Theory Uncertainties on Cosmic Rays Propagation

Implications for Dark Matter Searches

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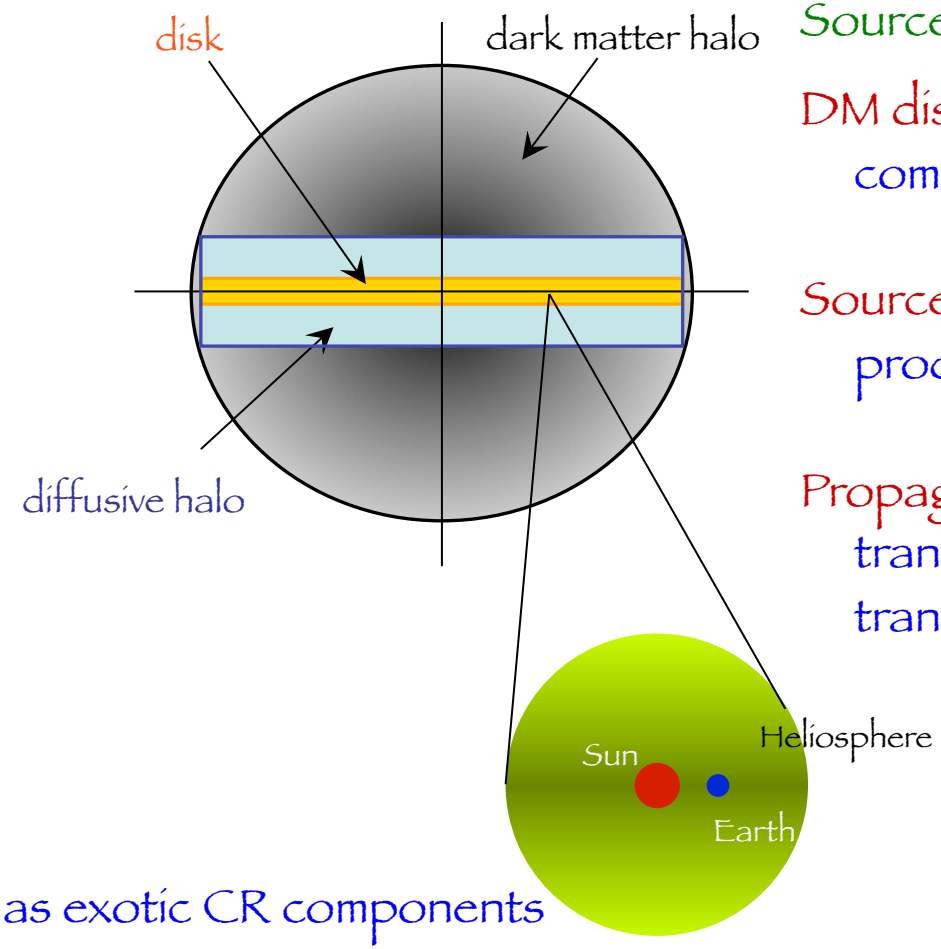
INFN Torino

Dark Matter Underground and in the Heavens – DMUH11

CERN – 25.07.2011

Galactic environment



Sources of uncertainties

DM distribution

combined effect with propagation

Source

production mechanism

Propagation

transport in the Galaxy

transport in the heliosphere (low T)

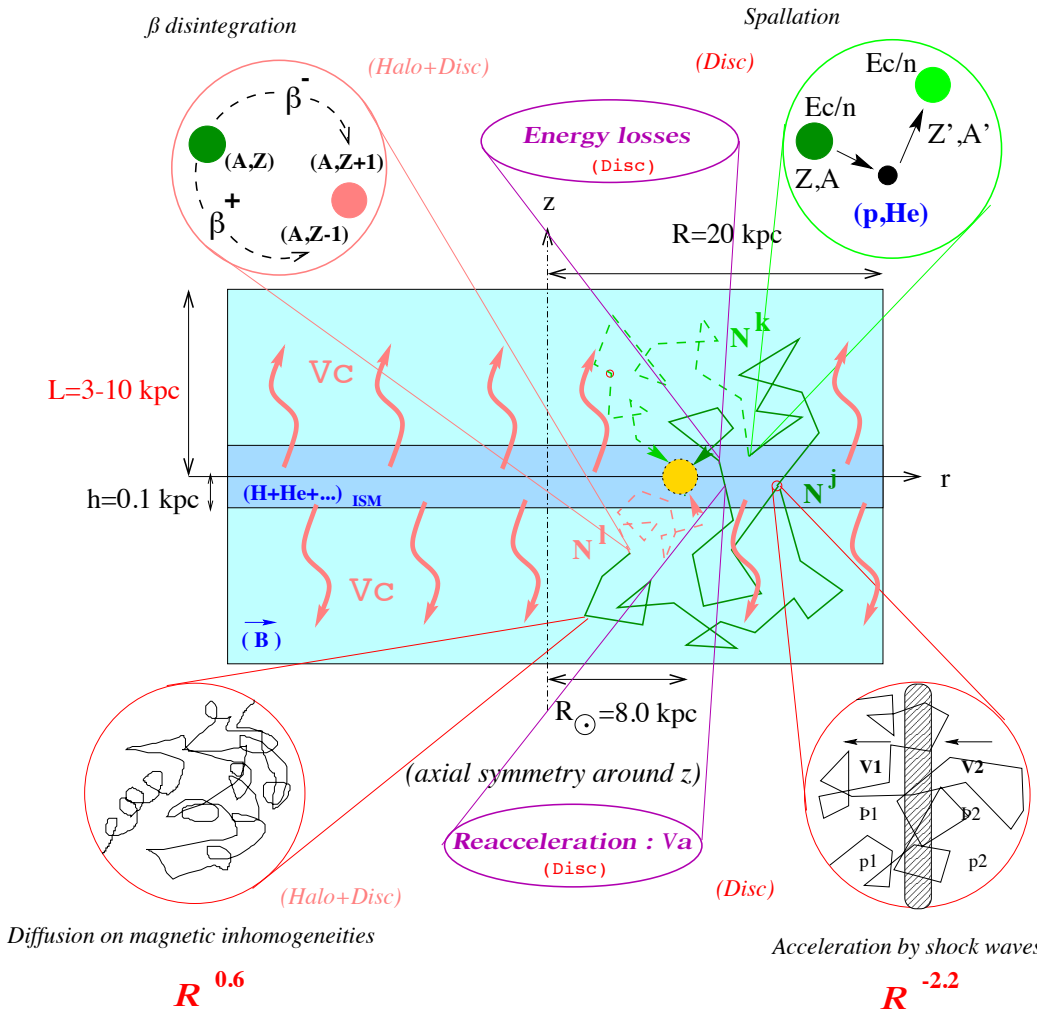
DM signals as exotic CR components

antiprotons

antideuterons

positrons/electrons

Galactic environment



Propagation equation

$$\psi = dn/dE$$

$$\boxed{\partial_z \left(V_C\, \psi\right) \;-\; K\, \Delta\psi \;+\; \partial_E \left\{ b^{\rm loss}(E)\, \psi \;-\; K_{EE}(E)\, \partial_E \psi \right\} \;=\; q\left(\mathbf{x}, E\right)}$$

convection diffusion energy losses reacceleration source term

Geometry: cylindrical diffusive halo (R, L) + thin disk (h)

Diffusion: uniform in the whole (disk + diffusive halo) volume $K(E) = K_0\, \beta\, (\mathcal{R}/1\ \mathrm{GV})^{\delta}$

Convection: galactic wind away from the disk in vertical direction V_c

Reacceleration on random hydrodynamic waves (in the disk only) $K_{EE} = \frac{2}{9}\, {V_a}^2\, \frac{E^2 \beta^4}{K(E)}$

Energy losses: interaction with the medium, dependent on the CR species

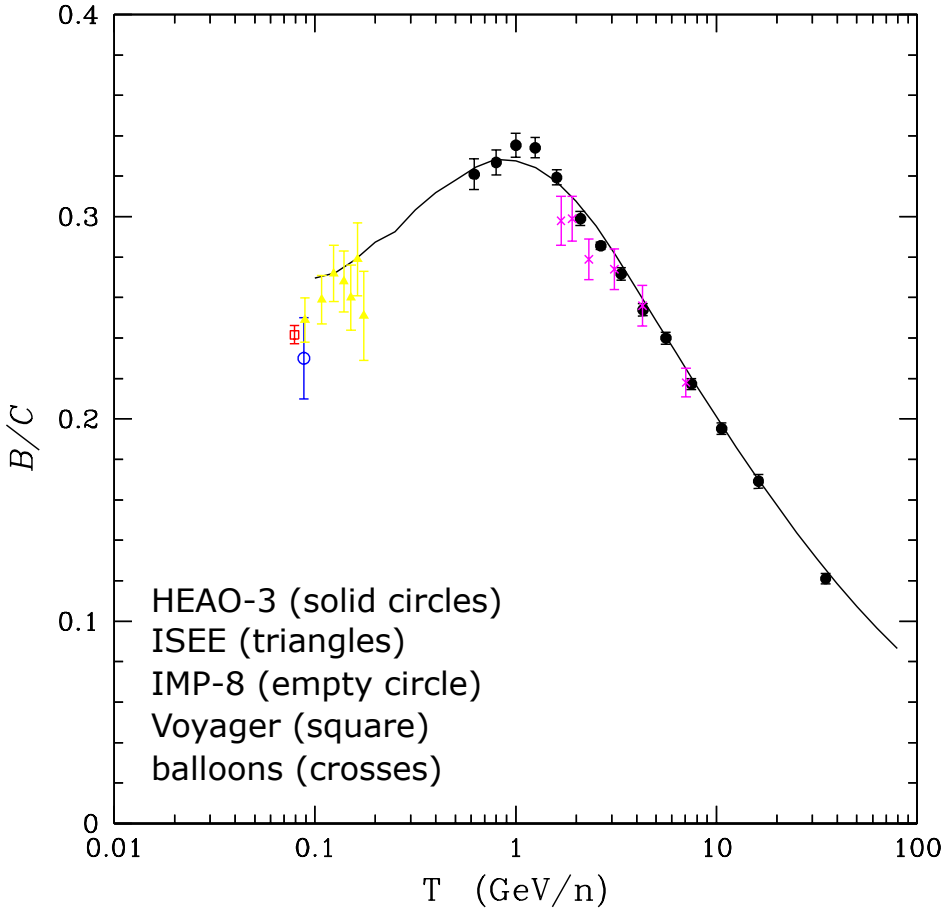
antip, antiD: ionization losses on neutral ISM
Coulomb losses on thermal electrons of ionized gas
adiabatic losses

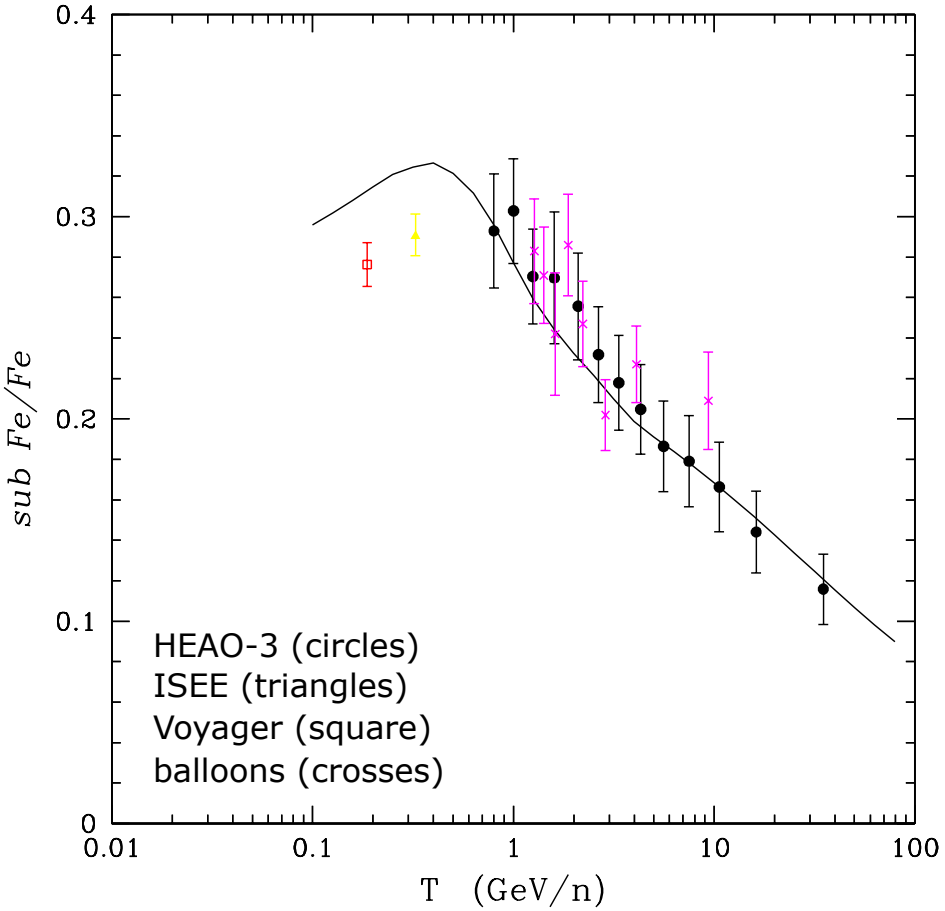
electrons/positrons: synchrotron on magnetic fields, inverse Compton on ISRF

Source/sink: production/destruction processes

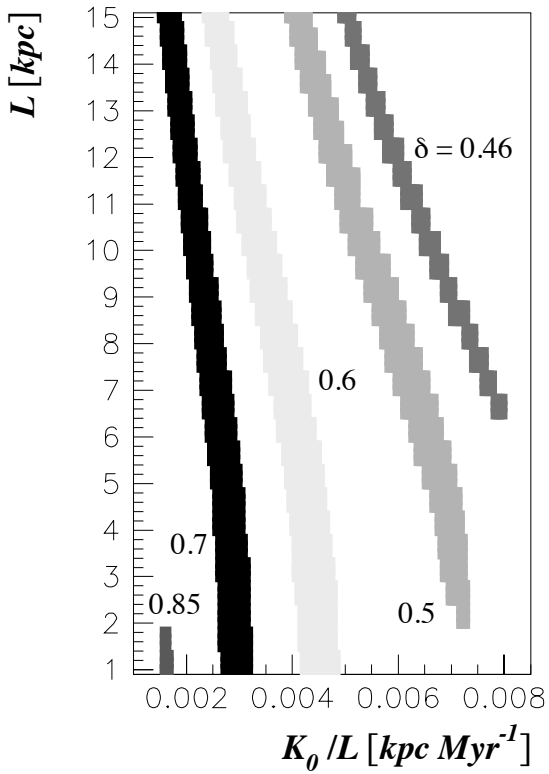
Bounds on the propagation model

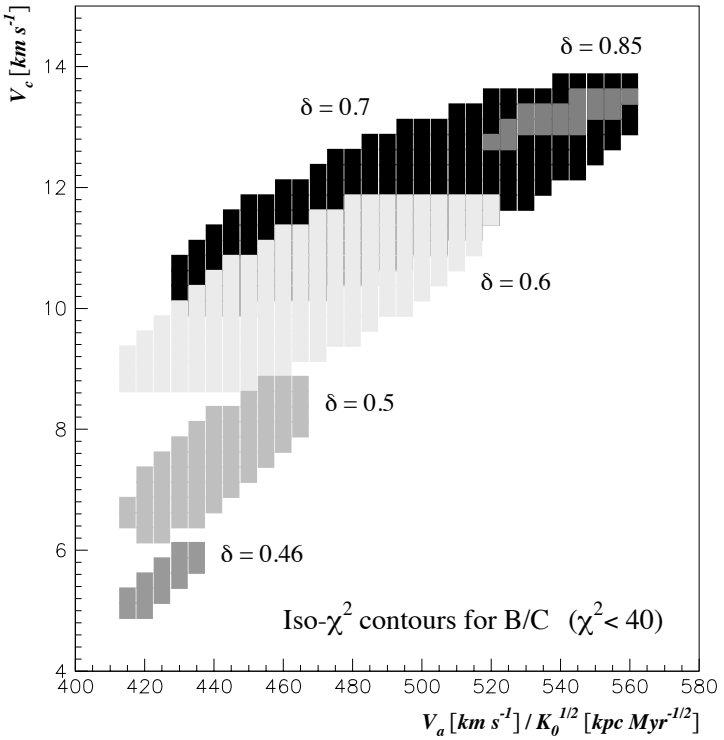
- Bounds are obtained by analyzing primary and secondary cosmic rays data within the specific propagation model
  - Secondary-to-primary ratio: average amount of matter traversed
  - Isotopic ratio of radioactive species: confinement time





