

Indirect astrophysical searches for WIMPs

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Outline

- Weakly Interacting Massive Particles (WIMPs) as dark matter candidates
- Neutralinos as a WIMP candidate
- Ways to search for WIMPs
- Comparison of different search strategies

Relic density

simple approach (more advanced in real life)

Decoupling occurs when

$$\Gamma < H$$

We have that

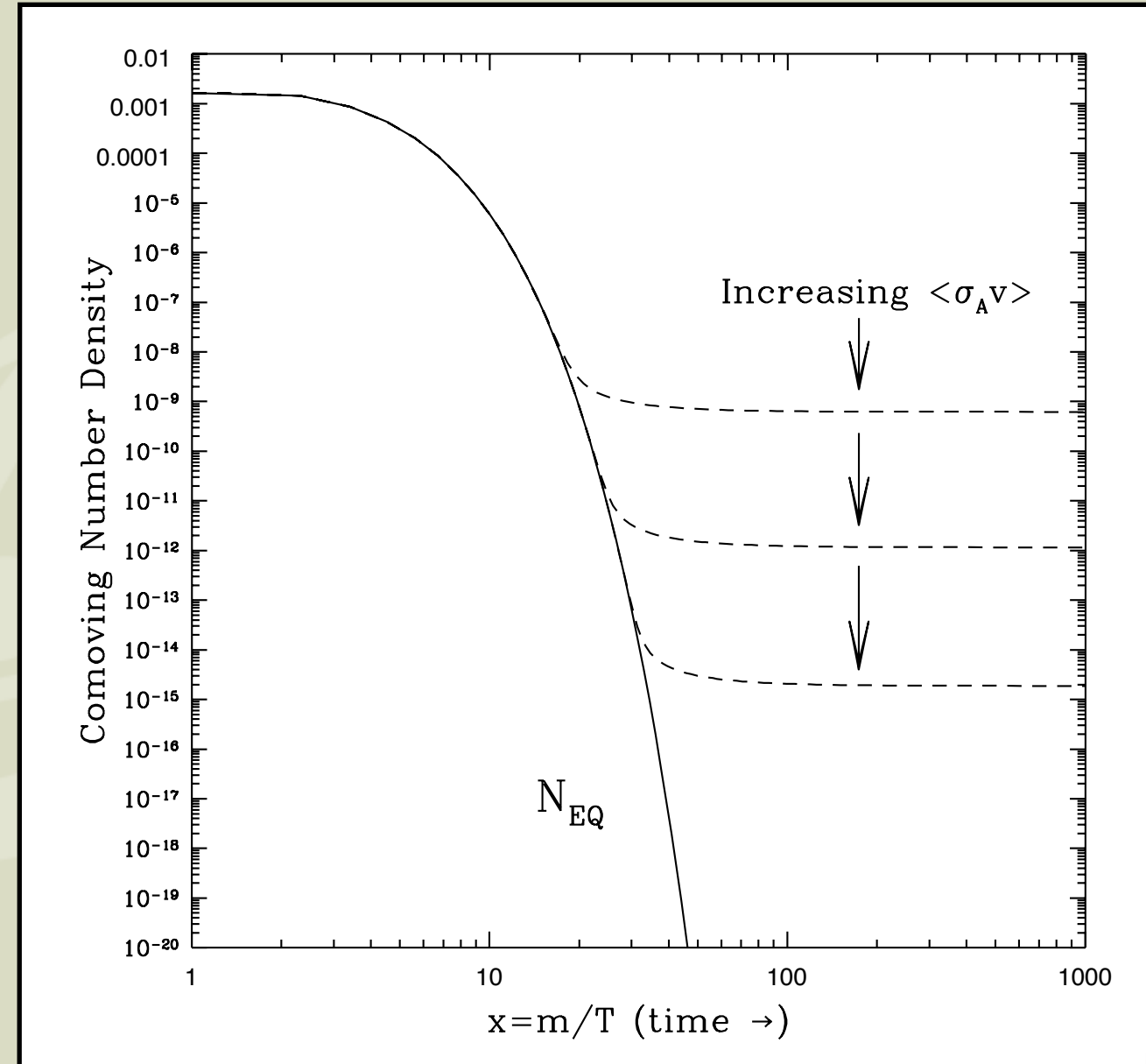
$$\Gamma = \langle \sigma_{\text{ann}} v \rangle n_\chi$$

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

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

$$\Gamma \simeq H \Rightarrow T_f \simeq \frac{m_\chi}{20}$$

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



$$\langle \sigma_{\text{ann}} v \rangle \simeq \langle \sigma_{\text{ann}} v \rangle_{\text{WIMP}} \Rightarrow \Omega_\chi h^2 \simeq 1$$

WIMP candidates

- Any weakly interacting massive particle could in principle work
- In supersymmetric extensions of the standard model, the lightest neutralino arises as a natural dark matter candidate. Will focus on this candidate as a concrete example.
- Other examples are e.g. Kaluza-Klein particles.

The neutralino as a WIMP

- Many ways to break supersymmetry exists. Will choose a phenomenological low-energy MSSM as one example and mSUGRA as another.

The neutralino:

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

The neutralino can be the lightest supersymmetric particle (LSP). If R-parity is conserved, it is stable.

The gaugino fraction

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

The MSSM parameters

- In phenomenologically motivated MSSM we fix parameters at the electro-weak scale

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

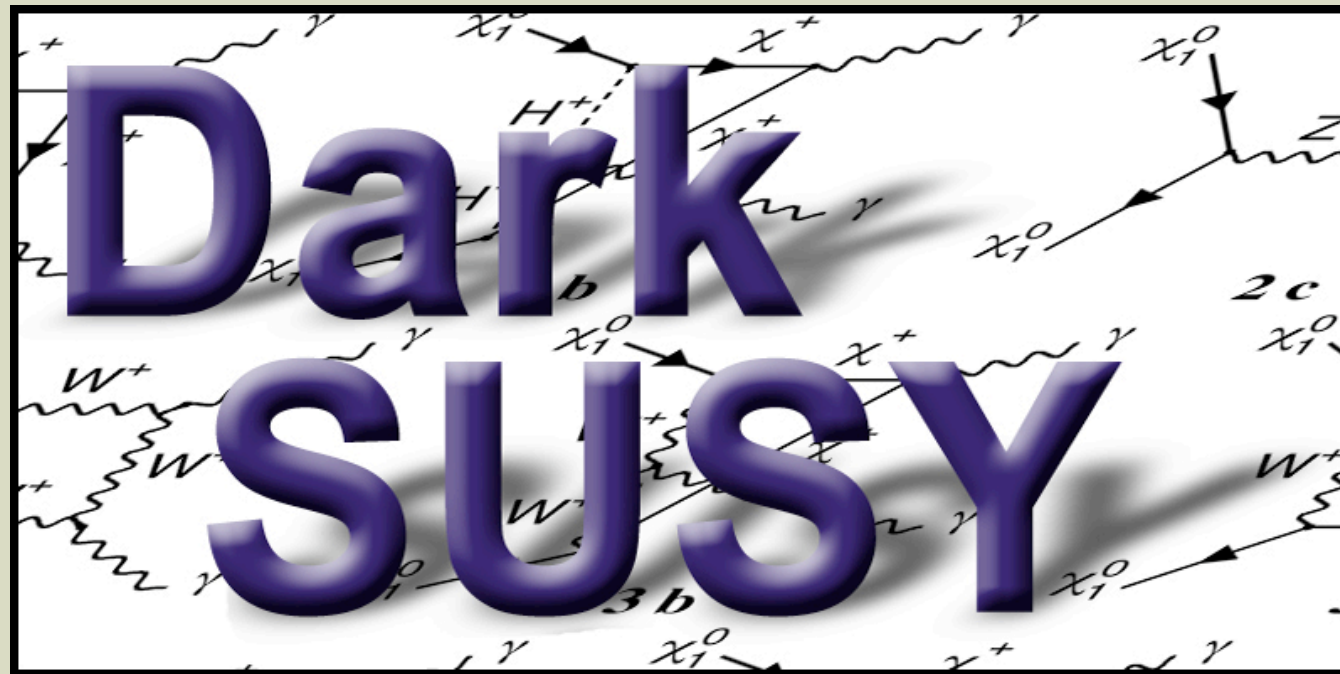
The neutralino in mSUGRA

- Fix mass parameters at GUT scale and run RGEs to low energy scale

$\text{sgn}(\mu)$	Sign of Higgsino mass parameter
$m_{1/2}$	Gaugino mass parameter (at GUT scale)
$\tan \beta$	Ratio of Higgs vacuum expectation values
m_0	Scalar mass parameter (at GUT scale)
A	Trilinear coupling (at GUT scale)

Interesting regions:

- stau coannihilation region
- funnel region
- focus point region
- stop coannihilation region



P. Gondolo, J. Edsjö, P. Ullio,
L. Bergström, M. Schelke
and E.A. Baltz

4.2 coming at
Tools 2008!

Version 4.1 available now

- MSSM or mSUGRA
- Masses and couplings
- Relic density
- Lab constraints
- Rates: neutrino telescopes
- Rates: gamma rays
- Rates: antiprotons, positrons, antideuteron
- Rates: direct detection

Journal of **C**osmology and **A**stroparticle **P**hysics
An IOP and SISSA journal

JCAP 06 (2004) 004 [astro-ph/0406204]

DarkSUSY: computing supersymmetric dark-matter properties numerically

P Gondolo¹, J Edsjö², P Ullio³, L Bergström², M Schelke²
and E A Baltz⁴

www.physto.se/~edsjo/darksusy

Uses FeynHiggs, HDecay and Isasugra.
v4.2 will also use galprop and include final state radiation and neutrino oscillations.

Calculational flowchart

- Select model parameters
- Calculate masses etc
- Check accelerator constraints
- Calculate the relic density
- Check if the relic density is cosmologically OK
- Calculate fluxes, rates, etc
- Calculation done with



DarkSUSY 4.1 available on
www.physto.se/~edsjo/darksusy
 JCAP 06 (2004) 004 [astro-ph/0406204]

The relic density

$$\Omega_{\chi} h^2 = 0.1113^{+0.0044}_{-0.0061}$$

from WMAP+SDSS LRG

D. Spergel et al., astro-ph/0603449

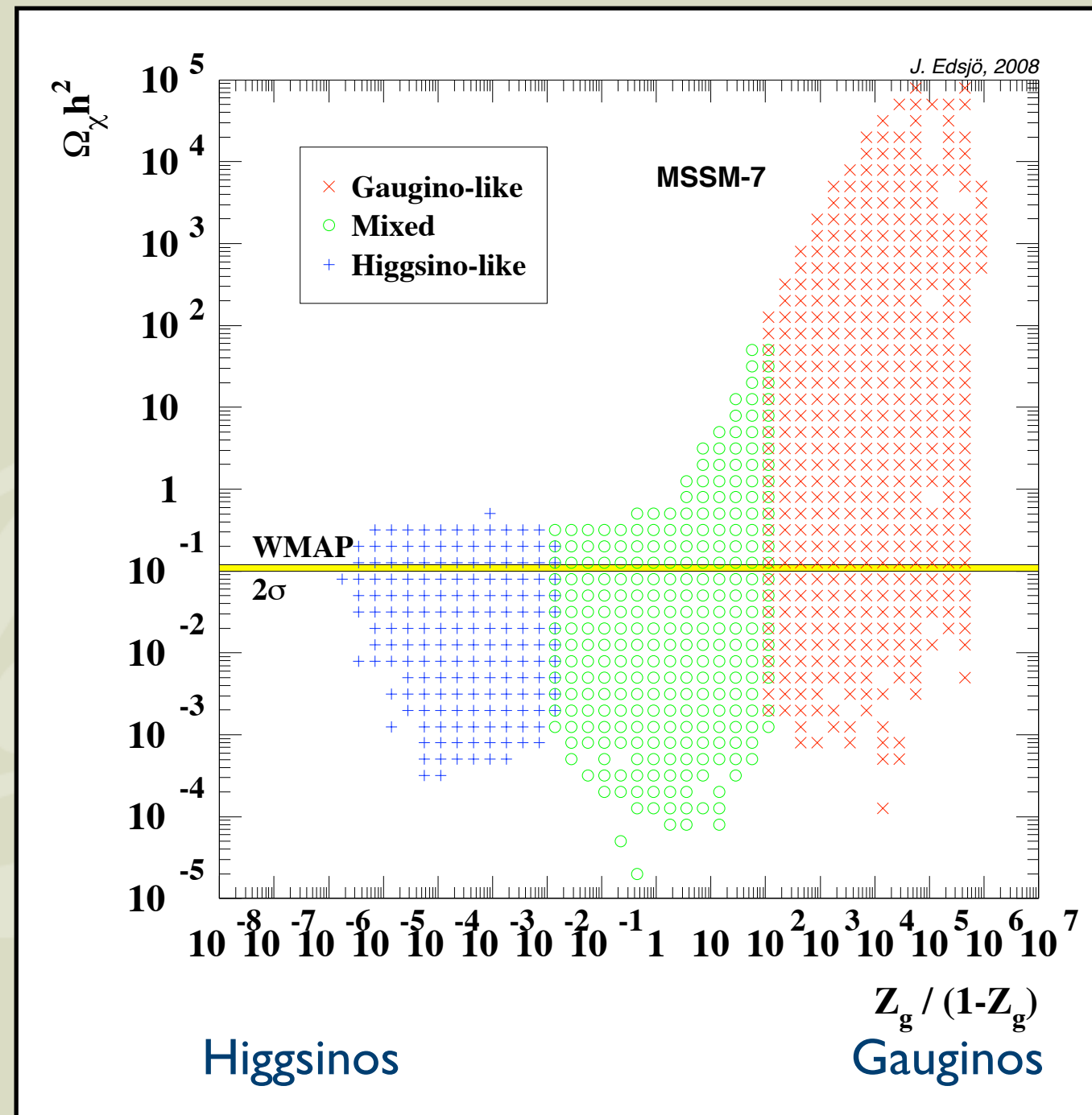
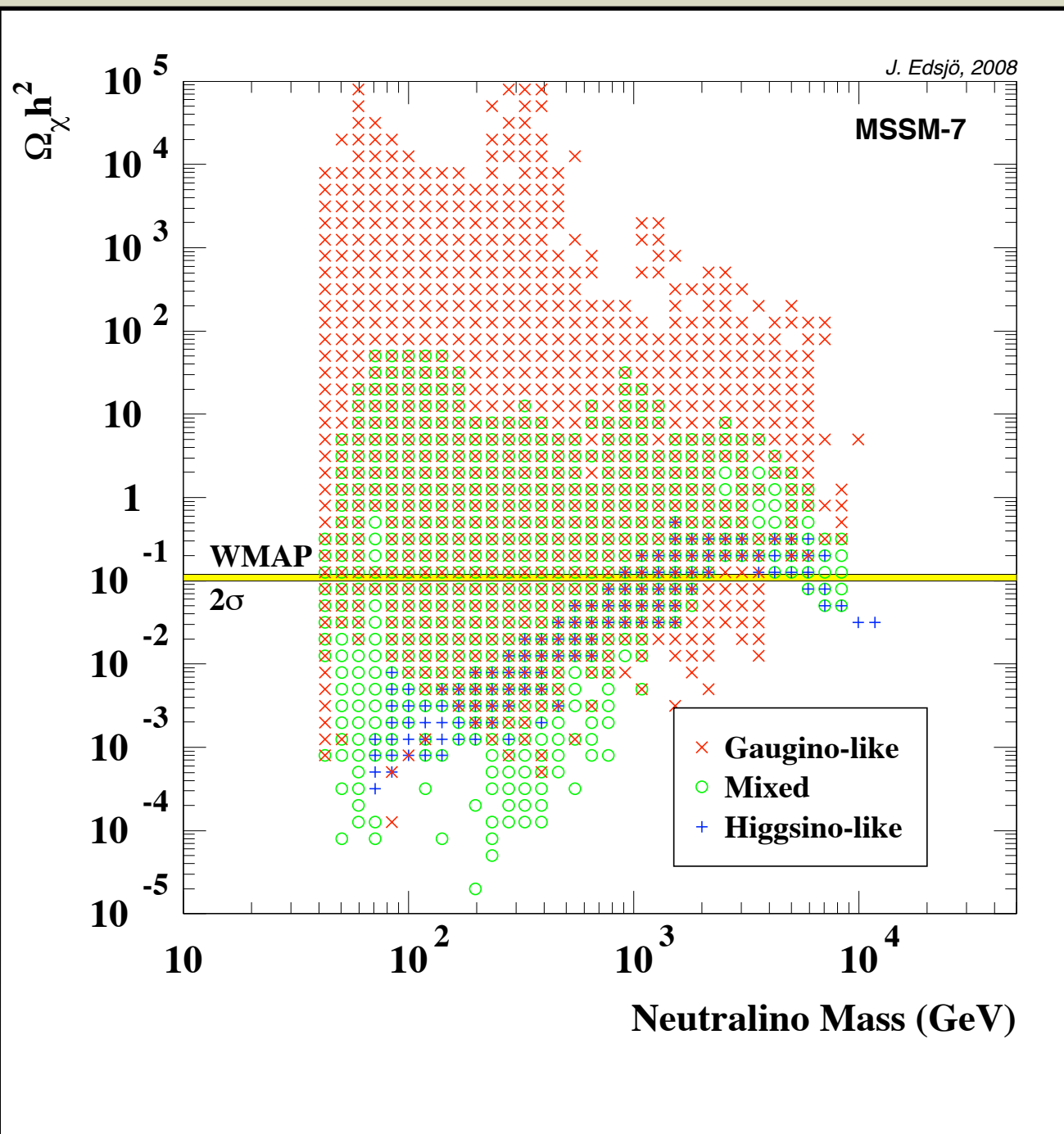
Relic density – accurate approach

- Solve the Boltzmann equation

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

- properly taking the thermal average $\langle \cdot \rangle$
- including the full annihilation cross section (including all final states, resonances and thresholds)
- including all so-called coannihilations between all neutralinos, charginos and sfermions

Relic density versus mass and composition



The neutralino is cosmologically interesting for a large range of parameter values

