# A look on supersymmetric dark matter through indirect signals


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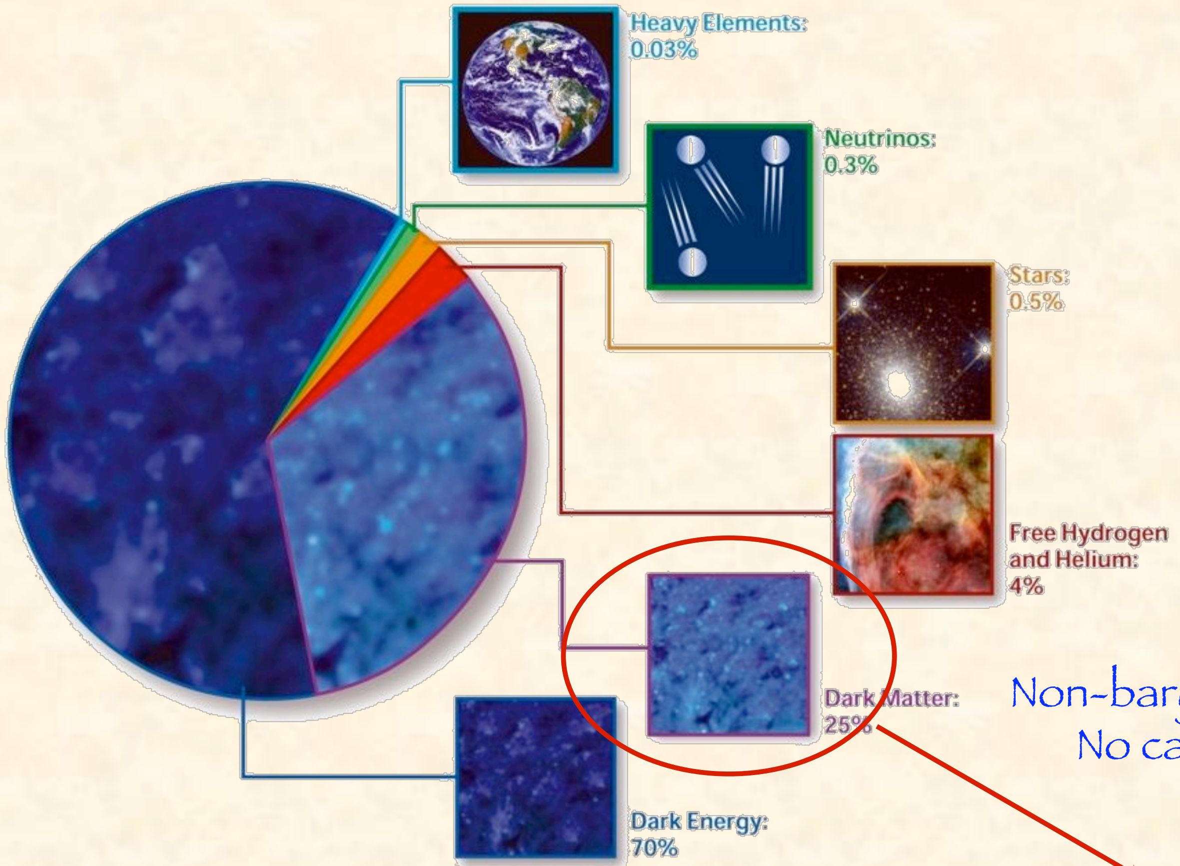
INFN Torino

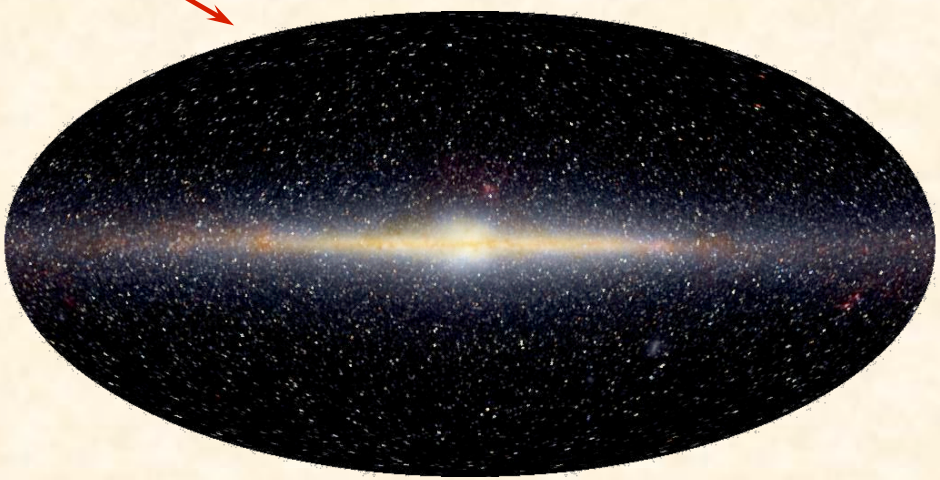


Theoretical miniWorkshop on Dark Matters
IFT-UAM/CSIC Madrid -17.09.2009

# Dark Matter




Non-baryonic (cold) dark matter is needed
No candidate in the Standard Model
New fundamental Physics



Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget

# Galactic Dark Matter

## CDM in galaxies:

- Massive particle with weak-type interactions (WIMP)
- Distributed to form a halo
  - Thermal component
  - Substructures
  - Non-thermal component

## Galactic dark matter detection:

- Identify types of signals
- Exploit specific signatures
- Exploit (anti)correlations among signals
- Study relevant backgrounds
- Quantify uncertainties

# MultiChannel search of dark matter

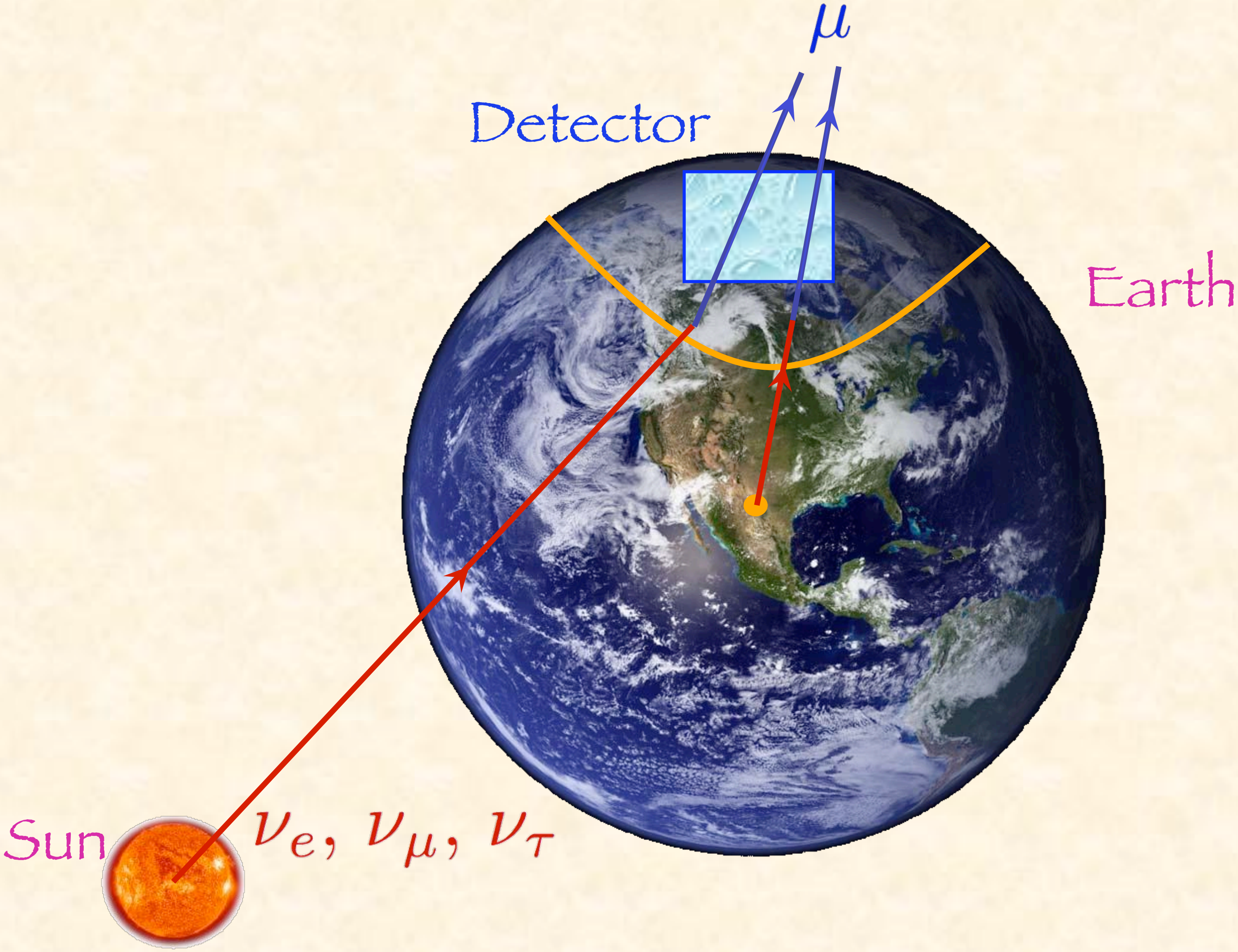
- Direct search: elastic scattering of $\chi$ off nuclei in a low background detector
  → recoil energy of the nucleus
  annual modulation of the rate
  directionality of the recoil

- Indirect searches:
  – signals due to $\chi\chi$ annihilation taking place inside celestial bodies (Sun, Earth) where $\chi$ have been captured and accumulated
    → Neutrino flux → up-going muons in a neutrino telescope
    source location/some spectral feature

  – signals due to $\chi\chi$ annihilation taking place in the galactic halo
    → Neutrinos — source location/some spectral feature
    → Photons
      - continuous gamma-ray flux — source location/some spectral feature
      - gamma-ray line — very good spectral feature
    → Positrons — spectral feature
    → Antiprotons — spectral feature
    → Antideuterons — very good spectral feature
    → Electrons/positrons → multiwavelength search (radio, X, gamma rays; SZ on CMB)

# Searches at Neutrino Telescopes

# Neutrino flux from the Earth or Sun



# Neutrino Production

- Neutrinos are produced by DM annihilation
  - Available channels depend on mass threshold

$$\chi\chi \to \nu\nu,\ l\bar{l},\ q\bar{q},\ W^+W^-,\ ZZ,\ \mathrm{Higgses},\ \mathrm{Higgs} + \mathrm{gauge}$$

  - Quark hadronize → neutrinos from hadron decay

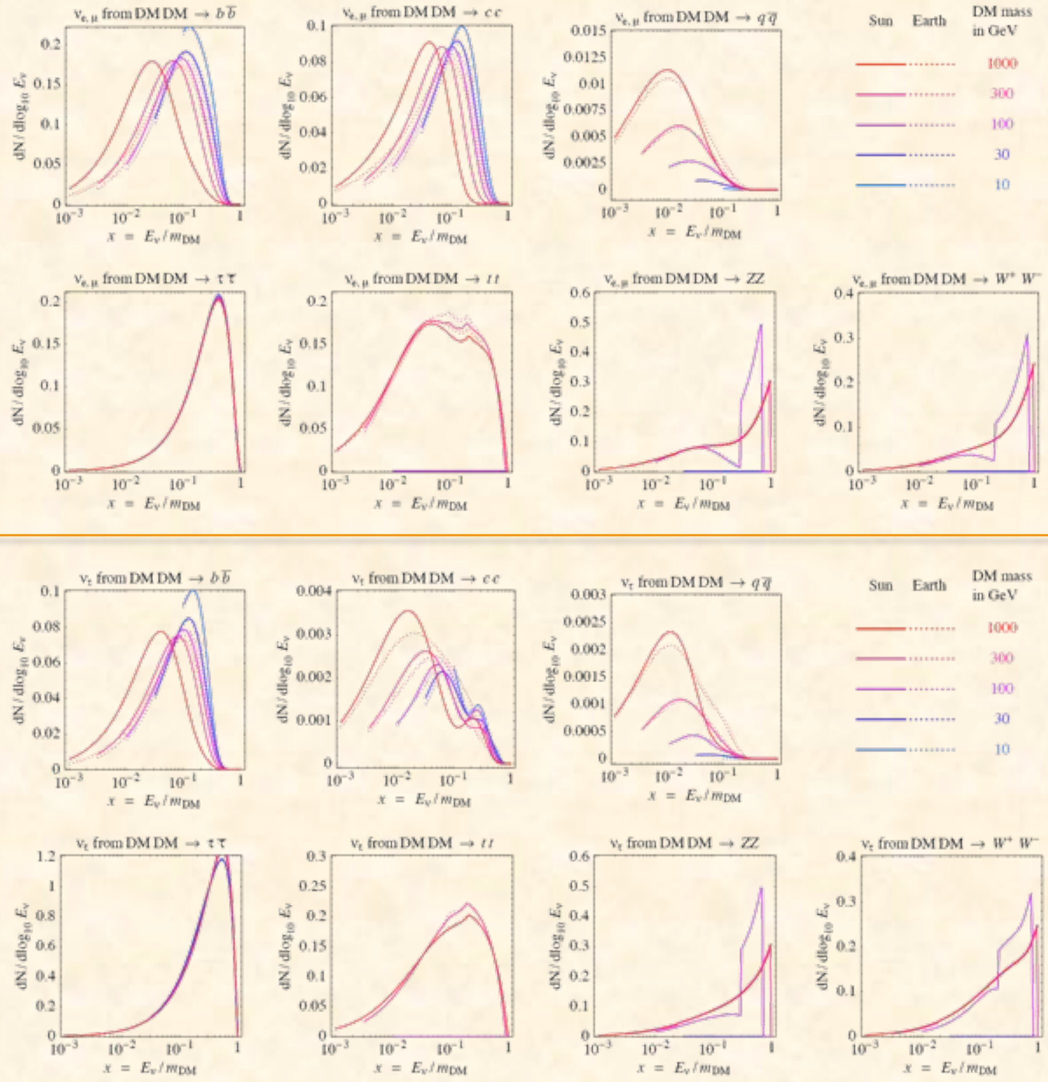
- Productions in Earth
  - Muons: stopped before decay → neutrinos below typical thresholds
  - Taus: decay almost as in vacuum
  - Light hadrons: typically stopped before decay
  - Heavy hadrons: typically decay before loosing significant energy

- Production in Sun
  - Leptons: stopping power of medium is stronger → softer neutrino spectra
  - Light hadrons: typically stopped before decay
  - Heavy hadrons: energy losses important, need modeling

# Spectra at production

$\nu_e, \nu_\mu$

$\nu_\tau$




M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

# Neutrino propagation

## Density matrix evolution

neutral-current processes

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm NC} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm in}$$

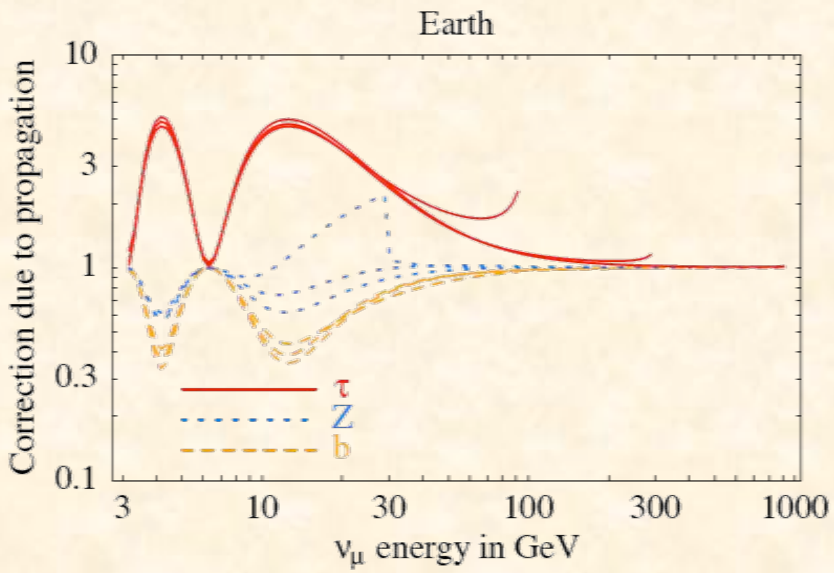
charged-current processes

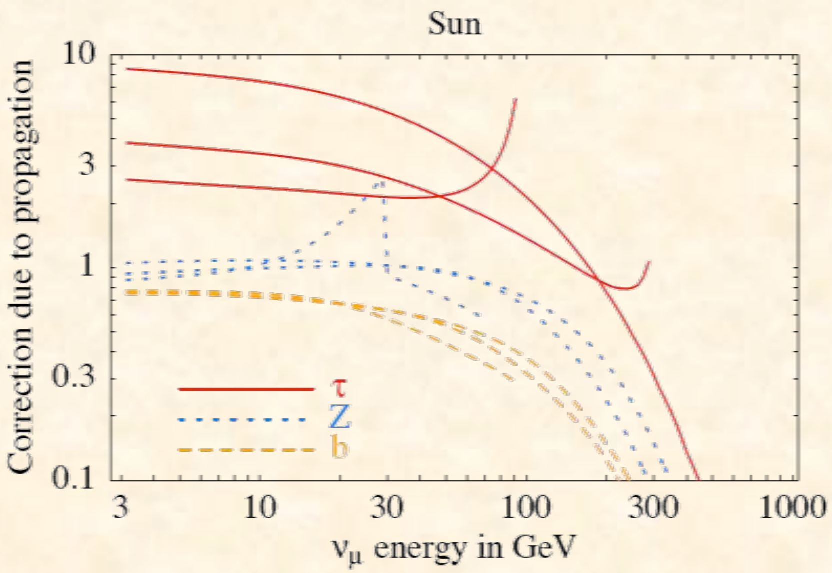
source

## Vacuum oscillations and MSW matter effect

$$\boldsymbol{H} = \frac{\boldsymbol{m}^\dagger \boldsymbol{m}}{2E_\nu} + \sqrt{2}G_{\rm F}\left[N_e\ \mathrm{diag}\,(1,0,0) - \frac{N_n}{2}\ \mathrm{diag}\,(1,1,1)\right]$$

# Effect of propagation




Earth:

- Affected only by "atmospheric" oscillation $\nu_\mu \leftrightarrow \nu_\tau$ at $E < 100$ GeV

