Galactic cosmic rays phenomenology: nuclei, antimatter, dark matter

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1. What are cosmic rays (CRs)
2. Searches for dark matter in CRs
3. Cross sections for CR phenomenology

CHARGED (GALACTIC) COSMIC RAYS

are charged particles (nuclei, isotopes, leptons, antiparticles) diffusing in the galactic magnetic field
Observed at Earth with E~ 10 MeV/n – 10^3 TeV/n

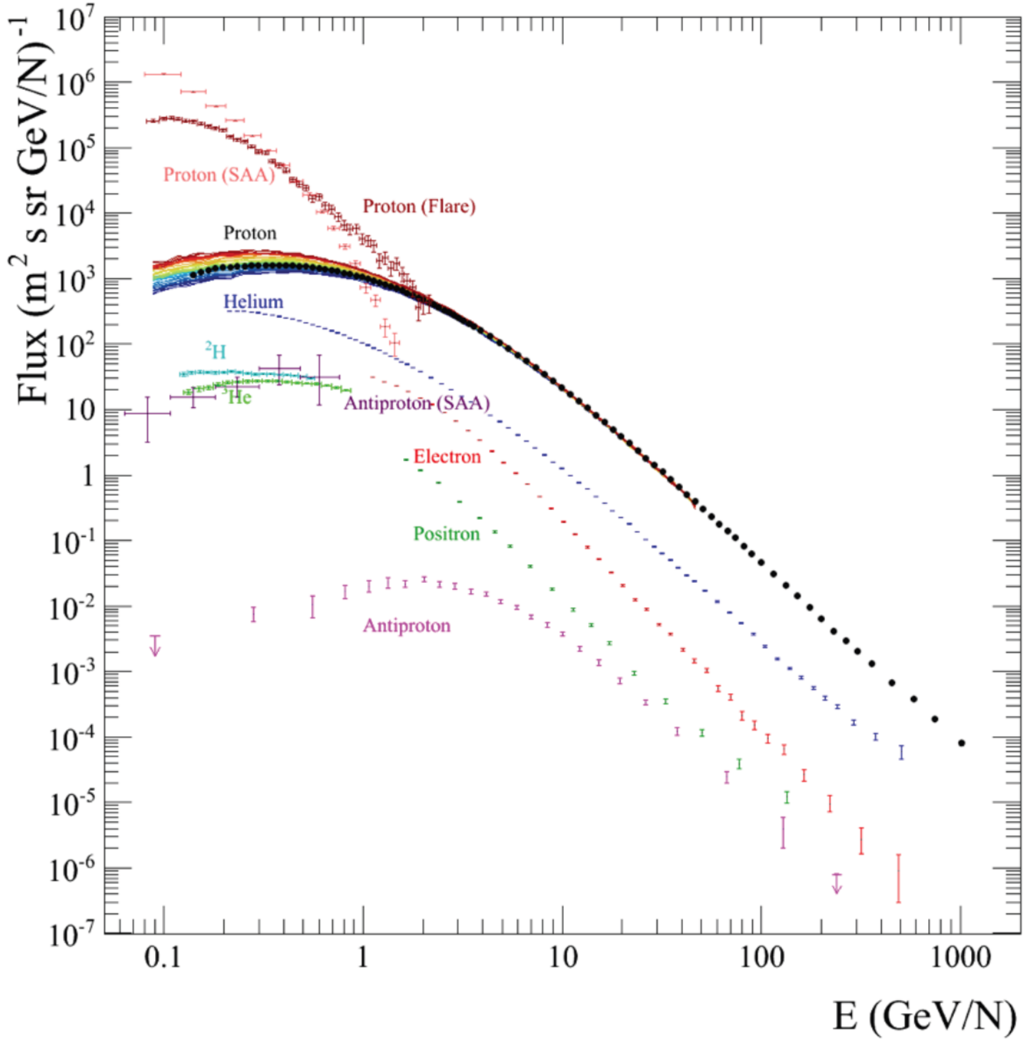
1. **SOURCES**
   PRIMARIES: directly produced in their sources
   SECONDARIES: produced by spallation reactions of primaries on the interstellar medium (ISM)

2. **ACCELERATION**
   SNR are considered the powerhouses for CRs.
   They can accelerate particles at least up to 10^2 TeV

3. **PROPAGATION**
   CRs are diffused in the Galaxy by the inhomogeneities of the galactic magnetic field.

\+ loose/gain energy with different mechanisms

All particle spectra (from Pamela experiment)



Credits: Valerio Formato & Mirko Boezio, Pamela Collaboration, 2013

Transport equation in diffusion models

Diffusion Convection

$$-\vec{\nabla}\left[K\vec{\nabla}N^j(E) - \vec{V}_c N^j(E)\right] - \Gamma^j N^j$$

$$-\frac{(\vec{\nabla}.\vec{V}_c)}{3}\frac{\partial}{\partial E}\left[\frac{p^2}{E}N^j(E)\right] = Q^j(E) +$$

$$\frac{\partial}{\partial E}\left[-b_{tot}(E)N^j(E) + \beta^2 K_{pp}\frac{\partial N^j(E)}{\partial E}\right]$$

Eneegy losses (EM) Reacceleration

Destruction on ISM

CR sources: primaries, **secondaries (spallations)**

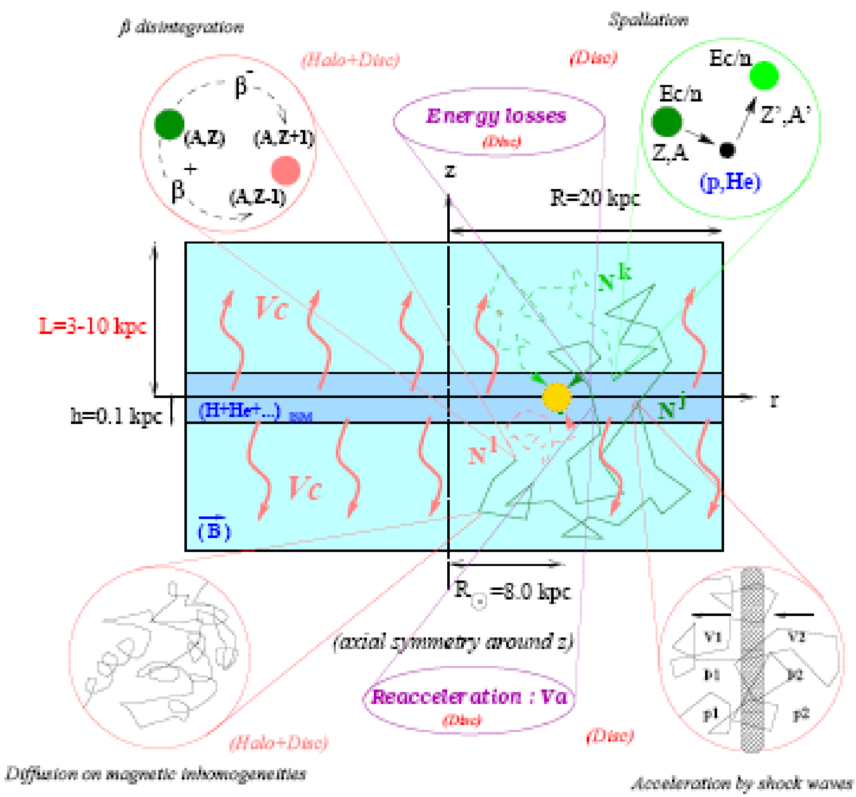
1. DESTRUCTION: $\Gamma = n_{ISM} v \sigma_R$, $\sigma_R = \sigma^{tot} - \sigma^{tot}{}_{el}$

2. SOURCES: $\bar{Q}^j \equiv q_0^j Q(E)\hat{q}_i + \sum_k^{m_k > m_j} \tilde{\Gamma}^{kj} N_i^k(0)$

Primary production in SNR

Secondary production by fragmentation of heavier nuclei

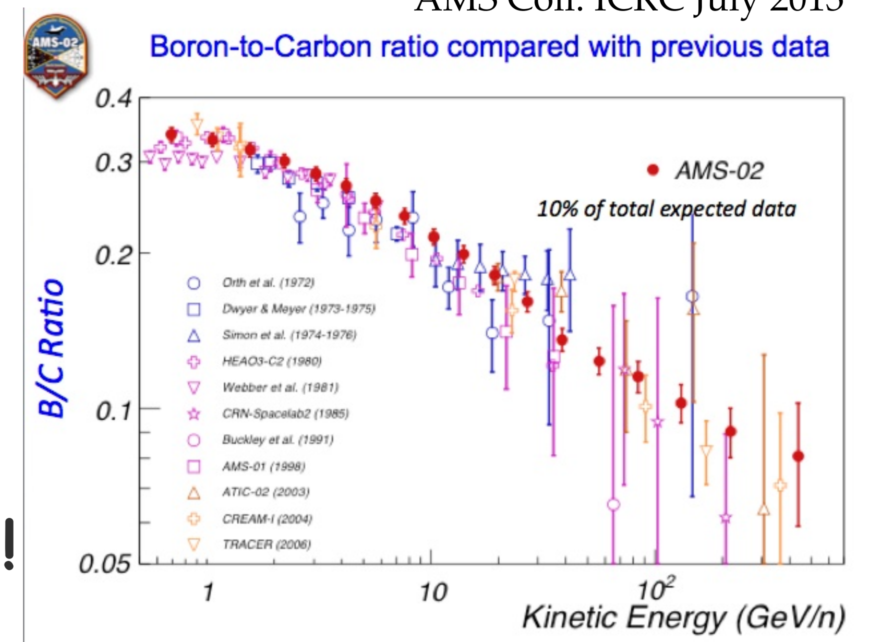
Cosmic antimatter fluxes from DM annihilation in the Milky Way halo



Diffusive models for CR propagation in the Galaxy

Jopikii & Parker 1970; Ptuskin & Ginzburg, 1976; Ginzburg, Khazan & Ptuskin 1980; Weber, Lee & Gupta 1992, ….;
Maurin, FD, Taillet, Salati 2001; Maurin, Taillet, FD 2002; Putze, Derome, Maurin 2010; Strong & Moskalenko 1998; Moskalenko, Strong, Ormes, Potgieter,2002; Shibata, Hareyama, Nakazawa, Saito 2004; 2006;); Evoli, Gaggero, Grasso, Maccione 2008; Di Bernardo et al. 2010; …

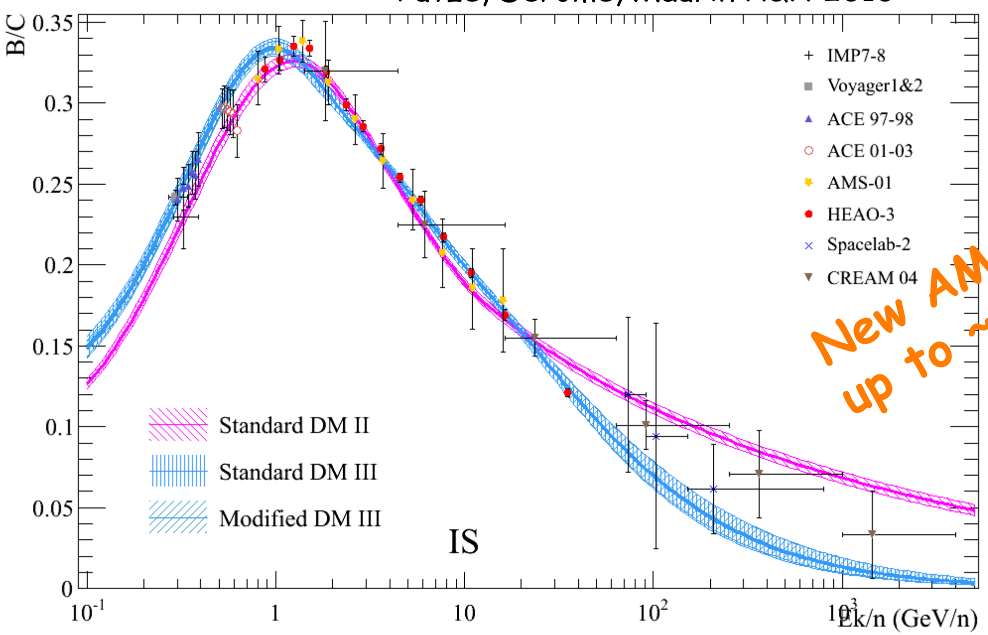
AMS Coll. ICRC July 2013



AMS data on CRs: great step forward for fixing Propagation and source models!

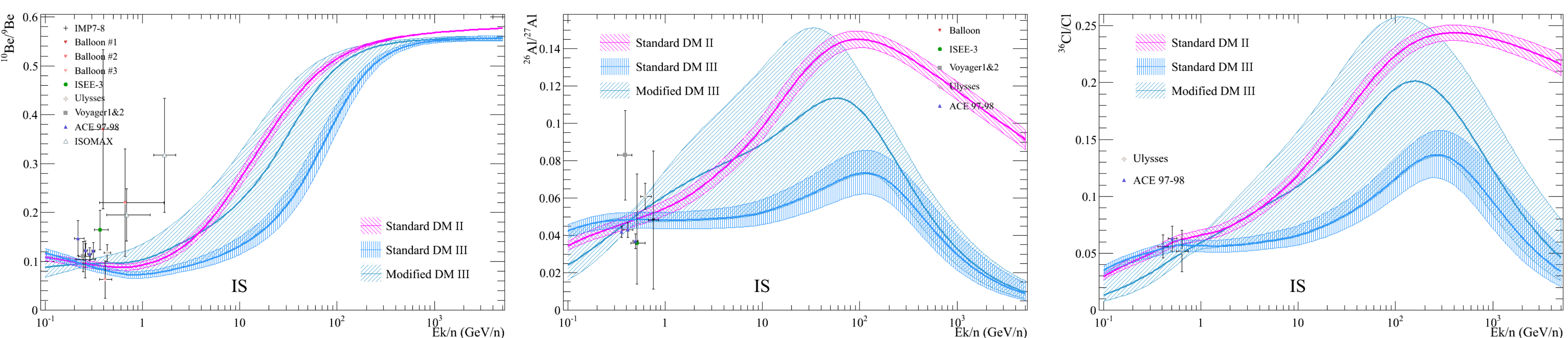
Propagation of CRs: DATA and MODELS
BORON/CARBON (B/C): A "STANDARD CANDLE"

