Particle Dark Matter
Searching for New Physics without Accelerators

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Catania - March 30, 2005

Evidence of Darkness

- The presence of large amounts of non-luminous components has been identified by different means on different scales:
  - Galactic scale — rotational curves
  - Extragalactic scale — abundance of clusters
  - Cosmological scale — high-redshift Sne, CMBR

  Lyman-α

- The current view:

$$\Omega_{\text{tot}} = 1.02 \pm 0.02$$
$$\Omega_M = 0.27 \pm 0.04$$
$$\Omega_\Lambda = 0.73 \pm 0.04$$

C.L. Bennet et al. (WMAP Collab.) Astrophys. J. Suppl. 148 (2003) 1

D.N.Spergel et al. (WMAP Collab.) Astrophys. J. Suppl. 148 (2003) 175

- We cannot explain these results with standard components:
  - Baryons (from BBN and CMB): $\Omega_B = 0.044 \pm 0.004$
  - Luminous matter: $\Omega_L \sim 0.003$

Three dark components in the Universe:

- Dark baryons
- Dark non-baryonic matter
- Dark energy

Both DM and DE ask for extension of the Standard Model of fundamental interactions

After WMAP *:

$$\Omega_{\rm CDM} h^2 : (0.095 \div 0.131) \quad [2\sigma]$$

* Combined with 2dGFRS, Lyman-α

Particle candidates for non-baryonic dark matter

- Non supersymmetric candidates
  - Massive neutrino
  - Axion
  - (...)
- Supersymmetric candidates
  - Neutralino
  - Sneutrino
  - Gravitino
  - Axino
  - Messenger fields
  - Stable non-topological solitons (Q-balls)
  - Heavy non-thermal relics
  - (...)
- Other candidates
  - Mirror baryons
  - Scalar fields
  - Kaluza-Klein fields
  - (...)

$\Omega_\nu h^2 < 0.076 \quad [95\%\text{C.L.}]$

$m_\nu < 0.23\ \text{eV} \quad (3\ \text{degenerate}\ \nu)$

- Low energy MSSM
- Minimal SUGRA
- Non-minimal SUGRA
  - Higgs sector
  - Sfermion sector
  - Gaugino sector
- Split supersymmetry

- Low energy MSSM with gaugino non-universality

$M_2 \quad \mu \quad \tan\beta \quad m_A \quad m_{\tilde{f}} \quad m_{\tilde{q}} \quad A$

$R = M_1/M_2$

Low energy MSSM with gaugino non-universality

- Neutralino: M_1 M_2 μ
- Chargino: M_2 μ $m_\chi^\pm$ bound → M_2 μ bound

LEP limit: $m_\chi^\pm \gtrsim 103$ GeV → $M_2, \mu \gtrsim 103$ GeV

with: $M_1 \simeq 0.5 M_2$ → $m_\chi \gtrsim 50$ GeV

with gaugino non-universality: $M_1 = R M_2$ and $R < 0.5$

lower limit decreases

Properties of light neutralinos

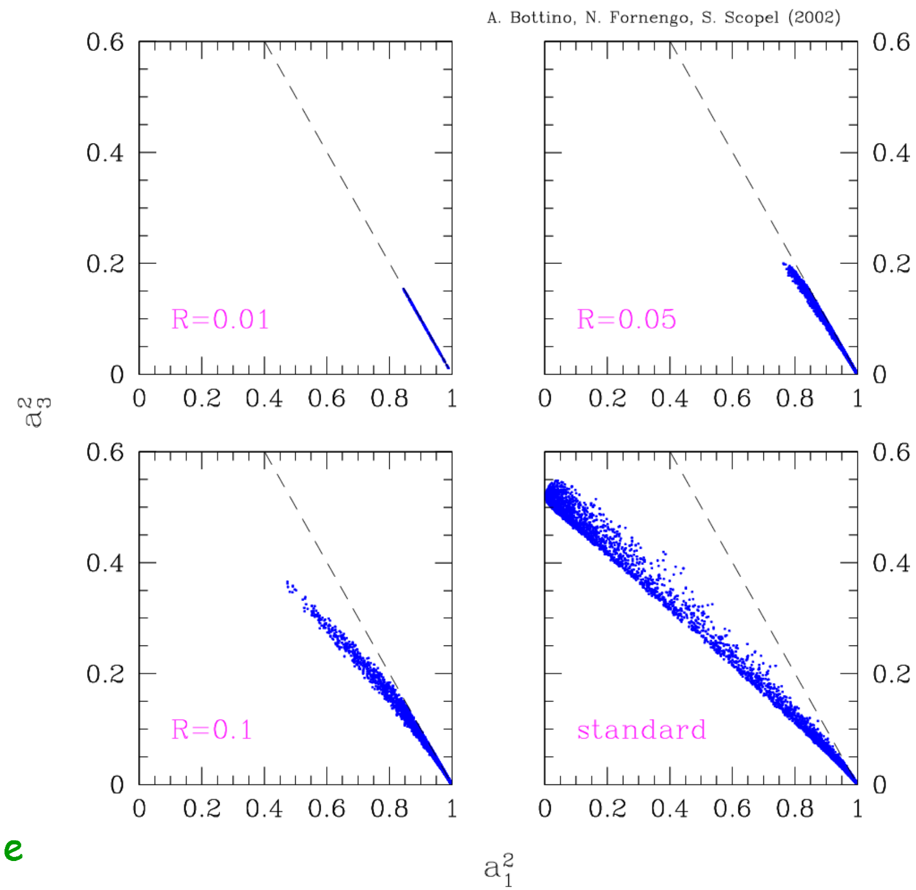
- For low values of R, neutralinos are dominated by the Bino component, with a mixture of higgsino$_1$:

$$\frac{|a_3|}{|a_1|} \simeq \sin\theta_W \sin\beta \frac{m_Z}{\mu} \lesssim 0.42 \sin\beta$$

- These features imply:
  - sizeable yukawa-type coupling to higgses
  - gauge-type coupling to sfermions
  - depressed coupling to Z boson

This implies that the contribution to the Z invisible width is quite small and the bound for very light neutralino is easily evaded

$$\chi = a_1 \tilde{B}^0 + a_2 \tilde{W}_3^0 + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0$$

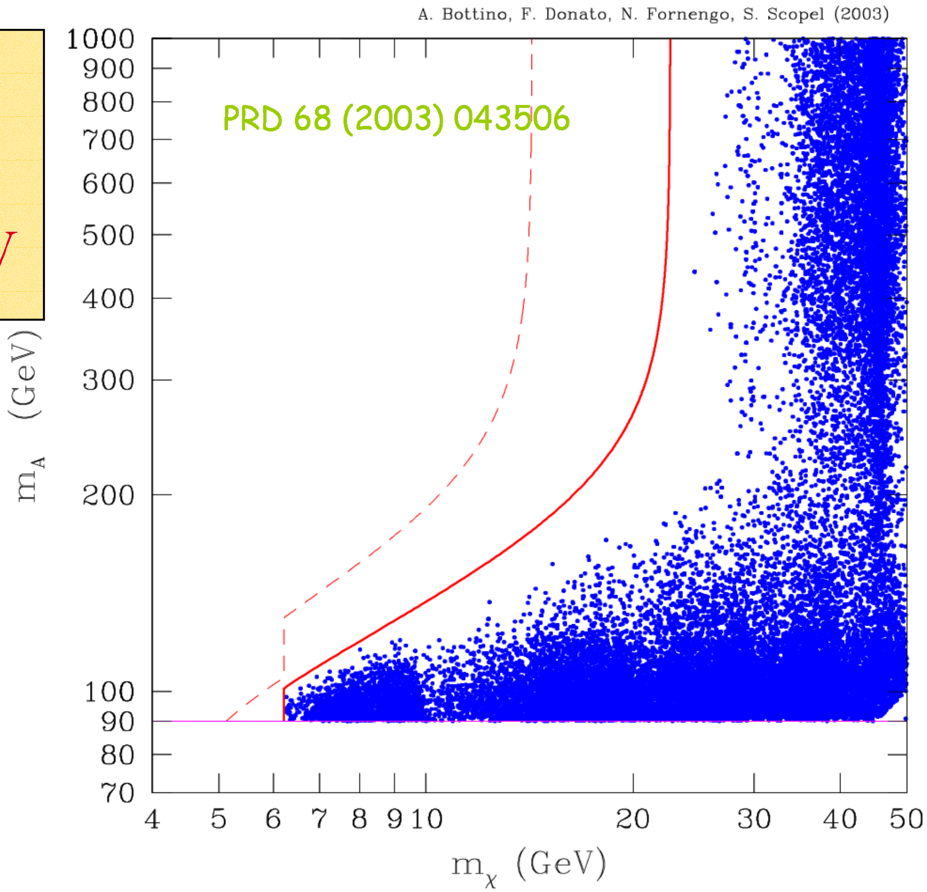


PRD 67 (2003) 063519

Cosmological lower bound on the neutralino mass

The cosmological limit on the amount of CDM allows to set an absolute lower bound on the neutralino mass

For: $m_A \lesssim 180$ GeV		$m_\chi > 6$ GeV
Otherwise:		$m_\chi > 22$ GeV



In this model Cosmology complements accelerator searches, for which a lower bound on the neutralino mass is not available

In the low-mass neutralino sector, also Higgses are relatively light

Searches for relic-particle dark matter

- Direct search: elastic scattering of χ off nuclei in a low background detector
  → recoil energy of the nucleus

- 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
  - signals due to $\chi\chi$ annihilation taking place in the galactic halo
    → neutrinos
    → photons
      ✓diffuse gamma-ray flux
      ✓gamma-ray line
      ✓radio
    → positrons
    → antiprotons
    → antideuterons

Searches for relic-particle dark matter

- Direct search: elastic scattering of χ off nuclei in a low background detector

Undergound experiments

DAMA/LIBRA, HDMS/GeniusTF, Cuoricino/Cuore (...)

IGEX, Rosebud; Edelweiss; CDMS, XENON, Zeplin, DRIFT, Elegants (...)

- Indirect searches:
  - signals due to $\chi\chi$ annihilation taking place inside celestial bodies (Sun, Earth) where χ have been captured and accumulated
    - → neutrino flux

Neutrino telescopes

SuperKamiokande, MACRO, Baksan, Amanda - Antares, IceCube (...)

  - signals due to $\chi\chi$ annihilation taking place in the galactic halo
    - → neutrinos
    - → photons
      - ✓diffuse gamma-ray flux
      - ✓gamma-ray line
      - ✓radio
    - → positrons
    - → antiprotons
    - → antideuterons

Detectors in space

BESS, Caprice, Heat - Pamela, AMS, GAPS (...)

EGRET, GLAST (...)

Air-Cerenkov detectors

HESS, Cangaroo, Magic, Auger, Veritas (...)

Searches for relic-particle dark matter

- Direct search: elastic scattering of χ off nuclei in a low background detector

$$\rho_l \quad f(\vec{v})$$

- Indirect searches:
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    - → neutrinos
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      - ✓diffuse gamma-ray flux
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    - → antiprotons
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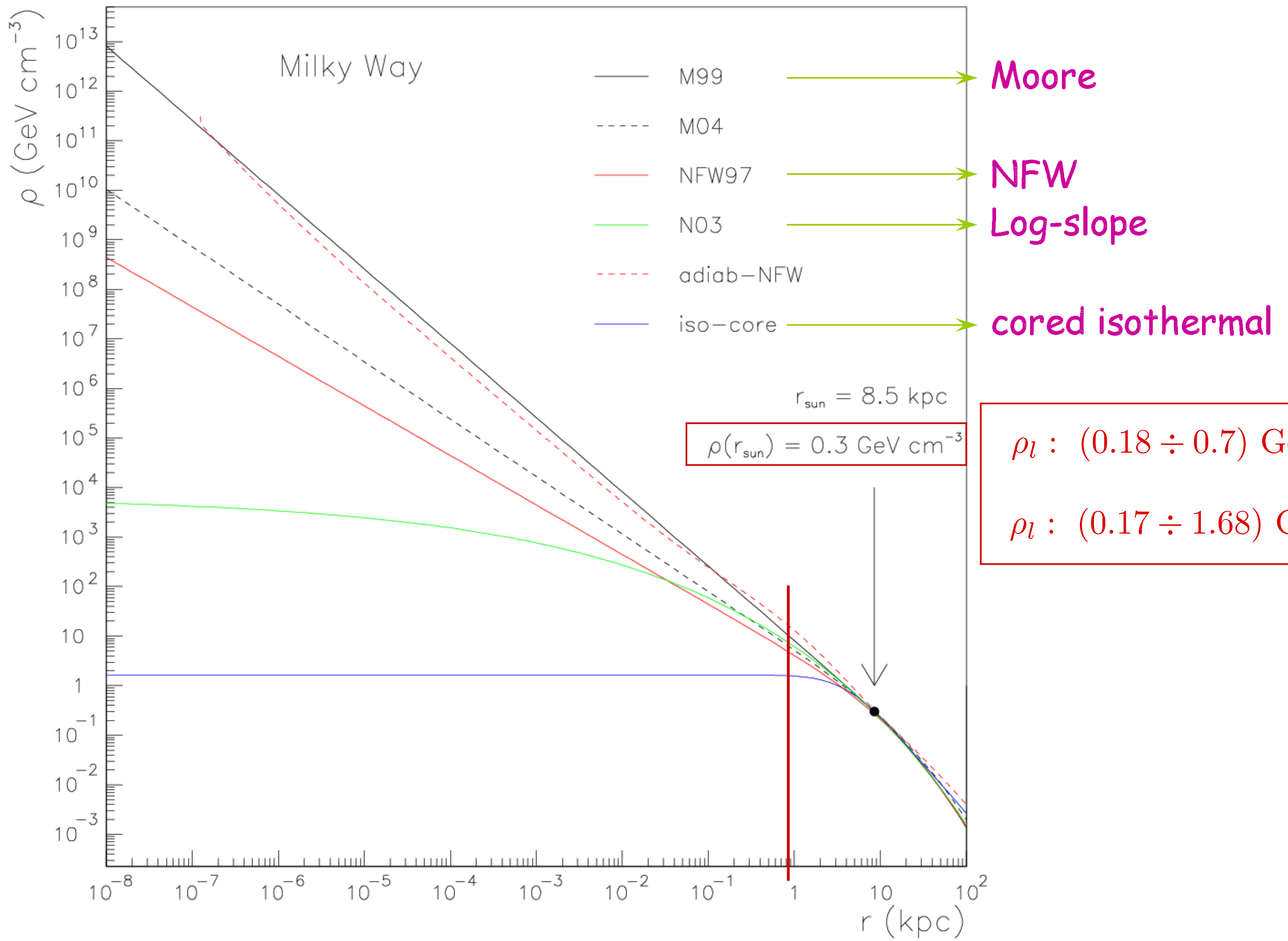
$$\rho^2(\vec{r})$$

