Dark Matter and Fermi

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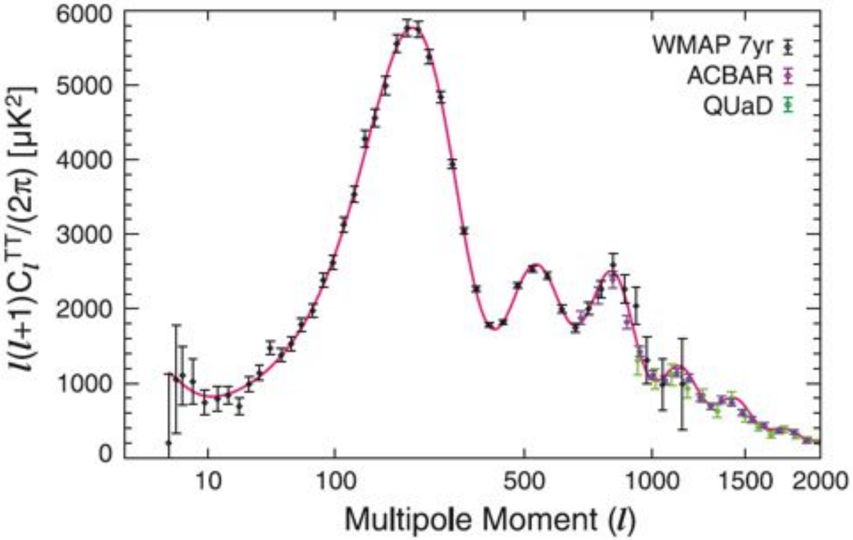


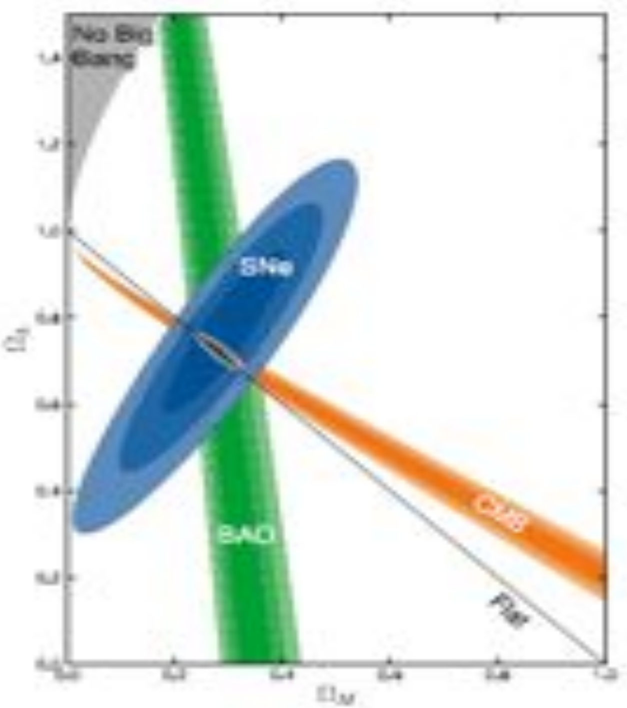
E. Komatsu et al. (WMAP team) , 2010

WMAP 2010:

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

$$\Omega_\Lambda = 0.727 \pm 0.030 \quad \boxed{\Omega_{CDM} h^2 = 0.1120 \pm 0.0056}$$

$$\Omega_B = 0.0455 \pm 0.0028 \quad h = 0.704 \pm 0.025$$



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

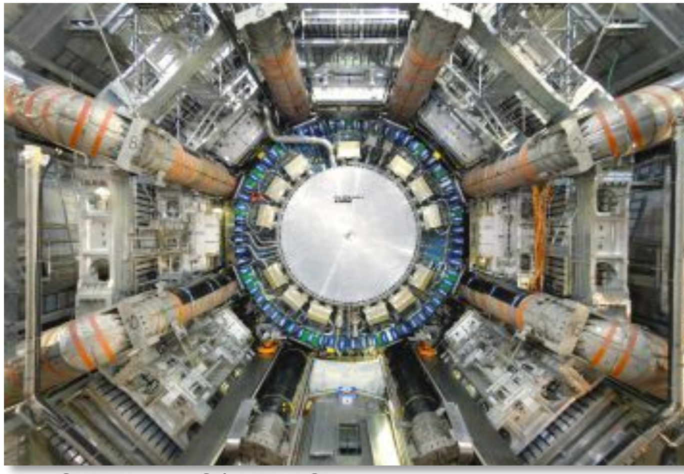
The particle physics connection: The "Weakly Interacting Massive Particle (WIMP) miracle". Is the CDM particle a WIMP?

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

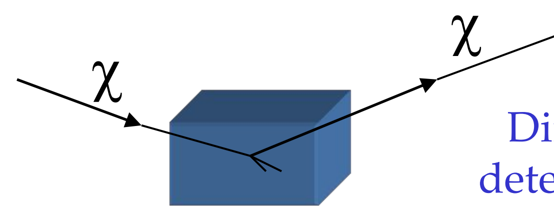
Prime example: Neutralino in supersymmetry is a WIMP.
Other interesting WIMPs: Lightest Kaluza-Klein particle – mass scale 600 – 1000 GeV, inert Higgs doublet – mass scale < 90 GeV, right-handed neutrinos,… Non-WIMP: axion.

Methods of WIMP Dark Matter detection:

- Discovery at accelerators (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, photons or antimatter in ground- or space-based experiments.
- For a convincing determination of the identity of dark matter, plausibly need detection by at least two independent experiments. For most methods, the background problem is very serious.



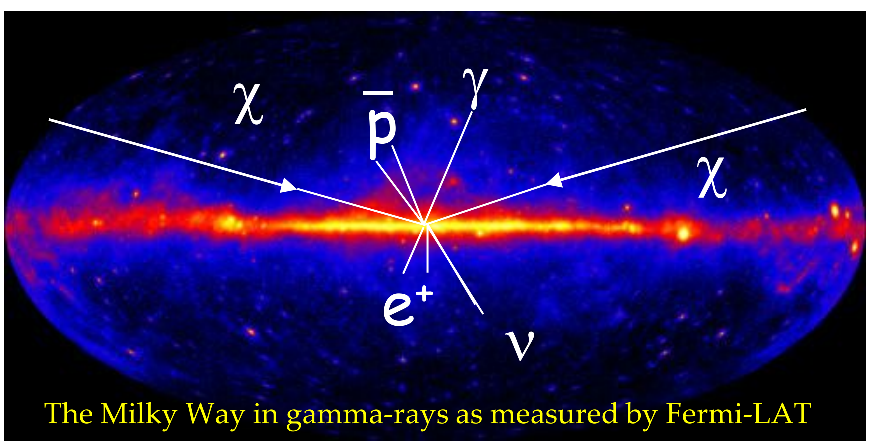
CERN LHC/ATLAS



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-LAT

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

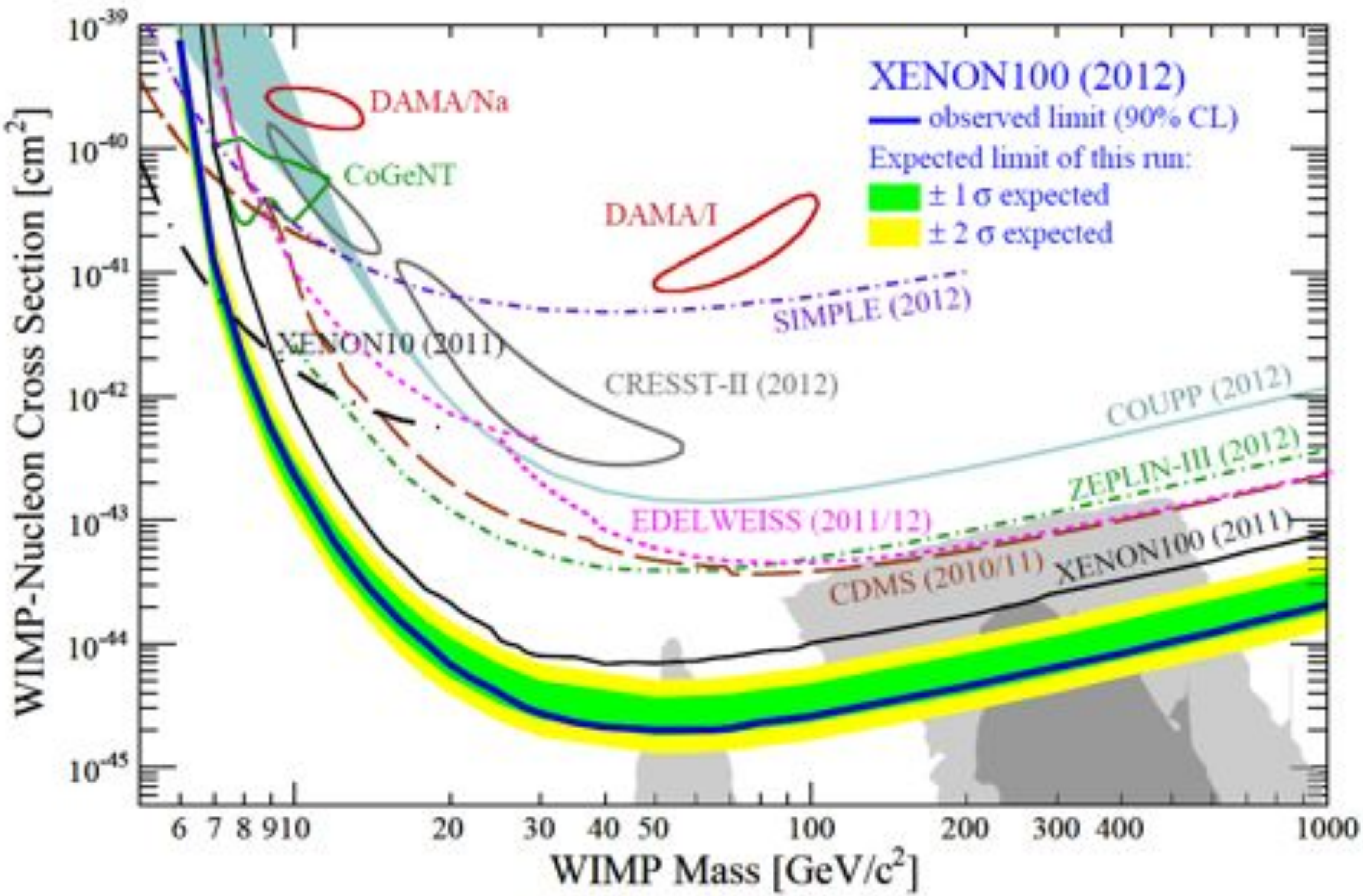
Annihilation rate enhanced for clumpy halo; near galactic centre and in nearby dwarf galaxies; also for larger systems like galaxy clusters, and large-scale cosmological structure (as seen in N-body simulations).

