Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

Collaborative Research Center TRR 257
Particle Physics Phenomenology after the Higgs Discovery

Emulation of Cosmic-Ray Antideuteron Fluxes from Dark Matter Annihilation

Based on ArXiv: 2406.18642

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Young Scientist Meeting 2024

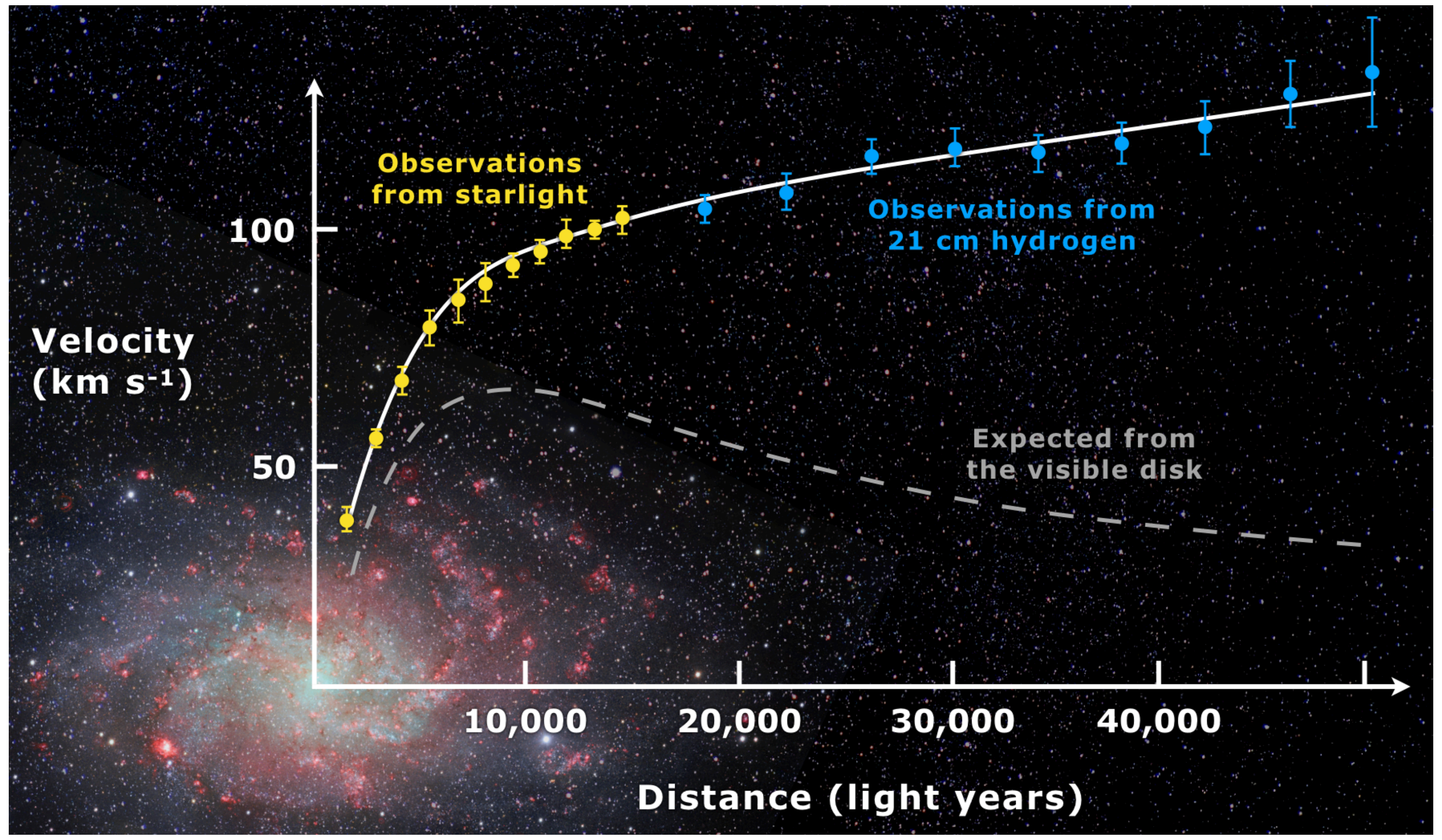
In collaboration with Jan Heisig, Michael Korsmeier, Michael Krämer and Kathrin Nippel

25.09.2024

Evidence for Dark Matter

Evidence for Dark Matter

Galaxy rotation curves



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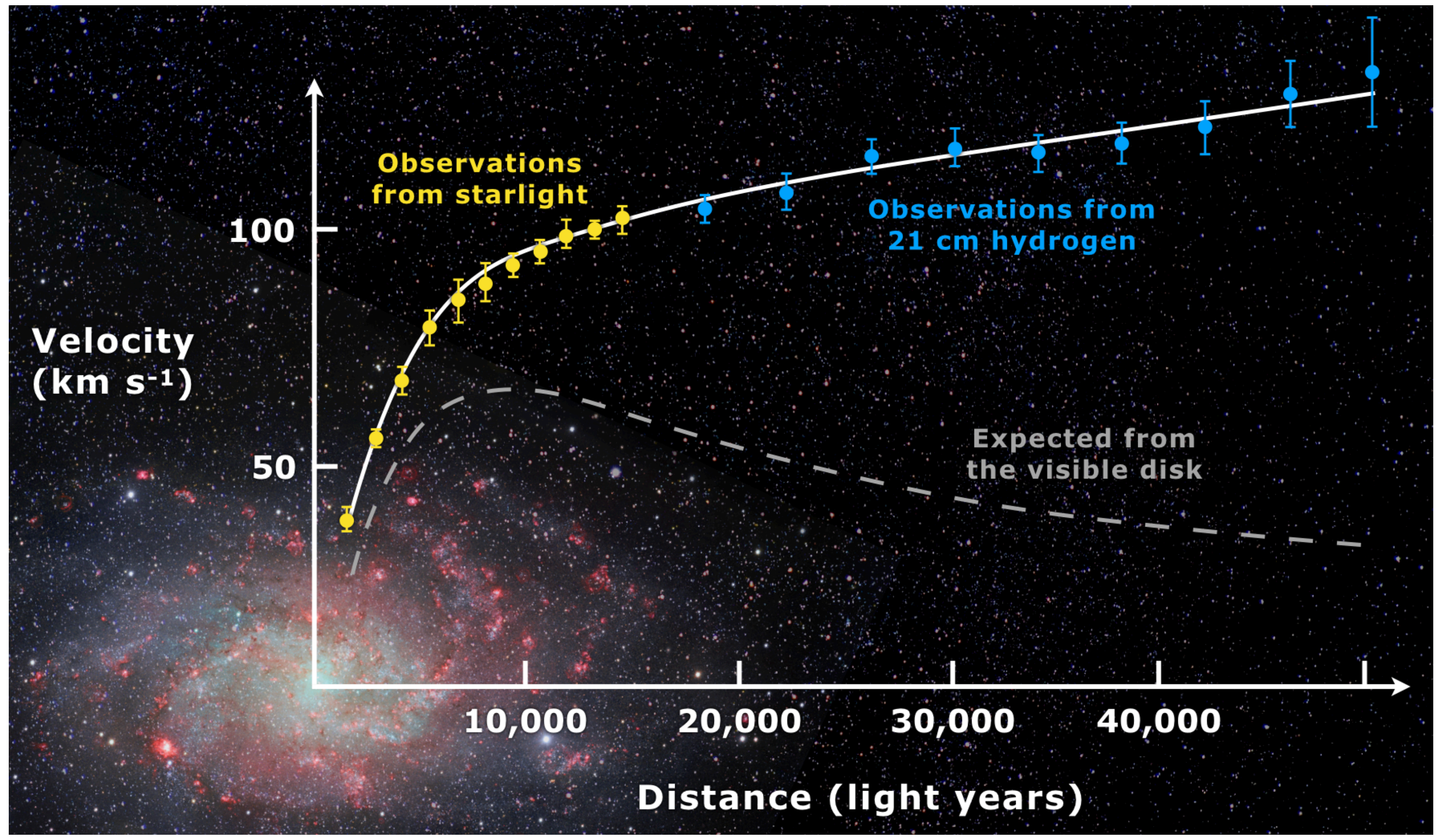
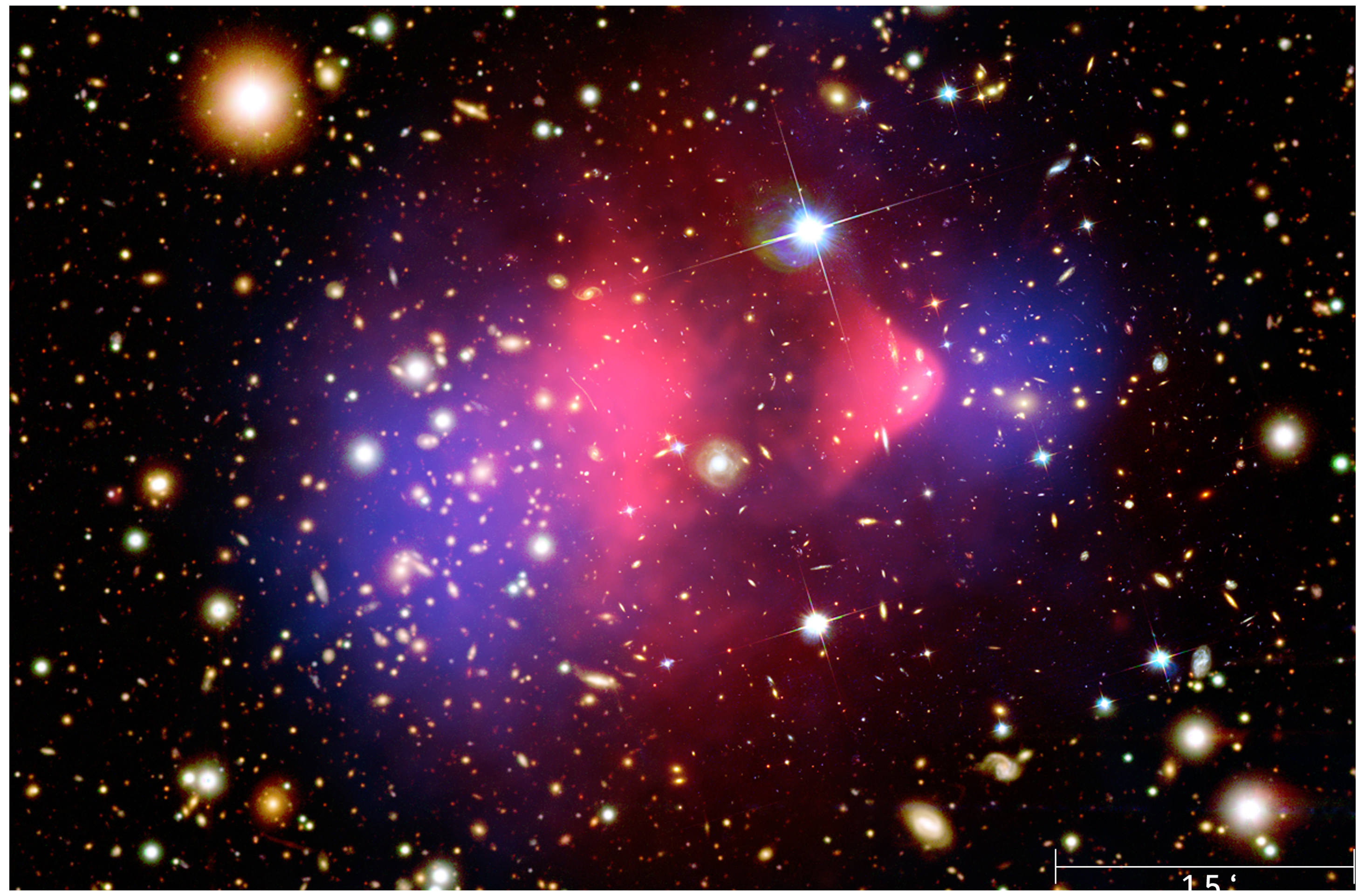


Gravitational lensing



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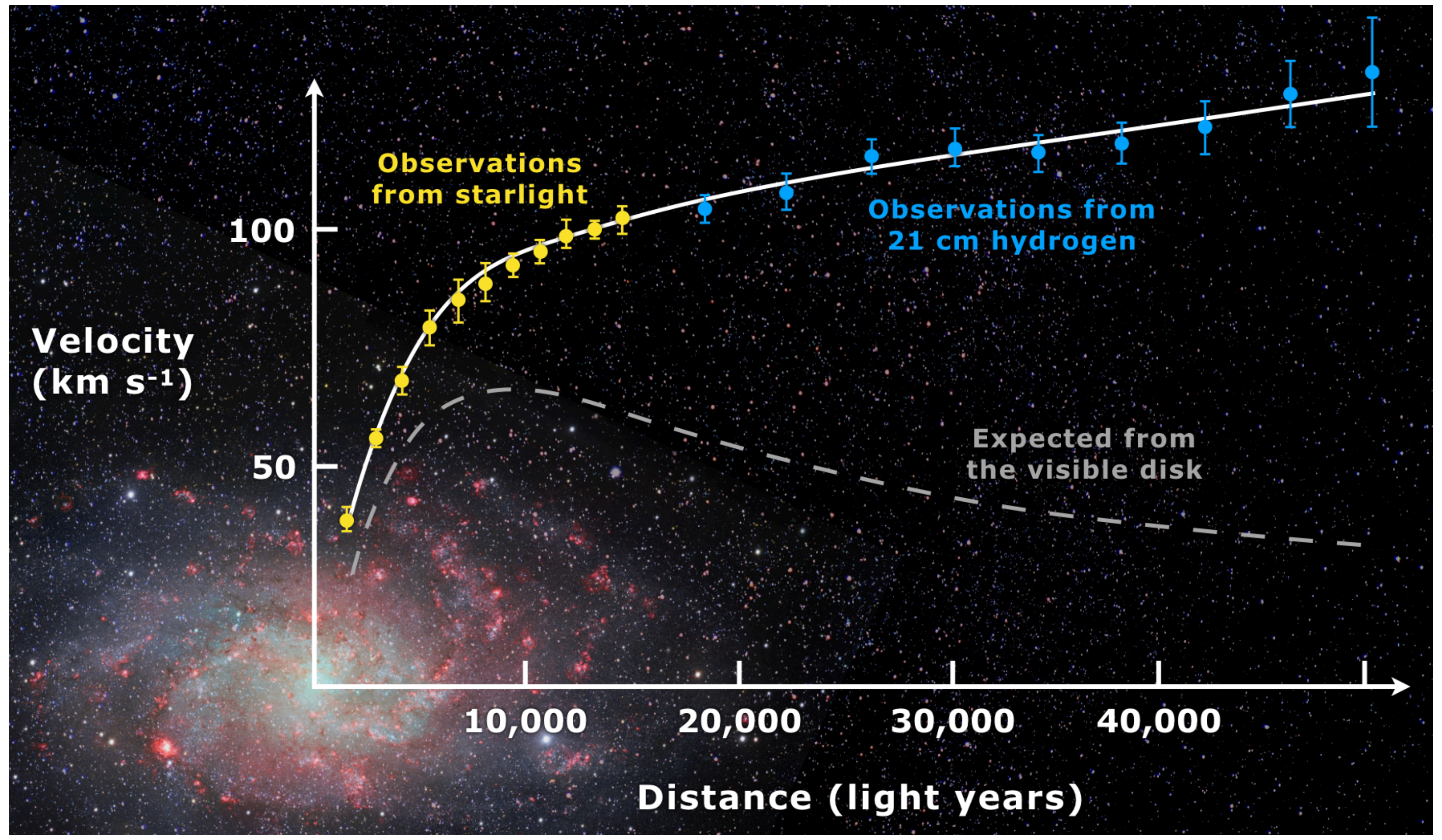

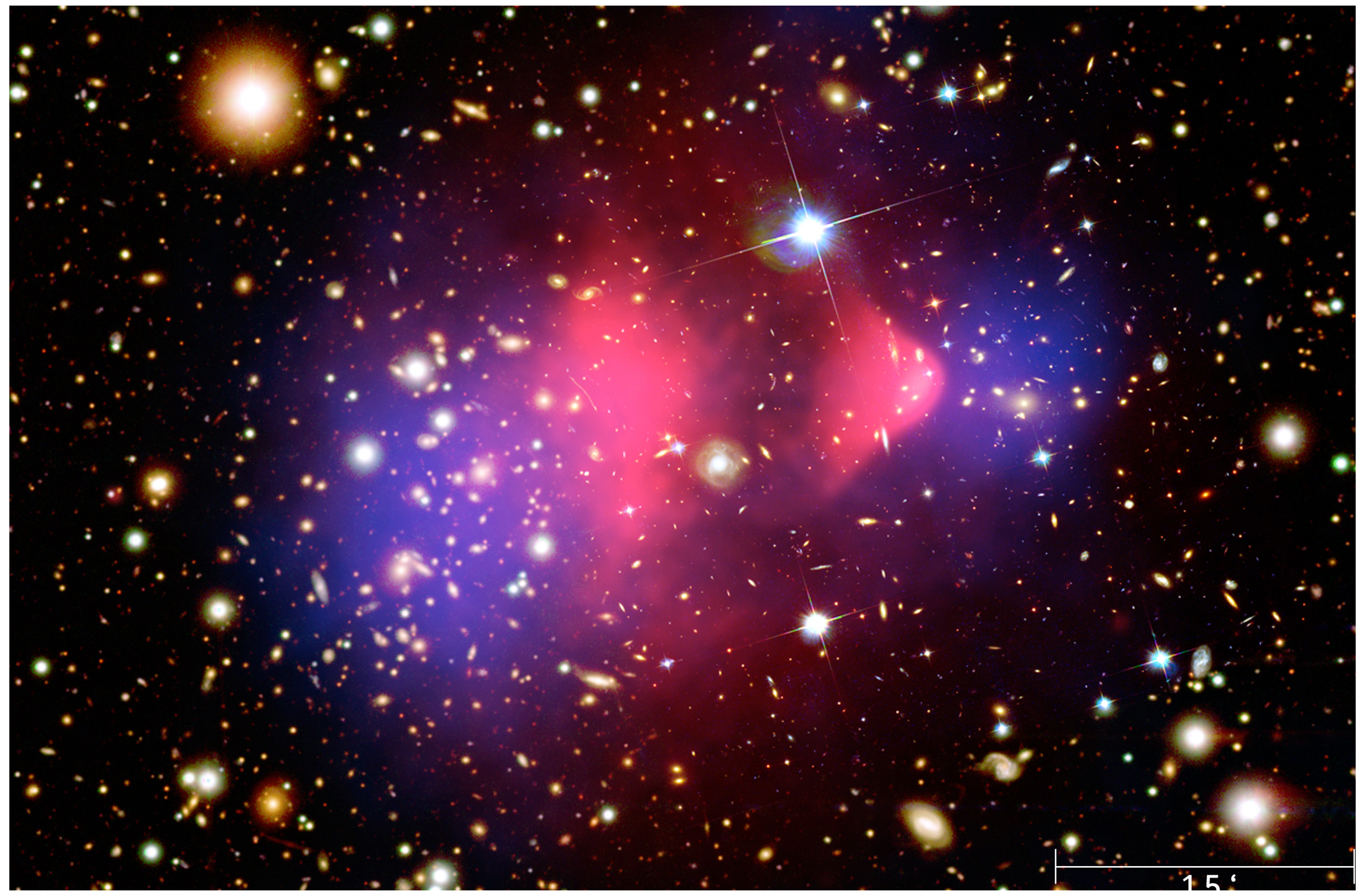

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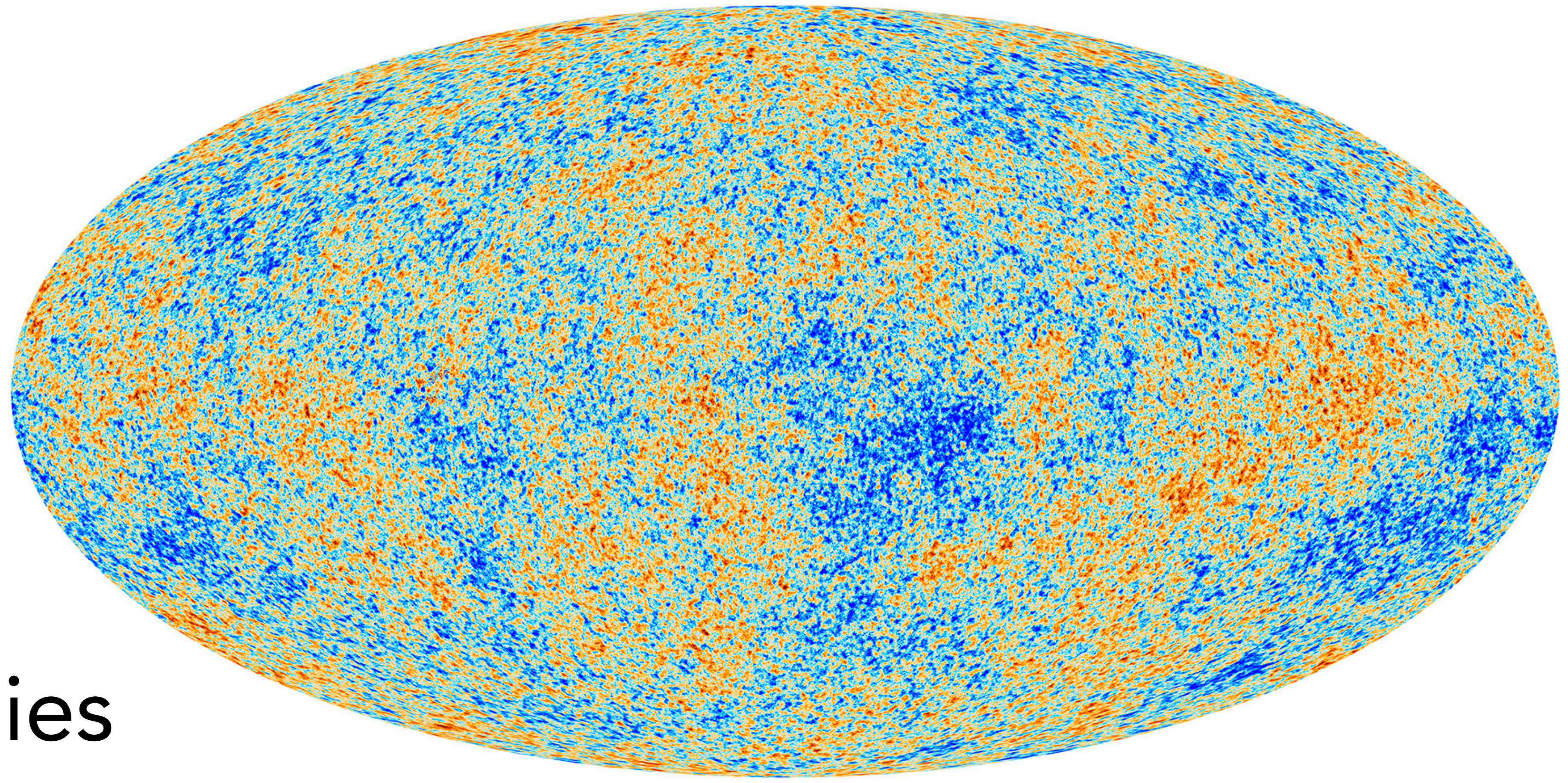

