Cosmology and the Dark Matter Frontier

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Standard cosmological model: ΛCDM model. (Assumes a homogeneous and isotropic average background)

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$

Measurements on the cosmic microwave background gives (and inflationary theories predicted) k = 0 to good accuracy.

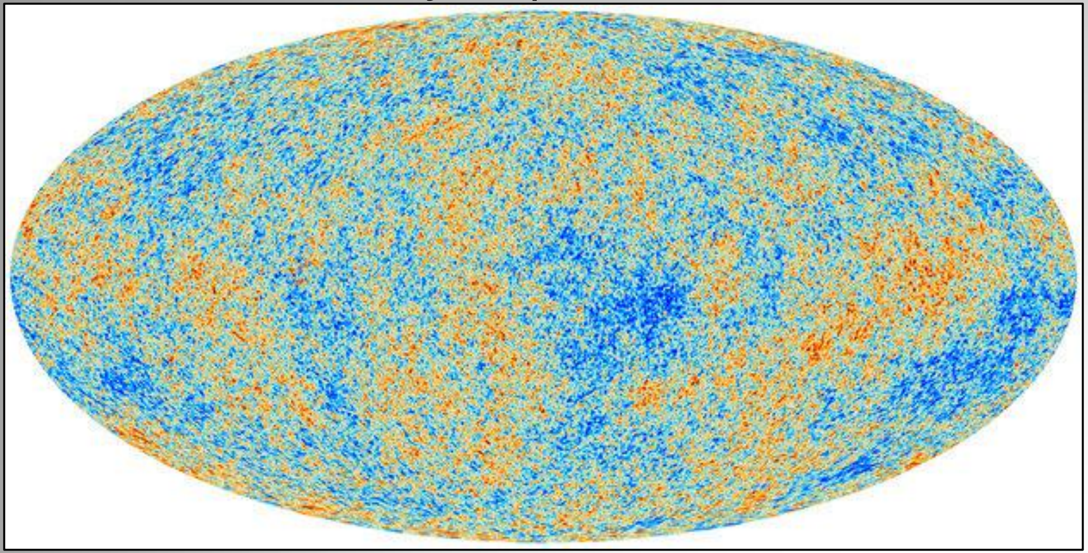
The scale factor *a(t)* follows equations derived from Einsteins equations in general relativity:

$$H(t)^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\left[\rho_B + \rho_{CDM} + \rho_R + \rho_\Lambda\right]$$ Friedmann's equation

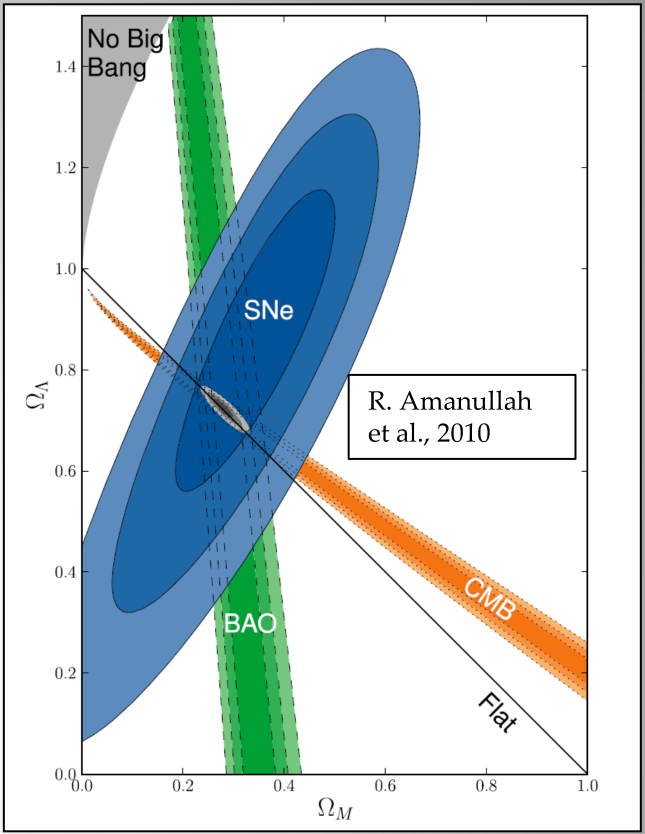
$$H(t_{now}) = h \cdot 100 \text{ kms}^{-1}\text{Mpc}^{-1}$$ with $h \sim 0.67$, $t_{now} \sim 13.8$ Gyr (*Planck* 2013)

$$\frac{2\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 = -8\pi G_N p$$ Acceleration equation

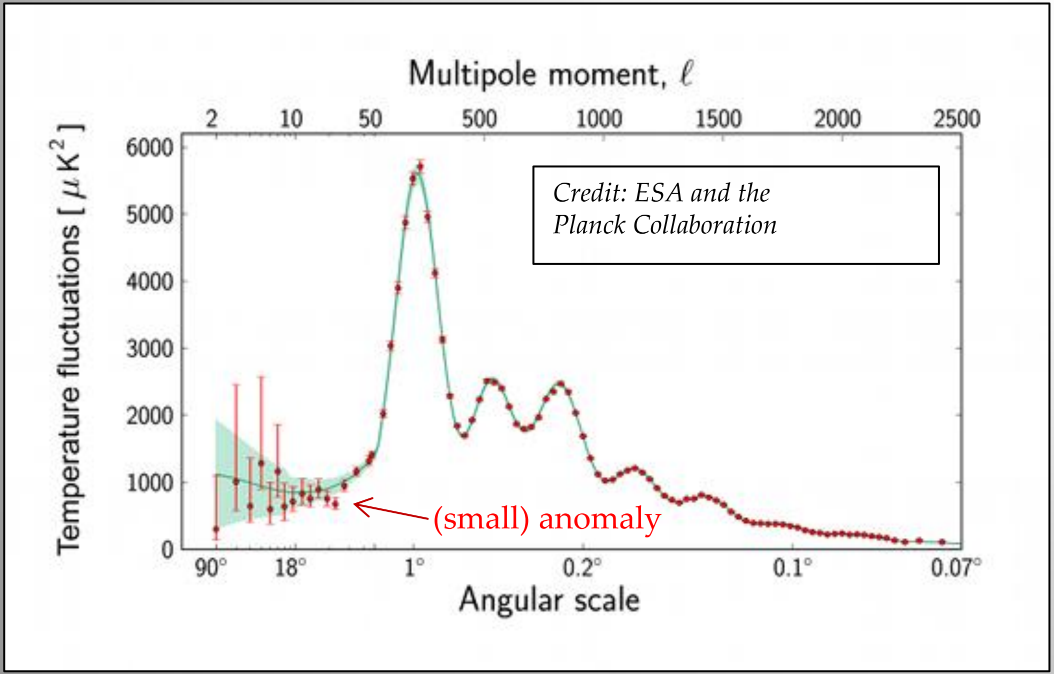
Planck Sky Map, March 2013



The *Planck* Collaboration, 2013



R. Amanullah et al., 2010



Credit: ESA and the Planck Collaboration

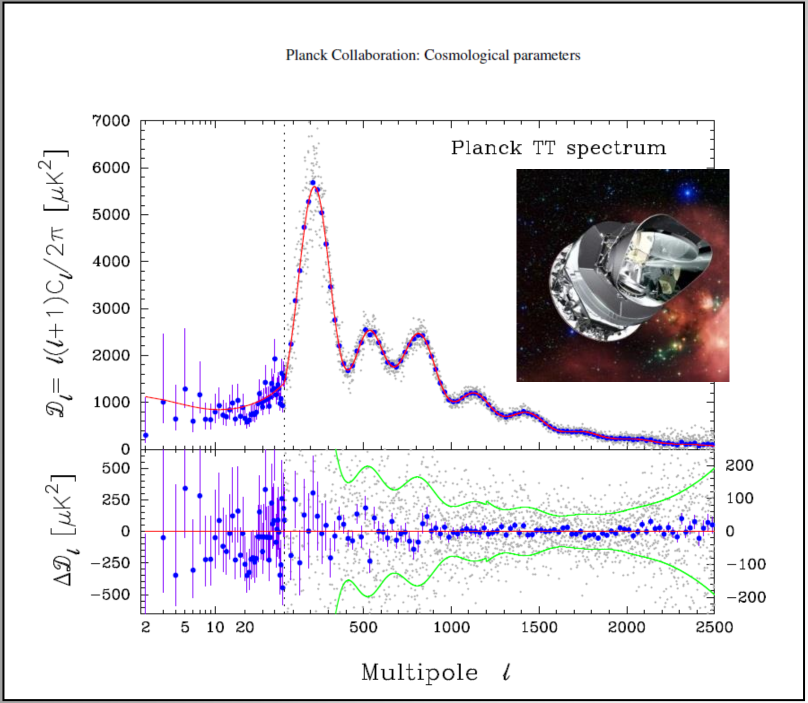
(small) anomaly

Planck 2013:

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

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

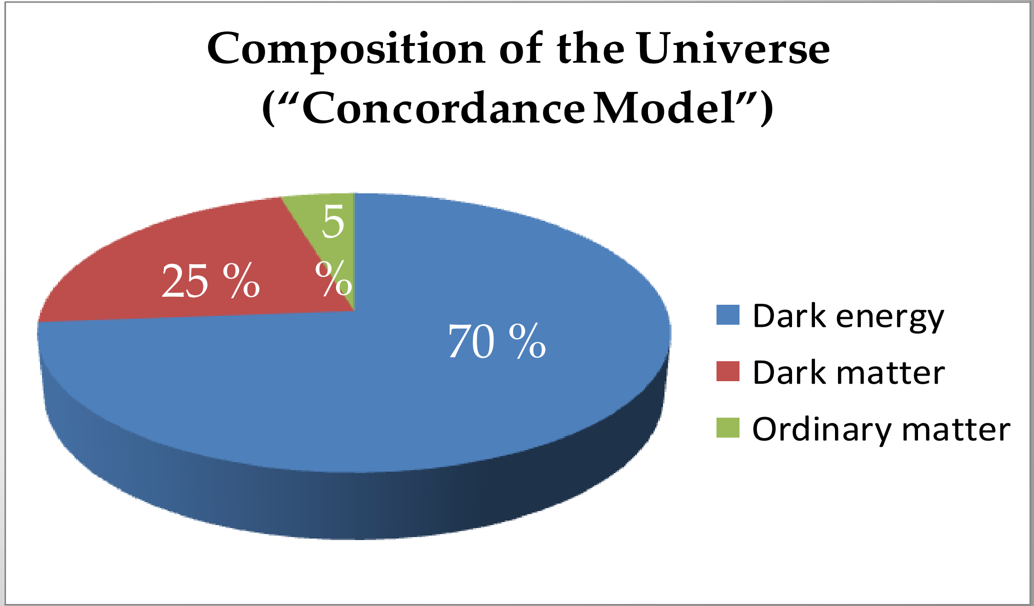
$$\Omega_B = 0.0489 \pm 0.0018 \qquad h = 0.673 \pm 0.012$$



$$\sum m_\nu < \begin{cases} 0.98\,\mathrm{eV} & (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}) \\ 0.32\,\mathrm{eV} & (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}+\mathrm{BAO}) \end{cases}$$

$$N_{\mathrm{eff}} = 3.30^{+0.54}_{-0.51} \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}+\mathrm{BAO})$$

$$f_{\mathrm{NL}}^{\mathrm{local}} = 2.7 \pm 5.8$$

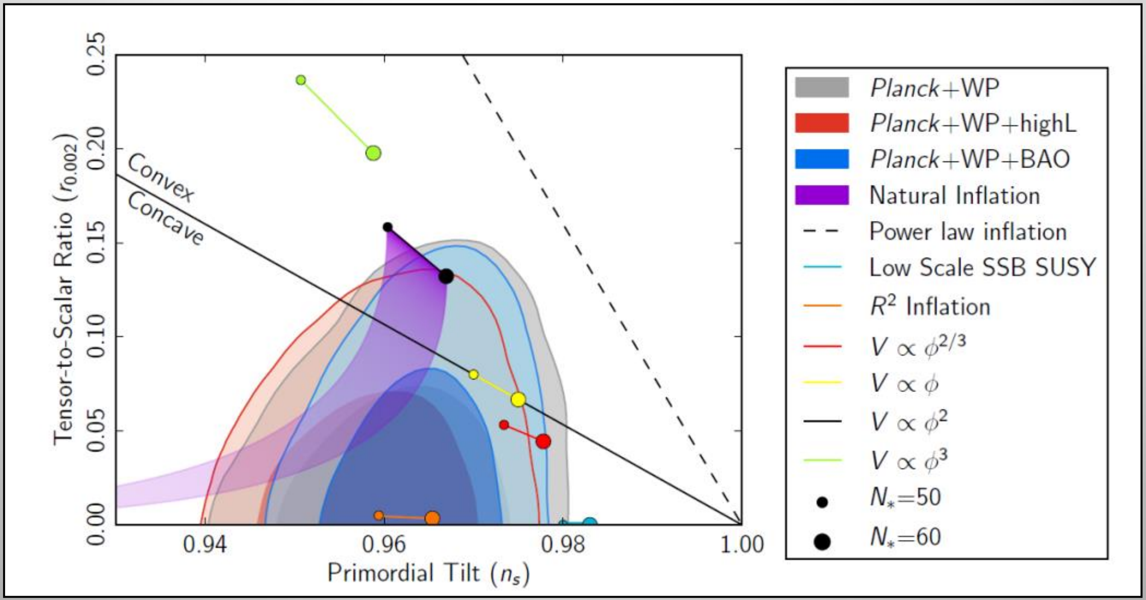

Composition of the Universe
("Concordance Model")

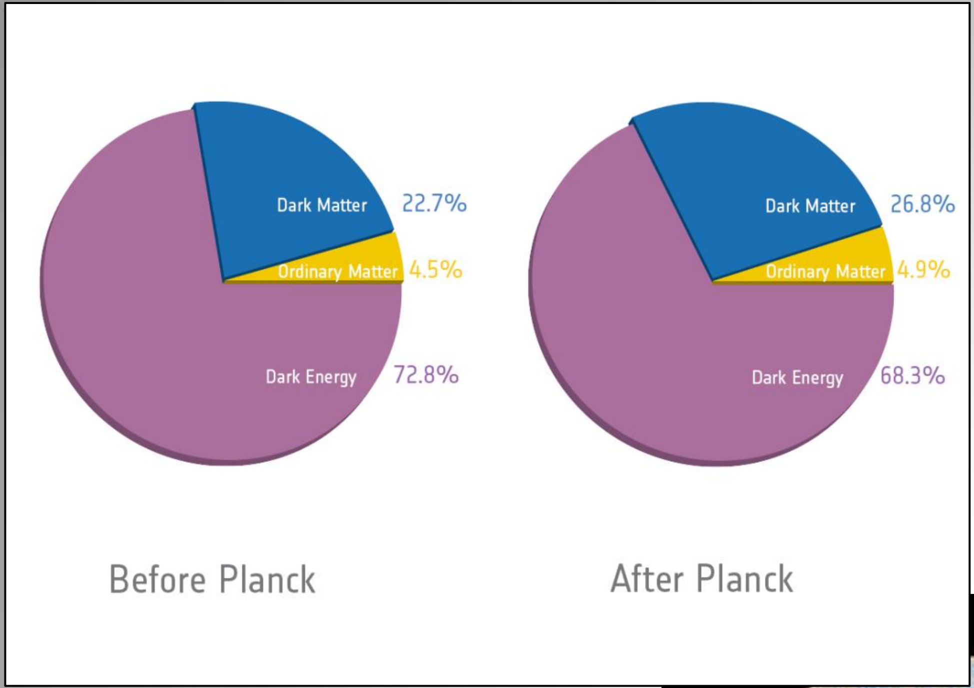
All measurements so far are consistent with this cosmological model

