Dark matter in the Galaxy

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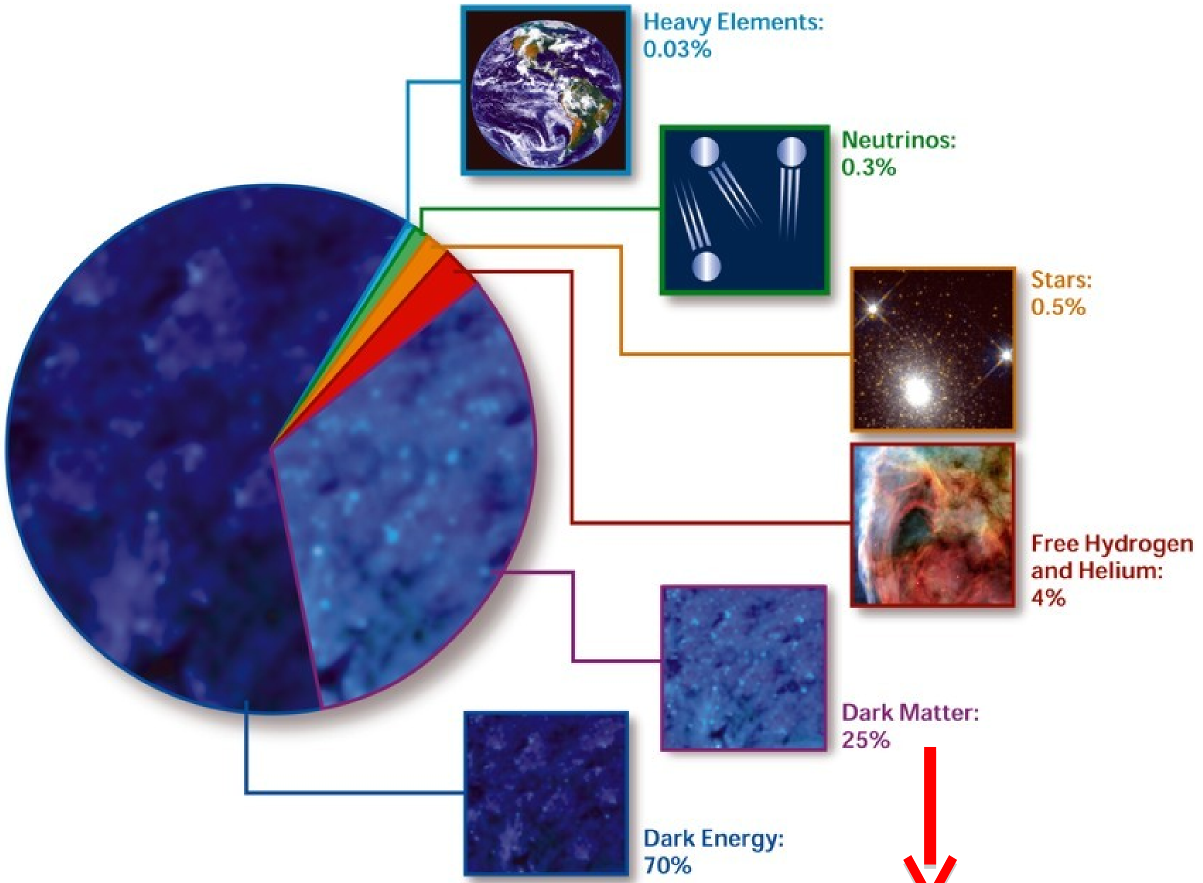
Firenze- April 28, 2017

The composition of the Universe



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

SIGNALS from RELIC WIMPs

Direct searches: elastic scattering of a WIMP off detector nuclei
Measure of the recoil energy
Annual modulation and directionality of the measured rate

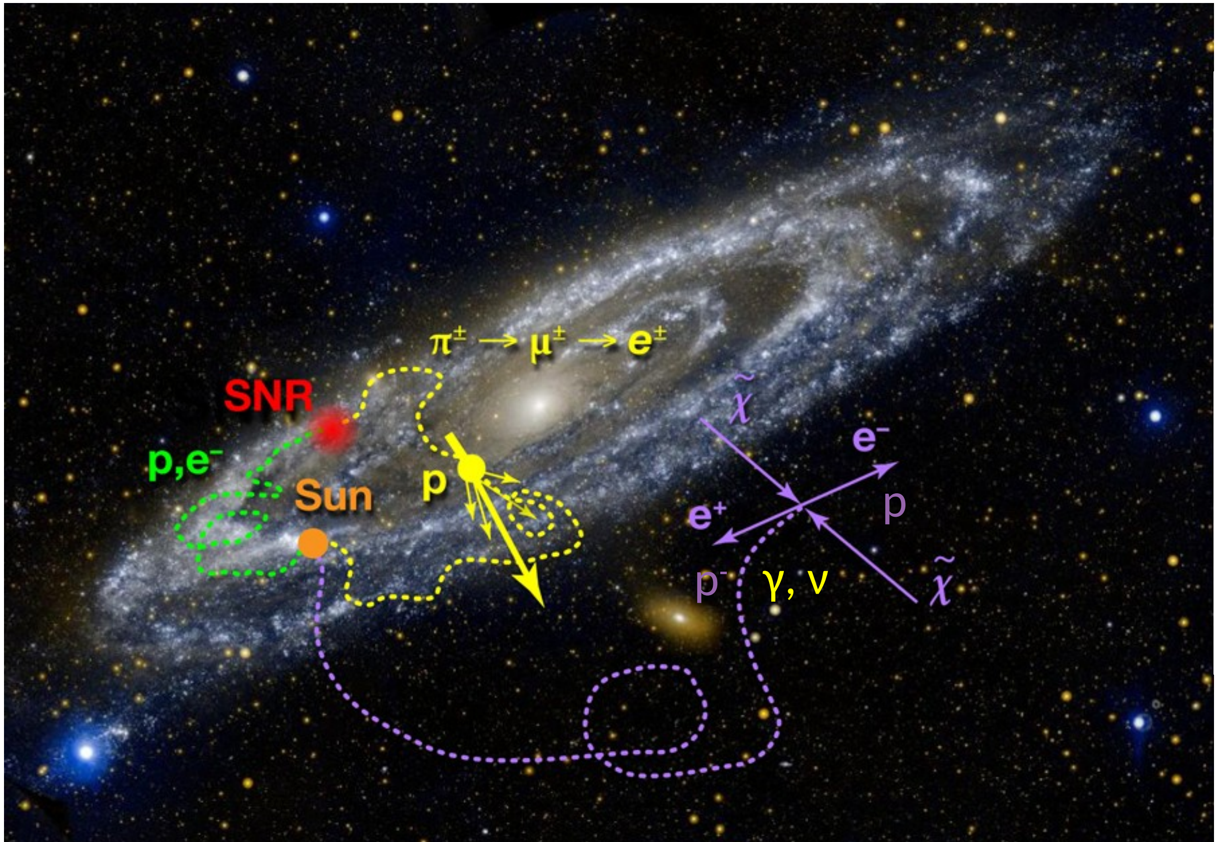
Indirect searches: in CRs

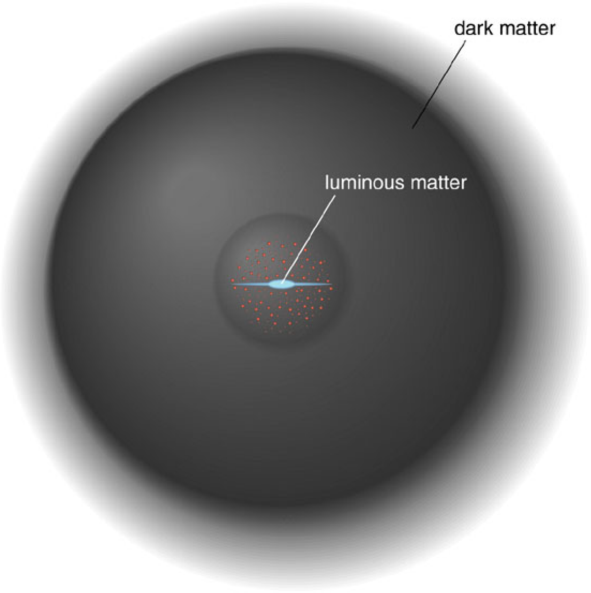
- signals due to annihilation of accumulated $\chi\chi$ in the centre of celestial bodies (Earth and Sun)
- signals due to $\chi\chi$ annihilation in the galactic halo

