Indirect rates

DarkSUSY 4.2
(pre-release, trunk @ rev 231)

DarkSUSY day, Stockholm, June 16, 2008

Indirect rates

- Gamma rays from the halo
- Antiprotons from the halo
- Antideuterium from the halo
- Positrons from the halo
- Neutrinos from the Sun/Earth

Gamma rays

GLAST in orbit and first survey run tested!

- Continuum emission (from quark jets, π^0's)
- Line emission ($\gamma\gamma$ and $Z\gamma$)
- Internal bremsstrahlung photons
- Routines to calculate the line of sight integral for different halo profiles

Why gamma rays?

- Rather high rates
- No attenuation (except from very close to dense sources)
- Point directly back to the source
- No diffusion model uncertainties as for charged particles
- There can be clear spectral signatures to look for

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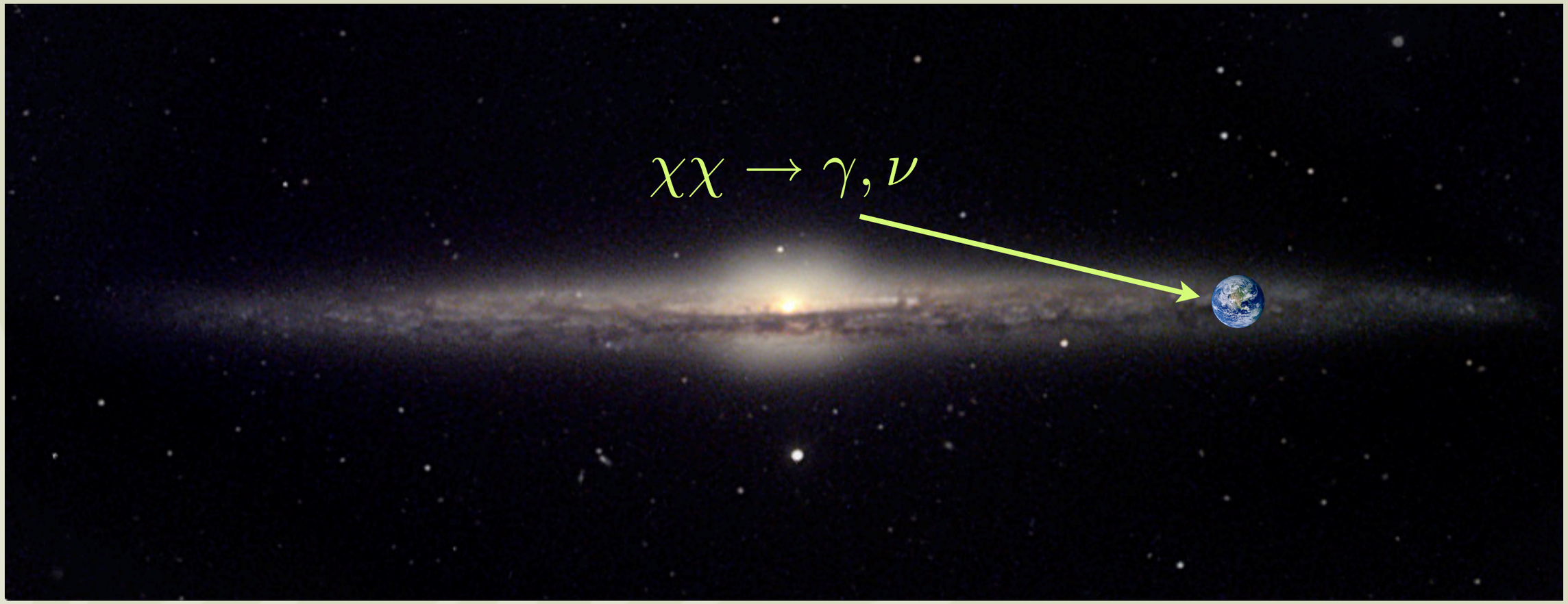
Annihilation in the halo



- Gamma rays can be searched for with e.g. Air Cherenkov Telescopes (ACTs) or GLAST (launch June 7, 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

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

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

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

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

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

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

with

Focus on this factor!

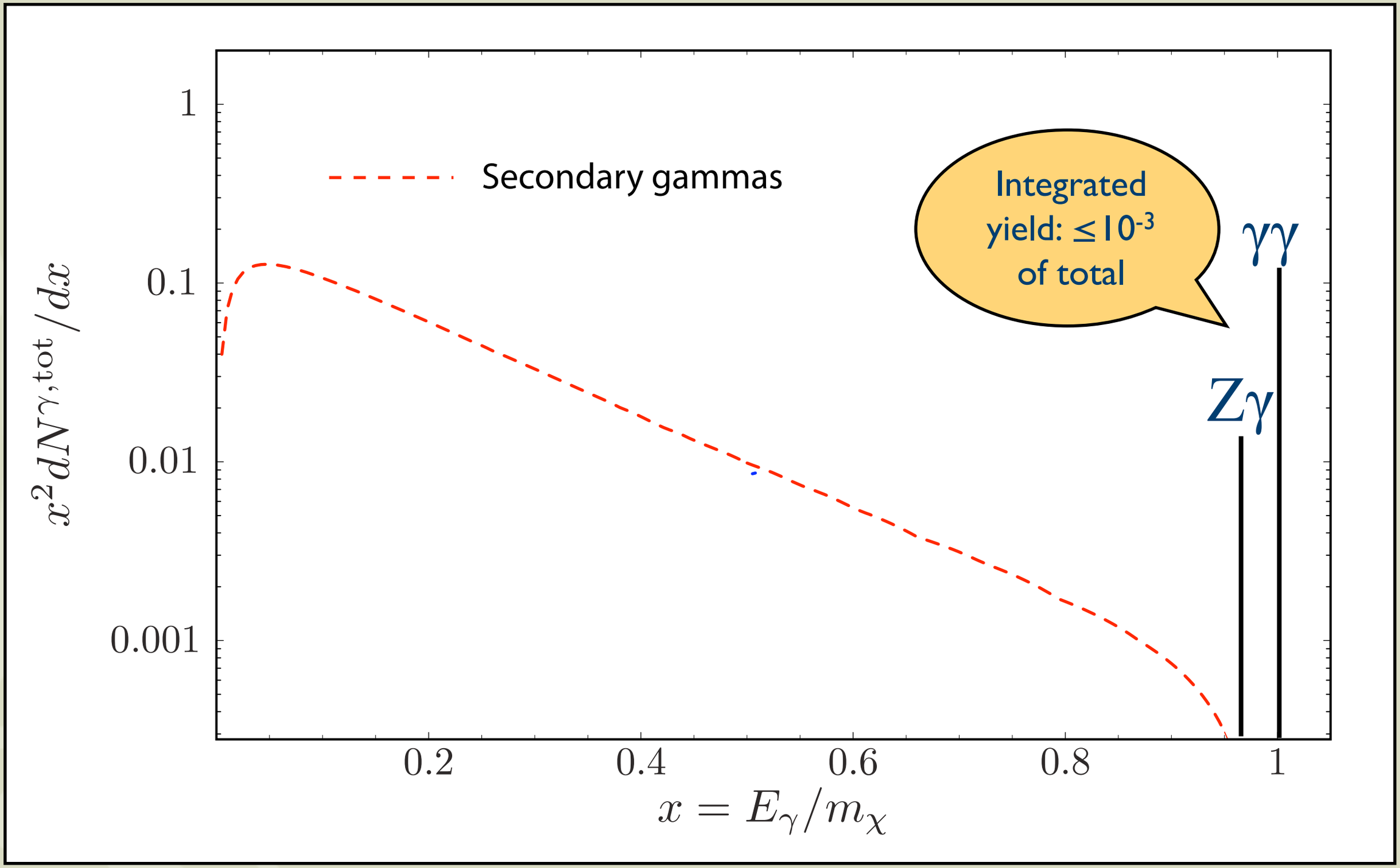
$$S = N_\gamma \frac{\langle \sigma v \rangle}{10^{-29}\ \mathrm{cm}^3\ \mathrm{s}^{-1}} \left(\frac{100\ \mathrm{GeV}}{m_\chi} \right)^2$$

Particle physics (SUSY, ...)

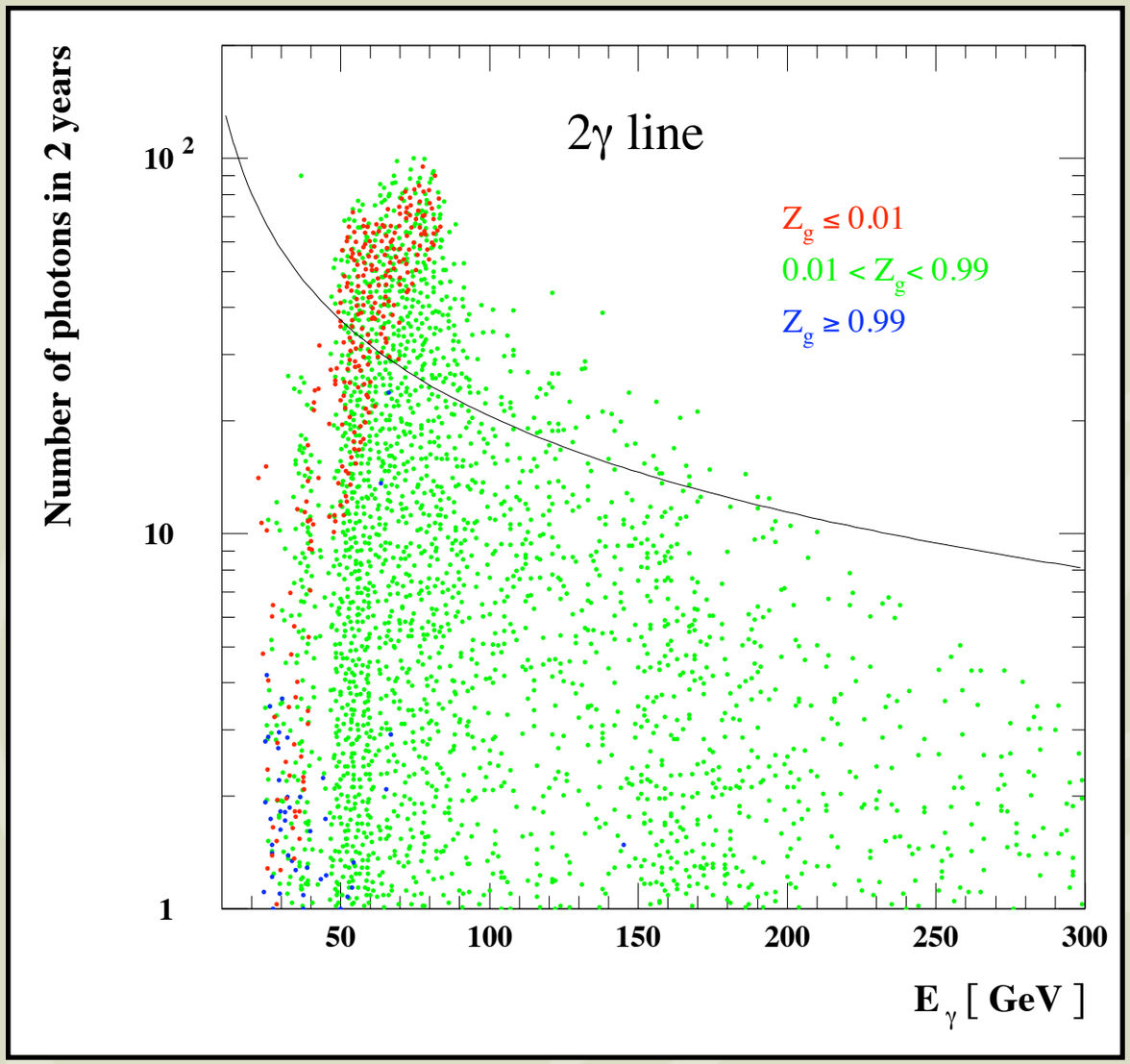
$$\langle J(\eta, \Delta\Omega) \rangle = \frac{1}{8.5\ \mathrm{kpc}} \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{\text{line of sight}} \left(\frac{\rho(l)}{0.3\ \mathrm{GeV/cm}^3} \right)^2 dl(\eta) d\Omega$$

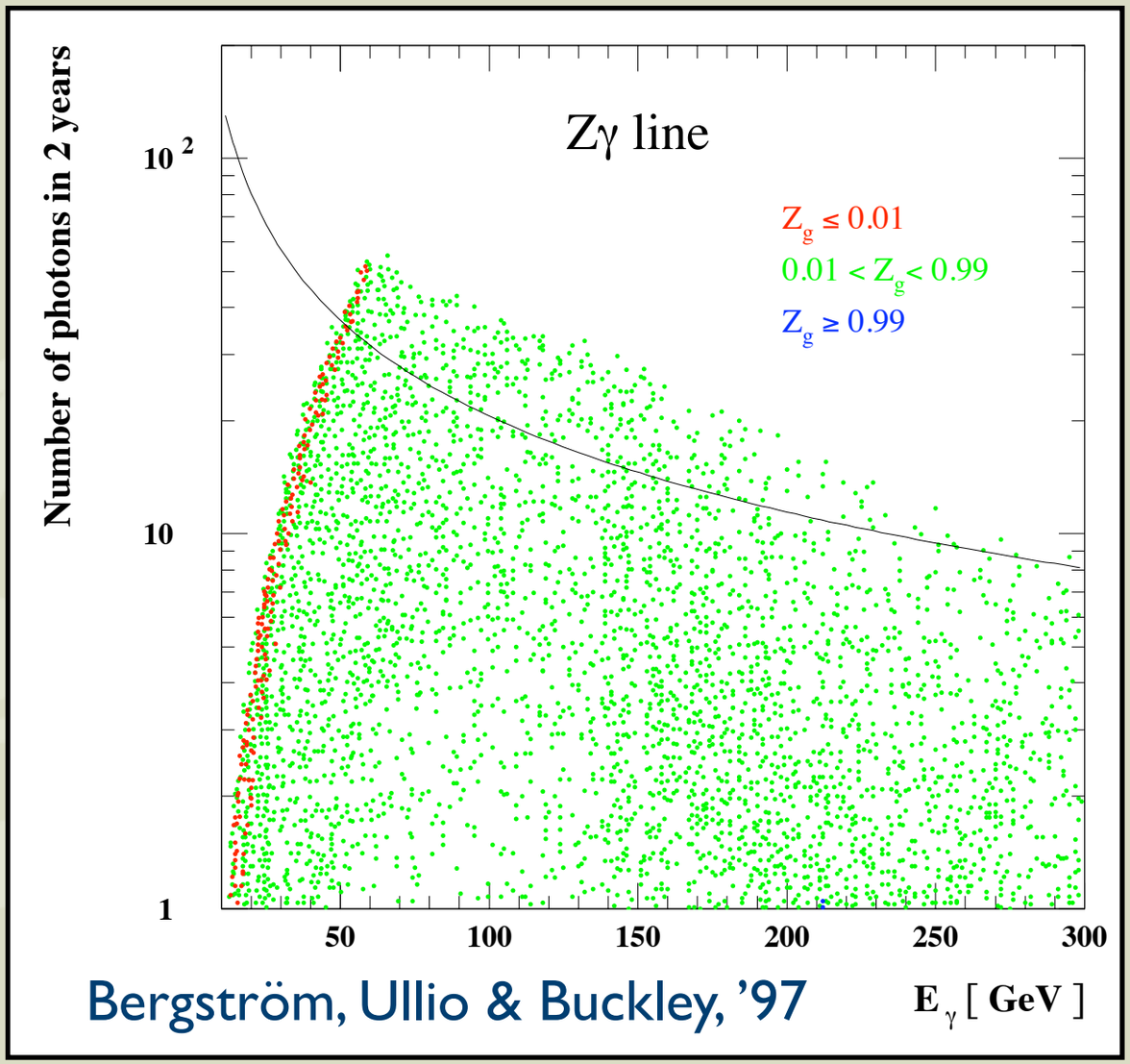
Astrophysics

Typical gamma ray spectrum



Gamma lines – rates in GLAST





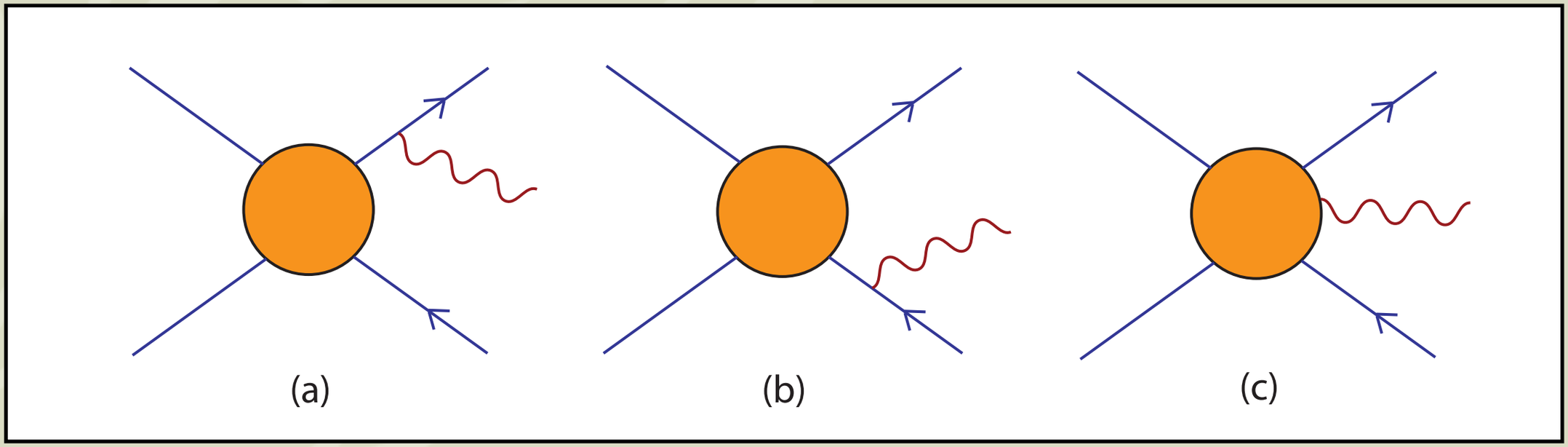
Bergström, Ullio & Buckley, '97

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

GLAST launch,
June 7, 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

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

- How large are these different contributions?

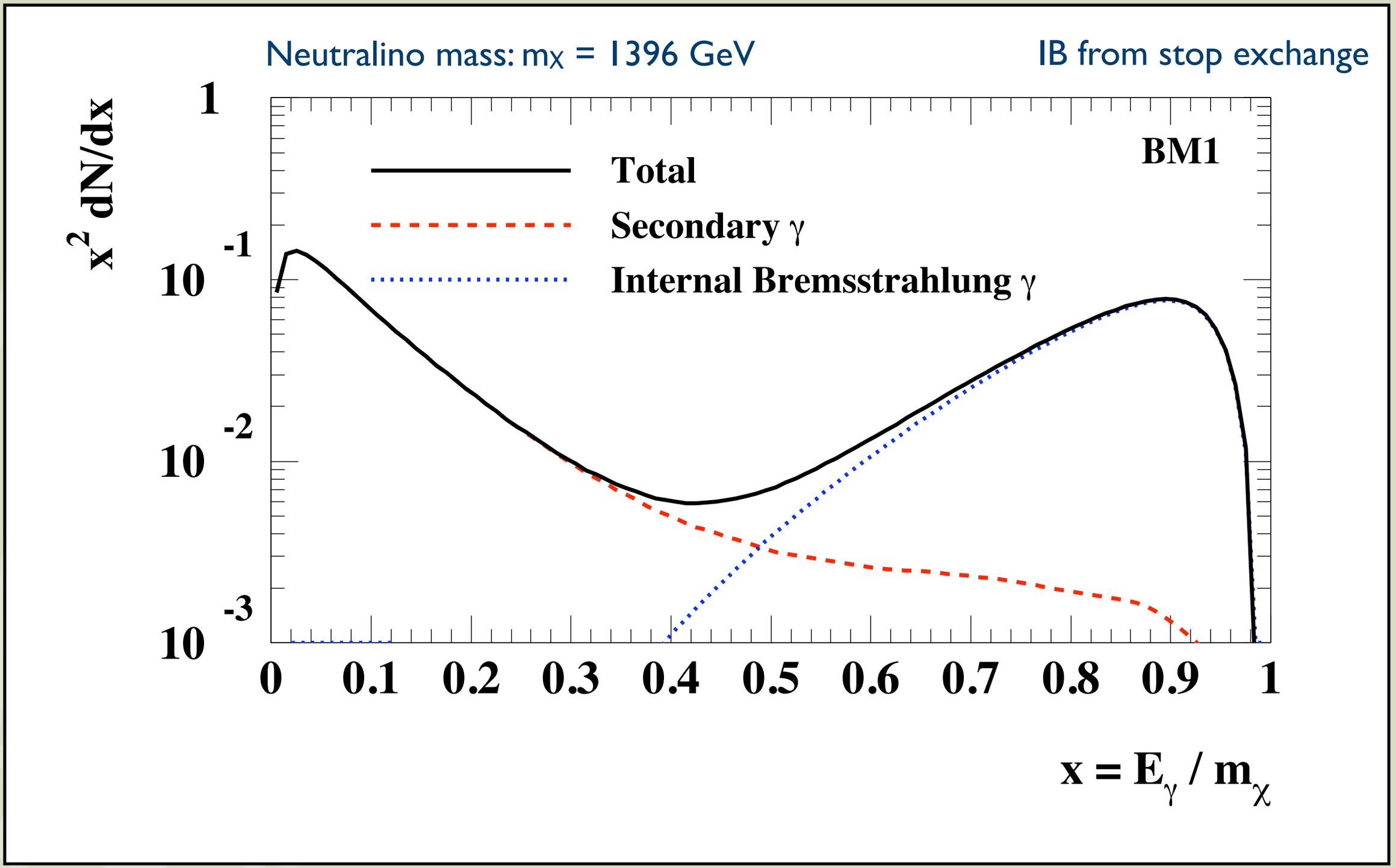
How big are these contributions for neutralinos?