D. Maurín, et al. , Astrophys.J.555:585-596,2001





D. Maurín, et al. , Astrophys.J.555:585-596,2001

Bounds on the propagation parameter

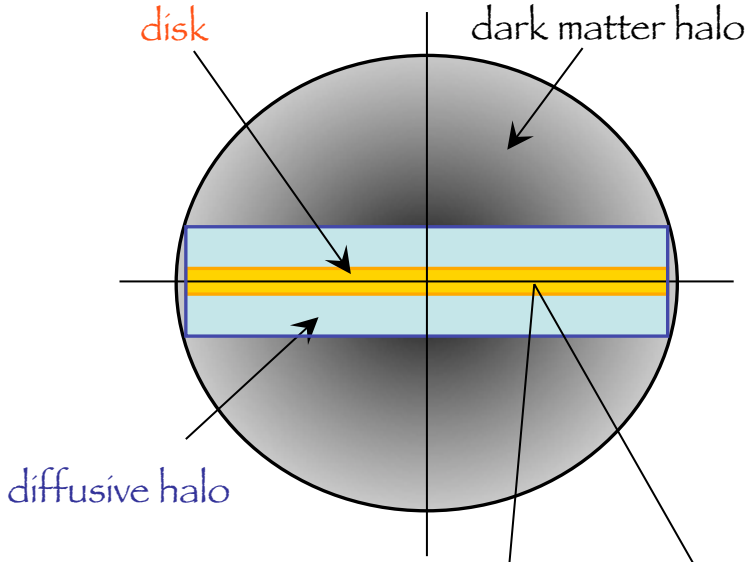
For the 2-zone diffusion model with cylindrical geometry

case	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/sec)	V_A (km/sec)	$\chi^2_{\rm B/C}$
max	0.46	0.0765	15	5	117.6	39.98
med	0.70	0.0112	4	12	52.9	25.68
min	0.85	0.0016	1	13.5	22.4	39.02

D. Maurin, et al. , Astrophys.J.555:585-596,2001

Antimatter in Cosmic Rays
Antiprotons

Antiproton signal



Secondaries

$$p_{\,\mathrm{CR}} + p_{\,\mathrm{ISM}} \longrightarrow \bar{p}$$
$$p_{\,\mathrm{CR}} + He_{\,\mathrm{ISM}} \longrightarrow \bar{p}$$
$$He_{\,\mathrm{CR}} + p_{\,\mathrm{ISM}} \longrightarrow \bar{p}$$

Produced in the disk

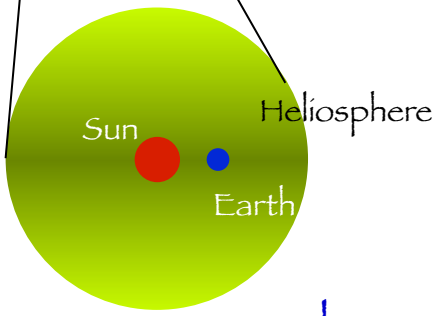
Propagation and energy redistribution in the diffusive halo

DM signal

$$\chi\chi \longrightarrow (\ldots) \longrightarrow p\bar{p}$$

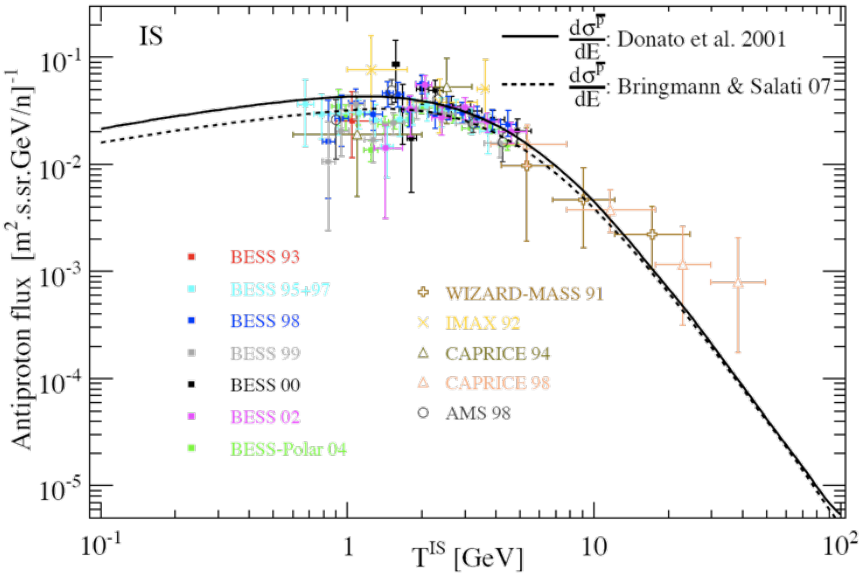
Produced in the DM halo

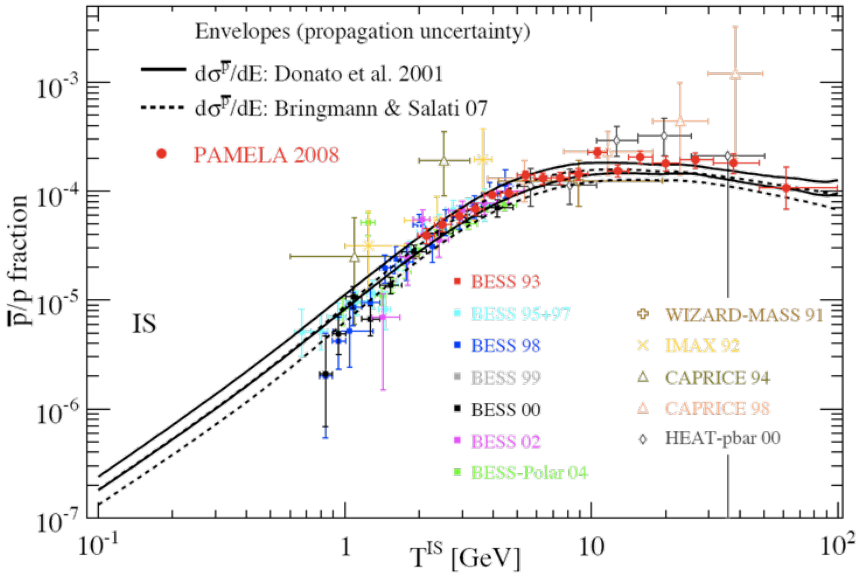
Propagation and energy redistribution in the diffusive halo



solar modulation

Secondary antiprotons



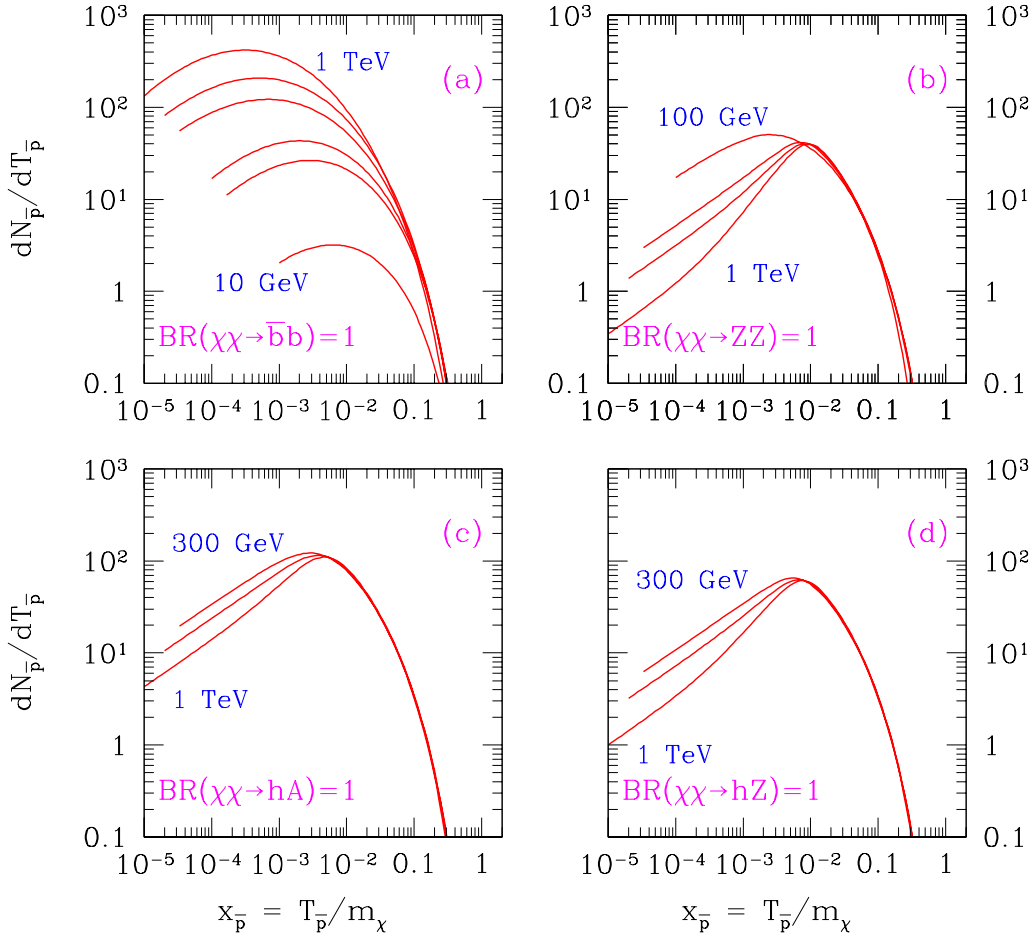


Antiproton flux

Antiproton/proton fraction

F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, arXiv.0810.5292 [astro-ph]

Source spectra from DM annihilation

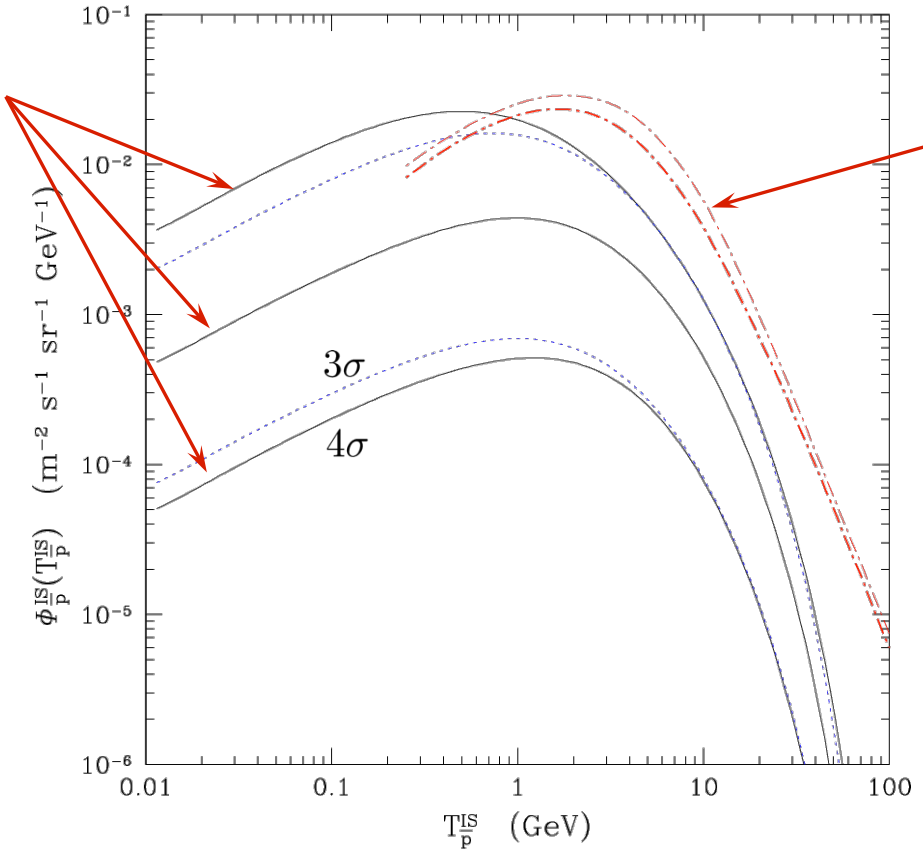


F. Donato, N. Fornengo, D. Maurín, P. Salati, R. Taillet, PRD 69 (2004) 0603501

Interstellar antiproton fluxes

Primaries (1)
(DM signal)

$m_\chi = 100$ GeV



Secondaries (2)
(background)

< 25% uncertainty

(1) F. Donato, N. Fornengo, D. Maurin, P. Salati, R. Taillet, PRD 69 (2004) 0603501

(2) D. Maurin et al. Astron. Astrophys. 381 (2002) 539

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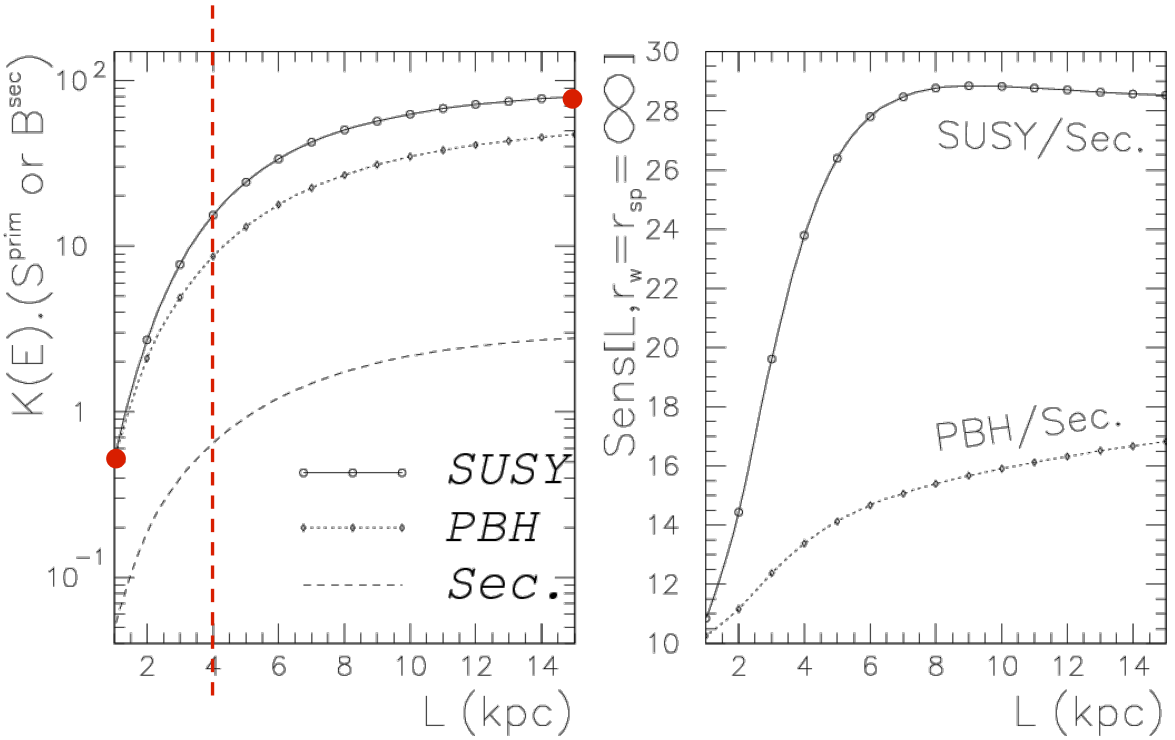
Dependence on height of diffusive halo

