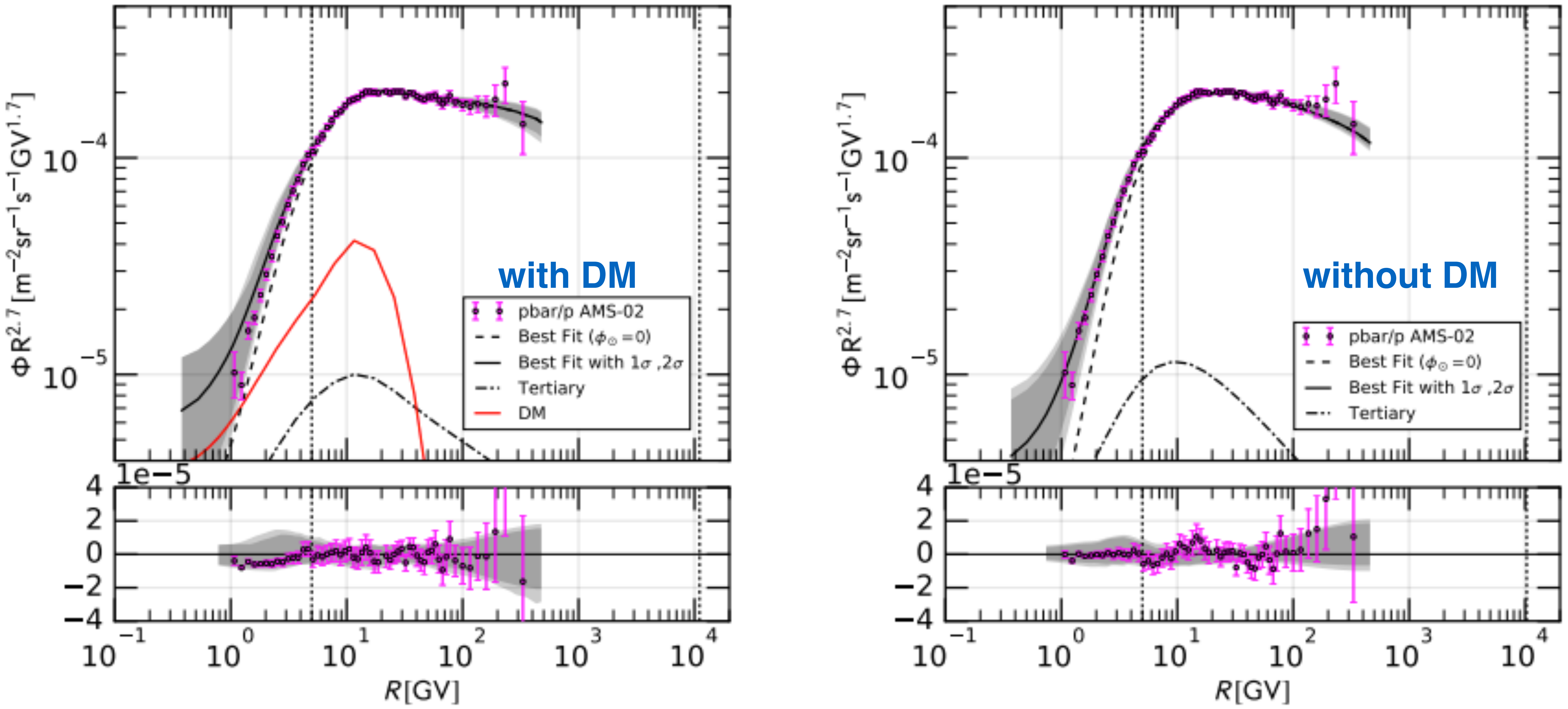
A closer look at secondary antiproton production in cosmic rays and its impact on dark matter indirect searches

Andrea Vittino (RWTH Aachen University)
In collaboration with Alejandro Ibarra and Franz Zimma (TUM, Munich)

dark matter searches with cosmic-ray antiprotons

From **2016**, different studies found an intriguing indication for a **DM signal** in the antiproton flux, for **DM masses near 80 GeV**, with a hadronic annihilation cross-section close to the thermal value



Cuoco, Krämer, Korsmeier. Phys.Rev.Lett. 118 (2017)

(analogous results in **Cui et al. Phys.Rev.Lett. 118 (2017)**)

Recently, several authors have conducted **in-depth investigations** on different aspects of the analysis:

- Secondary antiproton production cross section
- Solar modulation
- Correlation among the data

The **debate is continuing**, as some authors claim **the excess is robust**, while others claim that AMS antiprotons are **compatible with a pure secondary origin**

this talk

We will focus on the **secondary antiproton production cross section**. In particular, we will consider the **very low-energy regime**, close to the **production threshold**.

First, we will describe **how this cross section is modelled** and we will discuss some **potential shortcomings** of the models that are actually used.

Then, we will describe a **simple analytical model** to study the **effects** that the modelling of this cross section has on the **secondary antiproton spectrum** and on the **bounds on dark matter annihilation cross section**.

secondary antiproton production cross section

We focus here on **data-driven parametrizations**. Alternative : Monte Carlo models (but, in general, less reliable at low energies, which is the focus here)

Parametrisation by **Winkler** (from **Kappl and Winkler JCAP 09 (2014)** and **Winkler JCAP 02 (2017)**)

p + p reaction :

$$\sigma_{pp\to\bar{p}} = \sigma_{\bar{p}}^{0} + \sigma_{\bar{p}}^{\Lambda} + \sigma_{\bar{n}}^{0}$$

direct production — **Hyperon decay** — **antineutron decay**

$$f_{\bar{p}} = f_{\bar{p}}^{0}\,(2 + \Delta_{\mathrm{IS}} + 2\Delta_{\Lambda}) \quad \text{with} \quad f = E\frac{d^3\sigma}{dp^3}$$

Radial scaling (at c.m. energies > 10 GeV)

$$f_{\bar{p}}^{0}(\sqrt{s}, x_R, p_{\mathrm{T}}) \longrightarrow f_{\bar{p}}^{0}(x_R, p_{\mathrm{T}}) \quad \text{with} \quad x_R = \frac{E_{\bar{p}}^{*}}{E_{\bar{p},\mathrm{max}}^{*}}$$

$$f_{\bar{p}}^{0} = 399\,\mathrm{mb}\,(1 - x_R)^{7.76}\exp\left(-\frac{\mathrm{m_T}}{0.168\,\mathrm{GeV}}\right)$$

There are several alternative parametetrizations: **Tan and Ng 1982**, **Duperray et al. 2004**, **Di Mauro et al. 2014**, etc…

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$$f^0_{\bar{p}} \longrightarrow R\, f^0_{\bar{p}}$$

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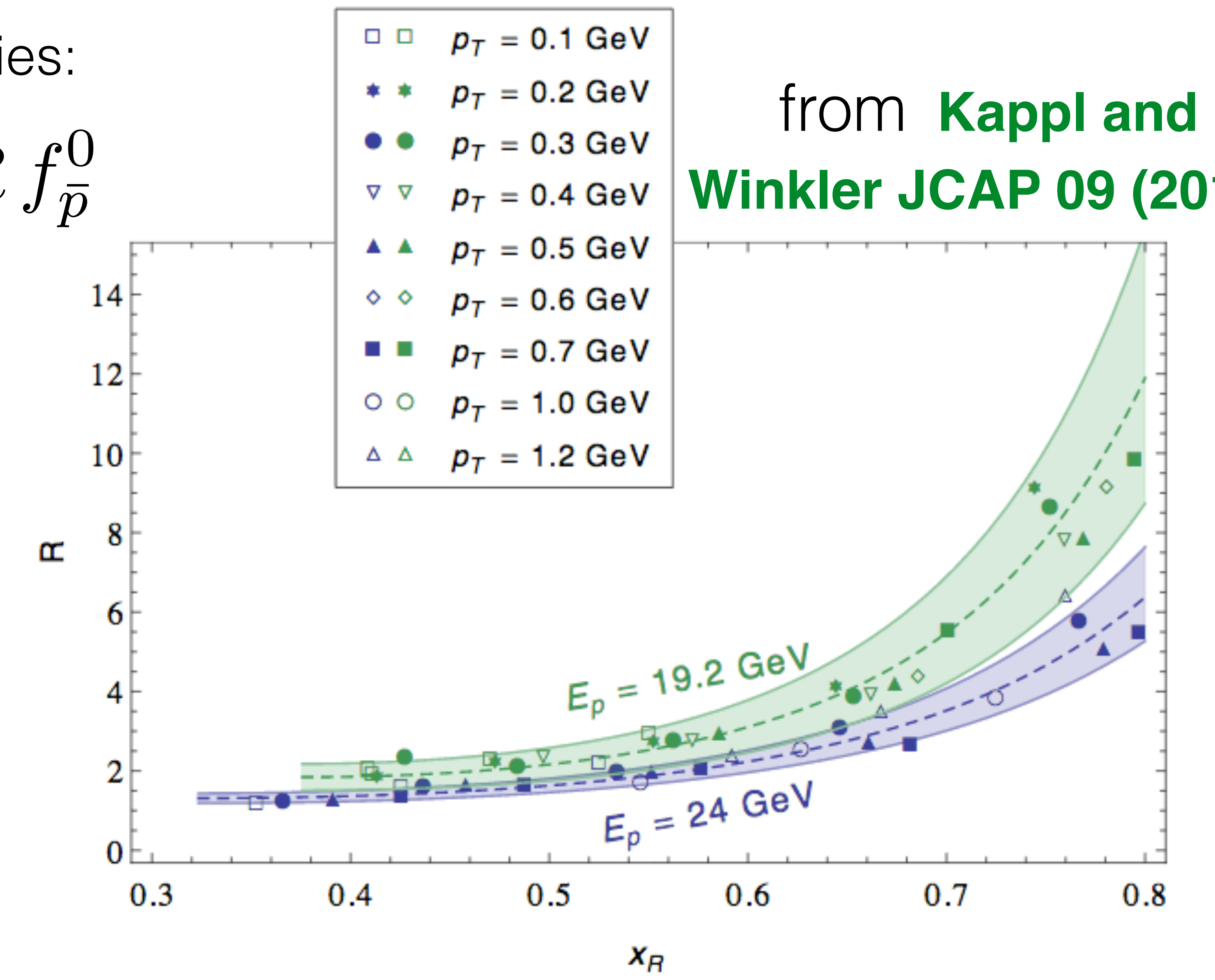

