

# Multichannel “cosmic ray” signatures of dark matter

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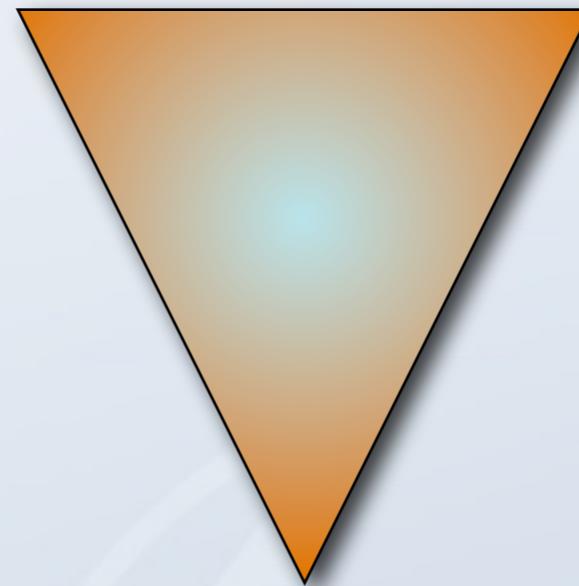
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idm2010  
Montpellier  
July 27, 2010



# Ways to search for dark matter

## Accelerator searches



## Direct searches

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

## Indirect searches

- Gamma rays from the galactic halo
- Gamma rays from external galaxies/ halos
- Neutrinos from the Earth
- Neutrinos from the Sun
- Antiprotons from the galactic halo
- Antideuterons from the galactic halo

- Positrons from the galactic halo
- Synchrotron radiation or neutrinos from the galactic center
- Inverse Compton Scattering
- Microwave haze from galactic center
- Dark Stars
- ...

Will not cover all of these...



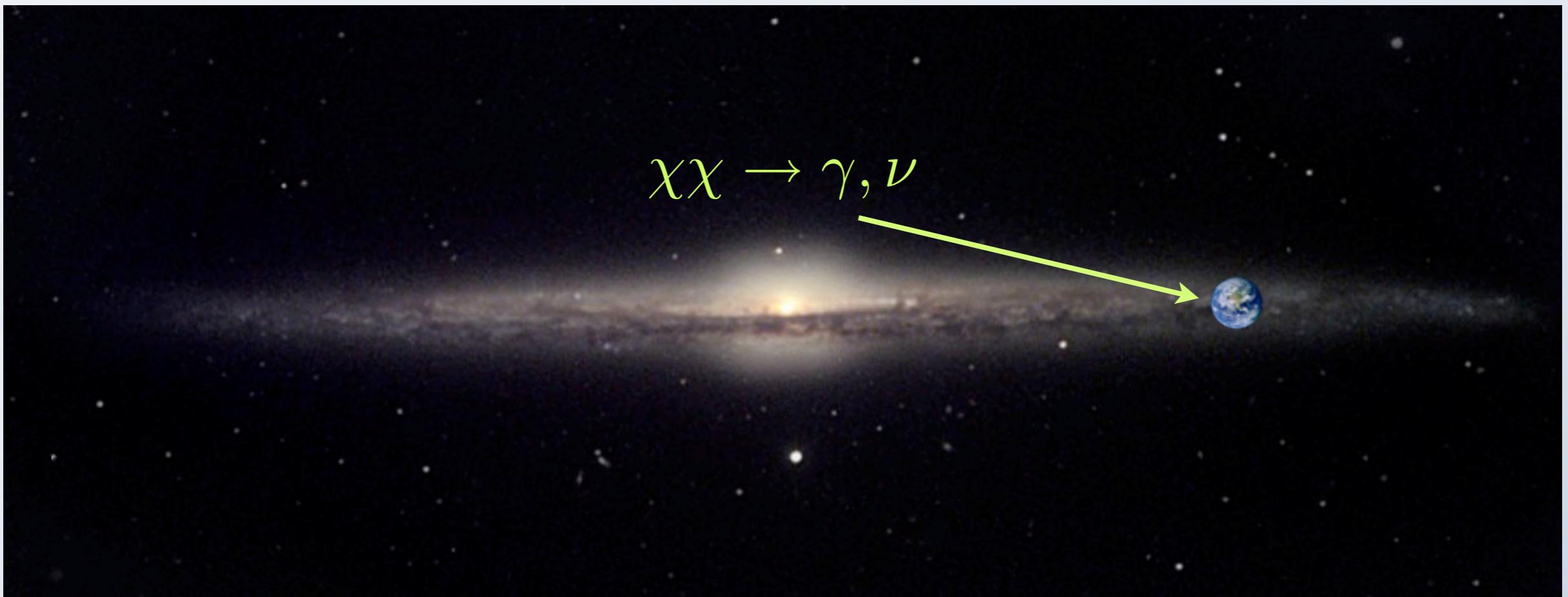
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# Outline

- Will focus on
  - some general ideas on cosmic ray searches (gamma rays, charged cosmic rays and neutrinos) and their uncertainties
  - leptophilic dark matter models explaining Pamela, Fermi and HESS as an example of how multichannel constraints are important
  - Future indirect searches: gamma rays?
- Will not cover neutrinos fully (see talks Wednesday and talk by Rott) or microwave haze (see Finkbeiner's talk).

# 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

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

with

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

Particle physics  
(SUSY, ...)

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

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

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

Astrophysics

# 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.

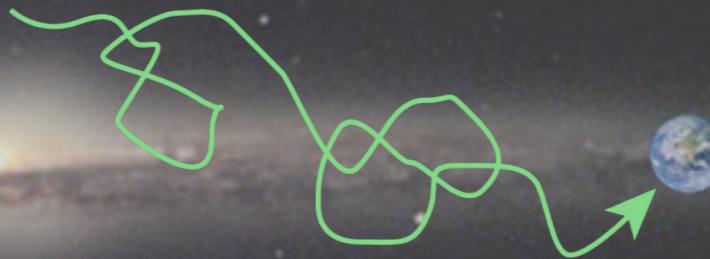


# Annihilation in the halo

## 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. Pamela, ATIC, Fermi.
- Future detectors are e.g. AMS, GAPS and Calet. AMS to be launched fall 2010.

# Diffusion equation

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



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

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

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

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

$\delta$  – 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

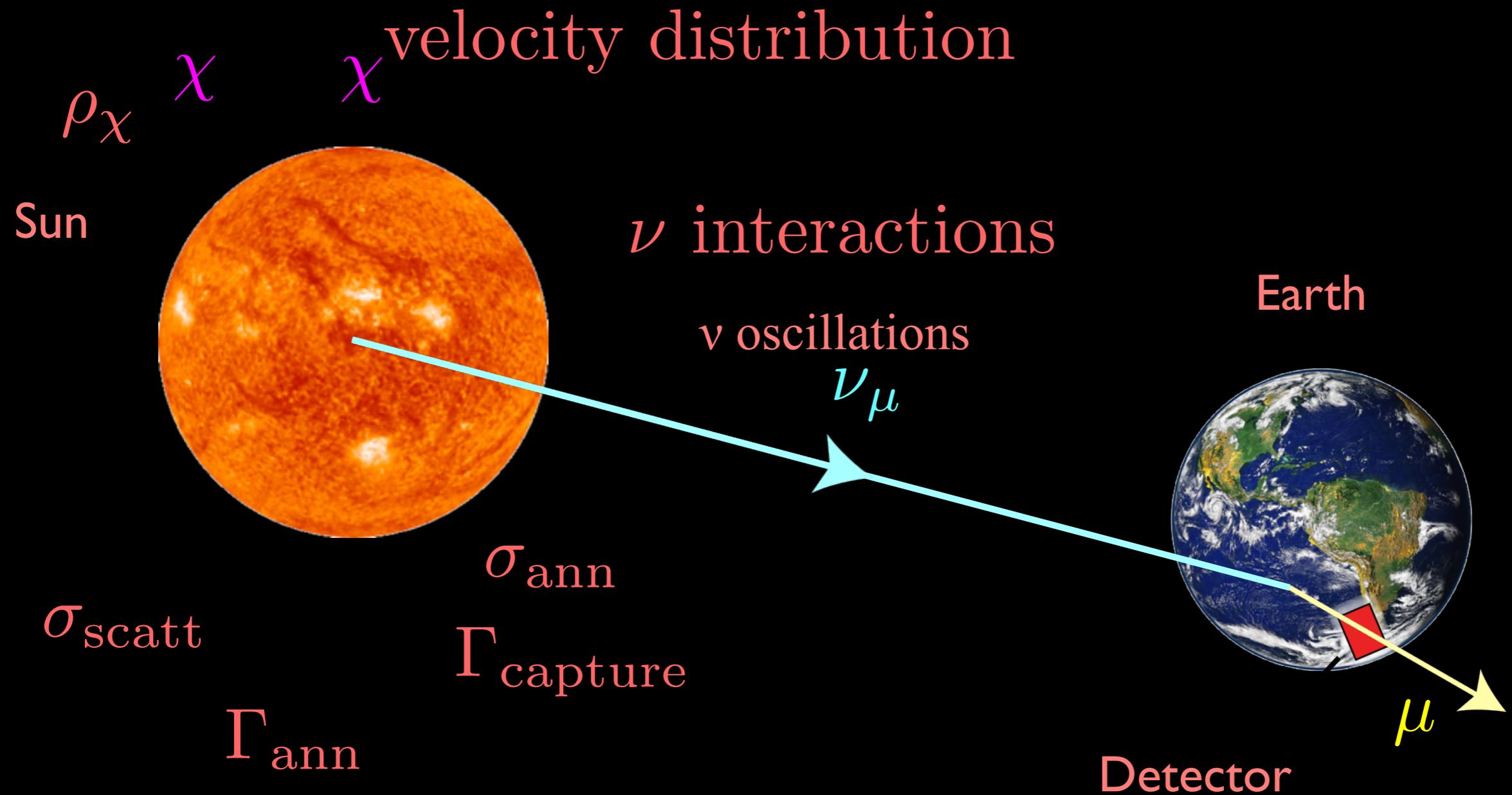
# Propagation

- By the fall of 2010, we “should” have 2–3 code releases:
  - Galprop (numerical), new version, Moskalenko et al
  - USINE (semi-analytical), first release, Maurin et al
  - Dragon (numerical), first release, Grasso et al
- All of which should have interfaces to DarkSUSY and other signal codes like micrOmegas

See talks by Lavalle and Taillet  
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# WIMP Capture



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

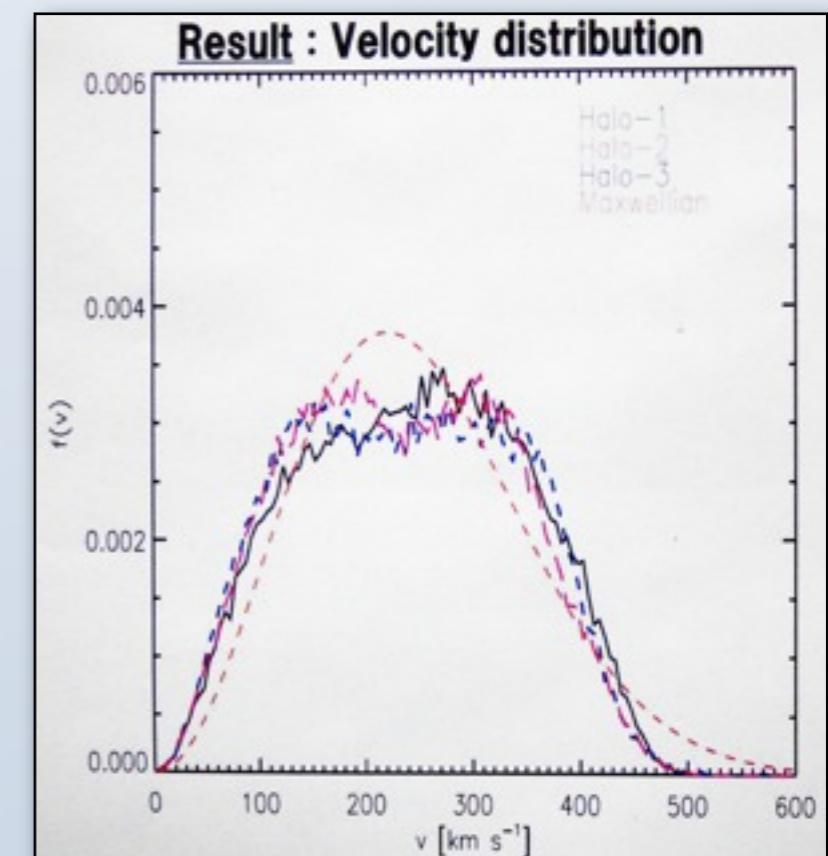
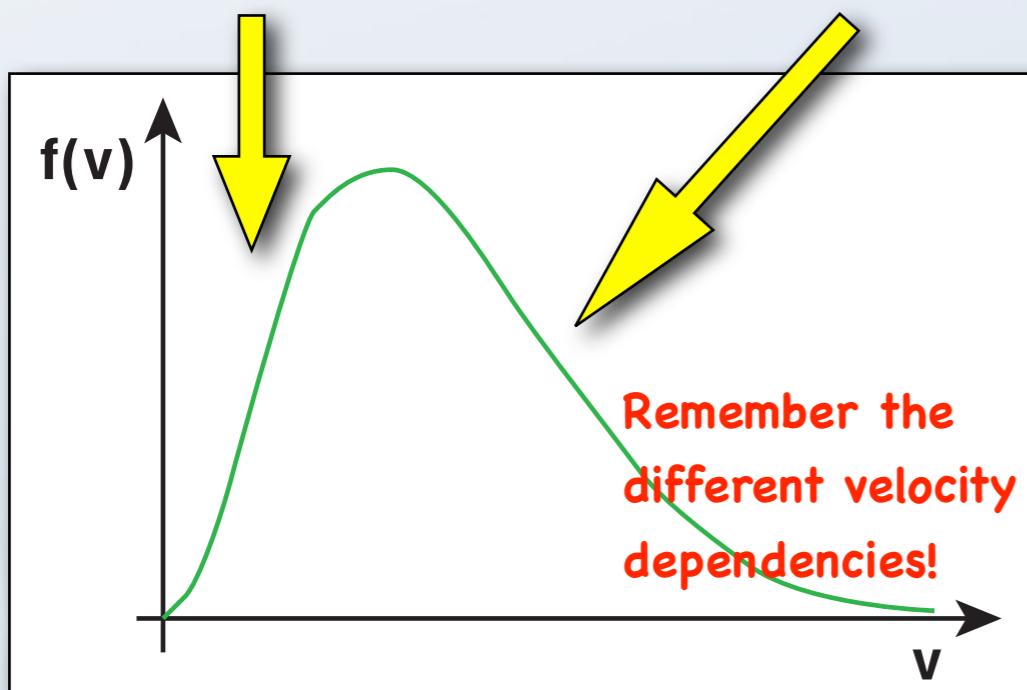
Freese '86  
Krauss, Srednicki & Wilczek '86  
Gaisser, Steigman & Tilav '86

