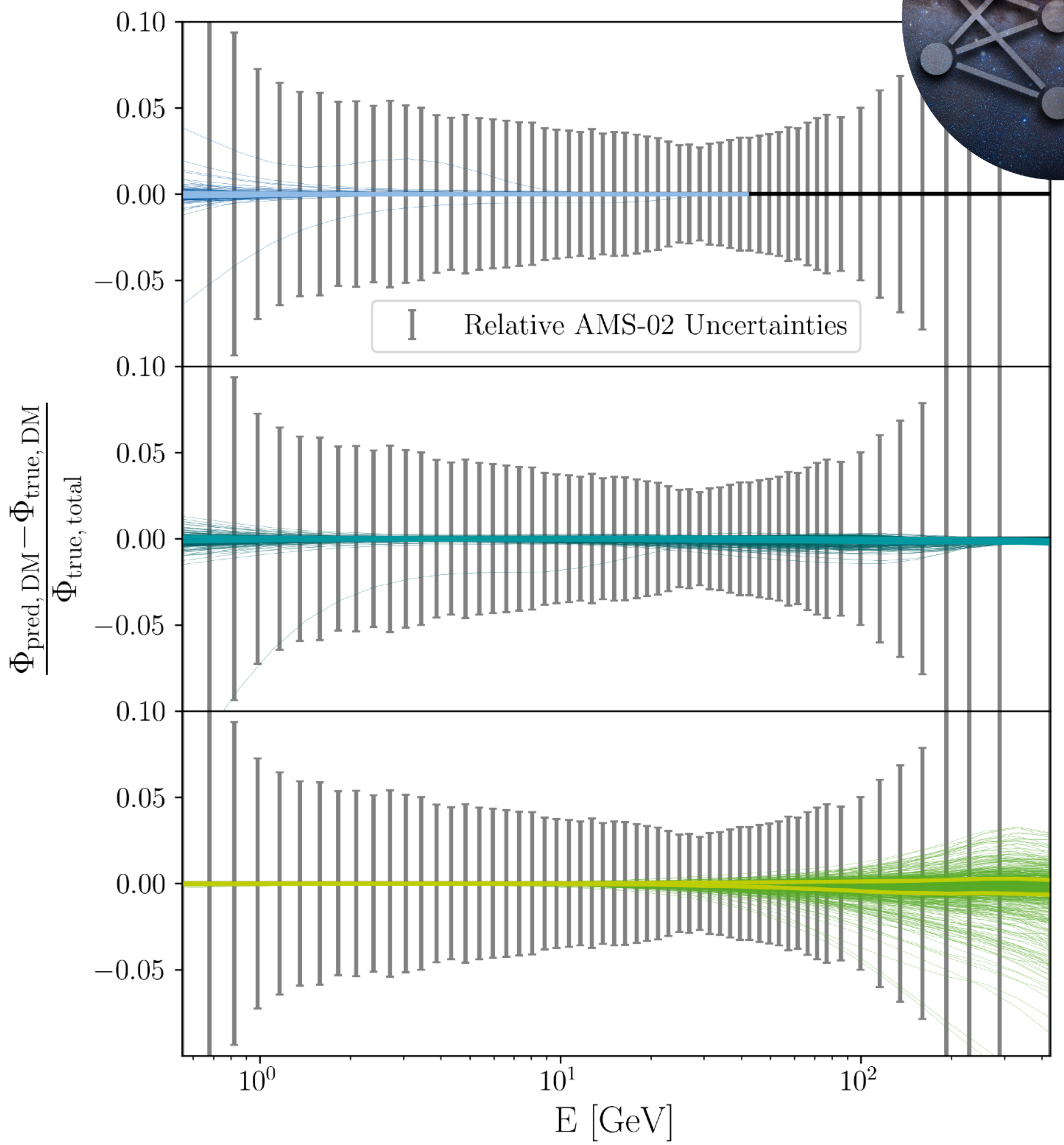
Hyperparameters	
Activation	ReLU
Dropout fraction	0.1 %
Optimizer	Adam, learning rate scheduling $l \in [10^{-2}, 10^{-5}]$, patience 10 epochs
Loss	Mean squared error (MSE)
Batch size	500
Validation split	20 %
Early stopping	Monitor val. loss, patience = 40

[Kahlhoefer, MK, et al. 2021]

$$\tilde{\phi}_s(E) = \log_{10}(E^{2.7}\phi(E)) \qquad \tilde{\phi}_{DM}(x) = \log_{10}(m_{DM}^3 x \phi(E))$$

