Dark Matter: Models, status and propects for identification

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Fritz Zwicky, 1933: *"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."*

Coma galaxy cluster

"It is, of course, possible that luminous plus dark (cold) matter together yield a significantly higher density..." - Zwicky 1933

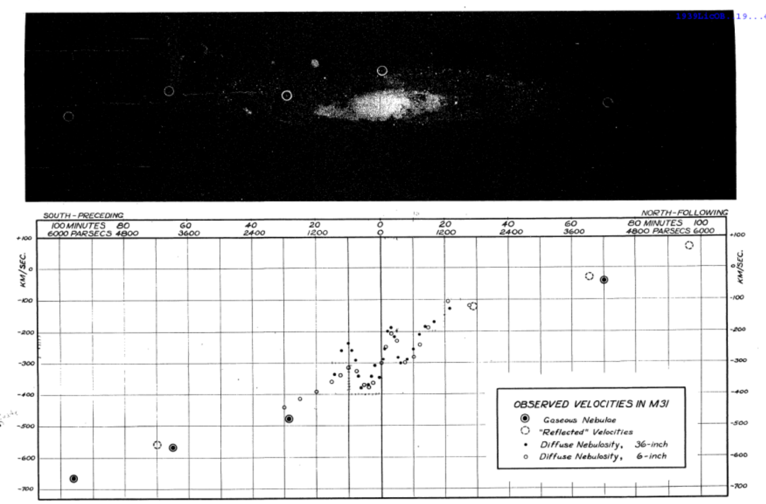
Smith (1936) confirmed Zwicky's results using Virgo cluster.

Zwicky (1937) notes that gravitational lensing may be used as a tool to estimate the total mass of galaxies.

Babcock (1939) measured rotation curve of M31 (Andromeda).

From Babcock's paper, 1939:

age mass per cubic parsec is 0.98⊙. 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

Look at a simple, spherically symmetric model of the mass density distribution $\rho(r)$ of a galaxy. The enclosed mass at radius r is:

$$M(R) \equiv M(r < R) = 4\pi \int_0^R \rho(r) r^2 dr$$

Consider a model of the galaxy which has a finite extent, $r(r) = 0$ for $r > R$. (In a real galaxy with visible matter only, R would correspond to the "optical radius".)

Then for $r > R$, $M(r) = const = M_0$, and if velocities are non-relativistic, we can use the Newtonian expression for the velocity of circular orbits

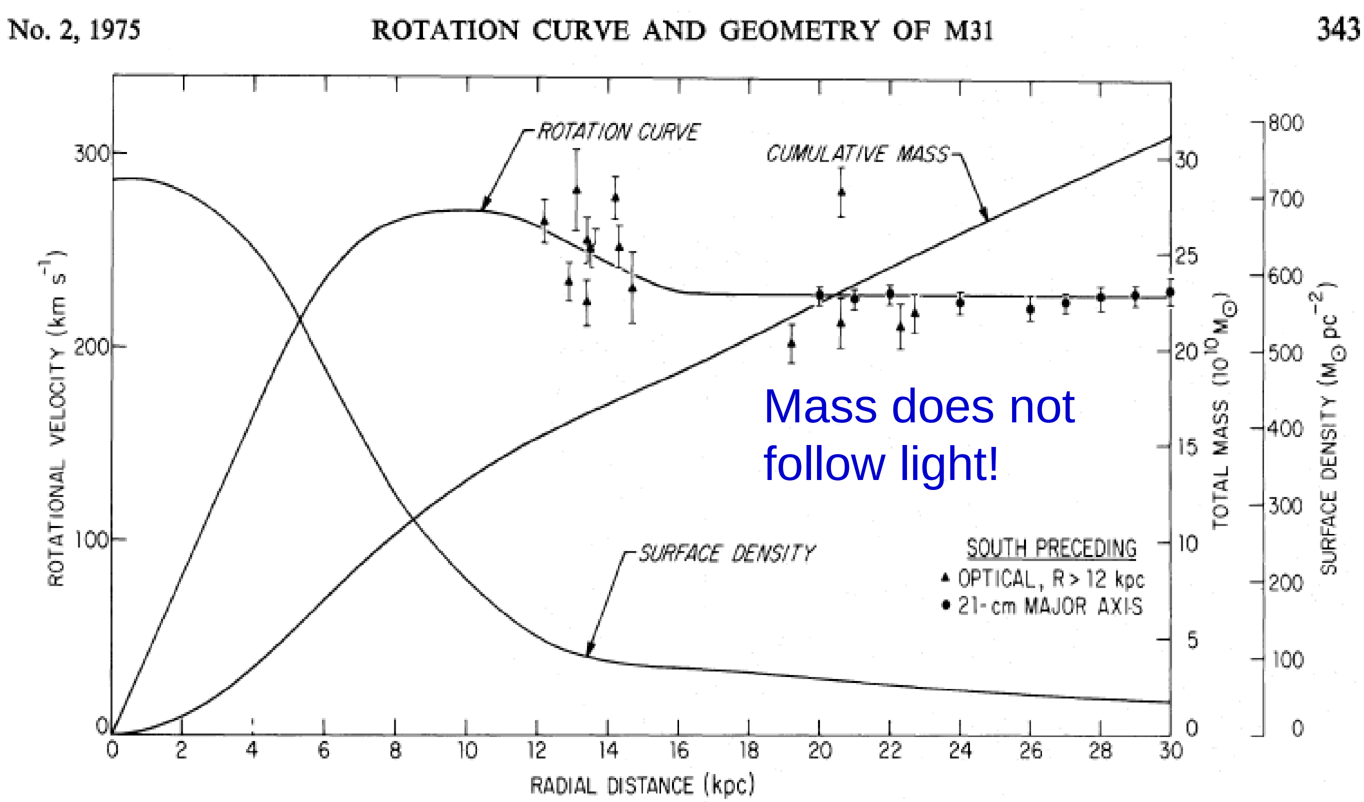
$$\frac{v^2}{r} = \frac{G_N M_0}{r^2},$$

or

$$v \sim r^{-\frac{1}{2}}$$

Thus, if the galaxy only contains visible material, the rotation curve should decrease beyond the "optical radius" R of the galaxy.

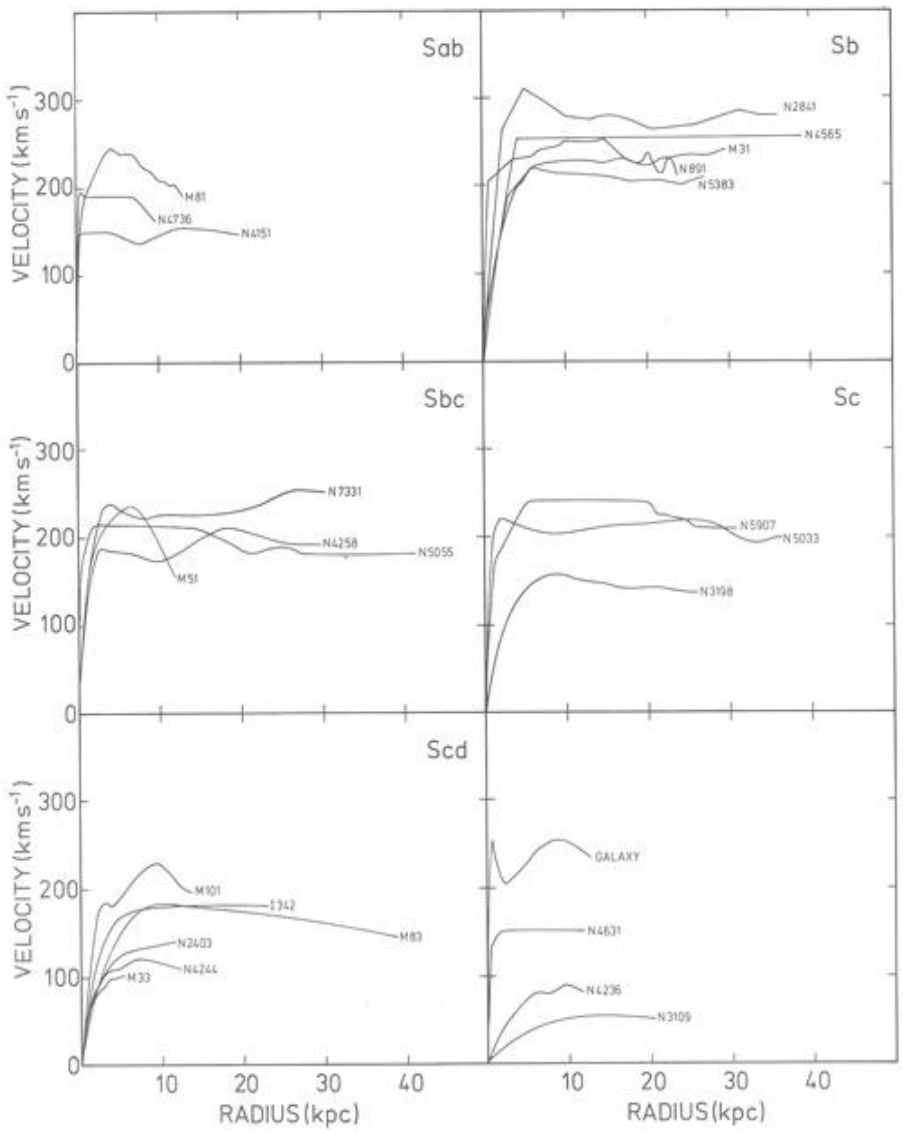
Rubin, Ford & Kent (1970), and Roberts & Whitehurst (1975) measured a flat rotation curve of M31 far outside the optical radius, in agreement with earlier 21 cm data (and with Babcock). Unseen, or “missing matter” – what is it? (Or, is Newtonian gravity failing on galactic scales? – Modified Newtonian Dynamics , MOND.)



Mass does not follow light!

Flat rotation curves are the rule:

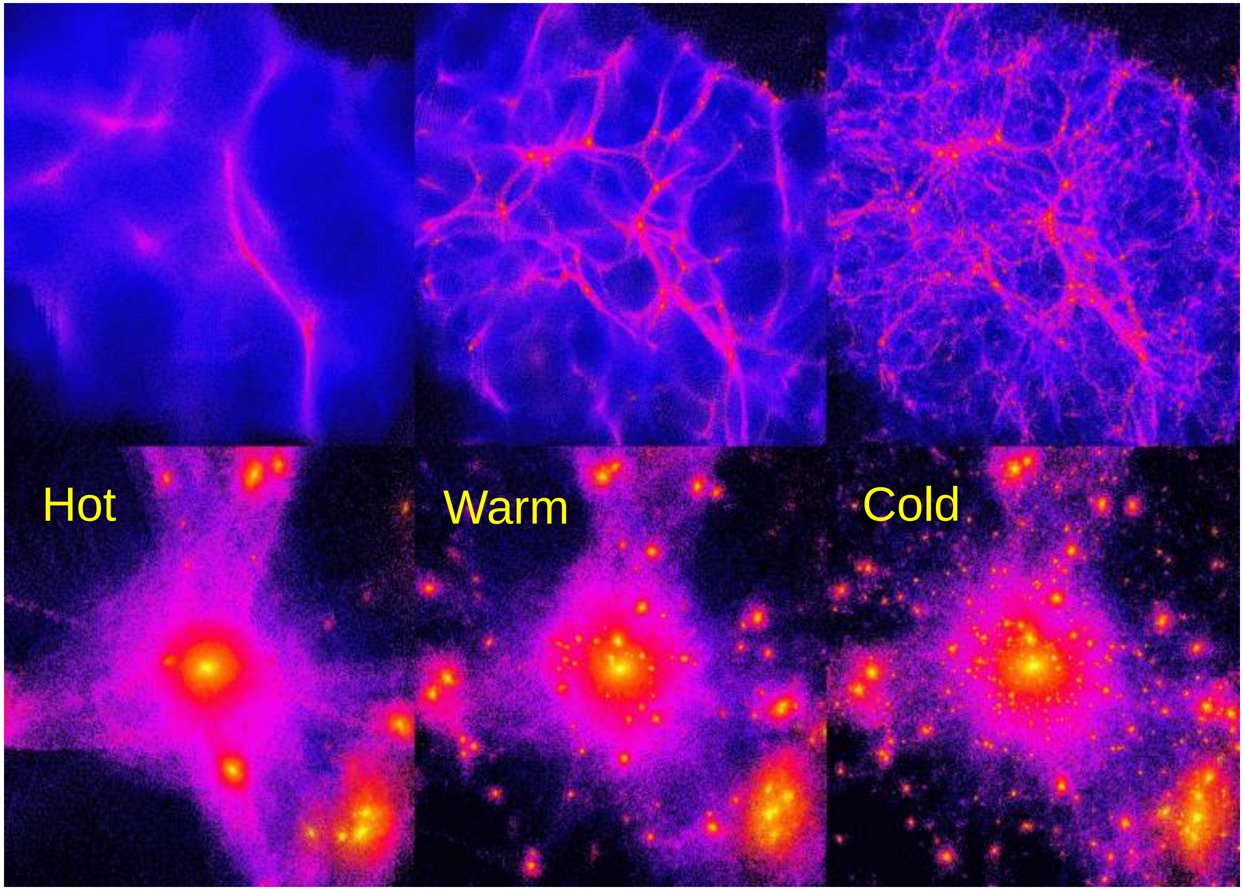
From 21 cm results in thesis of A. Bosma, 1978 (cf also Rubin, Thonnard & Ford, 1978):



Around 1982 came the Cold Dark Matter paradigm (Peebles; Bond, Szalay, Turner; Sciama): Structure formation scenarios (investigated through N-body simulations) favours hierarchical structure formation. Hot Dark Matter (like neutrinos) would first form structure at large scales (Zel'dovich "pancakes") which then fragments to smaller scales – does not agree with observations. The theoretical belief, based on inflation, was that $\Omega_M \equiv \rho_M / \rho_{crit} = 1$.

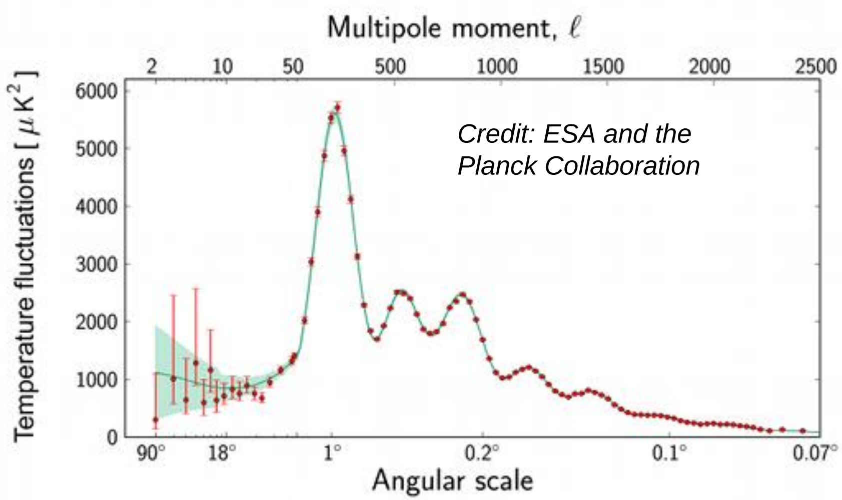
Melott et al 1983; Blumenthal, Faber, Primack & Rees 1984,…

Hot Dark Matter →

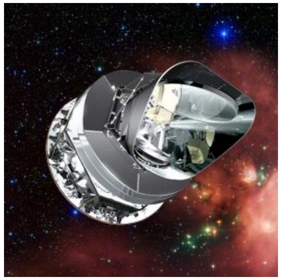


← Cold Dark Matter

B. Moore



PLANCK 2013:

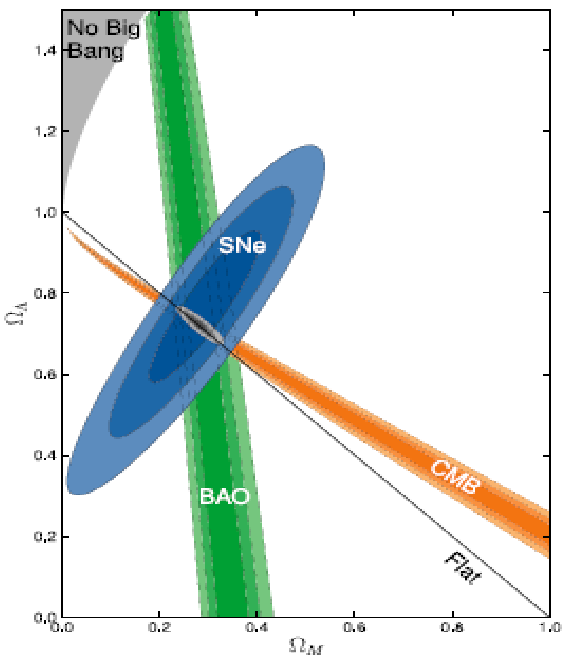


$$\Omega_{tot} \equiv \frac{\rho_{tot}}{\rho_{crit}} \approx 1.01 \pm 0.02$$

(agrees with inflation)

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

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



R. Amanullah et al. (SCP Collaboration), 2010

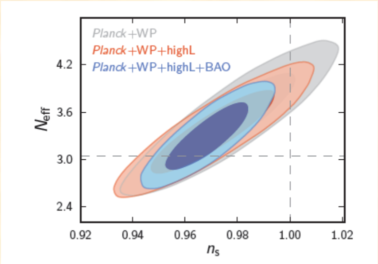
The ΛCDM Model:

Cold Dark Matter model meaning electrically neutral particles moving non-relativistically, i.e., slowly, when structure formed. In addition, the cosmological constant Λ being the dark energy, gives an accelerating expansion of the universe (cf. Nobel Prize 2011).

Planck: $N^{\nu}_{eff} = 3.3 \pm 0.5$

$\Omega_{CDM}\, h^2 = 0.12$

Seems to fit all cosmological data!



Note: "Dark Matter" was coined by Zwicky; maybe "Invisible Matter" would have been a better name…

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

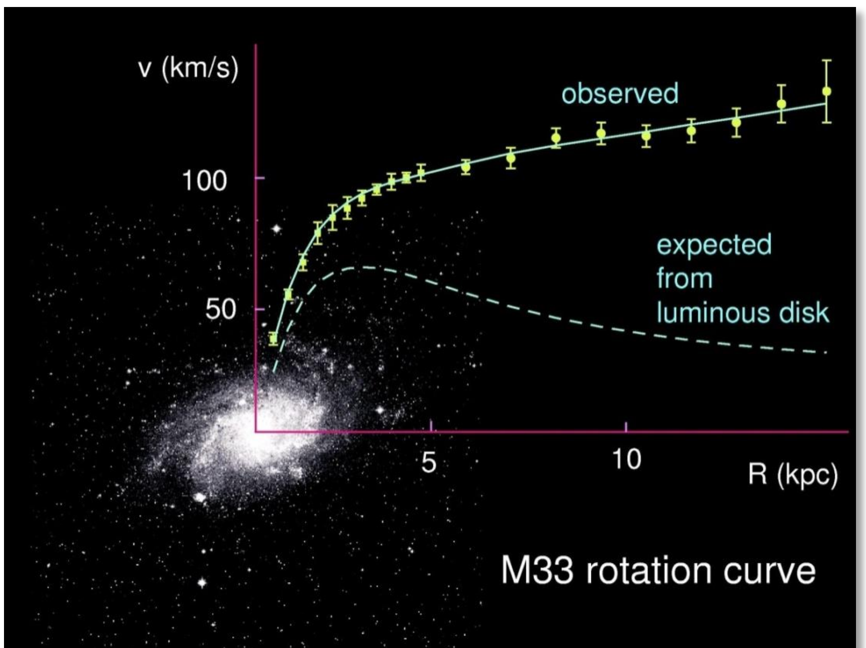
MOND:

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-\tilde{g}}\,\Big[\tilde{R} - \frac{1}{2}KF^{ab}F_{ab} + \lambda(A_aA^a+1) - \mu(\tilde{g}^{ab} - A^aA^b)\nabla_a\phi\nabla_b\phi - V(\mu)\Big]$$

where $g^{ab} = e^{2\phi}\tilde{g}^{ab} + 2\sinh(2\phi)A^aA^b\,.$

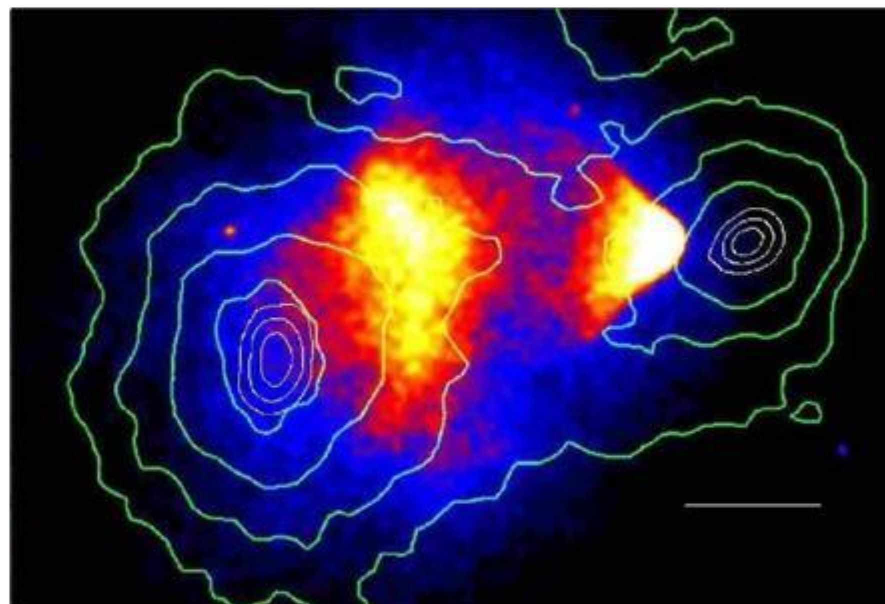
and $\frac{dV}{d\mu} = -\frac{3}{32\pi l_B^2\mu_0^2}\frac{\mu^2(\mu-2\mu_0)^2}{\mu_0-\mu}\,.$

Galaxy rotation curves



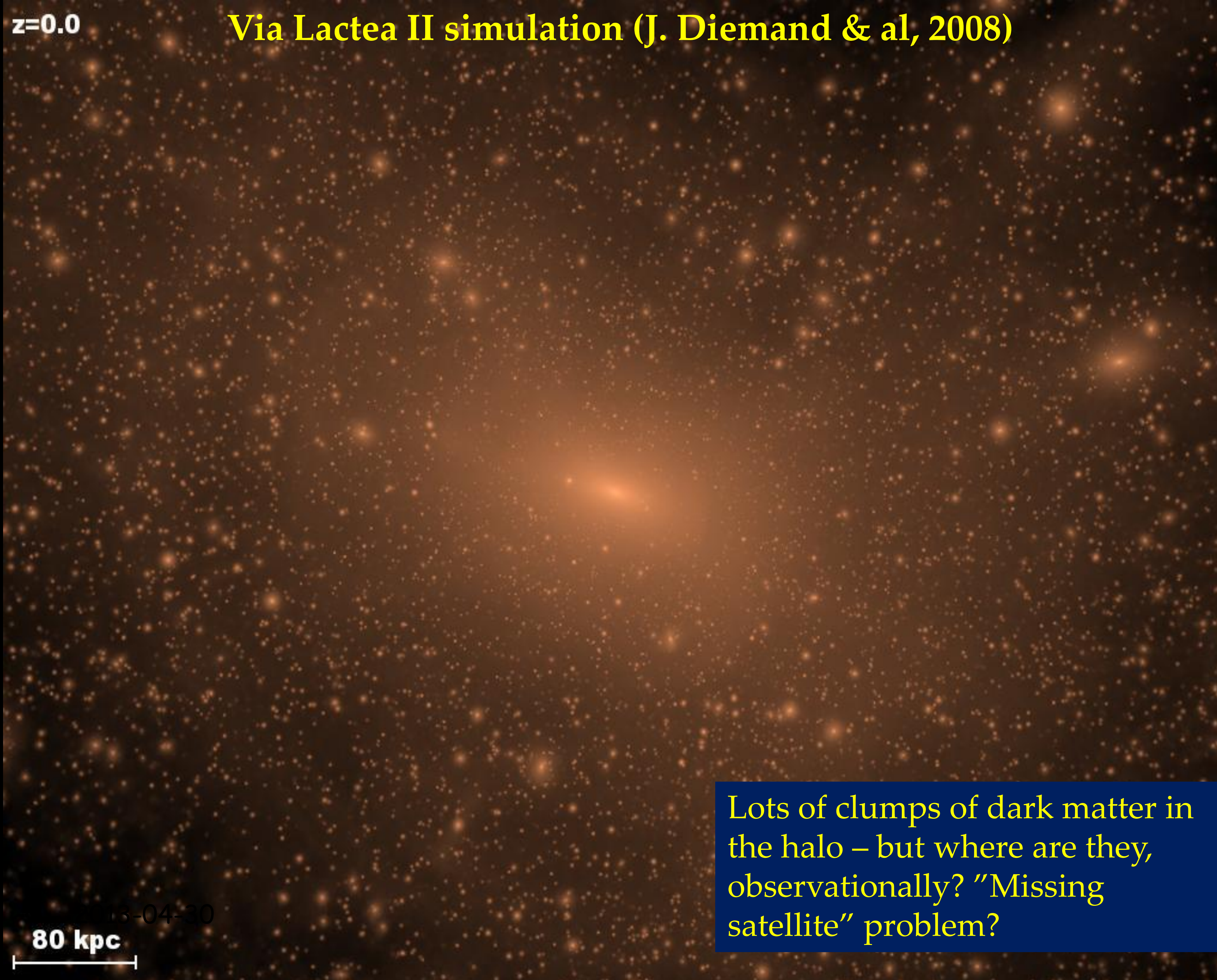
L.B., Rep. Prog. Phys. 2000

Colliding galaxy clusters



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

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



Lots of clumps of dark matter in the halo – but where are they, observationally? "Missing satellite" problem?

The situation today:

The existence of Dark Matter, especially Cold DM on cosmological scales, has been established by a host of different methods…

…but, the question remains:

What is it?

The particle physics connection: Freeze-out of Dark Matter Particles

Suppose we have a dark matter particle species χ

$$\chi + \overline{\chi} \leftrightarrow q\bar{q}, \ell\bar{\ell}, W^+W^-, X\bar{X}$$

↖ anything

Fundamental particle theory says $m_\chi = m_{\bar{\chi}}$; $\mu_\chi \approx 0$ (exact for photons and Majorana particles – these are their own antiparticles) ⇒ $n_\chi = n_{\bar{\chi}}$

Initial condition: when t → 0, T >> m_χ, interactions were extremely rapid

$$\Longrightarrow \quad n_\chi = n_\chi^{eq}(T)$$

$T >> m_\chi$:

$$n_\chi^{eq}(T) = \frac{\zeta(3)}{\pi^2} g_\chi T^3 \text{ for bosons,}$$

$$n_\chi^{eq}(T) = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_\chi T^3 \text{ for fermions}$$

$T << m_\chi :$ $$n_\chi^{eq}(T) = g_\chi \left(\frac{m_\chi T}{2\pi}\right)^{\frac{3}{2}} e^{-\frac{m_\chi}{T}}$$

$n_\chi :$ (number of particles)/(unit volume) $\Rightarrow$

$N_\chi \equiv a^3(t) n_\chi$ is number within $a^3(t)$

$$\dot{N}_\chi = \frac{d}{dt}\left(a^3(t) n_\chi\right) = -\langle \sigma_A v \rangle a^3 \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

$$\dot{n}_\chi + 3\frac{\dot{a}}{a} n_\chi = -\langle \sigma_A v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

annihilation rate

Rescale:

$$Y_\chi \equiv \frac{n_\chi}{s}; \quad x = \frac{m_\chi}{T}; \quad \Gamma_A = n_\chi^{eq} \langle \sigma_A v \rangle$$

The governing parameter is Γ_A/H

After some work, one finds

$$\frac{x}{Y_\chi^{eq}}\frac{dY_\chi}{dx} = -\frac{\Gamma_A}{H(x)}\left[\left(\frac{Y_\chi}{Y_\chi^{eq}}\right)^2 - 1\right]$$

Riccati's equation

Three cases:

(a) Relativistic particles at freeze-out (**hot dark matter**)

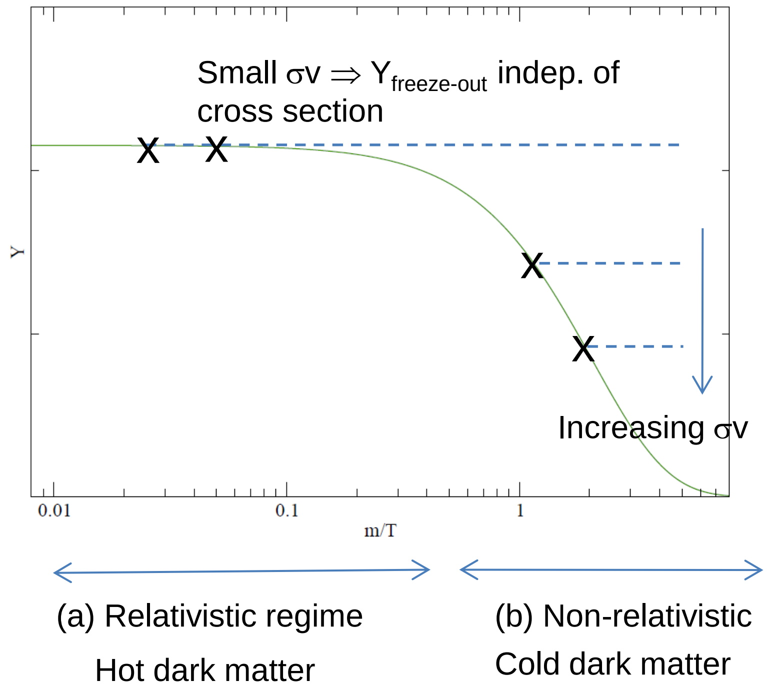
(b) Non-relativistic at freeze-out (**cold dark matter**)

{(c) In-between (**warm dark matter**) }

(a) $m_\chi << T_f$

$$Y_\chi(T \to 0) = Y_\chi^{eq}(T = T_f) = \frac{45\zeta(3)}{2\pi^4}\frac{g_{eff}}{g_{tot}^s(x_f)}$$

For a relativistic species, the relic number density per entropy density is almost independent of temperature and cross section. For a given cross section, the abundance follows the equilibrium curve, until $\Gamma < H$, when the abundance "freezes out":



Example, one hypothetical new massive neutrino: $g_{eff} = 2 \cdot \frac{3}{4}$

$T_F \sim 1$ MeV $\Rightarrow$ $g^s_{tot} = 2 + 4 \cdot \frac{7}{8} + 3 \cdot 2 \cdot \frac{7}{8} = 10.75$

(photons, $e^{\pm}$, left-handed neutrinos & antineutrinos)

$$\rho_\nu = m_\nu n_\nu = m_\nu Y_\nu \cdot s$$

$$\Longrightarrow \Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94 \text{ eV}}$$

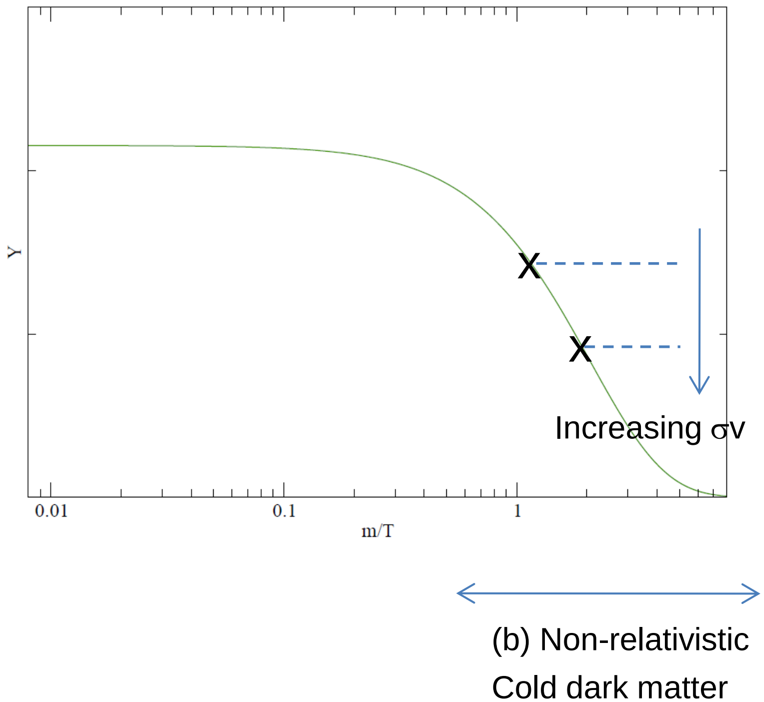
So, if the mass of the new neutrino would be 11 eV, it could explain the dark matter!?

