Dark matter searches in the sky and underground

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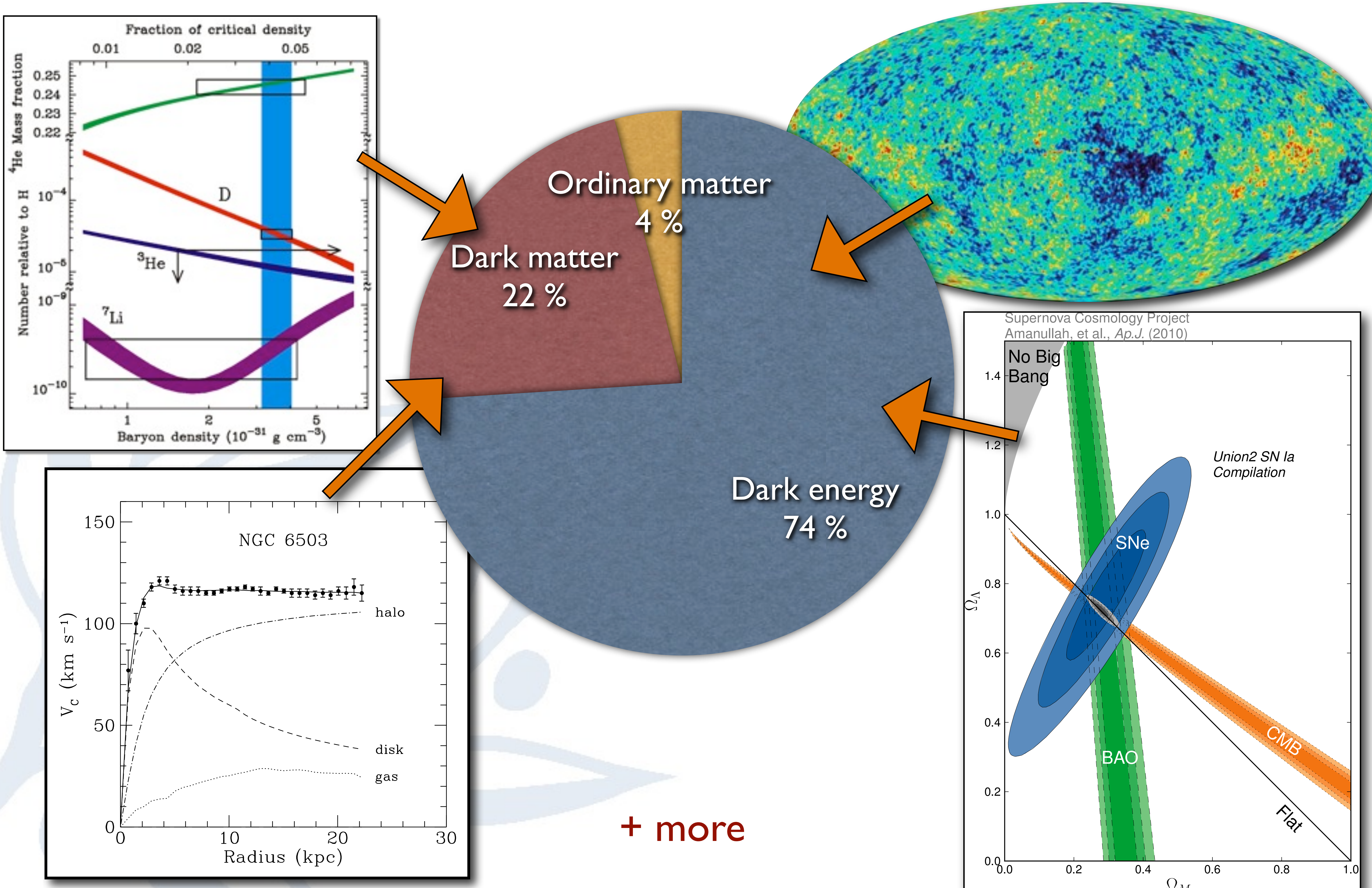
The need for dark matter



+ more

Ways to search for dark matter

Accelerator searches

- LHC (ATLAS)
- Rare decays
- ...

Direct searches

- Spin-independent scattering
- Spin-dependent scattering

DarkSUSY

Indirect searches

- Gamma rays from the galaxy
- Neutrinos from the Earth/Sun
- Antiprotons from the galactic halo
- Antideuterons from the galactic halo

- Positrons from the galactic halo
- Dark Stars
- ...

Need to treat all of these in a consistent manner, both regarding particle physics and astrophysics

Will not cover all of these...

Outline

- Particle physics dark matter
- Current status of direct detection of dark matter
- Some general ideas on cosmic ray searches (gamma rays, charged cosmic rays and neutrinos) and their uncertainties
- Future indirect searches: gamma rays?

Relic density

simple approach (more advanced in real life)

Decoupling occurs when

$$\Gamma < H$$

We have that

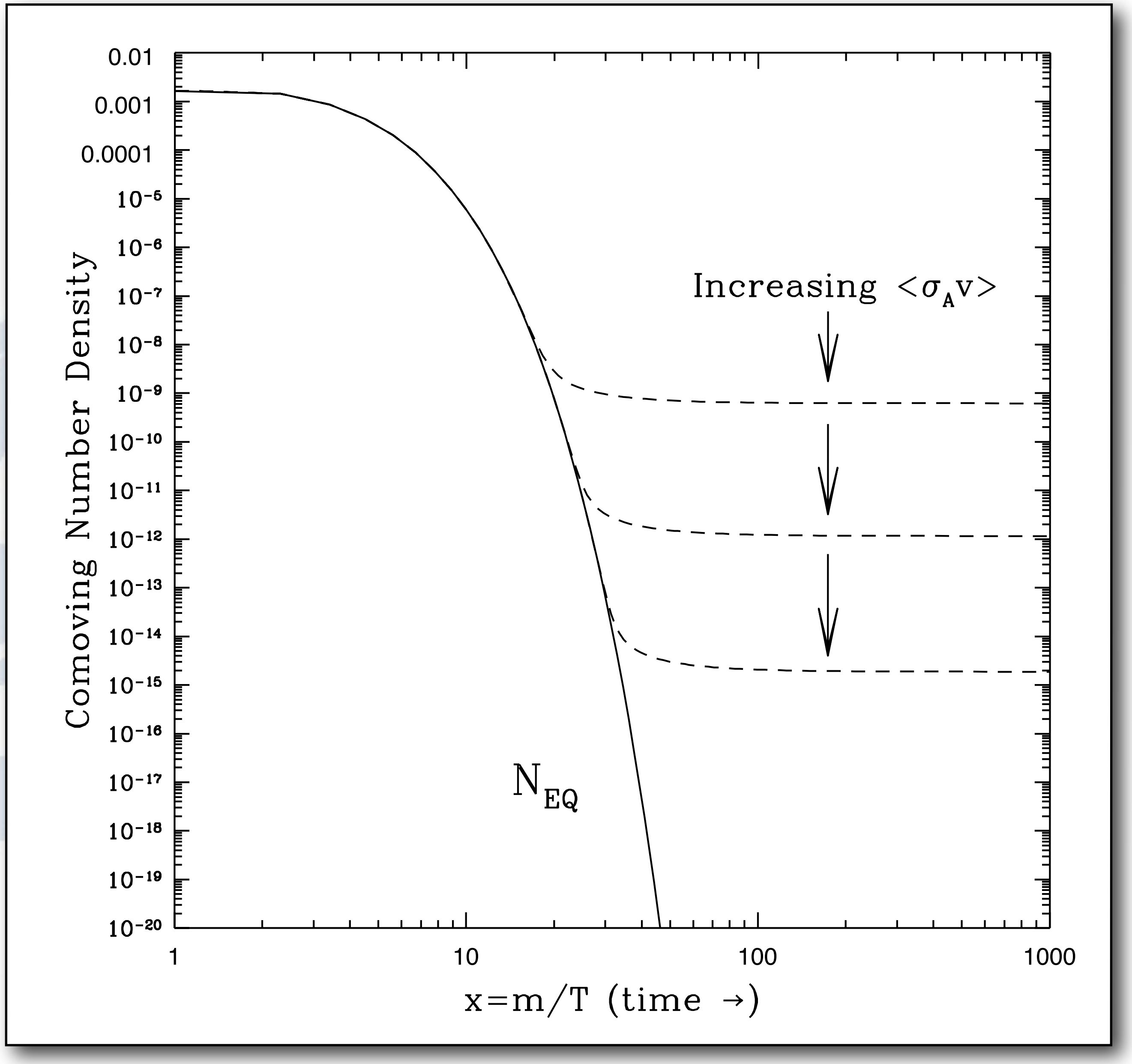
$$\Gamma = \langle \sigma_{\rm ann} v \rangle n_\chi$$

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

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

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

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



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

Many dark matter candidates

- A Weakly Interacting Massive Particle (WIMP) has the correct interaction strength, e.g.
  - Neutralinos - arise naturally in supersymmetric extensions of the standard model
  - Kaluza-Klein dark matter
  - Inert Higgs models
  - etc...

A few things to consider...

- The Minimal Supersymmetric Standard Model (MSSM) contains 124 free parameters (105 new compared to the SM).
- How do we choose these parameters?
- At what scale do we choose them?
- Do we calculate our model at tree-level or do we include loop corrections (to masses and vertices)

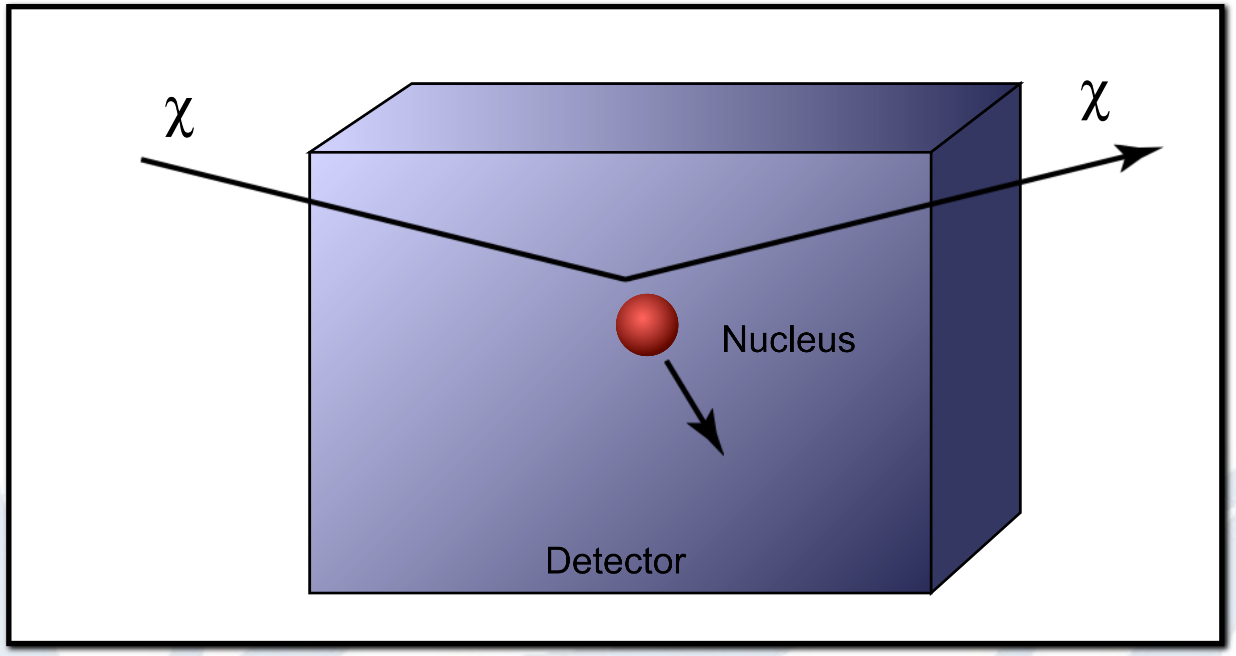
The supersymmetric mass spectrum

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	$\tilde{\chi}^\pm_{1,2}$	chargino
$H^\pm$	Higgs boson	$\tilde{H}^\pm$	Higgsino		
B	B-field	$\tilde{B}$	Bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
W^3	W^3-field	$\tilde{W}^3$	Wino		
H^0_1	Higgs boson	$\tilde{H}^0_1$	Higgsino		
H^0_2	Higgs boson				
H^0_3	Higgs boson	$\tilde{H}^0_2$	Higgsino		

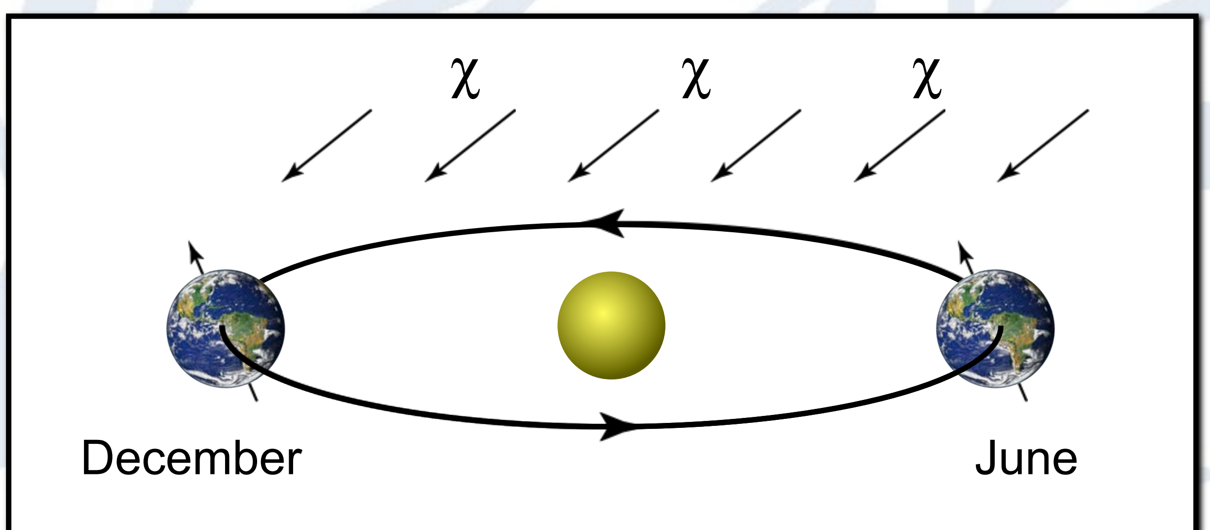
The lightest neutralino is a good dark matter candidate!

Direct detection

general principles

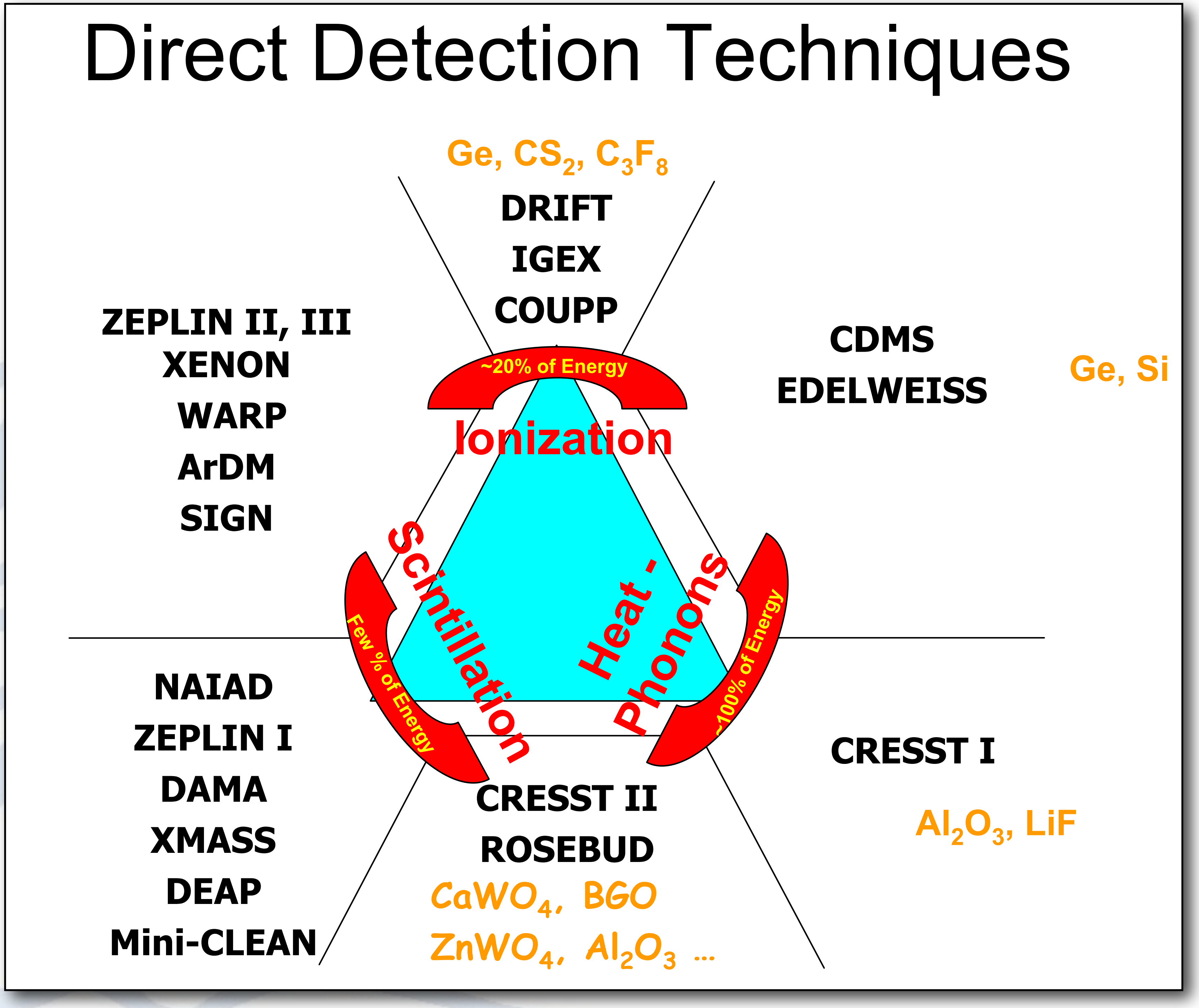


- WIMP + nucleus → WIMP + nucleus
- Measure recoil energy
- Suppress background enough to be sensitive to a signal, or...



- Search for an annual modulation due to the Earth's motion in the halo

Experimental routes



- Two ways of detection enables discrimination

Fig. from Bernard Sadoulet

Hints for a low-mass WIMP?

- CDMS (Ge) sees two events (~1.5 expected background)
- CoGeNT (Ge) sees exponential rise at low energies (claims it cannot be electronic noise)
- CRESST ($CaWO_4$)sees 32 events (expected background ~8.7). Probably background though.
- DAMA/LIBRA (NaI) sees annual modulation (8.9σ)

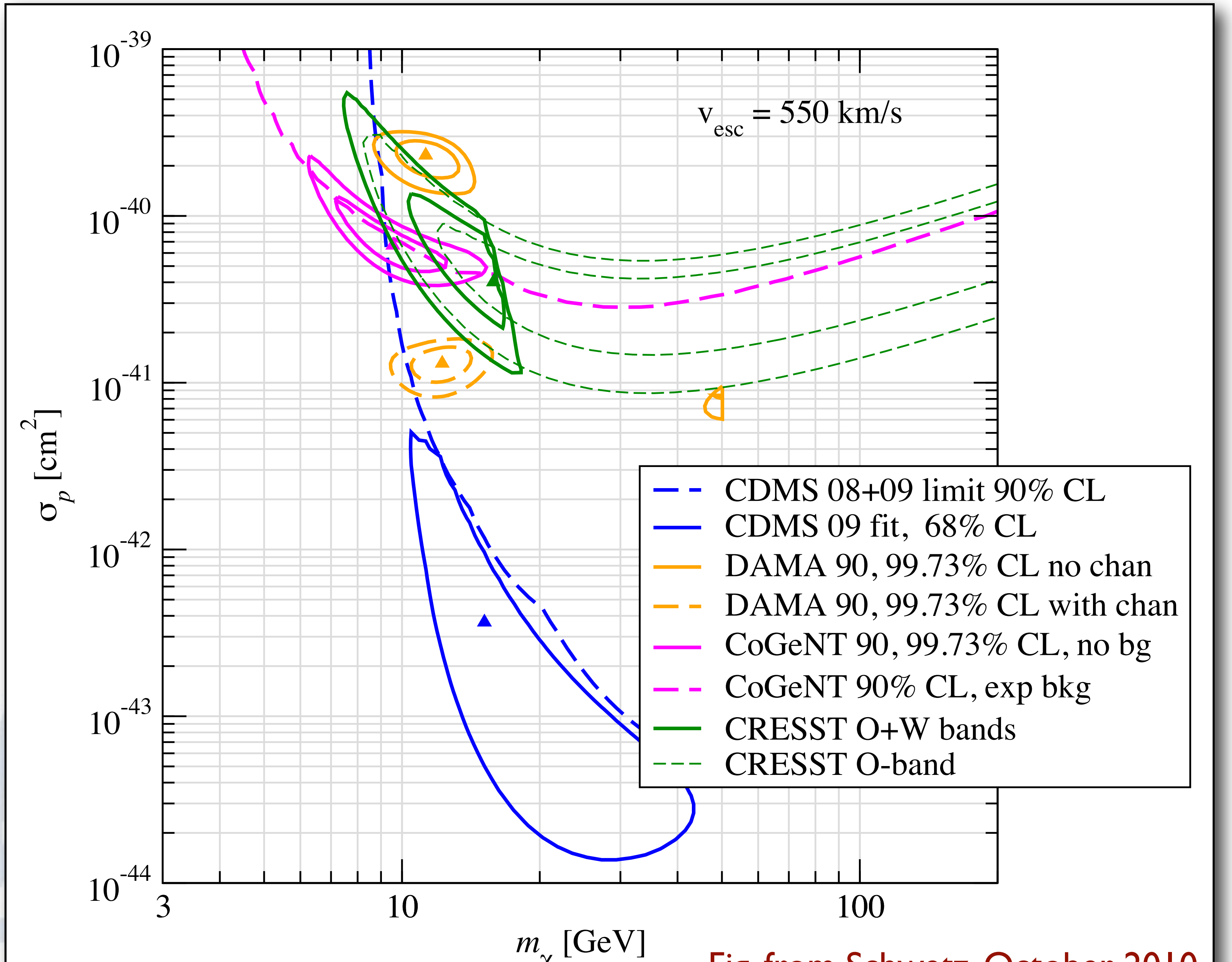
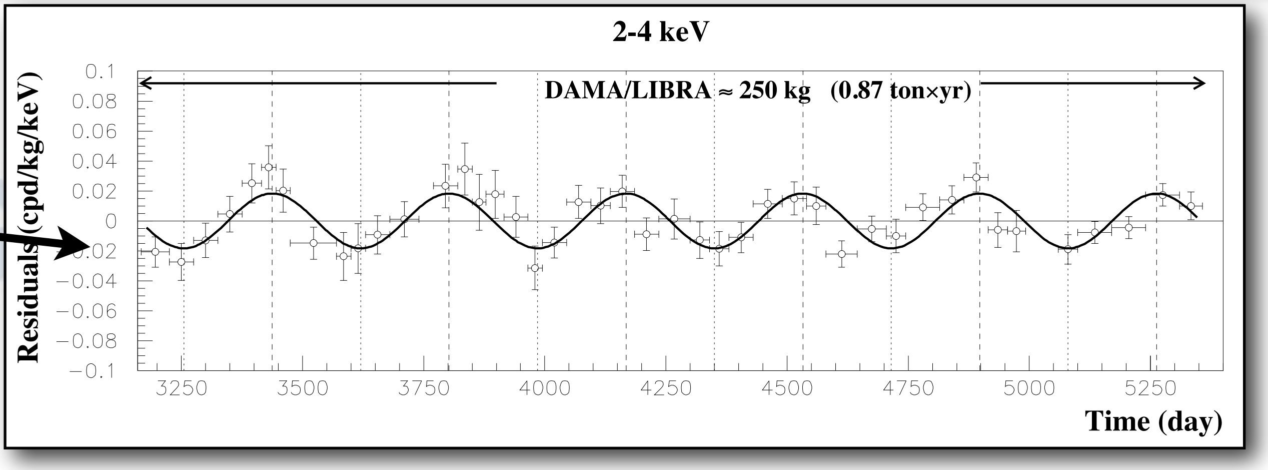


Fig. from Schwetz, October 2010



See also C. Savage (Stockholm)

Or maybe not...