secondary antiproton production cross section

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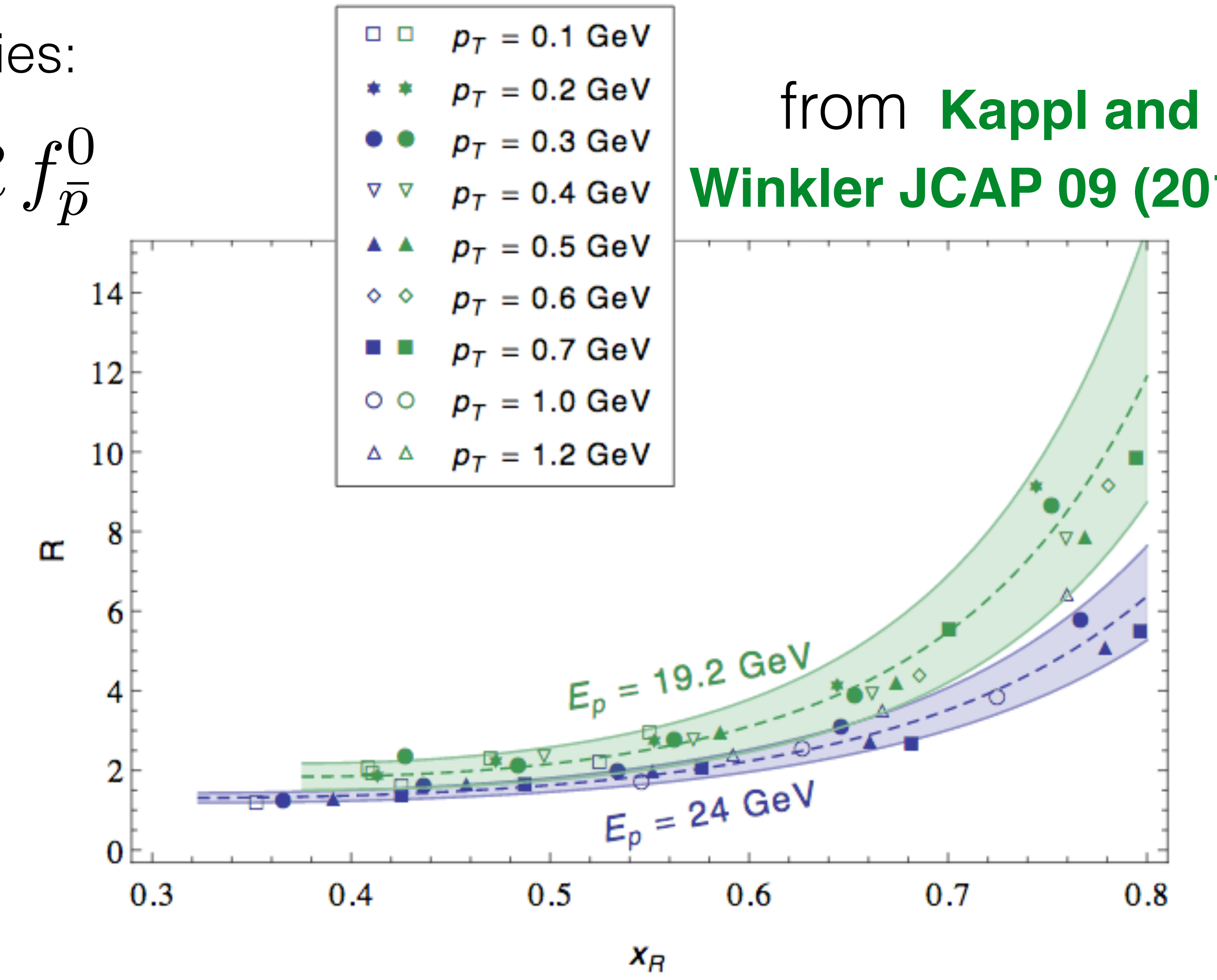
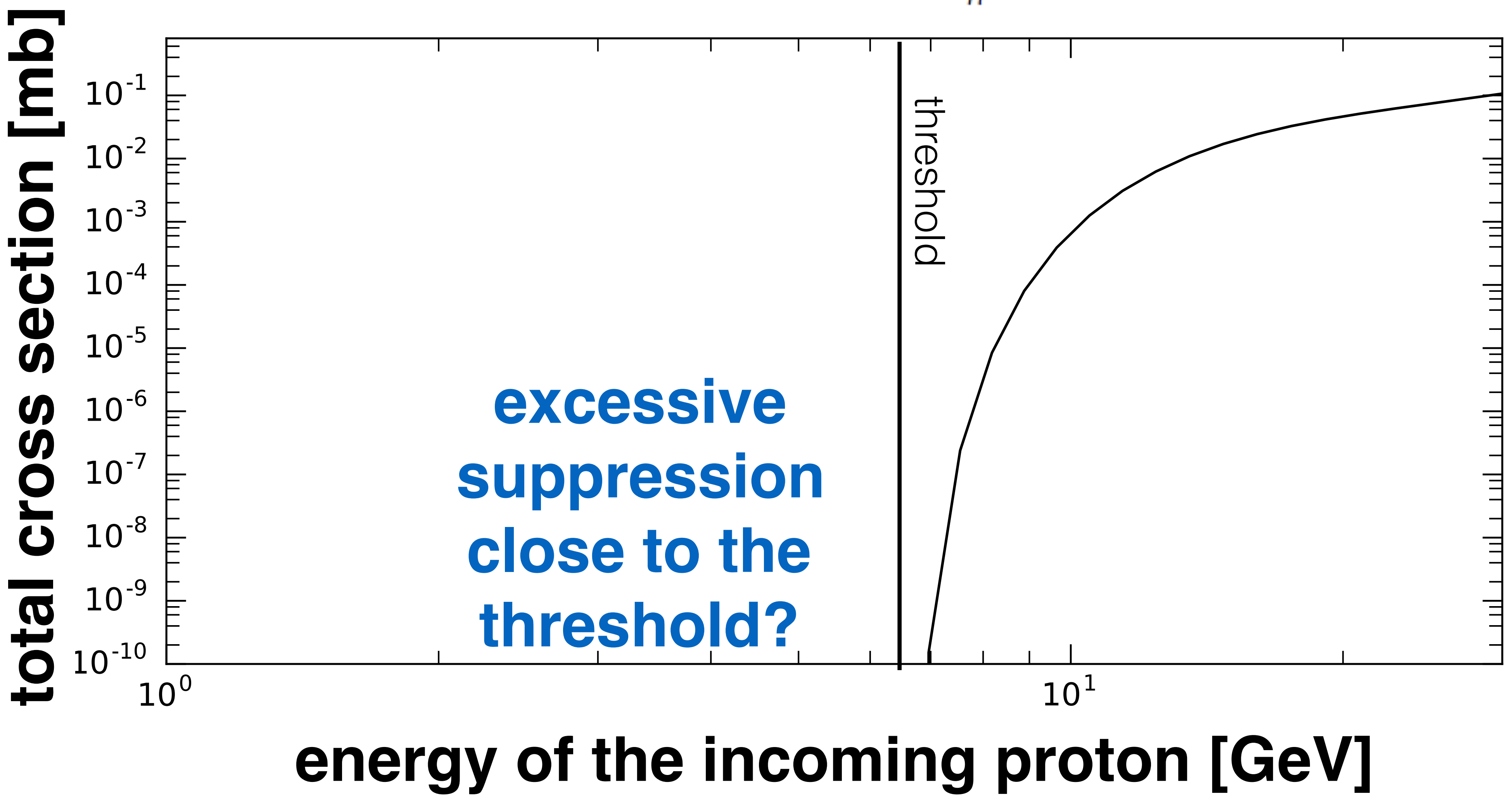




the cross section at low energies - the phase space model

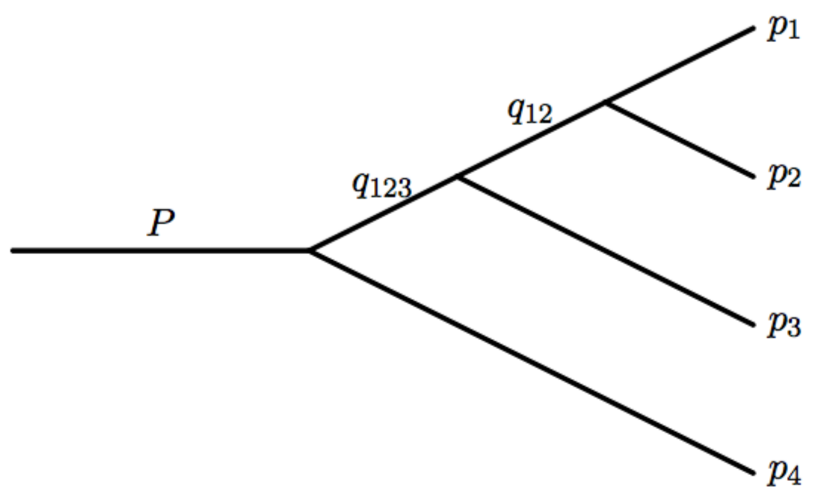
We want to model the **very low-energy behaviour** of the cross section that describes the **production of antiprotons in pp collisions**. In particular, we are interested in the reaction:

$$p + p \longrightarrow p + p + p + \bar{p}$$

In general, the cross section for a 2 -> n process can be written as:

