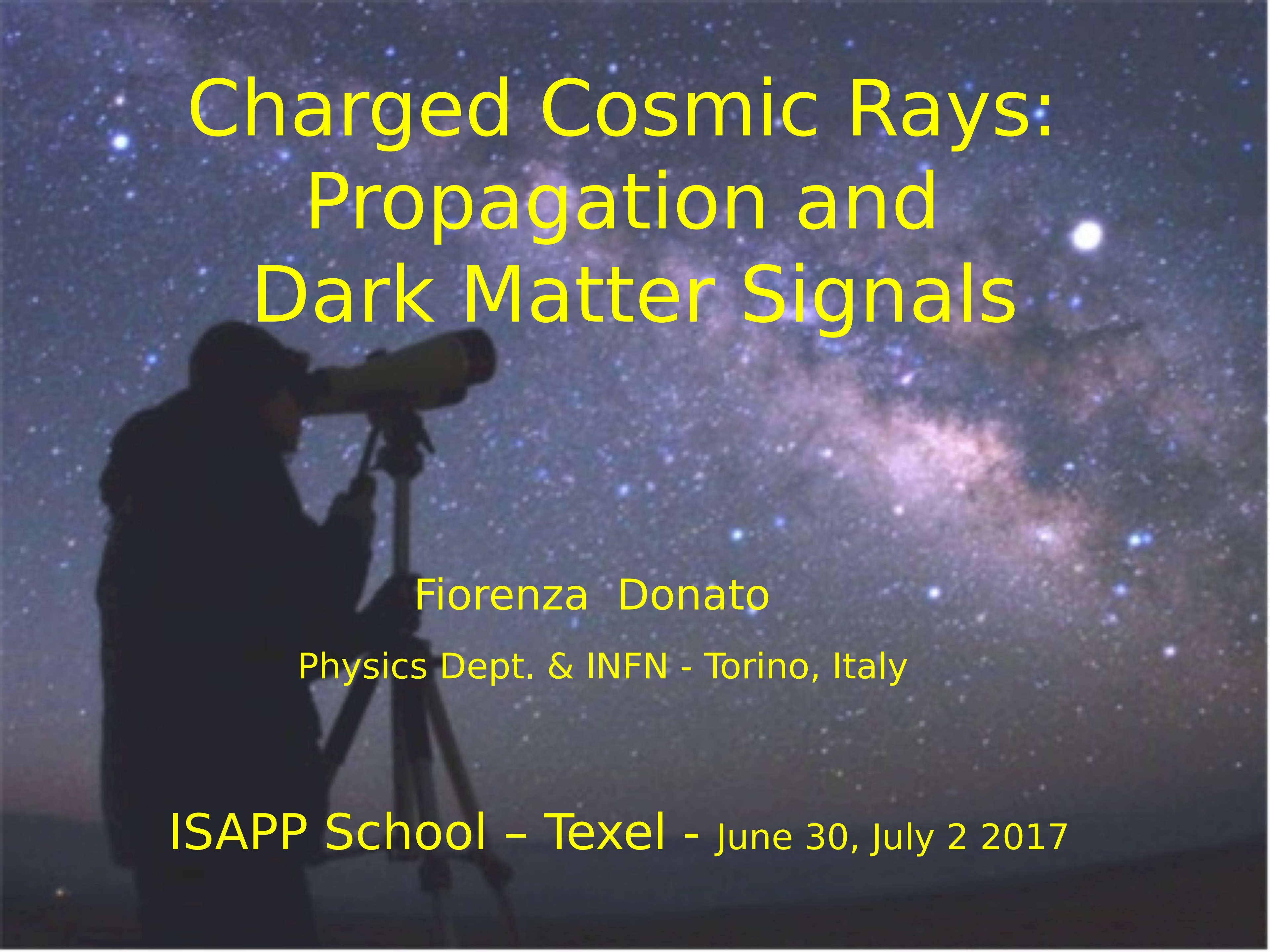
Charged Cosmic Rays: Propagation and Dark Matter Signals



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ISAPP School – Texel - June 30, July 2 2017

The discovery of Cosmic Rays

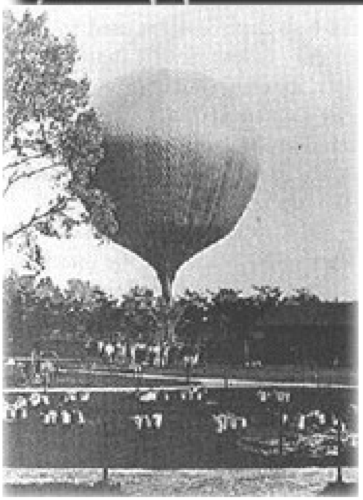
The charged cosmic radiation was **discovered** mainly accidentally, while
trying to understand the source of the air ionization.

The problem was first identified at the end of 18^{th} century, and led to
several Nobel prizes in the 20^{th} century.

Coulomb noticed that electricity dispersion (charge loss)
occurred mainly through air.

Pacini demonstrated that the radiation strength **decreased** while
going underwater, thus excluding that it was coming from the Earth
crust

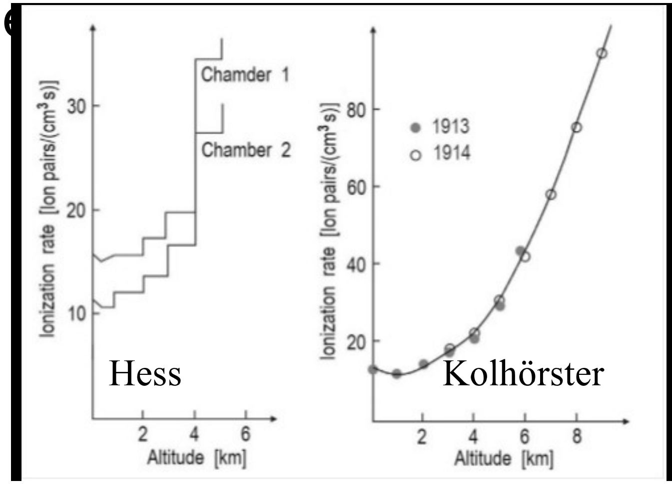
CR discovery: Victor F. HESS 1912



1912 VF Hess embarked on 7 flights onboard hot-air balloon. August 7, 1912 reached 5200m height.

In the data he collected, the radiation was increasing with the altitude: the opposite of what expected for radiation originating in the Earth crust.

He measured a “rain” of particles pervading the sky,
called cosmic rays (CRs).



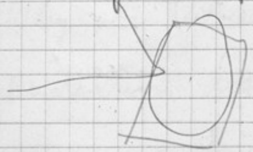
Enrico Fermi

On the Origin of the Cosmic Radiation, Phys. Rev. 75, 1169–1174 (1949)

Dec 4 1948

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields



Non relativistic case

MV^2

(M = mass of particle V = velocity of moving field

(Proof: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$$

$$= M(2vV + 2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision ($\text{prob} = \frac{v-V}{2v}$) gives energy gain

$$M(-2vV + 2V^2)$$

Average gain order

$$MV^2$$

Relativistic: order

$$w\beta^2$$

Notations

Absorption mean free path $\Lambda = 10^{26}$ cm

Absorption time $T = 3 \times 10^{15}$ years

Scattering mean free path λ

Scattering " " time τ

Time - energy relationship

$$w = Mc^2 e^{\frac{t}{\tau}\beta^2} \qquad \beta = \frac{V}{c} \simeq 10^{-4}$$

$$t = \frac{\tau}{\beta^2} \log \frac{w}{Mc^2}$$

Prob. distribution in ~~time~~ age

$$e^{-\frac{t}{T}} \frac{dt}{T} = \text{prob of age } t$$

$$= -d\, e^{-\frac{t}{T}}$$

$$e^{-\frac{t}{T}} = \left(\frac{Mc^2}{w}\right)^{\frac{\tau}{T\beta^2}}$$

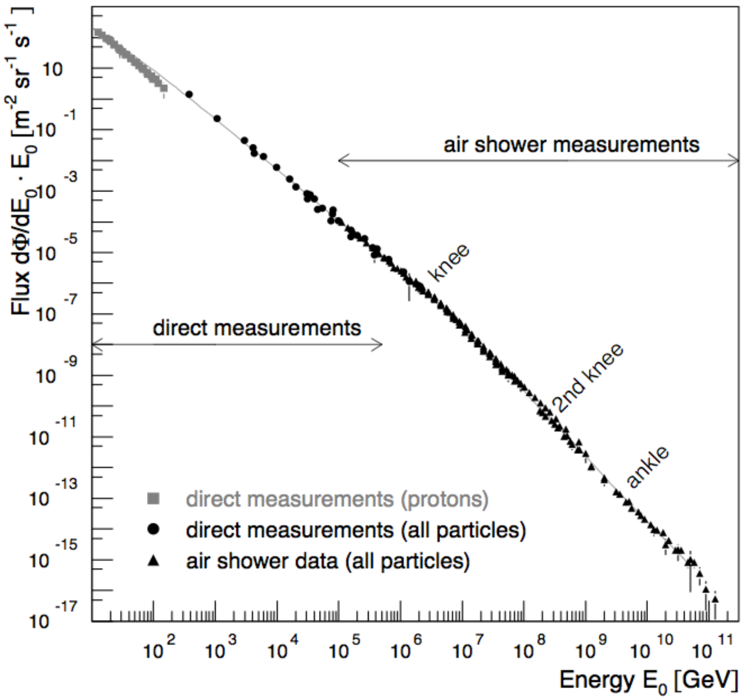
$$\text{prob} = \frac{\tau (Mc^2)^{\tau/T\beta^2}}{T\beta^2} \frac{dw}{w^{1+\frac{\tau}{T\beta^2}}}$$

Follows

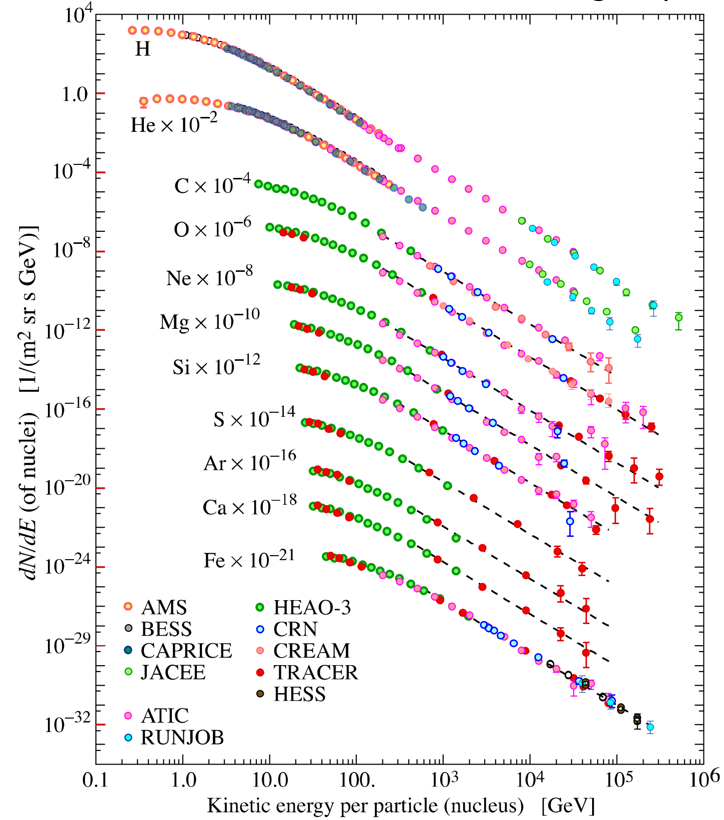
$$1 + \frac{\tau}{T\beta^2} = 2.9 \qquad \frac{\tau}{T\beta^2} = 1.9$$

Measured CR spectra

Bluemer et al 2009



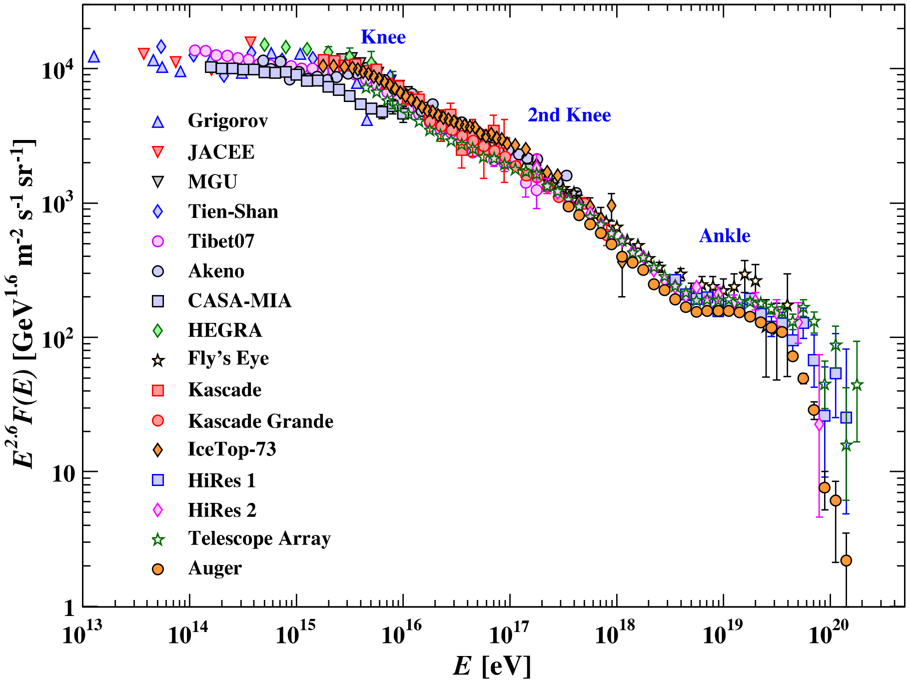
Particle data group



- Data taken across 14 o.o.m. in energy
- From antiprotons up to iron
- Intensity varies over 32 o.o.m.
- Spectra show energy power laws (~ $\mathbf{E^{-2.7}}$)

The highest energy CRs

ey are the highest energy particles
Measured by human experiments
(extensive air shower detectors).

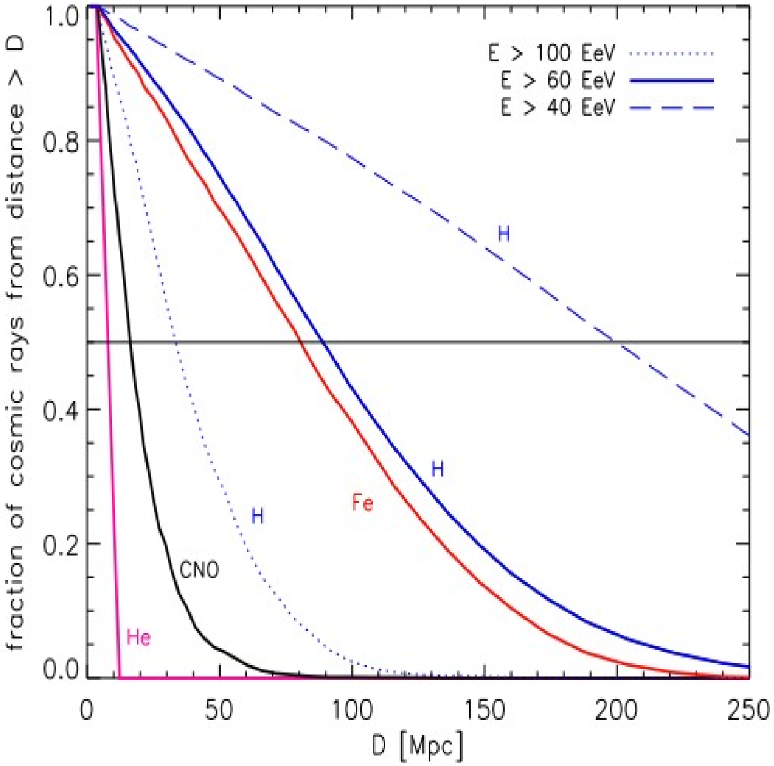


Difficult to identify the composition
At E~ $5 \cdot 10^{19}$ eV the spectrum
Shows the GZK cut off

GZK cut off

$p+\gamma_{CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0$

$p+\gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$



GZK horizon

Galactic Charged 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 up to 10^2 TeV

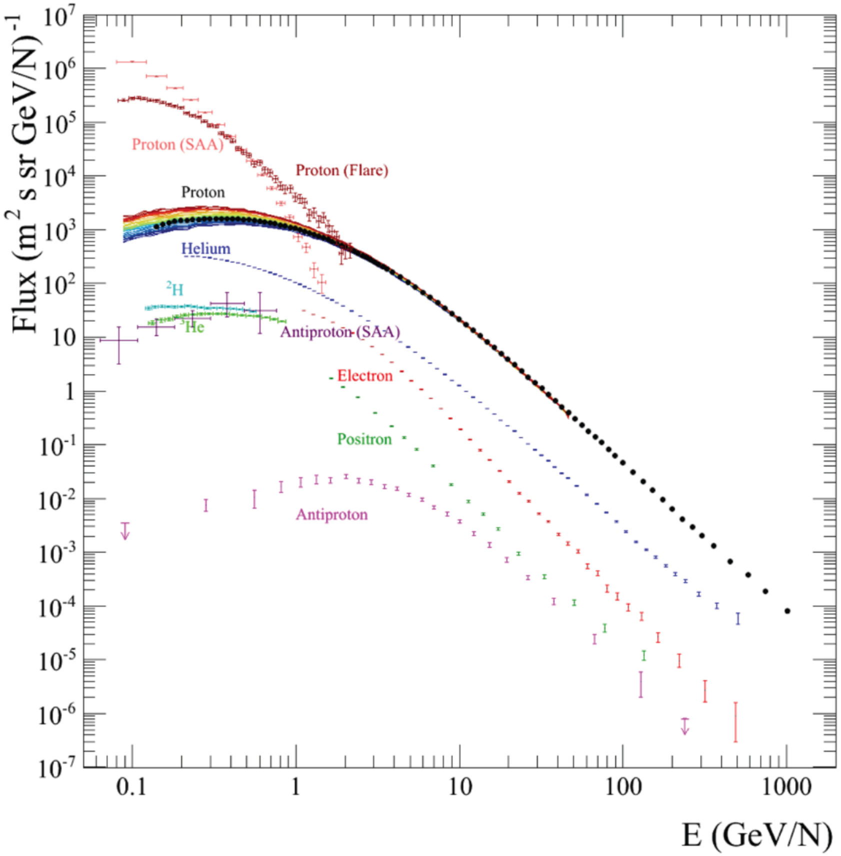
3. PROPAGATION

CRs diffuse in the Galaxy by the inhomogeneities of the galactic magnetic field

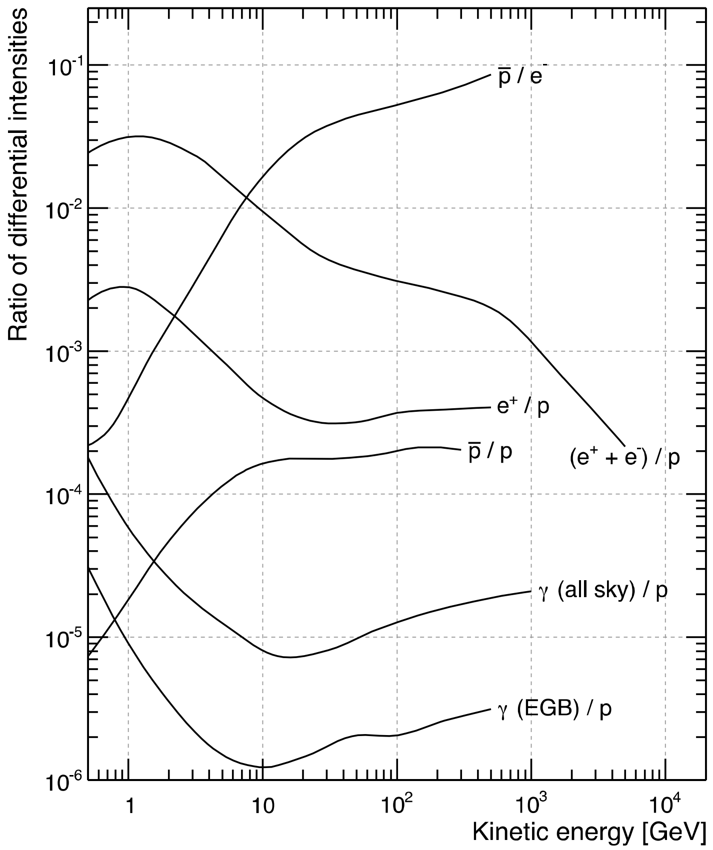
\+ loose/gain energy with different mechanisms