- CDMS Si data constrains these models severely
- Xenon-10/100 also constrains these models
- Very hard to reconcile with a “standard” elastic scattering WIMP.
- Alternative models exist, but it starts looking very contrived.
- Most likely these hints are not dark matter

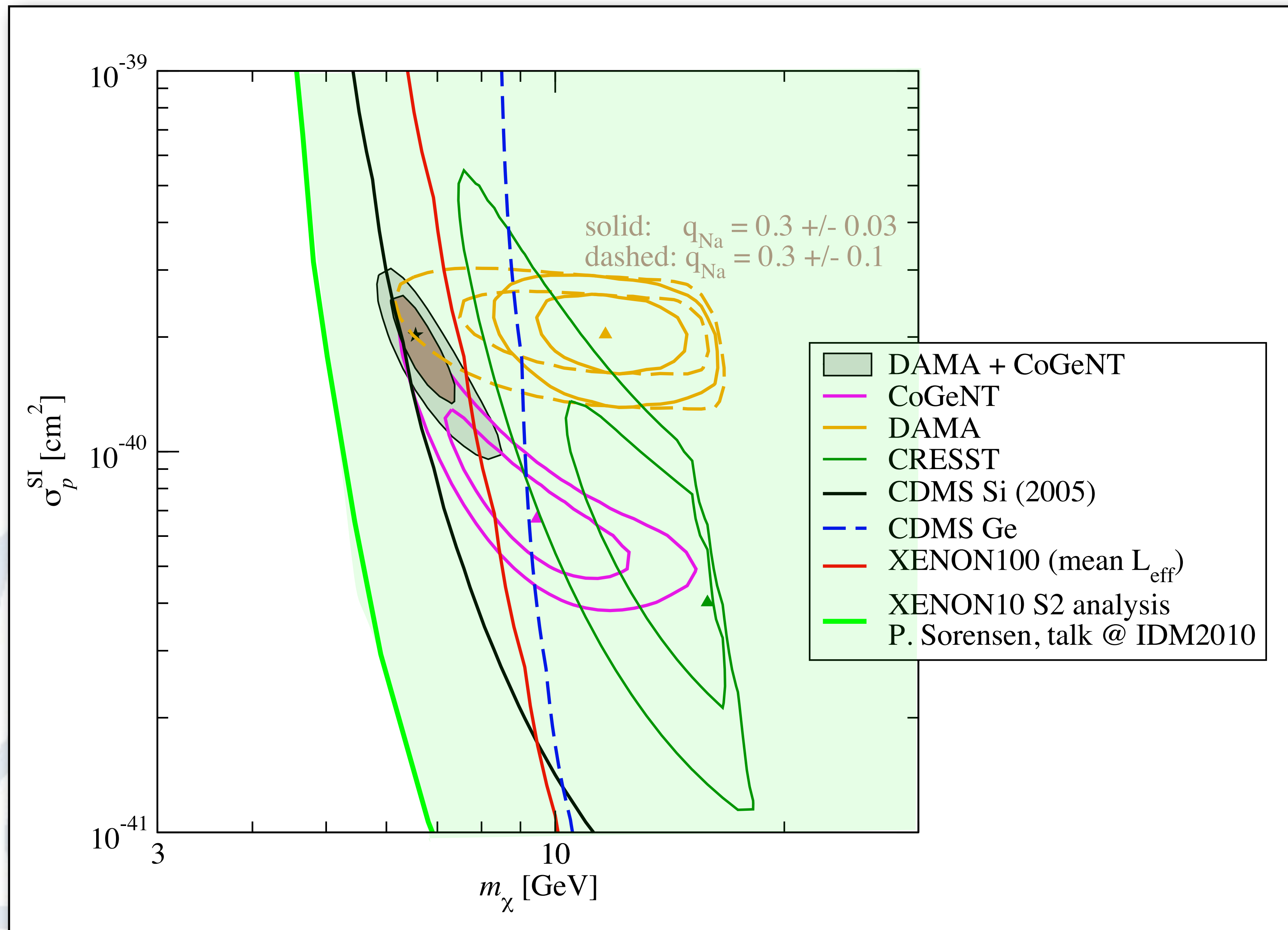
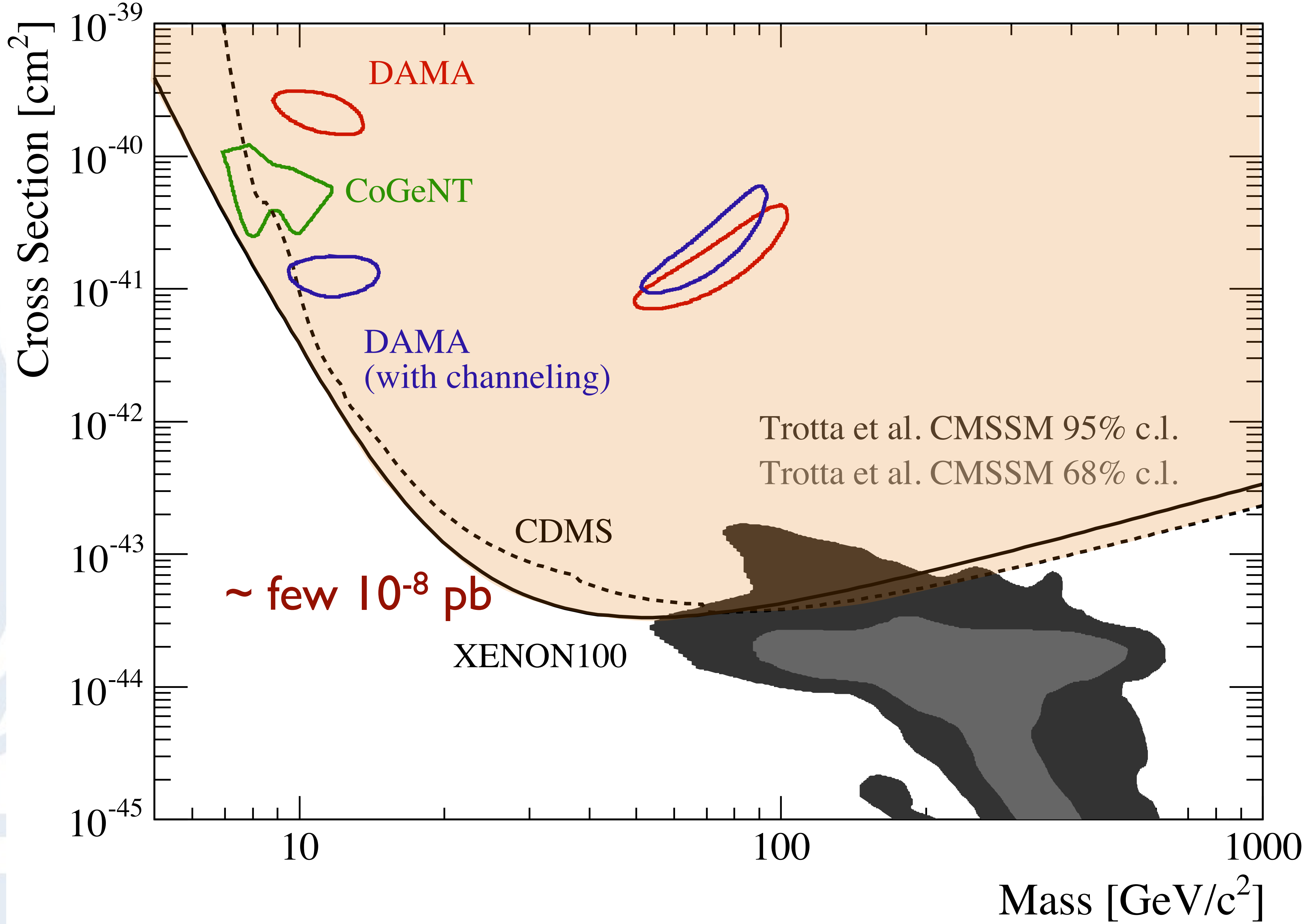


Fig. from Schwetz, October 2010

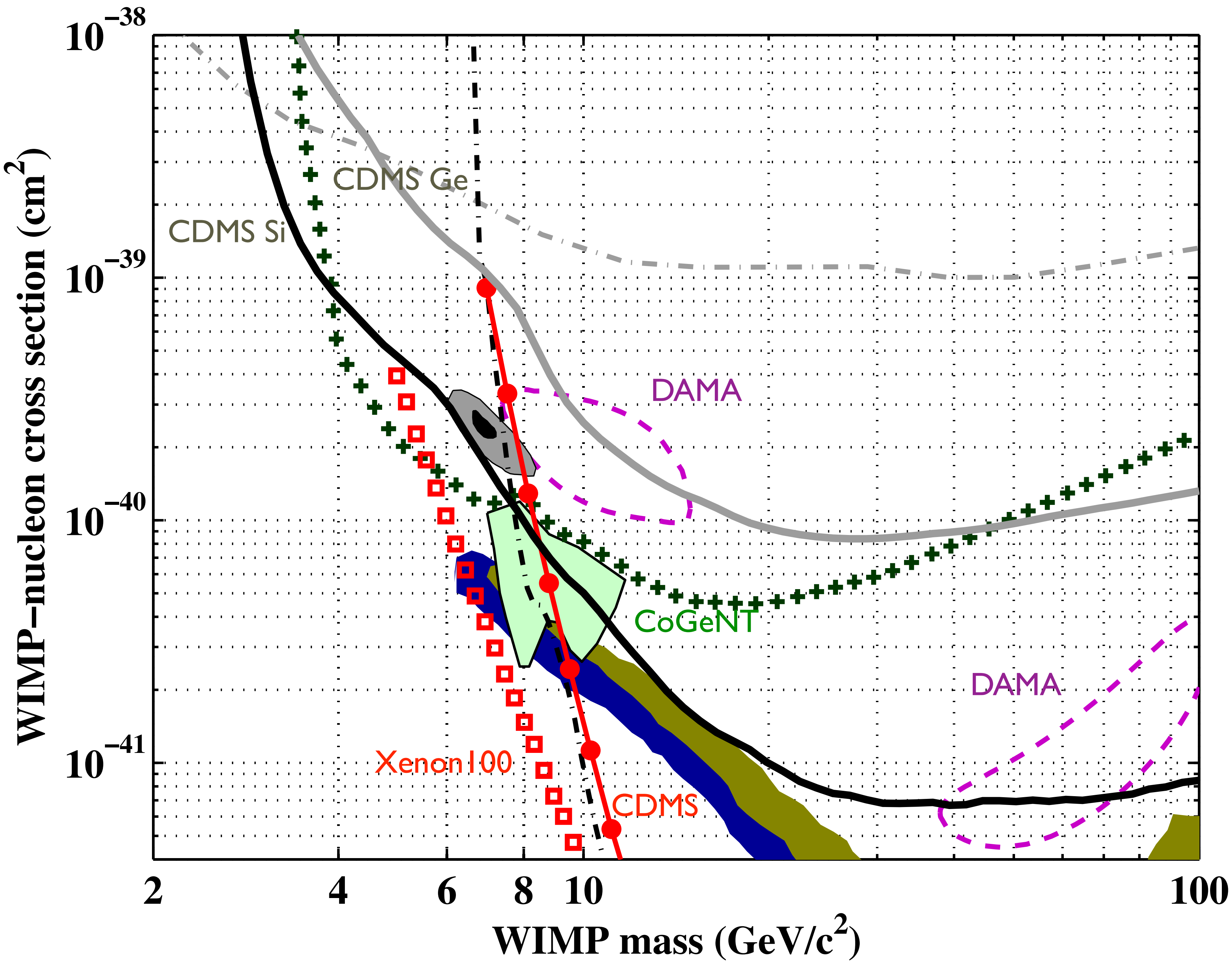
Xenon 100 results



Aprile et al, arXiv:1005.0380

Recent low-energy data

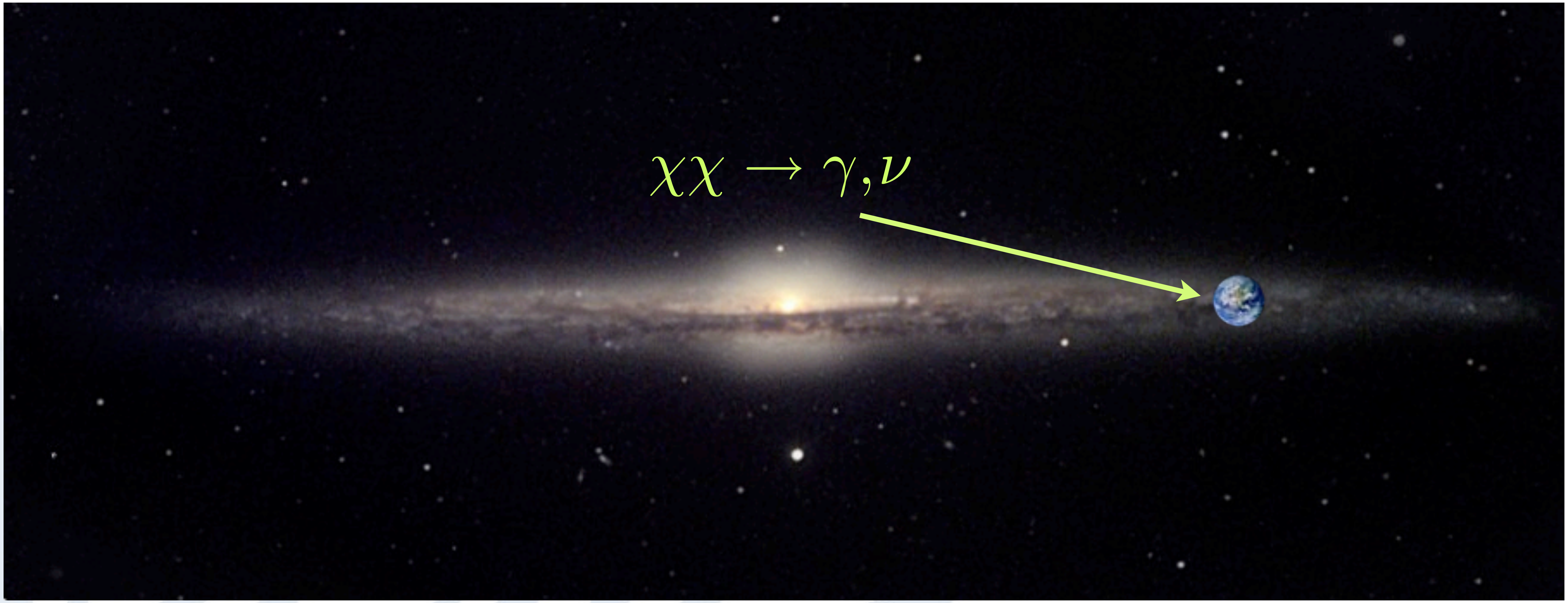
- Re-analysis of old CDMS data (from 2001–2002) to improve low-energy threshold
- Could be improved as much more data is on tape



CDMS, arXiv:1010.4290

Annihilation in the halo

Neutral annihilation products



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

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

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

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

Particle physics (SUSY, ...)

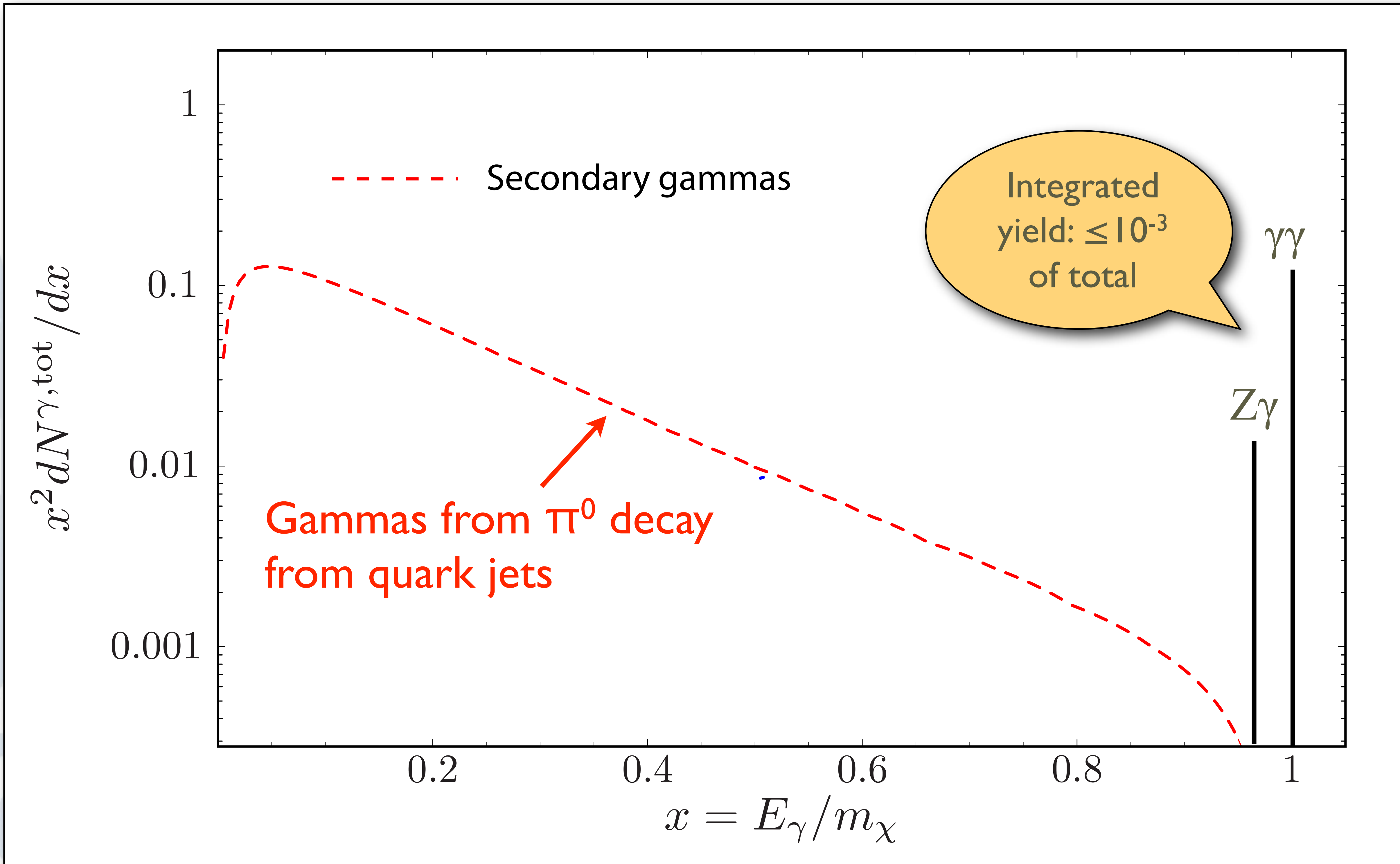
Need to include:
- continuous gammas
- IB/FSR (Internal Bremsstrahlung, Final State Radiation)
- Monochromatic gamma lines

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

Need to include:
- smooth halo, dark matter profile?
- substructures, how many/large?