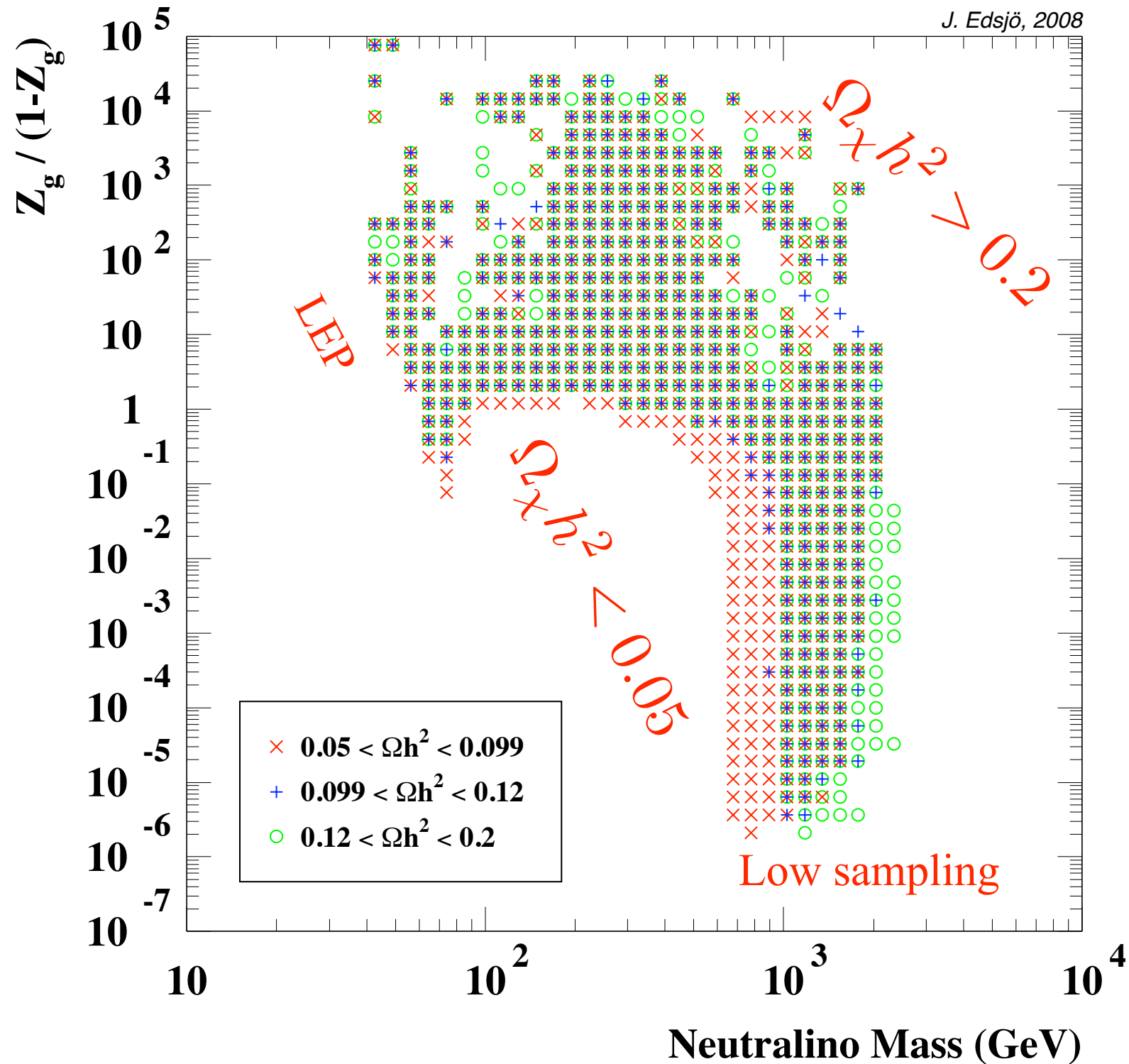
(No sfermion coannihilations in this plot yet)

The $m_\chi - Z_g$ parameter space

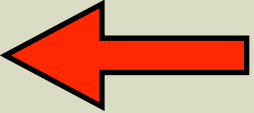
Gaugino

Mixed

Higgsino

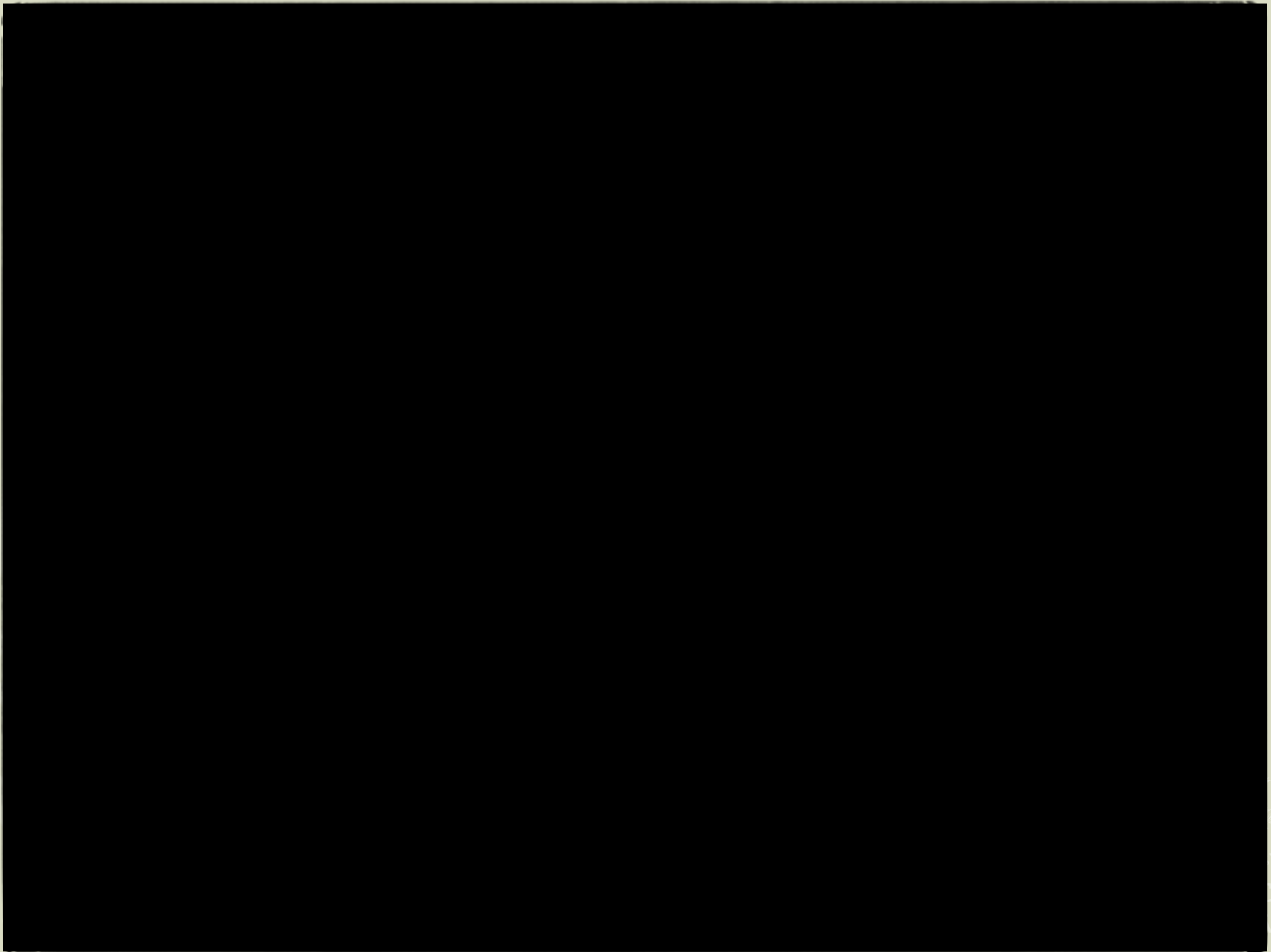


WIMP search strategies

- Direct detection  CDMS-II @ Soudan and XENON10 constrains our models already now
- Indirect detection:
 - gamma rays from the galactic halo Bergström and Snellman, '84
 - gamma rays from external galaxies/halos
 - neutrinos from the Earth Freese, '86; Krauss, Srednicki & Wilczek, '86
Gaisser, Steigman & Tilav, '86
 - neutrinos from the Sun Silk, Olive and Srednicki, '85
Gaisser, Steigman & Tilav, '86
 - antiprotons from the galactic halo Silk & Srednicki, '84
Stecker, Rudaz & Walsh, '85
 - antideuterons from the galactic halo Donato, Fornengo, Salati, '99
 - positrons from the galactic halo Silk & Srednicki, '84
 - synchrotron radiation or neutrinos from the galactic center Gondolo & Silk, '00
Bertone, Sigl & Silk '01
 - Microwave haze from galactic center Finkbeiner '04
 - Dark Stars Wai & Moskalenko, Freese & Gondolo, Iocco, Edsjö, Fairbairn & Scott

GLAST launch
June 11, 18.05

“...searching for unseen physics
in the stars of the galaxies...”



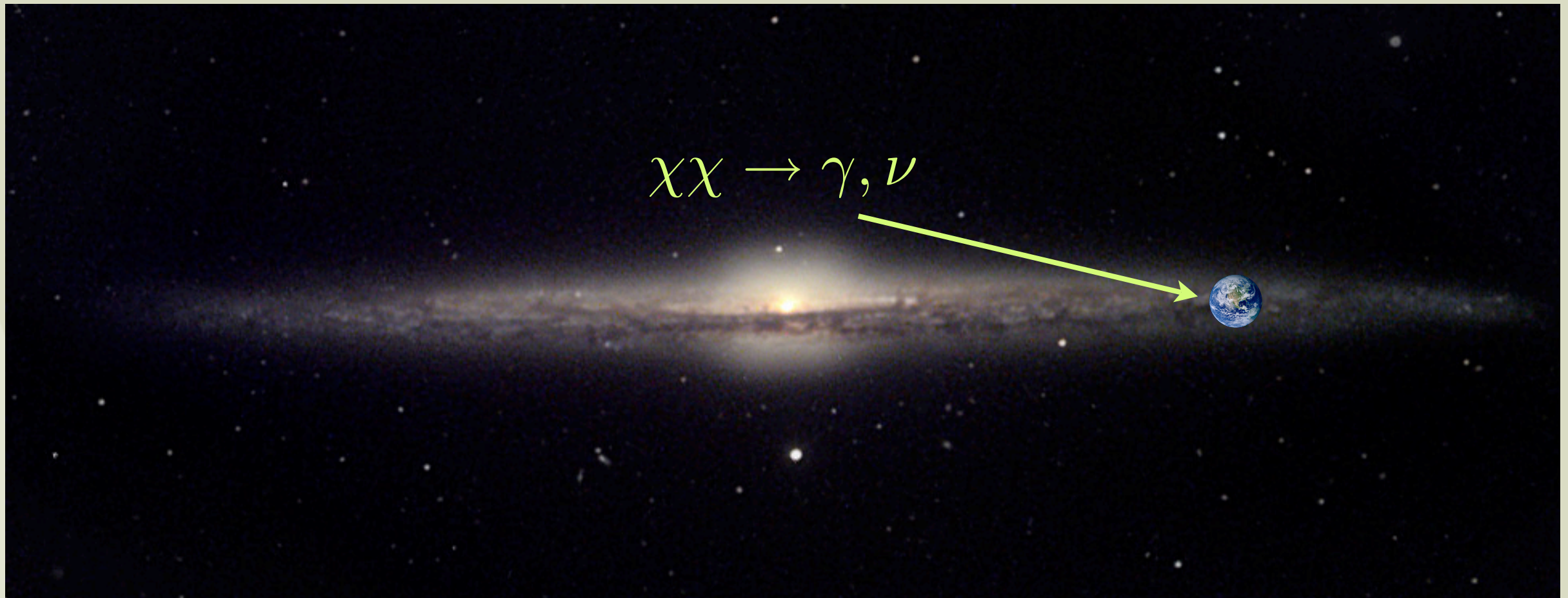
GLAST launch June 11, 2008 18.05

- Launch successful and GLAST is now in orbit
- *Day 1 - 14:*
Satellite testing and configuration
- *Day 15 - 60:*
Calibration of detectors and first science runs
- *Day 61 (mid Aug.) - :*
Full science data taking



Annihilation in the halo

Neutral annihilation products



- Gamma rays can be searched for with e.g. Air Cherenkov Telescopes (ACTs) or GLAST (launched June 11, 2008!).
- Signal depends strongly on the halo profile,

$$\Phi \propto \int_{\text{line of sight}} \rho^2 dl$$

Annihilation to gamma rays

- **Monochromatic**

At loop-level, annihilation can occur to

$$\gamma\gamma \Rightarrow E_\gamma = m_\chi$$

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

Features

- directionality – no propagation uncertainties
- low fluxes, but clear signature
- strong halo profile dependence

- **Continuous**

WIMP annihilation can also produce a continuum of gamma rays

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

Features (compared to lines)

- lower energy
- more gammas / annihilation
- rather high fluxes
- not a very clear signature

Gamma ray fluxes from the halo

We can write the flux as

$$\Phi_\gamma(\eta, \Delta\Omega) = 9.35 \cdot 10^{-14} S \times \langle J(\eta, \Delta\Omega) \rangle \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

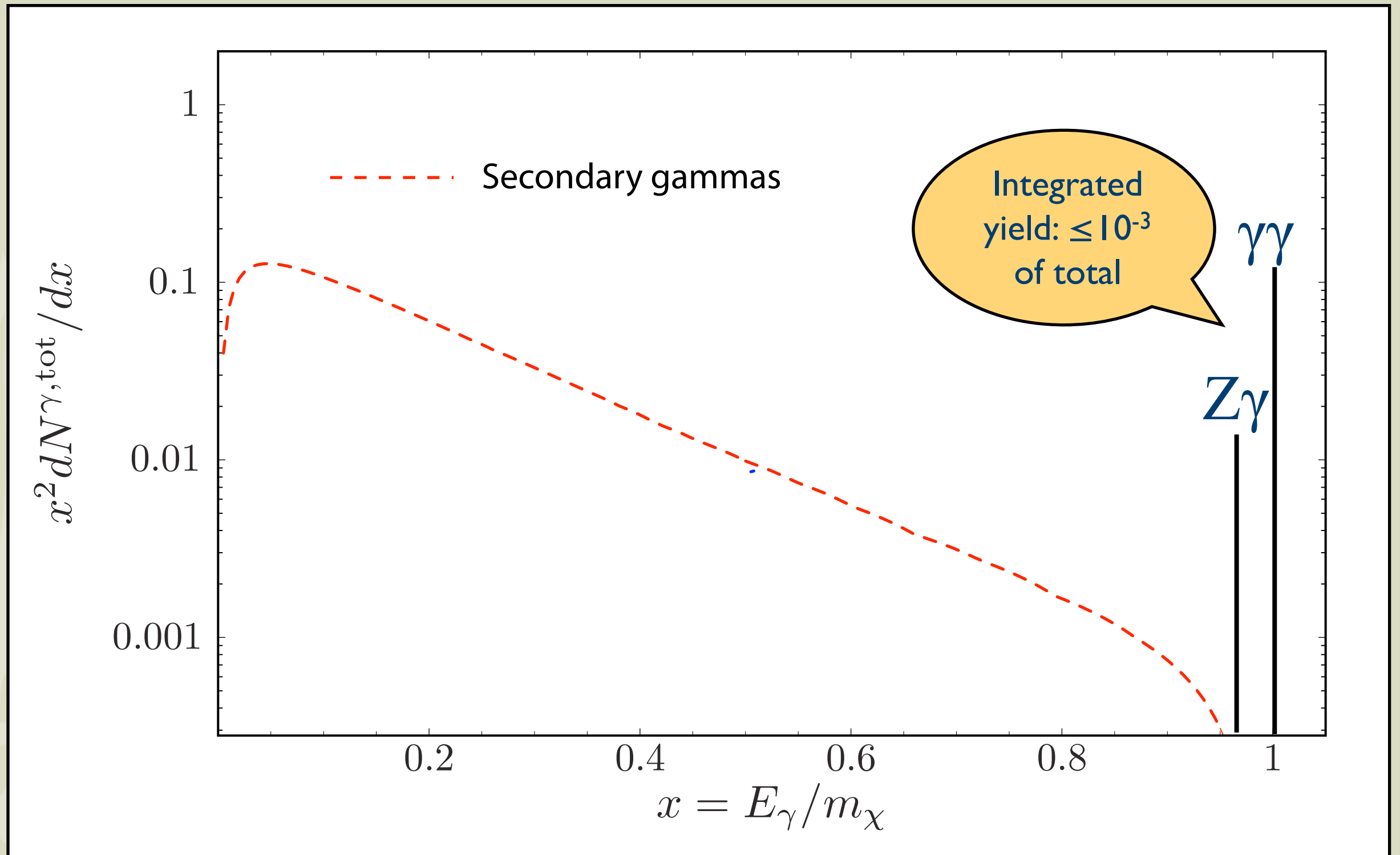
with

$$S = N_\gamma \frac{\langle \sigma v \rangle}{10^{-29} \text{ cm}^3 \text{ s}^{-1}} \left(\frac{100 \text{ GeV}}{m_\chi} \right)^2 \quad \text{Particle physics (SUSY, ...)}$$

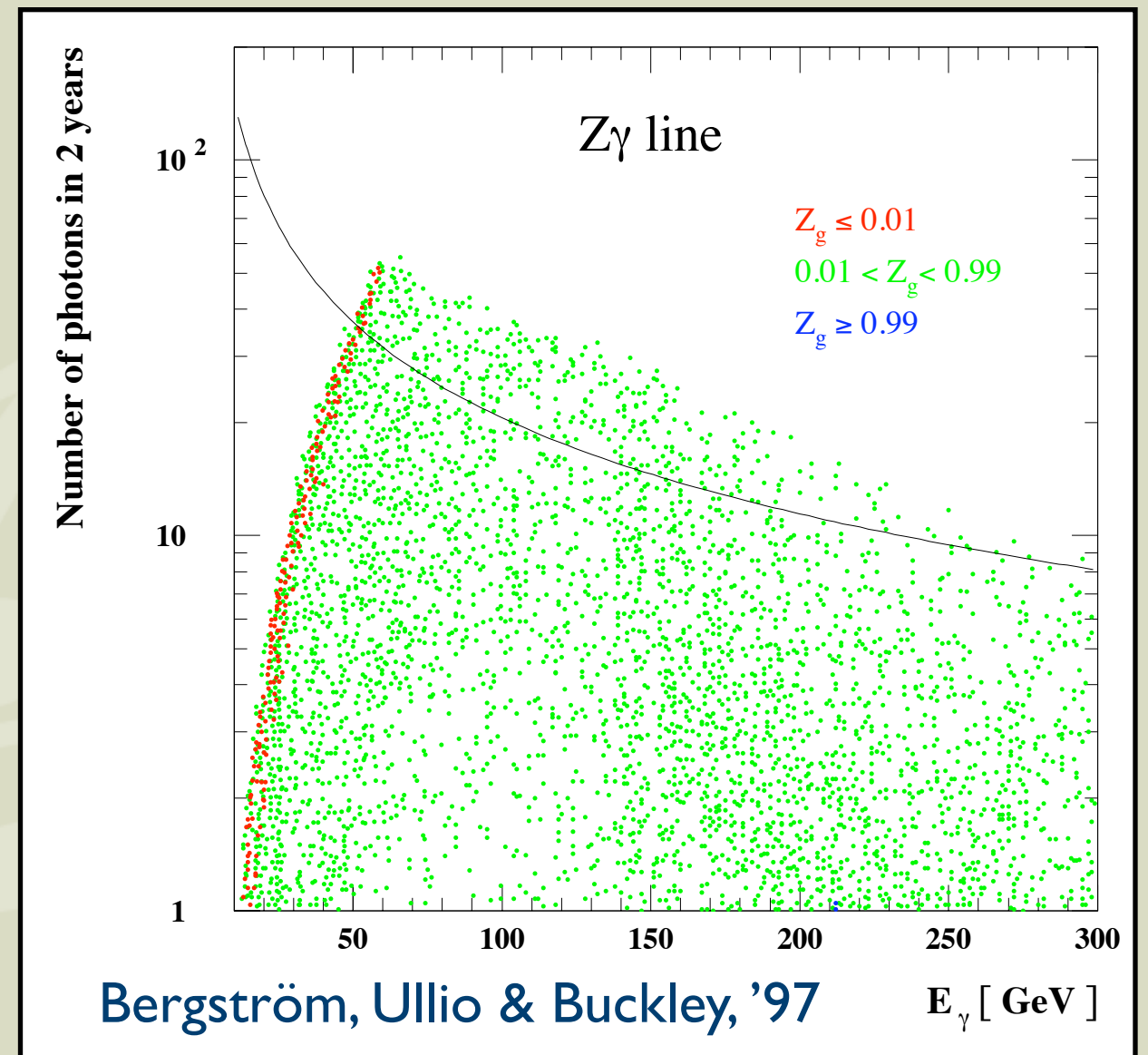
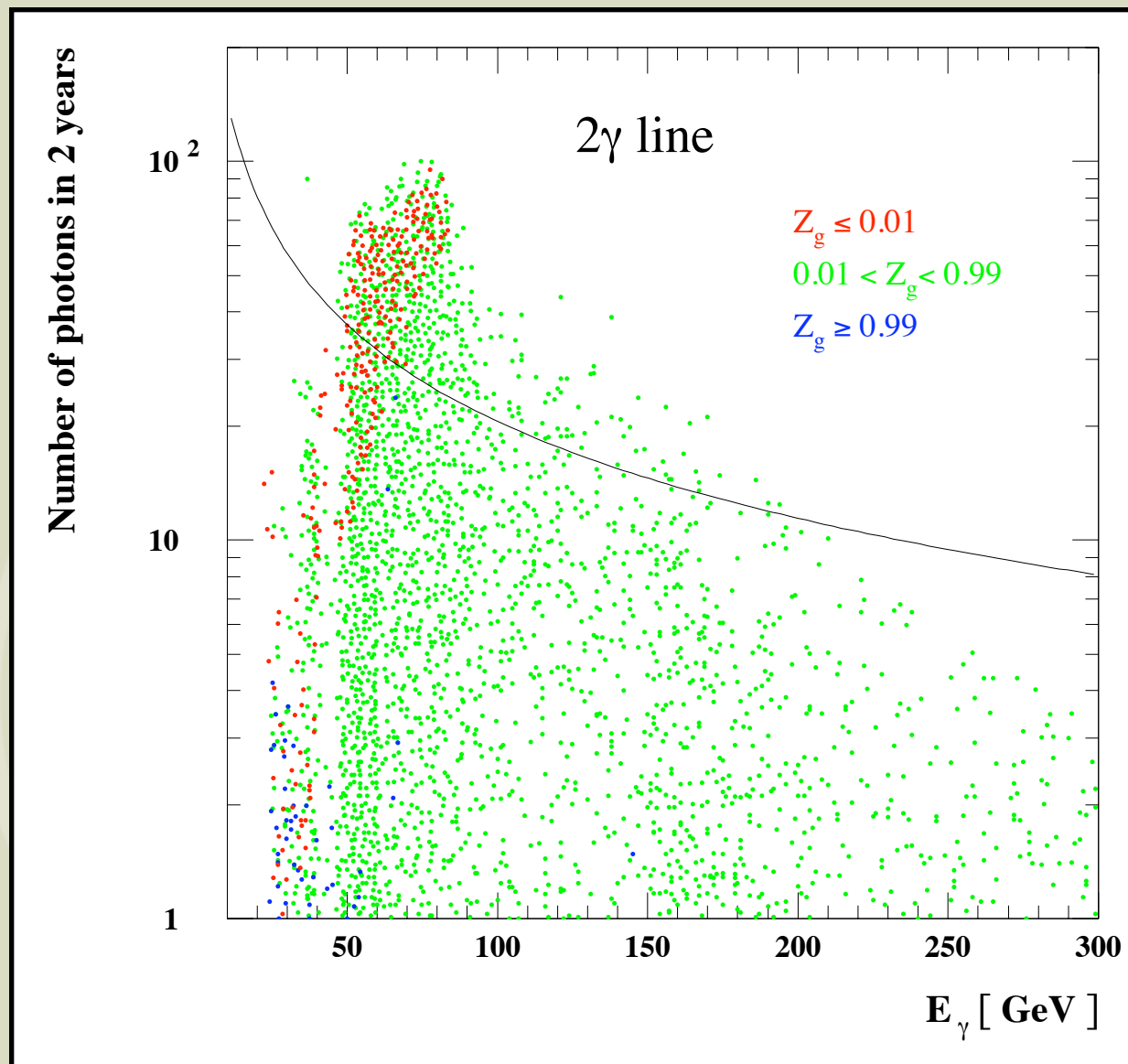
$$\langle J(\eta, \Delta\Omega) \rangle = \frac{1}{8.5 \text{ kpc}} \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{\text{line of sight}} \left(\frac{\rho(l)}{0.3 \text{ GeV/cm}^3} \right)^2 dl(\eta) d\Omega$$