Putze, Derome, Maurin A&A 2010

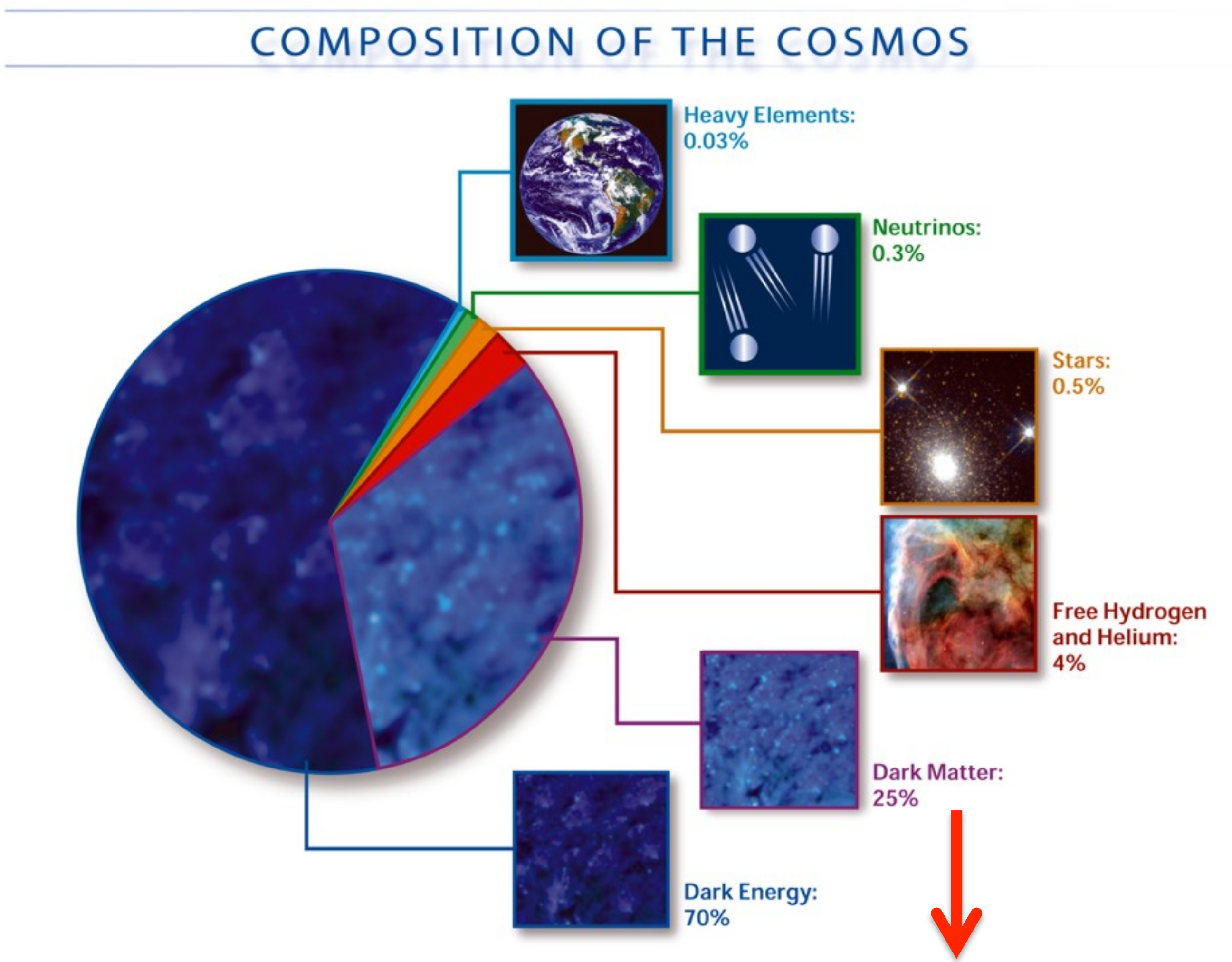


B/C: still high degeneracies in the **propagation models**

Radioactive isotopes could help break degenearcy



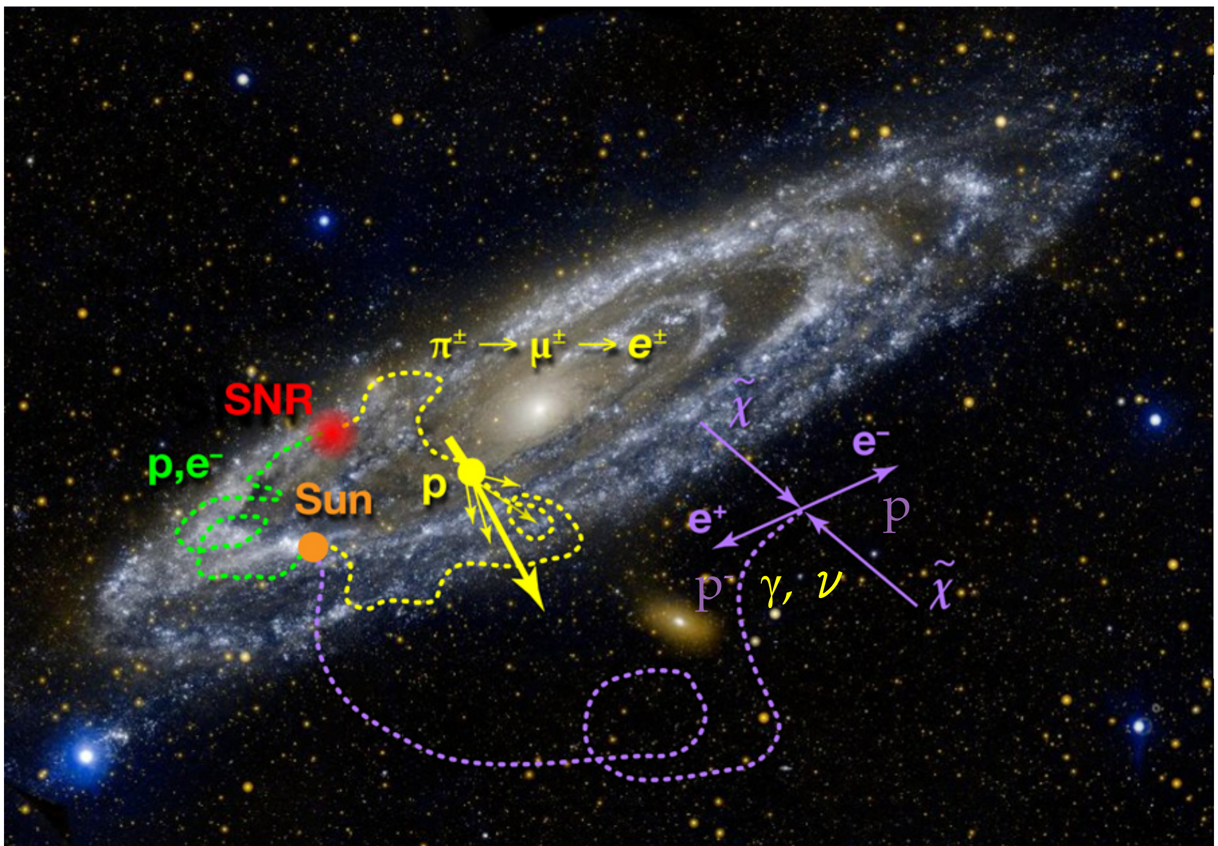
The composition of the Universe

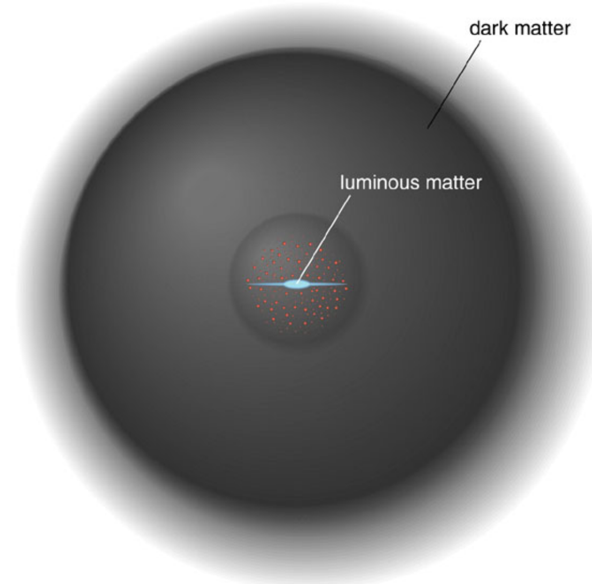


Hypothesis: the solution is a particle,
a WIMP (weakly interacting massive particle)

Indirect DARK MATTER searches

Dark matter can annihilate in pairs with standard model final states.
Low background expected for ANTIMATTER, and for neutrinos and gamma rays coming from dense DM sites





WIMP Dark Matter Indirect Searches

Annihilation inside celestial bodies:

→ ν at ν telescopes as up-going μ's

$$\Phi_\mu^{(\mathrm{Earth,Sun})} \propto < \sigma_{\mathrm{ann}} v > \frac{\rho_\chi}{m_\chi}$$

Annihilation in the galactic halo(s):

→ Photons (γ-rays, radio,...)

→ $e^+, \ \bar{p}, \ \bar{D}$

$$\Phi^{(\bar{p},\bar{D},e^+,\gamma)} \propto < \sigma_{\mathrm{ann}} v > \left(\frac{\rho_\chi}{m_\chi}\right)^2$$

ν and γ keep directionality

can be detected only if emitted from high χ density regions

Clue is **DM space distribution ρ(r)**

Charged particles diffuse in the galactic halo

antimatter searched as rare components in cosmic rays (CRs)

Clue is the **astrophysics of charged cosmic rays**

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

The case for antiprotons

Cosmic antiprotons

Antiprotons are produced in the Galaxy by **fragmentation**
of proton and He (and marginally heavier nuclei)
on the ISM (**secondary antiprotons**).

These antiprotons would be the background to
an exotic component due to
dark matter annihilation
in the galactic halo (**primary antiprotons**).

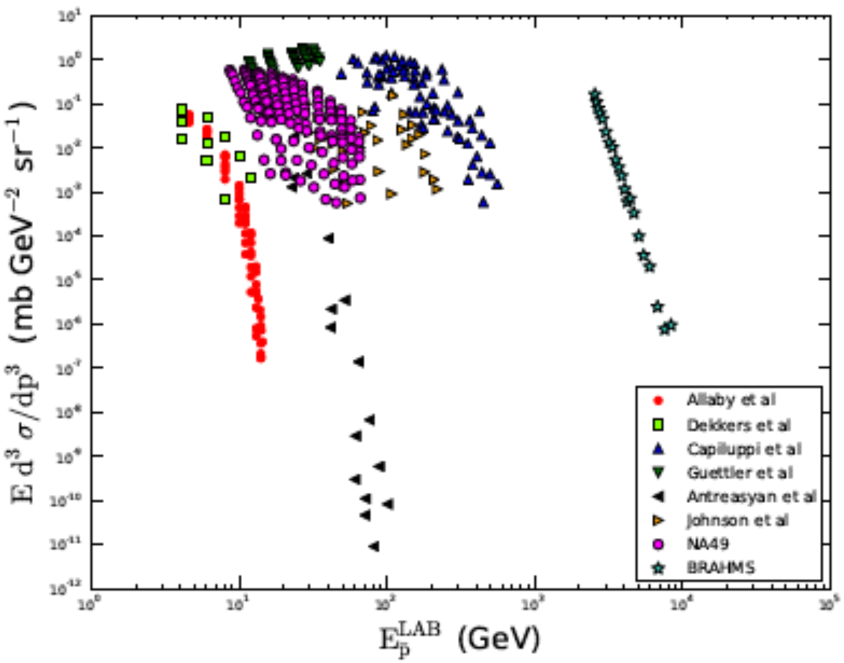
N. B. Thousands of cosmic antiprotons have already been
detected by balloon-borne (Bess, Caprice,….)
or satellite experiments (Pamela), and AMS-01,
and 290000 (out of 54 billion events) from AMS-02 on the ISS

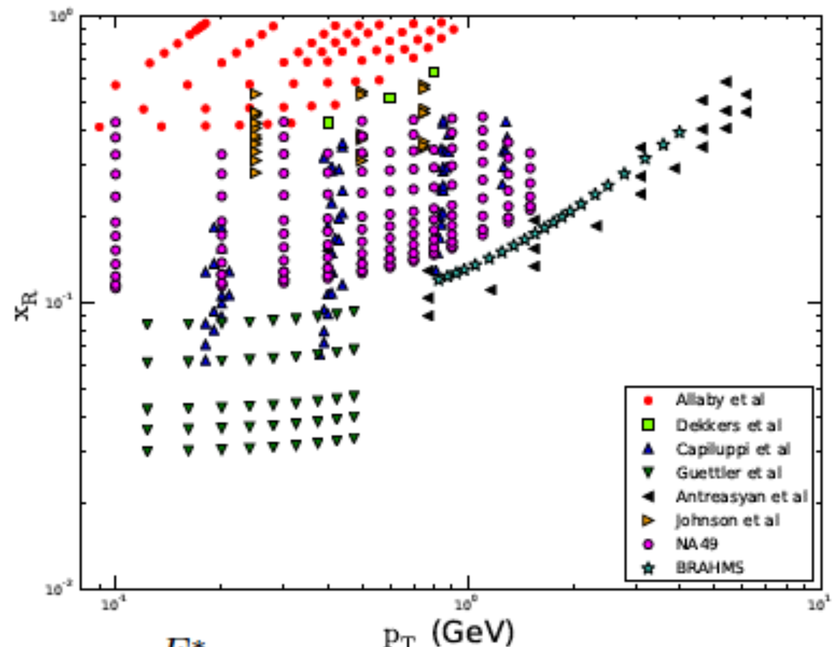
New analysis of p-p→pbar data

Di Mauro, FD, Goudelis, Serpico PRD 2014, 1408.0288; Kappl, Winkler 1408.0299, JCAP2014

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

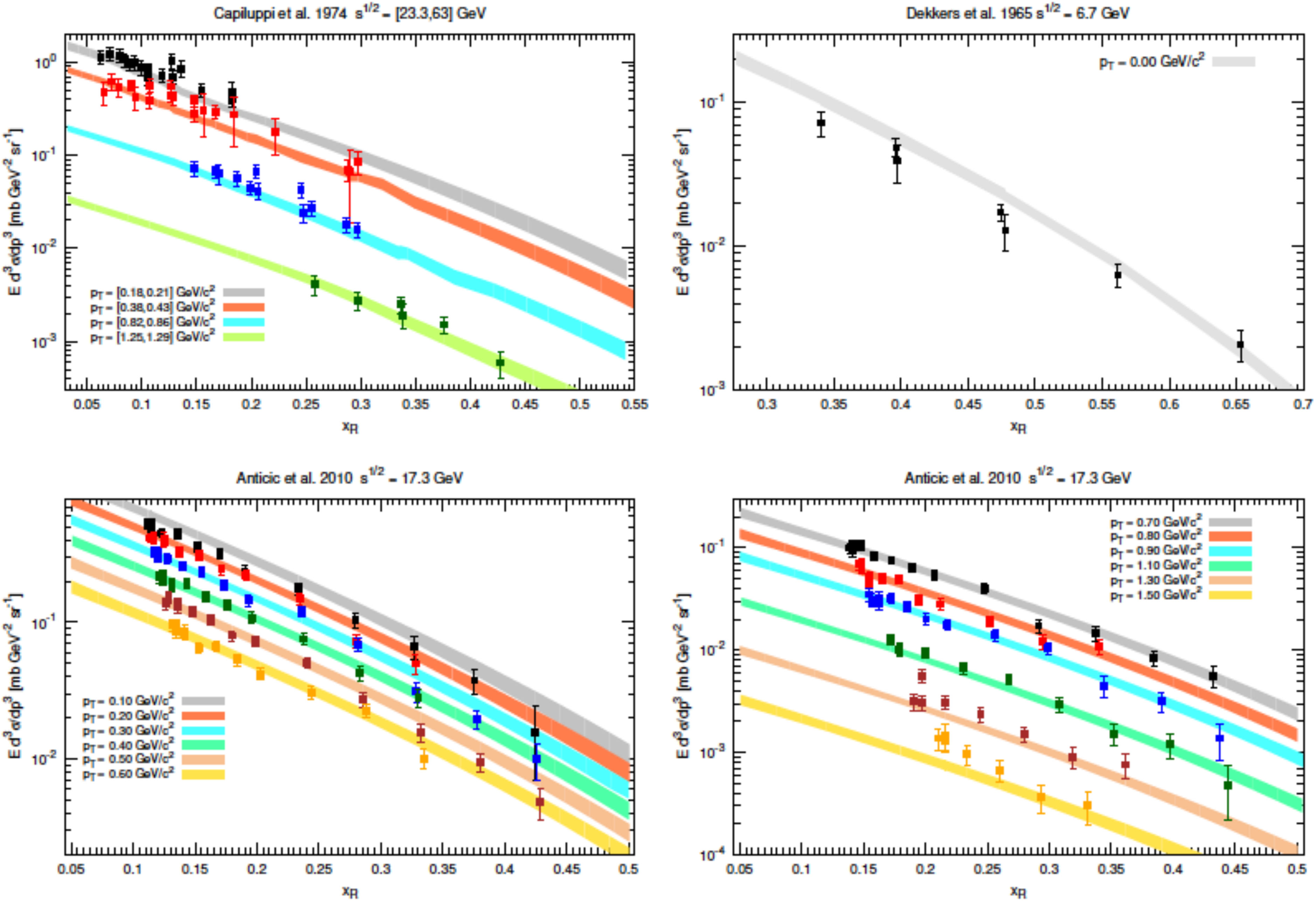
Existing data on the production cross section





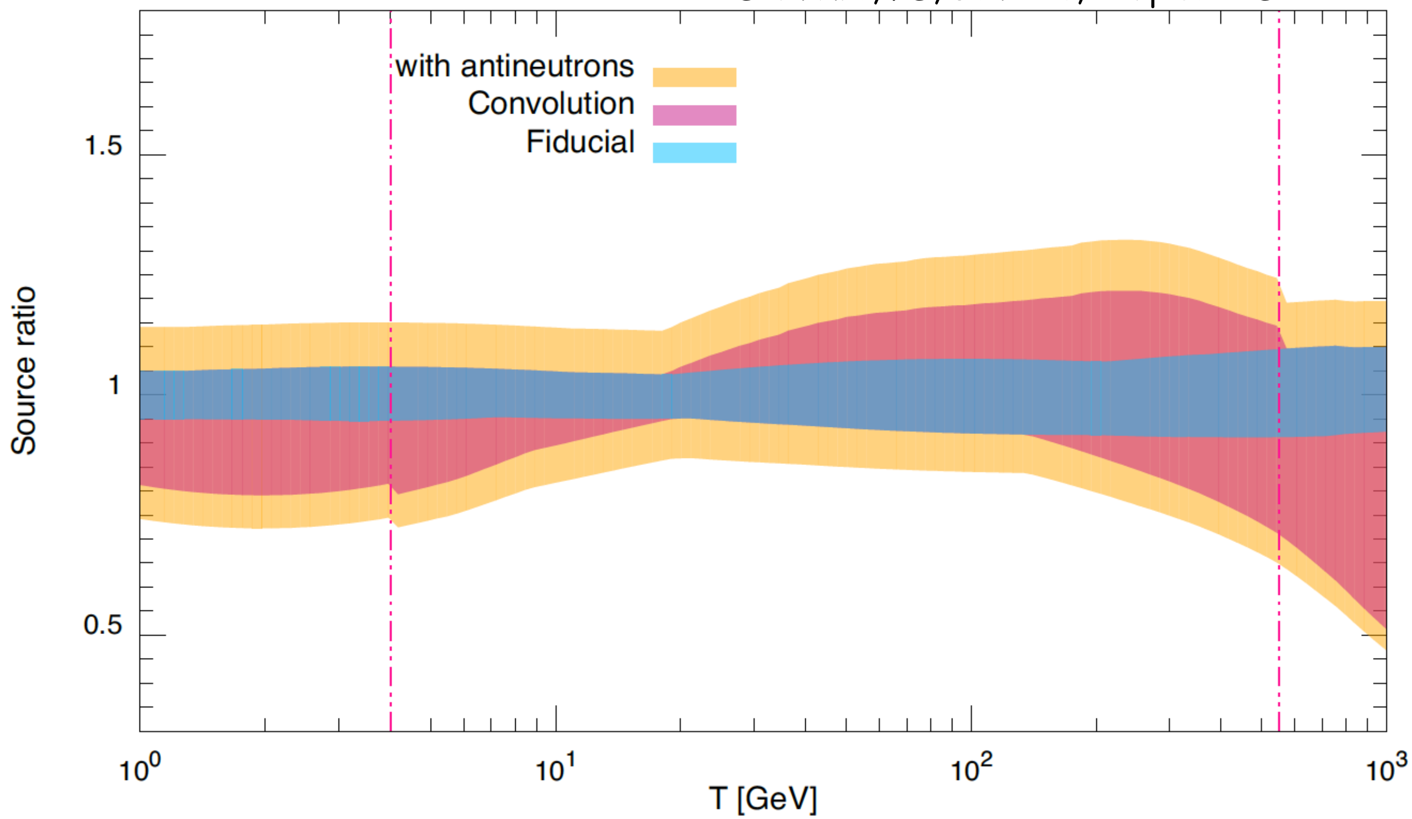
$$x_R = \frac{E^*_{\bar{p}}}{E^*_{\bar{p},\max}}$$

