”The future of cosmic ray astroparticle physics

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TeV Particel Astrophysics, CERN – 16.09.2016

I made a fierce selection of arguments

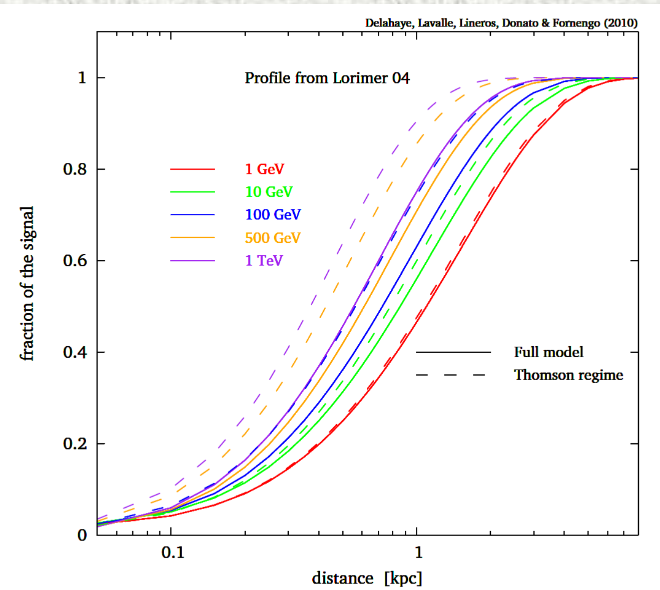
My sincere **apologies**
for all the missing items
not covered here

Many topics discussed in the parallel sessions Cosimc Rays,
Indirect Dark Matter Detection, Gamma Rays, at this TeVPA

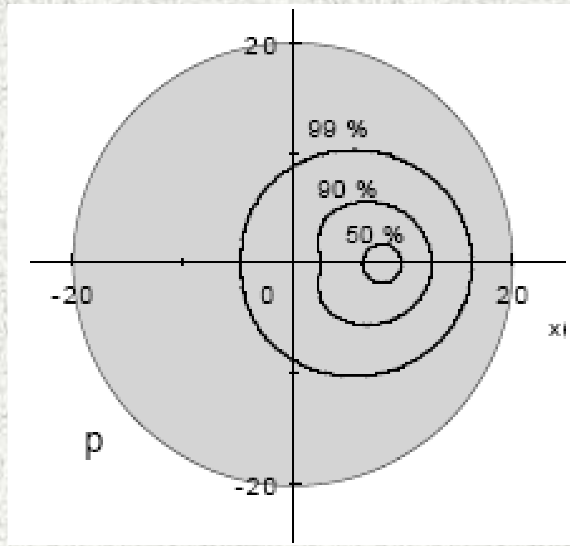
Where do these particles come from?

(if sources located in the galactic disk)

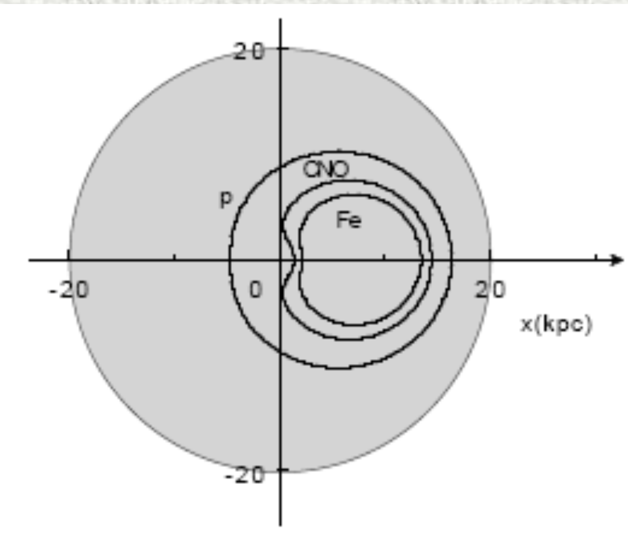
Electrons



Protons (~antiprotons)



Nuclei



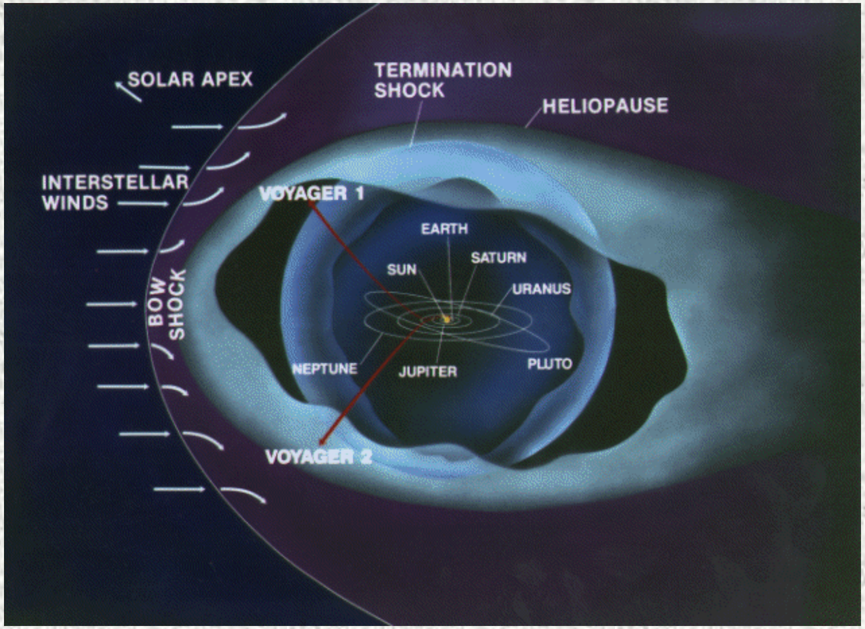
Energetic electrons are quite **local** due to **radiative cooling**
Stable hadrons arrive at Earth from farther places, depending on **spallations** on the interstellar medium (ISM: H, He)

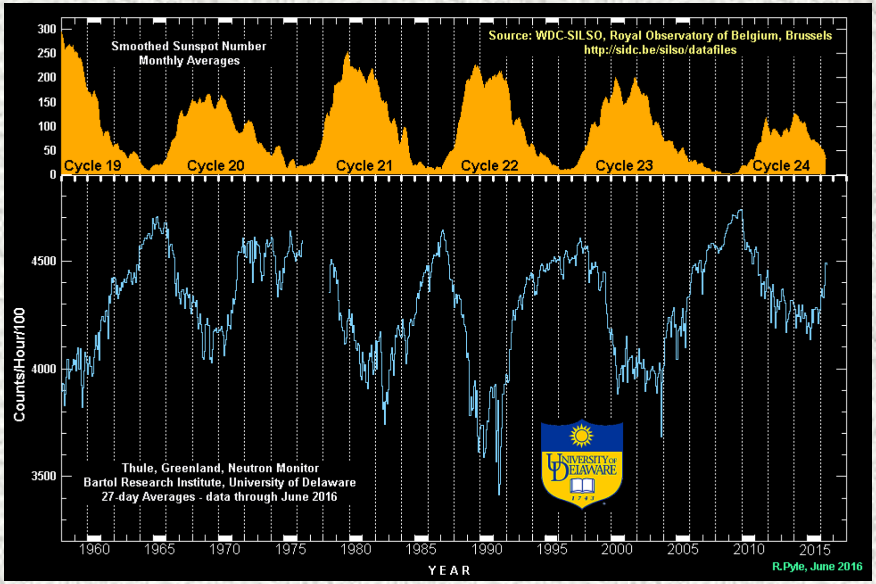
Different species explore different galactic environments

From the interstellar space to the Earth:
Obstacle 1: **THE SOLAR WIND**

Distorts charged particle spectra
Up to <u>few GeV IS energy.</u>
<u>Below ~ 10 MeV, solar particles dominate</u>

