Advances in the theoretical exploration of particle dark matter signals

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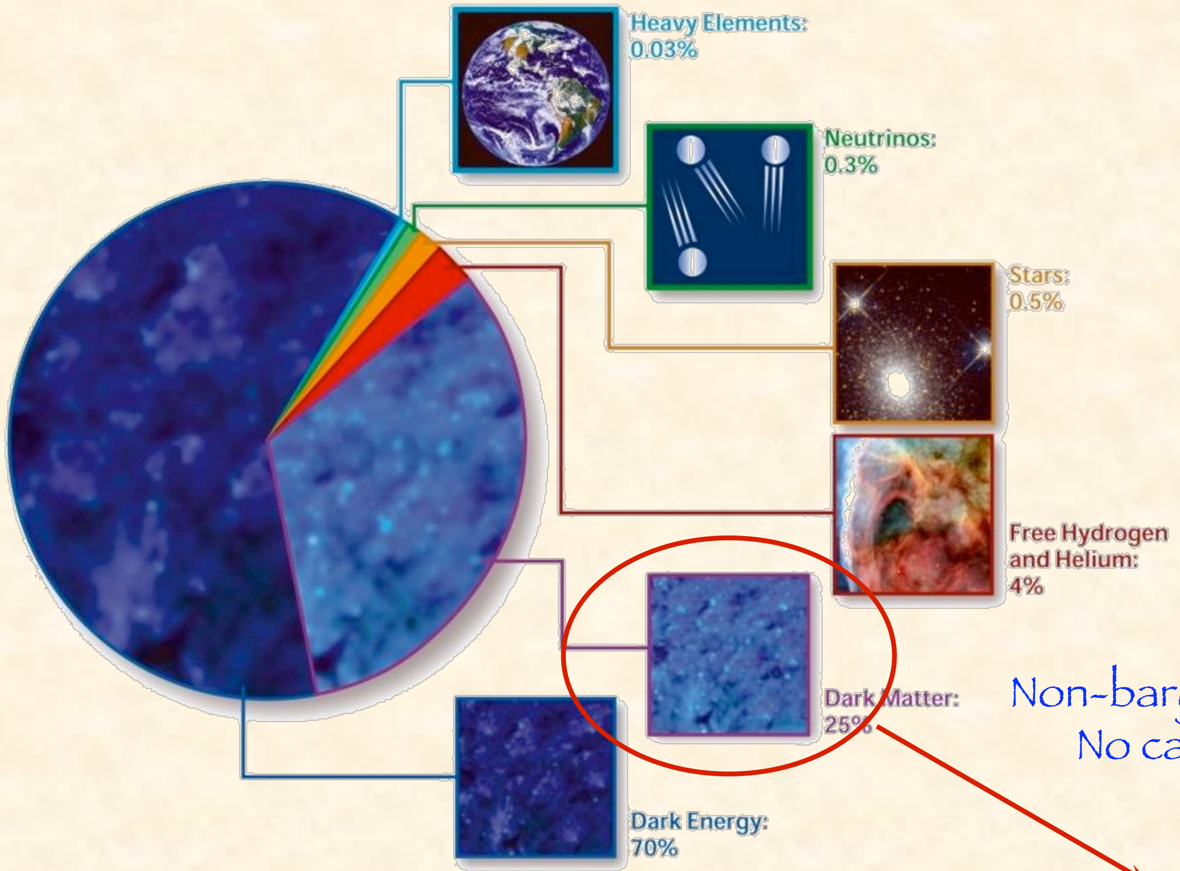
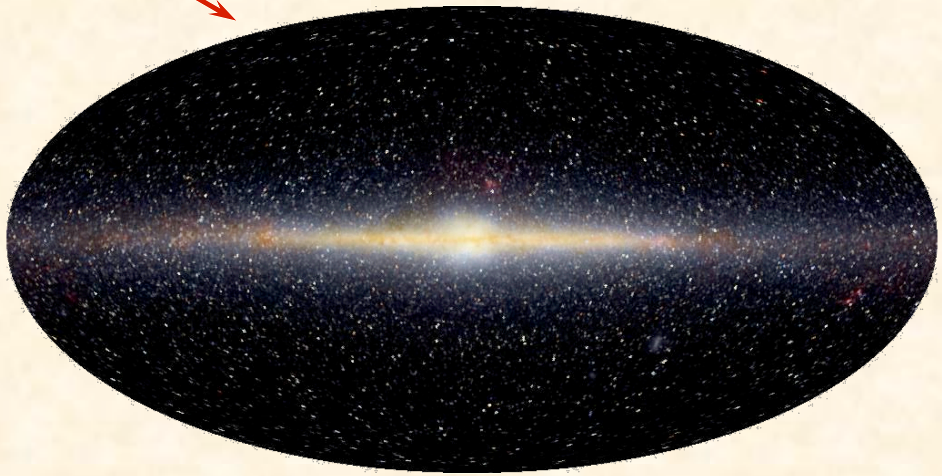
INFN Torino

14° Lomonosov Conference on Elementary Particle Physics
Moscow State University – 21.08.2009

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 χ 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 χ 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)

Direct Detection

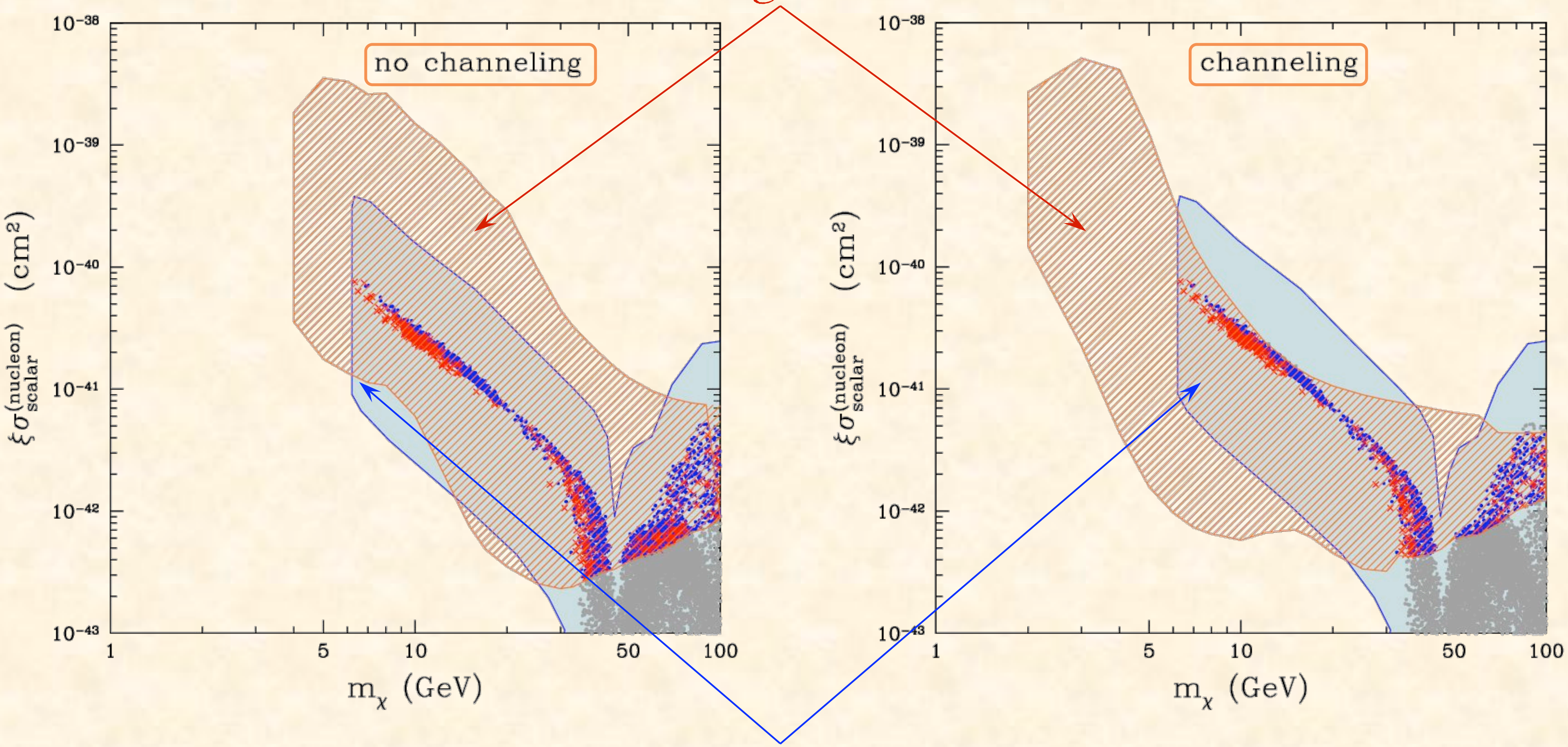
Direct detection experiments

- Background-rejection experiments (CDMS, Xenon, …)
  - Do not exploit a specific signature of the signal
  - Rely on strong reduction of background
  - Provide bounds on the particle DM properties (mass vs cross-section on nucleons)

- Annual modulation experiment (DAMA)
  - Exploits a specific signature
  - Highly stable over very long periods
  - Effect observed: implies a compatibility region in the mass vs cross section plane

DAMA annual modulation region

DAMA/LIBRA allowed region
(convolution over galactic halo models)

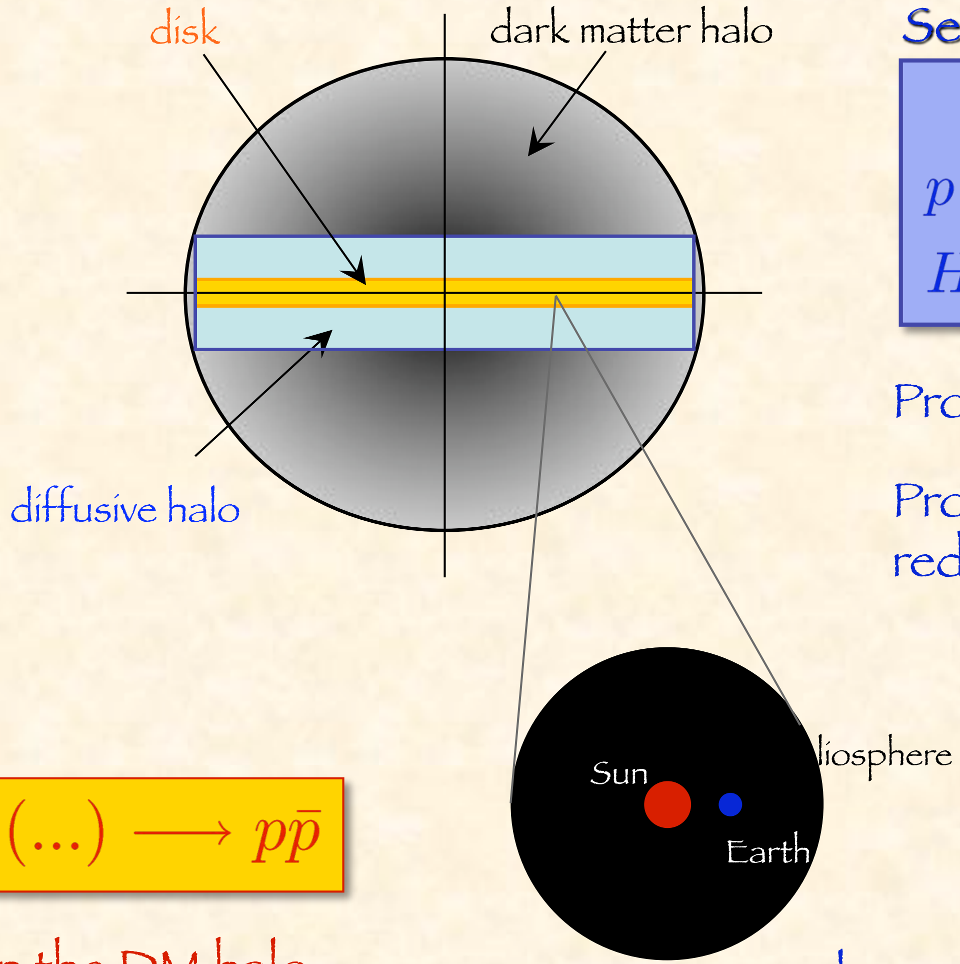


Neutralino DM: MSSM + gaugino non universal models
(includes hadronic uncertainites)

A. Bottino, F. Donato, N. Fornengo, S. Scopel, PRD 78 (2008) 083520

Antiprotons

Antiproton signal



Secondaries

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

Produced in the disk

Propagation and energy redistribution in the diffusive halo

solar modulation

DM signal

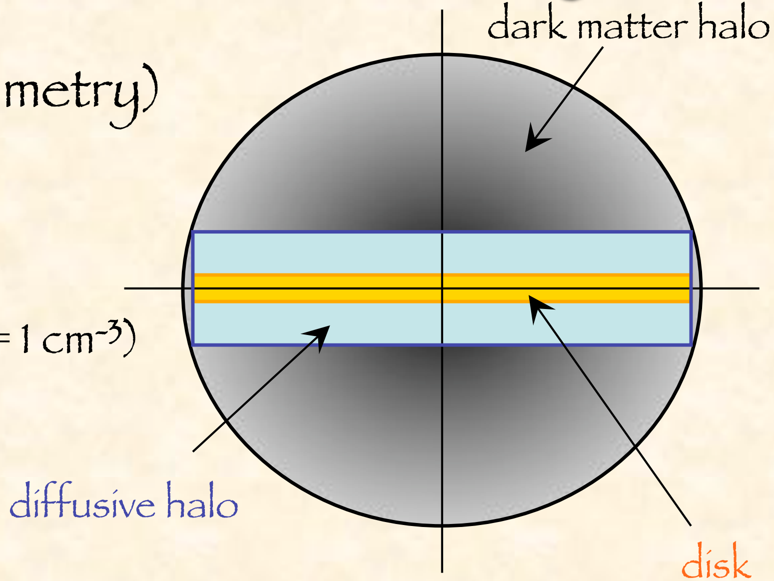
$$\chi\chi \longrightarrow (\ldots) \longrightarrow p\bar{p}$$

Produced in the DM halo

Propagation and energy redistribution in the diffusive halo

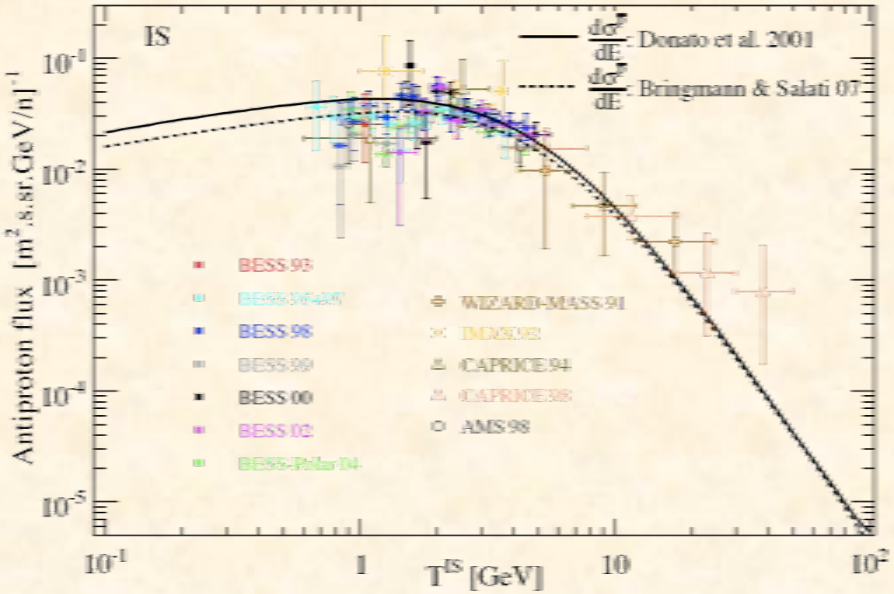
Diffusion and propagation in the Galaxy

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

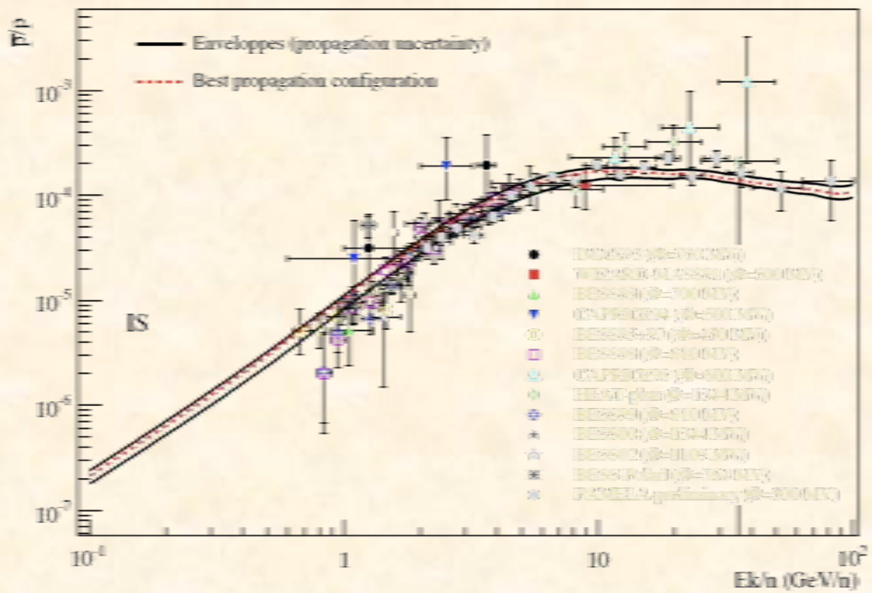


- Physical processes
  - Particle injection (source)
  - Spatial diffusion
  - Energy transport and losses
  - Scattering and/or annihilation
  - Galactic wind away from the disk in vertical direction
  - Reacceleration on random hydrodynamic waves