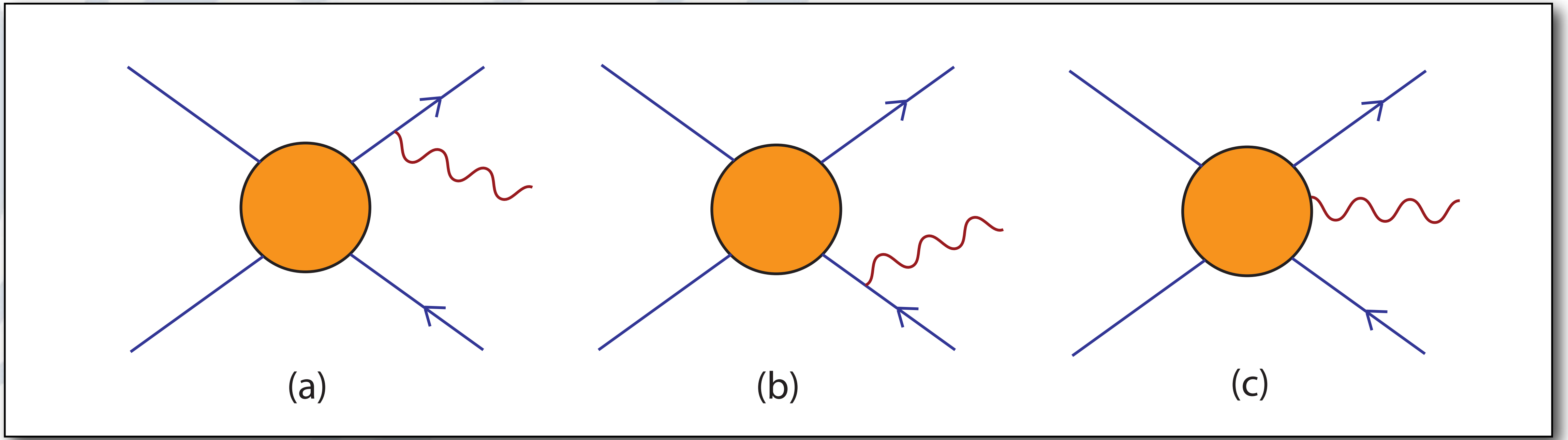
Astrophysics

Typical gamma ray spectrum

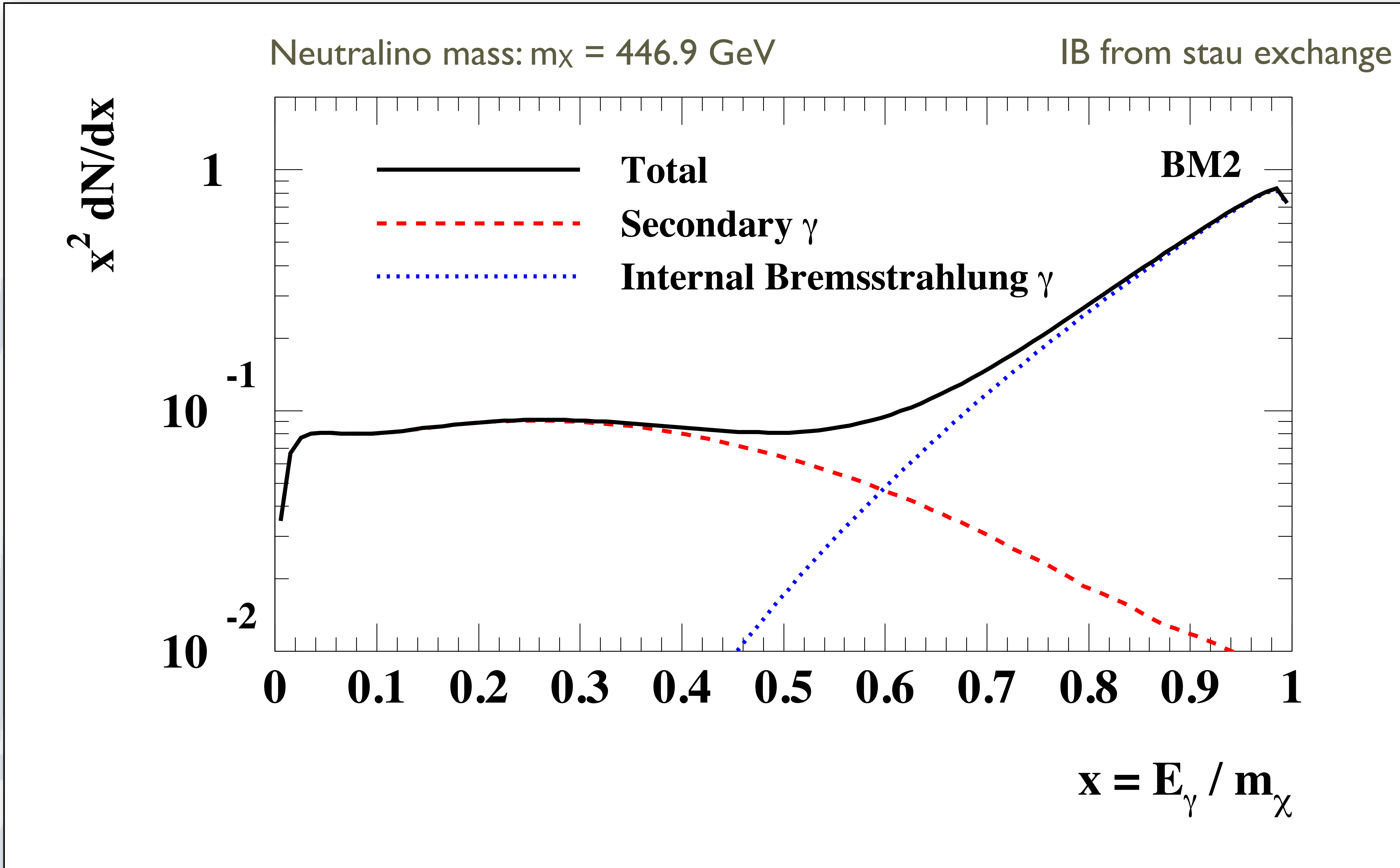


Internal Bremsstrahlung

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



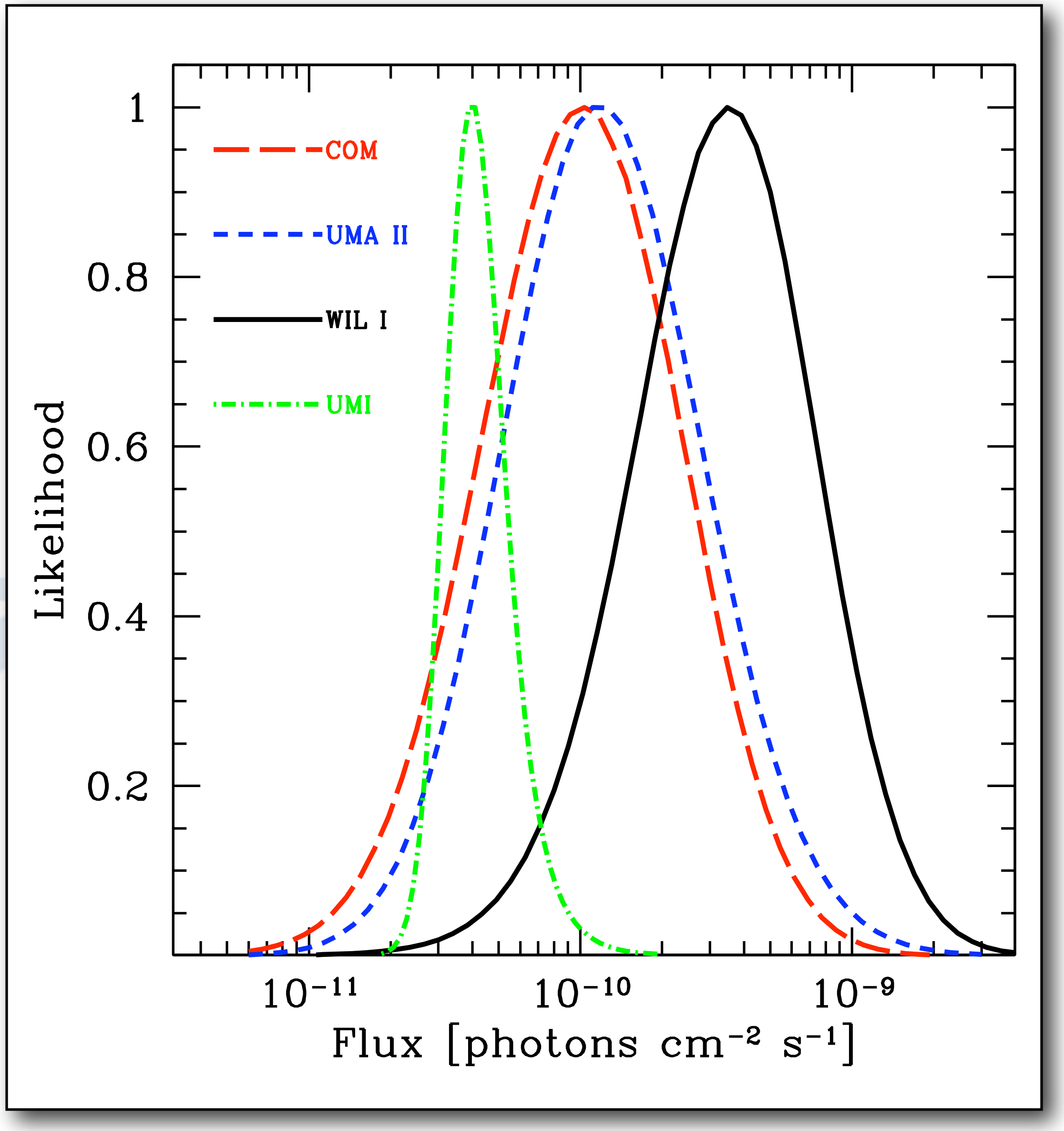
Gamma ray spectrum including IB photons



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

The J-factor

- The J-integral depends strongly on the halo profile, especially towards the galactic centre.
- Lower uncertainties exist by looking further away from the galactic centre.
- Alternatively, one can look at dwarf galaxies, but then there are uncertainties from the DM profile in them (see e.g. Strigari et al)



Strigari et al, arXiv: 0709.1510

Substructures

- Substructures could in principle boost the signal by orders of magnitude.
- However, recent N-body simulations indicate that the boost factor is of the order of
  - 5-15 (Via Lactea II)
  - 1-2 (Aquarius)

$$\Phi \propto \int_{l.o.s.} \rho^2 dl$$

$$\text{Boost factor: } B \simeq \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$$

- The boost factor will typically be different in different regions in the sky, smaller towards the galactic centre and possibly larger in other directions.

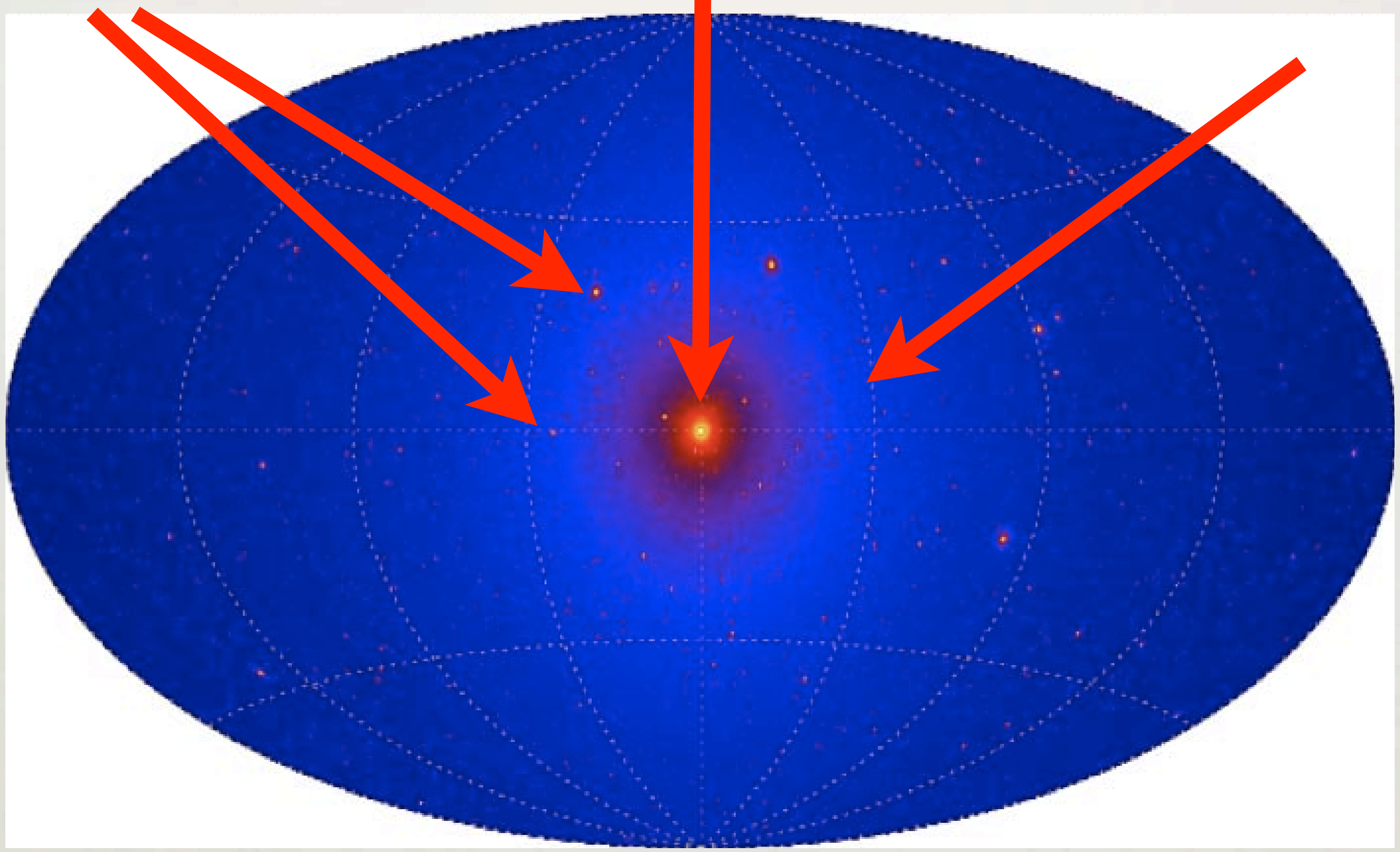
Slide from Simona Murgia, Fermi Symposium

Search Strategies

Galactic center:
Good statistics but source confusion/diffuse background

Satellites:
Low background and good source id, but low statistics

Milky Way halo:
Large statistics but diffuse background



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

And electrons!
Anisotropies

Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

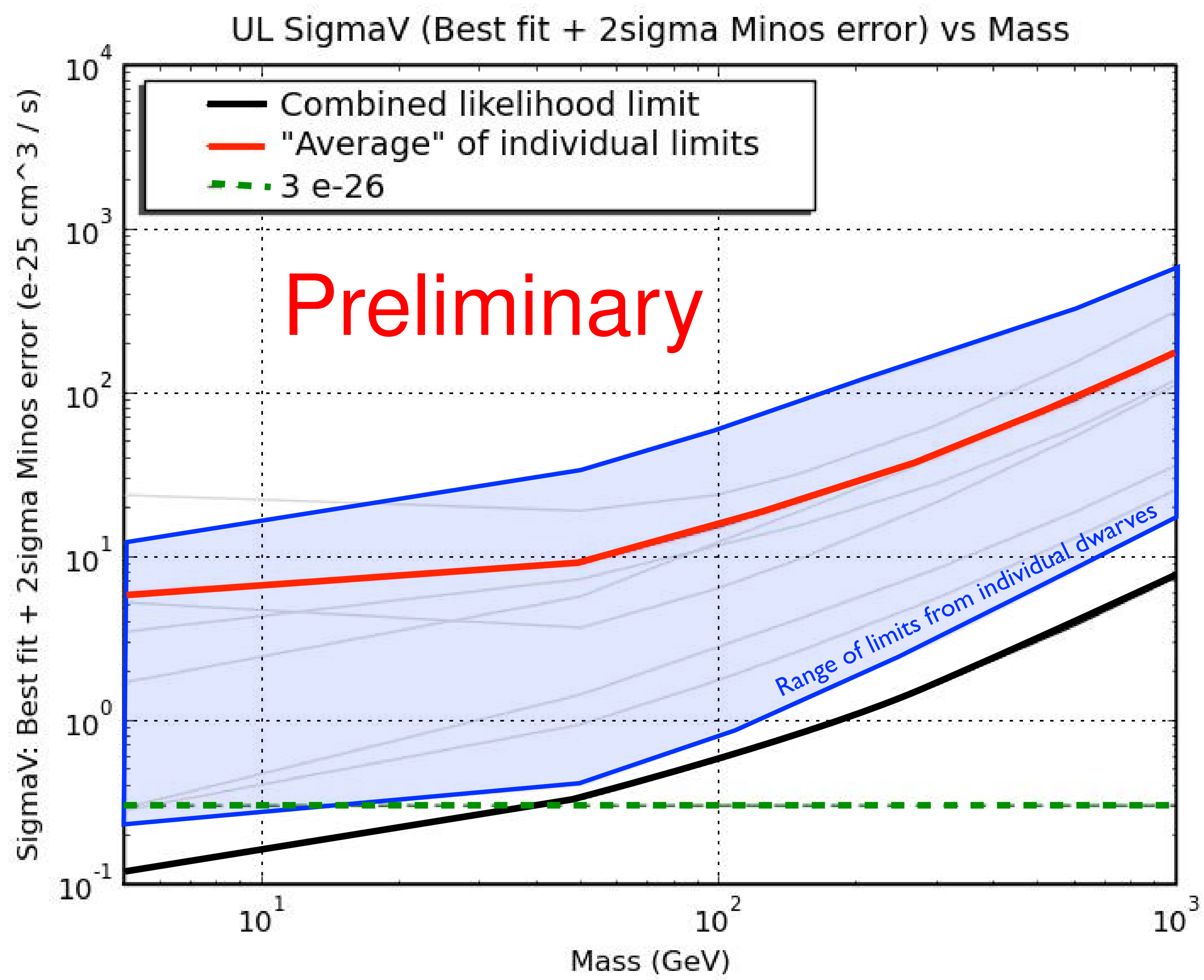
Galaxy clusters:
Low background but low statistics

Extra-galactic:
Large statistics, but astrophysics, galactic diffuse background

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

Stacked dwarf analysis from Fermi

From Maja Llena Garde, idm2010

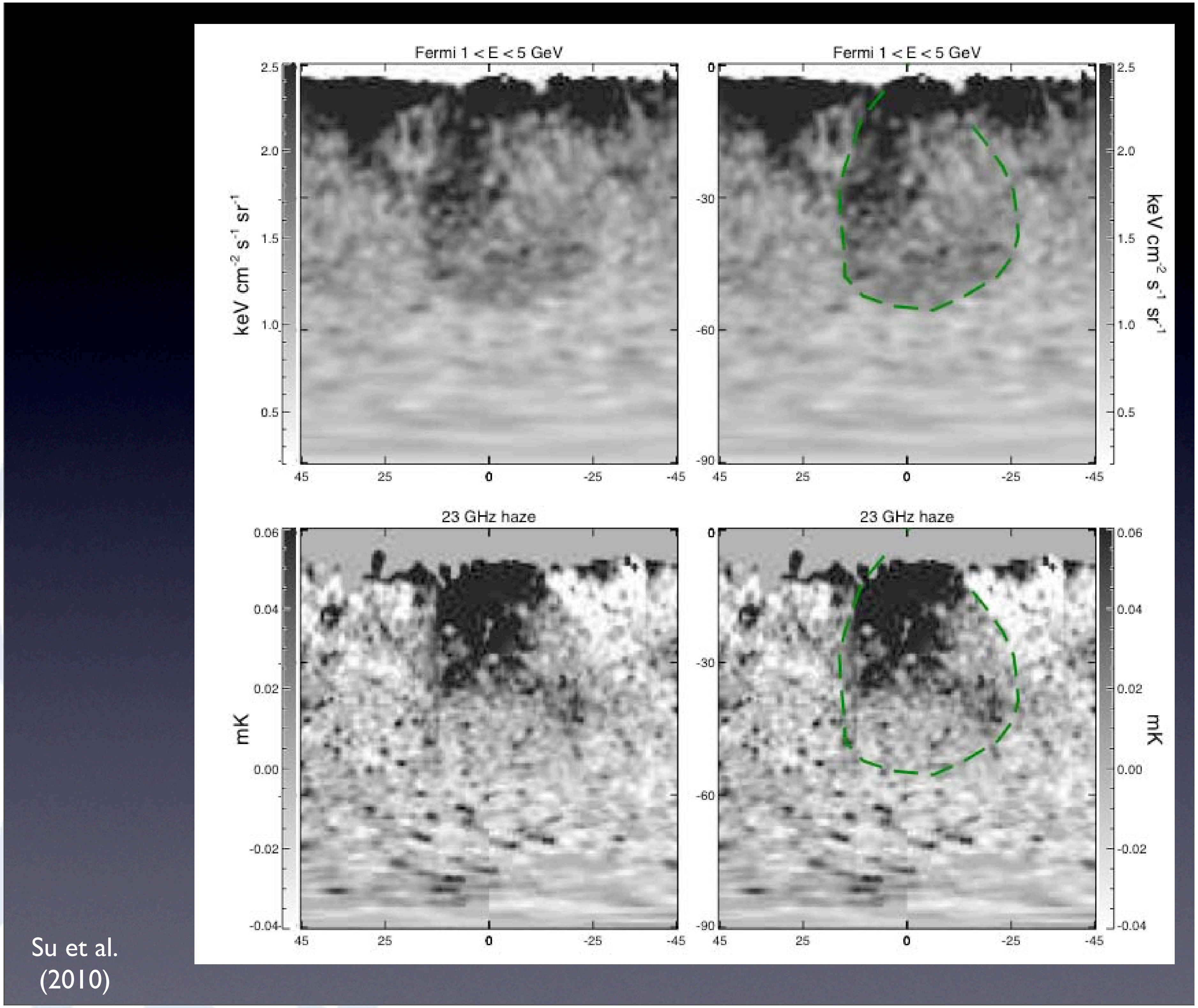


- Combined upper limit gives up to a factor 3 (45) better constraints compared to the best (average) dSph.
- The "average" limit of the individual cases is plotted here just to guide the eye. The grey lines are the individual limits and the dashed green line is the thermal WIMP cross-section.

We are reaching into the standard thermal WIMP region!!!

(Average J-value used here)

WMAP and Fermi haze

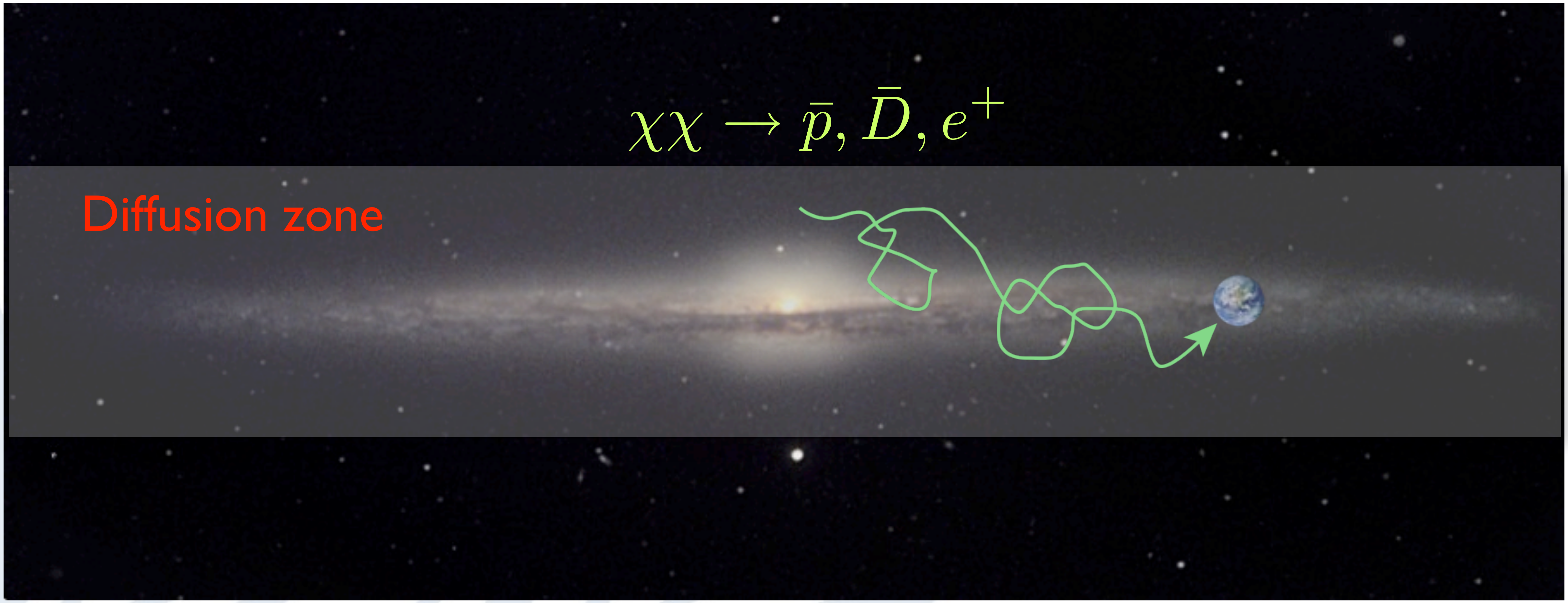


From Finkbeiner, idm2010

- Haze (WMAP and Fermi) evidence gets stronger, but support for dark matter interpretations weakens...
- Exist models (or ideas) by Biermann and Becker with quite different diffusion at the GC region
- Also, recent study of Aharonian et al on dynamical cosmic ray models claim to fit these observations reasonably well

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. Pamela, ATIC, Fermi.
- Future detectors are e.g. AMS, GAPS and Calet. AMS to be launched February 2011.

Diffusion equation

$$\partial_z (V_C \psi) - K \Delta\psi + \partial_E \left\{ b^{\rm loss}(E)\, \psi - K_{EE}(E)\, \partial_E \psi \right\} = Q(\mathbf{x}, E)$$

Wind — Spatial diffusion — Energy losses — Energy diffusion (reacceleration) — Source term

$$K(E) = K_0\, \beta\, (\mathcal{R}/1\,\mathrm{GV})^\delta$$

$$K_{EE} = \frac{2}{9} V_a^2 \frac{E^2 \beta^4}{K(E)}$$

$$Q(\mathbf{x}, E) \propto \rho^2 \langle \sigma v \rangle \frac{dN}{dE}$$

As the source term depends on the DM density squared, we are very sensitive to the halo profile and substructure.