Di Mauro, FD, Goudelis, Serpico PRD 2014



Uncertainties due p-p scattering

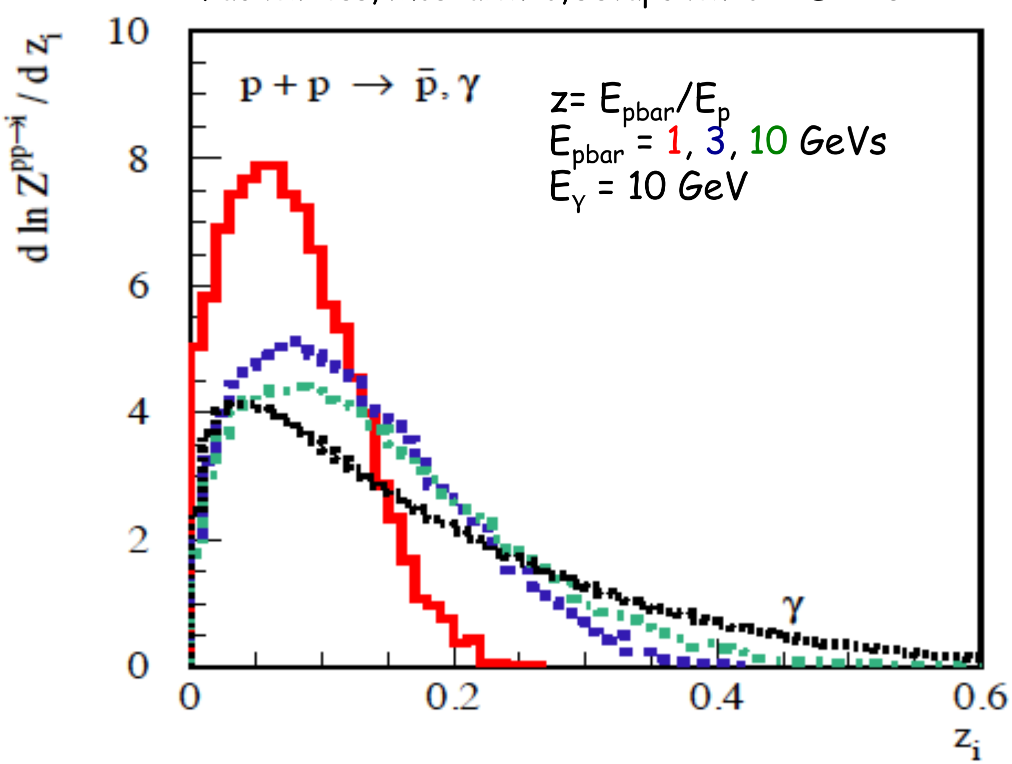
Di Mauro, FD, Goudelis, Serpico PRD 2014



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)

Protons → antiprotons

Kachelriess, Moskalenko,Ostapchenko PRD2015



The bulk of antiprotons

is produced by **protons**

with kinetic energy

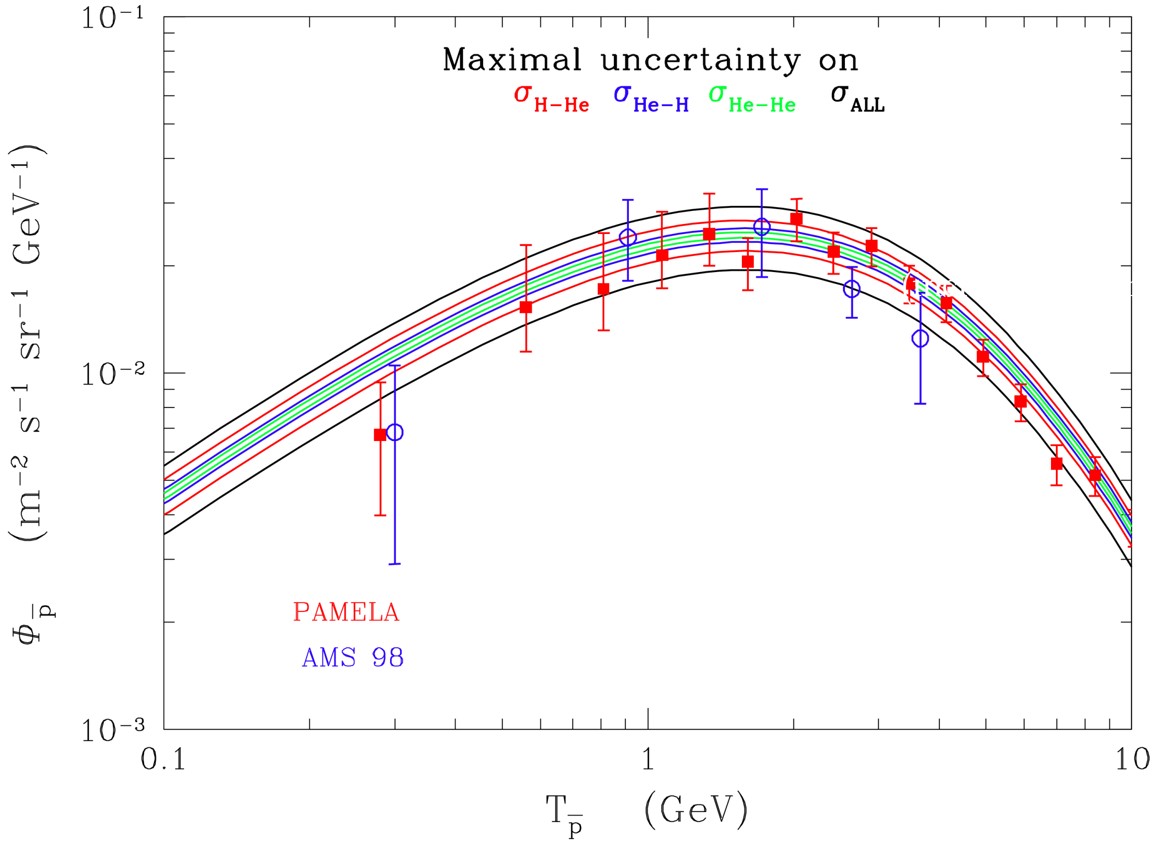
10-30 times greater

AMS energies ~ 1-500 GeV in E_{pbar} →

Proton energies with ~ few GeV – 10 TeV

Uncertainties on the antiproton flux from **nuclear cross sections**

(Donato+ ApJ 2001, PRL 2009)



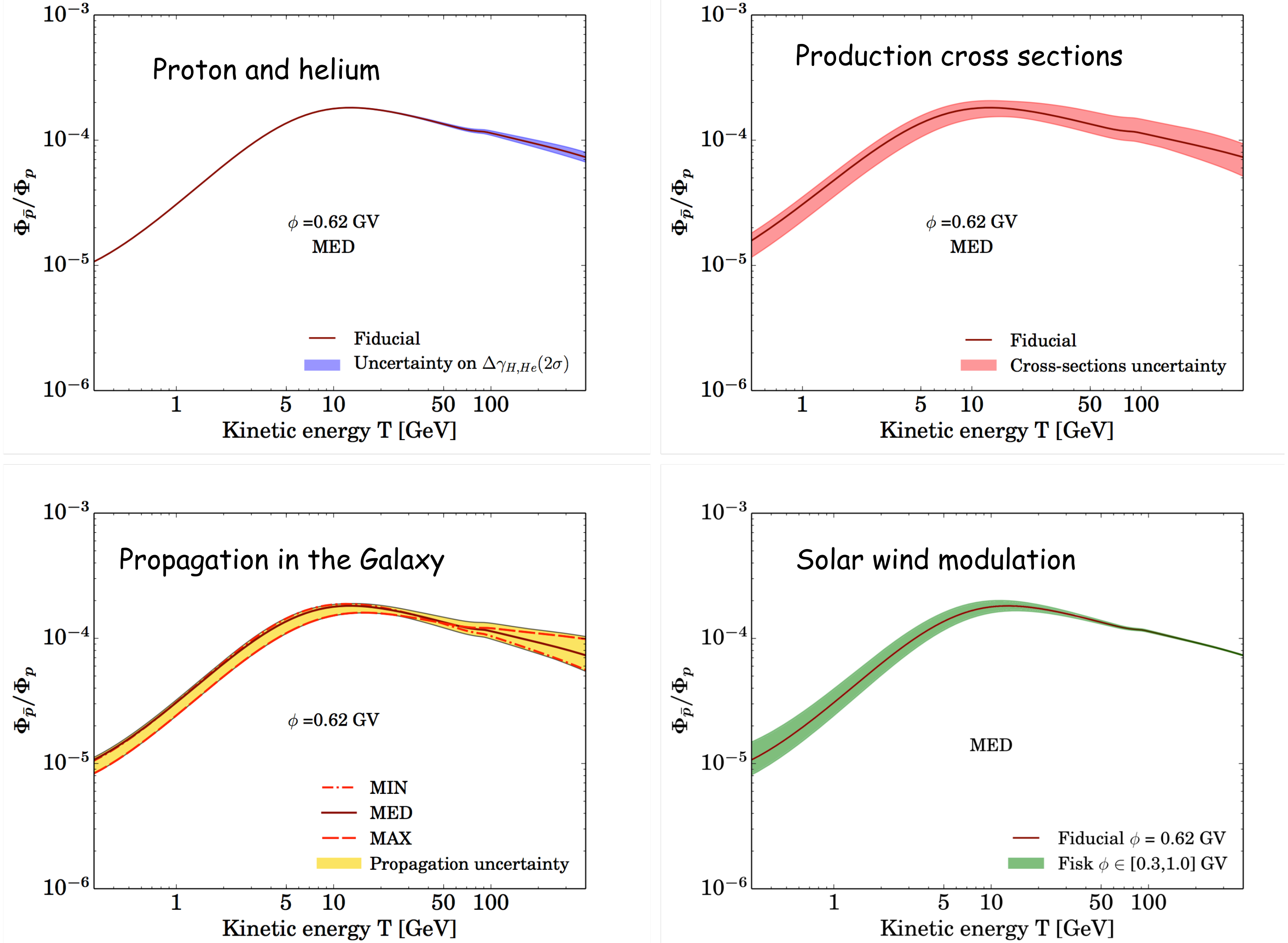
- pp: Tan& Ng
- H-He, He-H, He-He: DTUNUC MC
- Functional form for the cross section derived from other reactions, given **NO DATA!!**

Maximal uncertainty from p-He cross sections: 20-25%!

<u>Data from AMS-02 on cosmic antiprotons are at ~ 10% accuracy</u>

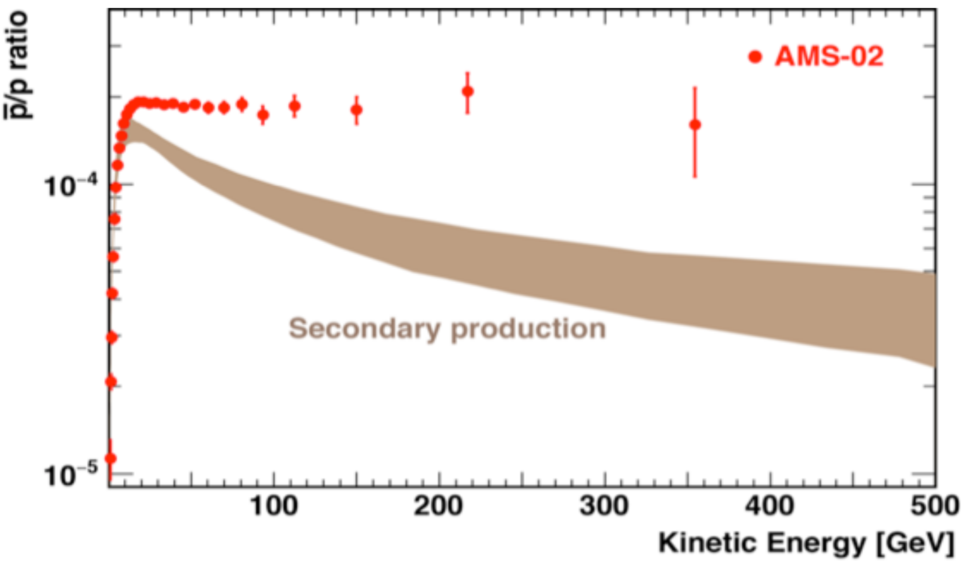
Secondary antiprotons: theoretical uncertainties

Giesen+ 1504.04276

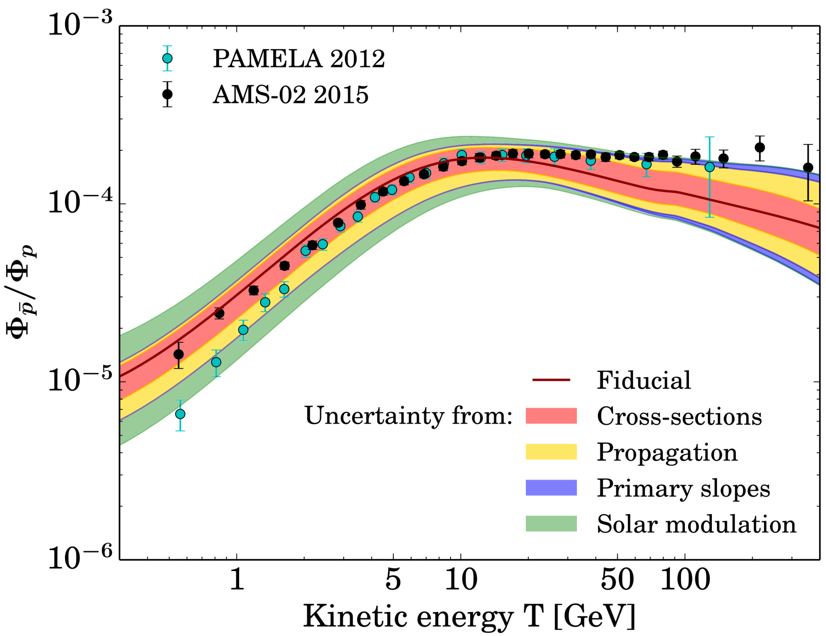


Prediction and AMS data

AMS Coll., Cern 15.04.2015



Giesen+ 1504.04276



Very recent AMS-02 results up to 450 GeV
Can be explained by secondary production in the Milky Way,
considering several theoretical uncertainties

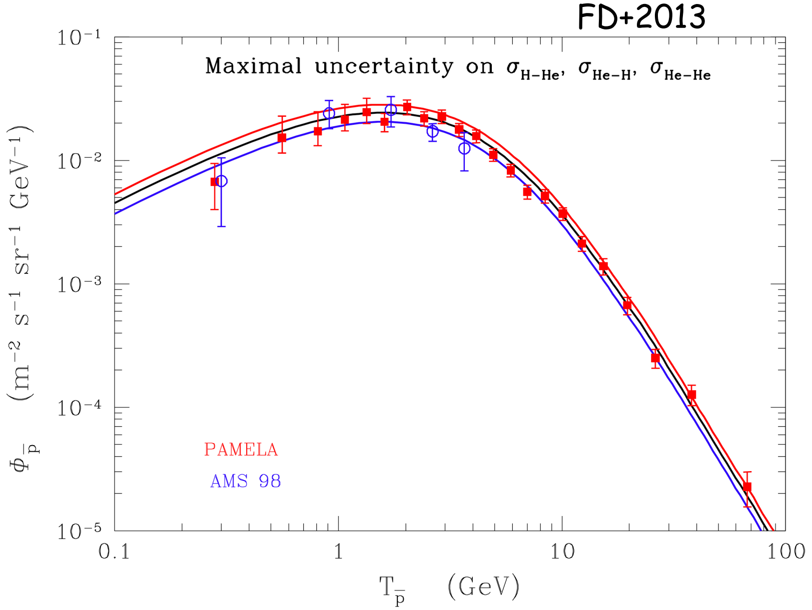
He cross sections: effect on DM interpretation

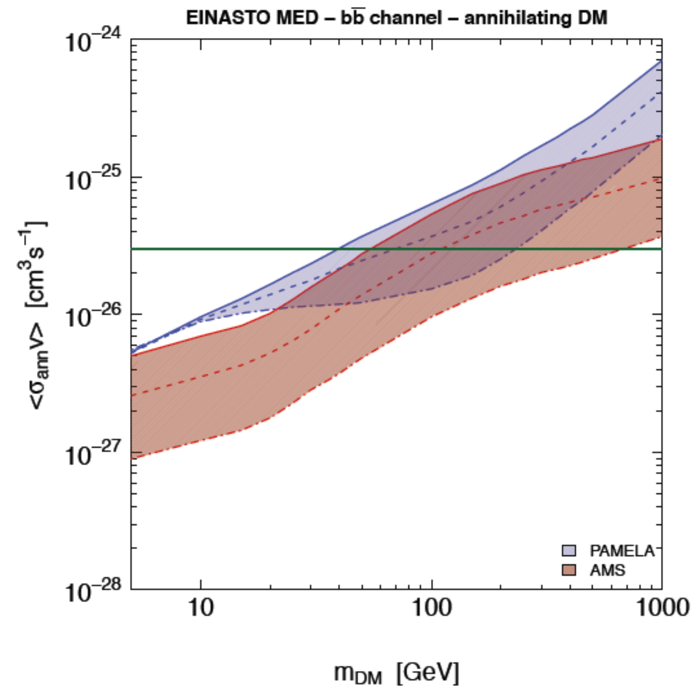
Uncertainties due to helium reactions range 40-50% on Secondary CR flux