The galactic CR spectra

Credits: Valerio Formato & Mirko Boezio 2013



Rare CRs and γ-rays

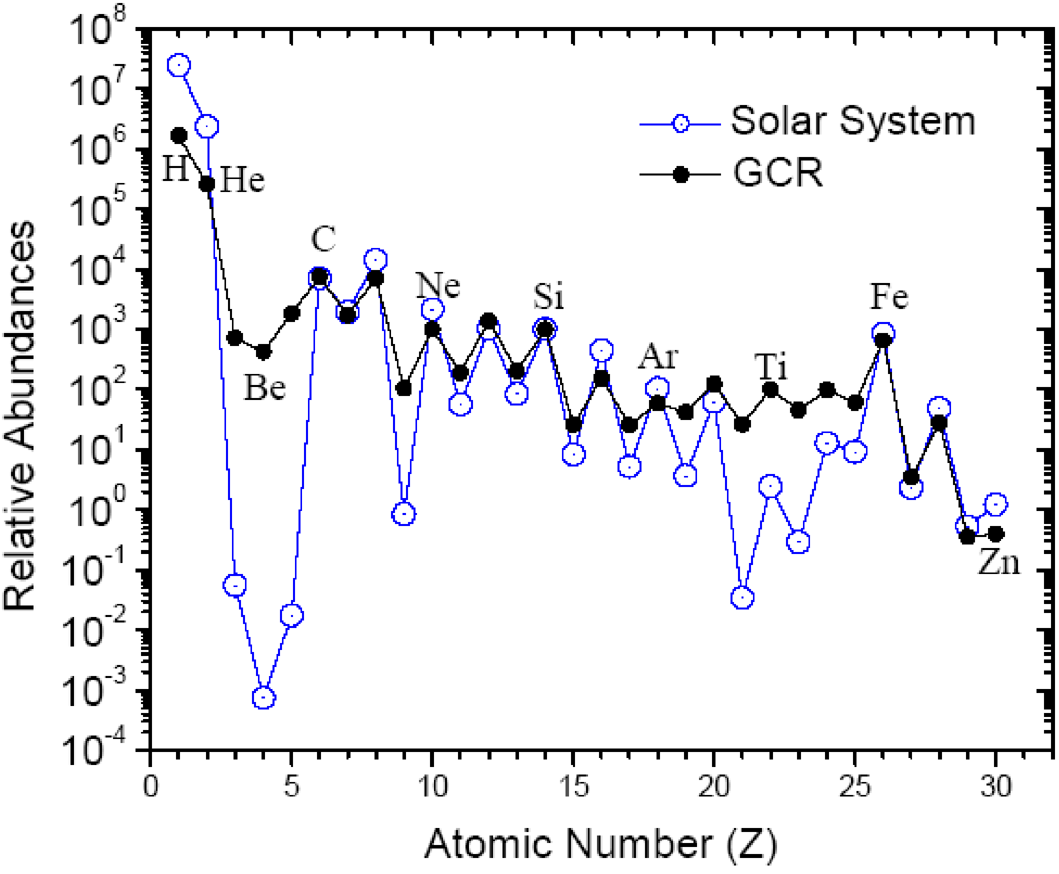


L Baldini, 1407.7631

Protons dominate at all energies wrt p

Antimatter and γ rays are rare

Cosmic Ray composition



Galactic Cosmic Rays have abundances similar to the Solar System ones except for Li-Be-B and sub-Fe nuclei: They are produced by spallation (fragmentation) of heavier nuclei on the Interstellar Medium (H, He)

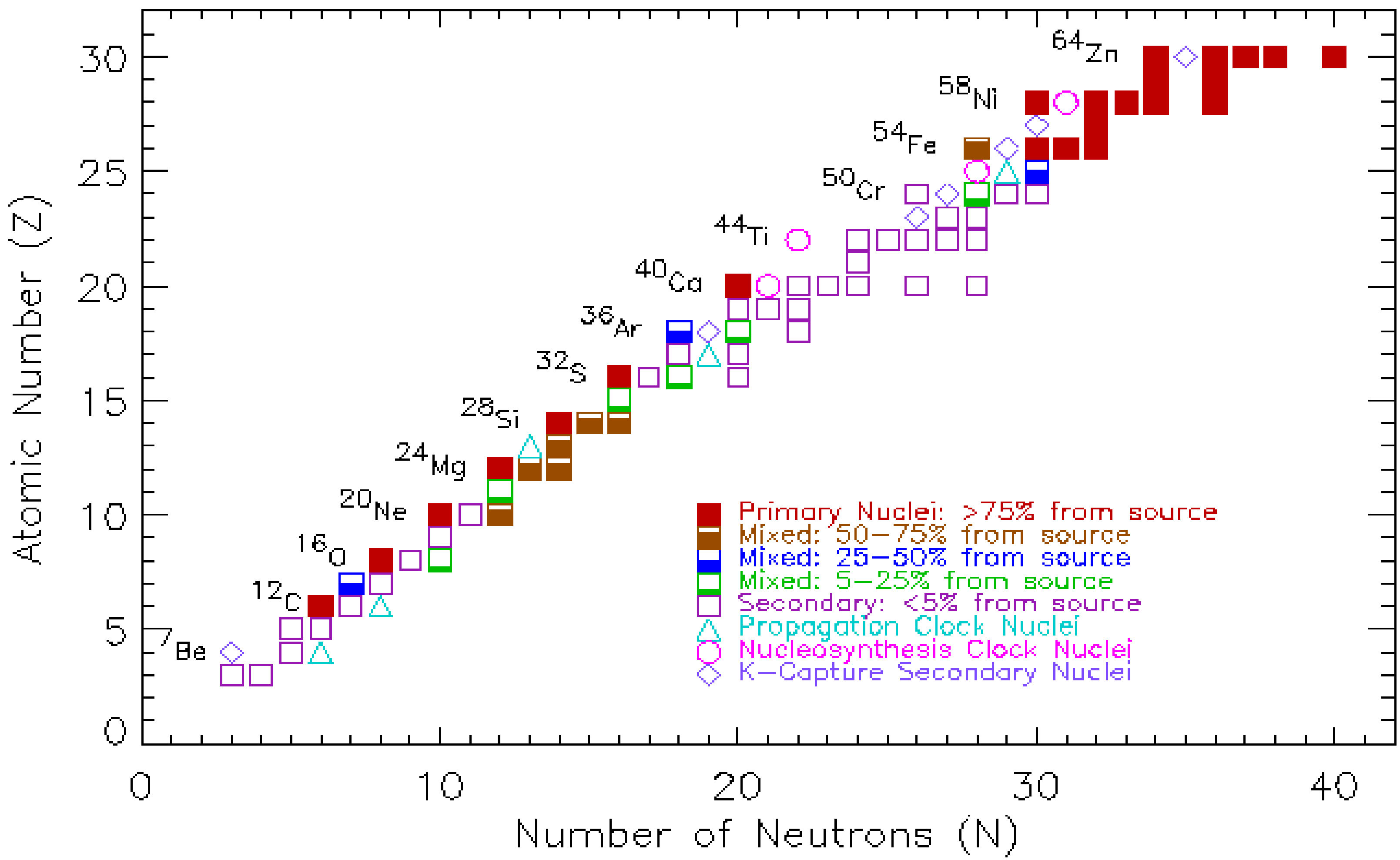
Primaries = present in sources:

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

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

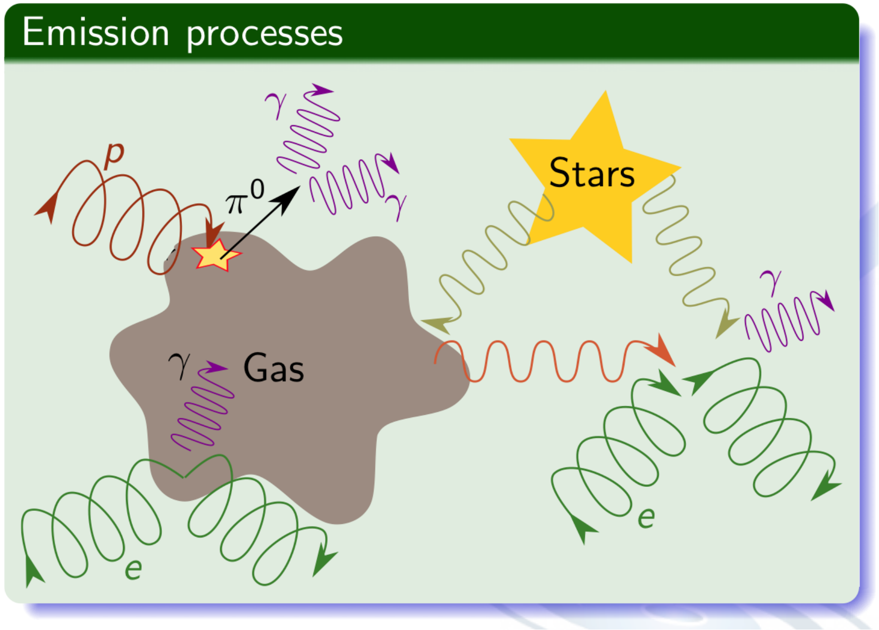
Secondaries = NOT present in sources, thus produced by **spallation** of primary CRs (p, He, C, O, Fe) on ISM

Nuclei: LiBeB, sub-Fe; e^+, p^+, d^+; ...



CRs as sources of γ-ray interstellar emission

From G. Johannesson



- p (He) + ISM (H, He) → … X ..
  → π^0 → 2γ
  (π^0 decay from interactions with IS gas)

- e- + photons → e- + γ
  (Inverse Compton)

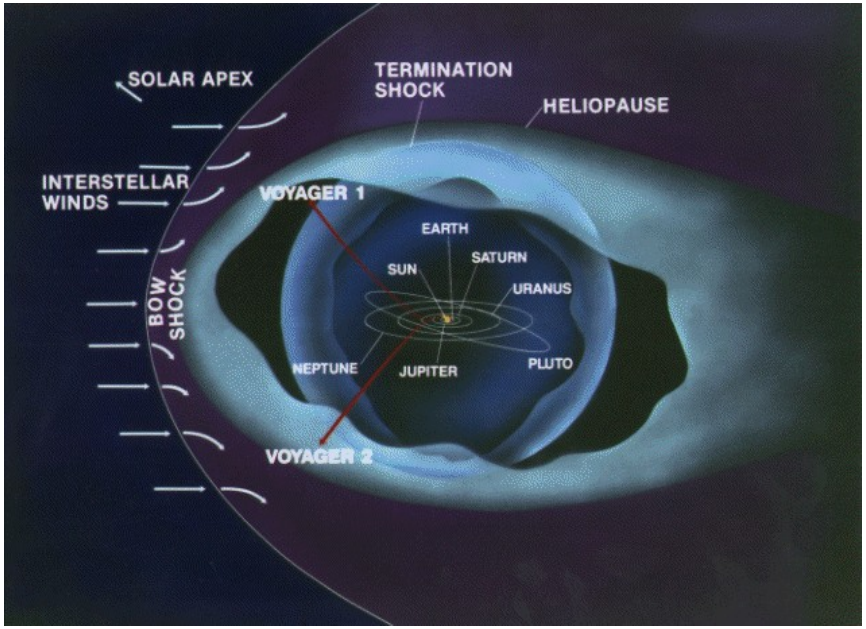
- Bremsstrahlung: e^- + ISM
  (radiation from interactions with IS gas atoms)

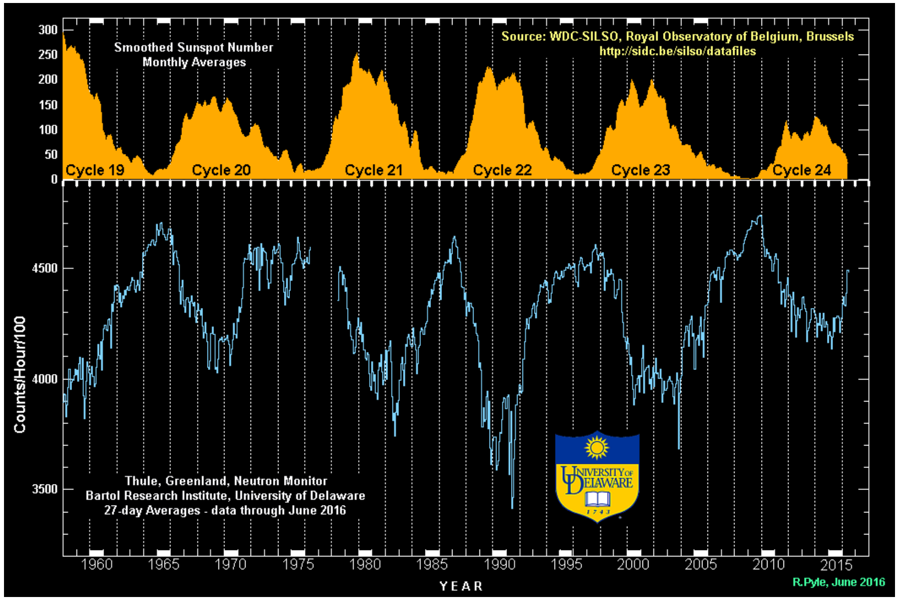
From the interstellar space to the Earth:
1: **THE SOLAR WIND**

Distorts charged particle spectra
Up to <u>10-20 GeV IS energy.</u>
<u>Below ~ 10 MeV, solar particles dominate</u>

The solar wind intensity is modulated on a 11-year cycle.

R.Pyle, Bartol





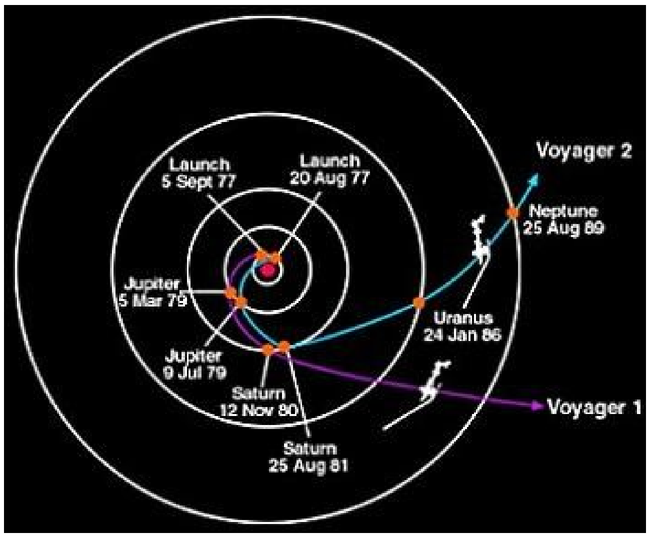
http://voyager.jpl.nasa.gov

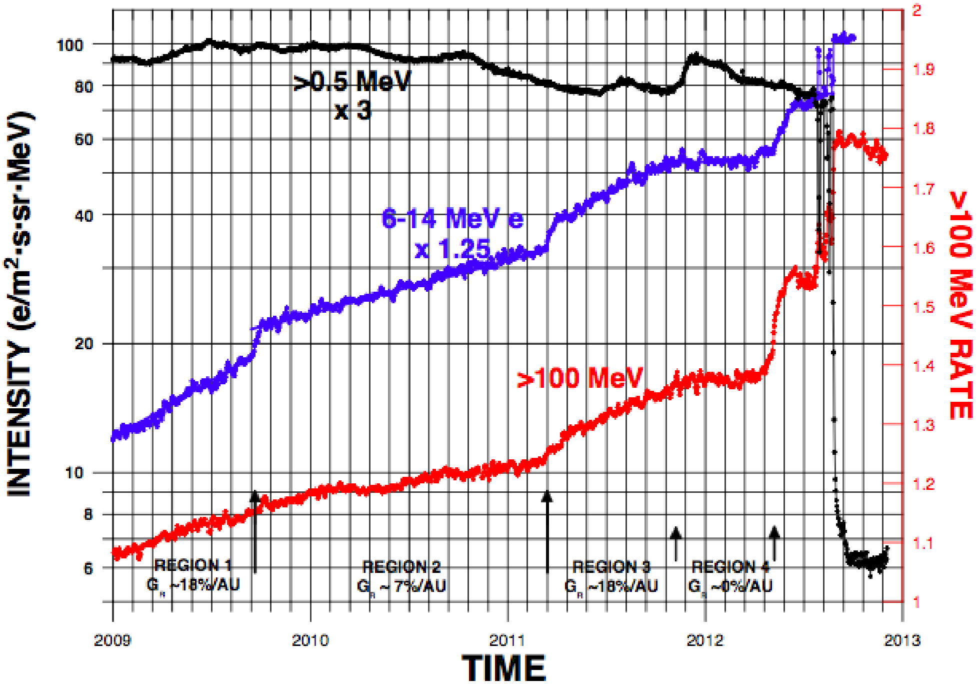
Low energy data statistics is favored during solar minima

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

arxiv:1212.0883

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





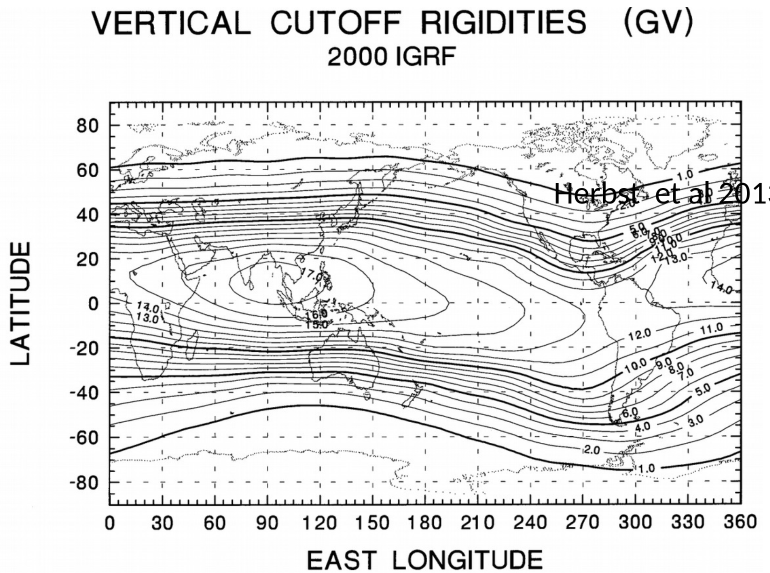
The Voyager probe is sending data from the true INTERSTELLAR SPACE!!
Now many decades in energy are covered by direct data on galactic CRs