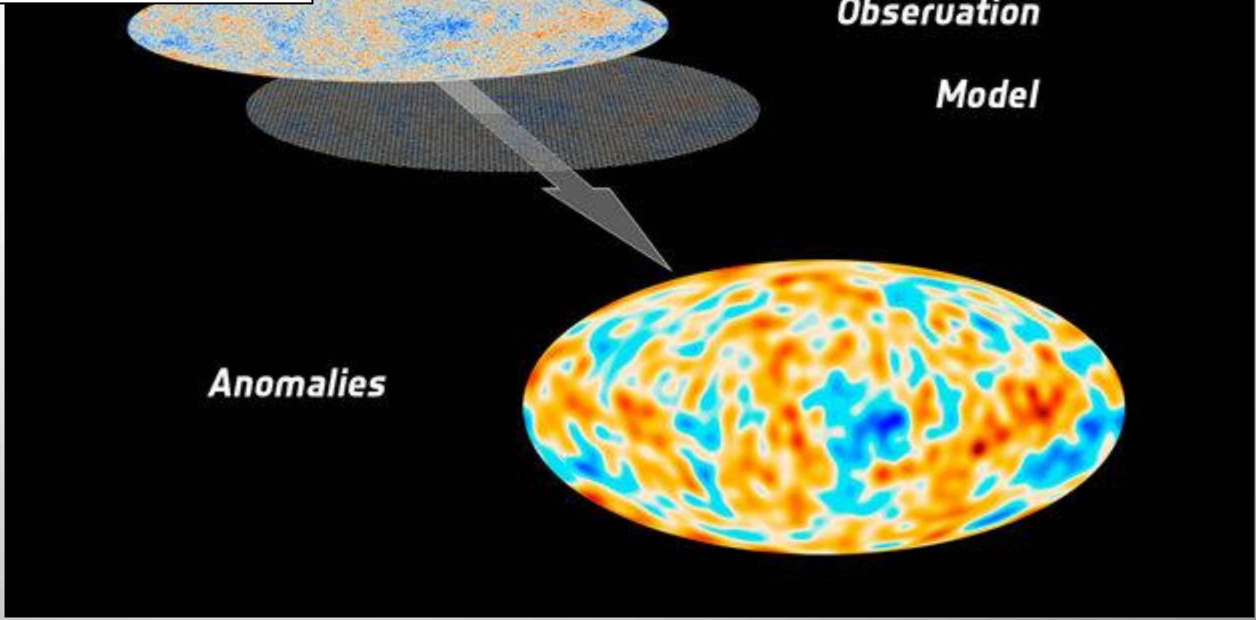
Tests of Cosmological Inflation

Cosmological inflation (A. Guth, 1980; A. Starobinsky, 1980; K. Sato, 1981; D. Kazanas, 1981; A. Linde, 1982, 1983; A. Albrecht & P. Steinhardt, 1982, …):

- Explains the horizon & flatness problem of the Universe
- Predicts that $\Omega_{tot} = 1$ to high accuracy
- Can becombined with quantum fluctuations in an effectively de Sitter phase to explain the seeds of cosmic perturbations (V. Mukhanov & N. Chibisov, 1980; several groups following the Nuffield workshop 1982)
- Inflation is a scenario, with many possible models surviving Planck data, and some showing tension:







Remaining ”anomalies ” are at the 2 - 3σ level

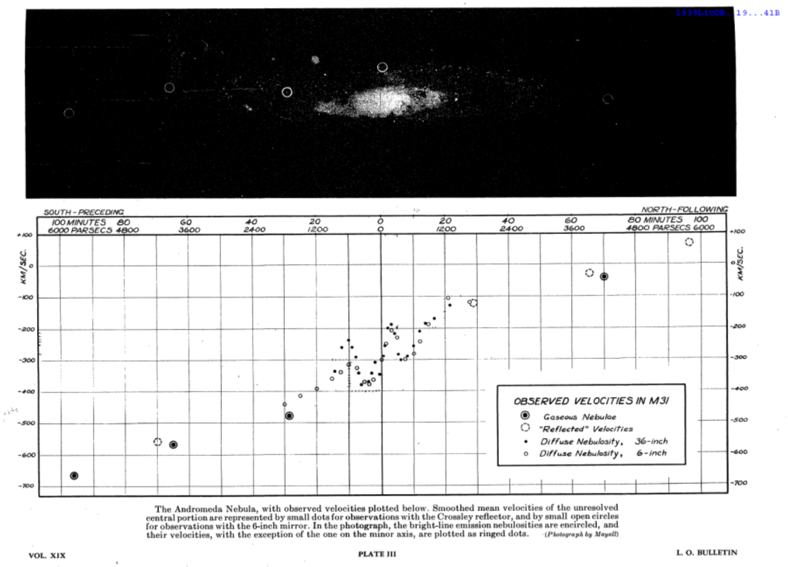
What is Dark Matter?

"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." Zwicky 1933

Babcock (1939) measured the optical rotation curve of M31 (Andromeda) – was verified much later by V. Rubin and W.K. Ford (1970).

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

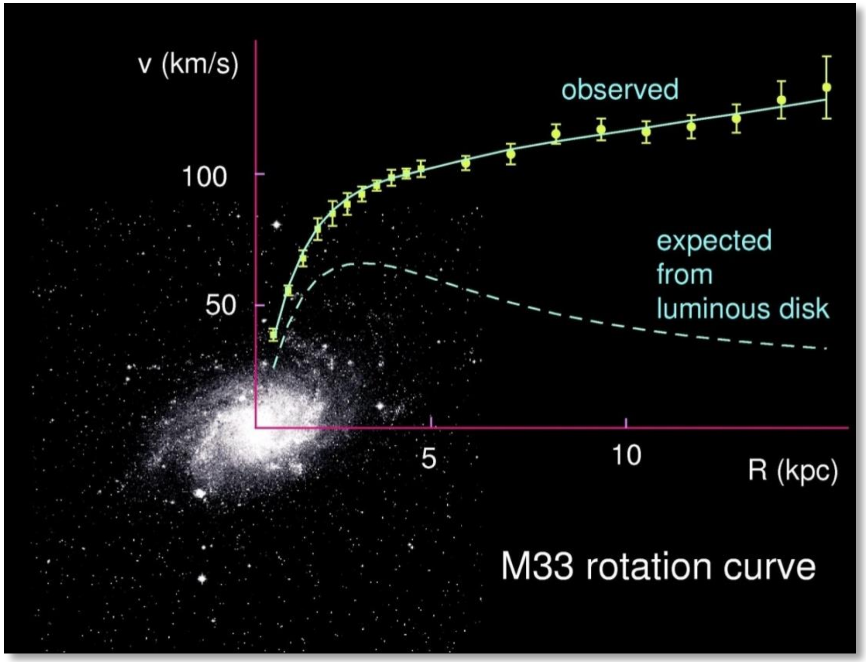
Dark matter needed on all scales!
⇒ Modified Newtonian Dynamics (MOND) and other *ad hoc* attemps to modify Einstein's or Newton's theory of gravitation do not seem viable

Einstein: $\boxed{S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-\tilde{g}}\,R\,.}$

MOND:

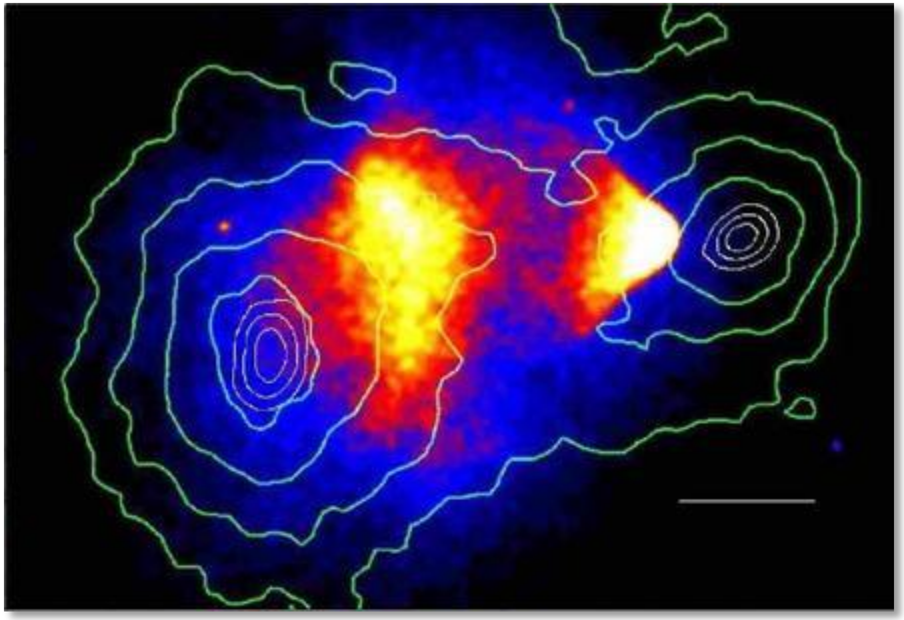
$$\boxed{\begin{aligned} S \;=\; & \frac{1}{16\pi G}\int d^4x\,\sqrt{-\tilde{g}}\,\Big[\tilde{R}-\frac{1}{2}KF^{ab}F_{ab}+\lambda(A_aA^a+1) \\ & -\mu(\tilde{g}^{ab}-A^aA^b)\nabla_a\phi\nabla_b\phi-V(\mu)\Big] \\ & \text{where}\quad g^{ab}=e^{2\phi}\tilde{g}^{ab}+2\sinh(2\phi)A^aA^b\,. \\ & \text{and}\quad \frac{dV}{d\mu}=-\frac{3}{32\pi l_B^2\mu_0^2}\frac{\mu^2(\mu-2\mu_0)^2}{\mu_0-\mu}\,. \end{aligned}}$$

Galaxy rotation curves



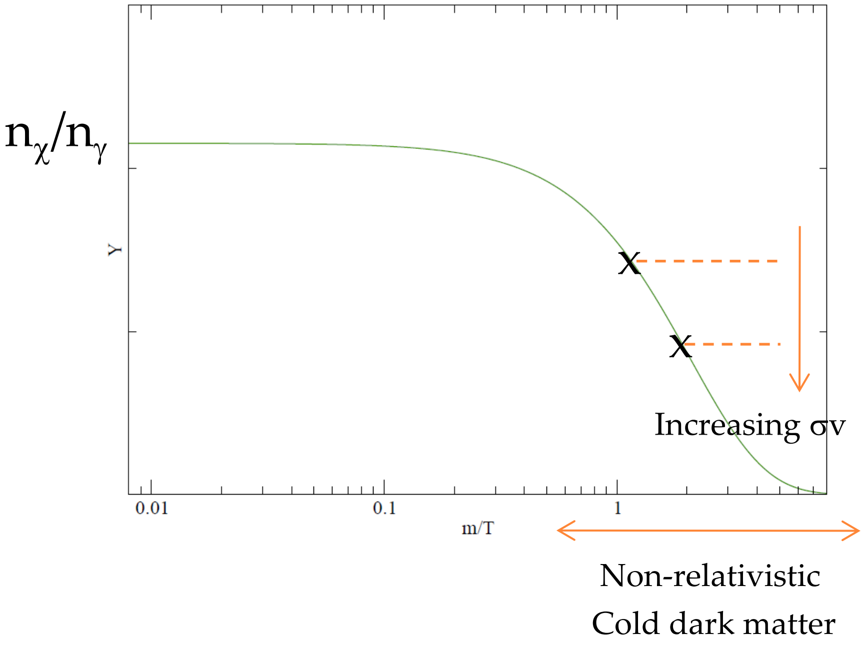
L.B., Rep. Prog. Phys. 2000

Colliding galaxy clusters



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

Cold Dark Matter: Solving the Boltzmann equation numerically in the non-relativistic decoupling regime one finds



$$\boxed{\Omega_{\chi^0} h^2 \simeq \frac{3\cdot 10^{-27}\ \mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_A v\rangle}}$$

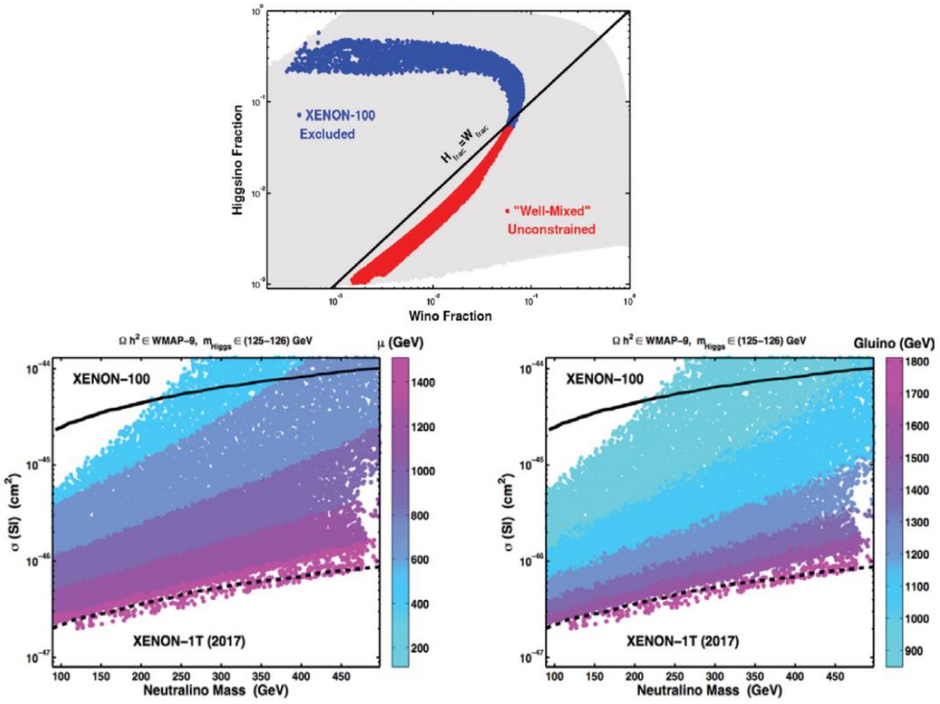
This means that a successful cold dark matter model should have (independently of the mass!):

$$\boxed{\langle \sigma_A v\rangle \simeq 3\cdot 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}}$$

That is, $\sigma_A v \sim 1$ pb. This is a typical weak interaction cross section, so these candidates for dark matter are called WIMPs (Weakly Interacting Massive Particles). The fact that one gets the correct relic density is sometimes called the ”WIMP miracle”. Good template: The lightest neutralino in supersymmetry (H. Goldberg, 1983; J. Ellis, J. Hagelin, D.V. Nanopoulos, K.A. Olive & M. Srednicki, 1984).