Diffusion parameters

- The most important diffusion parameters are

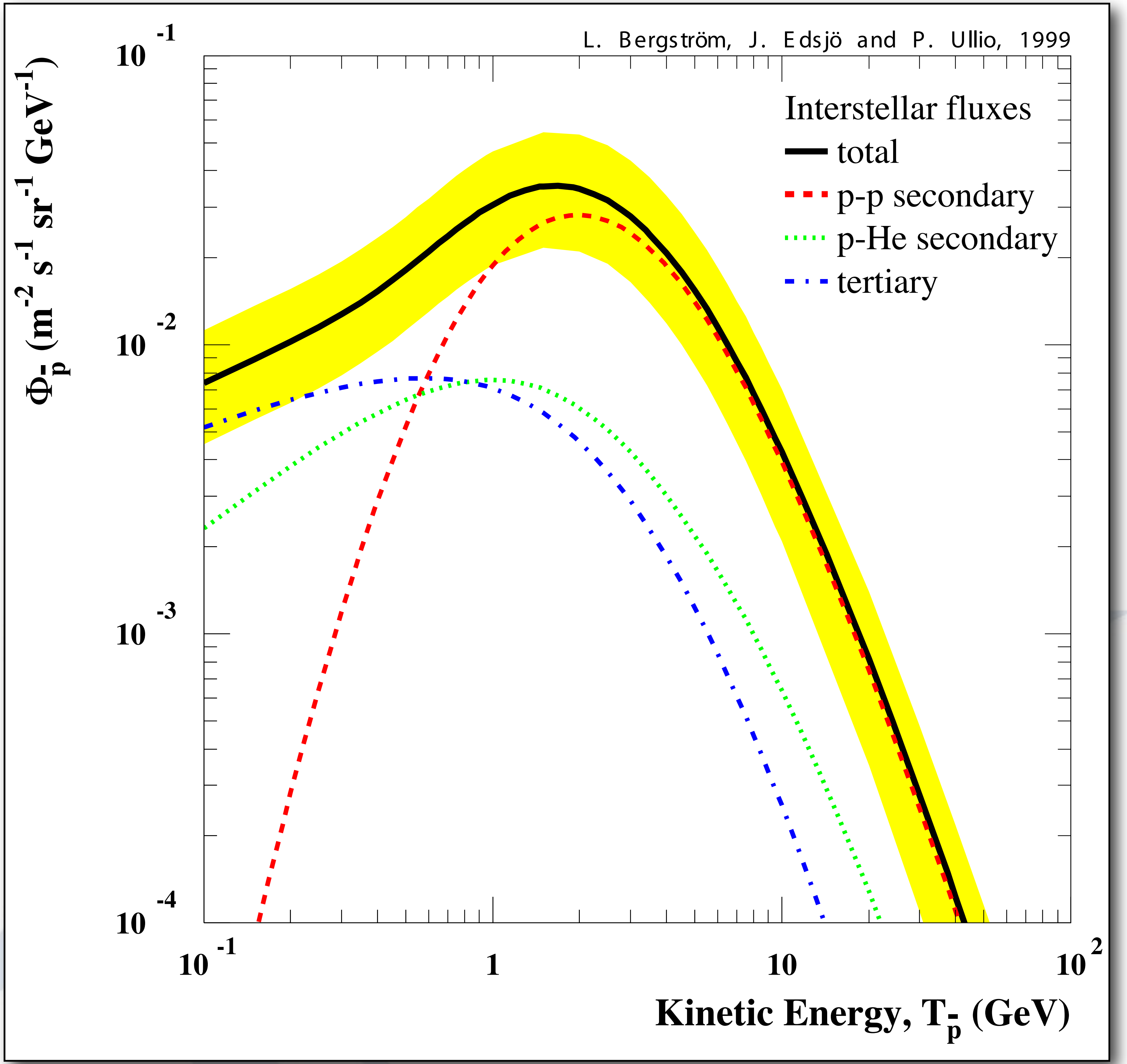
  K_0 (D_0) – diffusion coefficient

  δ – exponent for energy dependence of diffusion coefficient

  L – diffusion zone half height

- In addition, more parameters are needed for energy losses, galaxy radial extent, etc

Antiprotons – background



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

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

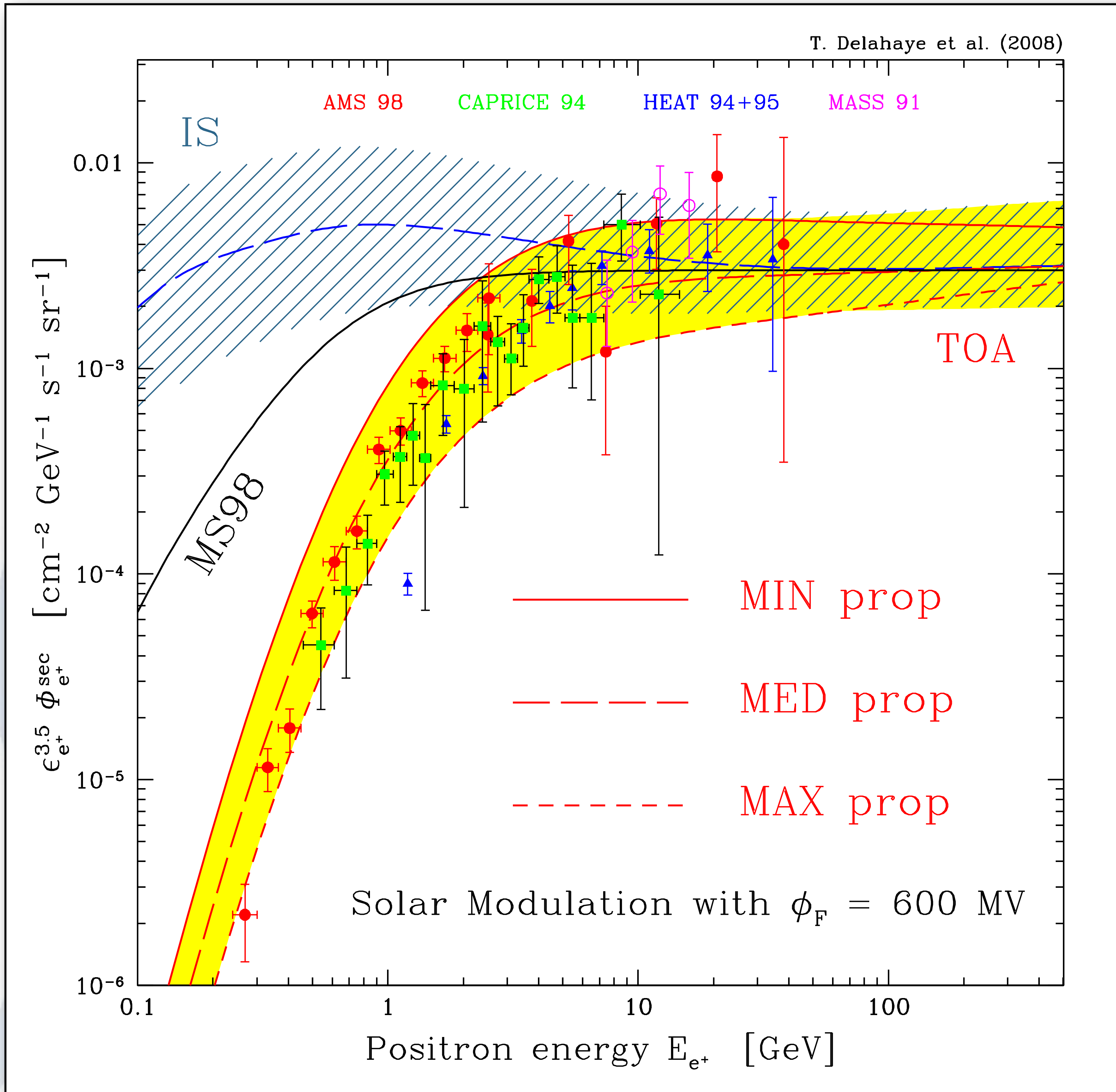
$$E_{\rm th} \simeq 7 m_p$$

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

- energy losses
- p-He interactions
- reacceleration

- are all important.

Background uncertainties

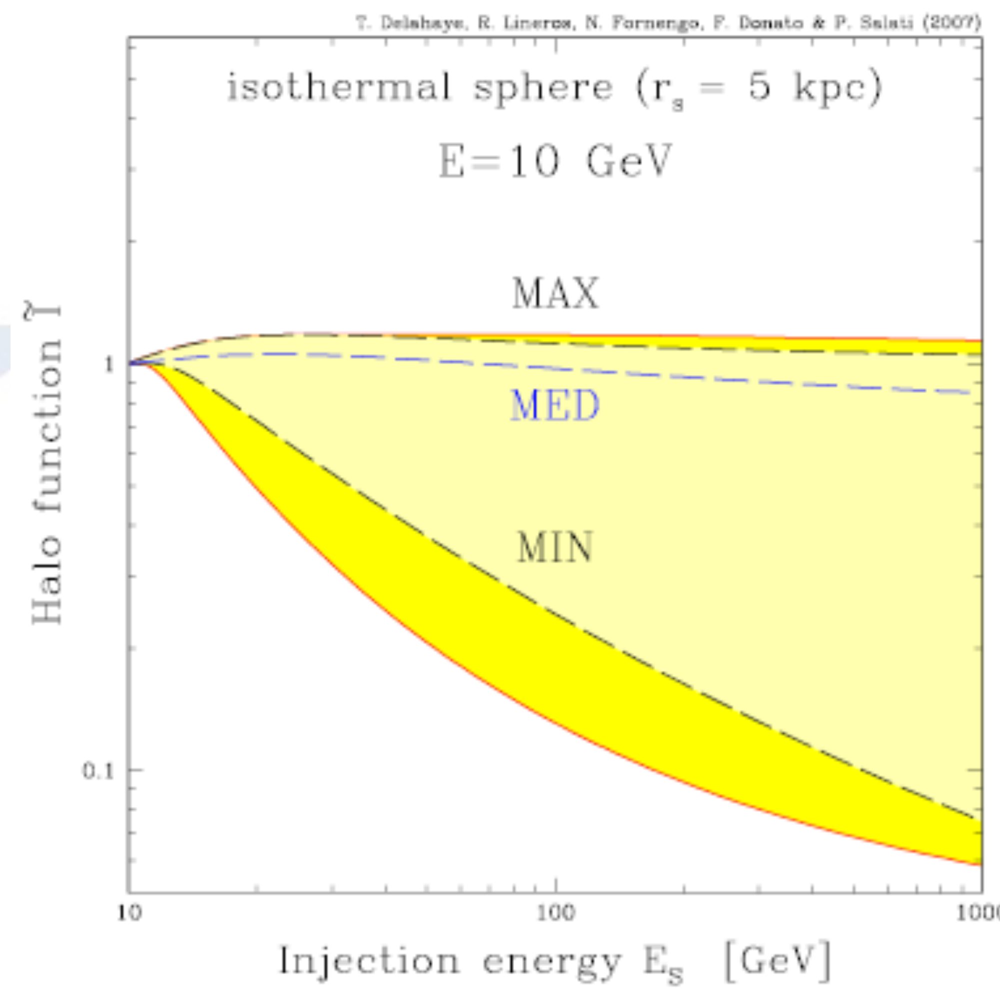


Delahaye et al, arXiv: 0809.5268

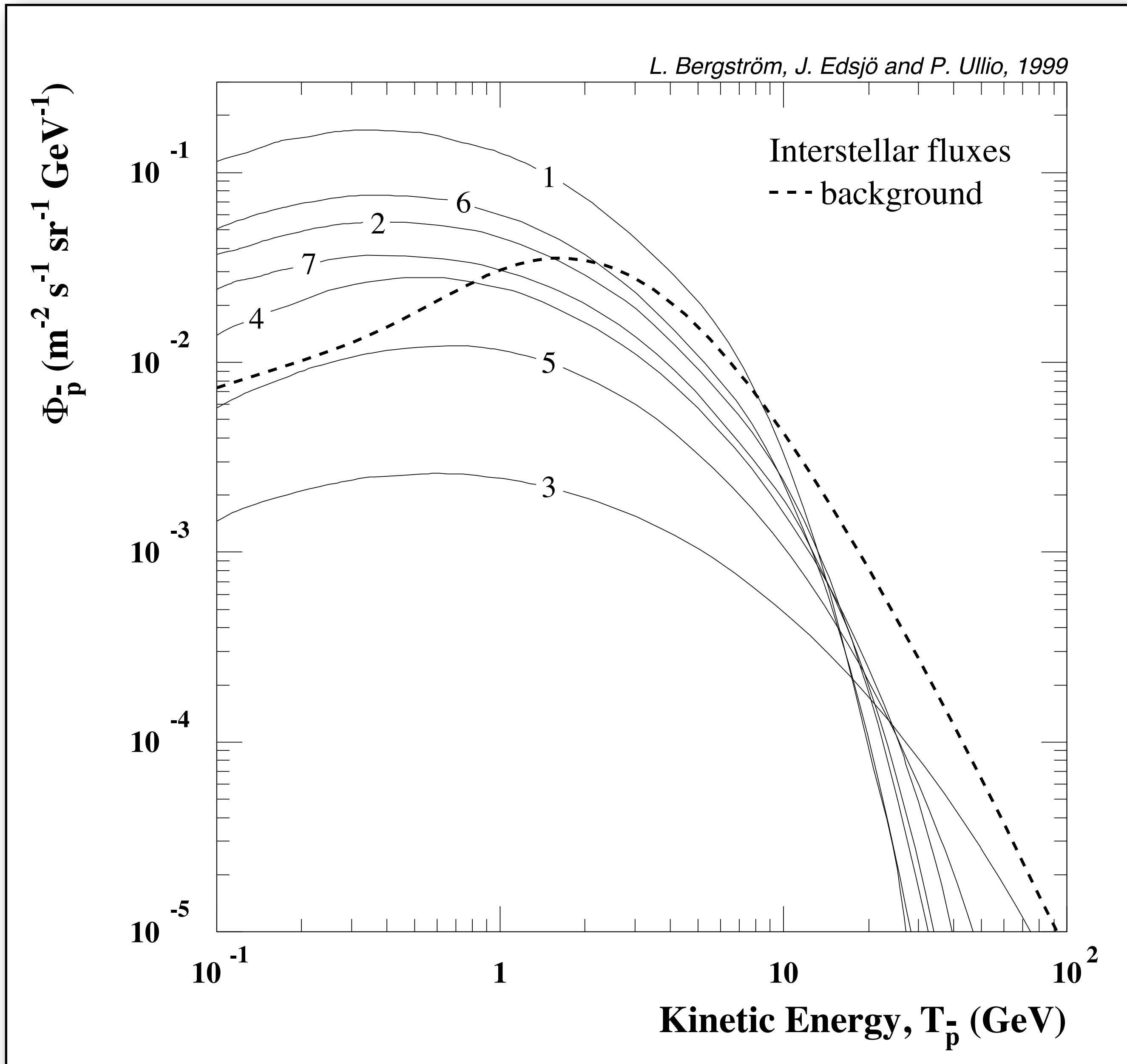
- Background uncertainties from propagation only.
- Additional uncertainties arise from energy loss uncertainties, injection spectra, production cross section etc

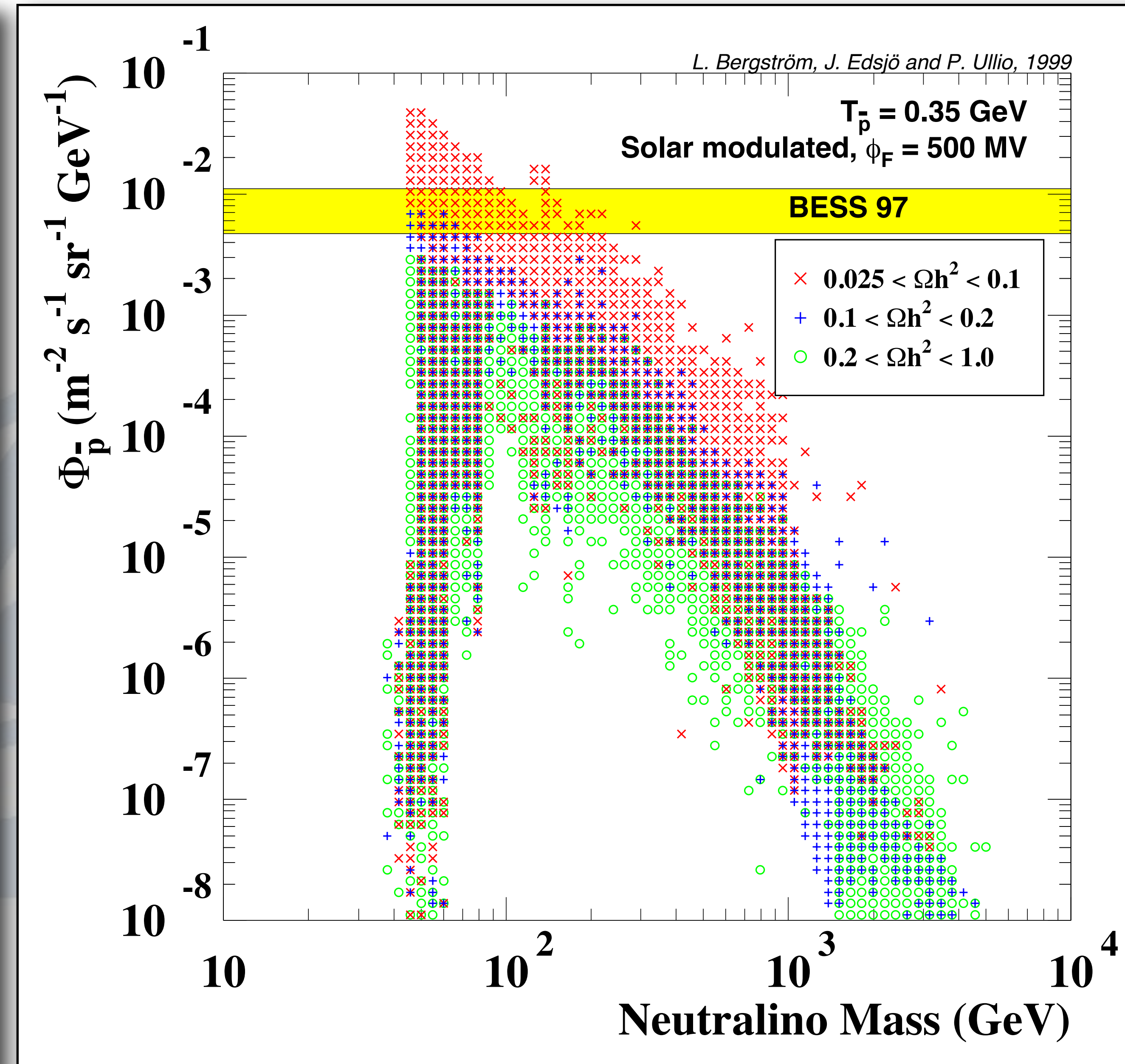
Degeneracy

- Degeneracy in D/L for fits to heavier isotopes (B/C, ...).
- However, DM signal typically increases with L (as our diffusion box includes more sources)
- Additional uncertainty on the dark matter signal



Antiprotons – signal

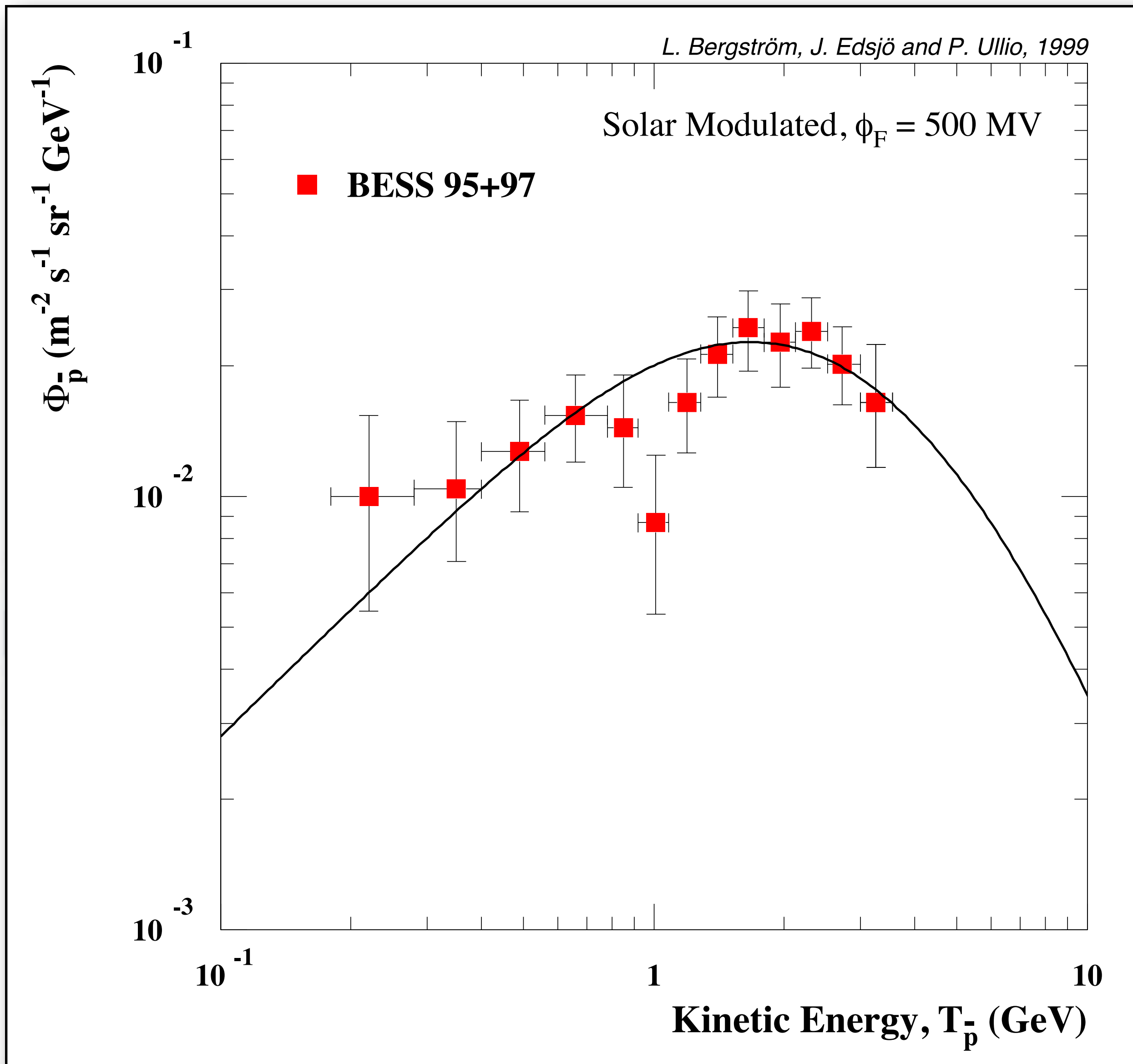




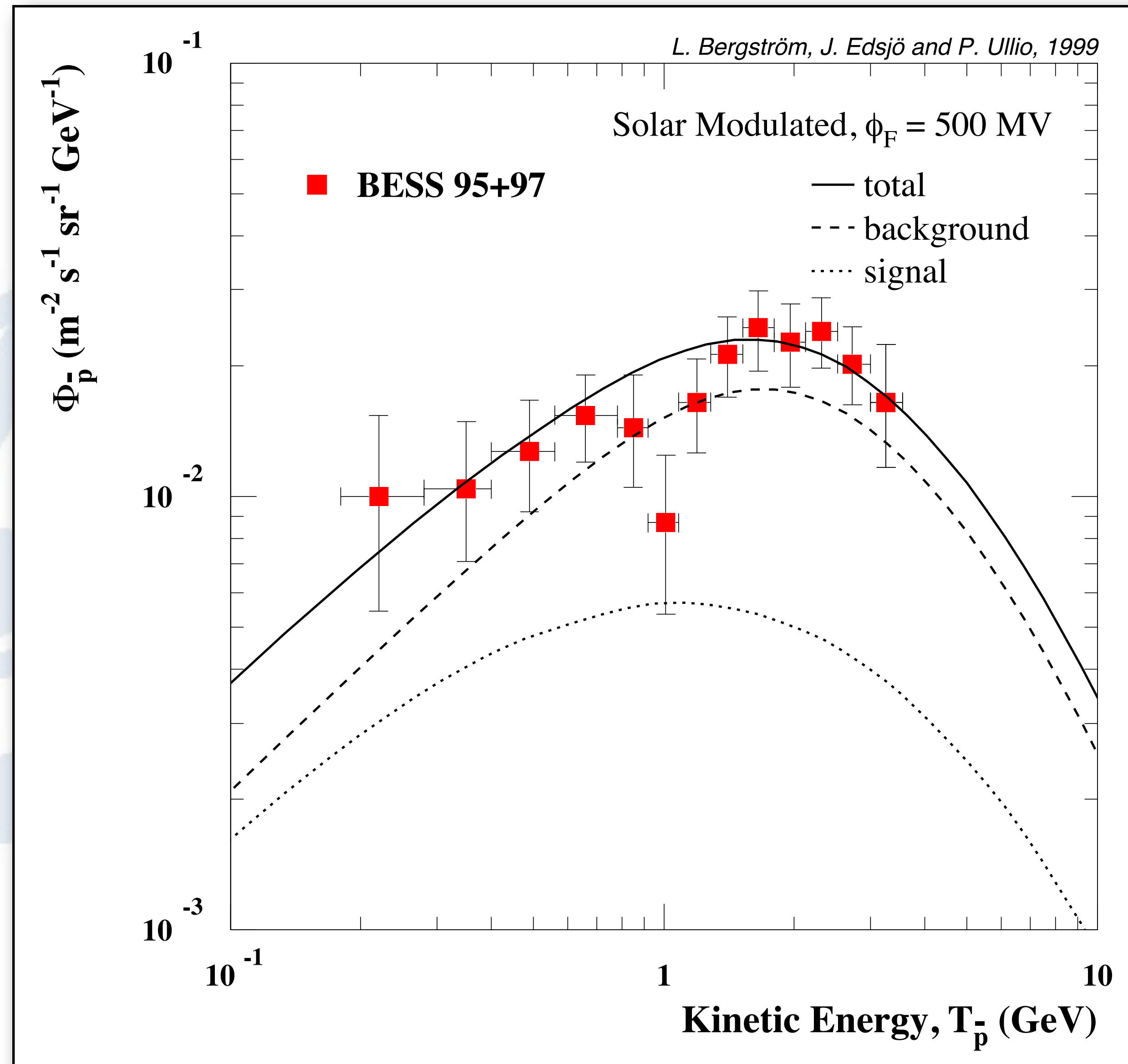
Easy to get high fluxes, but...

