Neutralinos as dark matter – can we see them?

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Outline

- Supersymmetric framework – MSSM
- Relic density calculation
- Ways to search for neutralinos as dark matter?
  - Direct detection
  - Annihilation products from the halo
  - Neutrino-induced muons from annihilation in the Earth/Sun
- Comparison of some signals

The MSSM – parameters

- μ – Higgsino mass parameter
- M_2 – Gaugino mass parameter
- $\tan\beta$ – ratio of Higgs vacuum expectation values
- m_A – mass of the CP-odd Higgs boson A / H_3^0
- m_0 – scalar mass parameter
- A_b – soft trilinear parameter
- A_t – soft trilinear parameter

Parameter	μ	M_2	$\tan\beta$	m_A	m_0	A_b/m_0	A_t/m_0
Unit	GeV	GeV	1	GeV	GeV	1	1
Min	-50000	-50000	1.0	0	100	-3	-3
Max	50000	50000	60.0	10000	30000	3	3

MSSM – general

The neutralino – χ

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0,$$

Gaugino fraction

$$Z_g = |N_{11}|^2 + |N_{12}|^2$$

Calculation flowchart

1. Select MSSM parameters
2. Calculate mass spectrum, couplings, ...
3. Check accelerator constraints: m_χ^+, m_χ^0, $m_{H_2^0}$, $BR(b \to s\gamma)$, ...
4. Calculate the relic density: $\Omega_\chi h^2$
5. Cosmologically interesting? $0.025 < \Omega_\chi h^2 < 1$
6. Calculate fluxes, rates, ...

Relic density - a simple approach

Decoupling occurs when

$$\Gamma \lesssim H$$

We have

$$\begin{aligned}
\Gamma &= \langle \sigma_{\text{ann}} v \rangle n_\chi^2 \\
n_\chi^{\text{eq}} &= \frac{g_\chi}{(2\pi)^3} \int f(\mathbf{p}) d^3\mathbf{p} = g_\chi \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} \\
H(T) &= 1.66 g_*^{1/2} \frac{T^2}{m_{\text{Pl}}}
\end{aligned}$$

$$\text{Use} \quad \Gamma \sim H \Rightarrow T_f \simeq \frac{m_\chi}{20}$$

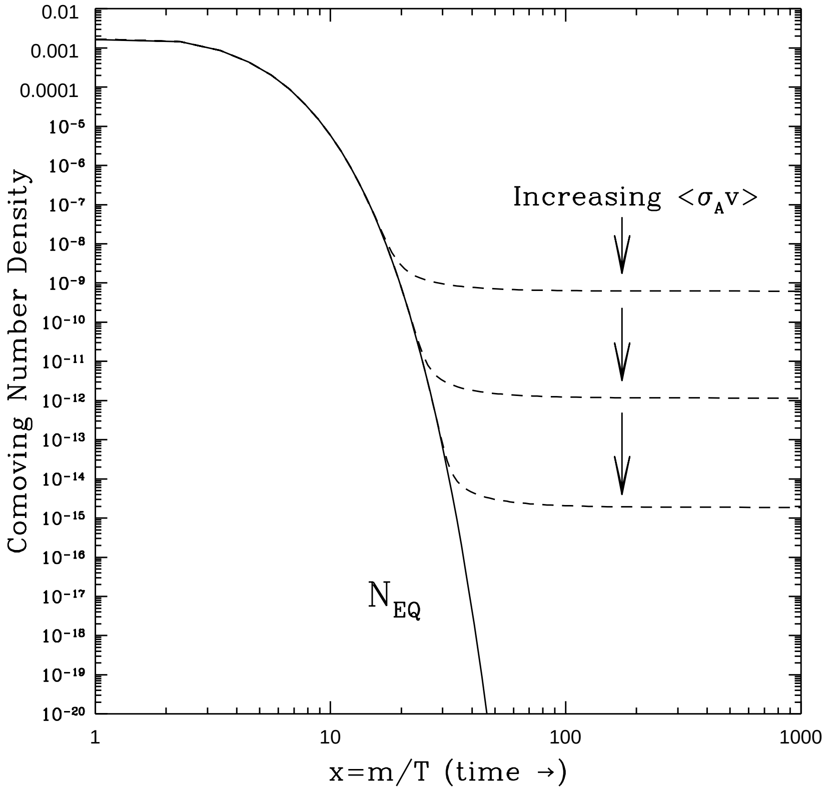
Comoving density, n_χ/s, conserved $\Rightarrow$

$$\frac{n_\chi^0}{s_0} = \frac{n_\chi}{s} = \frac{1.66 g_*^{1/2} T^2}{m_{\text{Pl}} \langle \sigma_{\text{ann}} v \rangle}$$

Use $s = 0.4 g_* T^3$, $T_f \simeq m_\chi/20$ and $g_* \simeq 100 \Rightarrow$

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi^0}{\rho_c^0} \simeq \frac{3 \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}$$

Relic density - why WIMPs?



$$\Gamma \sim H \Rightarrow$$

$$\Omega h^2 \simeq \frac{3 \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

$$\begin{aligned} \langle \sigma_{\mathrm{ann}} v \rangle_{WIMP} &\simeq \frac{\alpha_{ew}^2}{(100\mathrm{GeV})^2} \\ &\simeq 10^{-25}\ \mathrm{cm}^3\ \mathrm{s}^{-1} \end{aligned}$$

$$\Downarrow$$

$$\Omega \simeq \mathcal{O}(1)$$

G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267 (1996) 195.

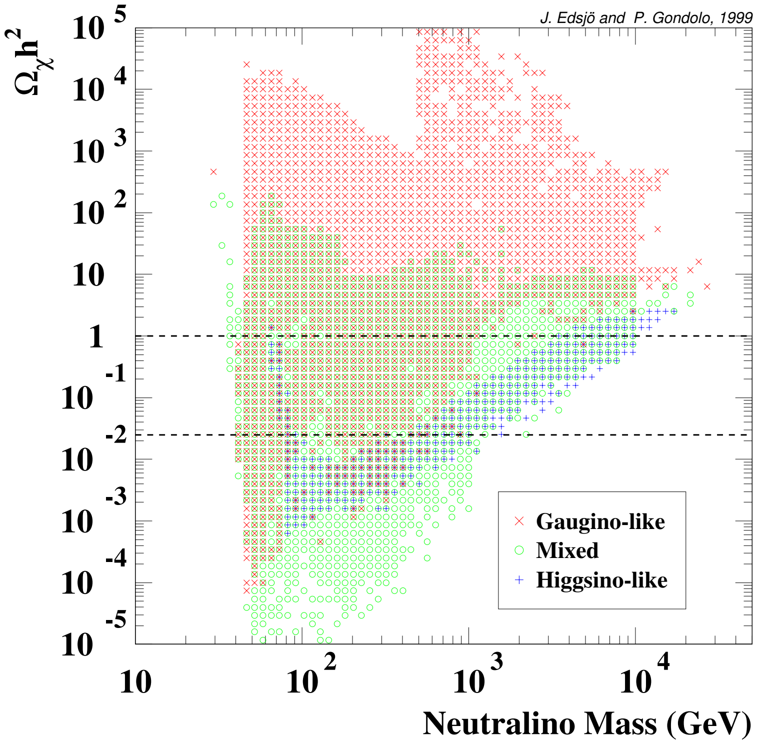
A more refined $\Omega_\chi h^2$ calculation

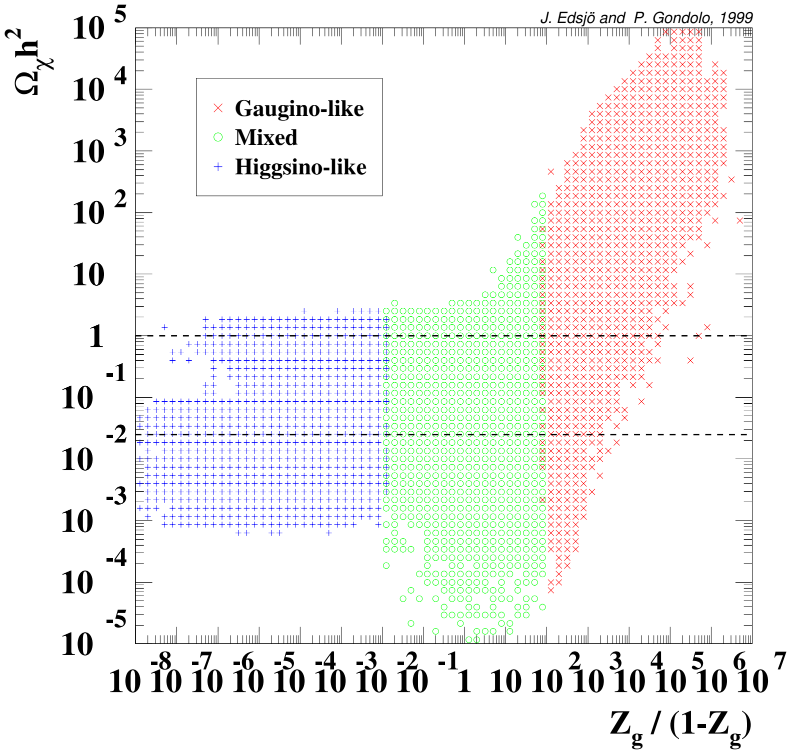
- For $\sigma_{\text{ann}} v$:
  - the full $\sqrt{s}$-dependence is included
  - thresholds are included
  - resonances are included
- Coannihilations are included:

$$\begin{aligned} \chi_1^0 \chi_1^0 &\rightarrow \ldots \\ \chi_1^0 \chi_2^0 &\rightarrow \ldots \\ \chi_1^0 \chi_1^+ &\rightarrow \ldots \\ \chi_1^+ \chi_1^- &\rightarrow \ldots \end{aligned}$$

- The evolution equation is solved numerically with high accuracy.

Relic density versus mass and composition



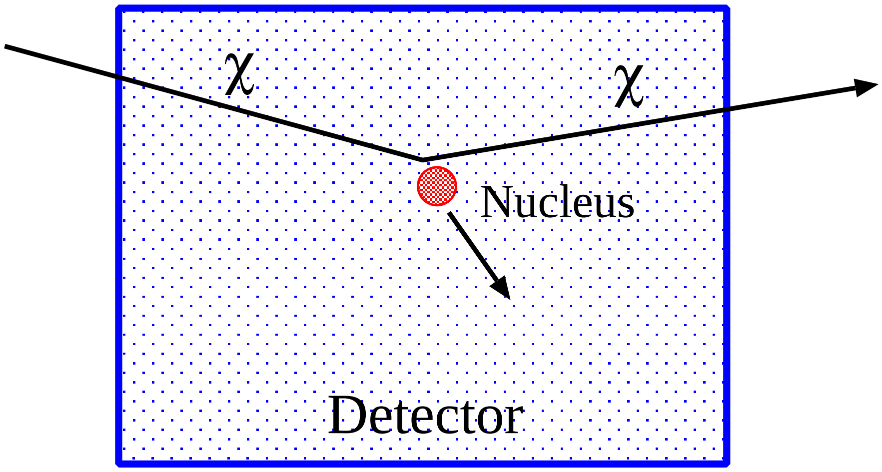


Ways to search for neutralino dark matter

- Direct detection
- Antiprotons from annihilation in the halo
- Positrons from annihilation in the halo
- Gamma rays from annihilation in the halo
- Neutrino-induced muons from annihilation in the Earth/Sun

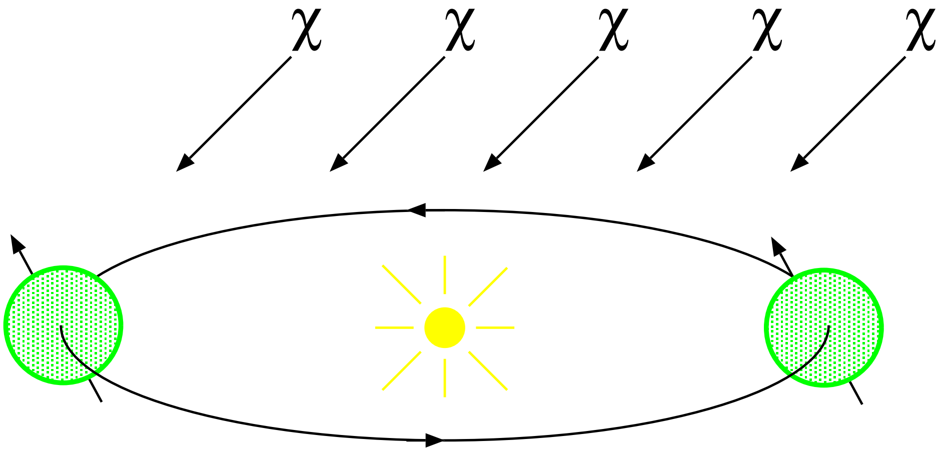
Direct detection - basic principles

- WIMP + nucleus → WIMP + nucleus
- Nuclear recoil energy measured



- Suppress background enough to be sensitive to a signal

- Search for an annual modulation



Direct detection - differential rate

$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{2 m_\chi m_r^2} F^2(Q) \int_{v_{\min}}^{\infty} \frac{f(v)}{v} dv$$

with

$$\begin{aligned}
Q &= \frac{|\mathbf{q}|^2}{2 m_N} = \frac{m_r^2 v^2}{m_N}(1 - \cos\theta_{CM}) \\
v_{\min} &= \sqrt{\frac{Q m_N}{2 m_r^2}} \\
m_r &= \frac{m_\chi m_N}{m_\chi + m_N}
\end{aligned}$$