One finds typically $T_f \sim \dfrac{m_\chi}{20}$ for the freeze-out temperature.

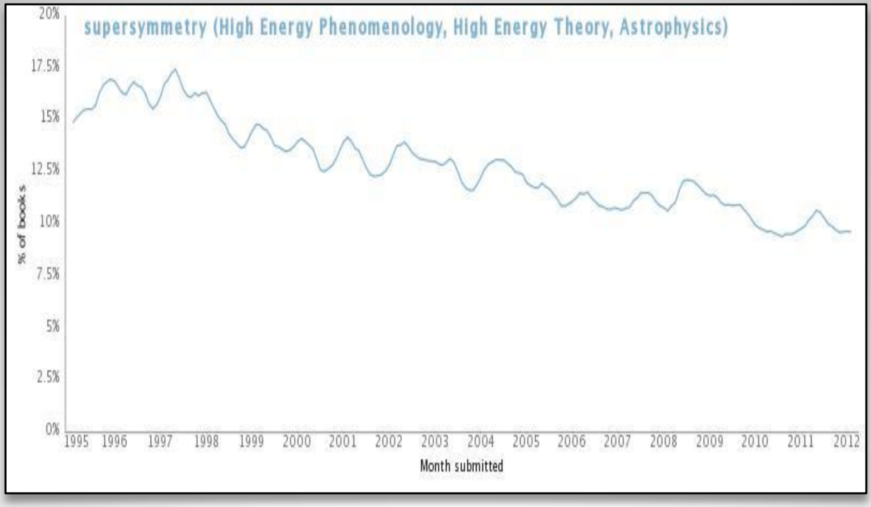
Freely available software package, written by P. Gondolo, J. Edsjö, L. B., P. Ullio, M. Schelke, E. Baltz, T. Bringmann and G. Duda.
http://www.darksusy.org



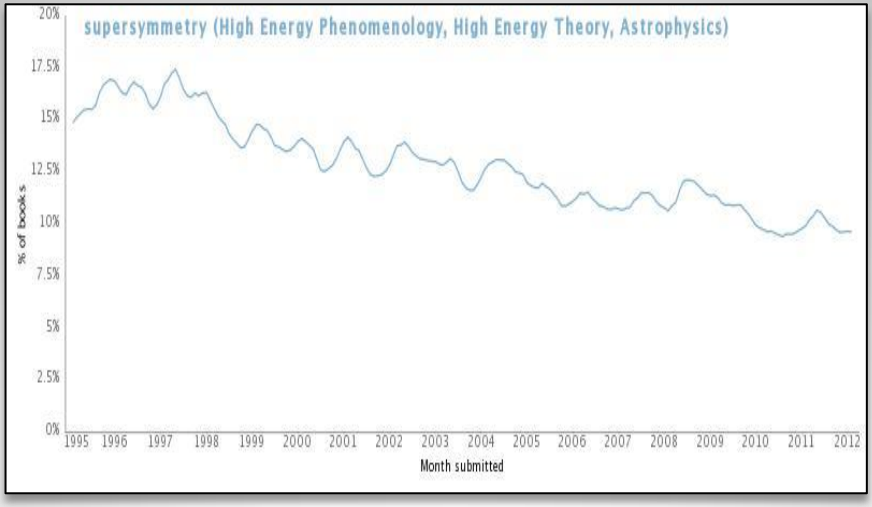
Example of parameter regions where the MSSM neutralino fullfils all constraints of LHC & Xenon-100 and gives correct relic density. (D. Feldman & P. Sandick, 1303.0329)

One problem for MSSM: While the (lightest) Higgs mass, ~126 GeV, is within the range predicted by SUSY, with radiative corrections (Y. Okada, M. Yamaguchi & T. Yanagida; J. Ellis, G. Ridolfi & F. Zwirner; H. Haber & R. Hempfling; 1991), it is on the high side which may necessitate some fine-tuning. Also squarks and gluinos (not seen at the LHC) have to have very large masses – not the spectrum one would first have guessed.
By introducing a scalar neutral supermultiplet, as in the NMSSM, some of these "problems" may be partly solved (see, e.g, R. Barbieri, D. Buttazzo, K. Kannike, F. Sala, A. Tesi,1304.3670.)
Also other interesting non-SUSY WIMPs are worth studying: Lightest Kaluza-Klein particle – mass scale 600 – 1000 GeV, Inert Higgs doublet, Right-handed neutrino, … Non-WIMP: Axion.

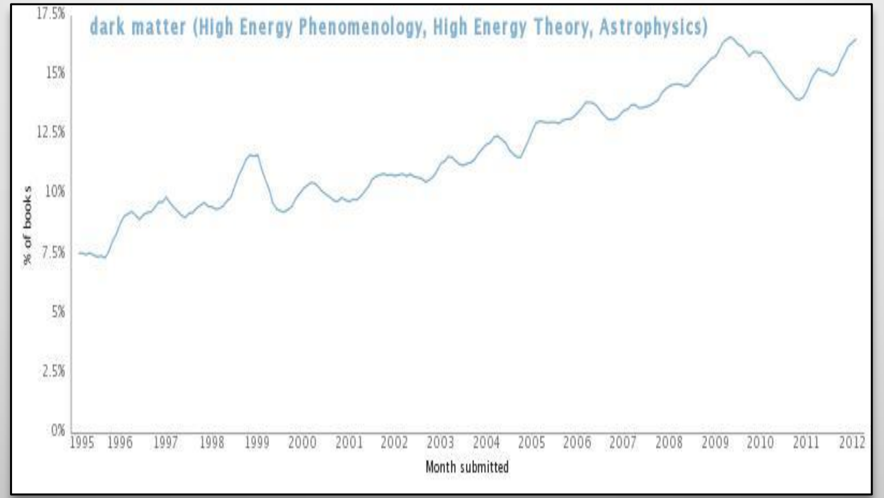
Statistics from arxiv.culturomics.org:



Statistics from arxiv.culturomics.org:



Supersymmetry still alive but has felt better times….



Dark matter

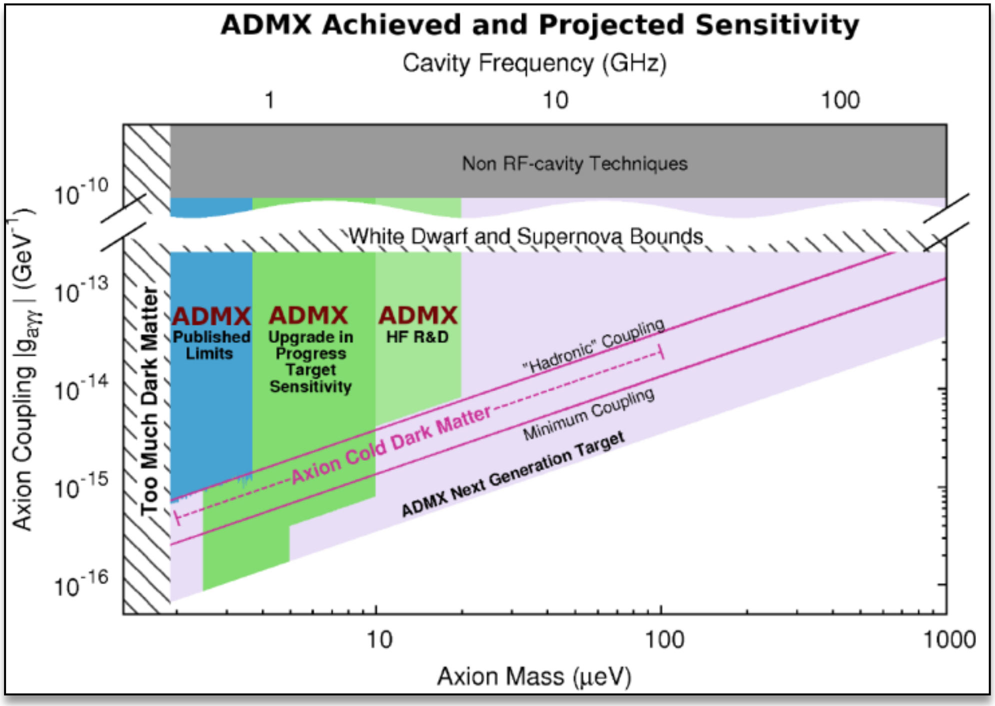
The axion

’t Hooft (1976) pointed out that in the presence of instantons the QCD action is modified with a CP-violating piece (which from experiment, e.g. the EDM of the neutron, is known to be very small):

$$S^q_{eff} = \int d^4x \mathcal{L}_{QCD} + i\theta q \qquad q = \frac{g_s^2}{32\pi^2}\int G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} d^4x$$

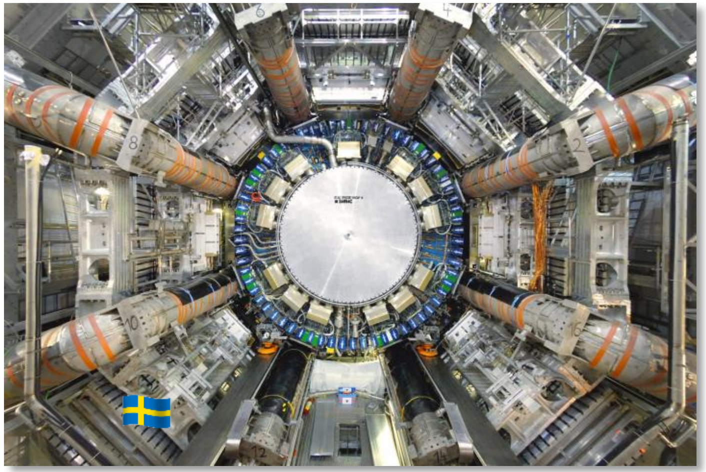
Peccei & Quinn (1977) ; Weinberg (1978) and Wilczek (1978): Goldstone-like pseudoscalar. Very weakly coupled, but behaves like Cold Dark Matter. Modifications (Kim; Shifman, Vainshtein & Zakharov, 1980; Dine, Fischler & Srednicki, 1981) made the axion ”invisible”, but Sikivie (1983) showed that the 2-photon coupling could be used to resonantly convert an axion to a photon in a strong, inhomogeneous magnetic field.

The ADMX experiment in Seattle (L. Rosenberg & al.), will have a greatly improved sensitivity to axion DM (2014-).

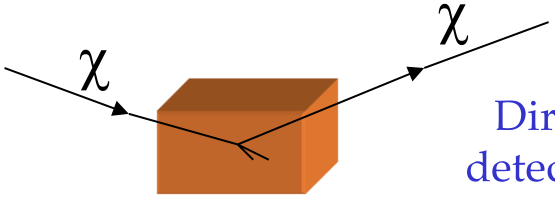


Methods of **WIMP** Dark Matter detection:

- 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.



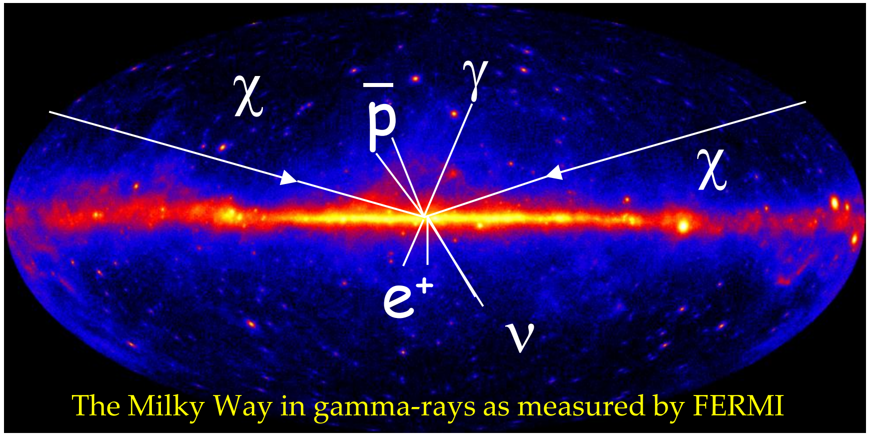
CERN LHC/ATLAS



Direct detection

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

Indirect detection



The Milky Way in gamma-rays as measured by FERMI

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

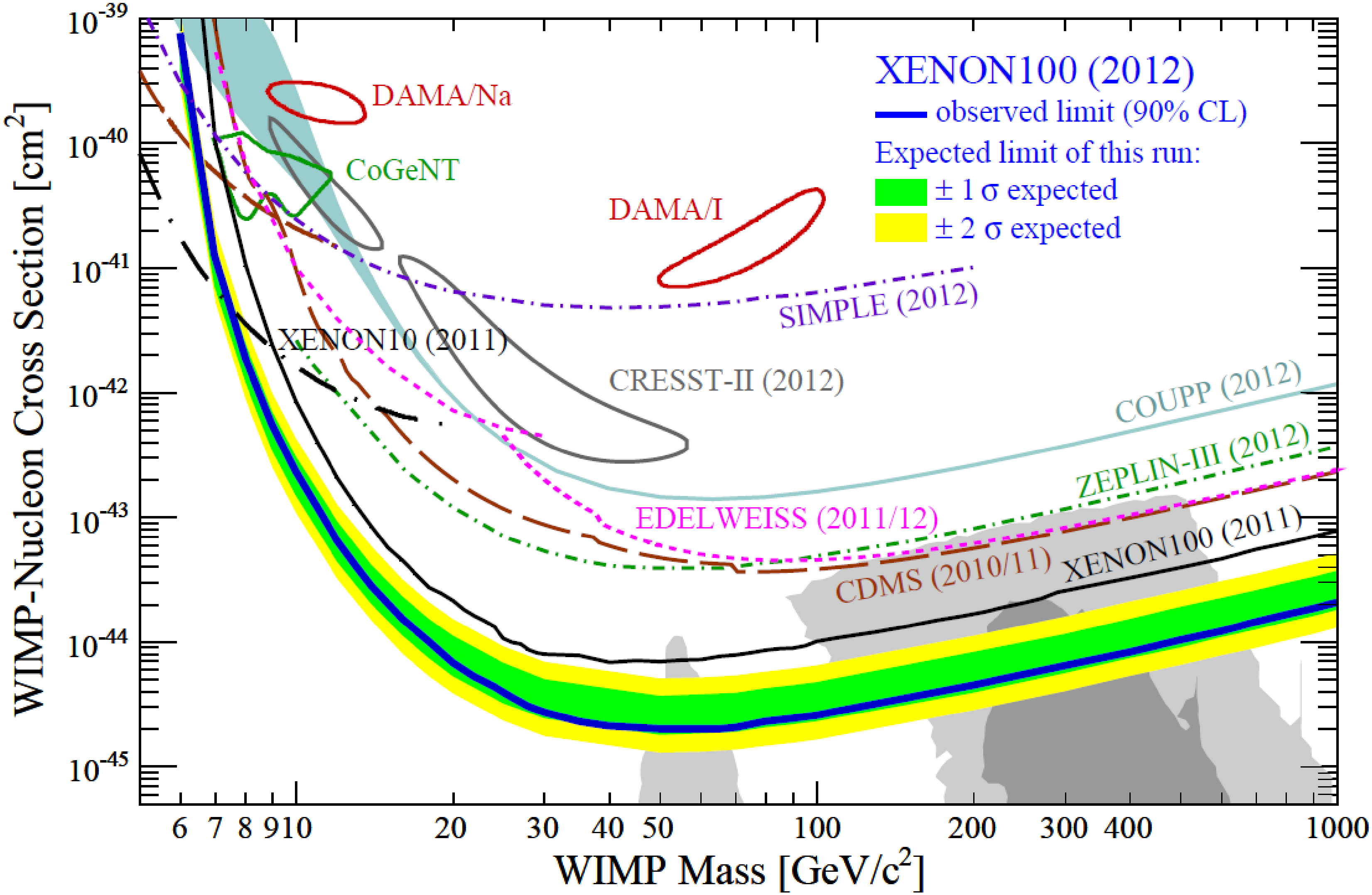
Annihilation rate enhanced for clumpy halo; near galactic centre and in subhalos, also for larger systems like galaxy clusters, cosmological structure (as seen in N-body simulations).