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

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

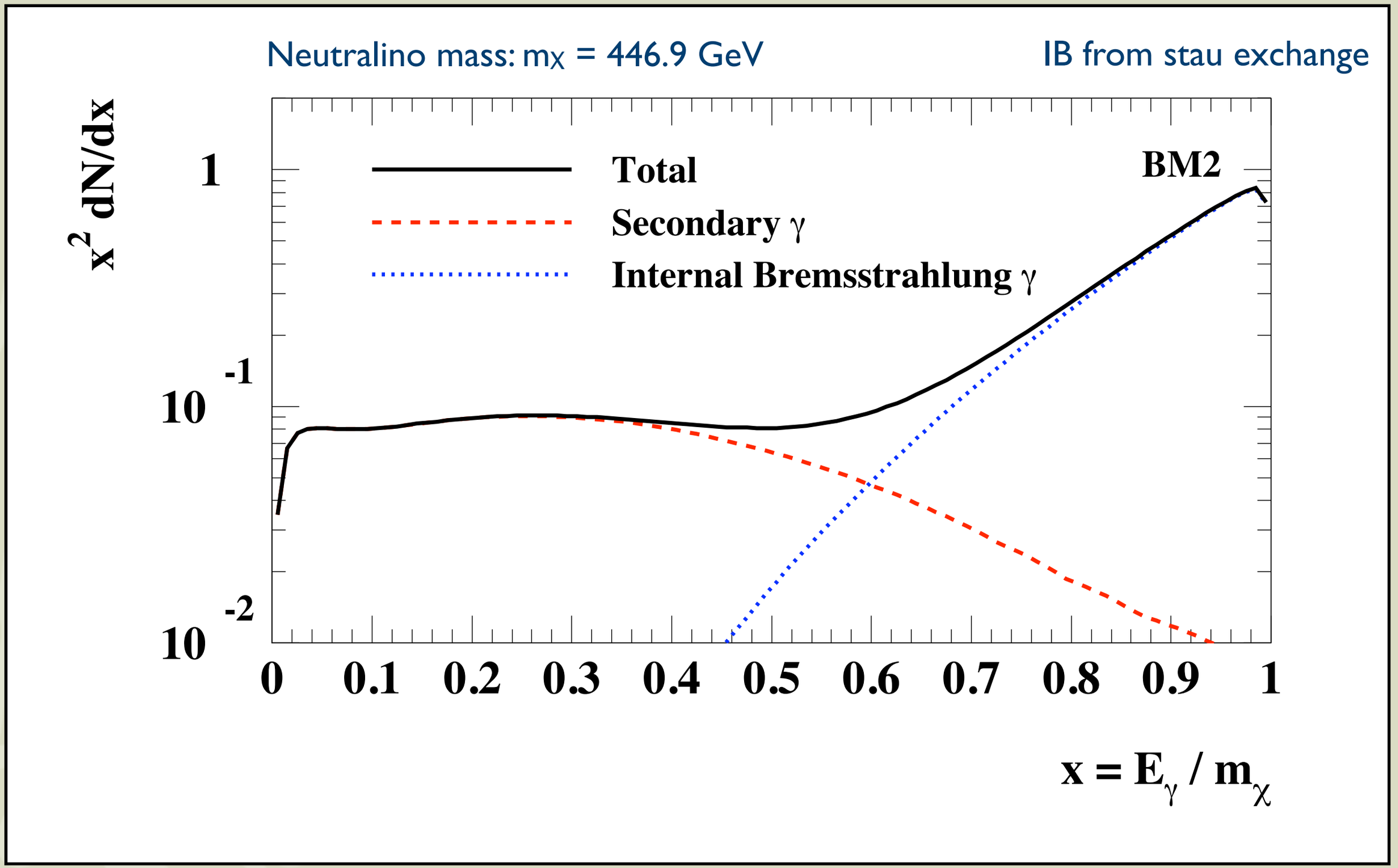
- However, when internal bremsstrahlung photons are added, the helicity suppression no longer holds. The cross section can then increase, even though we are punished by an additional factor of α
- These photons can in many cases dominate at high energies

Gamma ray spectrum including IB photons I



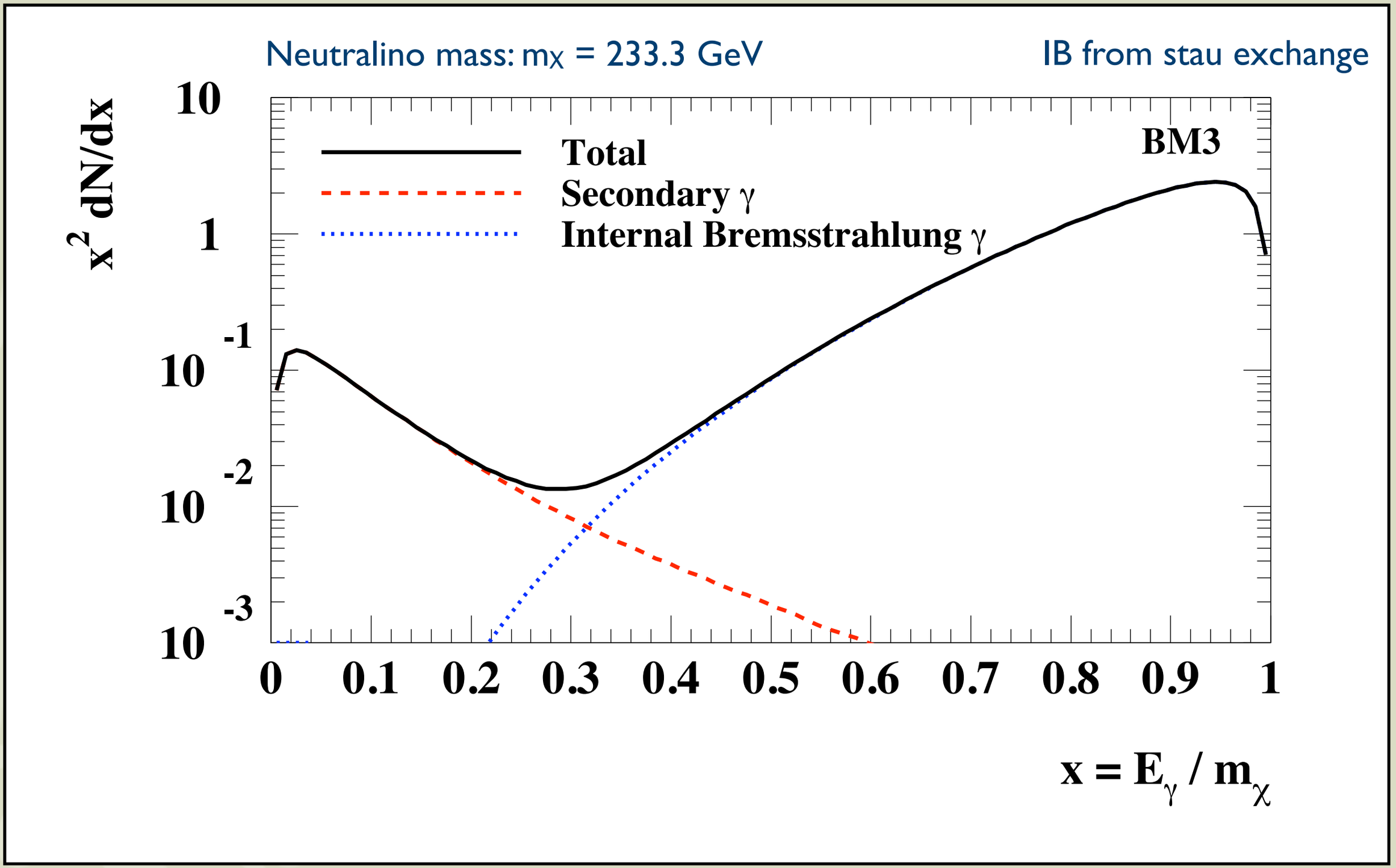
T. Bringmann, L. Bergström and J. Edsjö, arXiv: 0710.3169, JHEP 01 (2008) 049

Gamma ray spectrum including IB photons II



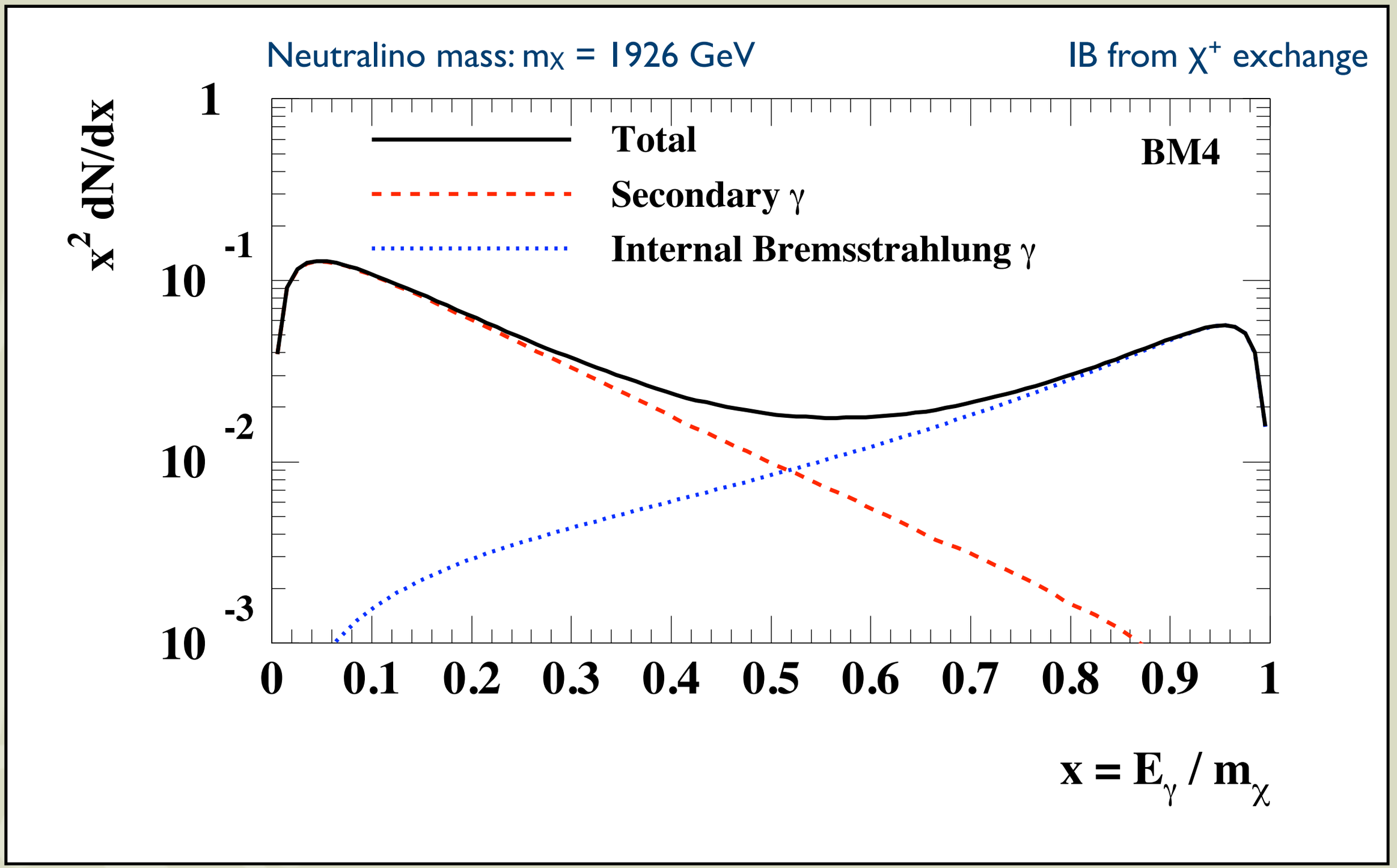
T. Bringmann, L. Bergström and J. Edsjö, arXiv: 0710.3169, JHEP 01 (2008) 049

Gamma ray spectrum including IB photons III



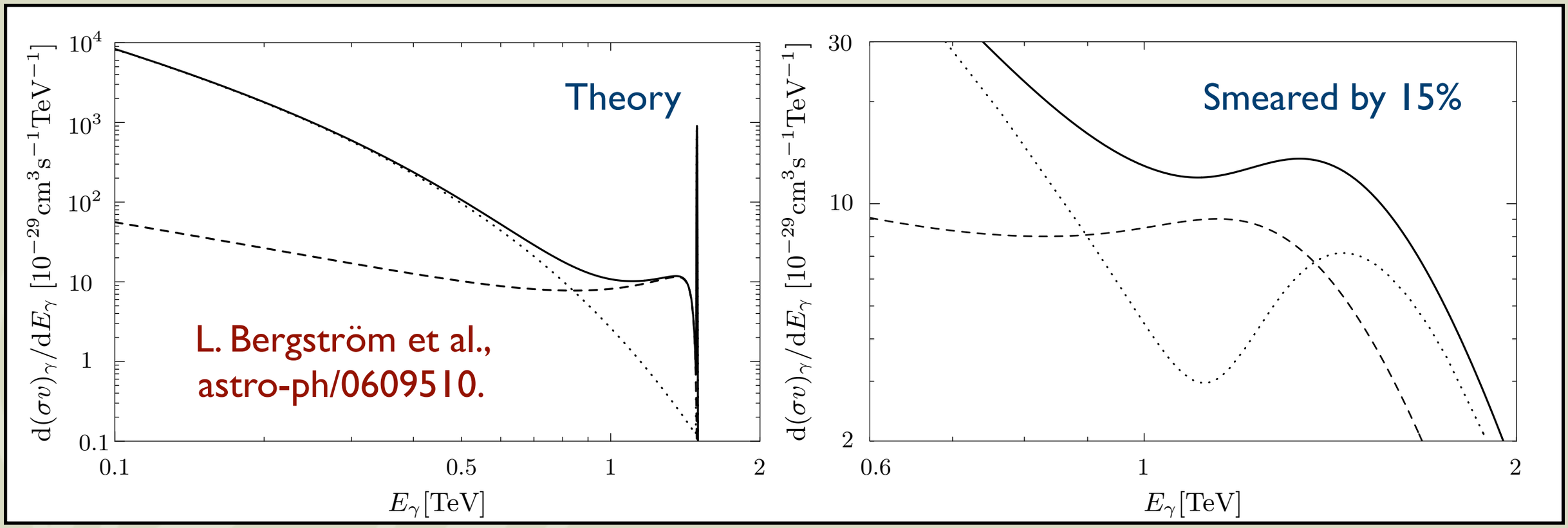
T. Bringmann, L. Bergström and J. Edsjö, arXiv: 0710.3169, JHEP 01 (2008) 049

Gamma ray spectrum including IB photons IV



T. Bringmann, L. Bergström and J. Edsjö, arXiv: 0710.3169, JHEP 01 (2008) 049

Example of experimental smearing



- W^+W^- channel via $\chi^\pm$ exchange

More quantitative...

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

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

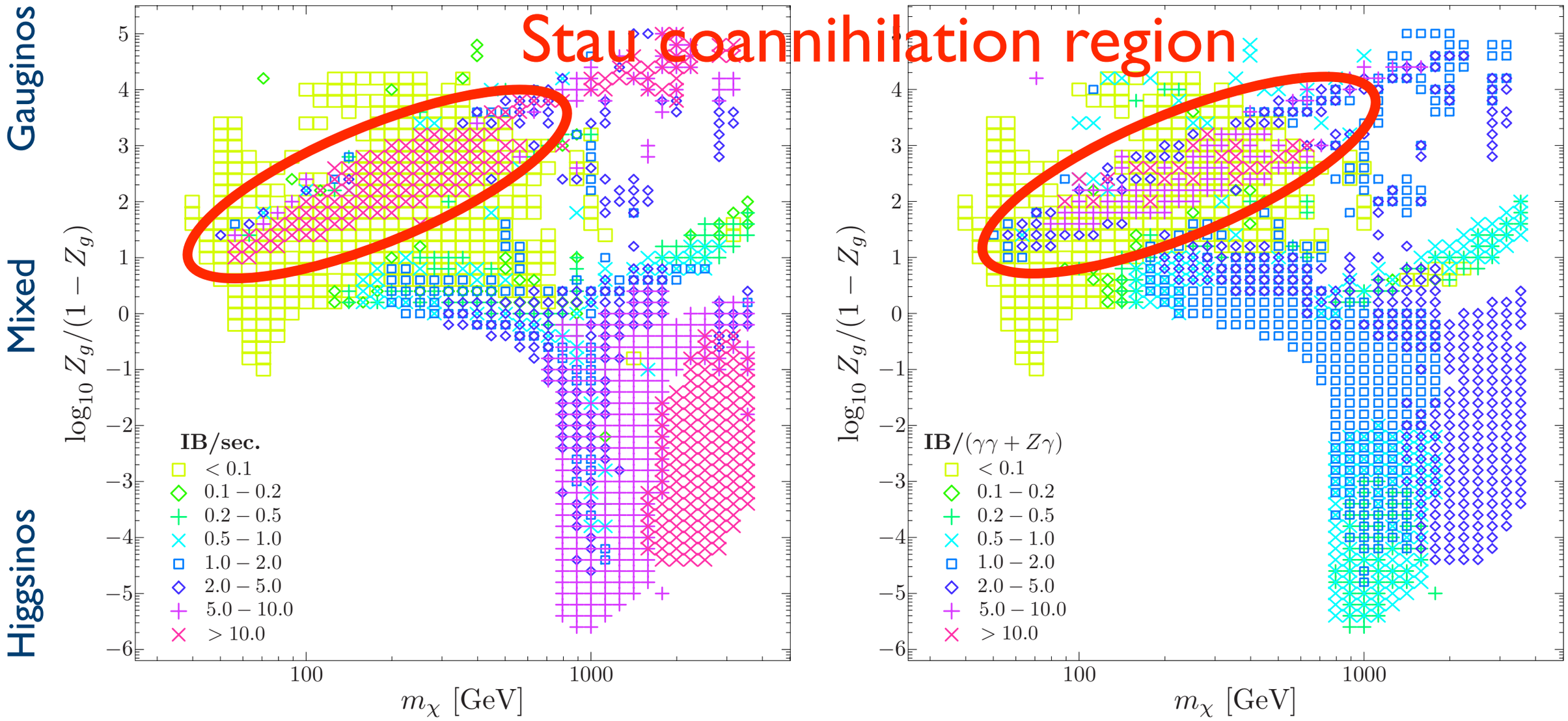
and divide S into the different parts

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

Internal Bremsstrahlung

When is it important?

MSSM and mSUGRA scans

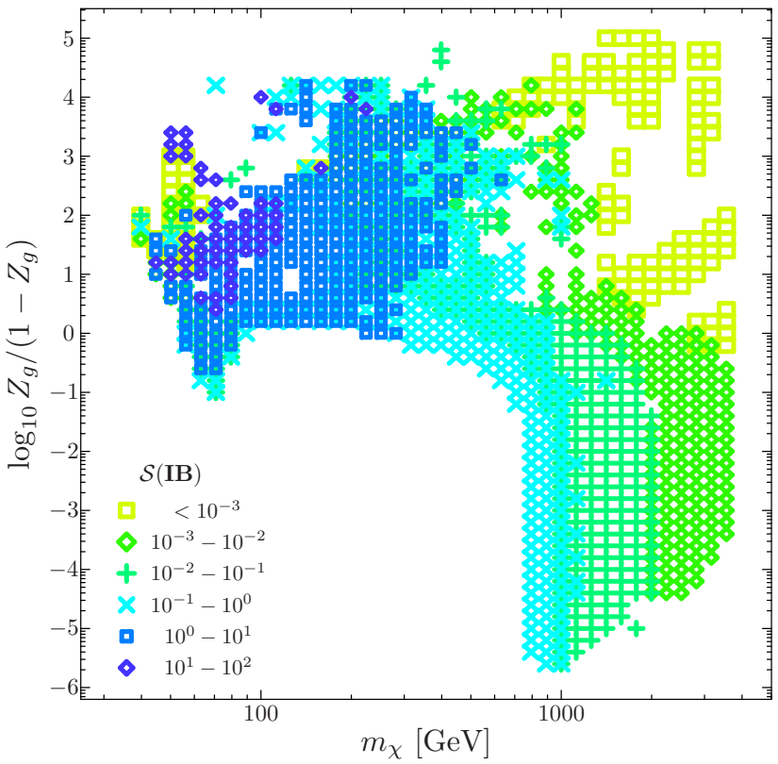


All models OK with WMAP and accelerator constraints. IB>0.6m_χ

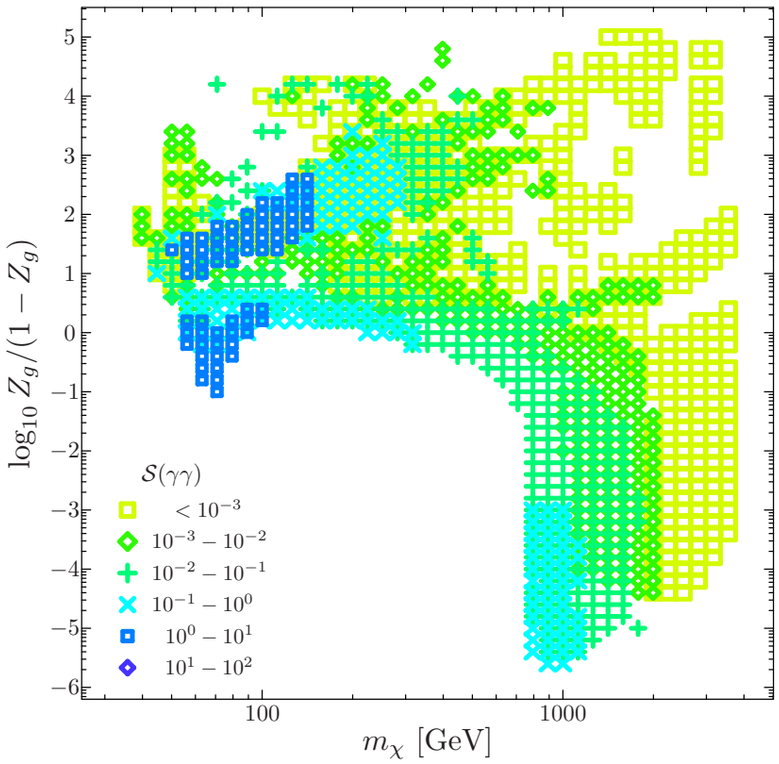
T. Bringmann, L. Bergström and J. Edsjö, arXiv: 0710.3169, JHEP 01 (2008) 049

