Dark Matter: Present Situation and Future Prospects

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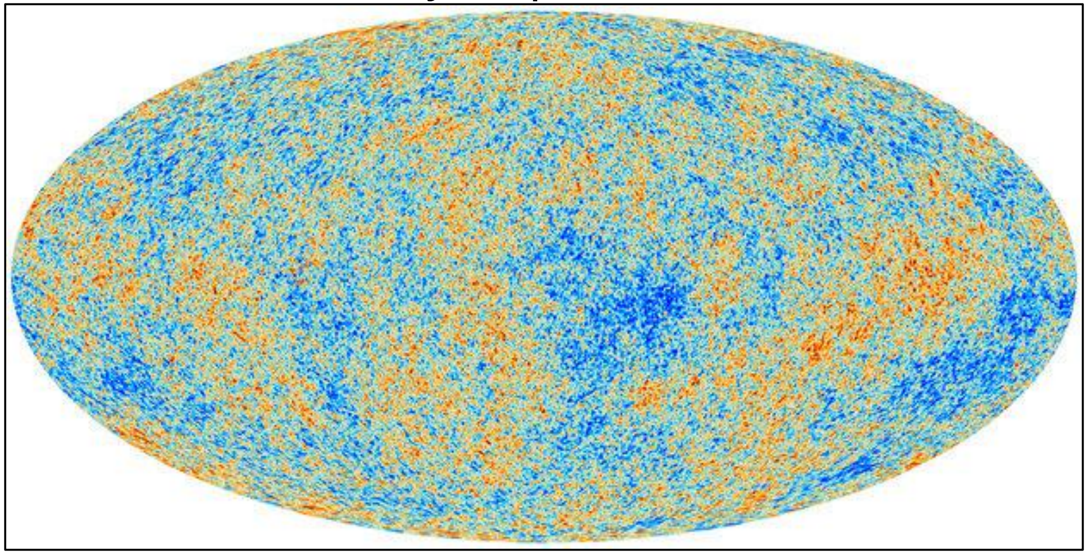
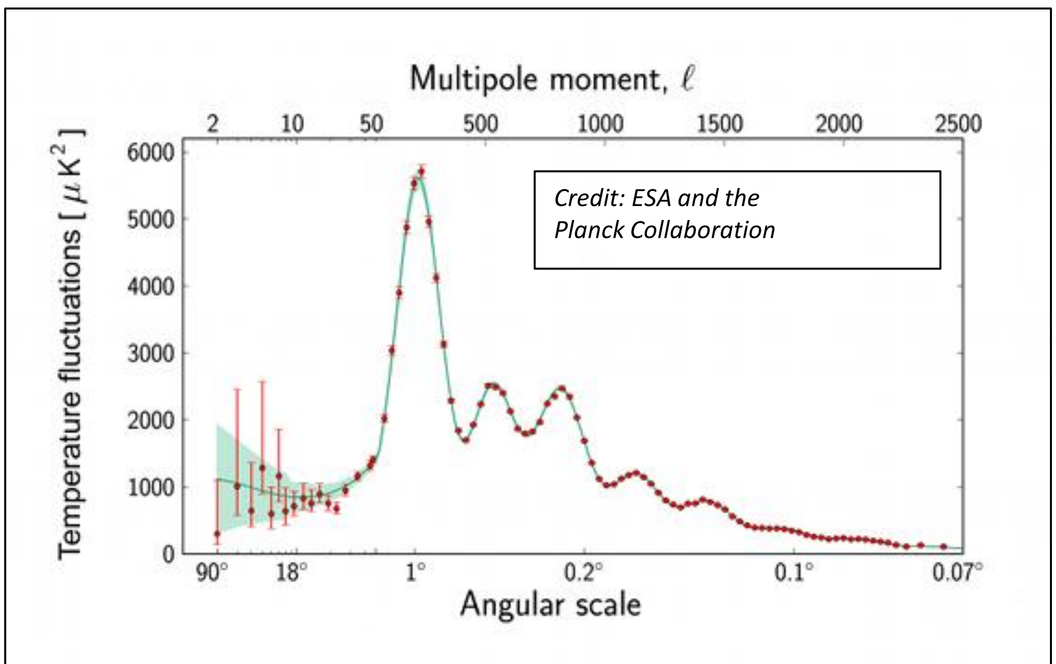
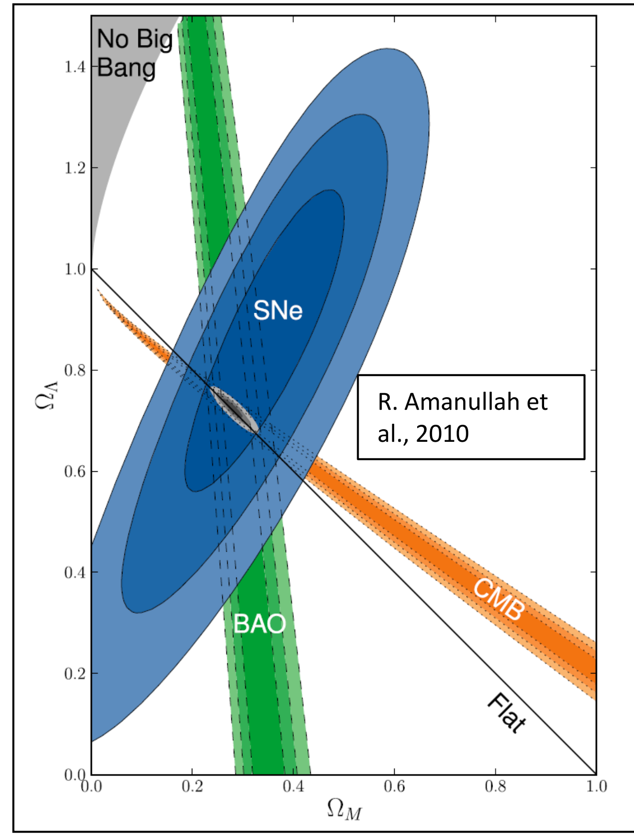
Planck Sky Map, March 2013



The *Planck* Collaboration, 2013





Planck 2013: ΛCDM rules!

$$\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} \approx 1.01 \pm 0.02$$

$$\Omega_\Lambda = 0.685 \pm 0.018 \quad \Omega_{CDM} h^2 = 0.1199 \pm 0.0027$$

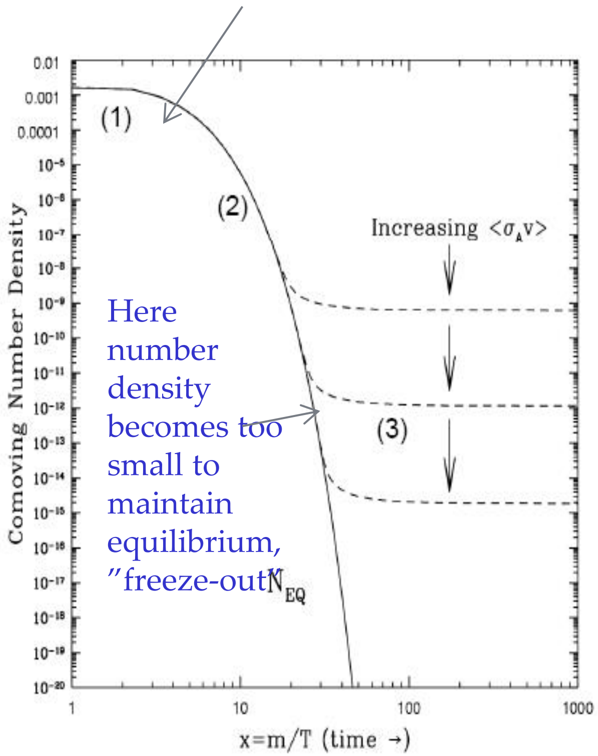
$$\Omega_B = 0.0489 \pm 0.0018 \quad h = 0.673 \pm 0.012$$

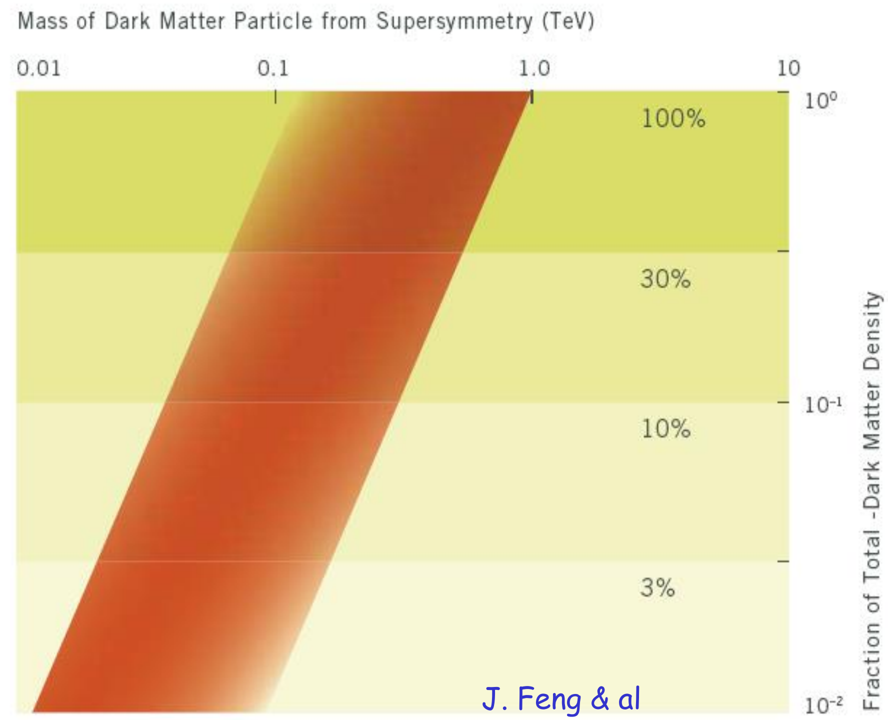
The particle physics connection: The "Weakly Interacting Massive Particle (WIMP) miracle". Is the CDM particle a WIMP?

Equilibirium curve for thermal production in the early universe. Here temperature was >> $2Mc^2$, so the particles were in thermal (chemical) equilibrium.

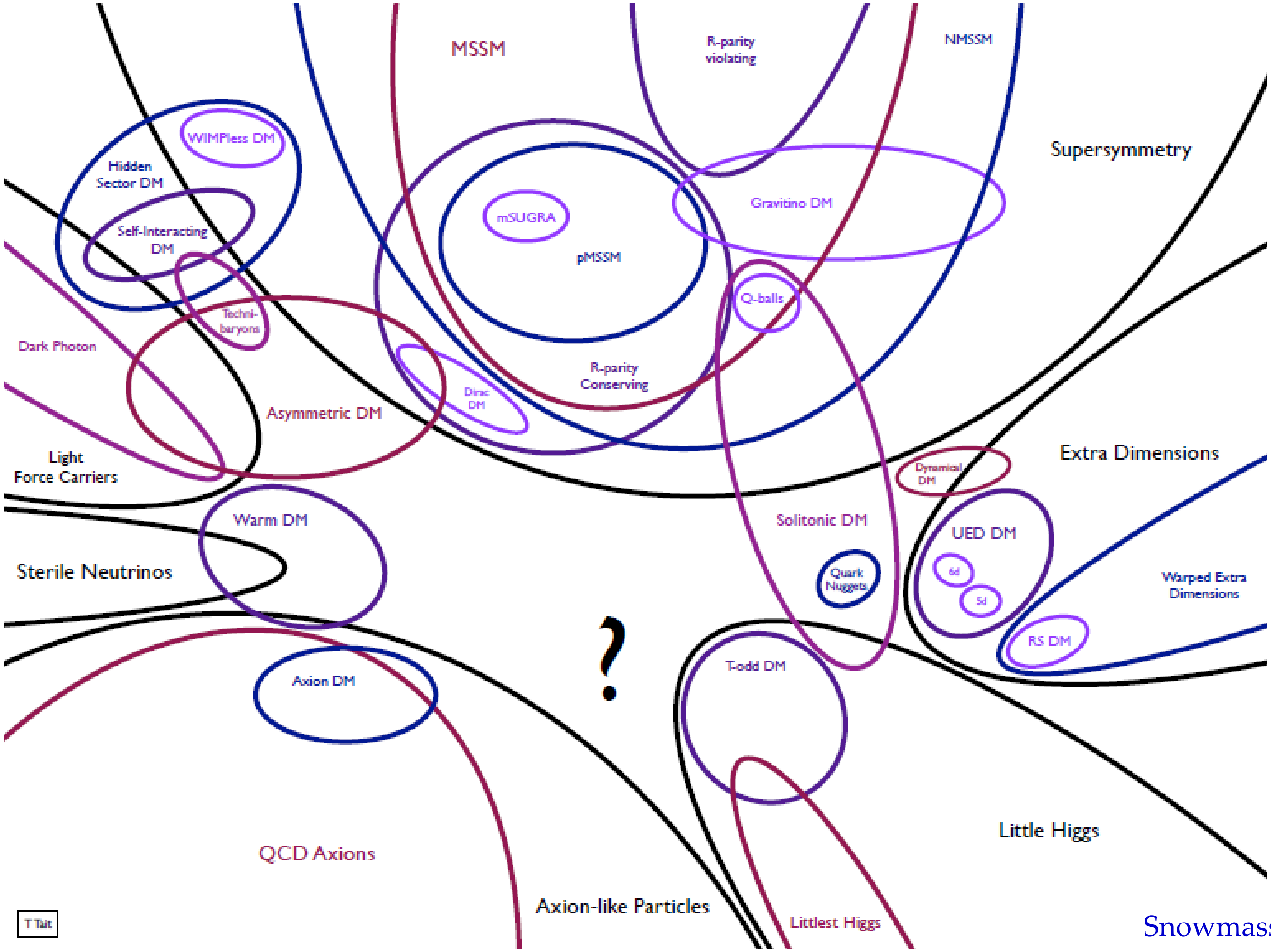
For thermal production, $\frac{\Omega_{WIMP} h^2}{0.11} \cong \frac{3 \cdot 10^{-26}\, cm^3 s^{-1}}{\langle \sigma v \rangle}$

With typical gauge couplings, and the weak interaction mass scale, 50 – 1000 GeV, for the DM particle, the observed relic density appears without fine-tuning. Example, supersymmetry (still a viable template at least before next LHC run):





Other interesting WIMPs: Lightest Kaluza-Klein particle – mass scale 600 – 1000 GeV, Inert Higgs doublet, massive ν_R,… Non-WIMPS: axions, sterile ν,...

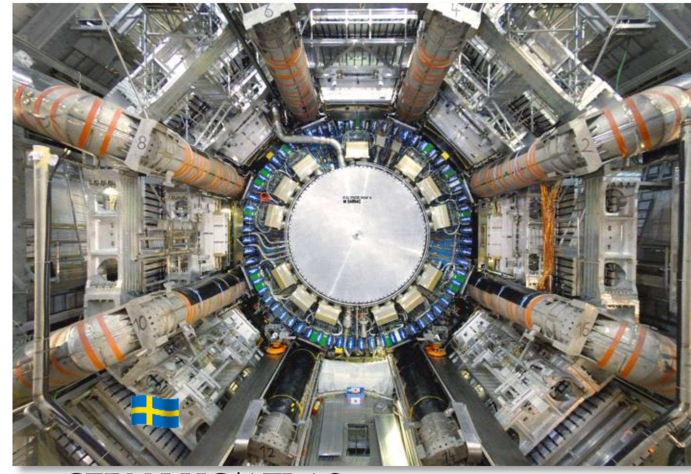


Snowmass report, 2014

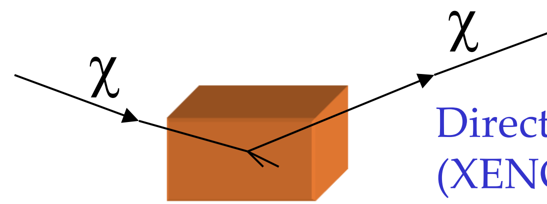
Figure 4-7. *The landscape of dark matter candidates [from T. Tait].*

Methods of **WIMP** Dark Matter detection:

- Discovery at accelerators (Fermilab, LHC, ILC…), if kinematically allowed. Can give mass scale, but no proof of required long lifetime.
- Direct detection of halo dark matter particles in terrestrial detectors. (J. Goodman & E. Witten, 1985)
- Indirect detection of particles produced in dark matter annihilation: neutrinos, gamma rays & other e.m. waves, antiprotons, antideuterons, positrons in ground- or space-based experiments. (J. Silk & M.Srednicki, 1984)
- For a convincing determination of the identity of dark matter, plausibly need detection by at least two different methods. For most methods, the background problem is very serious.