Direct and indirect detection of DM:
There have been many (false?) alarms during the last decade. Many of these phenomena would need contrived (non-WIMP) models for a dark matter explanation.

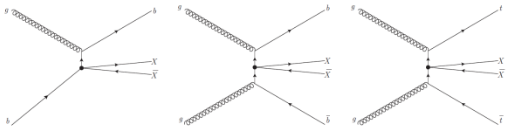
Indication	**Status**
DAMA annual modulation	Unexplained at the moment – in tension with other experiments
CoGeNT and CRESST excess events	Tension with other experiments (CDMS-II, XENON100)
EGRET excess of GeV photons	Due to instrument error (?) - not confirmed by Fermi-LAT collaboration
INTEGRAL 511 keV γ-line from galactic centre	Does not seem to have spherical symmetry - shows an asymmetry following the disk (?)
2009: PAMELA: Anomalous ratio e^+/e^-	May be due to DM, or pulsars - energy signature not unique for DM
Fermi-LAT positrons + electrons	May be due to DM, or pulsars - energy signature not unique for DM
Fermi-LAT γ-ray continuum excess around a few GeV, towards g.c.	Unexplained at the moment – very messy astrophysics
2012: Fermi 130 GeV line (T. Bringmann & al.; C.Weniger ; M. Su & D.Finkbeiner; A.Hektor & al.)	$3.1\sigma – 4.6\sigma$ effect, using public data, unexplained, not confirmed by Fermi-LAT
2013, April 3: AMS-02 (S.T.T. Ting & al.) Rising positron ratio confirmed – maybe DM?	May be due to DM, or pulsars - energy signature not unique for DM
2013, April 15: CDMS Si data: 3 events, best fit DM mass is 8.6 GeV	CDMS had 2 events a few years ago, turned out to be background. "… we do not believe this result rises to the level of discovery."

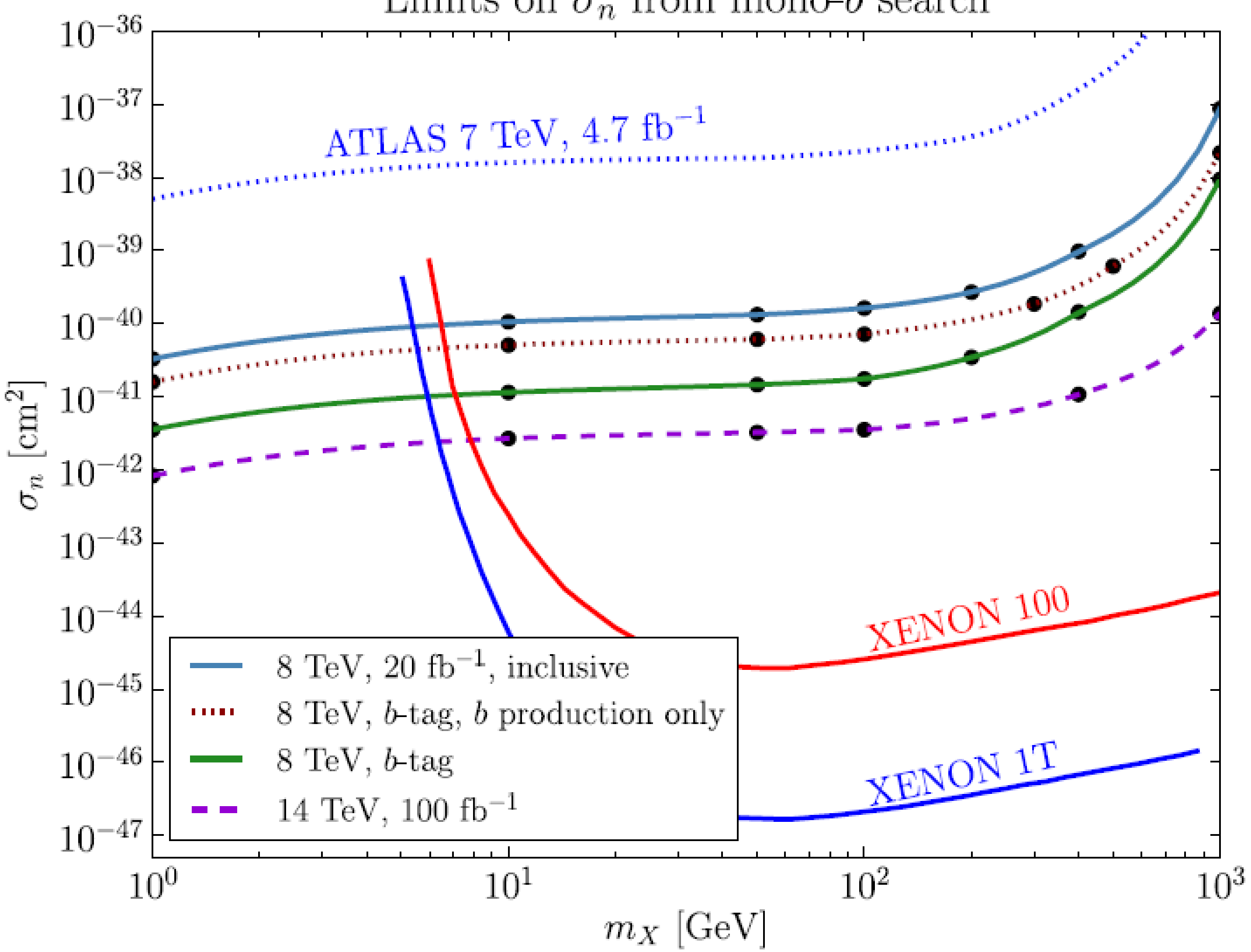
Direct detection limits, Xenon100 data, 2012:

CoGeNT and DAMA seem well excluded…



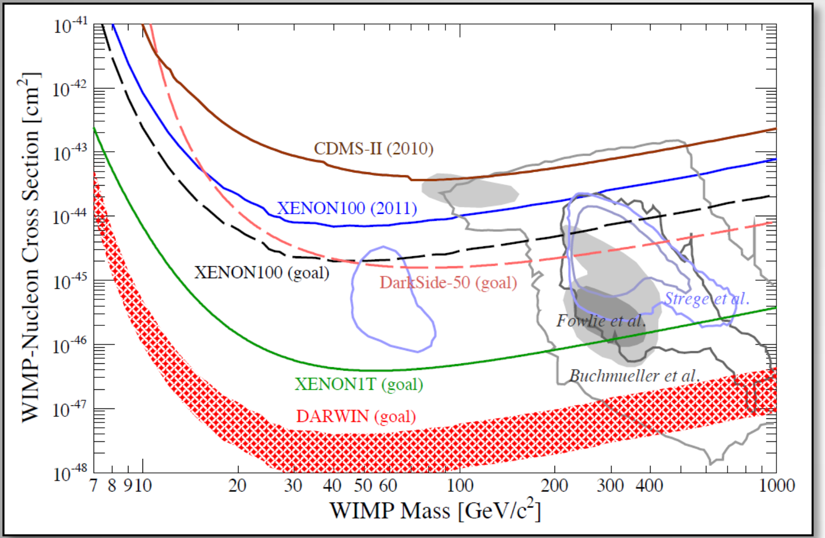
LHC limits may be complementary at low masses:



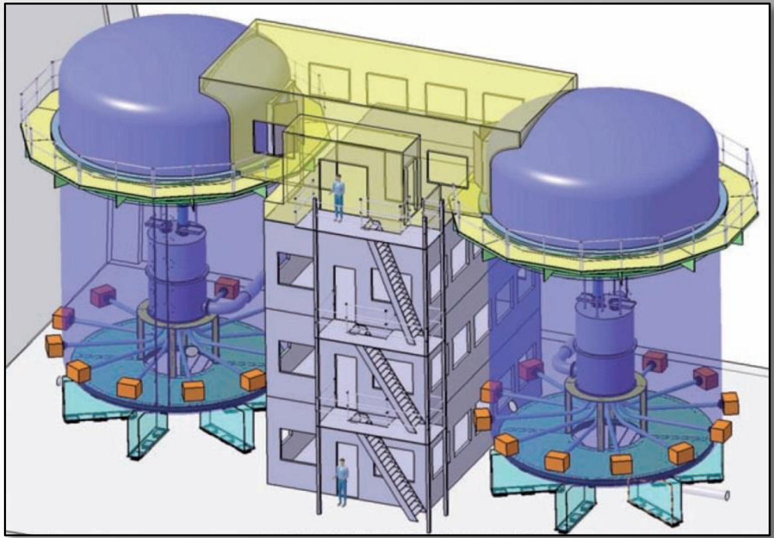


T. Lin, E.W. Kolb & L.-T. Wang, 1303.6638

Direct detection, future:

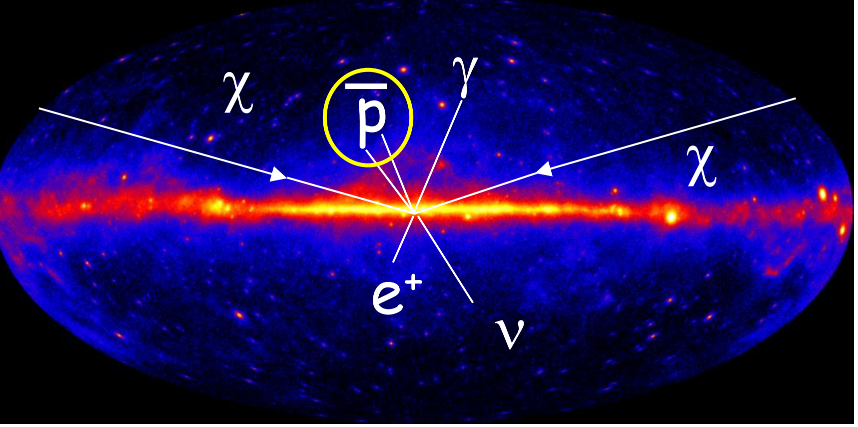


Darwin Collaboration, L. Baudis & al., 2012



EURECA Collaboration, G. Gerbier & al., 2012

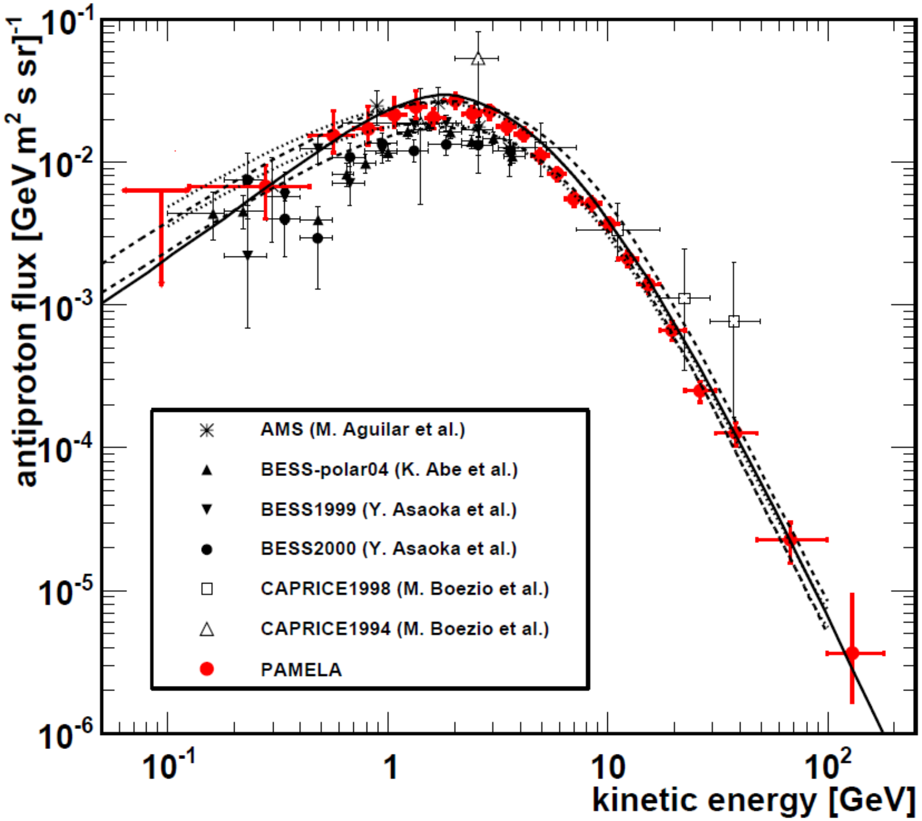
The improvement in sensitivity over the last ~ 15 years has been spectacular (factor of ~ 10 000), and future looks equally promising.

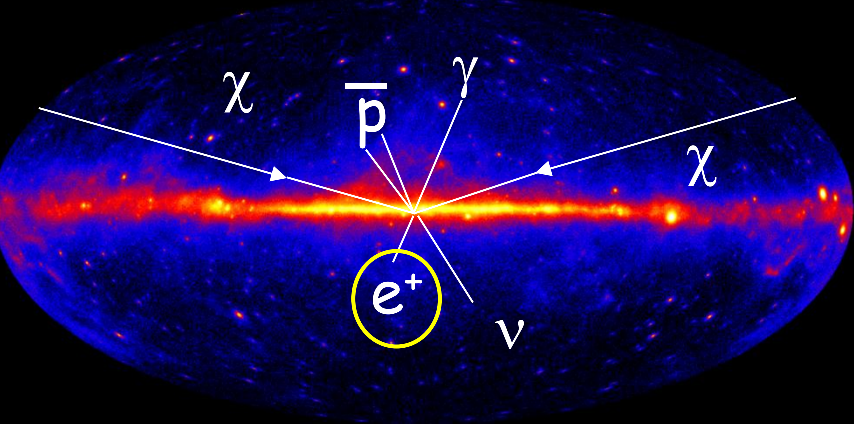


Antiprotons

Antiprotons at low energy can not be produced in pp collisions in the galaxy, so that may be DM signal?

