Dark Matter: Past, Present and Future

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Common lore: Edwin Hubble discovered the expansion of the Universe, in 1929. Fritz Zwicky discovered Dark Matter, in 1933.

Forgotten pioneer: Knut Lundmark, Sweden (1889 – 1958)

" … measurements by a Swedish astronomer, Knut Lundmark, were much more advanced than formerly appreciated. Lundmark was the first person to find observational evidence for expansion, in 1924 — three years before Lemaître and five years before Hubble. Lundmark's extragalactic distance estimates were far more accurate than Hubble's…"

Ian Steer, NASA/IPAC, Pasadena, arxiv:1212.1359; J. R. Astron. Soc. Can. 105 (2011) 18

New: Lundmark also, 3 years before Zwicky, found evidence for dark matter!

Knut Lundmark, Lund Medd. No125 (1930) 1 – 10 (Thanks to D.Dravins and A. L'Huillier, Lund University for digging out the original paper, in German, my translation):

"Under the condition that the mass-luminosity relation is valid for all stellar systems, the mass for the investigated systems can be computed using the total absolute magnitude M_{tot} which can be found when the distance is known and the total apparent m_{tot} is observed. The mass computed in this way, the luminous mass, does understandably not include the mass of the dark objects of the system (extinguished stars, dark clouds, meteors, comets, and so on). To determine the total mass or the gravitational mass, we need to rely on the five cases where one has detected an effect of rotation by spectrographical means. … A comparison between the two kinds of masses gives an estimate of the ratio of luminous and dark matter for some stellar systems (Table 4)."

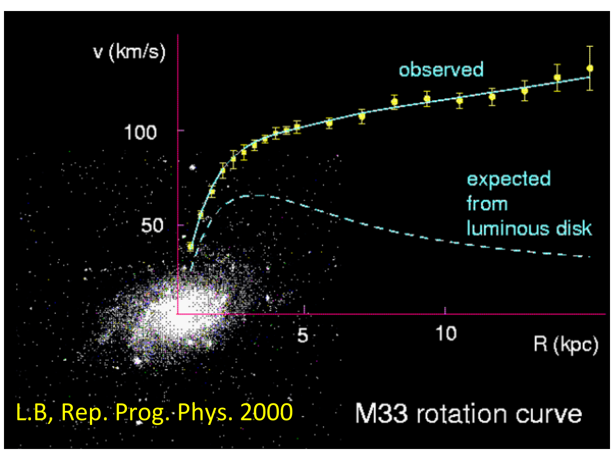

Tabelle 4.

Objekt	Verhältnis: Leuchtende + dunkle Materie / Leuchtende Materie
Messier 81	100:1 (?)
N. G. C. 4594	30:1
Andromedanebel	20:1
Messier 51	10:1
Milchstraßensystem	10:1
Messier 33	6:1

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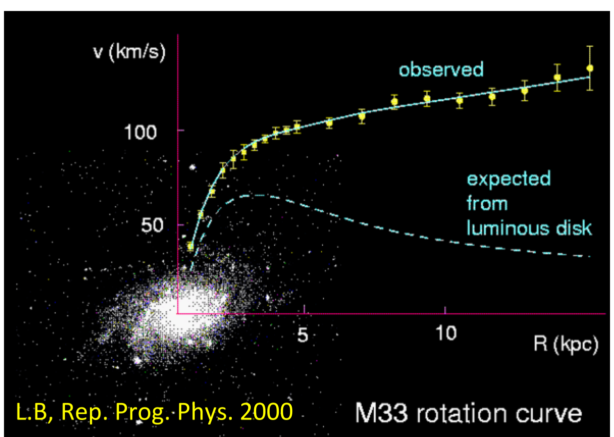

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Objekt	Ratio: $\frac{\text{Luminous + Dark Matter}}{\text{Luminous Matter}}$
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N. G. C. 4594	30:1
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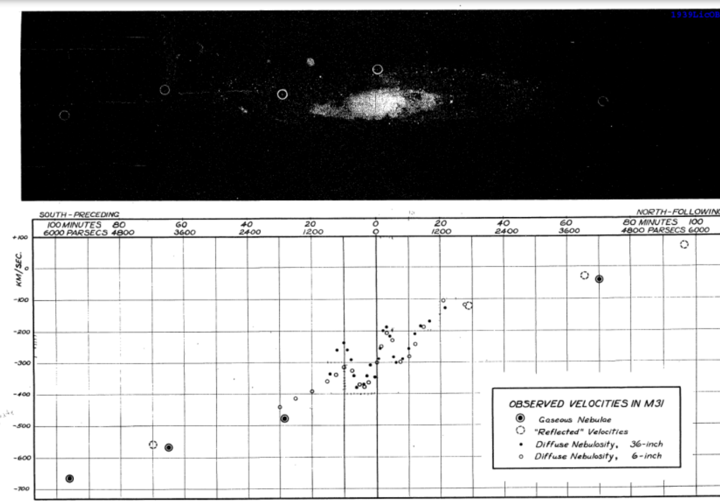
Other early gravitational observations of dark matter

Studying the velocities of galaxies in the Coma galaxy cluster, Fritz Zwicky used the virial theorem to conclude a large overdensity of non-luminous matter:

"If this over-density is confirmed we would arrive at the astonishing conclusion that dark matter is present with a much greater density than luminous matter." - F. Zwicky, 1933.

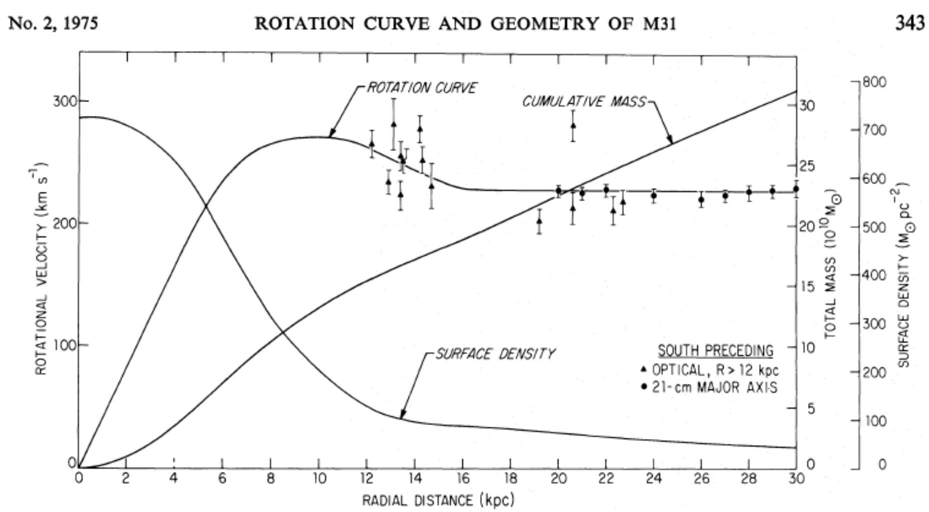
H.W. Babcock (1939) measured the optical rotation curve of M31 (Andromeda).
From Babcock's paper, 1939:

The total luminosity of M31 is found to be 2.1×10^9 times the luminosity of the sun, and the ratio of mass to luminosity, in solar units, is about 50. This last coefficient is much greater than that for the same relation in the vicinity of the sun. The difference can be attributed mainly to the very great mass calculated in the preceding section for the outer parts of the spiral on the basis of the unexpectedly large circular velocities of these parts.



The Andromeda Nebula, with observed velocities plotted below. Smoothed mean velocities of the unresolved central portion are represented by small dots for observations with the Crossley reflector, and by small open circles for observations with the 6-inch mirror. In the photograph, the bright-line emission nebulosities are encircled, and their velocities, with the exception of the one on the minor axis, are plotted as ringed dots. (Photograph by Mayall)

VOL. XIX PLATE III L. O. BULLETIN



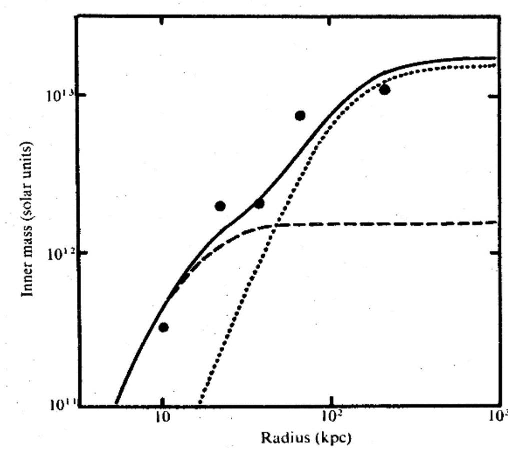


Fig. 2 The distribution of the mean inner mass, $\langle M(R) \rangle$, obtained from 105 pairs of galaxies. Symbols as in Fig. 1.

After that, essentially nothing happened for 30 years….

Then Rubin & Ford (1970), and Roberts & Whitehurst (1975) measured a flat rotation curve of M31 far outside the optical radius.

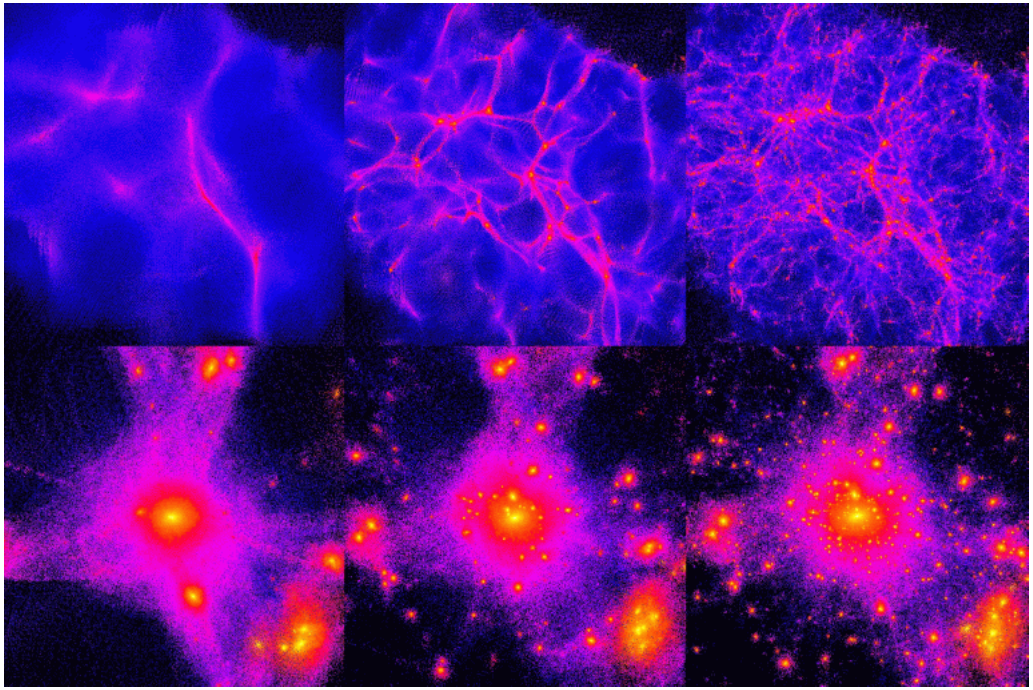
Einasto, Kaasik & Saar; Ostriker, Peebles & Yahil (1974):

Dark halos surround all galaxies and have masses ~ 10 times larger than luminous populations, thus dark matter is the dominant population in the universe: $\Omega_{DM} \sim 0.2$.

Around 1982 (Peebles; Bond, Szalay, Turner; Sciama) came the Cold Dark Matter paradigm: Structure formation scenarios (investigated through N-body simulations) favours hierarchical structure formation. The theoretical belief, based on inflation, was then that $\Omega_M = 1$

Melott et al, 1983; Blumenthal, Faber, Primack & Rees 1984,…

Hot Dark Matter →



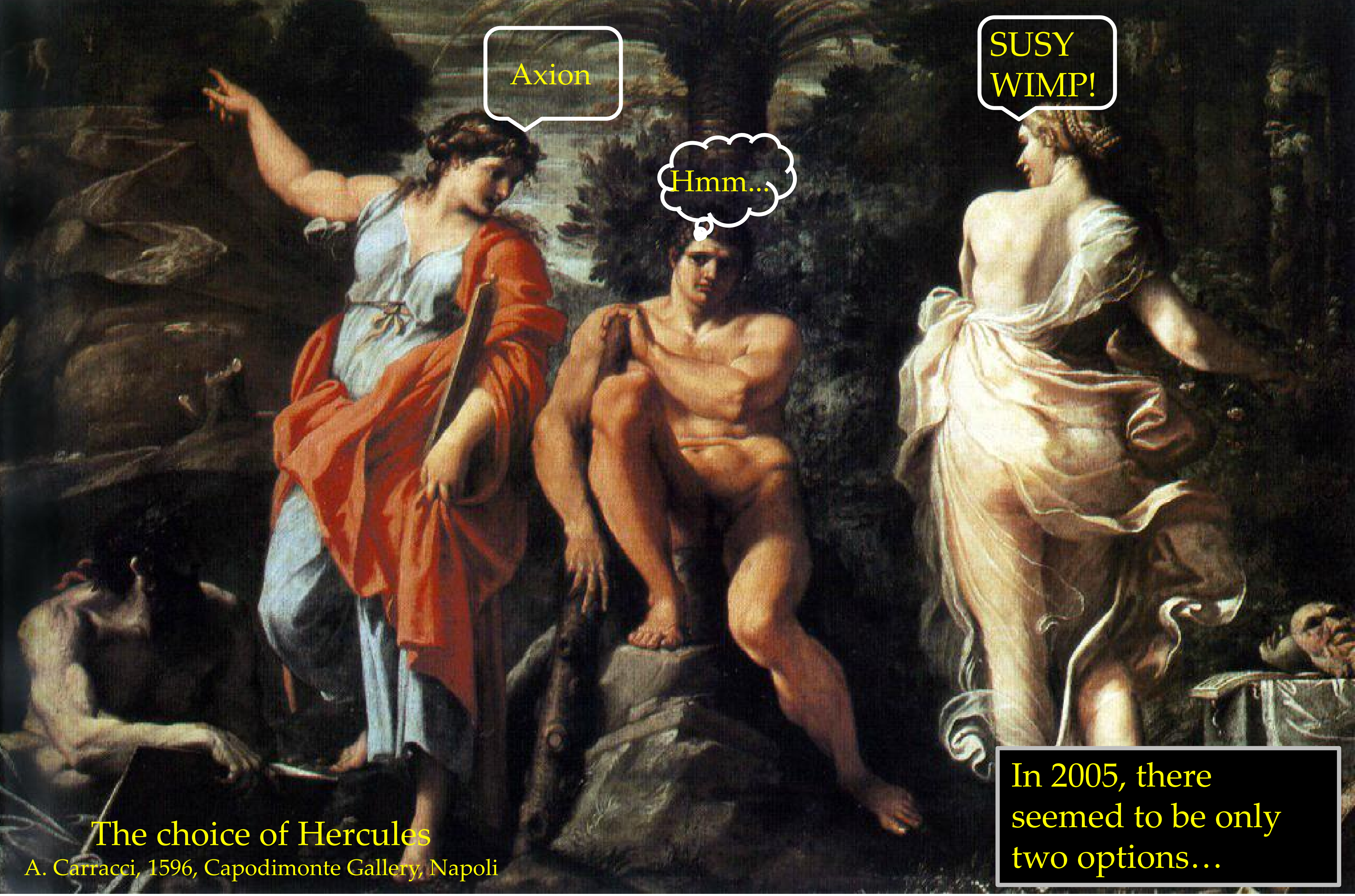
← Cold Dark Matter

B. Moore

After the successes of Big Bang nucleosynthesis and the observation of the cosmic microwave background, it seemed likely, in the late 1970's, that non-baryonic dark matter was needed.