Performance of Dark Ray Net

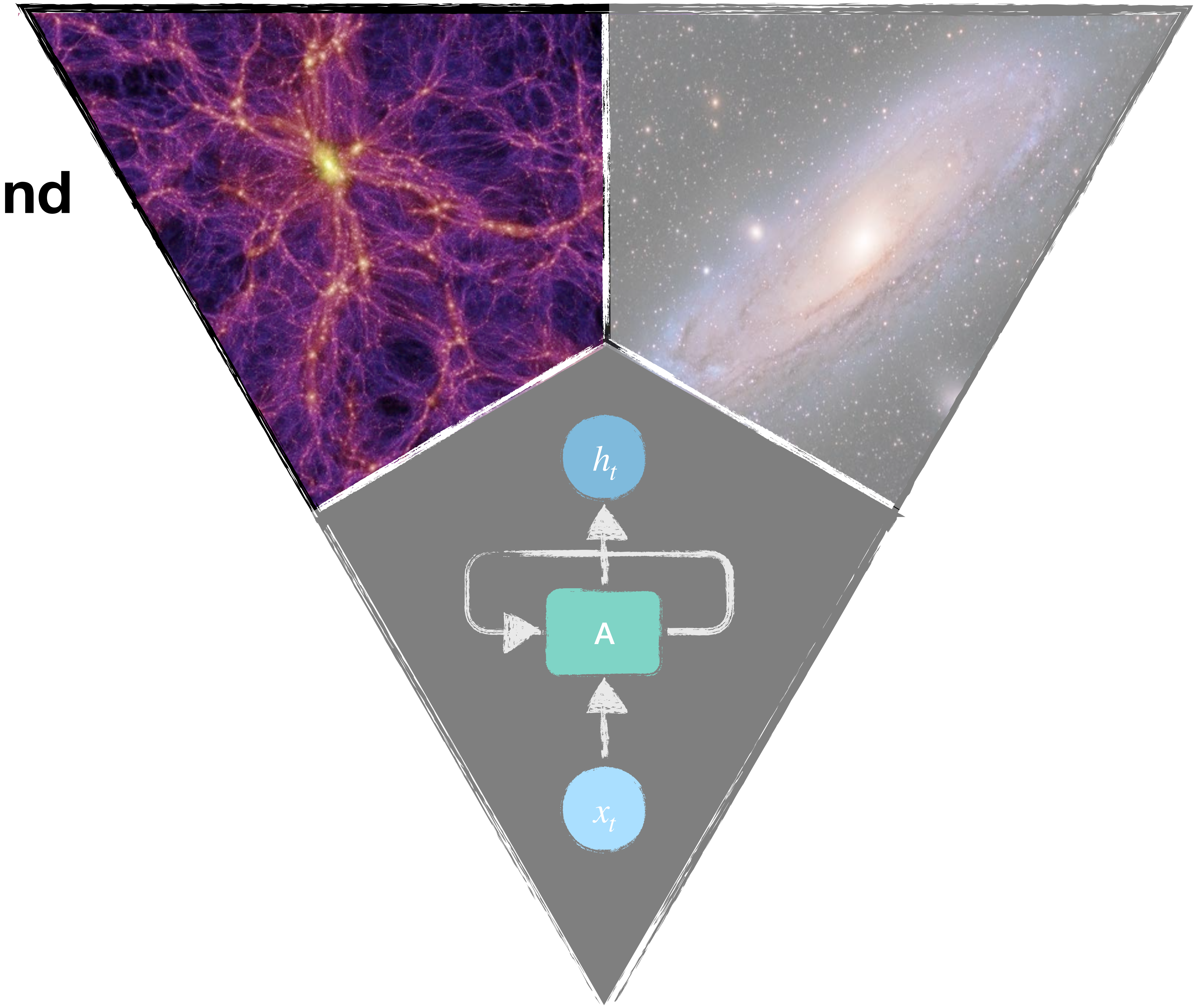




[Kahlhoefer, MK, et al. 2021]

Uncertainties from the NN prediction are almost negligible compared to AMS-02 measurement uncertainties.

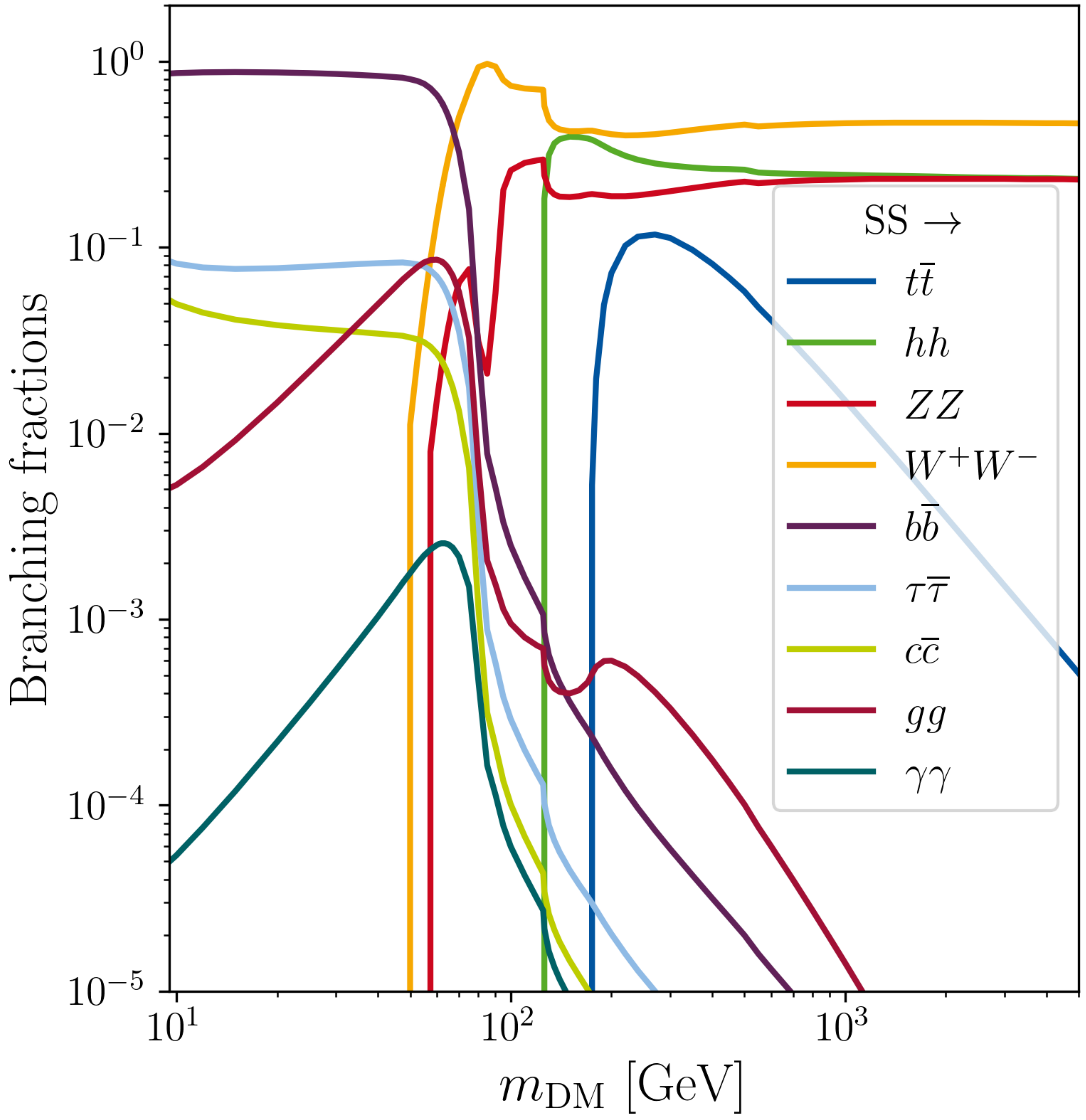
Motivation:
Dark Matter Limits and
Indirect Detection



