Direct and indirect dark matter detection strategies

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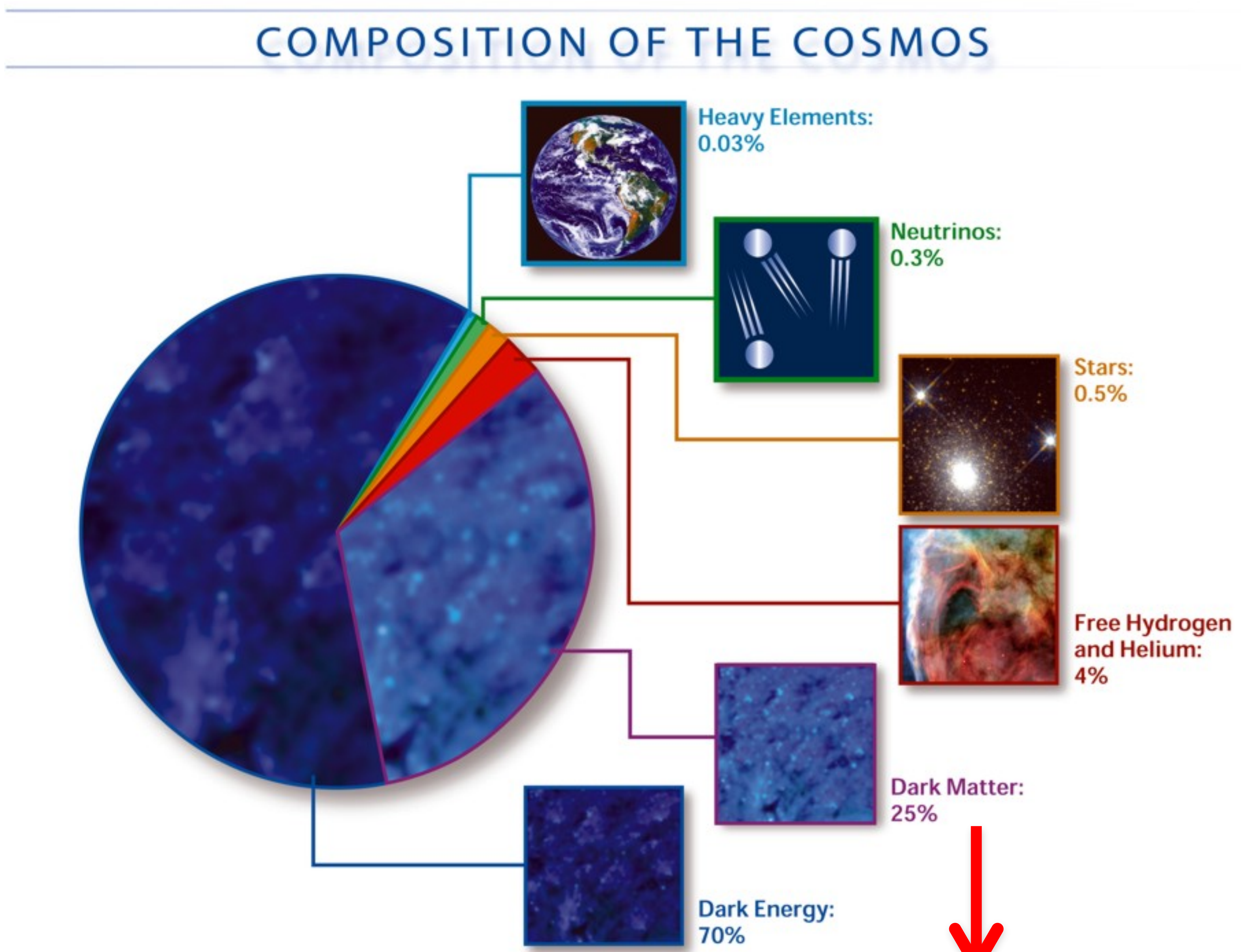
TNPI, Cortona 10.10.2019

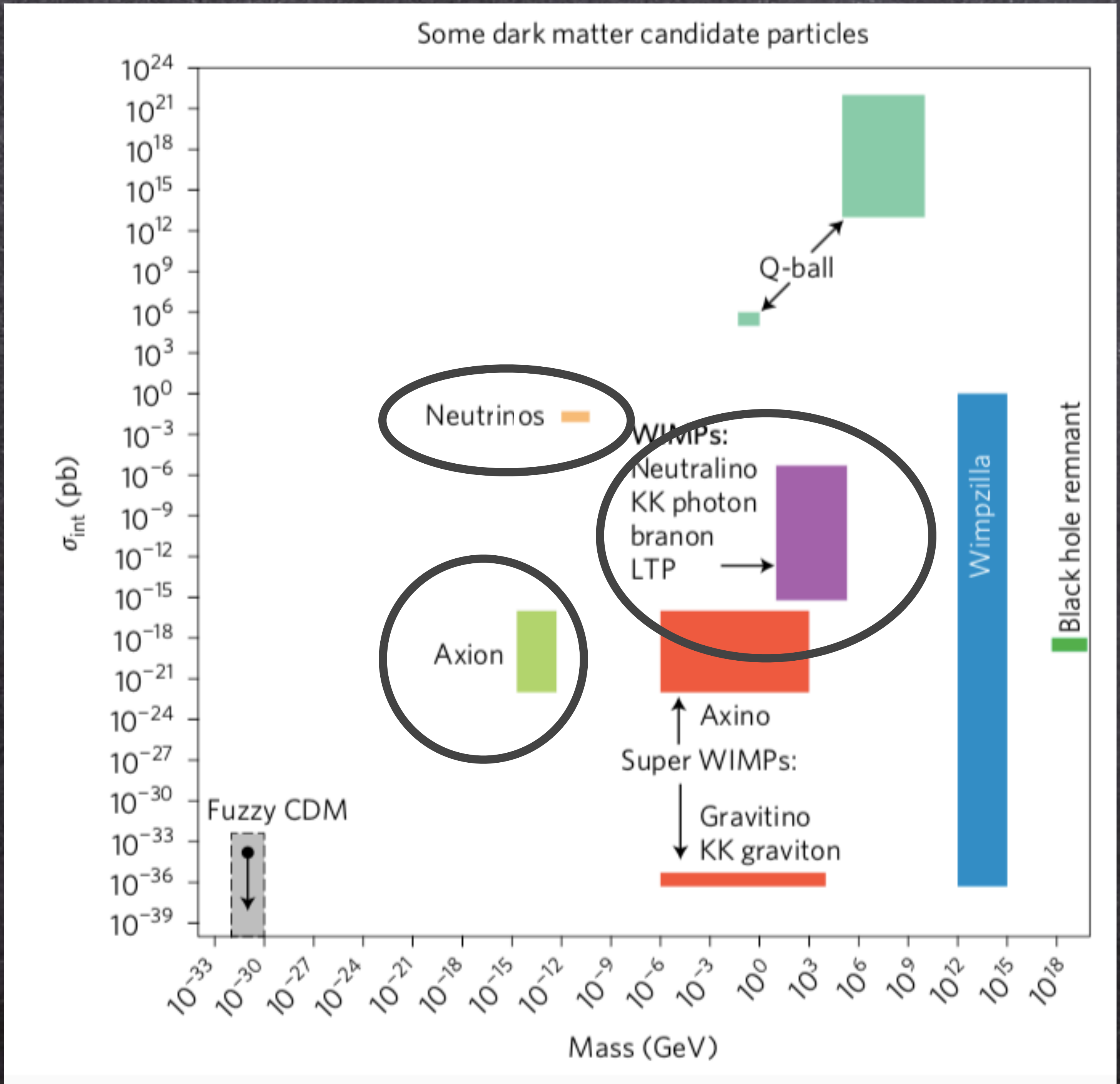
The composition of the Universe



One possible hypothesis: the solution is a particle,
a WIMP (weakly interacting massive particle)

Particle solutions to the Dark Matter (DM) mystery

Conrad&Reimer, Nature Phys. 2017



SIGNALS from RELIC WIMPs

Direct searches (deeply underground experiments) :

elastic scattering of a WIMP off detector nuclei

Measure of the recoil energy

Annual modulation and directionality of the measured rate

Indirect searches: in Cosmic Rays (mostly space based experiments)

signals due to annihilation of accumulated

$\chi\chi$ in the of Sun/Earth (neutrinos)

signals due to $\chi\chi$ annihilation in the galactic halo

(antimatter, gamma-rays)

New particles are searched at colliders but we cannot say anything about being the solution to the DM in the Universe!

WIMP INDIRECT SIGNALS

Annihilation inside celestial bodies (Sun, Earth): ν at neutrino telescopes as up-going muons

Annihilation in the galactic halo:

γ-rays (diffuse, monochromatic line), multiwavelength

antimatter, searched as rare components in cosmic rays (CRs)

$$e^+, \ \bar{p}, \ \bar{D}$$

ν and γ keep directionality

SOURCE DENSITY

Charged particles diffuse in the galactic halo

ASTROPHYSICS OF COSMIC RAYS!

DM direct detection

Measured process is DM - nucleus scattering:

DM + Nucleus (at rest) –> DM + Nucleus (E_recoil)

Recoil rate
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{min}(E_R)}^{v_{max}} dv\, f(v)\, v \frac{d\sigma}{dE_R}(v, E_R)$$

f(v) velocity distribution (Maxwell-Boltzmamn)

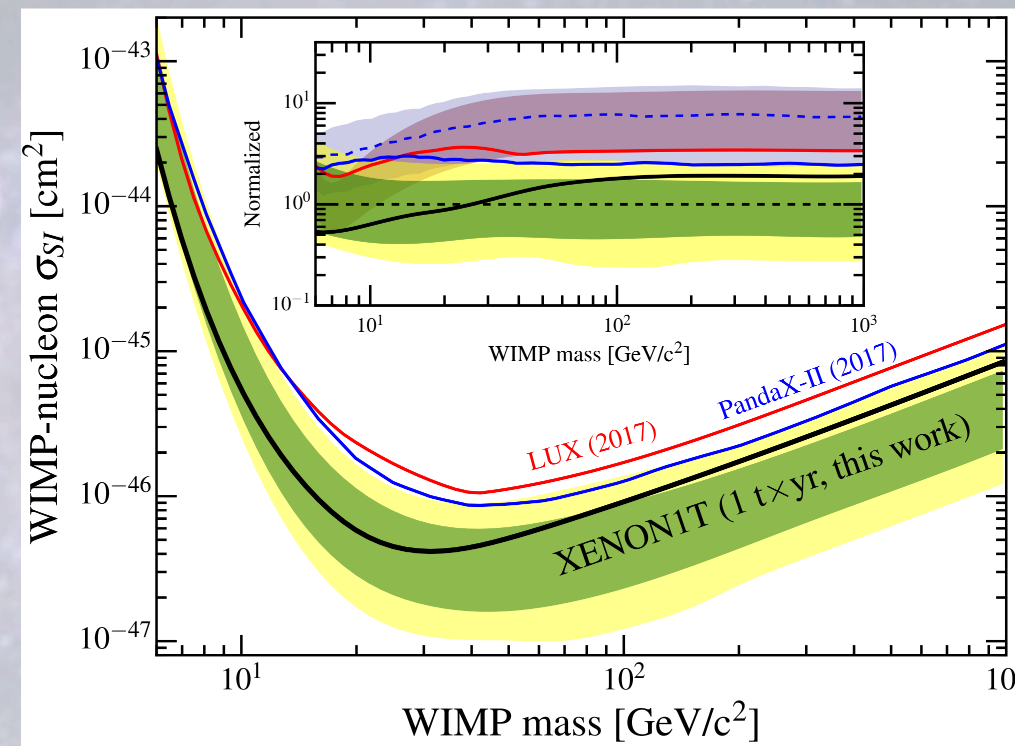
$$\frac{d\sigma}{dE_R}(v, E_R)$$

Elastic differential DM-nucleus cross section

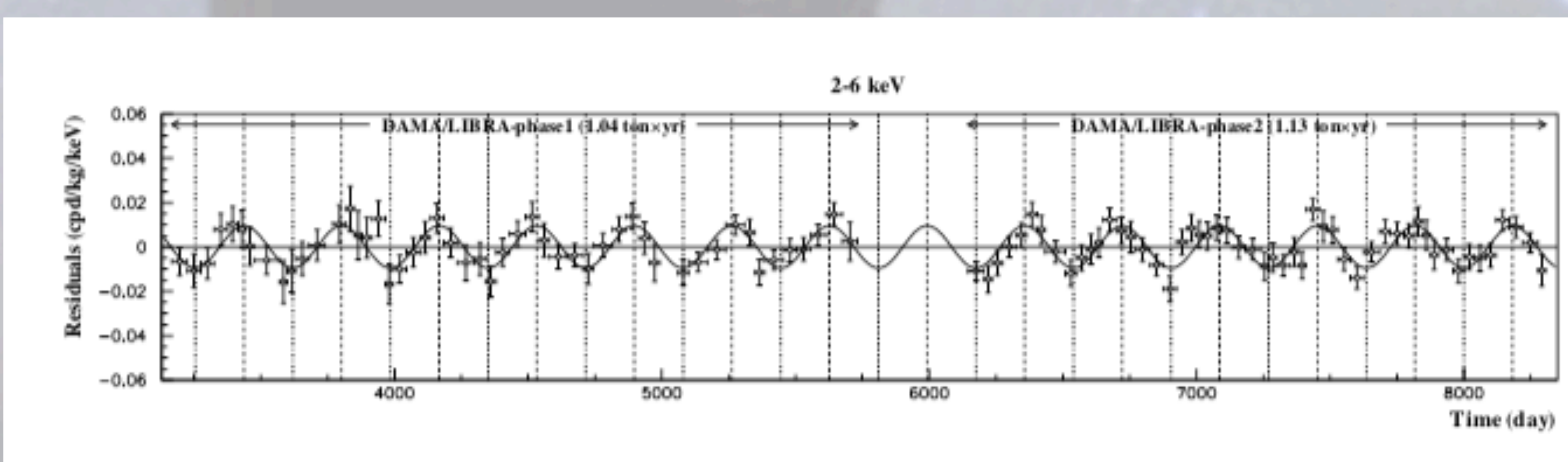
$$\frac{d\sigma}{dE_R} = \left(\frac{d\sigma}{dE_R}\right)_C + \left(\frac{d\sigma}{dE_R}\right)_{SD} \qquad \left(\frac{d\sigma}{dE_R}\right)_C = \frac{\sigma_C^0}{E_R^{max}} F^2(q)$$