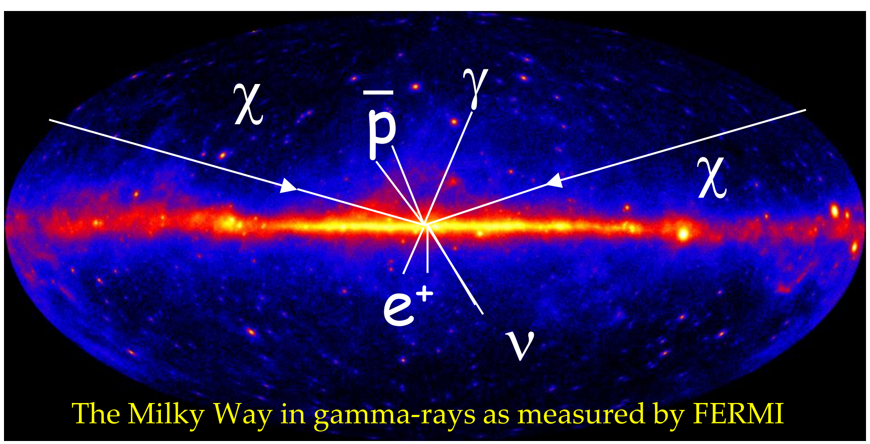
CERN LHC/ATLAS



Direct detection (XENON100, LUX, CDMS,..)

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

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, also for larger systems like galaxy clusters, cosmological structure (as seen in N-body simulations).

Many experiments have the sensitivity to find DM signals in fortuitous cases ⇒ Risk for false alarms *(Extraordinary claims require extraordinary evidence – C. Sagan)*

None of these is (yet) generally regarded as real detections of DM (but one or more **may** still be):

A "bump" in the γ-ray spectrum at a few GeV, from a "ringlike" DM structure in the galaxy (EGRET/ W. de Boer, 2004) – in tension with antiproton data. The EGRET excess seems to have been to a large part instrumental (Fermi-LAT, 2009).

A 511 keV line from the galactic centre region (seen in the INTEGRAL satellite, J. Knödlseder & al., 2003) – difficult to model as DM (maybe "exciting DM", D. Finkbeiner & N. Weiner, 2007); not exactly spherical distribution (G. Weidenspointner & al, 2008).

The DAMA/LIBRA annual modulation (R. Bernabei & al. 1997 - 2014) – not verified by other experiments. Like indications from CoGeNT and CRESST, in tension with Xenon100, LUX and SuperCDMS limits.

An unexpected rise in the positron ratio seen in the PAMELA experiment (M. Boezio & al. 2008), verified by AMS-02 (S. Ting & al., 2013) - needs unusually large "boost factors" and/or unconventional halo model for DM interpretation.

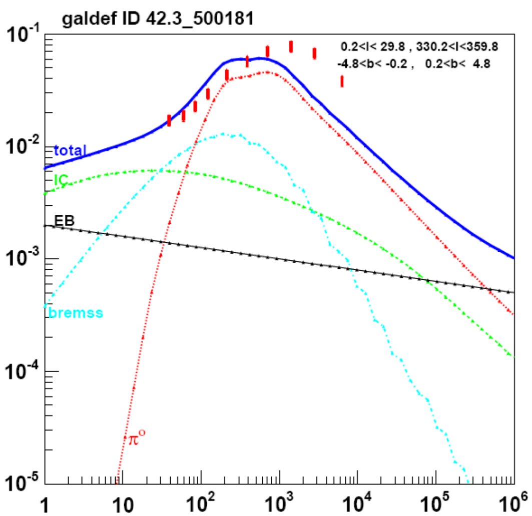
A 130 GeV γ-ray line feature seen in Fermi-LAT data (T. Bringmann & al.; C. Weniger, 2012) – seems to be partly instrumental, partly due to statistical fluke.

A GeV excess seen towards the g.c. in Fermi-LAT data (T. Daylan & al., 2014) – could be due to incomplete modelling of diffuse background (e.g., E. Carlson & S. Profumo; J.Petrovic, P. Serpico & G. Zaharijas).

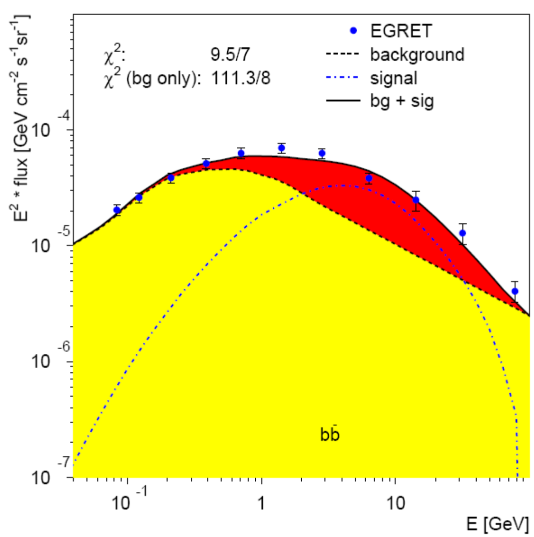
A 3.5 keV X-ray line due to decaying DM (E. Bulbul et al., 2014) – more data needed, not seen in the Milky Way (S. Riemer-Sorensen). May be due to unidentified nuclear lines? (T. Jeltema & S. Profumo.)

10-15 years ago - Interpreting the EGRET GeV excess towards the central Galaxy as due to dark matter (W. de Boer & al., 2004):

GALPROP fit

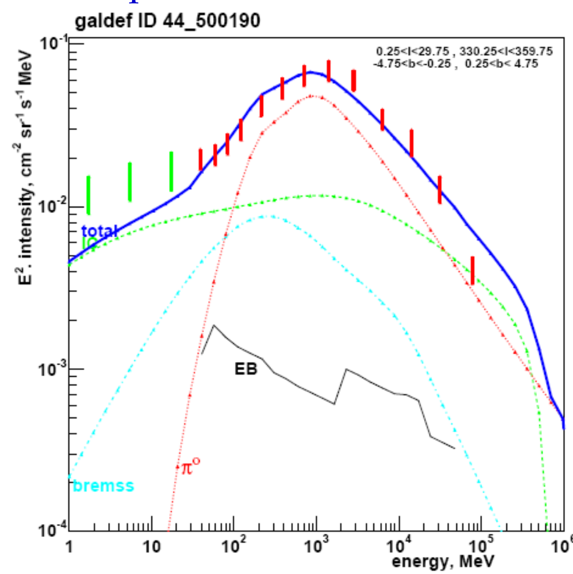


Adding 70 WIMP annihilating to $b\bar{b}$ (DarkSUSY)



Dark matter solution

Strong, Moskalenko & Reimer, 2004
Optimized GALPROP fit

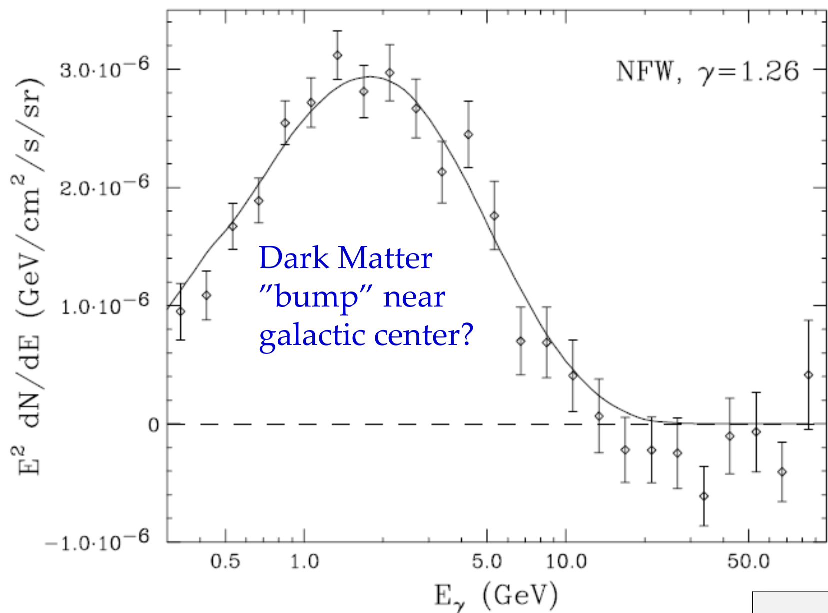


Astrophysical solution

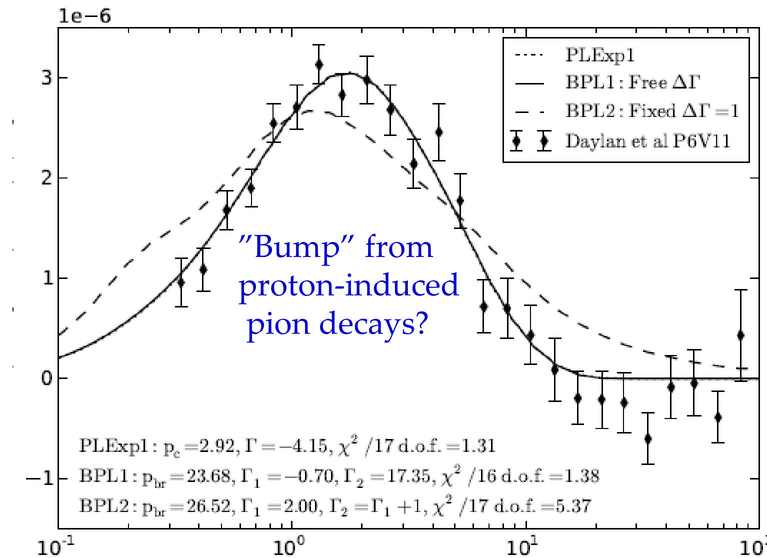
L.B., P. Ullio and J. Buckley 1998: "In fact, present EGRET observations are not inconsistent with a continuum spectrum originating from dark matter annihilations, but other explanations are possible as well"

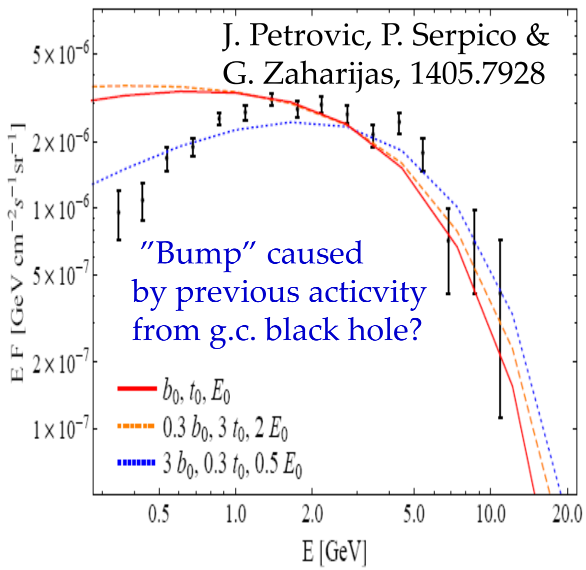
Déjà vu, 2014:

T. Daylan & al., 1402.6703



E. Carlson & S. Profumo, 1405.7685





L.B., 2014: "In fact, present Fermi observations are not inconsistent with a continuum spectrum originating from dark matter annihilations, but other explanations are possible as well"

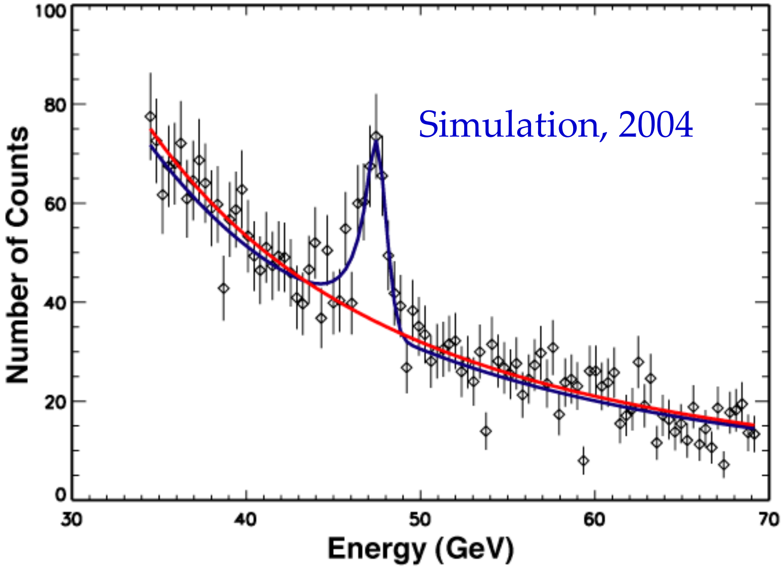
(c.f. recent strong limits from antimatter and radio emission, T. Bringmann, M. Vollman and C. Weniger, 1406.6027.)

”Smoking gun” for dark matter – a γ-ray line

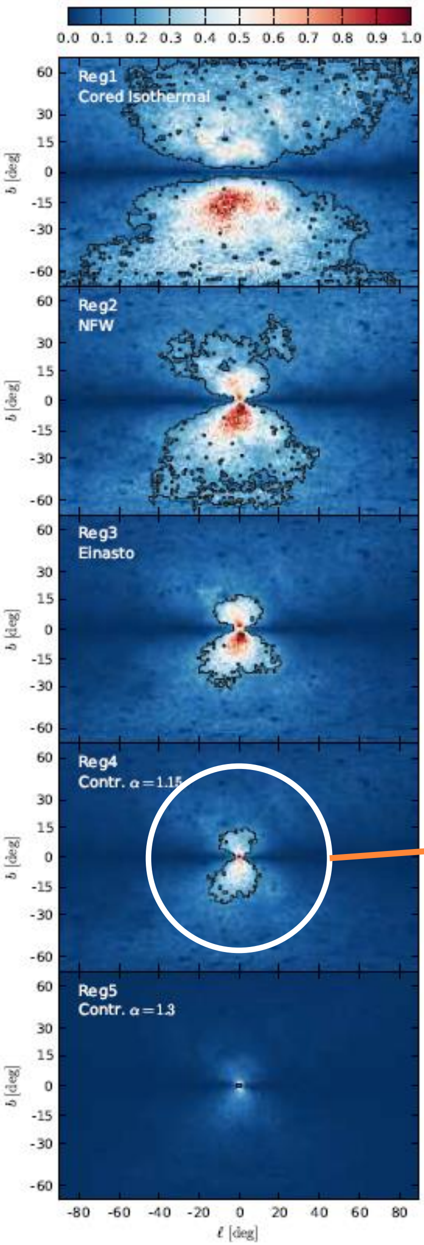
Fermi Gamma-ray Space Telescope

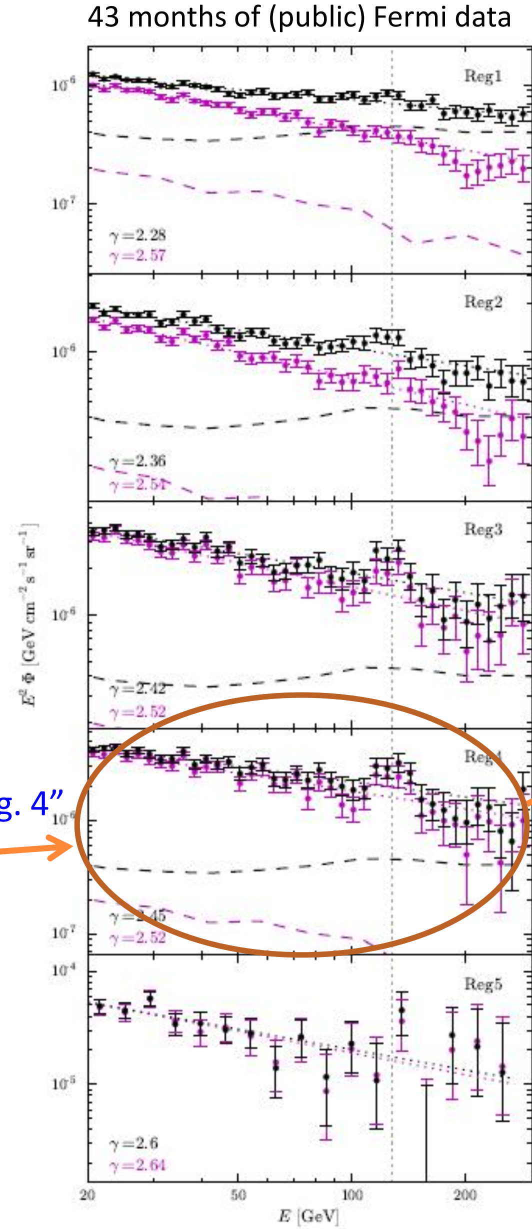
GAMMA-RAY LARGE AREA SPACE TELESCOPE

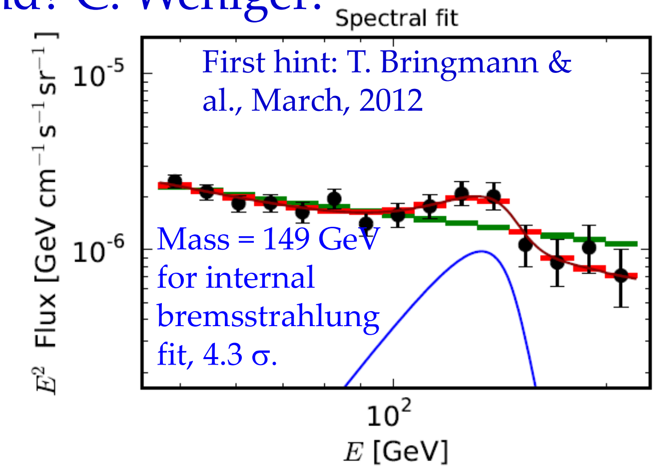
USA-France-Italy-Sweden-Japan (-Germany) collaboration, launch ~~2006~~ 2008