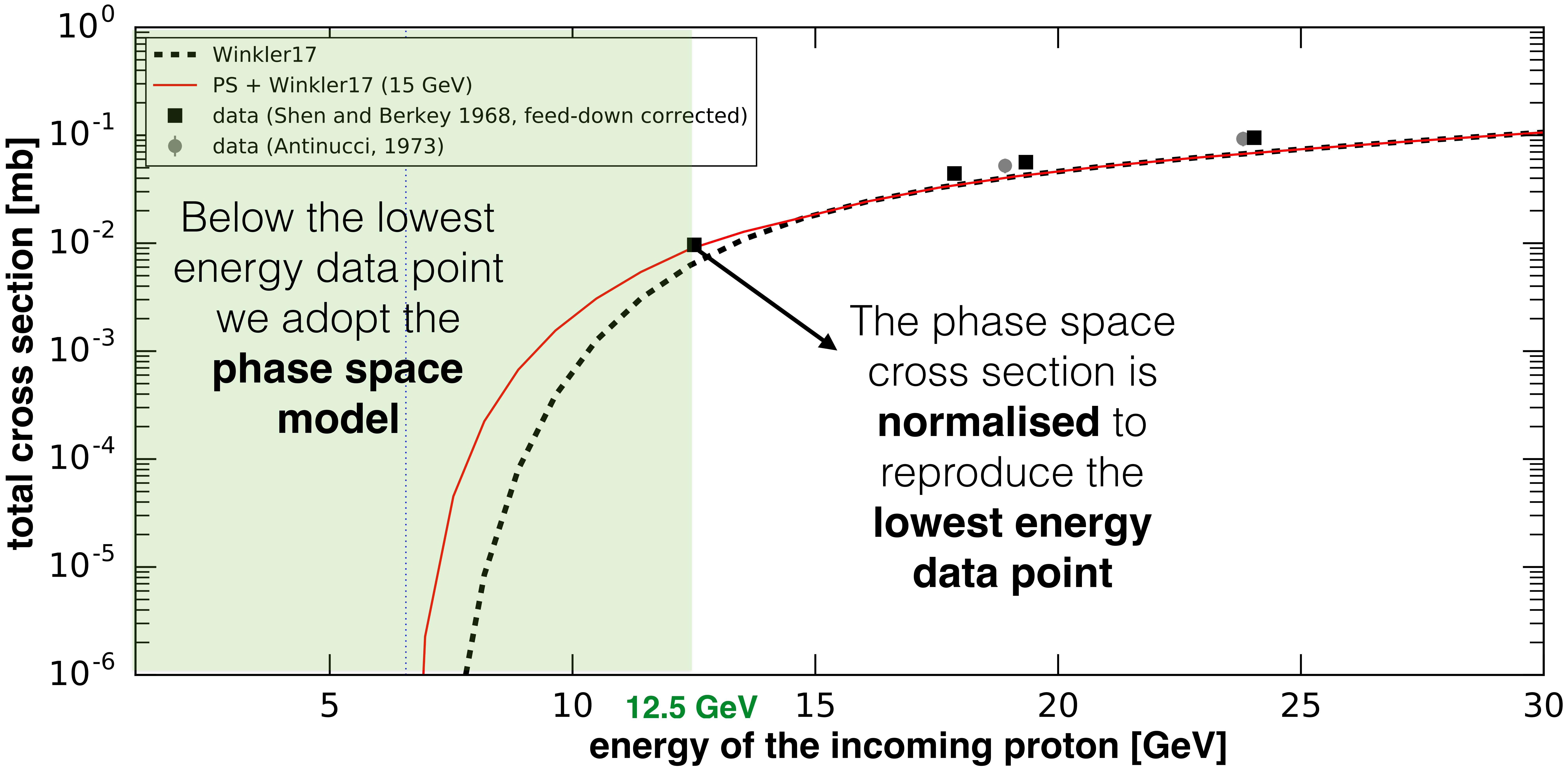
$$d\sigma = \frac{(2\pi)^4 |\mathcal{M}|^2}{4\sqrt{(p_1 \cdot p_2) - m_1^2 m_2^2}}\, d\Phi_n(p_1, p_2; p_3 \ldots p_{n+2}) \quad \text{with} \quad d\Phi_n(P; p_1, \ldots, p_n) = \delta^4(P - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3\, 2E_i}$$

- We assume a **constant matrix element** $\mathcal{M}$
- We write the phase space term analytically, by introducing intermediate particle-like end states, which we integrate out at the end:



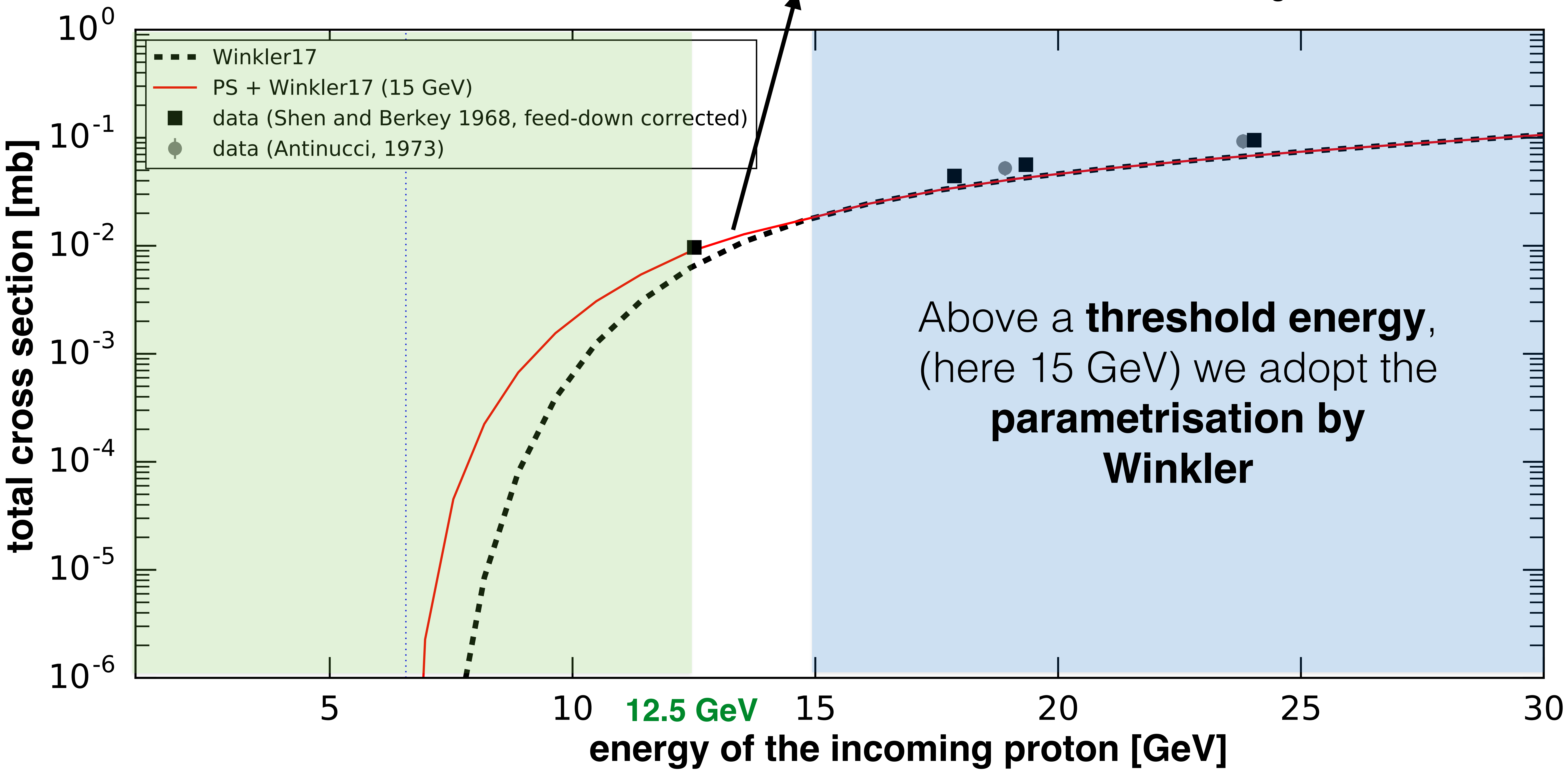
$$d\Phi_4 = \frac{ds_{123}}{2\pi} \frac{ds_{12}}{2\pi}\, d\Phi_2(P; q_{123}, p_4)\, d\Phi_2(q_{123}; q_{12}, p_3)\, d\Phi_2(q_{12}; p_1, p_2)$$