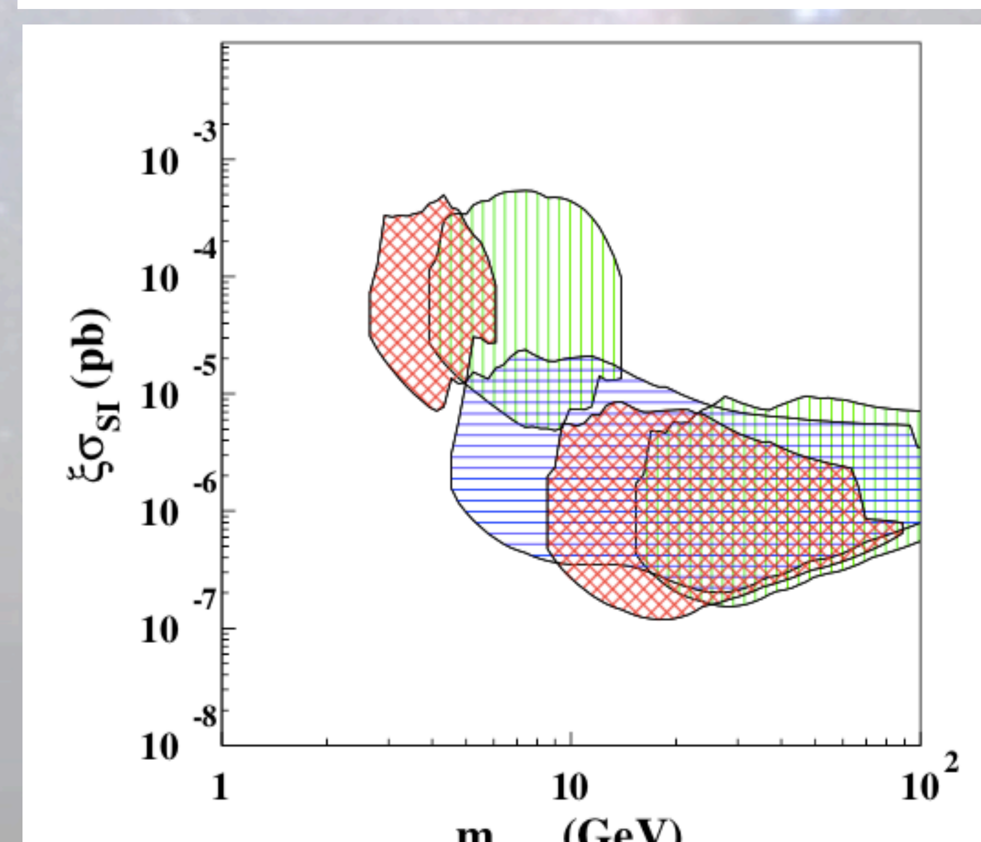
Direct detection observables

Xenon Coll. 1805.12562



- ✓ Differential rate
- ✓ Annual modulation
  (Earth revolution around the Sun)
- ✓ Directionality
- ✓ Diurnal modulation

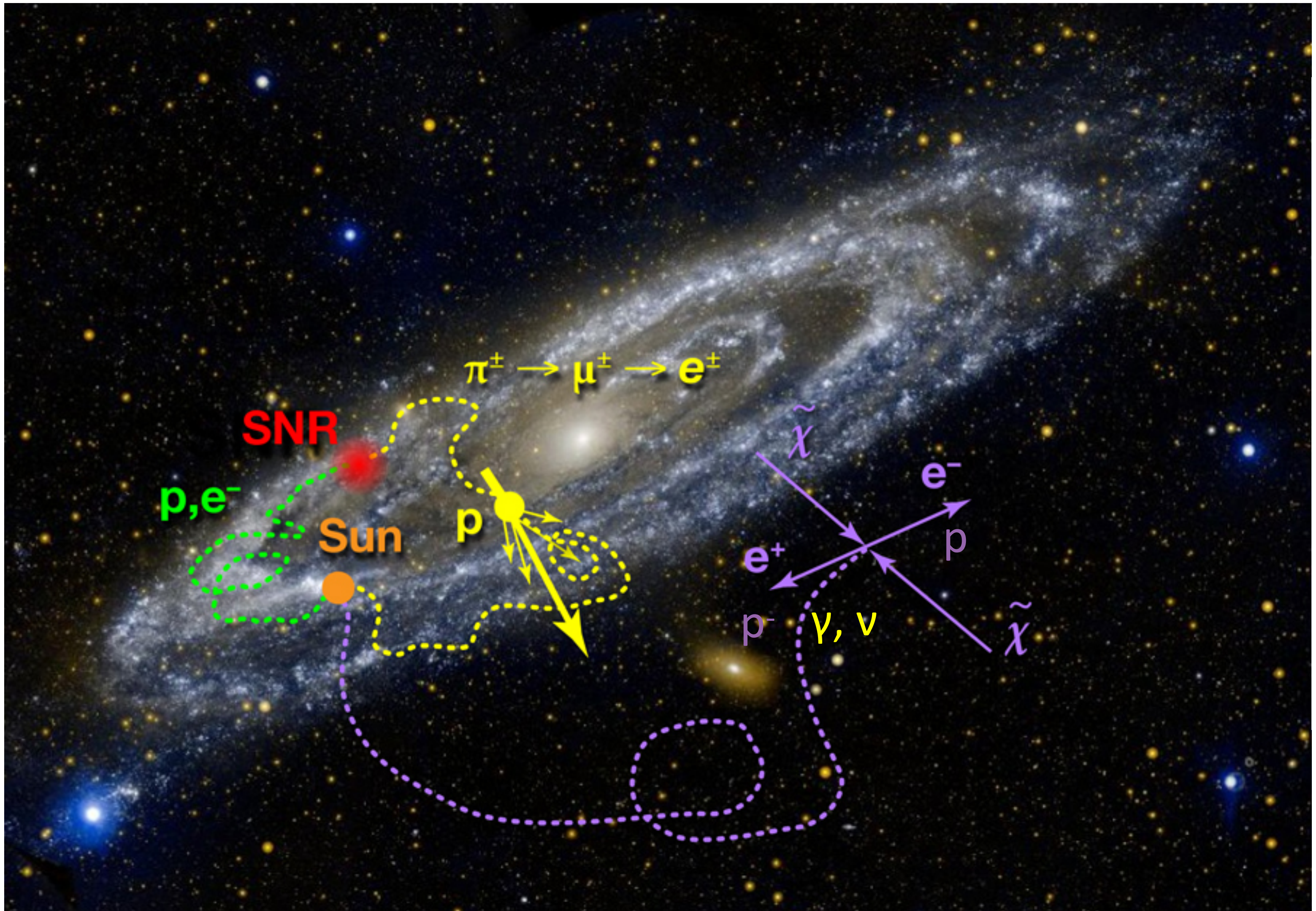


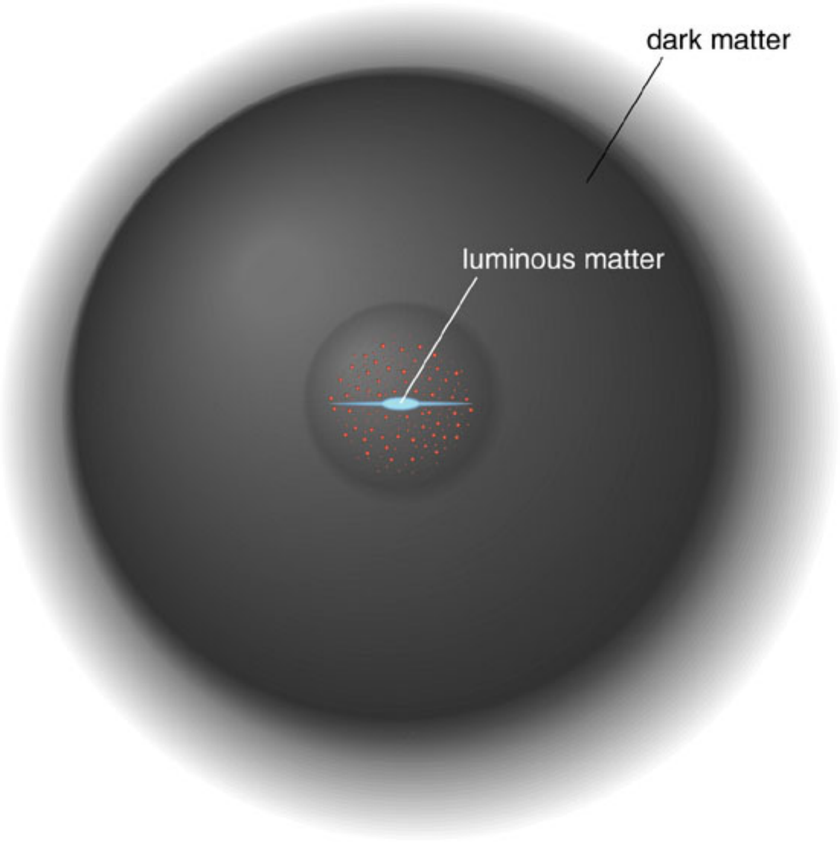


Dama Coll, Bernabei et al., 2018; 2019

Indirect DARK MATTER searches

Dark matter can annihilate in pairs with standard model final states.
Low background expected for cosmic **ANTIMATTER**, and for **NEUTRINOS** and **GAMMA RAYS** coming from dense DM sites