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 continuum photons	Due to instrument error (?) - not confirmed by Fermi-LAT collaboration
PAMELA: Anomalous ratio e^+/e^-	Confirmed by Fermi-LAT. May be due to DM, with high boost factor, or pulsars - energy signature not unique for DM
Fermi-LAT positrons + electrons	May be due to DM, with high boost factor, or pulsars - energy signature not unique for DM
Fermi-LAT γ-ray excess of continuous emission towards g.c.	Unexplained at the moment – very messy astrophysics
γ-ray continuum excess from galaxy clusters	Weak indications, point sources confuse?
Fermi-LAT 130 GeV structure from g.c. (T. Bringmann et al., C.Weniger, 2012) and from galaxy clusters (A.Hektor, M. Raidal & E. Tempel, 2012)	3.1 σ – 4.6 σ effect, using public data, unexplained, no Fermi-LAT statement yet

Direct detection limits, Xenon100 data, July 2012:

CoGeNT, CRESST and DAMA DM indications seem well excluded…

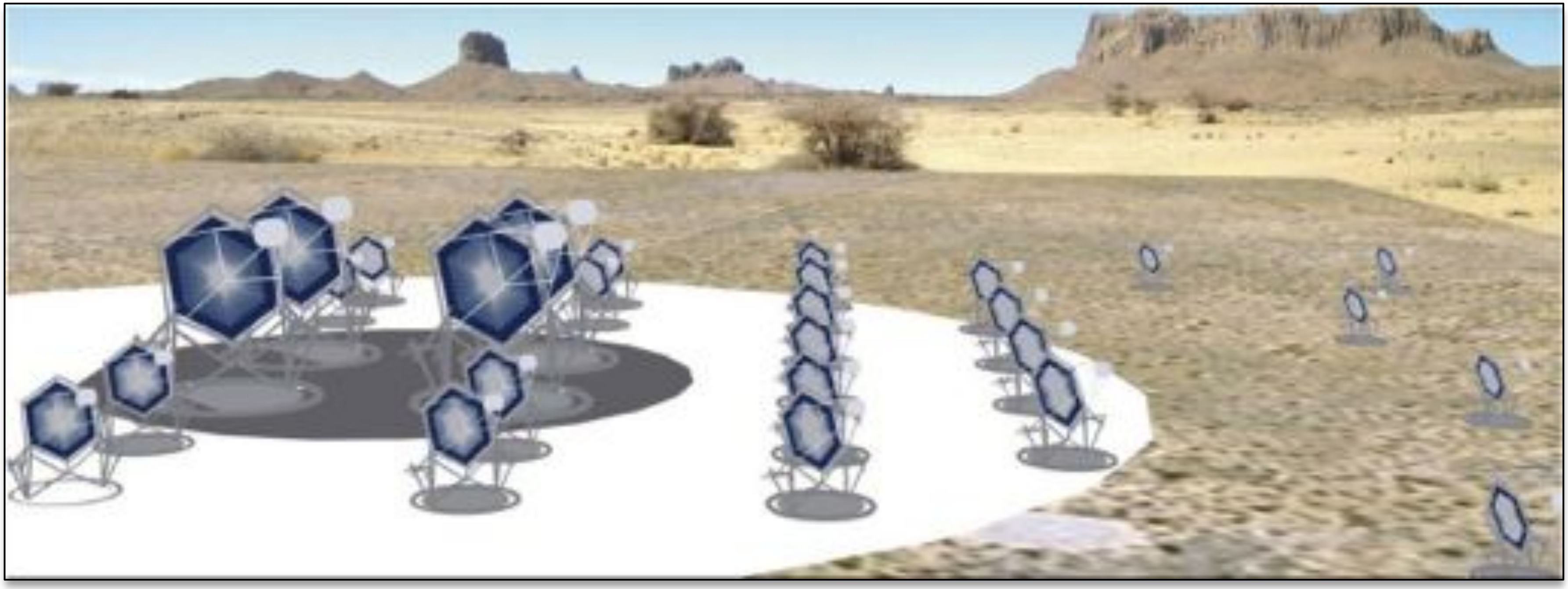


Indirect detection through γ-rays from DM annihilation

Fermi-LAT (Fermi Large Area Telescope)

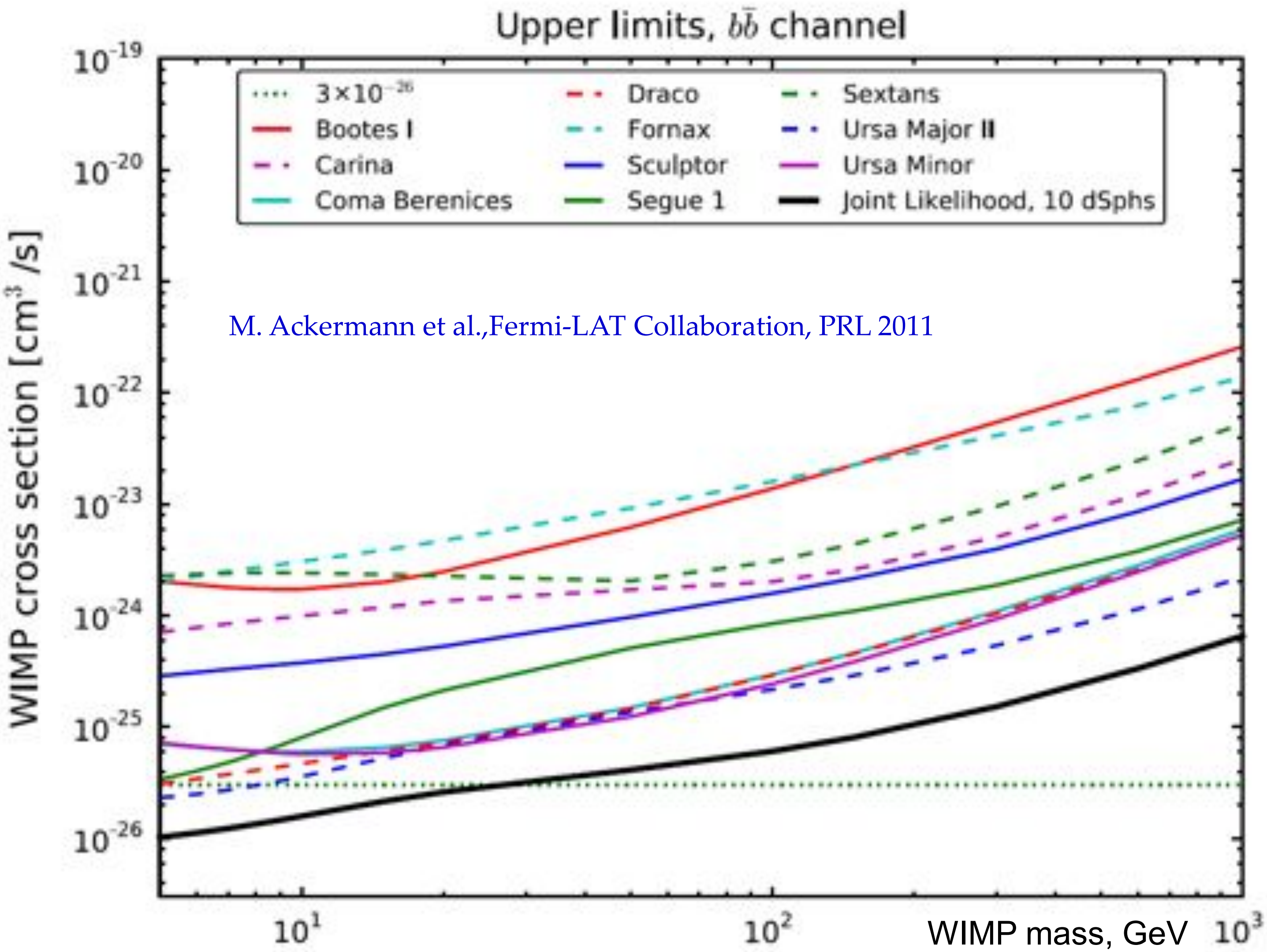
H.E.S.S. & H.E.S.S.-2

VERITAS



CTA (Cherenkov Telescope Array)

New promising indirect DM detection method: Stacking data from many dwarf galaxies,
J. Cohen-Tanugi, J. Conrad, M.L. Garde & Fermi-LAT Collaboration, PRL 2011;
A. Geringer-Sameth and S. Koushiappas, PRL 2011. See talk by Alex Drlica-Wagner later today.



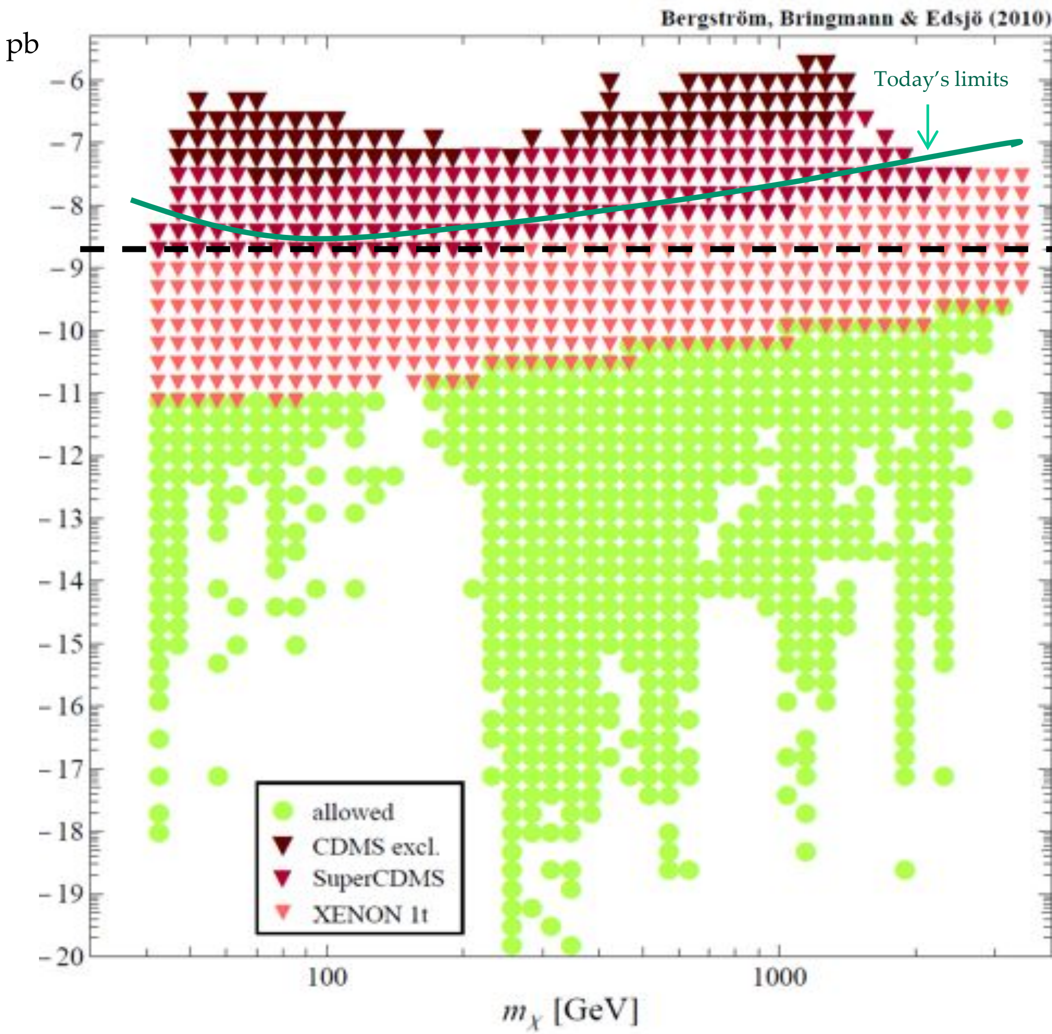
By stacking the data, sensitivity to the astrophysical "J-factor" may be minimized

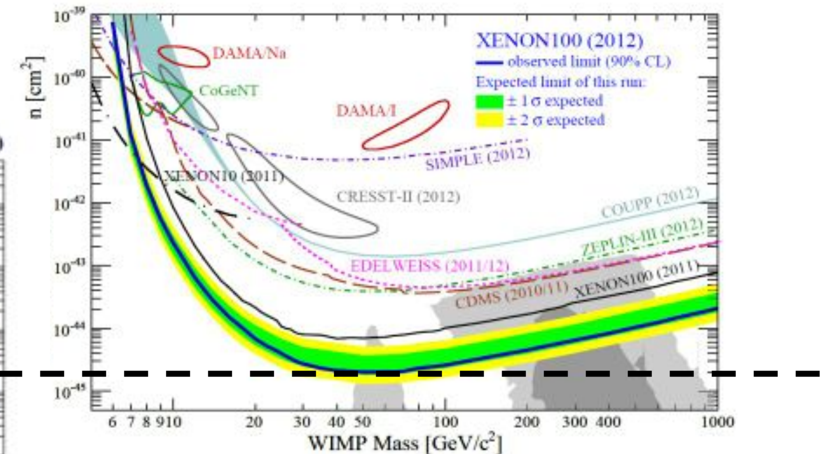
"Canonical" WIMP cross section

A very important result: For the first time, the WIMP cross section is reached in indrect detection!

