Indirect Detection of Dark Matter: Status and Prospects

Lars Bergström
The Oskar Klein Centre for Cosmoparticle Physics
AlbaNova
Stockholm University
lbe@fysik.su.se

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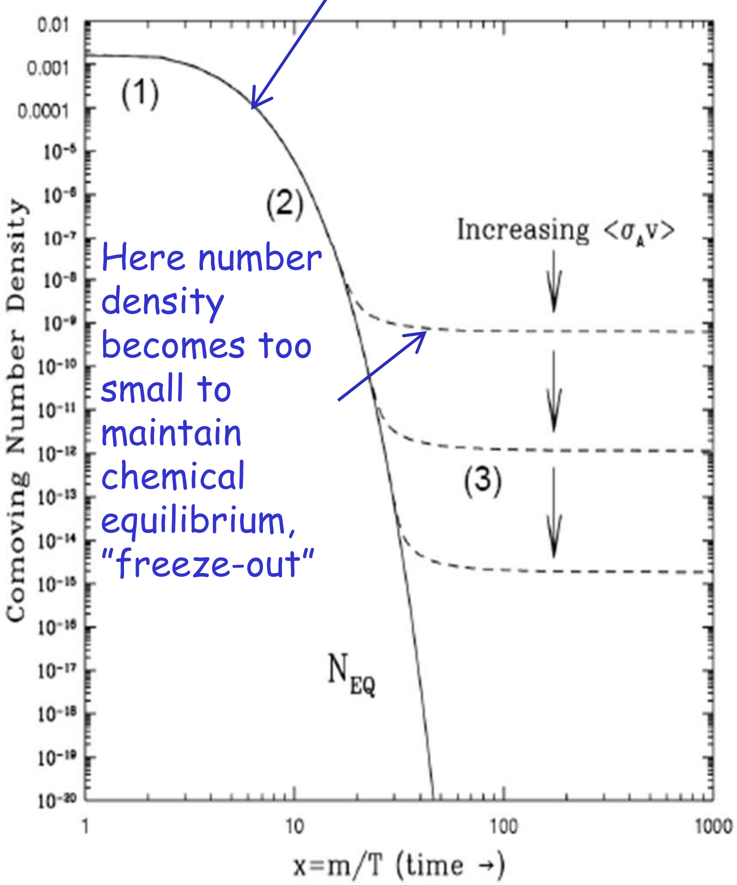
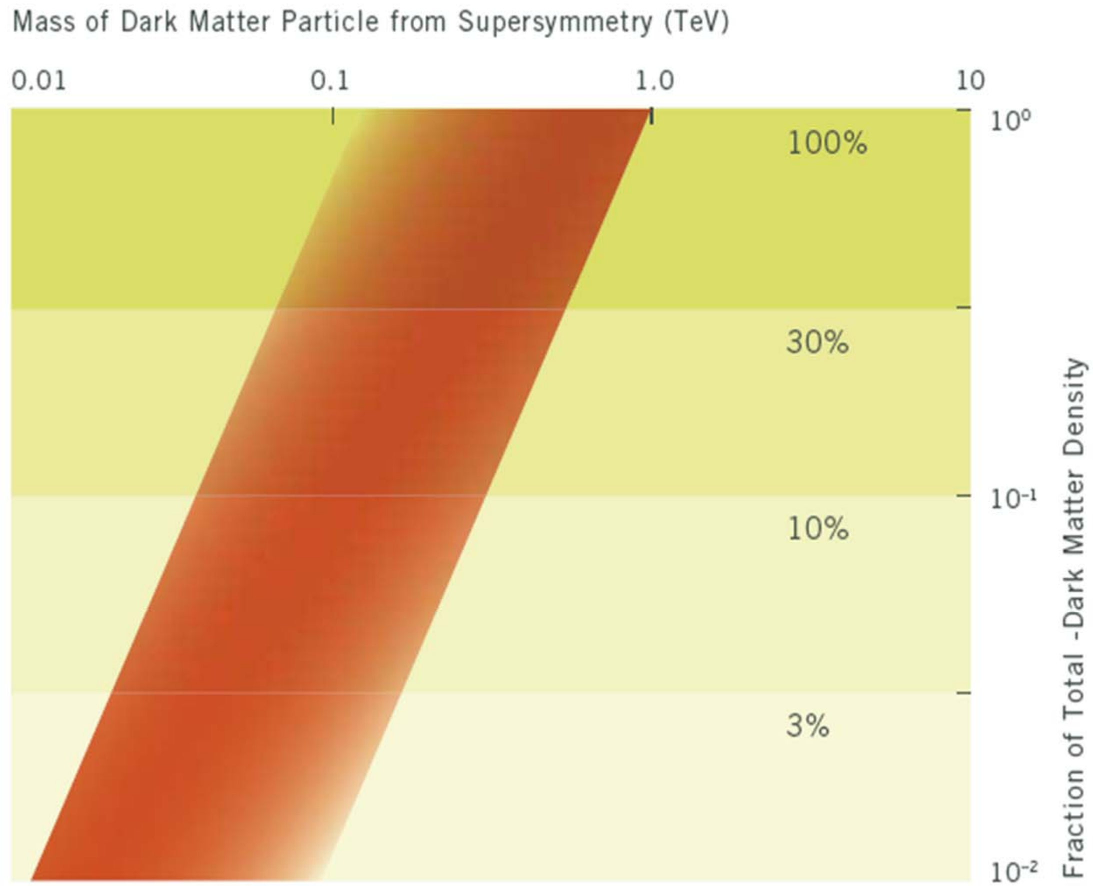
The "WIMP miracle": For electroweak weak gauge couplings and DM particle mass of the order of the electroweak mass scale, the relic density comes out as the WMAP measured one! Annihilation signals may then be detectable. (For decaying DM, see talk by Tran.)

Equilibirium curve in early universe



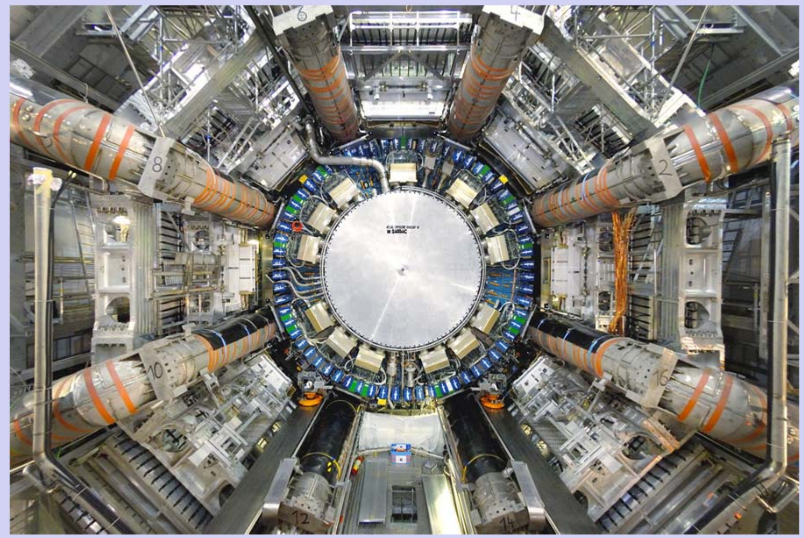
The mass range for SUSY WIMPs is roughly 10 GeV to a few TeV



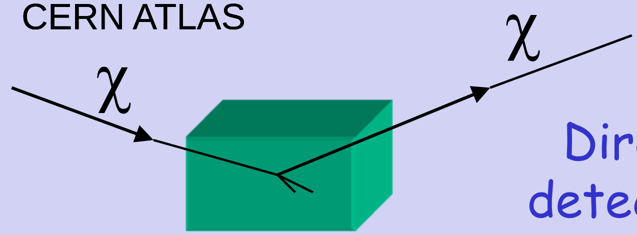
J. Feng & al, ILC report 2005

Methods of WIMP Dark Matter detection:

- Discovery at accelerators (Fermilab, LHC, ILC…).
- Direct detection of halo particles in terrestrial detectors.
- Indirect detection of neutrinos, gamma rays & other e.m. waves, antiprotons, antideuterons, positrons in ground- or space-based experiments.
- For a convincing determination of the identity of dark matter, plausibly need detection by at least two different methods.



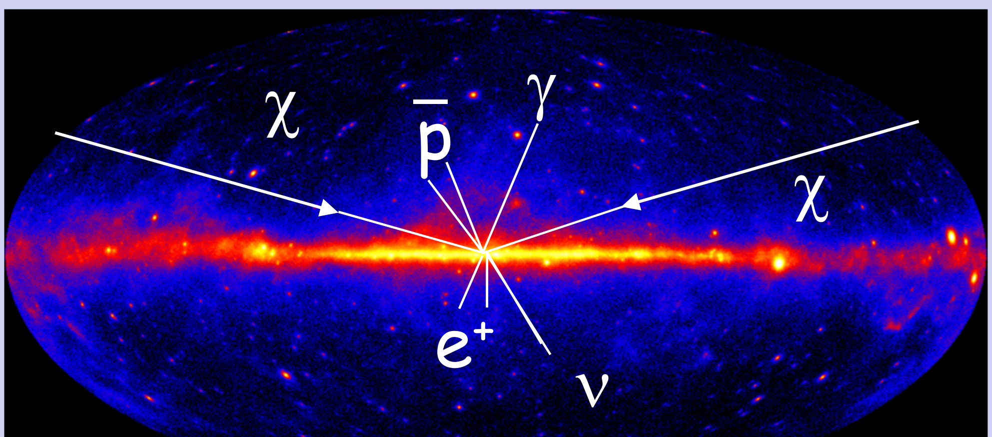
CERN ATLAS



Direct detection

$$\frac{d\sigma_{si}}{dq} = \frac{1}{\pi v^2}\left(Zf_p + (A-Z)f_n\right)^2 F_A(q) \propto A^2$$

Indirect detection



The Milky Way in gamma-rays as measured by FERMI

$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$

Annihilation rate enhanced for clumpy halo; near galactic centre and in subhalos

Compute everything with:

Dark SUSY

Tool for computing cosmological relic density, masses, branching ratios, direct and indirect detection cross sections for general WIMPs, especially – but not only - supersymmetric ones:

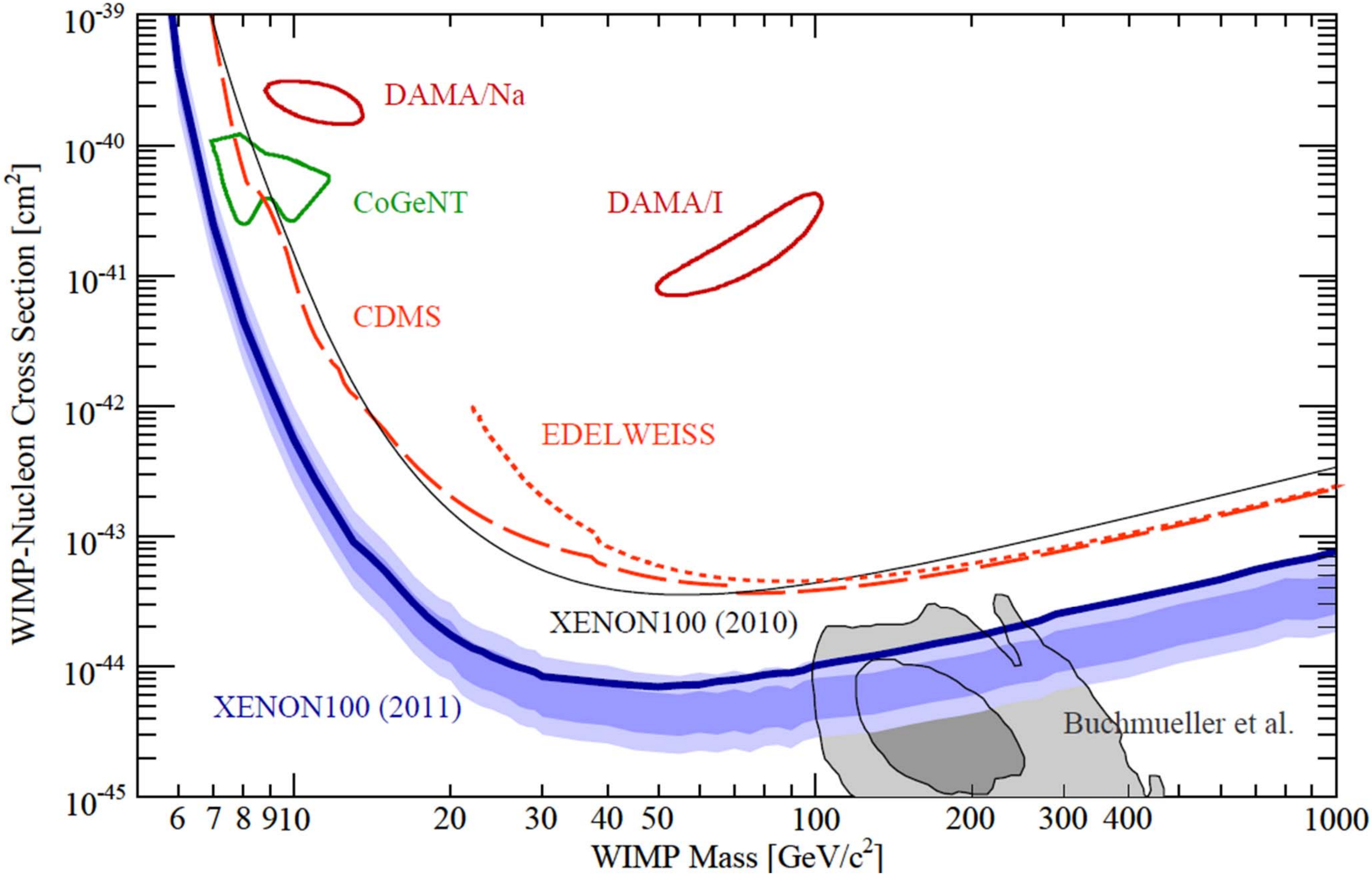
P. Gondolo, J. Edsjö, L.B., P. Ullio, Mia Schelke and E. A. Baltz, JCAP 2004 (with important additions by T. Bringmann and G. Dudas)

Other publicly available program: micrOMEGAs (G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, arXiv:0803.2360)

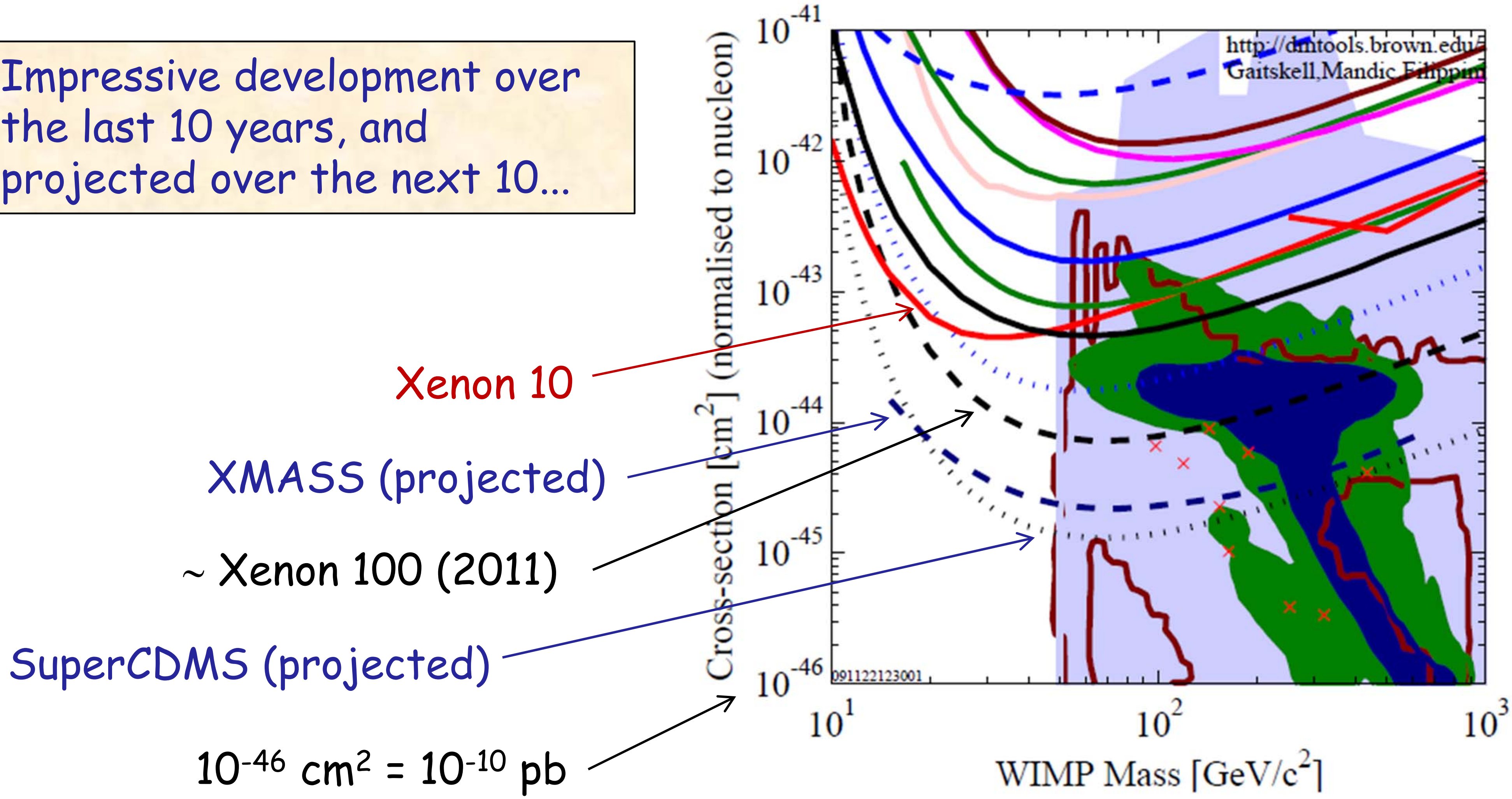
Nature need not be supersymmetric! But the neutralino – the lightest supersymmetric particle in R-parity conserving theories – has become a very useful template for a WIMP Dark Matter candidate. If an experiment is sensitive to SUSY DM, it automatically also can search for other WIMPs.

Direct detection of Dark Matter

Direct detection limits, steady progress. Xenon100 new data, April, 2011:

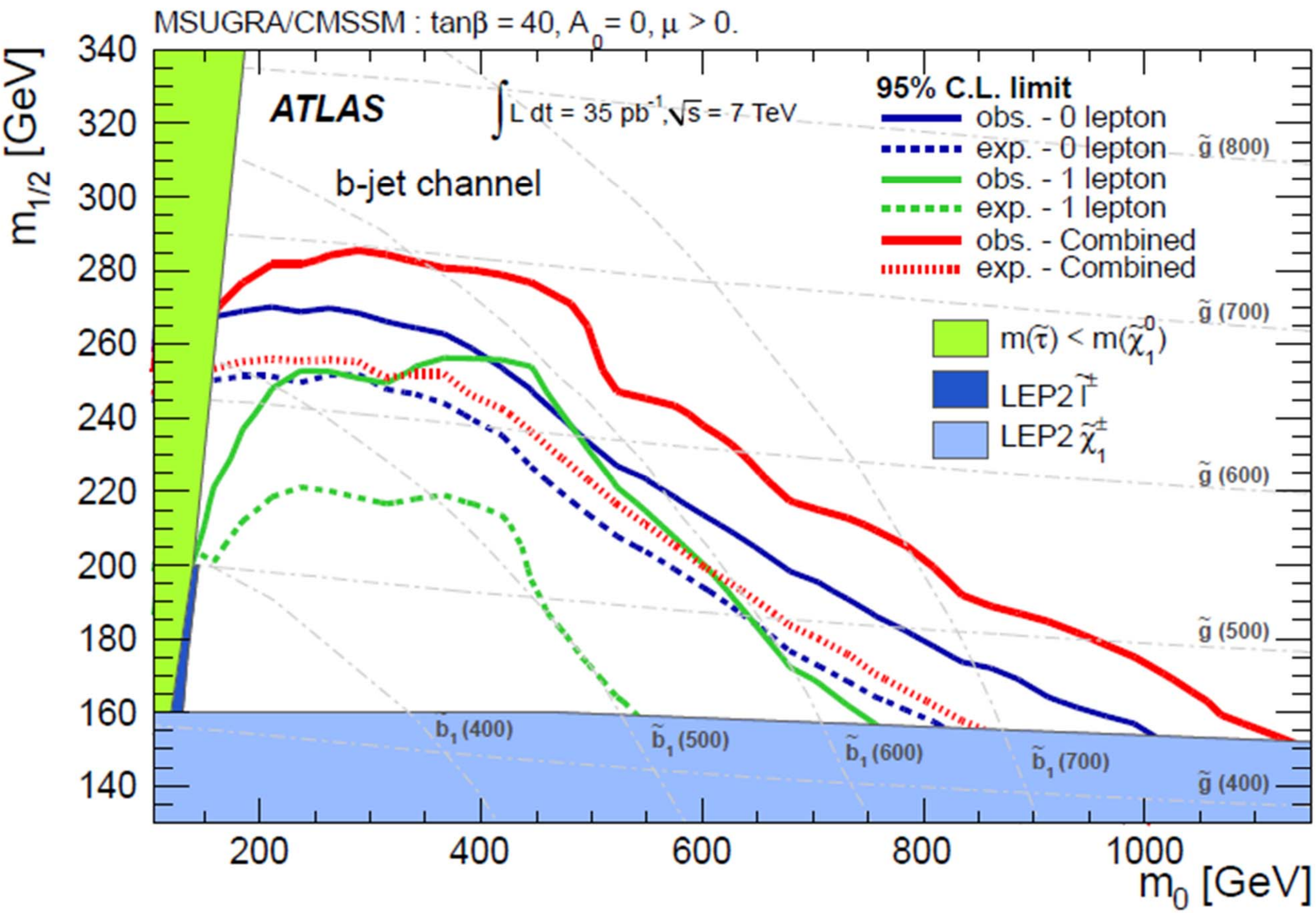


Impressive development over the last 10 years, and projected over the next 10...