Absolute strengths

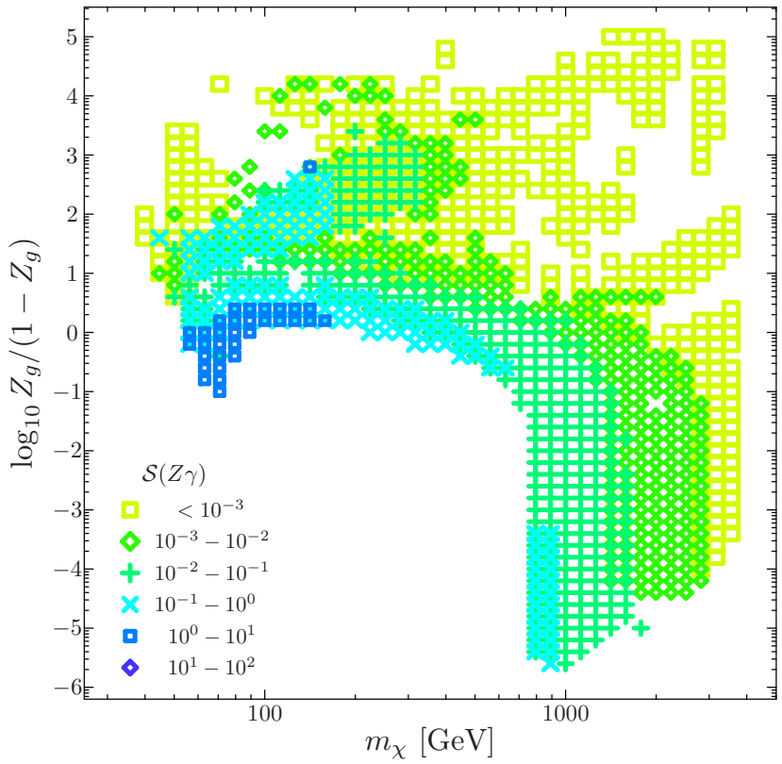
IB



$\gamma\gamma$



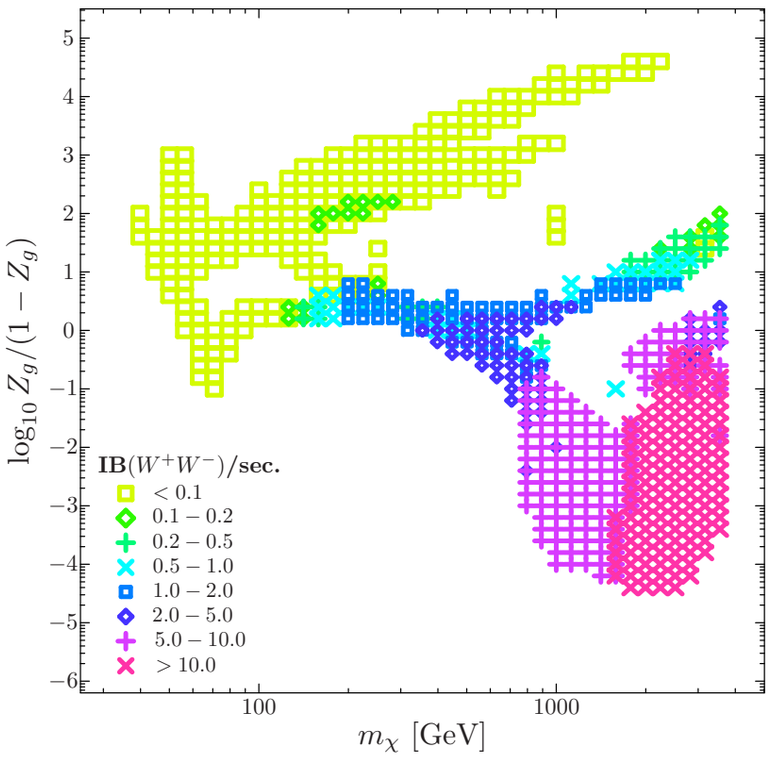
$Z\gamma$



IB can be more important than the lines

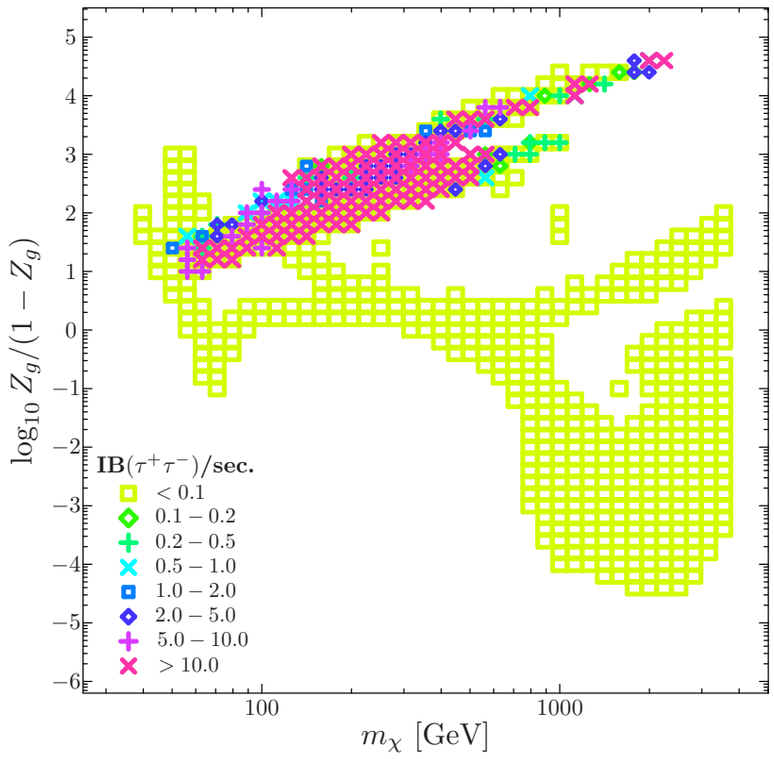
IB/sec. for mSUGRA

IB(W^+W^-)/sec.



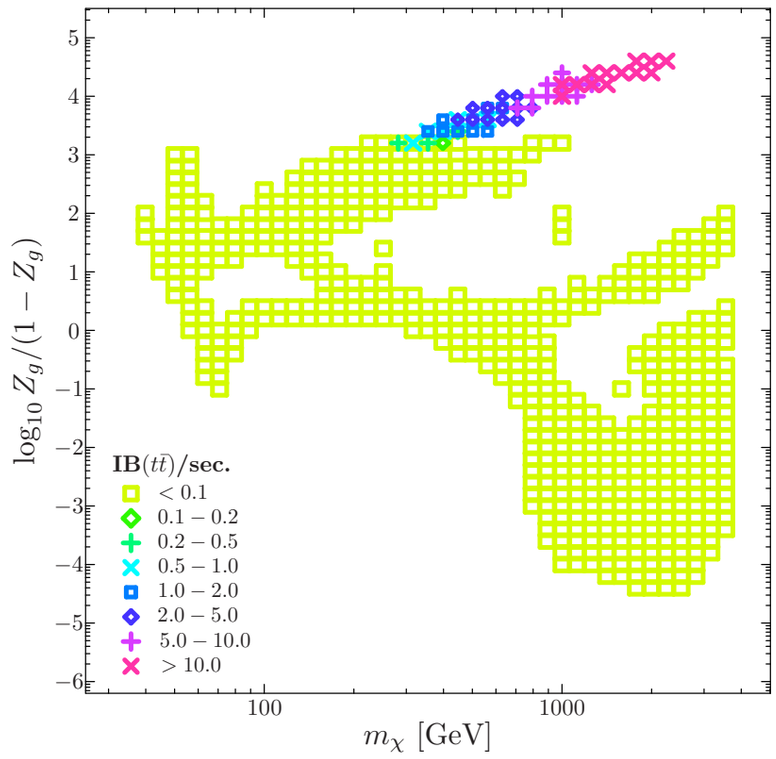
focus point region

IB($\tau^+\tau^-$)/sec.



stau coannihilation region

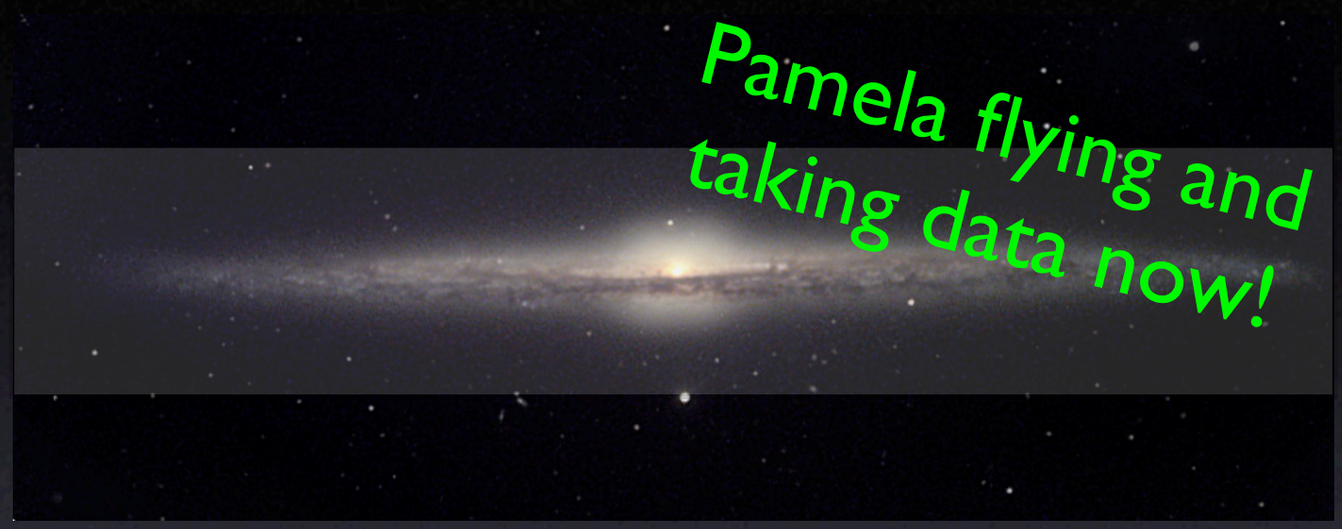
IB($t\bar{t}$)/sec.



stop coannihilation region

Charged cosmic rays

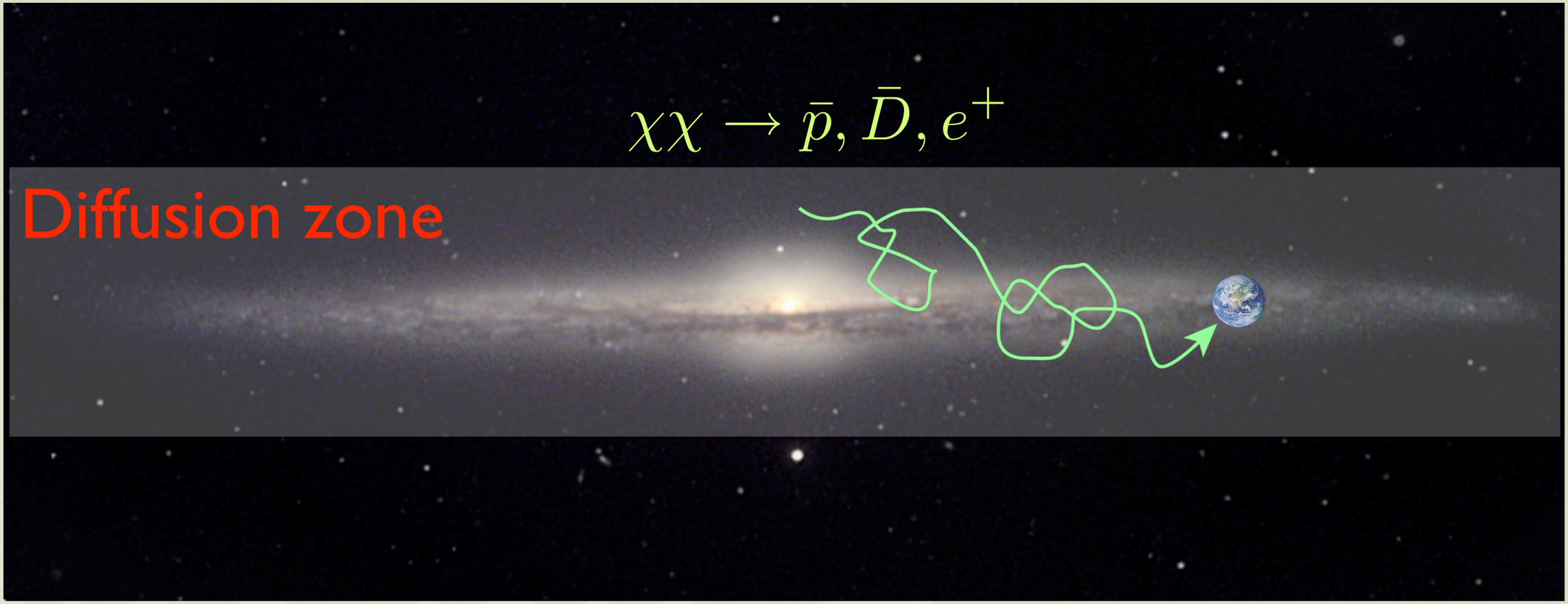
- Antiprotons
- Positrons
- Antideuterons



- Diffusion and energy losses included
- Different halo profiles (even clumpy halos)
- Different diffusion treatments, e.g. Moskalenko-Strong Green's functions
- (Very) beta-interface to GALPROP

Annihilation in the halo

Charged annihilation products



- 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.

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Diffusion model

- Cylindrical diffusion model with free escape at the boundaries
- Energy losses on the interstellar medium (for antiprotons and antideuterons) 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.

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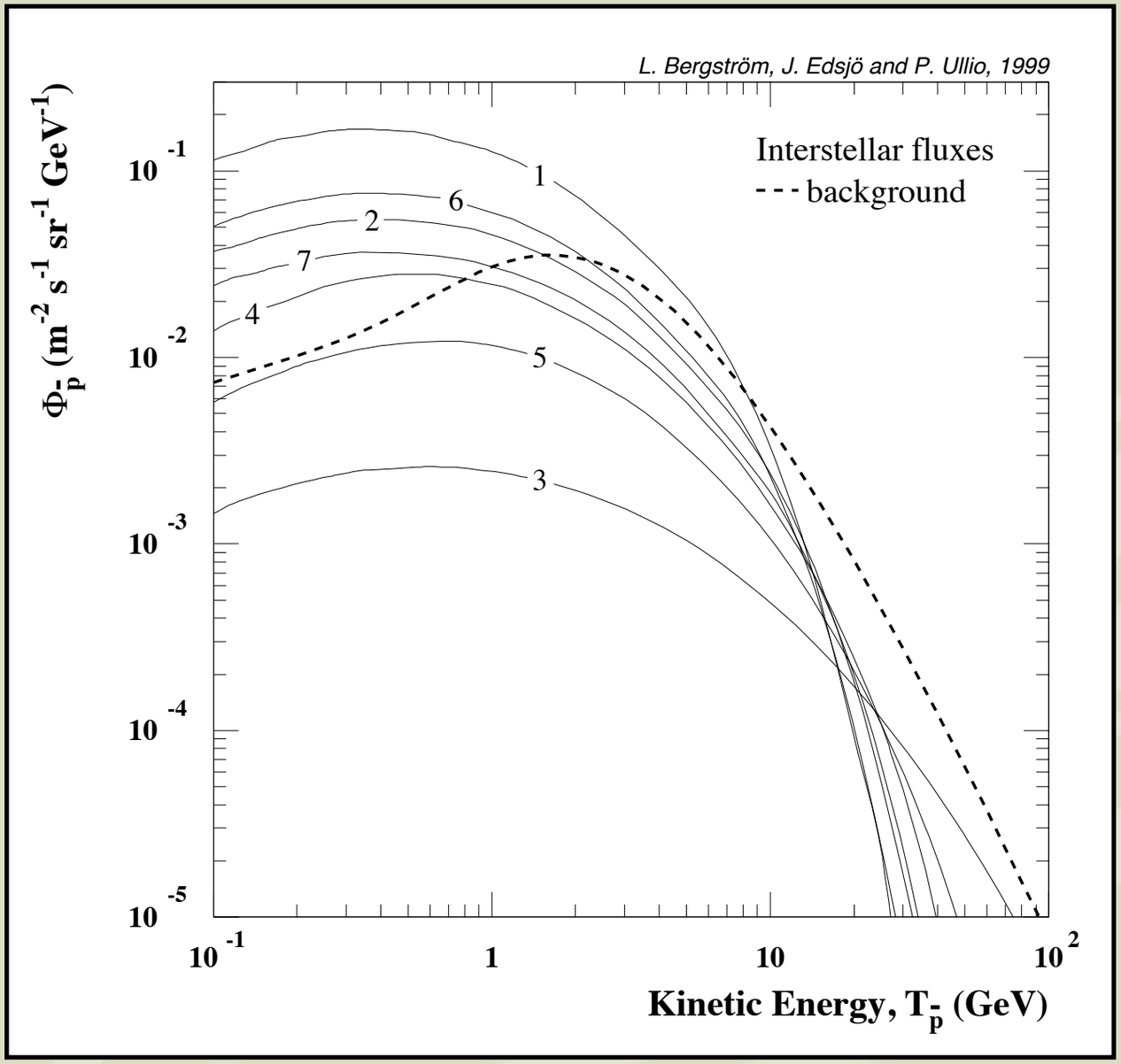
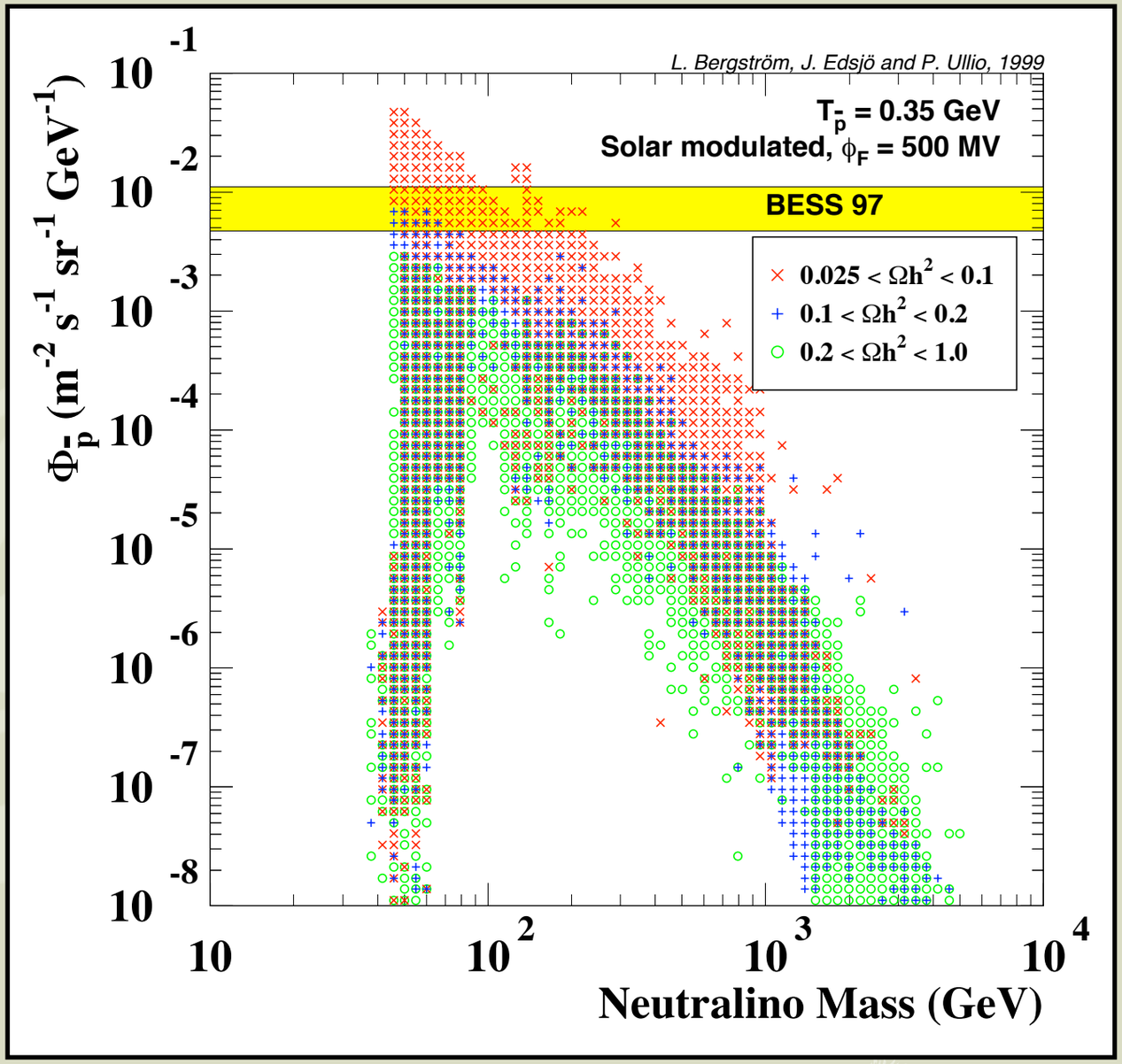
Antiprotons – signal





Easy to get high fluxes, but...