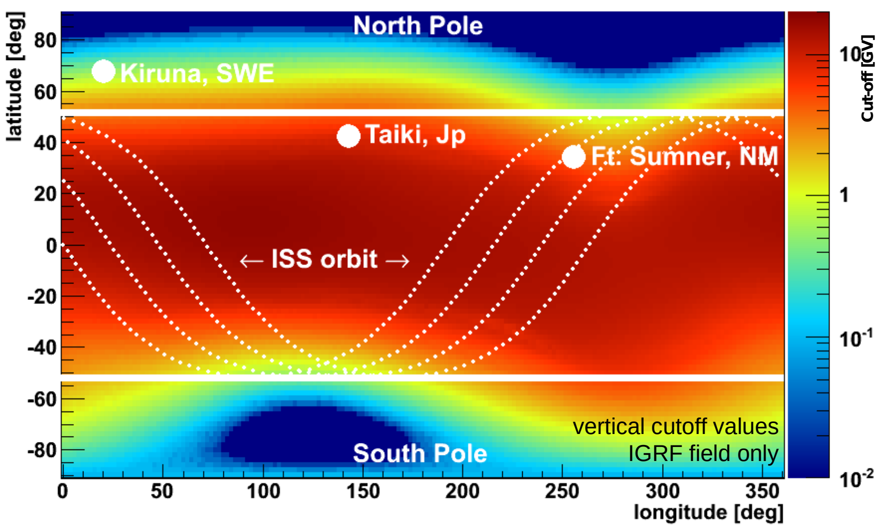
From the interstellar space to the Earth
2: **THE GEOMAGNETIC CUTOFF**

Störmer theory for dipole magnetic field predicts a rigidity cutoff:

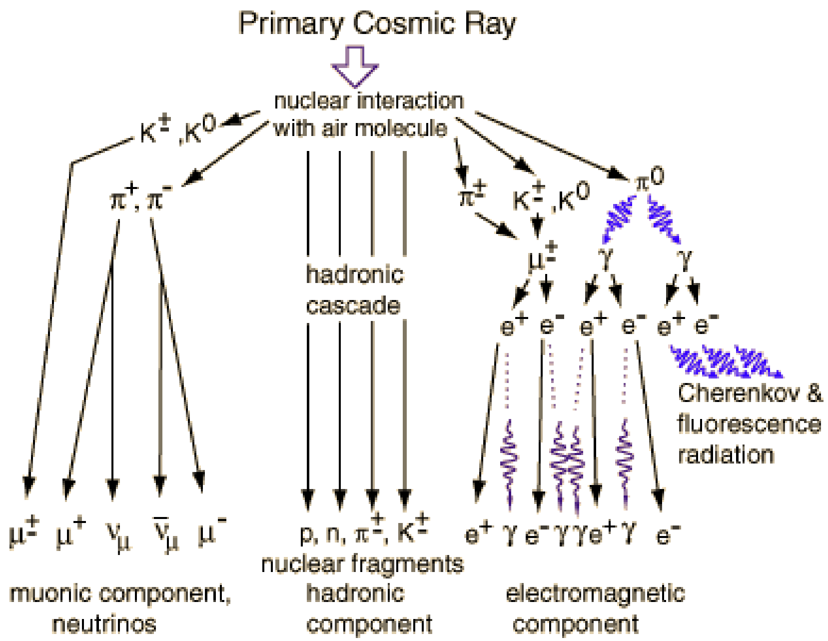
$R_c \sim 15 \cos^4\lambda$ GV (λ is the latitude)

Particle with $R < R_C$ cannot penetrate the Earth



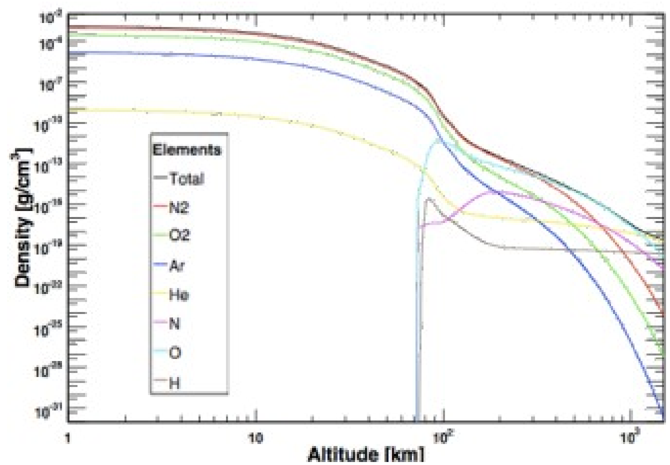


3: **THE ATMOSPHERE,**
a destructive target and a contamination



Indirect measurements of H.E. CRs rely on the atmosphere as the target for incoming CRs, producing very Informative air showers

Balloon borne experiments operate at a mean atmospheric depth of 4 g/cm², of the same order of the amount of matter encountered by CR wandering in the Galaxy



L. Derome

Experiments for E < O(10) GeV particles

better to run:

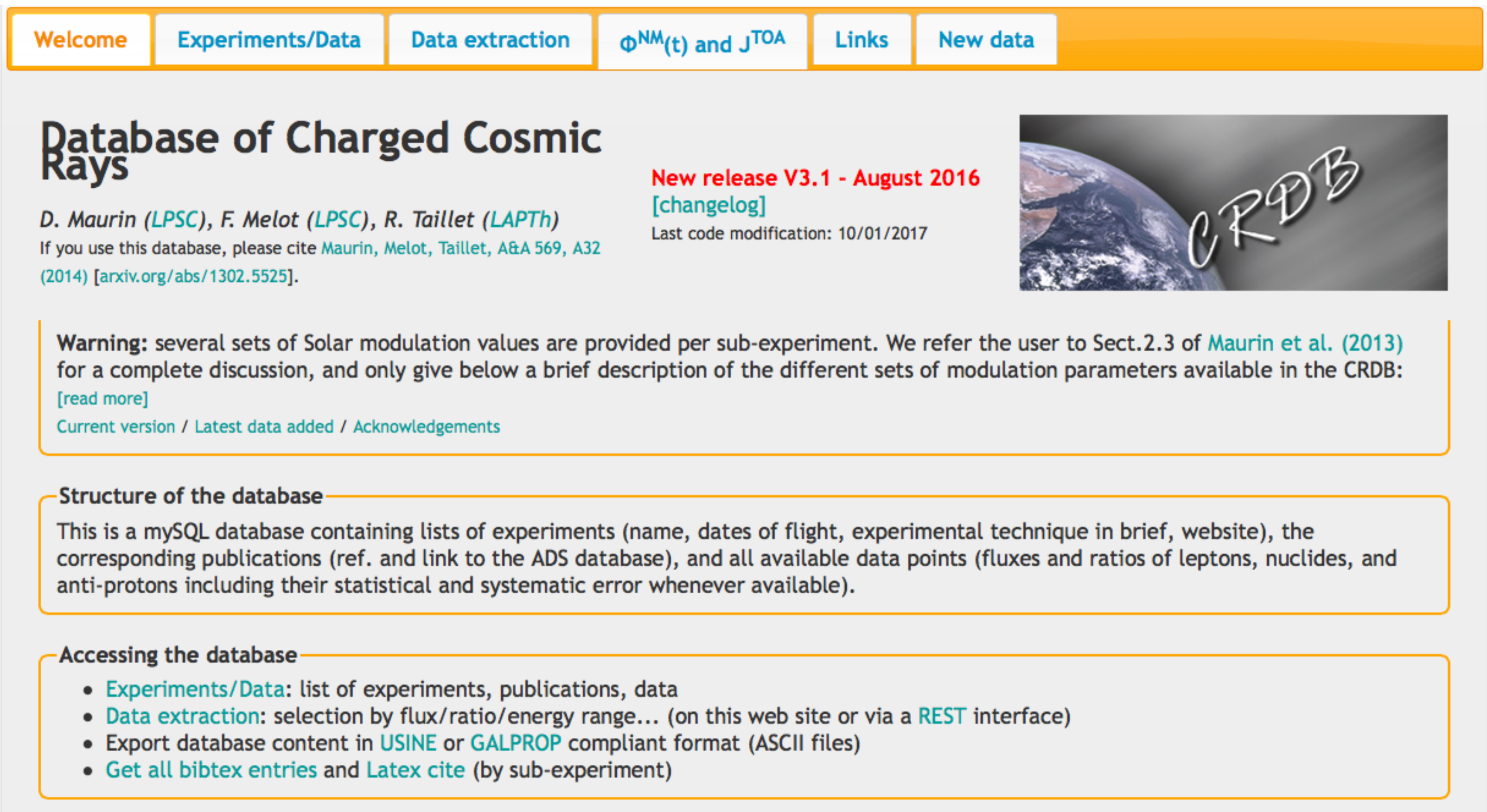
- during **solar minima**
- with **polar orbits**
- out of the **atmosphere**

Cosmic ray database

One can find a complete database for galactic CRs:

D. Maurin. F. Melot, R. Taillet arxiv:1302.5535, A & A 569, A32 (2014)

http://lpsc.in2p3.fr/crdb/#



Welcome | Experiments/Data | Data extraction | $\Phi^{NM}(t)$ and J^{TOA} | Links | New data

Database of Charged Cosmic Rays

D. Maurin (LPSC), F. Melot (LPSC), R. Taillet (LAPTh)

If you use this database, please cite Maurin, Melot, Taillet, A&A 569, A32 (2014) [arxiv.org/abs/1302.5525].

New release V3.1 - August 2016
[changelog]
Last code modification: 10/01/2017

Warning: several sets of Solar modulation values are provided per sub-experiment. We refer the user to Sect.2.3 of Maurin et al. (2013) for a complete discussion, and only give below a brief description of the different sets of modulation parameters available in the CRDB:
[read more]
Current version / Latest data added / Acknowledgements

Structure of the database

This is a mySQL database containing lists of experiments (name, dates of flight, experimental technique in brief, website), the corresponding publications (ref. and link to the ADS database), and all available data points (fluxes and ratios of leptons, nuclides, and anti-protons including their statistical and systematic error whenever available).

Accessing the database

- Experiments/Data: list of experiments, publications, data
- Data extraction: selection by flux/ratio/energy range... (on this web site or via a REST interface)
- Export database content in USINE or GALPROP compliant format (ASCII files)
- Get all bibtex entries and Latex cite (by sub-experiment)

Propagation of cosmic particles in the Galaxy

Note on useful quantities and units

X	Definition	Typical process
Rigidity	$R = pc/Ze$ (GV)	Magnetic f.: acceleration, diffusion
Total energy	$E^2 = p^2+m^2$ (GeV)	Energy measure (calorimeter)
Energy per nucleon	E/n (GeV/n)	CR showers
Kinetic en. per nucleon	T/n (GeV/n)	Nuclear fragmentations on ISM

Intensity of CRs $I = N^{er}/(m^2\ s\ sr)$

Differential Intensity $dI/dX = N^{er}/(X\ m^2\ s\ sr)$

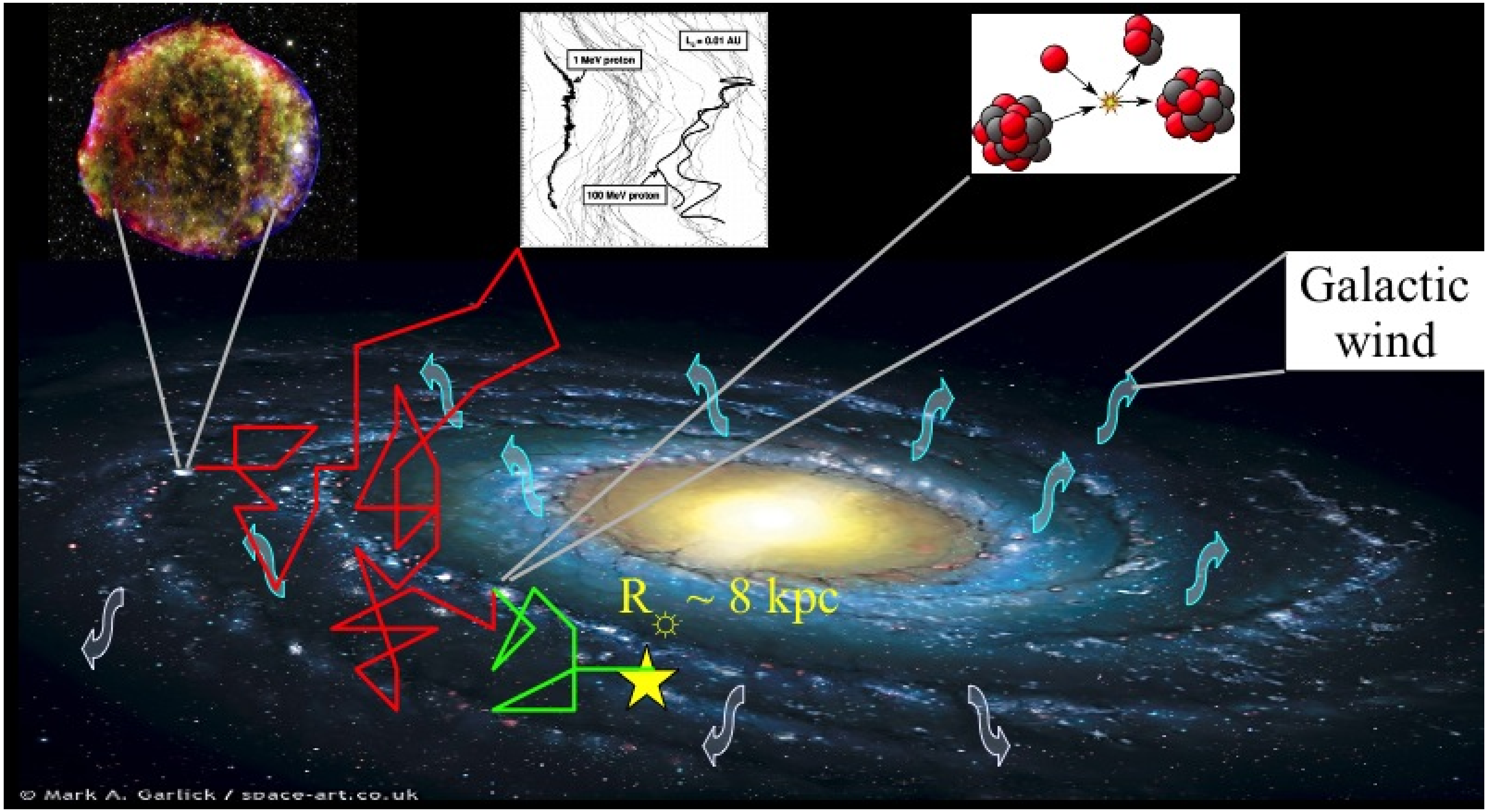
Differential Density $dN/dX = 4\pi/v\ (dI/dX)$

Propagation in the Galaxy

Sources, accelerators

Diffusion

Fragmentation; secondaries



from D. Maurin

Out of the disk, in the magnetic (diffusive) halo, Dark Matter sources

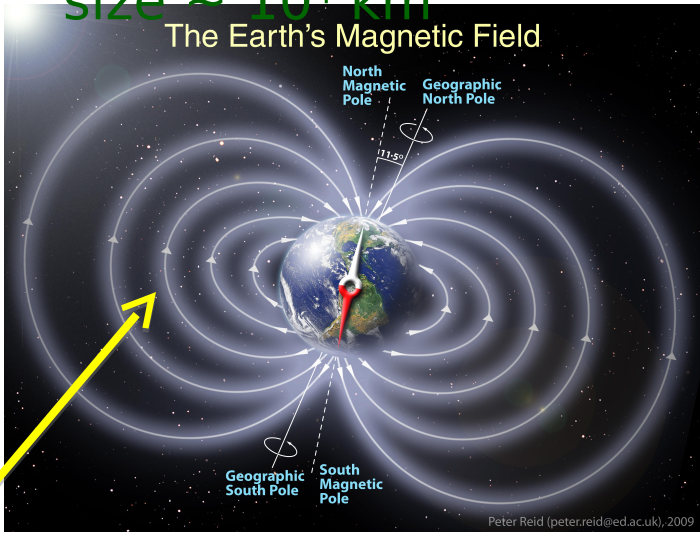
From the interstellar space to the Earth

1. IS space

size ~ 30 kpc, t ~20 Myr

3. Earth magnetic field,

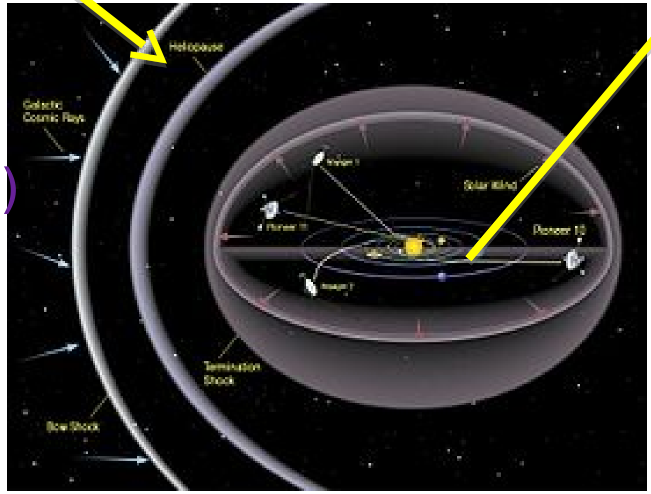
size ~ 10^4 km



2. Solar cavity

size ~1 AU (10^{-10} kpc)

t ~ years



Diffusion in the galactic magnetic field

The μG galactic magnetic disk is characterized by hydrodynamic turbulences with similar intensity.

Charged particles diffuse randomly following Fick's equation:

$$\vec{J} = -D\vec{\nabla}N(r,t)$$

Particles flow from a region of higher concentration to another of lower concentration, with a magnitude proportional to the density gradient.

- J is the ♯/(m^2s), the number of particles that flow through a surface in a unit time;
- D is the diffusion coefficient, m^2/s (kpc^2/Myr)

The Fick's equation couples to the continuity equation:

$$\frac{\partial N(r,t)}{\partial t} + \nabla\vec{J} = 0$$

The diffusion equation

$$\frac{\partial N(r,t)}{\partial t} + \nabla \vec{J} = 0$$

$$\vec{J} = -D\vec{\nabla} N(r,t)$$

$$\frac{\partial N(r,t)}{\partial t} - \nabla \cdot D\vec{\nabla} N(r,t) = 0$$

diffusion equation with null source term.

In 1D:

$$\frac{\partial N(z,t)}{\partial t} - D\frac{\partial^2 N(z,t)}{\partial z^2} = 0$$

With boundary conditions

$$N(t=0, z=0) = N_0$$

$$N(t, z=\pm\infty) = 0$$

The 1D solution is

$$N(z,t) = \frac{N_0}{\sqrt{4\pi D t}} \exp\left(\frac{-z^2}{4Dt}\right)$$

The density of diffusing particles decreases exponentially with distance

Diffusive length

From $$N(z,t) = \frac{N_0}{\sqrt{4\pi D t}} \exp\left(\frac{-z^2}{4Dt}\right)$$

we can compute the average diffusive length $$l_{\mathrm{diff}} = \sqrt{\langle z^2 \rangle} = \sqrt{2Dt}$$

for dimension = n $$l_{\mathrm{diff}} = \sqrt{2nDt}$$

Typically D is a function of energy (rigidity), thus the diffusive length increases mildly (sqrt) with the energy of the particle.
For typical values, it is ~ O(1)-O(10) kpc

D>=0.05 kpc^2/Myr, t>=20 Myr → l_{diff} >= sqrt(6x0.05x20) kpc ~2.5 kpc

Energy losses and gains

$$\frac{\partial N(z,t)}{\partial t} - D\frac{\partial^2 N(z,t)}{\partial z^2} = \frac{\partial}{\partial E}\left(-\left\langle\frac{\Delta E}{\Delta t}\right\rangle N(z,t)\right) + \frac{\partial}{\partial E}\left(D_{EE}\frac{\partial N}{\partial E}\right)$$

Losses

Gain

Coulomb
Ionization

Bremsstrahalung
Inverse Compton
Synchrotron

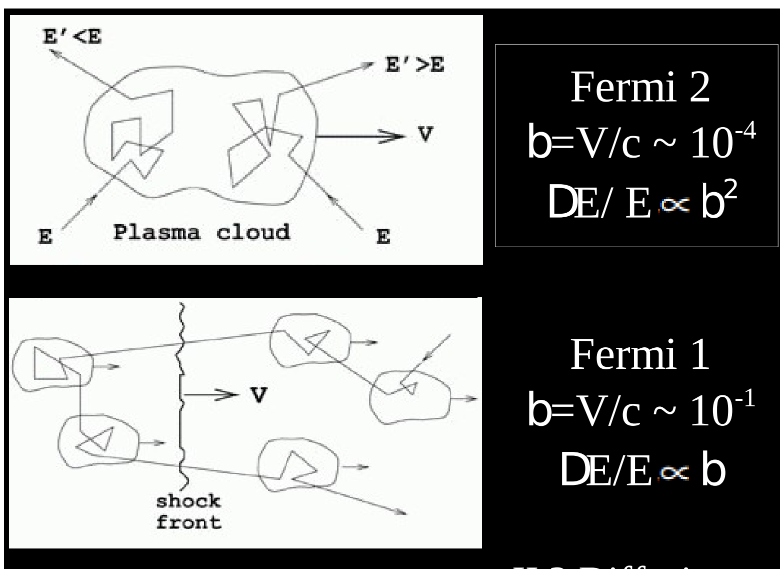
Catastrophic losses (destruction)

Reacceleration on
Magnetic turbulences

Reacceleration: diffusion in momentum space

It is a second order $\Delta E/E \sim \beta^2$ Fermi acceleration (E Fermi, 1949).