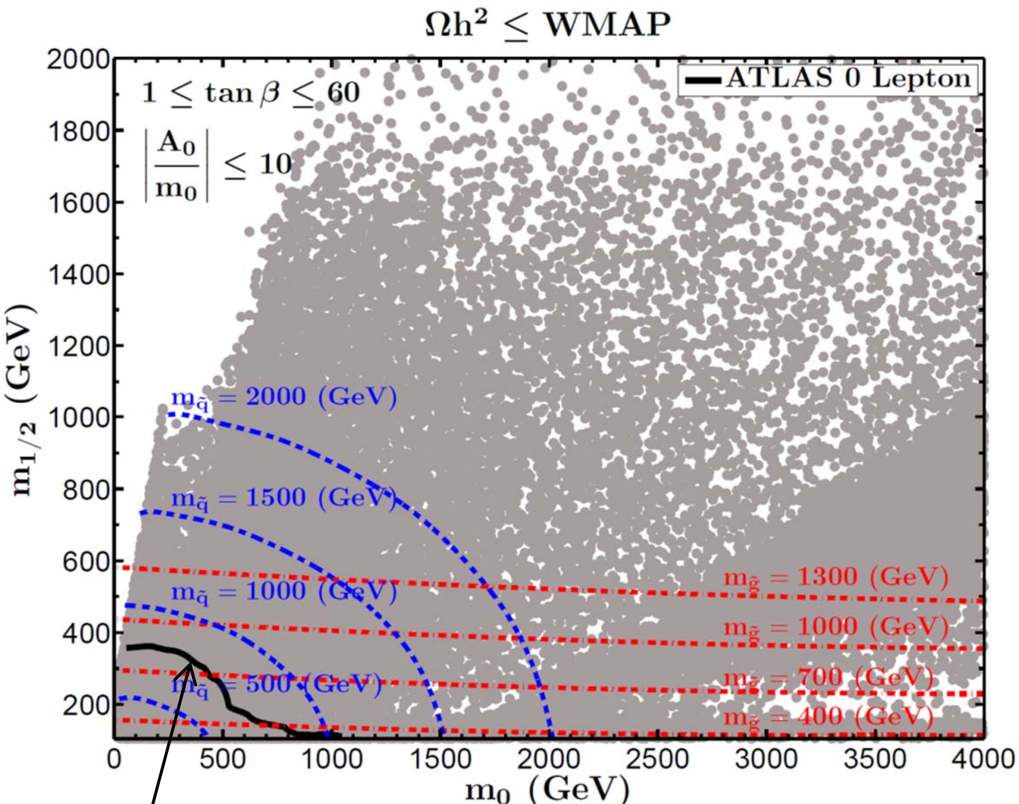
10^{-46} cm² = 10^{-10} pb

Detection of Dark Matter candidates at accelerators

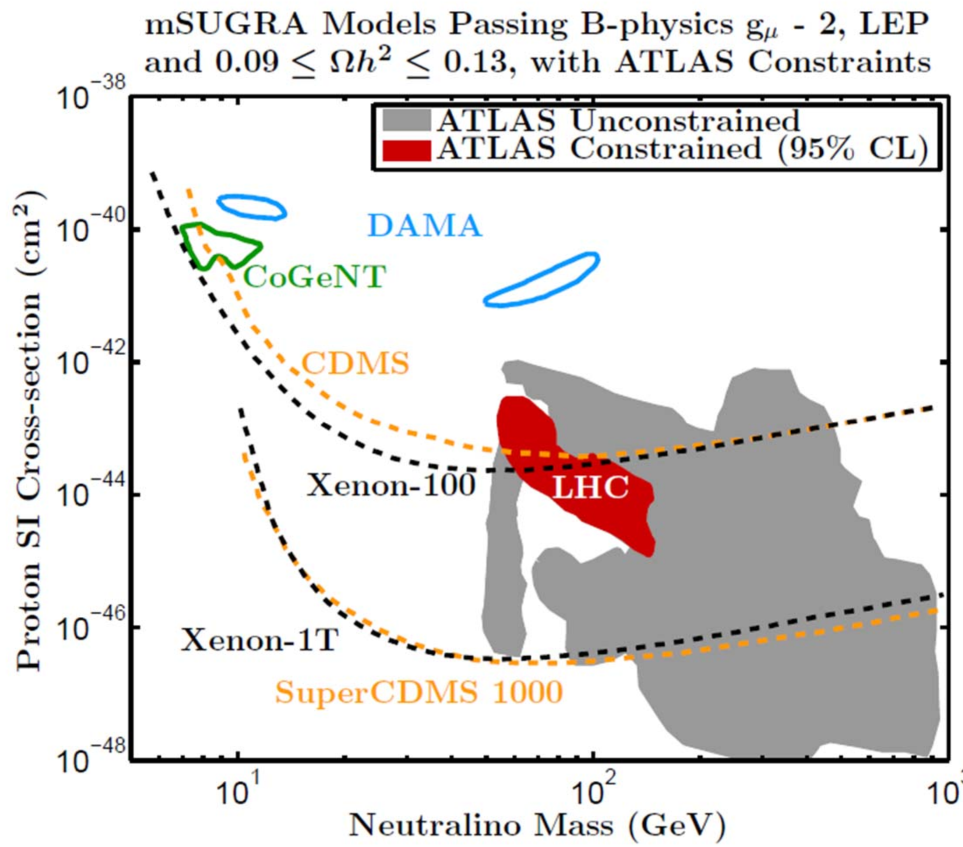


Results from CERN's ATLAS experiment, March 2011: No signs of supersymmetry yet

Should we be worried that SUSY is not yet seen at LHC?



arXiv:1103.1197



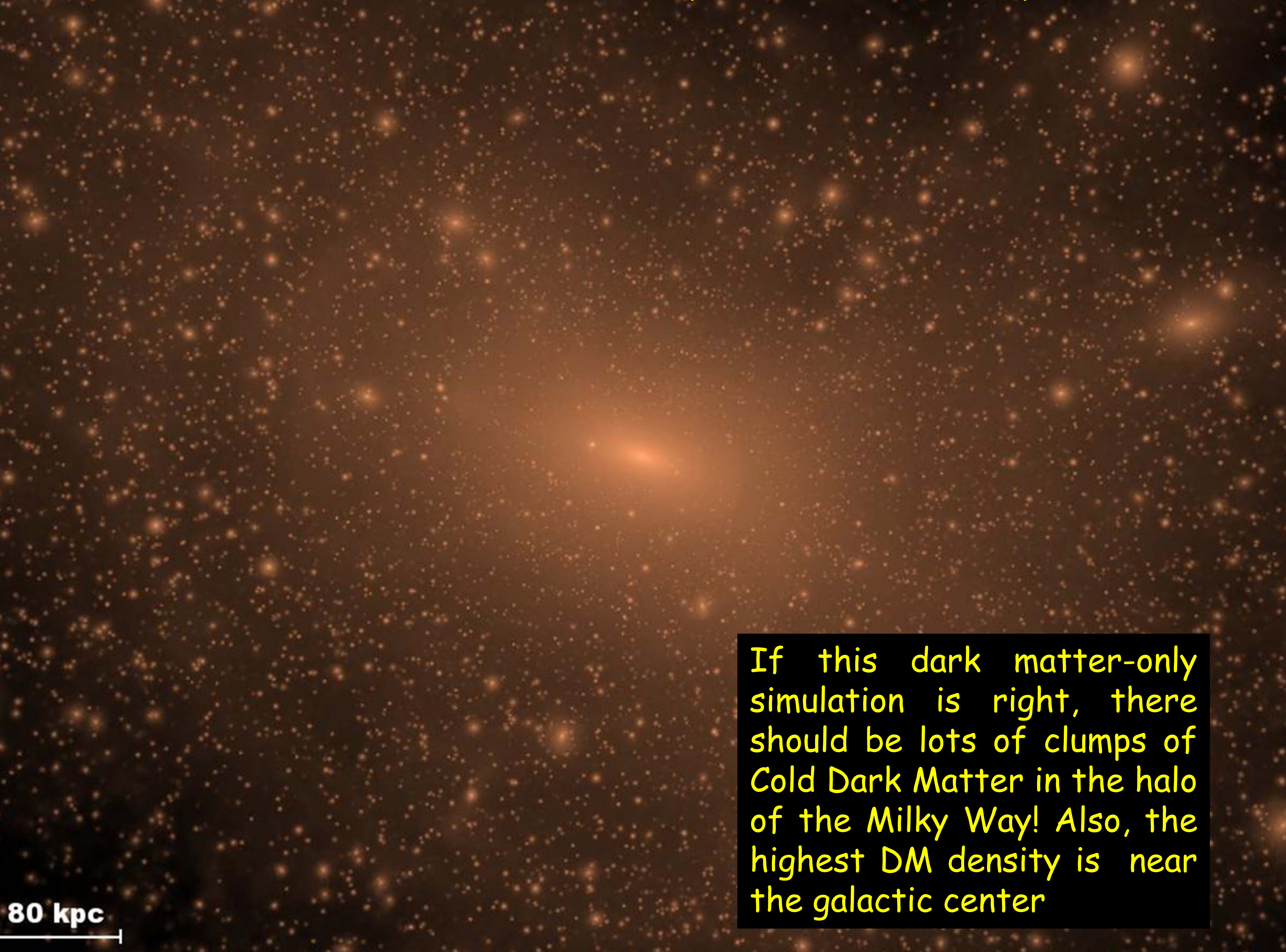
arXiv:1103.5031

Excluded by ATLAS

S. Akula & al., March 2011: Going from mSUGRA to Non-universal SUGRA, the small region probed at LHC is repopulated with models. In the general MSSM only a tiny portion of parameter space is touched (see later).

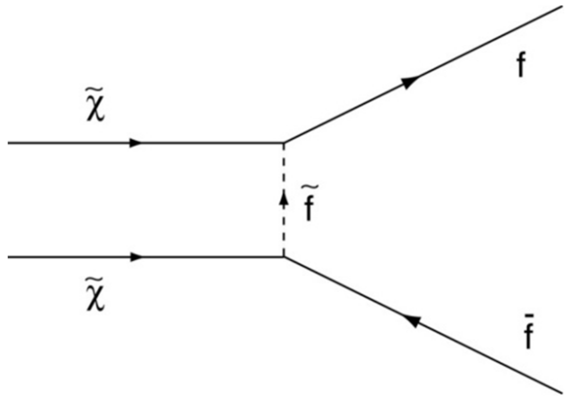
Indirect detection of Dark Matter

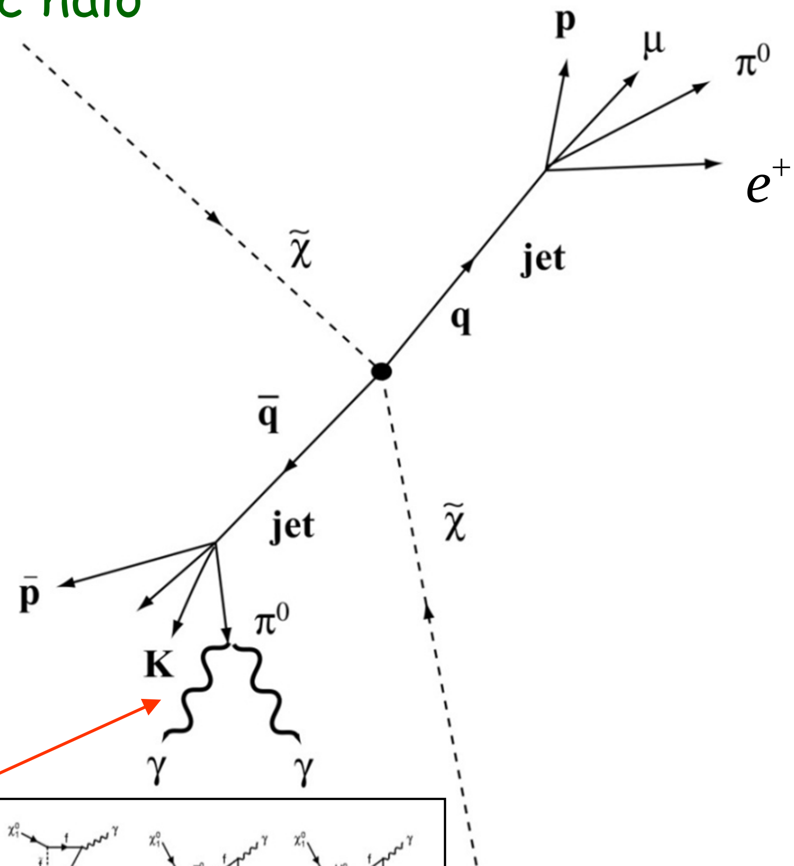
Via Lactea II CDM simulation (J. Diemand & al, 2008)



If this dark matter-only simulation is right, there should be lots of clumps of Cold Dark Matter in the halo of the Milky Way! Also, the highest DM density is near the galactic center

Example of indirect detection: annihilation of neutralinos in the galactic halo

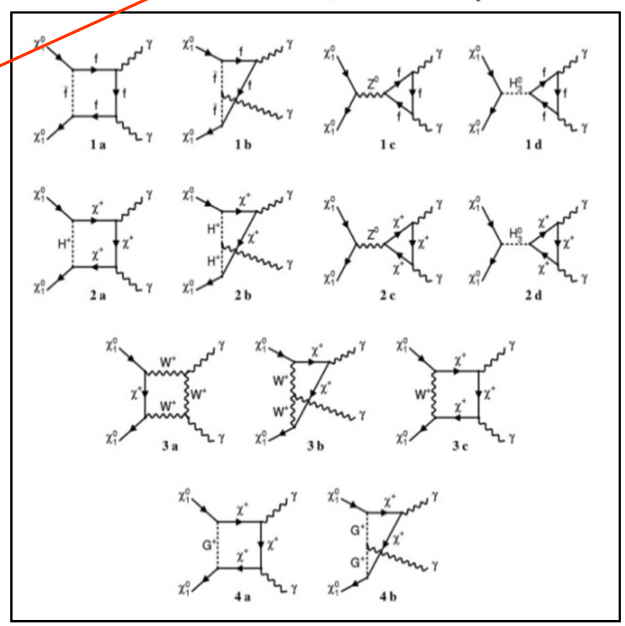




Majorana particles: helicity factor for fermions $\sigma v \sim m_f^2$

Note: equal amounts of matter and antimatter in annihilations

Decays from neutral pions, kaons etc give continuum: DarkSUSY uses PYTHIA.



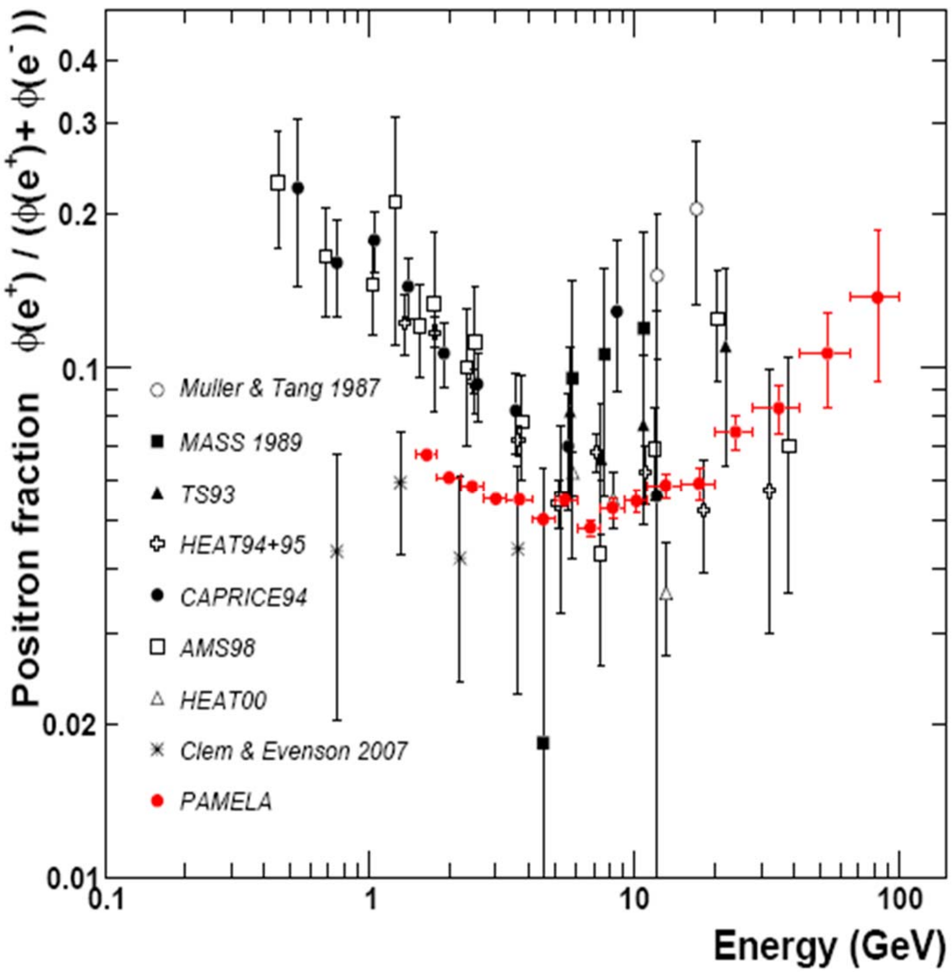
One-loop effect: 2γ or $Z\gamma$ final state gives narrow lines. Decaying DM may also give such a "smoking gun" signal

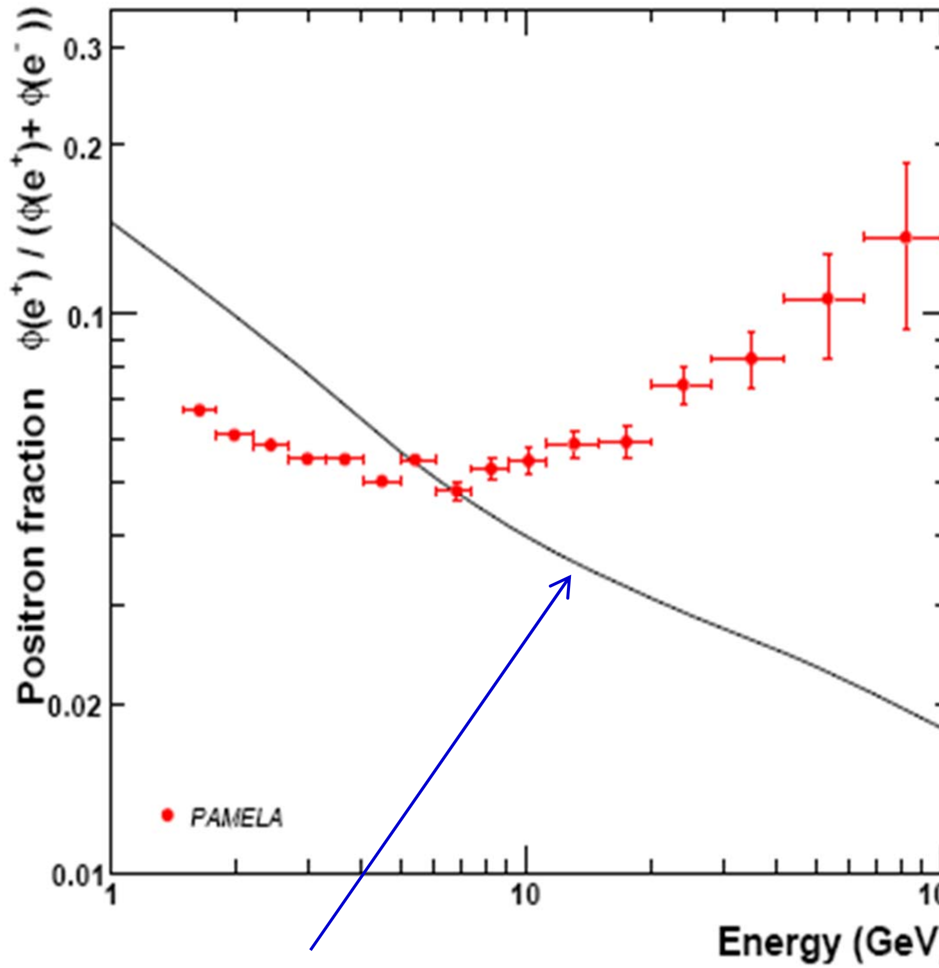
Final state radiation may have important effects

Antimatter from Dark Matter annihilations

The surprising PAMELA data on the positron ratio up to 100 GeV. (O. Adriani et al., Nature, 2009)

A very important result - an additional, primary source of positrons seems to be needed.