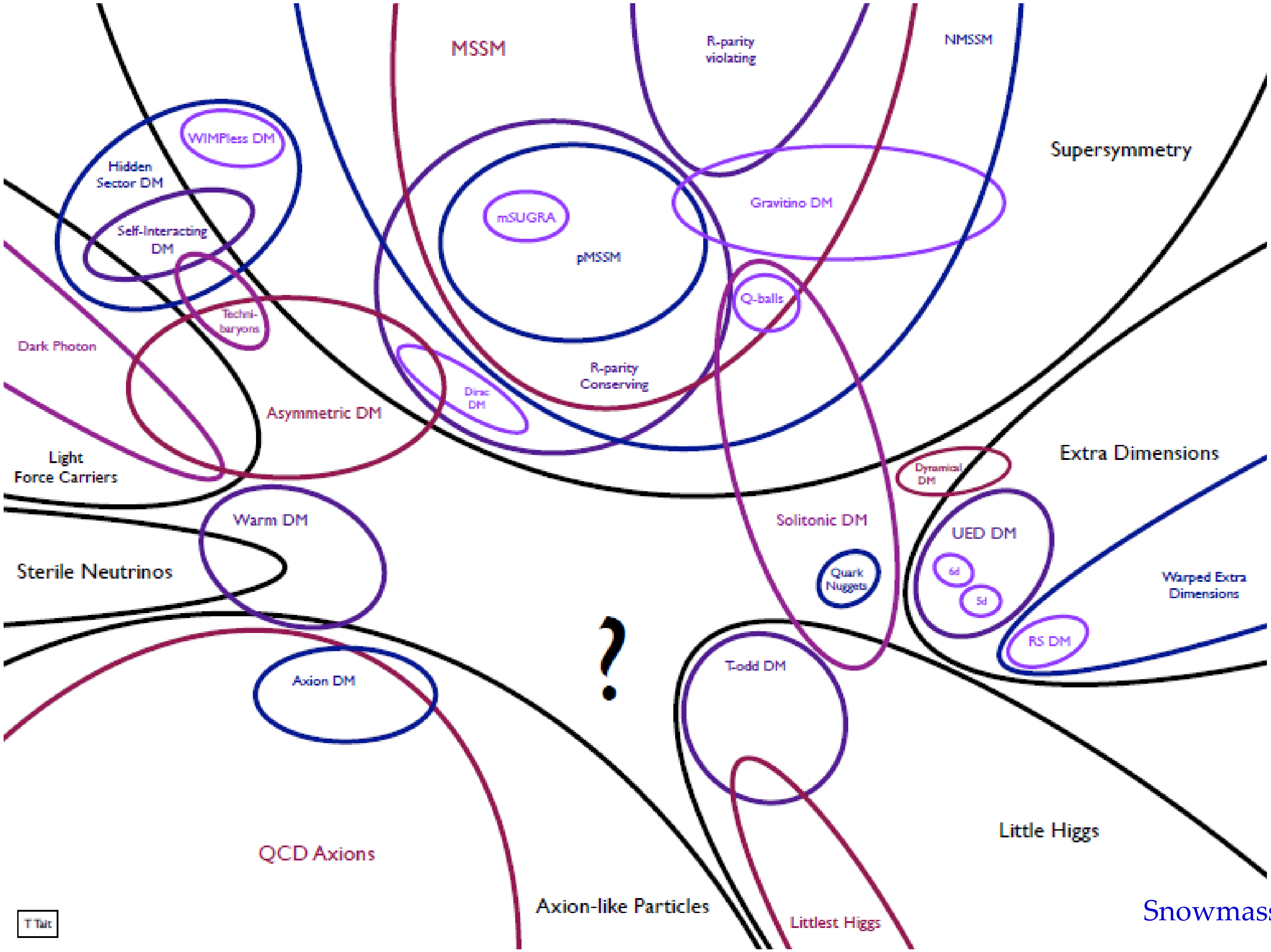
The track started to be "beaten":

- Massive neutrinos ("hot DM") (Gershtein & Zel'dovich, 1966, Lee & Weinberg 1977, Gunn & Tremaine, 1979,…)
- Axions (Peccei & Quinn, 1977, Wilczek 1978; Sikivie 1982, …)
- Supersymmetric particles (Pagels & Primack 1982; Goldberg 1983, Ellis & al, 1984, L.B. & Snellman 1986, …)
- General WIMPs (Steigman & Turner 1985, …)



The choice of Hercules
A. Carracci, 1596, Capodimonte Gallery, Napoli

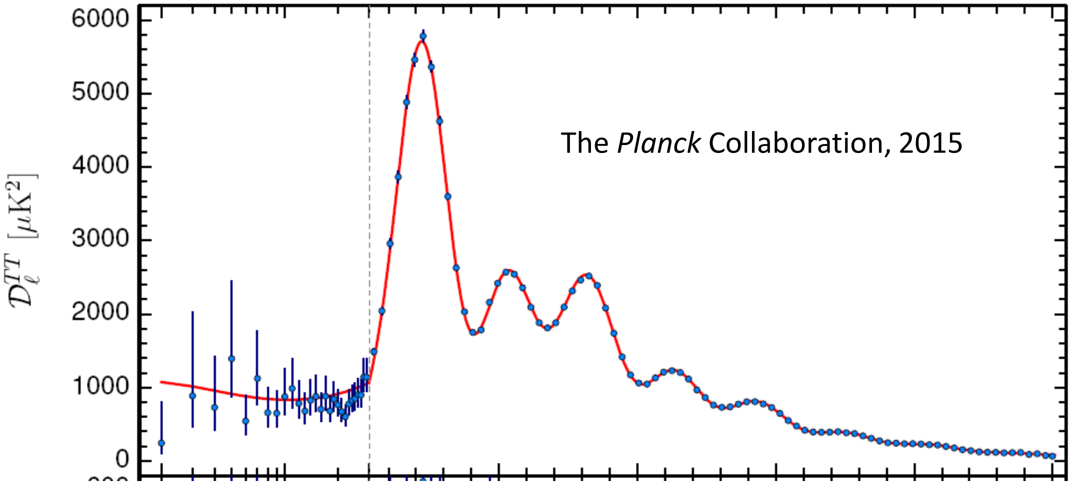
Today:

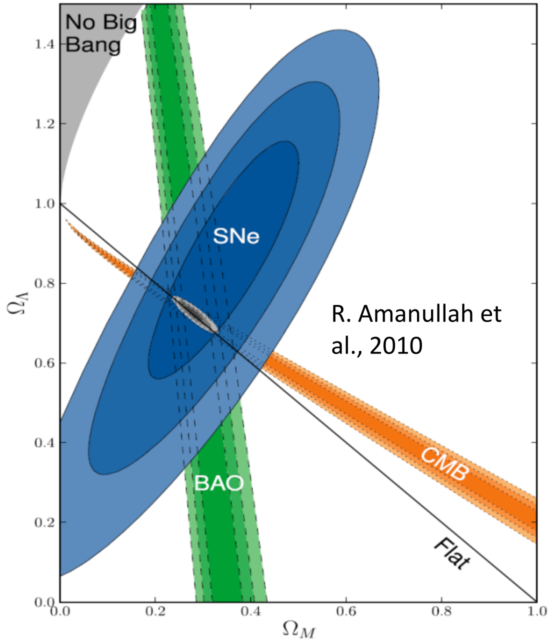


Snowmass report, 2014

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

But, dark matter does exist!





$$\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} \approx 1.000 \pm 0.005$$

55 σ

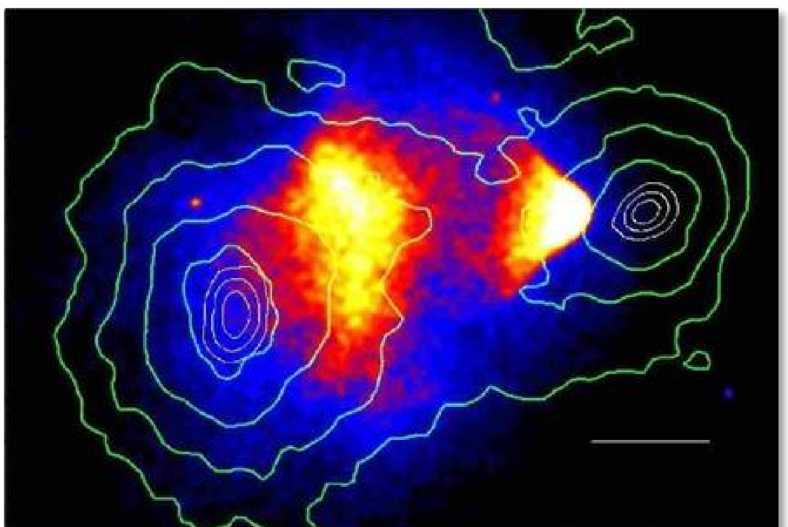
$$\Omega_\Lambda = 0.691 \pm 0.006 \quad \Omega_{CDM} h^2 = 0.1199 \pm 0.0022$$

$$\Omega_B = 0.04911 \pm 0.0015 \quad h = 0.6726 \pm 0.0098$$

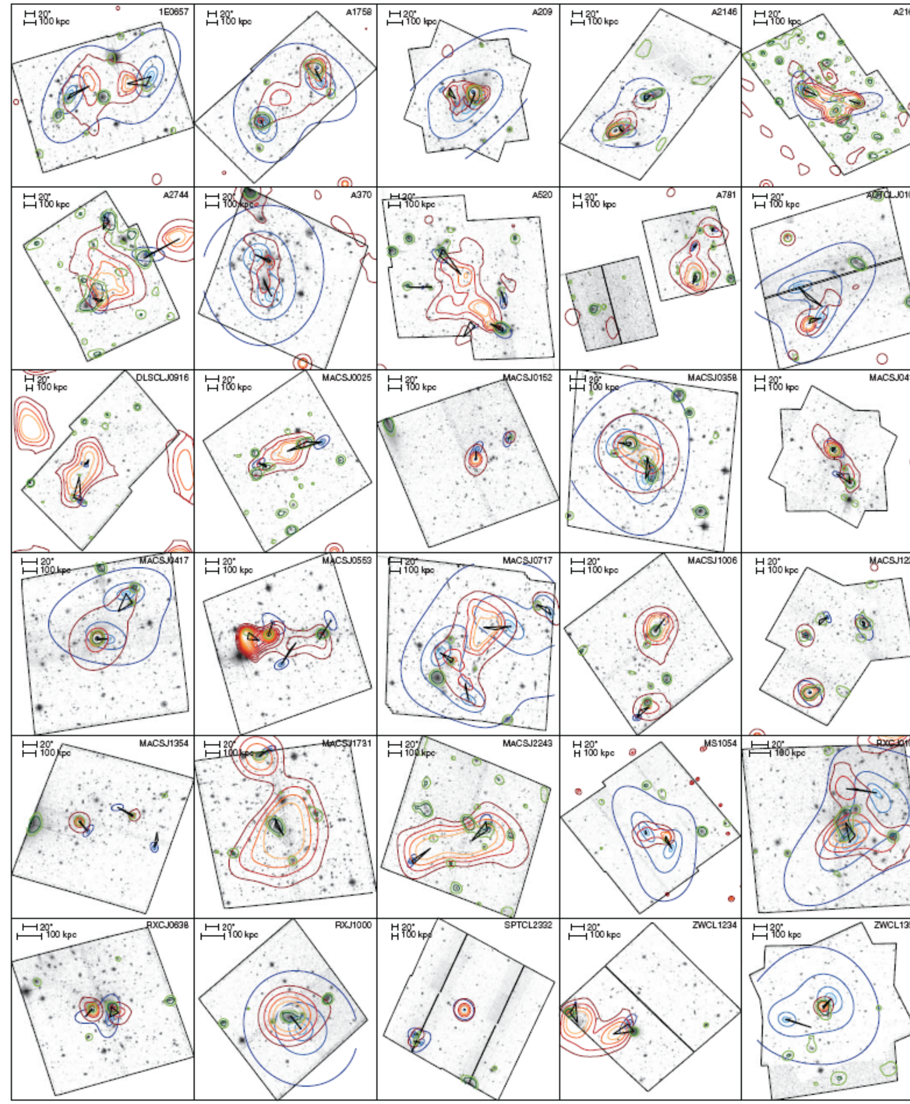
Oskar Klein centre

Data during last decade: Dark matter needed on all scales!

⇒ Modified Newtonian Dynamics (MOND) and other *ad hoc* attemps to modify Einstein’s or Newton’s theory of gravitation do not seem viable



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



D. Harvey & al., Science, March 27, 2015.
72 new colliding systems! (Also gives bounds on self-interacting DM.)

Here’s the dark matter!

DES, APS Meeting, April 13, 2015

Mass reconstruction through gravitational lensing.

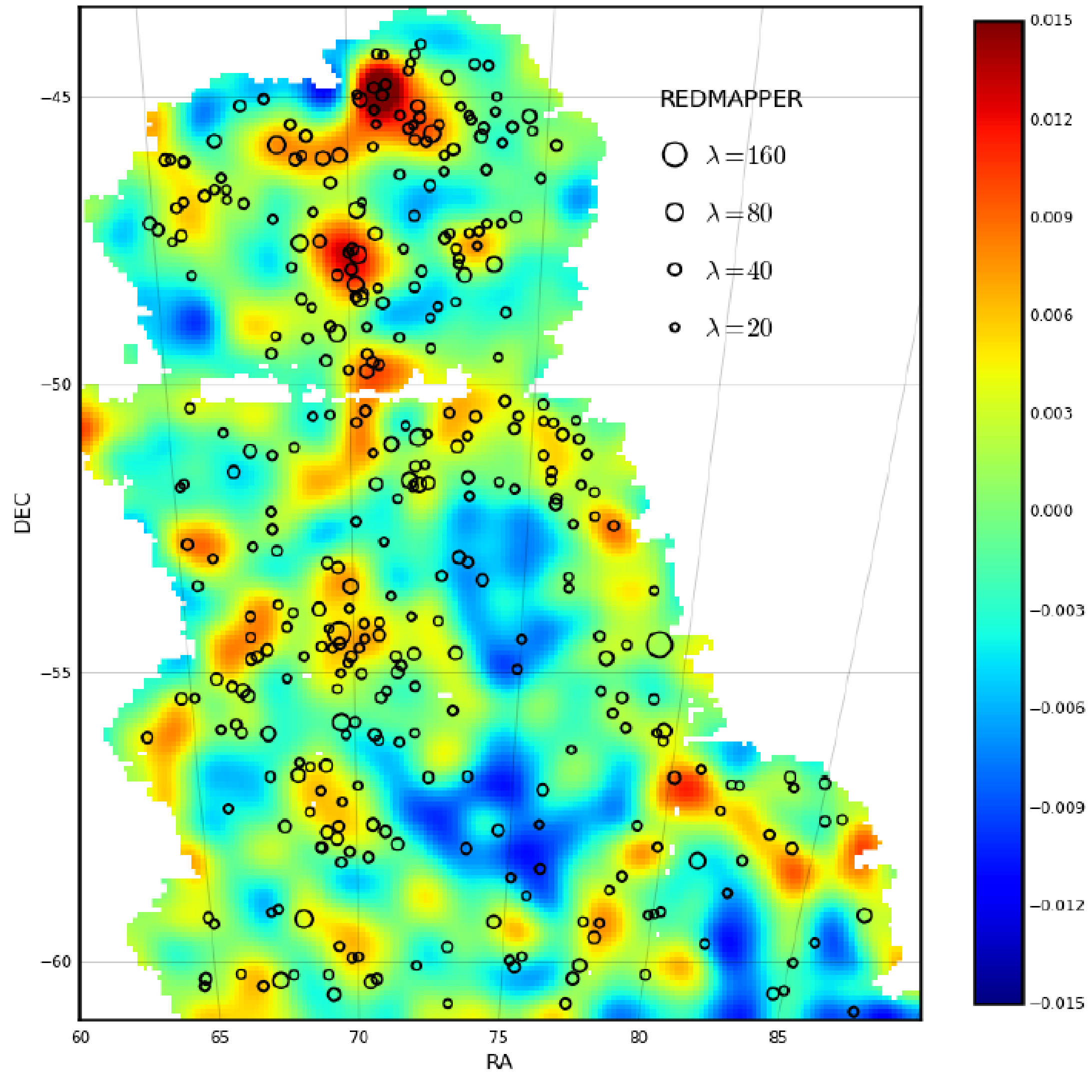


Figure 4. The DES SV mass map along with foreground galaxy clusters detected using the Redmapper algorithm. The clusters are overlaid as black circles with the size of the circles indicating the richness of the cluster. Only clusters with richness greater than 20 and redshift between 0.1 and 0.5 are shown in the figure. The upper right corner shows the correspondence of the optical richness to the size of the circle in the plot. It can be seen that there is significant correlation between the mass map and the distribution of galaxy clusters. Several superclusters and voids can be identified in the joint map.

