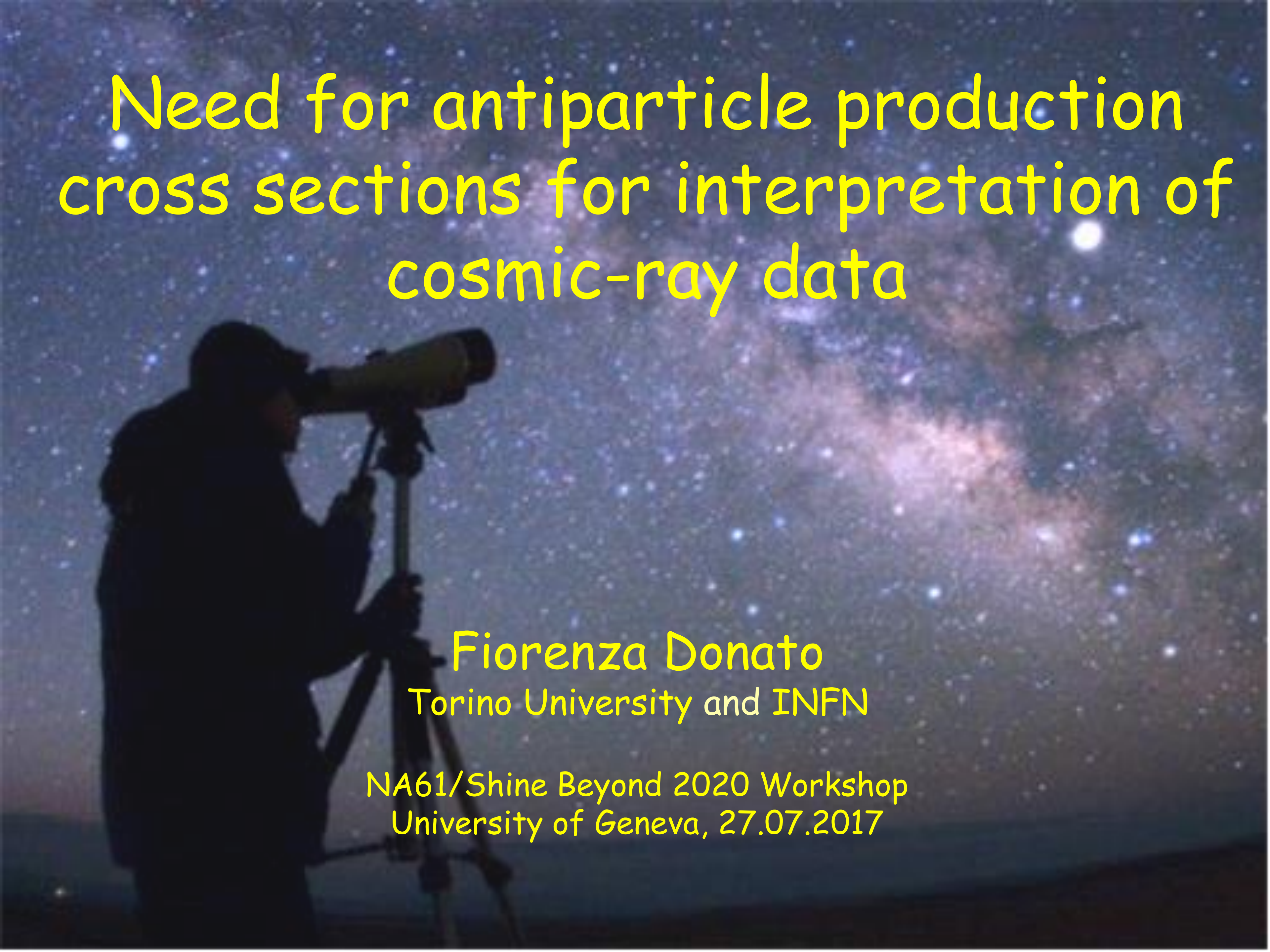
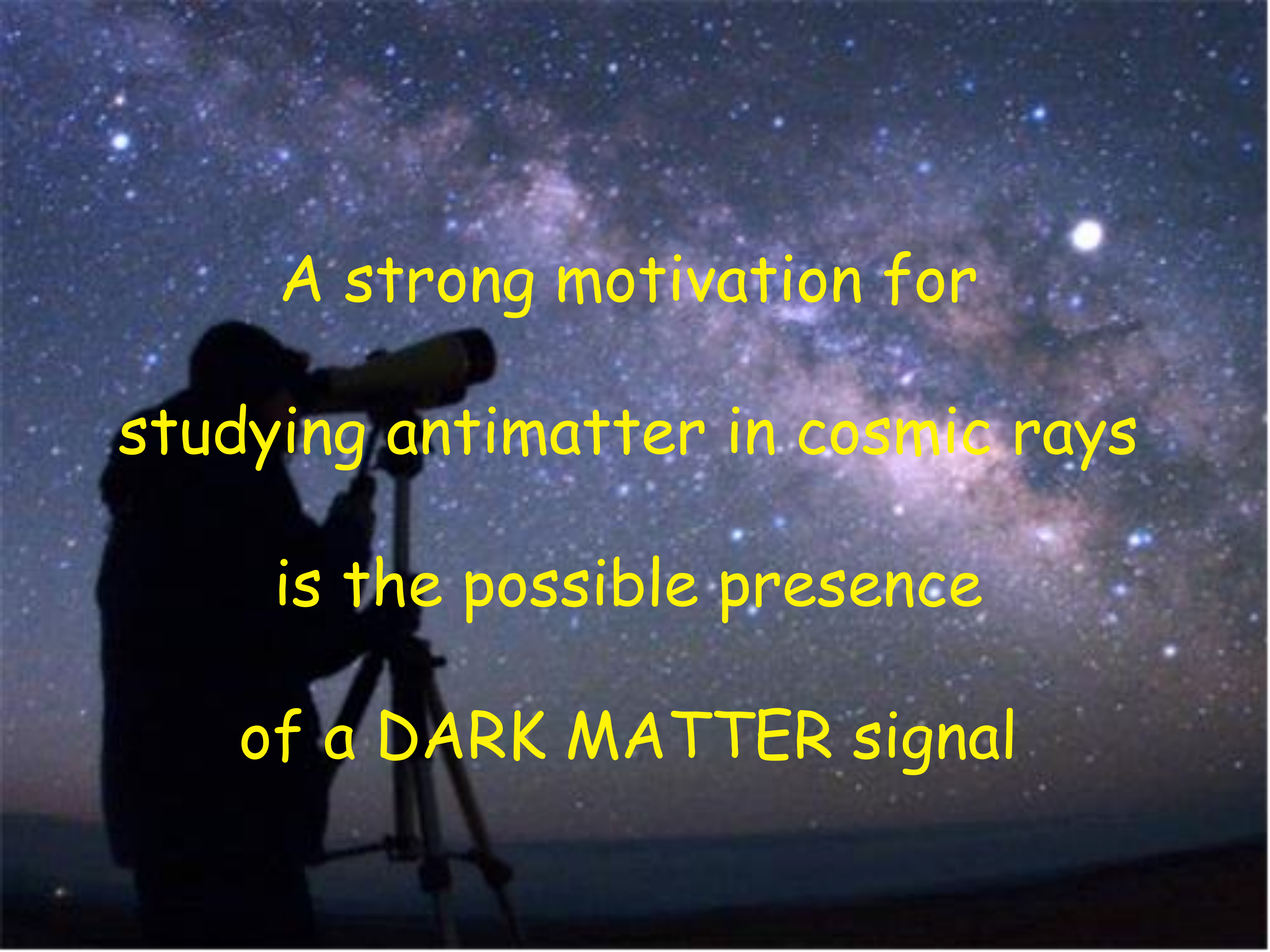


Need for antiparticle production cross sections for interpretation of cosmic-ray data