# A note about velocity distributions

Capture sensitive to the low-velocity region

Direct detection sensitive to higher velocities

Also, velocity distribution in the galaxy most likely not Maxwellian



Preliminary results from Shogo Masaki

- 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)

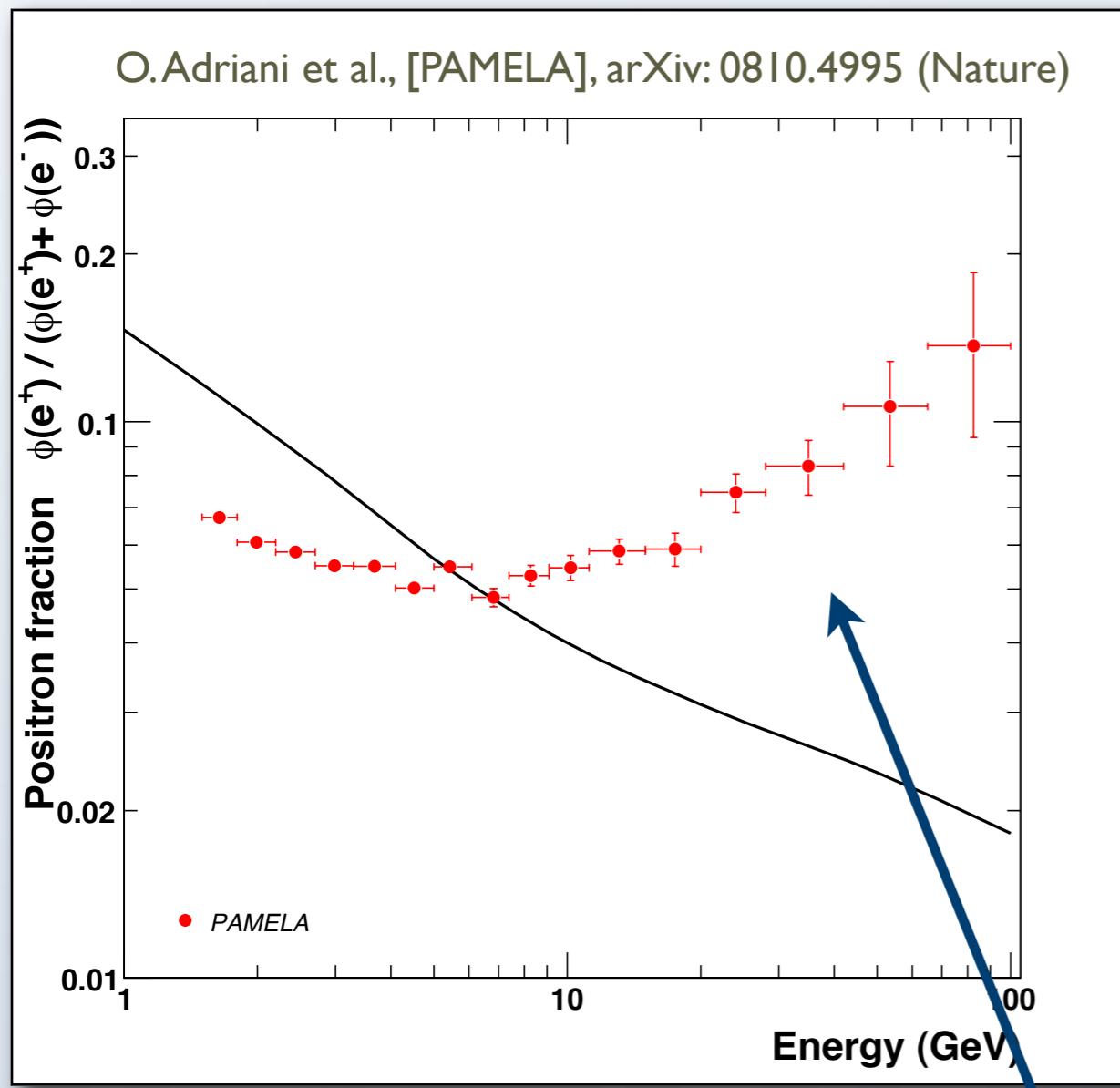
# Multi-channel approach

- Apart from the “standard” indirect search channels (gammas, antiprotons, positrons, neutrinos), we can also use other probes.
- As an example of the multi-channel approach, let’s focus on dark matter models giving good fits to Pamela, HESS and Fermi data

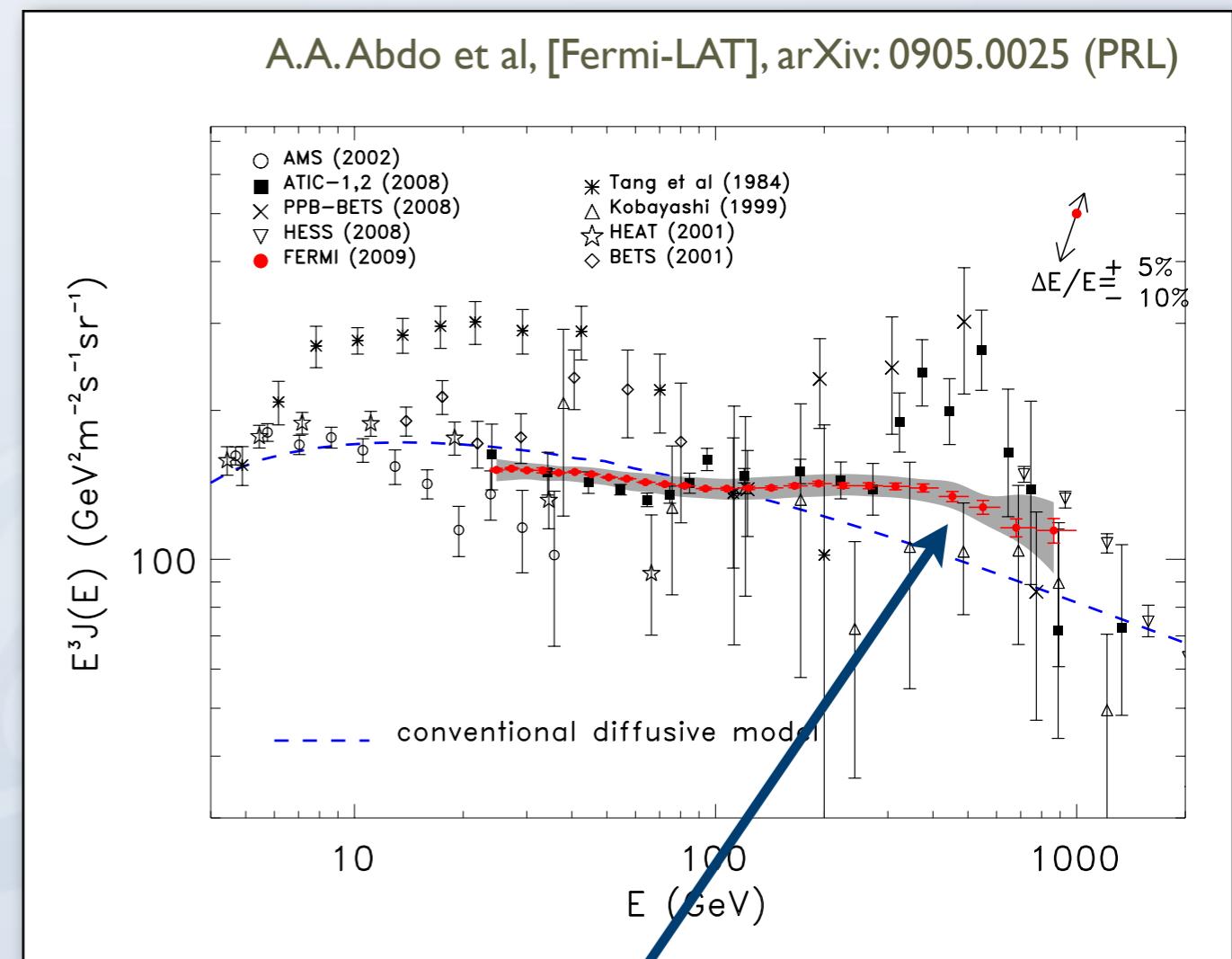


# Data and background expectations

## Positron fraction



## e<sup>+</sup>+e<sup>-</sup> spectrum



**What are these excesses compared to the background?**

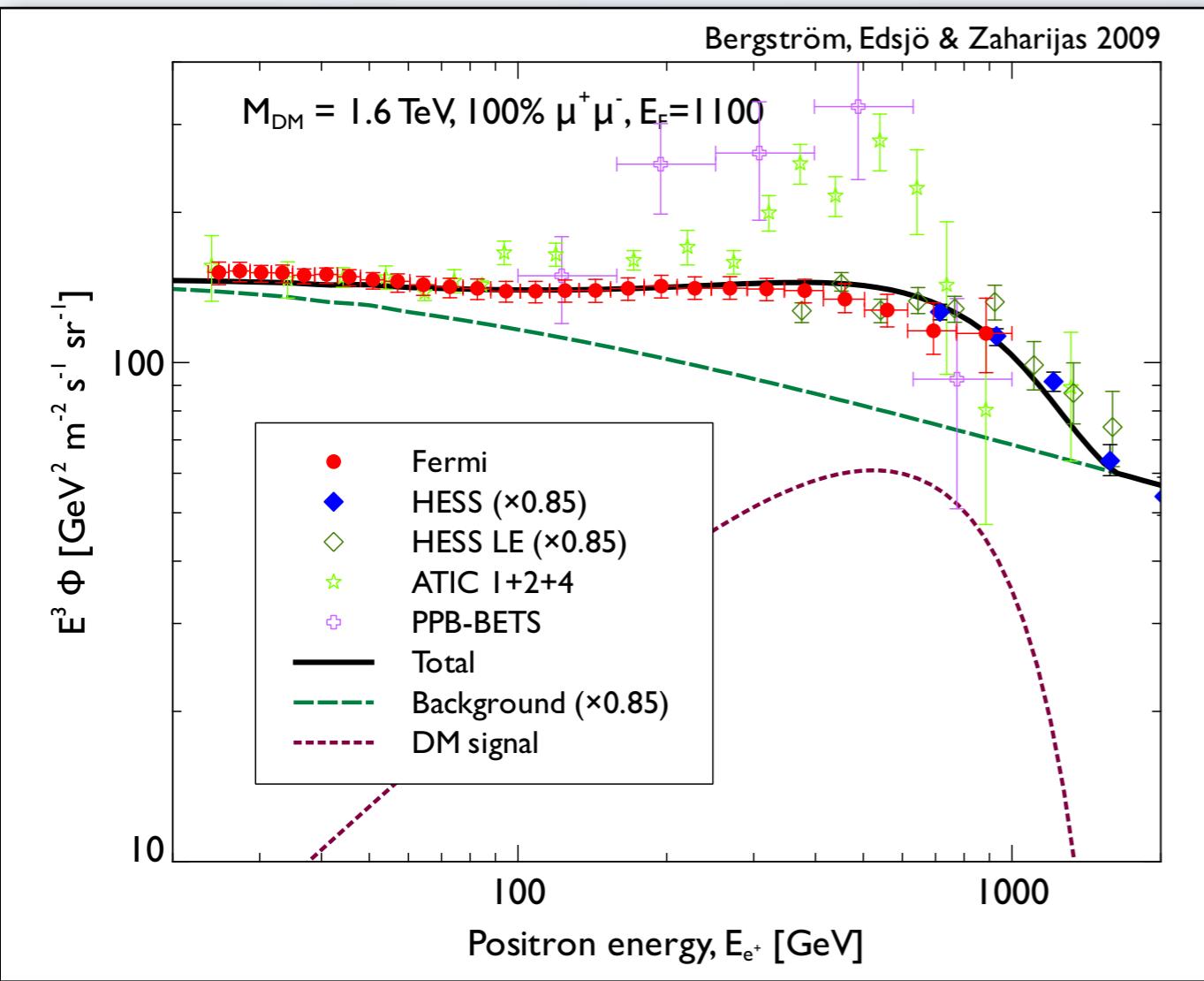
more than 550 papers written on Pamela since Nov. 2008  
...and more than 300 citing the Fermi-LAT paper from May 2009  
...of which all but at most one are wrong...?

