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

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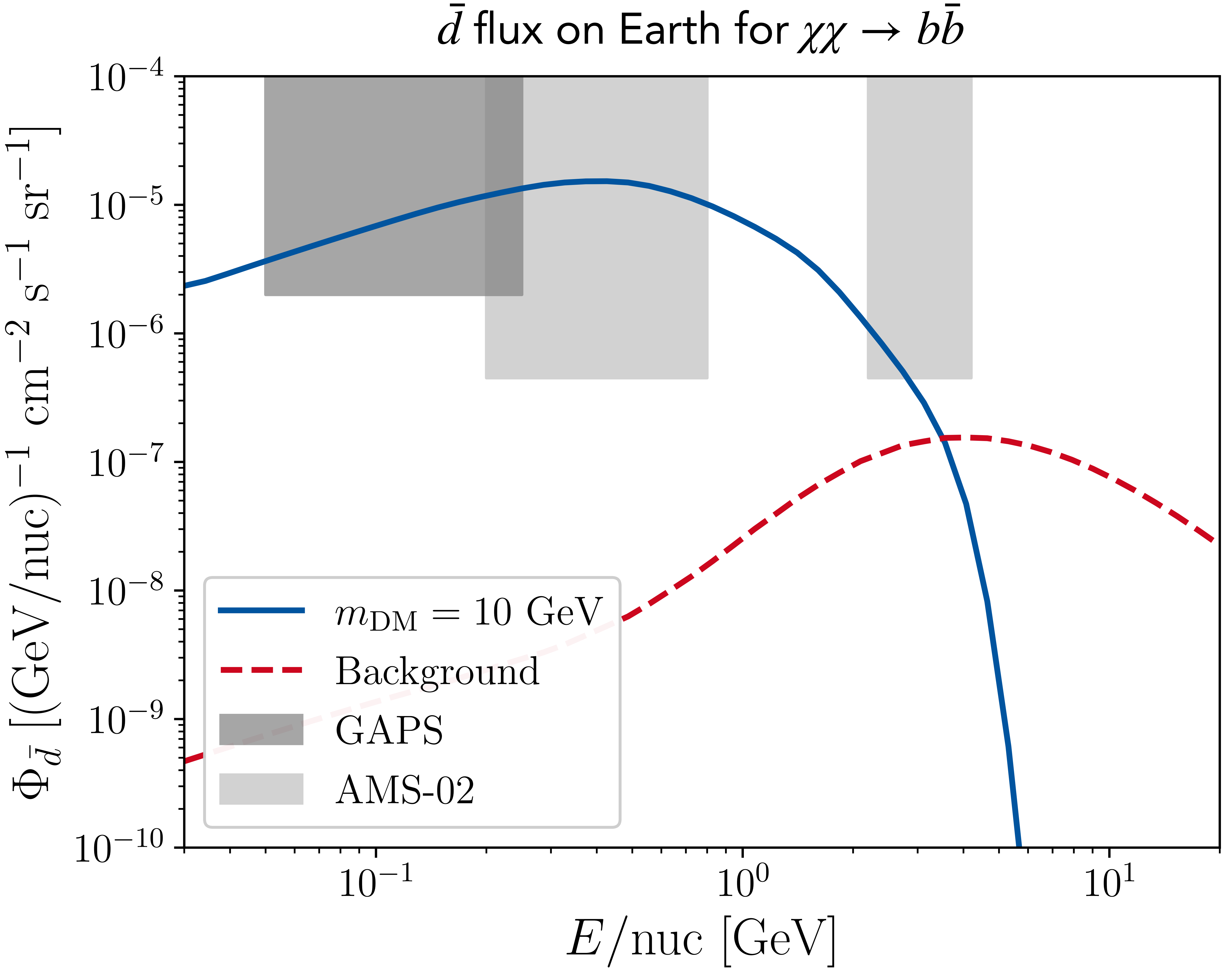
Why Antideuterons?

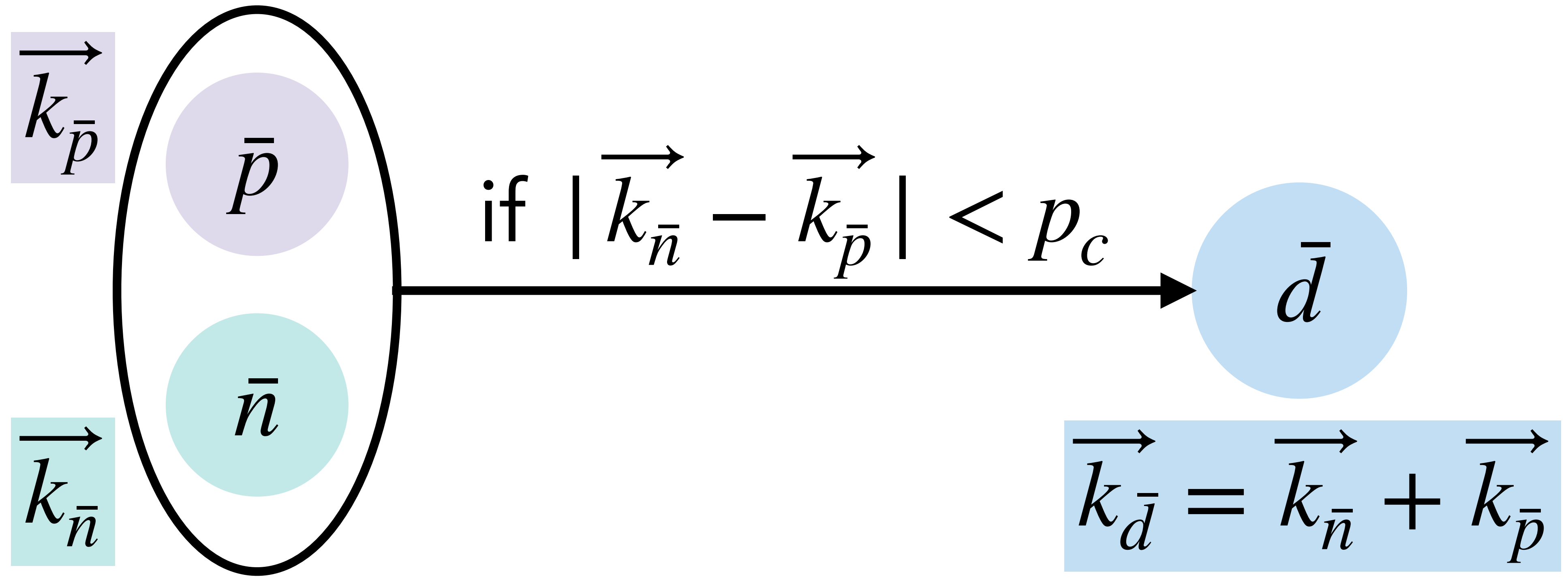
- Antimatter can be produced in dark matter annihilations
- Background from interactions of cosmic rays negligible at low energies for antinuclei but not for antiparticles
- New GAPS experiment & AMS-02 can detect low energy antinuclei




DM
DM
BSM Physics
$\overline{d}$
Where do Antideuterons come from?
GAPS


DM
DM
BSM Physics
$\overline{d}$
q, c, b, t, W, Z, H, g
DM
DM
SM
SM
Jet
Hadronization
$\overline{p}$
$\overline{n}$
Coalescence
$\overline{d}$
$p, n, \pi, \ldots$
Production
GAPS

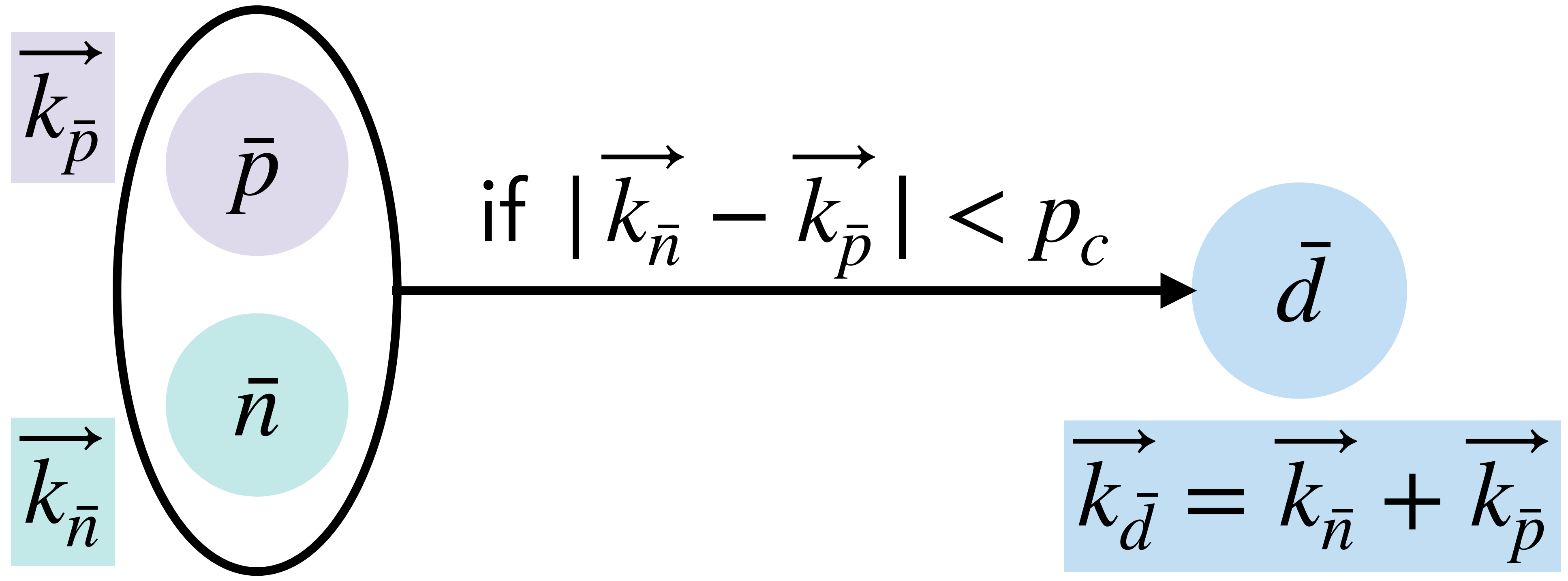
Production: Coalescence Mechanism



- Coalescence momentum p_c, determined from experiment

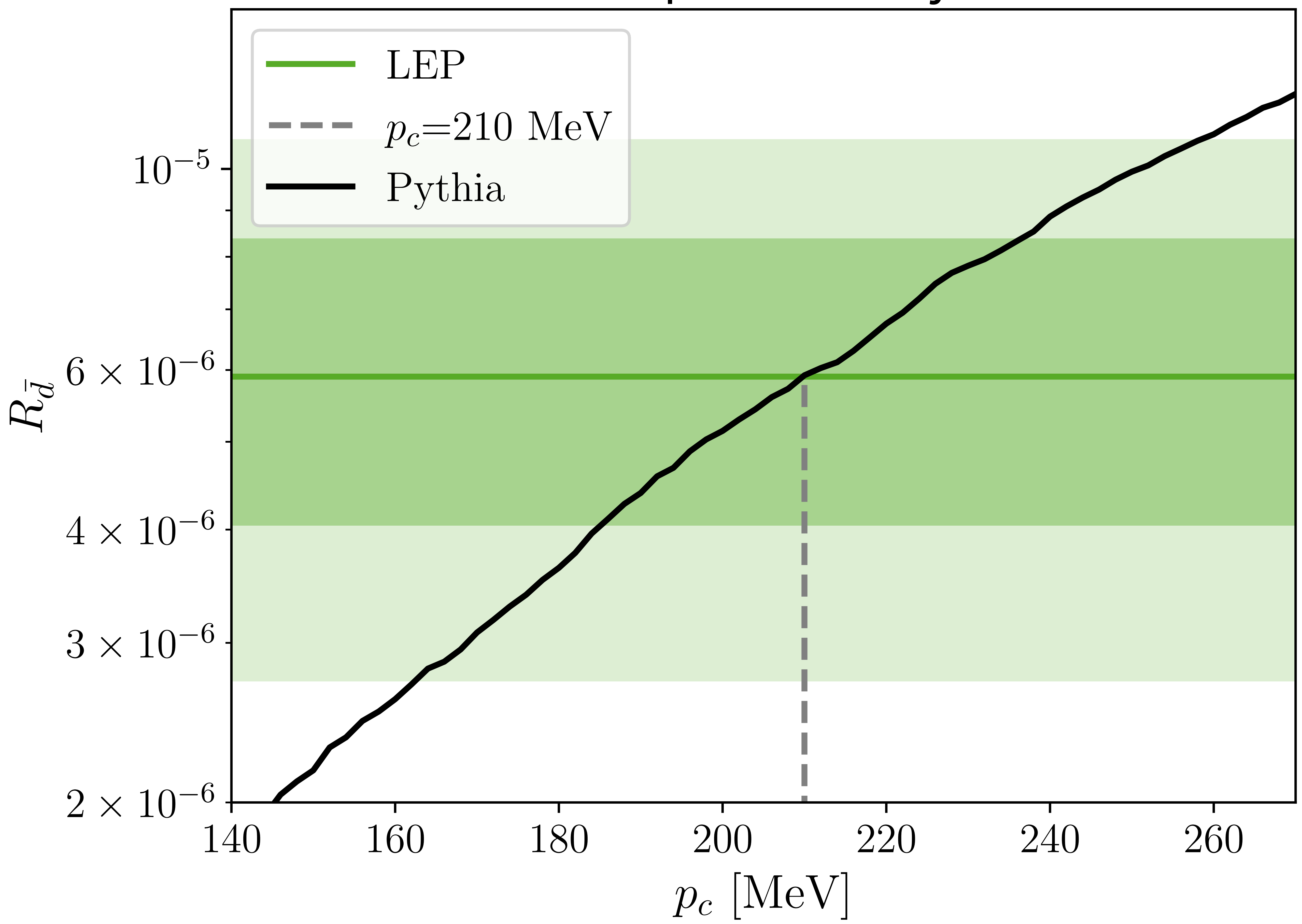
Fornengo+ [1306.4171]