Astrophysics

Typical gamma ray spectrum



Gamma lines – rates in GLAST



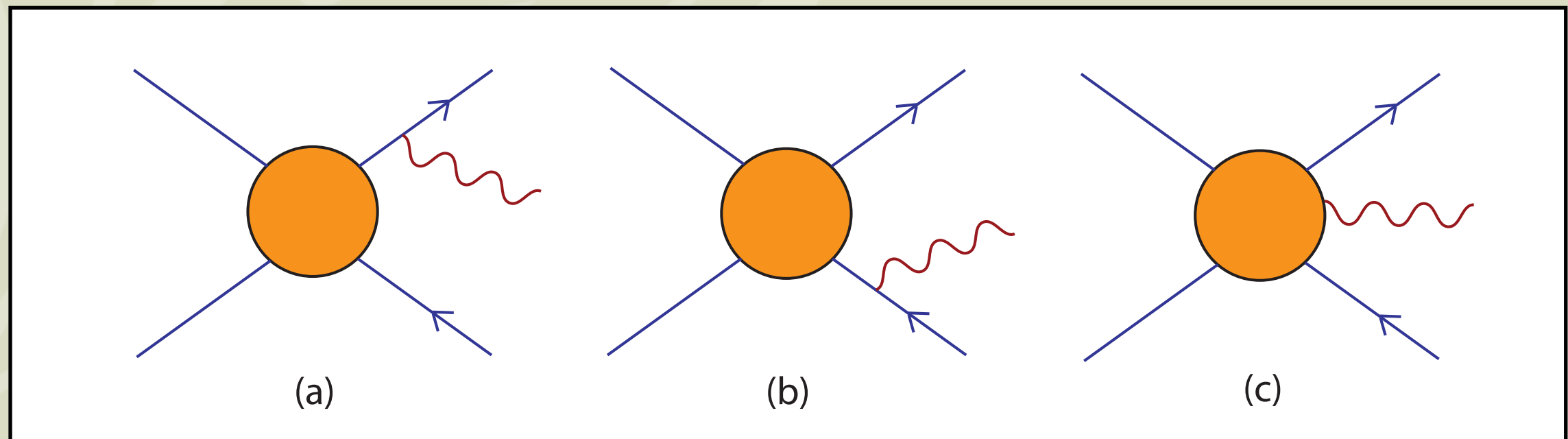
NFW halo profile, $\Delta\Omega \approx 1$ sr



GLAST launched
June 11, 2008

Internal Bremsstrahlung

- Whenever charged final states are present, photons can also be produced in internal bremsstrahlung processes



Internal Bremsstrahlung

- Bremsstrahlung effects for DM annihilation pointed out by Bergström, PLB 225 (1989) 372.
- Studied recently by e.g.
 - Beacom et al, arXiv: astro-ph/0409403
MeV dark matter
 - Bergström et al, PRL 95 (2005) 241301.
Ann. of gauginos / Higgsinos to W^+W^-
 - Birkedal et al, arXiv: hep-ph/0507194.
Universal forms derived
 - Bergström et al, PRL 94 (2005) 131301.
UED models.
- I will here report on a more general study for SUSY neutralinos

Contributions to the gamma flux

- We can write the contributions to the gamma flux as

$$\frac{dN^{\gamma,\text{tot}}}{dx} = \sum_f B_f \left(\frac{dN_f^{\gamma,\text{sec}}}{dx} + \frac{dN_f^{\gamma,\text{IB}}}{dx} + \frac{dN_f^{\gamma,\text{line}}}{dx} \right)$$

- How large are these different contributions?

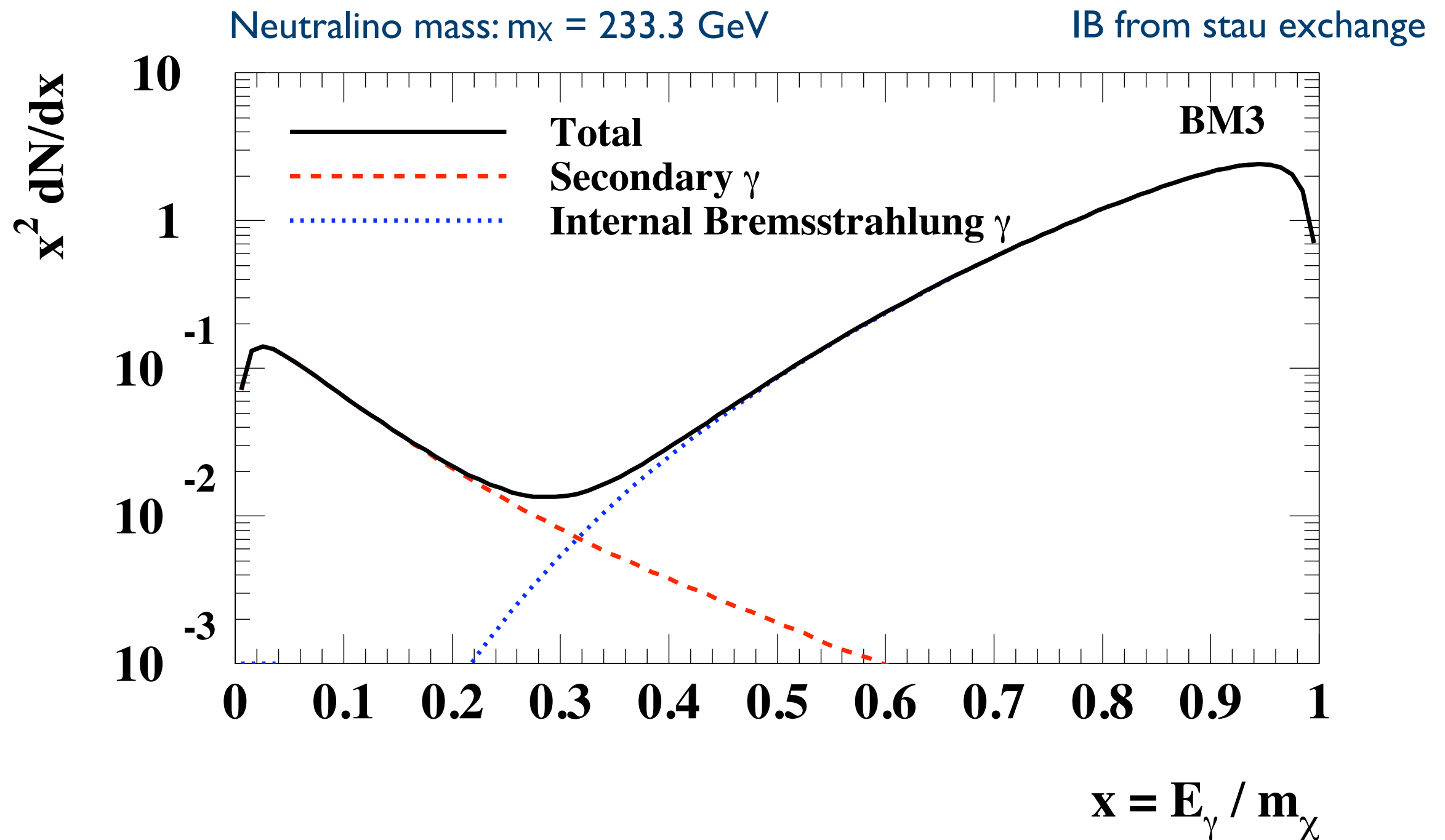
How big are these contributions for neutralinos?

- For Majorana fermion dark matter (e.g. neutralinos), annihilation to fermion-antifermion pairs is helicity suppressed at $v \rightarrow 0$

$$\sigma_{f\bar{f}} \propto \frac{m_f^2}{m_\chi^2}$$

- However, when internal bremsstrahlung photons are added, the helicity suppression no longer holds. The cross section can then increase, even though we are punished by an additional factor of α
- These photons can in many cases dominate at high energies

Gamma ray spectrum including IB photons III



More quantitative...

- Let's focus on the high energy part by redefining

$$S = \int_{0.6m_\chi}^{m_\chi} \frac{dN^\gamma}{dE} dE \frac{(\sigma v)}{10^{-29} \text{cm}^3 \text{s}^{-1}} \left(\frac{m_\chi}{100 \text{GeV}} \right)^{-2}$$

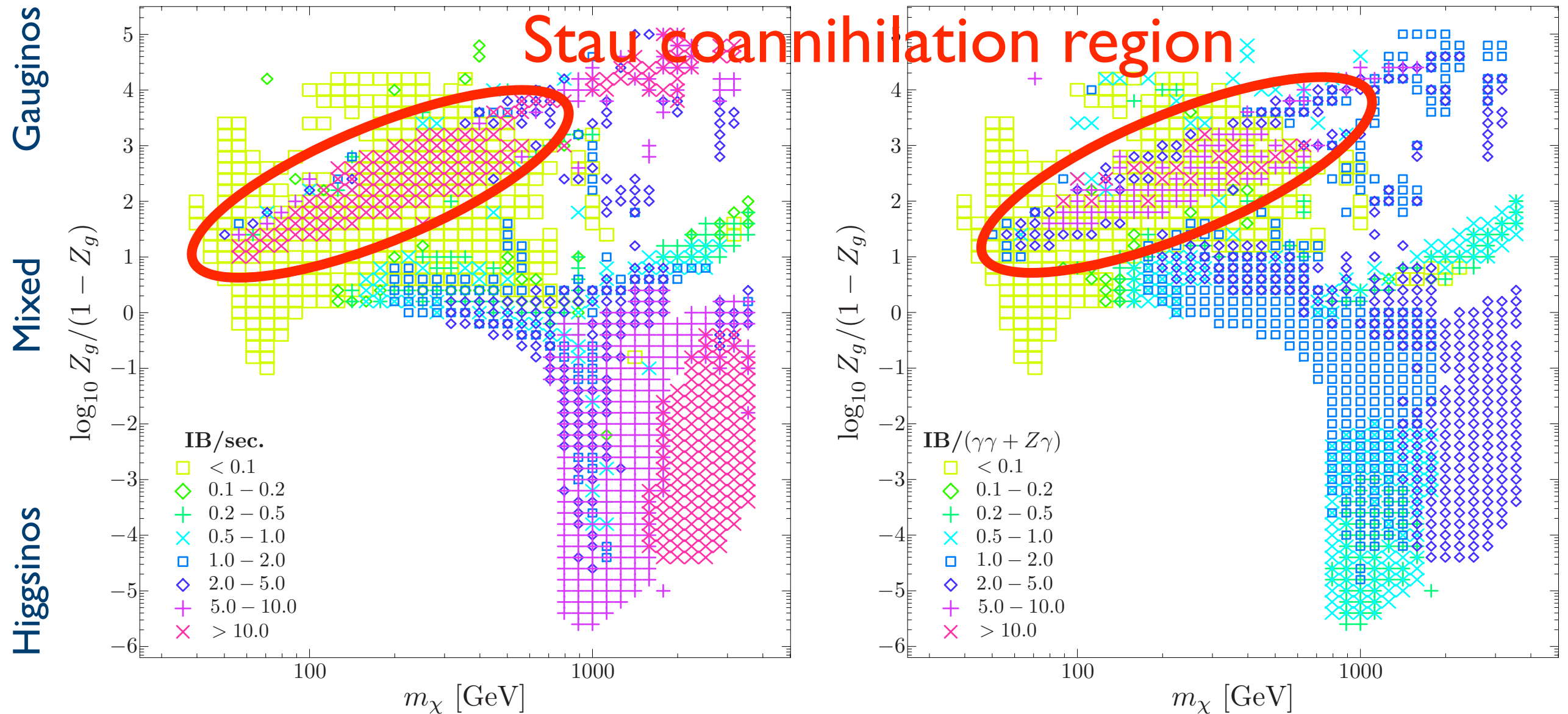
and divide S into the different parts

$$S = S_{\text{IB}} + S_{\text{sec.}} + S_{\text{lines}}$$

Internal Bremsstrahlung

When is it important?

MSSM and mSUGRA scans



All models OK with WMAP and accelerator constraints. $IB > 0.6 m_\chi$

Annihilation in the halo

Charged annihilation products

$$\chi\chi \rightarrow \bar{p}, \bar{D}, e^+$$

Diffusion zone



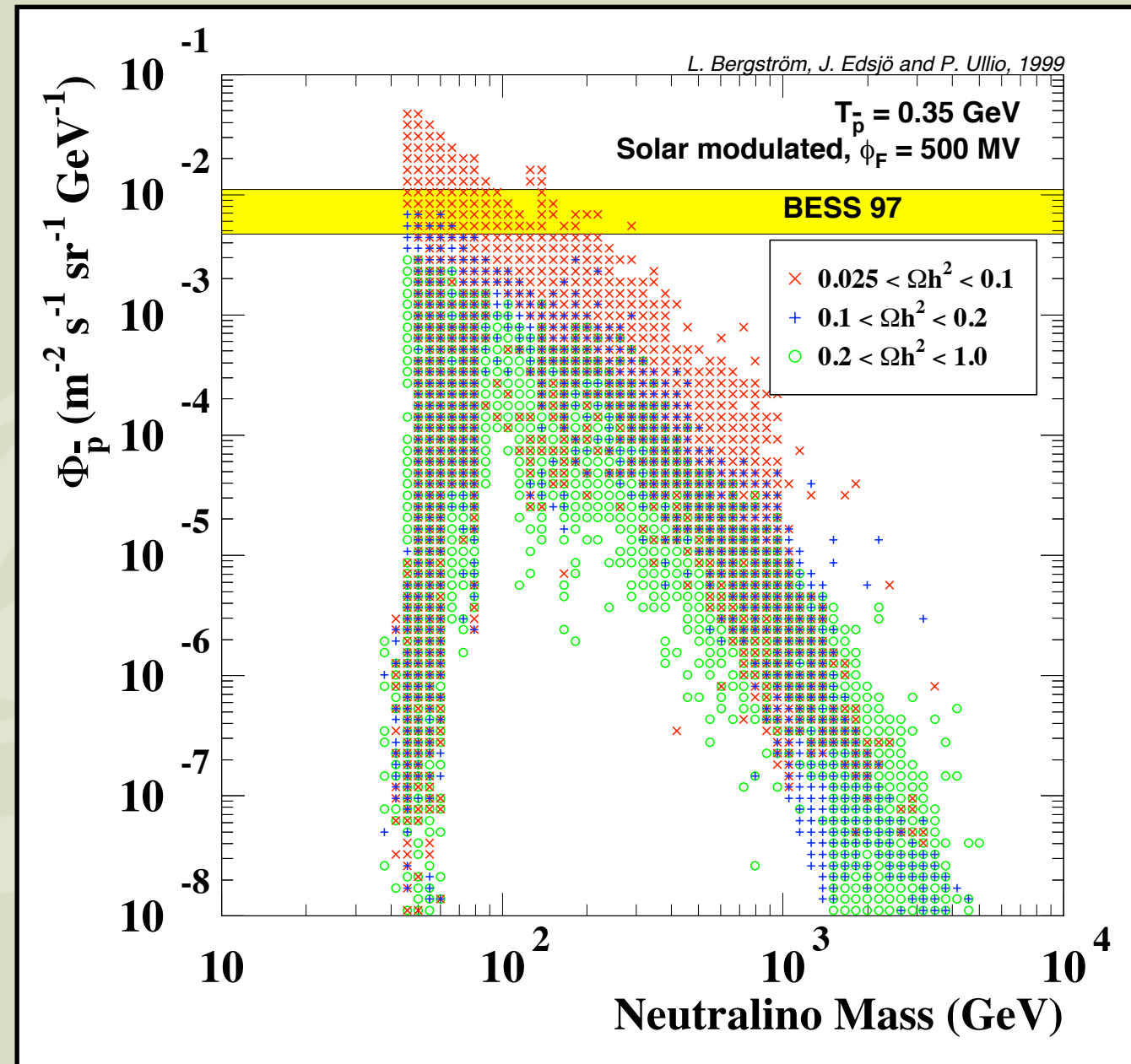
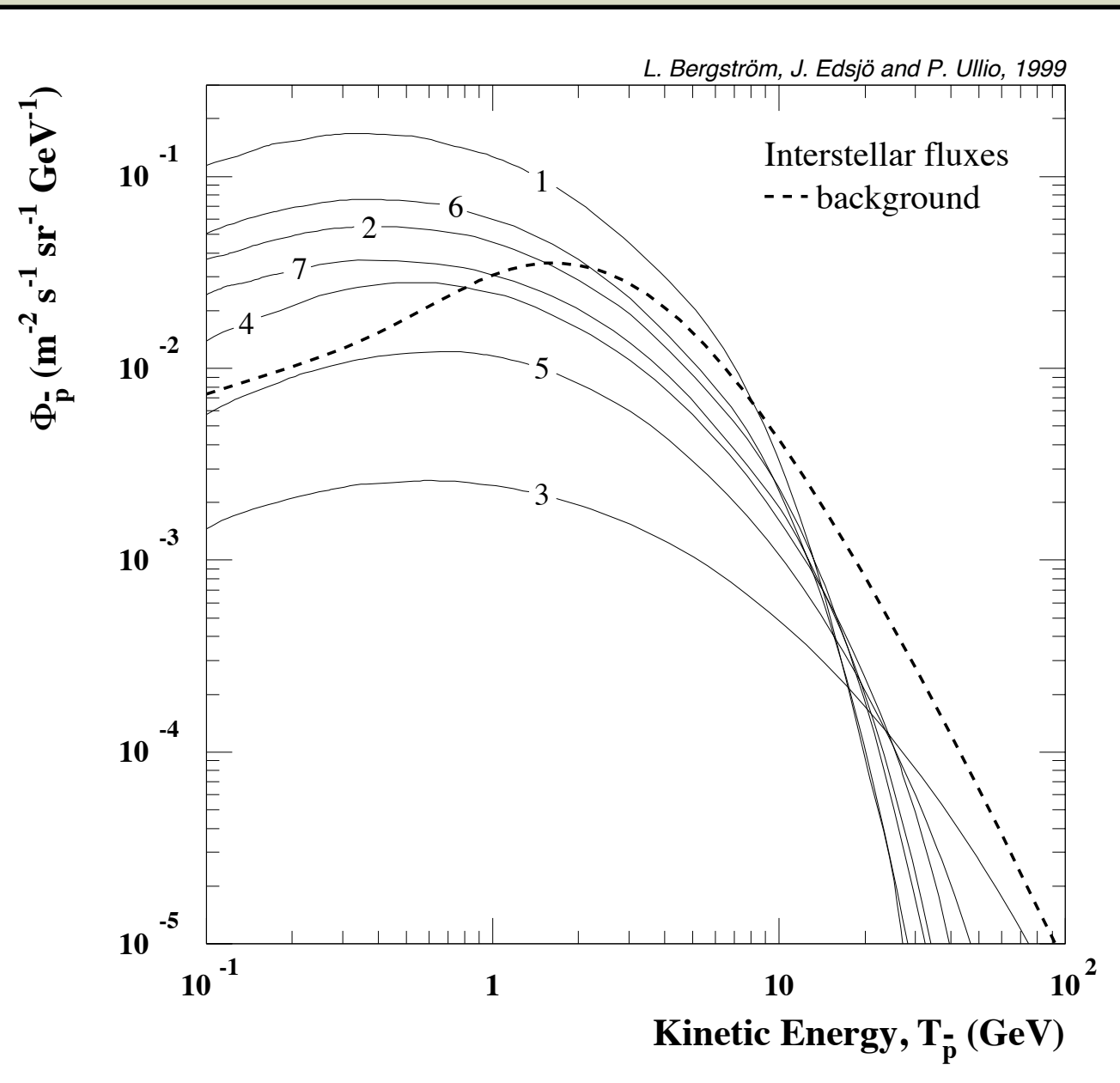
- Diffusion of charged particles. Diffusion model with parameters fixed from studies of conventional cosmic rays (especially unstable isotopes).
- Current detectors are e.g. HEAT, Caprice and BESS. Pamela was launched summer of 2006.
- Future detectors are e.g. AMS, GAPS and Calet.