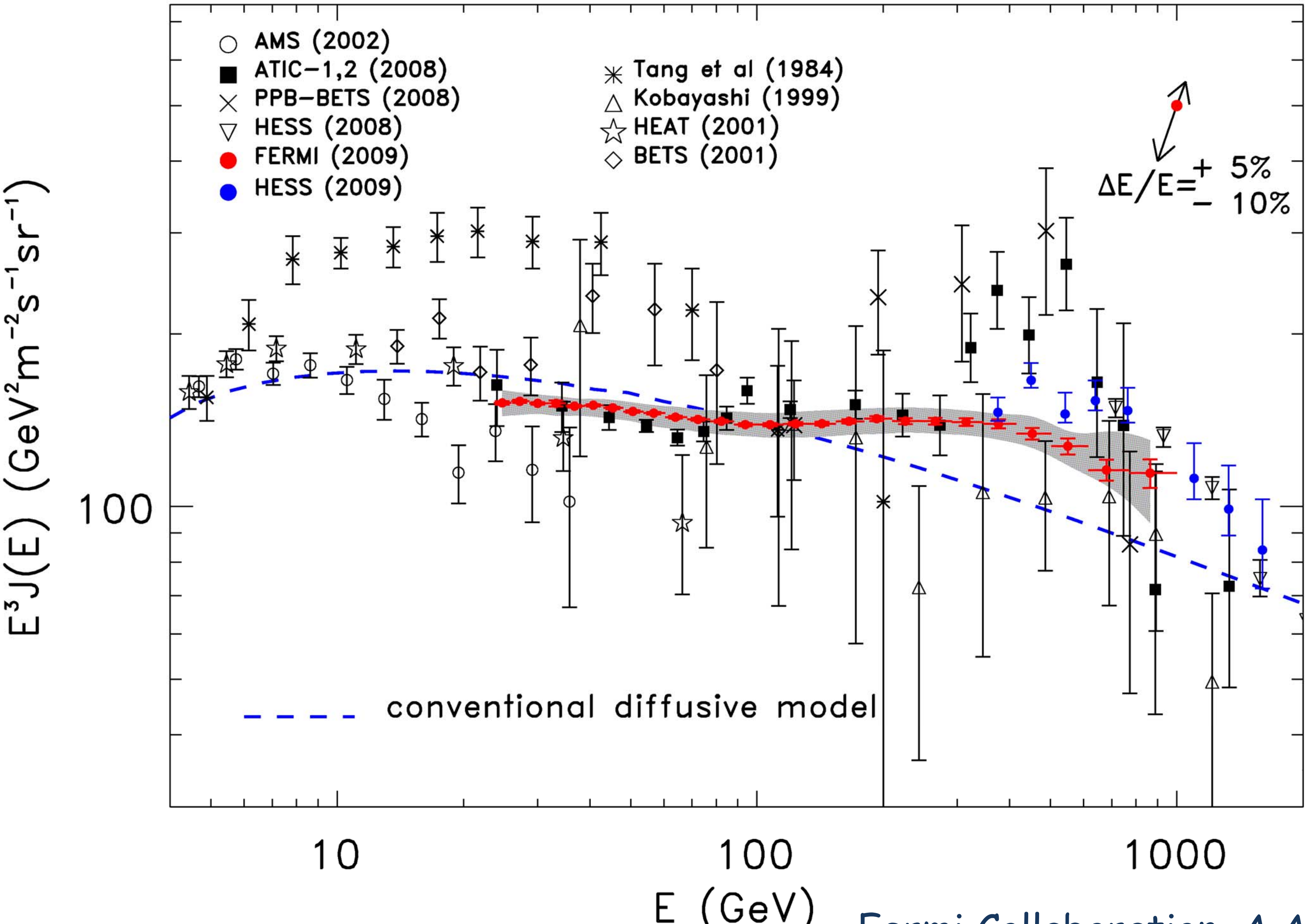




Prediction from secondary production by cosmic rays: Moskalenko & Strong, 1998 (cf also R. Trotta & al., arXiv:1011.0037)

A surprise also from FERMI

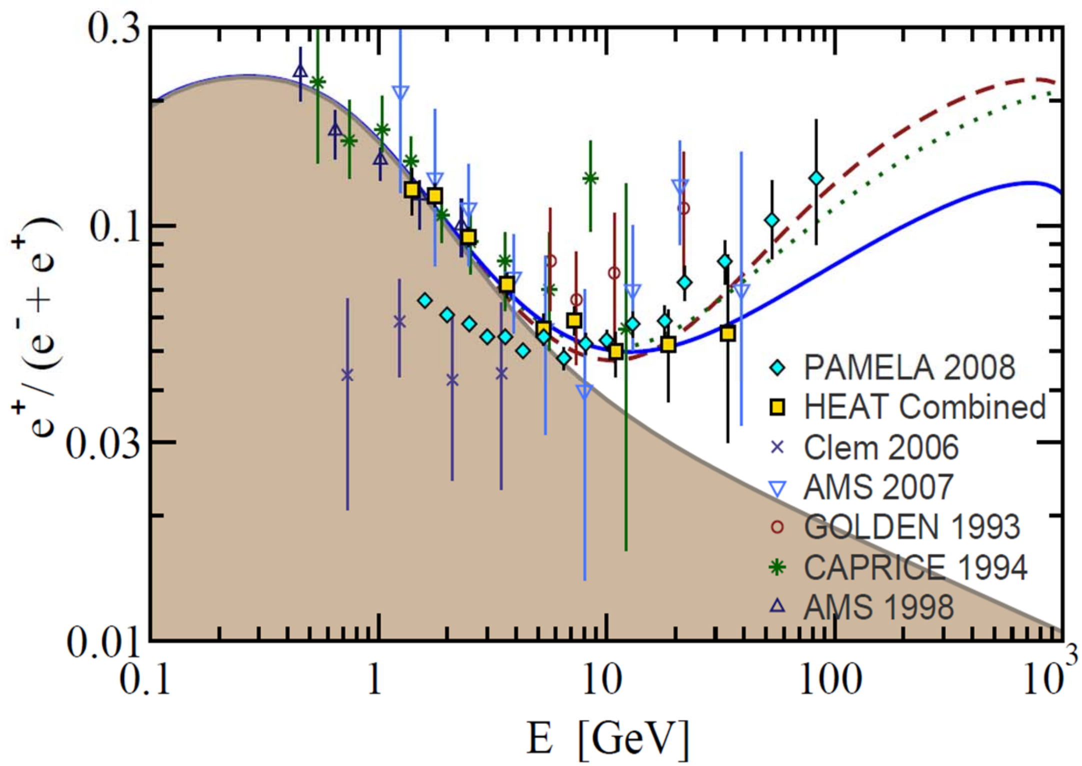
Sum of electron and positron flux versus energy:



Fermi Collaboration, A.A. Abdo & al, Phys. Rev. Lett., May, 2009

New modeling is needed. Two main possibilities:
1. Pulsars (or other supernova remnants)
2. Dark Matter

1. Positrons generated by a class of extreme objects: supernova remnants (pulsars), example:



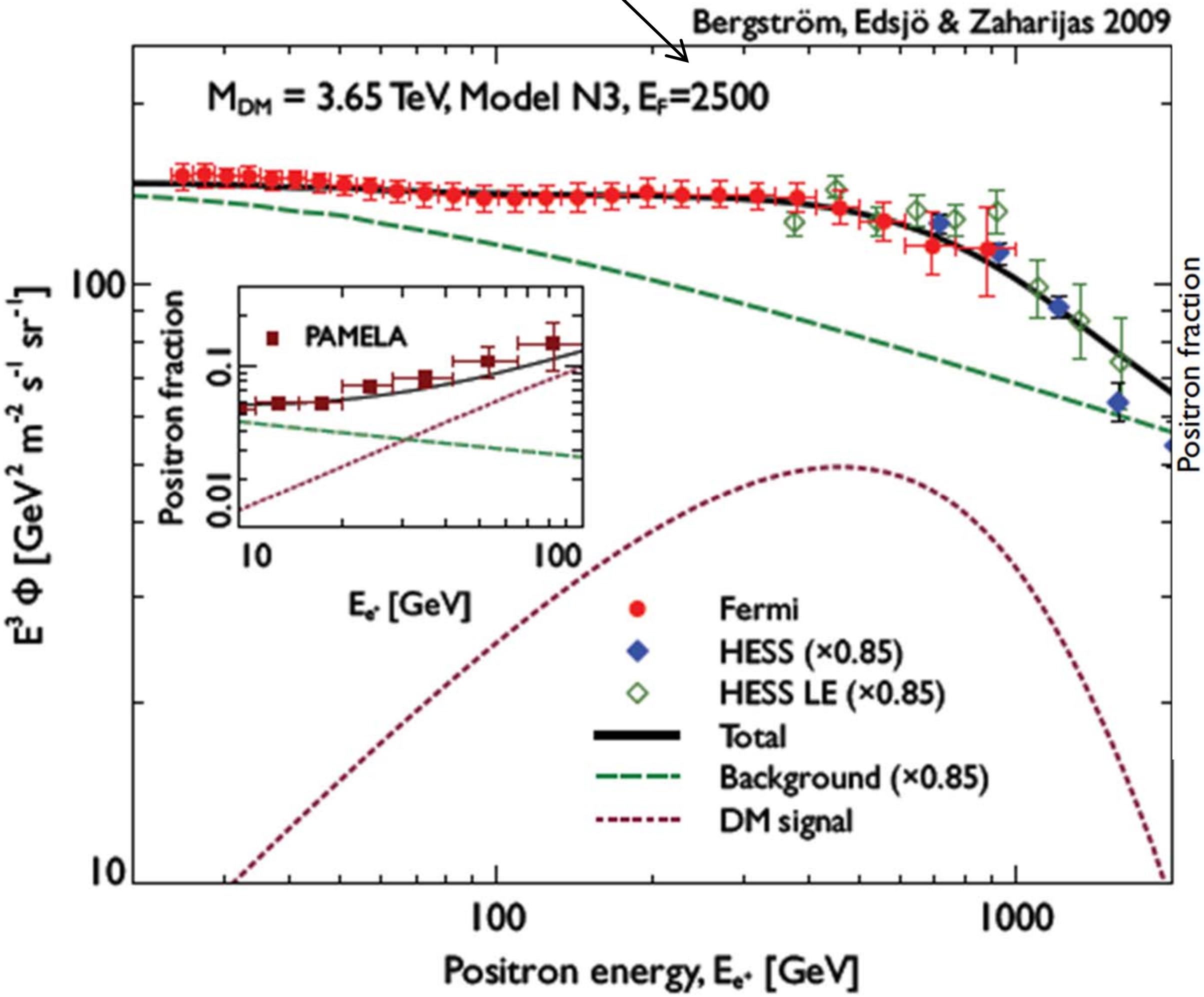
Geminga pulsar estimates

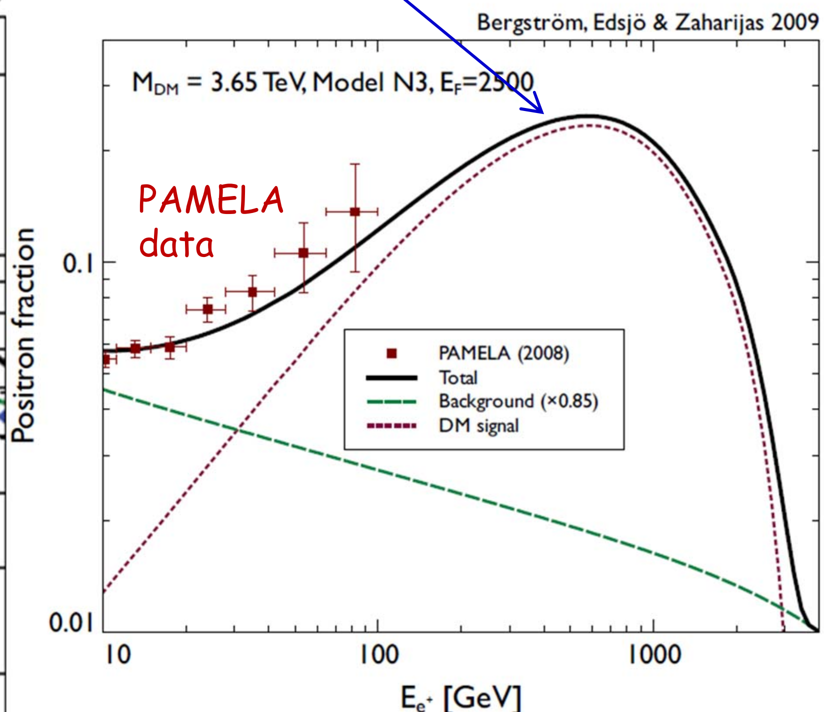
H. Yuksel, M. Kistler, T. Stanev, 2009

2. Dark Matter fit, example

Huge boost factor needed. Sommerfeld enhancement? See next talk, by T. Slatyer, and for gamma-ray tests, talk by G. Zaharijas

The energy dependence will be checked by AMS-2 (to be launched to the International Space Station next week - April 29, 2011)