Antiprotons – fits to BESS data

Background only



Background + signal



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

+ new Pamela data

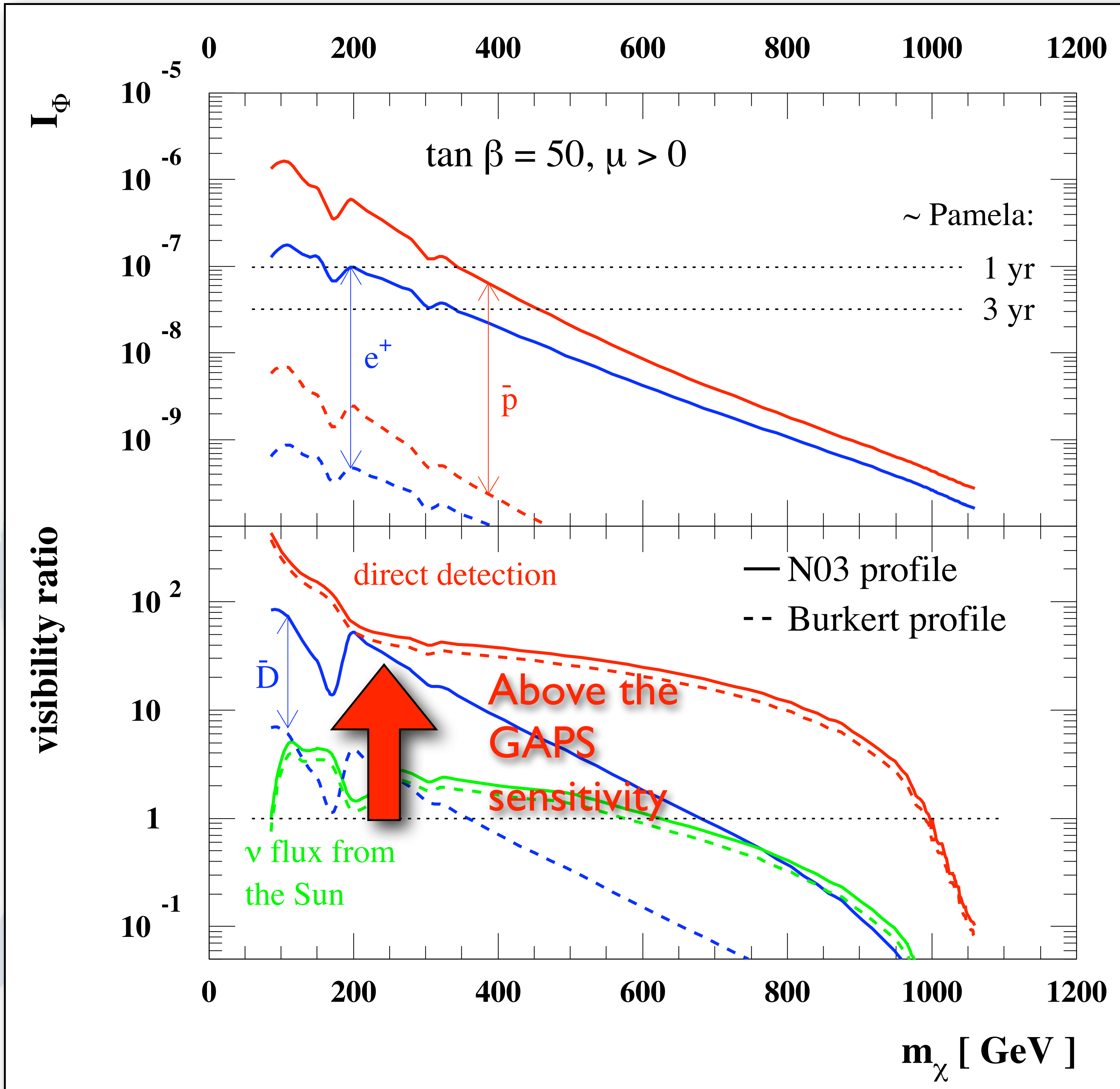
Antideuterons

- 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.

Future cosmic rays

Focus point region in mSUGRA



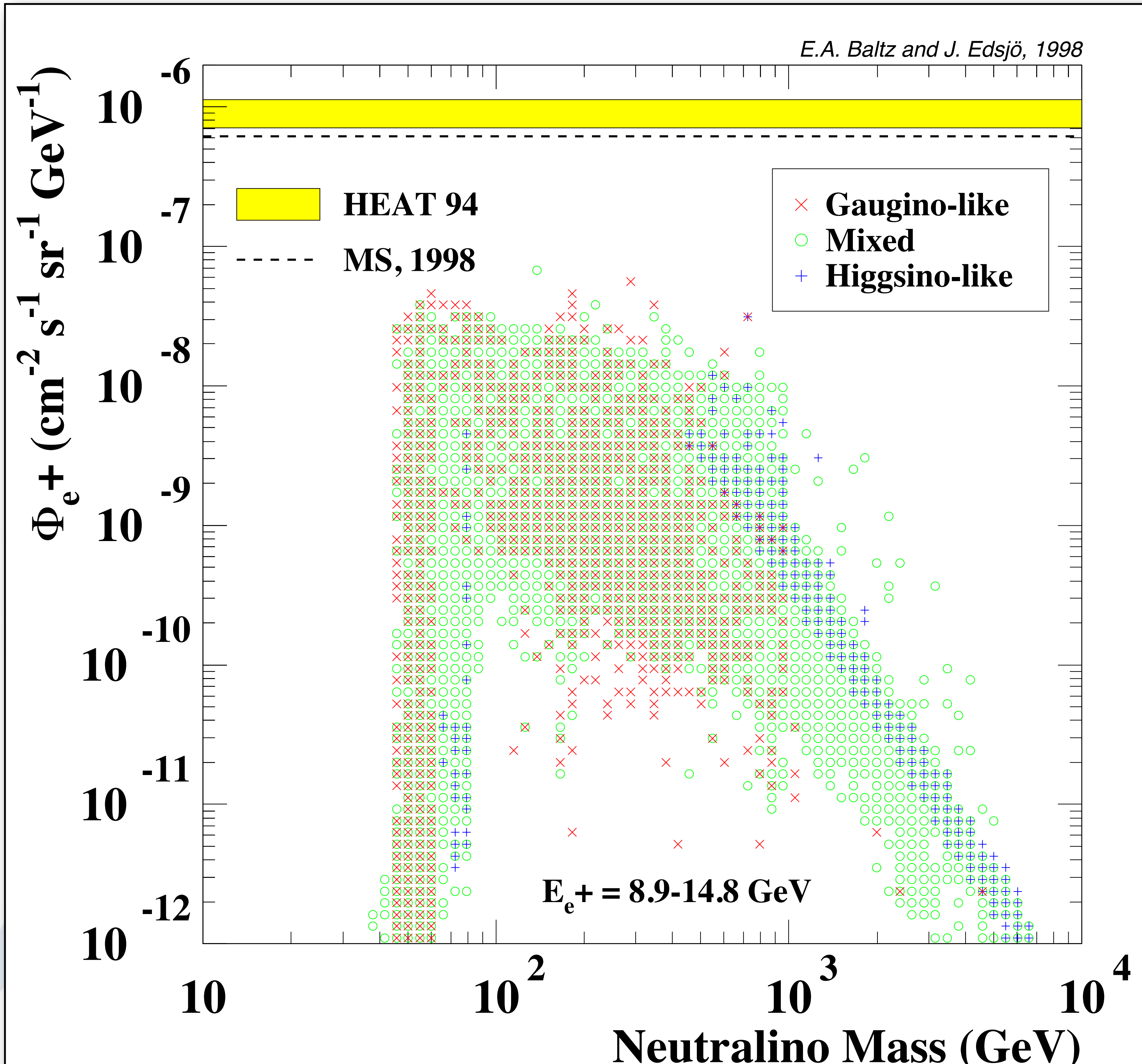
- Expected future sensitivities in two extreme halo models
- Antideuteron sensitivity with GAPS in the solar system
- Direct detection sensitivity of 1 ton Xenon detector

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

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

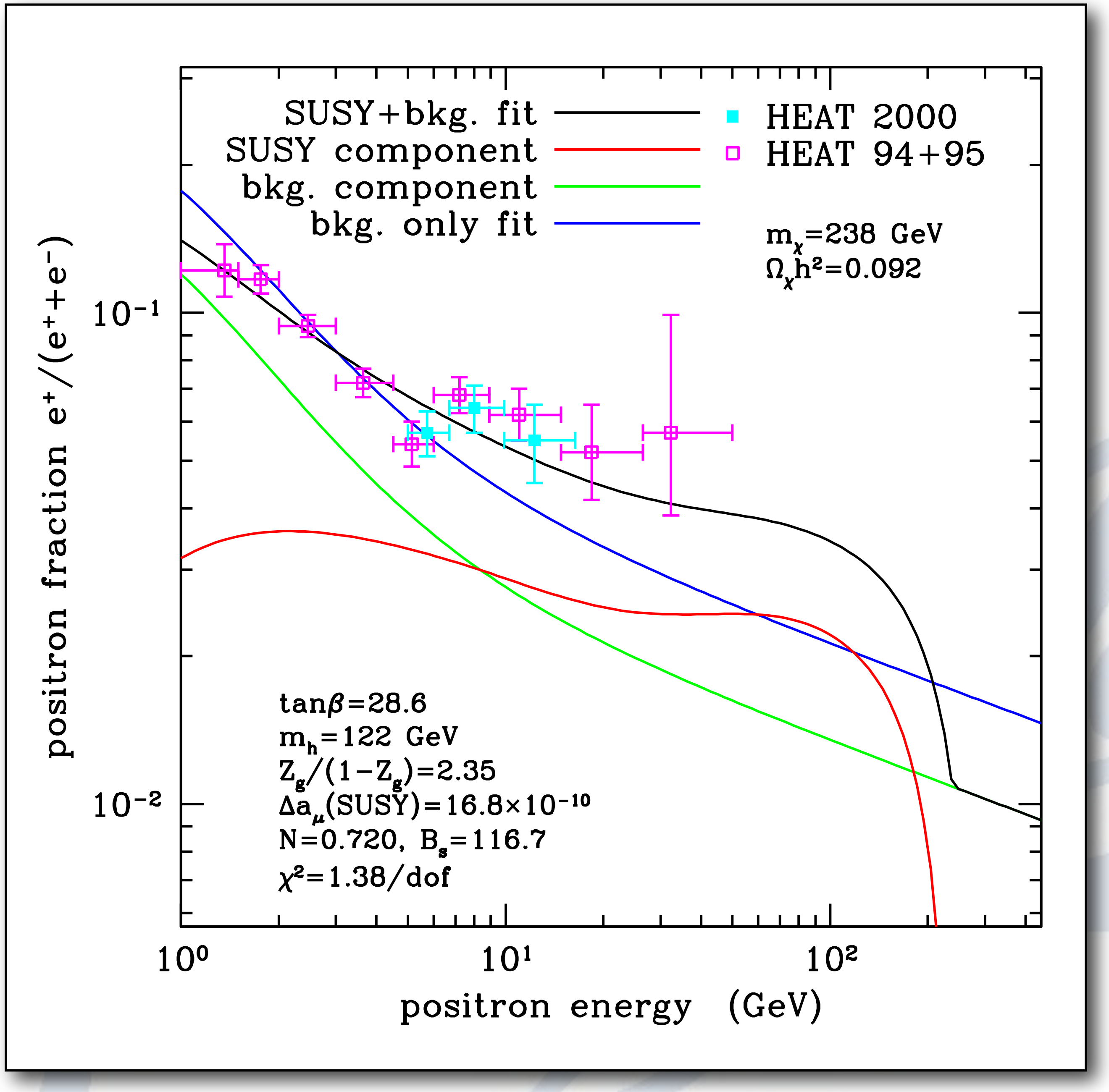
Positrons - signal

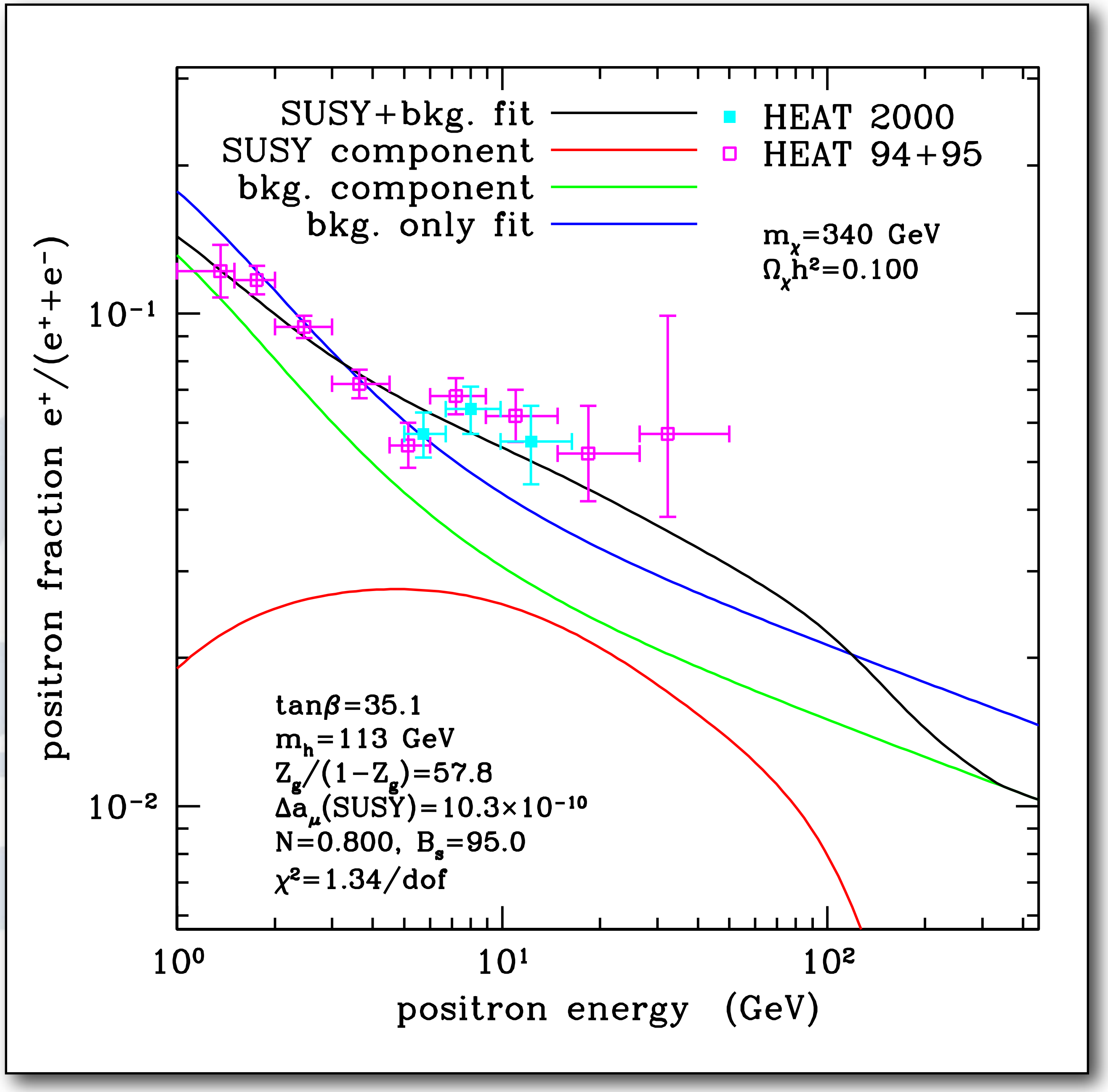


- Compared to antiprotons, the fluxes are typically lower (except possibly at high energies), but...

Positrons – example spectra

(as of a few years ago)



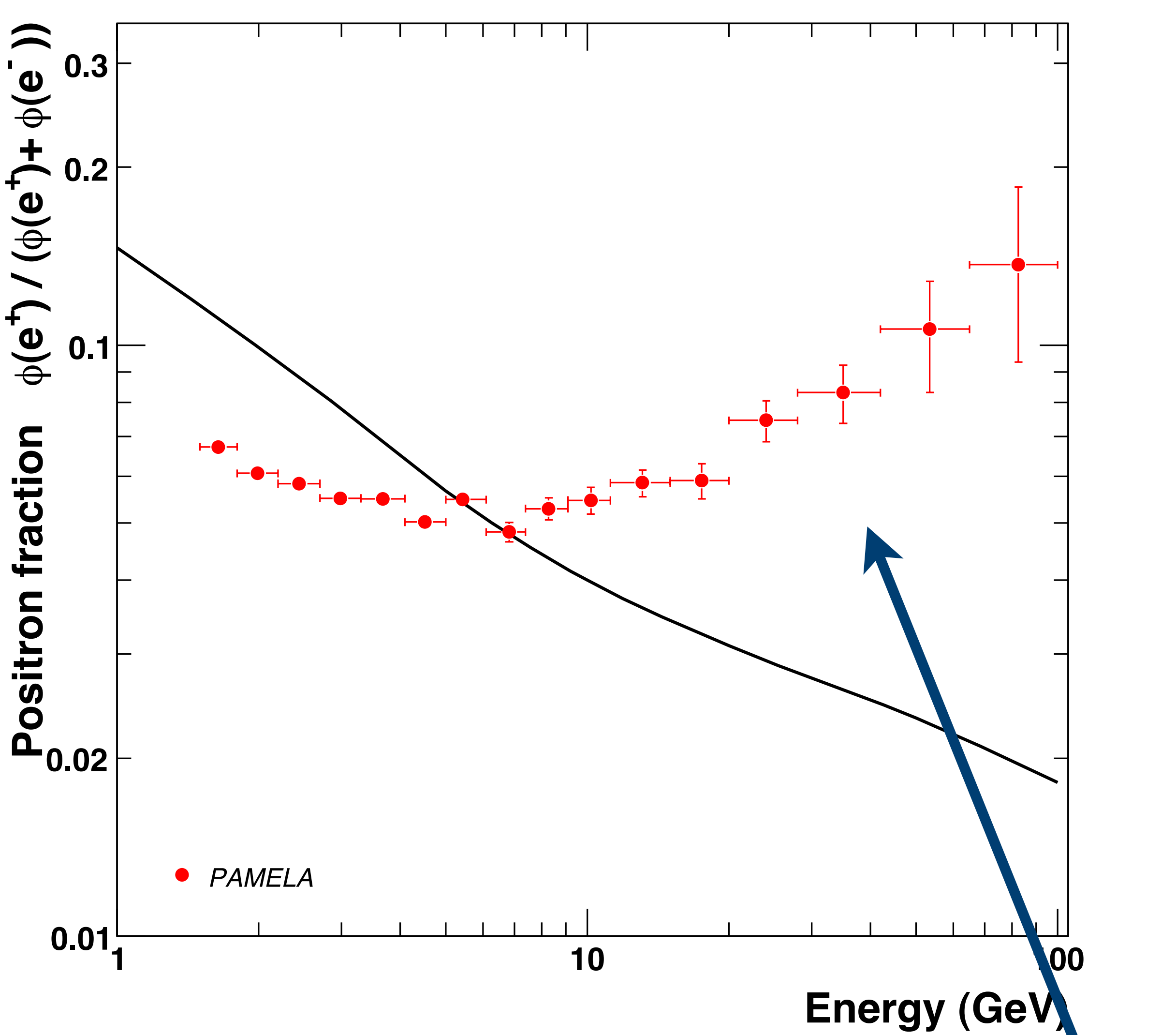


- the positron spectra can have features that could be detected!
- The signal strength needs to be boosted, e.g. by clumps, though...
- ...and the fit is not perfect