CRs collide on the magnetic scatterers.
It happens more head-on than tail-in scatters



From D. Maurin

$$\langle (\Delta E)^2 \rangle = 4E^2 \frac{V^2}{v^2}$$

$V=V_A$=scatterer speed, v=CR speed

$$V_A \sim \sqrt{\langle B^2 \rangle / \rho} \sim 20 \text{ km/s}$$

Reacceleration

The space diffusion coefficient and the momentum diffusion coefficient are correlated. If D(E) ~ R^{δ},

$$D_{xx}D_{pp} = p^2V_A^2\frac{1}{\delta(4-\delta)(4-\delta^2)} \geq \frac{1}{9}p^2V_A^2$$

(See Drury & Strong, A&A 2017)

The energy increase due to
reacceleration is mild,
and effective in the lowest
part (~ GeV) of the CR spectrum.

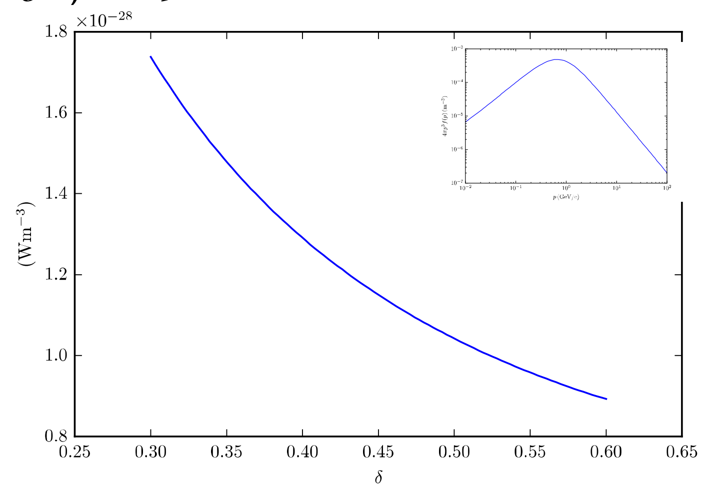
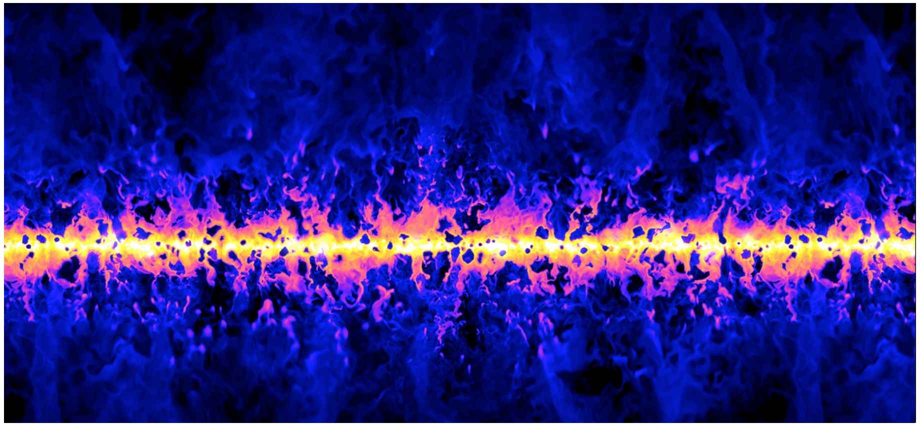


Fig. 4. The local reacceleration power density from Eq. 21, the Vos and Potgieter local interstellar spectrum, $V_A = 30\,\mathrm{km\,s^{-1}}$ and $D_0 = 10^{28}\mathrm{cm^2 s^{-1}}$

Convection

The stellar activity and the energetic phenomena associated with the lat
llar stages may push the ISM and the magnetic field out of the galactic
ne.

https://community.dur.ac.uk/r.g.bower/WordPressSite/blog/wordpress/?page_id=148



The net effect is a **galactic wind** perpendicularly outwards from the galactic plane.

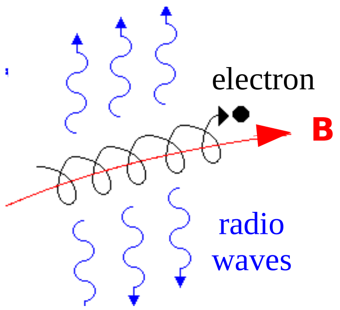
t adds a convective term to the diffusion equation:

$$\vec{J_C} = V_C N(r,t) \qquad V_c \sim 10 \text{ km/s}$$

And adiabatic losses in an expanding plasma $-\frac{1}{3}(\vec{\nabla} \cdot \vec{V_C})E$

Synchrotron e+e- energy losses

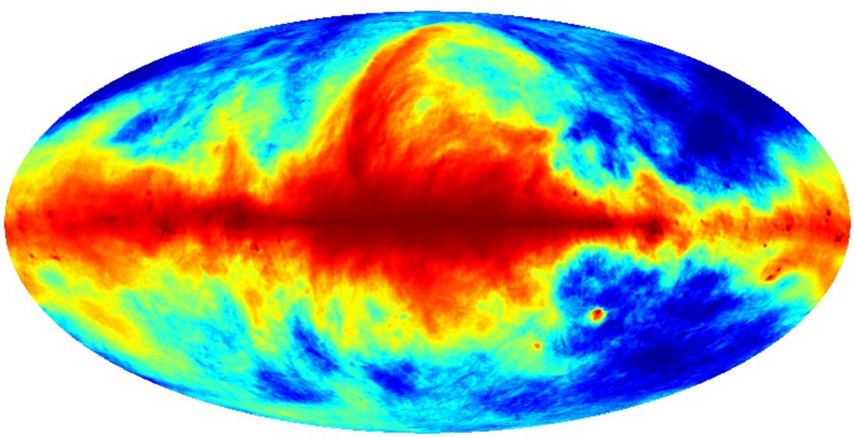
1. Synchrotron losses: an electric charge spiralizing in a magnetic field B.



Typical energy of the photons is in RADIO frequences

$$-\frac{dE}{dt}_{\text{sync}} \propto \sigma_T B_\perp \gamma^2 \qquad \sigma_T = \frac{8\pi}{3} r_e^2$$

Haslam map at 480 MHz



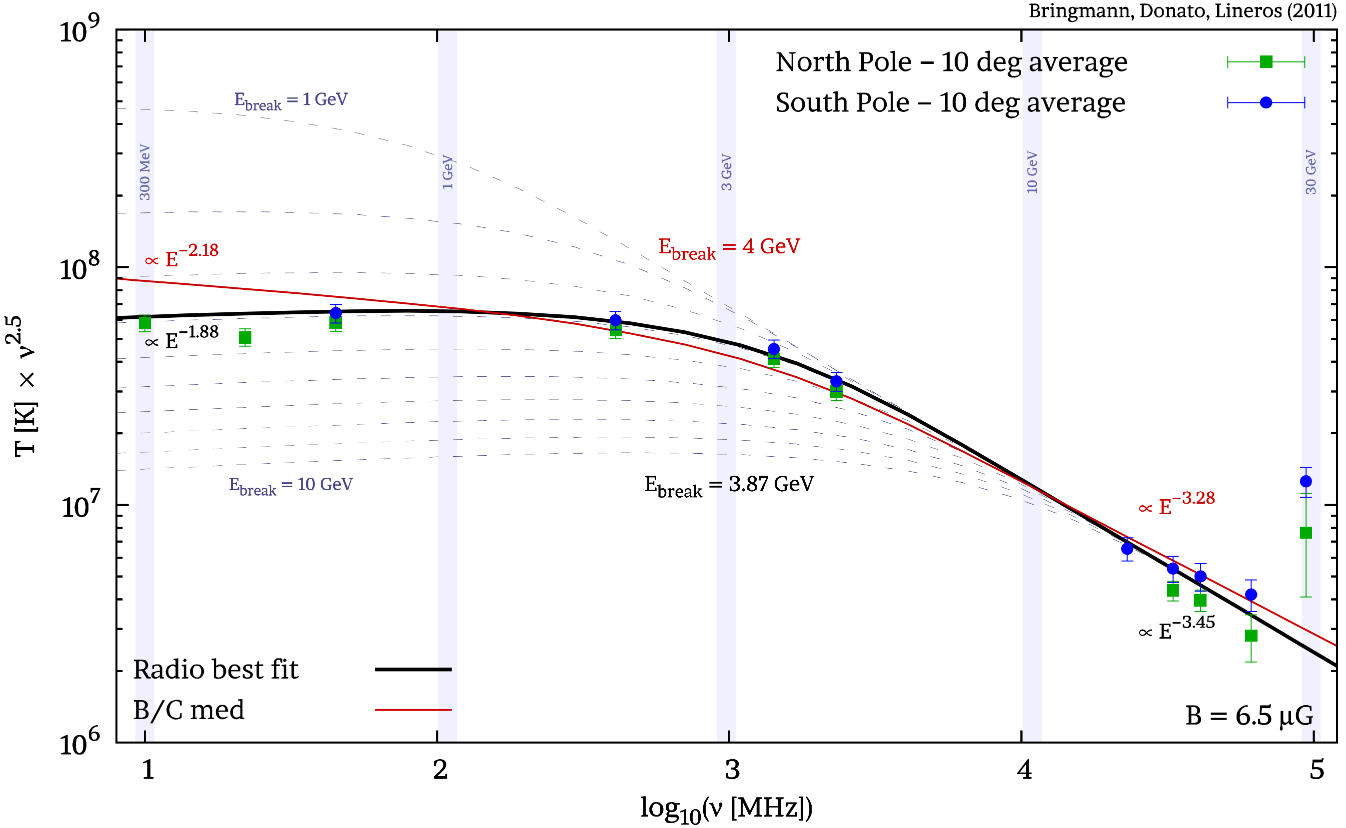
For typical electron spectra:

$$dn_e/dE \ \propto \ E^{-\gamma}$$

The radio spectrum is $T_b \propto \nu^{-\alpha}$

$$\alpha = (\gamma + 3)/2$$

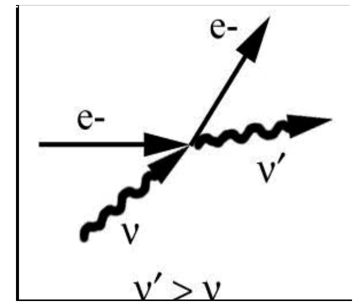
Galactic Electrons and synchrotron radiation



1 (30) GeV electrons → 100 MHz (GHz) photons

Inverse Compton e+e- Energy losses

2. Inverse Compton losses.
Energetic electrons upscatter background photons

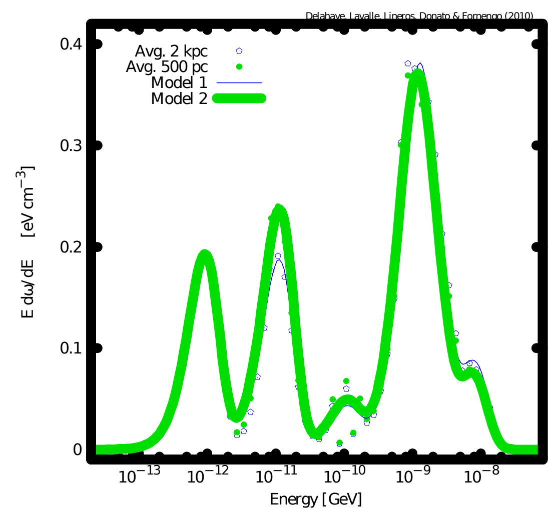


$$e^- + \gamma(E) \rightarrow e^- + \gamma(E')$$

Thomson $$-\frac{dE}{dt} = \frac{4}{3}\sigma_T\, c\, U_{rad}\, \gamma^2$$

or Klein-Nishina

$$-\frac{dE}{dt} = \frac{\sigma_T}{16}\frac{(m_e c\, k_b T_0)^2}{\hbar^3}\left\{\ln\frac{4\gamma\, k_b T_0}{m_e c^2} - 1.9805\right\}$$

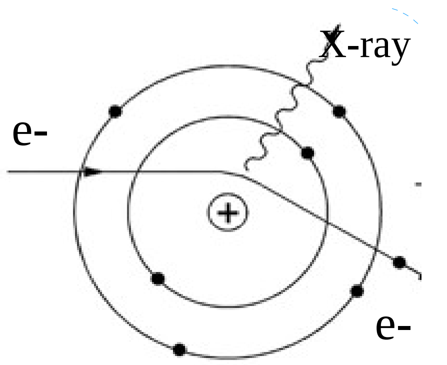


Crucial is the interstellar radiation field:
Visible, IR, UV

Bremsstrahlung, ionization, Coulomb e+e- energy losses

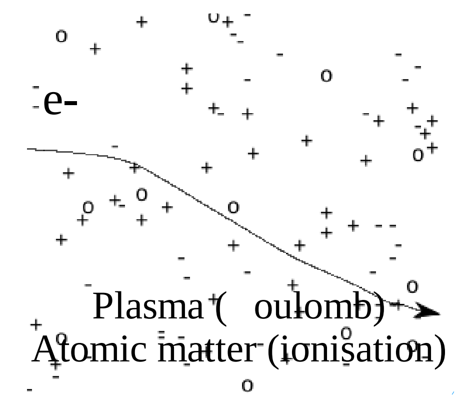
3. Bremsstrahlung (free-free) in the ISM

$$-\left.\frac{dE}{dt}\right|_{\rm brem} \propto \sigma_T n_{\rm ISM} \gamma$$



4. **Ionization, Coulomb**
Interaction with neutral matter (ionization) or with ionized plasma (Coulomb)

$$-\left.\frac{dE}{dt}\right|_{\rm ion(Coul)} \propto \sigma_T n_{\rm ISM(plasma)}$$



Nuclei energy losses

With respect to e^+e^-:

- $\sigma_T \rightarrow \sigma_N \sim Z^2 x 10^{-7}$
- γ is very different for e and p

$$\frac{\gamma_e}{\gamma_N}(E_e = E^N_{kin/n}) = \frac{m_e}{m_N} \sim 5 \cdot 10^{-4}$$

Energy losses for NUCLEI are suppressed by $Z^{2x}10^{-7}$ and by $5x10^{-4}$

The only significant losses for nuclei are

COULOMB and IONIZATION in the disc

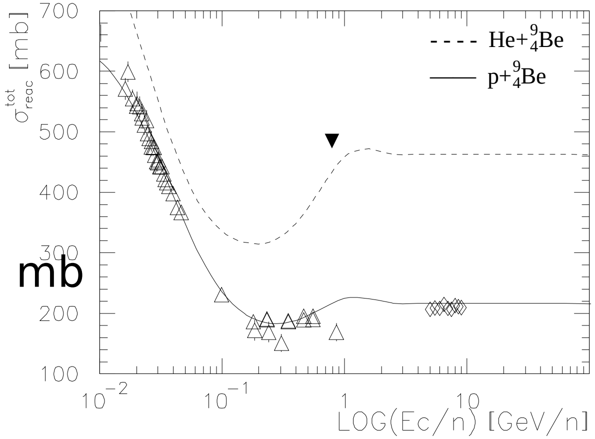
Nuclei: catastrophic losses

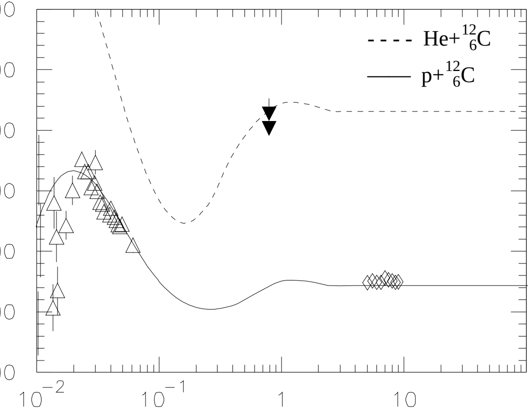
- Nuclei can **destroy** themselves in scattering off the ISM

$\sigma_{inel} = \sigma_{tot} - \sigma_{el}$

$\Gamma_{inel} = n_{ISM} v \sigma_{inel}$

σ_{inel}(p, C, Fe) ~ 40, 250, 750 mb





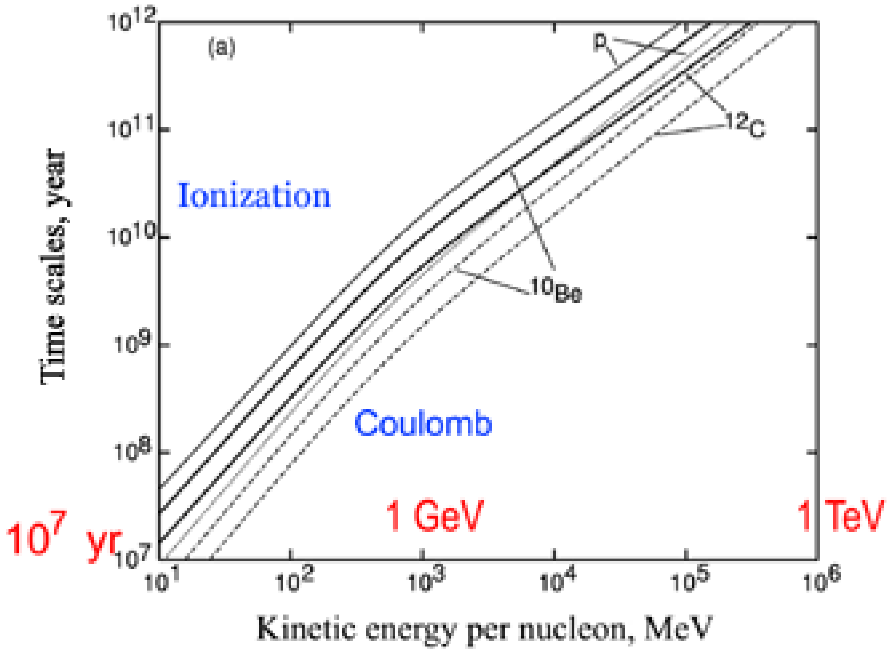
- Radioactive (beta) isotopes can **decay**