Effect of cross section uncertainty on DARK MATTER interpretation

Fornengo, Maccione, Vittino JCAP2014

FD+2013





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)
   - $p+H(He) \rightarrow p+n+\pi^+$
   - $p+H(He) \rightarrow X + K^\pm$

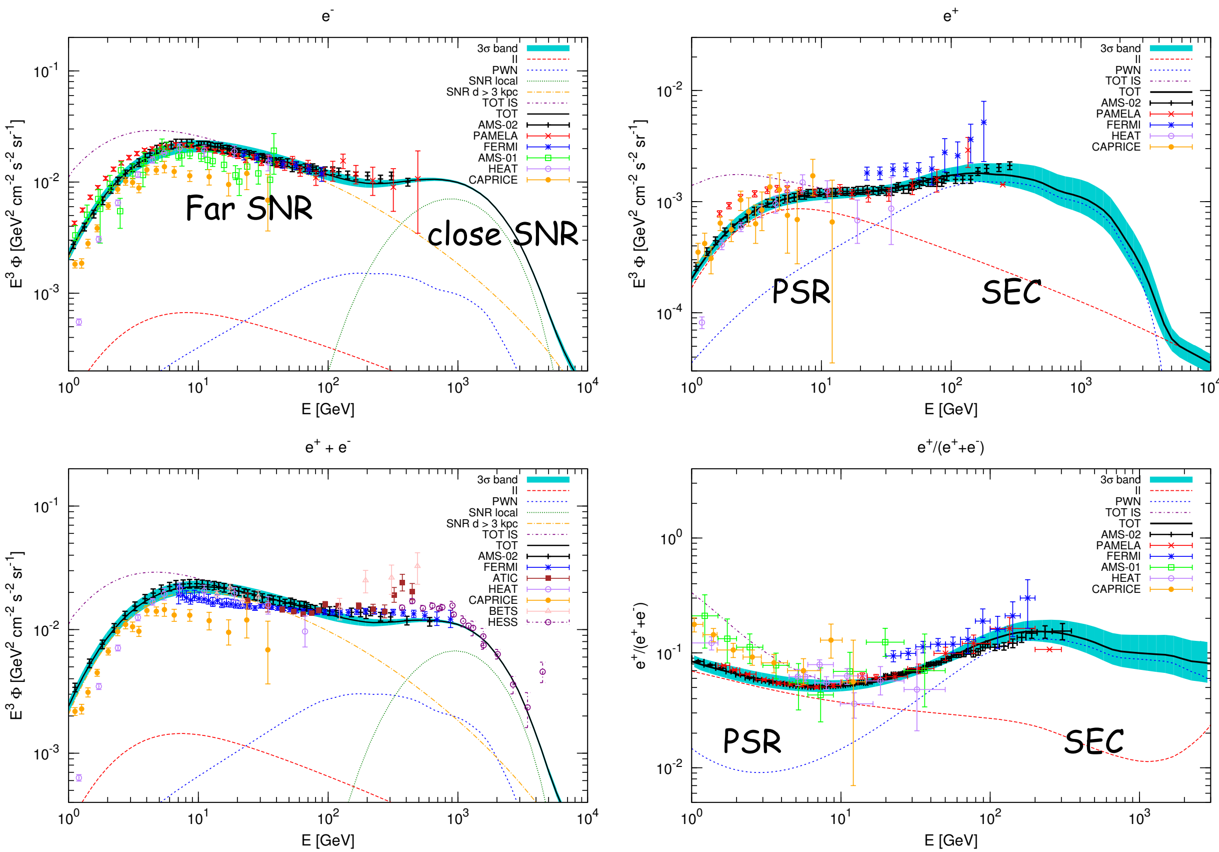
2. **Primary e- and e+ from Pulsars (PSR):**
   pair production in the strong PULSAR magnetoshpere

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

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

AMS lepton data: an astrophysical interpretation

Di Mauro, FD, Fornengo, Vittino JCAP 2014



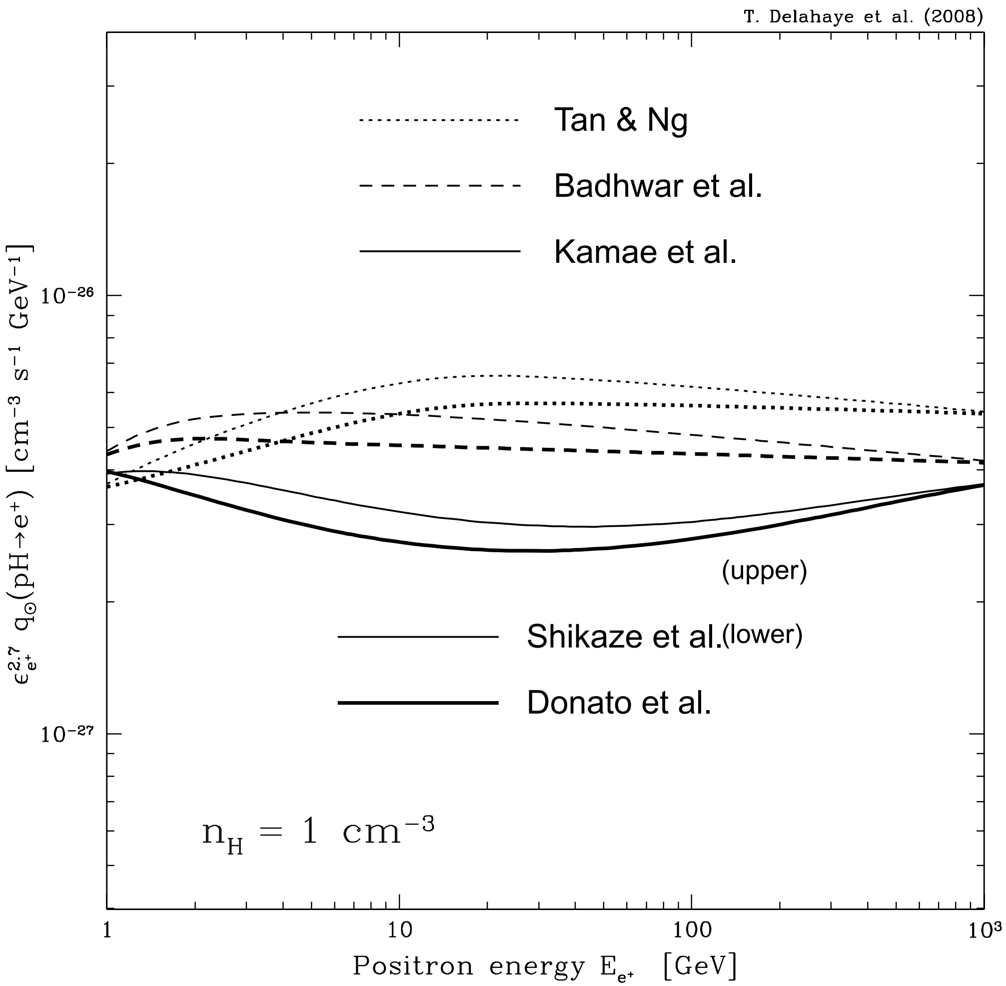
TH: Secondaries + supernovae + pulsars

EXP: Ams data precise + wide range →

Small features can bring strong information!

The secondary positron source term: effect of cross sections

Delahaye, FD, Fornengo, Lavalle, Lineros, Salati, Taillet A&A 2009



Effect of proton flux determination - negligible

Effect of production cross sections is not negligible!!

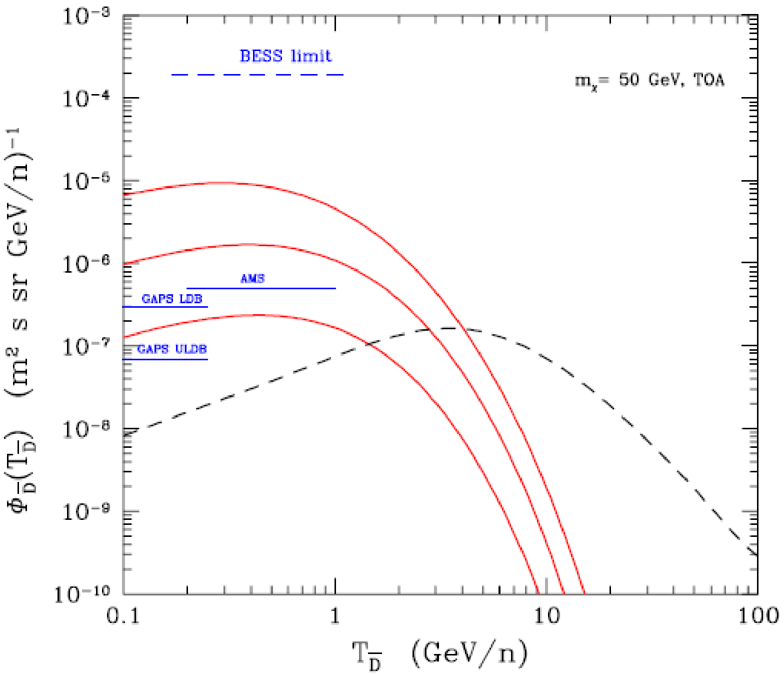
Up to factor 2 in p-p!

The case for antideuterons

COSMIC ANTIDEUTERONS

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

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).

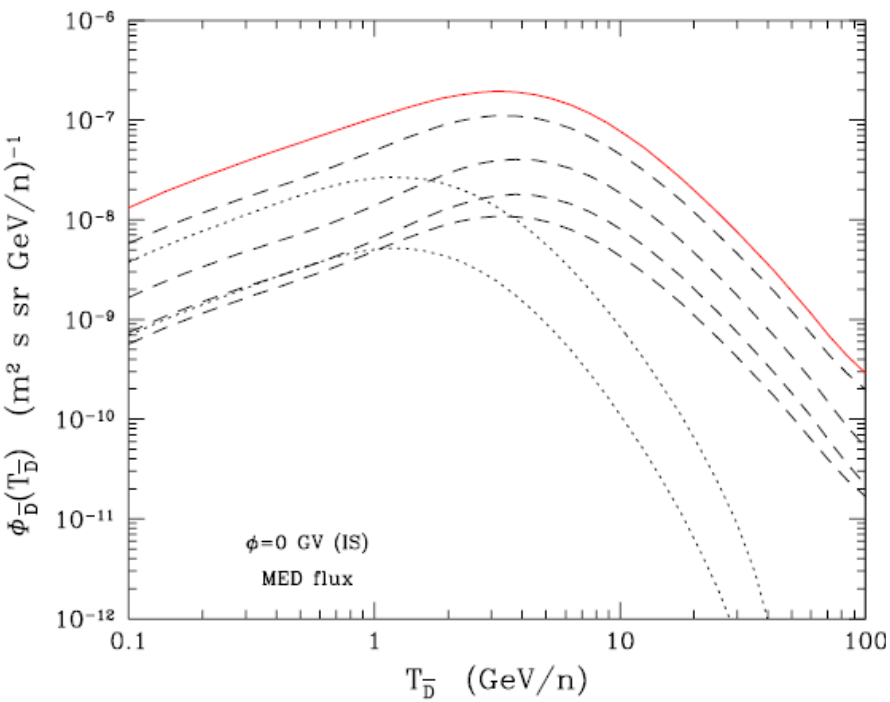
At variance, **dark matter** annihilate almost at rest

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

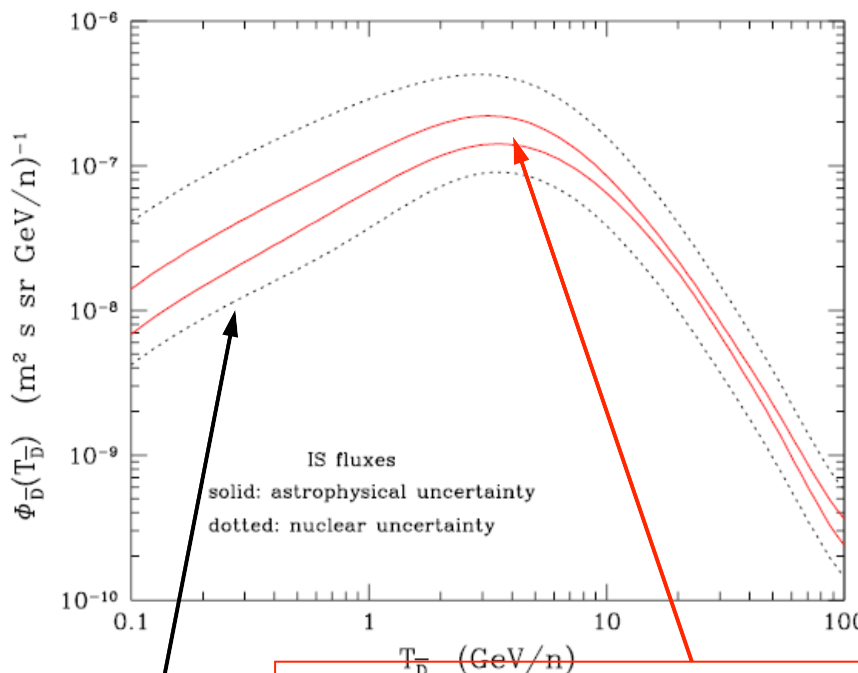
Secondary antideuterons

FD, Fornengo, Maurin PRD 2008

Contributions to secondaries



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

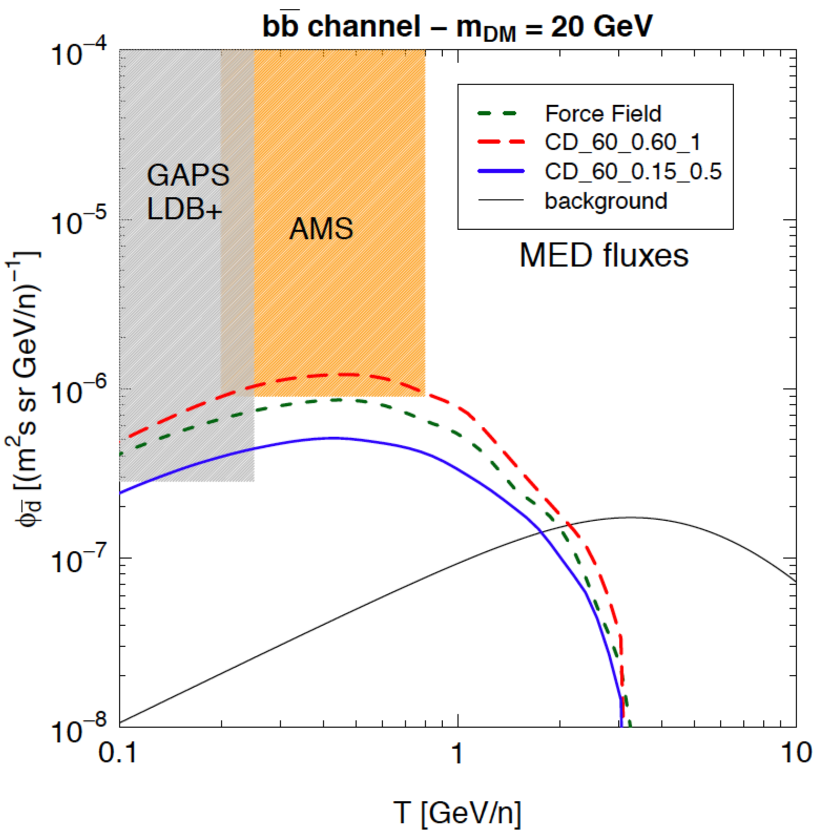


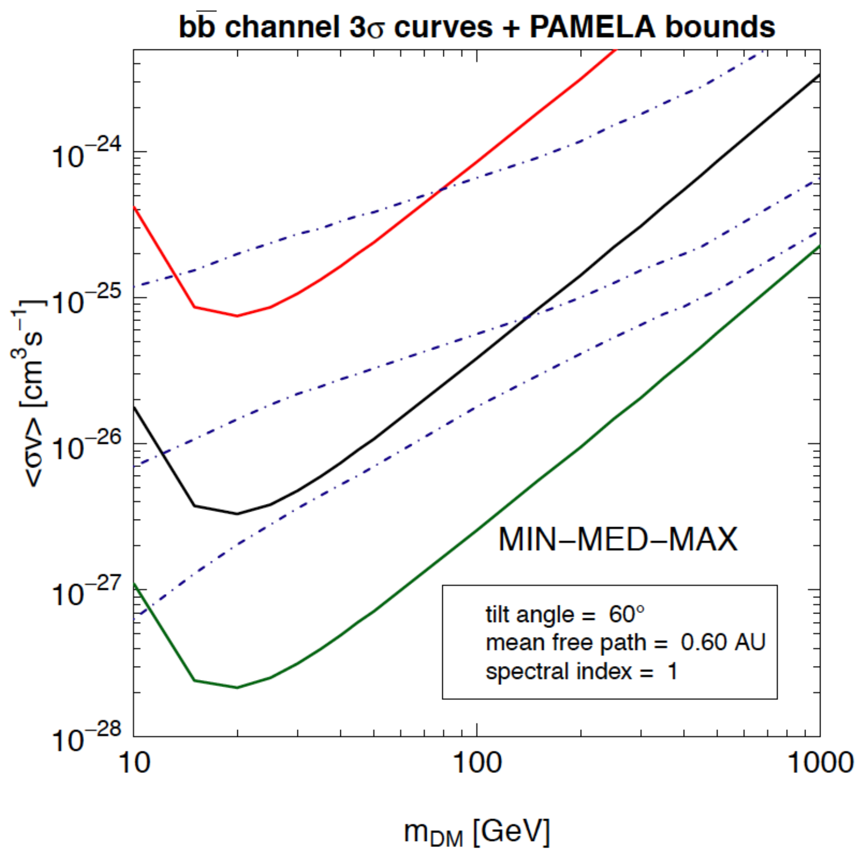
Propagation uncertainties
Compatibility with B/C

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

Antideuterons: Dark matter detection perspectives

Fornengo, Maccione, Vittino 1306.4171





3σ expected sensitivities

Prospects for 3σ detection of antideuteron with GAPS (dotted lines are Pamela bounds from antiprotons)

Few final remarks

The astrophysics of cosmic rays is entering an era of remarkable **precision** (AMS-02/ISS)

ANTIMATTER is a key element for testing galactic models and searching for DARK MATTER signals

Propagation uncertainties confined to less than 20%, close to be < 10%

The (production, total inelastic, inelastic non-annihilating, …) cross sections from Fe down, including isotopes and antimatter, rely on very few or (often) NO lab data!!