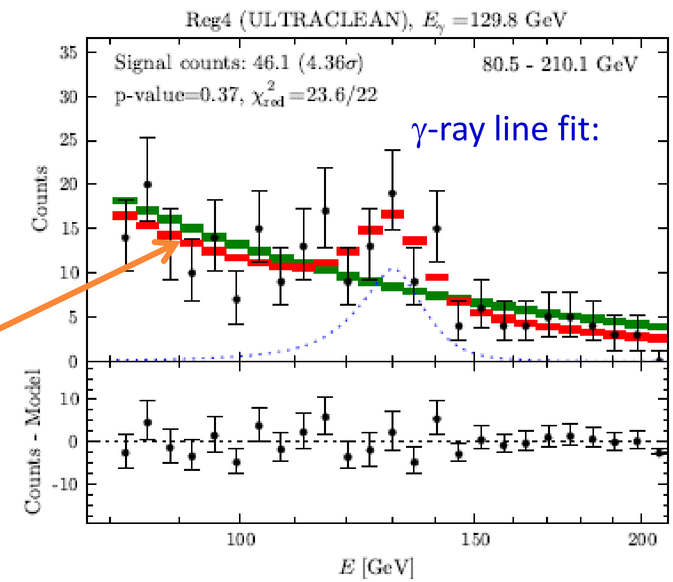


April, 2012 – Dream come true, smoking gun found? C. Weniger:



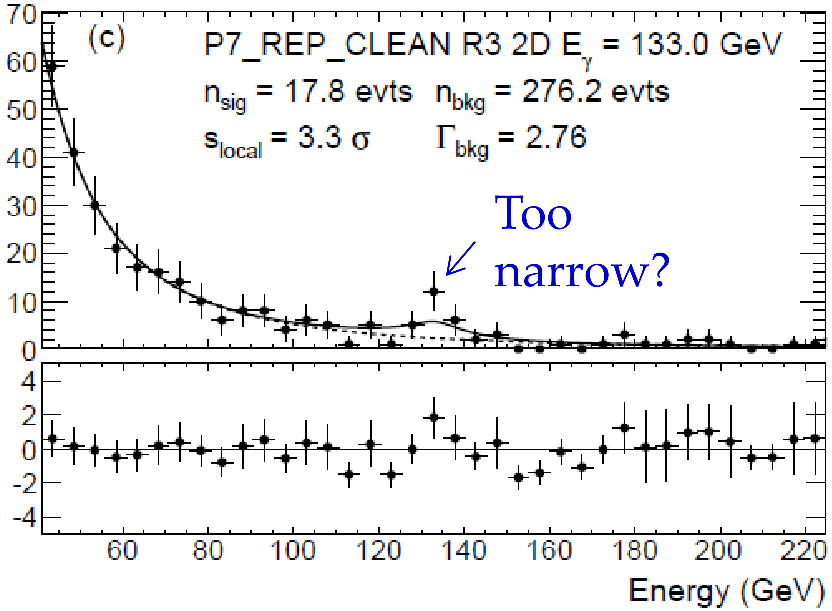


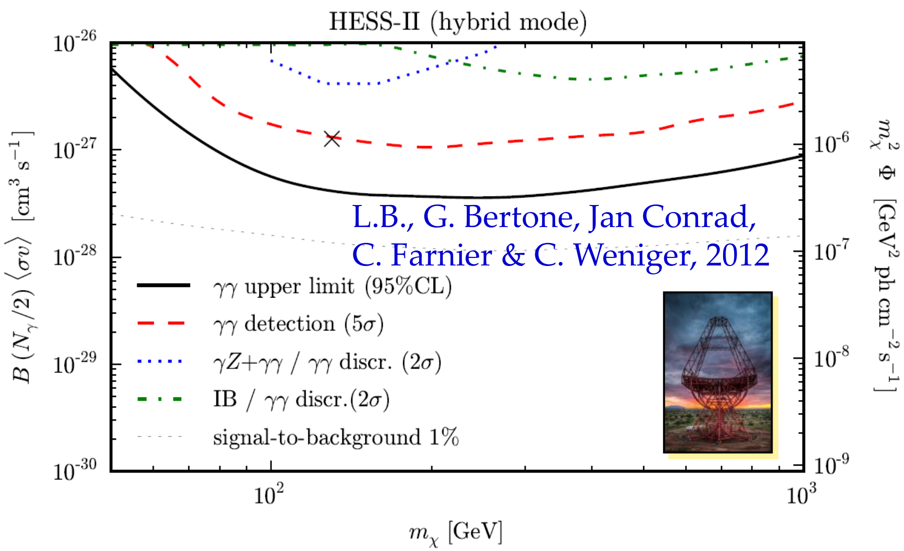




Mass = 130 GeV
Significance 4.6σ (3.3σ if ”look elsewhere” effect included)

2013 - Back to reality: The 130 GeV line was probably due to a combination of an instrumental effect and a statistical fluke (in the last two years, the statistical significance of the effect has gone down).

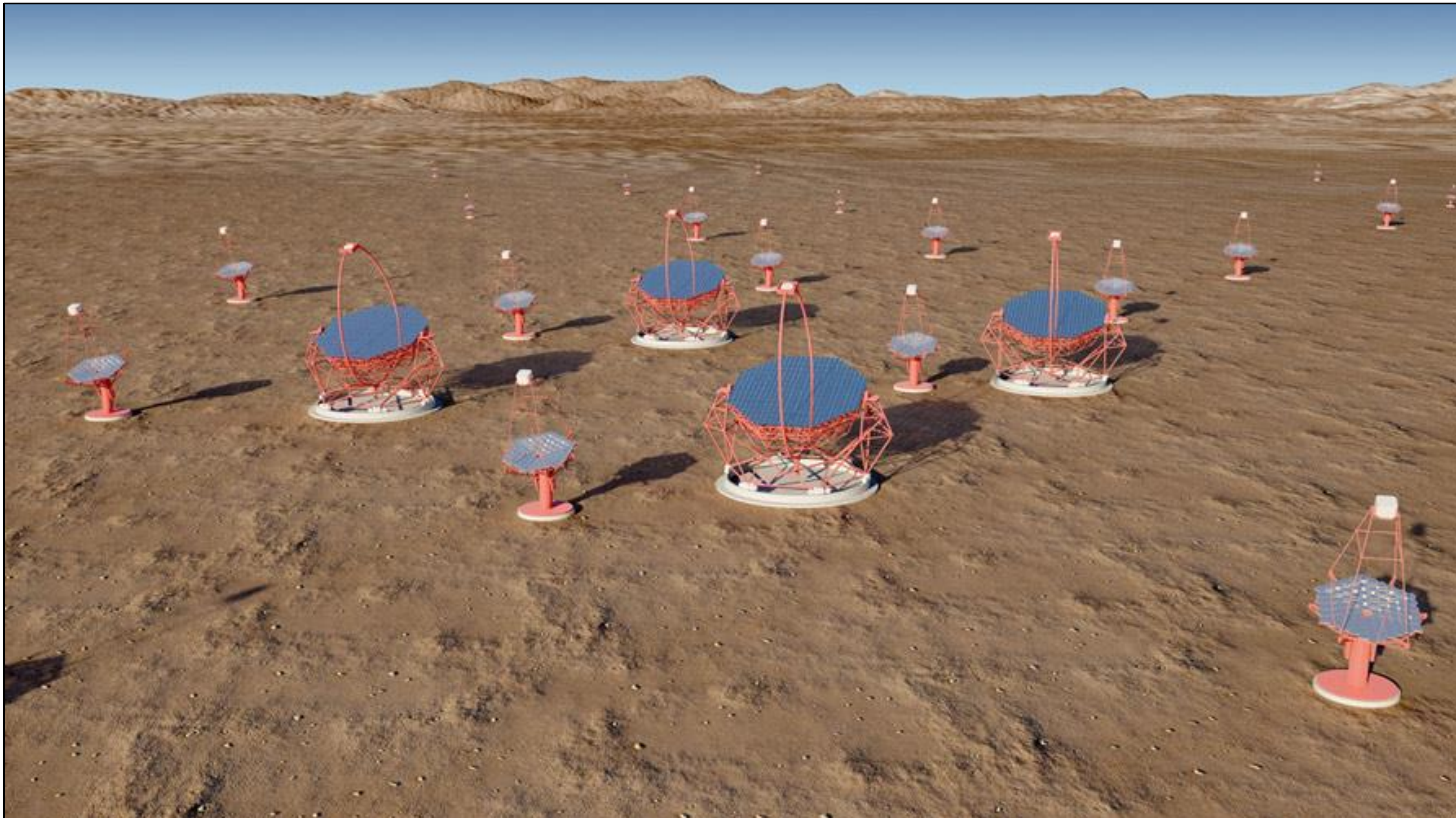




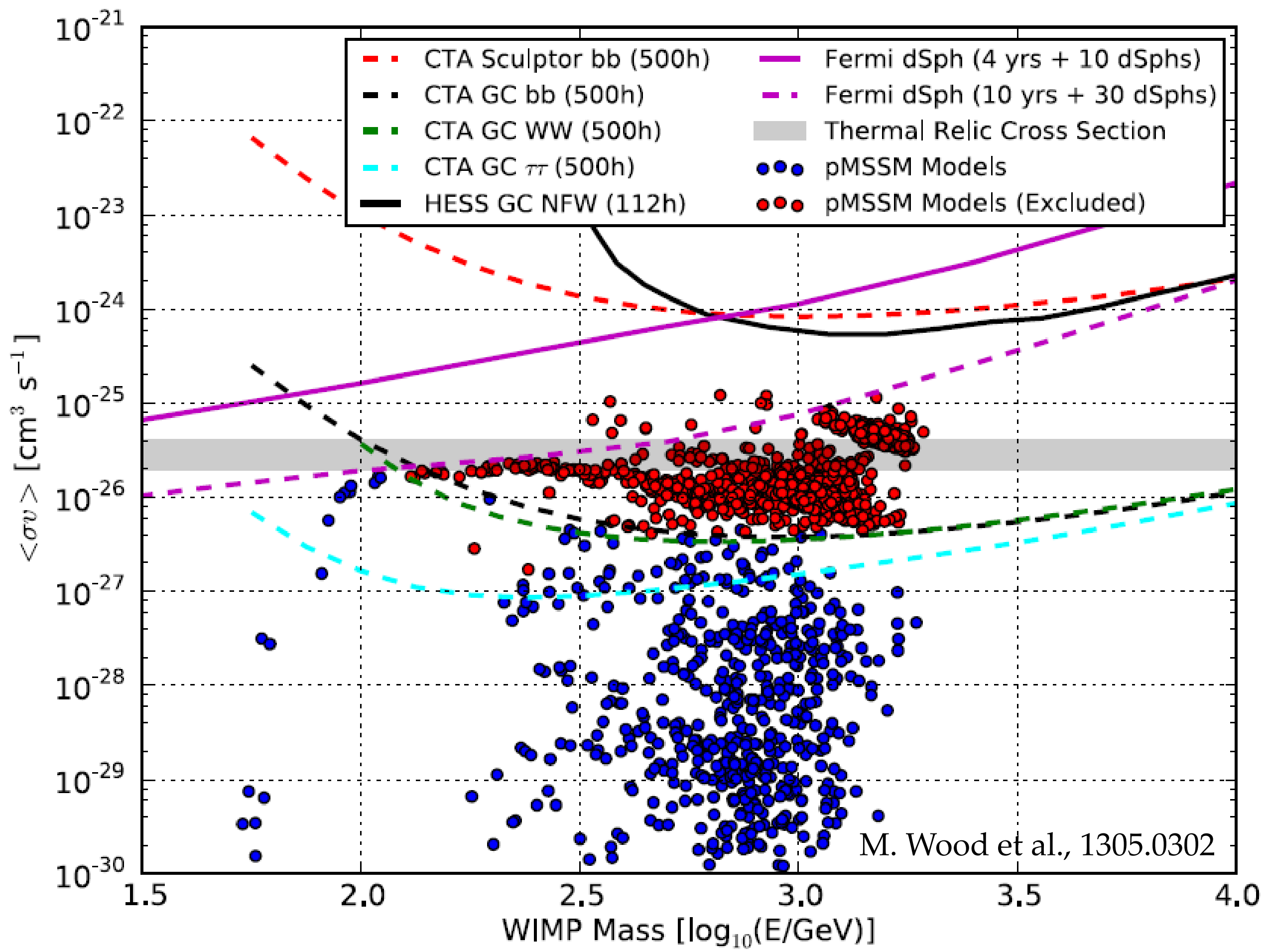
Fermi-LAT is now using a new mode of operation, with more sensitivity towards the gal. centre.

With HESS-II (currently data-taking) we should get a definite answer by October 2014.

CTA: The new window to the high-energy gamma-ray universe (c:a 2018-)



CTA may have good discovery potential, especially in the 100 GeV – few TeV region



Note: Systematics and diffuse emission background not included. More clever methods will probably be needed!

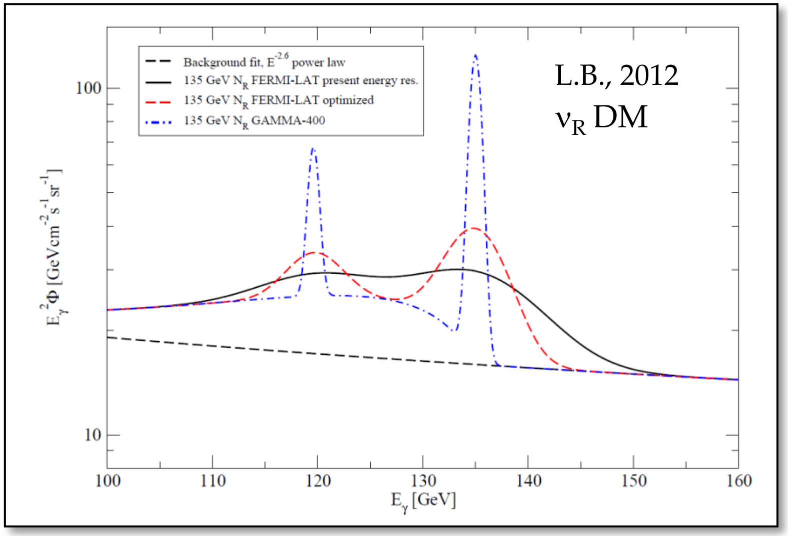
Future - No planned Fermi-LAT replacement in the US. The future seems to be in the East for gamma-ray space telescopes:

GAMMA-400, 100 MeV – 3 TeV, an approved Russian γ-ray satellite. Planned launch 2020. Energy resolution (100 GeV) ~ 1 %. Effective area ~ 0.4 m^2 . Angular resolution at 100 GeV ~ 0.01°

Dark Matter Particle Explorer, DAMPE: Satellite of similar performance. An approved Chinese γ-ray satellite. Planned launch 2016. (Precursor to HERD.)

