Dark Matter in the Universe

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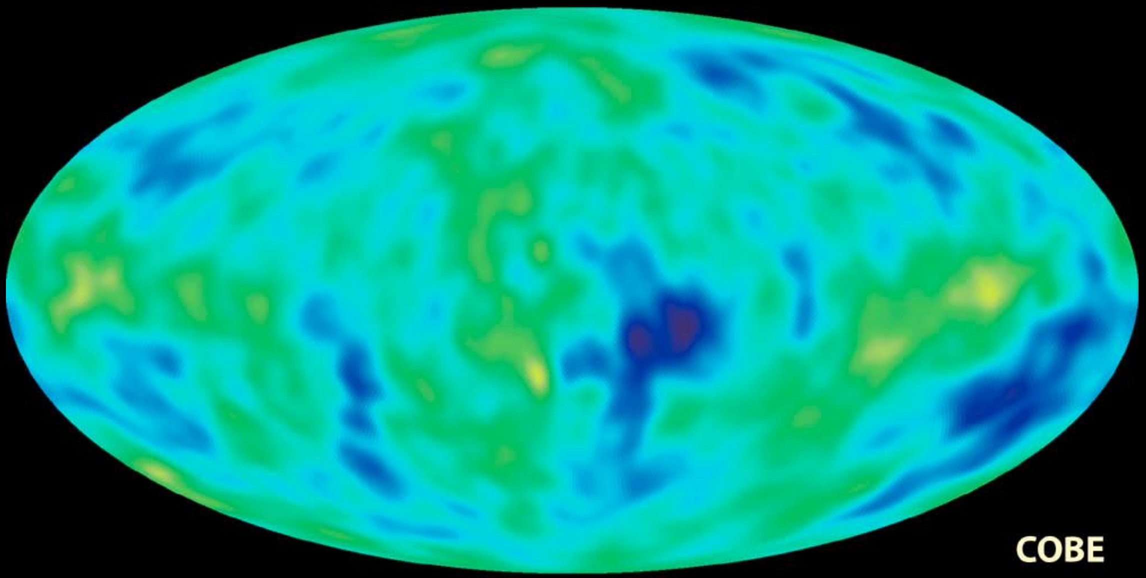
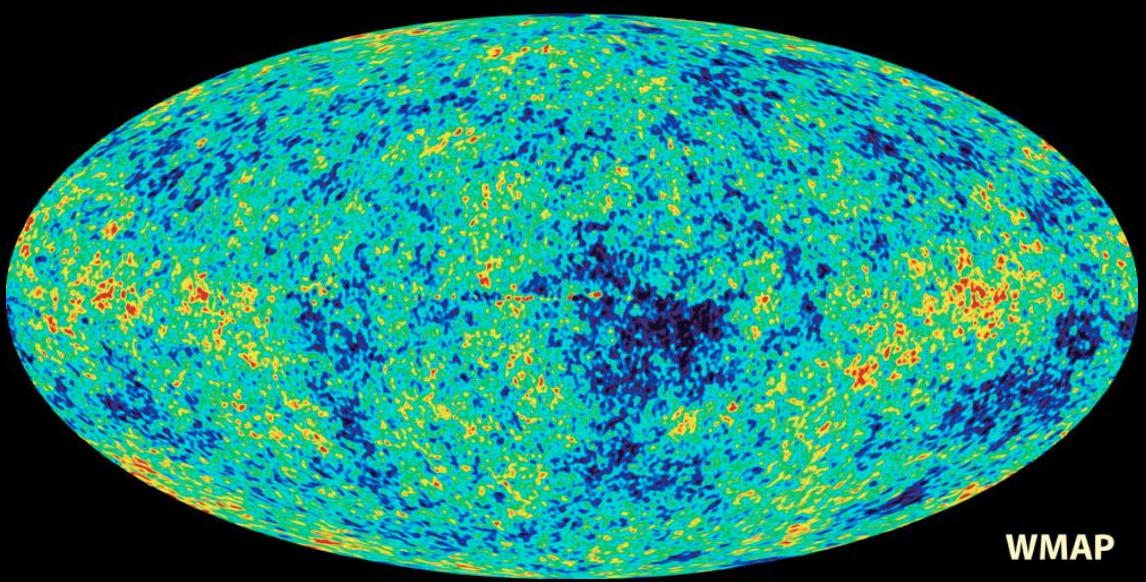
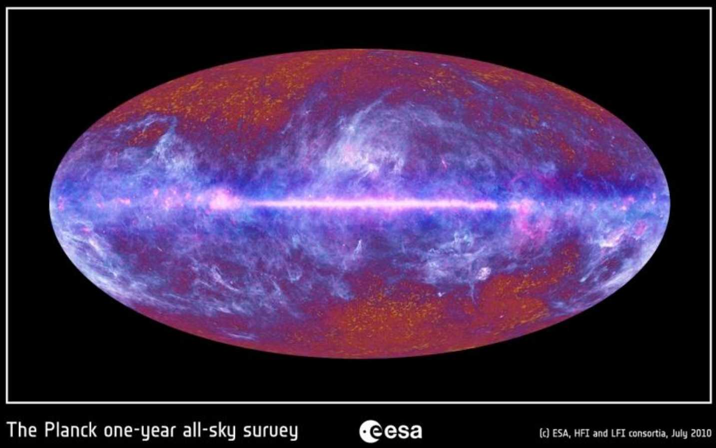
Fritz Zwicky, 1933: Velocity dispersion of galaxies in Coma cluster indicates presence of Dark Matter , $\sigma \sim 1000$ km/s $\Rightarrow M/L \sim 50$

"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."

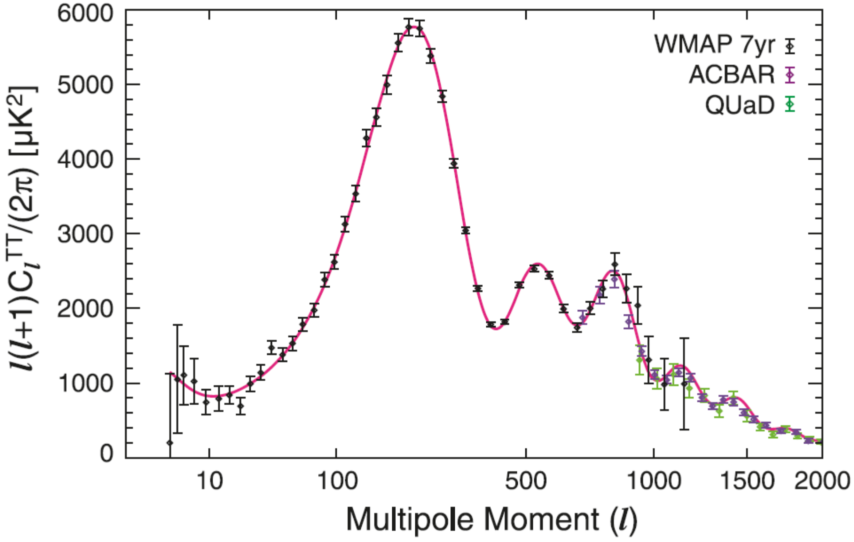






First sky map of Planck data 2010 - wait until 2011 for full release; 2012 for cosmology

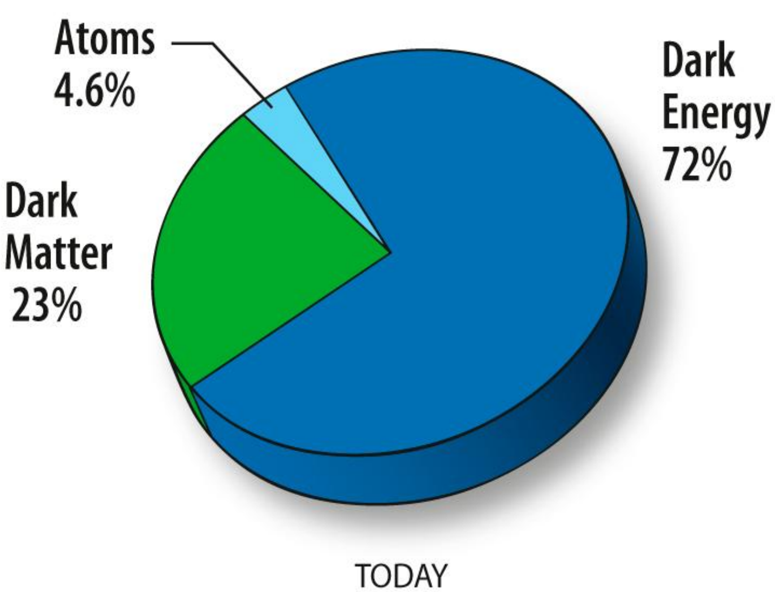
WMAP 2010:



$$\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} \approx 1.003 \pm 0.01$$

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

$\Omega_B = 0.0456 \pm 0.0016$ $h = 0.704 \pm 0.014$



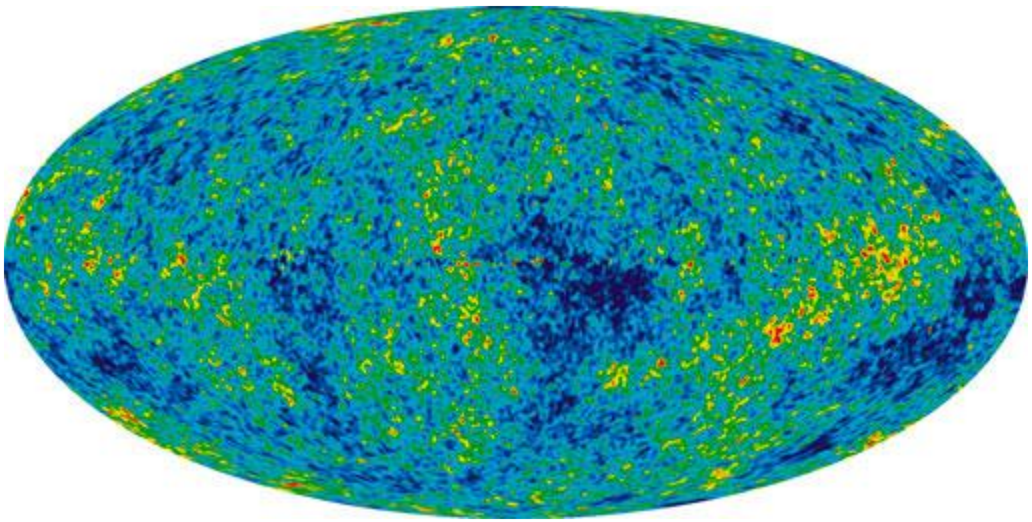
The ΛCDM Model:

Cold Dark Matter model (meaning the particles move non-relativistically, i.e., slowly) with a cosmological constant Λ being the dark energy.

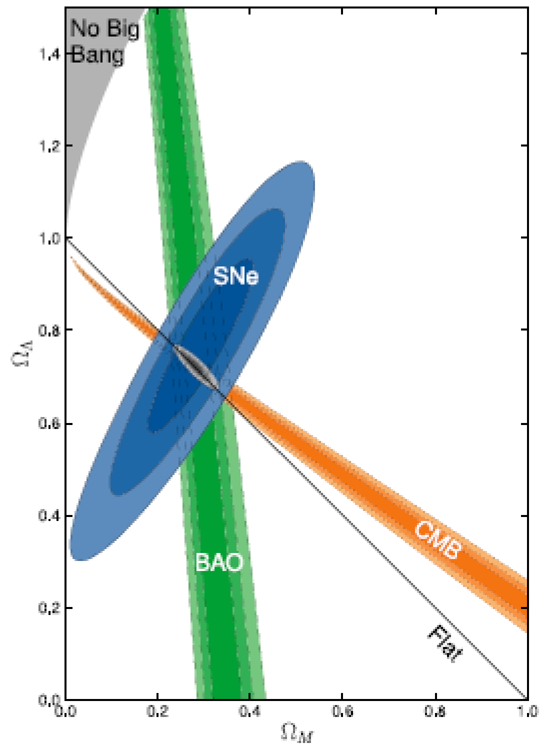
Seems to fit all cosmological data!

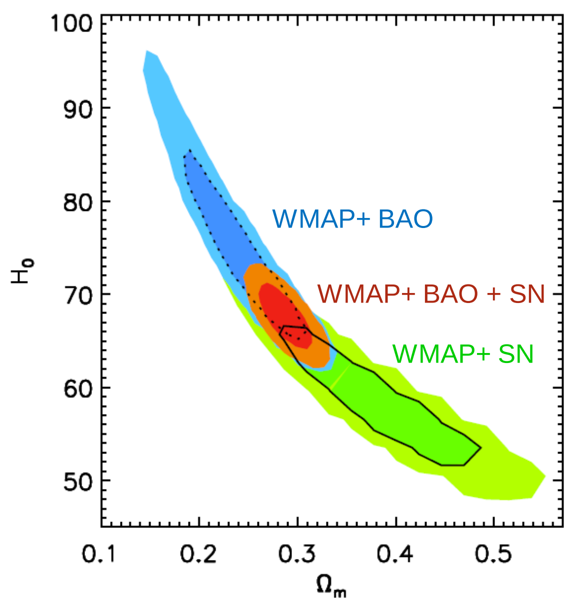
R. Amanullah et al., arXiv:1004.1711

WMAP 7-year sky map

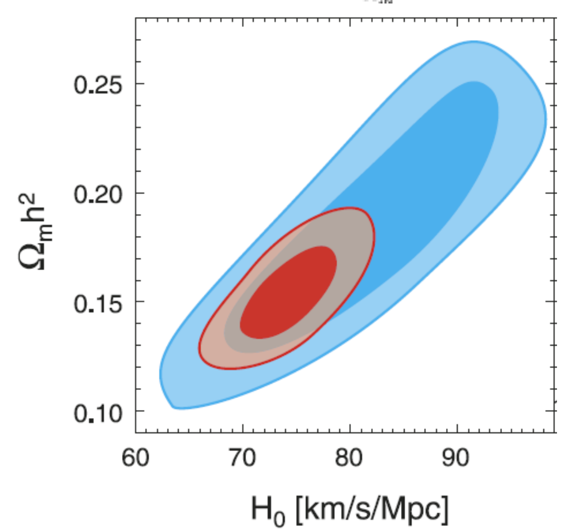


NASA/WMAP Science Team, 2010





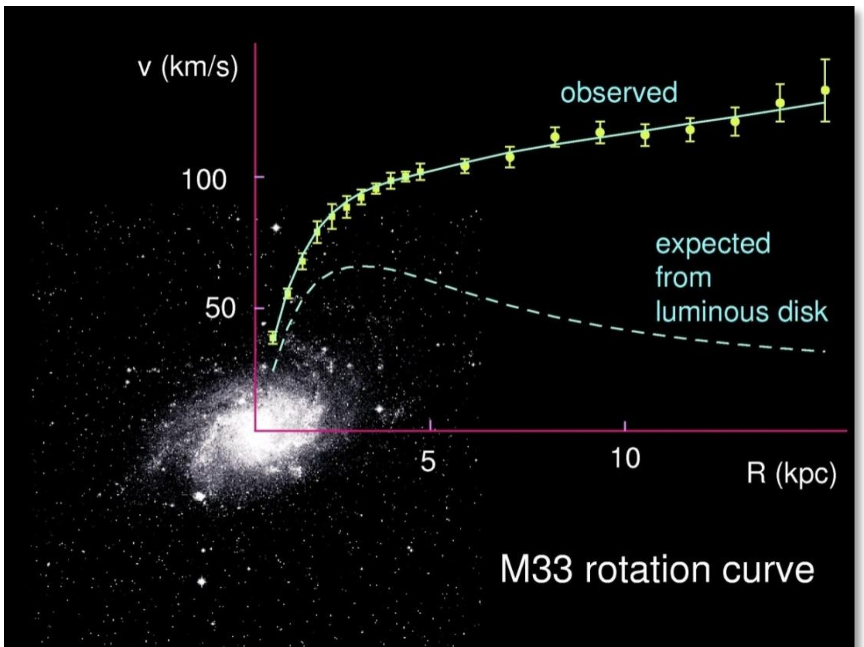
Baryon Acoustic Oscillations (BAO) SDSS,
W. Percival & al. 2009