Cosmic Rays:
Propagation and the
Role of Antiprotons

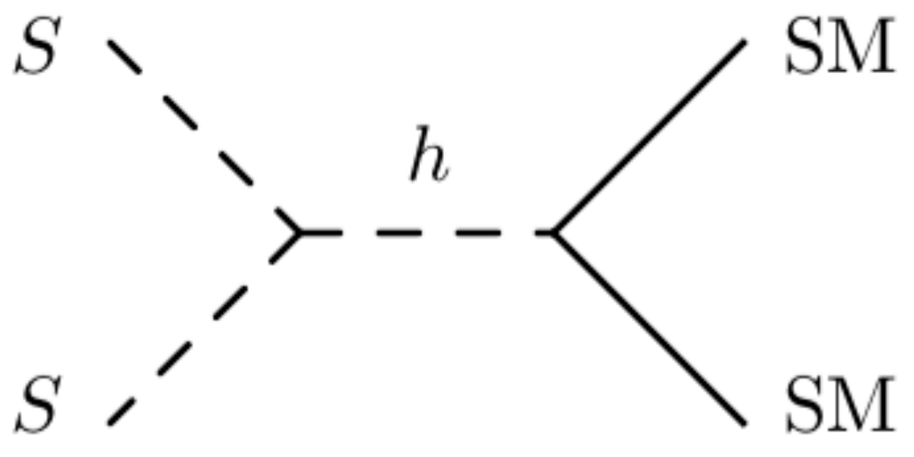
Speed-up: Neural Networks
and Importance Sampling

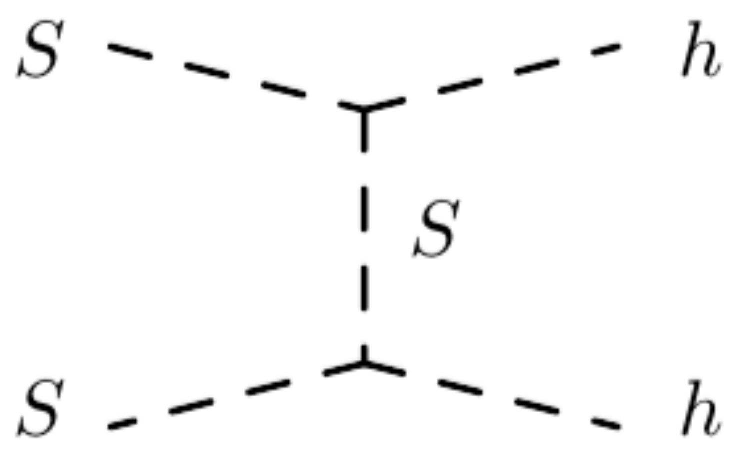
Application: Scalar Singlet DM



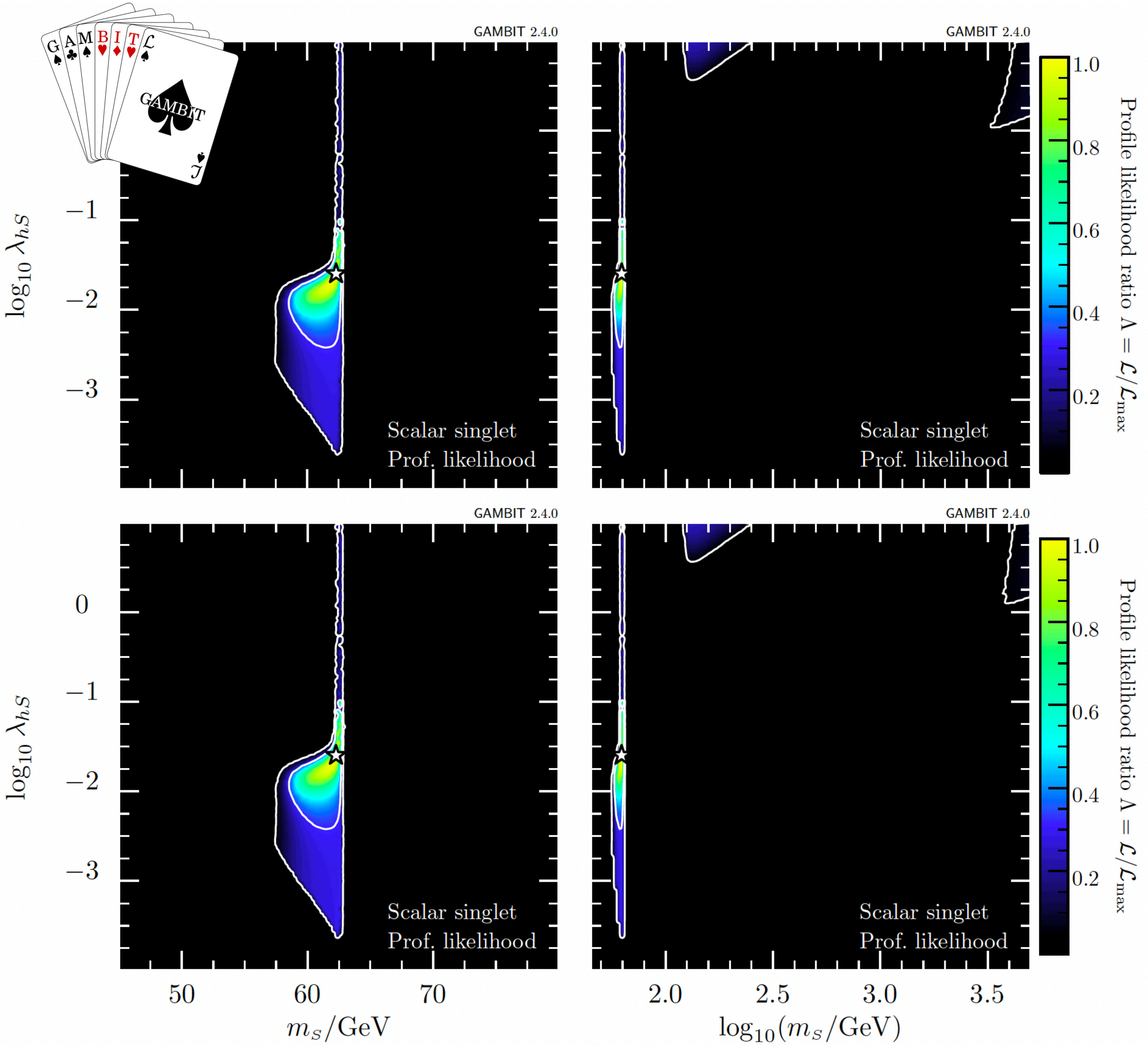
After EW symmetry breaking:

$$\mathscr{L} \supset -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HS} h^2 S^2 - \frac{1}{2}\lambda_{HS} vhS^2$$





