Neutralino Dark Matter
How can we find them?

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Outline

- Supersymmetric framework – MSSM
- Direct detection
- Indirect detection:
  - Gamma rays, antiprotons and positrons from the halo.
  - Neutrinos from the Earth / Sun.

Problems with the Standard Model

- Why are the masses and couplings as they are?
- The coupling constants almost converge at 10^{15}-10^{16} GeV. Hint for a Grand-Unified Theory?
- Is gravity unified at M_{Planck}?
- The mass of the Higgs boson gets huge radiative corrections. How is this prevented?

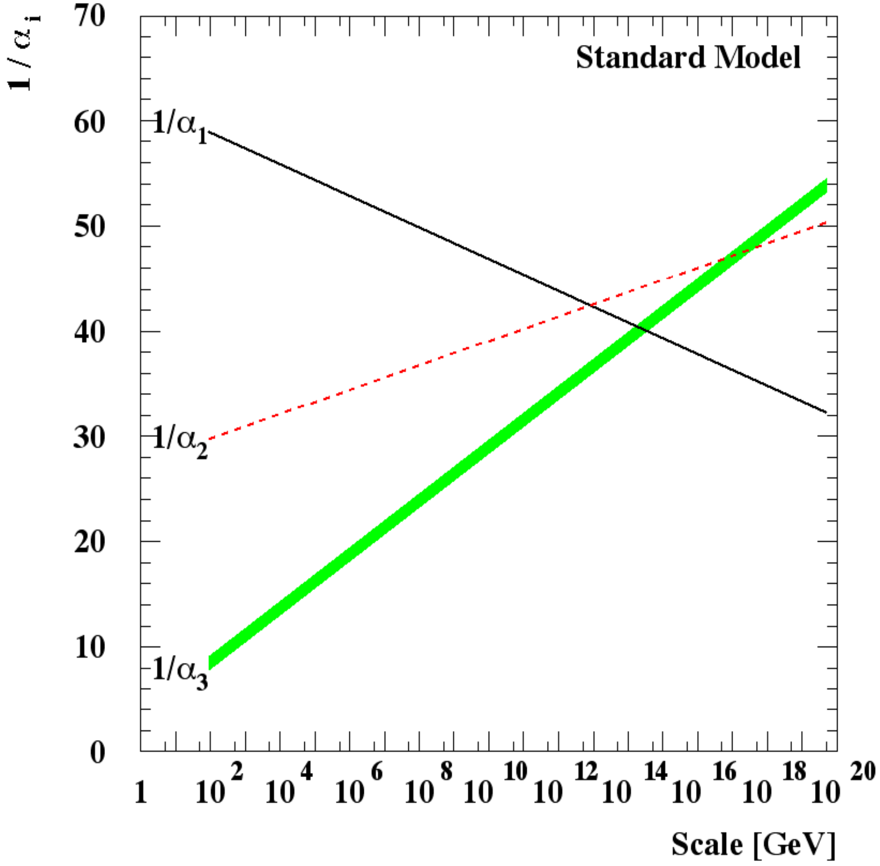
Why Supersymmetry?

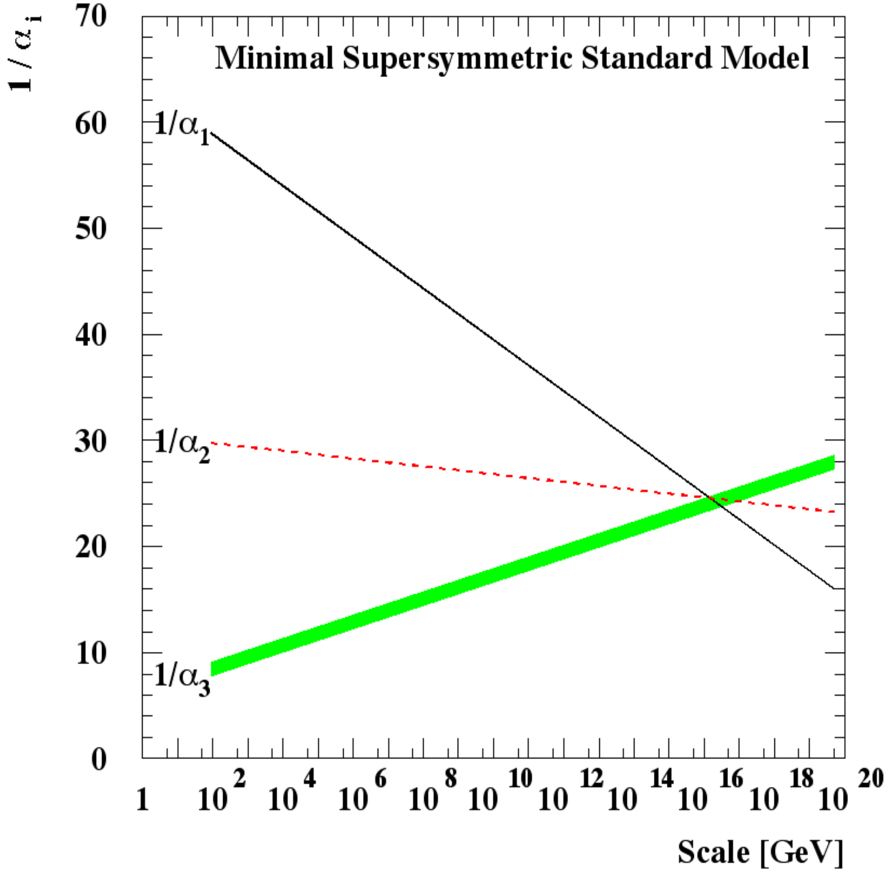
- The convergence of the coupling constants is even better.
- The radiative corrections to M_{Higgs} are finite.
- Supersymmetry seems essential for string theory.

BUT,

- We have so much freedom in how to construct a supersymmetric theory. What has nature chosen?
- String theory might tell us in the future!

Are the coupling constants unified at high energy?





No! It doesn’t seem as they unify at one point.

Yes! It seems that they do unify at one point!

The Minimal Supersymmetric Standard Model (MSSM)

The simplest extension of the Standard Model:

- One supersymmetric partner to each SM particle.
- Two Higgs doublets 5 physical Higgs bosons:

$$H_1^0,\ H_2^0,\ H_3^0 \text{ and } H^{\pm}$$

- The most general soft SUSY-breaking terms that preserve baryon number, lepton number and so called R-parity.

MSSM – Mass spectrum

Normal particles / fields		***Supersymmetric particles / fields***			
		Interaction eigenstates		**Mass eigenstates**	
Symbol	**Name**	**Symbol**	**Name**	**Symbol**	**Name**
$q = d,c,b,u,s,t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino	$\left.\right\}\tilde{\chi}^\pm_{1,2}$	chargino
$H^\mp$	Higgs boson	$\tilde{H}^\mp_{1/2}$	Higgsino		
B	B-field	$\tilde{B}$	bino	ü	
W^3	W^3-field	$\tilde{W}^3$	wino	ï	
H_1^0	Higgs boson	$\tilde{H}_1^0$	Higgsino	ý$\tilde{\chi}^0_{1,2,3,}$	neutralino
H_2^0	Higgs boson	$\tilde{H}_2^0$	Higgsino	ï	
H_{31}^0	Higgs boson			þ	

R=+1 R=–1

The MSSM – parameters

μ - Higgsino mass parameter

M_2 - Gaugino mass parameter

m_A - mass of CP-odd Higgs boson

$\tan\beta$ - ratio of Higgs vacuum expectation values

m_0 - scalar mass parameter

A_b - trilinear coupling, bottom sector

A_t - trilinear coupling, top sector

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	100	-3	-3
Max	+50000	+50000	60	10000	30000	3	3

The MSSM – general

The Lightest Supersymmetric Particle (LSP)

Usually the neutralino. If
R-parity is conserved, it is stable.

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

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

1. Select MSSM parameters
2. Calculate masses, etc
3. Check accelerator constraints
4. Calculate relic density
5. $0.025 < \Omega_\chi h^2 < 0.5$?
6. Calculate fluxes, rates,...

Calculation done with

Dark SUSY

Overview

DarkSUSY is a Fortran package for MSSM dark matter calculations. Calculable quantities include:

- Vertices
- Mass spectrum
- Accelerator bounds
- Relic density
- Scattering cross sections
- Rates in neutrino telescopes
- Fluxes from the halo: antiprotons, positrons, continuum gammas, gamma lines ($Z\gamma$ and $\gamma\gamma$) and neutrinos.

Download from `http://www.physto.se/~edsjo/darksusy/`

Relic density – simple approach

Decoupling occurs when

$$\Gamma < \mathrm{H}$$

We have

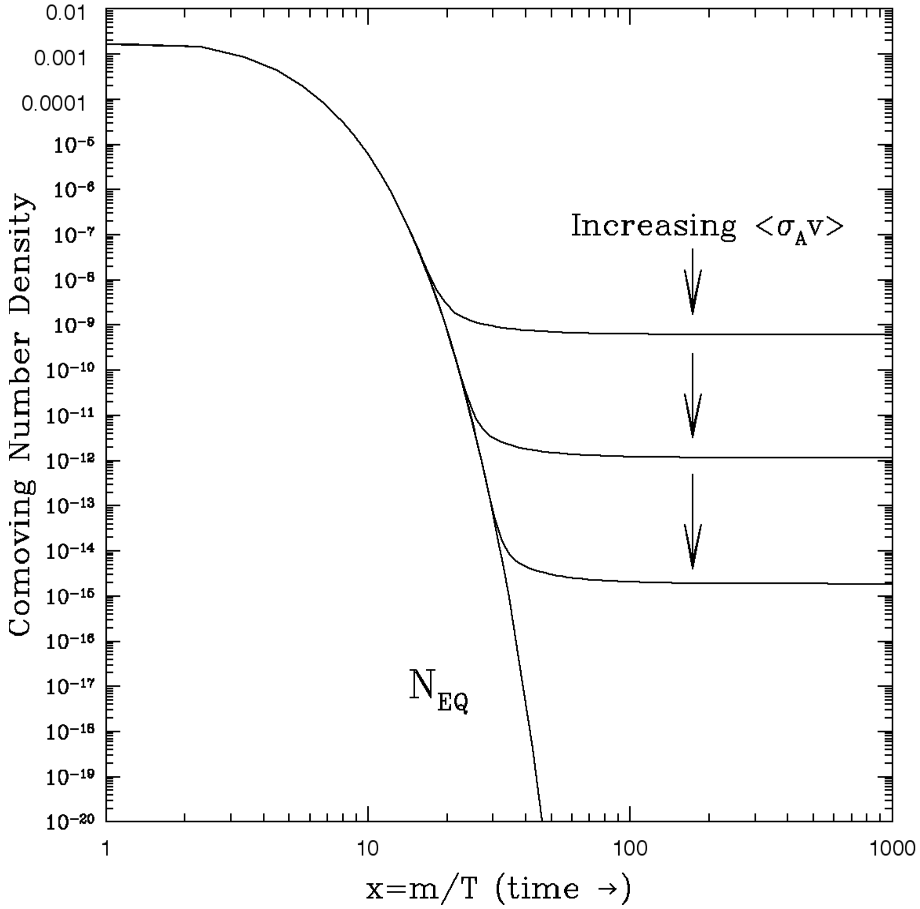
$$\Gamma = \langle \sigma_{ann} v \rangle \; n_\chi$$

$$n_\chi^{eq} = g_\chi \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi / T}$$

$$H(T) = 1.66 \; g_*^{1/2} \frac{T^2}{m_{Planck}}$$

$$\Gamma \approx H \qquad T_f \approx \frac{m_\chi}{20}$$

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \, cm^3 s^{-1}}{\langle \sigma_{ann} v \rangle}$$



$$\langle \sigma_{ann} v \rangle \approx \langle \sigma_{ann} v \rangle_{WIMP} \qquad \Omega \approx 1$$

Figure from Jungman, Kamionkowski and Griest, Phys. Rep. 267 (1996) 195.

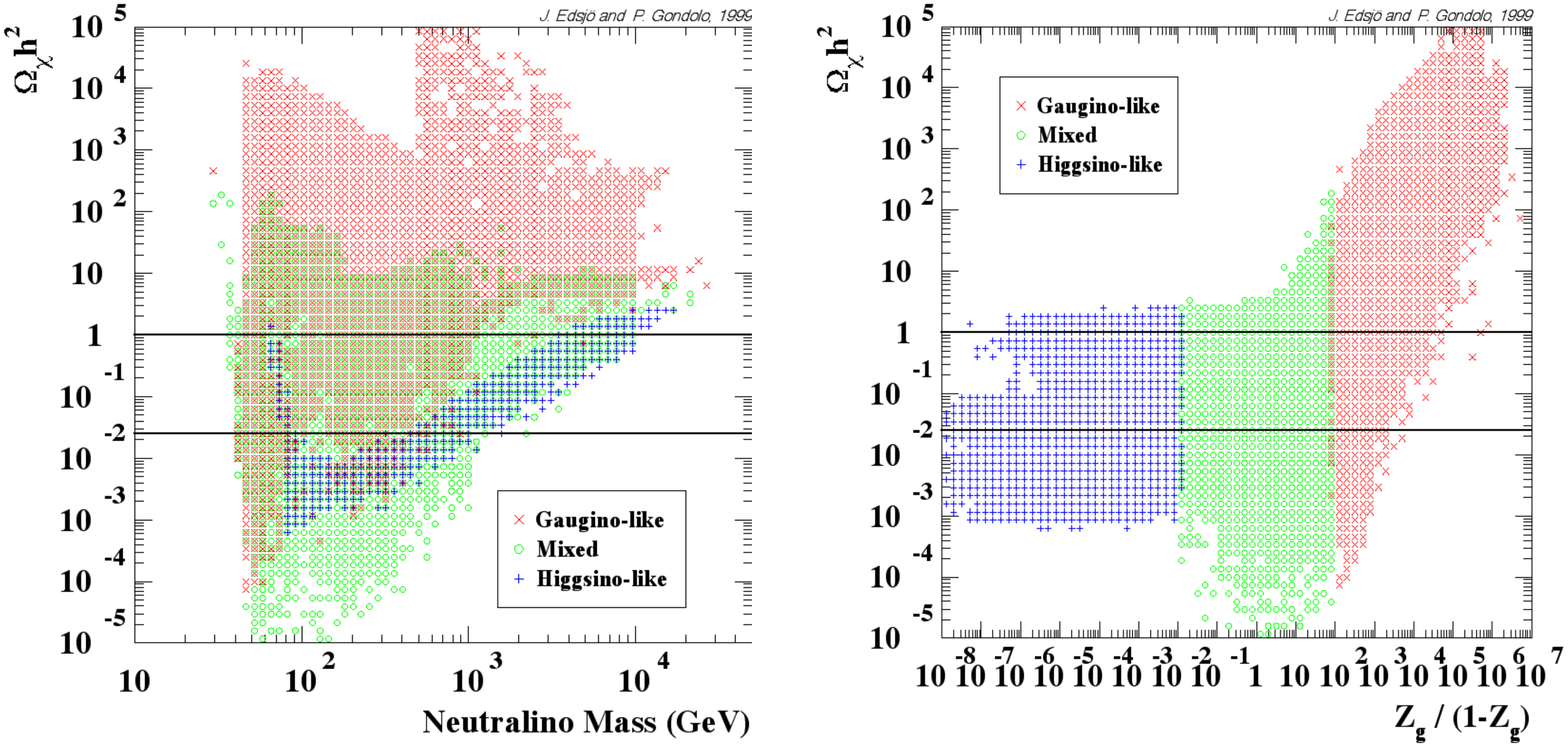
Relic density – accurate approach

Solve the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{ann} v \rangle \left(n^2 - n_{eq}^2 \right)$$

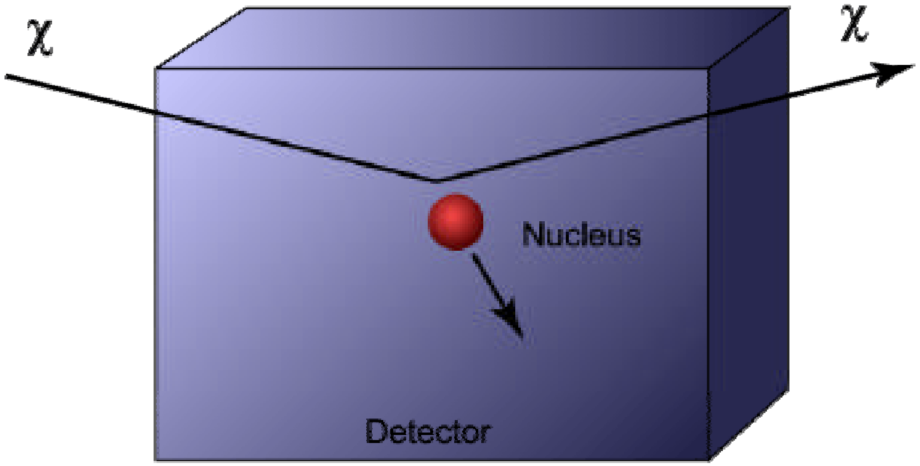
- properly taking the thermal average <·>
- including the full annihilation cross section (all annihilation channels, thresholds, resonances).
- including so called coannihilations between other SUSY particles present at freeze-out.