our cross section model



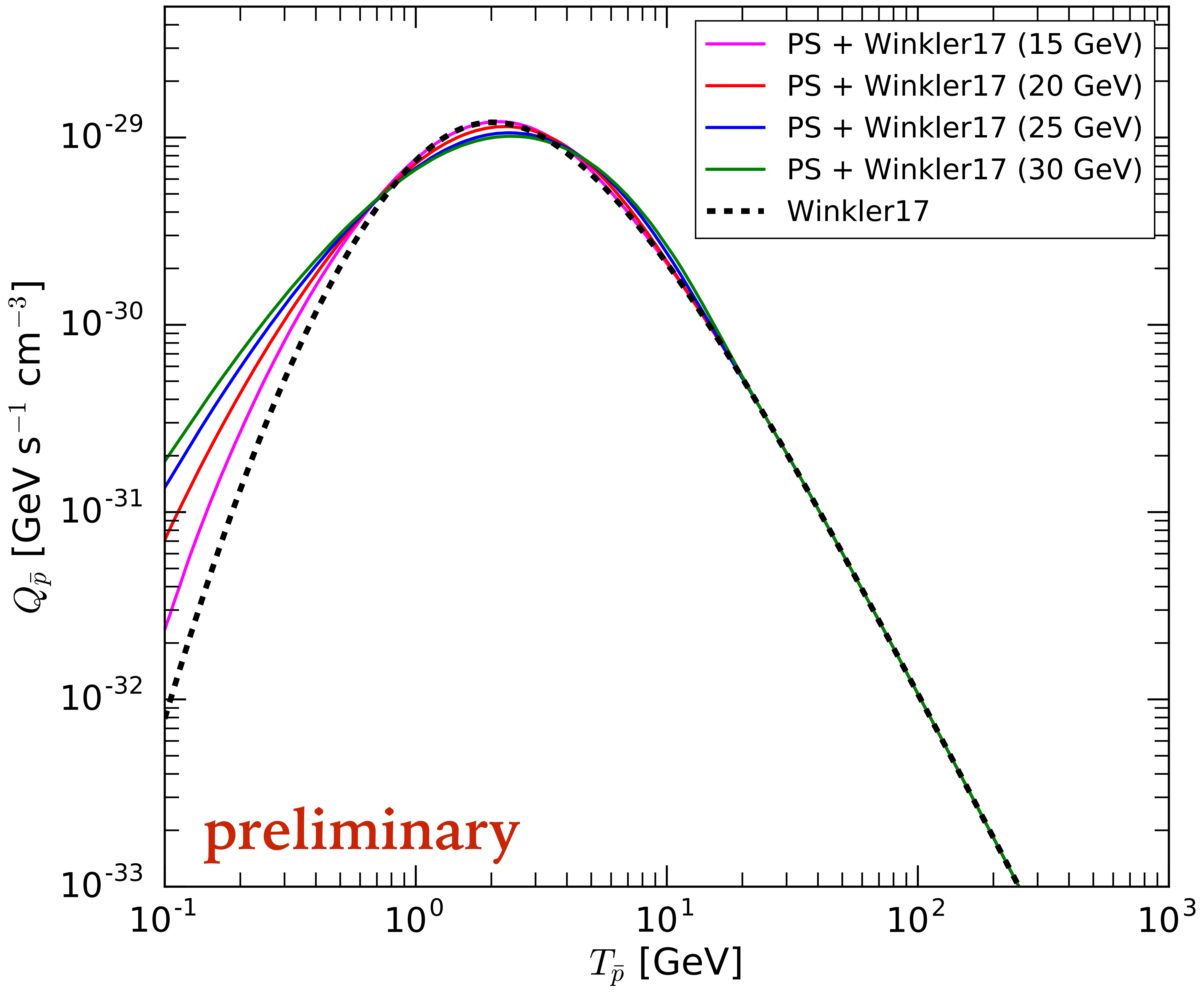
our cross section model

Phase space model, rescaled by means of a **linear interpolation** between the two regimes



secondary antiproton source term

$$\mathcal{Q}^{\bar{p}}_{\text{sec}}(\vec{x},\vec{p}) = 4\pi \sum_{j=\text{p,He}} \sum_{k=\text{H,He}} n_k \int dE_j \Phi_j(\vec{p}_j,\vec{x}) \frac{d\sigma}{dp}(j+k \to i+X)$$



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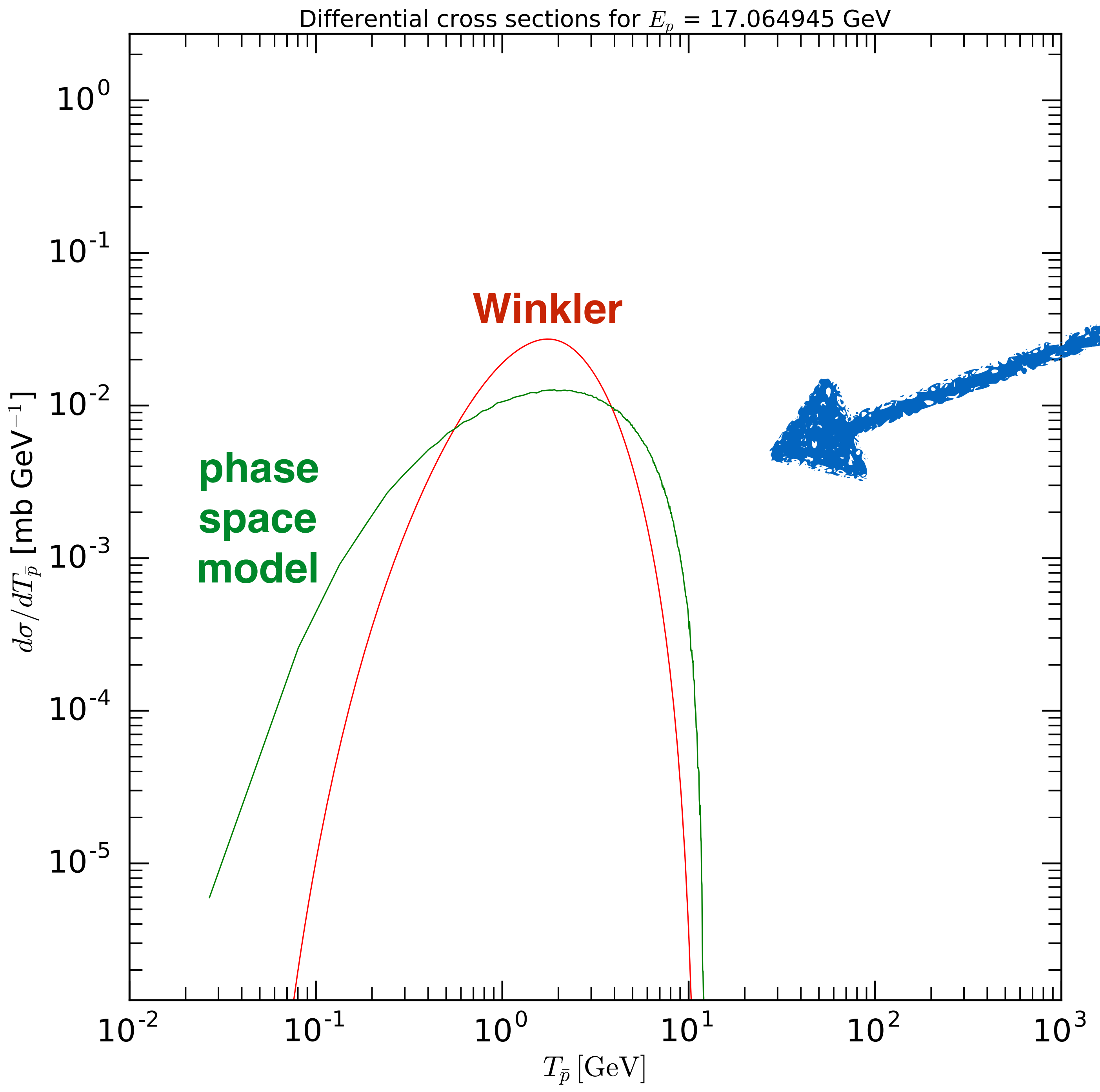
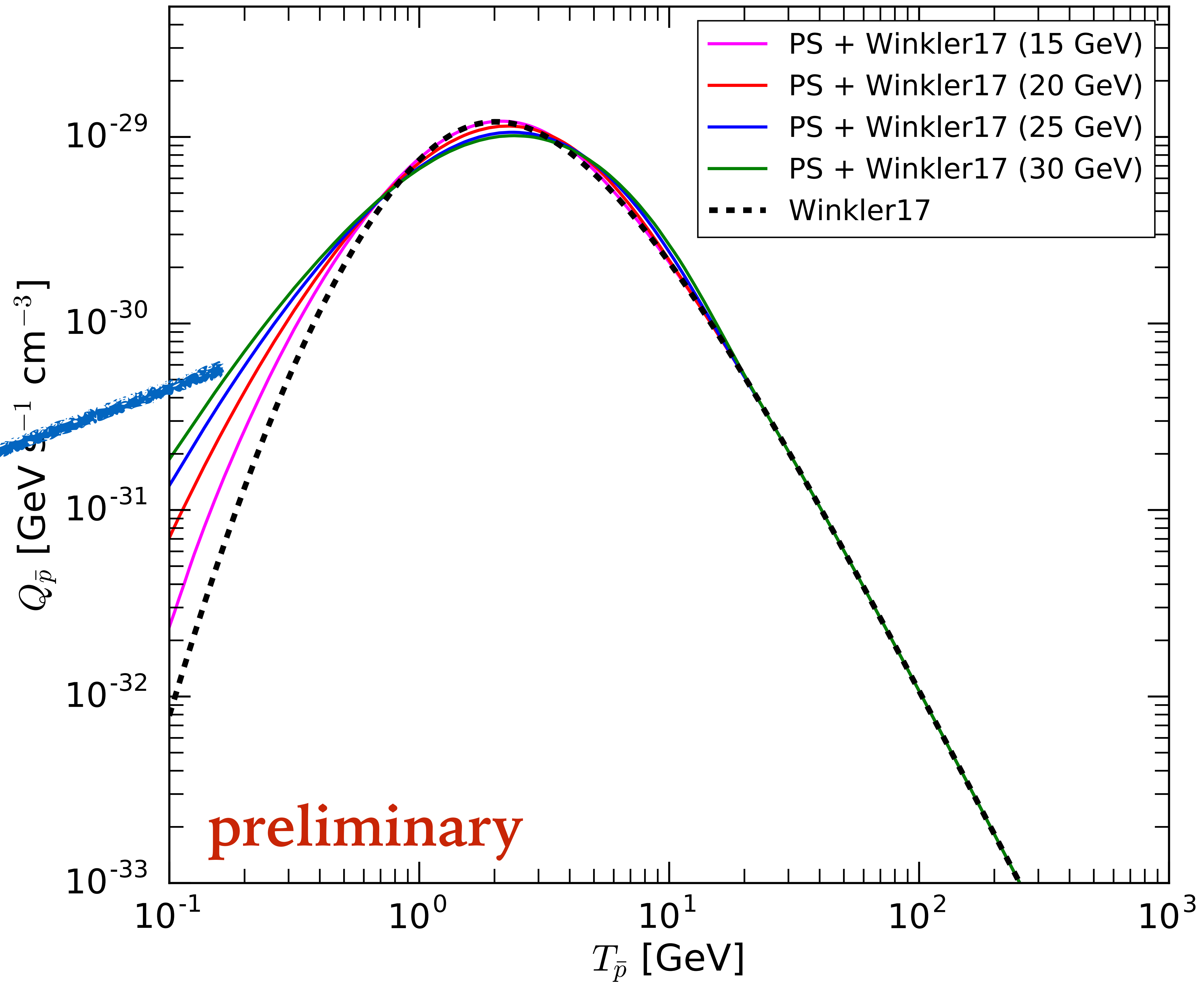