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

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





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

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

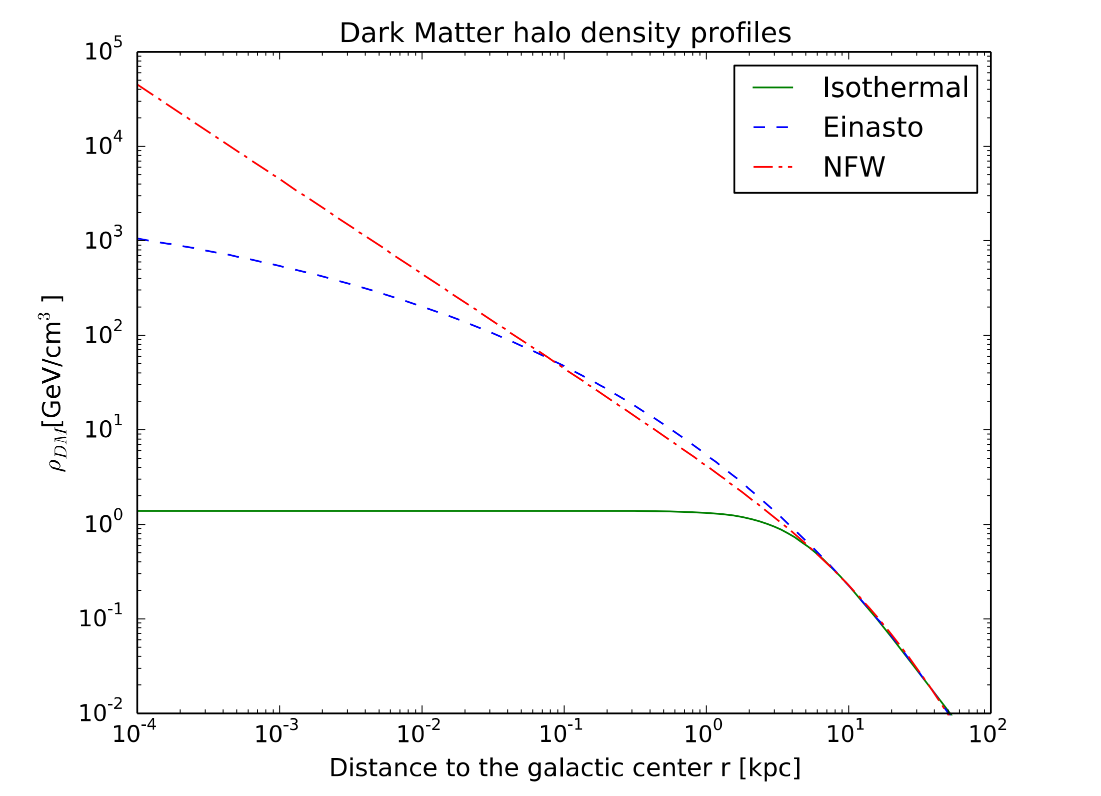
Decay

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

- $\rho(\vec{x})$ 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

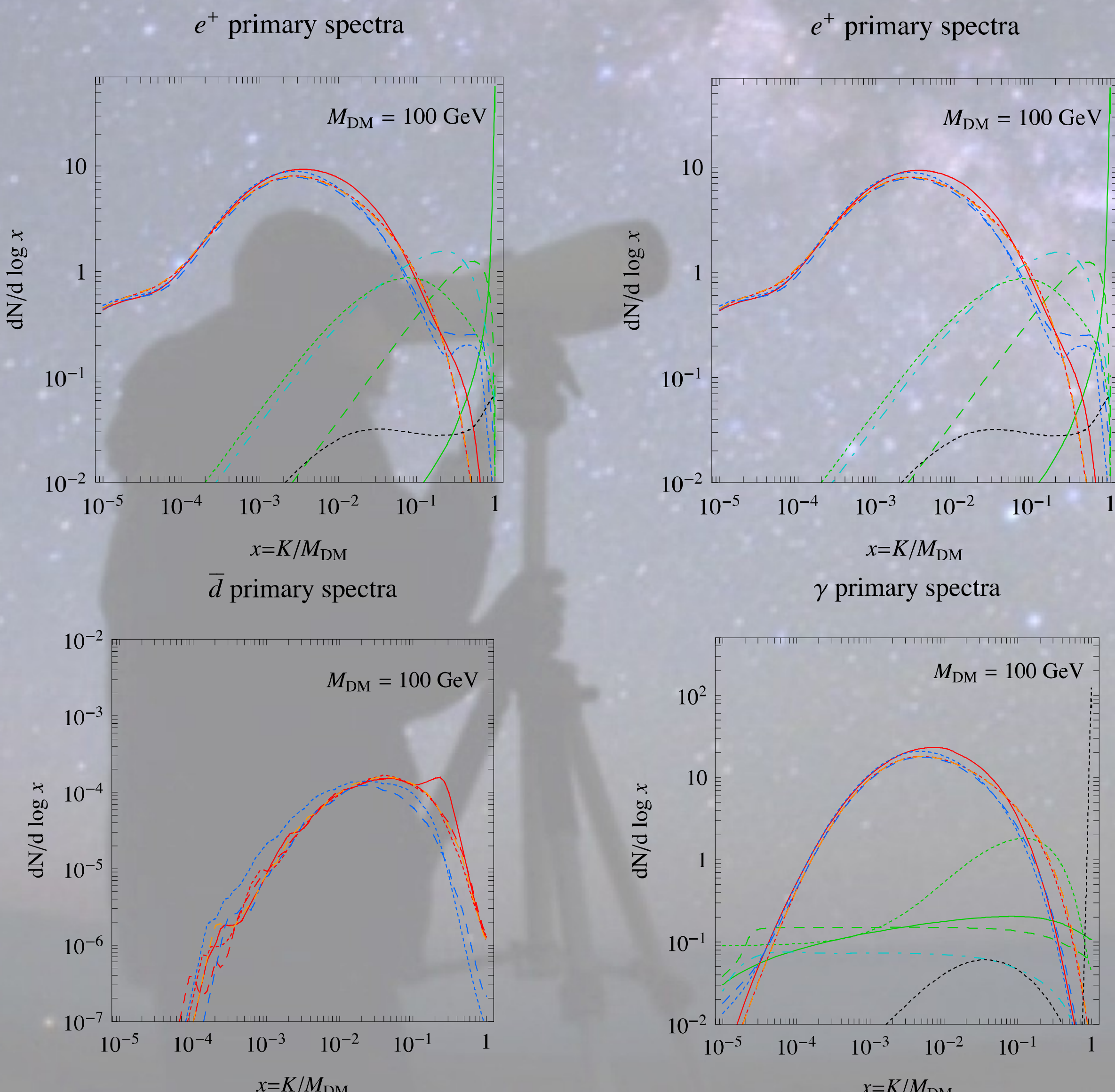
Dark Matter distribution in the MW halo ρ(r)

Derived from **rotational curves** (external galaxies), typically proving a cored profile (isothermal sphere) and from **N-body numerical simulations** of cosmic structures, typically leading to cuspy profiles in the galactic centers

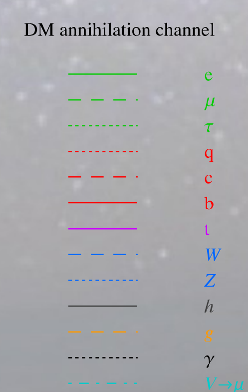


The very shape is relevant only for Gamma-rays (photons), not for charged particles wandering in the Galaxy

DM Production Spectra



Typically computed by Monte Carlo Generators, i.e. Pythia, Herwig, ...



Cirelli + 2012

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
Supernova remnants (SNR), pulsars, dark matter annihilation, …

SECONDARIES: produced by spallation reactions of primaries on the interstellar medium (ISM), made of **H and He**

2. ACCELERATION

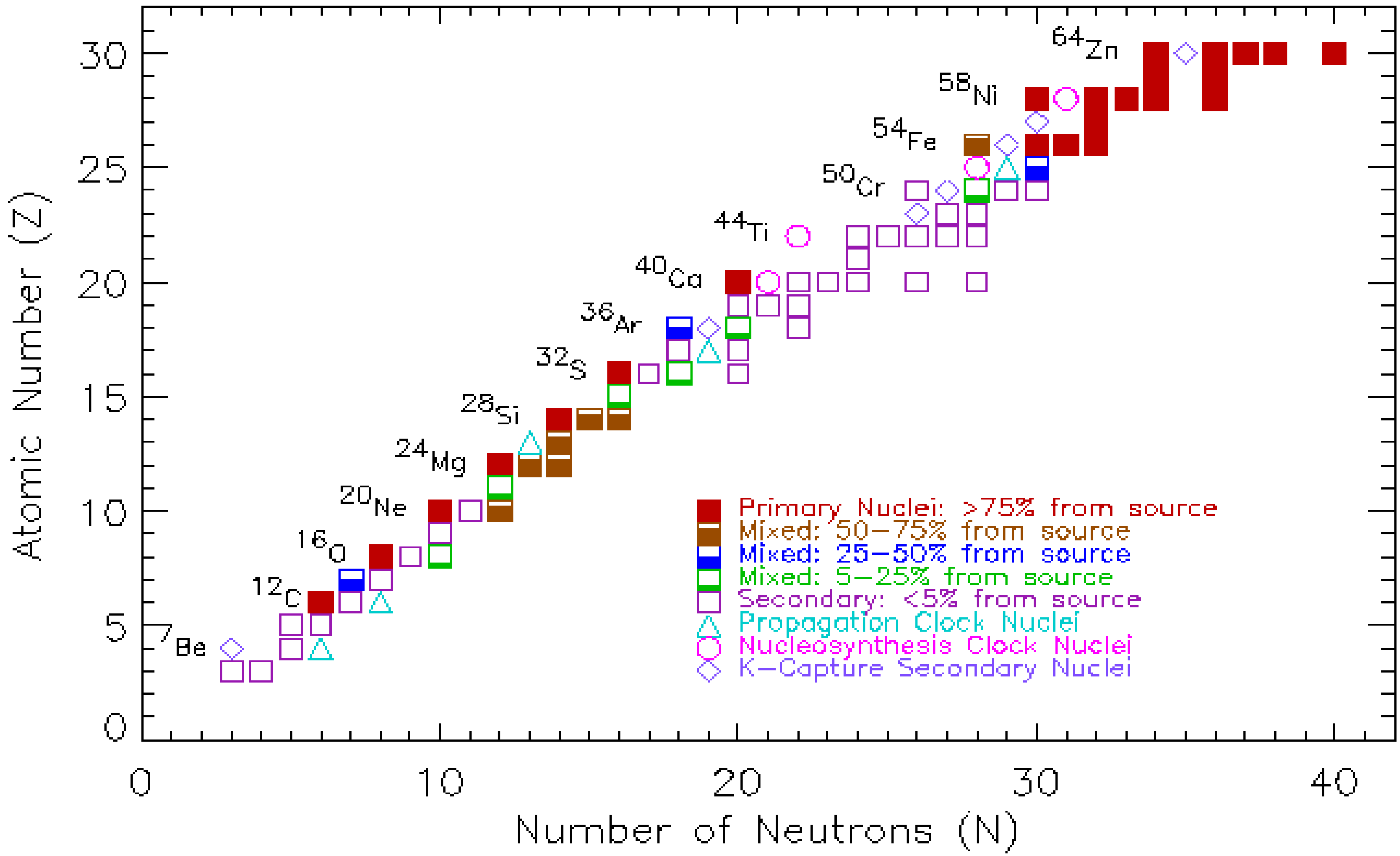
SNR are considered the powerhouses for CRs.
They can accelerate particles at least up to 10^2 TeV

3. PROPAGATION

CRs are diffused in the Galaxy galactic magnetic field (microGauss)

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

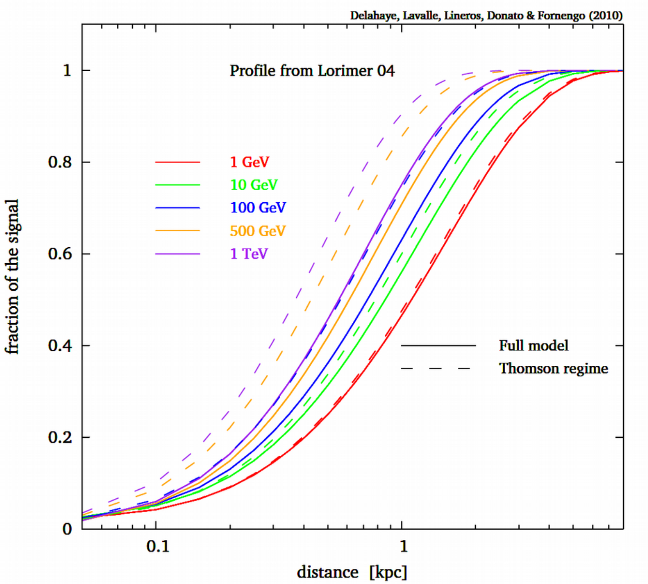
Secondaries = NOT present in sources, thus produced by
spallation of primary CRs (p, He, C, O, Fe) on ISM
Nuclei: LiBeB, sub-Fe, ... ;
e^+, p^+, d^+; ... from inelastic scatterings



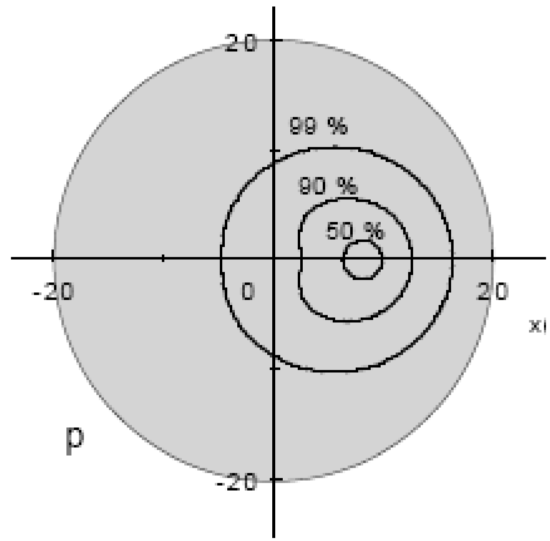
Where do these particles come from?

