Dark matter signatures in cosmic rays

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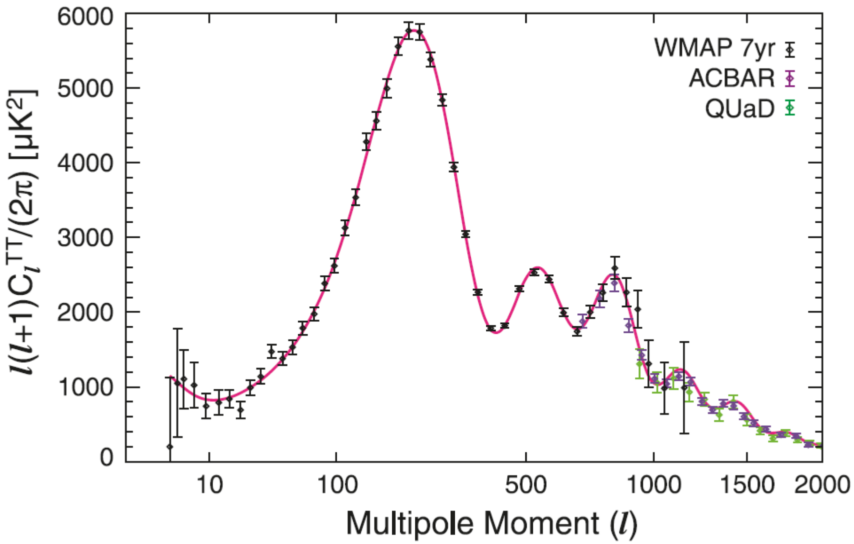
Fritz Zwicky, 1933: Velocity dispersion of galaxies in Coma cluster indicates presence of Dark Matter , $\sigma \sim 1000$ km/s $\Rightarrow$ M/L ~ 50

"If this over-density is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter."

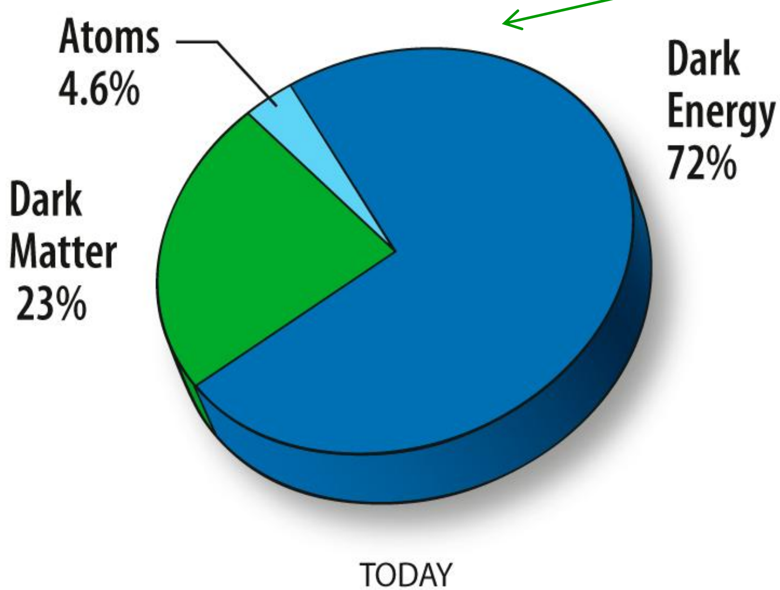


WMAP 2010:

$$\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} \approx 1.003 \pm 0.010$$

$$\Omega_{\Lambda} = 0.728 \pm 0.016; \quad \boxed{\Omega_{CDM} = 0.227 \pm 0.014}$$

$$\Omega_{B} = 0.0456 \pm 0.0016 \quad h = 0.704 \pm 0.014$$



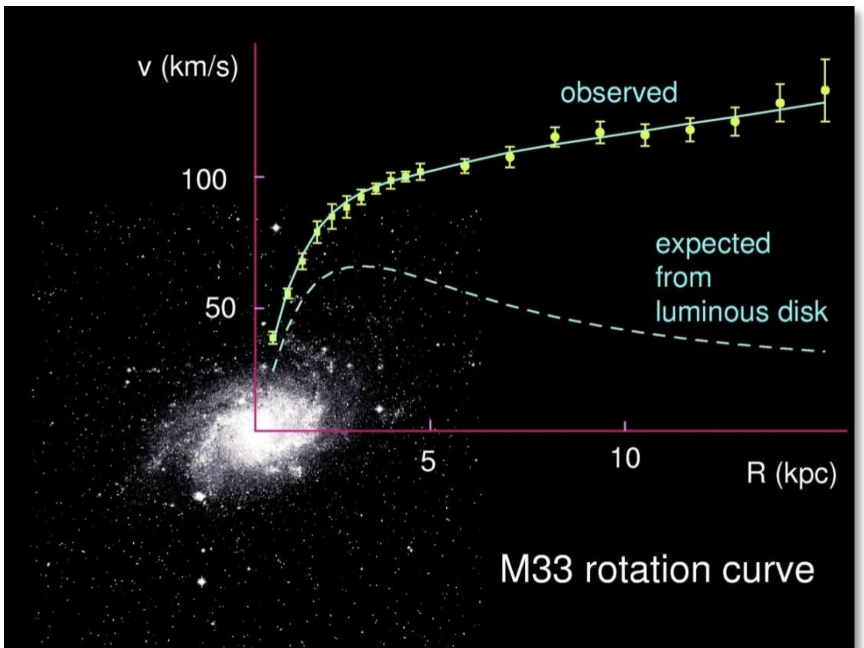
The energy densities now (13.75 billion years after the big bang).

The ΛCDM Model:

Cold Dark Matter Model (meaning the particles move non-relativistically, i.e., slowly) with a Cosmological Constant Λ being the dark energy.

Dark matter needed on all scales!
⇒ Modified Newtonian Dynamics (MOND) and other *ad hoc* attemps to modify Einstein or Newton gravity seem unnatural & unlikely

Galaxy rotation curves

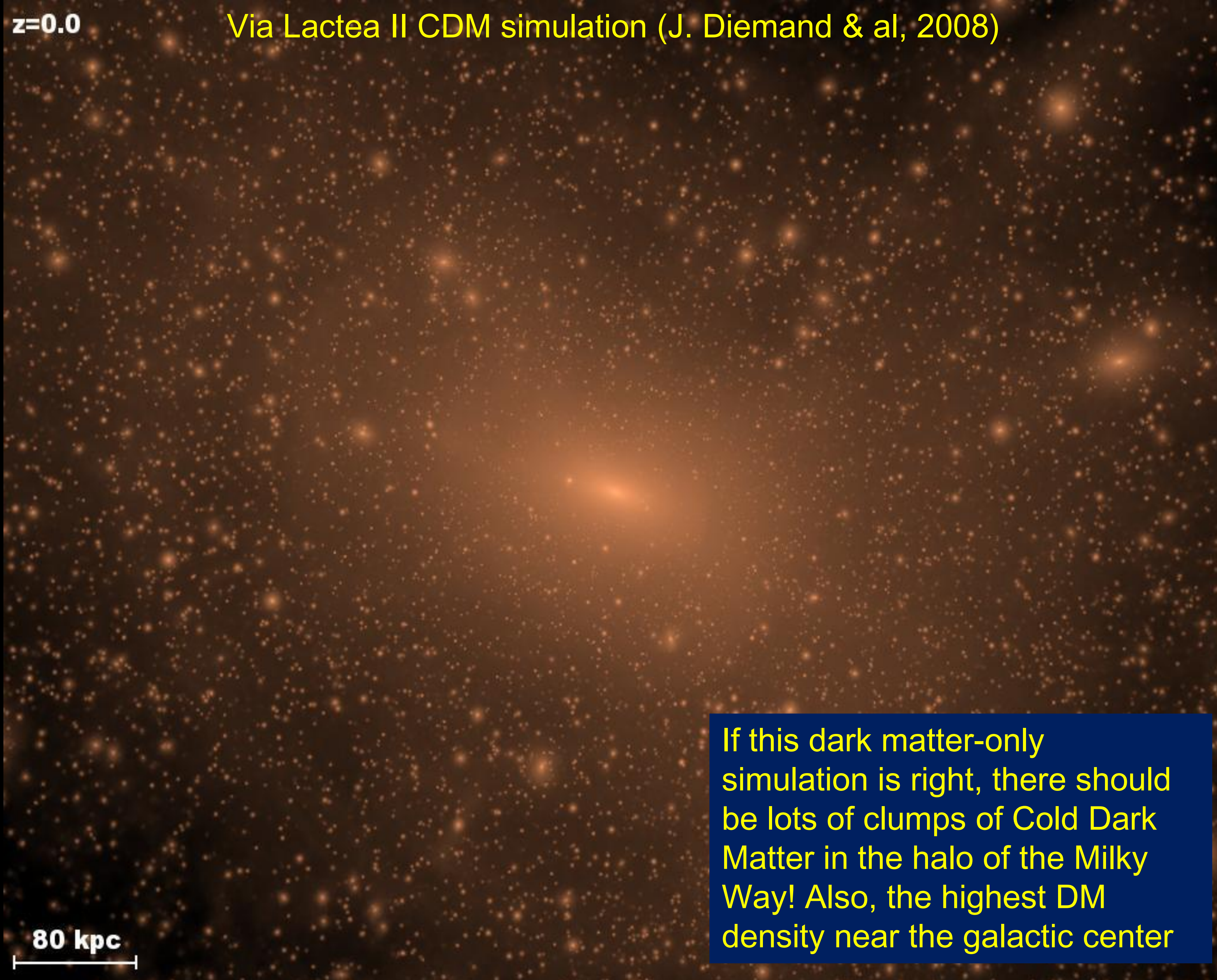


L.B., Rep. Prog. Phys. 2000

Colliding galaxy clusters

The "bullet cluster", D. Clowe et al., 2006

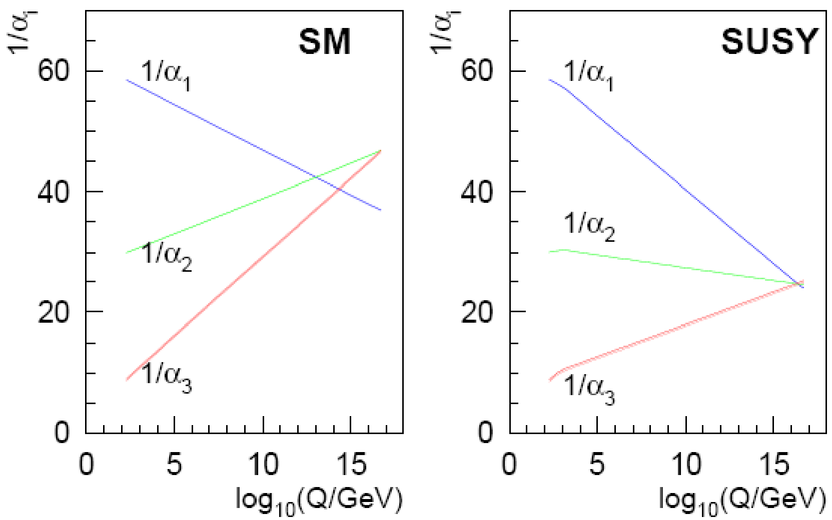
Via Lactea II CDM simulation (J. Diemand & al, 2008)