→ A HUGE EXPERIMENTAL PROGRAM IS REQUIRED FOR A SIGNIFICANT REDUCTION OF UNCERTAINTIES

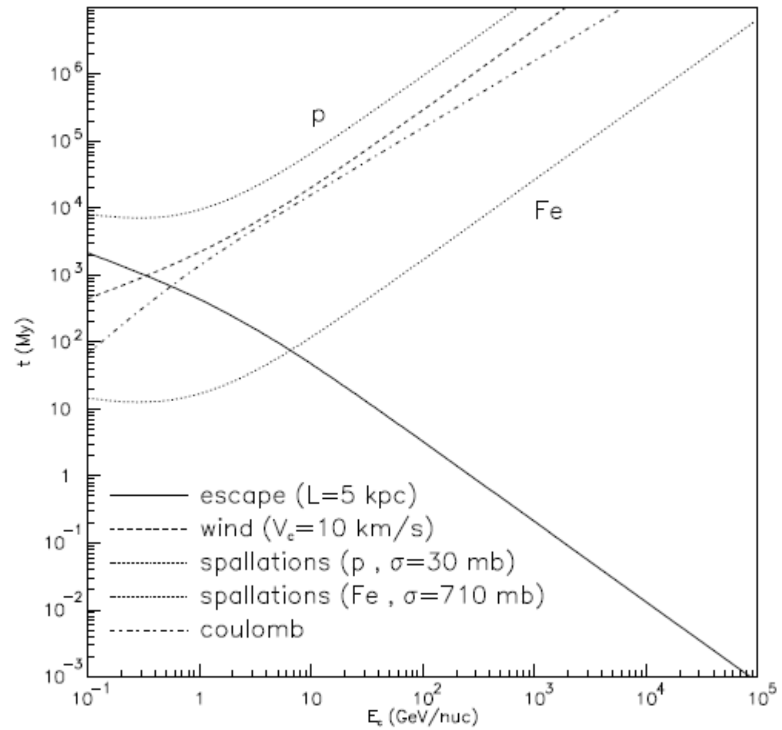
Proton-helium→ antiproton + X looks the most urgent case (contextually, measure of → e+, γ, D-)

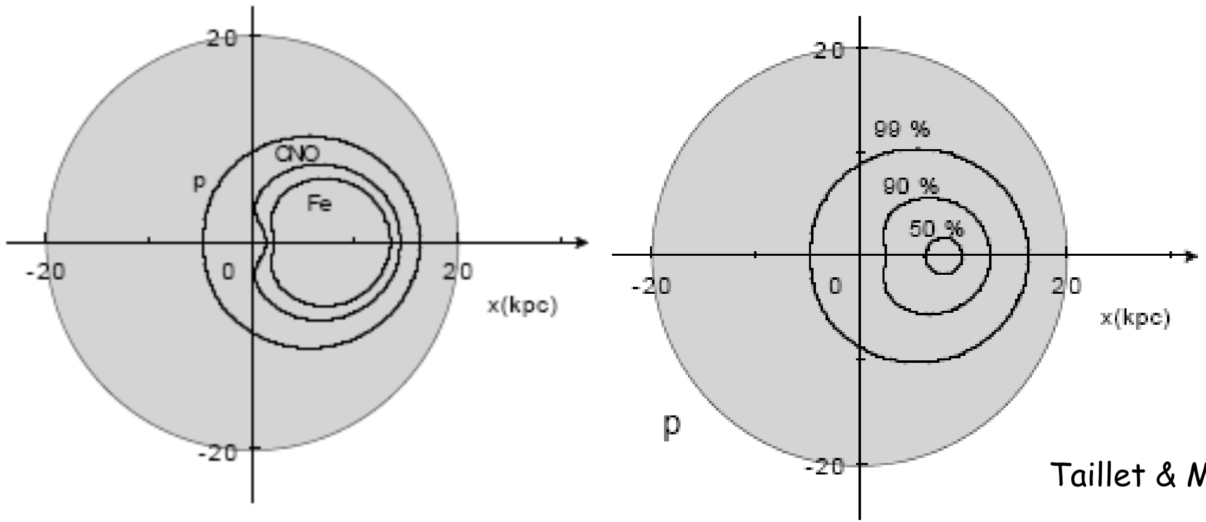
BACKUP SLIDES

Characteristic times and distances

The smaller the time,
the most effective the process is

Protons: escape E > 1 GeV
convection and e.m. losses E<1 GeV,
Iron: escape E > 1 GeV
Spallations E<10 GeV/n





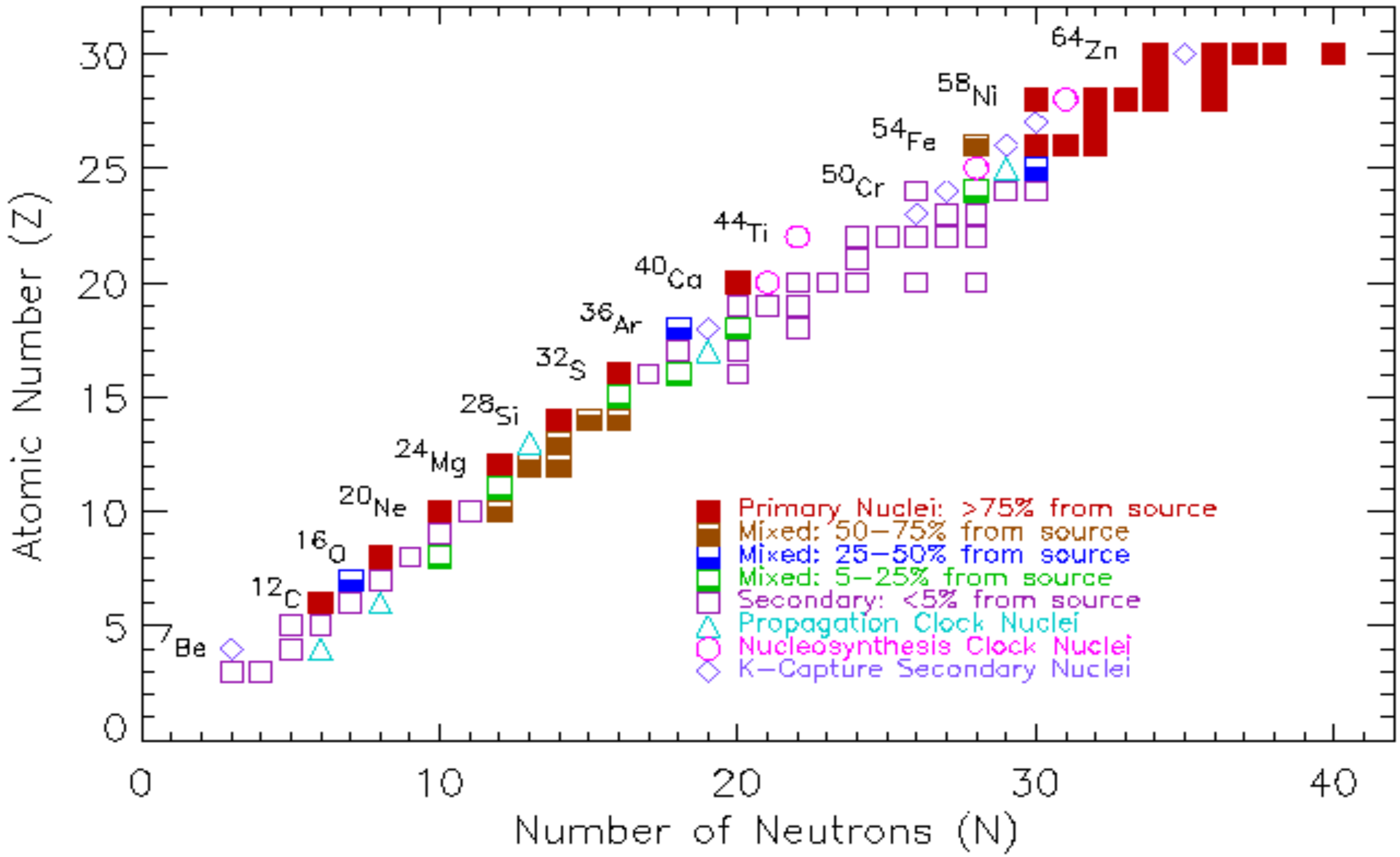
Fe more local than p

90% p from 5-6 kpc

Taillet & Maurin A&A 2003

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

Secondaries = NOT present in sources, thus produced by
spallation of primary CRs (p, He, C, O, Fe) on ISM
Nuclei: LiBeB, sub-Fe, … ;
e^+, p^+, d^+; … from inelastic scatterings



X-sec uncertainties: impact on GCR model parameters

(Slide from D. MAURIN)

Input: X-sections → **Minimisation**: Propagation model: free parameters δ, K_0, V_a; GCR data: B/C data from HEAO-3 (1979) → **Output**: Best-fit parameters

Maurin, Putze & Derome, A&A **516**, 67(2010)

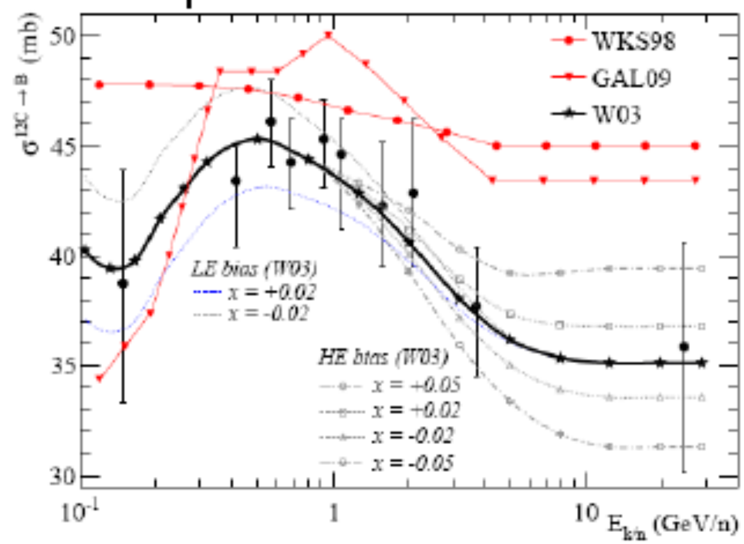
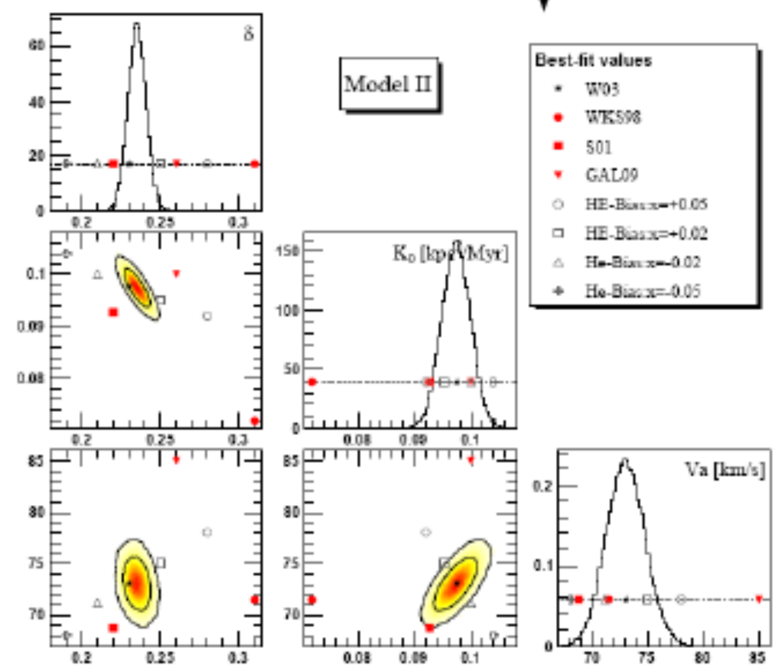


Fig. 3. Production cross-section for $^{12}C+H\to^{10,11}B$ (adapted from Webber et al. 2003). The standard sets are shown as solid lines (WKS98: red dots; GAL09: red down triangles; W03: black stars), and the biased sets in dotted ($|x| = 0.02$) and dashed ($|x| = 0.05$) lines.



- W03 and WKS98 are parameterisations of the same 'data' (energy bias)
- GAL09: modern nuclear codes normalised to LANL database [Moskalenko & Mashnik, astro-ph/0306367]

→ Systematics uncertainties (from X-sec) > statistical uncertainties (from GCR data)
… and AMS-02 is at least 100 better than HEAO-3!

Inelastic cross sections ($\sigma_R = \sigma^{tot} - \sigma^{tot}_{ela}$)

(Slide from D. MAURIN)

- Bradt & Peters (1950) $\sigma_R = \pi r_0^2 (A_{proj}^{1/3} + A_{cible}^{1/3} - b_0)^2$

- Letaw *et al.* (1970-2000): accuracy <2% for 2<Z<30 and E>300MeV/n

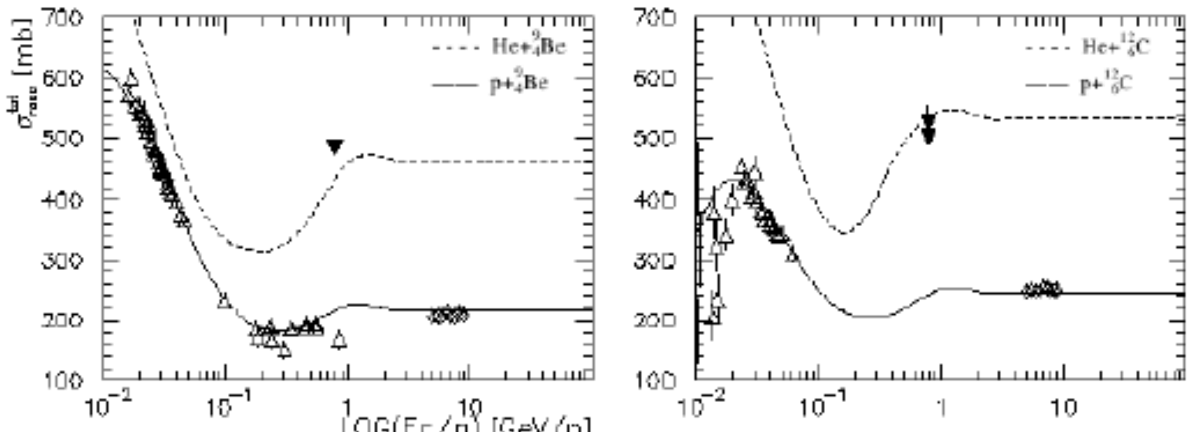
S.Barshay & al, Phys.Lett **51B**, 5 (1974)
J.R.Letaw & al, ApJSS **51**, 271 (1983)
R.Silberberg & C.H Tsao, Phys.Rep. **191**, 351 (1990)
L.Sihver & al, Phys.Rev.C **47**, 1225 (1993)
H.P.Wellish & D.Axen, Phys.Rev.C **54**, 1329 (1996)
R.Silberberg & al, ApJ **501**, 911 (1998)
C.H.Tsao & al, ApJ **501**, 920 (1998)

$$\sigma_R(E_k) = \sigma_R^{HE}\left[1 - 0.62\exp(-E_k/200)\sin(10.9E_k^{-0.28})\right] \ (mb)$$
$$\sigma_R^{HE} = 45A^{0.7}\left[1 + 0.016\sin(5.3 - 2.63\ln A)\right] \ (mb)$$

- Tripathi *et al.* (~2000): ~ or better (at low E) than Letaw *et al.*, valid for all N+N reaction!

R.K.Tripathi & al, NASA, Technical Paper **3621**, (1997)
R.K.Tripathi & al, NASA, Technical Paper **3656**, (1997)
R.K.Tripathi & al, NASA, Technical Paper **209726**, (1999)

$$\sigma_R = \pi r_0^2 \left(A_{proj}^{1/3} + A_{cible}^{1/3} + \delta_E\right)^2 \left(1 - R_c \frac{B}{E_{cm}}\right) X_m$$



Data from compilations:
Bobchenko 79, Tanihata 85,
Bauhoff 86, Carlson 96

→ Tripathi *et al.* is the one generally used in the field

Production cross sections (straight-ahead approx.)