Secondary antiprotons



Antiproton flux



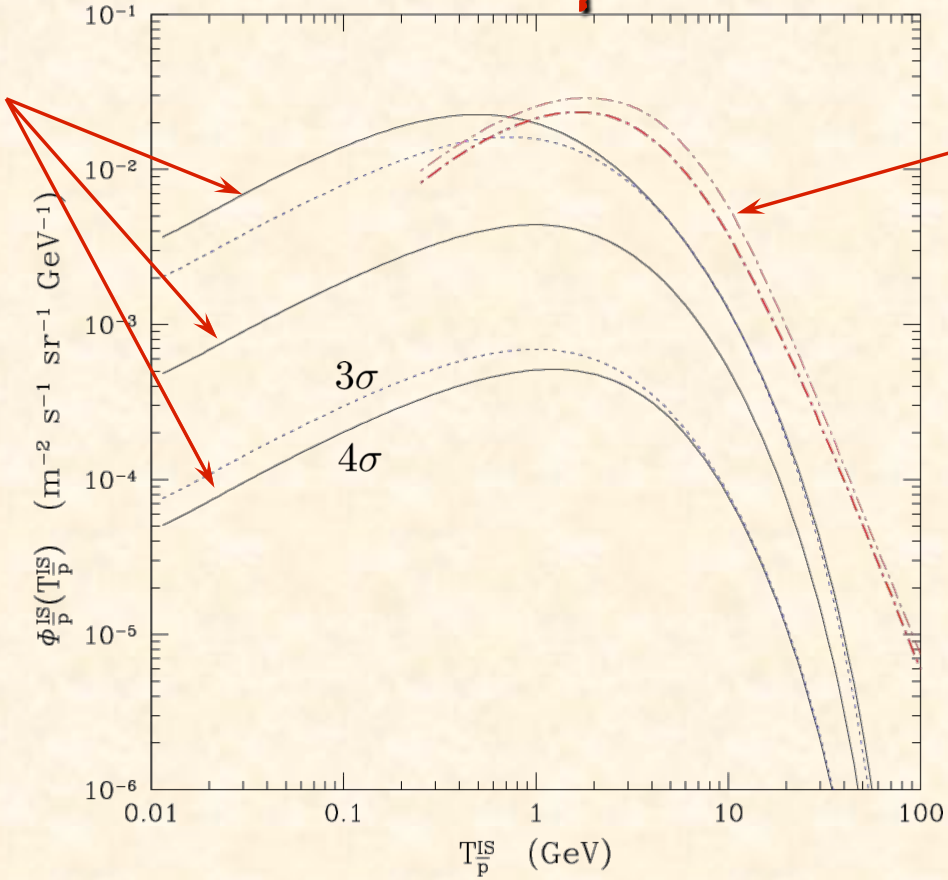
Antiproton/proton fraction

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

From B/C fit

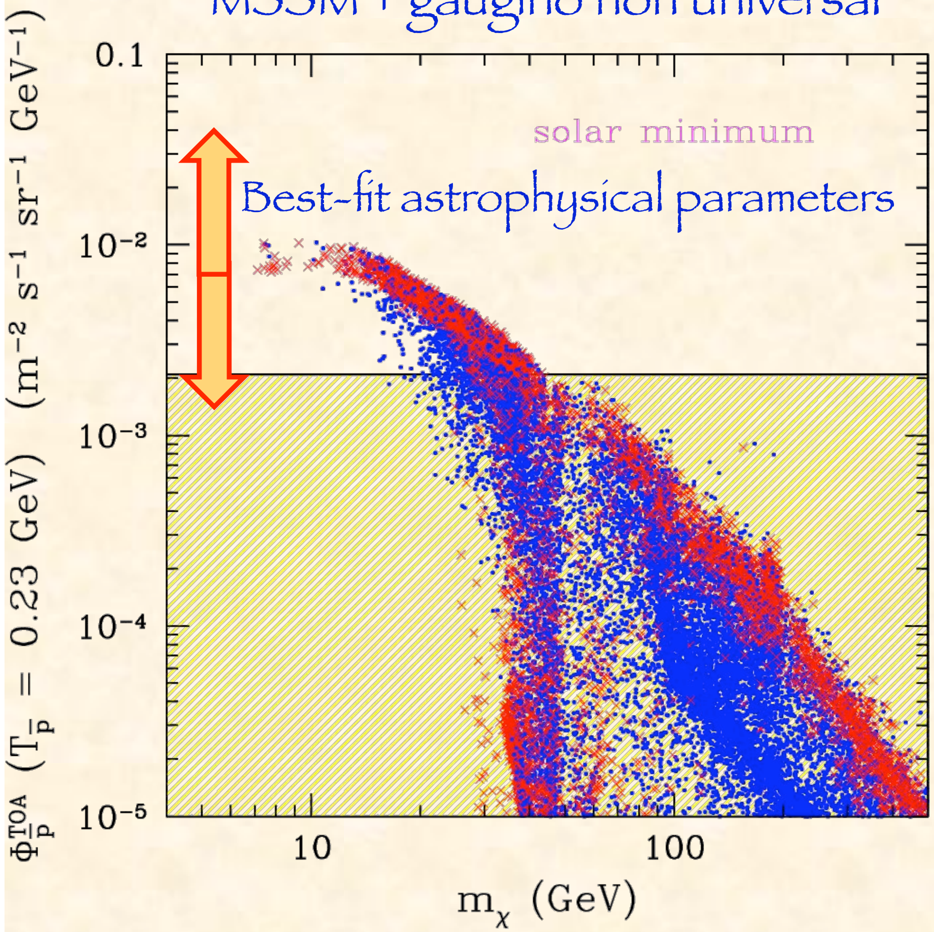
case	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/sec)	V_A (km/sec)	$\chi^2_{B/C}$
max	0.46	0.0765	15	5	117.6	39.98
med	0.70	0.0112	4	12	52.9	25.68
min	0.85	0.0016	1	13.5	22.4	39.02

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

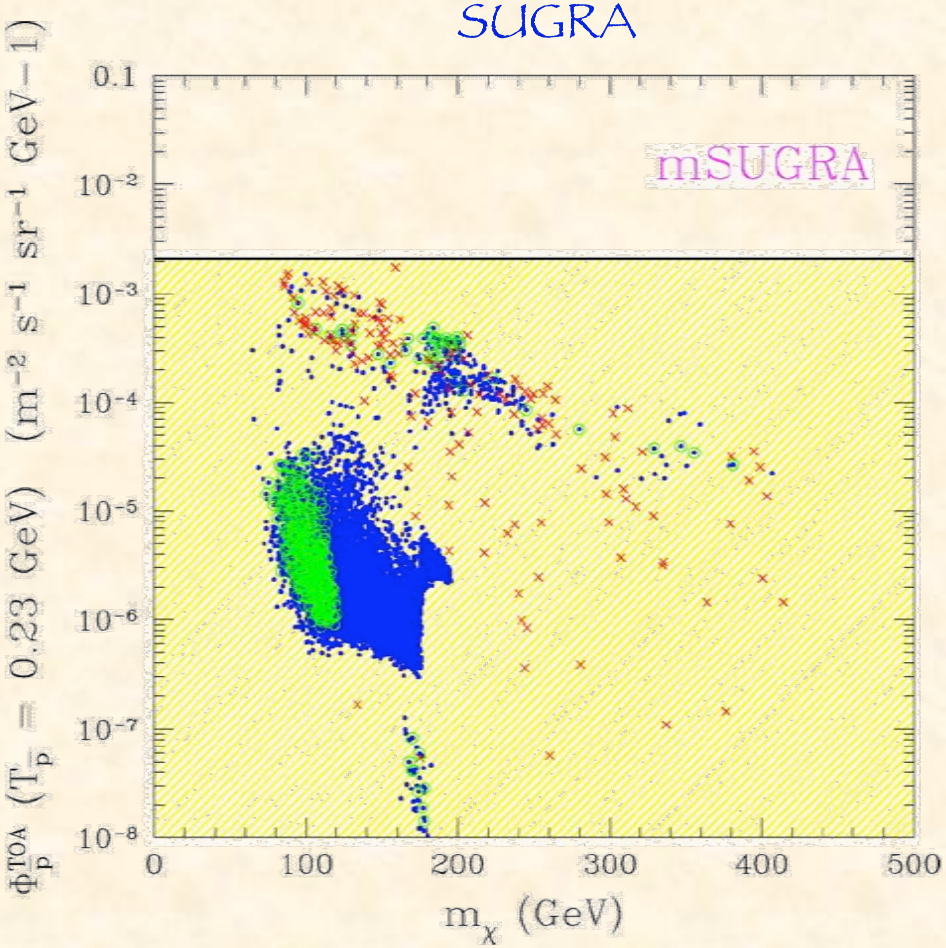
(2) D. Maurin et al. Astron. Astrophys. 381 (2002) 539

Theoretical predictions for neutralinos

MSSM + gaugino non universal



SUGRA

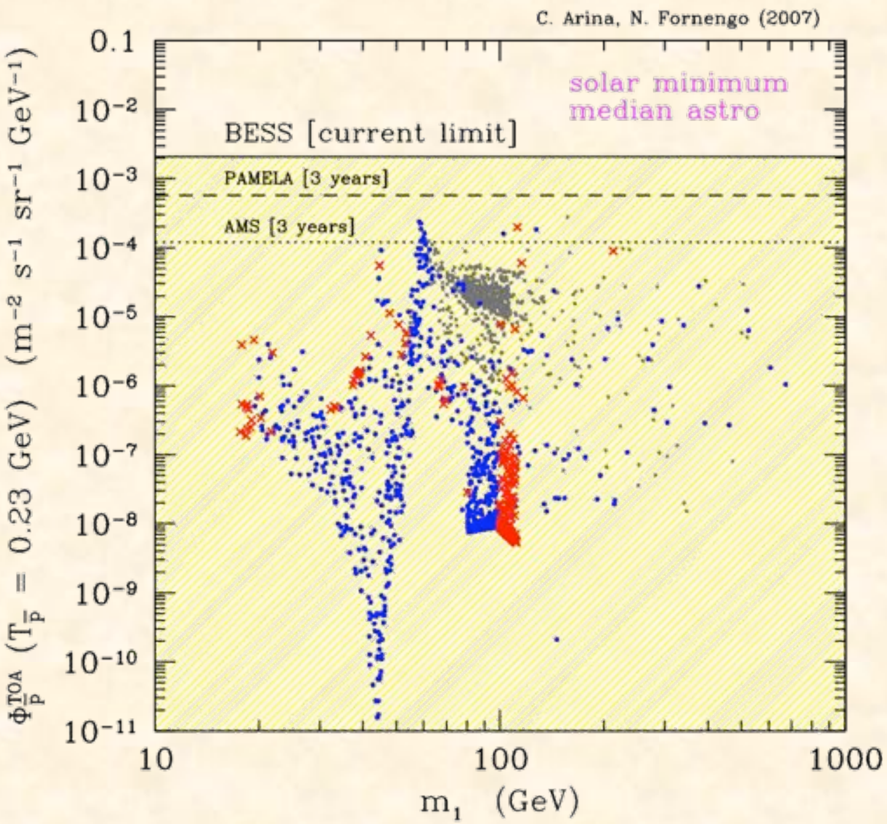


- cosmologically dominant neutralinos $0.095 \leq \Omega_\chi h^2 \leq 0.131$
- cosmologically subdominant neutralinos $\Omega_\chi h^2 < 0.095$

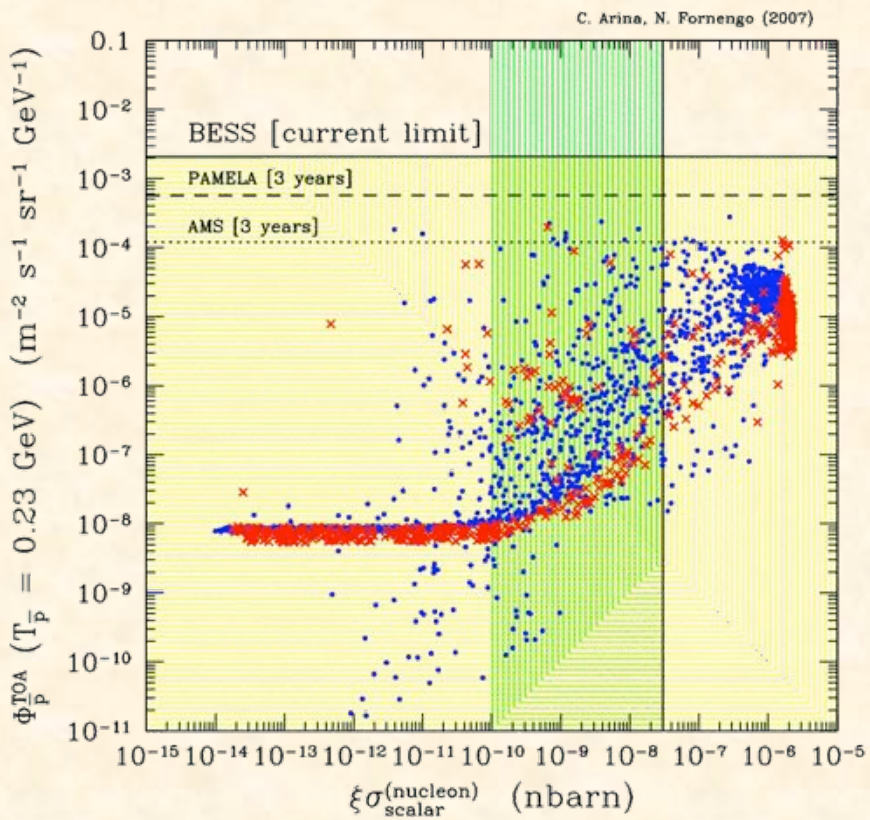
A. Bottino, F. Donato, N.F., S. Scopel, PRD 70 (2004) 015005