Unfortunately, it does not work. Relativistic particles (hot dark matter) can only form very large structures first, which then fragment into smaller structures. Observations of structure formation ⇒ Sum of neutrino masses < 1 eV (or > few keV; **warm dark matter**). Planck data (2013): $N_\nu = 3.3 \pm 0.5$.

A neutrino of mass 1 GeV, could in principle be cold dark matter, but this is ruled out by results from LEP at CERN (this would cause a larger decay width of Z).

Anyway, as neutrinos are known to be massive, but with masses probably of the order of 0.1 eV, means that a (small) part of the dark matter problem is solved – around 1 % of it should be neutrinos!

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



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

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

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

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 required cross section is sometimes called the ”WIMP miracle”.

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

No particle in the Standard Model (SM) seems to be able to be the dark matter (apart from the ~ 1% contribution from neutrinos). However, there are reasons from particle physics that SM has to be enlarged. Most studied scenario: The lightest supersymmetric particle, in the Minimal Supersymmetric Standard Model (MSSM), the neutralino.

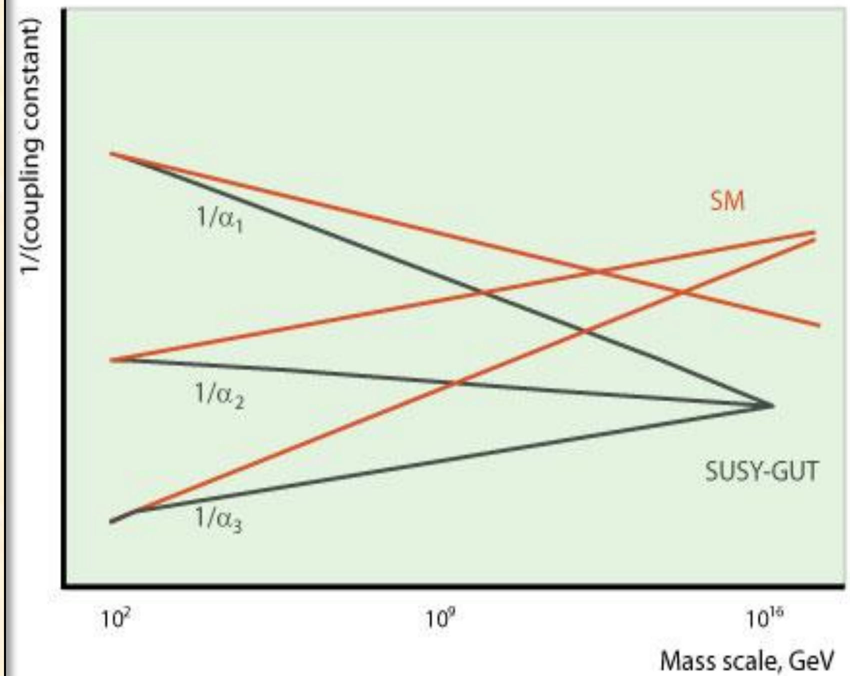
$$\chi^0 = a\tilde{\gamma} + b\tilde{Z}^0 + c\tilde{H}_1^0 + d\tilde{H}_2^0$$

A quantum mechanical mixture of photino, zino, and two higgsinos. The MSSM is still viable (it spans a huge parameter space) , but tension from non-observation of SUSY at LHC, especially for "constrained" models, CMSSM, MSUGRA,...

Supersymmetry

- Invented in the 1970's
- Necessary in most string theories
- Restores unification of couplings
- Solves the hierarchy problem (although tension with LHC data)
- Can give right scale for neutrino masses
- Predicted a light Higgs (< 130 GeV) – OK!
- May be detected at LHC (not yet…)
- Gives an excellent dark matter candidate (If R-parity is conserved ⇒ stable on cosmological timescales; needed for proton stability)
- Useful template for generic WIMP – Minimal Supersymmetric Standard Model (MSSM)

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



The lightest neutralino: The most natural SUSY dark matter candidate

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

Gaugino part   Higgsino part

Due to requirement of supersymmetry, the neutralino is a Majorana fermion, i.e., its own antiparticle

The lightest neutralino of the MSSM: the most natural SUSY dark matter candidate

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

$$\sum_{i=1}^{4} |a_i|^2 = 1;$$

$$|a_1|^2 + |a_2|^2 \equiv Z_g \quad \text{gaugino fraction}$$

$$|a_3|^2 + |a_4|^2 \equiv Z_h \ (= 1 - Z_g) \quad \text{higgsino fraction}$$

Neutralinos are Majorana particles (their own antiparticles)

Tree-level annihilation: $\tilde{\chi}^0 + \tilde{\chi}^0 \rightarrow f\,\bar{f}, W^+W^-, Z^0Z^0, H_{1,2}^0 H_3^0, \ldots$

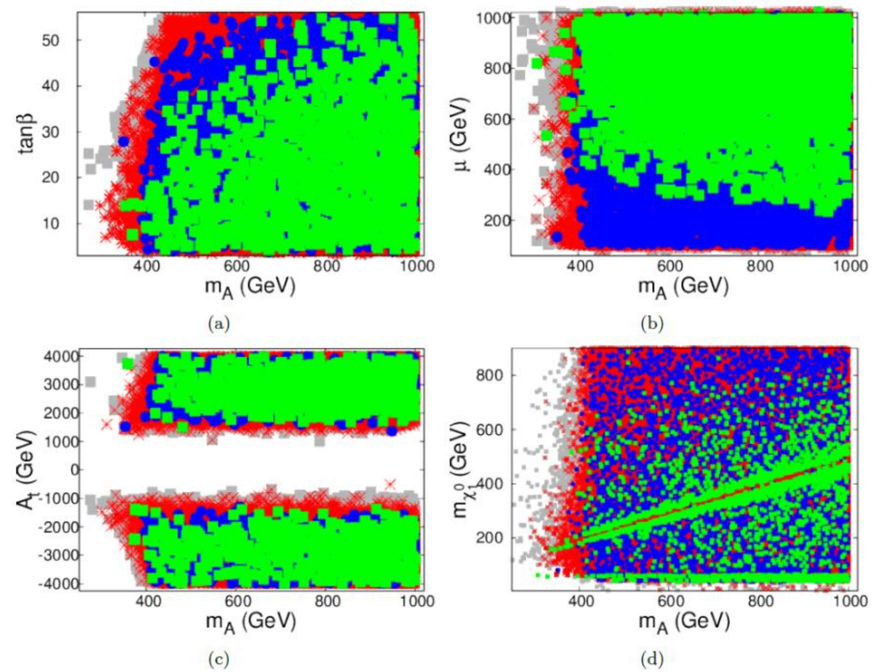
$$\frac{v}{c} \approx 10^{-3} << 1 \quad \text{in galactic halos} \Rightarrow \text{S-wave should dominate.}$$

However, due to Majorana property,

$\left(\tilde{\chi}^0\tilde{\chi}^0\right)_{^3S_1}$ is forbidden, and due to helicity

$$\left(\tilde{\chi}^0\tilde{\chi}^0\right)_{^1S_0} \rightarrow f\bar{f} \propto m_f^2$$

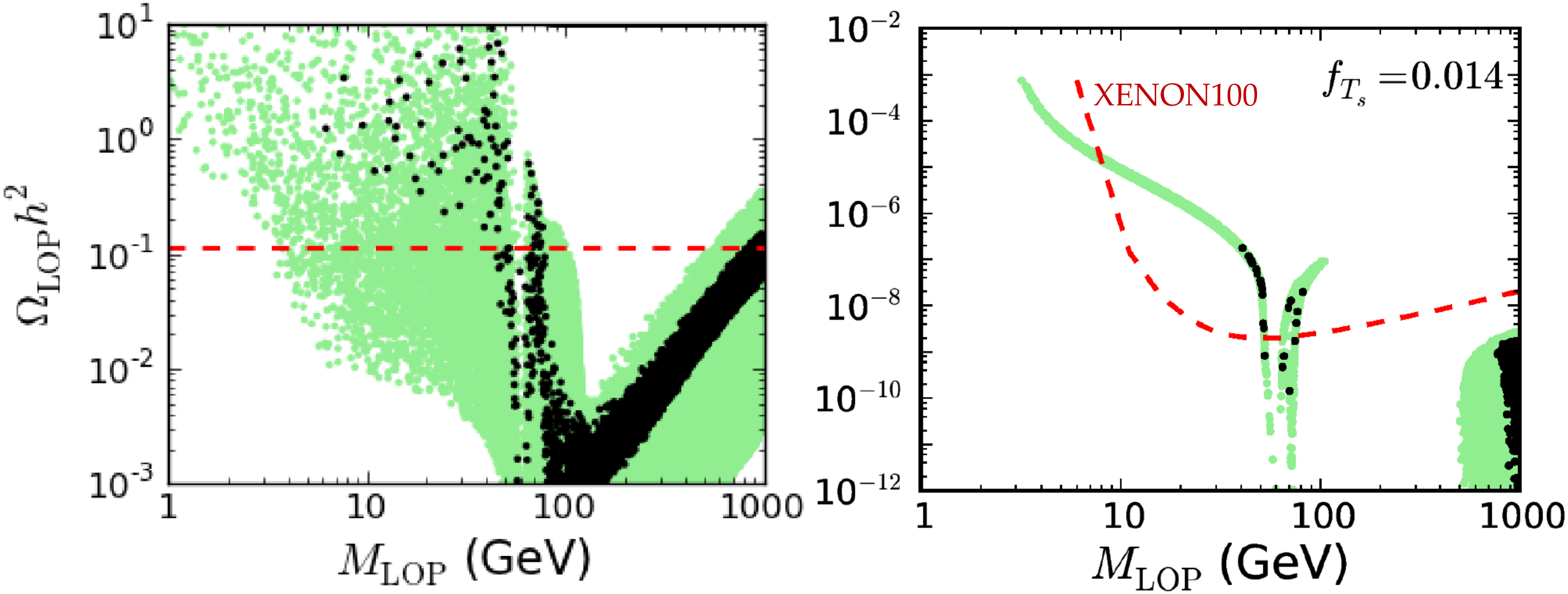
Parameter regions where the MSSM neutralino fullfils all constraints after LHC
(T. Han, Z. Liu & A. Natarajan 1303.3040):



One problem for MSSM: While the Higgs mass, ~125 GeV, is within the range predicted by SUSY, radiative corrections have to be very large, which needs some fine-tuning. Also squarks and gluinos have to have very large masses – not the spectrum one would first have guessed.

By introducing a scalar neutral supermultiplet, in the NMSSM, some of these problems may be ameliorated.

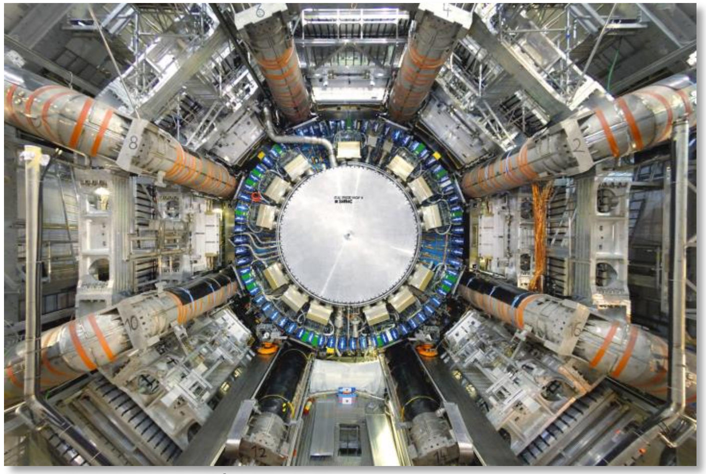
Also other interesting non-SUSY WIMPs are worth studying: Lightest Kaluza-Klein particle – mass scale 600 – 1000 GeV, Inert Higgs doublet, Right-handed neutrino, … Non-WIMP: Axion.



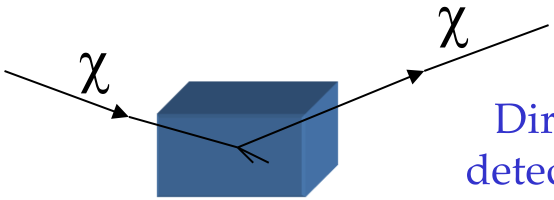
Inert Higgs Doublet Dark Matter (A. Goudelis, B. Herrmann & O, Stål, 1303.3010; cf. M. Gustafsson, 1106.1719; M. Krawczyk, D. Sokołowska & B. Świeżewska 1303.7102)

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.
- 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.
- 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.



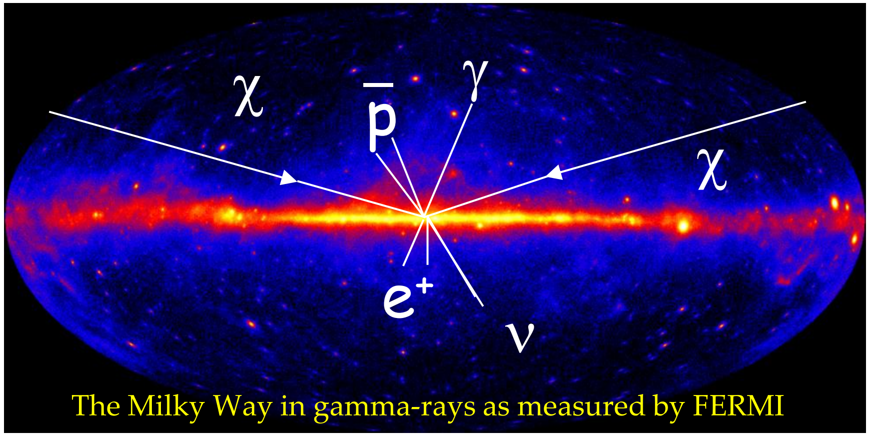
CERN LHC/ATLAS



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

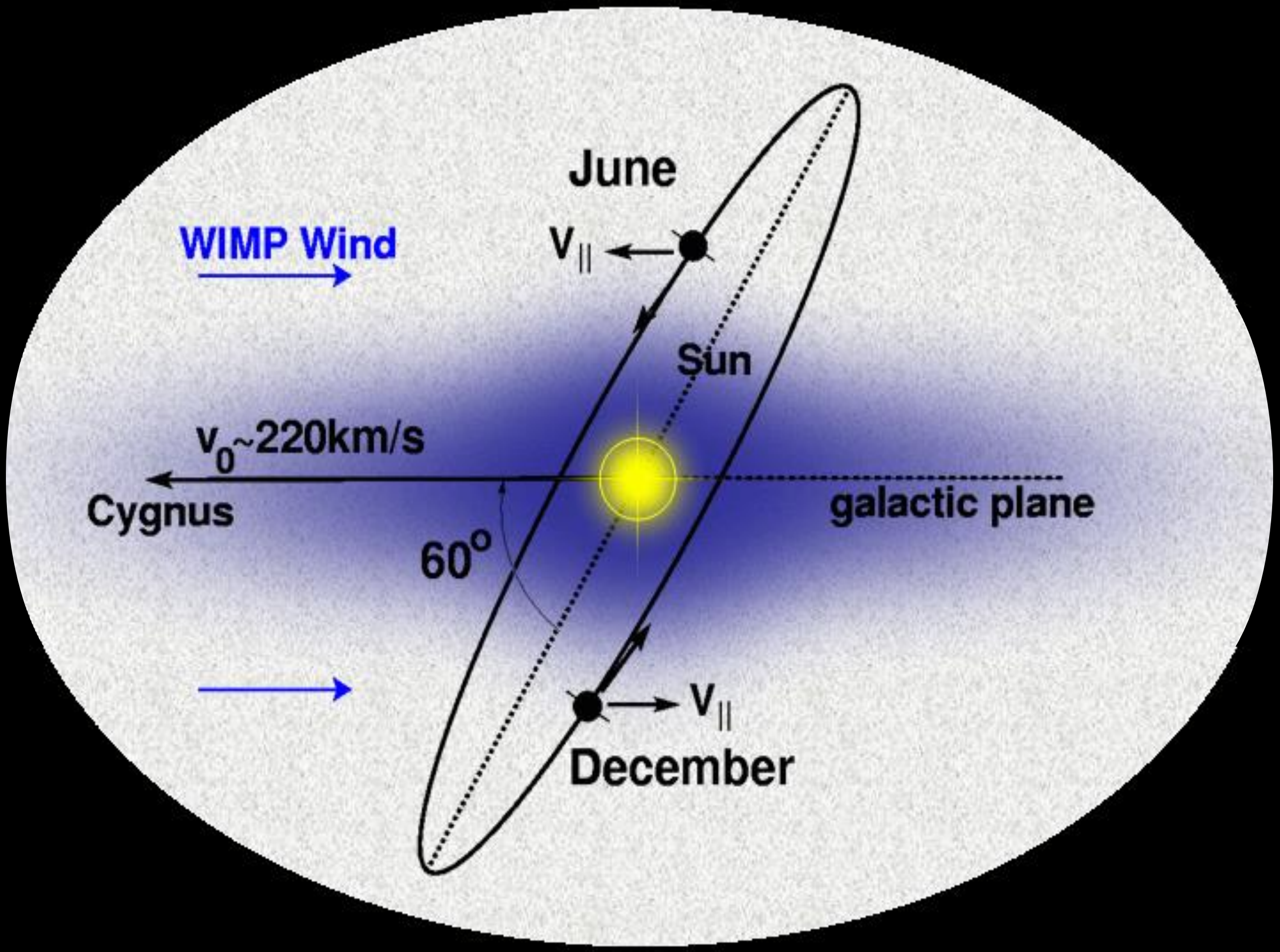


$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$

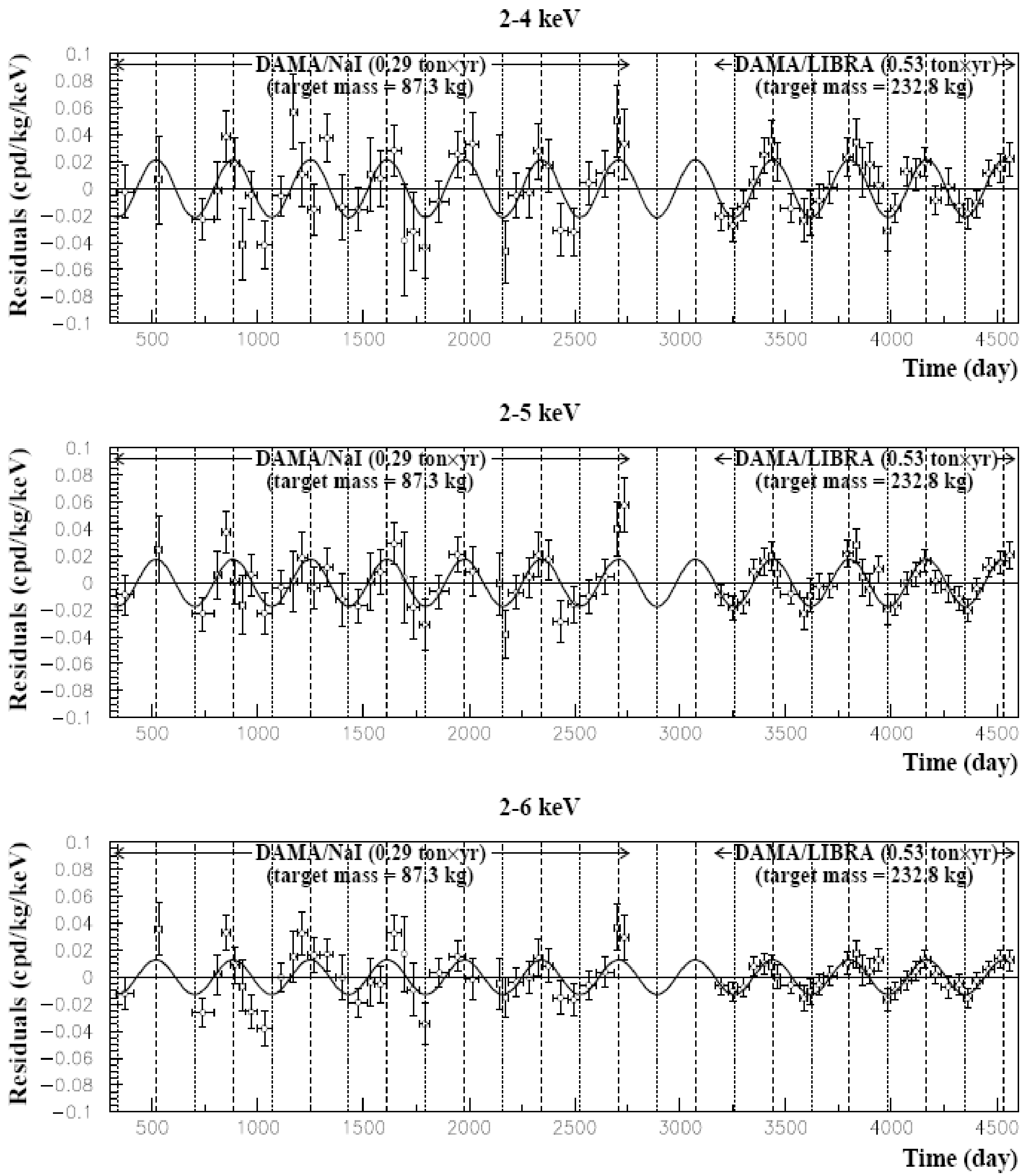
Annihilation rate enhanced for clumpy halo; near galactic centre and in subhalos, also for larger systems like galaxy clusters, cosmological structure (as seen in N-body simulations).

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 excess towards g.c.	Unexplained at the moment – very messy astrophysics
2012: Fermi 130 GeV line (T. Bringmann, C.Weniger & al., M. Su & D.Finkbeiner, A.Hektor & al.)	3.1 σ – 4.6 σ effect, using public data, unexplained, not confirmed by Fermi-LAT
2013, April 3: AMS-02 (S.T.T. Ting & al.) Rising positron ration 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."



A. Drukier, K. Freese and D. Spergel, 1986



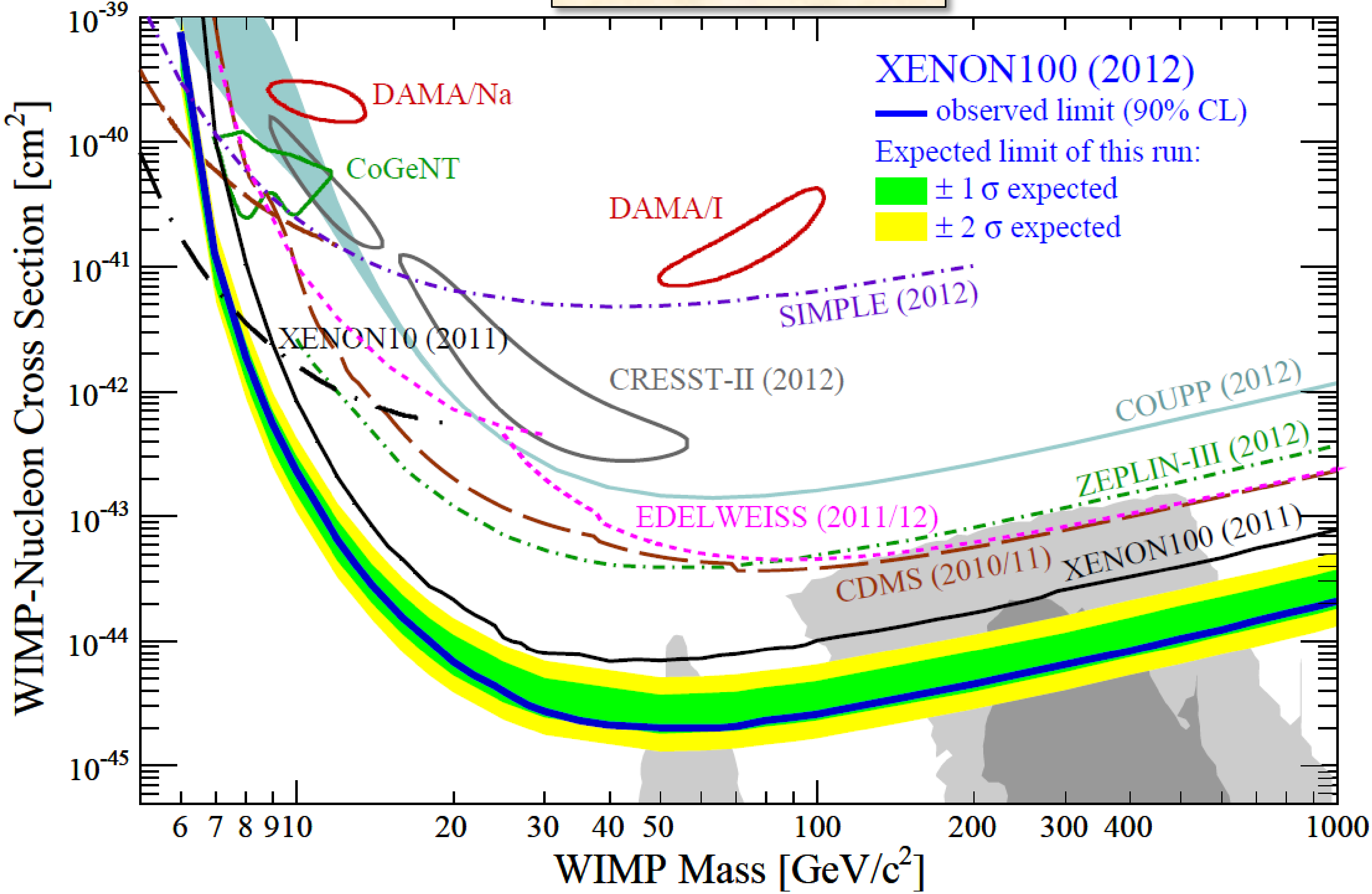
DAMA/LIBRA: Annual modulation of unknown cause. Consistent with dark matter signal (but not confirmed by other experiments).

Claimed significance: More than 8σ (!)