Fiorenza Donato
Torino University and INFN

NA61/Shine Beyond 2020 Workshop
University of Geneva, 27.07.2017



A strong motivation for

studying antimatter in cosmic rays

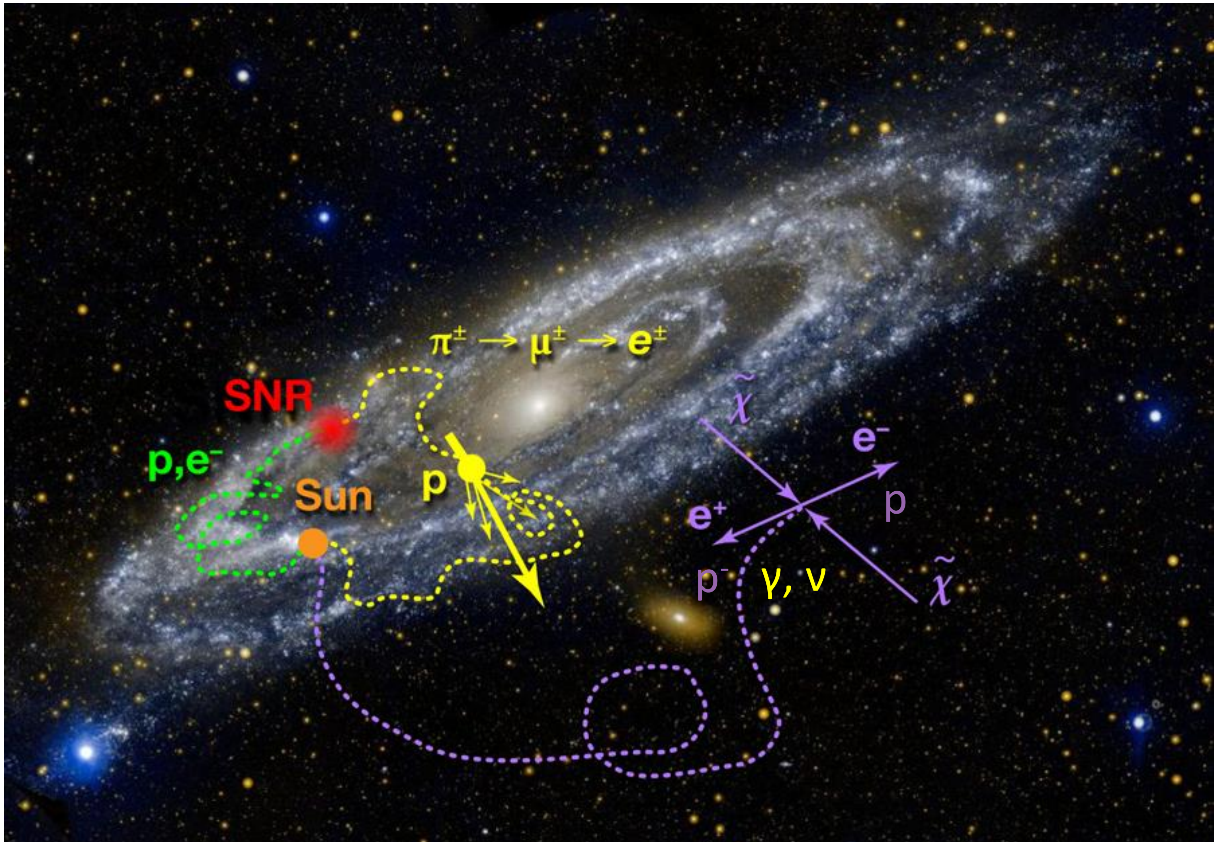
is the possible presence

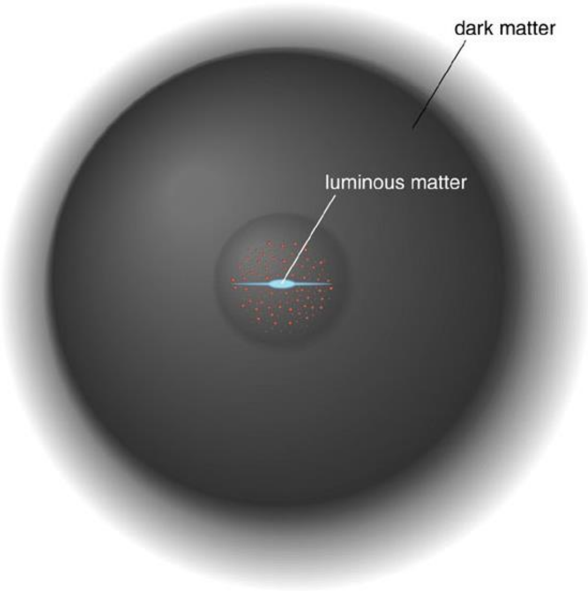
of a DARK MATTER signal

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.

Tine DM signals are searched for in cosmic antimatter and photons





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!

Antimatter sources from DARK MATTER

Annihilation

$$\mathcal{Q}_{\rm ann}(\vec{x}, E) = \epsilon \left(\frac{\rho(\vec{x})}{m_{DM}} \right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN^f_{e^\pm}}{dE}$$

Decay

$$\mathcal{Q}_{\rm dec}(\vec{x}, E) = \left(\frac{\rho(\vec{x})}{m_{DM}} \right) \sum_f \Gamma_f \frac{dN^f_{e^\pm}}{dE}$$

- $\rho(\vec{x})$ DM density in the halo of the MW
- m_{DM} DM mass
- $\langle \sigma v \rangle_f$ thermally averaged annihilation cross section in SM channel f
- Γ_f DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

Cosmic Rays (CRs) in the Galaxy

Primaries = produced in the sources:
Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)
e^+, p^+, d^+ from Dark Matter annihilation

Secondaries = NOT present in sources, produced by **spallation** of primary CRs (p, He, C, O, Fe) on the interstellar medium (ISM)
Nuclei: LiBeB, sub-Fe; e^+, p^+, d^+; ...

All species propagate in the Galaxy, dominated by diffusion on the magnetic fields and/or by intense energy losses (leptons)

See talk by D. Maurin

The solution to the diffusion equation: the role of cross sections

$$N^j(r,z) = \exp\left(\frac{V_c z}{2K}\right) \sum_{i=0}^{\infty} \frac{\bar{Q}^j_i}{A^j_i} \frac{\sinh\left[\frac{S^j_i (L-z)}{2}\right]}{\sinh\left[\frac{S^j_i L}{2}\right]} J_0\left(\zeta_i \frac{r}{R}\right)$$

$$\bar{Q}^j_i \equiv q^j_0 Q(E) \hat{q}_i + \sum_k^{m_k > m_j} \tilde{\Gamma}^{kj} N^k_i(0)$$

$$S^j_i \equiv \left(\frac{V_c^2}{K^2} + 4\frac{\zeta_i^2}{R^2} + 4\frac{\Gamma^{N^j}_{rad}}{K}\right)^{1/2}$$

$$A^j_i \equiv 2h\tilde{\Gamma}^{tot}_{N^j} + V_c + K S^j_i \coth\left(\frac{S^j_i L}{2}\right)$$

$\Gamma^{kj} = n_{ISM}\, \boldsymbol{\sigma}^{\mathbf{kj}}\, v$

Production

$\Gamma^{kj} = n_{ISM}\, \boldsymbol{\sigma}^{\mathbf{tot}}\, v$

Destruction

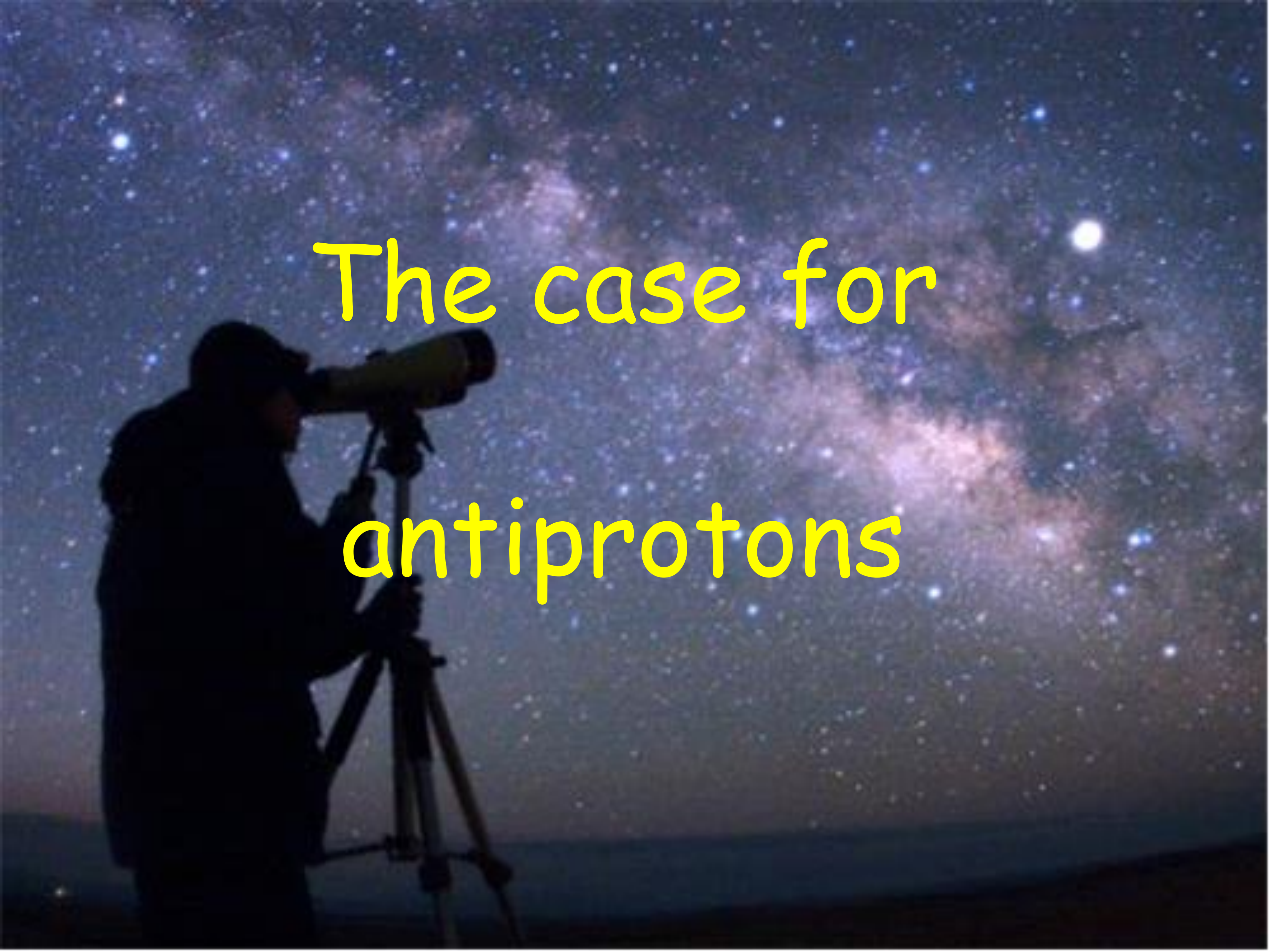
Production cross sections in the galactic cosmic ray modeling

H, He, C, O, Fe,… are present in the supernova remnant surroundings, and directly accelerated into the the interstellar medium (ISM)

All the other nuclei (Li, Be, B, p-, and e+, gamma, …) are produced by spallation of heavier nuclei with the atoms (H, He) of the ISM

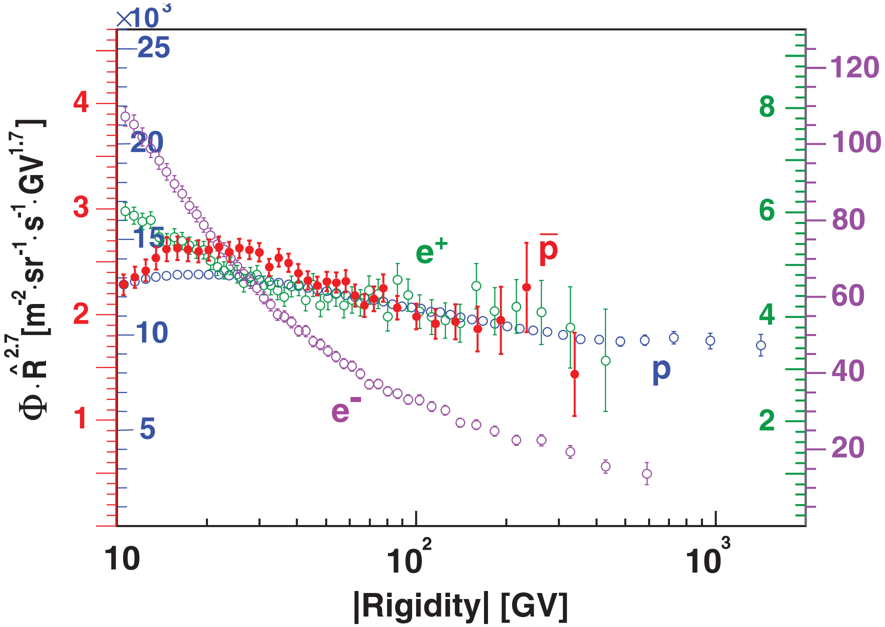
We need all the cross sections σ^{kj} - from Nichel down to proton - for the production of the j-particle from the heavier k-nucleus scattering off the H and He of the ISM

Remarkable for DARK MATTER signals is productions of: antiproton, antideuteron, positron and gamma rays.