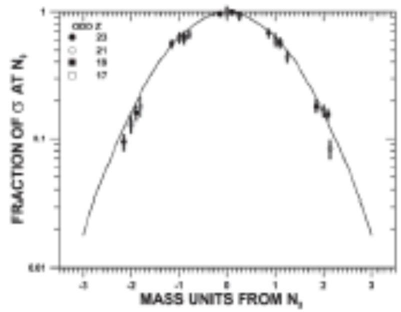
$$\int_0^\infty n_H v' N^k(T')\sigma^{kj}(T,T')dT' = \int_0^\infty n_H v' N^k(T')\sigma^{kj}(T)\delta(T-T')dT' = n_H v N^k(T)\sigma^{kj}(T)$$

Slide from
D. MAURIN

- **Semi-empirical approach** [Silberberg et Tsao]
  - for any Proj. + Targ. → Frag.
  - better than Webber if extrapolation (Z>30)

R.Silberberg & C.H.Tsao, ApJSS **25**, 315 (1973)
R.Silberberg & C.H.Tsao, ApJSS **35**, 129 (1977)
R.Silberberg & C.H.Tsao, ApJSS **35**, 137 (1977)
R.Silberberg & al, ApJSS **58**, 877 (1985)
R.Silberberg & C.H Tsao, Phys.Rep. **191**, 351 (1990)
L.Sihver & al, Phys.Rev.C **47**, 1225 (1993)
C.H.Tsao & al, Phys.Rev.C **47**, 1257 (1993)
C.J.Waddington, ApJ **470**, 1218 (1996)
R.Silberberg & al, ApJ **501**, 911 (1998)
C.H.Tsao & al, ApJ **501**, 920 (1998)
C.H.Tsao & al, ICRC **26**, HE.1.1.04 (1999)

- **Empirical approach** [Webber et al.]
  - for Proj. + H/He → Frag.
  - better than Silberberg on 'data' (Z<30)



P.Ferrando & al, Phys.Rev.C **37**, 1490 (1988)
W.R.Webber, J.C.Kish, D.A.Schrier, Phys.Rev.C 41
W.R.Webber & al, ApJ **508**, 940 (1998-a)
W.R.Webber & al, ApJ **508**, 949 (1998-b)
W.R.Webber & al, Phys.Rev.C **58**, 3539 (1998-c)
W.R. Webber et al., ApJSS 144, 153 (2003)

- **More recent empirical codes**
  - EPAX2 *http://www-w2k.gsi.de/hellstr/asp/gsi/epaxv21m.asp*
  - PHITS *phits.jaea.go.jp*

- **Microscopic description**
  - LAQGSM (Los Alamos Quark Gluon String Model)
  - NUCFRG2 (semi-empirical abrasion-ablation model)

L.W.Townsend & al, NASA, Technical Paper **3310**, (1993)
F.A.Cucinotta, NASA, Technical Paper **3354**, (1993)
J.P.Bondorf & al, Phys.Rep. **257**, 133 (1995)
J.W.Wilson & al, NASA, Technical Paper **3533**, (1995)
F.A.Cucinotta & al, NASA, Technical Paper **3594**, (1996)
C.R.Ramsey & al, Phys.Rev.C **57**, 982 (1998)
Zeitlin et al., Phys. Rev. C 77, 034605 (2008)
Zeitlin et al., AdSR 46, 728 (2010)
Zeitlin et al., Phys. Rev. C 83, 034909 (2011)

→ Webber *et al.* is the one generally used in the field (but for Z<3 nuclei) with claimed uncertainties <10% (fragments from Li → O) or <20% (from Fe)

<u>NB</u>: it is not straightforward to go from nuclear data/models to X-sec for GCRs

Transport equation in diffusion models

Diffusion — Convection

$$-\vec{\nabla}\left[K\vec{\nabla}N^j(E) - \vec{V}_c N^j(E)\right] - \Gamma^j N^j$$

Destruction on ISM

$$-\frac{(\vec{\nabla}.\vec{V}_c)}{3}\frac{\partial}{\partial E}\left[\frac{p^2}{E}N^j(E)\right] = Q^j(E) +$$

CR sources: primaries, **secondaries (spallations)**

$$\frac{\partial}{\partial E}\left[-b_{tot}(E)N^j(E) + \beta^2 K_{pp}\frac{\partial N^j(E)}{\partial E}\right]$$

Eneegy losses (EM) — Reacceleration

1. DESTRUCTION: $\Gamma = n_{ISM} v \sigma_R$, $\sigma_R = \sigma^{tot} - \sigma^{tot}_{el}$
2. SOURCES: $\bar{Q}^j \equiv q_0^j Q(E)\hat{q}_i + \sum_k^{m_k > m_j} \tilde{\Gamma}^{kj} N_i^k(0)$

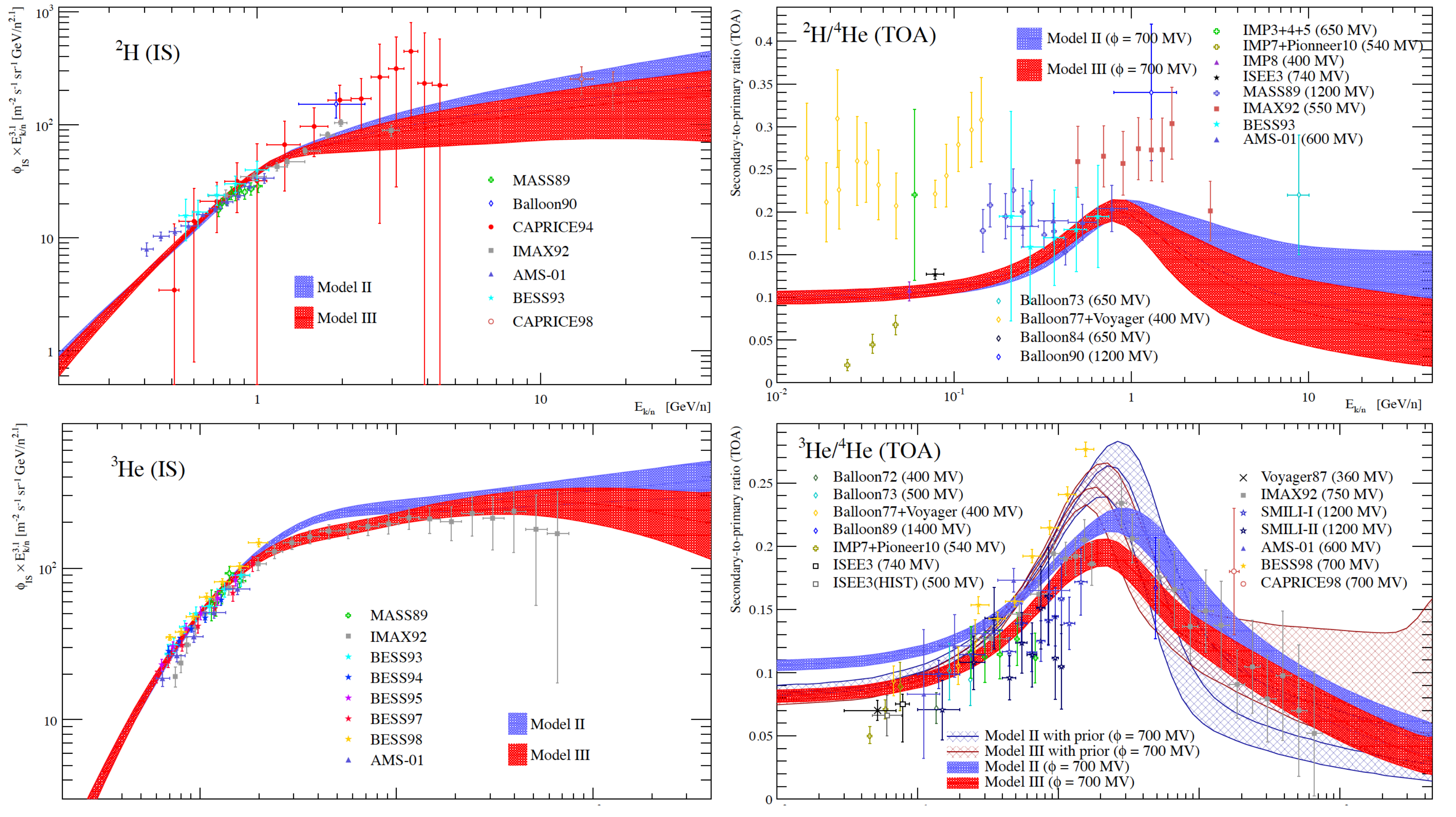
Primary production in SNR

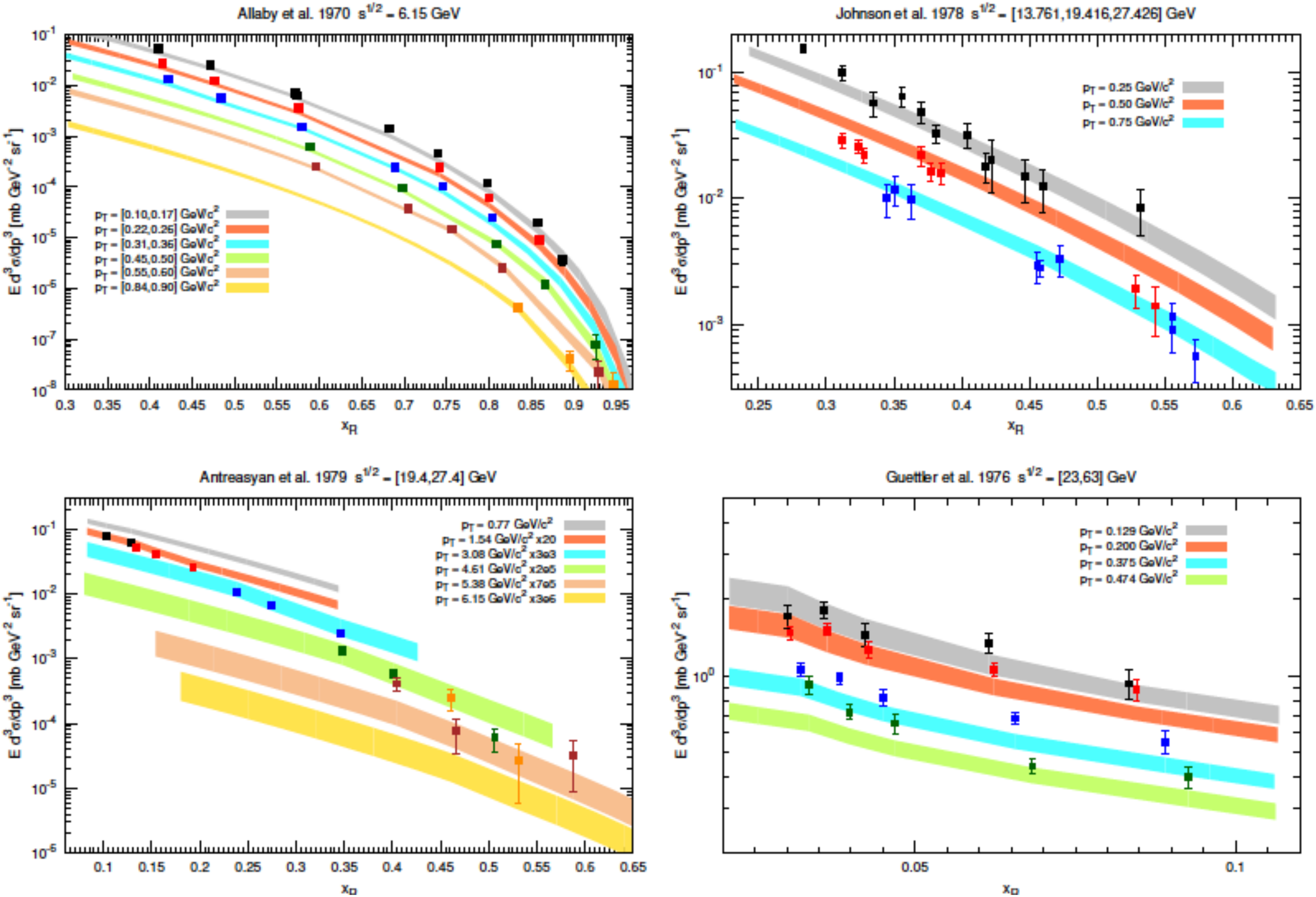
Secondary production by fragmentation of heavier nuclei

Z<=2 Nuclei

Coste, Derome, Maurin, Putze A&A 2012

^{1}H, ^{2}H, ^{3}He, ^{4}He almost as powerful as B/C
Noticeable effort on reliable cross sections





Allaby et al. 1970 s^1/2 = 6.15 GeV
pT = [0.10,0.17] GeV/c^2
pT = [0.22,0.26] GeV/c^2
pT = [0.31,0.36] GeV/c^2
pT = [0.45,0.50] GeV/c^2
pT = [0.55,0.60] GeV/c^2
pT = [0.84,0.90] GeV/c^2
E d^3σ/dp^3 [mb GeV^-2 sr^-1]
xR
Johnson et al. 1978 s^1/2 = [13.761,19.416,27.426] GeV
pT = 0.25 GeV/c^2
pT = 0.50 GeV/c^2
pT = 0.75 GeV/c^2
E d^3σ/dp^3 [mb GeV^-2 sr^-1]
xR
Antreasyan et al. 1979 s^1/2 = [19.4,27.4] GeV
pT = 0.77 GeV/c^2
pT = 1.54 GeV/c^2 x20
pT = 3.08 GeV/c^2 x3e3
pT = 4.61 GeV/c^2 x2e5
pT = 5.38 GeV/c^2 x7e5
pT = 6.15 GeV/c^2 x3e6
E d^3σ/dp^3 [mb GeV^-2 sr^-1]
xR
Guettler et al. 1976 s^1/2 = [23,63] GeV
pT = 0.129 GeV/c^2
pT = 0.200 GeV/c^2
pT = 0.375 GeV/c^2
pT = 0.474 GeV/c^2
E d^3σ/dp^3 [mb GeV^-2 sr^-1]
xR

The role of helium nuclei

Kachelriess, Moskalenko & Ostapchenko 2015

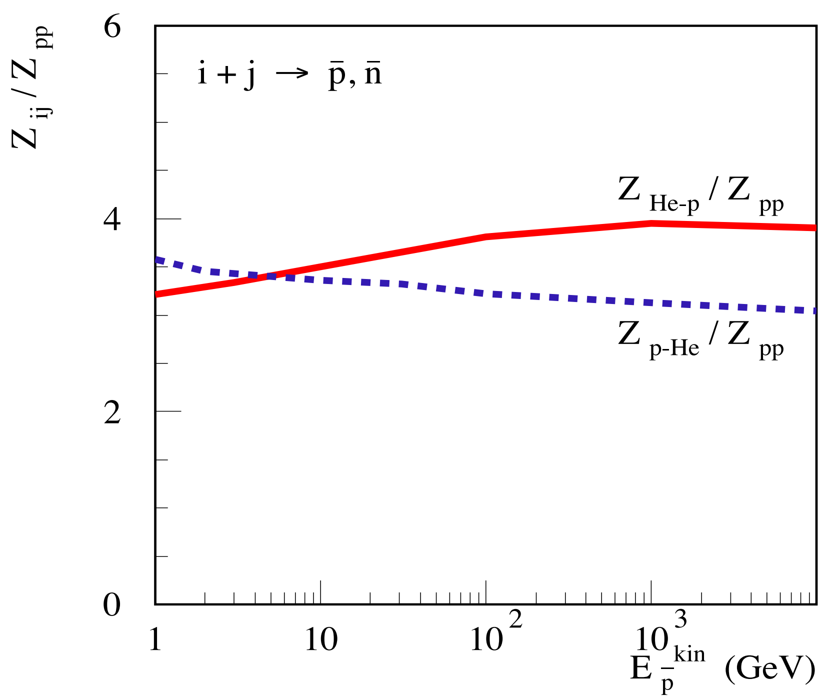
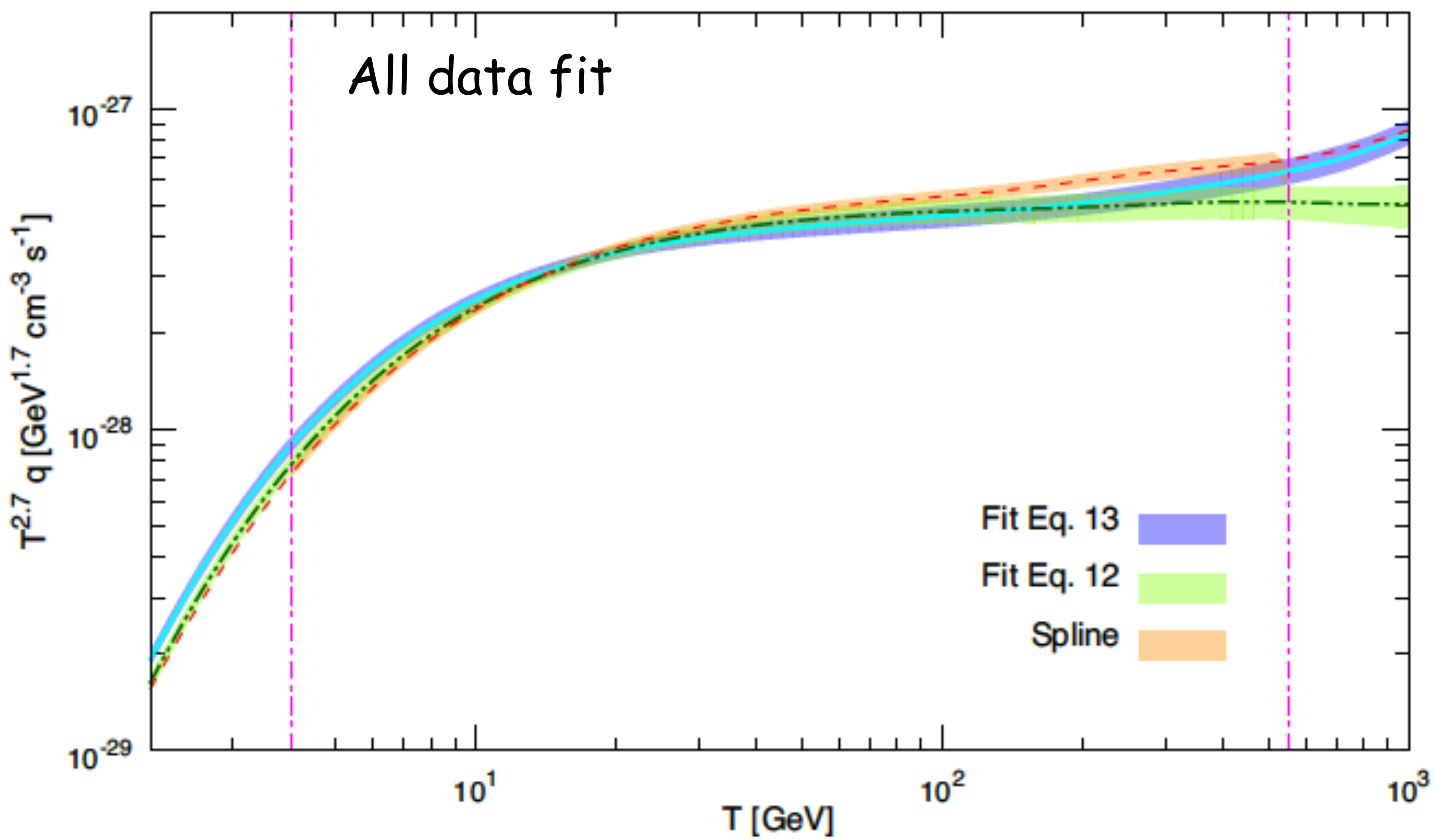


FIG. 7.— Energy dependence of the enhancement of the He p (solid, red) and p He (dashed, blue) contributions to the antiproton spectrum, relative to the pp-case, $Z_{\bar{p}}^{ij}(E_{\bar{p}}, \alpha)/Z_{\bar{p}}^{pp}(E_{\bar{p}}, \alpha)$ (plotted as a function of $E_{\bar{p}}^{\text{kin}}$), for $\alpha = 2.6$.