Diffusion model

- Cylindrical diffusion model with free escape at the boundaries
- Energy losses on the interstellar medium (for antiprotons and antideuteron) or starlight and CMB (for positrons)
- Reacceleration can change the energy of the particles (can partly be mimicked by a break in the diffusion coefficient)

Galprop interface in next
DarkSUSY release.

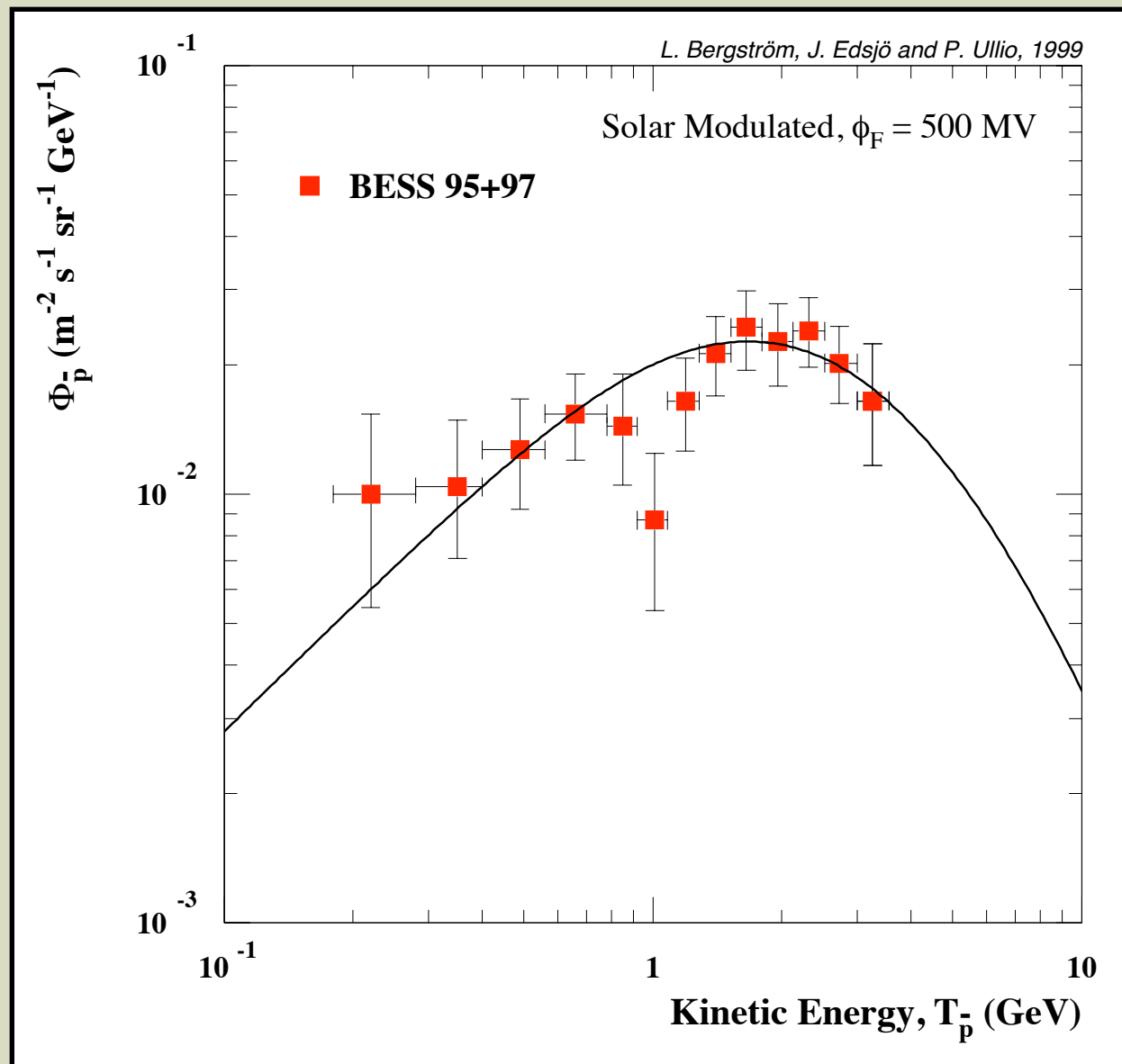
Antiprotons – signal



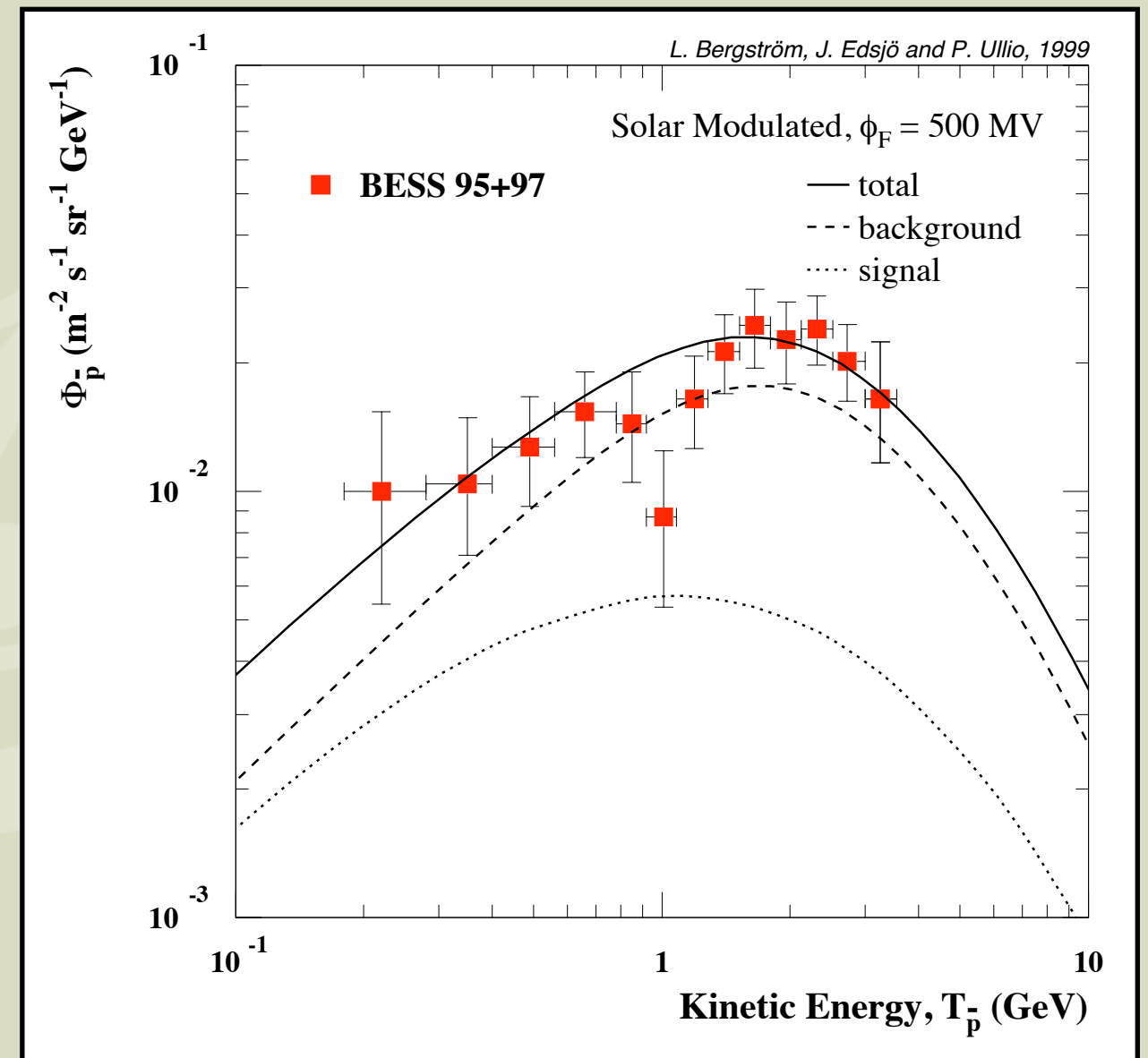
Easy to get high fluxes, but...

Antiprotons – fits to BESS data

Background only



Background + signal



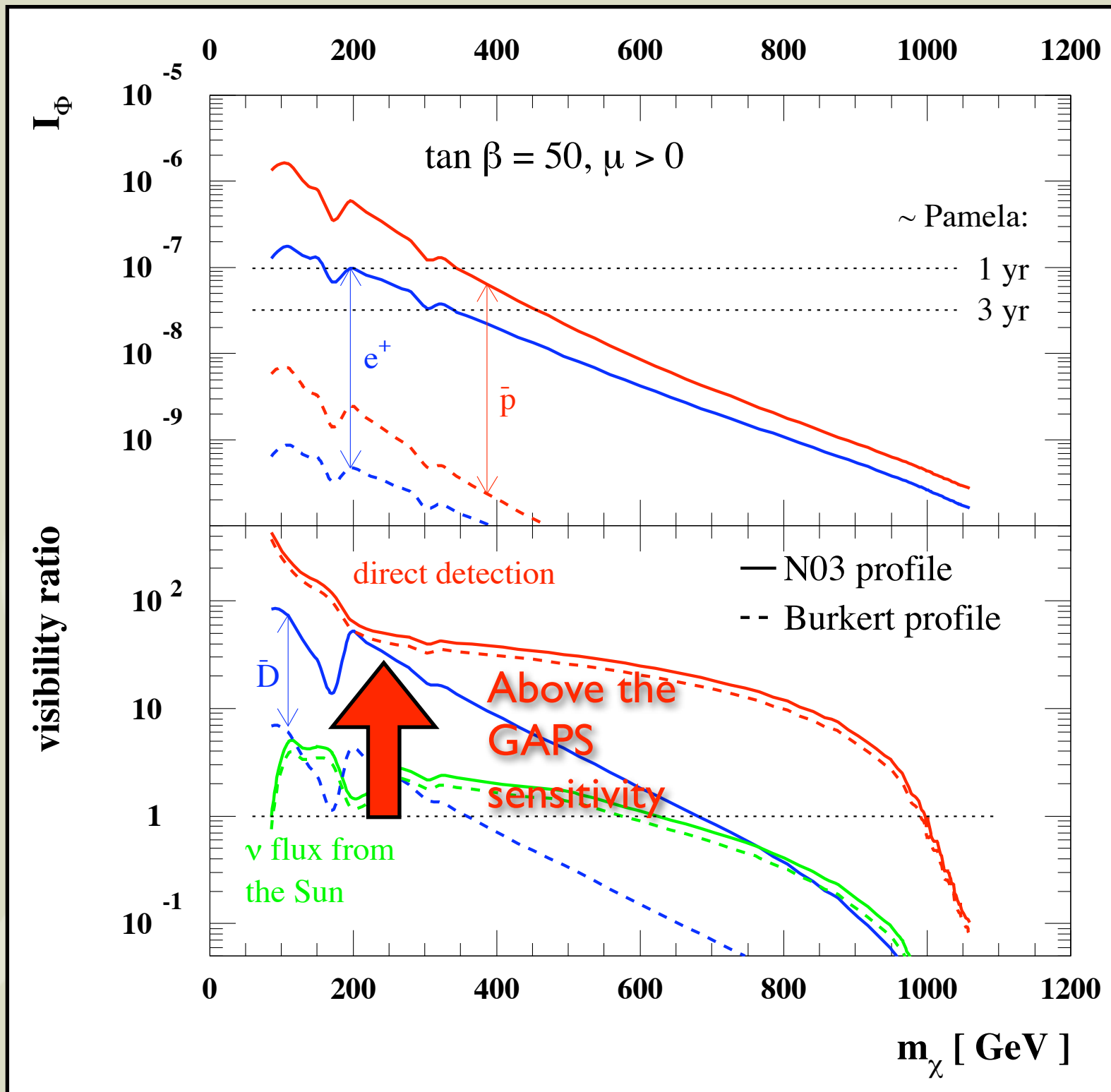
...room for, but no need for a signal!

Antideuteron

- Compared to antiprotons, the background of antideuterons is essentially zero at low energies.
- Search for a signal at e.g. 0.1-0.4 GeV, either in the solar system, but preferably in interstellar space.
- No current experiments, but possibly future: AMS, GAPS (Gaseous AntiParticle Spectrometer Mori et al., ApJ 566 (2002) 604).

Future cosmic rays

Focus point region in mSUGRA

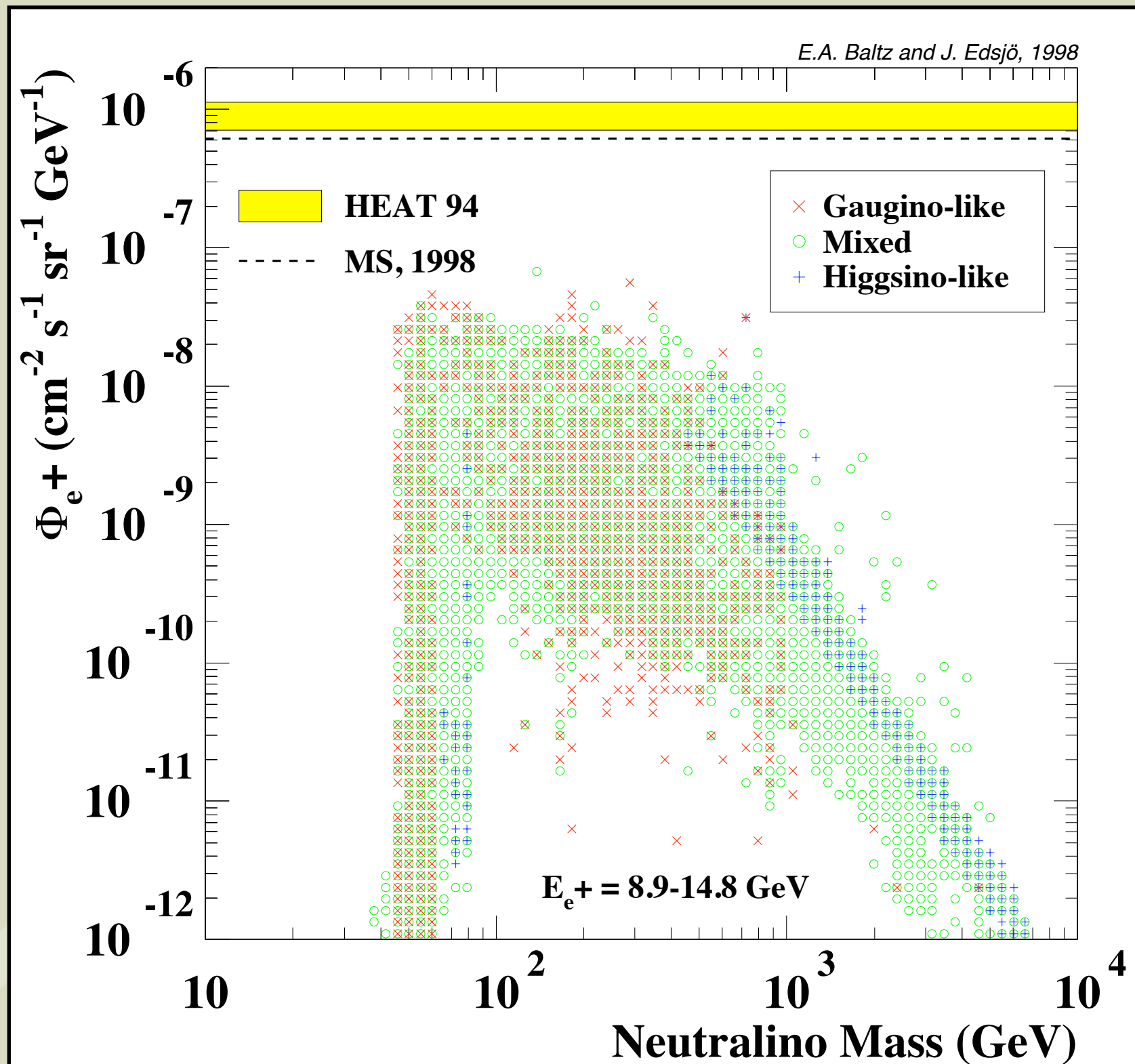


- Expected future sensitivities in two extreme halo models
- Antideuteron sensitivity with GAPS in the solar system
- Direct detection sensitivity of 1 ton Xenon detector