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 near the galactic center

Supersymmetry

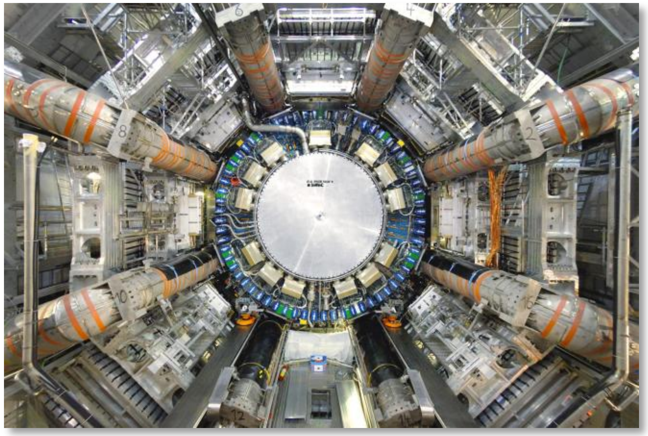
- Invented in the 1970's
- Necessary in most string theories
- Restores unification of couplings
- Can solve the so-called hierarchy problem
- Can give right scale for neutrino masses
- Predicts light Higgs (< 130 GeV)
- May be detected at Fermilab/LHC
- Gives an excellent dark matter candidate (A certain symmetry is conserved ⇒ stable on cosmological timescales)
- Useful as a template for generic "WIMP" (Weakly Interacting Massive Particle). The "WIMP miracle": gives required relic density without fine-tuning.



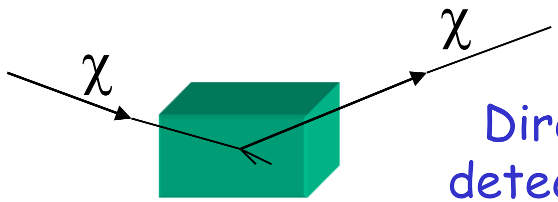
The lightest neutralino: The most natural SUSY dark matter candidate.
(Of course, there are other WIMPS: Kaluza-Klein particles, inert Higgs,….)

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.



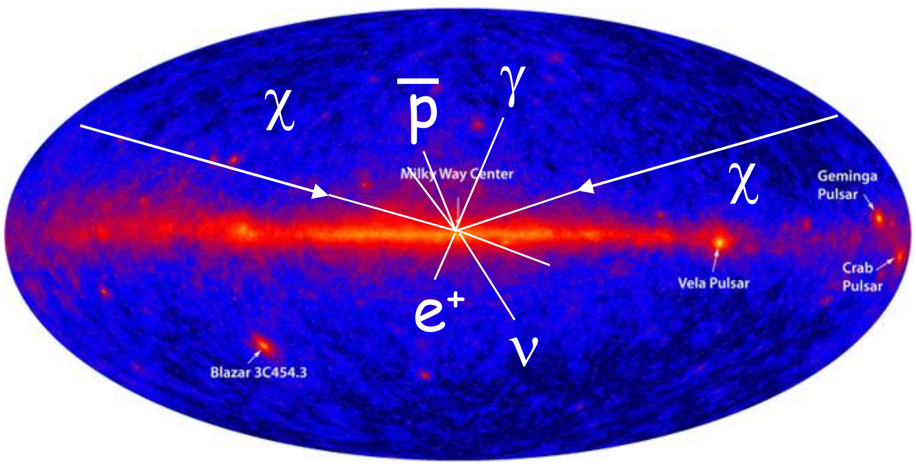
CERN ATLAS



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



FERMI's gamma-ray sky

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

Annihilation rate enhanced for clumpy halo; near galactic centre and in subhalos (dwarf galaxies)

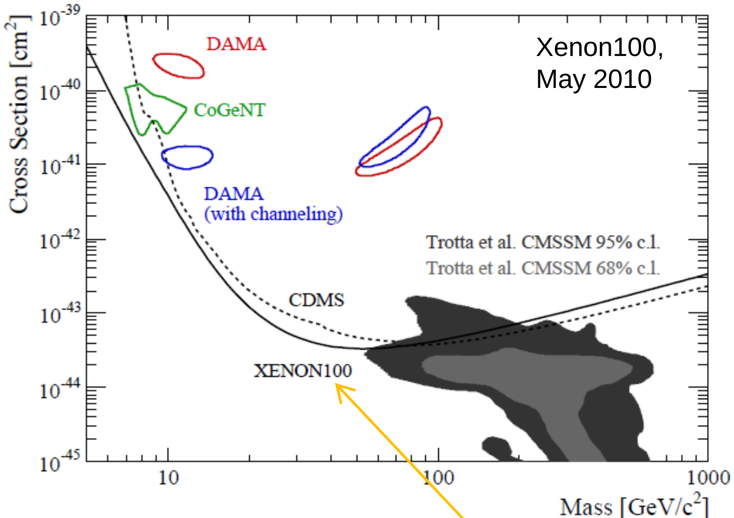
Tool for computing cosmological relic density, masses, branching ratios, direct and indirect detection cross sections for general WIMPs, especially supersymmetric ones:

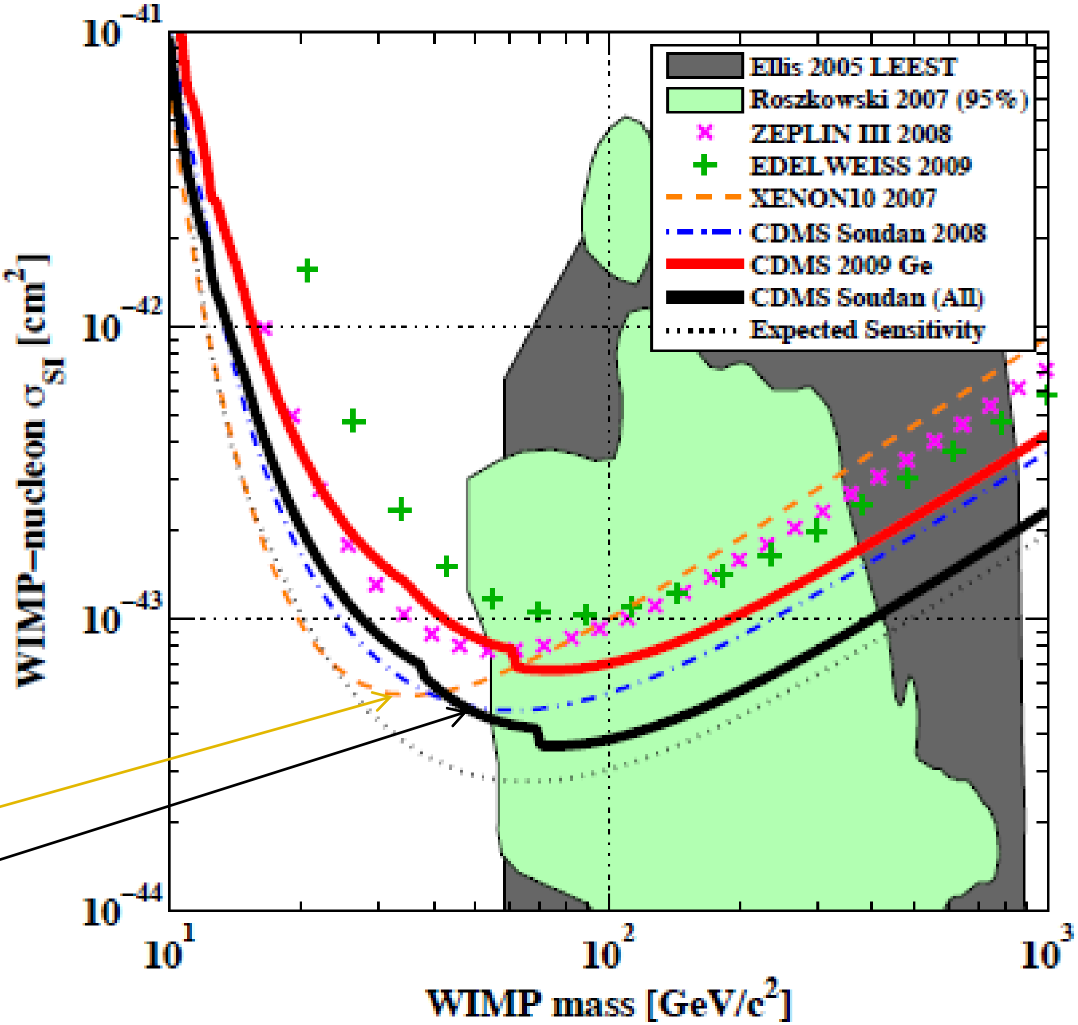
P. Gondolo, J. Edsjö, L.B., P. Ullio, Mia Schelke and E. A. Baltz, JCAP 2004 (with important additions by T. Bringmann and G. Dudas)

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 limits, steady progress – soon deploy new generation of detectors