Density profiles



ρ_l : $(0.18 \div 0.7)$ GeV cm^{-3} IS

ρ_l : $(0.17 \div 1.68)$ GeV cm^{-3}

In addition to a smooth density profile, there may also be a clumpy structure

Velocity DF

- The typical velocity DF of a relaxed DM halo is a truncated MB distribution (in the galactic rest frame):

$$f(v) = N \exp\left(-\frac{3v^2}{2\sigma^2}\right)\Bigg|_{v \leq v_{\rm esc}}$$

$$\sigma = 3v_0^2/2$$

$$v_0 = (220 \pm 50)\ \mathrm{km\ s^{-1}} \quad (90\%\ \mathrm{C.L.})$$

$$v_{\rm esc} = (450 \div 650)\ \mathrm{km\ s^{-1}} \quad (90\%\ \mathrm{C.L.})$$

- May be anisotropic

- Depending on the formation history, non-thermal component may also be present [e.g. streams]

Dark Matter Direct Searches

Direct detection

- Direct detection relies on the elastic scattering of neutralinos off the nuclei of the detector

$$\frac{\mathrm{d}\mathcal{R}}{\mathrm{d}E_{\mathrm{R}}} = \frac{\rho_\chi^{\mathrm{loc}}}{m_\chi} \sum_i N_{T,i} \int_{v_{\min(E_{\mathrm{R}})}}^{v_{\max}} \mathrm{d}v\, f(v)\, v \frac{\mathrm{d}\sigma_{\mathrm{el},i}}{\mathrm{d}E_{\mathrm{R}}}(v, E_{\mathrm{R}})$$

$$E_{\mathrm{R}} = \frac{m_{\mathrm{red}}^2 v^2 (1 - \cos\theta^*)}{m_i}$$

$$v_{\min(E_{\mathrm{R}})} = (m_i E_{\mathrm{R}} / 2 m_{\mathrm{red}}^2)^{1/2}$$

- Since WIMPs have typical velocities of order 200-300 Km s^{-1}

$$< E_{\mathrm{R}} > \approx \mathrm{KeV} \left(\frac{m_i}{\mathrm{GeV}}\right) \left(\frac{m_\chi}{m_\chi + m_i}\right)^2$$

recoil energies in the KeV range

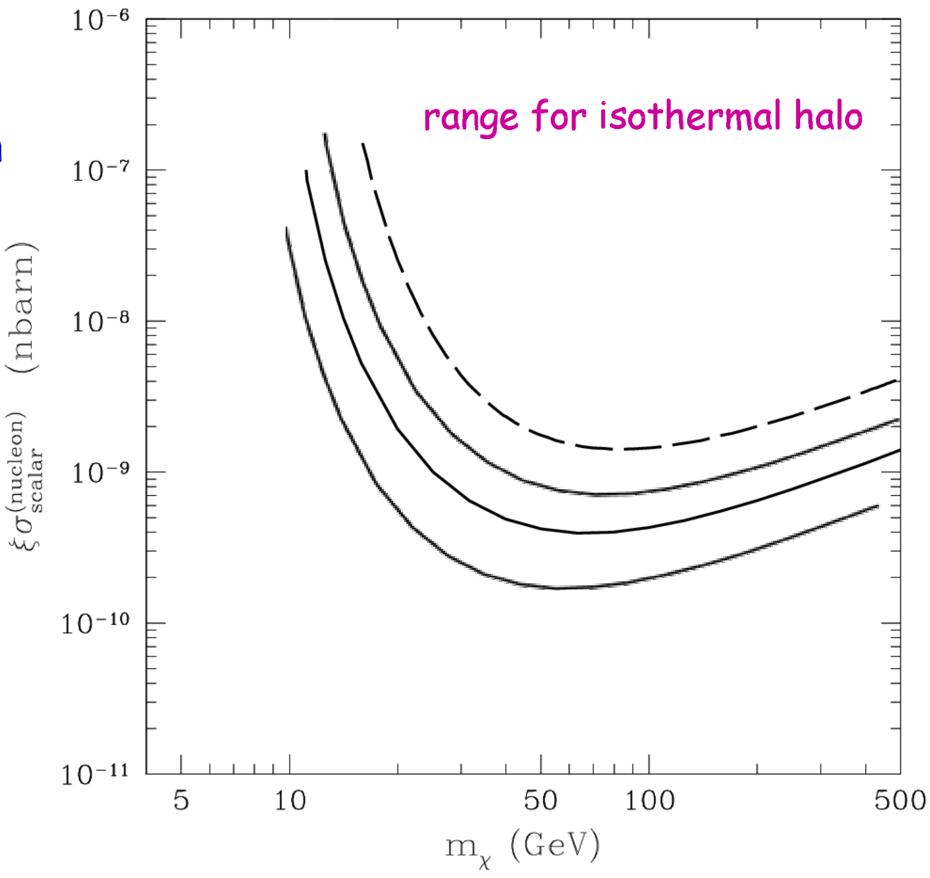
Direct searches: upper limits

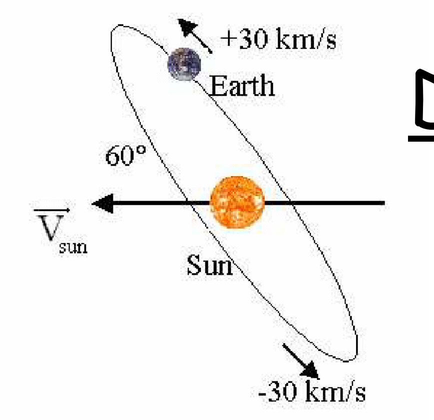
standard isothermal galactic halo

CDMS II @ Soudan (solid)
[D.S. Akerib et al., astro-ph/0405033]

EDELWEISS (dashed)
[A. Benoit et al., PLB 545 (2002) 43]

WIMP-nucleon
elastic scattering
coherent cross section





DAMA annual modulation result

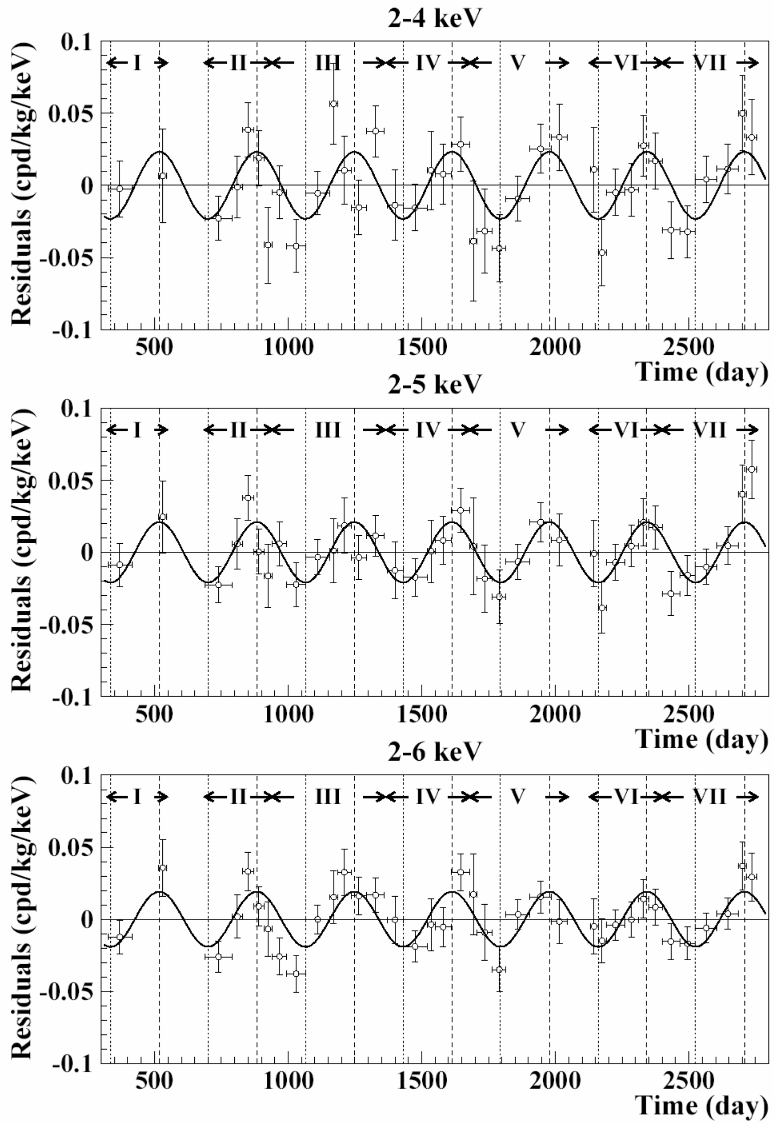
- DAMA/NaI
  - 100 kg NaI(Tl)
  - Located in the LNGS

- Reported a modulation effect over a 7 year cycle at 6.3 C.L.

$$S_m = (0.0200 \pm 0.032)\ \mathrm{cpd/kg/keV}$$

$$t_0 = (140 \pm 22)\ \mathrm{day}$$

$$T = (1.00 \pm 0.01)\ \mathrm{yr}$$



[R. Bernabei et al., Riv. N. Cim. 26 n. 1 (2003) 1]

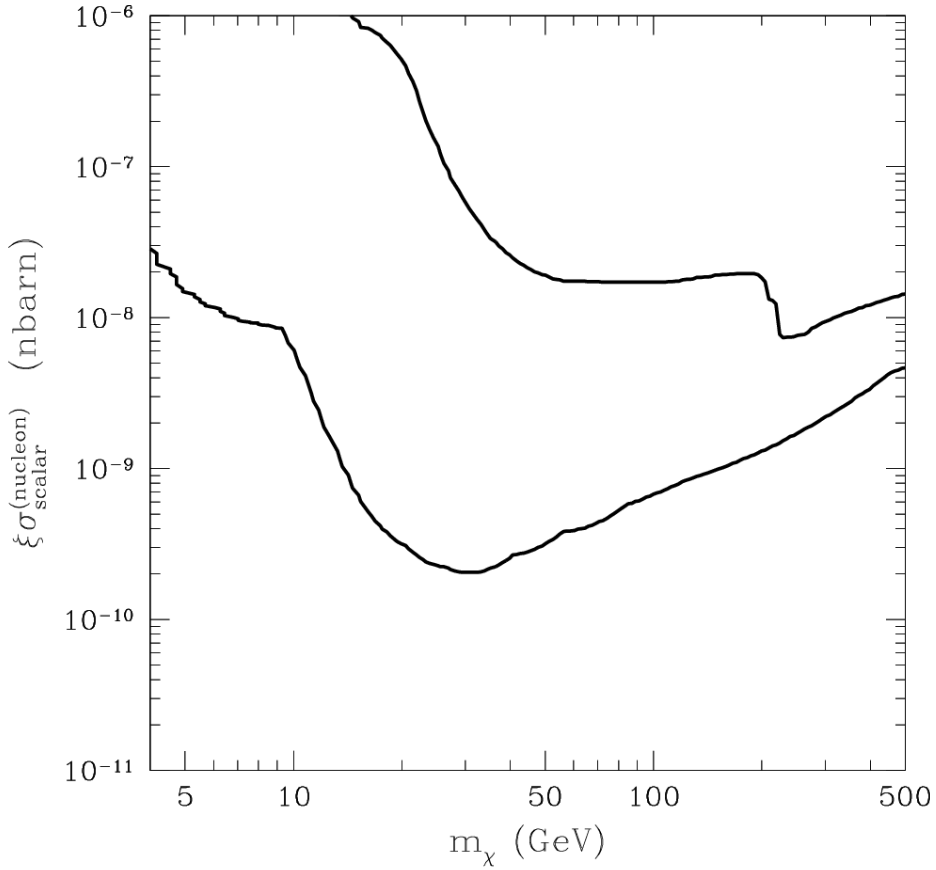
The total exposure is 107731 kg · day.