WMAP 7-year, Komatsu & al., 2010

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



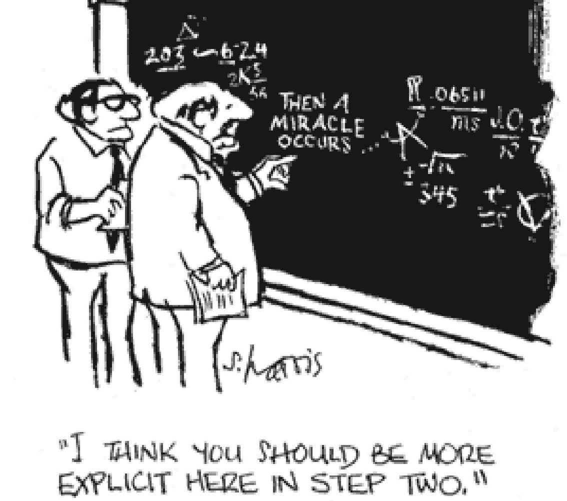
L.B., Rep. Prog. Phys. 2000

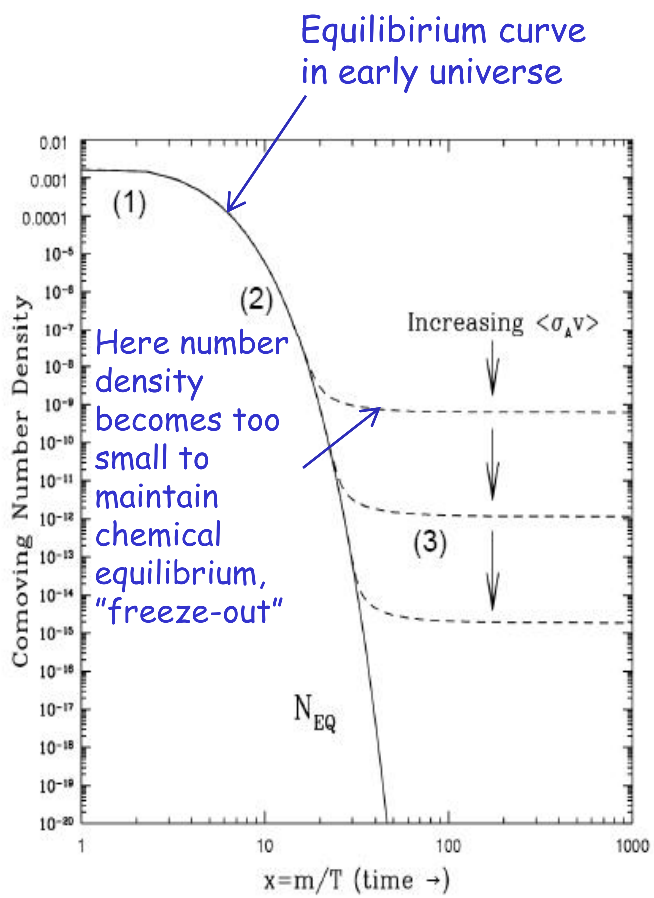
Colliding galaxy clusters

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

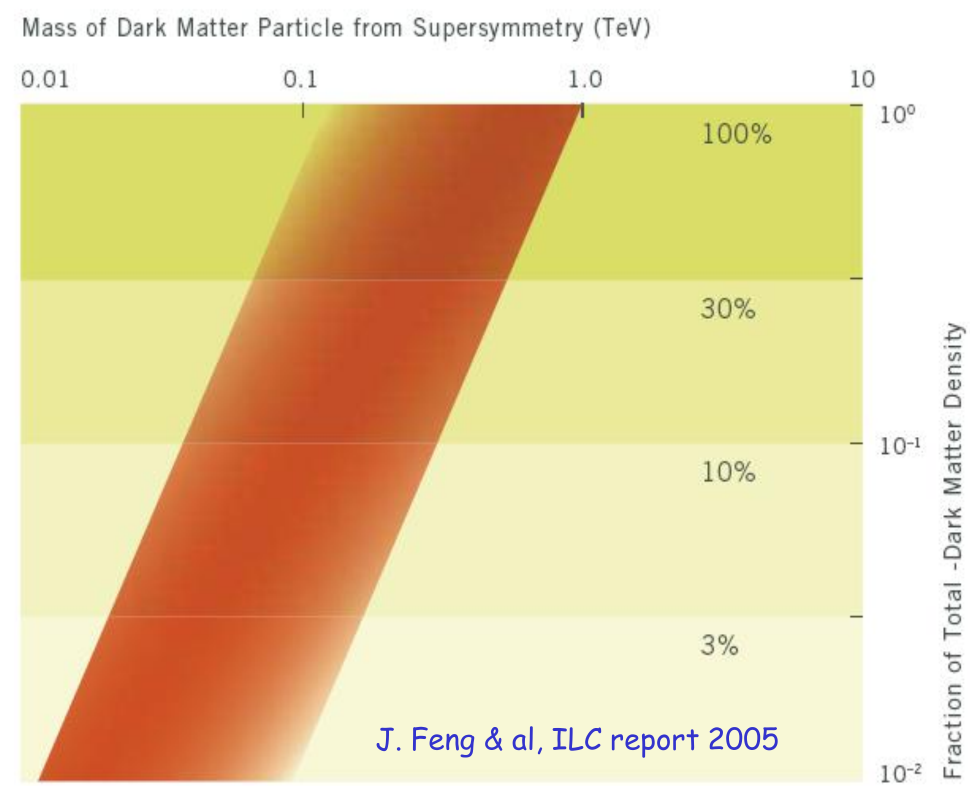
The "WIMP miracle"

The weak interaction mass scale and ordinary gauge couplings give right relic DM density withour fine-tuning



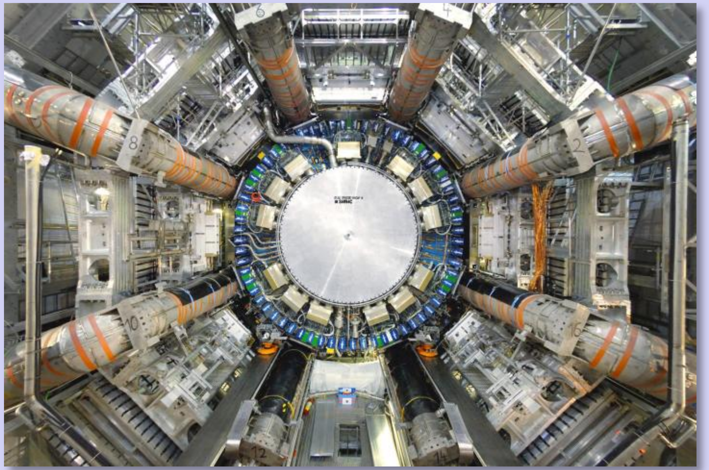


The "natural" mass range for WIMPs is roughly 10 GeV to a few TeV

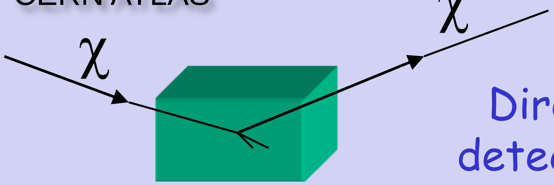


Methods of WIMP Dark Matter detection:

- 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.



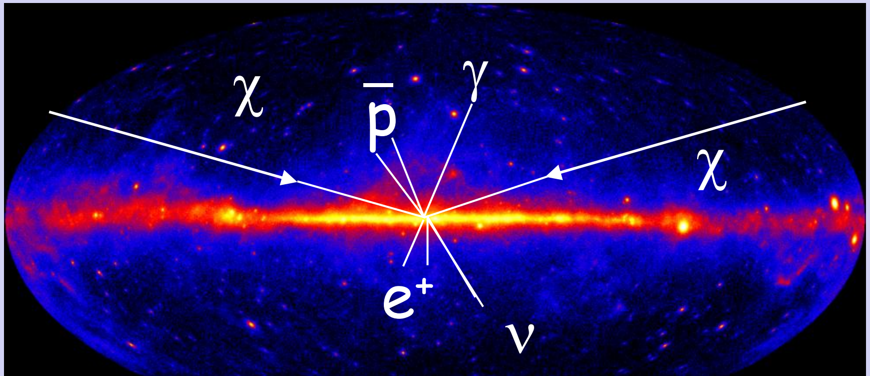
CERN ATLAS



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



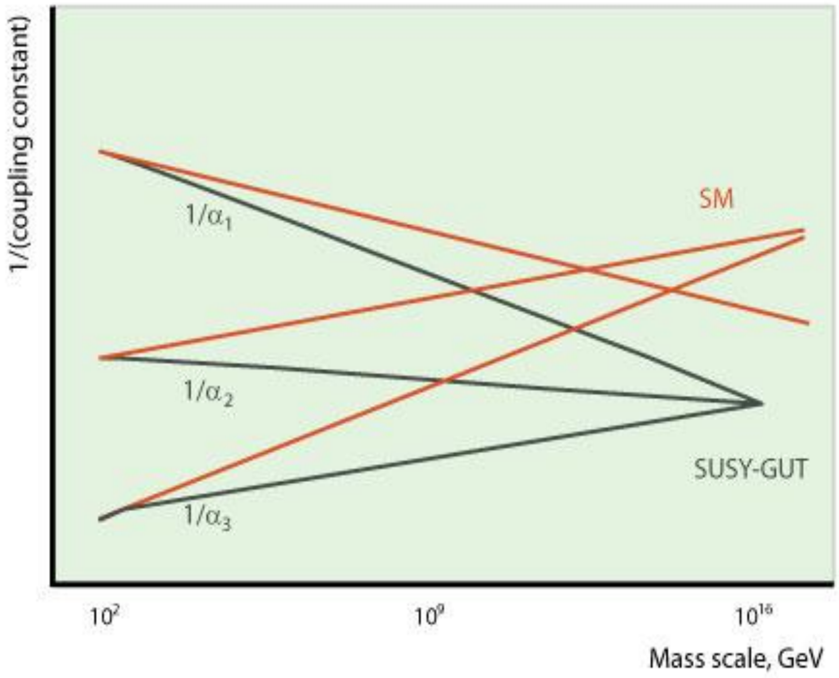
The Milky Way in gamma-rays as measured by FERMI

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

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

Supersymmetry

- Invented in the 1970's
- Necessary in most string theories
- Restores unification of couplings
- Can solve the 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 (If R-parity is conserved $\Rightarrow$ stable on cosmological timescales)
- Useful as a template for generic "WIMP" (Weakly Interacting Massive Particle)



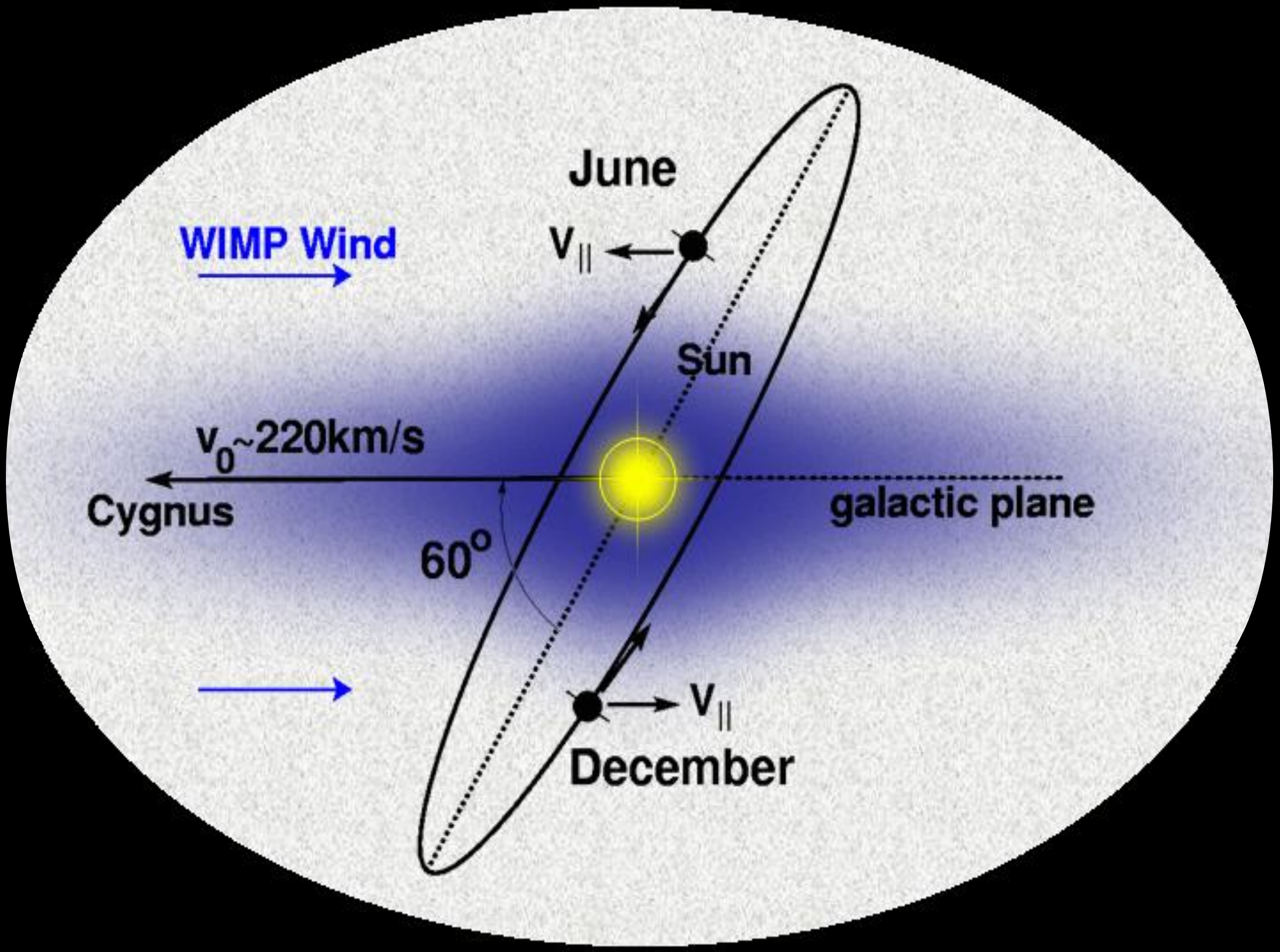
The lightest neutralino: The most natural SUSY dark matter candidate

$$\tilde{\chi}^0 = a_1\tilde{\gamma} + a_2\tilde{Z}^0 + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0$$

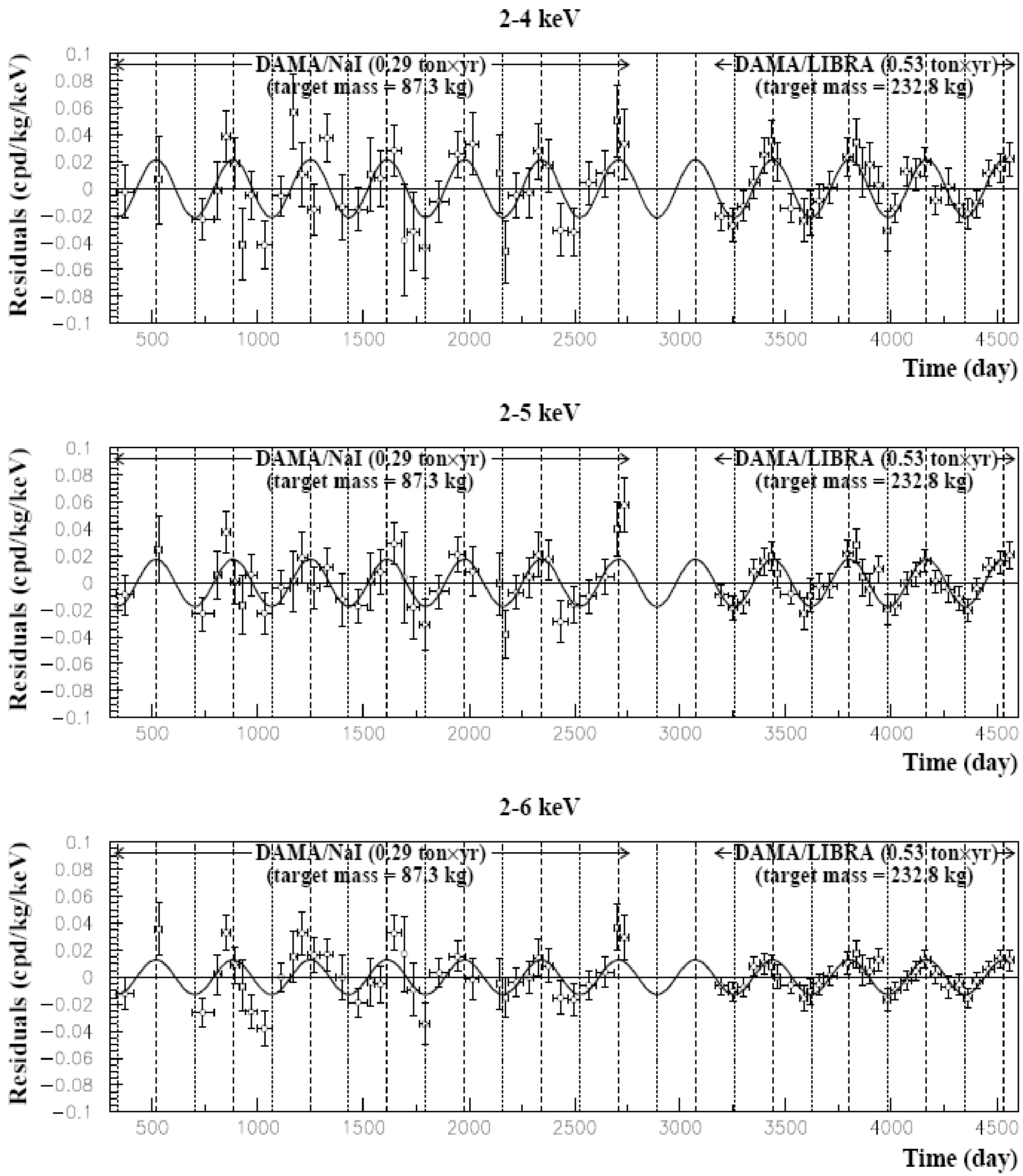
Gaugino part Higgsino part

What is dark matter?
Nobody knows…
There have been many (false?) alarms during the last decade. Most of these phenomena would need contrived (non-WIMP) models for a dark matter explanation:

Indication	Status
DAMA annual modulation	Unexplained at the moment
EGRET excess of GeV photons	Due to instrument error (?) - not confirmed by FERMI
INTEGRAL 511 keV γ-line from galactic centre	Does not seem to have spherical symmetry - shows an asymmetry which follows the disk (?)
PAMELA: Anomalous ratio e^+/e^-	Possibly due to pulsars - energy signature not unique for DM
Fermi positrons + electrons	Possibly due to pulsars- energy signature not unique for DM
FERMI excess towards g.c.	Unexplained at the moment
CoGeNT/CDMS excess events	Tension with other data



Drukier, Freese, Spergel, 1986

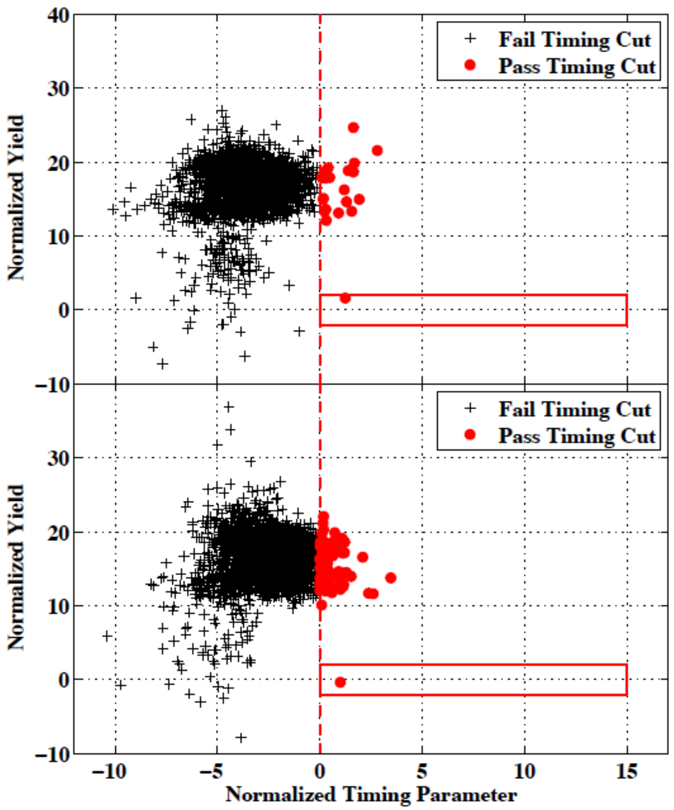


DAMA/LIBRA: Annual modulation of unknown cause. Consistent with dark matter signal (but not confirmed by any other experiment).