Data and background expectations

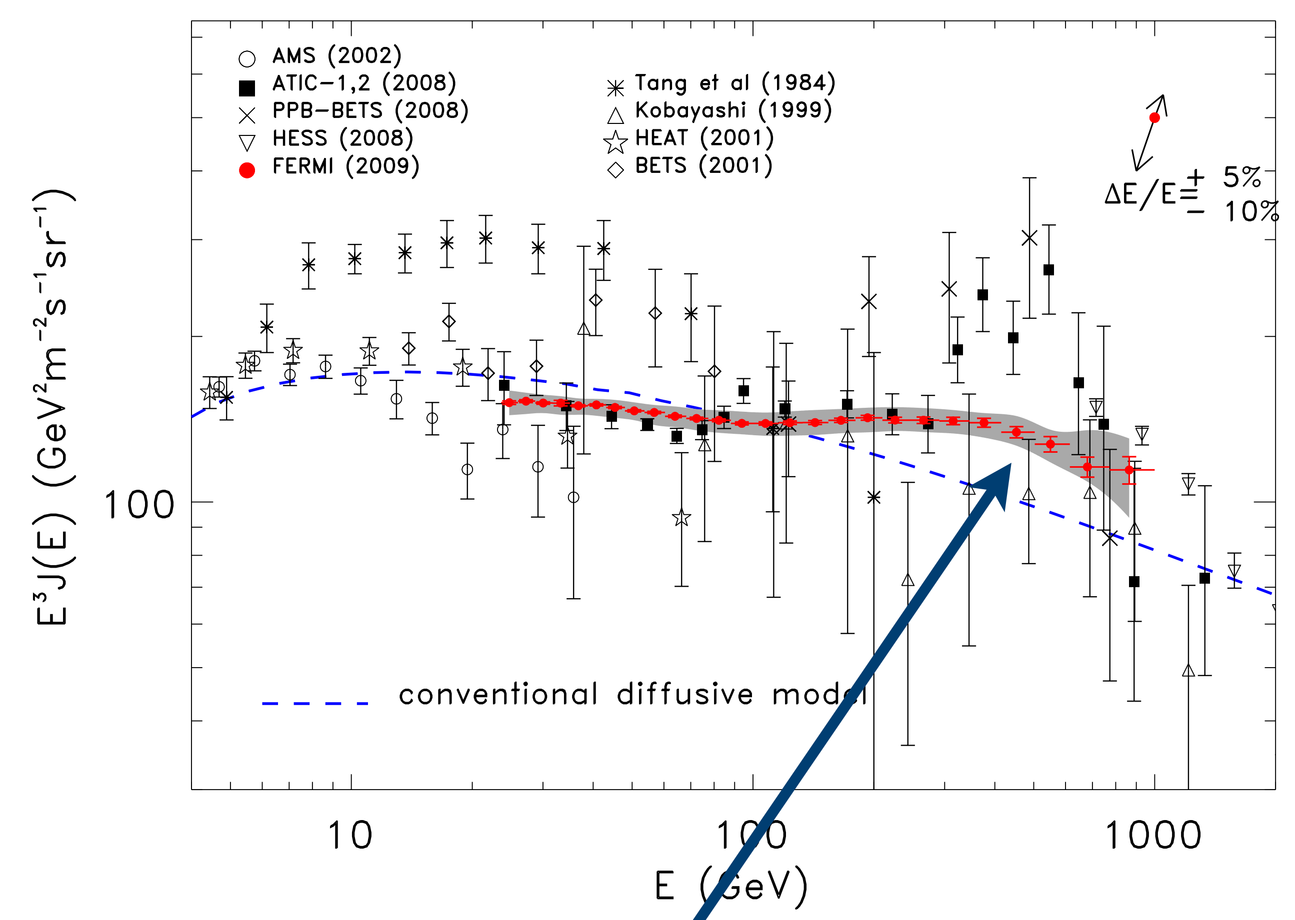
Positron fraction

O. Adriani et al., [PAMELA], arXiv: 0810.4995 (Nature)



e⁺+e⁻ spectrum

A.A. Abdo et al, [Fermi-LAT], arXiv: 0905.0025 (PRL)



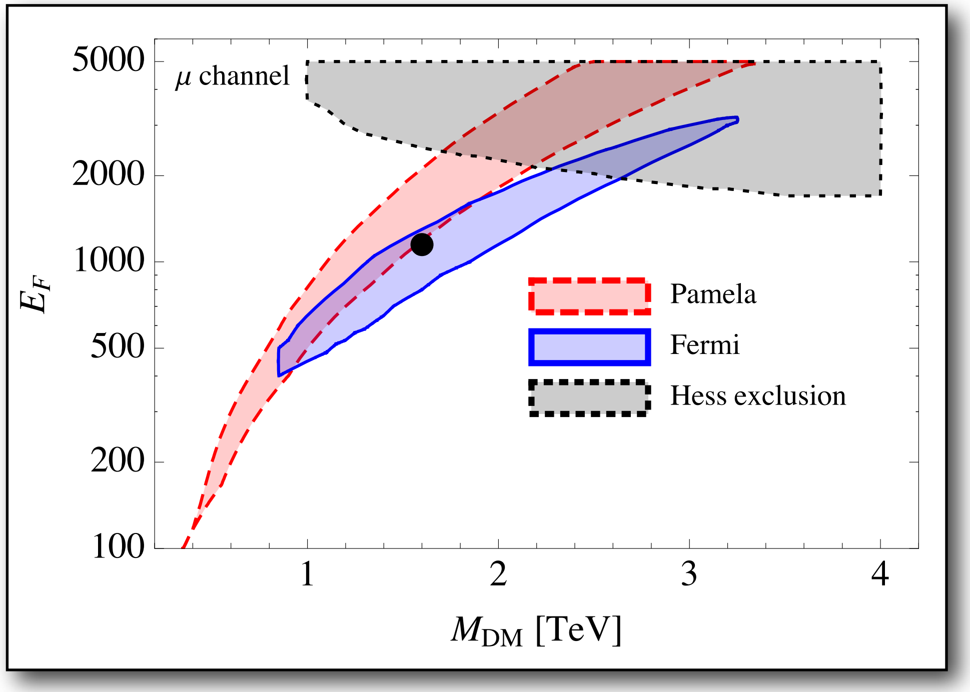
What are these excesses compared to the background?

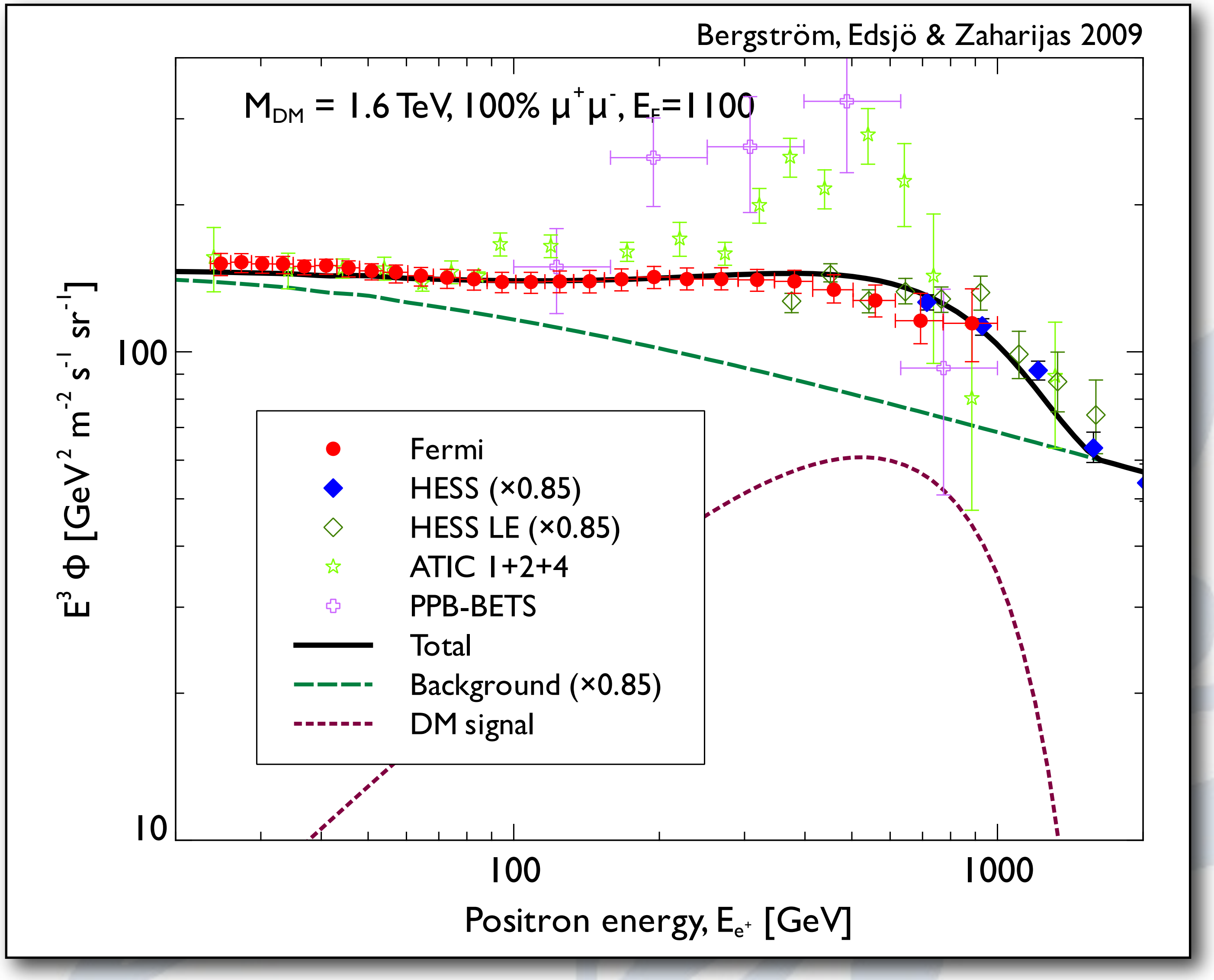
more than 630 papers written on Pamela since Nov. 2008

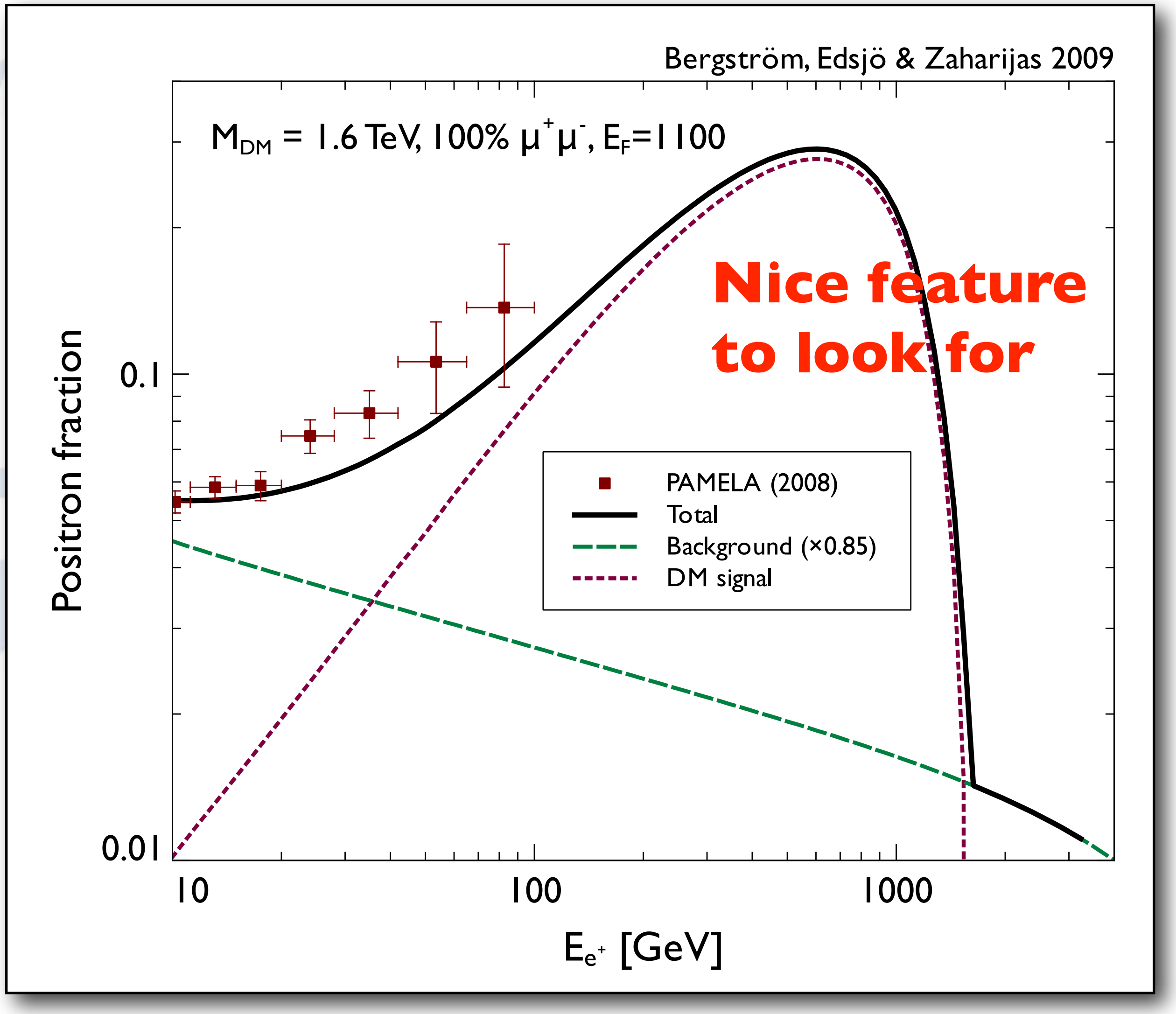
...and more than 370 citing the Fermi-LAT paper from May 2009

...of which all but maybe one are wrong...?

Dark matter – μ channel







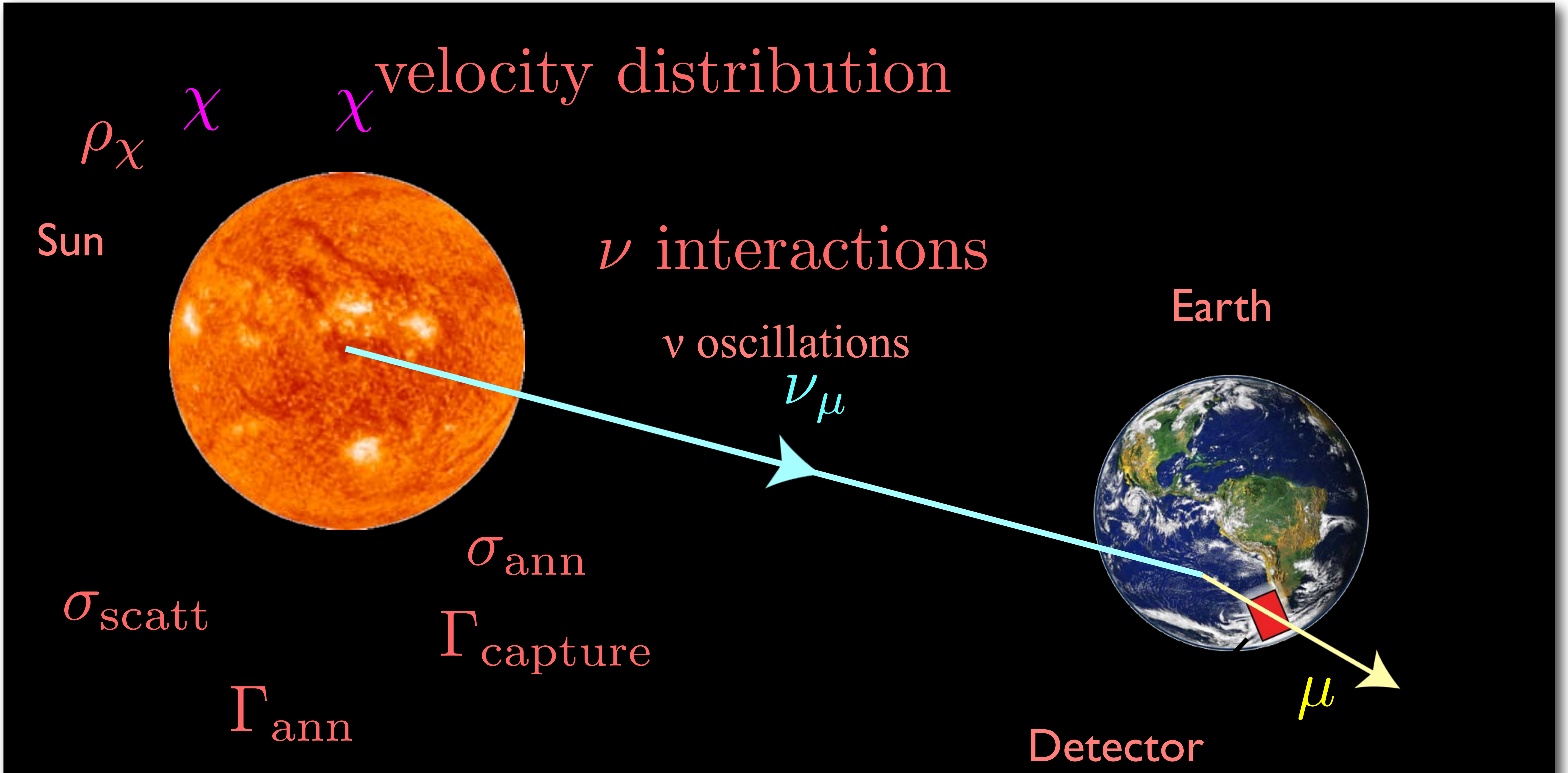
Cored isothermal profile assumed here

We get good fits to Fermi, HESS and PAMELA data

Possible explanations for the excess

- The diffuse background model is wrong?
- The local astrophysical sources (pulsars, reacceleration at SNR, localized SNR, ...) give a contribution?
- Dark matter annihilations give a contribution?
- There is no excess (non-standard diffusion)
- ...

Solar neutrinos – WIMP Capture



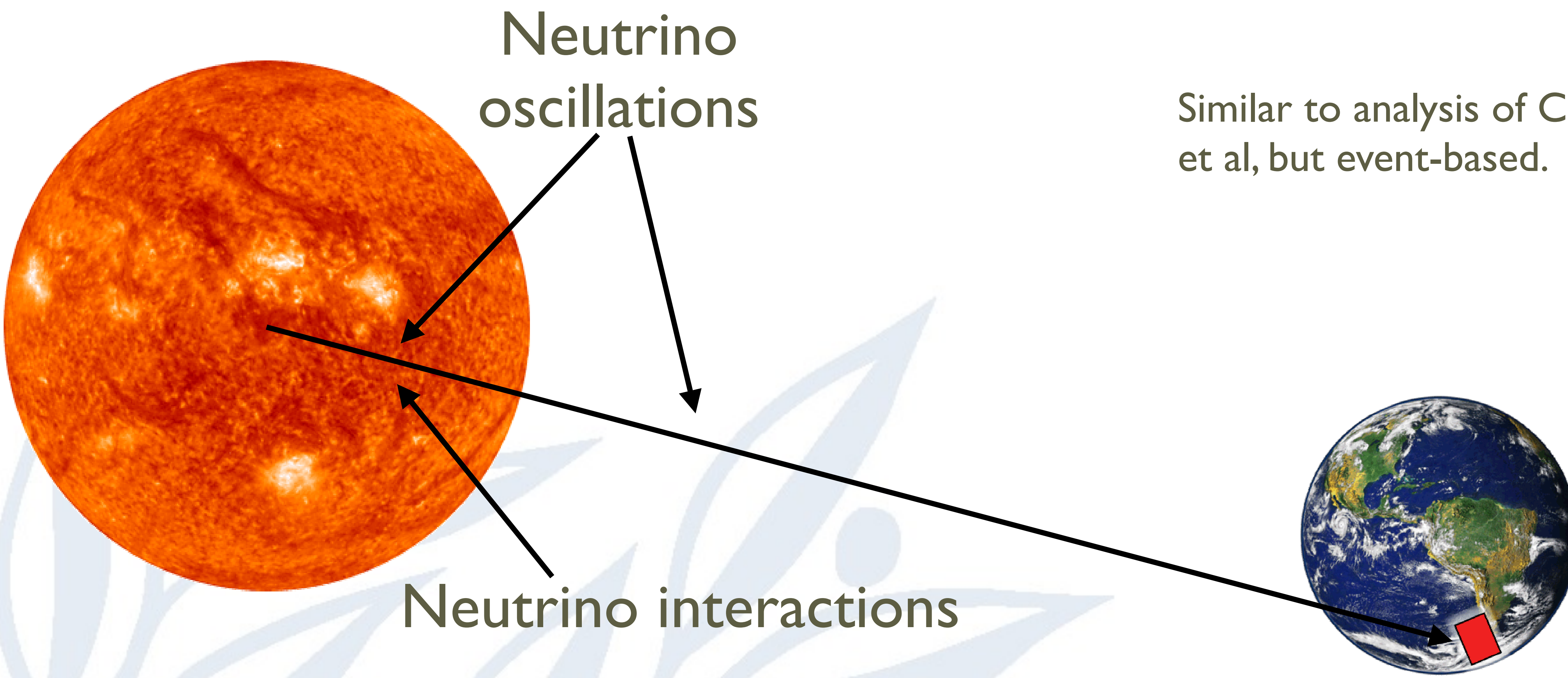
Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

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

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

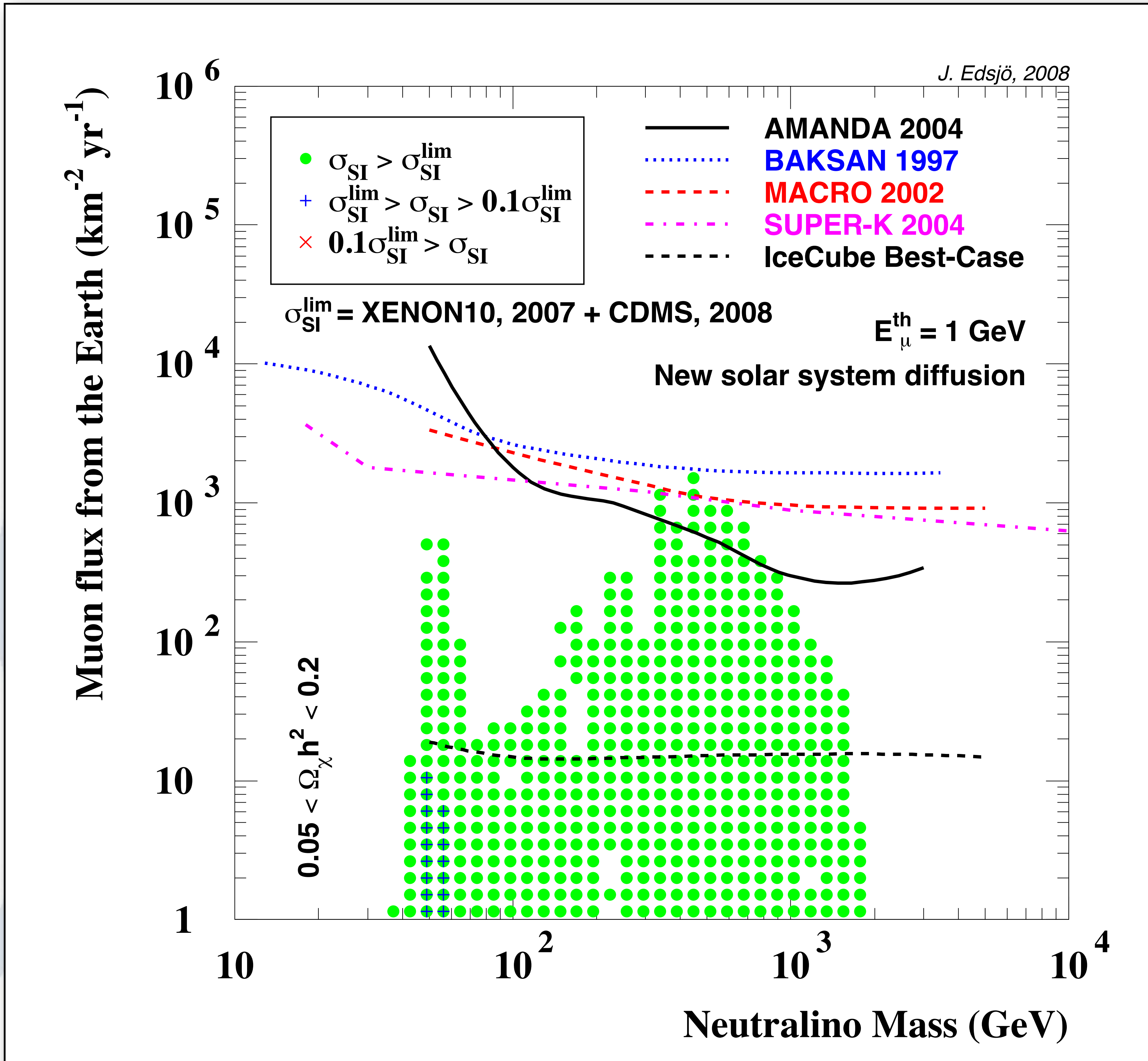
Neutrino oscillations

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.fysik.su.se/~edsjo/wimpsim
- Main results are included in DarkSUSY.