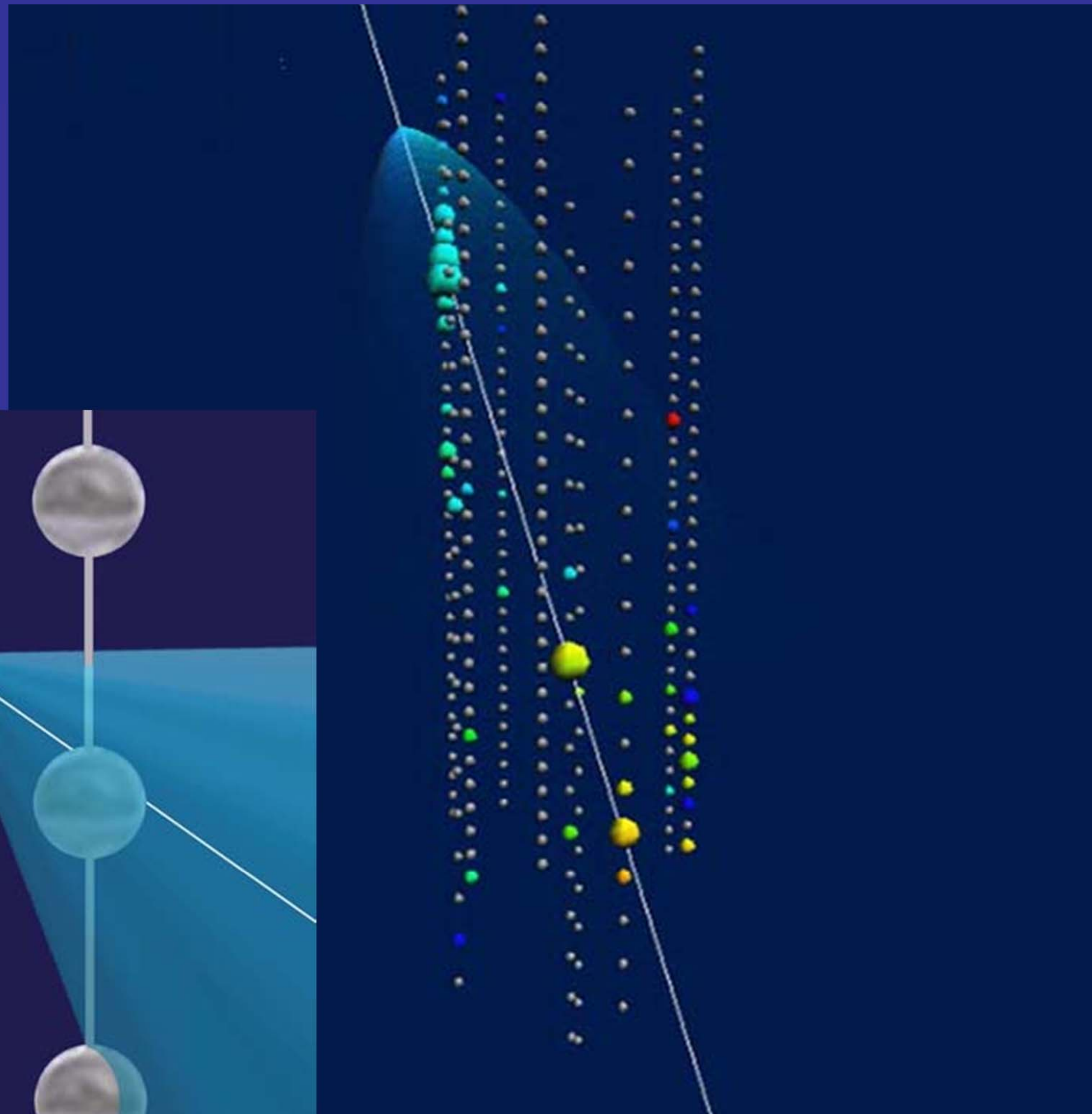


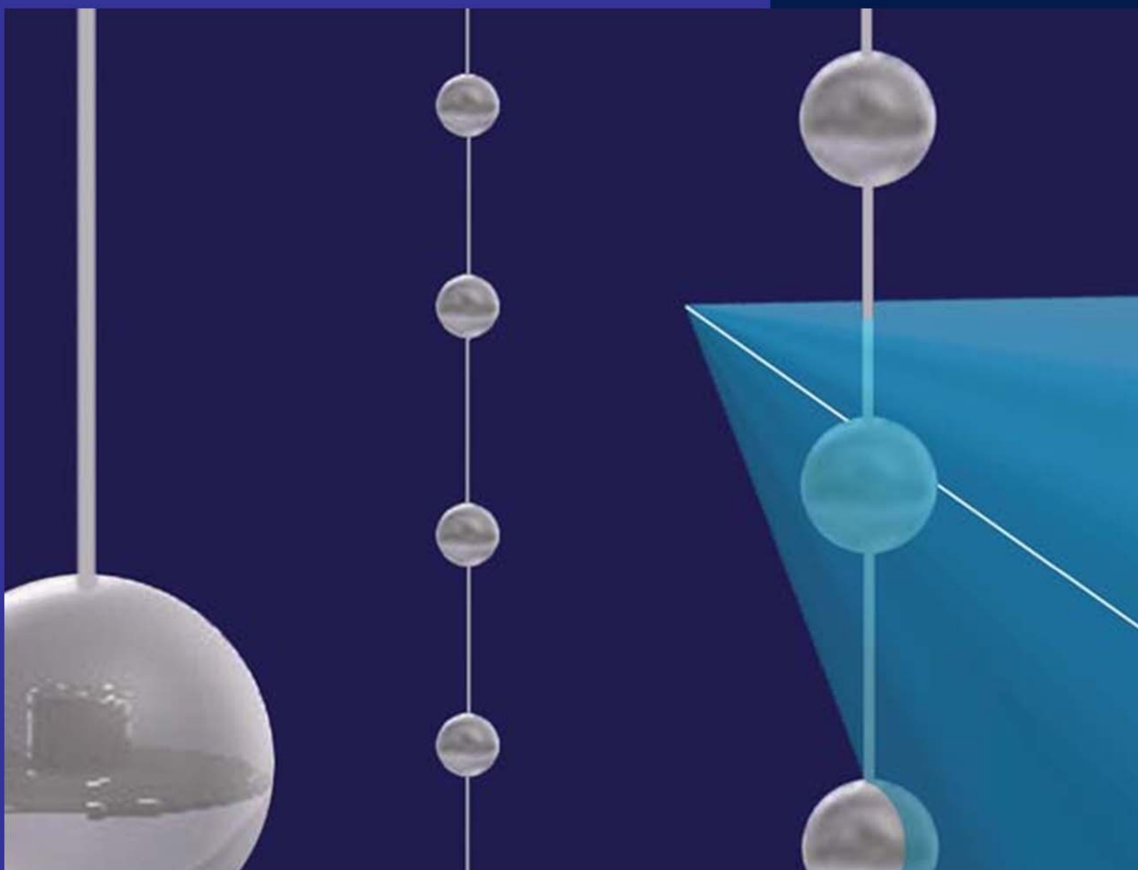


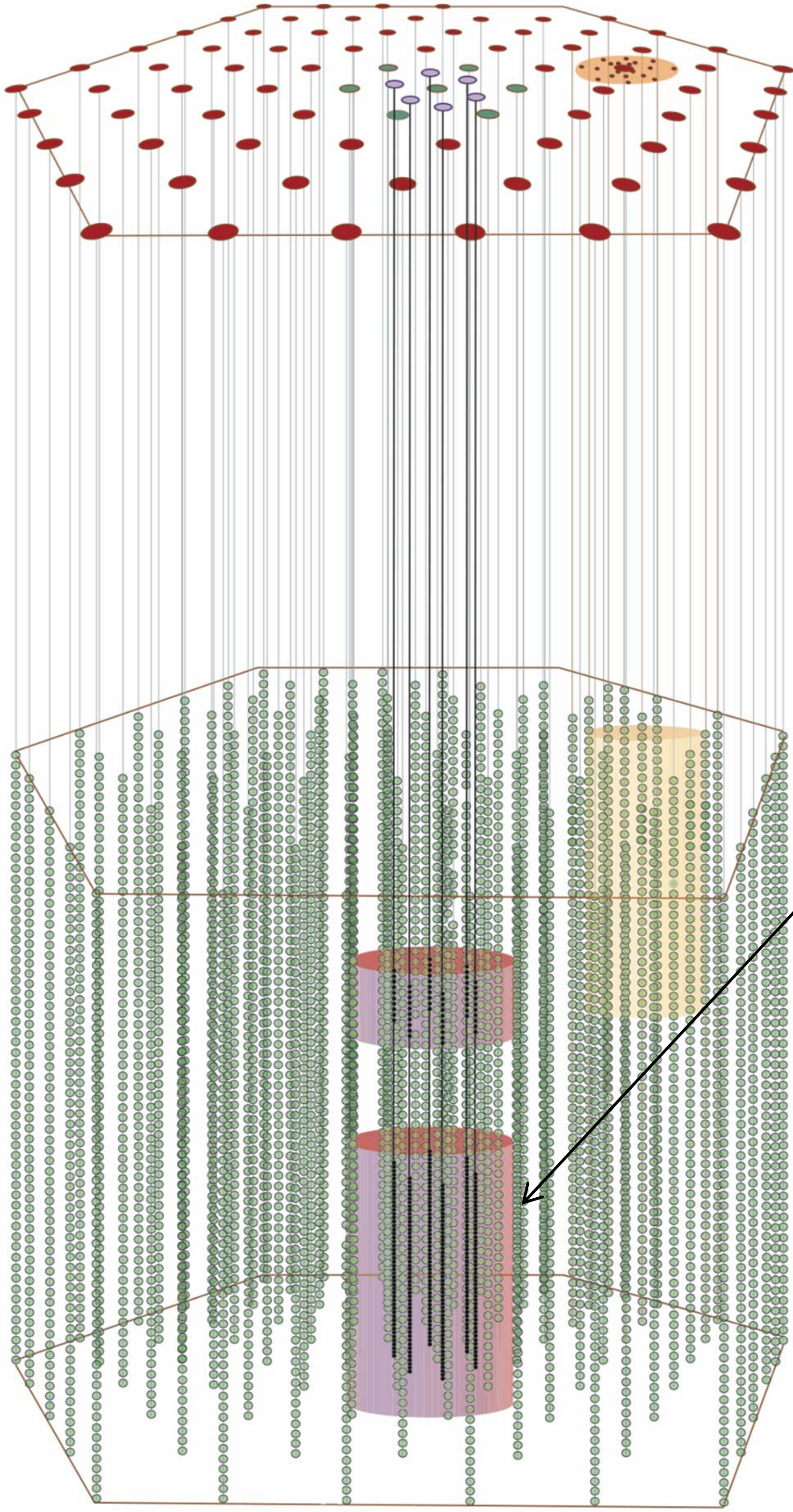
L.B., J. Edsjö and G. Zaharijas, PRL 2009.

Neutrinos from Dark Matter annihilations

IceCube: the under-ice detector at the South Pole.
Construction was completed January 2011!





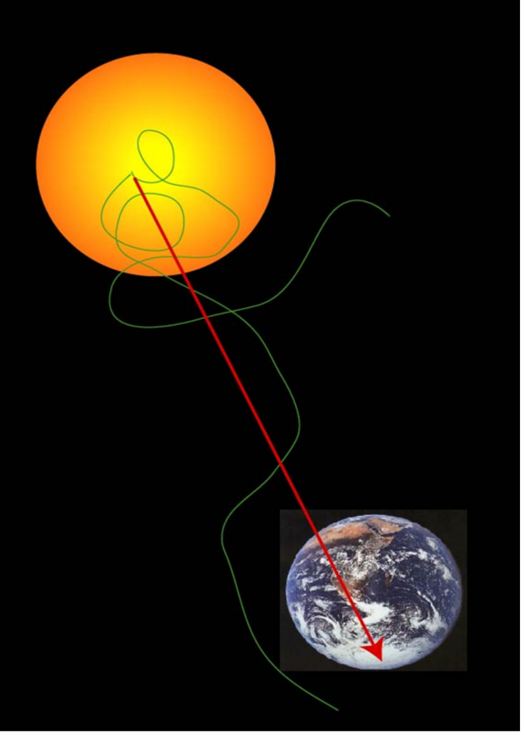


IceCube: The Neutrino Telescope at the South Pole

New project within IceCube (initiated and to a large part funded from Sweden): IceCube Deep Core

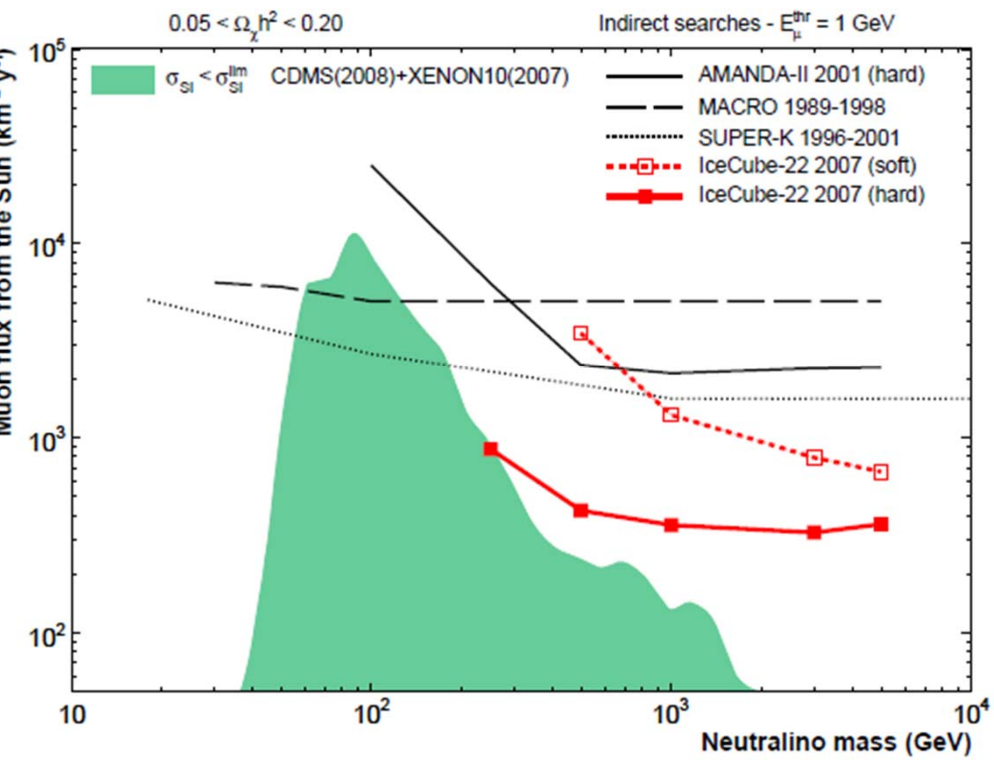
Was deployed at the South Pole 2009/2010

A further expansion of Deep Core is presently being discussed

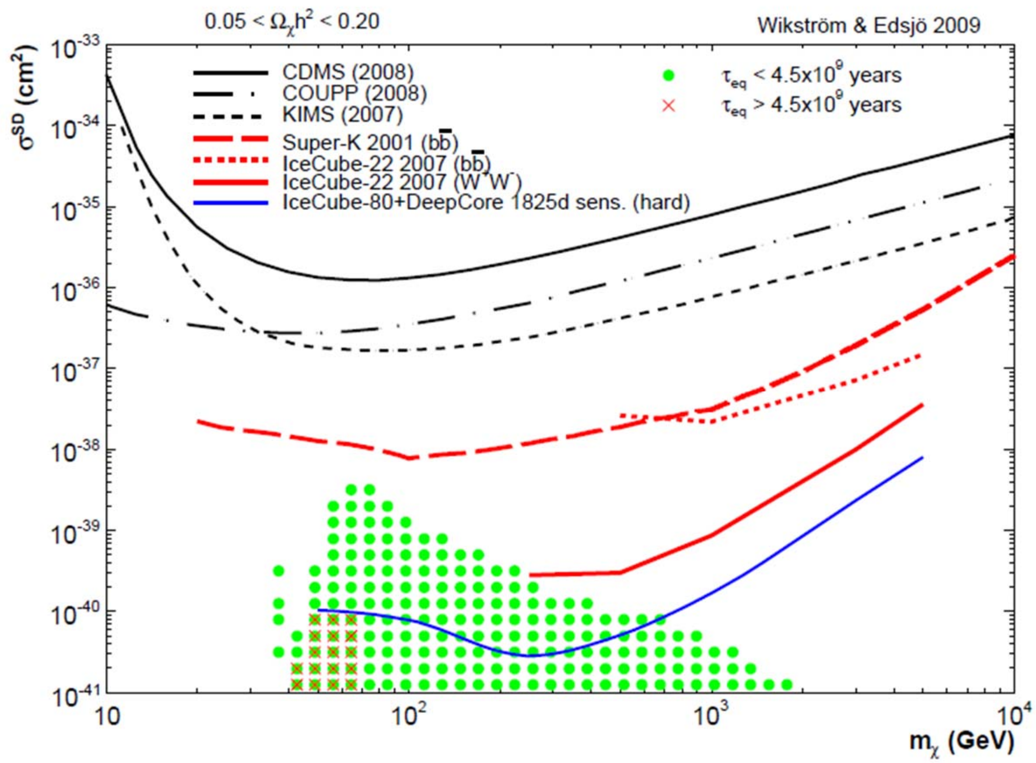


Neutrinos from DM annihilation in the Sun, IceCube-22 limits (2009) on spin dependent interactions – are just about starting to touch the interesting region in parameter space.

Neutrinos from the centre of the Earth are sensitive to spin-independent cross section and cannot compete with direct detection.



IceCube Collaboration, R. Abbasi et al., PRD 2010.



G. Wikström and J. Edsjö, JCAP 2009.

γ-rays from Dark Matter annihilations

One major uncertainty for indirect detection, especially of gamma-rays: The halo dark matter density distribution at small scales is virtually unknown. Gamma-ray rates towards the Galactic Center may vary by factor of 1000 or more. However, much less sensitivity (about a factor 2 – 10) for objects (such as dwarf galaxies) contained in the angular resolution cone.

Fits to N-body simulations

$$\rho_{\rm Einasto}(r) = \rho_s e^{\left(-\frac{2}{\alpha}\left[\left(\frac{r}{a}\right)^{\alpha} - 1\right]\right)}, \quad \alpha \approx 0.17$$

$$\rho_{\rm NFW}(r) = \frac{c}{r(a+r)^2};$$

Fits to rotation curves

$$\rho_{\rm Burkert}(r) = \frac{c}{(r+a)(a^2+r^2)};$$

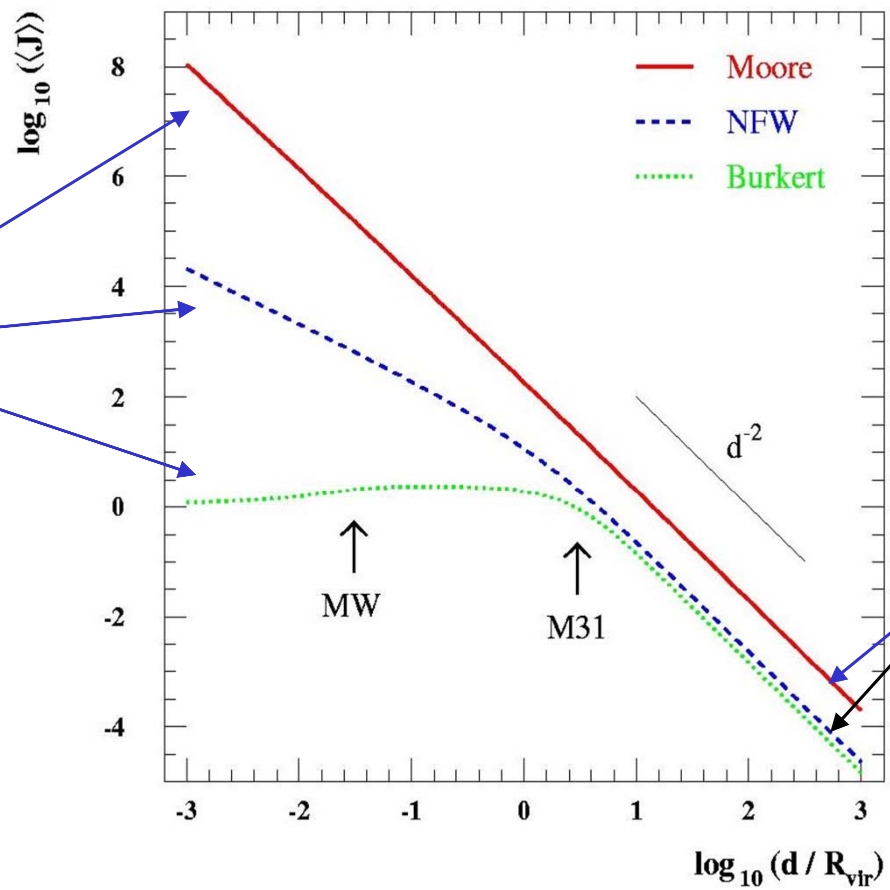
$$\rho_{\rm Isothermal}(r) = \frac{c}{a^2+r^2};$$

At the solar position, the local density is around 0.39 ± 0.03 GeV/cm^3 (R. Catena & P. Ullio, 2010)

DM Indirect Detection rate = (Particle)×(Astro) $\bar{J}(\hat{n};\Delta\Omega) \equiv \frac{1}{\Delta\Omega}\int d\Omega \int \frac{dl}{(8.5\,kpc)}\left(\frac{\rho(\vec{r})}{0.3\,GeV/cm^3}\right)^2$

~ <σv> ~ J

Note large uncertainty of flux for nearby objects (Milky Way center, LMC)



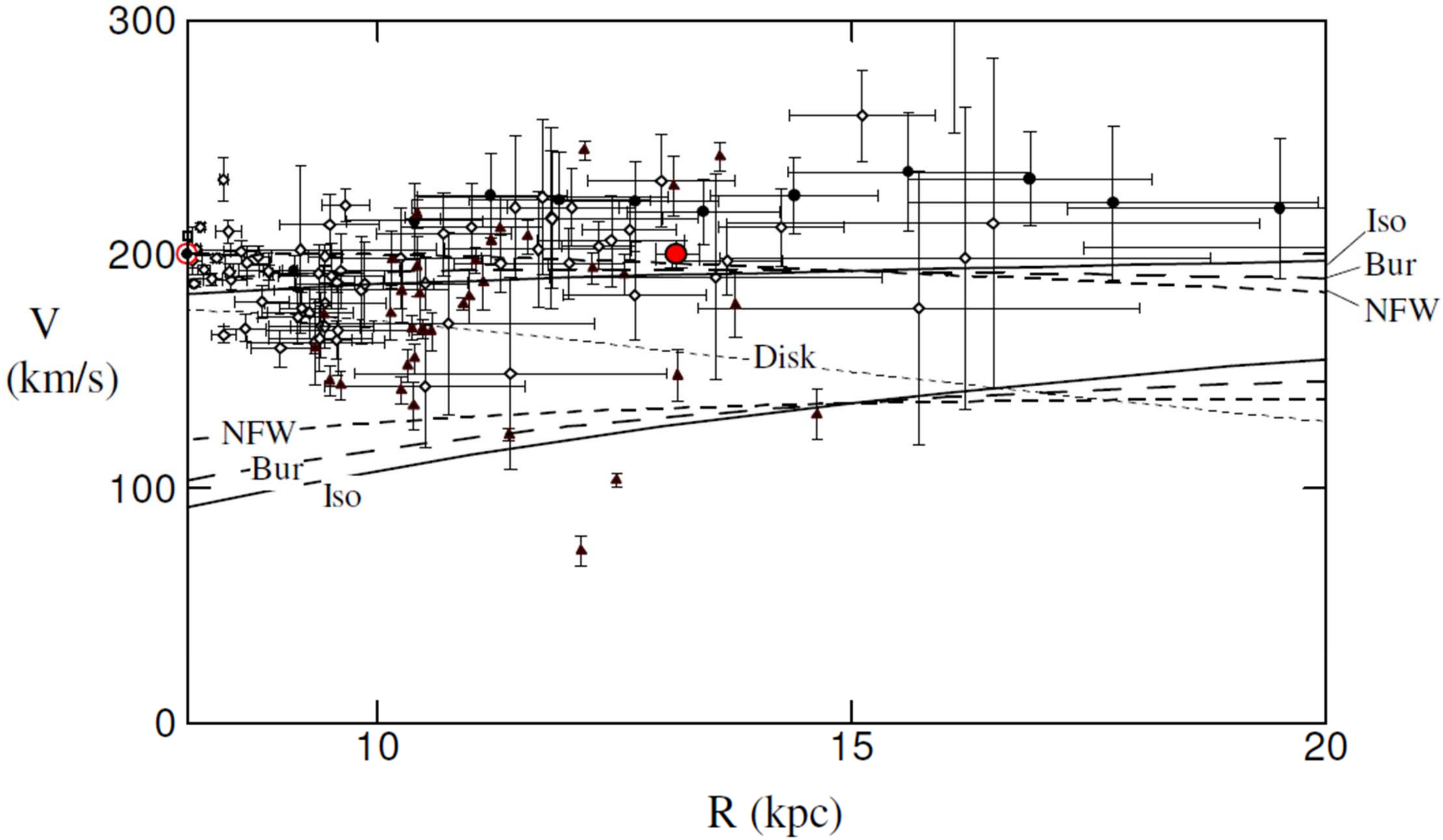
In this region (for cosmological distances), the uncertainty is much smaller

P. Ullio, L.B., J. Edsjö, 2002

FIG. 4: Scaling of the collected γ-ray flux with the distance d between the detector and the center of a halo, for three different halo profiles. The angular acceptance of the detector is assumed to be $\Delta\Omega = 10^{-3}$sr. The plot is for a $10^{12} M_\odot$ halo, the arrows indicate the position on the horizontal axis for the Milky Way and Andromeda; the case for other masses is analogous.

Can't we determine right halo model from MW rotation curve?