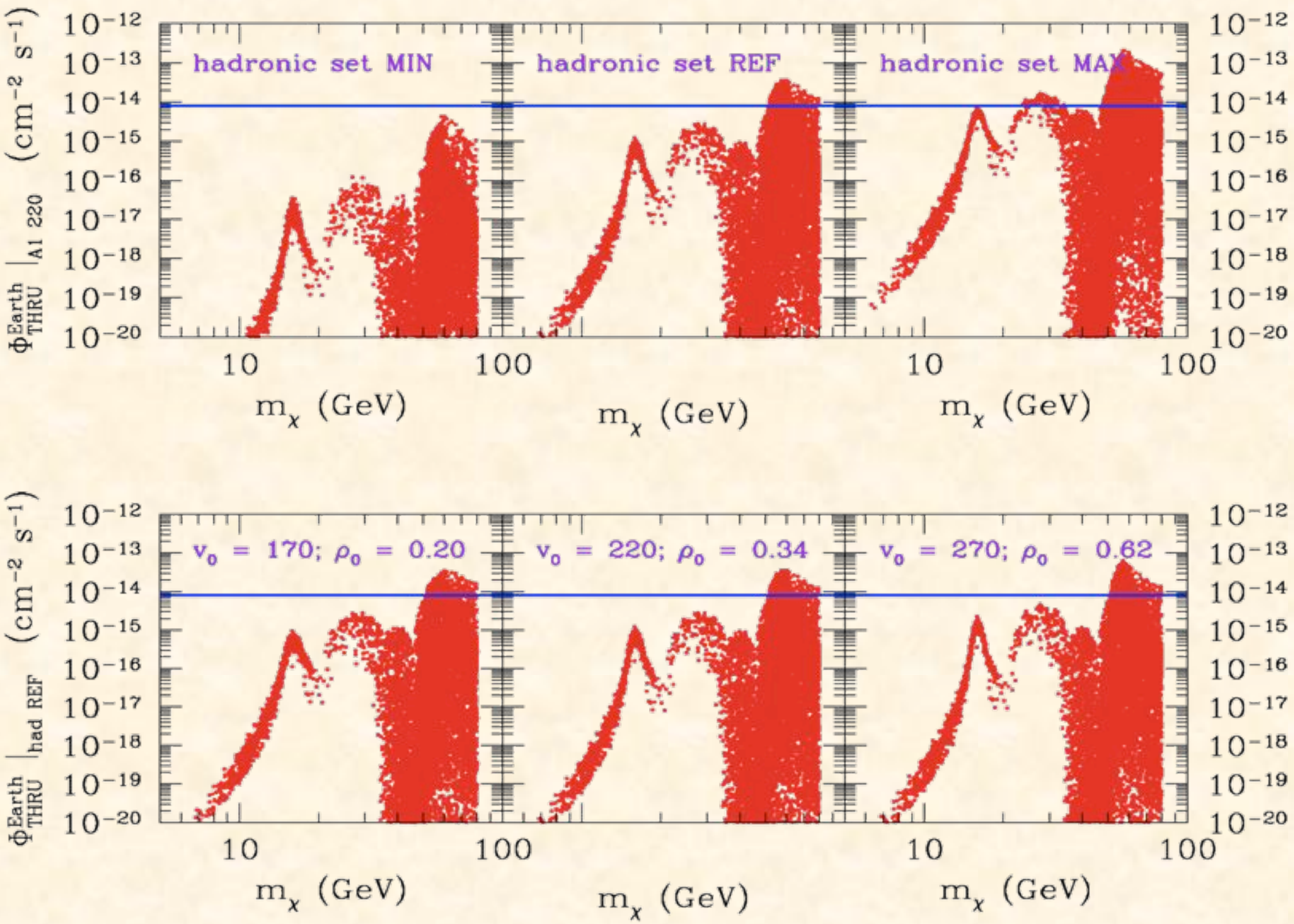
Sun:

- Affected by average "solar" and "atmospheric" oscillations
- Absorption suppresses neutrinos for $E > 100$ GeV (partially converted to lower energy neutrinos (by NC and regeneration)

M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

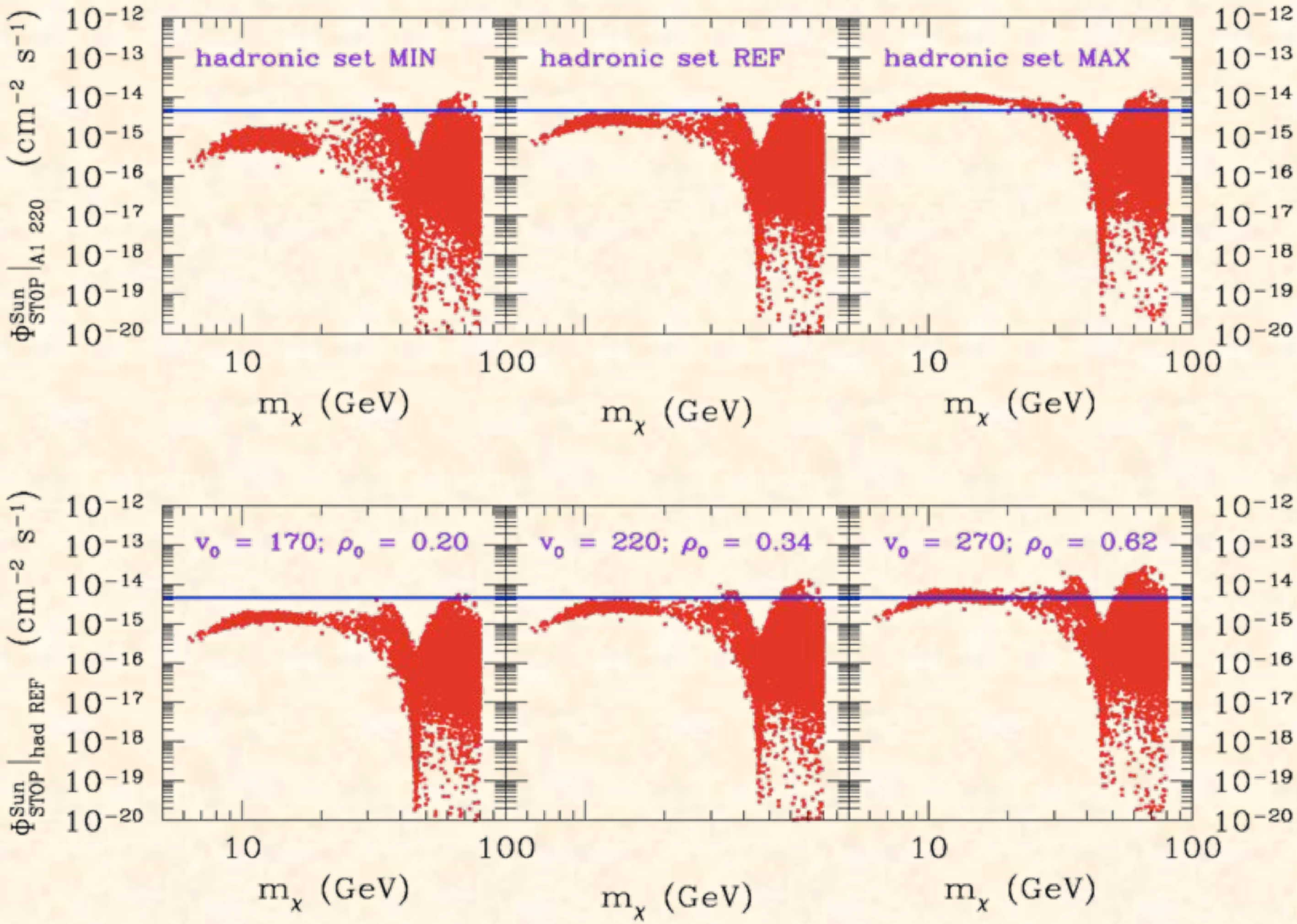
See also: M. Blennow, J. Edsjo, T. Ohlsson, JCAP 0801 (2008) 021 for an event-based MC approach

# Earth signal: through-going muons




V. Niro, A. Bottino, N.Fornengo, S. Scopel, arXiv:0909.2348

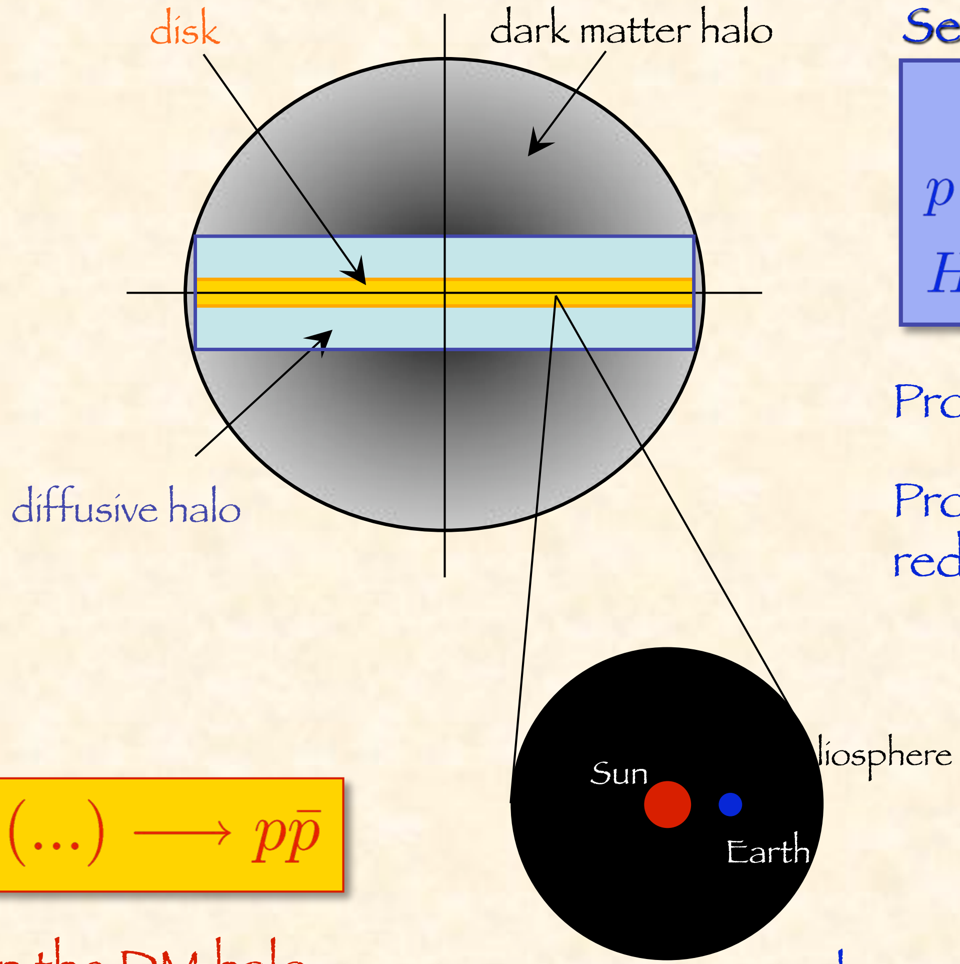
# Sun signal: stopping muons




V. Niro, A. Bottino, N.Fornengo, S. Scopel, arXiv:0909.2348

# Antiprotons

# Antiproton signal




## Secondaries

$$\begin{array}{rcl} p_{\,\mathrm{CR}} + p_{\,\mathrm{ISM}} & \longrightarrow & \bar{p} \\ p_{\,\mathrm{CR}} + He_{\,\mathrm{ISM}} & \longrightarrow & \bar{p} \\ He_{\,\mathrm{CR}} + p_{\,\mathrm{ISM}} & \longrightarrow & \bar{p} \end{array}$$

Produced in the disk

Propagation and energy redistribution in the diffusive halo

solar modulation

## DM signal

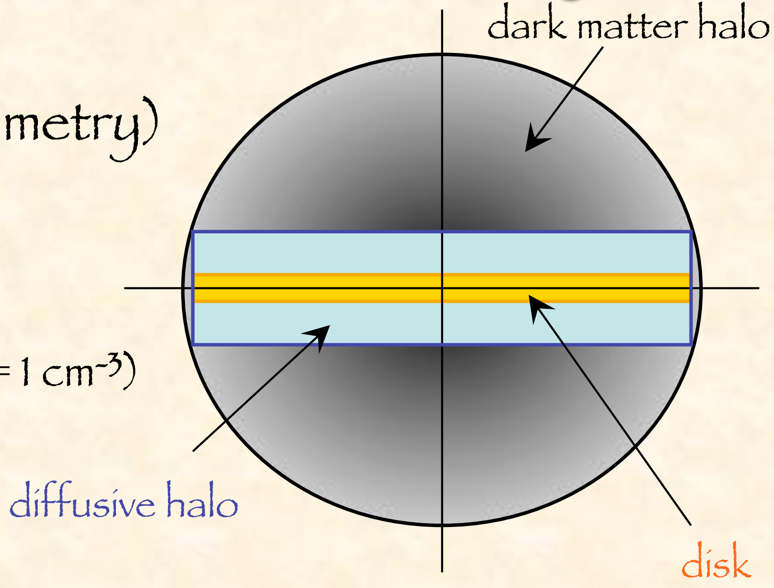
$$\chi\chi \longrightarrow (\ldots) \longrightarrow p\bar{p}$$

Produced in the DM halo

Propagation and energy redistribution in the diffusive halo

# Diffusion and propagation in the Galaxy

- Two-zone diffusion model (cylindrical symmetry)
  - Thin disk
    - ✓ Radius R = 20 kpc
    - ✓ Thickness h = 100 pc
    - ✓ Surface density of IS gas: $\boldsymbol{\Sigma} = 2hn_{ISM}$ ($n_{ISM} = 1\ \mathrm{cm}^{-3}$)
  - Diffusive halo
    - ✓ Radius R
    - ✓ Height L




- Physical processes
  - Diffusion: uniform in the whole (disk + diffusive halo) volume
  - Inelastic (non-annihilating) scattering and annihilation
  - Galactic wind away from the disk in vertical direction
  - Energy losses:
    - ✓ Ionization: interaction with the neutral IS matter
    - ✓ Coulomb scattering: interaction with ionized plasma (thermal electrons)
  - Reacceleration on random hydrodynamic waves (in the disk only)

$$q_{\bar{p}}^{\rm DM}(r,z,T_{\bar{p}}) \xrightarrow{\text{Propagation in the Galaxy}} \Phi^{\bar{p}}(r,z,T_{\bar{p}})$$

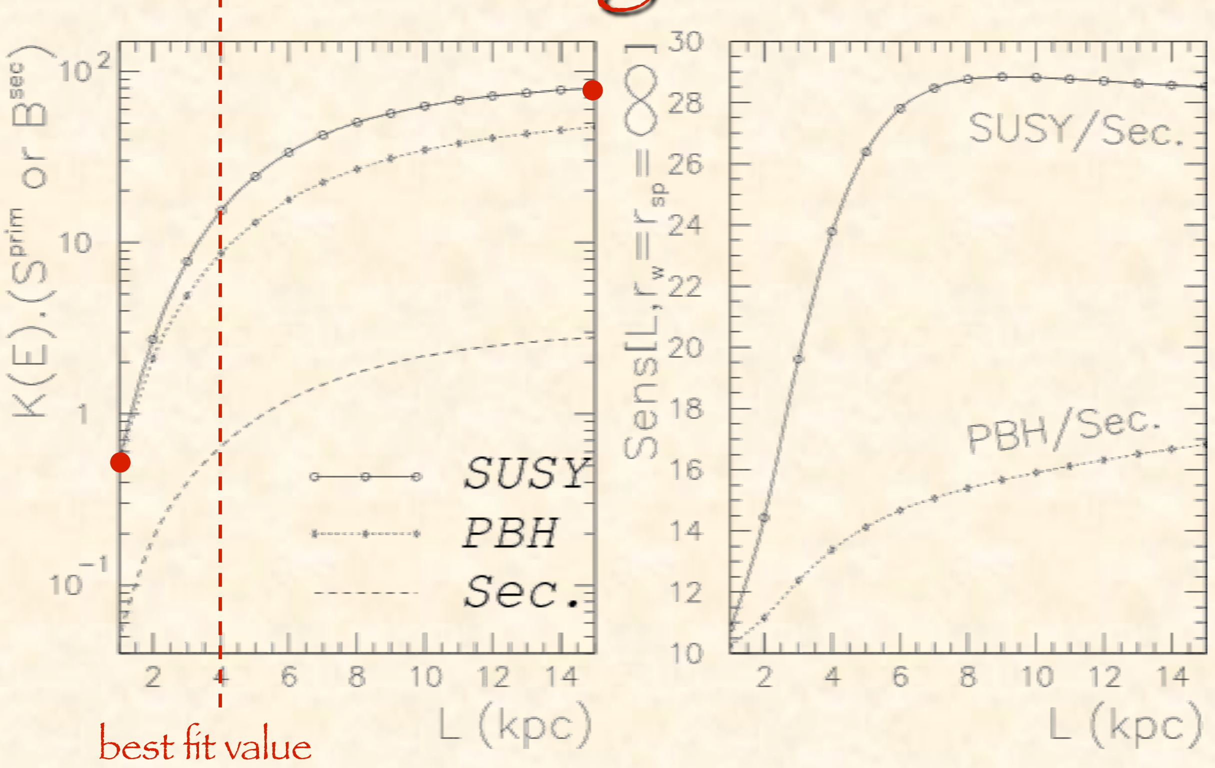
- solution of the steady-state diffusion equation with energy losses and reacceleration
- depends on a number of astrophysical parameters:
  - diffusion coefficient $K(E) = K_0 \beta (\mathcal{R}/1\,\mathrm{GV})^{\delta}$
  - height of the diffusive halo $L$
  - galactic wind velocity $V_c$
  - Alfven velocity (reacceleration) $V_A$

The params are constrained by stable nuclei propagation, mainly B/C

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

| case | $\delta$ | $K_0$ (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 |

# Dependence on height of diffusive halo

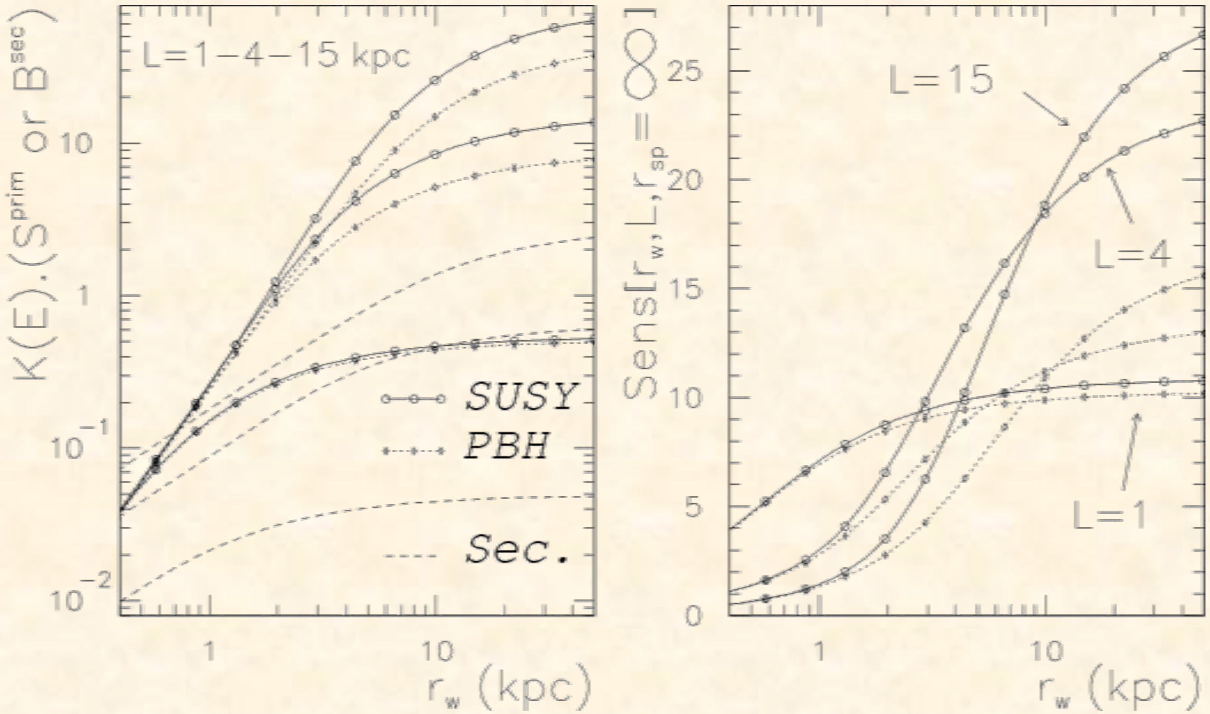



- L determines the extension of the confinement region:
  - For small L, only the sources very close to the solar neighborhood can contribute
  - As L increases, confinement is more efficient and more sources contribute