CMB anisotropies

Evidence for Dark Matter

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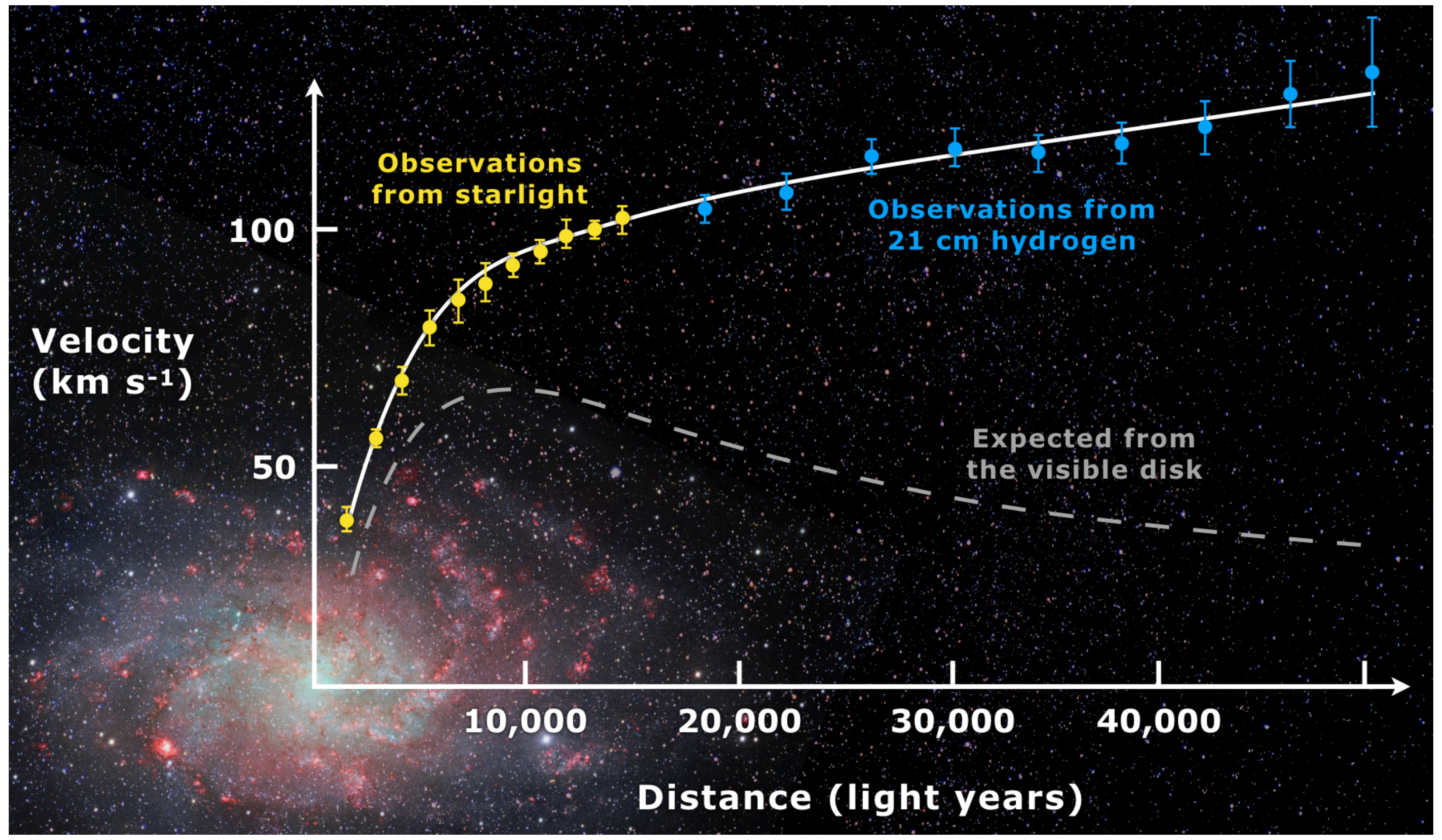

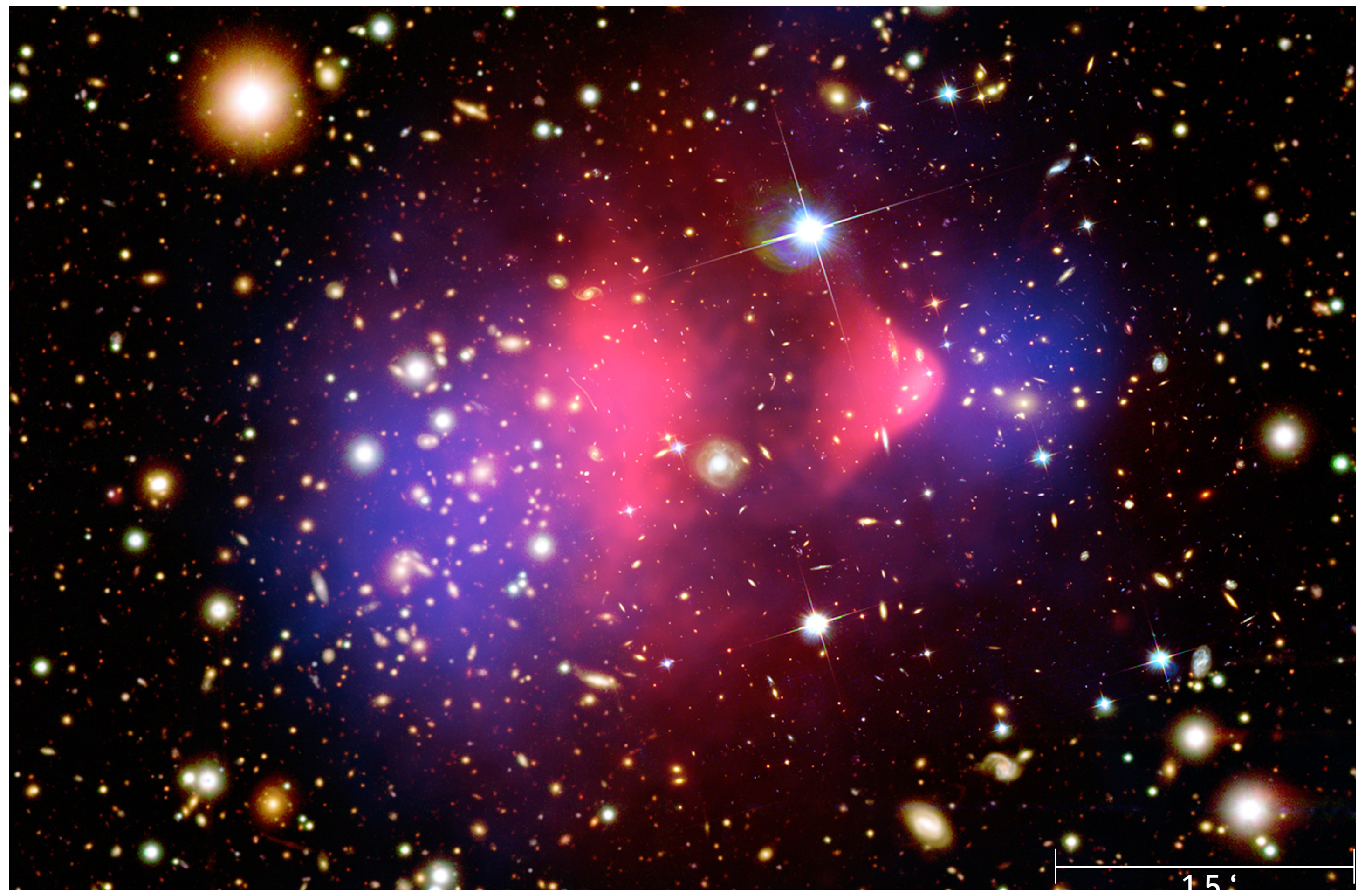

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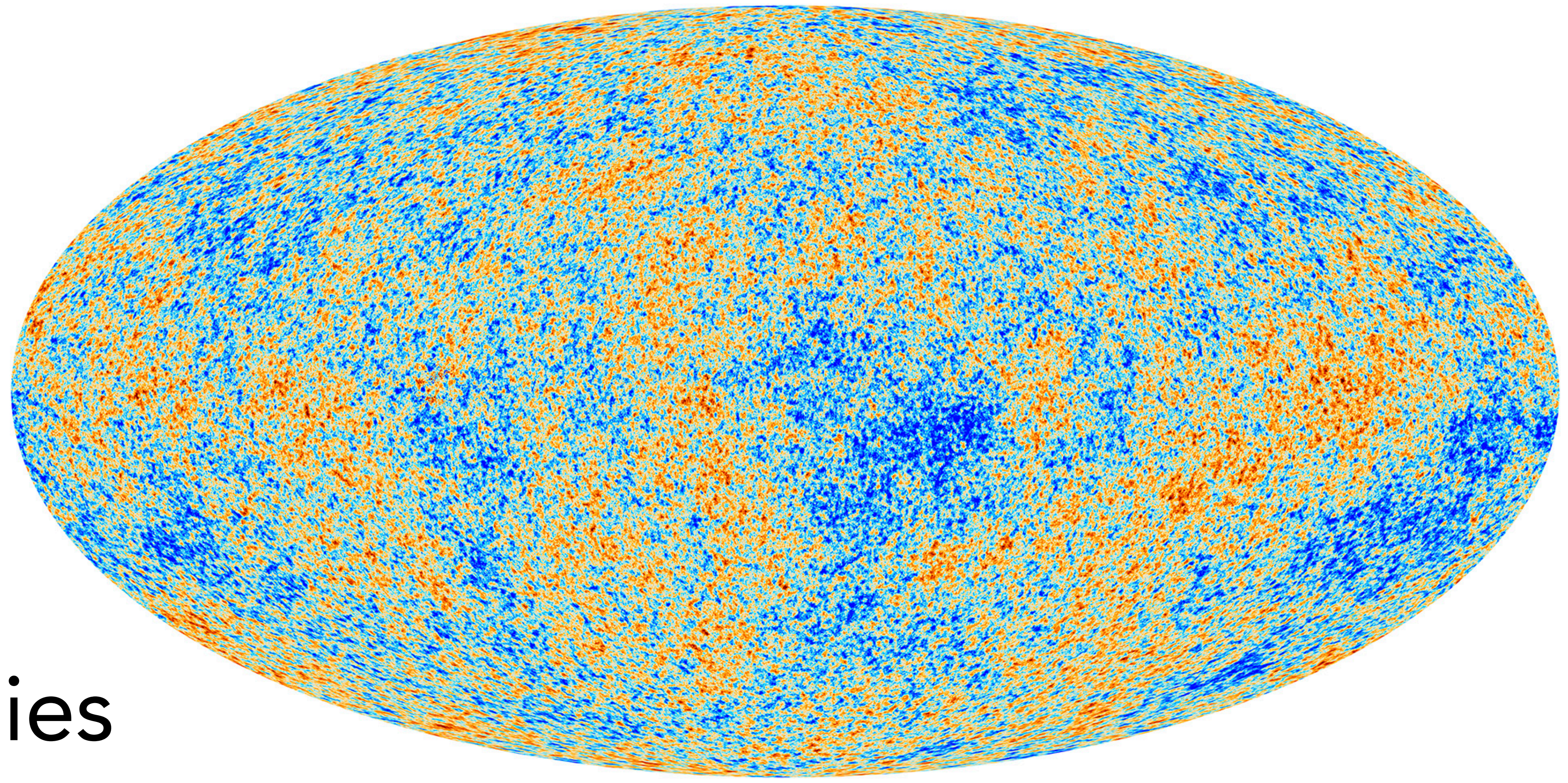

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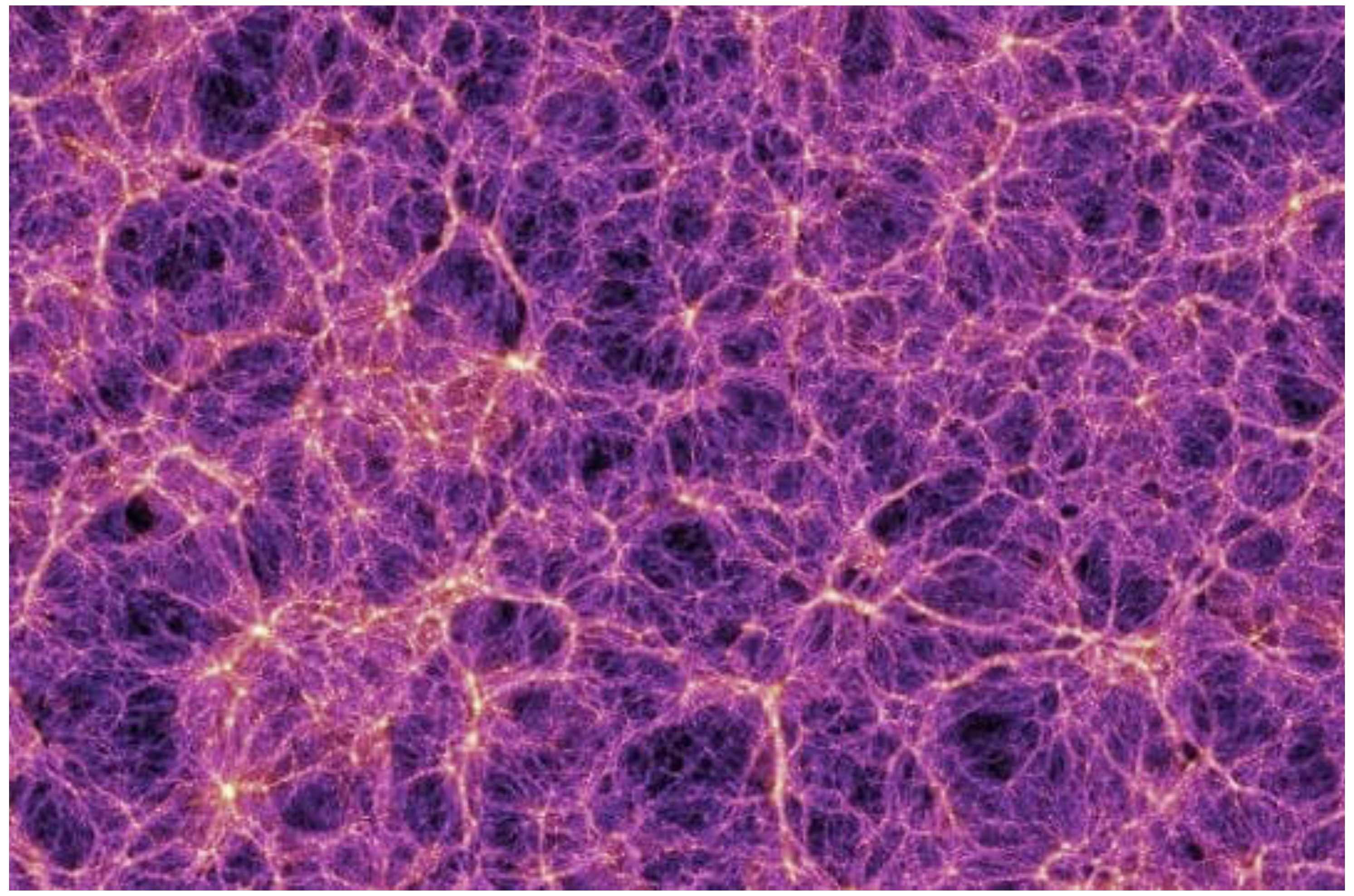
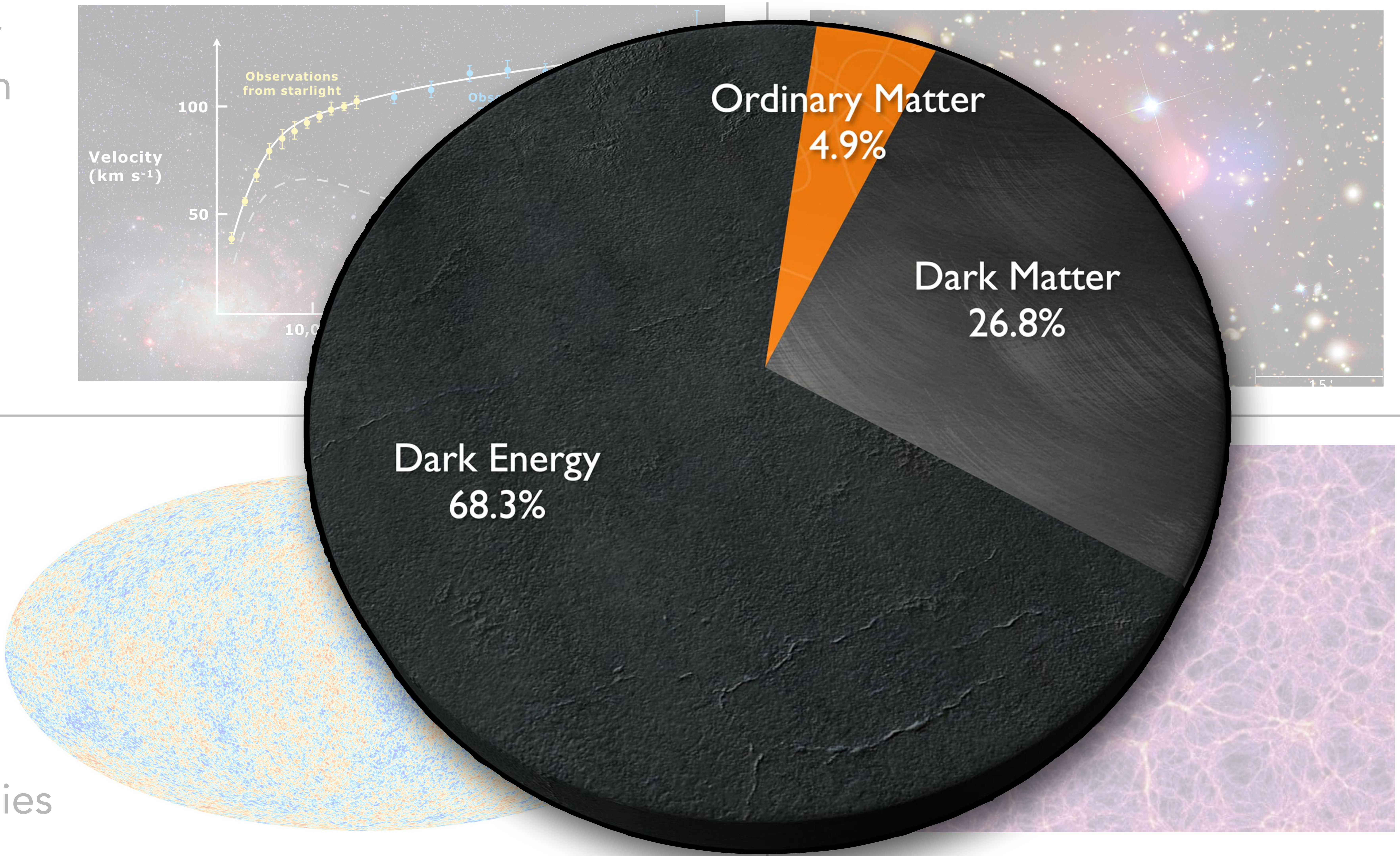