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

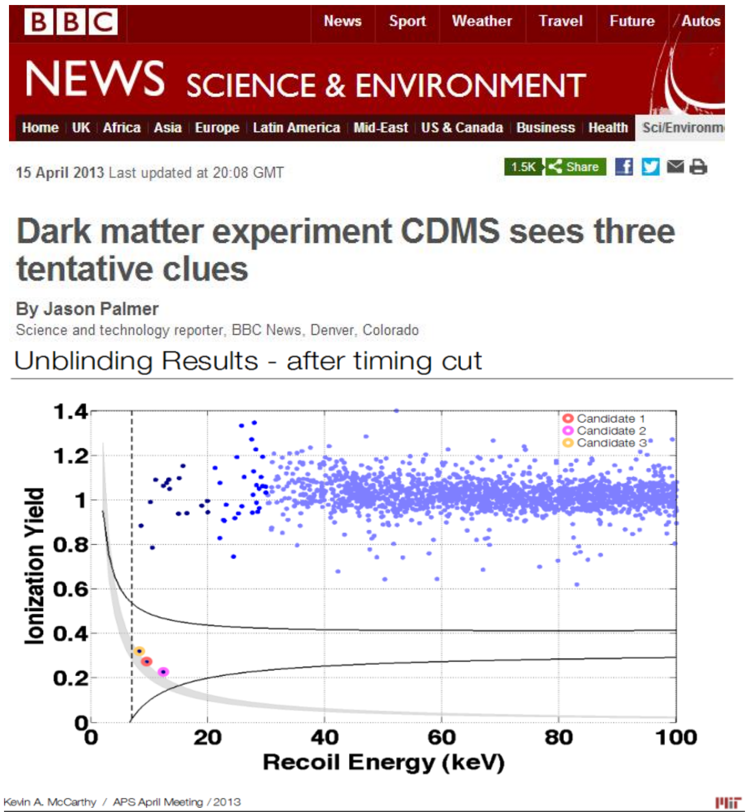
Direct detection limits, Xenon100 data, July 2012:

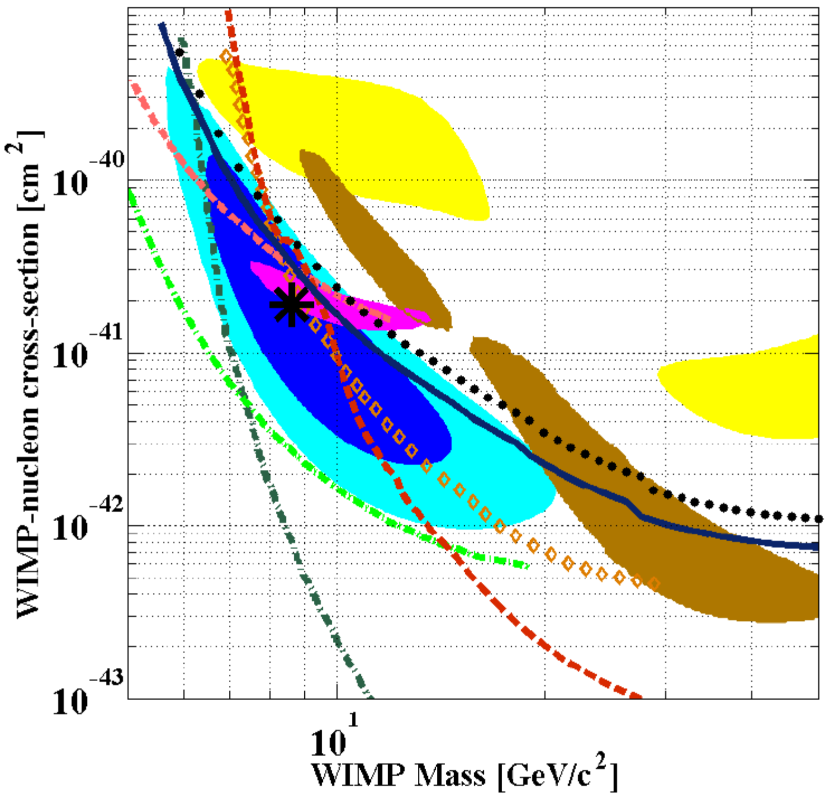
CoGeNT and DAMA
seem well excluded…



New result on indirect detection from CDMS II:

Dark Matter Search Results Using the Silicon Detectors of CDMS II

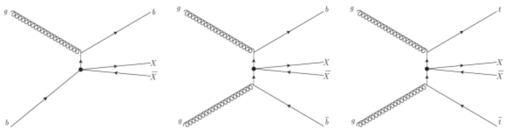


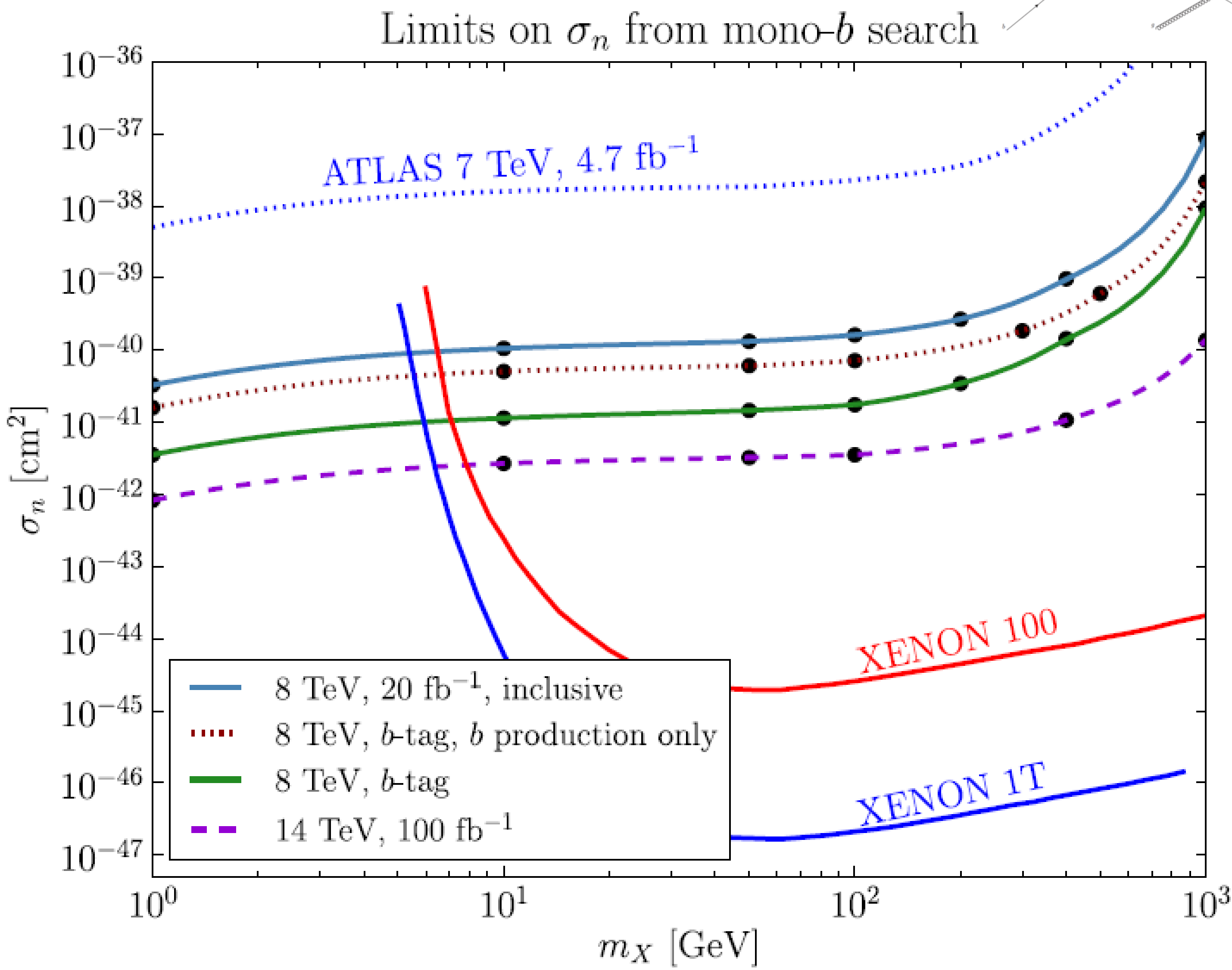


Citing the preprint: Though this result favors a WIMP interpretation over the known-background-only hypothesis, we do not believe this result rises to the level of a discovery.

Sumary: The hunt continues…

LHC limits may be complementary t low masses:

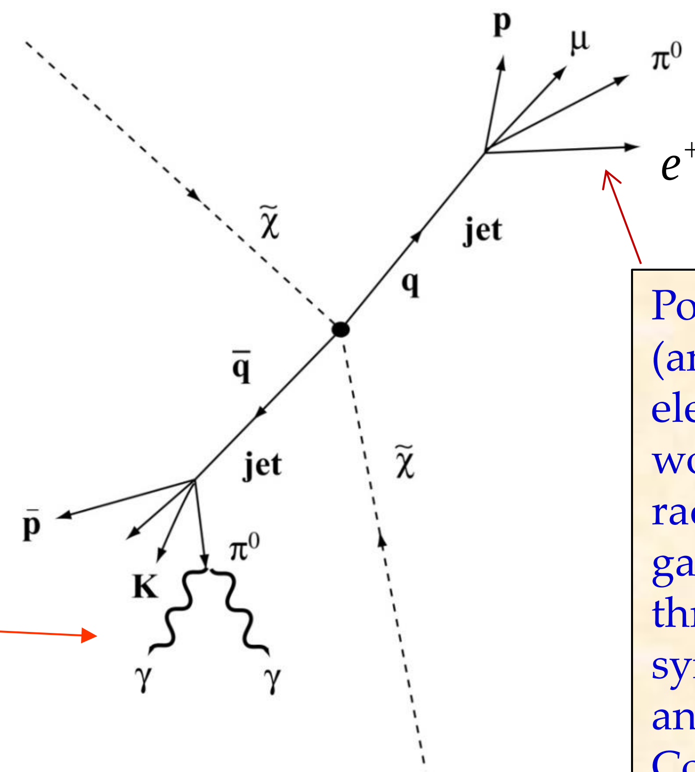




T. Lin, E.W. Kolb & L.-T. Wang, 1303.6638

Indirect detection: How dark matter shines - annihilation of WIMPs in the galactic halo

Note: equal amounts of matter and antimatter are created in annihilations - this may be a good signature! (Positrons, antiprotons, anti-deuterons.)



Positrons (and electrons) would also radiate gamma rays through synchrotron and inverse Compton radiation

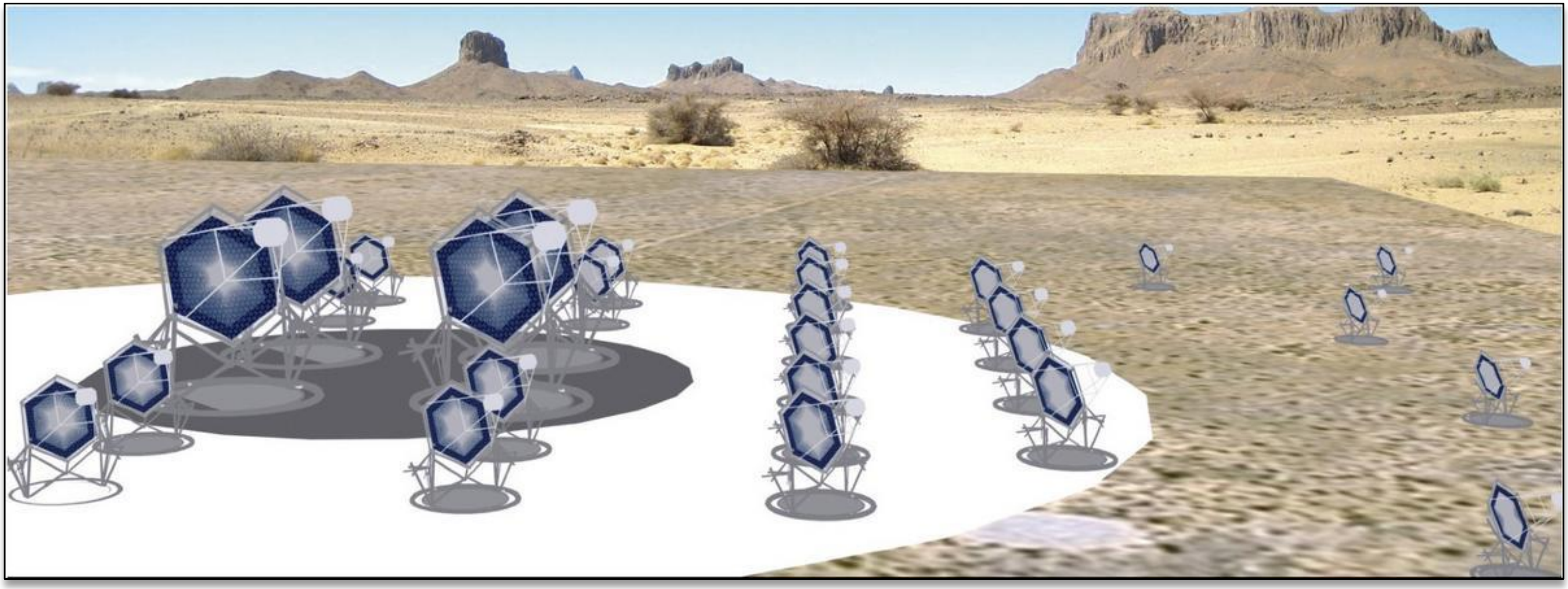
Photons (gamma-rays, i.e. very energetic light) come from decays of particles like neutral pions. Also direct annihilation to 2 gamma-rays is possible: would give a ”smoking gun” gamma-ray line at the energy $m_\chi c^2$.

Indirect detection through γ-rays from DM annihilation

Fermi-LAT (Fermi Large Area Telescope)

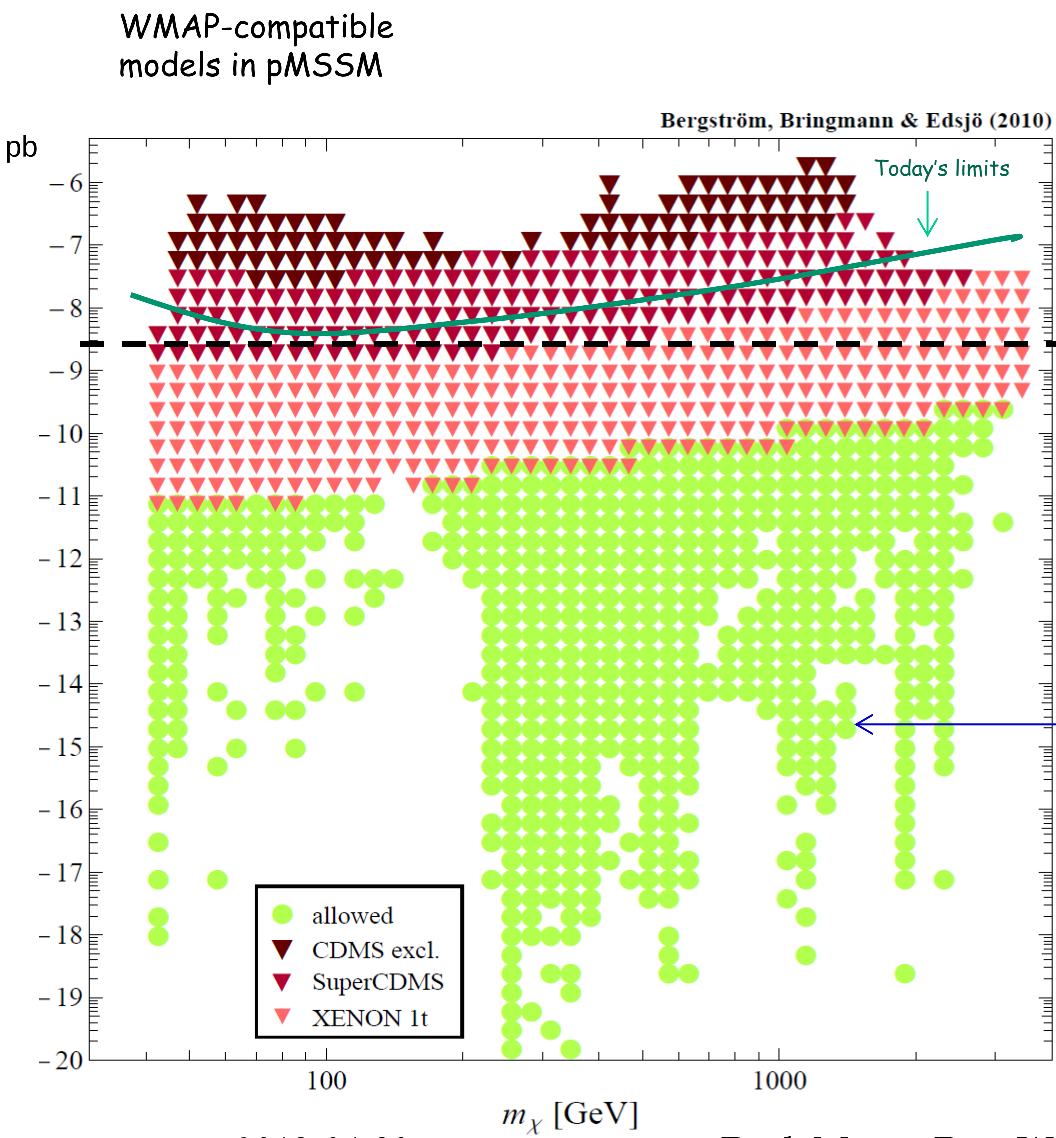
H.E.S.S. & H.E.S.S.-2

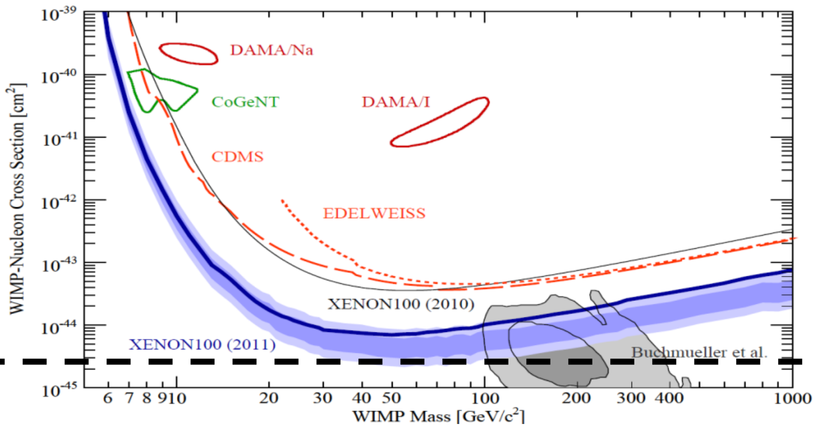
VERITAS



CTA (Cherenkov Telescope Array)

The Dark Matter Array (DMA) – a dedicated DM experiment?

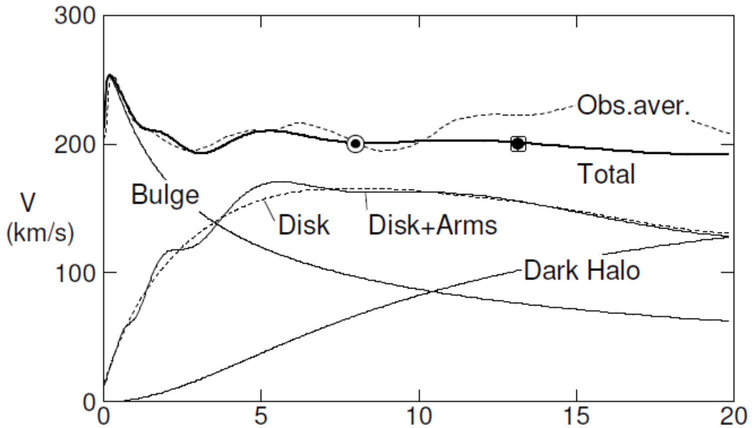


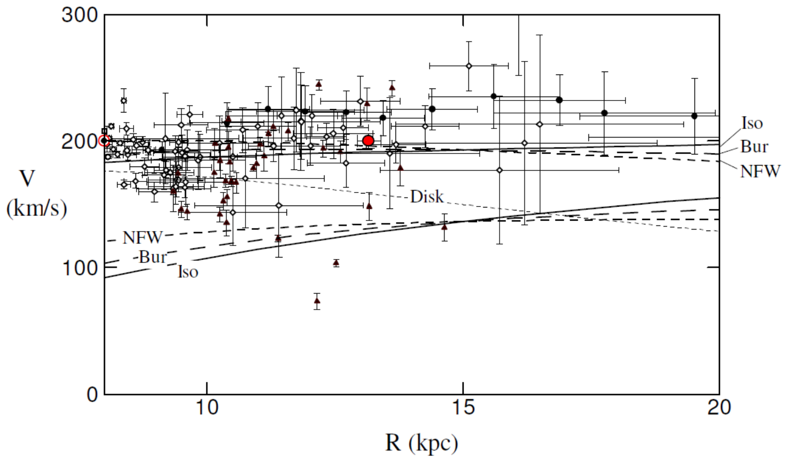


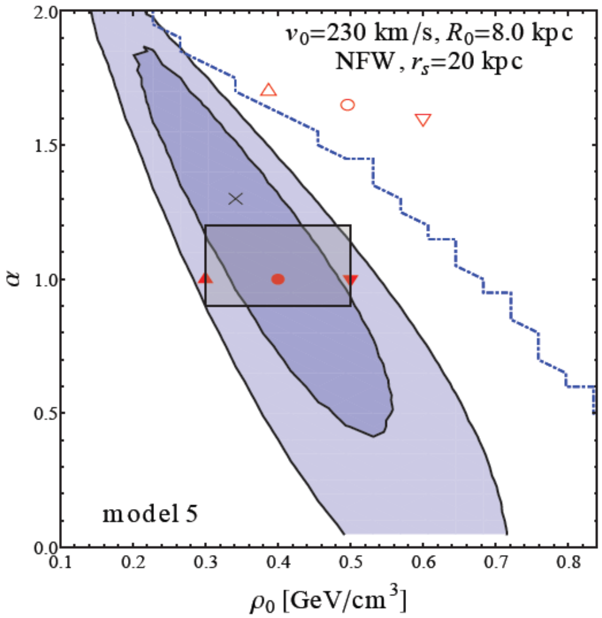
The parameter space continues, 10 more orders of magnitude in direct detection cross section!

Can't we determine right halo model from the Milky Way rotation curve?

No, unfortunately not: Y. Sofue, M. Honma & T. Omodaka, 2008







$$\rho_{DM}(r) = \bar{\rho}_s (r/r_s)^{-\alpha} (1 + r/r_s)^{-3+\alpha} \quad \text{(NFW)}$$

Using also microlensing data, F. Iocco, M. Pato, G. Bertone and P. Jetzer, 2011

One major uncertainty for indirect detection, especially of gamma-rays: The halo dark matter density distribution at small scales is virtually unknown. Gamma-ray rates towards the Galactic Center may vary by factor of 1000 or more. Adiabatic contraction of DM may give a more cuspy profile.

Fits to N-body simulations – (almost) singular

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

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

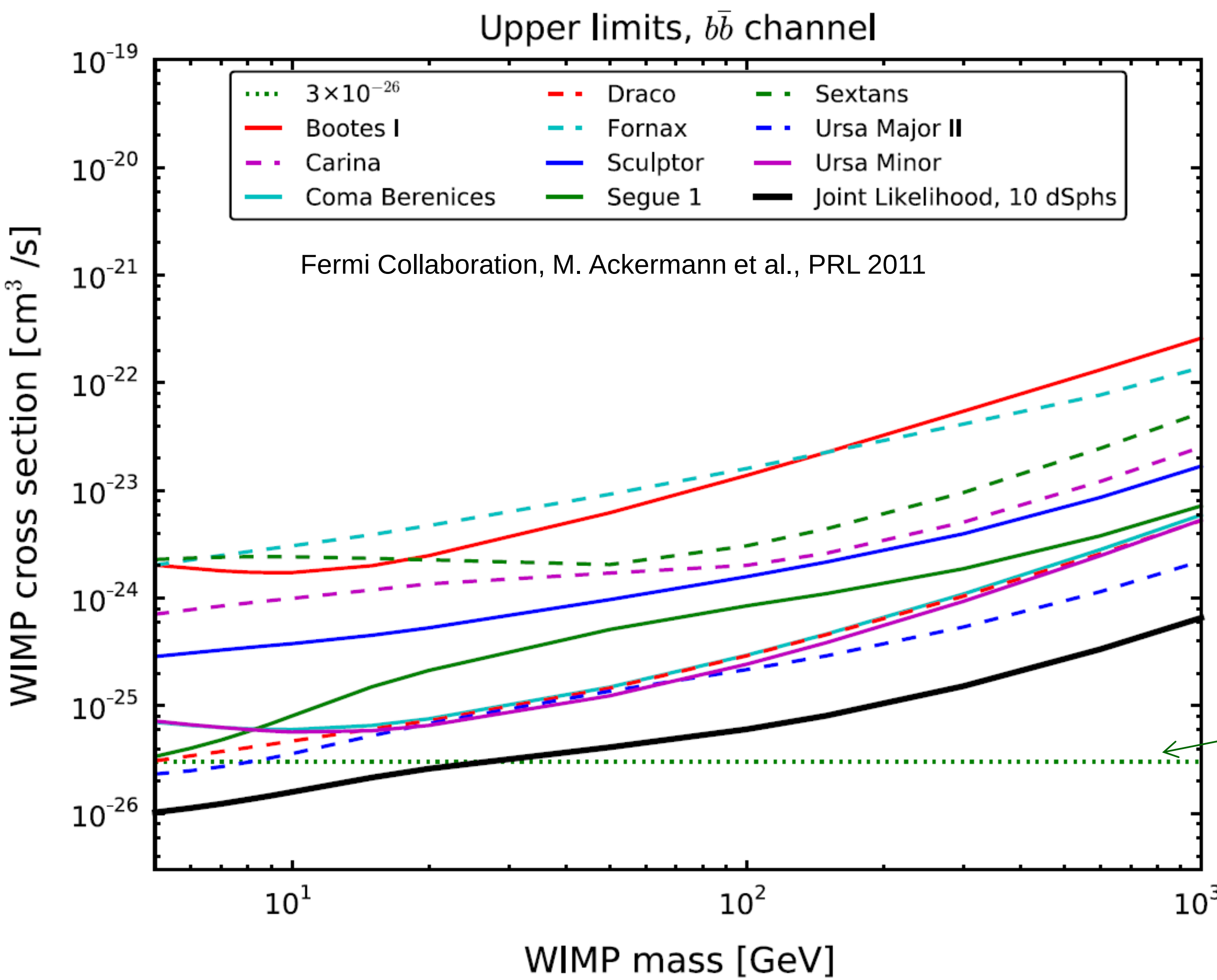
Fits to rotation curves (cored)

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

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

At the solar position, the local density, assuming spherical symmetry, is 0.39 ± 0.03 GeV/cm^3 (R. Catena & P. Ullio, 2010)

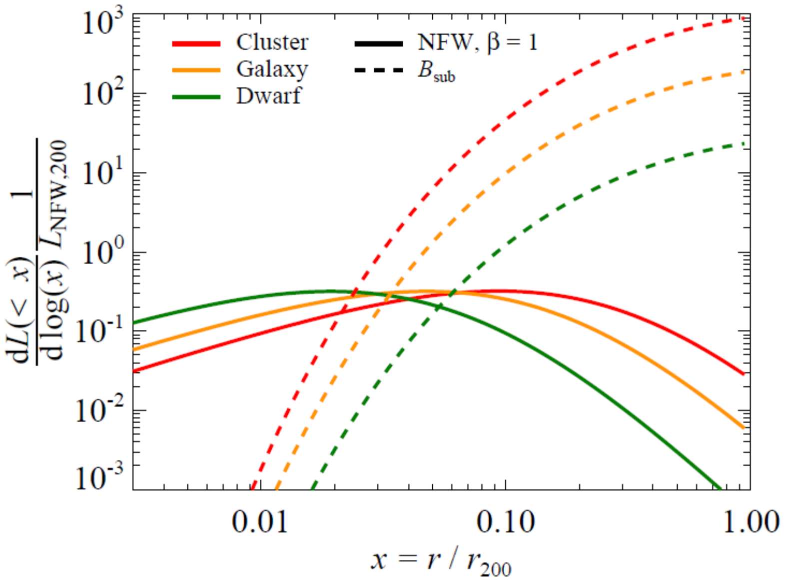
New promising experimental DM detection method: Stacking data from many dwarf galaxies, FERMI Collaboration, esp. Maja Garde & Jan Conrad, (Phys. Rev. Letters, December, 2011)



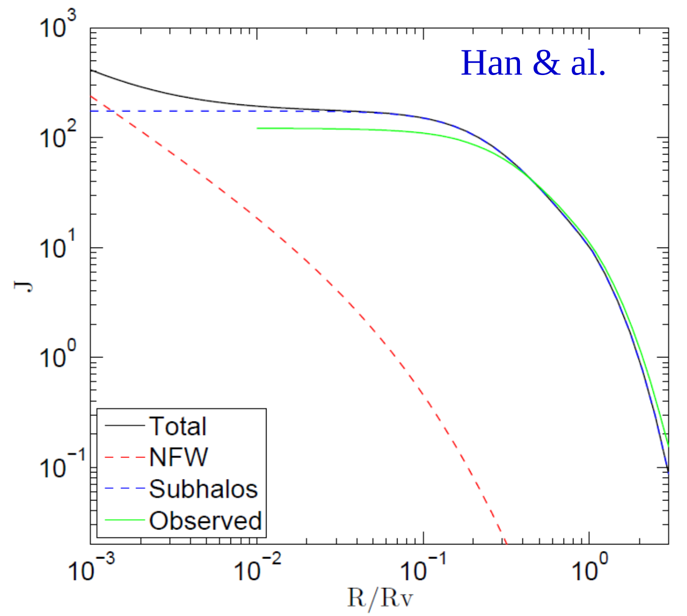
By stacking the data, sensitivity to the J-factor may be minimized

"Canonical" WIMP cross section

Possible signals also from Galaxy clusters



A. Pinzke, C. Pfrommer and L.B., Phys. Rev. D, 2011 (arXiv:1105.3240).

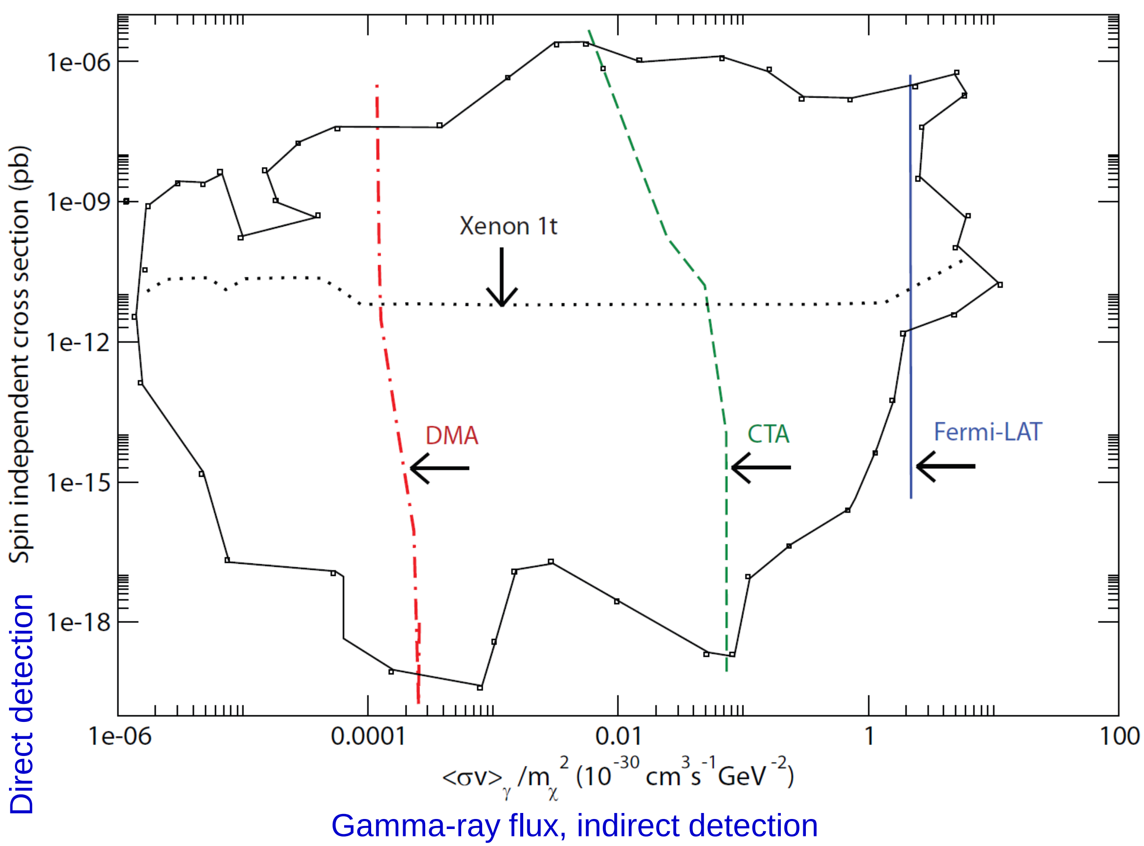


J. Han, C.S. Frenk, V.R. Eke, L. Gao and S.D.M. White, arXiv:1201.1003.

Tidal effects are smaller for clusters ⇒ boost factor of the order of 1000 possible (without Sommerfeld enhancement!). Predicted signal/noise is roughly a factor of 10 better for clusters than for dwarf galaxies! (See also L. Gao et al.)