Warning to model builders ”off the trodden path”:

Einstein’s (apocryphic) version of Occam’s razor *”Everything should be kept as simple as possible, but no simpler.”*

Current examples:

The Higgs field looks quite standard.

The basic model of the Universe is the by comparison almost trivial ΛCDM – it fits all large scale observations so far.

Models of inflation may be quite involved, having large non-gaussianities – present Planck data consistent with no non-gaussian fluctuations.

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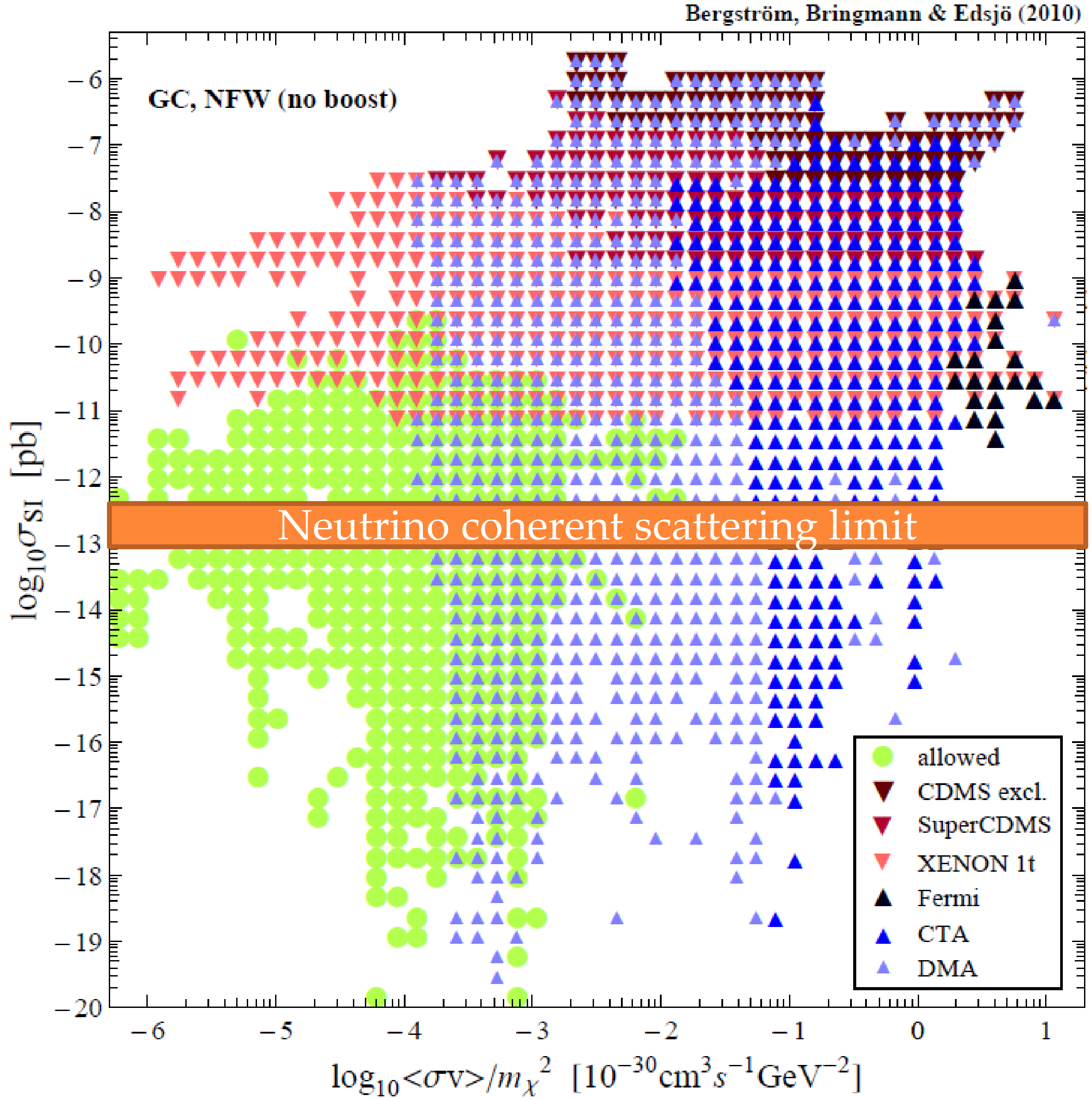
Reasons to not give in too easily on "beaten path" WIMPS:

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...



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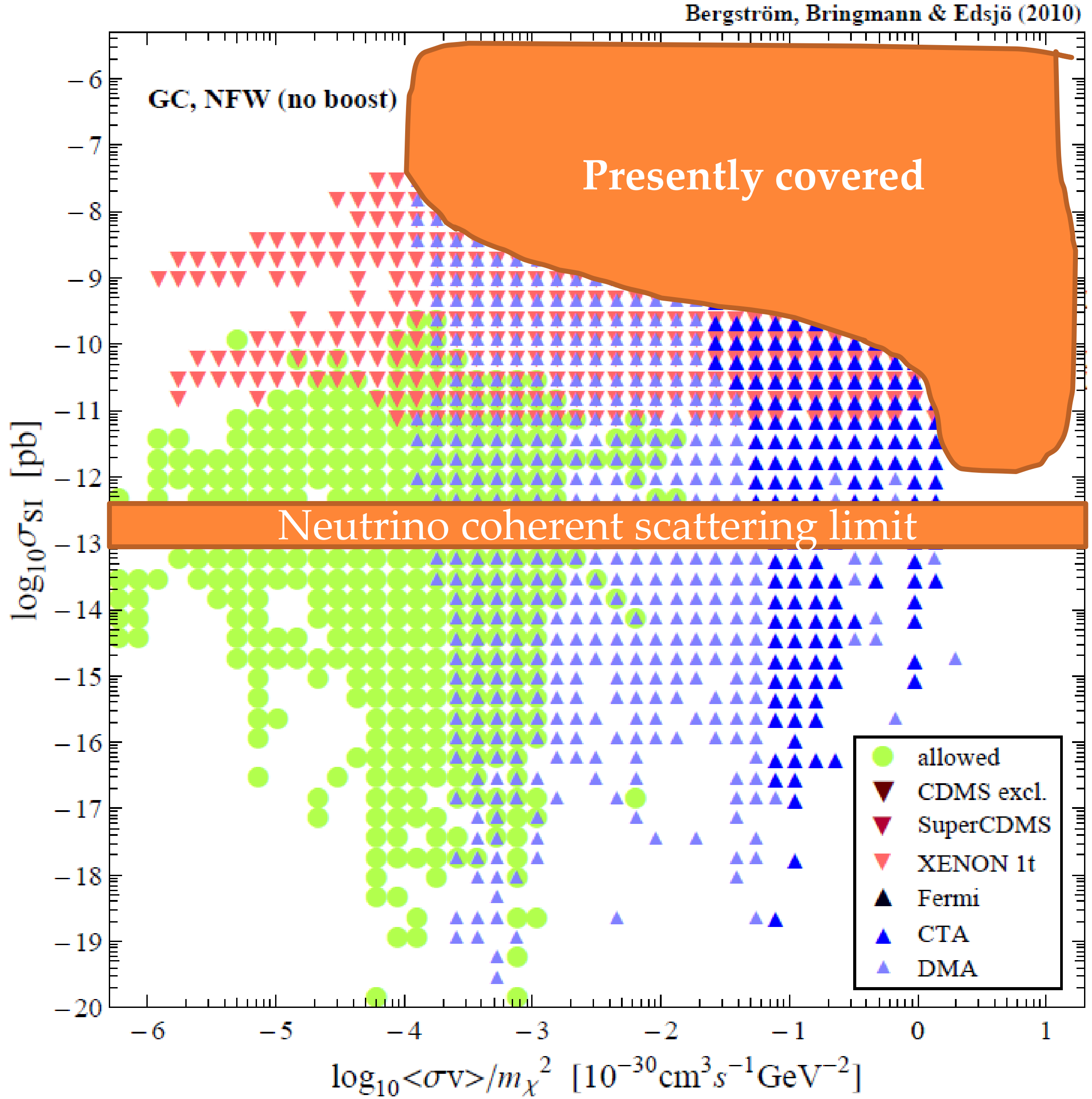


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Suggest the Standard Model May Acc
for the Stuff
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matter may be made of macroscopic objects as
as a few ounces up to the size of a good asteroi
probably as dense as a neutron star or the nucle
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Dark matter becomes less 'ghostly'
By Paul Rincon
Science editor, BBC News website
15 April 2015 Science & Environment

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 detection of DM (but one or more **may** still be):

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

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) – not confirmed by Fermi-LAT; was probably partly instrumental, partly due to statistical fluke.

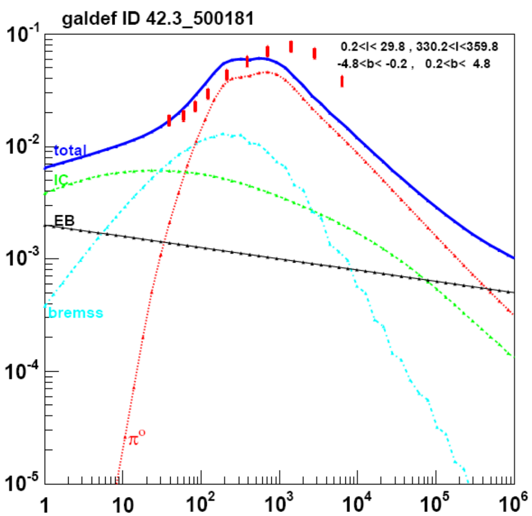
A GeV excess seen towards the g.c. in public Fermi-LAT data (D. Hooper & L. Goodenough; D. Hooper & T. Linden, 2011; T. Daylan & al., 2014) – could be due to incomplete modeling of diffuse astrophysical sources (e.g., proton-induced, E. Carlson & S. Profumo; leptons, J. Petrovic, P. Serpico & G. Zaharijas, 2014).

A GeV excess seen towards one of the newly discovered DES dwarf galaxies in public Fermi-LAT data (A. Geringer-Sameth & al., 1503.02320; 2.3 to 3.7 σ) – not confirmed by Fermi-LAT (1503.02632; ~ 1.5 σ)

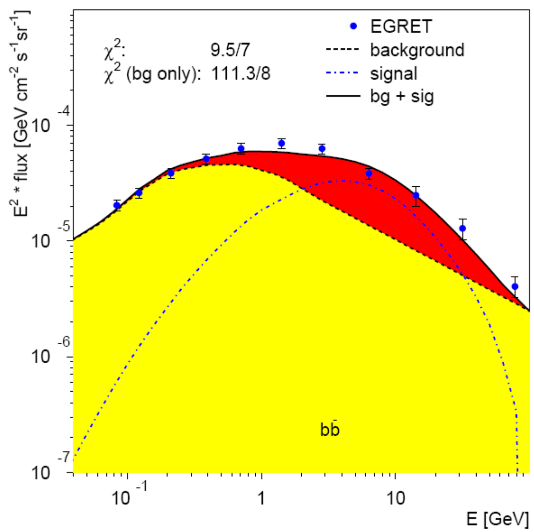
A 3.5 keV X-ray line due to decaying DM (E. Bulbul et al.; A, Boyarsky et al., 2014) – some problems, e.g., not right morphology? (E. Carlson, T. Jeltema & S. Profumo, 1411.1758). Wait for ASTRO-H…

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

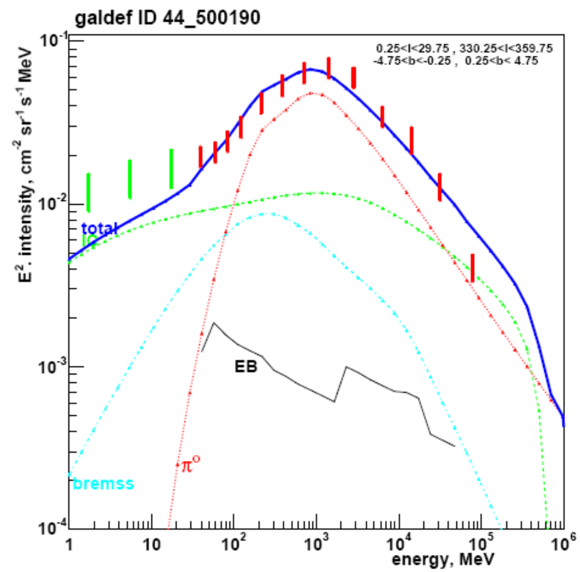


Adding 70 WIMP annihilating to $b\bar{b}$ (W. de Boer & al. 2004, DarkSUSY)



Dark matter solution

However, Strong, Moskalenko & Reimer, 2004, "optimized fit"

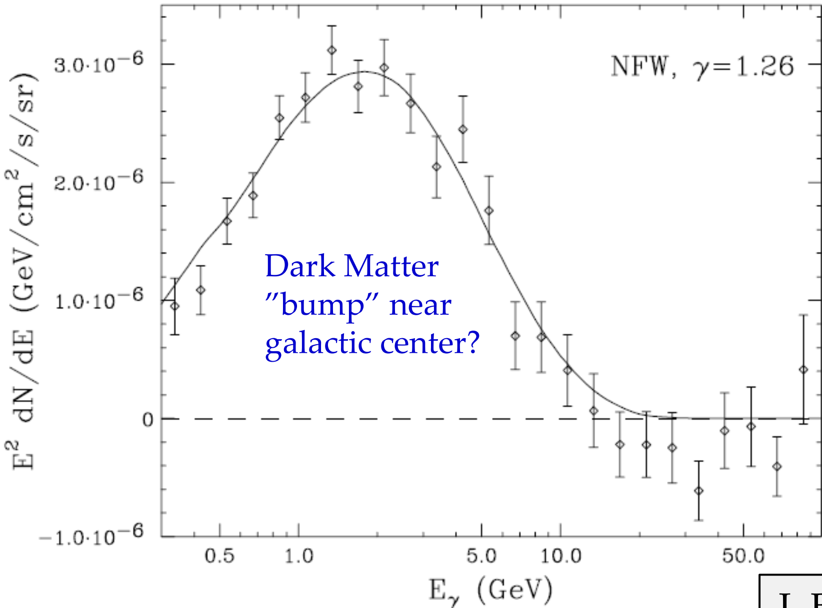


Astrophysical solution

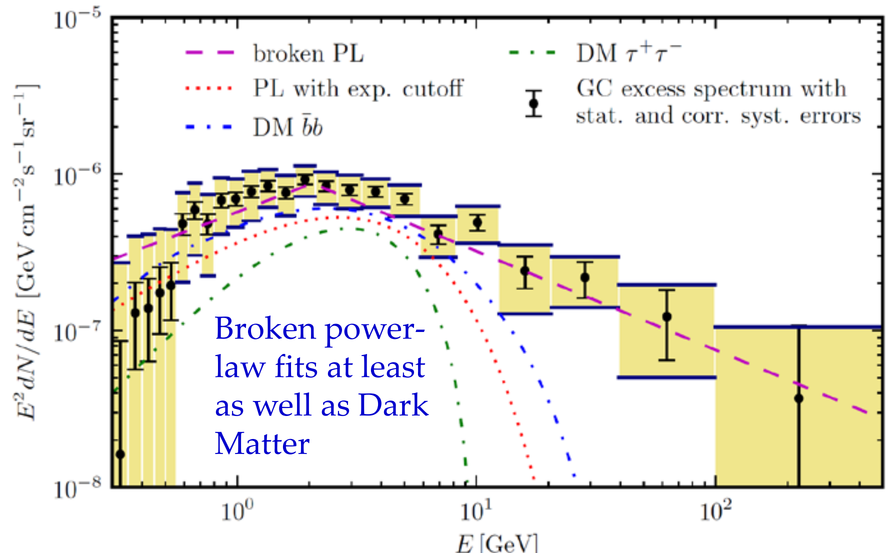
L.B., P. Ullio and J. Buckley 1998: "In fact, present EGRET observations are not inconsistent with a continuum spectrum originating from dark matter annihilations, but other explanations are possible as well"