Claimed significance: More than 8σ !

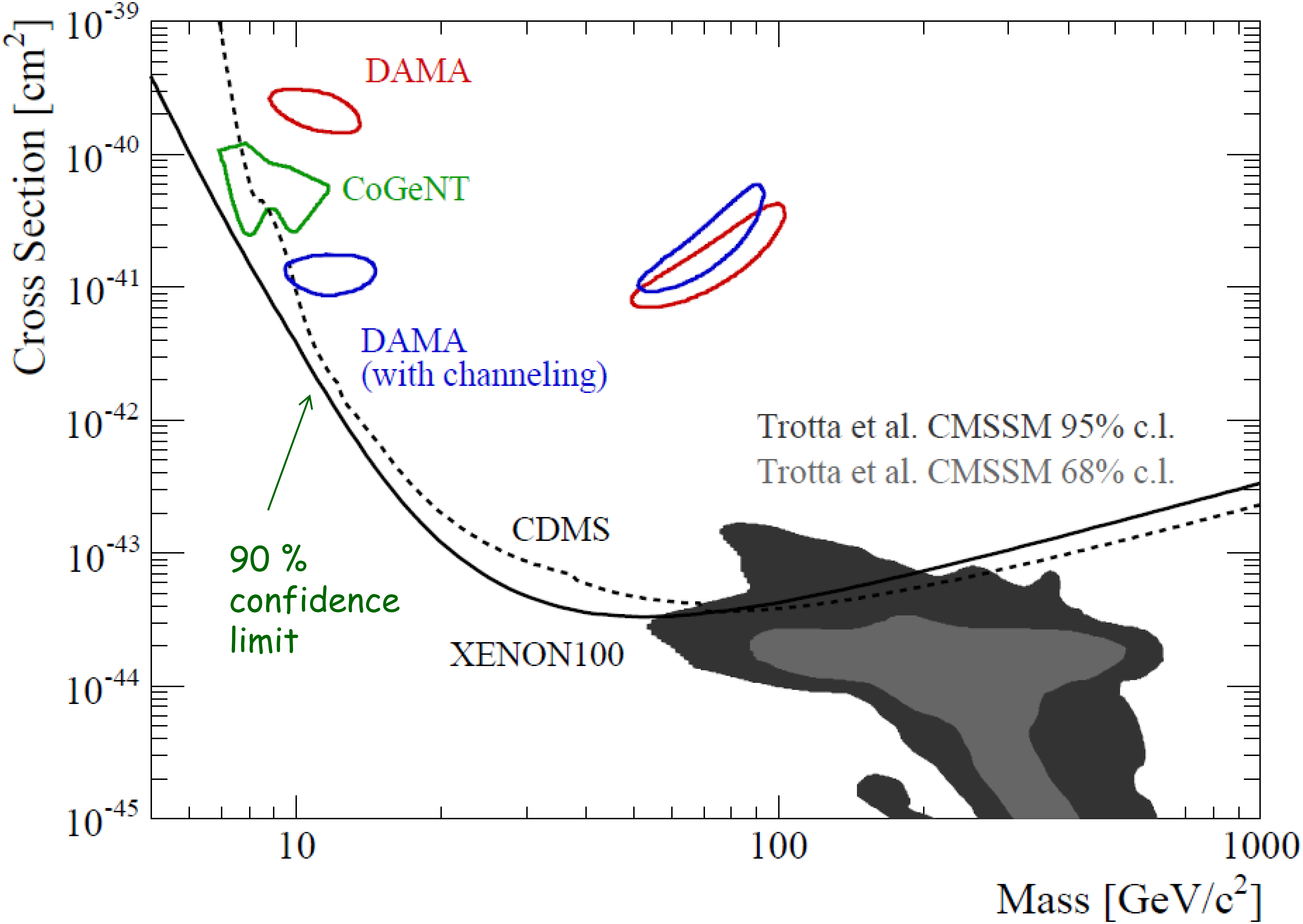
What is it? Does not fit in in standard WIMP scenario…

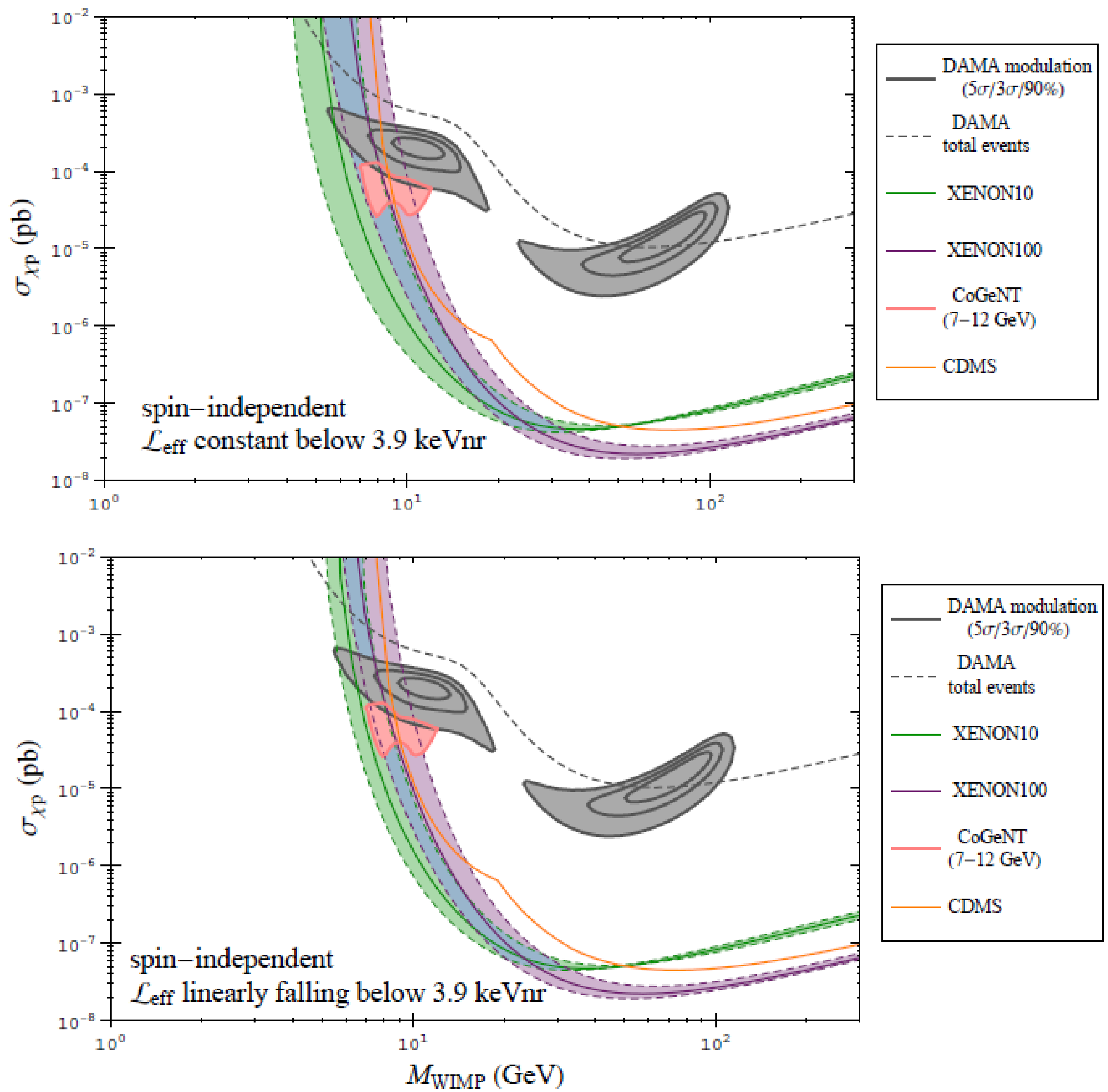
CDMS II result, December 2009:
what are these 2 events?



On the other hand, combining 2007 and 2008 data, expect 1.8 background events, see 2 events. Data from Xenon100 do not confirm an excess.

XENON100 results (from 11-day run!), May, 2010:



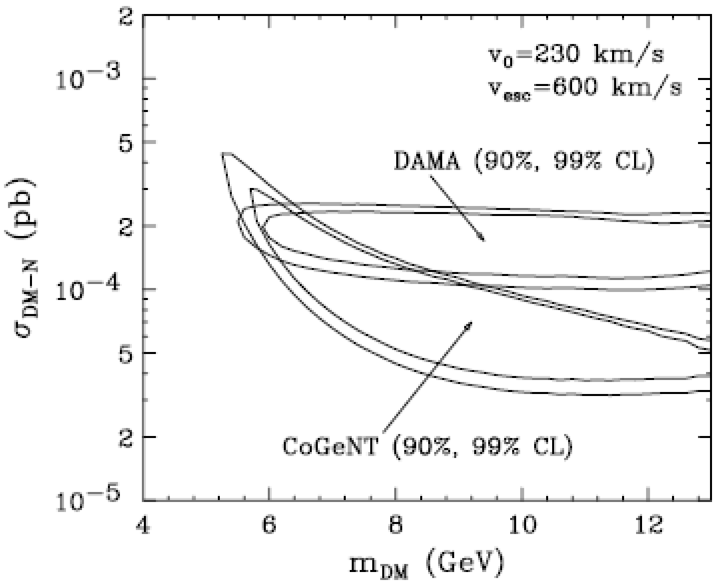


DAMA results are not reproduced by any other experiments, except perhaps CoGeNT

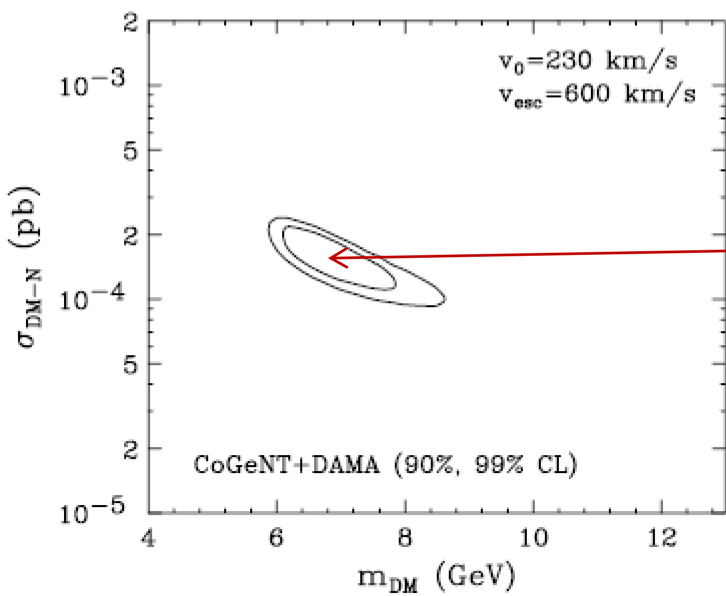
However, limits depend strongly on assumption of sensitivity for low-energy recoils in Xenon. If DAMA and CoGeNT are seeing a signal, mass is around 8-12 GeV.

C. Savage, G. Gelmini, P. Gondolo and K. Freese, arXiv:1006.0972

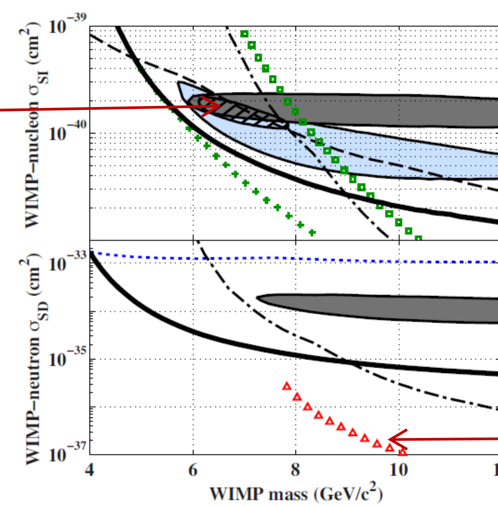
Region where DAMA and CoGeNT coexist?



D. Hooper, J.I. Collar, J. Hall, D. McKinsey and C. Kelso, arXiv:1007.1005

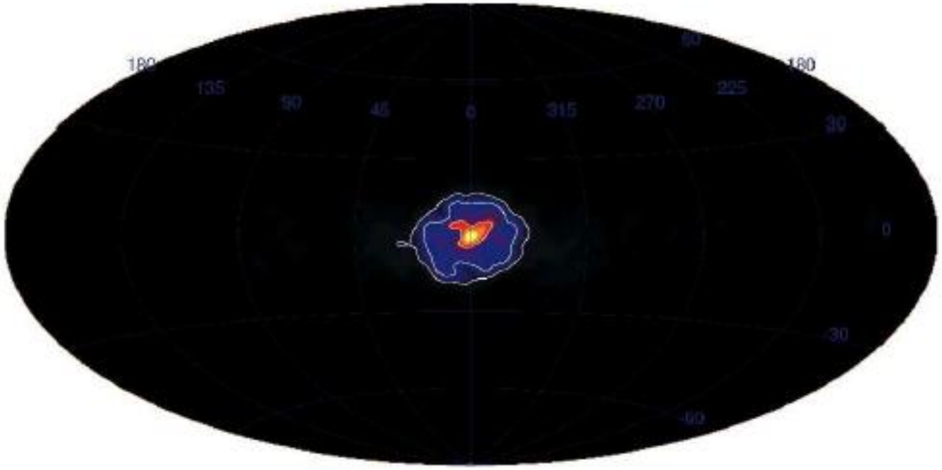


Excluded by new low-threshold analysis of CDMS II, Z. Ahmed & al., arXiv:1011.2482:

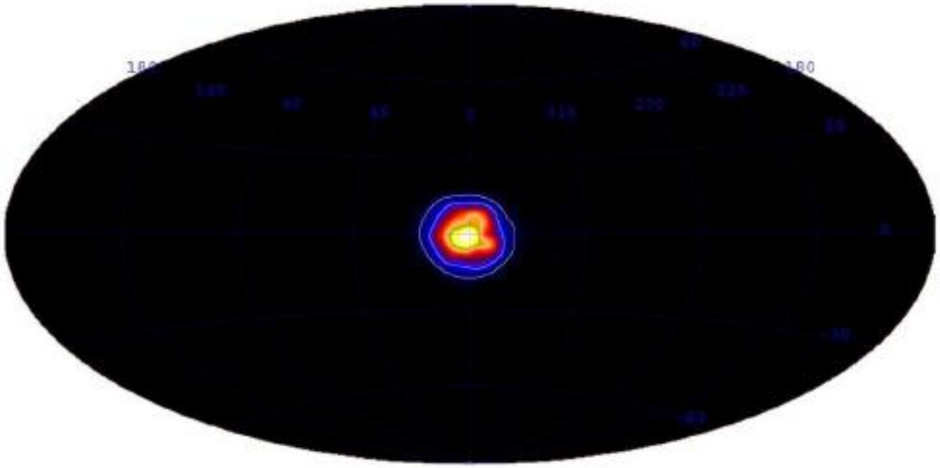


CDMS II

XENON10

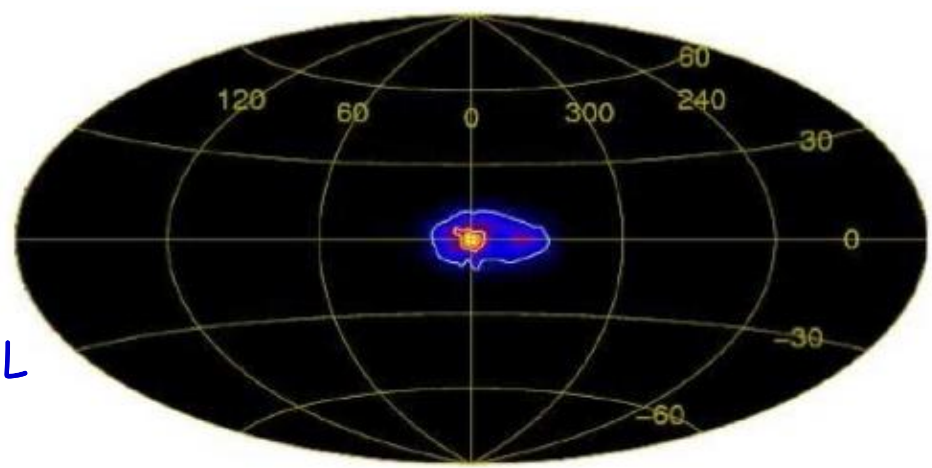


INTEGRAL 511 keV line,
after one year of data
(J. Knödlsedler & al., 2005)



INTEGRAL positronium
continuum (G. Weidenspointner
& al., 2006)

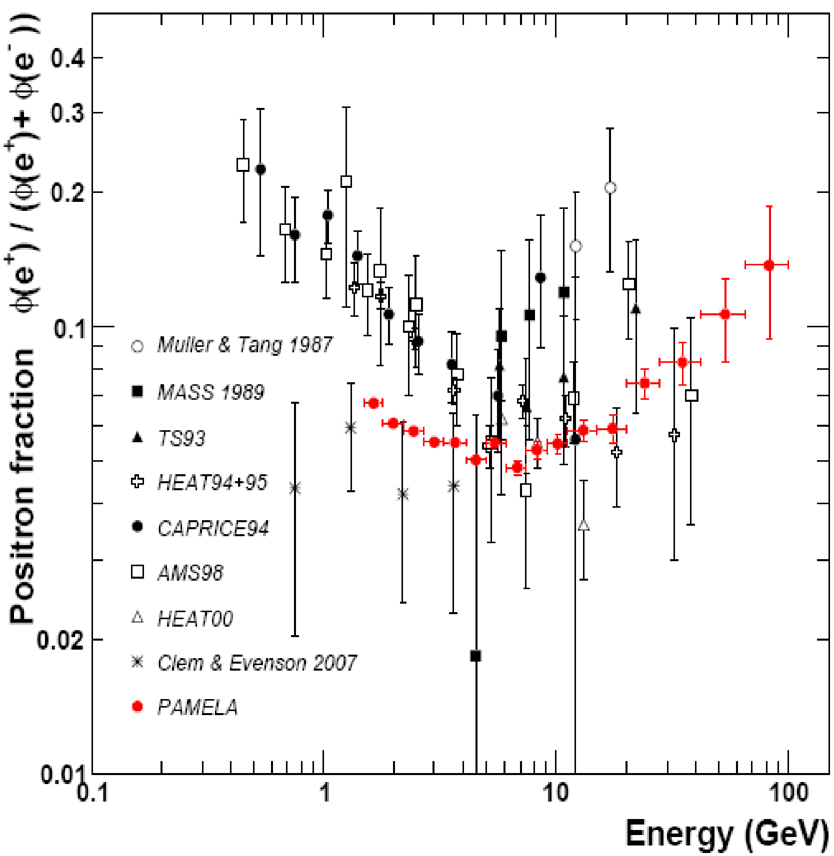
INTEGRAL 511 keV line, after 5
years of data (G. Weidenspointner
& al., 2008)

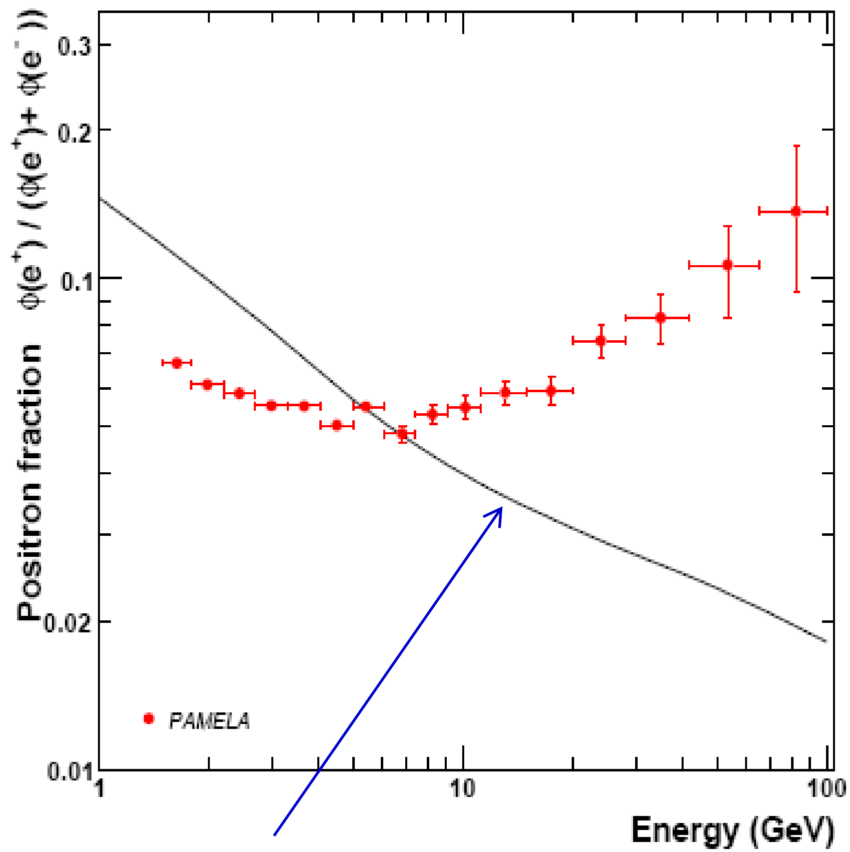


Starting to look asymmetric ? -
future studies will tell (INTEGRAL
will operate until 2012, at least)

The surprising PAMELA data on the positron ratio up to 100 GeV. (O. Adriani et al., Nature 458, 607 (2009))

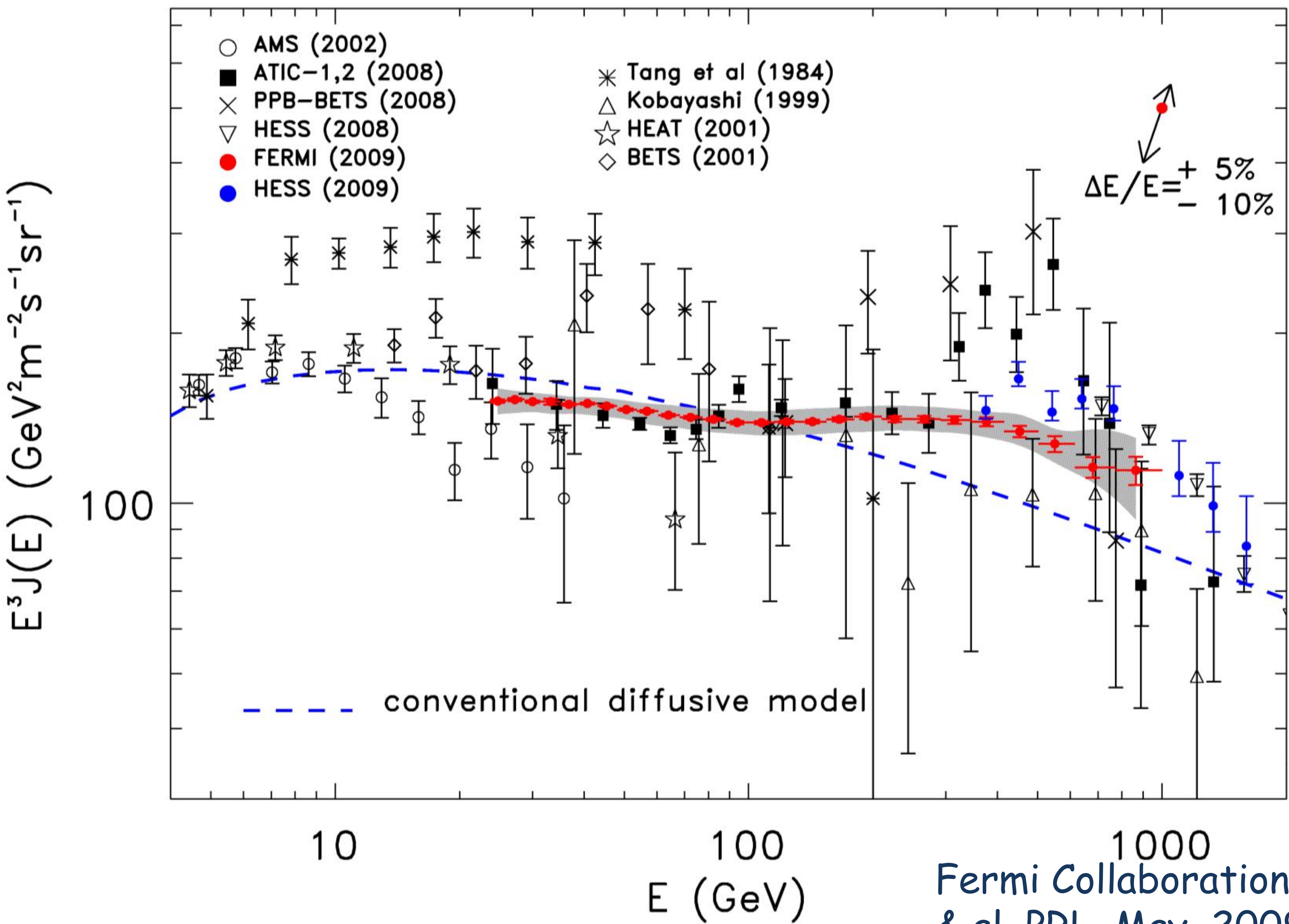
A very important result (more than 600 citations already)! An additional, primary source of positrons seems to be needed.





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

Recent data from the Fermi satellite (sum of electrons and positrons):

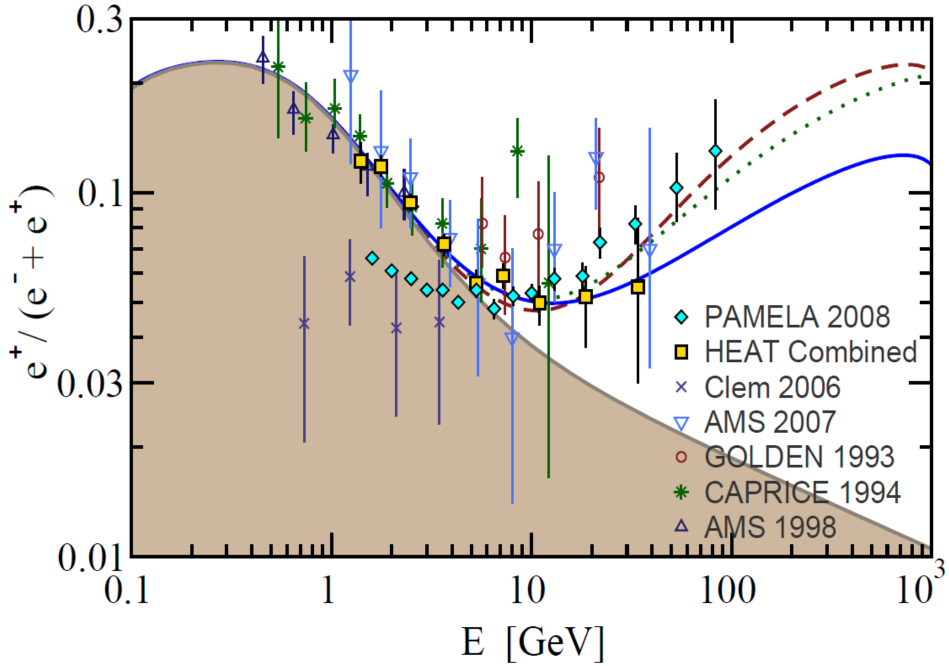


Fermi Collaboration, A.A. Abdo & al, PRL, May, 2009

A new contribution needed, such as
- Pulsars (or other supernova remnants)
- Dark Matter

Positrons generated by a class of extreme objects: supernova remnants (pulsars):

Vela pulsar (supernova remnant)

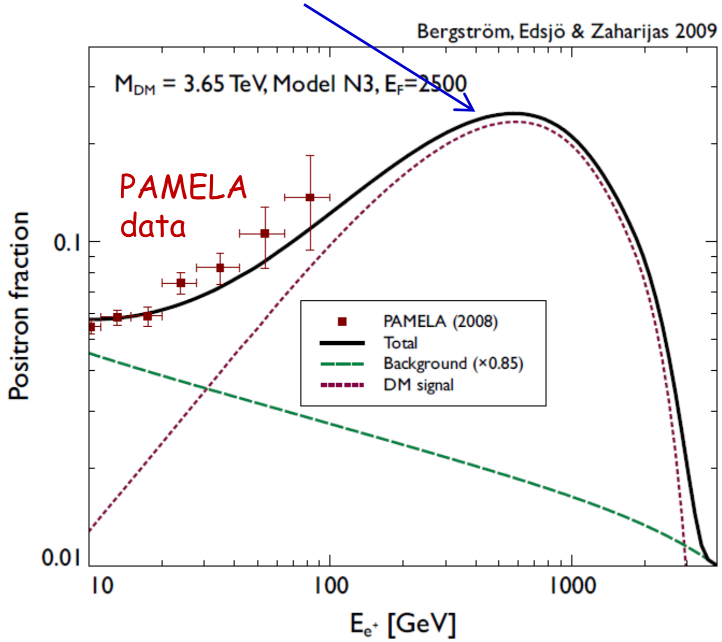


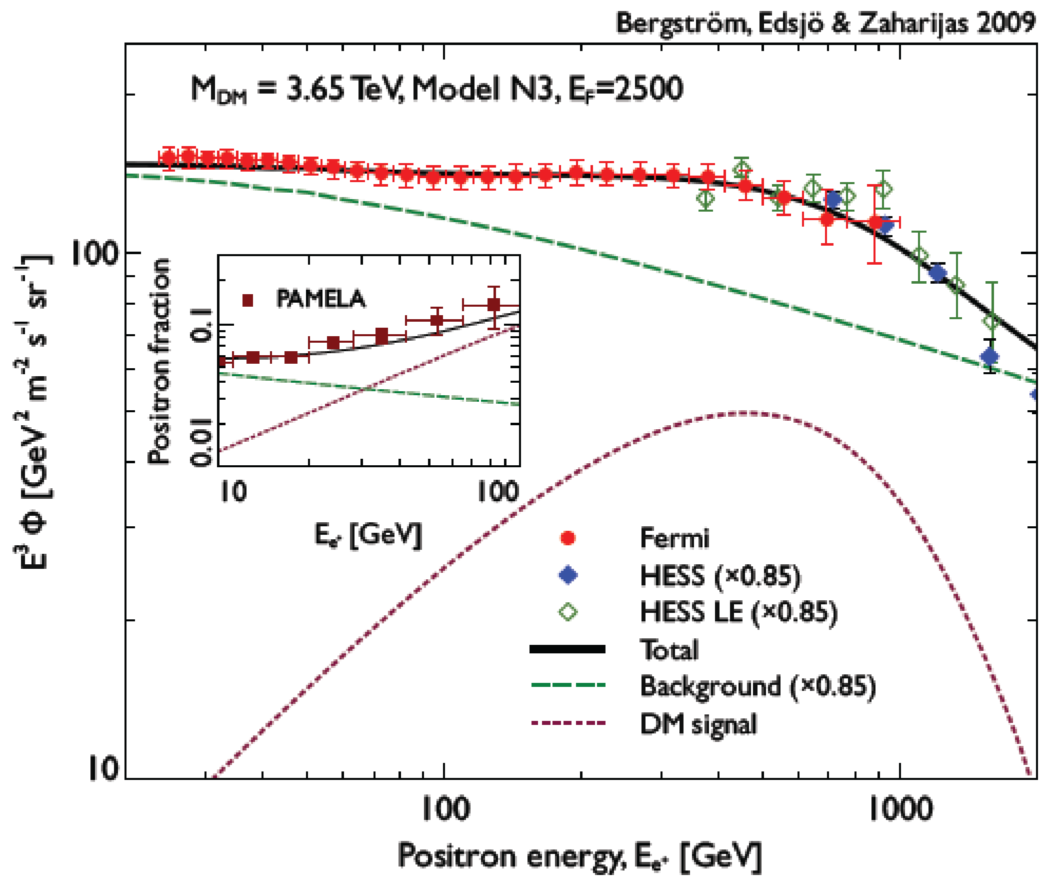
Geminga pulsar estimates

Yuksel, Kistler, Stanev, 2008 (cf. Aharonian, Atoyan and Völk, 1995; Kobayashi et al., 2004). Acceleration in old Supernova Remnants (Blasi & Serpico, 2009): Prediction of antiproton/proton ratio rising above 100 GeV – PAMELA will test