The solar wind intensity is modulated on a 11-year cycle.
Data statistics is favored during Solar minima



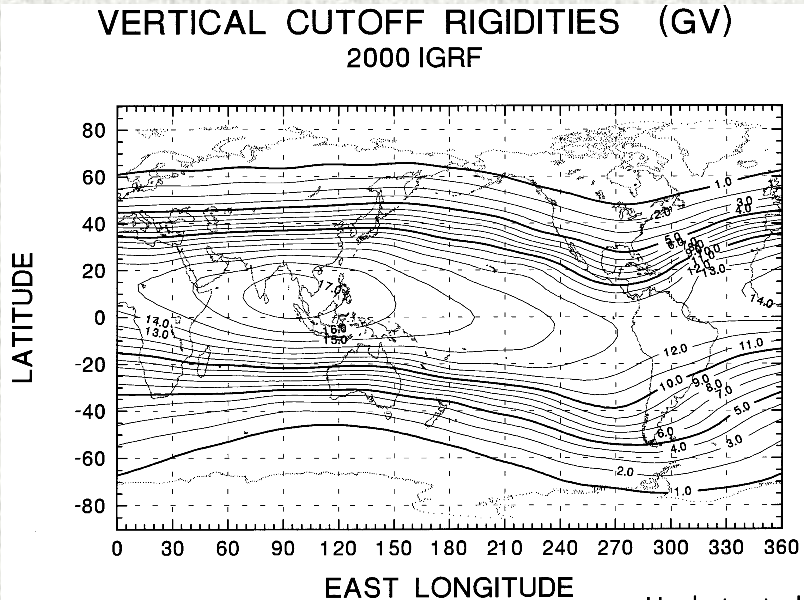


http://voyager.jpl.nasa.gov

R.Pyle, Bartol

From the interstellar space to the Earth

Obstacle 2: **THE GEOMAGNETIC CUTOFF**



Herbst et al 2013

Particles with rigidities below

$R_c \sim 15 \cos^4\lambda$ GV

are shielded by the Earth magnetic field

Obstacle 3: **THE ATMOSPHERE**

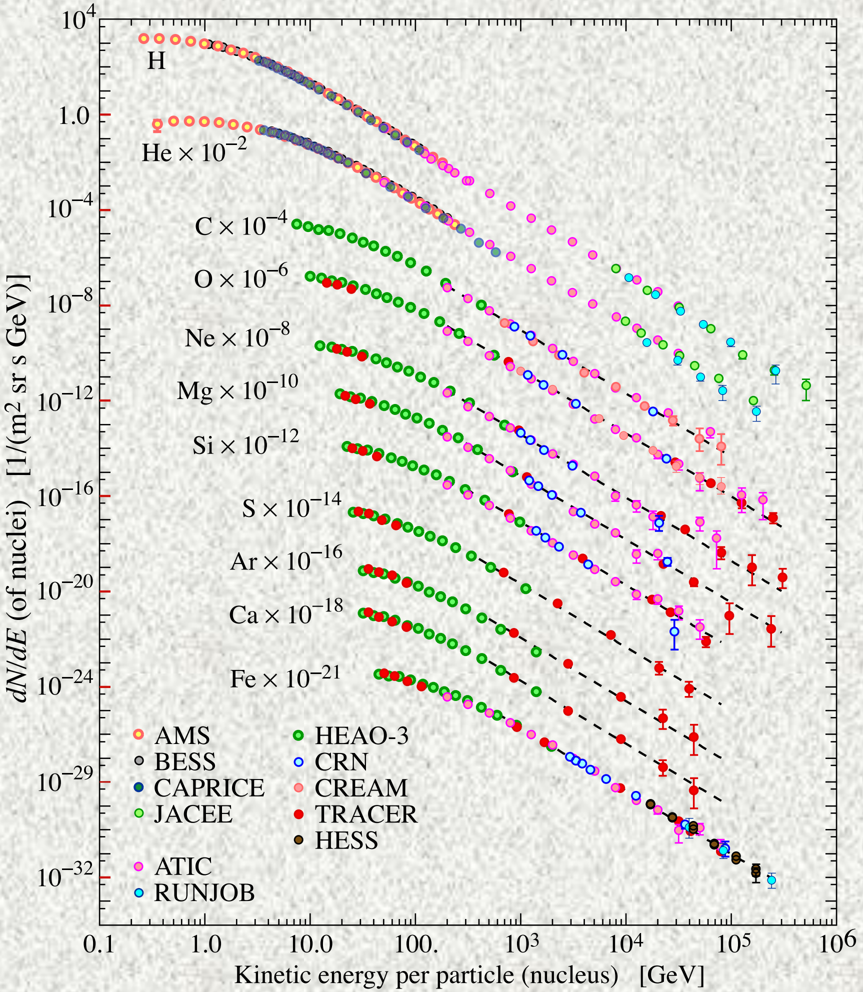
It contaminates the IS flux, and is a destructive target

Experiments for E < O(10) GeV better run during solar minima, polar orbit/poles, out of the atmosphere

The charged cosmic ray spectra

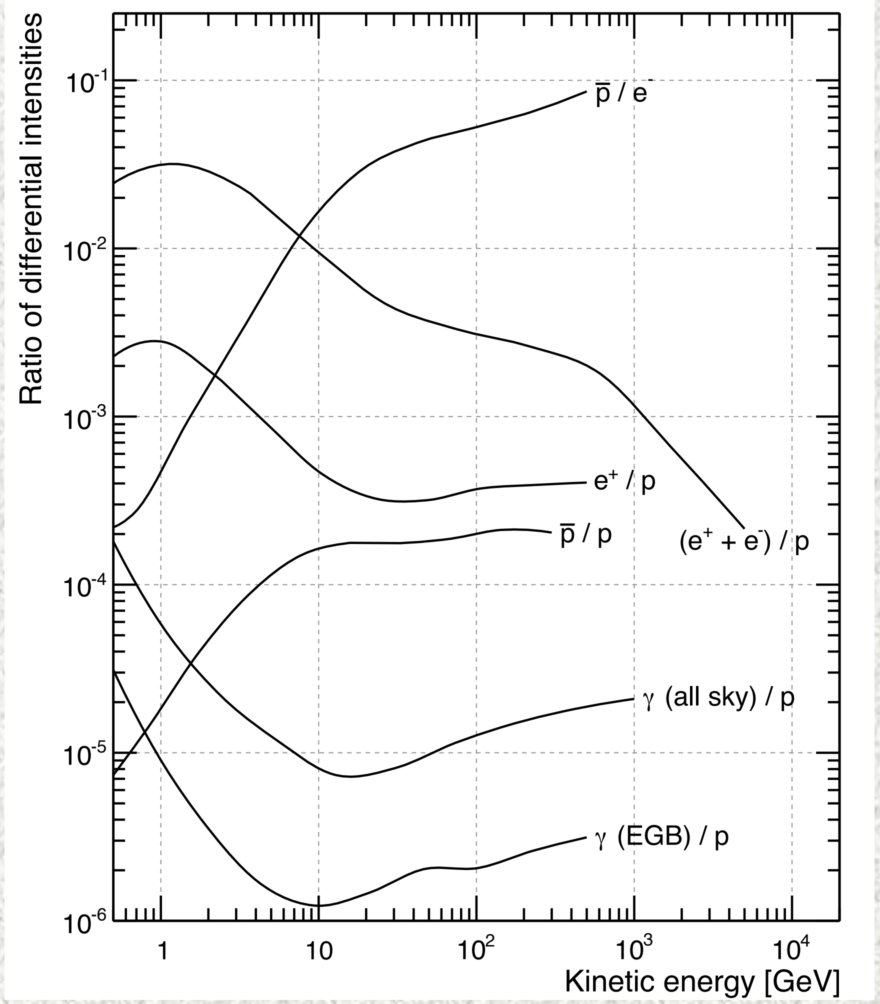
Talks by J. McEnery, R. Blandford, C. Weniger