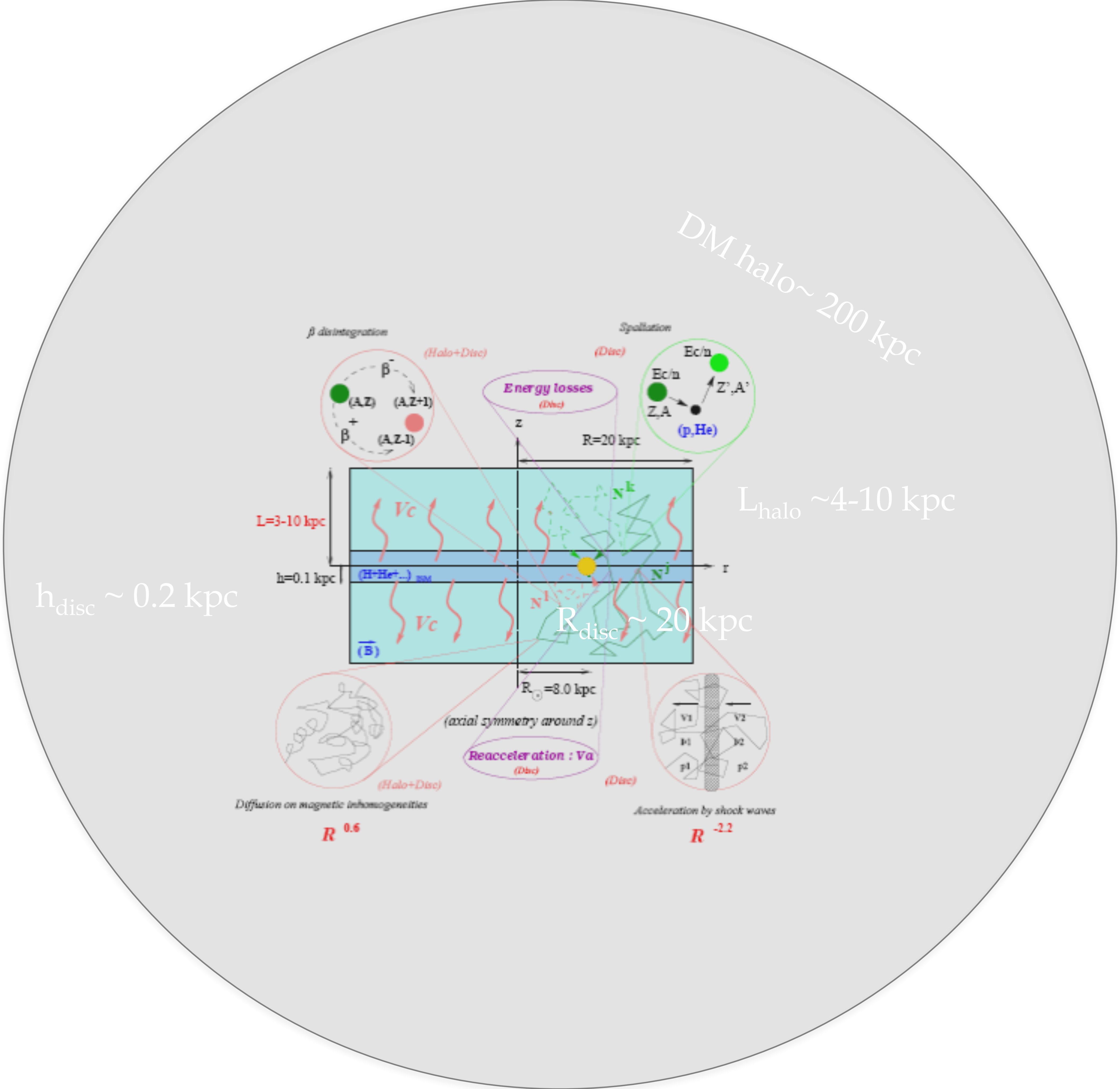
Primary and secondary CRs in the Galaxy

Primaries: produced in the sources (SNR and Pulsars)
H, He, CNO, Fe; e-, e+; possibly e^+, p^-, d^- from Dark Matter annihilation

Secondaries: produced by spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM): Li, Be, B, sub-Fe, [...], (radioactive) isotopes ; e^+, p^-, d^-

At first order, we understand fluxes at Earth as shaped by few, simple, isotropic effects:

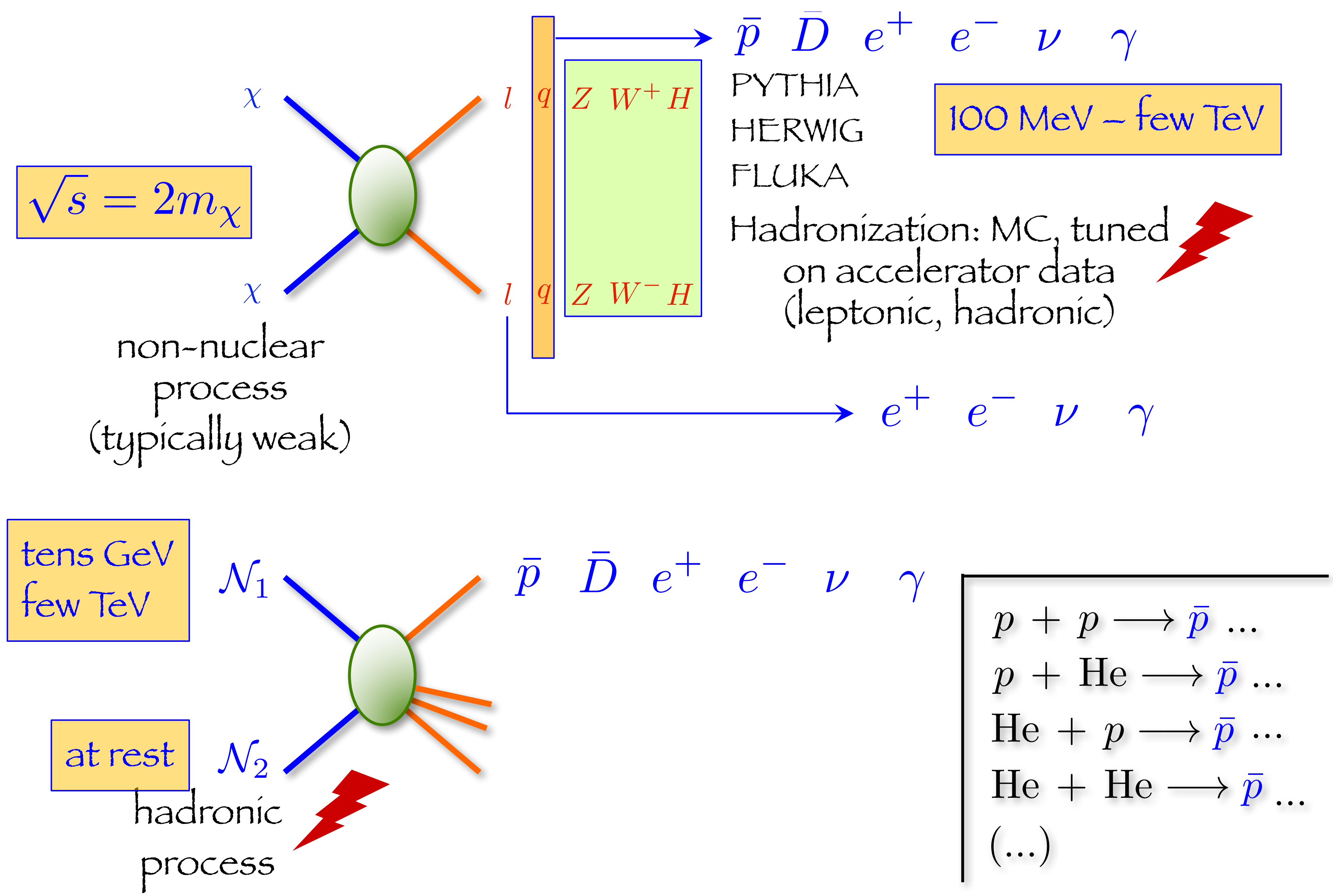
- acceleration in shocked stellar environments (SNR, PWN)
- particle interactions between CRs and ISM
- diffusion of the galactic magnetic fields
- particle energy losses



DM halo~ 200 kpc
L$_{halo}$ ~4-10 kpc
h$_{disc}$ ~ 0.2 kpc
R$_{disc}$ ~ 20 kpc
β disintegration
Spallation
(Halo+Disc)
(Disc)
Energy losses
(Disc)
R=20 kpc
L=3-10 kpc
h=0.1 kpc
Vc
(axial symmetry around z)
Reacceleration : Va
(Disc)
Diffusion on magnetic inhomogeneities
Acceleration by shock waves
R 0.6
R -2.2