$\Gamma_{dec} = \ln(2)/(\gamma t_{1/2})$

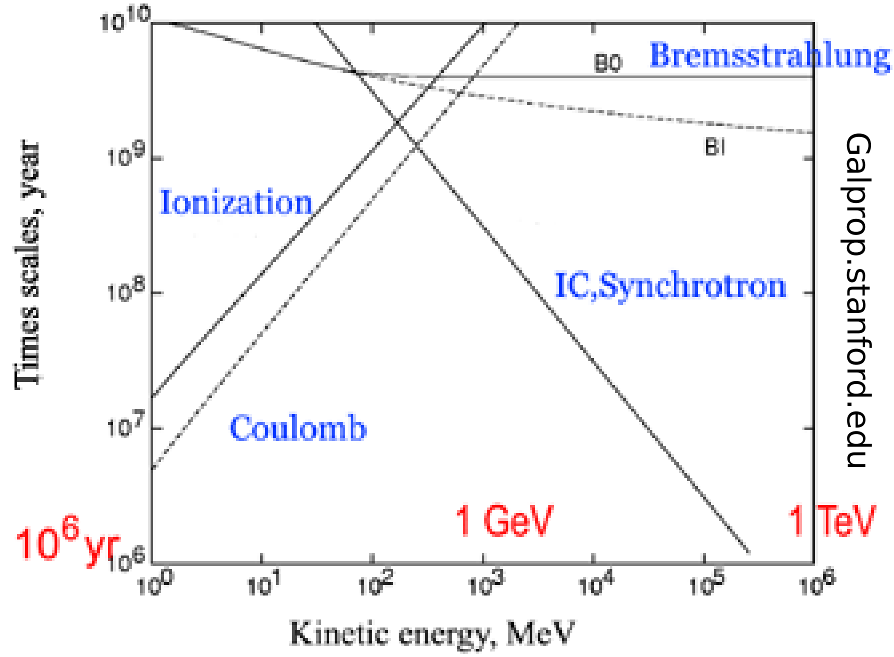
- Electronic **capture** (and stripping, much lower effciency)

Energy losses: nuclei and leptons

nucleons



electrons & positrons



The smaller the time, the stronger the effect

The diffusion coefficient

It describes effectively the scattering of charged particles on the irregularities of the galactic magnetic field. In principle, a tensor:

$$\boldsymbol{\kappa} = \begin{pmatrix} \kappa_\perp & \kappa_A & 0 \\ -\kappa_A & \kappa_\perp & 0 \\ 0 & 0 & \kappa_{||} \end{pmatrix}$$

$\kappa_{||}$: Diffusion along B

$\kappa_\perp$: Diffusion perp. to B

κ_A: Drift effects

- It can be derived analytically (i.e. in quasi-linear theory, $\delta B << B$)
- Or with numerical simulations, not yet very predictive

The interaction particle – turbulence is resonant, and maximal when the irregularities are // to the regular magnetic field:

$k_{//} = \pm s/(r_g \mu)$ *s=integer, for cyclotron order; μ is the pitch angle,* r_g = *R/B gyroradius*

$k_{//} \sim 1/3\ v r_g / P$, with

$$P = \int \Delta B(k)^2 / B^2$$

If $B(k)^2 \sim k^{-a}$ ($k \sim 1/r_g$) $k_{//}$ is a power law.

a=5/3 → $K(R) \sim R^{1/3}$, **Kolmogorov** spectrum

a=3/2 → $K(R) \sim R^{1/2}$, **Kraichnan** spectrum

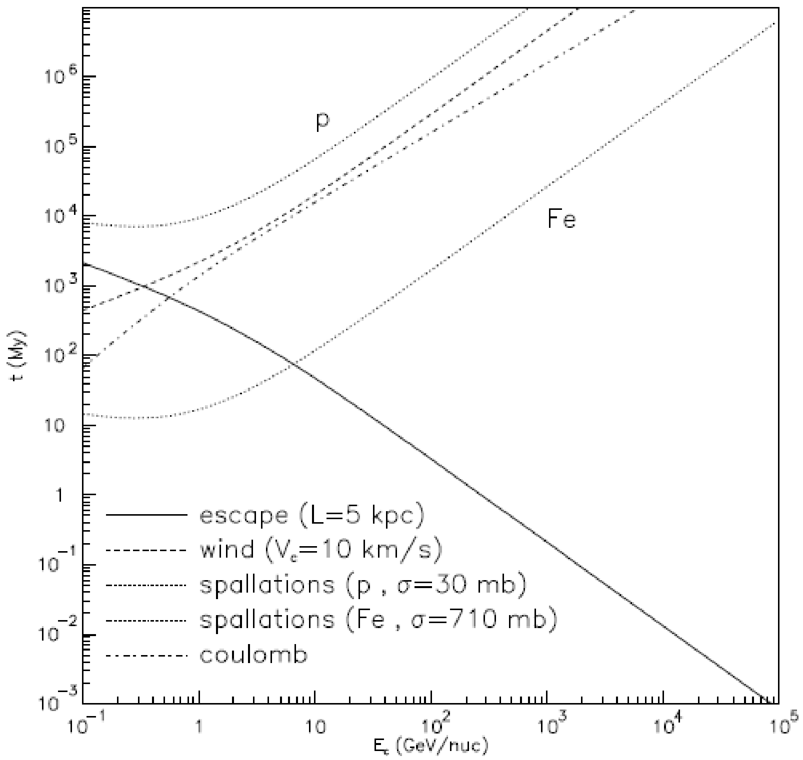
Characteristic times for various processes

For a particle to reach z and come back (diffusion time) : $t_D \approx z^2/K(E)$

At the same time, convection time: $t_C = z/V_C$

A particle in z can come back to the disk only if $t_C < T_D \rightarrow z_{max} = K/V_C$

N. B. The smaller the time, the most effective the process is



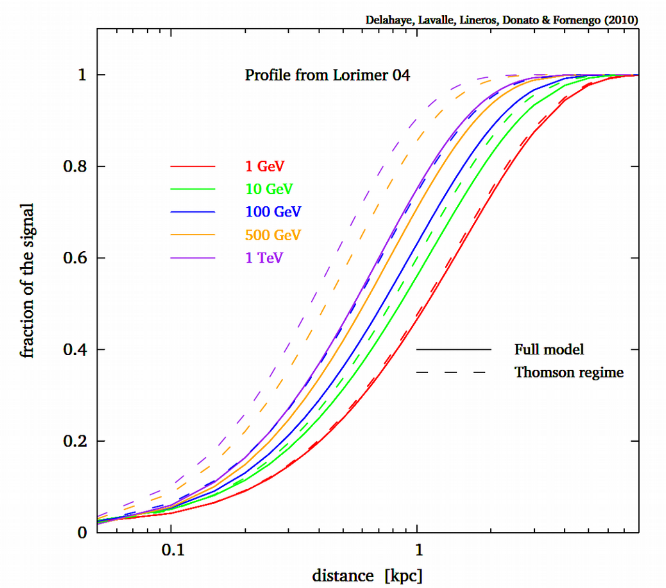
For protons: escape dominates > 1 GeV
E<1 GeV, convection and e.m. losses

For iron: Spallations dominate for E<10 GeV/n

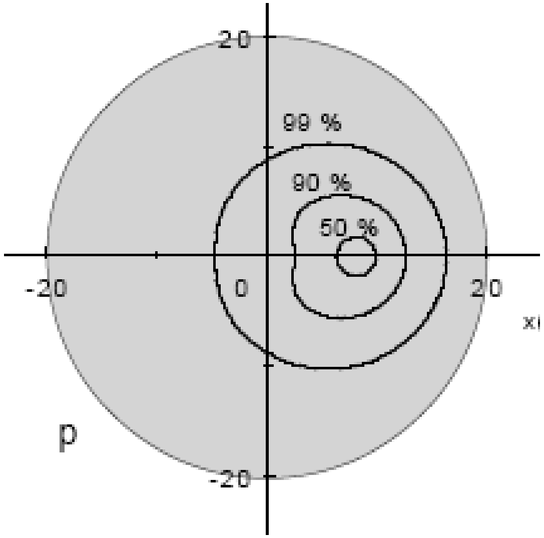
Where do these particles come from?

(if sources located in the galactic disk)

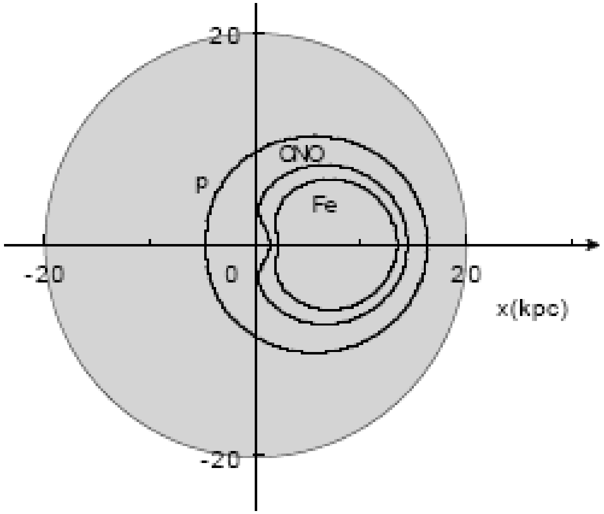
Electrons



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

Transport equation in diffusion models for flux (intensity) $N^j(E)$

$$\Gamma^j = \Gamma^{j,inel} + \Gamma^{j,\,rad}$$

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

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

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

$$b_{\rm tot} = b_{\rm loss} + b_{\rm reac}$$

$$b_{\rm loss}(E) = \left(\frac{dE}{dt}\right)_{\rm Ion} + \left(\frac{dE}{dt}\right)_{\rm Coul} + \left(\frac{dE}{dt}\right)_{\rm Adiab}$$

Primary production (SNR, PSR, DM)

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

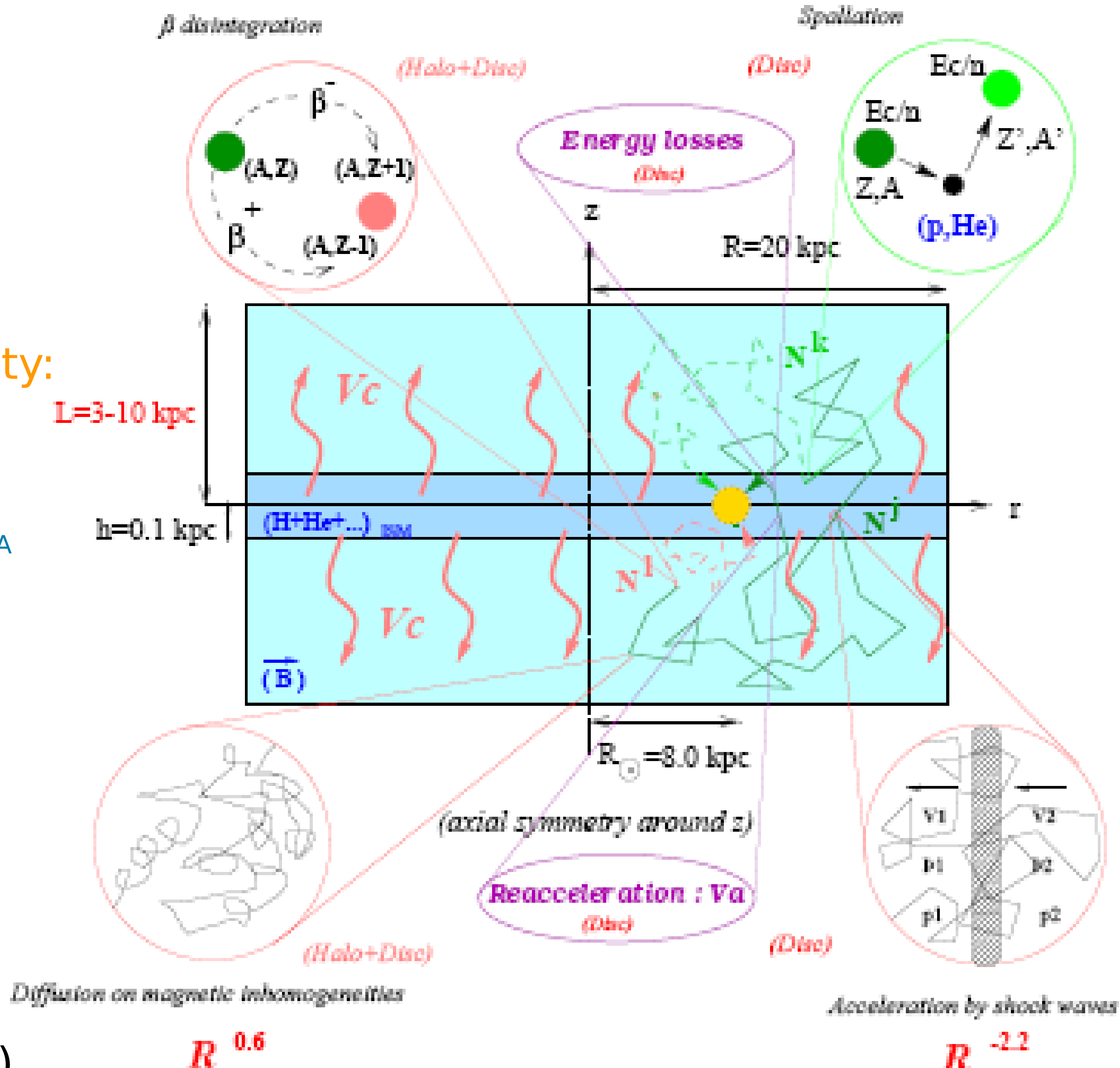
Secondary production by fragmentation

It is a second order differential equation in space and in energy

Particles diffusing in the Galaxy

- Diffusion coefficient: **$K(R)=K_0\beta R^{\delta}$**
- Convective velocity: V_c
- Alfven velocity: V_A
- Diffusive halo thickness: L
- Acceleration spectrum: $Q(E)=q_0p^{\alpha}$

K_0, δ, V_c, V_A, L, (α)



The solution to the diffusion equation in the cylindrical symmtery

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

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

$$S_i^j \equiv \left(\frac{V_c^2}{K^2} + 4\frac{\zeta_i^2}{R^2} + 4\frac{\Gamma_{rad}^{N^j}}{K}\right)^{1/2}$$

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

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

Production

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

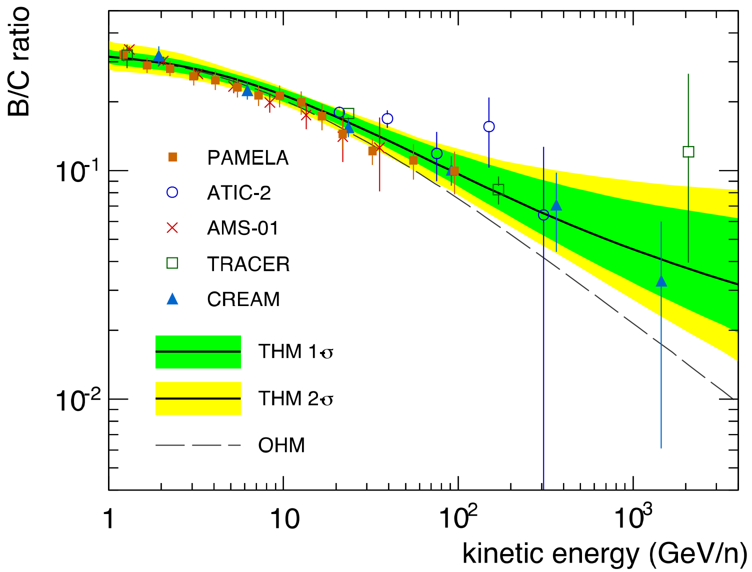
Destruction

See simple trends ...

Fixing the diffusion coefficient
Boron-to-Carbon: a standard candle?

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

Feng, Tomassetti, Oliva PRD 2016



B/C = Sec/Prim

$\sim Q_{sec}(E)/Q_{prim}(E)$

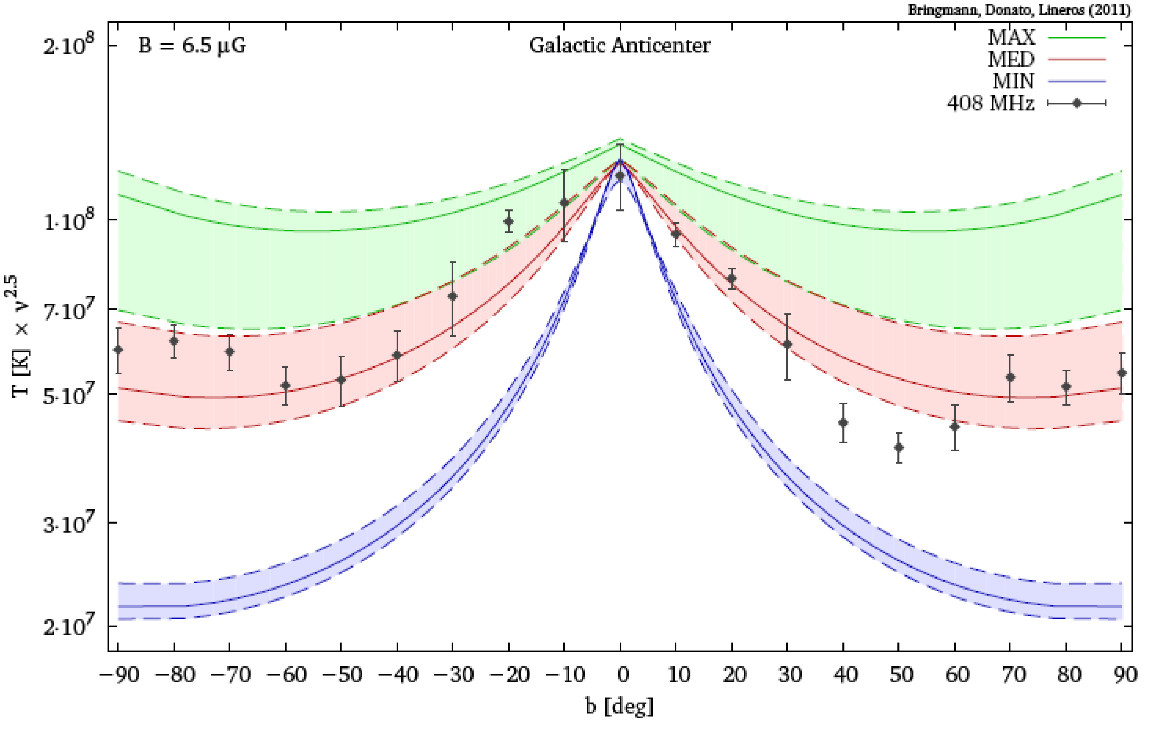
$\sim Q_{prim}(E)/K(E) \,/\, Q_{prim}(E)$

$\sim K(E)$

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

Fixing L: Radio data vs latitude

Bringmann, FD, LIneros JCAP 2012



Shaded: varying K_0 and L within B/C constraints (Maurin et al. APJ 2001)

Mod.	prop. parameters			radio data (χ^2/d.o.f.)		
	L [kpc]	K_0 $\left[\frac{\mathrm{kpc}^2}{\mathrm{Myr}}\right]$	δ	22 MHz	408 MHz	1.42 GHz
min	1	0.0016	0.85	14.4	13.4	13.5
med	4	0.0112	0.70	4.4	4.7	4.7
max	15	0.0765	0.46	15.4	10.6	8.7

Very small magnetic halos seem disfavoured

The role of high energy particle physics in CR physics

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

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

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

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

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 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

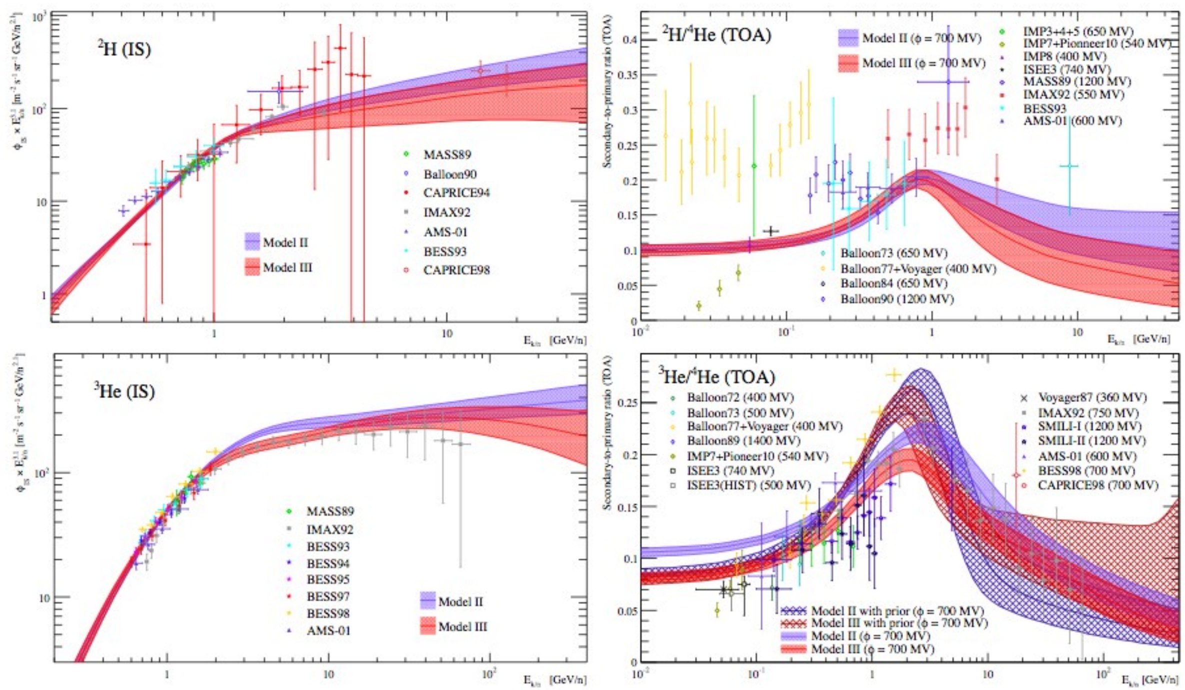
Remarkable for DARK MATTER signals : antiproton, antideuteron, positron and gamma rays.