Production: Coalescence Mechanism



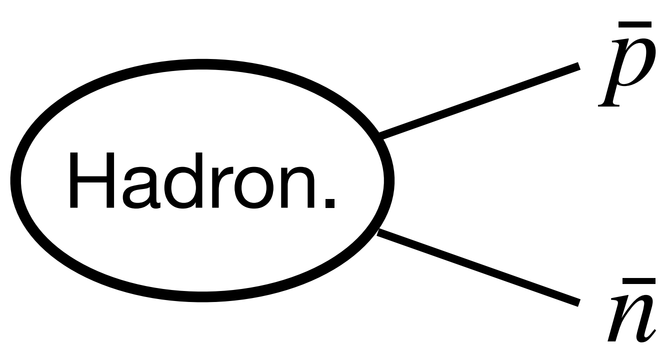
- Coalescence momentum p_c, determined from experiment
- Match number of antideuterons from simulated hadronic Z-decays to amount measured by LEP
- Spatial separation smaller than 2 fm

Number of $\bar{d}$ per Z-decay in LEP

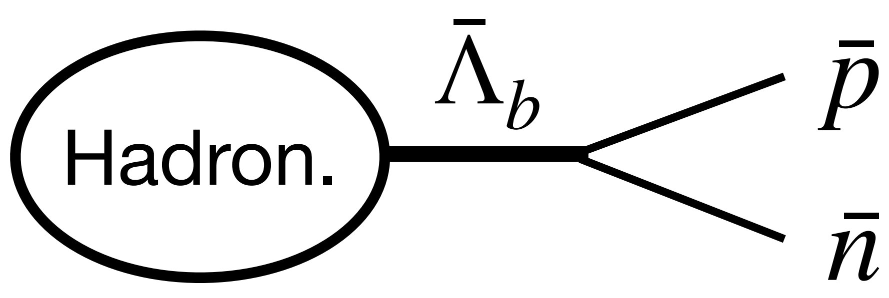


Fornengo+ [1306.4171]

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



Prompt

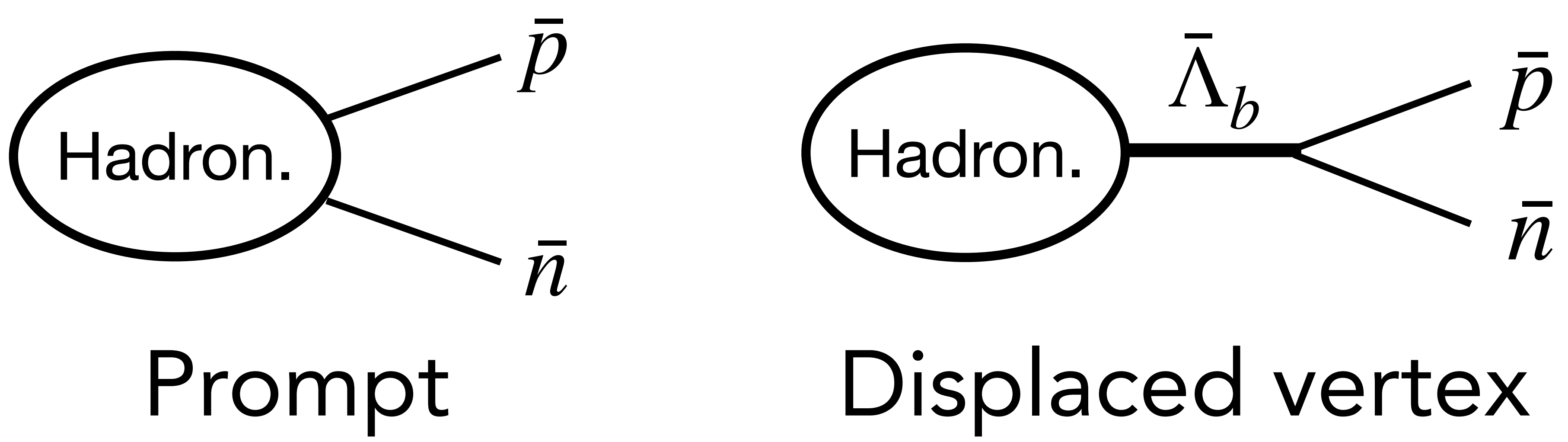


Displaced vertex

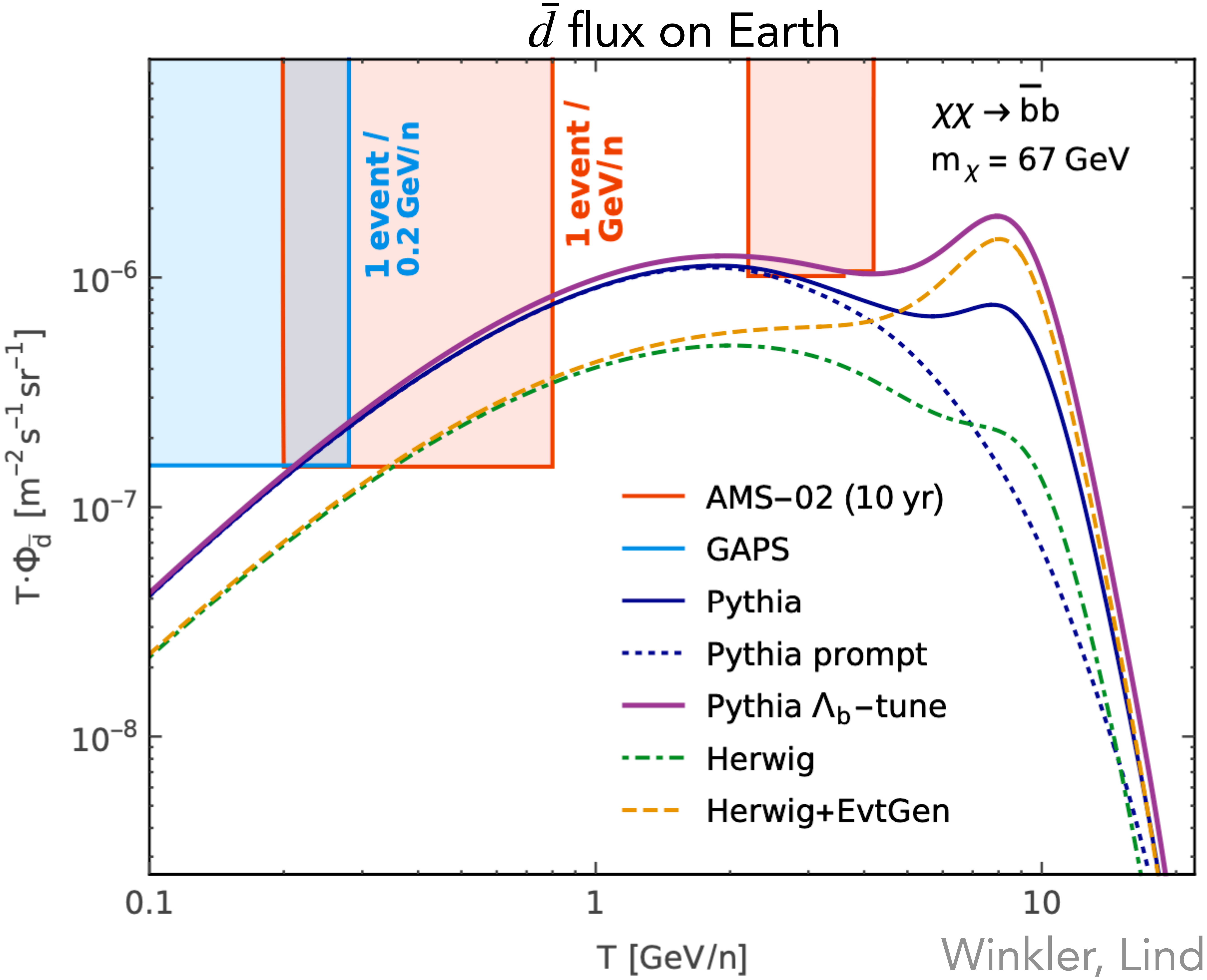
- $m_{\bar{\Lambda}_b} = 5.6$ GeV → decays into particles with small relative momenta → boosts $\bar{d}$ production

Winkler, Linden [2006.16251]

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



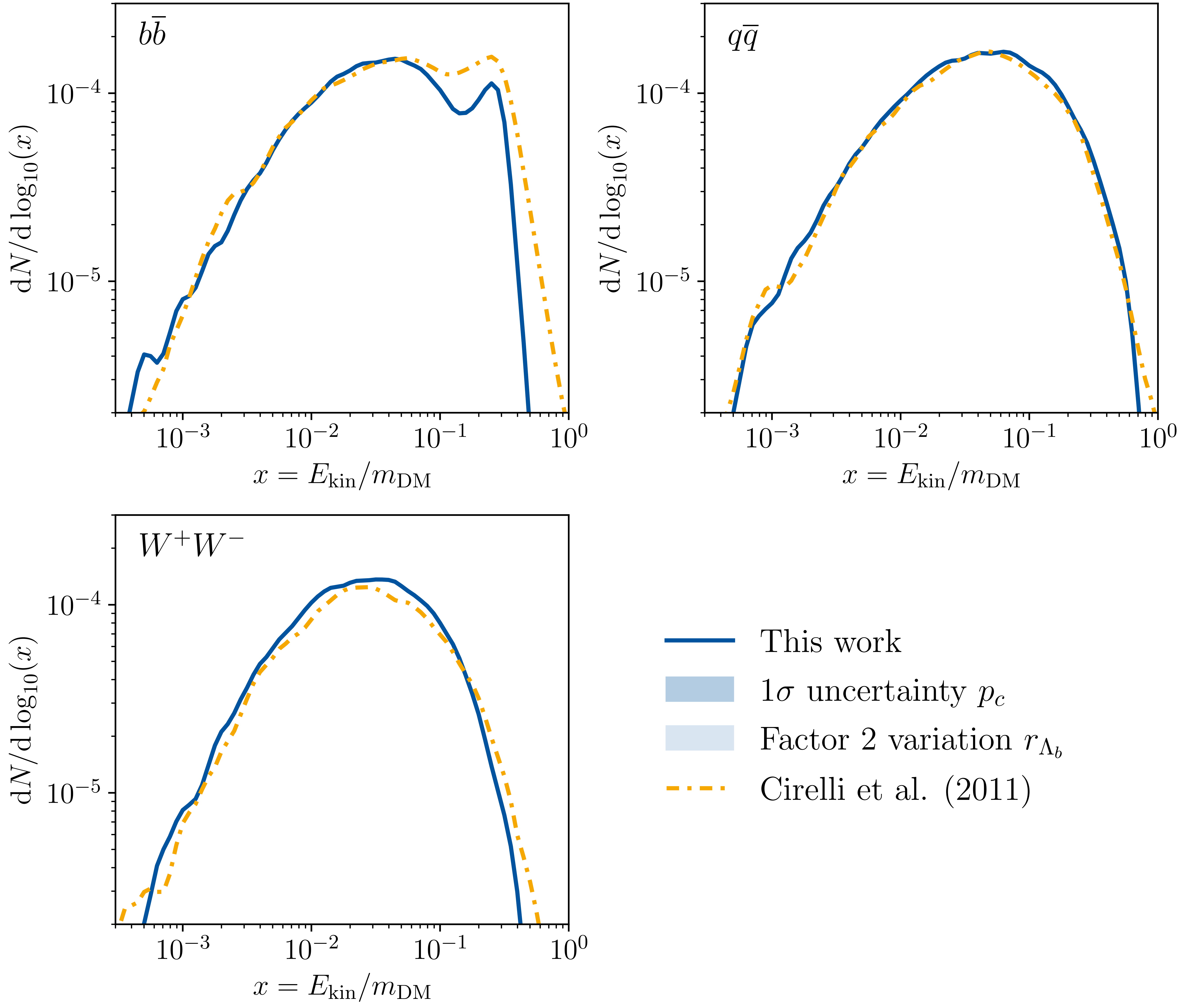
- $m_{\bar{\Lambda}_b} = 5.6$ GeV → decays into particles with small relative momenta → boosts $\bar{d}$ production
- Rescale $\bar{\Lambda}_b$ production in PYTHIA to match measurement of transition ratio $f(b \to \Lambda_b)$ with extra parameter $r_{\Lambda_b} \approx 3$



Winkler, Linden [2006.16251]