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

# Dependence on galactic wind velocity

$$r_{\rm w} \equiv \frac{2K(E)}{V_c}$$

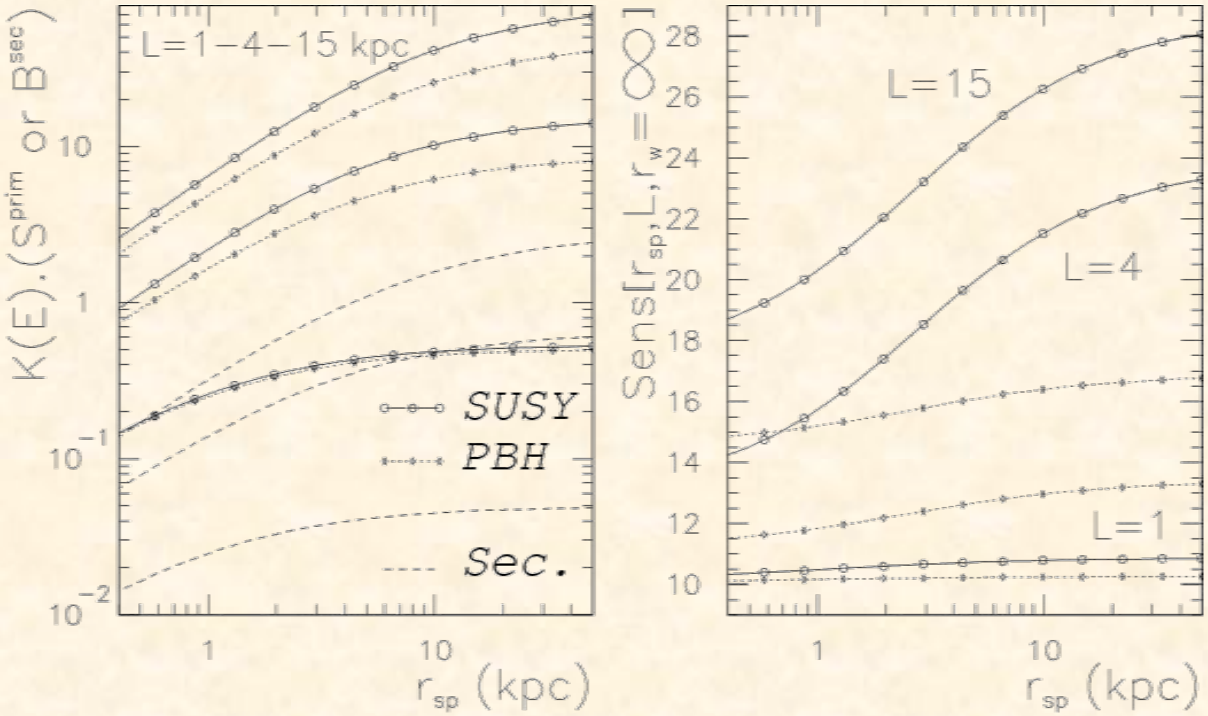



- The galactic wind blows the particles away from the disk (convection), leading to an effective size of the diffusive halo of the order of $r_W$
- There is a competition between L and $r_W$:
  - For large L, the evolution is driven by $r_W$
  - For small $r_W$ all curves converge, independently of L, 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

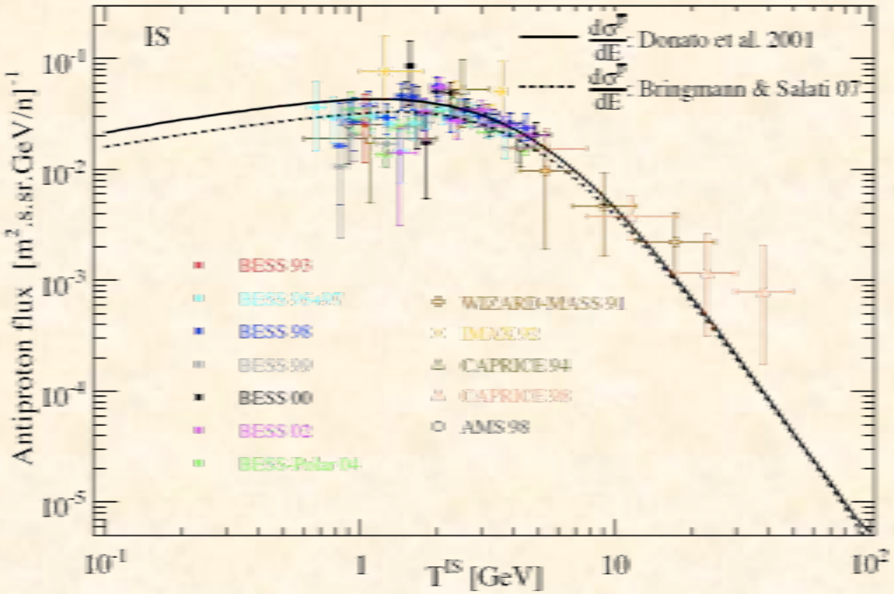
$$r_{\rm sp} \equiv \frac{K(E)}{h\Gamma_{\rm inel}(E)}$$



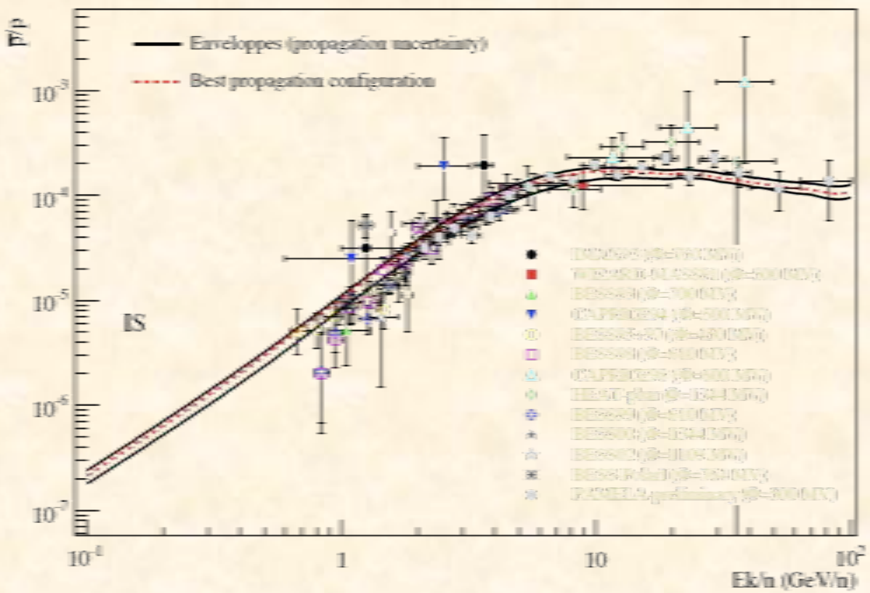

- At low energies particles are destroyed more easily, since the probability to cross the disk (and therefore to interact with matter) increases relatively to escape (diffusive or convective)
- There is a competition between L , $r_W$ and $r_{SP}$:
  - The effect of $r_{SP}$ is milder: the cut-off due 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

# Secondary antiprotons




Antiproton flux



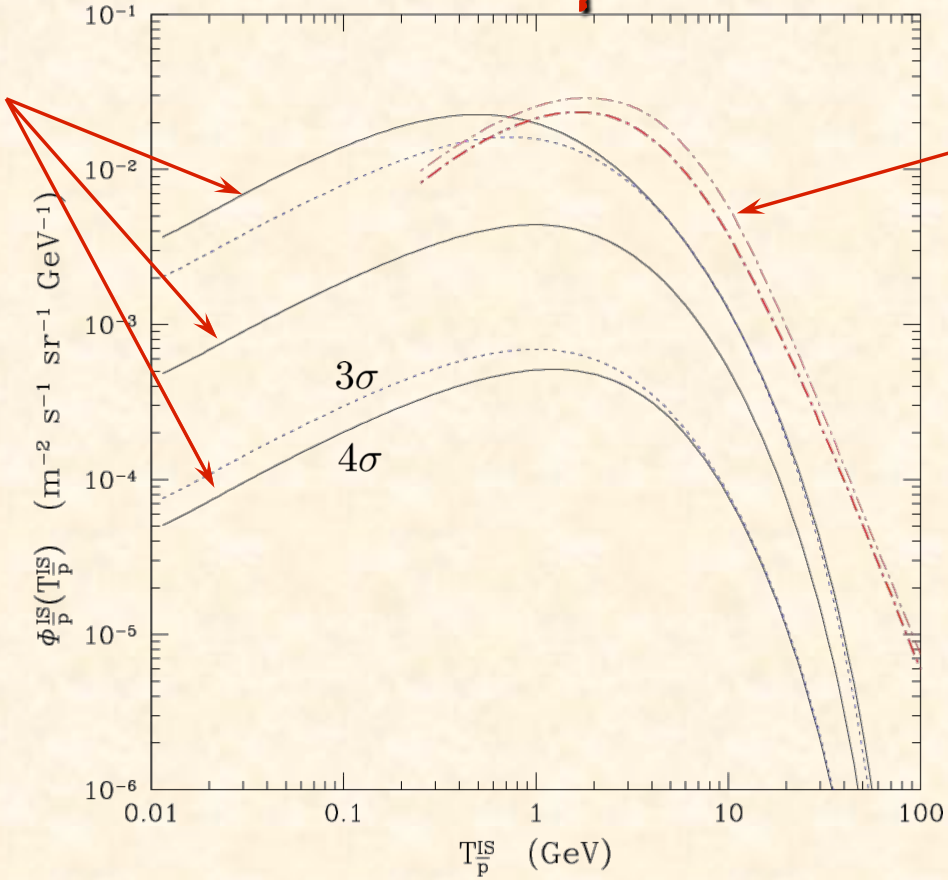

Antiproton/proton fraction

F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, PRL 102 (2009) 071301

# Interstellar antiproton fluxes

Primaries [1]
(DM signal)

$m_\chi = 100$ GeV




Secondaries [2]
(background)

< 25% uncertainty

| case | $\delta$ | $K_0$ $(\mathrm{kpc}^2/\mathrm{Myr})$ | $L$ (kpc) | $V_c$ (km/sec) | $V_A$ (km/sec) | $\chi^2_{B/C}$ |
|---|---|---|---|---|---|---|
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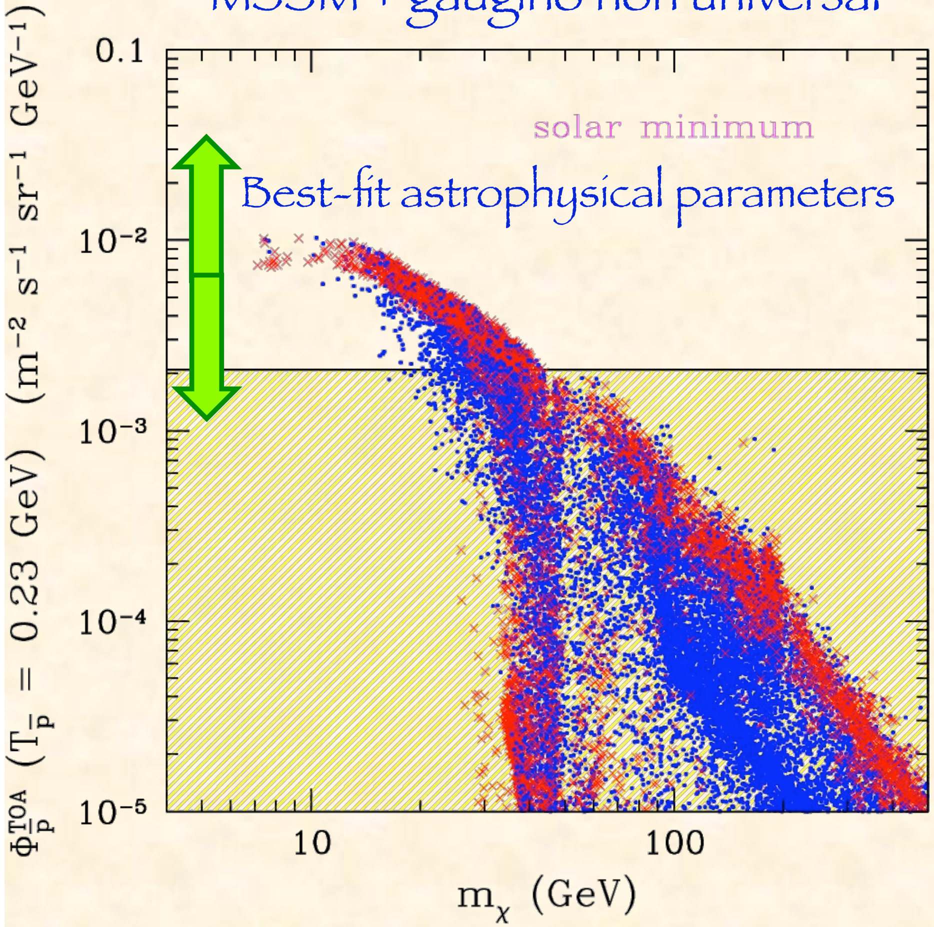
(1) F. Donato, N. Fornengo, D. Maurin, P. Salati, R. Taillet, PRD 69 (2004) 0603501

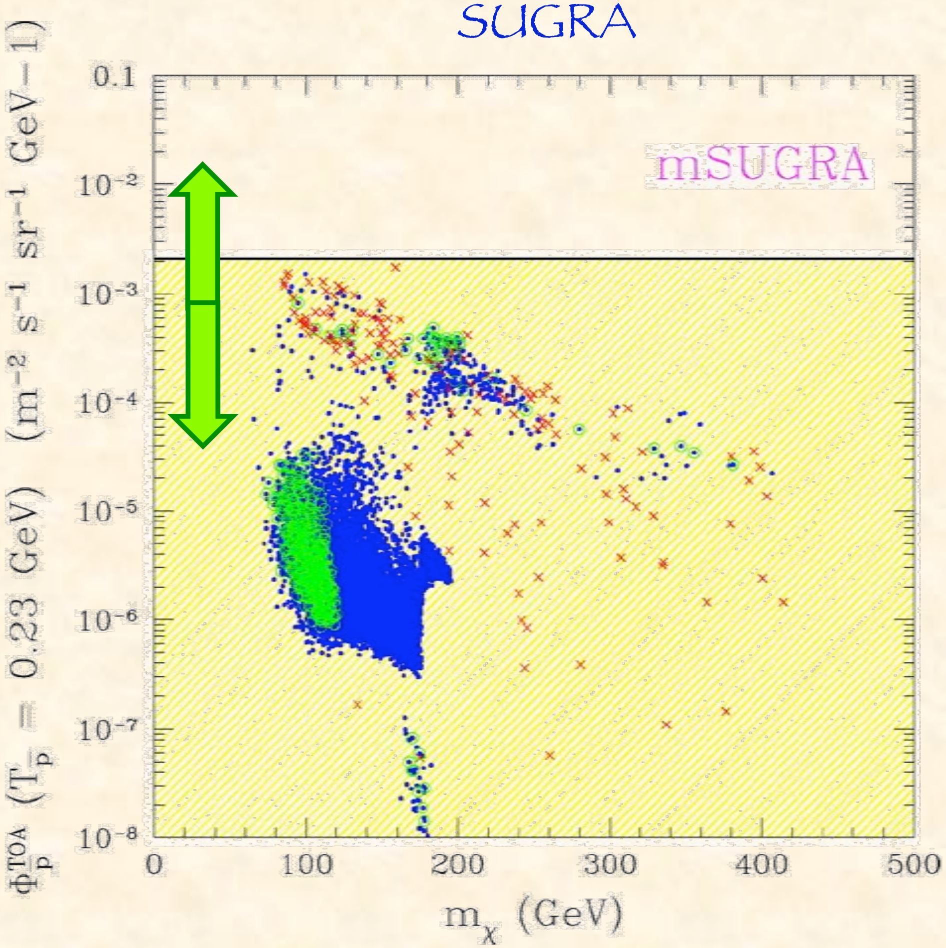
(2) D. Maurin et al. Astron. Astrophys. 381 (2002) 539

# Theoretical predictions for neutralinos

MSSM + gaugino non universal




SUGRA

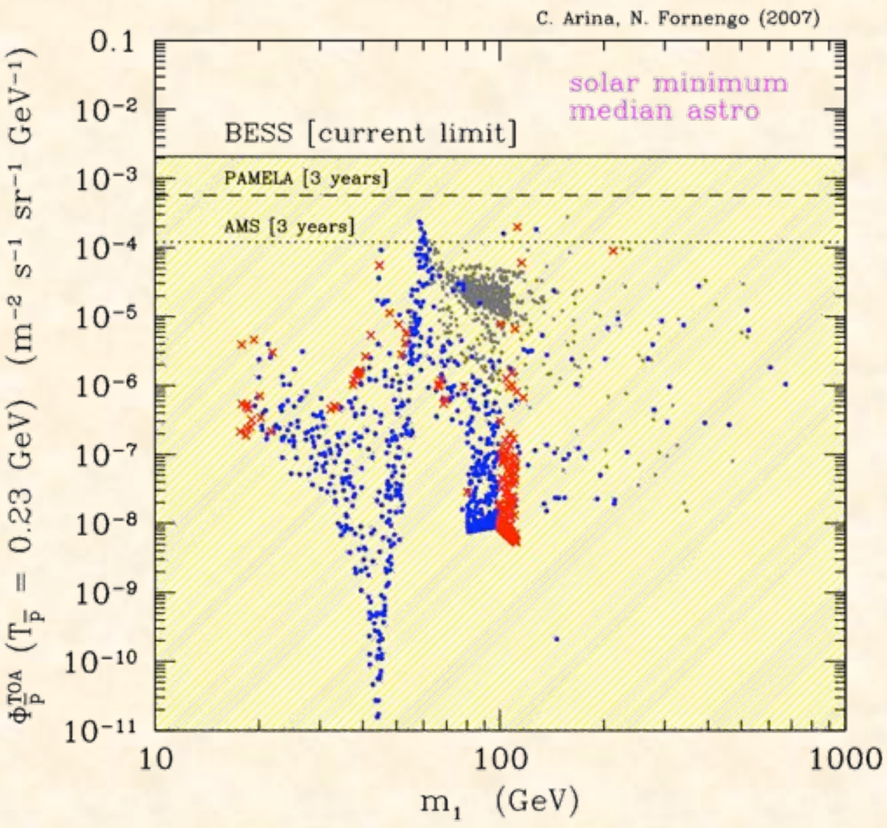



- cosmologically dominant neutralinos $0.095 \leq \Omega_\chi h^2 \leq 0.131$
- cosmologically subdominant neutralinos $\Omega_\chi h^2 < 0.095$

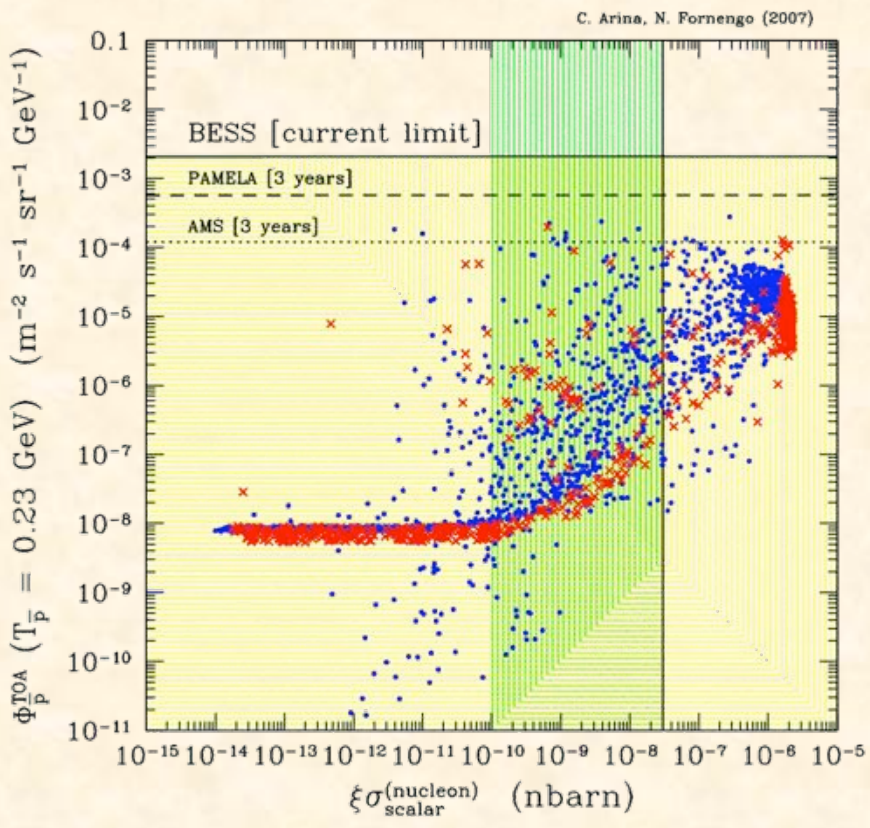
A. Bottino, F. Donato, N.F., S. Scopel, PRD 70 (2004) 015005