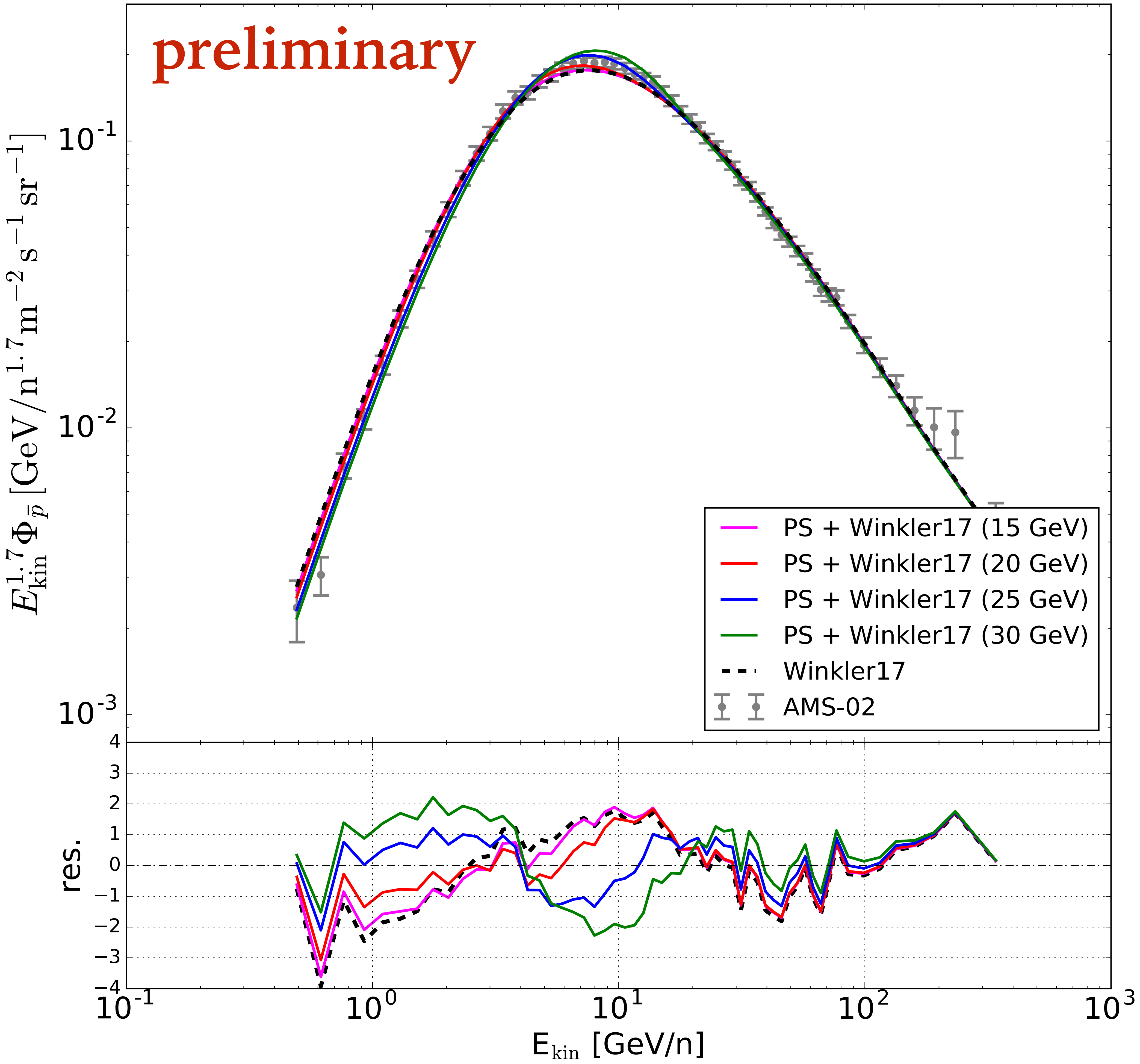
secondary antiproton flux at Earth

transport equation

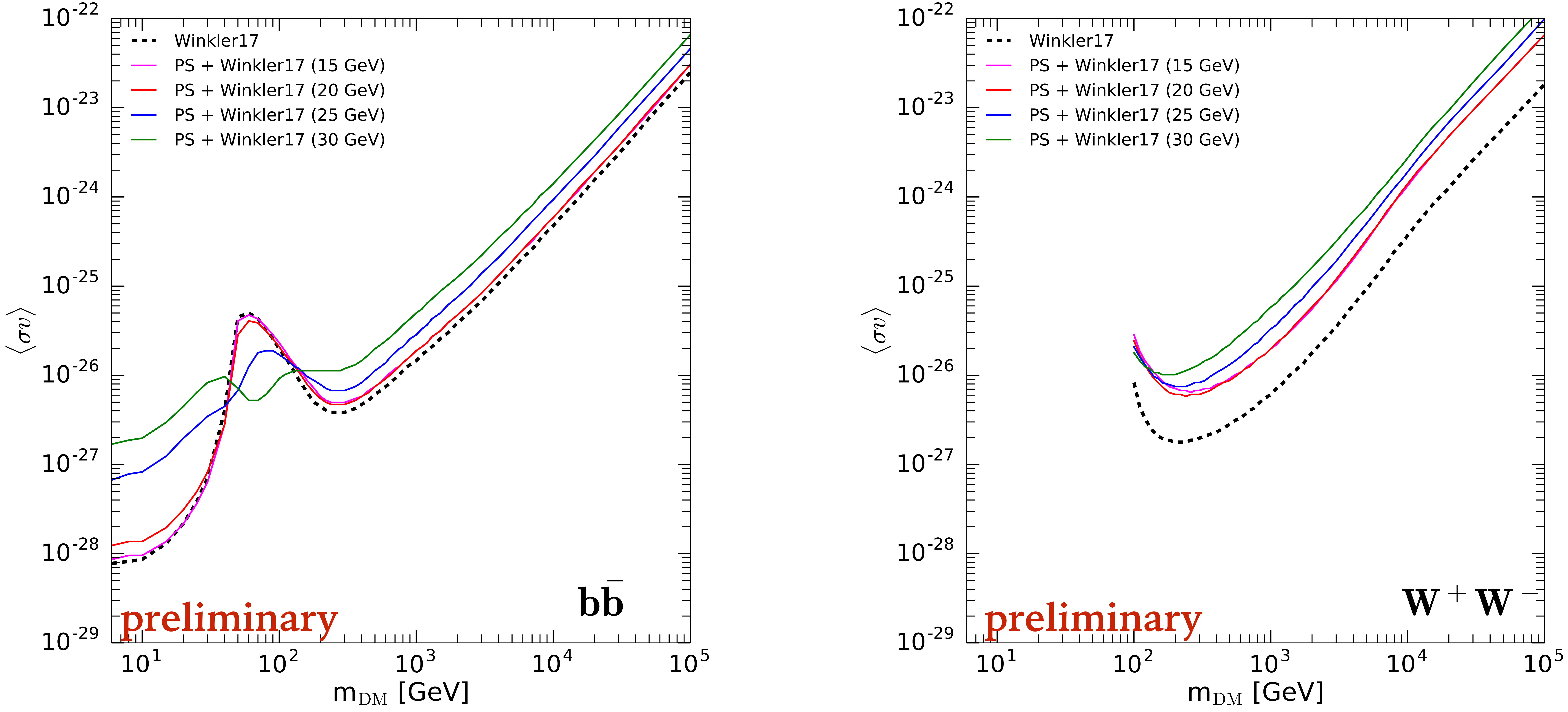
$$\frac{\partial N_i}{\partial t} - \nabla \cdot (D_{xx}\nabla N_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_w\right)N_i\right] = \mathcal{Q} - \frac{N_i}{\tau_i^f} + \sum_j \Gamma^s_{j\to i}(N_j) - \frac{N_i}{\tau_i^r} + \sum_j \frac{N_j}{\tau^r_{j\to i}}$$

- We determine the propagation parameters by **fitting AMS proton, Helium and antiproton data**
- We model solar modulation with a **force-field approximation**