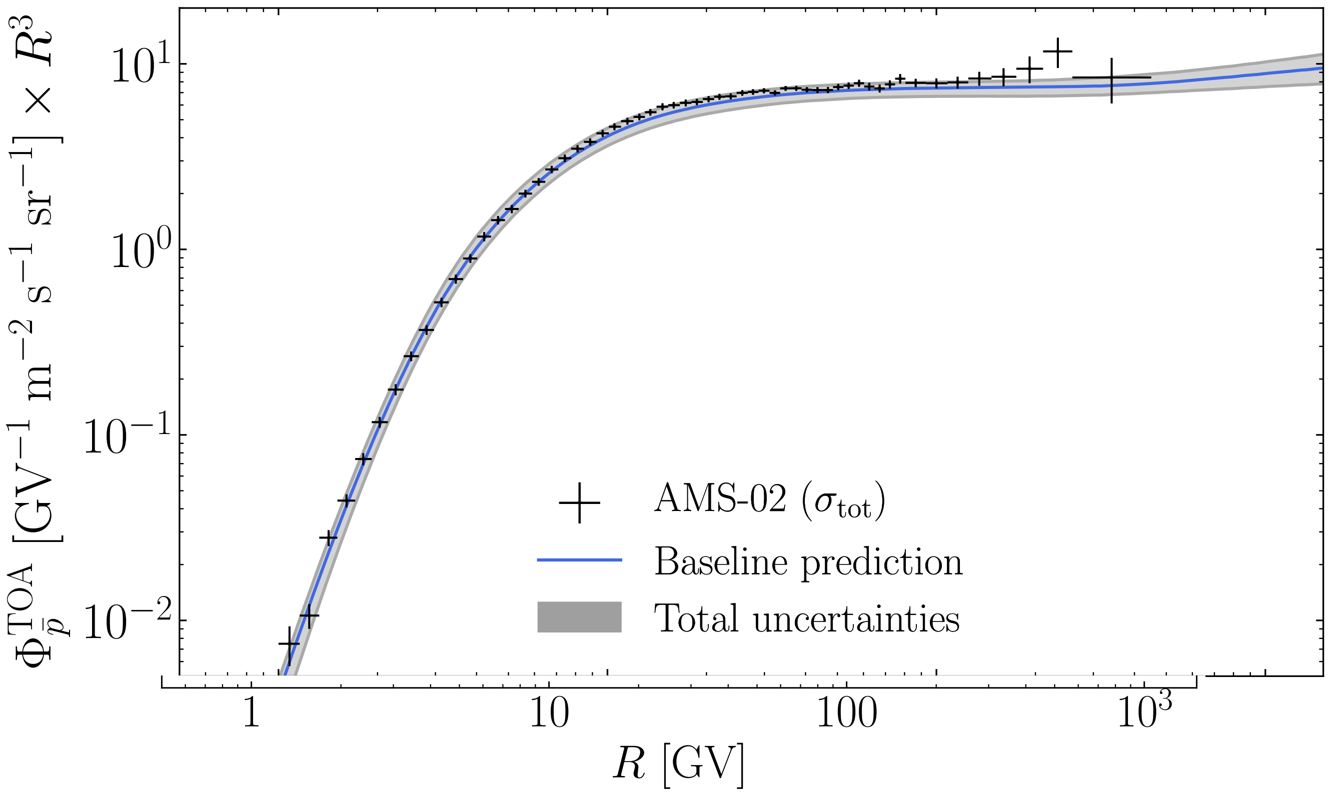
The case for antiprotons

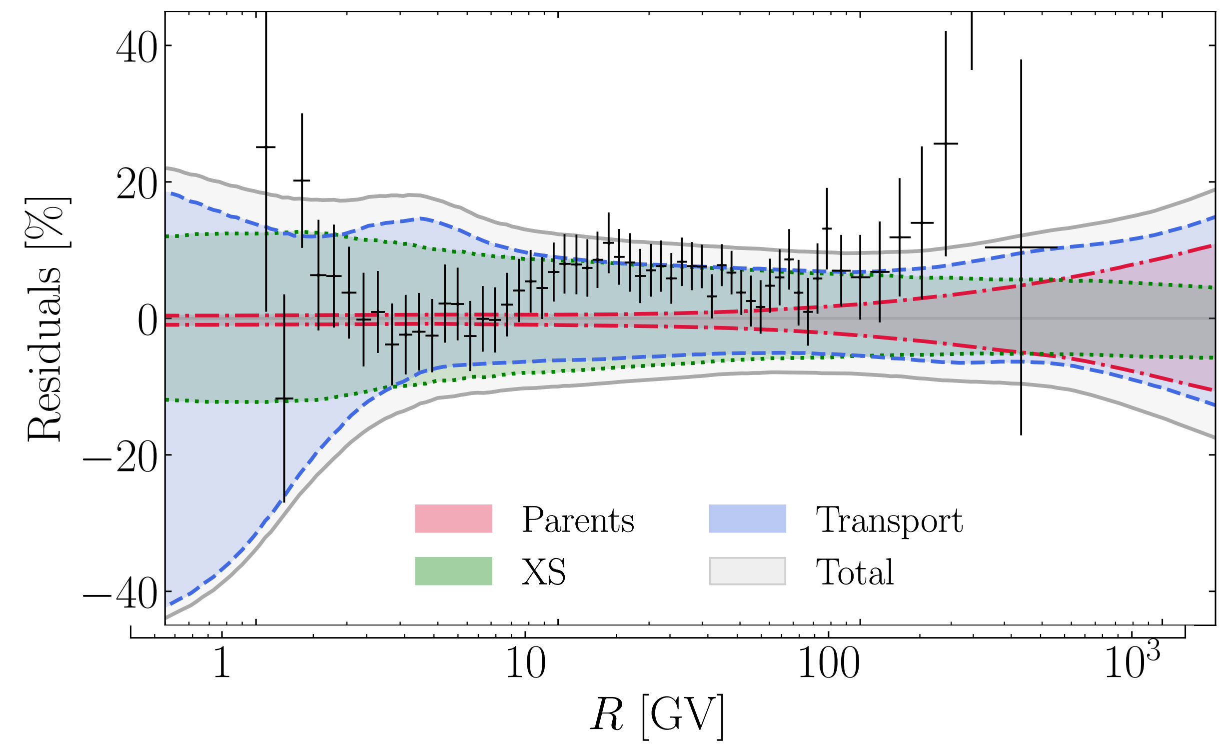
Injection spectra from DM and CRs



Data vs predictions

M. Boudaud, Y. Genolini, L. Derome, J.Lavalle, D.Maurin, P. Salati, P.D. Serpico 1906.07119



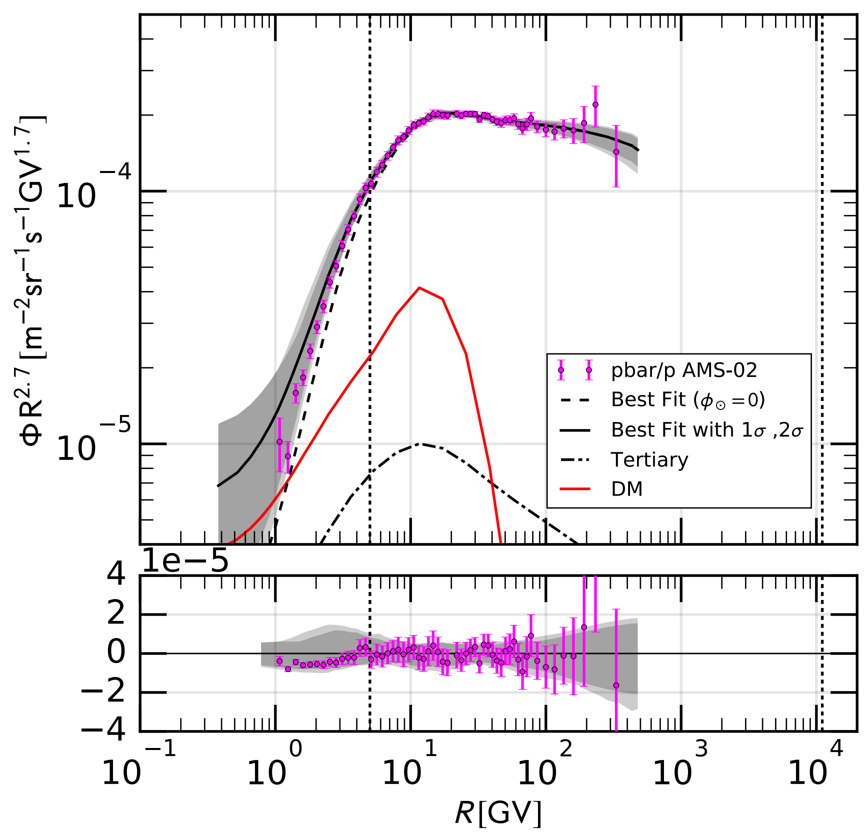


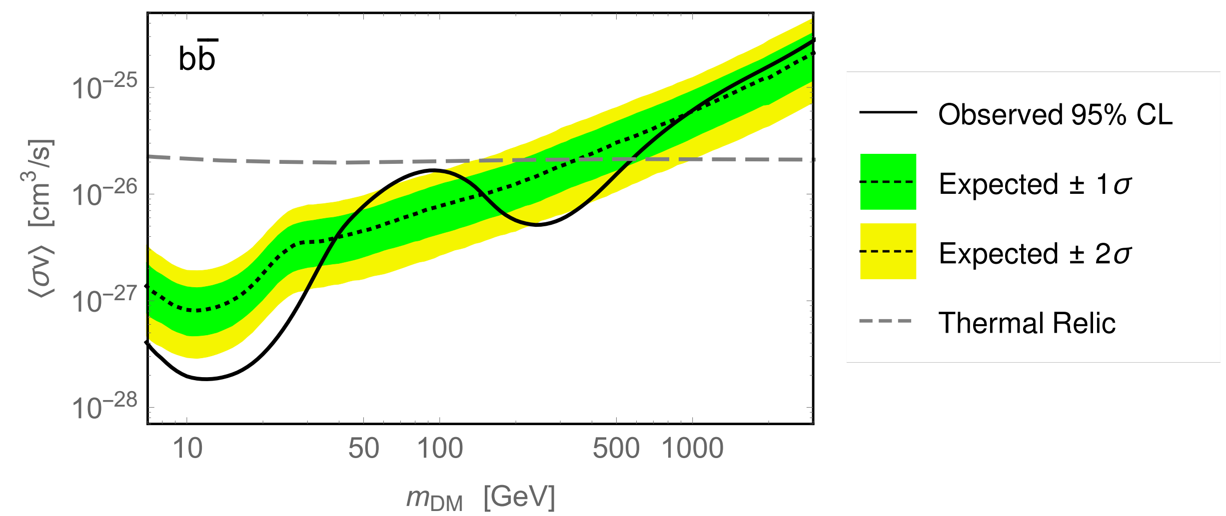
AMS-02 antiprotons are consistent with a secondary astrophysical origin, so from inelastic scatterings of relativistic cosmic ray nuclei (p, He, CNO) off the interstellar medium (H, He) (Donato et al. PRL 20019)

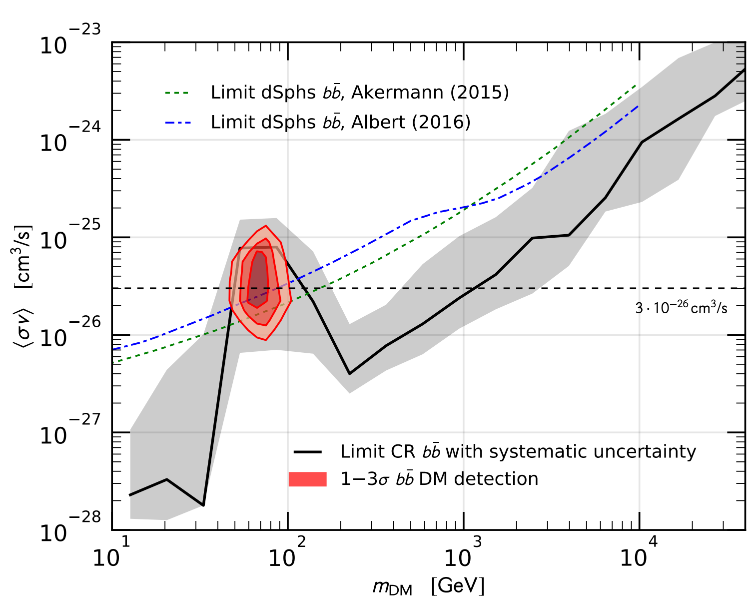
Nuclear physics is a relevant theoretical uncertainty.

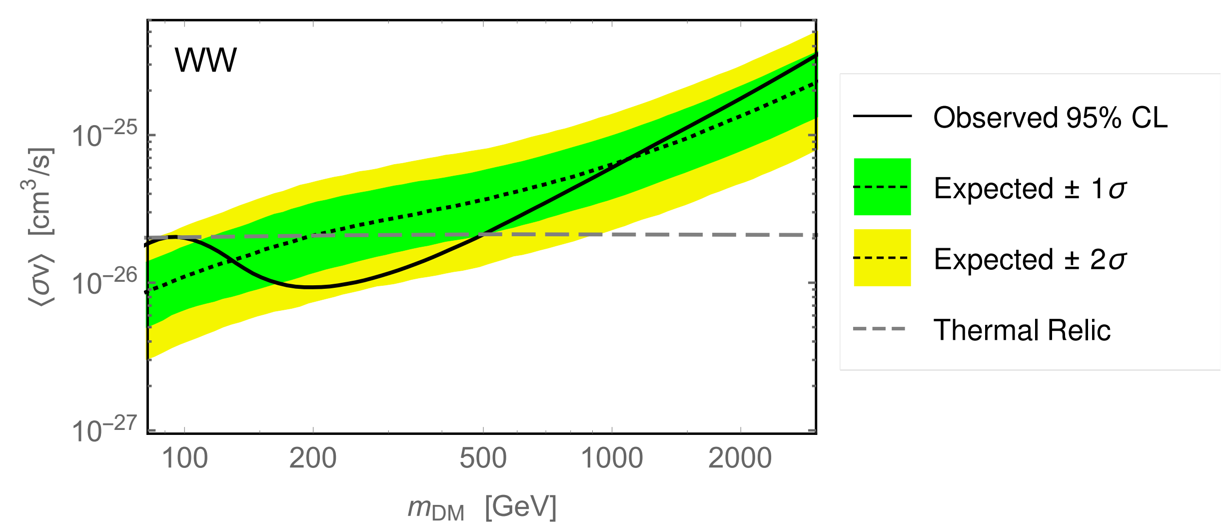
Possible contribution from dark matter

Cuoco, Korsmeier, Kraemer PRL 2017









A signal is hinted.
Upper bounds can be set on the annihilation cross section

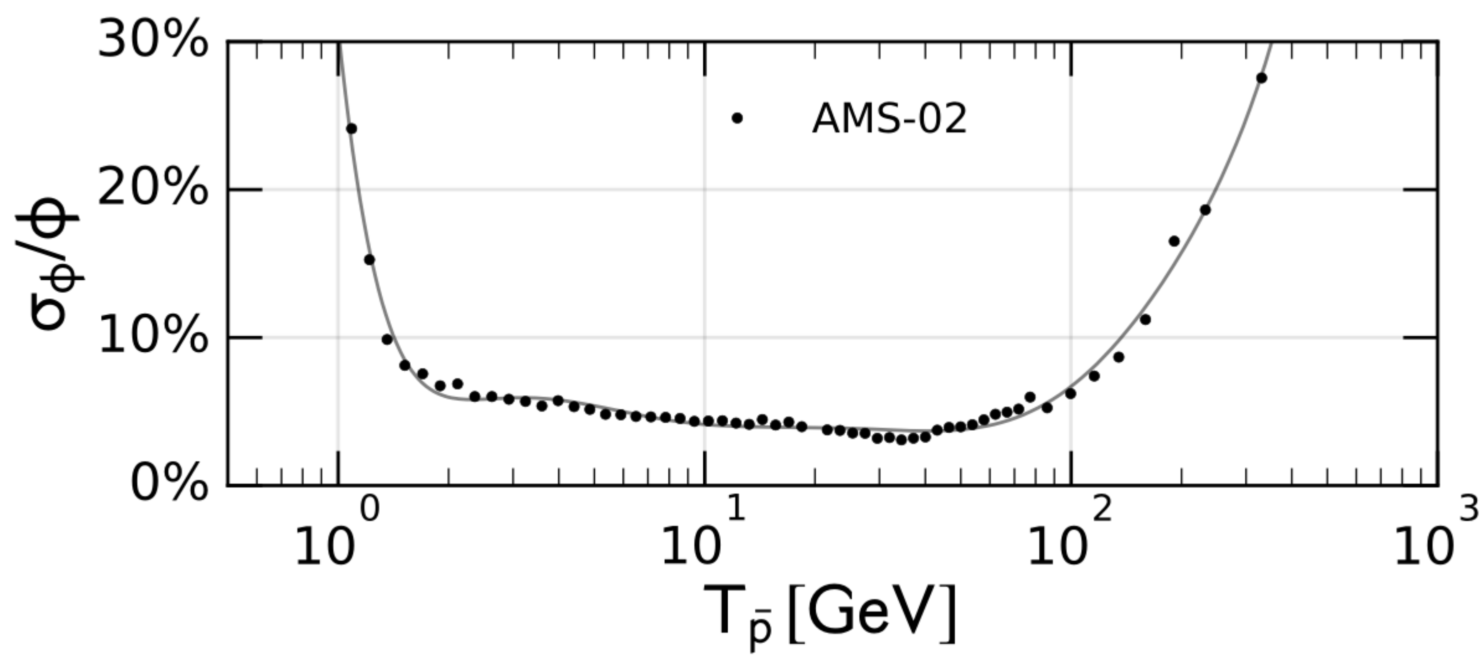
Antiproton production by inelastic scatterings

FD, Korsmeier, Di Mauro PRD 2017

$$q_{ij}(T_{\bar{p}}) = \int_{T_{\rm th}}^{\infty} dT_i \; 4\pi \, n_{{\rm ISM},j} \, \phi_i(T_i) \, \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}})$$

Source term

i, j = proton, helium
(both in the CRs and in the ISM)