Positron fluxes from neutralinos

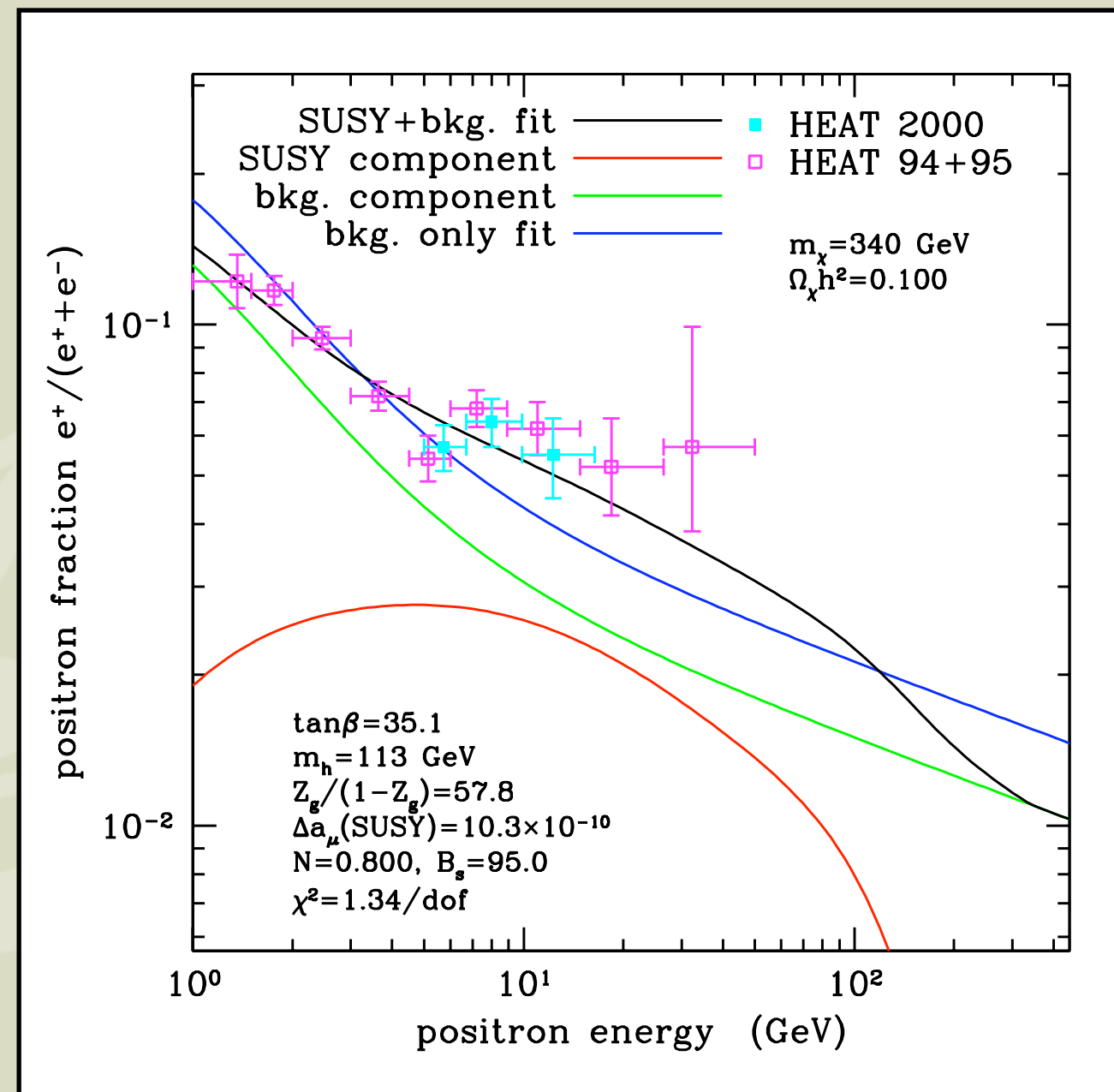
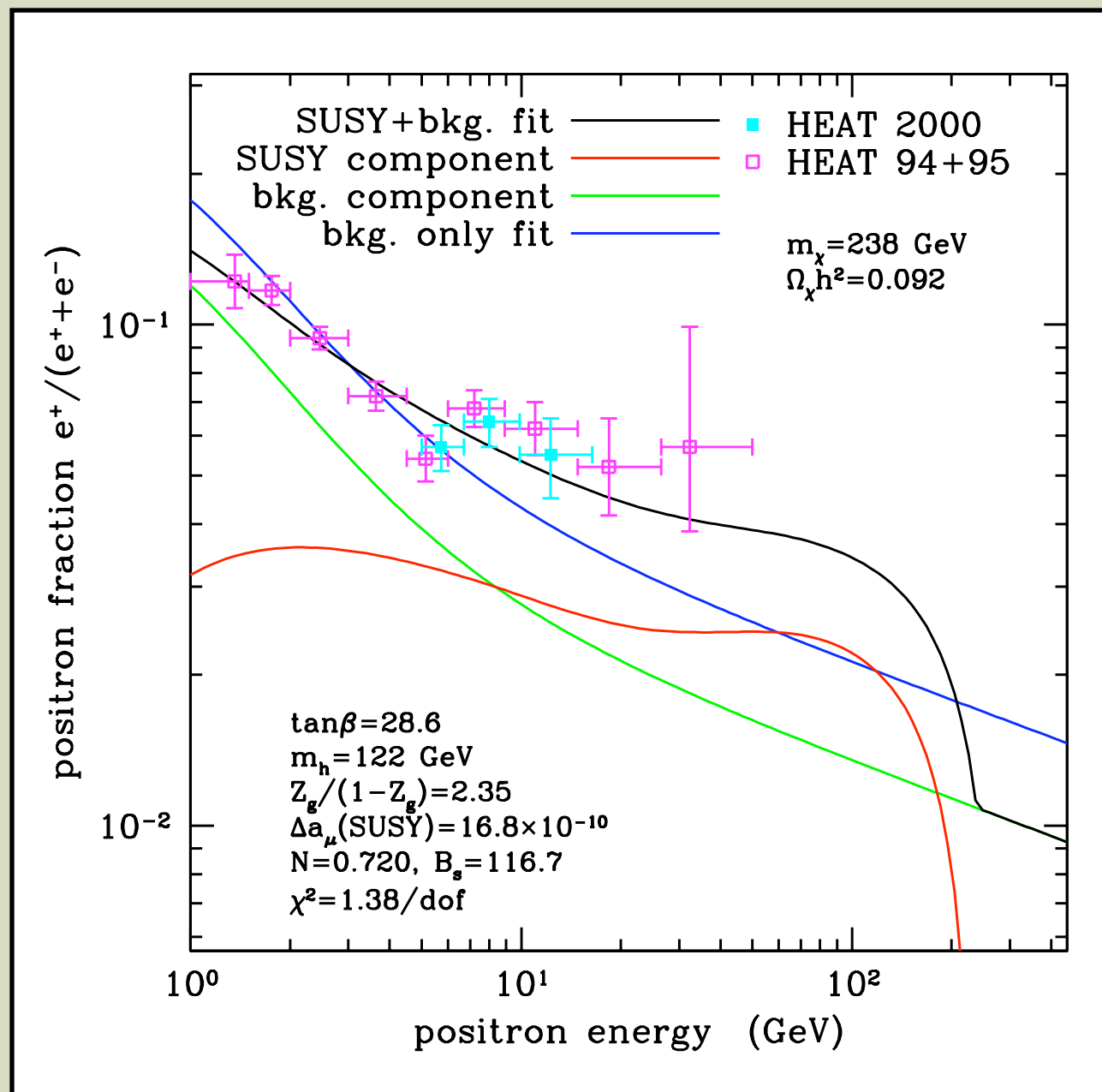
- Compared to antiprotons,
 - energy losses are much more important
 - higher energies due to more prompt annihilation channels (ZZ, W^+W^- , etc)
 - propagation uncertainties are higher
 - solar modulation uncertainties are higher

Positrons - signal



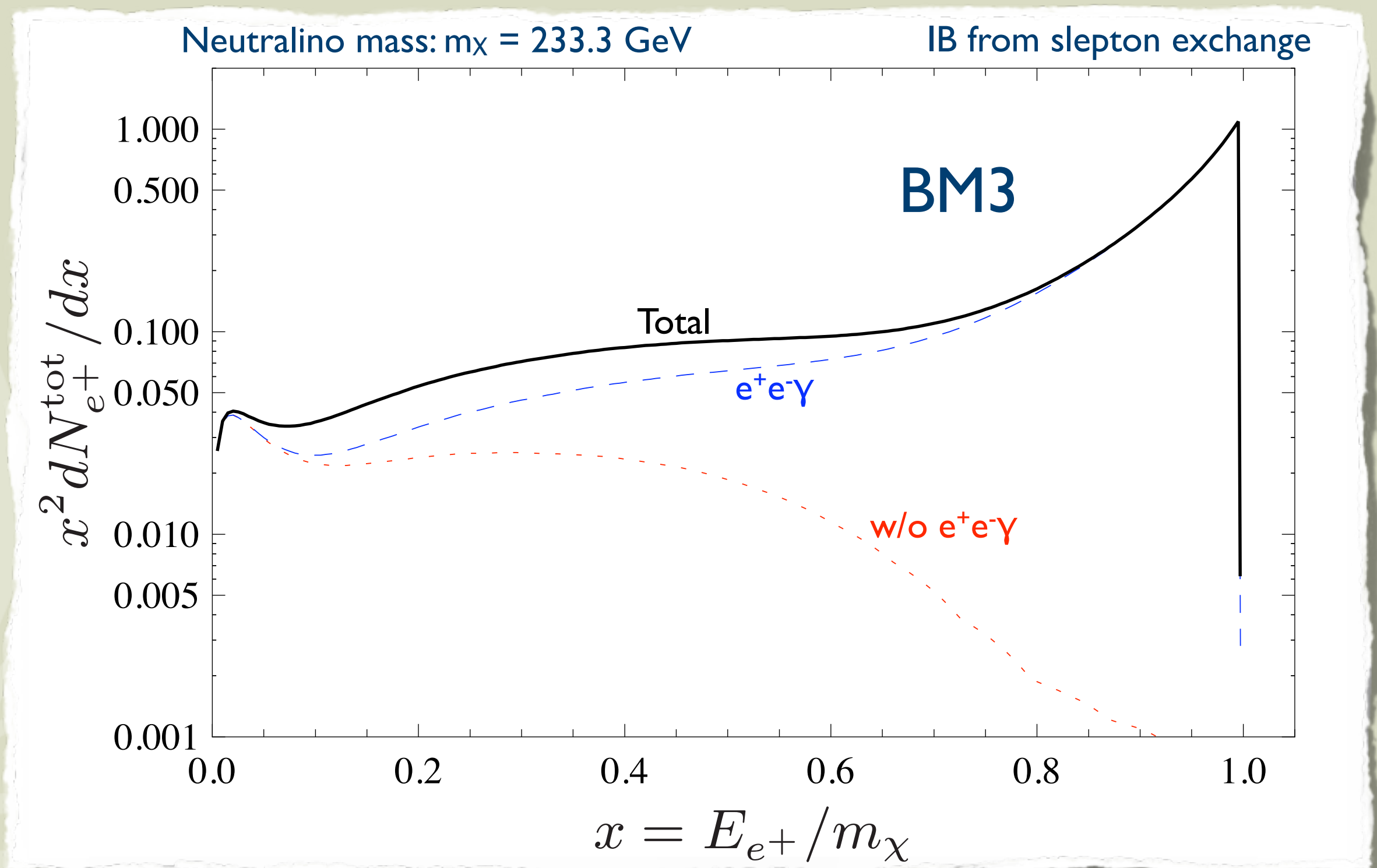
- Compared to antiprotons, the fluxes are typically lower (except possibly at high energies), but...

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...
- ...and the fit is not perfect

Example mSUGRA e^+ spectrum with IB contributions



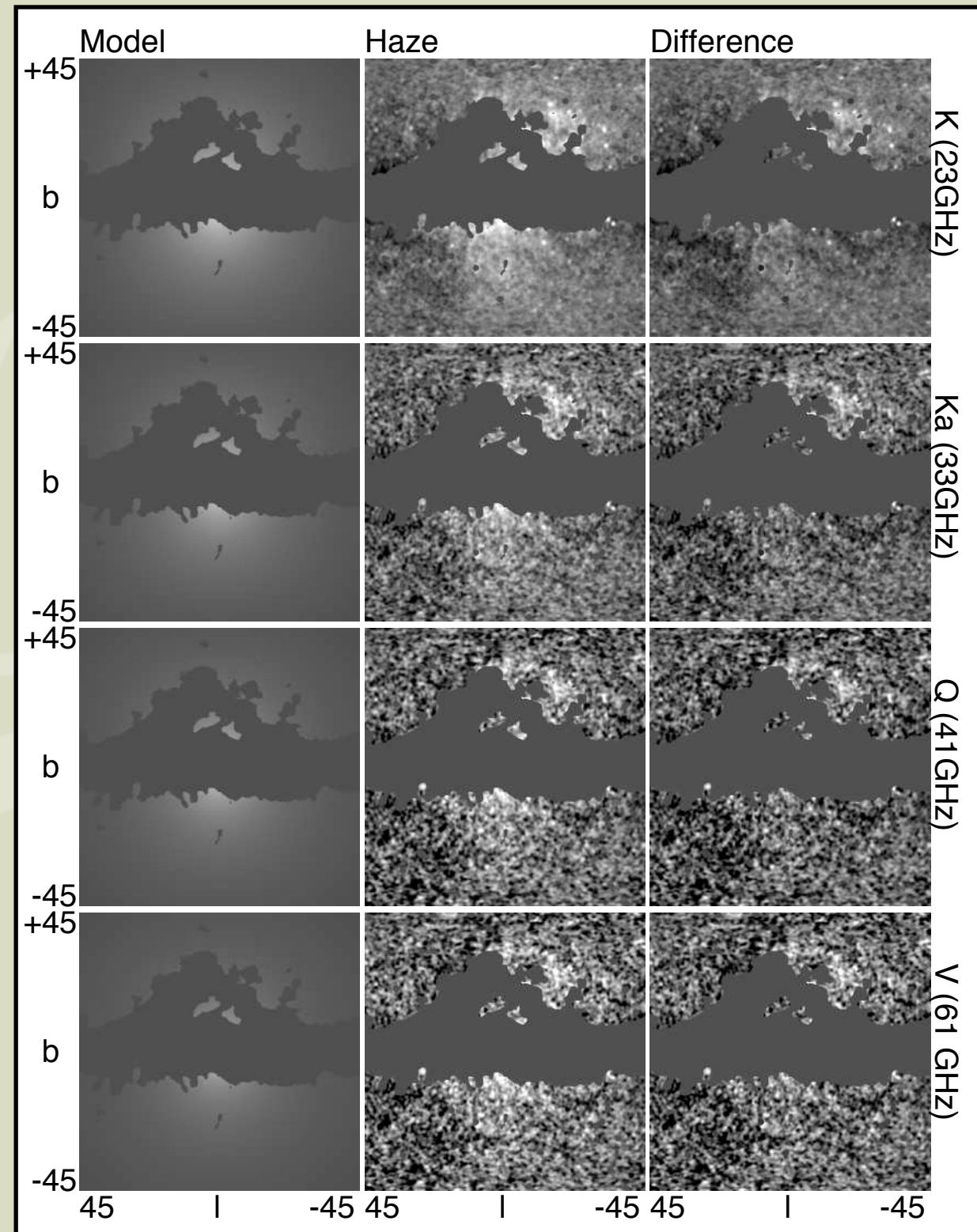
Very nice spectral feature!

WMAP excess as neutralino annihilation

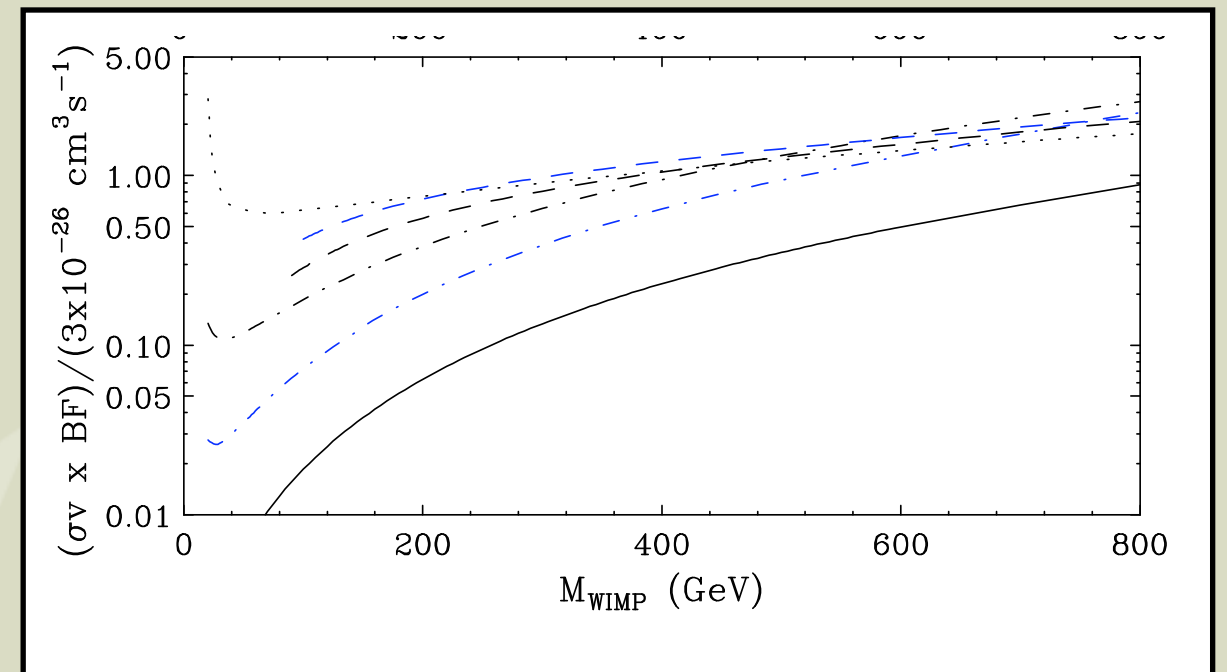
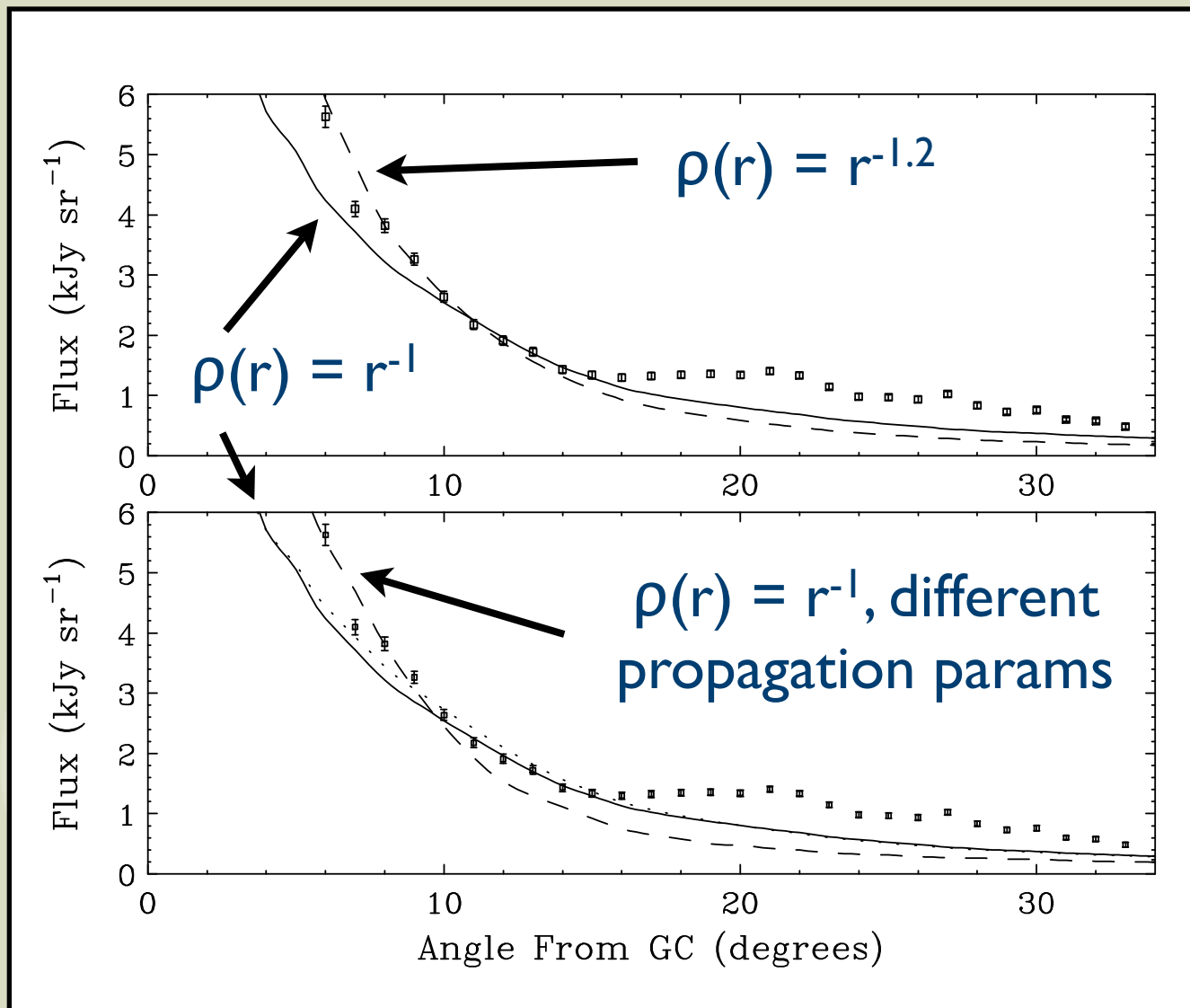
WMAP excess