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

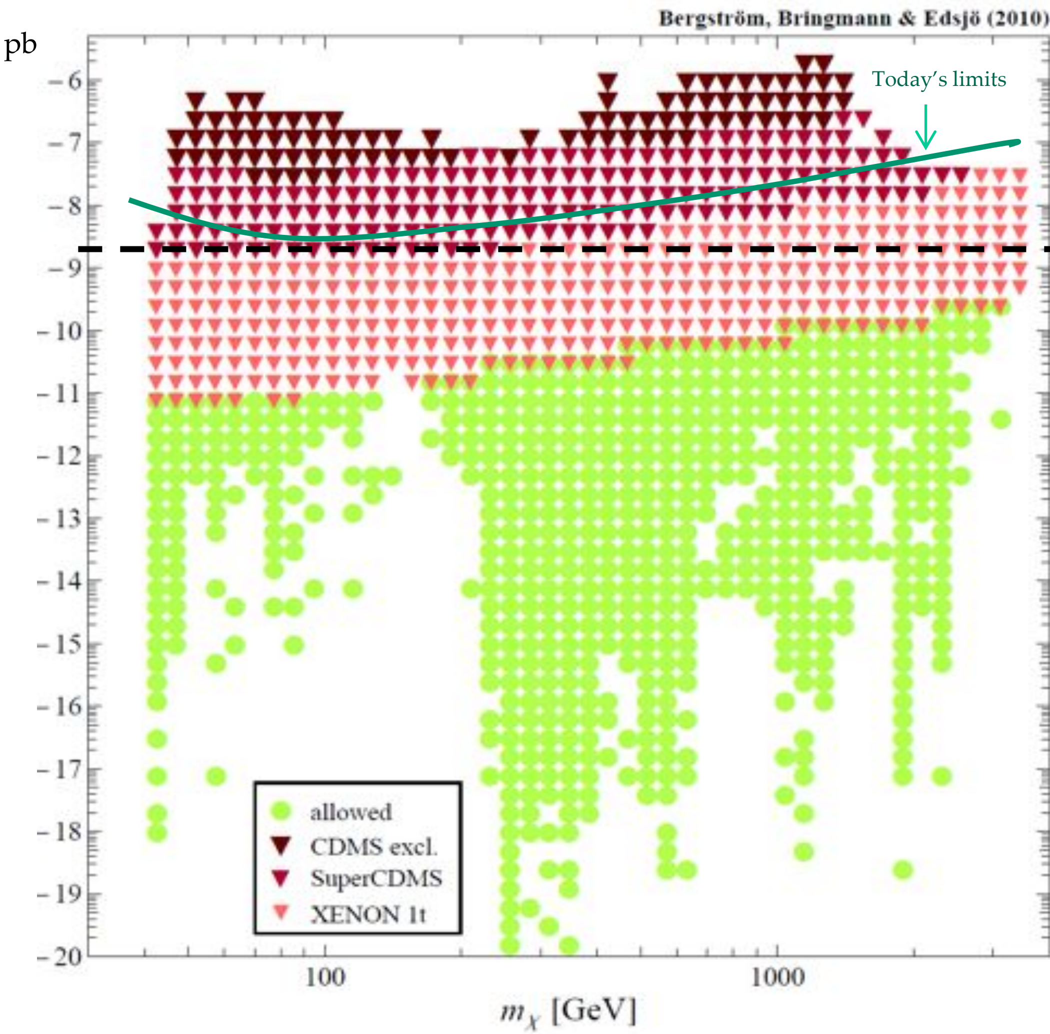
WMAP-compatible
models in pMSSM

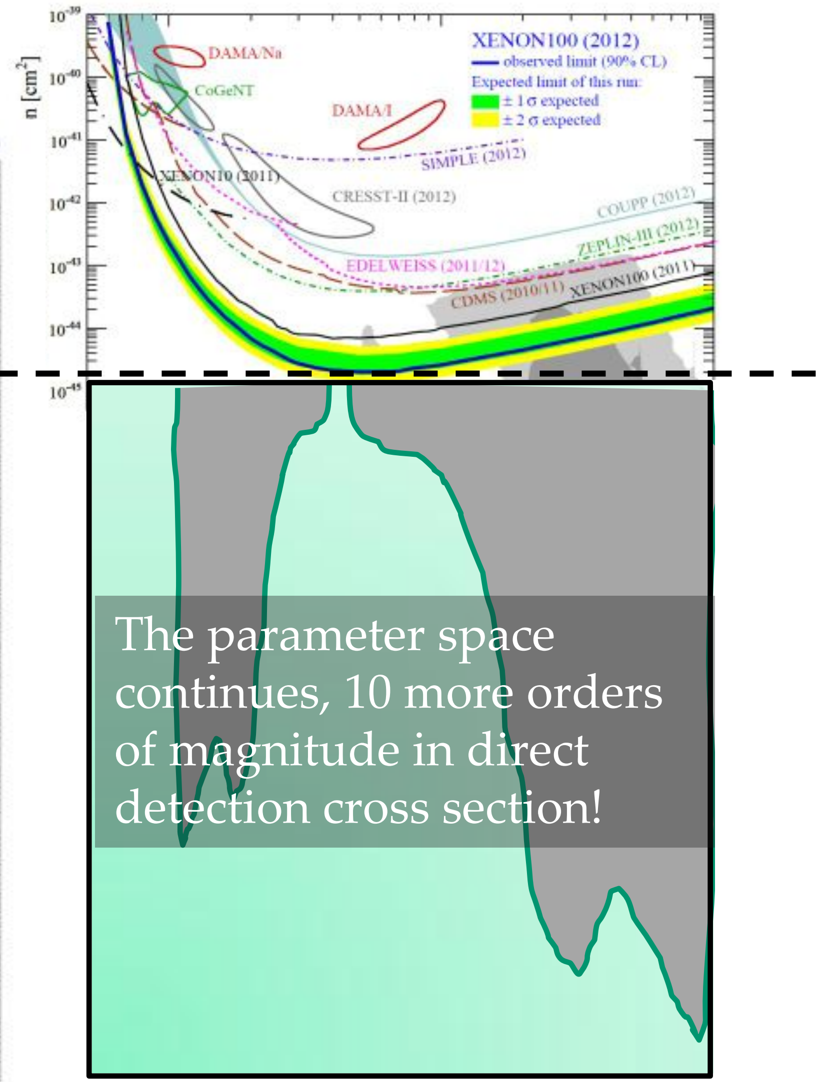




The Dark Matter Array (DMA) – a dedicated DM experiment?

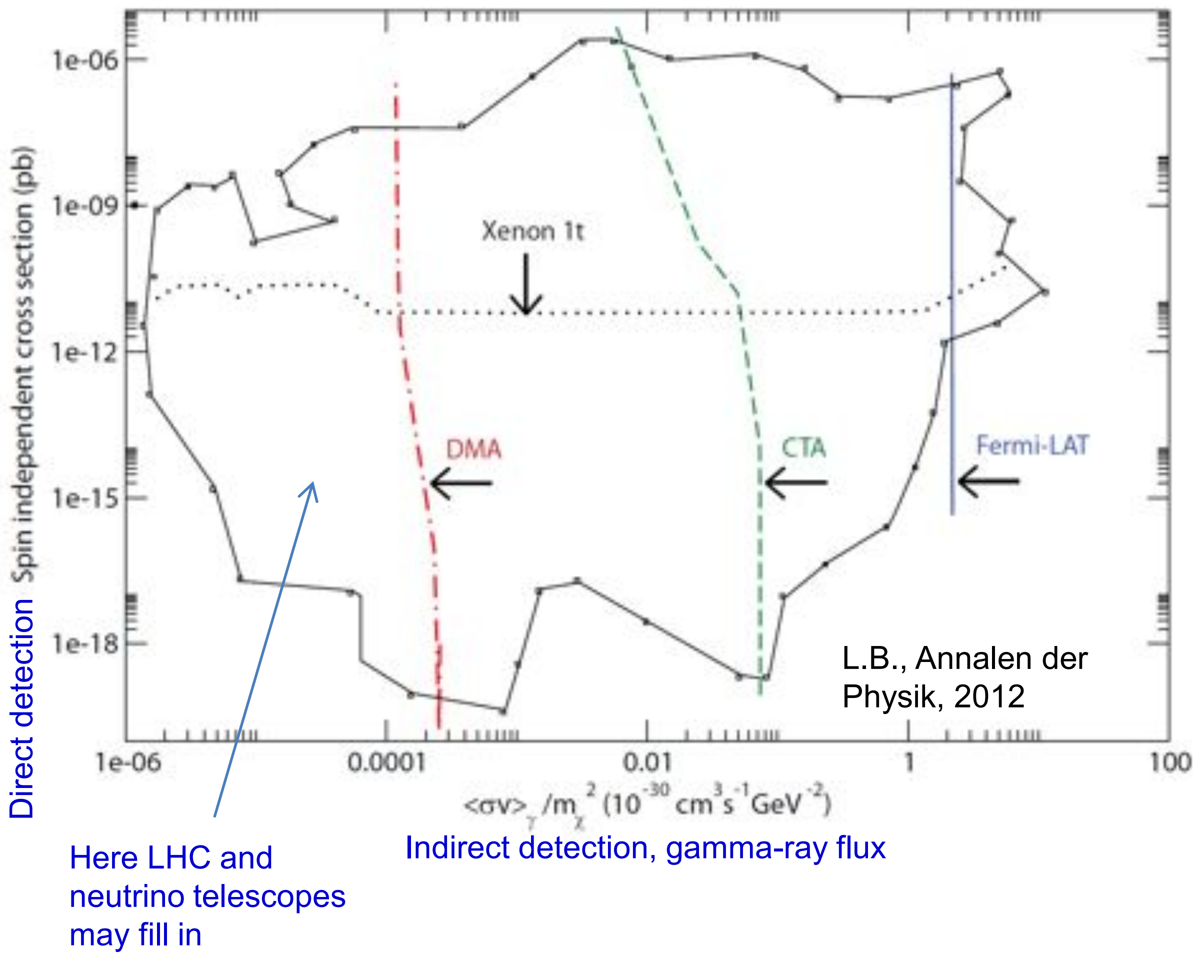
WMAP-compatible models in pMSSM





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

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 dedicated gamma-ray detector for dark matter? (T. Bringmann, L.B., J. Edsjö, 2011)

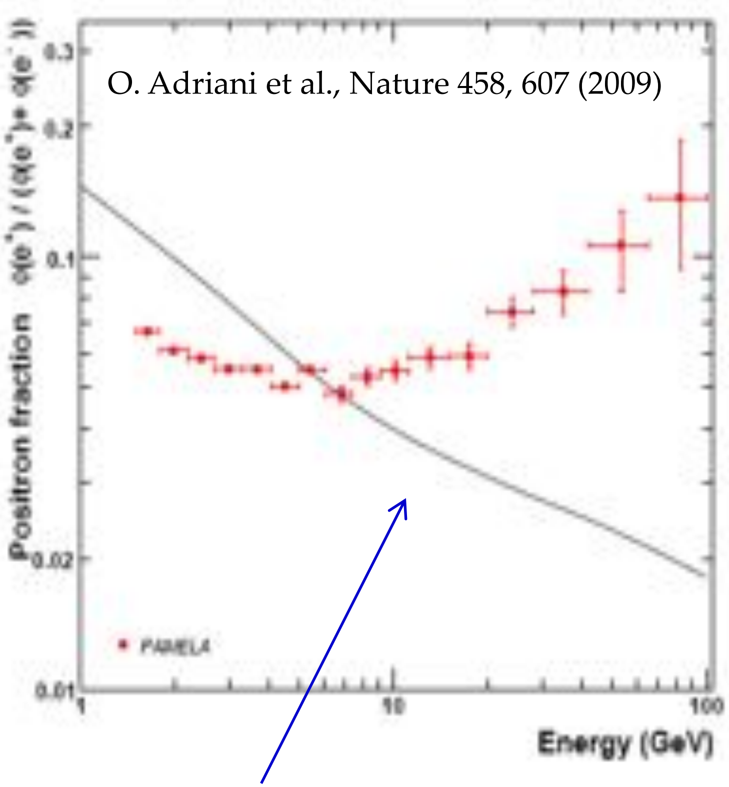
General pMSSM scan, WMAP-compatible relic density. Check if $S/(S+B)^{0.5} > 5$ in the "best" bin (and demand $S > 5$)

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

Construction time ~ 10 years, maybe starting by backfilling CTA with mid-size telescopes (J. Buckley & al.)