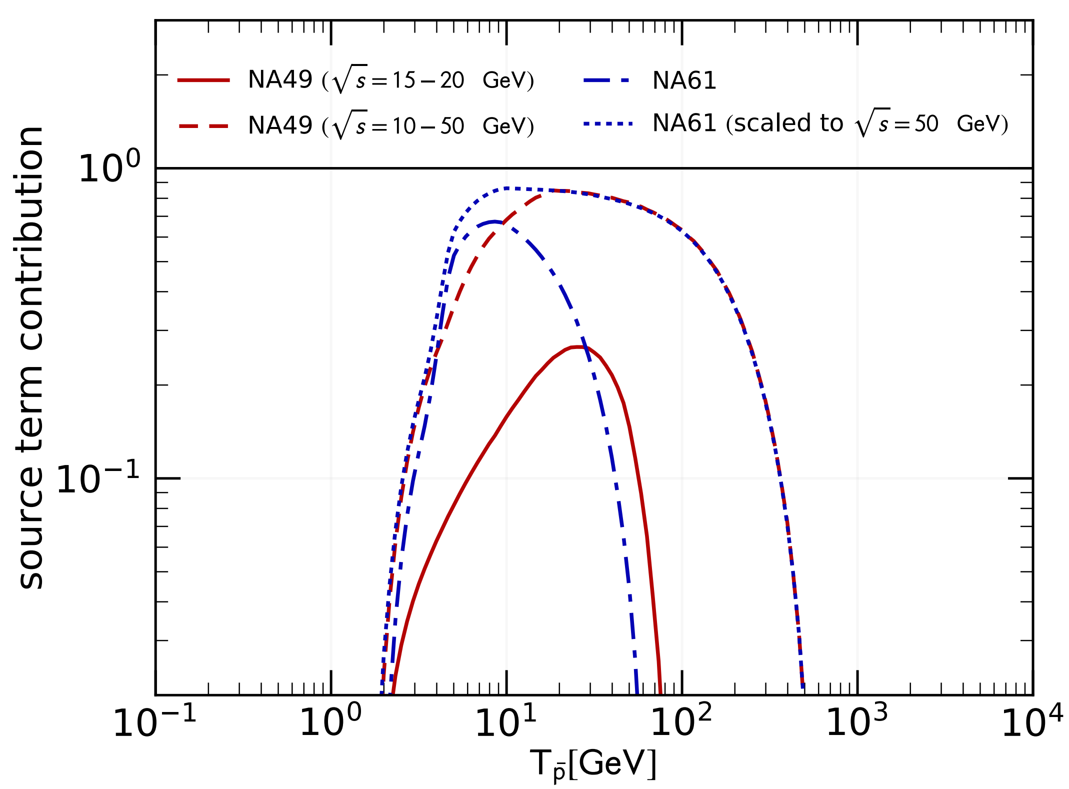
Cosmic antiproton data are very precise:
production cross sections should be known with high accuracy
in order not to introduce high theoretical uncertainties

New fixed-target data for the antiproton XS

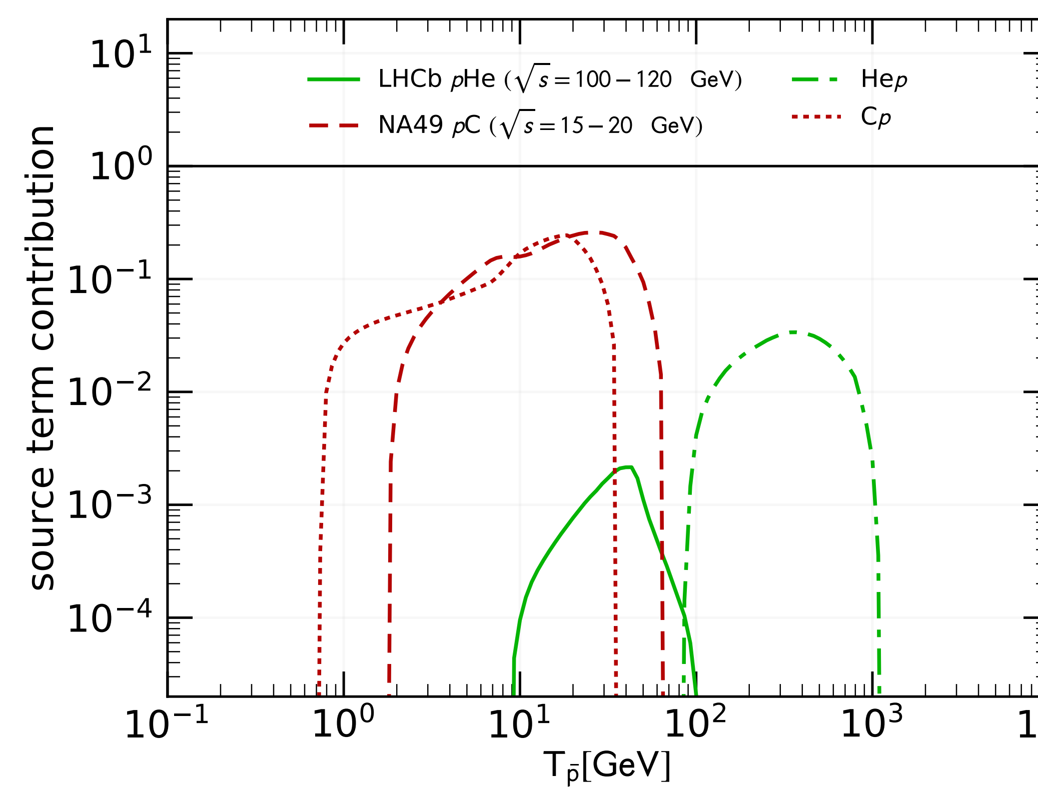
FD, Korsmeier, Di Mauro PRD 2018

pp —> pbar+X	pHe —> pbar + X
NA61 (Aduszkiewicz Eur. Phys. J. C77 (2017))	**LHCb** (Graziani et al. Moriond 2017)
$\sqrt{s}$=7.7, 8.8, 12.3 and 17.3 GeV	$\sqrt{s} = 110$ GeV
T_p = 31, 40, 80, 158 GeV	T_p = 6.5 TeV

Fraction of the pp source term covered by the kinematical parameters space



Fraction of the p-nucelus source term covered by the kinematical parameters space

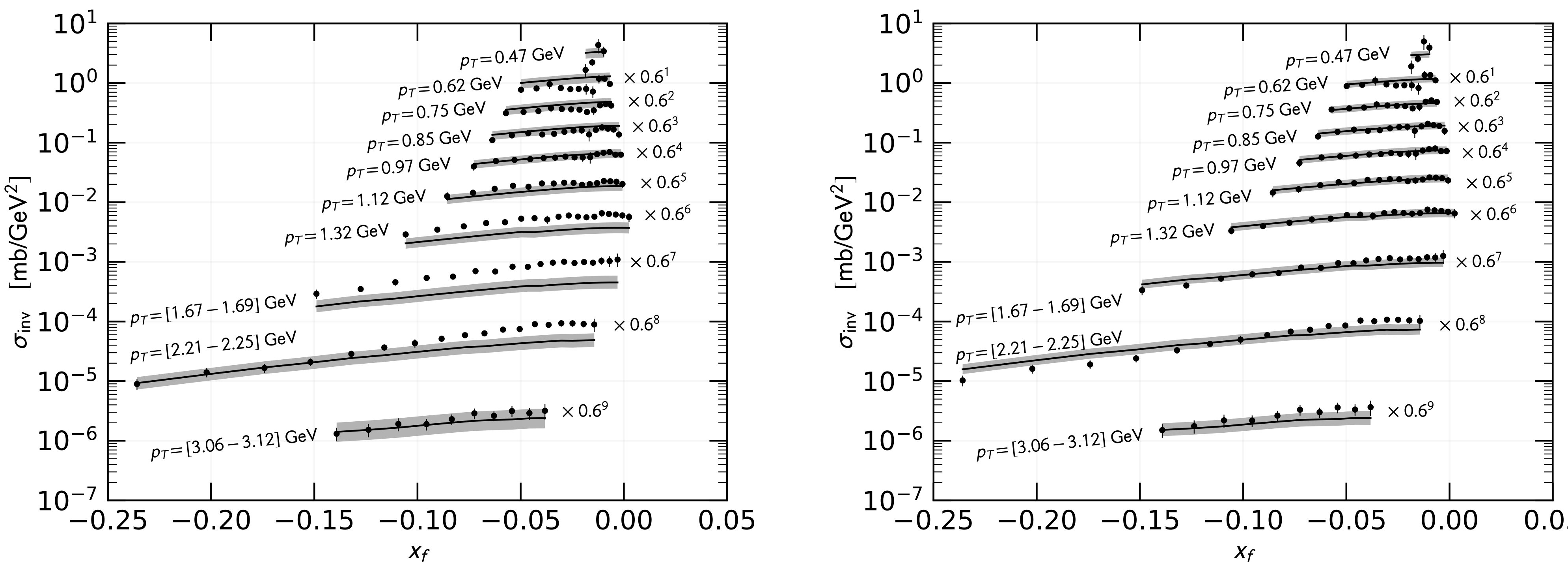


High-energy data analysis

Korsmeier, FD, Di Mauro, PRD 2018

1. Fit to NA61 pp —> pbar + X data
2. Calibration of pA XS on NA49 pC —> pbar + X data
3. Inclusion of LHC pHe —> pbar + X data

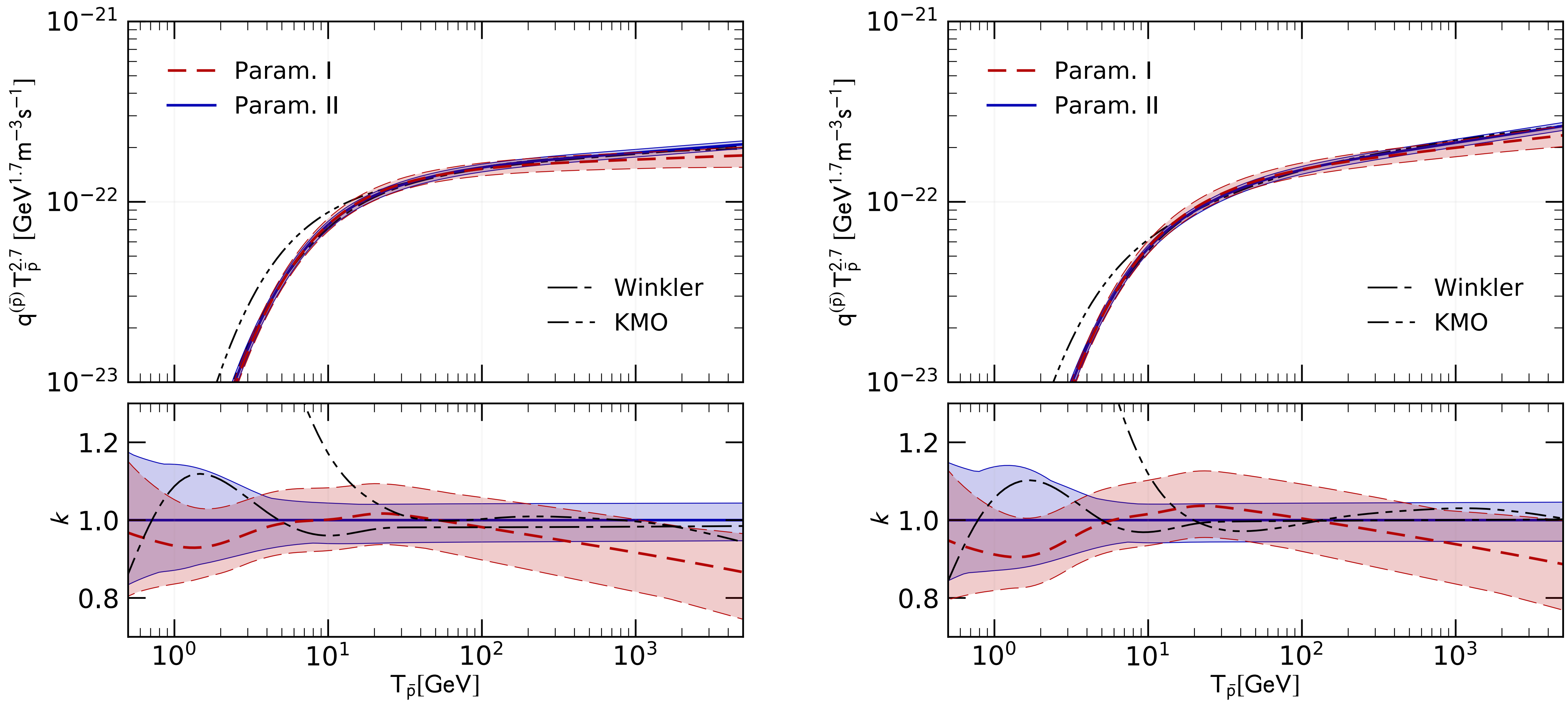
Parametrization I



LHCb data agree better with one of the two pp parameterizations.
They select the high energy behavior of the Lorentz invariant cross section