*Intriguing, but
speculative*

- In the WMAP data there may be an excess towards the galactic center
- Simple model with a 100 GeV neutralino, annihilating, giving e^+e^- that emit synchrotron radiation



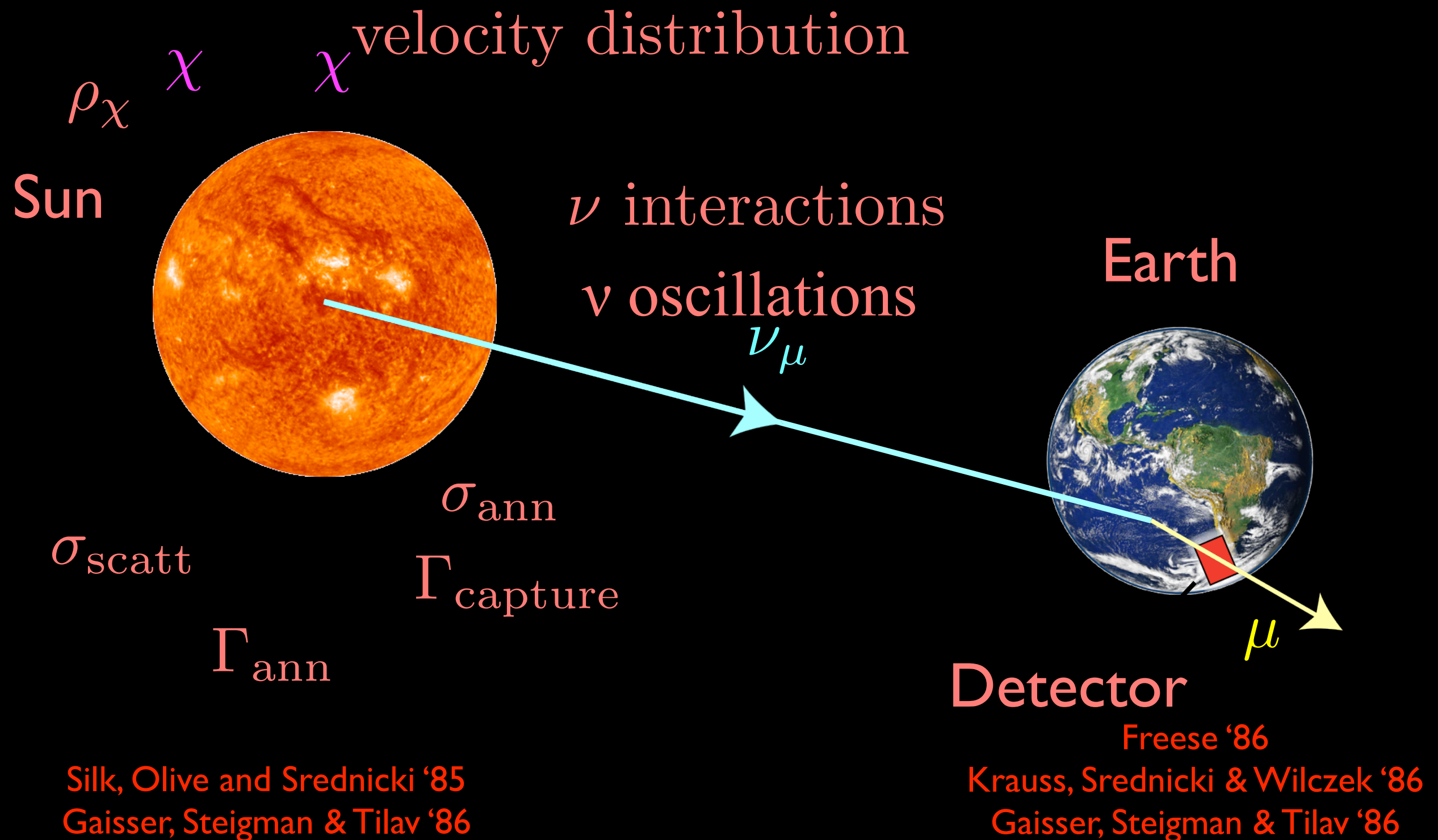
The haze - evidence for dark matter?



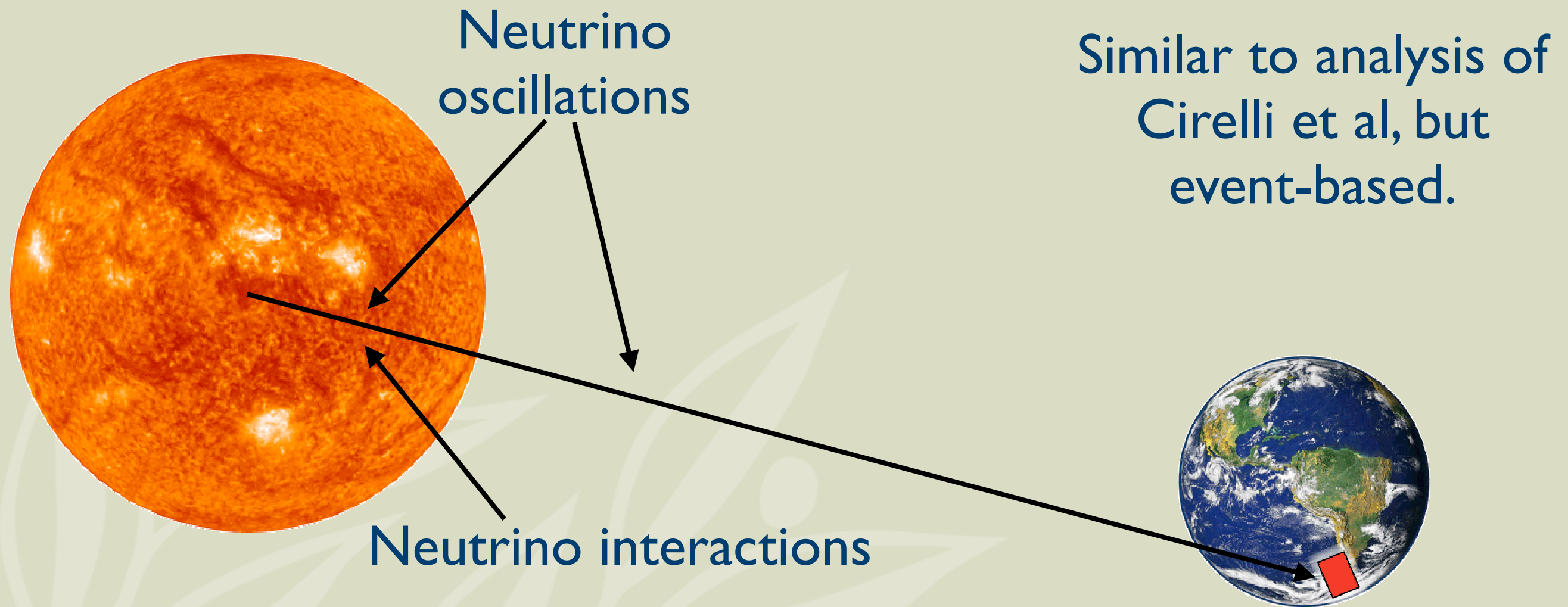
- WIMPs from 100 GeV - few TeV OK
- $\rho(r) = r^{-1.2}$ fits nicely
- Claim: conventional signals (thermal dust, spinning dust, ionized gas and synchrotron emission) does not fit, neither spatially nor spectral shape.
- Should be observable in gamma rays with GLAST

$\chi \chi \rightarrow \dots \rightarrow e^+ e^-$
 $\Rightarrow$ synchrotron emission

Neutralino Capture



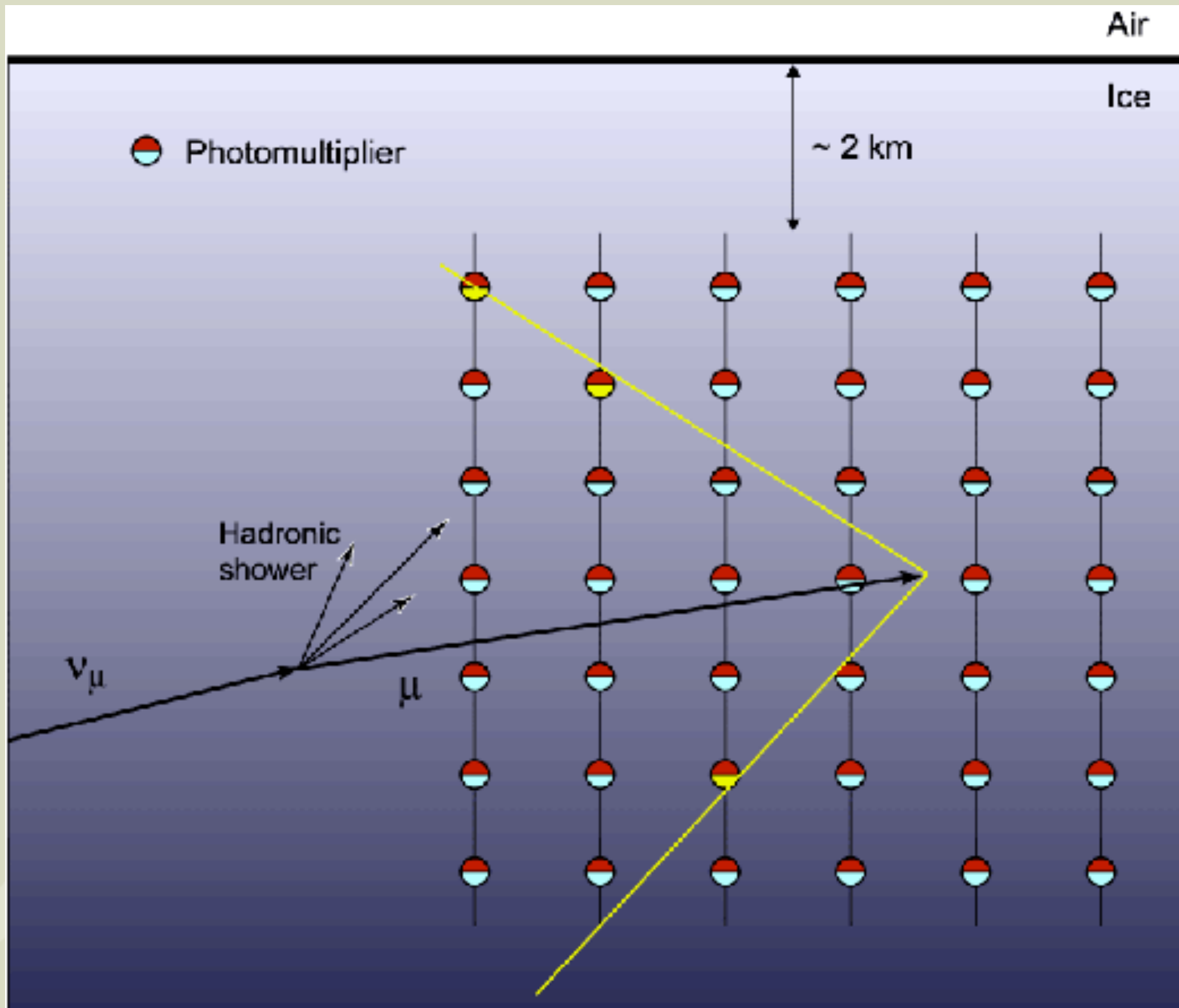
Neutrino oscillations



- New numerical calculation of interactions and oscillations in a fully three-flavour scenario. Regeneration from tau leptons also included.
- **Publicly available code:** WimpSim:WimpAnn + WimpEvent suitable for event Monte Carlo codes: www.physto.se/~edsjo/wimpsim
- Main results will be included in next DarkSUSY release.

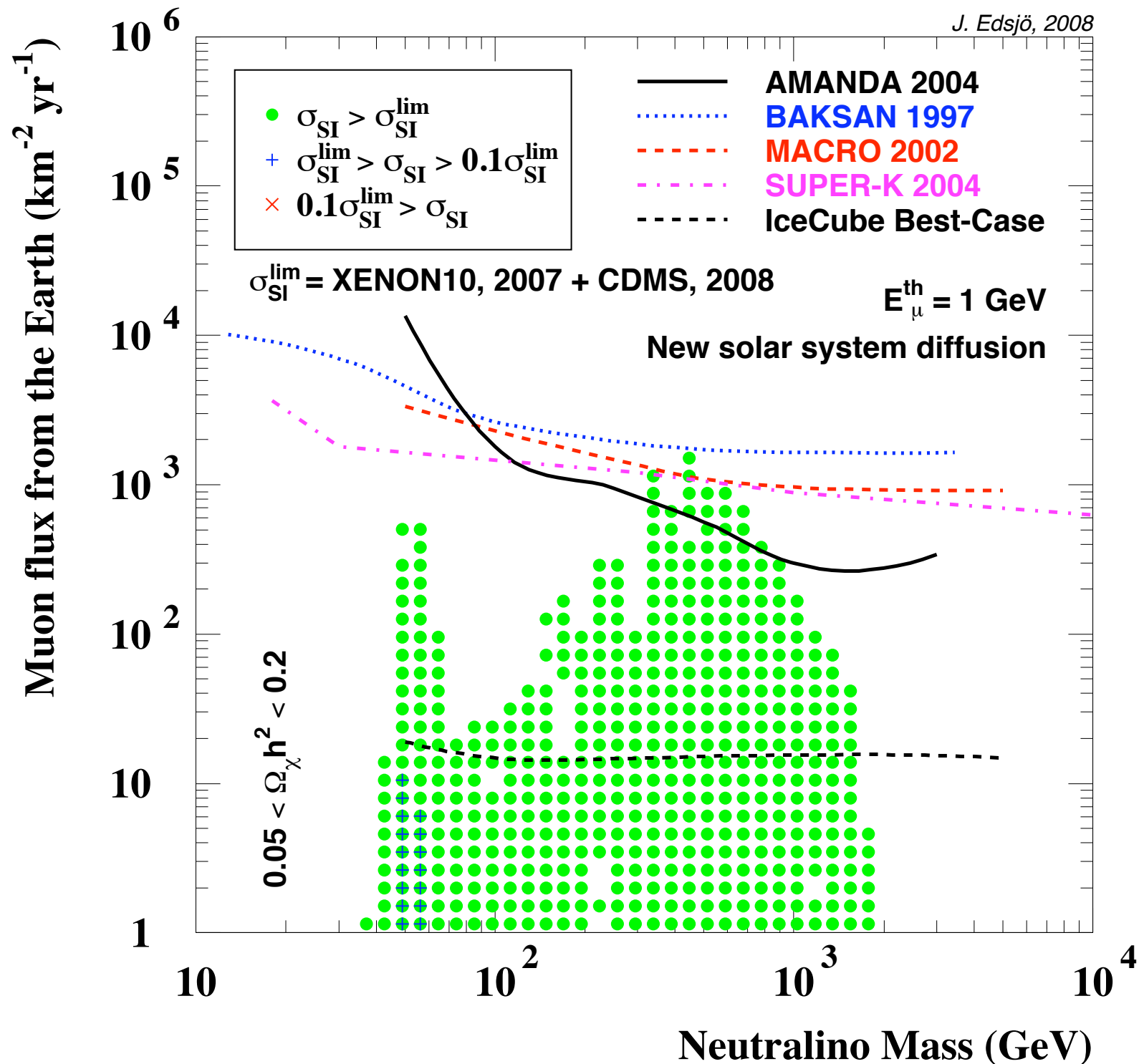
Neutrino Telescopes

how do they work?