HERD: Instrument on Chinese Space Station. Energy resolution (100 GeV) ~ 1 %. Effective acceptance ~ 4 m^2sr. Angular resolution (100 GeV) ~ 0.01°. Planned launch around 2020.

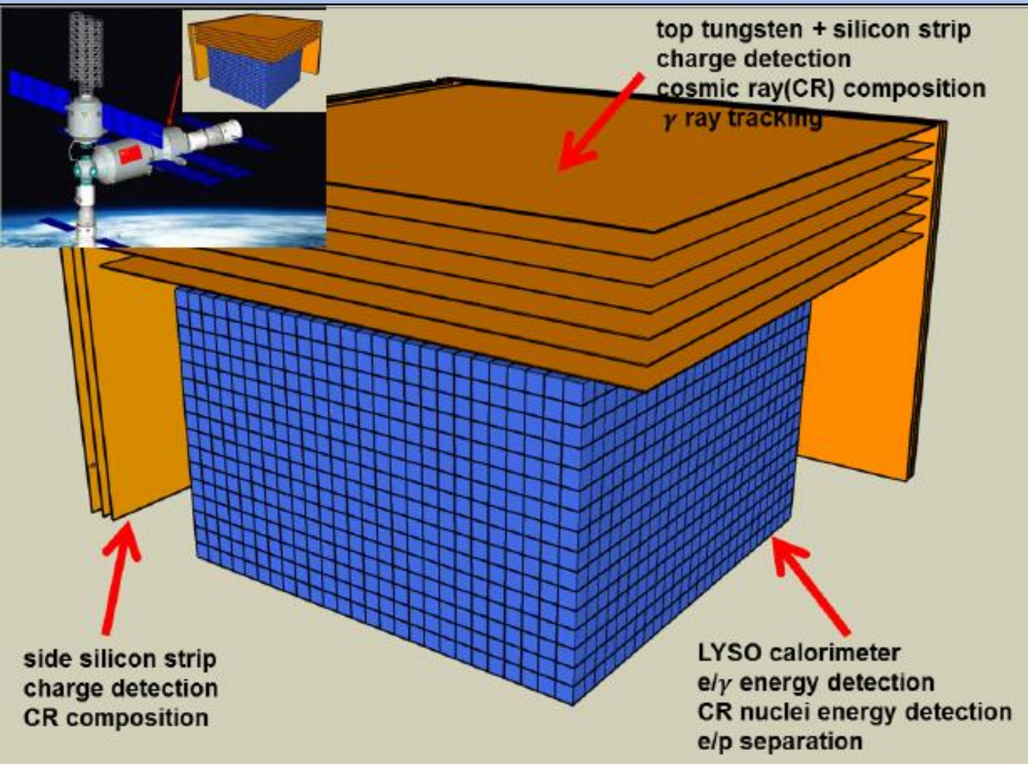
All three have detection of dark matter as one key science driver

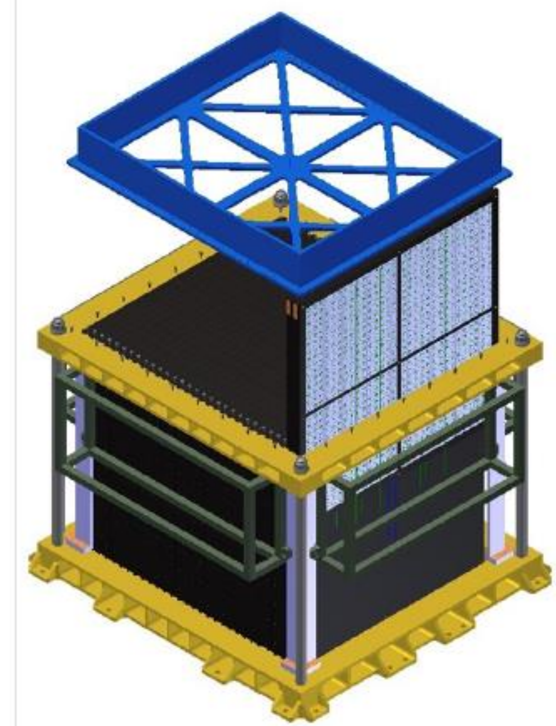


Ideal, e.g., for looking for spectral DM-induced features, like searching for γ-ray lines! Can search for γ-ray structures, with unprecedented precision.

New models with large line features and other energy structures, e.g., scalar DM: F. Giacchino & al., 2013; A. Ibarra & al., 2014.

High-Energy Radiation Detector (HERD), 1407.4866

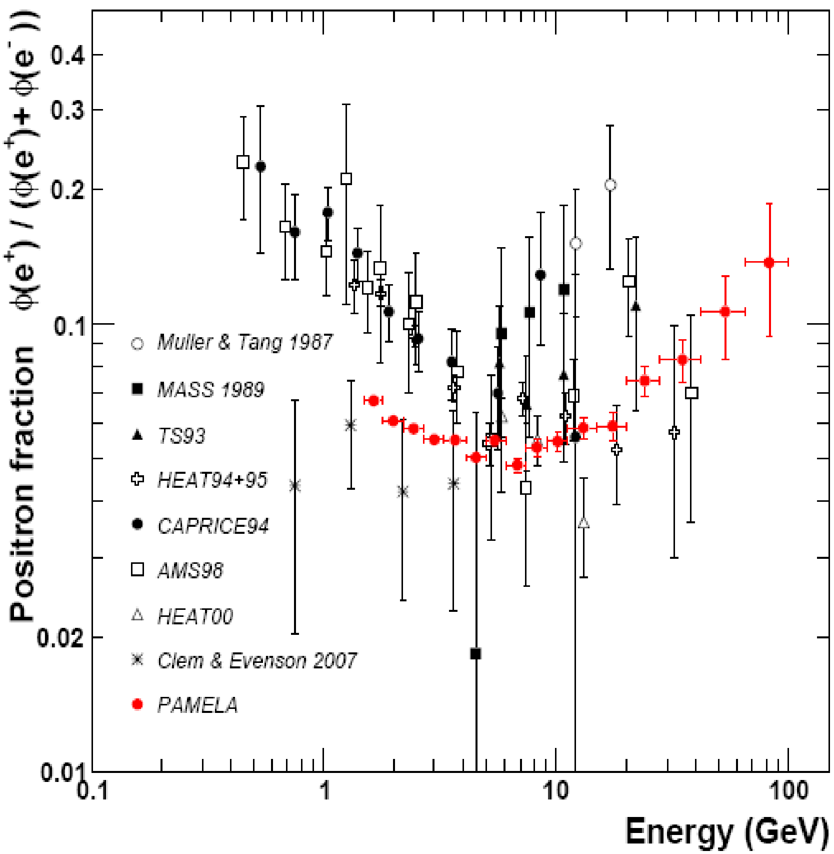


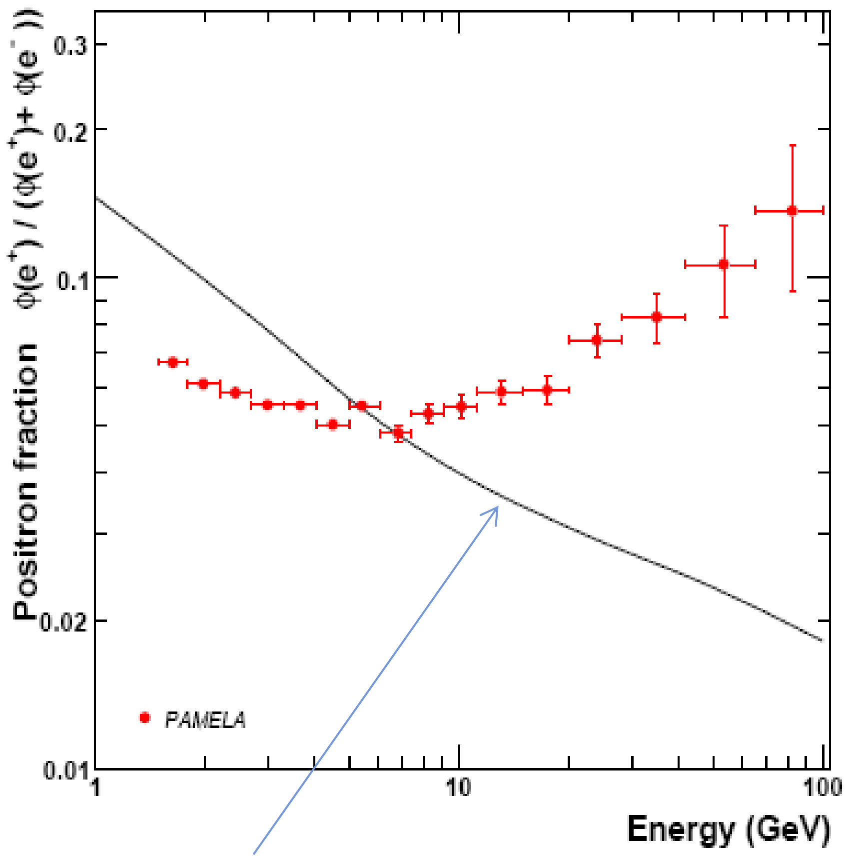


Particle	γ/e	CR	γ/e	CR	γ/e	p	e/p	e	p
Para.	energy	energy	$\Delta\theta$	ΔC	$\Delta E/E$	$\Delta E/E$	sep.	$A_{\rm eff}$	$A_{\rm eff}$
Perfor.	100 MeV -10 TeV	GeV -PeV	0.1°	∼0.1 c.u	$<1\%$ @200 GeV	20%	$< 10^{-5}$	3.7 m^2sr @600 GeV	2.6 m^2sr @400 TeV

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

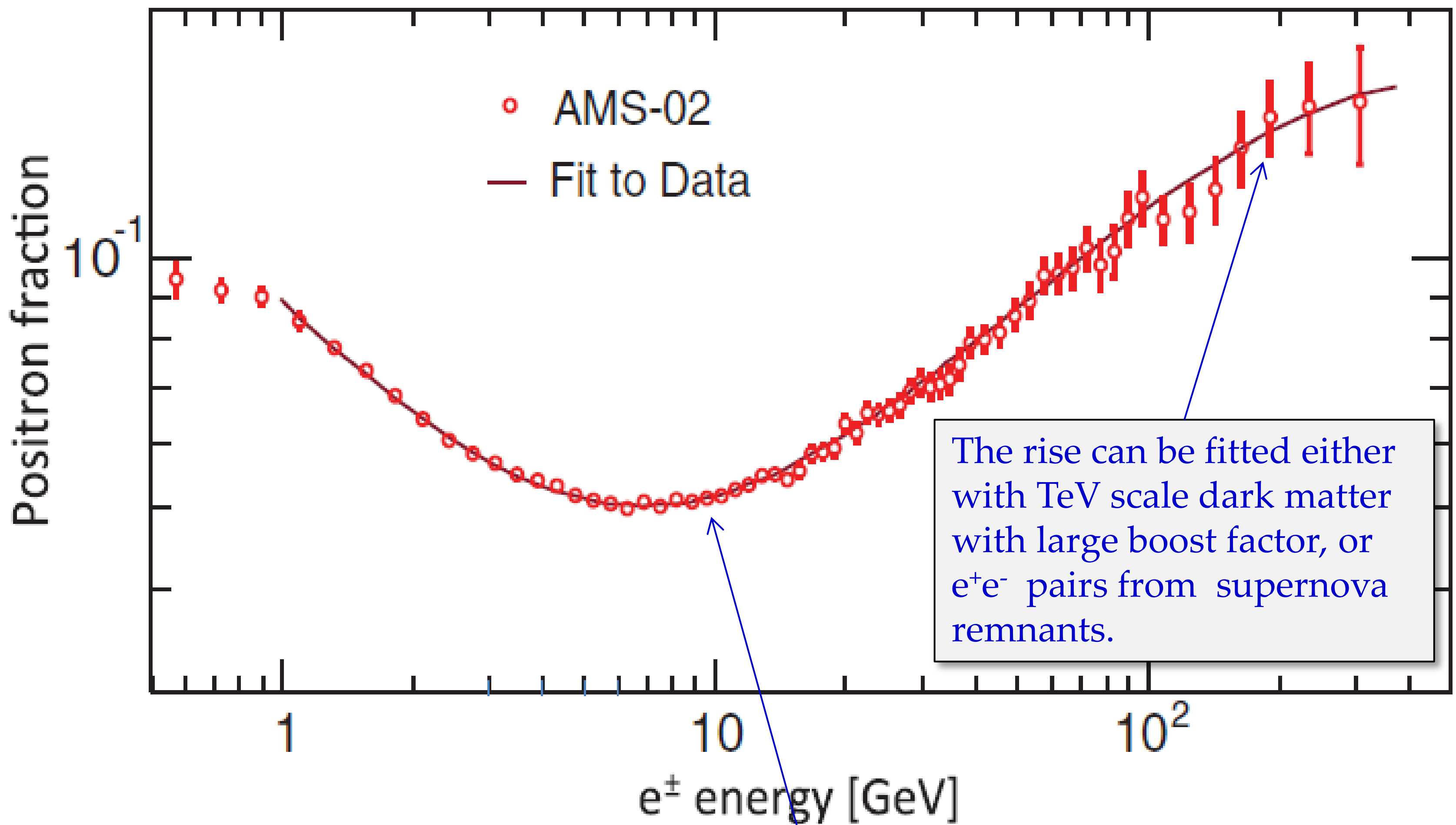
A very important result. An additional, primary source of positrons seems to be needed.





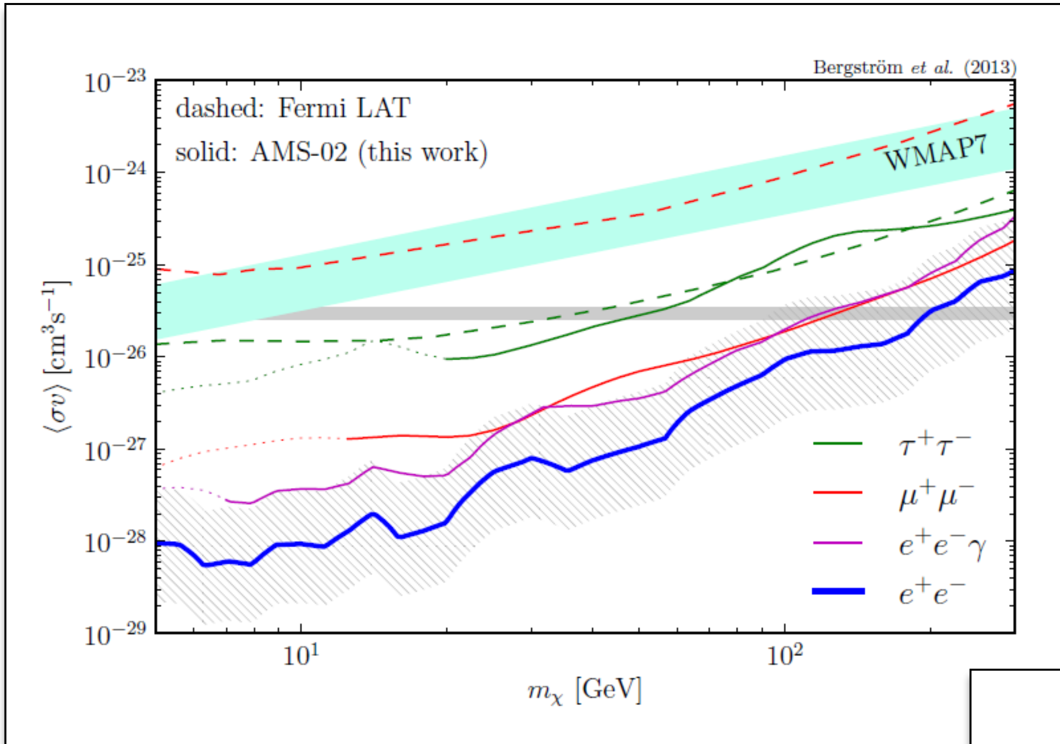
Prediction from secondary production by cosmic rays: Moskalenko & Strong, 1998

The rise was confirmed with AMS-02 on the International Space Station, 2013:



The rise can be fitted either with TeV scale dark matter with large boost factor, or e^+e^- pairs from supernova remnants.

Note high precision of the very smooth AMS-02 data.
Future: The experiment will give data for at least 10 more years.