Nuclei



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

Rare CRs and γ-rays

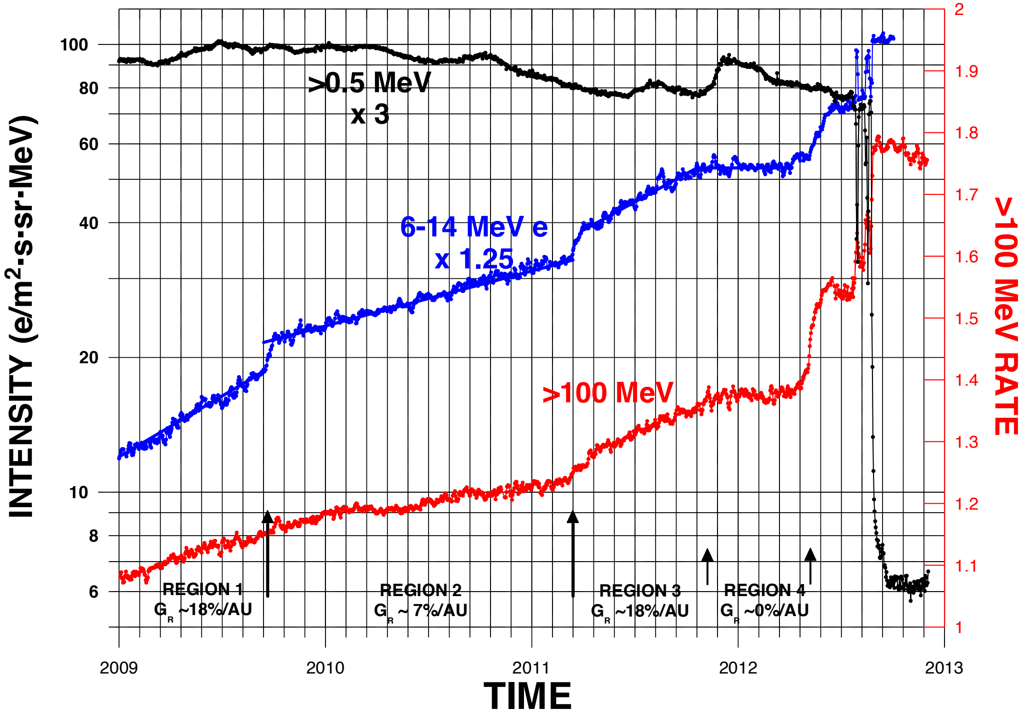


L Baldini, 1407.7631

AT VOYAGER 1 STARTING ON ABOUT AUGUST 25, 2012 AT A DISTANCE OF 121.7 AU FROM THE SUN, A SUDDEN SUSTAINED DISAPPEARANCE OF ANOMALOUS COSMIC RAYS AND AN UNUSUALLY LARGE SUDDEN SUSTAINED INCREASE OF GALACTIC COSMIC RAY H AND HE NUCLEI AND ELECTRONS OCCURRED

W.R. Webber[1], F.B. McDonald[2+], A.C. Cummings[3], E.C. Stone[3],
B. Heikkila[5] and N. Lal[5]

arxiv:1212.0883, Science 2013

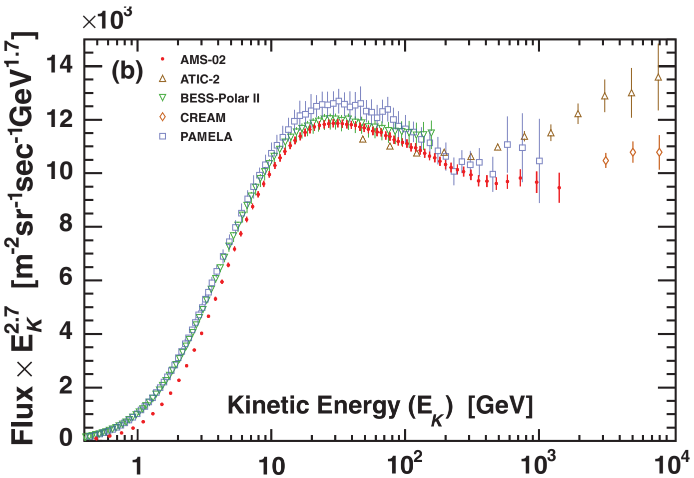


The Voyager probe – sent in 1977 - is sending data from the true INTERSTELLAR SPACE

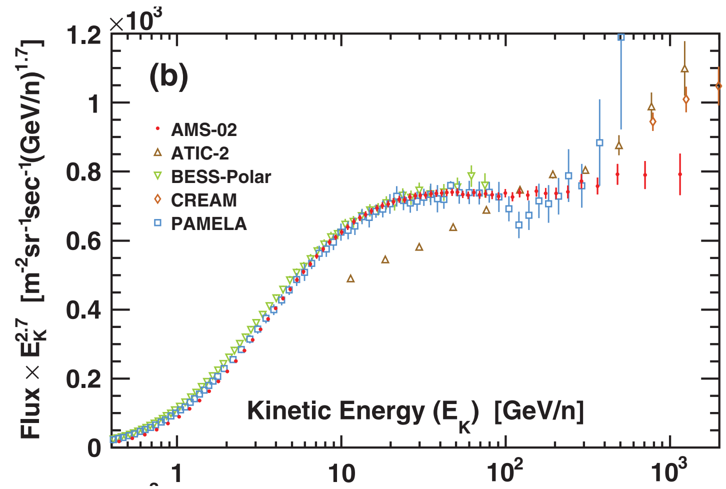
Now many decades in energy are covered by direct data on galactic CRs

Proton and Helium fluxes

AMS PRL114, 2015

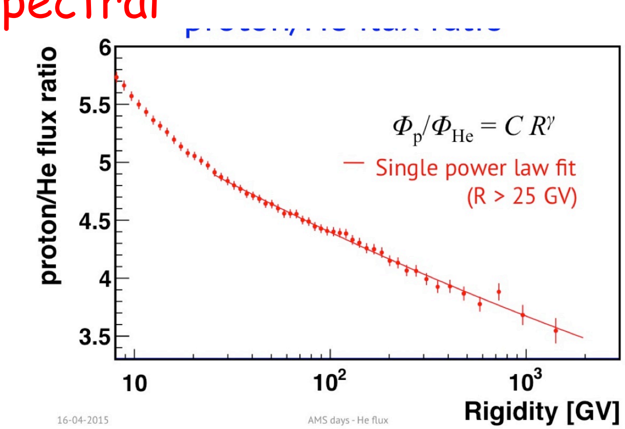


AMS PRL115, 2015



- 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 ($\Delta\gamma$~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; Merthsch & Sarkar 2009; ...)