Large scale structures

Evidence for Dark Matter

Galaxy rotation curves

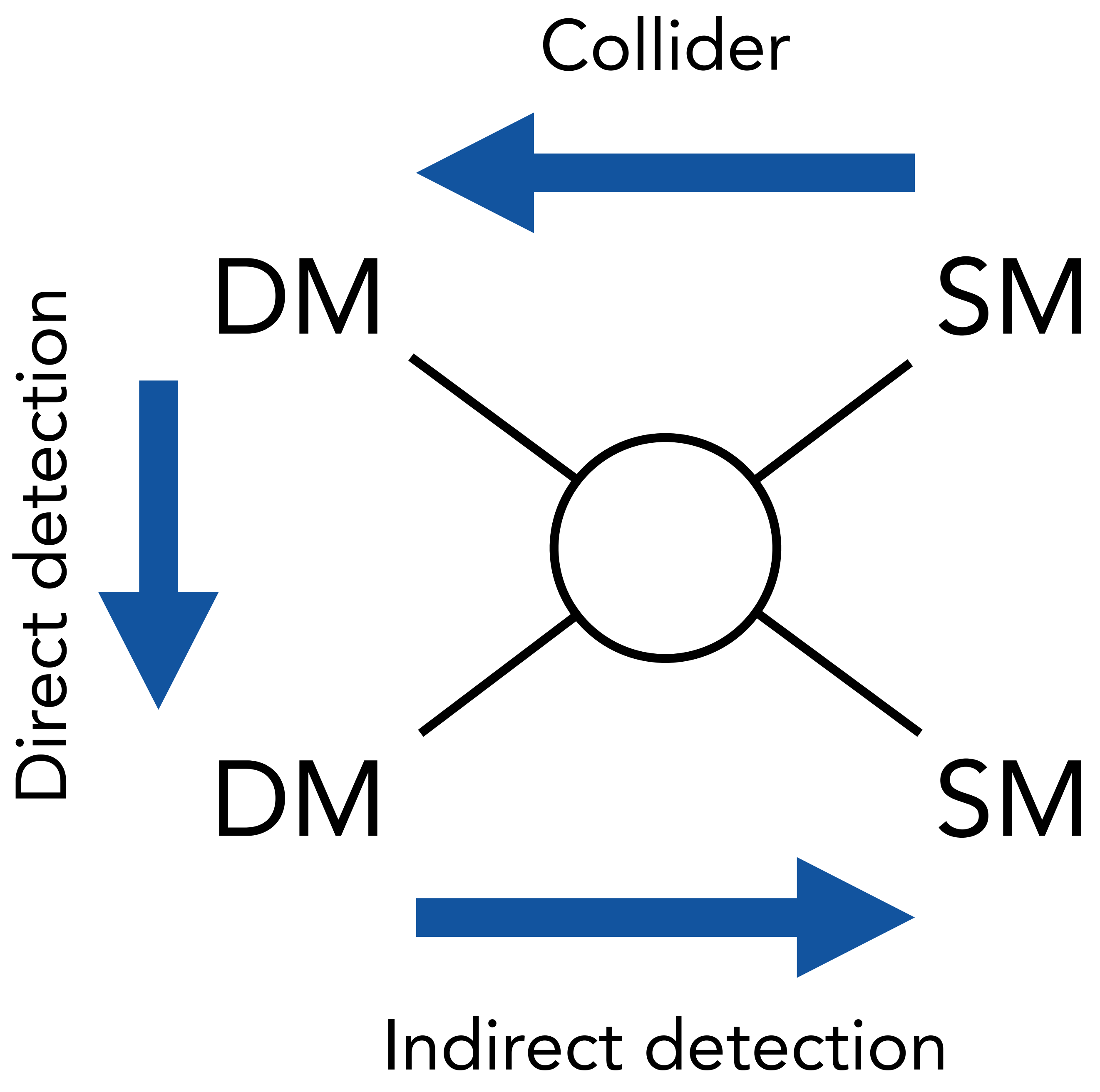
Gravitational lensing



CMB anisotropies

Large scale structures

Searches for Dark Matter



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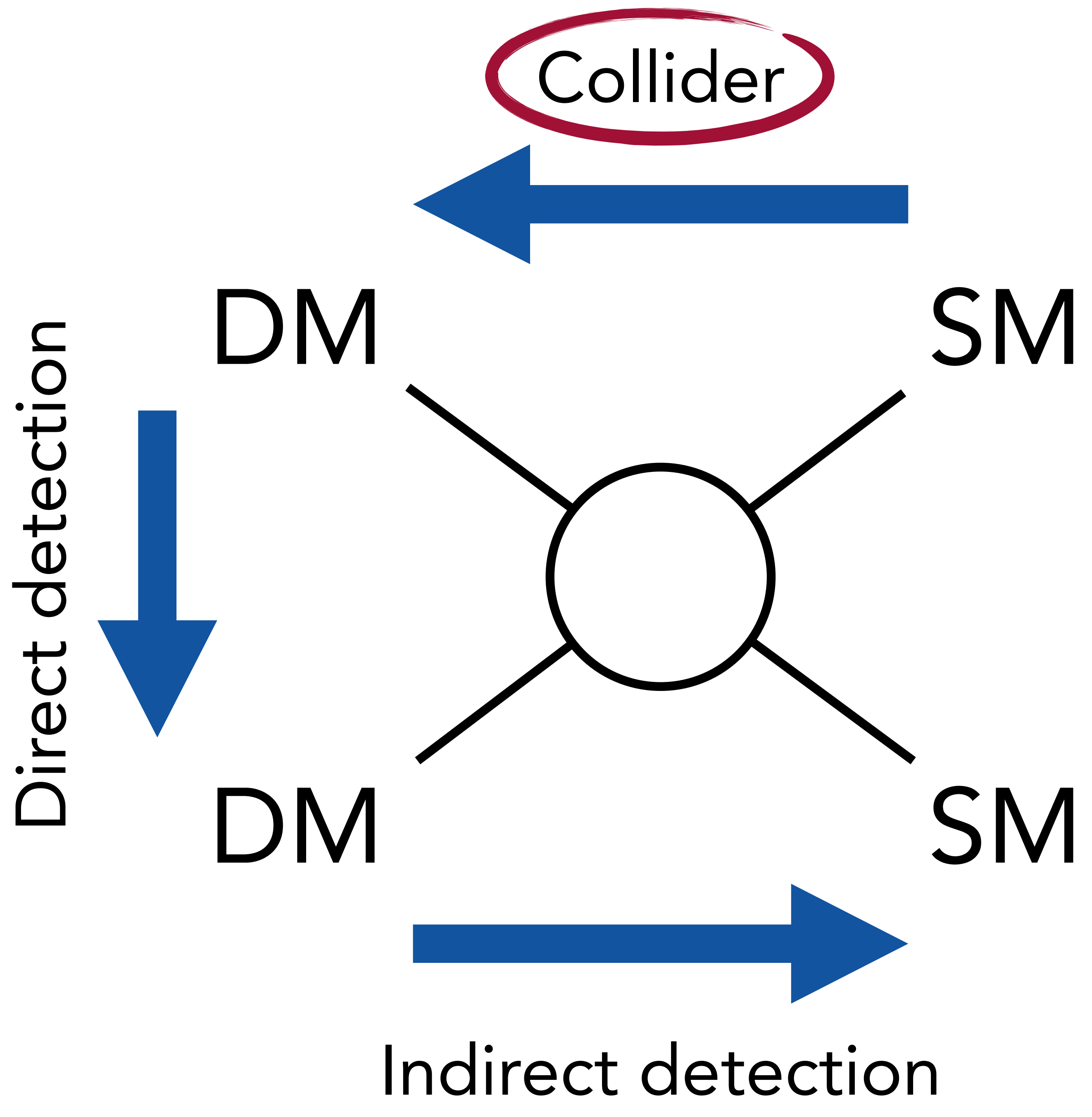
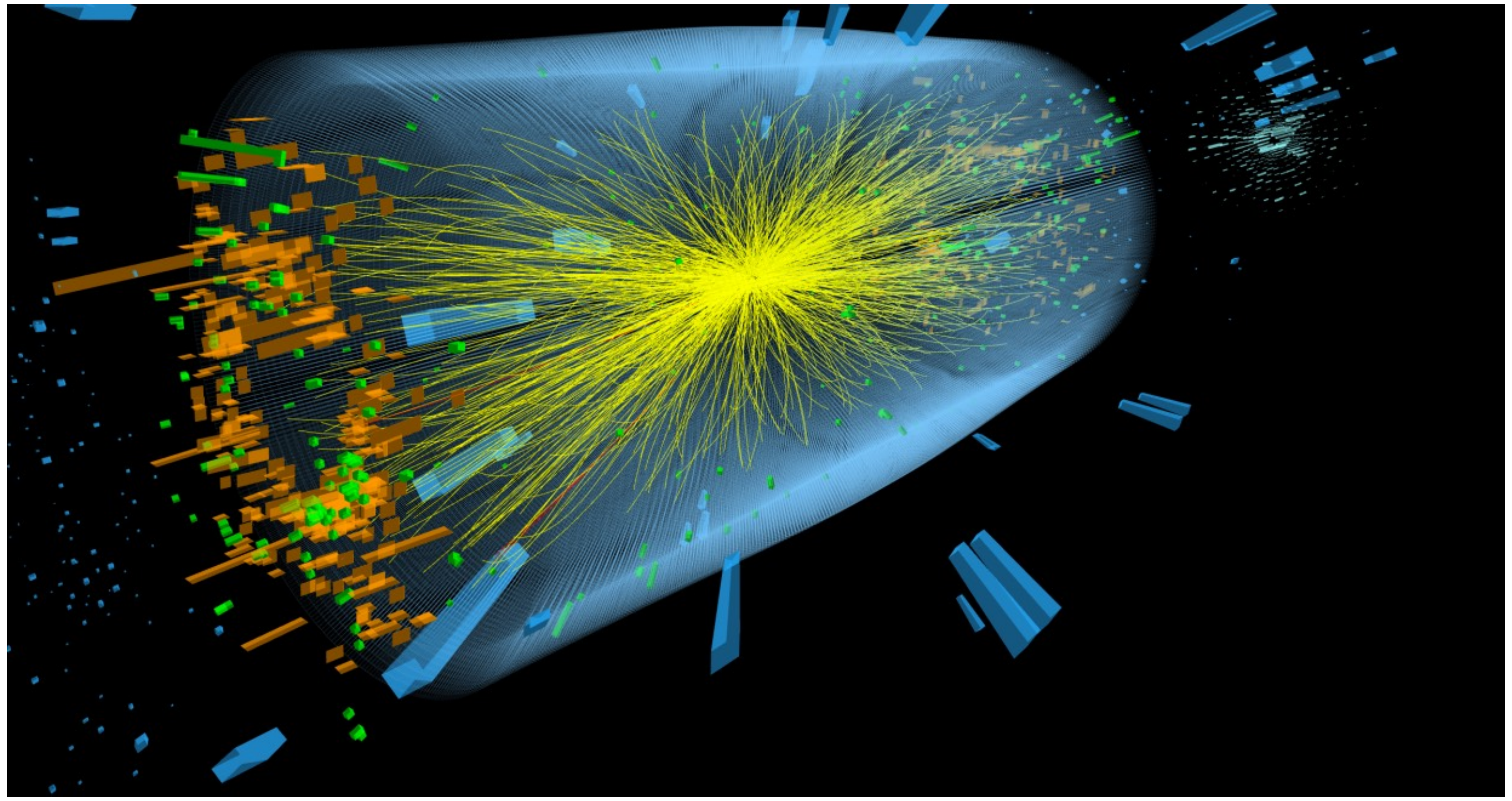
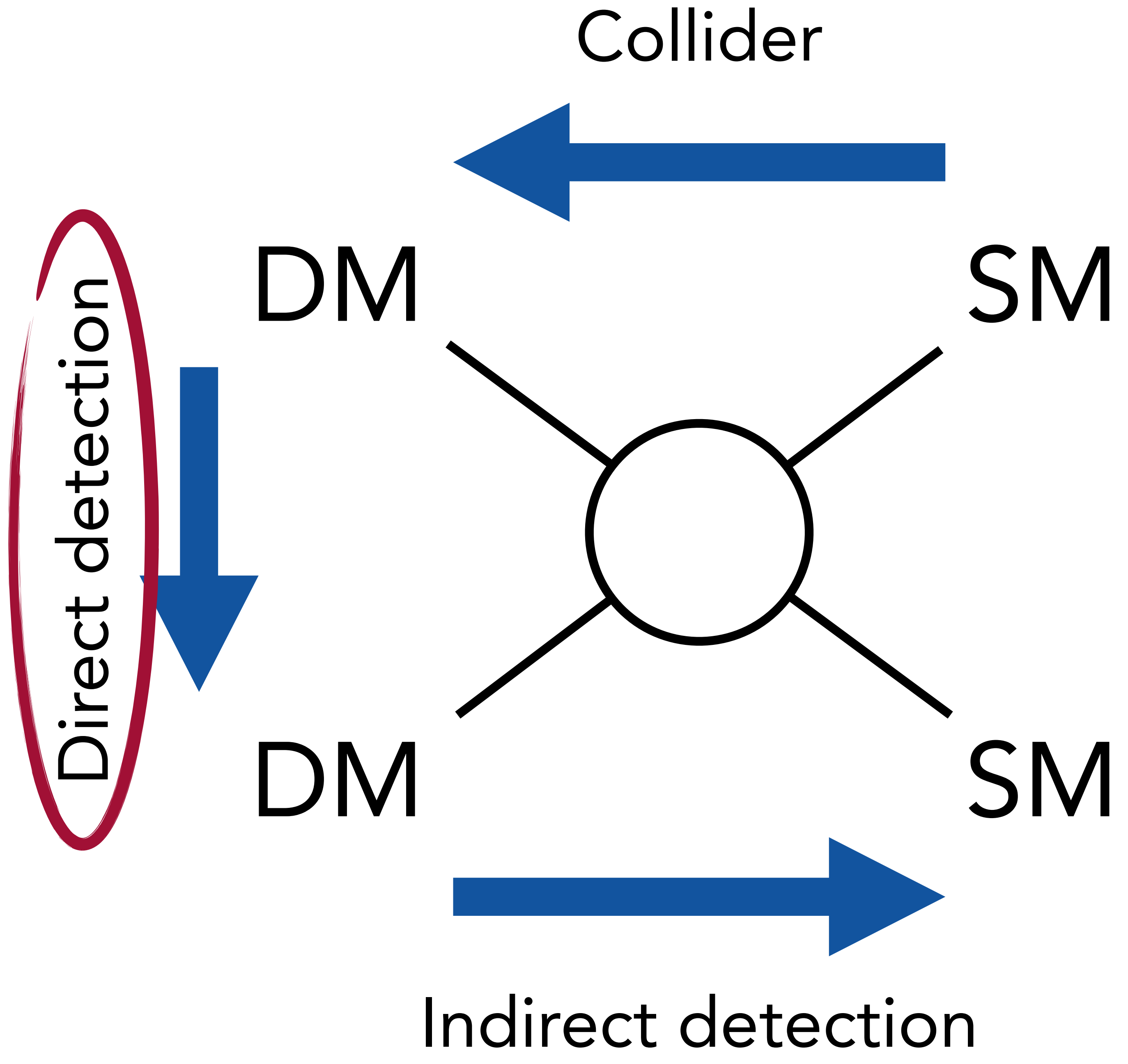


- High energy colliders could produce DM
- Look for anomalies, missing energy
- Use for example results from ATLAS, CMS and LHCb

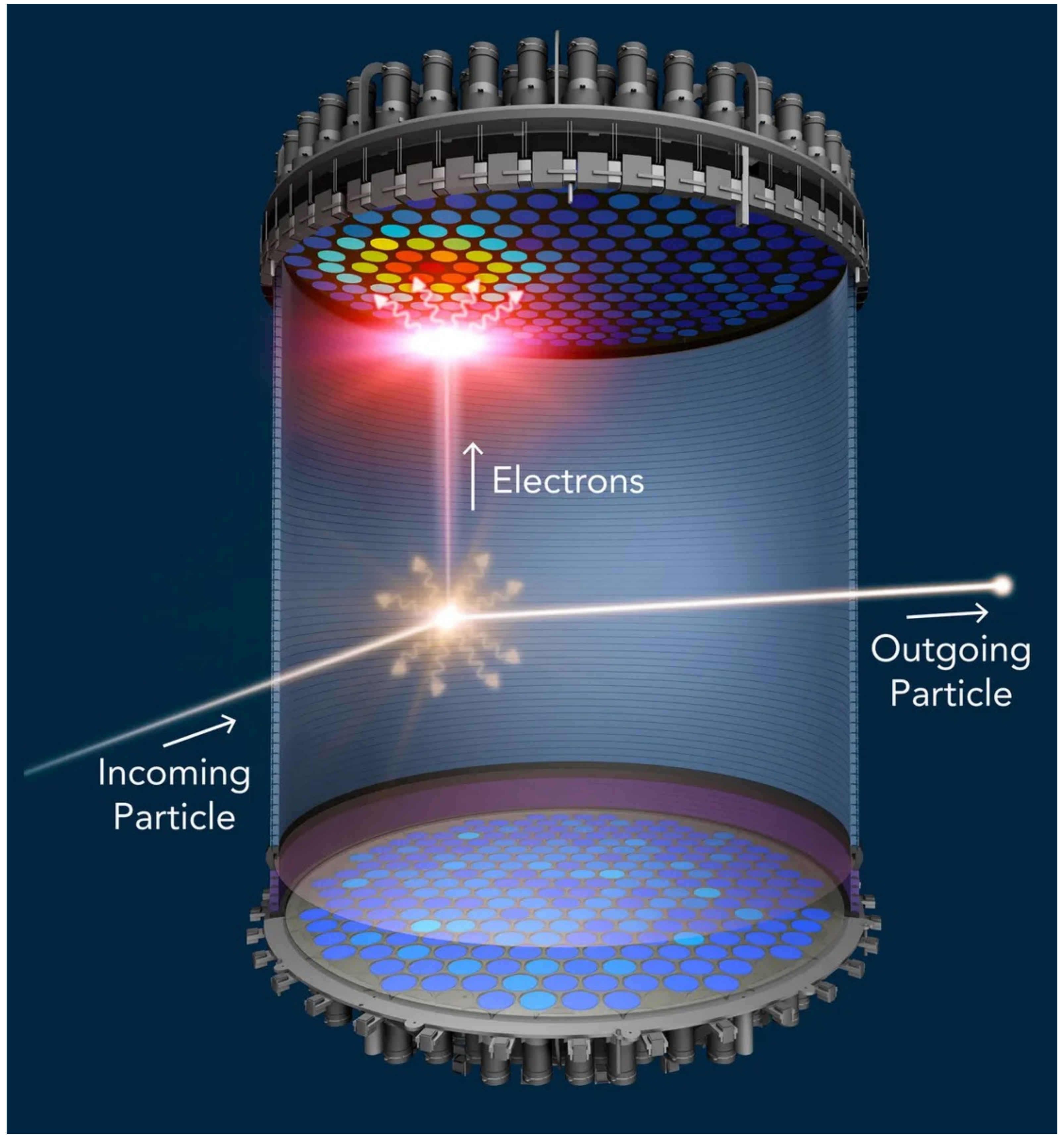


[CERN]

Searches for Dark Matter

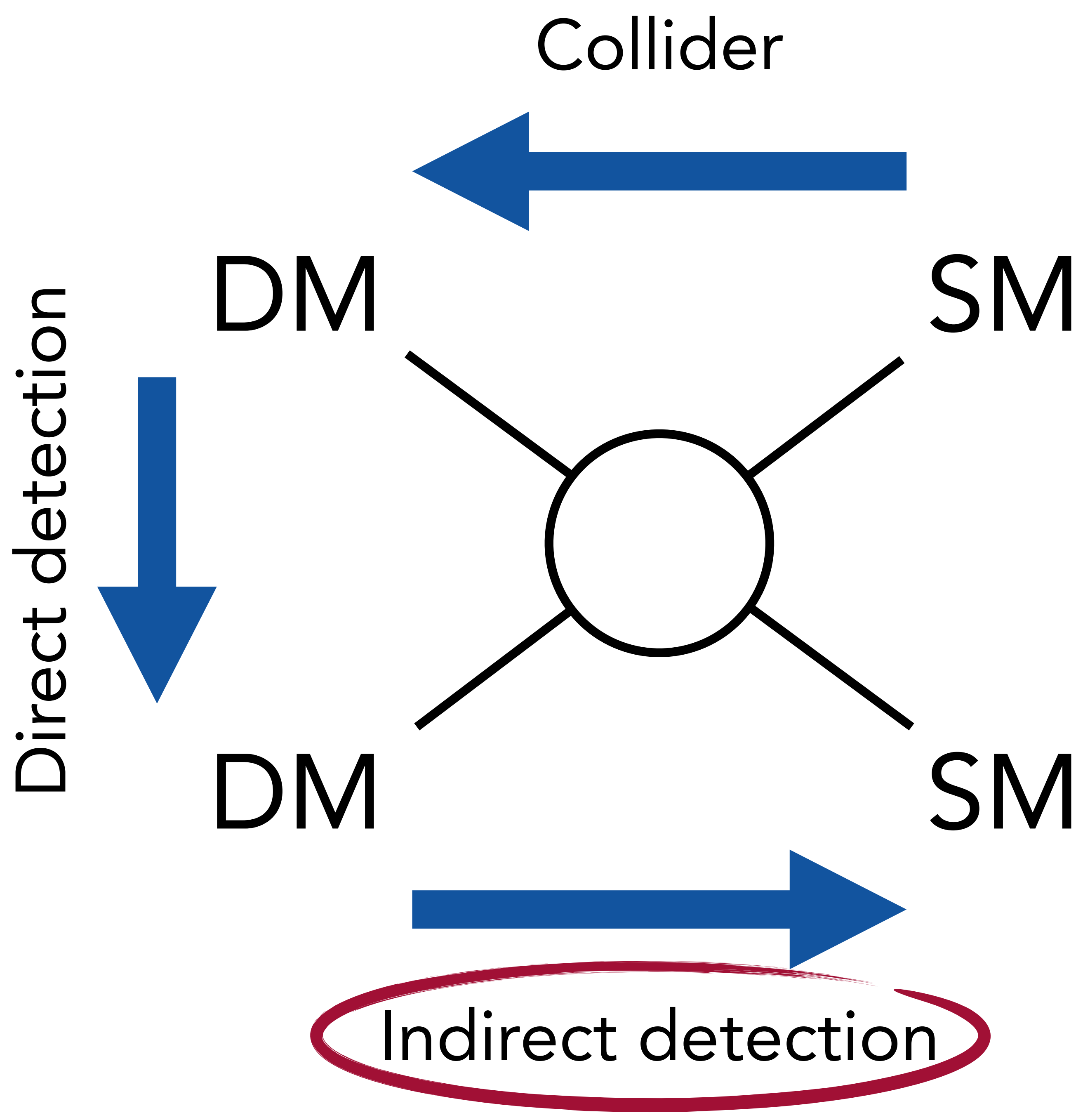


- DM particle scatters off target nuclei
- Observe
  - recoil energy spectrum
  - recoil direction
  - change of signal with time



[SLAC National Accelerator Laboratory]