# 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)
- ...

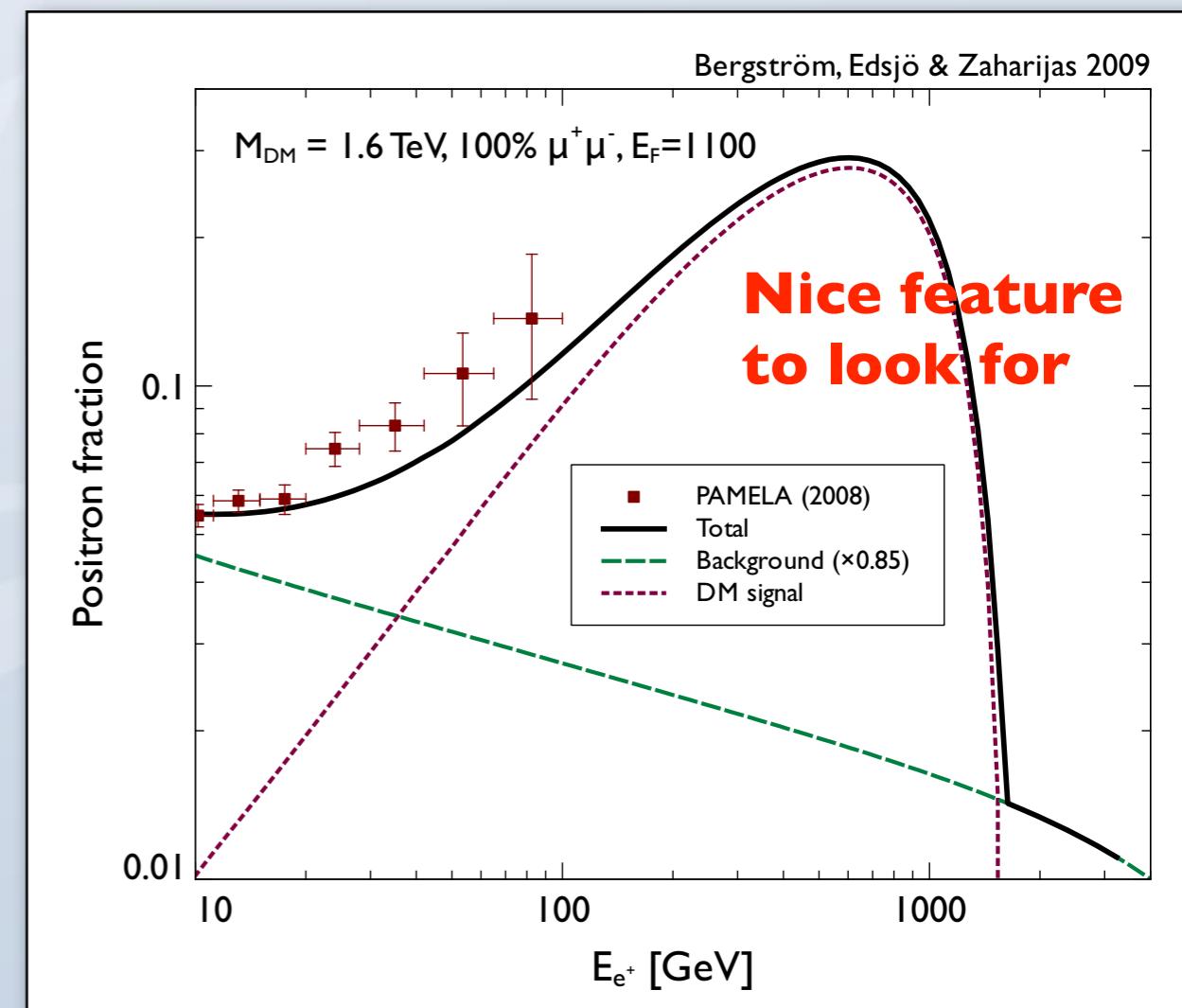
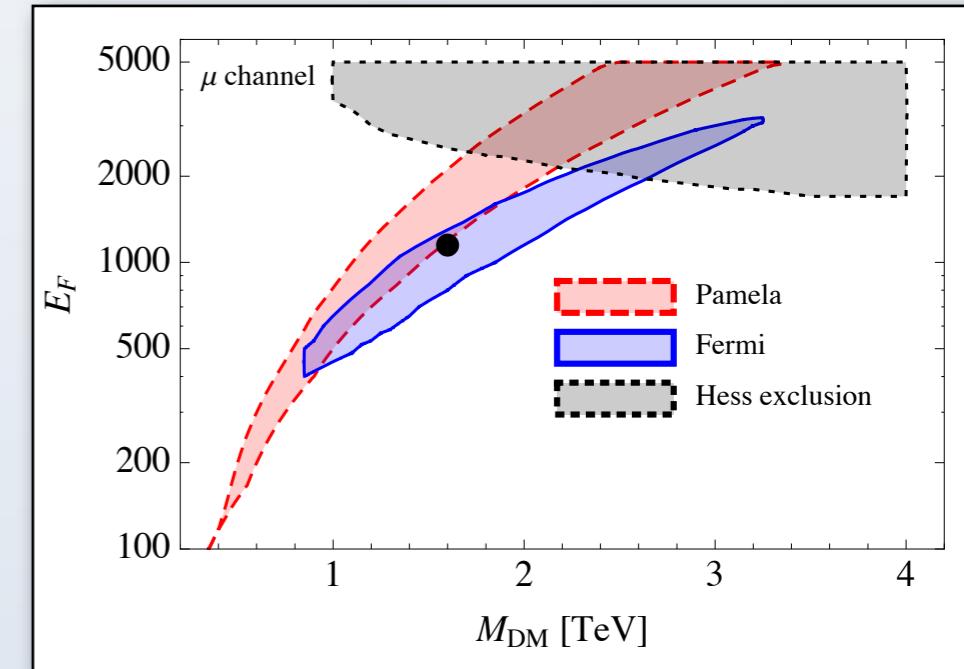


# Dark matter – $\mu$ channel

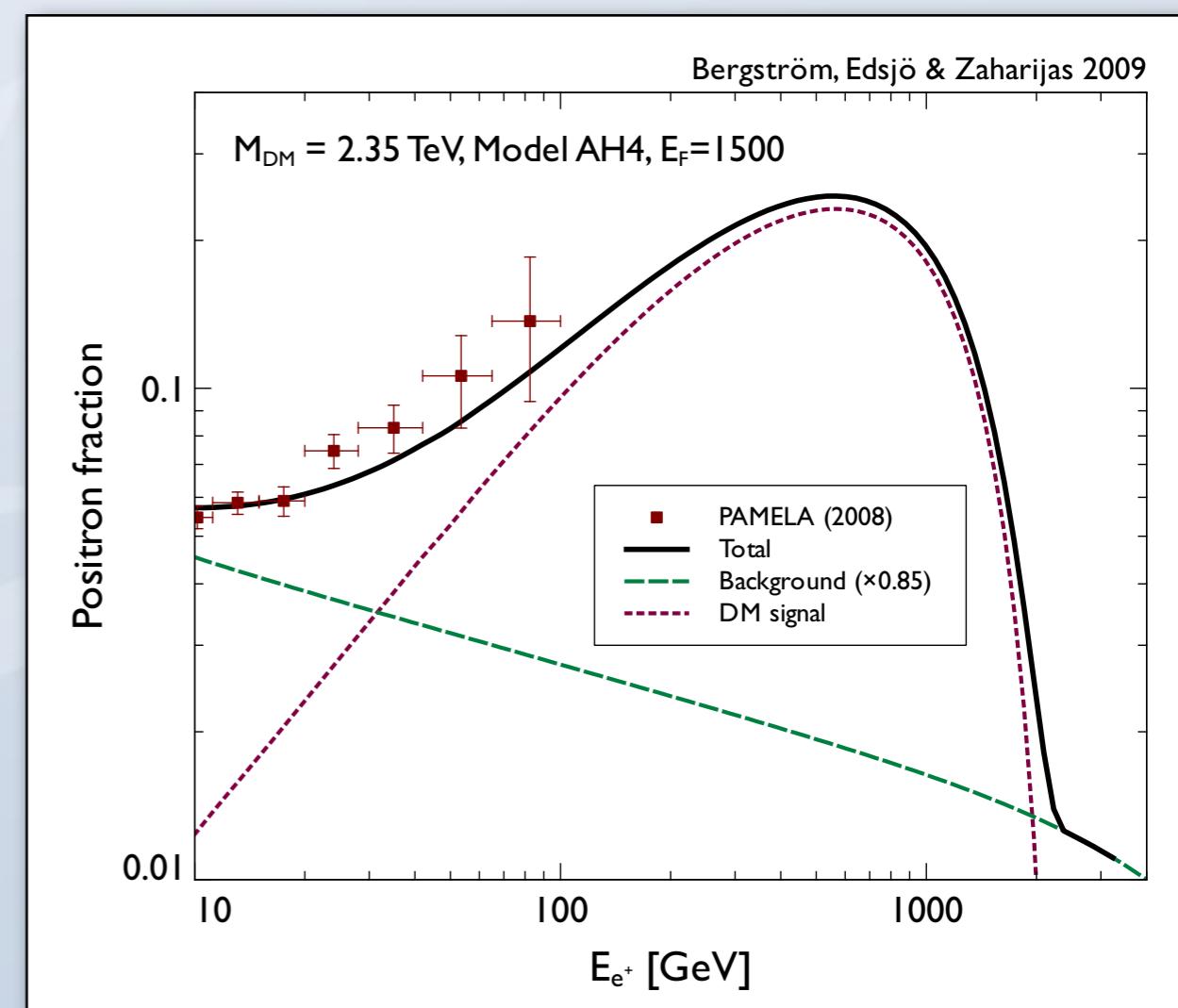
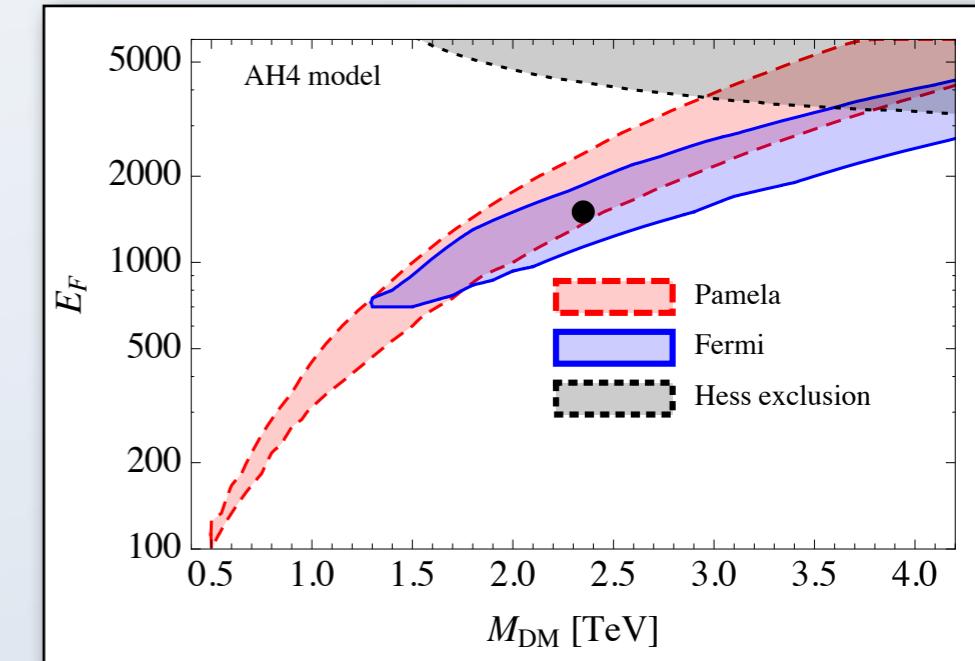
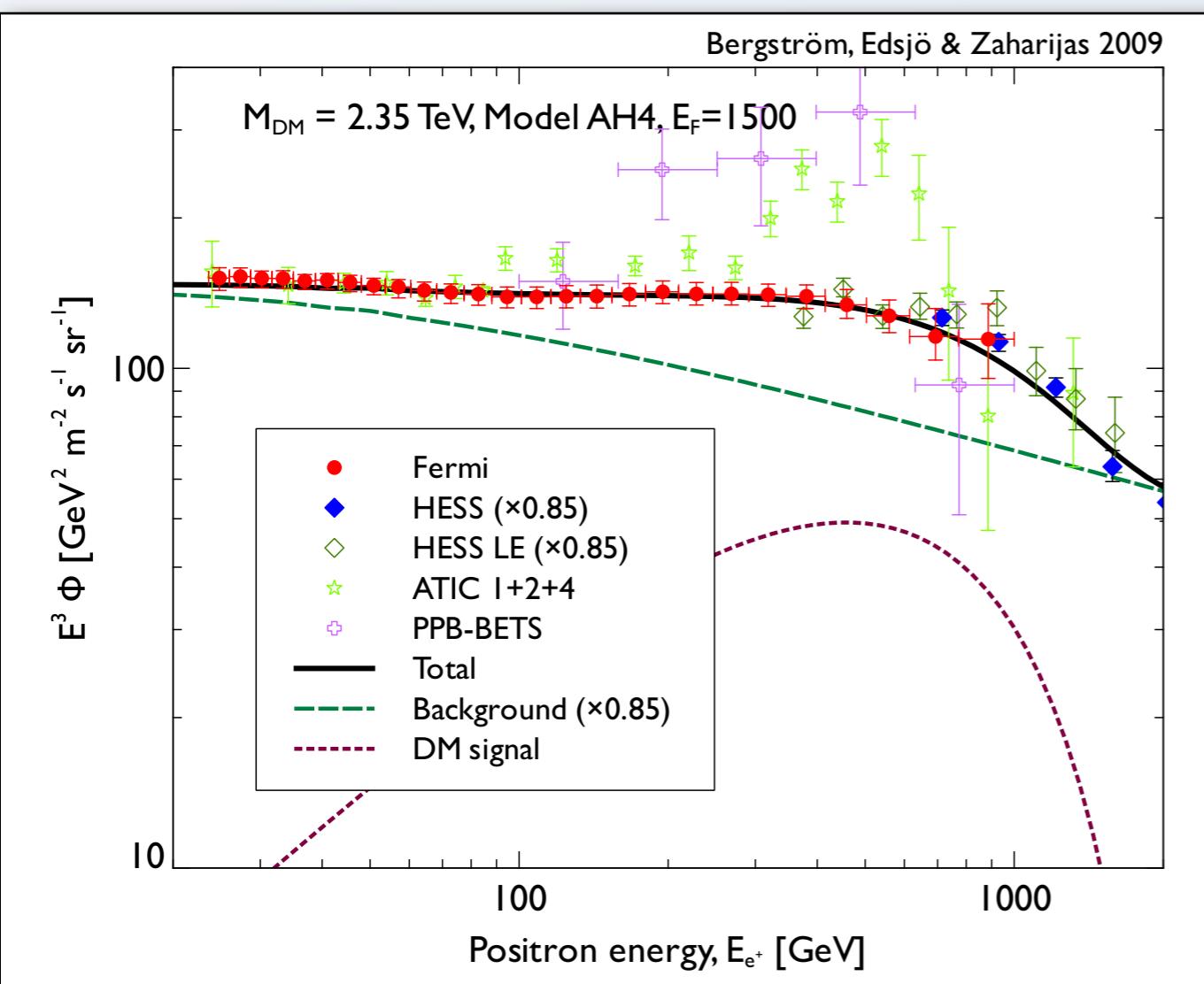