$F(Q)$ – form factor

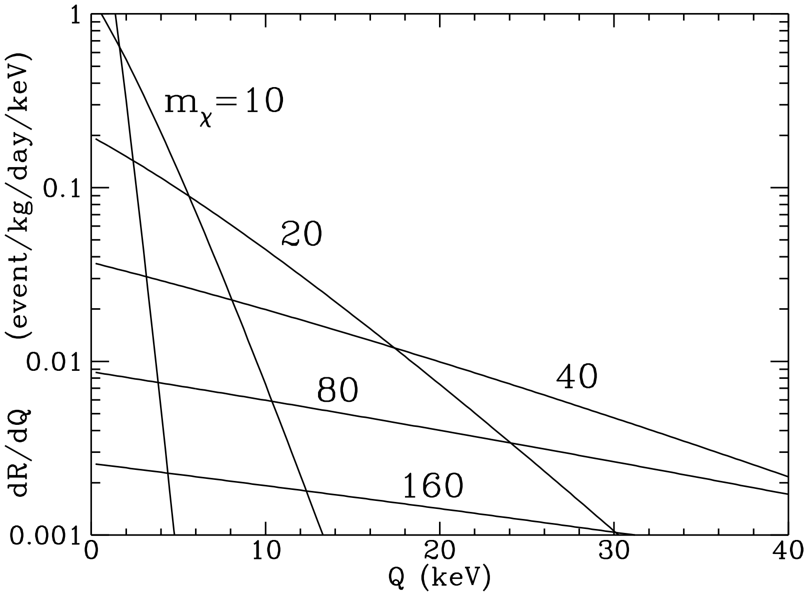
σ_0 – elastic scattering cross section

ρ_0 – local dark matter density (~ 0.3 GeV/cm^3)

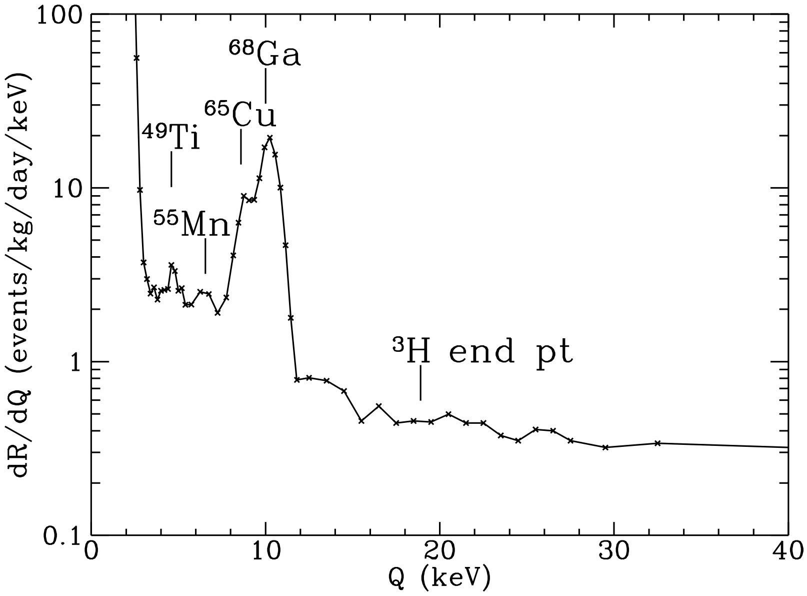
$f(v)$ – velocity distribution

Direct detection - example spectra

Differential rate for different m_χ

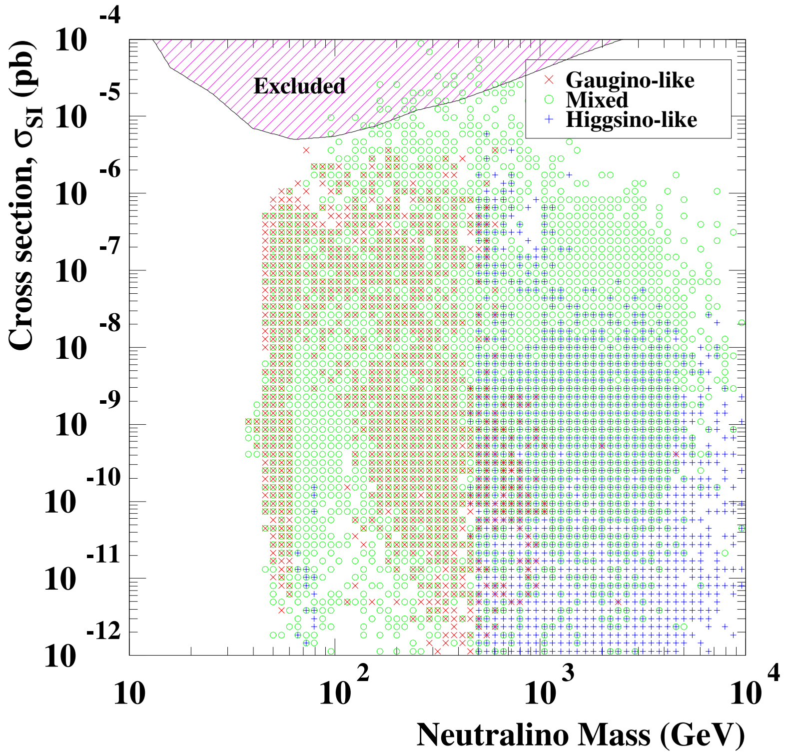


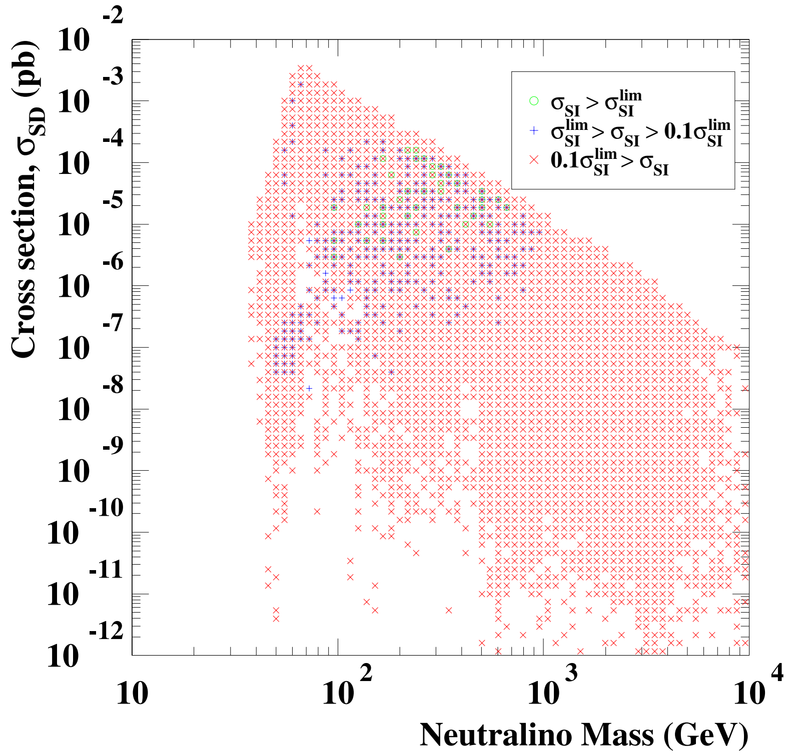
Gamma-ray background in a Ge-detector



G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. **267**(1996)195.

Direct detection - signals & limits



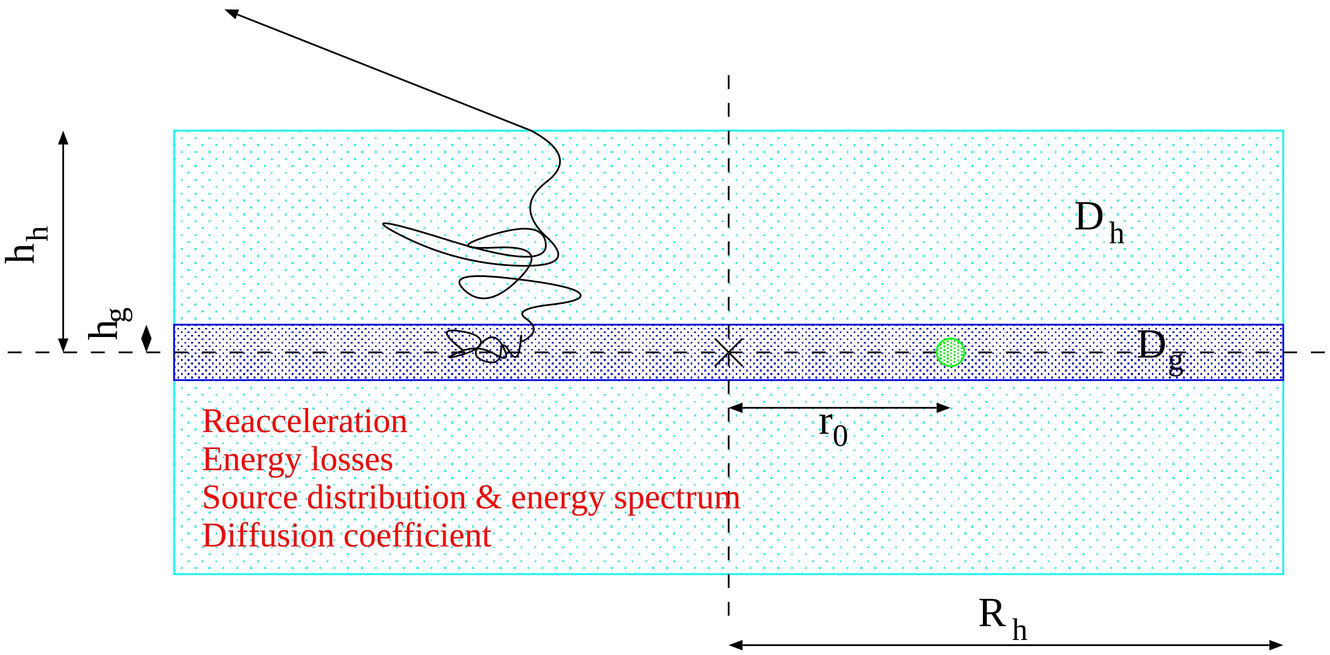


$0.025 < \Omega_\chi h^2 < 1$

Antiprotons from neutralinos

- Halo and propagation model
- Background
- Signal from neutralinos

Galaxy model



$$
\begin{aligned}
h_g &\simeq 0.1 \text{ kpc} \\
h_h &\simeq 3-20 \text{ kpc} \\
r_0 &\simeq 8.5 \text{ kpc} \\
R_h &\simeq 20 \text{ kpc} \\
D_l &\simeq D_l^0 \left(1+\frac{R}{R^0}\right)^{0.6} \\
D^0 &\simeq 6 \times 10^{27} \text{ cm}^2 \text{ s}^{-1} \\
R &= p/|Z| \quad - \quad \text{rigidity} \\
R^0 &\simeq 3 \text{ GV}
\end{aligned}
$$

Galaxy model II

Propagation model

- We use the diffusion model with free escape at the boundaries.

Halo profile

- We use mainly the modified isothermal sphere, but compare with the Navarro, Frenk & White and Kravtsov et al. profiles.

Energy losses – tertiary $\bar{p}$

- The non-annihilation inelastic cross section gives rise to energy losses.
- The energy distribution of the scattered $\bar{p}$ is assumed to be *flat*.
- Included in the diffusion equation as a *'tertiary'* source function,

$p - He$ **interactions**

Naively, there would be a very low background flux below 1 GeV since even the minimal reaction

$$p + p \to \bar{p} + p + p + p$$

has a threshold of $E_{\mathrm{th}} \simeq 7 m_p$.

However, $p - He$ interactions are important:

- On their way out of a nucleus, $\bar{p}$ lose energy and we get low-energy $\bar{p}$ emerging, so called *sub-threshold* effects occur.

- We model the cross section according to Letaw, Silberberg & Tsao (ApJ S51 (1983) 271) and the sub-threshold effects according to Sibirtsev et al. (nucl-th/9710044).