The precison of the AMS-02 data allows stringent limits on Dark Matter annihilation to positrons, muons, and taus. (L.B., T. Bring-mann, I. Cholis, D. Hooper & C. Weniger, PRL 2013; A. Ibarra, A. Lamperstorfer and J. Silk, PRD 2014)

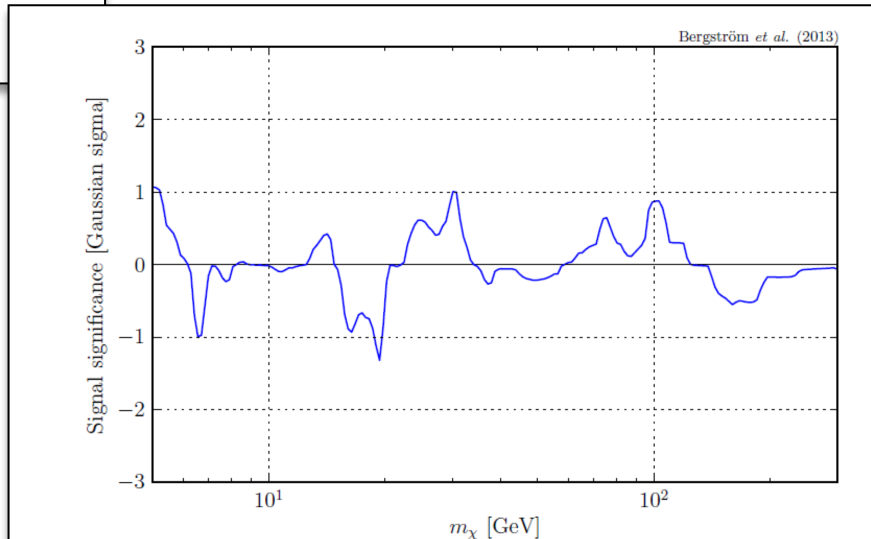


FIG. 6. Significance for a contribution from a e^+e^- DM signal to the AMS-02 positron fraction, for different DM energies, in units of Gaussian sigma. Negative values correspond to negative (but unphysical) signal normalizations.

One can also search for "bumps", none found so far – wait and see…

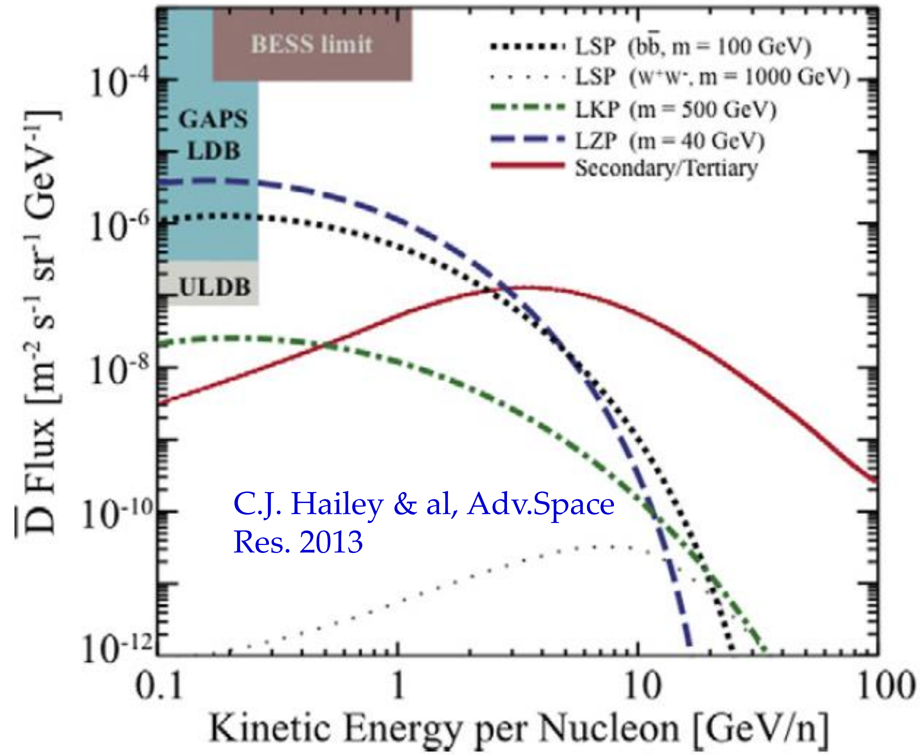
Antiprotons may be created by DM annihilation or decay. However, the signature not unique.

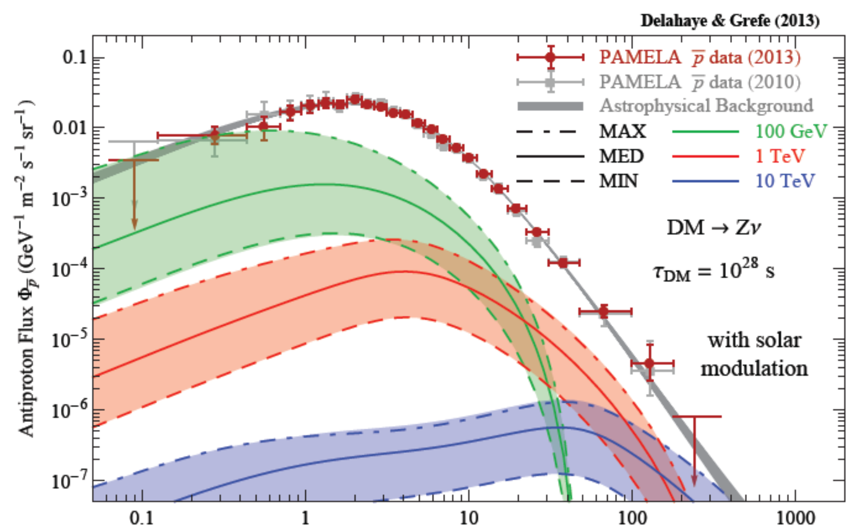
Future: Antideuterons maybe better ”smoking gun” DM signal – but rare? (Donato et al., 2000). GAPS ballon experiment (2015?) will have some sensitivity.

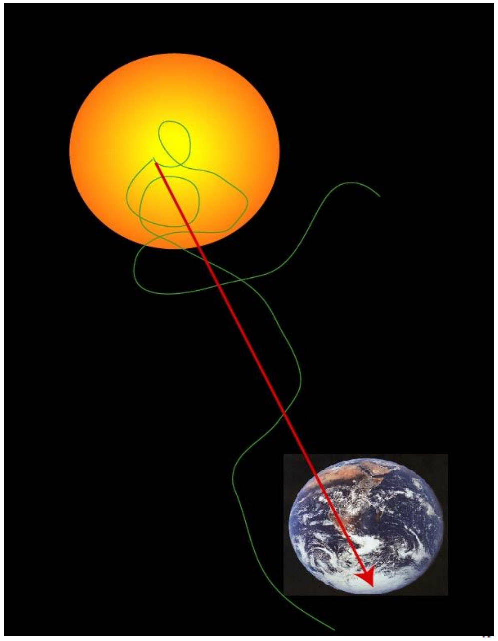
Antiprotons still a good **check of models.**

Examples: Decaying gravitino DM (T. Delahaye and M.Grefe, 2013), limits on g.c. γ-ray excess (T. Bringmann, M. Vollman & C. Weniger, June 24, 2014)

Soon: High-quality antiproton data from AMS-02 (later this year?)



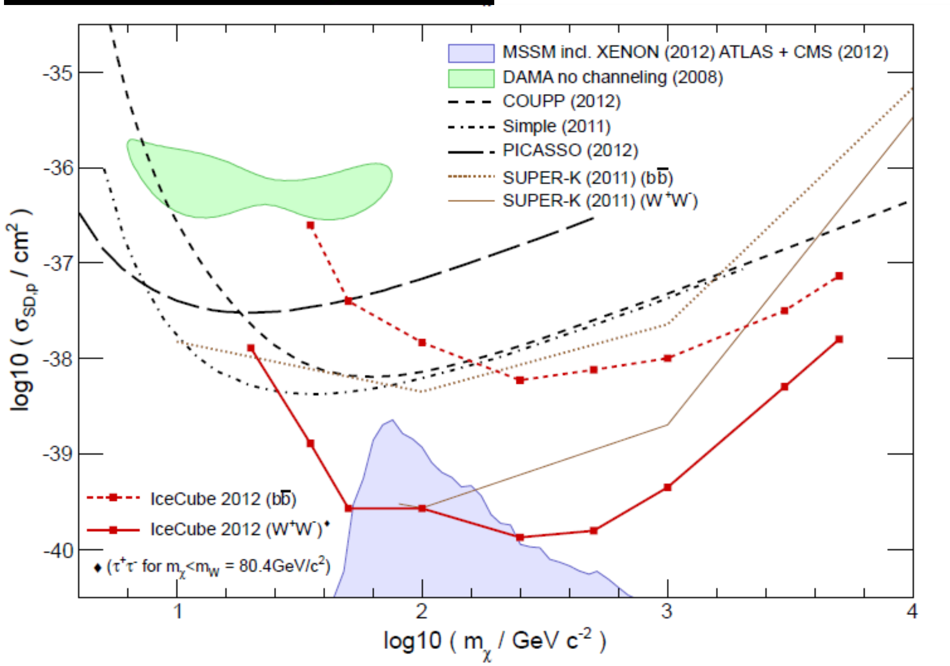


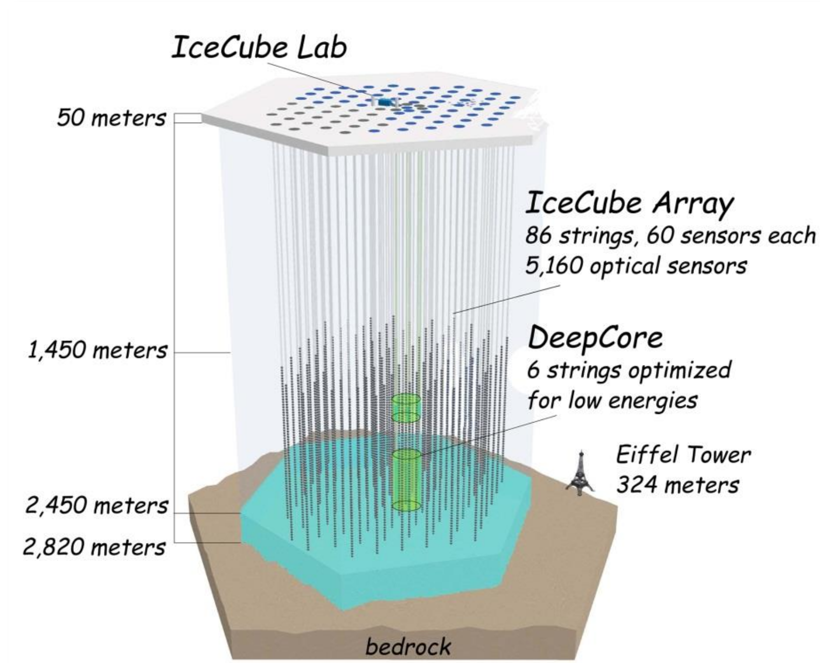


Indirect detection by neutrinos from annihilation in the Sun:

Present: Competitive, due to high proton content of the Sun ⇒ sensitive to **spin-dependent** interactions

Future: New planned addition PINGU (2020?-), will lower threshold further. May be combined with a larger area extended IceCube

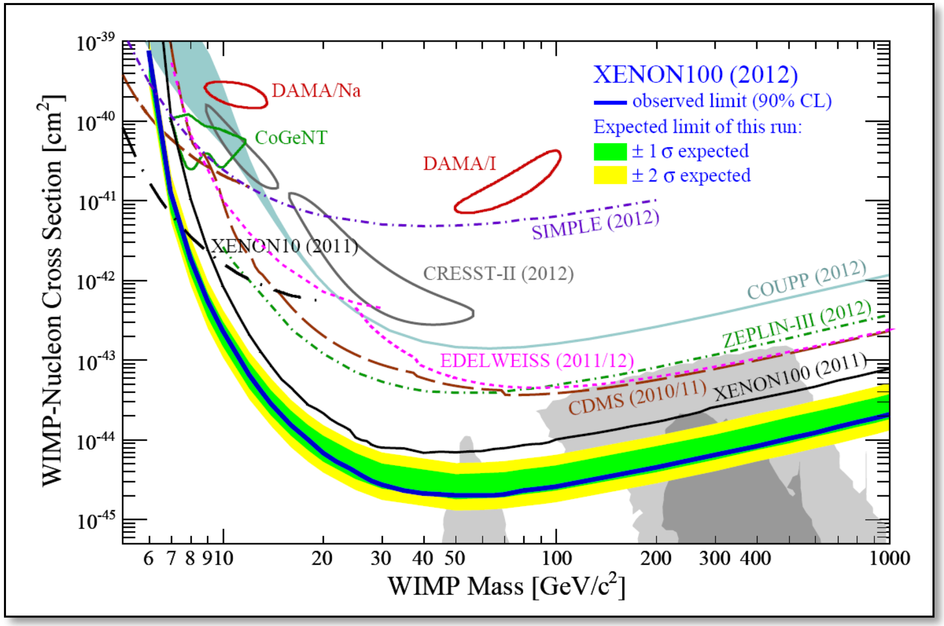




IceCube Collaboration, PRL, 2013

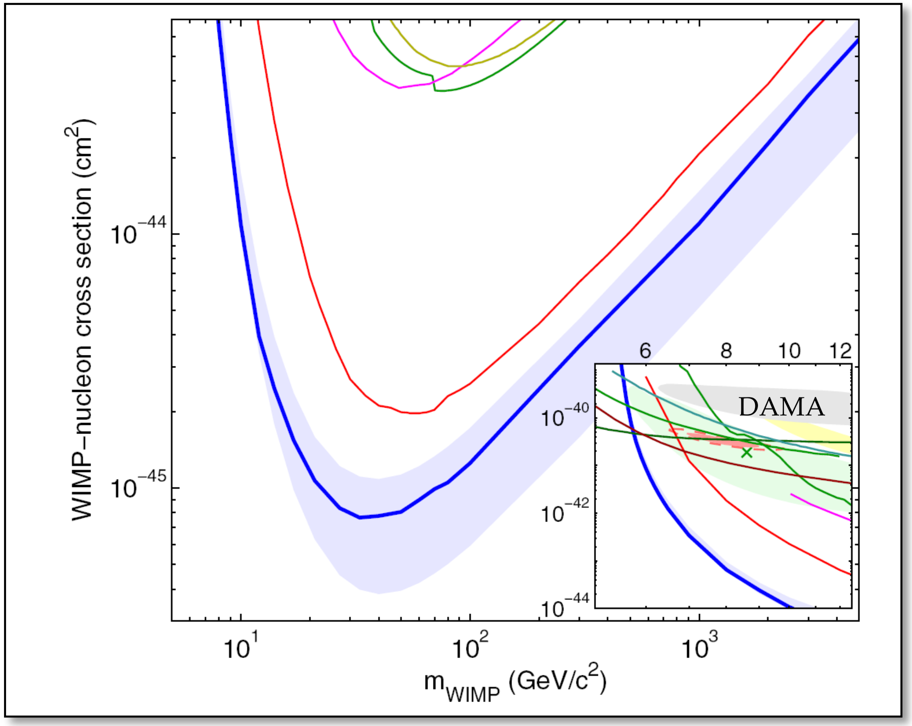
DM direct detection searches – a success story. Three orders of magnitude increase in sensitivity over 10 years!
At the moment (2014), Li-Xe detectors are leading the race (and for low masses SuperCDMS – solid state detector), and seem to exclude scattering rates needed to explain the positive signals in DAMA/CoGeNT/CRESST:

XENON100

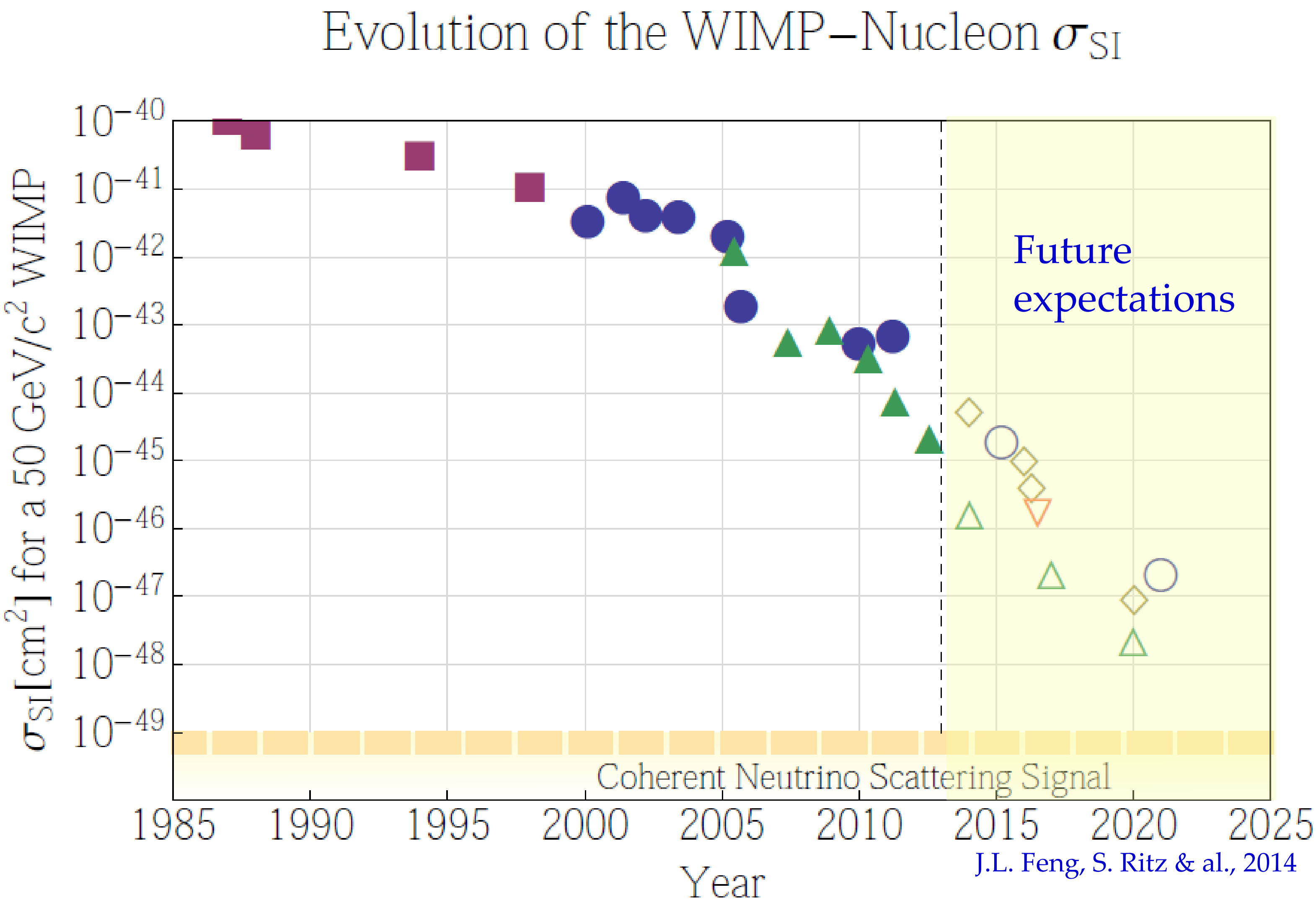


E. Aprile & al., Phys. Rev. Lett. 109 (2012) 181301

LUX



D.S. Akerib & al., Phys. Rev. Lett. 112 (2014) 091303



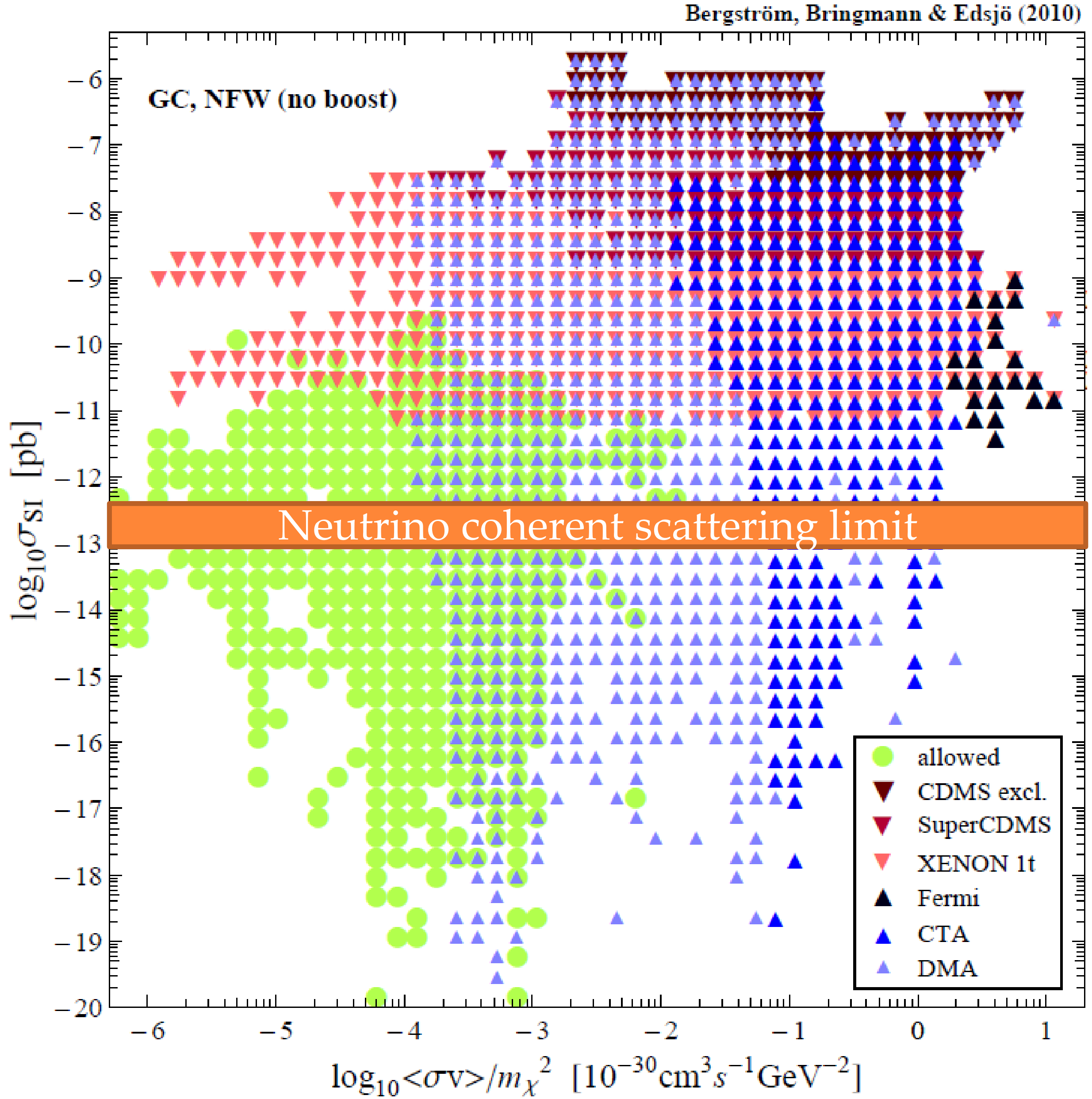
Evolution of the WIMP–Nucleon σ_{SI}
σ_{SI}[cm^2] for a 50 GeV/c^2 WIMP
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
Future expectations
Coherent Neutrino Scattering Signal
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year
J.L. Feng, S. Ritz & al., 2014

Comparison direct – indirect DM detection

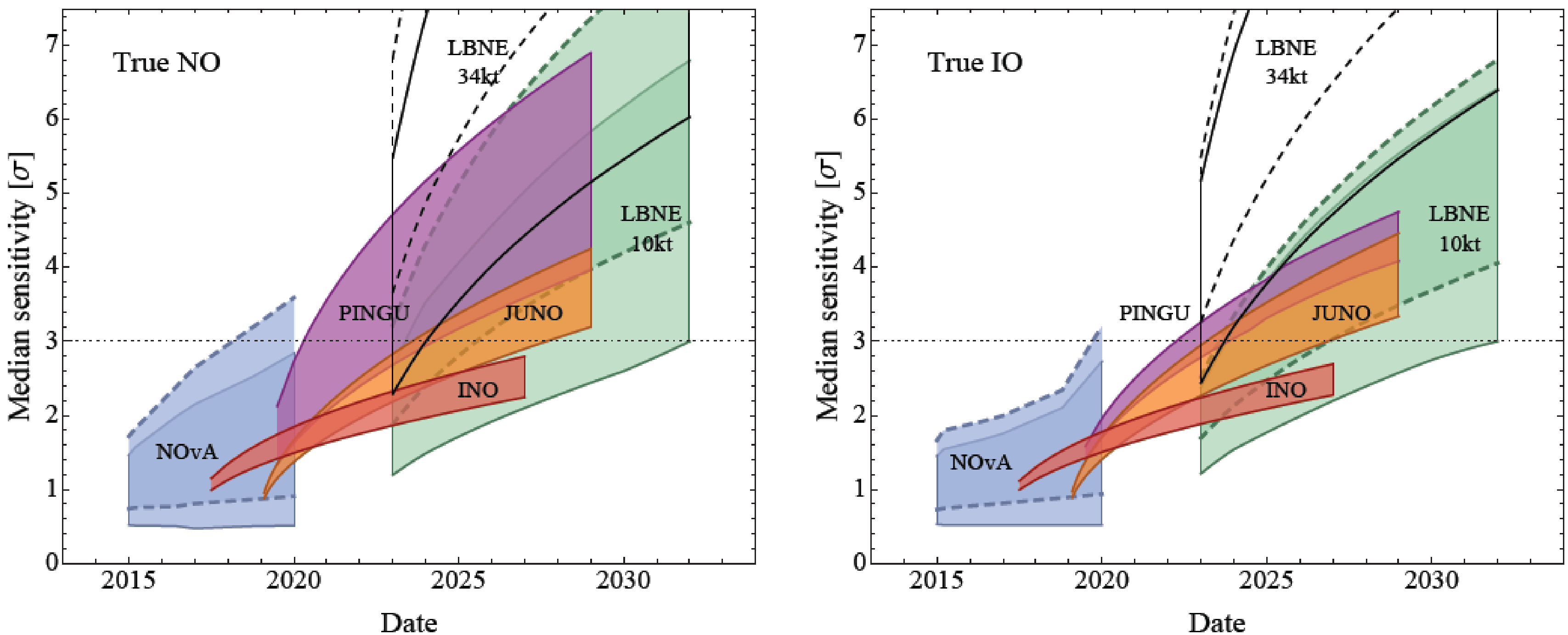
pMSSM scan – but should be regarded as generic for various WIMPs

(L.B., T. Bringmann & J. Edsjö, PRD 2011)

There will always be regions beyond reach…

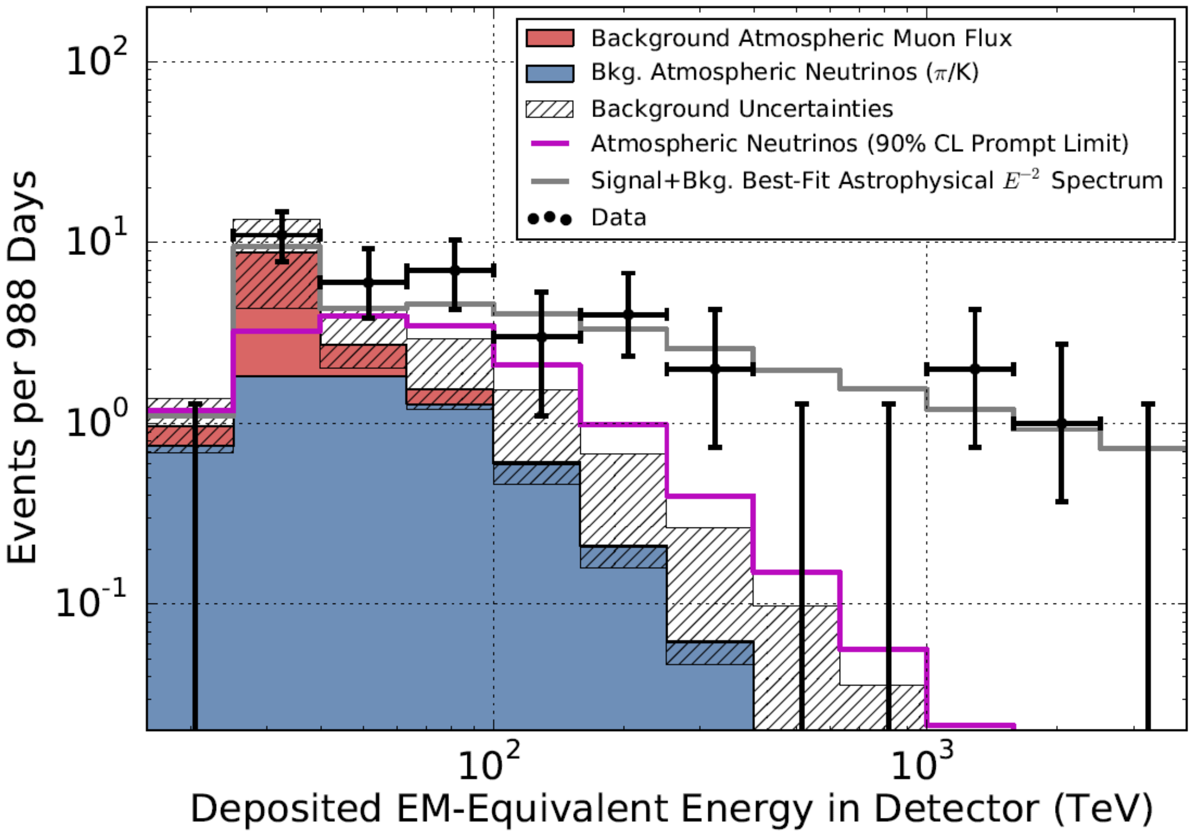


Netrino physics, main questions: Is the hierarchy of masses normal or inverted? How strong is CP violation?



M. Blennow, P. Coloma, P. Huber & T. Schwetz, 2013.
(Also ambitious plans in Europe, LBNO/LAGUNA, A. Rubbia & al, ESSnuSB, T. Ekelöf et al.)

IceCube is finally seeing a cosmic signal!
Plans have started to increase the size by a factor of a 10 – this could be in conjunction with also buiding the PINGU insert. Will KM3Net follow?



The IceCube Collaboration, May 2014, 1405.5303

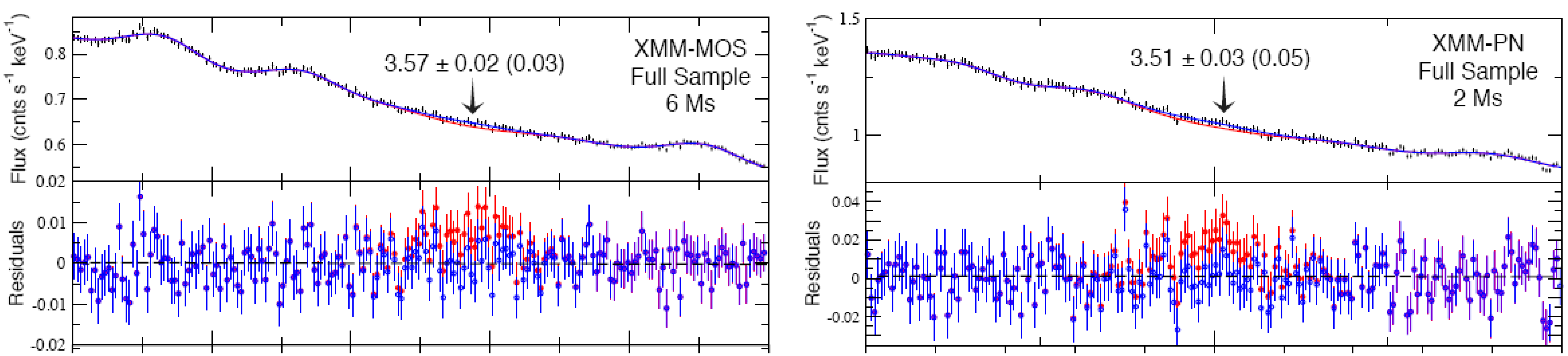
A 7 keV sterile neutrino as Dark Matter?

It could decay, $\nu_s \rightarrow \nu + \gamma$, with γ almost monoenergetic in the X-ray band, $E_\gamma \approx 3.5$ keV. The rate depends on the mixing with active neutrinos, and

$$\tau \simeq 7.2 \times 10^{29} \text{ sec} \left(\frac{10^{-4}}{\sin(2\theta)}\right)^2 \left(\frac{1 \text{ keV}}{m_s}\right)^5$$

As long as 0.5 keV < m_s < 100 keV, this is consistent with existing bounds (but a considerable fine-tuning of mixing angle and mass is needed to get a barely observable but not overwhelming signal).