The antiproton source spectrum

Korsmeier, FD, Di Mauro, 1802.03030, PRD i2018



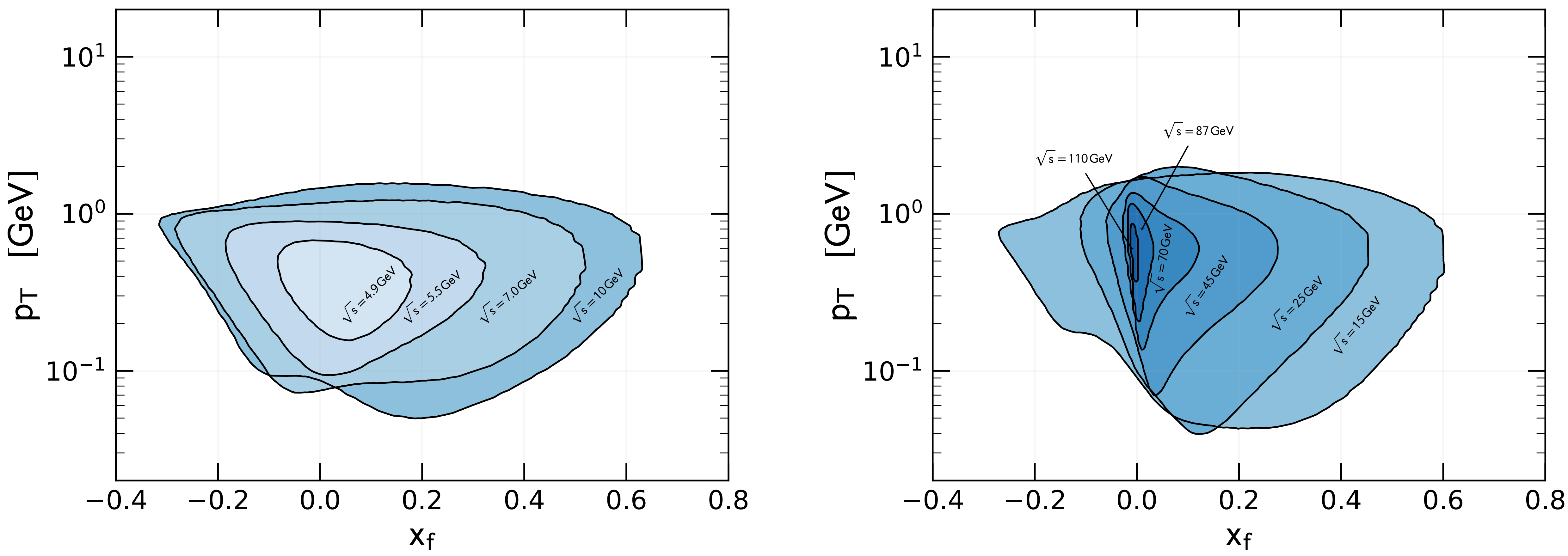
Param II is preferred by the fits.

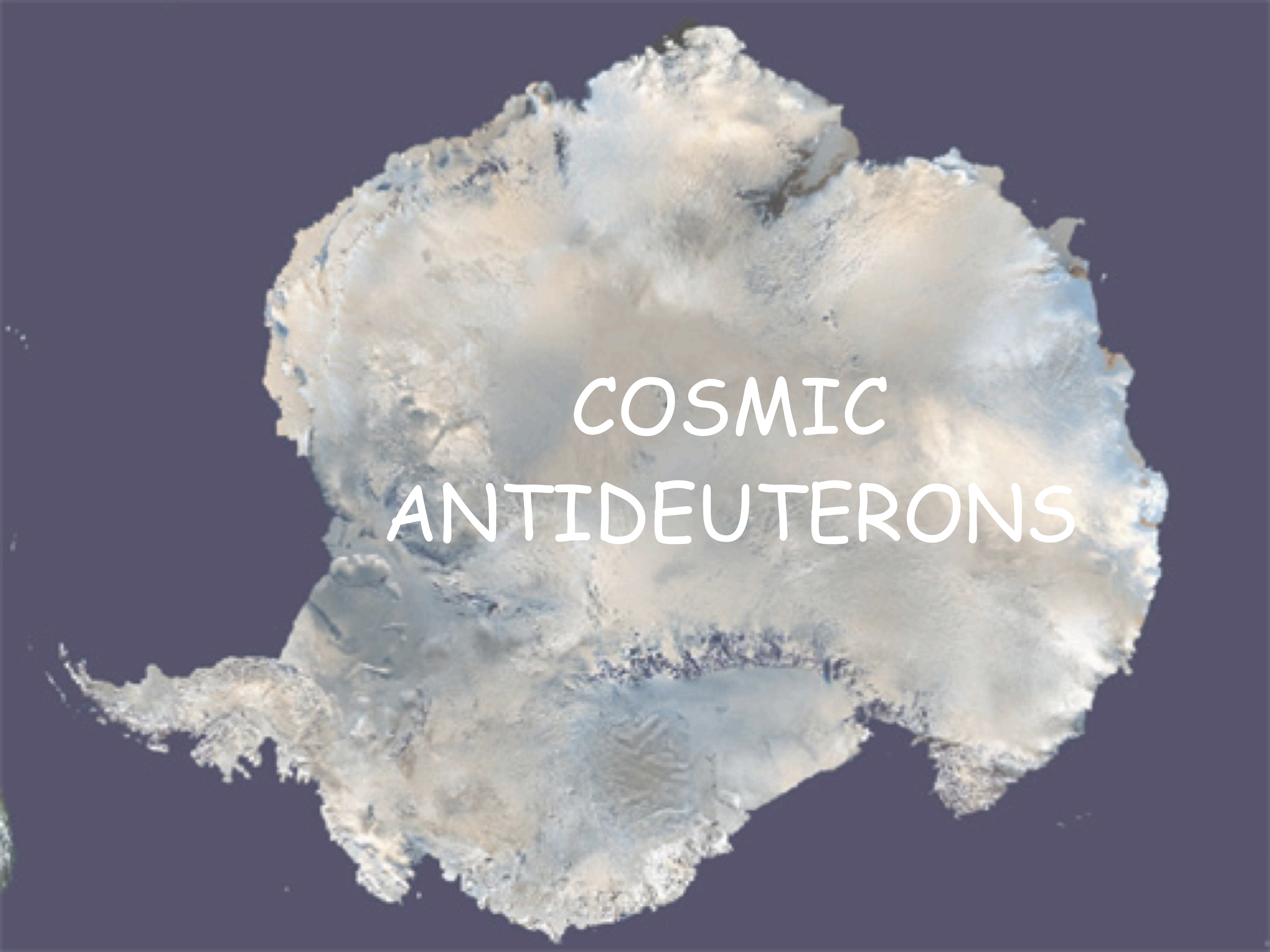
The effect of LHCb data is to select a h.e. trend of the pbar source term.

A harder trend is preferred.

Uncertainties still range about 10-15%, and increase at low energies.

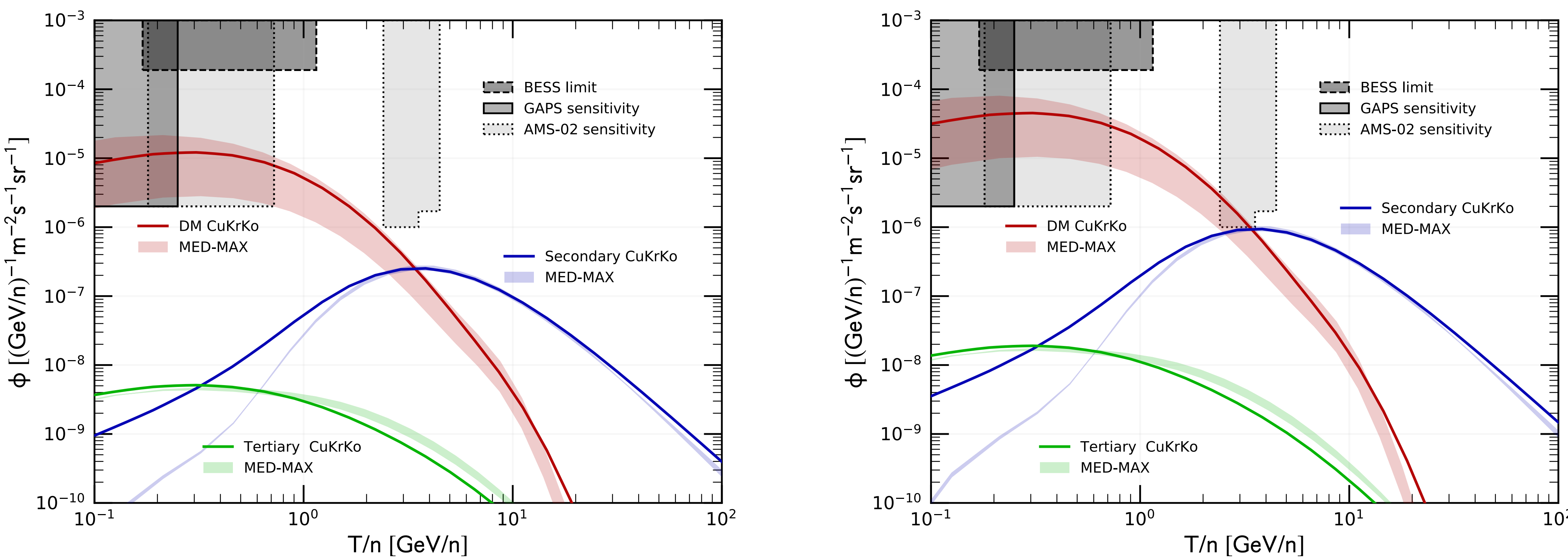
For next generation experiments





COSMIC ANTIDEUTERONS

Possible **antideuteron** verification of Dark Matter hint in antiprotons

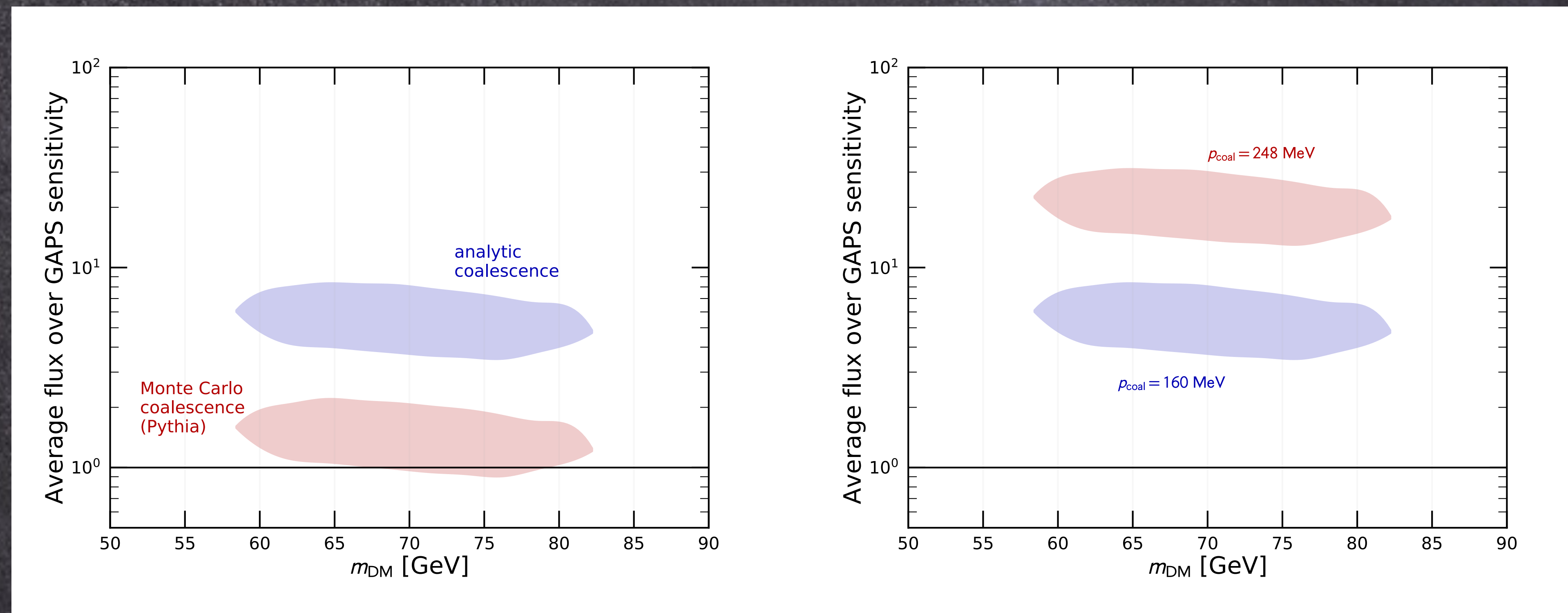


DM antiprotons possibly hidden in AMS data are potentially testable by AMS and GAPS