However, p-He reactions and energy losses due to scattering of antiprotons ⇒ low-energy gap is filled in. BESS, AMS, CAPRICE and PAMELA data are compatible with conventional production by cosmic rays. Antideuterons may be a better signal – but rare. (Donato, Fornengo & Salati, 2000; R. Ong & al., GAPS, 2013)





Positrons

The Astrophysical part for positrons has some uncertainty (faster energy loss than antiprotons): Diffusion equation (see, e.g., Baltz and Edsjö, 1999; T. Delahaye & al., 2010):

$$\frac{\partial}{\partial t} f_{e^+}(E,\vec{r}) = K(E)\nabla^2 f_{e^+}(E,\vec{r}) + \frac{\partial}{\partial E}\left[b(E) f_{e^+}(E,\vec{r})\right] + Q(E,\vec{r})$$

Energy-dependent diffusion coefficient

Energy loss (mostly synchrotron and Inverse Compton)

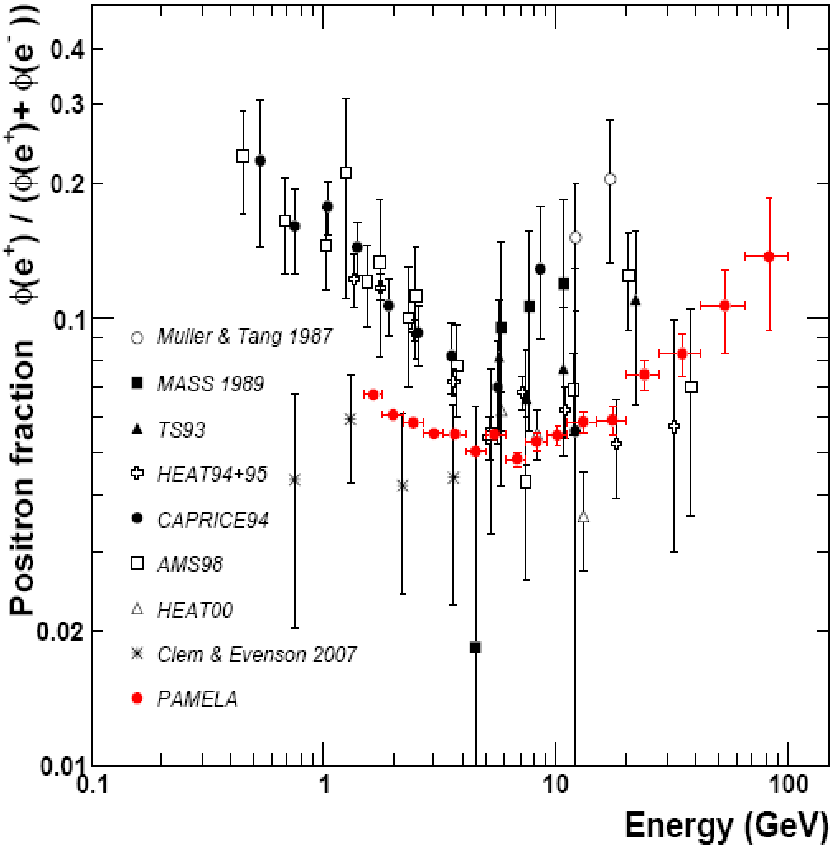
Source term (from darm matter annihilation or e.g. pulsars)

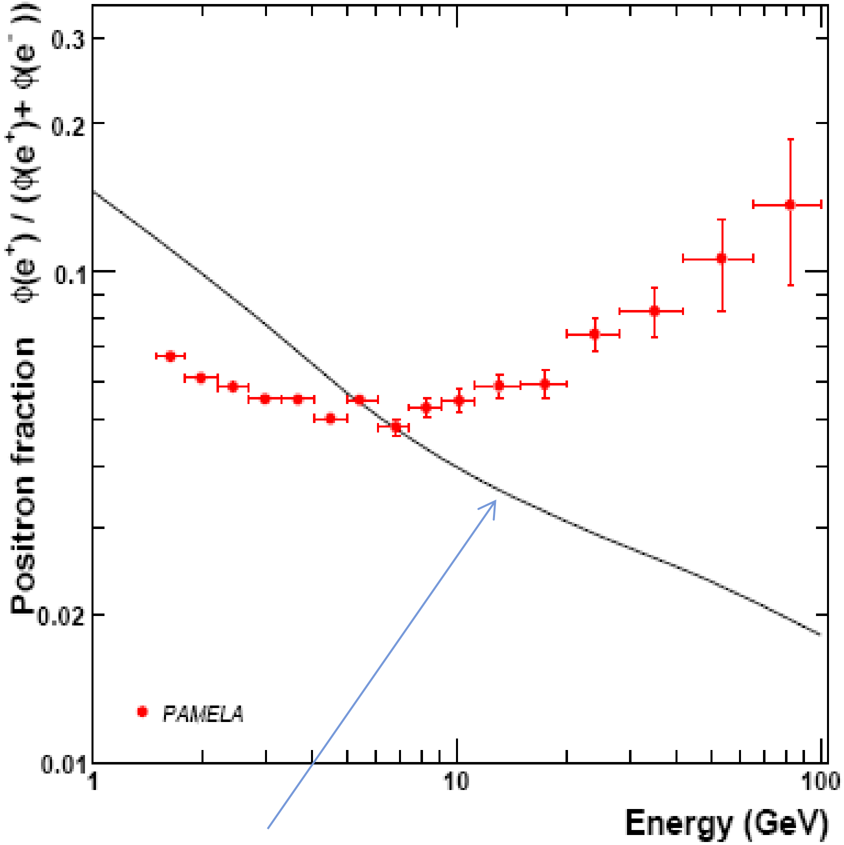
$$\begin{aligned} b(E) &= 10^{-16}(E/1\ \mathrm{GeV})^2 \quad (\mathrm{GeV s^{-1}}) \\ K(E) &= 3.3\times 10^{27}\left[3^{0.6} + (E/1\ \mathrm{GeV})^{0.6}\right] \quad (\mathrm{cm^2 s^{-1}}) \end{aligned}$$

Can be calibrated by fitting light element ratios in cosmic rays.

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

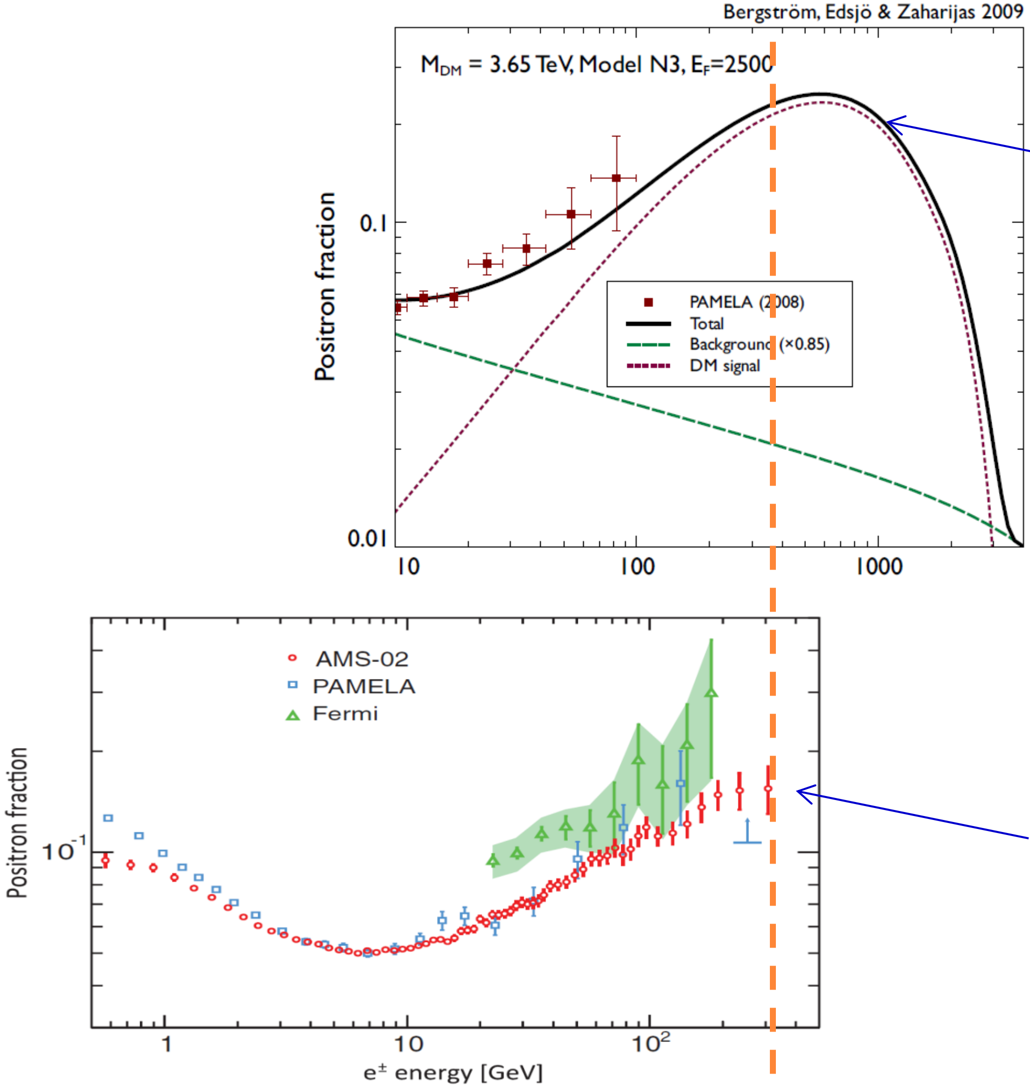
A very important result. An additional, primary source of positrons seems to be needed.





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

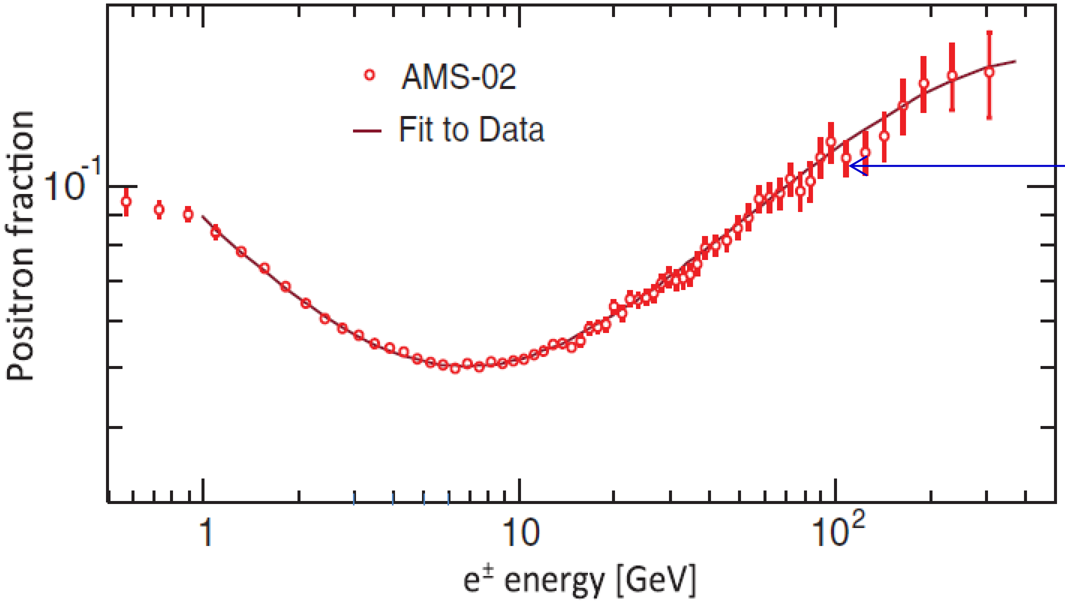
L.B., J. Edsjö, G. Zaharijas, 2009:



Prediction:
fall-off after rise
(Note very large
mass, $M_{DM} = 3.65$ TeV,
and ”boost factor”,
$E_f = 2500$, needed.)

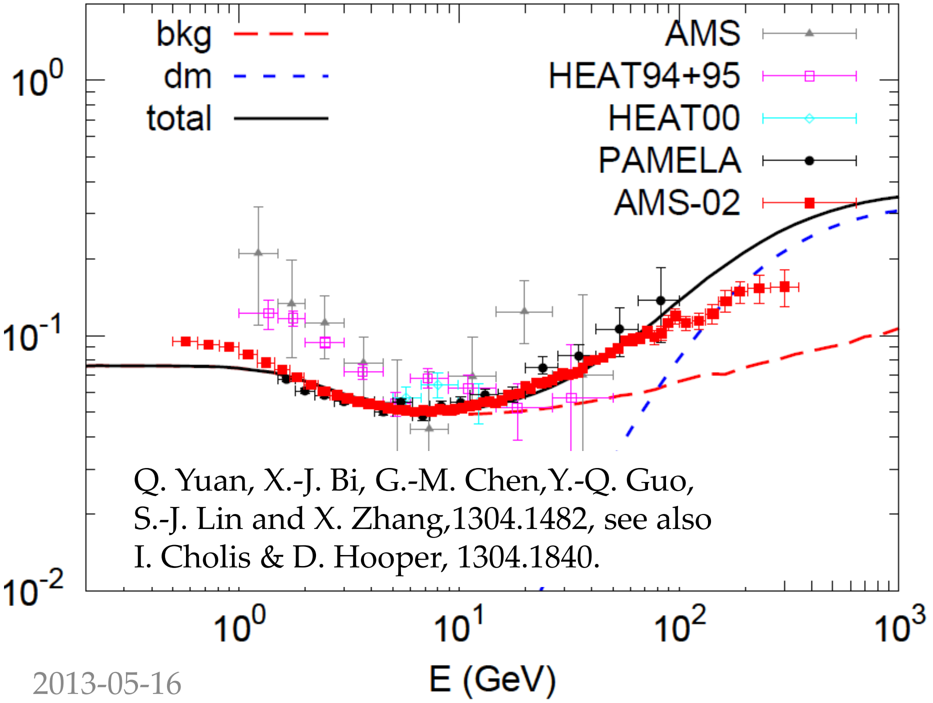
Indications of a
fall-off?

New AMS-02 data, April, 2013

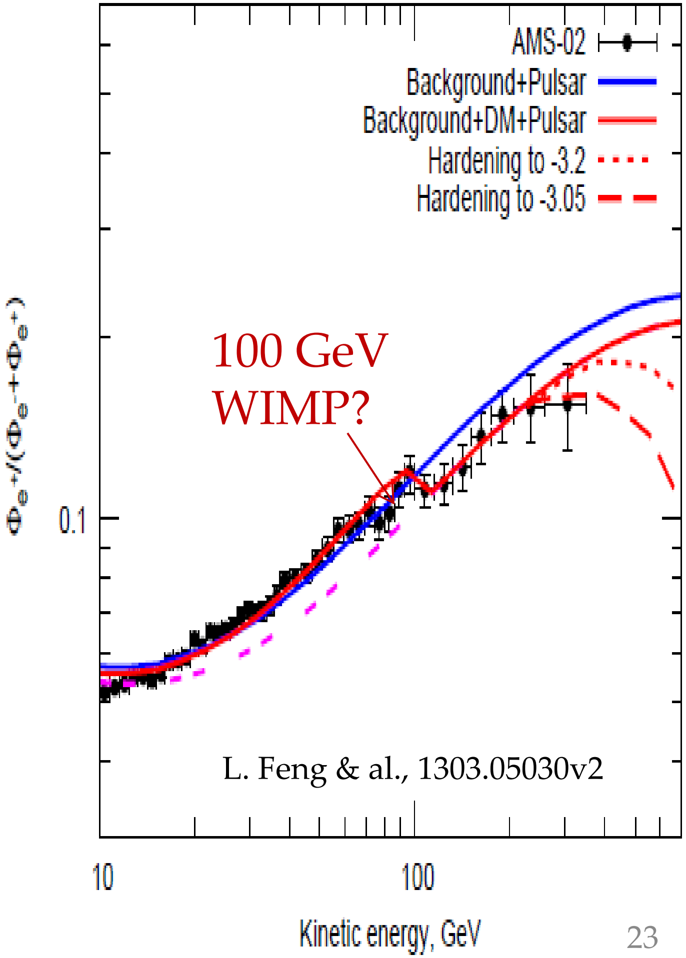


Is there a step here?