Primaries = present in sources:

Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)

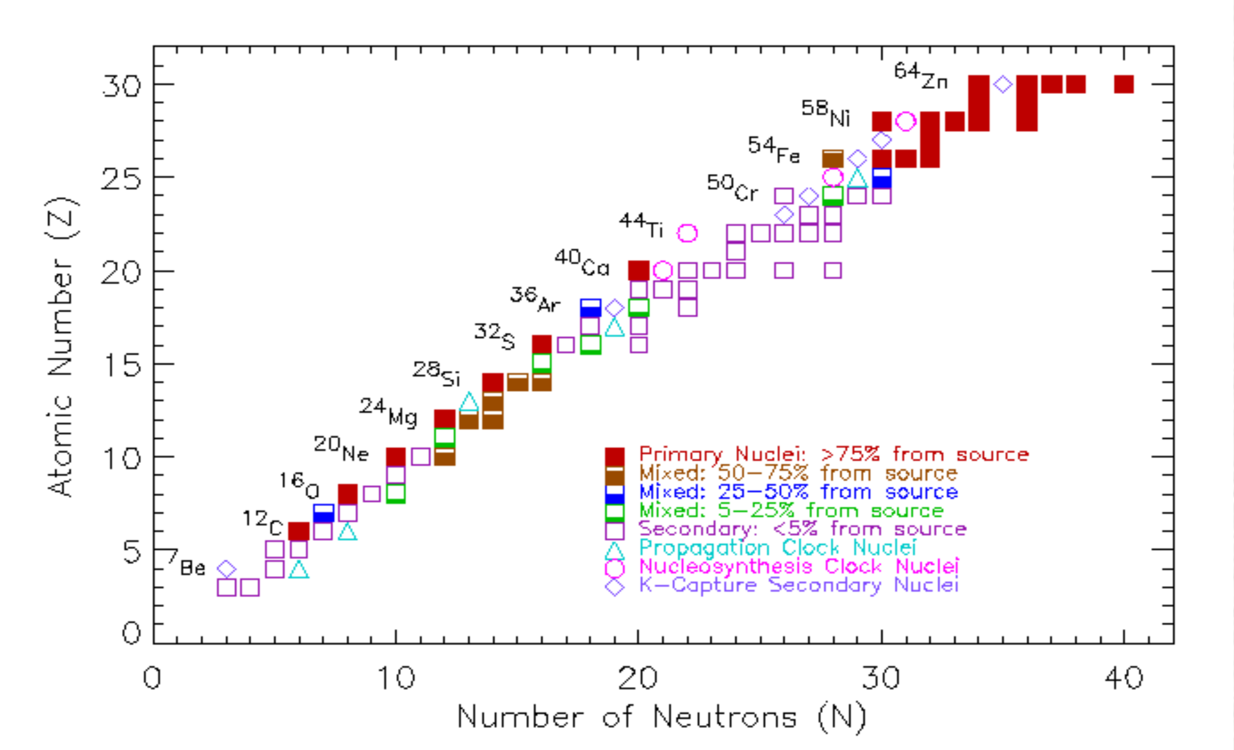
e^+, p^+, d^+ from Dark Matter annihilation

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

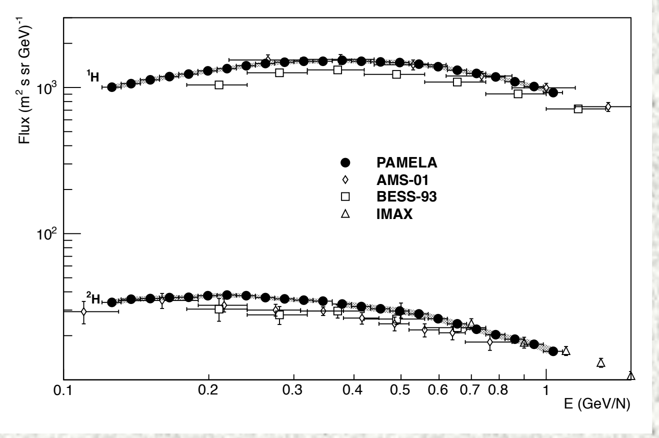


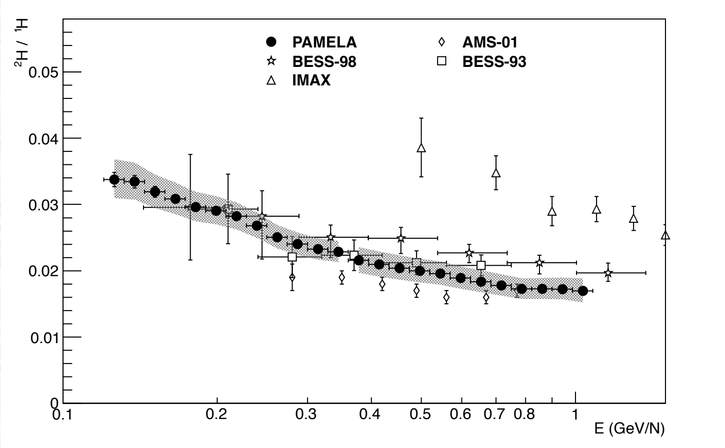
Isotopes are very informative of their origin and on the transport in the Galaxy

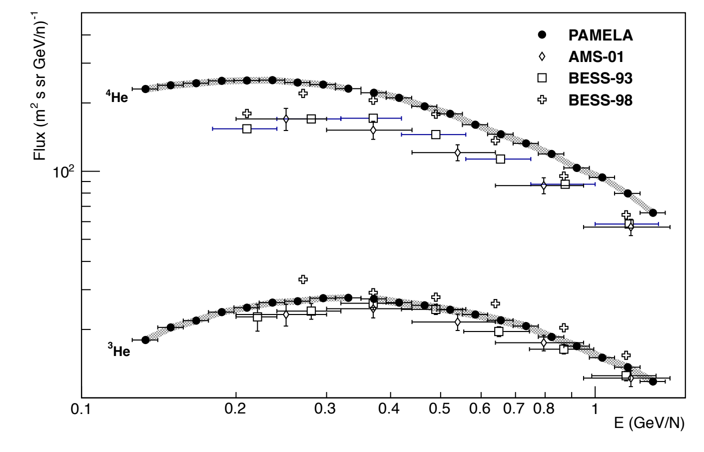
FUTURE: We would largely benefit by measurements in wide energy ranges, for many isotopes, included the radioactive ones