Antideuteron Injection Spectra

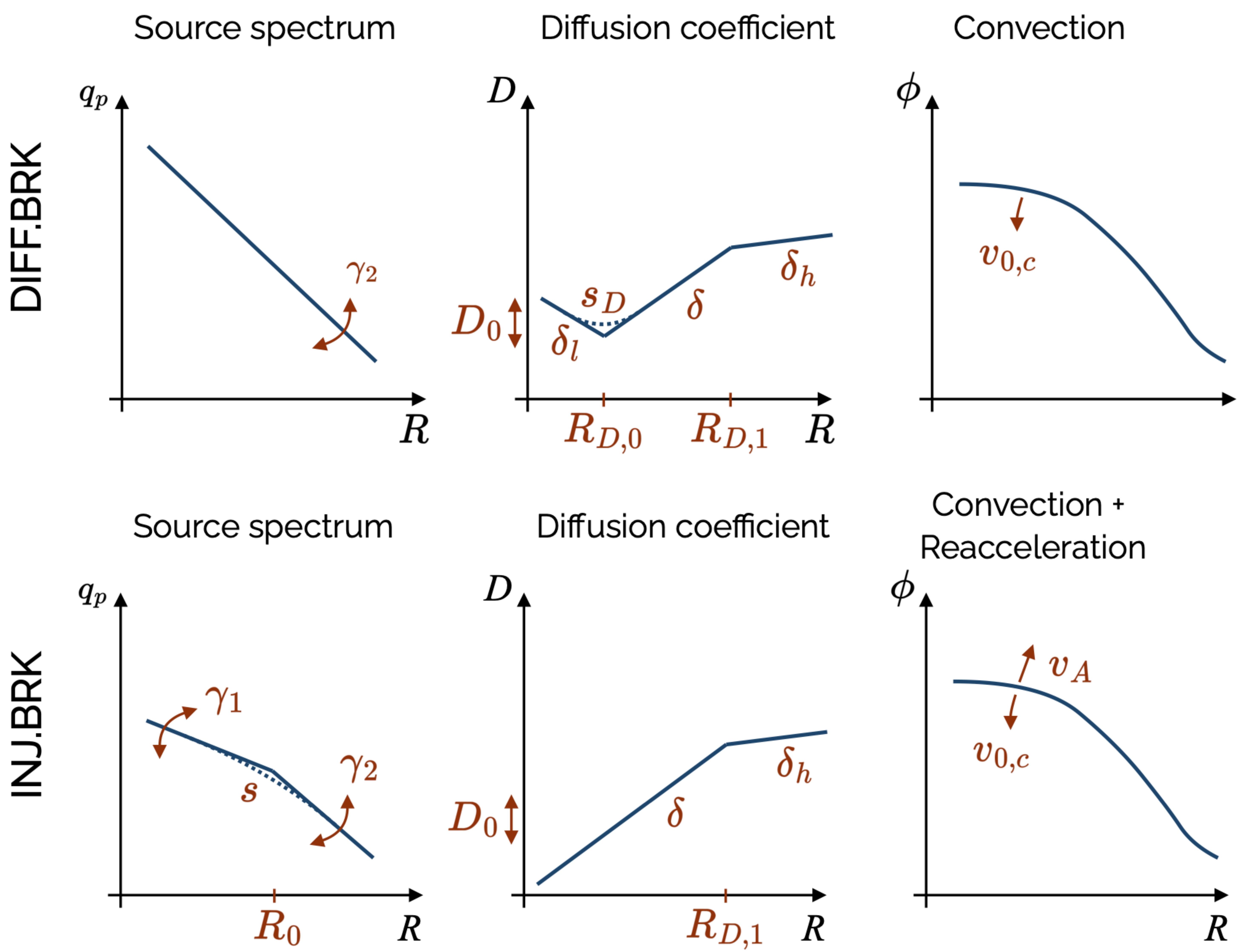
- Generated spectra for $m_{\mathrm{DM}} = 100\,\mathrm{GeV}$ using MadDM and Pythia 8.2
- Include $\bar{d}$ produced at initial vertex and through Λ_b decay
- Compare to PPPC4DMID [1012.4515] (used Pythia 8.1)




Propagation
DM
DM
BSM
Physics
$\overline{d}$
Galactic
Propagation
Solar
Modulation
GAPS

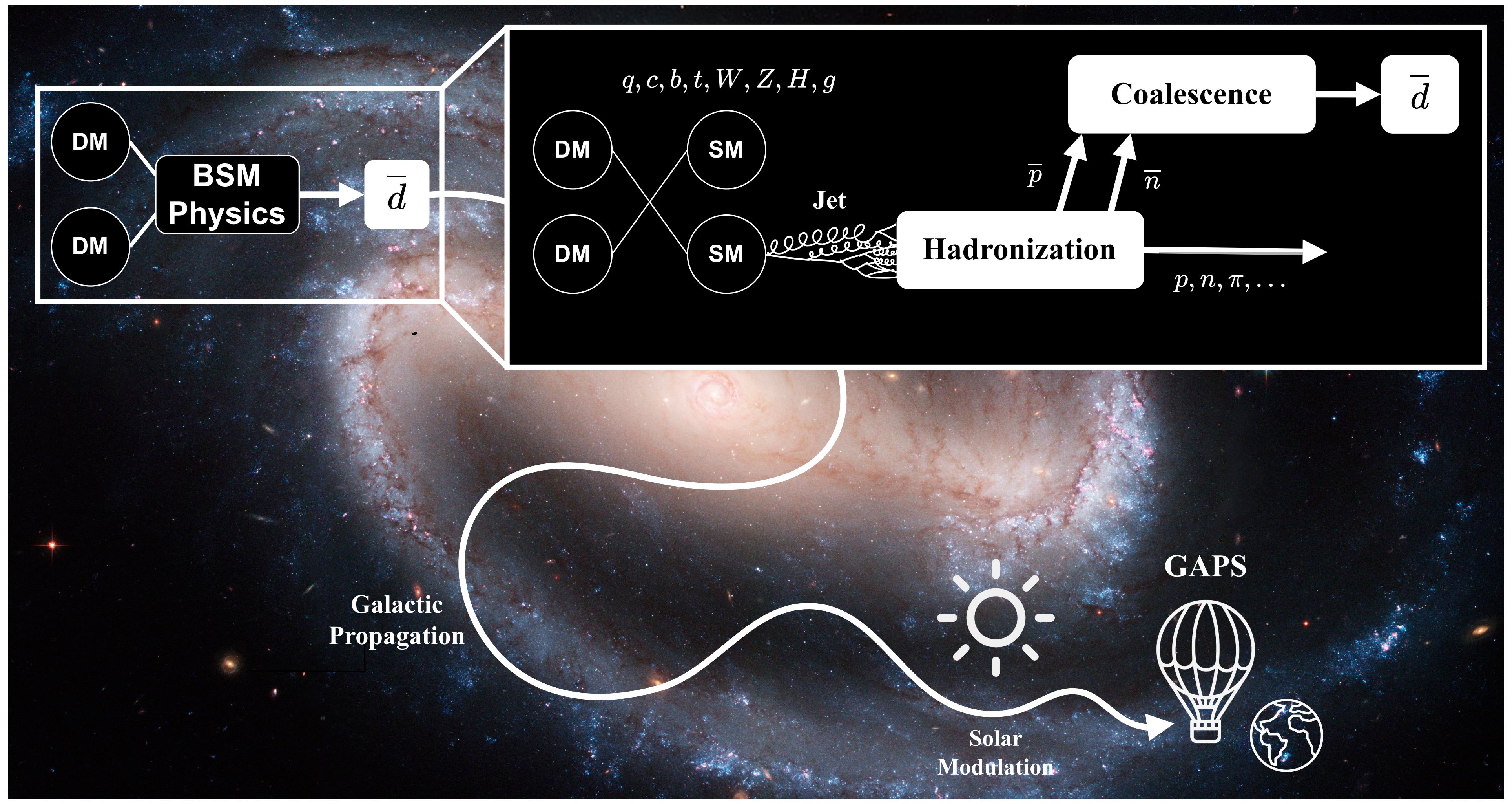
Antideuteron Propagation

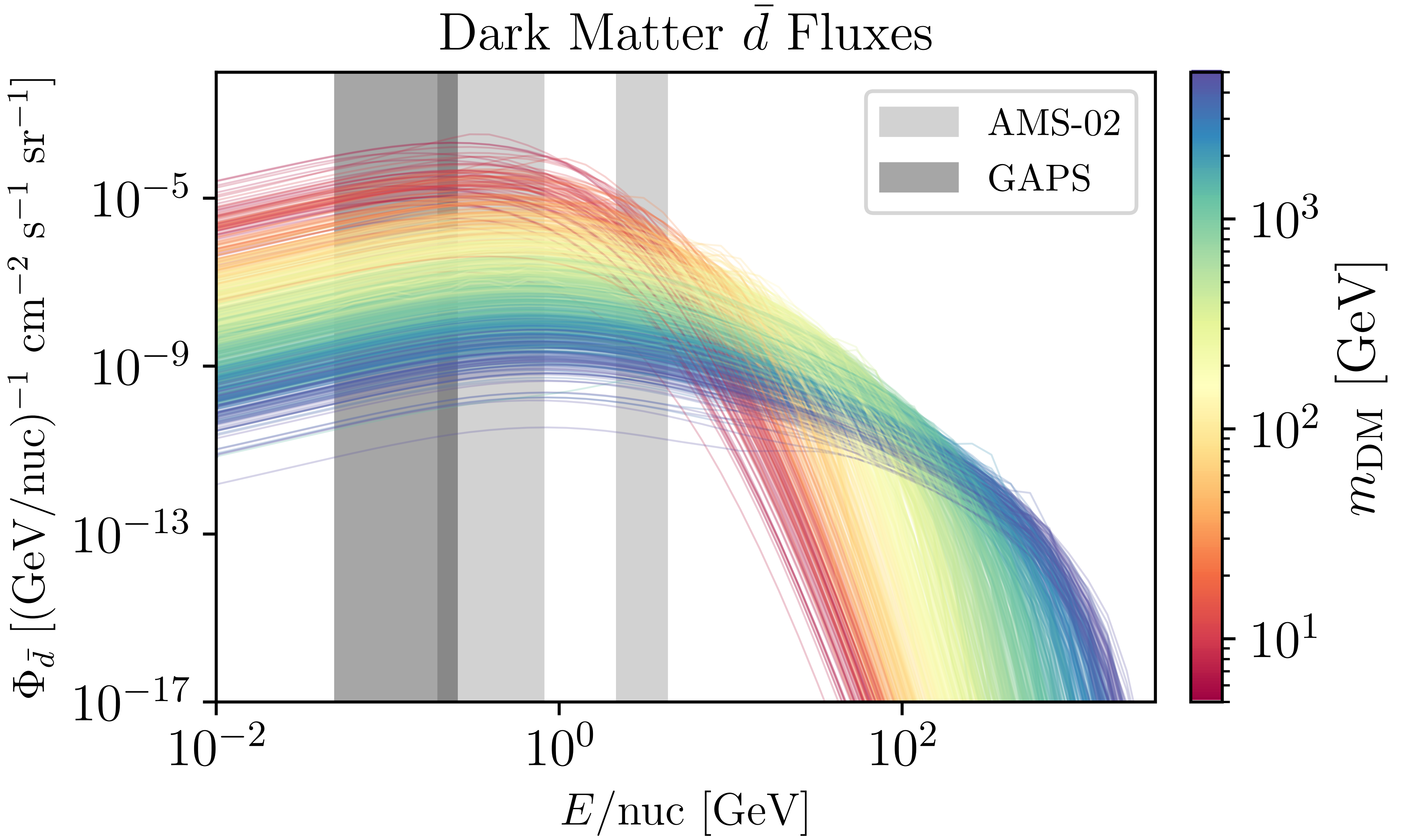
- Use diffusion break and injection break models following Korsmeier, Cuoco [2112.08381]
- Use propagation tool GALPROP
- Implement secondary and tertiary $\bar{d}$ with analytic coalescence model