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

Sneutrinos in Left-Right models



Antiproton flux vs. sneutrino mass

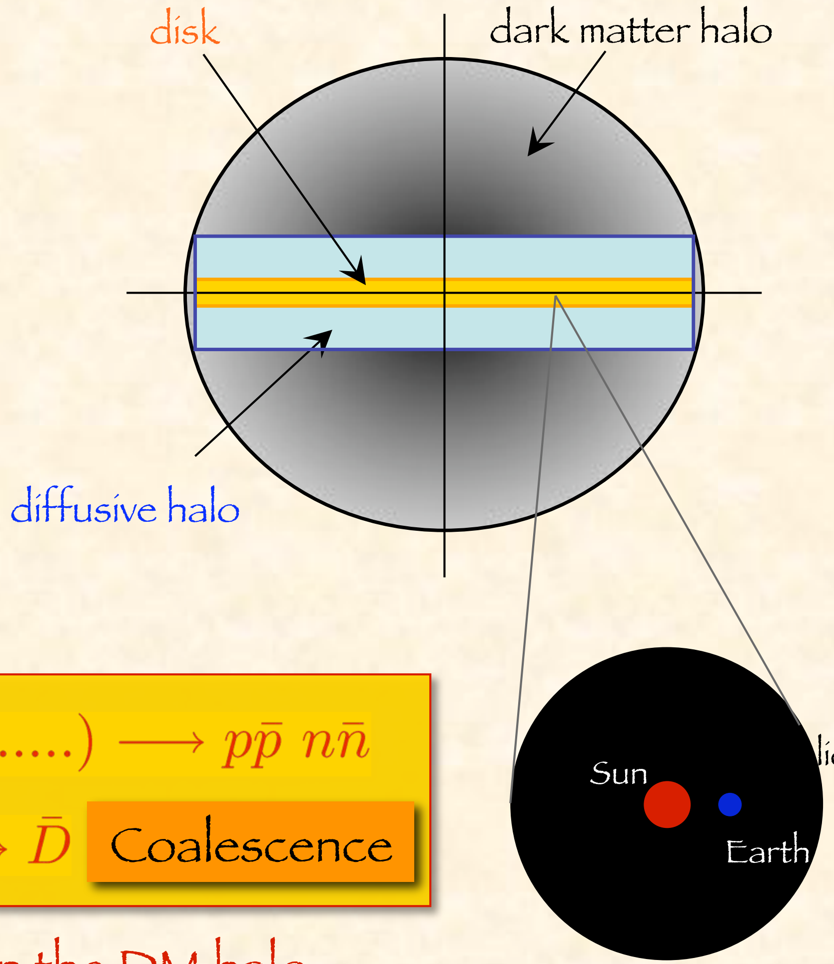


Antiproton flux vs. direct detection cross-section

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

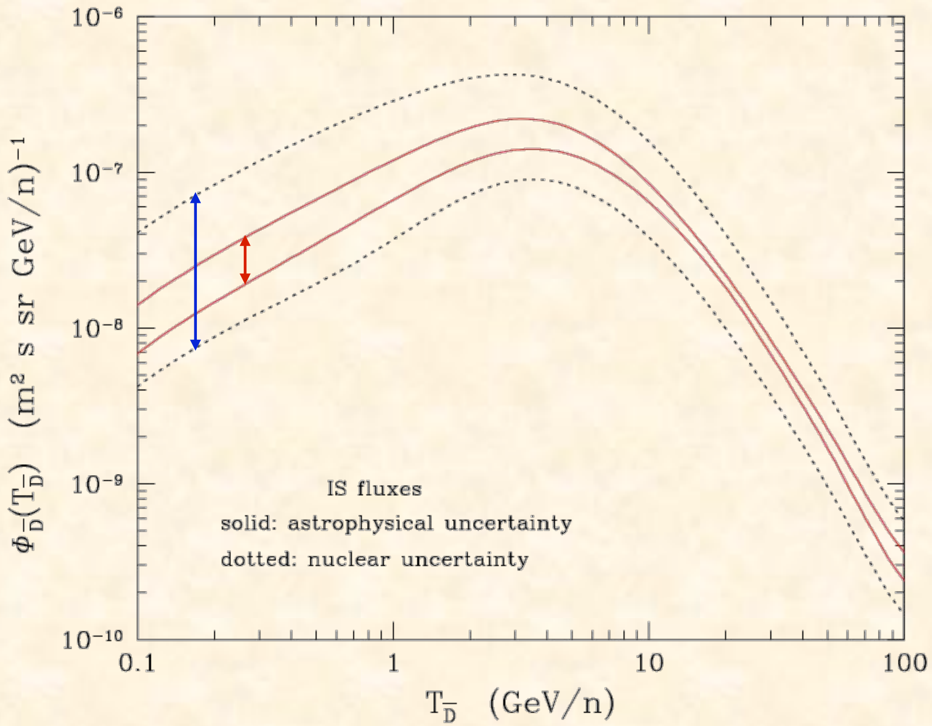
Secondaries and their uncertainties

Astrophysical uncertainties:

- Transport
- Energy losses and redistribution

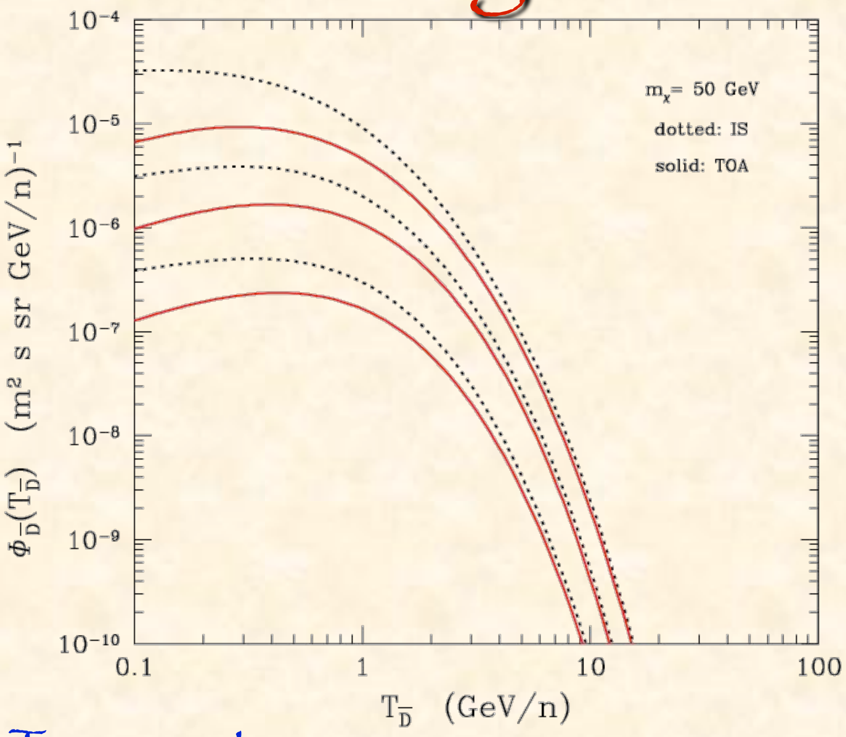
Nuclear uncertainties (very conservative):

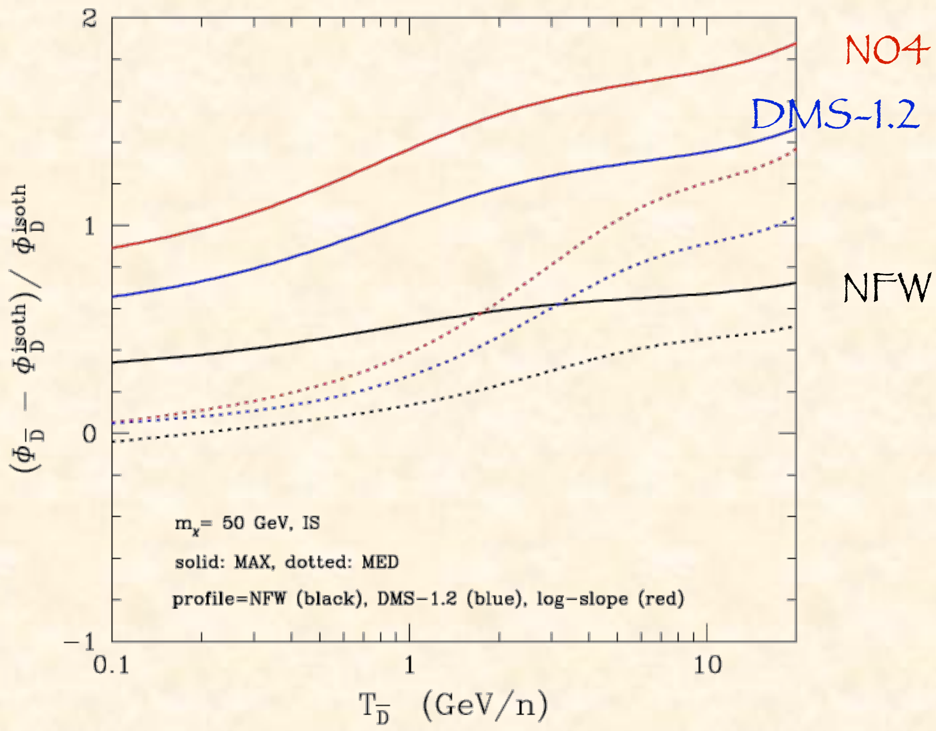
- Elementary production processes
- Coalescence



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

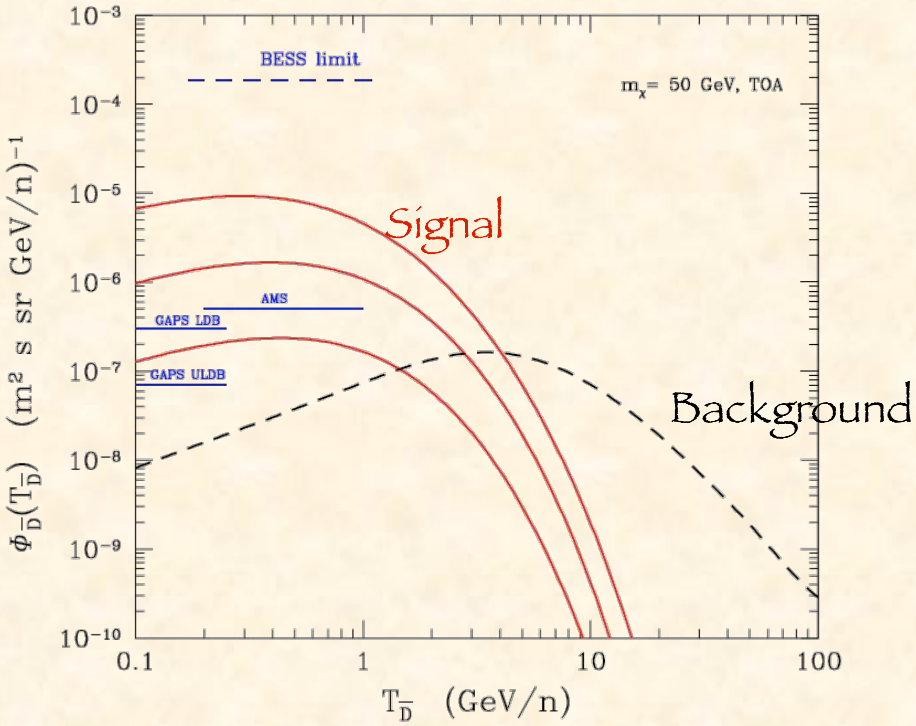
Energy redistribution:

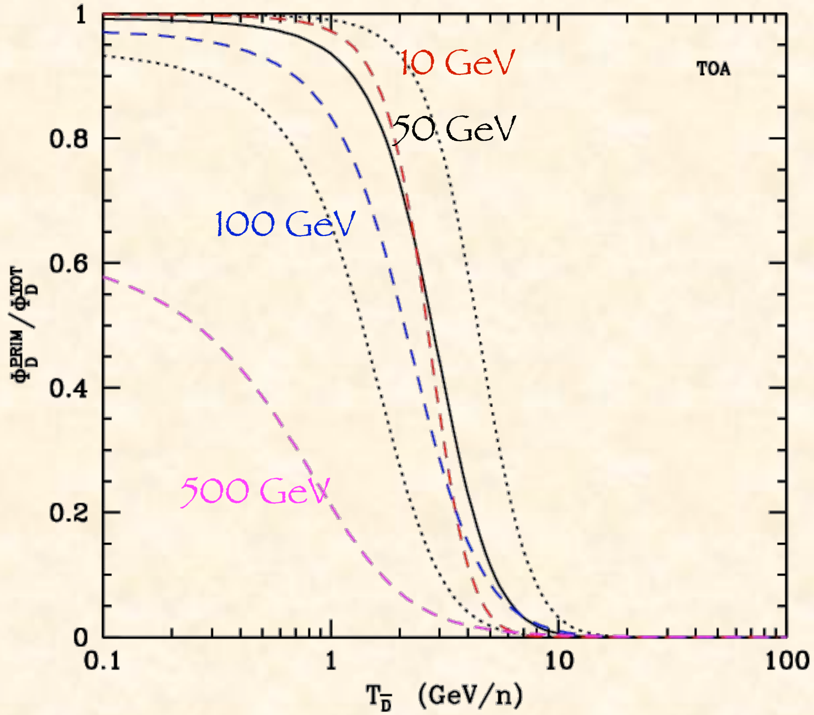
- Loss
- Reacceleration
- Tertiary redistribution

Change of DM halo profile
[for fixed local density]

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

TOA fluxes and S/B gain





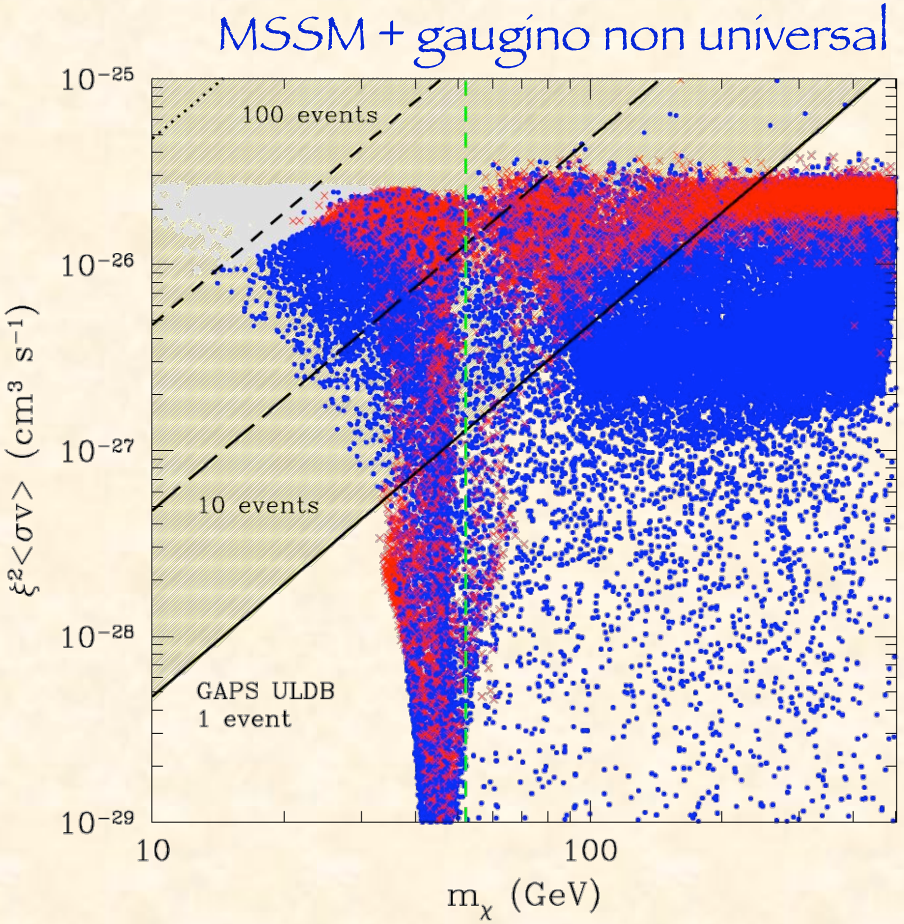
Signal with uncertainty band for:

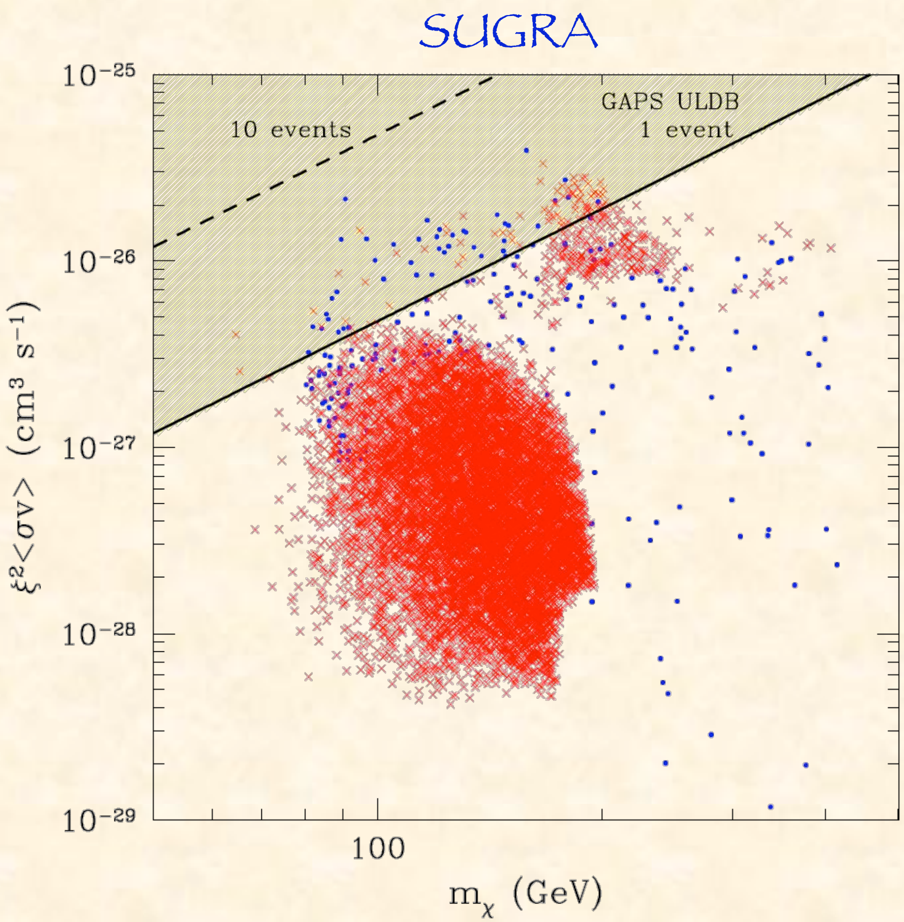
- 50 GeV WIMP mass
- WMAP relic abundance

Signal/(Back+Signal) ratio

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

Theoretical predictions





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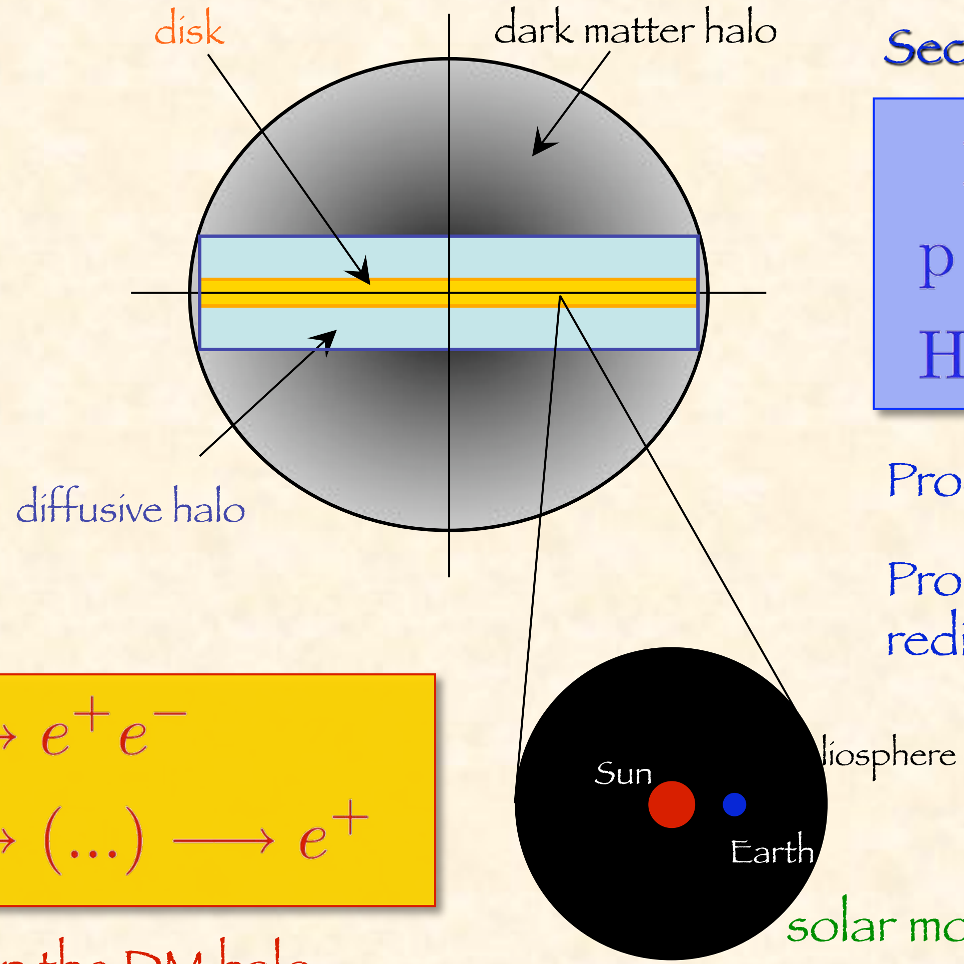
- cosmologically subdominant neutralinos $\Omega_\chi h^2 < 0.095$

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

Positrons

Cosmic positrons



Secondaries

$$p_{CR} + p_{ISM} \longrightarrow e^+$$
$$p_{CR} + He_{ISM} \longrightarrow e^+$$
$$He_{CR} + p_{ISM} \longrightarrow e^+$$

Produced in the disk

Propagation and energy redistribution in the diffusive halo

DM signal

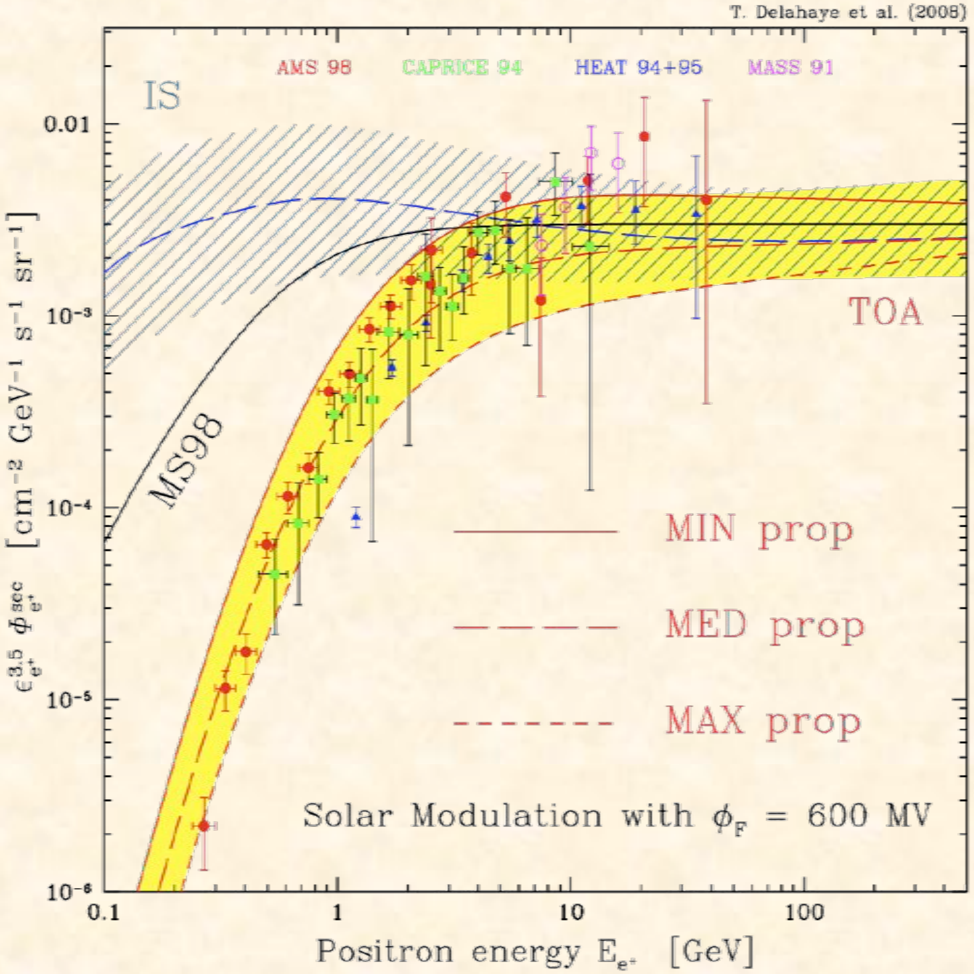
$$\chi\chi \longrightarrow e^+e^-$$
$$\chi\chi \longrightarrow (\ldots) \longrightarrow e^+$$

Produced in the DM halo

Propagation and energy redistribution in the diffusive halo

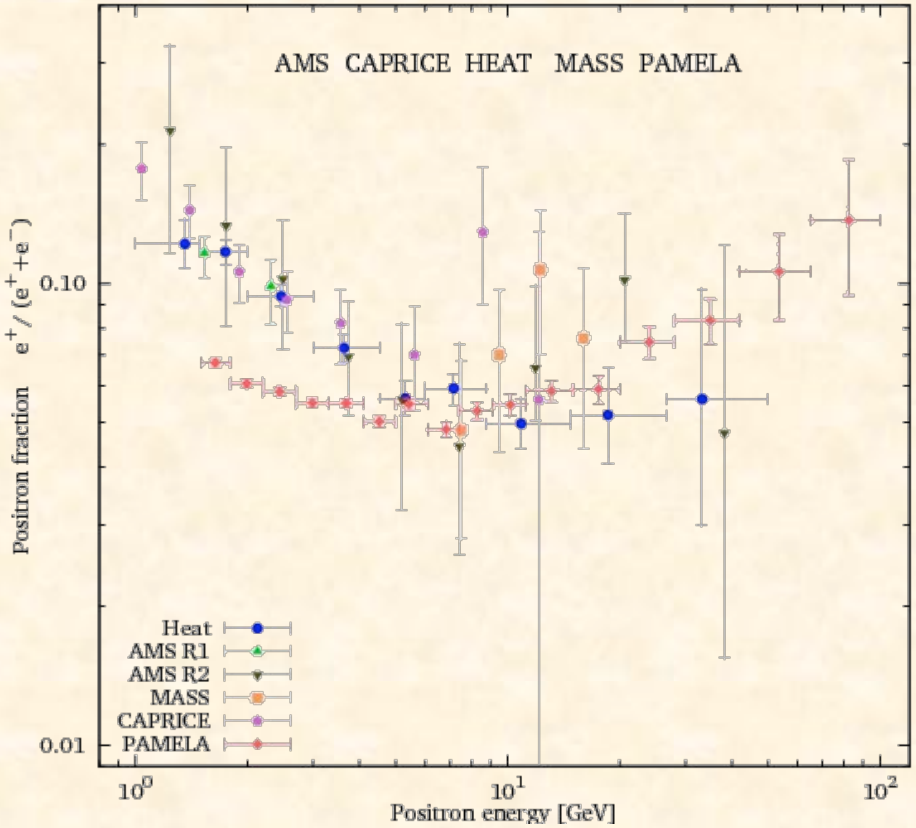
Astrophysical sources
(e.g.: pulsars)

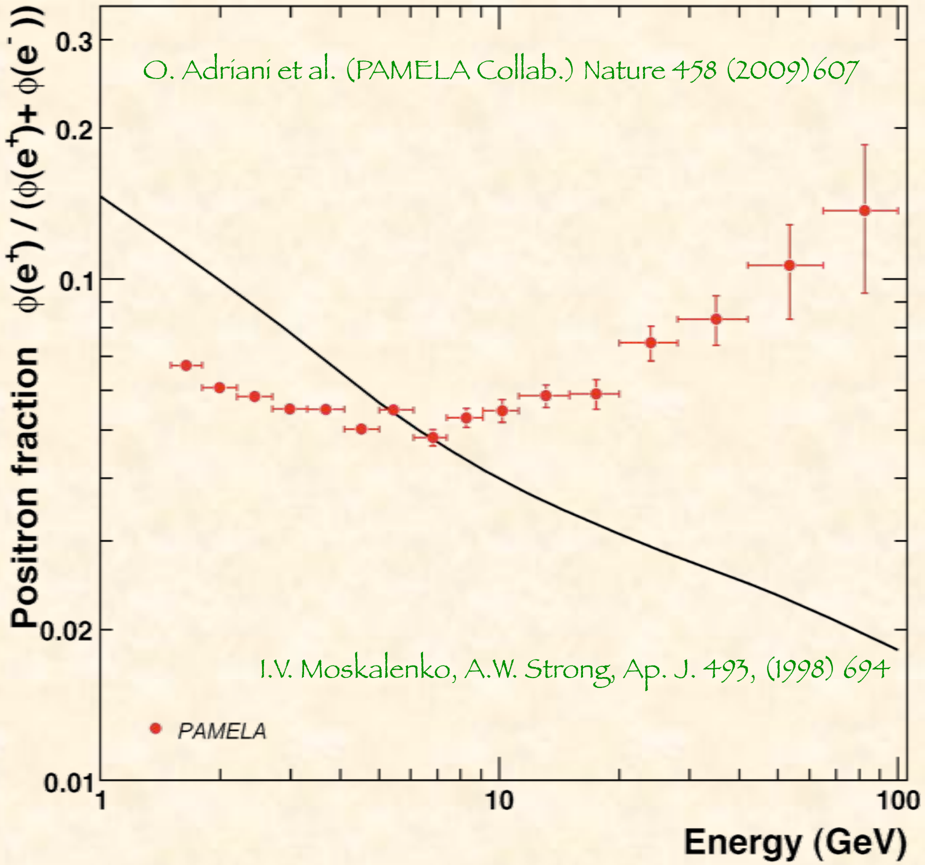
Secondary positrons: propagation uncertainties



T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle, P. Salati, R. Taillet, Astron. & Astrophys., 501, 3 (2009) 821

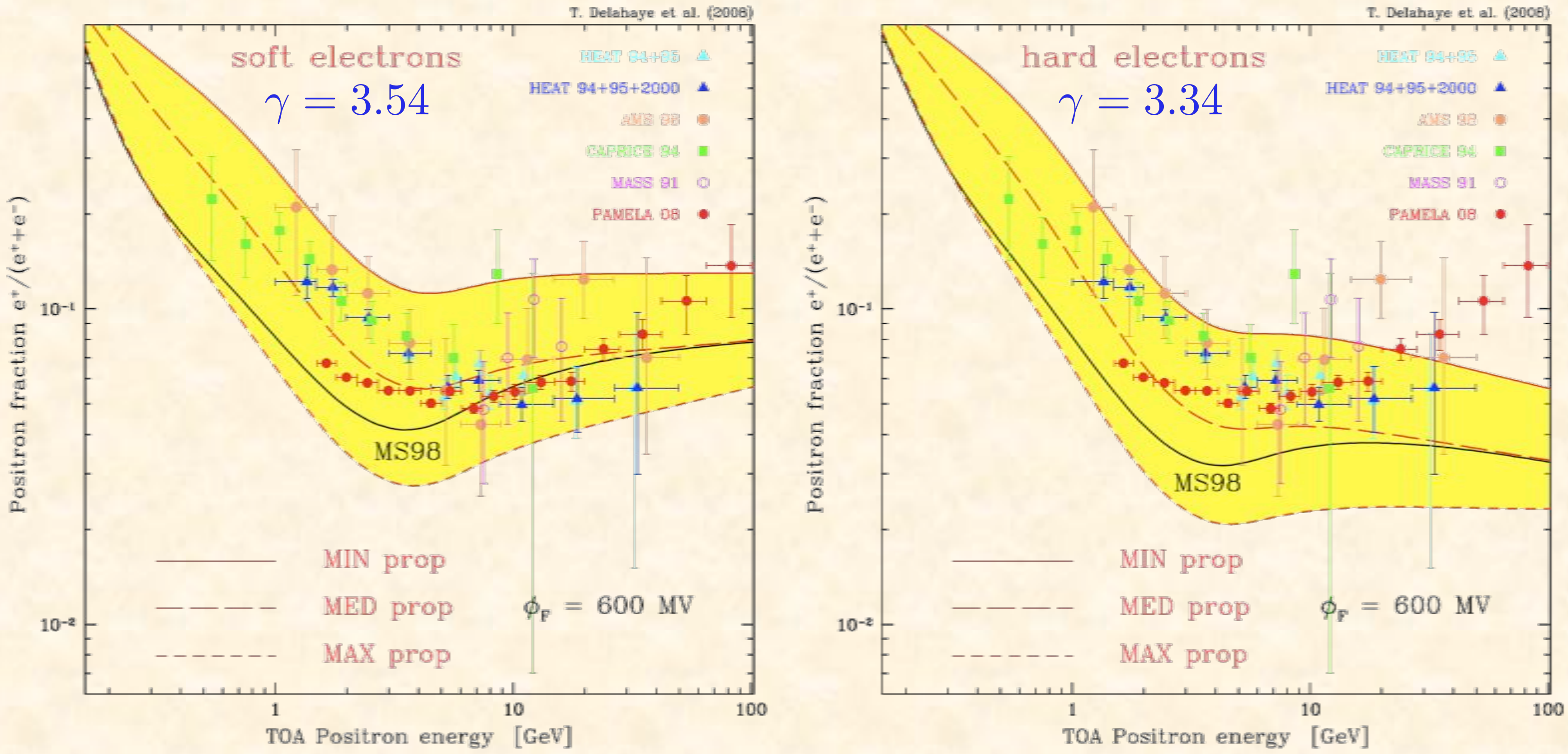
Positron fraction





Positron fraction

T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle, P. Salati, R. Taillet, Astron. & Astrophys., 501, 3 (2009) 821