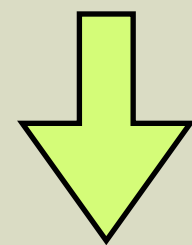


- The neutrino scatters off a nucleus in the ice, producing a muon
- The muon emits Cherenkov radiation
- The PM tubes detect the radiation from which the muon (and neutrino) angle can be reconstructed

Neutrino-induced muon fluxes from the Earth

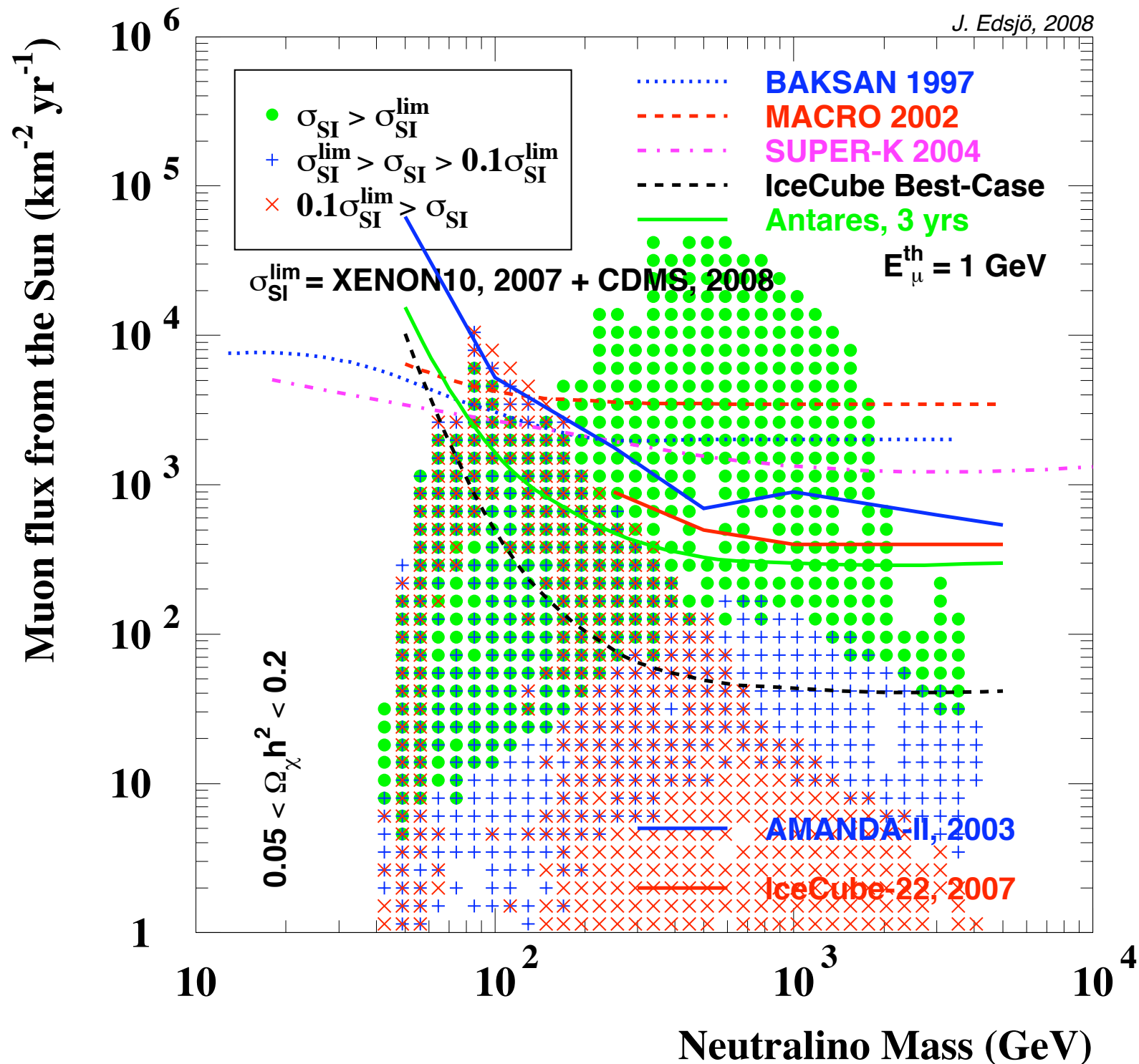


- Direct detection and the neutrino signal from the Earth are both sensitive to the spin-independent scattering cross section



- Large correlation

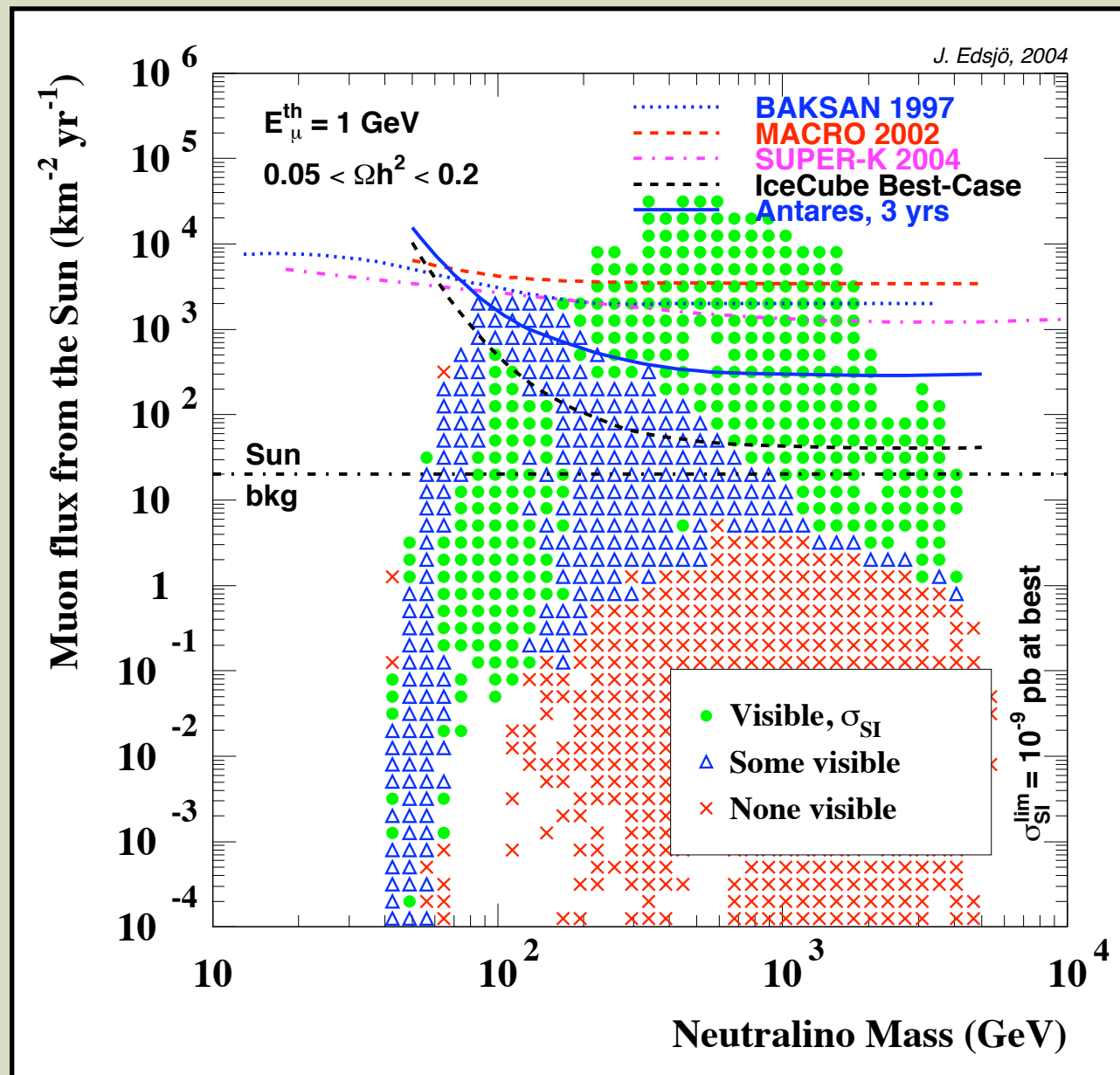
Neutrino-induced muon fluxes from the Sun



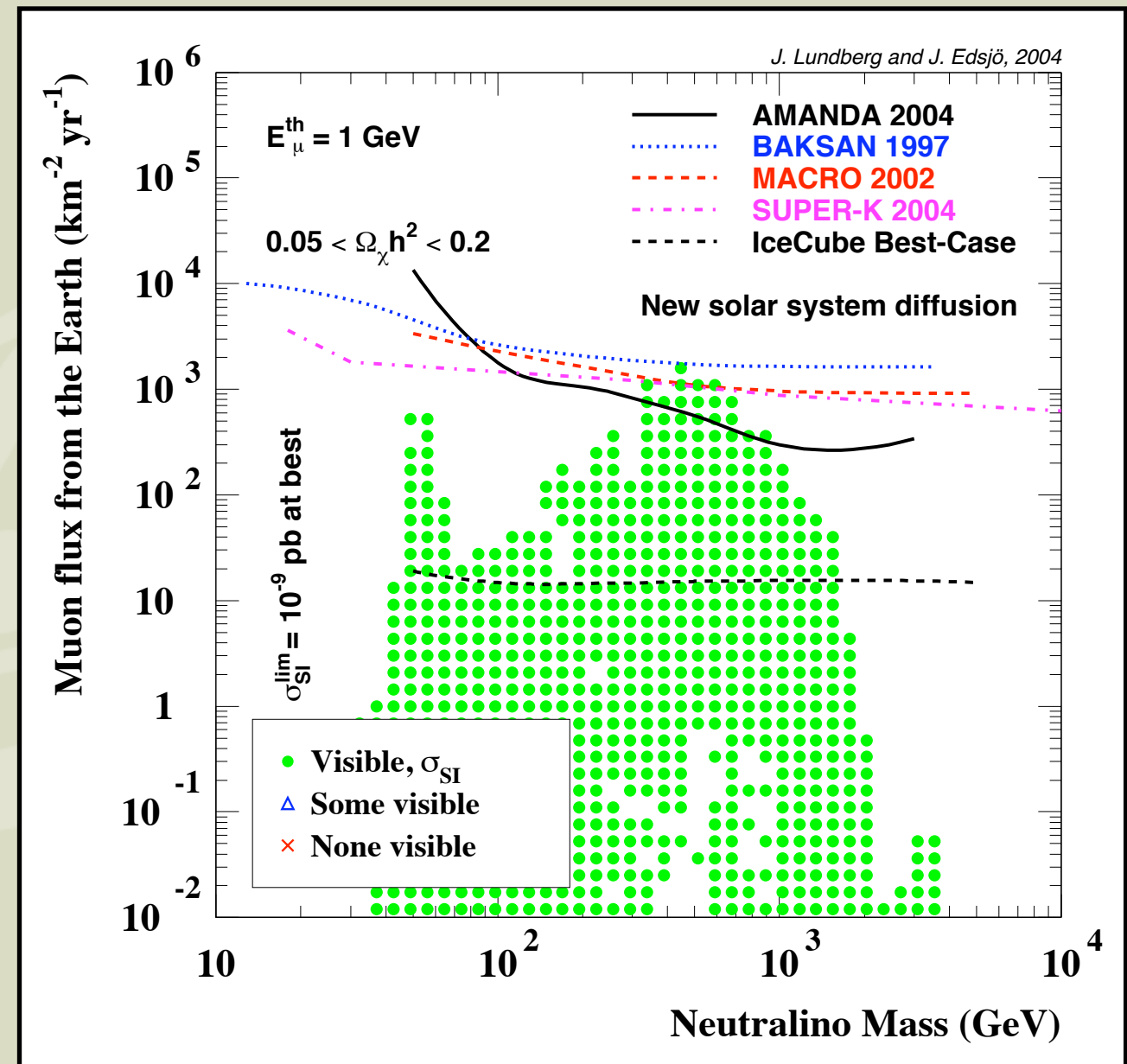
- Compared to the Earth, much better complementarity due to spin-dependent capture in the Sun.

Neutrino-induced fluxes and future direct detection limits

Sun



Earth



Future direct detection limit is assumed to be Ge like with a sensitivity down to 10^{-9} pb .

Comparison of future searches

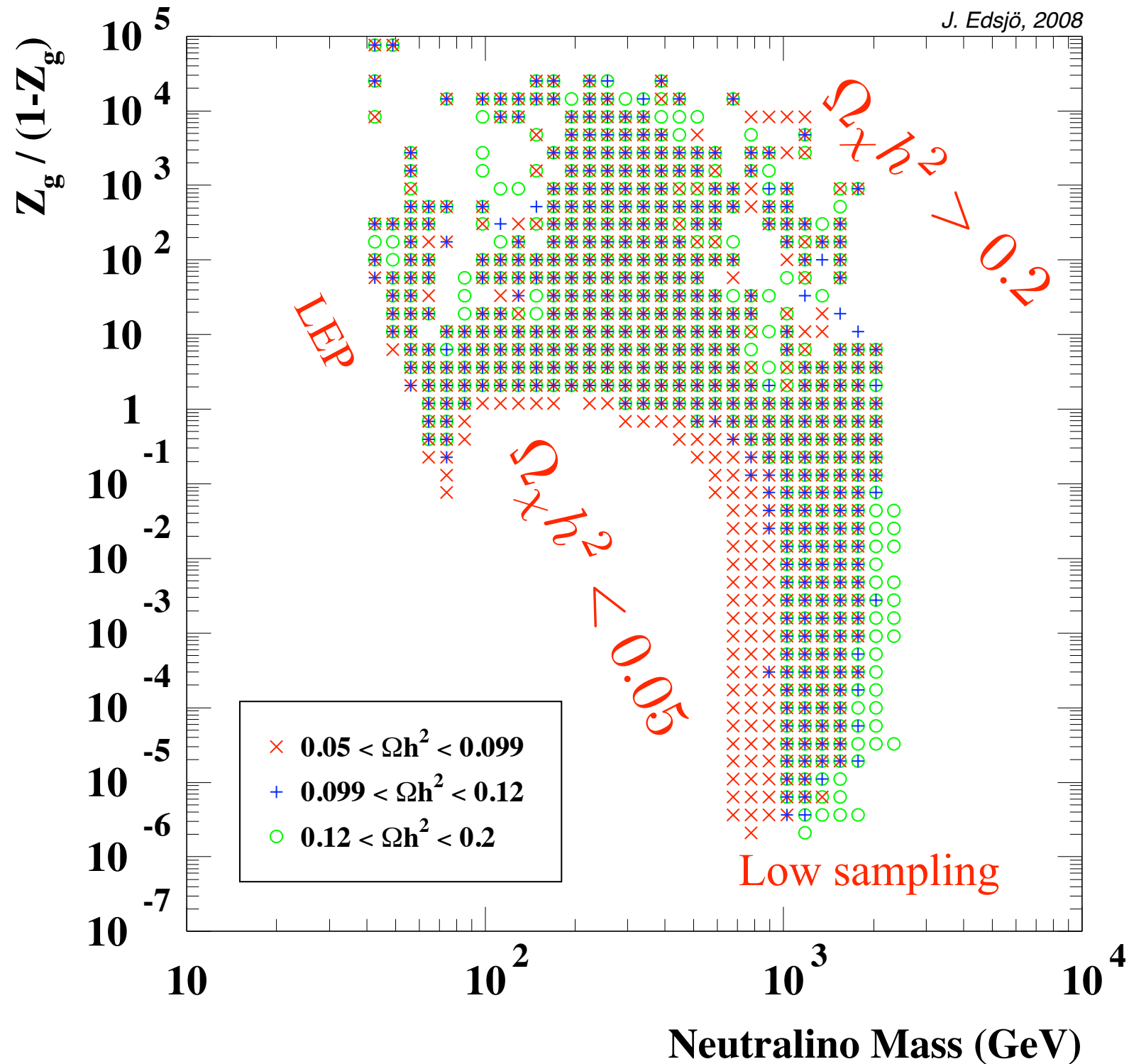
- We will now compare future expected sensitivities in reasonably optimistic scenarios:
 - Cuspy halo profiles (NFW) for cosmic ray signatures (no spike though)
 - Expected sensitivities of various searches in the coming 5–10 years

Comparing future searches in the $m_\chi - Z_g$ parameter space

Gaugino

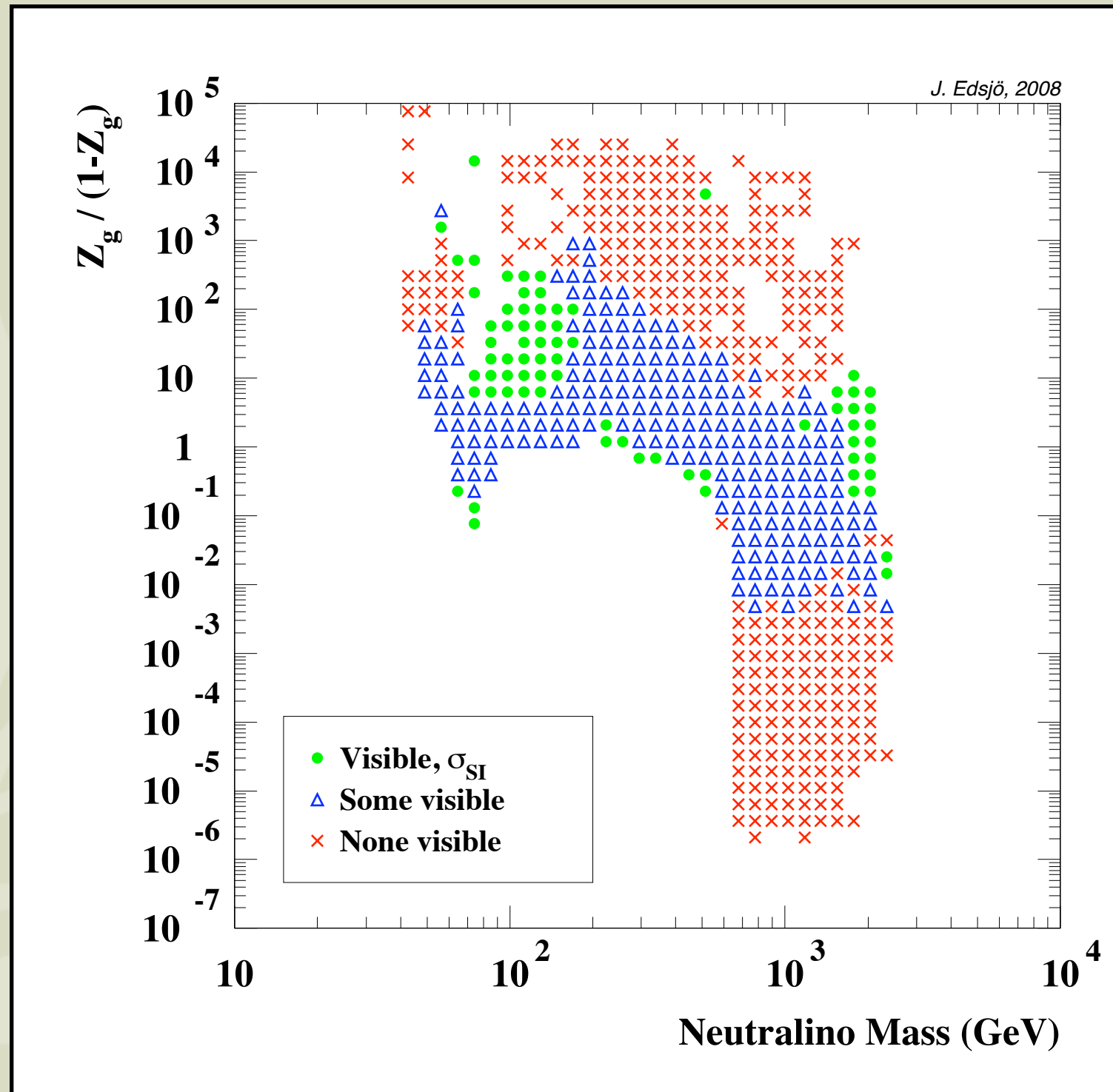
Mixed

Higgsino



Comparison of future searches I

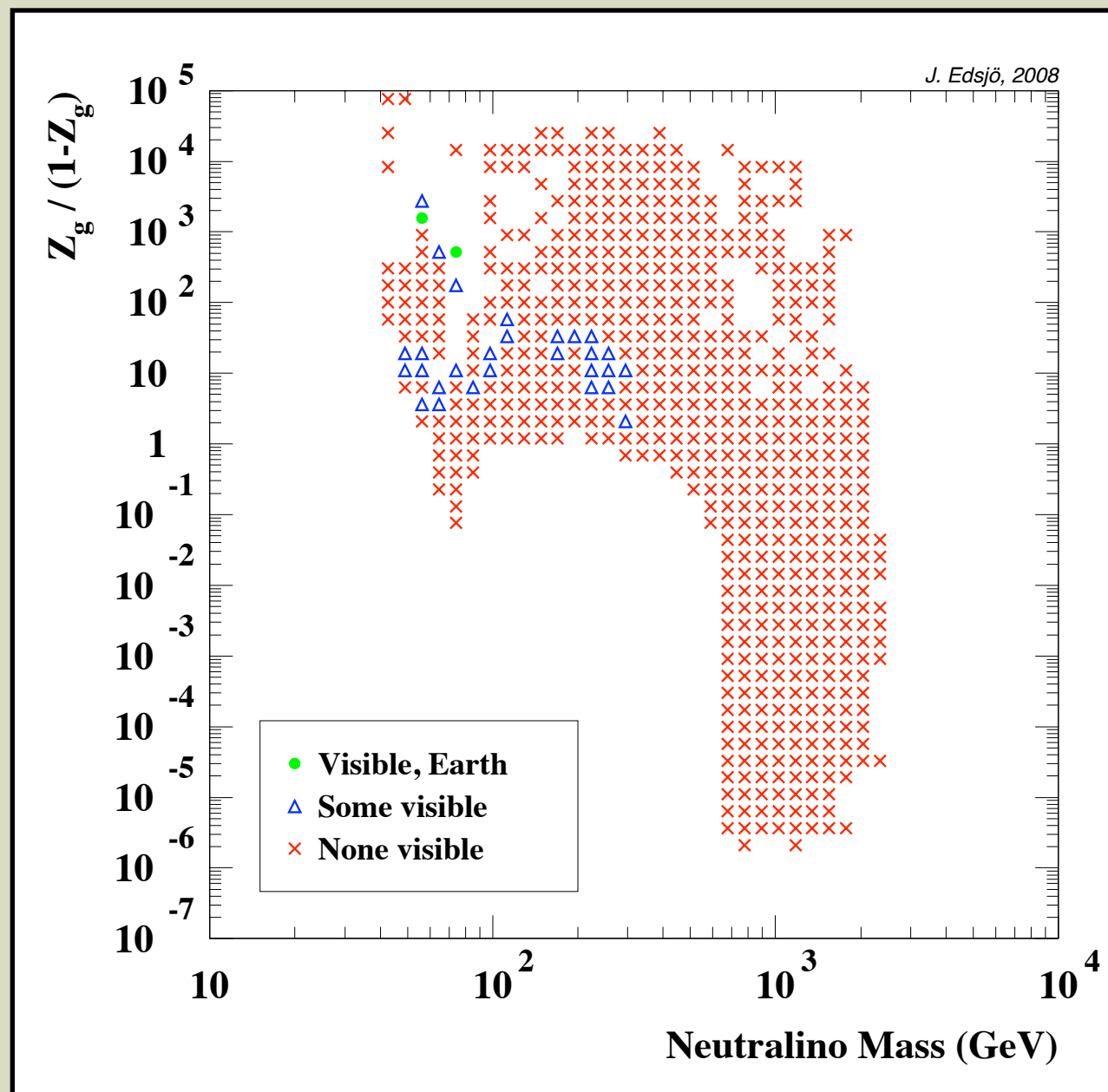
Direct detection, SI



Future limit is assumed to be Ge-like with a sensitivity down to 10^{-9} pb.