E. Bulbul & al., Feb 2014, stacked XMM-Newton data from 73 clusters (1402.2301):



Is this a real dark matter line, or something given by systematics?

Timeline:

Later same week, Feb. 2014, Boyarski & al., claimed verification of line towards M31 and Perseus cluster in XMM-Newton data (1402.4119).

In May, S. Riemer-Sorensen noted that the line could not be found in Chandra data towards the galactic centre.

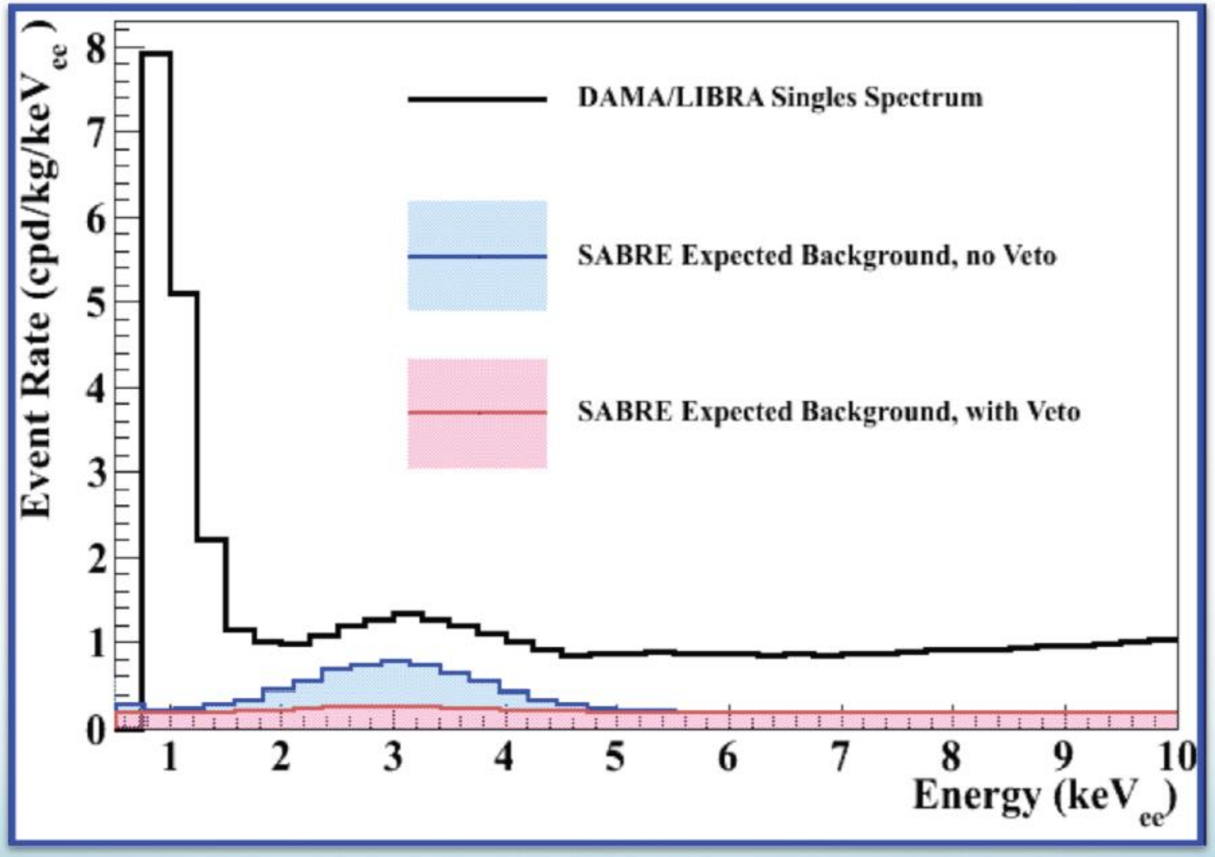
The day before yesterday, T. Jeltsema and S. Profumo in the paper ”Dark Matter Searches going Bananas” (1408.1699) suggested that the analyses of Bulbul & al and of Boyarsky & al have overlooked the effects of Potassium and Chlorine lines, and that the significance if including them is smaller than 1 σ.

Yesterday, Boyarsky & al. claim to have verified the line towards the g.c. using XMM data. However, they comment on Riemer-Sorensen: *”If one considers the abundance of potassium as a completely free parameter (as it was done in [Riemer-Sorensen] for the Chandra data of the Galactic Center), one can find an acceptable fit of the XMM GC data without an additional line at 3.539 keV.”*

To be continued... (To me, it seems already like another case of ”false alarm”.)

An astroparticle physicist's wishlist for the next 10 years: What we need	Will happen?	How?
New ideas on detection of non-WIMPs, like axions or axion-like particles	?	ADMX, CARRACK, CAPP, IAXO,…
CTA and space gamma-ray experiment(s) for lower energies, replacing Fermi-LAT	v	CTA, GAMMA-400, DAMPE, HERD
Good space experiments on antimatter detection: positrons, antiprotons and antideuterons.	v	AMS-02, HERD, GAPS?
Second- and third-generation direct detection experiments, ideally both noble gas and solid state detectors, with different target materials, and a decisive test of DAMA/LIBRA	v	LUX, XENON-1t, SuperCDMS, XMASS, PandaX, DarkSide, ANAIS, SABRE, DM-Ice,... → G3
Indications from LHC of new physics, and a linear collider for detailed studies	?	CERN - let us hope…, ILC, FCC, …
For neutrinos, experiments to determine hierarchy and CP phase. Also determine whether sterile neutrinos exist, perhaps being the Dark Matter	?	LNBF/LBNO?, PINGU, JUNO, ESSnuSB, X-ray line searches?
For cosmology, test of CMB B-mode polarization, and precision measurements of cosmological parameters.	v	BICEP2-Keck Array, CMBPol, EUCLID, LSST, DESI... → CMB-S4
New direct detection experiments for gravitational waves	v	Advanced LIGO and VIRGO, KAGRA (Japan) LISA pathfinder, Einstein Telescope, maybe LISA

DAMA has been with us, unexplained, since 1997, showing annual modulation, consistent with DM, at present with 9.2σ statistical significance.
Finally, a NaI experiment with superior sensitity is being planned, SABRE (F. Calaprice & al., Princeton Univ.)
SABRE: Sodium-iodide with Active Background Rejection
J. Xu, UCLA DM Conference talk, 2014:



* This spectrum was made using NaI powder radioactivity; crystal can be better.
* External background is estimated to be relatively small compared to internal.

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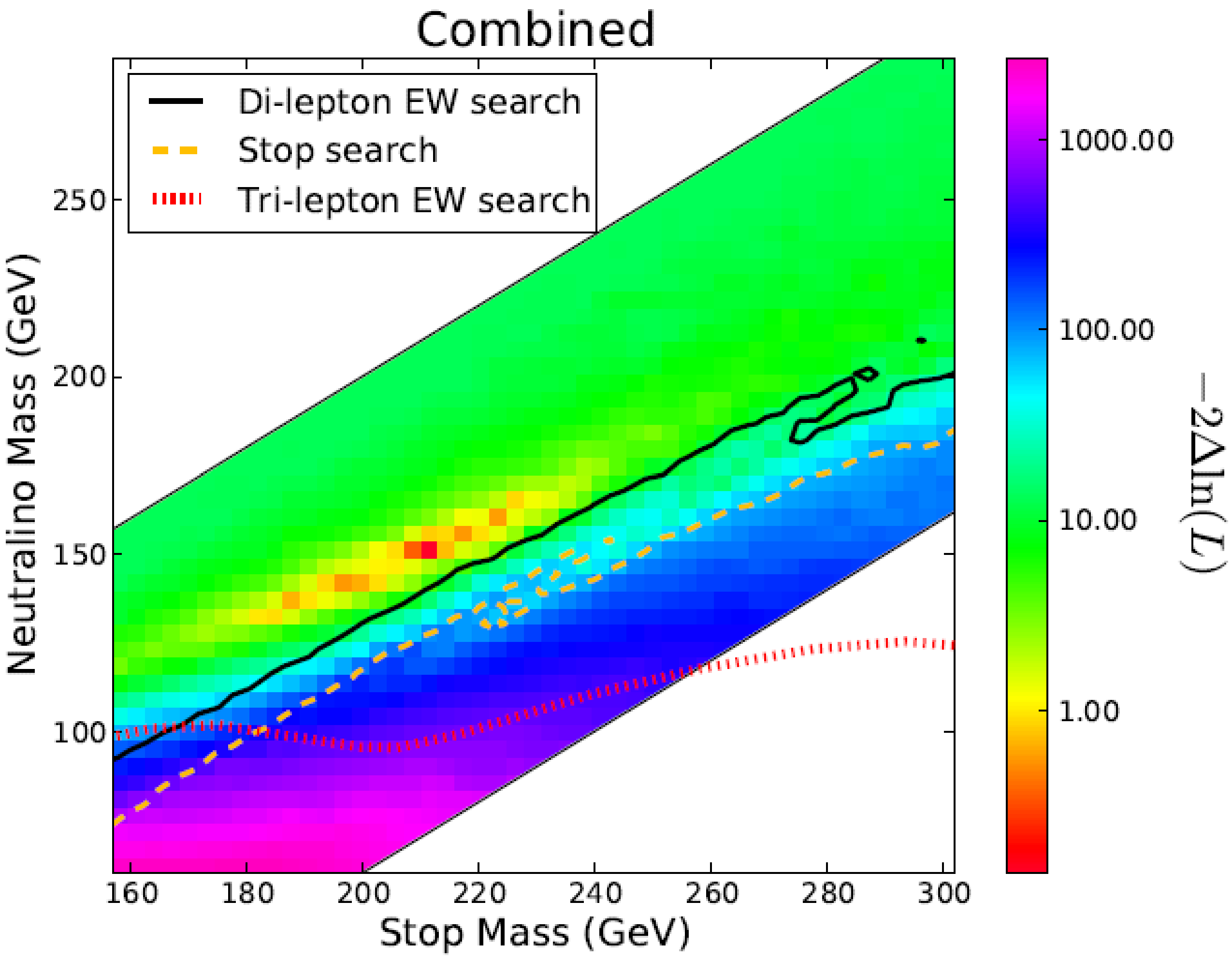

Fit of ~ 3σ excess in W^+W^- production seen by ATLAS and CMS
J.S. Kim, K. Rolbiecki, K. Sakurai and J. Tattersall, 1406.0858
(see also D. Curtin, P. Meade and P.-J. Tien, 1406.0848)

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Galaxy clusters – where dark matter was first found!

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."

Modern work: γ-rays from DM annihilation in galaxy clusters:

V. Berezinsky, V. Dokushaev, Y. Eroschenko, 2003

S. Colafrancesco, S. Profumo and P. Ullio, 2007

T. Jeltema, J. Kehayias and S. Profumo; A. Pinzke, C. Pfrommer and L.B., 2009 – potential promising clusters identified; M. Sanchez-Conde & al; A. Pinzke, C. Pfrommer and L.B.; L. Gao, C.S. Frenk, A. Jenkins, V. Springel and S.D.M. White, 2011 – importance of substructure

J. Han, C.S. Frenk, V.R. Eke, L. Gao and S.D.M. White, Jan. 2012 – Fermi-LAT signal claimed from Virgo, Fornax and Coma clusters (public data); J. Han, C.S. Frenk, V.R. Eke, L. Gao, S.D.M. White, A. Boyarsky, D. Malyshev and O. Ruchayskiy, July 2012 – ”DM signal” was due to point source

A.Hektor, M. Raidal and E. Tempel, 2012 - the 130 GeV g.c. ”Weniger line” seen also from stacked clusters . However, very large angular regions needed to see a signal.

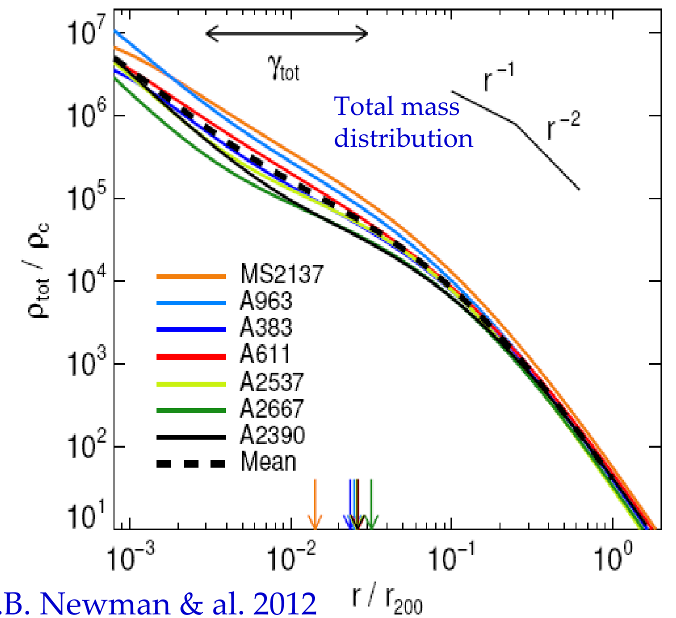
A. B. Newman & al., 2012 – Galaxy cluster total density profiles agree very well with NFW DM shape, however, DM component seems more shallow!?

Fermi-LAT collaboration, 2013; C. Weniger -2014: Significance of g.c. line has decreased

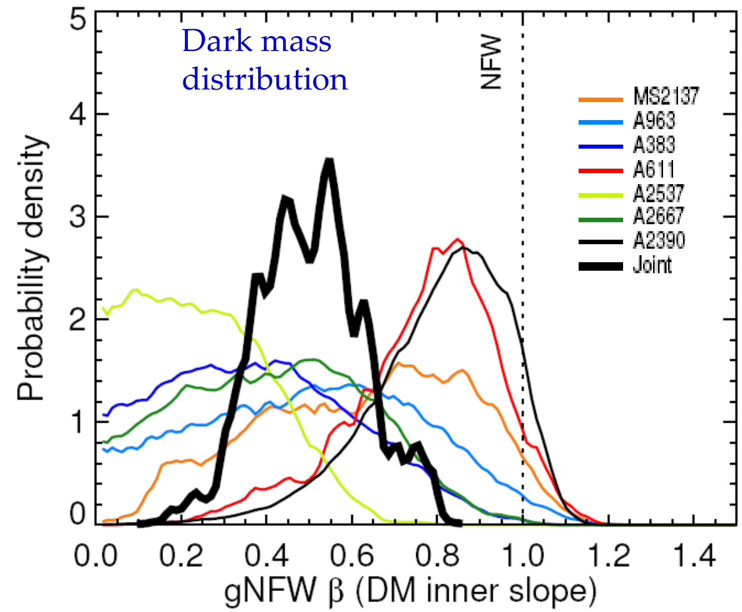
M. Ackermann & al. (Fermi-LAT), 2013 & 2014 – observational limits from sample of some 50 clusters

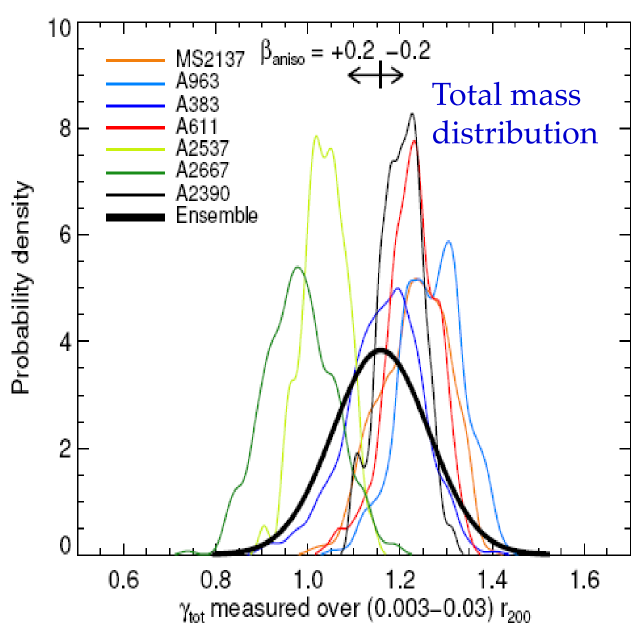
Total Density Over Three Decades in Radius 25

A.B. Newman, T. Treu, R.S. Ellis and D.J. Sand, 2012:



A.B. Newman & al. 2012





New, surprising measurement of 7 relaxed clusters (weak & strong lensing, stellar kinematics – Subaru, Keck and HST) – Total density follows NFW (CDM only) profile, but dark mass seems to have shallower profile, or even a core, near the center.
Is this due to CDM interactions (e.g., tidal friction when satellite halos merge), or is the DM decaying or self-interacting?