Relic density vs mass and composition

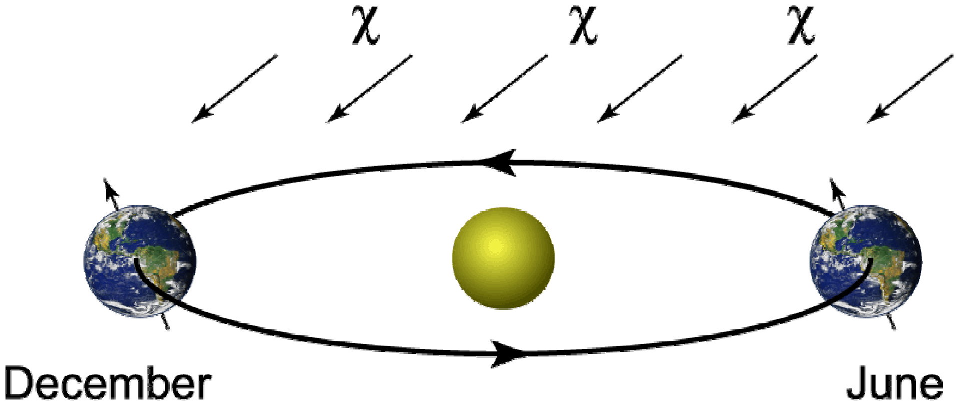


The neutralino is cosmologically interesting for a wide range of masses and compositions!

Direct detection - general principles



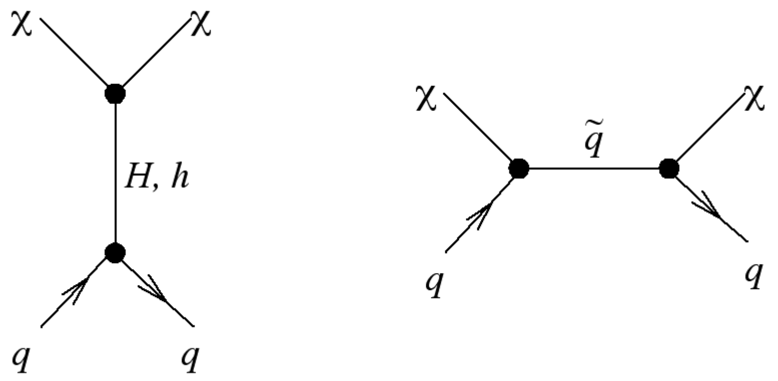
- WIMP + nucleus → WIMP + nucleus
- Measure the nuclear recoil energy
- Suppress backgrounds enough to be sensitive to a signal, or...



- Search for an annual modulation due to the Earth's motion around the Sun

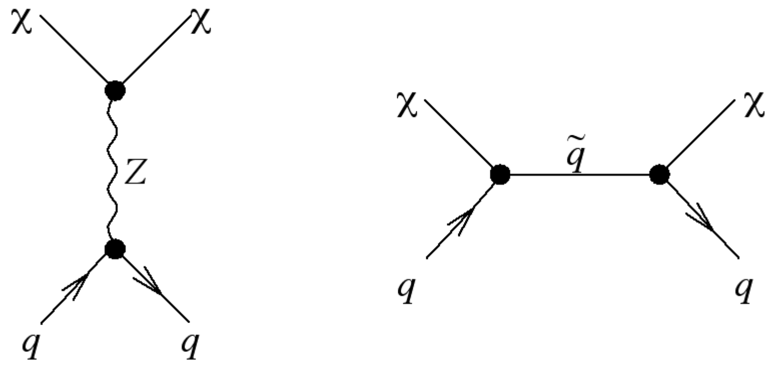
Direct detection – scattering diagrams

Spin-independent scattering



+ diagrams with gluons

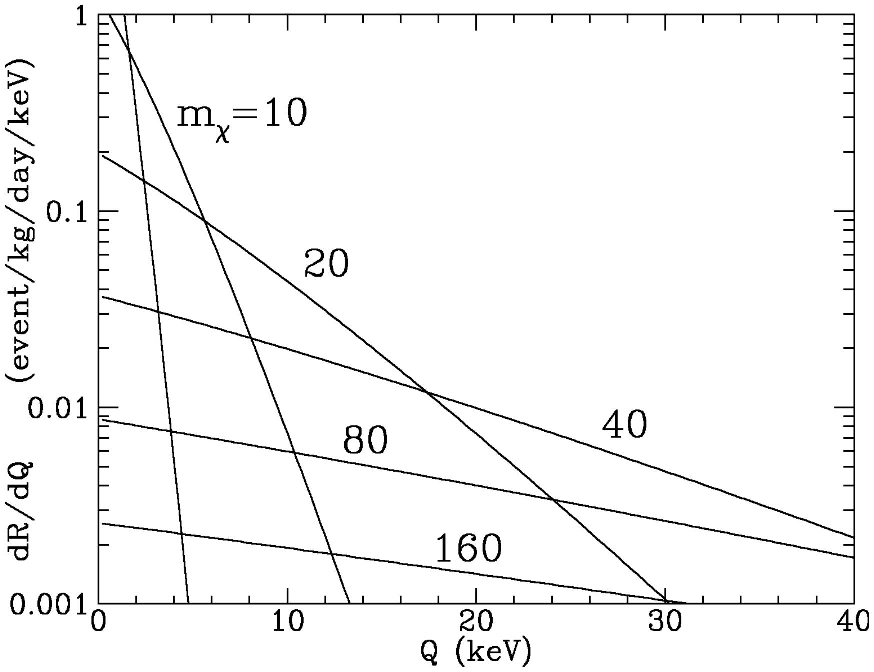
Spin-dependent scattering



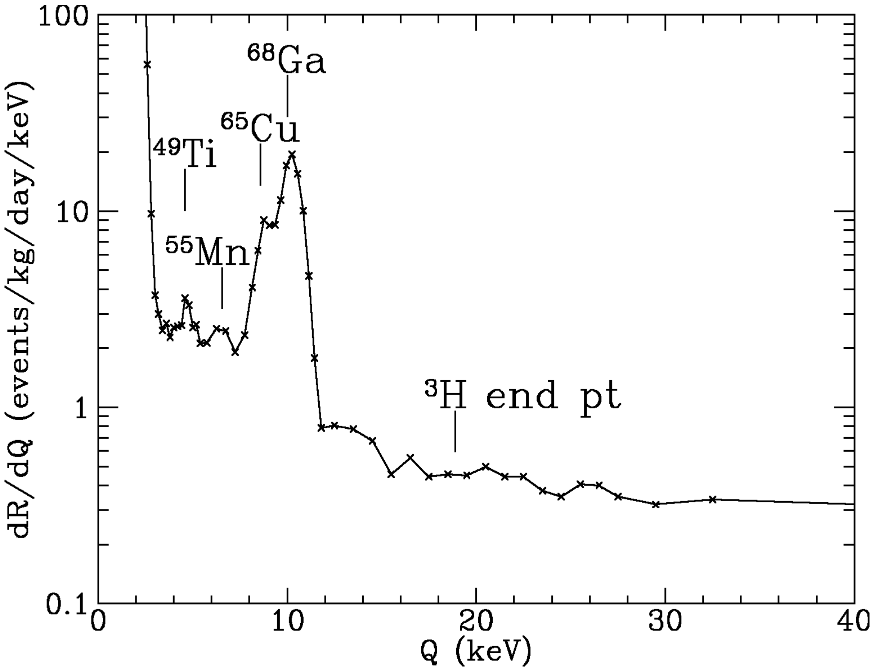
Diagrams from Jungman, Kamionkowski and Griest,
Phys. Rep. 267 (1996) 195.

Direct detection – example spectra

Differential rate



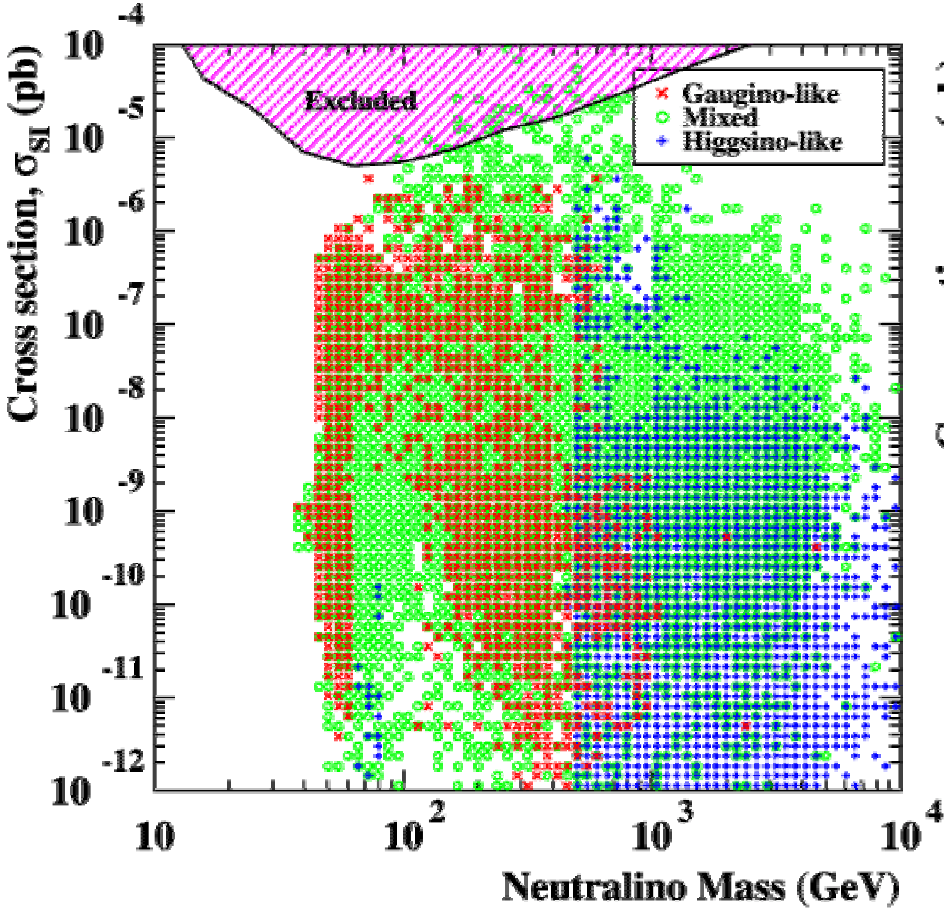
Gamma background in Ge-detector



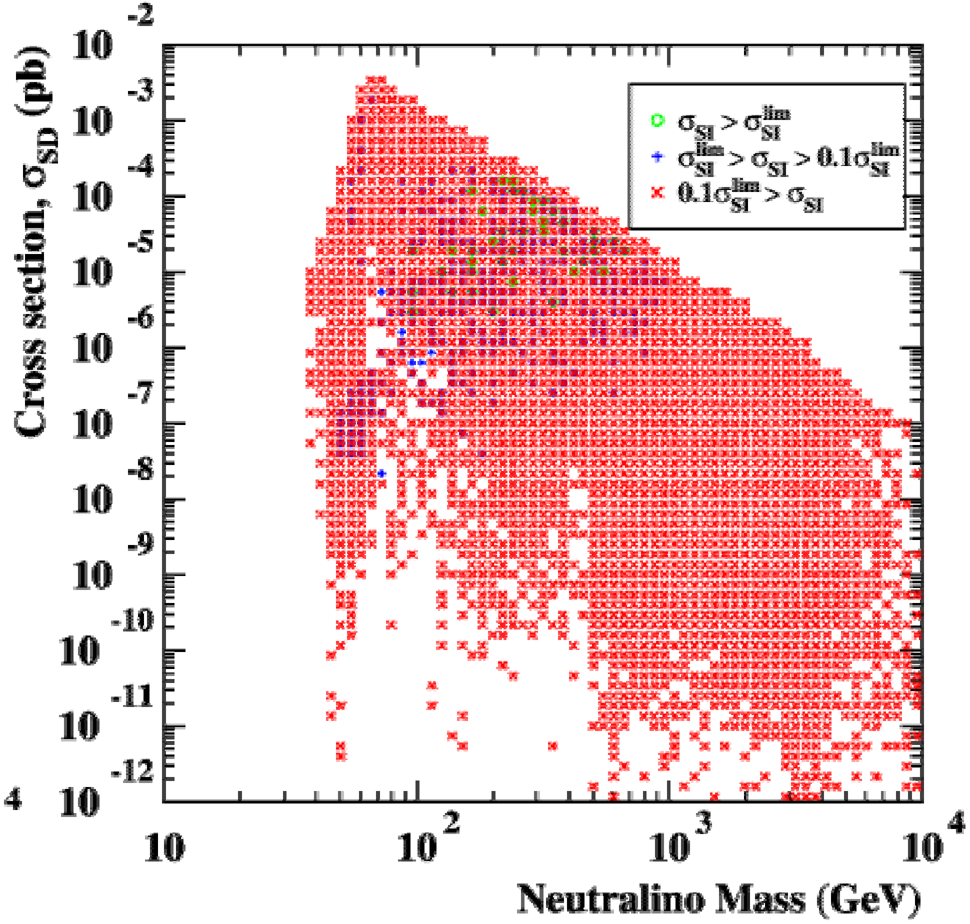
Figures from Jungman, Kamionkowski and Griest,
Phys. Rep. 267 (1996) 195.

Direct detection – current limits

Spin-independent scattering



Spin-dependent scattering



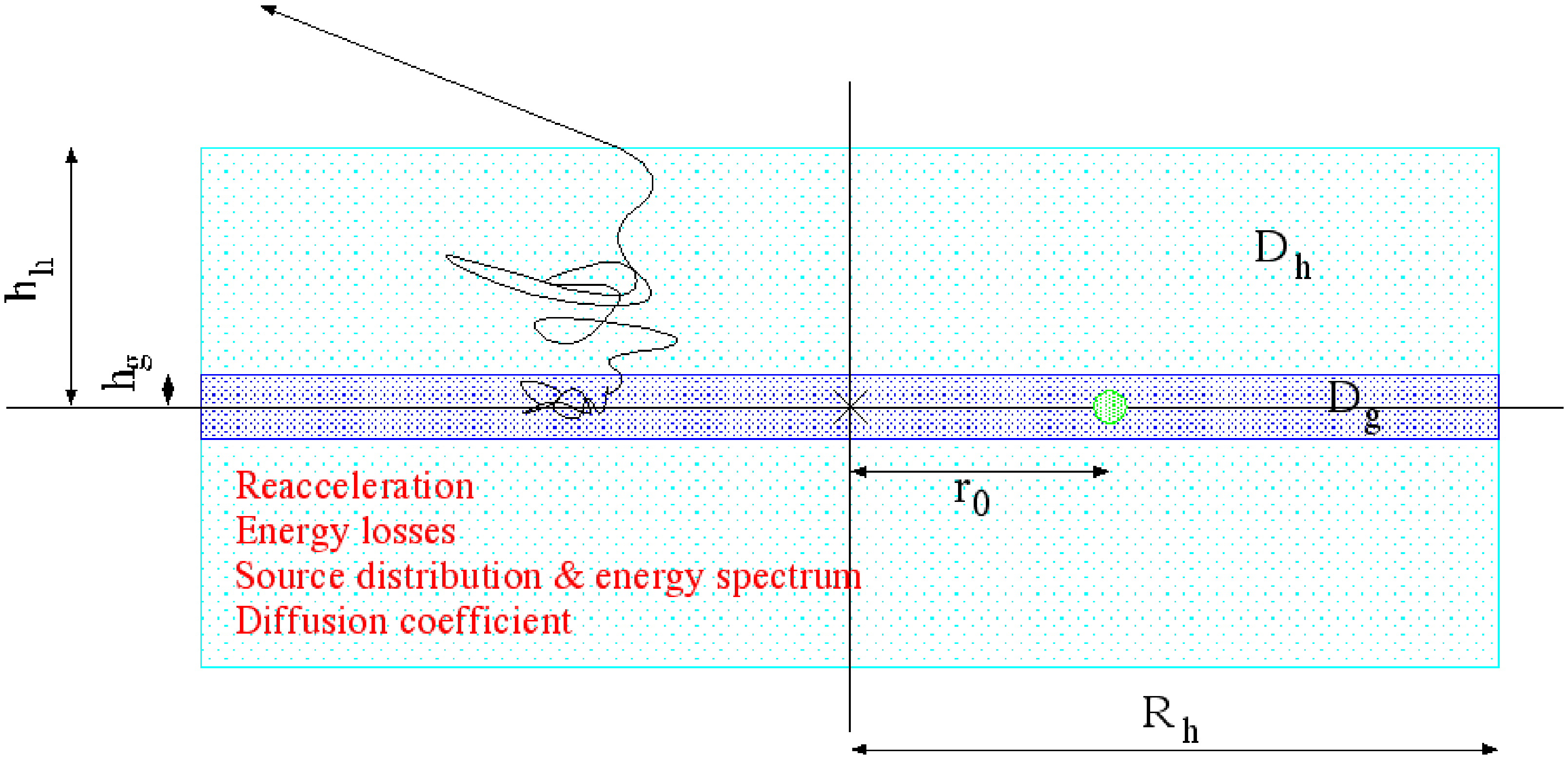
Direct detection experiments have started exploring the MSSM parameter space!