AMS-02 will give data for 18 more years…

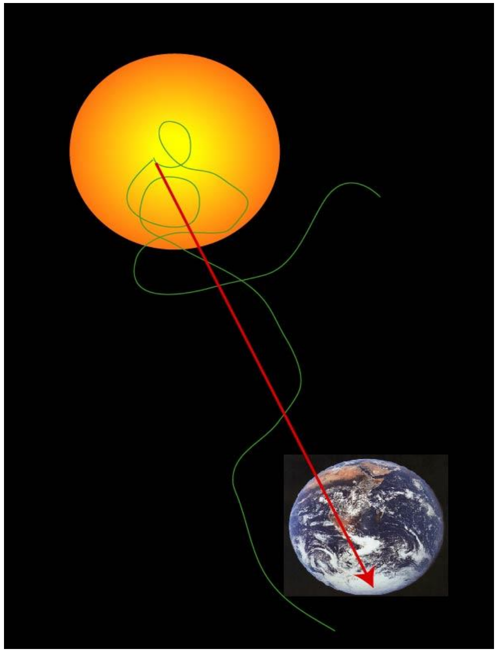


Q. Yuan, X.-J. Bi, G.-M. Chen,Y.-Q. Guo,
S.-J. Lin and X. Zhang,1304.1482, see also
I. Cholis & D. Hooper, 1304.1840.



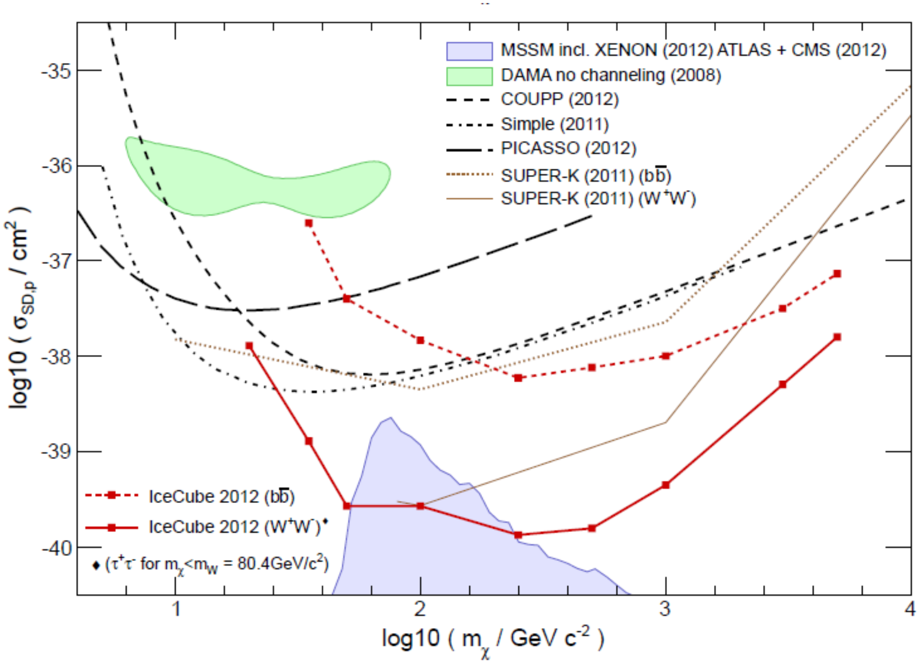
100 GeV
WIMP?

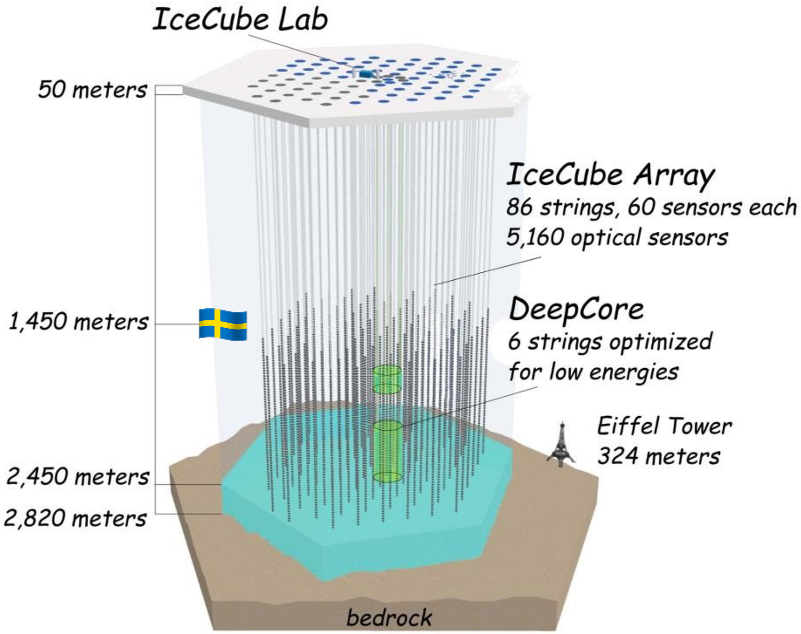
L. Feng & al., 1303.05030v2



Indirect detection by neutrinos from annihilation in the Sun:

Competitive, due to high proton content of the Sun ⇒ sensitive to spin-dependent interactions. With IceCube-79 and DeepCore-6 operational now, a large new region will be probed.
(Neutrinos from the Earth: Not competitive with spin-independent direct detection searches due to spin-0 elements only in the Earth).





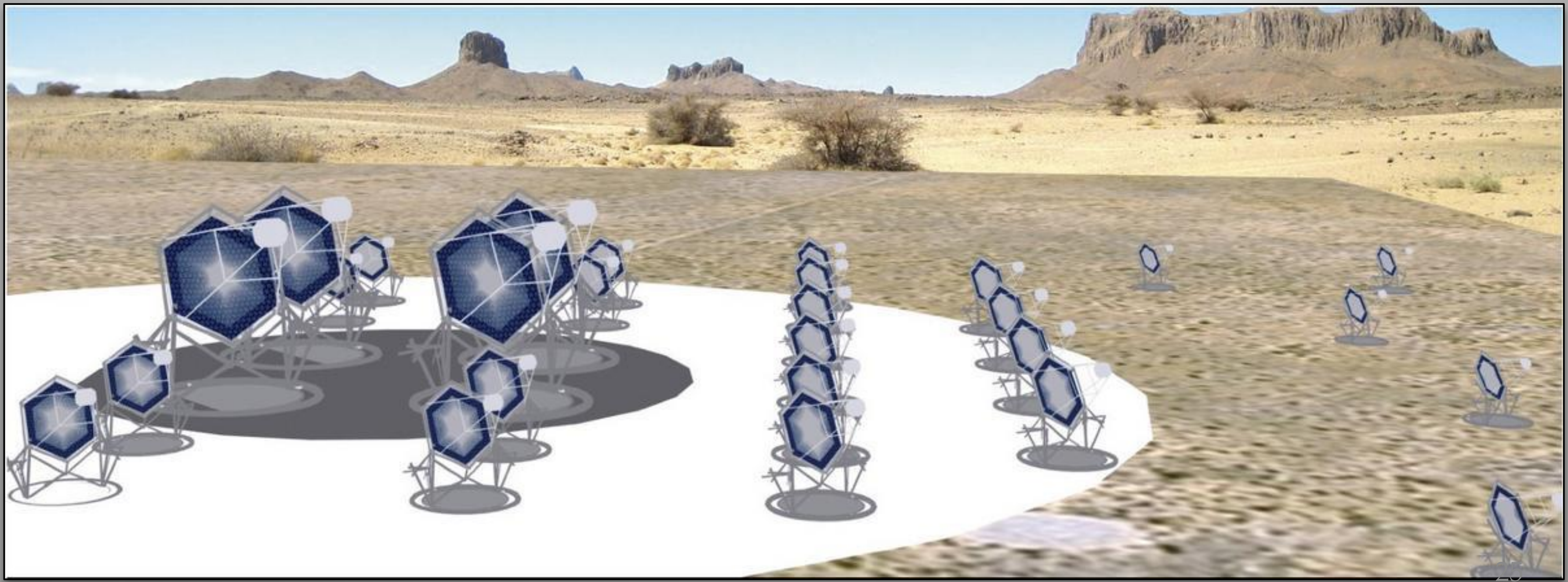
IceCube Collaboration, Phys.Rev.Lett. 110 (2013) 131302

Indirect detection through γ-rays from DM annihilation

Fermi-LAT (Fermi Large Area Telescope)

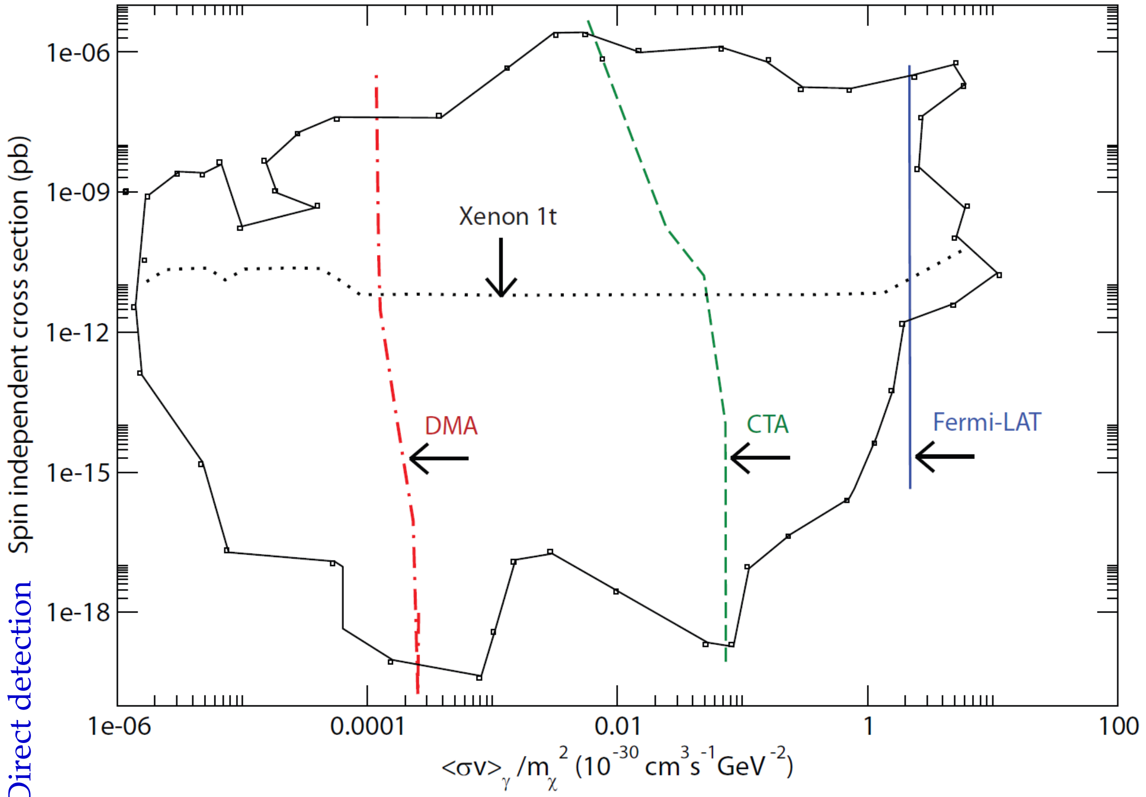
H.E.S.S. & H.E.S.S.-2

VERITAS



CTA (Cherenkov Telescope Array)

Complementarity between LHC, direct & indirect detection. DM search in γ-rays may be a window for particle physics beyond the Standard Model!



Direct detection

Gamma-ray flux, indirect detection

DMA: Dark Matter Array - a hypothetical dedicated gamma-ray detector for dark matter? (T. Bringmann, L.B., J. Edsjö, 2011)

General pMSSM scan, WMAP-compatible relic density. Check if $S/(S+B)^{0.5} > 5$ in the "best" bin (and demand $S > 5$)

DMA would be a particle physics experiment, cost ~ 1 G€. Challenging hard- and software development needed.

Construction time ~ 10 years, with principle tested in 5@5-type detector at 5 km in a few years…

A ”smoking gun”? - the gamma-ray line (L.B. & H. Snellman, 1988; L.B. & P. Ullio, 1997):

Here

$$F(x)=\begin{cases}\arcsin^2\sqrt{x}\,, & x<1\,,\\ [\pi^2-\ln^2(\sqrt{x}+\sqrt{x-1})^2]/4 & \\ \qquad +i\pi\ln(\sqrt{x}+\sqrt{x-1}), & x>1\,.\end{cases} \tag{28}$$

This gives

$$\sigma(\lambda\bar{\lambda}\to\gamma\gamma)=m_\lambda^2 a_\lambda^2 \alpha^2 v_{\rm rel}^{-1}\pi^{-3} \times\Big|\sum_f \mu_f^2 a_f Q_f^2 F(1/\mu_f^2)\Big|^2 , \tag{29}$$

where the sum is over all quarks and leptons (including a factor N_C for color) and a top-quark mass of 50 GeV has been assumed (our results are quite insensitive to this).