(if sources located in the galactic disk)

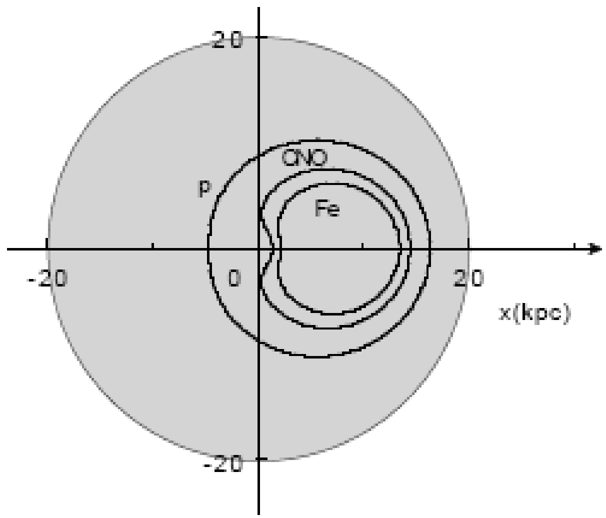
Electrons



Protons (~antiprotons)



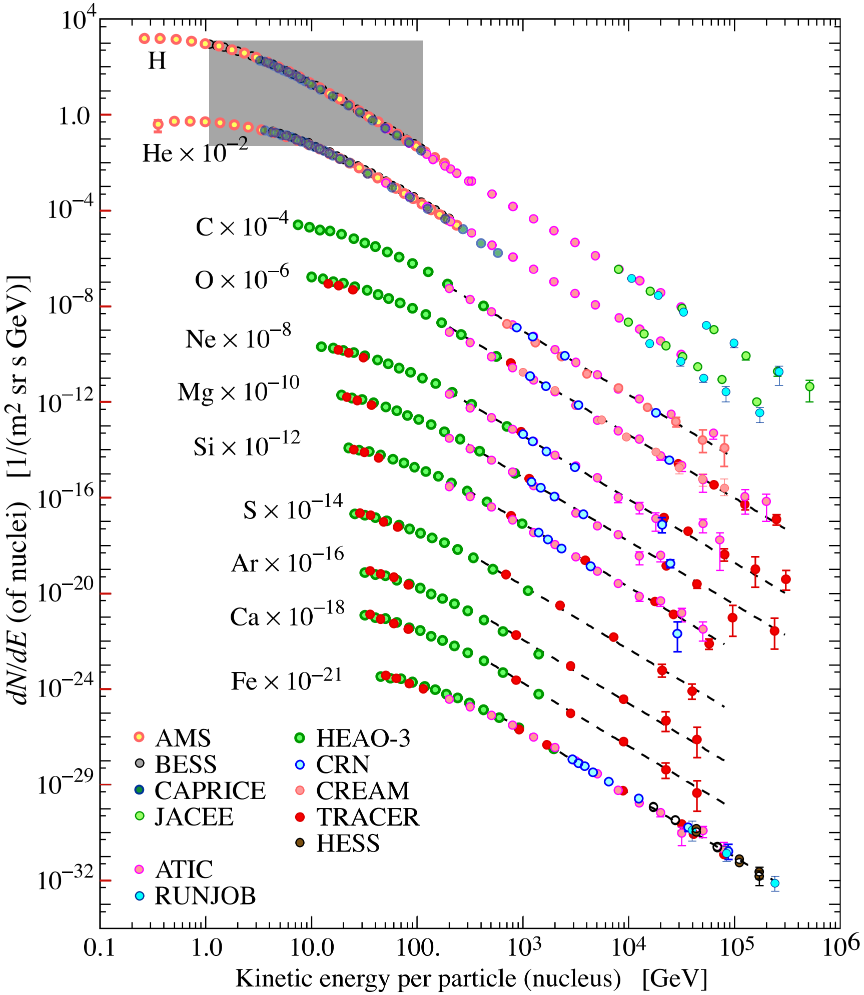
Nuclei



Energetic electrons are quite **local** due to **radiative cooling**
Stable hadrons arrive at Earth from farther places, depending on **spallations** on the interstellar medium (ISM: H, He)

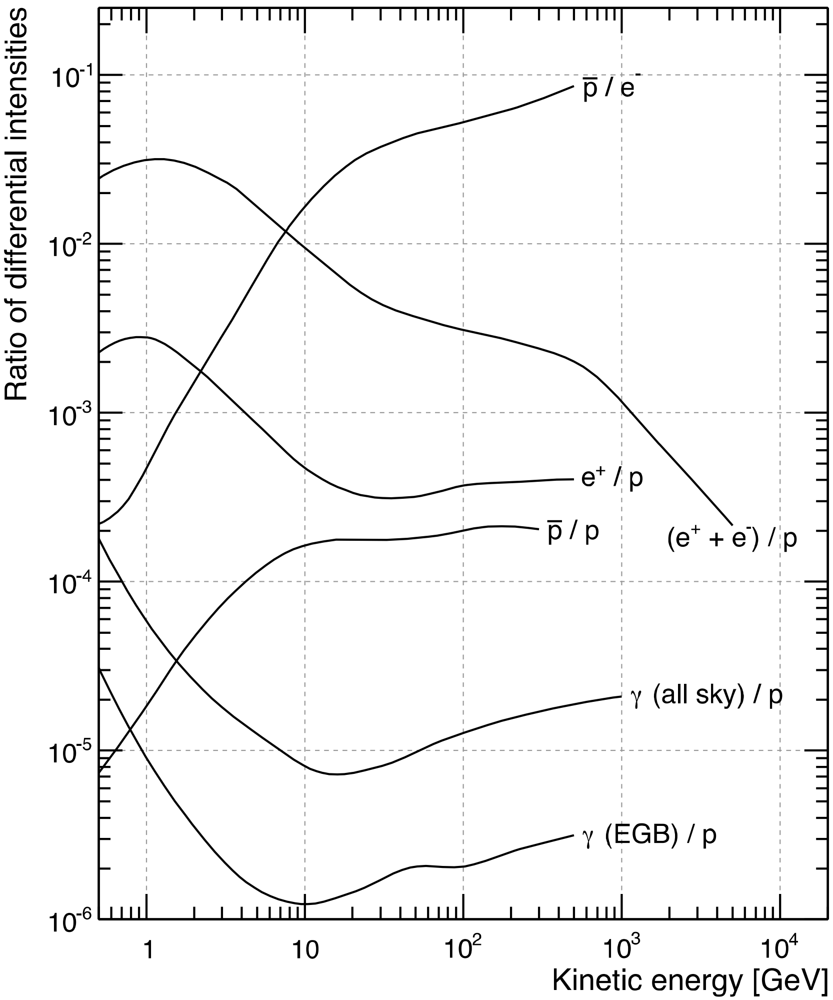
Different species explore different galactic environments

Charged cosmic rays intensity



PDG, Fig. created by
P. Boyler and D. Muller

Rare CRs and γ-rays



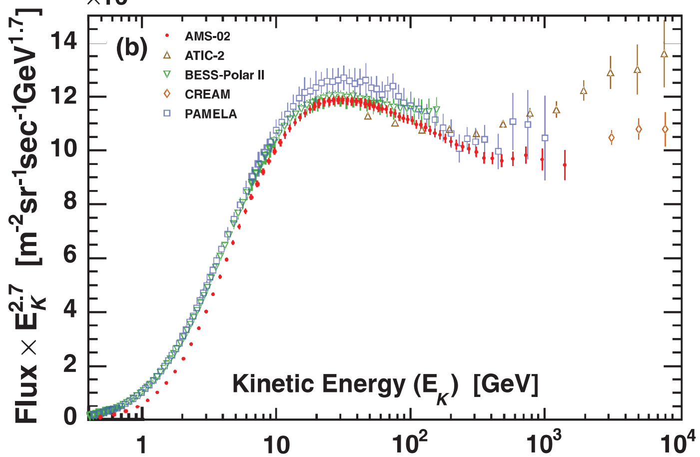
L Baldini, 1407.7631

The SOURCES of CRs cannot be tested by CRs

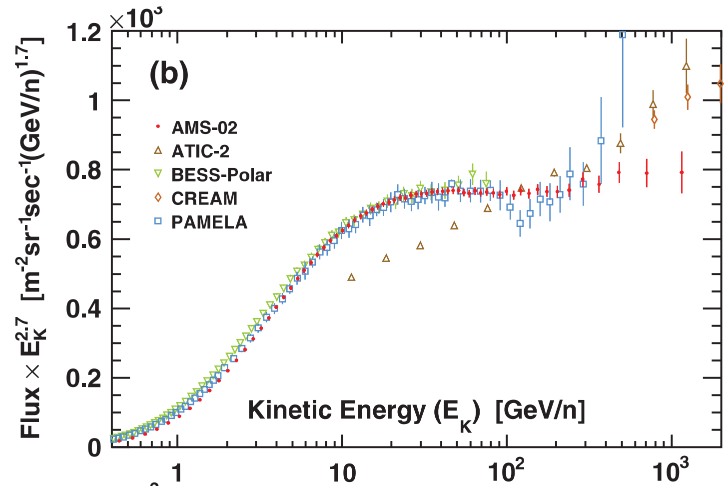
SPECIES	SOURCES	TEST
Primary nuclei, e- gamma-rays	Supernova remnants	EM: radio, X-rays, + simulations
Primary e- & e+	Pulsar Wind Nebulae	EM (more difficult) + simulations
Secondary nuclei & leptons	CRs on the ISM	Colliders
Antimatter, Gamma rays	Dark Matter	Colliders (hopefully)

Proton and Helium fluxes

AMS PRL114, 2015



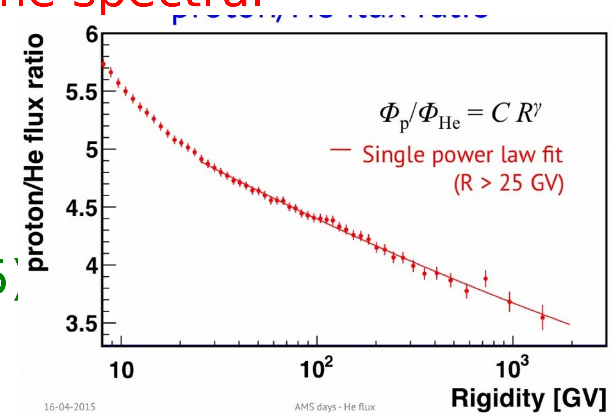
AMS PRL115, 2015



- AMS data confirm the Pamela spectral break at ~ 300 GeV/n in both p and He (also hinted by Fermi-LAT)

- Discrepant hardening: p and He do not share same spectral index (Δγ~0.1, He harder)