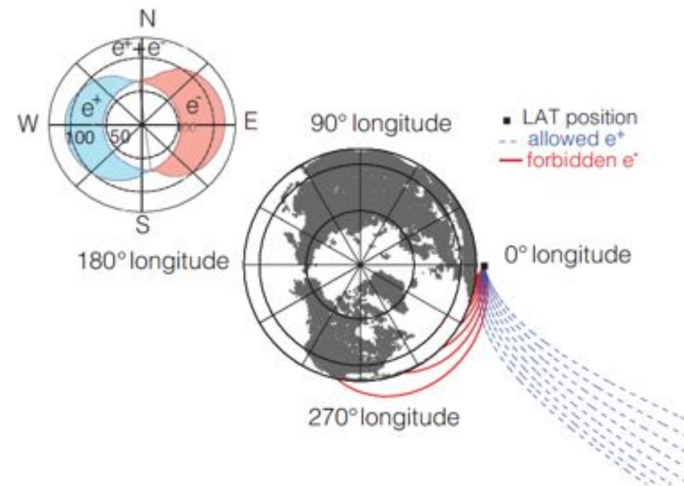
Antimatter, 2008-9: The surprising PAMELA data on the positron ratio up to 100 GeV. Verified up to 200 GeV by Fermi-LAT, 2011.

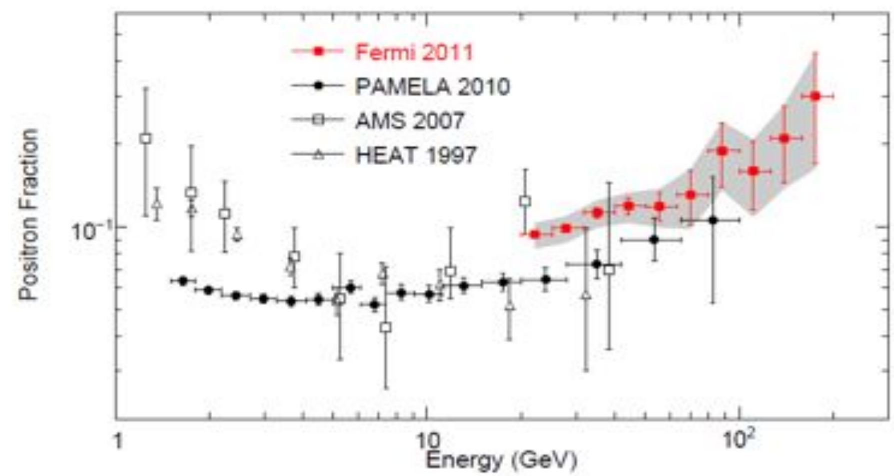
An additional, primary source of positrons seems to be needed. Could it be dark matter?



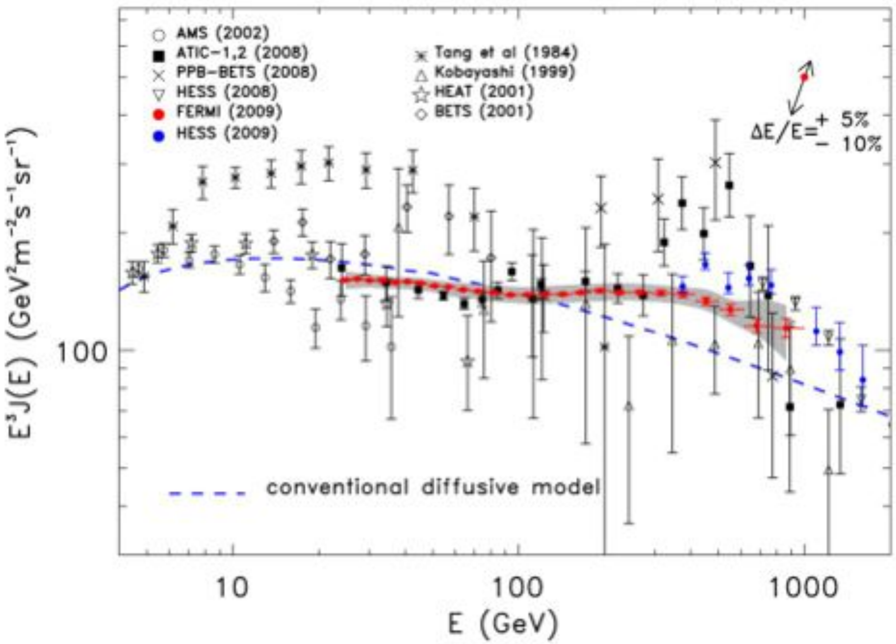
Prediction from secondary production by cosmic rays: Moskalenko & Strong, 1998

Fermi-LAT, PRL 2011

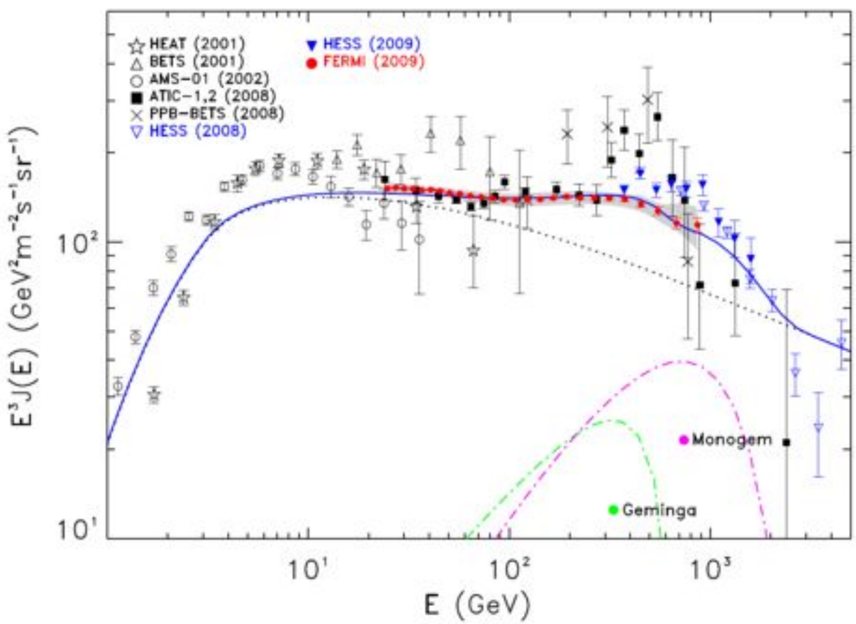




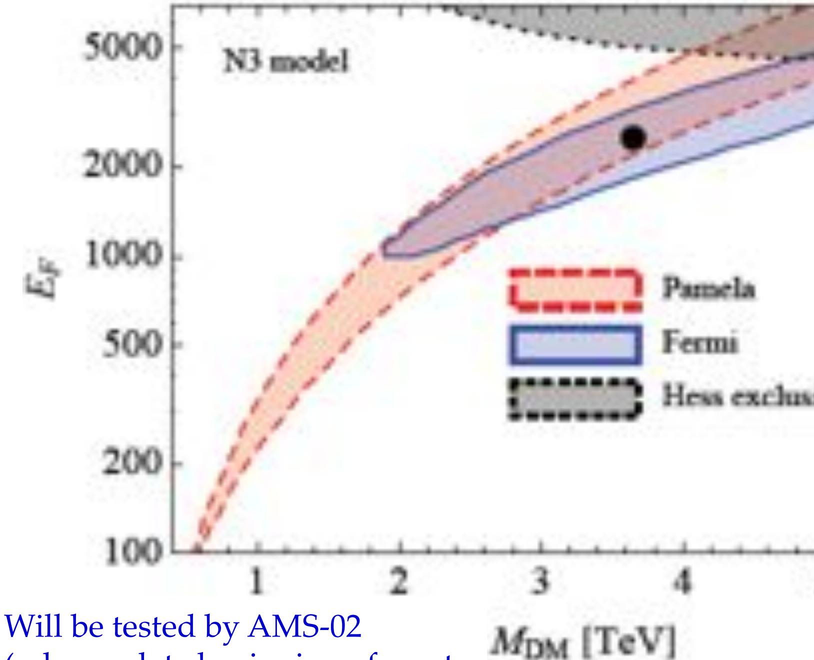
Fermi-LAT, 2009: Significant "bump" in electron + positron distribution



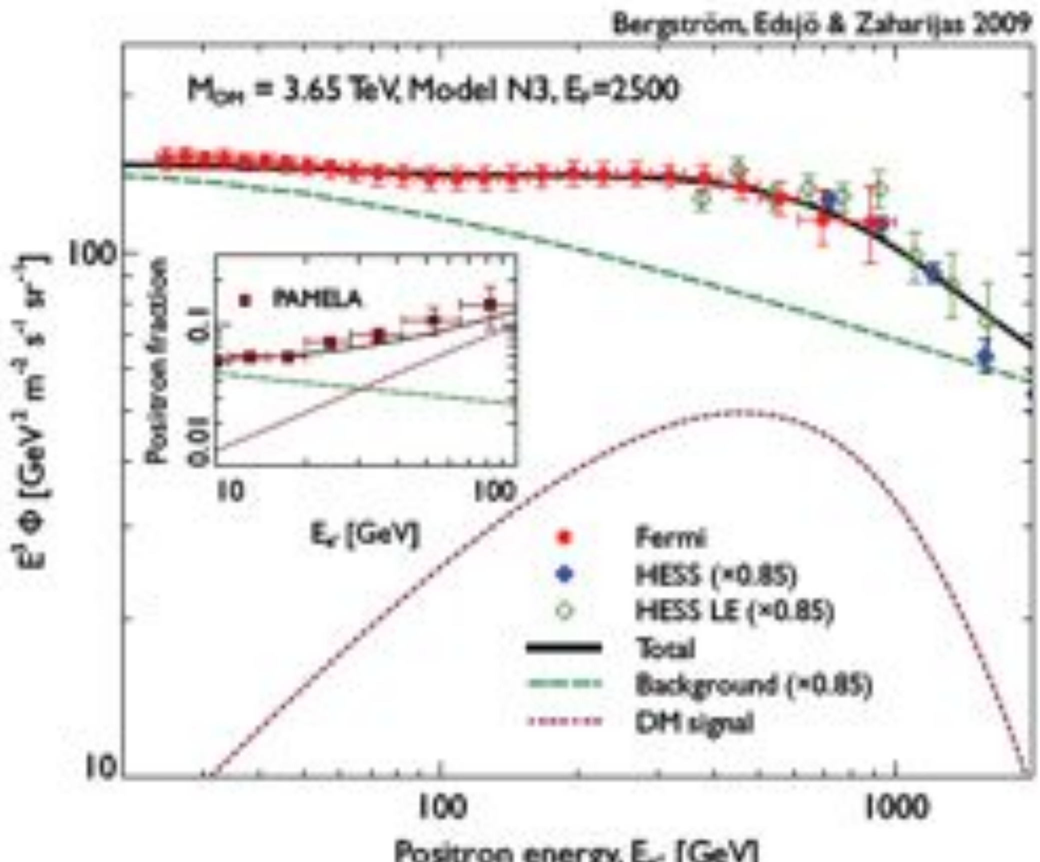
D. Grasso et al. (Fermi-LAT Collaboration), 2009: Pulsars can give a good fit to the data…