- Uncertainty of this treatment: $\sim$ 50%
  Data on $p - He$ interactions is needed!

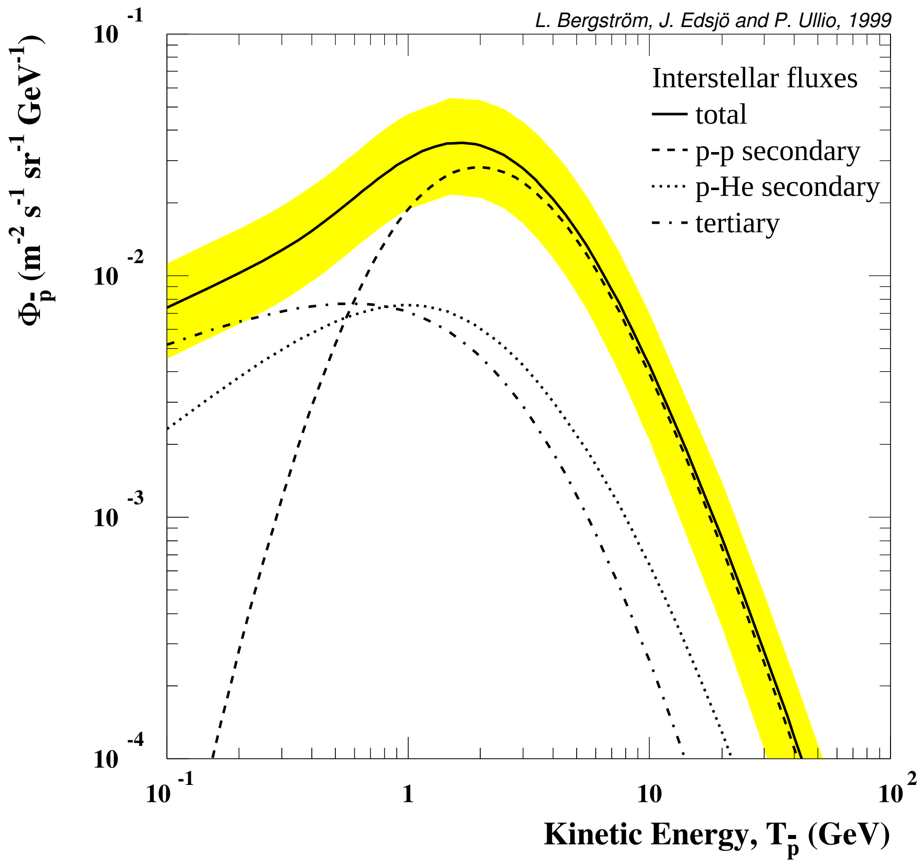
Antiprotons – backgrounds

Naively, there would be a very low background flux below 1 GeV, but ...

- Energy losses are important
- $p - He$ interactions are important

$$\Downarrow$$

The low-energy window is filled!



Antiprotons – signal from χ

Source function

$$Q_{\bar{p}}^{\chi}(T,\vec{x}) = (\sigma_{\text{ann}}v)\left(\frac{\rho_\chi(\vec{x})}{m_\chi}\right)^2 \sum_f B_f \frac{dN_f}{dT}$$

Given the galaxy and propagation parameters and a halo profile.

$$\Downarrow$$

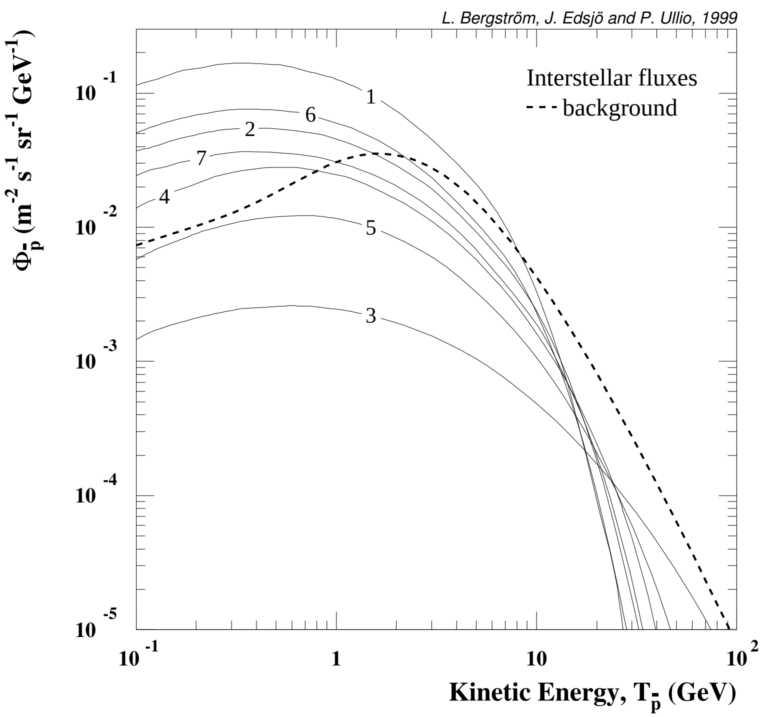
$$\Phi_{\bar{p}}^{\text{interstellar}}(T_{\bar{p}})$$

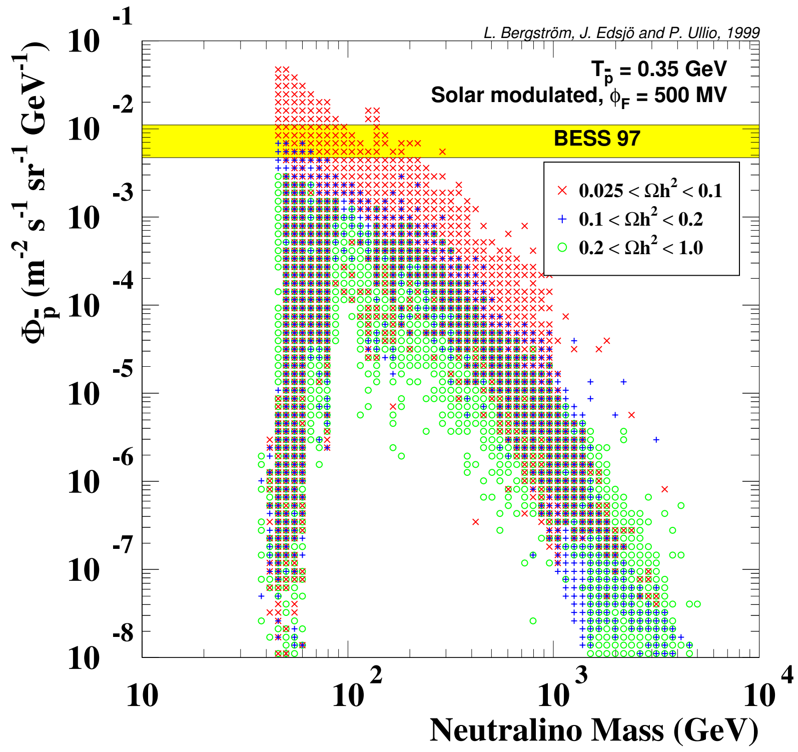
Solar modulation

$$\begin{aligned}
\frac{d\Phi_\oplus}{dT_\oplus}(T_\oplus) &= \frac{R_\oplus^2}{R_b^2}\frac{d\Phi_b}{dT_b}(T_b) \\
E_b &= E_\oplus + |Ze|\phi_F
\end{aligned}$$

We compare with Bess and use $\phi_F = 500$ MV.

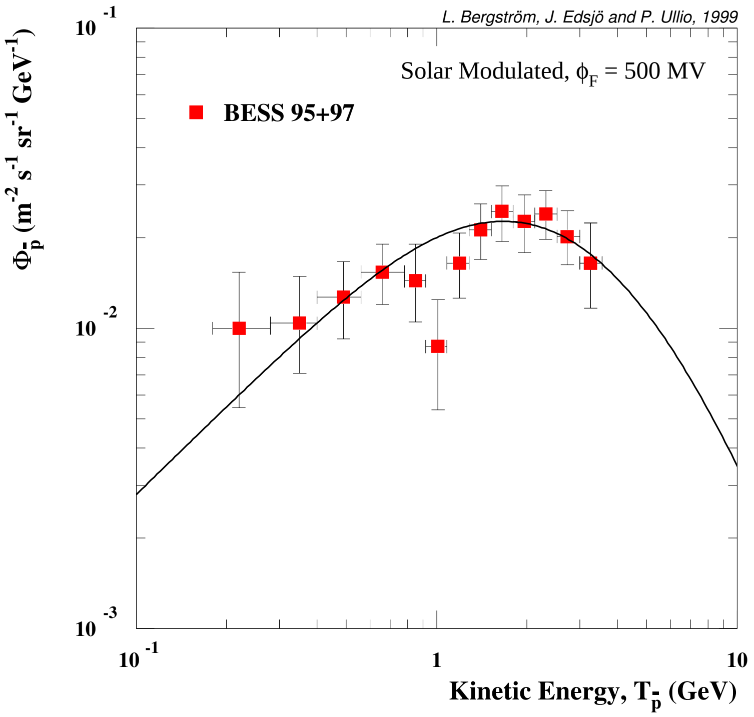
Antiprotons – spectra and BESS



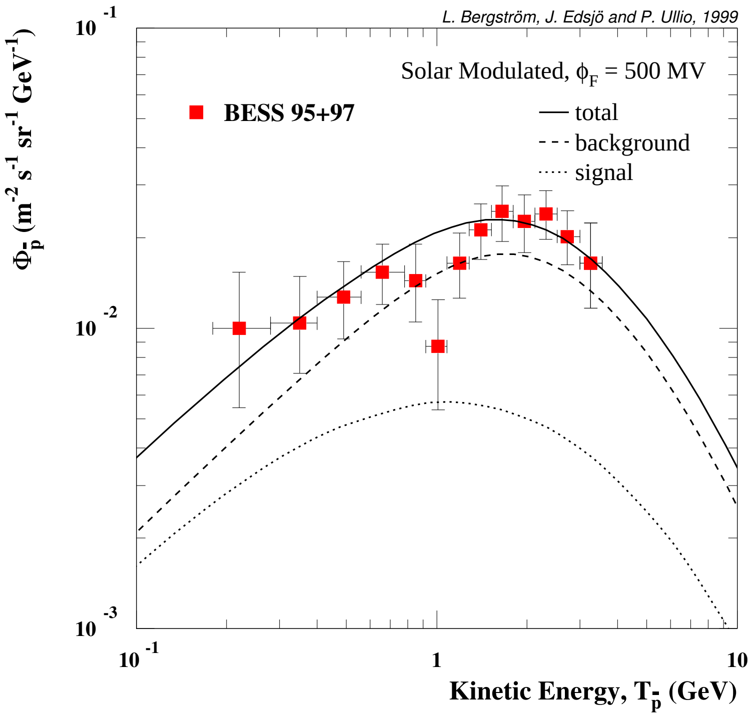


Fits to BESS 95+97 measurements

Background only



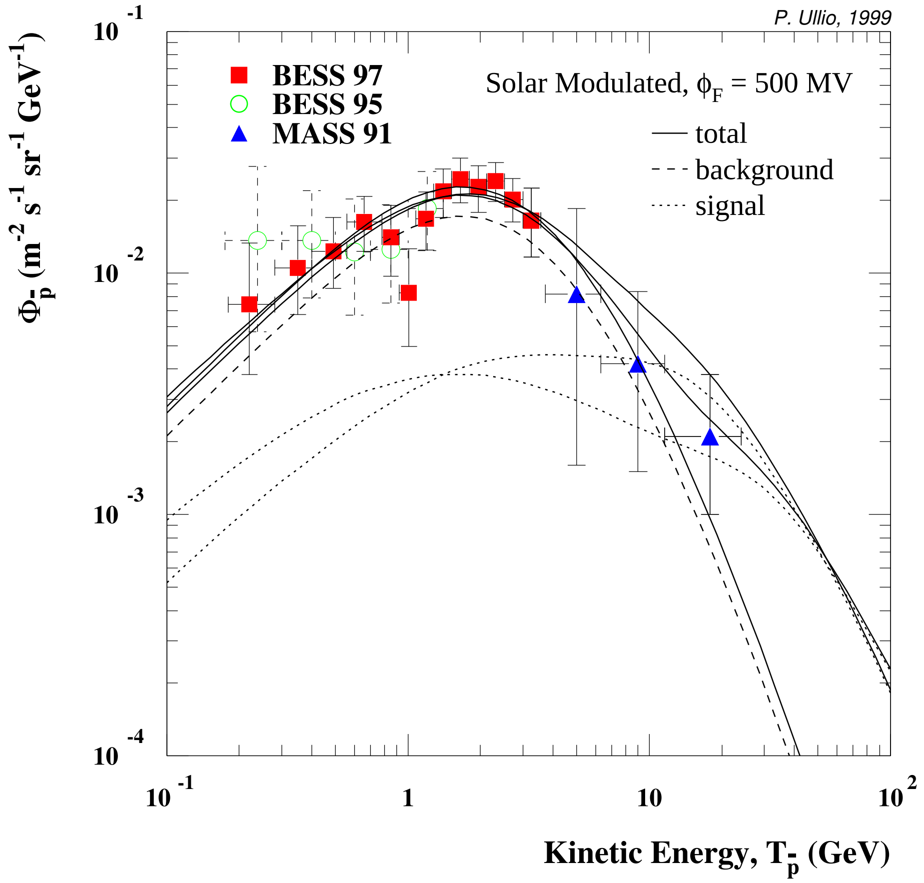
Background+signal



$\Rightarrow$ No need for, but room for, a signal!