Xenon

New CDMS result, 2009

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

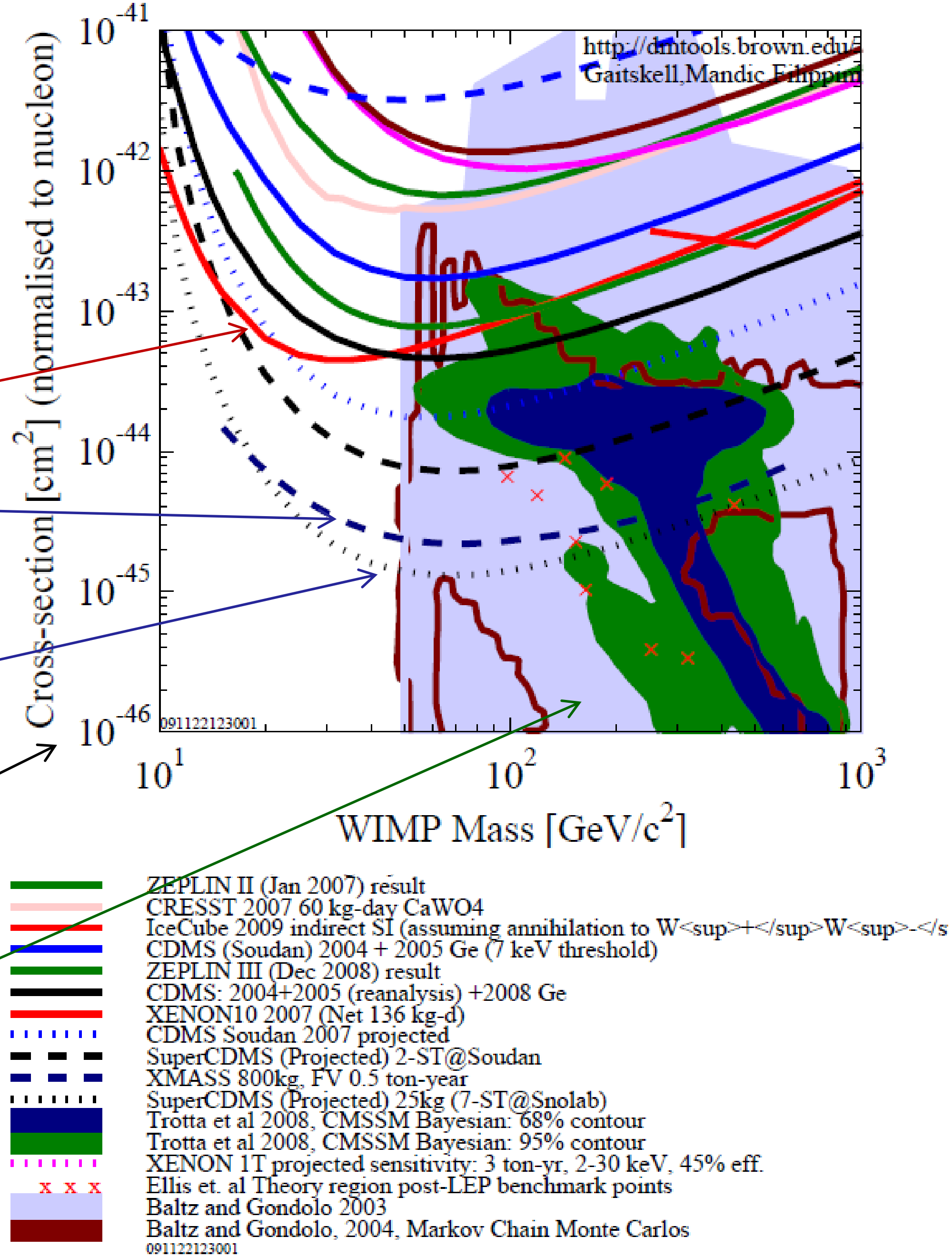
Xenon 10

XMASS (projected)

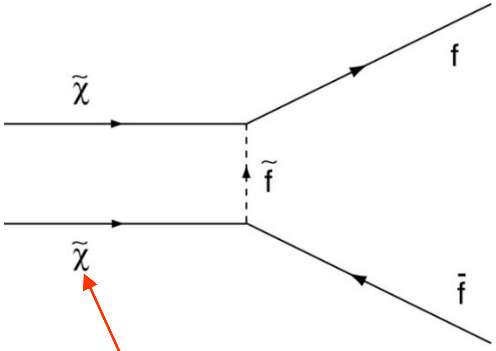
SuperCDMS (projected)

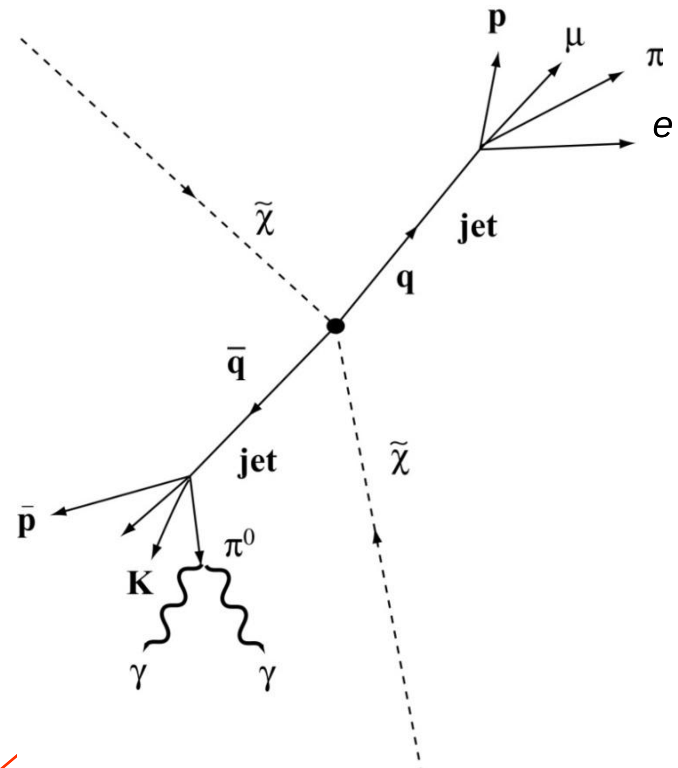
10^{-46} cm^2 = 10^{-10} pb

Is there a floor to this parameter space?



Indirect detection, example: annihilation of neutralinos in the galactic halo

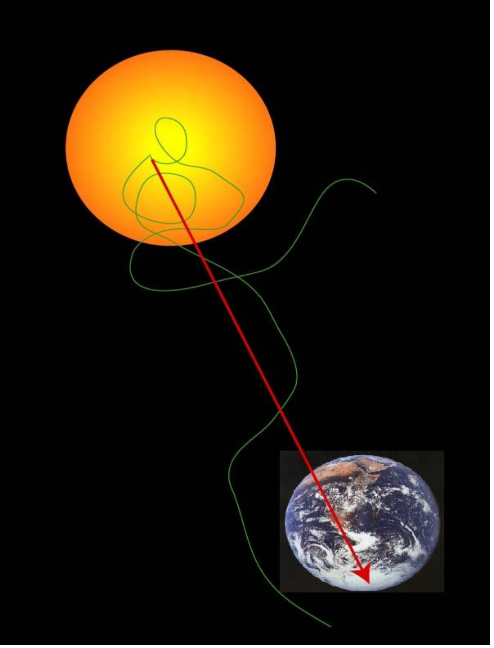




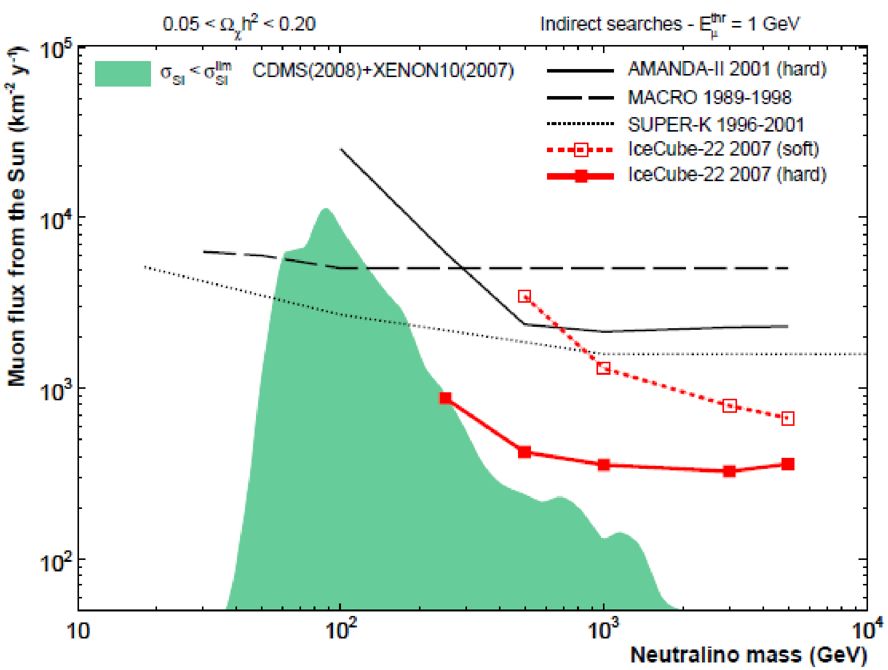
Majorana particles: helicity factor for fermions $\sigma v \sim m_f^2$

Note: equal amounts of matter and antimatter in annihilations

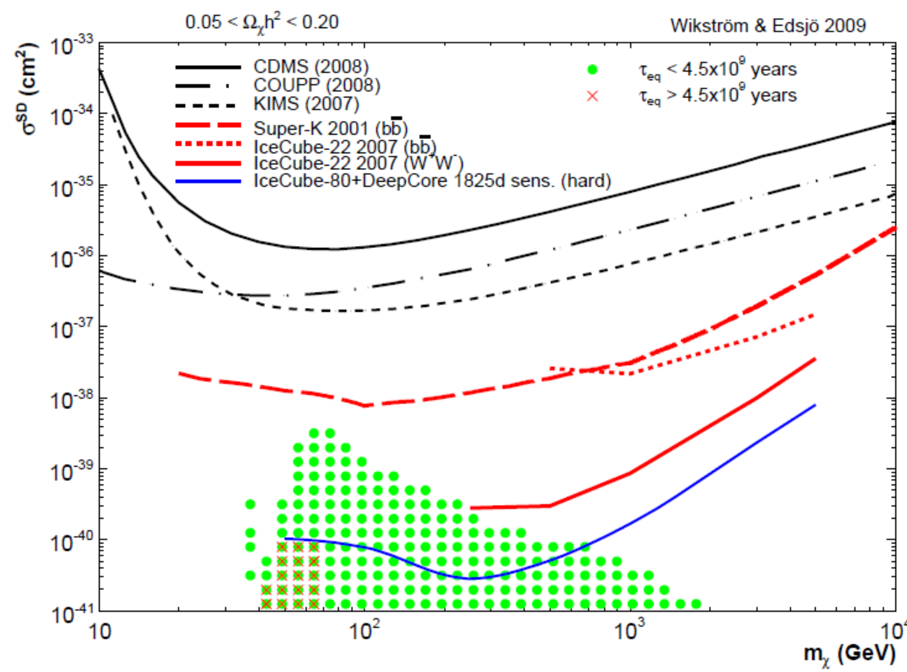
Decays from neutral pions, kaons etc:
DarkSUSY uses PYTHIA.