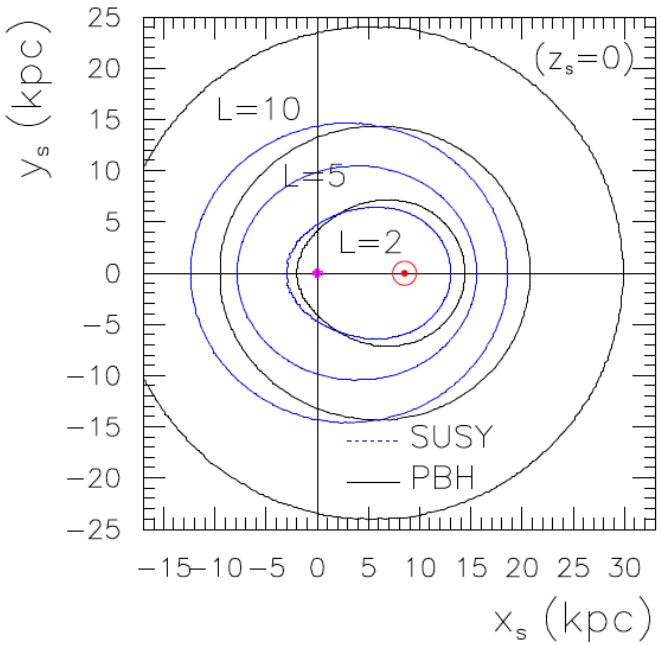


- L determines the extension of the confinement region:
  - For small L, only the sources very close to the solar neighborhood can contribute
  - As L increases, confinement is more efficient and more sources contribute

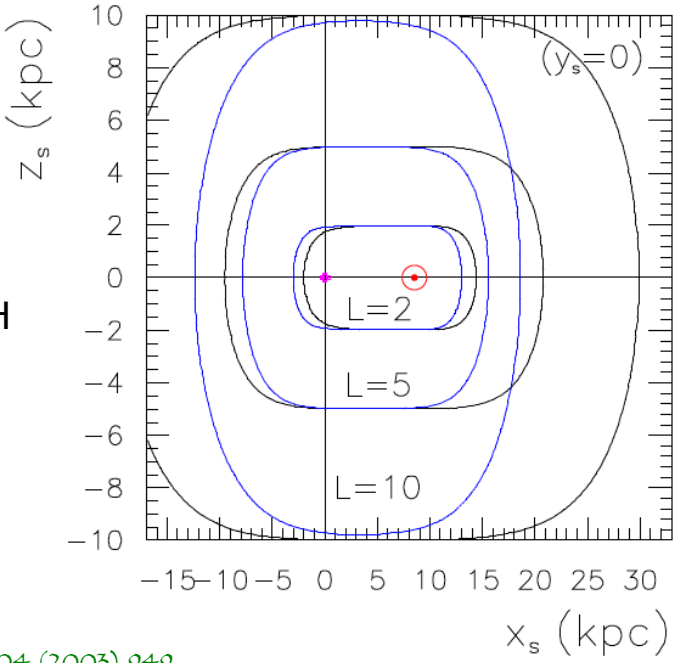
F. Donato, N.Fornengo, D. Maurin, P. Salati, R. Taillet, PRD 69 (2003) 063501

Spatial origin of the antiproton signal

Effective volumes



Blue: DM
Black: PBH



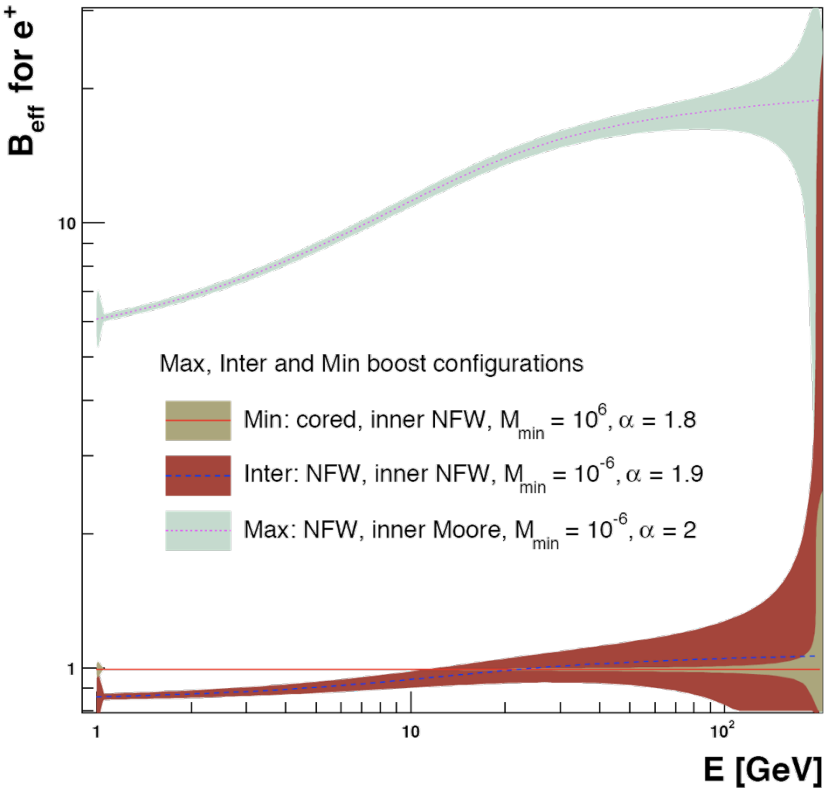
D. Maurín and R. Taillet, AA 404 (2003) 949

Effect of changing DM profile on antiproton flux at Earth

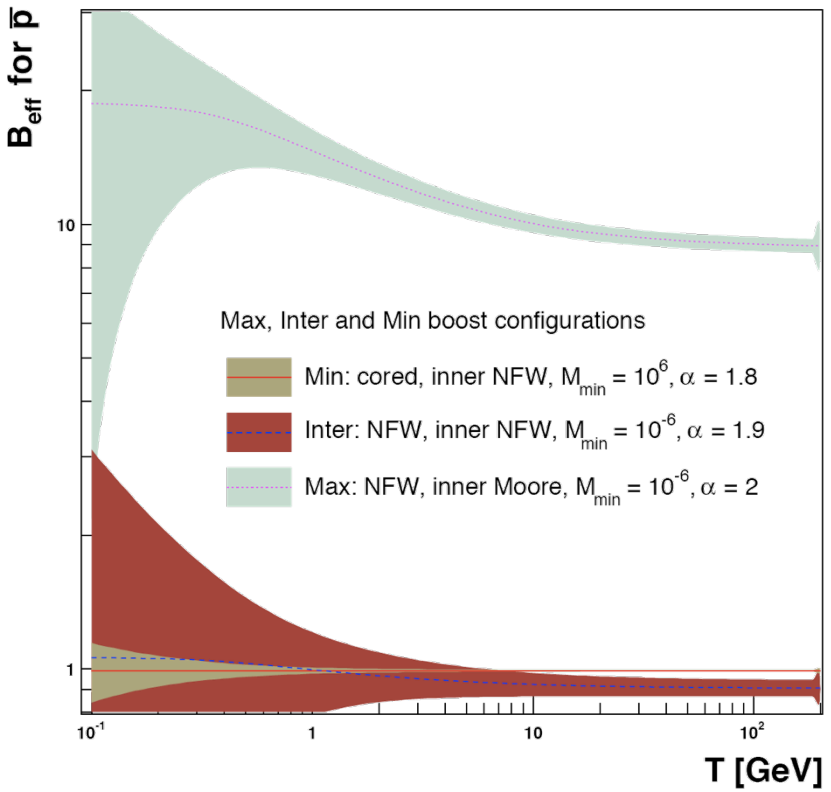
$L(\mathrm{kpc}), r_\mathrm{w}, r_\mathrm{sp}$	$\frac{S^{\mathrm{prim}}_{a=2.5}-S^{\mathrm{prim}}_{\mathrm{ref}}}{S^{\mathrm{prim}}_{\mathrm{ref}}}$	$\frac{S^{\mathrm{prim}}_{a=5}-S^{\mathrm{prim}}_{\mathrm{ref}}}{S^{\mathrm{prim}}_{\mathrm{ref}}}$	$\frac{S^{\mathrm{prim}}_{\mathrm{NFW}}-S^{\mathrm{prim}}_{\mathrm{ref}}}{S^{\mathrm{prim}}_{\mathrm{ref}}}$
15, 28.66, 25.54	−69.5%	+23.9%	+19%
4, 2.38, 4.41	−21.5%	+9.9%	~0%
1, 0.33, 0.69	<1%	<0.2%	~0%

F. Donato, et al., PRD 69 (2003) 063501

Substructures



Positrons

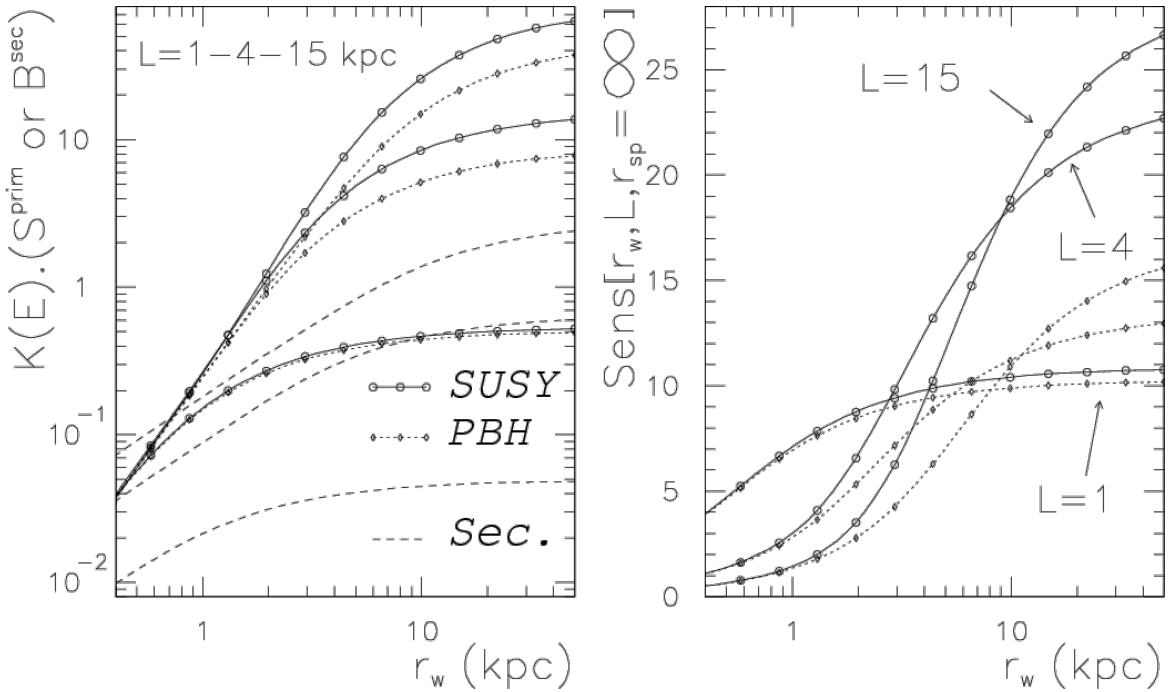


Antiprotons

J. Lavalle, Q. Yuan, D. Maurin, X.J. Bi, A&A 479 (2008) 427

Dependence on galactic wind velocity

$$r_w \equiv \frac{2K(E)}{V_c}$$

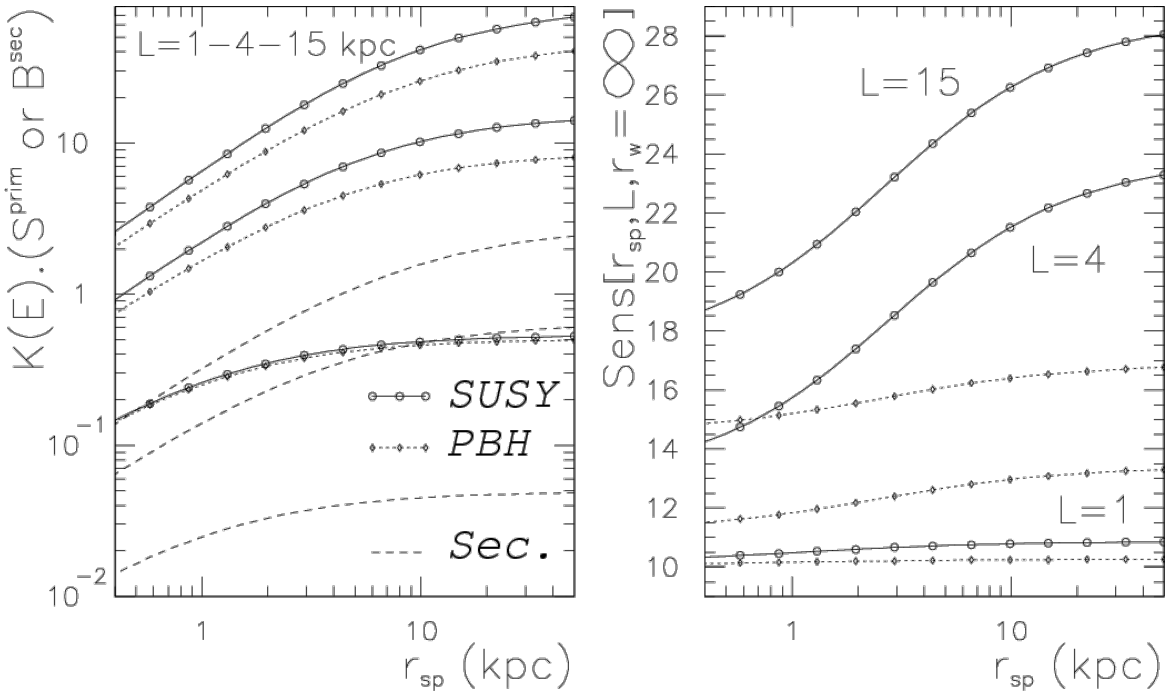


- The galactic wind blows the particles away from the disk (convection), leading to an effective size of the diffusive halo of the order of r_w
- There is a competition between L and r_w:
  - For large L, the evolution is driven by r_w
  - For small r_w all curves converge, independently of L, because the CR are convected away before being able to reach the boundaries of the diffusion region