No, unfortunately not:



Y. Sofue, M. Honma & T. Omodaka, 2008

Effects of MW halo substructure

V. Springel et al., Nature, 2008 (Aquarius project)

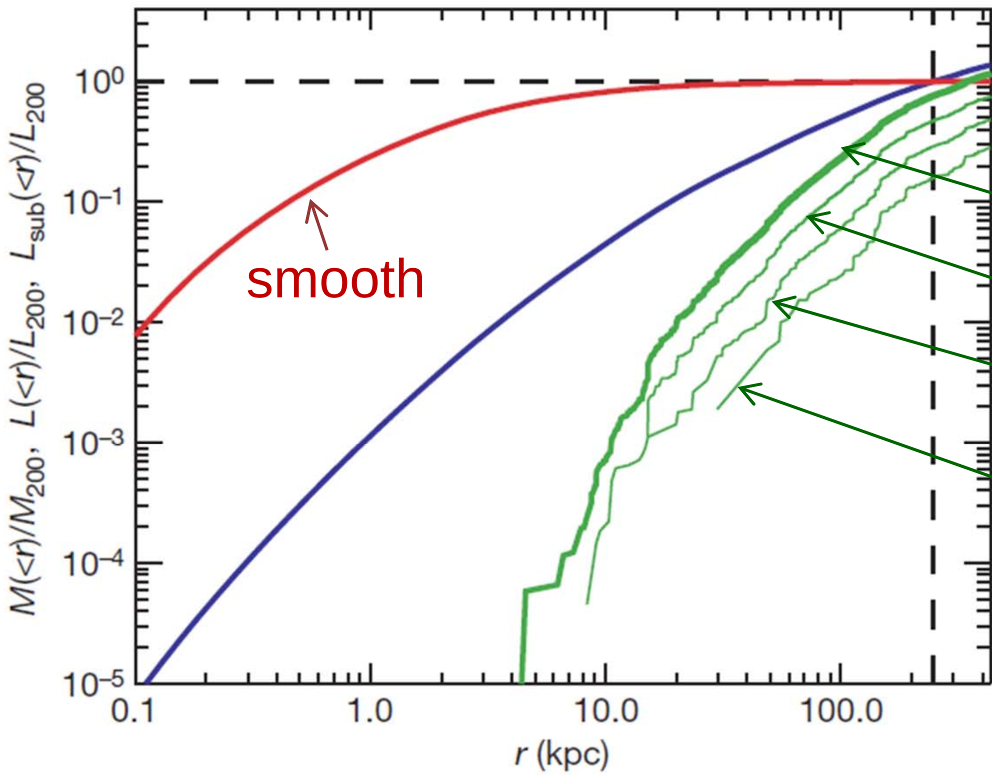


Figure 3 | Radial dependence of the enclosed mass and annihilation luminosity of various halo components. The blue line gives enclosed dark

Contribution from DM clumps depends on the low-mass cutoff of the simulation. So far, only down to 10^5 solar masses:

$M_{min} = 10^5\ M_{Sun}$

$M_{min} = 10^6\ M_{Sun}$

$M_{min} = 10^7\ M_{Sun}$

$M_{min} = 10^8\ M_{Sun}$

Extrapolation of the behaviour to the smallest scales for Cold Dark Matter, at least down to $10^{-6}\ M_{sun}$, gives a "boost factor" of over 200 compared to a smooth halo, when the Galaxy is viewed from far away. (However, Diemand, Kuhlen, et al. 2009, of the Via Lactea project, seem to get somewhat smaller boost.)

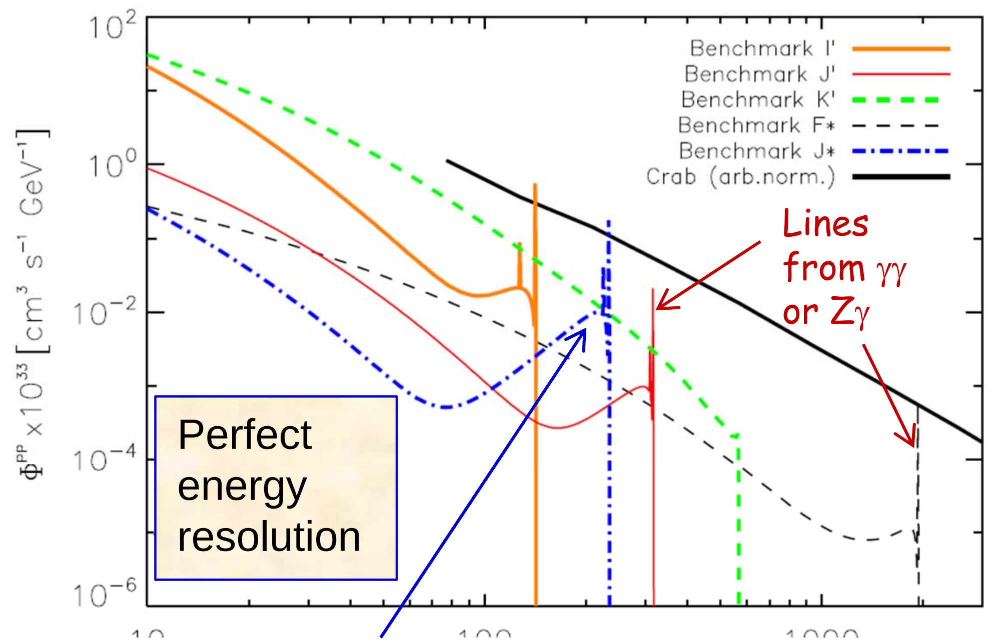
Indirect detection through γ-rays.
Three types of signal:

- Continuous from π^0, K^0, … decays
- Monoenergetic line from quantum loop effects, $\chi\chi \rightarrow \gamma\gamma$ and $Z\gamma$
- Internal bremsstrahlung from QED process.

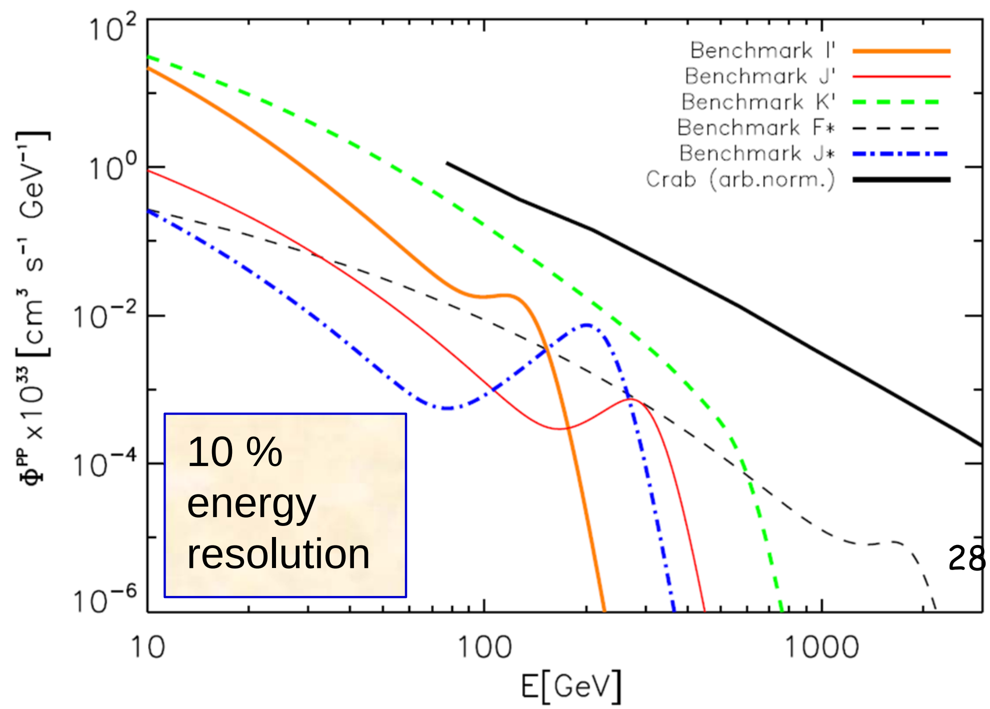
Enhanced flux possible thanks to halo density profile and substructure (as predicted by N-body simulations of CDM).

Good spectral (and angular) signatures!

But, in some cases, large uncertainties in the predictions of absolute rates.

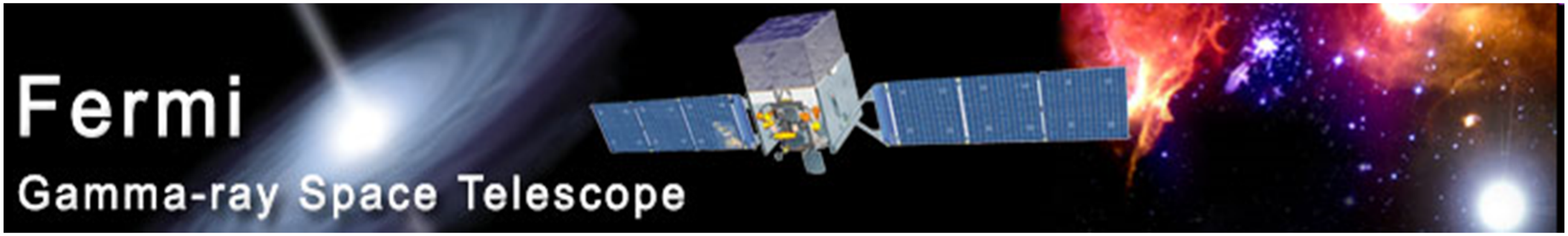


New contribution: Internal bremsstrahlung (T. Bringmann, L.B., J. Edsjö, 2008)

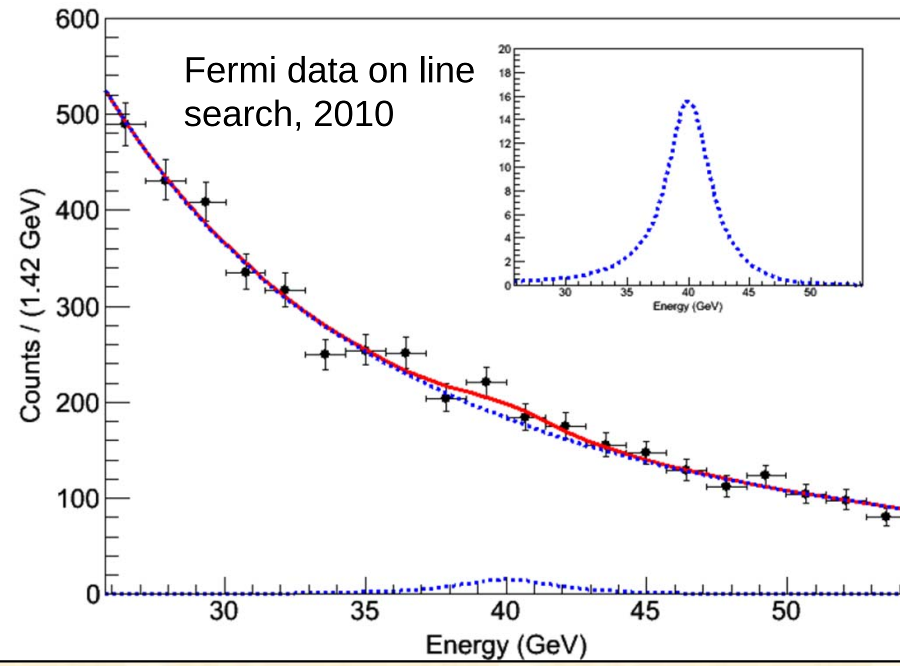


T. Bringmann, M. Doro & M. Fornasa, 2008

Gamma-rays from dark matter annihilations:

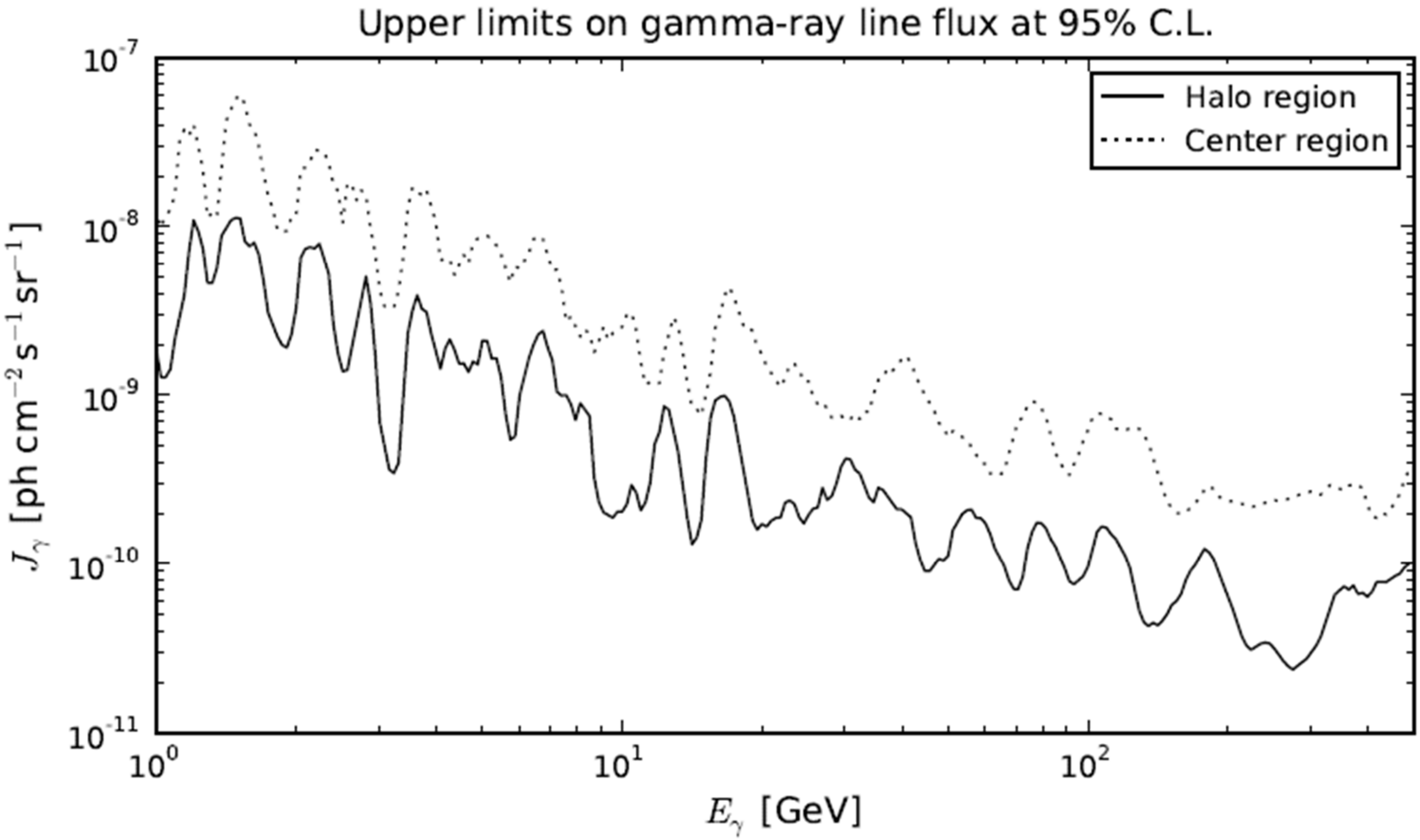


USA-France-Italy-Sweden-Japan – Germany collaboration, launched June 2008.



Fermi can search for dark matter signals in gamma-rays up to 300 GeV – no unambiguous signal found so far (but still not probing much of SUSY parameter space, for example). Will give data for several more years. See talk by G. Zaharijas this afternoon.

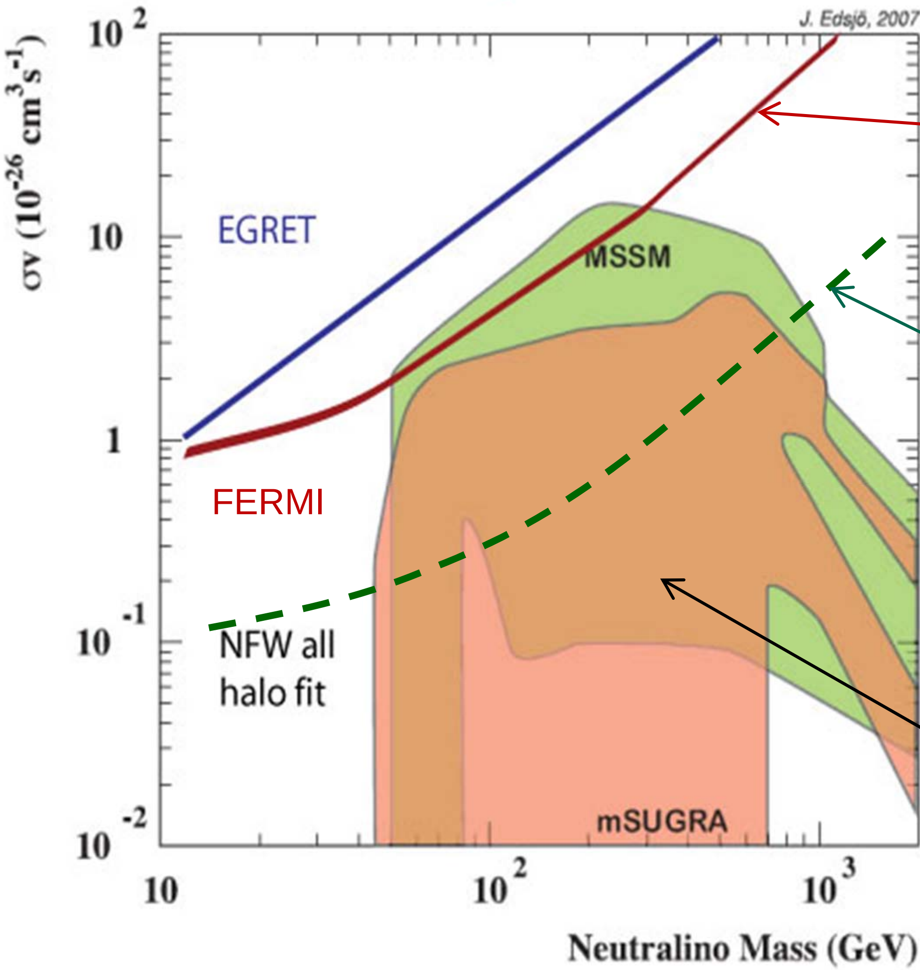
Analysis of 28 months of Fermi data (lines from loop-induced annihilations, or decaying DM):



G. Vertongen & C. Weniger, Jan. 2011

Gamma-rays, 3σ exclusion limit, 1 year of Fermi data, pre-launch predictions

Note: the regions with high gamma rates are very weakly correlated with models of high direct detection rates $\Rightarrow$ complementarity (see later)



"Conservative" approach, g.c.,

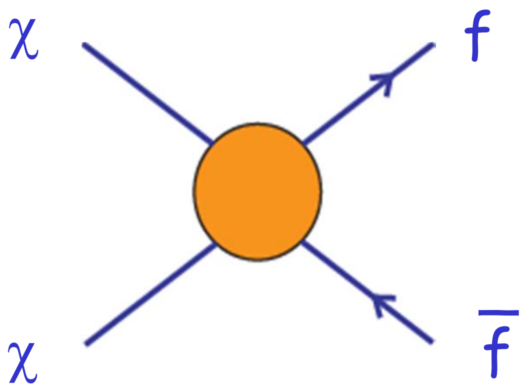
NFW halo profile assumed, no substructure.

Including all halo, with substructure

Will not be probed by Fermi, but by next generation of (ground-based) gamma-ray instruments.

Fermi/GLAST working group on Dark Matter and New Physics, E.A. Baltz & al., JCAP, 2008.

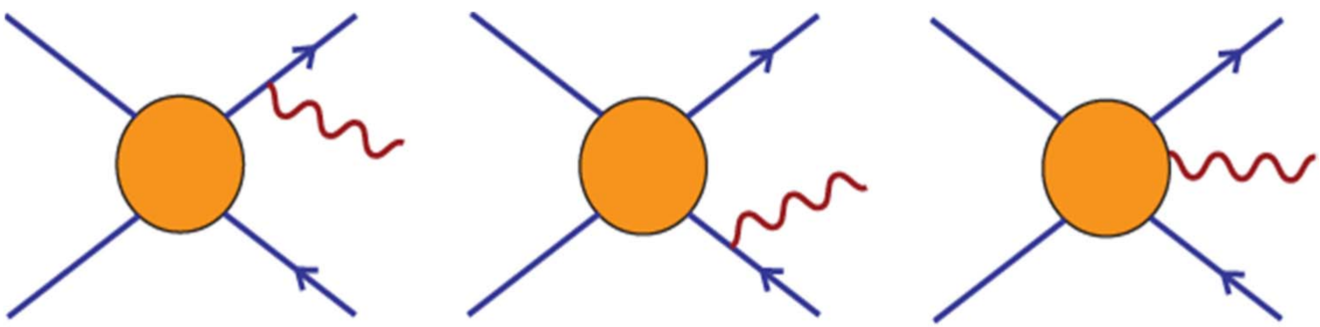
Progress on Old and New observational Themes for Majorana particles



$\sim m_f$ for Majorana particles in limit $v/c \rightarrow 0$

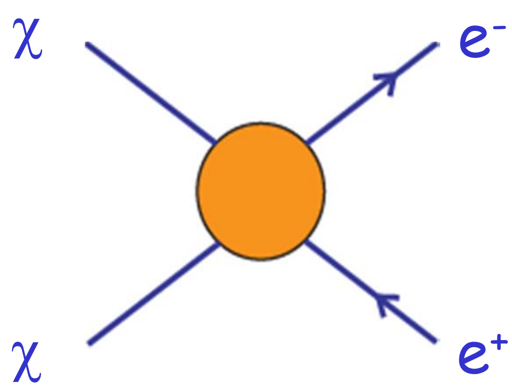
"Final state radiation"

"Internal bremsstrahlung", IB



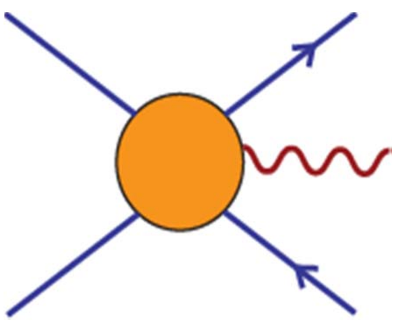
$\sim m_f$ $\sim m_f$ No m_f suppression!