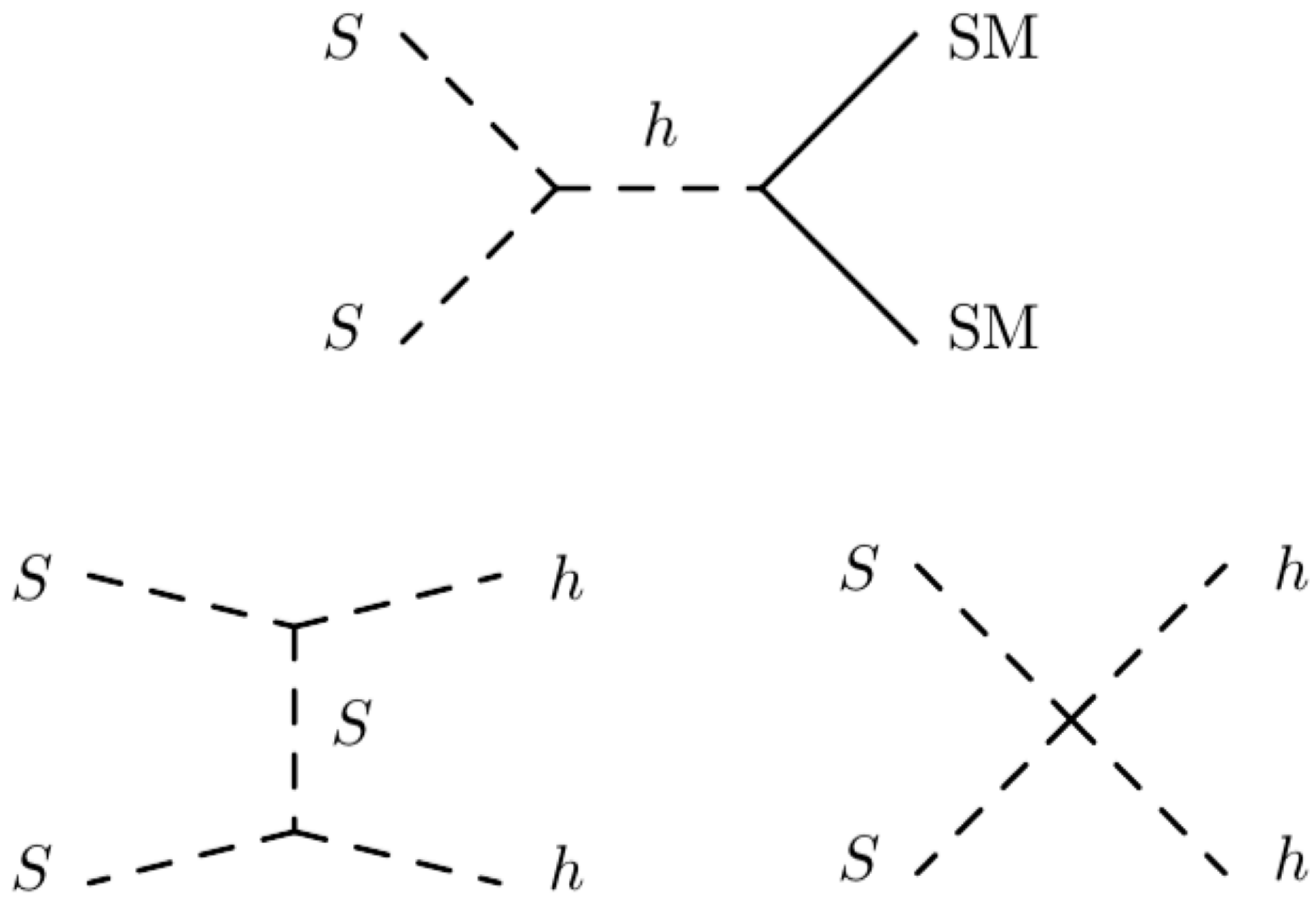
Application: Scalar Singlet DM



[Balan, MK, et al. 2023]

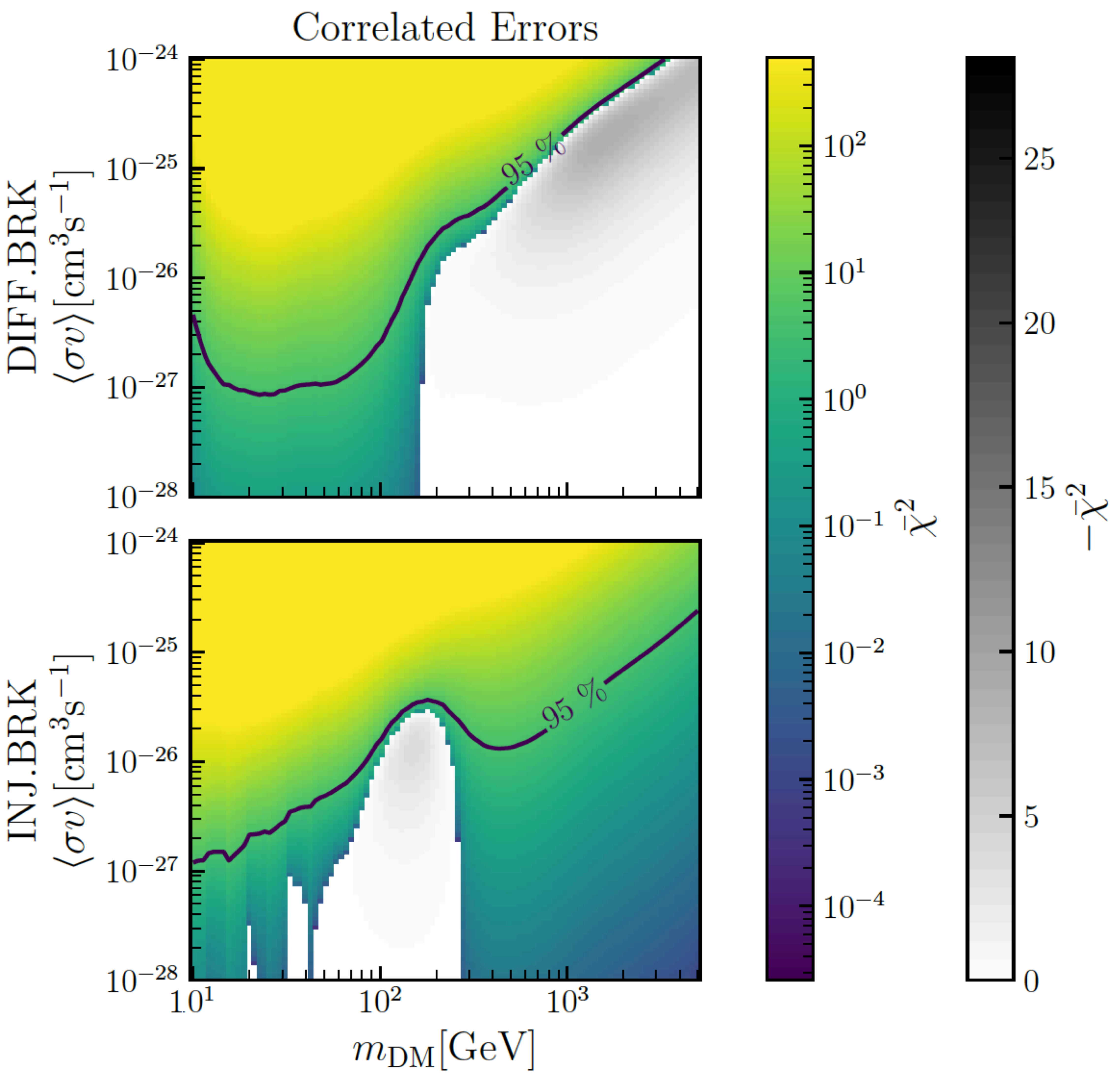
After EW symmetry breaking:

$$\mathcal{L} \supset -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HS} h^2 S^2 - \frac{1}{2}\lambda_{HS} vhS^2$$



Summary

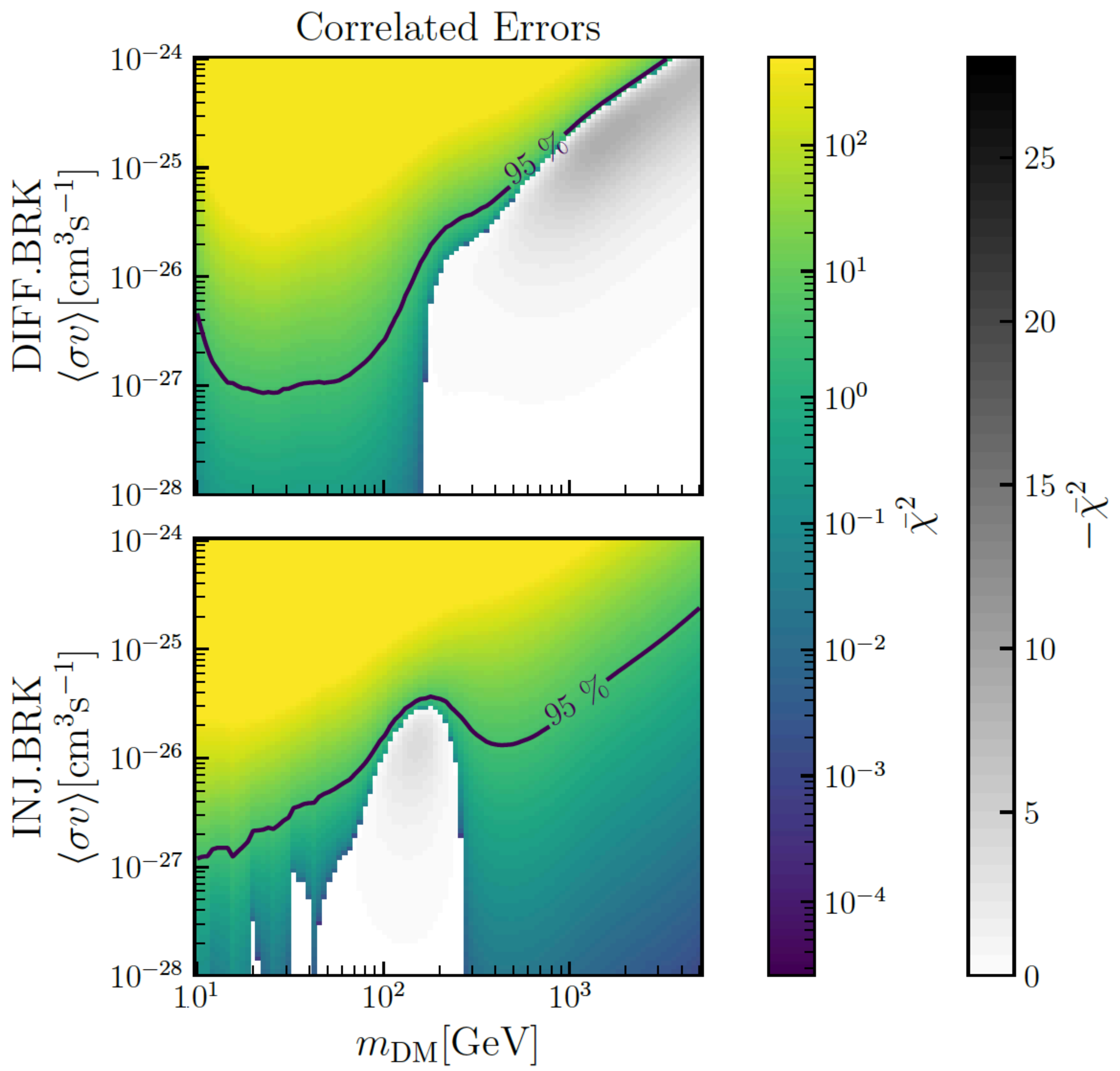
pbarlike



[Balan, MK, et al. 2023]