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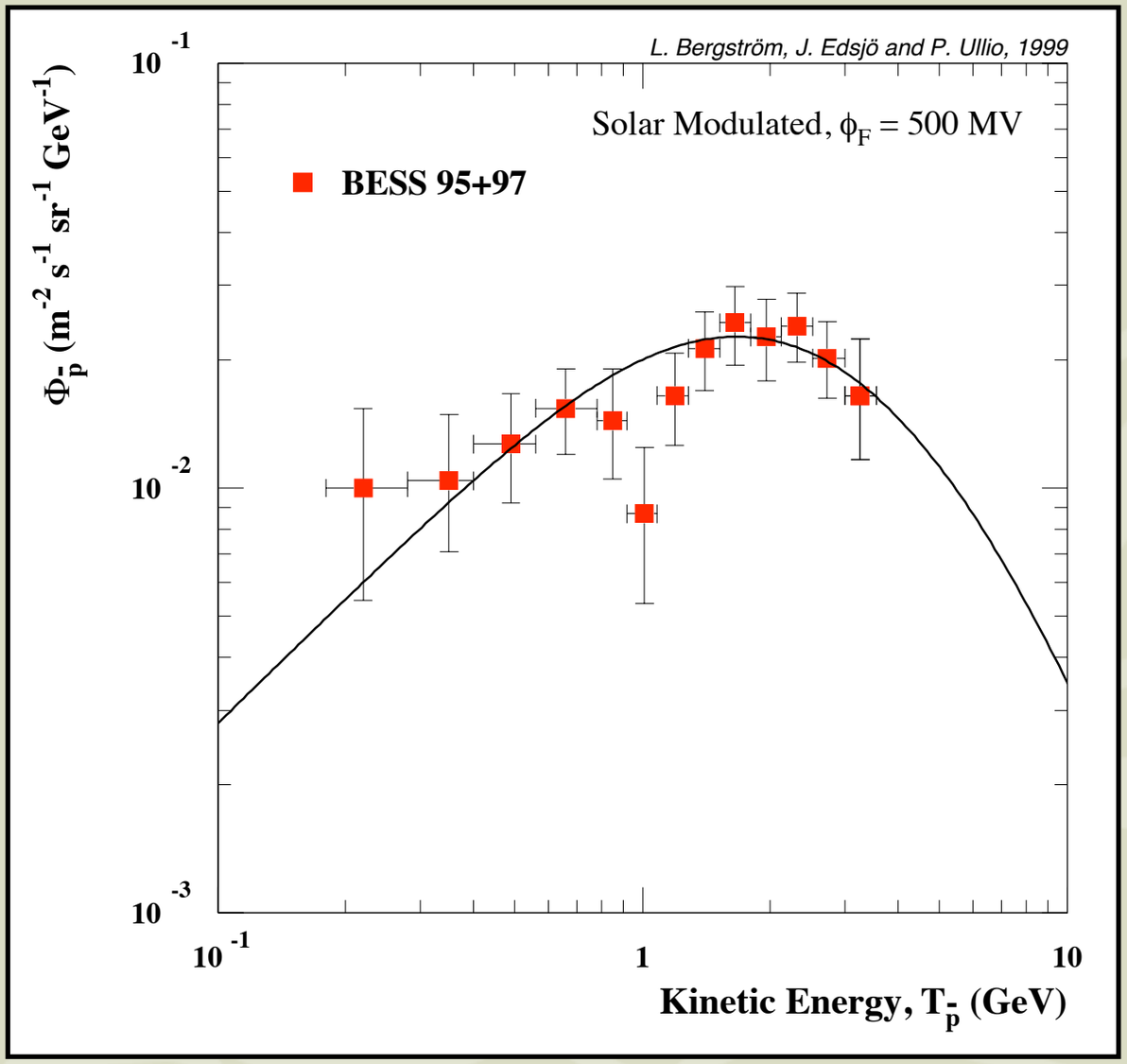
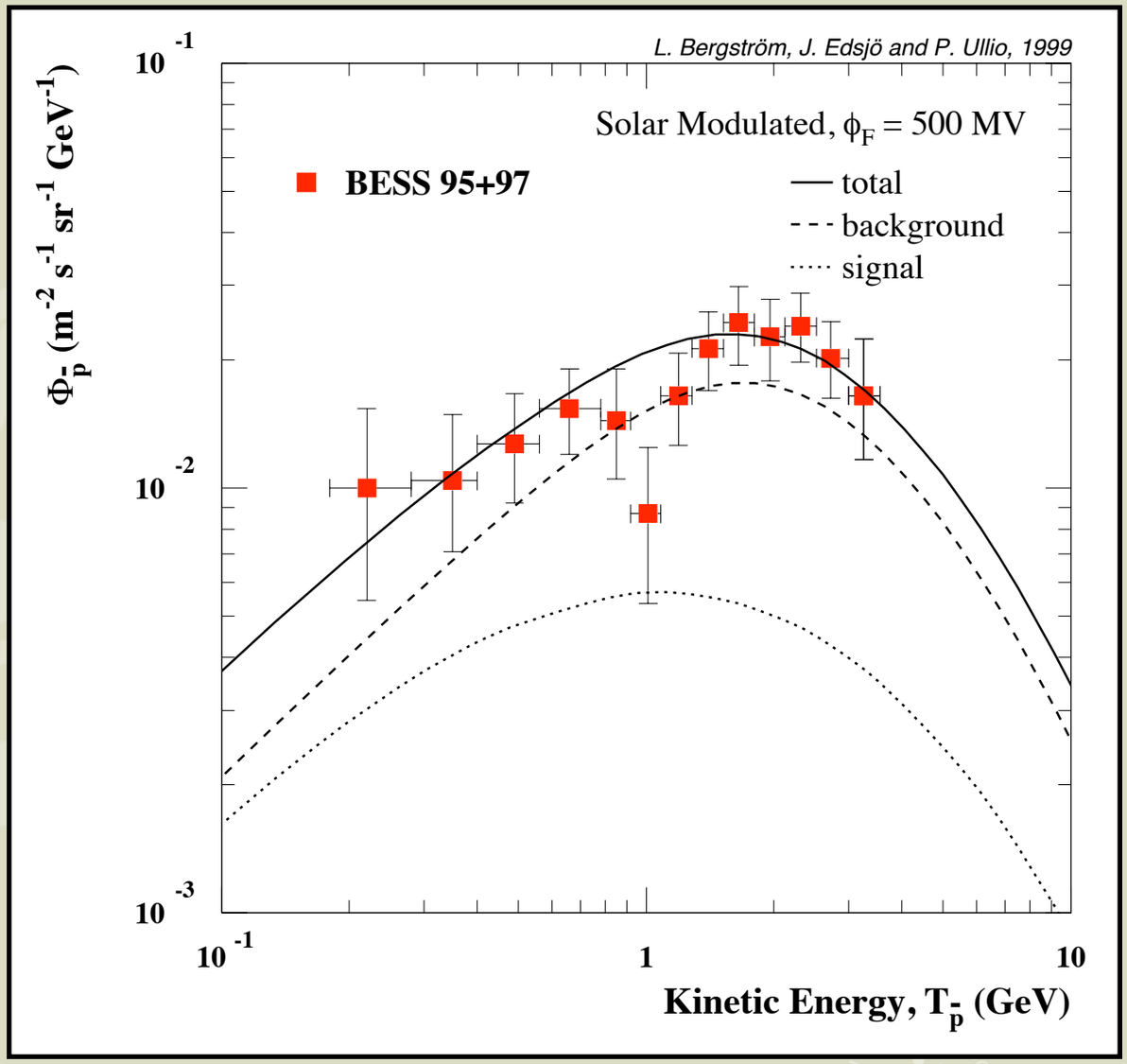
Antiprotons – fits to BESS data

Background only



Background + signal



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

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Antideuterons

- 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).

F. Donato, N. Fornengo and P. Salati,
Phys. Rev. D62 (2000) 043003.

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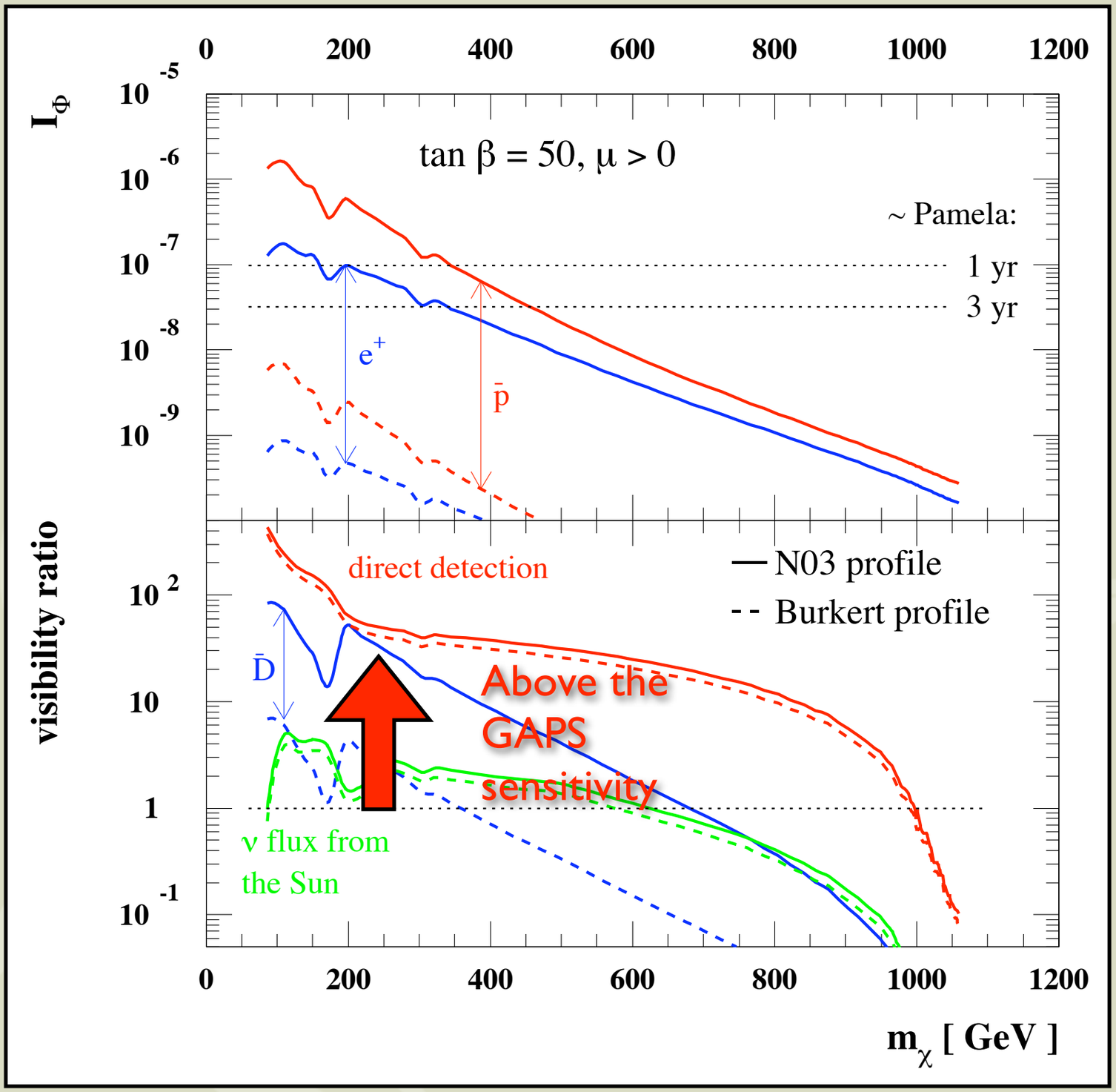
Future cosmic rays

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

Edsjö, Schelke and Ullio, JCAP 09 (2004) 004.

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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

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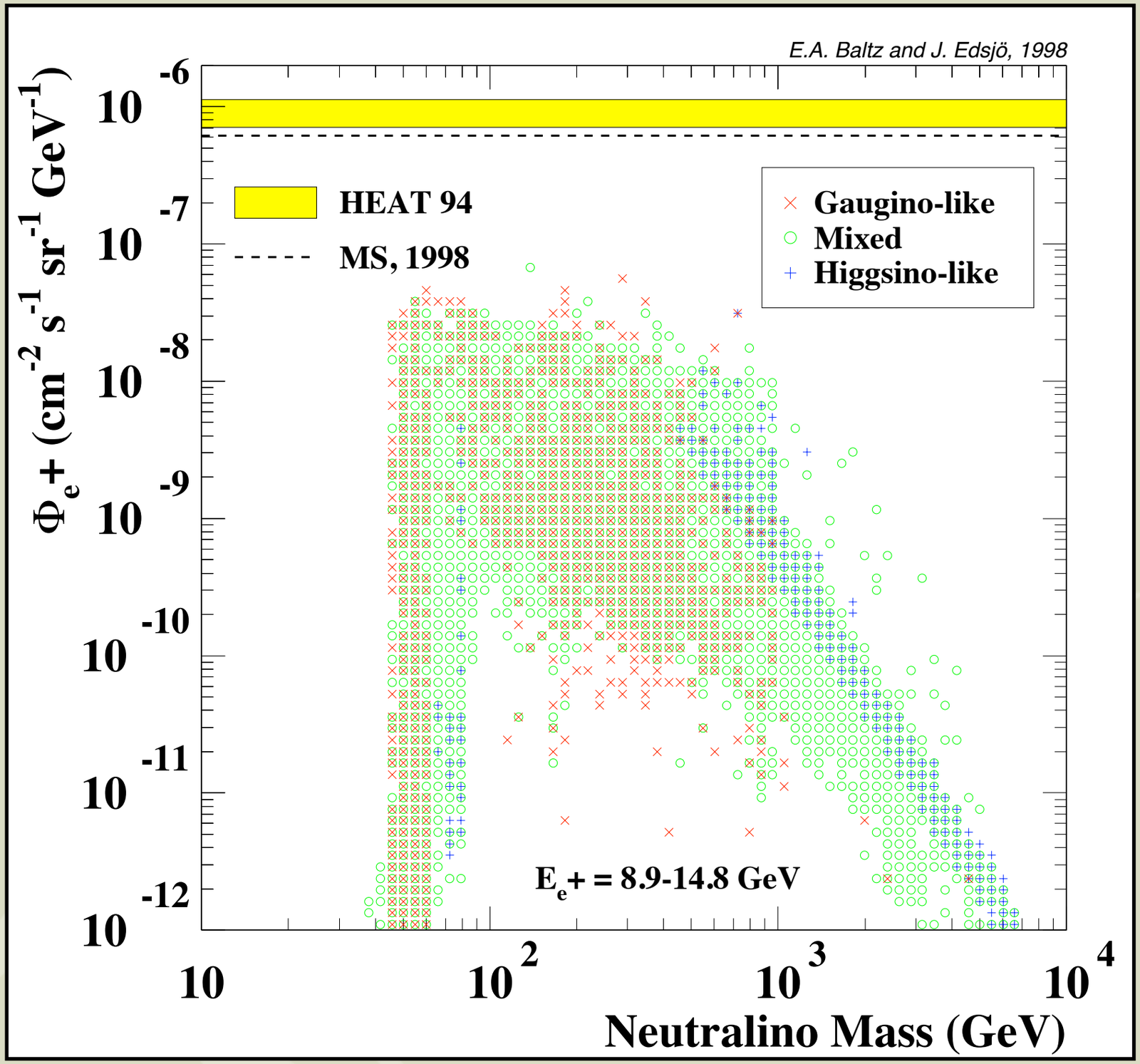
Positrons - signal



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

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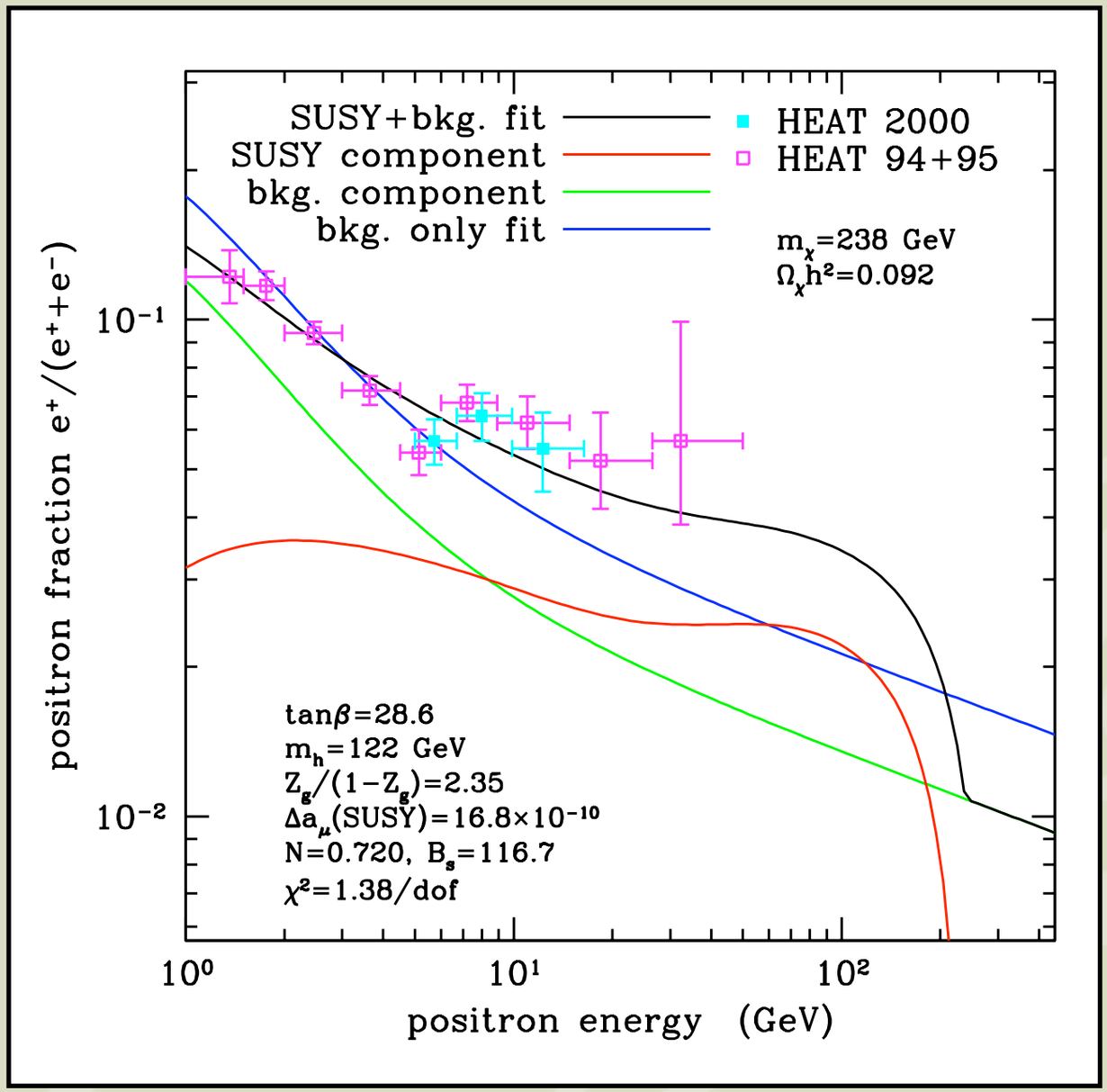
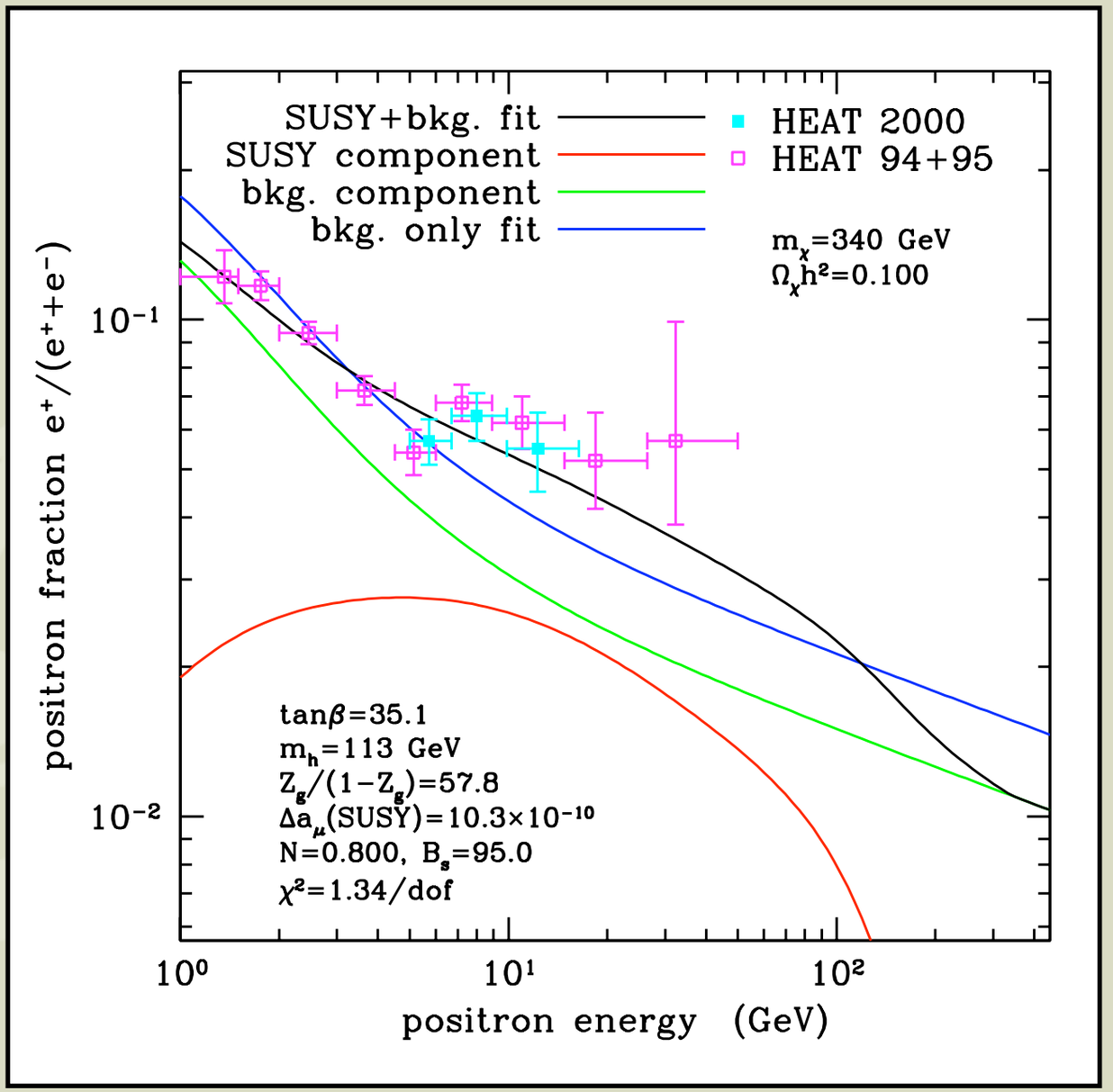
Positrons – example spectra





- 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

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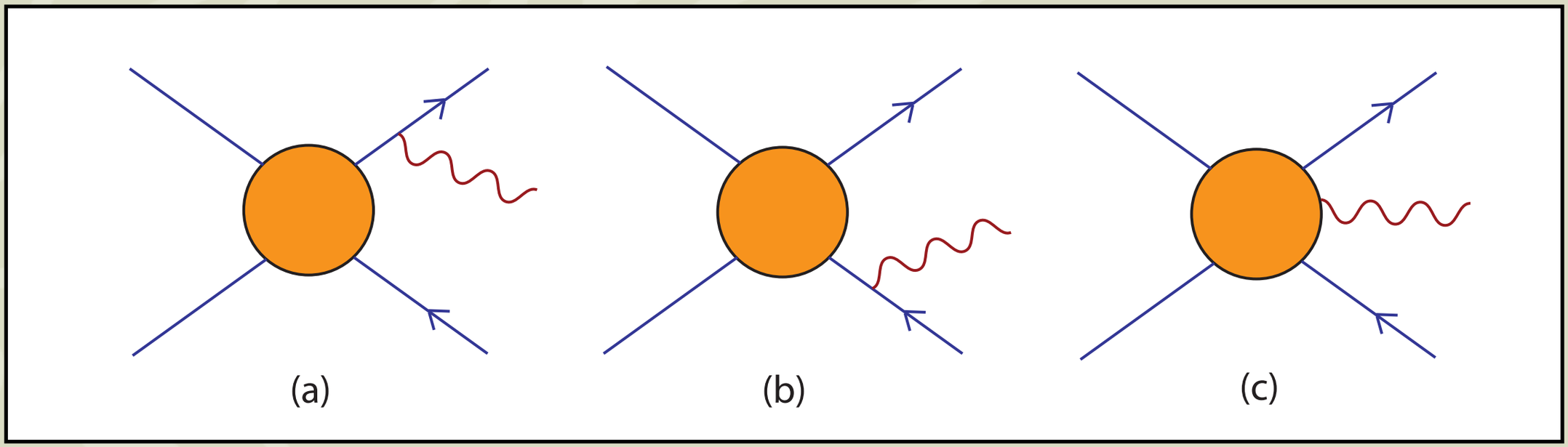
So, what about IB for the positrons?

L. Bergström, T. Bringmann and J. Edsjö, work in progress

- Annihilations to e^+e^- is helicity suppressed for Majorana fermion WIMPs (e.g. neutralinos)
- Hence, direct annihilation to e^+e^- is never important
- BUT, internal bremsstrahlung of photons cause the cross section for annihilation into $e^+e^-\gamma$ to increase. Can it be enhanced enough to be of importance or e^+ searches?



When is the effect large?