Model	p (72 data points)	He (68 data points)	$\bar{p}$ (57 data points)	Total (197 data points)
Winkler	60.6	39.4	84.3	184.2
Winkler + PS 15 GeV	61.9	38.1	75.8	175.8
Winkler + PS 20 GeV	61.0	37.4	52.7	151.2
Winkler + PS 25 GeV	62.0	40.5	40.7	143.3
Winkler + PS 30 GeV	60.9	40.7	82.4	183.9



dark matter bounds



95% C.L. bounds obtained by marginalising over the force field potential of solar modulation

conclusions and outlook

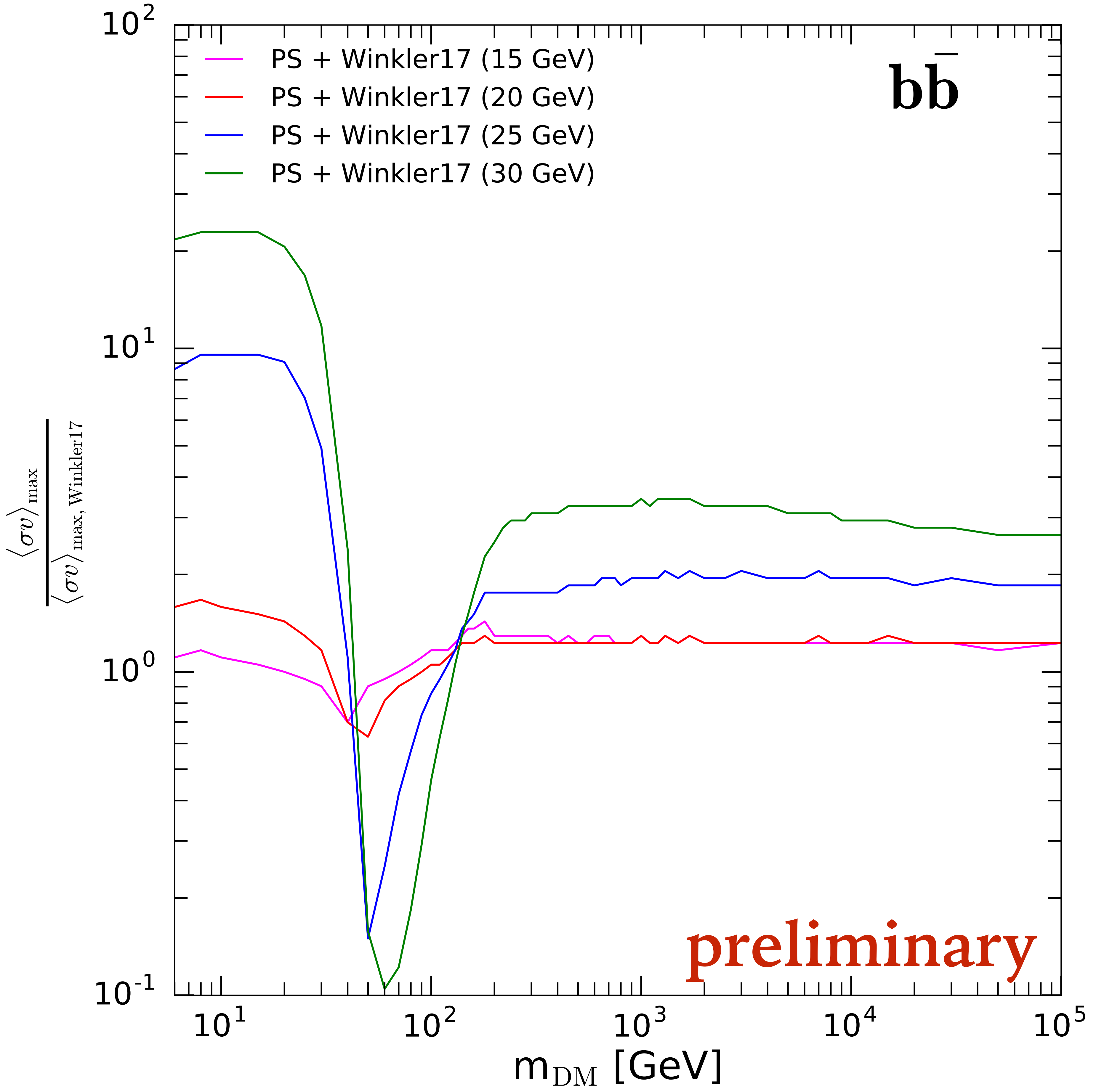
We have illustrated a **very simple analytical model** to describe the **low-energy behaviour** of the **secondary antiproton production cross section**

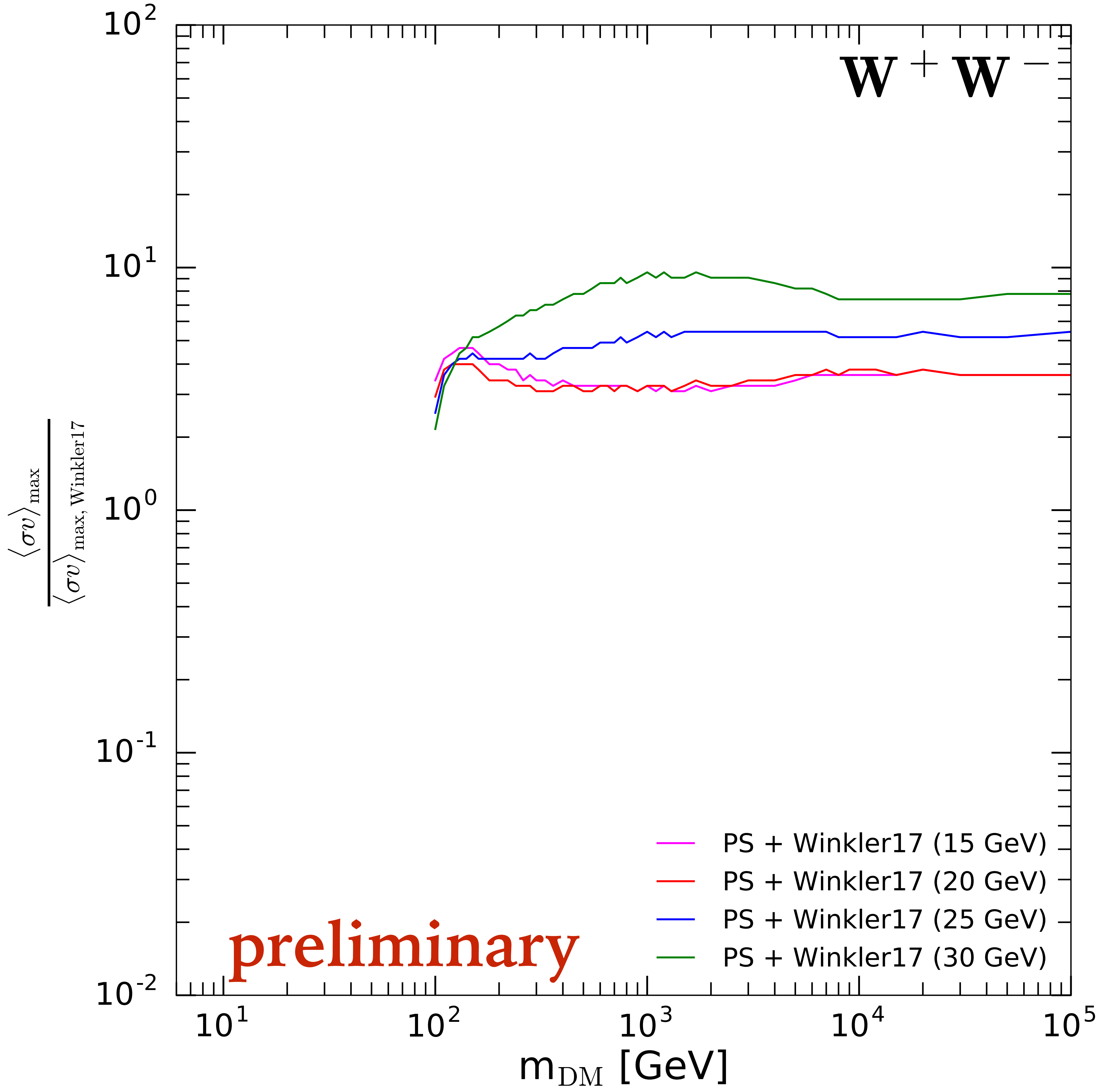
By applying such model we have shown that **changes in this cross section** can have a quite **large impact on dark matter searches**. Achieving **a better understanding of the very low energy regime** is thus an **important step** in understanding potential dark matter signals.

Obviously, our **phase space model** is very likely to be an **oversimplification**. We are currently working on refining it by including effects that could be relevant (resonances, formation of bound states, final state interactions …)

Back-up slides

dark matter bounds





ratio between the bounds obtained within a given model and the ones given by the Winkler17 model