Implications of a clumpy halo

- The fluxes increase
- Features may emerge at higher energies from high-mass neutralinos



P. Ullio, astro-ph/9904086

Positron fluxes from neutralino annihilation in the halo

Compared to antiprotons,

- energy losses are much more important
- essentially only local halo properties are important
- higher energies due to more prompt annihilation channels:

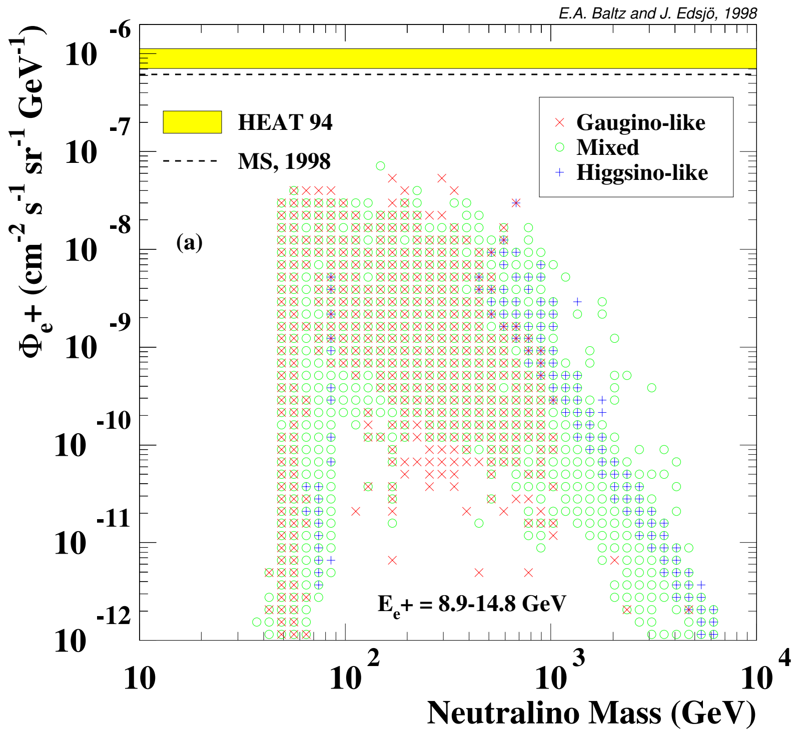
$$\begin{aligned}
&\chi\,\chi \to e^+\,e^- \\
&\chi\,\chi \to W^+\,W^- \to e^+\,\nu_e\,e^-\,\bar{\nu}_e \\
&\chi\,\chi \to \tau^+\,\tau^- \to e^+\,\nu_e\,\bar{\nu}_\tau\,e^-\,\bar{\nu}_e\,\nu_\tau
\end{aligned}$$

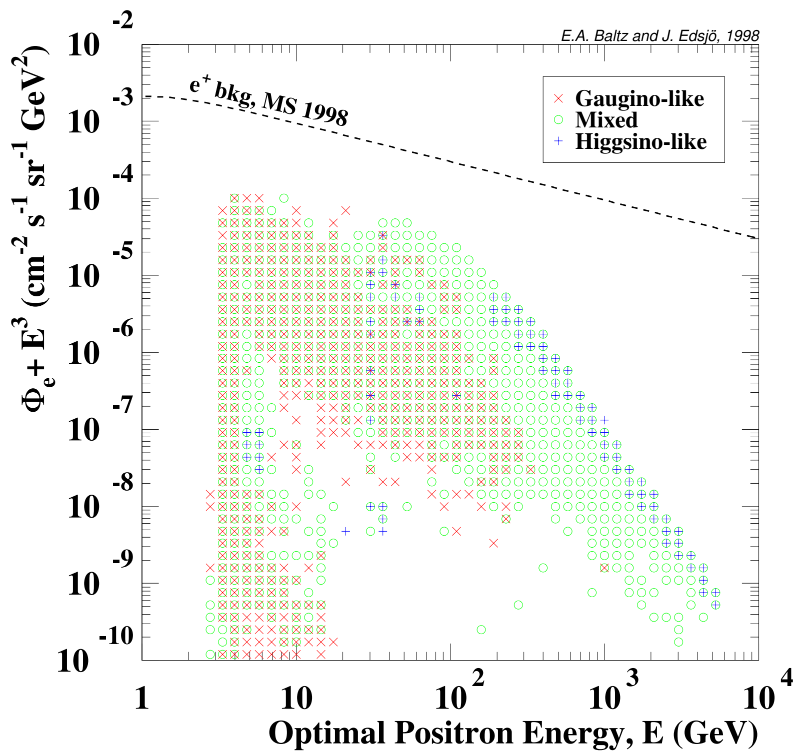
etc.

- propagation uncertainties are higher
- solar modulation uncertainties are higher

To reduce some uncertainties, positron fractions are often considered.

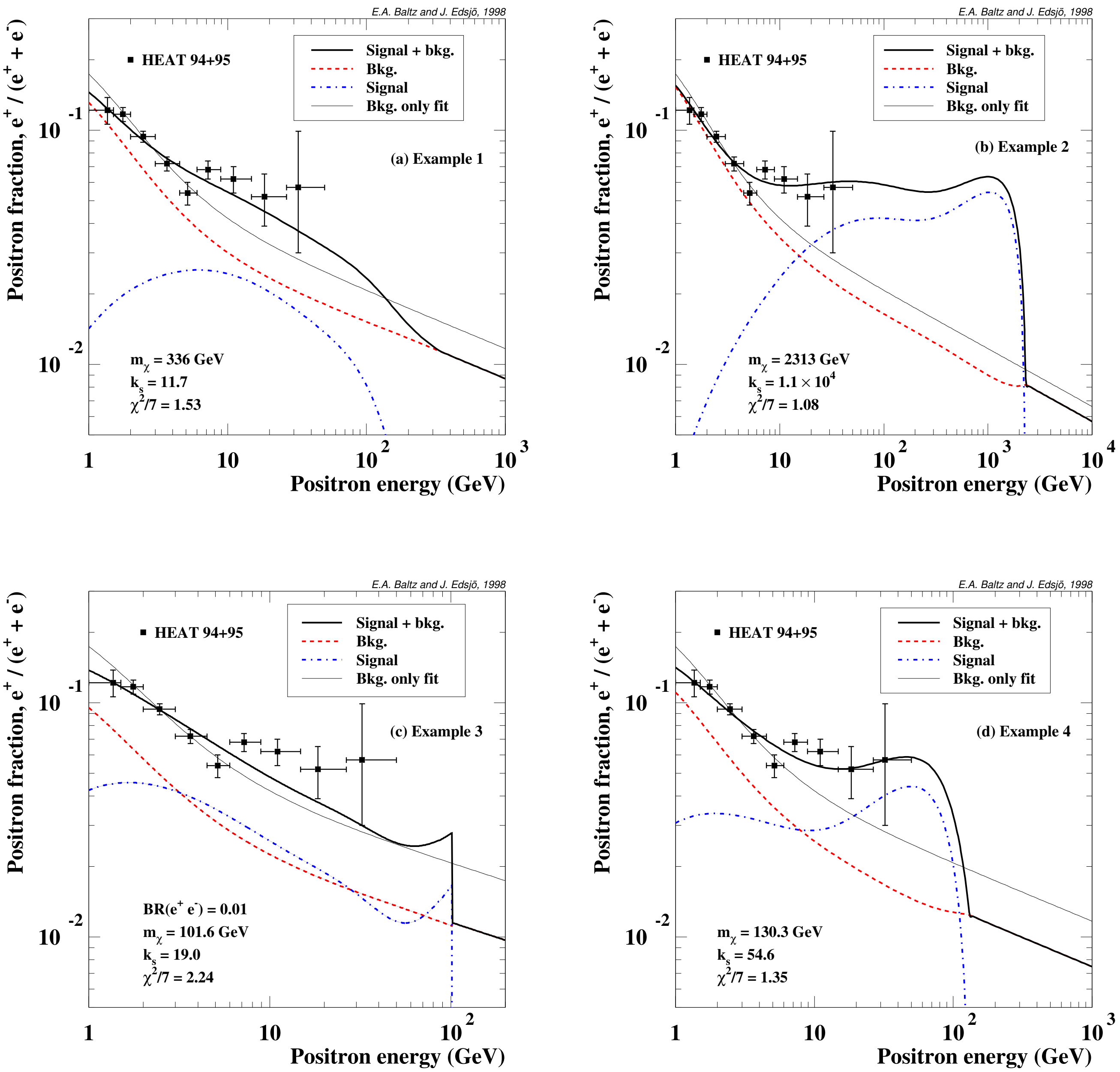
Positrons - signal fluxes





$0.025 < \Omega_\chi h^2 < 1$

Positrons - example spectra



Gamma lines - principle

At one-loop

- $\gamma\gamma \Rightarrow E_\gamma = m_\chi$
- $Z\gamma \Rightarrow E_\gamma = m_\chi - \frac{m_Z^2}{4m_\chi}$

i.e. *monochromatic* gamma rays.

Features

- γs keep their direction – no propagation uncertainties
- $\Phi_\gamma \propto \int_{\text{line of sight}} \rho_\chi^2 dl$
  $\Rightarrow$ Large halo profile dependence for directions close to the galactic centre
- The fluxes are generally low, but the signature is very clear

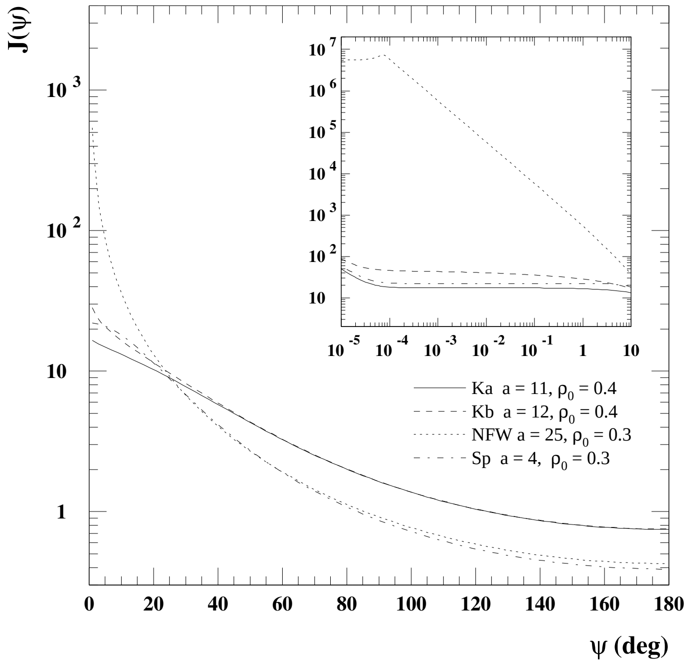
Halo profiles

Spherical family of density profiles

$$\rho(r) = \rho_0 \left(\frac{r_0}{r}\right)^{\gamma} \left[\frac{1+(r_0/a)^{\alpha}}{1+(r/a)^{\alpha}}\right]^{(\beta-\gamma)/\alpha}$$

$$\propto \begin{cases} \frac{1}{r^{\gamma}} & , \quad r \ll a \\ \frac{1}{r^{\beta}} & , \quad r \gg a \end{cases}$$