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

# Sneutrinos in Left-Right models




antiprotons vs. mass

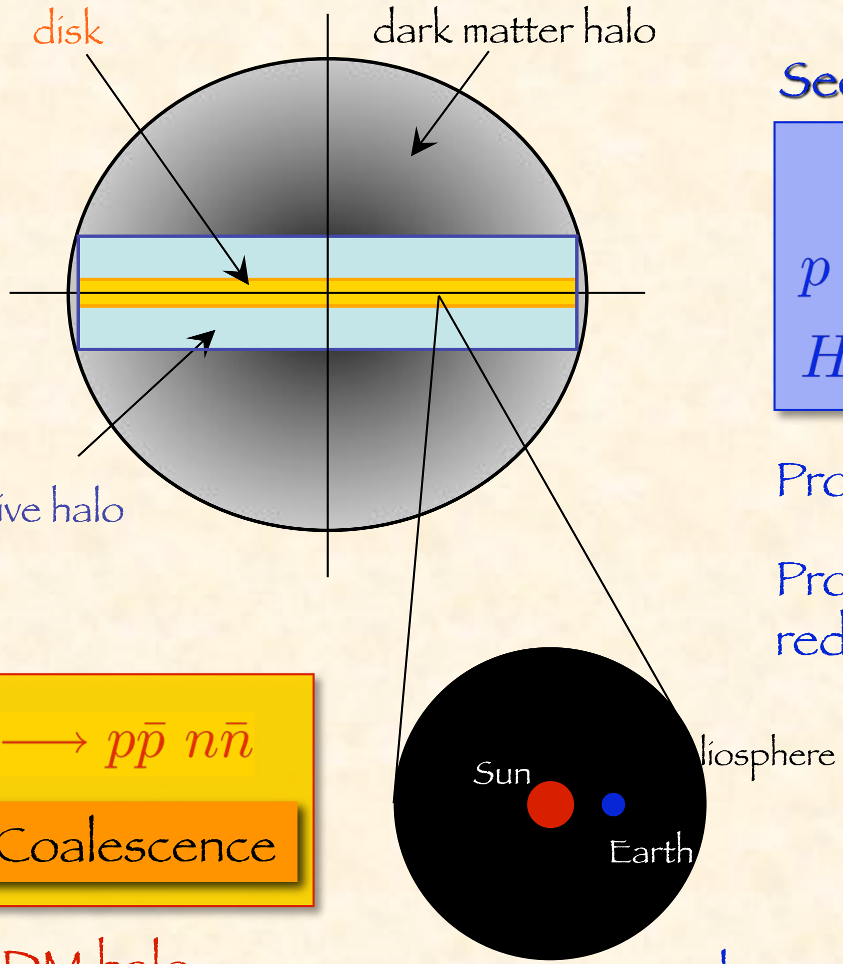



antiprotons vs. direct detection

# Antideuterons

# Cosmic antideuterons

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




## Secondaries

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

Produced in the disk

Propagation and energy redistribution in the diffusive halo

## DM signal

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

$$\bar{p} + \bar{n} \longrightarrow \bar{D}$$ Coalescence

Produced in the DM halo

Propagation and energy redistribution in the diffusive halo

solar modulation

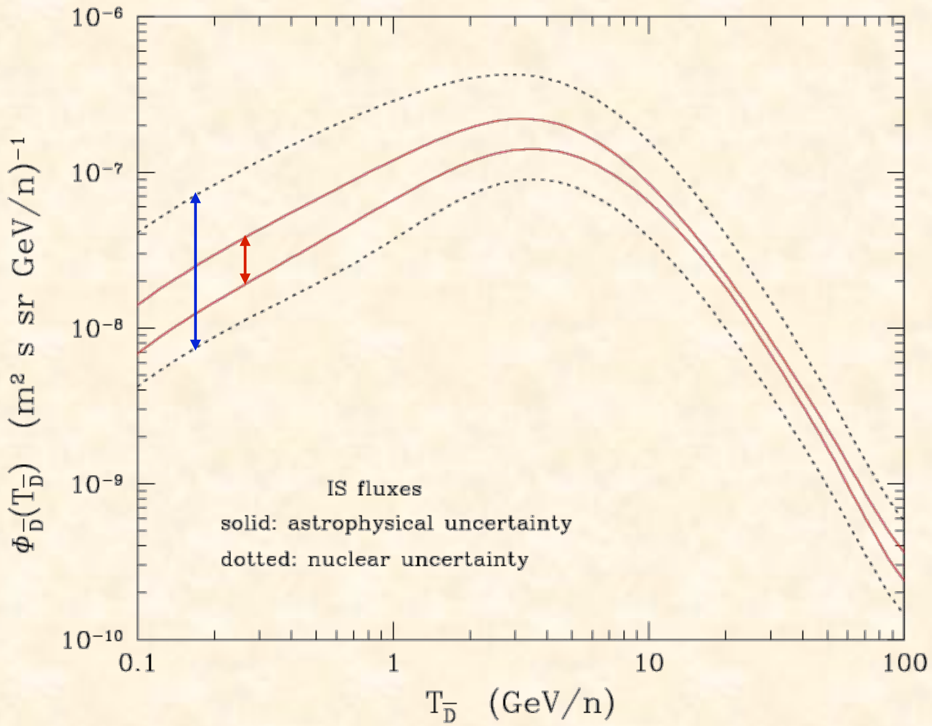
# Secondaries and their uncertainties

Astrophysical:

- Transport
- Energy losses and redistribution

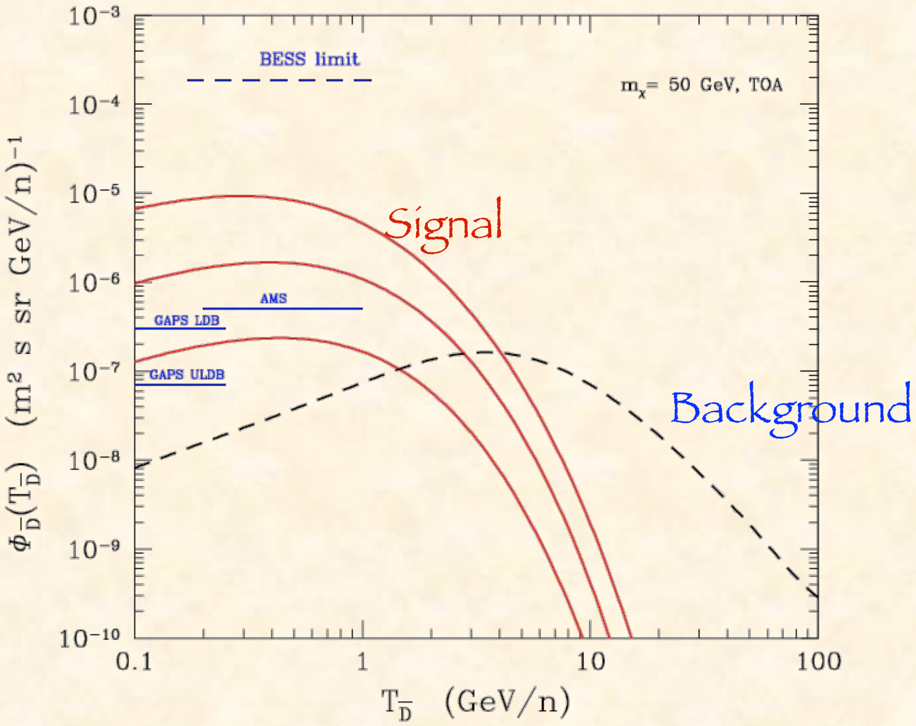
Nuclear (very conservative):

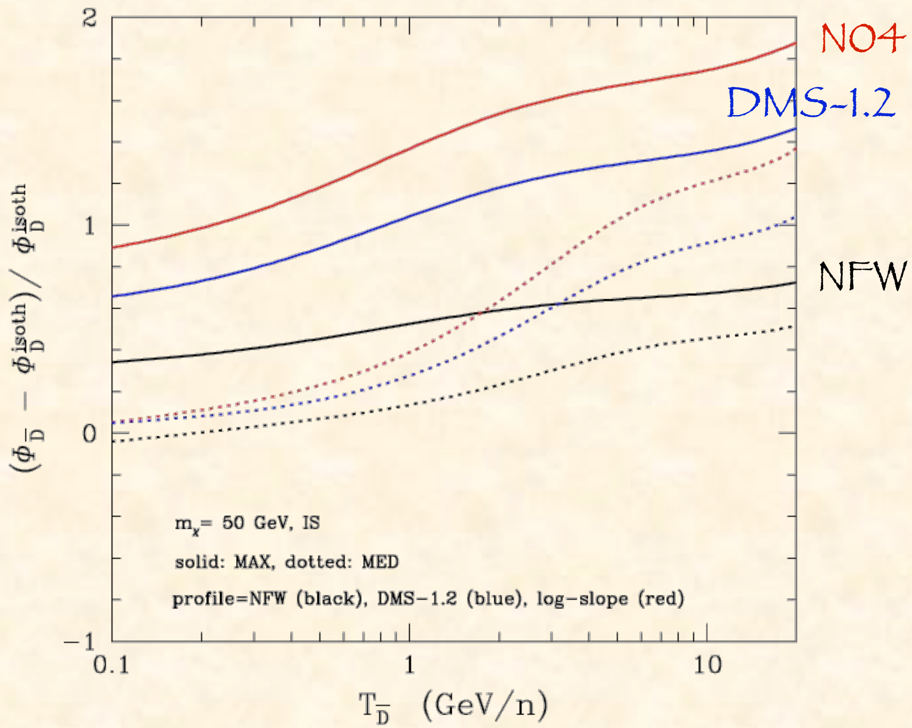
- Elementary production processes
- Coalescence




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

# TOA fluxes and S/B gain



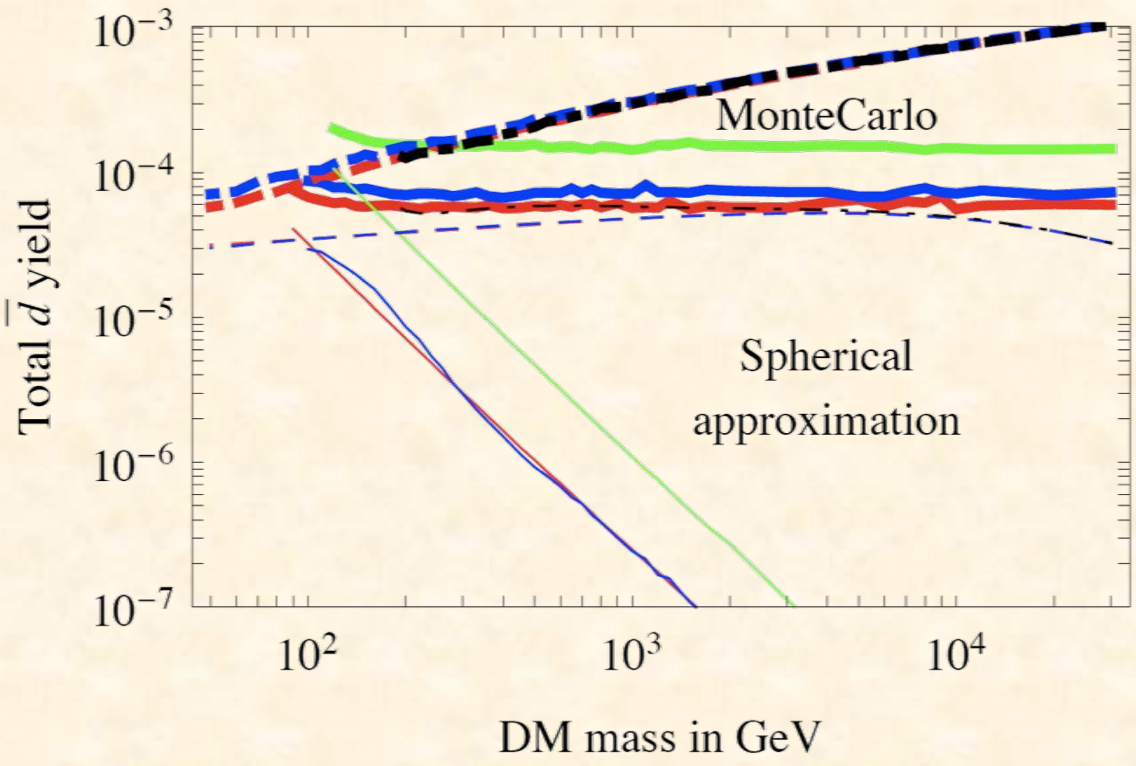




Signal with uncertainty band for:

- 50 GeV WIMP mass
- WMAP relic abundance

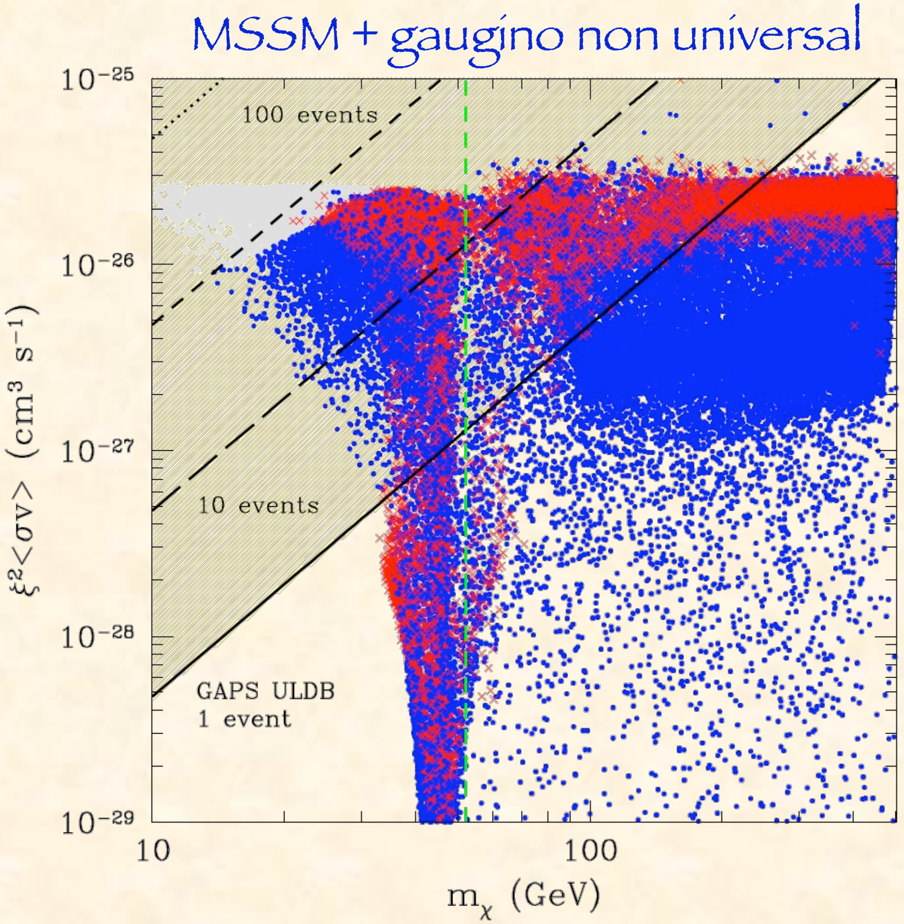
Change of DM halo profile
[fixed local density]

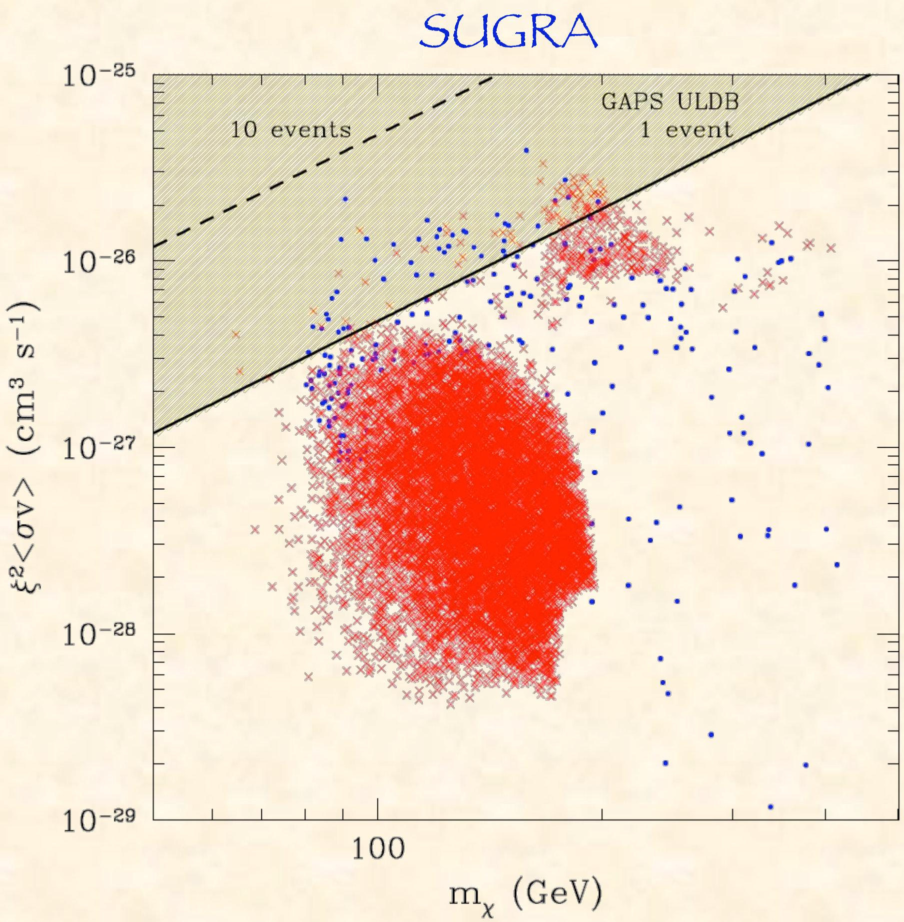
A. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506