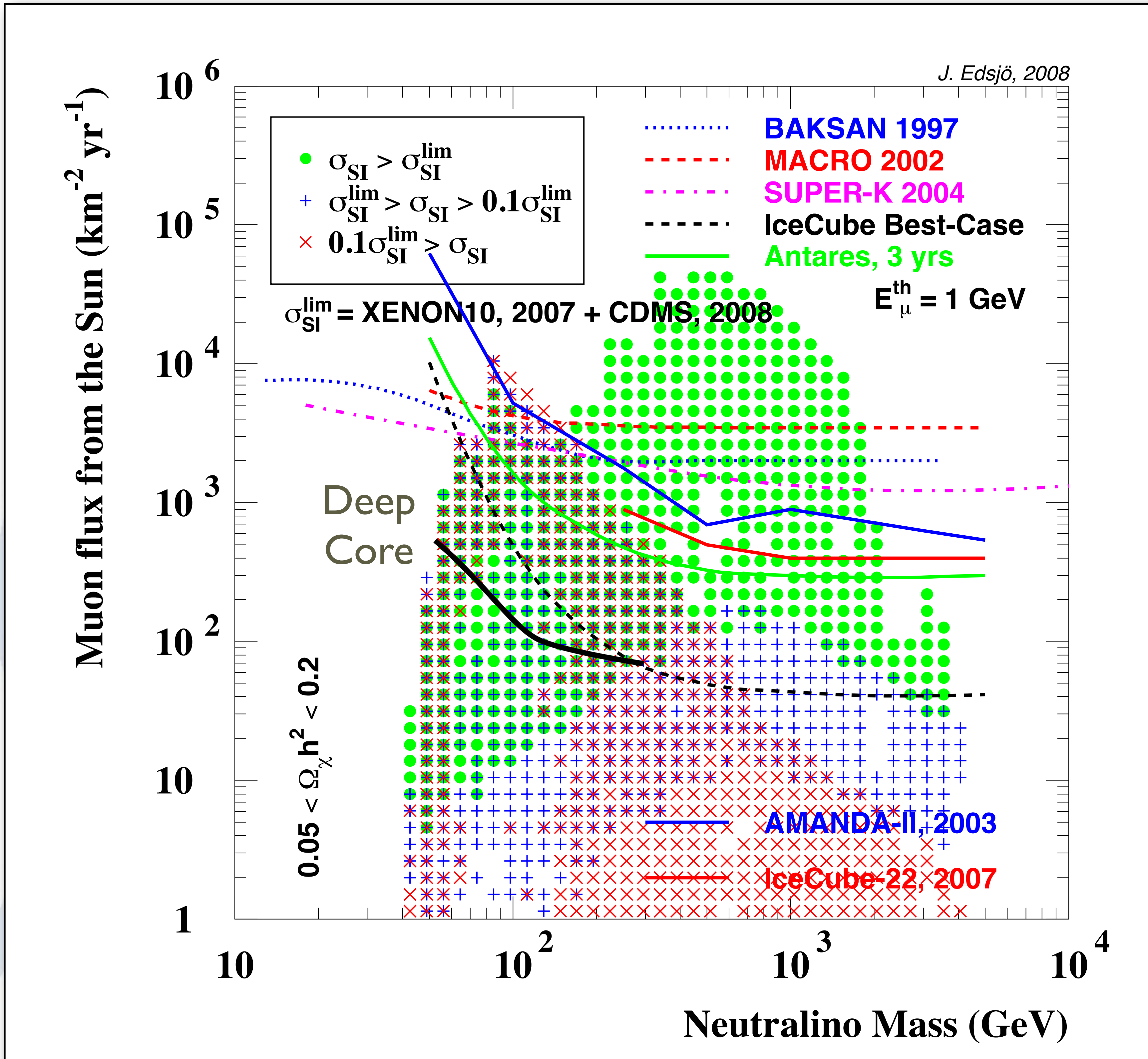
Neutrino-induced muon fluxes from the Earth



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

- Large correlation

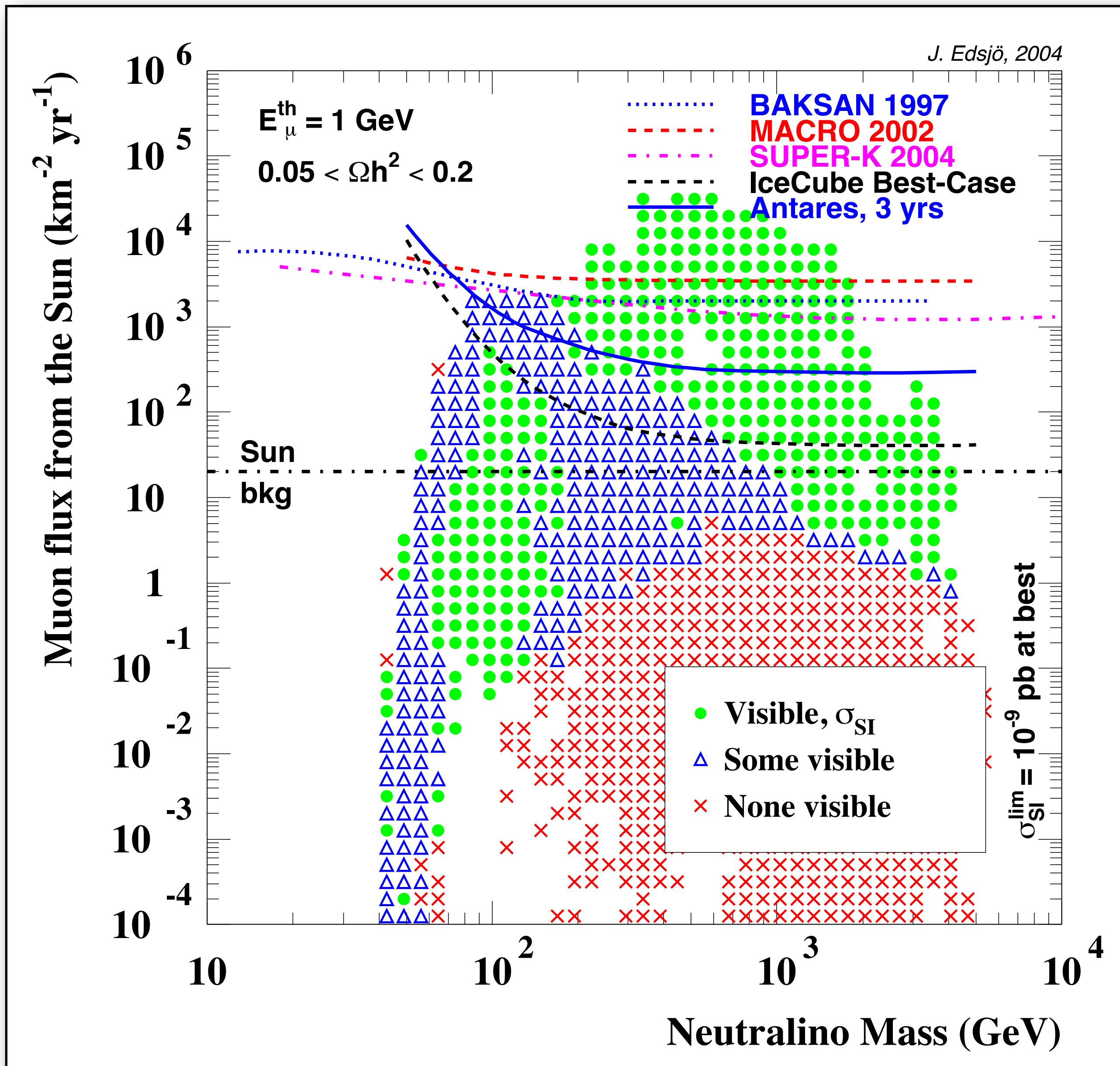
Neutrino-induced muon fluxes from the Sun



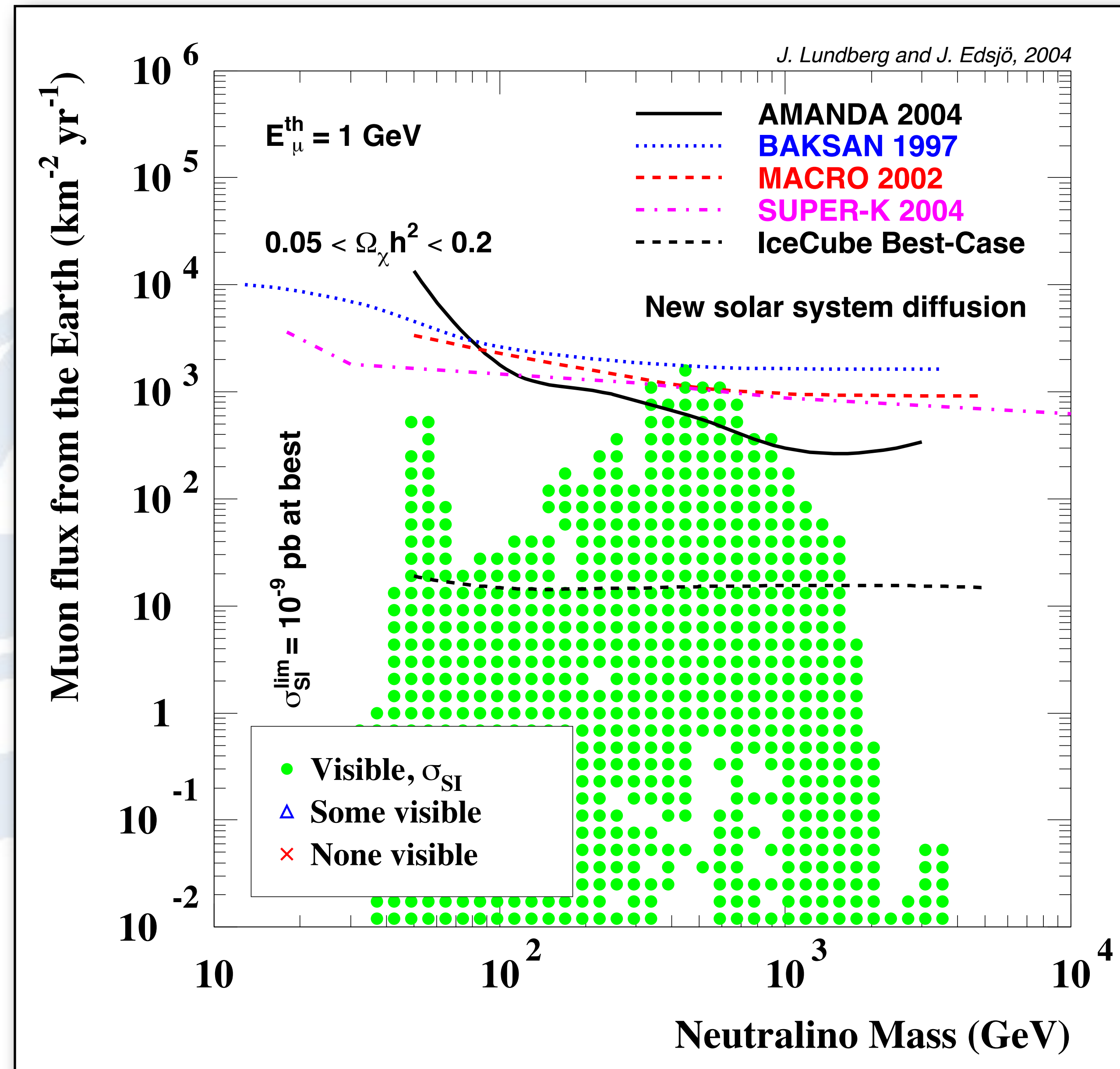
- Compared to the Earth, much better complementarity due to spin-dependent capture in the Sun.

Neutrino-induced fluxes and future direct detection limits

Sun



Earth



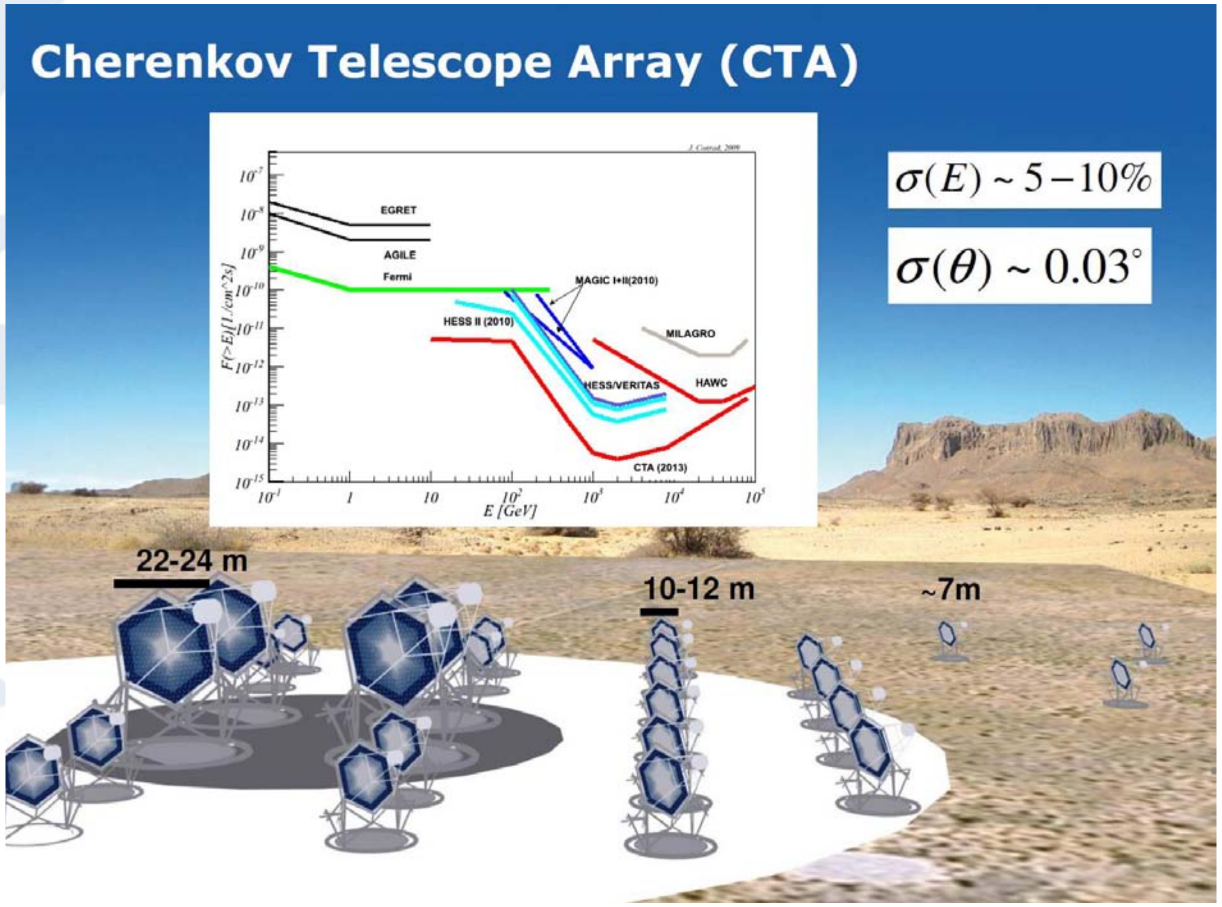
Future direct detection limit is assumed to be Ge like with a sensitivity down to 10^{-9} pb (1 tonne).

What is needed to really find dark matter in the cosmic rays?

- Bigger and better antiparticle cosmic ray detectors (AMS, Calet, etc). But how do we distinguish dark matter from conventional astrophysical sources (SNR, pulsars, ...)?
- Or maybe we should go for gamma ray signatures? No propagation uncertainties, but maybe not as clear spectral features (unless we have gamma lines or IB cut-offs).

CTAs?

- A Cherenkov Telescope Array (CTA) is a large improvement over current Cherenkov telescopes, but it is a multi-purpose detector.
- A CTA has a limited field of view and we can only optimistically hope for ~50 hrs of observation at DM sources
- What if we had a dedicated array just for dark matter
- Let’s be optimistic and...



J. Conrad, 2009

...think
BIG!

BIG ⇒ DMA = Dark Matter Array

- Let's be optimistic and consider a DMA with
  - CTA-like design, but with

$$A^{\rm eff}_{\rm DMA} \sim 10 \times A^{\rm eff}_{\rm CTA} \sim 10\,{\rm km}^2$$

  - low energy threshold (10 GeV)
  - dedicated for dark matter searches, t_{obs} ~ 5000 hrs feasible

⇒ Factor of 1000 better than CTA on A_{eff} x t_{obs} + lower threshold

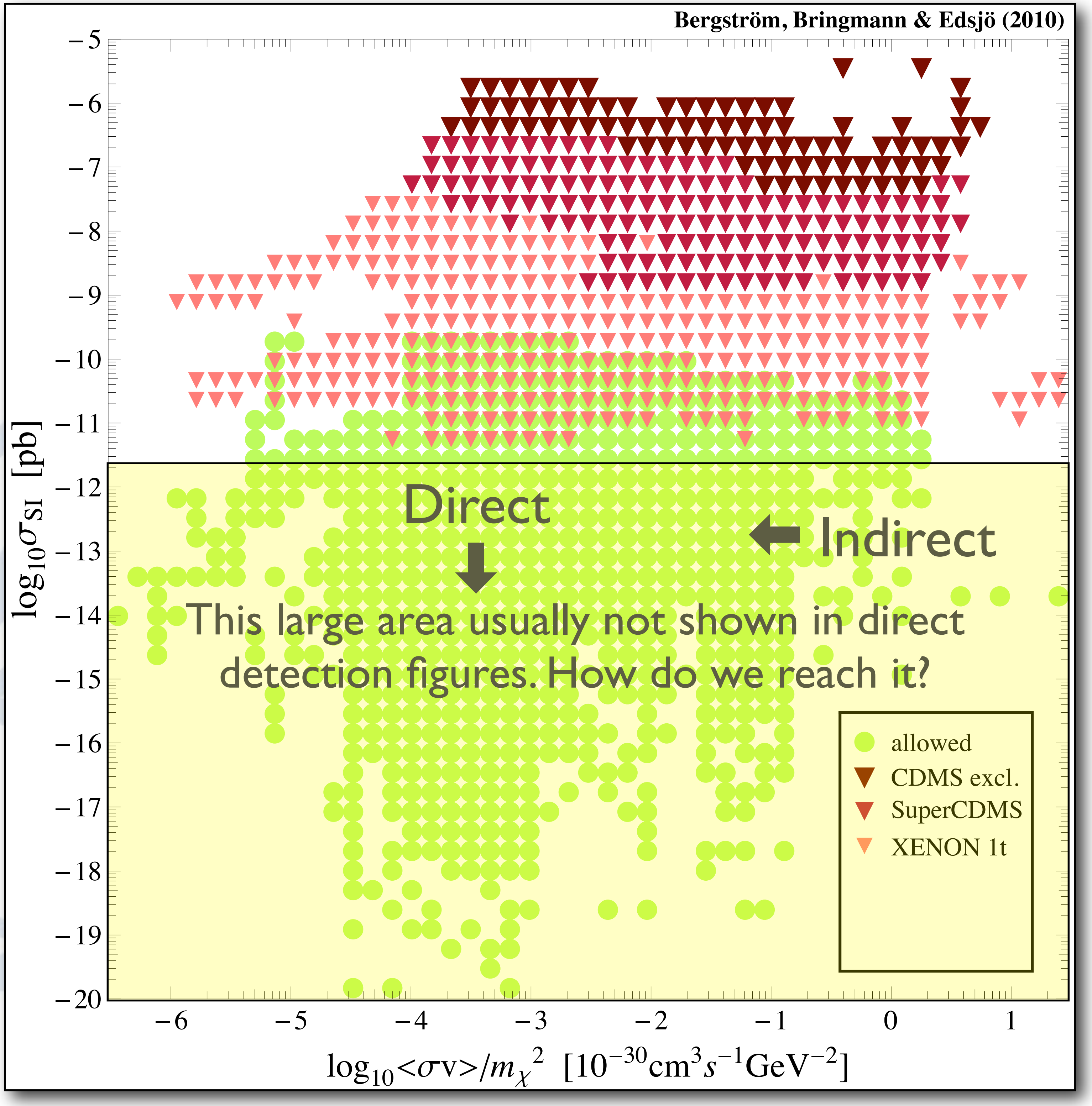
Is it only a dream?

- Maybe, but in principle possible.
  Let's investigate what DMA could do before disregarding the idea.
- Compare with "5@5", Aharonian et al 2001.