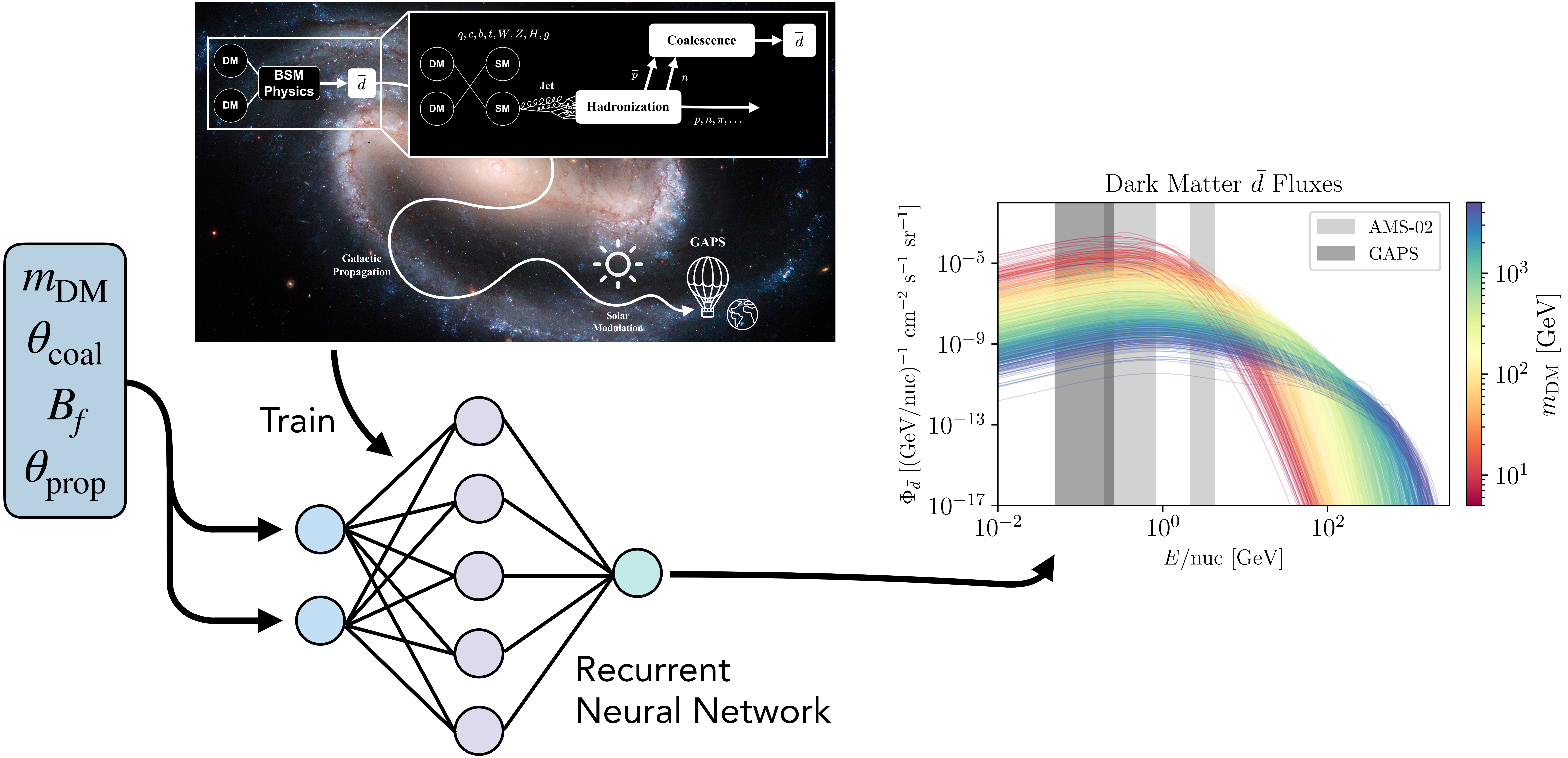
Speed-up Antideuteron Simulation

m_{DM}
θ_{coal}
B_f
θ_{prop}



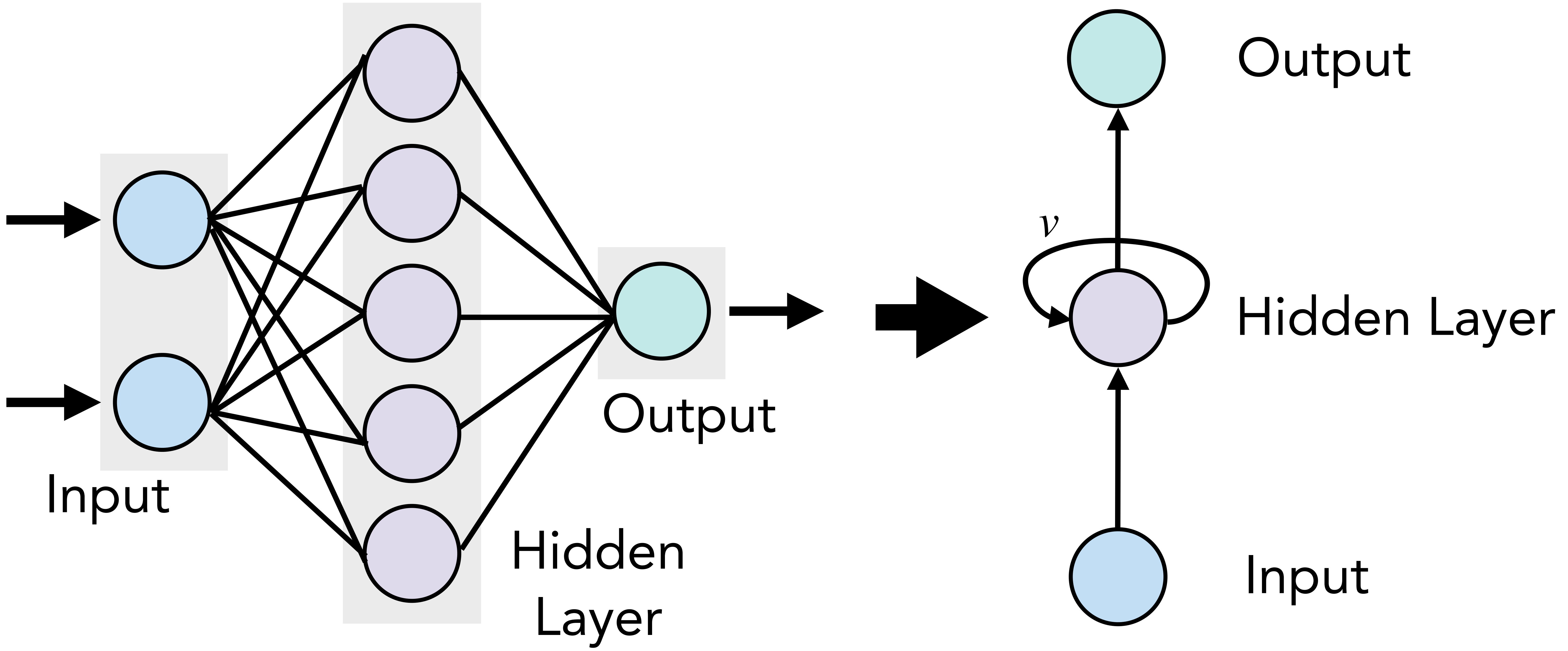


Speed-up Antideuteron Simulation



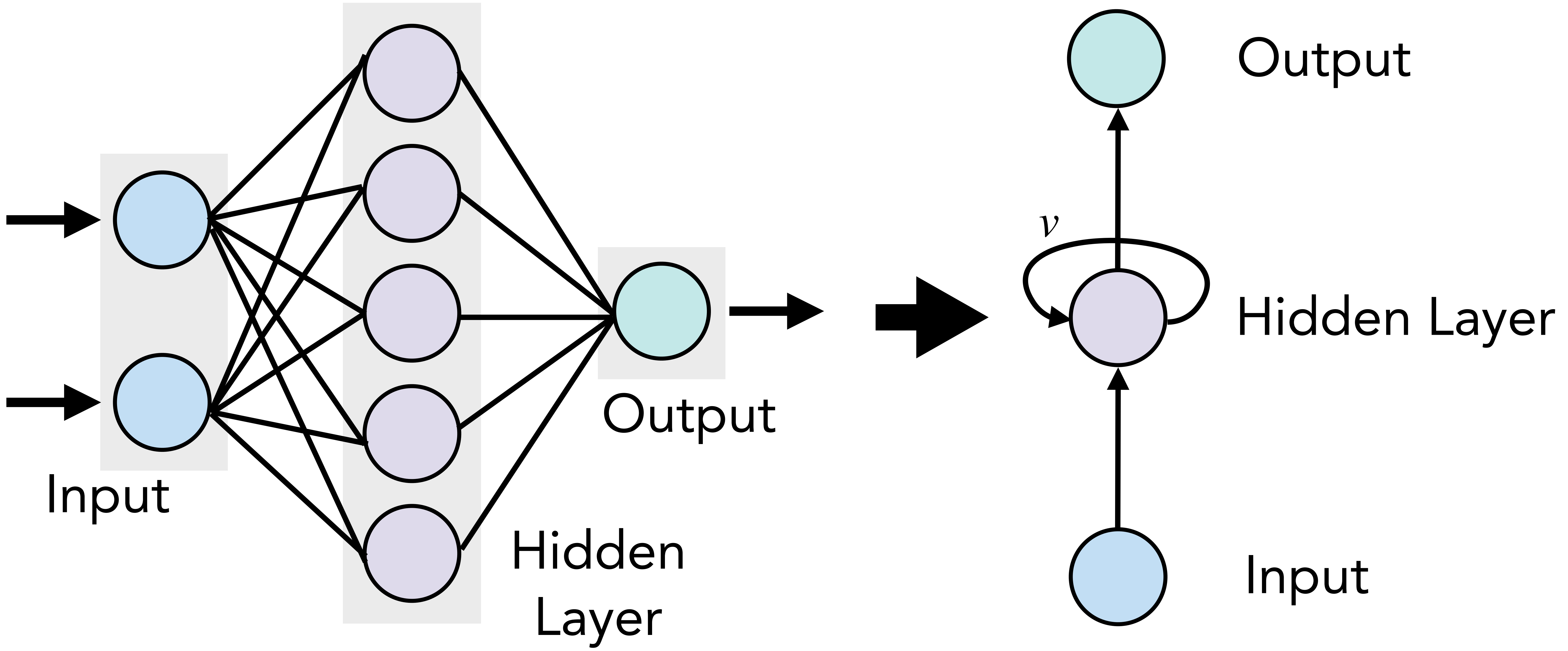
Neural Network

- 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 $\mathcal{O}(10^{-2})$

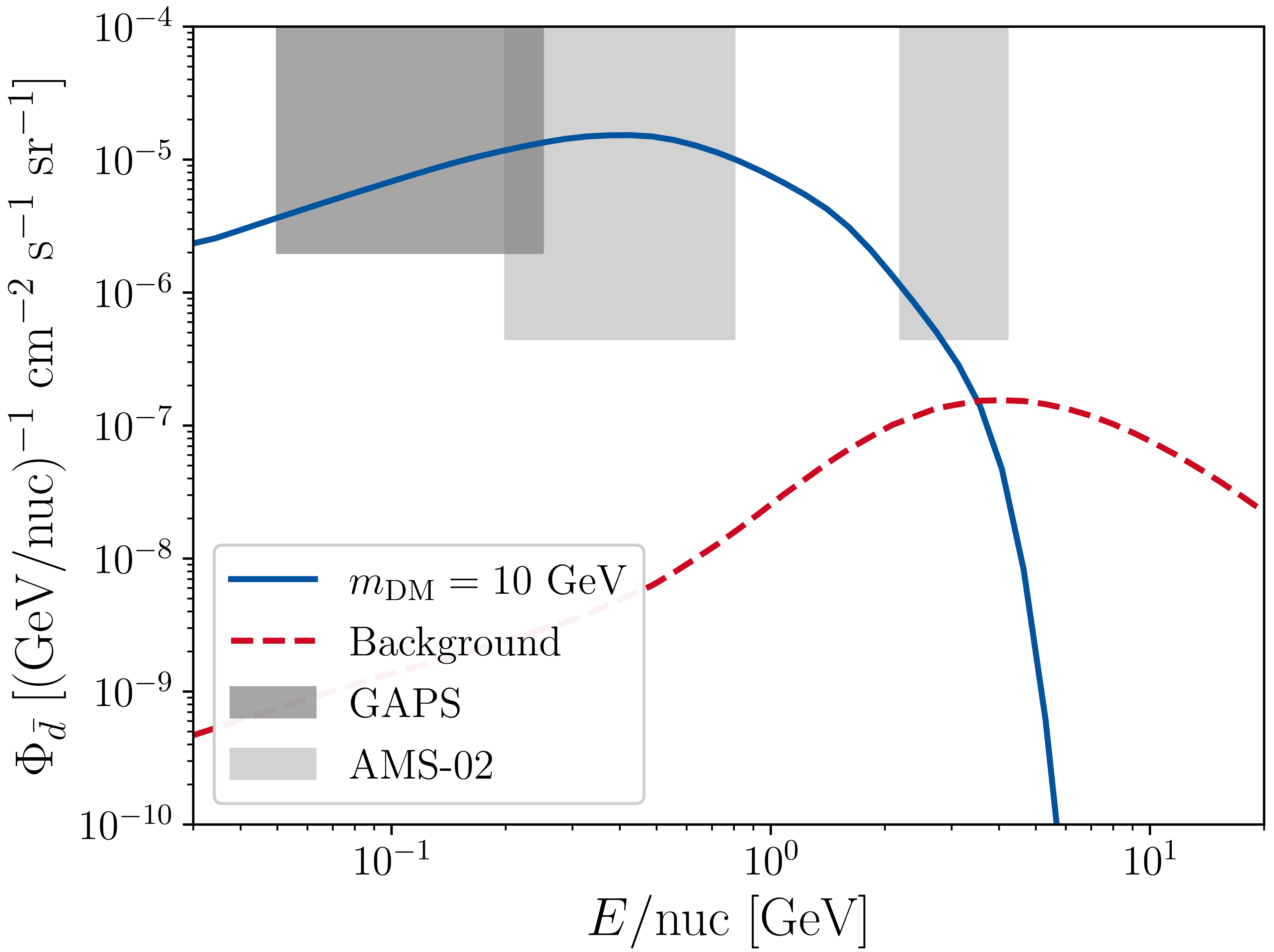


Network available in

https://github.com/kathrinnp/DarkRayNet

Prediction of Sensitivity Factor

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

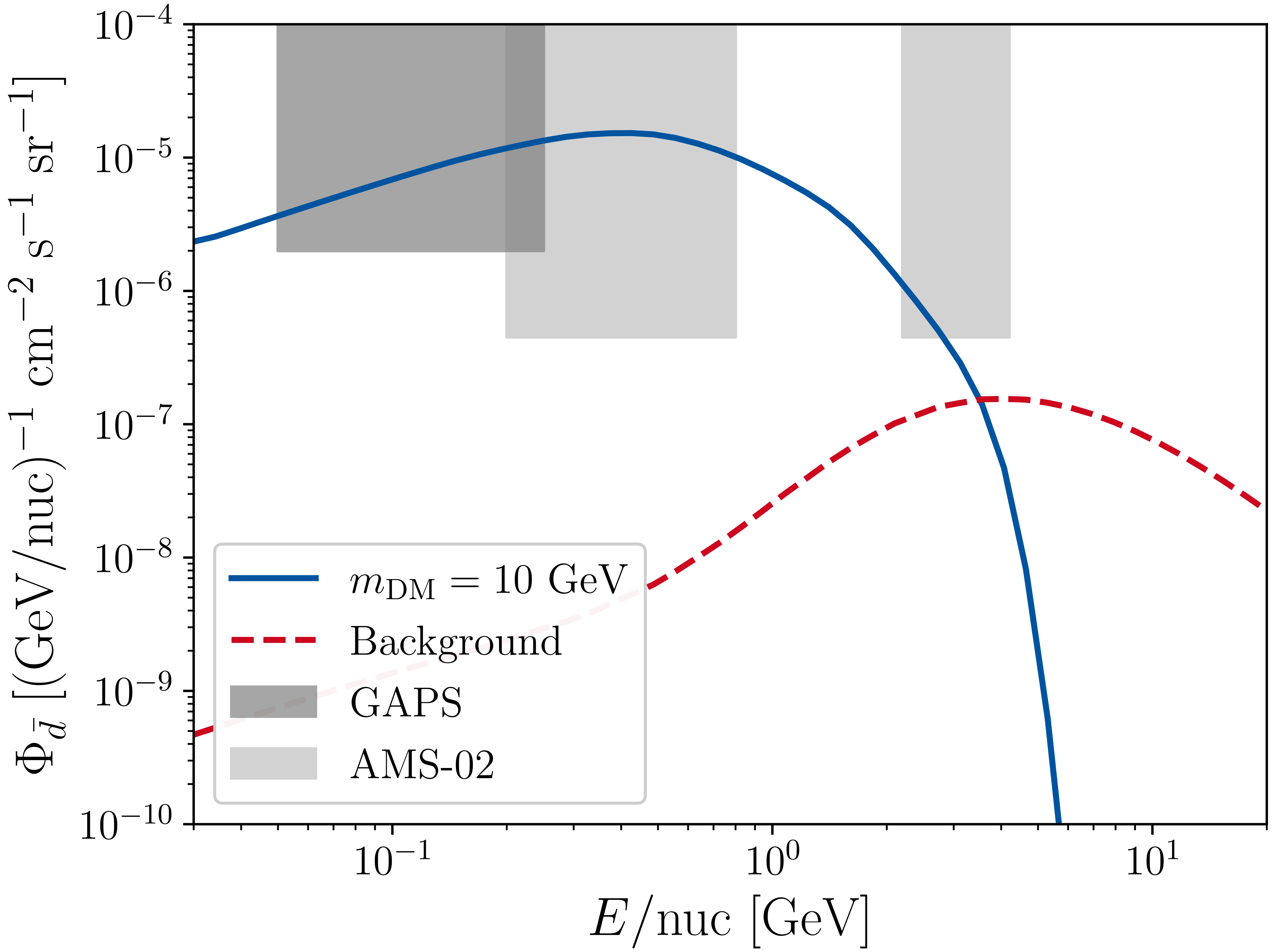


Prediction of Sensitivity Factor