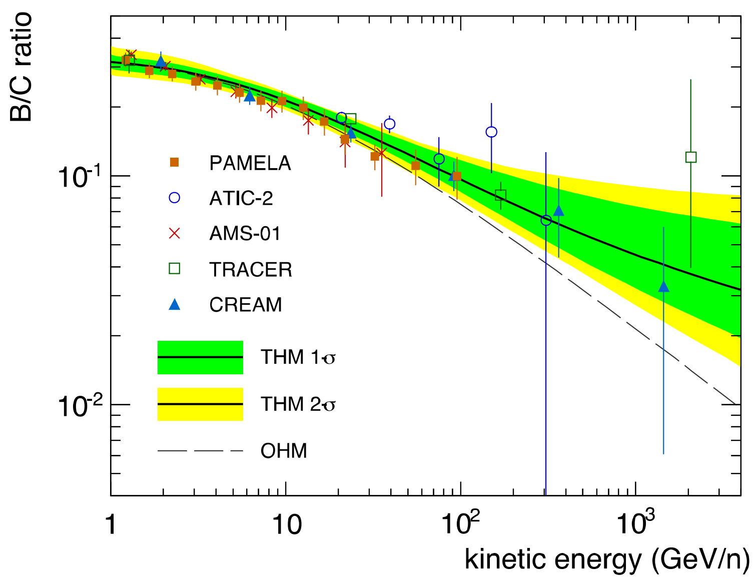
- Many interpretations have been proposed, relying on sources, propagation, local models, interactions (for a review, P. Serpico at ICRC 2015) (Tomassetti & FD 2015; Mertsch & Sarkar 2009; …)



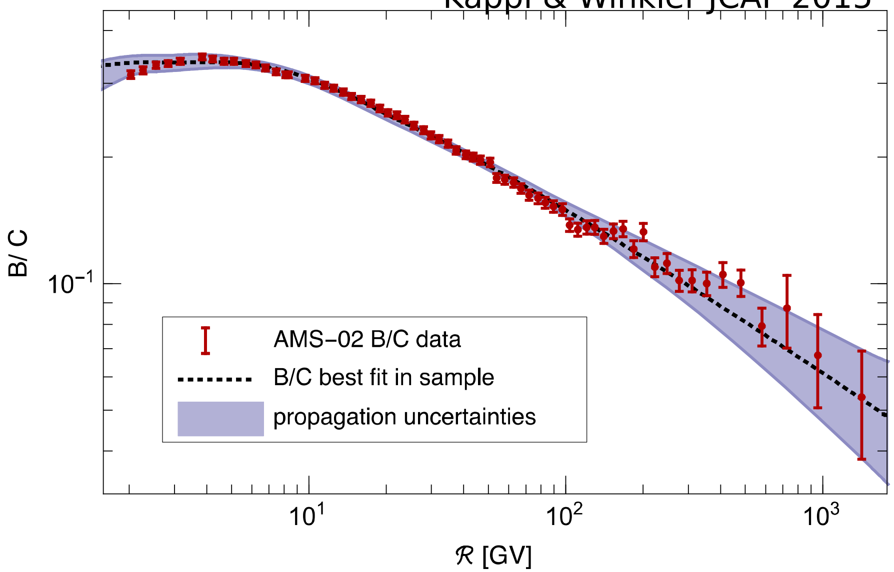
Boron-to-Carbon: a standard candle for fixing GALACTIC PROPAGATION

- Li, Be, B are produced by fragmentation of heavier nuclei (mostly C, N, O) on H and He: production cross sections
- B/C is very sensitive to **propagation effects**, kind of standard candle

Feng, Tomassetti, Oliva PRD 2016



Kappl & Winkler JCAP 2015



B/C (AMS, PRL 117, 2016) does not show features at high energies

At first order, we understand B/C within Fermi acceleration and isotropic diffusion. This may be no longer sufficient when dealing with data at higher energies, gamma-ray data, other species

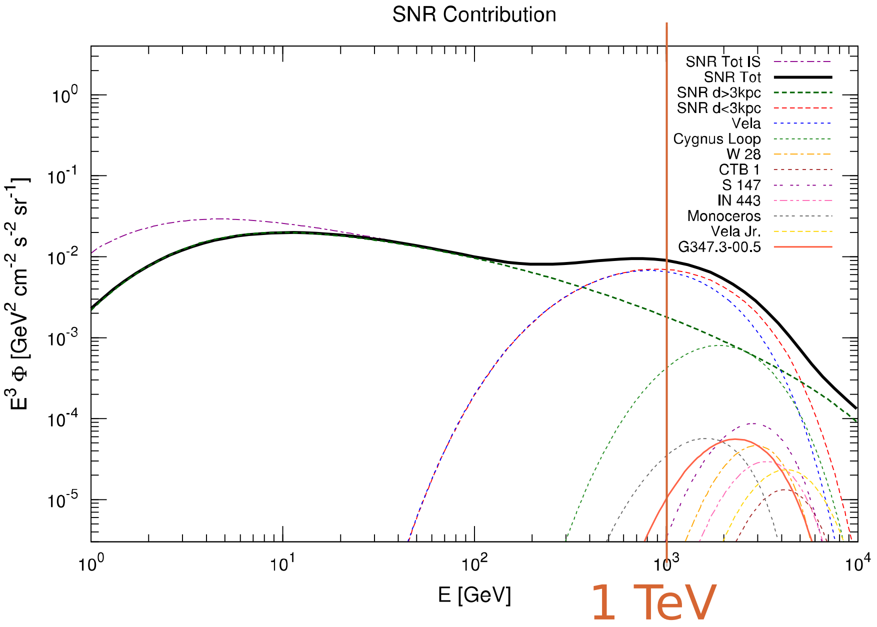
The case for

positrons

Sources of e+ and e-

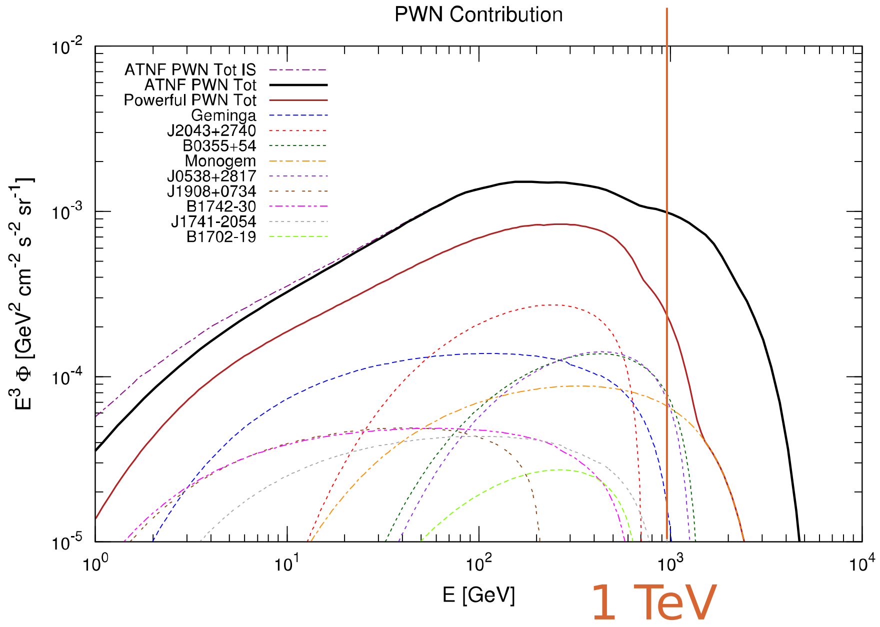
Di Mauro, FD, Fornengo, Vittino JCAP 2014