Dark Matter fit

The energy dependence will be checked by AMS-2 (to be launched to the International Space Station early next year)

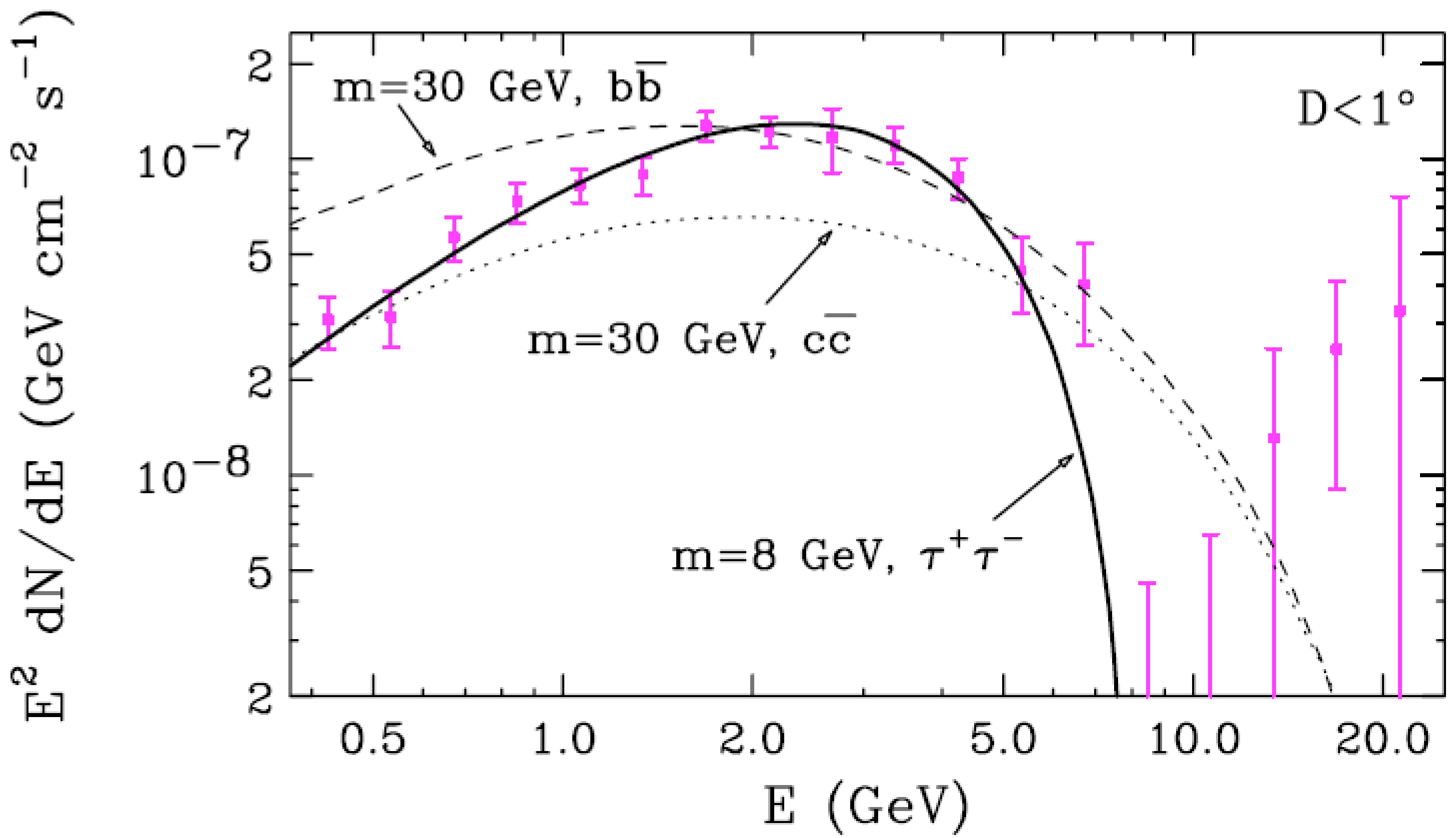




L.B., J. Edsjö and G. Zaharijas, PRL 2009.

For DM, annihilation into muons and/or taus seem to be necessary, and isothermal (not NFW) profile. Very large boost factor, around 1000, needed (Sommerfeld enhancement?).

FERMI 2-year (public) data
towards galactic centre:



D. Hooper and L. Goodenough, arXiv:1010.2752

8 GeV WIMP? Conclusion strongly dependent on background assumption.
Analysis from FERMI collaboration ongoing…

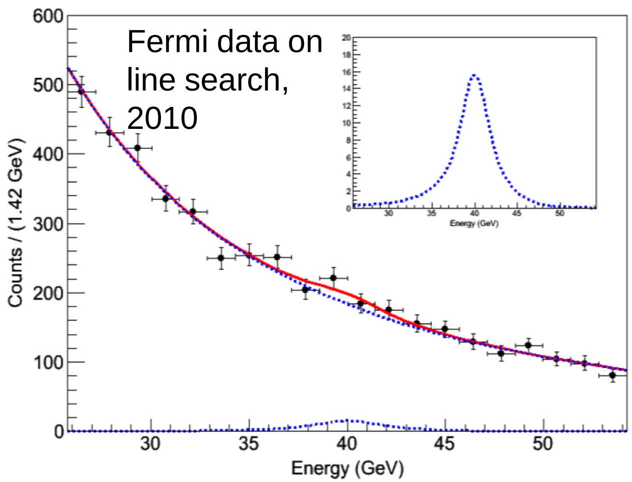
Example of more "conventional" Dark Matter model:
One extra, Inert, Higgs Doublet (Barbieri, Hall & Rychkov, 2006)

$\Rightarrow$ Ordinary Higgs can be as heavy as 400 GeV without violation of electro-weak precision tests

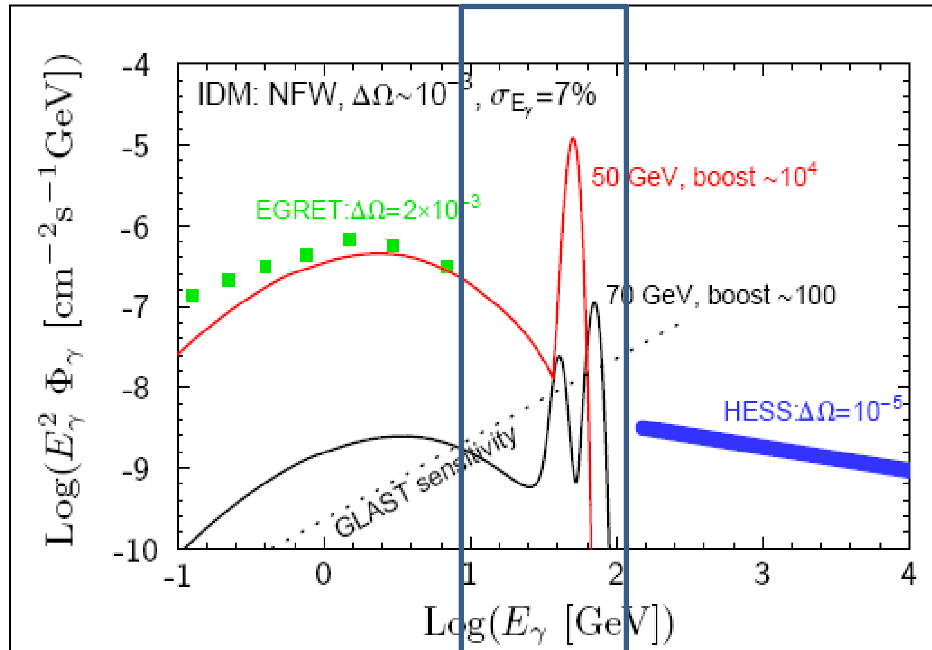
$\Rightarrow$ 40 - 70 GeV inert Higgs gives correct Dark Matter density

$\Rightarrow$ The perfect candidate for detection in Fermi…

But so far no signal:



No data existed in this range!
Fermi starts filling it!



M. Gustafsson , L.B., J. Edsjö, E. Lundström, PRL 2007

Can also be searched for at LHC through

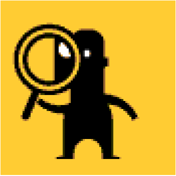
$$pp \to W^* \to HA \text{ or } HS$$
$$pp \to Z^*(\gamma^*) \to SA \text{ or } H^+H^-$$

Partial summary

Despite some interesting, but definitely not conclusive, hints of dark matter, it seems as we are back to square one, and still need to find out -

What is the Dark Matter?

Back to the main lead: SUSY



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

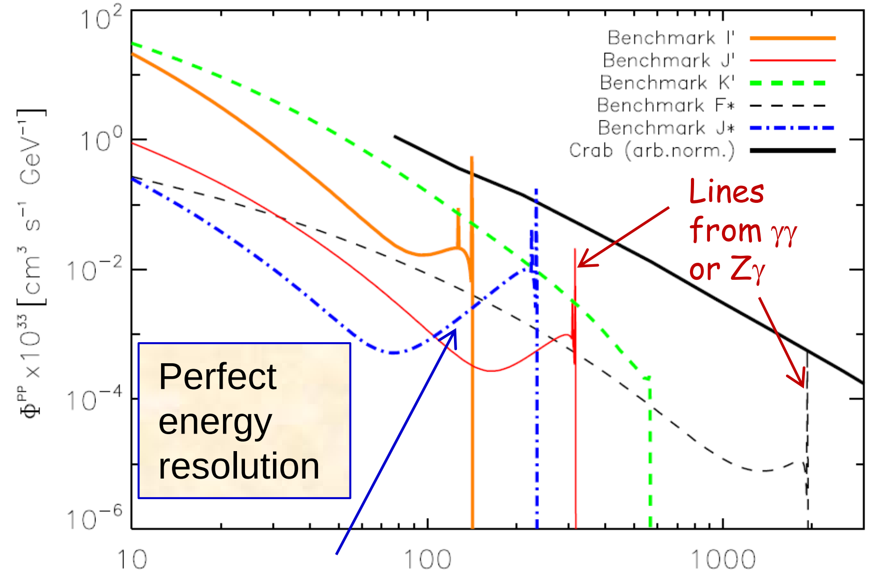
- Continuous from π^0, K^0, … decays.
- Monoenergetic line from quantum loop effects, $\chi\chi\rightarrow\gamma\gamma$ and $Z\gamma$.

- Internal bremsstrahlung from QED process.

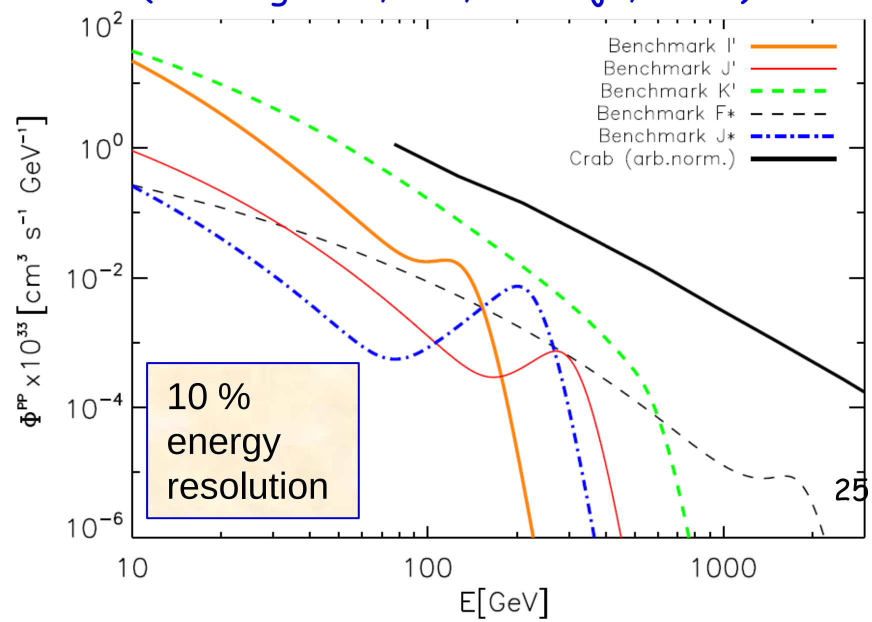
Enhanced flux possible thanks to halo density profile and substructure (as predicted by N-body simulations of CDM).

Good spectral and angular signatures!

But uncertainties in the predictions of absolute rates, due e.g. to poorly known DM density profile.

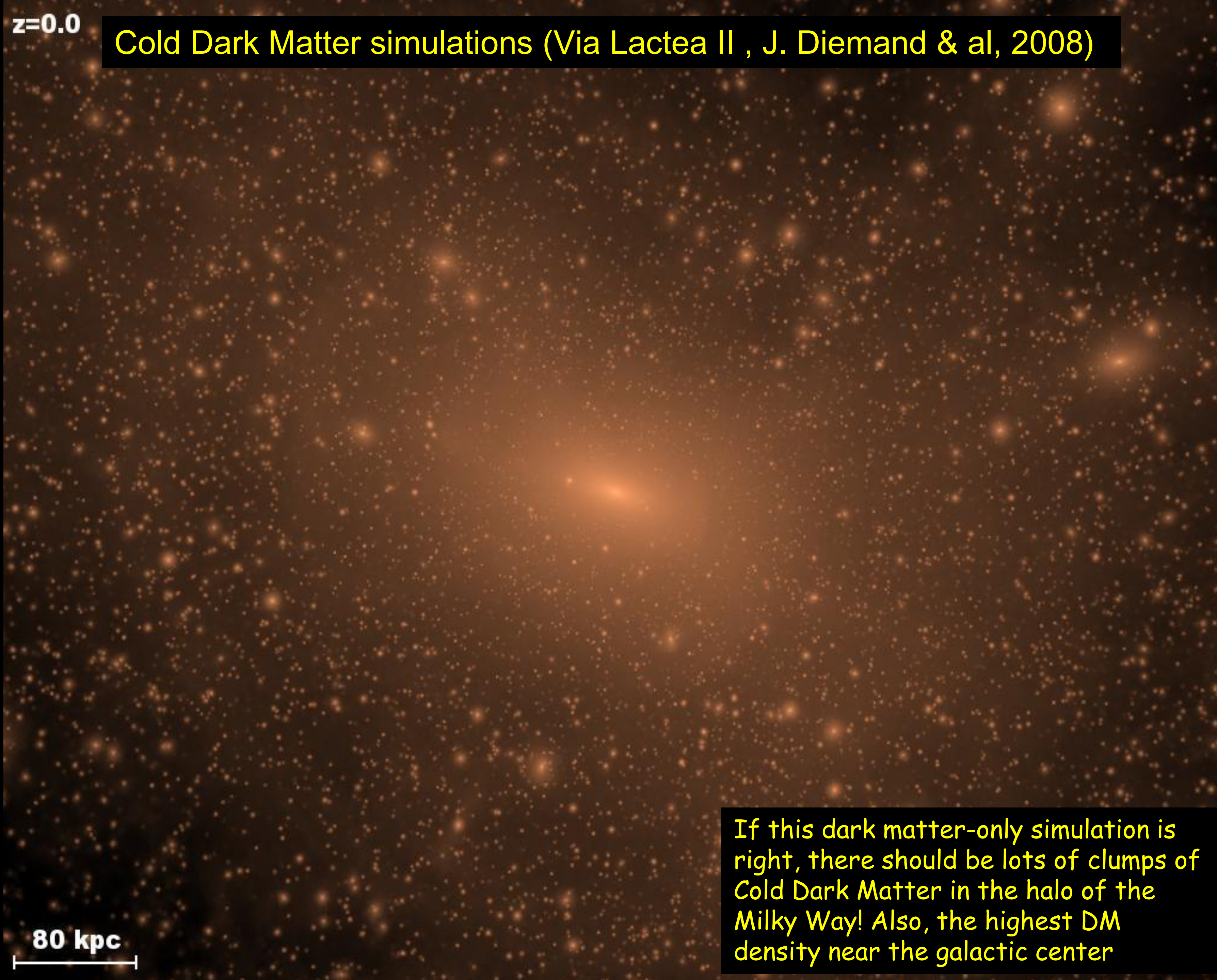


New contribution: Internal bremsstrahlung (T. Bringmann, L.B., J. Edsjö, 2007)



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

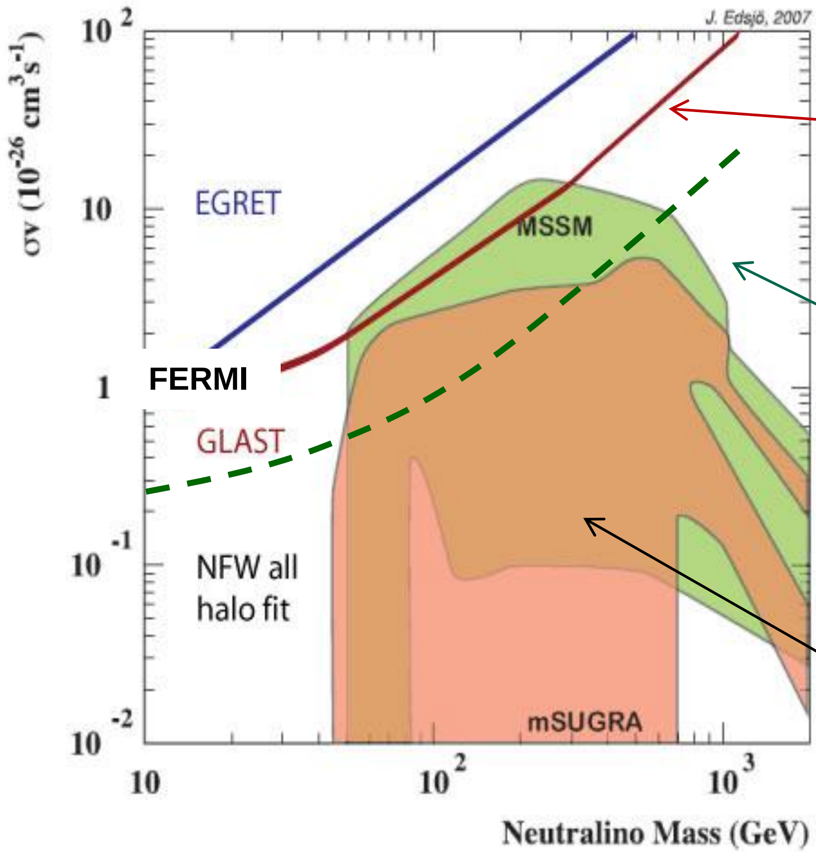
Cold Dark Matter simulations (Via Lactea II , J. Diemand & al, 2008)



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

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



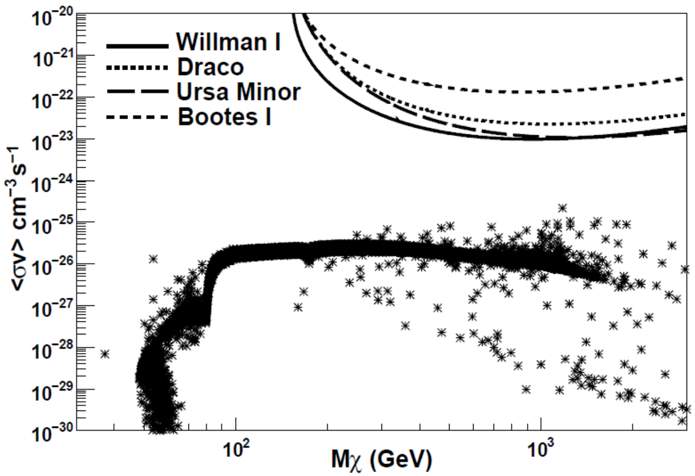
"Conservative" approach, g.c.,

NFW halo profile assumed, no substructure.