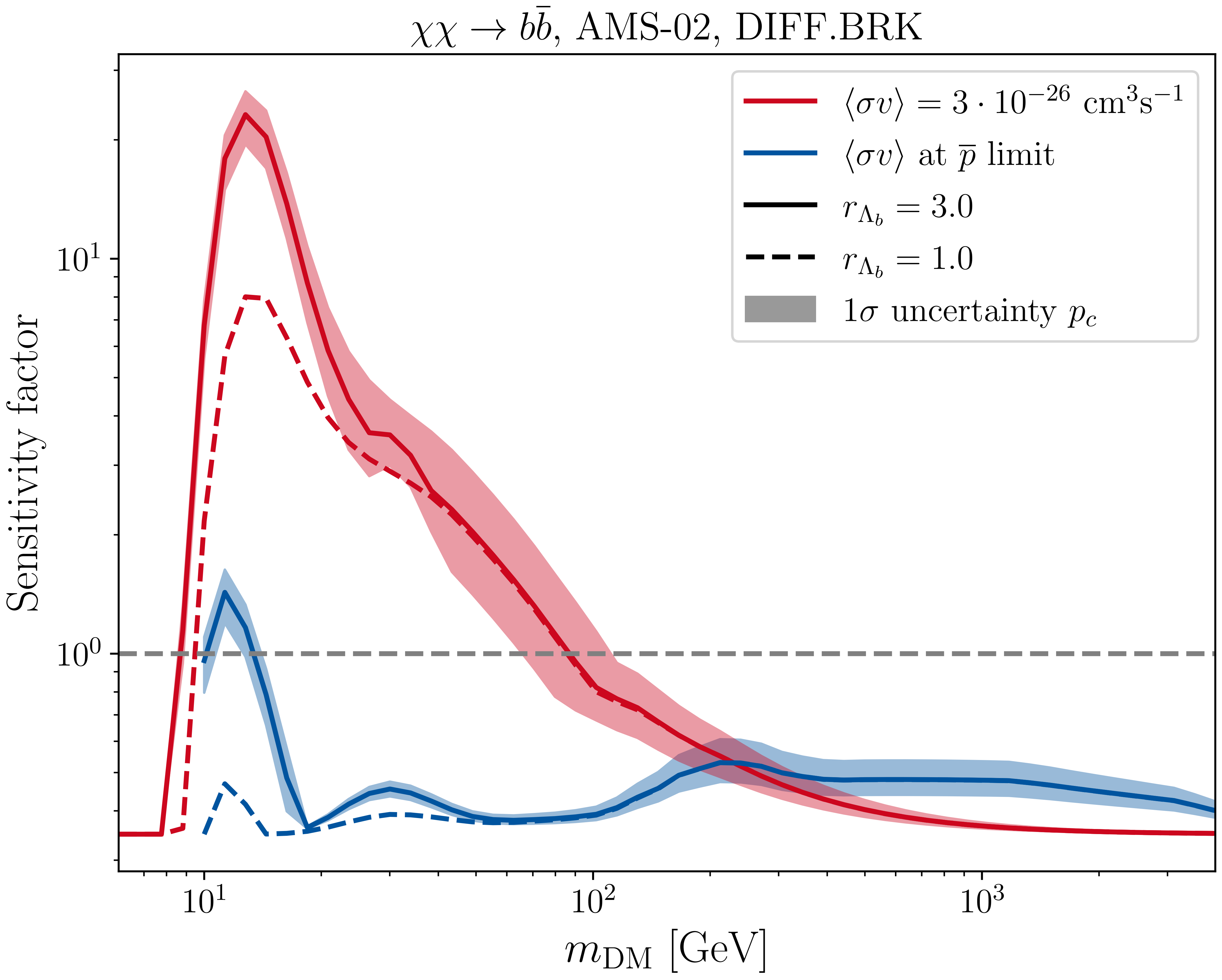
- Generate fluxes for set of propagation parameters $\{\theta_{\text{prop},i}\}$ sampled from posterior of $p, \bar{p}$ and He fit
- Apply force-field approximation to account for solar modulation
- Marginalize over $\{\theta_{\text{prop},i}\}$:

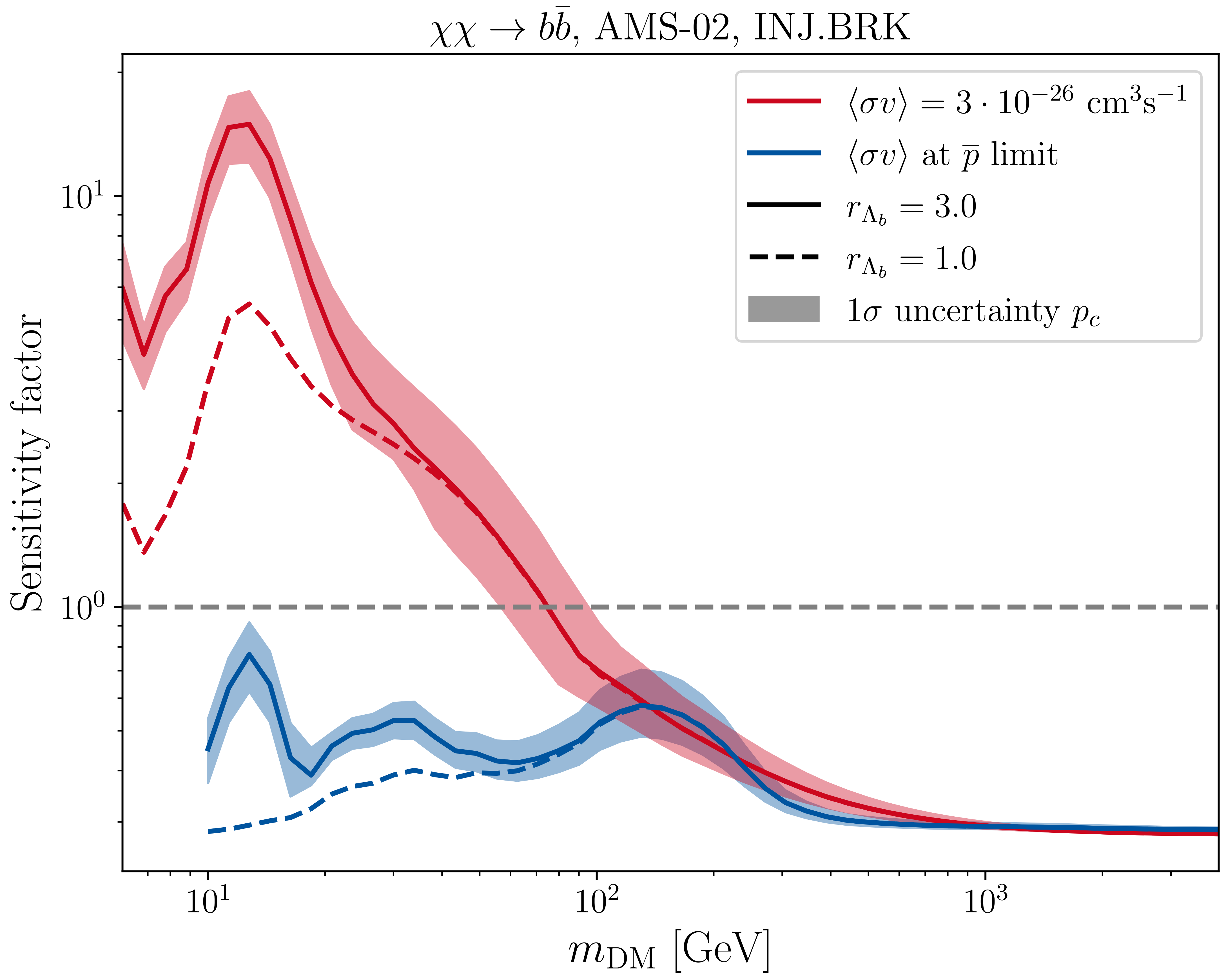
$$\langle \Phi_{\bar{d}} \rangle = \frac{\sum_i \Phi_{\bar{d},i} \frac{\mathscr{L}_{\text{DM}}(\theta_{\text{prop},i}, x_{\text{DM}})}{\mathscr{L}(\theta_{\text{prop},i})}}{\sum_i \frac{\mathscr{L}_{\text{DM}}(\theta_{\text{prop},i}, x_{\text{DM}})}{\mathscr{L}(\theta_{\text{prop},i})}}$$