Déjà vu, 2014:

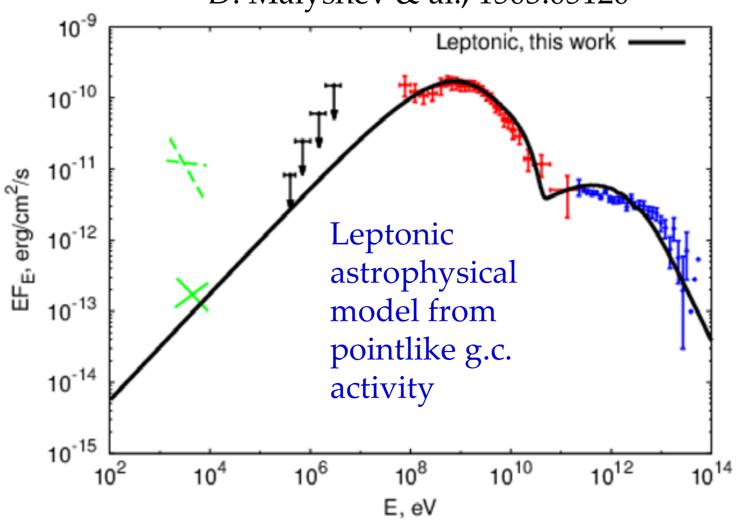
T. Daylan & al., 1402.6703



F. Calore, I. Cholis & C. Weniger, 1409.0042



D. Malyshev & al., 1503.05120



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"

A multitude of DM models (including even the MSSM – A. Achterberg & al., 1502.05703) may explain the data.
Unfortunately, the g.c. is a very messy place with, e.g., an unknown population of millsecond pulsars (see, e.g., R.M. O'Leary & al., 1504.02477).

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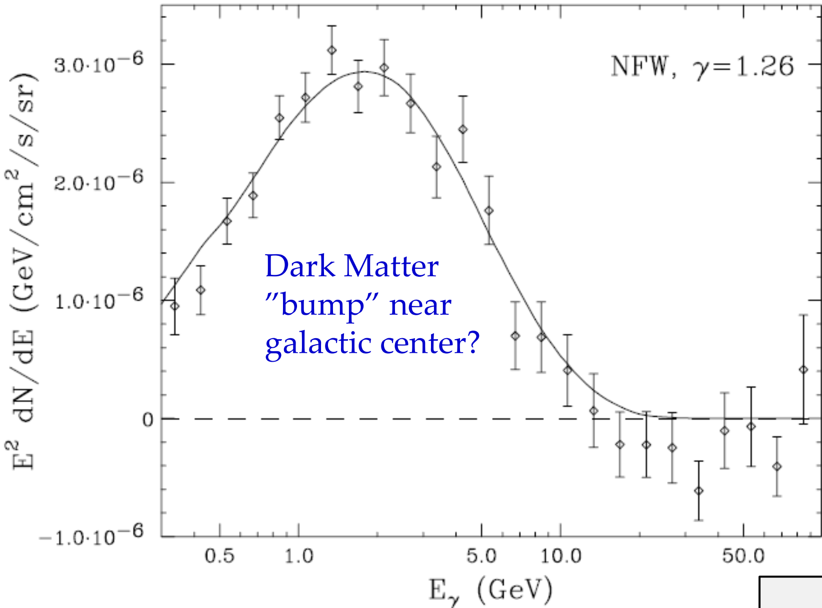

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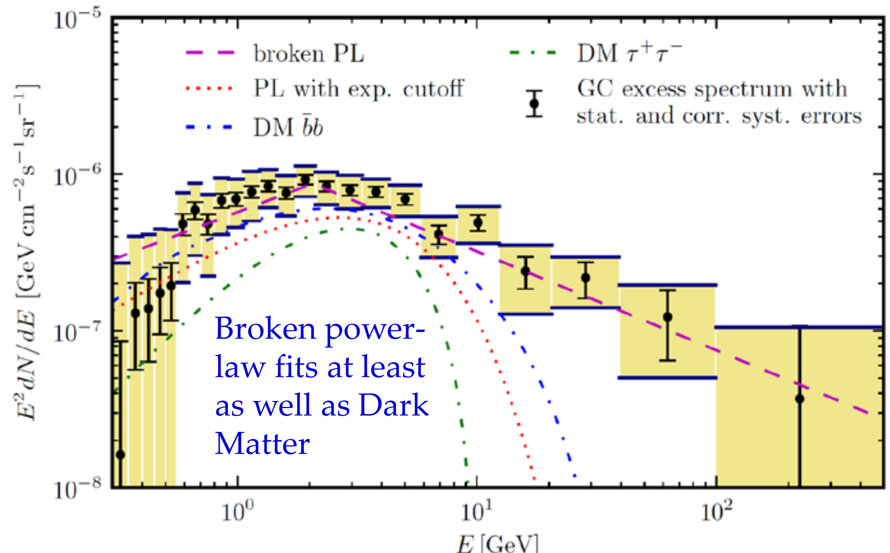

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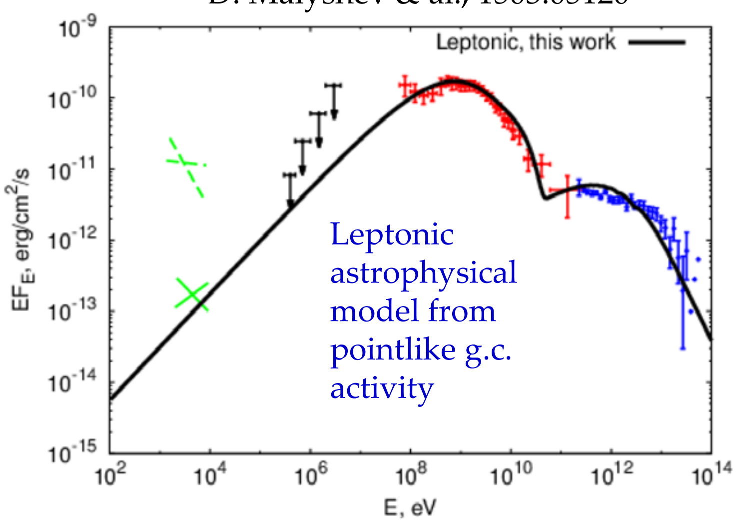

L.B., 2015: "In fact, present Fermi observations are not inconsistent with a continuum spectrum originating from dark matter annihilations, but other explanations are possible as well"

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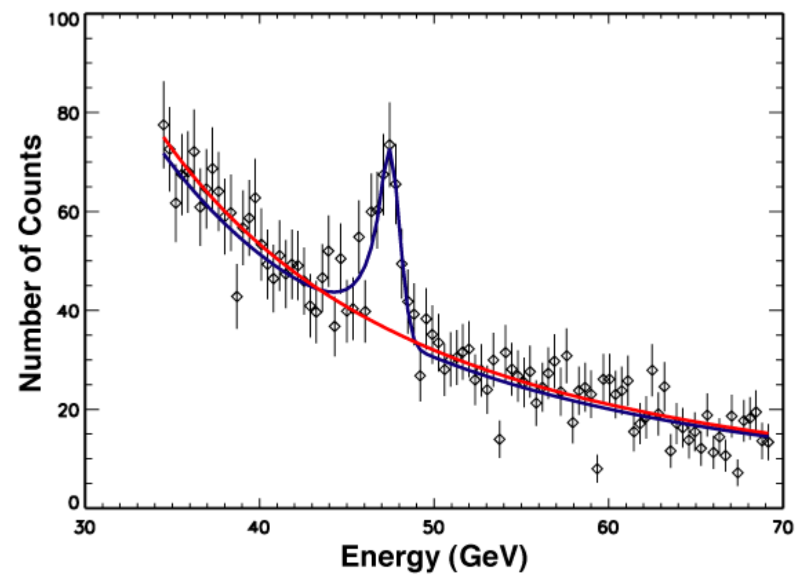
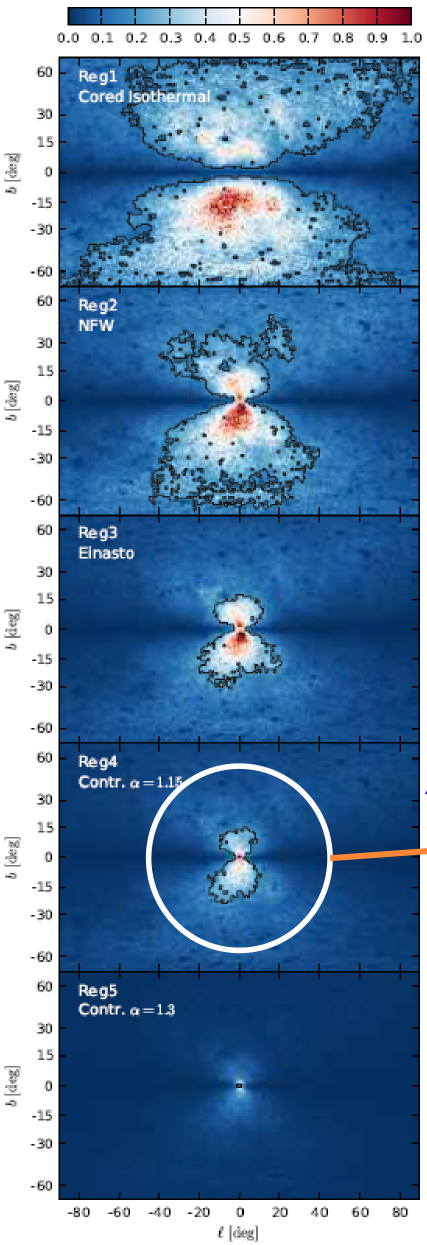
Since a diffuse gamma-ray distribution can have many astrophysical sources, L.B., P. Ullio and J. Buckley in 1998 pointed out the gamma-ray line at $E = M_\chi$ as a "smoking gun" for Dark Matter. 10 years later, in 2008: Great hope for finding the γ-ray line.

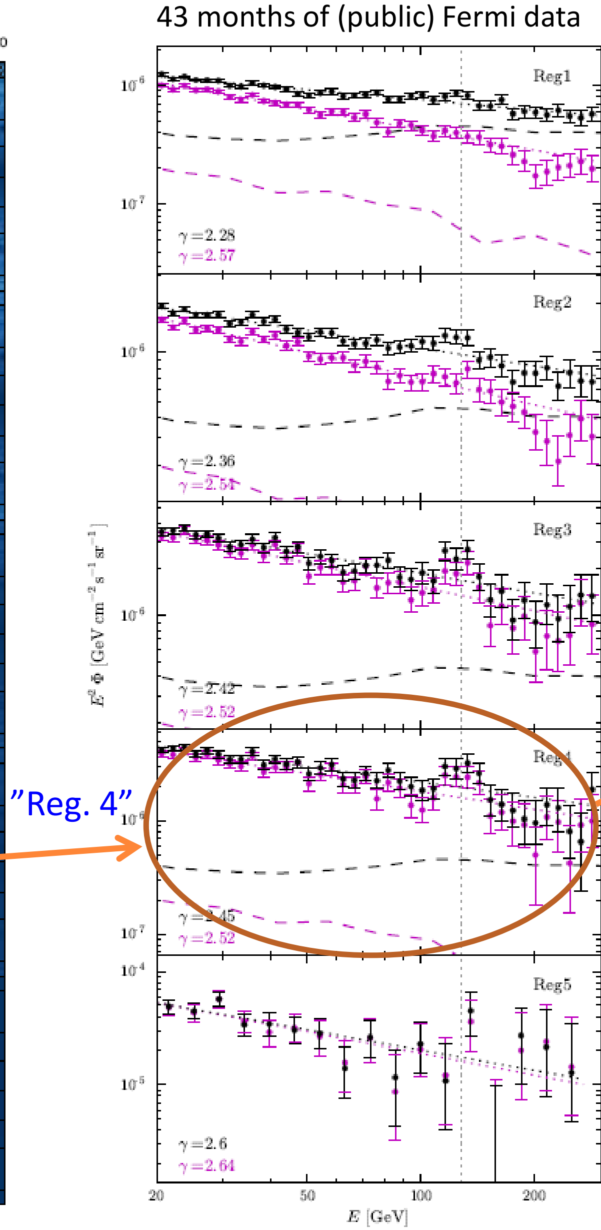
USA-France-Italy-Sweden-Japan collaboration, launch 2008

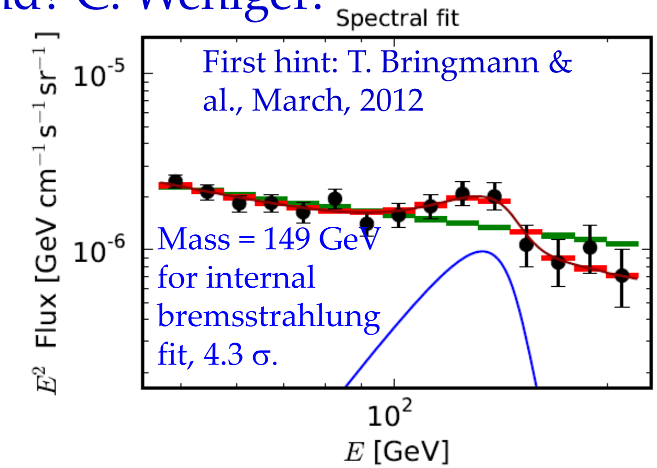


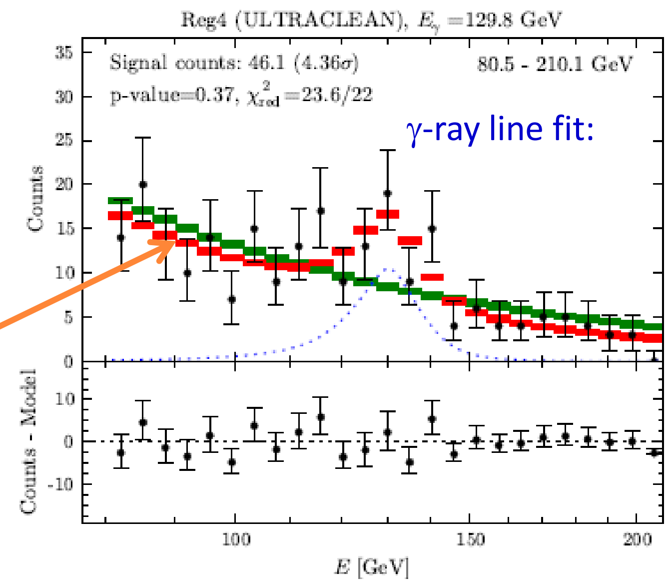
Example of line search from the GLAST proposal (GLAST was renamed to Fermi-LAT after launch).