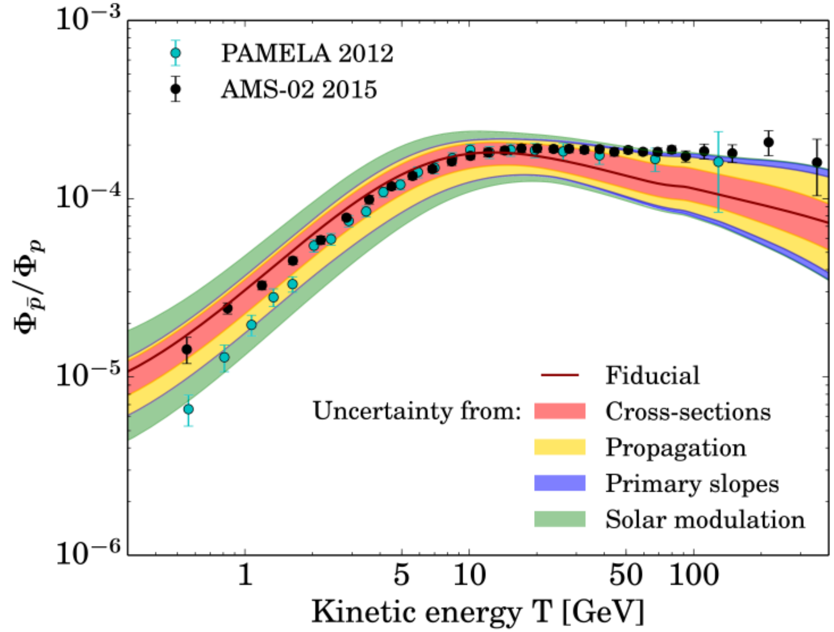

The case for
antiprotons

Antiproton data as of 2017

AMS Coll., PRL 2016



Giesen+ 1504.04276



AMS-02 results from below GeV up to 400 GeV
Could be explained by secondary production in the Milky Way

The most relevant theoretical uncertainty is due to production CROSS SECTIONS

Antiproton production cross sections

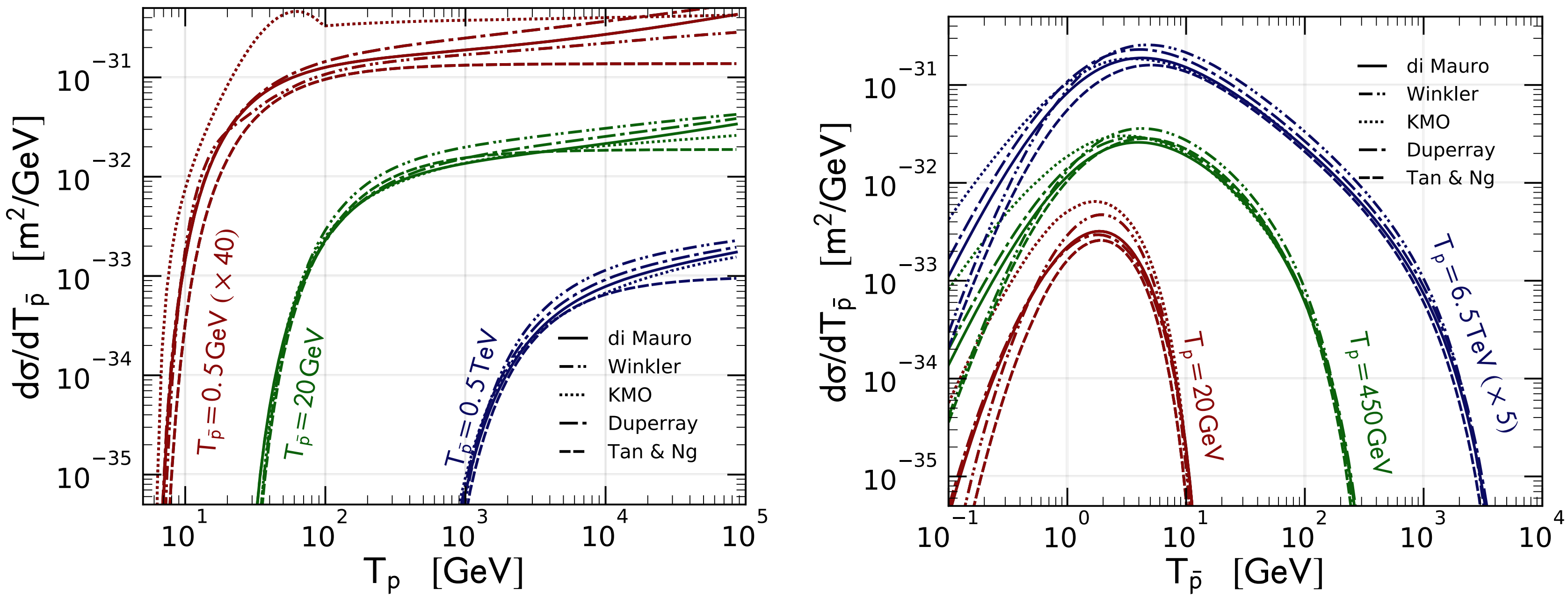
FD, Korsmeier, Di Mauro PRD 2017

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

Source term

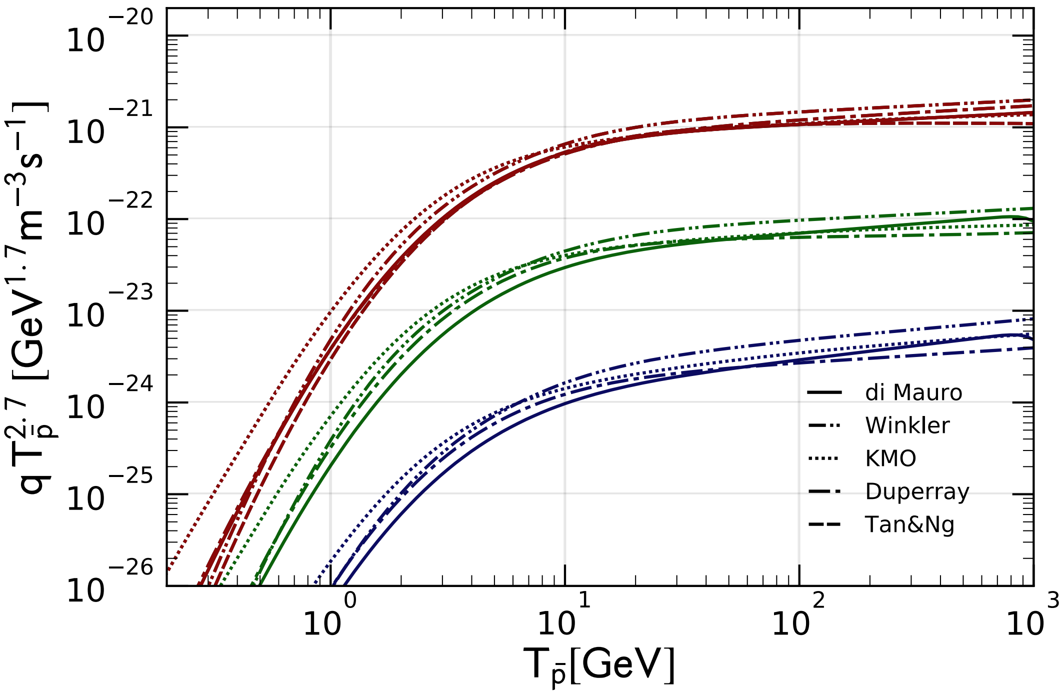
i, j = proton, helium
(both in the CRs and in the ISM)

pp



- Reasonable agreement for 10 GeV <T <100 GeV
- Deviations for T<10 GeV

The antiproton source term



Uncertainty in

the cross sections

reflect directly

on the source term

and then in the flux

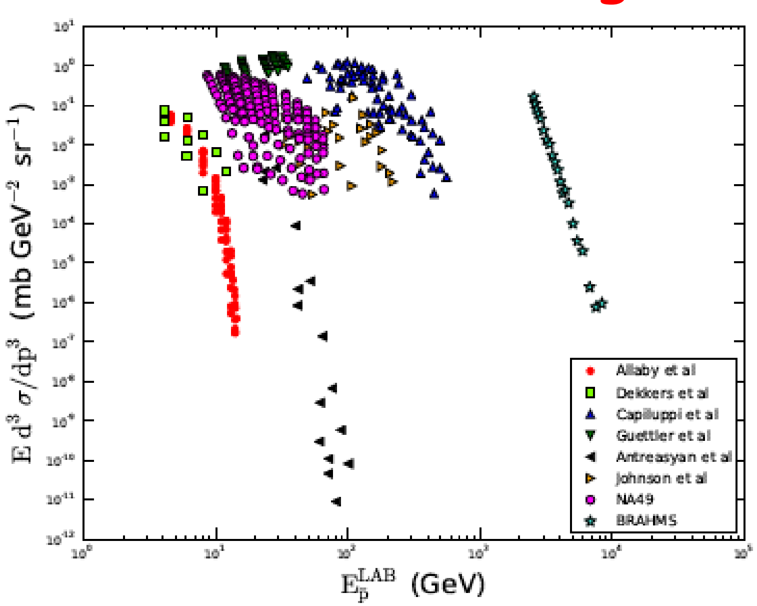
predicted at the Earth

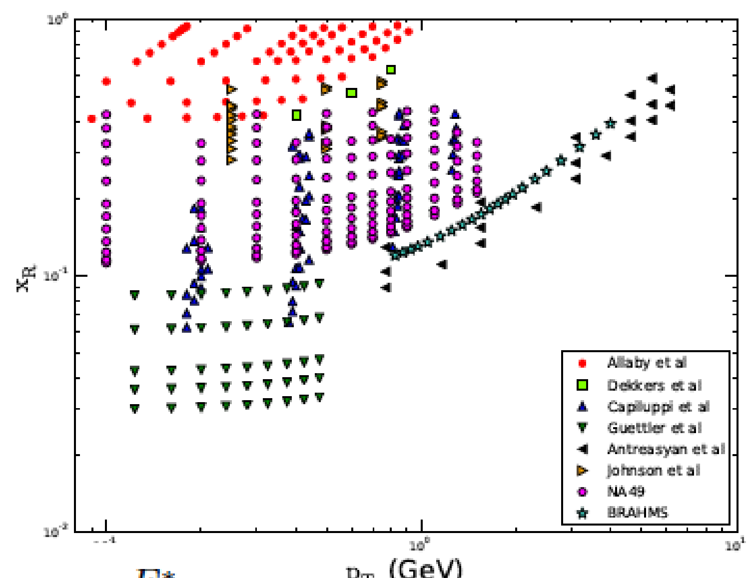
p-p→pbar cross section data

Di Mauro, FD, Goudelis, Serpico PRD 2014, 1408.0288; Kappl, Winkler 1408.0299

$$q_{\bar{p}}^{pp}(E_{\bar{p}}) = \int_{E_{\rm th}}^{+\infty} \boxed{\frac{d\sigma_{p\,p\to\bar{p}}}{dE_{\bar{p}}}(E_p, E_{\bar{p}})} n_H (4\pi\Phi_p(E_p)) dE_p$$