Clusters may also be suitable for stacking of FERMI data (J. Conrad, S. Zimmer & al).

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



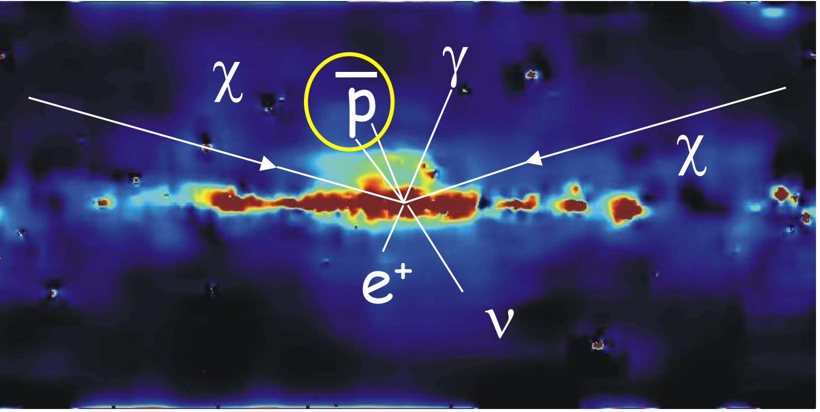
DMA: Dark Matter Array - a hypothetical dedicated gamma-ray detector for dark matter? (T. Bringmann, L.B., J. Edsjö, 2011)

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 GEUR. 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…

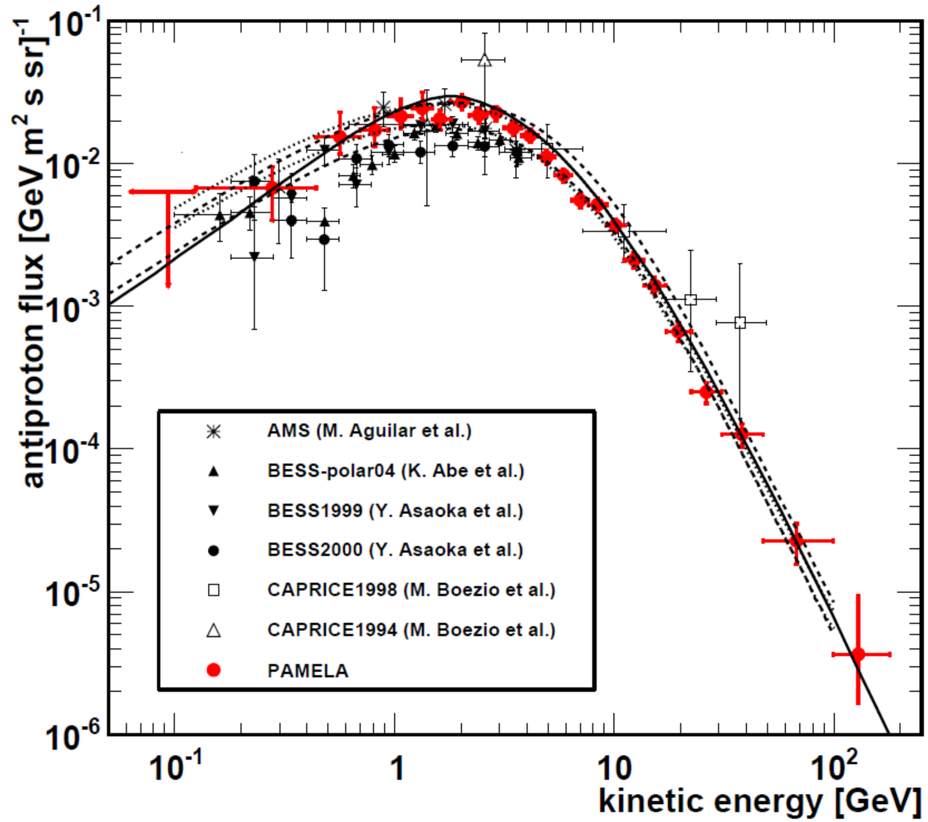
Break



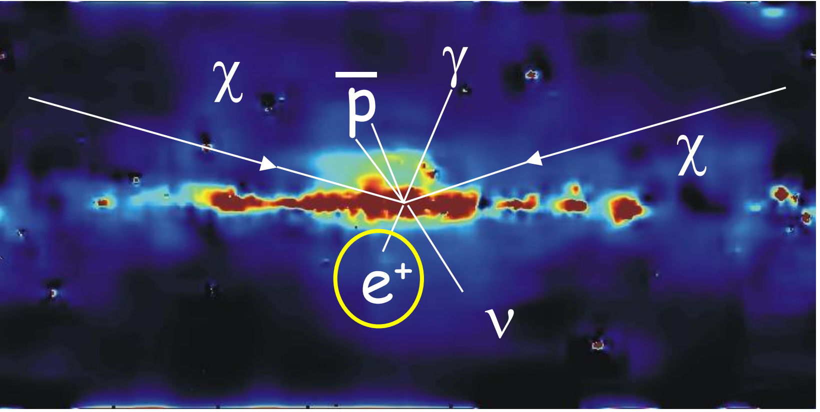
Antiprotons

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 et al., 2000)



PAMELA, O. Adriani et al, PRL 2009



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)

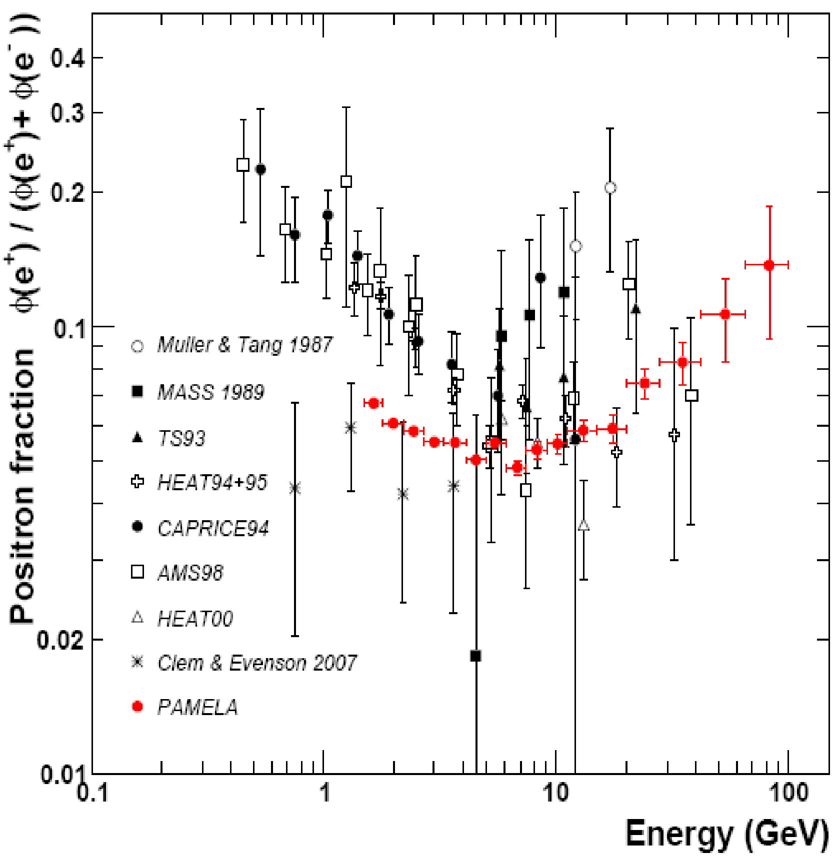
Source term (from annihilation or e.g. pulsars)

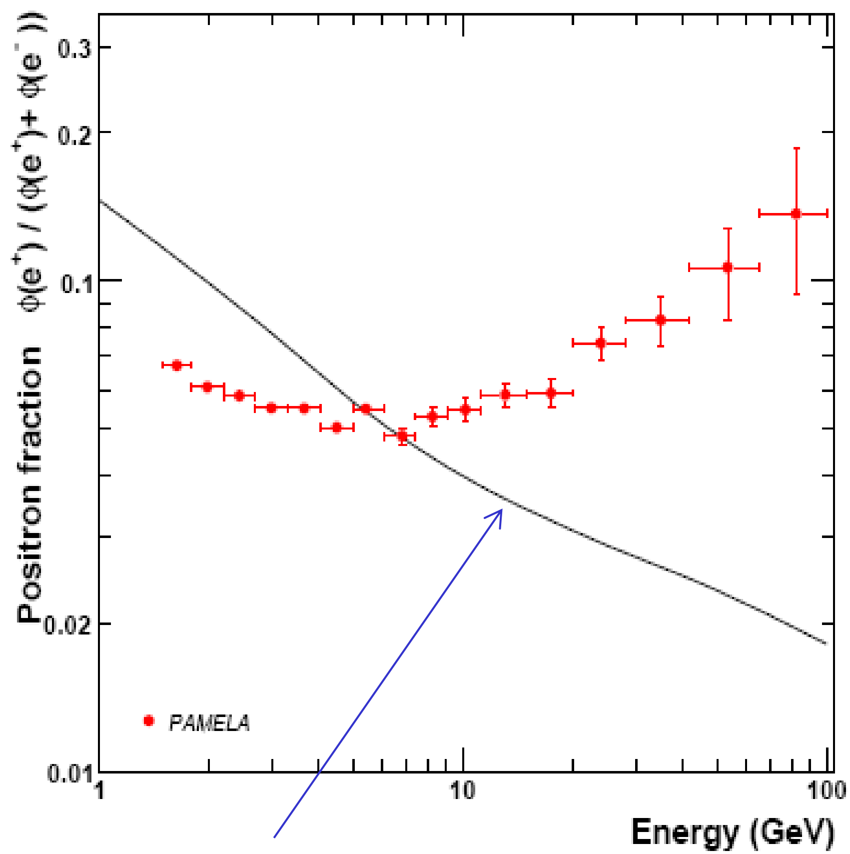
$$b(E) = 10^{-16}(E/1\ \mathrm{GeV})^2 \quad (\mathrm{GeVs}^{-1})$$

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

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

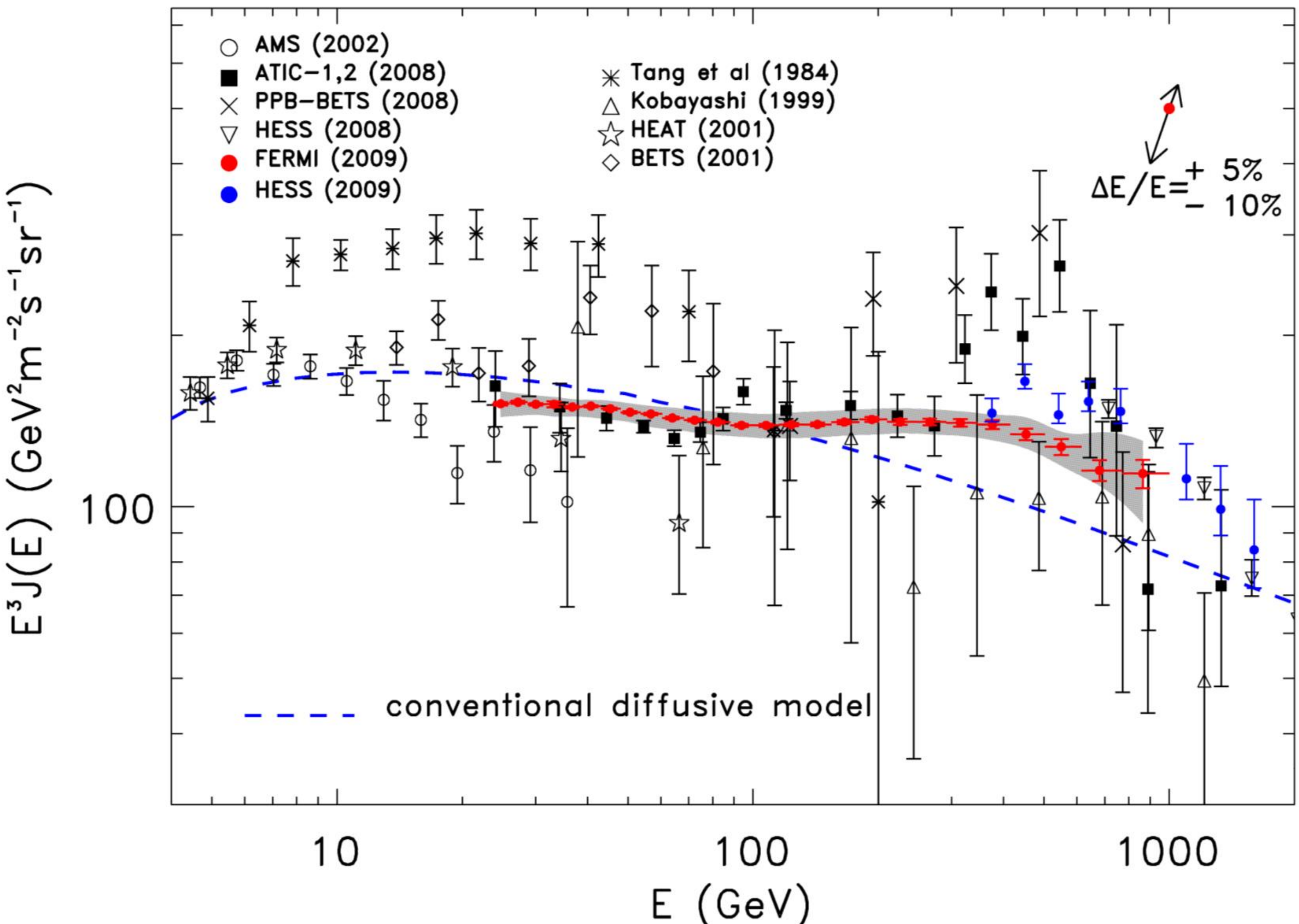
A very important result (more than 1000 citations so far!) An additional, primary source of positrons seems to be needed.





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

Data from the Fermi satellite, May 2009 (sum of electrons and positrons):



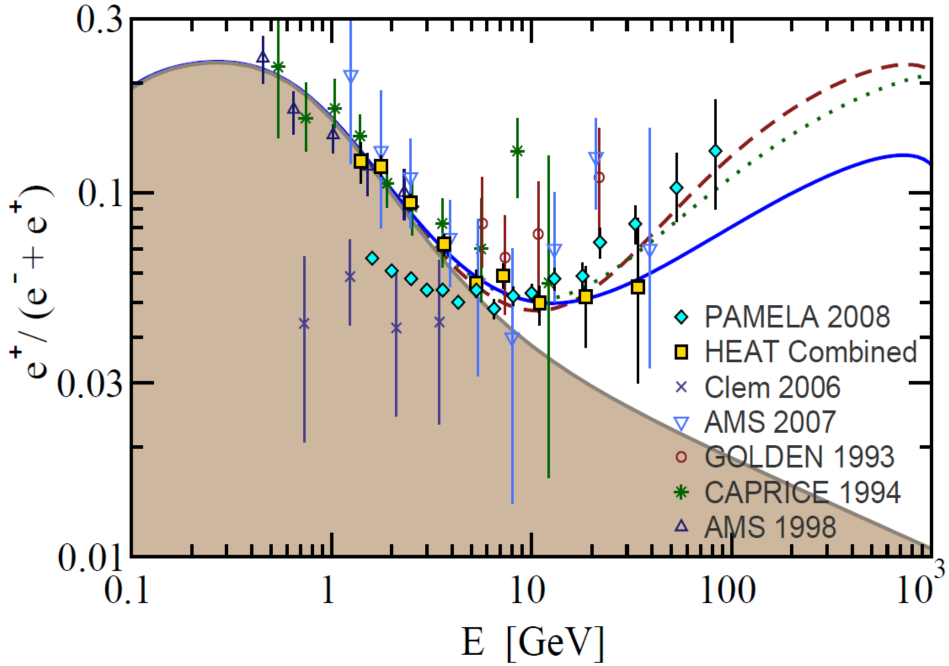
Fermi Collaboration, A.A. Abdo & al, PRL, May, 2009

Possible explanations:

1. Pulsars (or other supernova remnants)
2. Dark Matter
3. Something else

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

Vela pulsar (supernova remnant)



Geminga pulsar estimates

Yuksel, Kistler, Stanev, 2008 (cf. Aharonian, Atoyan and Völk, 1995; Kobayashi et al., 2004). Acceleration in old Supernova Remnants (Blasi & Serpico, 2009): Prediction of antiproton/proton ratio rising above 100 GeV – PAMELA see very little, AMS-02 will test – later this year (?).

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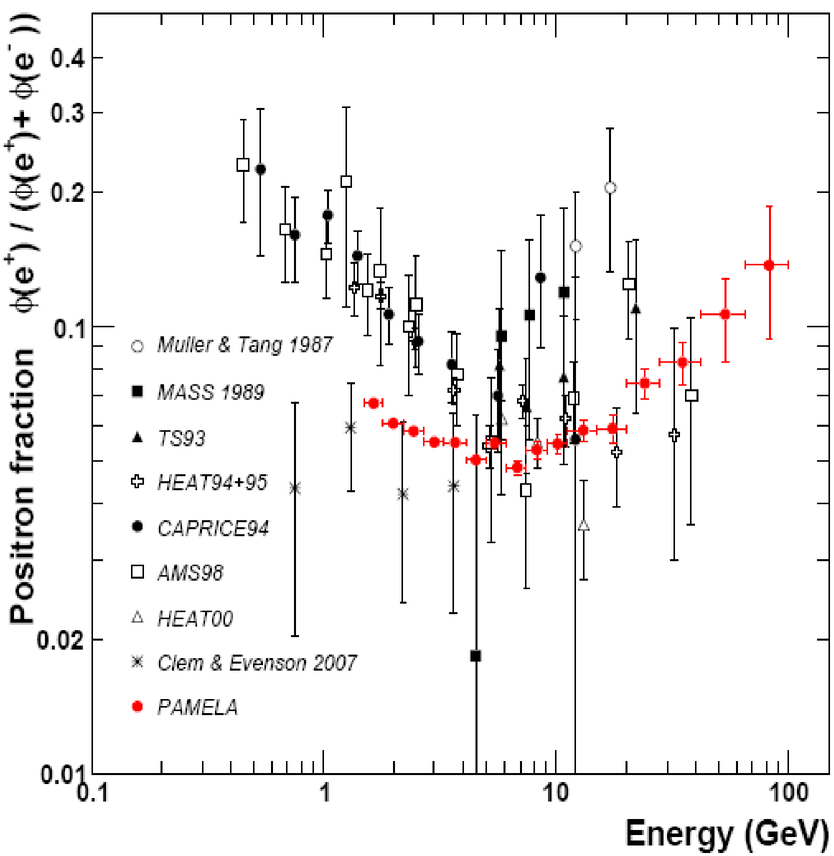

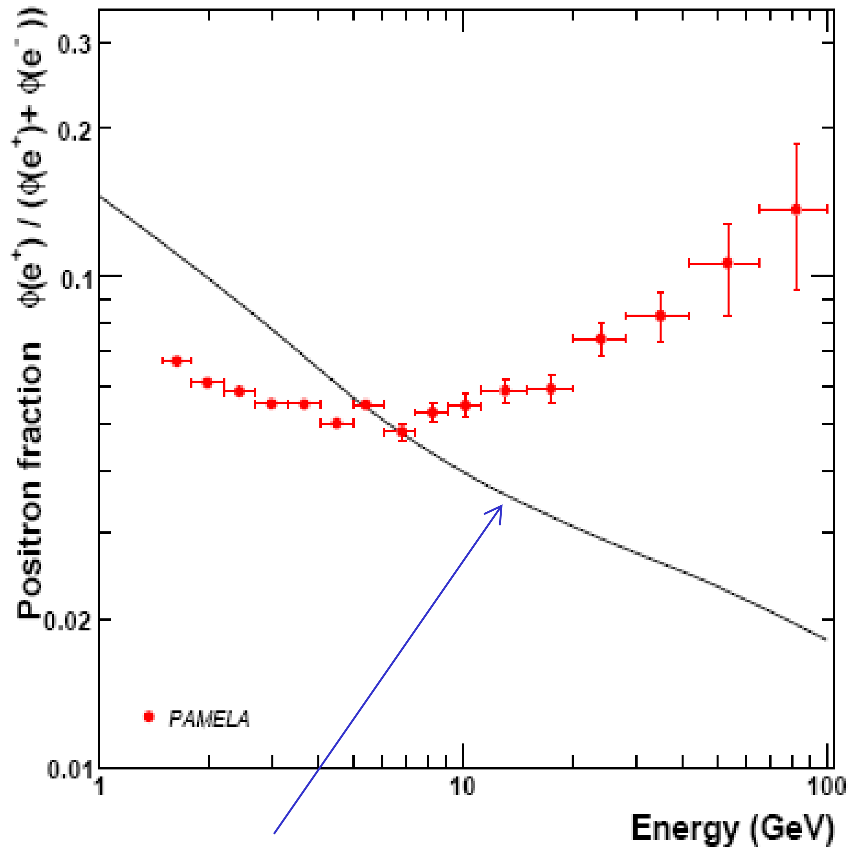

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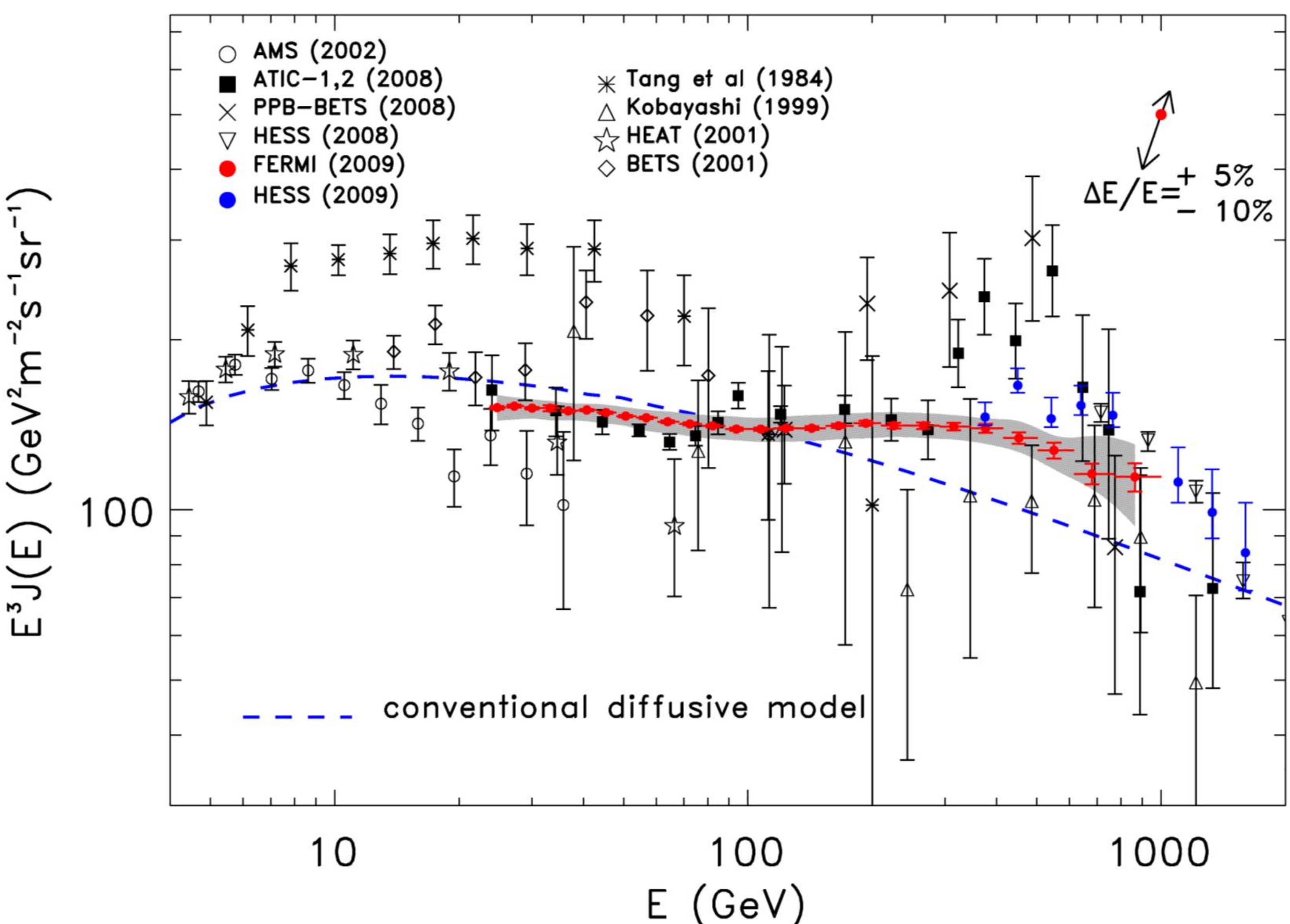

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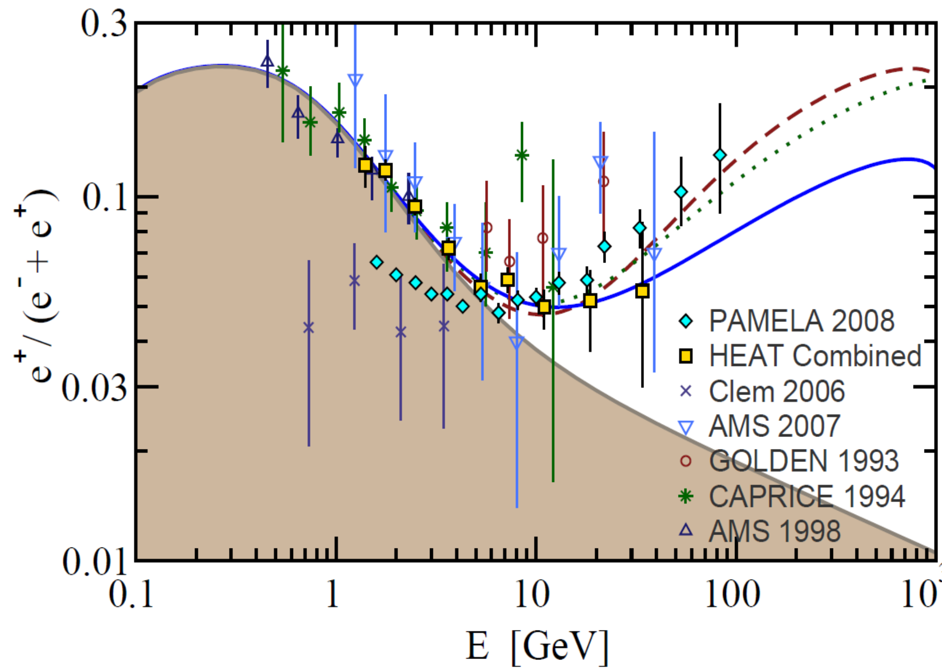