F. Donato, N.Fornengo, D. Maurin, P. Salati, R. Taillet, PRD 69 (2003) 063501

Dependence on rate of spallation

$$r_{\rm sp} \equiv \frac{K(E)}{h\Gamma_{\rm inel}(E)}$$



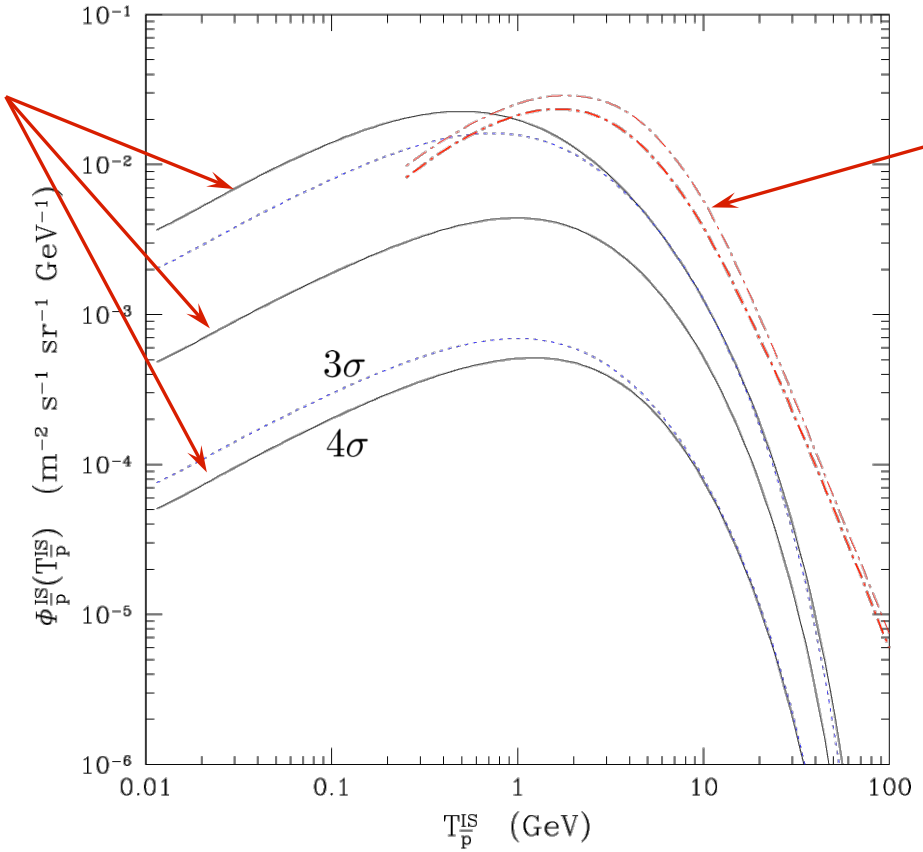
- At low energies particles are destroyed more easily, since the probability to cross the disk (and therefore to interact with matter) increases relatively to escape (diffusive or convective)
- There is a competition between L , r_W and r_{SP}:
  - The effect of r_{SP} is milder: the cut-off due to spallation is less efficient than diffusion or convection to prevent particles coming from faraway from reaching us

F. Donato, N.Fornengo, D. Maurin, P. Salati, R. Taillet, PRD 69 (2003) 063501

Interstellar antiproton fluxes

Primaries
(DM signal)

$m_\chi = 100$ GeV



Secondaries
(background)

< 25% uncertainty

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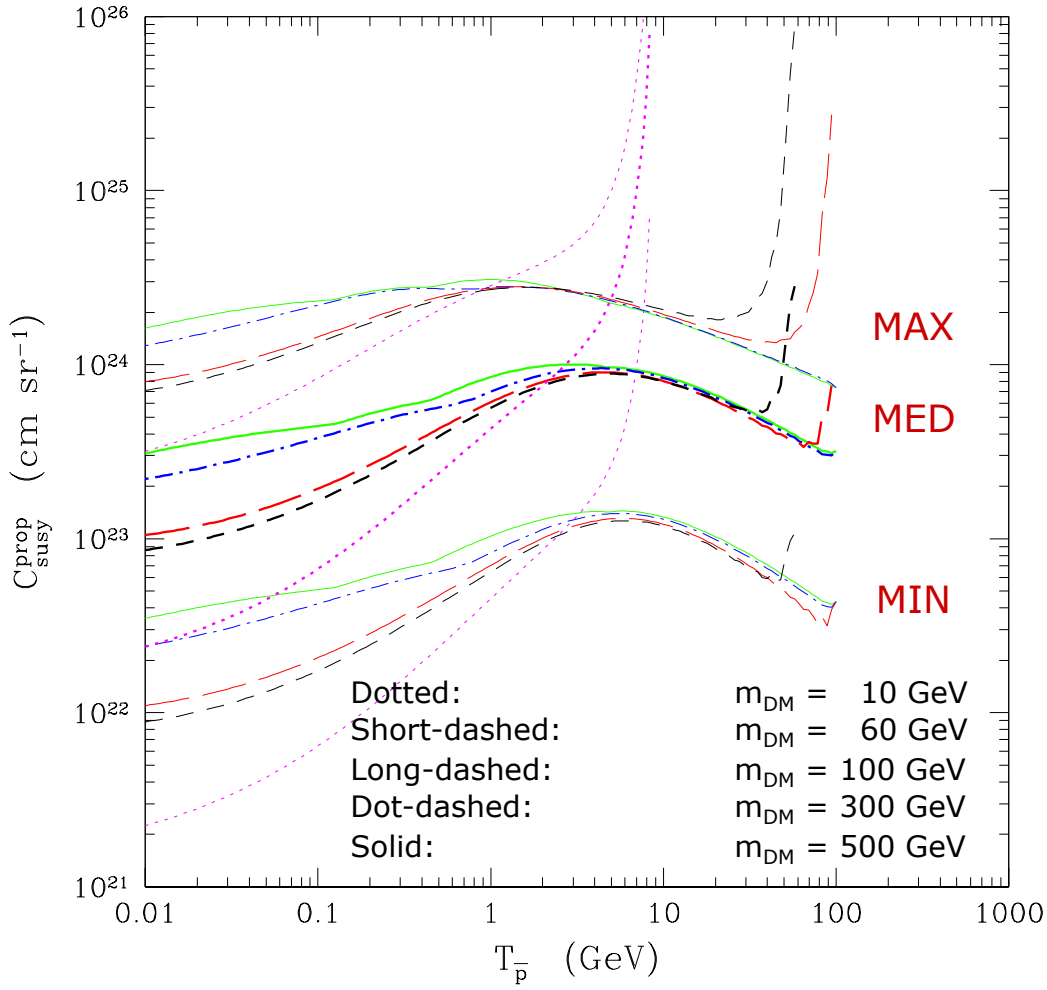
Effect of propagation

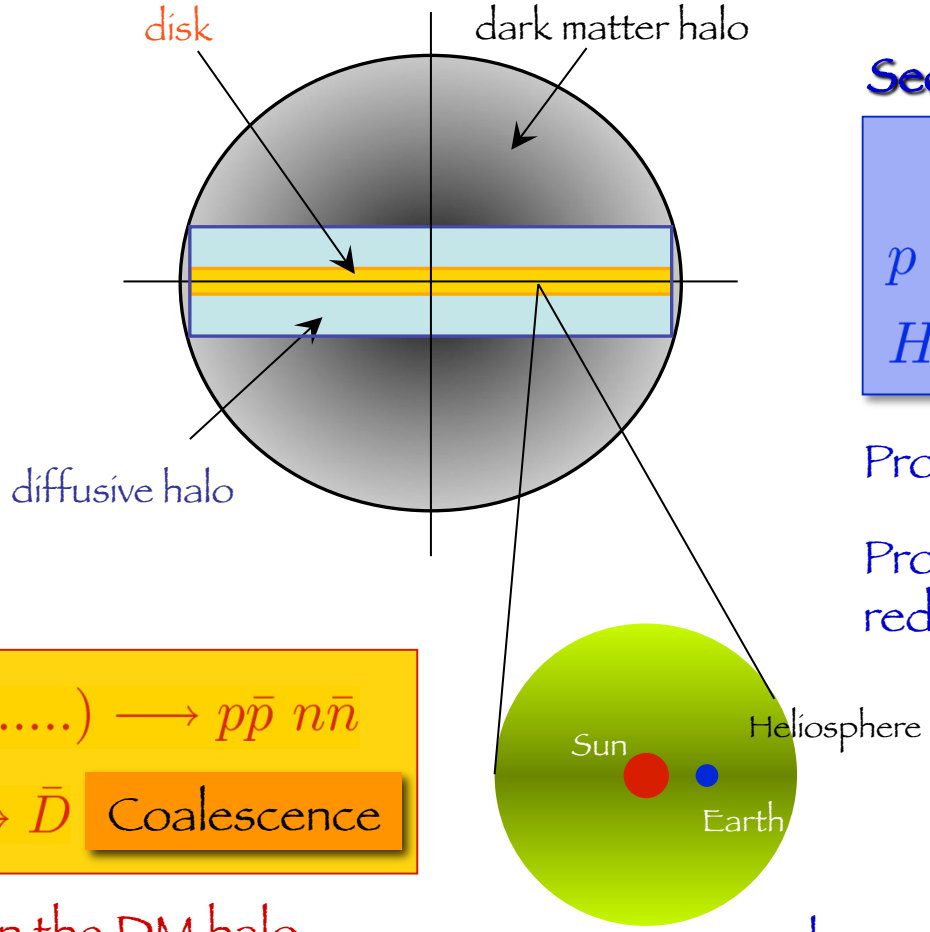
$$C^{prop} \approx \frac{\text{TOA flux}}{\text{source spectrum}}$$



Antimatter in Cosmic Rays
Antideuterons

Cosmic antideuterons

F. Donato, N. Fornengo, P. Salati, PRD 62 (2000) 043003



Secondaries

$$p_{\,\mathrm{CR}} + p_{\,\mathrm{ISM}} \longrightarrow \bar{D}$$
$$p_{\,\mathrm{CR}} + He_{\,\mathrm{ISM}} \longrightarrow \bar{D}$$
$$He_{\,\mathrm{CR}} + p_{\,\mathrm{ISM}} \longrightarrow \bar{D}$$

Produced in the disk

Propagation and energy redistribution in the diffusive halo

DM signal

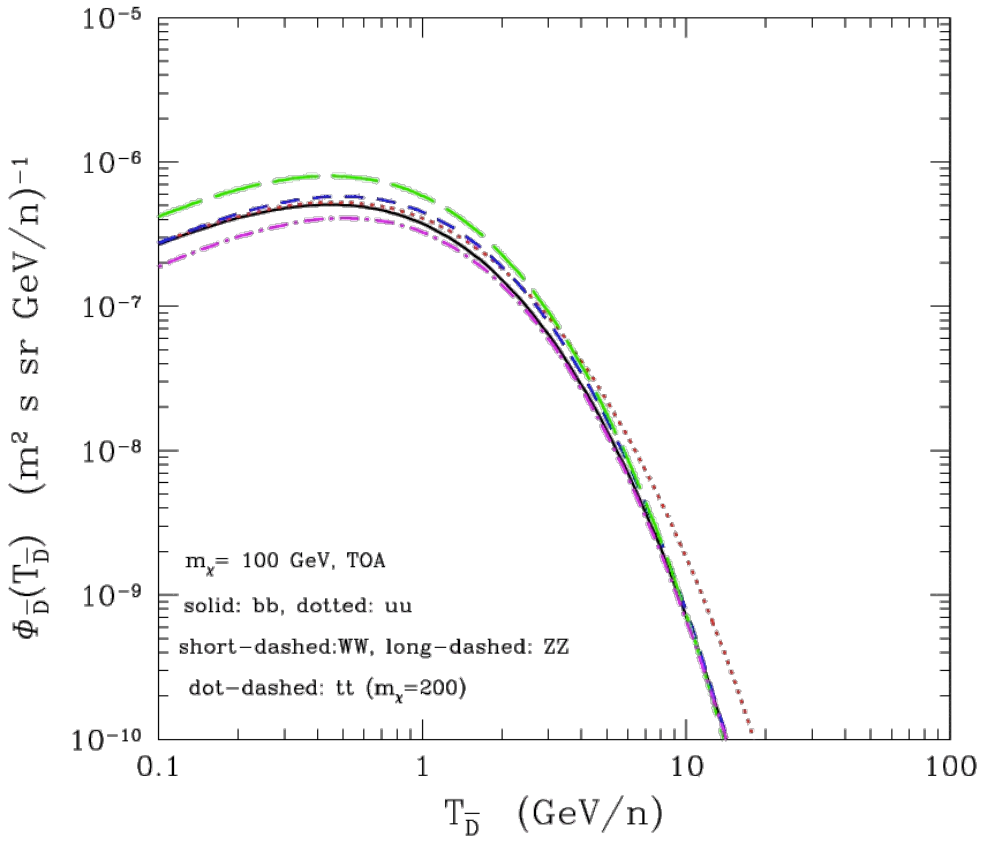
$$\chi\chi \longrightarrow (.....) \longrightarrow p\bar{p}\ n\bar{n}$$
$$\bar{p} + \bar{n} \longrightarrow \bar{D}$$ Coalescence

Produced in the DM halo

Propagation and energy redistribution in the diffusive halo

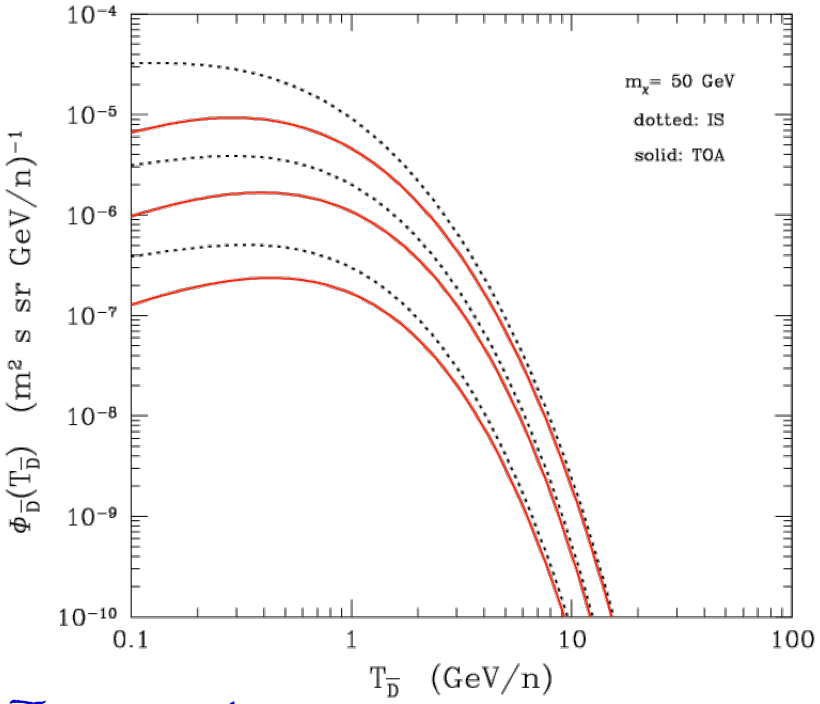
solar modulation

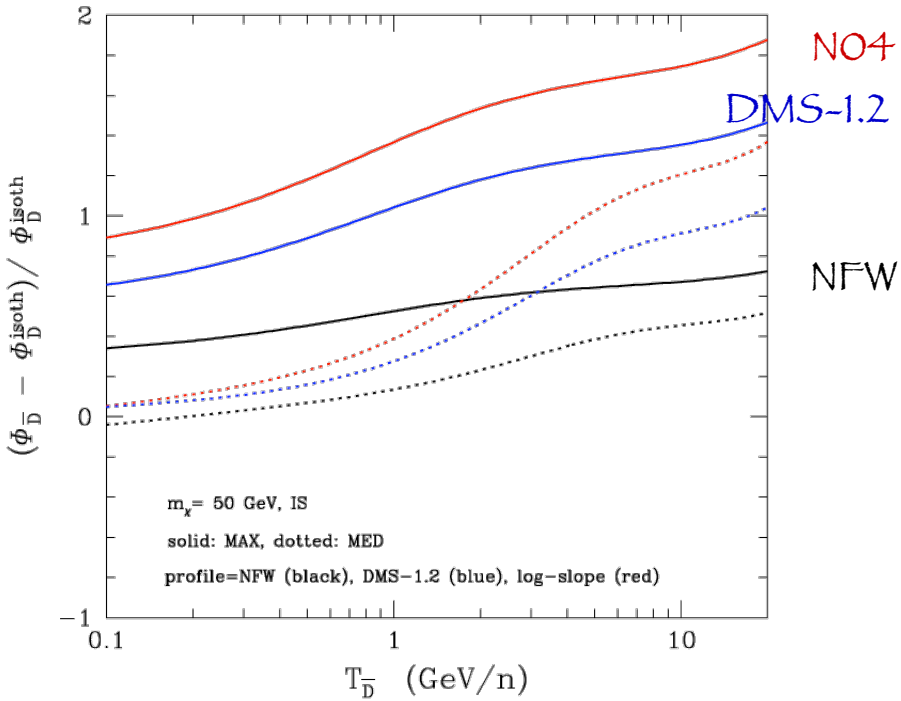
Antideuteron signal: channel dependence



A. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

Signal and its uncertainties





Transport:

- High-energies: diffusive halo size L
- Low-energies: L + galactic wind

Energy redistribution (not dramatic):

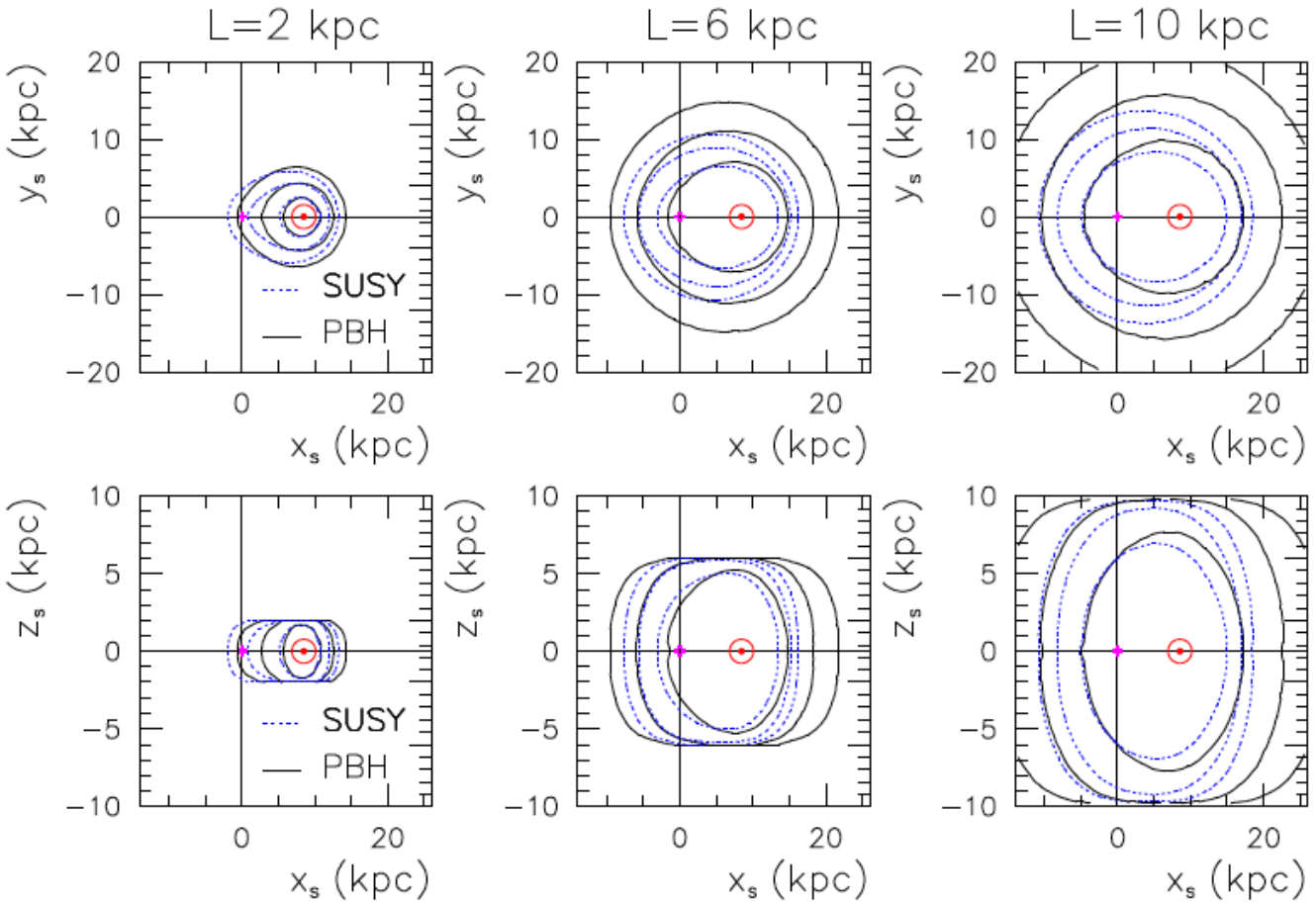
- Loss
- Reacceleration
- Tertiary redistribution

Change of DM halo profile
[fixed local density]

F. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

Effective volumes for antideuterons

Blue: DM
Black: PBH



From ext to int line: delta = 0.35, 0.60, 0.85

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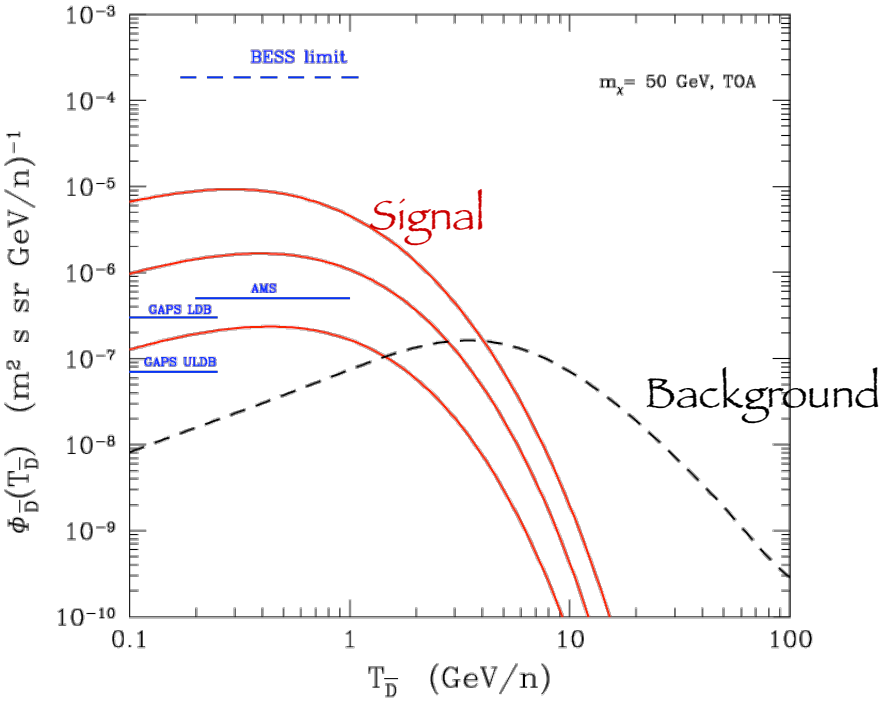
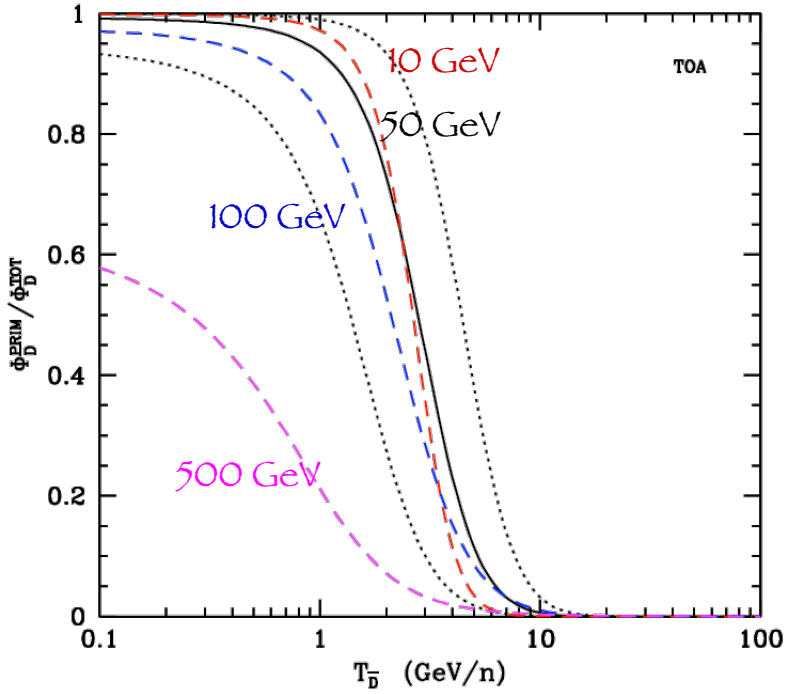
TOA fluxes and S/B gain





Signal with uncertainty band for:

- 50 GeV WIMP mass
- WMAP relic abundance

Signal/(Back+Signal) ratio

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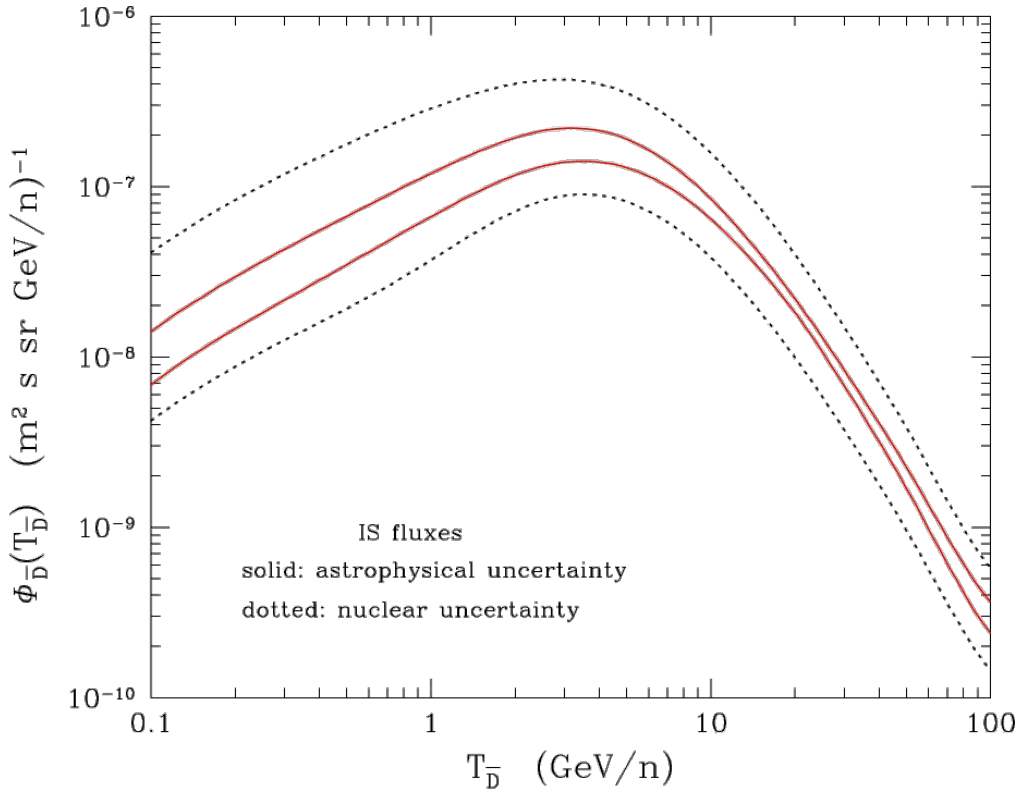
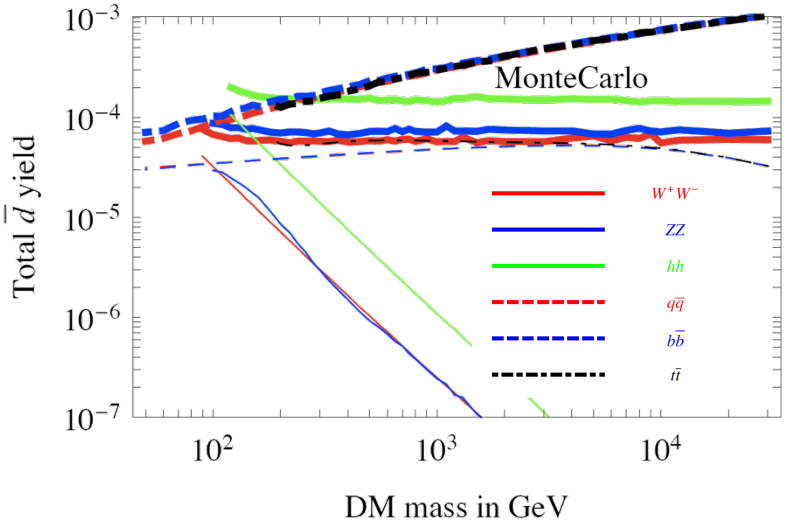
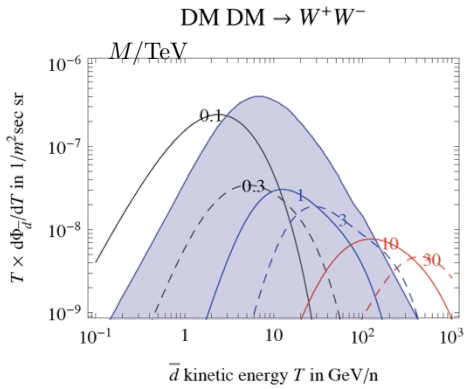
Secondaries and its uncertainties

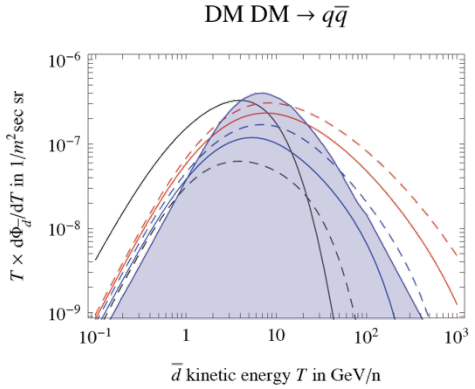


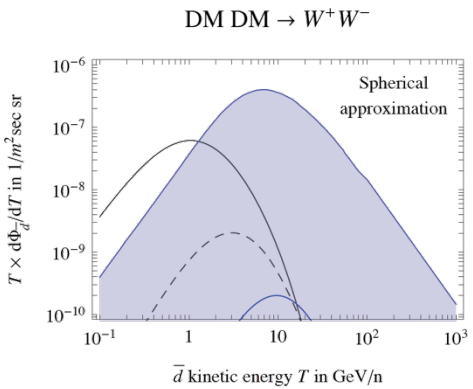
A. Donato, N. Fornengo, D. Maurín, PRD 78 (2008) 043506