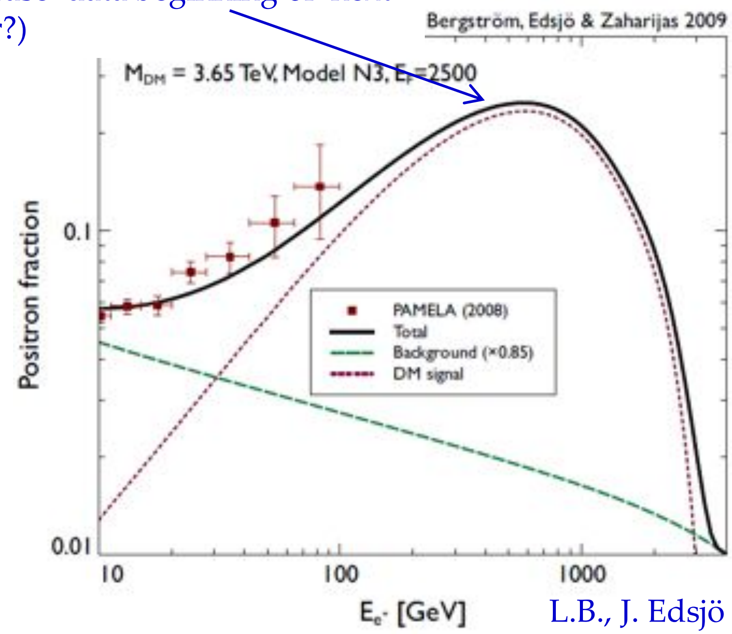
… as can dark matter, for example:



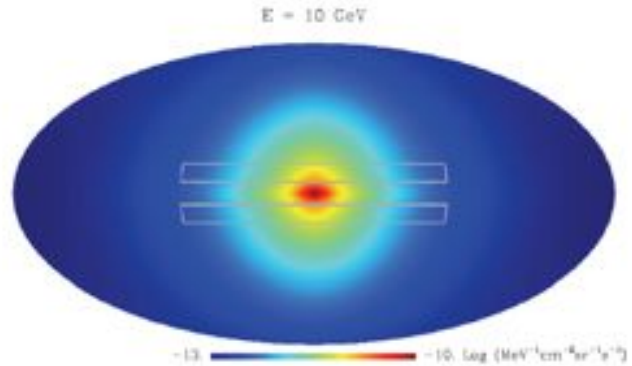
Just one out of O(100) different proposed models; "Sommerfeld enhancement" is natural in some of these. However, need extreme boost factors, and ways to suppress very large predicted γ and radio flux.

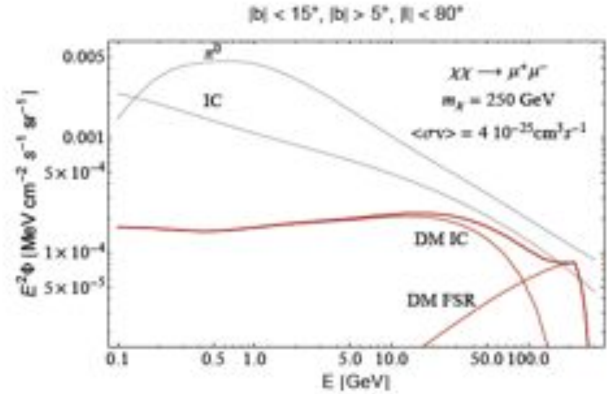


Will be tested by AMS-02 (release data beginning of next year?)

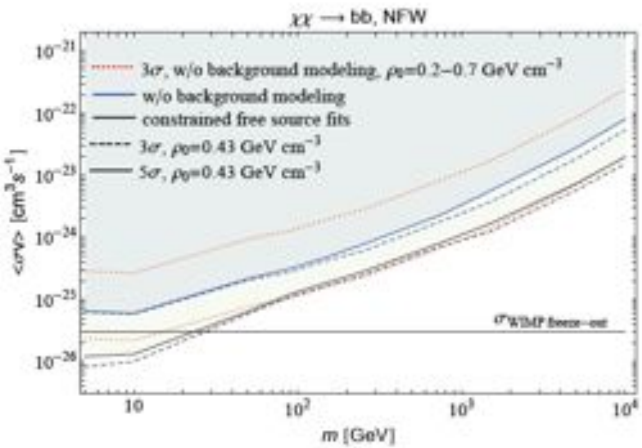


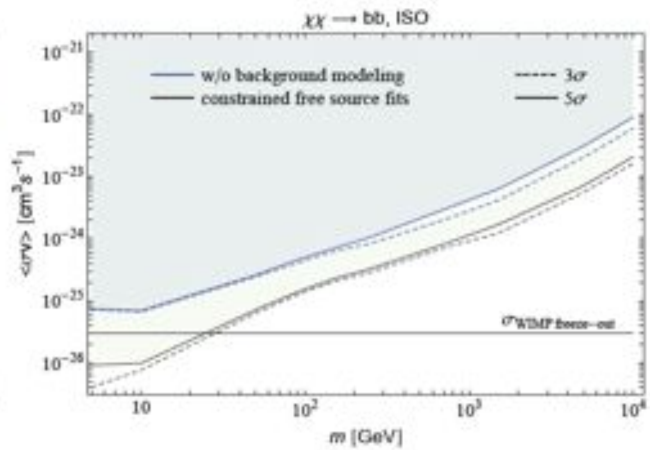
L.B., J. Edsjö and G. Zaharijas, PRL 2009.



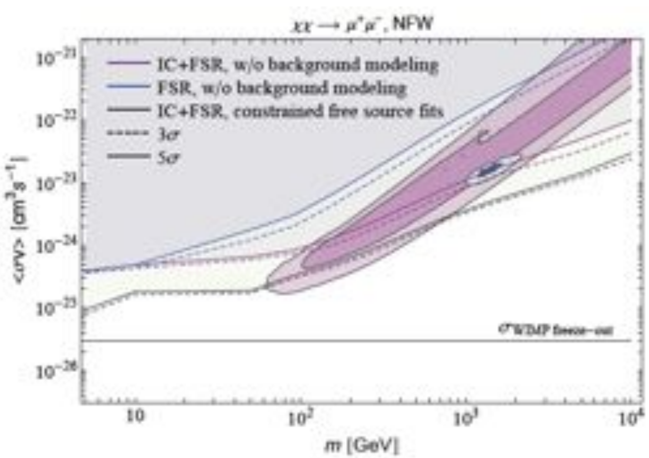


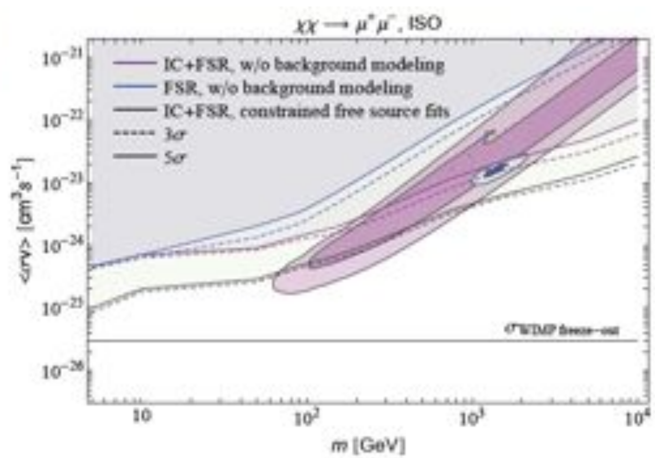
Halo DM analysis:
J .Conrad, A. Cuoco, Z.Yang, G. Zaharijas, Fermi-LAT Collaboration (Ap.J., in press)





Similar sensitivity as dwarf galaxy analysis for canonical DM particle annihilating to b quarks





DM interpretation of PAMELA + Fermi-LAT positron excess (almost?) ruled out

See talk by Gabrijela Zaharijas

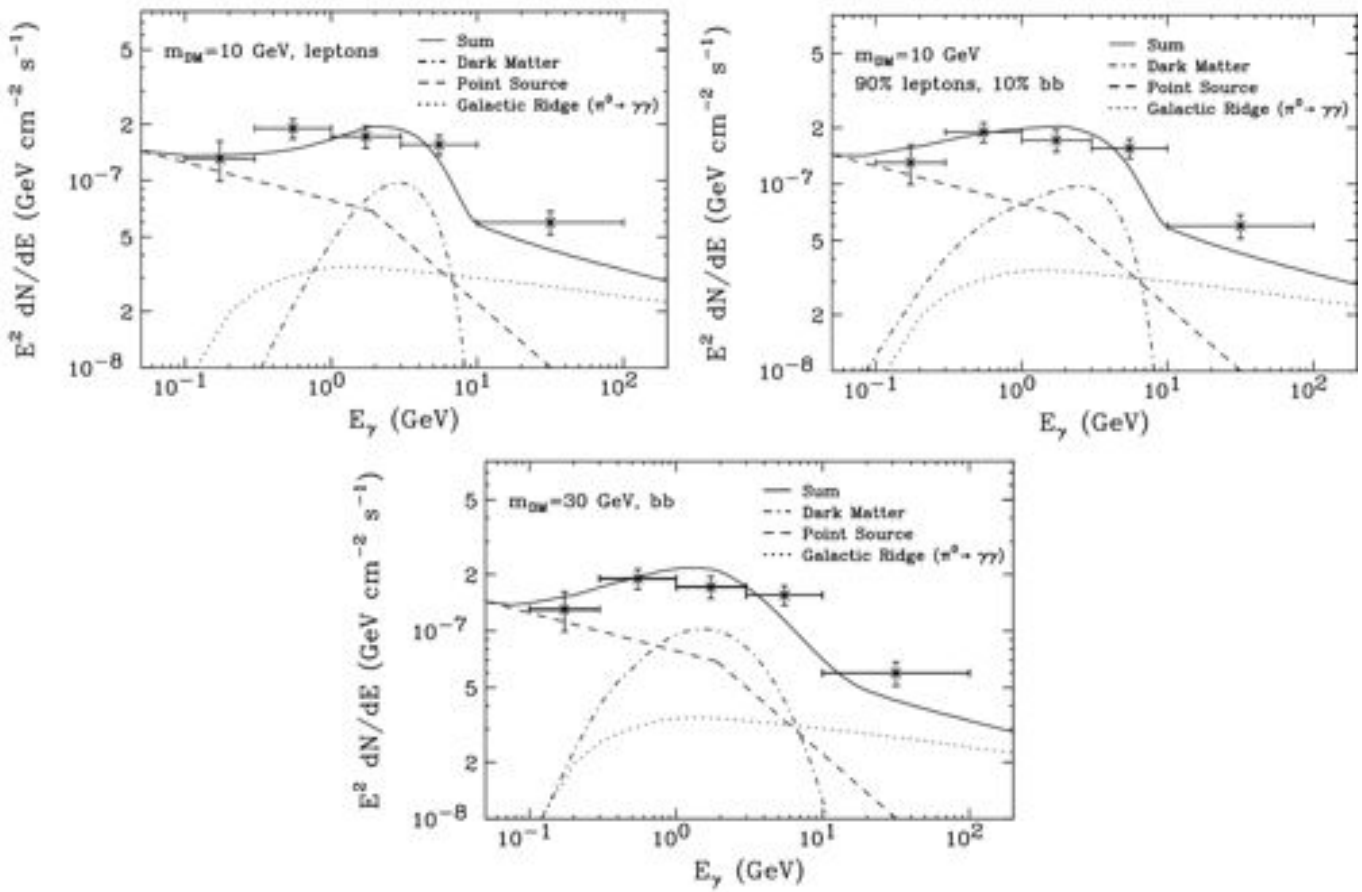
Gamma-rays from a 10 – 30 GeV WIMP from the galactic centre? D. Hooper (with L. Goodenough, 2009-10; T. Linden, 2011), Fermi-LAT public data. See talk by Tim Linden.

D. Hooper and T.Linden, 2011.

Using the remarkable source of public Fermi-LAT data!