Direct vs indirect

- ~10^6 models (mSUGRA + MSSM).
- Within 3σ WMAP bound on relic density
- Accelerator constraints OK

Preliminary
Bergström, Bringmann & Edsjö, in prep. 2010

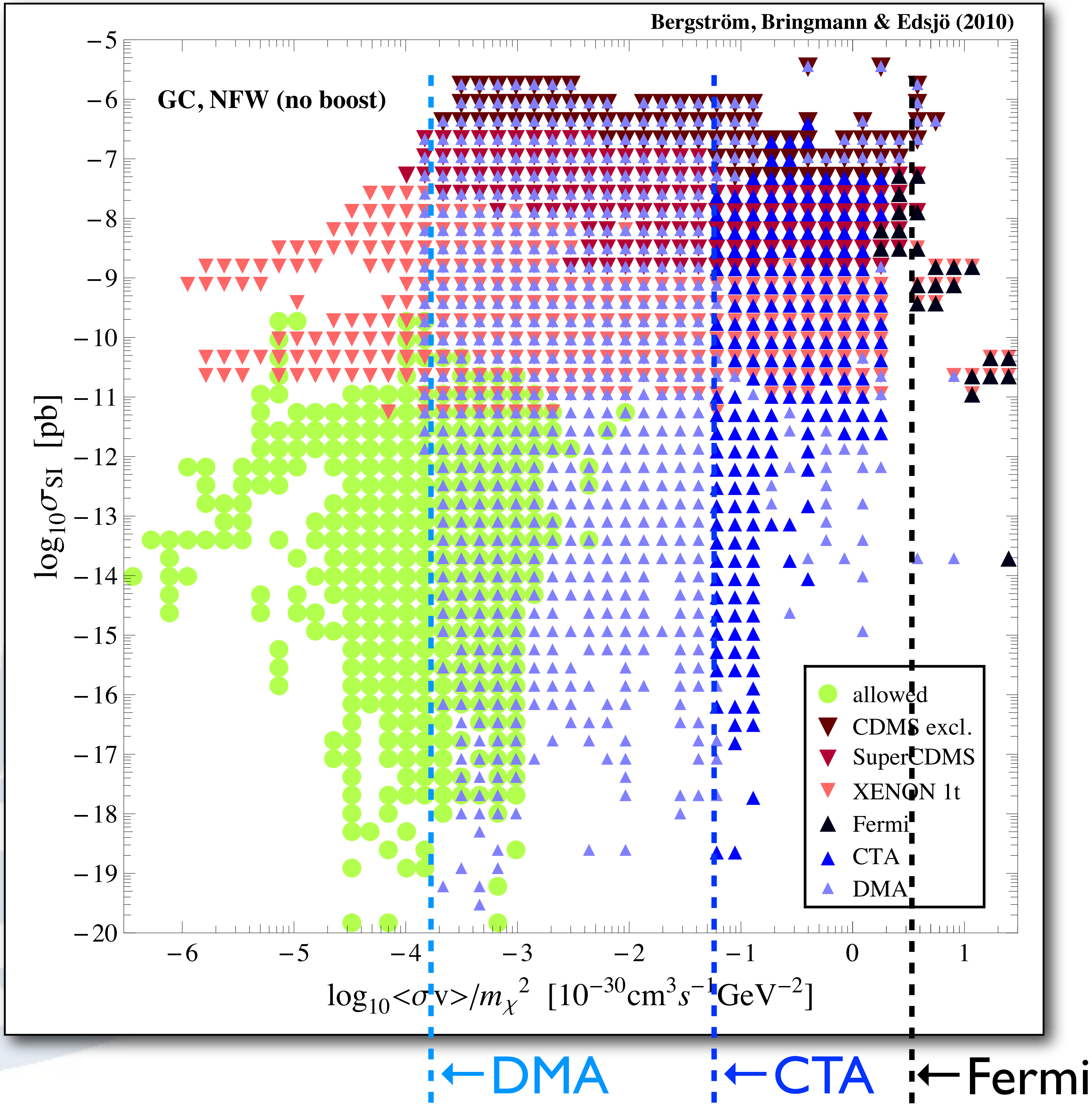


What can a DMA do?

- Assume 5000 hrs towards the galactic centre (GC)
- Assume that the angular resolution is good enough to separate the HESS source from the GC
- Assume smooth diffuse background as measured by Fermi (from S. Digel, Fermi Symposium, Nov. 2009), extrapolated as power law above 100 GeV
- Demand that $S/(S+B)^{0.5} > 5$ in best energy bin to claim sensitivity

Direct vs indirect

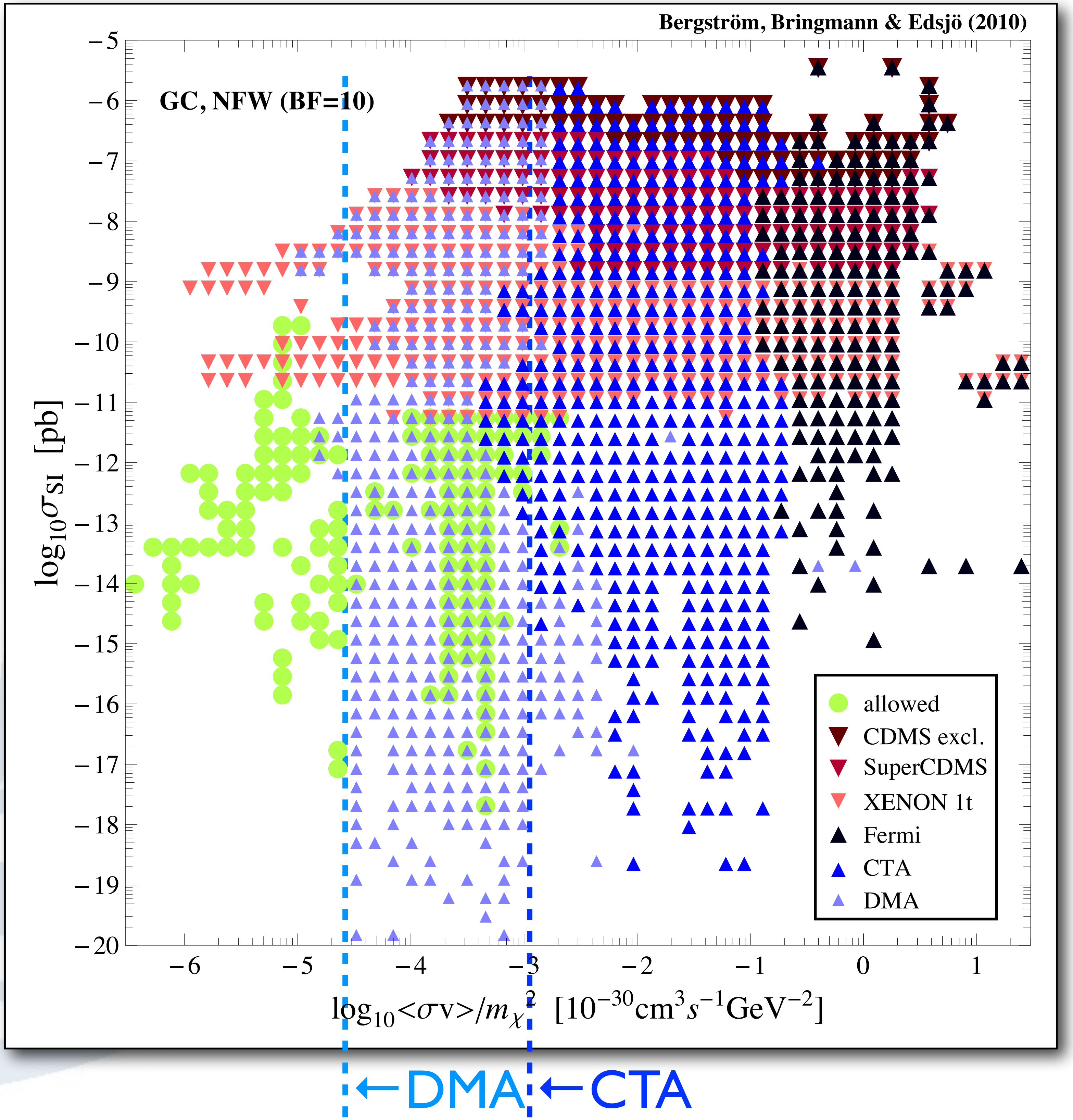
- NFW
- No boost



Preliminary
Bergström, Bringmann & Edsjö, in prep. 2010

Direct vs indirect

- NFW
- Bost factor = 10

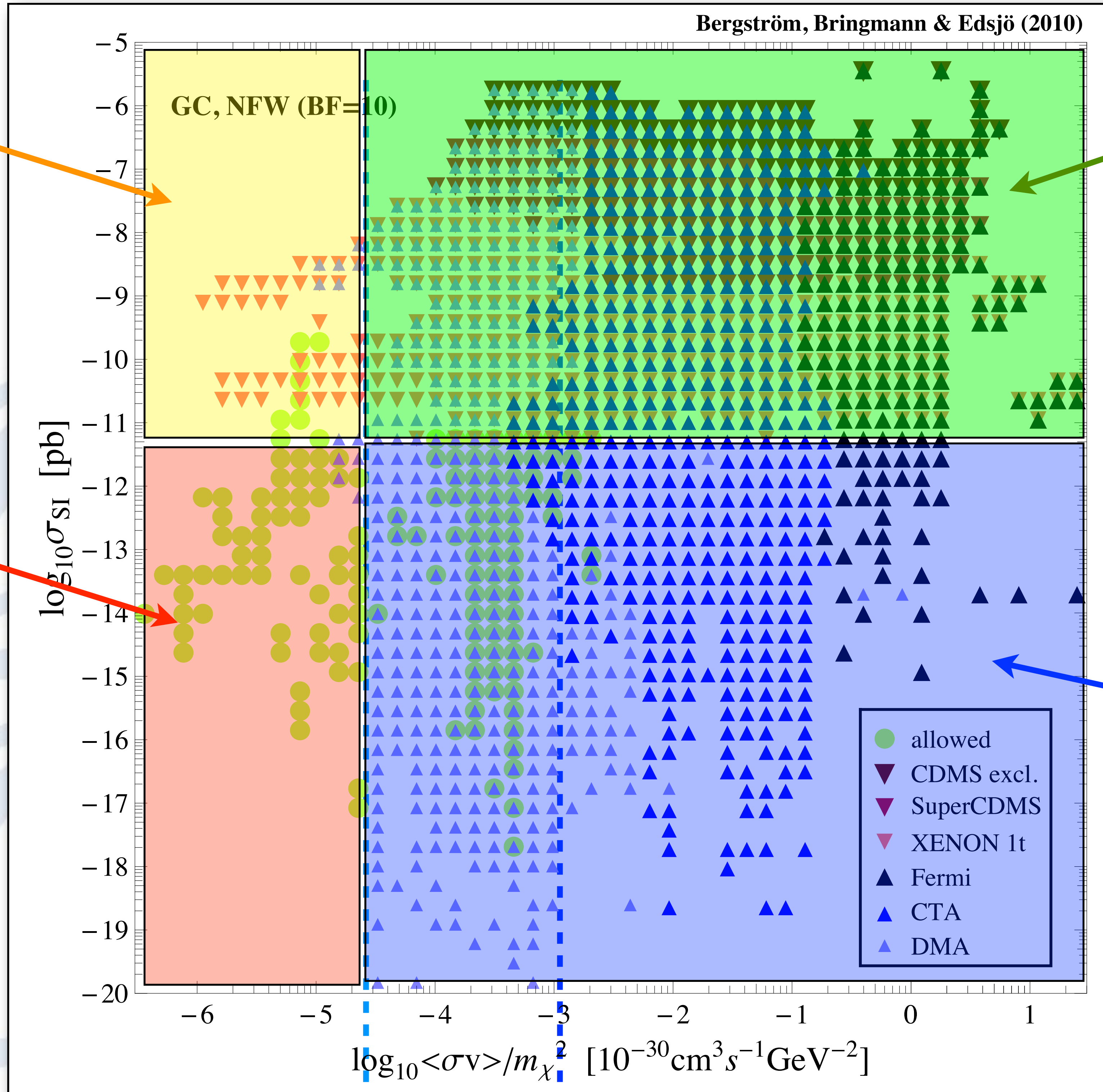


Preliminary
Bergström, Bringmann & Edsjö, in prep. 2010

Direct vs indirect

Direct detection territory!

The impossible part...



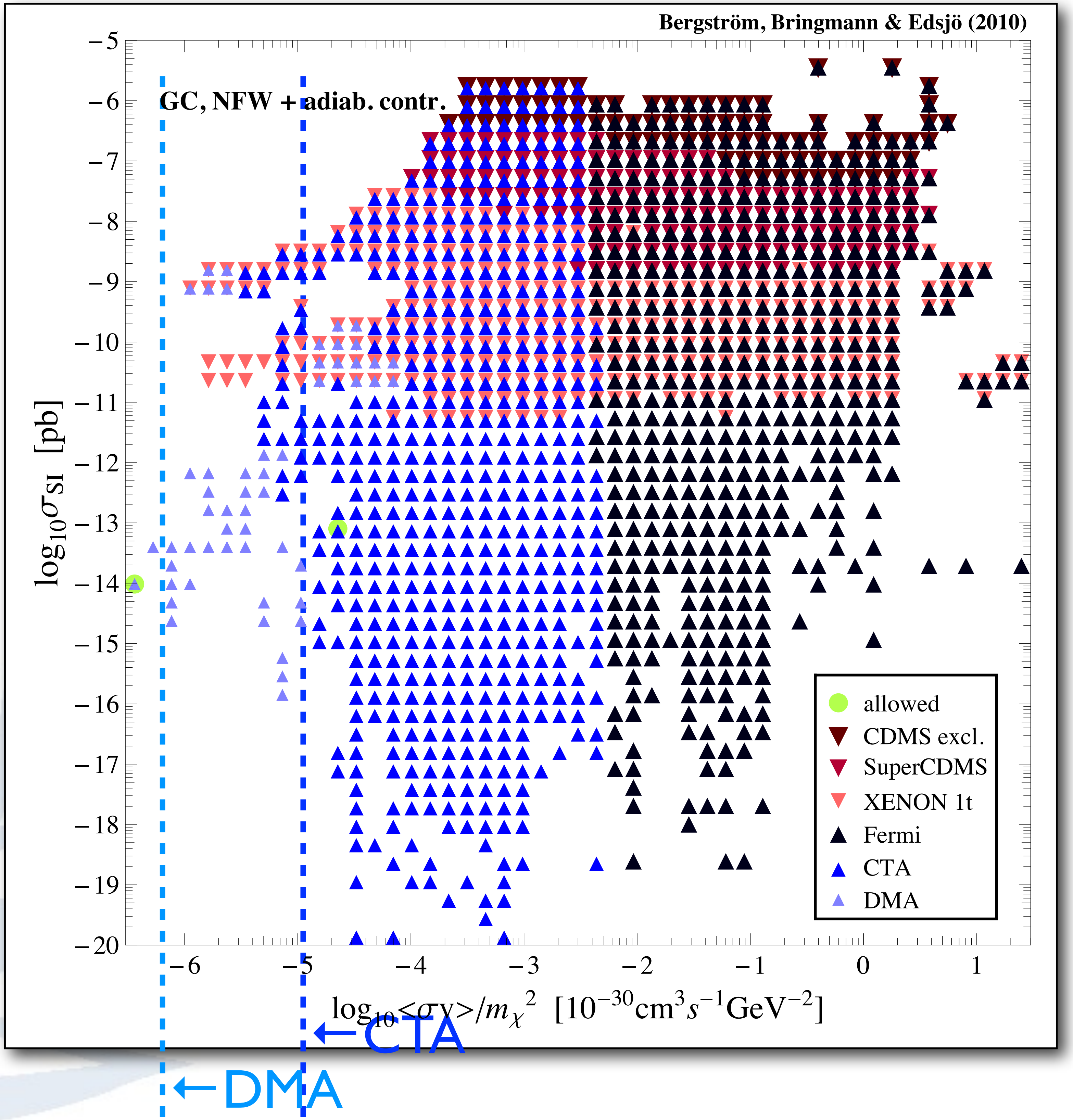
Sweet spot: Both direct detection and indirect detection should see a signal

Indirect detection territory!

←DMA ←CTA

Preliminary
Bergström, Bringmann & Edsjö, in prep. 2010

Direct vs indirect

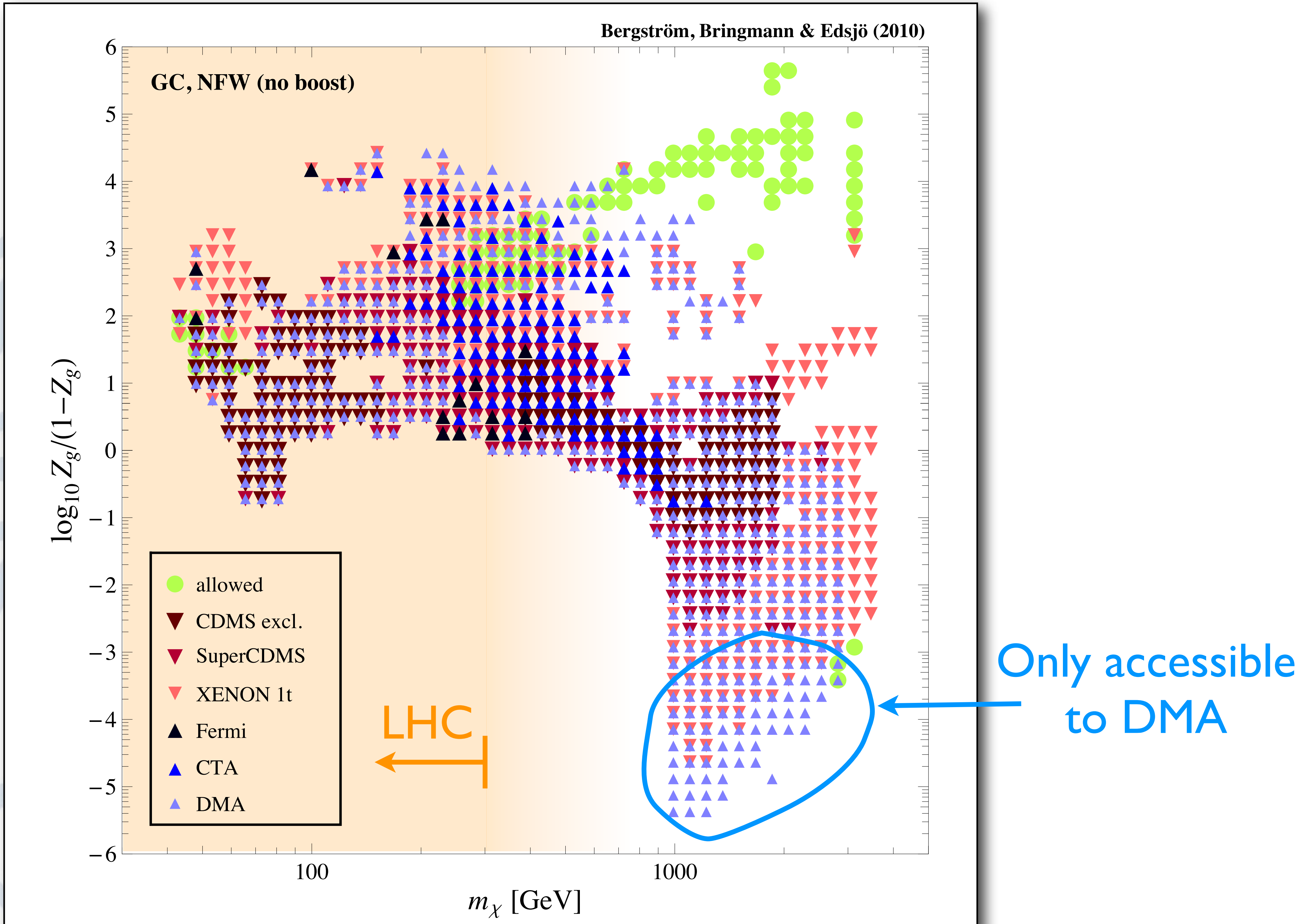


- NFW
- Adiabatic contraction

Preliminary
Bergström, Bringmann & Edsjö, in prep. 2010

Another possibility which is more robust to astrophysical uncertainties is to look at dwarfs instead.

Complementarity



LHC reach

- LHC will probe most models up to a few hundred GeV in sparticle masses, for some models even higher
- Crucial to get data in an as model independent way as possible.
- Publish likelihoods?

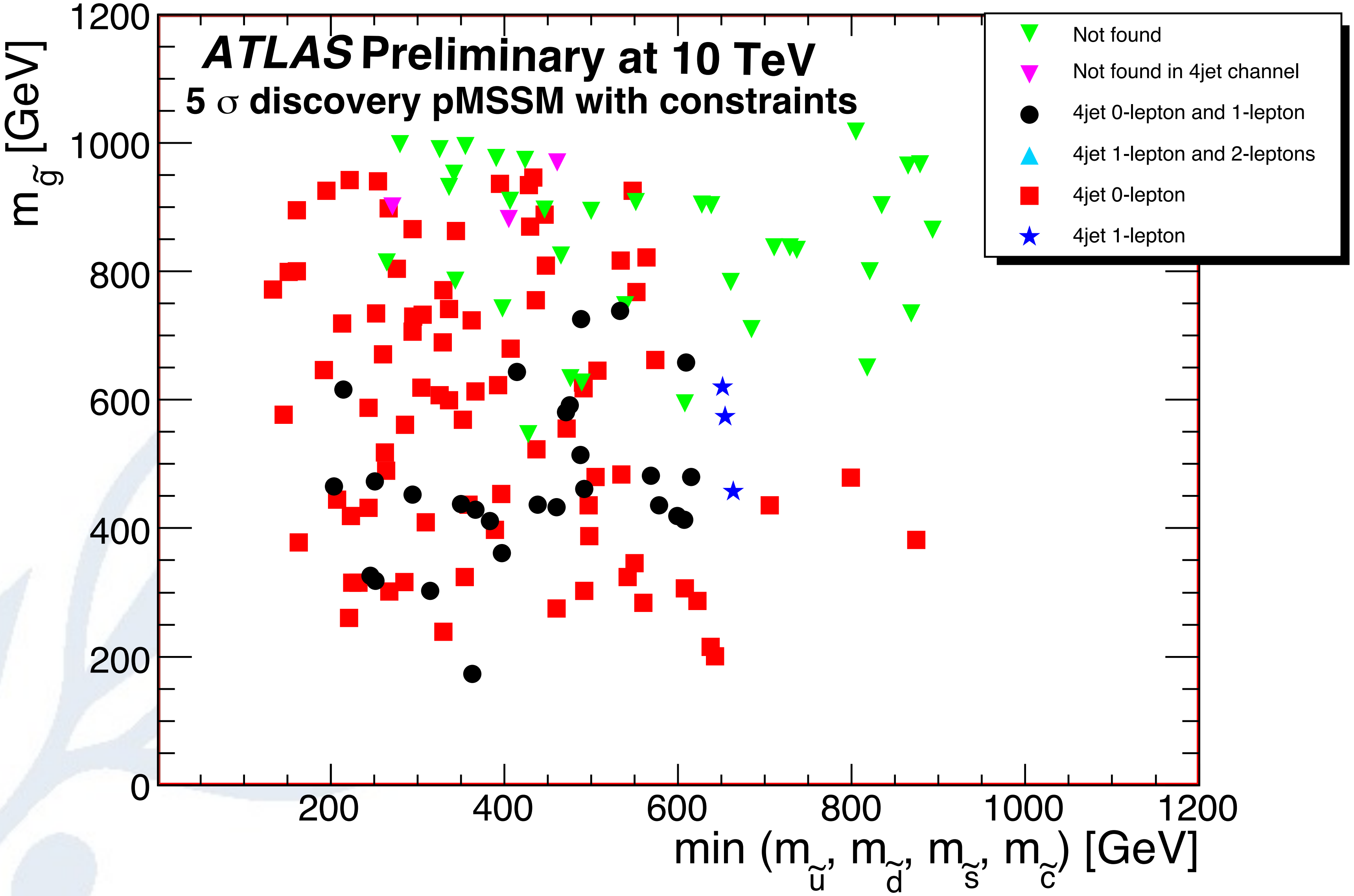


Fig. from ATL-PUB-2009-084 (ATLAS public note)

DarkSUSY

- For any of these multi-channel searches, it is crucial to use consistent tools, like e.g. DarkSUSY (developed mainly in Stockholm), where all calculations can be performed with consistent particle physics and astrophysics assumptions.
- To download DarkSUSY:

www.darksusy.org

Conclusions

- Many ways to search for dark matter: accelerators, direct and indirect.
- Use as many of these as possible to test/constrain our models
- Crucial to perform these calculations in a consistent framework, with e.g. a tool like DarkSUSY
- A dedicated Dark Matter Array (DMA) may prove useful to reach previously unreachable parts of the parameter space. Complementary to direct searches.