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



Sensitivity AMS-02

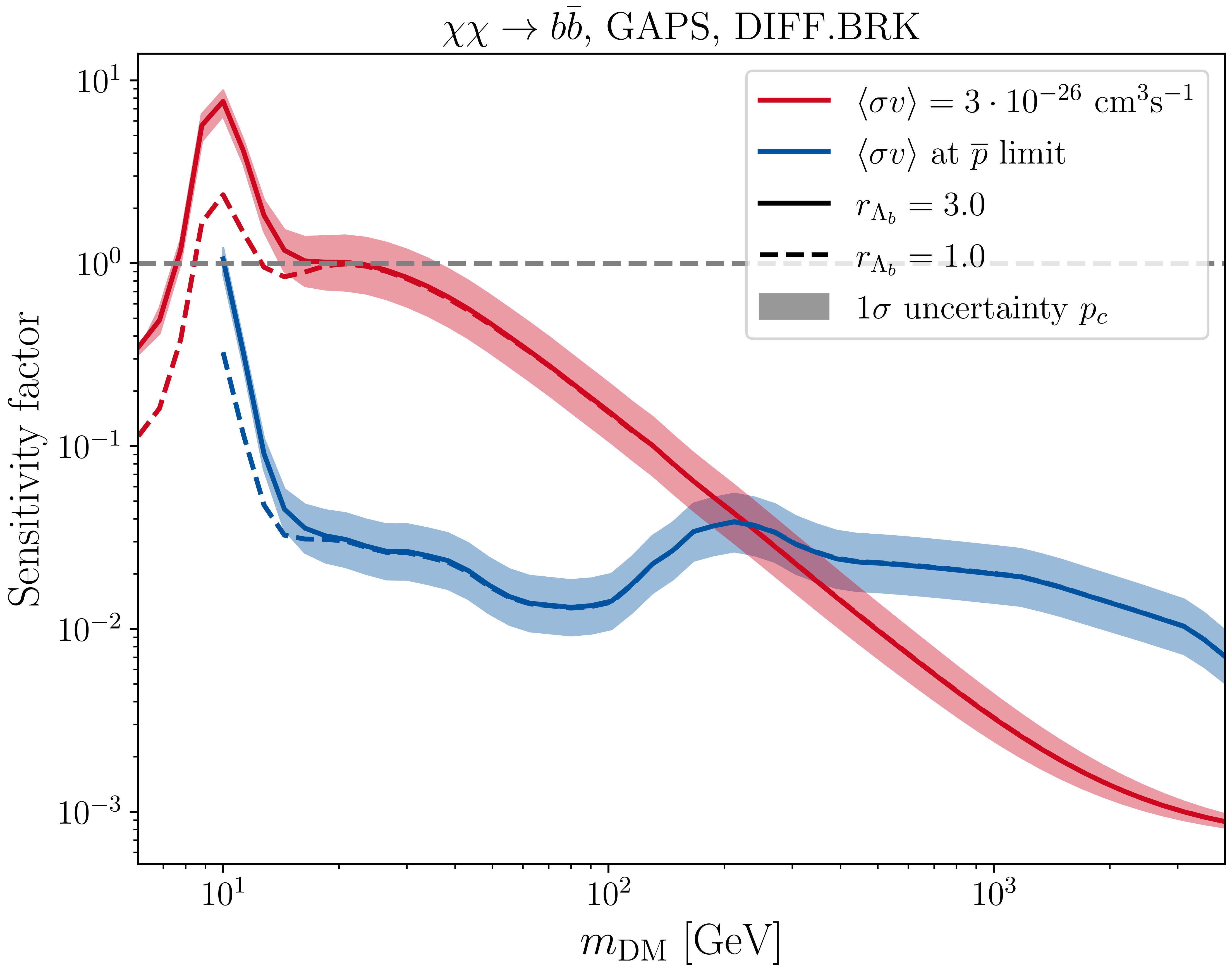


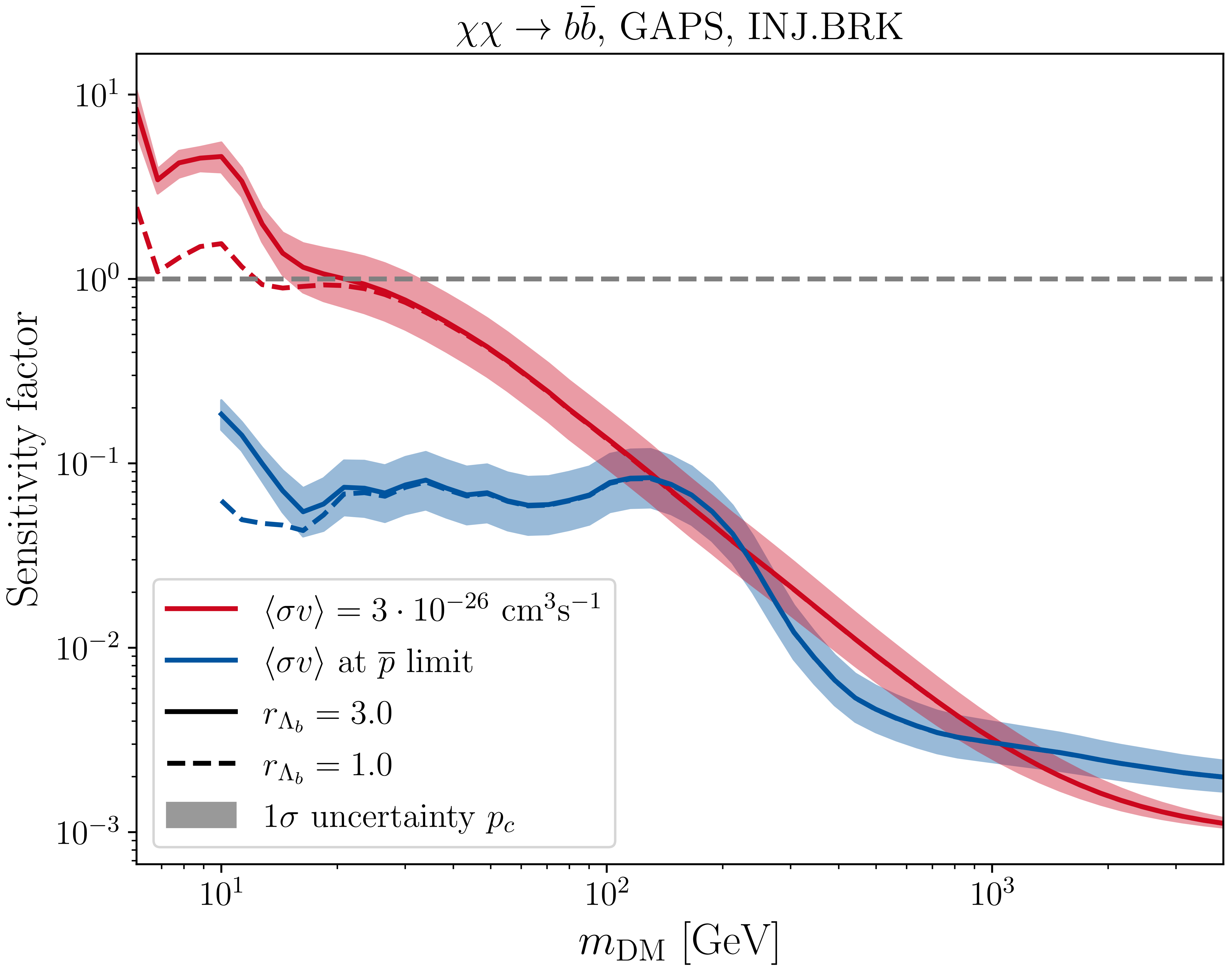


➡ Assuming $\bar{p}$ limit, sensitivity only to small DM masses (depending on propagation model)

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

Sensitivity GAPS





➡ Sensitivity only to small DM masses, independent test to AMS-02

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

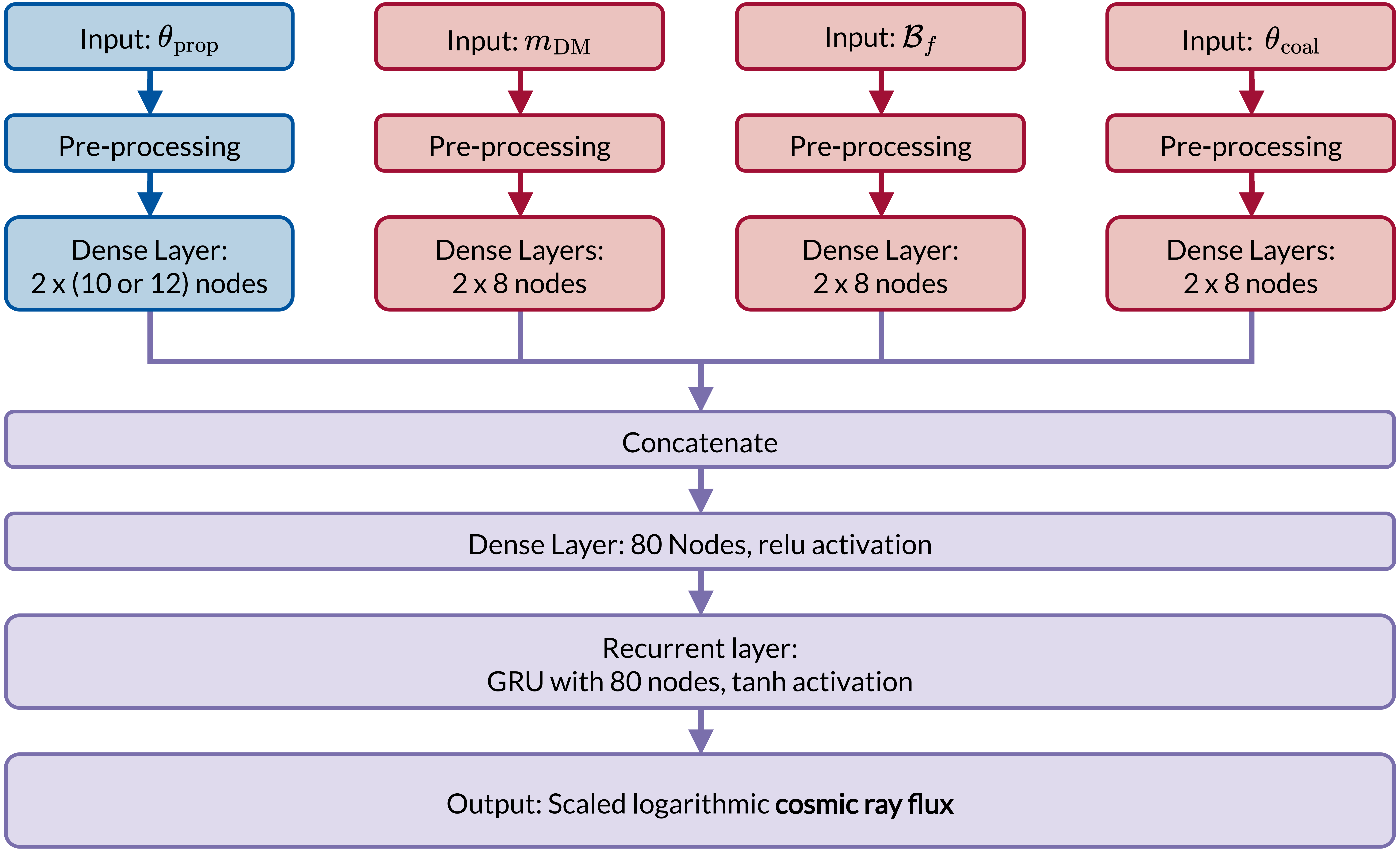
- Antideuterons are great for indirect detection because of negligible background
- Predicted **fluxes of antideuterons** on Earth for varying DM models including **uncertainties from antideuteron production**
- Calculating fluxes is slow → trained Neural Network **DarkRayNet**, available on GitHub, 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 $b\bar{b}$

Thank you!