Uncertainties on the detection predictions

FD, Fornengo, Korsmeier, PRD 2018

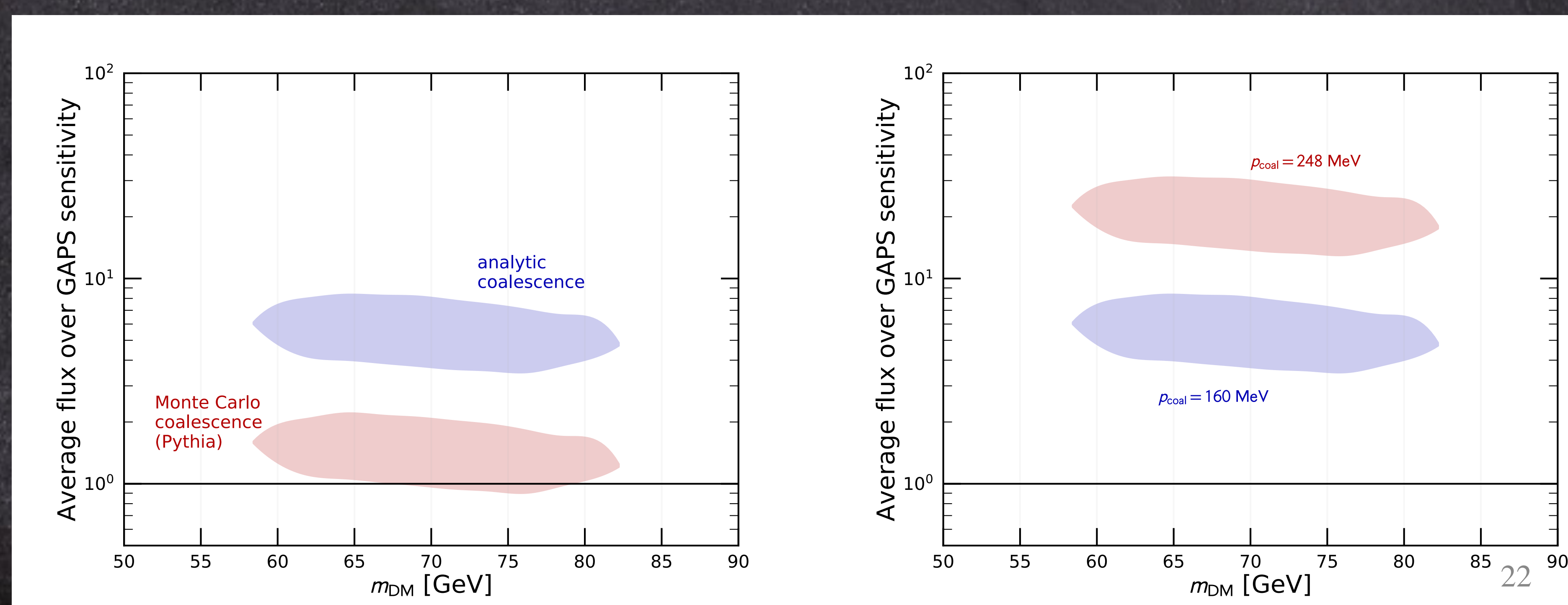
Coalescence Model:
a factor > 10
(does not affect pbar flux)



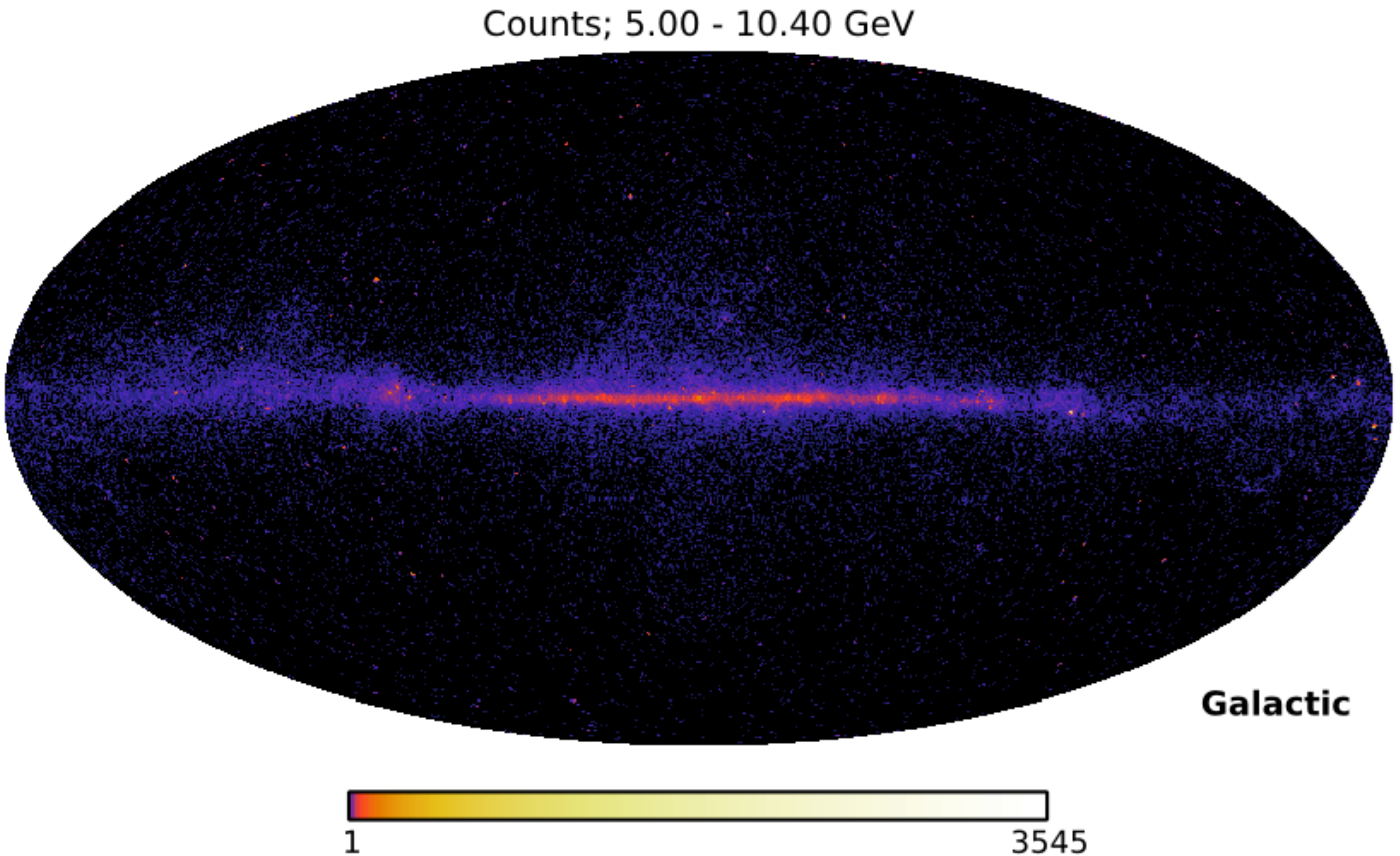
(a) Coalescence model

(b) Coalescence momentum

Propagation models:
a factor > 10
(affects pbar flux)



The invaluable gamma-ray sky



The photon count composition

Emission of gamma-rays is predicted from:

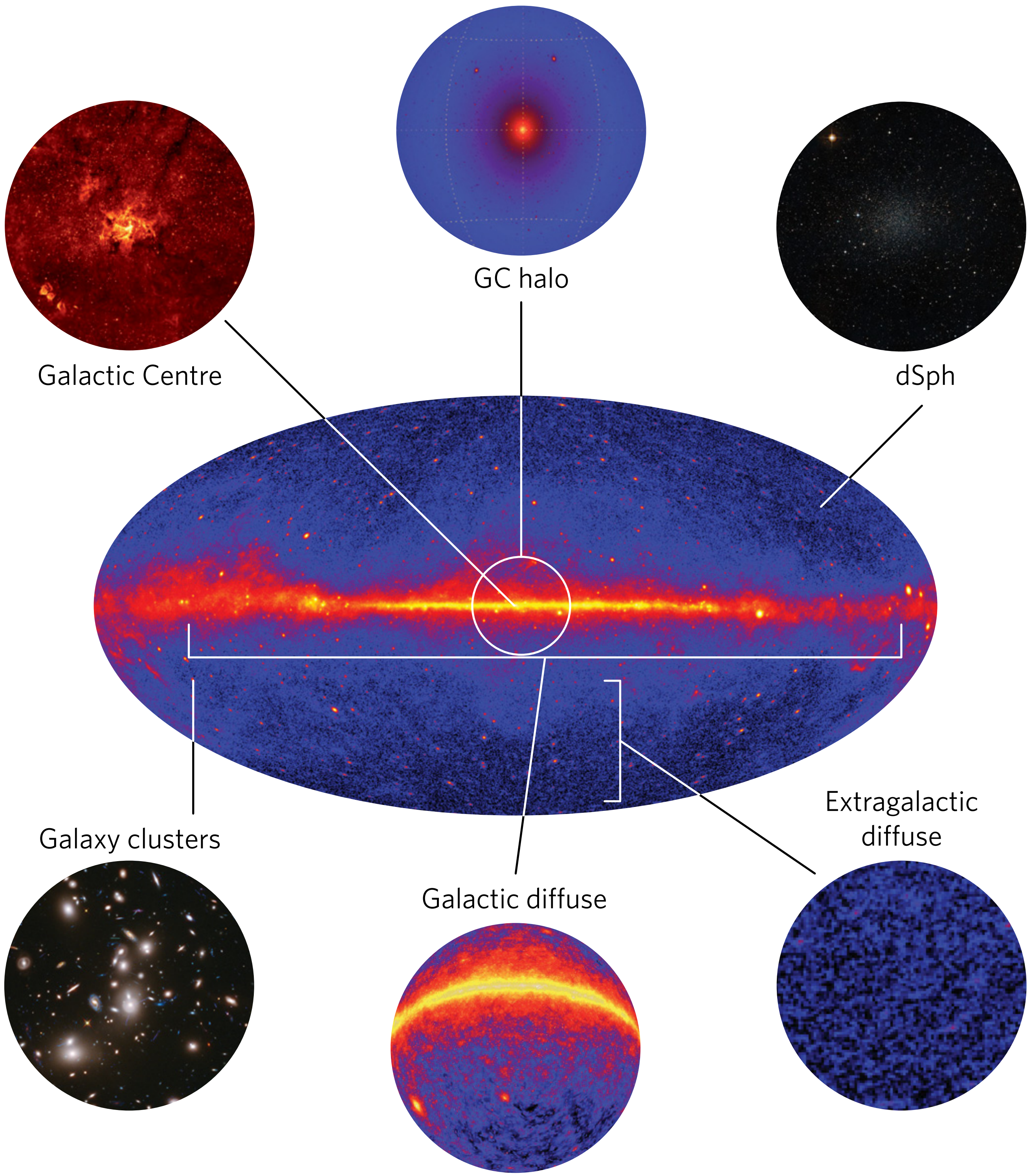
- The **Galactic** gas (HI, HII, DNG): π^0 decay
- A **Galactic** Inverse Compton (IC) photon population
- An isotropic (mostly extragalactic) background