Searches for Dark Matter



Collider

DM

SM

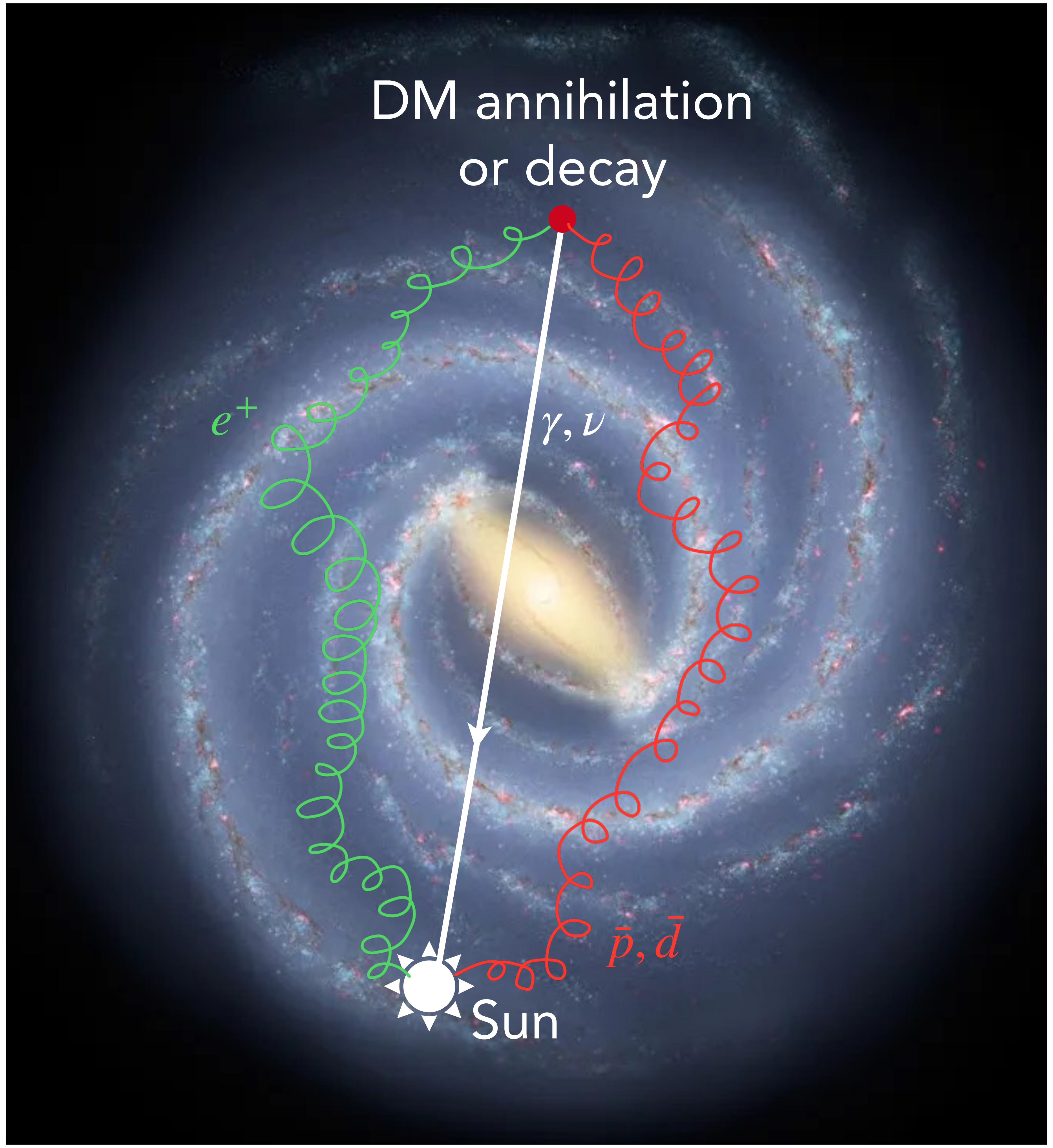
Direct detection

DM

SM

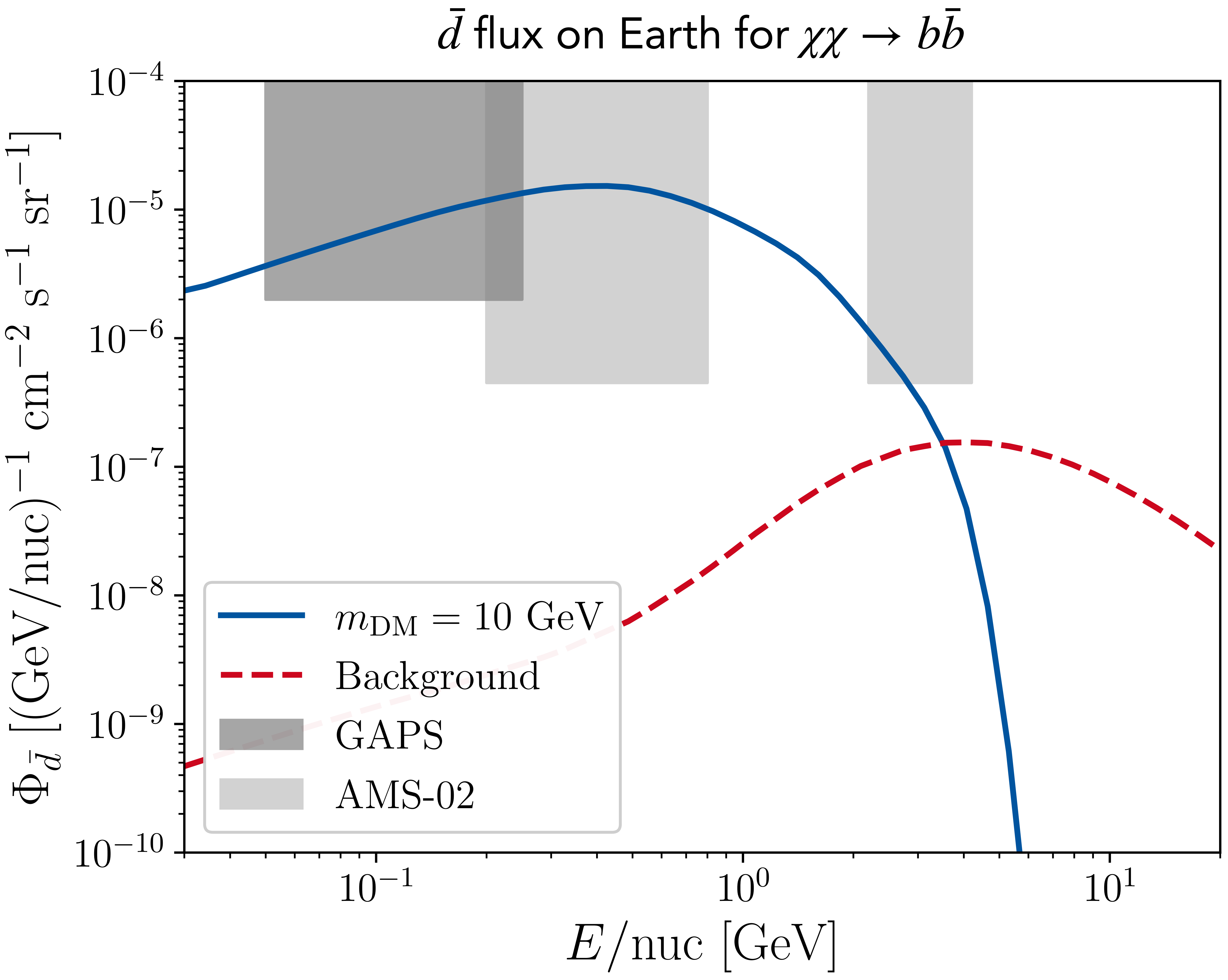
Indirect detection

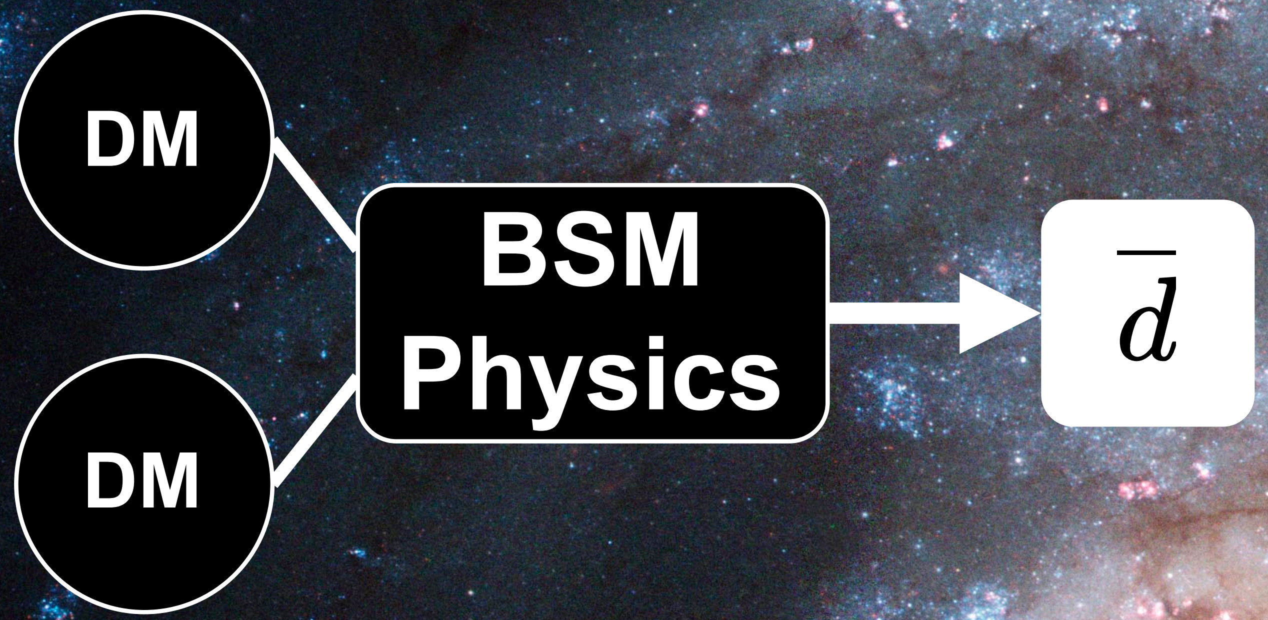
- DM annihilates or decays into SM particles in galaxy
- Detect resulting cosmic rays on Earth with AMS-02, Fermi LAT, H.E.S.S., …
- Look for excess over background (can be difficult) → use antideuterons



Why Antideuterons?

- Antimatter can be produced in dark matter annihilations
- Background from interactions of cosmic rays negligible at low energies for antinuclei but not for antiparticles
- New GAPS experiment & AMS-02 can detect low energy antinuclei




DM

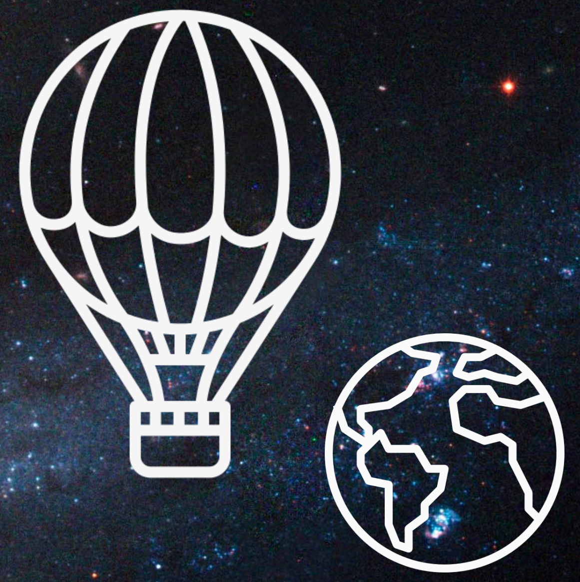
DM

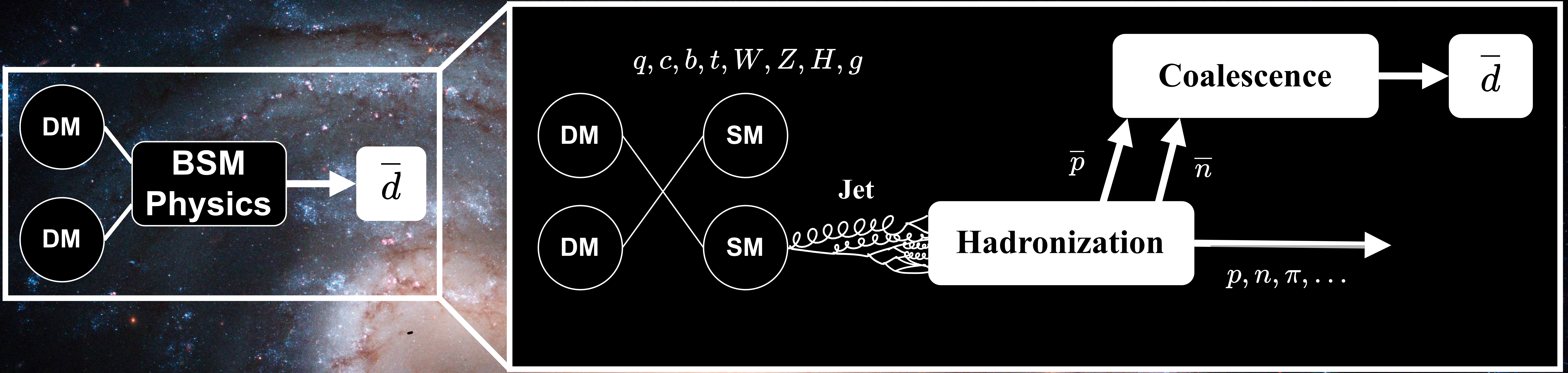
BSM Physics

$\bar{d}$

Where do Antideuterons come from?

GAPS





DM

DM

BSM Physics

$\bar{d}$

q, c, b, t, W, Z, H, g

DM

DM

SM

SM

Jet

Hadronization

$p, n, \pi, \dots$

$\bar{p}$

$\bar{n}$

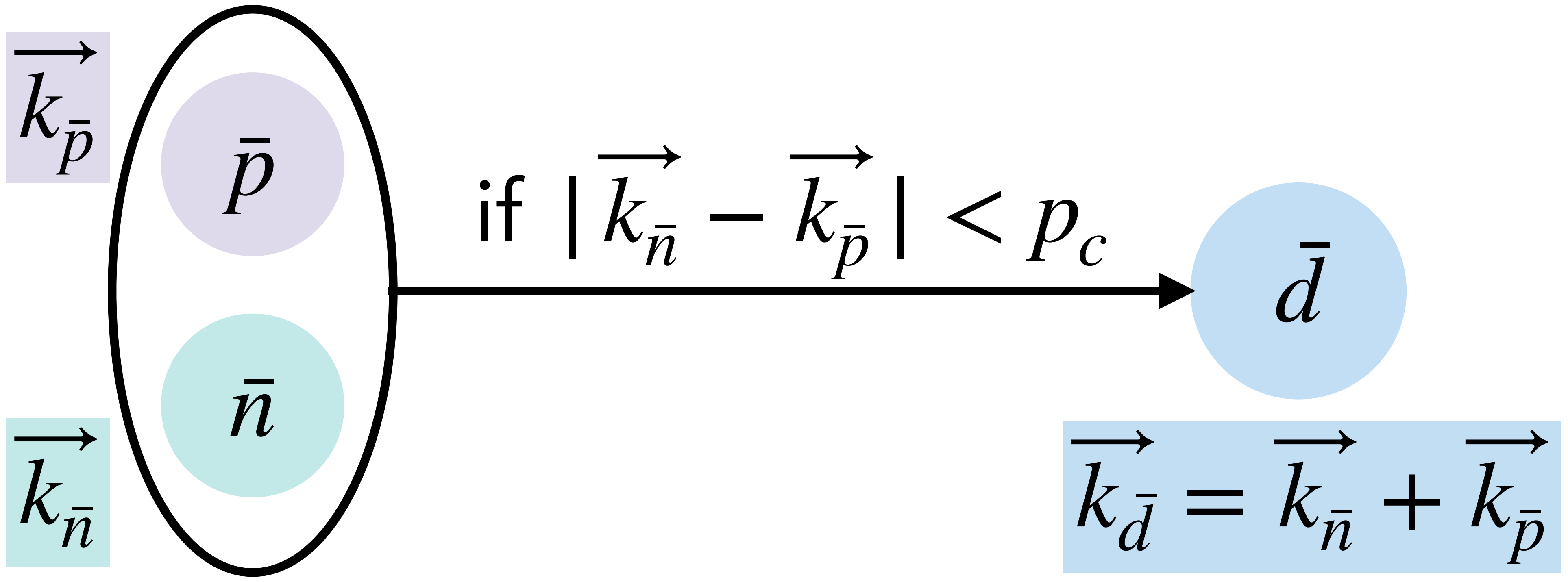
Coalescence

$\bar{d}$

Production

GAPS

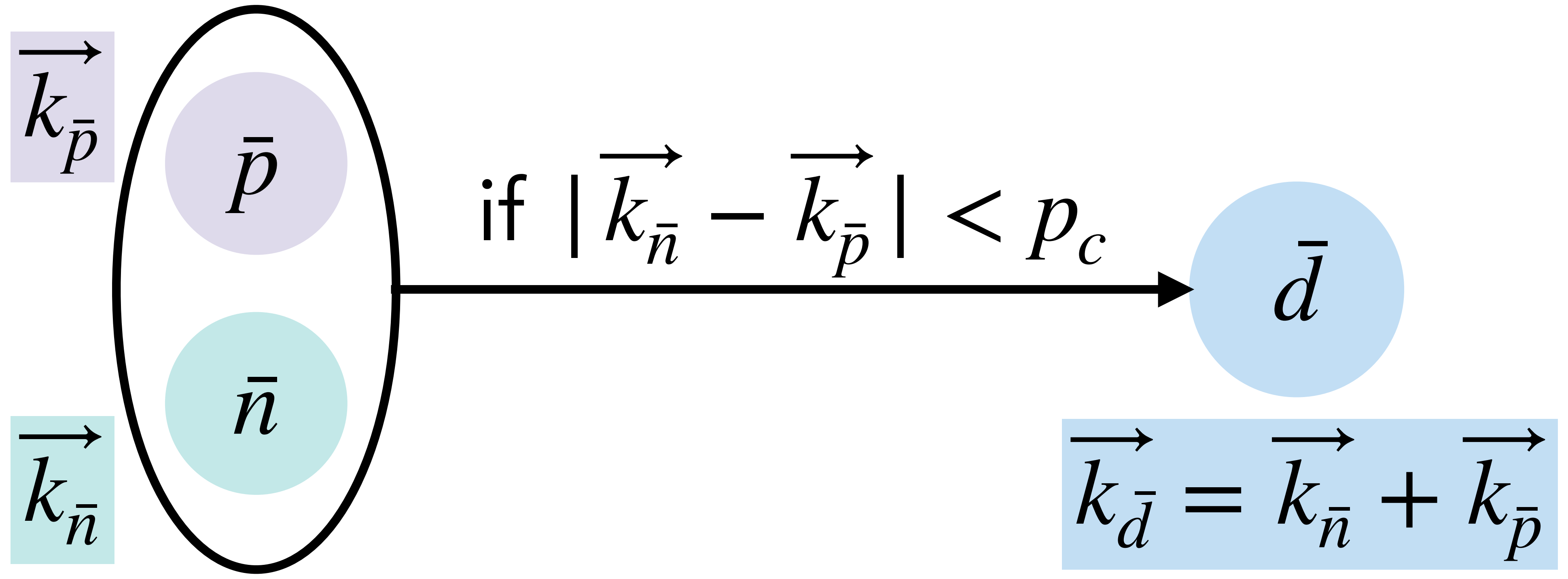
Production: Coalescence Mechanism



- Coalescence momentum p_c, determined from experiment

Fornengo+ [1306.4171]

Production: Coalescence Mechanism



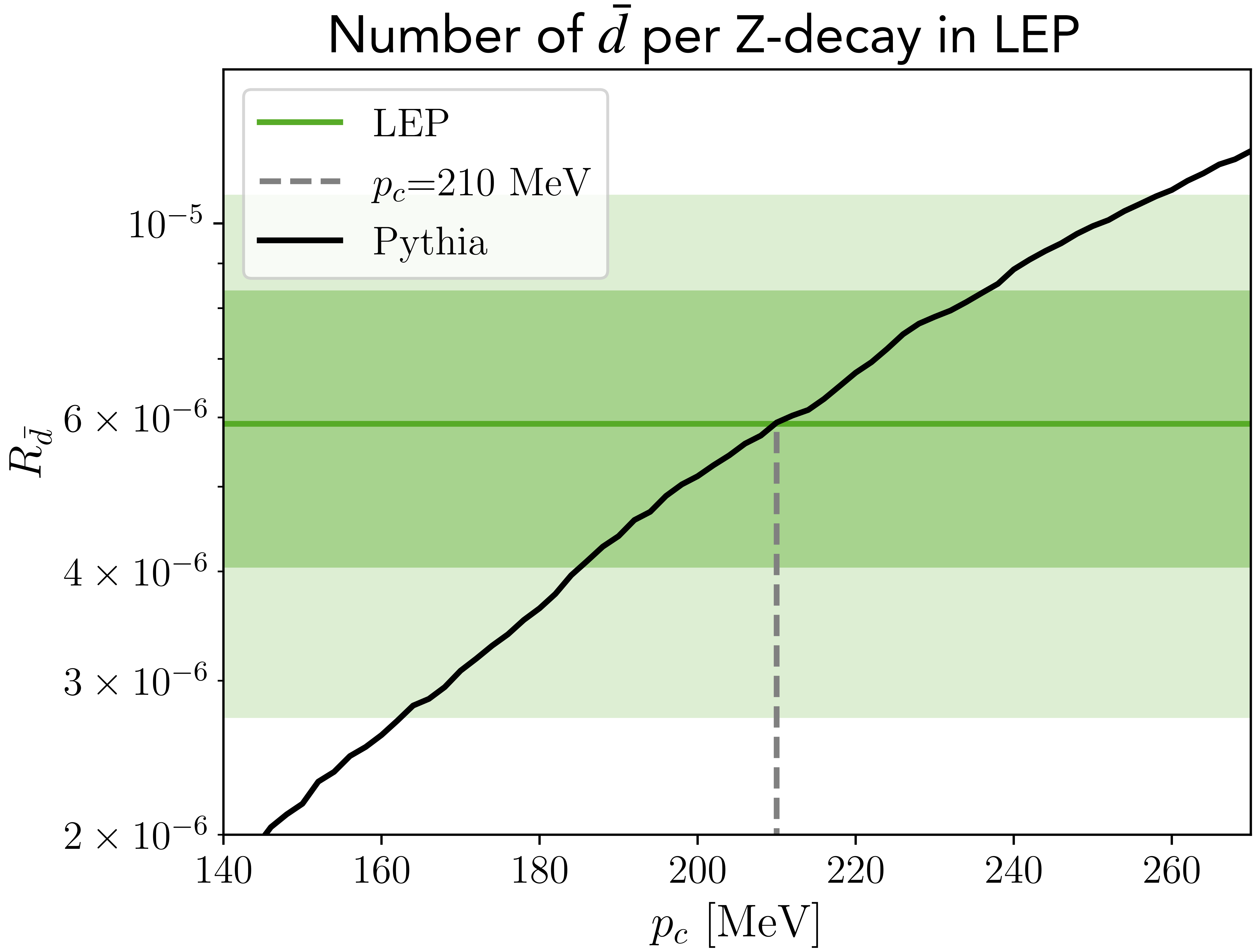
$\vec{k}_{\bar{p}}$ $\bar{p}$

$\bar{n}$ $\vec{k}_{\bar{n}}$

if $|\vec{k}_{\bar{n}} - \vec{k}_{\bar{p}}| < p_c$ $\bar{d}$

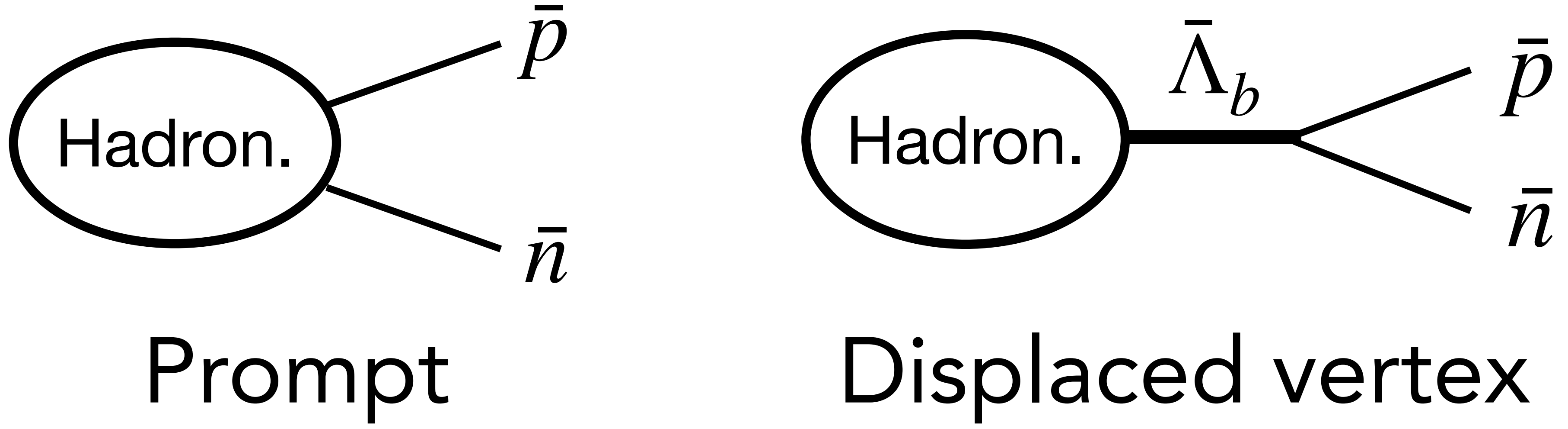
$\vec{k}_{\bar{d}} = \vec{k}_{\bar{n}} + \vec{k}_{\bar{p}}$

- Coalescence momentum p_c, determined from experiment
- Match number of antideuterons from simulated hadronic Z-decays to amount measured by LEP
- Spatial separation smaller than 2 fm



Fornengo+ [1306.4171]

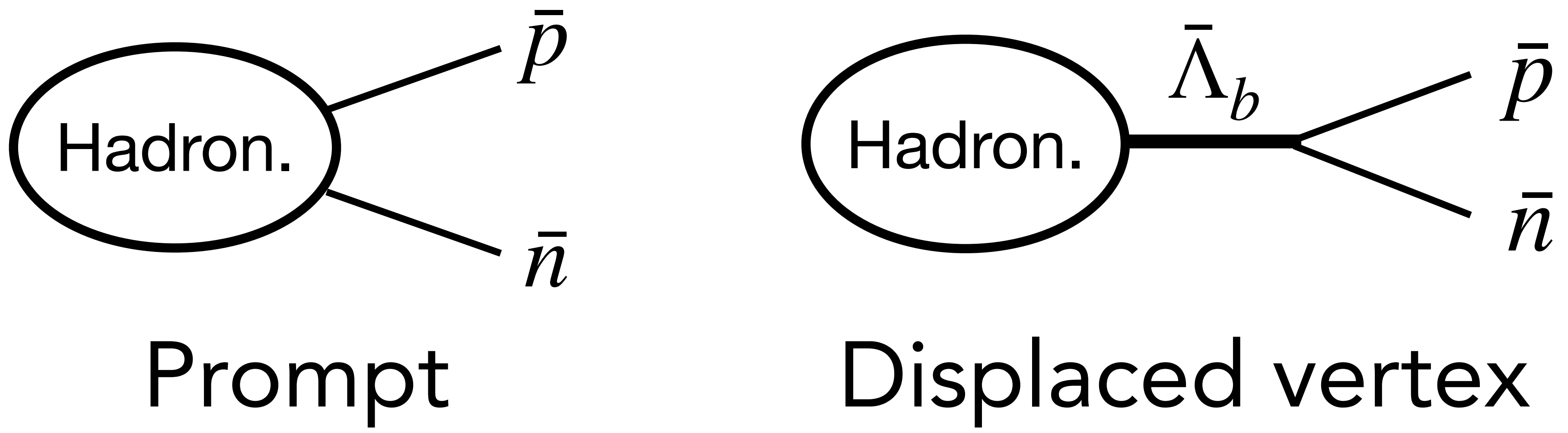
Antideuterons from $\bar{\Lambda}_b$ Decay