PAMELA data point toward an “excess”

Electrons

- Electrons are a key ingredient in the positron fraction (as relevant as the positrons themselves …)
  - Secondary component: subdominant
  - Primary components: dominant
    - SNR
    - Pulsars

Strong & Moskalenko
Grasso et al.
Blasi et al.
Serpico, Profumo, Hooper, (…)

currently under study to determine a new predicion with astrophysical uncertainties (T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle)

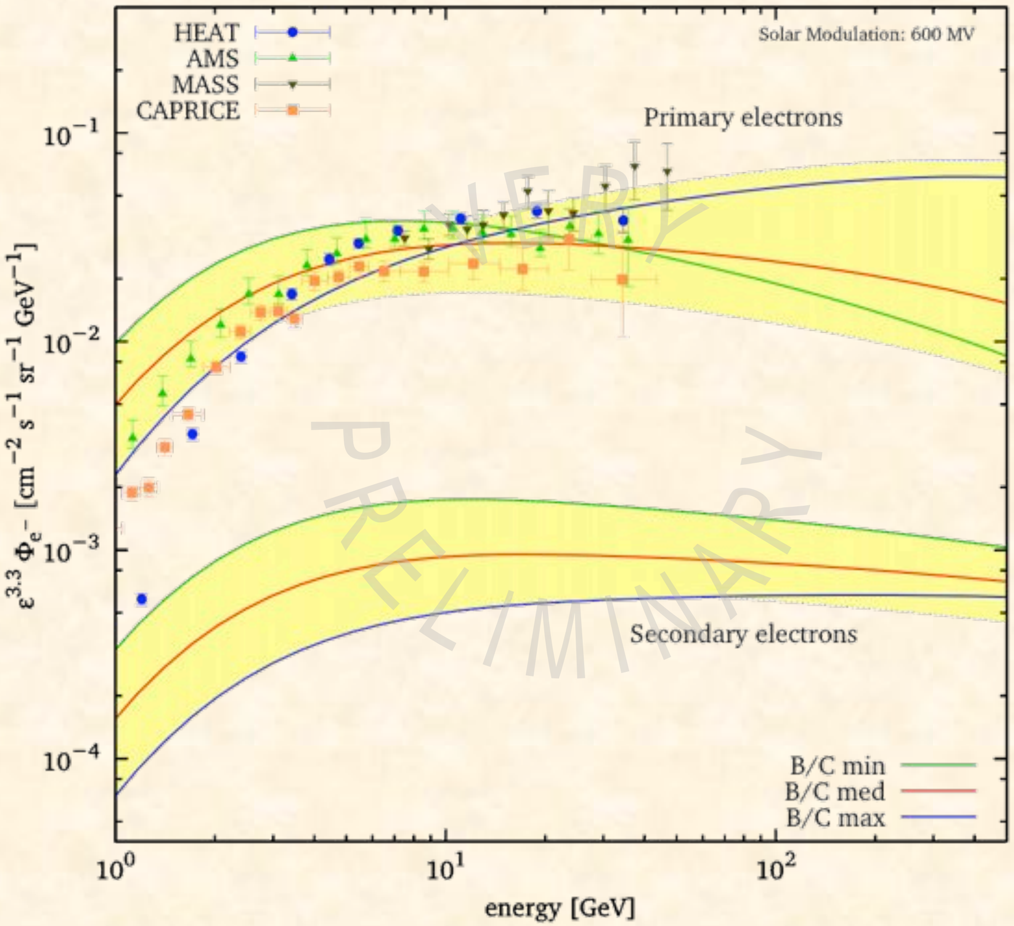
- SNR as electron sources:
  - Close SNR from catalogue + far SNR as a continuum
  - Modelling of the injection sources: energy spectra, luminosities, age
  - (...)

- Relativistic effects on the interaction cross sections for energy losses

- Uncertainties on propagation, consistent with the analisys on antiprotons, antideuterium, positrons

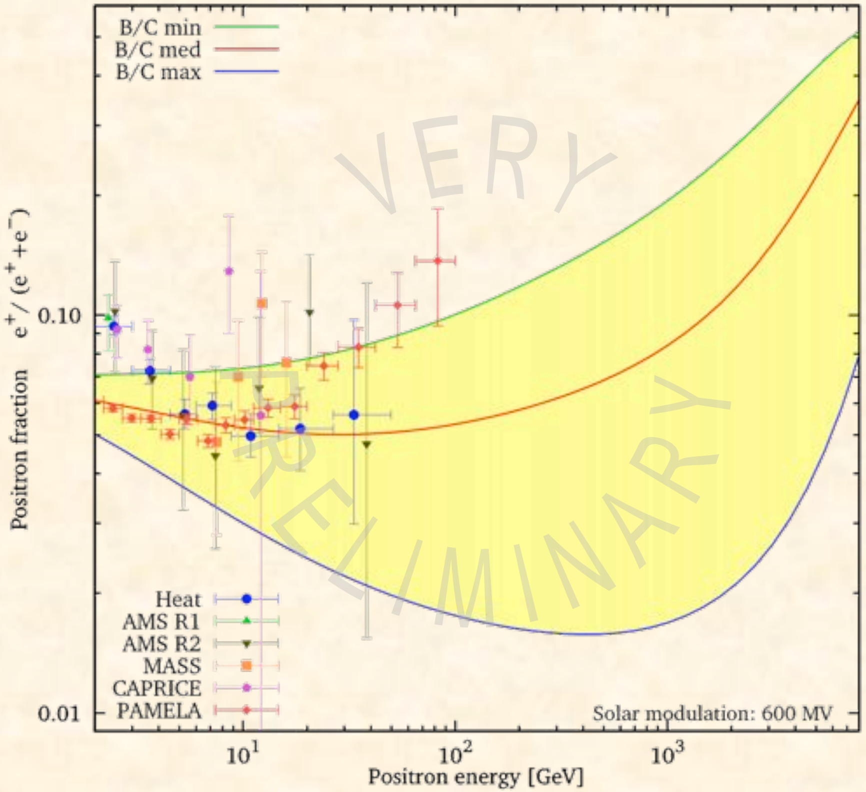
(T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle)