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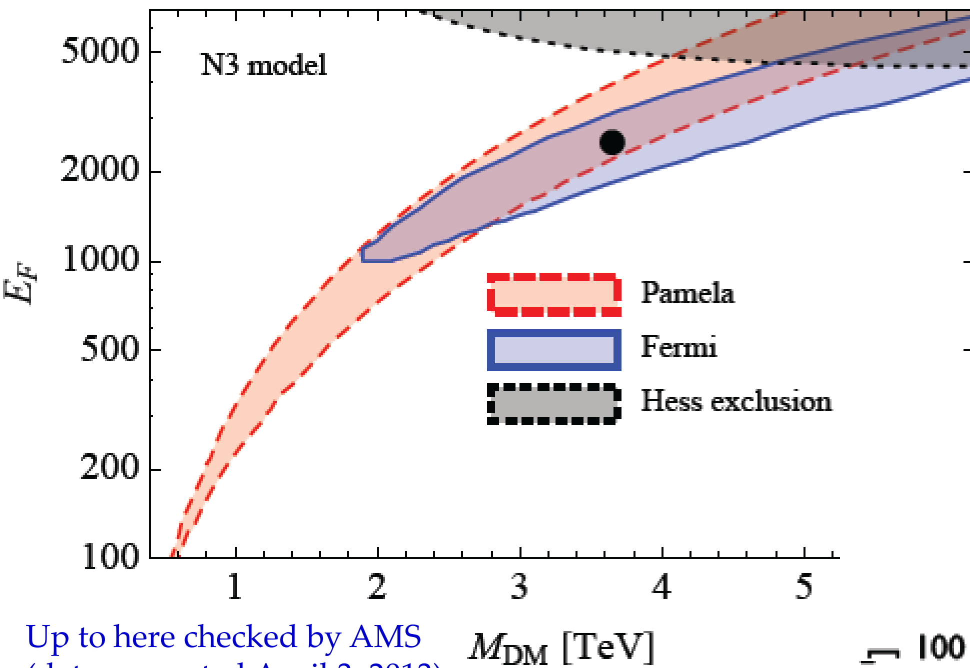
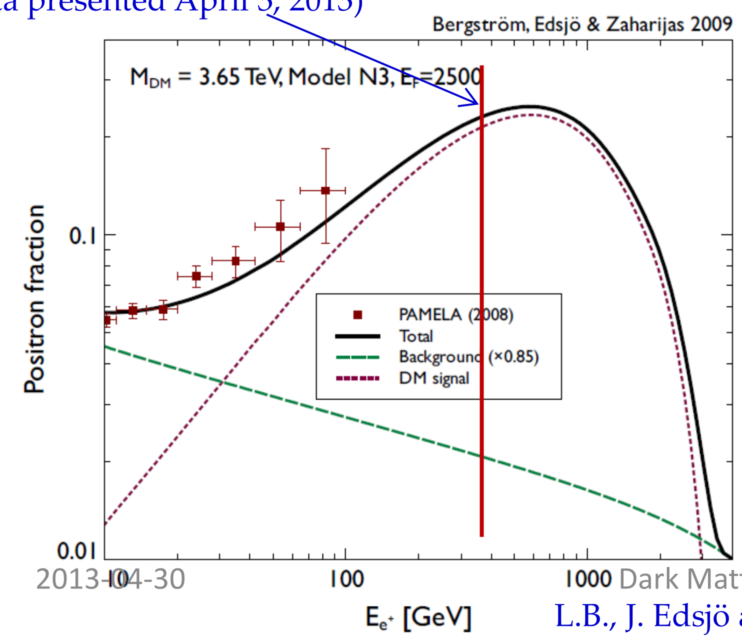
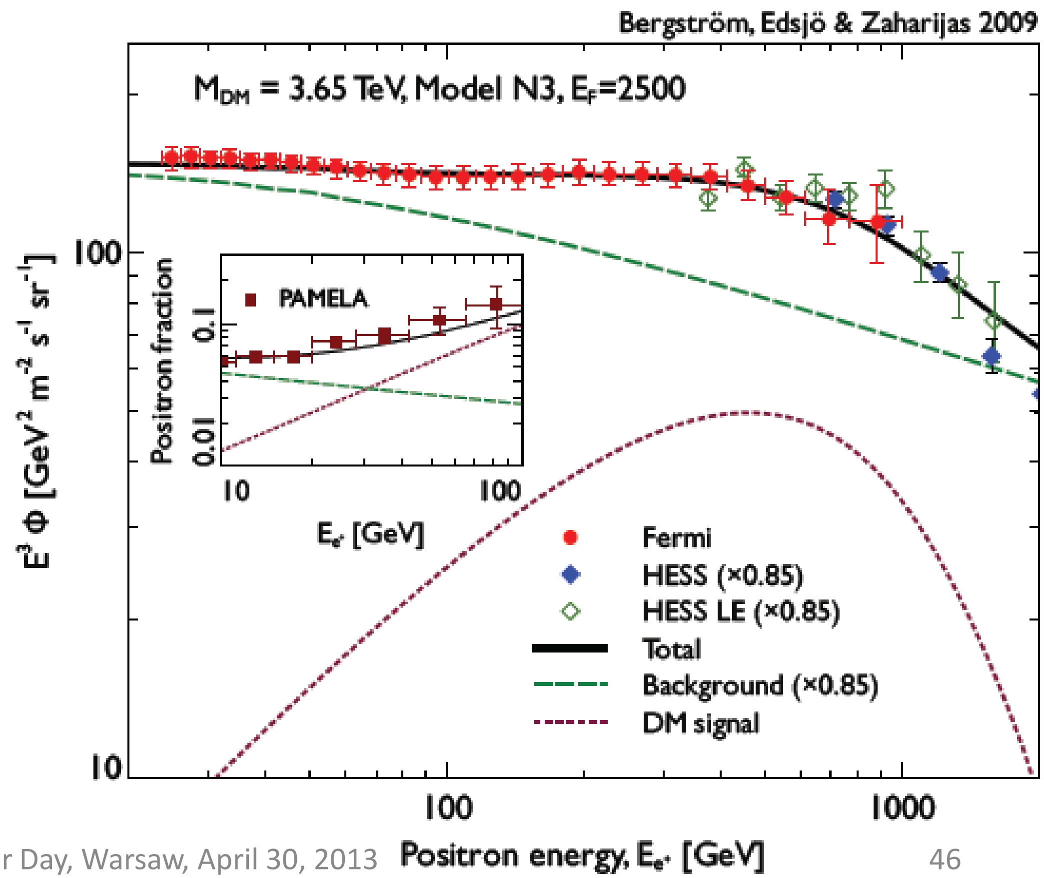
Dark matter example:

Model of Nomura and Thaler, annihilation into a+σ, with a → $\mu^+\mu^-$, axion-like, and σ scalar (maybe supersymmetric). Sommerfeld enhancement is natural in these models - but maybe not big enough? (Feng, Kaplinghat, Yu, 2009).



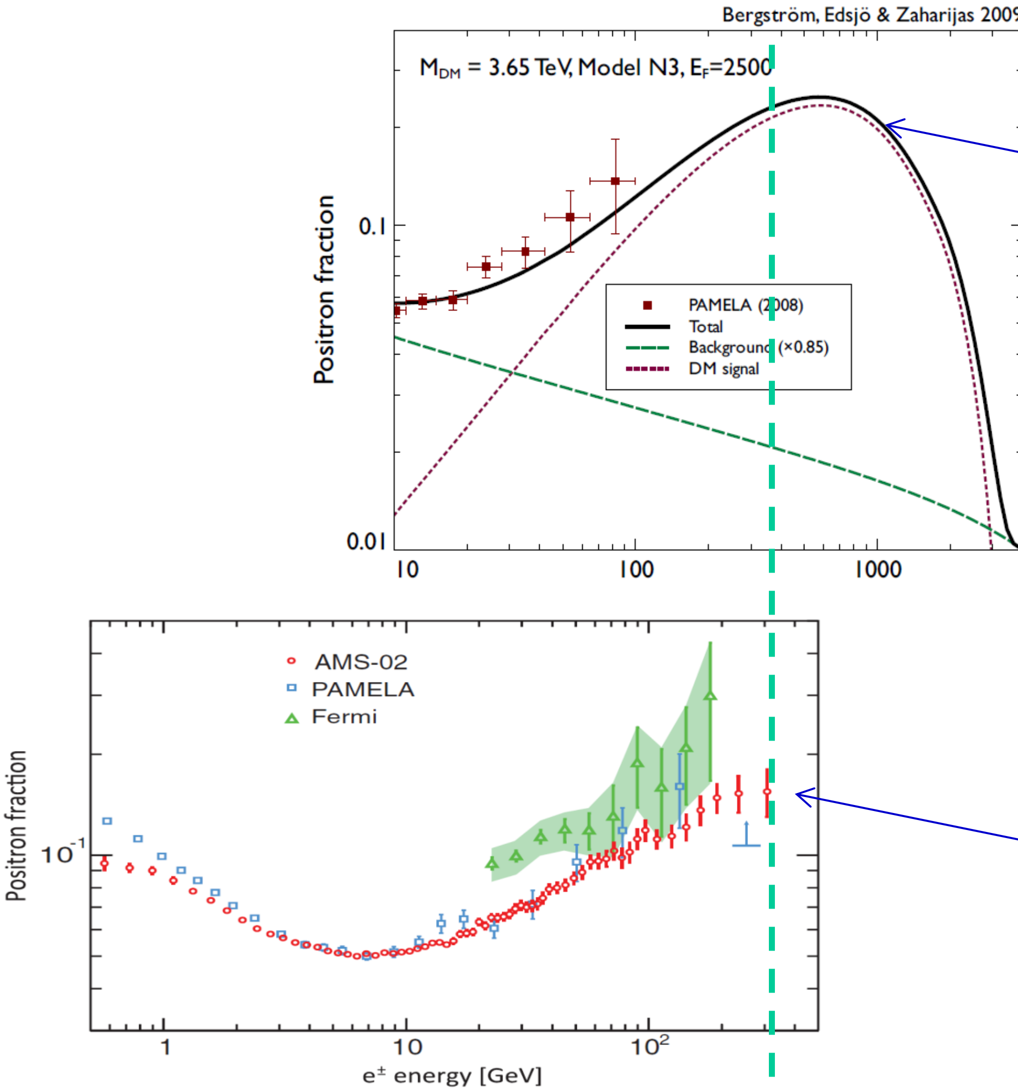
Up to here checked by AMS (data presented April 3, 2013)





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

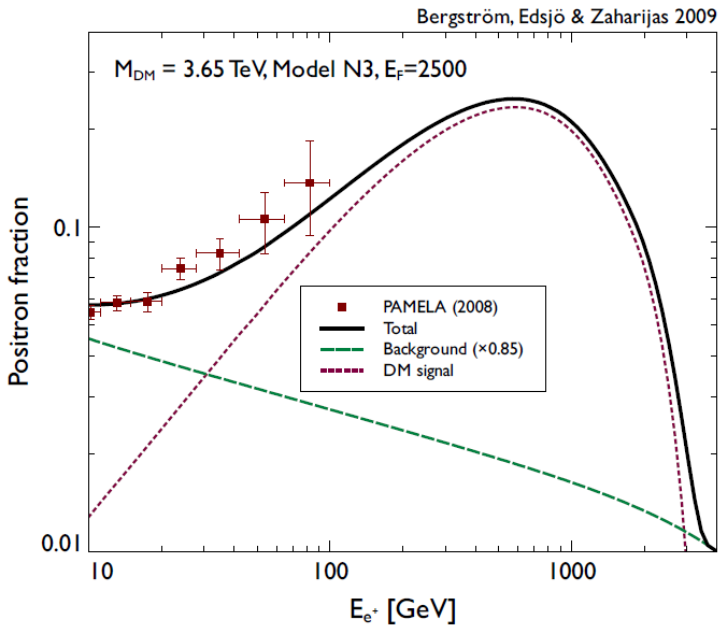
L.B., J. Edsjö, G. Zaharijas, 2009:

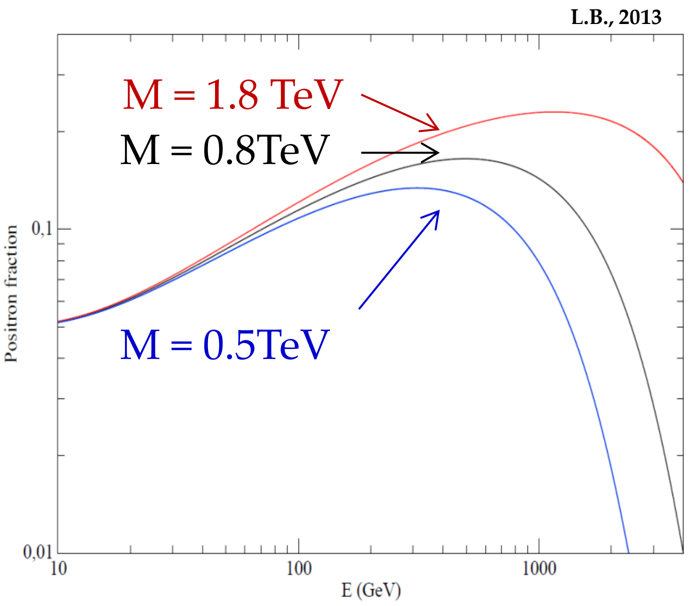


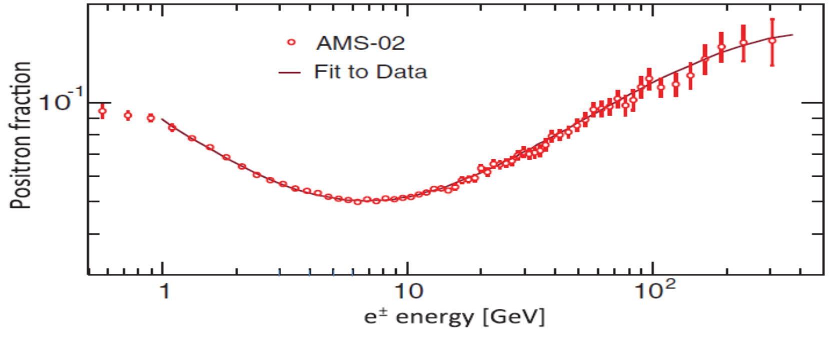
Prediction:
fall-off after rise

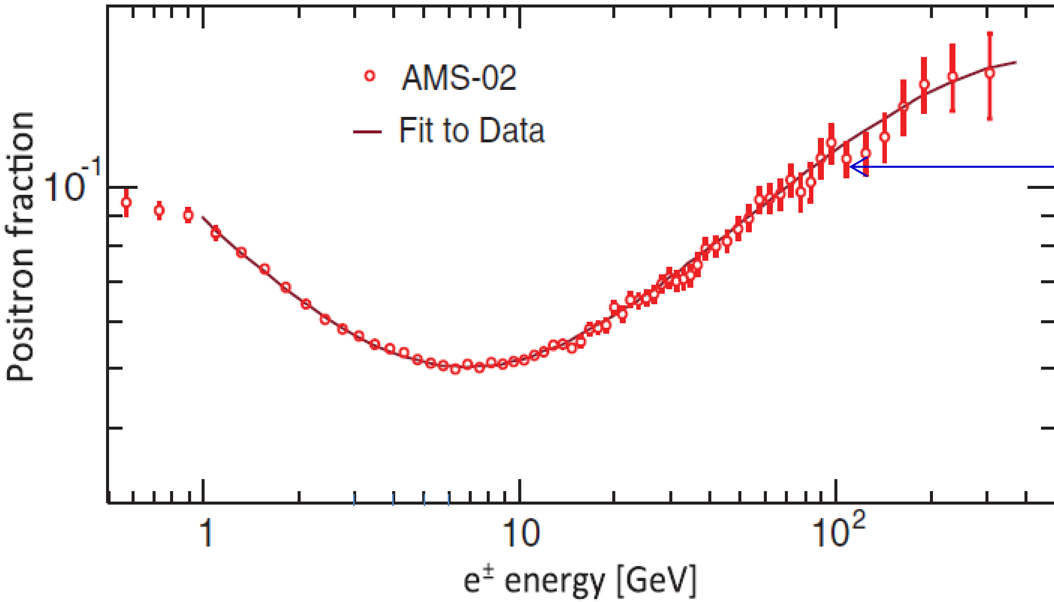
Indications of a
fall-off?

New AMS-02 data, April, 2013

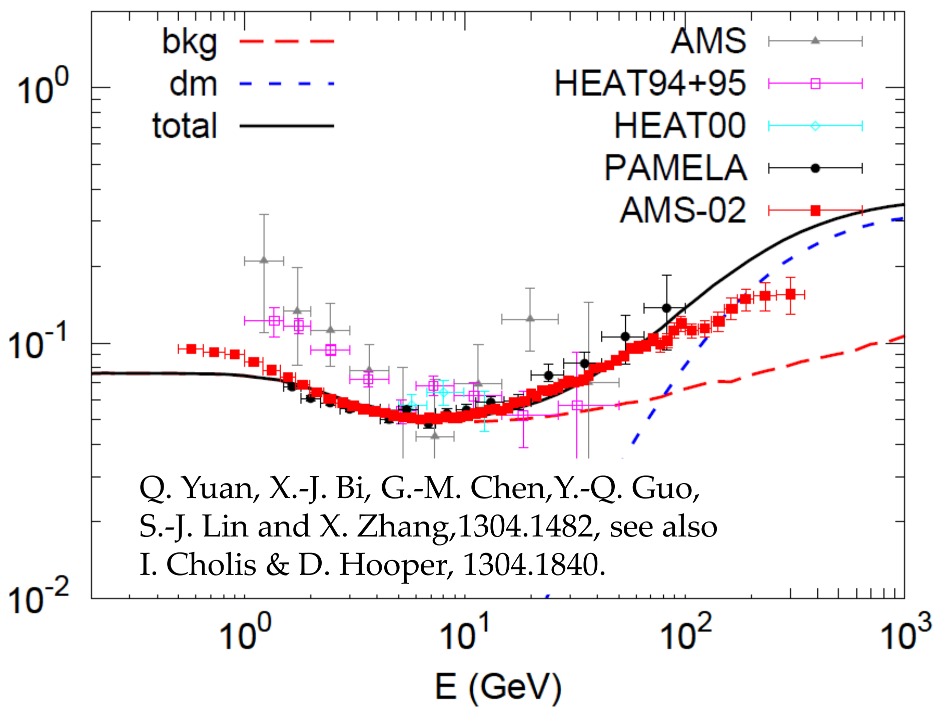

Bergström, Edsjö & Zaharijas 2009
M_DM = 3.65 TeV, Model N3, E_F=2500
PAMELA (2008)
Total
Background (×0.85)
DM signal
Positron fraction
0.1
0.01
10
100
1000
E_e+ [GeV]

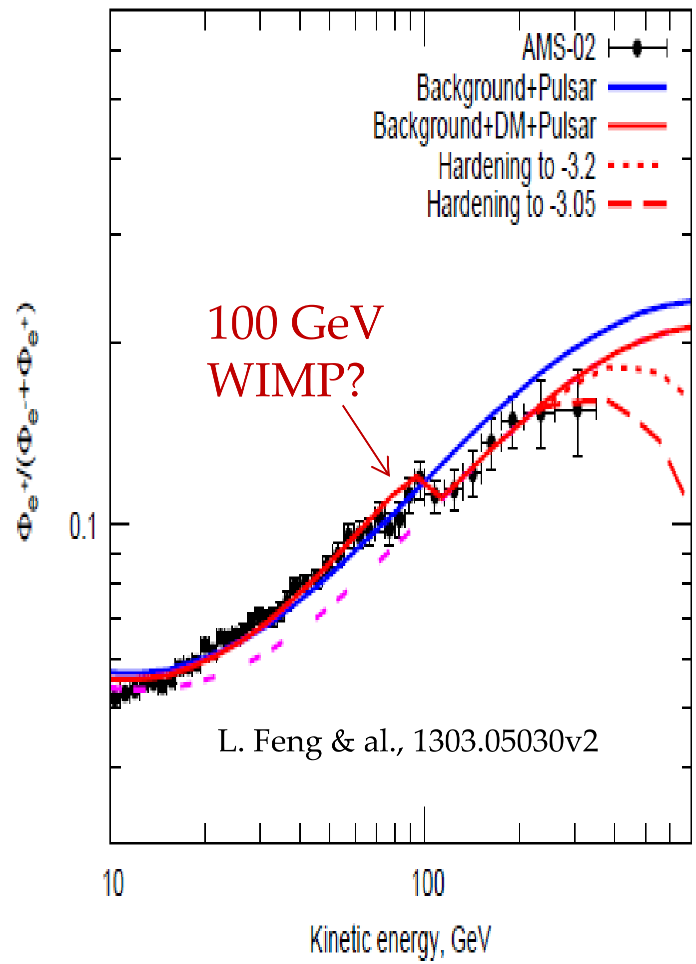

L.B., 2013
M = 1.8 TeV
M = 0.8TeV
M = 0.5TeV
Positron fraction
0,1
0,01
10
100
1000
E (GeV)


AMS-02
Fit to Data
Positron fraction
10^-1
1
10
10^2
e± energy [GeV]



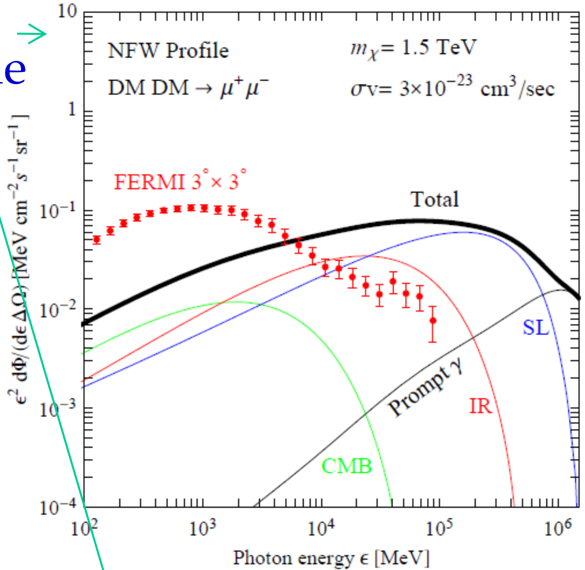
Is there a step here?

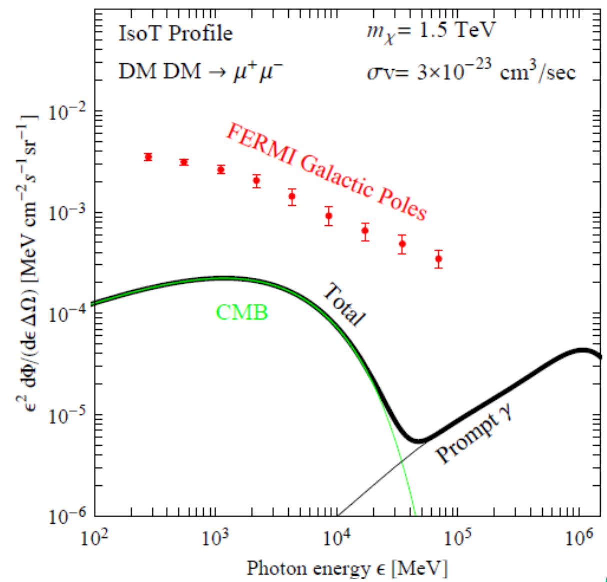




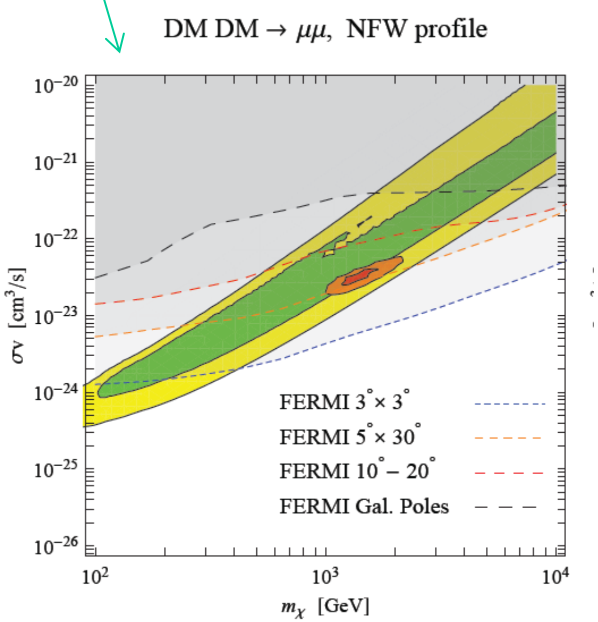
Consistency tests: M. Cirelli, P. Panci & P.D. Serpico, Dec. 2009

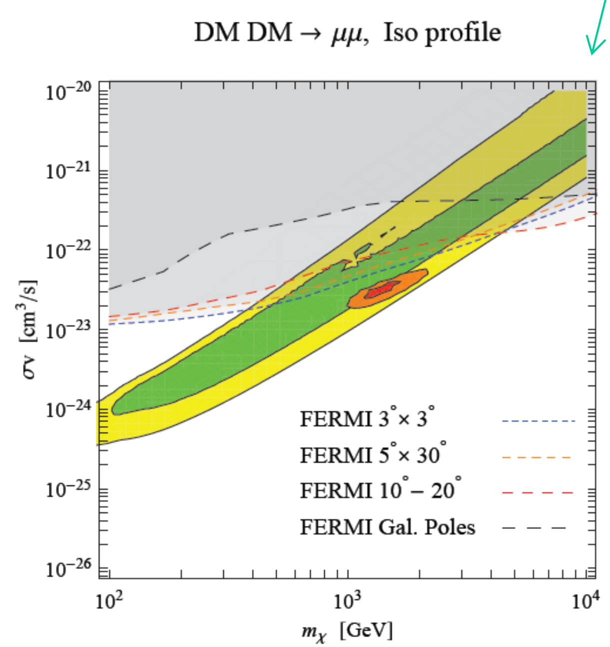
NFW profile





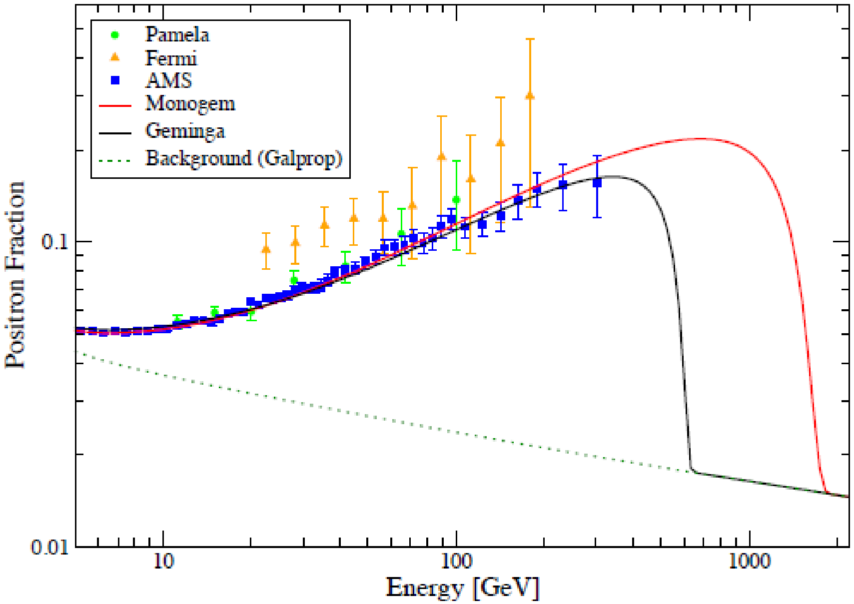
Cored isothermal profile

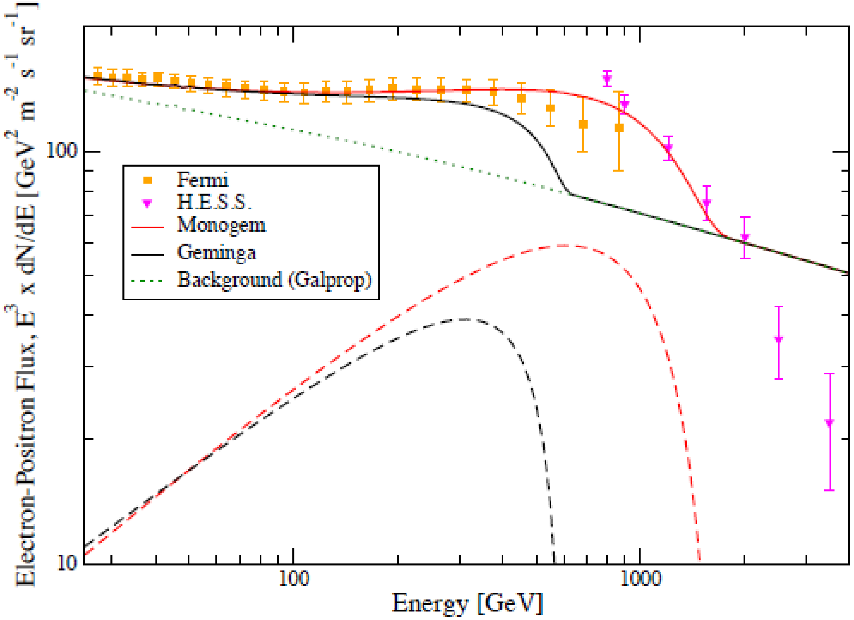


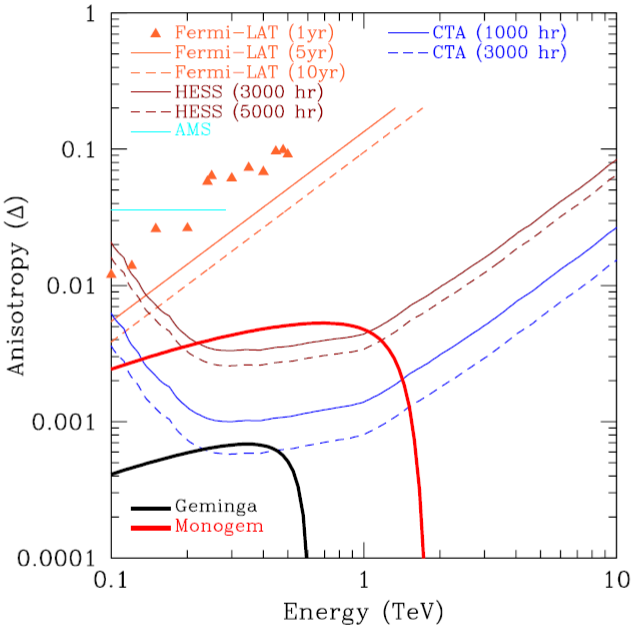


cf. also I. Cholis, G. Dobler, D. Finkbeiner, L. Goodenough, T. Slatyer & N. Weiner, 2009; M. Papucci & A. Strumia, 2009