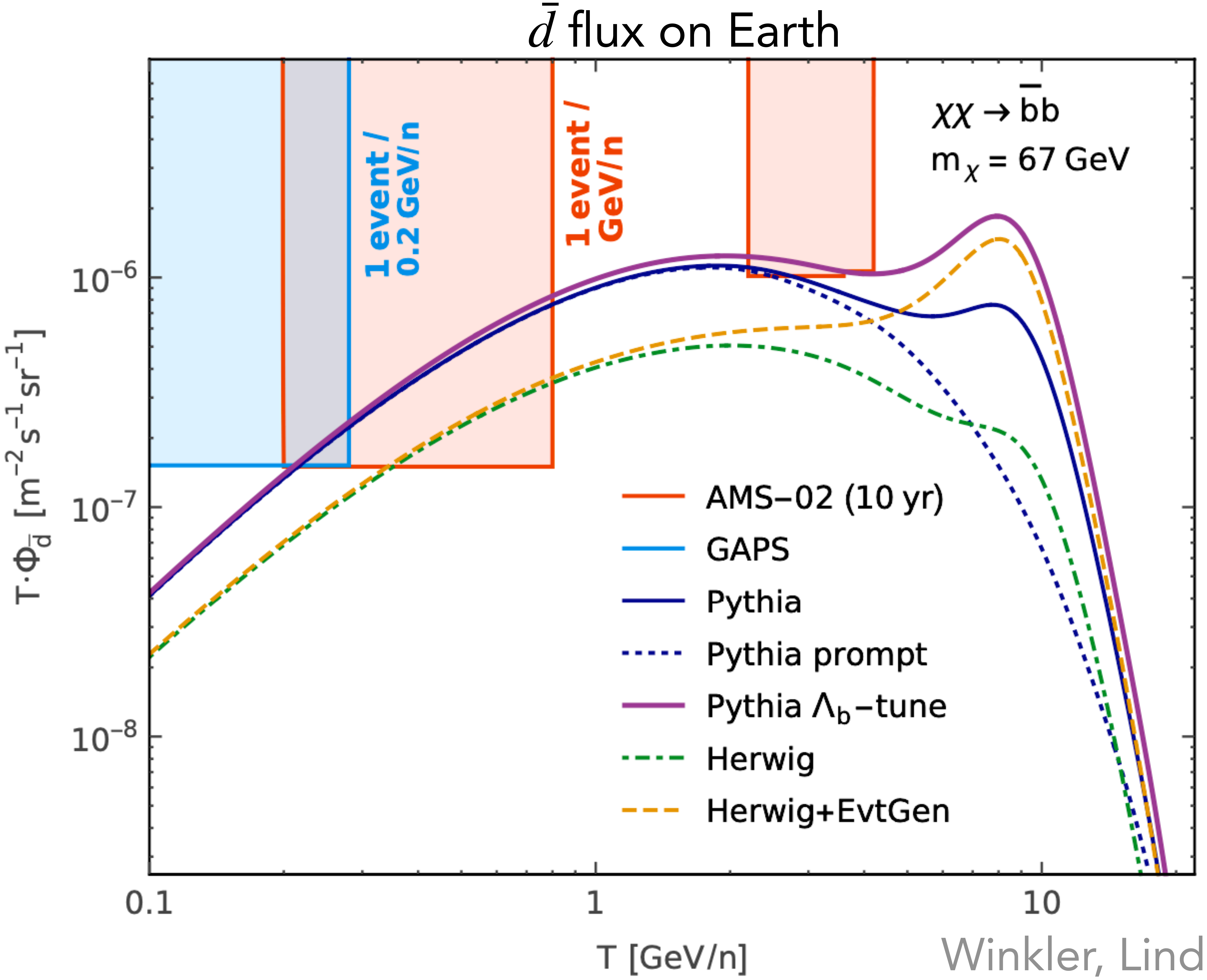
- $m_{\bar{\Lambda}_b} = 5.6$ GeV → decays into particles with small relative momenta → boosts $\bar{d}$ production

Winkler, Linden [2006.16251]

Antideuterons from $\bar{\Lambda}_b$ Decay

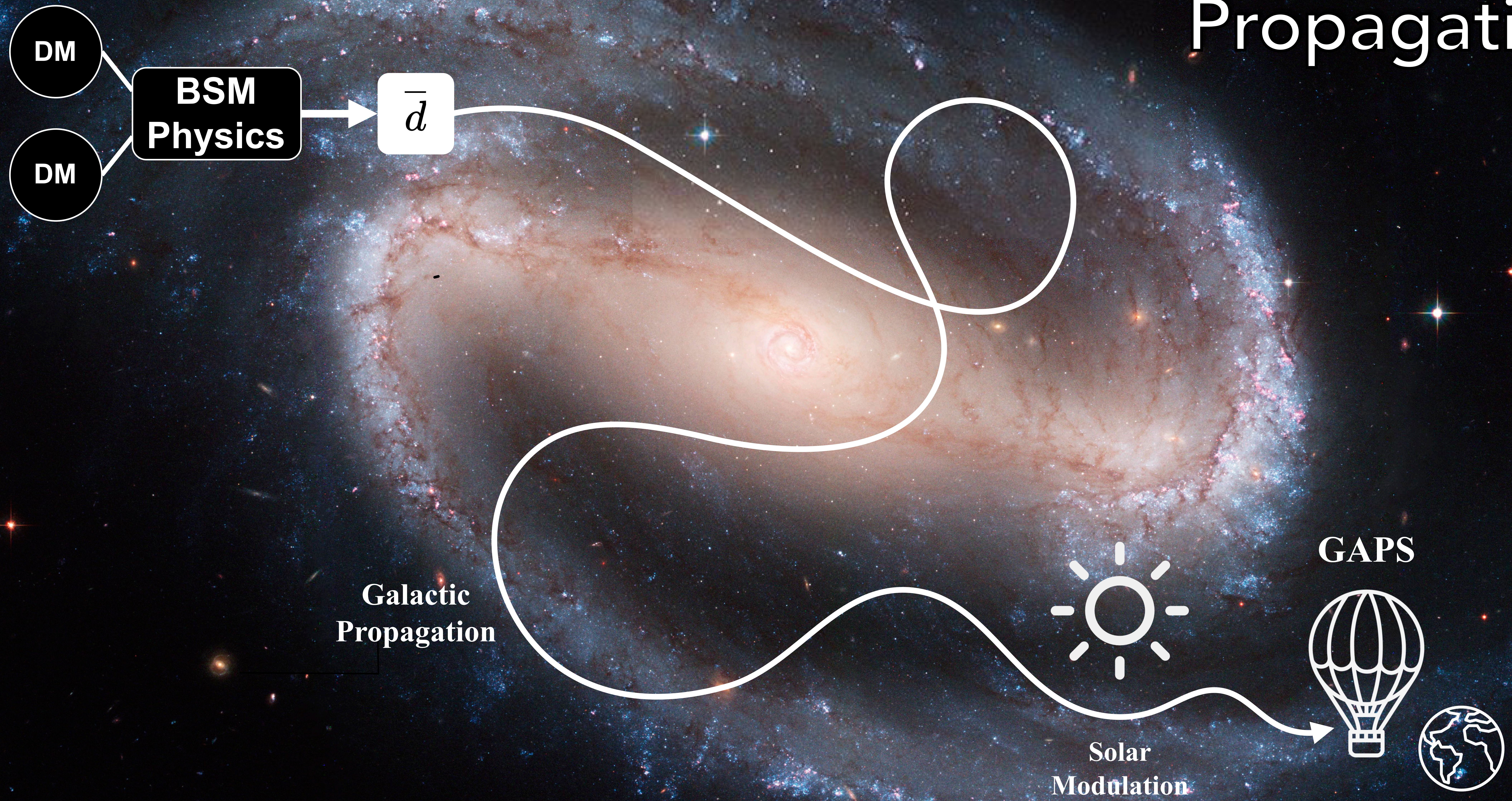


- $m_{\bar{\Lambda}_b} = 5.6$ GeV → decays into particles with small relative momenta → boosts $\bar{d}$ production
- Rescale $\bar{\Lambda}_b$ production in PYTHIA to match measurement of transition ratio $f(b \rightarrow \Lambda_b)$ with extra parameter $r_{\Lambda_b} \approx 3$



Winkler, Linden [2006.16251]

Propagation



Antideuteron Propagation

- Use diffusion break cosmic ray (CR) propagation model in Balan et al. [2303.07362] for differential particle number density ψ

$$\frac{\partial\psi(\vec{x},p,t)}{\partial t} = q(\vec{x},p) + \vec{\nabla}\cdot(D_{xx}\cdot\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\frac{\mathrm{d}p}{\mathrm{d}t}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

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- Source term for primary (from DM), secondary (from CRs) antideuterons

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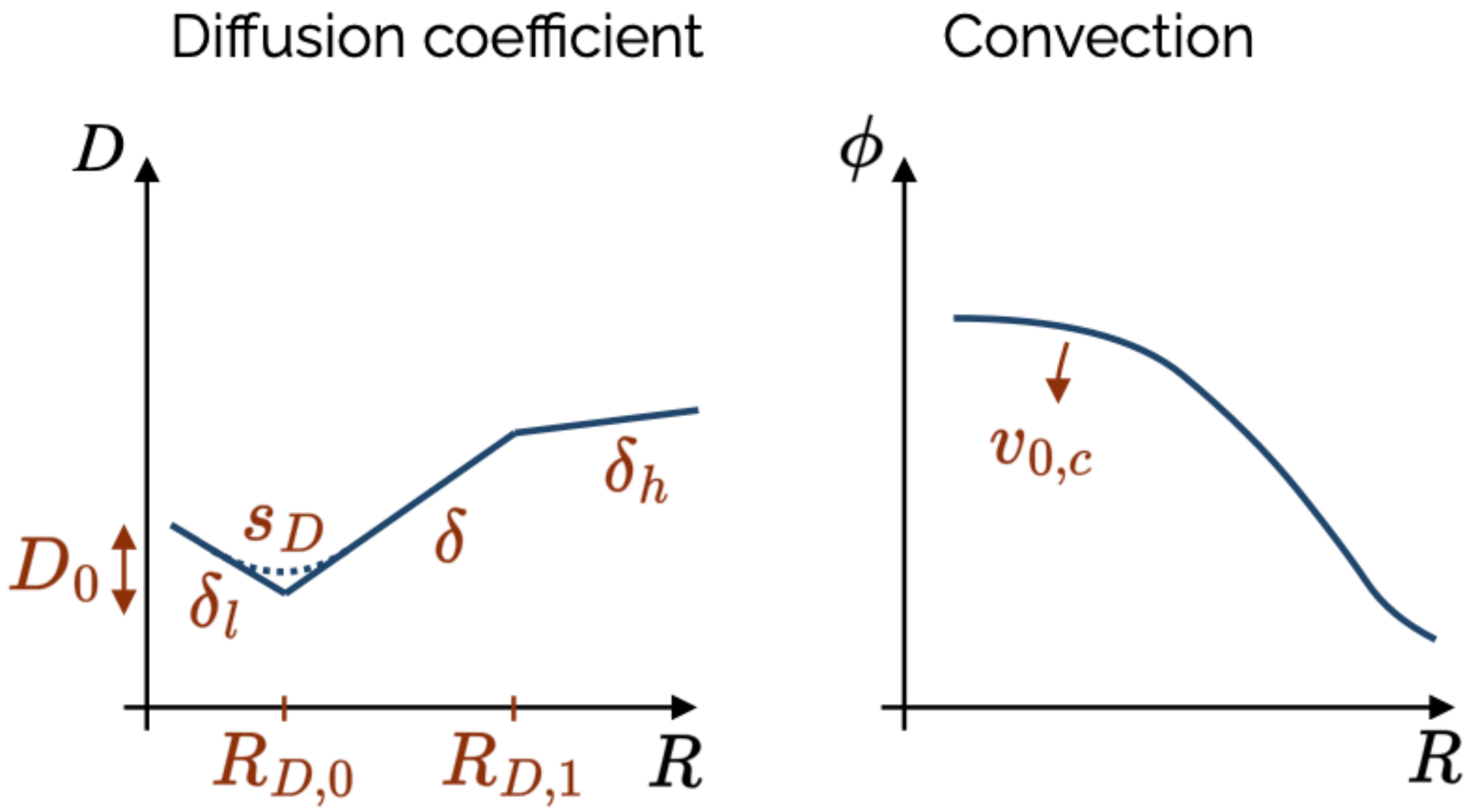
- Spatial diffusion and convection
- Diffusion coefficient modeled as double-broken power law
- Constant convection velocity $\vec{V}_\mathrm{c} = v_{0,\mathrm{c}}\,\mathrm{sign}(z)\,\vec{e}_z$



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- Reacceleration by scattering off magnetic Alfvén waves modeled by diffusion in momentum space

- Depends on Alfvén velocity v_A and spatial diffusion coefficient: $D_{pp} \sim \frac{v_\mathrm{A}}{D_{xx}}$

Antideuteron Propagation

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- Continuous energy losses from
  - ionization and Coulomb collisions
  - adiabatic energy losses
- Catastrophic energy losses by fragmentation and decay

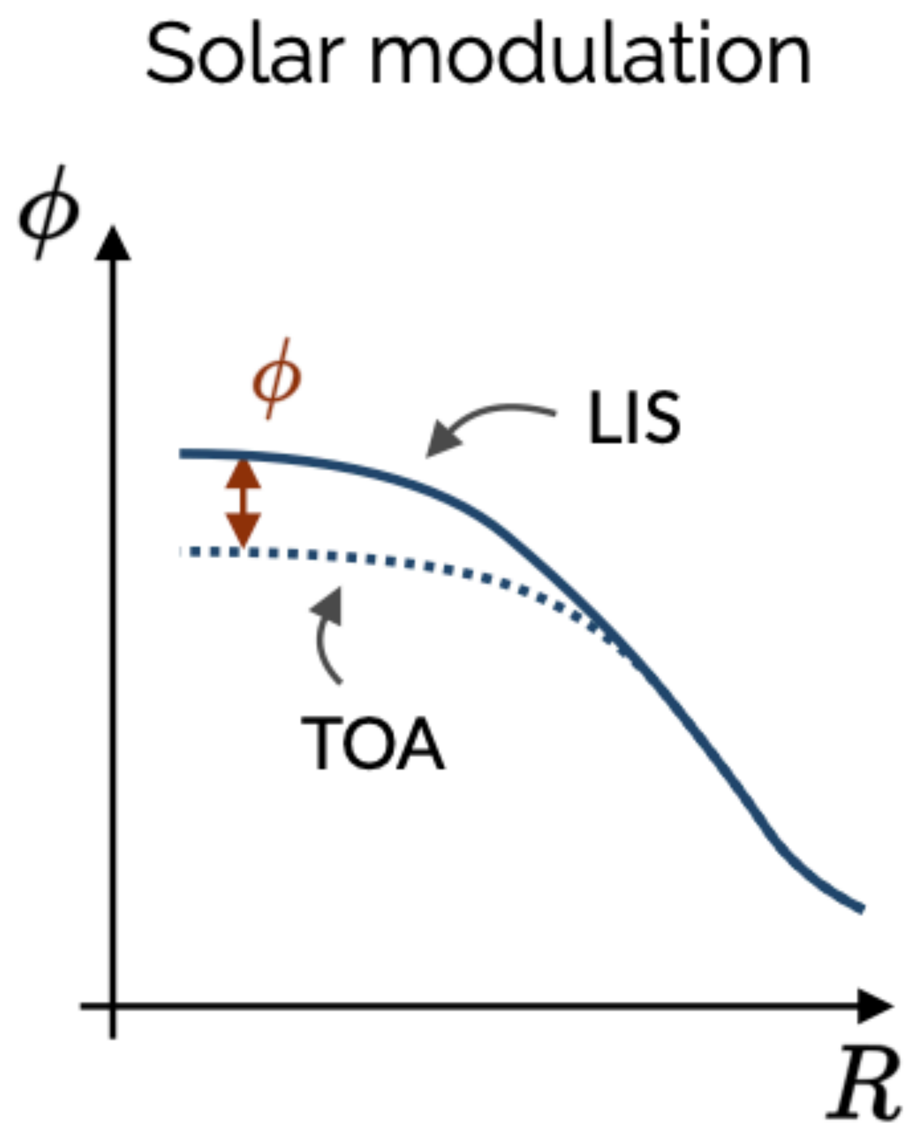
Solar Modulation

- Antideuterons are deflected and decelerated by solar winds → top-of-atmosphere (TOA) flux smaller than local interstellar (LIS) flux
- Model impact with force-field approximation:

$$\phi_{\mathrm{TOA}}(E_{\mathrm{TOA}}) = \frac{E_{\mathrm{TOA}}^2 - m^2}{E_{\mathrm{LIS}}^2 - m^2}\phi_{\mathrm{LIS}}(E_{\mathrm{LIS}}),$$

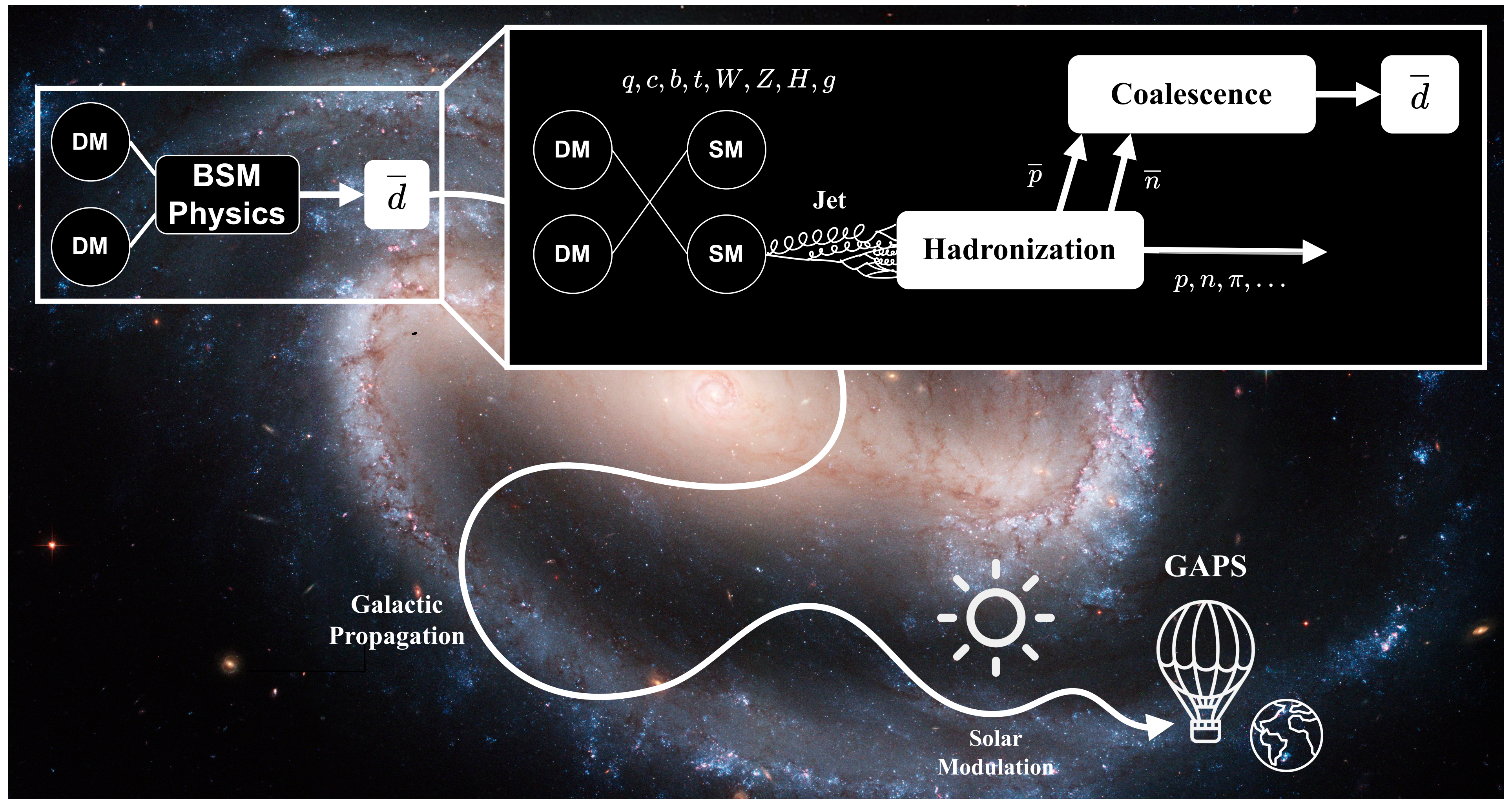
$$E_{\mathrm{TOA}} = E_{\mathrm{LIS}} - e|Z|\varphi$$