Direct searches: DAMA result

DAMA allowed region

for a wide variation of galactic halo models

[R. Bernabei et al., Riv. N. Cim. 26 n. 1 (2003) 1]



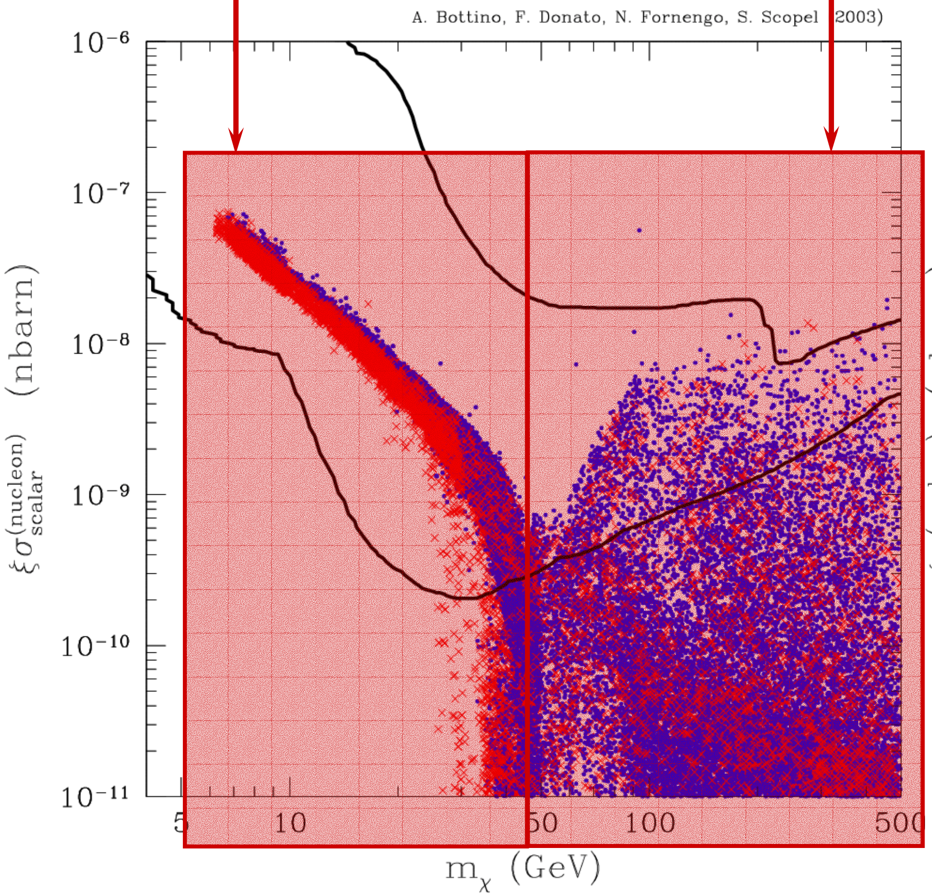
Direct searches

Gaugino Non-Universal MSSM

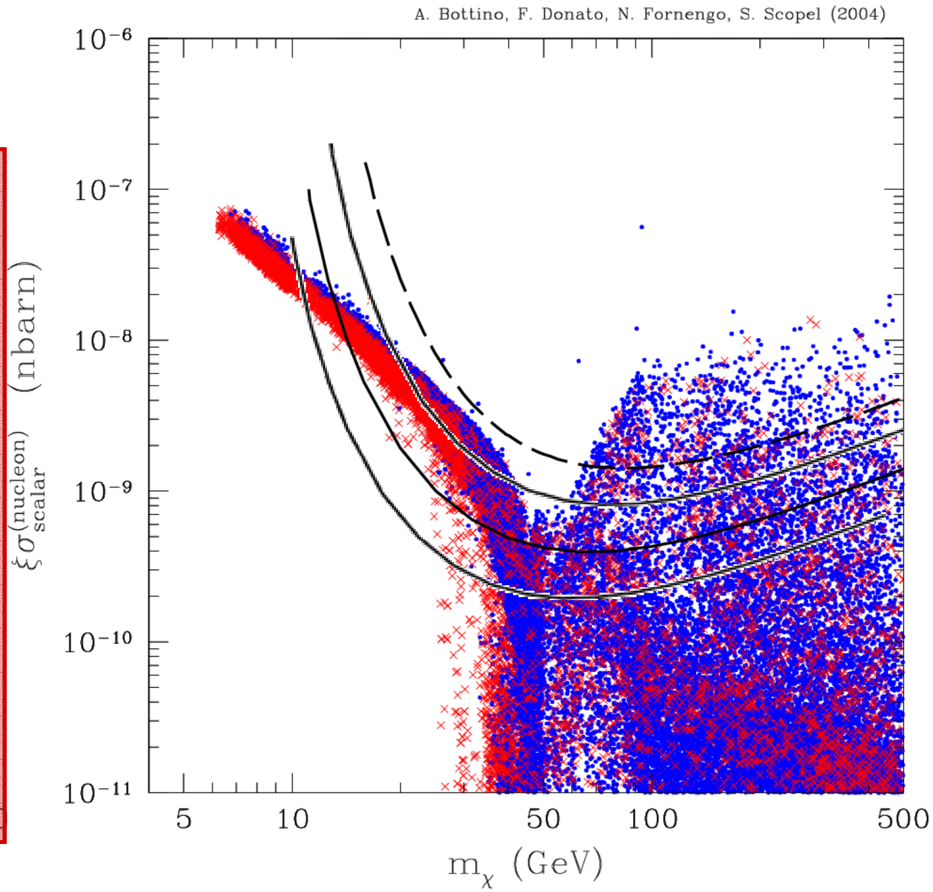
Gaugino Universal MSSM

PRD 69 (2003) 037302

DAMA allowed region



CDMS II (solid) - EDELWEISS (dashed)