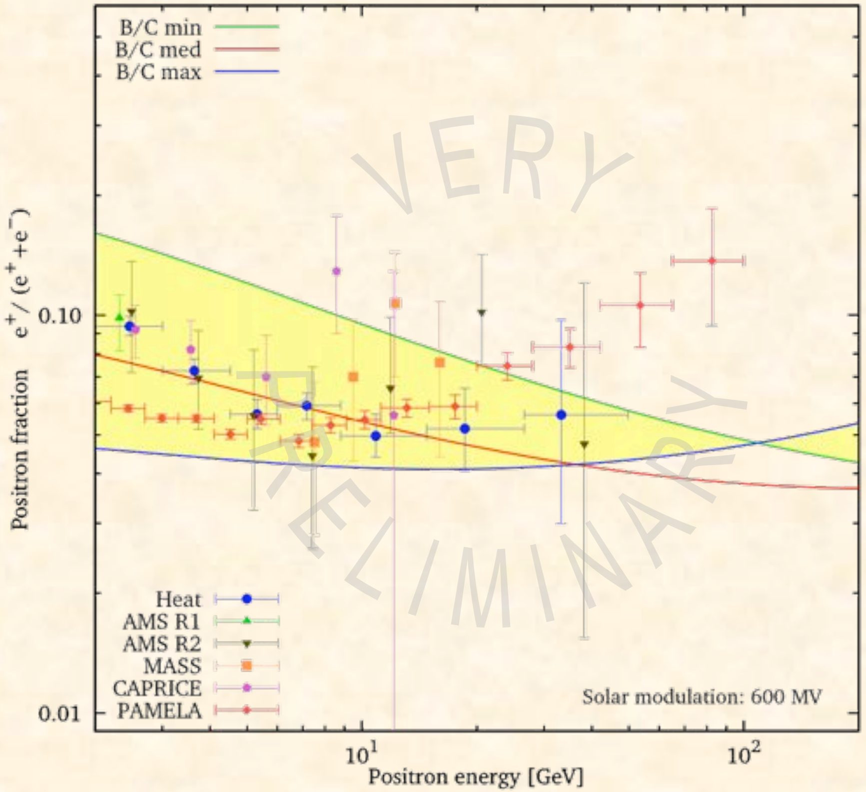
Primary electrons



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

Positron fraction



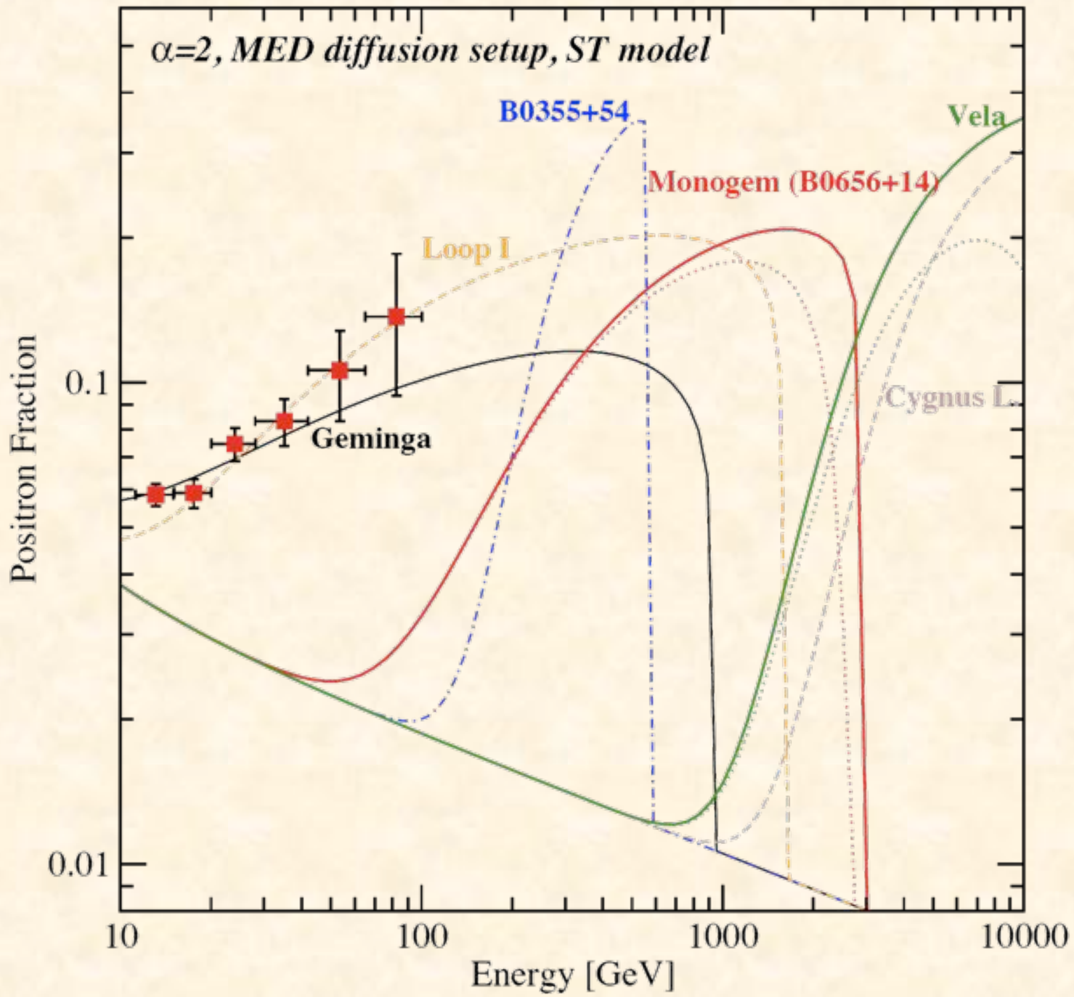


Electrons: primaries from SNR + secondaries

Positrons: secondaries

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

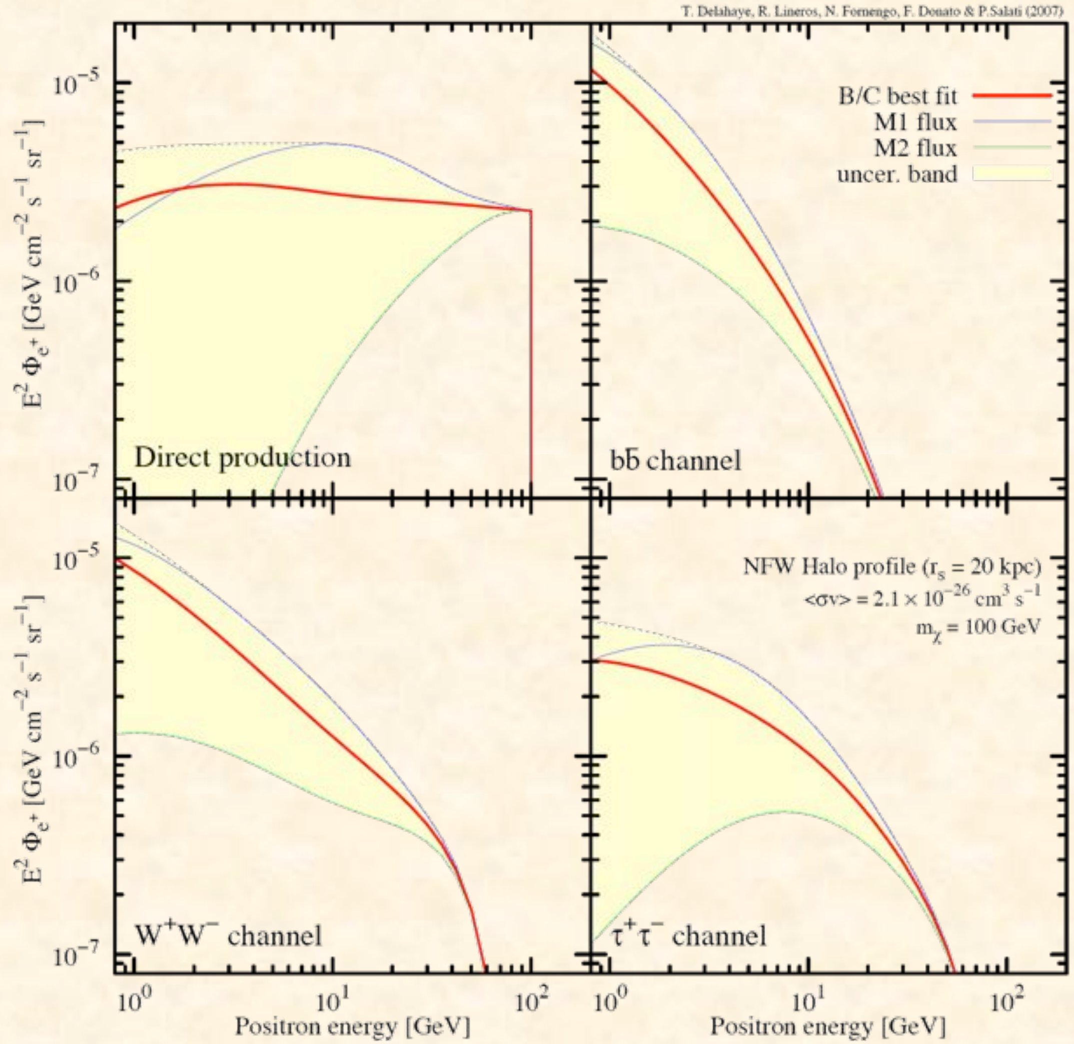
Positrons from astrophysical sources



S. Profumo, arXiv:0812.4457v2 [astro-ph]

DM signal: astrophysical uncertainties

m_χ = 100 GeV



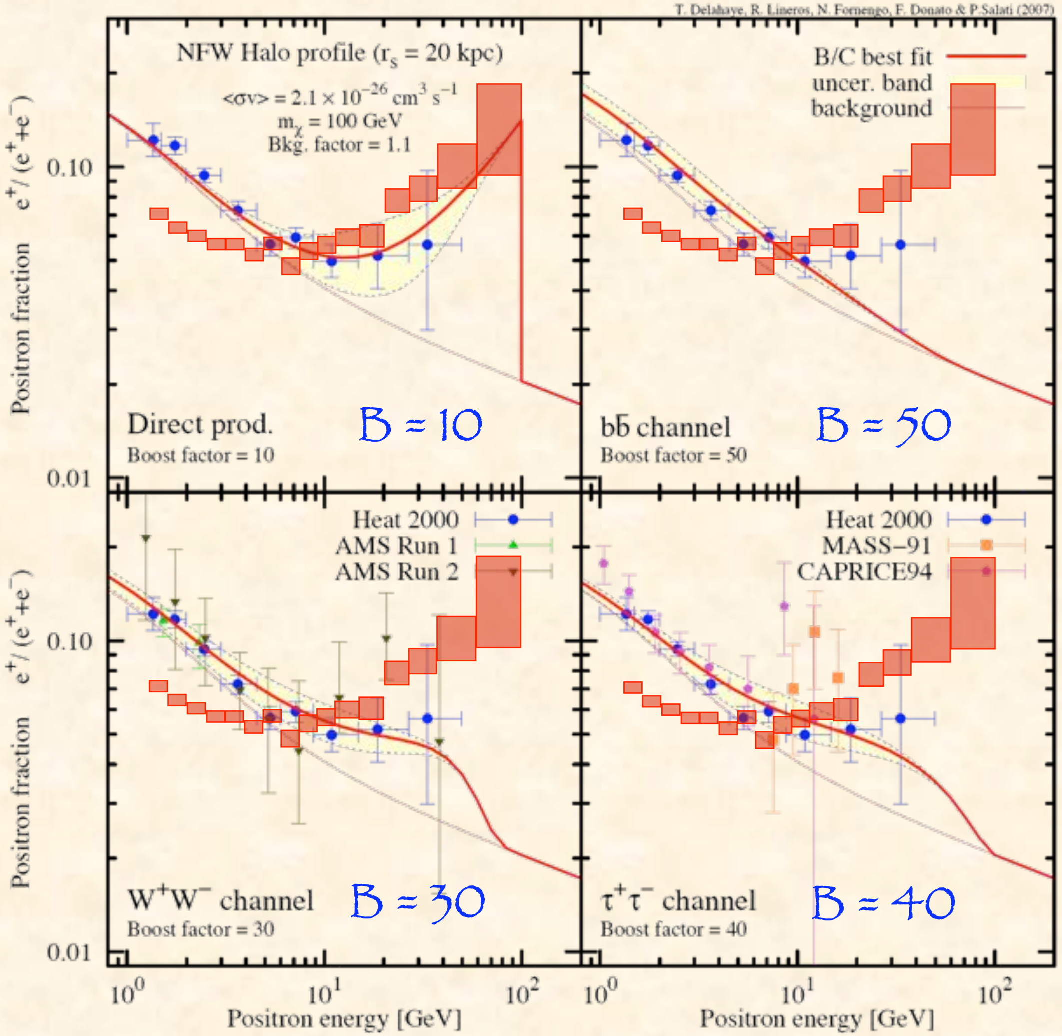
T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

Positron fraction: including a DM signal

$m_\chi \simeq 100$ GeV

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

■ PAMELA 2008



Smooth NFW halo

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

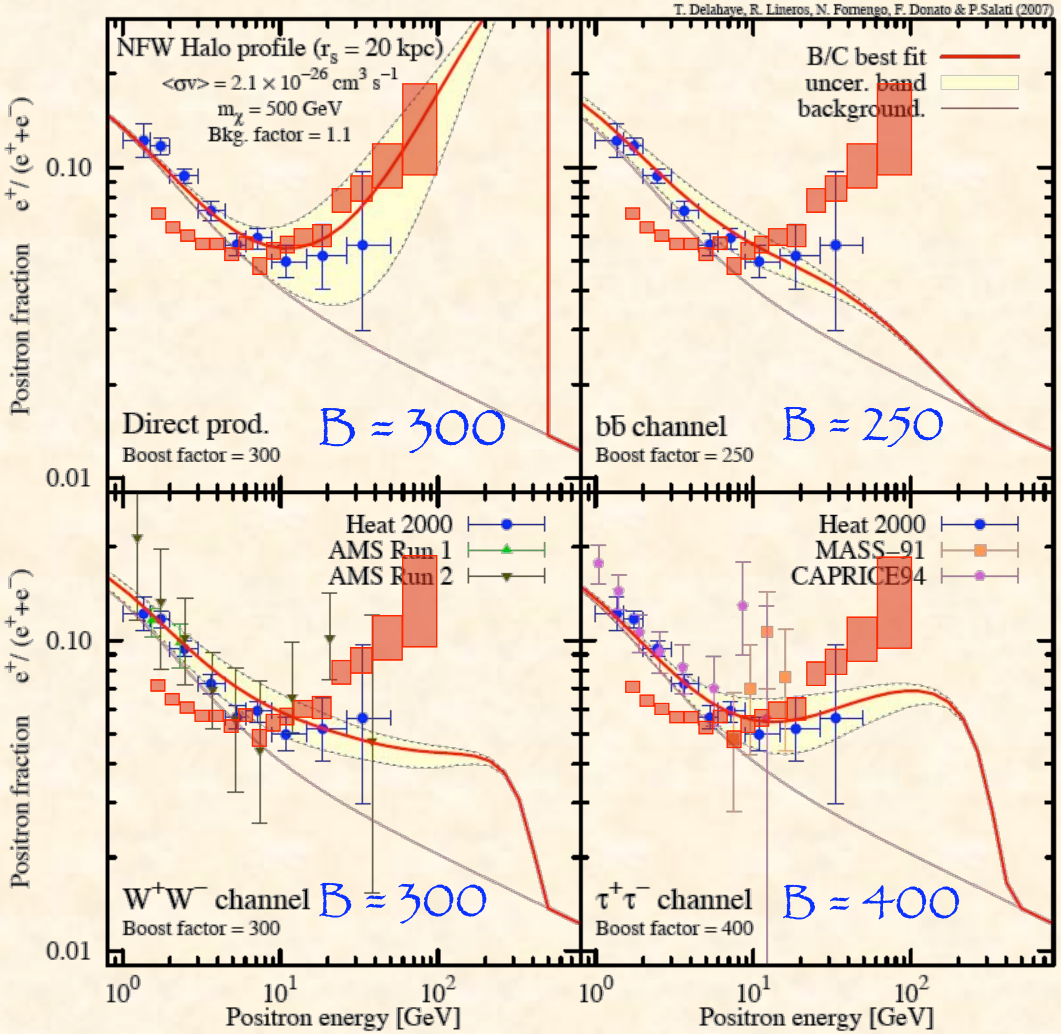
Annihilation cross section consistent with WMAP for a thermal relic

Uncertainty from DM fluxes only

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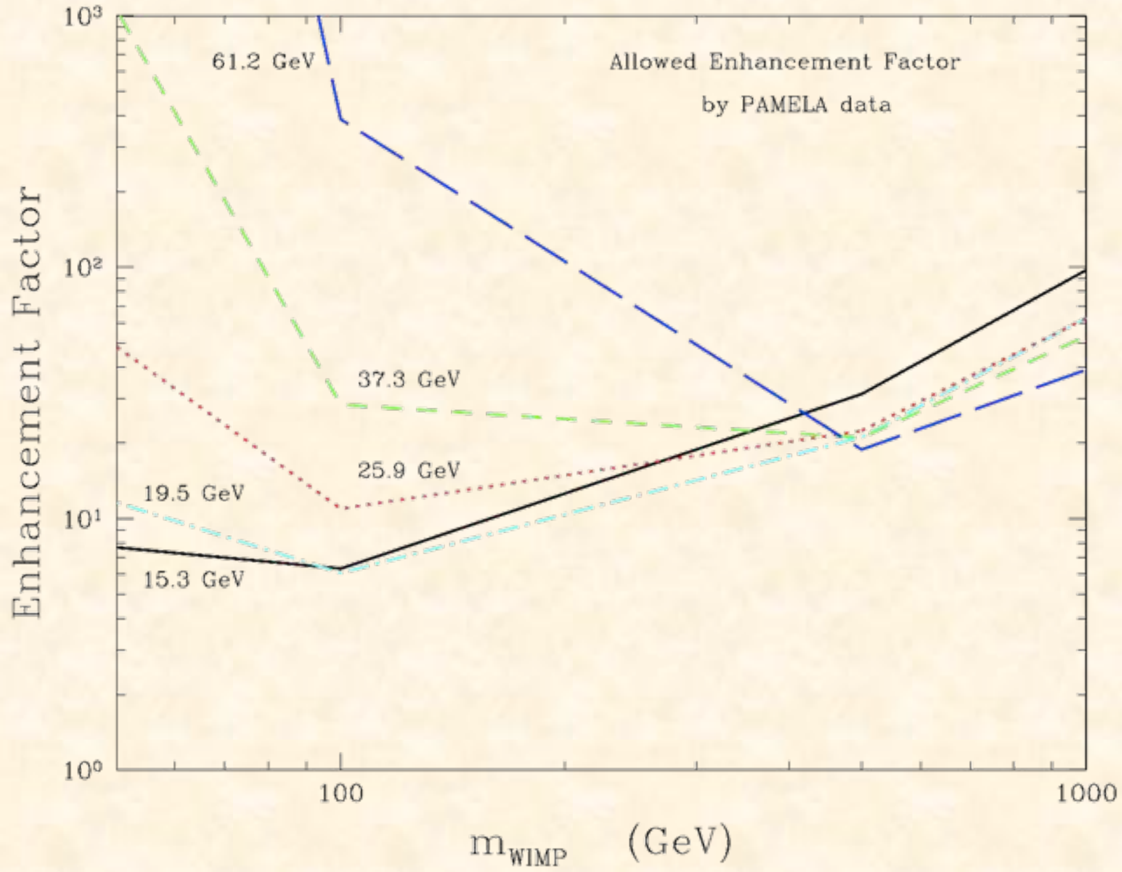
T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

For annihilation cross section consistent with WMAP

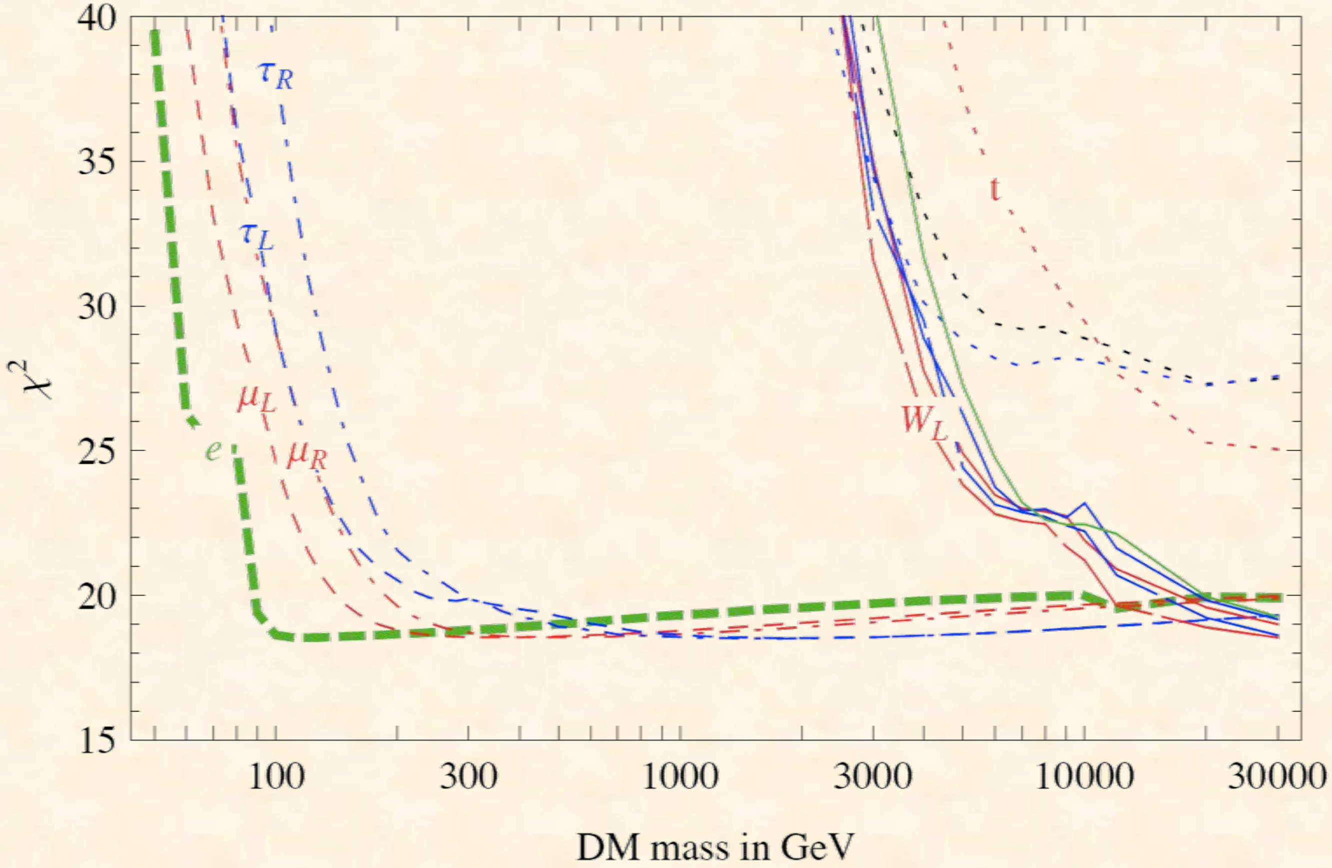
Smooth NFW halo

Constraint on boost from antiprotons



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

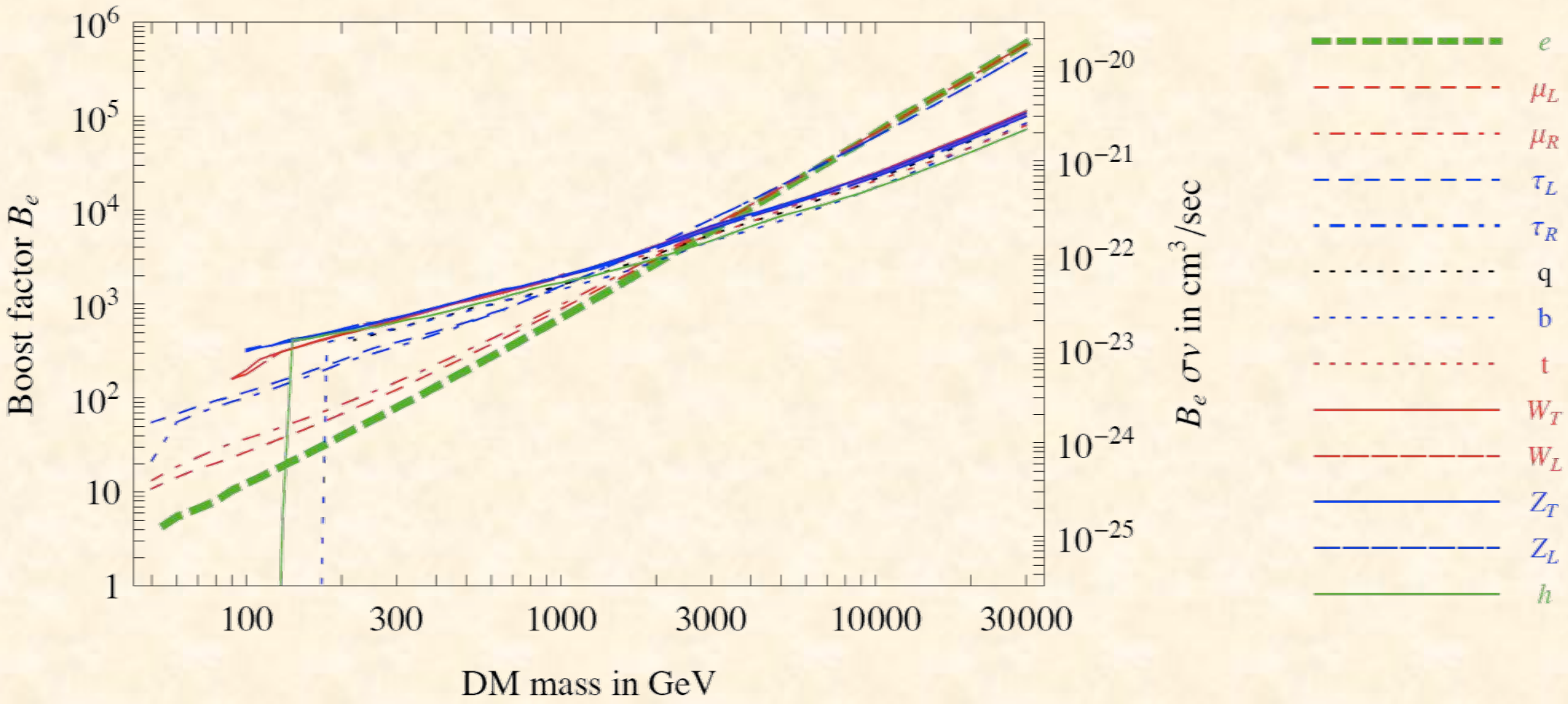
Model independent analysis



Fit on positron + antiproton data
(with S&M background, no theoretical uncertainties)