https://github.com/kathrinnp/DarkRayNet

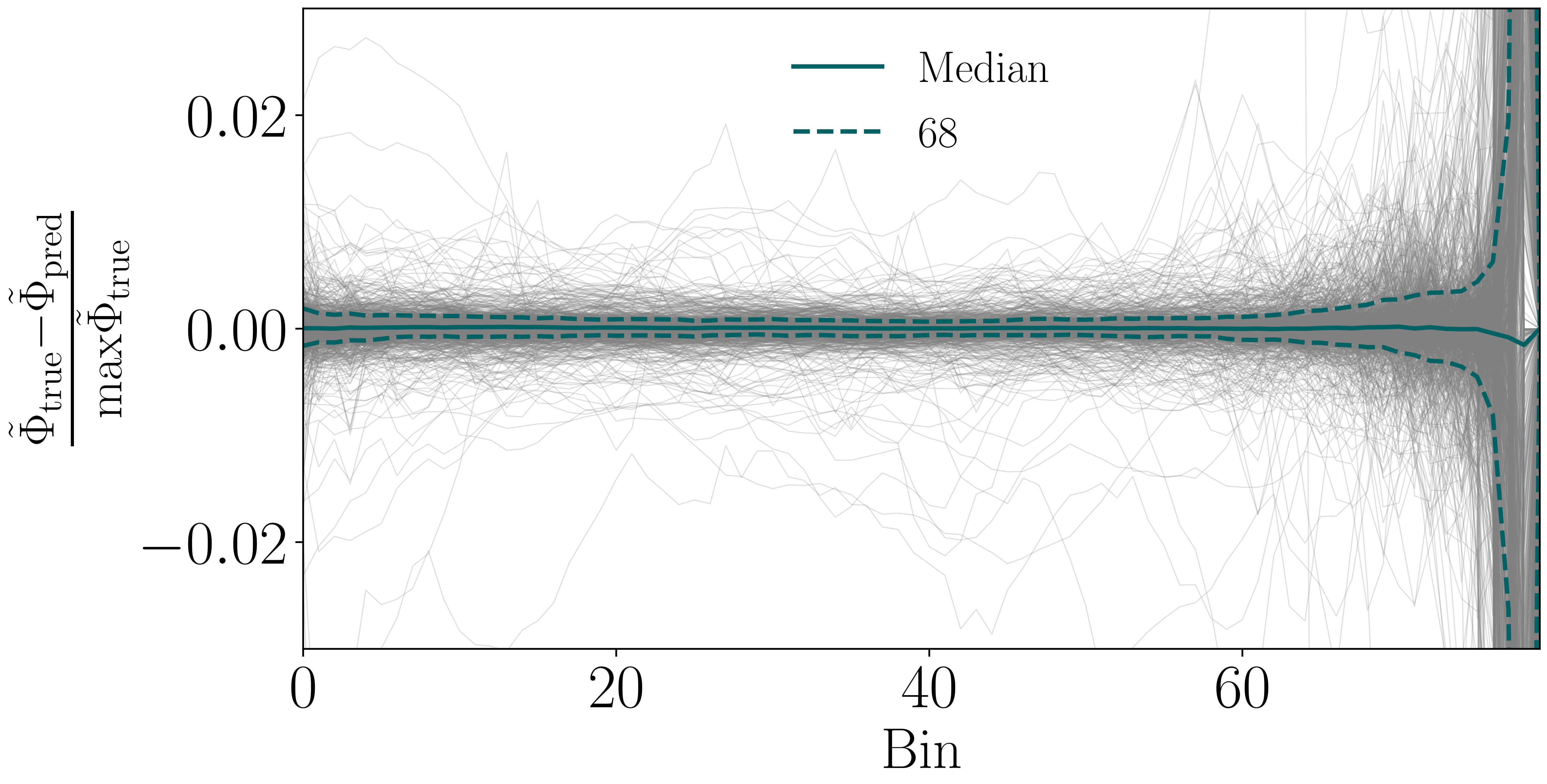
Backup Slides

Network Architecture

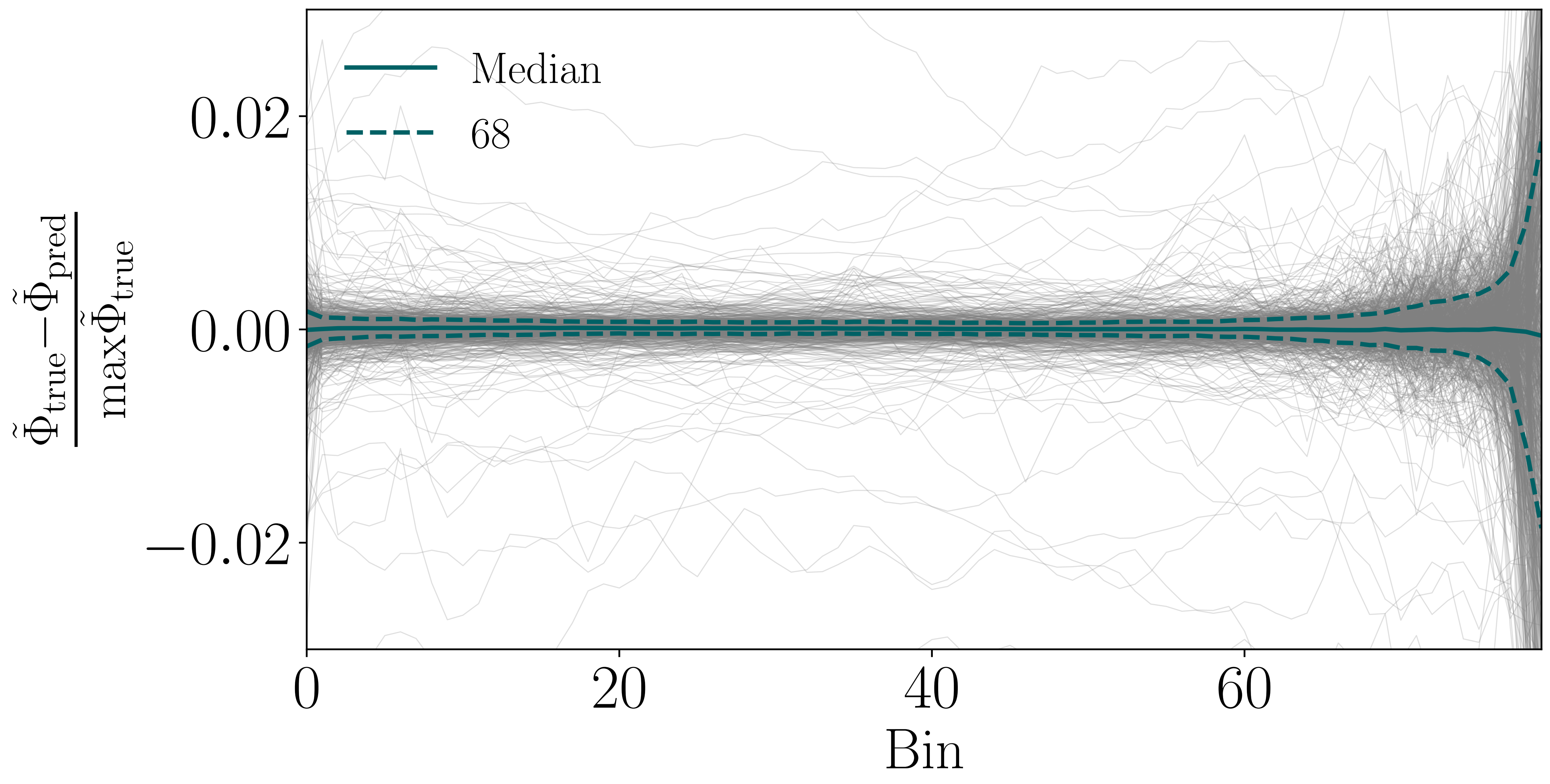


Network Performance

DIFF.BRK model

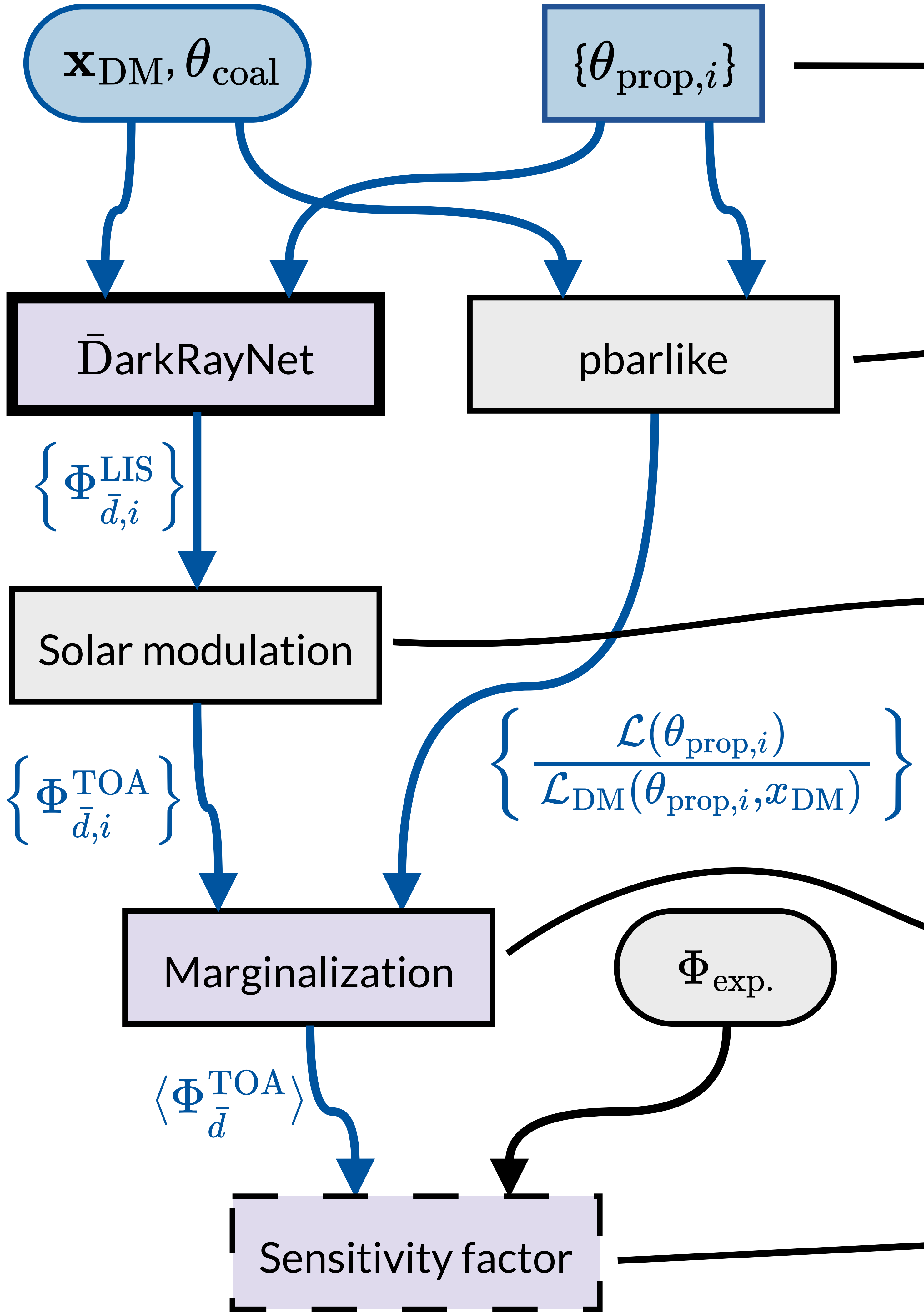


INJ.BRK model



- 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

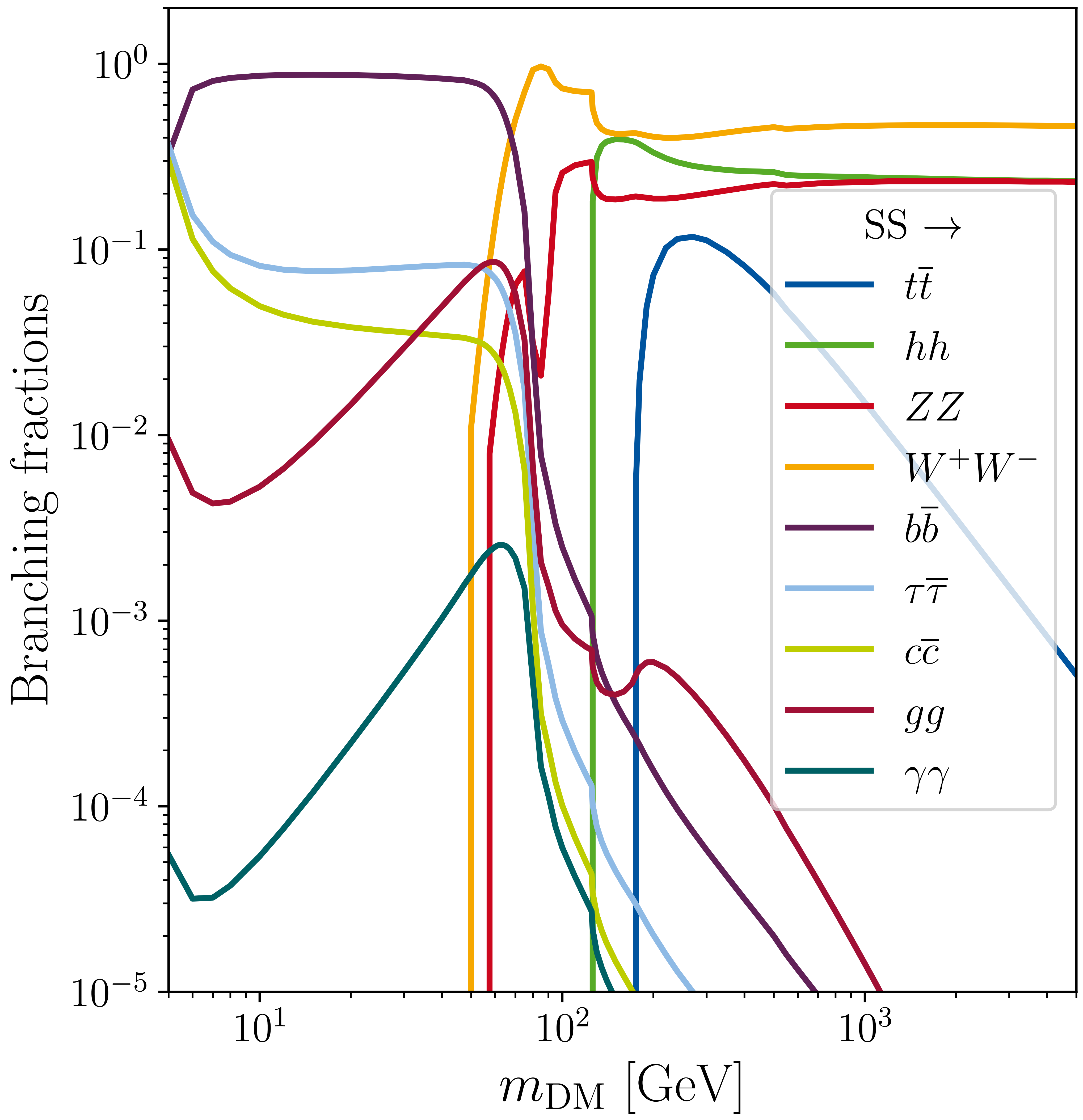
Experiment	Energy range [GeV/nuc]	$\Phi_{\mathrm{sens},E_{\mathrm{exp}}}$ $[\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,(\mathrm{GeV/nuc})^{-1}]$	
GAPS	$[0.05, 0.25]$	2×10^{-6}	GAPS Collaboration [1506.02513]
AMS-02	$[0.2,\ 0.8]$ and $[2.2,\ 4.2]$	4.5×10^{-7}	Choutko, Giovacchini [ICRC 2008]

Propagation Parameters & Priors

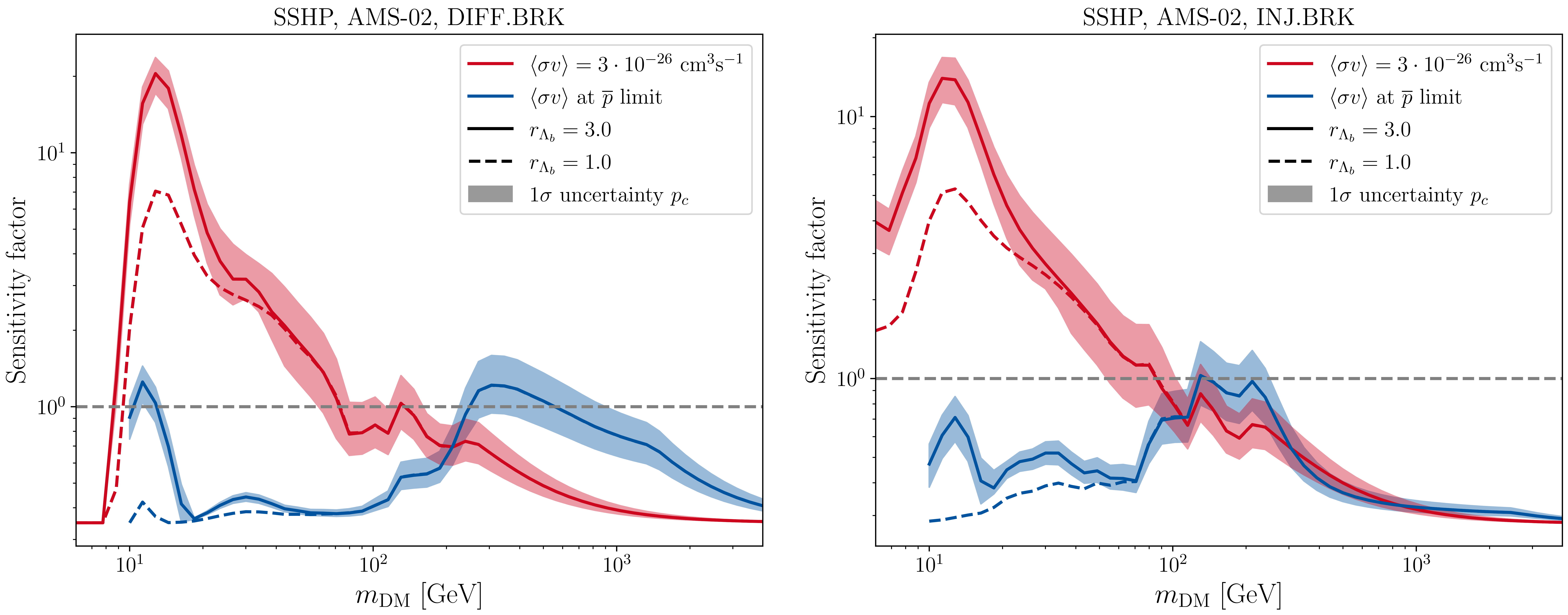
Parameters	Priors	DIFF.BRK	INJ.BRK
$\gamma_{1,p}$	$1.2 - 2.1$	✓	✓
γ_1	$1.2 - 2.1$	✓	✓
$\gamma_{2,p}$	$2.1 - 2.6$	✓	✓
γ_2	$2.1 - 2.6$	✓	✓
R_0 [GV]	$1.0 - 20$	✗	✓
s	$0.1 - 0.7$	✗	✓
D_0 [10^{28} cm^2/s]	$0.5 - 10.0$	✓	✓
δ_l	$-1.0 - 0.5$	✓	✓
δ	$0.3 - 0.7$	✓	✓
$\delta_h - \delta$	$-0.2 - 0.0$	✓	✓
$R_{D,0}$ [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