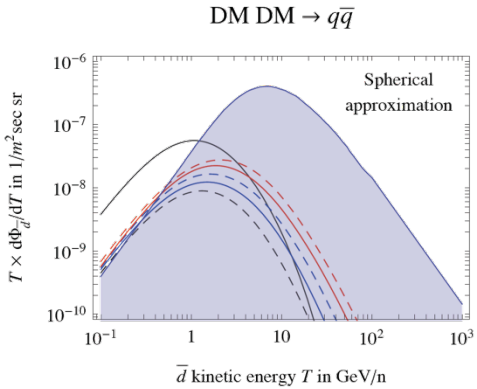
Coalescence revisited







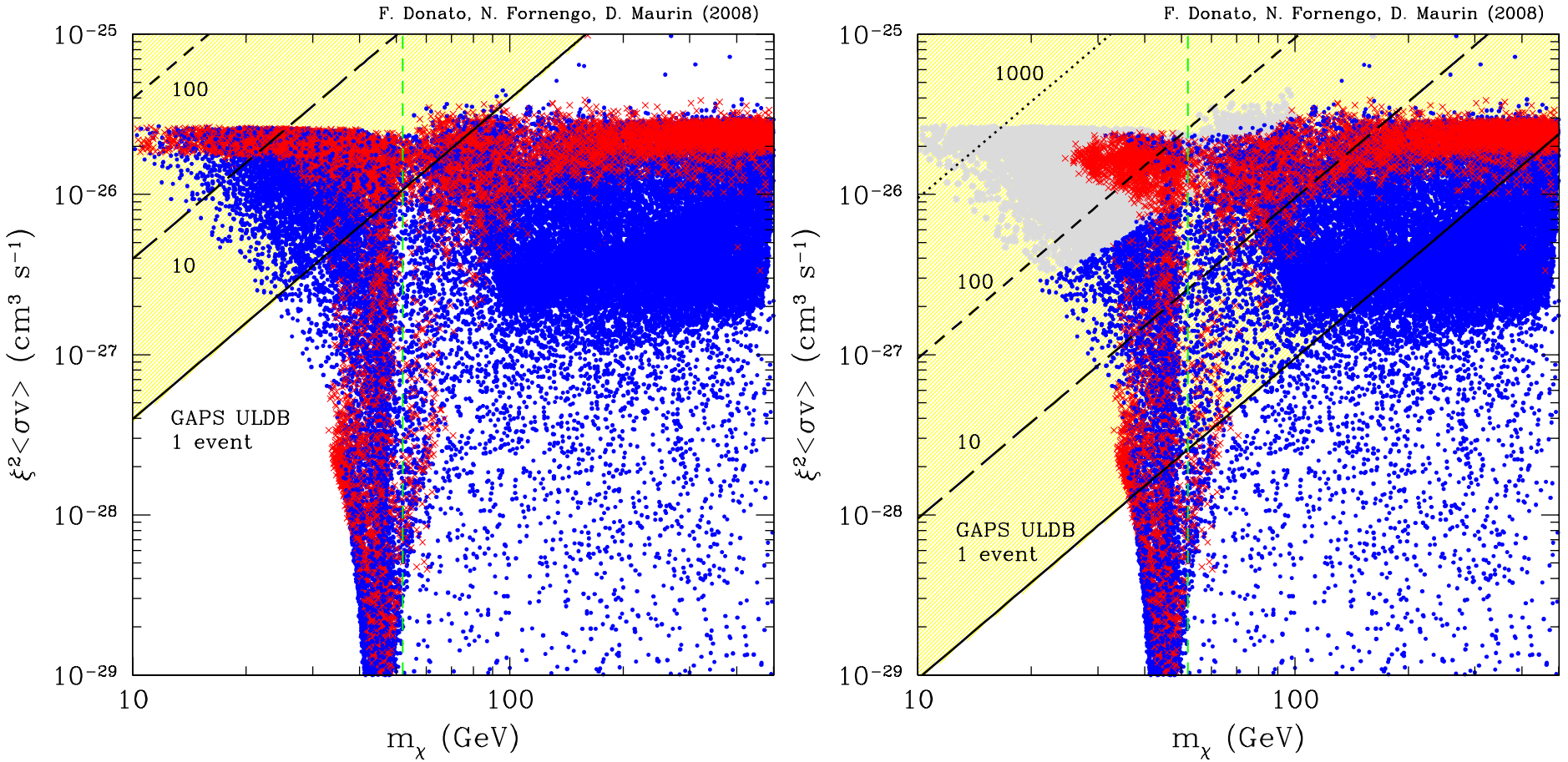




$$\sigma v = \max(1, M/300\,\mathrm{GeV})^2 \cdot \sigma v_{\mathrm{cosmo}}$$

M. Kadastik, M. Raidal, A. Strumia, arXiv:0908.1578

Impact of uncertainties on DM antiD searches

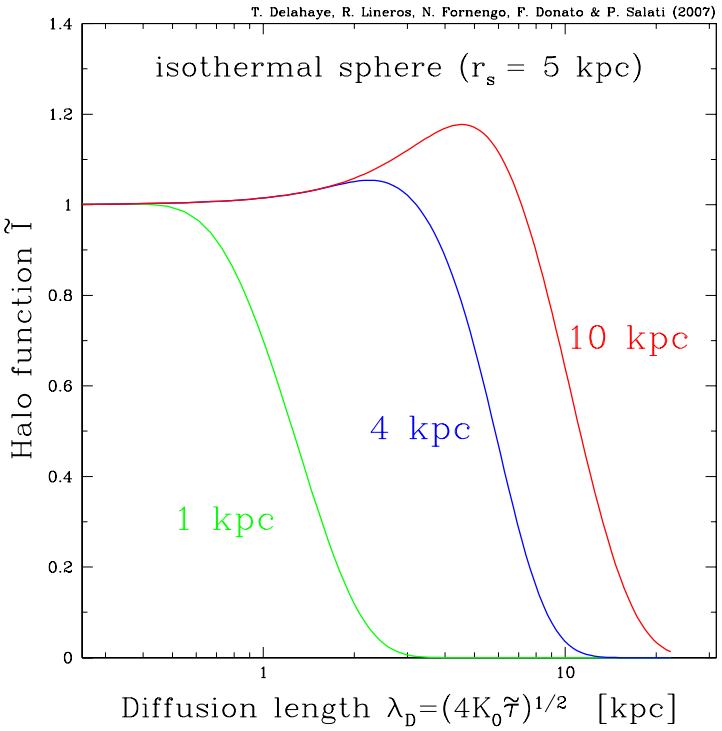


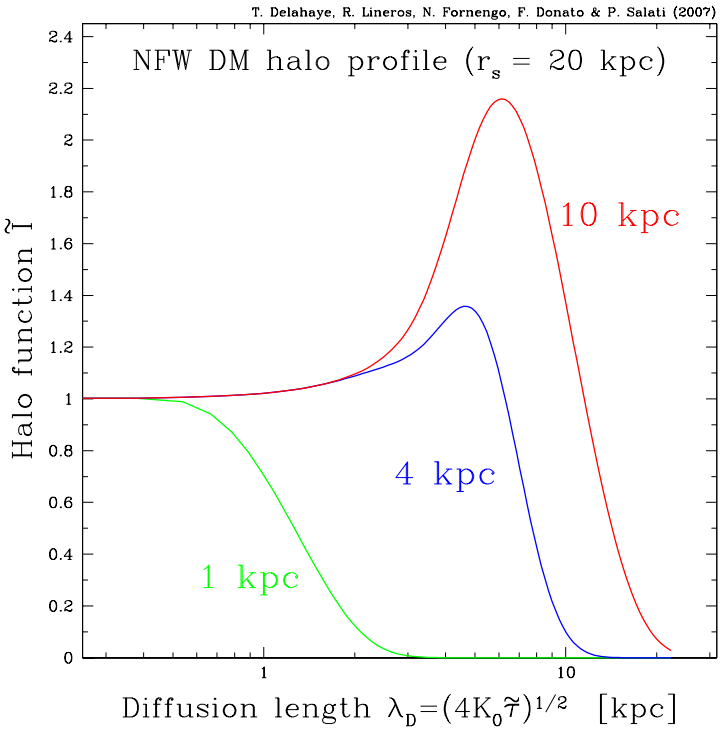
Neutralino DM in a low-energy MSSM

Antimatter in Cosmic Rays
Positrons

Positron "halo function"

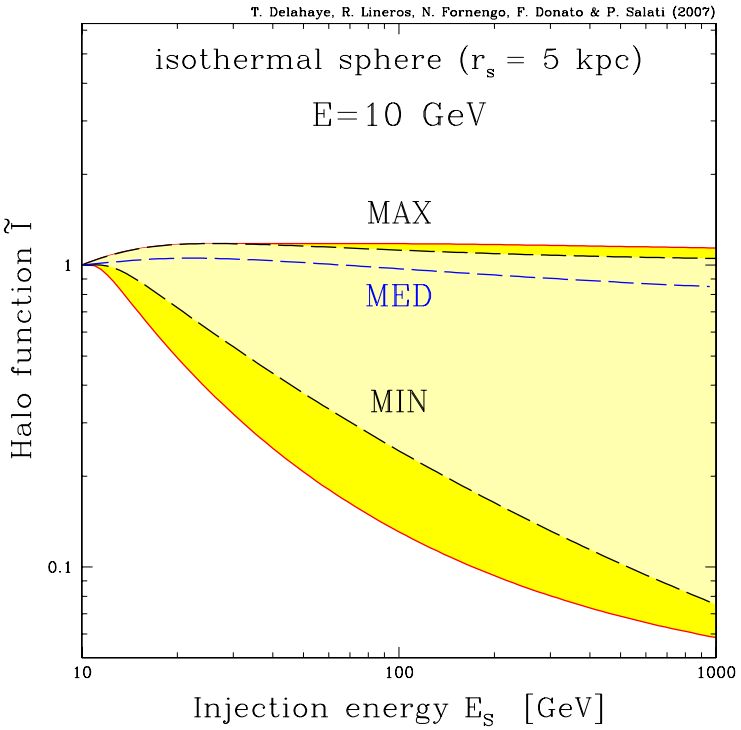
$$\Phi_{e^+} = \frac{\beta_{e^+}}{4\pi} \kappa \frac{\tau_E}{\epsilon^2} \int_{\epsilon}^{+\infty} d\epsilon_S \, f(\epsilon_S) \, \tilde{I}(\lambda_D)$$

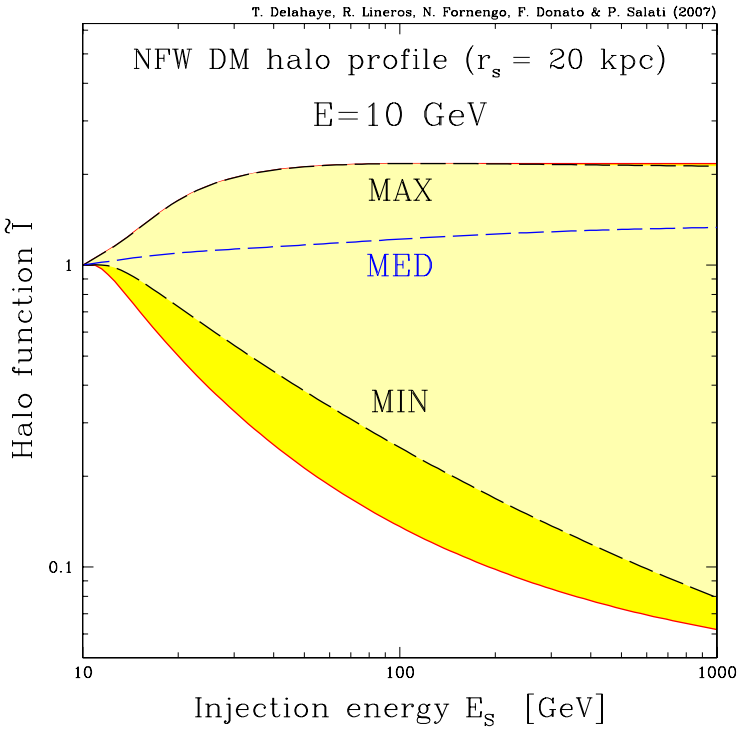




T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

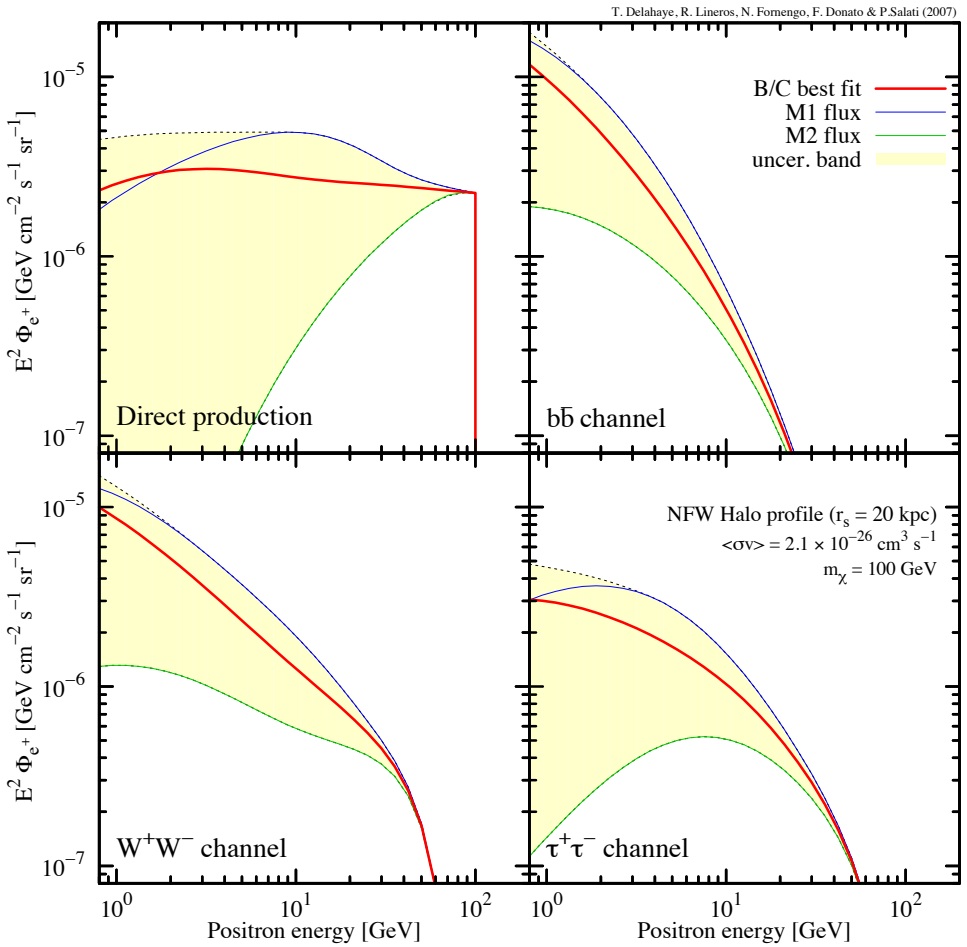
Positron "halo function"





T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

Positron fluxes from DM annihilation



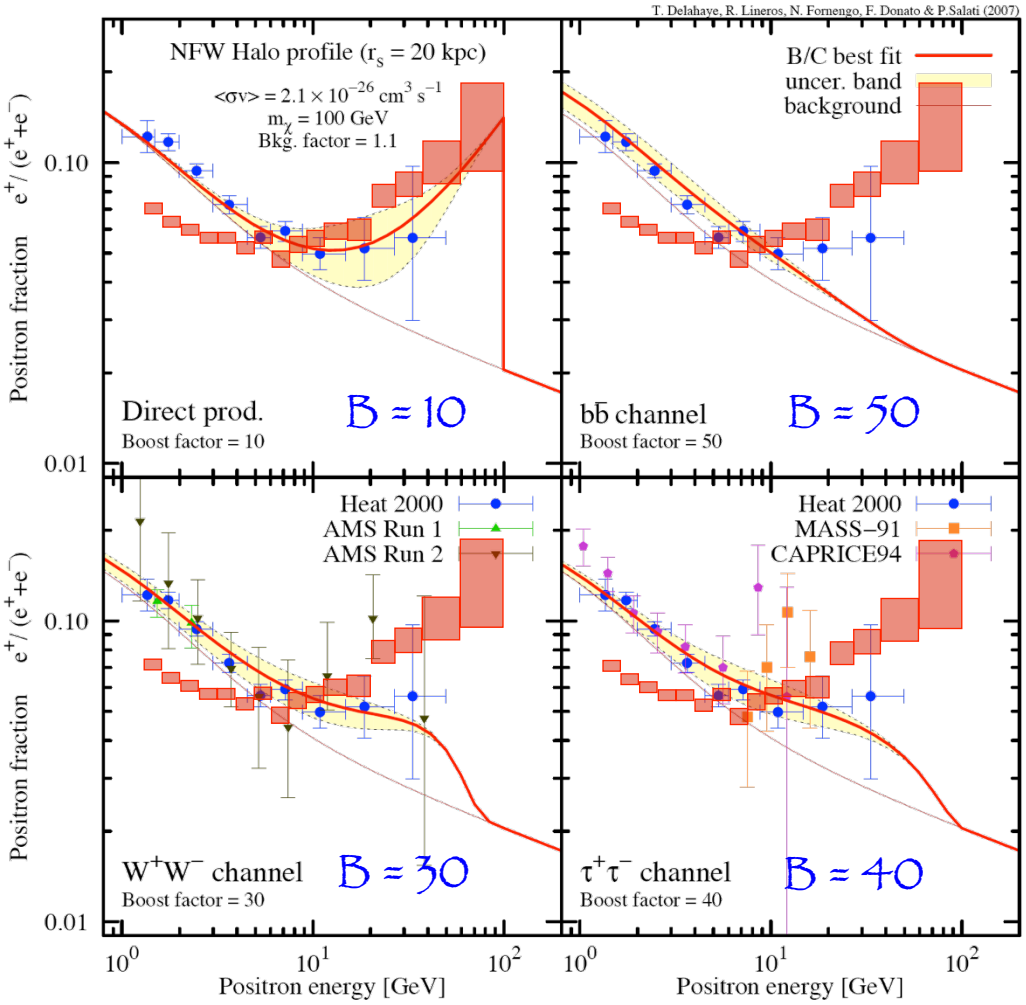
T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