Example

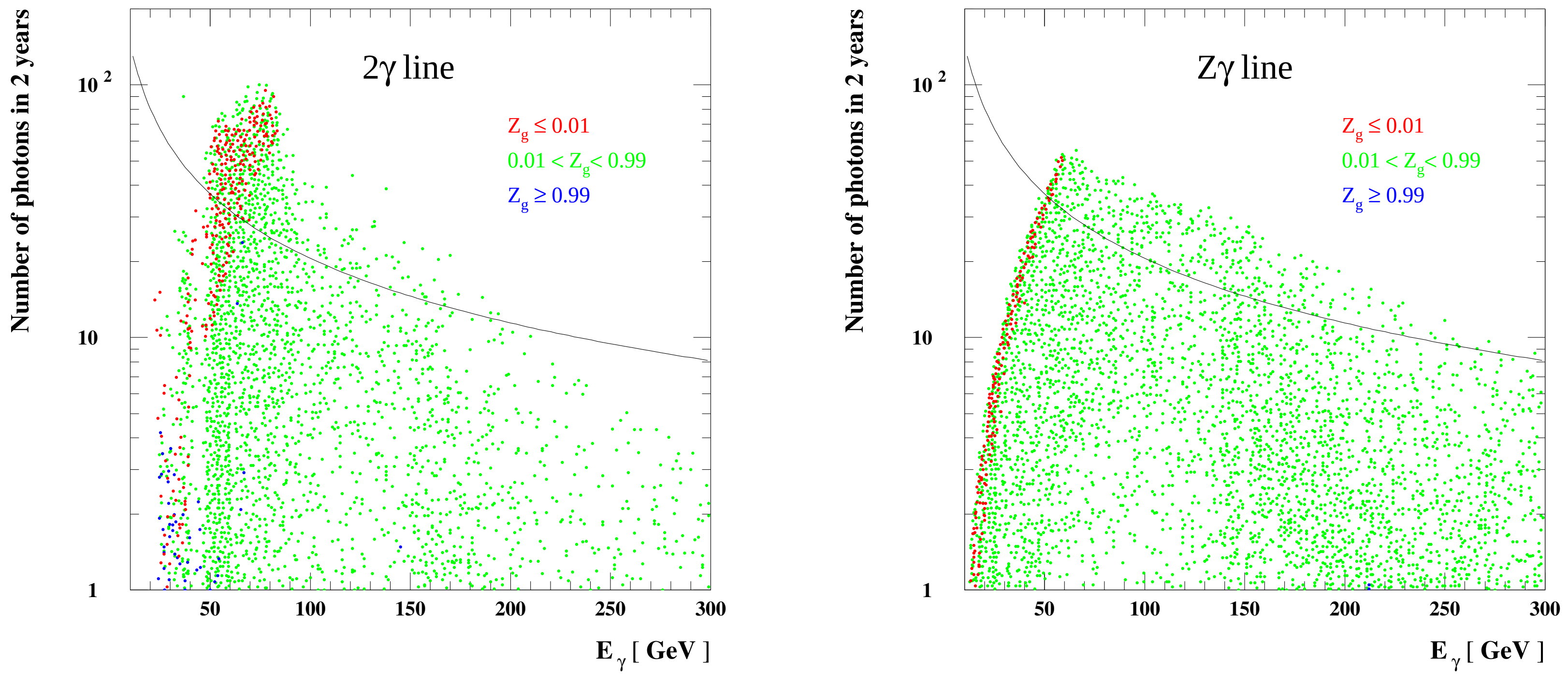


Profile	(α, β, γ)
Ka	$(2, 3, 0.2)$
Kb	$(2, 3, 0.4)$
NFW	$(1, 3, 1)$
Mod. Iso. Sph.	$(2, 2, 0)$

L. Bergström, P. Ullio and J. Buckley, Astrop. Phys. **9** (1998) 137.

Gamma lines - rates in GLAST

NFW halo profile and GLAST 5σ detection limit



L. Bergström, P. Ullio and J. Buckley, Astrop. Phys. **9** (1998) 137.

Continuum gammas - principle

From final state jets we also get continuum γ rays

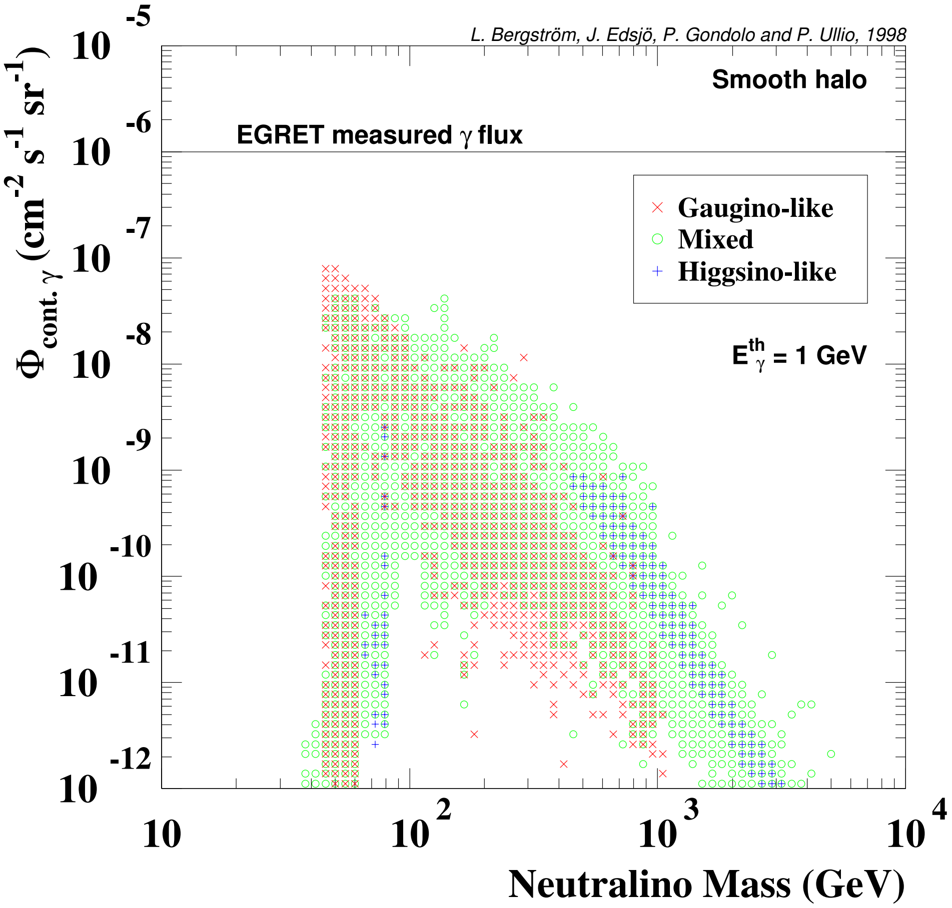
$$\chi\chi \to \ldots \to \pi^0 \to \gamma\gamma$$

Compared to γ lines, we get

- much lower energy γs
- many more γs per annihilation
- rather high fluxes, even away from the galactic centre
- not a very clear signature

Continuum gammas - fluxes

Flux at high galactic latitudes $\Rightarrow$ small halo profile dependence

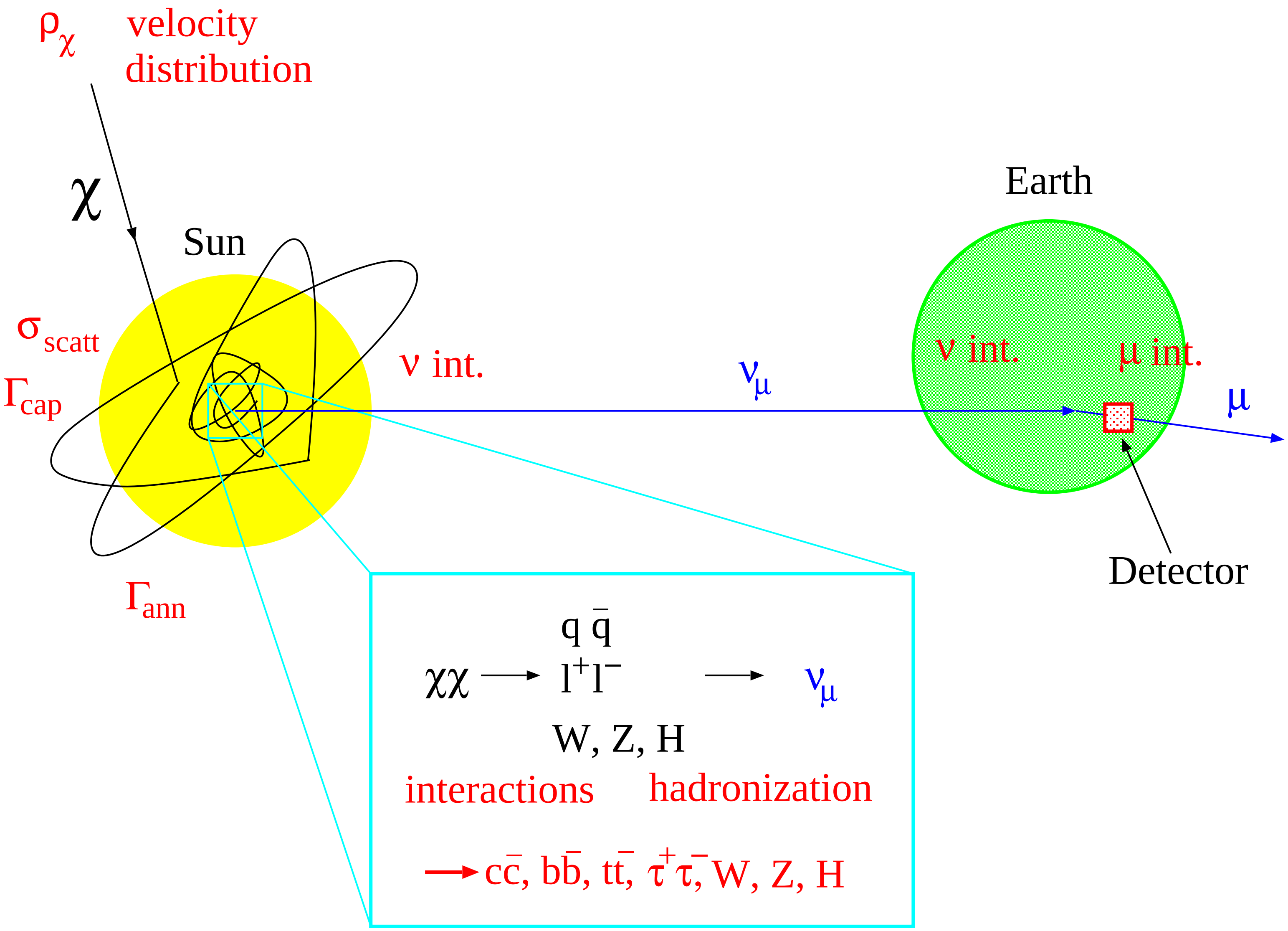


$0.025 < \Omega_\chi h^2 < 1$

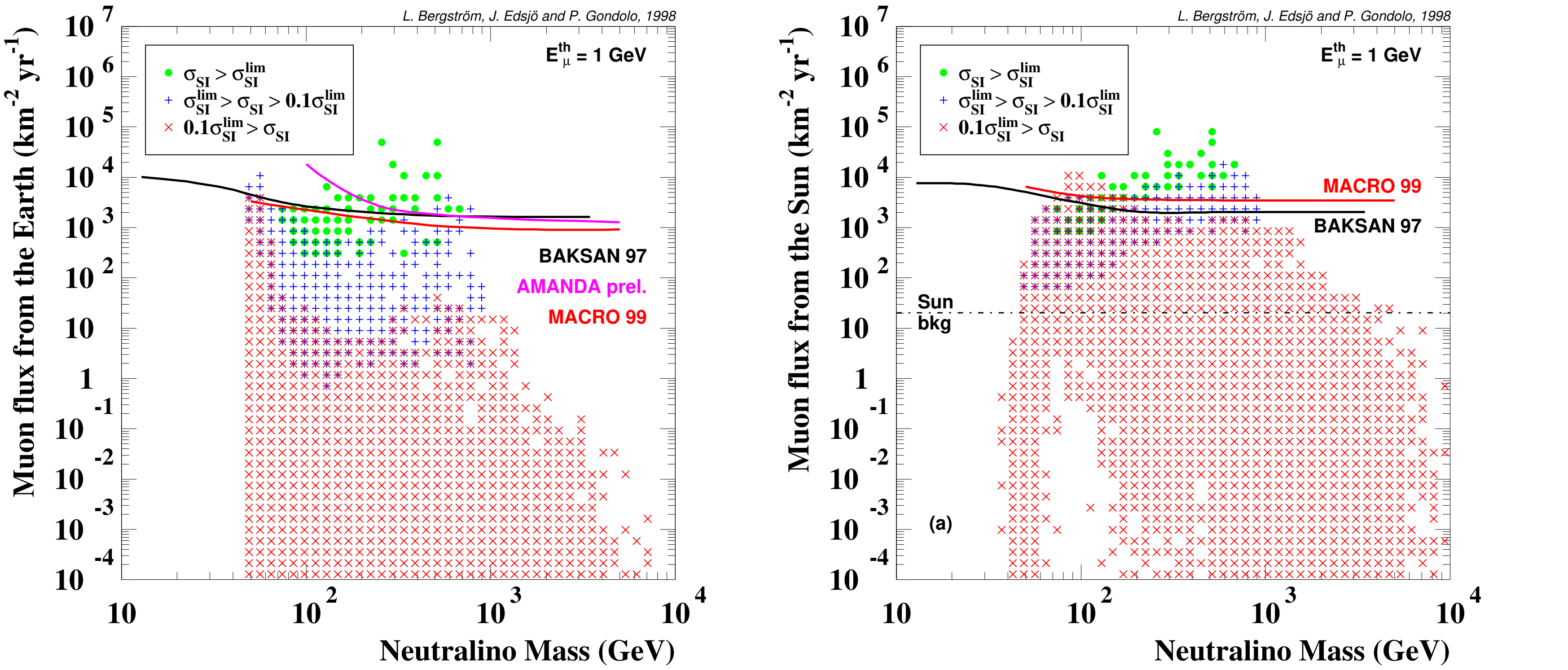
Neutralino annihilation in the Earth/Sun