Note: The cosmic p flux is ~ 10 times higher than He flux

Antiproton source spectrum from p-p channels



$$E\frac{d^3\sigma}{dp^3} = \sigma_{\rm in}(s)(1-x_R)^{C_1}e^{-C_2x_R} \left[C_3(\sqrt{s})^{C_4}e^{-C_5p_T} + C_6(\sqrt{s})^{C_7}e^{-C_8p_T^2}\right]. \quad (12)$$

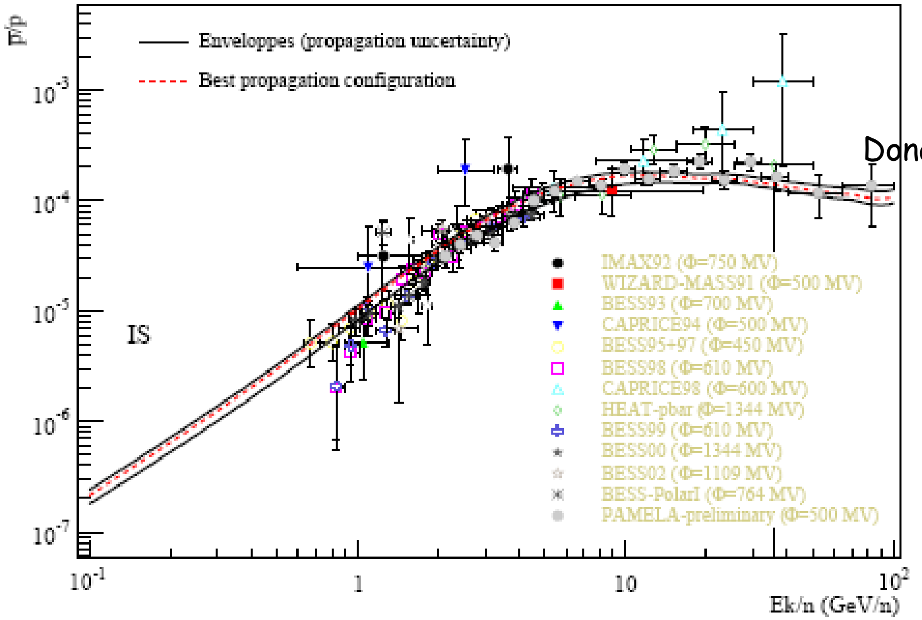
$$E\frac{d^3\sigma}{dp^3} = \sigma_{\rm in}(s)(1-x_R)^{C_1}e^{-C_2x_R} \left|[C_3(\sqrt{s})^{C_4}e^{-C_5p_T} + C_6(\sqrt{s})^{C_7}e^{-C_8p_T^2} + C_9(\sqrt{s})^{C_{10}}e^{-C_{11}p_T^3}]\right|, \quad (13)$$

Different analytical functions give similar chi2, but different extrapolation out of validity ranges → uncertainties at low and high energies

Antiproton in CRs: data and models

Theoretical calculations compatible with CR models

Powerful tool for DARK MATTER models

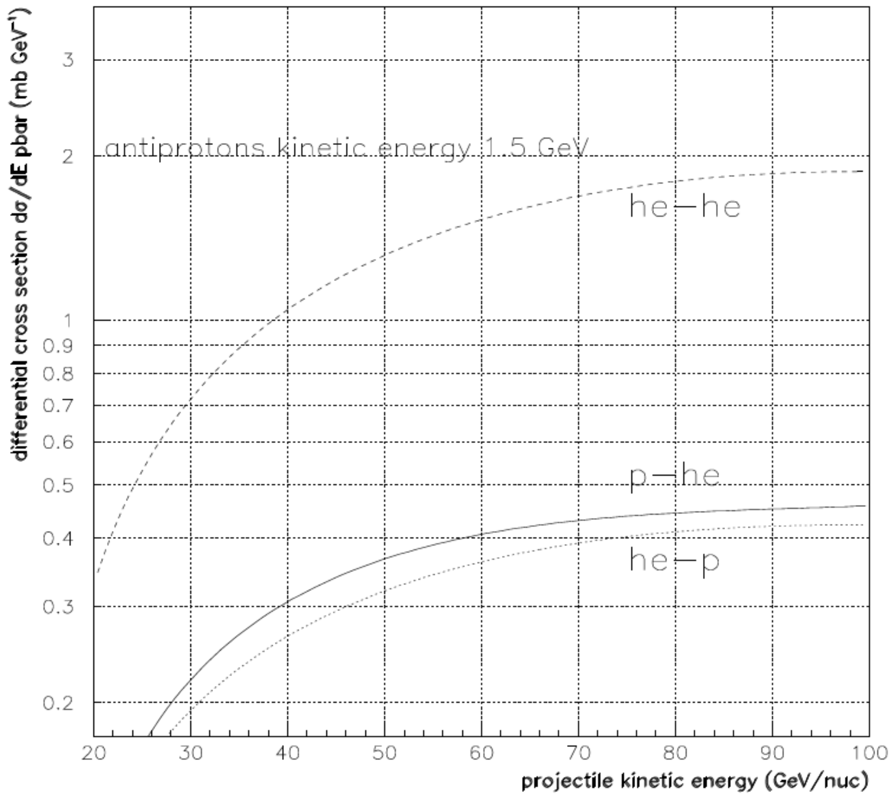


Donato et al. PRL 2009

<u>NO need for new phenomena (astrophysical / particle physics)</u>

AMS-02 data now at high accuracy 1 – 450 GeV

Differential antiproton cross section



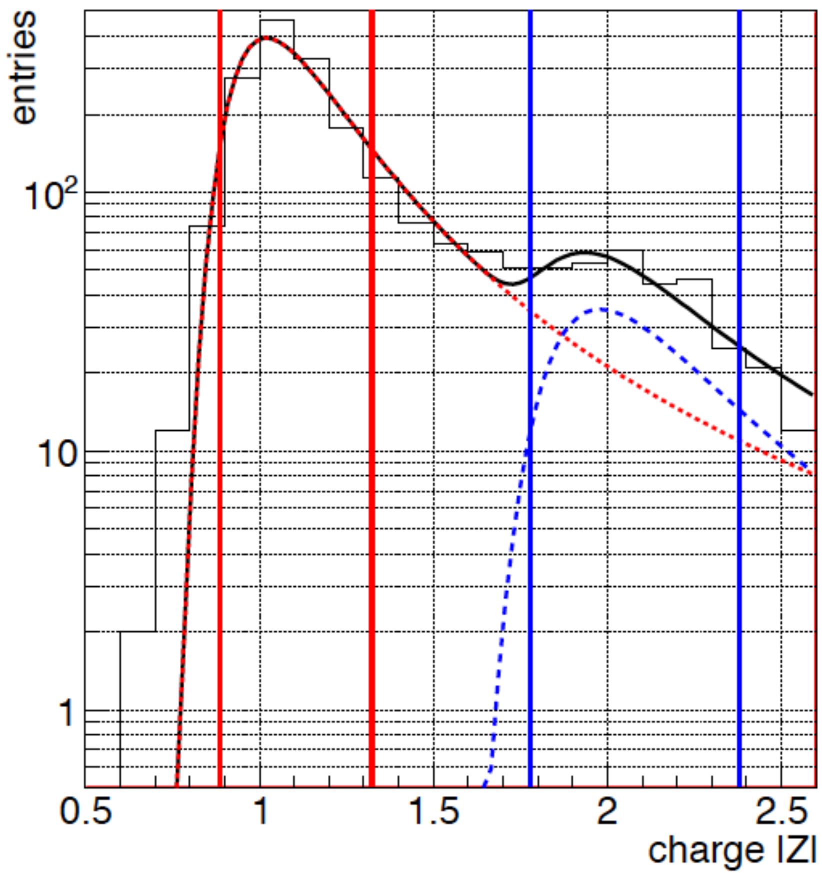
Given that:

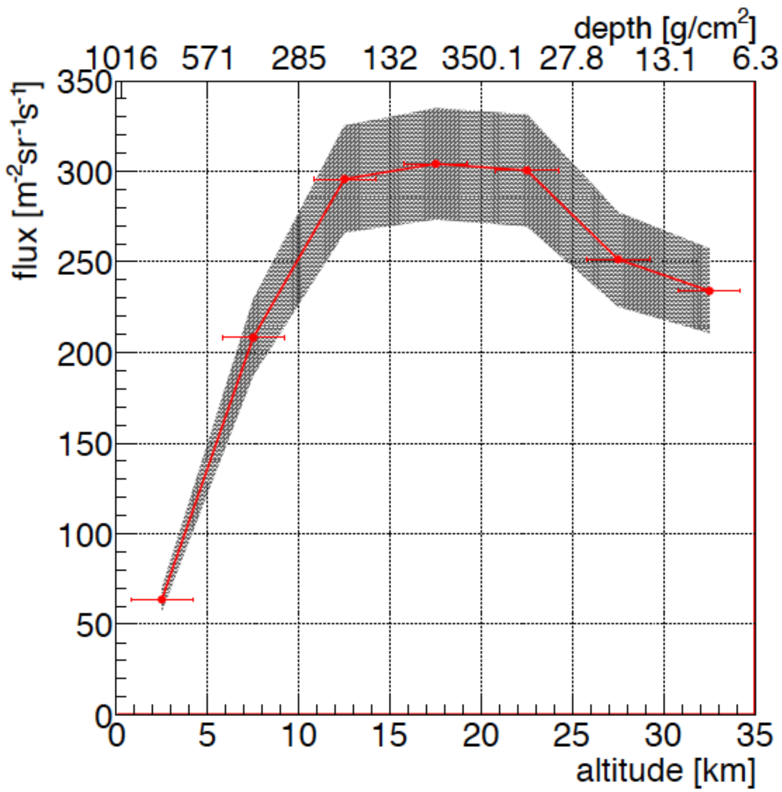
1. In the ISM n_H=0.9/cm^3, n_{He}=0.1/cm^3,
2. the cosmic p flux is ~ 10 higher than He

→ the main production channel involving He is p_{CR}-He_{ISM}

GAPS prototype flight

P. von Doetinchem et al. 1307.3538





Propagation of e^+ & e^-

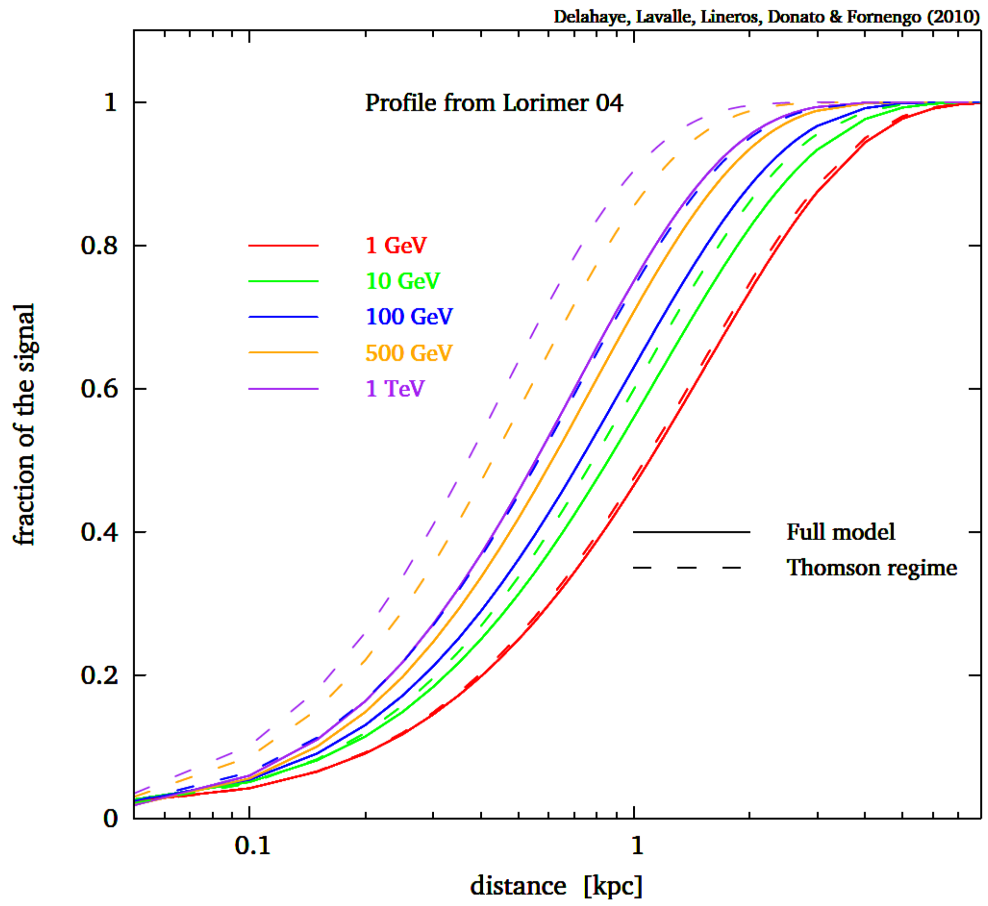
Delahaye, Lavalle, Lineros, FD, Fornengo, Salati, Taillet A&A 2009

Diffusive semi-analytical model:
Thin disk and confinement halo
Free parameters fixed by B/C

Above few GeV: only spatial diffusion and energy losses

Energetic positrons & electron are quite local

Relativistic (KN) energy losses induce a longer propagation scale



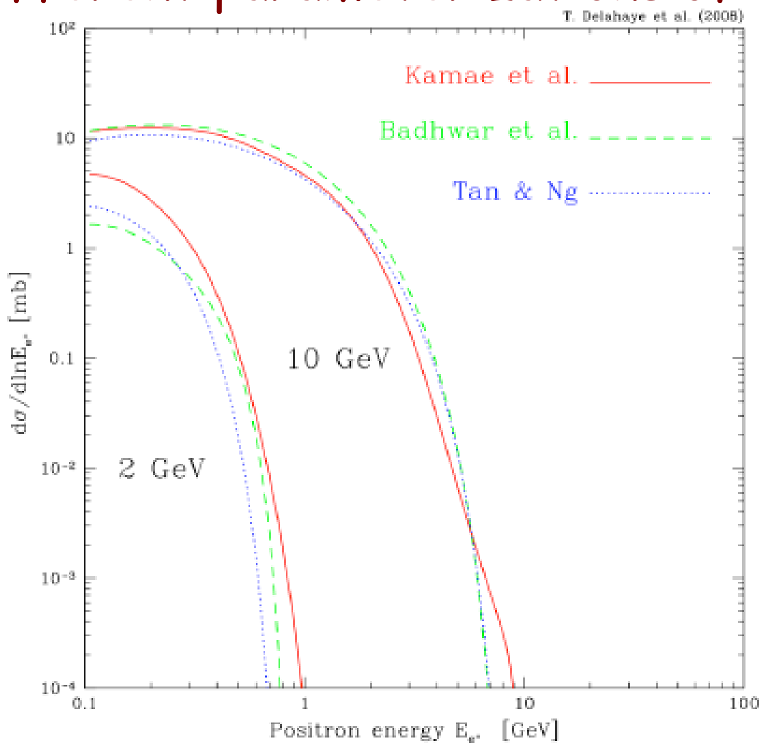
95%(80%) for 2kpc and E>100(10) GeV

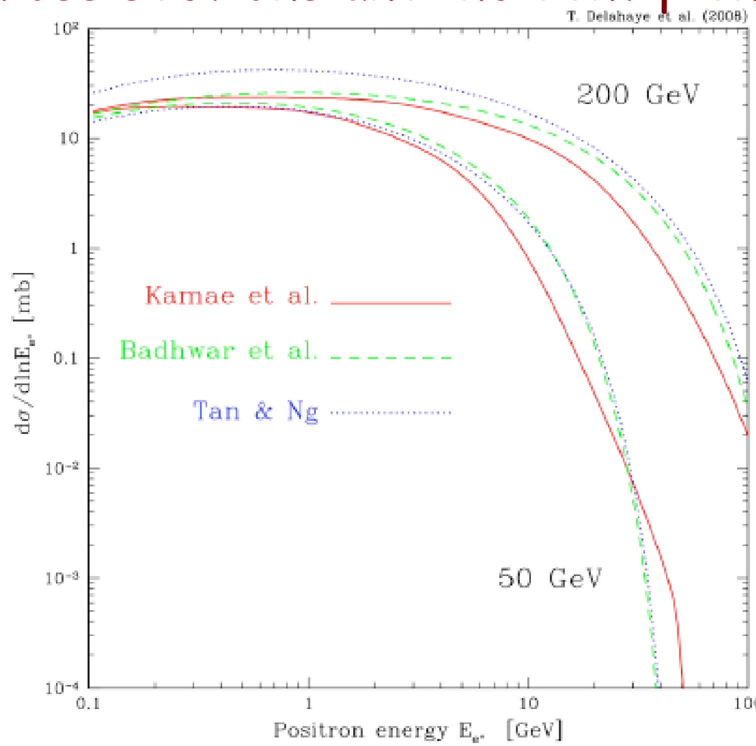
Secondary positron production

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

- p+H → p+Δ^+ → p+π^0 & n+π^+ (mainly below 3 GeV)
- p+H → p+n+ π^+
- p+H → X + $K^\pm$