To calculate the branching ratio for $\lambda\bar{\lambda}\to\gamma\gamma$ to $\lambda\bar{\lambda}\to c\bar{c}$ we assume a common mass $\tilde{m}$ for all squarks and

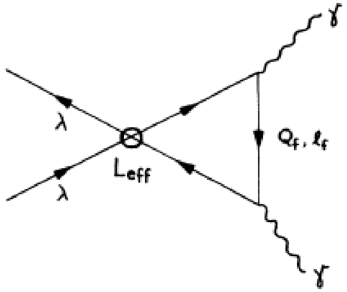
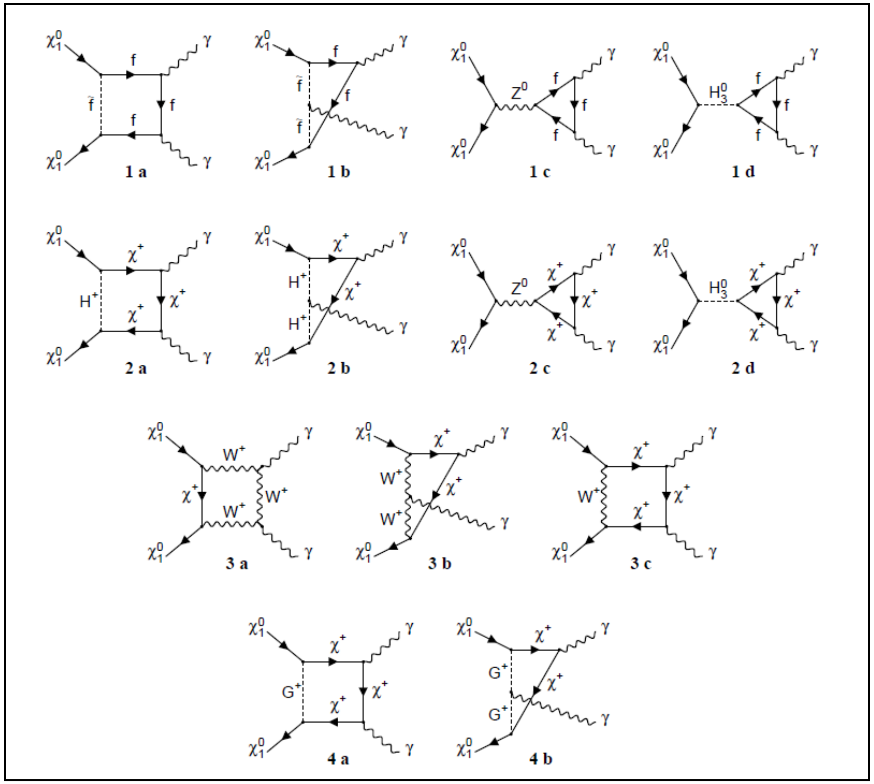


FIG. 3. Effective loop diagrams that contribute to the process $\lambda\bar{\lambda}\to\gamma\gamma$.

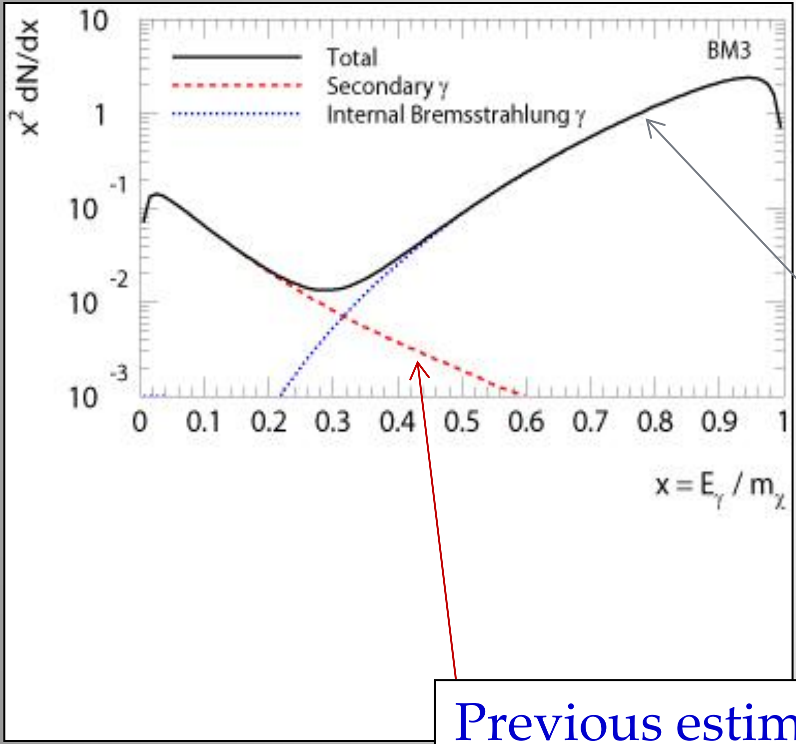


L.B. & H. Snellman, Phys. Rev. D (1988)

L.B. & P. Ullio, Nucl. Phys. B (1997)

QED corrections (Internal Bremsstrahlung) in the MSSM – a way to avoid helicity suppression in annihilation to fermions: good news for detection in gamma-rays:

T. Bringmann, L.B. & J. Edsjö, JHEP, 2008



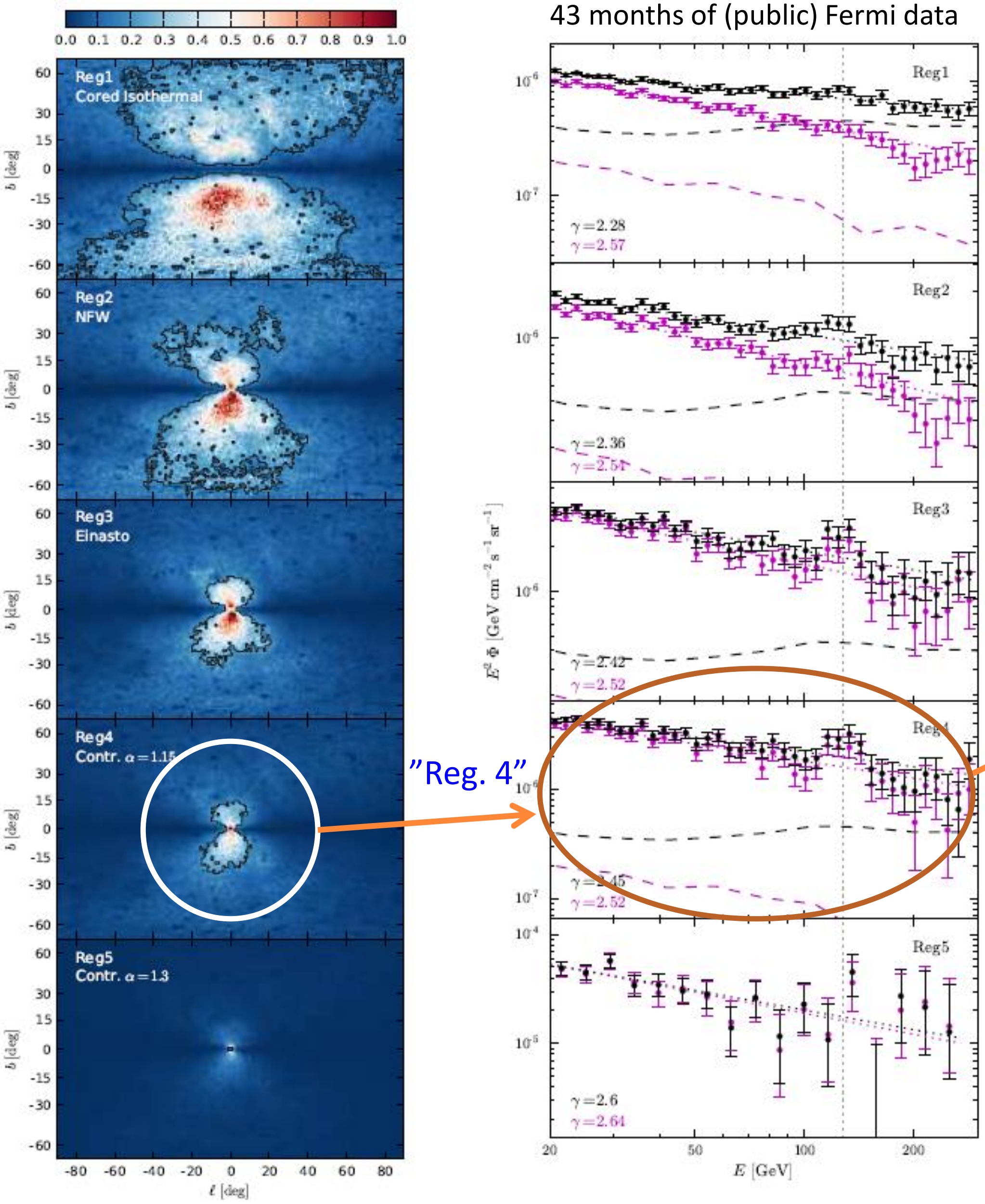
Example: DM mass = 233 GeV, has WMAP-compatible relic density (stau coannihilation region).

Calculation including Internal Bremsstrahlung (DarkSUSY 5.1).

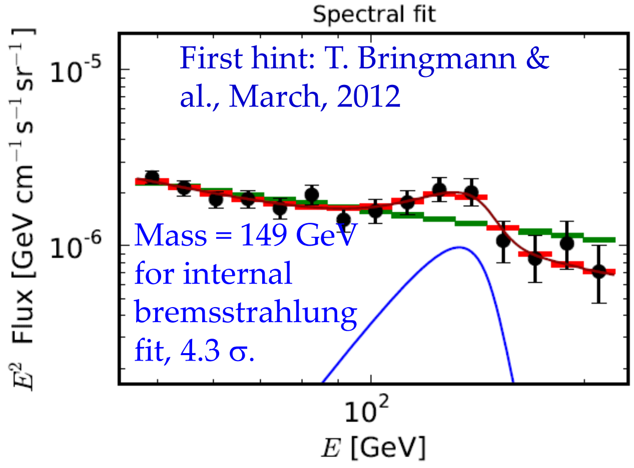
Previous estimate of gamma-ray spectrum

April, 2012: C. Weniger

43 months of (public) Fermi data

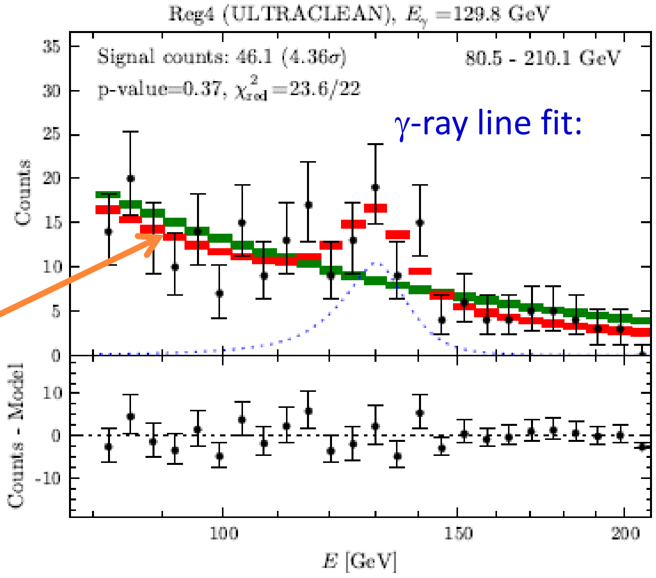


”Reg. 4”



First hint: T. Bringmann & al., March, 2012

Mass = 149 GeV for internal bremsstrahlung fit, 4.3 σ.



γ-ray line fit:

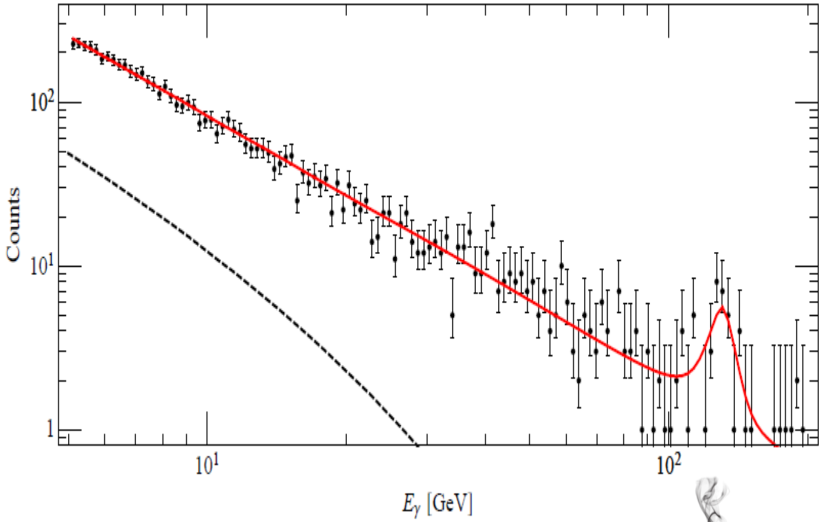
Mass = 130 GeV
Significance 4.6σ (3.3σ if ”look elsewhere” effect included)

T. Bringmann & al. arXiv:1203.1312; M. Buckley and D. Hooper, 1205.6811; W. Buchmuller & M. Garny, 1206.7056; T. Cohen, M. Lisanti, T. Slatyer & J. Wacker, 1207.0800; I. Cholis, M. Tavakoli & P. Ullio, 1207.1468:

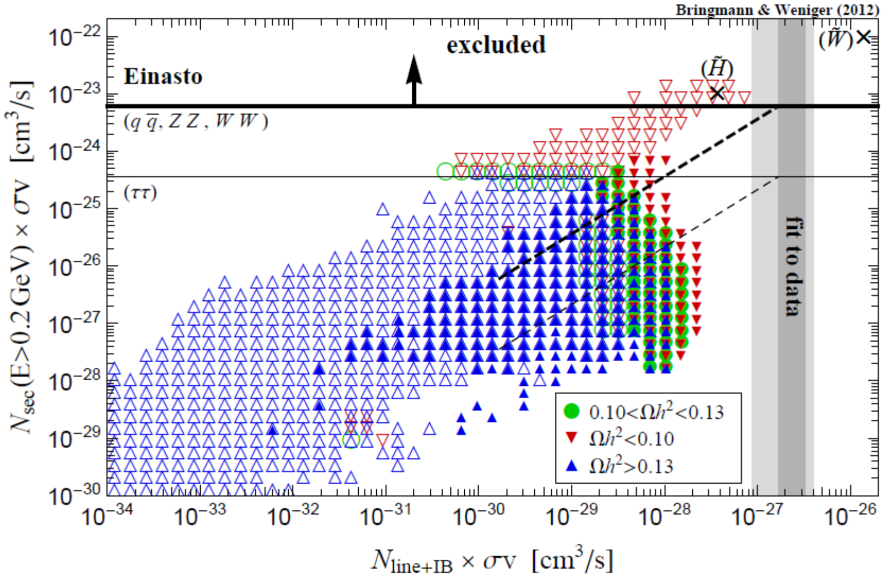
Very little room for a continuum contribution → many SUSY models ruled out.

T. Bringmann & C. Weniger (arXiv:1208.5481): There are still viable MSSM models, but cross section seems ~ factor of 10 too small (but see later).

T. Cohen, M. Lisanti, T. Slatyer & J. Wacker, June 2012



Smoking gun



There have been some 60-70 ”postdictions” of this gamma-ray signature (2012-13). Was anything like this predicted? Yes, example: A leptonic WIMP – a ”LIMP”.