Pulsars: T. Linden & D. Hooper, 1304.1791

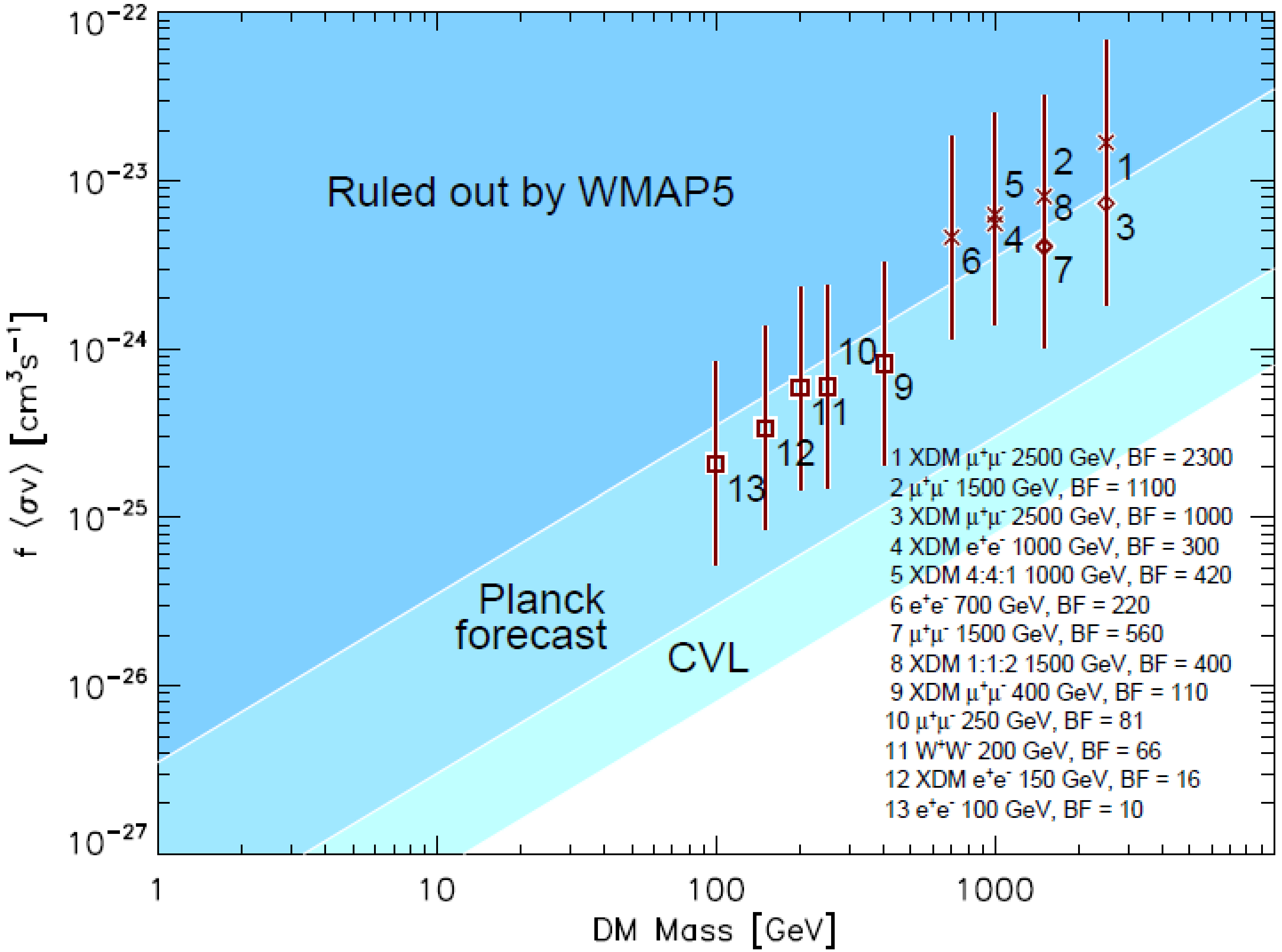






Anisotropy should be measurable with HESS and/or CTA

Planck will be important (no analysis yet):



Slatyer, Padmanhaban and Finkbeiner, 2009

WMAP 9-year limits on e.m. injection from DM

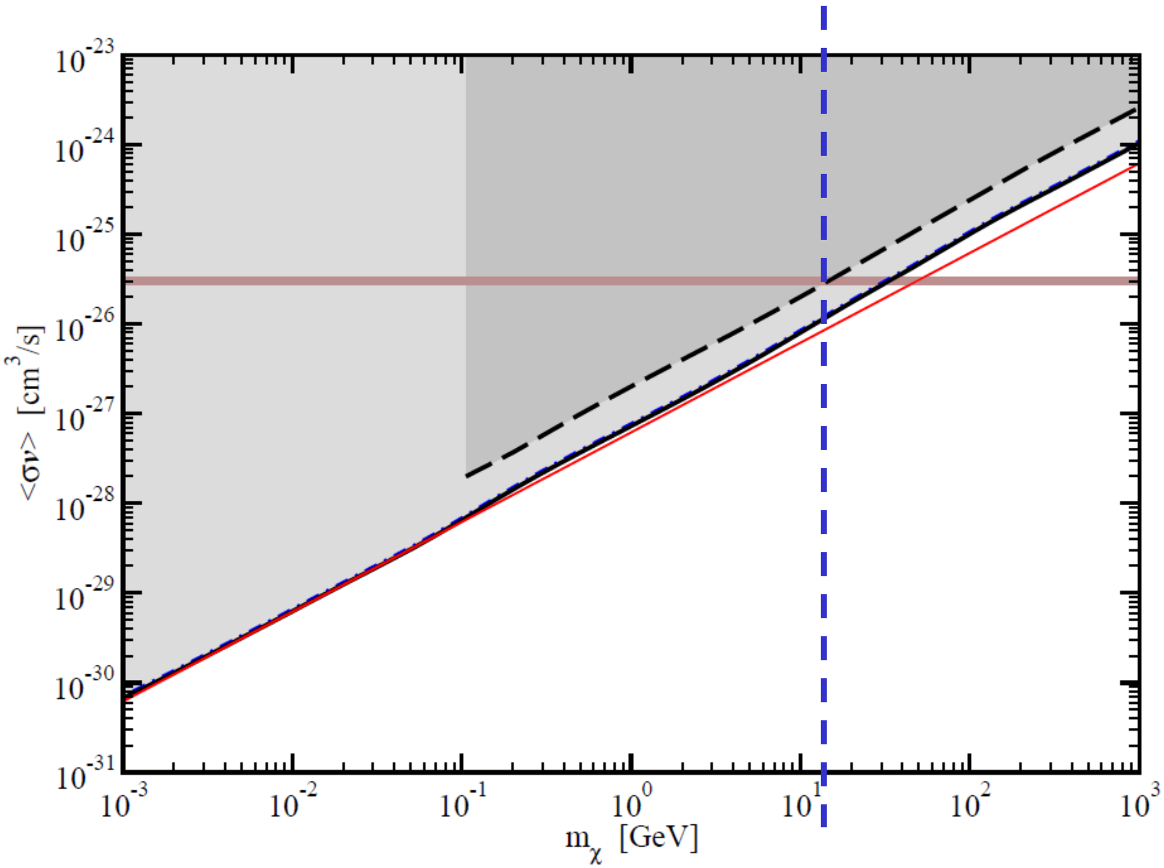


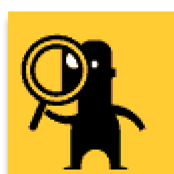
FIG. 7. 95% CL limits on the DM annihilation cross section $\langle\sigma v\rangle$ as a function of the DM mass m_χ for the "SPT" (WMAP9+SPT'11+HST+BAO) and "ACT" (WMAP9+ACT'10+HST+BAO) datasets. The middle solid black (SPT'11) and dot–dashed blue (ACT'10) lines assume an effective deposition efficiency $f_{\rm eff}(m_\chi)$ for $\chi\chi \to e^+e^-$. For the lower solid red line (SPT'11) we assume perfect efficiency, $f(z, m_\chi) = 1$, for $\chi\chi \to e^+e^-$. The upper dashed black line (SPT'11) shows the bounds for $\chi\chi \to \mu^+\mu^-$ with the corresponding effective energy deposition efficiency $f_{\rm eff}(m_\chi)$ for this channel. Note that the results are identical when we include the contribution from DM annihilation in halos as parametrized in this work (see the text). We also show the value of the canonical thermal annihilation cross section, $\langle\sigma v\rangle = 3 \times 10^{-26} {\rm cm}^3{\rm s}^{-1}$.

L. Lopez-Honorez & al., 1303.5094 (Still no results from Planck, 2013)

Conclusion so far:

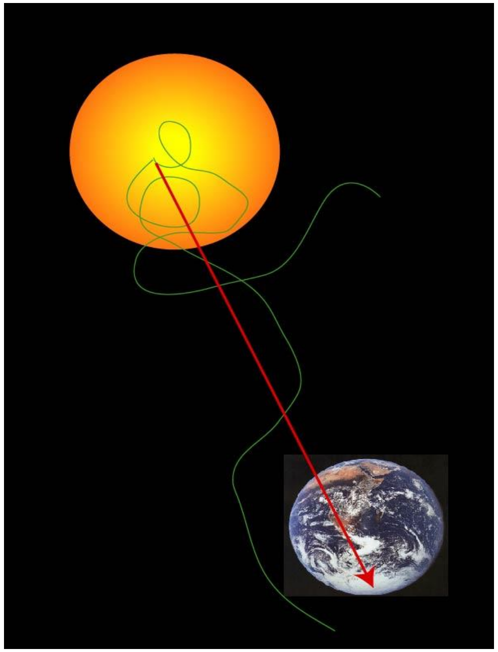
Despite candidates for DM signals existing it is difficult to prove that a viable dark matter particle is the cause.

There are well-motivated, other astrophysical and detector-related processes that may give essentially identical distributions.



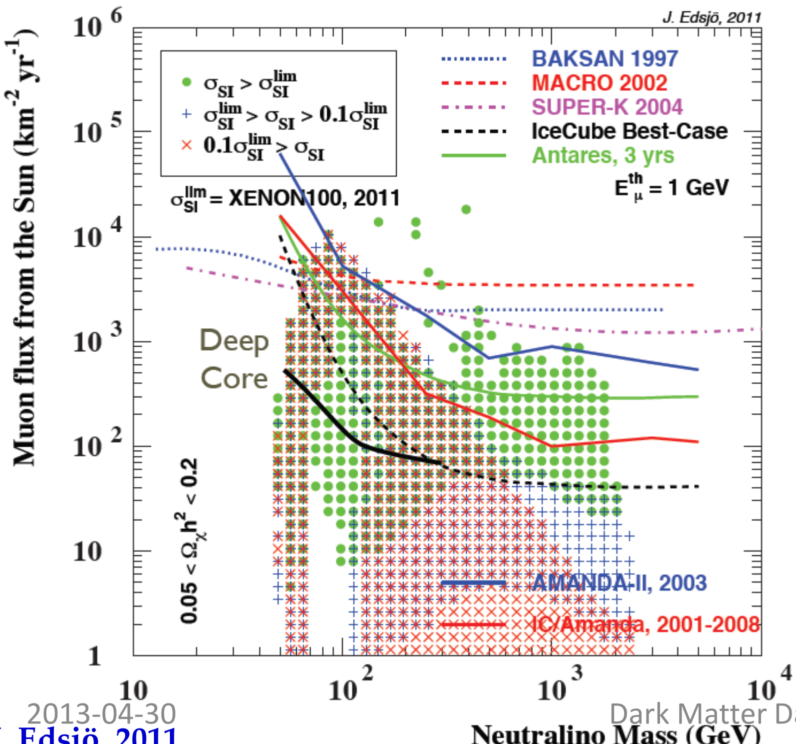
How do we find the DM suspect?

Smoking gun →

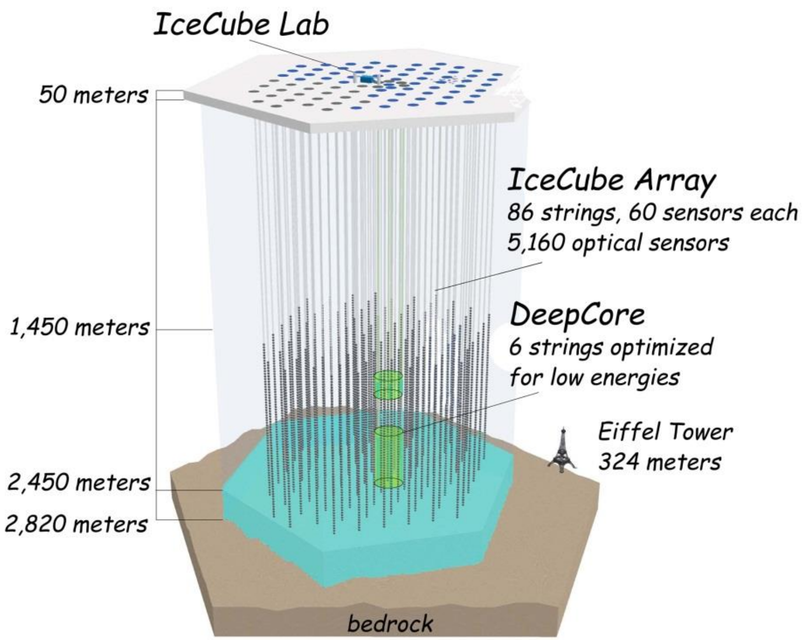


Indirect detection by neutrinos from annihilation in the Sun:

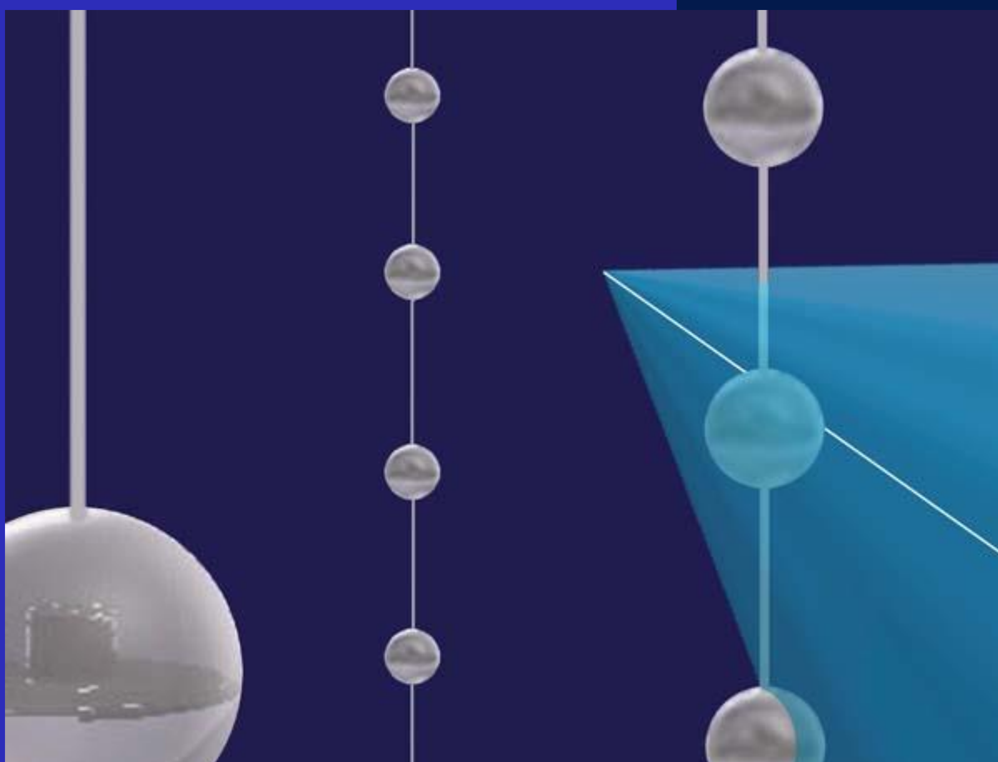
Competitive, due to high proton content of the Sun ⇒ sensitive to spin-dependent interactions. With full IceCube-80 and DeepCore-6 inset operational now, a large new region will be probed.
(Neutrinos from the Earth: Not competitive with spin-independent direct detection searches due to spin-0 elements only in the Earth).

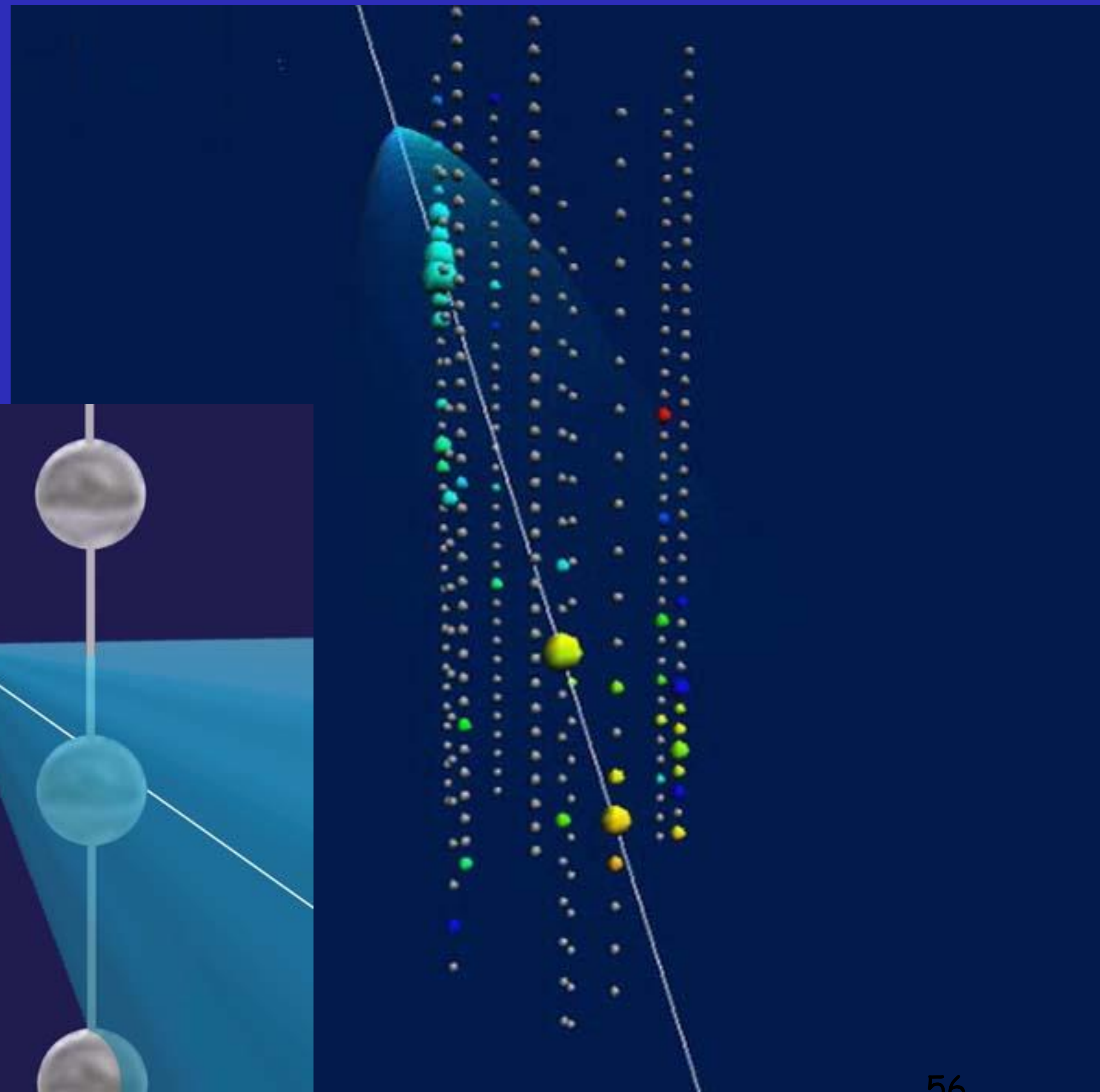


J. Edsjö, 2011



IceCube



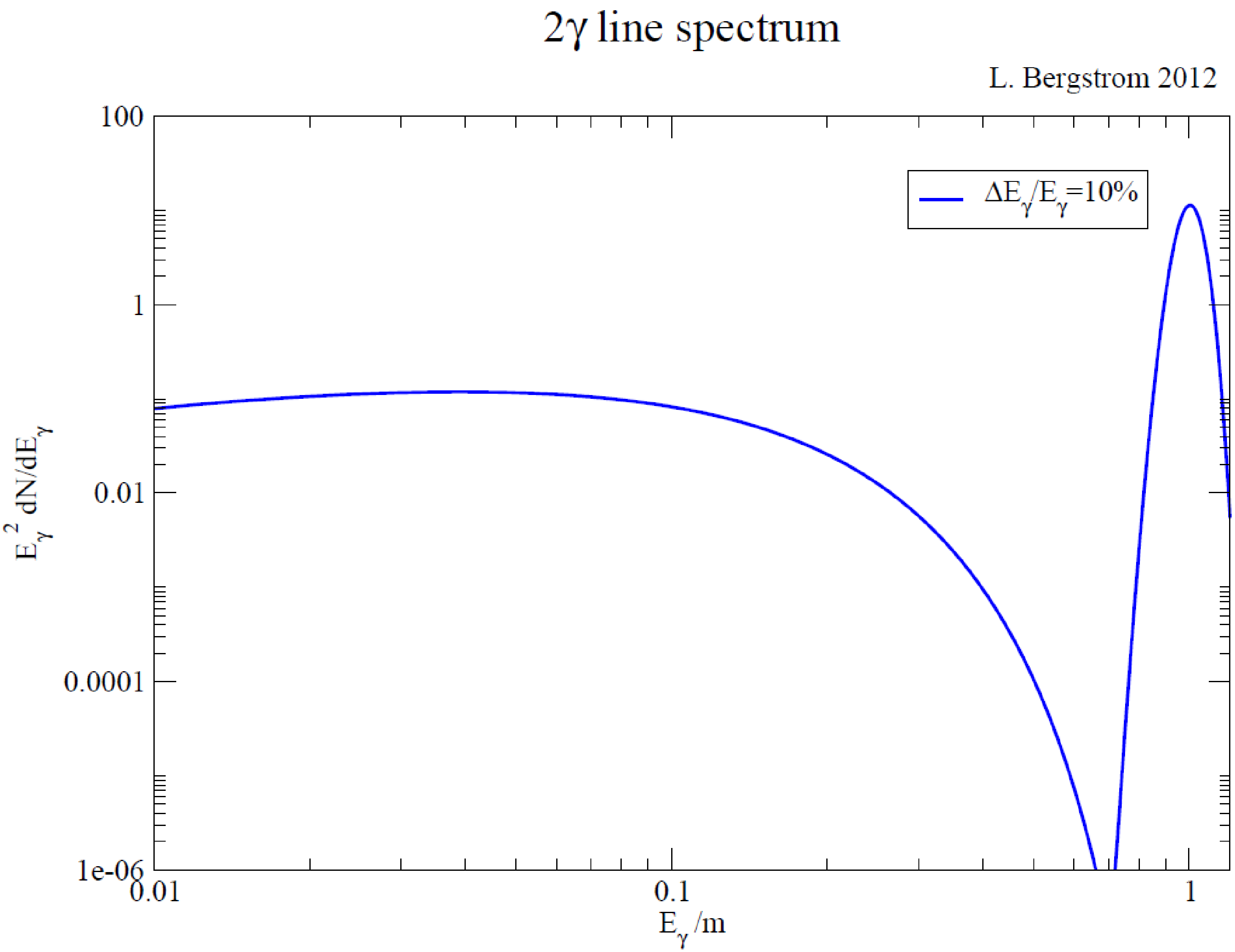


Summary for neutrinos

Can not be detected from annihilation in the halo (the interaction rate of neutrinos are too small), except perhaps in the case of an extreme concentration of DM (a ”spike”) near the black hole at the galactic center.

However, gravitational trapping of DM in the Sun may give a signal with a striking signature. The Earth seems less promising due to the strong limits now coming from direct detection.

The "smoking gun" signal in the gamma-ray energy distribution



Computing the gamma-ray line (L.B. & H. Snellman, 1988; L.B. & P. Ullio, 1997):

Here

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

This gives

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

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

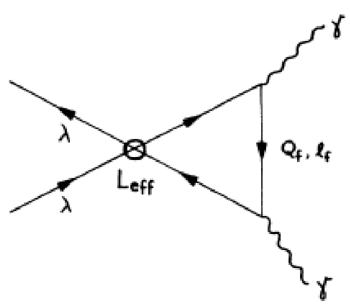
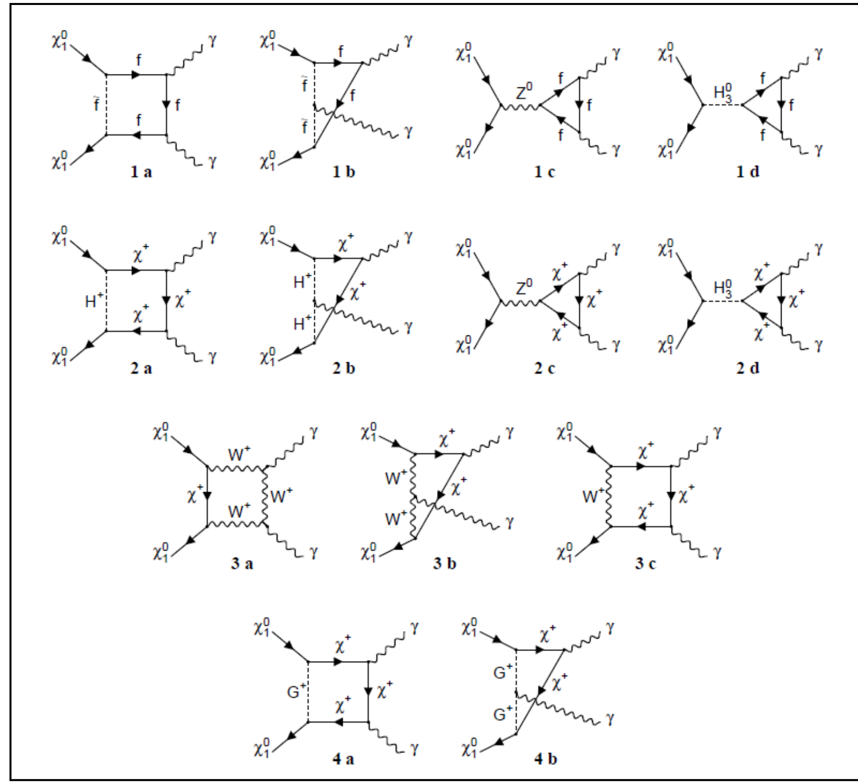


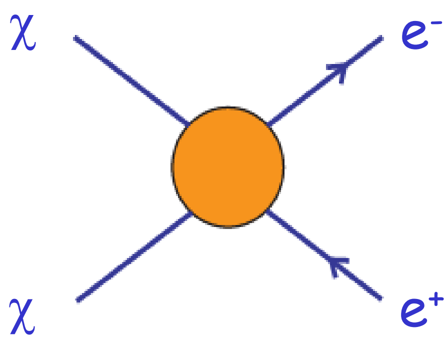
FIG. 3. Effective loop diagrams that contribute to the process $\lambda\bar{\lambda}\to\gamma\gamma$.



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

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

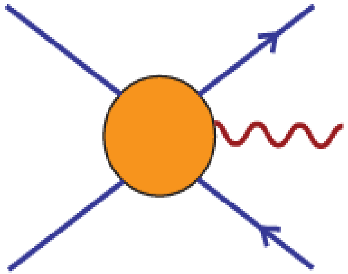
Internal bremsstrahlung: The surprising size of QED "corrections" for slowly annihilating Majorana particles. Example: e^+e^- channel



Annihilation rate $(\sigma v)_0 \sim 3\cdot10^{-26}$ $cm^{-3}s^{-1}$ at freeze-out, due to p-wave at $(v/c)^2 \sim 0.3$. $\Omega_{CDM}h^2 = 0.1$ for mass ~ 100 - 500 GeV.

Annihilation rate today is in the s-wave, since $v/c \sim 10^{-3}$ i.e. almost at rest. This is suppressed by factor $(m_e/m_\chi)^2$ for Majorana particles.

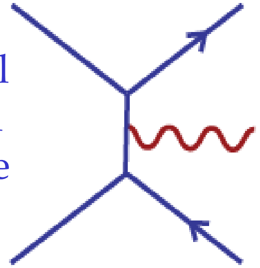
Impossible to detect! Even adding p-wave, it is too small, by orders of magnitude.