Annihilation in the halo

Neutralinos can annihilate in the halo producing

- antiprotons
- positrons
- gamma rays
- synchrotron radiation (from e^+/e^- in magn. fields)
- neutrinos

Model of the Milky Way



Reacceleration
Energy losses
Source distribution & energy spectrum
Diffusion coefficient

$h_g \approx 0.1$ kpc
$h_h \approx 3$–20 kpc
$r_0 \approx 8.5$ kpc
$R_h \approx 20$ kpc

$D_l \approx D_l^0 (1+R/R_0)^{0.6}$
$D^0 \approx 6\times10^{27}$ cm^2 s^{-1}
$R \approx p/|Z|$
$R_0 \approx 3$ GV

Galaxy model

Propagation model

The diffusion model with free escape at the boundaries

Halo profile

Modified isothermal sphere, Navarro, Frenk and White, Moore et al., etc.

Energy losses

Inelastic scattering gives rise to energy losses (included as a ‘tertiary’ source function for antiprotons).

The diffusion equation

$$\frac{\partial N}{dt} = \underbrace{\left(D(R,\vec{x}) \quad N(E,\vec{x})\right)}_{\text{Diffusion}} - \underbrace{\left(\vec{u}(\vec{x})N(E,\vec{x})\right)}_{\text{Galactic wind}} - \underbrace{\frac{\partial}{\partial E}\left[b(E,\vec{x})N(E,\vec{x})\right]}_{\text{Energy loss}} + \underbrace{Q(E,\vec{x})}_{\text{Source}}$$

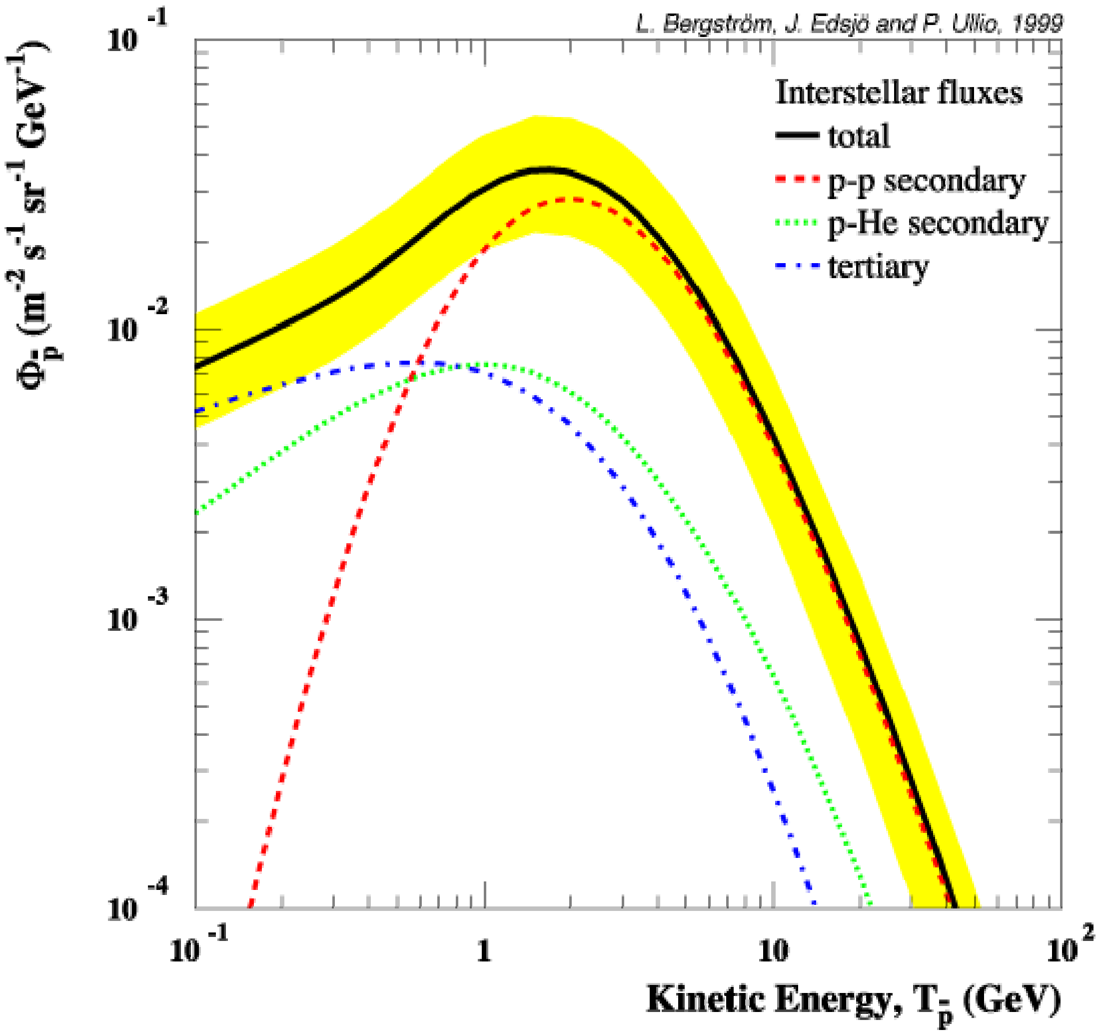
$R \quad = \quad \frac{p}{|Z|}$ = Rigidity

$N(E,\vec{x}) \quad = \quad$ particle density

$\frac{\partial N}{\partial t} = 0$ for stationary solution

The diffusion, galaxy and energy loss parameters are derived from cosmic ray studies.

Antiproton background


L. Bergström, J. Edsjö and P. Ullio, 1999

Background antiprotons are produced when cosmic rays hit the interstellar medium:

$$p + p \rightarrow \bar{p} + p + p + p$$

$$E_{th} \approx 7 m_p$$

Naively, the background below 1 GeV would be very small, but...

- energy losses
- p-He interactions
- reacceleration

are all important.

Antiproton signal from neutralinos

Antiproton source function

$$Q_{\bar{p}}(T,\vec{x}) = (\sigma_{ann} v)\left(\frac{\rho_{\chi}(\vec{x})}{m_{\chi}}\right)^{2} \sum_{f} B_{f} \frac{dN_{f}}{dT}$$

Put into the diffusion equation taking the galaxy model into account.

$$\Downarrow$$

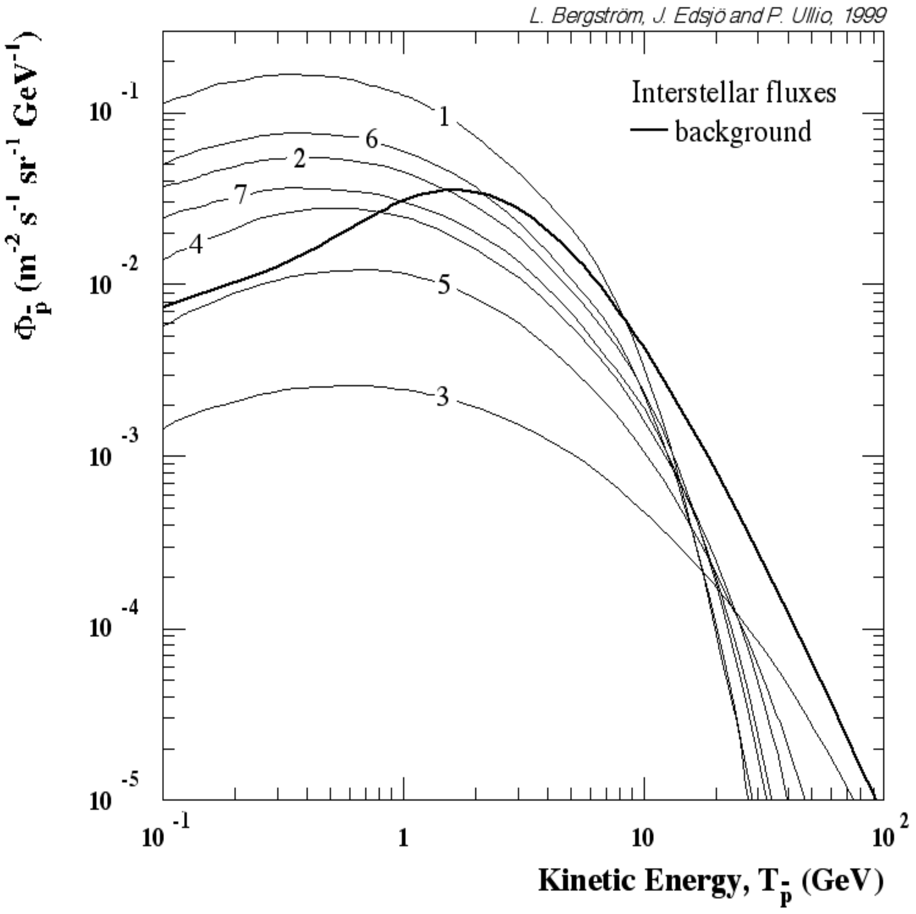
$$\Phi_{\bar{p}}^{\text{interstellar}}(T_{\bar{p}})$$

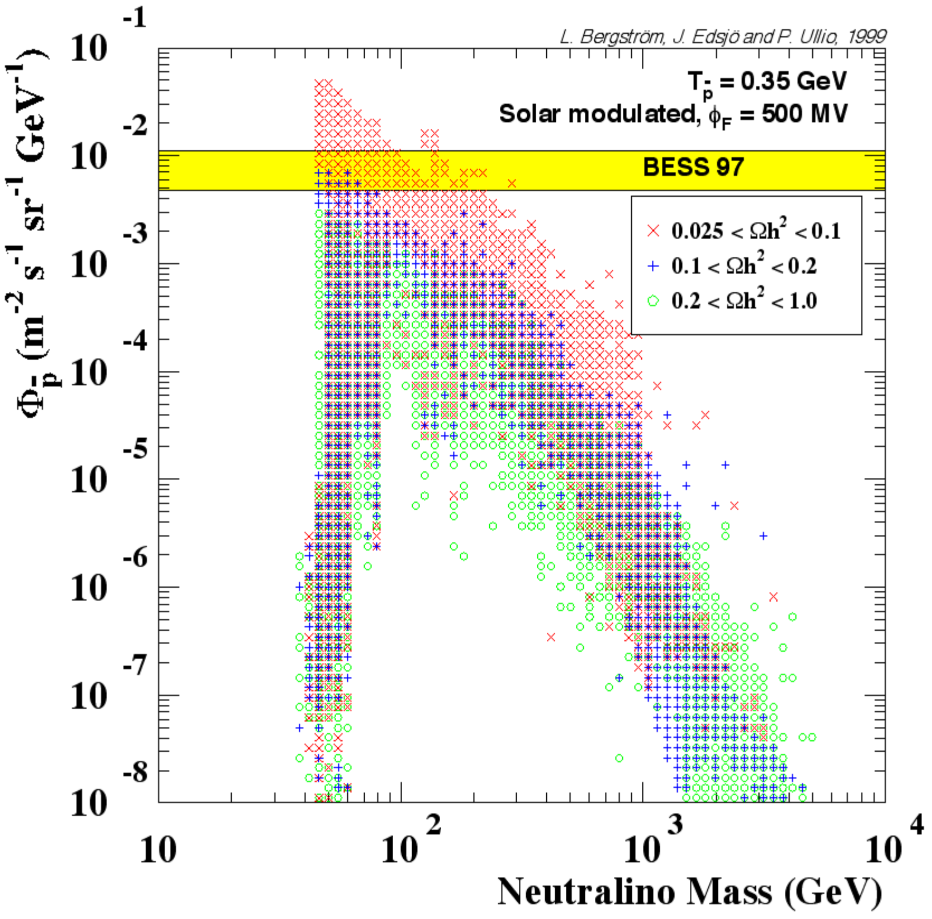
The antiprotons meet the solar wind. Take this modulation into account.

$$\Downarrow$$

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

Antiproton signal

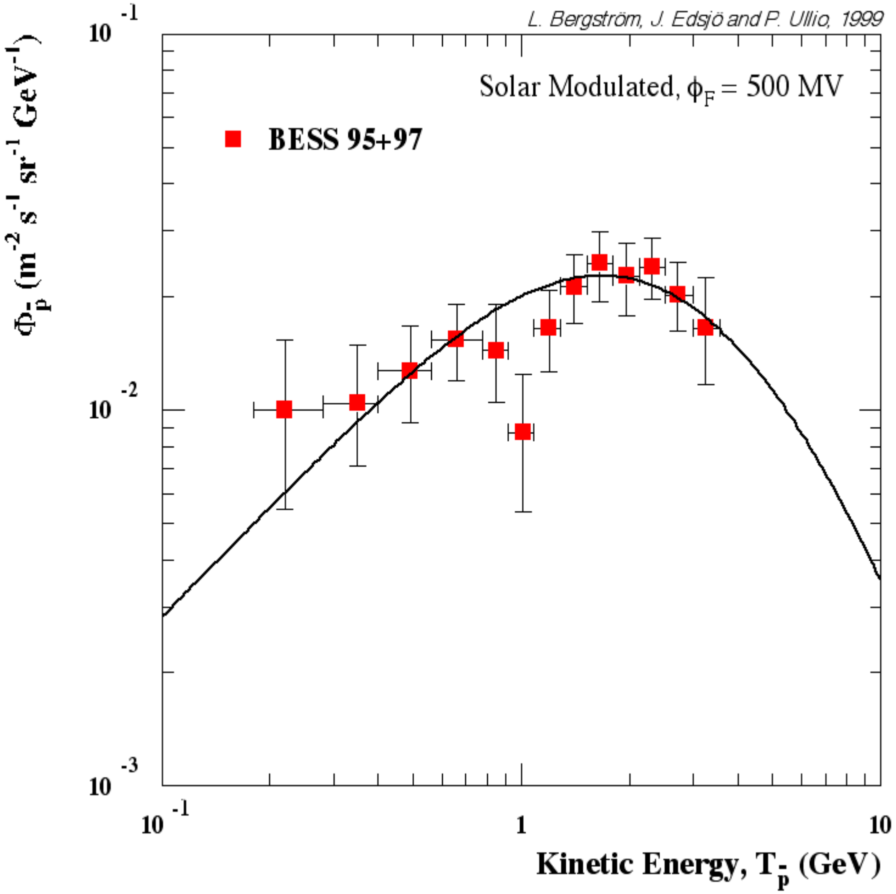




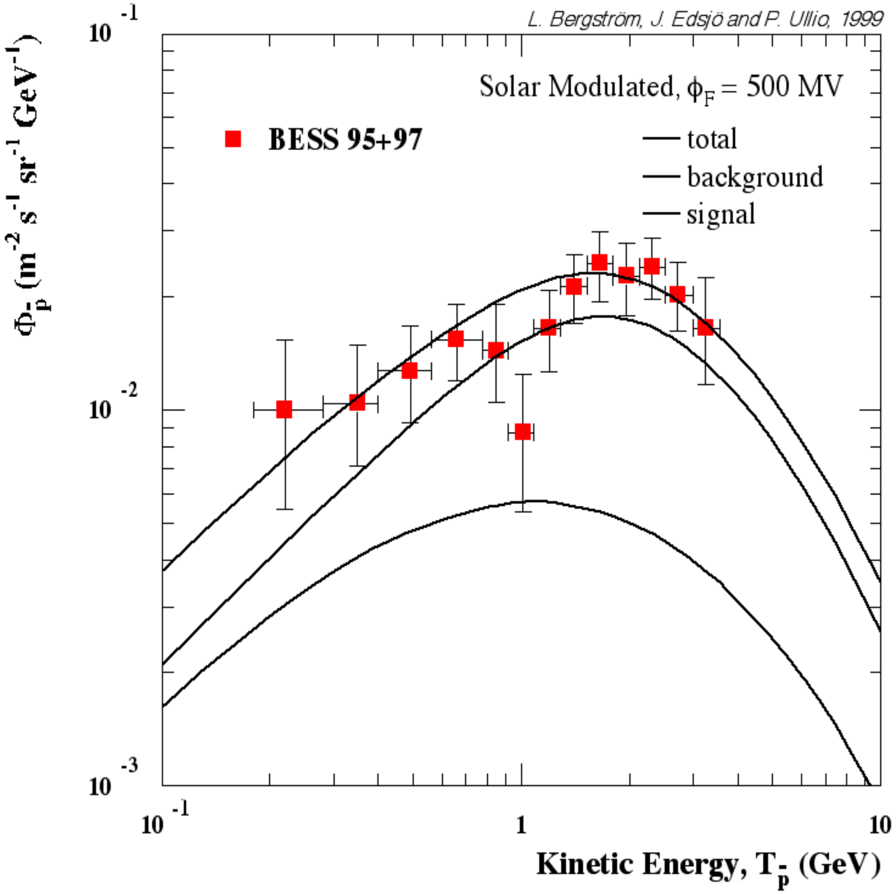
Easy to get high fluxes, but...