Cored isothermal  
profile assumed here

We get good fits to Fermi, HESS and PAMELA data



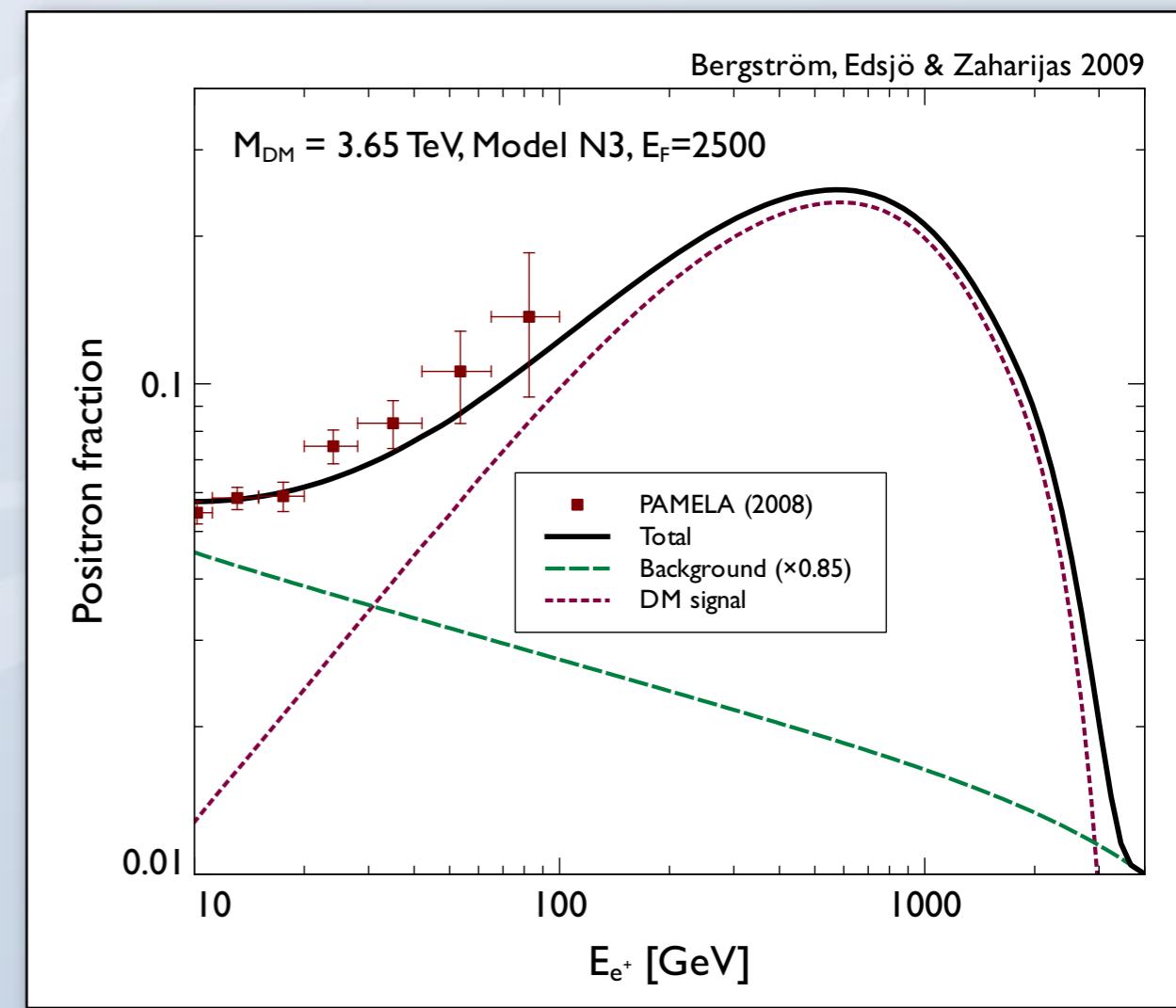
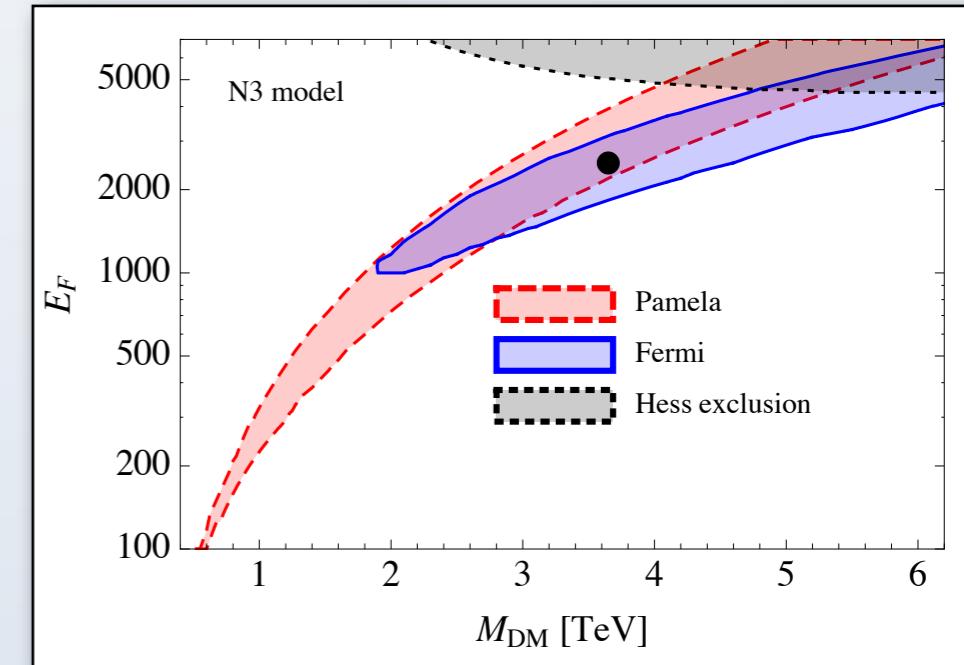
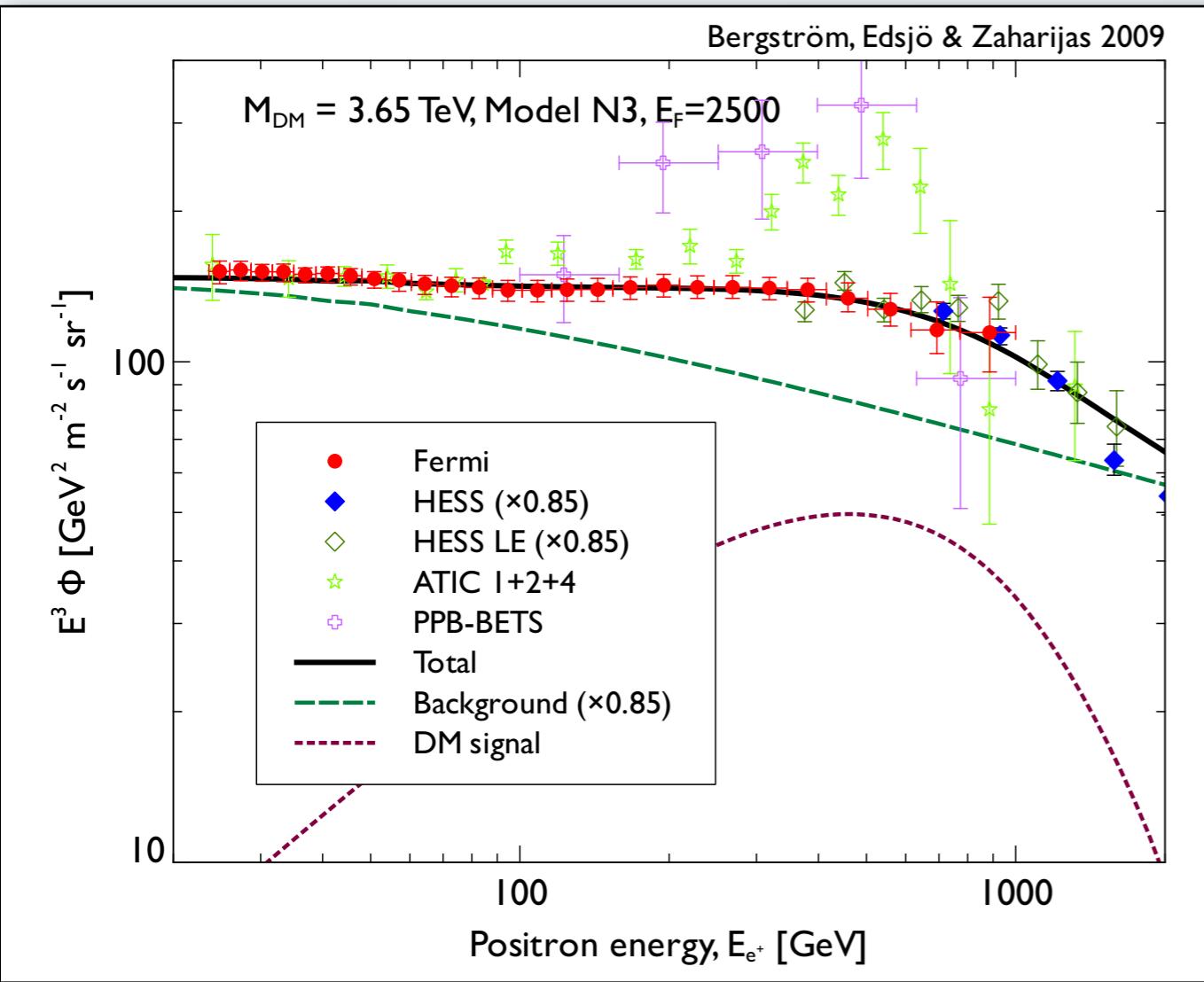
# Results – AH4 model



$$DM + DM \rightarrow \phi\phi, \phi \rightarrow \mu^+ \mu^-$$

$$m_\phi = 0.25 \text{ GeV}$$

# Results – N3 model



$$DM + DM \rightarrow sa, a \rightarrow \mu^+ \mu^-, s \rightarrow aa$$

$$m_s = 20 \text{ GeV} \quad m_a = 0.5 \text{ GeV}$$

# Fits

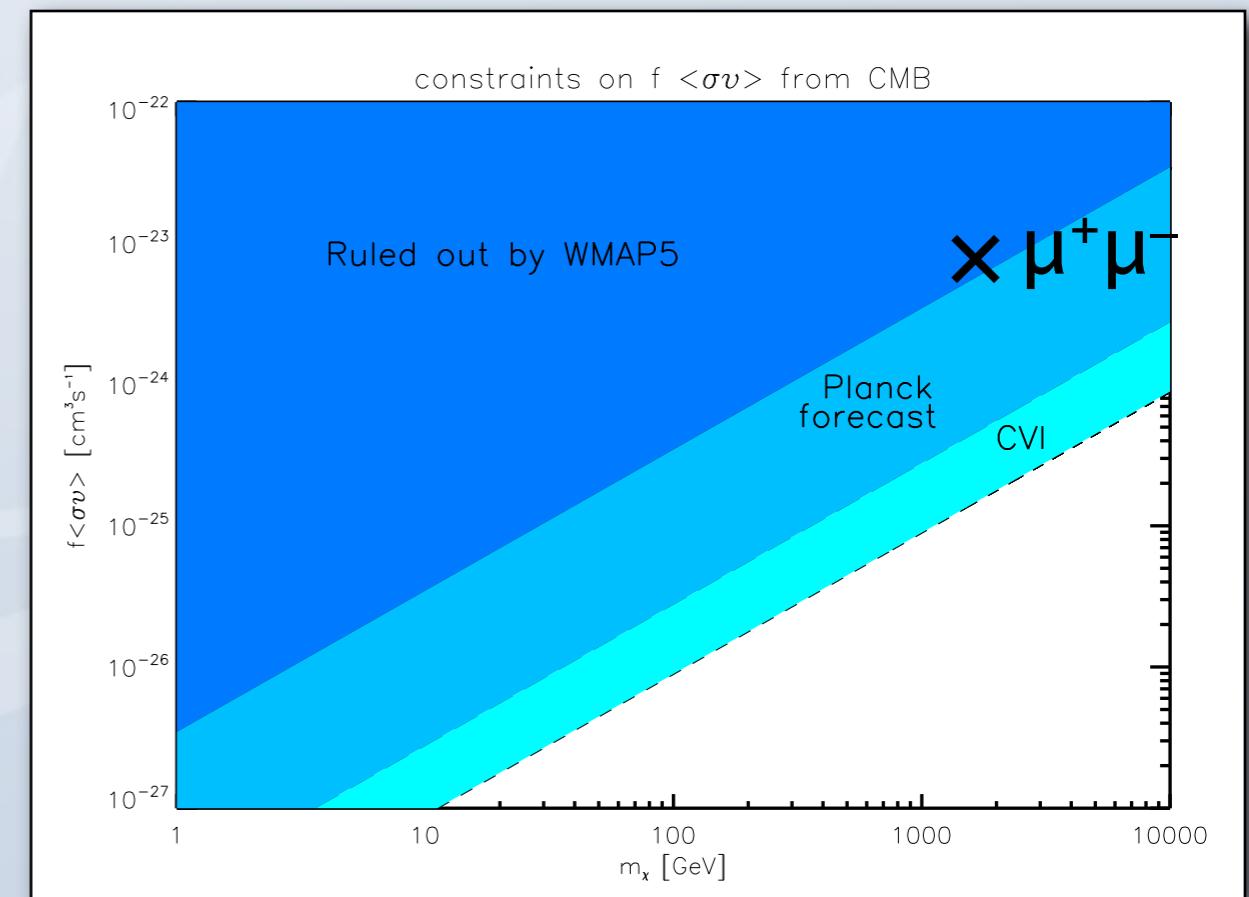
- We can get very good fits to both Fermi, HESS and PAMELA data with ‘off-the-shelf’ halo, diffusion and background models
- Masses in the range 1–4 TeV fit well
- However, we need to assume enhancement factors of the order of 1000 (e.g. from Sommerfeld enhancements).
- Note: we have focused on muons as they give very good fits. Some electrons and tau leptons are certainly also possible though.