Indirect detection: Neutrinos from the Sun, IceCube-22 new limits (2009) on spin dependent interactions – just about starting to touch the interesting region in parameter space:

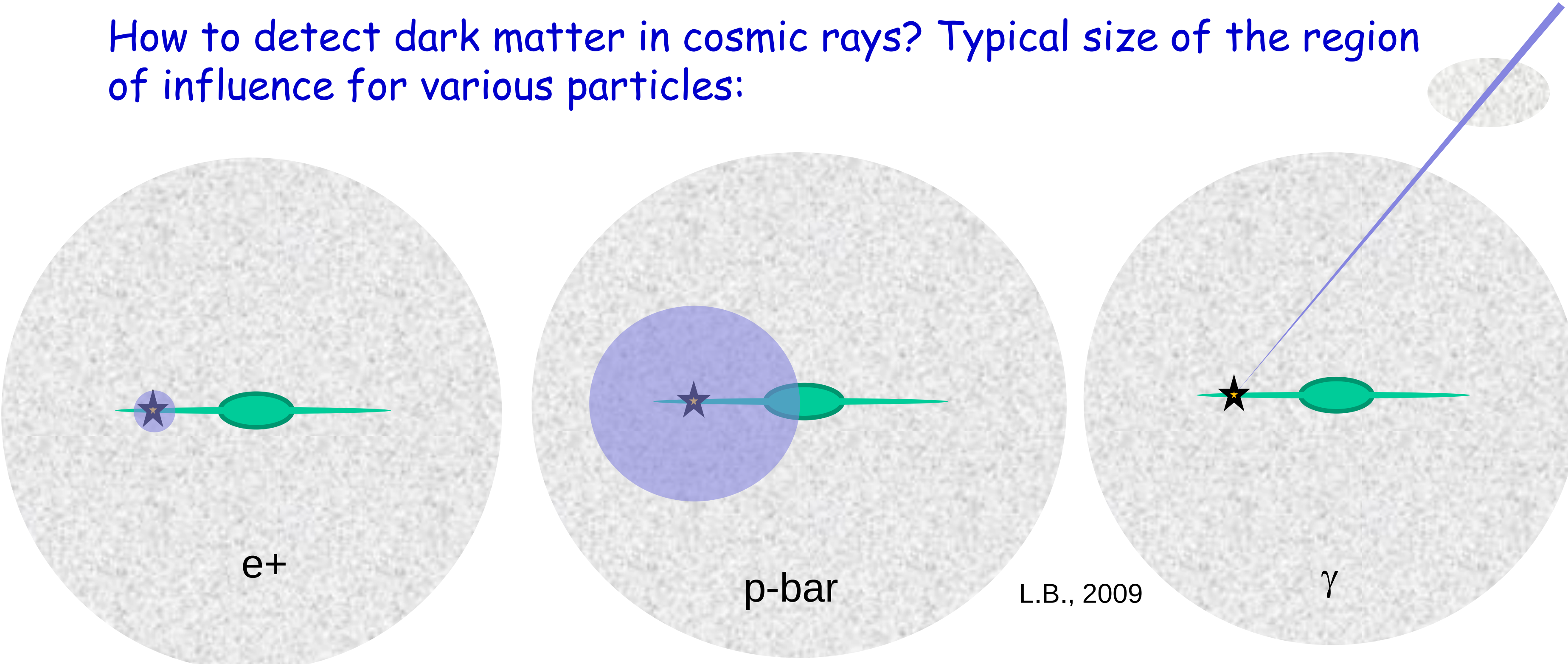


IceCube Collaboration, R. Abbasi et al. 2009



G. Wikström and J. Edsjö, 2009

How to detect dark matter in cosmic rays? Typical size of the region of influence for various particles:



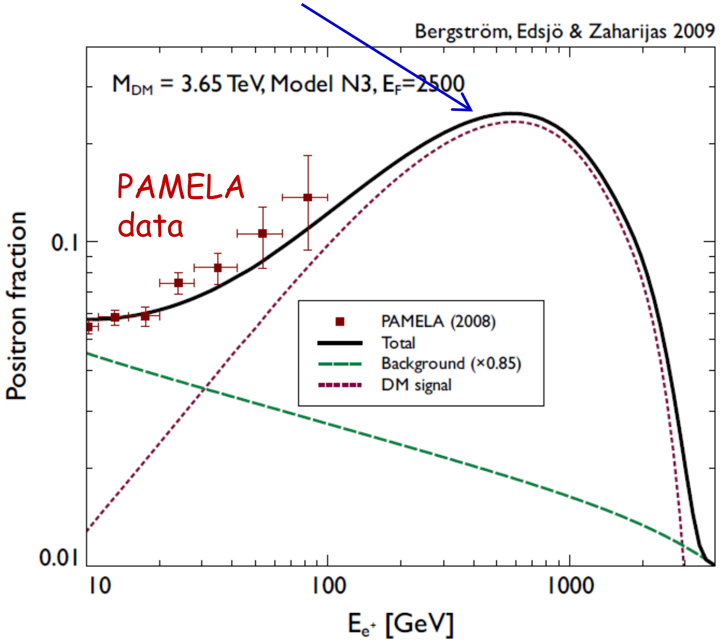
Positrons. Lose energy fast by inverse Compton and synchrotron radiation. For 500 GeV, less than a cubic parsec is important. No directional sensitivity, except for very local sources.

Antiprotons. Lose energy much slower . For 500 GeV, influence radius is roughly distance to galactic centre. Essentially no directional sensitivity.

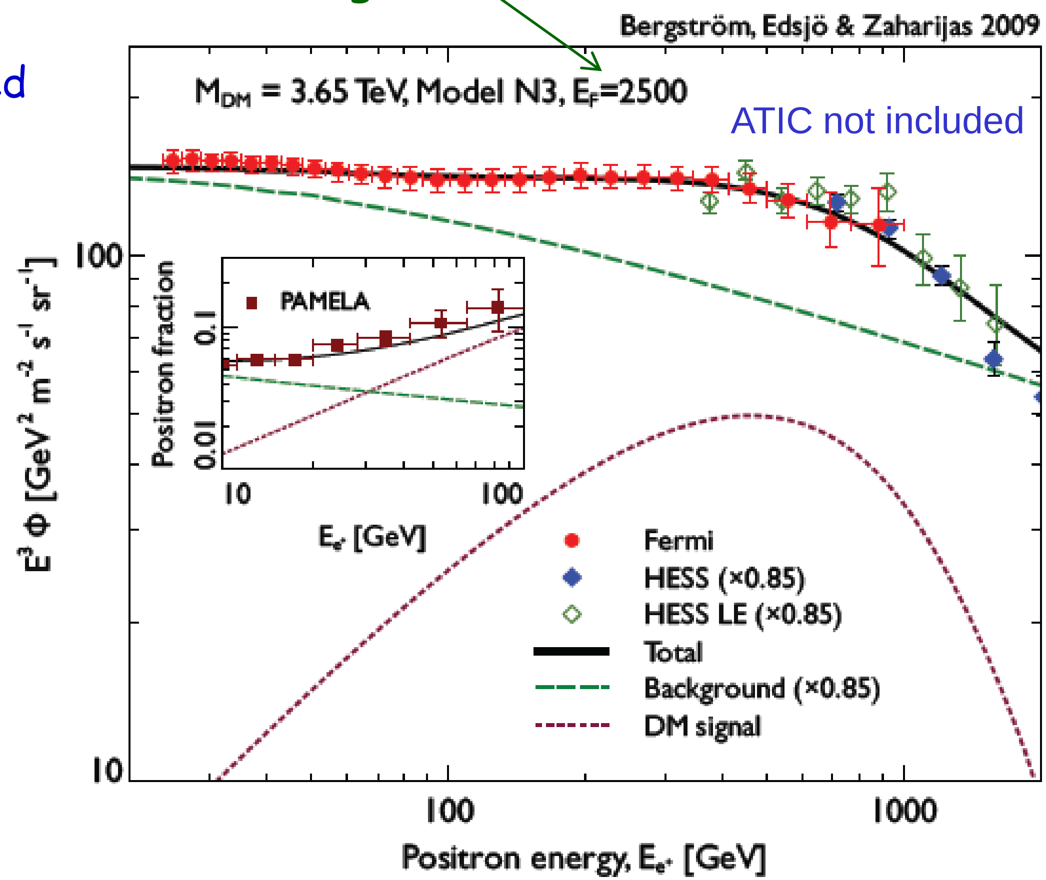
Gamma-rays. Do not lose energy at all on any galactic scale. Rates may be enhanced for lines of sight where the dark matter density is large. Spectral and directional signature.