Existing data on p-p → pbar + X





$$x_R = \frac{E^*_{\bar{p}}}{E^*_{\bar{p},\rm max}}$$

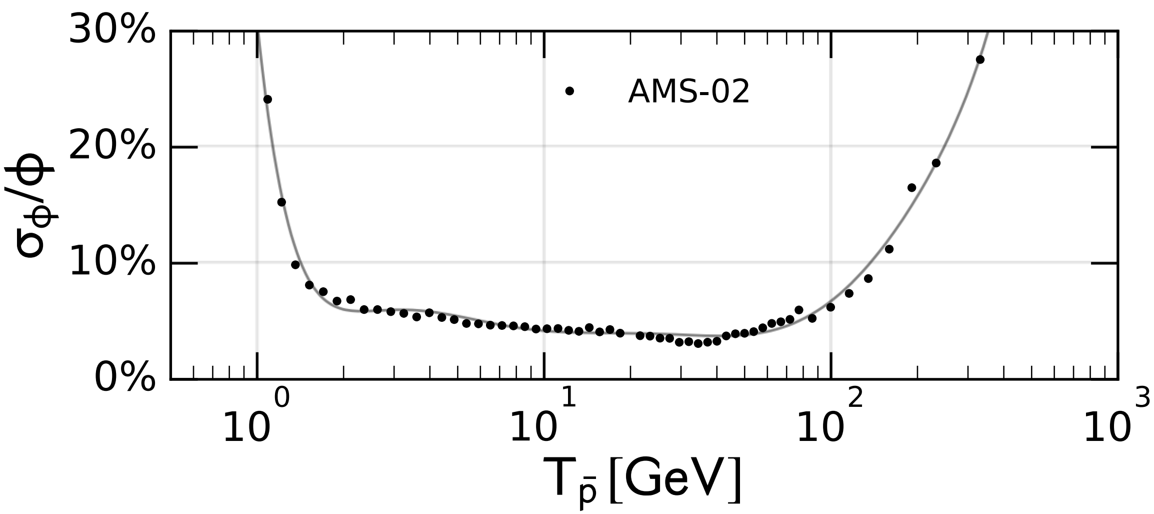
What do we need?

Requirement on the cross section

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

$$= 2\pi p_{\bar{p}} \int_{-\infty}^{\infty} d\eta \frac{1}{\cosh^2(\eta)} \sigma_{\mathrm{inv}}$$

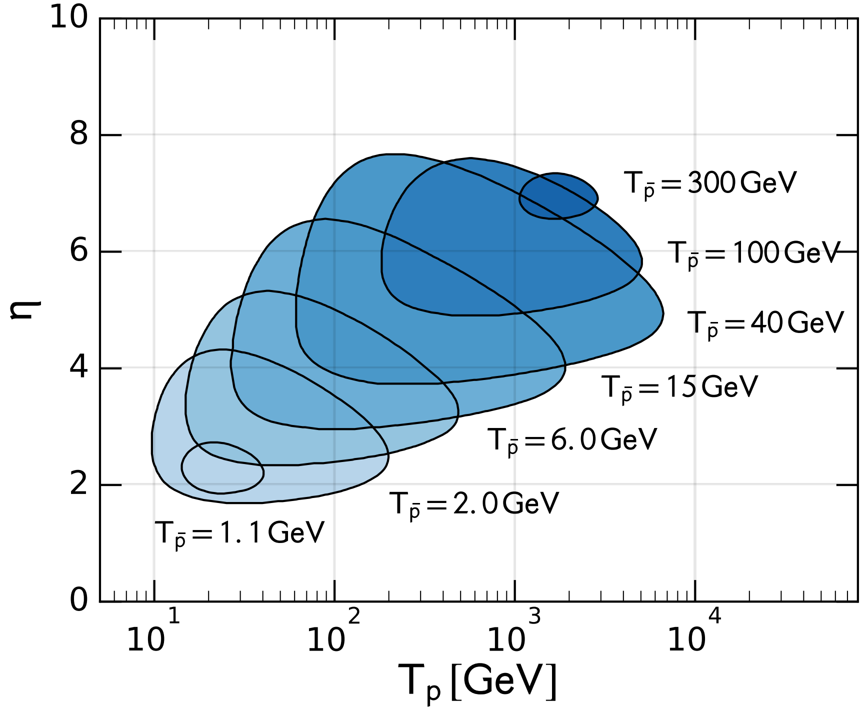
$$\{T, T_{\bar{p}}, \cos(\theta)\} \quad \{\sqrt{s}, x_{\mathrm{R}}, p_{\mathrm{T}}\}$$



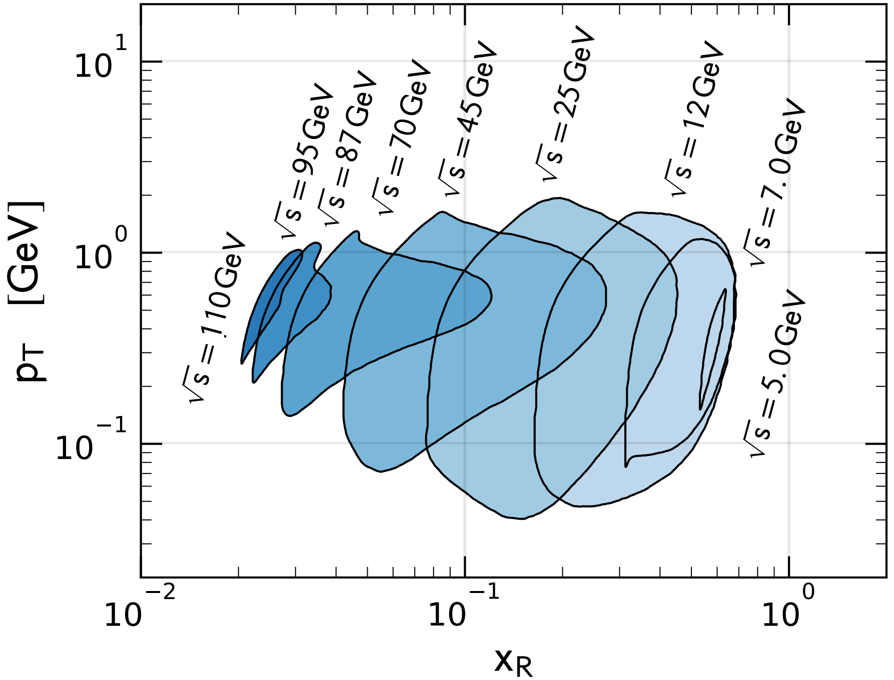
Which level of accuracy on cross section do we need in order to match (not exceed) the accuracy in CR data?

Parameter space to be covered

Fixed target

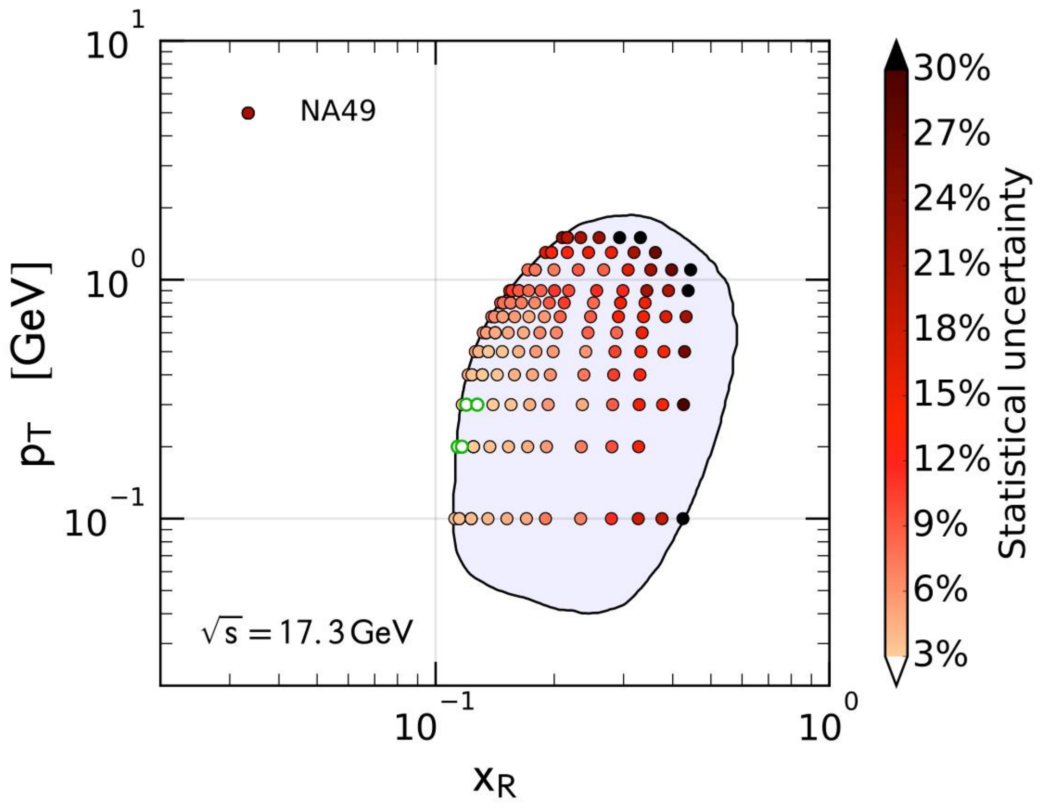


Lab frame



AMS02 accuracy is reached if pp→pbar cross section is measured with 3% accuracy inside the regions, 30% outside.