Antiprotons – fits to Bess data

Background only



Background + signal



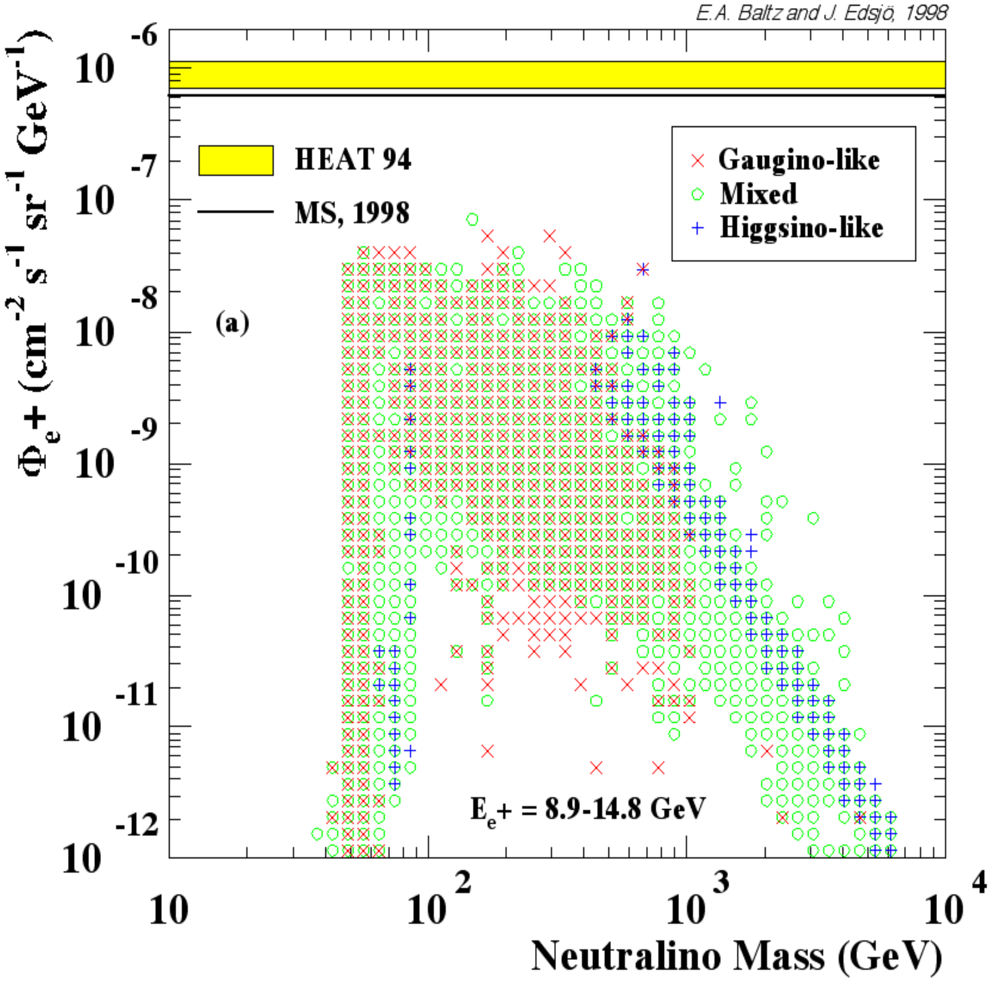
⇒ No need for, but room for a signal.

Positron fluxes from neutralinos

Compared to antiprotons,

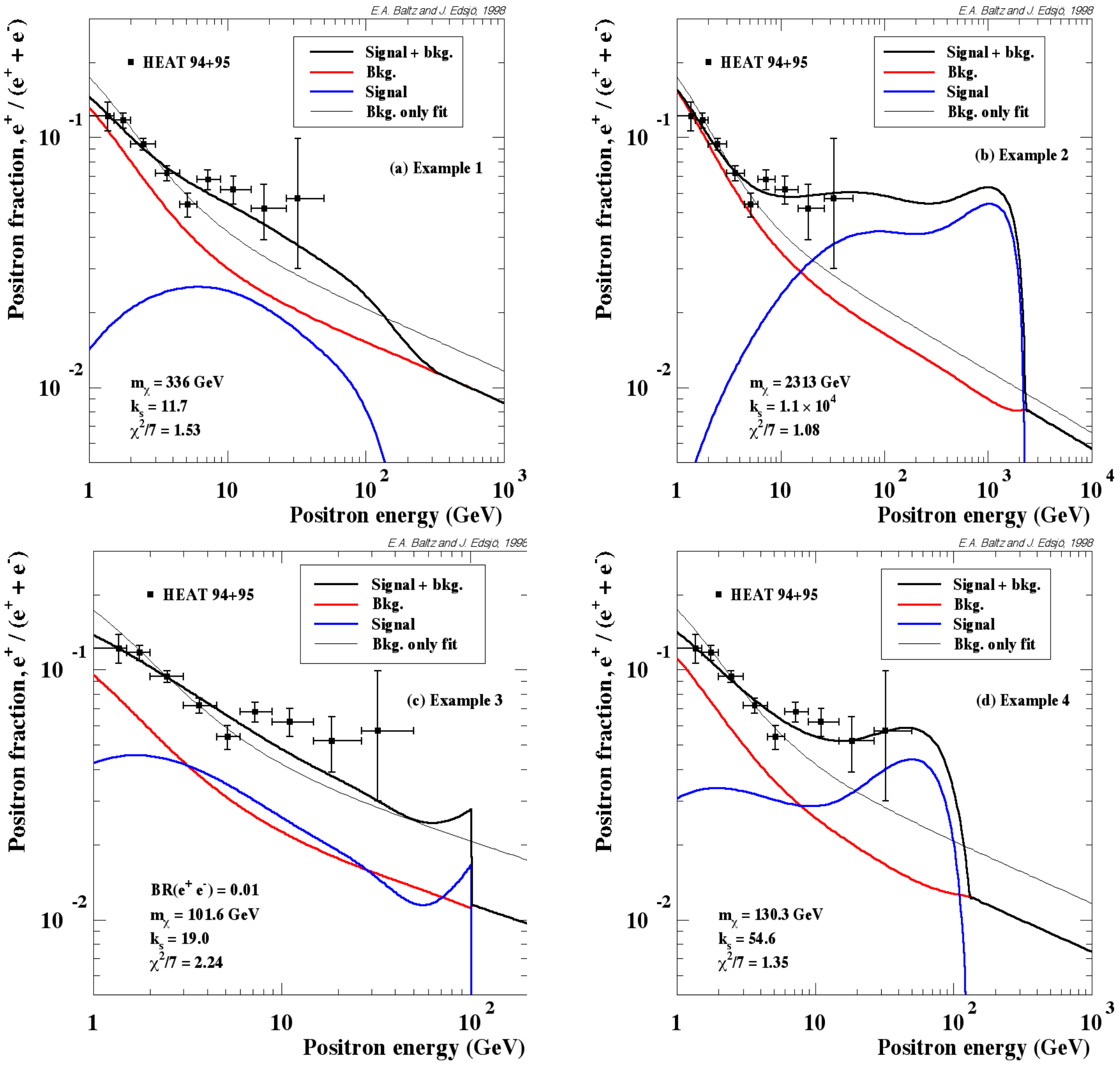
- energy losses are much more important
- essentially only local halo properties are important
- higher energies due to more prompt annihilation channels (ZZ, W^+W^-, etc)
- propagation uncertainties are higher
- solar modulation uncertainties are higher

Positrons – signal fluxes



Compared to antiprotons, the fluxes are typically lower (except at high masses), but...

Positrons – example spectra



...the positron spectra can have features that could be detected!

The signal strength needs to be boosted, e.g. by clumps, though.

Gamma lines

At one-loop, neutralinos can annihilate to

$$\gamma\gamma \qquad E_\gamma = m_\chi$$

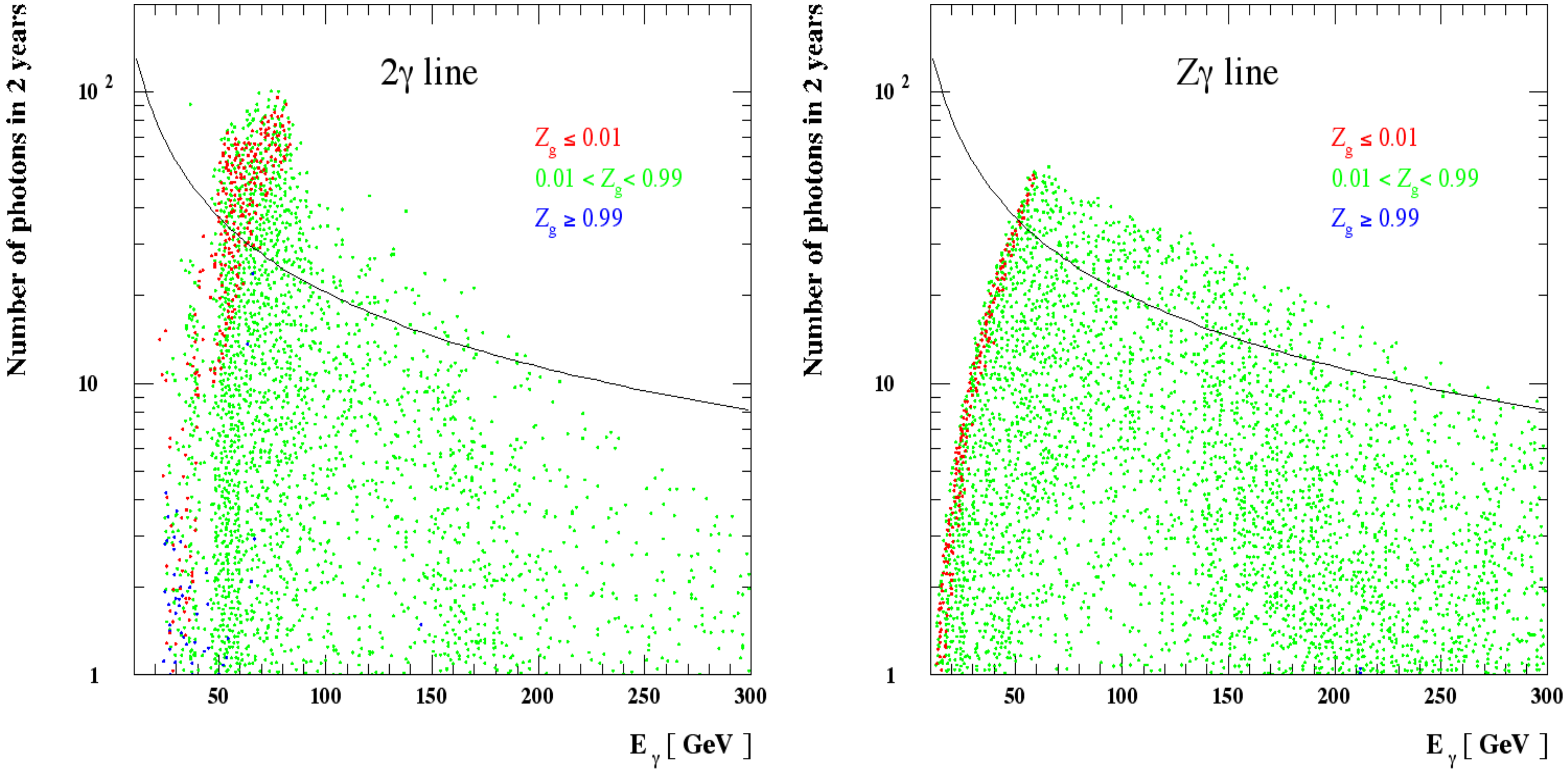
$$Z\gamma \qquad E_\gamma = m_\chi - \frac{m_Z^2}{4m_\chi}$$

i.e. *monochromatic* gamma rays.

Features of monochromatic gamma rays:

- they keep their direction – no propagation uncertainties
- the fluxes are generally low, but the signature is very clear
- the flux (especially towards the galactic center) depends strongly on the halo profile

Gamma lines – rates in GLAST



Continuum gamma rays

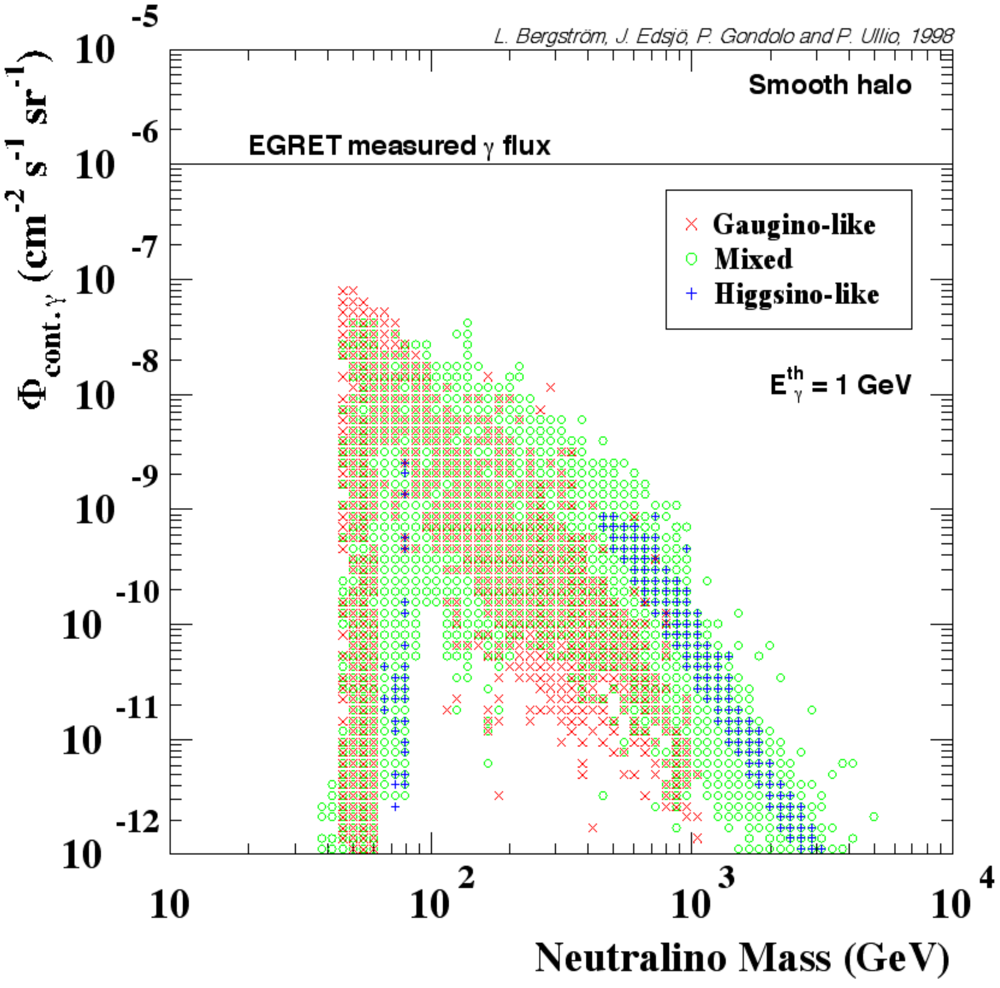
From final state jets, we also get continuum γ rays:

$$\chi\chi \rightarrow \cdots \rightarrow \pi^0 \rightarrow \gamma\gamma$$

Features compared to gamma lines:

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

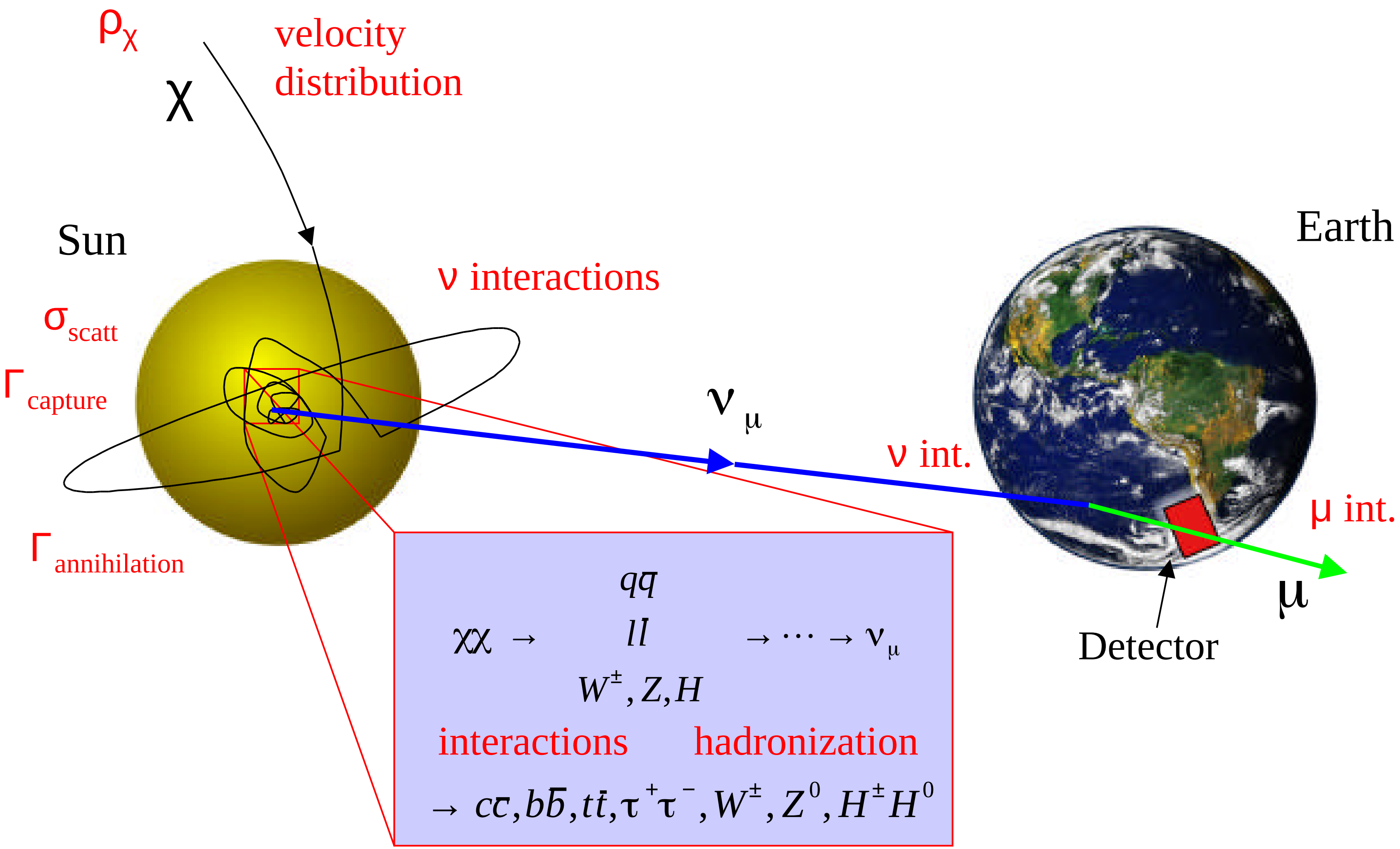
Continuum gammas – fluxes



Flux at high galactic latitudes

small halo profile dependence

Neutralino capture and annihilation

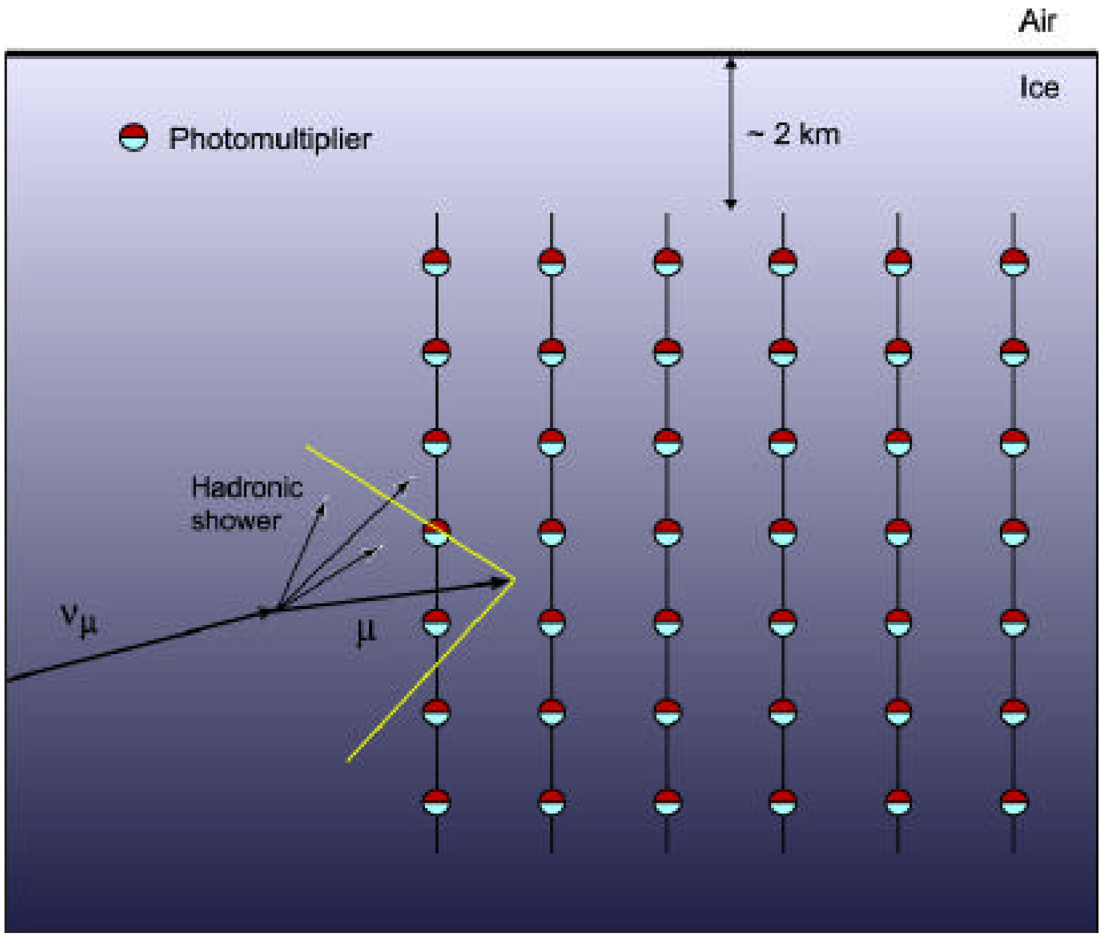


$$\chi\chi \to \begin{matrix} q\bar{q} \\ l\bar{l} \\ W^\pm, Z, H \end{matrix} \to \cdots \to \nu_\mu$$

interactions hadronization

$$\to c\bar{c}, b\bar{b}, t\bar{t}, \tau^+\tau^-, W^\pm, Z^0, H^\pm H^0$$

Neutrino telescopes – how do they work?



- The neutrino interacts with a nucleus in the ice and creates a muon.
- The muon emits *Cherenkov radiation*.
- The radiation is recorded by photomultipliers and the muon track can be reconstructed.

Neutrino telescopes

Capture and annihilation

Evolution equation

$$\frac{dN}{dt} = C - C_A N^2 - C_E N$$

Capture Annihilation Evaporation (negligible)

Solution

$$\Gamma_A = \frac{1}{2} C \tanh^2 \frac{t}{\tau}$$

$$\tau = \frac{1}{\sqrt{C C_A}}$$

Dependencies

C – f(v), ρ_χ, σ_{scatt}, composition of Earth/Sun

C_A – σ_{ann}, $\rho(r)$ in Earth/Sun

Neutrino telescopes – Capture

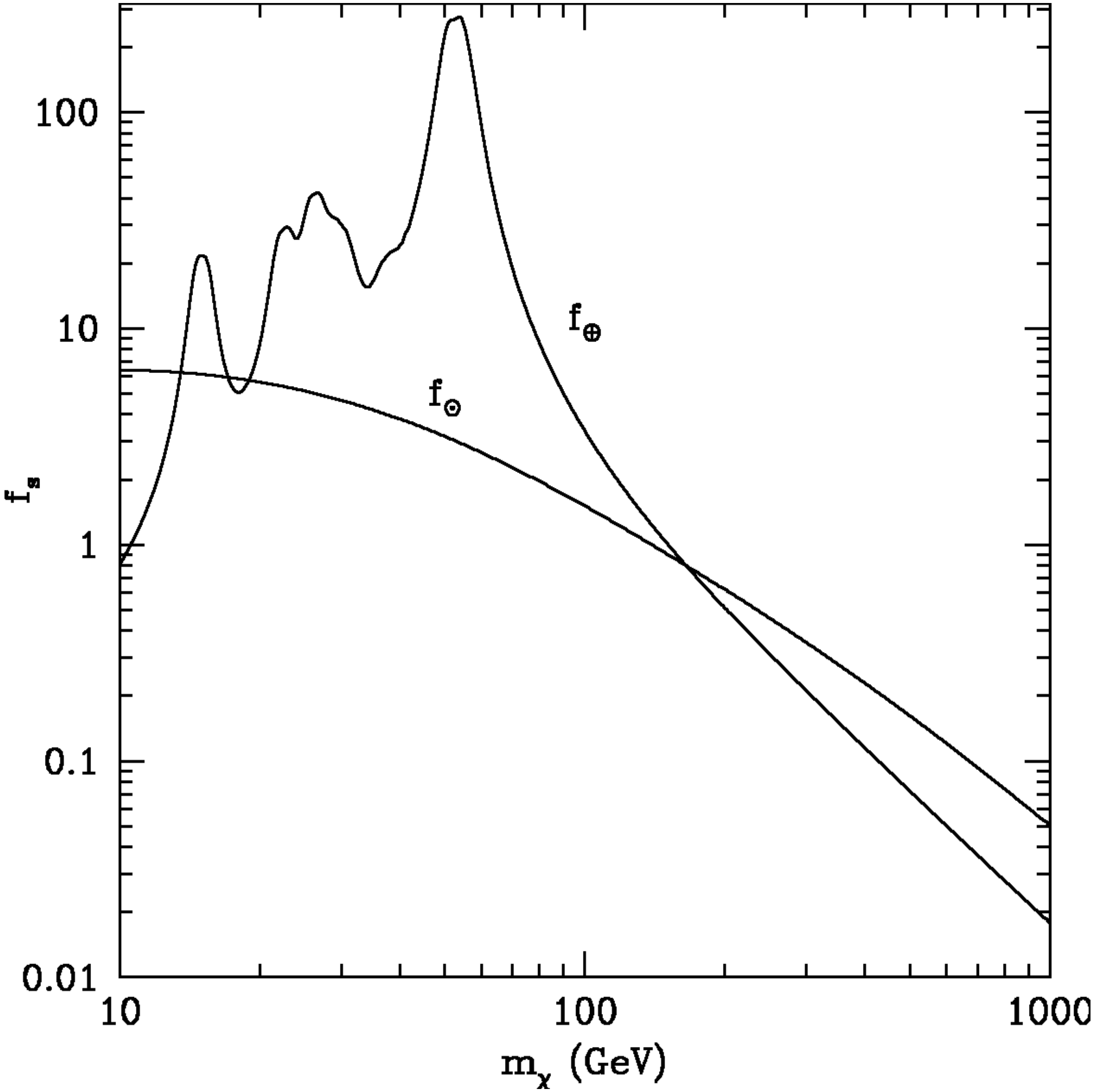


Figure from Jungman, Kamionkowski and Griest, Phys. Rep. 267 (1996) 195.

Capture in Sun

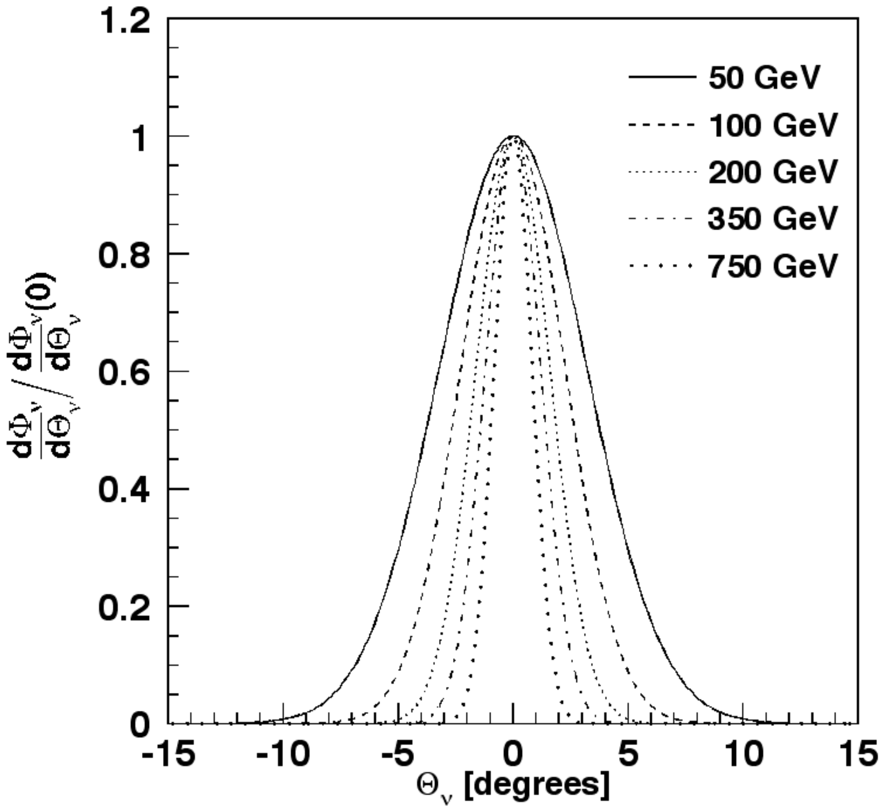
- Mostly on Hydrogen
- Both spin-independent and spin-dependent scattering.

Capture in Earth

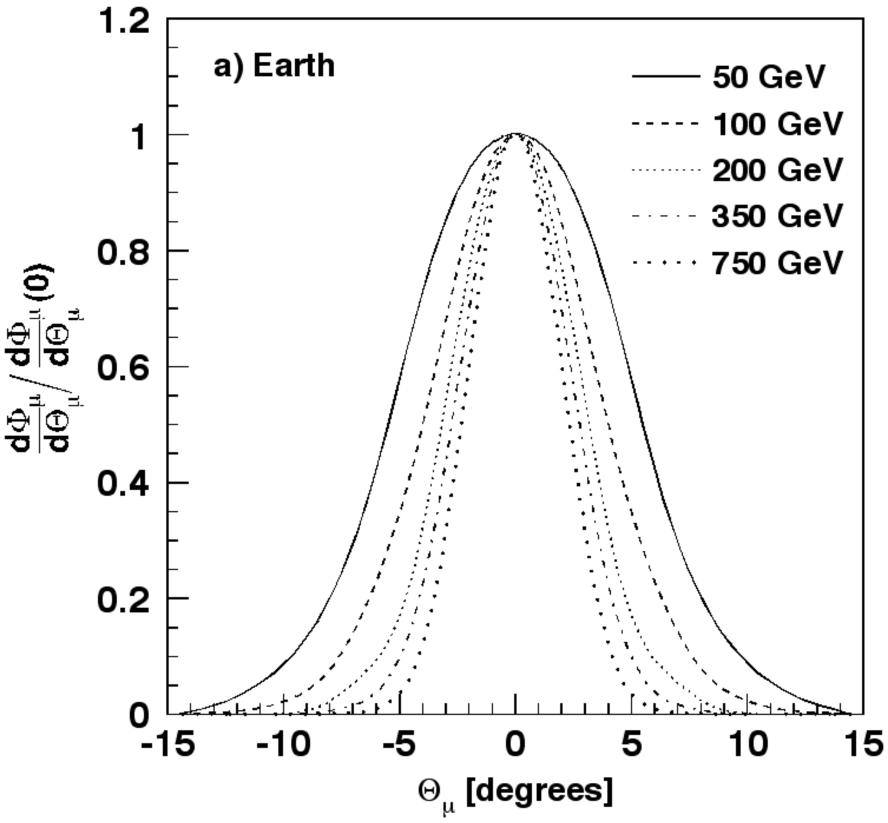
- Mostly on Iron
- Essentially only spin-independent scattering.
- Resonant scattering when the mass matches Iron.