Electrons



Supernova remnants

Positrons

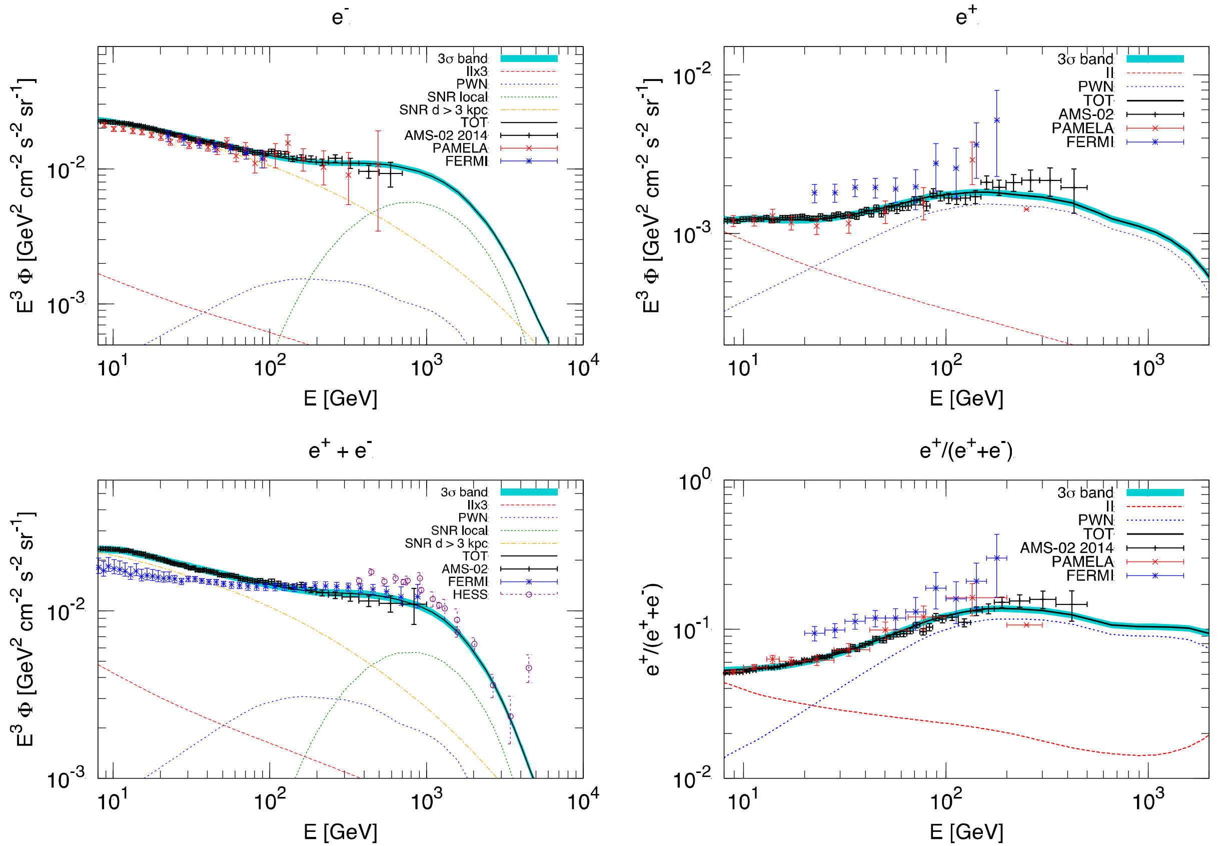


Pulsars

These SNR and PWN sources taken from the radio **ATNF** catalog

AMS lepton data:
an astrophysical interpretation

Di Mauro, FD, Fornengo, Vittino JCAP 2016



TH: Secondaries + supernovae + pulsars

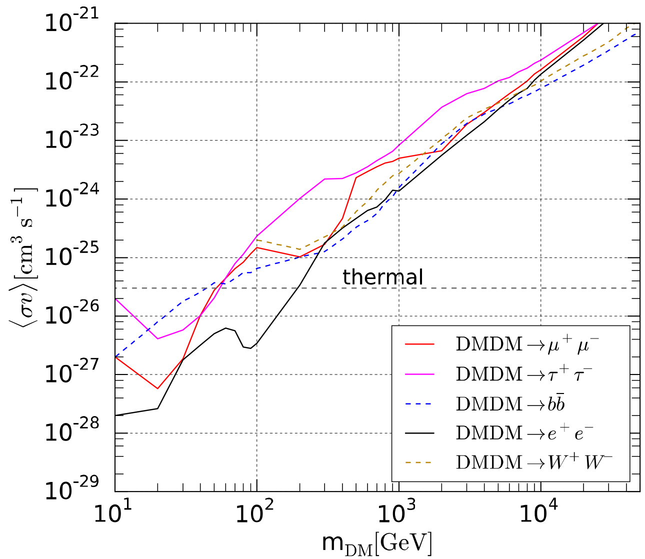
EXP: AMS data precise on wide range

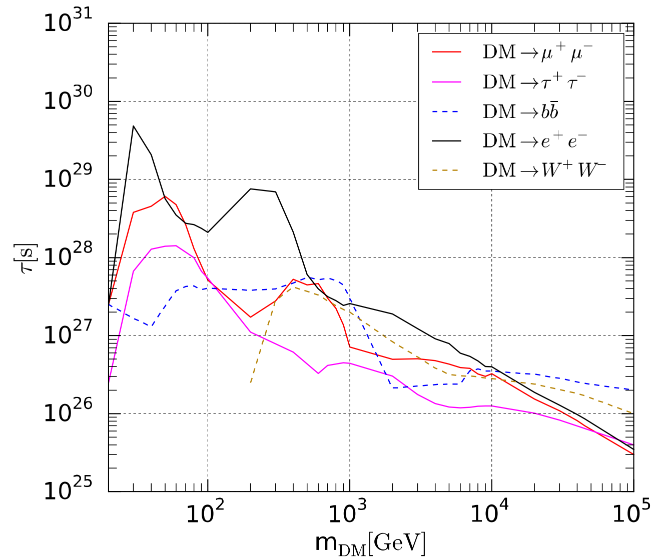
Small features can bring strong information

Adding a Dark Matter component:

Upper bounds on annihilation cross section/decay time from fitting AMS-02 lepton data

Di Mauro, FD, Fornengo, Vittino JCAP 2016



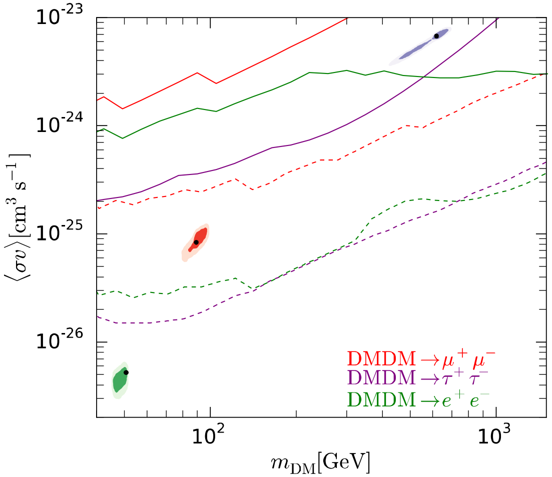


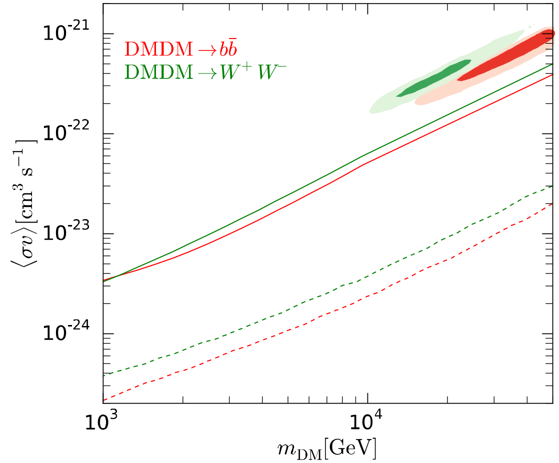
The upper bounds are obtained with astrophysical components AND a contribution from Dark Matter annihilation / decay

(MED propation model, Einasto DM radial density profile).

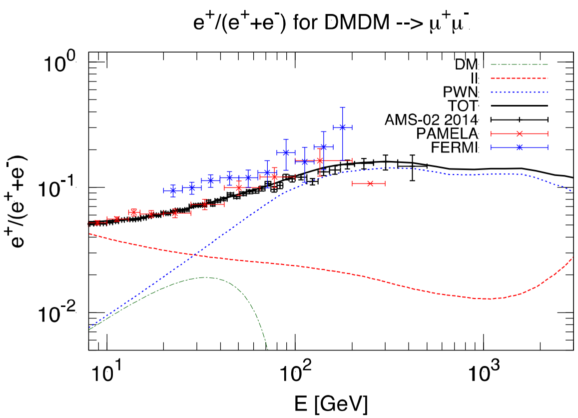
Limits on annihilation cross section at the thermal value
For m<200 GeV and e^+e^- annihilation channel

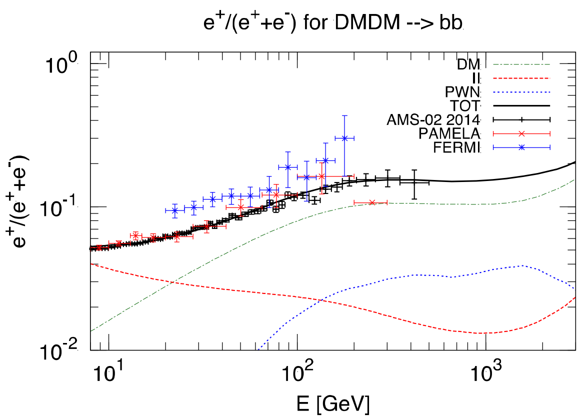
Searching for a DM signal





Upper bounds are from Fermi-LAT gamma ray data at latitudes > 20
(Di Mauro&FD PRD2015)



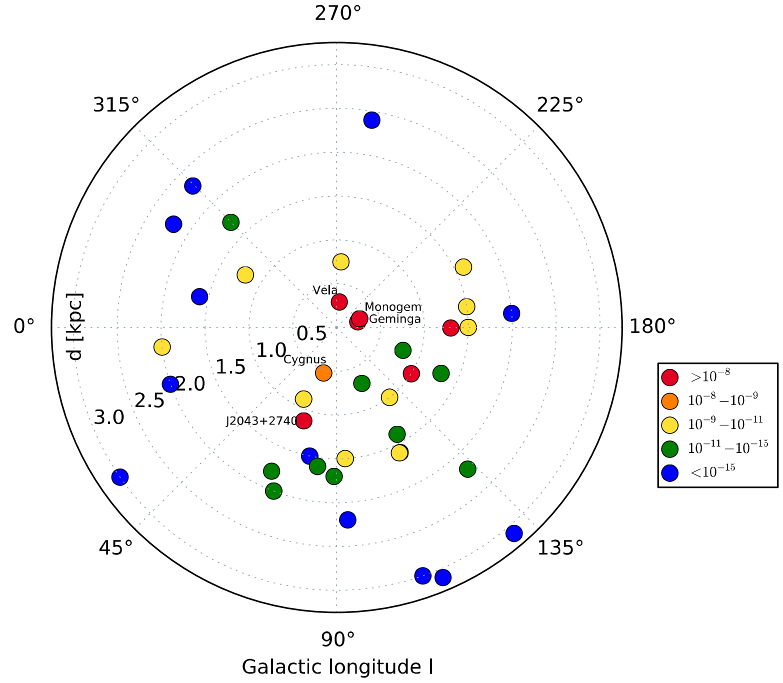


Positron fraction vs detected energy: DM component is
added to secondary and PWN
spectra

When also m_{DM} is let free to vary, the fit with **DM improves** w.r.t the scenario with astrophysical contributions only.

Leptonic (hadronic) annihilation channels are compatible (in tension) with upper bounds from DM searches in high latitude Fermi-LAT gamma rays

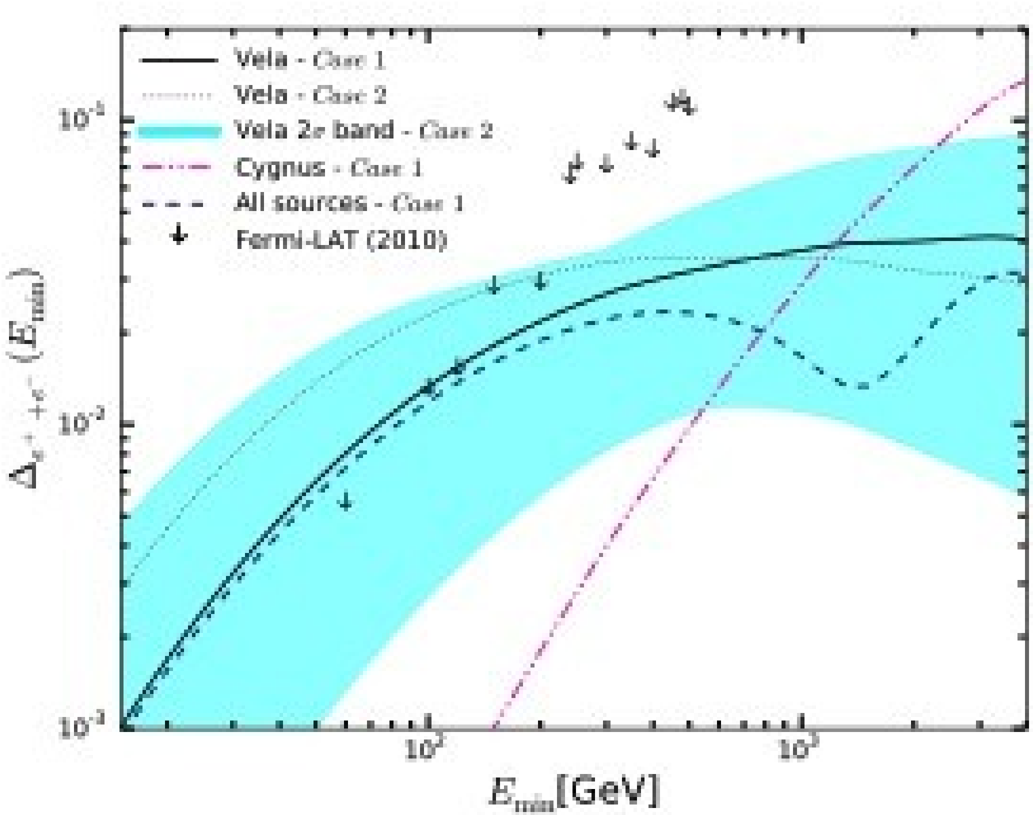
Is there a further – as well as fluxes - way to inspect the effect local sources of e+ e-?