- Typically, the $e^+e^-\gamma$ cross section can be large when the selectrons are light
- This can happen e.g. in the stau coannihilation region in mSUGRA
- In MSSM-7, it only happens when essentially all sfermions are light (and typically the slectron is not that light in these cases). However, this is just an artefact of how MSSM-7 is parameterized. Hence, introduce...

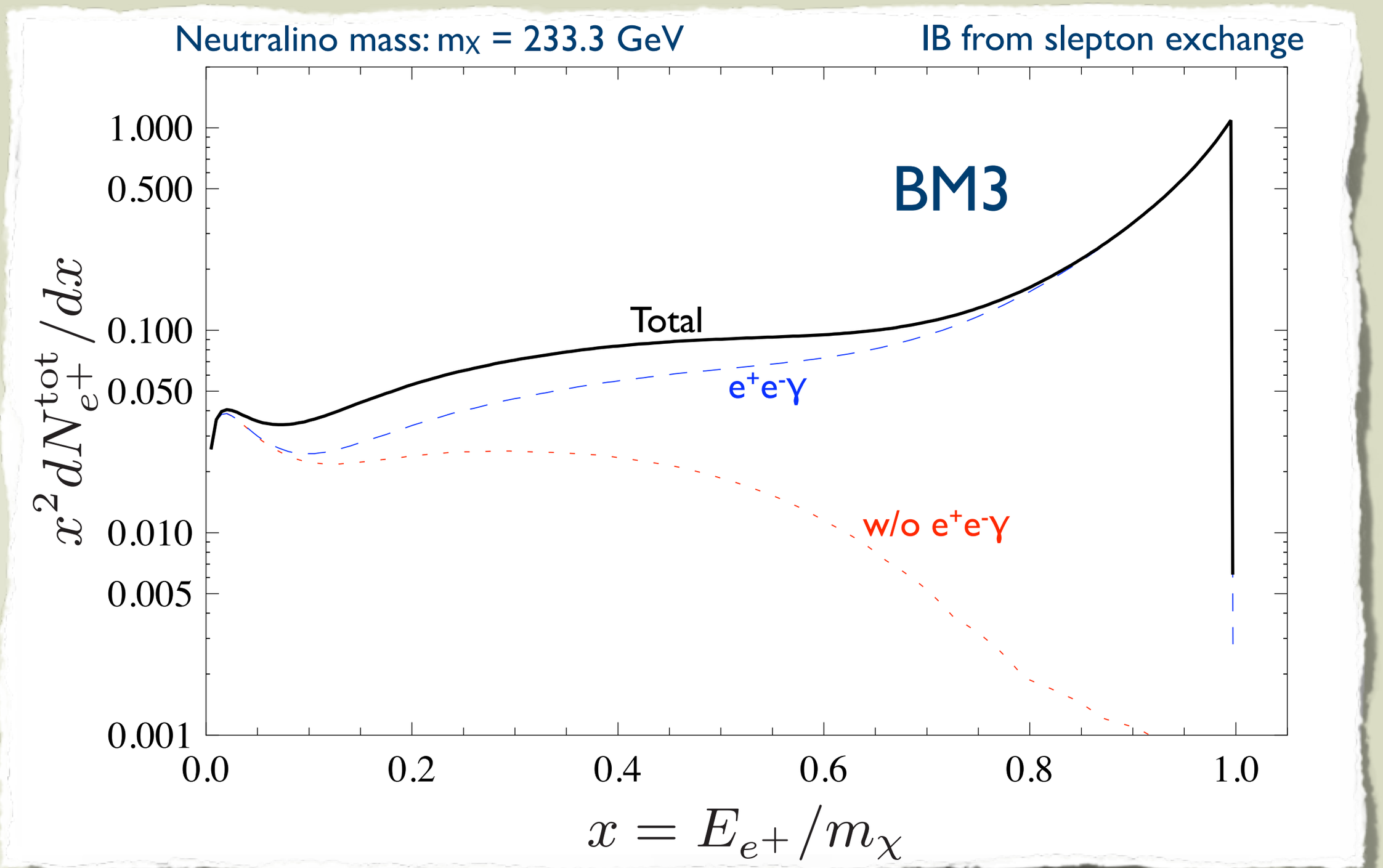
MSSM-9

- In order to get light selectrons and allow more freedom for the neutralino composition, we introduce MSSM-9 with two more parameters:

μ	Higgsino mass parameter	
M_1	Gaugino mass parameter	New
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	
$m_{\tilde{e}}$	Selectron mass parameter (not mass directly)	New
A_b	Trilinear coupling, bottom sector	
A_t	Trilinear coupling, top sector	

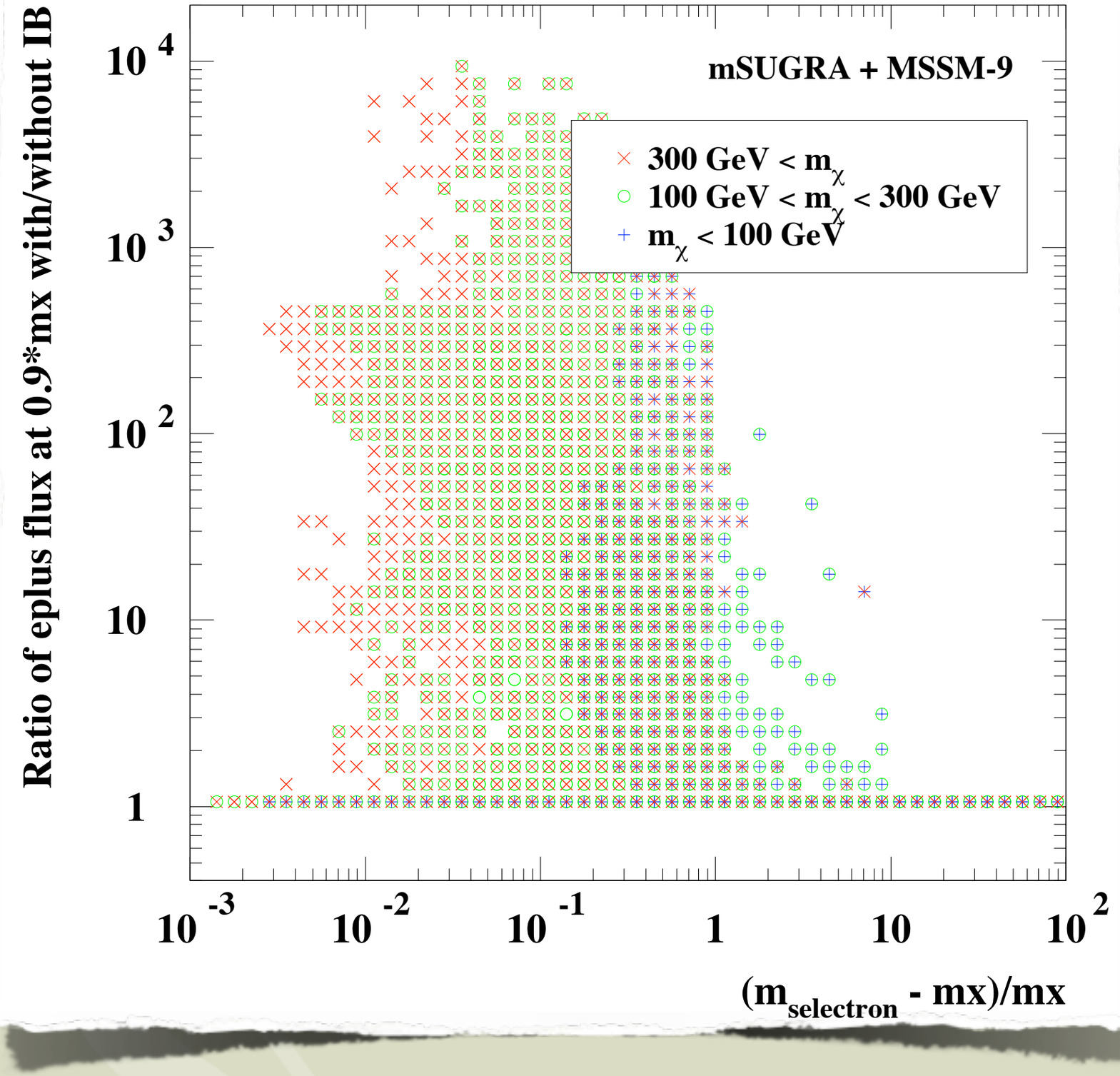
$$\mathcal{M}^2_{\tilde{e}} = \begin{pmatrix} \mathbf{M}_L^2 + \mathbf{m}_e\mathbf{m}_e^\dagger + D^e_{LL}\mathbf{1} & -\mathbf{m}_e^\dagger(\mathbf{A}_E^\dagger + \mu^* \tan\beta) \\ -(\mathbf{A}_E + \mu\tan\beta)\mathbf{m}_e & \mathbf{M}_E^2 + \mathbf{m}_e^\dagger\mathbf{m}_e + D^e_{RR}\mathbf{1} \end{pmatrix}.$$

Example mSUGRA e^+ spectrum



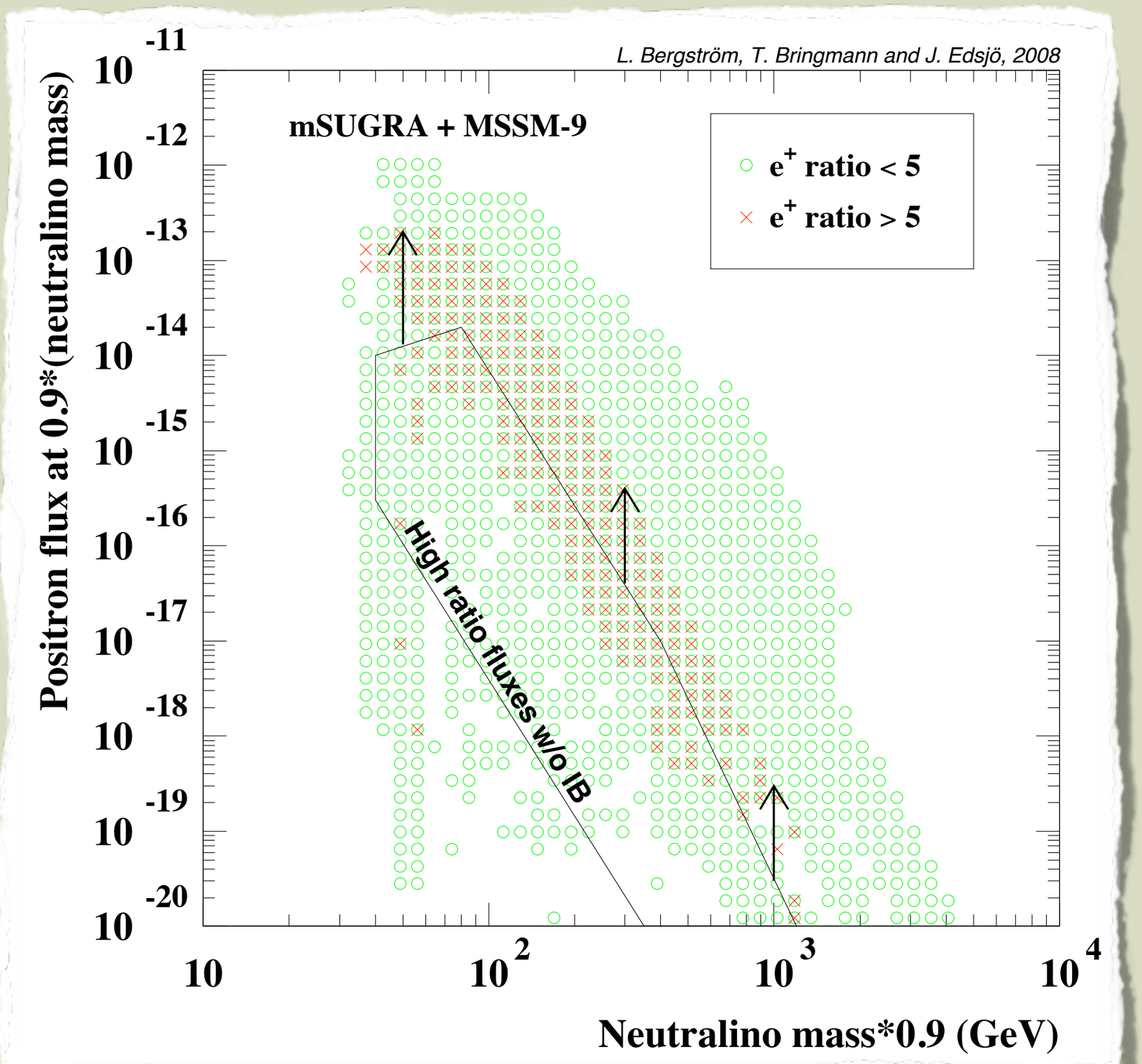
Very nice spectral feature!

Enhancement factors at $0.9m_\chi$



It is possible to get huge enhancement factors

Absolute fluxes



- IB enhances the positron fluxes significantly for some models
- The models that get large enhancements had low fluxes to start with
- Even after enhancement, the fluxes are not very high, BUT they have a nice spectral feature!

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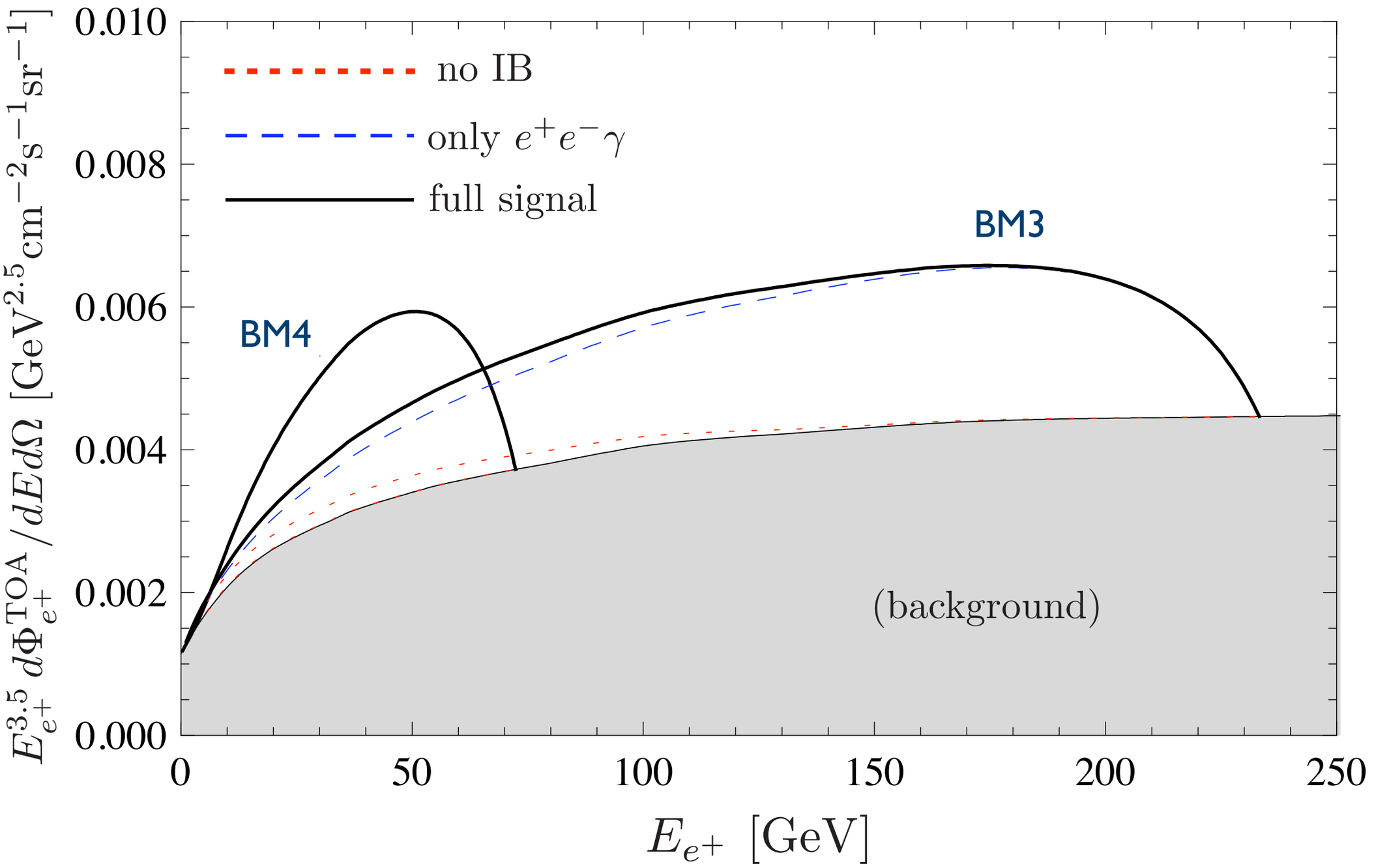
Spectrum after propagation



Nice features, but a boost factor of 5000...

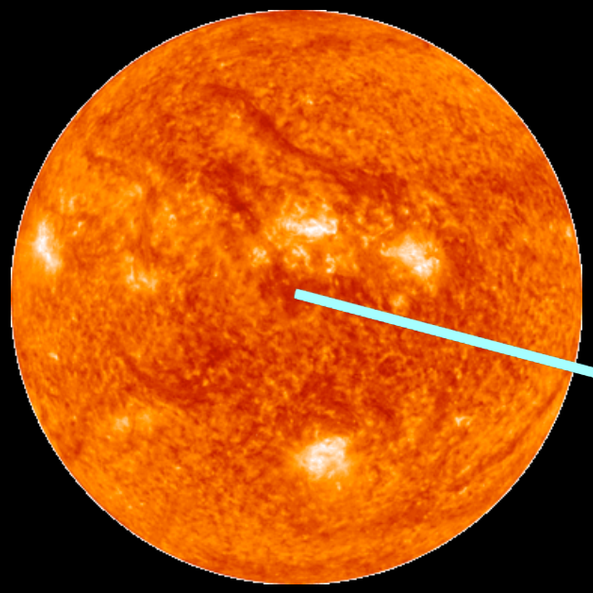
Neutrinos from Sun/Earth

- Rate of neutrino-induced muons in neutrino telescopes
- Neutrino scattering and absorption in Sun included
- Fully numerical capture calculation with any velocity distribution
- New solar system diffusion yielding depletion of capture by the Earth
- Damour-Krauss population of WIMPs
- Neutrino oscillations, all flavours and hadronic showers

Neutralino Capture

ρ_χ χ χ velocity distribution

Sun



ν interactions

ν oscillations

ν_μ

Earth

μ

Detector

$\sigma_{\rm scatt}$

$\sigma_{\rm ann}$

$\Gamma_{\rm capture}$

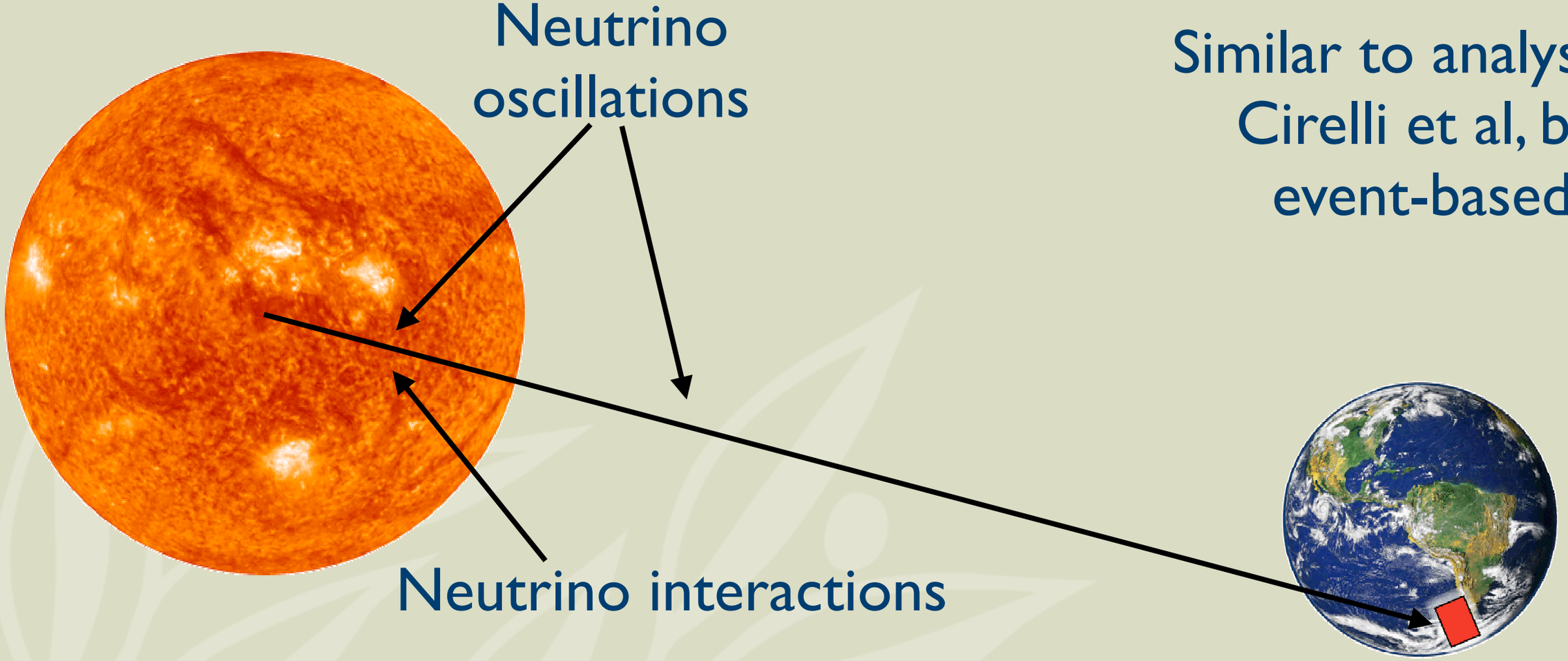
$\Gamma_{\rm ann}$

Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

M. Blennow, J. Edsjö and
T. Ohlsson, JCAP01 (2008) 021

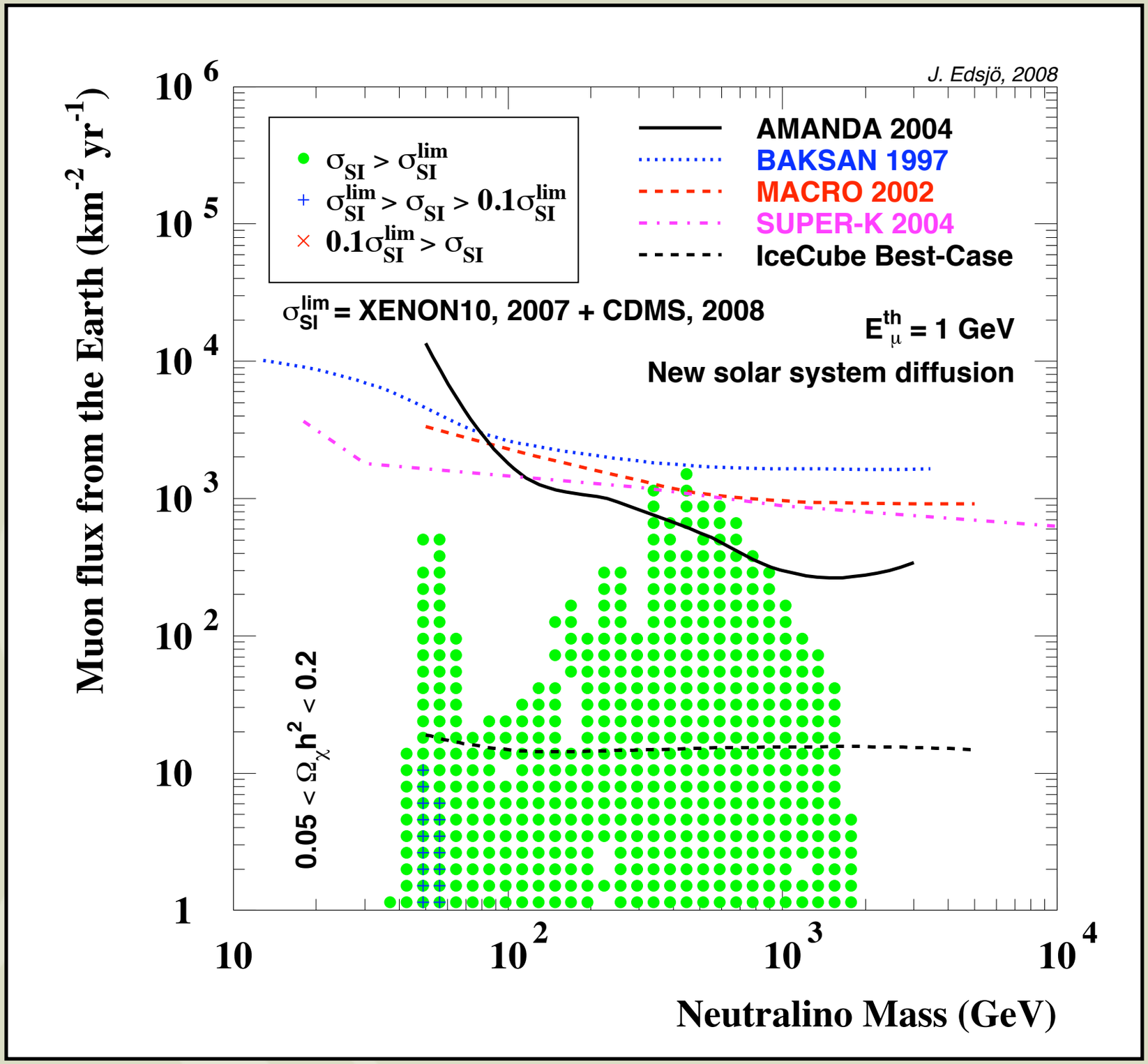
Neutrino oscillations



Similar to analysis of Cirelli et al, but event-based.