Summary

pbarlike

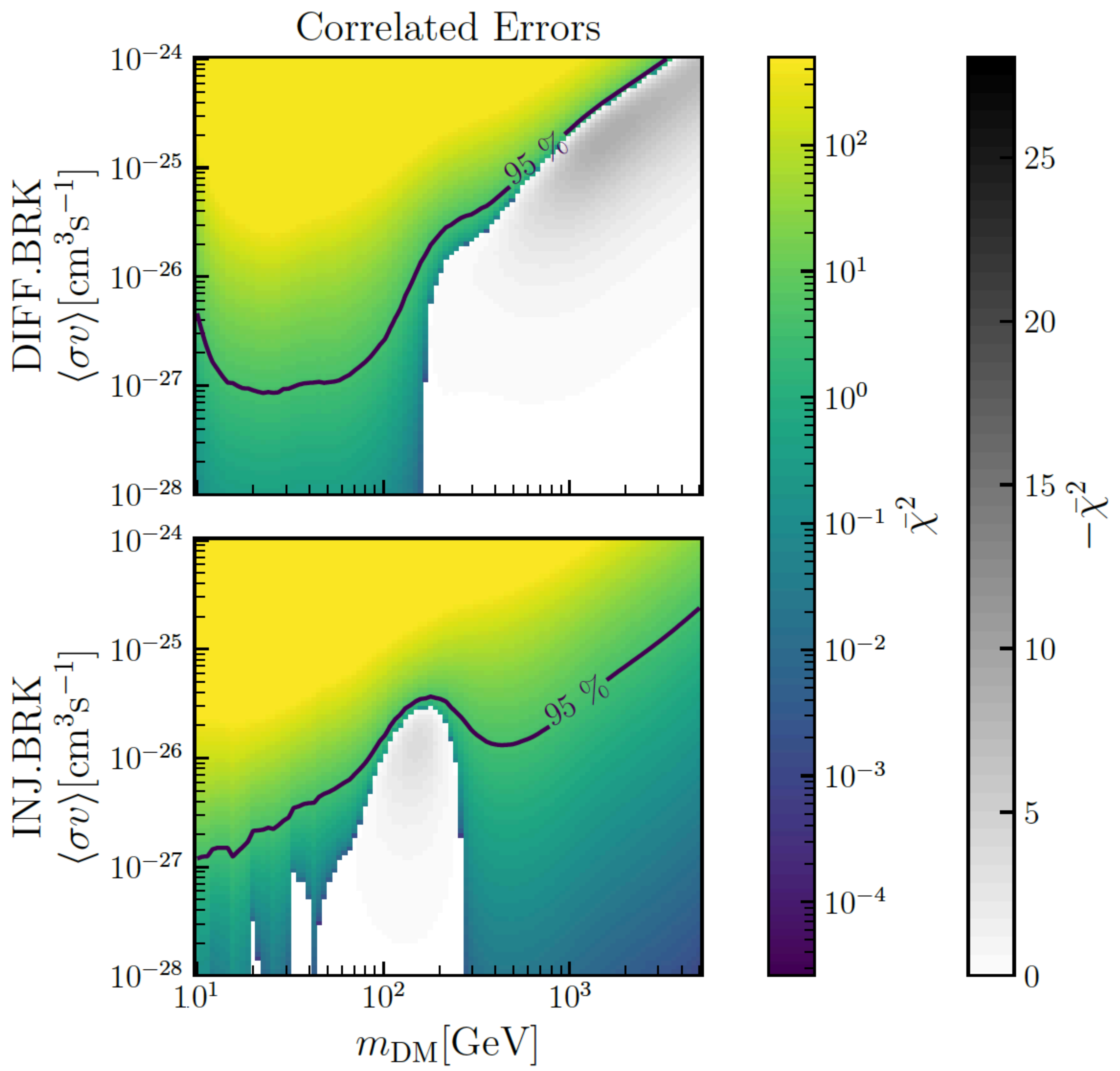


[Balan, MK, et al. 2023]

Fast DM Limits from CR antiprotons

Summary

pbarlike



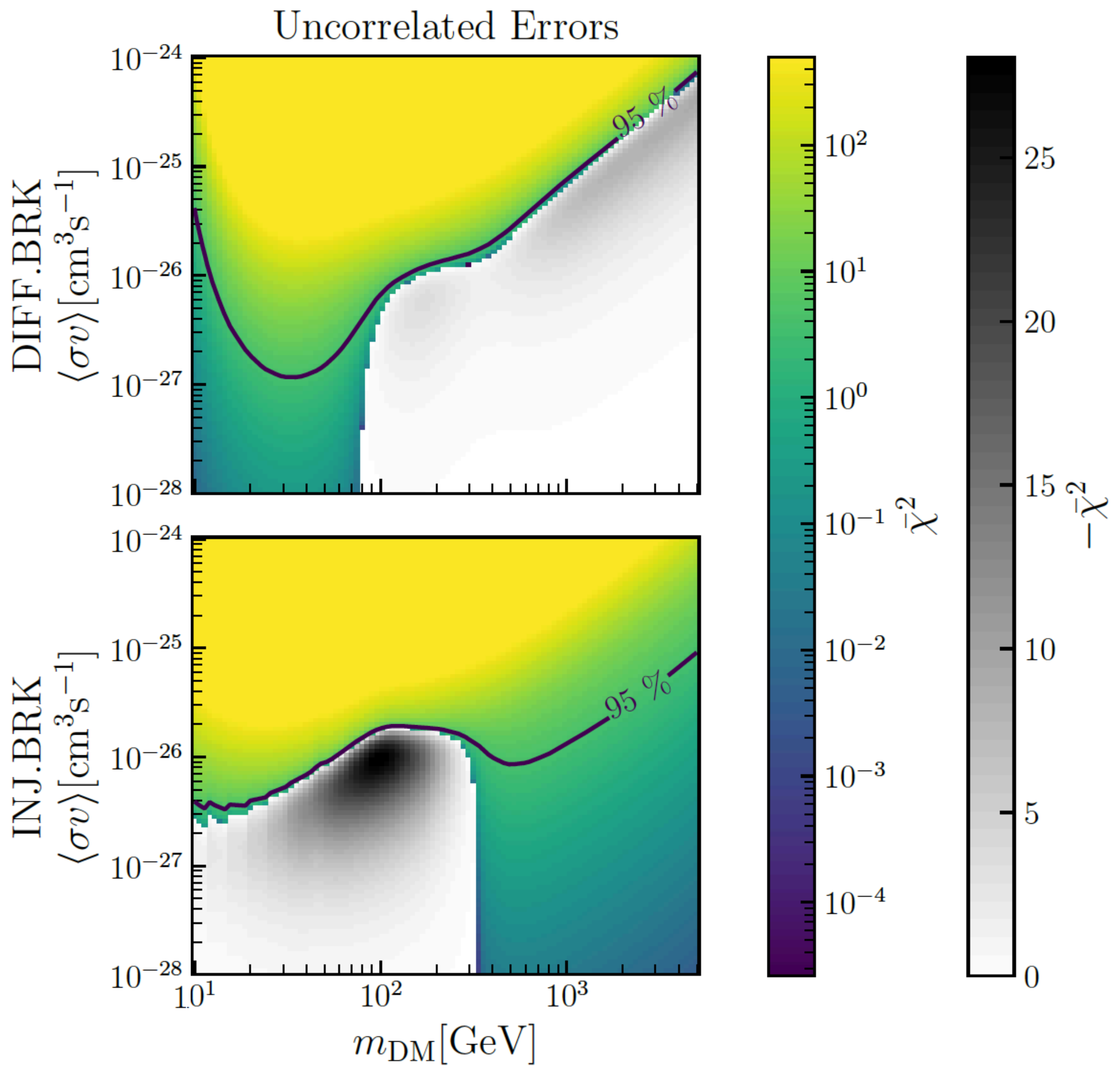
[Balan, MK, et al. 2023]