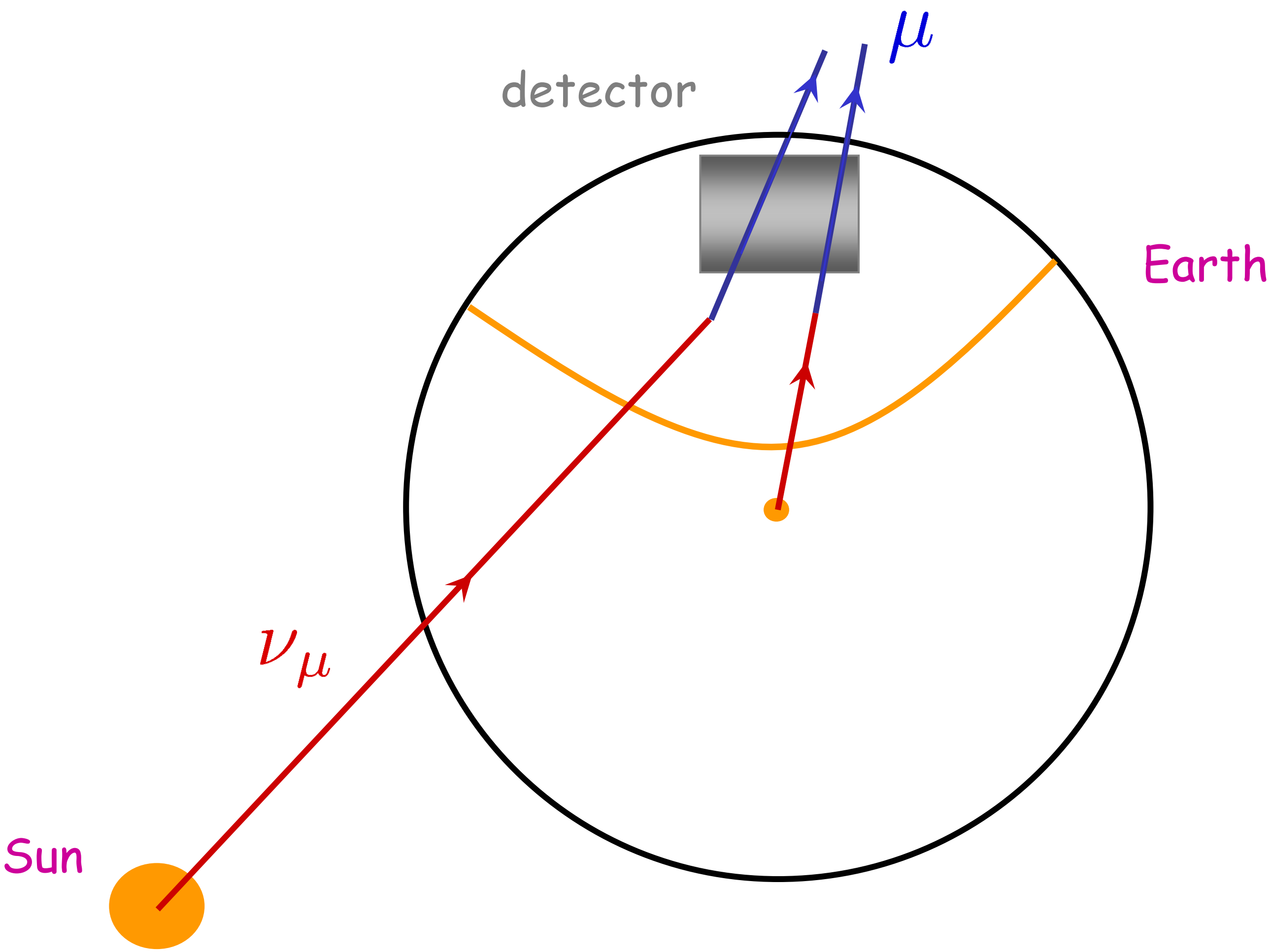


× cosmologically dominant neutralinos

• cosmologically subdominant neutralinos

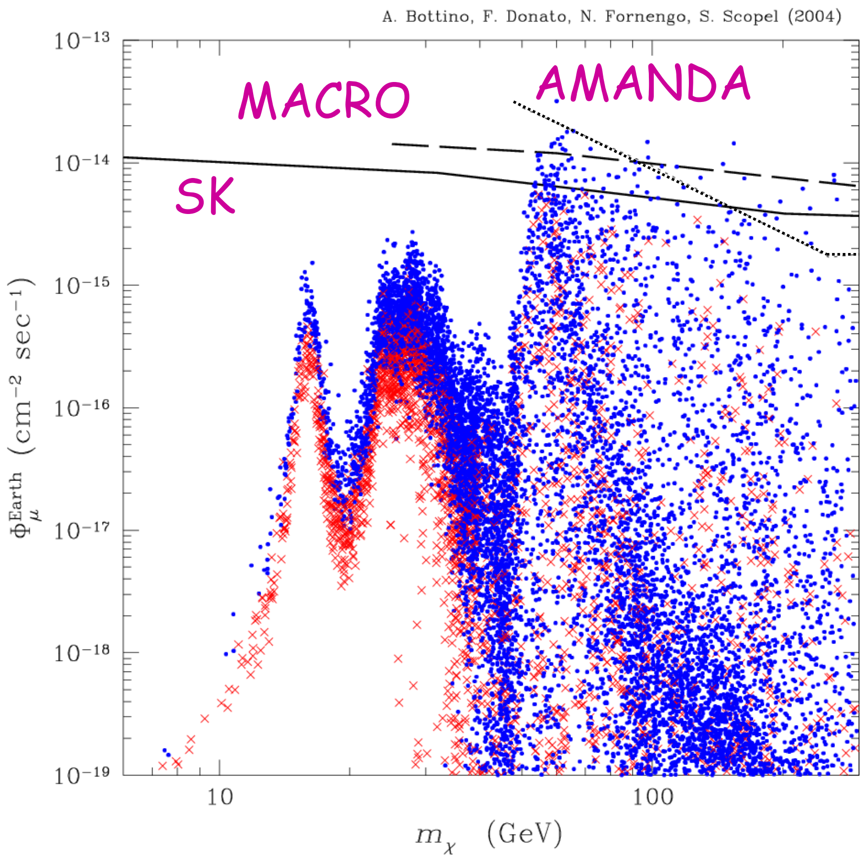
Dark Matter Indirect Searches

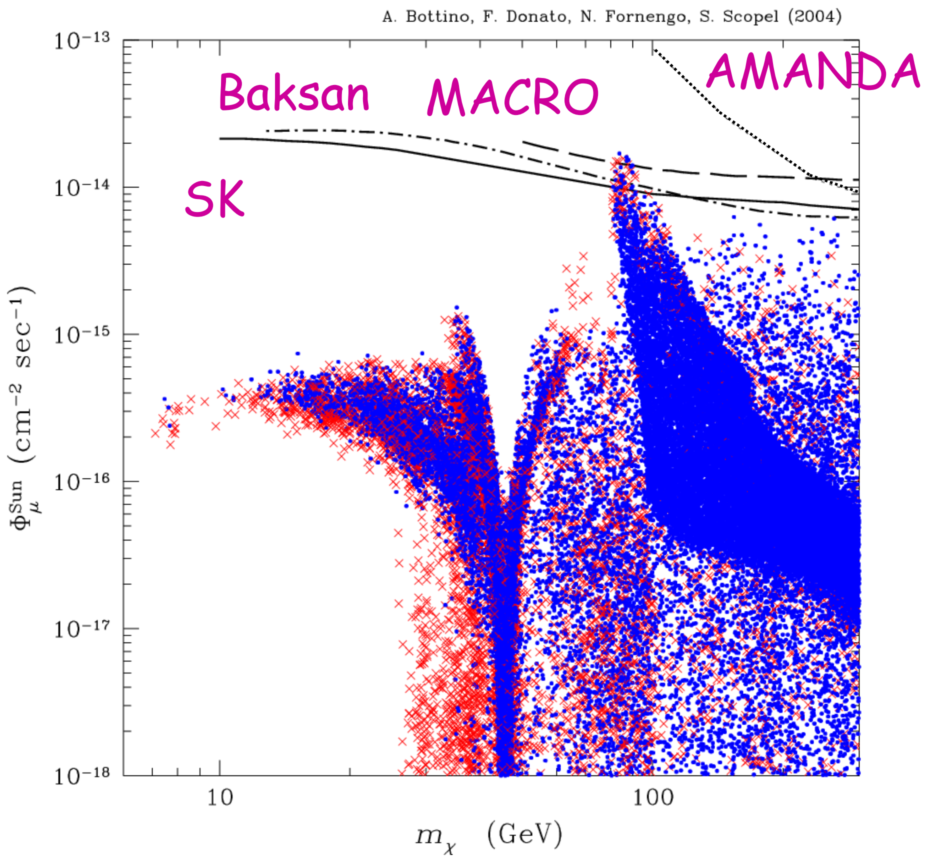
Neutrino flux from the Earth or Sun



conversion target largely increased

Signal in a neutrino telescope



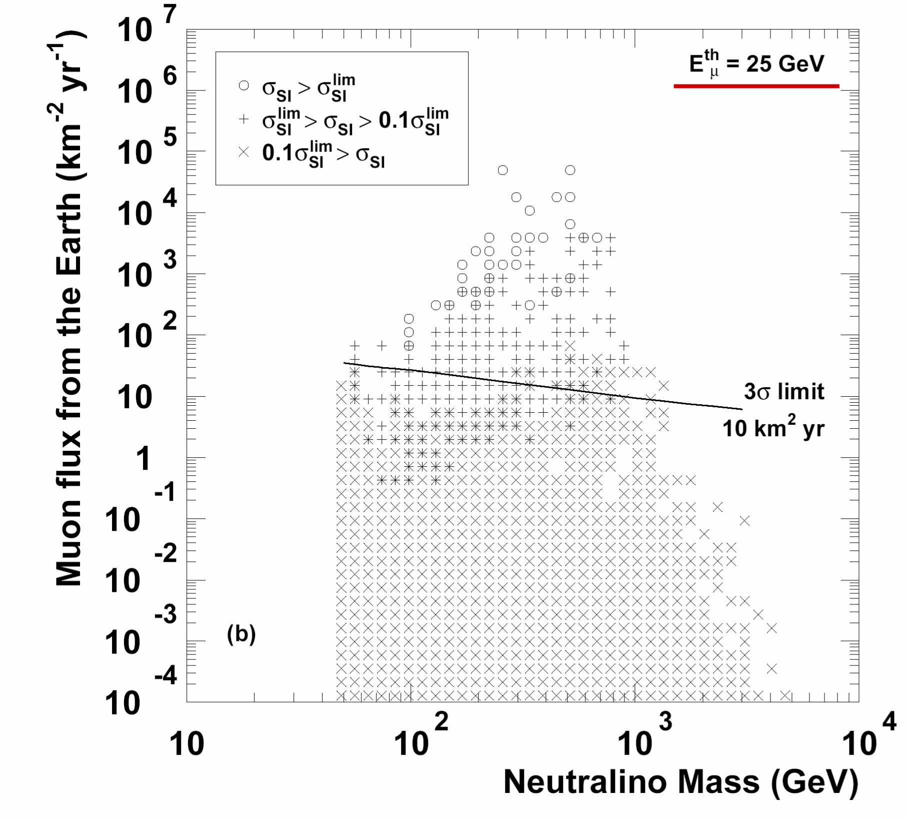


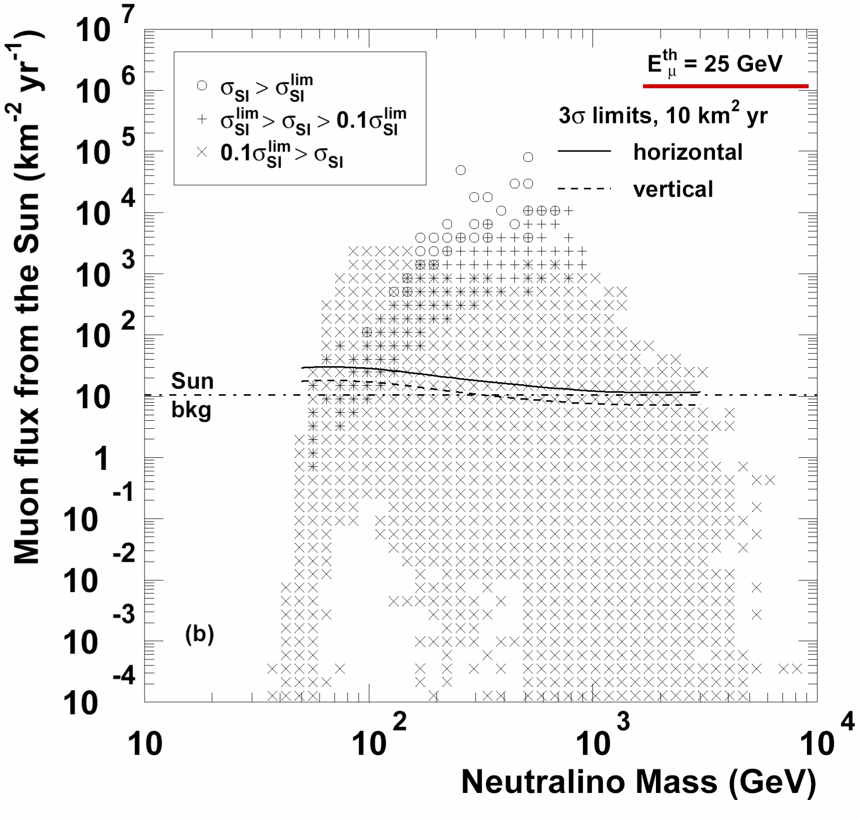
$$E_\mu^{\rm th} = 1 \text{ GeV}$$

PRD 70 (2004) 015005

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

Prospects for future detectors





L. Bergstrom. J. Edsjo, P. Gondolo, PRD 58 (1998) 103519

Antiproton flux

- Dark matter annihilation in the galactic halo can produce antiprotons:

$$\chi\chi \longrightarrow p\bar{p} \qquad q_{\bar{p}}^{\rm susy}(T_{\bar{p}})$$ differential rate

- Antiprotons diffuse in the Galaxy until they reach the boundary of the heliosphere:

$$q_{\bar{p}}^{\rm susy}(T_{\bar{p}}) \longrightarrow \Phi_{\bar{p}}^{\rm susy,IS}(T_{\bar{p}})$$ interstellar flux

- Inside the heliosphere, antiprotons propagate against the solar wind:

$$\Phi_{\bar{p}}^{\rm susy,IS}(T_{\bar{p}}) \longrightarrow \Phi_{\bar{p}}^{\rm susy,TOA}(T'_{\bar{p}})$$ top of atmosphere flux

- Antiprotons are also produced in galactic disk by interactions of cosmic rays with the interstellar medium

$$\begin{aligned} p_{\rm \ CR} + p_{\rm \ ISM} &\longrightarrow \bar{p} \\ p_{\rm \ CR} + He_{\rm \ ISM} &\longrightarrow \bar{p} \\ He_{\rm \ CR} + p_{\rm \ ISM} &\longrightarrow \bar{p} \end{aligned}$$

$$q_{\bar{p}}^{\rm sec}(T_{\bar{p}}) \longrightarrow \Phi_{\bar{p}}^{\rm sec,IS}(T_{\bar{p}}) \longrightarrow \Phi_{\bar{p}}^{\rm sec,TOA}(T'_{\bar{p}})$$

Antiproton source term

- Source term from neutralino self-annihilation:

$$q_{\bar{p}}^{\rm susy}(r,z;T_{\bar{p}}) = \frac{1}{2}\langle\sigma_{\rm ann}v\rangle_0 \; g_{\bar{p}}(T_{\bar{p}}) \left(\frac{\rho_\chi(r,z)}{m_\chi}\right)^2$$

  - Differential spectrum: $$g(T_{\bar{p}}) = \sum_F {\rm BR}(\chi\chi \to {\rm F}) \left(\frac{dN_{\bar{p}}^F}{dT_{\bar{p}}}\right)$$

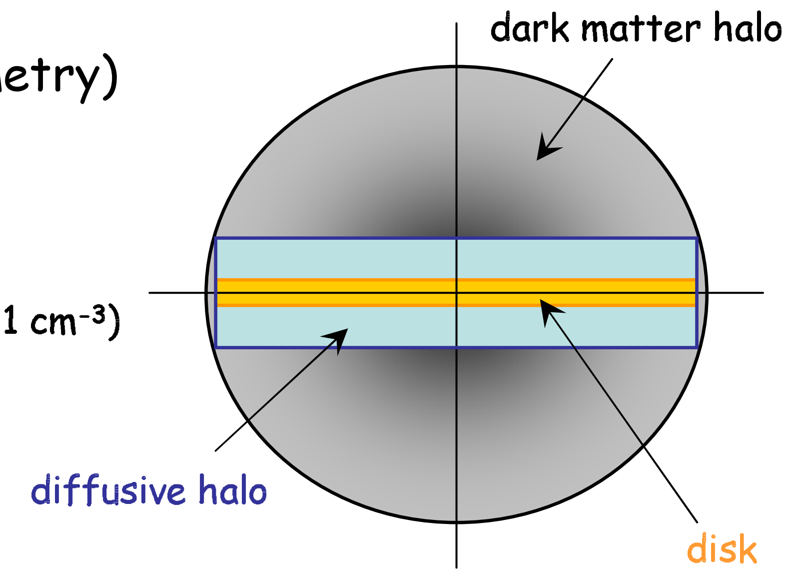
  - DM density profile: $$\rho_\chi(r,z) = \xi\rho_{\rm DM}(r,z)$$

    where: $$\xi = \min(1, \Omega_\chi h^2/0.095)$$

[$0.095 \leq \Omega_{\rm CDM}h^2 \leq 0.131$ after WMAP]

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
  - 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)

$q_{\bar{p}}^{\rm susy}(r,z,T_{\bar{p}})$ —— 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 $K(E) = K_0 \beta (\mathcal{R}/1\,{\rm GV})^\delta$
  - 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

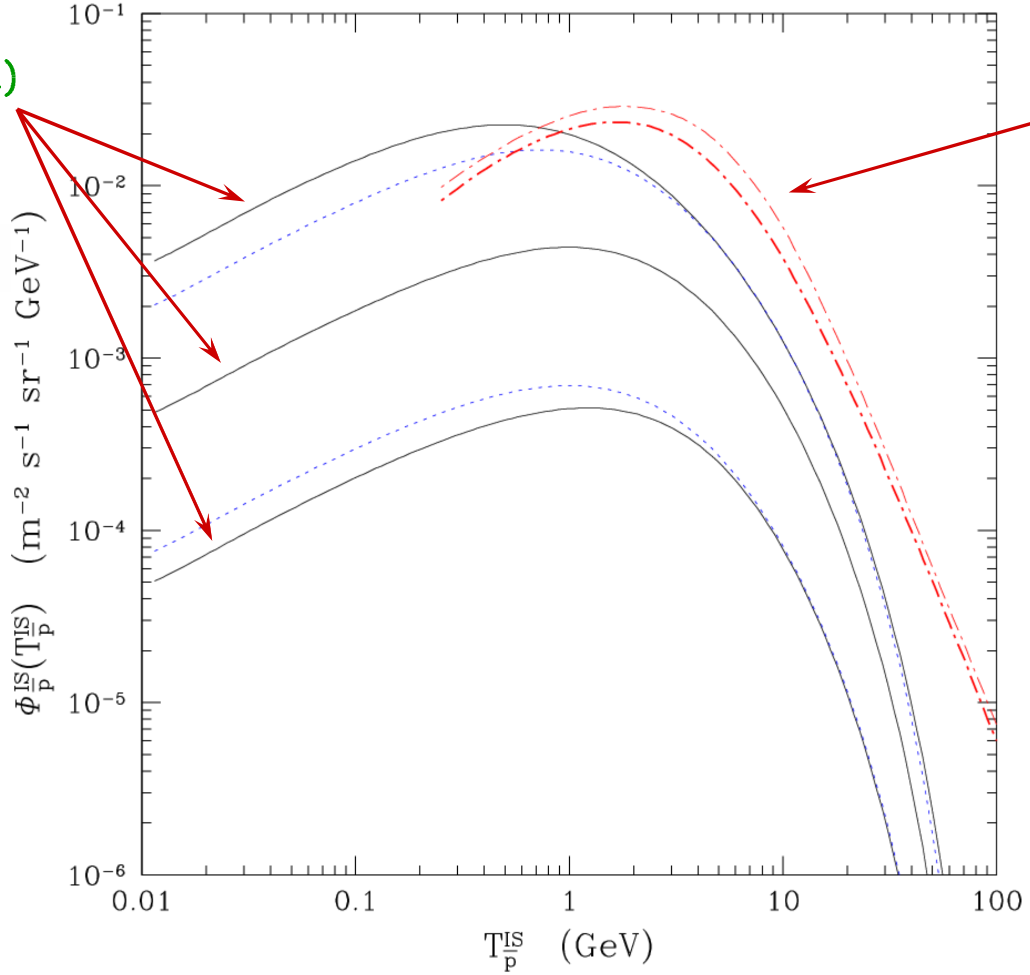
[D. Maurin et al. Astron. Astrophys. 381 (2002) 539]

case	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

IS antiproton fluxes

primaries [1]
(DM signal)

$m_\chi = 100$ GeV



secondaries [2]
(background)