To improve, need better angular and energy resolution in the 1 – 20 GeV range.

Eventually, a gamma-ray line at the DM mass could be seen – would be very convincing!



Review: D. Hooper, arXiv:1201.1303, “The empirical evidence for 10 GeV Dark Matter”

However, at present DM interpretation is not unique (cf. K. Abazajian & M. Kaplinghat, 2012):

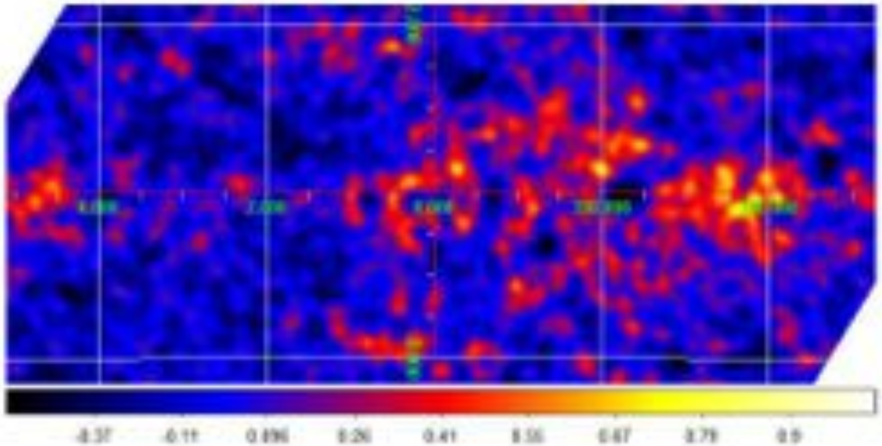
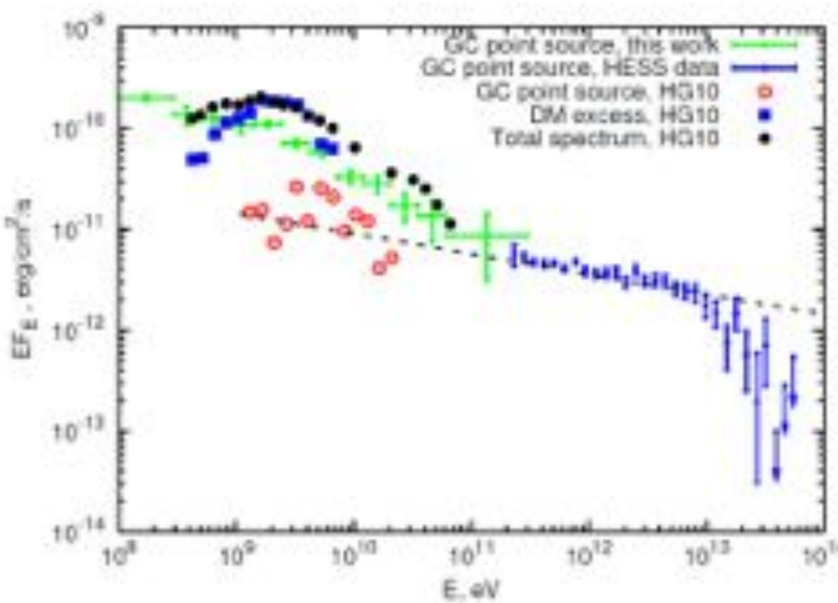
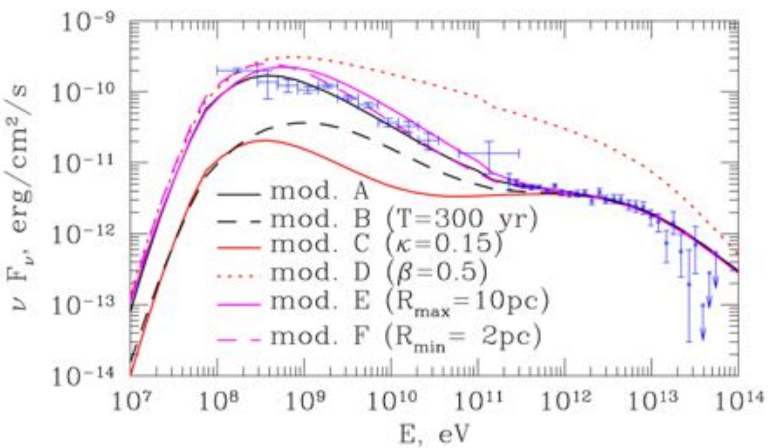


Figure 1. The map of significance of residuals for the region around the Galactic Center.

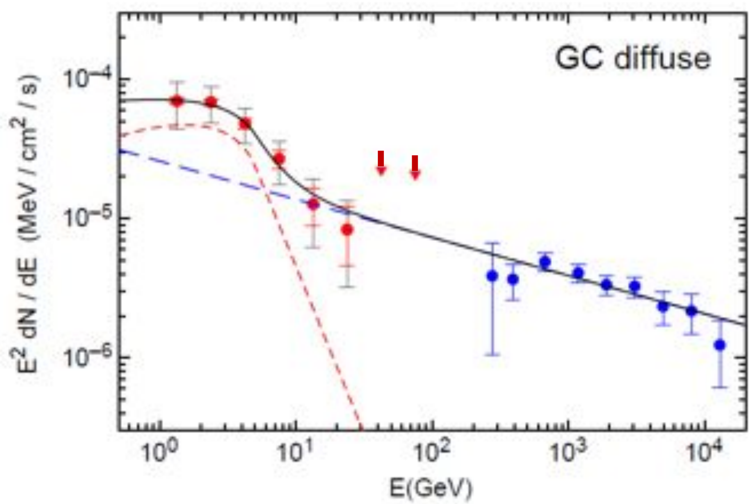
A. Boyarsky, D. Malyshev and O. Ruchayskiy, 2010





M. Chernyakova, D. Malyshev, F. Aharonian, R. Crocker and D. Jones, 2010.

Interacting Cosmic Rays with Molecular Clouds: A Bremsstrahlung Origin of Diffuse High Energy Emission from the Inner 2°×1° of the Galactic Center



F. Yusef-Zadeh & al, arXiv:1206.6882

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.

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How do we find the DM suspect?

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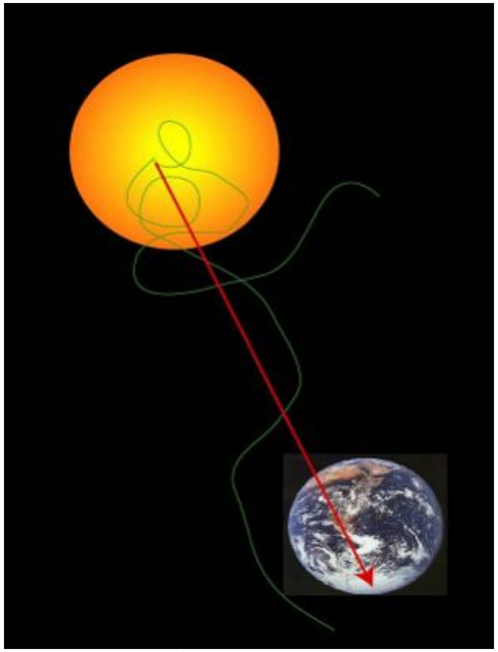
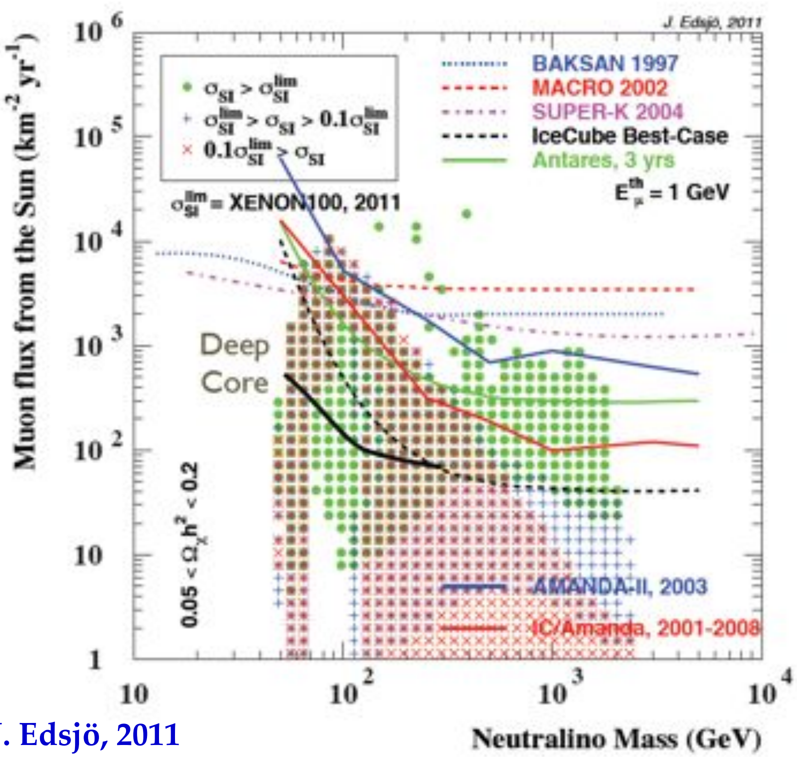
Despite candidates for DM signals existing it is difficult to prove that a viable dark matter particle is the cause. There are well-motivated, other astrophysical and detector-related processes that may give essentially identical distributions.

How do we find the DM suspect?

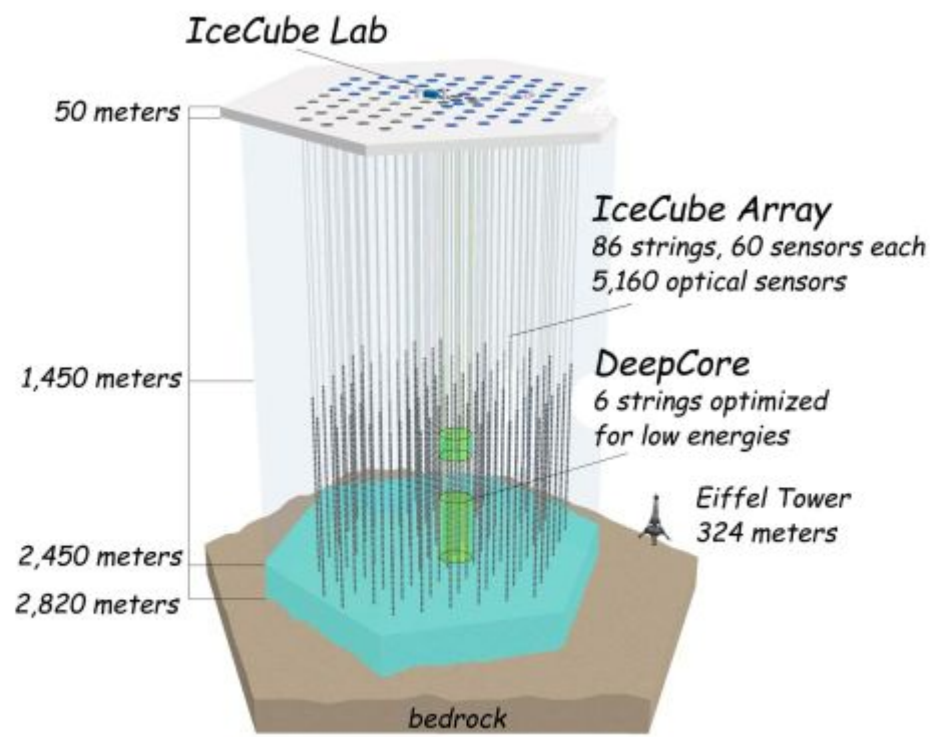
Smoking gun →



Indirect detection by neutrinos from annihilation in the Sun:
Has no astrophysical background above a few events $km^{-3}\ yr^{-1}$.
Competitive, due to high hydrogen 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 in the Earth.)