Positron fraction: including a DM signal

$m_\chi \approx 100$ GeV

Smooth NFW halo

- PAMELA



$\langle \sigma v \rangle = 2.1 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

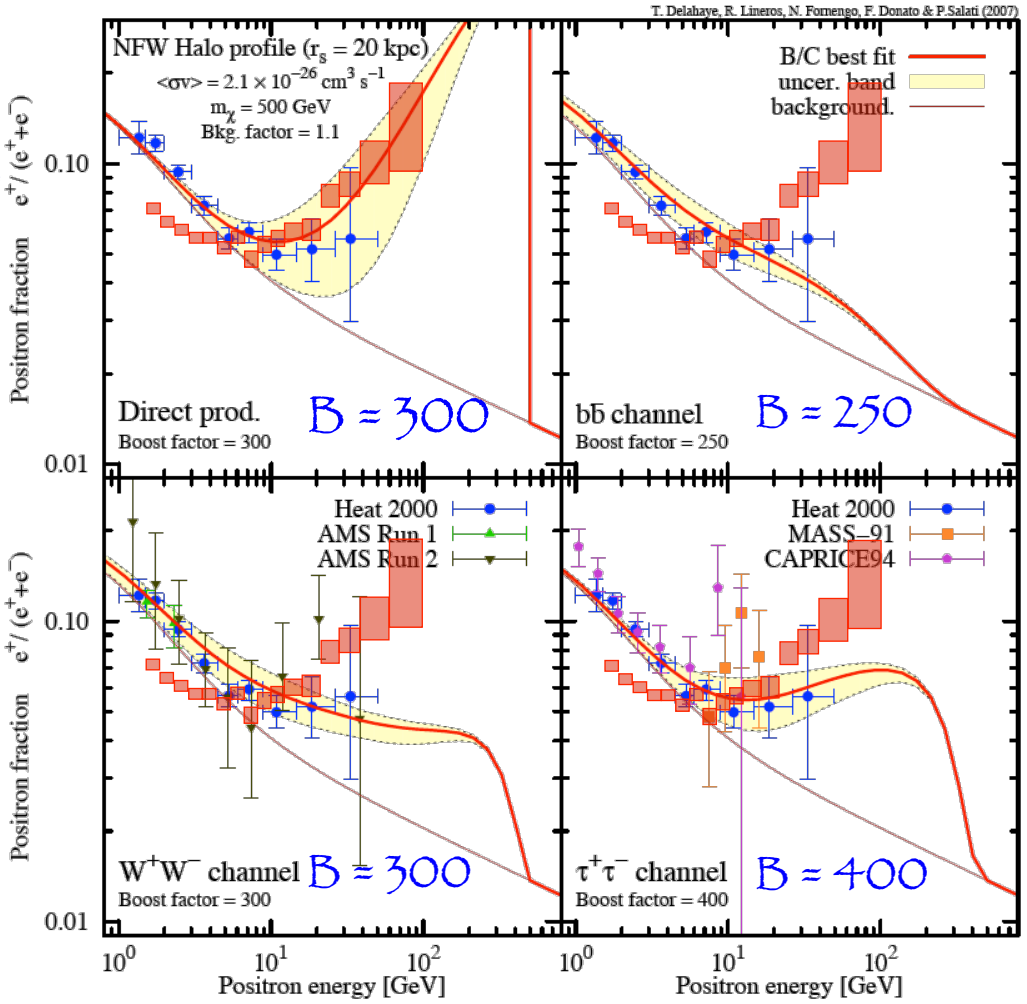
Uncertainties on the DM signal ONLY!

Positron fraction: including a DM signal

$m_\chi \simeq 500$ GeV

Smooth NFW halo

- PAMELA



$\langle \sigma v \rangle = 2.1 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

Uncertainties on the DM signal ONLY!

Electrons and positrons in Cosmic Rays

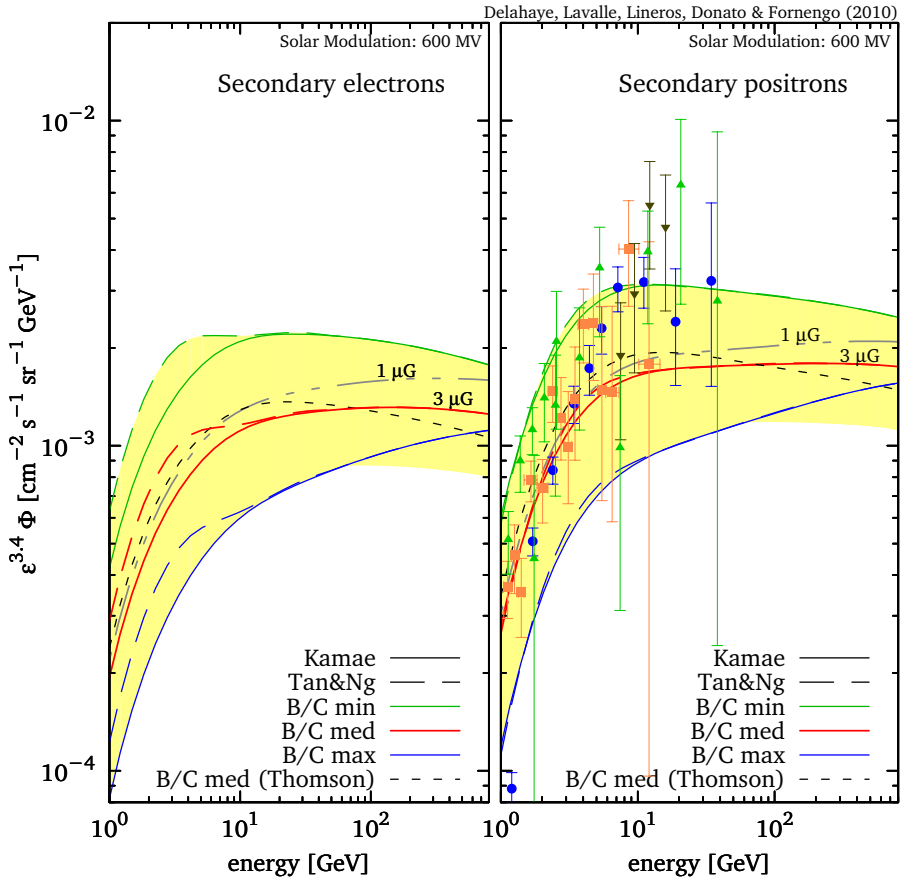
Primaries:

e- from SN remnants
e+,e- from pulsars
DM annihilation, decay

Secondaries:

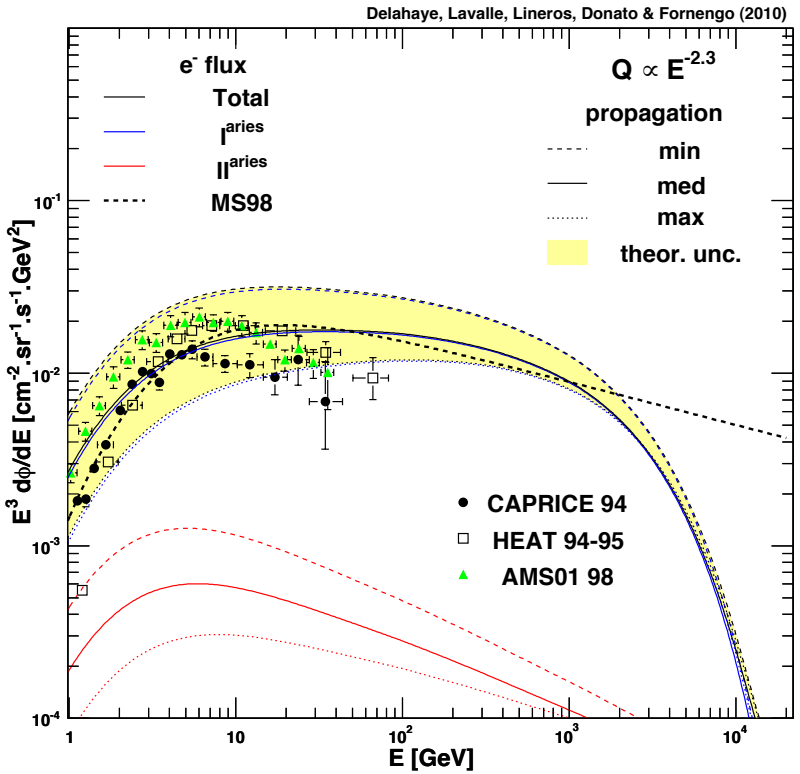
$$p + H \longrightarrow (...)\ \pi^{\pm} \longrightarrow (...)\ e^{\pm}$$

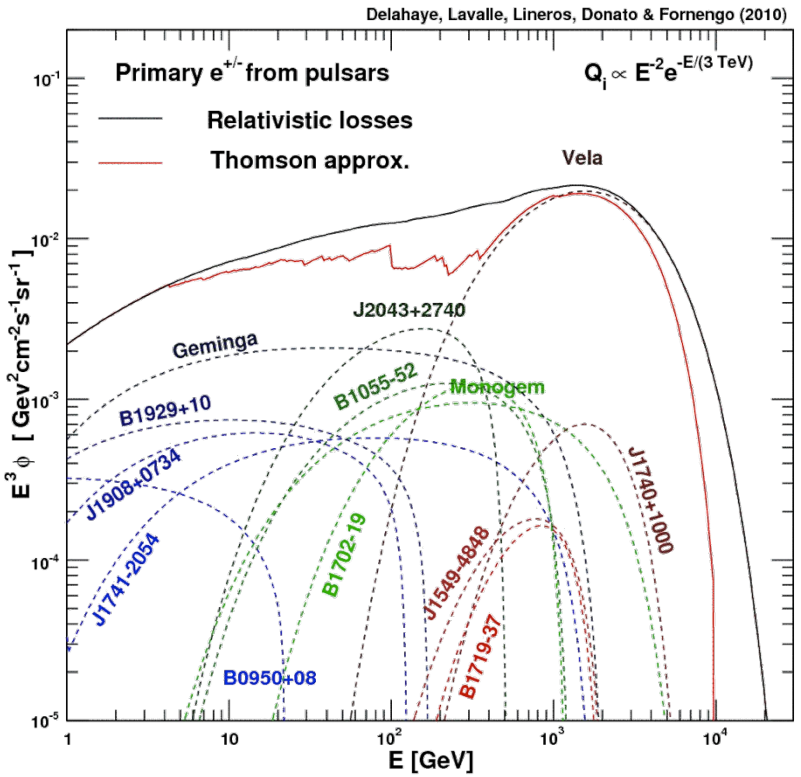
Secondary e^+,e^- : fluxes



T. Delahaye, J. Lavalle, R. Lineros, F. Donato, N. Fornengo, A&A 524 (2010) A51

Primary e^+,e^-



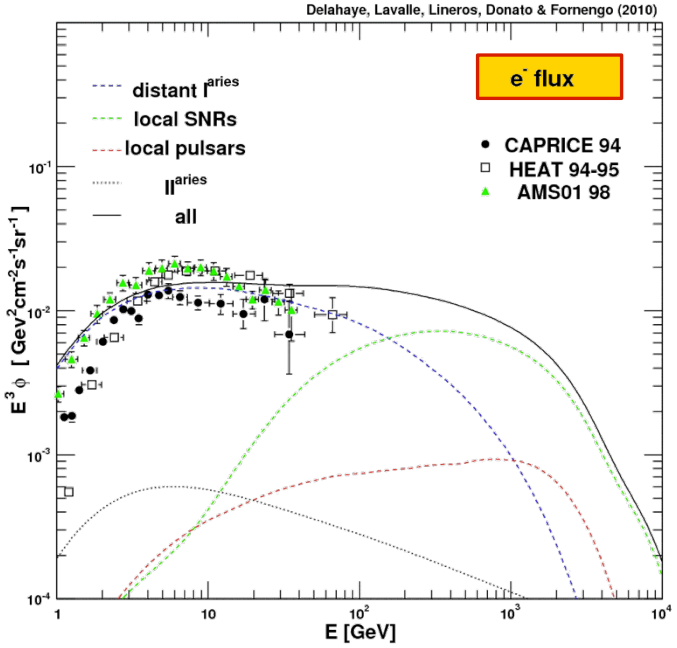


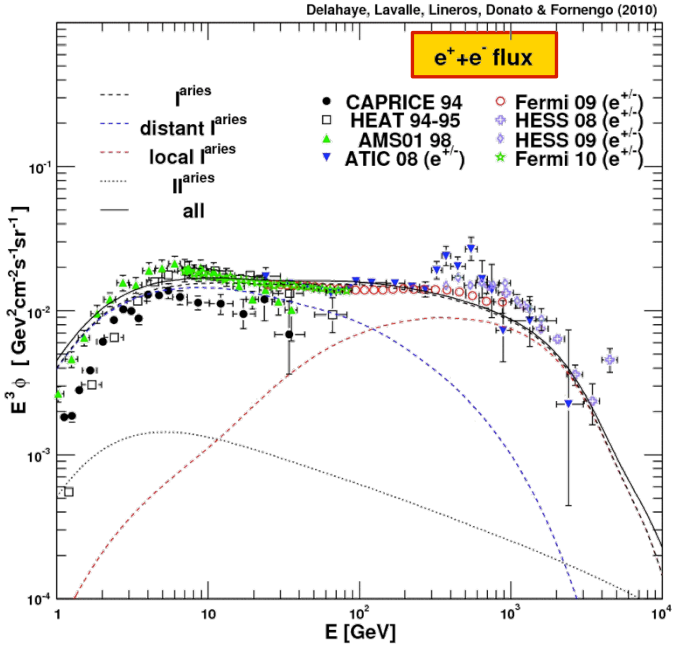
Distant sources (smooth)