Anisotropy from nearby lepton sources

S. Manconi, M. Di Mauro, F. Donato, arxiv 1611.06237, JCAP 2017

Anisotropy from nearby SNRs
AMS-02 fluxes used as priors



Dipole anisotropy in a diffusion model:

$$\Delta(E)_{e^+ + e^-} = \frac{3K(E)}{c} \frac{2d_s}{\lambda^2(E, E_s)} \frac{\psi^s_{e^+ + e^-}(E)}{\psi^{tot}_{e^+ + e^-}(E)}$$

Here, integrated from E_{min} to 5 TeV

Dipole anisotropy from Vela dominates, is predicted with 5-10 uncertainty, and sets close to Fermi-LAT (1 year data) upper bounds. Anisotropy from the collection of sources is dominated by Vela and Cygnus

The case for antiprotons

Cosmic antiprotons

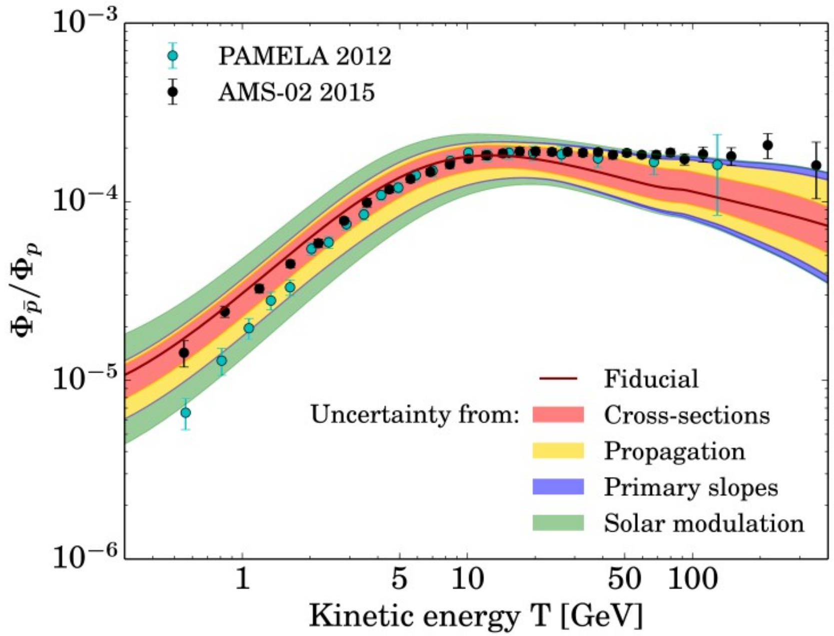
Antiprotons are produced in the Galaxy by
fragmentation
of proton and He (and marginally heavier nuclei)
on the ISM (**secondary antiprotons**).

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

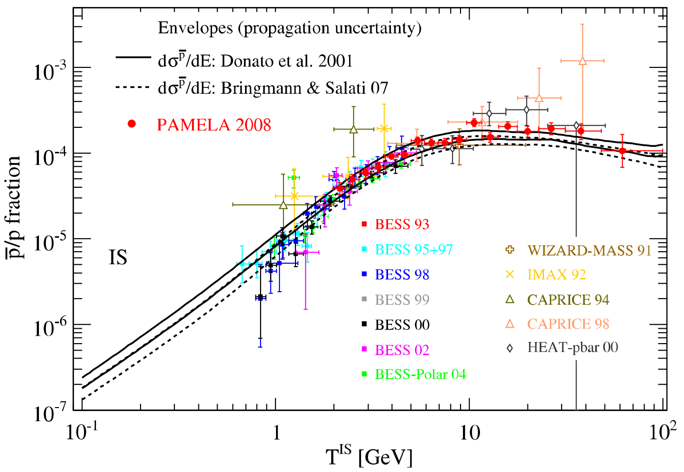
N. B. Thousands of cosmic antiprotons have already been
detected by balloon-borne (Bess, Caprice,...)
or satellite experiments (Pamela), and AMS-01,
and 290000 (out of 54 billion events) from AMS-02 on the ISS

Interpretation of AMS-02 p-/p data

Giesen+ 1504.04276



Donato, Maurin, Brun, Delahaye, Salati PRL 2009

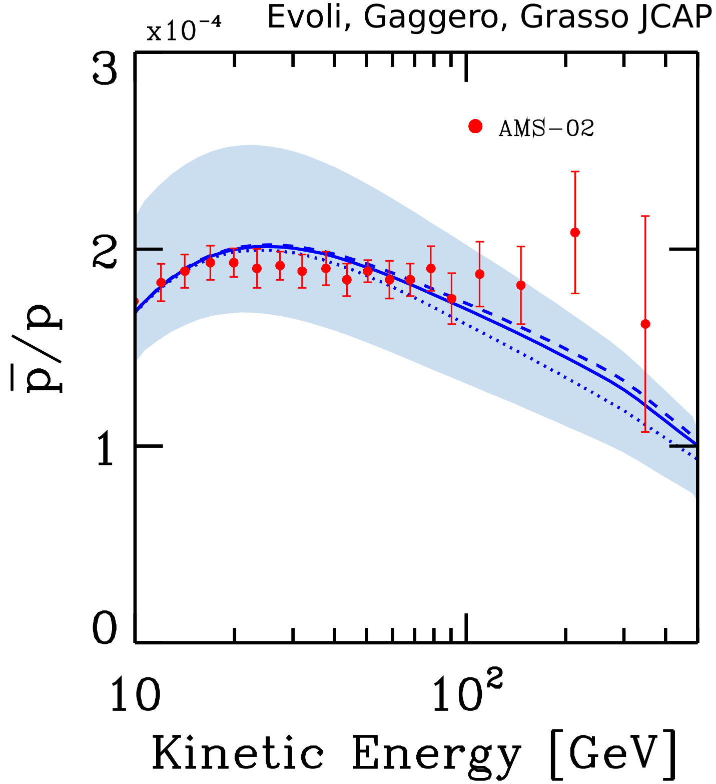


Propagation treated according to MIN-MED-MAX (Donato+2004), HEAO3 B/C
AMS-02 results from below GeV up to 400 GeV
could be explained by secondary production in the Milky Way

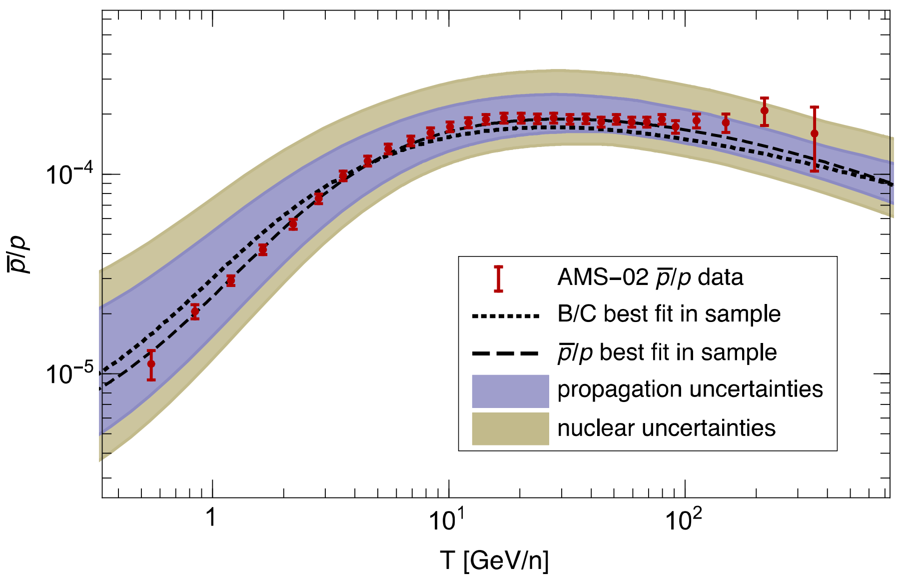
Most relevant theoretical uncertainty is due to nuclear CROSS SECTIONS
(Donato, Maurin, Salati, Taillet, Barrau, Boudoul 2001)

Interpretation of AMS-02 p-/p data

Evoli, Gaggero, Grasso JCAP 2015



Kappl, Reinert, Winkler JCAP 2015

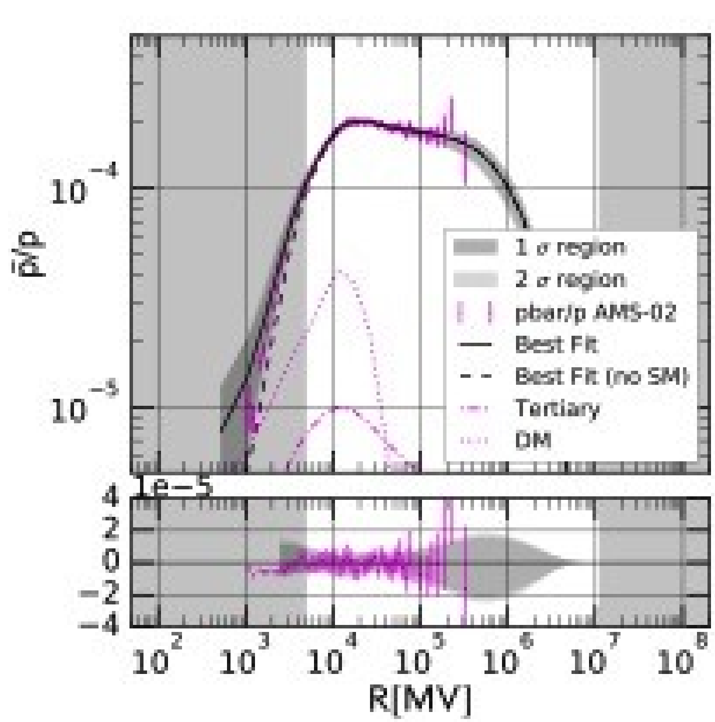


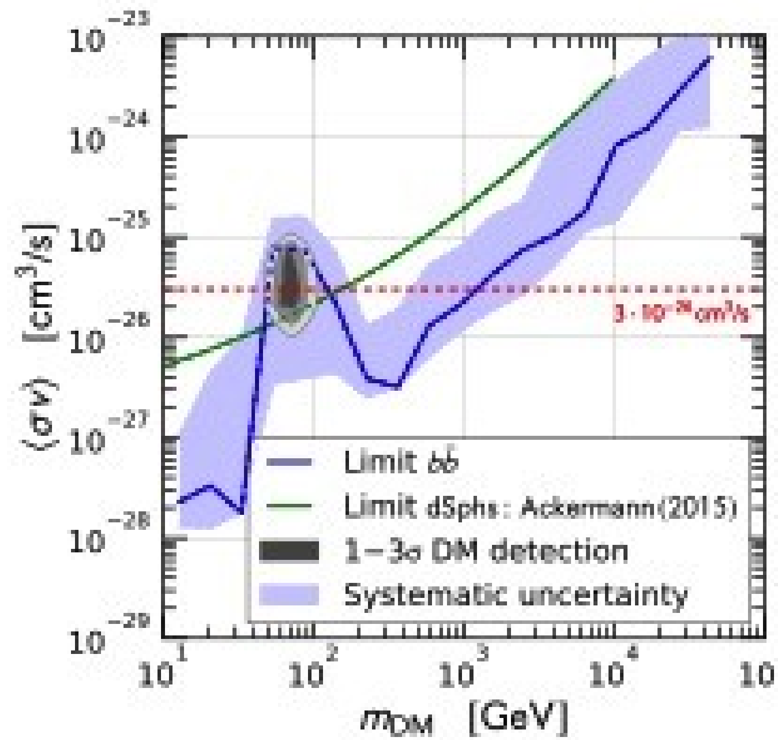
Propagation model fitted on preliminary AMS-02 B/C data
Greatest uncertainty set by nuclear cross sections

Background antiproton can explain data naturally, mainly because of the small diffusion coefficient slope

DM constraints from AMS-02

Cuoco, Kraemer, Korsmeier PRL 2017





Hint for a DM signal with m_{DM} ~ 80 GeV and thermal cross section
Data are very precise and sensitive at tens GeV.
Conservatively, strong upper bounds on ann. cross section.