Comparison with pp data

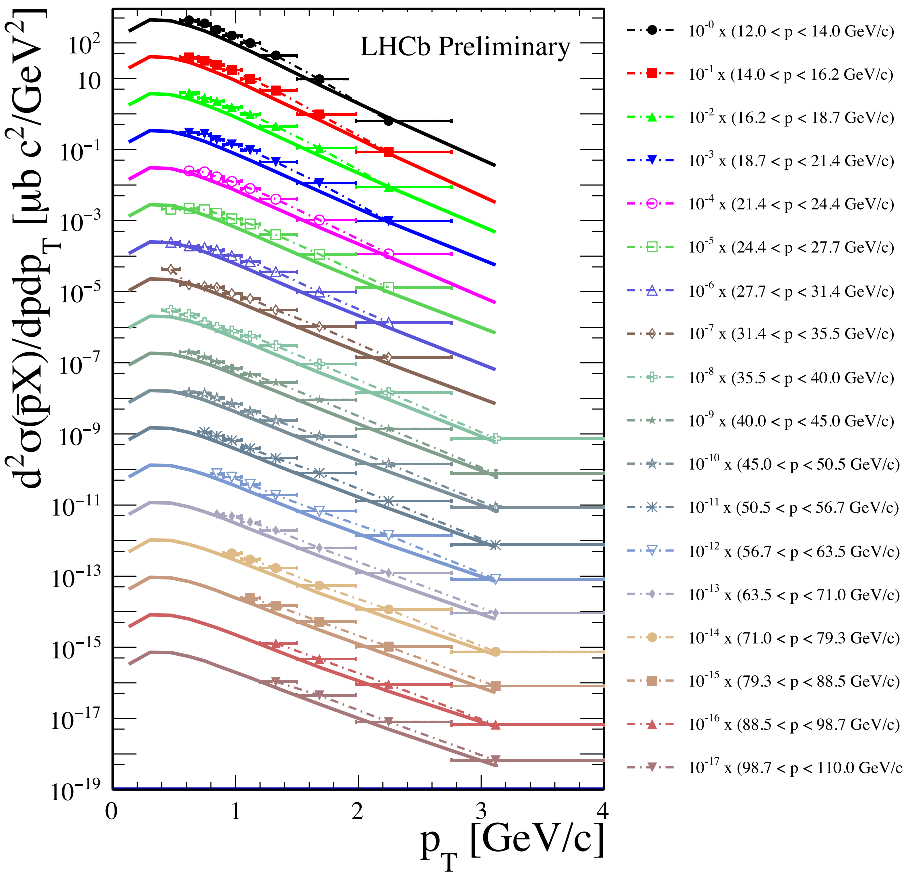


- The covered parameter space is appropriate
- The level of accuracy is not adequate
- NA61 data are strongly welcome

LHCb pHe → p- cross section data

G Graziani for LHCb, Moriond 2017

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

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

The EPOS LHC prediction

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

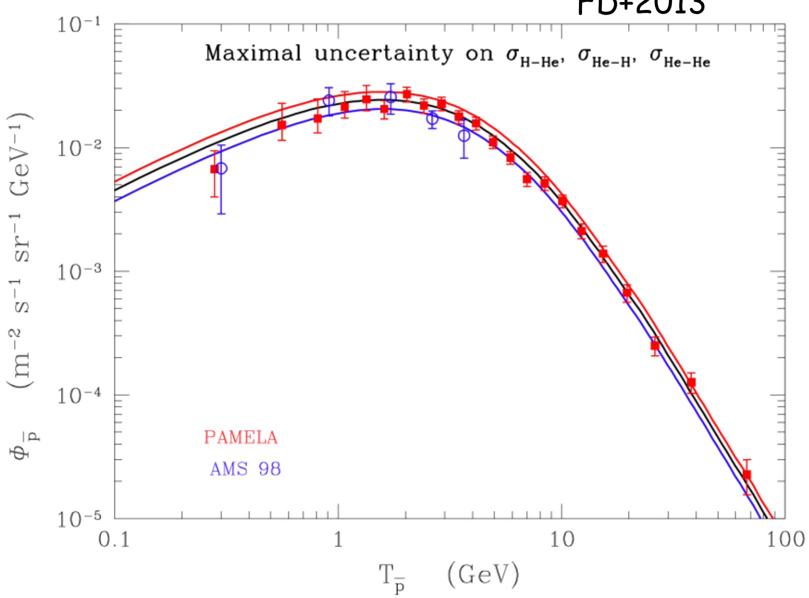
is 118 mb, ratio is 1.19 ± 0.08.

FD, Korsmeier, Di Mauro in preparation

Reactions involving helium & higher energies

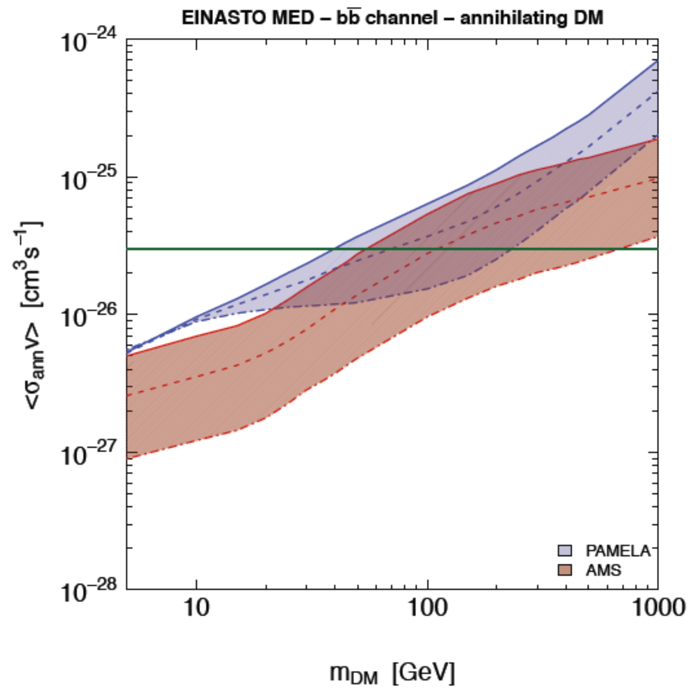
Uncertainties due to helium reactions range 40-50% on Secondary CR flux

FD+2013



Effect of cross section uncertainty on DARK MATTER interpretation

Fornengo, Maccione, Vittino JCAP2014



AMS-02 is providing data with much higher precision up to hundreds of GeV
Their interpretation risks to be seriously limited by nuclear physics

The case for

positrons

Sources of positrons in the Milky Way

Sources of e^+ and e^- in the Galaxy:

1. Secondary $e^+ e^-$: spallation of cosmic p and He on the ISM (H, He)
   * $p+H(He) \rightarrow p+\Delta^+ \rightarrow p+\pi^0$ & $n+\pi^+$ (mainly below 3 GeV)
   * $p+H(He) \rightarrow p+n+\pi^+$
   * $p+H(He) \rightarrow X + K^{\pm}$

2. Primary e- and e+ from Pulsars (PSR):
   pair production in the strong PULSAR magnetoshpere

3. Primary e- from SNR: 1° type Fermi acceleration mechanism

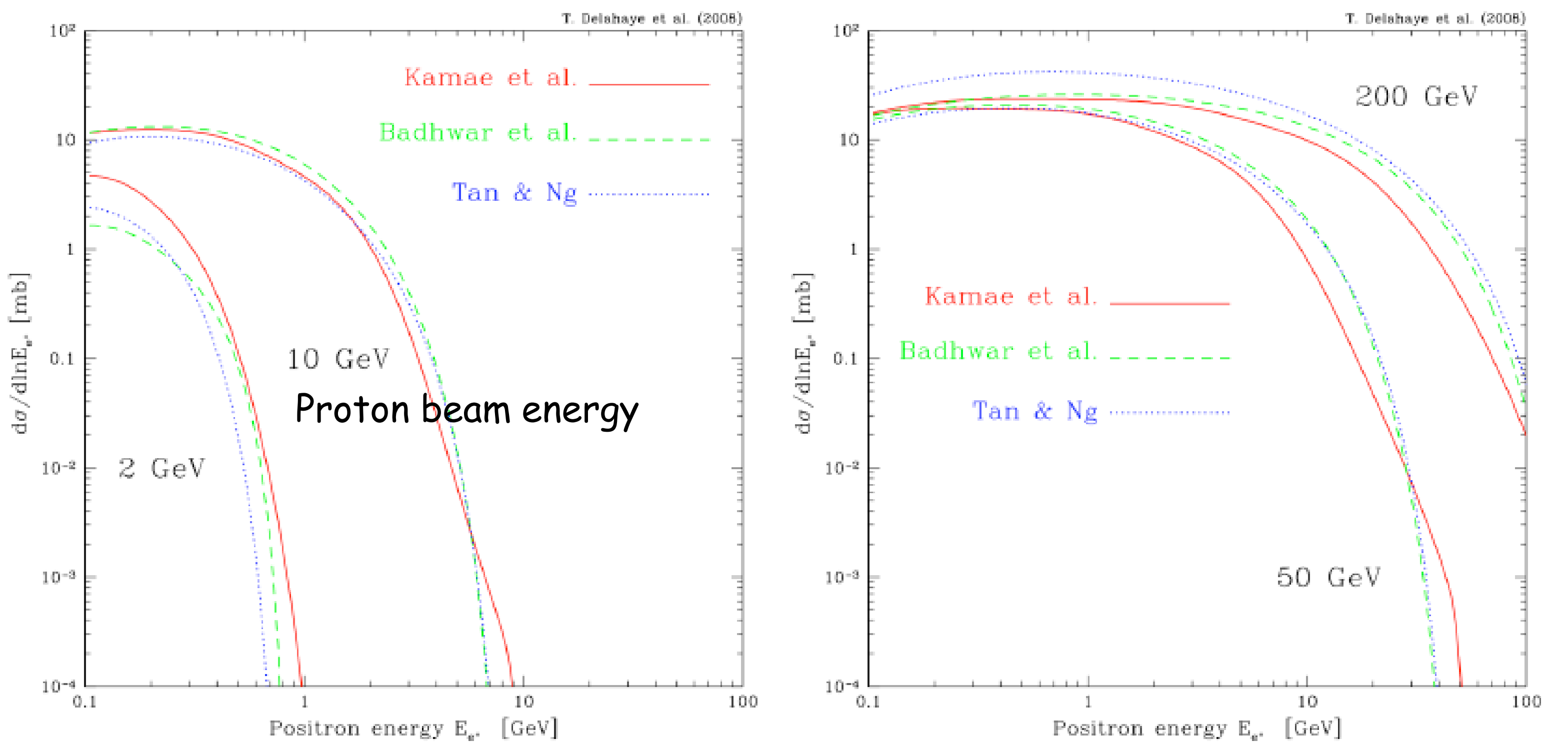
4. Primary $e^+ e^-$ from exotic sources (DARK MATTER)