Pamela and Fermi excess - Dark Matter fit

The energy dependence will be checked by AMS-02 (to be launched to the International Space Station later this year)

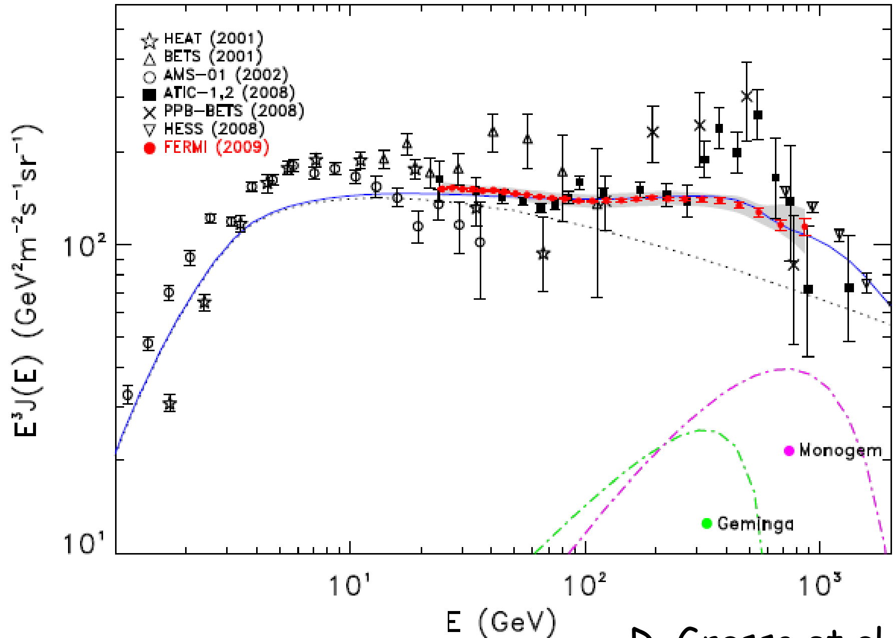


Huge boost factor needed

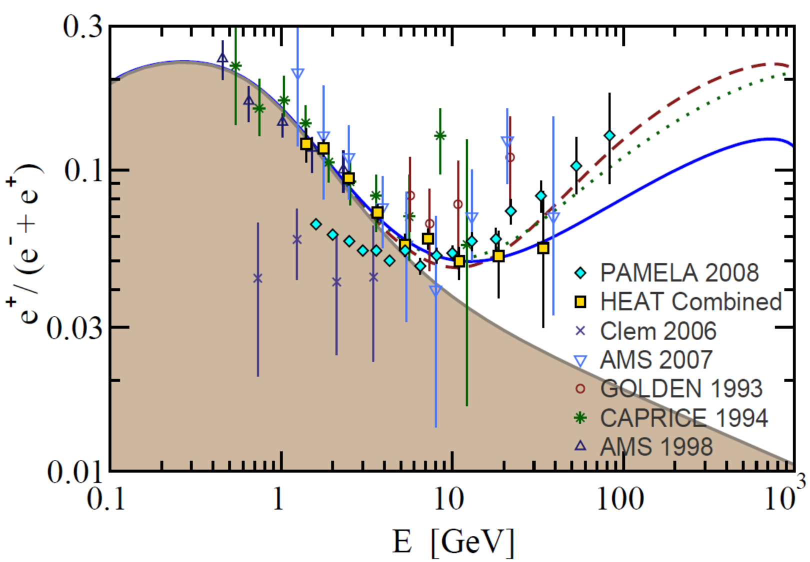


L.B., J. Edsjö and G. Zaharijas, PRL 2009.

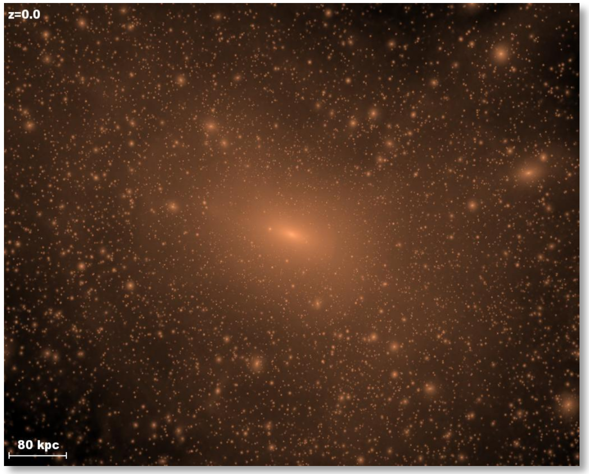
However, the DM spectral fit is not unique, e.g., nearby pulsars :



D. Grasso et al., 2009



Geminga pulsar estimates, Yüksel, Kistler, Stanev, 2008 (cf. Aharonian, Atoyan and Völk, 1995; Kobayashi et al., 2004)



One problem when using the excellent directionality 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) for objects (such as dwarf galaxies) contained in the angular resolution cone.

Fits to N-body simulations

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

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

Fits to rotation curves

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

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

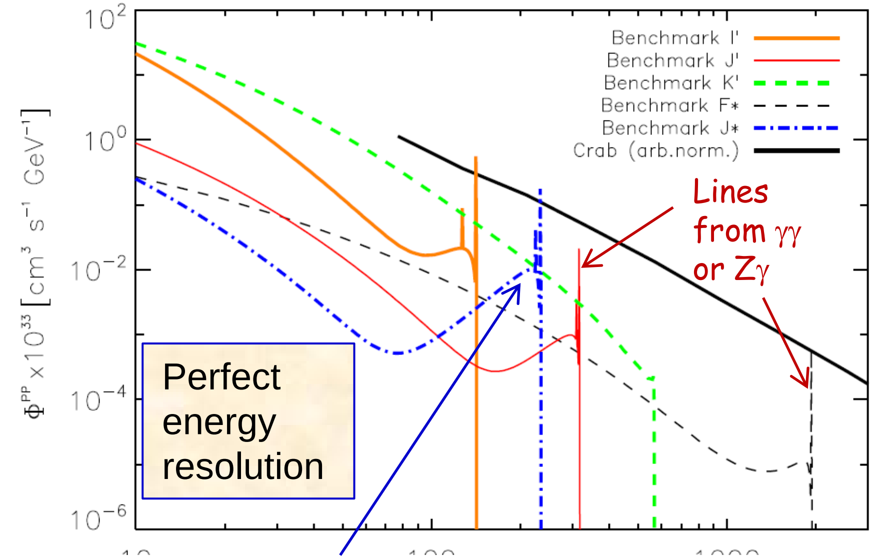
Indirect detection through γ-rays.
Several types of signal:

- 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.
- Inverse Compton radiation of electrons and positrons generated in annihilations.

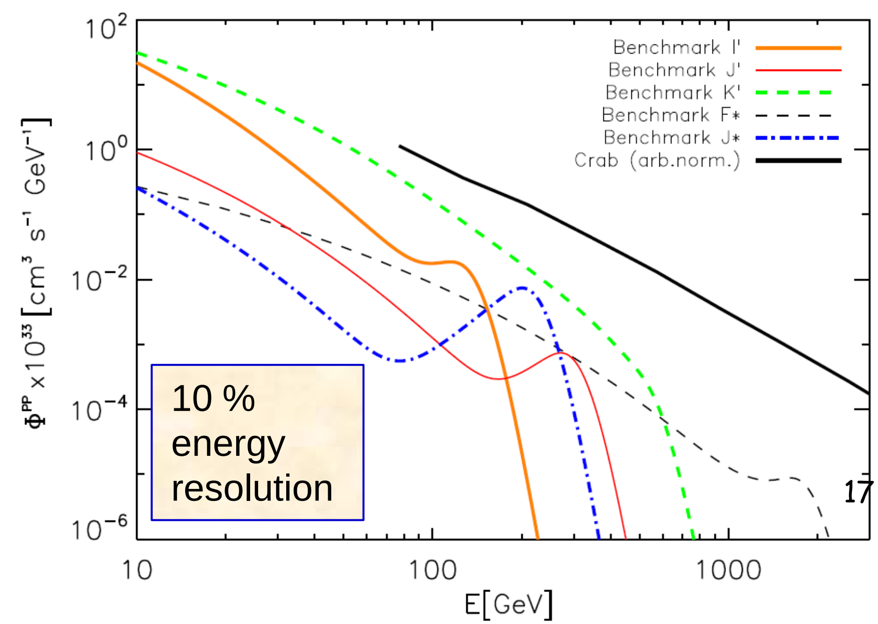
Enhanced flux possible thanks to halo density profile and substructure (as predicted by N-body simulations of CDM).

Good spectral and angular signatures!

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

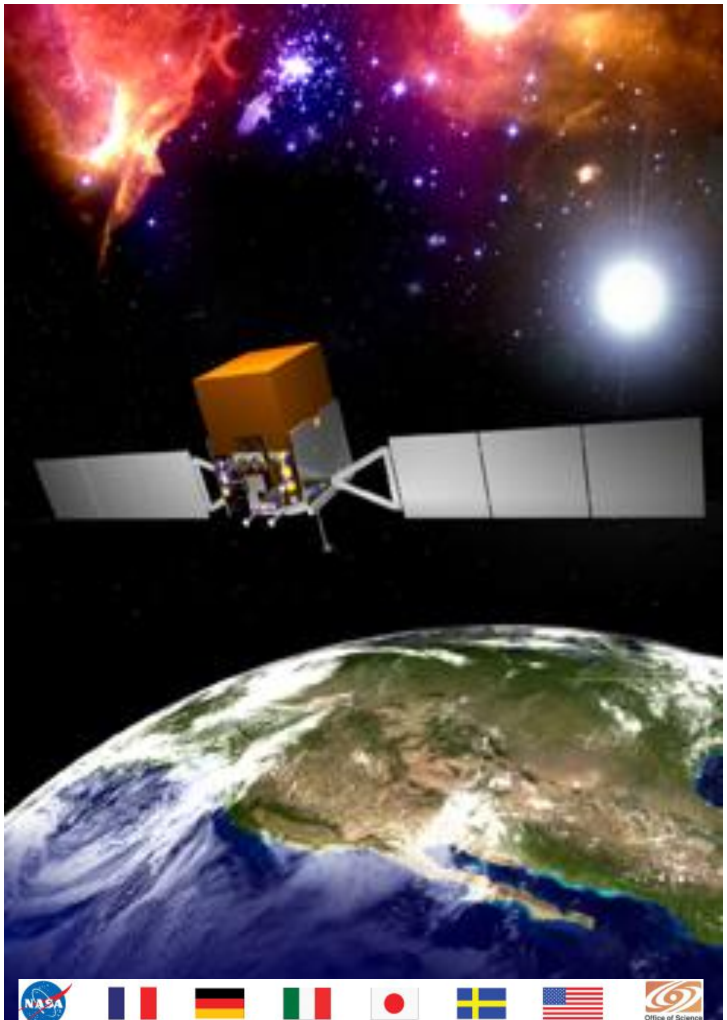


New contribution: Internal bremsstrahlung
(T. Bringmann, L.B., J. Edsjö, 2007)