Including all halo, with substructure

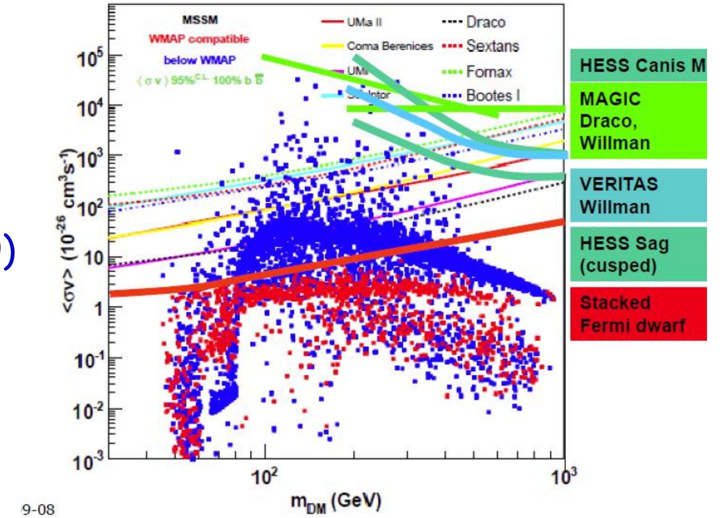
Will not be probed by Fermi, but by next generation of (ground-based) gamma-ray instruments, like CTA

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



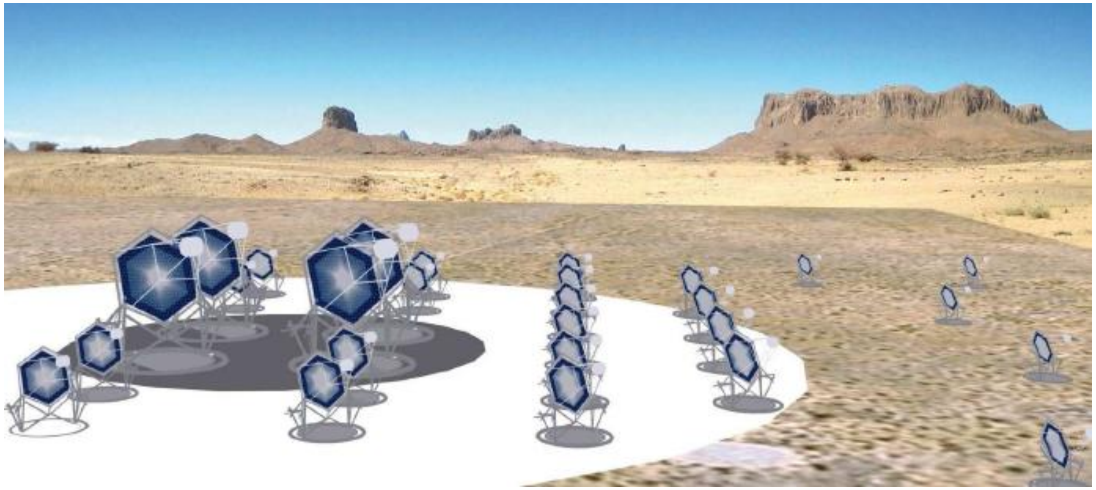
Example of present best limits from ground-based experiments (VERITAS, June 2010)

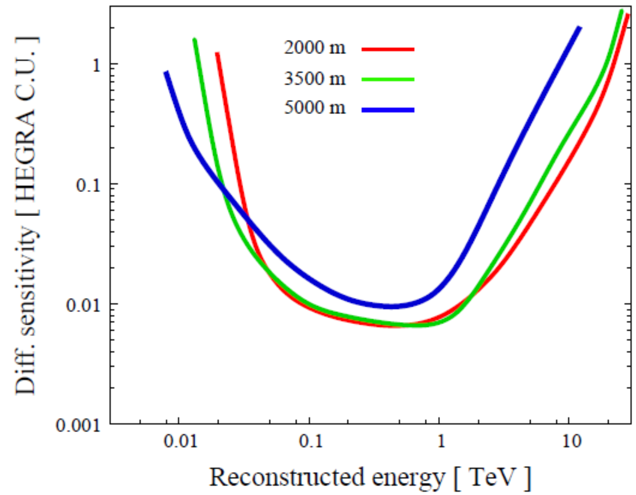
FERMI gets better limits, also for low-mass models, by stacking many dwarfs.



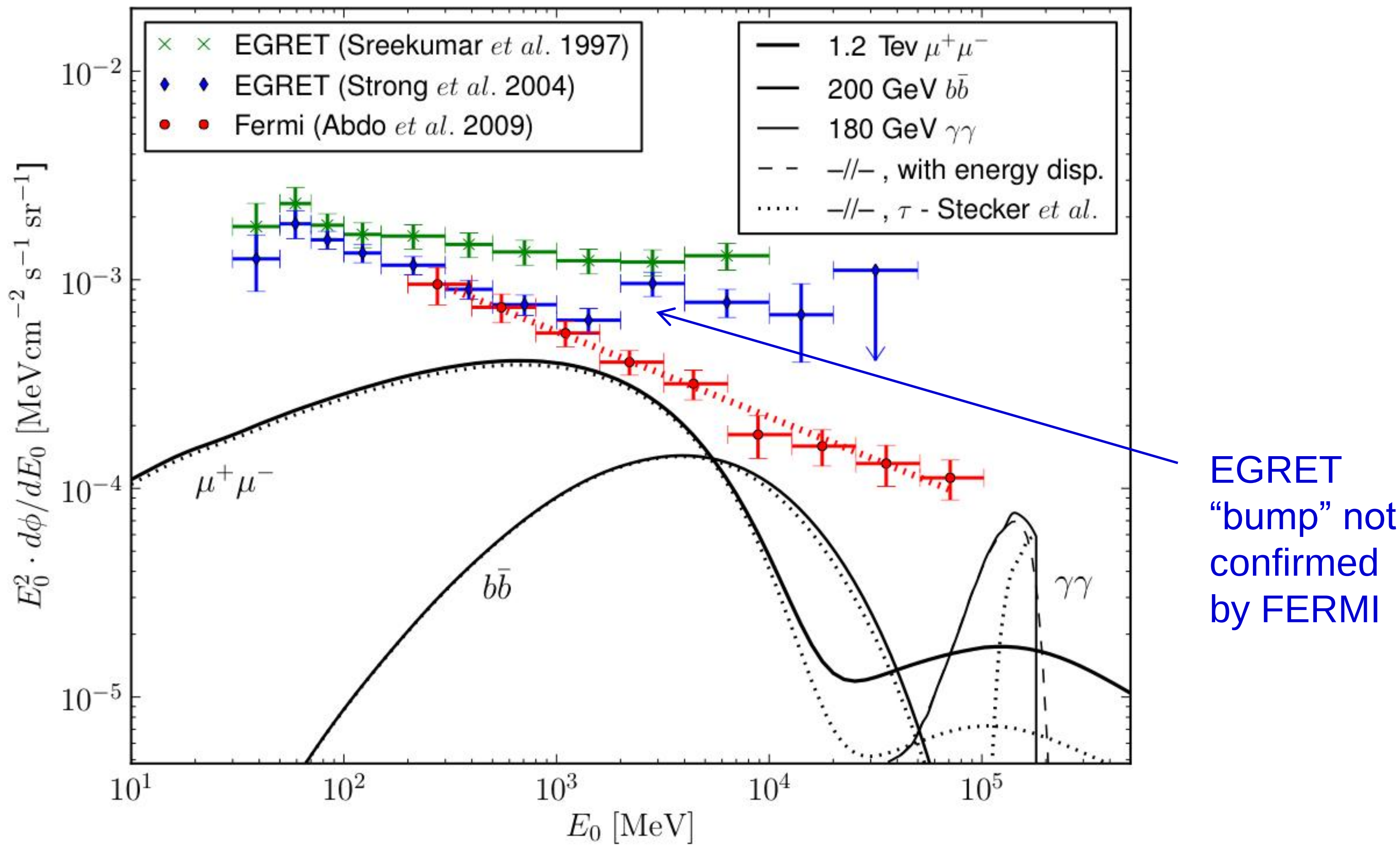
J. Conrad for FERMI collab., IDM talk (2010)

The future? First, of course, CTA!

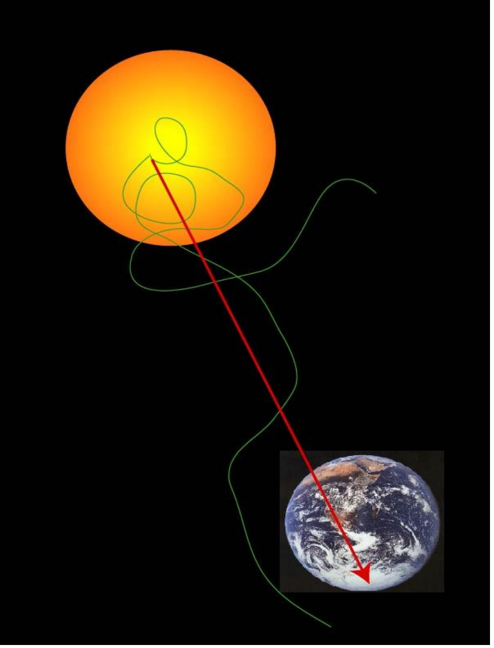




From design report of CTA, W. Hofmann & M. Martinez et al., arXiv:1008.3703

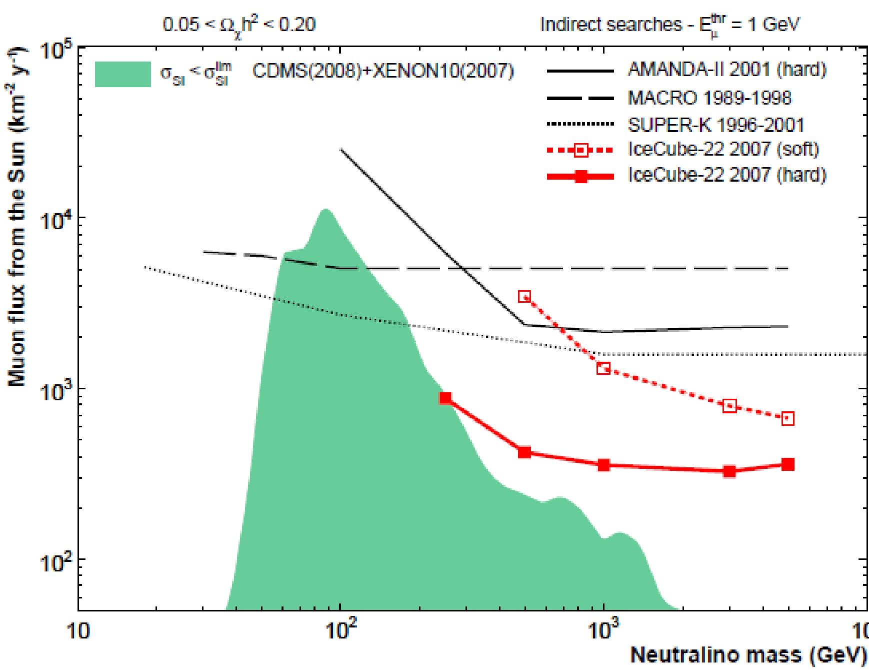


Extragalactic diffuse gamma-radiation, FERMI Collaboration, 2010

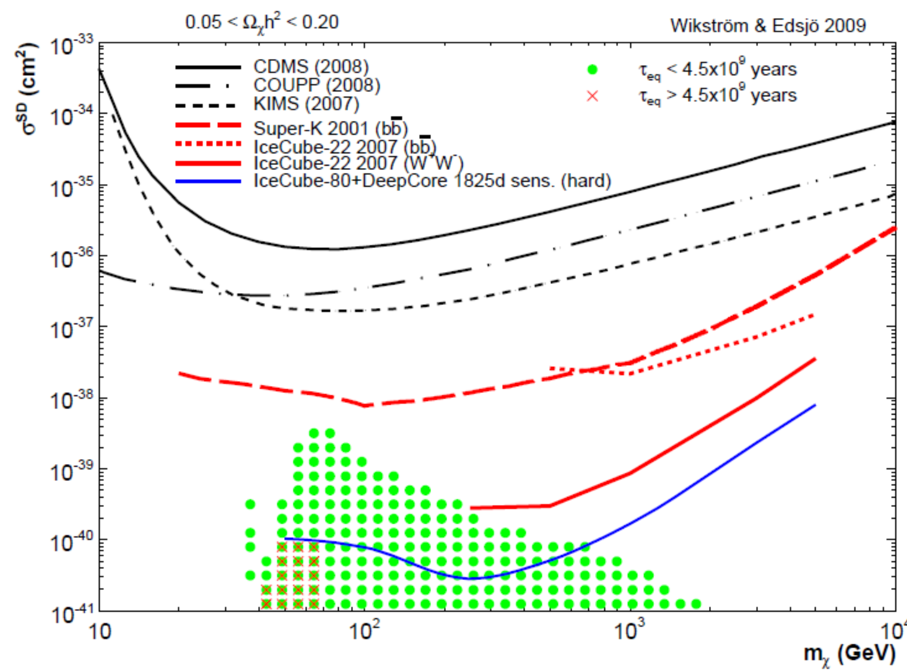


Another method with good signature:

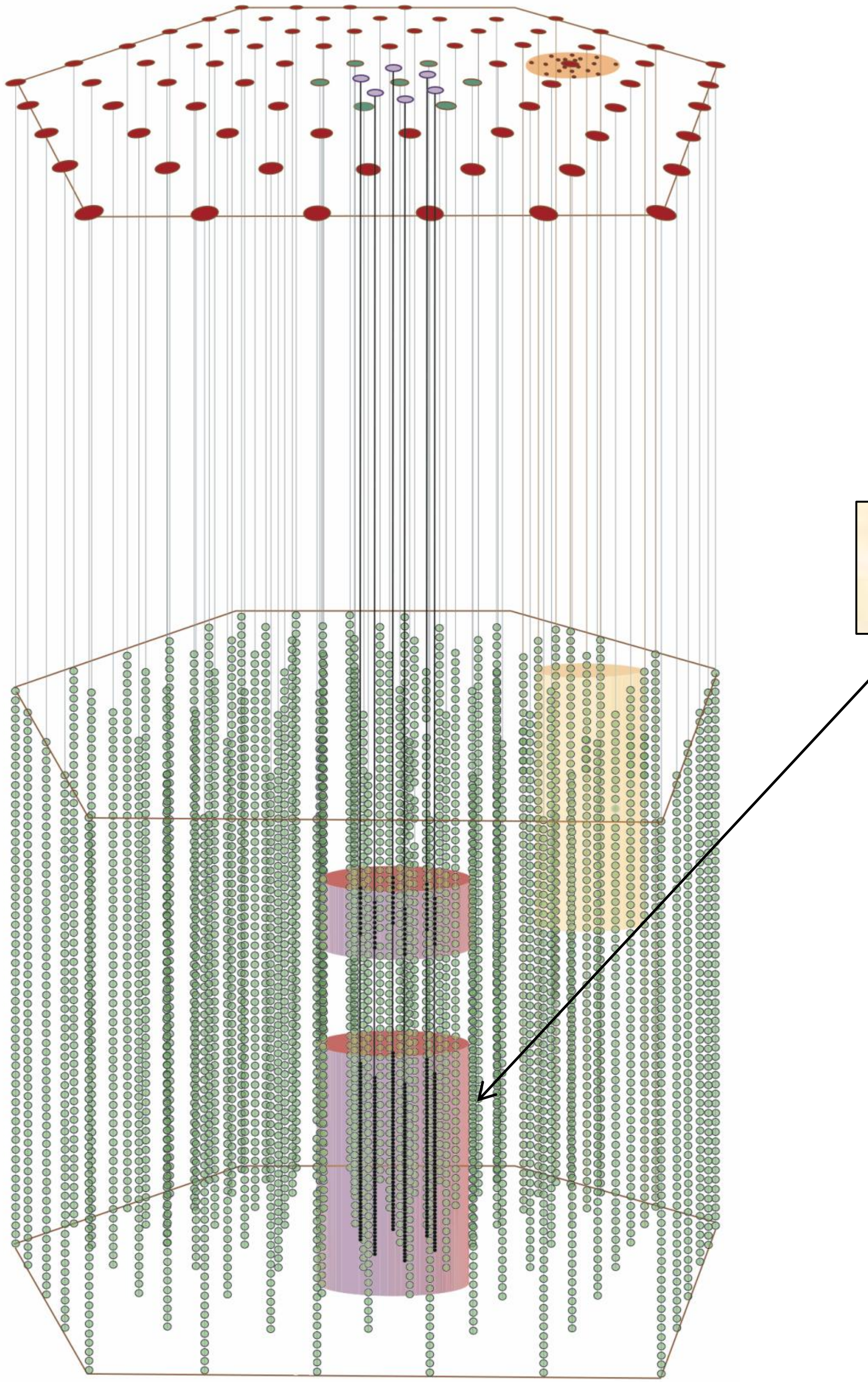
Neutrinos from the Sun, IceCube-22 limits (2009) on spin dependent interactions – just about starting to touch the interesting region in parameter space. IceCube is soon completed with 80 strings + DeepCore:



IceCube Collaboration, R. Abbasi et al., arXiv:0902.2460



G. Wikström and J. Edsjö, arXiv:0903.2986



New project within IceCube:
IceCube Deep Core

Was deployed at the South Pole last season

Direct detection:

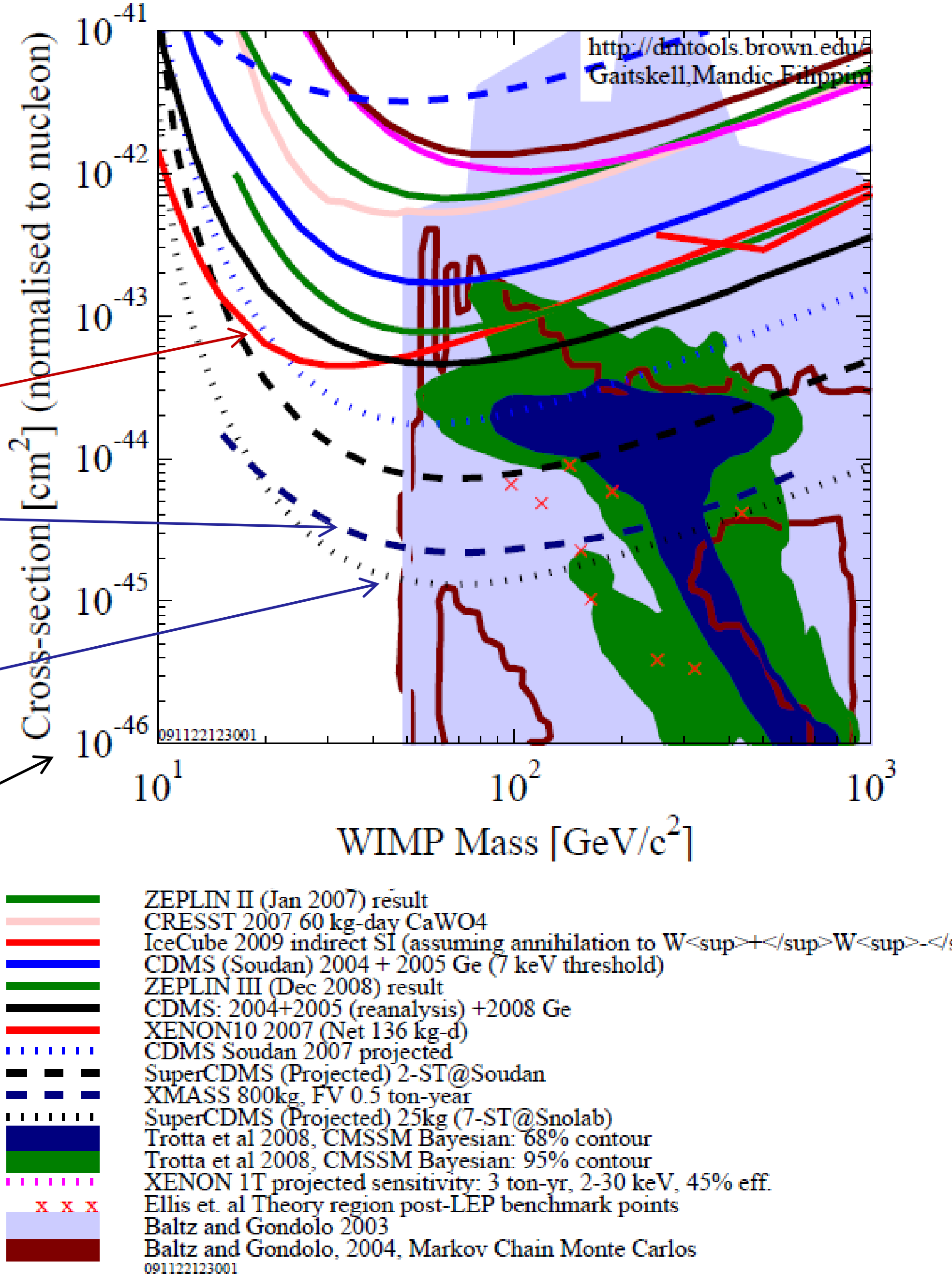
Impressive development over the last 10 years, and projected over the next 10...

XENON 10

XMASS (projected)

SuperCDMS (projected)

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



Comparison between reaches of direct (Super-CDMS, XENON 1t) and indirect detection through gamma-rays (FERMI-LAT, CTA, DMA)

DMA - The Dark Matter Array: A hypothetical, dedicated detector for indirect detection of Dark Matter!

Parameters for the first try of this thought experiment:

Area = 10 x CTA
Exposure time (over 10 years) 5000 h
Energy threshold 10 GeV
PSF 0.02° (as CTA), but 0.1° below 40 GeV. Maybe a SuperCTA at the ALMA site?

This would be a particle physics experiment (Cost: 1000 MEUR ? Roughly one year of CERN running cost…)

Setup for analysis (L.B., T. Bringmann & J. Edsjö, arXiv:1011.xxxx):

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

Parameters for experiments:

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

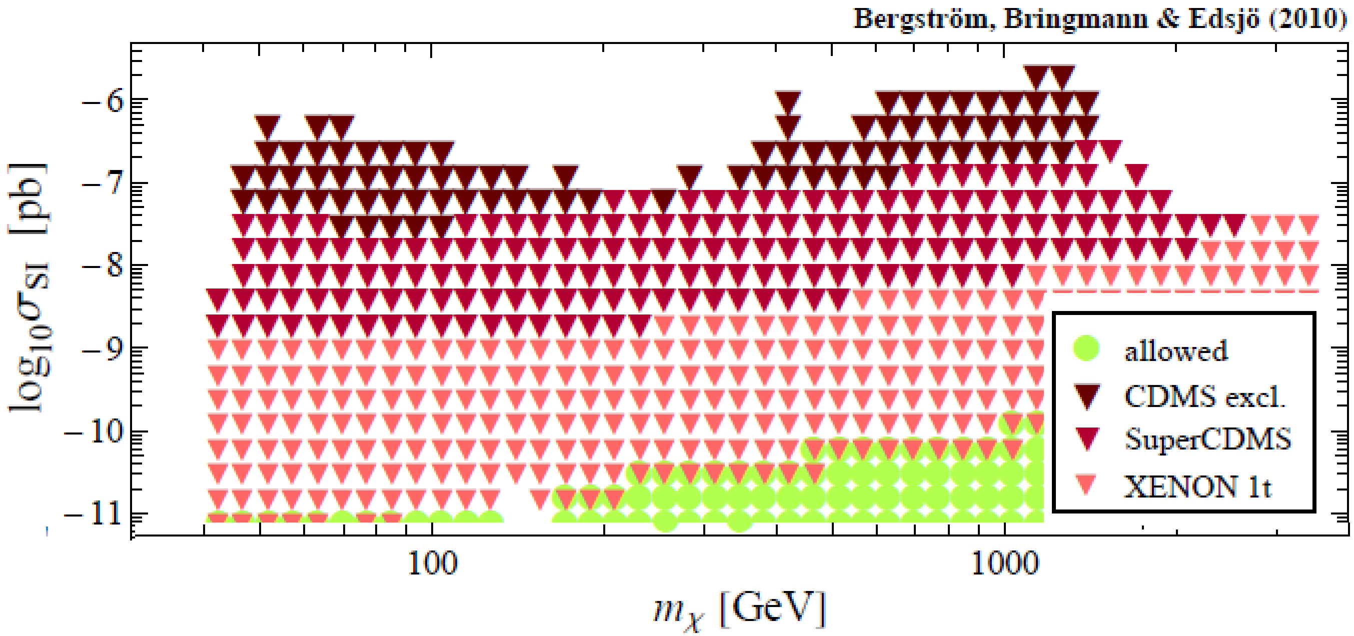
SuperCDMS: As described in T. Bruch, 2010.

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

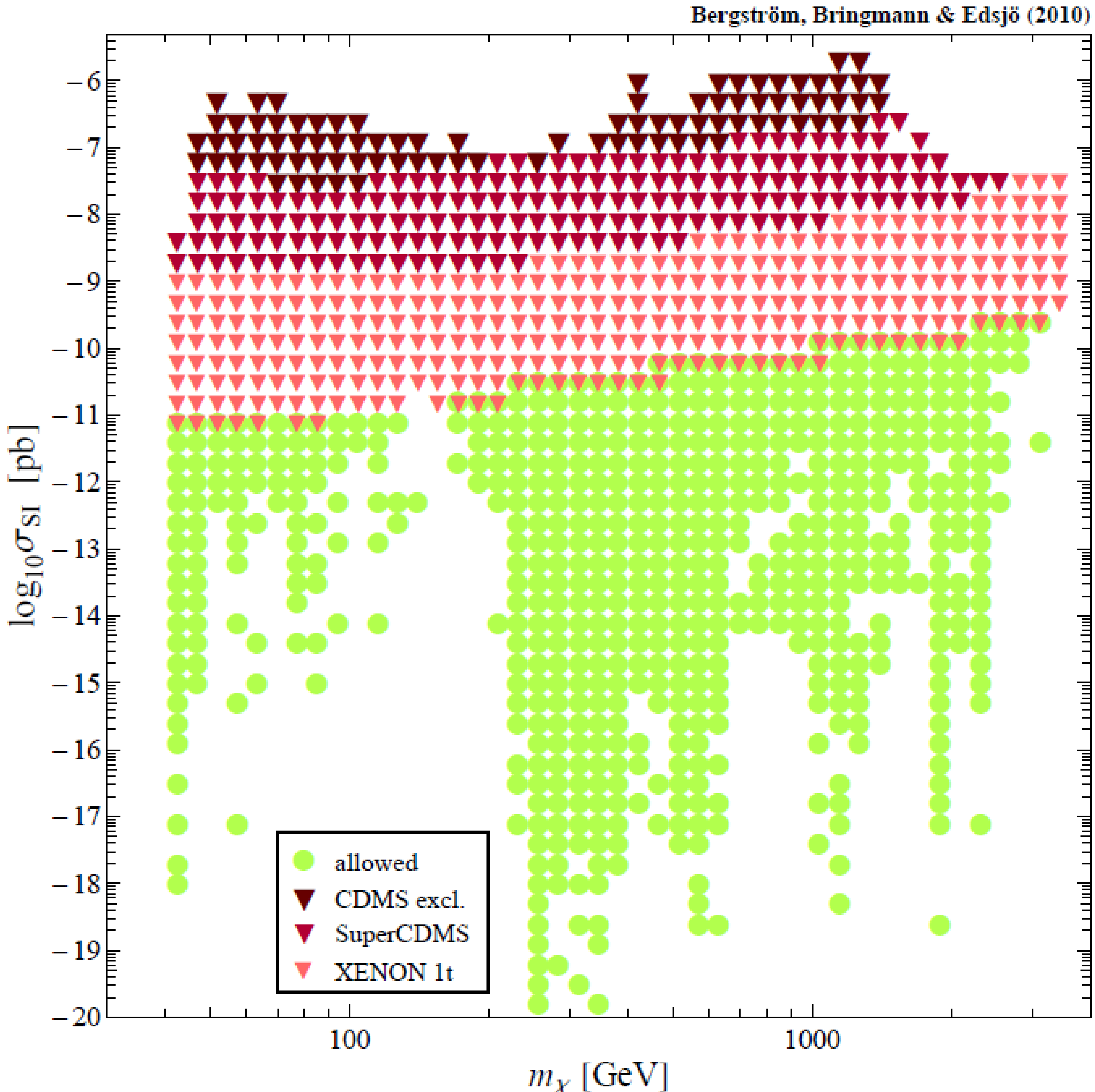
FERMI-LAT: Effective exposure 1 year (= 5 years observing time), 20 log-bins between 1 och 300 GeV, everything else according to LAT home page.

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

DMA: Energy threshold 10 GeV, max $A_{eff} = 2\times10^7$ m^2, integration time 5000 hours.



Bergström, Bringmann & Edsjö (2010)
−6
−7
−8
−9
−10
−11
$\log_{10}\sigma_{SI}$ [pb]
100
1000
m_χ [GeV]
allowed
CDMS excl.
SuperCDMS
XENON 1t