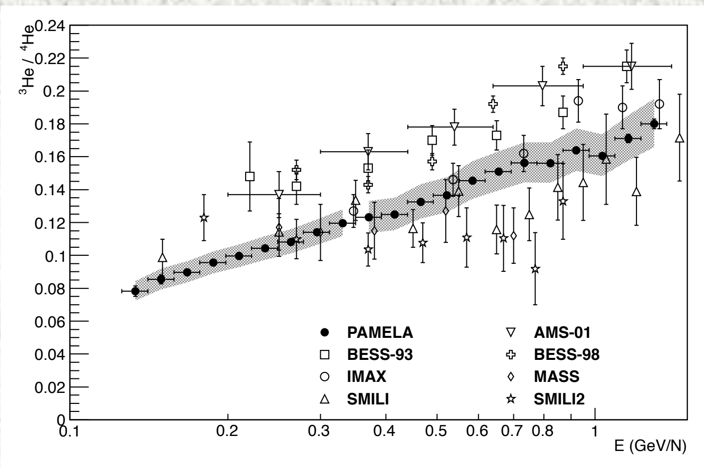
Data from light isotopes

Pamela Coll. ApJ 818, 2016









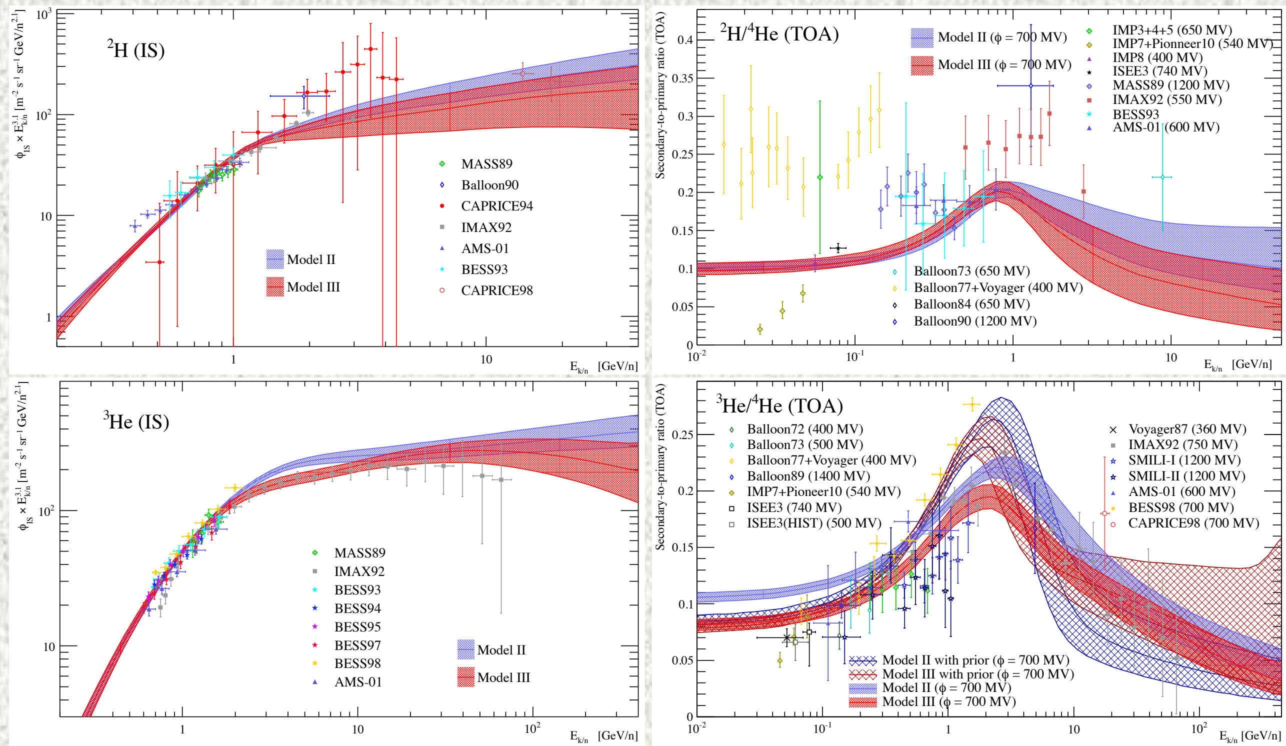
Pamela data show clear trends with energy

Constraining galactic cosmic rays with light isotopes

Coste, Derome, Maurin, Putze A&A 2012

Different models derived from B/C

Higher δ for red



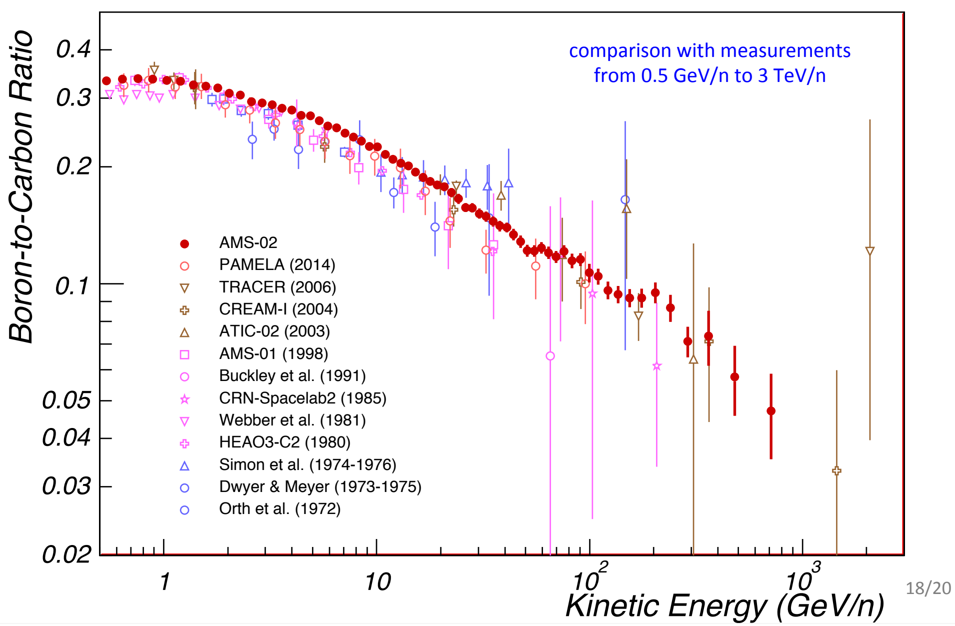
Pre-Pamela theoretical analysis:

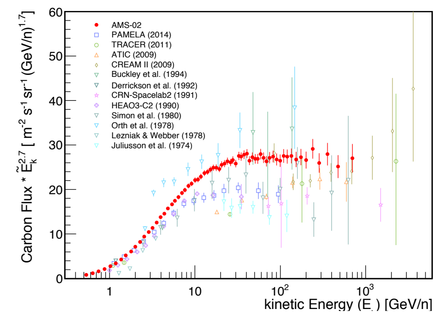
some of these models are already excluded by Pamela light isotopes data

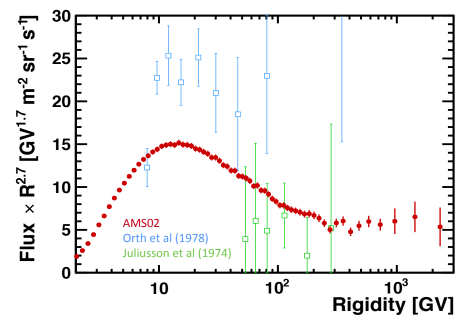
FUTURE: Data on significantly wider energies would be useful for studies of propagation in the Galaxy, and also for heavier isotopes

Boron-to-Carbon: a standard candle?

- Li, Be, B are produced by fragmentation of heavier nuclei
- C is primary
- B/C is very sensitive to propagation effects







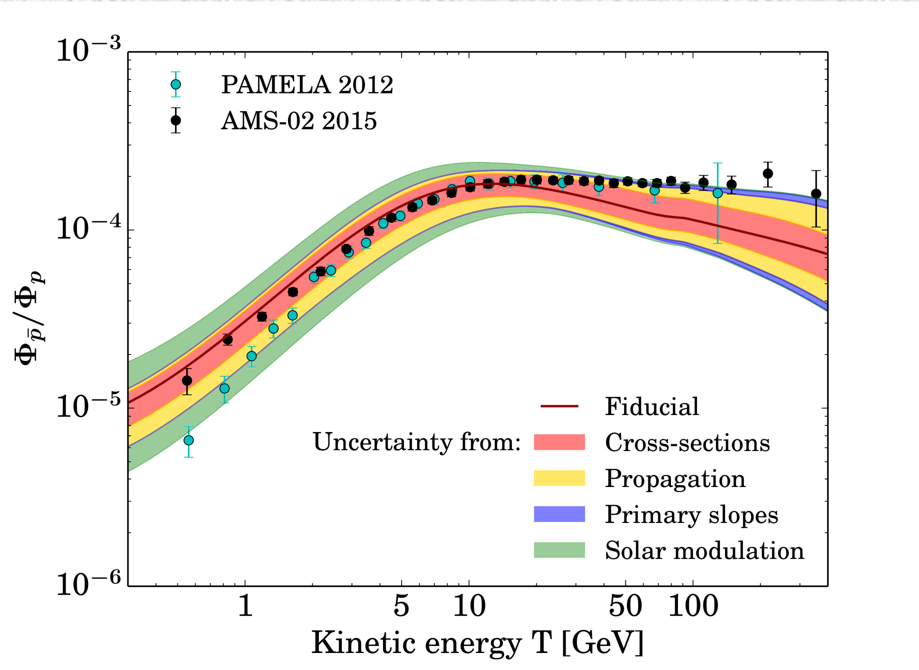
Talks by Schael; Korsmeier

- ✓ B/C does not show features at high energies
- ✓ Li goes flat at high en., unexpected