transport parameters

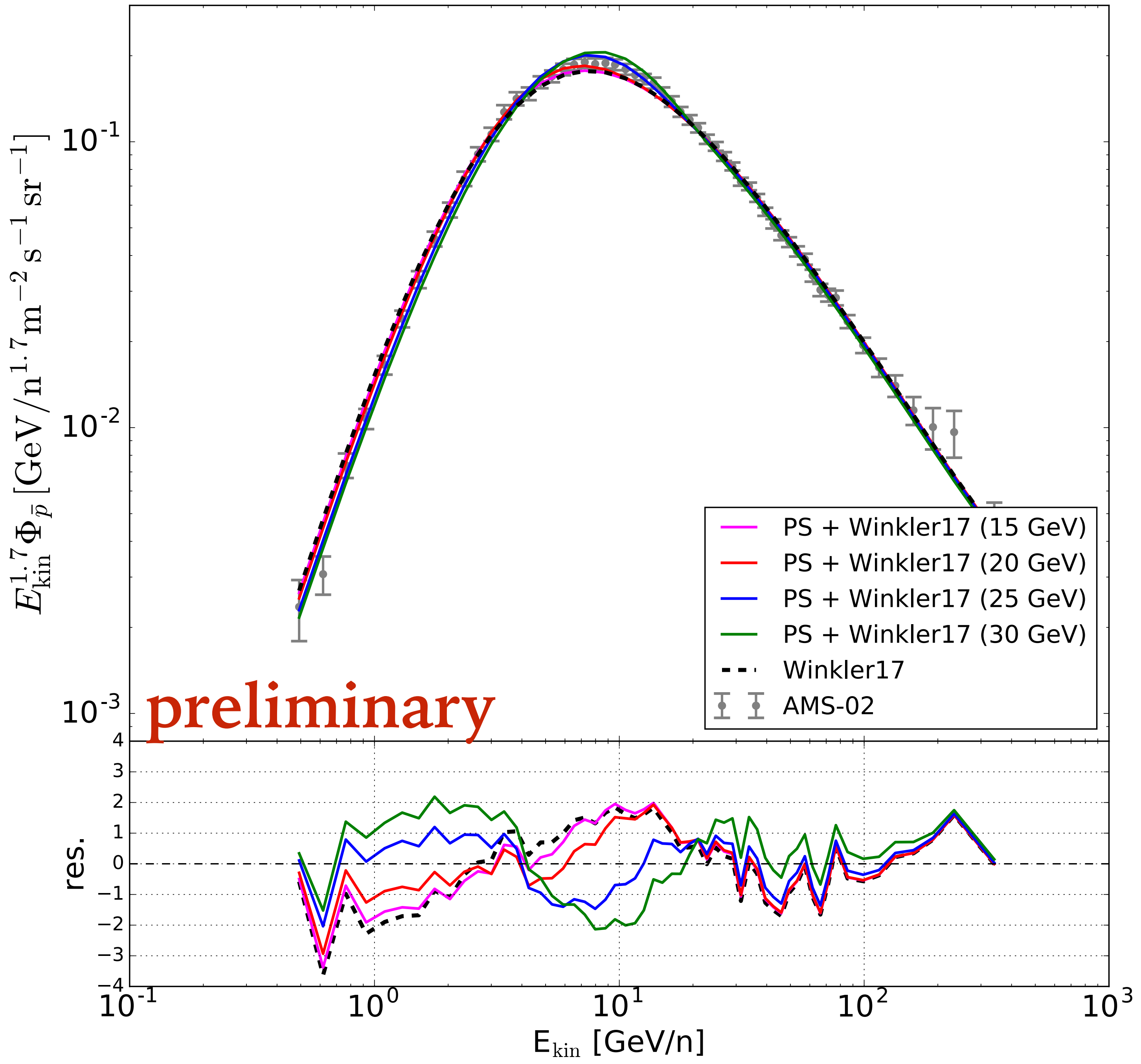
	Winkler	Winkler + PS 15 GeV	Winkler + PS 20 GeV	Winkler + PS 25 GeV	Winkler + PS 30 GeV
D_0 [10^{28} cm$^2 s^{-1}$]	3.57	3.57	3.59	3.59	3.63
δ_1	0.47	0.47	0.47	0.47	0.48
δ_2	0.37	0.38	0.38	0.37	0.37
$\mathcal{R}_\mathrm{b}$ [GV]	179.63	179.59	177.42	179.32	178.06
v_A [kms^{-1}]	23.74	23.88	24.12	23.28	23.59
dv_c/dz [kms^{-1}kpc^{-1}]	0.70	0.70	0.71	0.70	0.71
$\gamma_{p,1}$	2.13	2.13	2.13	2.13	2.12
$\gamma_{p,2}$	2.39	2.39	2.39	2.39	2.39
ρ_p [GV]	10.16	10.17	10.16	10.19	10.16
$\gamma_{He,1}$	2.18	2.17	2.15	2.18	2.17
$\gamma_{He,2}$	2.30	2.30	2.30	2.30	2.30
ρ_He [GV]	10.10	10.09	10.09	10.10	10.10
φ_p [GV]	0.76	0.77	0.77	0.76	0.75
φ_He [GV]	0.61	0.60	0.56	0.61	0.60
$\varphi_{\bar{\mathrm{p}}}$ [GV]	0.96	0.99	1.00	1.03	1.07

transport parameters - fit to B/C data

transport equation

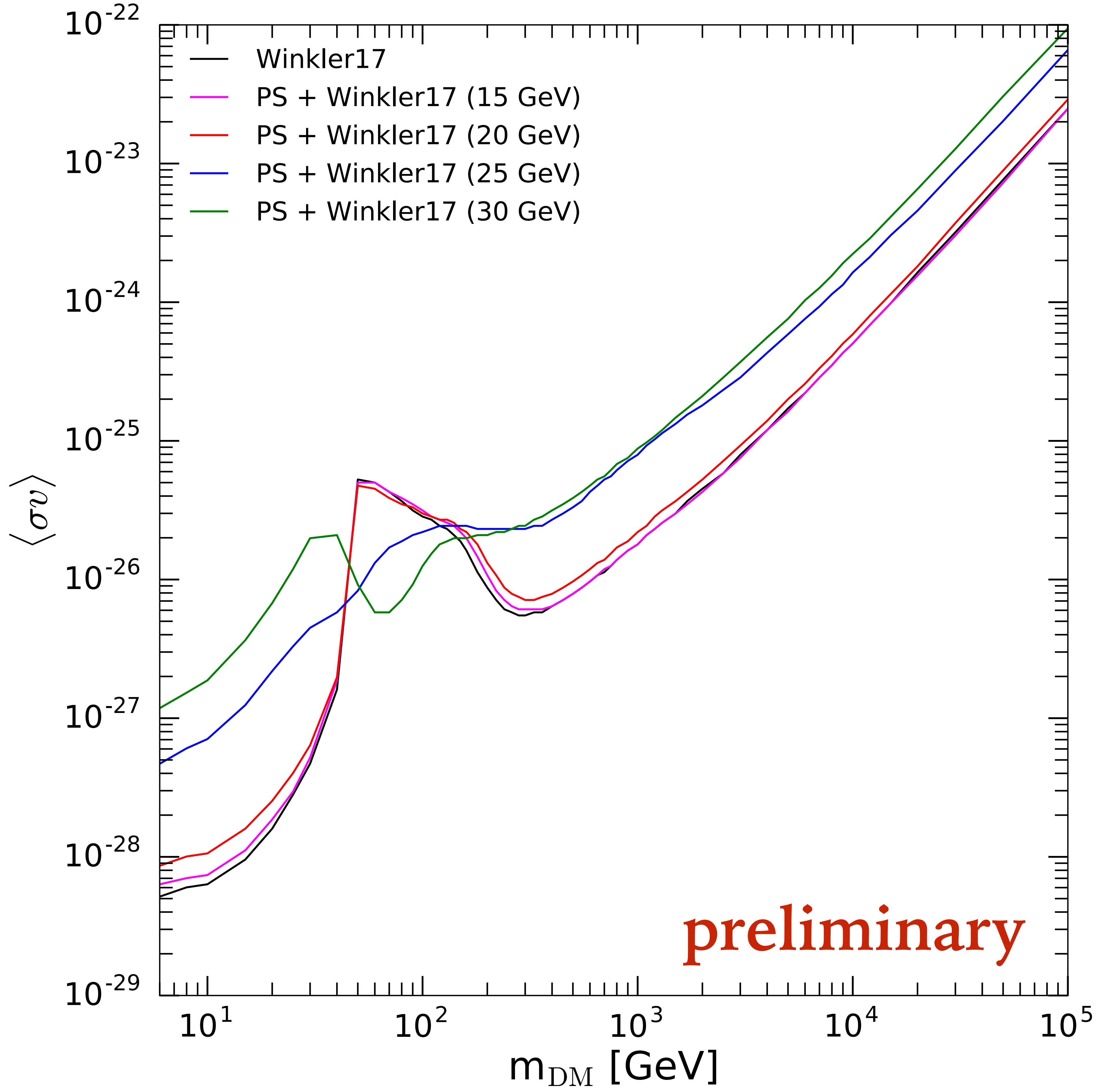
$$\frac{\partial N_i}{\partial t} - \nabla \cdot (D_{xx} \nabla N_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] =$$
$$\mathcal{Q} - \frac{N_i}{\tau_i^f} + \sum_j \Gamma_{j\to i}^s(N_j) - \frac{N_i}{\tau_i^r} + \sum_j \frac{N_j}{\tau_{j\to i}^r}$$

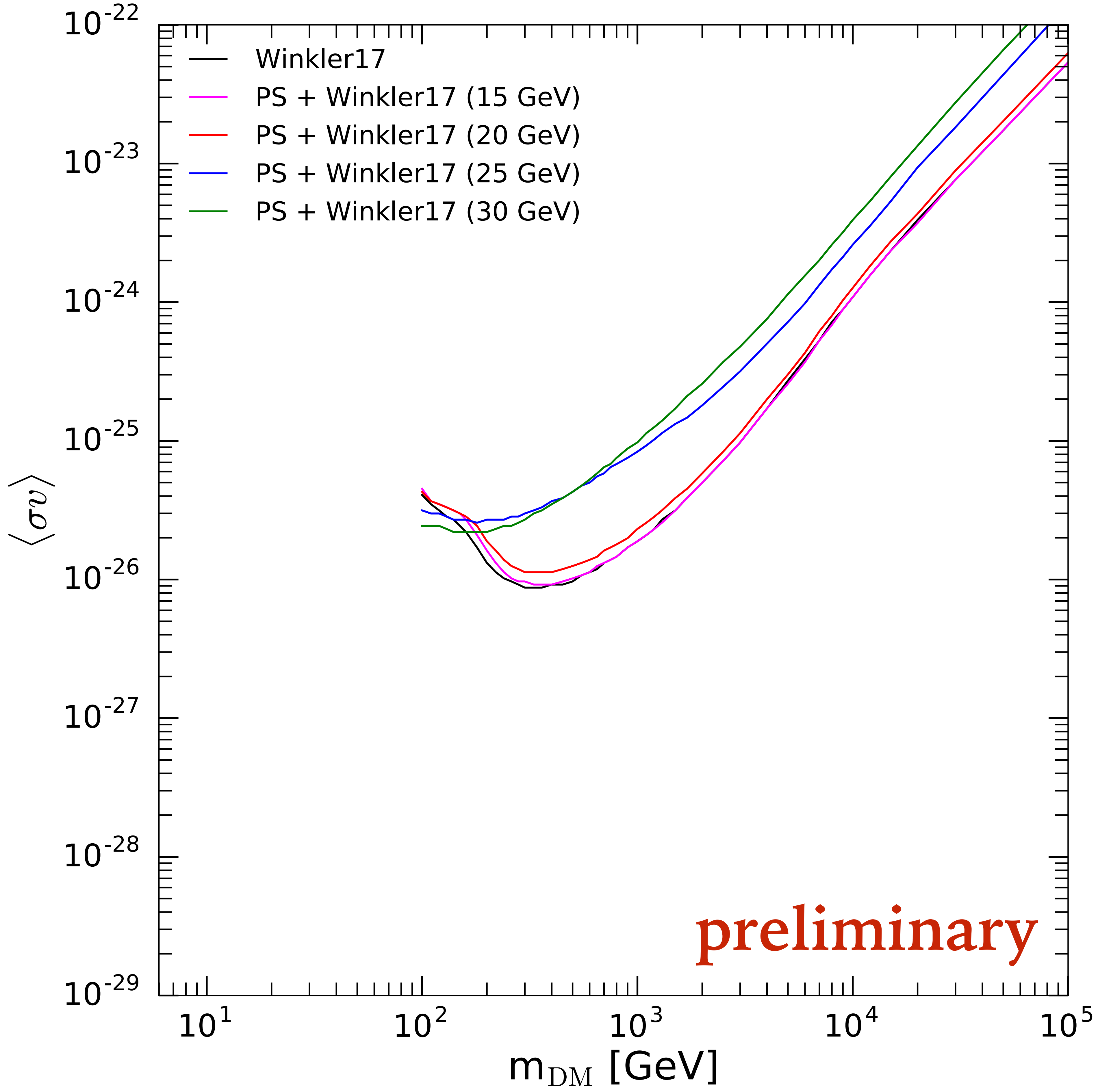
- We determine the propagation parameters by fitting AMS **proton**, **Helium** and **B/C** data
- We model **solar modulation** with a **force-field approximation**
- We assign a **free normalization** (different for each cross section model under consideration) to the **secondary antiproton flux**