Bergström, Bringmann & Edsjö (2010)
−6
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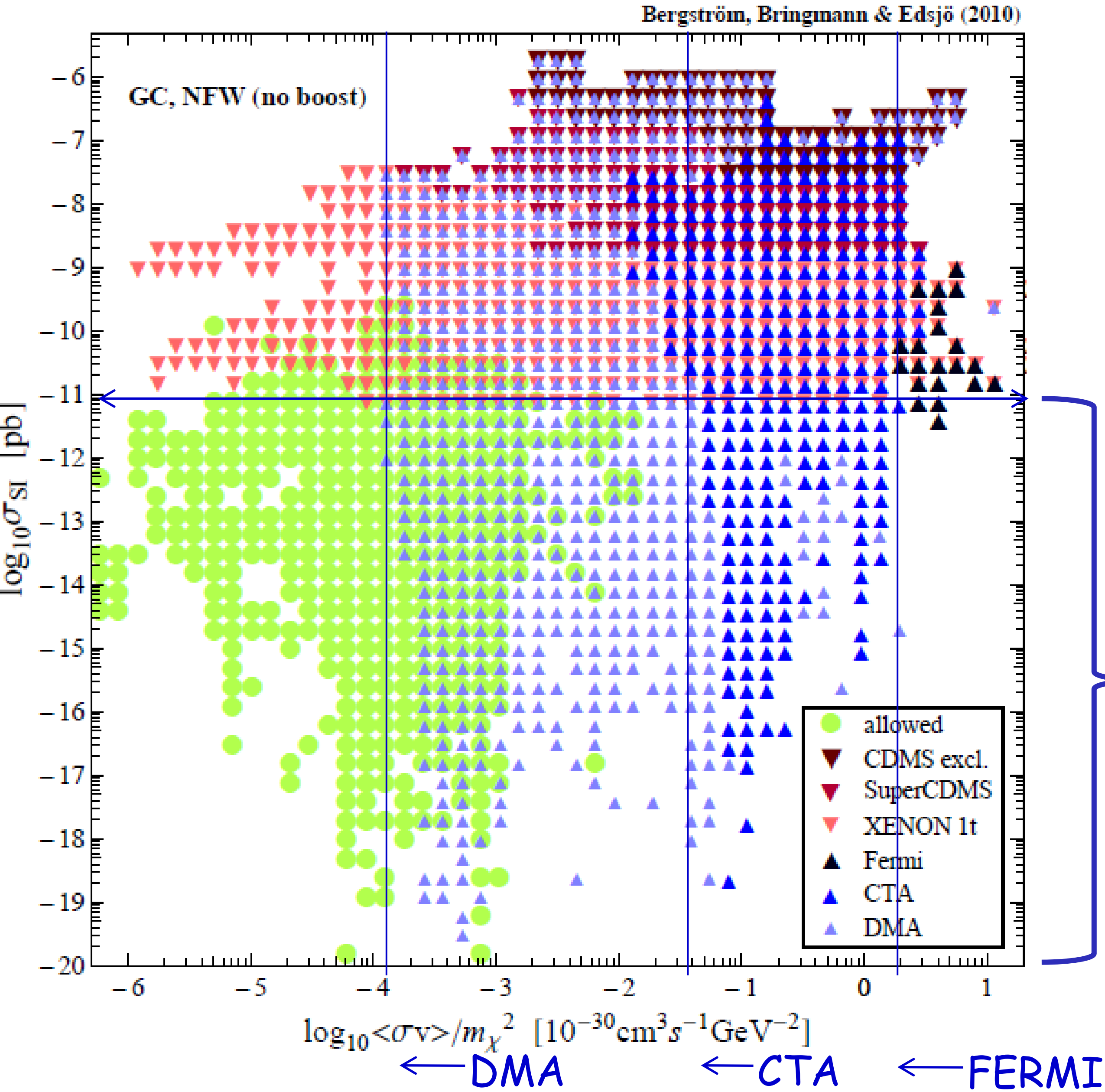
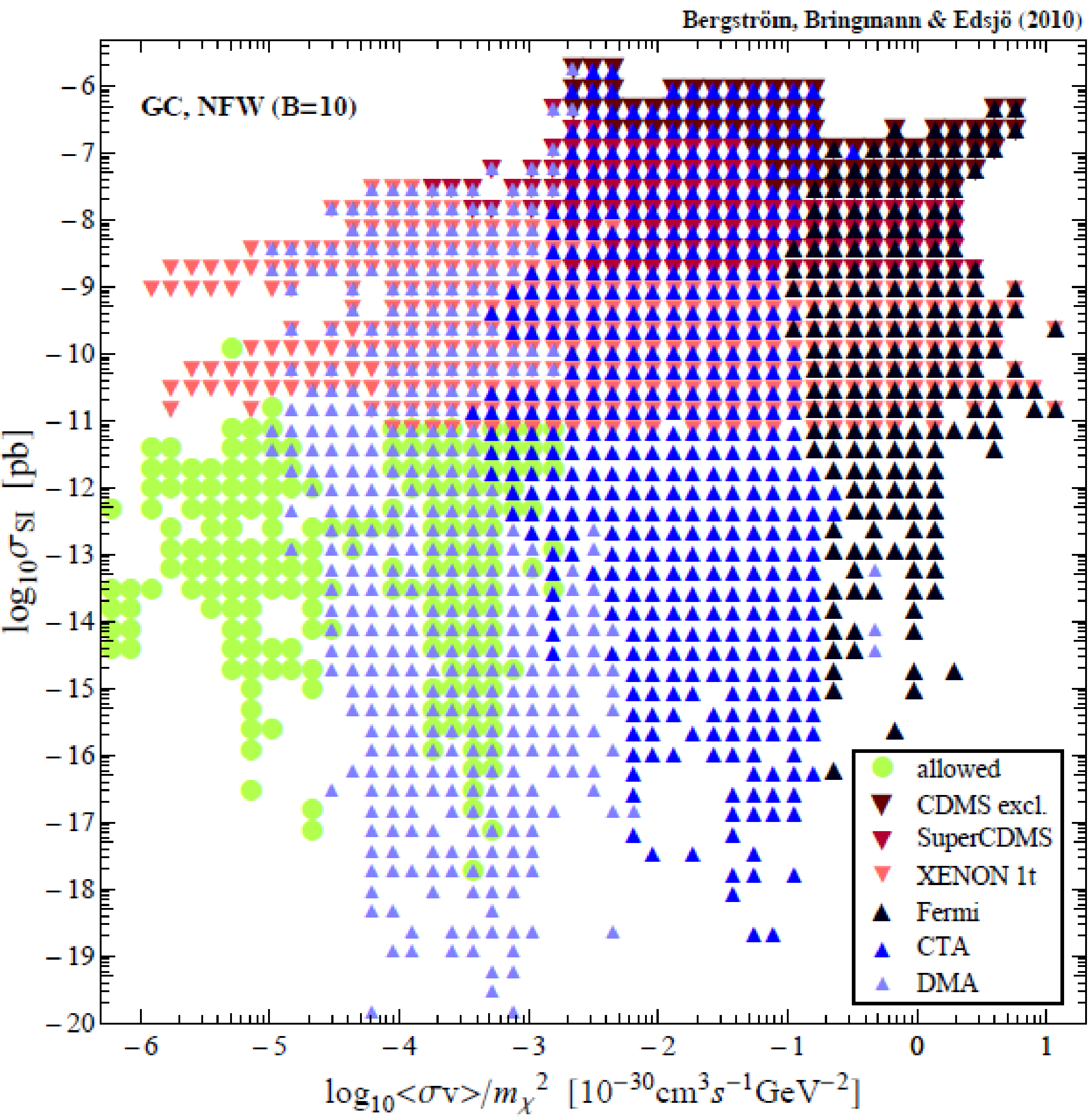
$\log_{10}\sigma_{SI}$ [pb]
100
1000
m_χ [GeV]
allowed
CDMS excl.
SuperCDMS
XENON 1t



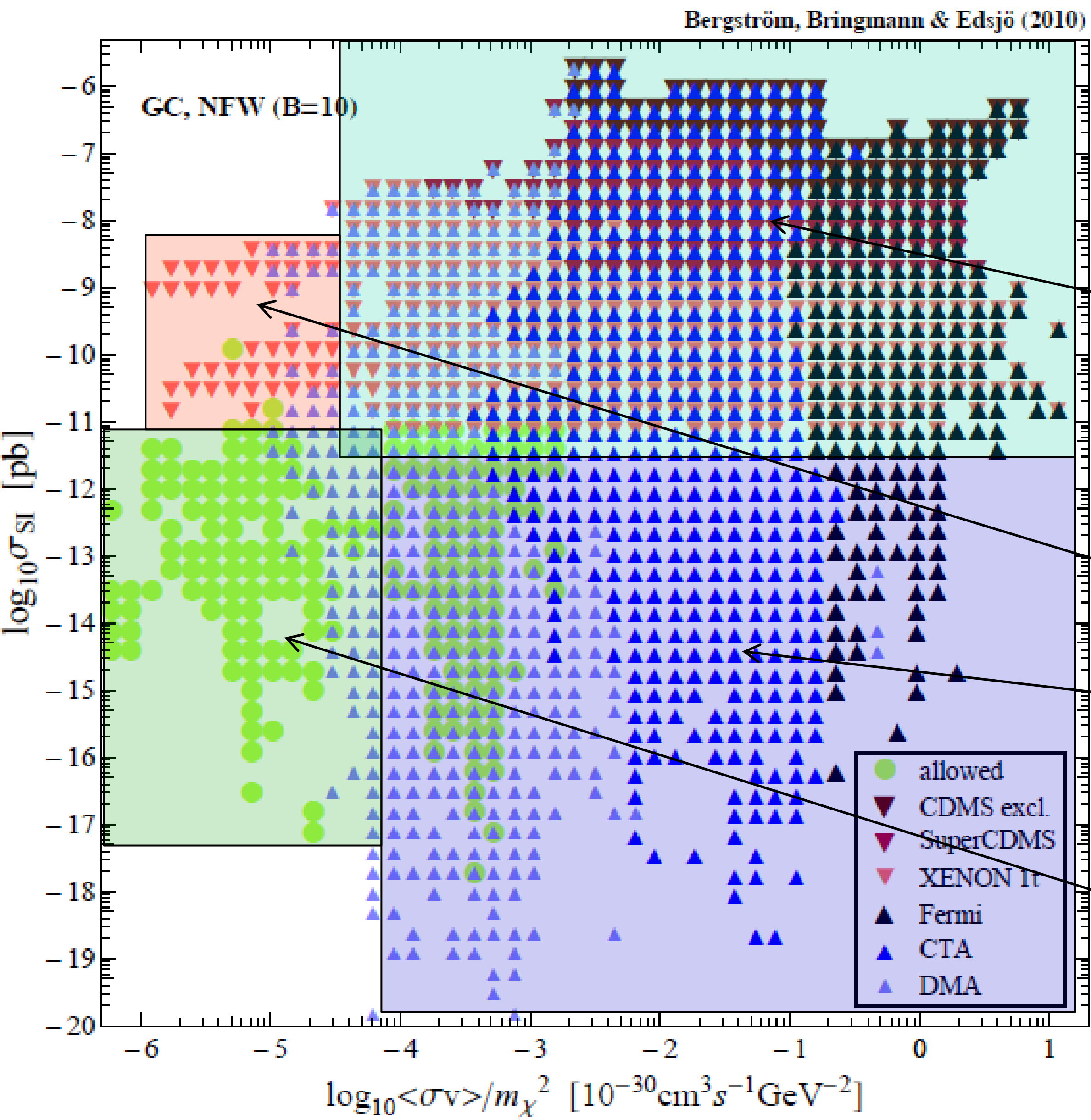
Assume background according to S. Digel, Fermi Symposium, 2009 (extrapolated as power-law for E > 100 GeV).

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

9 orders of magnitude in direct detection cross section - usually not shown!



NFW with moderate boost, looks even better…

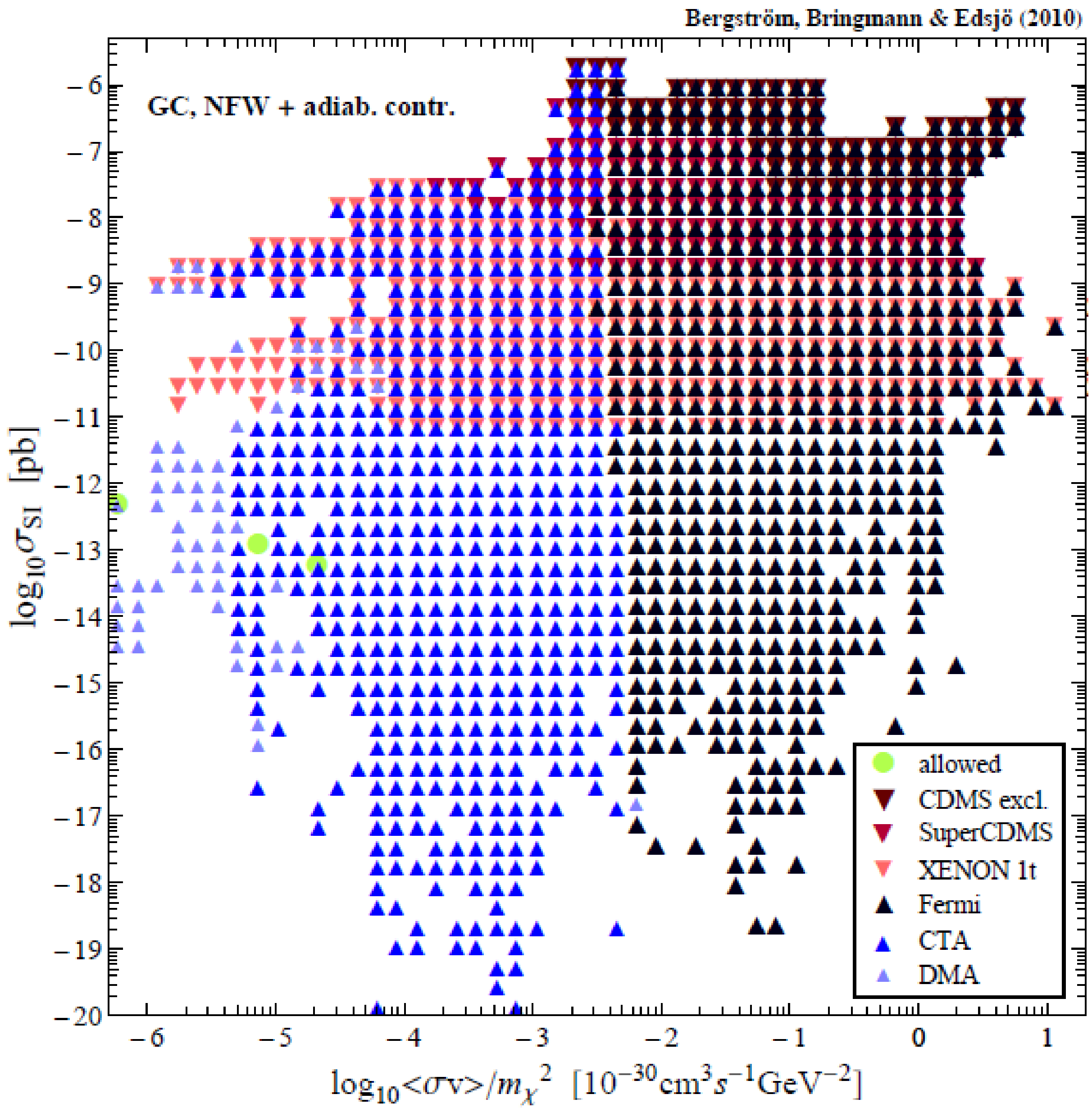


The sweet part of parameter space: direct and indirect detection can be used independently

Here direct detection rules

Here indirect detection rules

The very difficult part…

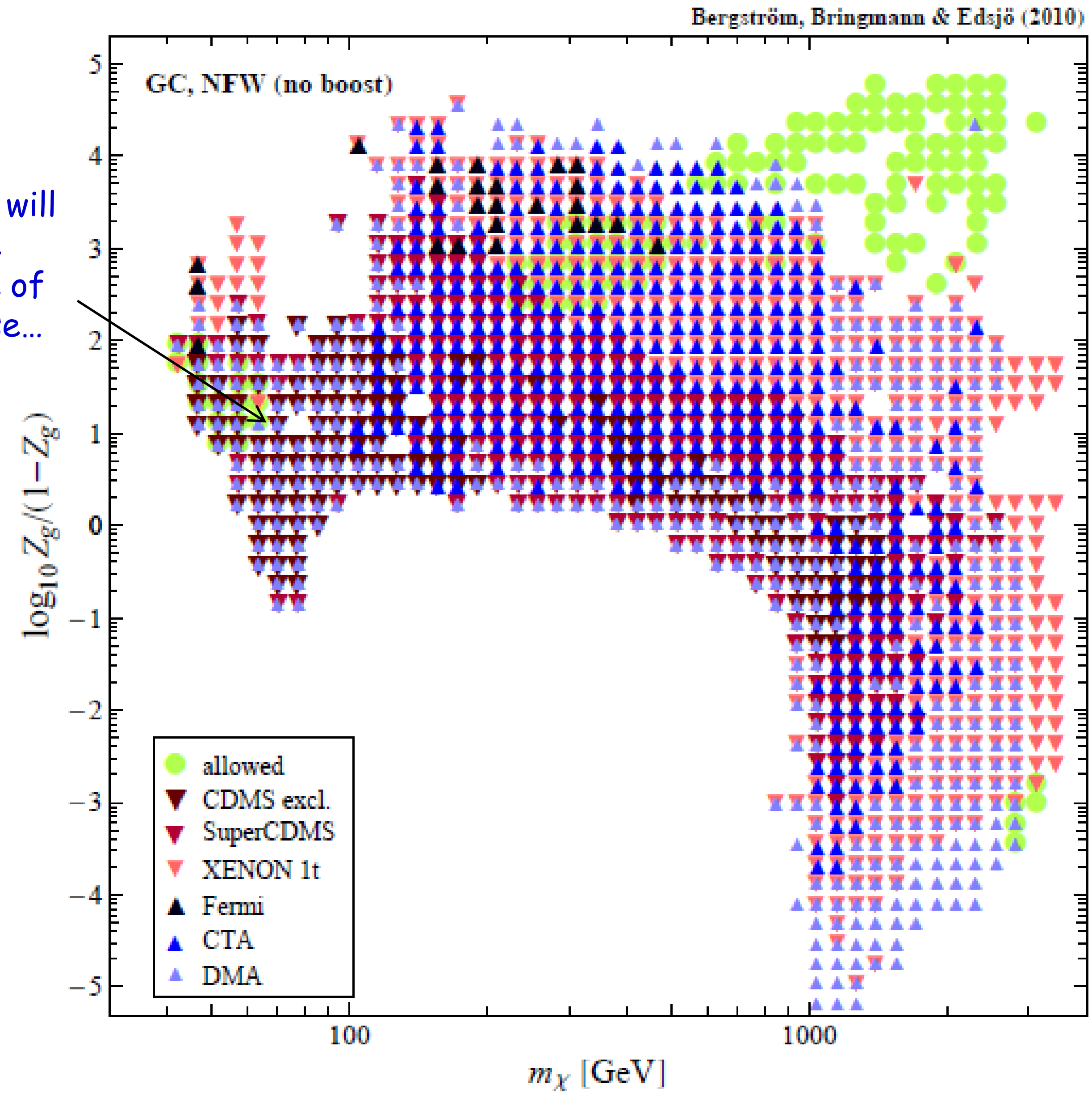


NFW + adiabatic contraction

Dream scenario for FERMI & CTA.

However, indications are that adiabatic contraction is much smaller (M.W. Auger & al., 2010).

LHC will take care of these...



For models with M > 1 TeV, gamma-ray rates may/should be enhanced by the Sommerfeld effect (Hisano & al., 2004) - not yet included (cf. A.Hryczuk, R. Iengo, P. Ullio, arXiv:1010.2172).

Conclusions:

Dark Matter exists - but we do not know what it is!

It will be hunted by LHC, direct detectors, Fermi and CTA (and IceCUBE, Super-K,...).

But to make real progress and cover a large part of parameter space that neither accelerators nor direct detectors can possibly ever reach - we may want to think about a

Dark Matter Array!

The end