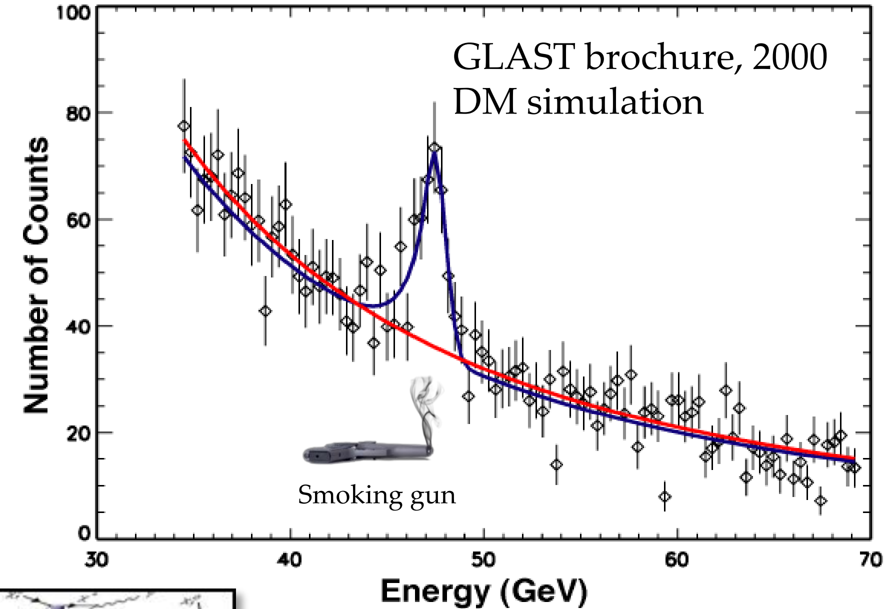
J. Edsjö, 2011



The smoking gun in gamma-rays (L.B. & H. Snellman, 1988):

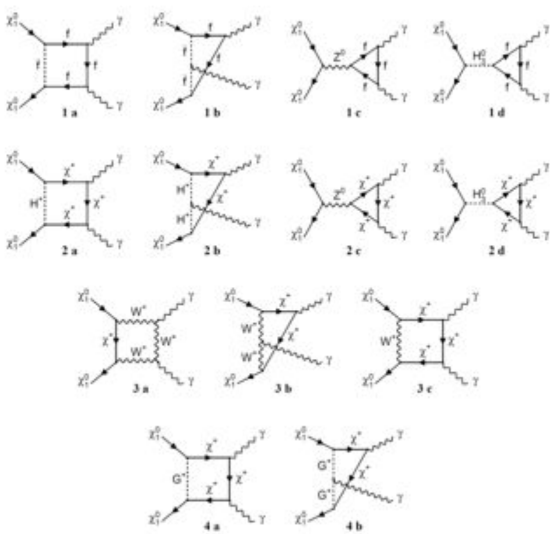
$$\chi + \chi \rightarrow \gamma + \gamma$$

Annihilation nearly at rest, $v/c \sim 10^{-3} \Rightarrow$ line with $E_\gamma = m_\chi$, intrinsic width $\Delta E/E \sim 10^{-3}$. However, has to be induced by loops of charged particles; gives suppressed rate.

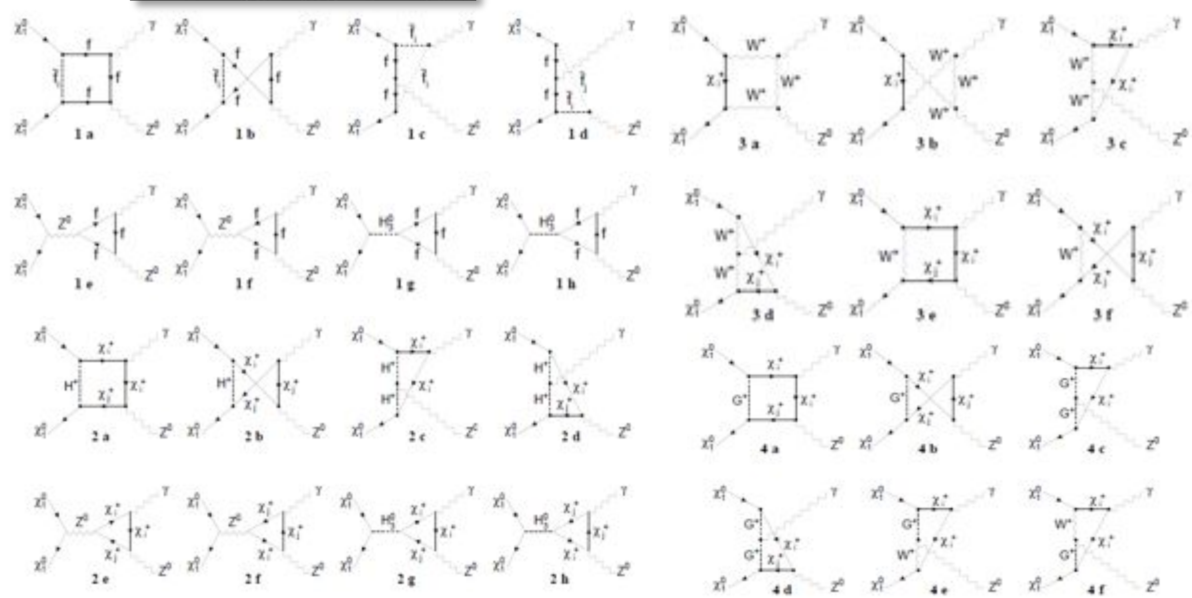


L.B. & P. Ullio, 1998:

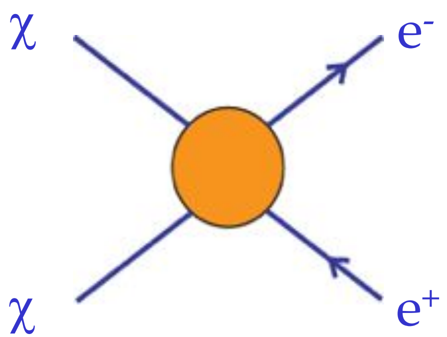
Dark SUSY



$$\chi + \chi \rightarrow \gamma + \gamma, \gamma + Z$$



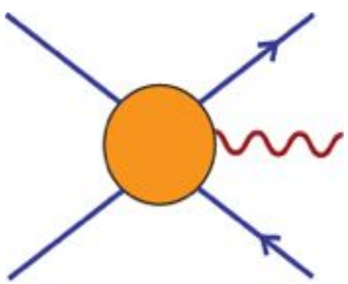
The world record in QED corrections - for slowly moving, annihilating Majorana particles. Example: e^+e^- channel:



WIMP annihilation rate $(\sigma v)_0 \sim 3 \cdot 10^{-26}$ $cm^{-3}s^{-1}$ at freeze-out.

Annihilation rate today (S-wave),
$\sigma v \sim (m_e/m_\chi)^2 \sim 10^{-37}$ cm^3s^{-1}.

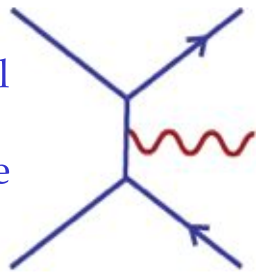
Impossible to detect!



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 10^9 instead! May give detectable gamma-ray rates – with good signature!

t-channel
scalar
exchange



(L.B. 1989; E.A. Baltz & L.B. 2002, 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:;T. Bringmann & al., 2012.)

QED corrections (Internal Bremsstrahlung) - Good news for detection in gamma-rays:

JHEP, 2008

New Gamma-Ray Contributions to Supersymmetric Dark Matter Annihilation

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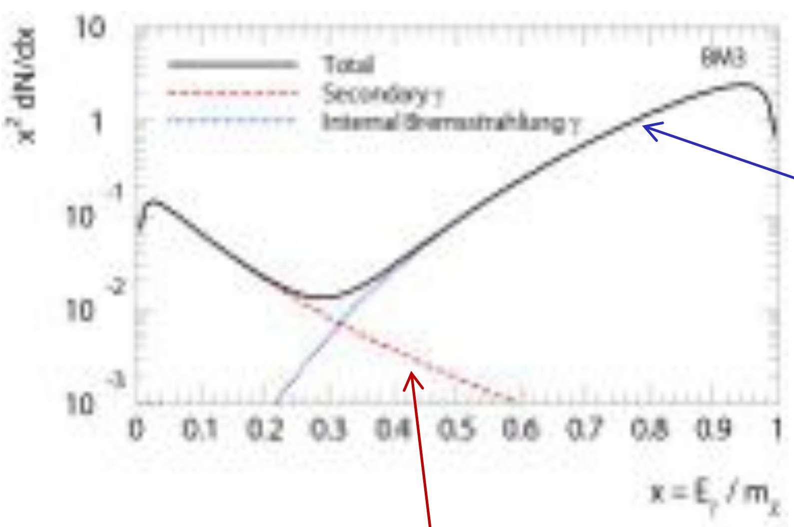
Lars Bergström† and Joakim Edsjö‡
Department of Physics, Stockholm University, AlbaNova University Center, SE - 106 91 Stockholm, Sweden
(Dated: October 16, 2007)



Example: benchmark point BM3, mass = 233 GeV, fulfills all LHC 2012 constraints, has WMAP-compatible relic density (stau coannihilation region).

New calculation including Internal Bremsstrahlung (DarkSUSY 5.1).
Spectral peak near 200 GeV could be just inside the Fermi range (after 10 yrs)

Previous estimate of gamma-ray spectrum

PREPARED FOR SUBMISSION TO JCAP

TUM-HEP 828/12
MPP-2012-54

Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation

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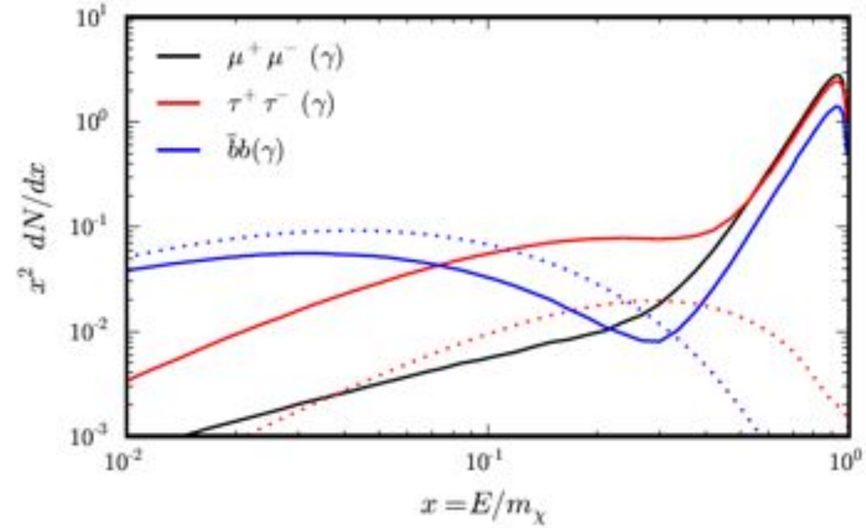
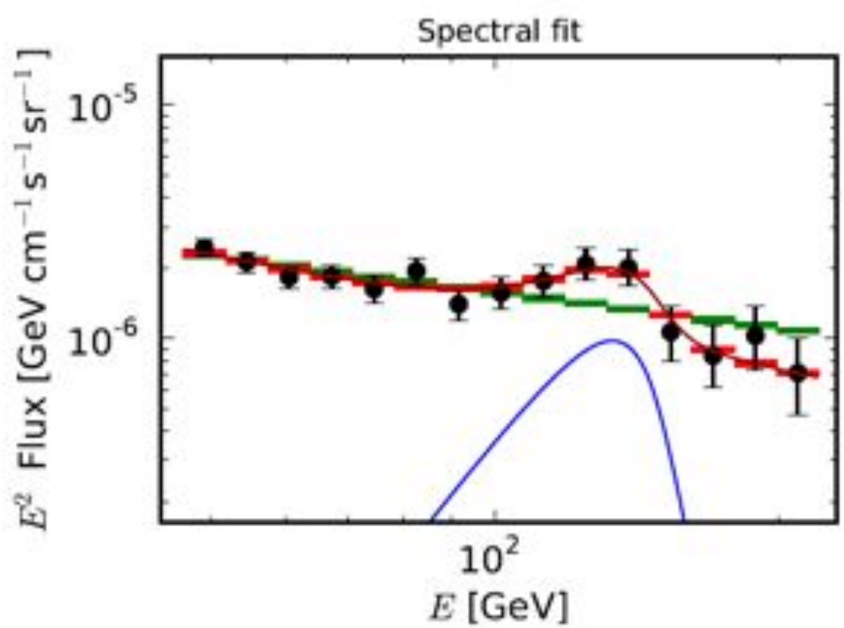
Abstract. A commonly encountered obstacle in indirect searches for galactic dark matter is how to disentangle possible signals from astrophysical backgrounds. Given that such signals are most likely subdominant, the search for pronounced spectral features plays a key role for indirect detection experiments; 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