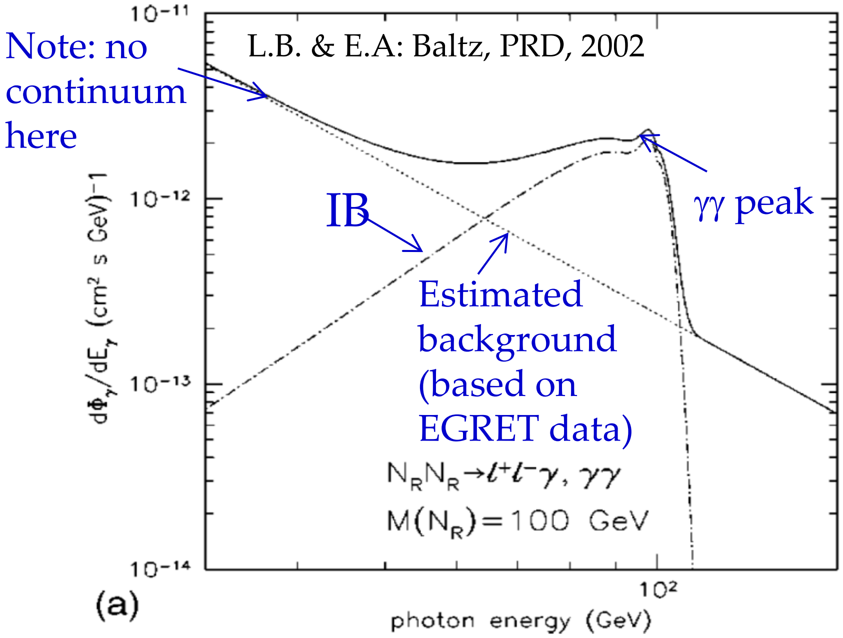
E.A. Baltz & L.B., Phys Rev D, 2002. Well motivated candidate from particle physics: The right-handed neutrino N_R (in ”radiative see-saw” models) as the dark matter candidate – May explain observed ~ 0.1 eV neutrino masses, also muon g-2 anomaly & baryon asymmetry of universe. Internal bremsstrahlung plus γγ and Zγ annihilation will give a peculiar spectrum:

$$\sigma v\left(N_R N_R \rightarrow \ell^+\ell^-\right) = \frac{g_\ell^4}{8\pi m_N^4 (1+f^2)^2}\left[m_\ell^2 + \underbrace{\frac{2}{3}\left(\frac{1+f^4}{(1+f^2)^2}\right) m_N^2 v^2}_{} + \ldots\right]$$

$$f = m_S/m_N$$

S wave part determines the lowest order cross section today

P wave part sets relic WIMP density in early universe

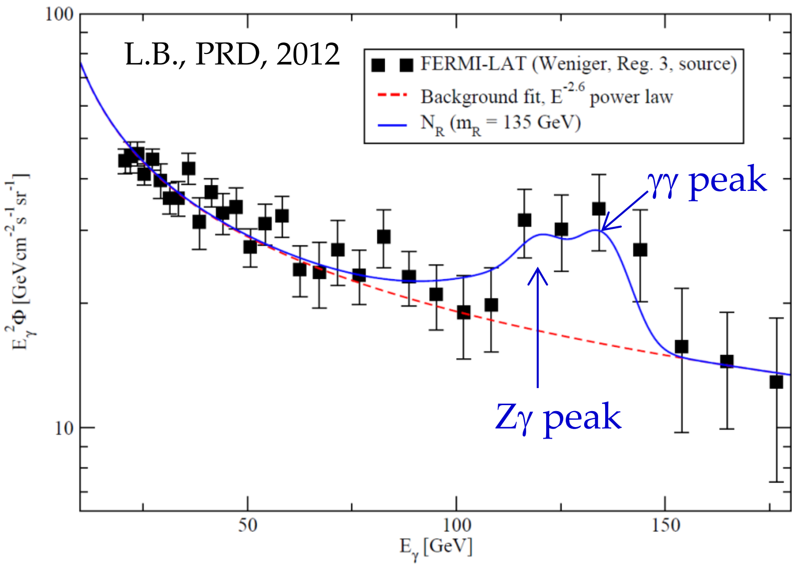

L.B. & E.A: Baltz, PRD, 2002

Note: no continuum here

IB

γγ peak

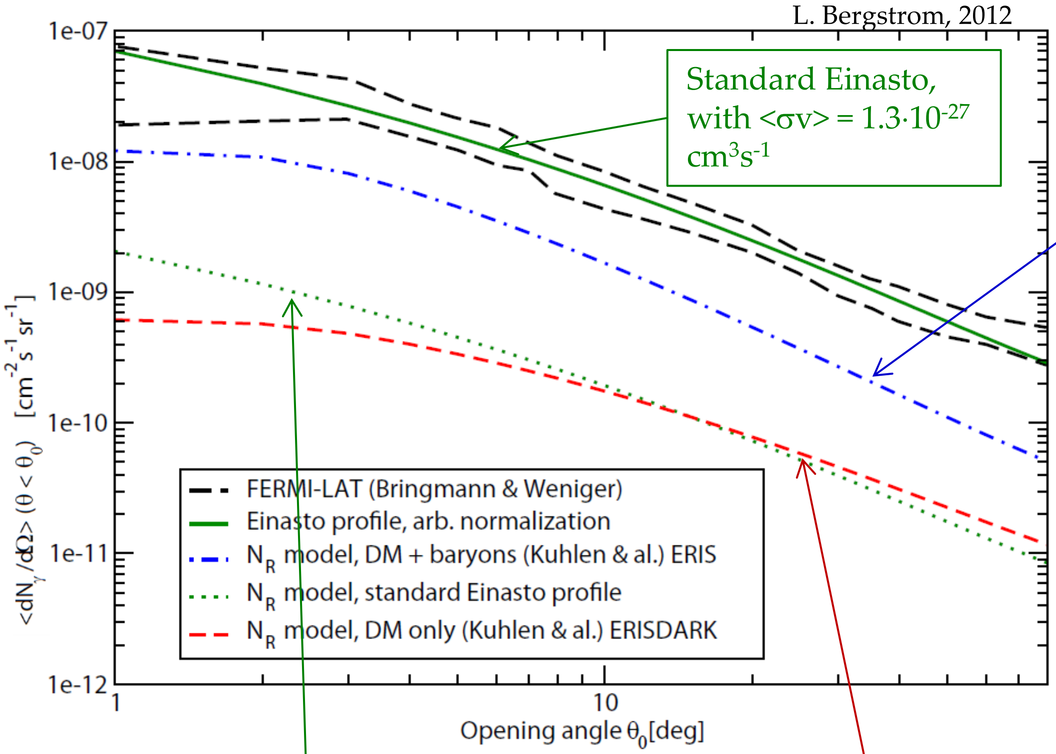
Estimated background (based on EGRET data)


L.B., PRD, 2012

γγ peak

Zγ peak

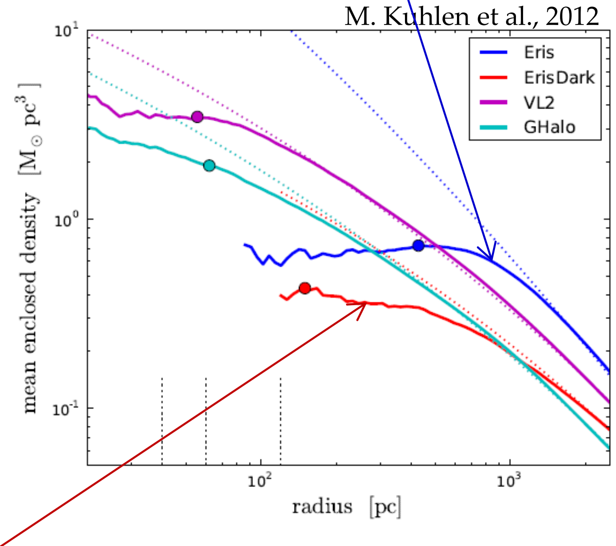
DM simulations including baryons (M. Kuhlen & al., 2012). Gives factor 6-8 enhancement of rate:



L. Bergstrom, 2012

Standard Einasto, with $\langle\sigma v\rangle = 1.3\cdot10^{-27}$ cm^3s^{-1}

N_R prediction, $\langle\sigma v\rangle = 1.0\cdot10^{-28}$ cm^3s^{-1}, using ERIS DM (M. Kuhlen & al,) plus baryons halo distribution



M. Kuhlen et al., 2012

N_R prediction, $\langle\sigma v\rangle = 1.0\cdot10^{-28}$ cm^3s^{-1} using standard Einasto DM only halo

ERISDARK, DM only halo distribution

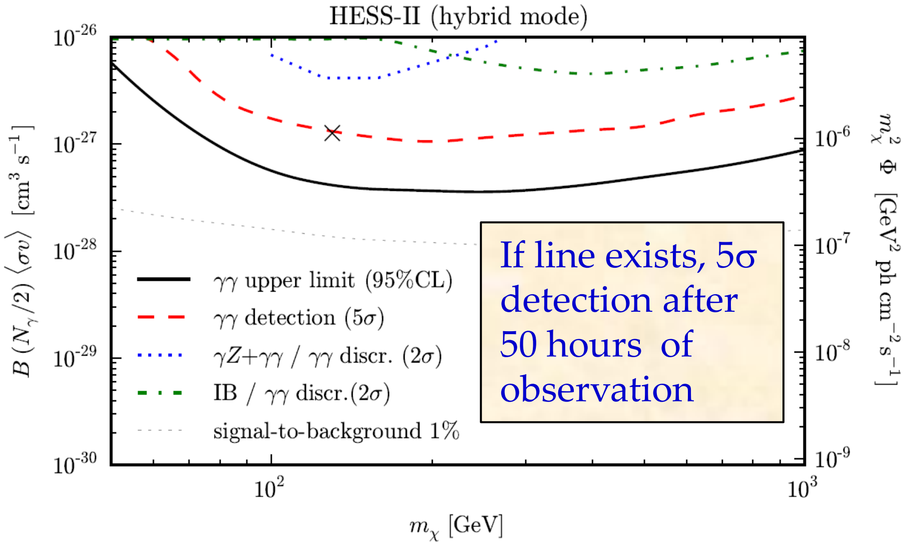
Only factor 2-3 missing ⇒ Rate problem essentially solved!
However, maybe more unconventional models of DM distribution needed, e.g., "Double Dísk DM" (J.J. Fan, A. Katz, L. Randall & M. Reese, 2013)

A new player in the game: HESS-II in Namibia

28 m segmented –mirror telescope,
300 mirror segments out of 875 funded by Sweden (Jan Conrad & L.B.)

Saw first light in August, 2012

Ideal viewing conditions for galactic centre April – August 2013



If line exists, 5σ detection after 50 hours of observation

L.B., G. Bertone, Jan Conrad, C. Farnier & C. Weniger, 1207.6773 (JCAP 2012):

E. Bloom et al., arxiv:1303.2733

Search of the Earth Limb Fermi Data and Non-Galactic Center Region Fermi Data for Signs of Narrow Lines

E. Bloom, E. Charles, E. Izaguirre, A. Snyder
KIPAC-SLAC, Stanford University, 2572 Sand Hill Road, Menlo Park, CA, 94025 USA
A. Albert, B. Winer, Z. Yang
The Ohio State University, 1739 N High St, Columbus, OH 43210 USA
R. Essig
Stony Brook University, Stony Brook, NY 11794 USA
On Behalf of the Fermi-LAT Collaboration

3.1. Significant feature at 135 GeV

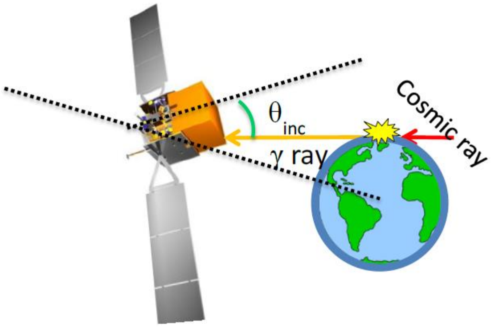
There is a significant feature at 135 GeV in gamma rays from the Earth's limb.

- Feature appears somewhat narrower than the LAT resolution PDF.
- A *LAT_θ* < 60° cut and fitting different energy windows produces different significances for the feature.

Other control region: the "inverse region of interest":

- No feature at 135 GeV is evident.
- Given the Earth limb data results, the lack of a 135 GeV feature in the Inverse ROI is currently a bit mysterious.
  - At face value does not support a common systematic that makes a feature at 135 GeV in the gamma-ray data.

"Earth limb":



3.4. No consistent interpretation of the GC 135 GeV feature

The LAT Collaboration does not have a consistent interpretation of the GC 135 GeV feature originating from a systematic error at this time.

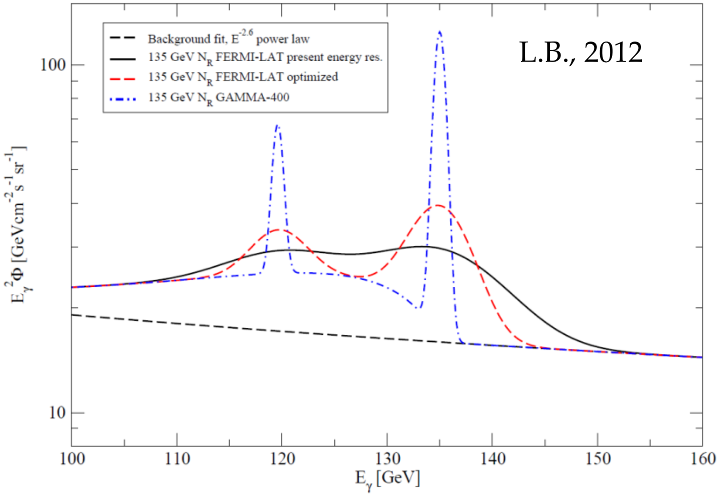
The future for gamma-ray space telescopes?

GAMMA-400, 100 MeV – 3 TeV, an approved Russian γ-ray satellite. Planned launch 2017-18.
Energy resolution (100 GeV) ~ 1 %. Effective area ~ 0.4 m^2 . Angular resolution (100 GeV) ~ 0.01°

DAMPE: Satellite of similar performance. An approved Chinese γ-ray satellite. Planned launch 2015-16.

HERD: Instrument on Chinese Space Station. Energy resolution (100 GeV) ~ 1 %. Effective area ~ 1 m^2. 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! If the 130 - 135 GeV structure exists, it should be seen with more than 10σ significance (L.B., G. Bertone, J. Conrad, C. Farnier & C. Weniger, JCAP 2012). Otherwise, the parameter space of viable models will be probed with unprecedented precision.

Open Questions:

1. How will we know if dark energy is different from a cosmological constant?
2. How much effort (and money) should we spend on finding WIMPs?
3. Will the Fermi 130 GeV line survive HESS-II?

So what is the line?	Pro	Con	How test?
1. A gamma-ray structure from dark matter annihilation	”Smoking gun” energy distribution - cannot be mimicked by anything known in astrophysics. Angular distribution agrees with Einasto profile from cosmological DM simulations. Same, but weaker, signal seen from galaxy clusters.	One or more ”hotspots” offset from exact g.c. No continuum at lower energies. Rate seems on the large side, by factor of 3 - 10 .	More data. For Fermi, change observation strategy to optimize viewing of g.c. Use other detectors (HESS-II) and/or other targets (clusters, dwarf galaxies, halo with galactic centre excluded,…).
2. A systematic error of Fermi-LAT (remember the fate of the EGRET ”bump”)	A 130 GeV excess is seen also in ”earth limb” data – which is unrelated to DM.	Seems difficult to connect an anomaly in the limb to the 130 GeV excess towards the g.c.	Dedicated runs viewing the earth limb. Check other angular regions on the sky. Improve data quality (”Pass 8”).
3. A rare statistical fluctuation	Only some 40 – 60 events in the signal. Background is not well studied above 100 GeV.	More than 3 sigma fluctuations are indeed rare (unless there are underestimated systematic errors) .	More data. See 1. Use particle physicists rule to wait for 5σ until accepting effect.