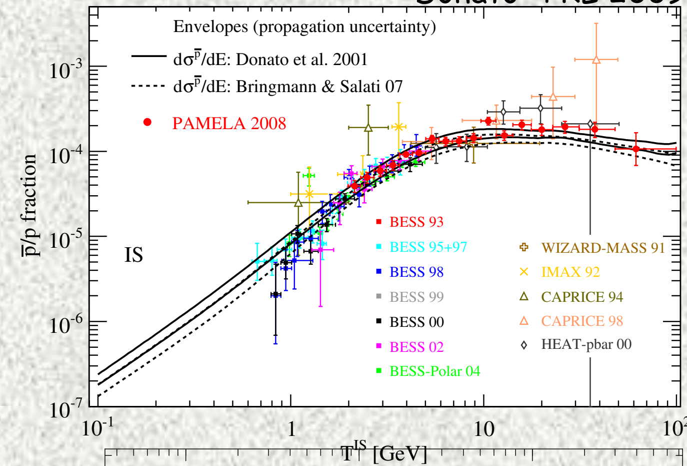
At first order, we understand B/C within Fermi acceleration and isotropic diffusion. This may be no longer sufficient when dealing with data at higher energies, gamma-ray data, other species

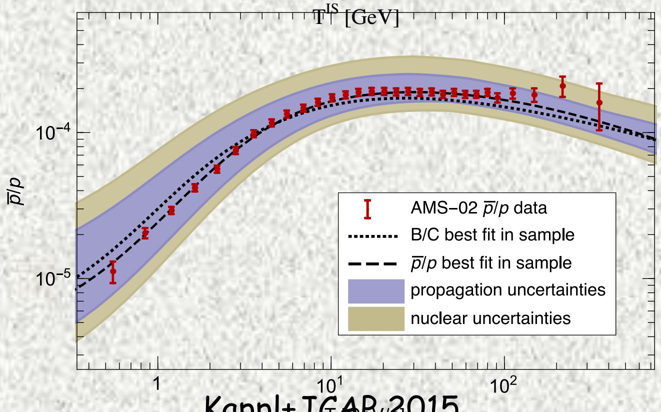
Antiprotons on wide energy range

Giesen+ JCAP 2015



Donato+ PRL 2009





Kappl+JCAP 2015

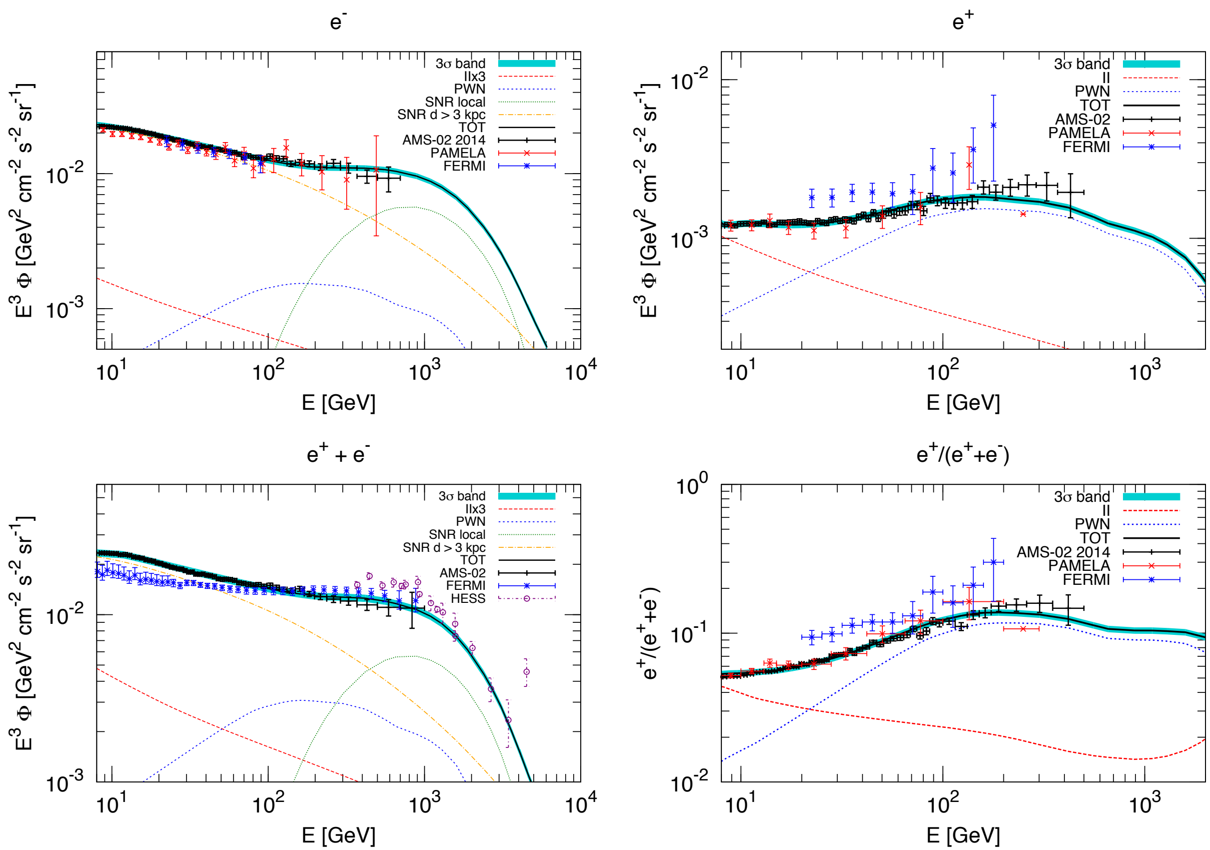
Talk by P. Salati

And Evoli+2015, Tomassetti 2015

Still, data do not force to exotic interpretations. Most relevant theoretical uncertainty is due to nuclear CROSS SECTIONS

Leptons

Di Mauro, FD, Fornengo, Vittino JCAP 2014, 2016



Talks by M Di Mauro, M. Vecchi, Y Genolini, M.Boudaud

EXP: Pamela, AMS, Fermi. In fair agreement

TH: Secondaries + supernovae + pulsars

Small features can bring strong information

Still no definite pattern (data and models)

The sources of CRs cannot be tested by CRs

Talks by Caprioli; Gabici

SPECIES	SOURCES	TEST
Primary nuclei, e-	Supernova remnants	EM: radio, X-rays, gamma-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 (probably) (talk by M. Mangano)

The role of high energy particle physics in CR physics

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

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

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

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

Production cross section

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

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 the interstellar medium (ISM)

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

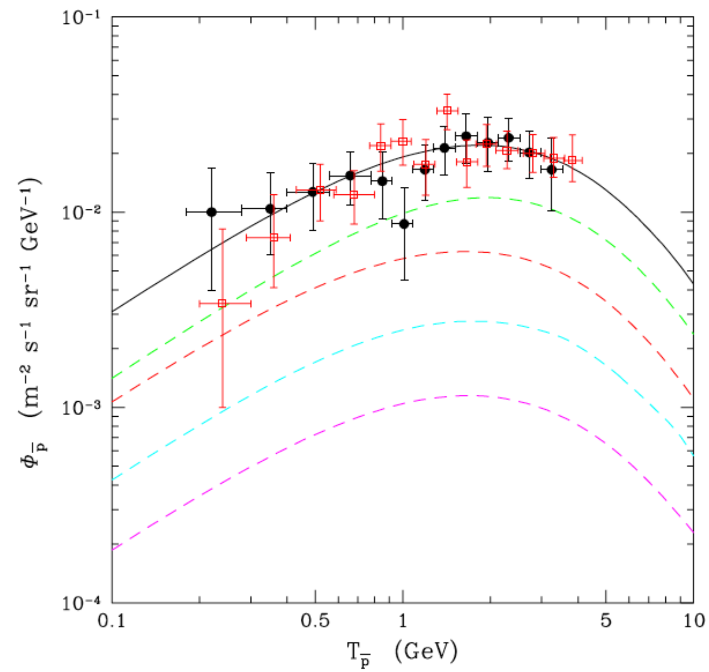
Remarkable for DARK MATTER signals : antiproton, antideuteron, positron and gamma rays.