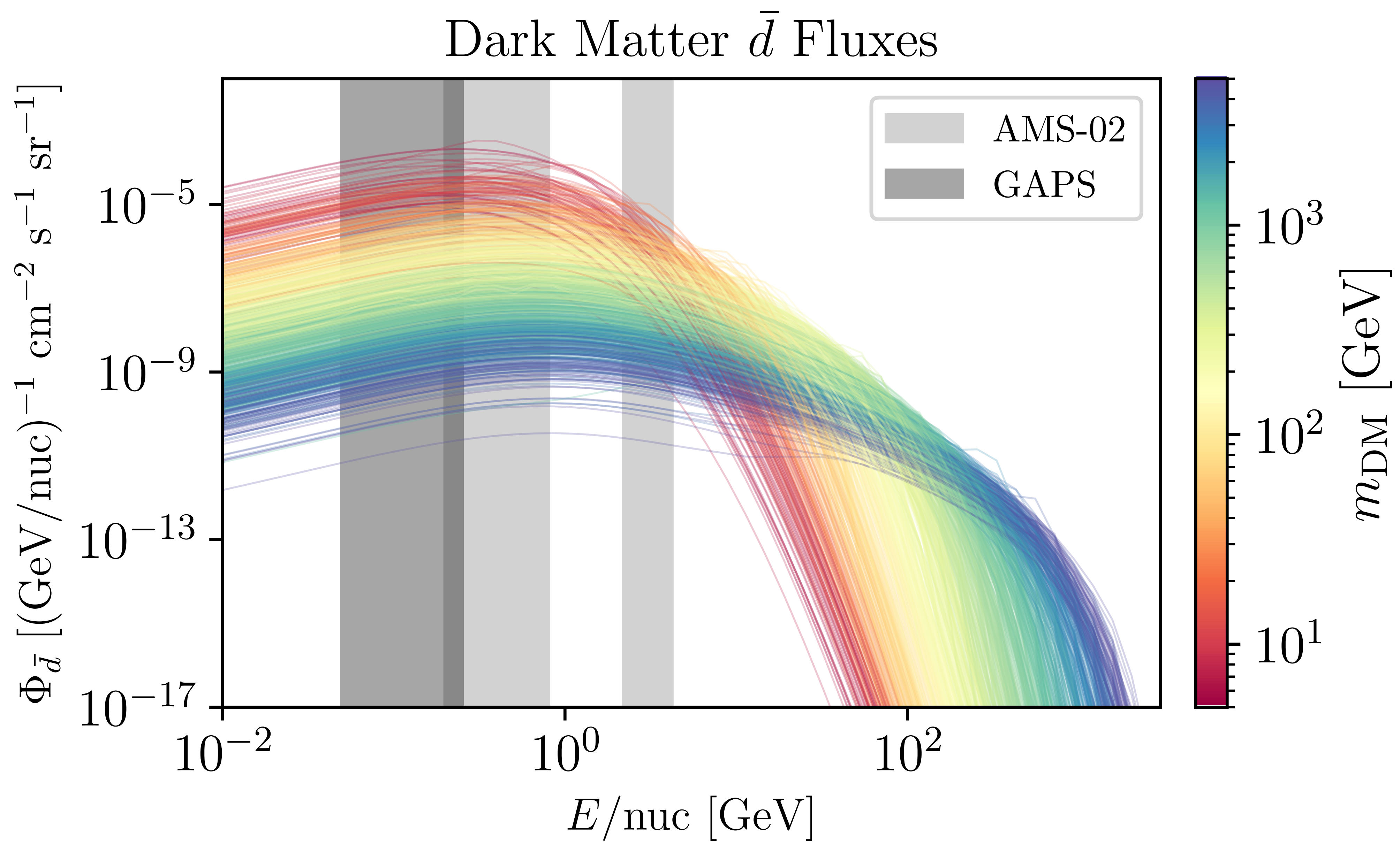
- Solar modulation potential φ depends on solar activity



Speed-up Antideuteron Simulation

m_{DM}
θ_{coal}
B_f
θ_{prop}





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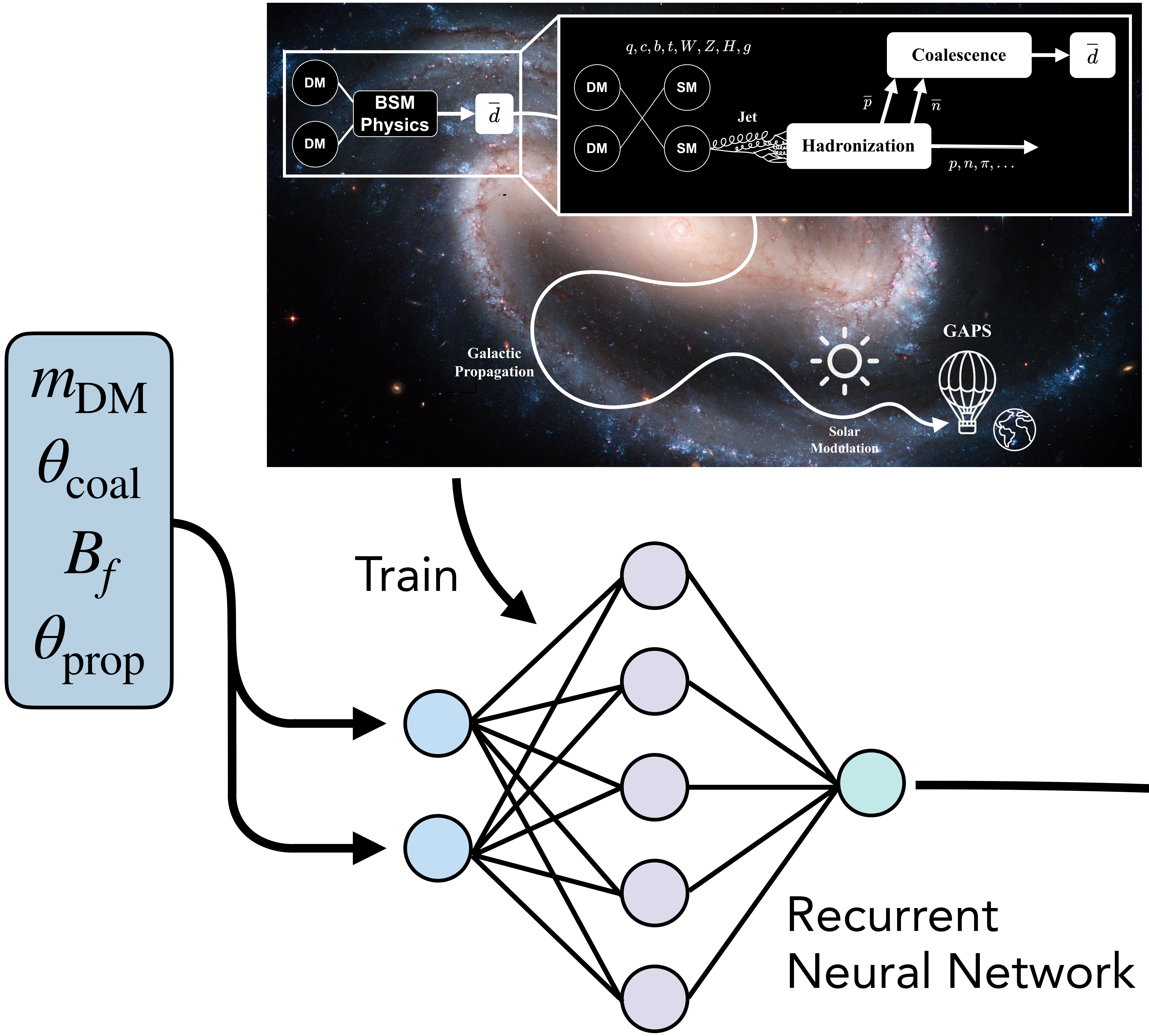
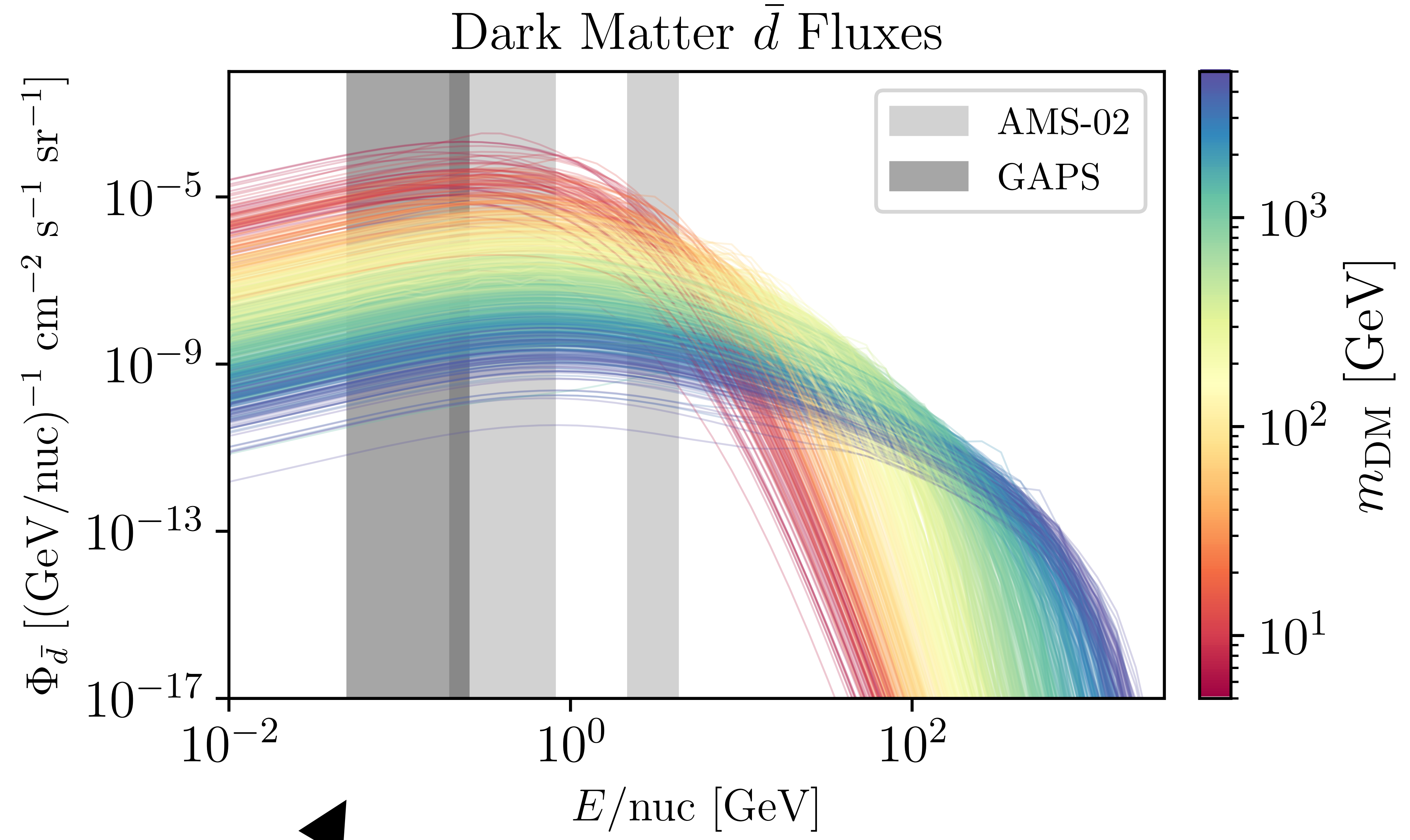


m_{DM}
θ_{coal}
B_f
θ_{prop}

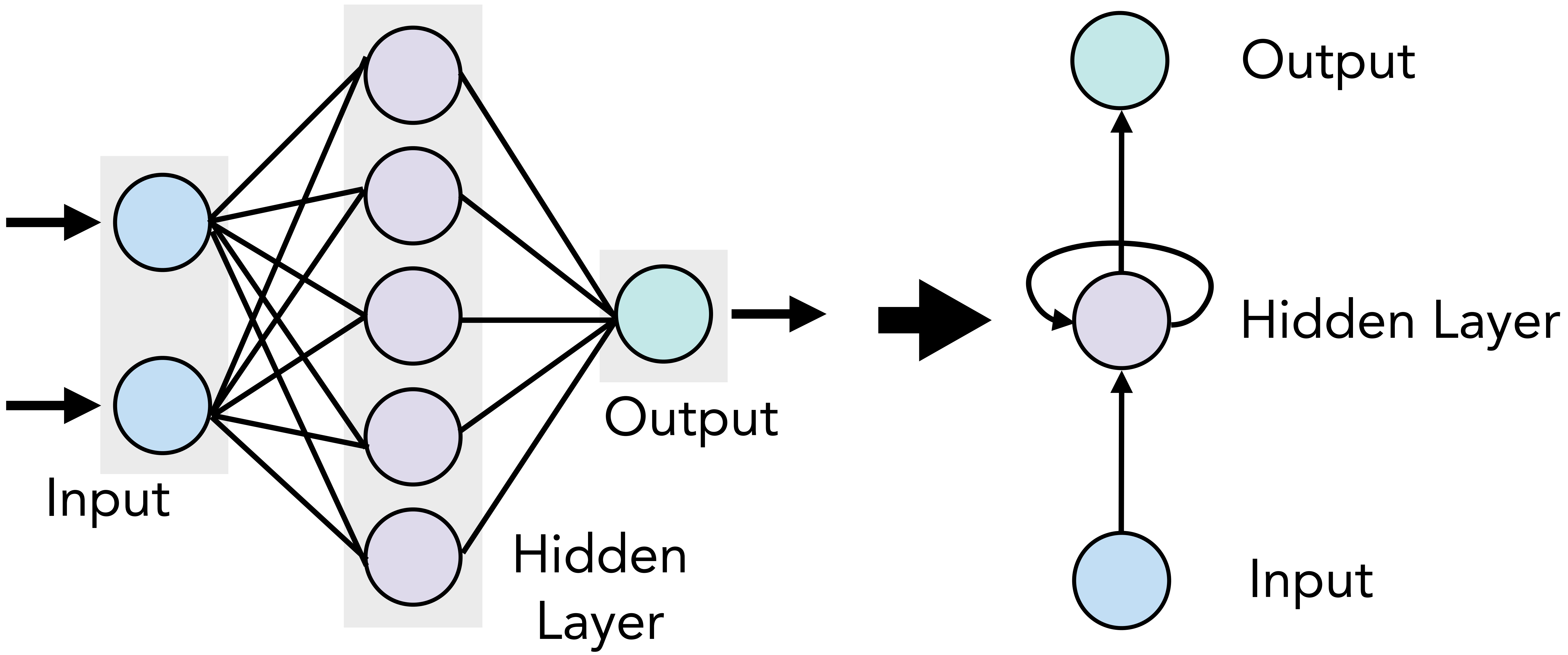
Train

Recurrent
Neural Network



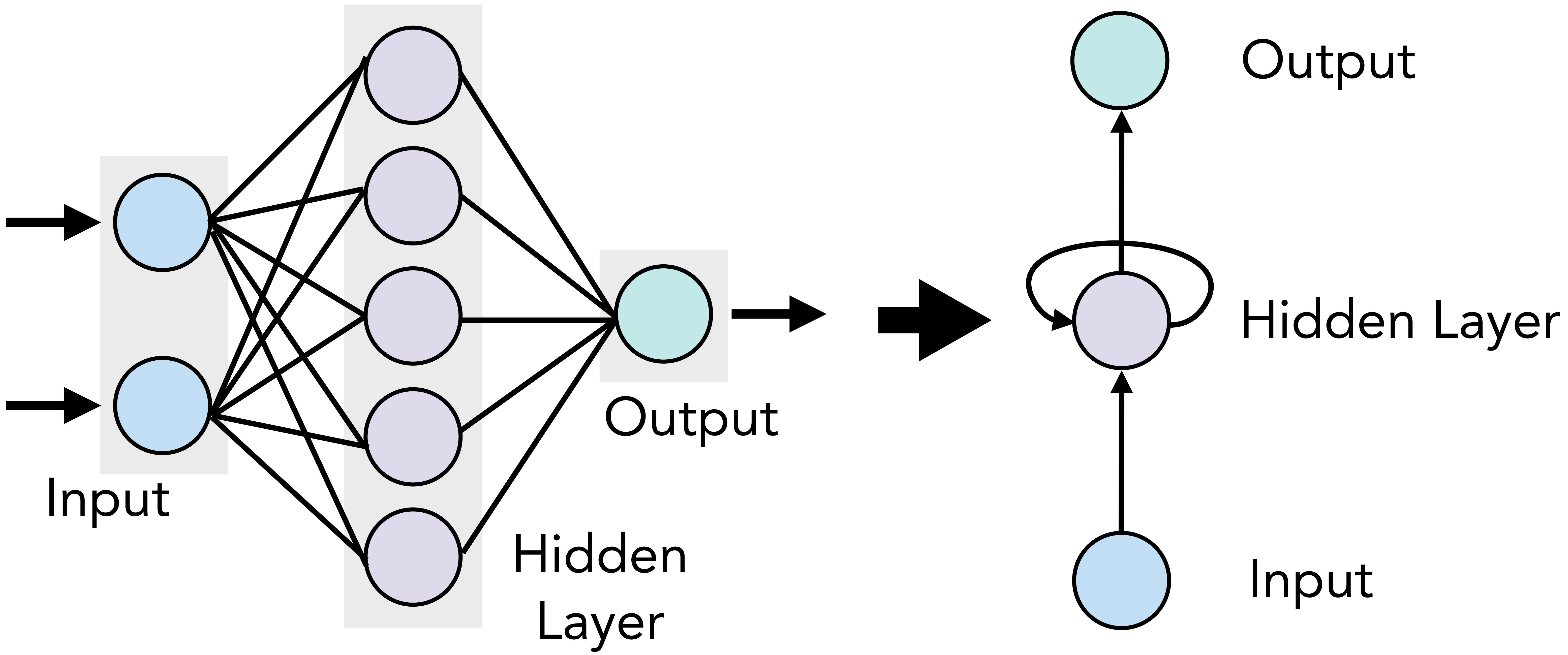
Neural Network

- Recurrent Neural Networks (RNN) use output of particular layer as input of the same layer → can account for correlations between energy bins



Neural Network

- Recurrent Neural Networks (RNN) use output of particular layer as input of the same layer → can account for correlations between energy bins
- Similar to Kahlhoefer et al. [2107.12395] and Balan et al. [2303.07362]
- Relative error of network $\mathcal{O}(10^{-2})$

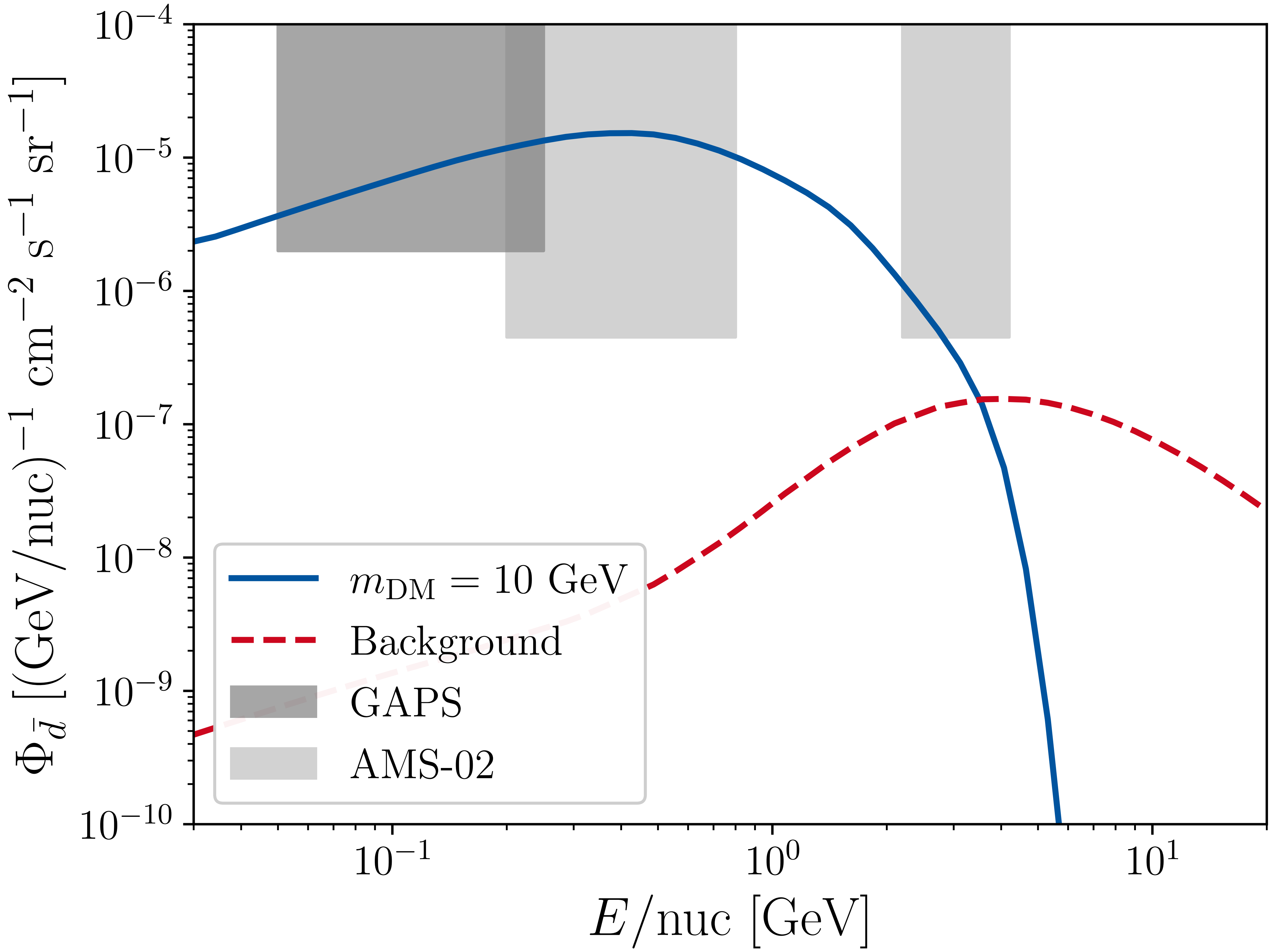


Network available in

https://github.com/kathrinnp/DarkRayNet

Prediction of Sensitivity Factor

- Generate fluxes for set of propagation parameters $\{\theta_{\text{prop},i}\}$ sampled from posterior of $p, \bar{p}$ and He fit
- Apply force-field approximation to account for solar modulation