# Constraints from the galactic centre and dwarf spheroidals

- These models just barely escape gamma and synchrotron constraints from the galactic centre and dwarf spheroidals (Bergström et al, arXiv:0812.3985)
- For a steeper halo profile than the isothermal sphere considered here, the models would be excluded (too much synchrotron radiation/gamma)

# Constraints from the CMB

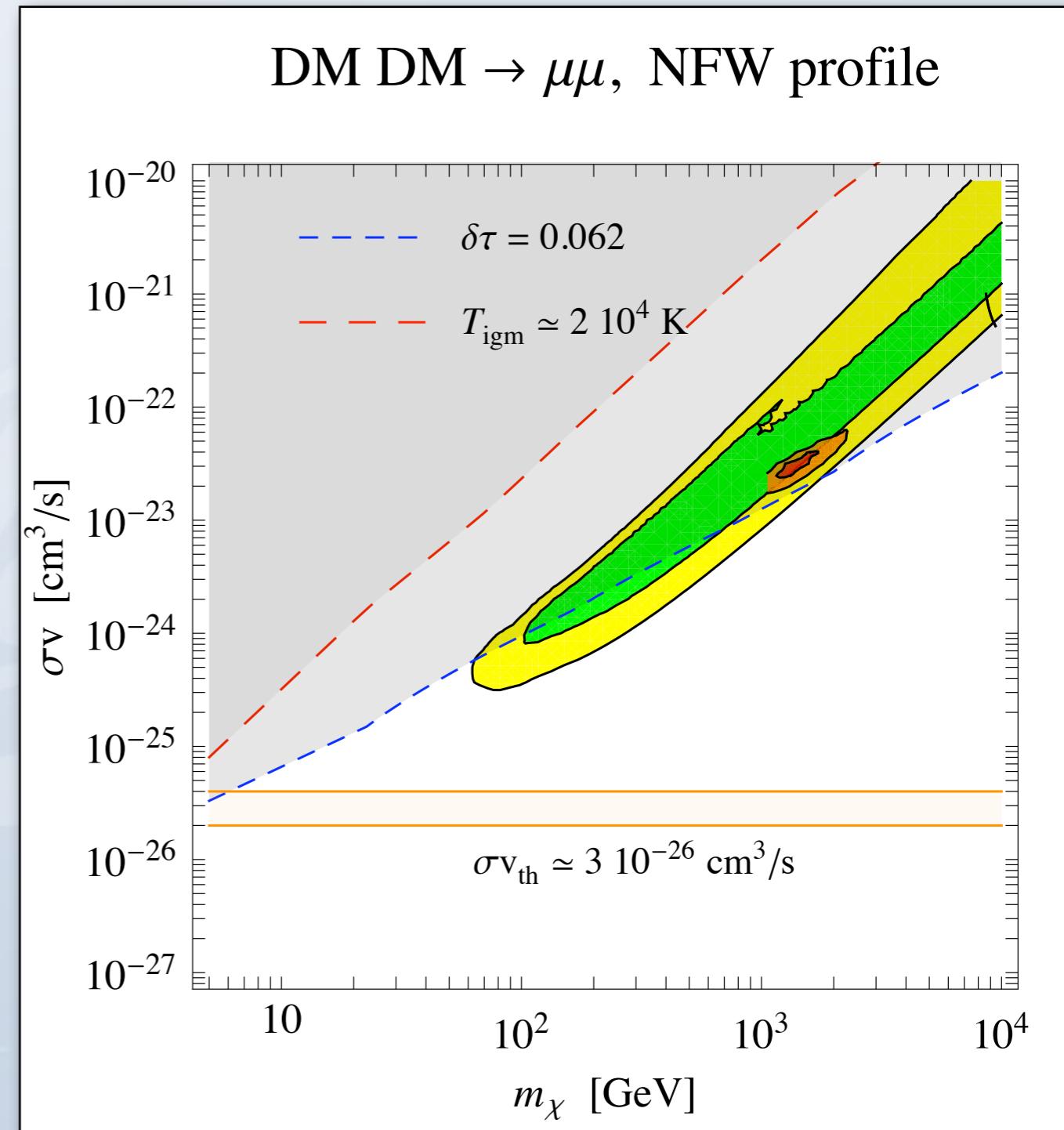
- For Sommerfeld enhanced models (AH & N models), effects could also arise in the cosmic microwave background radiation. The models we have considered here are (just barely) OK with current constraints, but can be probed with Planck (launched May 14!).



Galli et al, arXiv:0905.0003;  
see also Slatyer et al, arXiv:0906.1197)  
and talk by locco

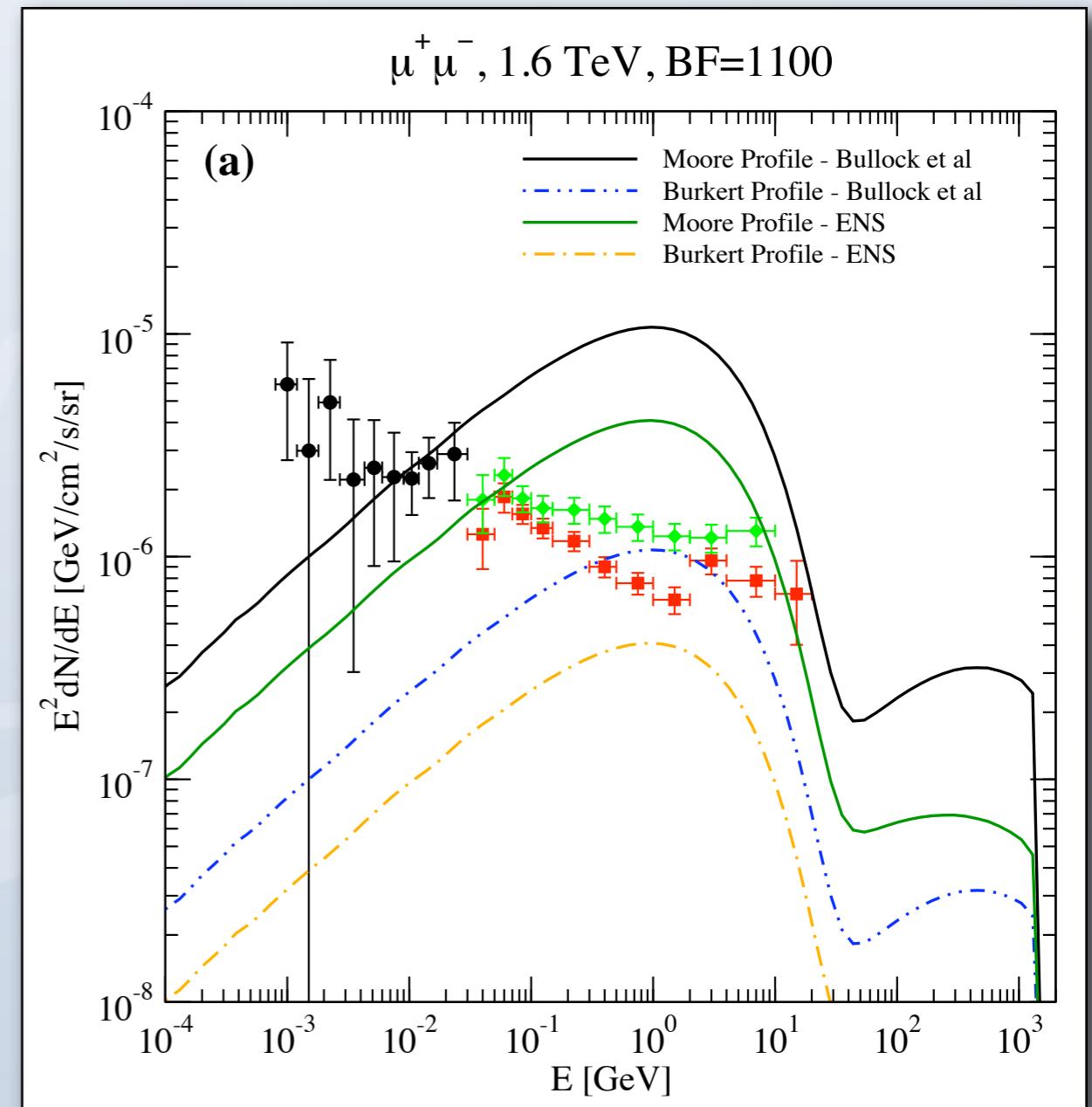
# Constraints from heating and reionization of the intergalactic gas

- DM annihilations would at time of structure formation heat and reionize the intergalactic gas
- Measurements of the optical depth constrain the amount of heating and reionization allowed
- Current models are (given the uncertainties) just barely OK with current constraints



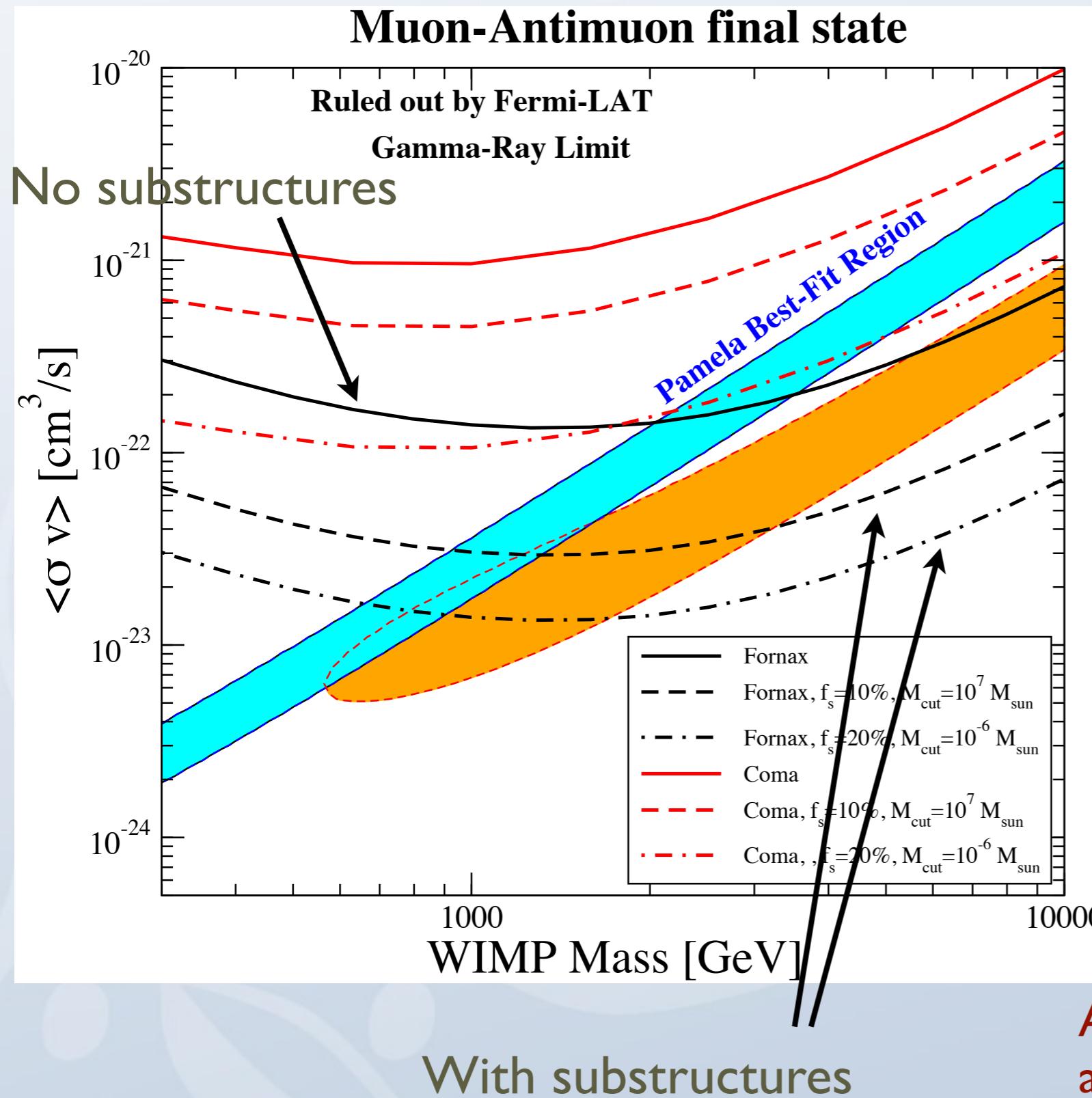
# ICS on CMB also gives constraints

- Inverse Compton Scattering on the CMB in cosmological halos can give a contribution in gamma rays
- For optimistic halo models and structure formation setups, these models are excluded, but for more conservative models, these DM models are OK



Profumo & Jeltema, arXiv:0906.0001  
See also Belikov & Hooper, arXiv:0906.2251

# Galaxy clusters give constraints



- Galaxy clusters also constrain these type of models.
- They are OK right now, but there is some tension, depending on how much of the mass is in substructure