Angular Spread of WIMP signal – Earth

Neutrinos



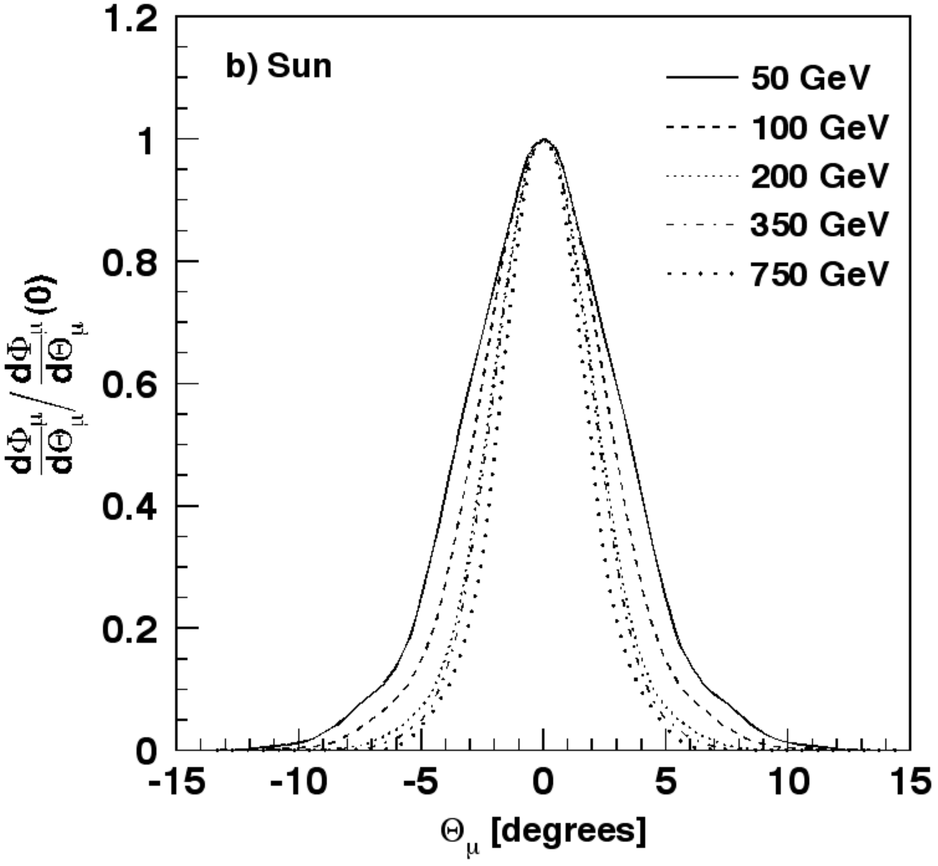
Neutrino-induced muons



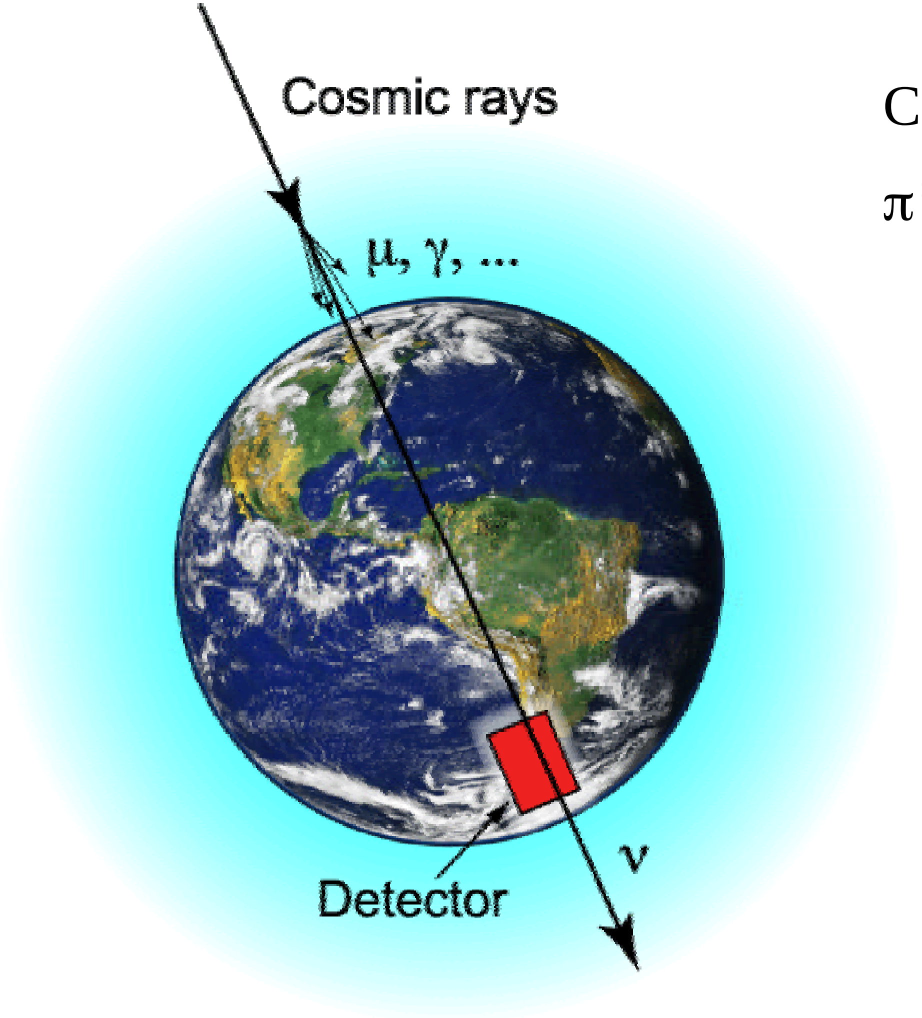
Angular Spread of WIMP signal – Sun

The angular spread decreases with increasing WIMP mass, making it easier to discriminate against the background of atmospheric neutrinos.

Neutrino-induced muons



Neutrinos and muons from the Earth’s atmosphere



$$\text{Cosmic rays} + \text{atmosphere} \rightarrow \pi, K, \ldots$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\downarrow$$

$$e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

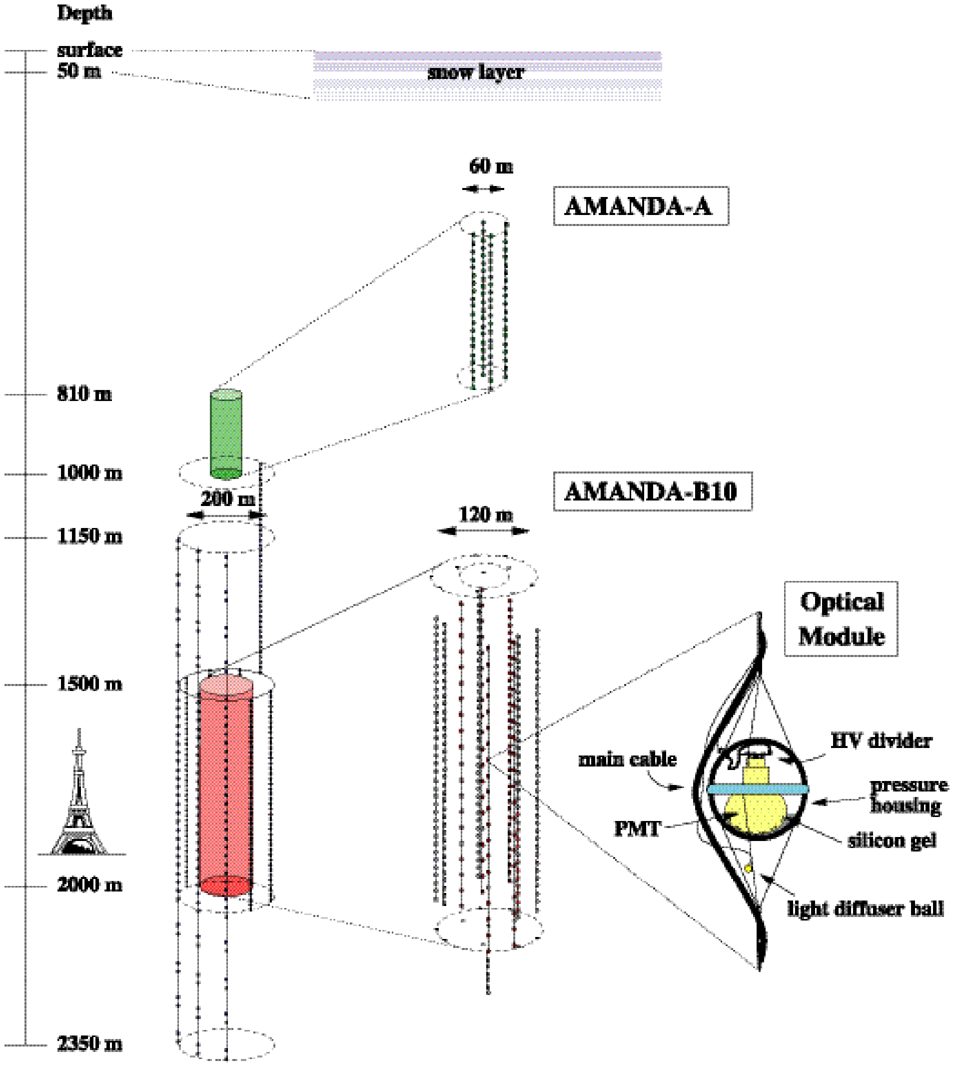
Use the Earth as a **filter** by looking for upgoing muons.

Only atmospheric neutrinos remain as a background.

Searches for neutrinos from WIMPs

- IMB
- Macro
- Baksan
- Kamiokande, Super-Kamiokande
- Amanda, ICE^3
- Antares
- ...

The Amanda detector

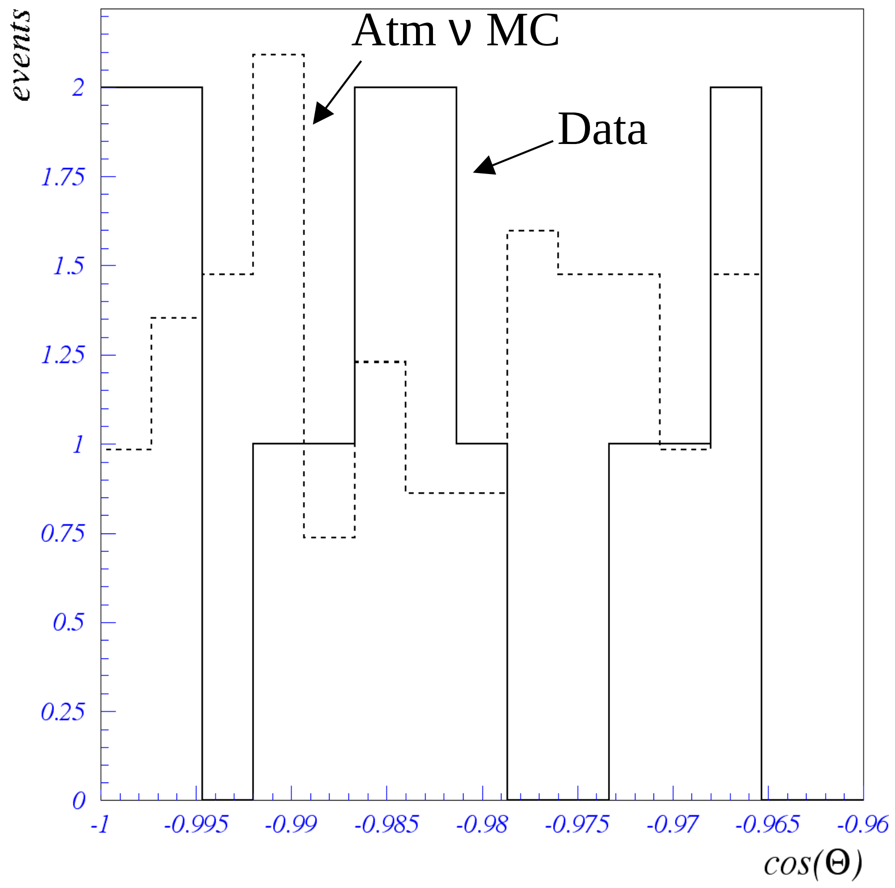


AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

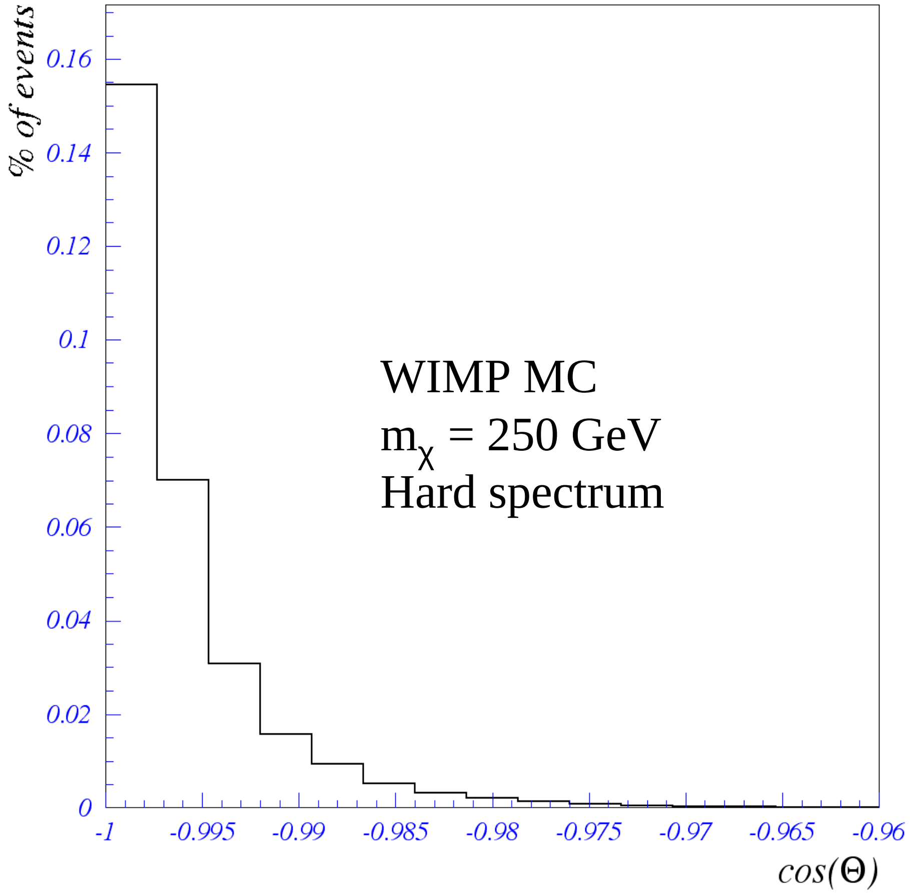
zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

Event distributions
Amanda B10, 1997 years data

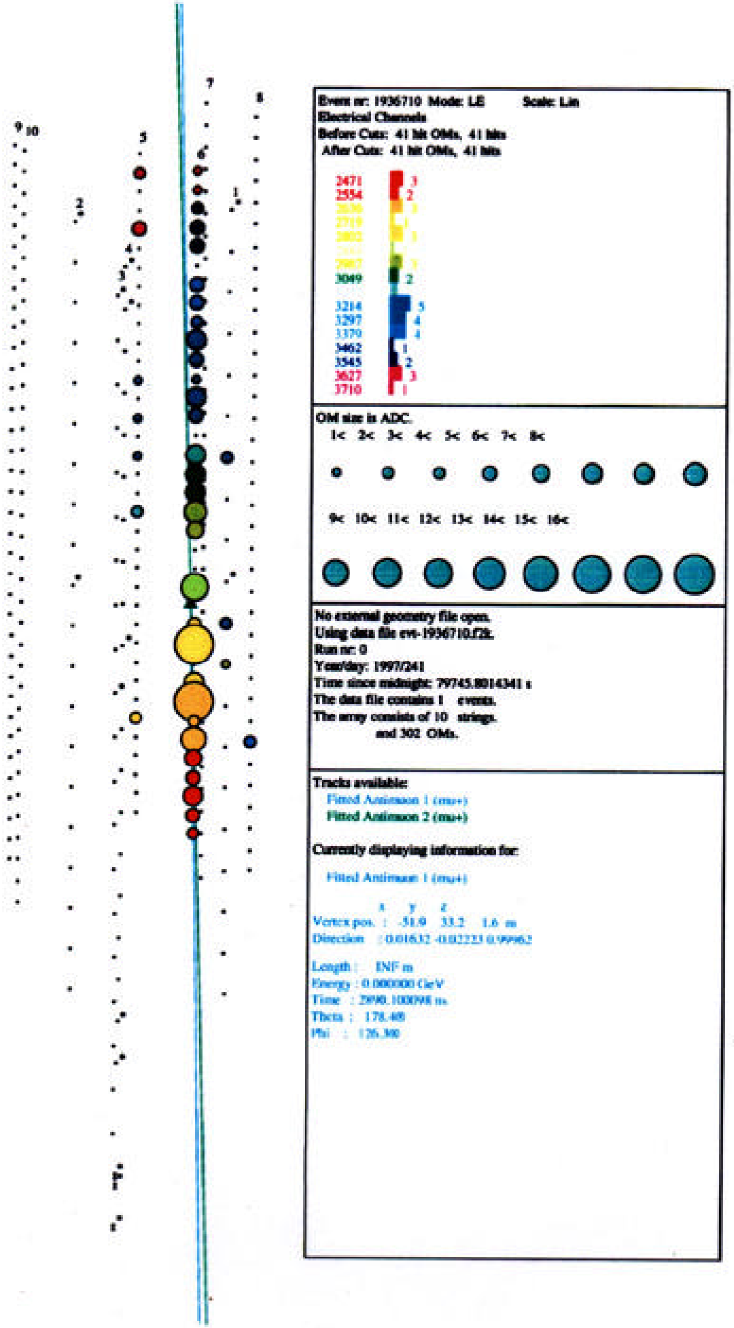

Atm ν MC

Data


WIMP MC
m_χ = 250 GeV
Hard spectrum

AMANDA
ν-candidate

- Early photons are red, late photons are blue. More photons are larger circles.
- Bottom of array is towards center of the Earth.
- The muon is clearly traveling in the upward direction.