Secondary antiprotons in CRs

Produced by spallation reactions on the interstellar medium (ISM)

$$\left.\begin{array}{l} p_{CR} + H_{ISM} \\ p_{CR} + He_{ISM} \\ He_{CR} + H_{ISM} \\ He_{CR} + He_{ISM} \end{array}\right\} \bar{p} + X$$

FD, Maurin, Salati, Taillet, Barrau, Boudoul 2001



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

ALL CROSS SECTIONS INVOLVING <u>HELIUM</u> HAVE NEVER BEEN MEASURED AND ARE DERIVED FROM DATA on HEAVIER NUCLEI

High energy experiments contribution to the CR and dark matter physics

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

- ✓ Data points falling in ~ 0.1 - 400 GeV antiproton energy
  →proton beam ~ 10 times more energetic
- ✓ Errors < 10%
- ✓ Determination of the role of neutrons at % level

LHCb

has acquired large samples of collisions of 6.5 TeV protons on He at rest

using the SMOG internal gas target,

and plans to take more data this year with

4 TeV proton beam energy.

The analysis is in progress and is expected to provide a measurement of the antiproton production with good acceptance

up to about 100 GeV

Interest expressed by the COMPASS Collaboration for its science program beyond 2020

A workshop dedicated
To the issue of cross sections in
Cosmic rays physics is organized
At CERN:

XSCRC:
Cross sections for Cosmic Rays @ CERN

March 29-31, 2017

Web site opened soon

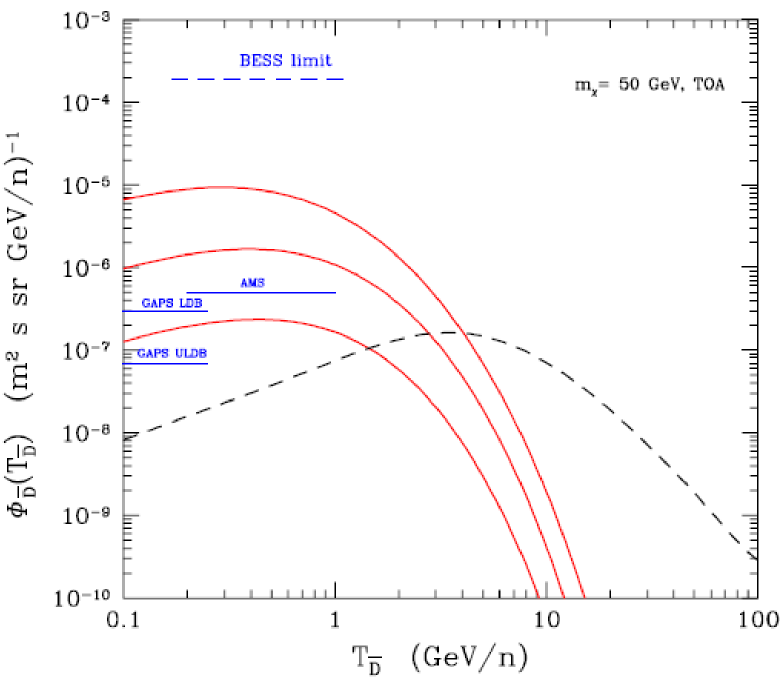
The case for antideuterons

COSMIC ANTIDEUTERONS

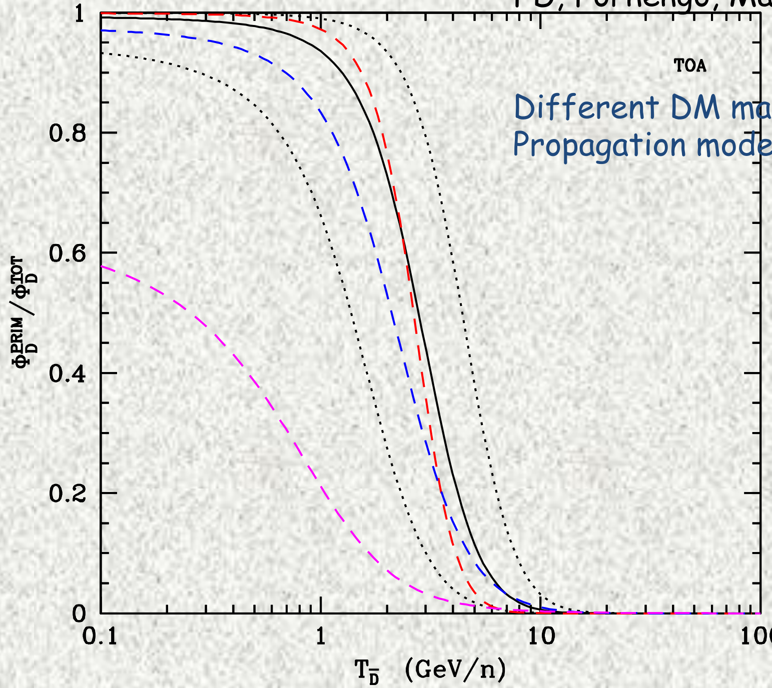
FD, Fornengo, Salati 2000; FD, Fornengo, Maurin PRD 2008; 2008; Kadastik, Raidal, Strumia PLB 2010; Ibarra, Wild JCAP 2013; Fornengo, Maccione, Vittino JCAP 2013; Aramaki et al, Phys. Rep. 2015