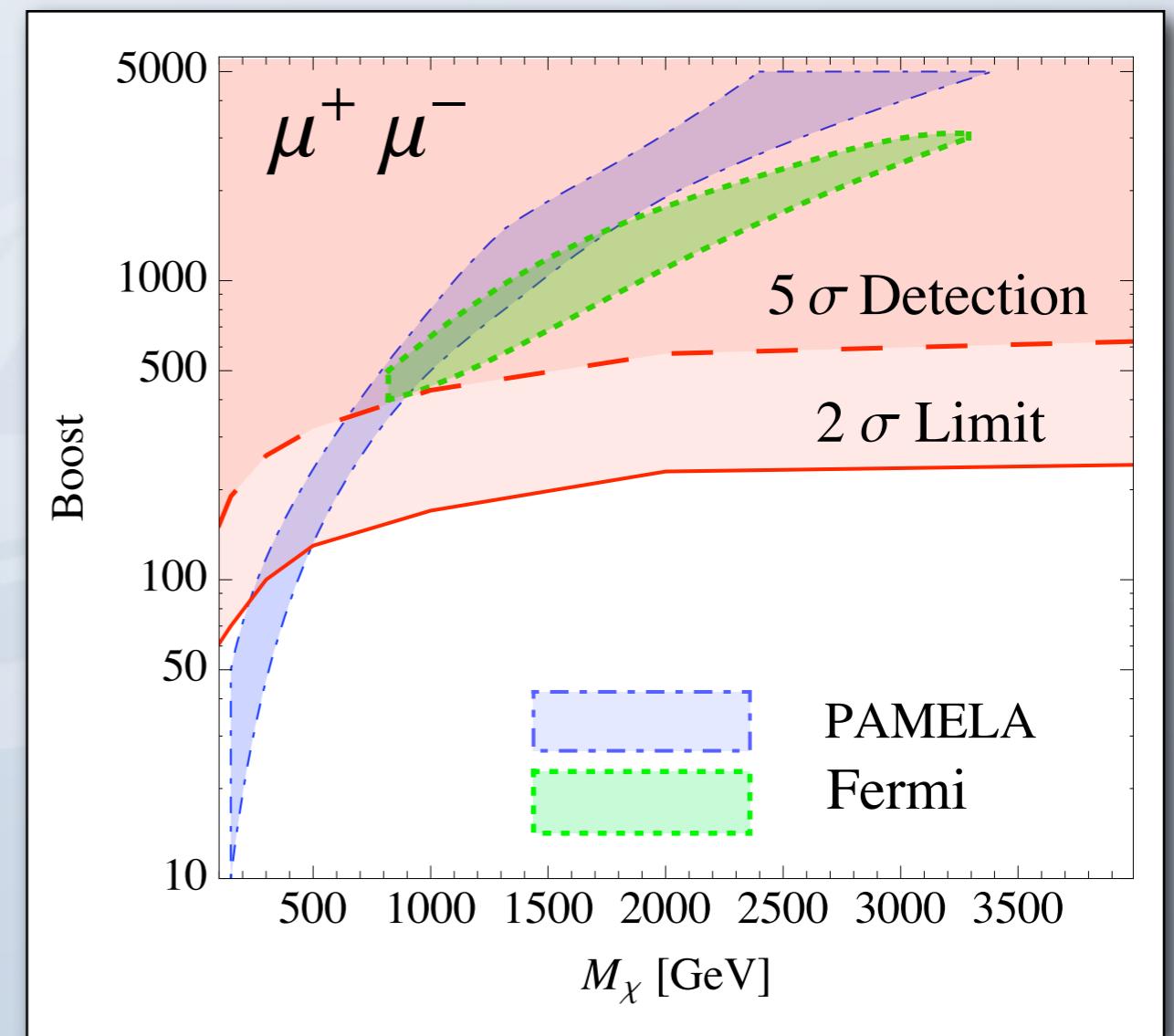
Ackermann et al [Fermi],  
arXiv:1002.2239, JCAP.  
Stockholm University



# Constraints from neutrinos

- DM annihilations at the galactic centre produce neutrinos that can be searched for with e.g. IceCube/DeepCore
- With a less steep profile, the sensitivity is reduced though

Sensitivity for NFW and 5 years of IceCube/DeepCore operation



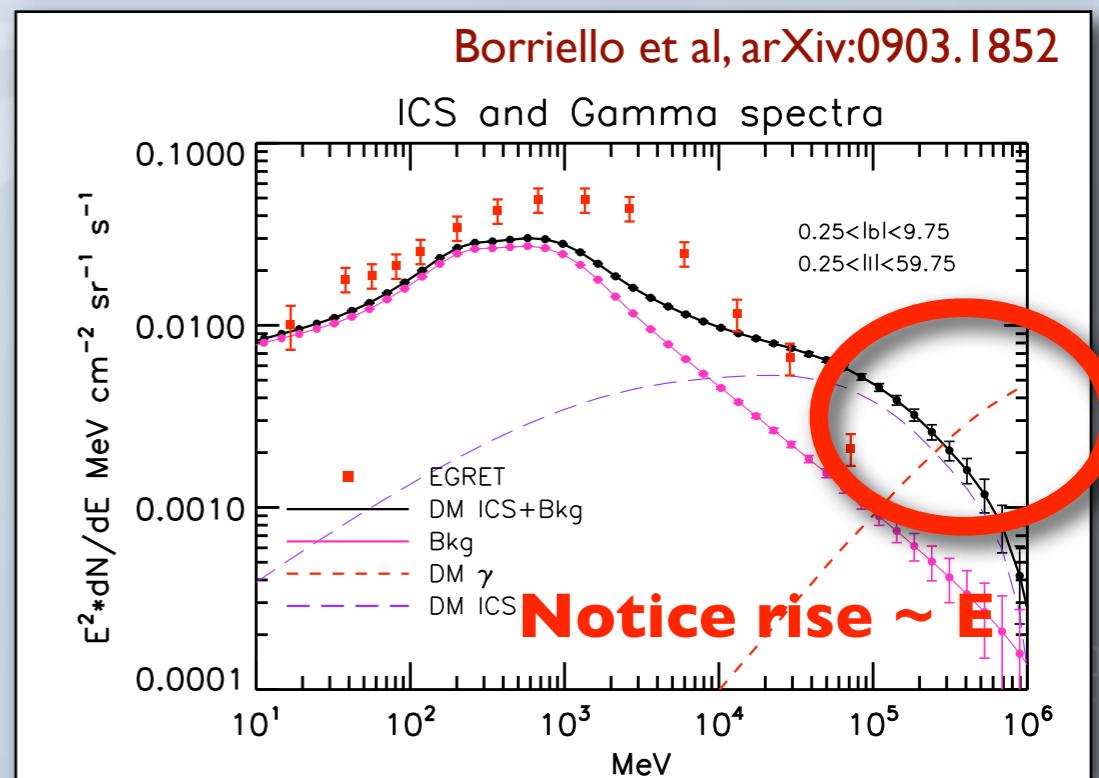
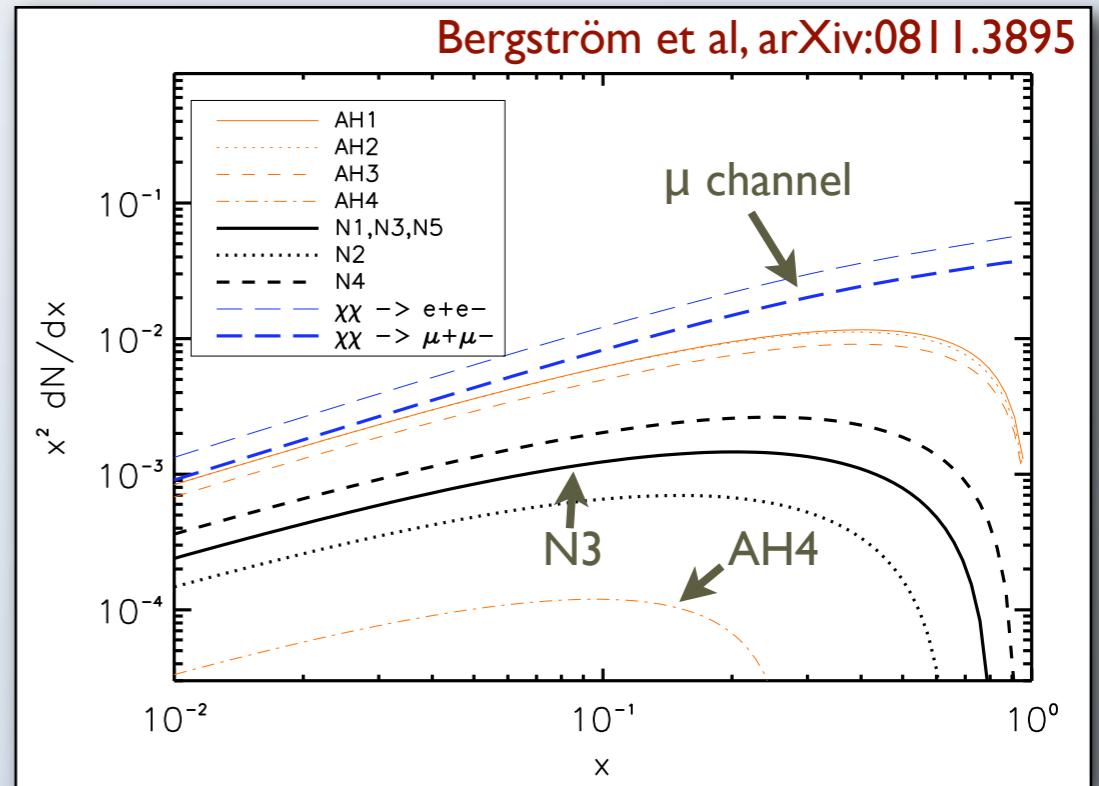
# Additional features of the dark matter models

- As we produce many charged leptons, we expect final state radiation giving a

$$\frac{dN}{dE_\gamma} \propto E_\gamma^{-1}$$

spectrum of gamma rays

- These should provide a distinctive signature to search for from e.g. the galactic centre, especially for the muon channel model
- We would also get gammas from Inverse Compton Scattering (ICS) on the interstellar radiation field



# Other features

- The galactic diffuse emission will be more spherical from dark matter than from other sources (DM dominates at mid-high latitudes,  $E_\gamma > 100$  GeV)
- Discrimination between dark matter and astrophysical explanations possible with e.g. Fermi

## Inverse Compton from DM

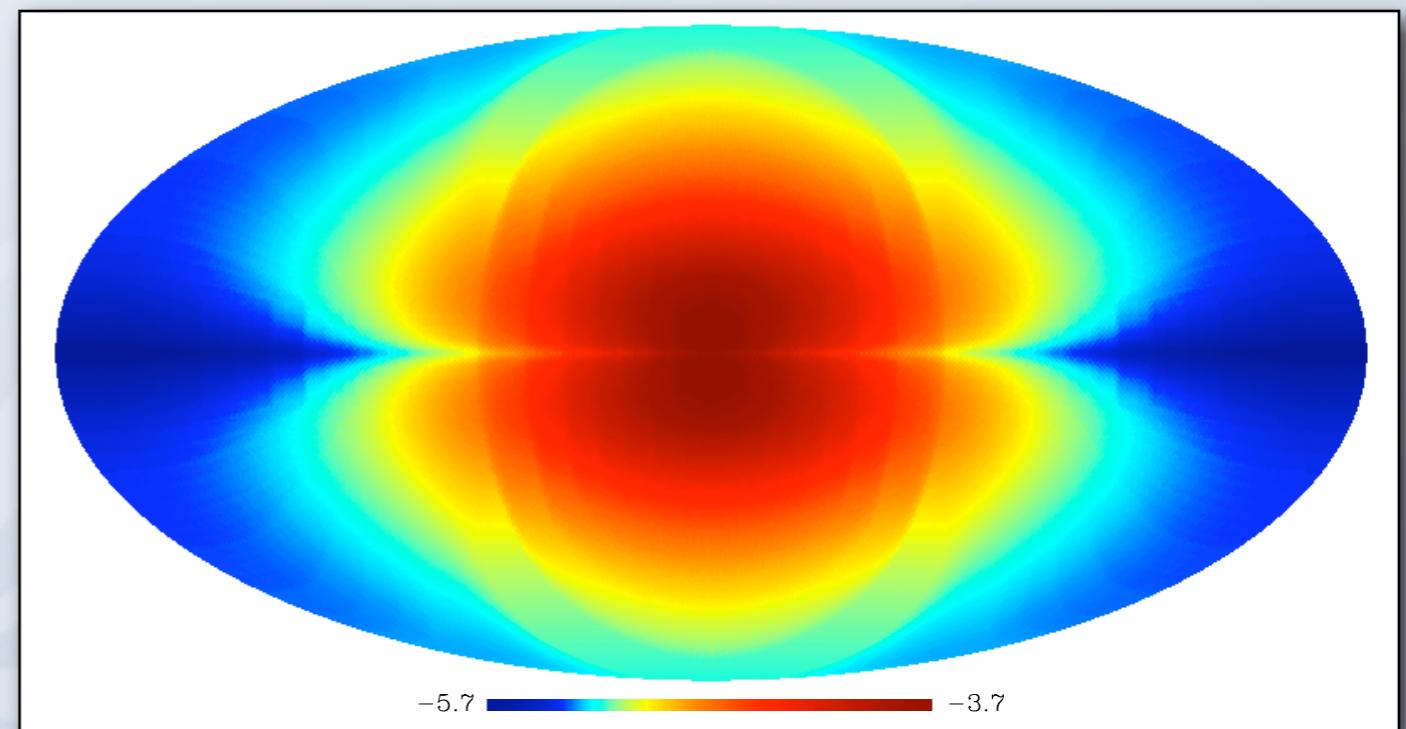


Fig. from Regis and Ullio,  
arXiv:0904.4645

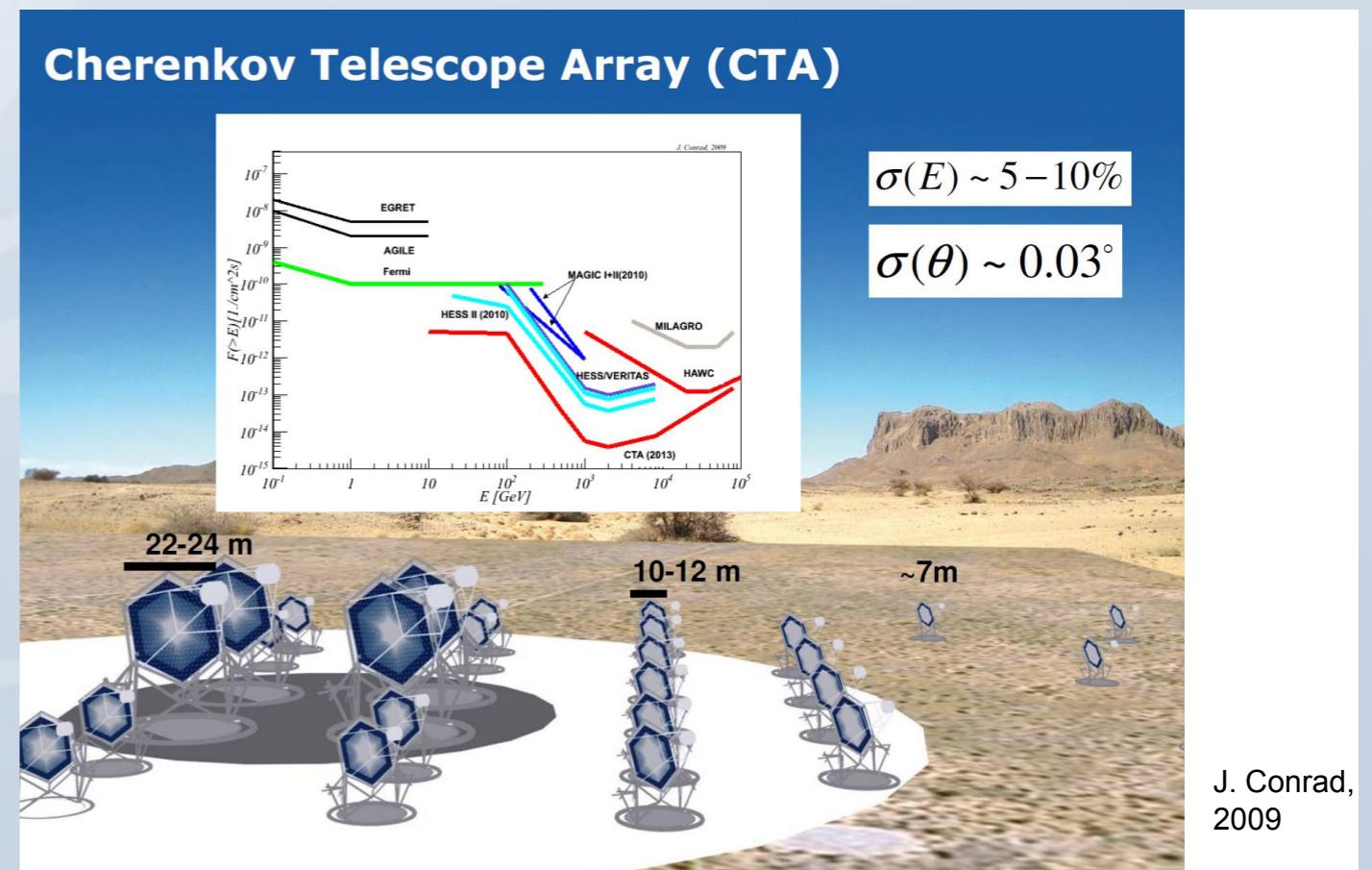
# What is needed to really find dark matter in the cosmic rays?