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





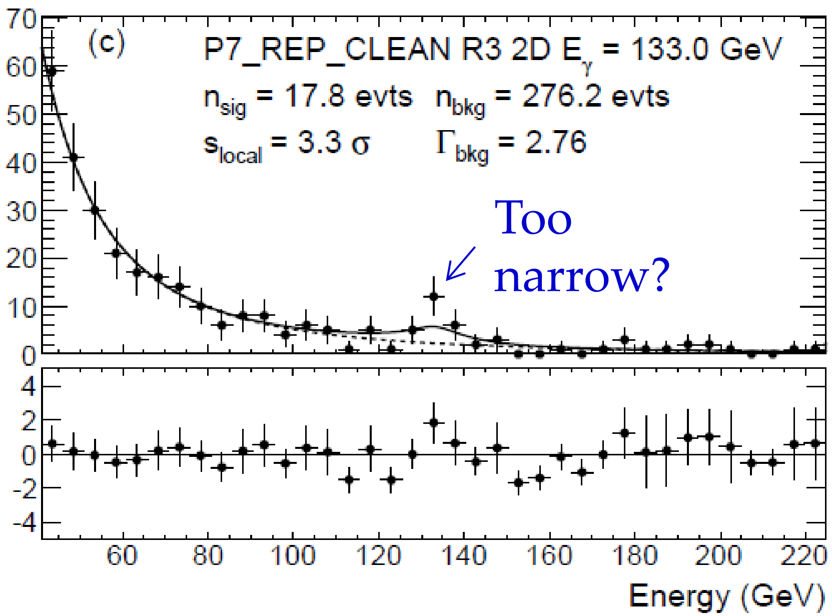




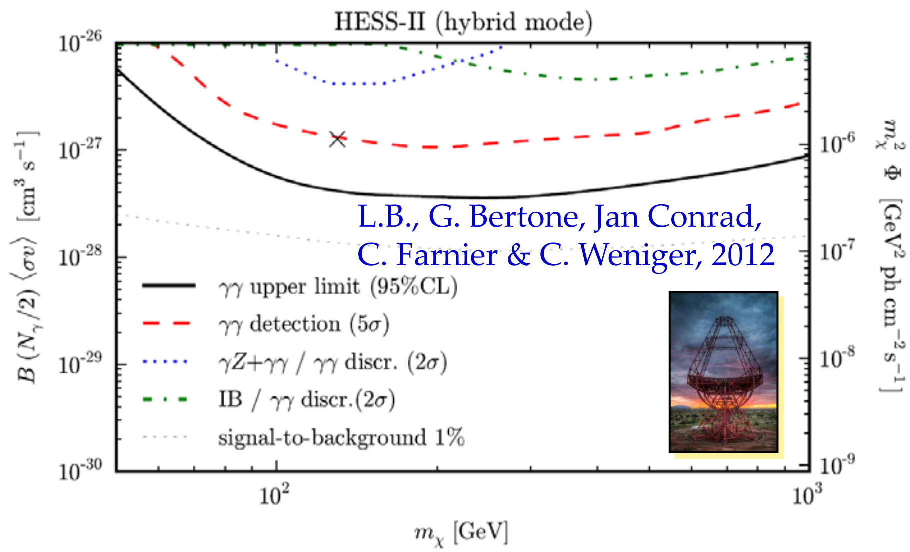
Mass = 130 GeV

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 fluctuation (in the last two years, the statistical significance of the effect has gone down).

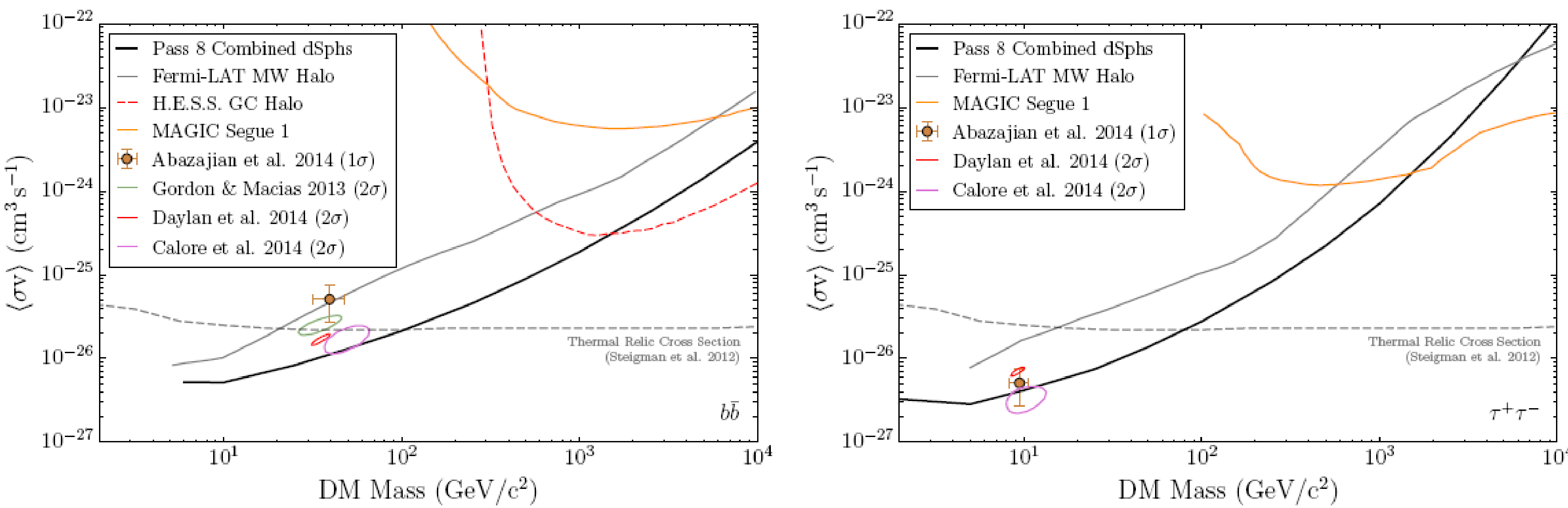


Fermi-LAT collaboration, 2013.



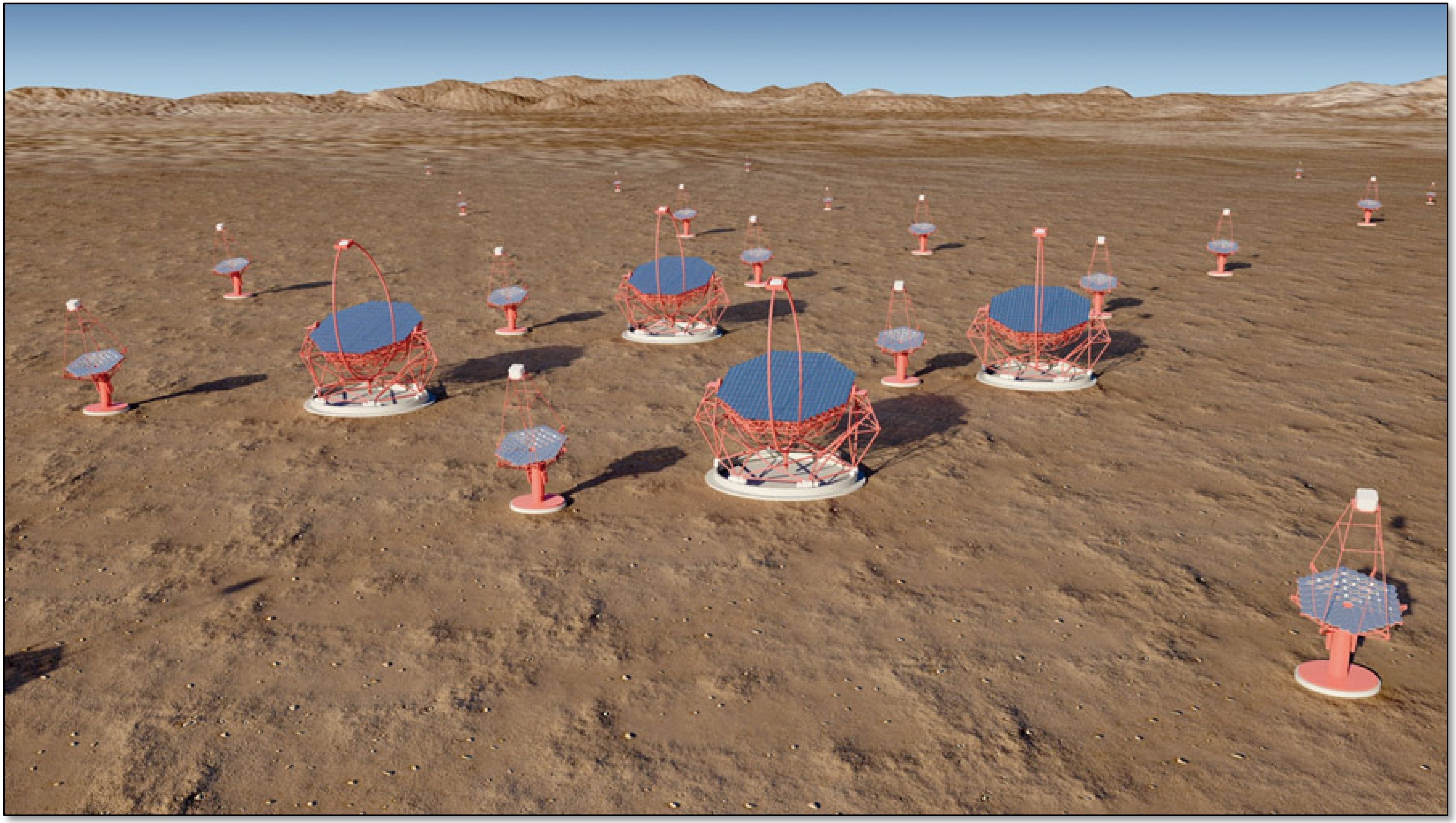
With HESS-II (currently data-taking) we should get a definite answer in the fall, 2015.

The Fermi Collaboration 6-year study of dwarf galaxies (1503.02641) gives strong limits on gamma-ray signal from DM annihilations:

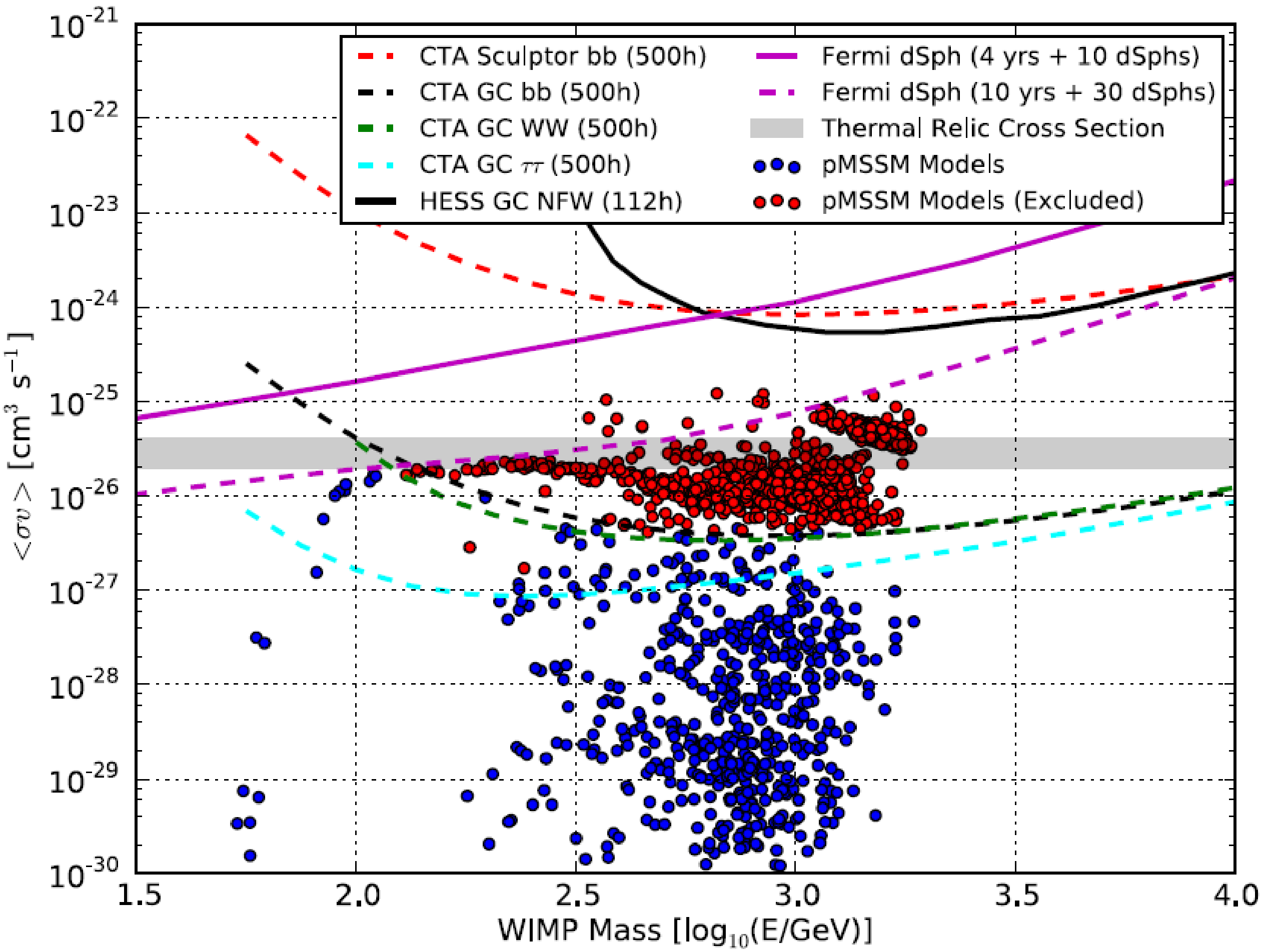


Tension is starting to appear with claims of g.c. signal...