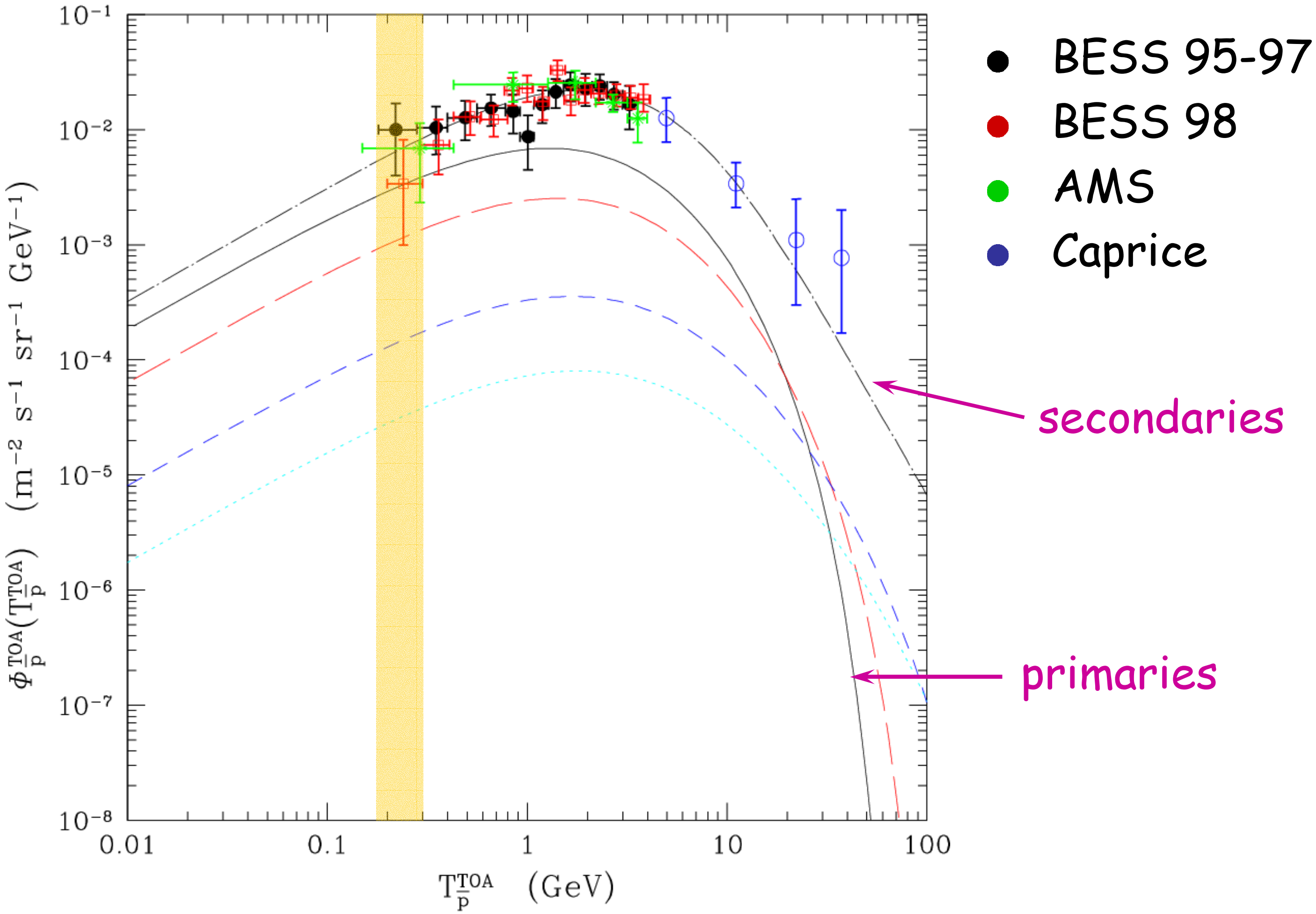
< 25% uncertainty

(1) F. Donato, N. Fornengo, D. Maurin, P. Salati, R. Taillet
PRD 69 (2004) 0603501 [astro-ph/0306207]

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

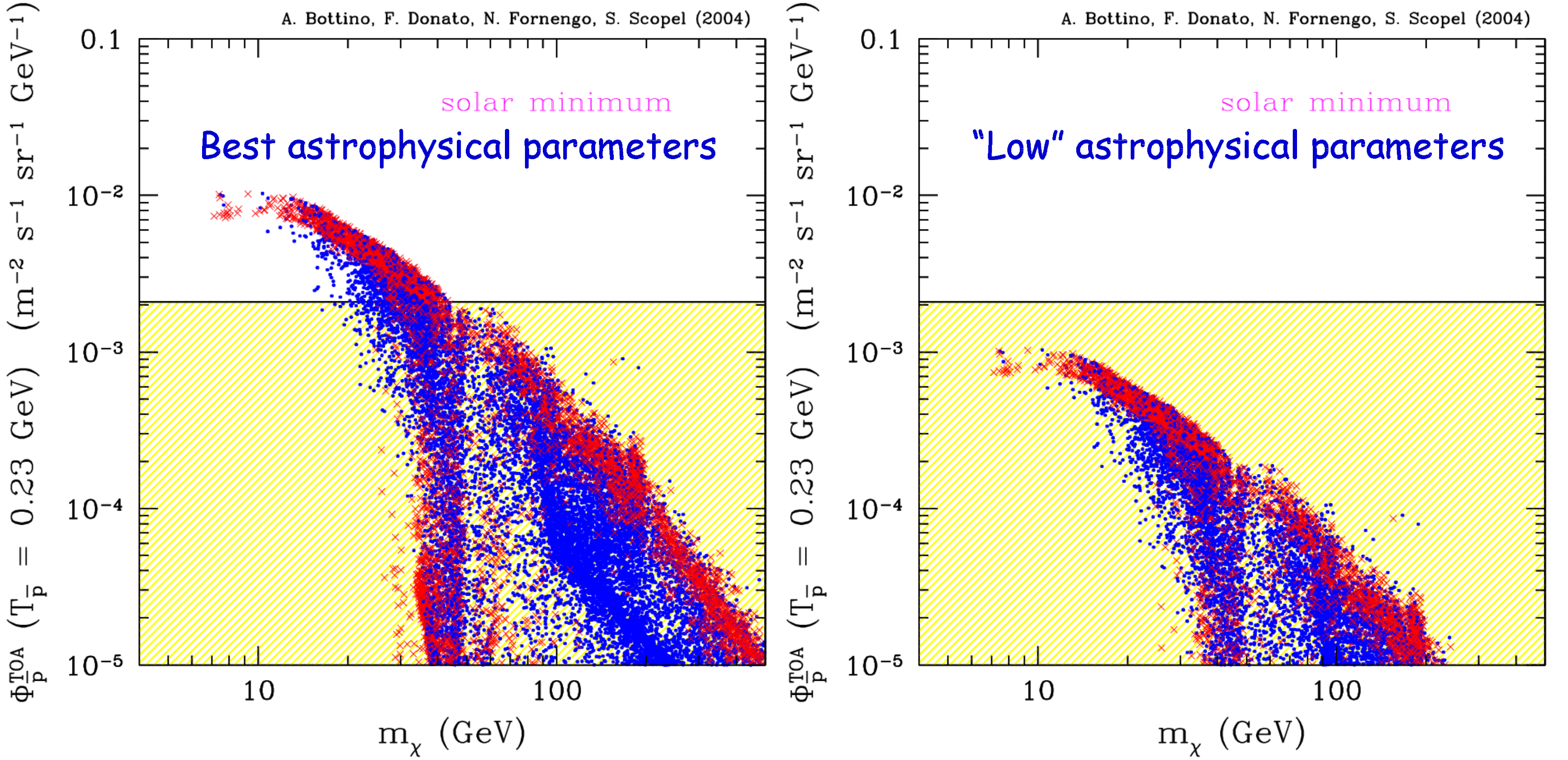
TOA fluxes and comparison with data

solar minimum



- Quite good agreement between secondaries and data
- Not much room left for a primary component, especially in the low-energy tail

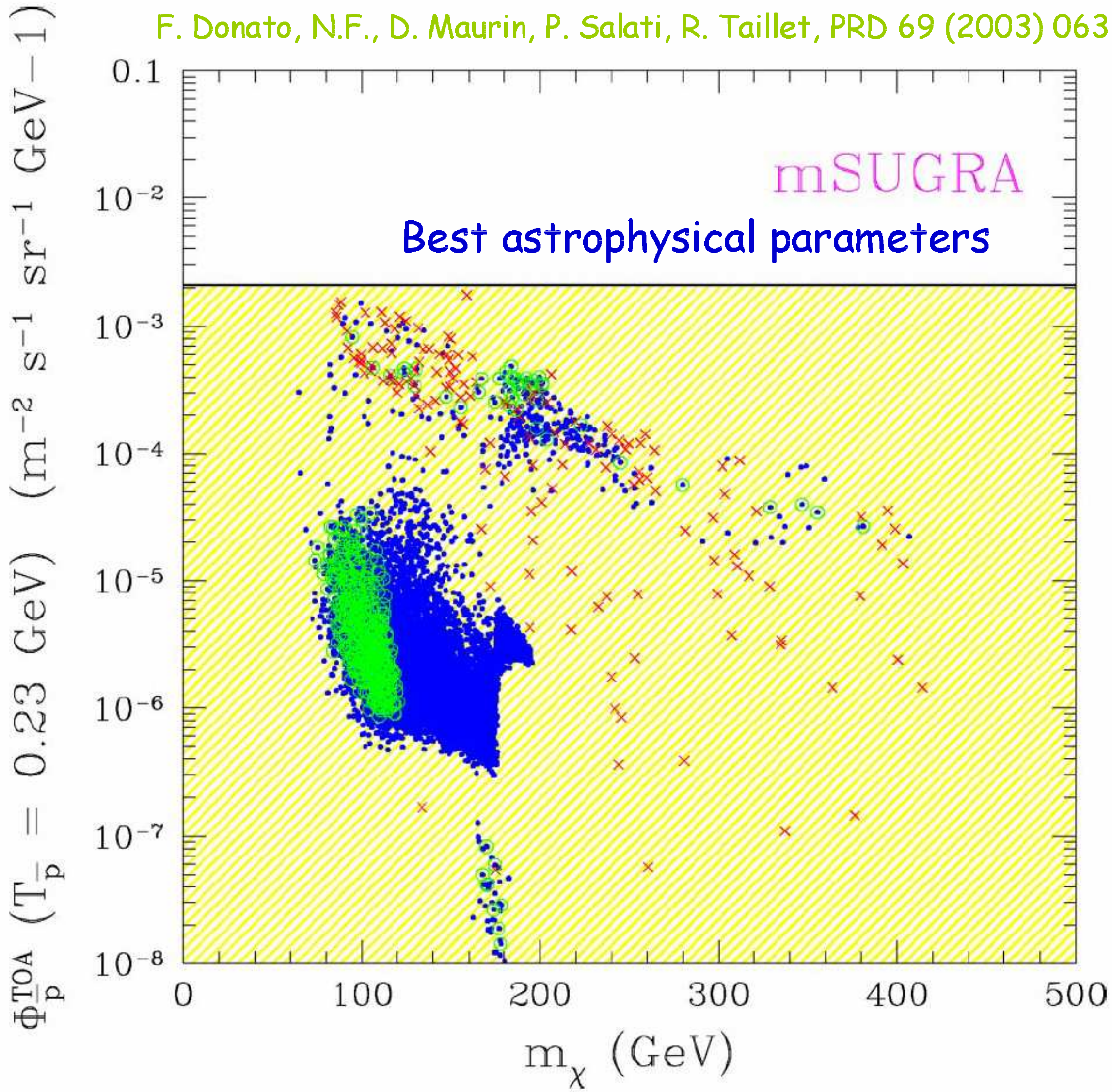
Antiproton flux



PRD 70 (2004) 015005

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

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



Antideuterons

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

- Neutralino self-annihilation can produce antideuterons through the processes:

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

- Antiprotons and antineutrons must be produced in the same phase space in order to be able to merge (coalescence model)

- Once antideuterons are formed, they are subject to diffusion and energy losses analogous to the antiproton case:

$$q_{\bar{D}}^{\rm susy}(T_{\bar{p}}) \longrightarrow \Phi_{\bar{D}}^{\rm susy,IS}(T_{\bar{D}}) \longrightarrow \Phi_{\bar{D}}^{\rm susy,TOA}(T'_{\bar{D}})$$