The role of high energy particle physics in CR physics

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

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

$$S_i^j \equiv \left(\frac{V_c^2}{K^2} + 4\frac{\zeta_i^2}{R^2} + 4\frac{\Gamma_{rad}^{N^j}}{K}\right)^{1/2} \qquad A_i^j \equiv 2h\tilde{\Gamma}^{tot}_{N^j} + V_c + K S_i^j \coth\left(\frac{S_i^j L}{2}\right)$$

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

Production cross section

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

Destruction cross section

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 interstellar medium (ISM)

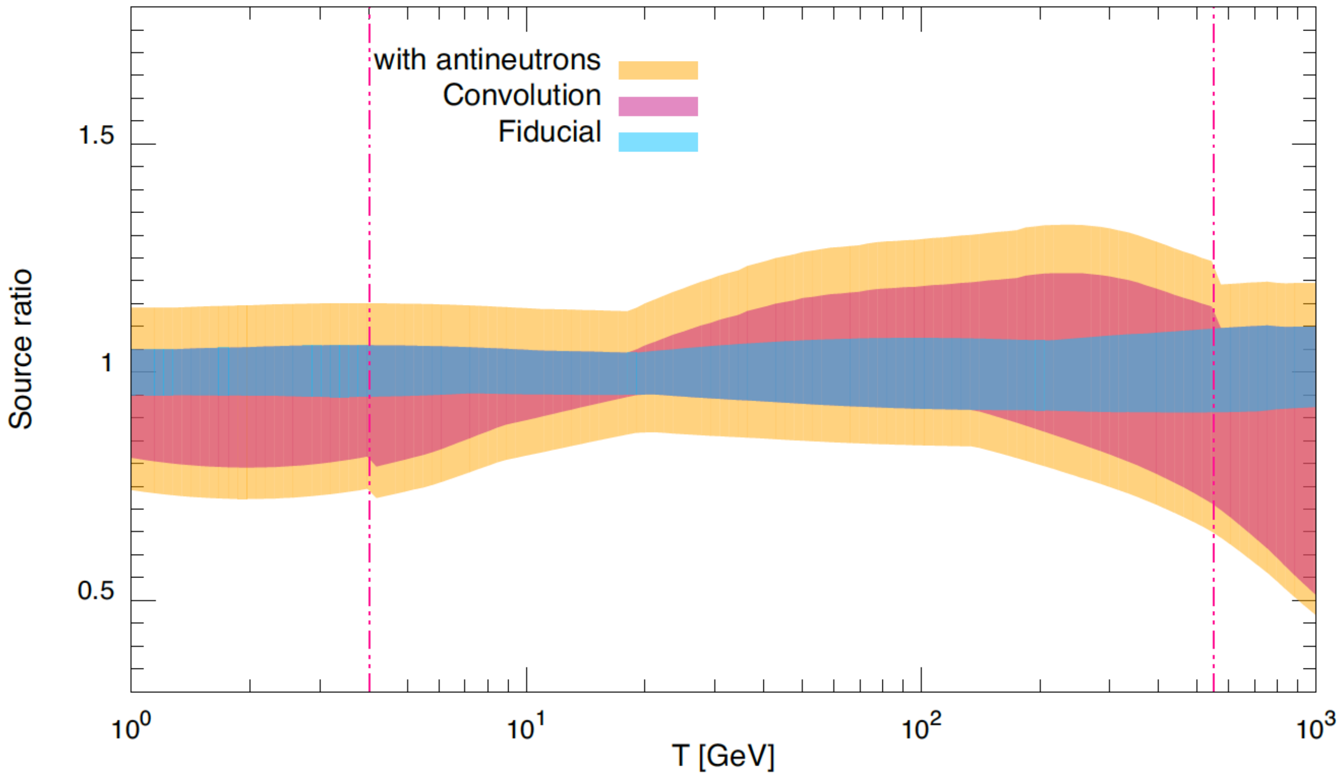
All the other nuclei (Li, Be, B, p-, and e+, gamma, ...) are produced by spallation of heavier nuclei with the atoms (H, He) of the ISM

We need all the cross sections $\boldsymbol{\sigma}^{\mathbf{kj}}$ - 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 : antiproton, antideuteron, positron and gamma rays.

Uncertainties due p-p scattering

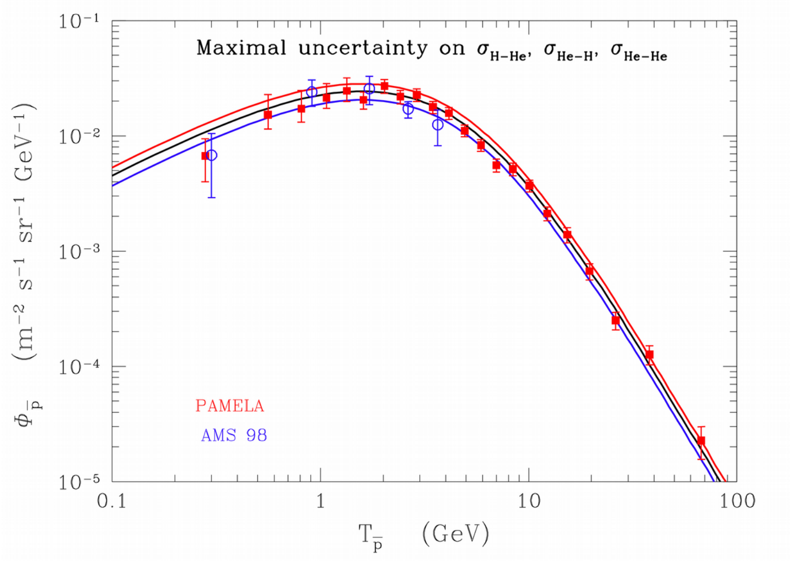
Di Mauro, FD, Goudelis, Serpico PRD 2014



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)

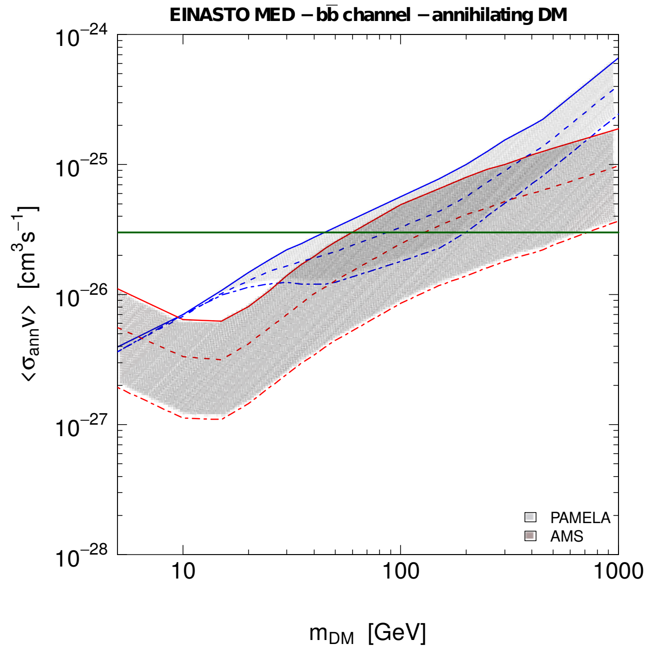
Cross section uncertainties on p-

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



AMS-02 is providing data with few % precision up to hundreds of GeV
Their interpretation – also in terms of DARK MATTER – can be seriously limited by nuclear physics

High energy experiments contribution to the CR and dark matter physics

FD, Korsmeier, Di Mauro 2017

The antiproton production case is the most challenging.

$$q_{\bar{p}} = \int_{E_{threshold}}^{+\infty} \boxed{\frac{d\sigma_{p\,ISM \to \bar{p}}}{dE_{\bar{p}}}(E_p, E_{\bar{p}})} n_{ISM}(4\pi\Phi_p(r, E_p))dE_p$$

Needed:

1. Data for p-He → antiproton + X
2. Better determination of p-p → antiproton + X

LHCb Coll. has recently taken data on pHe→p- at 6.5 and 4 TeV with SMOG inside LHC.