- Neutralino capture
- Neutrino-induced muon fluxes
- Implications of a new χ population

Neutralino capture – basics

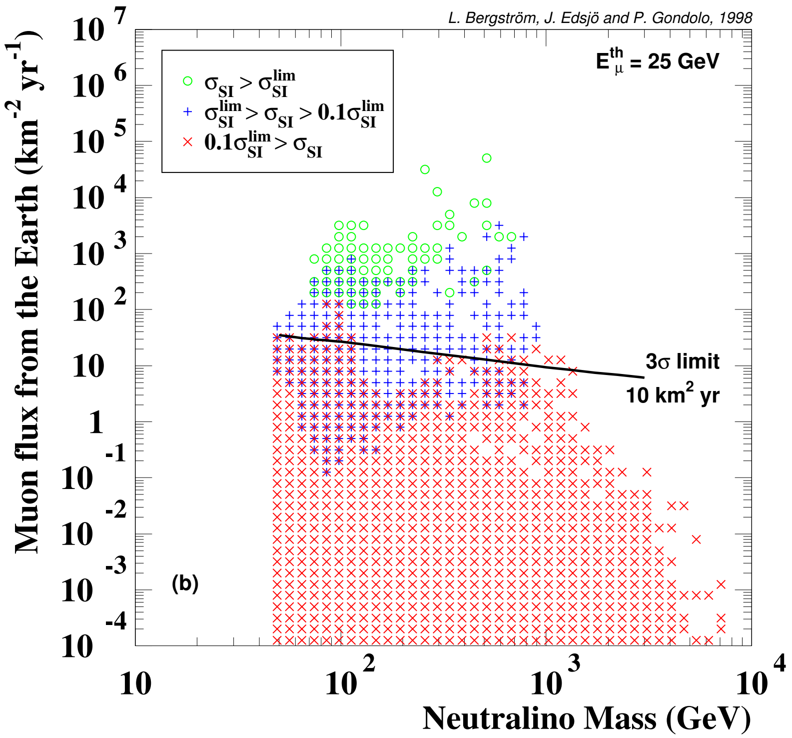


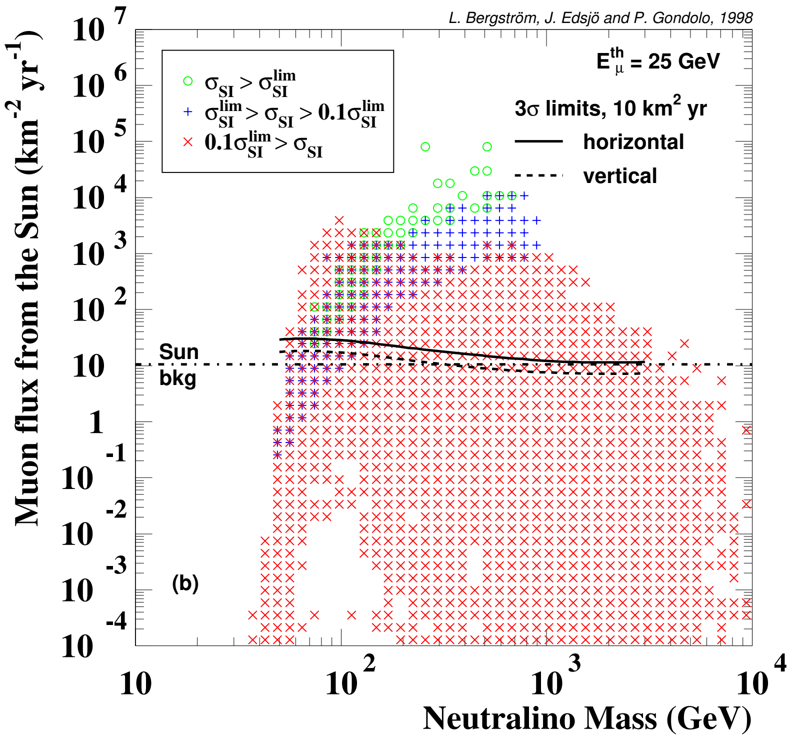
ν telescopes – Φ_μ vs m_χ, $E_\mu^{\mathrm{th}} = 1$ GeV



$0.025 < \Omega_\chi h^2 < 1$ L. Bergström, J. Edsjö and P. Gondolo, PRD **58** (1998) 103519

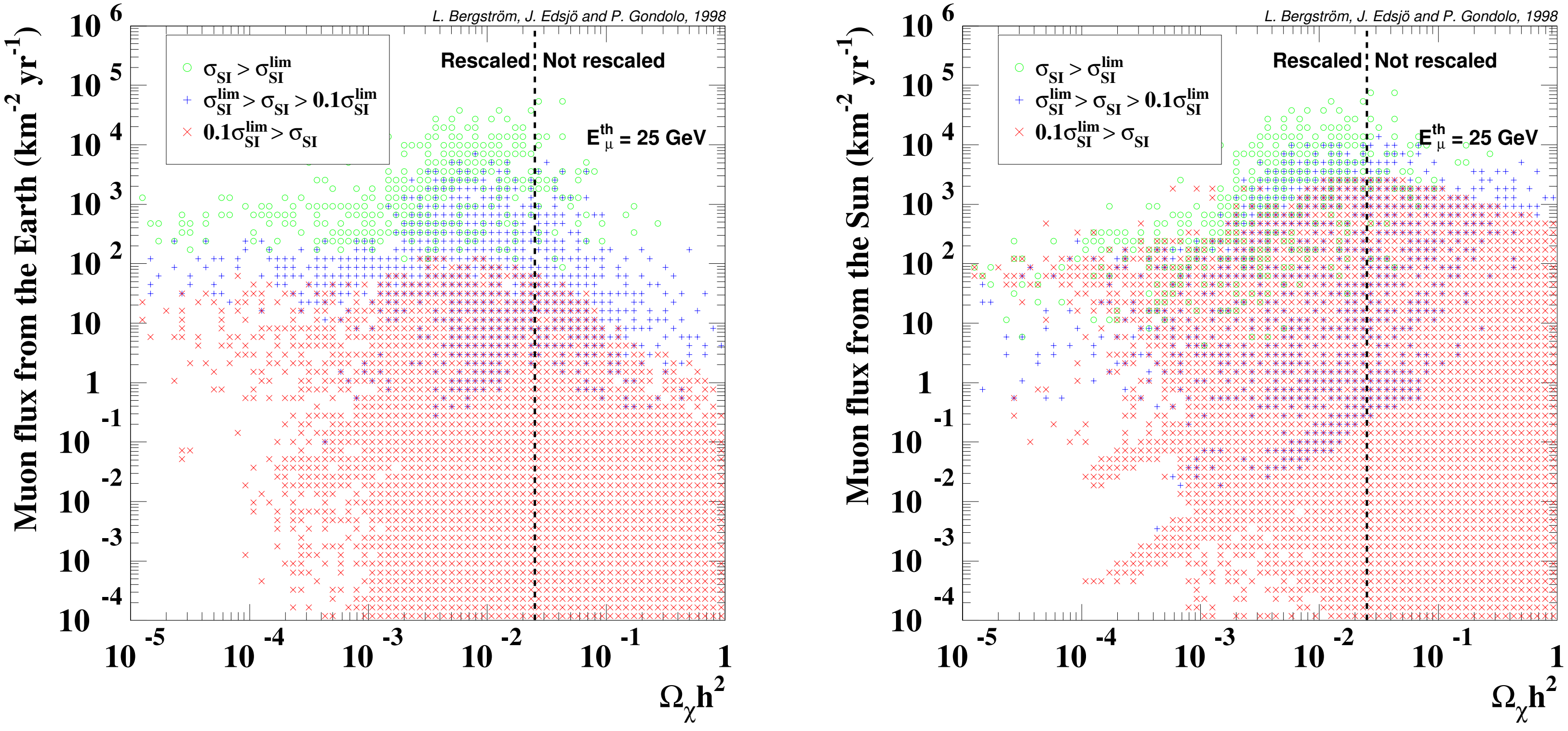
ν **telescopes** – Φ_μ **vs** m_χ, $E_\mu^{\text{th}} = 25$ **GeV**





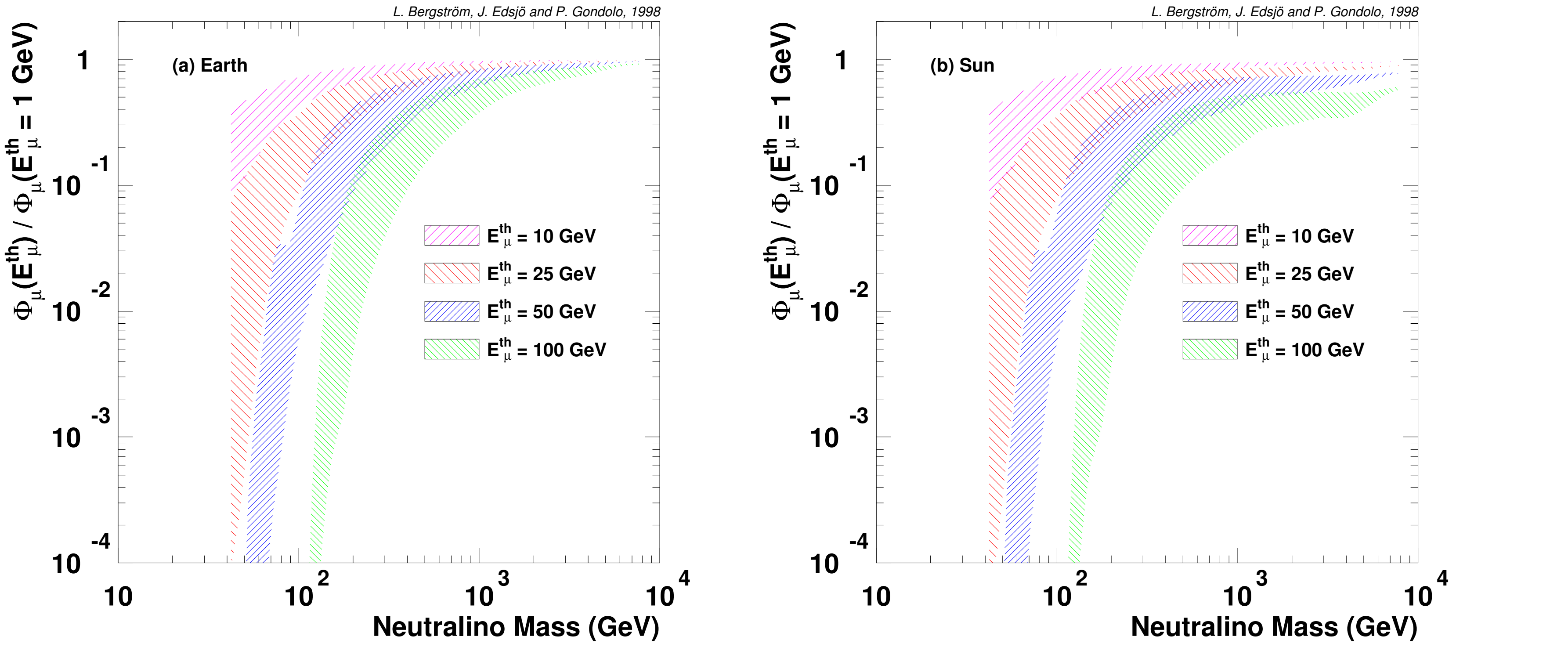
$0.025 < \Omega_\chi h^2 < 1$ L. Bergström, J. Edsjö and P. Gondolo, PRD **58** (1998) 103519