Secondary positron production

Spallation of proton and helium nuclei on the ISM (H, He)

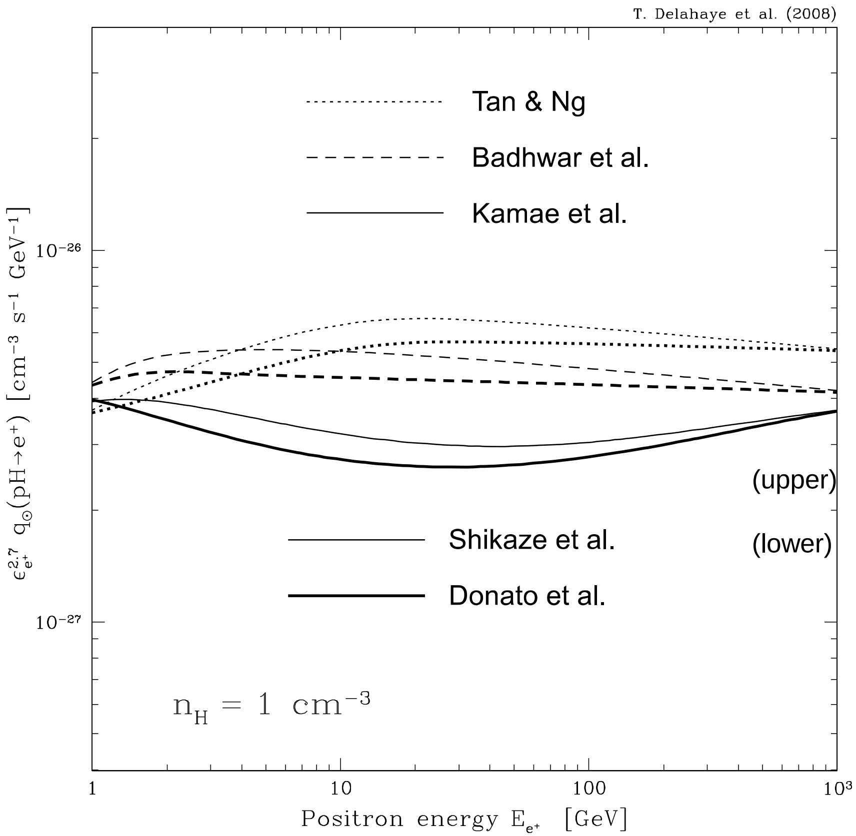
- $p+H \rightarrow p+\Delta^+ \rightarrow p+\pi^0$ & $n+\pi^+$ (mainly below 3 GeV)
- $p+H \rightarrow p+n+\pi^+$
- $p+H \rightarrow X + K^\pm$

Different parameterizations of $p+p \rightarrow e^+ + X$ cross

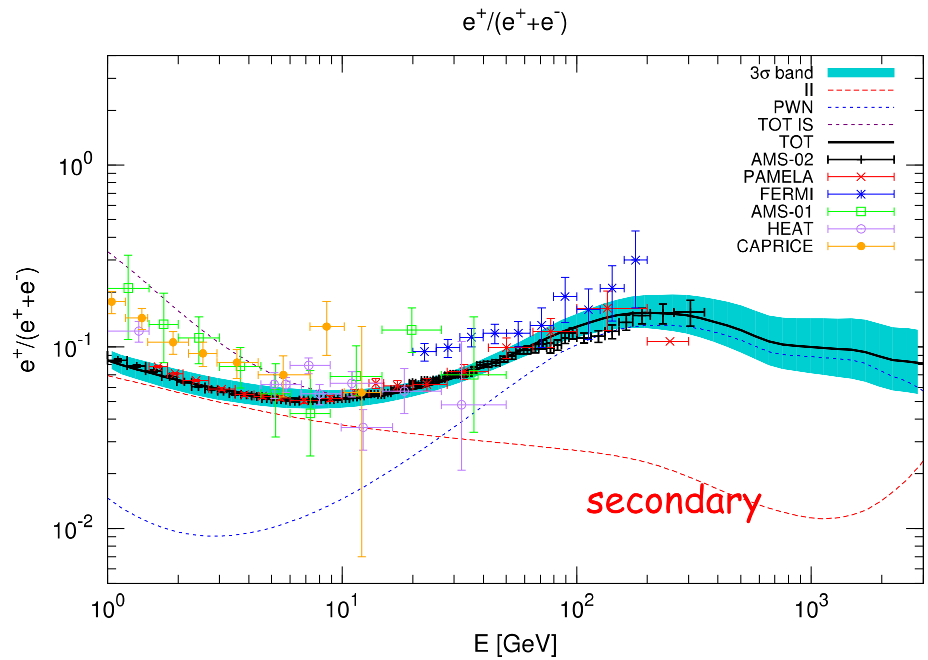


The positron source term

Uncertainties on the production cross sections up to factor 2



Secondary positrons relevant for E < 50 GeV



Data needed for p+p and p+He → e^+ + X

The case for

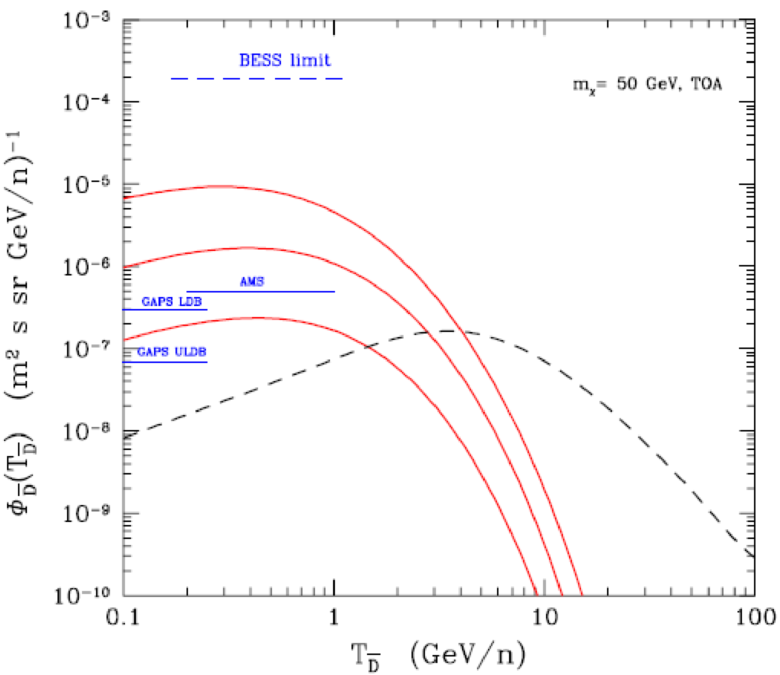
antideuterons

COSMIC ANTIDEUTERONS

FD, Fornengo, Maurin PRD 2001; 2008; Kadastik, Raidal, Strumia PLB2010; Ibarra, Wild JCAP2013; Fornengo, Maccione, Vittino JCAP 2013; …

See talk by Nicola Tomassetti

In order for fusion to take place, the two antinucleons must have low kinetic energy



Kinematics of **spallation** reactions prevents the formation of very low antiprotons (antineutrons).

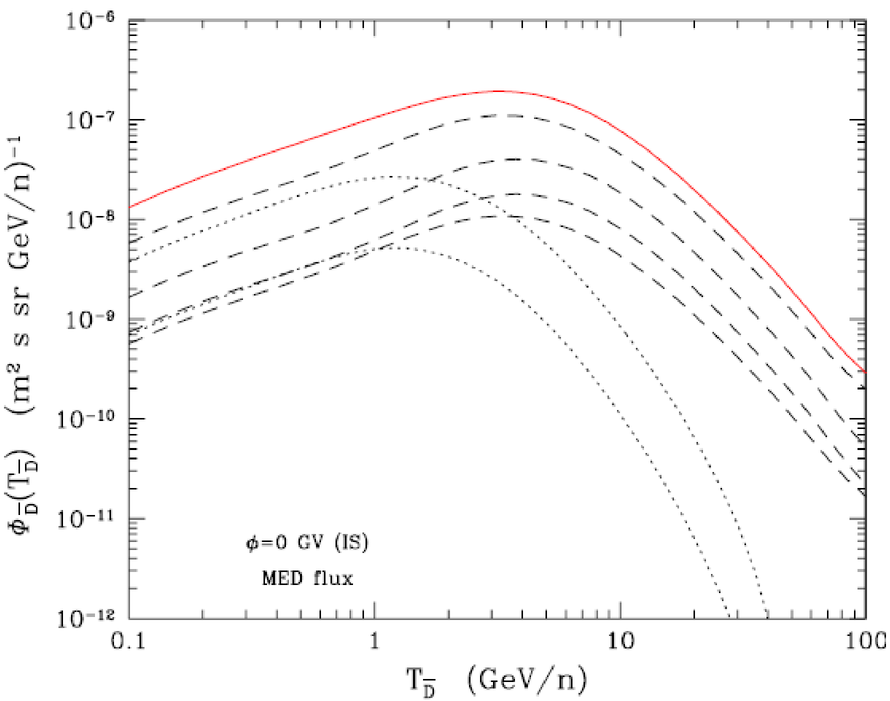
At variance, **dark matter** annihilate almost at rest