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

# Antideuterons




- cosmologically dominant neutralinos $0.095 \leq \Omega_\chi h^2 \leq 0.131$
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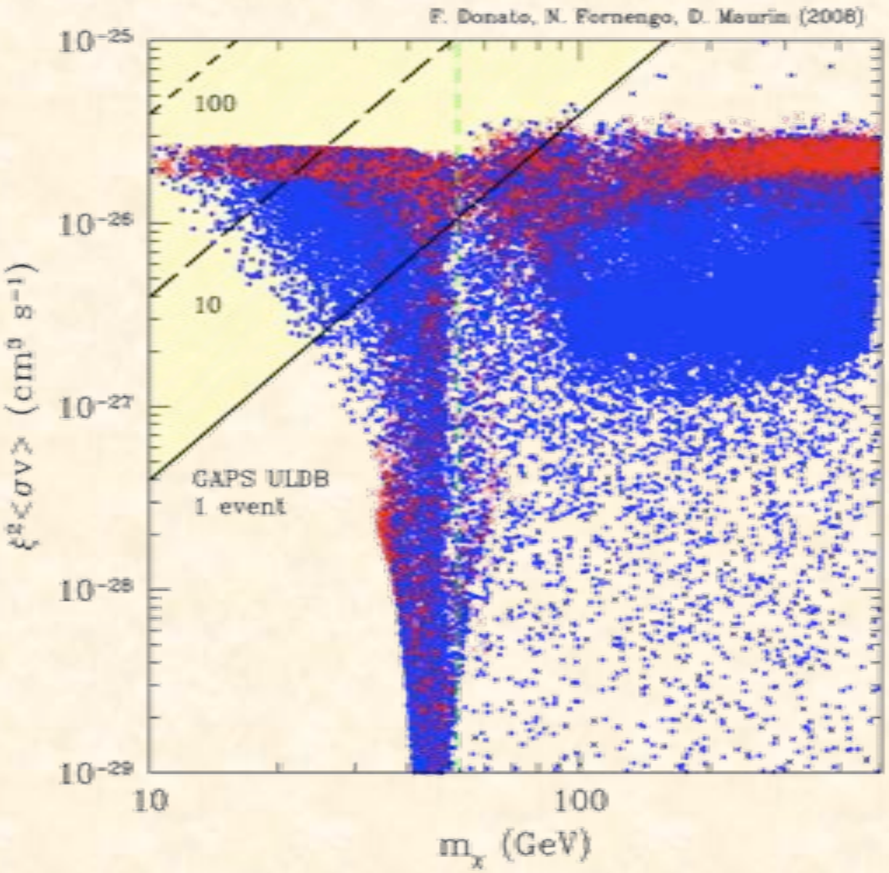
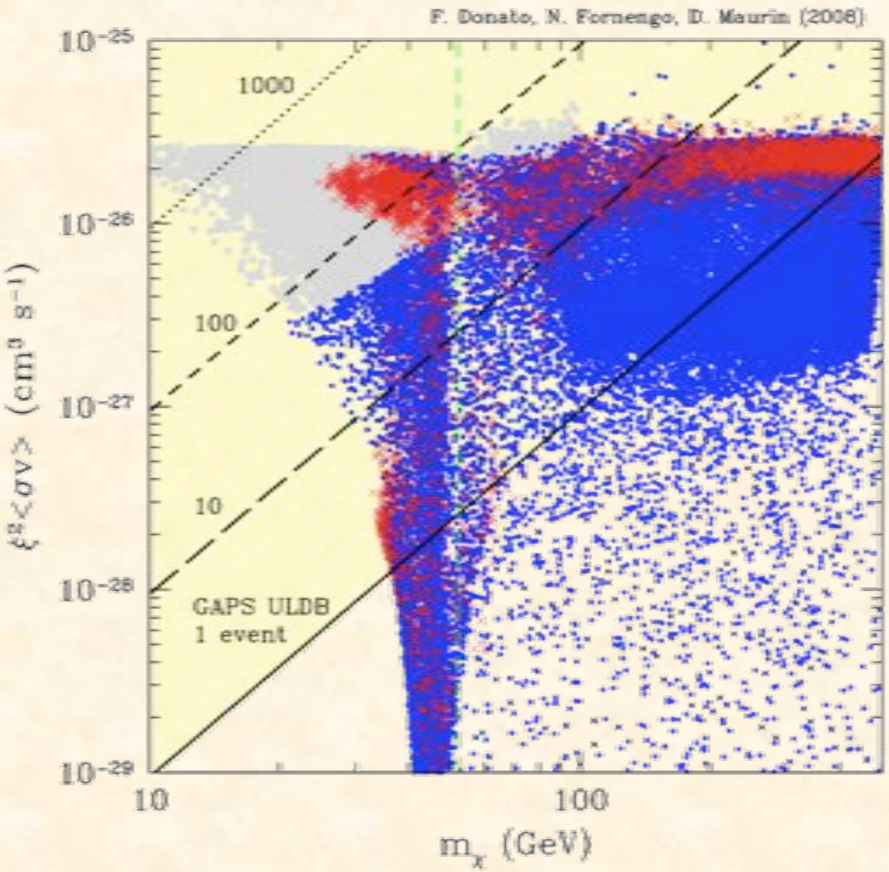
A. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

# Antideuterons




MIN

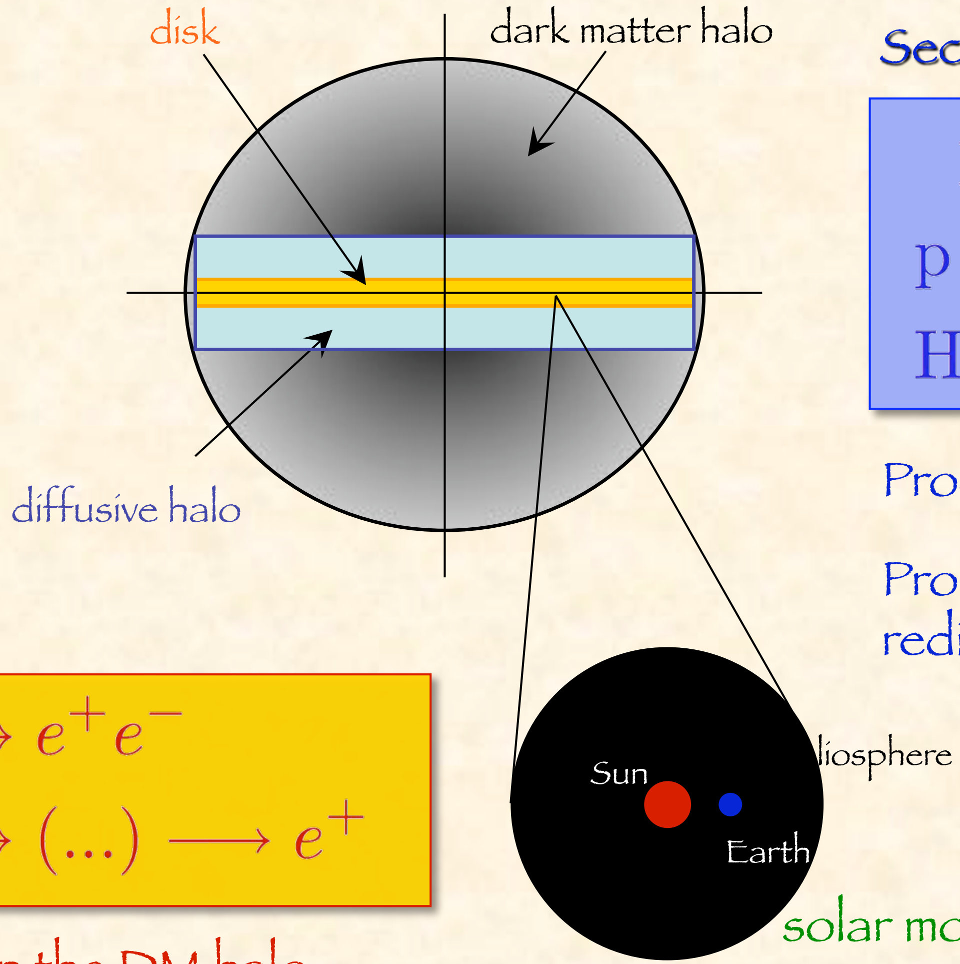



MAX

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

# Positrons

# Cosmic positrons




## Secondaries

$$
\begin{aligned}
p_{\mathrm{CR}} + p_{\mathrm{ISM}} &\longrightarrow e^+ \\
p_{\mathrm{CR}} + \mathrm{He}_{\mathrm{ISM}} &\longrightarrow e^+ \\
\mathrm{He}_{\mathrm{CR}} + p_{\mathrm{ISM}} &\longrightarrow e^+
\end{aligned}
$$

Produced in the disk

Propagation and energy redistribution in the diffusive halo

## DM signal

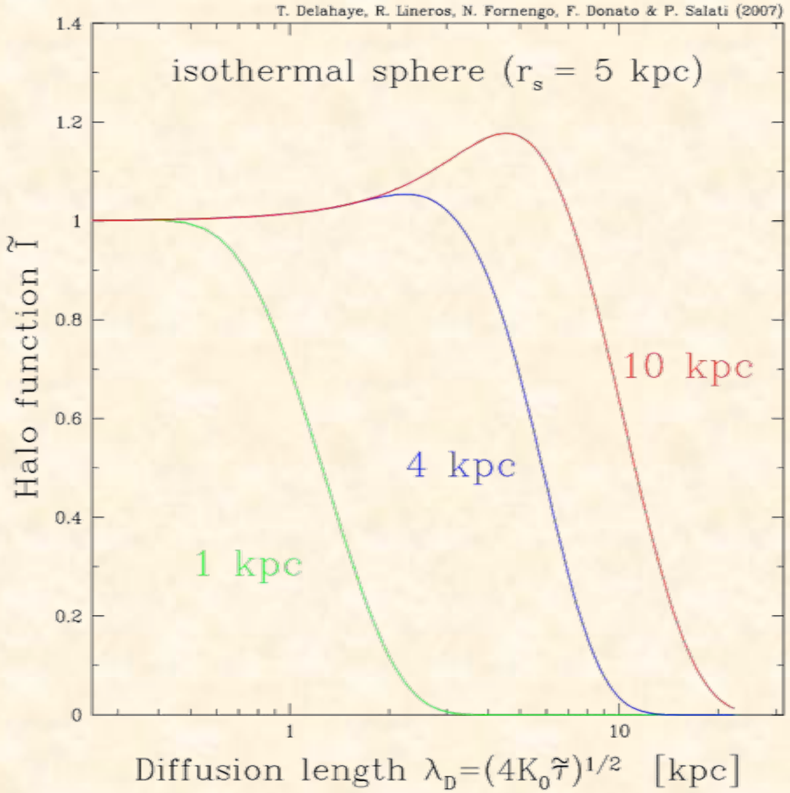
$$
\begin{aligned}
\chi\chi &\longrightarrow e^+e^- \\
\chi\chi &\longrightarrow (\ldots) \longrightarrow e^+
\end{aligned}
$$

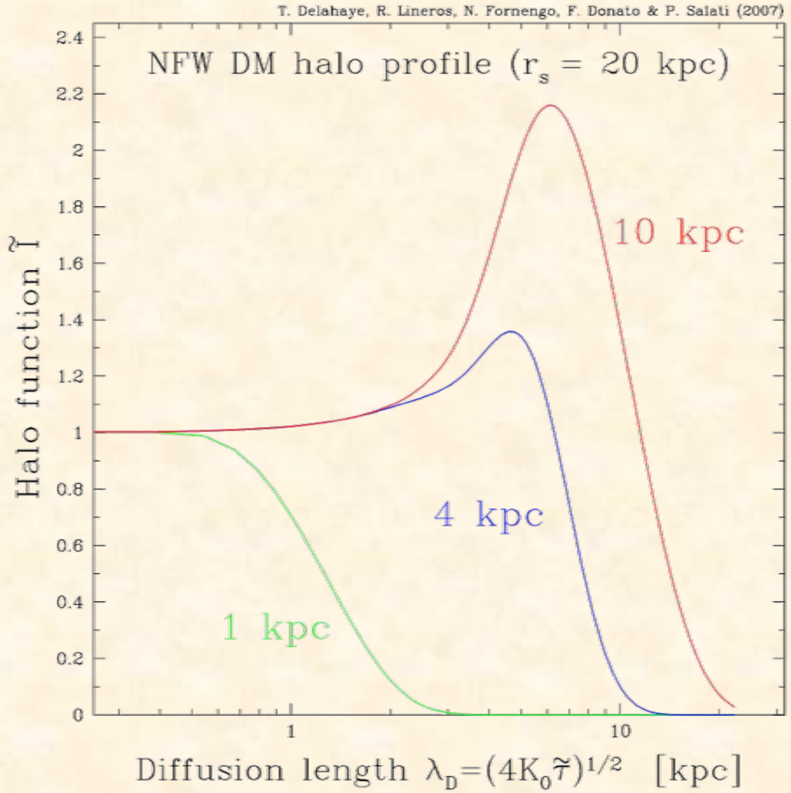
Produced in the DM halo

Propagation and energy redistribution in the diffusive halo

Astrophysical sources (e.g.: pulsars)

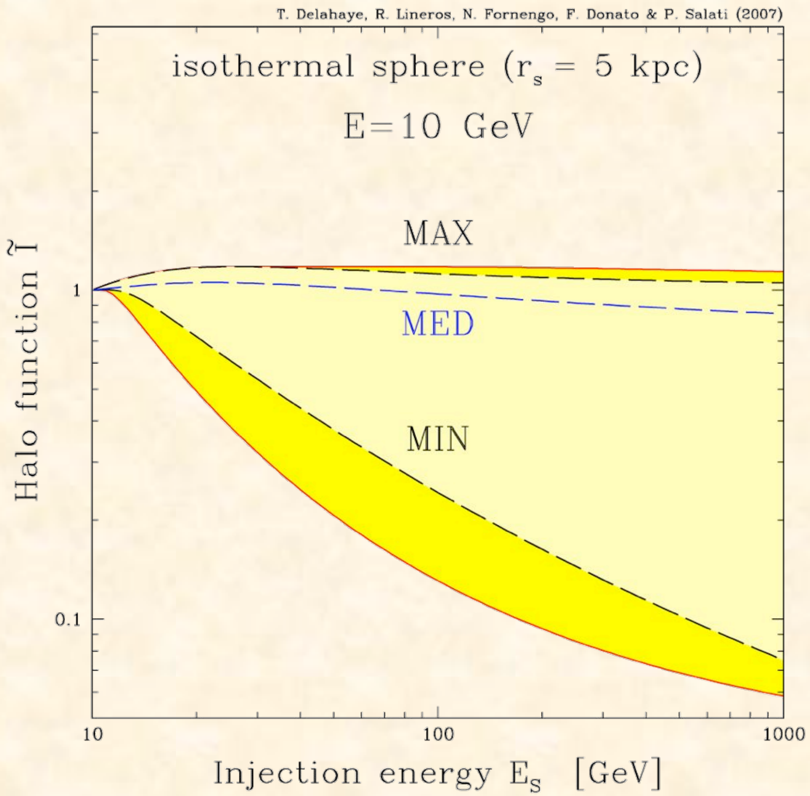
# Halo function dependence on L and DM profile