Example, Majorana particle annihilating only into electrons and positrons (e.g., SUSY DM, if the selectron is much lighter than other sfermions):



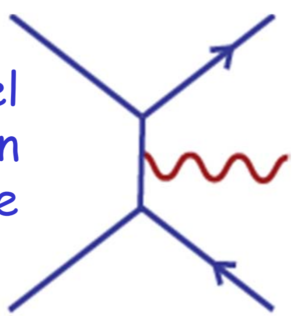
Annihilation rate $(\sigma v)_0 \sim 3{\cdot}10^{-26}$ cm^{-3}s^{-1} at freeze-out, due to p-wave at $(v/c)^2 \sim 0.3$. $\Omega_{CDM}h^2 = 0.1$ for mass ~ 500 GeV.

Annihilation rate today (S-wave)
$\sigma v \sim 10^{-25}\,(m_e/m_\chi)^2$ cm^{3}s^{-1} ~ 10^{-37} cm^{3}s^{-1} for $v/c \sim 10^{-3}$.
Impossible to detect! Even adding P-wave, it is too small, by orders of magnitude.



Direct emission (inner bremsstrahlung) QED "correction":
$(\sigma v)_{QED}/\,(\sigma v)_0 \sim (\alpha/\pi)\,(m_\chi/m_e)^2 \sim 10^9 \Rightarrow 10^{-28}$ cm^{3}s^{-1}

The "expected" QED correction of a few per cent is here a factor of 10^9 instead! May give detectable gamma-ray rates – with good signature!



t-channel selectron exchange

(**Old** calculation, L.B. 1989; **Newer** E.A. Baltz & L.B. 2003, T. Bringmann, L.B. & J. Edsjö, 2008. **Newest** M. Ciafalone, M. Cirelli, D. Comelli, A. De Simone, A. Riotto & A. Urbano, April 15, 2011; N. F. Bell, J.B. Dent, A.J. Galea,T.D. Jacques, L.M. Krauss and T.J.Weiler, April 19, 2011)

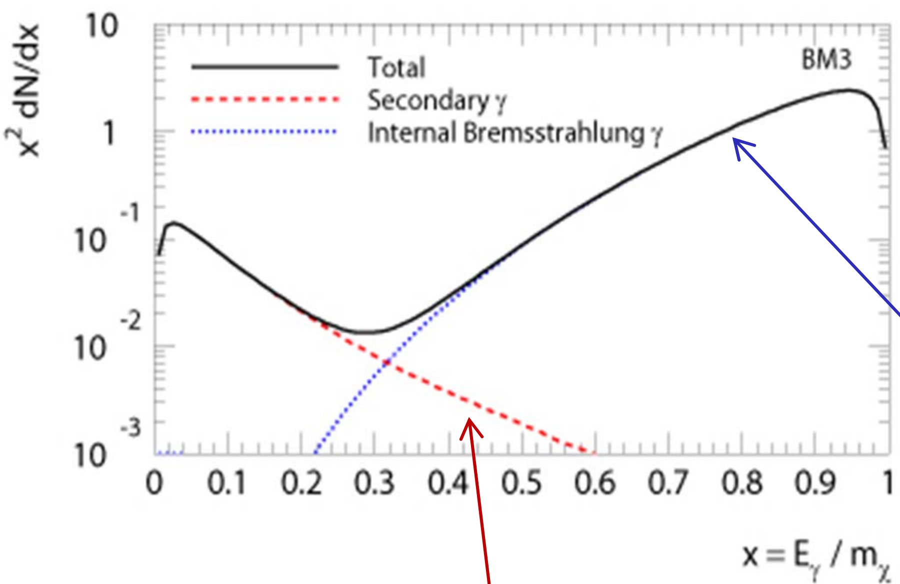
QED corrections (Internal Bremsstrahlung) in the MSSM: good news for detection probability in gamma-rays:

New Gamma-Ray Contributions to Supersymmetric Dark Matter Annihilation

JHEP, 2008

Torsten Bringmann*
SISSA/ISAS and INFN, via Beirut 2 - 4, I - 34013 Trieste, Italy

Lars Bergström† and Joakim Edsjö‡
Department of Physics, Stockholm University, AlbaNova University Center, SE - 106 91 Stockholm, Sweden
(Dated: October 16, 2007)

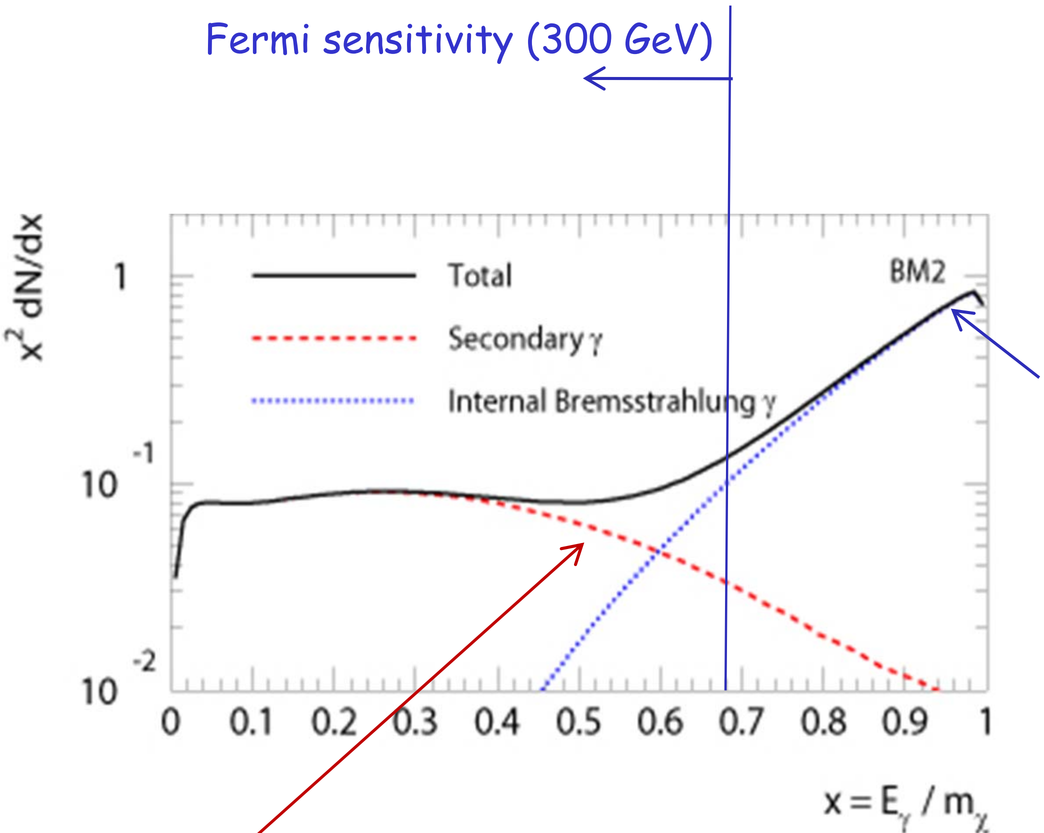


Example: benchmark point BM3, mass = 233 GeV, fulfils all accelerator constraints, has WMAP-compatible relic density (stau coannihilation region).

New calculation including Internal Bremsstrahlung (DarkSUSY 5.1). Spectral drop at 233 GeV could be just inside the Fermi range (5 yrs -> 10 yrs?)

Previous estimate of gamma-ray spectrum

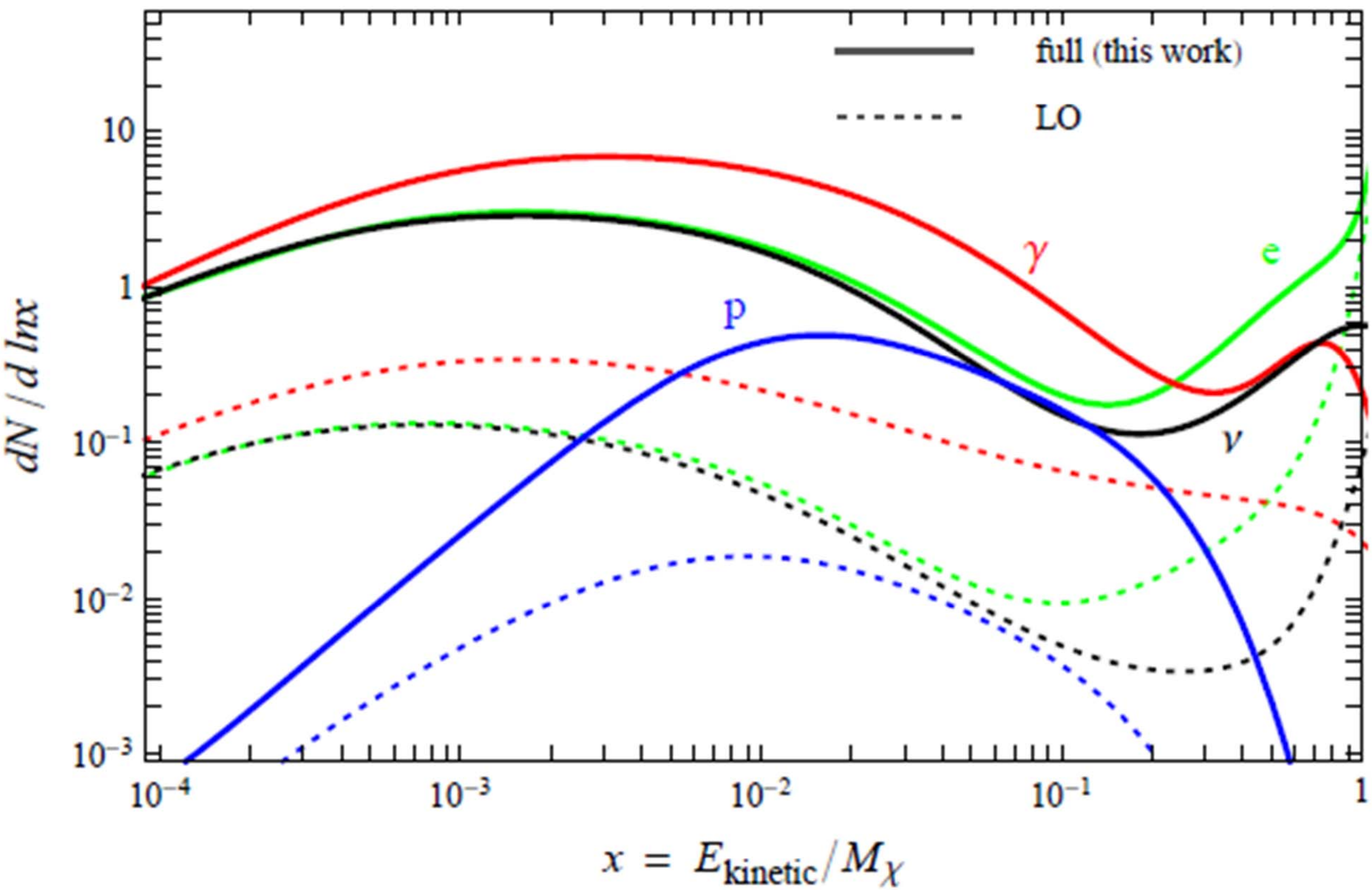
Effect generally increases with mass:



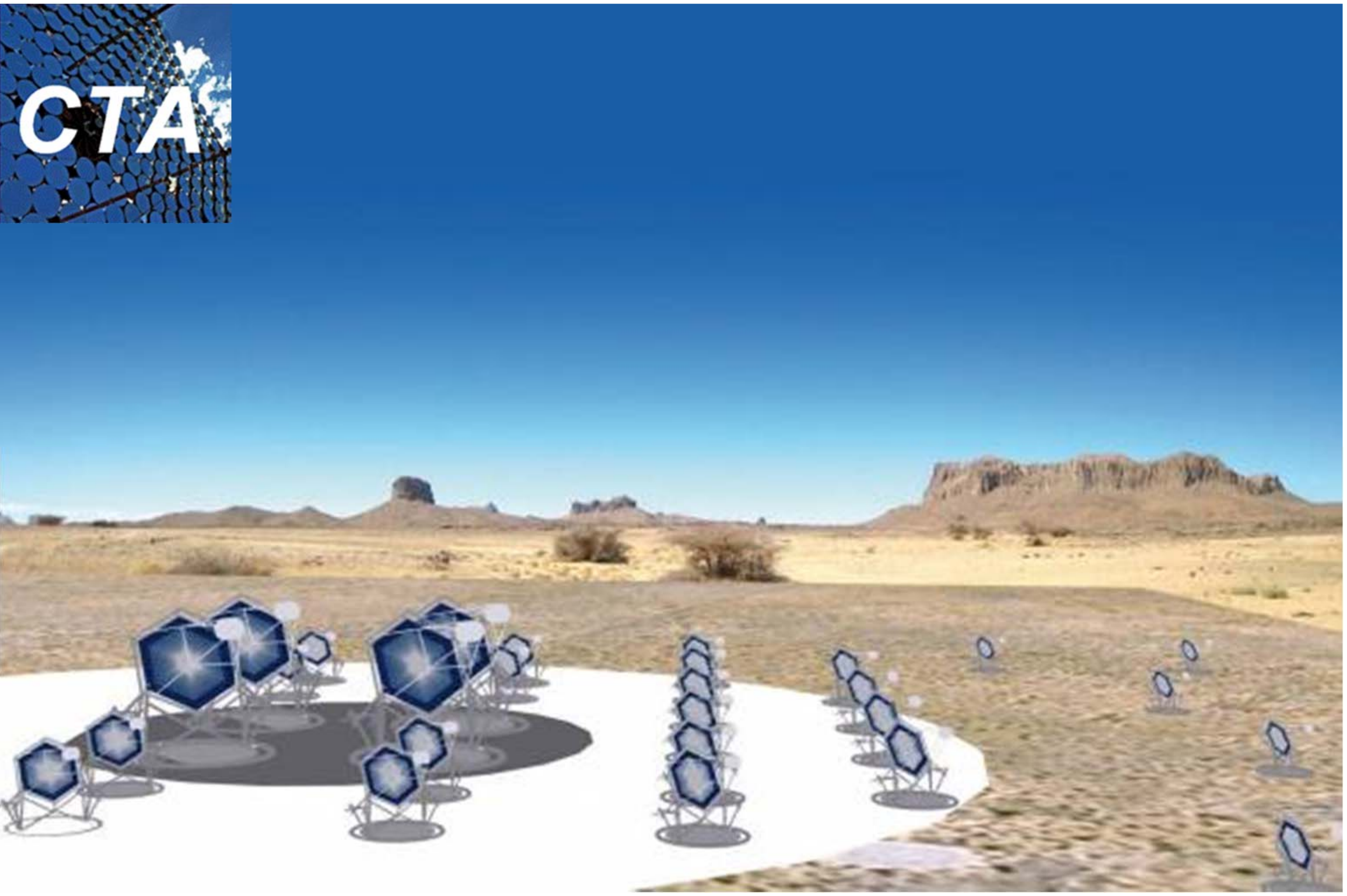
Example: benchmark point BM2, mass = 447 GeV, fulfills all accelerator constraints, has WMAP relic density

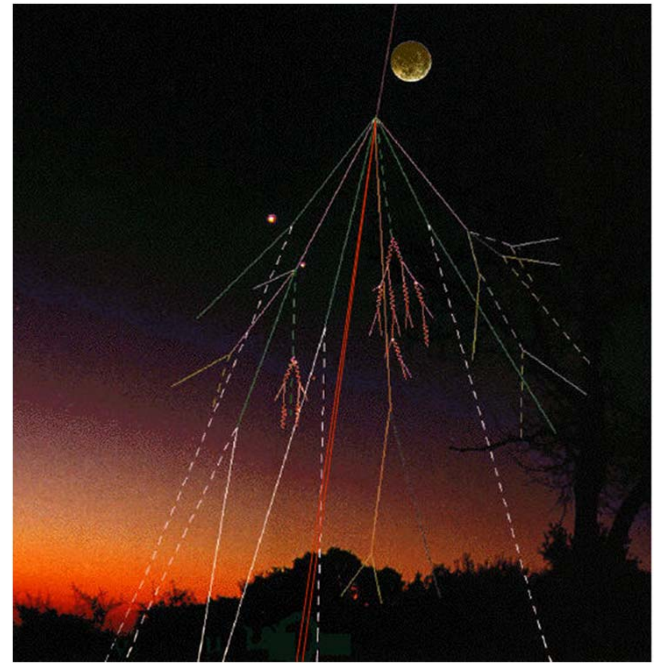
Calculation including Internal Bremsstrahlung (DarkSUSY 5.1). Energy falls just outside the Fermi energy range…
A windown of opportunity of new imaging ACT arrays!

Previous estimate of gamma-ray spectrum



Full calculation of radiative effects of all electroweak gauge bosons, M. Ciafalone, M. Cirelli, D. Comelli, A. De Simone, A. Riotto & A. Urbano, 2011. (See talk by Urbano this afternoon.)



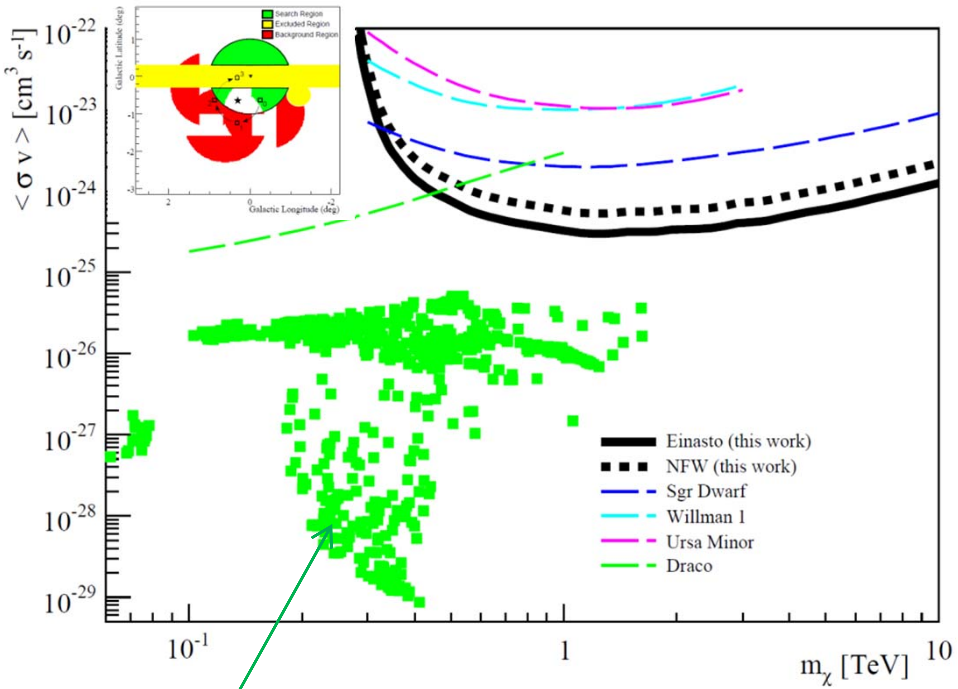


CTA – Cherenkov Telescope Array. Large international collaboration, Europe + US. Ready by 2018? Total cost > 100 M€.