- 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).



# 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...



...think  
**BIG!**



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# BIG $\Rightarrow$ DMA = Dark Matter Array

- Let's be optimistic and consider a DMA with
  - CTA-like design, but with
$$A_{\text{DMA}}^{\text{eff}} \sim 10 \times A_{\text{CTA}}^{\text{eff}} \sim 10 \text{ km}^2$$
  - low energy threshold (10 GeV)
  - dedicated for dark matter searches,  
 $t_{\text{obs}} \sim 5000$  hrs feasible

$\Rightarrow$  Factor of 1000 better than CTA on  $A_{\text{eff}} \times t_{\text{obs}}$  + lower threshold

# Is it only a dream?

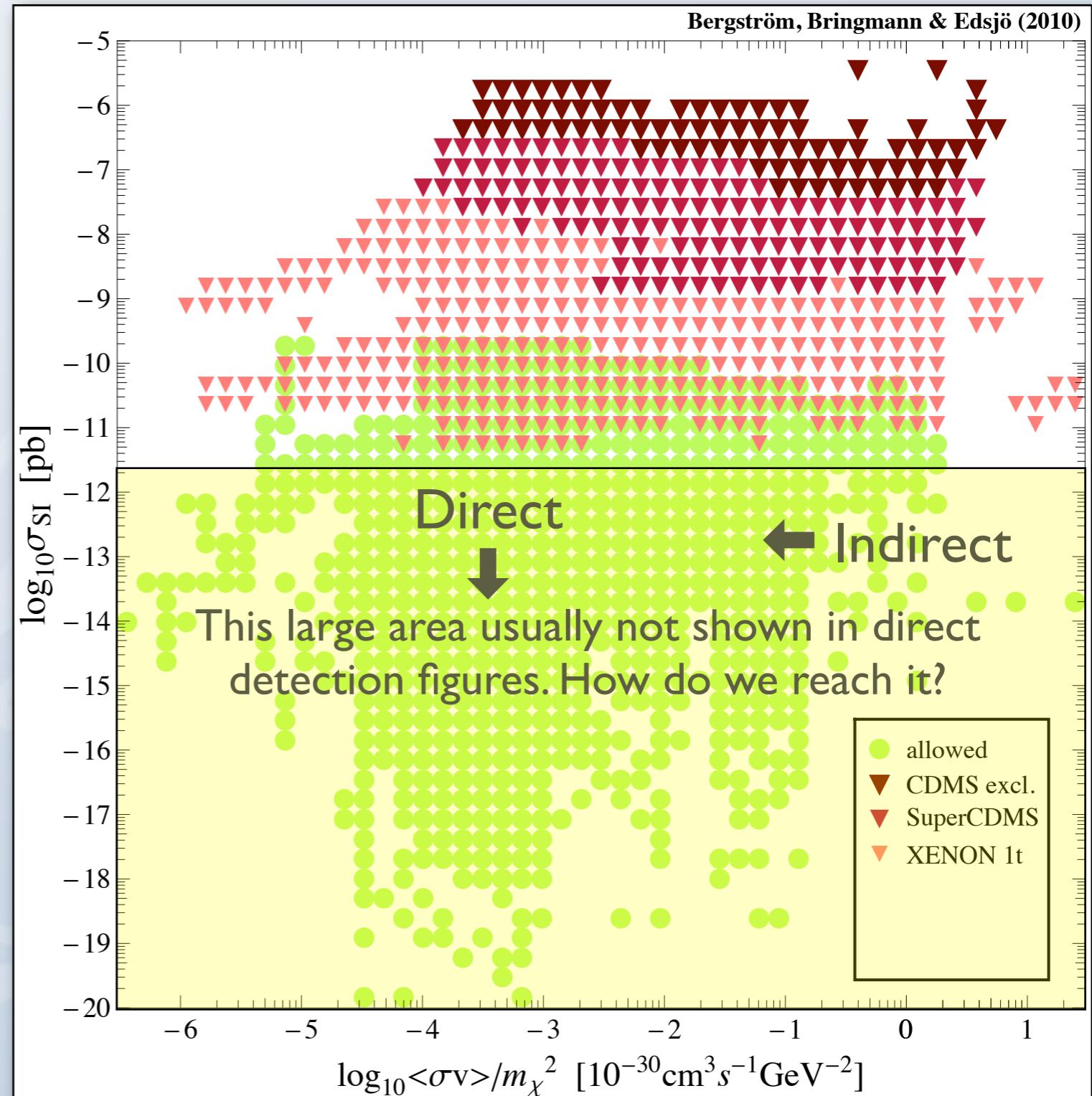
- Maybe, but in principle possible.  
Let's investigate what DMA could do before disregarding the idea.
- Compare with “5@5”, Aharonian et al 2001.



# Direct vs indirect

- $\sim 10^6$  models (mSUGRA + MSSM).
- Within  $3\sigma$  WMAP bound on relic density
- Accelerator constraints OK

Preliminary  
Bergström, Bringmann & Edsjö,  
in prep. 2010



# Setup for DMA analysis

- Large scan of MSSM and mSUGRA parameter space ( $\sim 10^6$  models) satisfying WMAP  $3\sigma$  bound on relic density and accelerator constraints.
- Experiment sensitivities from
  - **CDMS:** As published in Z. Ahmed & al., 2010
  - **SuperCDMS:** As described in T. Bruch, 2010
  - **Xenon 1t:** As described in K. Arisaka & al., 2008
  - **FERMI-LAT:** Effective exposure 1 year (= 5 years observing time), 20 log-bins between 1 och 300 GeV, everything else according to LAT home page
  - **CTA:** Energy threshold 40 GeV, 17 bins up to 5 TeV, sensitivity curve according to Bernlöhr (2007), integration time 50 hours, effective area as in Arribas (thesis) - max  $A_{\text{eff}} \sim 2 \times 10^6 \text{ m}^2$
  - **DMA:** Energy threshold 10 GeV, sensitivity curve CTA/sqrt(1000), max  $A_{\text{eff}} = 2 \times 10^7 \text{ m}^2$ , integration time 5000 hours.

# What can a DMA do?

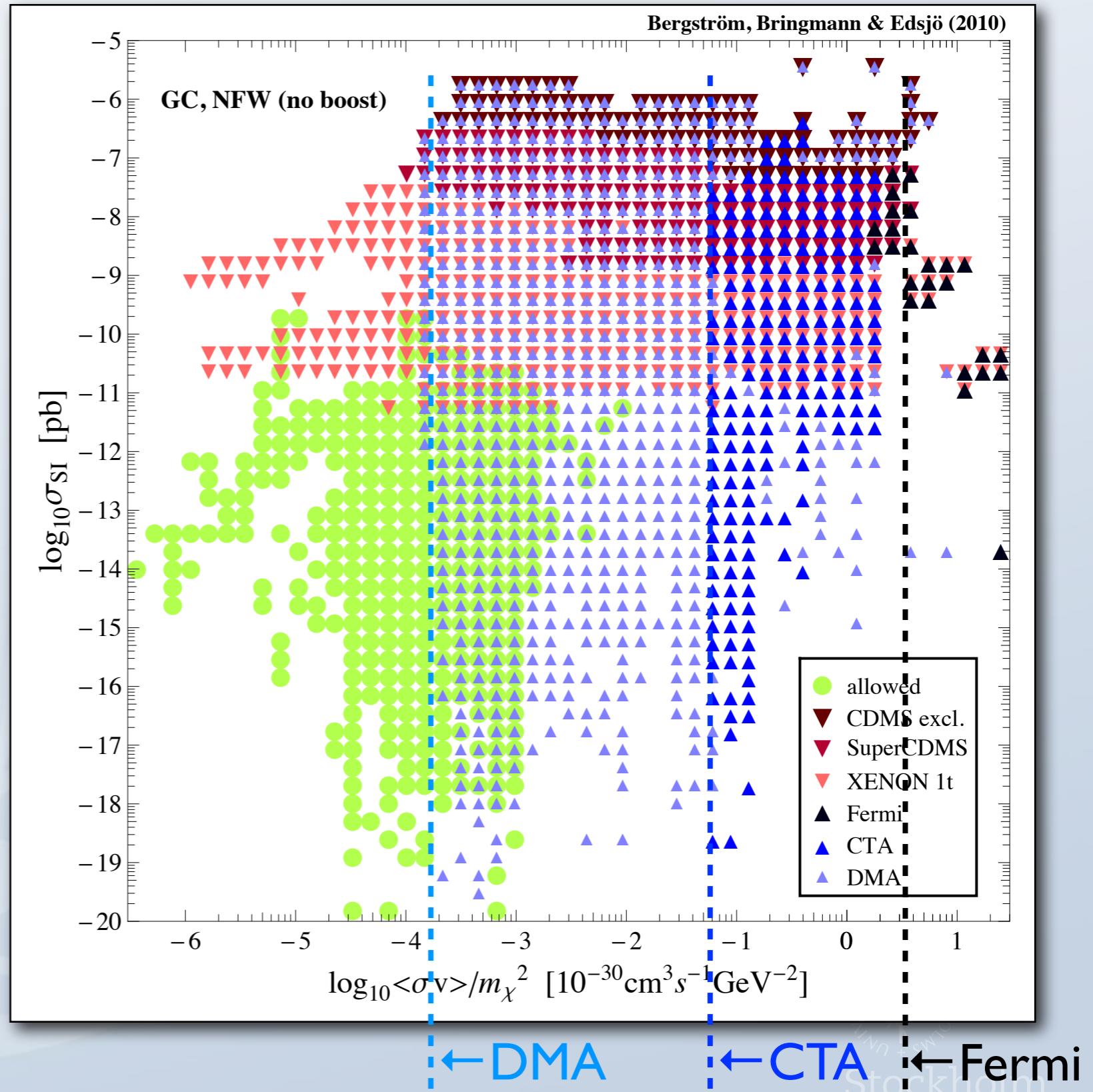
- Assume 5000 hrs towards the galactic centre (GC)
- Assume that the angular resolution is good enough to separate the HESS source from the GC
- Assume smooth diffuse background as measured by Fermi (from S. Digel, Fermi Symposium, Nov. 2009), extrapolated as power law above 100 GeV
- Demand that  $S/(S+B)^{0.5}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



# Direct vs indirect

- NFW
- No boost

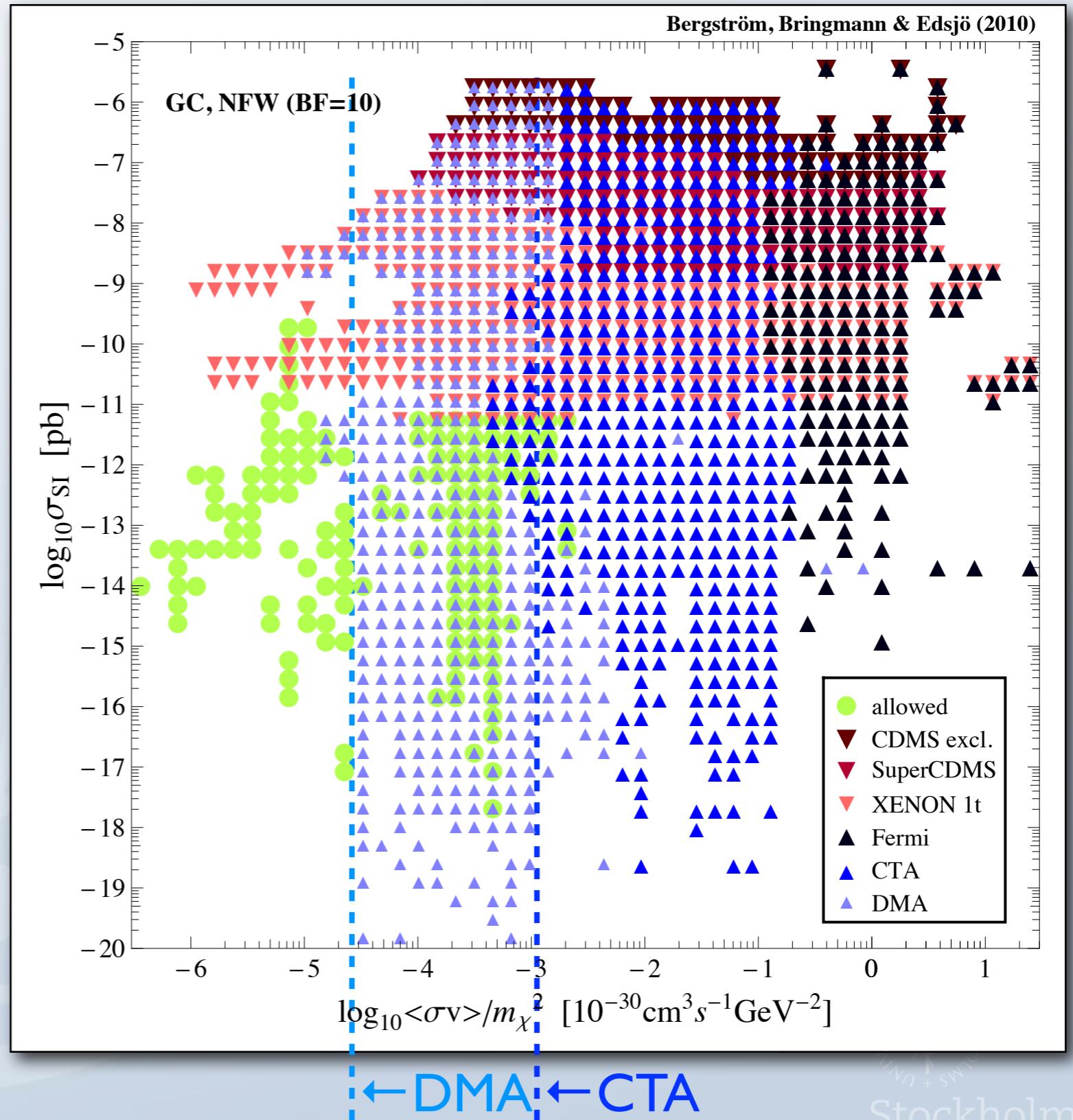
Preliminary  
Bergström, Bringmann & Edsjö,  
in prep. 2010