- 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 are included in DarkSUSY.

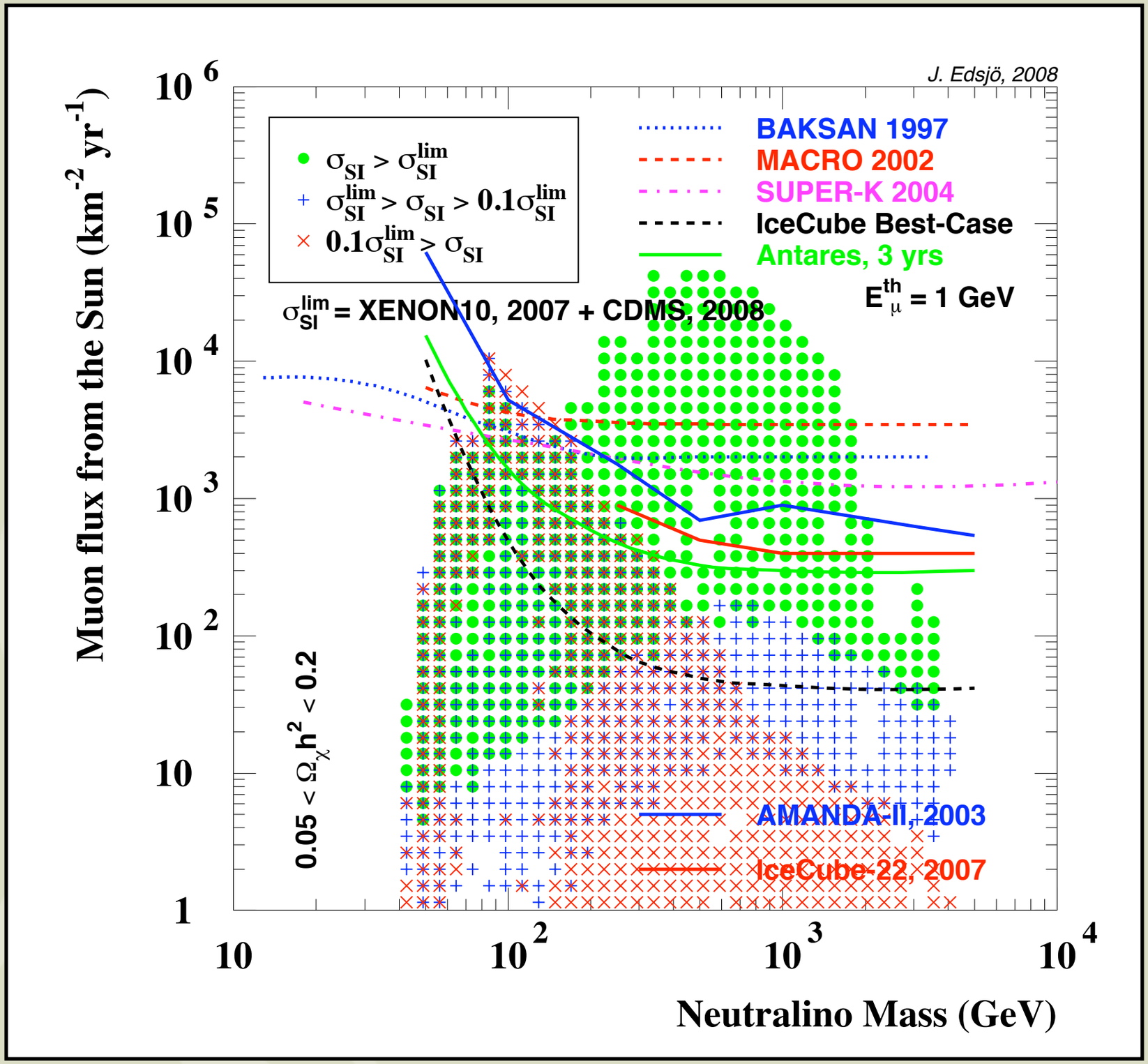
Neutrino-induced muon fluxes from the Earth



- 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.

WimpSim - standalone simulation package

J. Edsjö, M. Blennow and T. Ohlsson

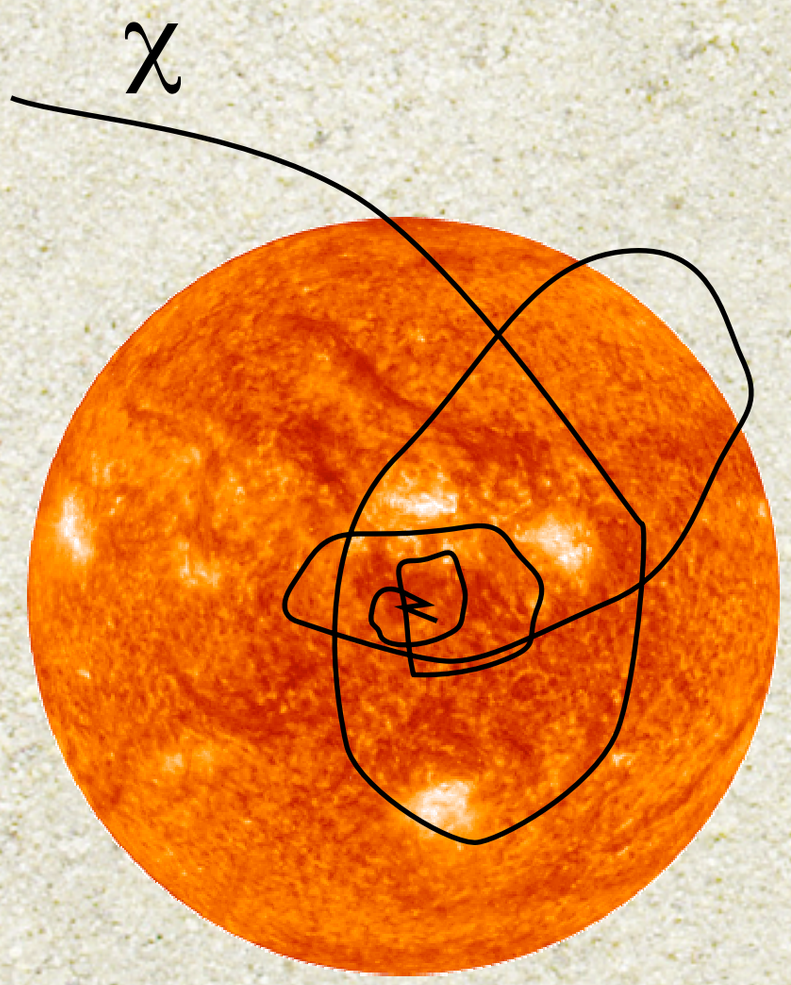
- **WimpAnn**

  - treats annihilations in the Sun/Earth and propagates the neutrinos to 1 AU (for the Sun), or leaves them in the center of the Earth for annihilations in the Earth

- **WimpEvent**

  - Takes the neutrinos from WimpAnn and propagates them further to the detector, including neutrino oscillation and geometry effects

WimpAnn - annihilation in the Sun/Earth



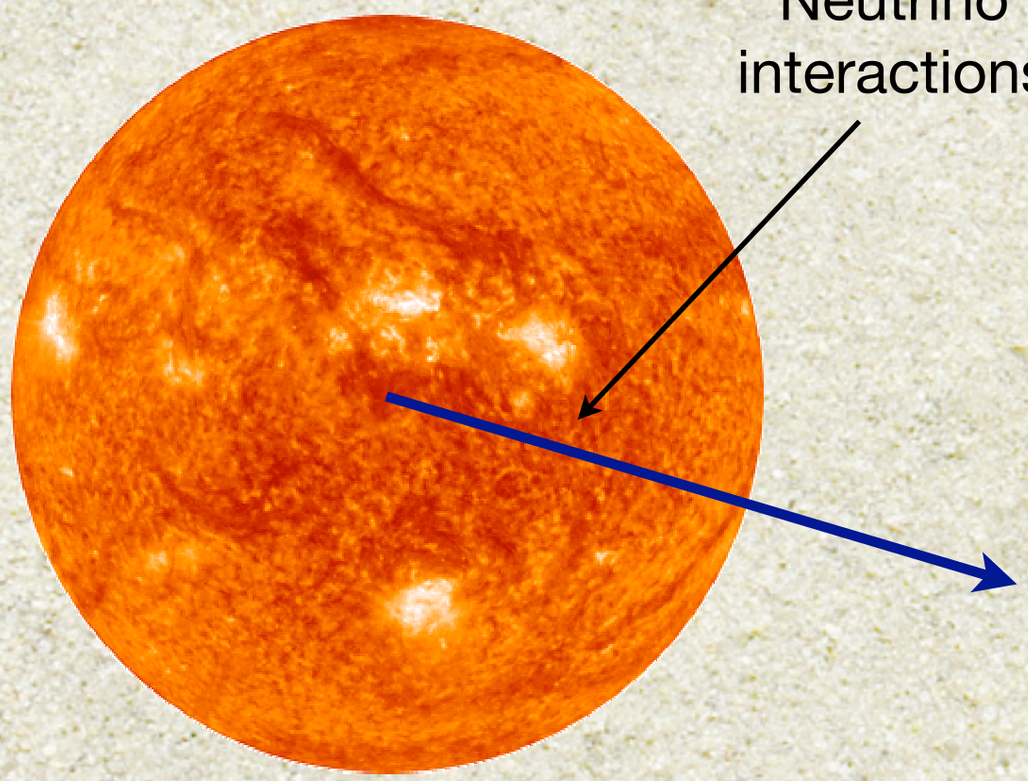
- WIMPs in the Milky Way halo can scatter in the Sun(Earth) and be gravitationally bound to the Sun(Earth).
- Eventually they will scatter again and sink to the core.
- In the core, WIMPs will accumulate and can annihilate and produce neutrinos

$$\chi\chi \rightarrow \left\{ \begin{array}{c} b\bar{b} \\ t\bar{t} \\ \tau^-\tau^+ \\ W^-W^+ \\ Z^0Z^0 \\ \nu_\alpha\bar{\nu}_\alpha \\ H^\pm W^\pm \\ H_i^0 Z^0 \end{array} \right\} = \cdots = \nu_\alpha$$

Annihilations simulated with Pythia 6.414

Silk, Olive and Srednicki ’85
Gaisser, Steigman and Tilav ’86
Freese ’86
Krauss, Srednicki & Wilczek ’86
Gaisser, Steigman & Tilav ’86

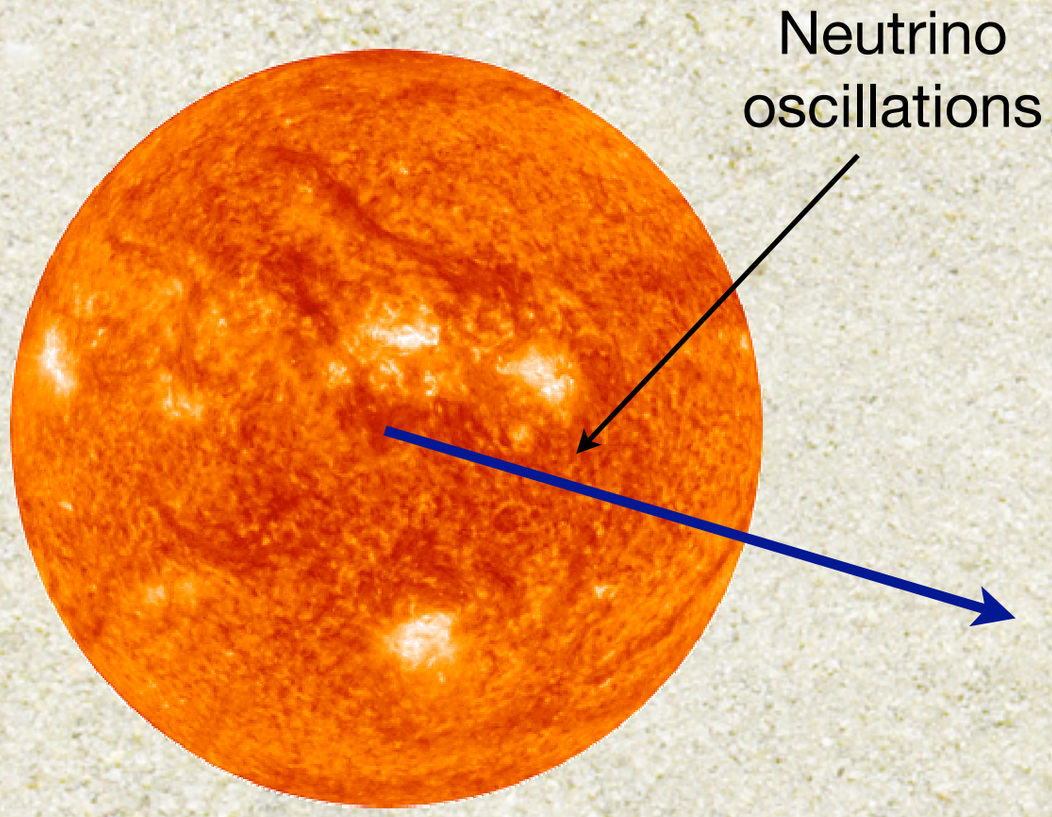
nusigma – New neutrino interaction package



Simulations done with new code nusigma using CTEQ6 structure functions.

- On the way out of the Sun, the neutrino can participate in both *charged* and *neutral* current interactions
- Neutral currents degrade the energy of the neutrino
- Charged currents give a charged lepton: electrons and muons get stopped before they can give neutrinos, but tau leptons will decay and give neutrinos (regeneration)

Neutrino oscillations



Default parameters

$\theta_{12} = 33.2^\circ \pm 4.9^\circ,$

$\theta_{13} = 0 \pm 12.5^\circ,$

$\theta_{23} = 45.0^\circ \pm 10.6^\circ,$

$\delta \in [0, 2\pi),$

$\Delta m^2_{21} = (8.1^{+1.0}_{-0.9}) \cdot 10^{-5}\,\mathrm{eV}^2,$

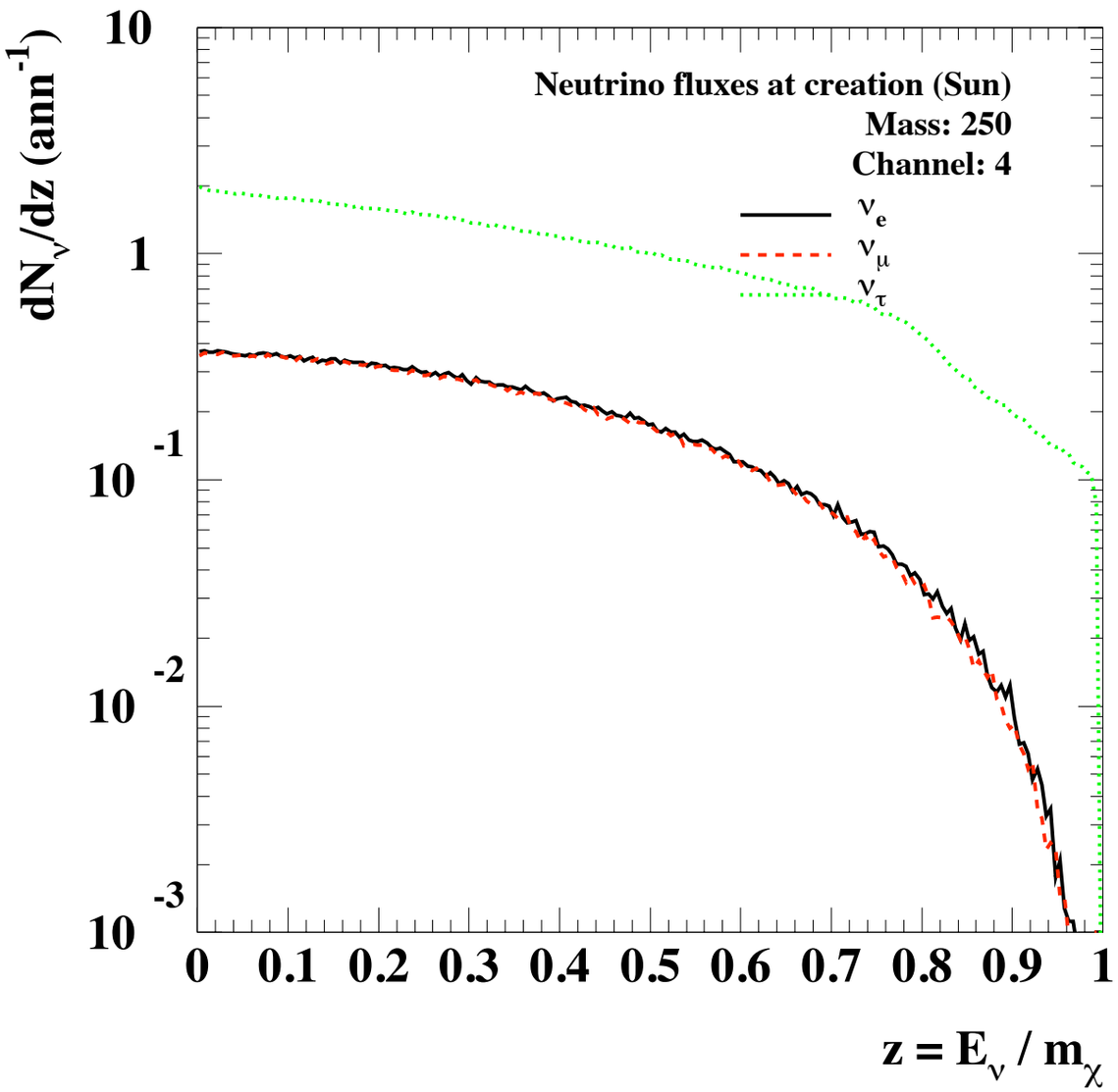
$|\Delta m^2_{31}| = (2.2^{+1.1}_{-0.8}) \cdot 10^{-3}\,\mathrm{eV}^2,$

- We use a completely general three-neutrino oscillation code (with both matter and vacuum oscillations included) and a realistic solar model (Bahcall, Serenelli & Basu, 2005).
- At the surface of the Sun, we get the fluxes in a general format (with amplitudes and phases)
- Neutrino oscillations and interactions are treated simultaneously