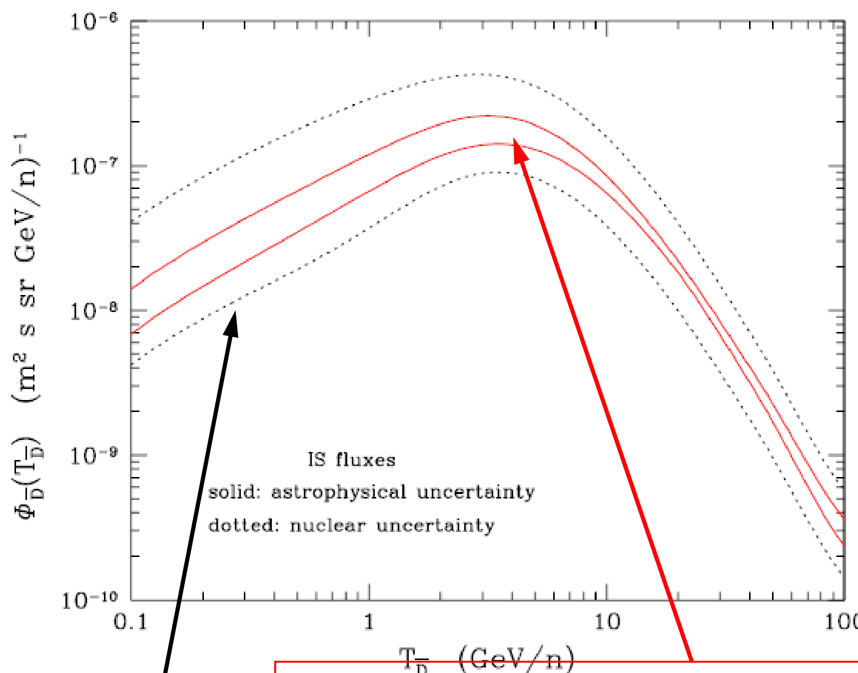
N.B: Up to now, NO ANTIDEUTERON has been detected yet.
Several expriments are on the road: AMS/ISS, BESS-Polar, GAPS …

Secondary antideuterons

FD, Fornengo, Maurin PRD 2008

Contributions to secondaries





p-p, p-He,
He-H, He-He
H- pbar, He-pbar

Propagation uncertainties
Compatibility with B/C

Nuclear uncertainties
Production cross sections & P_{coal}
Production from antiprotons
Non-annihilating cross sections

Conclusions

ANTIMATTER (antiproton, antideuterons) in cosmic rays is a clue ingredient in order search for (or set limits) to **dark matter** annihilating in the halo of the Milky Way

Propagation uncertainties are now confined to <10-20%, and are going to be further reduced by AMS-02 data

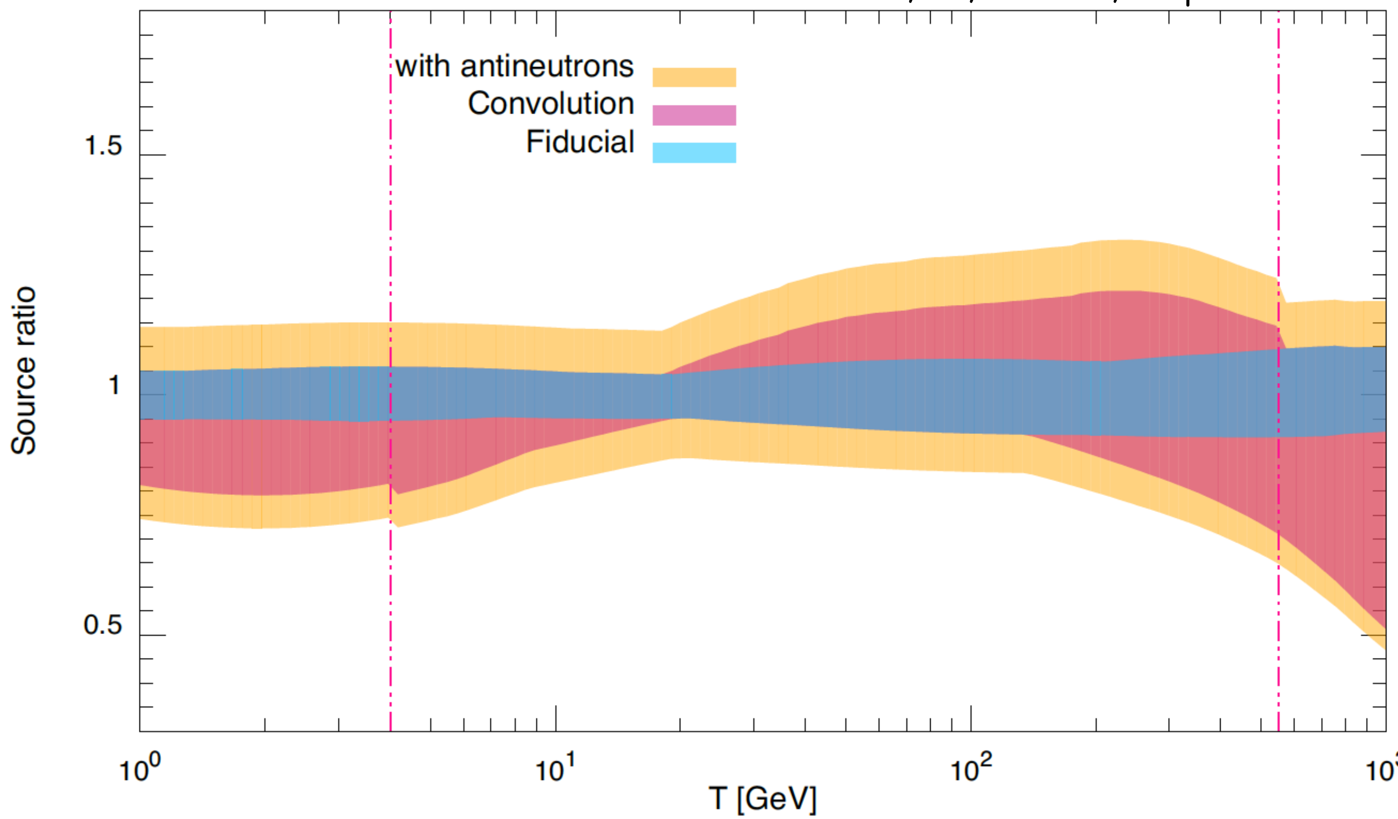
Cosmic **antiproton data** are expected with few% errors, while nuclear physics may bring uncertainties ~ 50%

The lack of data on several lab cross section puts **serious limits** in the interpretation of forthcoming cosmic ray data.

A direct measurement of **p-**, **γ**, **e^+**, **D^-** production from p + p, and p+He → p- + X, ...
is mandatory in order to interpret unambiguously future cosmic ray data.

Uncertainties due p-p scattering

Di Mauro, FD, Goudelis, Serpico PRD 2014

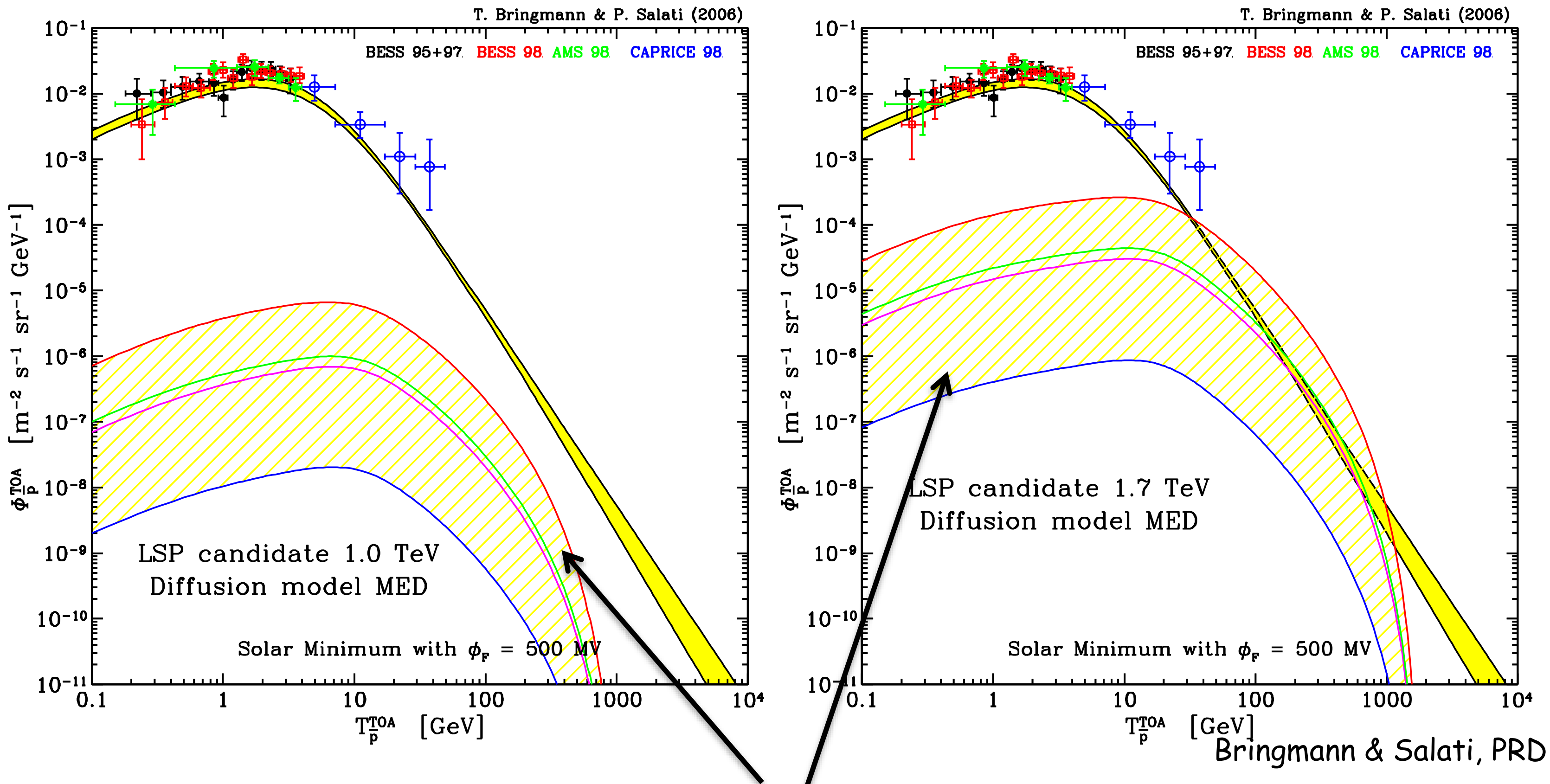


Uncertainties in the pbar production spectrum from p-p scattering are at least 10%.
Conservative: 20% at low energies (GeV) up to 50% (TeV)
(data expected at least up to ~ 500 GeV)

BACKUP SLIDES

Antiprotons: secondary vs Dark Matter component

Uncertainties due to propagation in the Galaxy



Bringmann & Salati, PRD 2007

Dark matter

AMS on the International Space Station

Unique instrument in space:

Courtesy of B. Bertucci

- no other magnetic spectrometer planned for next 20 years.
- Simultaneous measurements of all CR components with different sub-detectors: redundant particle identification and reduced systematics uncertainties.