Fast DM Limits from CR antiprotons

State of the art propagation and uncertainty treatment

Summary

pbarlike



[Balan, MK, et al. 2023]

Fast DM Limits from CR antiprotons

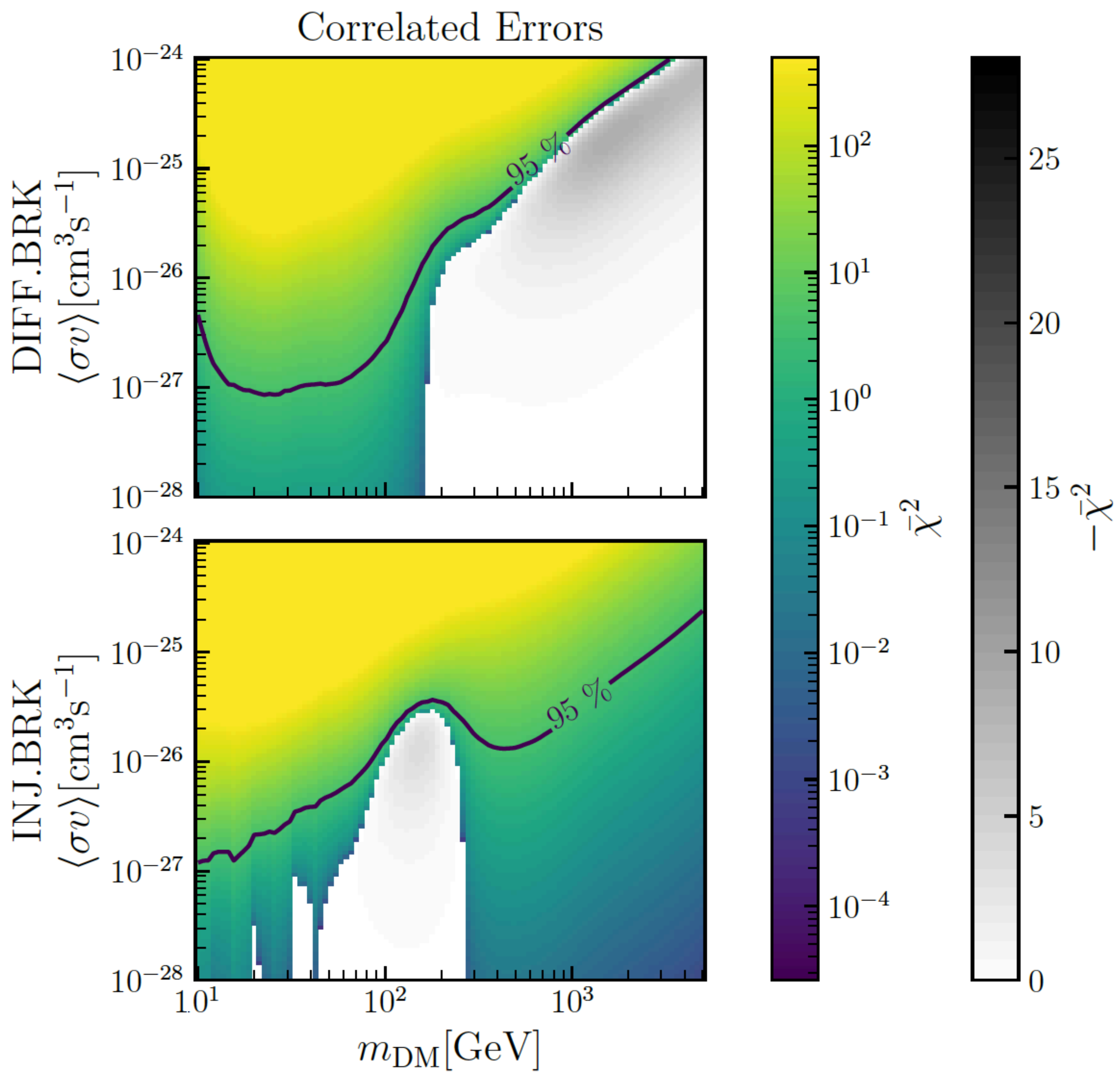
State of the art propagation and uncertainty treatment