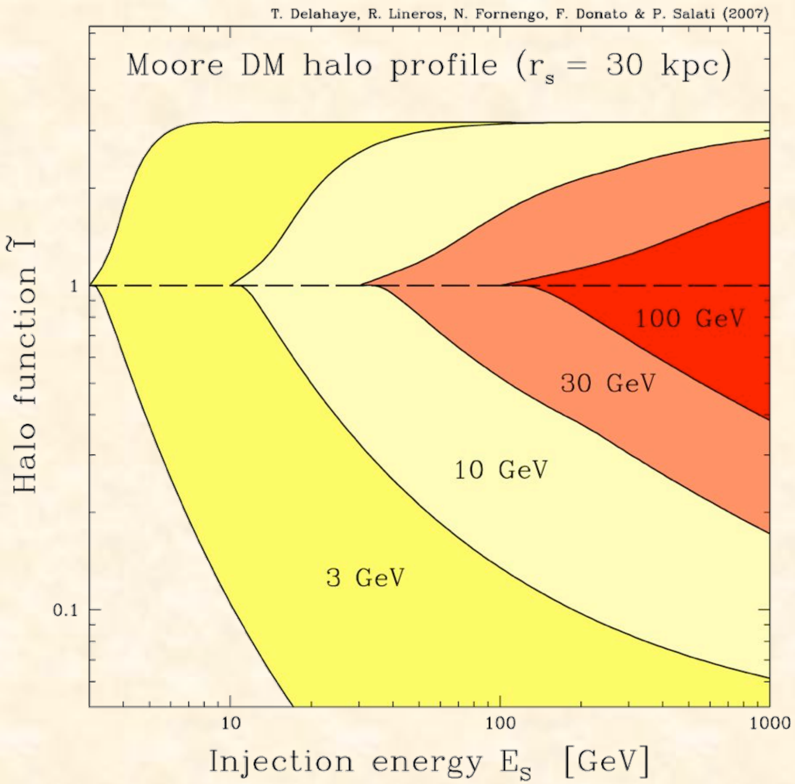



T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

# Uncertainty on the halo function



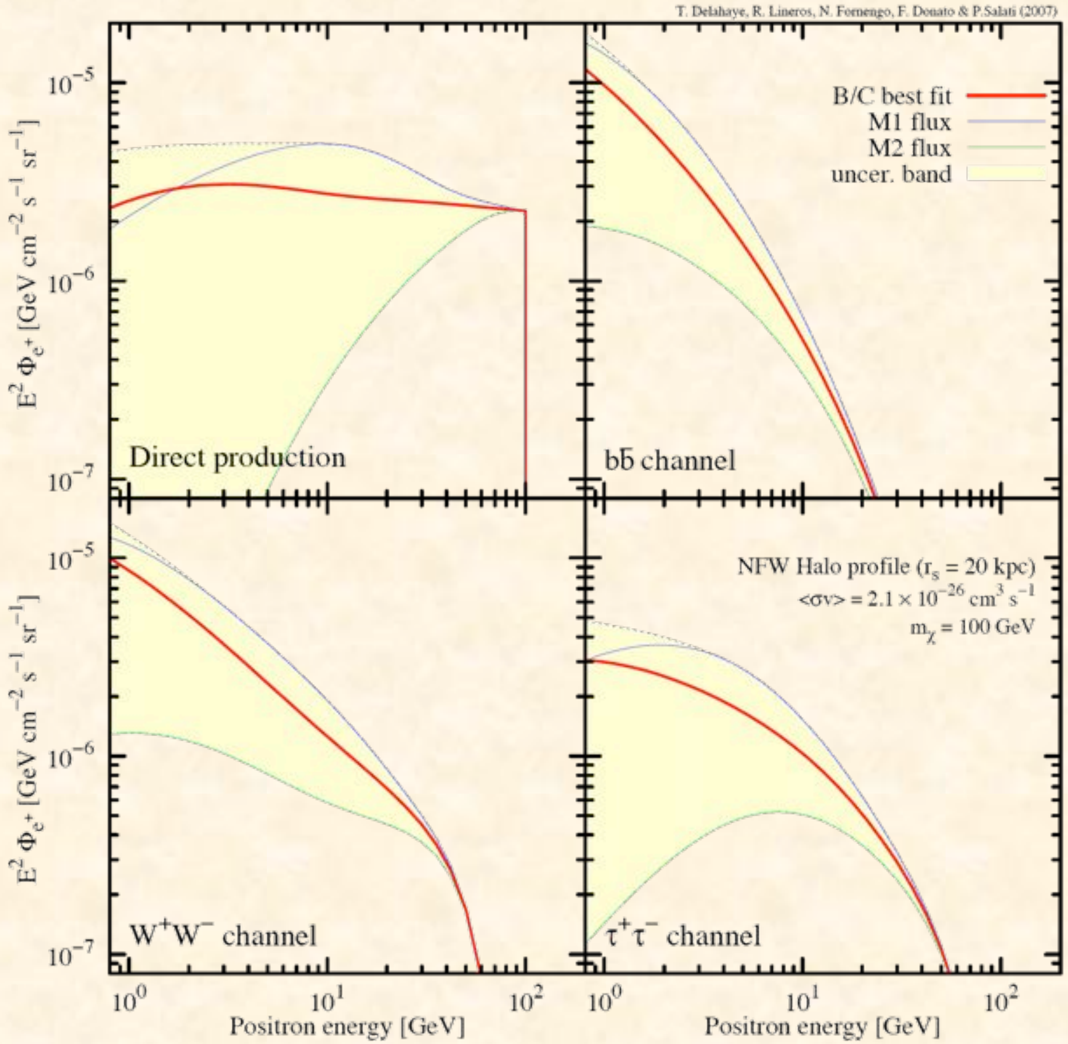




"observed" energy: E ≃ 10 GeV

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

# DM signal: astrophysical uncertainties

$m_\chi$ = 100 GeV

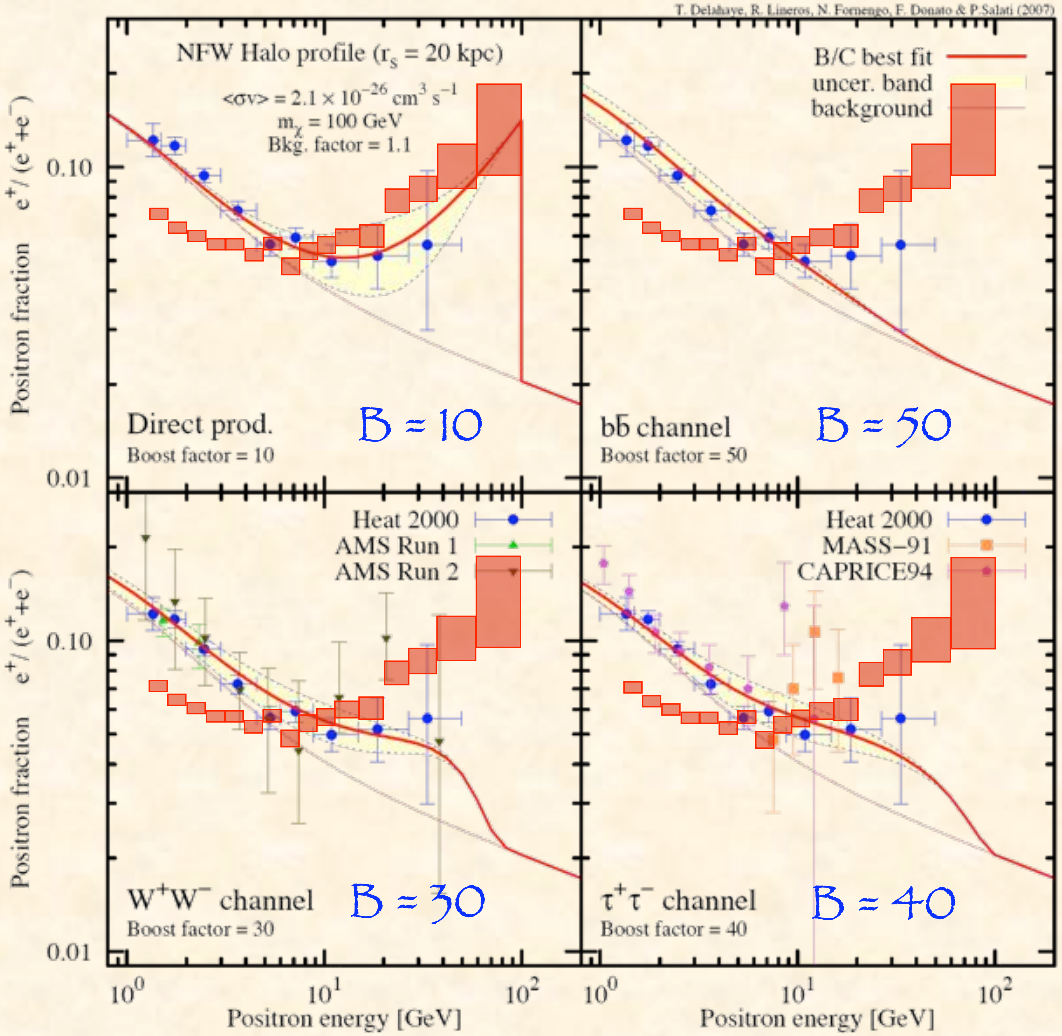



T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

# Positron fraction: including a DM signal

$m_\chi$ = 100 GeV

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

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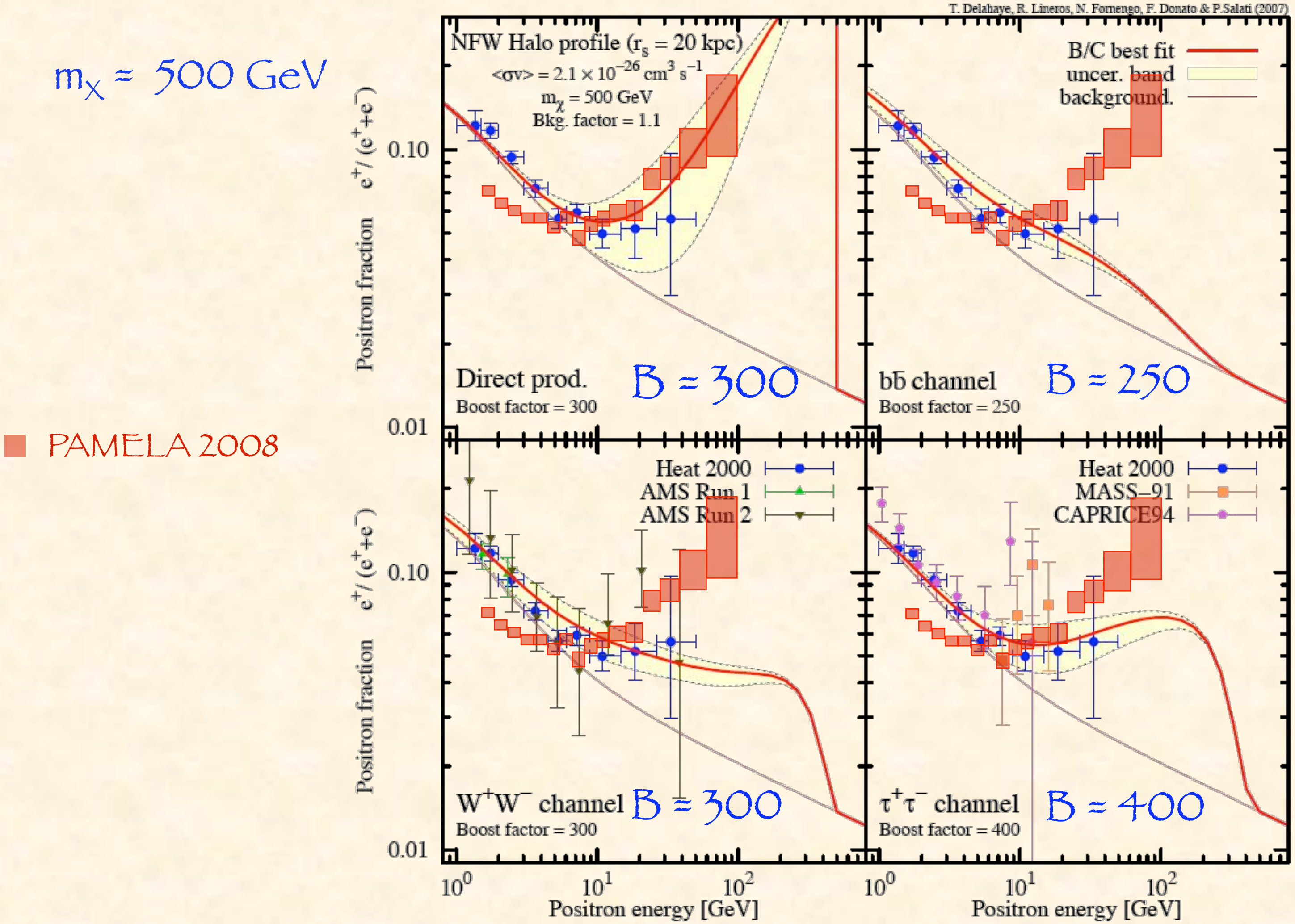
For annihilation cross section consistent with WMAP for a thermal relic

Smooth NFW halo

# Positron fraction: including a DM signal

$m_\chi \simeq$ 500 GeV

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

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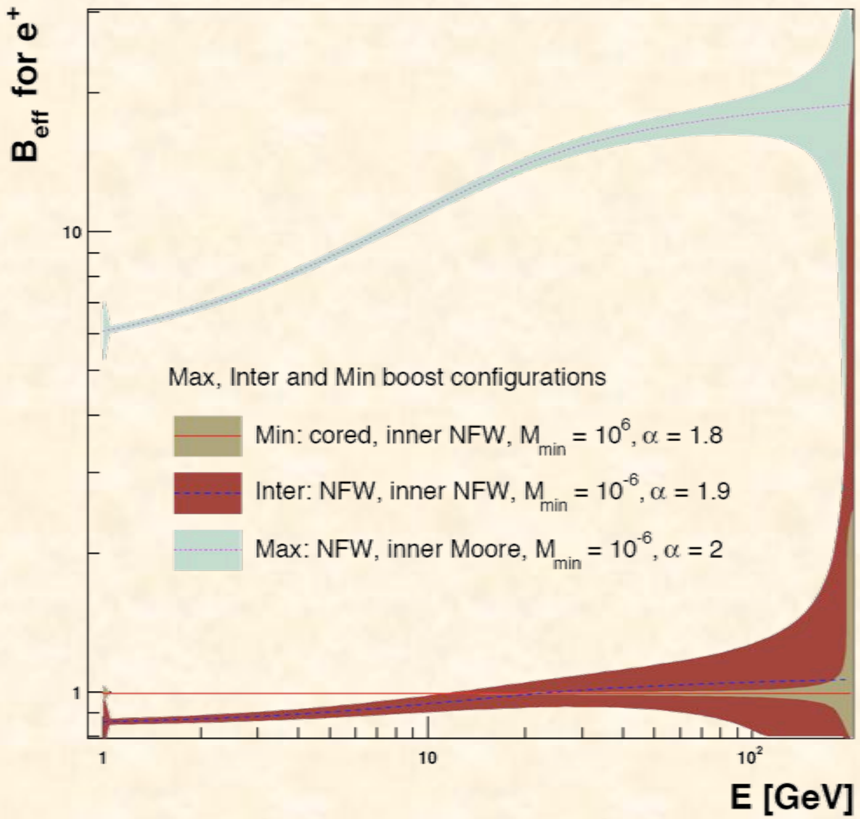
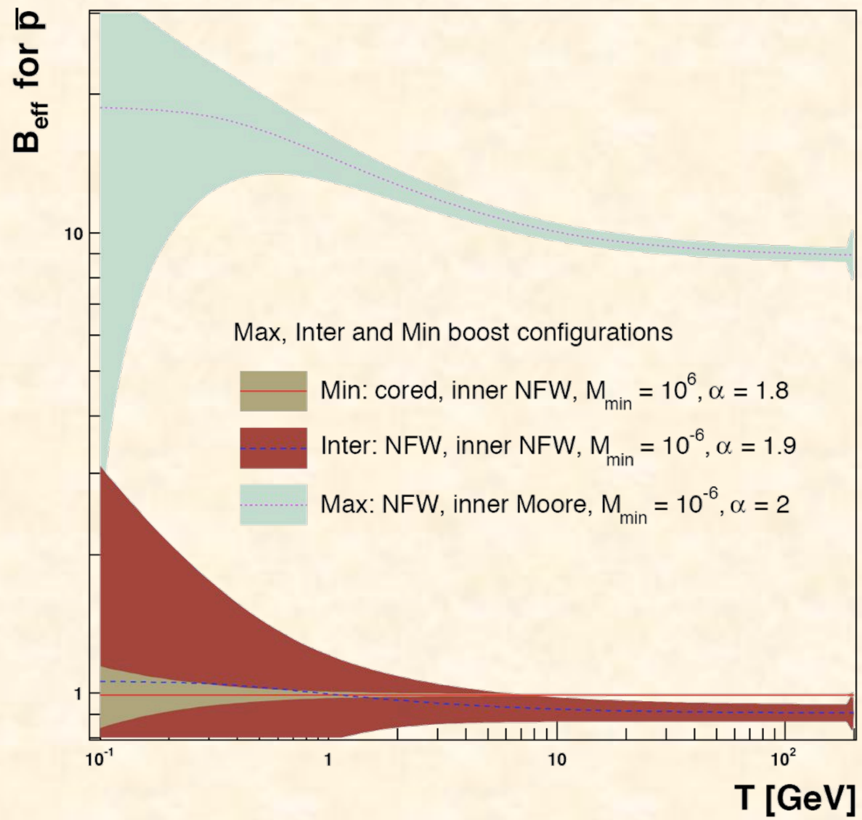
For annihilation cross section consistent with WMAP

Smooth NFW halo

# Astrophysical boost



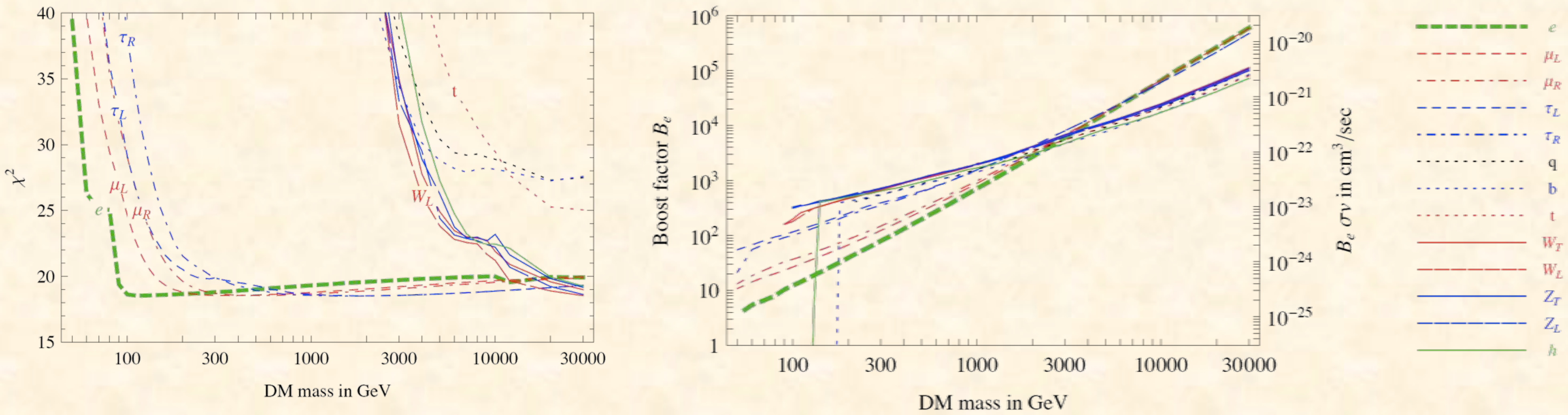

Positrons




Antiprotons

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

# Model independent analysis




M. Cirelli, M. Kadastik, M. Raidal, A. Strumia, arXiv:0809.2409v3 [hep-ph]

Fit on positron and antiproton data (with S&M background)

Hadrophobic or very heavy DM: does not fit well SUSY candidates

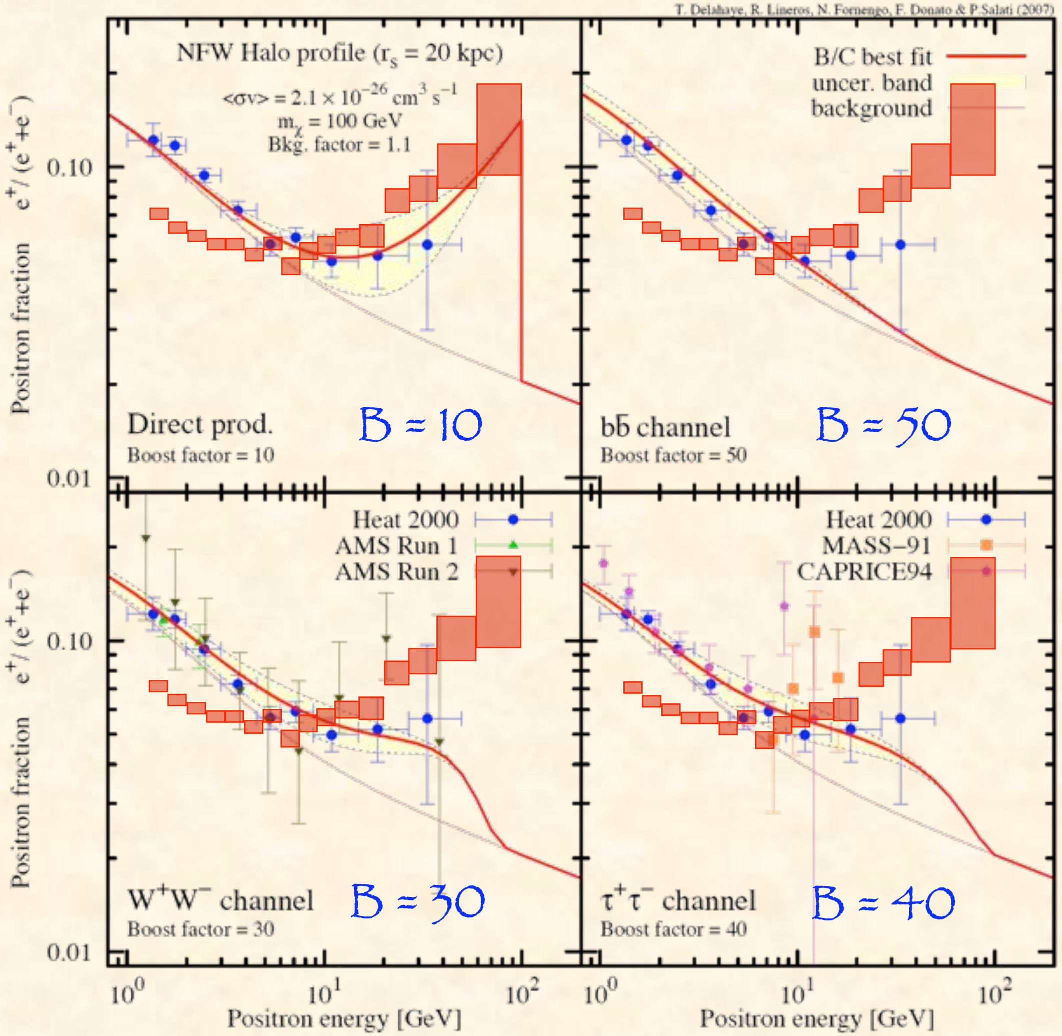
See also: V. Barger, W.-Y. Keung, D. Marfatia, G. Shaughnessy, arXiv:0809.0162v2 [hep-ph]
D. Grasso et al., arXiv:0905.0636v1 [astro-ph.HE] : L. Bergstrom, J. Esjo, G. Zaharijas, arXiv:0905.0333 [astro-ph.HE]
P. Meade, M. Papucci, A. Strumia, T. Volansky, arXiv:0905.0480 [hep-ph]