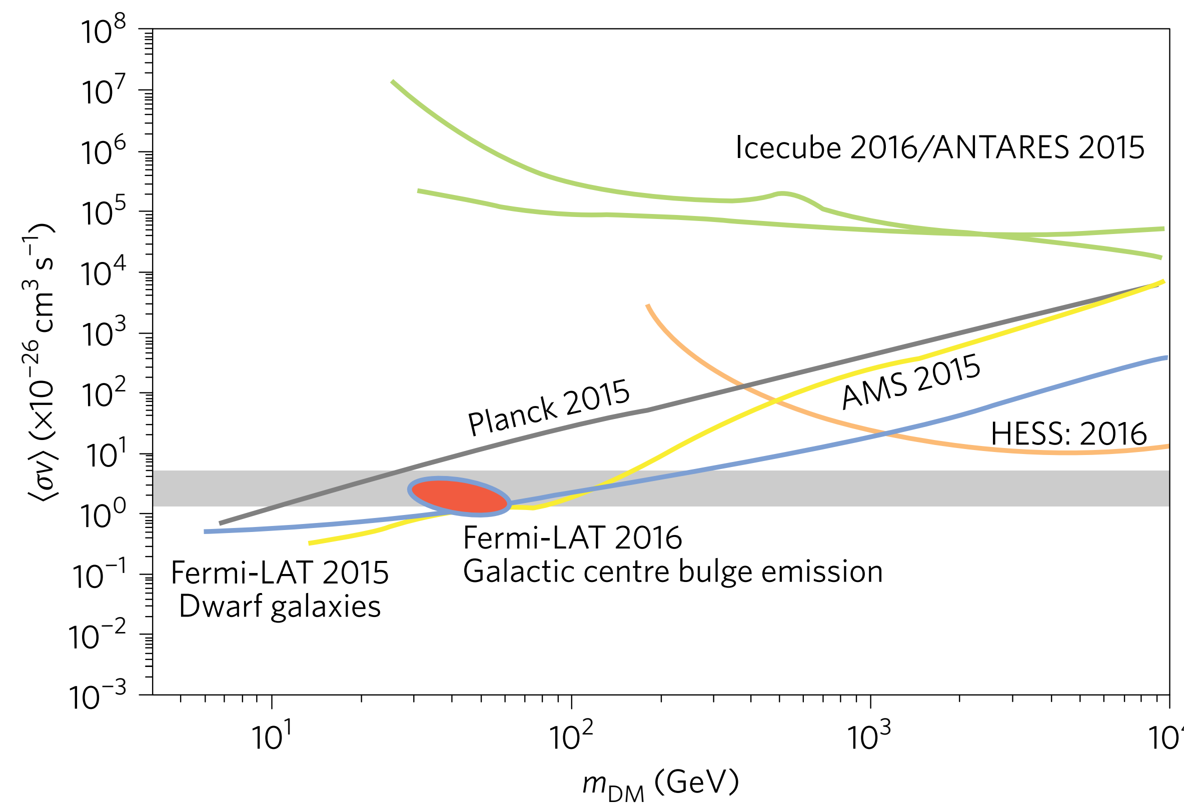
- Point sources
- Extended sources (included Fermi Bubbles and Loop I)
- Sun and Moon
- Residual Earth Limb (negligible for E> 200 MeV)
- **Diffuse emission from Dark Matter annihilation**

The diffuse γ-ray emission of the Galaxy dominates over point sources (x 5 at E > 50 MeV), 50% from latitudes $|b|<6^{o}$

Results from gamma rays

Conrad & Reimer 2017





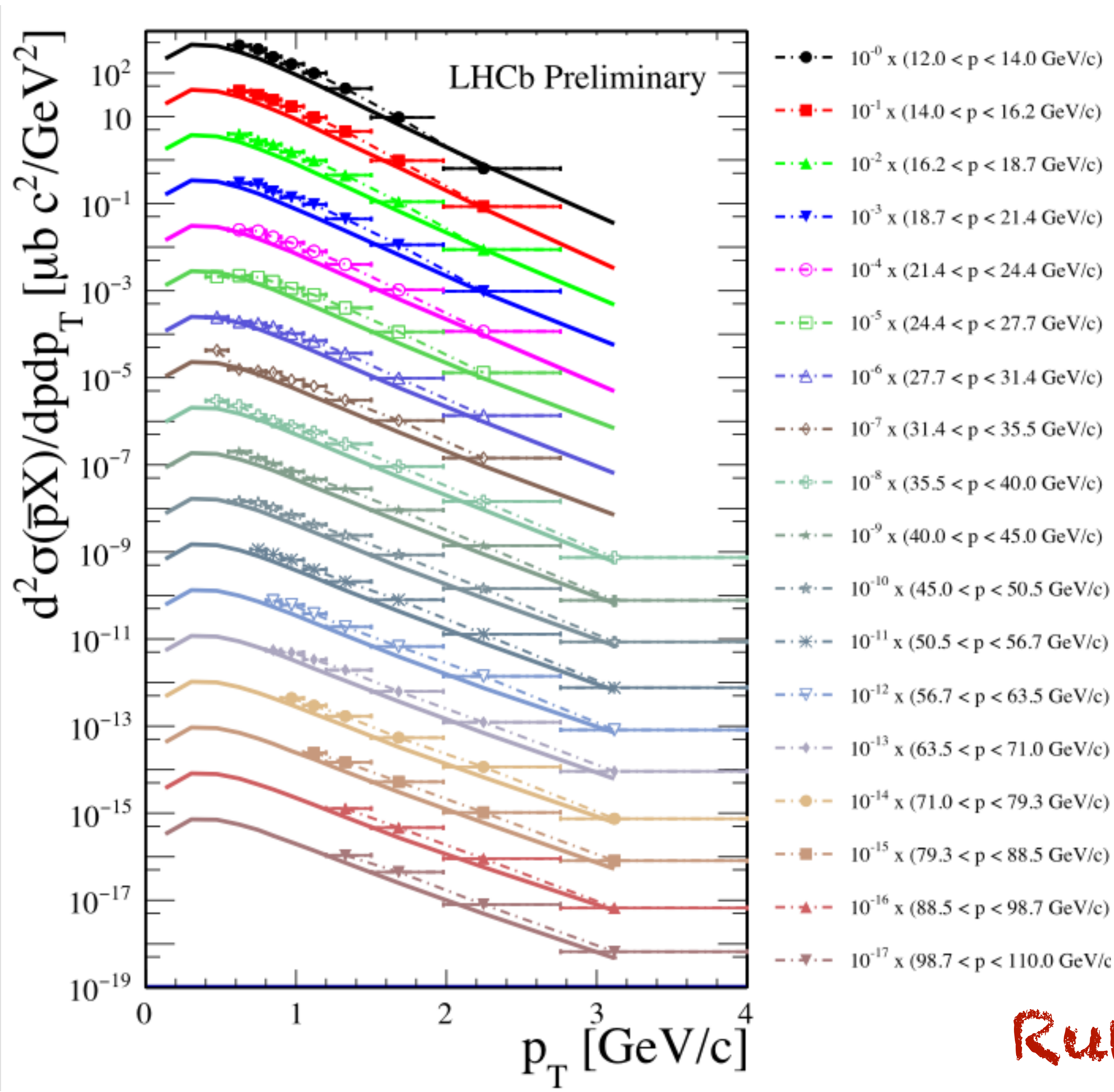
So far no clear excess ascribable to DM
Dwarf galaxies, baryon suppressed, are the best places to find γ rays from halo DM

Conclusions

- Data from space (cosmology; cosmic charged and gamma rays) induce a remarkable progress in understanding our Galaxy. Its data reach unprecedented precision (few %).
- No clear excess due to DM is seen by indirect detection means
- The production cross sections for secondary nuclei are often the main source of theoretical uncertainty
- High energy physics is addressing new data at the service of high precision cosmic ray data
- Improvements in calculations of the nuclear cross sections will certainly remain data driven in the near future

LHCb pHe —> p-X cross section data

First data ever has been collected by LHCb in fixed target mode



Result for **prompt** production (excluding weak decays of hyperons)

The total inelastic cross section is also measured to be

$$\sigma_{inel}^{LHCb} = (140 \pm 10)\ \text{mb}$$

The EPOS LHC prediction

[T. Pierog at al, Phys. Rev. C92 (2015), 034906]

is 118 mb, ratio is 1.19 ± 0.08.

Run at 4 TeV p beam energy is under analysis by the collaboration

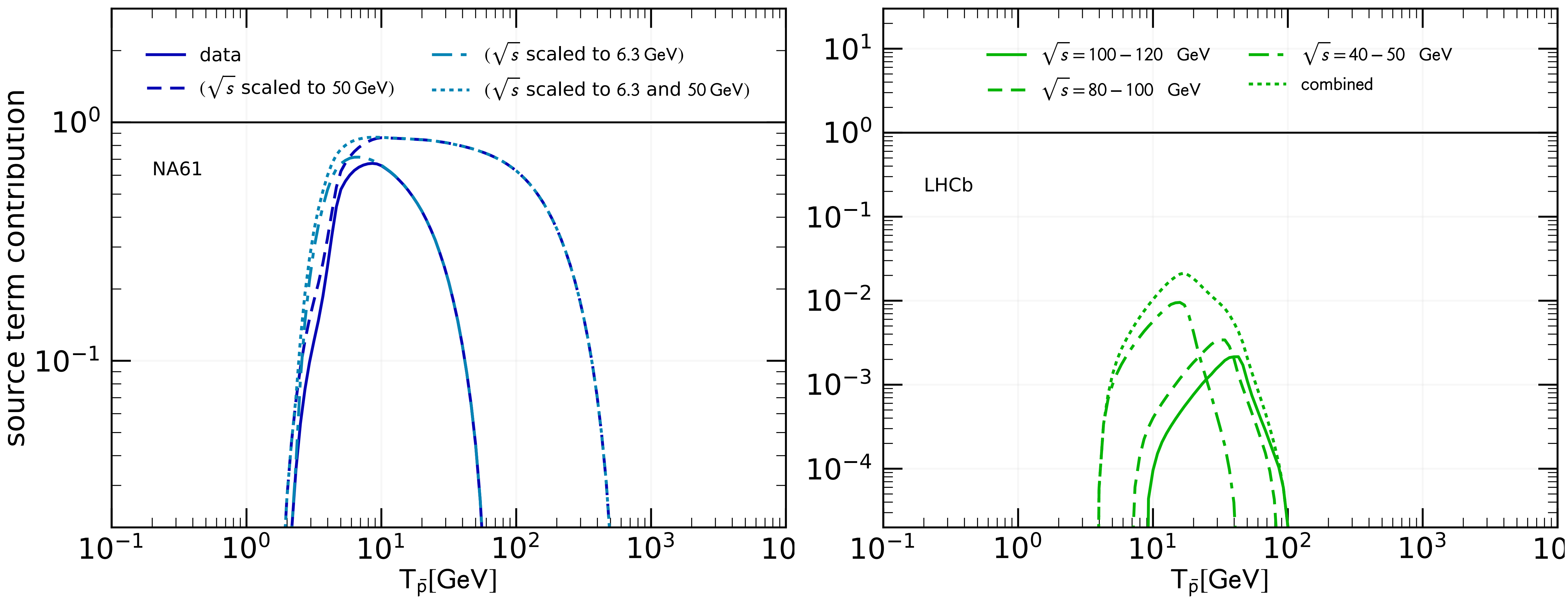
General idea for matching the accuracy

$$\{\sqrt{s}, x_{\mathrm{R}}, p_{\mathrm{T}}\} \qquad \{T, T_{\bar{p}}, \cos(\theta)\}$$

$$\frac{d\sigma}{dT_{\bar{p}}}(T, T_{\bar{p}}) = 2\pi p_{\bar{p}} \int_{-1}^{1} d\cos(\theta)\ \sigma_{\mathrm{inv}}$$

$$= 2\pi p_{\bar{p}} \int_{-\infty}^{\infty} d\eta\ \frac{1}{\cosh^2(\eta)}\,\sigma_{\mathrm{inv}} \qquad \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Predictions for future extensions of experiments



Re-analysis of the cross section parameterization

- Fit of two most recent (analytic) parametrizations for antiproton production in *pp* collisions
- Fit of *pA* parametrization by rescaling from *pp*

Experiment	CM-Energy [GeV]	Channel
NA49	17.3	*pp*
NA61	7.7, 8.8, 12.3, 17.3	*pp*
Dekkers	6.1, 6.7	*pp*
LHCb	110	*p*He
NA49	17.3	*p*C

χ^2-fit of the *pp* parametrization to *pp* data

↓ Fix the *pp* parameters

χ^2-fit of the *pA* rescaling factor to *pA* data

Param. I

$$\sigma_{\rm inv}(\sqrt{s}, x_{\rm R}, p_{\rm T}) = \sigma_{\rm in}(1-x_{\rm R})^{C_1} \exp(-C_2 x_{\rm R}) \times \left[C_3 \left(\sqrt{s}\right)^{C4} \exp(-C_5 p_{\rm T}) + C_6 \left(\sqrt{s}\right)^{C7} \exp\left(-C_8 p_{\rm T}^2\right)\right]$$

Param. II

$$\sigma_{\rm inv}(\sqrt{s}, x_{\rm R}, p_{\rm T}) = \sigma_{\rm in} R\, C_1 (1-x_{\rm R})^{C_2} \times \left[1 + \frac{X}{\rm GeV}(m_T - m_p)\right]^{\frac{-1}{C_3 X}}$$

$$R = \begin{cases} 1 & \sqrt{s} \geq 10\,\mathrm{GeV} \\ \left[1 + C_5 \left(10 - \frac{\sqrt{s}}{\rm GeV}\right)^5\right] \times \exp\left[C_6 \left(10 - \frac{\sqrt{s}}{\rm GeV}\right)^2 \times (x_{\rm R} - x_{R,\rm min})^2\right] & \text{elsewhere} \end{cases}$$

$$\sigma_{\rm inv}^{pA}(\sqrt{s}, x_f, p_{\rm T}) = f^{pA}(A, x_f, \mathcal{D})\; \sigma_{\rm inv}^{pp}(\sqrt{s}, x_{\rm R}, p_{\rm T})$$

$$\sigma_{\rm inv}^{\rm Galaxy} = \sigma_{\rm inv}(2 + \Delta_{\rm IS} + 2\Delta_{\Lambda}$$