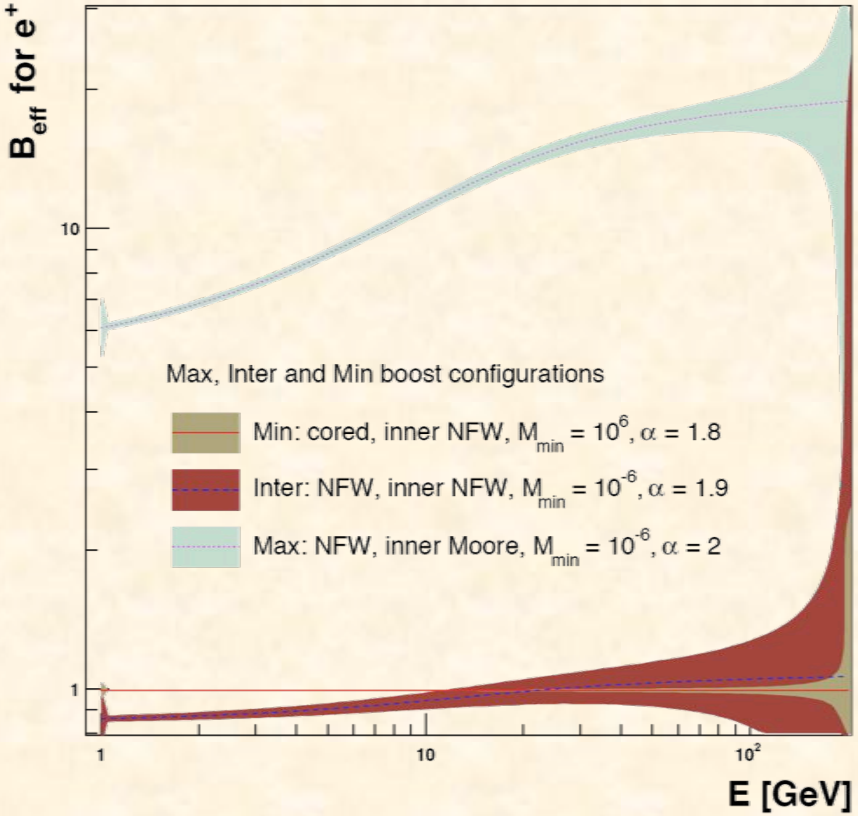
M. Cirelli, M. Kadastik, M. Raidal, A. Strumia, arXiv:0809.2409v3 [hep-ph]
See also: V. Barger, W.-Y. Keung, D. Marfatia, G. Shaughnessy, arXiv:0809.0162v2 [hep-ph]

Model independent analysis

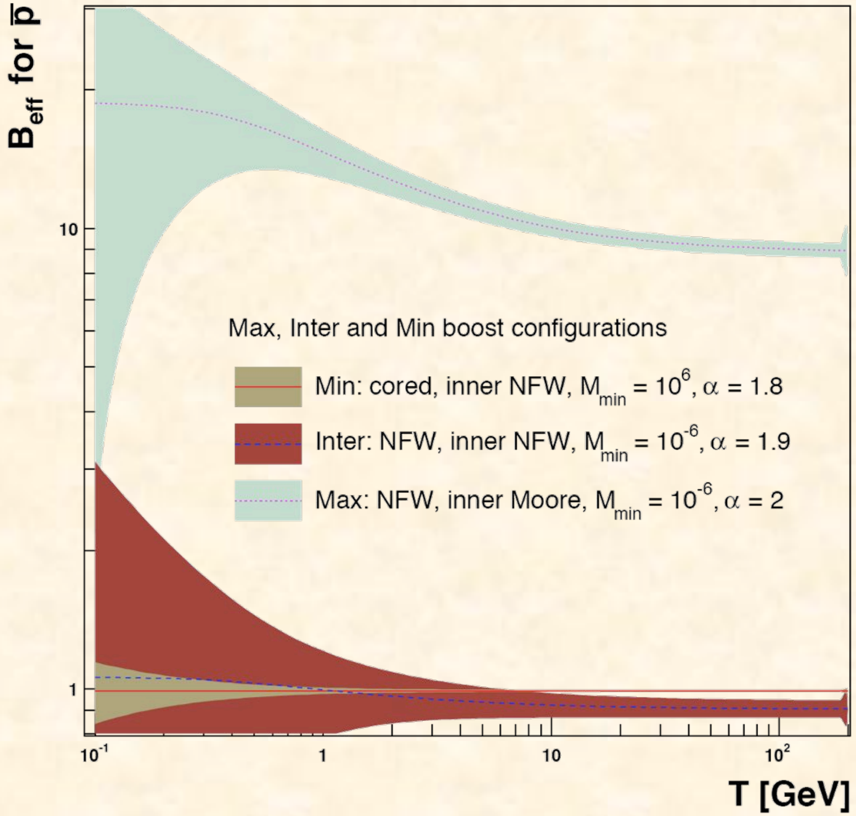


M. Cirelli, M. Kadastik, M. Raidal, A. Strumia, arXiv:0809.2409v3 [hep-ph]

Astrophysical boost



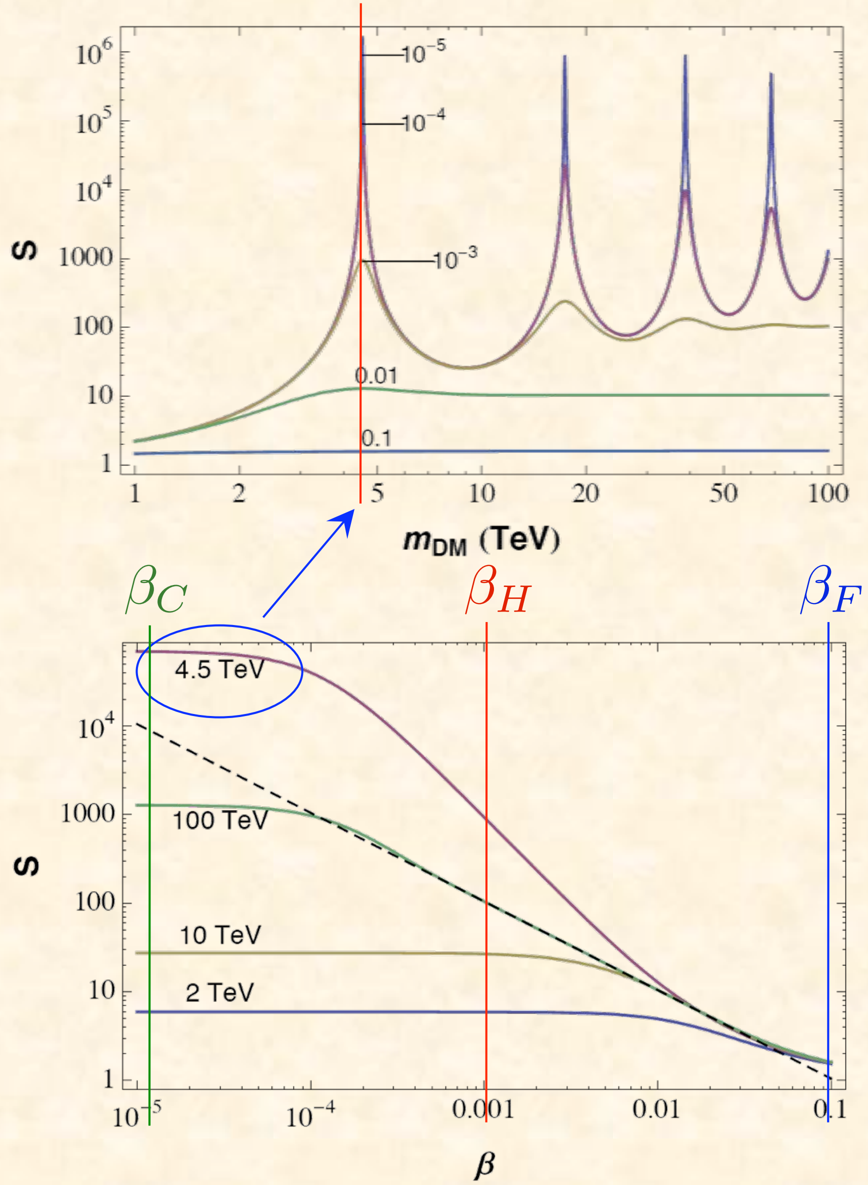
Positrons



Antiprotons

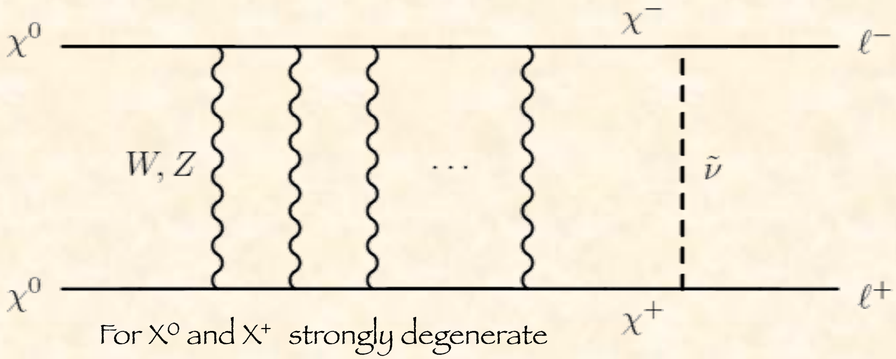
J. Lavalle, Q. Yuan, D. Maurin, X.J. Bi, A&A 479 (2008) 427

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)

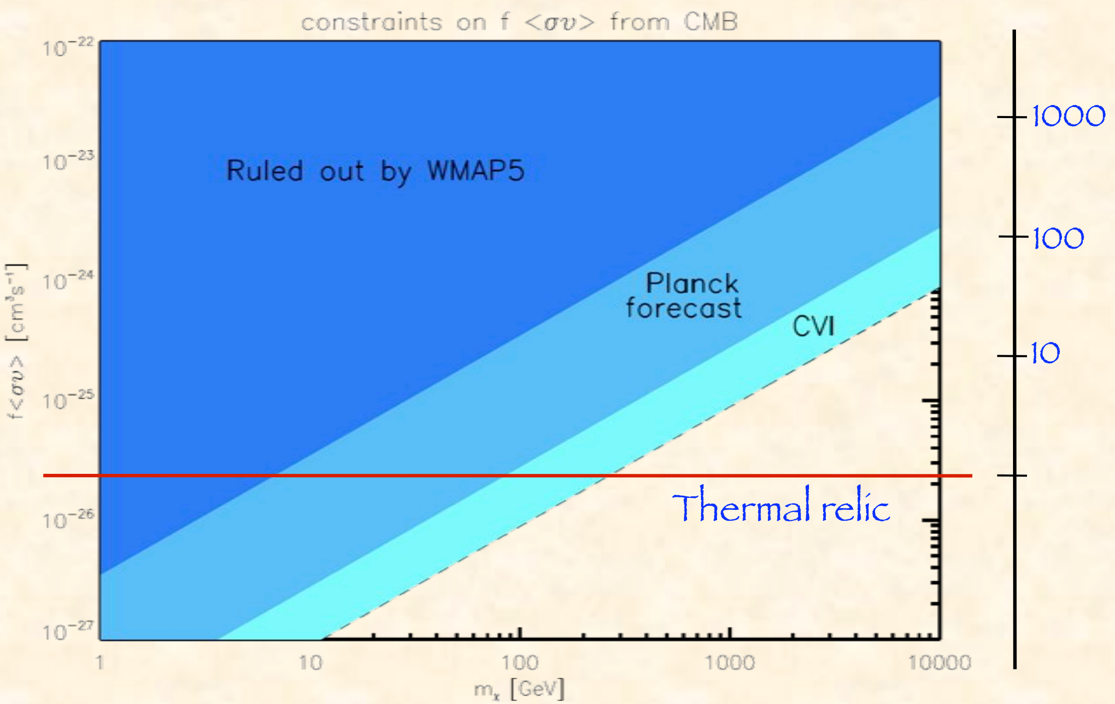


See also:

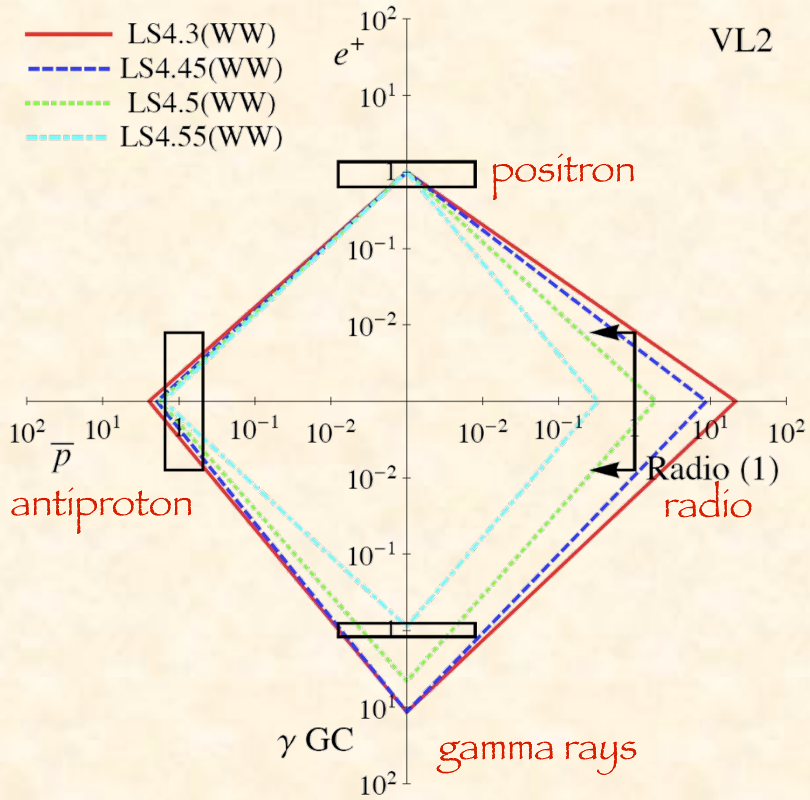
J. Hisano, M. Nagai, M. Nojiri, M. Senami, PRL 92 (2004) 031303
J. Hisano, S. Matsumoto, M. Nojiri, S. Saito, PRD, 71 (2005) 063528
M. Cirelli, A. Strumia, M. Tamburini, NPB 787 (2007)
J. March-Russell, S. M. West, D. Cumberbatch, D. Hooper, JHEP 0807 (2008) 058
N. Arkani-Hamed, D. P. Finkbeiner, T. 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]