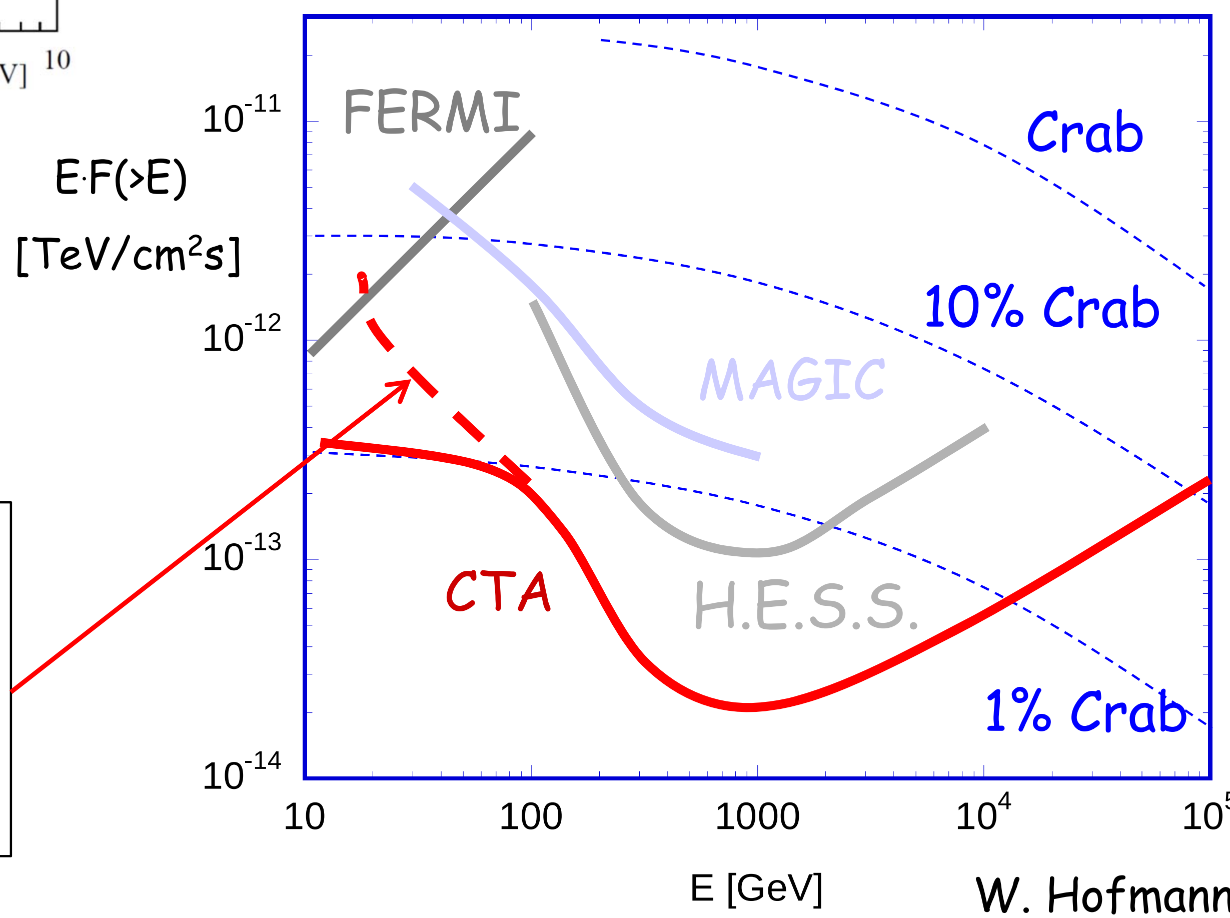
Multipurpose instrument, will detect supermassive black holes (AGNs), supernova remnants,…
… and in spare time, search for a dark matter signal.

Gamma-ray intitiates a shower of particles, which radiate Cherenkov light that can be detected. The shape of the air shower is different for gamma-rays and protons.

Present best limits towards the g.c. from ground-based experiments (HESS, March 2011)



SUSY models



W. Hofmann

Maybe with CTA one can reach the required sensitivity. However, it seems that energy threshold may be too large…

New promising method: Stacking data from many dwarf galaxies, Fermi preliminary, 2011

dSph stacking with the Fermi-LAT — Maja Llena Garde

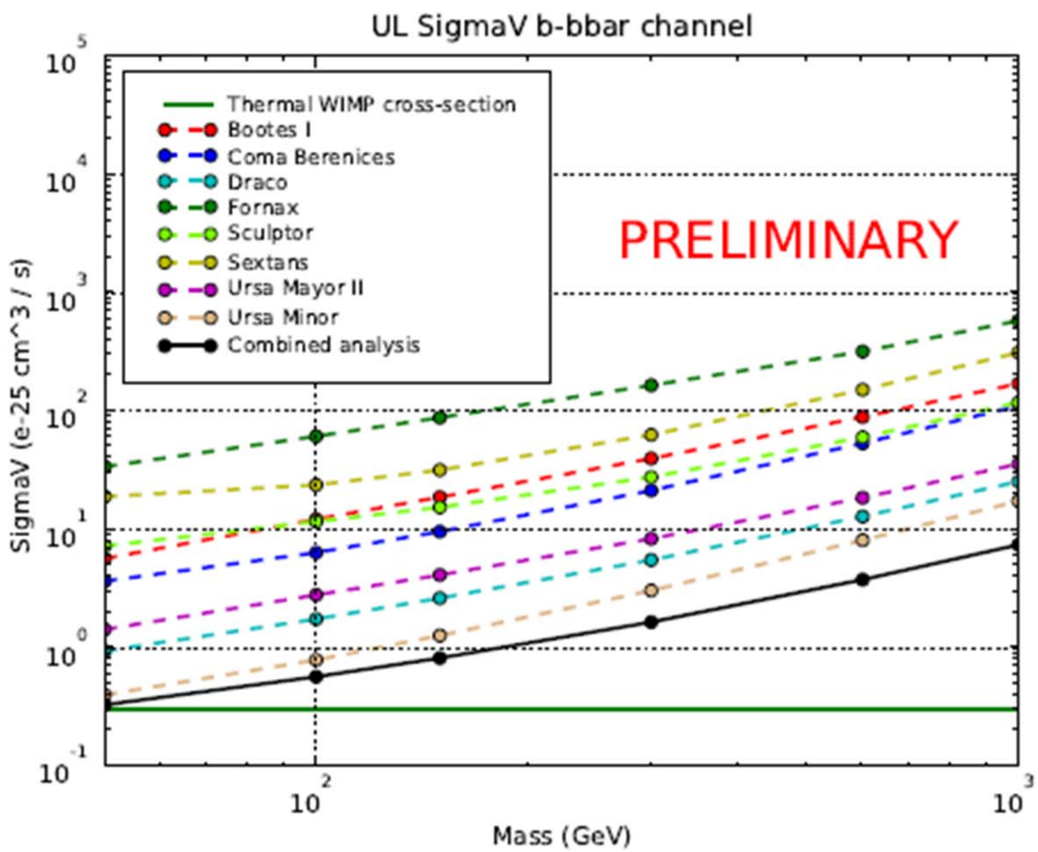
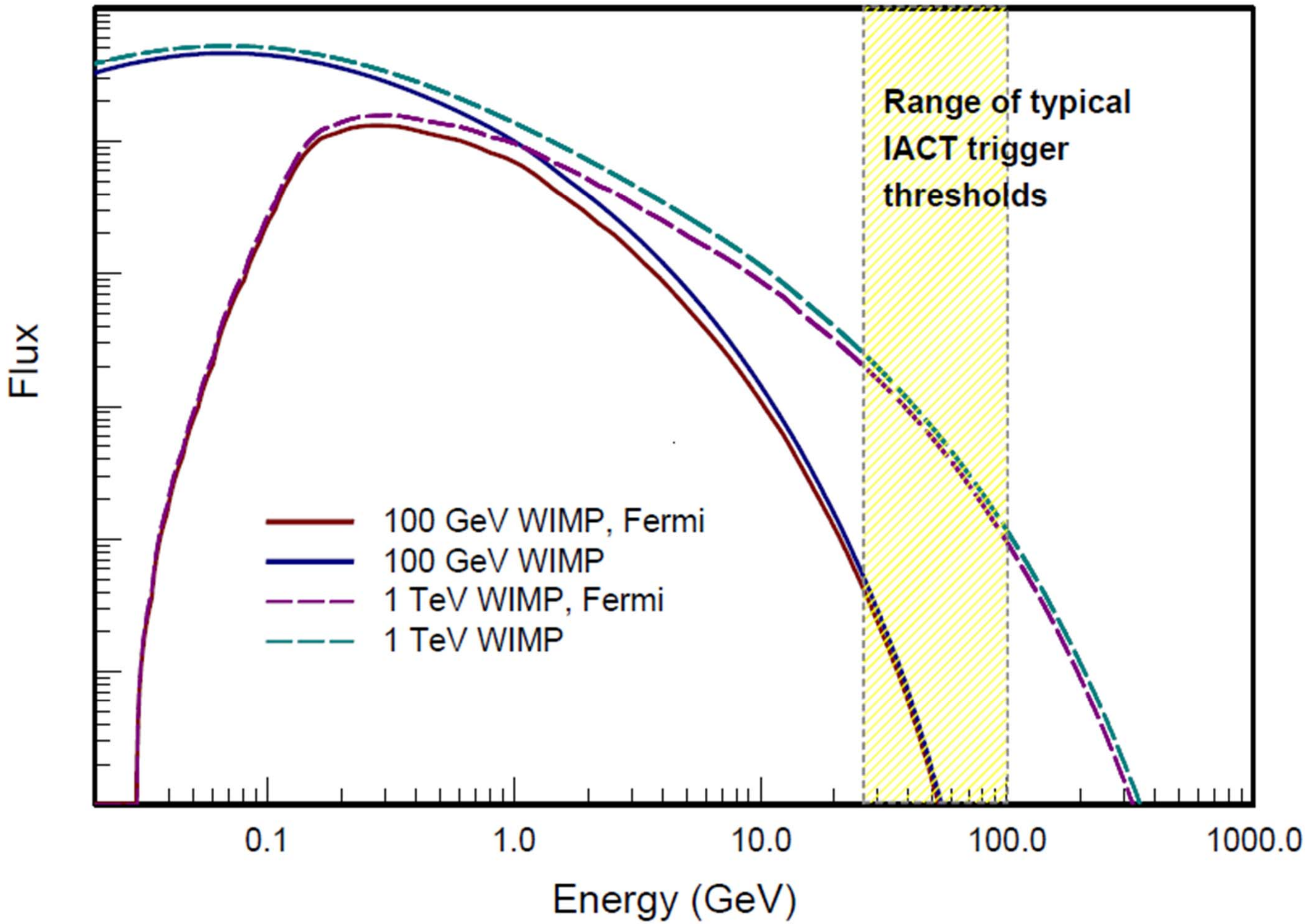
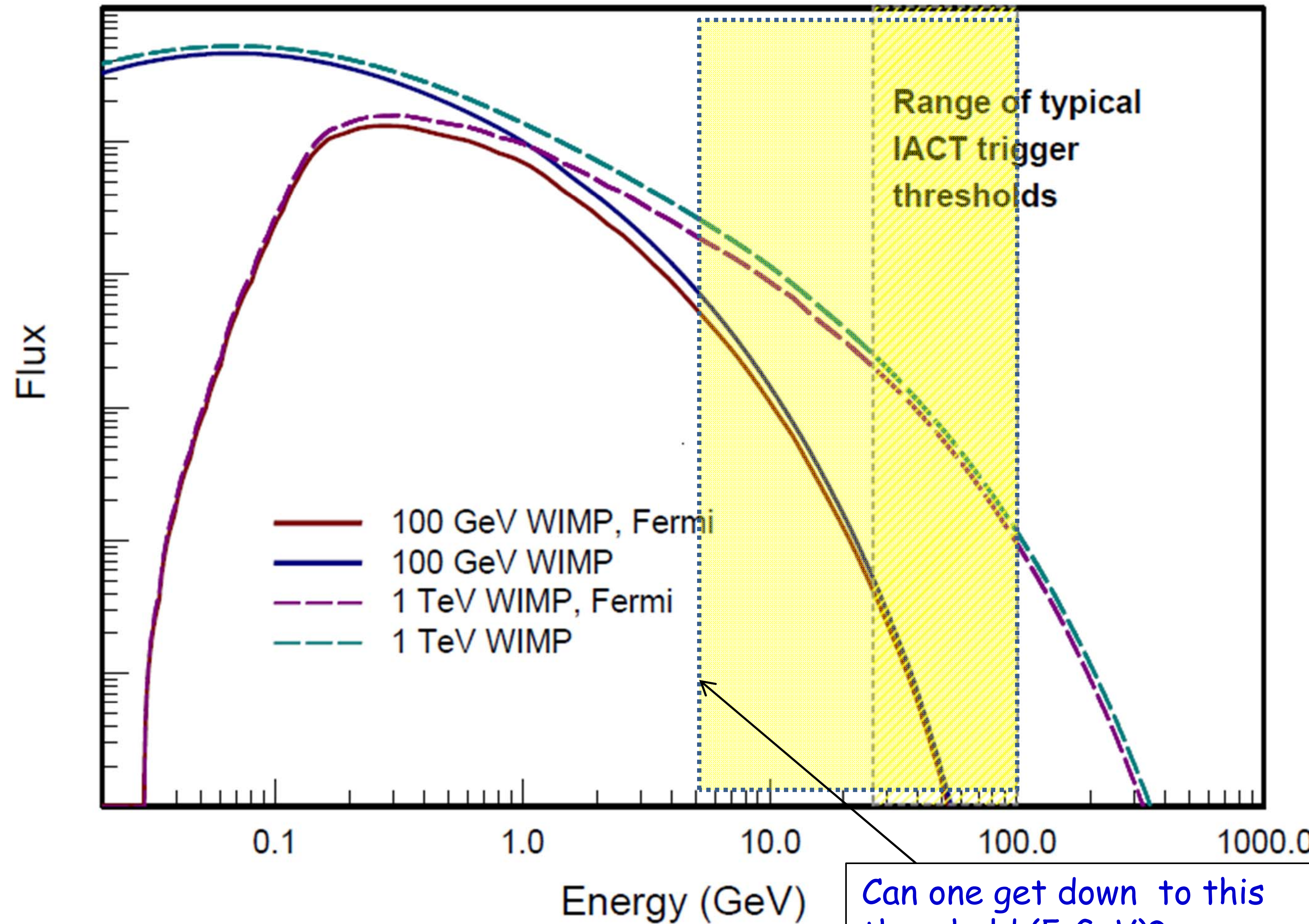


Figure 1: Upper limits on WIMP annihilation cross section for annihilation into 100% $b\bar{b}$, σv evaluated at m_{WIMP} = 50, 100, 150, 300, 600 and 1000 GeV. The expected thermal WIMP cross-section is plotted as a reference. The limits are 84% two-sided.



T.A. Porter, R.P. Johnson and P.W. Graham, April 2011



T.A. Porter, R.P. Johnson and P.W. Graham, April 2011

Can one get down to this threshold (5 GeV)?
F. Aharonian, A.K. Konopelko, H.J. Völk and H. Quintana, 2000: Yes, 5@5 – 5 GeV at 5000 m above sea.

DMA - The Dark Matter Array: A dedicated detector for indirect detection of Dark Matter?

CTA will - like H.E.S.S., MAGIC and VERITAS - be a multipurpose array. Transient and point-source events (AGNs, SNRs,...) have a very active community and will be much in focus ⇒ exposure time for dark matter search will be limited (maybe ~ 50 h at most for a single object).

The Dark Matter problem has appeared as one of the most outstanding problems of natural science. Large (and expensive) equipment is being deployed and planned for accelerators (LHC, CLIC...) and direct detection (SuperCDMS, Xenon 1t, Eureca,...).

Thus why not think about what can be done with a DEDICATED Dark Matter detector for indirect detection - not (for now) worrying about the cost or manpower? (Would cost roughly 1 G €, or 1 year of running CERN...)

Parameters for the first try of this thought experiment: Area = 10 x CTA, exposure time (say, over 10 years) 5000 h ⇒ sensitivity better than CTA by factor around 30. Energy threshold 10 GeV, PSF 0.02° (as CTA), but 0.1° below 40 GeV. Maybe 5@5, a SuperCTA at the ALMA site?

Setup for analysis (L.B., T. Bringmann & J. Edsjö, PRD 2011):

Large scan of MSSM and mSUGRA parameter space, satisfying all experimental constraints, giving WMAP-consistent relic density.

Parameters for experiments:

CDMS: As published in Z. Ahmed & al., 2010.

SuperCDMS: As described in T. Bruch, 2010.

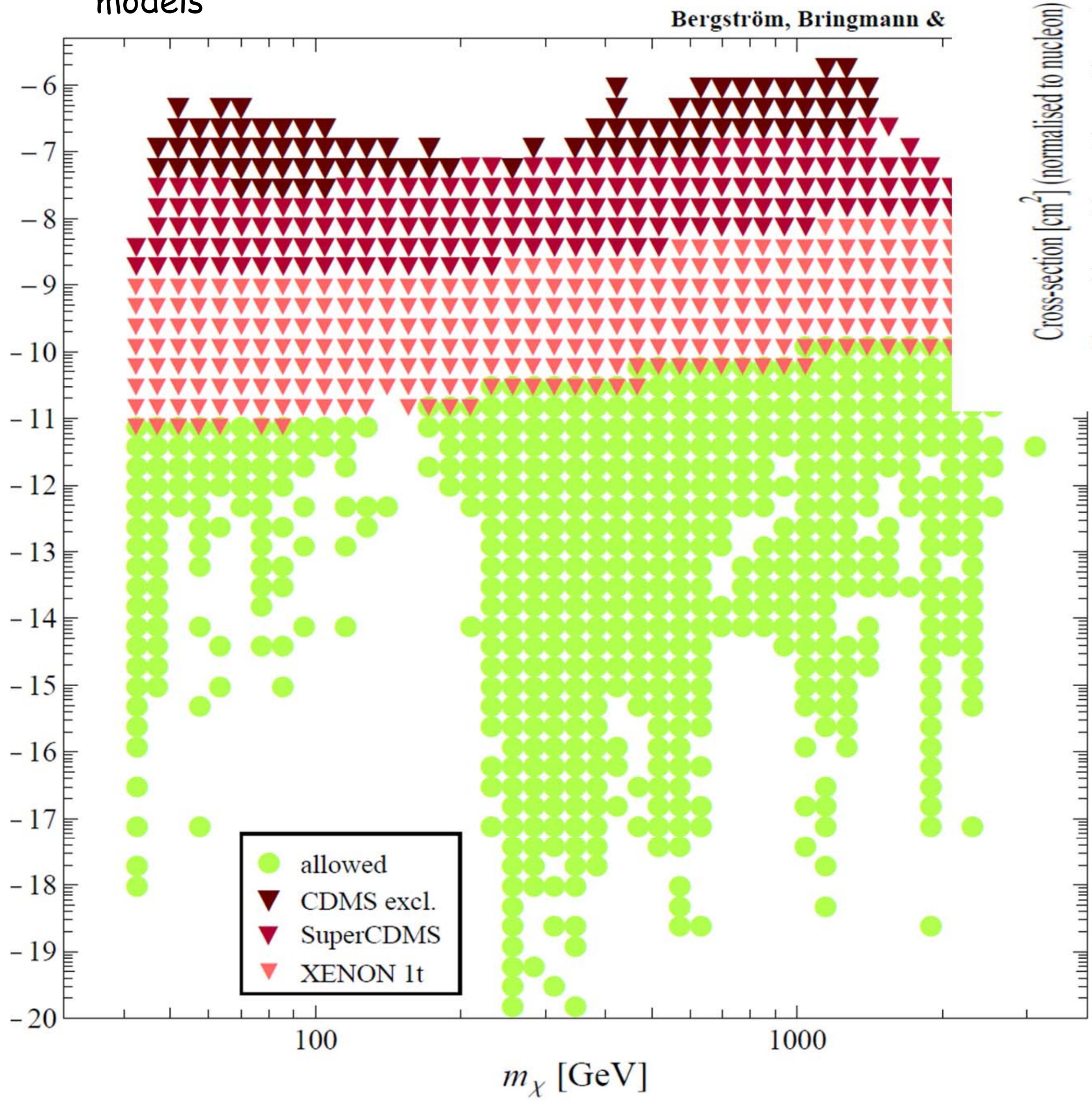
Xenon 1t: As described in K. Arisaka & al., 2008.

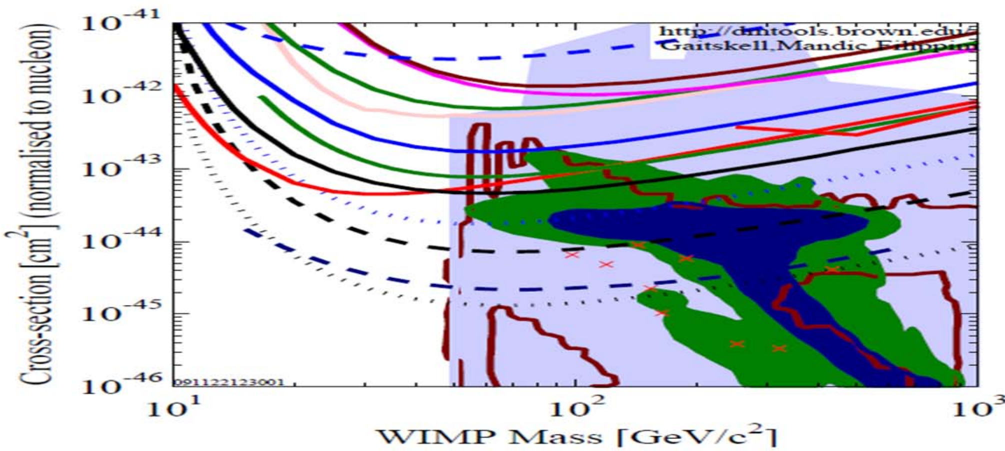
FERMI-LAT: Effective exposure 1 year (= 5 years observing time), 20 log-bins between 1 och 300 GeV, everything else according to LAT specifications.

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 $A_{eff} \sim 2 \times 10^6$ m^2.