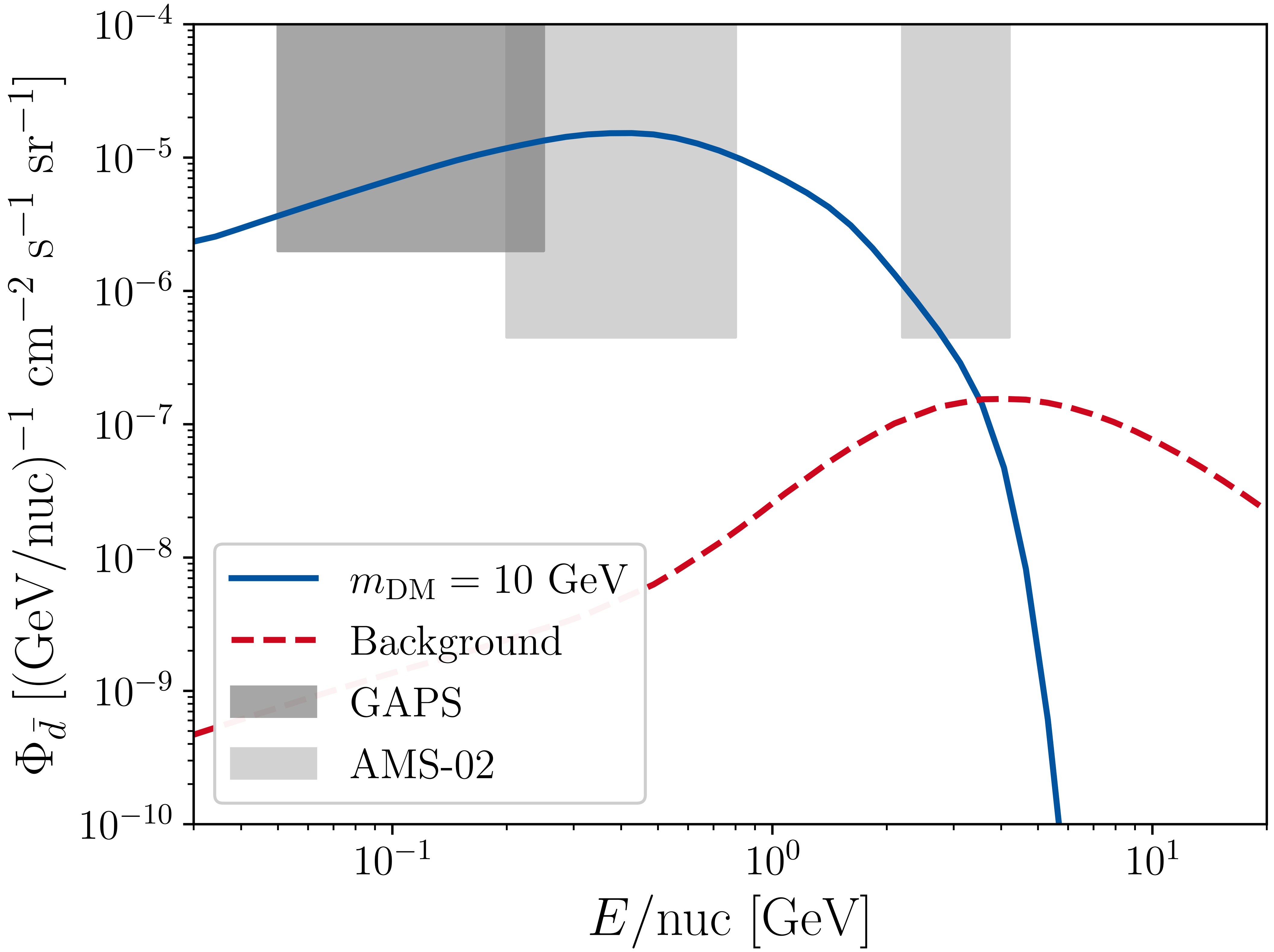


Prediction of Sensitivity Factor

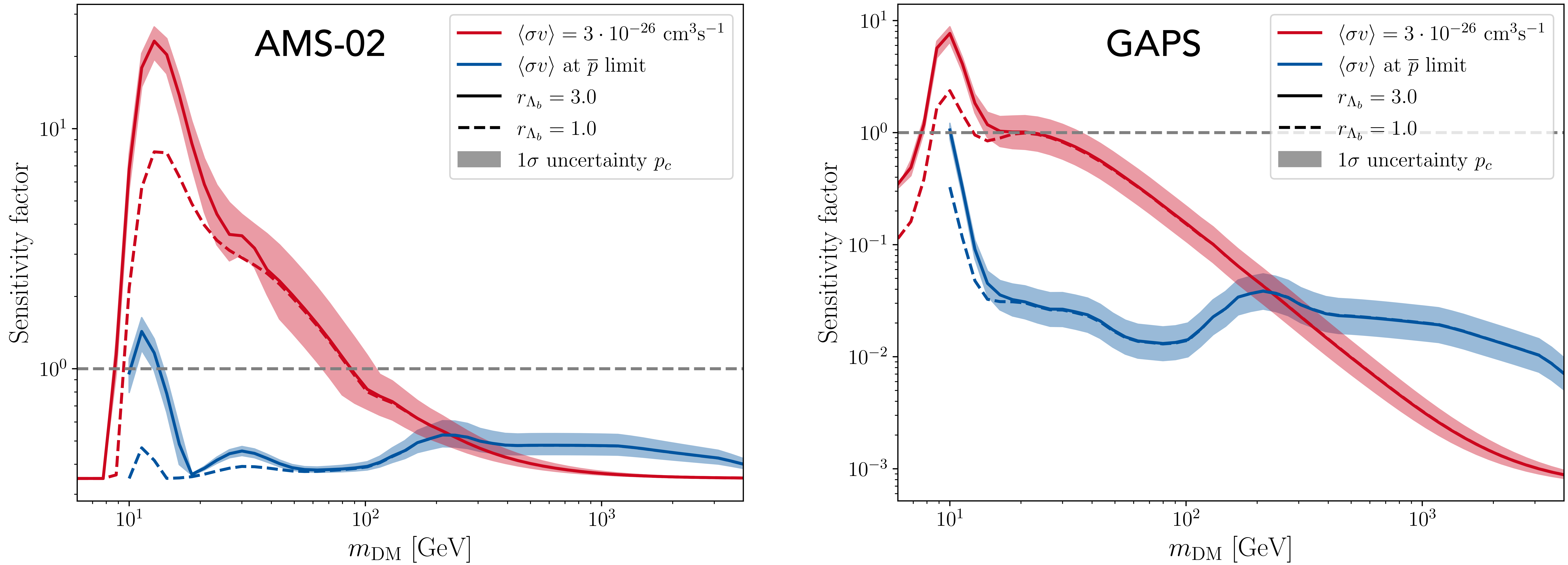
- Generate fluxes for set of propagation parameters $\{\theta_{\mathrm{prop},i}\}$ sampled from posterior of $p, \bar{p}$ and He fit
- Apply force-field approximation to account for solar modulation
- Marginalize over $\{\theta_{\mathrm{prop},i}\}$:

$$\langle \Phi_{\bar{d}} \rangle = \frac{\sum_i \Phi_{\bar{d},i} \frac{\mathscr{L}_{\mathrm{DM}}(\theta_{\mathrm{prop},i}, x_{\mathrm{DM}})}{\mathscr{L}(\theta_{\mathrm{prop},i})}}{\sum_i \frac{\mathscr{L}_{\mathrm{DM}}(\theta_{\mathrm{prop},i}, x_{\mathrm{DM}})}{\mathscr{L}(\theta_{\mathrm{prop},i})}}$$

- Calculate sensitivity factor: $\frac{\langle \Phi_{\bar{d}} \rangle}{\Phi_{\mathrm{exp.}}}$



Sensitivity Annihilation into $b\bar{b}$



➡ Assuming $\bar{p}$ limit, sensitivity only to small DM masses

➡ GAPS independent test to AMS-02

$\bar{p}$ limit from Balan et al. [2303.07362]

Conclusion

- Antideuterons are great for indirect detection because of negligible background
- Predicted fluxes of antideuterons on Earth for varying DM models including uncertainties from antideuteron production
- Calculating fluxes is slow → trained Neural Network DarkRayNet, available on GitHub, can be used for arbitrary DM models
- Obtained sensitivity factor for AMS-02 and GAPS
- AMS-02 and GAPS only sensitive to low DM masses if DM annihilates into $b\bar{b}$

https://github.com/kathrinnp/DarkRayNet

Conclusion

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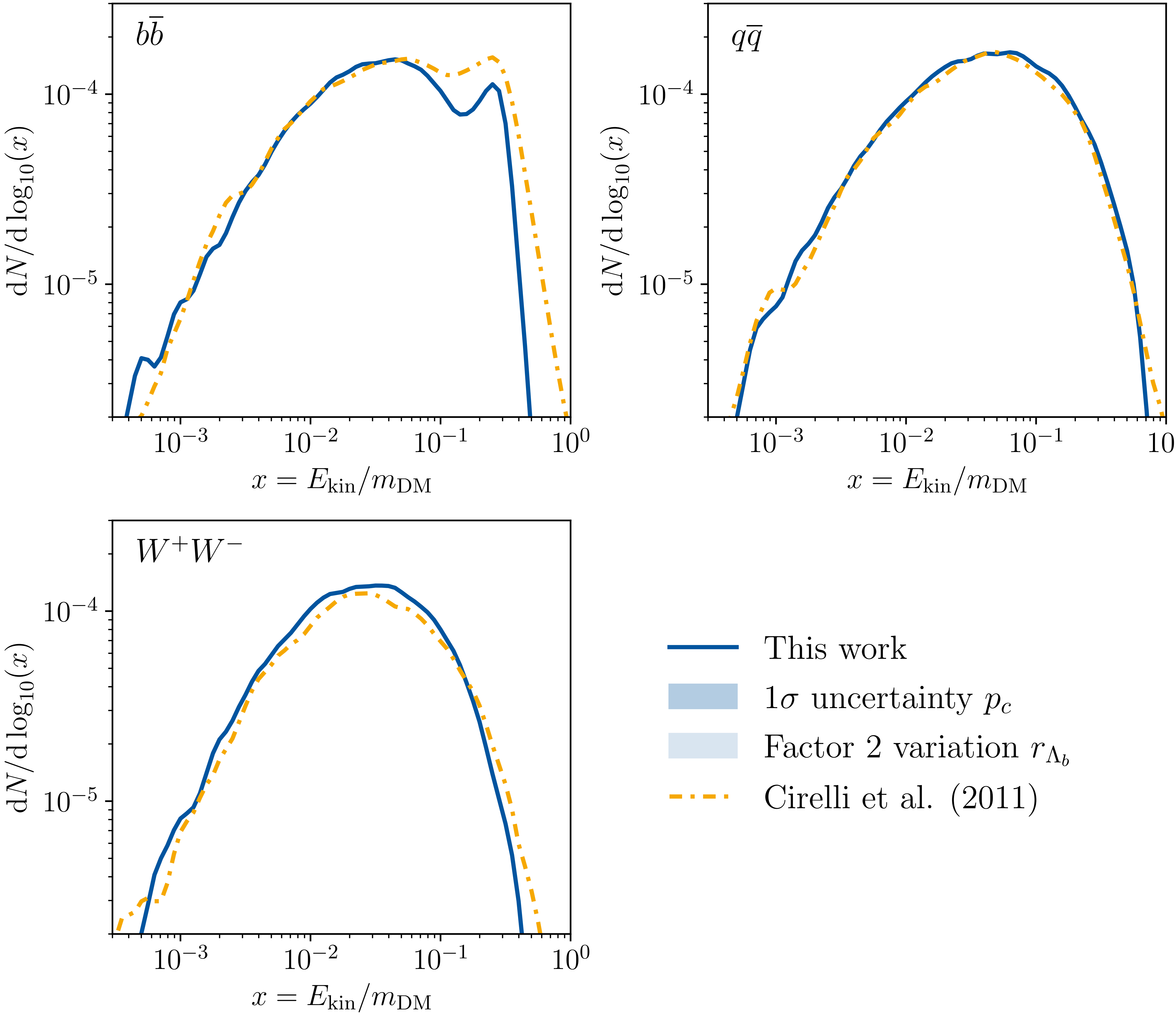
https://github.com/kathrinnp/DarkRayNet

Thank you!

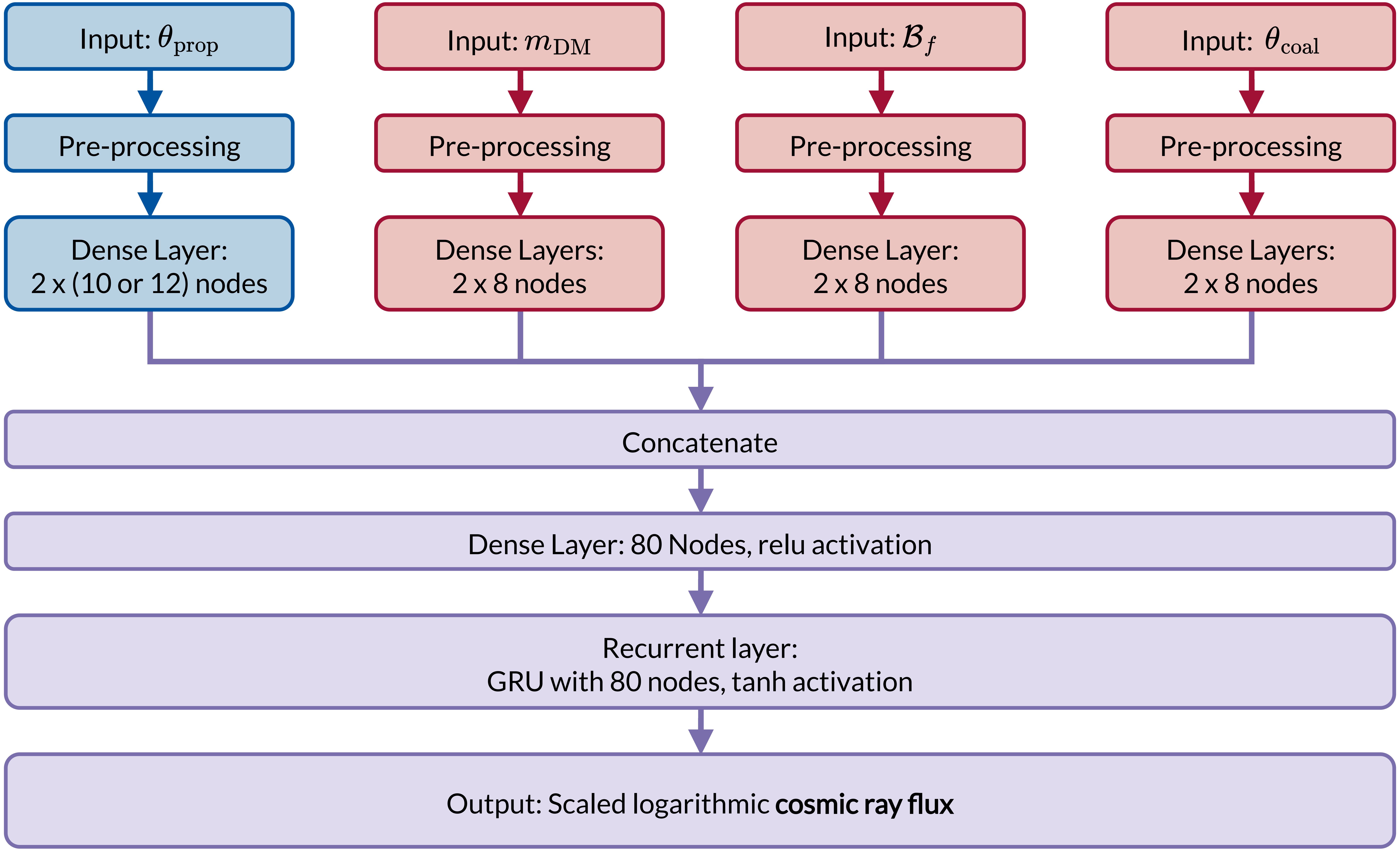
Backup Slides

Antideuteron Injection Spectra

- Generated spectra for $m_{\mathrm{DM}} = 100\,\mathrm{GeV}$ using MadDM and Pythia 8.2
- Include $\bar{d}$ produced at initial vertex and through Λ_b decay
- Compare to PPPC4DMID [1012.4515] (used Pythia 8.1)



Network Architecture



Input: θ_{prop}

Pre-processing

Dense Layer:
2 x (10 or 12) nodes

Input: m_{DM}

Pre-processing

Dense Layers:
2 x 8 nodes

Input: $\mathcal{B}_f$

Pre-processing

Dense Layer:
2 x 8 nodes

Input: θ_{coal}

Pre-processing

Dense Layers:
2 x 8 nodes

Concatenate

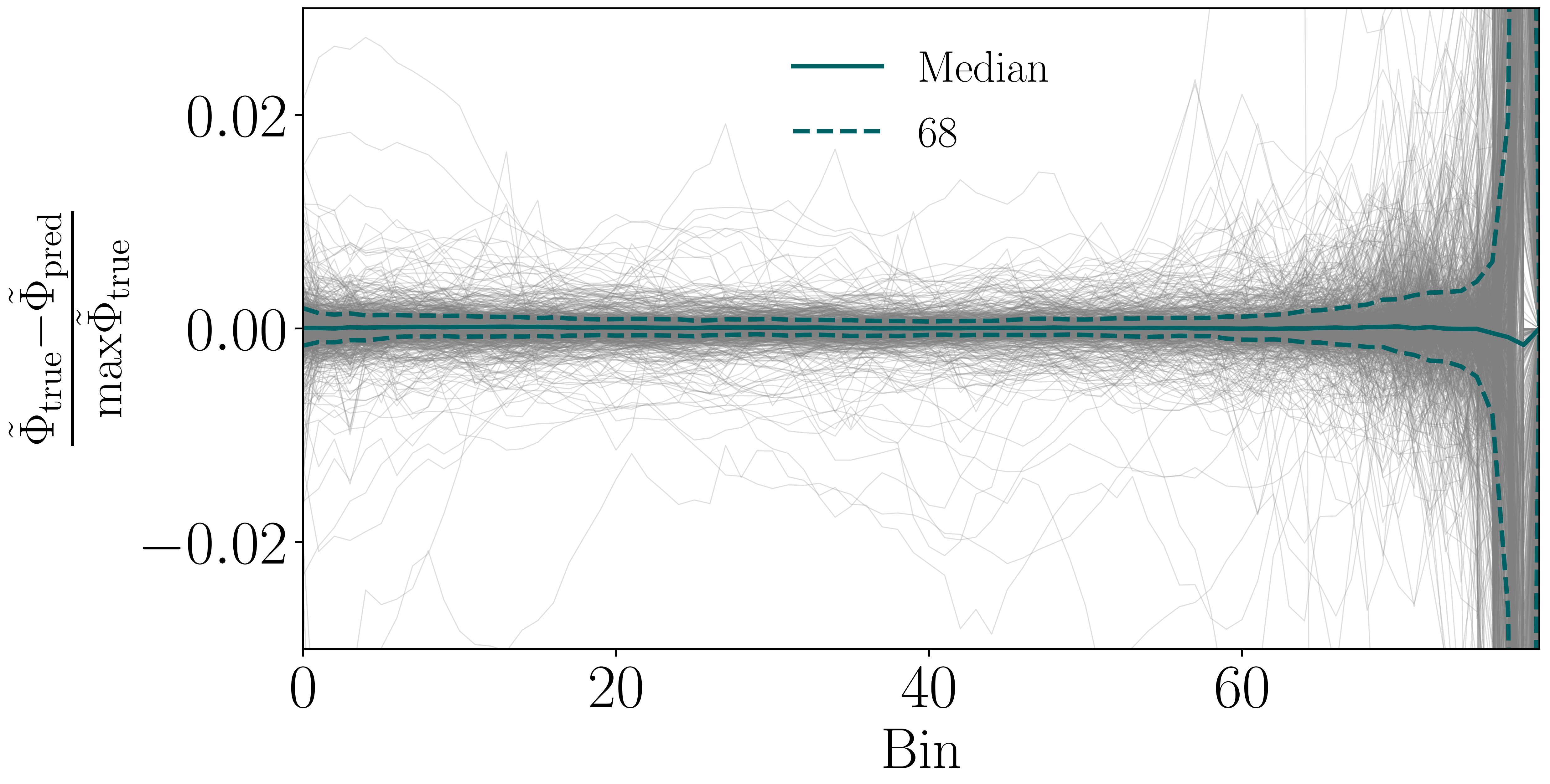
Dense Layer: 80 Nodes, relu activation

Recurrent layer:
GRU with 80 nodes, tanh activation

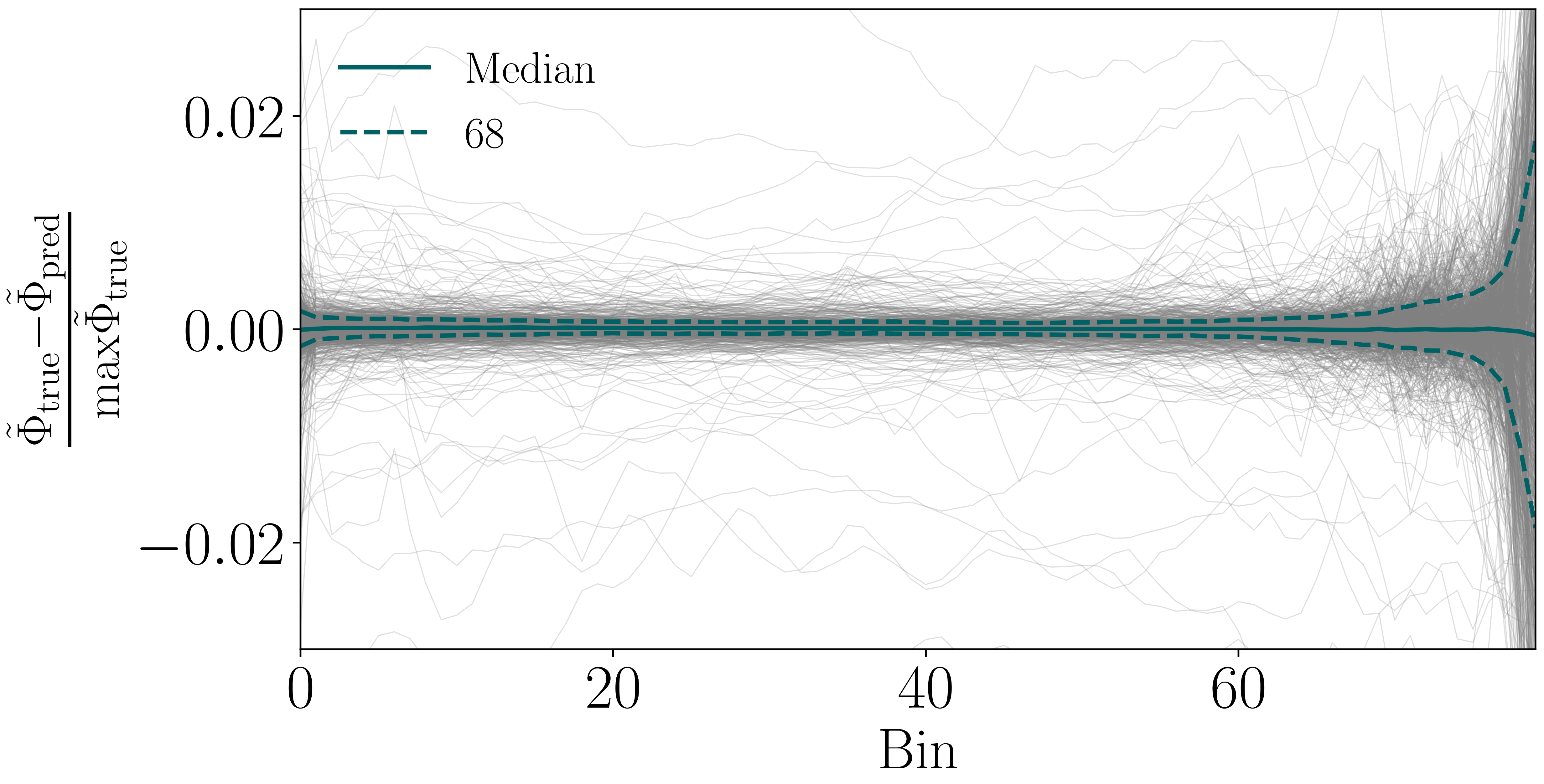
Output: Scaled logarithmic **cosmic ray flux**