ν telescopes – Φ_μ vs $\Omega_\chi h^2$



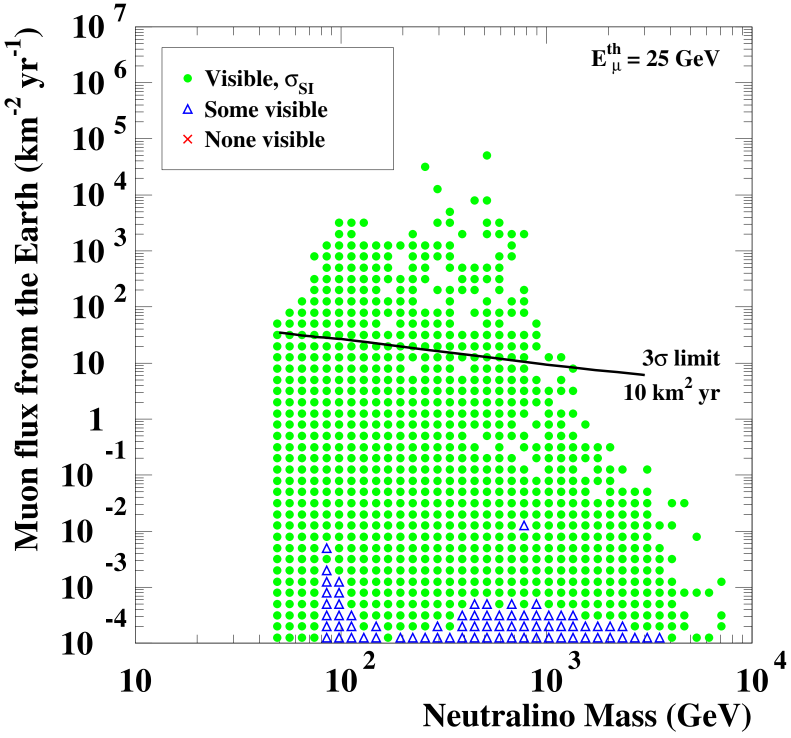
L. Bergström, J. Edsjö and P. Gondolo, PRD **58** (1998) 103519

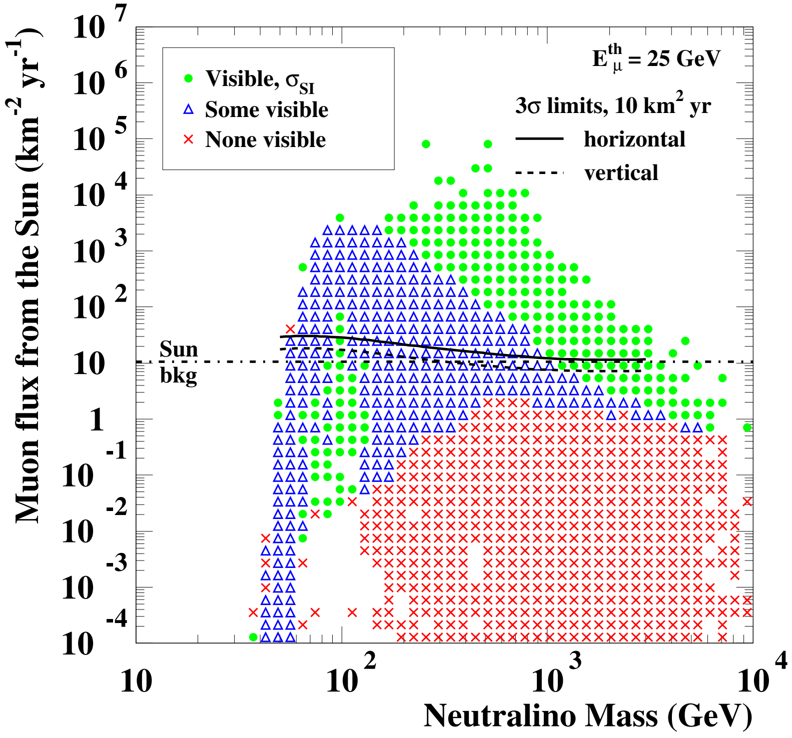
ν telescopes – threshold dependence



$0.025 < \Omega_\chi h^2 < 1$ L. Bergström, J. Edsjö and P. Gondolo, PRD **58** (1998) 103519

$\Phi_{\mu}^{\mathrm{Earth/Sun}}$ and future GENIUS / CRESST limits



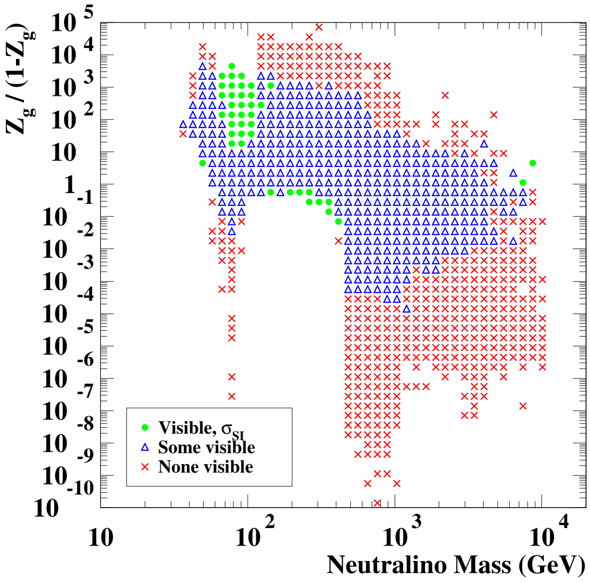


$0.025 < \Omega_\chi h^2 < 1$

E.A. Baltz, J. Edsjö and P. Gondolo

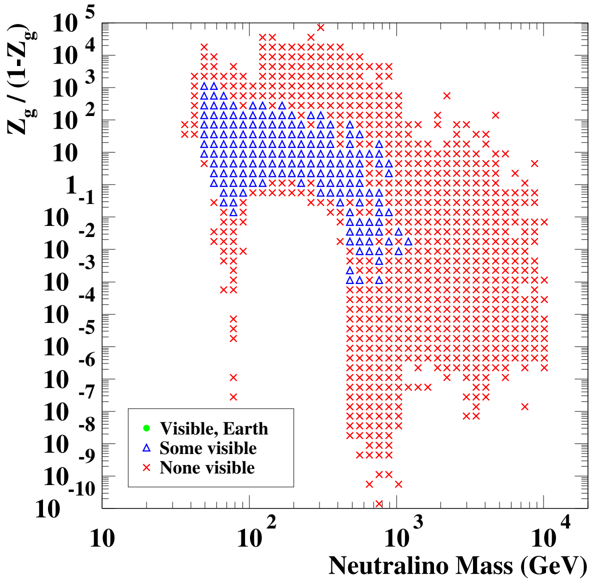
MSSM parameter space – future probed regions I

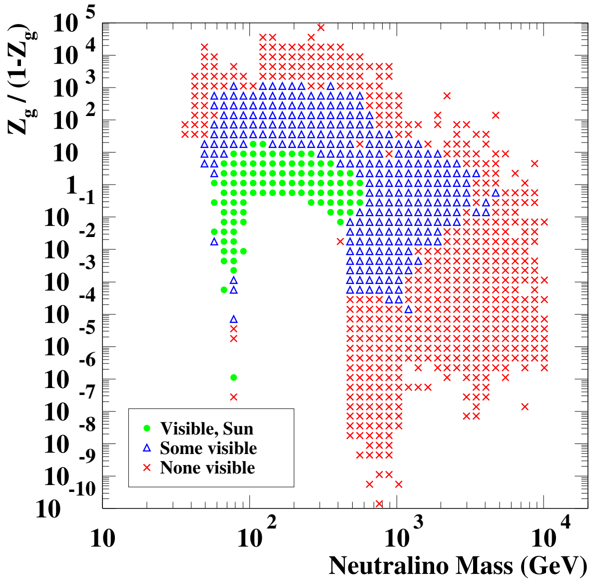
GENIUS/CRESST



$\Phi_\mu^{\mathrm{Earth}}$

Φ_μ^{Sun}





$0.025 < \Omega_\chi h^2 < 1$

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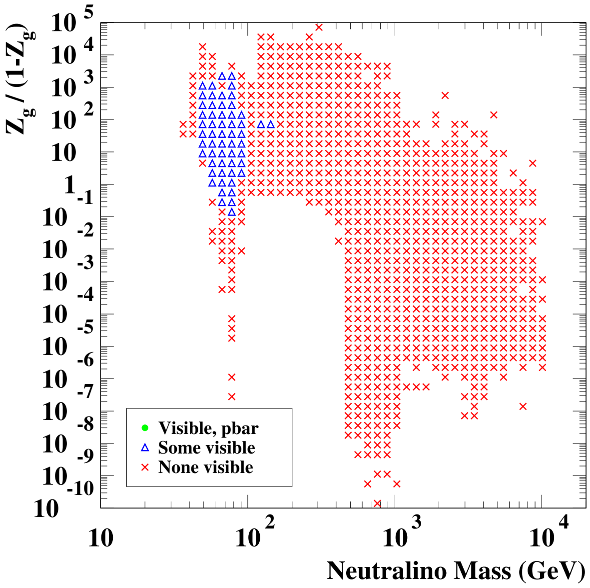
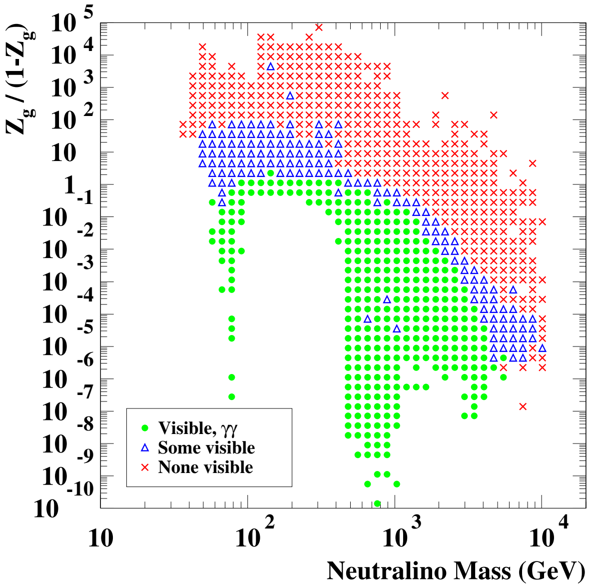
MSSM parameter space – future probed regions II

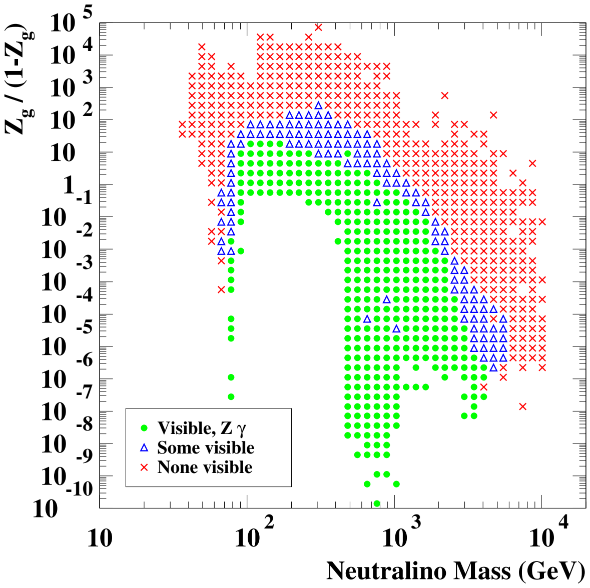
$\Phi_{\bar{p}}$



$\gamma\gamma$



$Z\gamma$



$0.025 < \Omega_\chi h^2 < 1$

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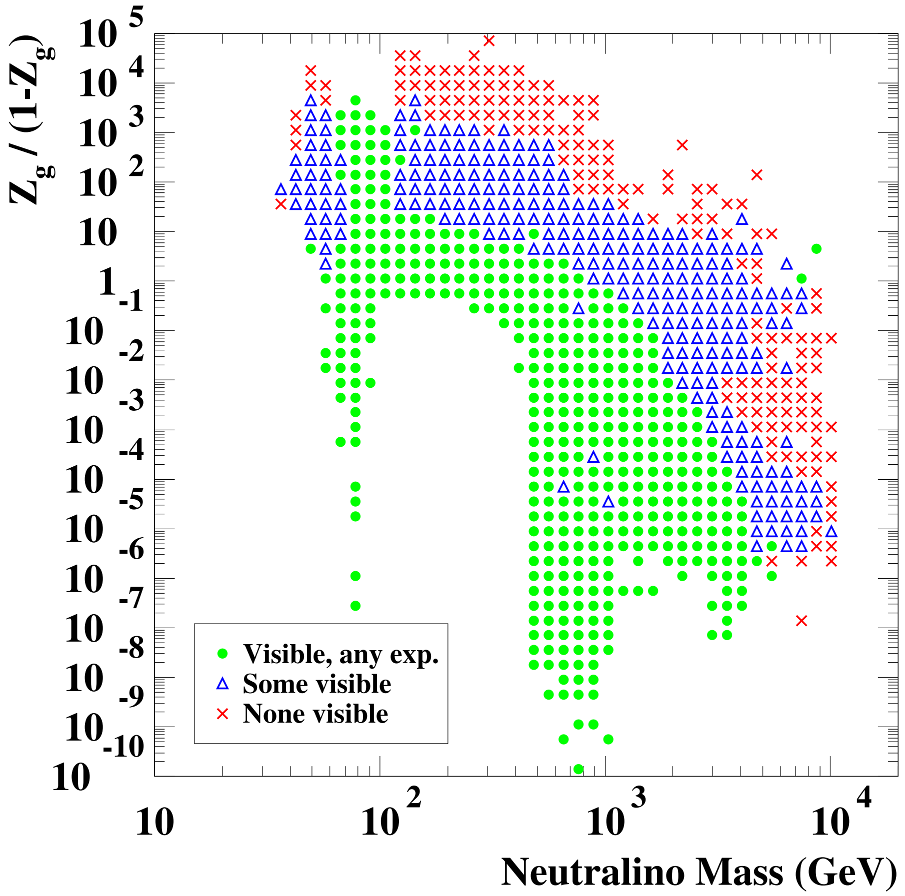
MSSM parameter space – future probed regions III