G.Graziani at Moriond 03/2017

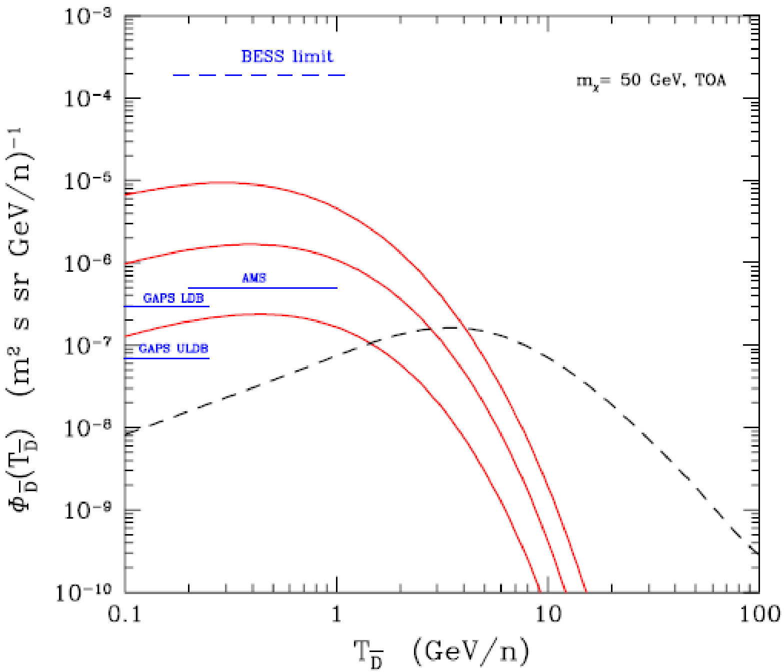
The case for antideuterons

COSMIC ANTIDEUTERONS

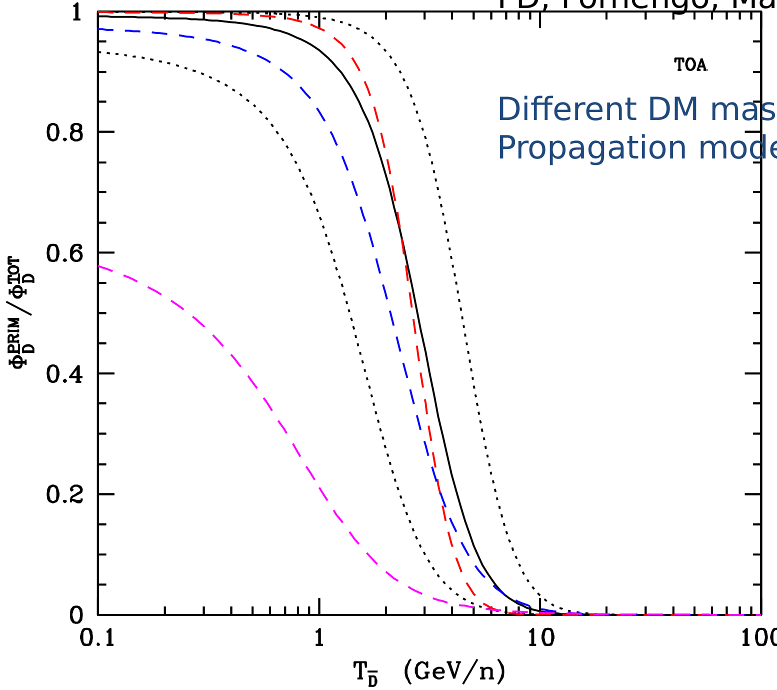
FD, Fornengo, Salati 2000;lFD, Fornengo, Maurin PRD 2008; 2008; Kadastik, Raidal, Strumia PLB 2010; Ibarra, Wild JCAP 2013;
Fornengo, Maccione, Vittino JCAP 2013; Aramaki et al, Phys. Rep. 2015

In order for fusion to take place, the antiproton and antineutron must have low kinetic energy

FD, Fornengo, Salati 2000

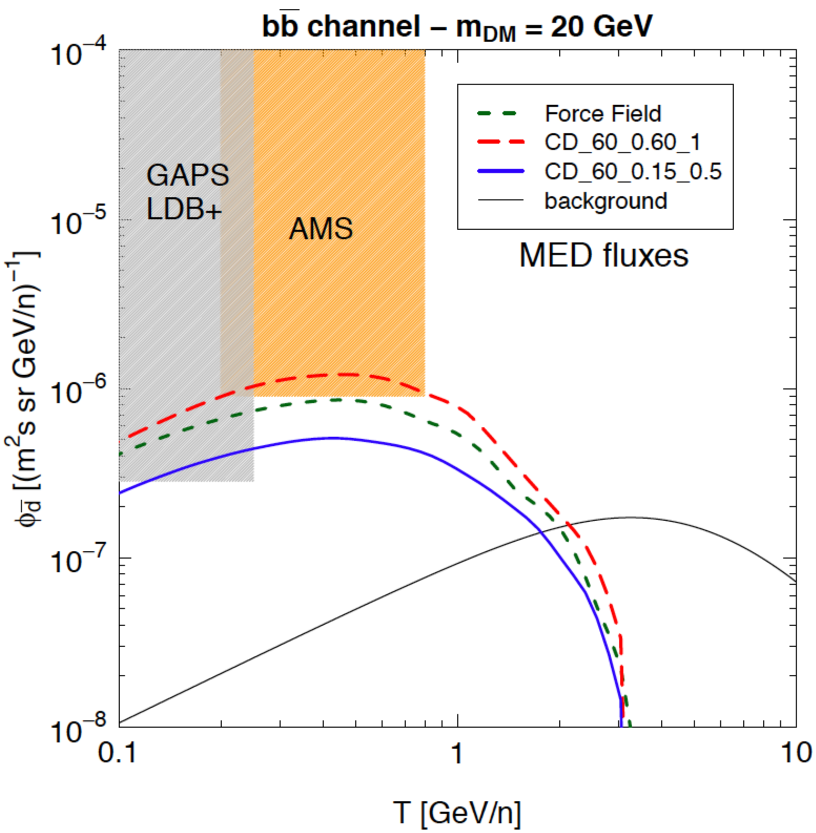


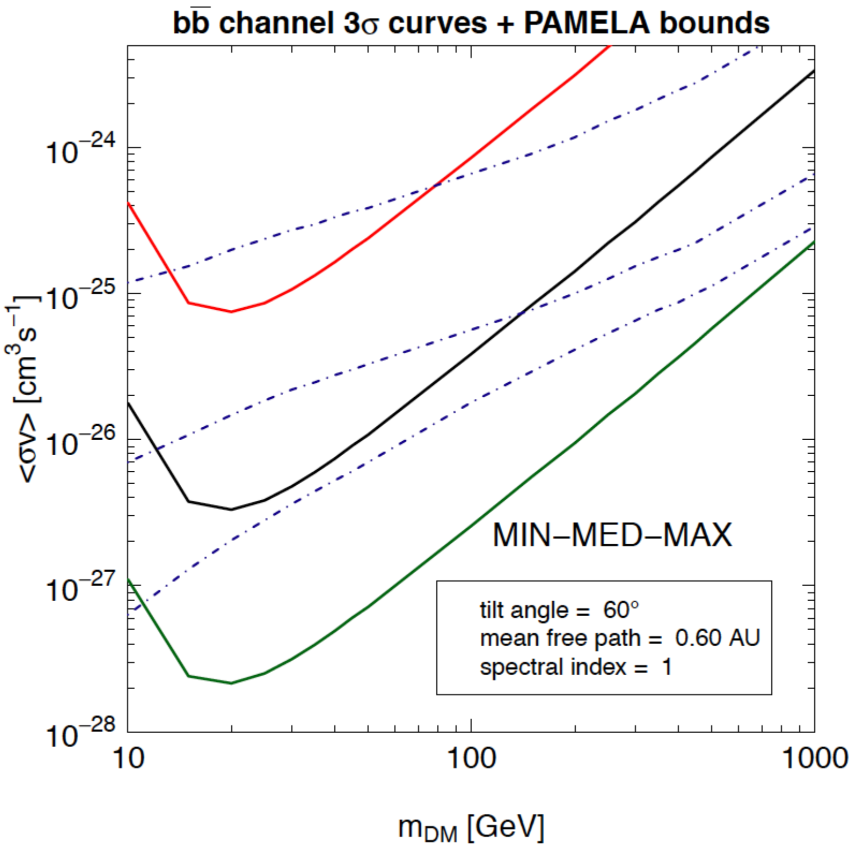
FD, Fornengo, Maurin 2008



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)

Columbia U, UC Berkeley
UCLA, U Hawaii,
MIT, INFN

GAPS has been favorably reviewed by NASA

NASA is going to found it

It will likely fly on a balloon at the South Pole in 4-5 years, measuring antiprotons and Antideuterons below GeV

DM direct detection

Measured process is DM – nucleus scattering:

DM + N(at rest) → DM + N(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 (MB)

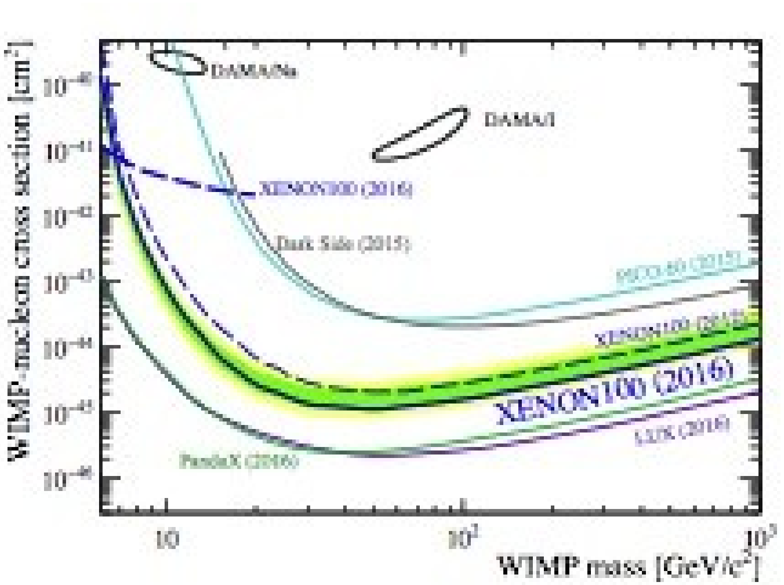
$d\sigma/dE_R$ Elastic differential DM-nucleus cross section

Direct detection observables

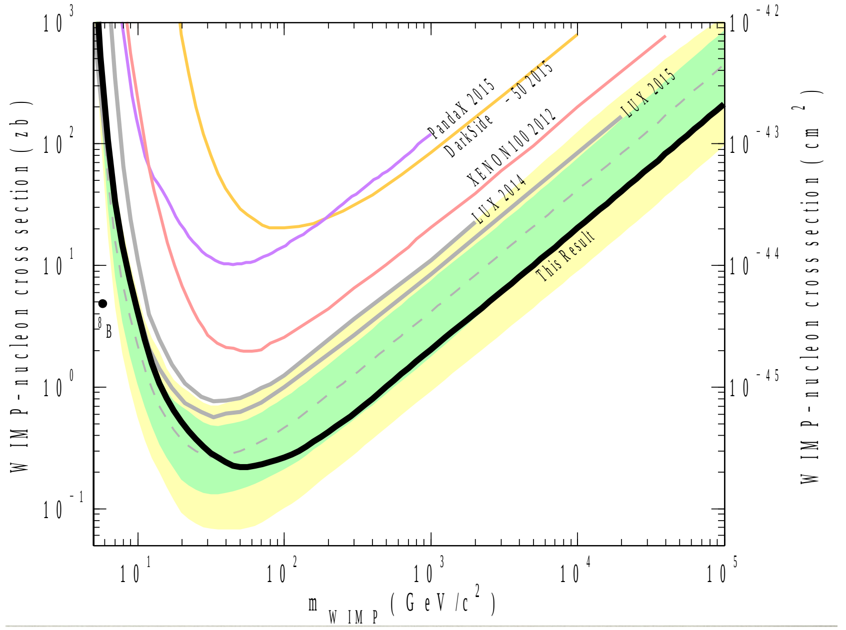
- ✓ Differential rate
- ✓ Directionality
- ✓ Annual modulation (Earth revolution around the Sun)
- ✓ Diurnal modulation

Present experimental situation

Experiments shielded against CRs, radioactivity, neutron sources → deep underground labs



Xenon 100 Coll. PRL 2016



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Final remarks

Existing data on antimatter do not necessarily require exotic (DM) interpretation, but need a highly precise astrophysical treatment of the backgrounds and the regions in which they are produced and propagated.

- **POSITRONS** are well fitted by known, powerful galactic sources.

  DM interpretation still open, but less natural

- **ANTIPROTONS** are a powerful constraining means on the DM annihilation intensity

- **ANTIDEUTERONS** are challenging, but with the highest detection potentials

- **DIRECT DETECTION** is the golden channel, very challenging, big efforts growing and growing