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

FD, Fornengo, Salati 2000



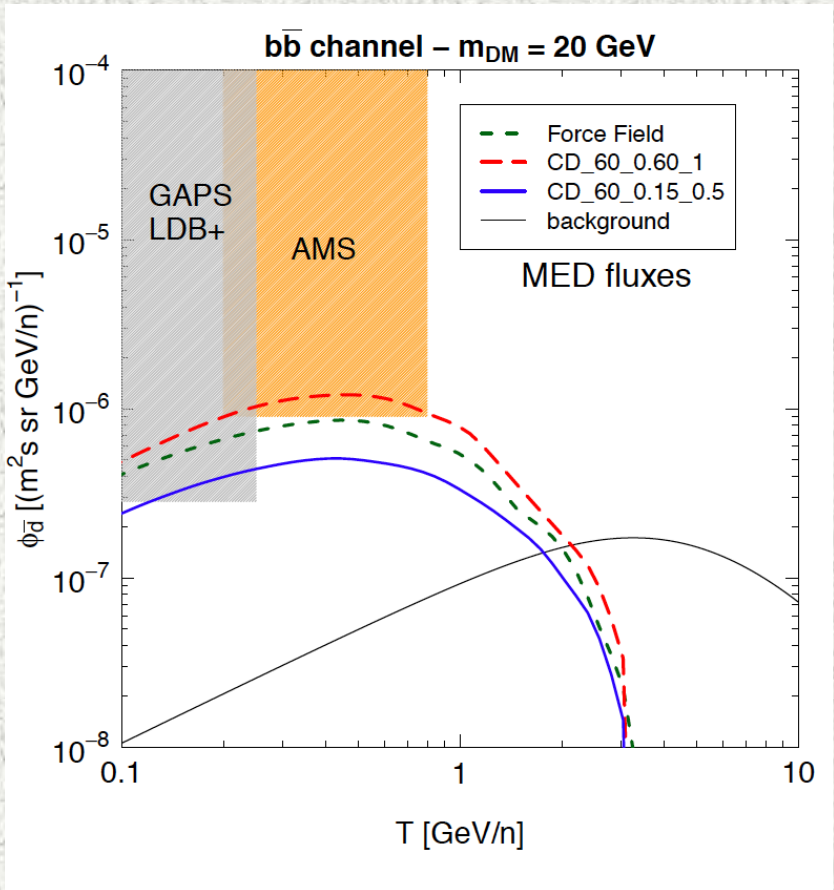
FD, Fornengo, Maurin 2008

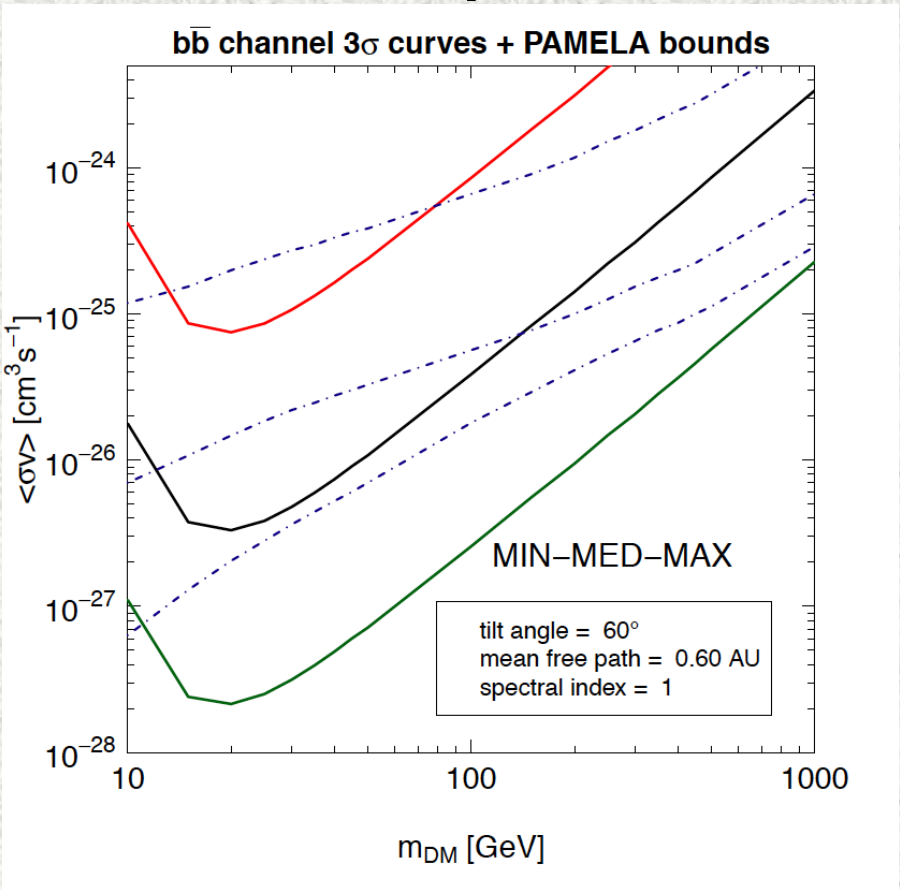


The GAPS experiment has been then proposed to fly on a balloon in Antarctica

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 intends to fund it, contingent on approval on NASA budget (See talk by P. von Doetinchem)

It will likely fly on a balloon at the South Pole in 4-5 years

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 section for p and He off the gas)
- Inverse Compton (Models for electrons at the GC, Interstellar Radiation Field – CMB, IR, optic)
- Bremsstrahalung (Models for electrons at the GC, gas distribution)

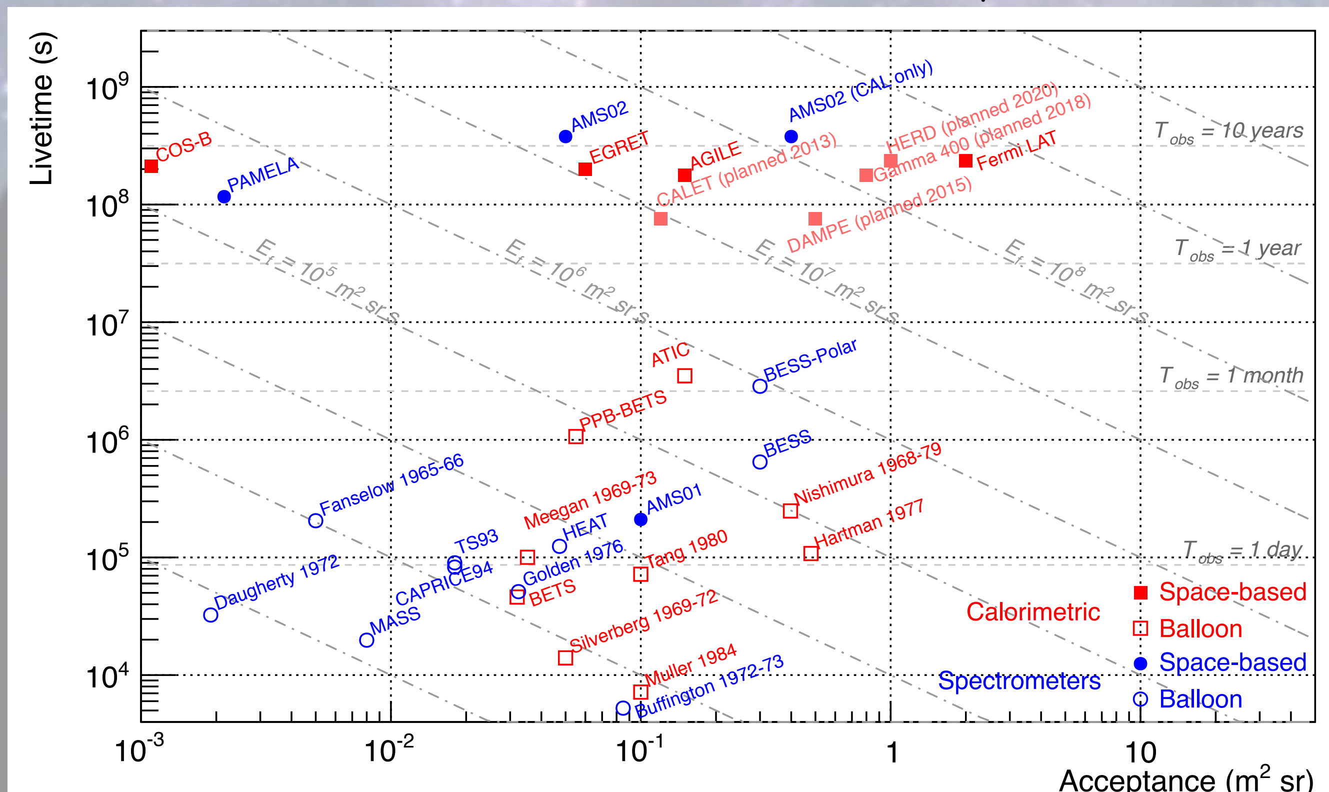
- All points need a detailed model for propagation, and input fluxes in the whole Galaxy

This case should be a priority in the next years.
Multi-wavelength, multi-messenger, multi-technique approach

Talks by L. Tibaldo, C. Evoli

Understanding
cosmic p, He, B/C, etc. with great accuracy from below GeV up to at least 10^2 TeV

Courtesy of L. Baldini (1201.0988)



We should probably think about bringing a SUPERCONDUCTING MAGNET into space and having an extremely powerful tool (apt rockets are needed ...)

Conclusions

- **Data** on CRs are understood at first order. Many features in the most recent data – Pamela made an amazing breakthrough, AMS has unprecedented precision – need further, understanding and open new **mysteries**

- **Dark matter** is a big mystery: its indirect detection, if any, will be likely associate to a tiny effect → very precise data

- Great progress is needed with phenomenological **models** of transport in the Galaxy

- **HIGH ENERGY PHYSICS**: we need many (MANY!) data on cross sections.

First data for antiproton production in pHe expected by LHCb

CERN may have a primary role

The physics of galactic
(electromagnetic and charged) cosmic rays and the indirect dark matter searches needs to be (is already!)
Multi-channel, multi-wavelength, multi-technique.

Progress will be granted in many areas.
Do not forget:
The beam of cosmic rays never turns off!!!

In addition to big projects,
also **small**, dedicated space experiments (having solid, although circumscribed physics cases)
are worth to be supported by the community