# Positron fraction: including a DM signal

$m_\chi \approx 100$ GeV

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

■ PAMELA 2008

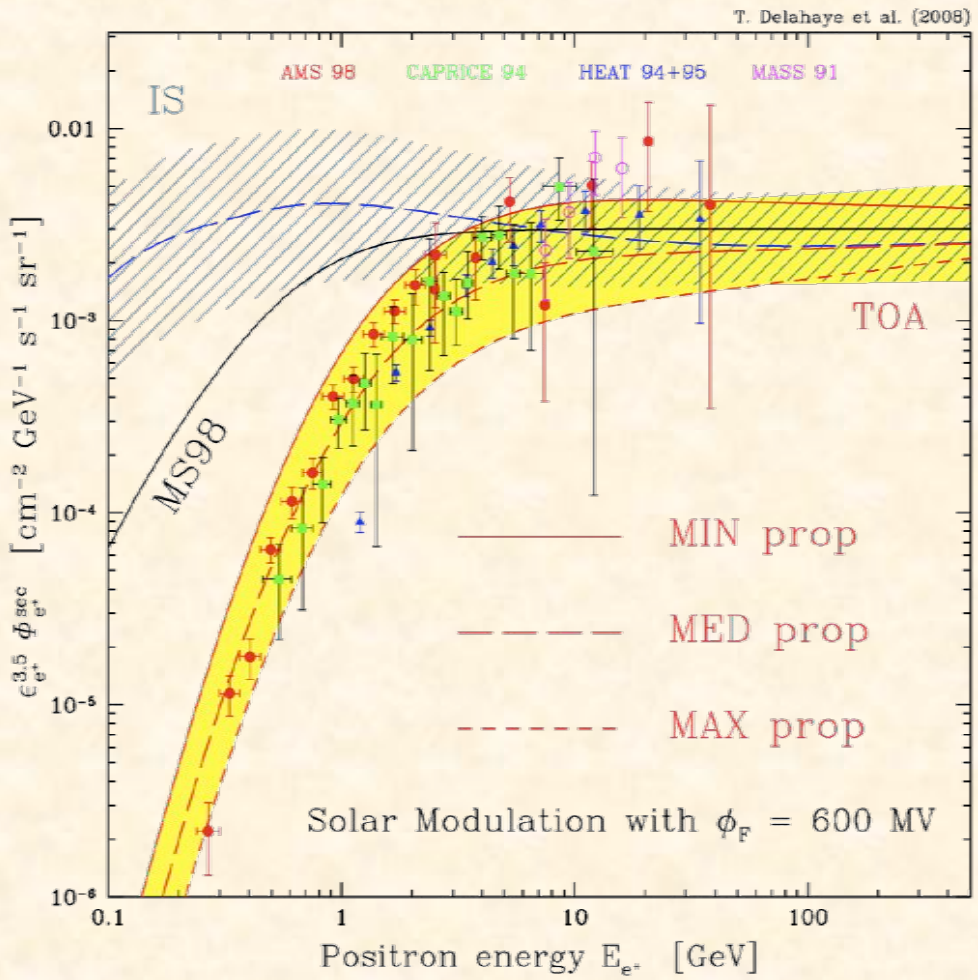



T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

For annihilation cross section consistent with WMAP for a thermal relic

Smooth NFW halo

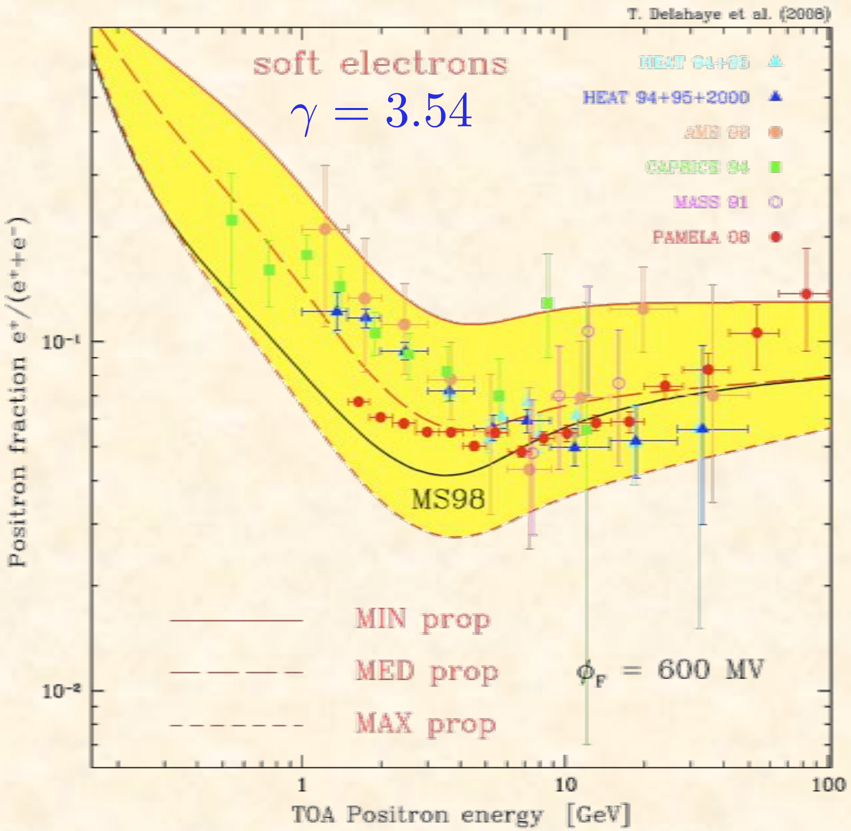
# Secondary positrons: propagation uncertainties

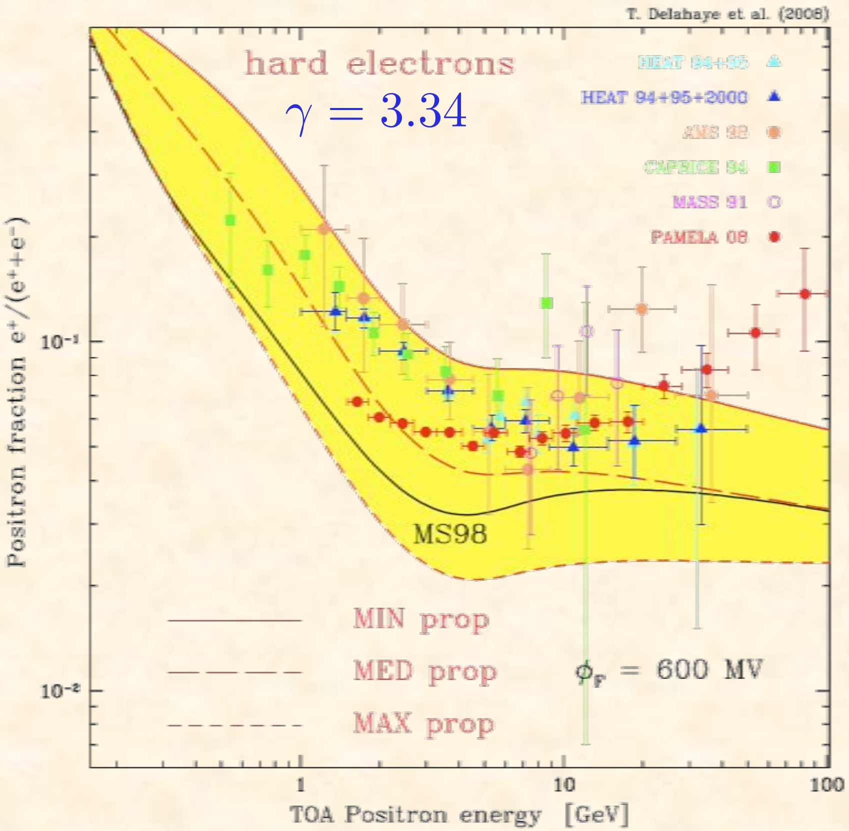



T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle, P. Salati, R. TailletAstronon. & Astroph. 501 (2009) 821

# Positron fraction

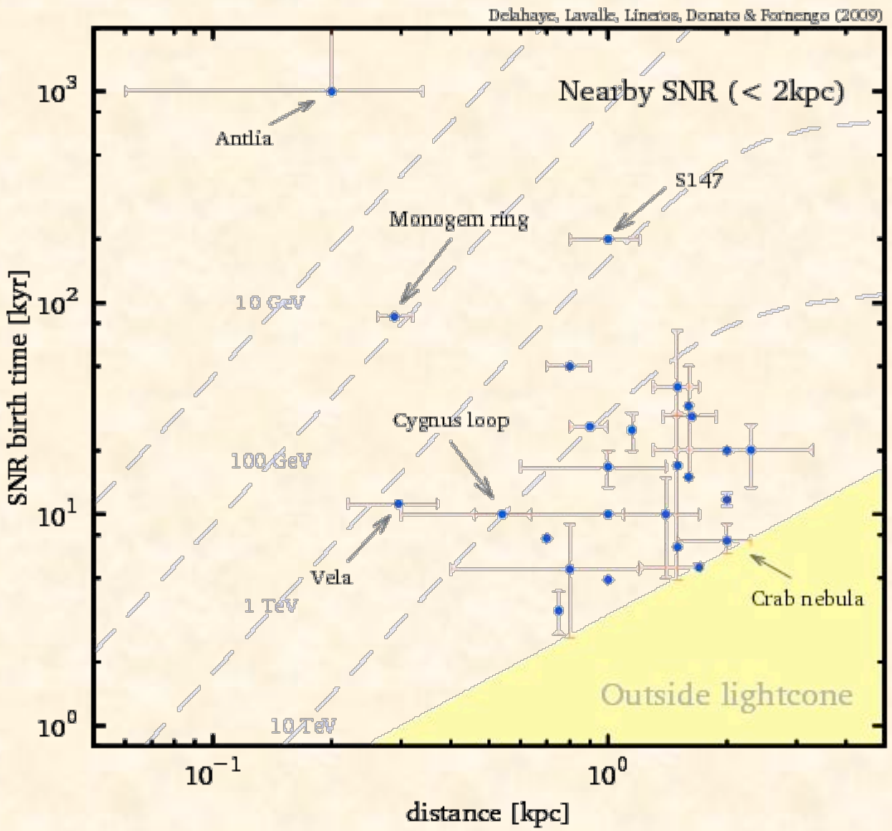
T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle, P. Salati, R. Taillet (arXiv:0809.5268 [astro-ph])

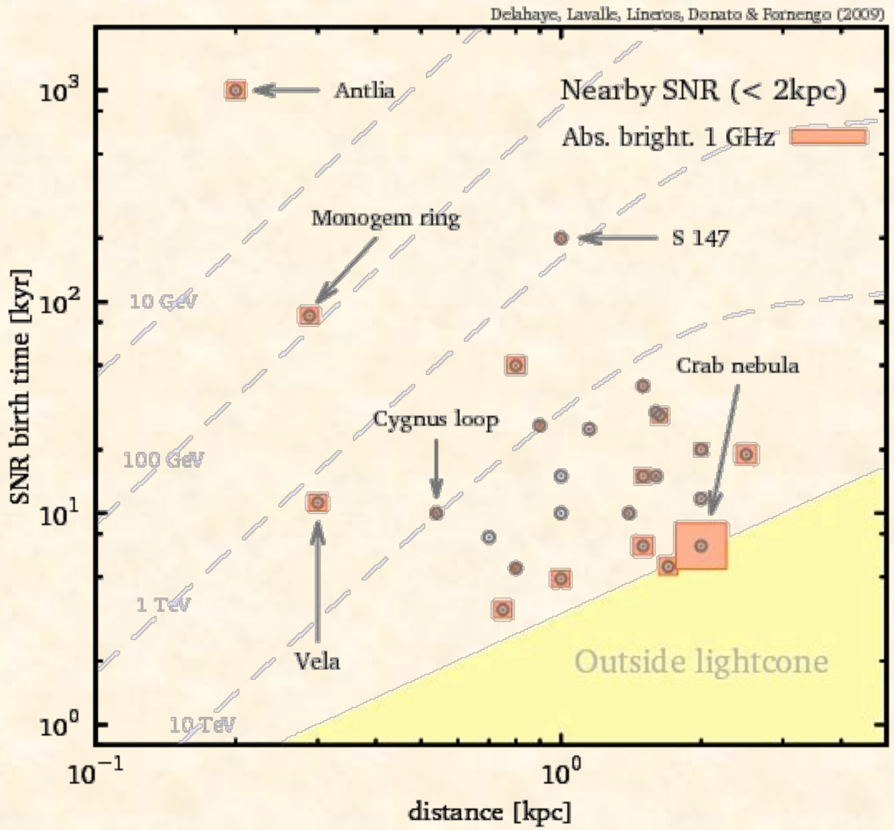


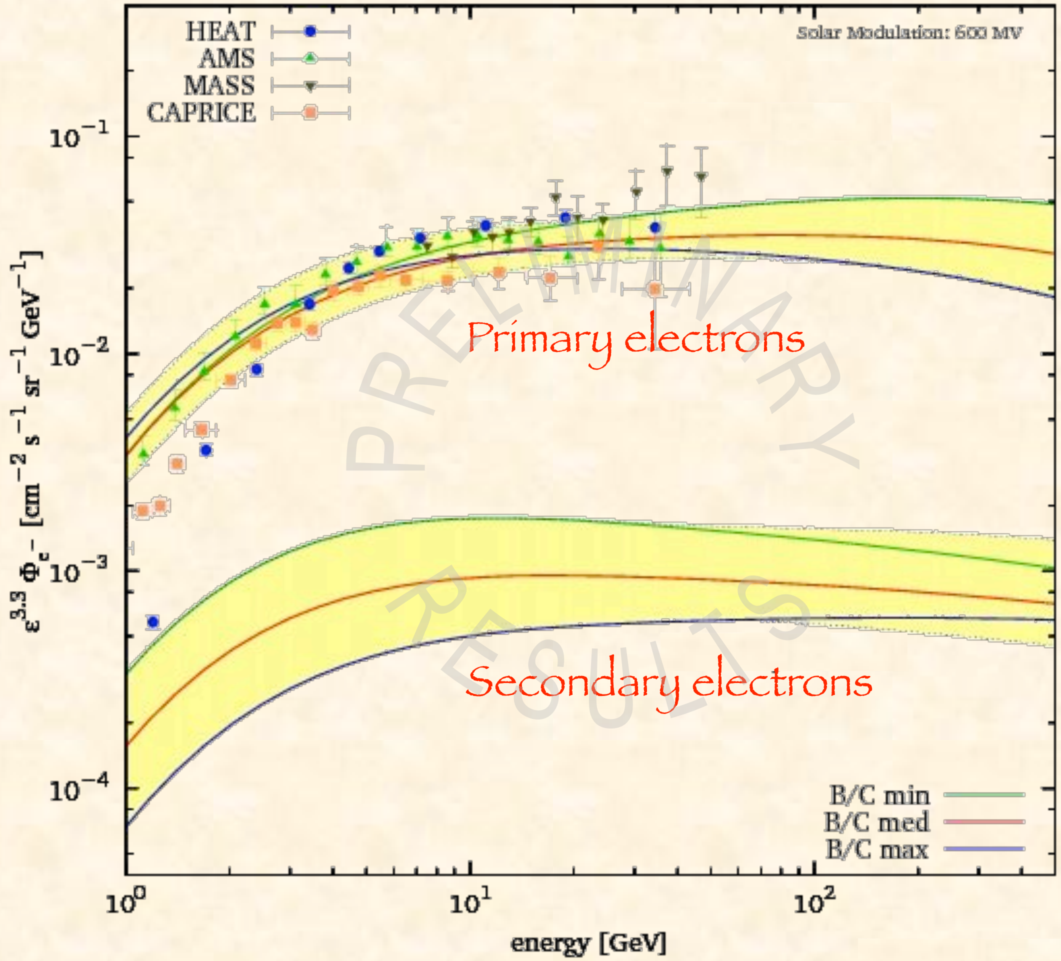

PAMELA data point toward an “excess”