Summary

pbarlike

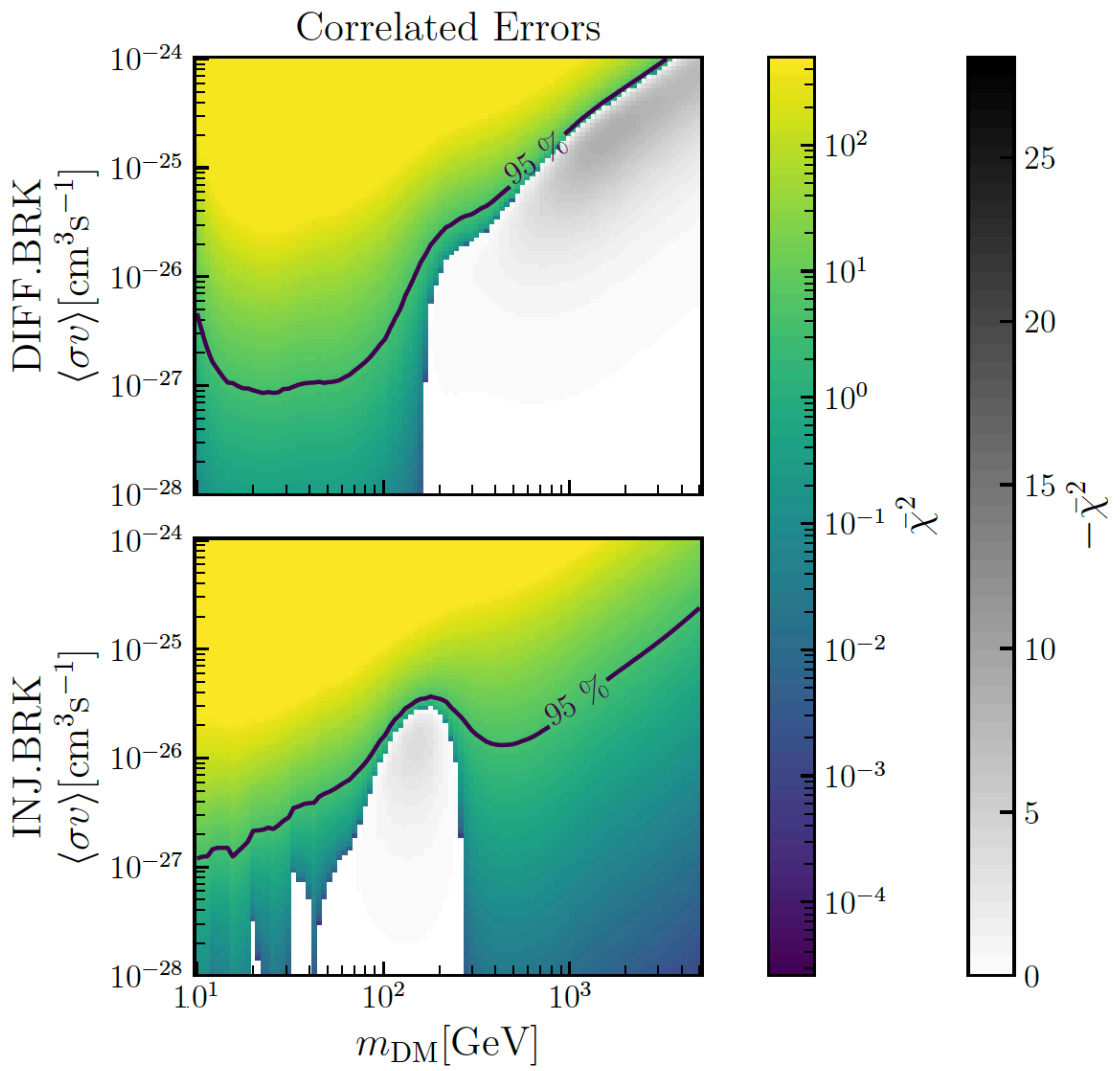


[Balan, MK, et al. 2023]

Fast DM Limits from CR antiprotons

State of the art propagation and uncertainty treatment

Summary



[Balan, MK, et al. 2023]

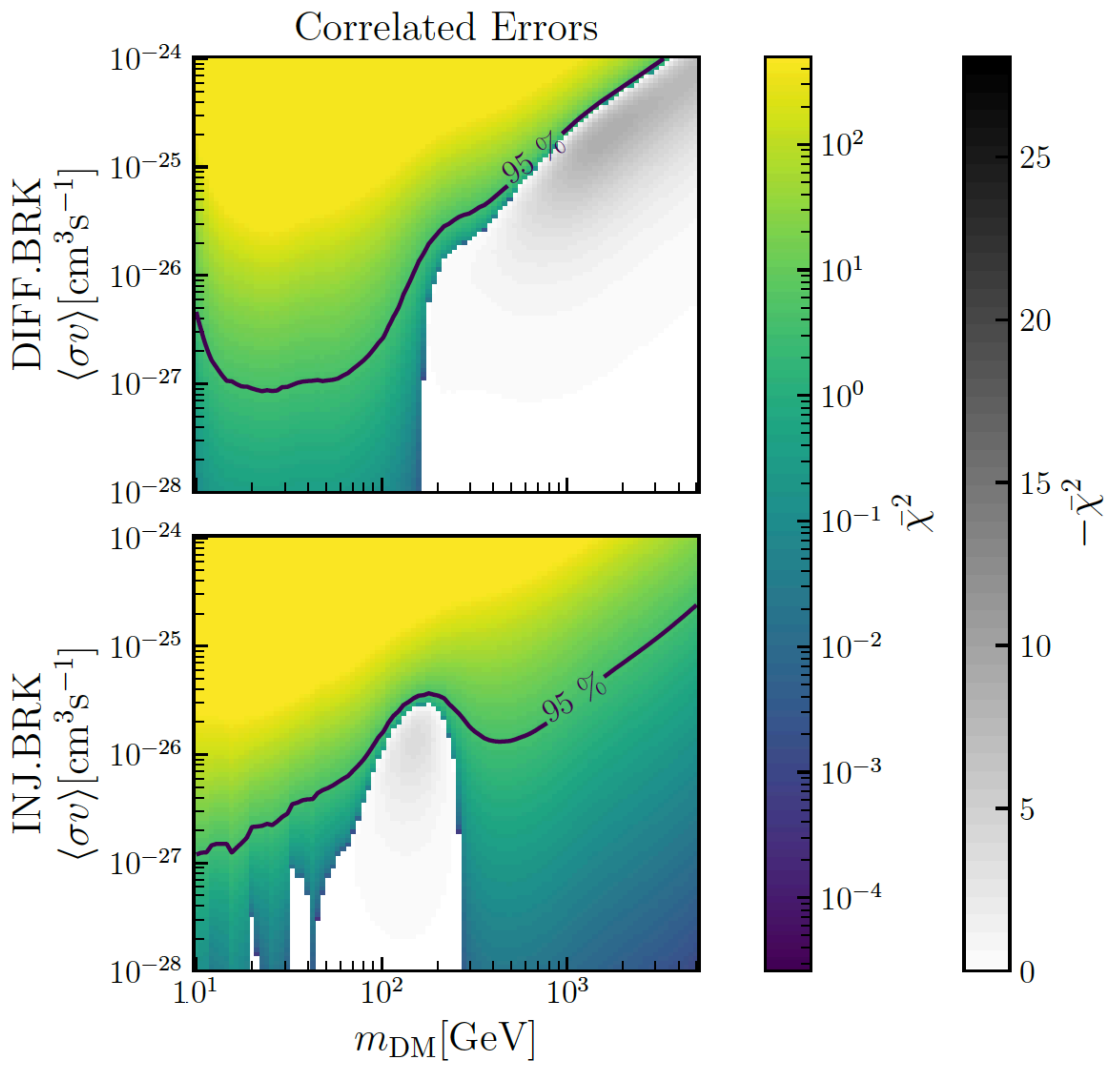
pbarlike

Fast DM Limits from CR antiprotons

State of the art propagation and uncertainty treatment

Public code for CR spectra and likelihood marginalization

Summary



[Balan, MK, et al. 2023]

pbarlike

Fast DM Limits from CR antiprotons

State of the art propagation and uncertainty treatment

Public code for CR spectra and likelihood marginalization

Global fits with GAMBIT