γ–ray signal not yet seen from clusters…
New modeling, e.g., G. Brunetti and T.W. Jones, 1401.7519:

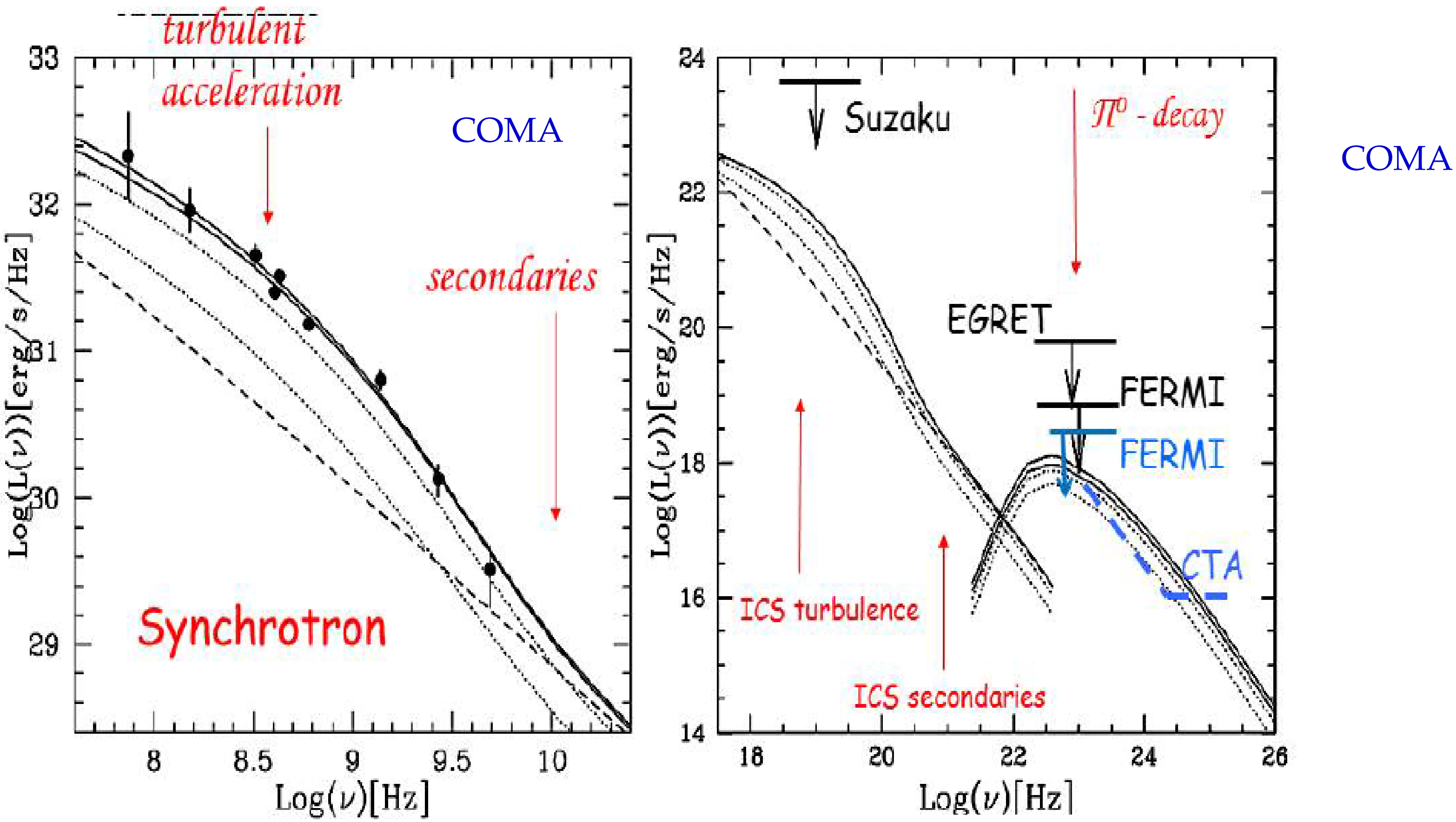


TABLE 3
Joint Scale Factor Limits

Fermi-LAT, 2013

Model	Combined	CC	NCC
Pinzke & Pfrommer (2010)	0.40 (7.4)	0.49 (4.7)	0.44 (2.4)
constant X_{CR} (ICM model)	0.48 (7.2)	0.64 (4.9)	0.49 (2.4)
constant P_{CR} (flat model)	1.78 (9.7)	3.02 (5.2)	1.71 (5.0)

The low flux was unexpected (cf. A. Pinzke & C. Pfrommer, 2010), however may be good for DM searches (less background).

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

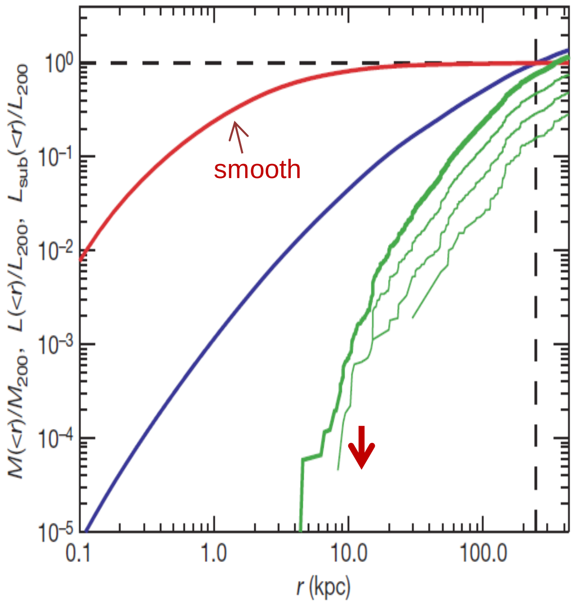


Figure 3 | Radial dependence of the enclosed mass and annihilation luminosity of various halo components. The blue line gives enclosed dark

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

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Prospects of detecting gamma-ray emission from galaxy clusters: Cosmic rays and dark matter annihilations

Anders Pinzke,[1,*] Christoph Pfrommer,[2,†] and Lars Bergström[3,‡]

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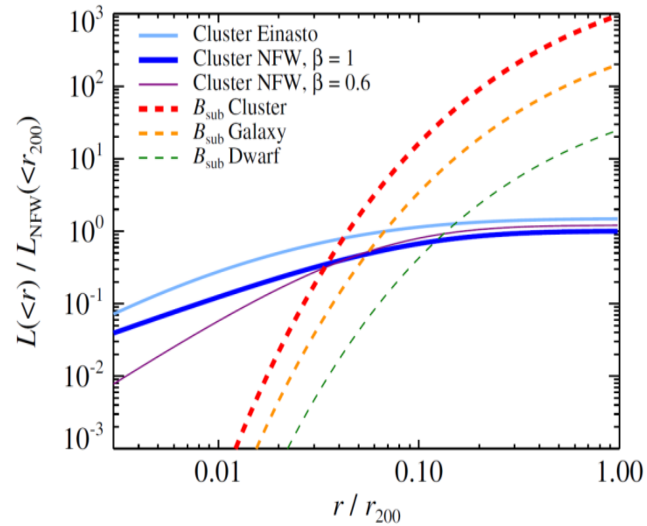
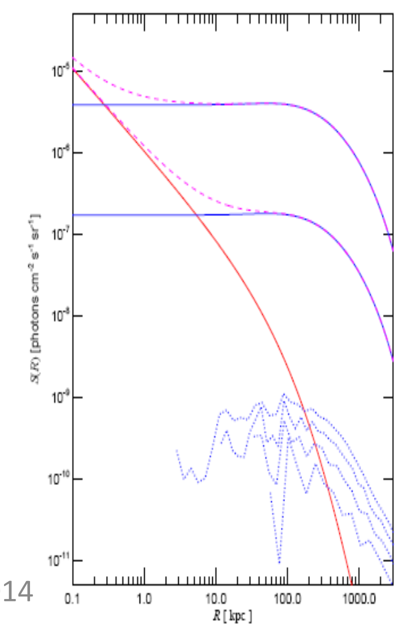
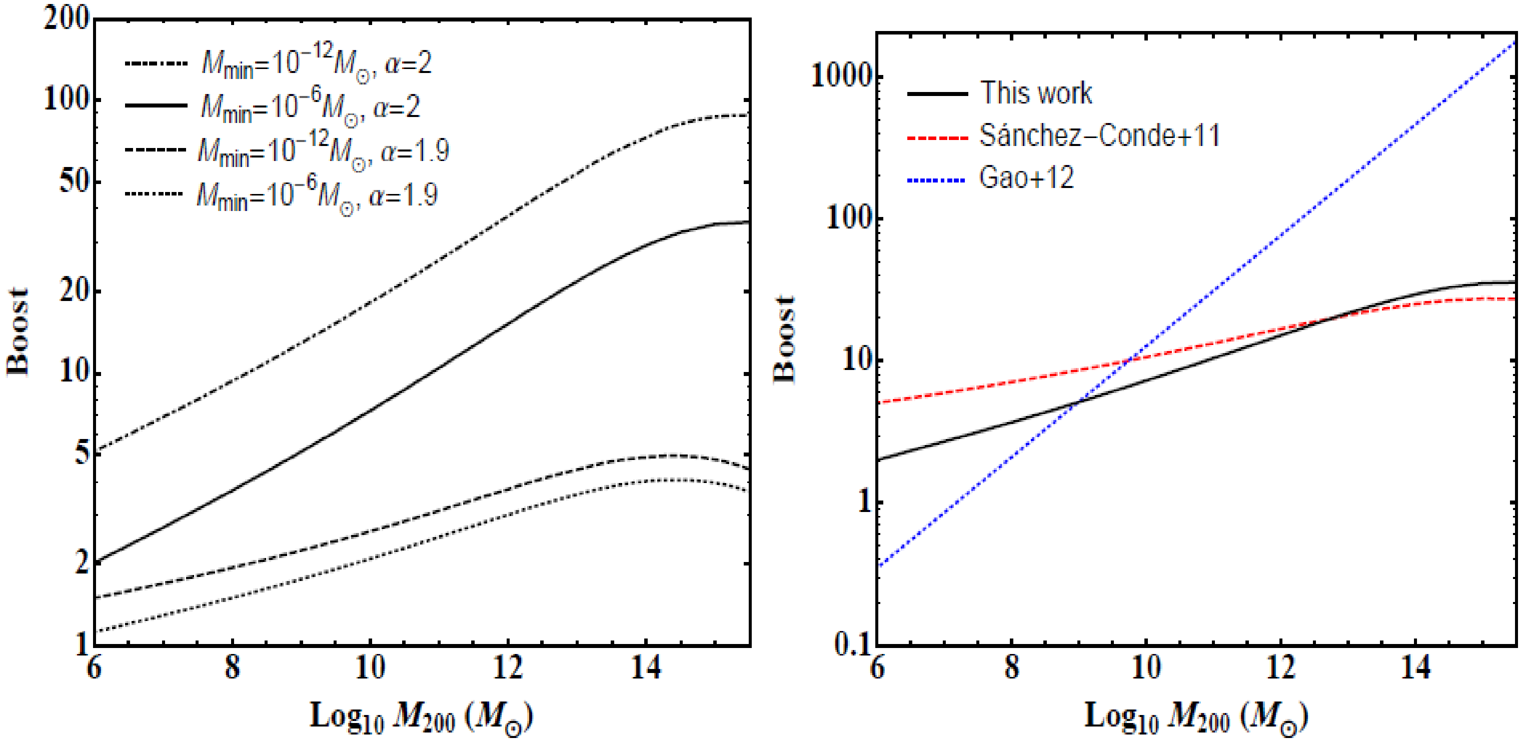


Extrapolation of the behaviour to the smallest scales for Cold Dark Matter, typically 10^{-6} M_{sun}, gives a "boost factor" of over 200 compared to a smooth halo, when the Galaxy is viewed from far away.

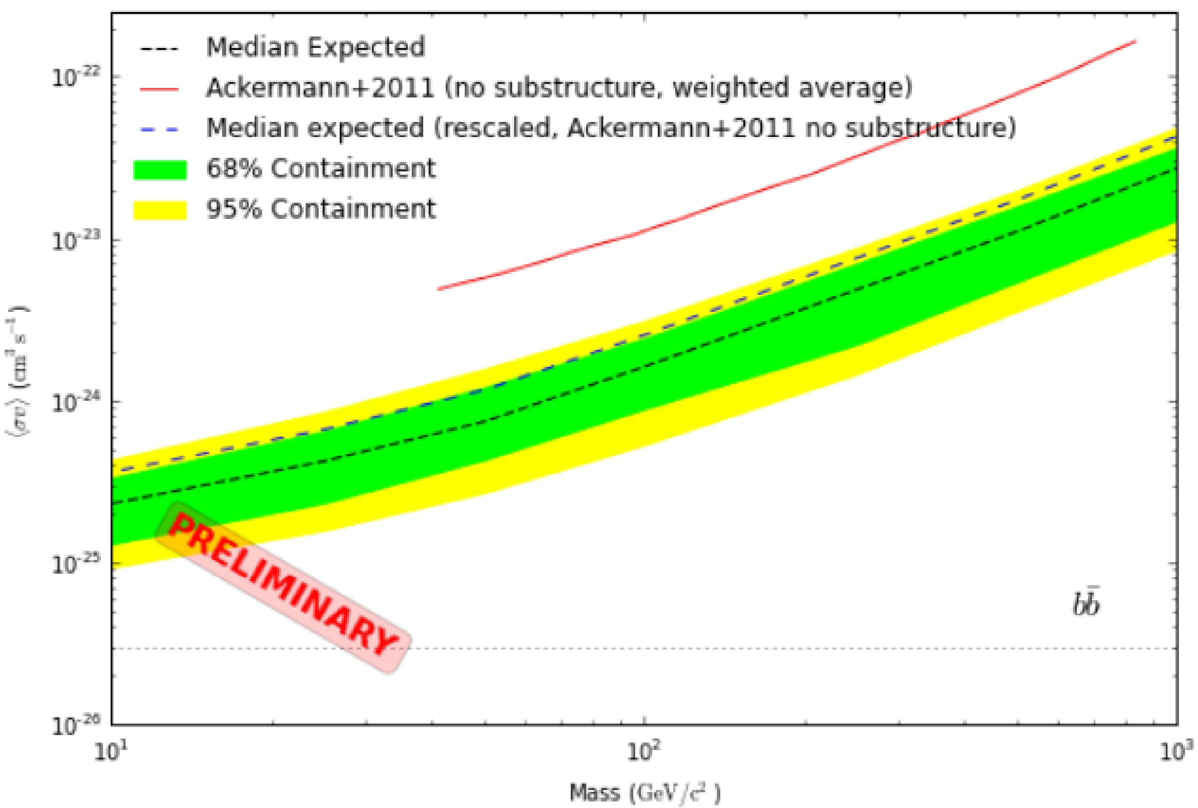


L. Gao, C. S. Frenk, A. Jenkins, V. Springel and S. D. M. White, 2012, Phoenix simulation.

However, the extrapolation to low subhalo masses is uncertain, e.g. M. Sánchez-Conde & F. Prada, 1312.1729, find lower boost factor by an order of magnitude than L. Gao, C. S. Frenk, A. Jenkins, V. Springel and S. D. M. White, 2012:



If this analysis of the boost factor is correct, we will probably **not** see a DM signal from clusters. More high-resolution analyses are clearly needed!



New expected Fermi-LAT reach (S. Zimmer, talk given at TeVPA/iDM, Amsterdam, June 2014).

This assumes the new (lower) boost factor.

Data will soon appear...

It will be crucial to better determine the amount of substructure in clusters to make firm predictions about DM detection.

However, the first detected events from clusters with Fermi **may** be from DM annhilation!

Conclusions

- Dark Matter has been ”detected” in many experiments, with varying mass and signal strengths. No detection has yet been confirmed by an independent measurement. Several claims seem to be due to systematics and/or poor modeling of backgrunds.
- The many ”false alarms” were most probably caused by wishful thinking in experiments that have potential sensitivity to **actually detect DM** for favourable values of parameters (mass, cross section,...)
- We have to keep calm and skeptical also in the future, as new detectors grow even more powerful.
- But, eventually, a **confirmed signal** should be found – or will we give up on one of the most enigmatic problems in contemporary science?

The End