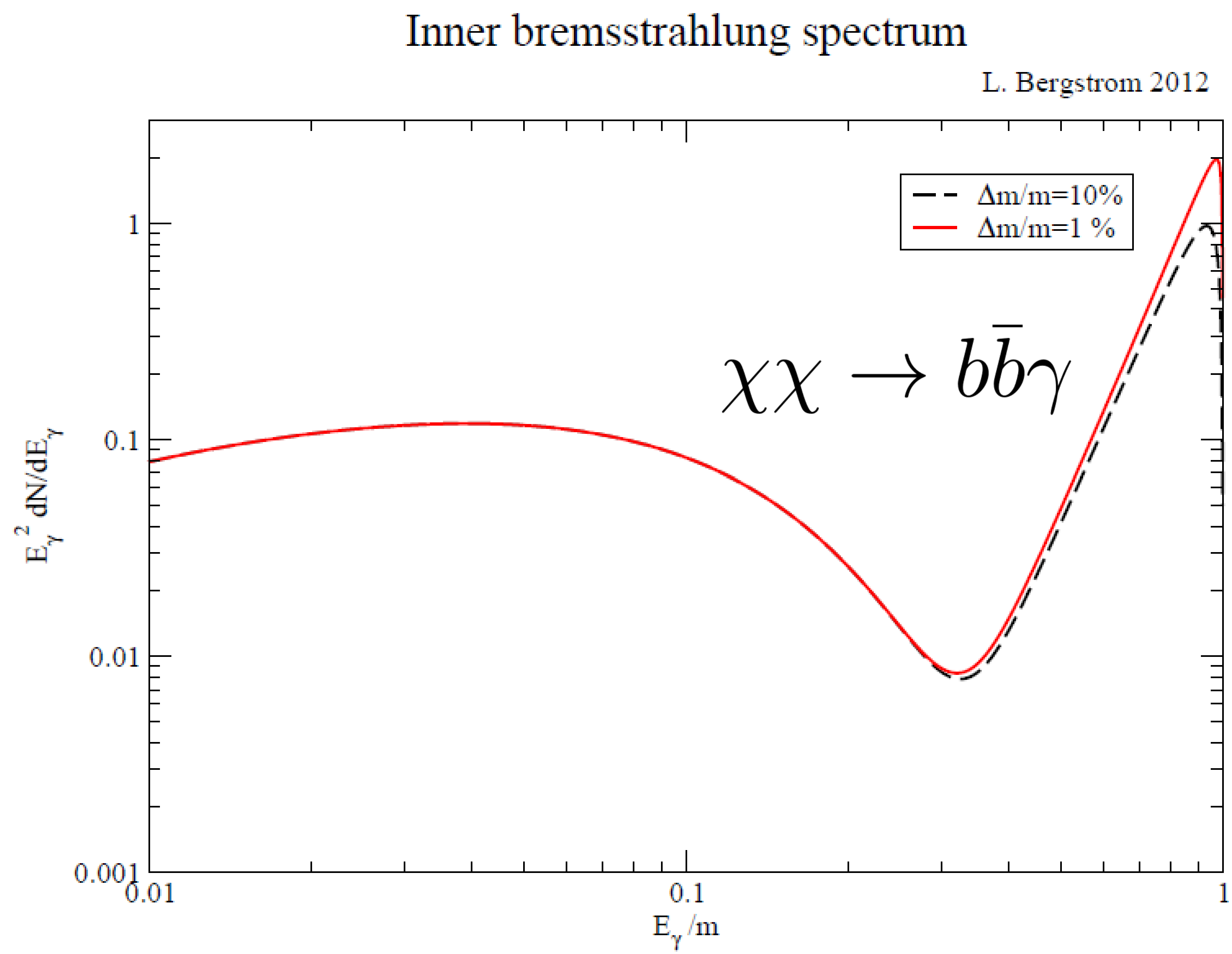
Direct emission (inner bremsstrahlung) QED "correction": $(\sigma v)_{QED}/ (\sigma v)_0 \sim (\alpha/\pi)\ (m_\chi/m_e)^2 \sim 10^9 \Rightarrow 10^{-28}$ cm^3s^{-1}

The "expected" QED correction of a few per cent is here a factor of 10^8 instead! May give detectable gamma-ray rates – with good signature!

t-channel selectron exchange



(L.B. 1989; E.A. Baltz & L.B. 2003, T. Bringmann, L.B. & J. Edsjö, 2008; M. Ciafalone, M. Cirelli, D. Comelli, A. De Simone, A. Riotto & A. Urbano, 2011; N. F. Bell, J.B. Dent, A.J. Galea,T.D. Jacques, L.M. Krauss and T.J.Weiler, 2011)



Inner bremsstrahlung spectrum
L. Bergstrom 2012
Δm/m=10%
Δm/m=1 %
$\chi\chi \rightarrow b\bar{b}\gamma$
$E_\gamma^2\, dN/dE_\gamma$
1
0.1
0.01
0.001
0.01
0.1
1
E_γ/m

QED corrections (Internal Bremsstrahlung) in the MSSM: good news for detection probability in gamma-rays:

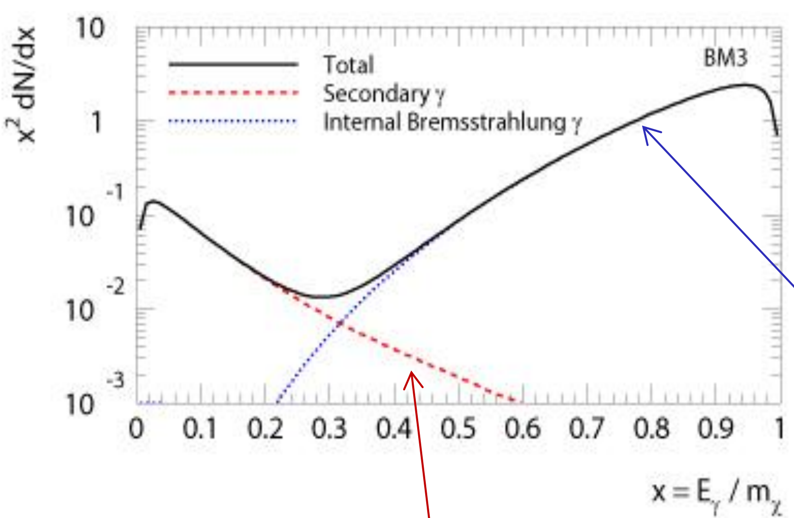
New Gamma-Ray Contributions to Supersymmetric Dark Matter Annihilation

JHEP, 2008

Torsten Bringmann*
SISSA/ISAS and INFN, via Beirut 2 - 4, I - 34013 Trieste, Italy

Lars Bergström† and Joakim Edsjö‡
Department of Physics, Stockholm University, AlbaNova University Center, SE - 106 91 Stockholm, Sweden

(Dated: October 16, 2007)



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

Predictions for the standard WIMP template, SUSY:

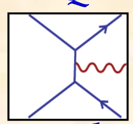
Indirect detection of SUSY DM through g-rays. Three types of signal:

• Continuous from π^0, K^0, … decays.

• Monoenergetic line from quantum loop effects, cc→γγ and Zγ.

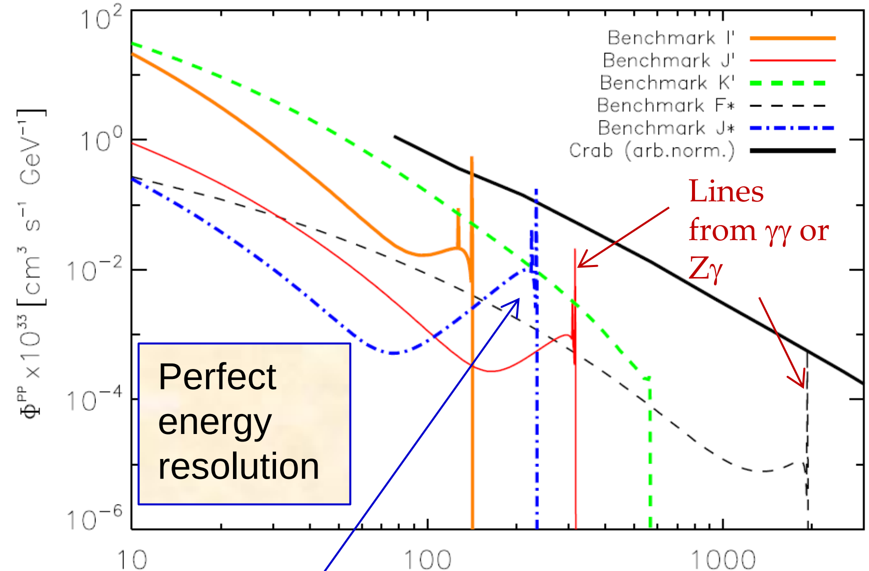
Smoking gun →

• Internal bremsstrahlung from QED process.

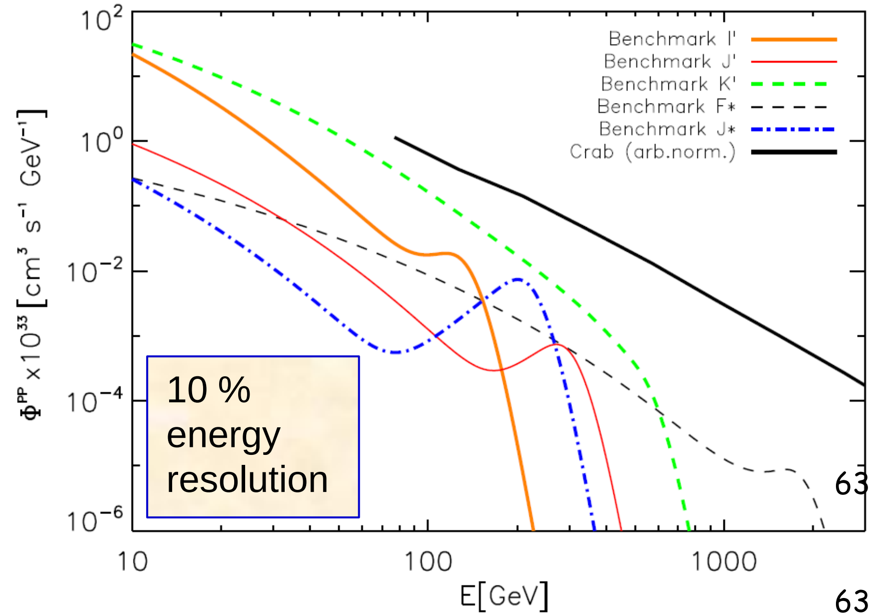


Enhanced flux possible thanks to halo density profile and substructure (as predicted by N-body simulations of CDM).

Good spectral and angular signatures! But uncertainties in the predictions of absolute rates, due e.g. to poorly known DM density profile.

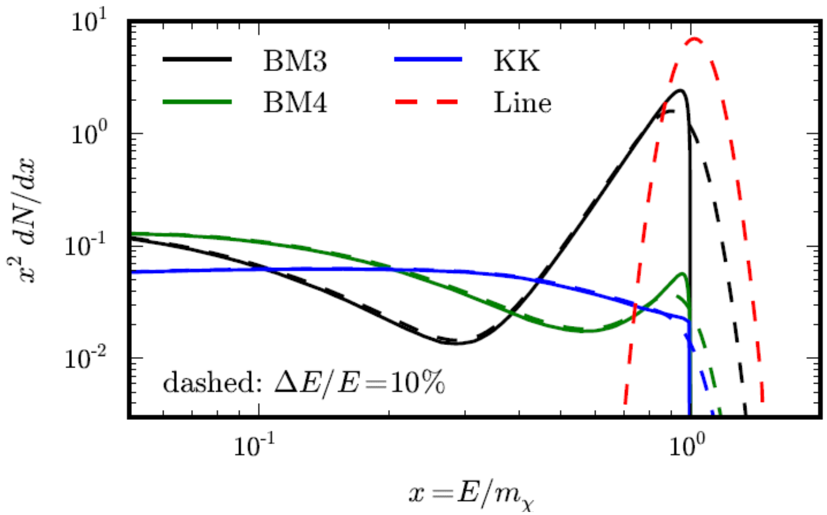


New contribution: Internal bremsstrahlung (T. Bringmann, L.B., J. Edsjö, 2007)

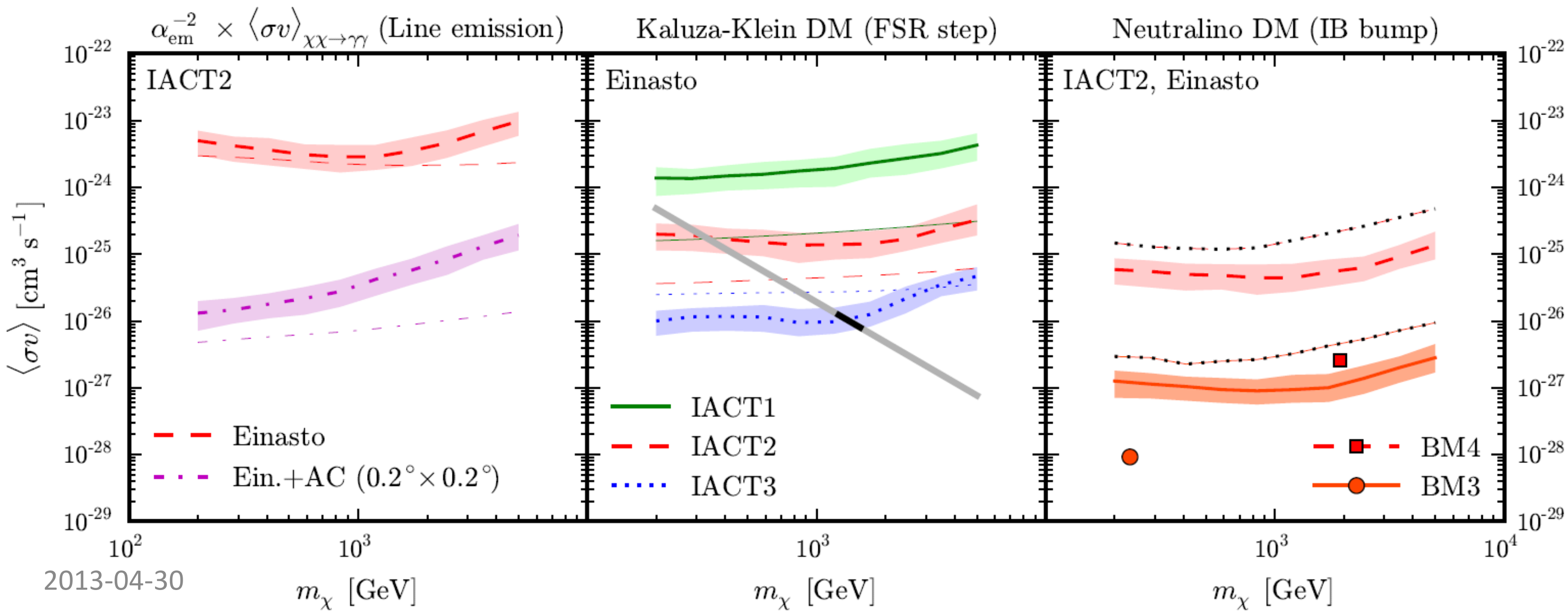


T. Bringmann, M. Doro & M. Fornasa, 2008; cf. L.B., P.Ullio & J. Buckley 1998.

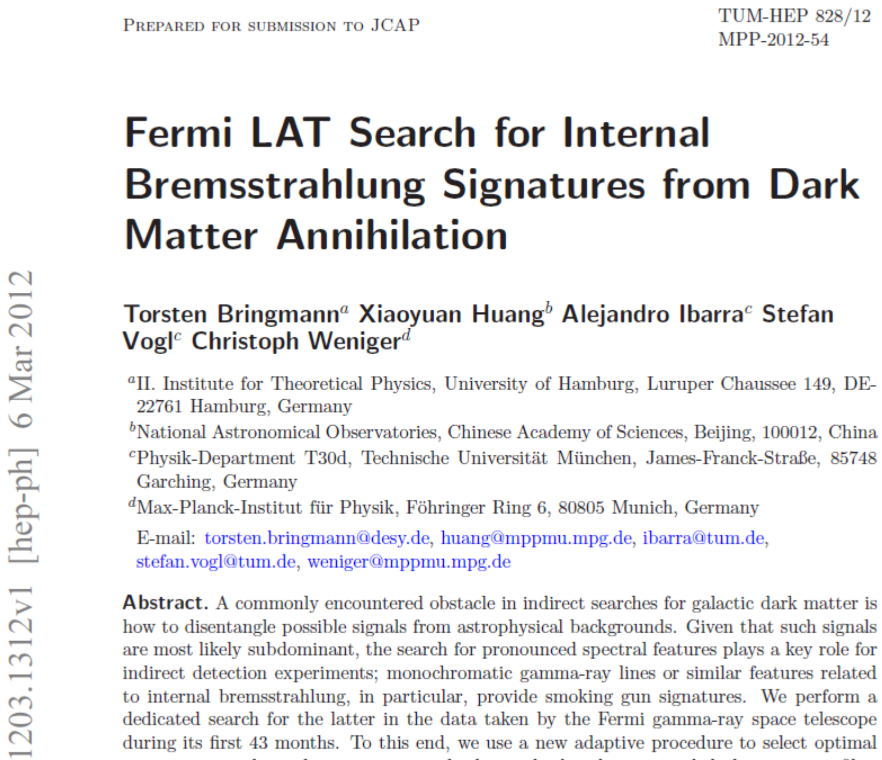
T. Bringmann, F. Calore, G. Vertongen & C. Weniger Phys. Rev. D, 2011



Can one make use of the peculiar spectral features?



The surprising line or IB signal found in public Fermi-Lat data, March 2012


PREPARED FOR SUBMISSION TO JCAP

TUM-HEP 828/12
MPP-2012-54

1203.1312v1 [hep-ph] 6 Mar 2012

Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation

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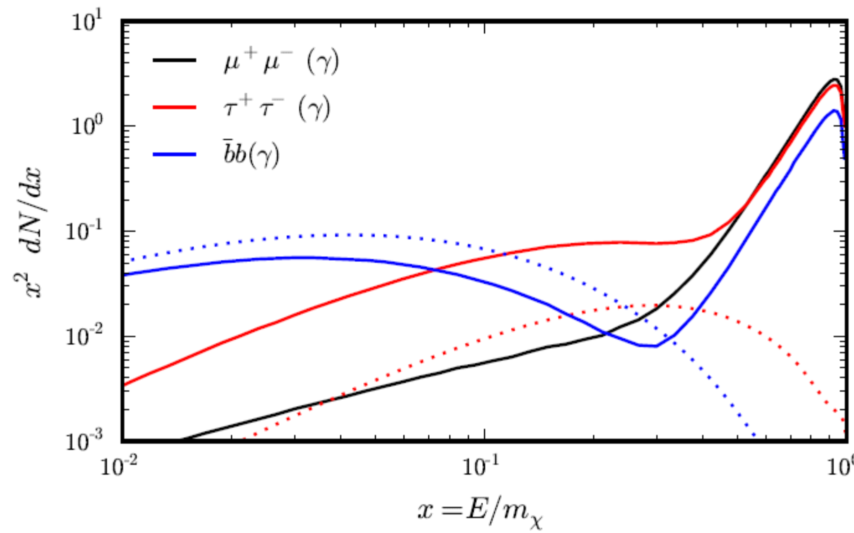
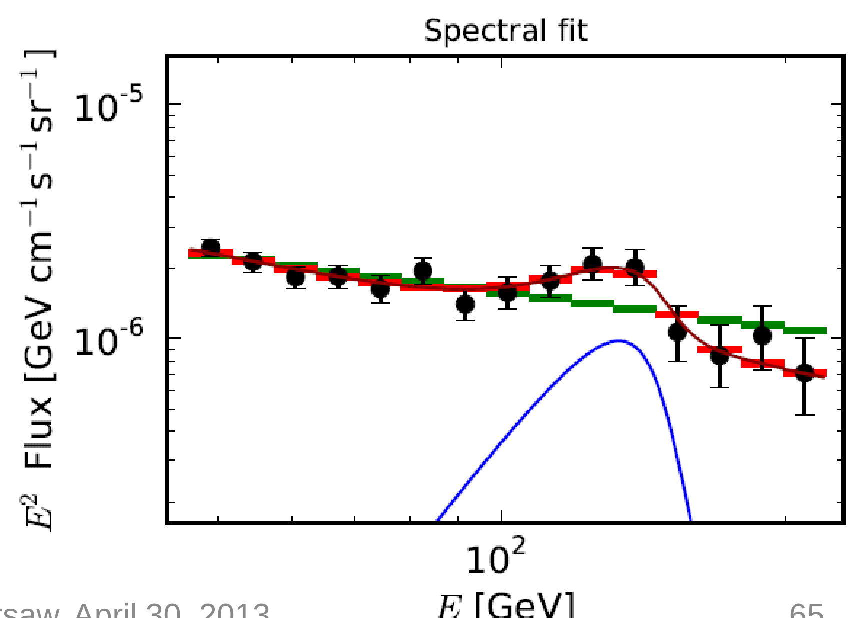
[a]II. Institute for Theoretical Physics, University of Hamburg, Luruper Chaussee 149, DE-22761 Hamburg, Germany
[b]National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012, China
[c]Physik-Department T30d, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany
[d]Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany

E-mail: torsten.bringmann@desy.de, huang@mppmu.mpg.de, ibarra@tum.de, stefan.vogl@tum.de, weniger@mppmu.mpg.de

Abstract. A commonly encountered obstacle in indirect searches for galactic dark matter is how to disentangle possible signals from astrophysical backgrounds. Given that such signals are most likely subdominant, the search for pronounced spectral features plays a key role for indirect detection experiments; monochromatic gamma-ray lines or similar features related to internal bremsstrahlung, in particular, provide smoking gun signatures. We perform a dedicated search for the latter in the data taken by the Fermi gamma-ray space telescope during its first 43 months. To this end, we use a new adaptive procedure to select optimal

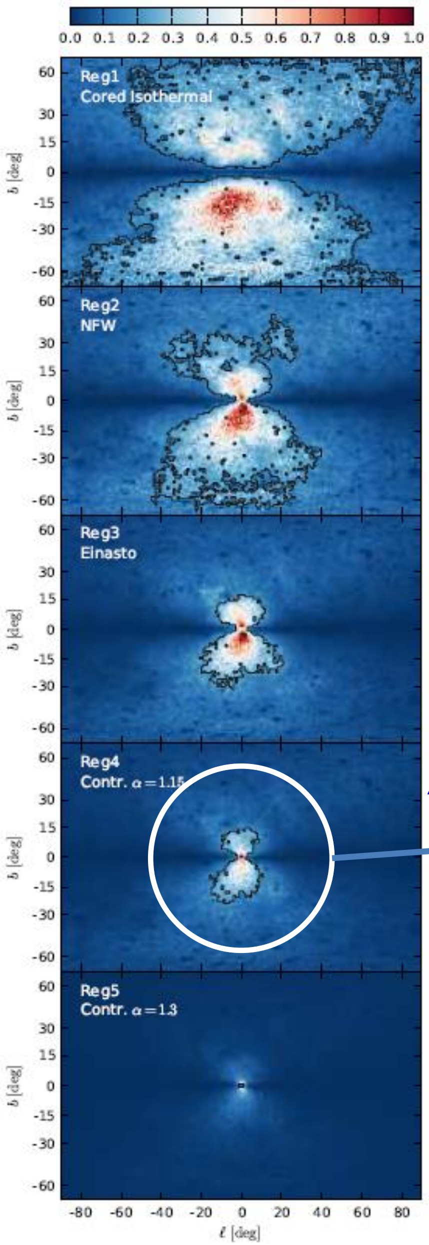


43 months of (public) Fermi data

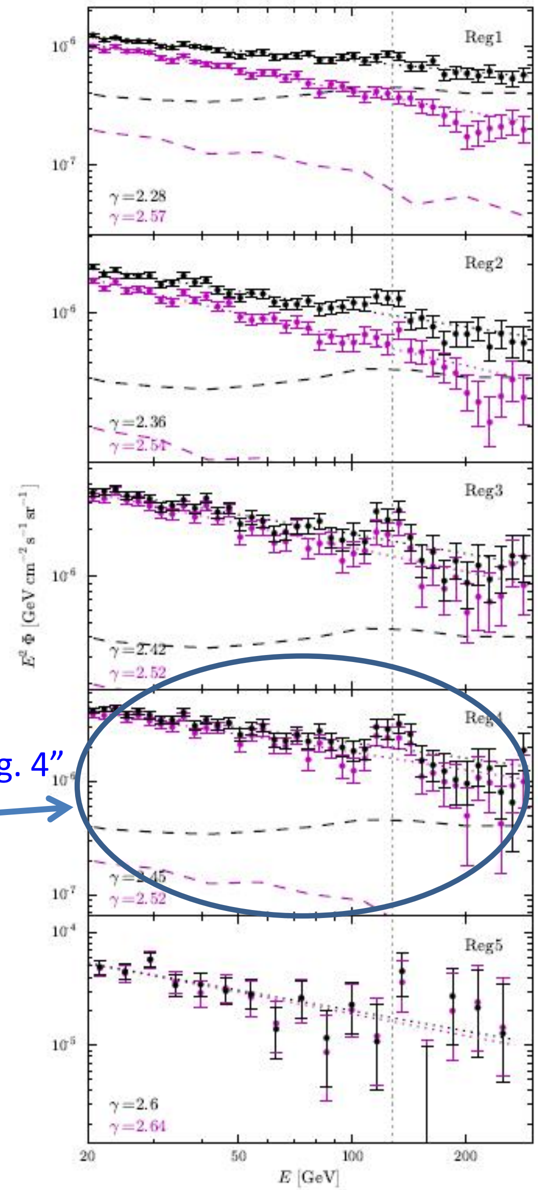


Mass = 149 GeV
Significance 4.3σ (3.1σ if "look elsewhere" effect included)

April, 2012: C. Weniger

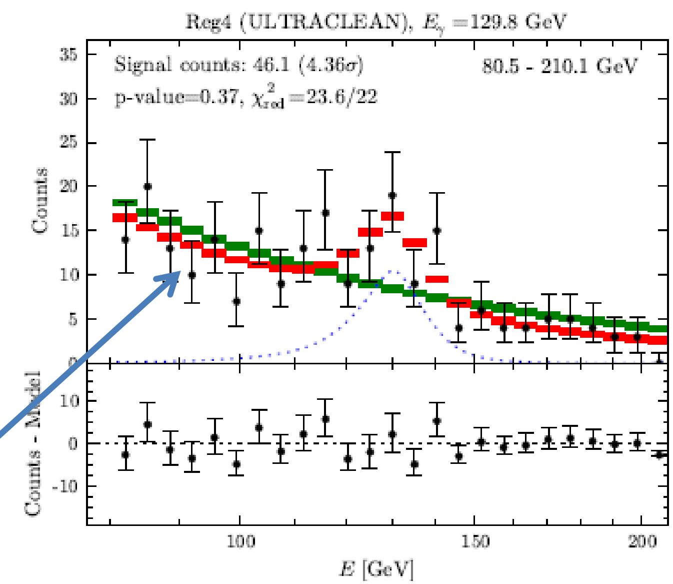


"Reg. 4"

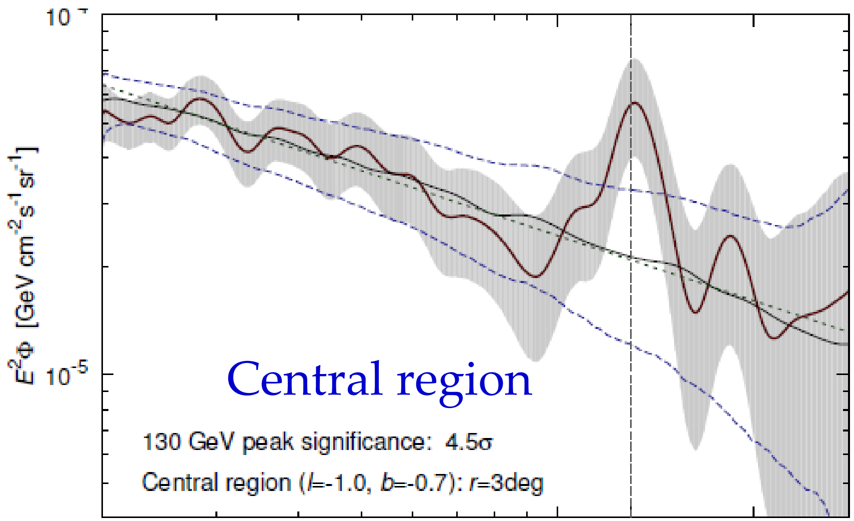


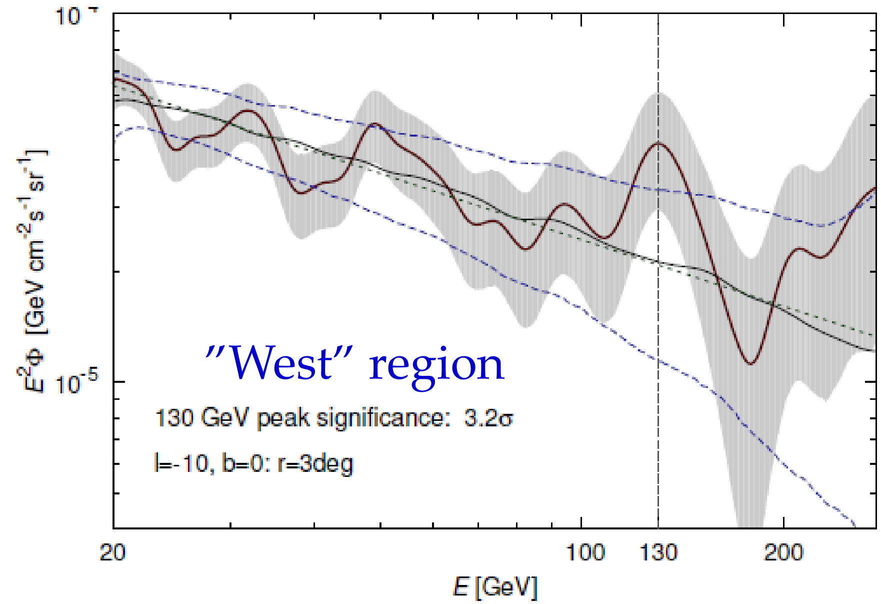
43 months of (public) Fermi data

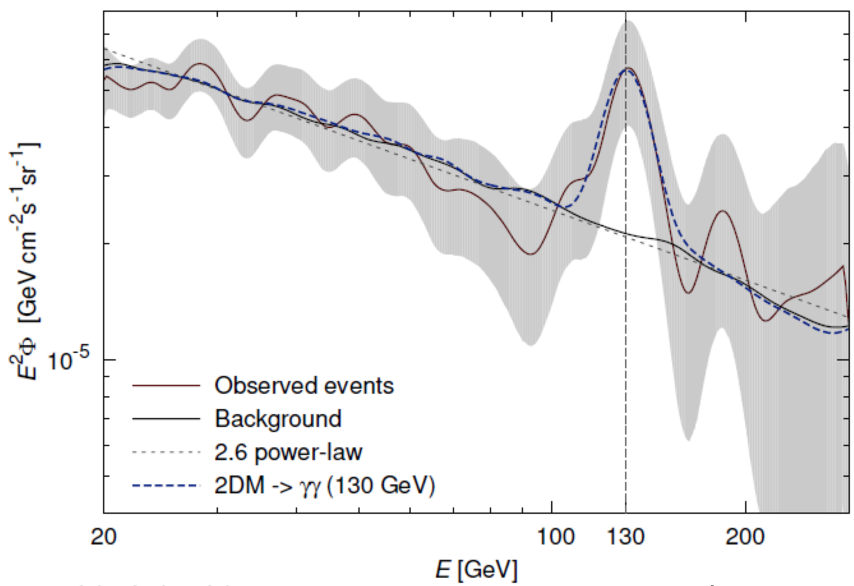
γ-ray line fit:



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

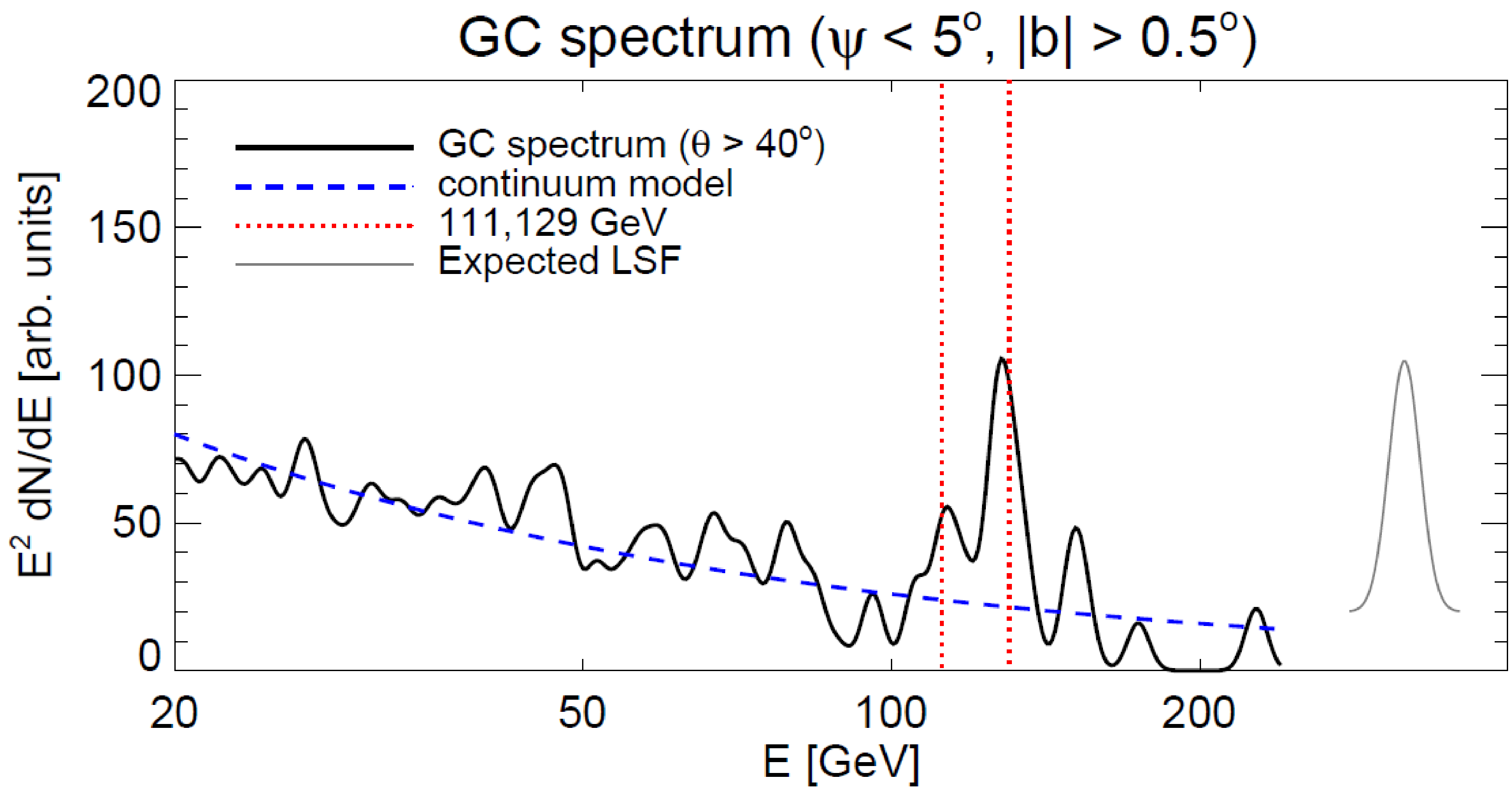






E. Tempel, A. Hektor and M. Raidal, May 2012:
Independent confirmation of the existence of the excess, and that it is not correlated with Fermi bubbles.

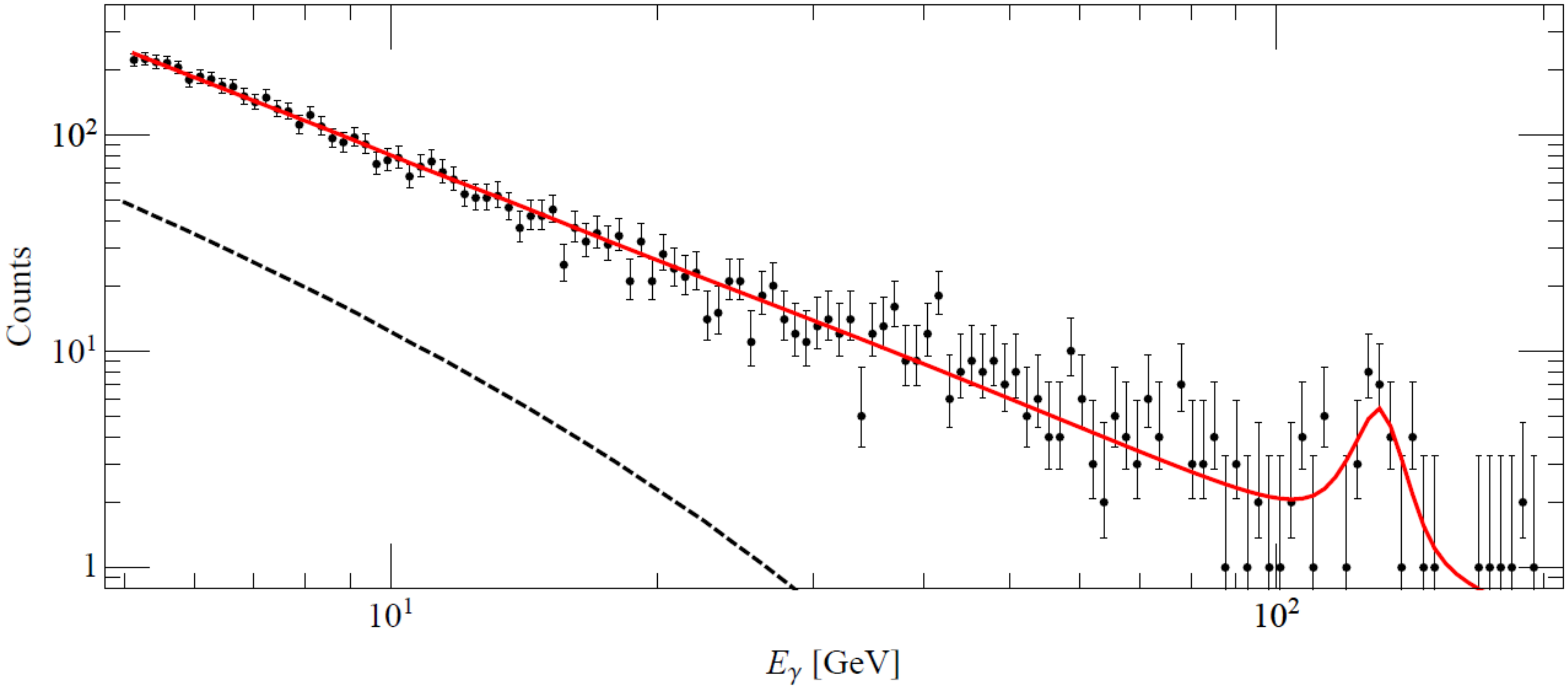
Best fit: $\gamma\gamma$ line, mass m_χ = 130 GeV



Another independent verification: M. Su and D. Finkbeiner, June 2012

T. Cohen, M. Lisanti, T. Slatyer & J. Wacker, arxiv:1207.0800:

Very little room for a continuum contribution -> some SUSY models ruled out



Fermi-LAT public data

L.B. & E.A. Baltz, Phys Rev D, 2002

The right-handed neutrino N_R (in "radiative see-saw" models) may be the dark matter candidate, and internal bremsstrahlung plus γγ annihilation will give a peculiar spectrum

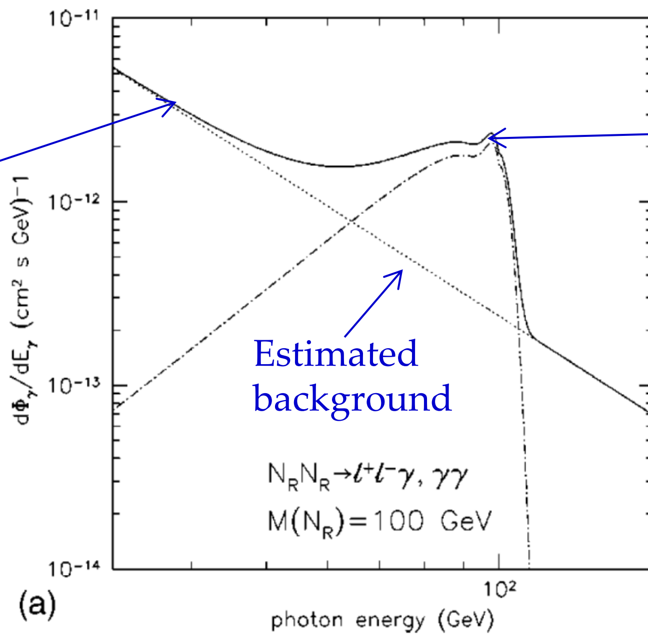
$$\sigma v\left(N_R N_R \rightarrow \ell^+\ell^-\right) = \frac{g_\ell^4}{8\pi m_N^4 (1+f^2)^2}\left[m_\ell^2 + \frac{2}{3}\left(\frac{1+f^4}{(1+f^2)^2}\right) m_N^2 v^2 + \ldots\right]$$

s wave part

p wave part

$f = m_S/m_N$

Note: no continuum here

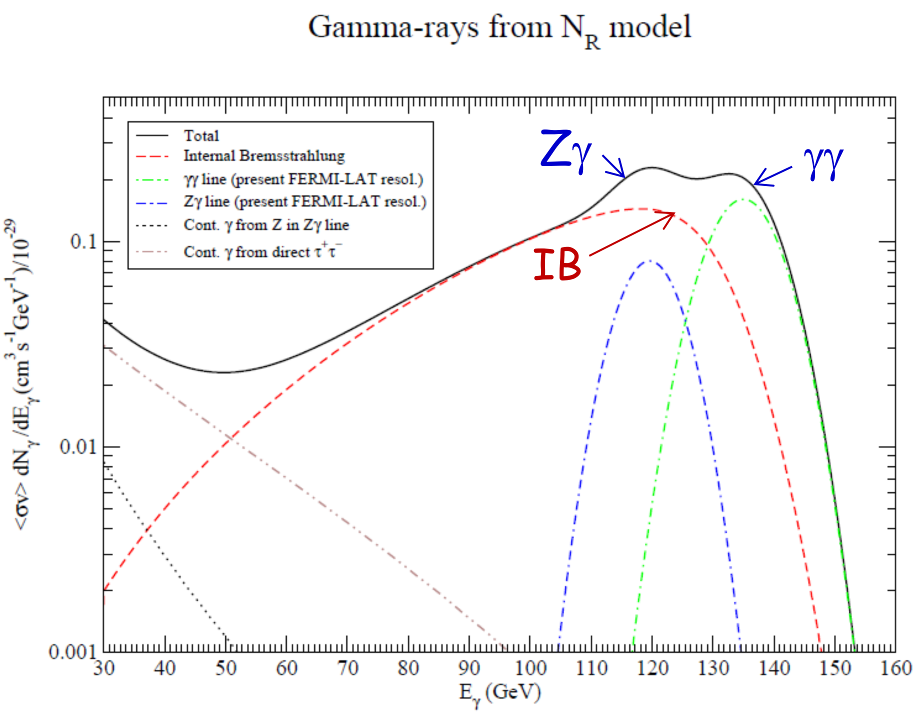


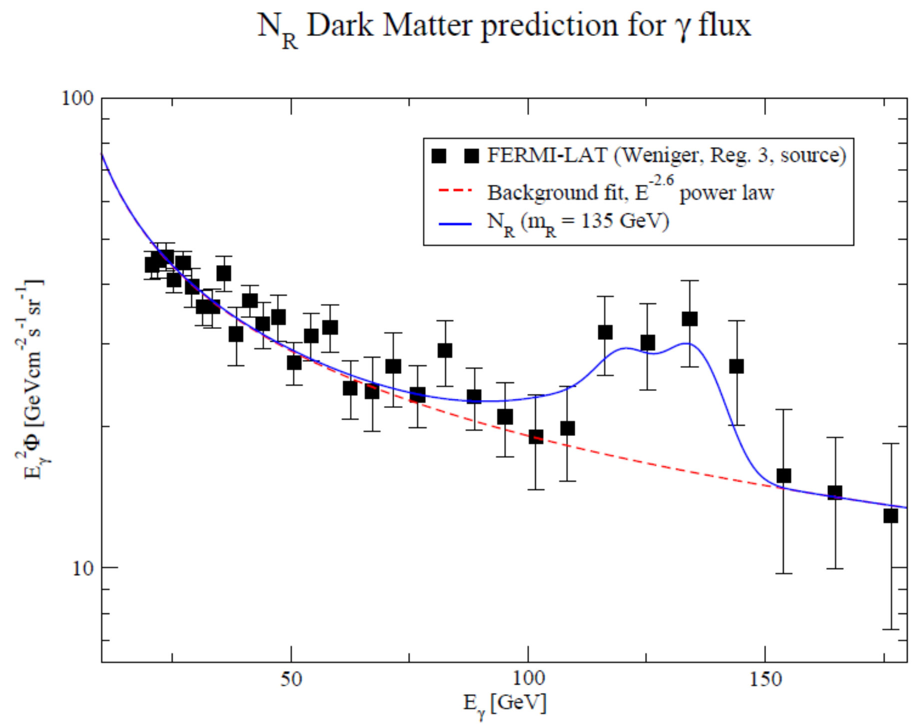
(a)

γγ peak

L.B.: Re-analysis of N_R model, mass 135 GeV (Phys Rev D 2012):

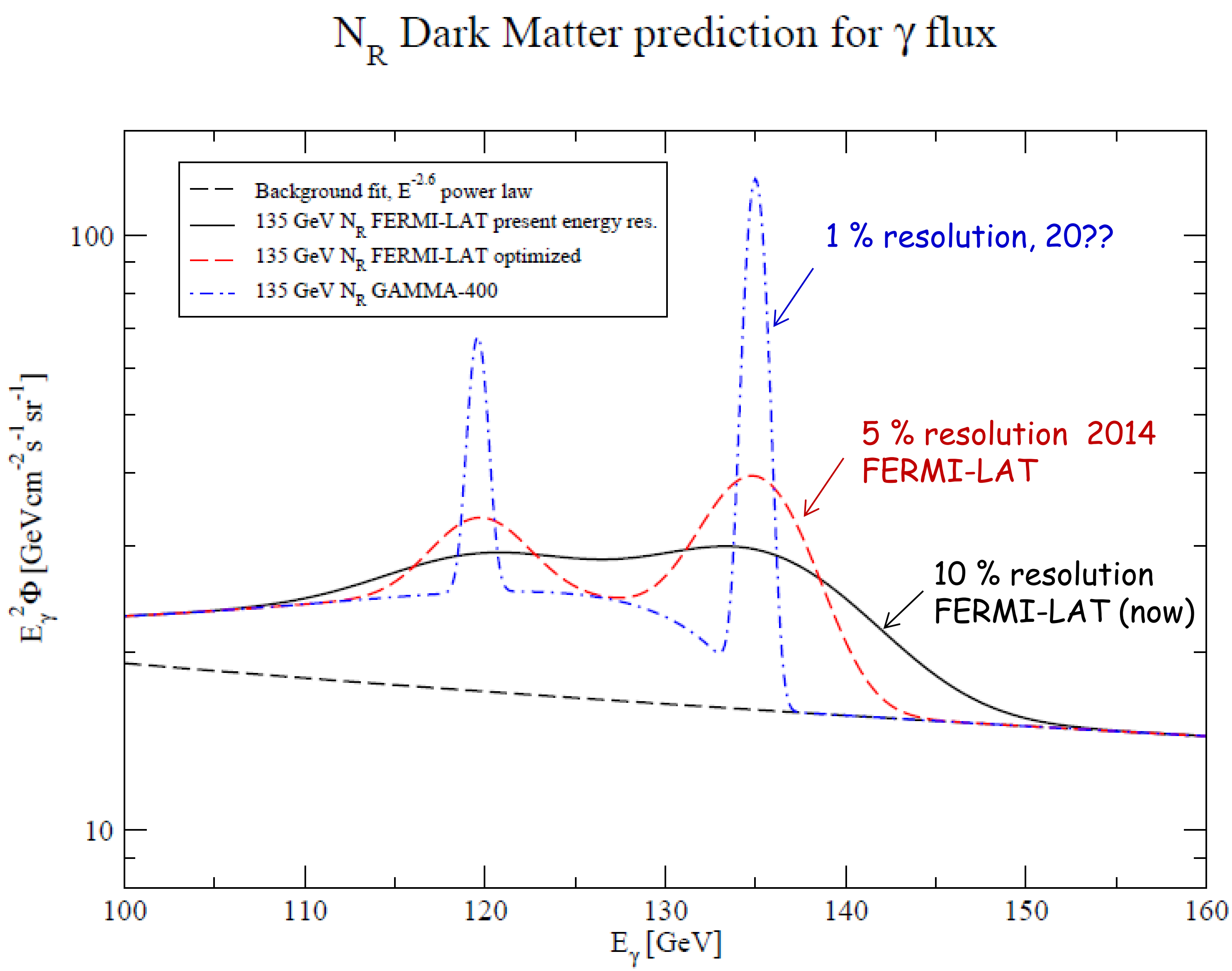
- Add Zγ line (neglected in paper with Baltz)
- Adjust absolute rate
- Compare with data





Assume Fermi-LAT energy resolution, ~ 10 %

The future:



N_R Dark Matter prediction for γ flux
Background fit, E^-2.6 power law
135 GeV N_R FERMI-LAT present energy res.
135 GeV N_R FERMI-LAT optimized
135 GeV N_R GAMMA-400
1 % resolution, 20??
5 % resolution 2014
FERMI-LAT
10 % resolution
FERMI-LAT (now)
100
10
100
110
120
130
140
150
160
E_γ [GeV]
E_γ^2 Φ [GeVcm^-2 s^-1 sr^-1]

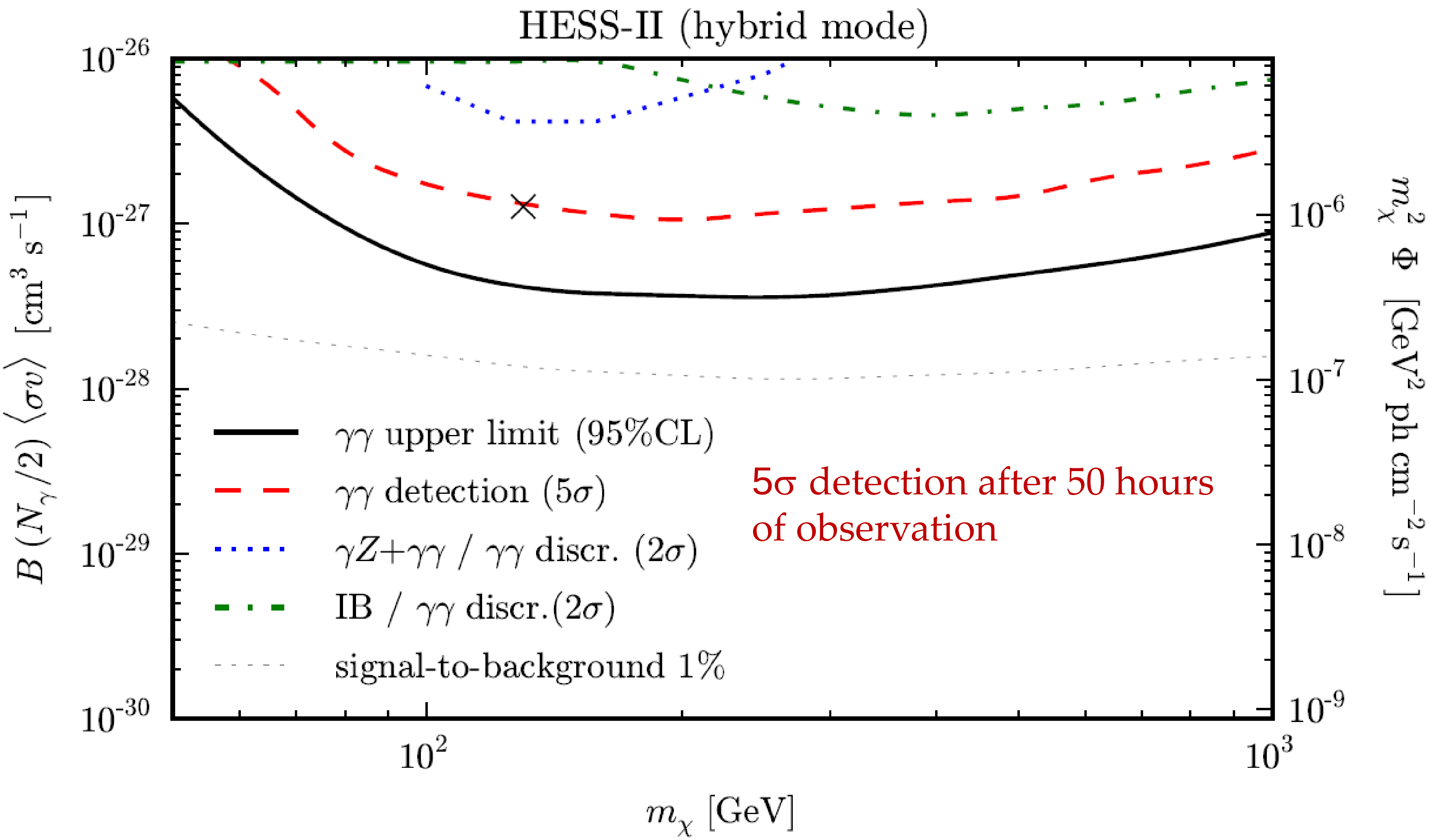
A new player in the game: HESS-II in Namibia

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

Saw first light in August, 2012

Ideal viewing conditions for galactic centre April – August 2013

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



We have to be cautious:

- Statistics is relatively low, and background not well studies in this energy range.
- The Fermi-LAT collaboration have not yet confirmed the effect. They have some spurious signal from the Earth's limb also appearing at ~ 130 GeV – may this point to an (unknown) instrumental effect?

The good news is that within one or two years we will definitely know: Fermi-LAT may have collected data with higher energy resolution, and HESS-II may have conclusively either verified or ruled out the signal.

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

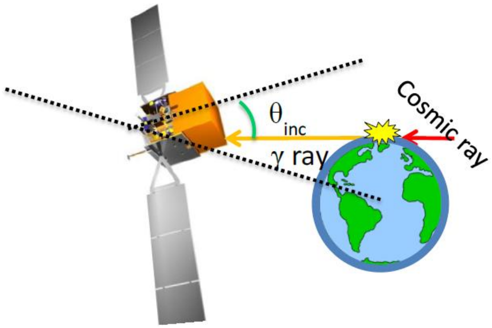
E. Bloom, E. Charles, E. Izaguirre, A. Snyder
KIPAC-SLAC, Stanford University, 2572 Sand Hill Road, Menlo Park, CA, 94025 USA
A. Albert, B. Winer, Z. Yang
The Ohio State University, 1739 N High St, Columbus, OH 43210 USA
R. Essig
Stony Brook University, Stony Brook, NY 11794 USA
On Behalf of the Fermi-LAT 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 $LAT\_\theta < 60°$ cut and fitting different energy windows produces different significances for the feature.

"Earth limb":



3.3. Inverse ROI for P7Rep

- 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.

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 10s significance (L.B., G. Bertone, J. Conrad, C. Farnier & C. Weniger, JCAP, in press). Otherwise, the parameter space of viable models will be probed with unprecedented precision.

NEWS & ANALYSIS

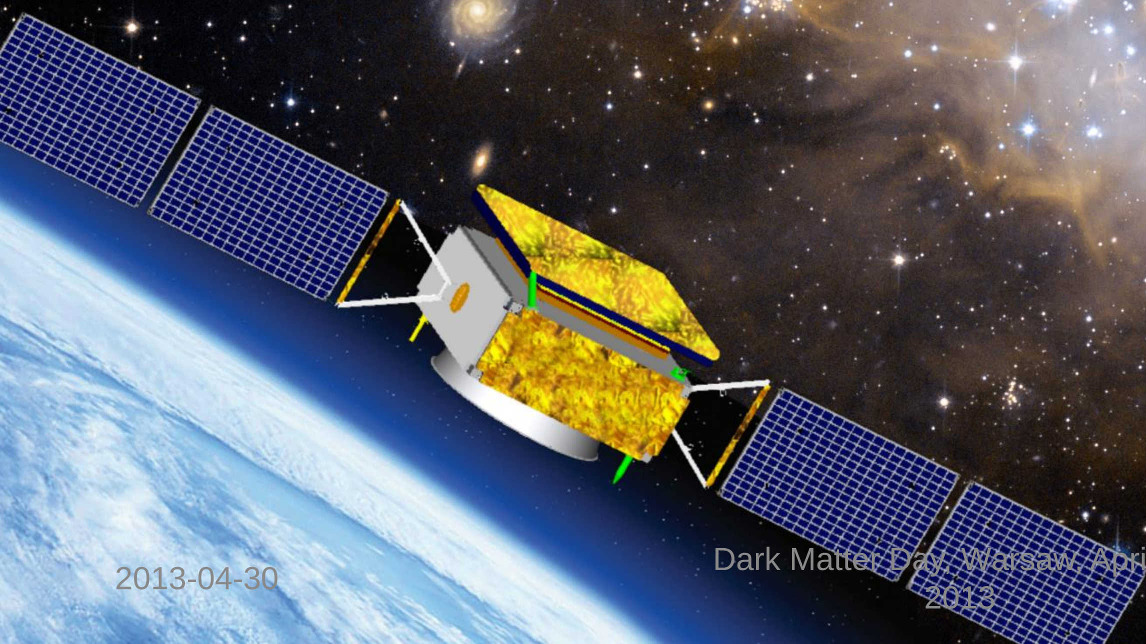
SCIENCE, May 20, 2011

SPACE SCIENCE

Chinese Academy Takes Space Under Its Wing

LOFTY AMBITIONS

Mission	Chief scientist	Goals	Estimated launch
HXMT	Li Tipei, CAS Institute of High Energy Physics and Tsinghua University	Survey of x-ray sources; detailed observations of known objects	2014
Shijian-10	Hu Wenrui, CAS Institute of Mechanics	Study physical and biological systems in microgravity and strong radiation environment	Early 2015
KuaFu Project	William Liu, Canadian Space Agency and CAS Center for Space Science and Applied Research	Study solar influence on space weather	Mid-2015
Dark Matter Satellite	Chang Jin, CAS Purple Mountain Observatory	Search for dark matter; study cosmic ray acceleration	Late 2015
Quantum Science Satellite	Pan Jianwei, University of Science and Technology of China	Quantum key distribution for secure communication; long-distance quantum entanglement	2016



The Chinese initiative: The Dark Matter Satellite (DAMPE)

Conclusions

- Most of the experimental DM indications are not particularly convincing at the present time.
- Fermi-LAT already has competitive limits for low masses, but maybe indications of line(s) and/or internal bremsstrahlung at 130 - 135 GeV. We will soon know whether it is a real effect.
- IceCube has a window of opportunity for spin-dependent DM scattering.
- The field is entering a very interesting period: CERN LHC has been running at 8 TeV at full luminosity, and in a couple of years at 14 TeV; XENON 1t is being installed; IceCube and DeepCore are operational; Fermi will collect at least 5 more years of data; AMS-02 will collect data for 18 more years, CTA, Gamma-400, DAMPE and HERD may operate by 2018, and perhaps even a dedicated DM array, DMA some years later.
- However, as many experiments now enter regions of parameter space where a DM signal *could* be found, we also have to be prepared for false alarms.
- These are exciting times for dark matter searches !

The End