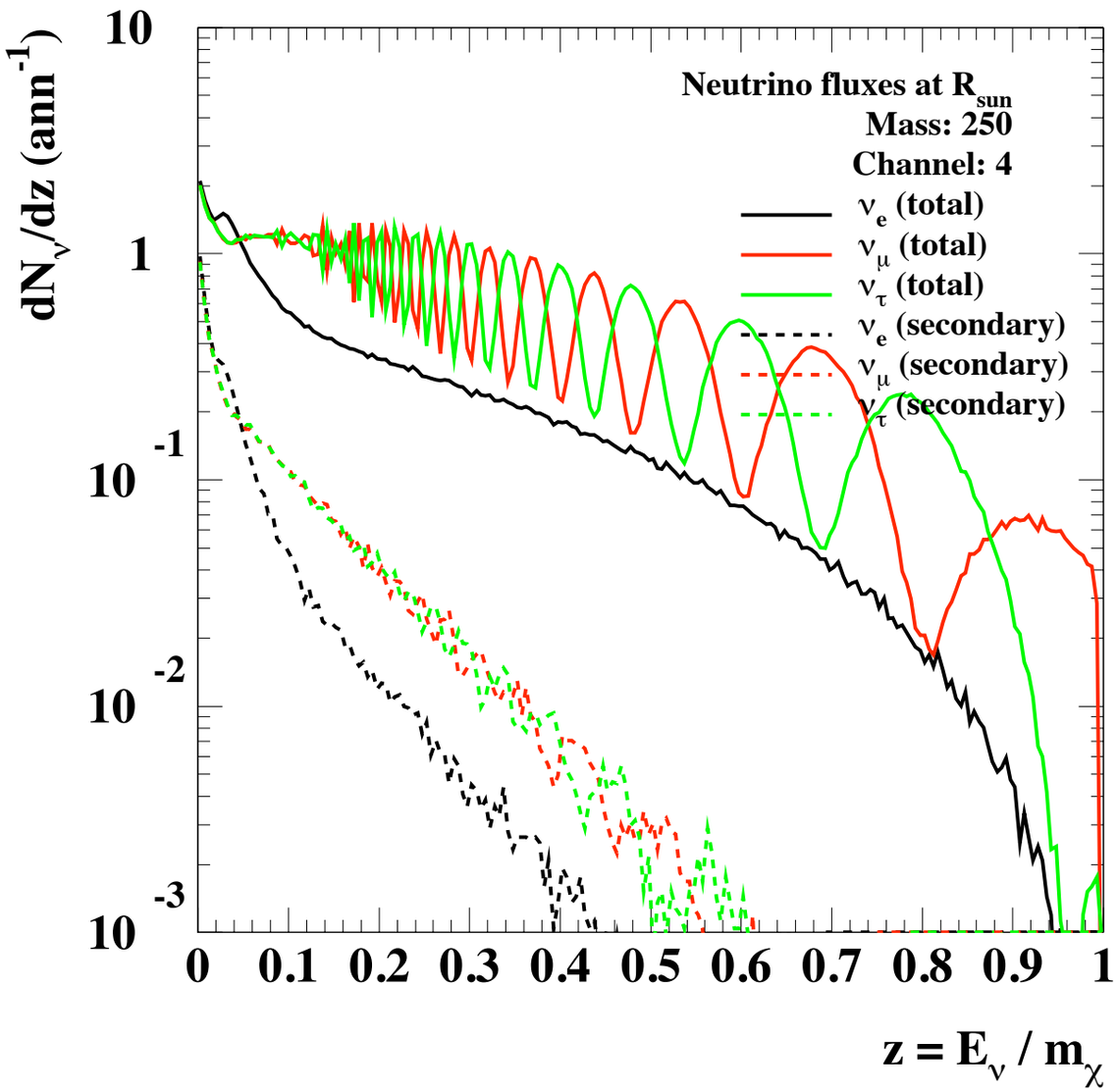
Neutrino oscillations - spectra after Sun

Example: annihilation to $\tau^- \tau^+$ at m_χ=250 GeV

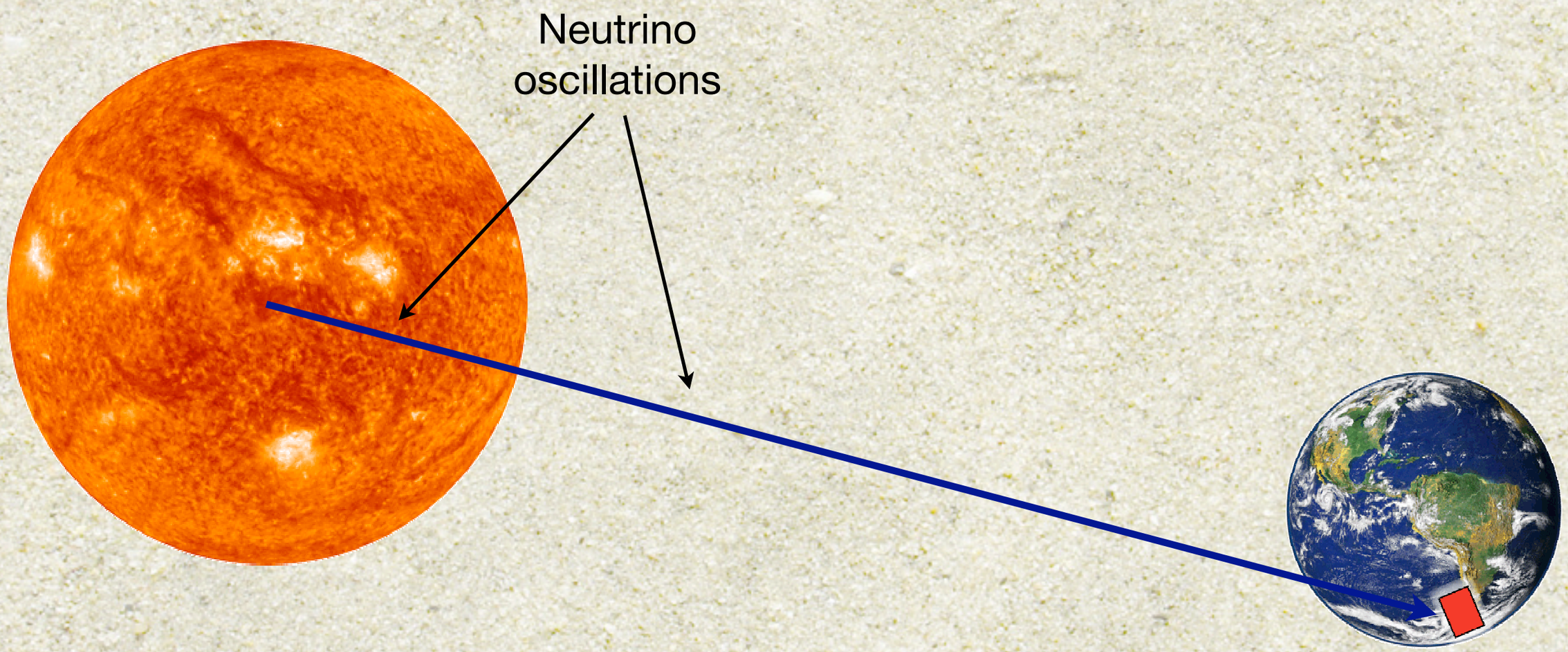
At the centre



At the surface



Propagation to Earth: WimpAnn takes the WIMPs to 1 AU

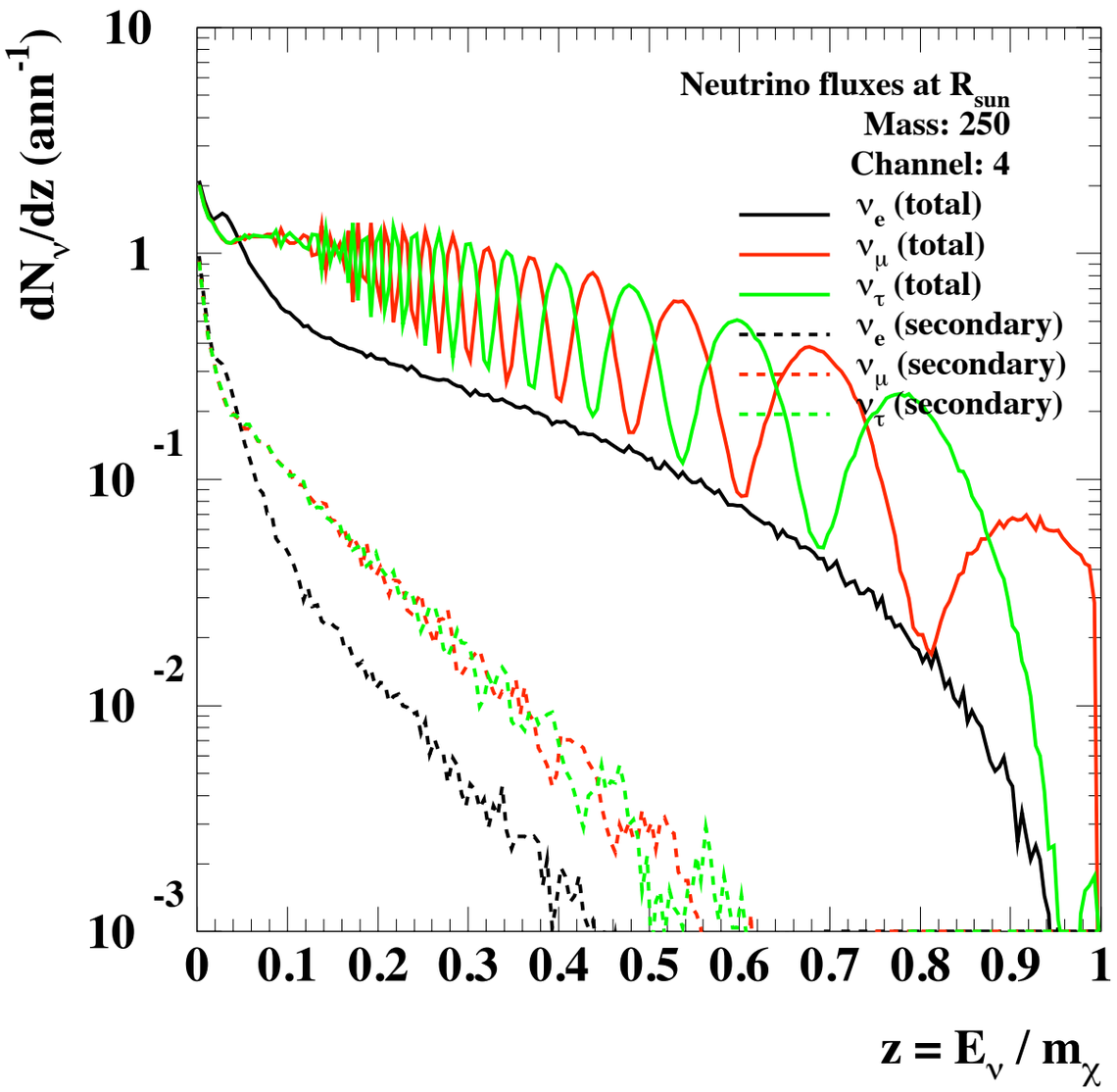


- Vacuum oscillations to the Earth included in the same three-neutrino setup

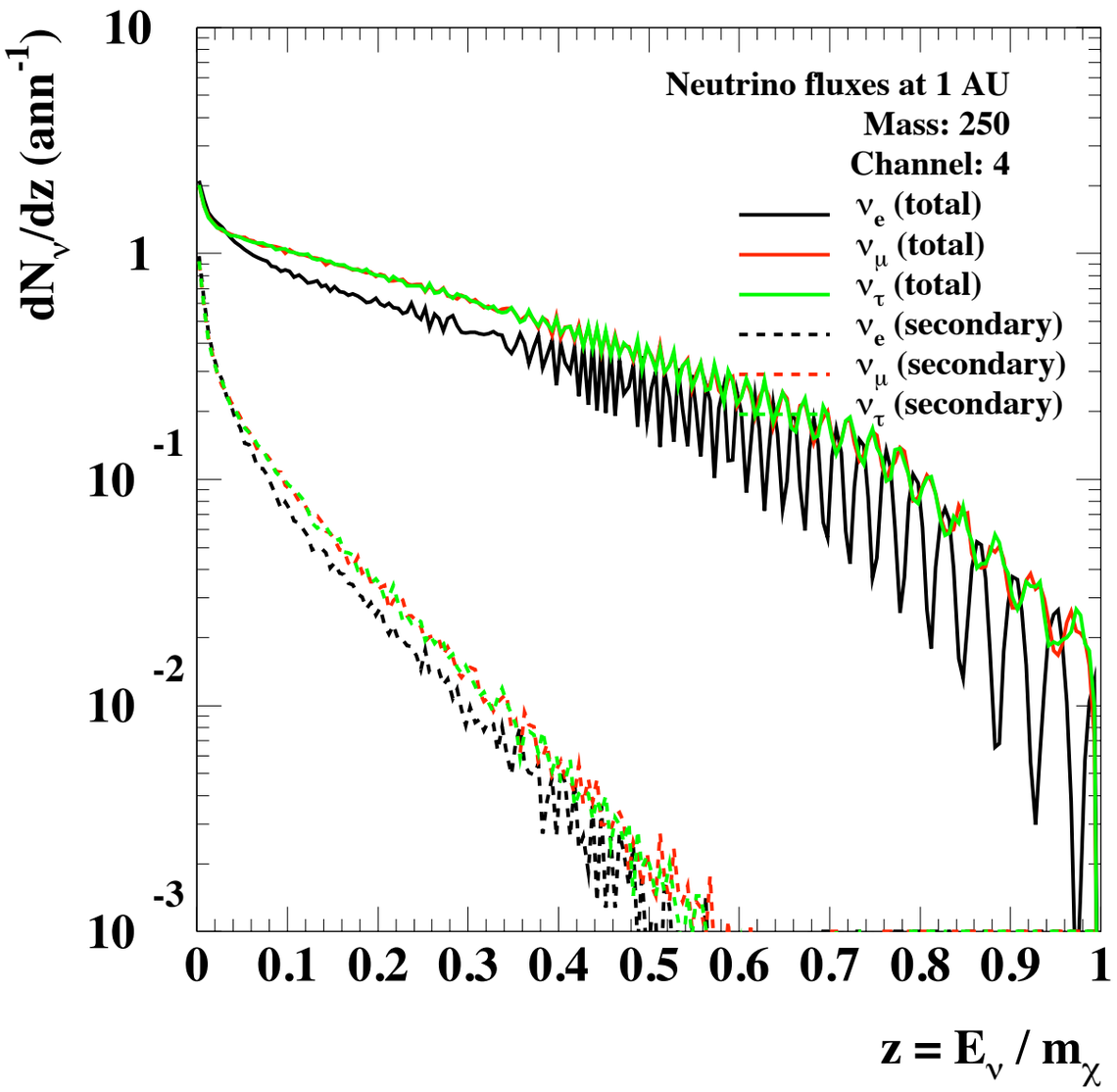
Example of propagation to 1 AU (Earth)

Example: annihilation to $\tau^- \tau^+$ at m_χ=250 GeV

At the surface



At 1 AU



Summary of oscillation effects

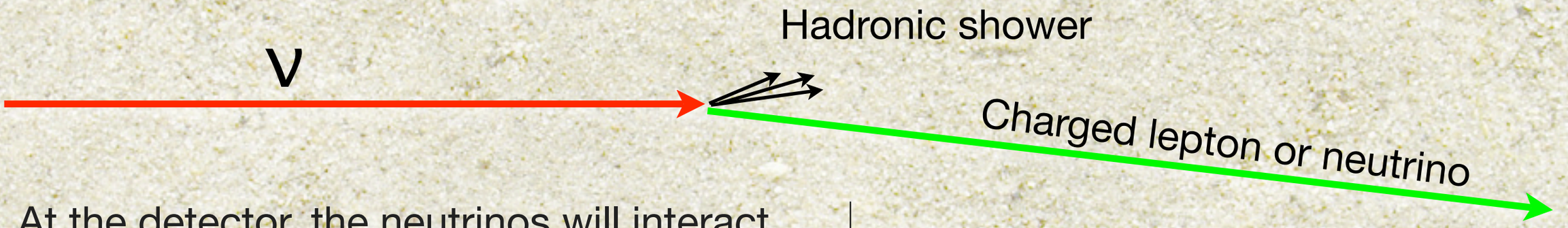
Sun

- At typical WIMP energies (10-10000 GeV), oscillations effectively:
  - average ν_μ and ν_τ on the way out of the Sun (below 25 GeV all flavours are mixed)
  - average (not fully though) ν_μ/ν_τ and ν_e on the way to the Earth

Earth

- Essentially no effects of oscillations (except below 50 GeV where ν_μ and ν_τ are mixed)

Interactions at the detector



- At the detector, the neutrinos will interact, via
  - **neutral currents:** producing a neutrino and a hadronic shower
  - **charged currents:** producing a charged lepton and a hadronic shower
- These interactions are simulated with new code nusigma.
- If muons, the leptons are also propagated through the detector (with energy losses and multiple Coulomb scattering).

- Output is written to summary files and event files with:
  - neutrinos (all flavours and also antineutrinos)
  - charged leptons at the neutrino-nucleon vertex
  - μ^- and μ^+ fluxes at (a thin) detector
- This is done on an event by event basis to be suitable for neutrino telescope Monte Carlos

WimpSim summary files in DarkSUSY

- Simulations for 19 masses from 10 GeV to 10 TeV have been performed for all ‘fundamental’ annihilation channels: d d-bar, u u-bar, s s-bar, c c-bar, b b-bar, t t-bar, gluon gluon, W^+W^-, Z^0 Z^0, mu- mu+, tau- tau+, nu_e nu_e-bar, nu_mu nu_mu-bar, nu_tau, nu_tau-bar. For each mass and channel, 10^7 events are generated.
- These neutrinos are then let to interact via NC or CC interactions at the detector (for simplicity, IceCube is chosen) and we have stored distributions of
  - all flavour neutrinos at the detector (1-6)
  - all flavour charged leptons at neutrino-nucleon vertex (7-12)
  - mu- and mu+ after propagation at detector (at an imaginary plane) (13-14)
  - hadronic showers from CC interactions for all flavours (15-20)
  - hadronic showers from NC interactions for all flavours (21-26)
- All these are stored both integrated (in energy and angle) and differential (in energy and angle).

Putting everything together

- The routine dswayieldf returns the yield for a given mass, energy, angle, annihilation channel and type (previous slide). This routine reads and interpolates in the summary tables from WimpSim.
- For a given SUSY model, one can preferably call dswayield that returns the summed yield for all annihilation channels for the given model. Higgses in the final state (e.g. from the channel Z H) are taken care of by integration over their decay angles in flight (and properly Lorentz-boosting the yields) using the know decay widhts of the Higgses.
- The routine dsntrates
  - calculates these yields and
  - calculates the capture and annihilation rates in the Sun and Earth given the scattering and annihilation cross sections, and puts this together for the flux of neutrino-induced muons (mu- & mu+) at the detector.

Side-remark on neutrino and muon fluxes

- The results of WimpSim are also put together as a conversion script which can convert between various fluxes with different thresholds:

  http://copsosx03.physto.se/cgi-bin/edsjo/wimpsim/flxconv.cgi

- This can be useful for comparisons between different experiments with different thresholds for example.

Neutrino Telescopes

Capture and annihilation

Evolution equation

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

Solution

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

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

Dependencies

$$C \sim \begin{cases} f(v), \rho_\chi, \sigma_{\text{scatt}}, \\ \text{composition of Earth/Sun} \end{cases}$$

$$C_A \sim \sigma_{\text{ann}}, \rho(r) \text{ in Earth/Sun}$$

Neutrino Telescopes

Capture

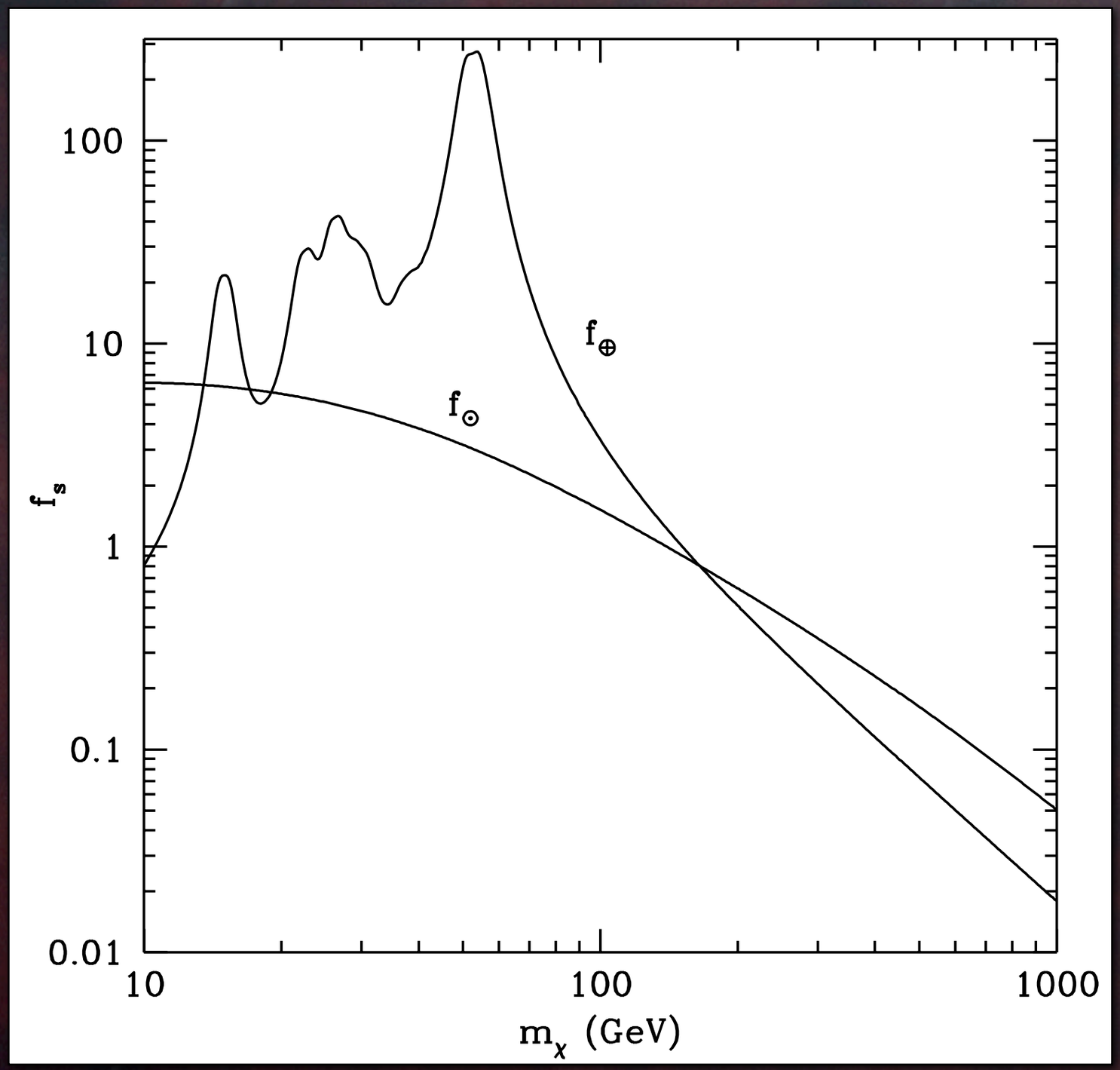


Figure from Jungman, Kamionkowski and Griest

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 mass matches element in Earth
- Capture from WIMPs bound in the solar system

Review of capture rate calculations

- 1985: Press & Spergel, ApJ 296 (1985) 679:
  Capture in the Sun

- 1987: Gould, ApJ 321 (1987) 571:
  Refined Press & Spergel's calculation for the Earth.

- 1988: Gould, ApJ 328 (1988) 919:
  Pointed out that the Earth cannot capture efficiently from the halo since the Earth is deep within the potential well of the Sun ($v_{esc} \approx 42$ km/s)

- 1991: Gould, ApJ 368 (1991) 610:
  WIMPs will diffuse around in the solar system due to gravitational scattering off the planets. Net result is that the velocity distribution at Earth is approximately as if the Earth was in free space, i.e. the 1987 expressions are still valid.

Capture by the Earth

- When the halo WIMPs have reached the Earth, they have gained speed by the Sun's attraction. Hence, capture is very inefficient.

- However, these halo WIMPs diffuse in the solar system by action of the other planets

Gould, ApJ 368 (1991) 610

- The phase space density of these solar system WIMPs is the same as if Earth was in free space...