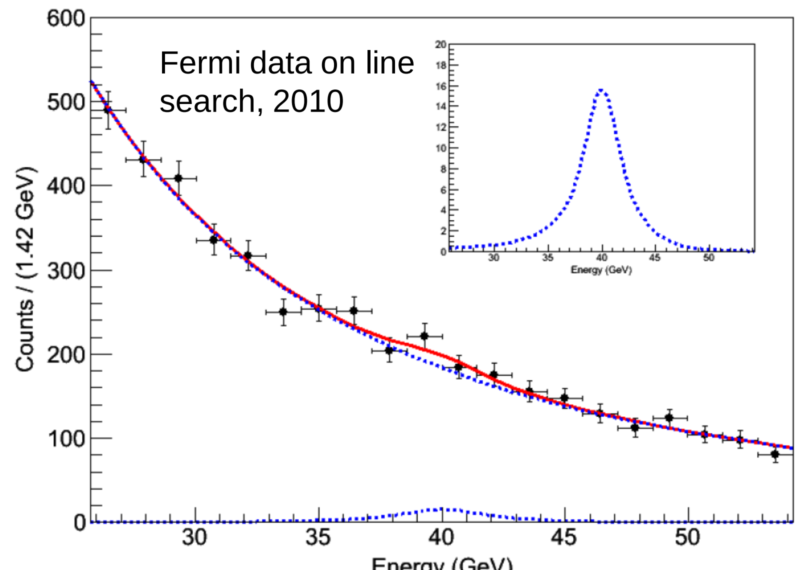


T. Bringmann, M. Doro & M. Fornasa, 2008; cf. L.B., P.Ullio & J. Buckley 1998.

Gamma-ray lines from dark matter annihilations:



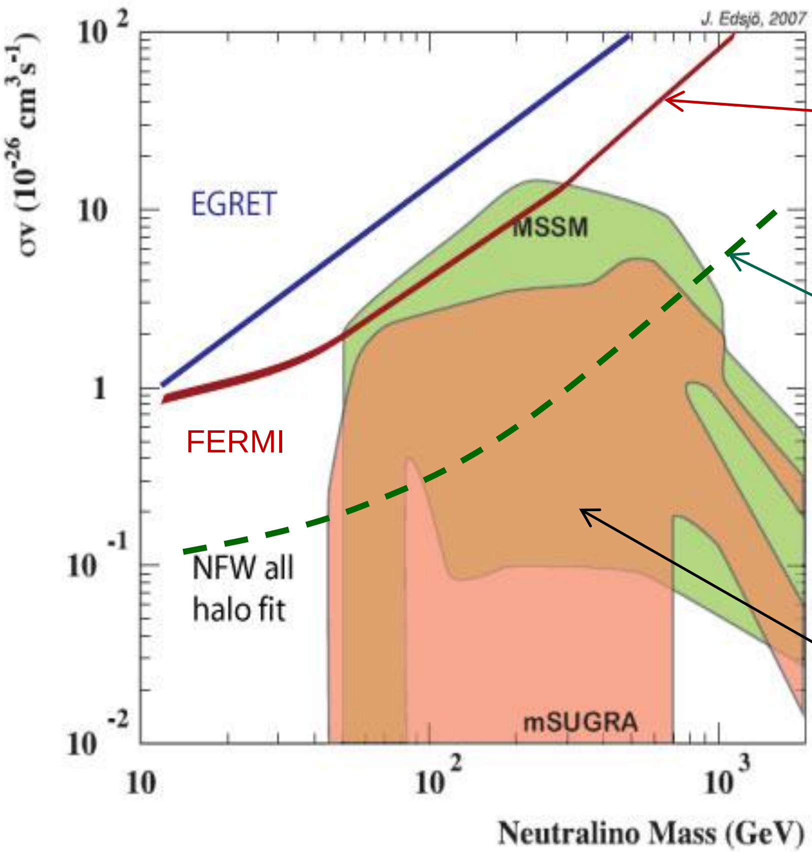
USA-France-Italy-Sweden-Japan – Germany collaboration, launched June 2008.



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.

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 ⇒ complementarity (see later)



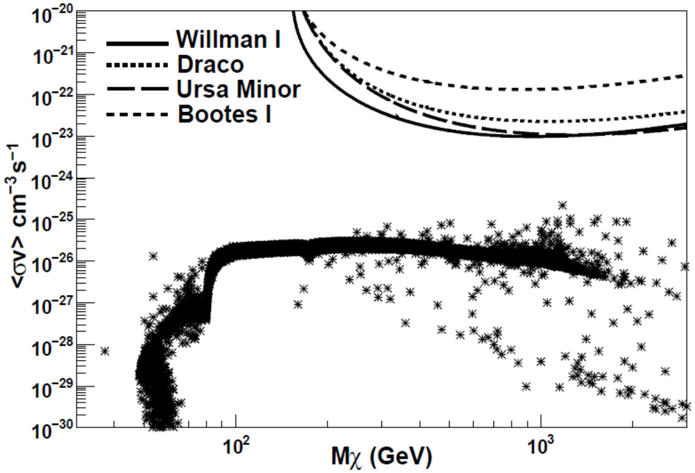
"Conservative" approach, g.c.,

NFW halo profile assumed, no substructure.

Including all halo, with substructure

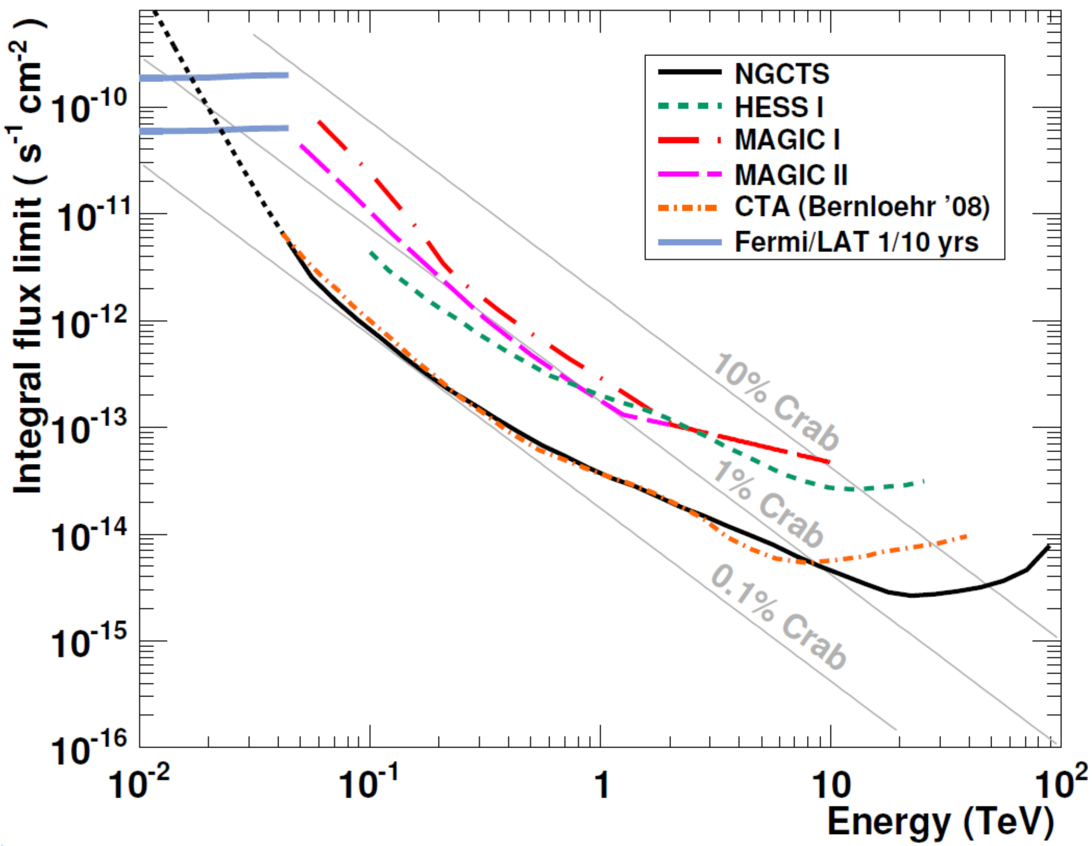
Will not be probed by Fermi, but by next generation of (ground-based) gamma-ray instruments, like CTA/AGIS

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



Example of present best limits from ground-based experiments (VERITAS, June 2010)

The future? Possible Cherenkov Telescope Array (CTA) in Europe and AGIS in the US (which now has become CTA-US).



M. Raue & D. Mazin, COSPAR 2010, Bremen

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 sciences. Large (and expensive) equipment is being deployed and planned for accelerator (LHC, ILC…) and direct detection (SuperCDMS, Xenon 1t…) searches.

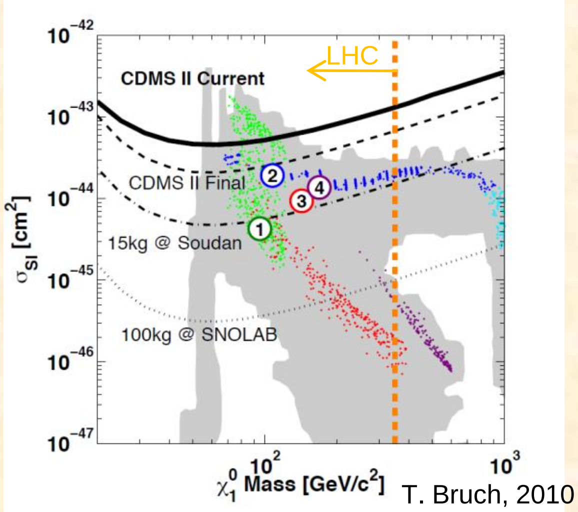
Thus why not THINK BIG: What can be done with a DEDICATED Dark Matter detector for indirect detection - not (for now) worrying about the cost or manpower?

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 sqrt(1000). Energy threshold 10 GeV, PSF 0.02° (as CTA), but 0.1° below 40 GeV. Maybe a SuperCTA at the ALMA site?

Setup for analysis (L.B., T. Bringmann & J. Edsjö, to appear):

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.