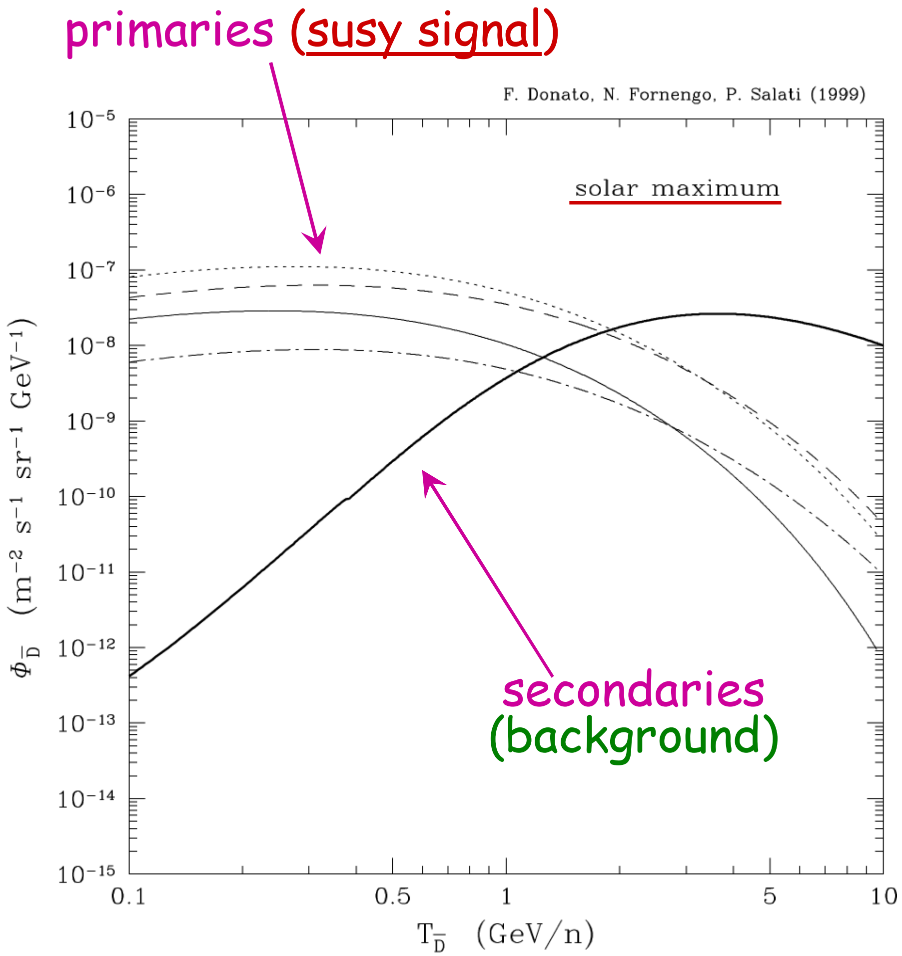
Fragmentation is very important for antideuterons (B = 2.2 MeV)

- Standard spallation processes can also produce antideuterons:

$$\begin{aligned} p_{\rm CR} + p_{\rm ISM} &\longrightarrow \bar{D} \\ p_{\rm CR} + He_{\rm ISM} &\longrightarrow \bar{D} \\ He_{\rm CR} + p_{\rm ISM} &\longrightarrow \bar{D} \end{aligned} \qquad \Phi_{\bar{D}}^{\rm sec,TOA}(T'_{\bar{D}})$$

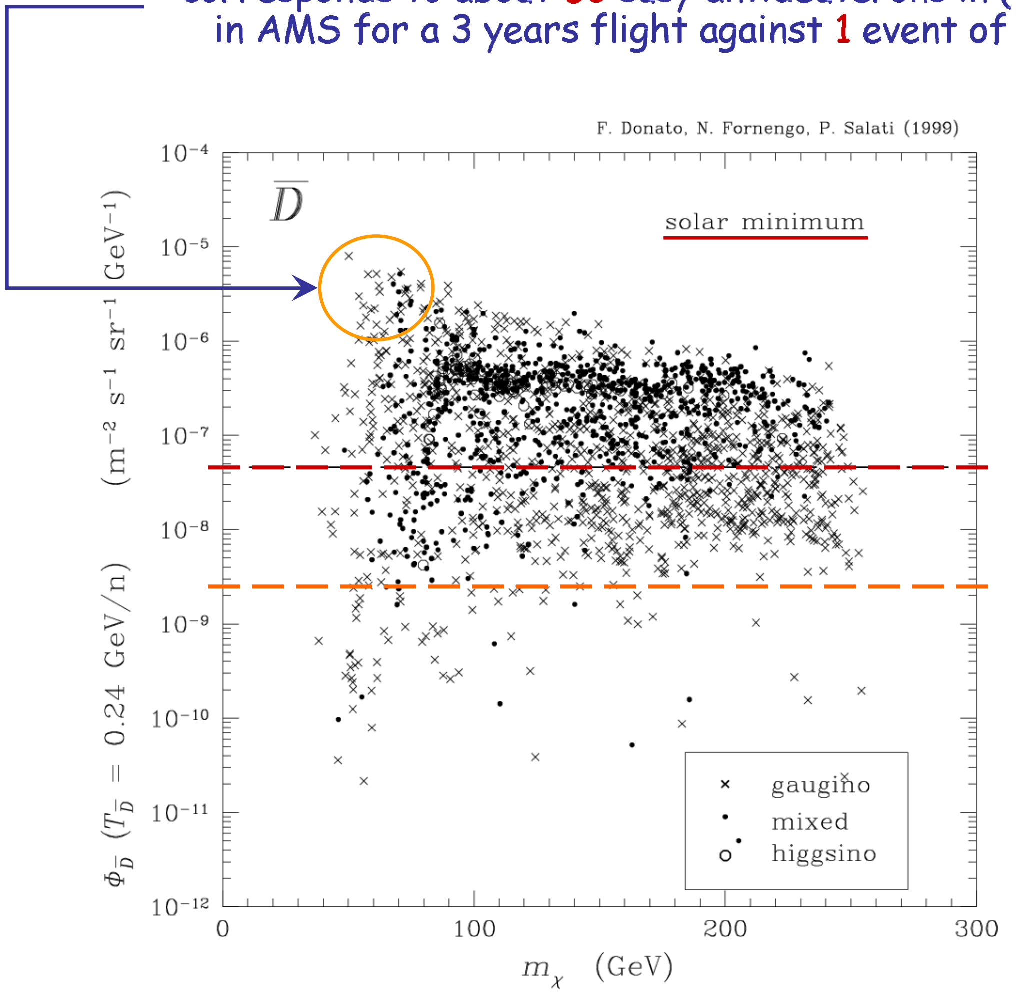
TOA Antideuteron flux

PRD 62 (2000) 043003



Antideuteron flux

corresponds to about 60 susy antideuterons in (0.1—3) GeV/n
in AMS for a 3 years flight against 1 event of background



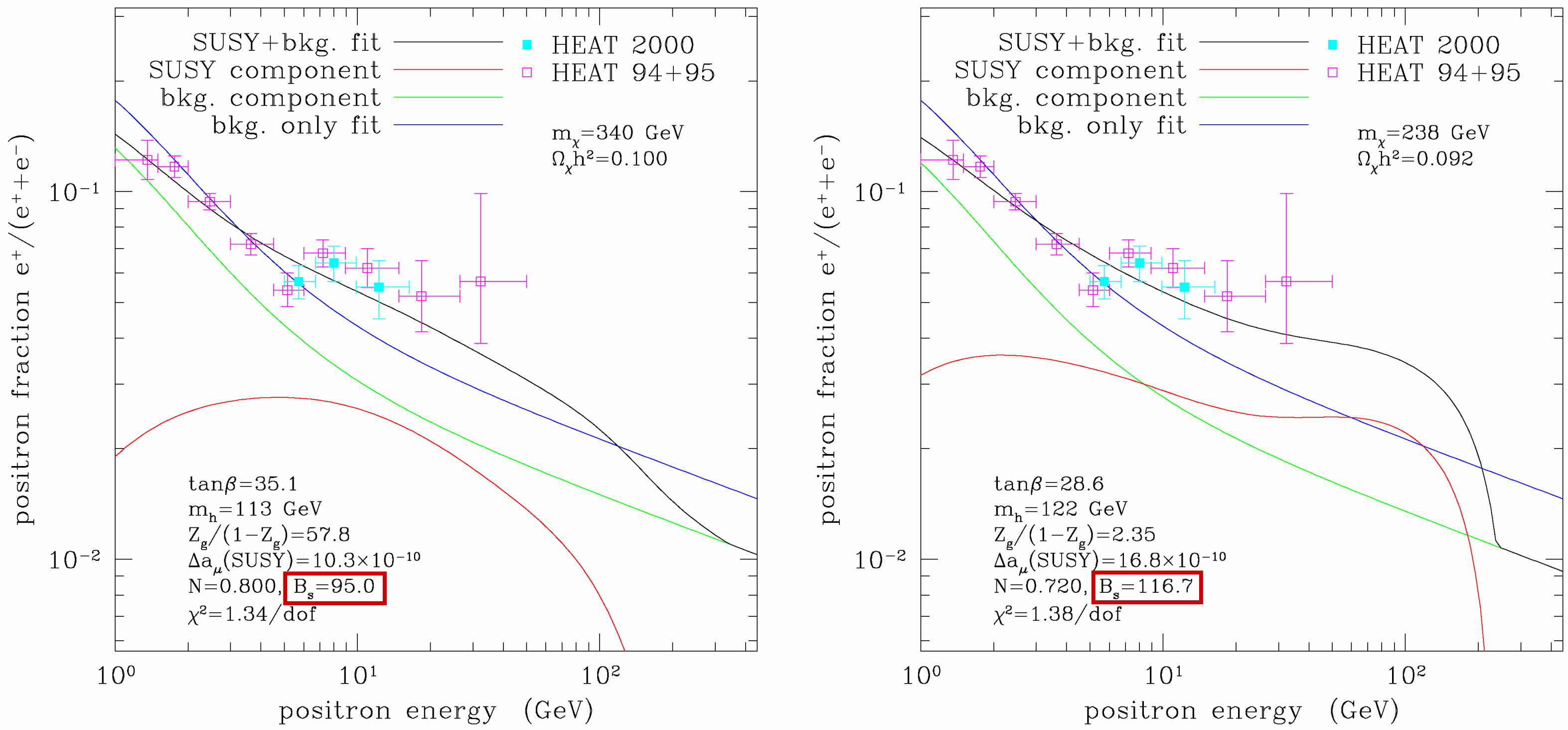
PRD 62 (2000) 043003

AMS estimated sensitivity (3 yrs on board of ISS) F. Donato, N. Fornengo, P. Salati, PRD 62 (2000) 043003

GAPS estimated sensitivity K. Mori et al., Ap.J. 566 (2002) 604

Positron flux

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



A. Baltz et al., PRD 65 (2002) 063511

Gamma-ray flux

- Photon flux from neutralino self-annihilation:

$$\Phi_\gamma^{\rm susy}(E_\gamma) = \frac{1}{2}\frac{\langle\sigma_{\rm ann}v\rangle_0}{m_\chi}\; g_\gamma(E_\gamma)\int_0^{L_{\rm max}} \rho_\chi^2(r,z)dl$$

l : line of sight

- Differential spectrum: $$g(E_\gamma) = \sum_F {\rm BR}(\chi\chi\to{\rm F})\left(\frac{dN_\gamma^F}{dE_\gamma}\right)$$

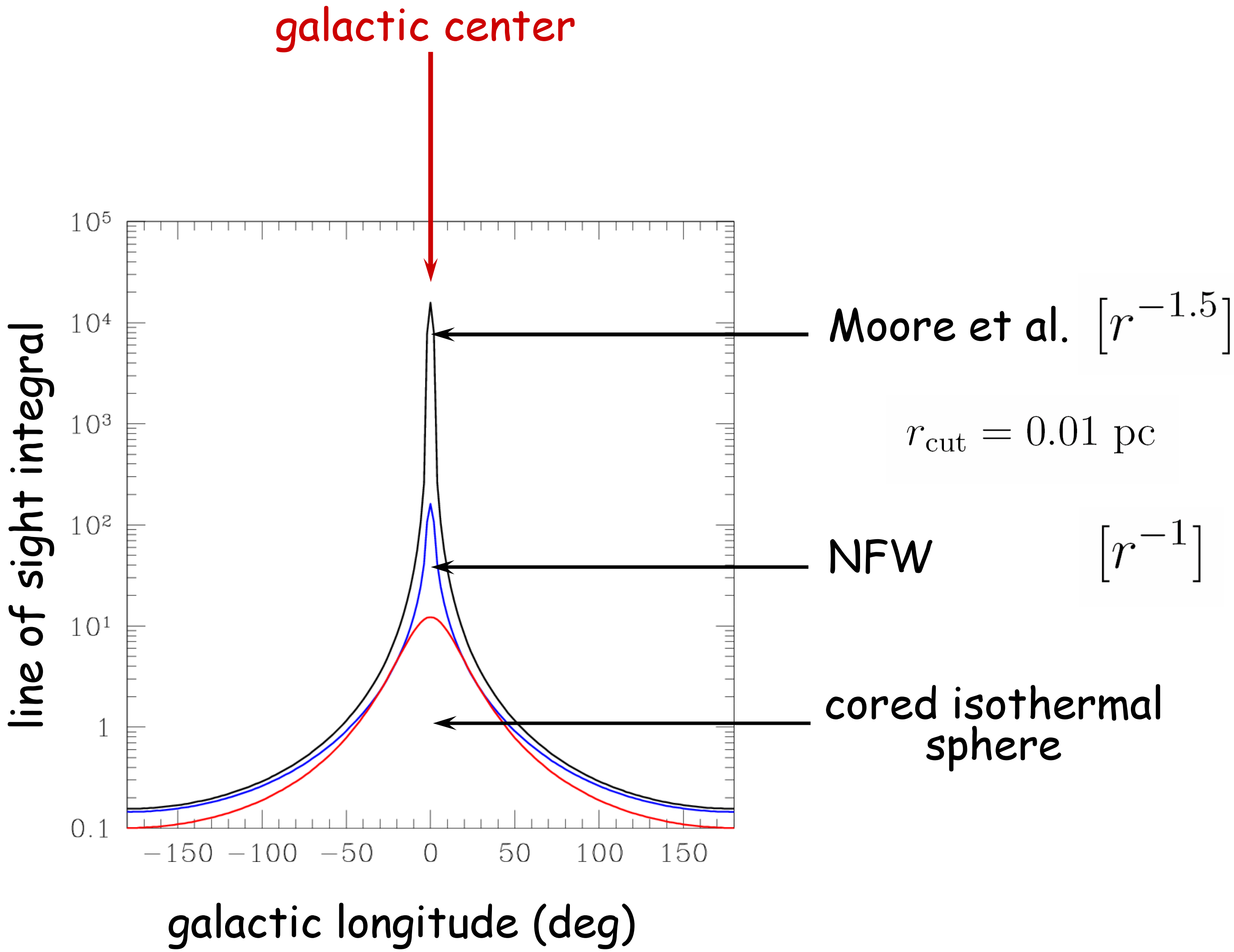
- DM density profile: $$\rho_\chi(r,z) = \xi\rho_{\rm DM}(r,z)$$

where: $$\xi = \min(1, \Omega_\chi h^2/0.095)$$

[$0.095 \le \Omega_{\rm CDM}h^2 \le 0.131$ after WMAP]