Constraining galactic cosmic rays with light isotopes

Coste, Derome, Maurin, Putze A&A 2012

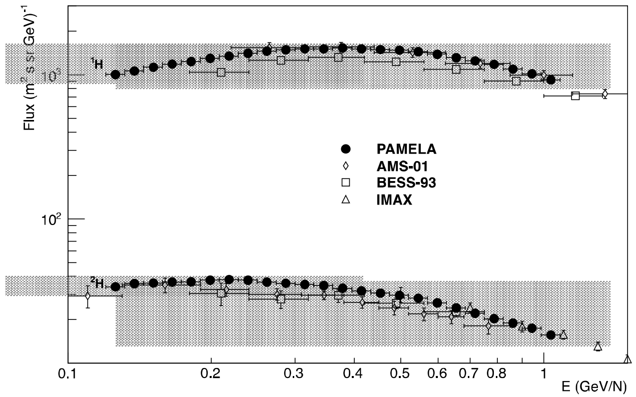
Different models derived from B/C

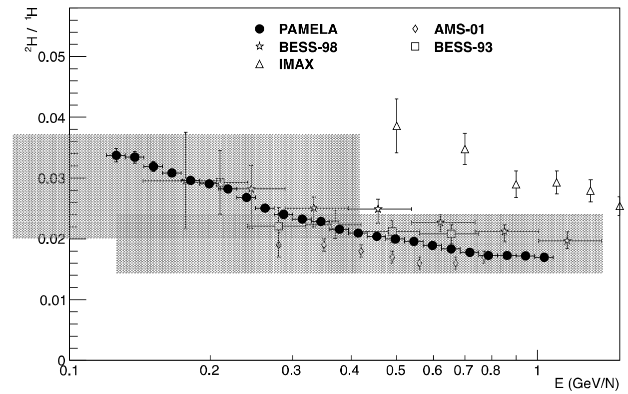
Higher δ for red



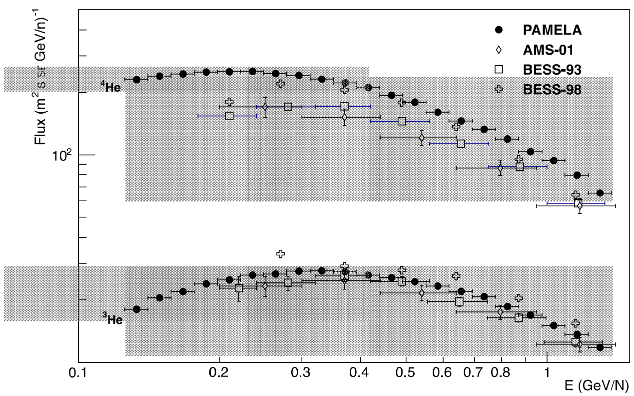
Pre-Pamela theoretical analysis:
some of these models are already excluded by Pamela light isotopes data

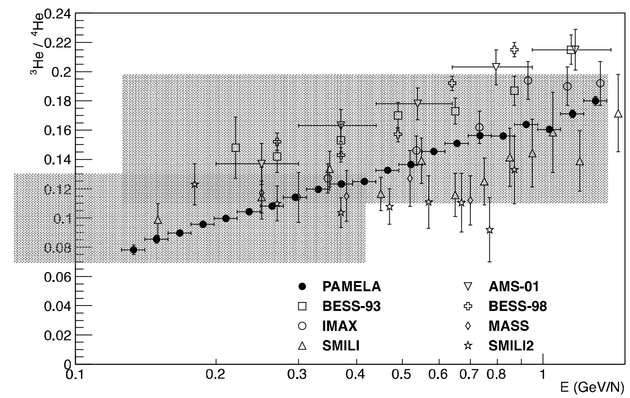
Data from light isotopes





Pamela Coll. ApJ 818, 2016





Data show clear trends.

Future data on significantly wider energies would be useful
for studies of propagation in the Galaxy, and also for heavier isotopes

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

Antiprotons in CRs
Secondary component

Secondary antiprotons in cosmic rays (CR) are produced by spallation reactions on the interstellar medium (ISM)

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

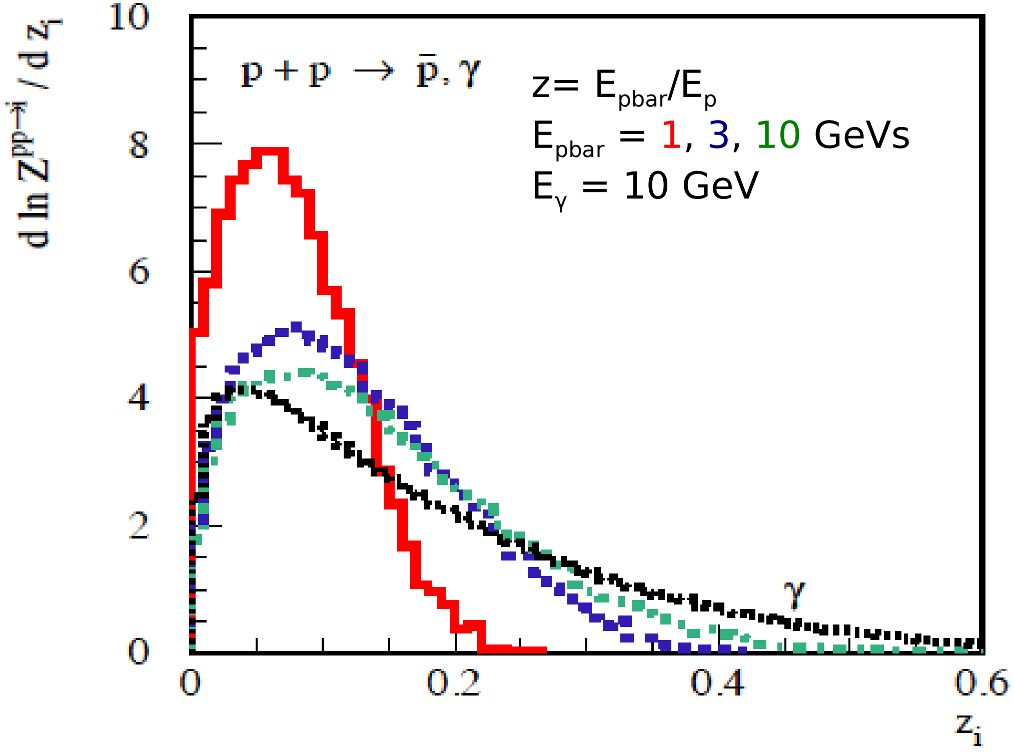
The production threshold for p+p → p- + ppp is $E_{p,min} = 7m_p$

To calculate the **secondary** antiproton flux:

- p and He in CRs *(measured fluxes)*
- Nuclear cross sections *(data + MonteCarlo)*
- Propagation *(diffusive models)*

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} →

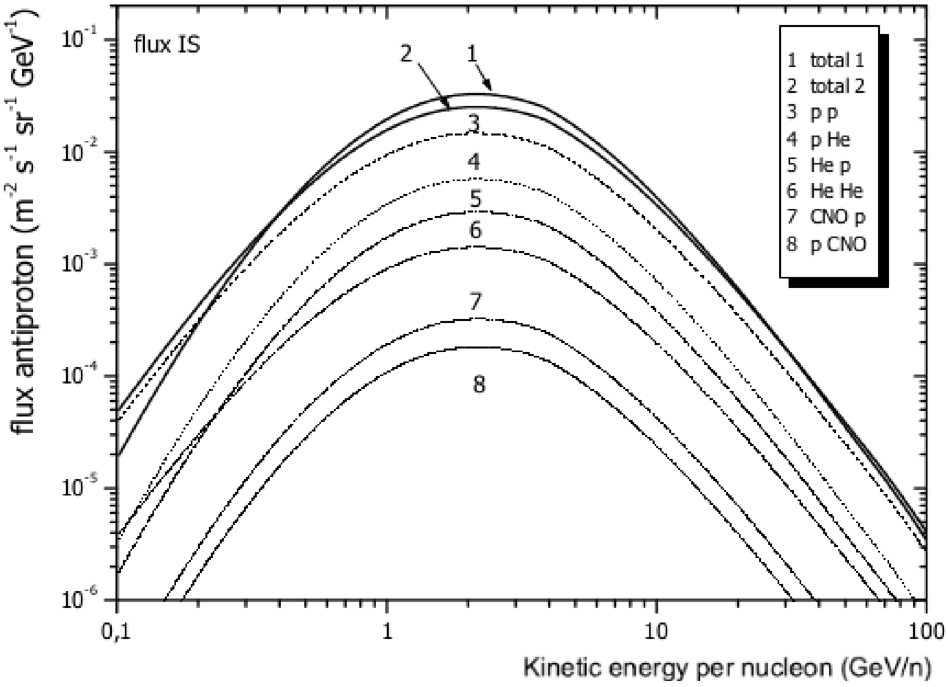
Proton energies with ~ few GeV – 10 TeV

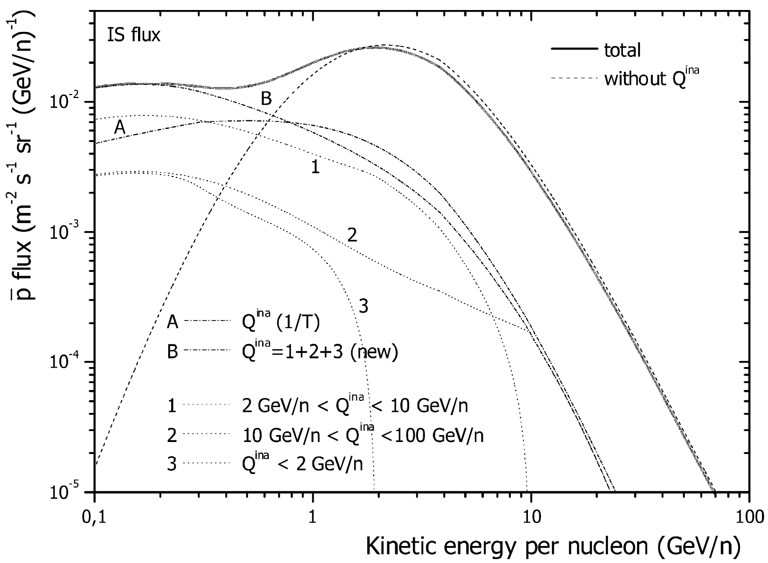
Also Fluka analysis in progress: Mazziotta+ 1508.00201
Many secondary nuclei, emphasis on gamma rays

The antiproton sources

$$Q^{\rm sec}(T_{\bar p}) = 2 \sum_{\rm i=CRs}^{\rm p,He,CNO} \sum_{\rm j=ISM}^{\rm H,He,CNO} 4\pi n_j \int_{6m_p}^{\infty} \frac{d\sigma^{\rm i+j}}{dT_{\bar p}} \times (T_{\bar p}, T_i)\Phi_i(T_i)dT_i,$$

$$Q^{\rm ter}(T_{\bar p}) = 4\pi . n_p \Big[2 \int_{T_{\bar p}}^{\infty} \frac{d\sigma^{\bar p p \to \bar p X}}{dT_{\bar p}} (T'_{\bar p}, T_{\bar p}) \Phi_{\bar p}(T'_{\bar p}) dT'_{\bar p} - 2\sigma_{\rm NAR}^{\bar p p \to \bar p X}(T_{\bar p})\Phi_{\bar p}(T_{\bar p}) \Big],$$

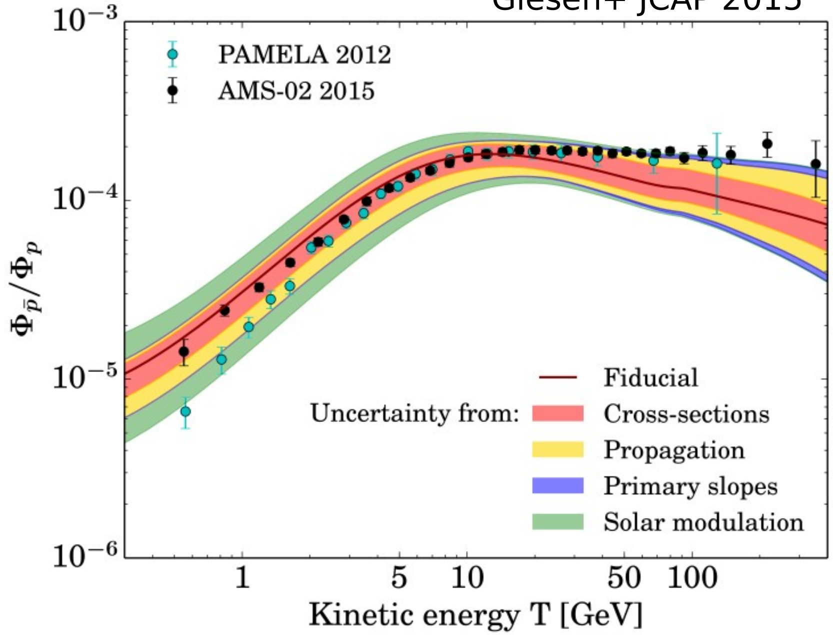




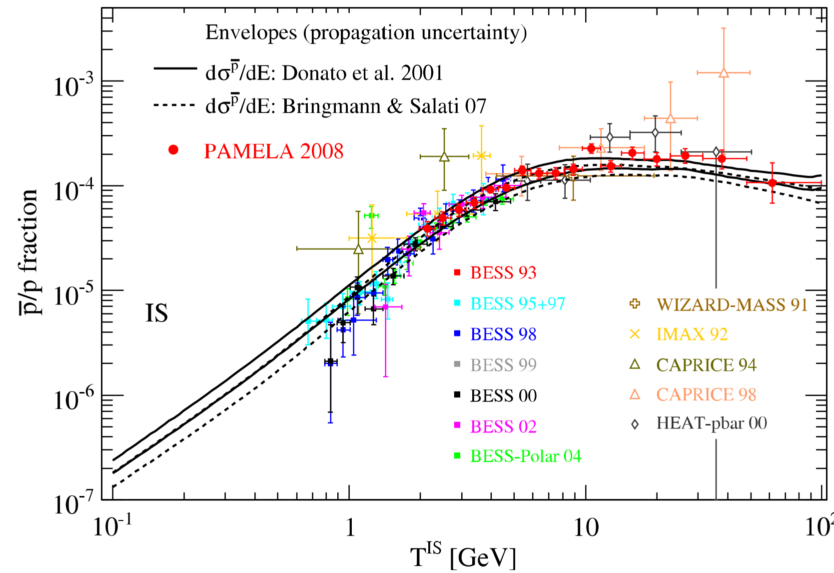
Duperray et al. PRD 2005

Antiprotons on wide energy range

Giesen+ JCAP 2015



Donato+ PRL 2009



Data do not force exotic (Dark Matter) interpretations

Interactions of CRs with the ISM explain observed speactra

Most relevant theoretical uncertainty is due to pbar production CROSS SECTIONS

Positrons

Sources of e^+ & e^- in the Milky Way

1. Secondary e^+ e^-: spallation of cosmic p and He on the ISM (H, He)

2. Primary e^- and e^+ from Pulsars (PSR, PWN):
   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): relic WIMPs annihilate in the galactic dark halo)

Sources	e^-	e^+	Energy Spectrum
Cosmic ray spallation on ISM	✓	✓	$q_{e^\pm}(\vec{x}, E_e) = 4\pi n_{ISM}(\vec{x}) \int dE_{CR}\, \Phi_{CR}(\vec{x}, E_{CR}) \frac{d\sigma}{dE_e}(E_{CR}, E_e)$
Supernova Remnants	✓	-	$Q(E) = Q_{0,SNRs} \left(\frac{E}{E_0}\right)^{-\gamma_{SNRs}} \exp\left(-\frac{E}{E_{c,SNRs}}\right)$
Pulsars	✓	✓	$Q(E) = Q_{0,PSR} \left(\frac{E}{E_0}\right)^{-\gamma_{PSR}} \exp\left(-\frac{E}{E_{c,PSR}}\right)$
Dark Matter	✓	✓	$Q_{ann}(\vec{x}, E) = \frac{1}{2}\left(\frac{\rho(\vec{x})}{m_{DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN^f_{e^\pm}}{dE}$

Positrons in CRs
Secondary component

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

And all reactions involving He.

Data available for pH, Monte Carlos or rescalings for the other reactions

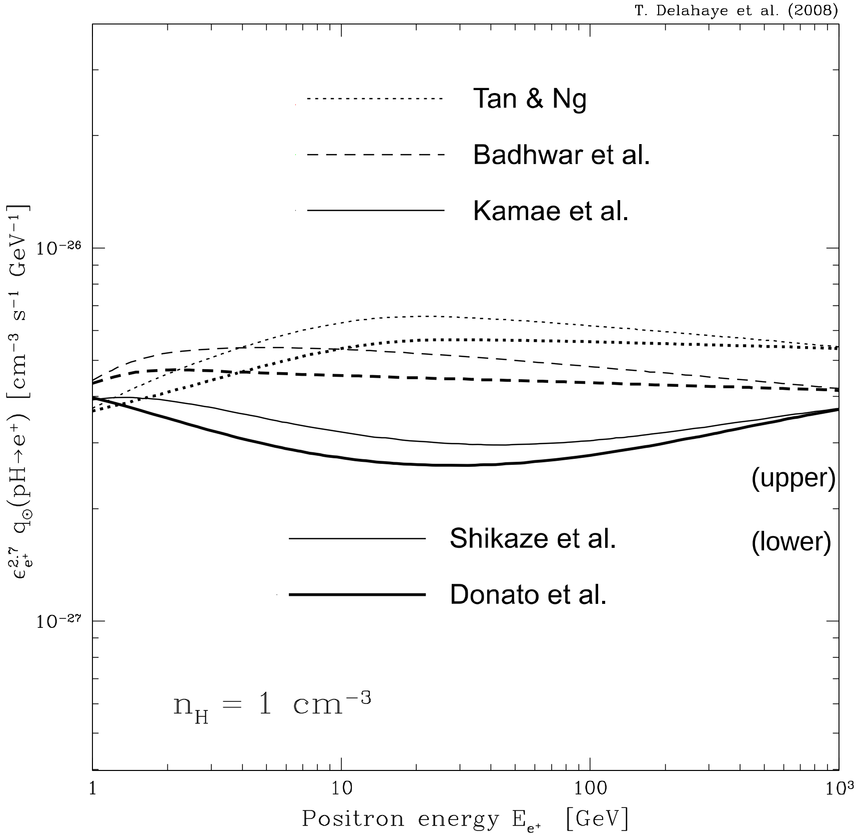
Diffusive semi-analytical model may be employed.