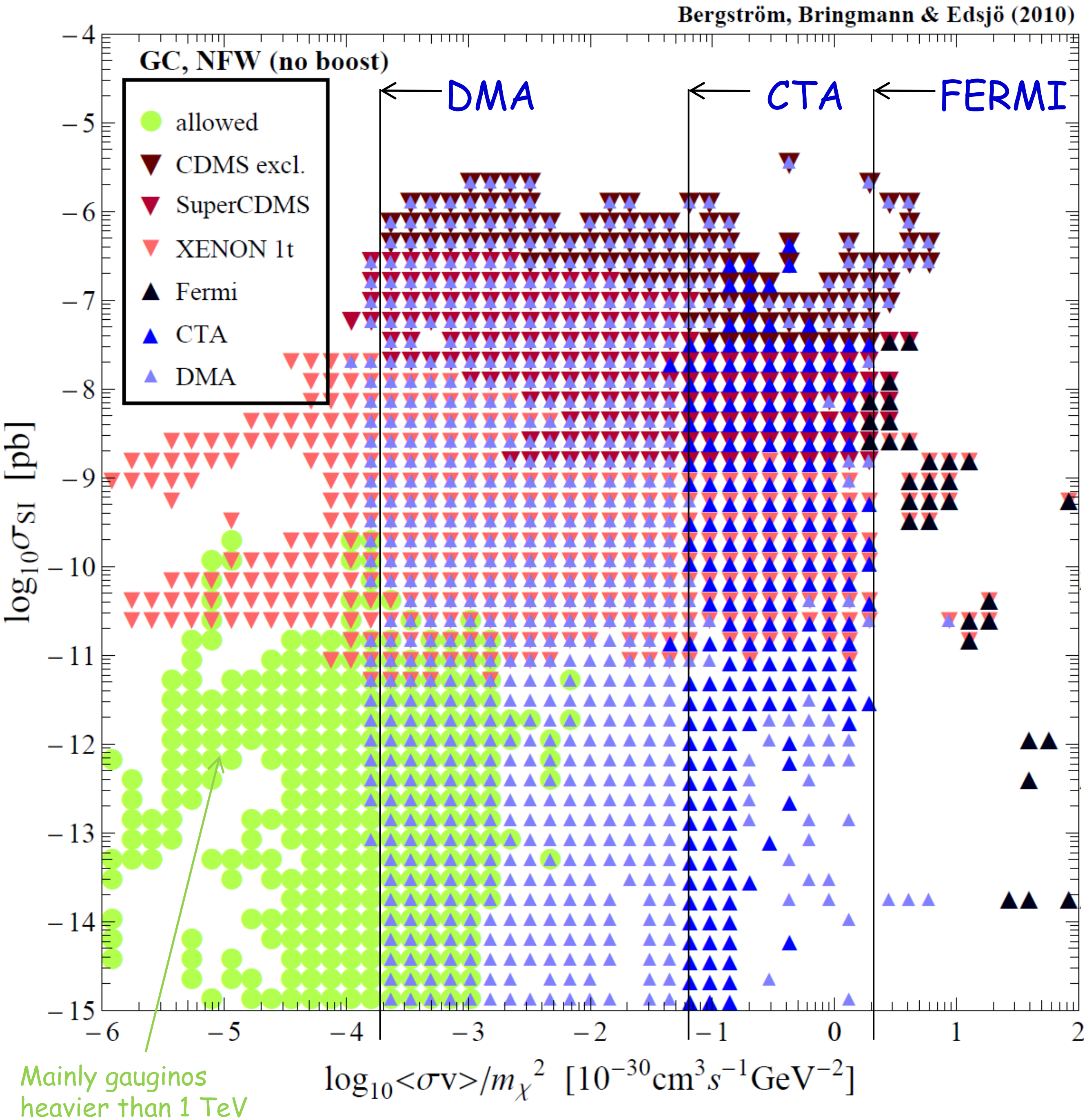
SuperCDMS: As described in T. Bruch, 2010.

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 home page.

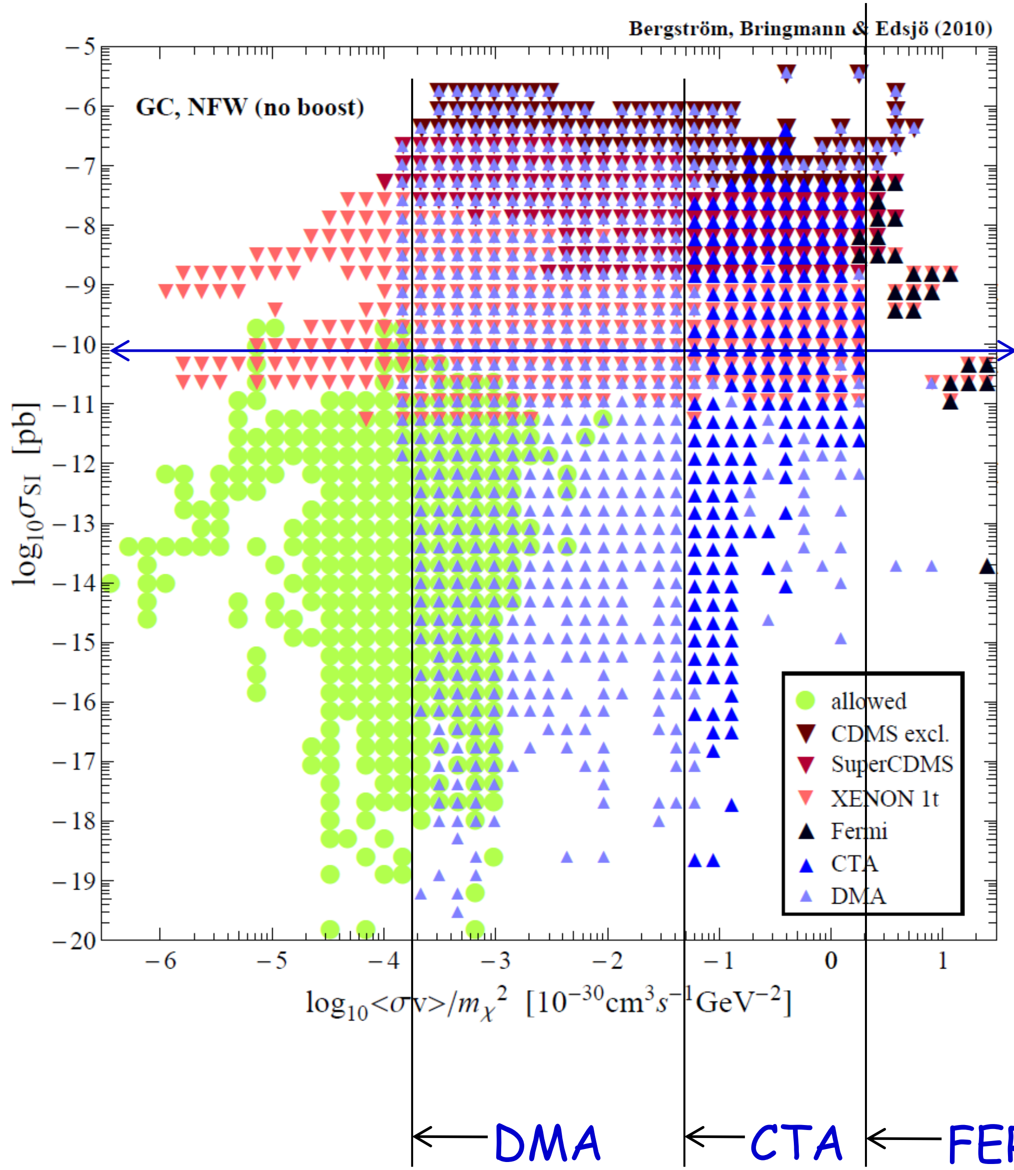
CTA: Energy threshold 40 GeV, 17 bins up to 5 TeV, sensitivity curve according to Bernlöhr (2007), integration time 50 hours, effective area as in Arribas (thesis) - max $A_{eff} \sim 2 \times 10^6$ m^2.

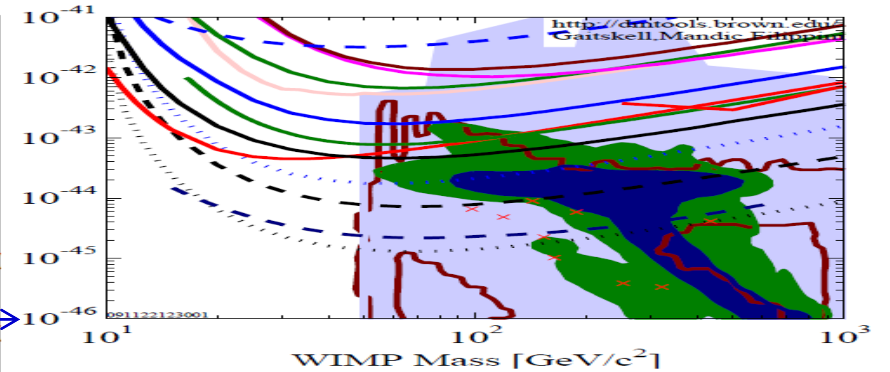
DMA: Energy threshold 10 GeV, sensitivity curve CTA/sqrt(1000), max $A_{eff} = 2 \times 10^7$ m^2, integration time 5000 hours.



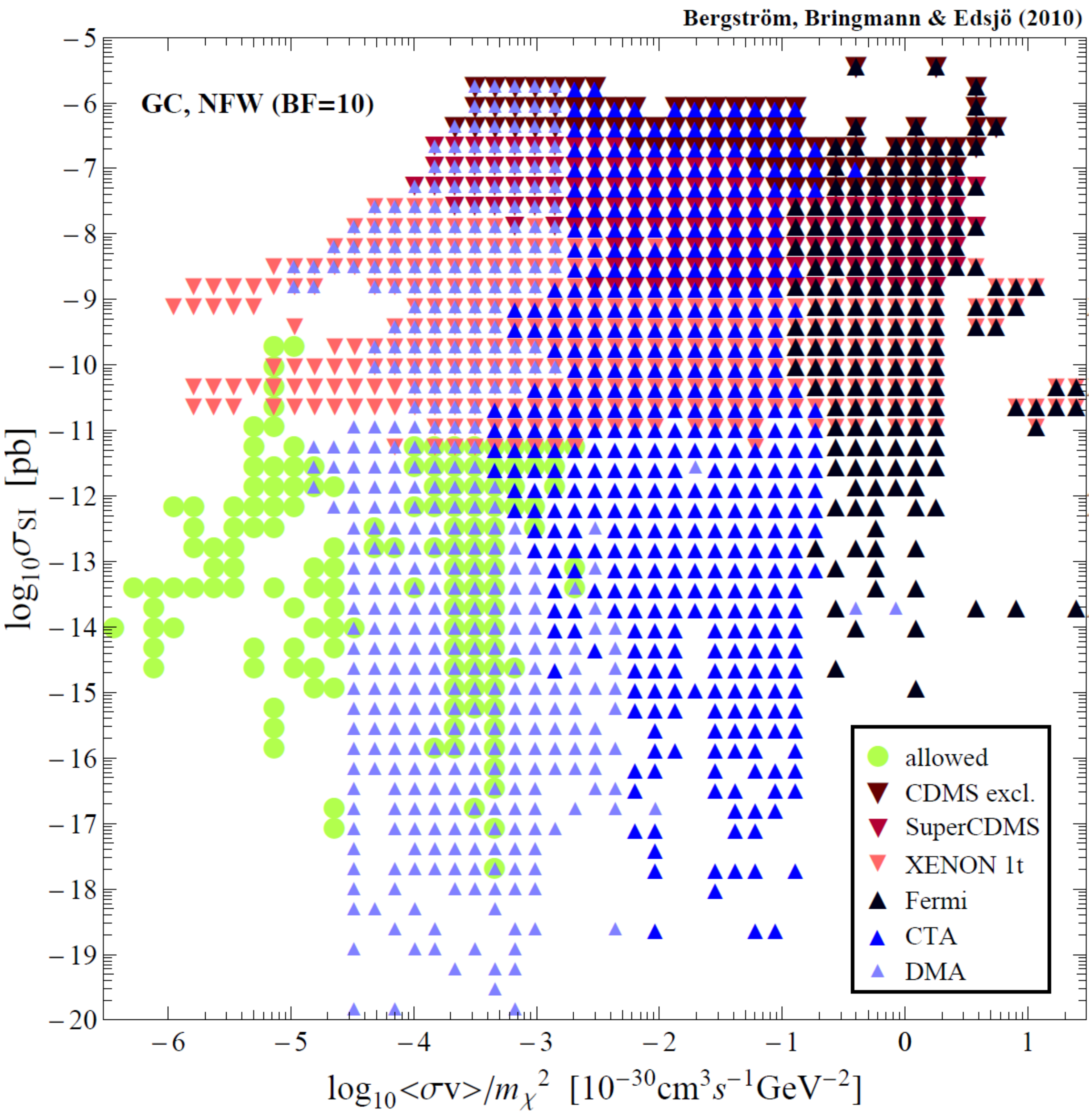
Assumed background according to S. Digel, Fermi Symposium, 2009 (extrapolated as power-law for E > 100 GeV).