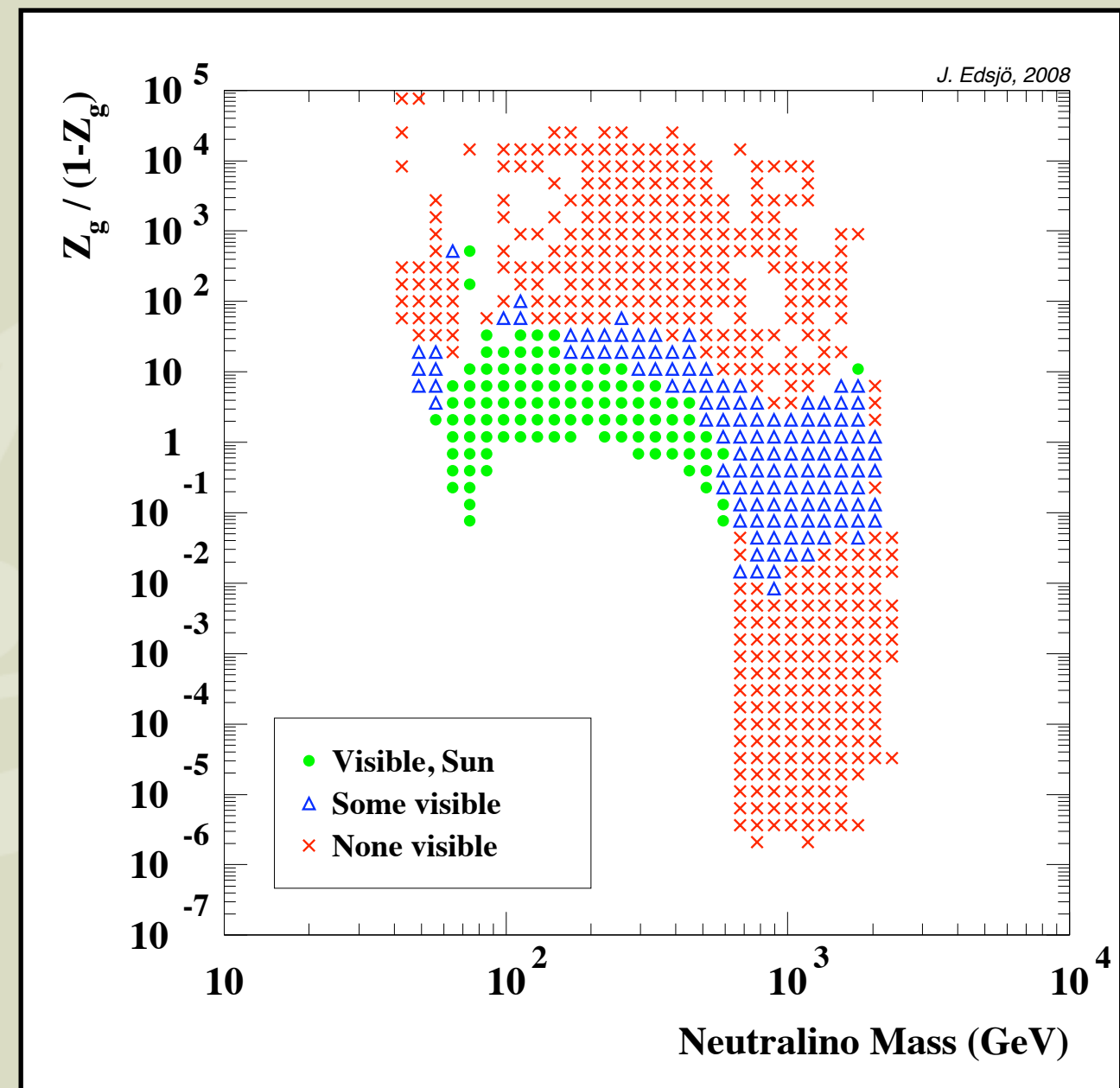
Comparison of future searches II

Earth



IceCube-like, 1 km³ running for 10 years (10 years live time)

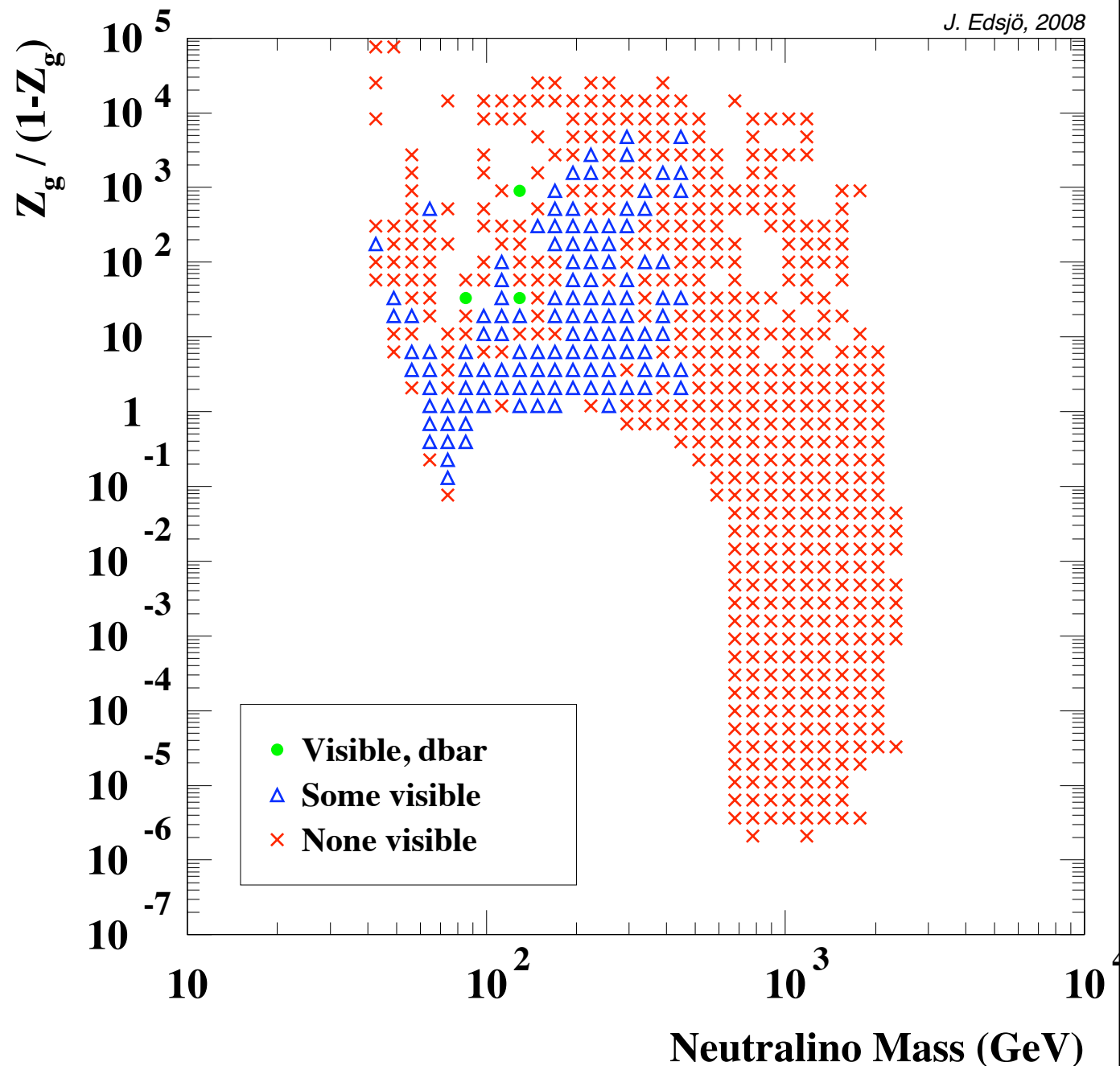
Sun



IceCube-like, 1 km³ running for 10 years (5 years live time)

Comparison of future searches III

Antideuteron

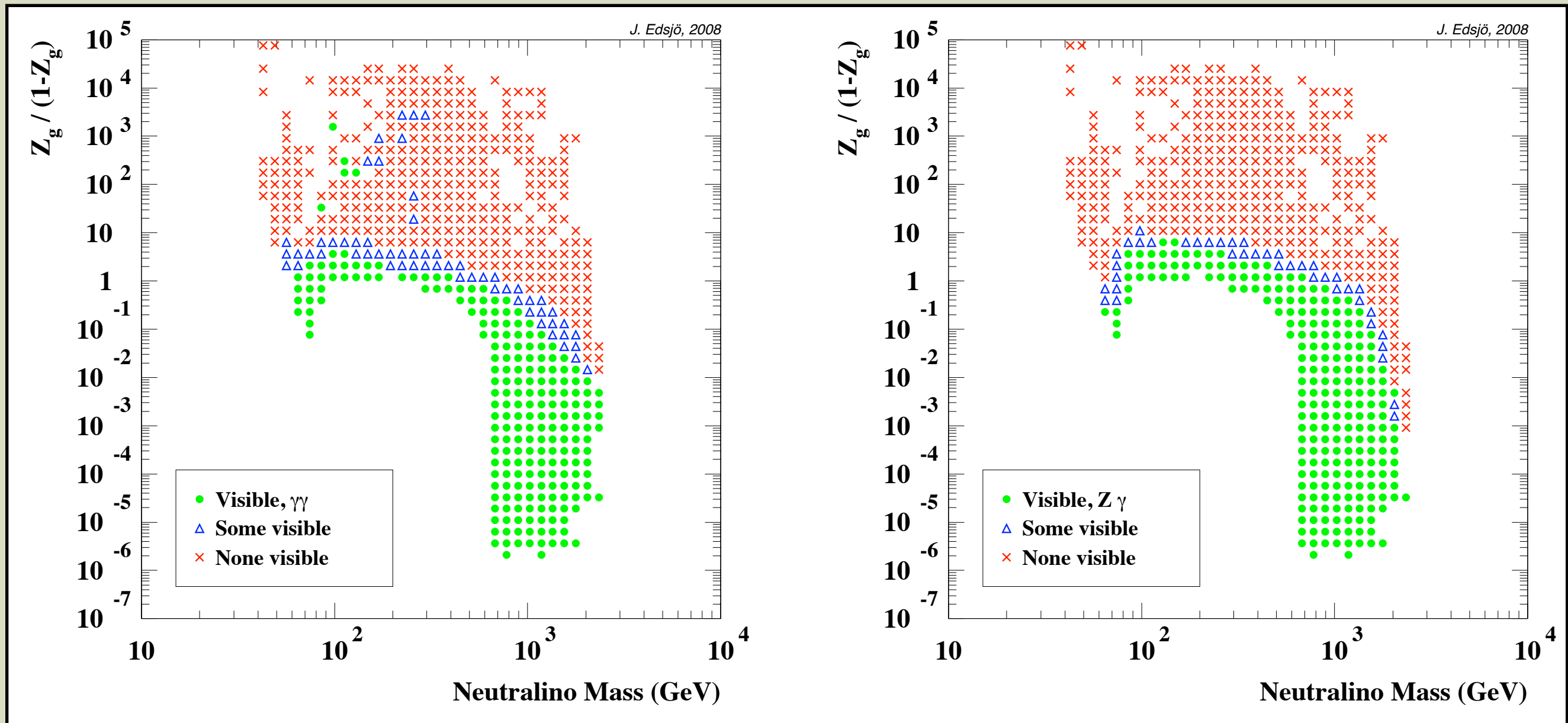


- Compare with future suggested mission GAPS (Gaseous AntiParticle Spectrometer, K. Mori et al, ApJ 566 (2002) 604)
- Require at least one event (background ≈ 0) at low energies with e.g. GAPS
- Antideuteron production yields from F. Donato, N. Fornengo and P. Salati, Phys. Rev. D62 (2000) 043003.

Comparison of future searches IV

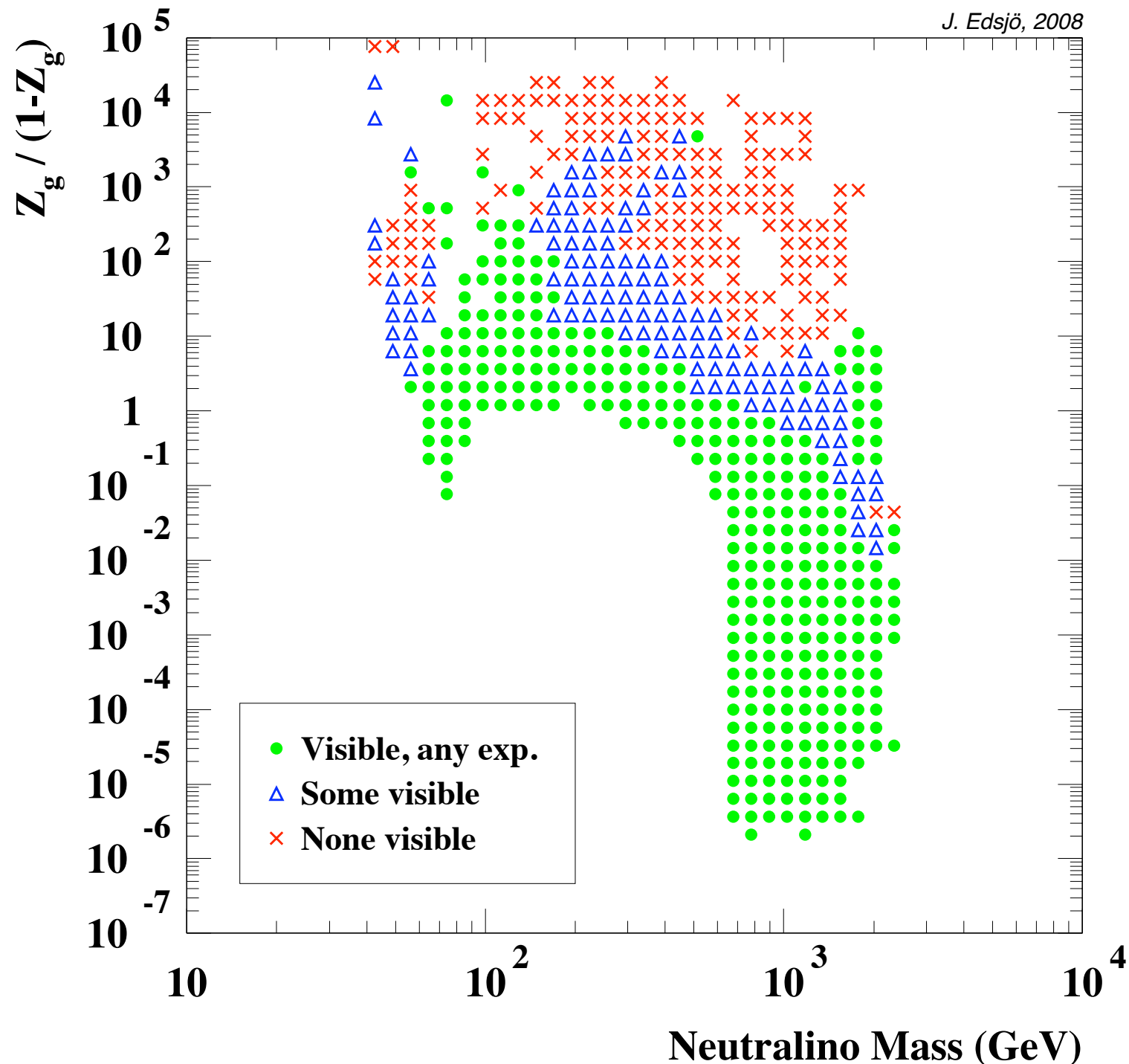
$\gamma\gamma$

$Z\gamma$



Significant signal in ACTs or GLAST towards the galactic center with a NFW profile.

Comparison of future searches V



- Large parts of the MSSM parameter space can be probed by future experiments
- The halo model is assumed to be an optimistic NFW profile.
- LHC e.g., will cut into this plane mainly from the left.

Summary of searches

Signal	High rates	Clear signature
Gamma ray lines	No	Yes
Continuous gammas	Yes	No
Antiprotons from halo	Yes	No
Antideuteron from halo	Yes	No/Yes
Positrons from halo	No	Yes
Neutrinos from Sun	Yes	Yes
Neutrinos from Earth	No	Yes
Signals from galactic center	Yes	No
Direct detection	Yes	Yes
Microwave haze	Yes?	No?
Dark Stars	Maybe	Maybe

Conclusions

- Detection prospects of WIMPs (neutralinos, Kaluza-Klein particles, ...) are reasonably good.
- For 'standard' halo models, direct detection seems more promising than the neutrino-flux from the Earth. The neutrino-flux from the Sun is complementary to direct detection due to spin-dependent capture in the Sun
- Gamma rays searches with GLAST have very good prospects
GLAST is now in orbit!!!
- Searching for various charged cosmic rays can also prove fruitful, even if the astrophysical uncertainties can be large. Searching for antideuterons seems promising.

IDM 2008

idm2008.albanova.se

18-22 August 2008

AlbaNova, Stockholm, Sweden

- Dark matter candidates
- Dark matter direct searches
- Dark matter indirect searches
- Connections with accelerator searches
- Halo models and structure formation

7th International Workshop on Identification of Dark Matter

- Gravitational lensing
- Neutrino physics
- Cosmology and dark energy



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Day

June 16, 9-16, FB51, AlbaNova

- Lectures
- Hands-on sessions
- Register on <http://agenda.albanova.se/conferenceDisplay.py?confId=802> if you wish to attend