Above few GeV: only spatial diffusion and energy losses

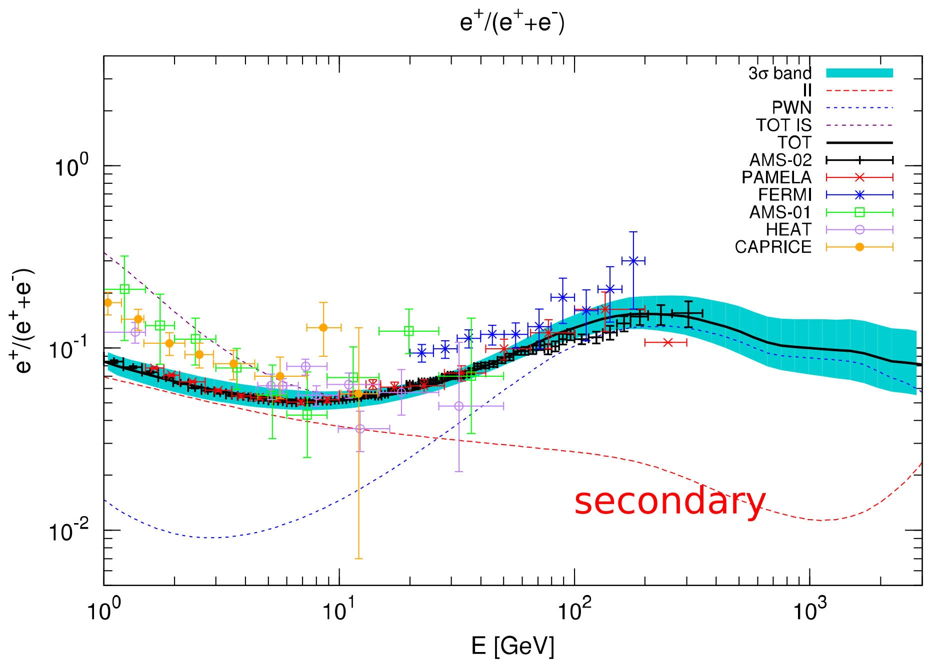
At higher energies: only energy losses

The positron source term

Uncertainties on the production cross sections up to factor 2



Secondary positrons relevant for E < 50 GeV

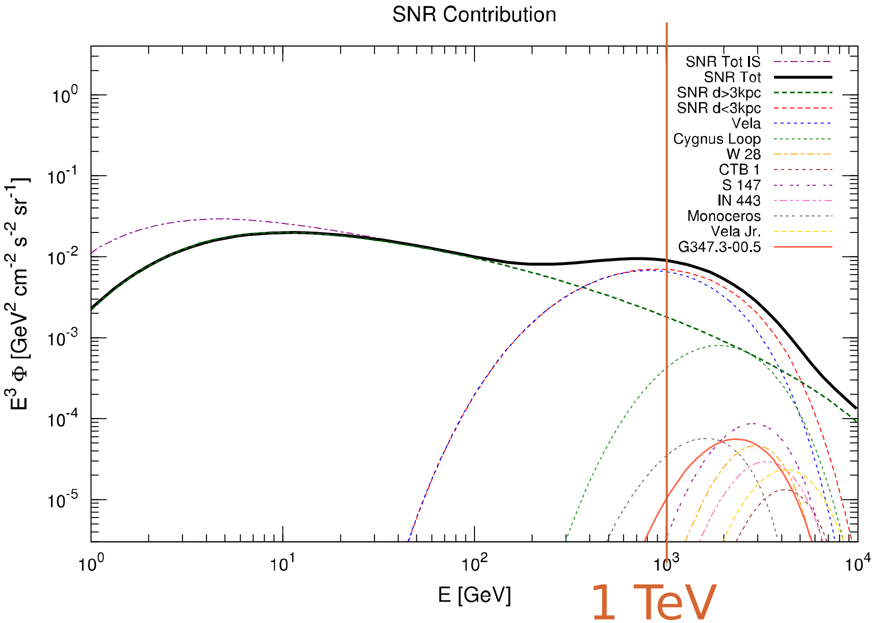


Data needed for p+p and p+He → e^+ + X

Sources of e+ and e-

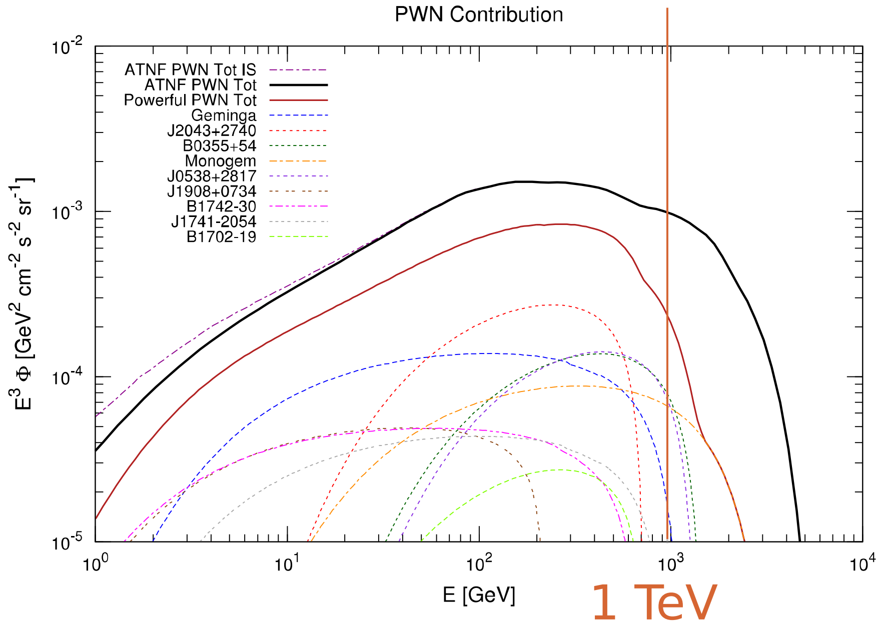
Di Mauro, FD, Fornengo, Vittino JCAP 2014

Electrons



Supernova remnants

Positrons



Pulsars

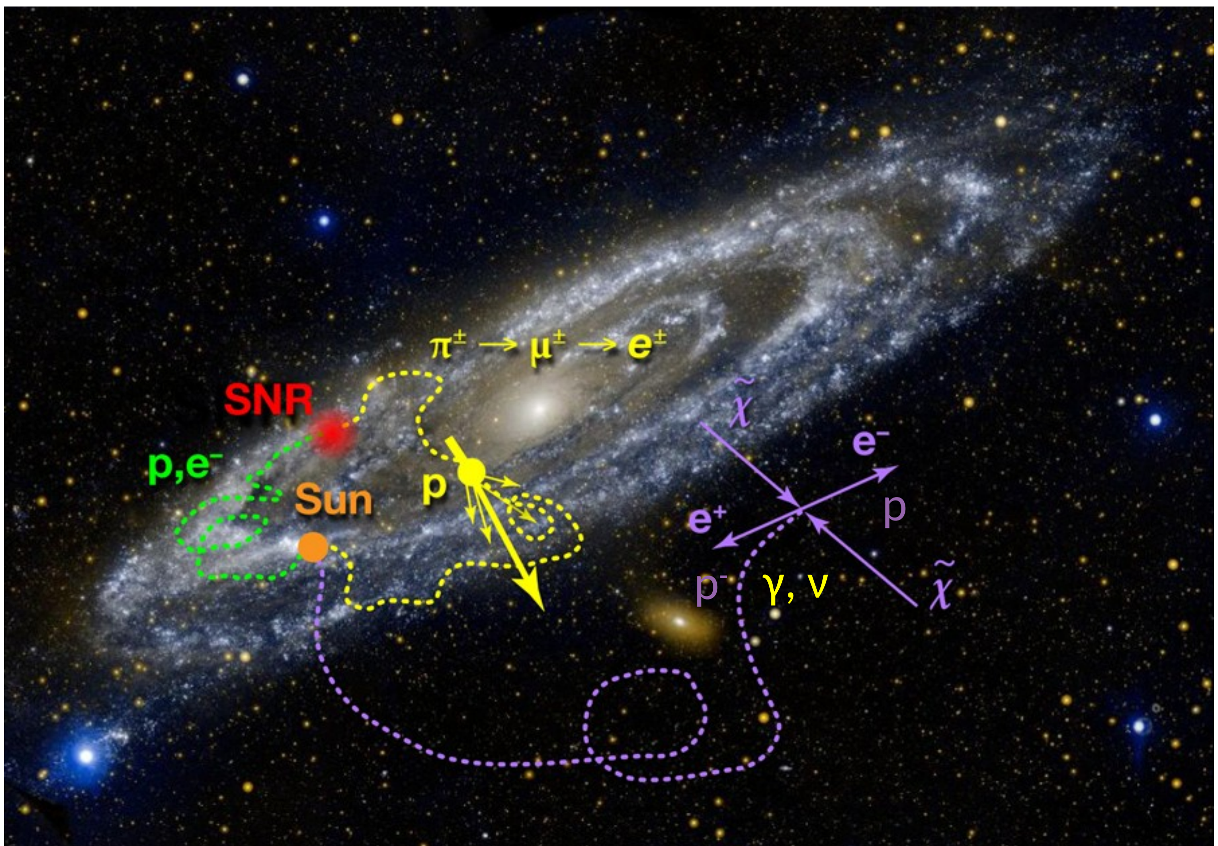
These SNR and PWN sources taken from the radio **ATNF** catalog

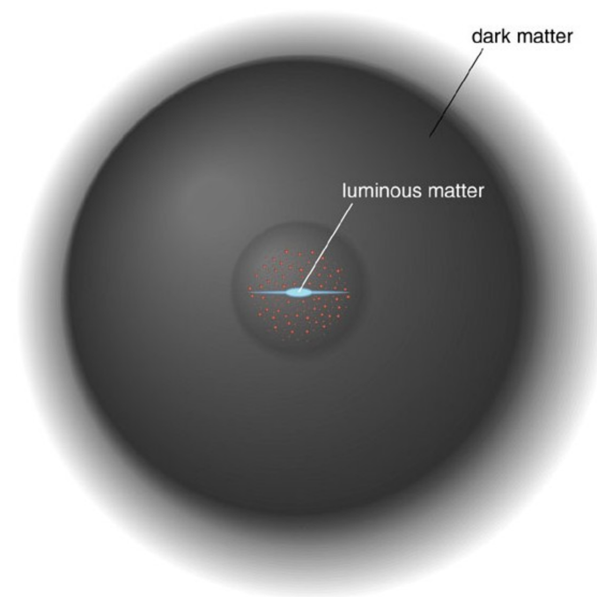
Dark matter in the cosmic radiation

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

See F. Calore's Lectures

Annihilation

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

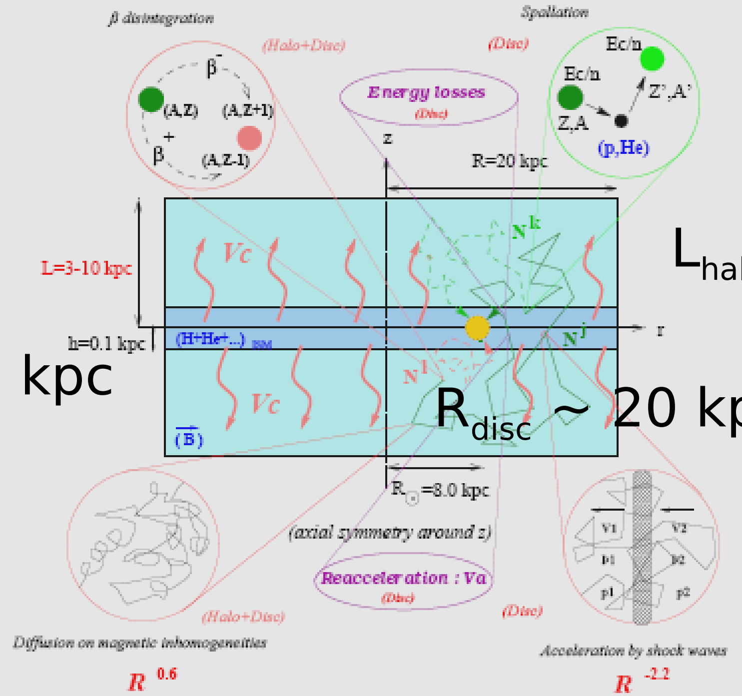
Decay

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

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

DM Sources are also

DM halo~ 200 kpc



L_{halo} ~4-10 kpc

h_{disc} ~ 0.2 kpc

R_{disc} ~ 20 kpc

in the diffusive halo

Elementary Methodology for DM indirect detection with charged CRs

- Identify DM sources – A particle physics problem
  (see G. Gelmini and F. Calore’s lectures)
- Locate sources in the DM halo – A cosmology problem
  (see M. Vogelsberger’s lectures)
- Propagate the sources in the diffusive halo – An astrophysics problem
- **Compute very carefully all the possible backgrounds**
- Derive upper bounds on DM properties, typically annihilation cross section
- Or discover DM through a peculiar (IF ANY) signatures

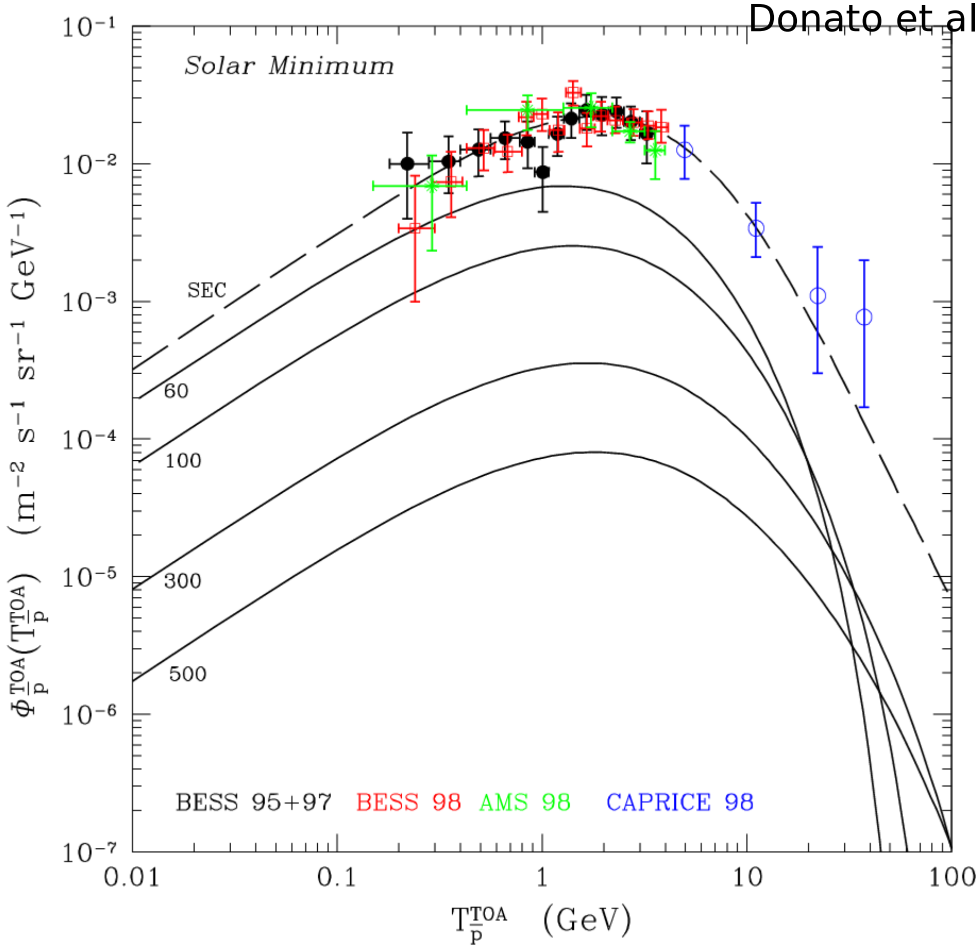
PRIMARY and SECONDARY ANTIPROTONS

Donato et al. PRD 2004

- - - Secondaries
(CRs on the ISM)

____ Primaries
(Dark Matter)

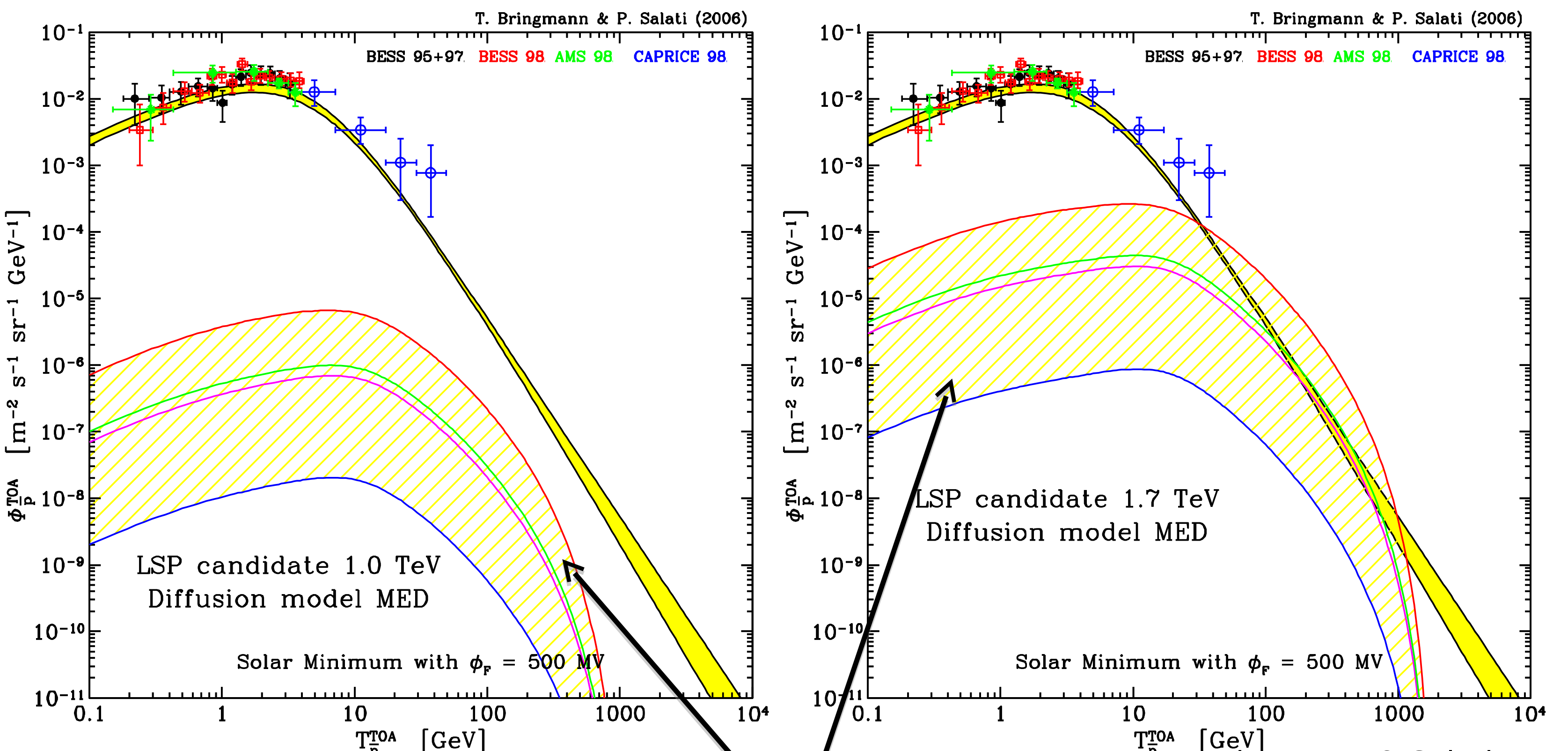
m_χ=60-100-300-500 GeV



At low energies, primary and secondary antiproton fluxes have **indistinguishable** shapes