CTA: The new window to the high-energy gamma-ray universe (c:a 2019 -)

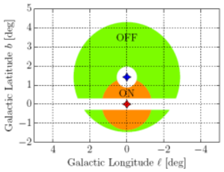


CTA (2019 -) may have good discovery potential, especially in the 100 GeV – few TeV region

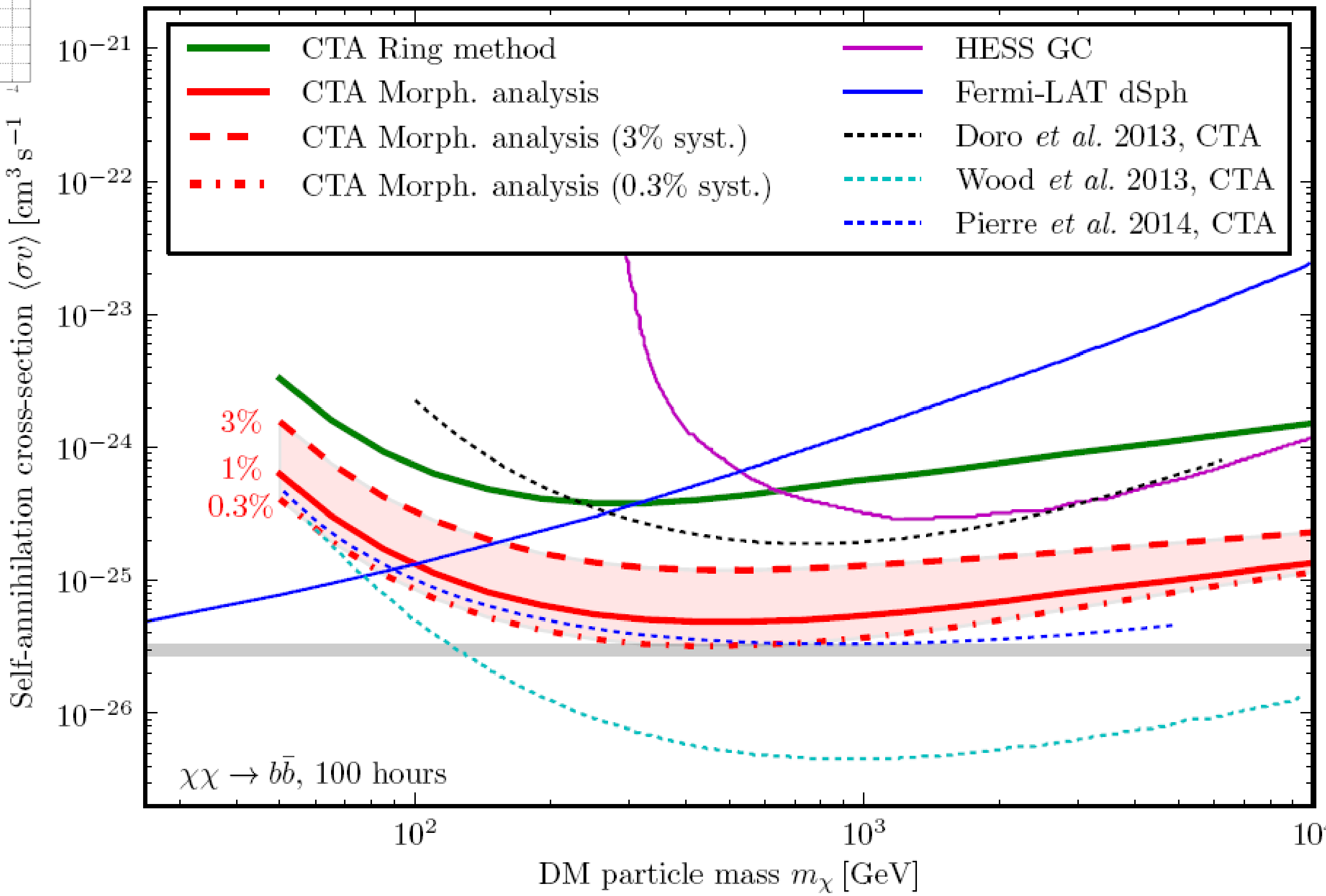


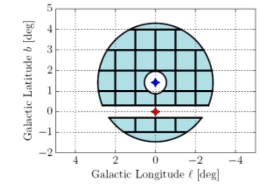
Systematics and diffuse emission background not included

M. Wood et al., 1305.0302



Ring method





Morph. method

With systematics and diffuse emission background included,
H. Silverwood, C. Weniger, P. Scott and G. Bertone, 1408.4131. More clever methods will be needed!

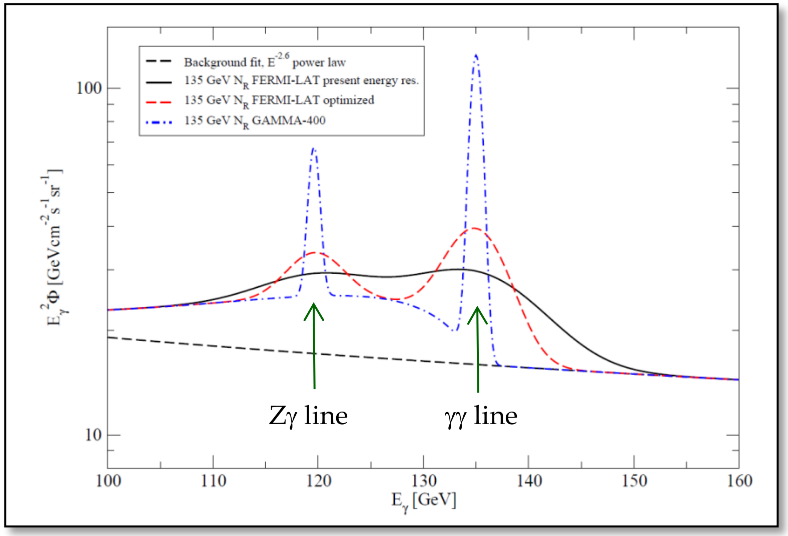
Future for space detectors ?- No planned Fermi-LAT replacement in the US. The future seems to be in the East for gamma-ray space telescopes:

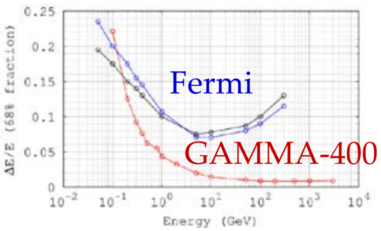
GAMMA-400, emergy range 100 MeV – 3 TeV, an approved Russian γ-ray satellite. Planned launch 2020. Energy resolution (100 GeV) ~ 1 % (cf. Fermi 10 %). Effective acceptance ~ 3 m^{2}sr (Fermi 2.4 m^{2}sr). Angular resolution at 100 GeV ~ 0.01° (Fermi 0.1 – 0.2°)

Dark Matter Particle Explorer, DAMPE: Satellite of similar enery resolution as GAMMA-400, but 1/10 the acceptance. An approved Chinese satellite. Planned launch 2016. (Precursor to HERD.)

HERD: Instrument on Chinese Space Station. Energy resolution (100 GeV) ~ 1 %. Effective acceptance ~ 4 m^{2}sr (cf. Fermi 2.4 m^{2}sr). Angular resolution (100 GeV) ~ 0.01°. Planned launch around 2020.

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

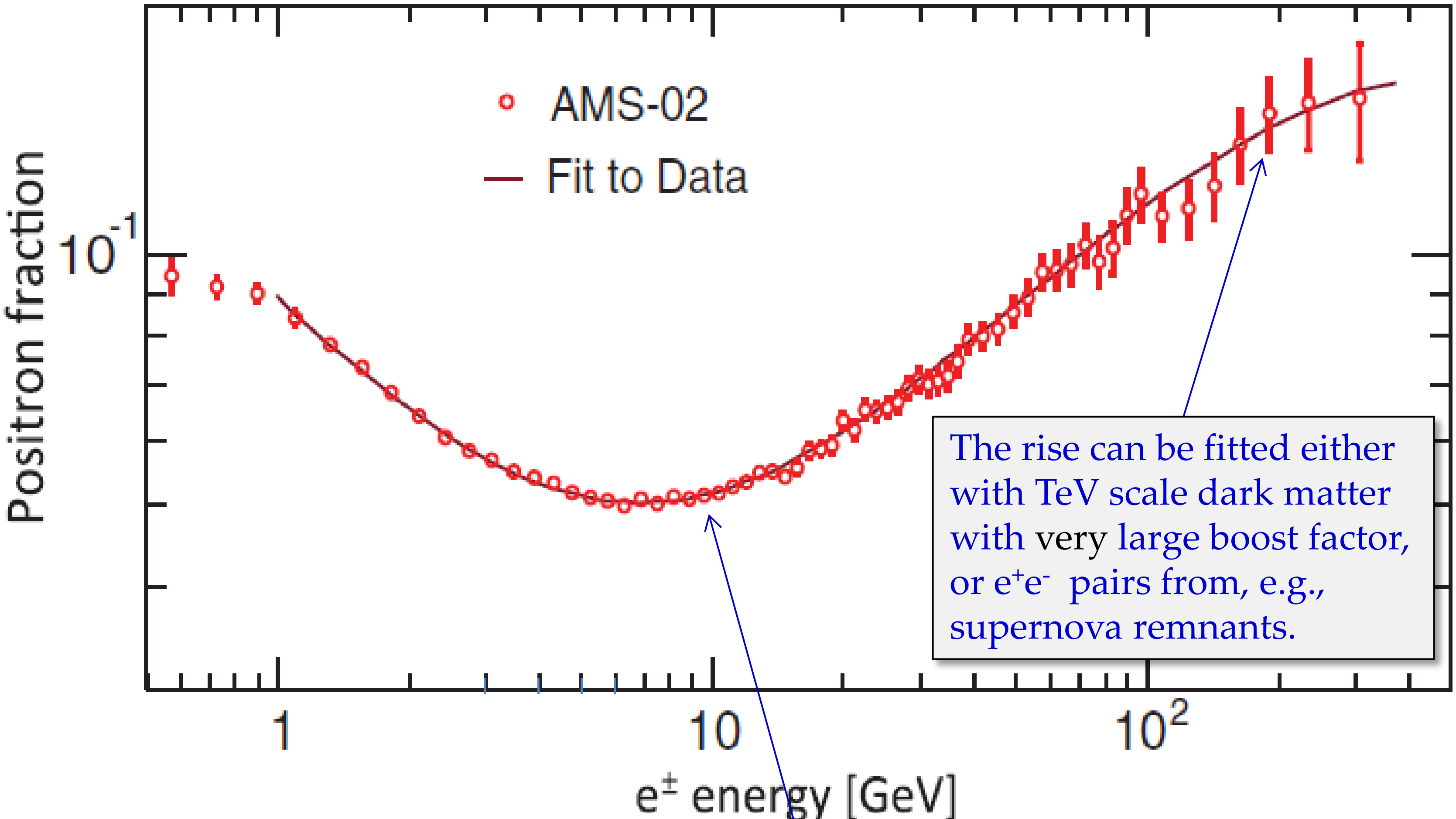




Ideal, e.g., for looking for spectral DM-induced features, like searching for γ-ray lines! Can search for γ-ray structures, with unprecedented precision.

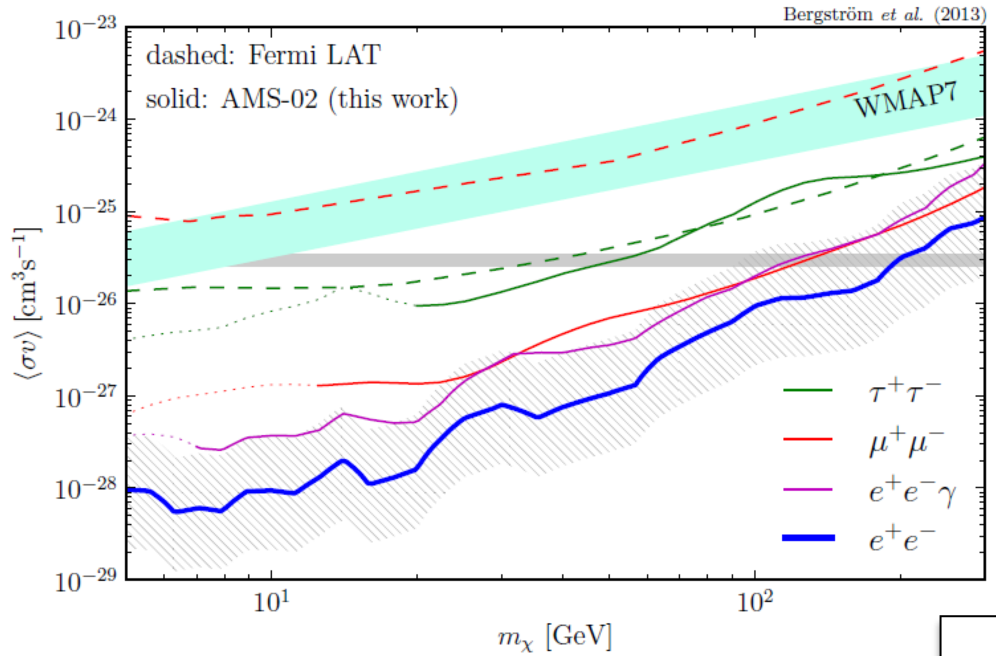
Several WIMP models exist with large line features and other energy structures, e.g., F. Giacchino & al., 2013; A. Ibarra & al., 2014. Also, line search in new low-energy gamma-ray telescopes , K.K. Boddy & J. Kumar., 1504.04024.

Antimatter – positron fraction, AMS-02 on the International Space Station:



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

Note high precision of the very smooth AMS-02 data.
Future: The experiment will give data for 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. Bringmann, I. Cholis, D. Hooper & C. Weniger, PRL 2013; A. Ibarra, A. Lamperstorfer and J. Silk, PRD 2014)

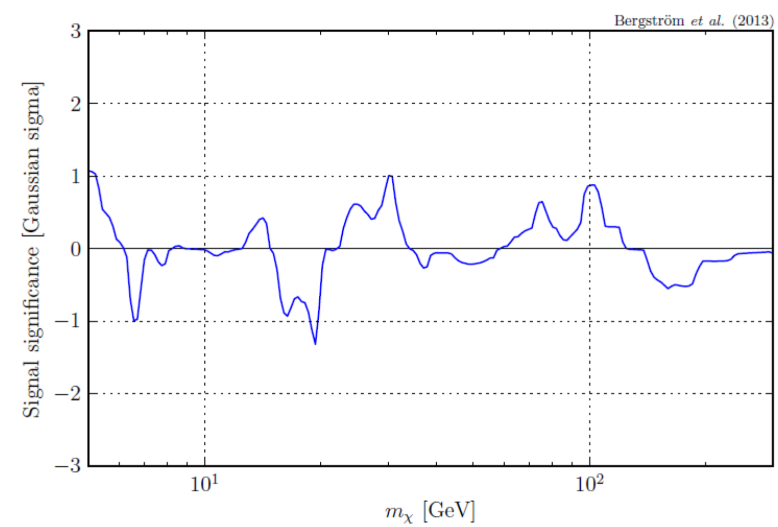
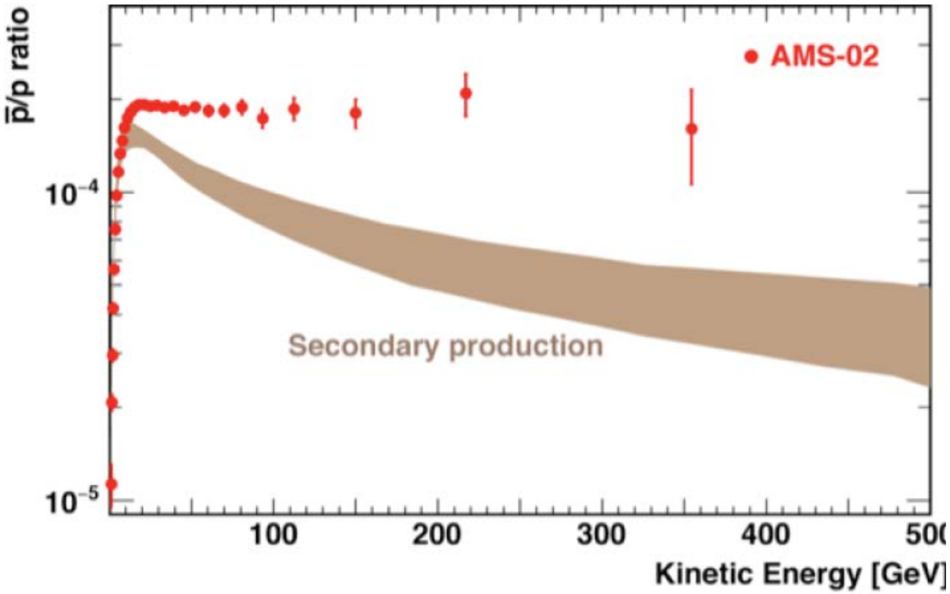
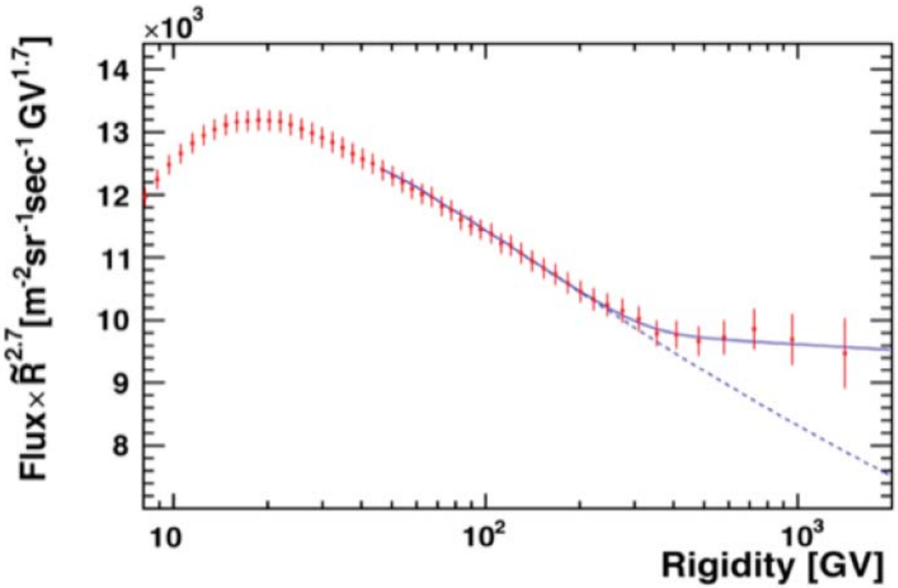


FIG. 6. Significance for a contribution from a e^+e^- DM signal to the AMS-02 positron fraction, for different DM energies, in units of Gaussian sigma. Negative values correspond to negative (but unphysical) signal normalizations.