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

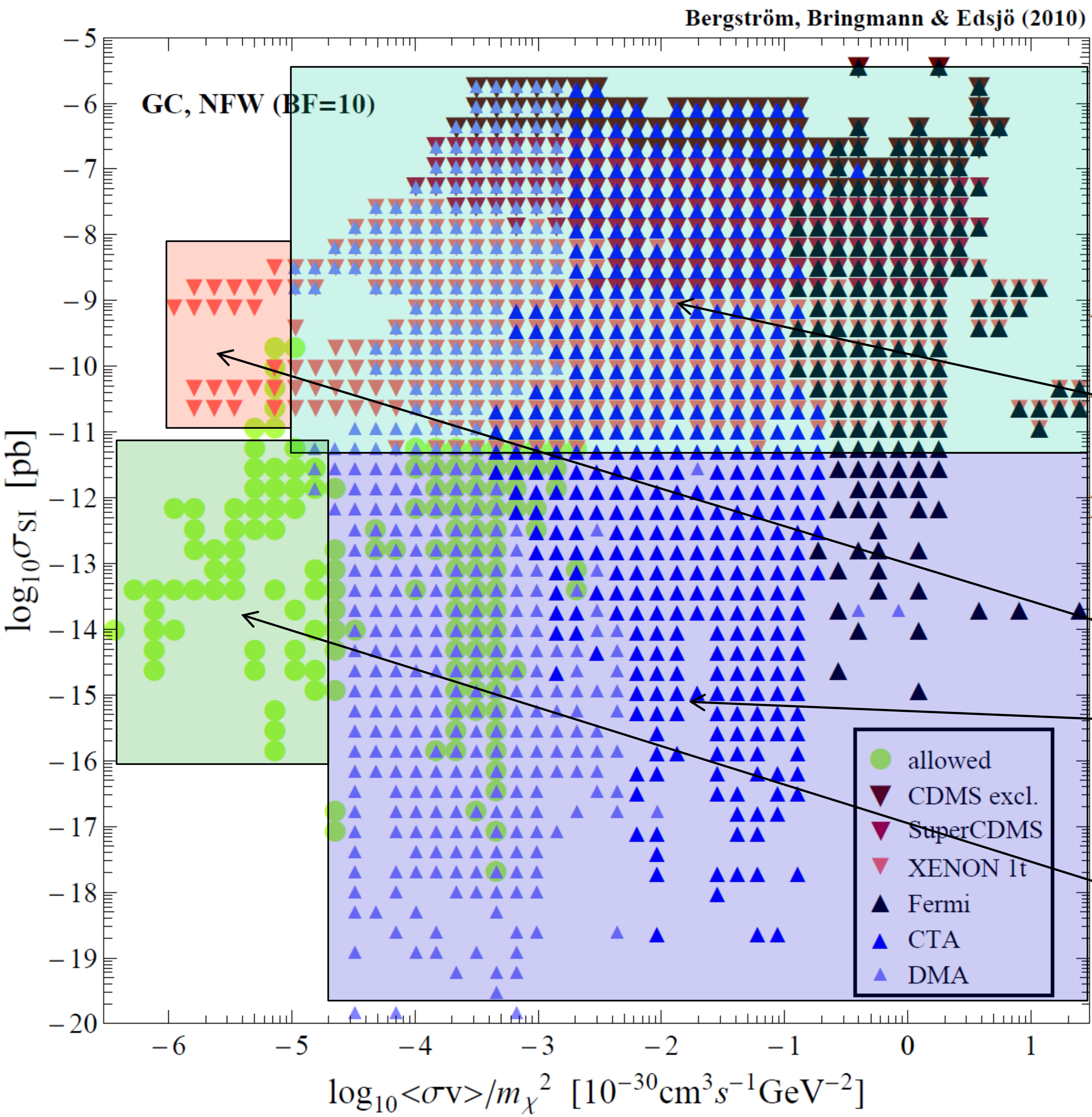




The parameter space does indeed continue (10 more orders of magnitude in direct detection cross section!)



NFW with moderate boost, looks even better...



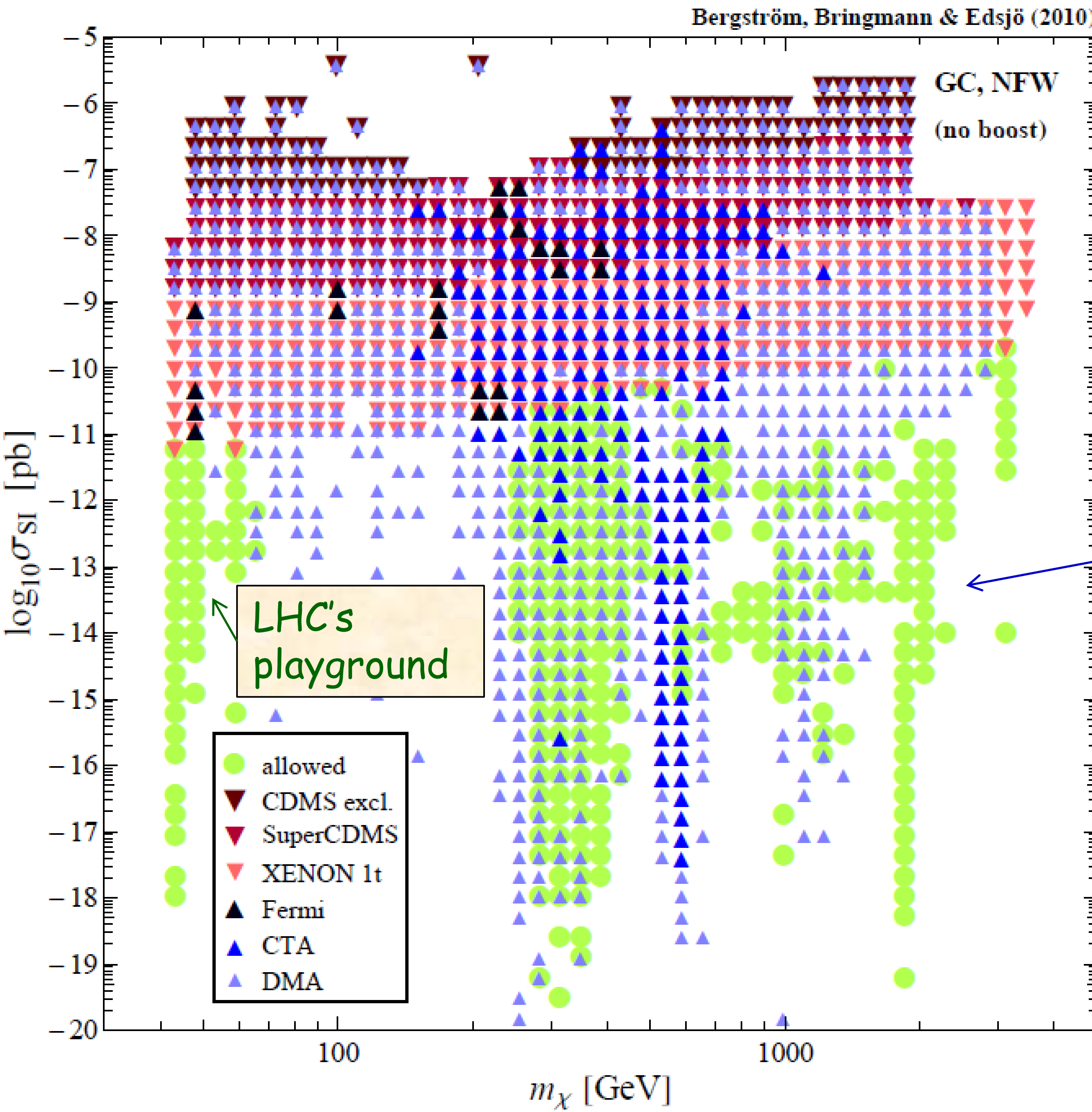
NFW with moderate boost, looks even better...

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

Here direct detection rules

Here indirect detection rules

The impossible part, or?...



Here gamma-ray rates may/should be enhanced by the Sommerfeld effect (Hisano & al., 2004) - not yet included .

Conclusions:

Dark Matter exists!

It will be hunted by LHC, direct detectors, and in various cosmic rays (indirect detection). These searches complement each other.

Several experiments like Fermi, PAMELA, IceCube, Super-K may have the potential for discovery. Dark Matter may have been seen by PAMELA and FERMI already, but no convincing model or confirming evidence from other channels yet. AMS-2 and IceCube may hopefully give more information.

To make real progress and cover a large part of parameter space that accelerators and direct detectors can hardly ever reach - we may need CTA and a future dedicated Dark Matter indirect detection experiment - the

DMA - Dark Matter Array!

The end