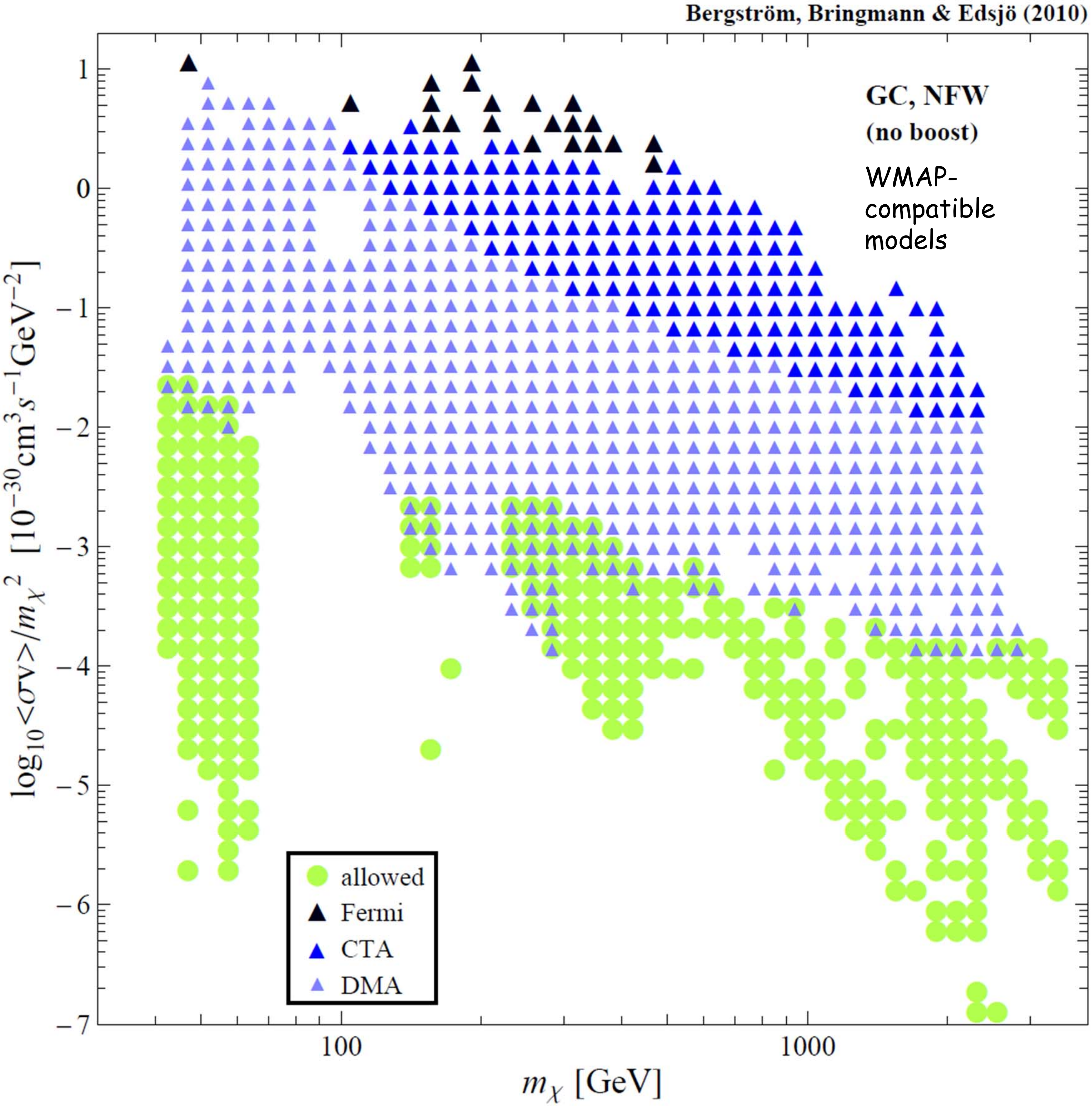
DMA: Energy threshold 10 GeV, max $A_{eff} = 2 \times 10^7$ m^2, integration time 5000 hours.

WMAP-compatible models

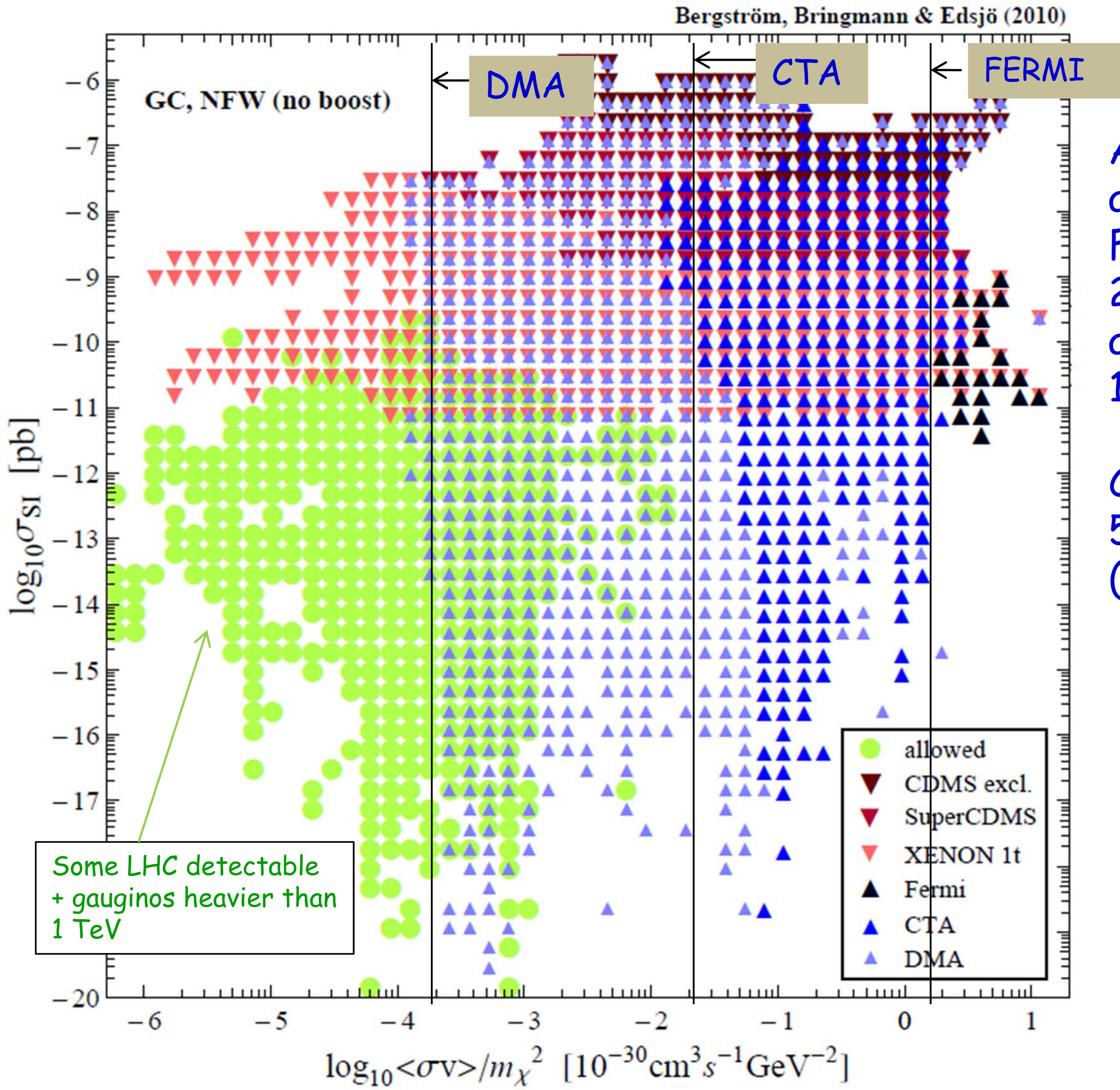




The parameter space does indeed continue (10 more orders of magnitude in direct detection cross section!)

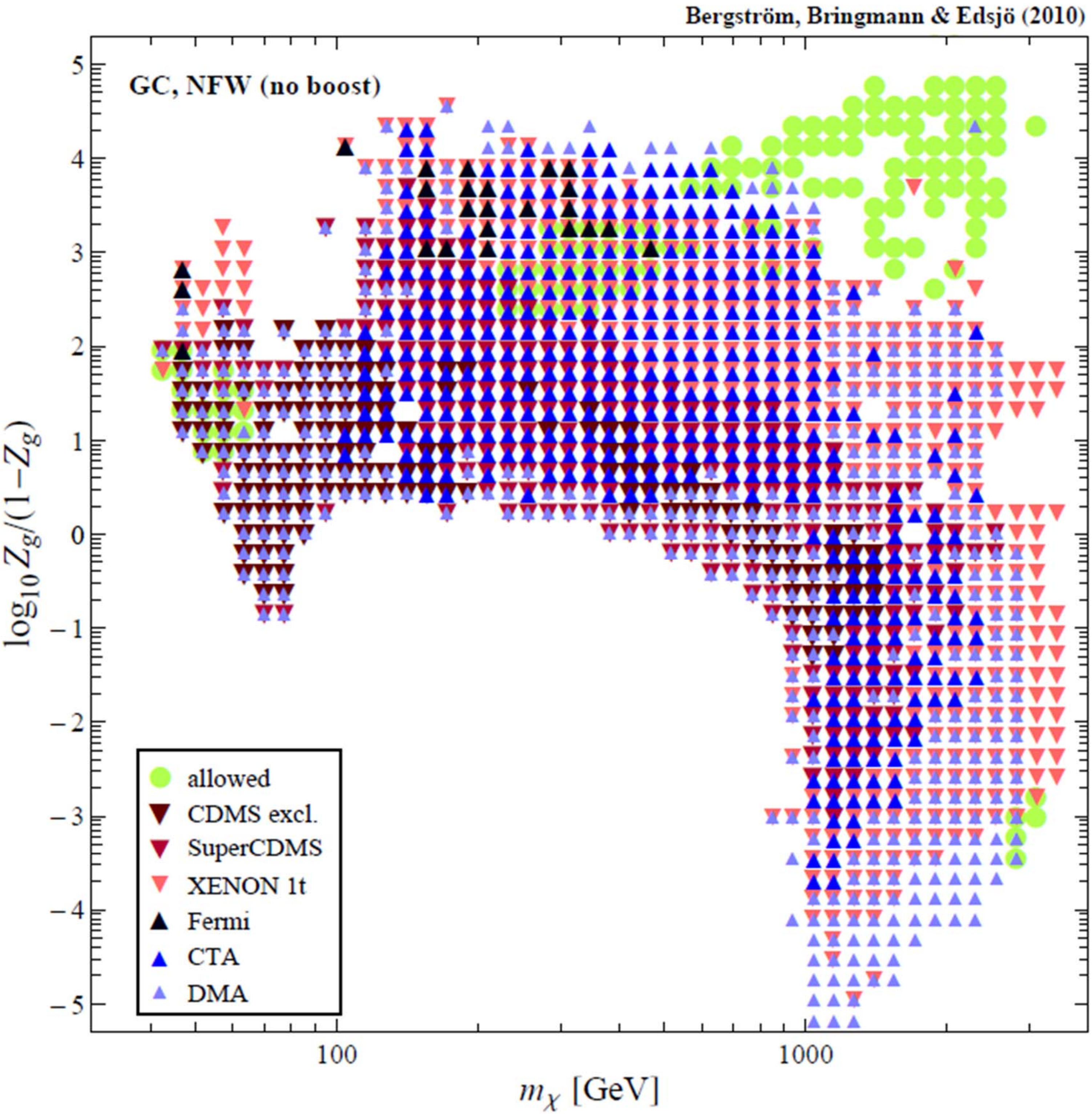


Bergström, Bringmann & Edsjö (2010)
GC, NFW
(no boost)
WMAP-
compatible
models
allowed
Fermi
CTA
DMA
$\log_{10}\langle\sigma v\rangle/m_\chi^2$ [$10^{-30}\mathrm{cm}^3 s^{-1}\mathrm{GeV}^{-2}$]
m_χ [GeV]
1
0
−1
−2
−3
−4
−5
−6
−7
100
1000

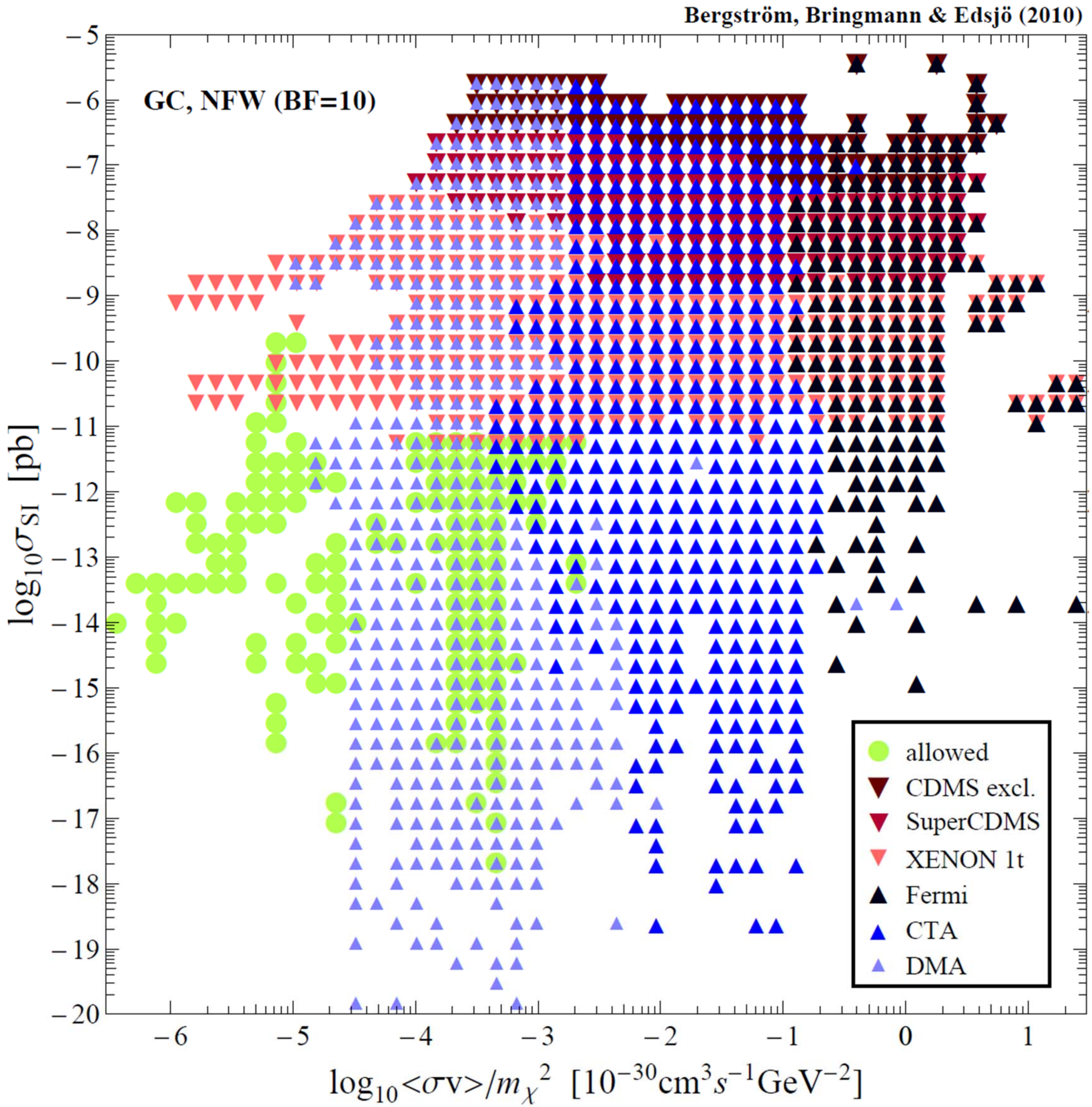


Assumed background according to S. Digel, Fermi Symposium, 2009 (extrapolated as power-law for E > 100 GeV).

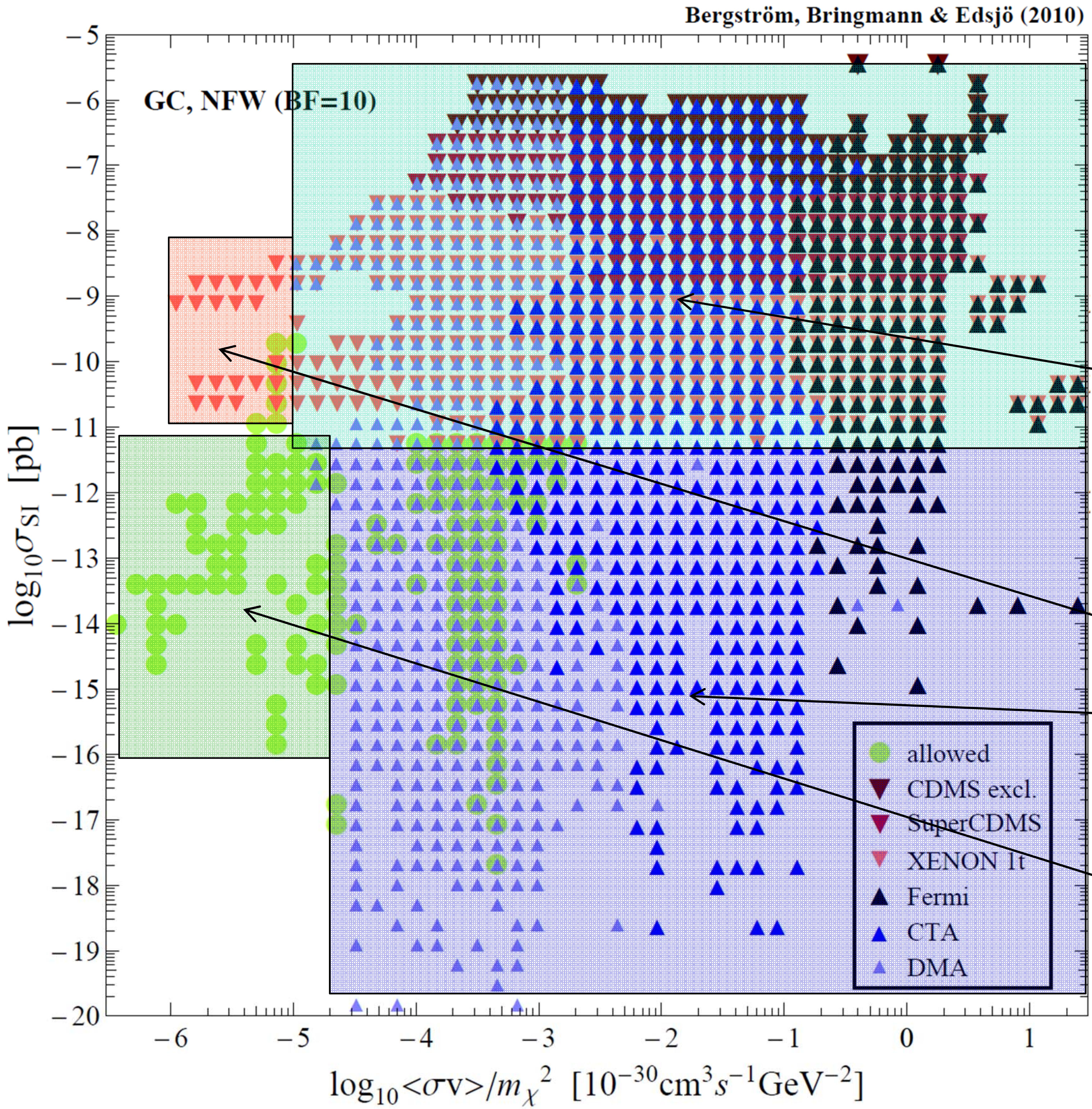
Check if $S/(S+B)^{0.5} > 5$ in the "best" bin (and demand $S > 5$)



Bergström, Bringmann & Edsjö (2010)
GC, NFW (no boost)
allowed
CDMS excl.
SuperCDMS
XENON 1t
Fermi
CTA
DMA
$\log_{10} Z_g/(1-Z_g)$
m_χ [GeV]
5
4
3
2
1
0
−1
−2
−3
−4
−5
100
1000



NFW with moderate boost, looks even better...



NFW with moderate boost, looks even better...

The sweet part of parameter space: direct and indirect detection can be used independently

Here direct detection rules

Here indirect detection rules

The very difficult part...

Conclusions:

- No observational effect so far unambiguously associated with dark matter.
- On the other hand, experiments are just now reaching the required sensitivity to probe, e.g, SUSY models for dark matter.
- LHC does not probe very far in SUSY parameter space, except in the simplest models.
- To probe WIMP more completely, may need a dedicated indirect detection experiment.
- Interesting decade ahead! - AMS02, IceCube, Super-CDMS, Eureca, Xenon 1t, CTA, DMA (?)

Vision of
supersymmetric
elegance, but…

…we should be prepared for surprises.

The end