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

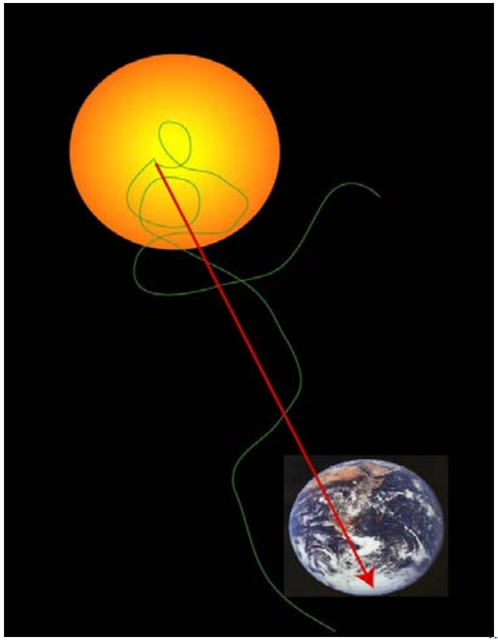
... but, what is this? AMS-02 data from a couple of days ago:





From the press release: "... require a comprehensive model to ascertain if their origin is from **dark matter**, astrophysical sources, acceleration mechanisms or a combination."

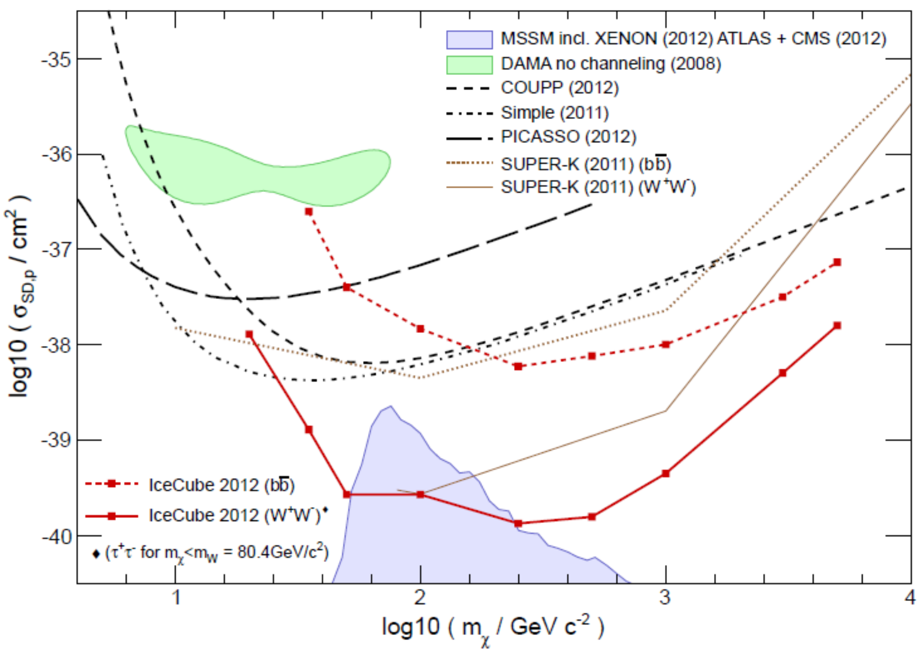
On the other hand, G. Giessen & al., today, 1504.04276: "We find **no unambiguous evidence for a significant excess with respect to expectations [in the AMS-02 results]**. Yet, some preference for thicker halos and a flatter energy dependence of the diffusion coefficient starts to emerge. Also, we provide an **assessment of the room left for exotic components such as Galactic Dark Matter annihilation or decay, deriving new stringent constraints**."

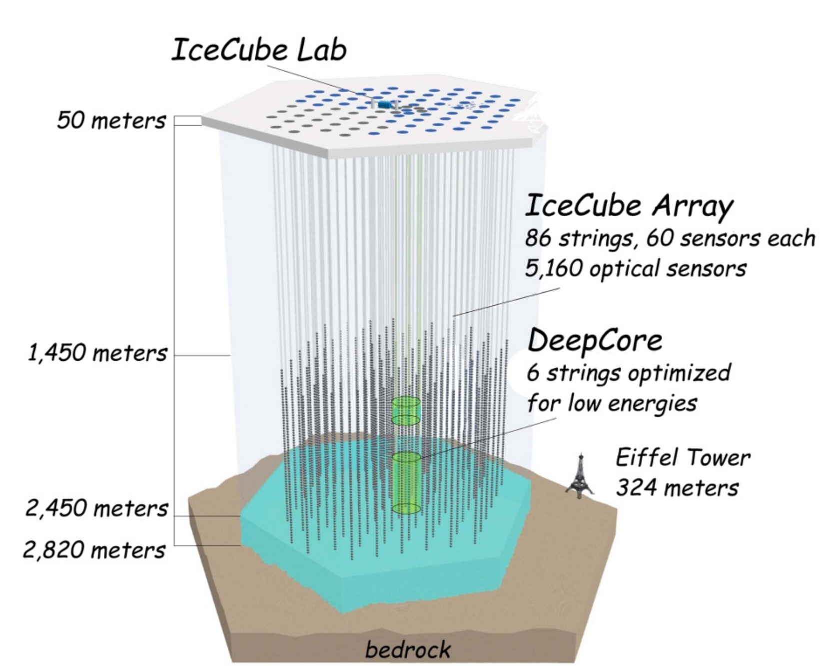


Indirect detection by neutrinos from annihilation in the Sun:

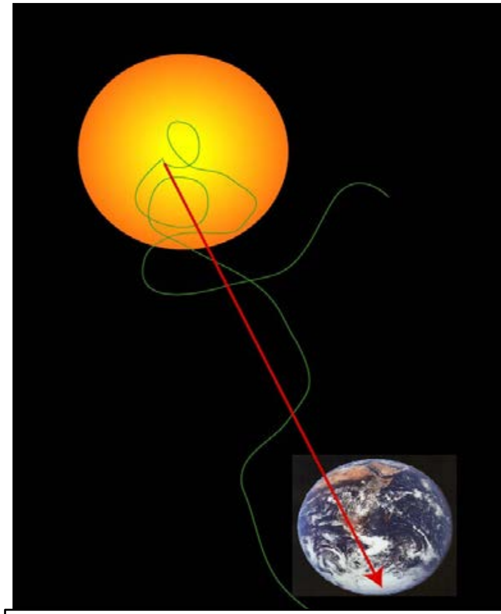
Present: Competitive, due to high proton content of the Sun ⇒ sensitive to **spin-dependent** interactions

Future: New planned addition PINGU (2020?-), cf. KM3NET/ORCA, will lower threshold further. May be combined with a larger area extended IceCube. However, Super-K is sensitive also to lower masses.





IceCube Collaboration, PRL, 2013



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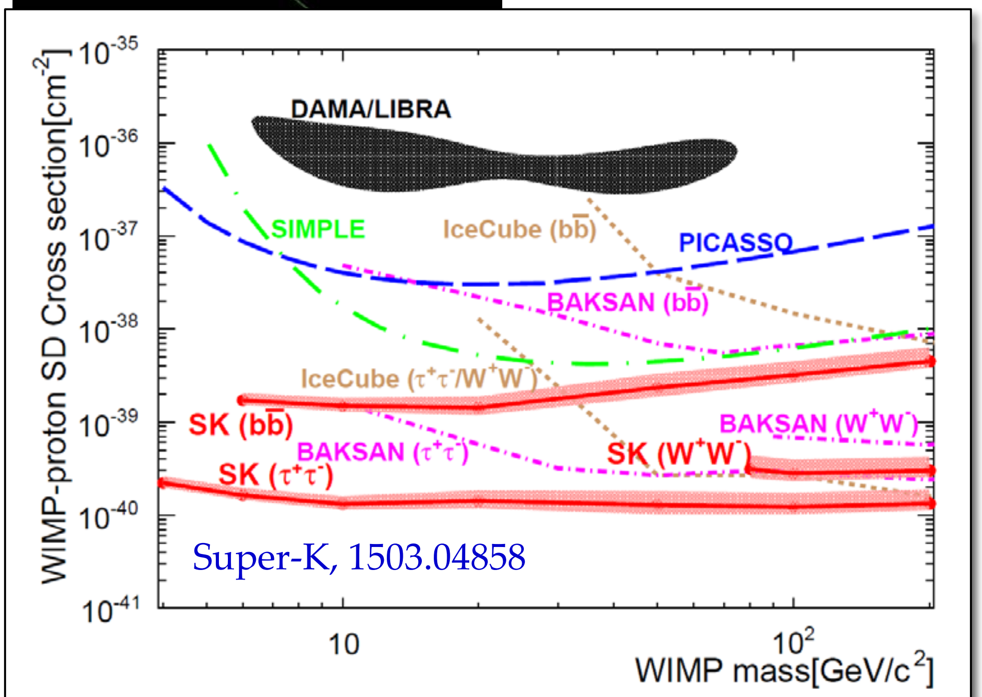
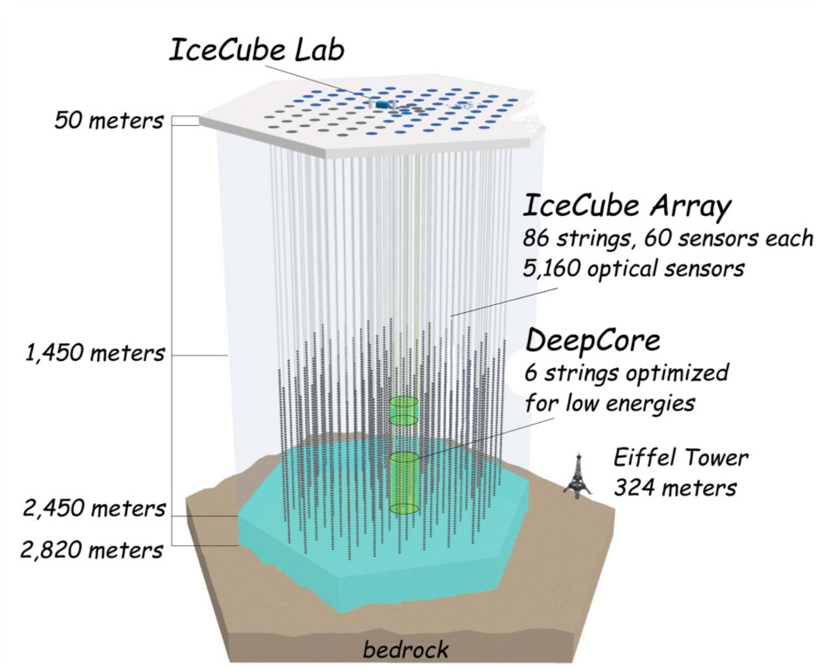
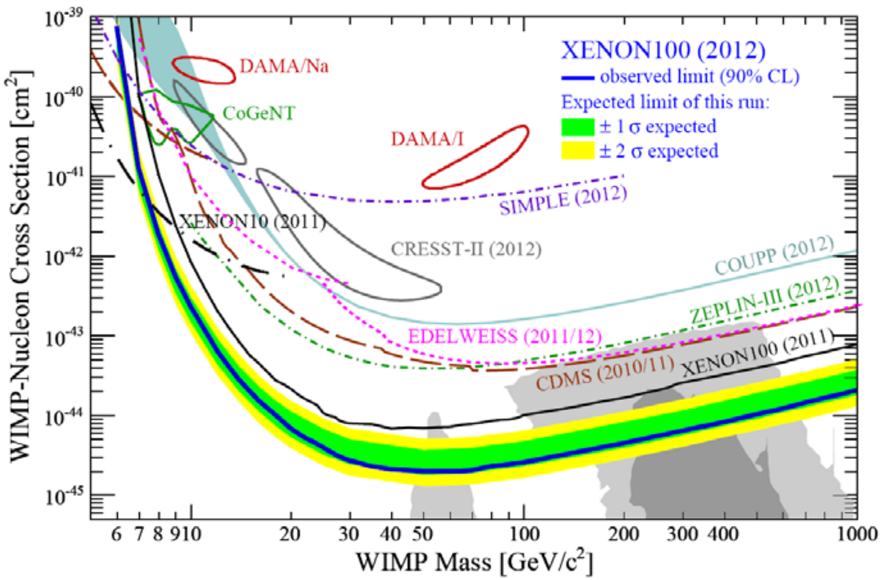


Super-K Collaboration, 2015



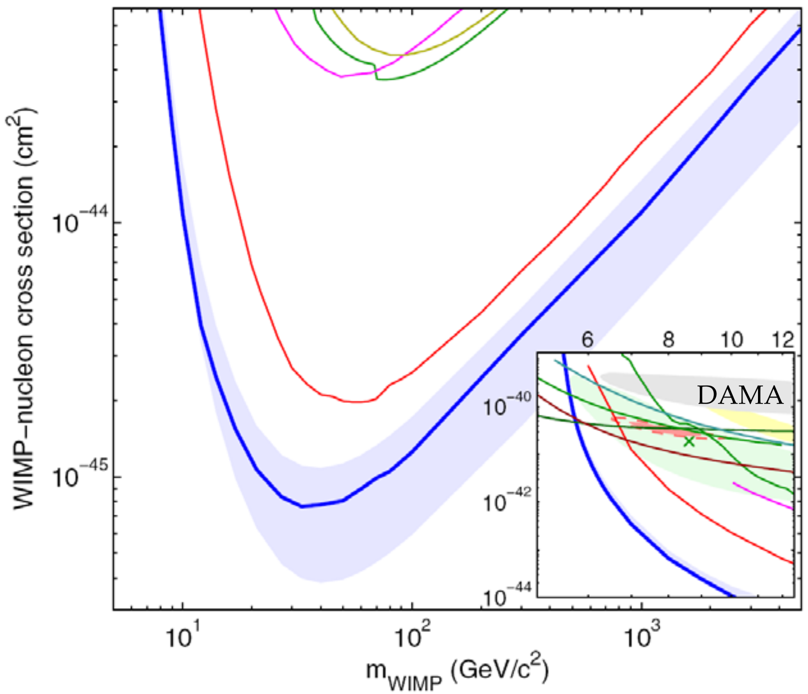
DM direct detection searches – a success story. Three orders of magnitude increase in sensitivity over 10 years!
At the moment (2015), Li-Xe detectors are leading the race (and for low masses SuperCDMS), and seem to exclude scattering rates needed to explain the positive signals in DAMA/CoGeNT/CRESST:

XENON100



E. Aprile & al., PRL 2012.

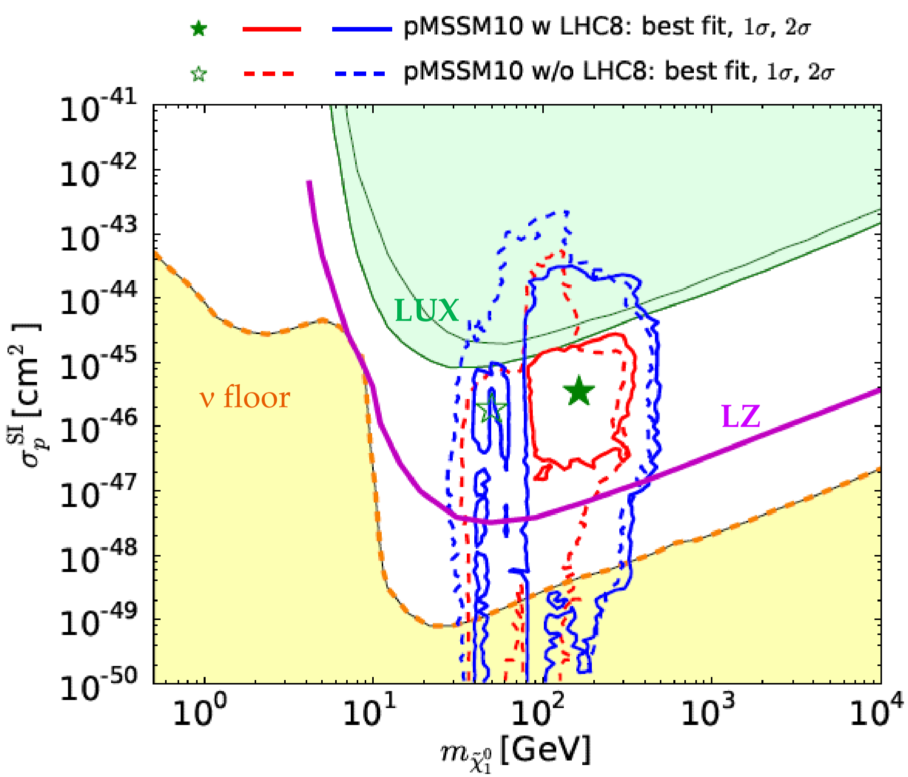
LUX



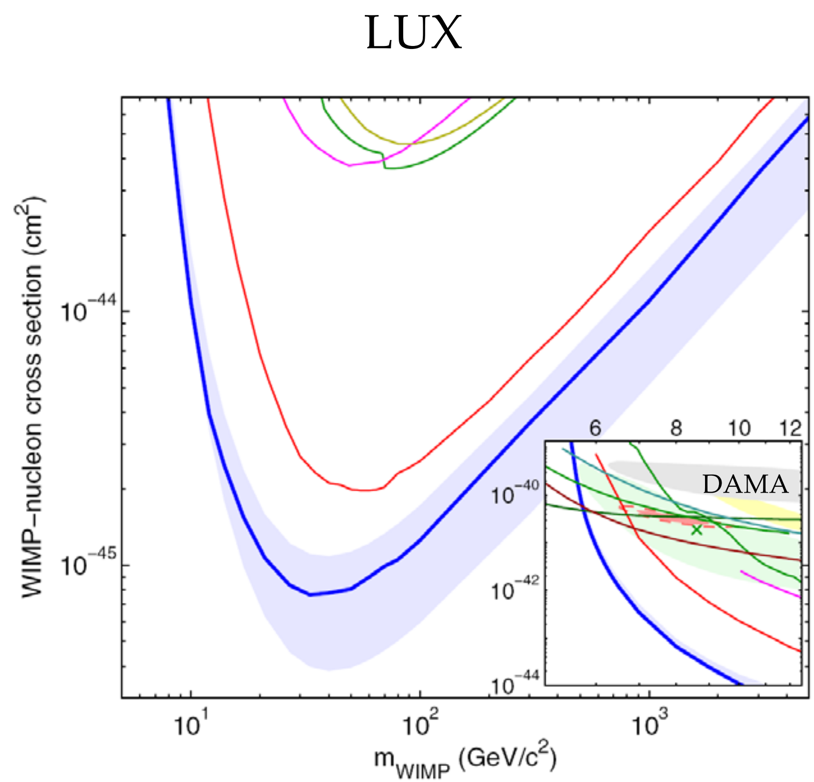
D.S. Akerib & al., PRL 2014.

Maybe detection of Supersymmetric DM neutralino WIMP is just around the corner...

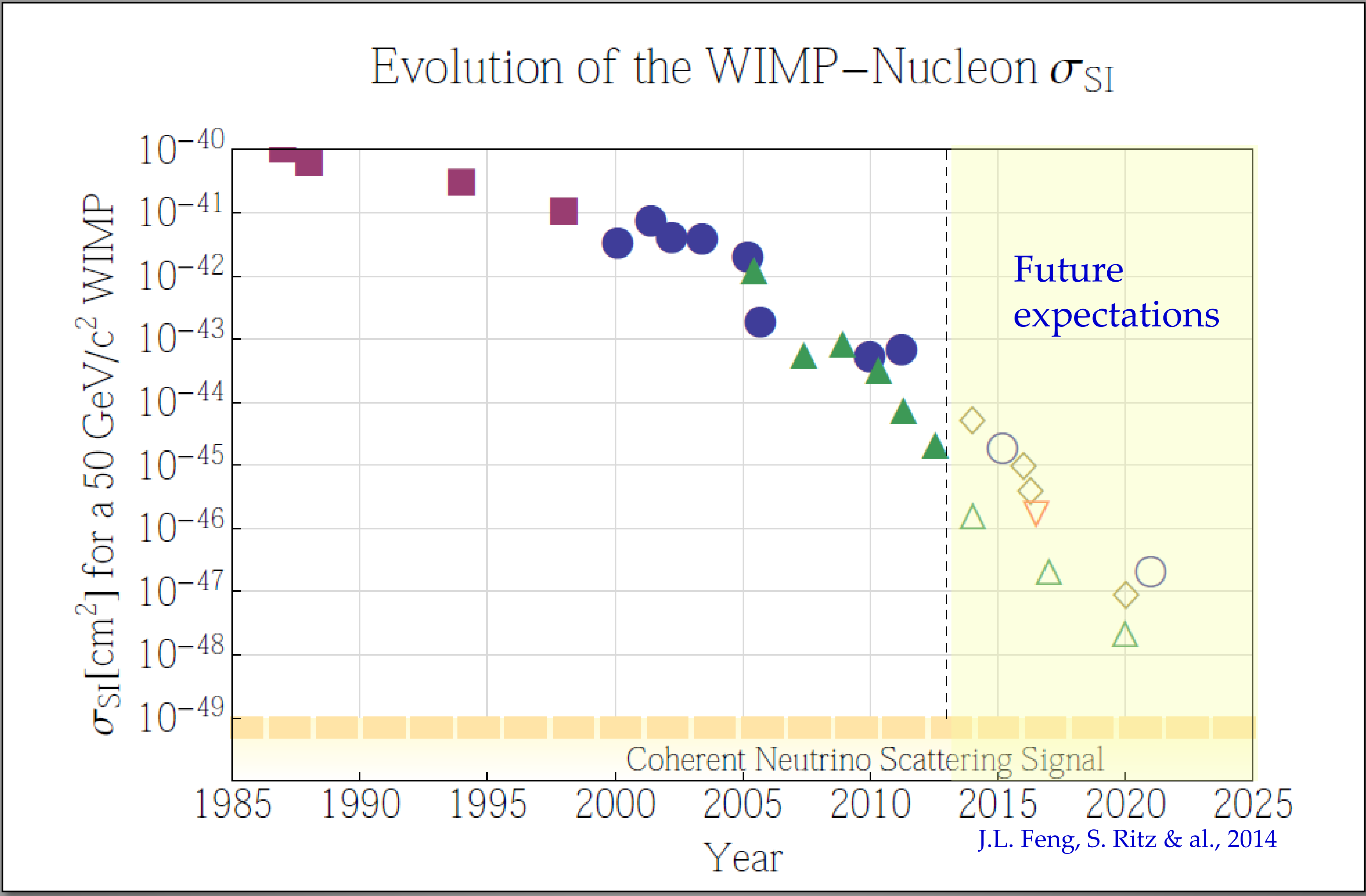
K.J. de Vries, E.A. Bagnaschi, O. Buchmueller, R. Cavanaugh, M. Citron, A. De Roeck, M.J. Dolan, J.R. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, S. Malik, J. Marrouche, D. Martnez Santos, K.A. Olive, K. Sakurai, G. Weiglein, 1504.03260.



K.J. de Vries & al., 1504.03260



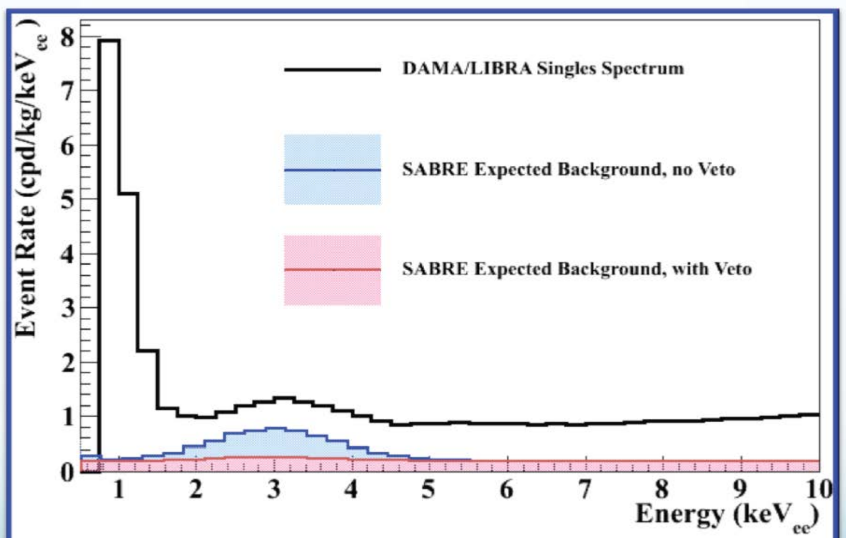
D.S. Akerib & al., PRL 2014.


Evolution of the WIMP–Nucleon σ_{SI}
$\sigma_{SI}[\mathrm{cm}^2]$ 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

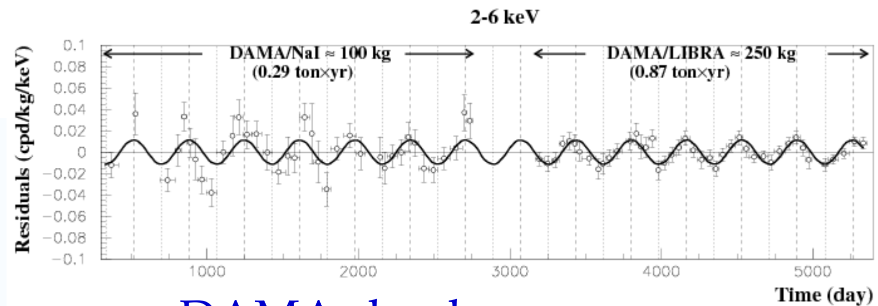
DAMA has been with us, unexplained, since 1997, showing annual modulation, consistent with DM, at present with 9.2σ statistical significance. Finally, a NaI experiment with superior sensitity is being planned, SABRE (F. Calaprice & al., Princeton Univ.) SABRE: Sodium-iodide with Active Background Rejection

J. Xu, UCLA DM Conference talk, 2014:

Expected SABRE Background



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



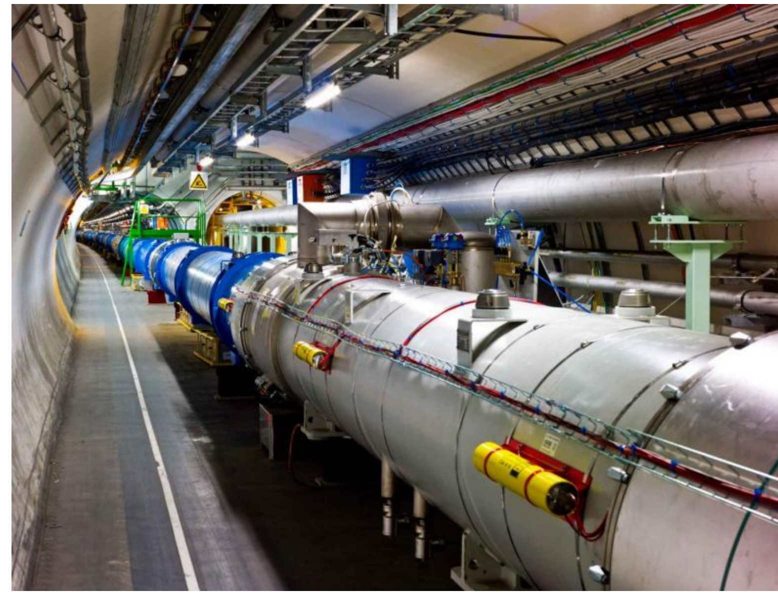
DAMA clearly sees an oscillation – but what is it?

A dark matter 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 – this workshop!	v?	ADMX, CARRACK, CAPP, IAXO,…
CTA and space gamma-ray experiment(s) also for lower energies and better angular resolution, replacing Fermi-LAT	v	CTA, GAMMA-400, DAMPE, PANGU?, HERD
Good space experiments on charged cosmic ray detection including antimatter: positrons, antiprotons and antideuterons.	v	AMS-02, Calet, 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 or new circular 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, ORCA, ASTRO-H,...
For cosmology, test of CMB B-mode polarization, and precision measurements of cosmological parameters.	v	BICEP3, SPIDER, CMBPol, EUCLID, LSST, DESI,...

Exciting times ahead!

XENON 1t currently being prepared in the Gran Sasso Lab.

LHC just restarting, at 13 TeV



DAMPE (Dark Matter Particle Explorer) soon to be launched

Conclusions

The Dark Matter search has had a remarkably interesting last decade, with order-of-magnitude improvements of experiments possible also in the next decade.

The fundamental question still stands: Dark Matter exists, but what is it? Maybe we have to move ”off the beaten track” (but please do not be too impatient...).

Seemingly false alarms of discovery of Dark Matter in recent years show that confirmation using alternative, complementary methods probably will be needed to convince the general physics community.

How many unfounded press releases can the Dark Matter community tolerate before we lose credibility?

We will need goodwill, as some new projects are of ”big science” type and will need global support and coordination.

In Europe, we have ApPEC and ESFRI which will soon publish Roadmaps for European astropartice physics for the coming decade.

The hunt for Dark Matter goes into a decisive decade… Will the mystery be solved in time for the 100-year anniversary of Knut Lundmarks's remarkable observation, in 2030?

The End