Operating since May 19, 2011 onboard the ISS :

> five years in orbit, > 90 billion events collected

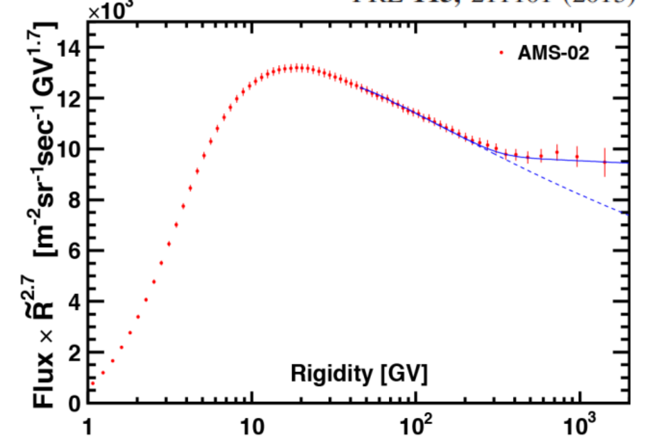
- all detectors fully operational. **ISS lifetime ≥ 2024**

Fundamental physics:

- Indirect DM search with anti-particles:
Measurement of: e^+, e^-, anti-p, (anti-d) in an unexplored energy range and O(%) accuracy

- Baryogenesis & search for nuclear anti-matter:
anti-He, anti-nuclei (Z>2)

PRL **115,** 211101 (2015)

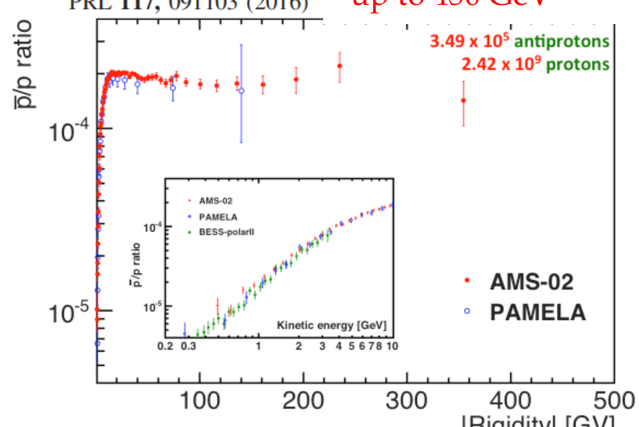


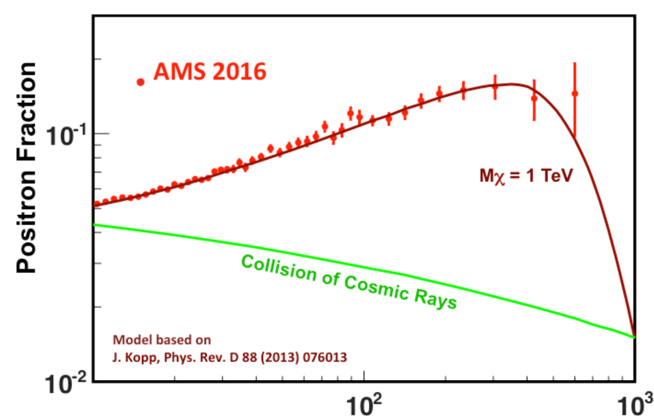
Energy and precision

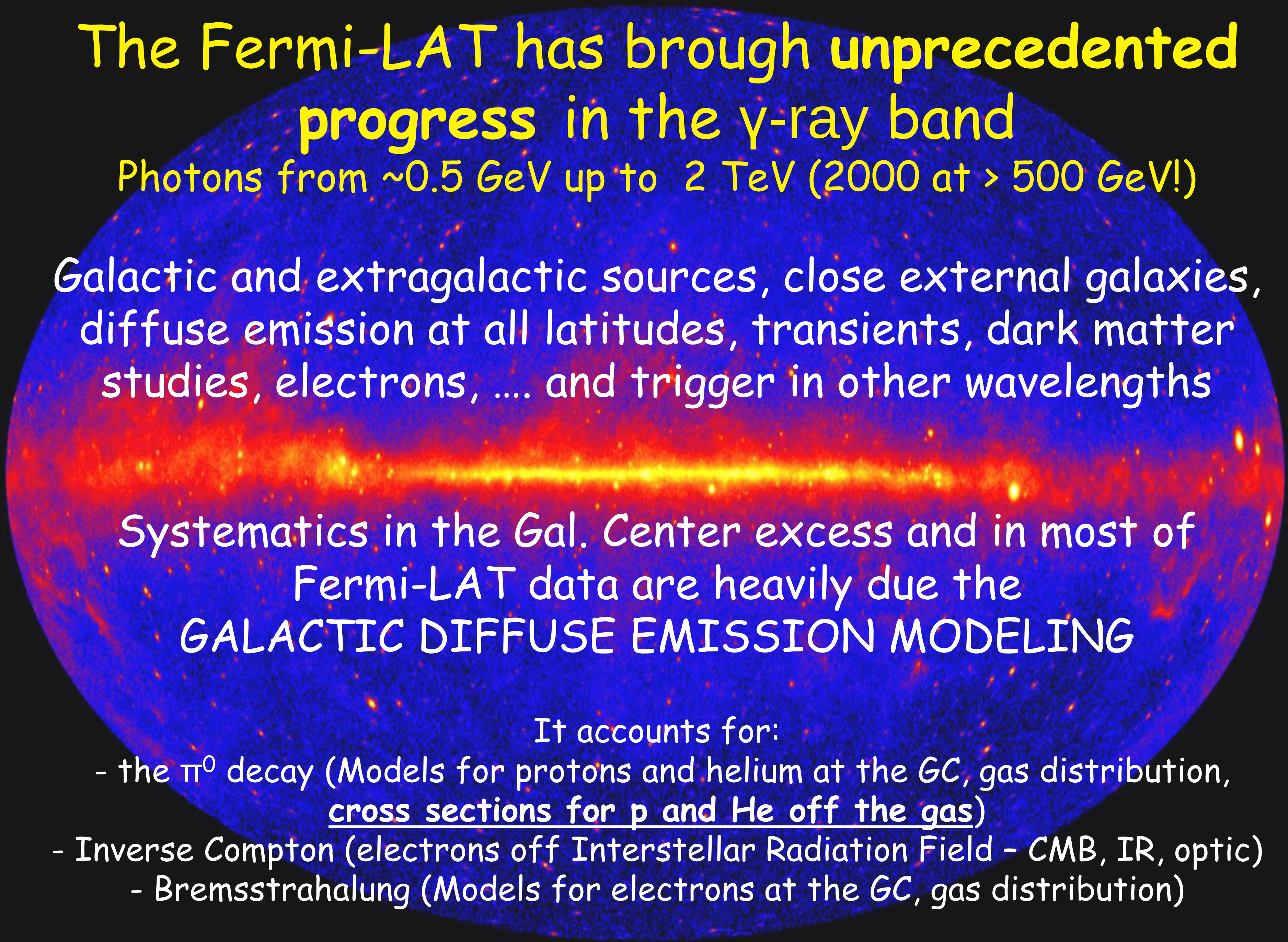
Energy range from GeV to TeV
Max energy for
primary nuclei (P, He, C, O)
Unlimited by statistics.
For p-, e+ and second. nuclei
Stat. limits at O(100) GeV
(20-30% at higher energies)
Low energy systematics is 2-3%

PRL **117,** 091103 (2016)

AMS 2016
up to 450 GeV







The Fermi-LAT has brough **unprecedented progress** in the γ-ray band

Photons from ~0.5 GeV up to 2 TeV (2000 at > 500 GeV!)

Galactic and extragalactic sources, close external galaxies, diffuse emission at all latitudes, transients, dark matter studies, electrons, …. and trigger in other wavelengths

Systematics in the Gal. Center excess and in most of Fermi-LAT data are heavily due the GALACTIC DIFFUSE EMISSION MODELING

It accounts for:

- the π^0 decay (Models for protons and helium at the GC, gas distribution, **cross sections for p and He off the gas**)
- Inverse Compton (electrons off Interstellar Radiation Field – CMB, IR, optic)
- Bremsstrahalung (Models for electrons at the GC, gas distribution)

Running detectors

Experiment	Peak G [m^2 sr] $e^{\pm}$	γ	p/nuclei	T_{obs} [year]	$\sigma E/E$ $e^{\pm}$, γ	p/nuclei
Agile	–	0.1	–	> 7	$\sim$ 100% 400 MeV	–
AMS-02	0.05			20	2% @ 50 GeV	–
ATIC	0.24			0.15	2% 150 GeV	35%
CREAM	–	–	0.43	0.5	6% 200 GeV	40%
Fermi	2.8 @ 50 GeV[a]	2.0 @ 10 GeV	–	10	5–15%	–
PaMeLa	0.00215	–	0.00215	7	5–10%	–
TRACER	–	–	4.73[b]	0.05	–	See [21]
CALET 08/2015	0.12			5	2% @ 1 TeV	40% @ 1 TeV
DAMPE 12/2015	0.3	0.2	0.2	3	1.5% @ 800 GeV	40% @ 800 GeV
~~Gamma-400[c]~~	0.5			7	1% @ 10 GeV	–
~~Gamma-400 (CC[d])~~	3.4 @ 1 TeV		3.9 @ 1 TeV	7	2% @ 1 TeV	35% @ 1 TeV[e]
HERD	> 3		> 2	10	1% @ 100 GeV	20% @ 1 TeV

L Baldini, 1407.7631