Network Performance

DIFF.BRK model

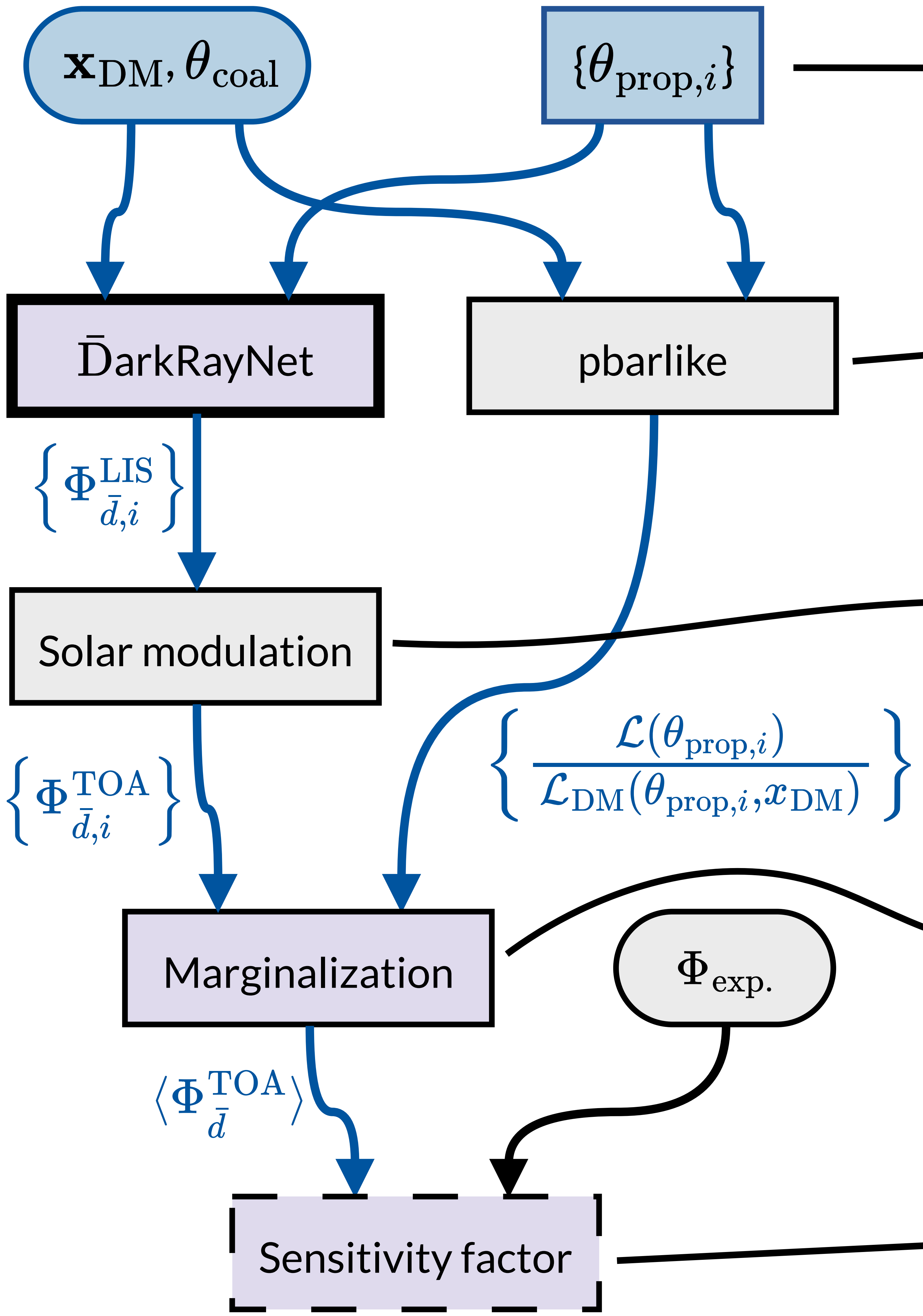


INJ.BRK model



- Relative difference of most transformed fluxes at most 6×10^{-4}
- Translates to relative error of $\mathcal{O}(10^{-2})$ in the actual flux

Prediction of Sensitivity Factor



- $\{\theta_{\mathrm{prop},i}\}$: posterior sample of propagation parameters from $p, \bar{p}$ and He fit
- pbarlike [2303.07362]: antiproton likelihood calculator
- Solar modulation: force-field approximation, solar potential depends on experiment
- Marginalization: $\sum_i \Phi^{\mathrm{TOA}}_{\bar{d},i} \frac{\mathscr{L}_{\mathrm{DM}}(\theta_{\mathrm{prop},i}, x_{DM})}{\mathscr{L}(\theta_{\mathrm{prop},i})}$
- Sensitivity factor: $\frac{\langle \Phi_{\bar{d}} \rangle}{\Phi_{\mathrm{exp.}}}$

Experimental Sensitivities

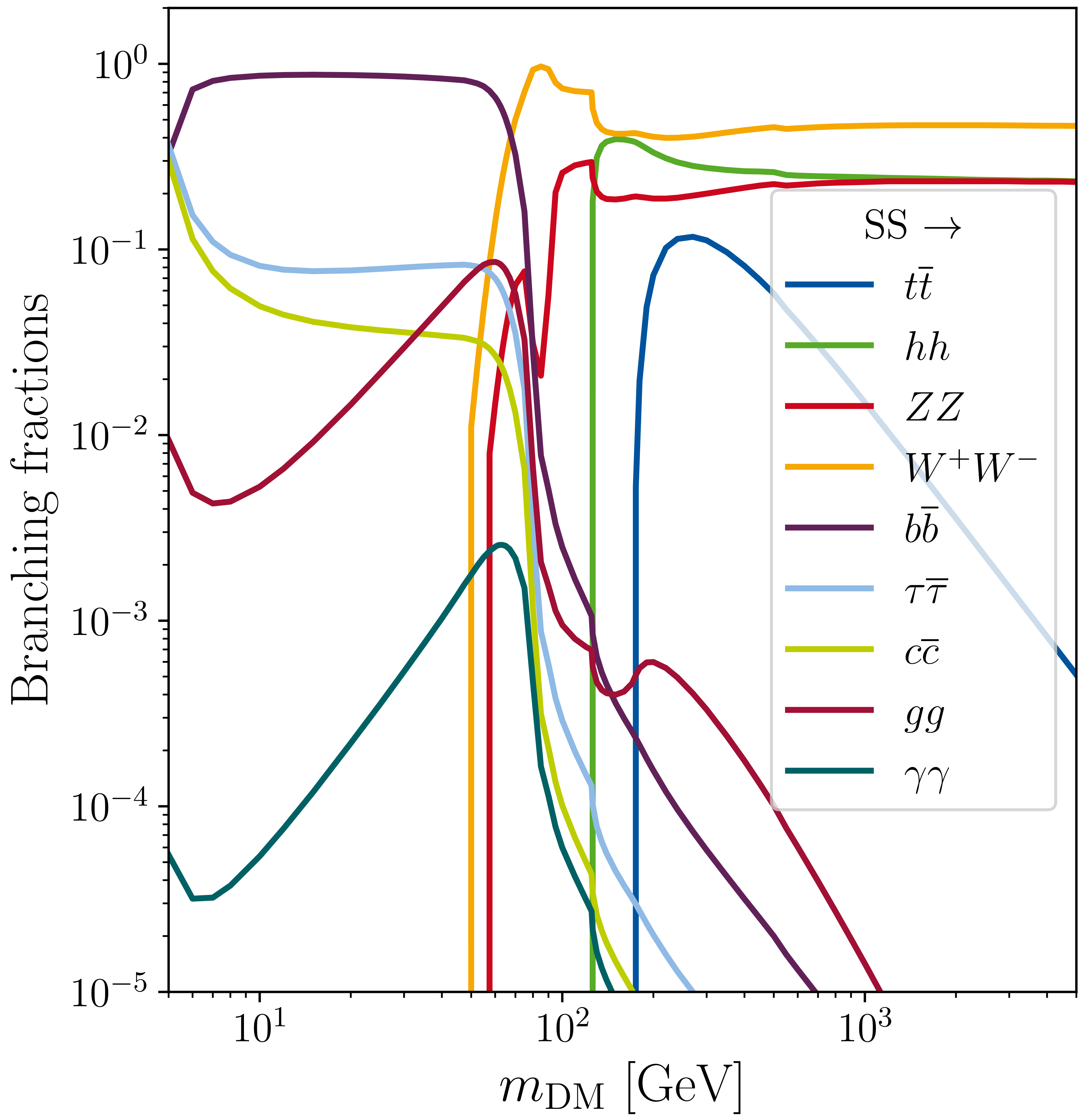
Experiment	Energy range [GeV/nuc]	$\Phi_{\text{sens},E_{\text{exp}}}$ $[\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,(\text{GeV/nuc})^{-1}]$	
GAPS	$[0.05, 0.25]$	2×10^{-6}	GAPS Collaboration [1506.02513]
AMS-02	$[0.2,\ 0.8]$ and $[2.2,\ 4.2]$	4.5×10^{-7}	Choutko, Giovacchini [ICRC 2008]

Propagation Parameters & Priors

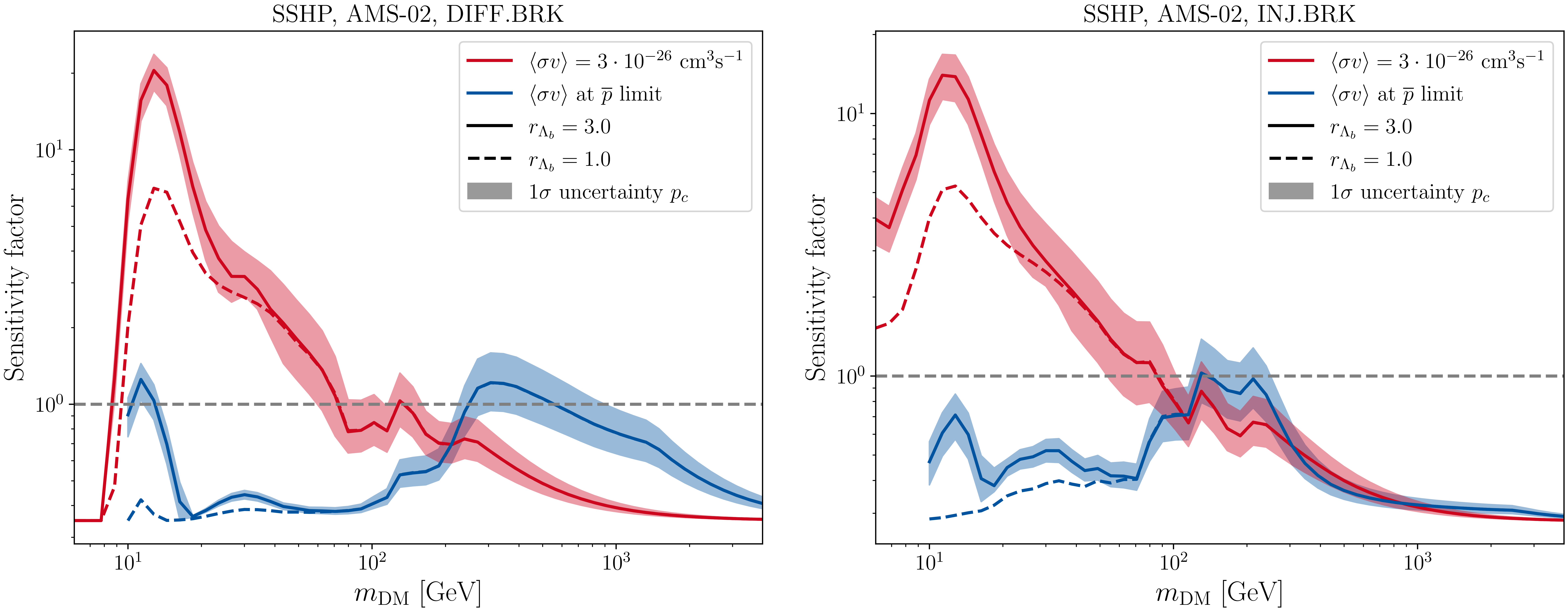
Parameters	**Priors**	**DIFF.BRK**	**INJ.BRK**
$\gamma_{1,p}$	$1.2 - 2.1$	✓	✓
γ_1	$1.2 - 2.1$	✓	✓
$\gamma_{2,p}$	$2.1 - 2.6$	✓	✓
γ_2	$2.1 - 2.6$	✓	✓
R_0 [GV]	$1.0 - 20$	✗	✓
s	$0.1 - 0.7$	✗	✓
D_0 [10^{28} cm^2/s]	$0.5 - 10.0$	✓	✓
δ_l	$-1.0 - 0.5$	✓	✓
δ	$0.3 - 0.7$	✓	✓
$\delta_h - \delta$	$-0.2 - 0.0$	✓	✓
$R_{D,0}$ [GV]	$1.0 - 20.0$	✓	✗
s_D	$0.1 - 0.9$	✓	✗
$R_{D,1}$ [10^3]	$100 - 500$	✓	✓
v_{A} [km/s]	$0 - 30$	✗	✓
$v_{0,\mathrm{c}}$ [km/s]	$0 - 60$	✓	✓

Singlet Scalar Higgs Portal

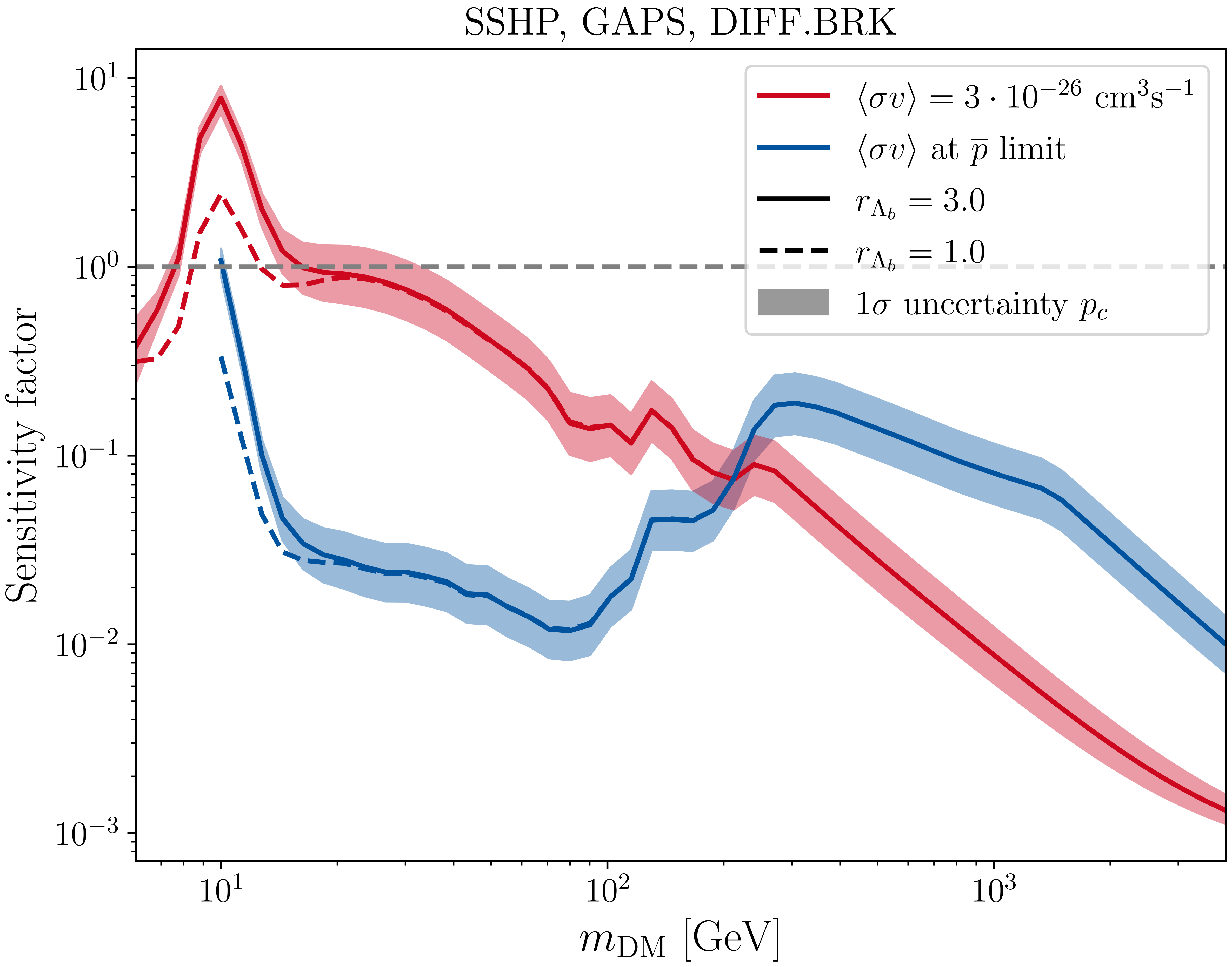
- SM extended by gauge-singlet real scalar
- Portal coupling to Higgs fixed to explain measured relic abundance

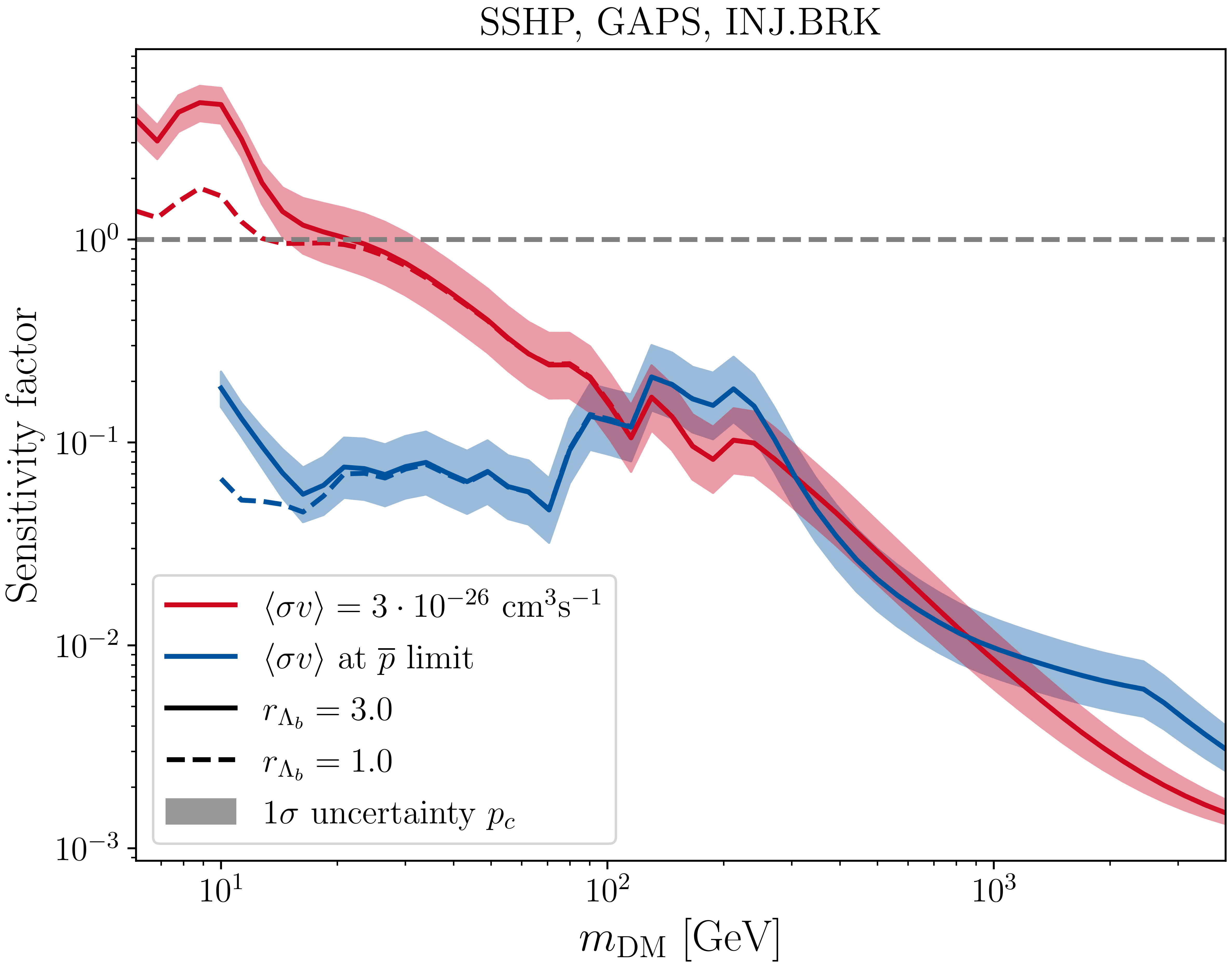


SSHP Sensitivity AMS-02

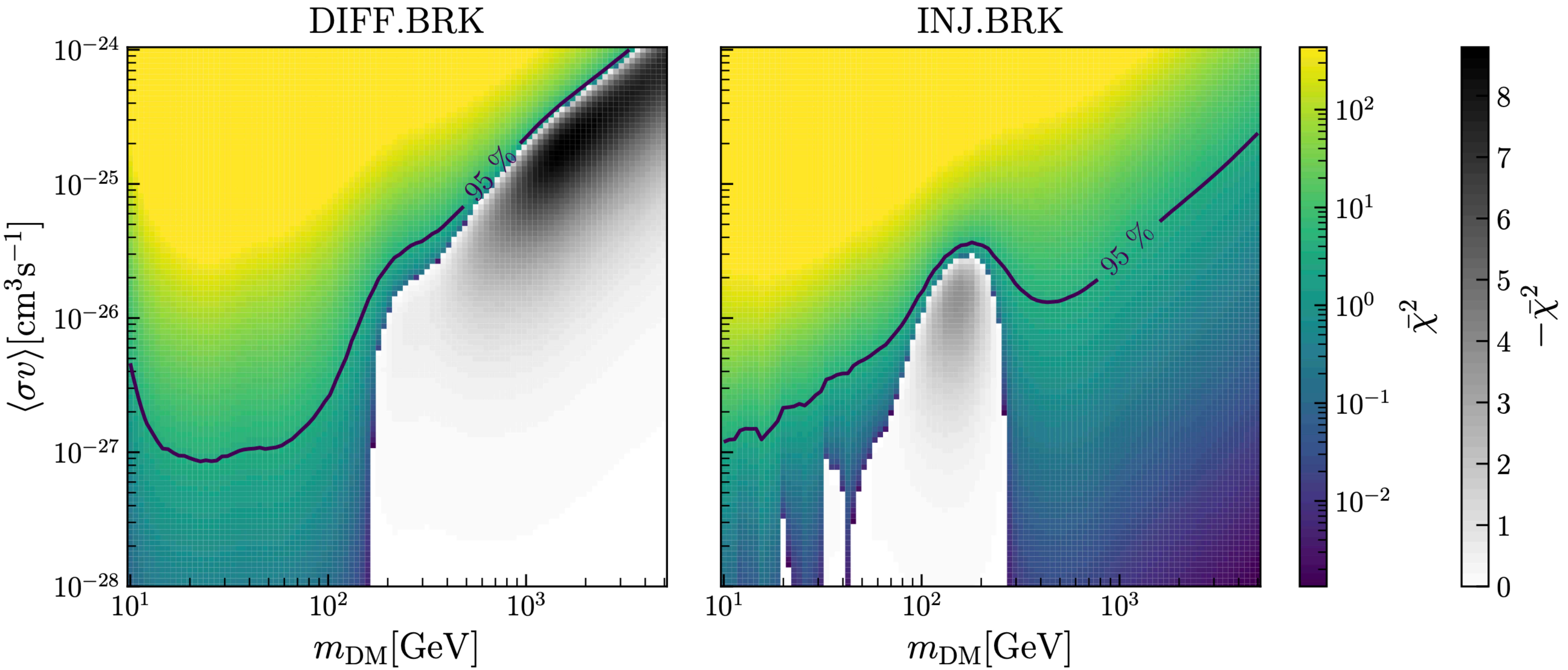


SSHP Sensitivity GAPS


SSHP, GAPS, DIFF.BRK


SSHP, GAPS, INJ.BRK

$\bar{p}$ Limit



Limits for DM annihilation into $b\bar{b}$, from Balan et al. [2303.07362]