# Direct vs indirect

- NFW
- Boost factor = 10

Preliminary  
 Bergström, Bringmann & Edsjö,  
 in prep. 2010

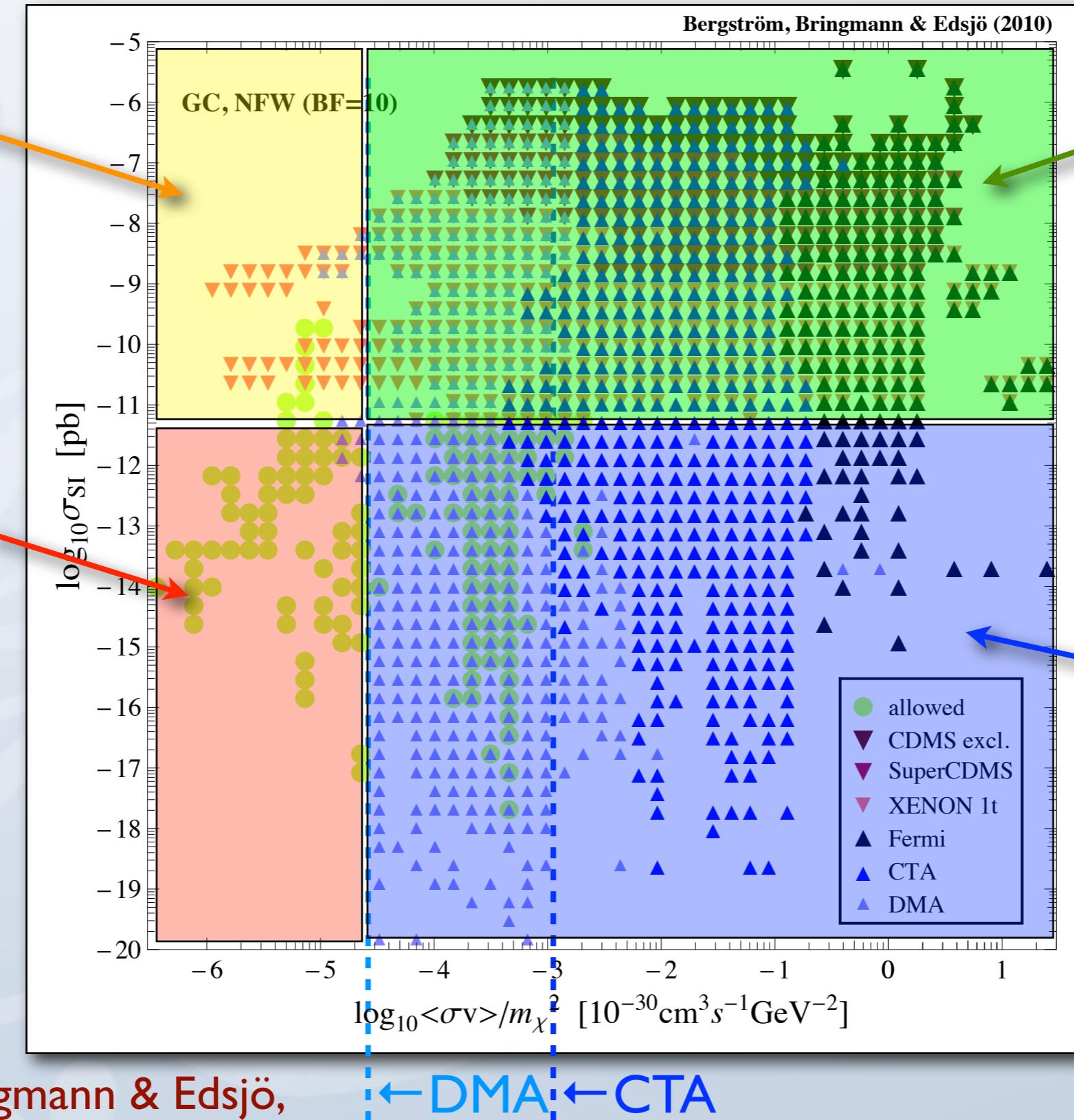


# Direct vs indirect

Direct detection  
territory!

The impossible  
part...

Preliminary  
Bergström, Bringmann & Edsjö,  
in prep. 2010

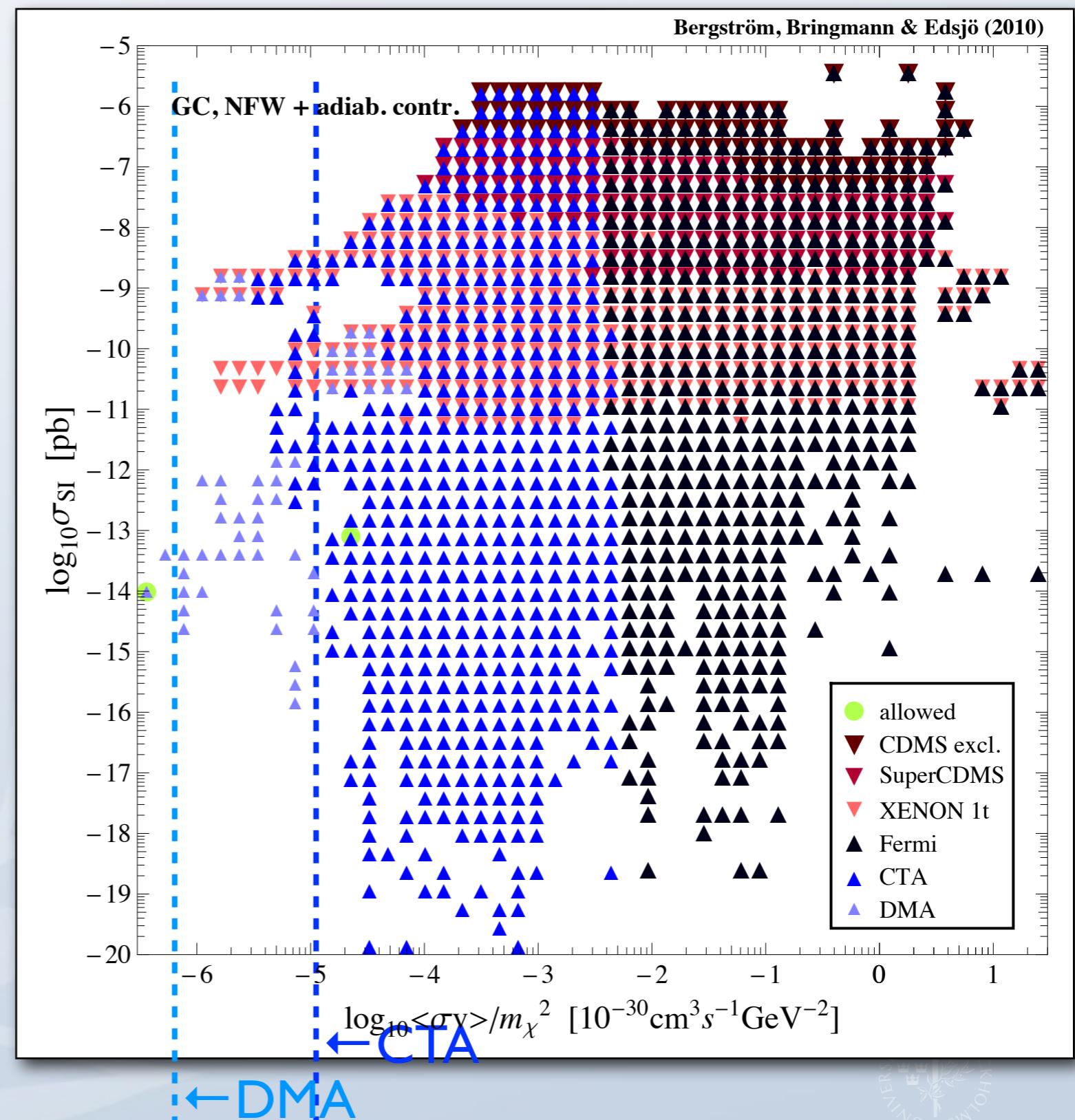


Sweet spot: Both  
direct detection  
and indirect  
detection should  
see a signal

# Direct vs indirect

- NFW
- Adiabatic contraction

Preliminary  
Bergström, Bringmann & Edsjö,  
in prep. 2010

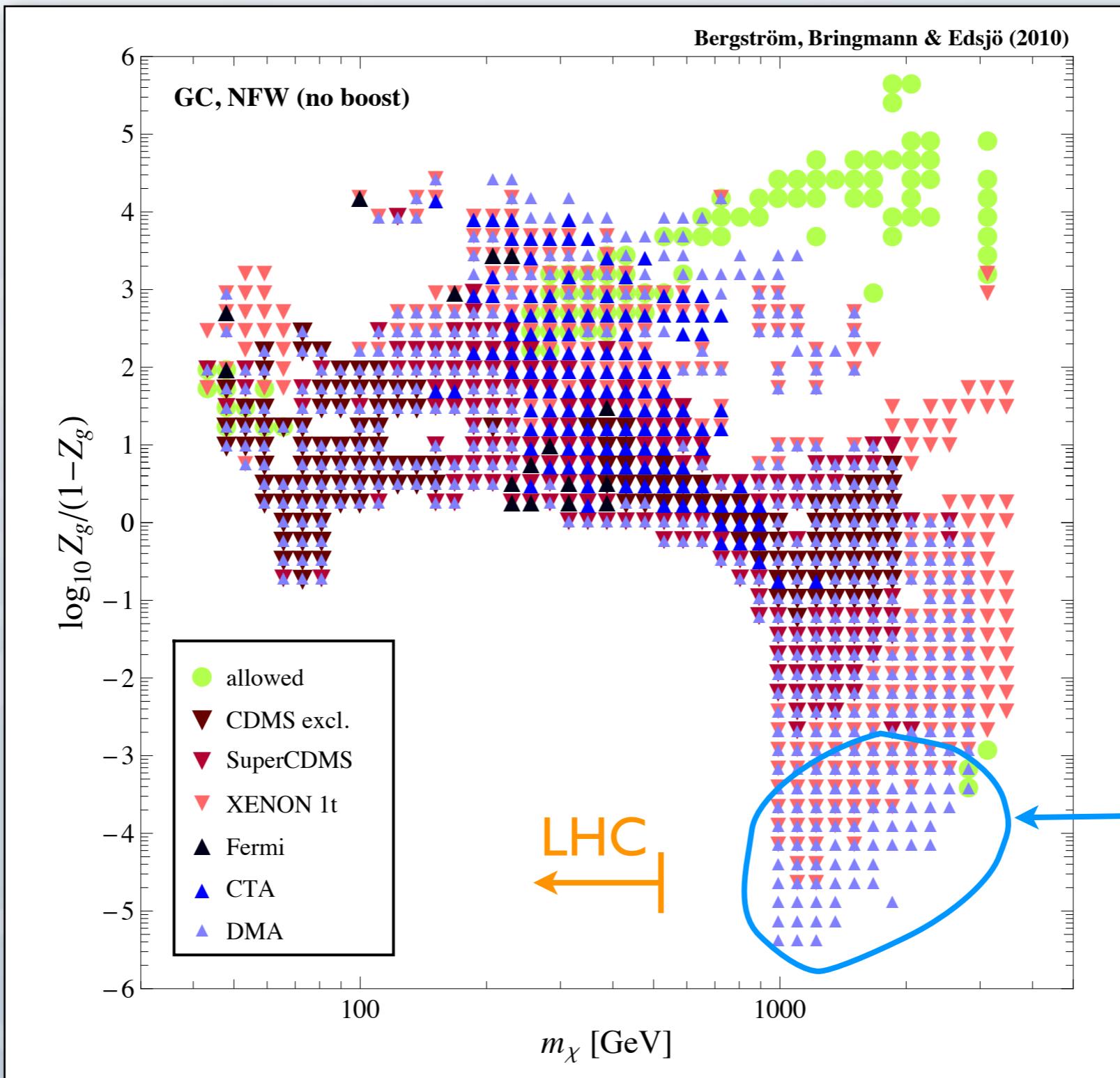


Another possibility which is more robust to astrophysical uncertainties is to look at dwarves instead.



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# Complementarity



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# DarkSUSY

- For any of these multi-channel searches, it is crucial to use consistent tools, like e.g. DarkSUSY (or micrOmegas), where all calculations can be performed with consistent particle physics and astrophysics assumptions.
- To download DarkSUSY:  
<http://www.physto.se/~edsjo/darksusy>



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# 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 or micrOmegas
- A dedicated Dark Matter Array (DMA) may prove useful to reach previously unreachable parts of the parameter space. Complementary to direct searches.