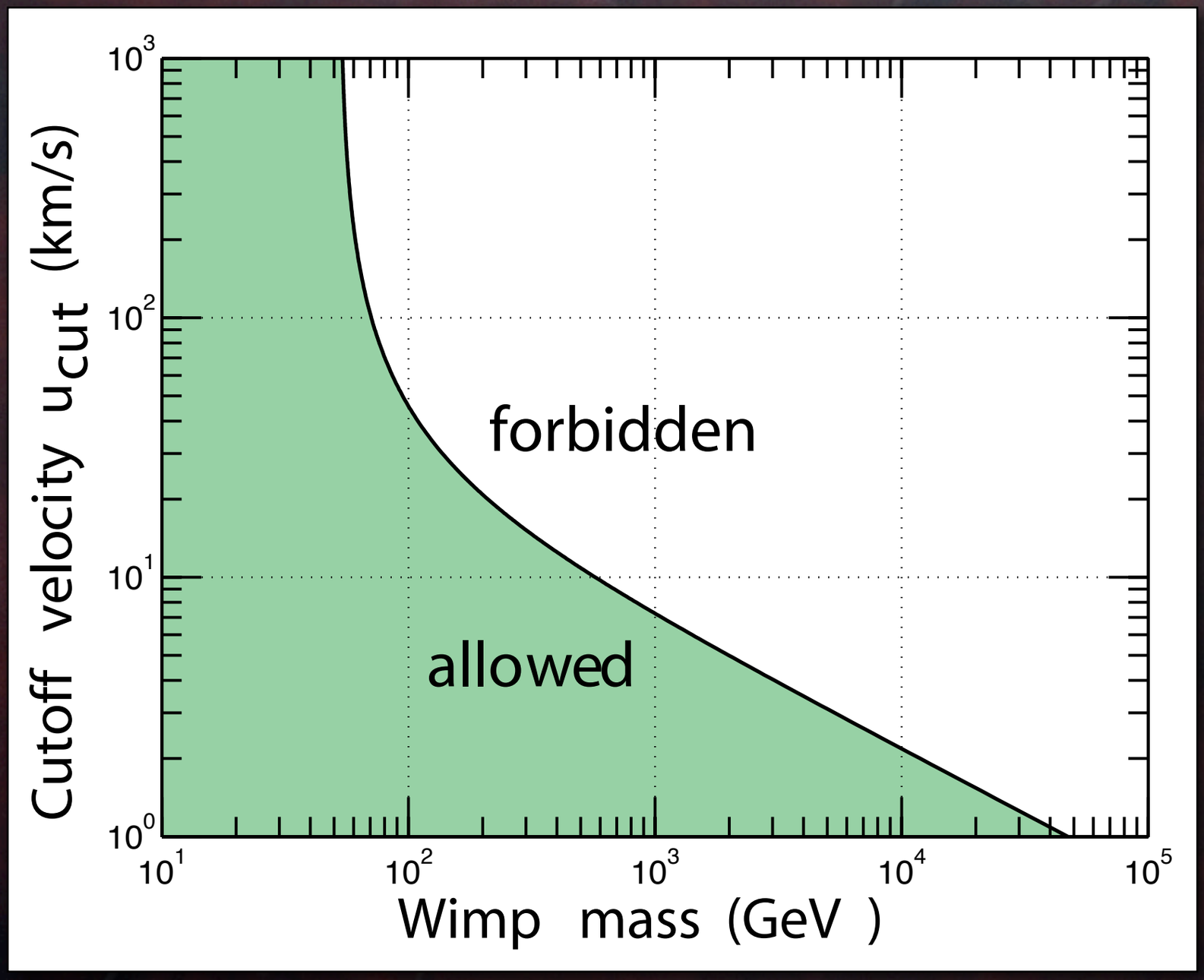
- ...if it were not for solar capture that depletes the density.

Gould and Alam, ApJ 549 (2001) 72
J. Lundberg and J. Edsjö, PRD69 (2004) 123505

Earth Capture

Why are low velocities needed?

- Capture can only occur when a WIMP scatters off a nucleus to a velocity less than the escape velocity



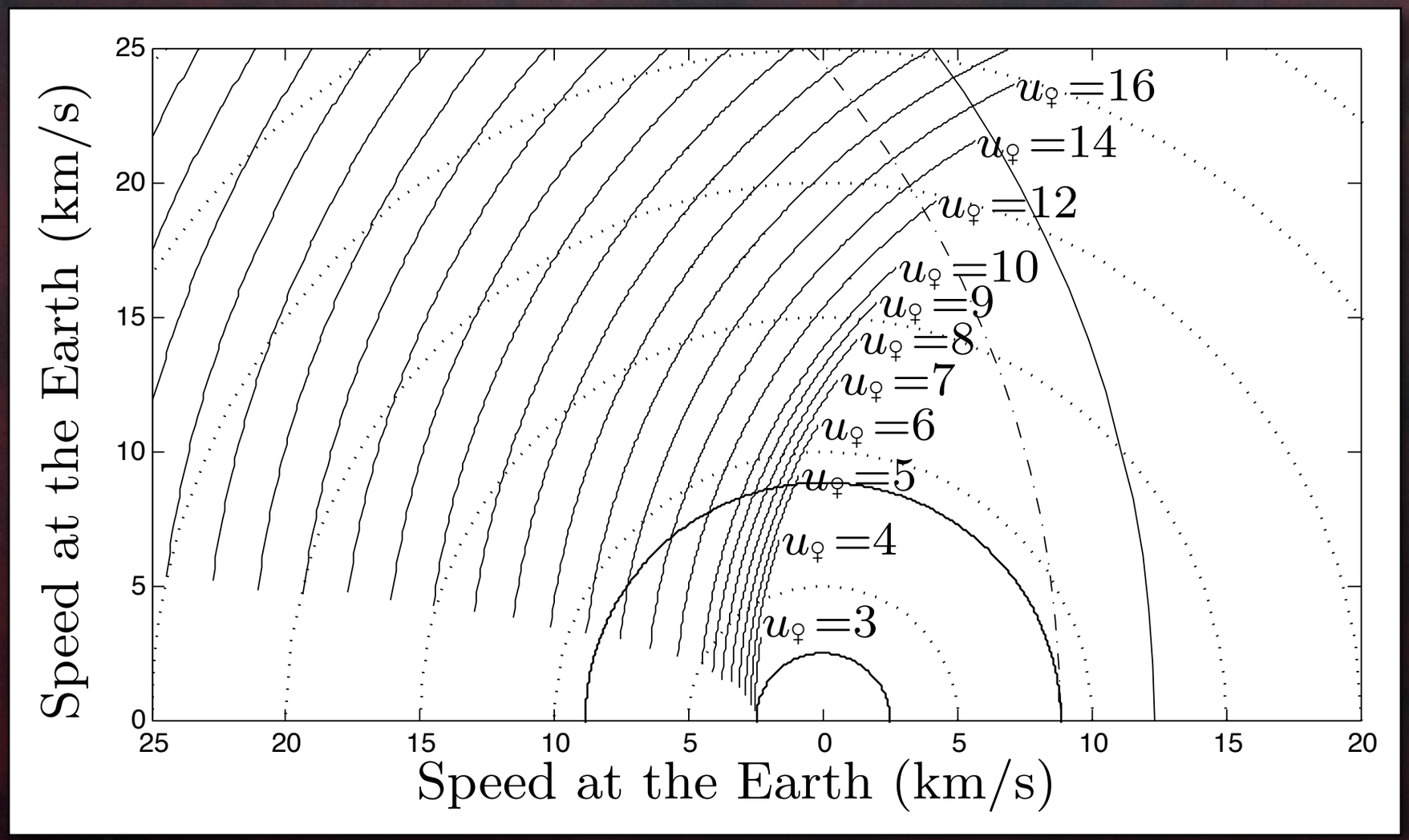
For capture on Fe, we can only capture WIMPs if the velocity is lower than

$$u_{\rm cut} = 2\frac{\sqrt{M_\chi M_{Fe}}}{M_\chi - M_{Fe}} v_{\rm esc}$$

or, alternatively, for a given lowest velocity, we can only capture WIMPs up to a maximal mass.

Diffusion effects of the planets

- Gravitational scattering off one planet causes diffusion along spheres of constant velocity with respect to that planet.
- When seen from another planet's frame, the velocity can have changed.



The net effect is that Venus and Jupiter diffuse to velocities down to 2.5 km/s

Neglecting solar capture, the velocity distribution at Earth is 'as in free space'

A. Gould, ApJ 368 (1991) 610, J. Lundberg & J. Edsjö, PRD69 (2004) 123505.

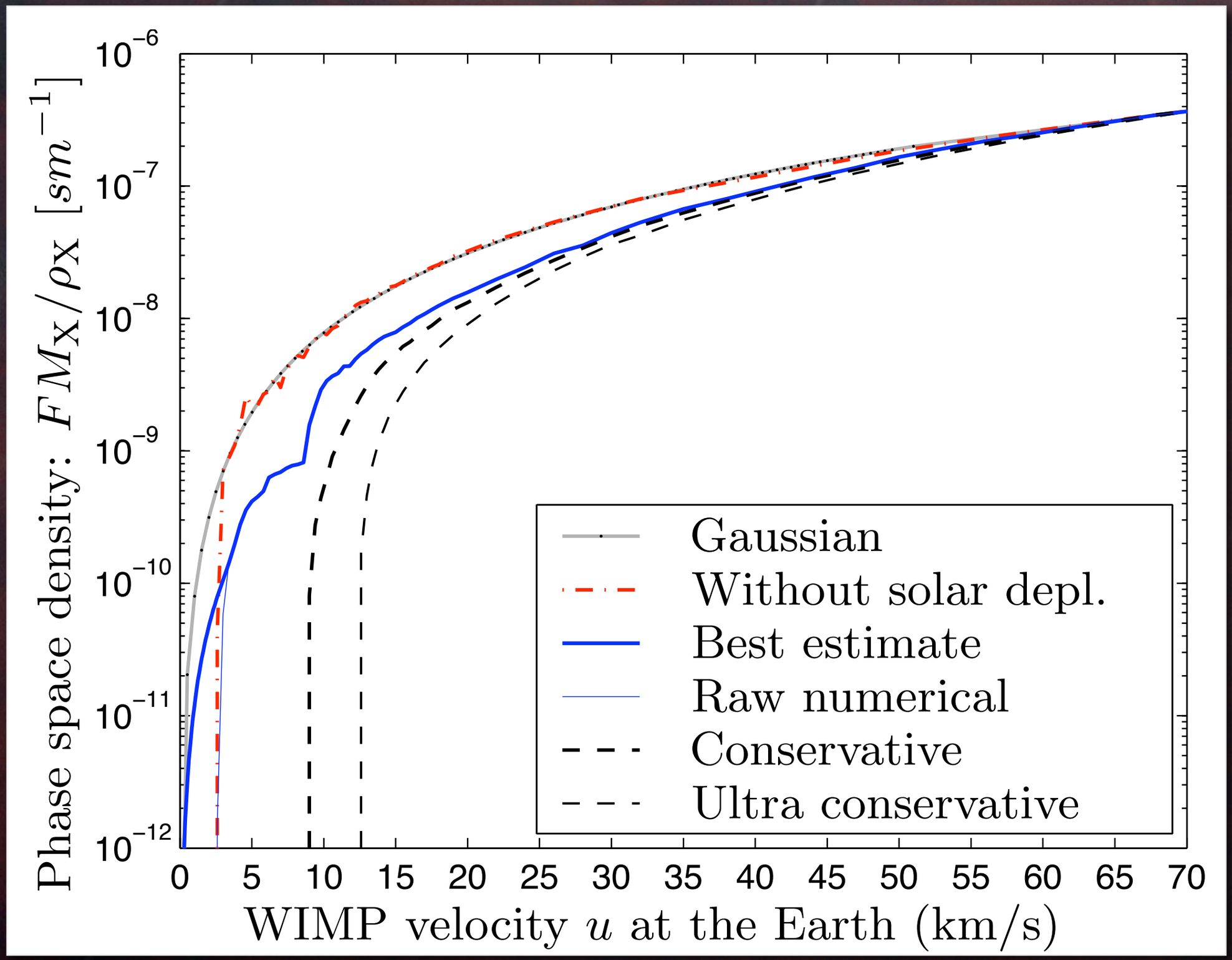
Possible problems: solar capture

- 1994: Farinella et al, Nature 371 (1994) 314:
  Simulations of asteroids thrown out of the asteroid belt showed that they were typically forced into the Sun in less than $2{\cdot}10^6$ years.

- 2001: Gould and Alam, ApJ 549 (2001) 72:
  If Farinella's results hold for general WIMP orbits, the bound WIMPs in the solar system could be depleted.

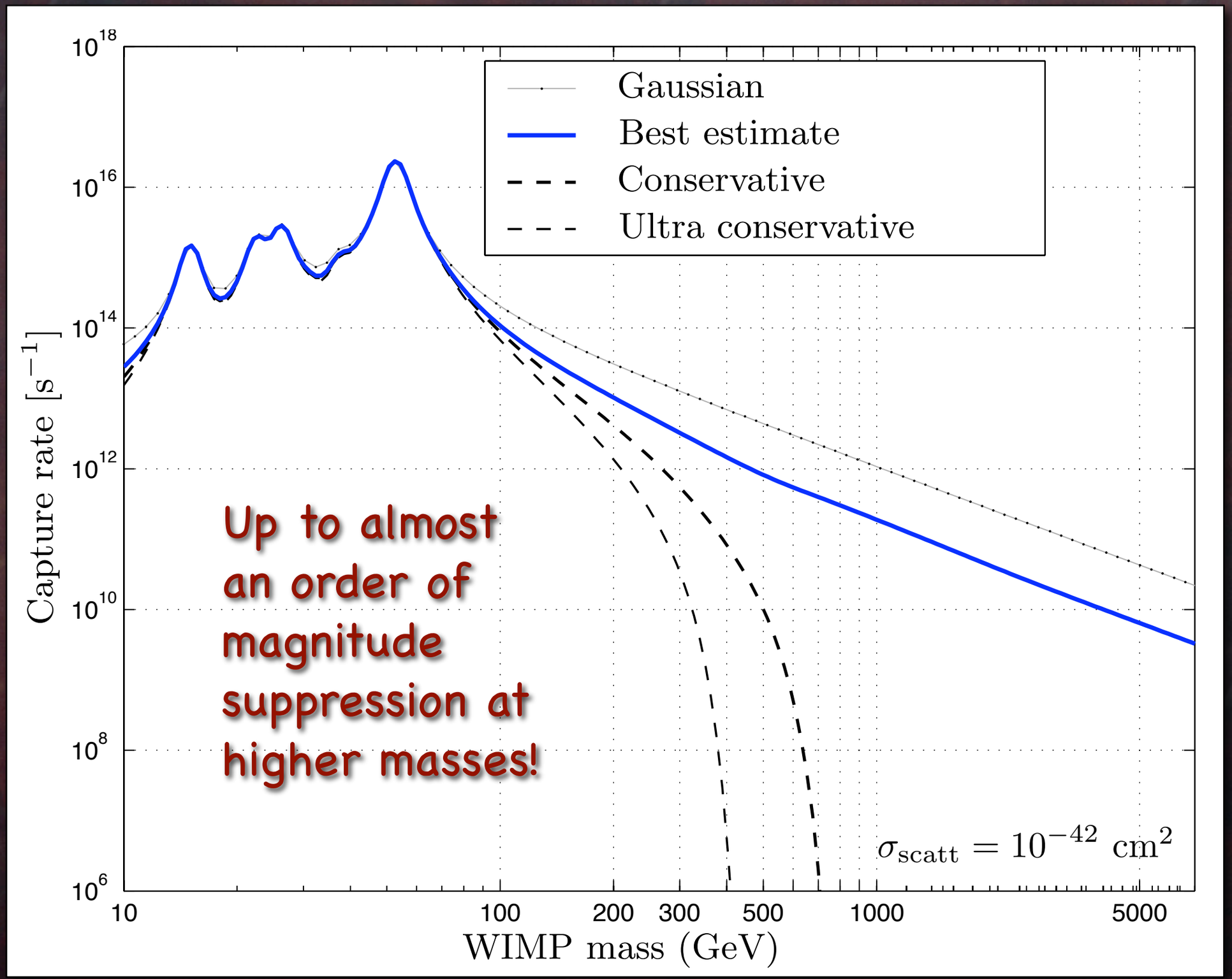
- 2004: J. Lundberg and J. Edsjö, PRD69 (2004) 123505:
  Numerical simulation of WIMP orbits to find out if this is the case.

Velocity distribution at Earth

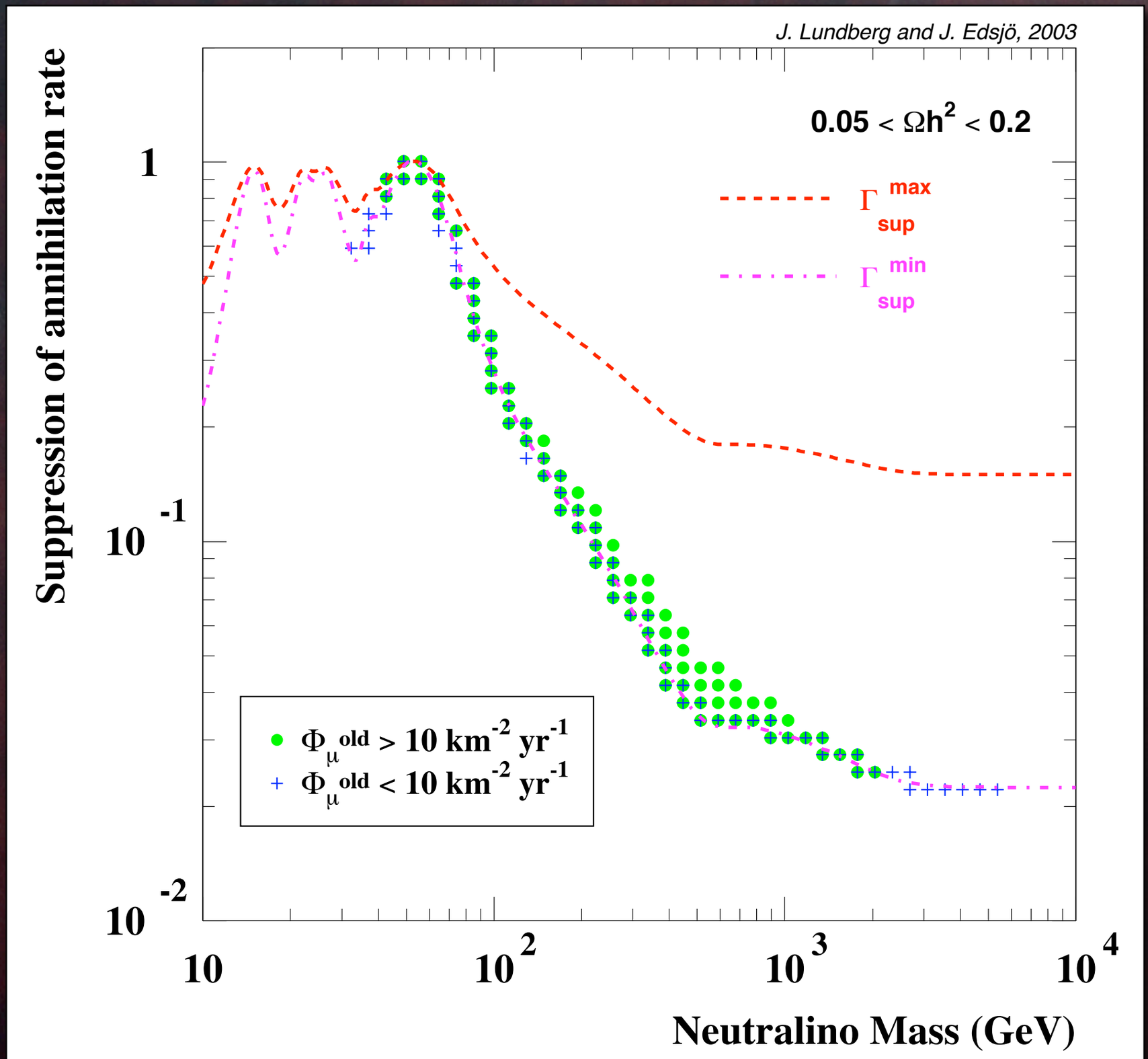


- Without solar capture, Gould's results of 'capture as in free space' are confirmed.
- Including solar capture, we get a significant suppression at low velocities, not as bad as initially thought, but still significant

Earth capture rates



Earth annihilation rates



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

Annihilation and capture is not in equilibrium in the Earth

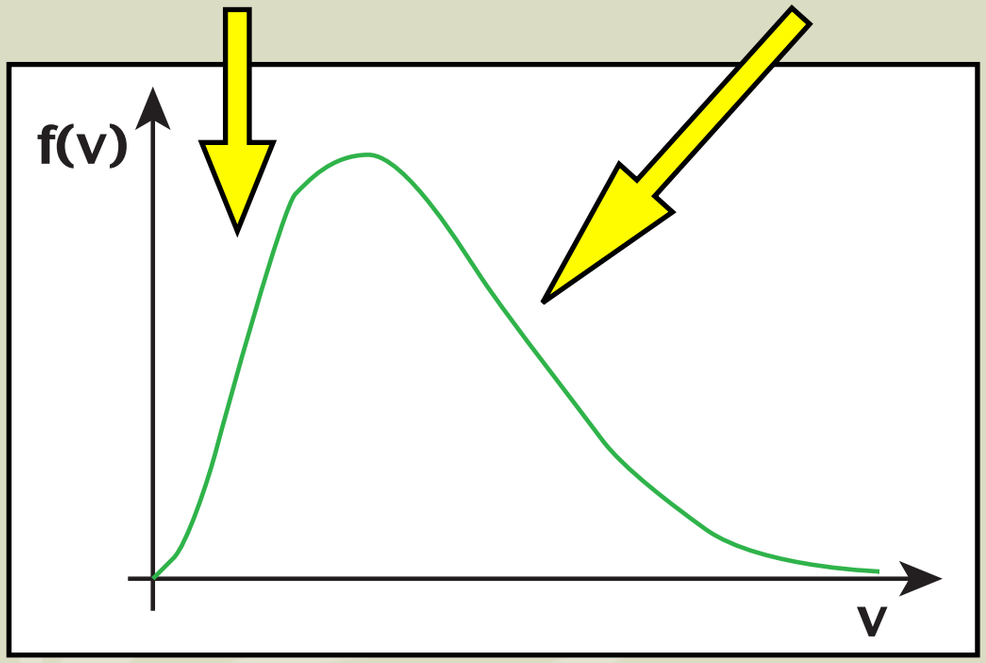
⇩

The annihilation rates are suppressed by up to almost two orders of magnitude!

A note about velocity distributions

Capture sensitive to the low-velocity region

Direct detection sensitive to higher velocities



Remember the different velocity dependencies!

- BUT, we cannot fiddle too much with this without violating the dynamical constraints from the Milky Way
- Also, the local density NOW is most likely not lower than the average by a factor of two (M. Kamionkowski and S.M. Koushiappas, arXiv: 0801.3269)