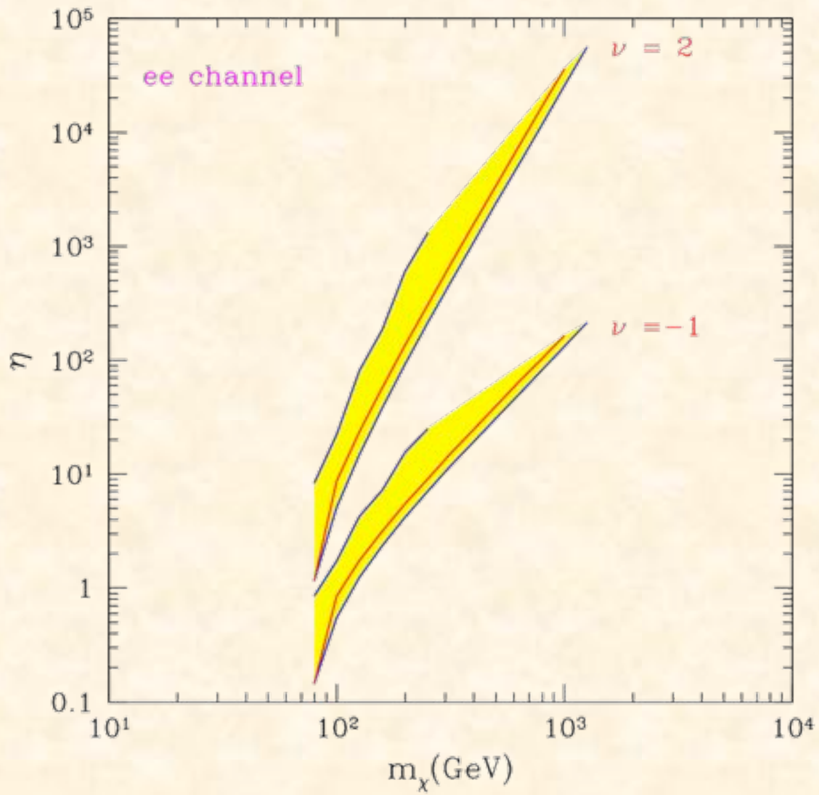
Cosmological boost

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

$\nu =$ 2: Brane Cosmology
1: Kination Cosmology
0: GR + extra-fields
-1: Scalar-Tensor Cosmology

- ✧ Enhanced Hubble rate
- ✧ Anticipated decoupling
- ✧ Larger annihilation cross section to match WMAP CDM abundance
- ✧ Larger indirect detection signals

- ✧ Boosts equally leptonic and hadronic channels



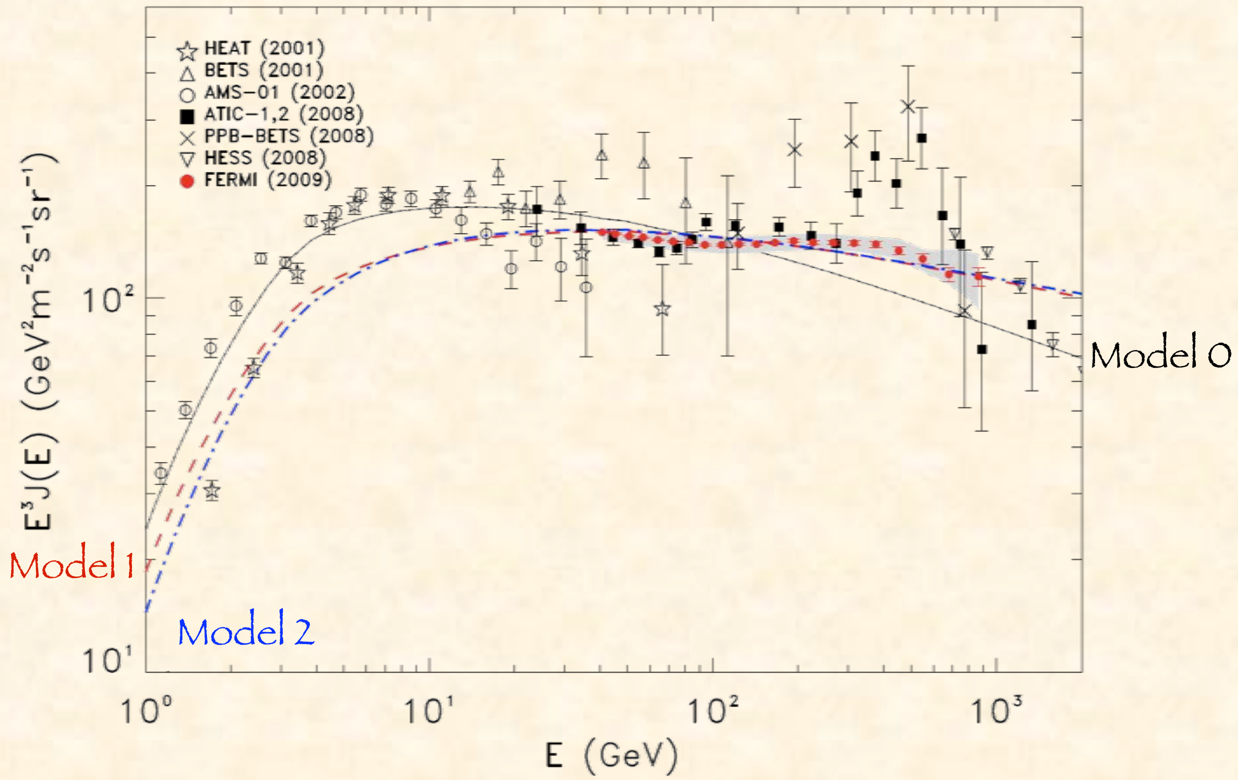
Antiproton + Radio + Gamma
constraints imposed

R. Catena, N. Fornengo, A. Masiero, M. Pato, L. Pieri, M. Pietroni, in progress

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

Positrons + electrons

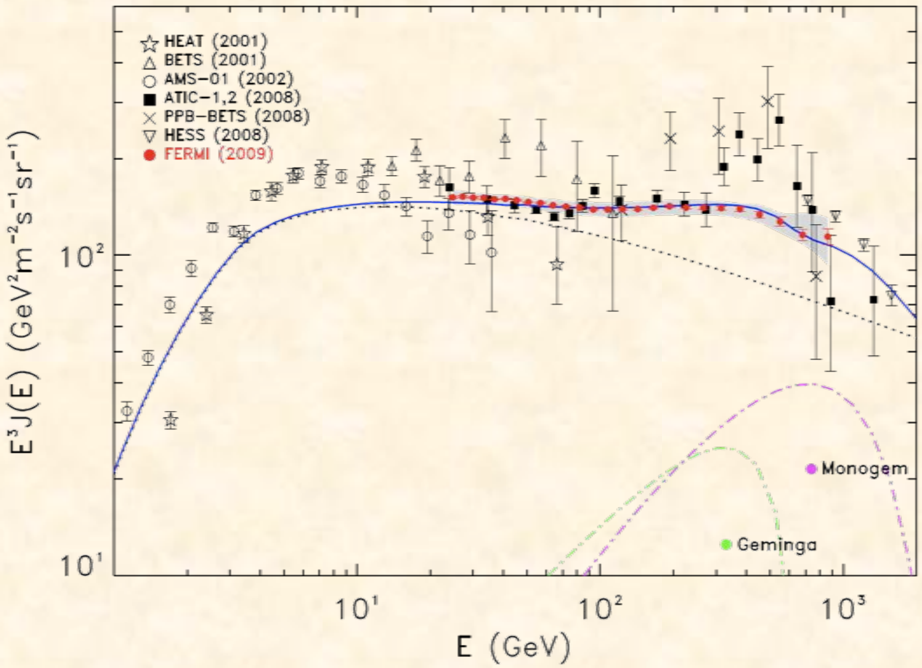
Electrons + Positrons: FERMI data

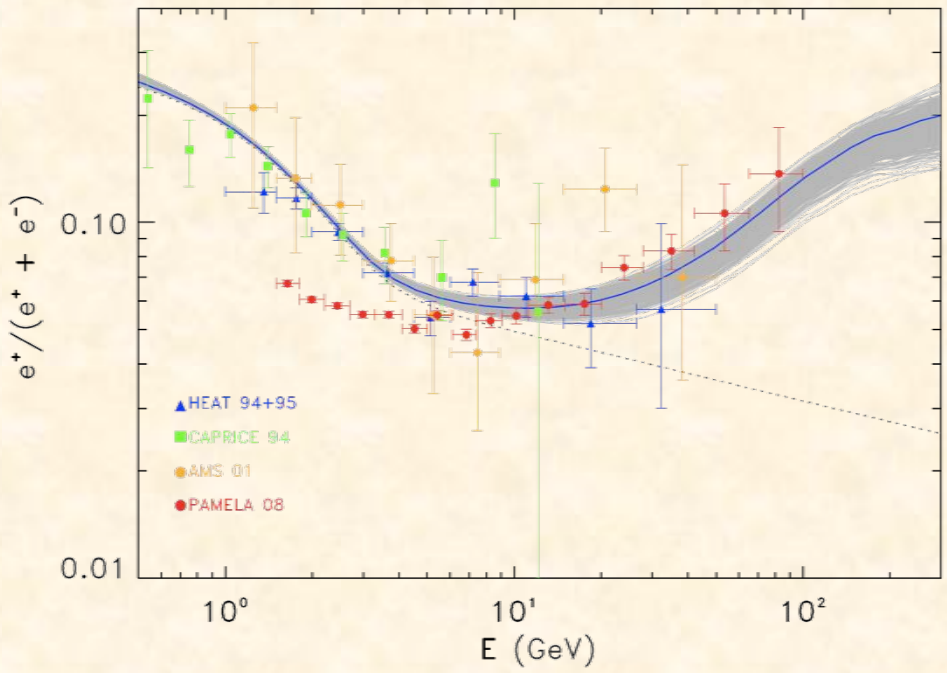


Model #	D_0 (cm^2s^{-1})	δ	z_h (kpc)	γ_0	N_{e^-} $(m^{-2}s^{-1}sr^{-1}GeV^{-1})$	γ_0^p
0	3.6×10^{28}	0.33	4	2.54	1.3×10^{-4}	2.42
1	3.6×10^{28}	0.33	4	2.42	1.3×10^{-4}	2.42
2	1.3×10^{28}	0.60	4	2.33	1.3×10^{-4}	2.1

A. Abdo et al. (FERMI Collab.), PRL 102 (2009)
D. Grasso et al., arXiv:0905.0636v1 [astro-ph.HE]

Electrons + Positrons: FERMI data

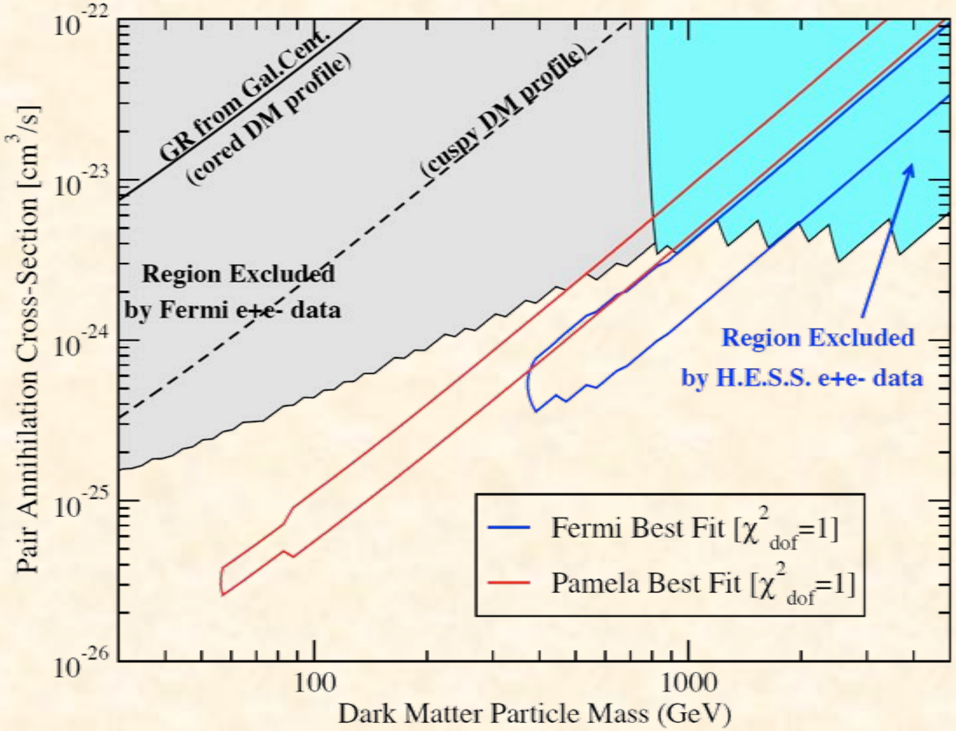




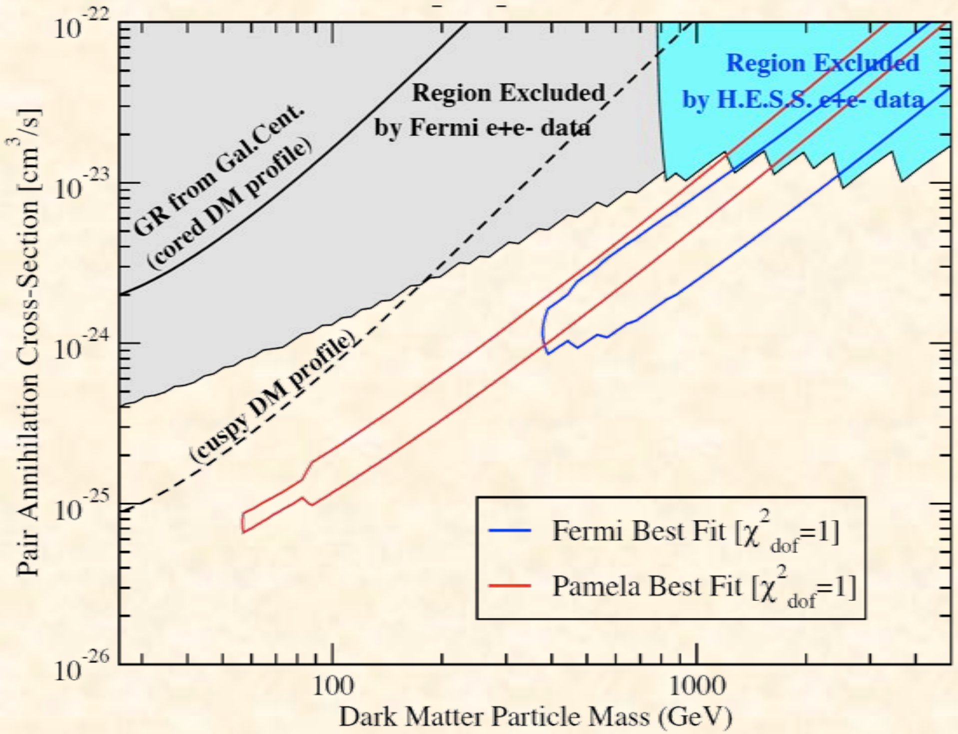
Adding d < 1 Kpc pulsars

A. Abdo et al. (FERMI Collab.), PRL 102 (2009)
D. Grasso et al., arXiv:0905.0636v1 [astro-ph.HE]

DM interpretation



Annihilation into e^+e^-



"Democratic annihilation into leptons"

D. Grasso et al., arXiv:0905.0636v1 [astro-ph.HE]

See also: 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]

Summary: Direct Detection

- Direct detection
  - Signature offered by annual modulation of the rate
    - DAMA/NaI and DAMA/Libra observe annual modulation in low-energy single-hit events
    - In susy models, this effect is compatible with relic dark matter candidates, like:
      - Neutralinos both in the MSSM and in gaugino non-universal schemes
      - Sneutrinos in LR models or models with L-violation and see-saw neutrino mass generation
  - Total counting rate: allows to set bounds
    - CDMS, Xenon10 and others currently probe a fraction of MSSM parameter space for neutralino or sneutrino dark matter
    - Extension of the probe depends on astrophysical (galactic halo properties) and nuclear physics (DM-nucleus interaction) assumptions
  - Other possible signatures (future): directionality of the recoil, diurnal effects

Summary: Indirect Detection thru Antimatter

- AntiDeuterons
  - strong feature at low-energies: offer the best possibility to detect a signal
  - theoretical uncertainties large, but do not significantly limit discovery potential

- AntiProtons
  - mild feature at low energies, but suitable to set (potentially relevant) bounds
  - theoretical uncertainties large: needed to set proper bounds
  - possible features at high energies, but requires "boost"
  - current data show no anomaly → bound on acceptable boosts

- Positrons (+ Electrons)
  - may posses spectral features (depending on the annihilation channel), typically require "boosts"
  - PAMELA data on positron fraction exhibit "anomalous" rise (may be astrophysical: e.g. pulsars, SNR)
  - FERMI data on electron+positrons exhibit a mild bump (may be astrophysical)
  - If DM: annihilation into leptons largely preferred (or very heavy DM)