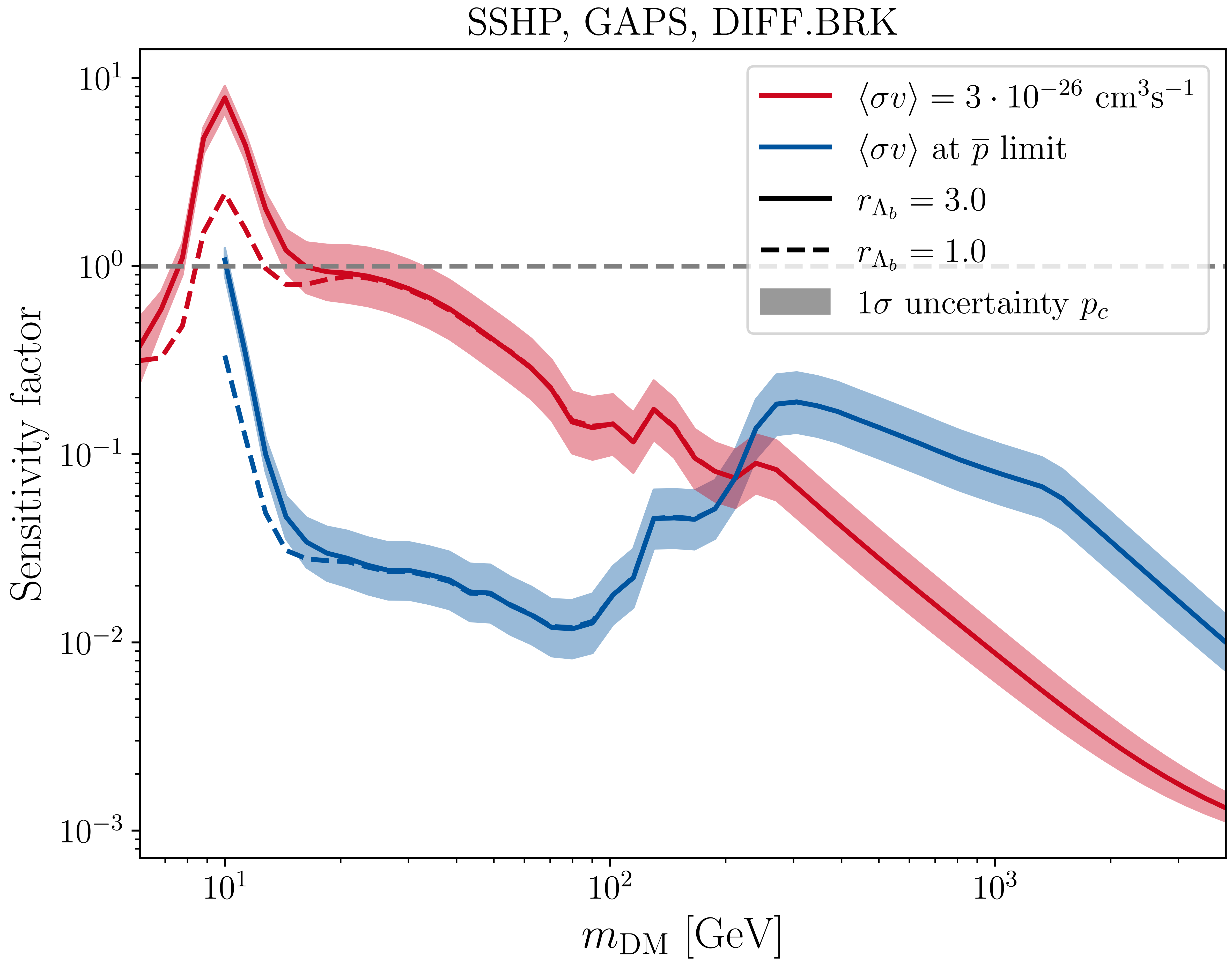
- SM extended by gauge-singlet real scalar
- Portal coupling to Higgs fixed to explain measured relic abundance

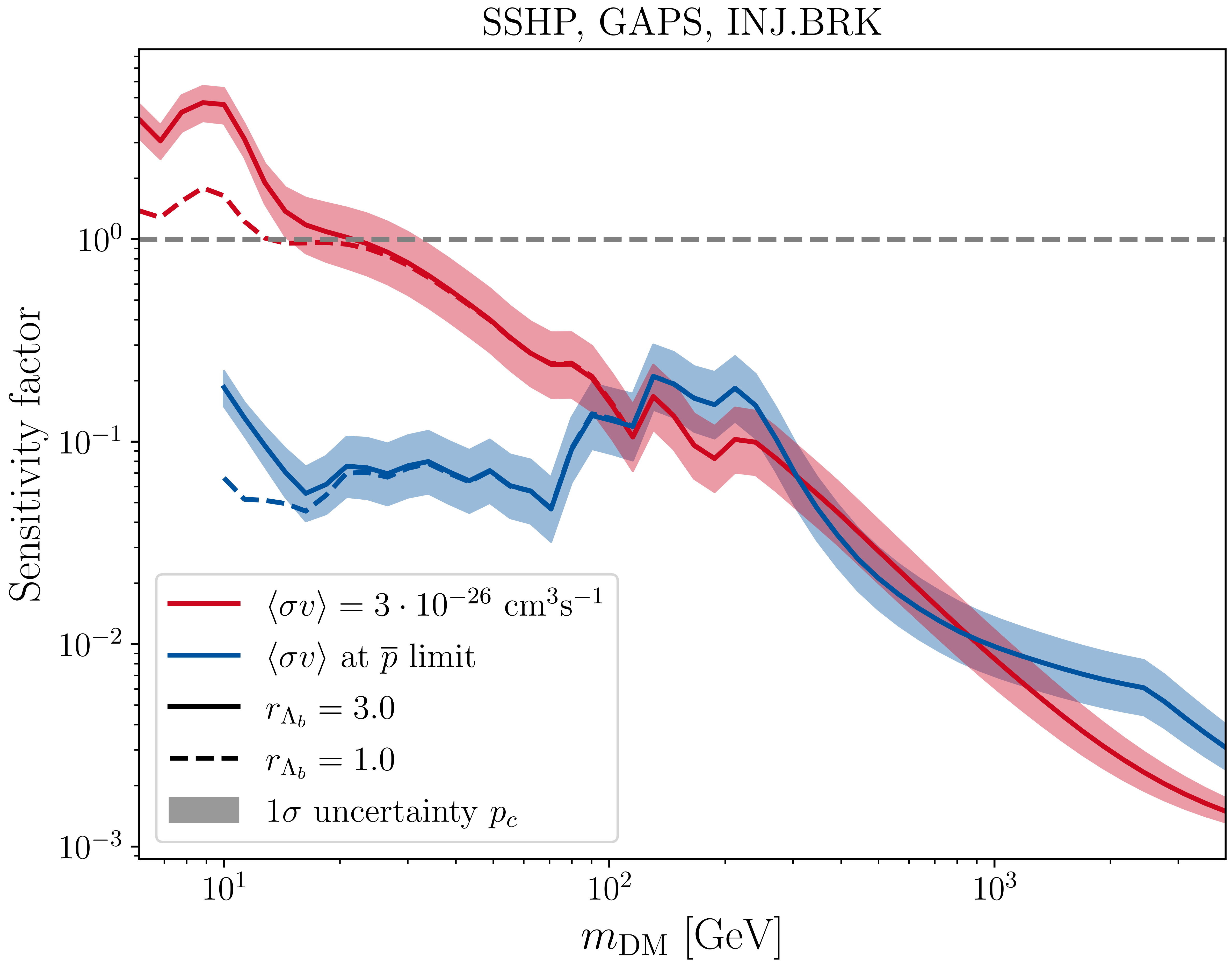


SSHP Sensitivity AMS-02



SSHP Sensitivity GAPS



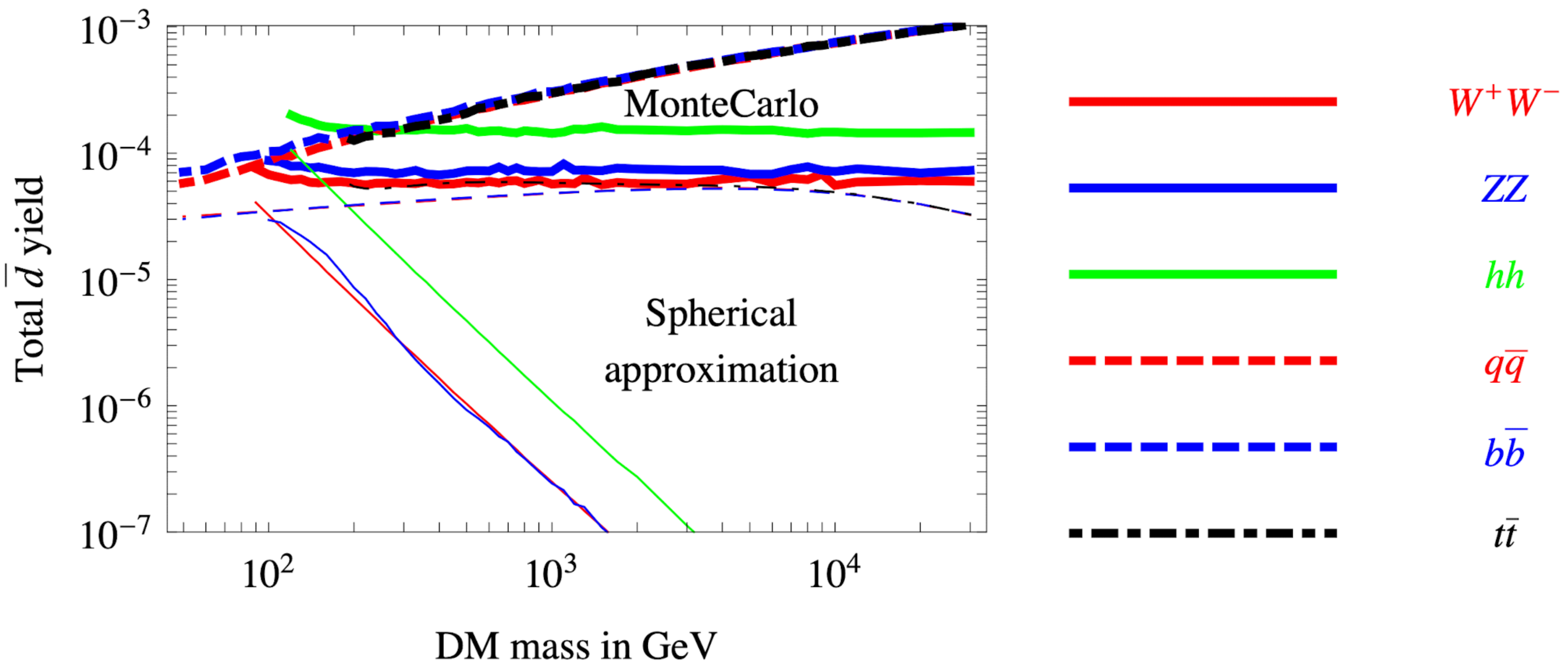


Analytic Coalescence Model

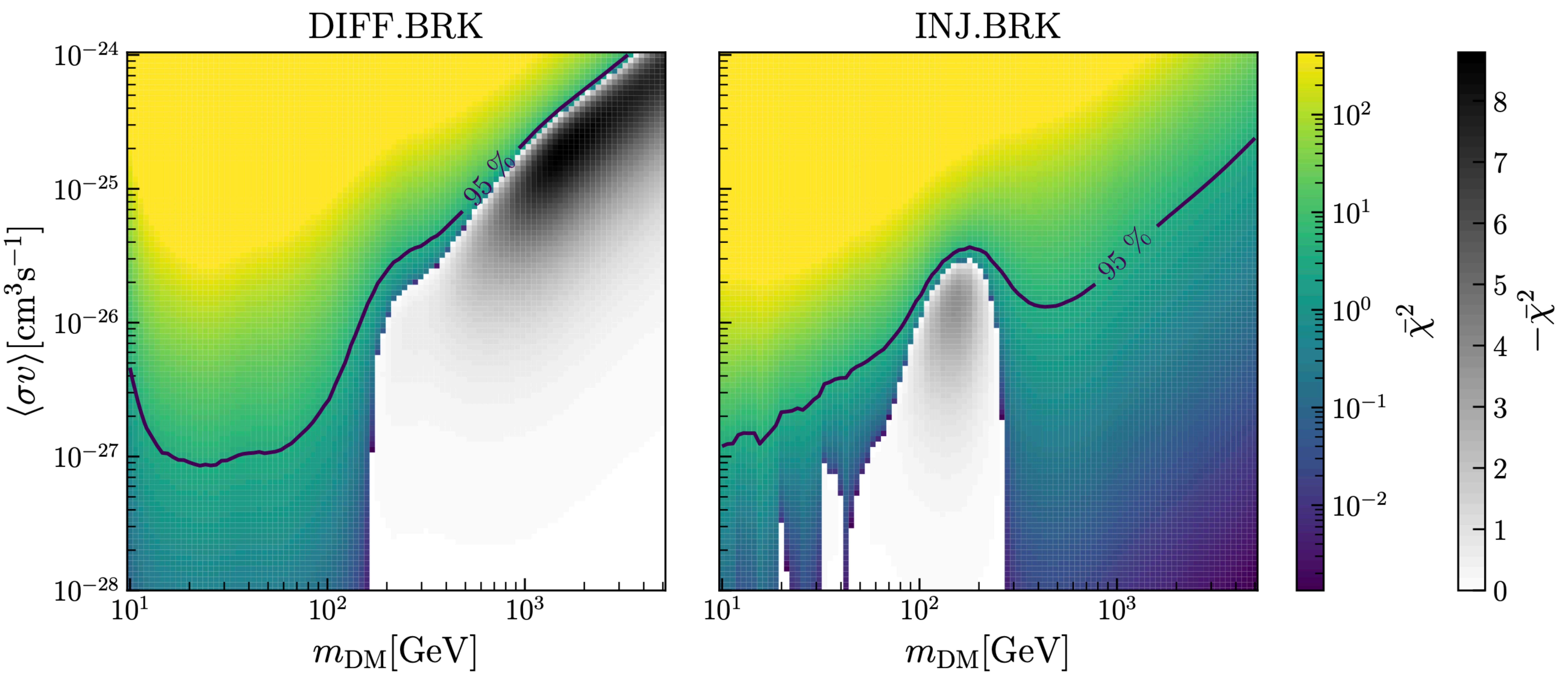
- Assume uncorrelated $\bar{p}, \bar{n}$ distributions

$$\frac{dN_d}{dx_d} = \frac{p_0^3}{3M^2 m_p} \frac{1}{\sqrt{x_d^2 + 4m_p x_d / M}} \frac{dN_p}{dx_p} \frac{dN_n}{dx_n}$$

Kadastik+ [0908.1578]



$\bar{p}$ Limit



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