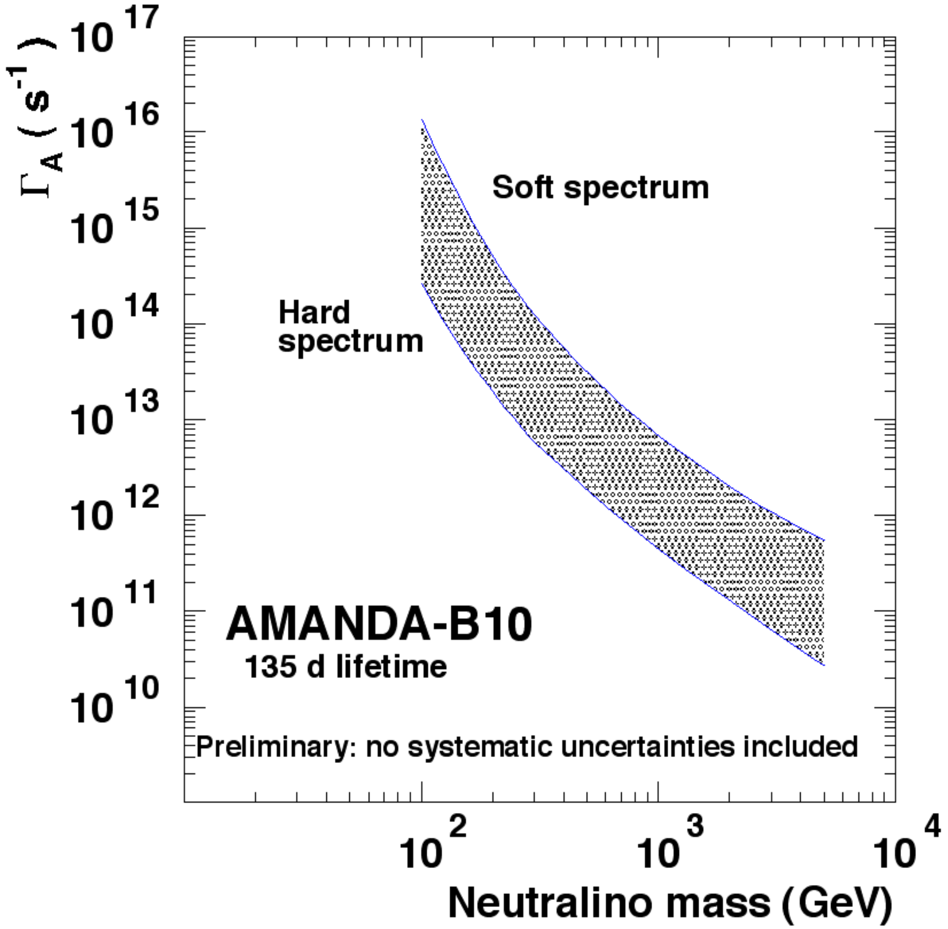


```
Event nr: 1936710  Mode: LE        Scale: Lin
Electrical Channels
Before Cuts:  41 hit OMs,  41 hits
 After Cuts:  41 hit OMs,  41 hits

No external geometry file open.
Using data file evt-1936710.f2k.
Run nr: 0
Year/day: 1997/241
Time since midnight: 79745.8014341 s
The data file contains 1    events.
The array consists of 10   strings.
              and 302  OMs.

Tracks available:
   Fitted Antimuon 1 (mu+)
   Fitted Antimuon 2 (mu+)

Currently displaying information for:

   Fitted Antimuon 1 (mu+)

                x       y       z
Vertex pos.  :  -31.9    33.2    1.6  m
Direction    : 0.01632 -0.02223 0.99962

Length :    INF m
Energy : 0.000000 GeV
Time   : 2990.100098 ns
Theta  :   178.48
Phi    :   126.30
```

Limits: Annihilation rate

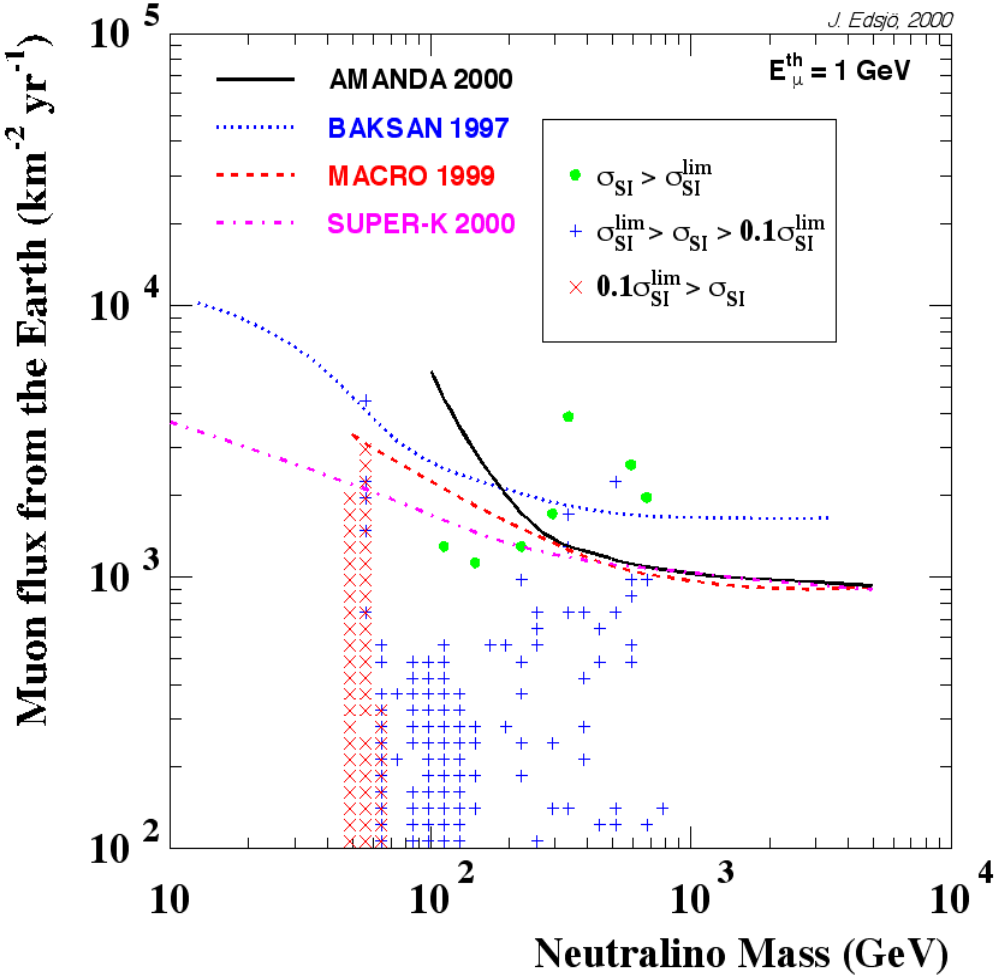
- Derived limits on the annihilation rate in the center of the Earth.

- **Preliminary:** systematic uncertainties are not included.



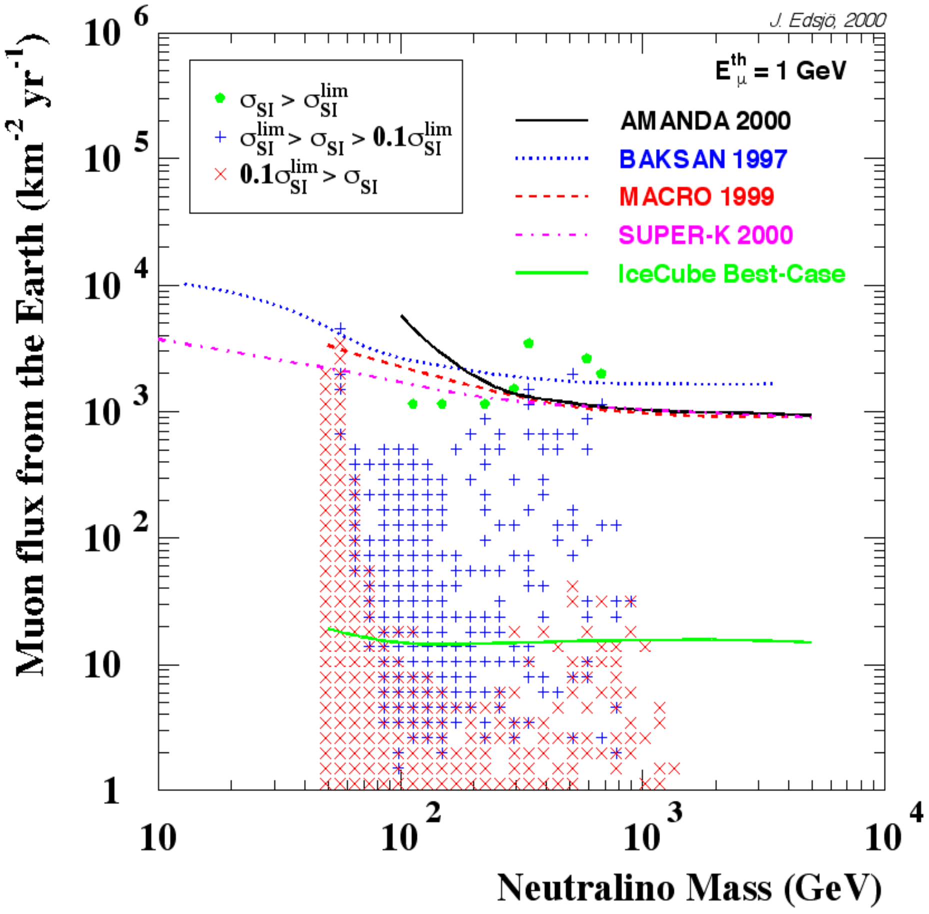
Limits: μ flux from the Earth

- AMANDA limits comparable to MACRO, Baksan and Super-Kamiokande.
- **Preliminary:** systematic uncertainties are not included.

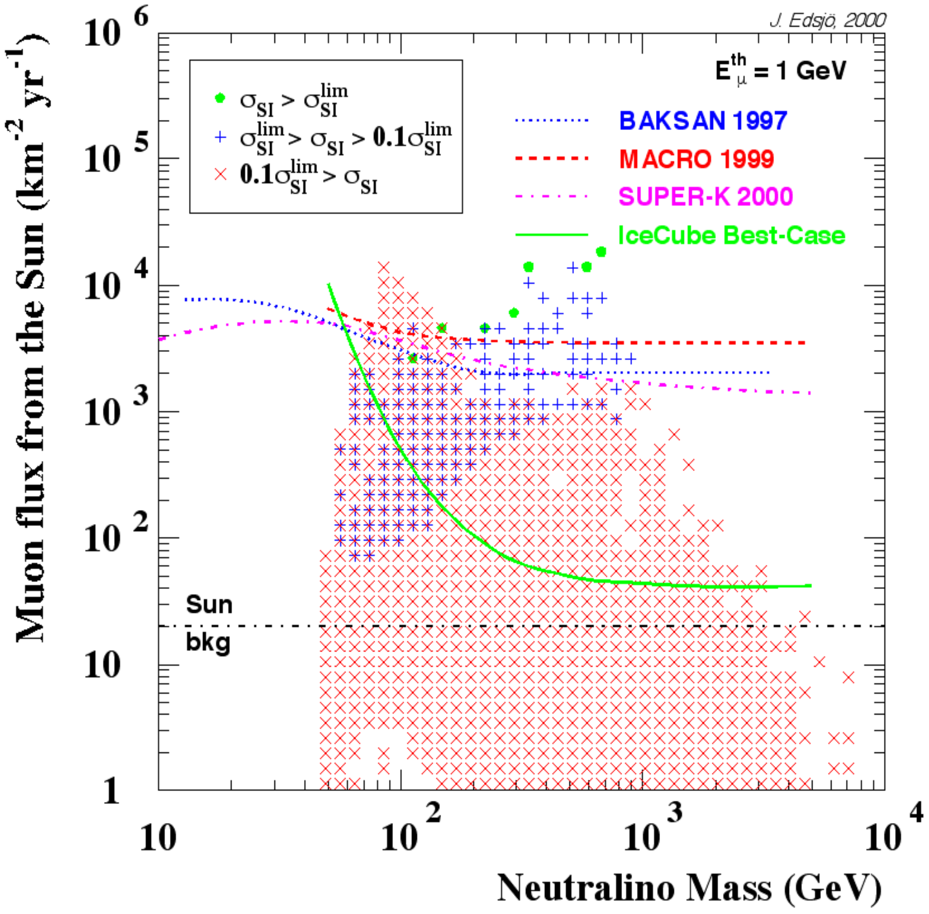


Predicted fluxes and searches

Earth



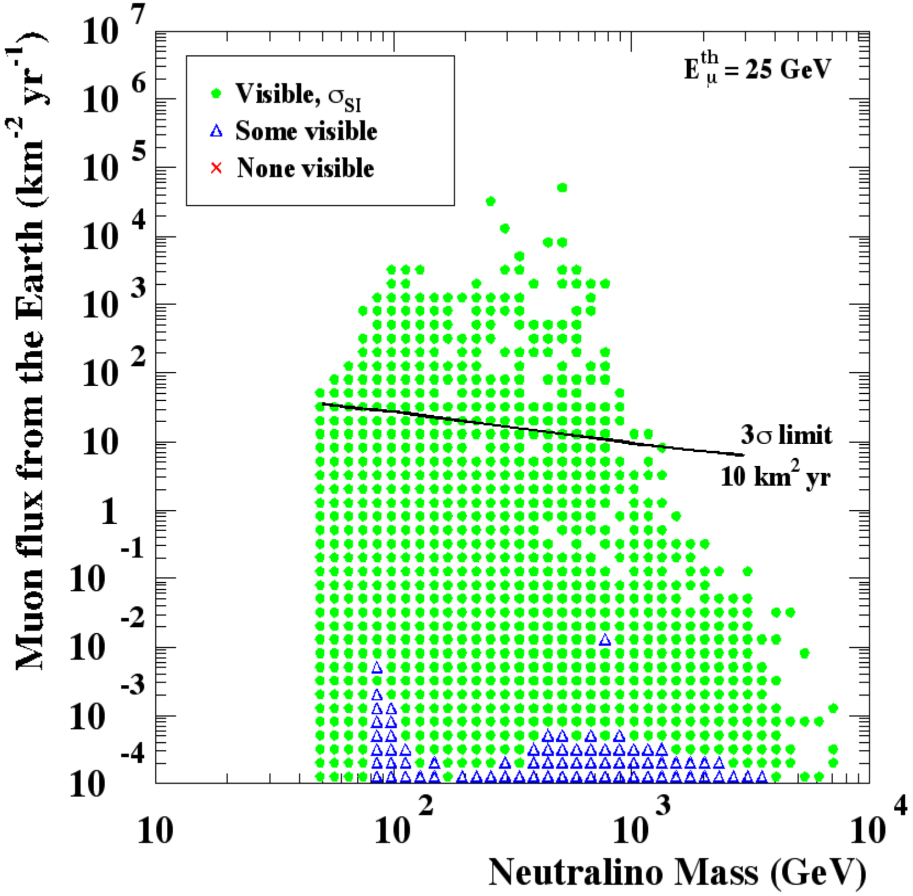
Sun



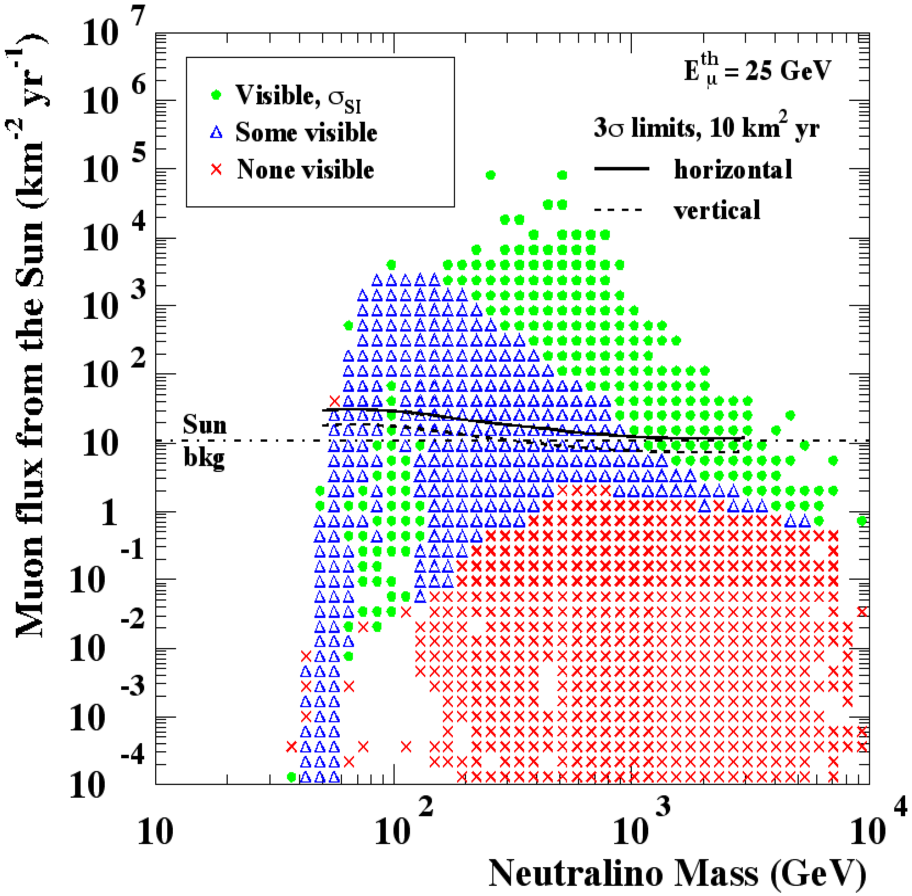
Neutrino telescopes have started exploring the MSSM parameter space!