All dark matter searches combined



$0.025 < \Omega_\chi h^2 < 1$

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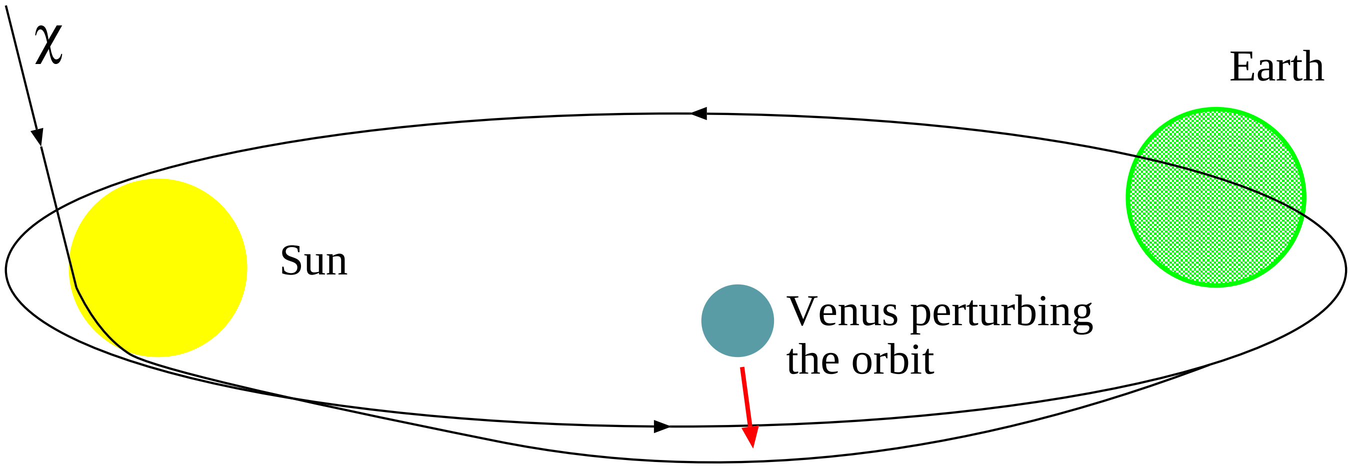
New population of WIMPs



- WIMPs scatter in the outskirts of the Sun and end up in bound Sun-crossing orbits

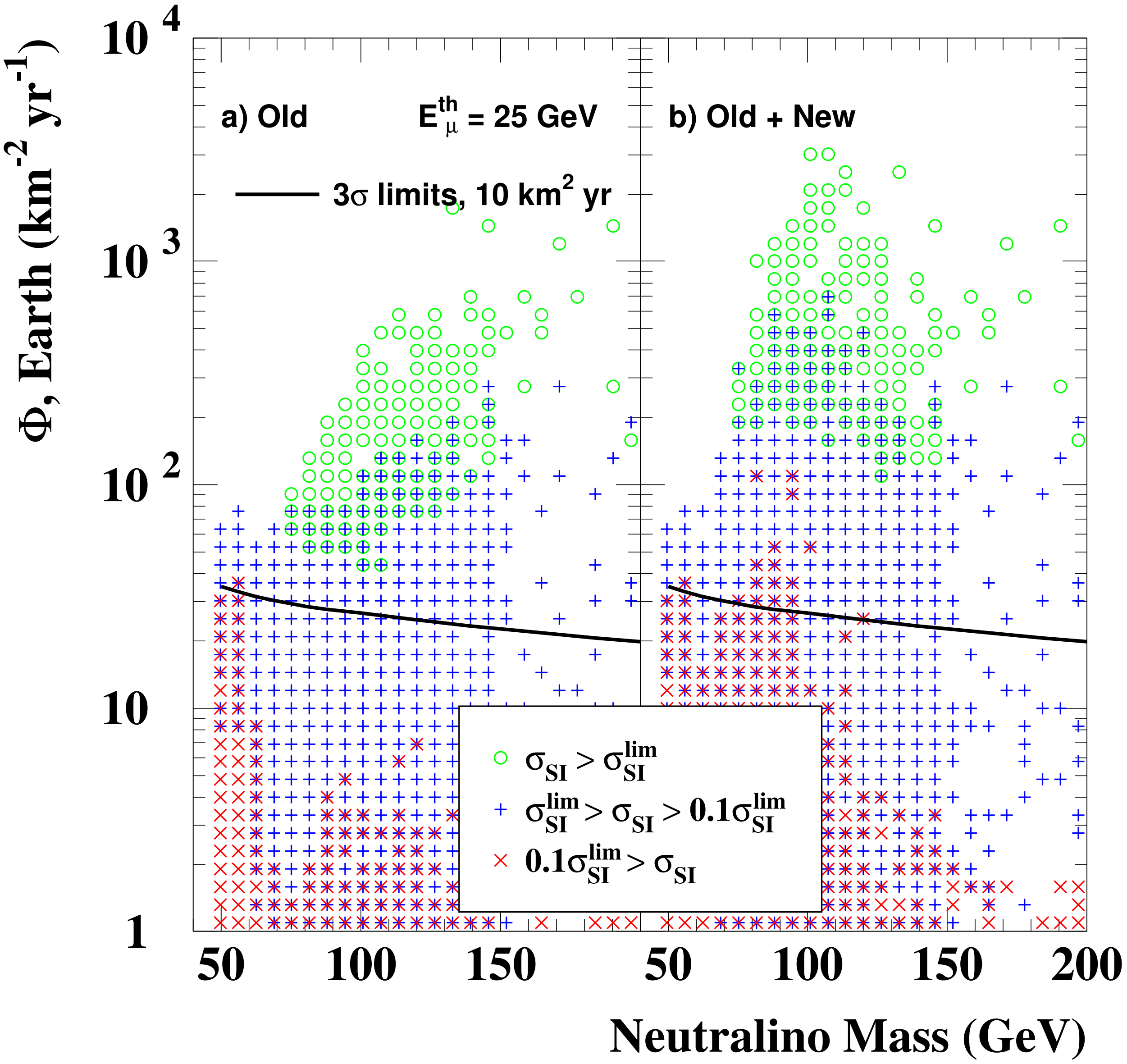
- Venus and/or Jupiter perturb the orbit

$$\Downarrow$$

Nearly radial orbits that *do not cross* the Sun, but *do cross* the Earth.

L. Bergström, T. Damour, J. Edsjö, L.M. Krauss and P. Ullio
`hep-ph/9905446`

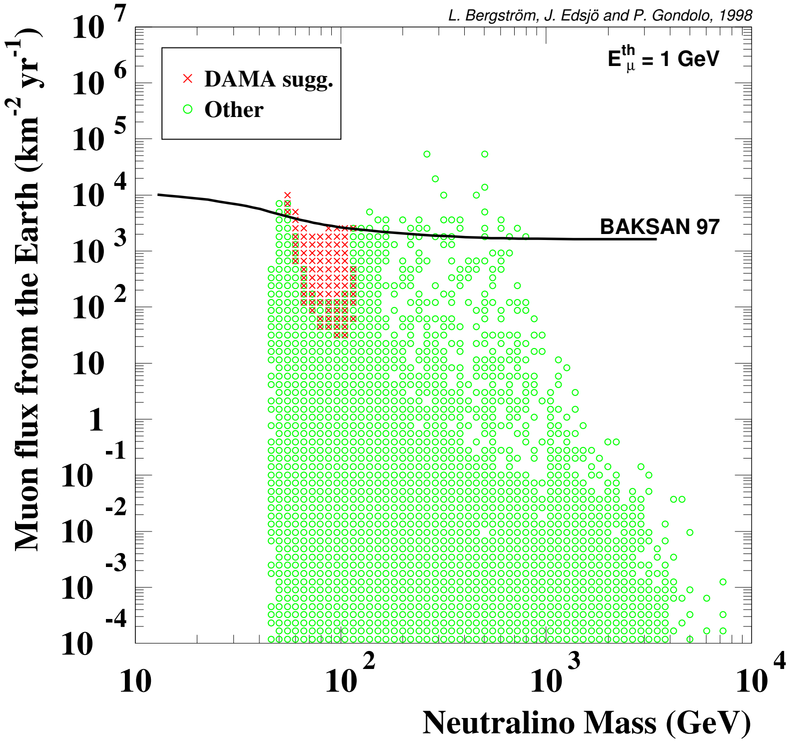
Absolute fluxes – $E_\mu^{\rm th} = 25$ GeV



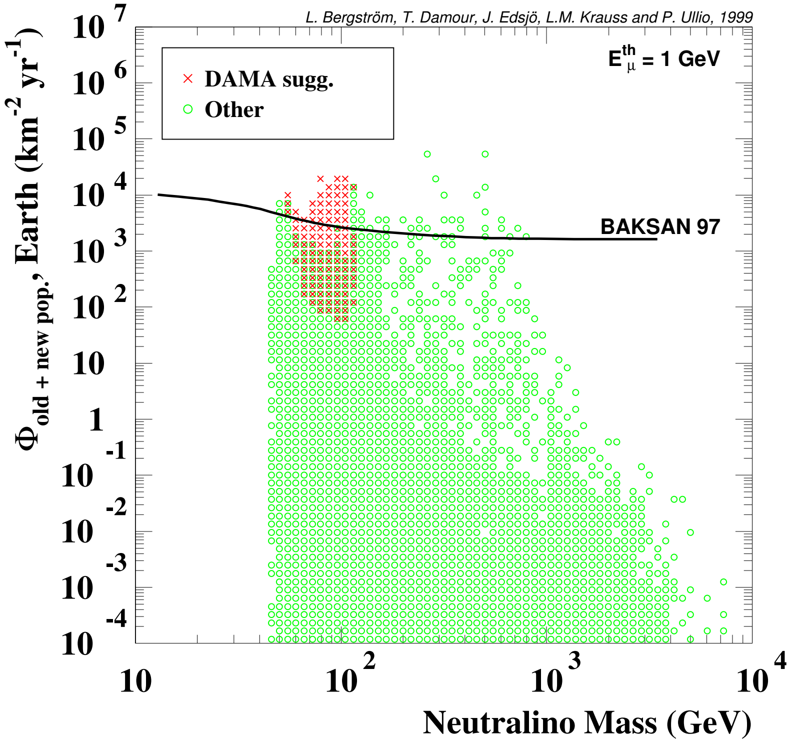
L. Bergström, T. Damour, J. Edsjö, L.M. Krauss and P. Ullio, `hep-ph/9905446`

DAMA region and neutrino telescopes

without new population



with new population



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Conclusions I

- Direct detection experiments have started exploring the MSSM parameter space.

- If *energy losses* and $p - He$ *interactions* are included, the low-energy window for $\bar{p}$ below 1 GeV is filled.

- The fluxes of $\bar{p}$ from neutralino annihilations can be very high, but it lacks distinct features unless the halo is clumpy.

- There is no need for a $\bar{p}$ signal, but due to the uncertainties, there is still room for one.

- The flux of positrons is usually low, but features can be present to indicate a signal.

- The flux of gamma rays can be high and for monochromatic gamma rays a signal would be a ‘smoking gun’ for neutralino dark matter.

Conclusions II

- Neutrino telescopes have started exploring the MSSM parameter space.
- Compared to future direct detection experiments, the neutrino flux from the Sun has a good potential for a big array (and preferably low threshold).
- The new population of WIMPs that have scattered in the outskirts of the Sun can increase the flux from the Earth for m_χ=60–120 GeV with more than an order of magnitude.