All data			
Model	$N_{\bar{p}}$	$\varphi_{\bar{p}}$	$\chi^2_{\bar{p}}$ [57 data points]
Winkler	0.96	0.73	81.04
Winkler + PS 15 GeV	0.96	0.76	74.00
Winkler + PS 20 GeV	0.96	0.77	52.21
Winkler + PS 25 GeV	0.95	0.77	39.67
Winkler + PS 30 GeV	0.92	0.78	82.97

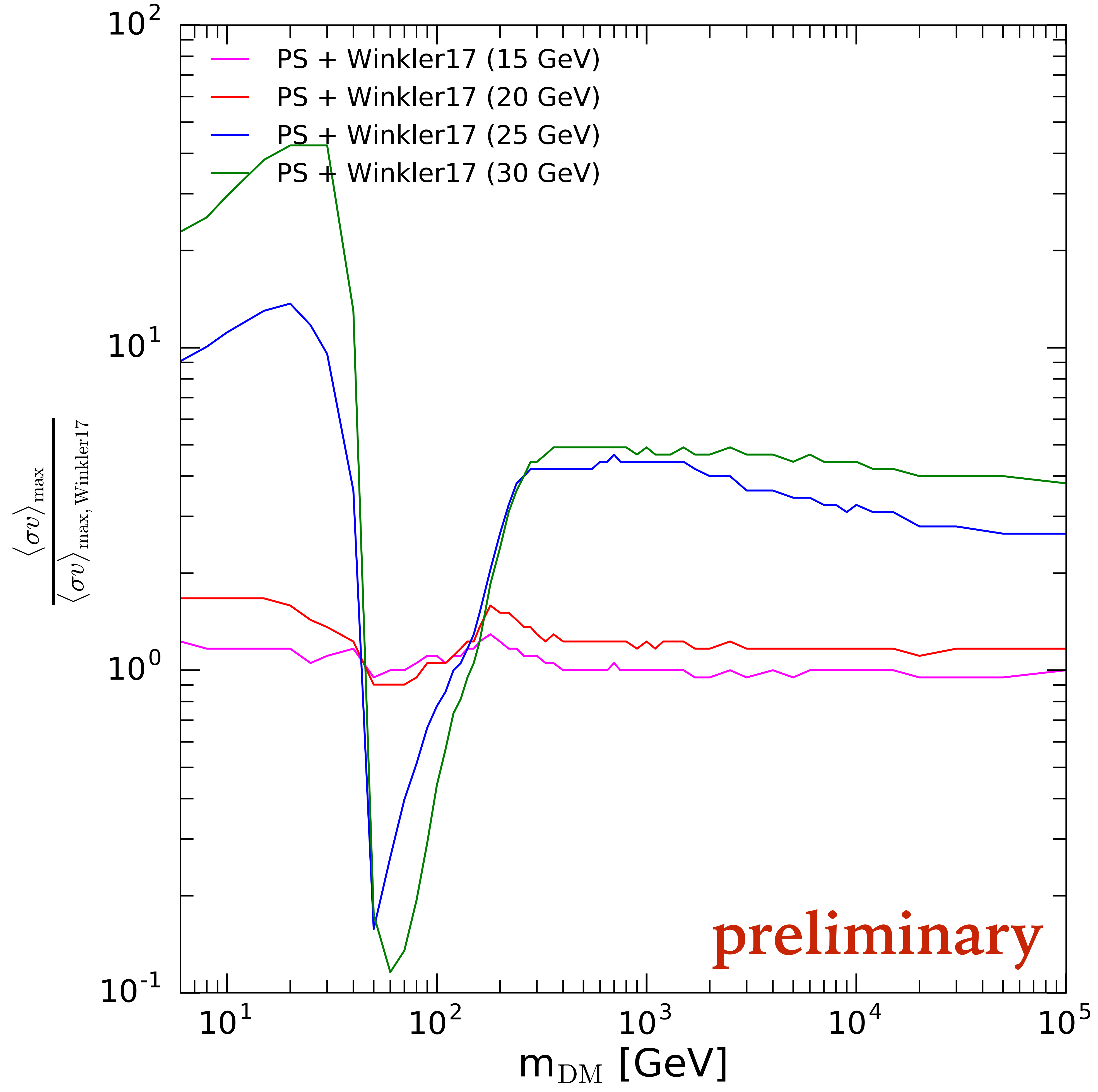
dark matter bounds - fit to B/C data

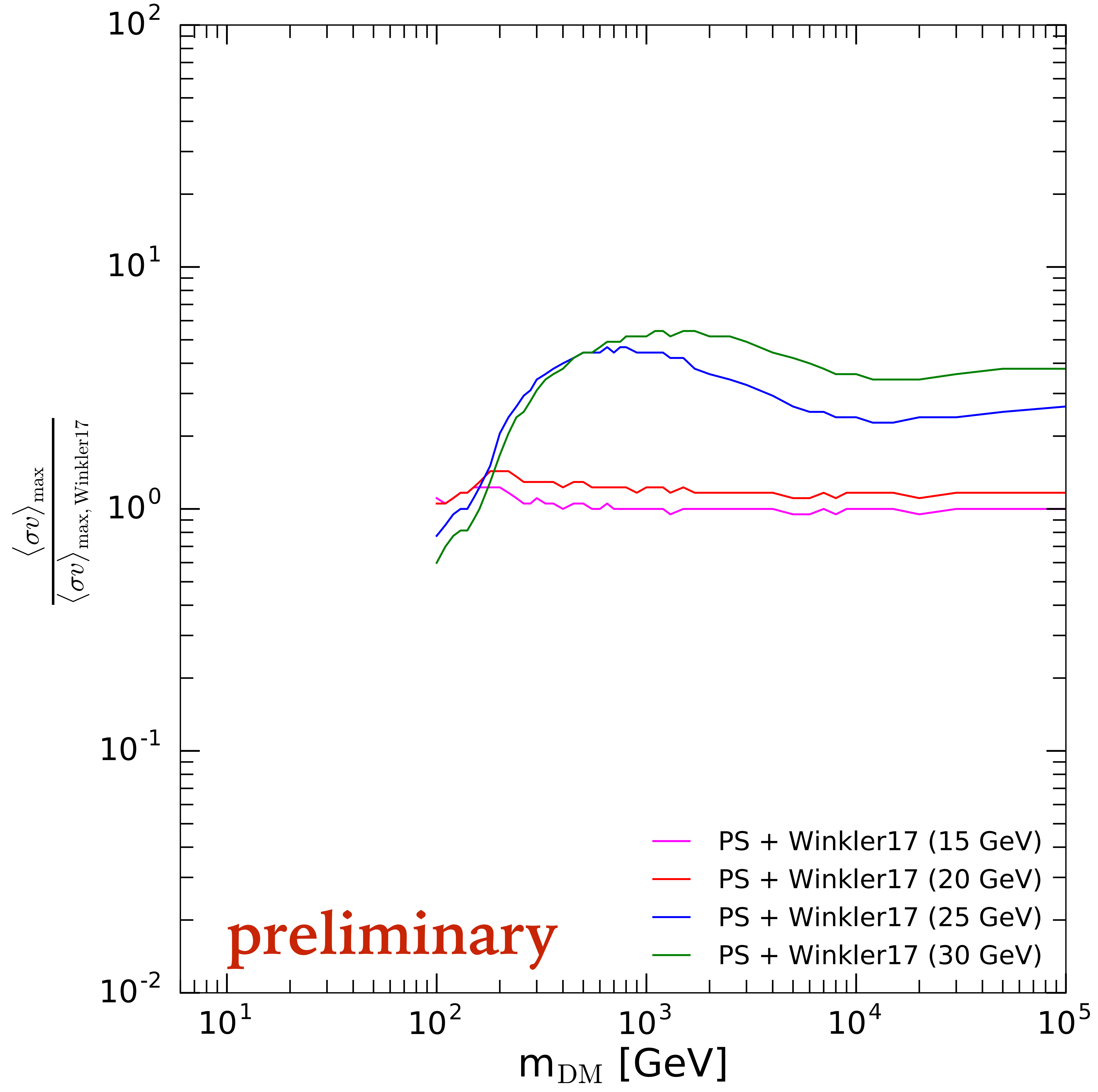




95% C.L. bounds obtained by marginalising over the force field potential of solar modulation and the normalisation of the secondary antiproton flux

dark matter bounds - fit to B/C data





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