Flux from Earth/Sun and future GENIUS/CRESST limits

Earth



Sun



Comparing different searches

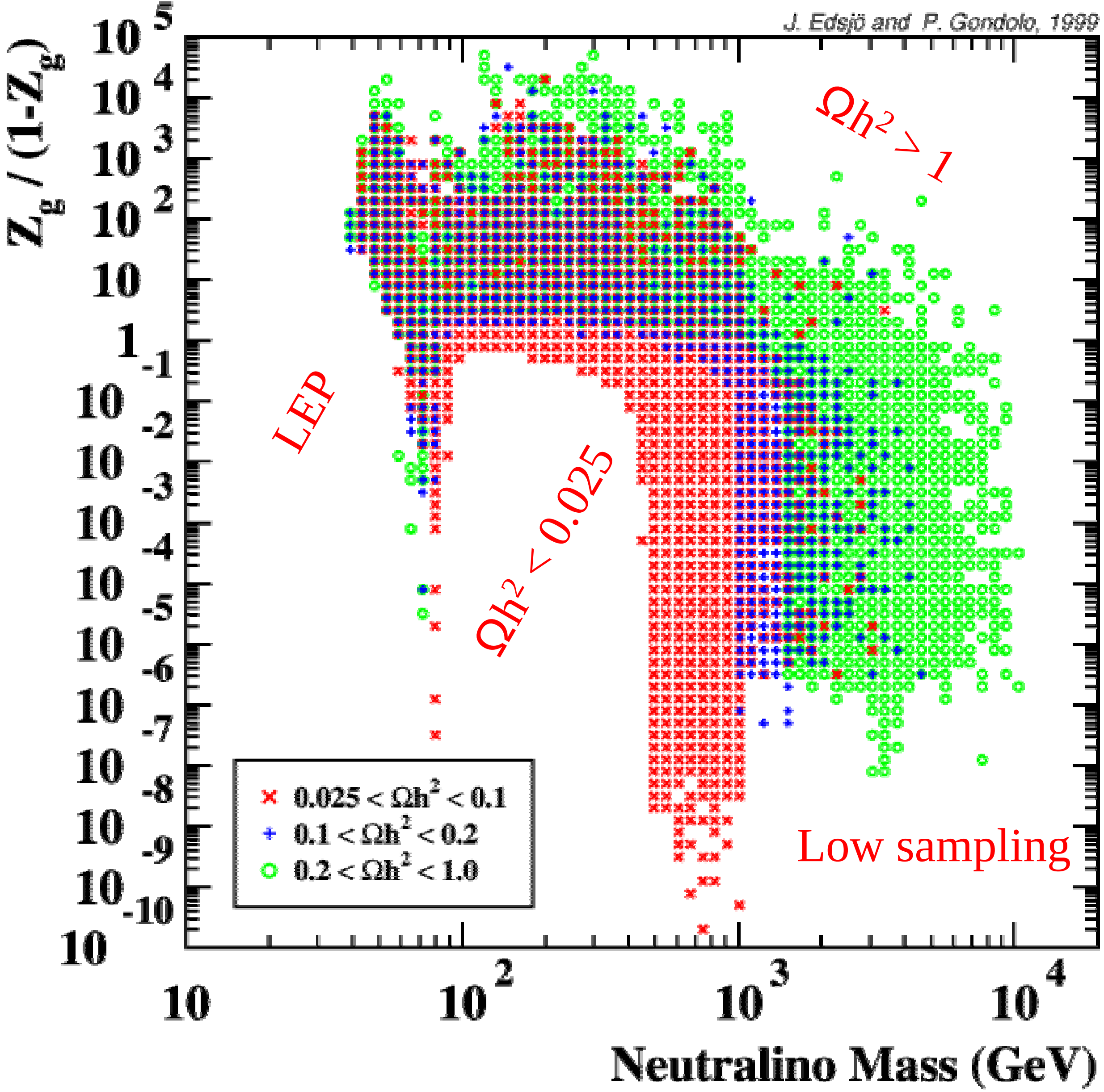
- Take all future searches with expected sensitivities within the coming 5–10 years.
- Determine which areas in the m_χ-Z_g parameter space they can explore.
- Compare!

The m_χ-Z_g parameter space

Gauginos

Mixed

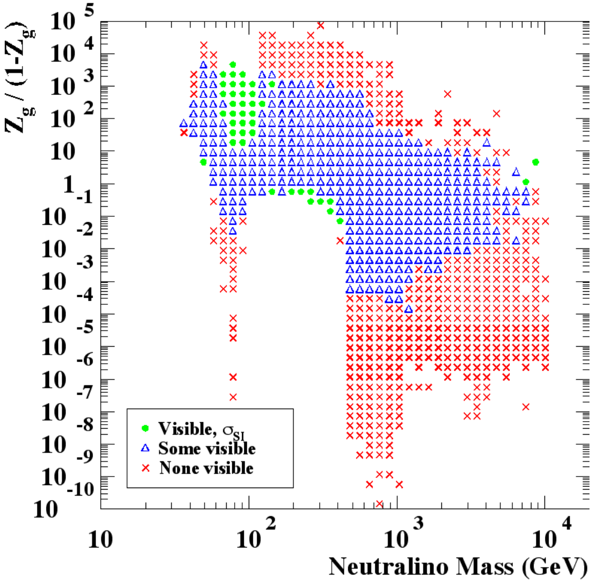
Higgsinos



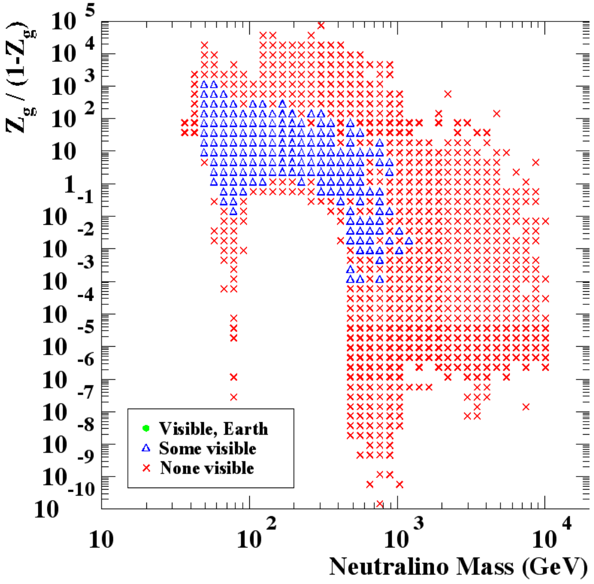
MSSM parameter space

Future probed regions I

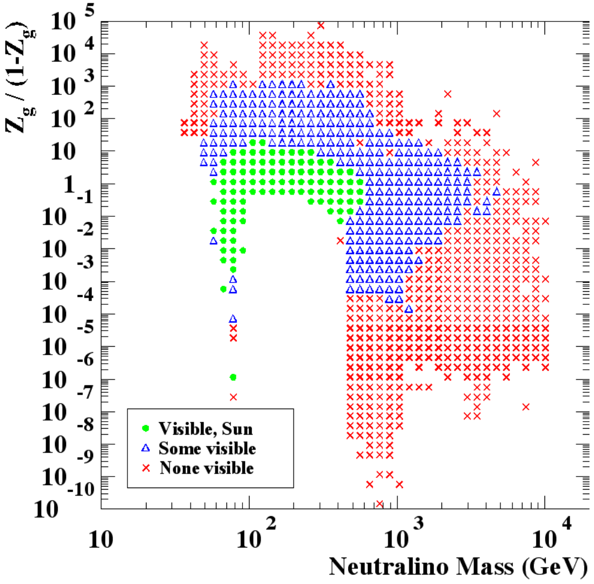
Direct detection
Genius/Cresst



Earth, km^3

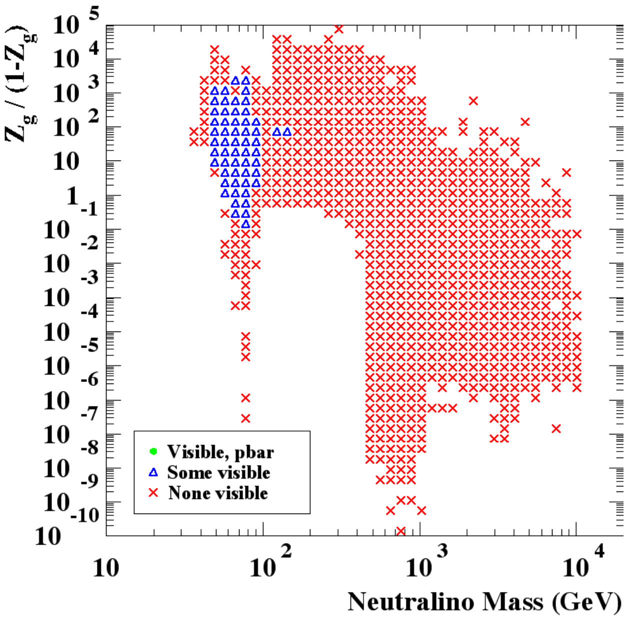


Sun, km^3

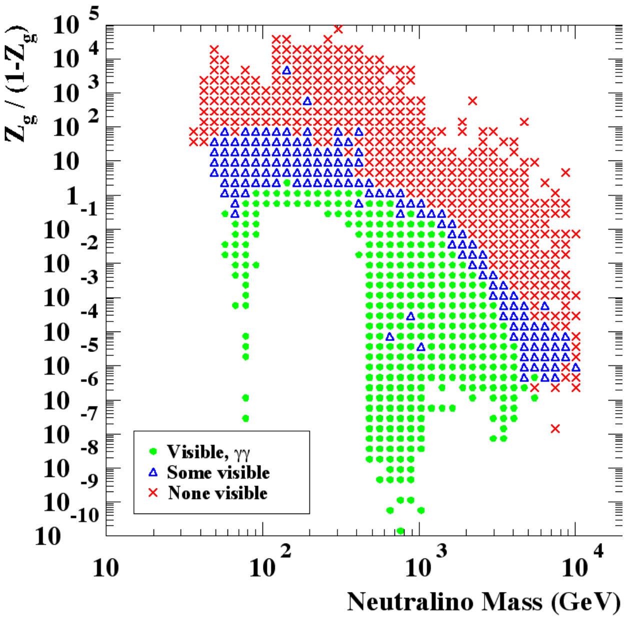


MSSM parameter space
Future probed regions II

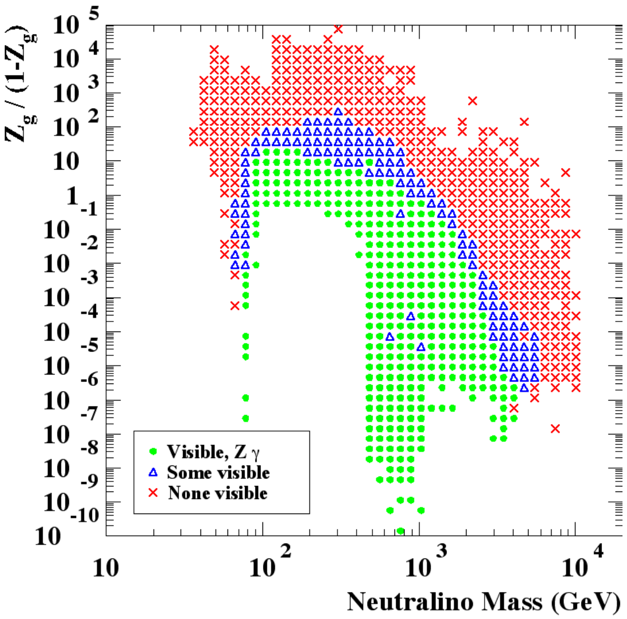
Antiprotons



γγ

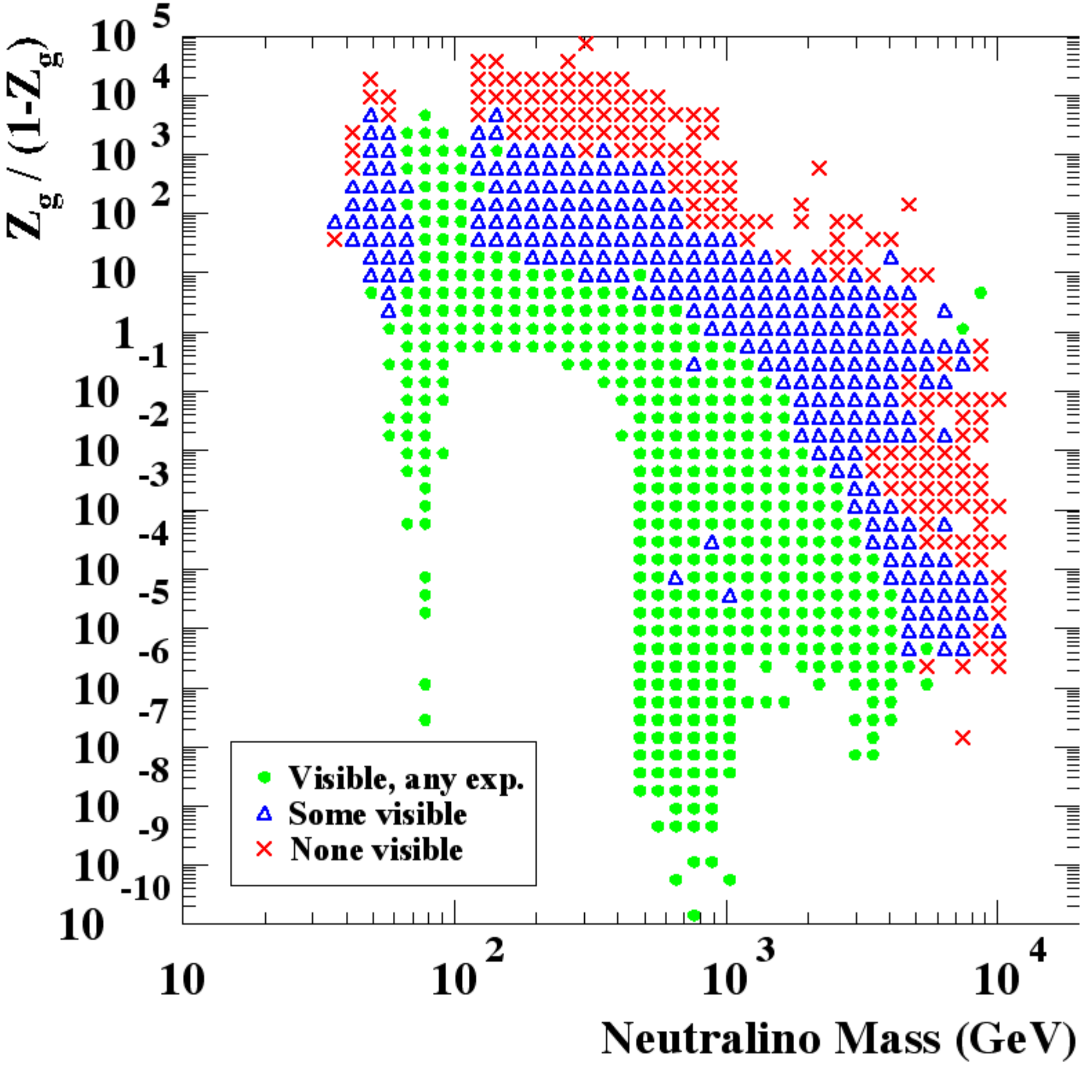


Zγ



MSSM parameter space

All dark matter searches combined



Large parts of the parameter space can be probed by future searches.

Conclusions

- The neutralino is a natural WIMP dark matter candidate.
- The rates (direct and indirect) in many different experiments can be high and sometimes have a nice feature to be distinguished from the background.
- Several experiments have started exploring the MSSM parameter space.

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