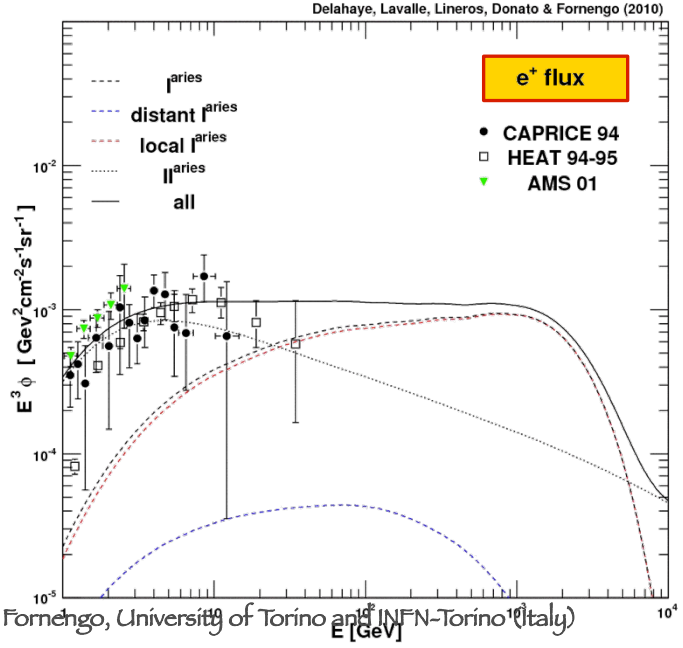
Local sources

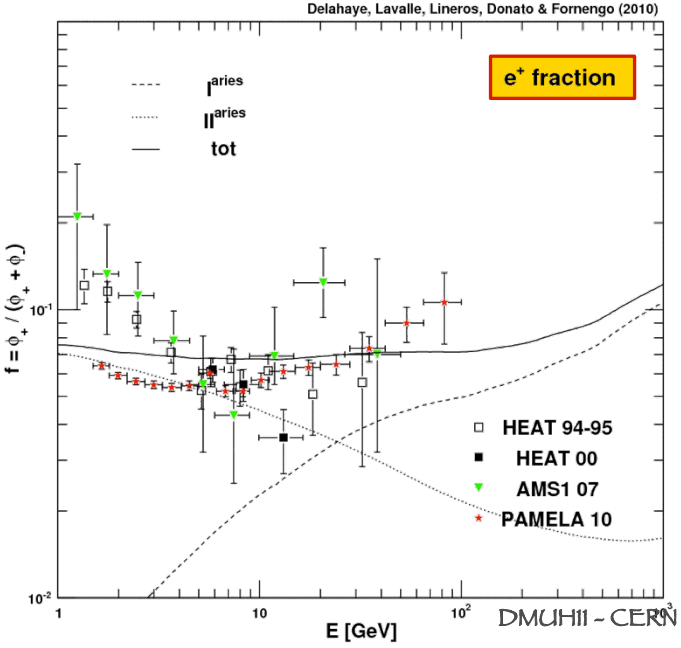
J. Lavalle, T. Delahaye, R. Lineros, F. Donato, N. Fornengo, arXiv:1002.1910 [astro-ph.HE]

Total fluxes of e^+,e^-









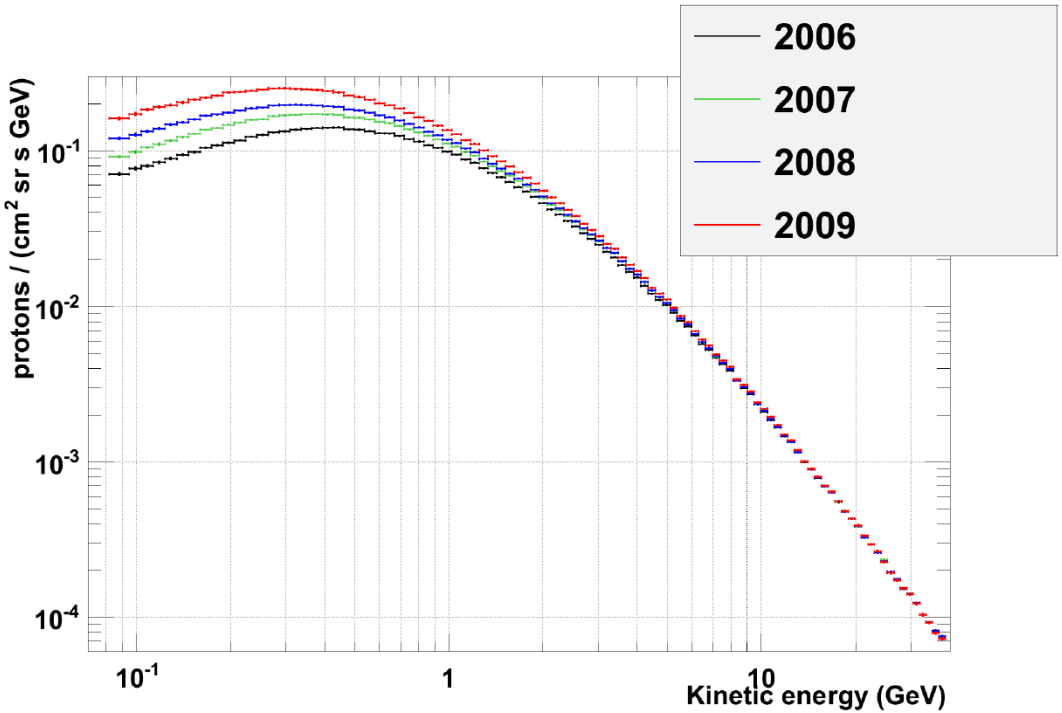
J. Lavalle, T. Delahaye, R. Lineros, F. Donato, N. Fornengo, arXiv:1002.1910 [astro-ph.HE]

Solar modulation

- Affects low T energies (below about 10 GeV)
- Coorelated with the 11-year solar cycle
- Typically treated in the force-field approximation
  - one parameter, function of solar cycle
- More realistic transport in the heliosphere needed
- Charge dependent effects may be present

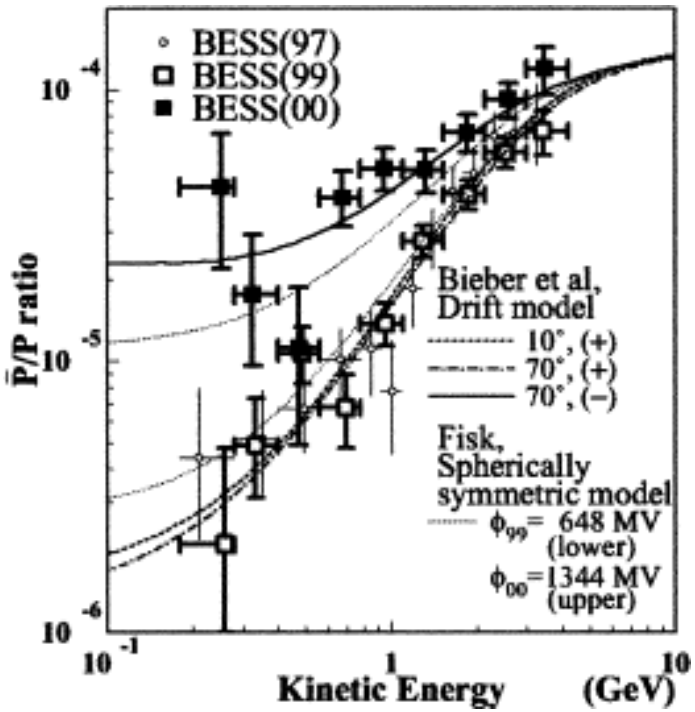
Solar modulation

Protons



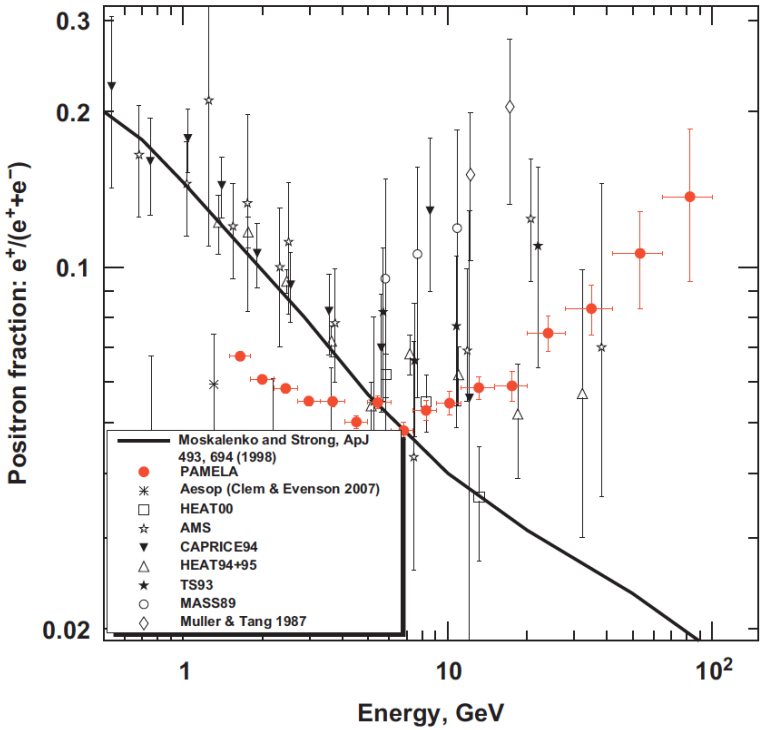
Picozza, Sparvoli et al. (PAMELA Collab),
Astrophys. Space Sci. Trans., *7*, 85–91, 2011

Antip/p ratio

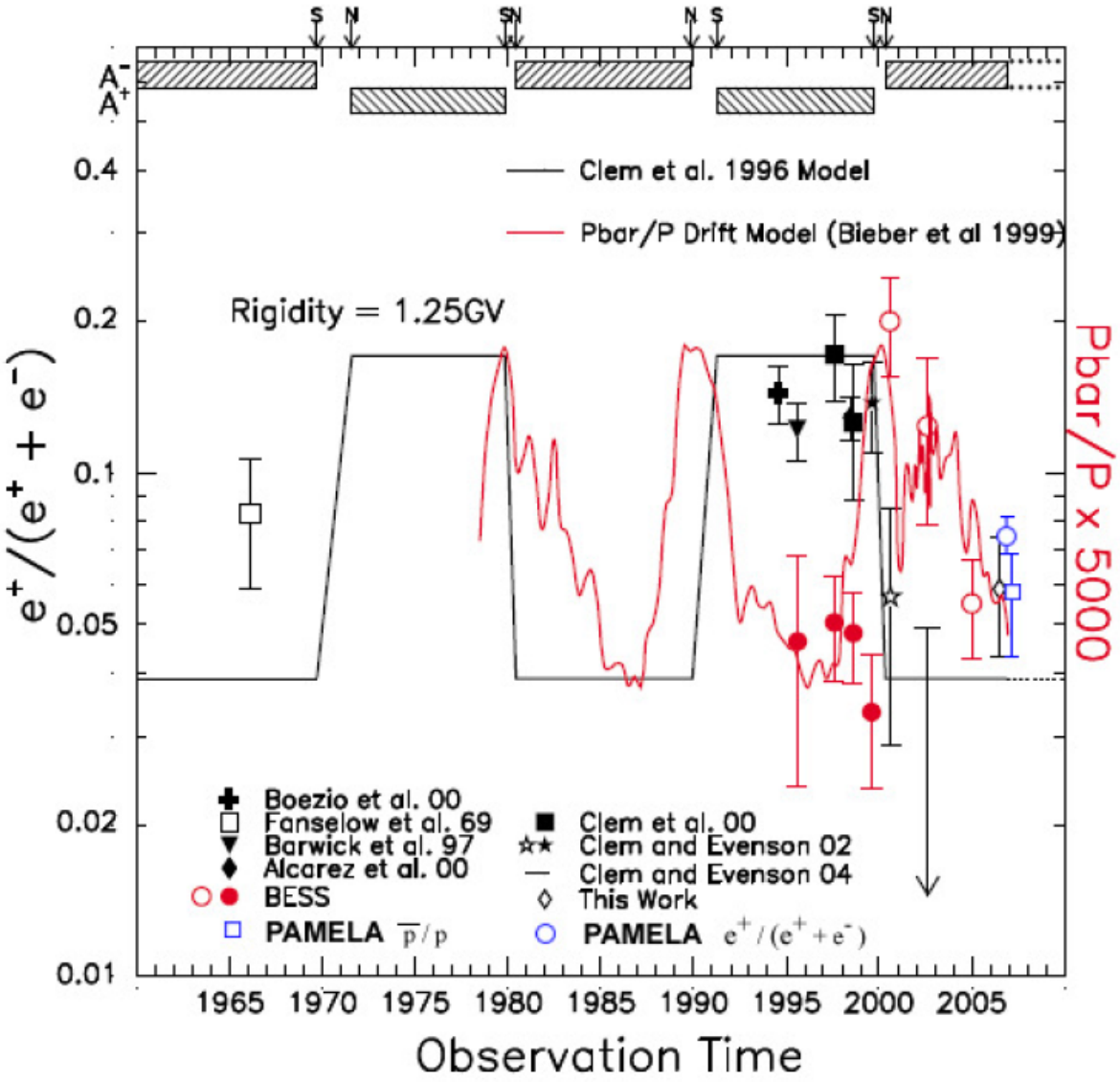


Mitchell et al. (BESS Collab.),
Adv. Space Res. 35 (2005) 135

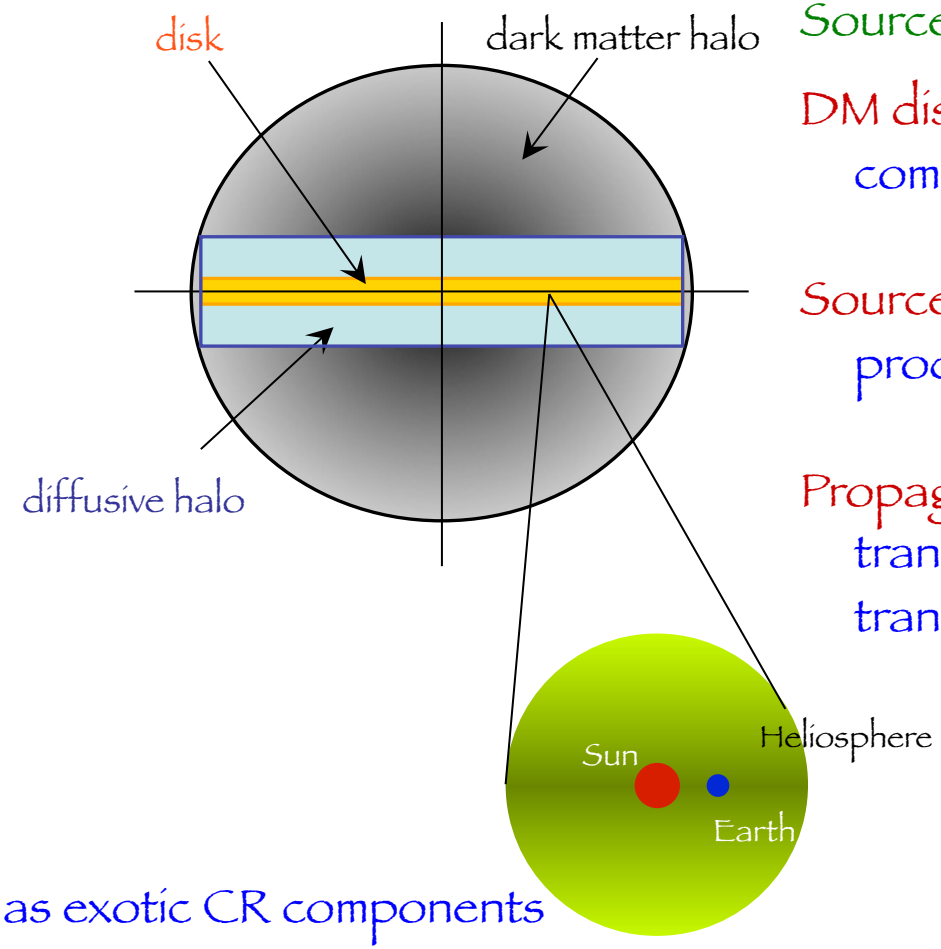
Positron fraction



Mocchiutti ei al. (PAMELA Collab.),
NIM A 630 (2011) 28


S N SN N S SN
A-
A+
Clem et al. 1996 Model
Pbar/P Drift Model (Bieber et al 1999)
Rigidity = 1.25GV
e+/(e+ + e-)
Pbar/P x 5000
0.4
0.2
0.1
0.05
0.02
0.01
Boezio et al. 00
Fanselow et al. 69
Barwick et al. 97
Alcarez et al. 00
BESS
PAMELA p̄/p
Clem et al. 00
Clem and Evenson 02
Clem and Evenson 04
This Work
PAMELA e+/(e+ + e-)
1965 1970 1975 1980 1985 1990 1995 2000 2005
Observation Time

Galactic environment



Sources of uncertainties

DM distribution

combined effect with propagation

Source

production mechanism

Propagation

transport in the Galaxy

transport in the heliosphere (low T)

DM signals as exotic CR components

antiprotons

antideuterons

positrons/electrons