- The gamma flux is strongly dependent on the DM density profile:

galactic latitude: 0°

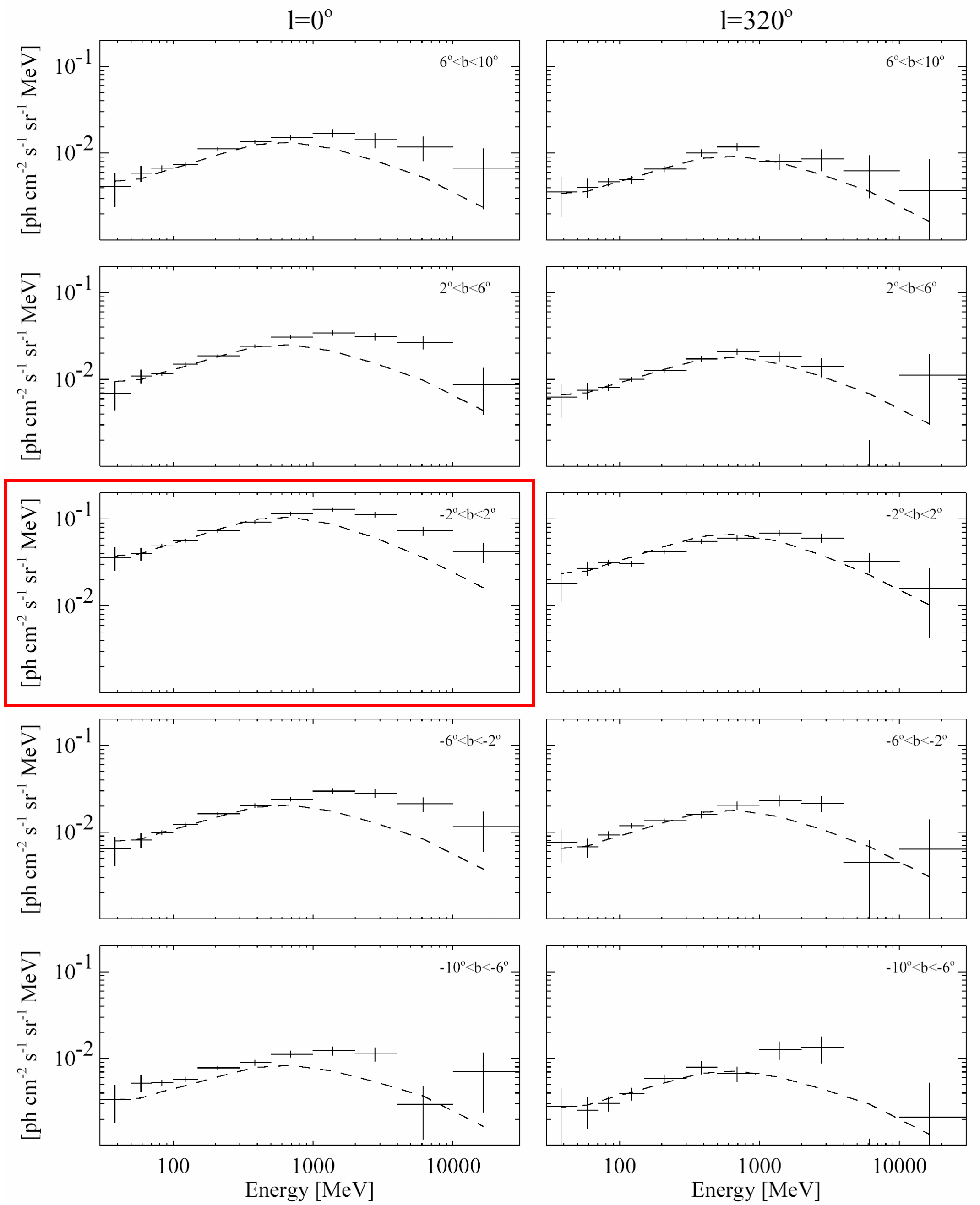


EGRET: diffuse gamma rays from the galactic plane

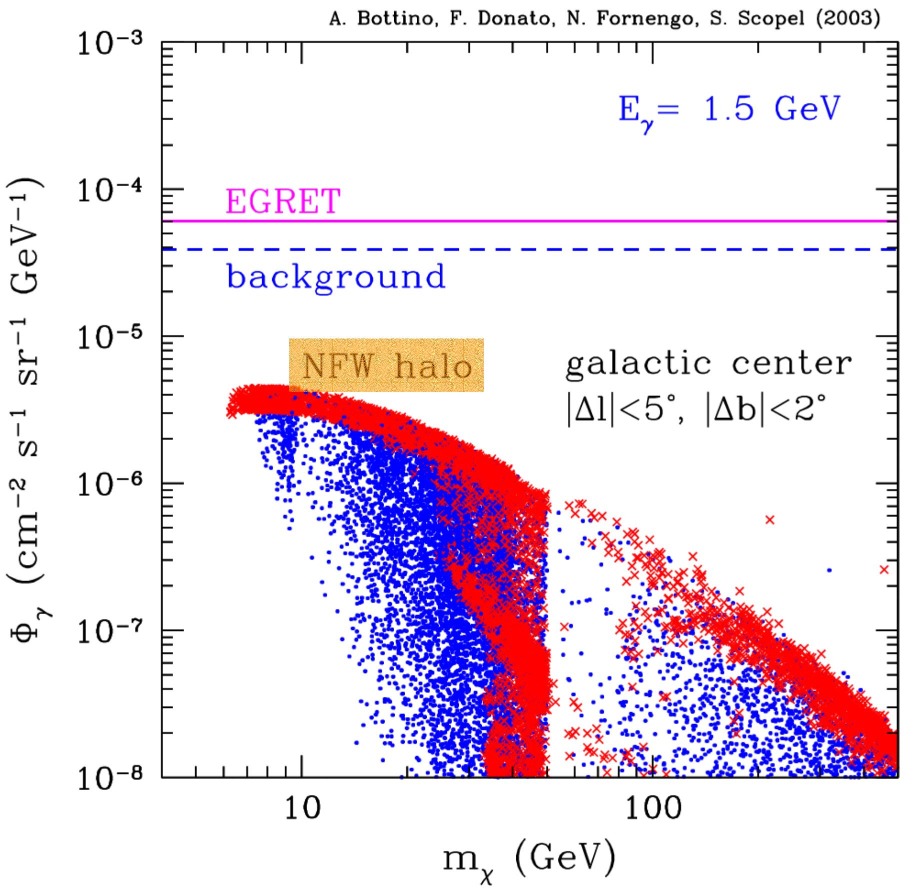
[Ap.J 481 (1997) 205]

excess observed

galactic center
l=0°, b=0°



Gamma-ray flux



PRD 70 (2004) 015005

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

- The dependence of the line of sight integral on the DM density profile toward the GC is sizeable:

$I_{\Delta\psi}$ in units of $\mathrm{GeV}^2\ \mathrm{cm}^{-6}$ kpc for $|\Delta l| \leq 5°$, $|\Delta b| \leq 2°$

Isothermal	Isothermal	NFW	Moore et al.	r–dependent log–slope
$a = 3.5$ kpc	$a = 2.5$ kpc	$a = 25$ kpc $r_c = 0.01$ pc	$a = 30$ kpc $r_c = 0.01$ pc	$\alpha = 0.142$ $r_{-2} = 26.4$ kpc $\rho_{-2} = 0.035$ GeV cm^{-3}
18.5	42.5	184.2	10866	600

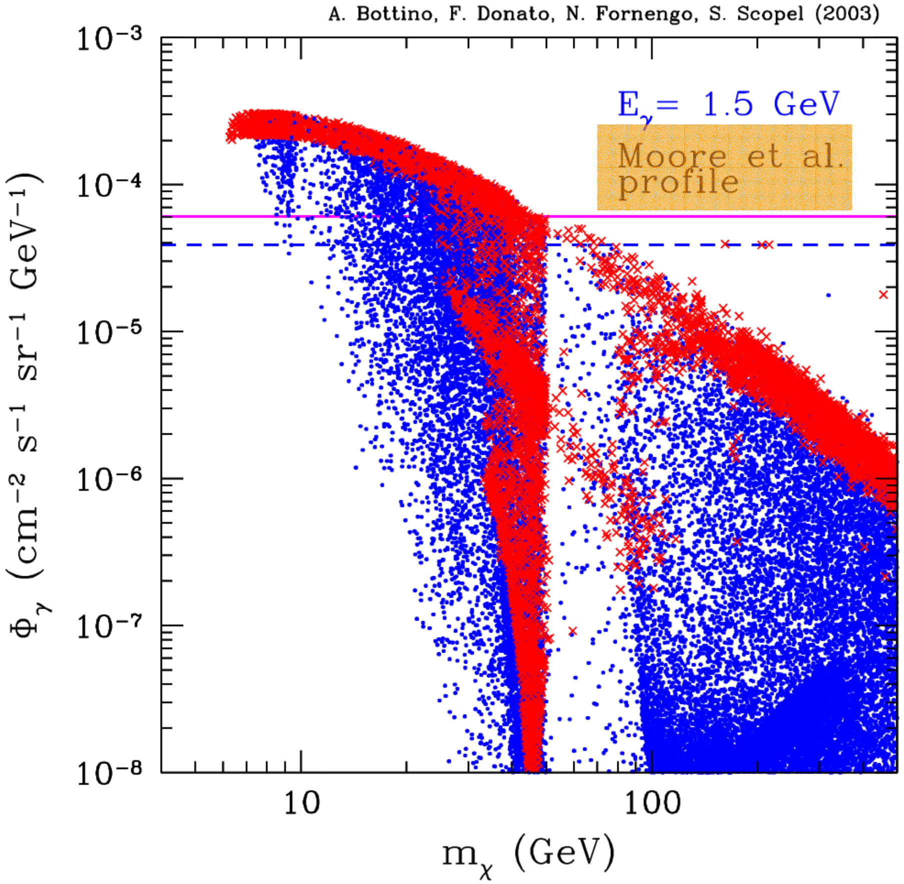
× 0.10   × 0.23   1   × 59   × 3.2

$\rho(r) \sim r^{-1}$ $\qquad$ $\rho(r) \sim r^{-1.5}$ $\qquad$ $-\frac{d\ln\rho(r)}{d\ln r} = r^{-\alpha}$

[J. F. Navarro et al., astro-ph/0311231]

Notice that the effect of baryons could even produce steeper profiles

Gamma-ray flux



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There may be detection potential also for a Log-slope DM profile, in the low mass range below 25-30 GeV

The spectral shape of the EGRET excess from the GC can be explained by 30-40 GeV neutralinos (*)