Antiprotons: secondary vs Dark Matter component

Uncertainties due to propagation in the Galaxy

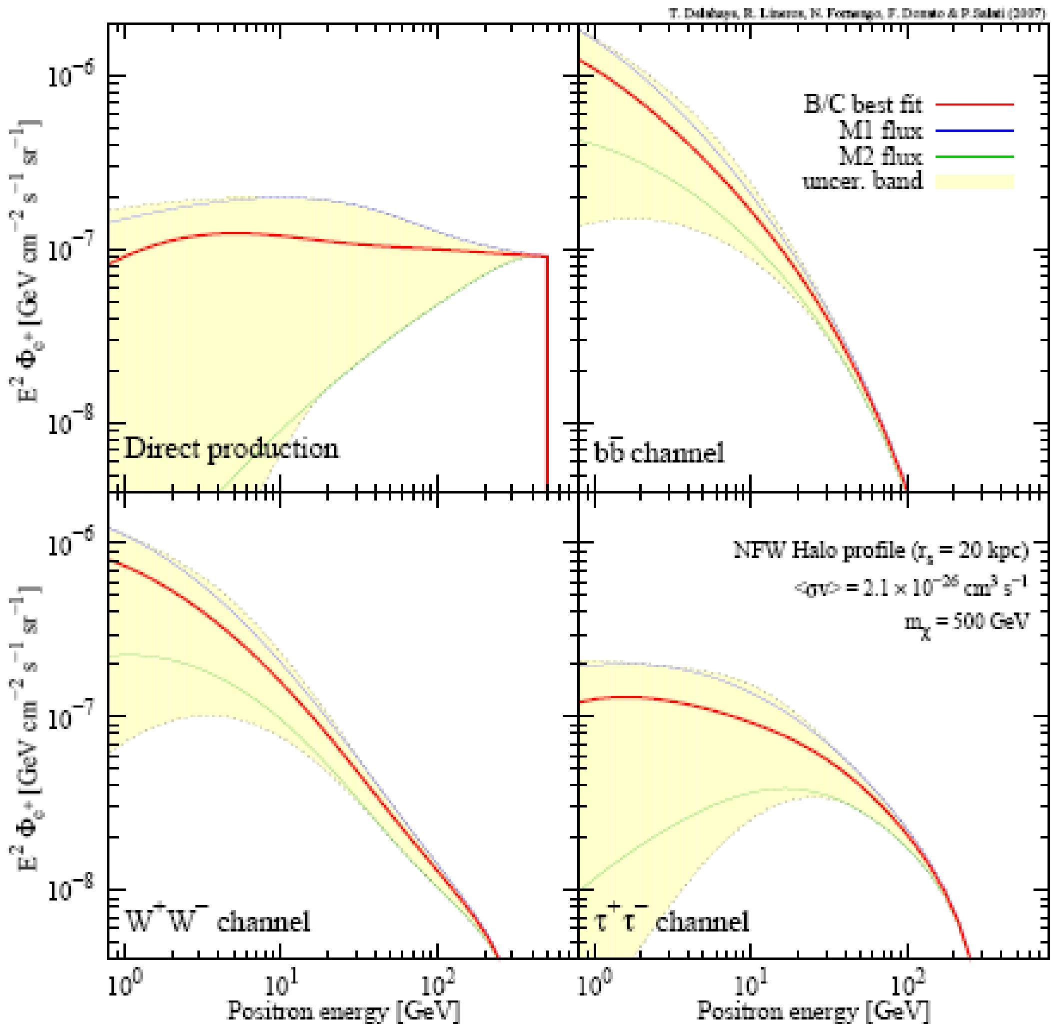


Bringmann & Salati, PRD 2007

Dark matter

Positron fluxes: effect of annihilation channels

Delahaye et al. PRD 2008



m_{DM}=500 GeV

Direct annnihilation in e+, or in tau, are **harder** than bb or gauge boson

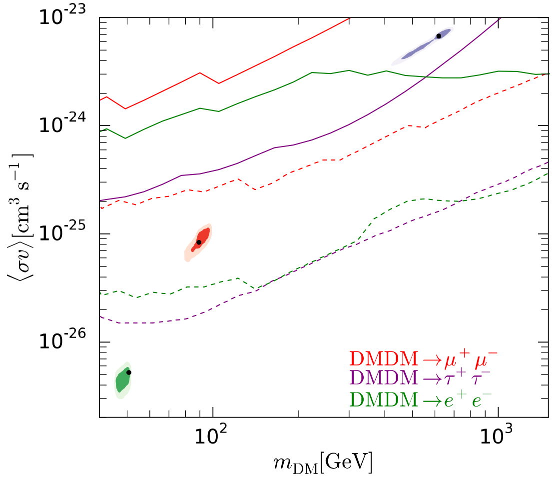
In typical SUSY models annihilation in leptons is helicity **suppressed** wrt quark production

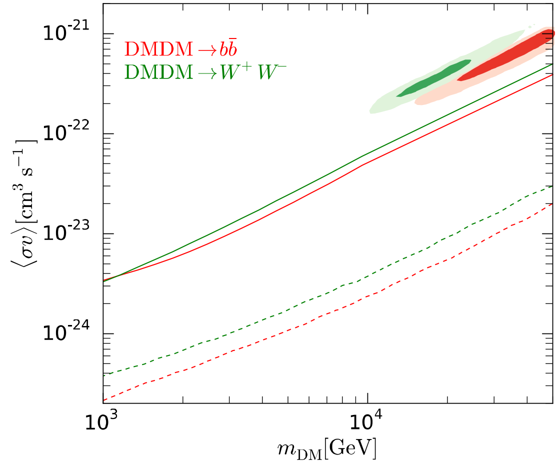
Uncertainties on primaries is
3-5, depending on:

- Energy
- Annihilation channel
- DM distribution

Searching for a DM signal

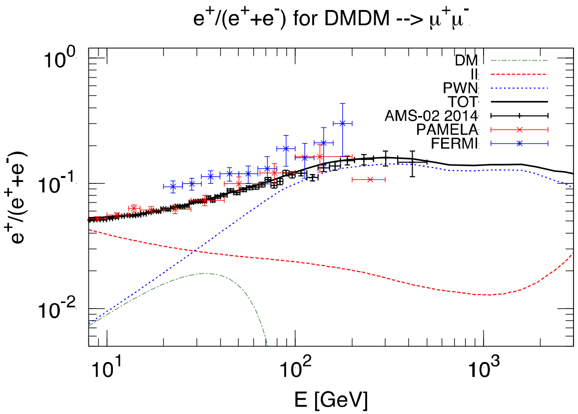
Di Mauro, FD, Fornengo, Vittino 2016

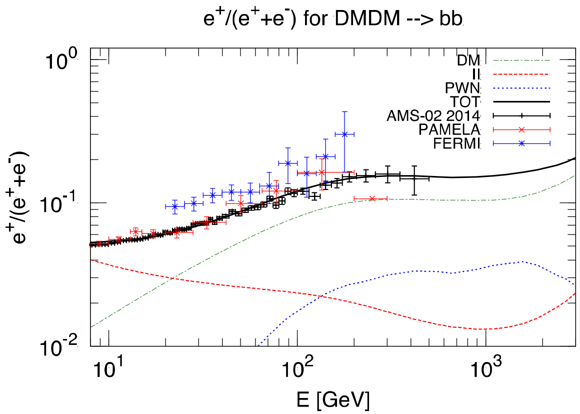




Upper bounds are from Fermi-LAT gamma ray data at latitudes > 20

(Di Mauro&FD PRD2015)





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

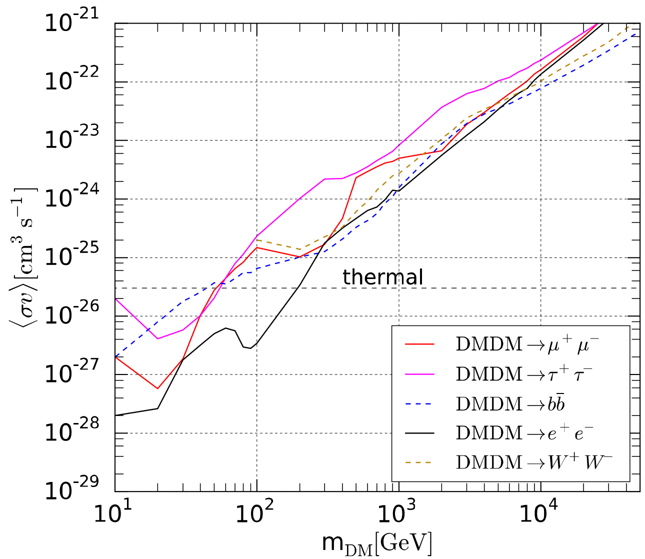
When also m_{DM} is let free to vary, the fit with **DM improves** w.r.t the scenario with astrophysical contributions only.

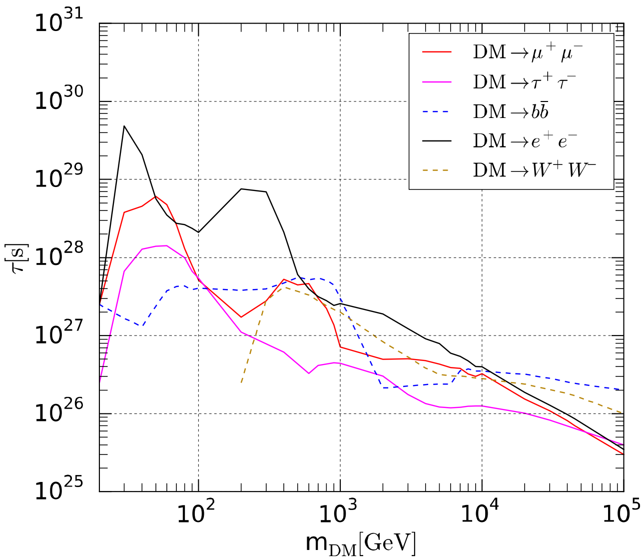
Leptonic (hadronic) annihilation channels are compatible (in tension) with upper bounds from DM searches in high latitude Fermi-LAT gamma rays

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

ANTIDEUTERONS from RELIC WIMPS

FD, Fornengo, Salati PRD 62 (2000)043003

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 annihilates almost at rest

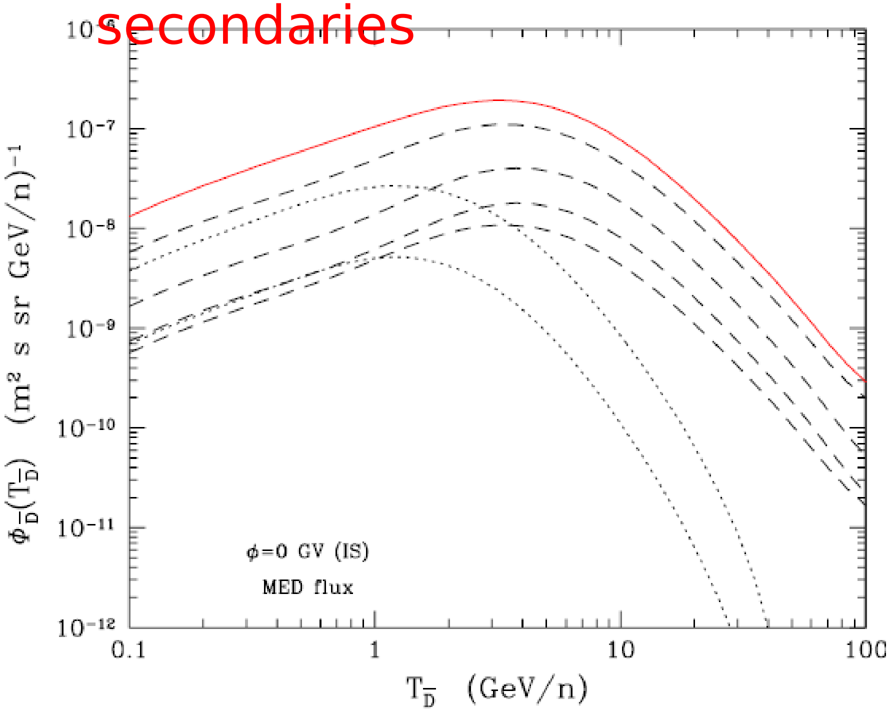
$$\frac{dN_{\bar{D}}}{dE_{\bar{D}}} = \left(\frac{4\,P_{\rm coal}{}^3}{3\,k_{\bar{D}}}\right)\left(\frac{m_{\bar{D}}}{m_{\bar{p}}\,m_{\bar{n}}}\right)\sum_{\rm F,h} B_{\chi \rm h}^{(\rm F)} \left\{\frac{dN_{\bar{p}}^{\rm h}}{dE_{\bar{p}}}\left(E_{\bar{p}} = \frac{E_{\bar{D}}}{2}\right)\right\}^2$$

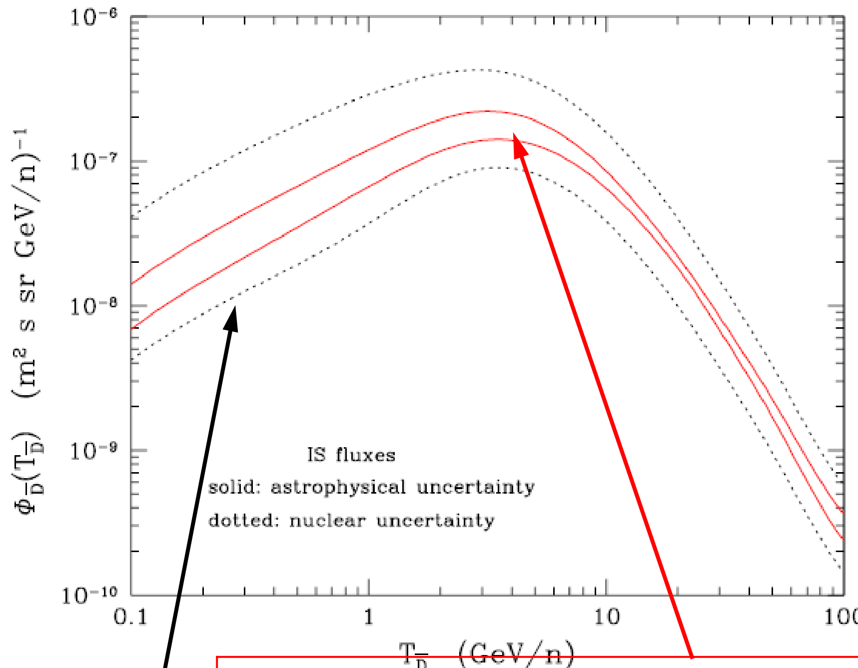
Up to now, NO ANTIDEUTERON has been detected yet.

Secondary antideuterons

FD, Fornengo, Maurin PRD 2008

Contributions to secondaries





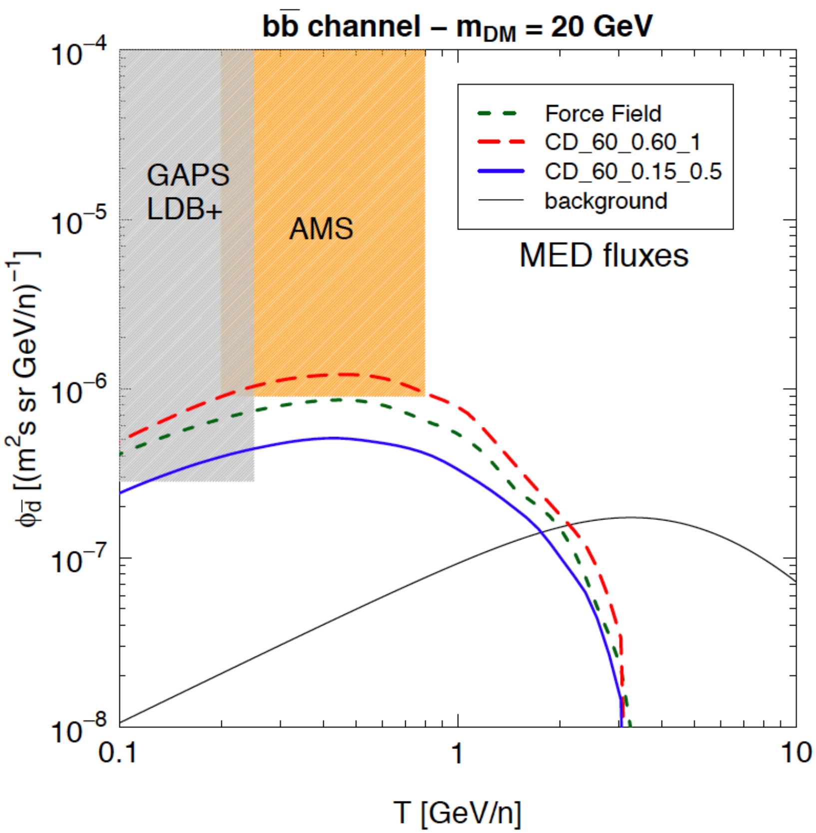
p-p, p-He,
He-H, He-He
H- pbar, He-pbar

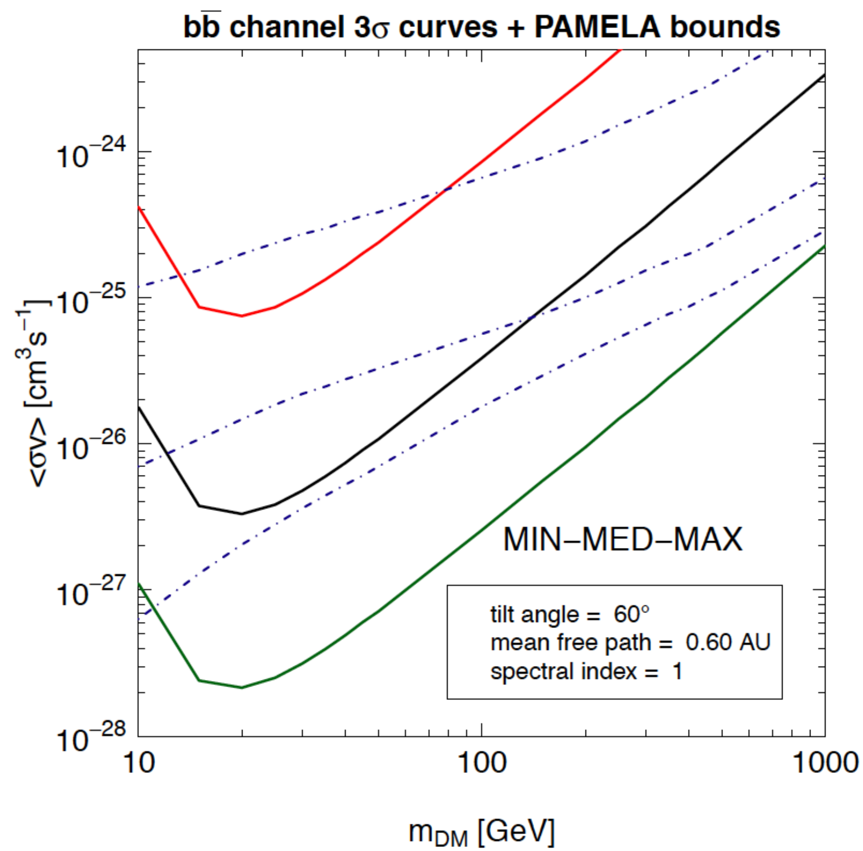
Propagation uncertainties
Compatibility with B/C

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

Antideuterons:
Dark matter detection perspectives

Fornengo, Maccione, Vittino JCAP 2013 (1306.4171)





3σ expected sensitivities

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

Some references

- Malcom Longair: High energy astrophysics
- Berezinskii et al: Astrophysics of Cosmic rays
- Aa.Vv. Particle Dark Matter (Ed. G Bertone)
  → https://arxiv.org/abs/1003.4124
- Castellina, Donato: Astrophysics of Galactic charged cosmic rays, Springer 2012, https://arxiv.org/abs/1110.2981