Different parameterizations of cross sections and incident p energy



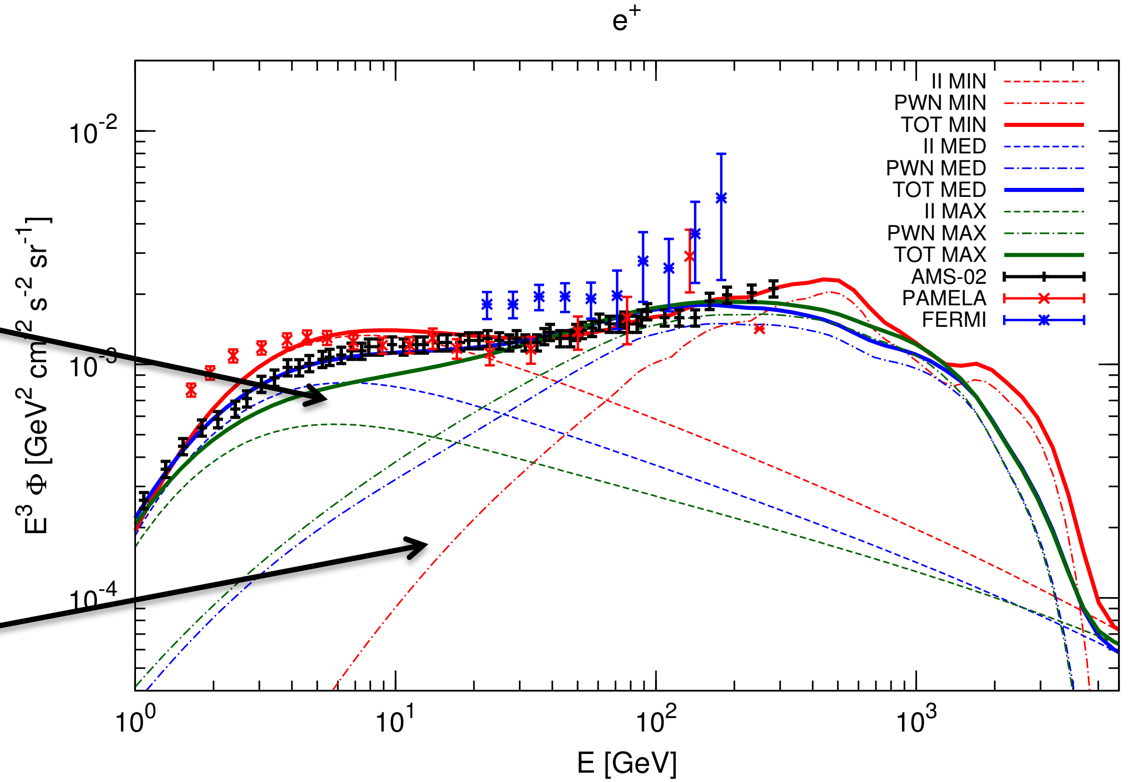


Low energy positrons: the power of AMS precision data

Di Mauro, FD, Fornengo, Vittino JCAP 2014; Lavalle, Maurin, Putze PRD 2014

Secondaries in
3 propagation models

Pulsars in
3 propagation models



AMS POSITRON data at low energy are so **precise** to start **constraining** the Milky Way models (as well as B/C)!

The case for

gamma rays

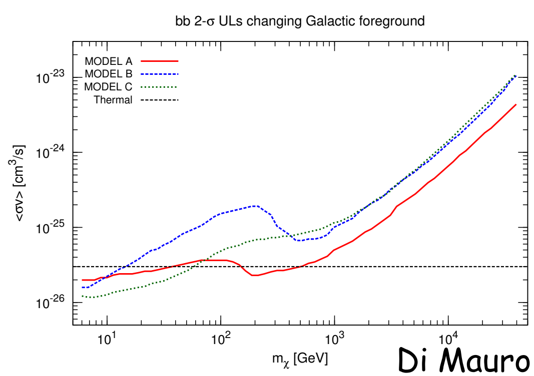
(very briefly)

$p+He \rightarrow \pi^0 \rightarrow 2\gamma$: galactic foreground in the Fermi-LAT data

Contextually to p+He→ antiprotons, it would be of very interesting to measure also the photons (**gamma rays**) coming from the hadronization processes via π^0 decay.

This process occurs in the galactic disk and enters the calculation of the galactic emission, crucial for understanding:

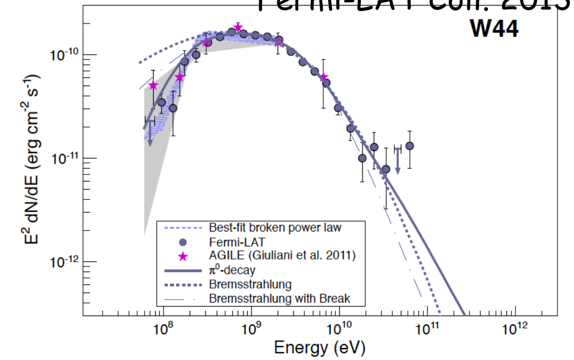
1. DARK MATTER annihilation
   (Galaxy, dwarf spheroidal galaxies, ..)



Di Mauro & FD 2015

2. ORIGIN of COSMIC RAYS
   galaxy emission, SNRs, ..

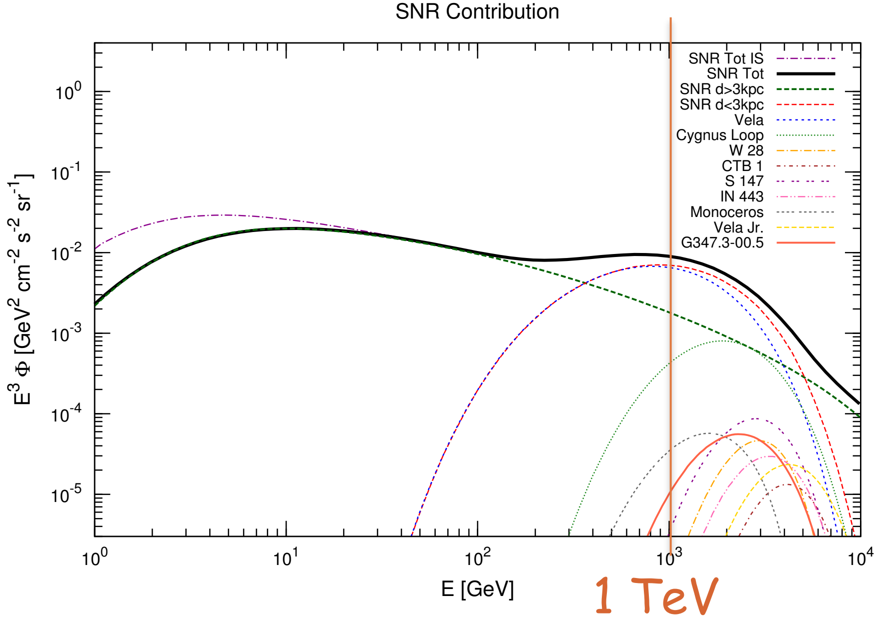
Fermi-LAT Coll. 2013



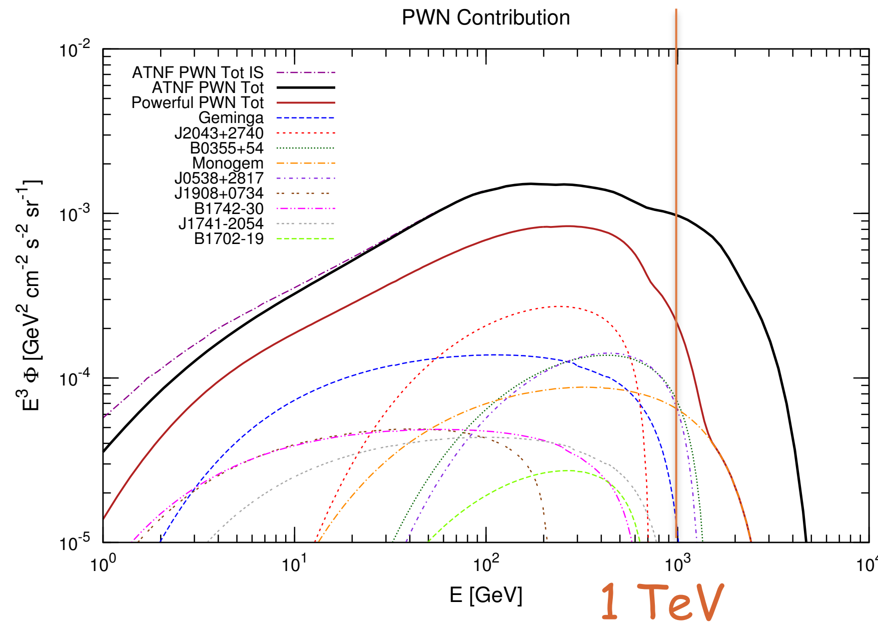
Astrophysical sources of e+ e-

Di Mauro, FD, Fornengo, Vittino JCAP 2014

Electrons



Positrons



Supernova remnants

Pulsars

Partial contributions from CR nuclei

$$\epsilon_{ij}^{\bar{p}}(E_{\bar{p}}) = \frac{q_{\bar{p}}^{ij}(E_{\bar{p}})}{q_{\bar{p}}^{pp}(E_{\bar{p}})}$$

Kachelriß+2015

$$q_{\bar{p}}^{ij}(E_{\bar{p}}) = n_j \int_{E_{\rm thr}(E_{\bar{p}})}^{\infty} dE \, \frac{d\sigma^{ij\to\bar{p}}(E, E_{\bar{p}})}{dE_{\bar{p}}} \, I_i(E)$$

11

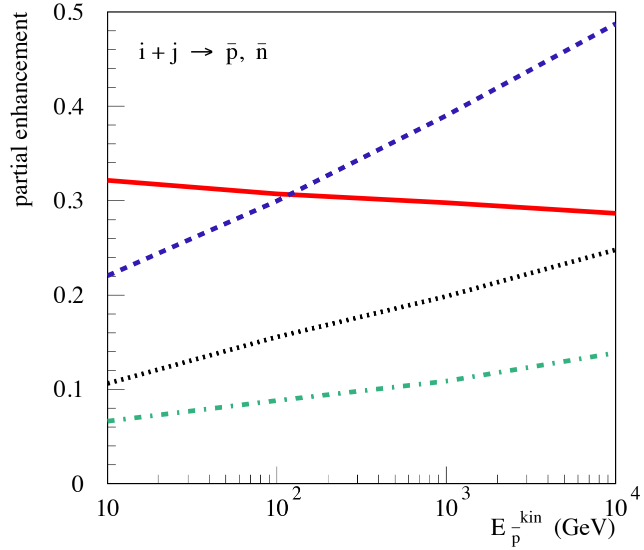


FIG. 8.— Energy dependence of partial contributions $\epsilon_{ij}^{\bar{p}}(E_{\bar{p}})$ to the nuclear enhancement factor from different interaction channels: pHe (solid, red), Hep (dashed, blue), He He (dot-dashed, green), and all others (dotted, black); the CR composition given in Table 2 is used.

The contribution of He nuclei, in CRs and in ISM, is similar (50%) of the p-p one

Secondary antiprotons in cosmic rays (CR)

Produced by spallation reactions on the interstellar medium (ISM)

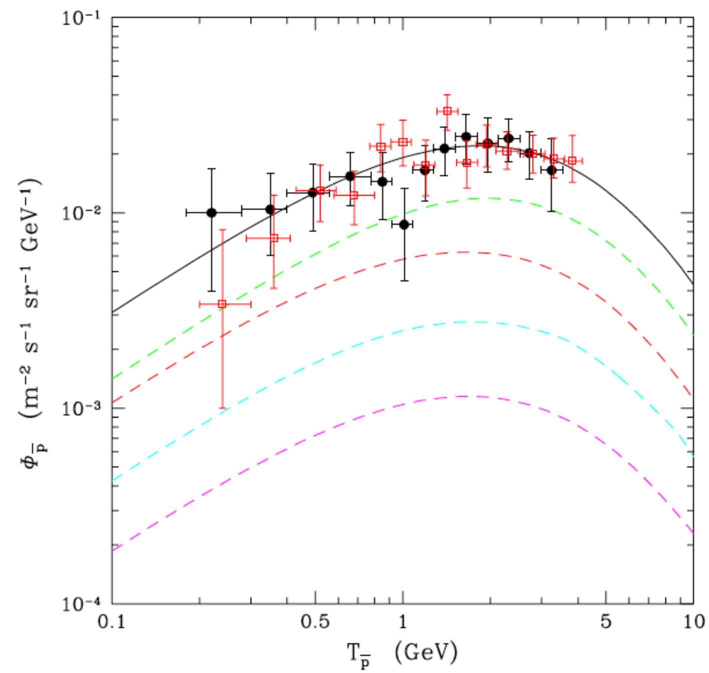
$p_{CR} + H_{ISM}$

$p_{CR} + He_{ISM}$

$He_{CR} + H_{ISM}$

$He_{CR} + He_{ISM}$

$\} \; \bar{p} + X$



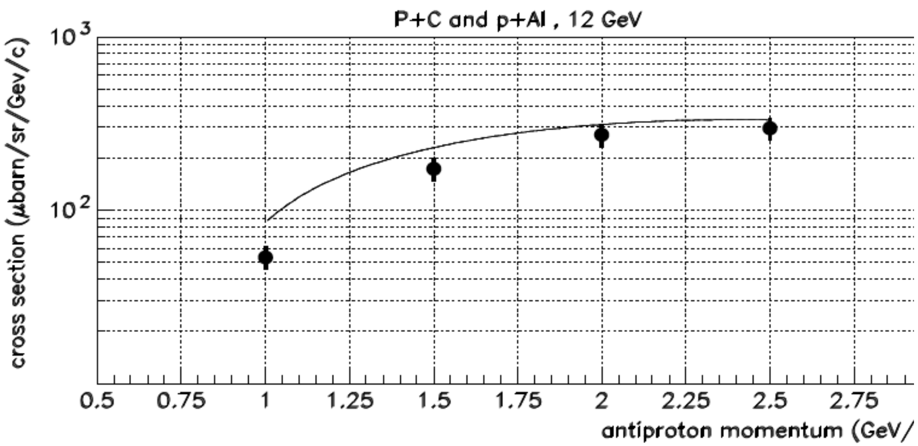
The only measured cross section is p-p → $\bar{p}$ + X

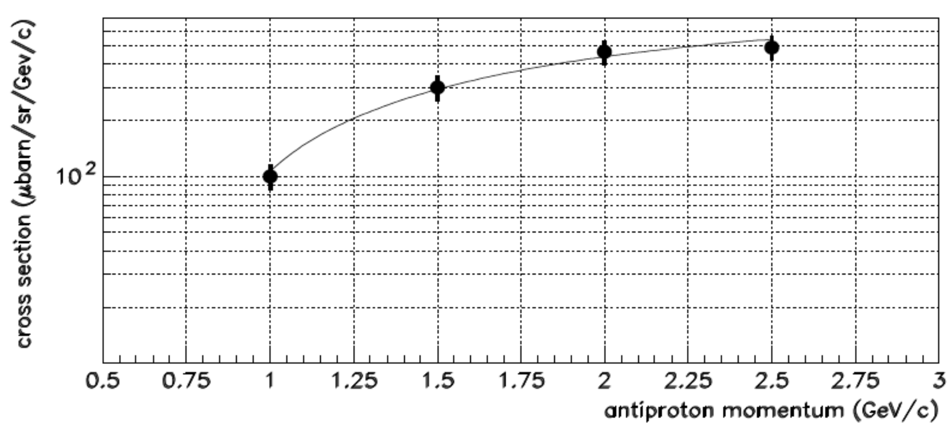
ALL CROSS SECTIONS INVOLVING He (projectile or target) ARE DERIVED FROM OTHER DATA!!

Antiproton production from p and He

1. p+p: $\sigma_{p+p \rightarrow antiprotons}$ NA49 data analysis
(Di Mauro, FD, Goudelis, Serpico PRD 2014; Kappl, Winkler JCAP 2014)
or analytical expression (Tan & Ng, PRD26 1982, 1983

2. p+ He, He+p, He+He: σ(p + He → antiprotons): NO DATA
→ derived from MonteCarlo simulations, i.e. DTUNUC
verified on p+C,p+Al and heavier nuclei (Duperray et al. 2003, 2005; Donato et al. ApJ 563 (2001)172)





Data from Sugaya+1998; fit: DTUNUC

Donato+ ApJ2001