# Supernova remnants



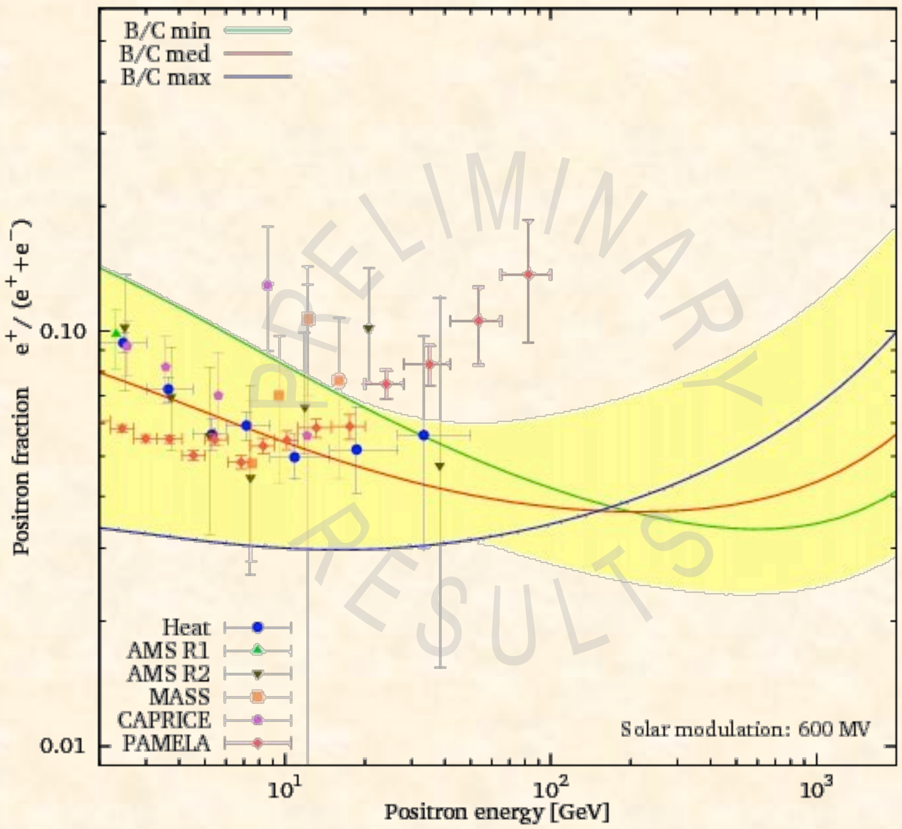



# Electrons from SNR

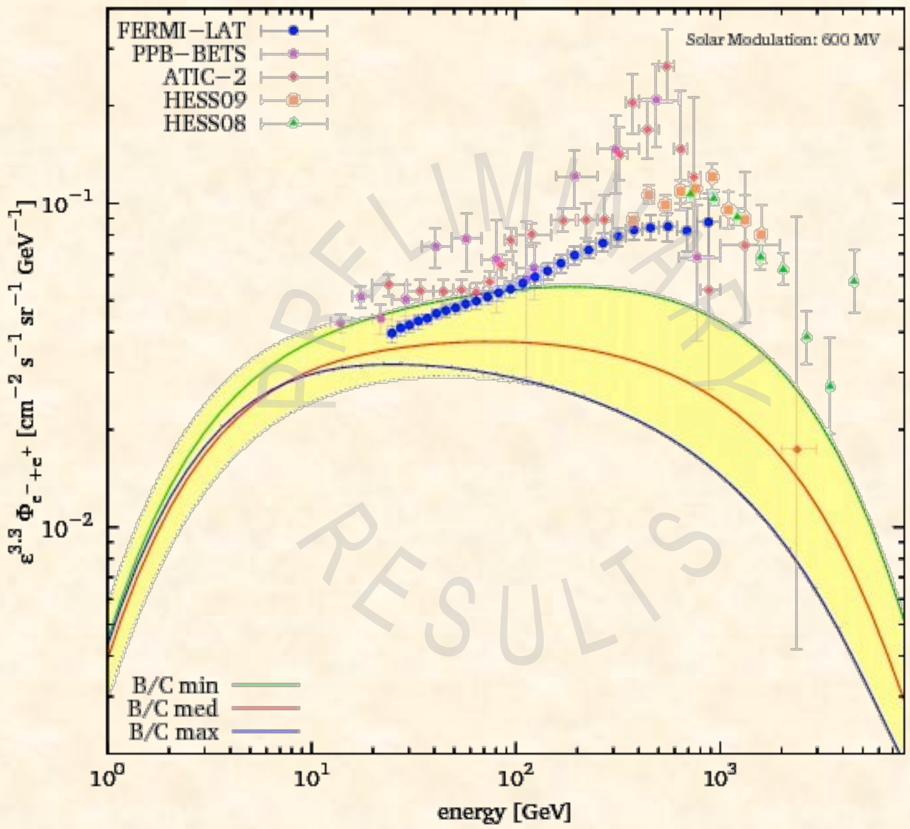



T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle, in progress

## Positron fraction

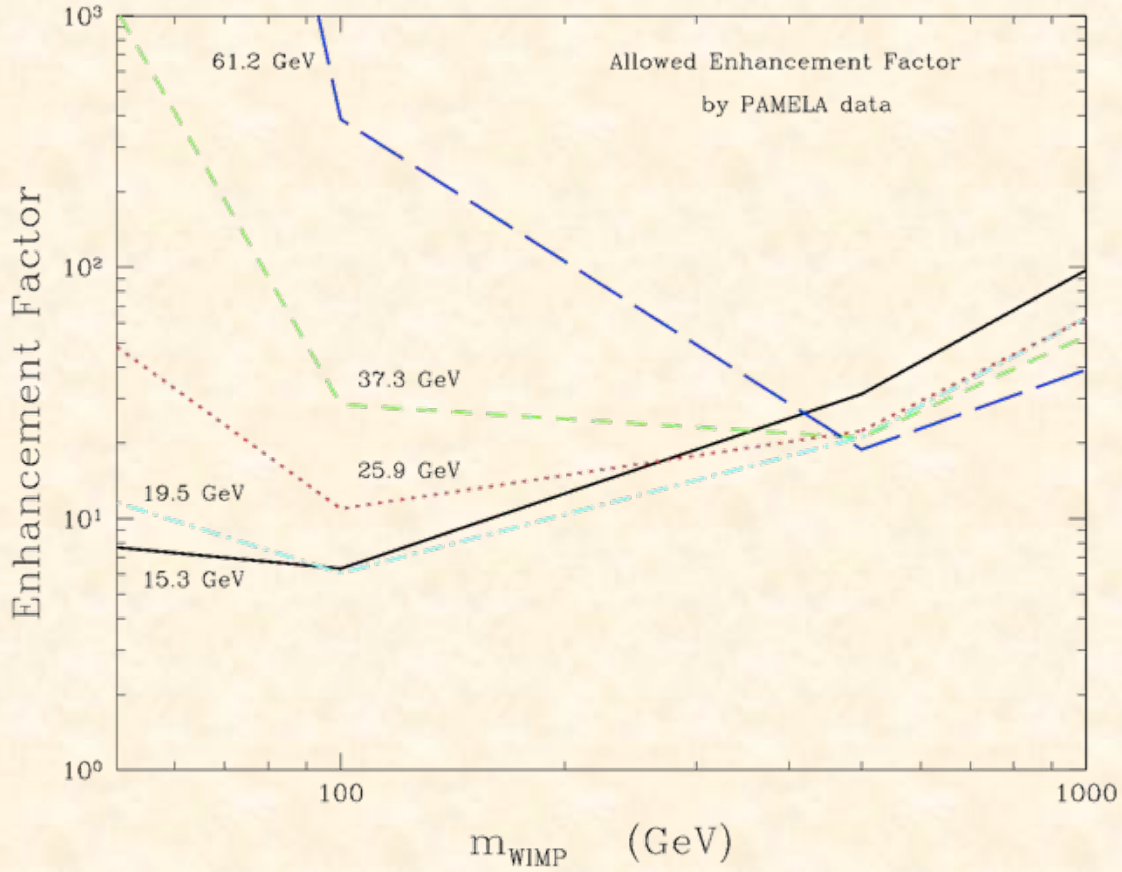



## Electrons + positrons



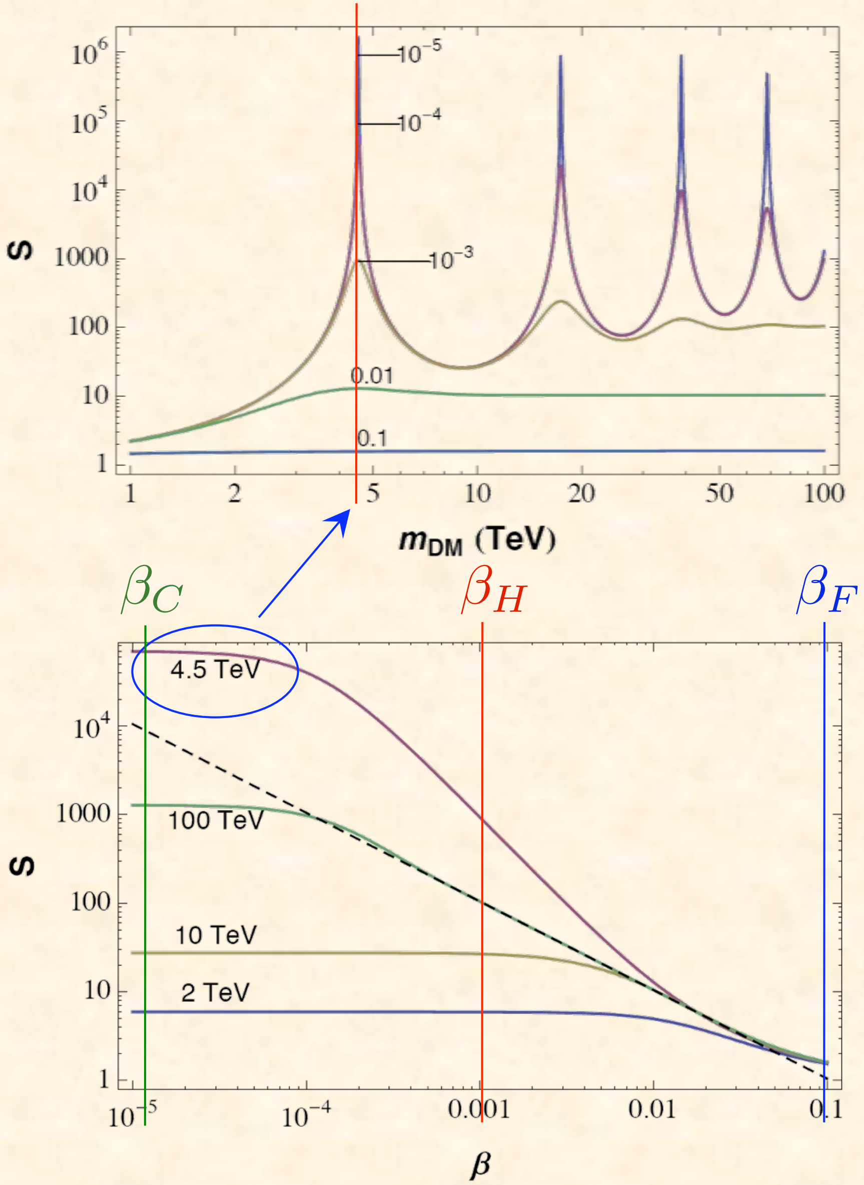

T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle, in progress

# Constraint on boost from antiprotons



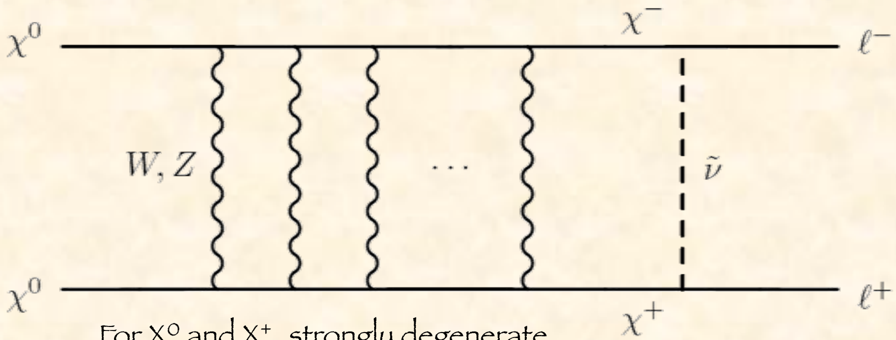

F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, PRL 102 (2009) 071301

# Particle physics boost: Sommerfeld effect




M. Lattanzi, J. Silk, arXiv:0812.0360v1 [astro-ph]

It may work differently for different annihilation channles (e.g. fermions wrt gauge bosons)



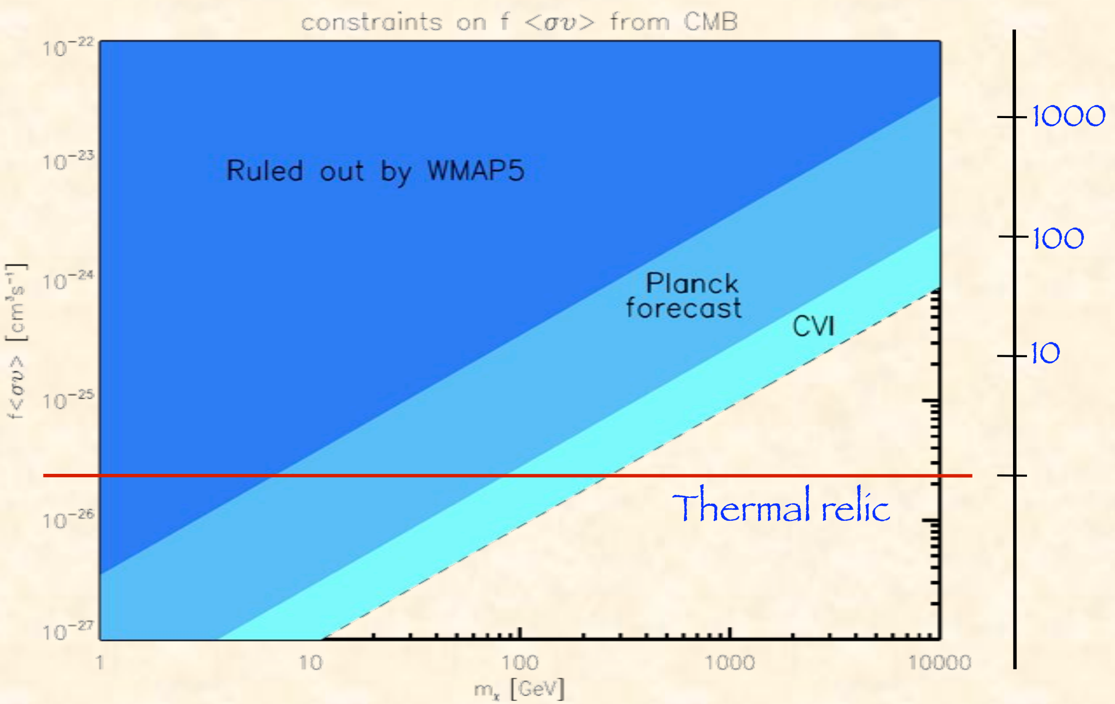

For $X^0$ and $X^+$ strongly degenerate

See also:

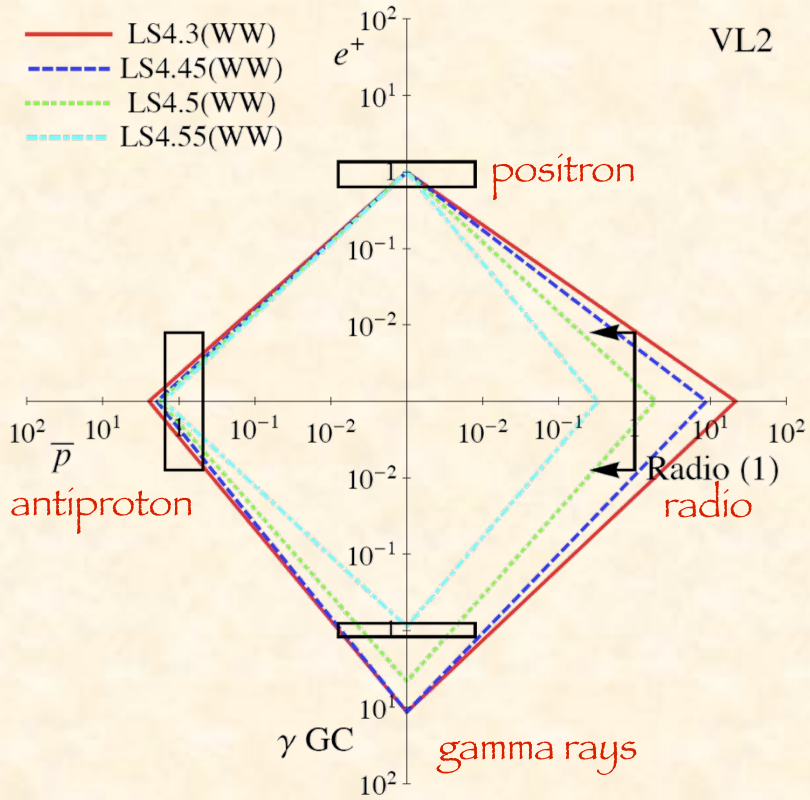

J. Hisano, M. Nagai, M. Nojiri, M. Senami, PRL 92 (2004) 031303
J. Hisano, S. Matsumoto, M. Nojiri, S. Saito, PRD, 71 (2005) 063528
M. Cirelli, A. Strumia, M. Tamburini, NPB 787 (2007)
J. March-Russell, S. M. West, D. Cumberbatch, D. Hooper, JHEP 0807 (2008) 058
N. Arkani-Hamed, D. P. Finkbeiner, T. Slatyer, N. Weiner, arXiv:0810.0713 [hep-ph]
M. Cirelli, M. Kadastik, M. Raidal, A. Strumia, arXiv:0809.2409v3 [hep-ph]

# Bounds on Sommerfeld boost

From CMB




From multiwavelength

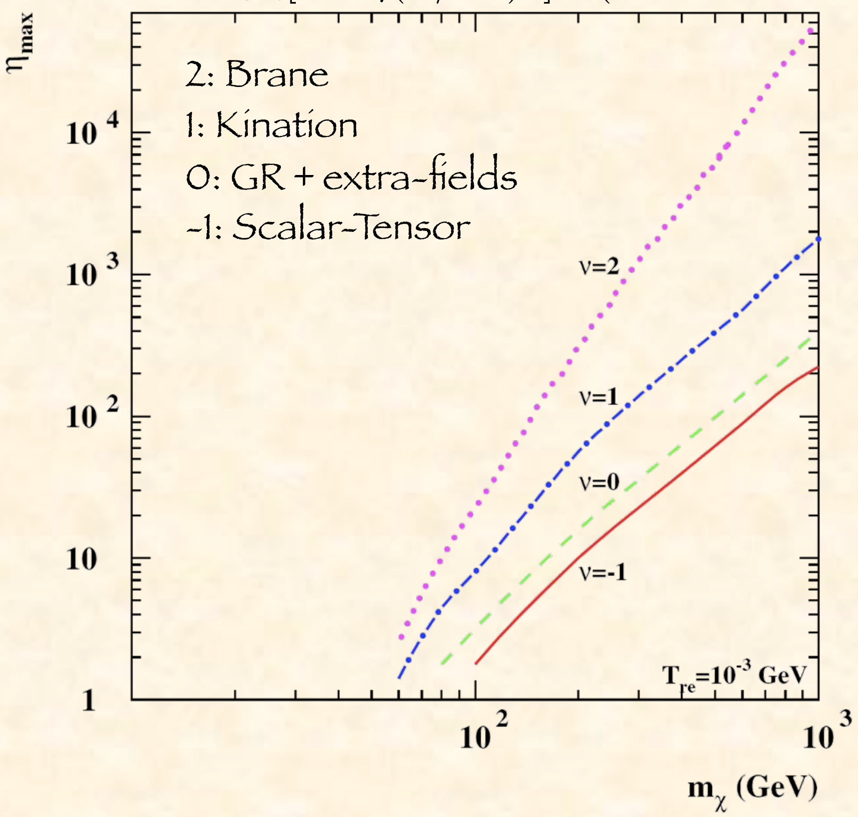



S. Galli, F. Iocco, G. Bertone, A. Melchiorri, arXiv:0905.0003v1 [astro-ph]

M. Pato, L. Pieri, G. Bertone, 0905.0372v1 [astro-ph.HE]

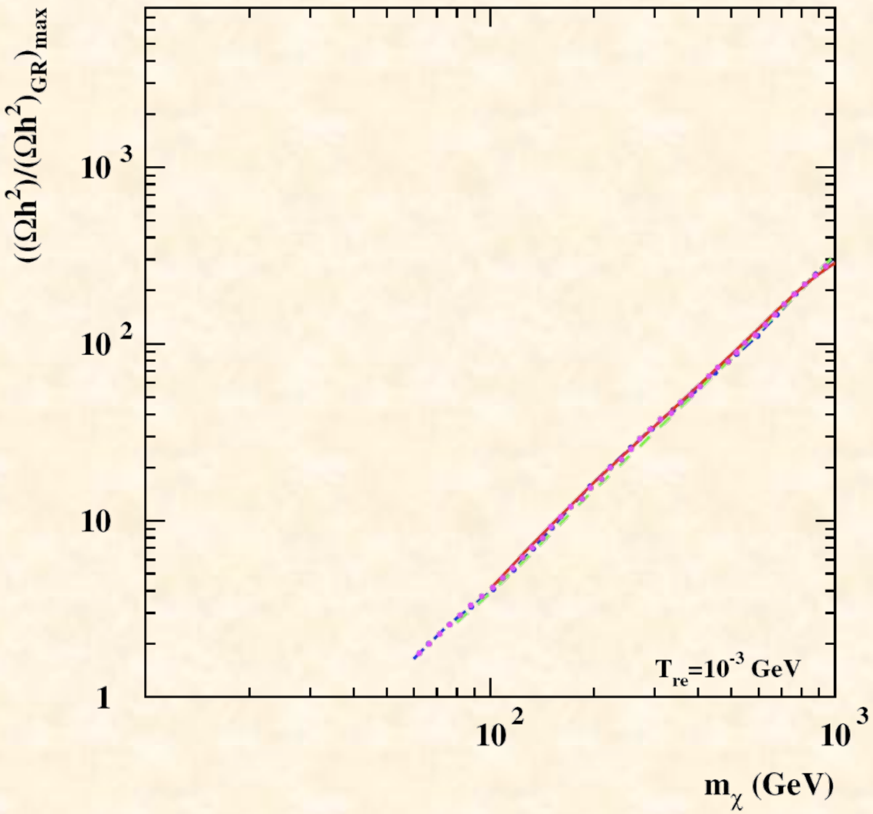
# Cosmological boost

$$H = H_{\mathrm{GR}}[1 + \eta(T/T_F)^\nu] \quad (\text{for } T > T_{\mathrm{BBM}})$$




Maximal enchancement of
Hubble rate at freeze-out
consistent with antiproton data

$$B = \langle\sigma v\rangle^{\mathrm{WMAP}} / \langle\sigma v\rangle^{\mathrm{WMAP}}_{\mathrm{GR}}$$




Induced boost

Boosts equally leptonic and hadronic channels

M. Schelke, R. Catena, N. Fornengo, A. Masiero, M. Pietroni, PRD 74 (2006) 083505

# Summary: Indirect Detection

- AntiDeuterons
  - Strong feature at low-energies: offer the best possibility to detect a signal
- AntiProtons
  - Mild feature at low energies, but suitable to set (potentially relevant) bounds
  - Possible features at high energies, but requires "boost"
  - Data show no anomaly (latest from PAMELA)
- Positrons
  - May posses spectral features, typically require "boosts"
  - PAMELA data on positron fraction exhibit "anomalous" rise (may be astrophysical: e.g. pulsars)
  - FERMI data on electron+positrons exhibit a mild bump (may be astrophysical) [HESS; ATIC]
- Gamma Rays
  - May posses spectral features
  - Line: amazing signature, but typically strongly suppressed (very hard for some DM candidates)
  - FERMI: currently no anomaly above the galactic center
  - Astrophysical background relevant, especially at the galactic center
- Neutrinos from Earth and Sun
  - Spectral and angular features
  - Affected by uncertainties similar to direct detection: astrophysical, hadronic
  - Potentially accessible, especially from the Sun