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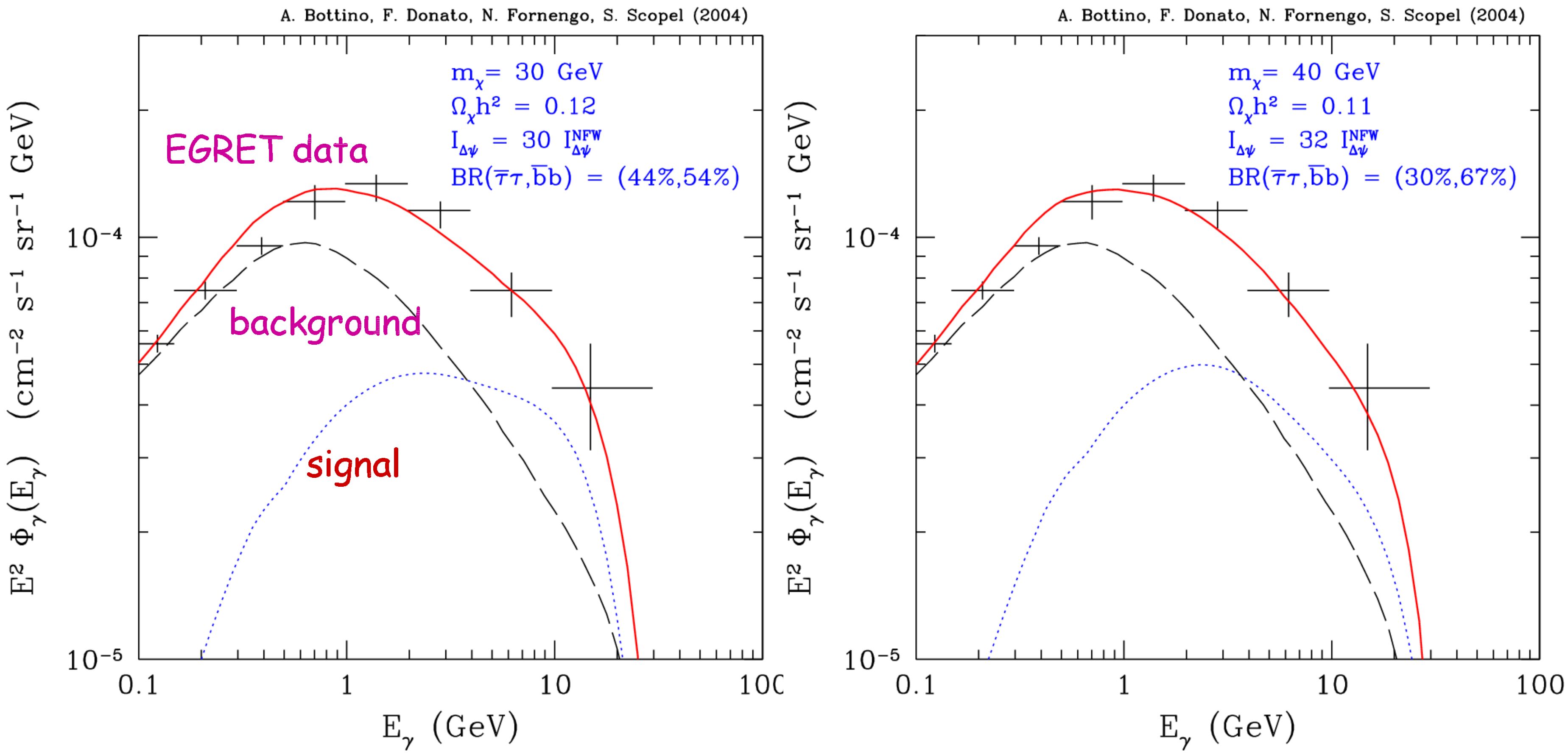
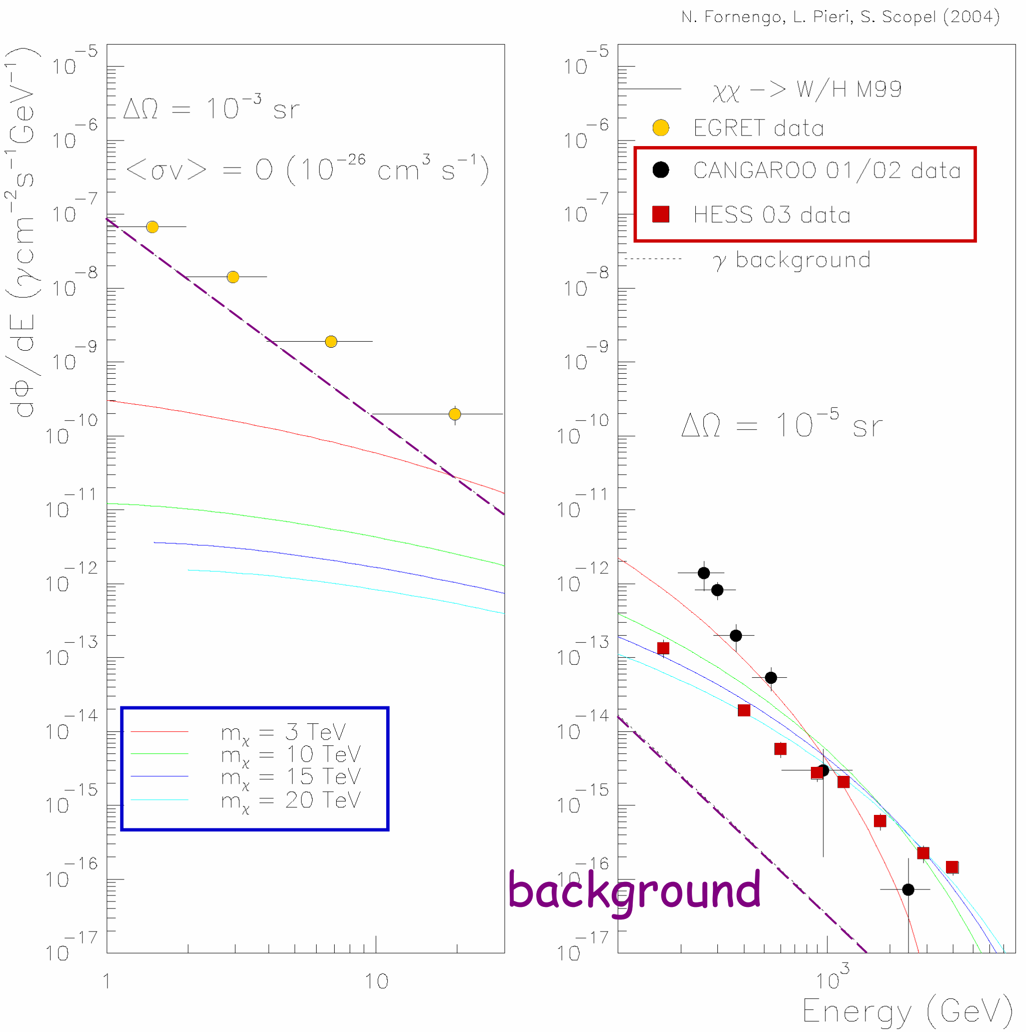


requires some degree of overdensity

(*) For interpretation of EGRET spectral shape with heavier neutralinos, see e.g.:
A. Cesarini et al., Astropart. Phys. 21 (2004) 267
W. de Boer et al., astro-ph/0408272

Air Cerenkov detectors

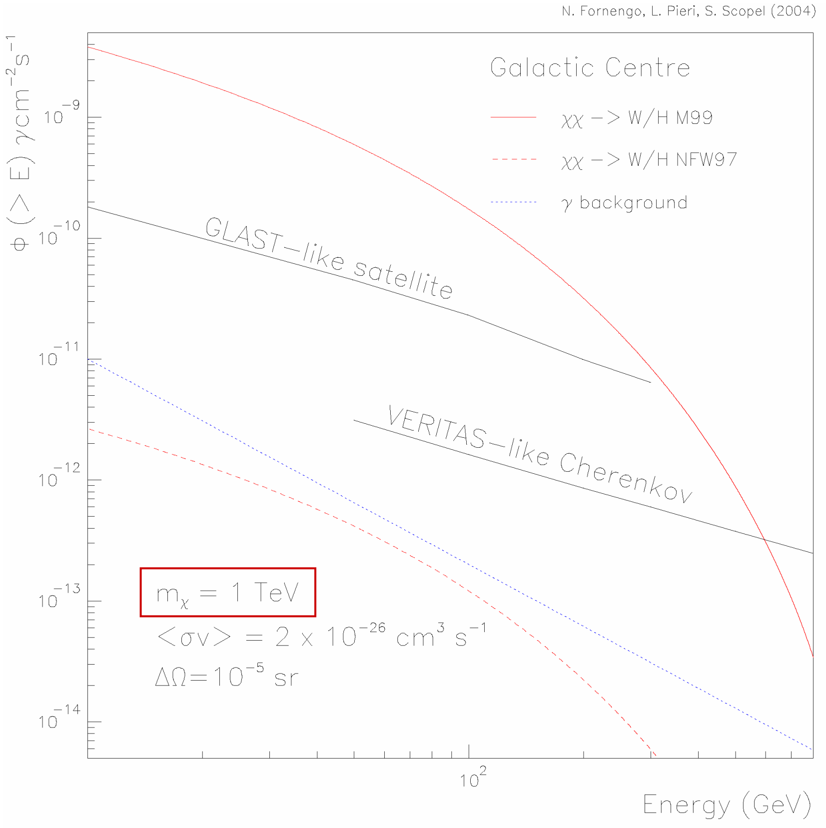


galactic center

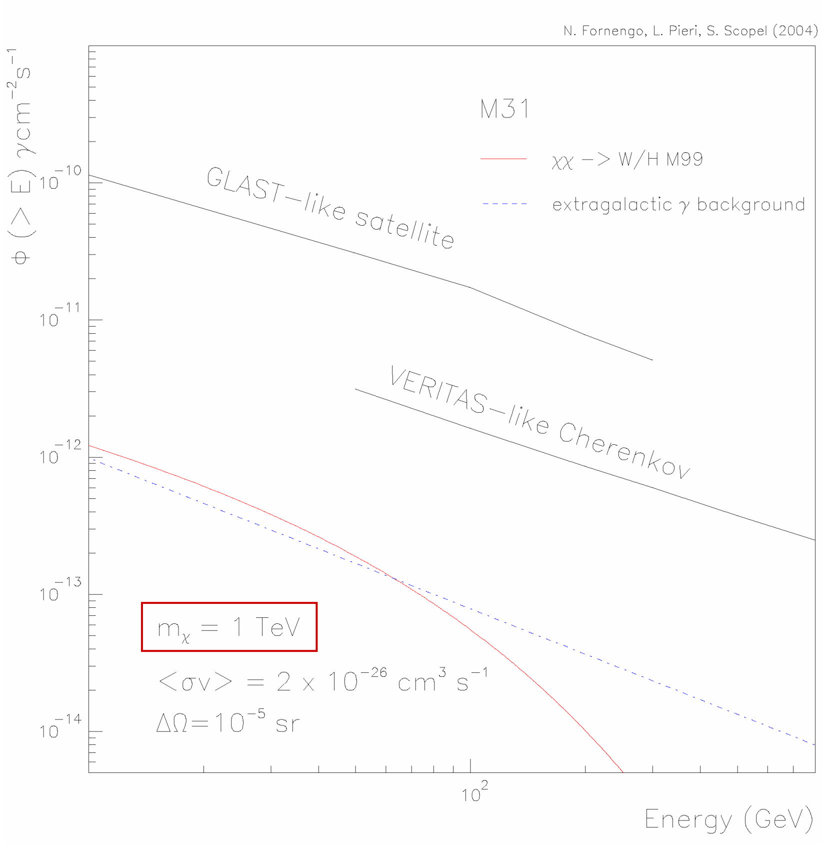
PRD 70 (2004) 103259

Future detectors sensitivities

Galactic center



M31 galaxy



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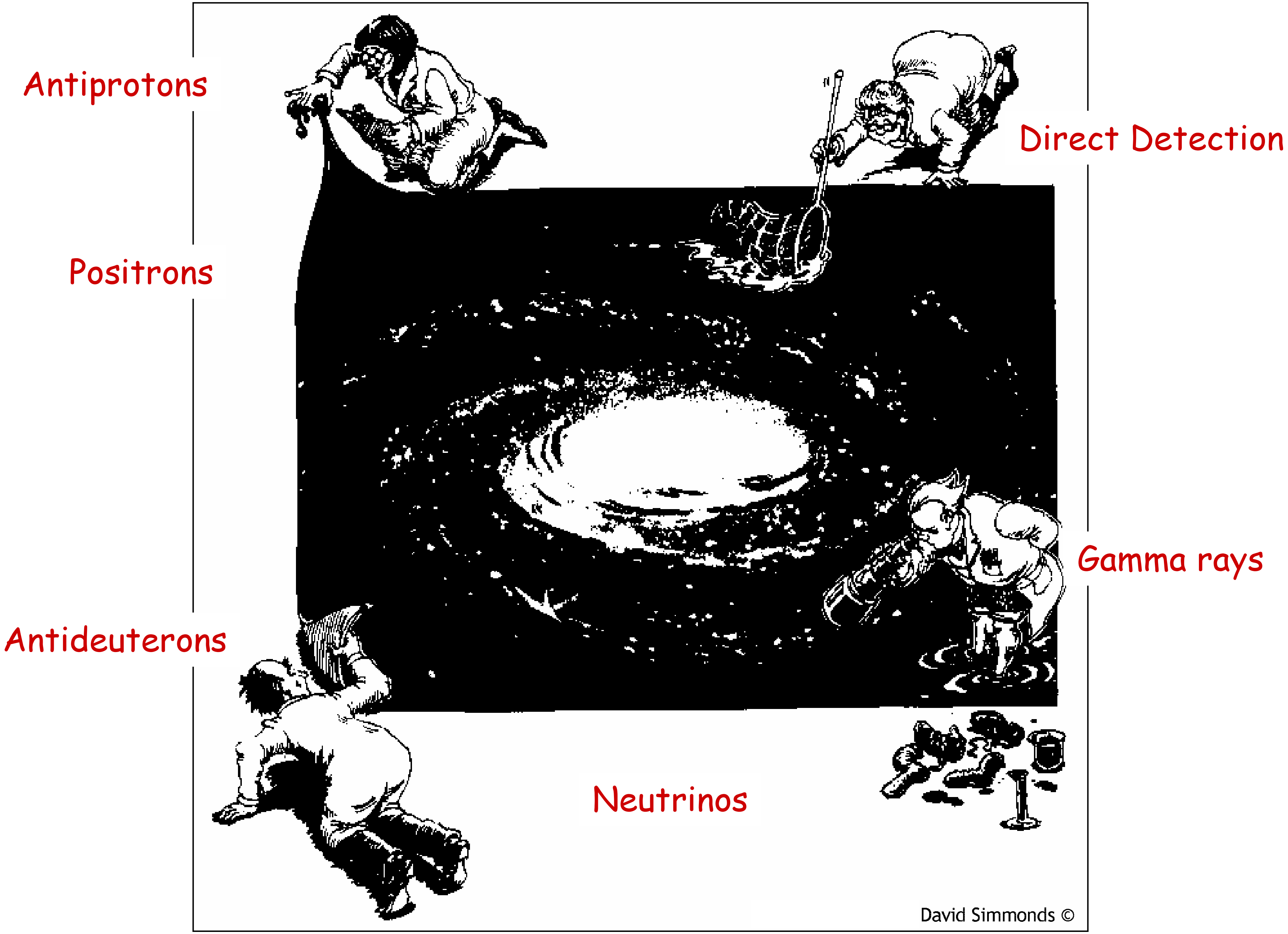
Antiprotons
Direct Detection
Positrons
Gamma rays
Antideuterons
Neutrinos
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