1203.1312v1 [hep-ph] 6 Mar 2012

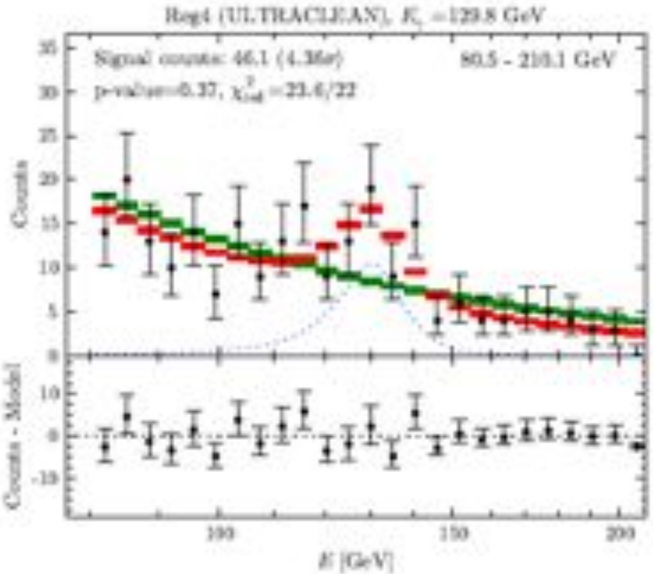


43 months of (public) Fermi data



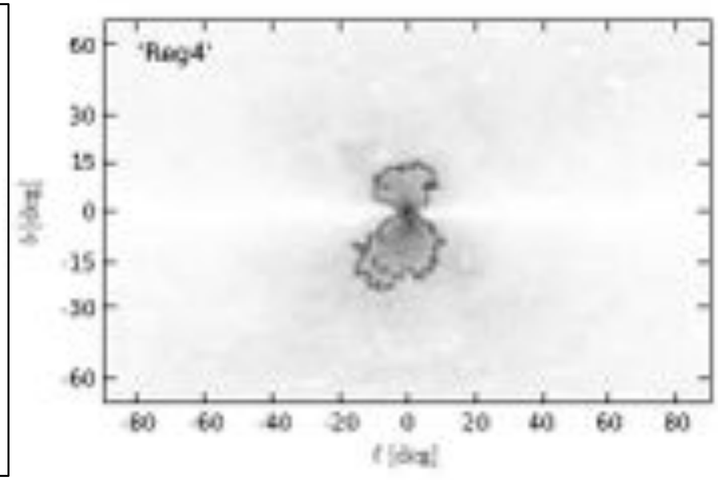
Mass = 149 GeV for internal bremsstrahlung fit. Significance 4.3 σ (3.1 σ if "look elsewhere" effect included).

Also: Pointed our that upper limits from g.c. are potentially more constraining than from dwarf galaxies.

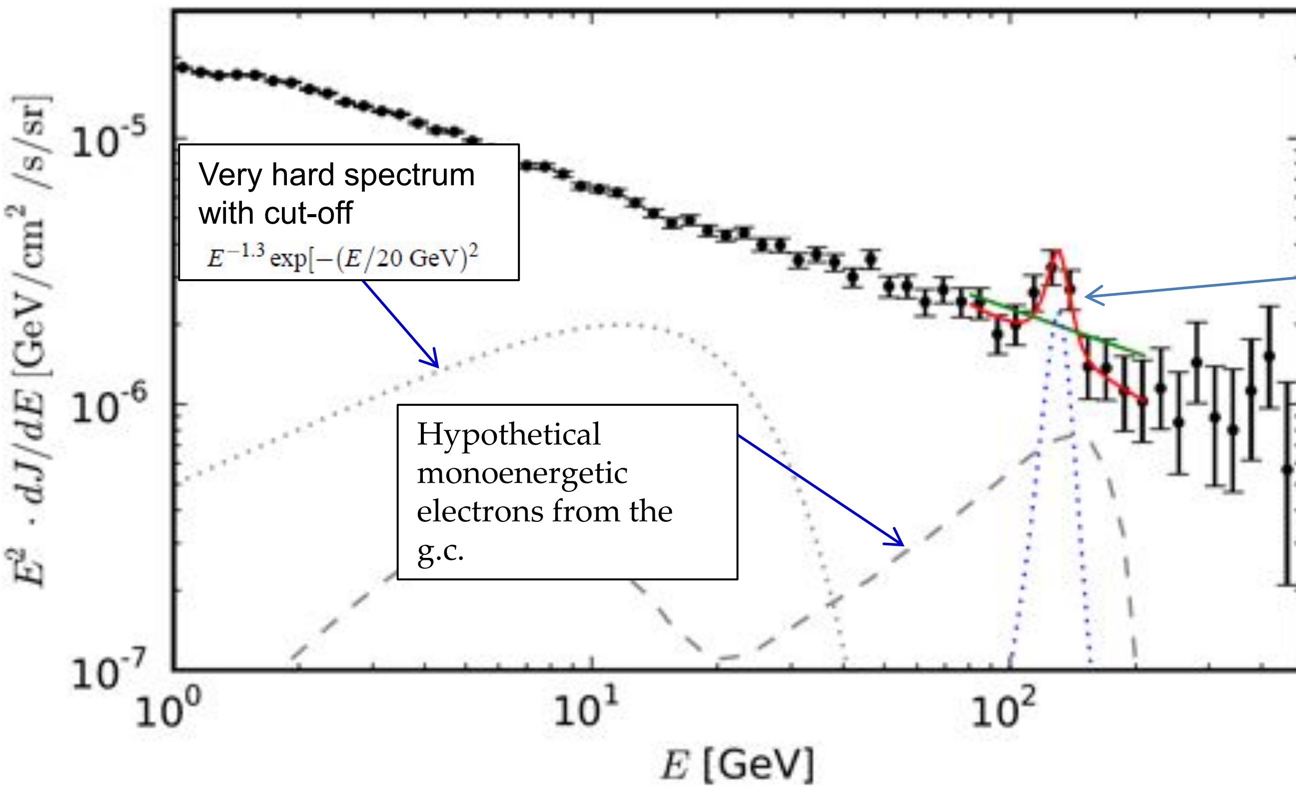


April, 2012:
43 months of (public) Fermi-LAT data.
C. Weniger, JCAP 2012. Fit to gamma-ray line.

See talk by Christoph Weniger.

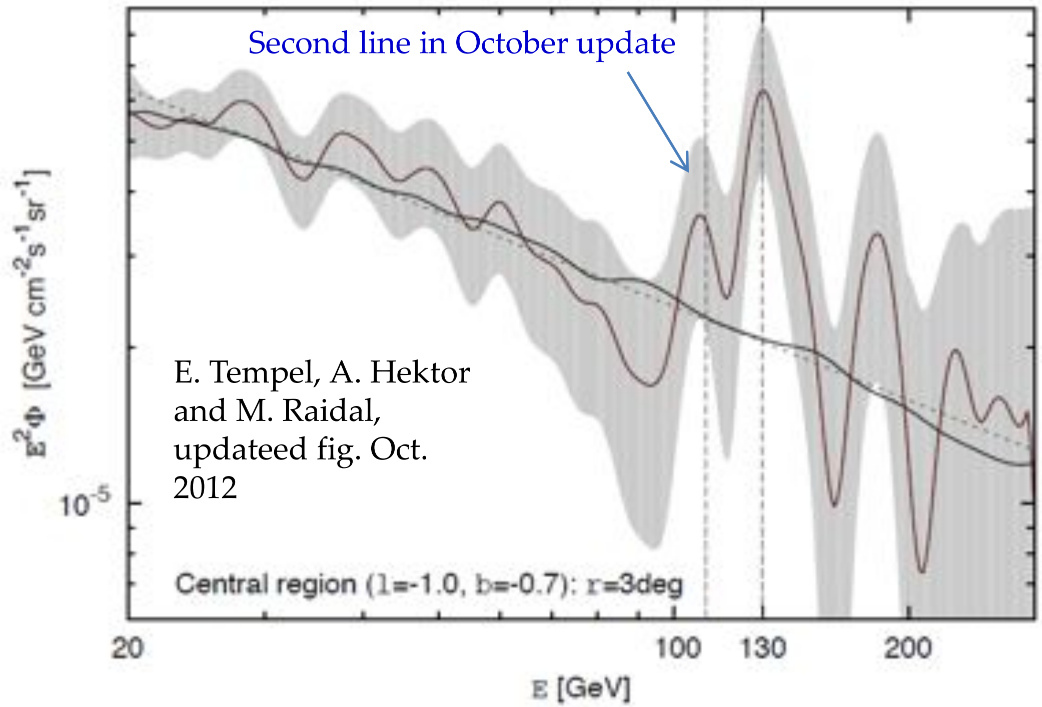


γ-ray line fit:



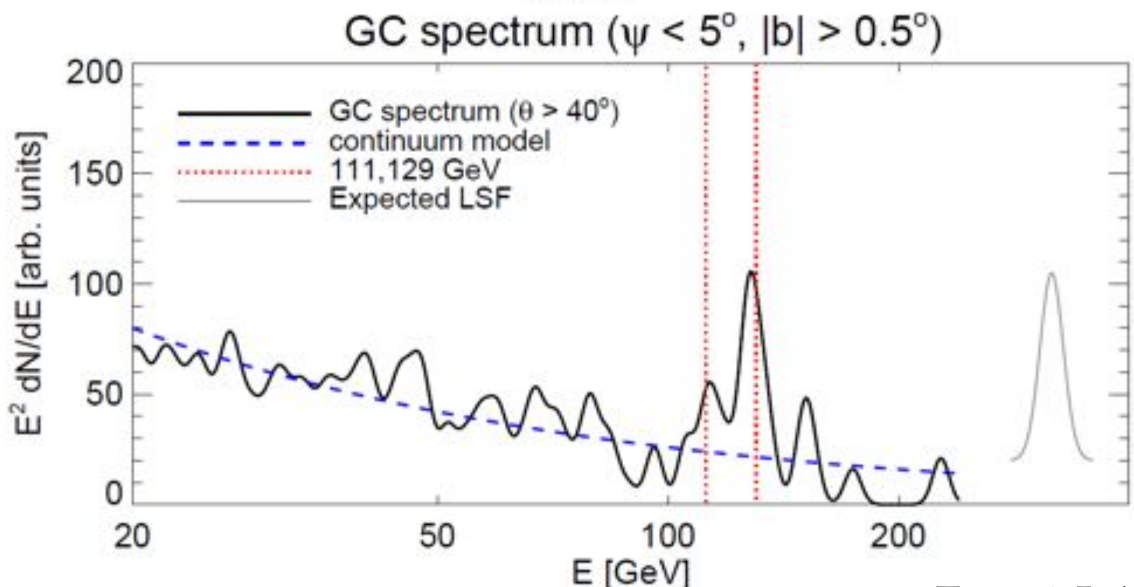
Mass = 130 GeV.
Significance 4.6 σ
(3.2 σ if ”look elsewhere” effect included) .

C. Weniger Gamma-2012, Heidelberg, Proc.



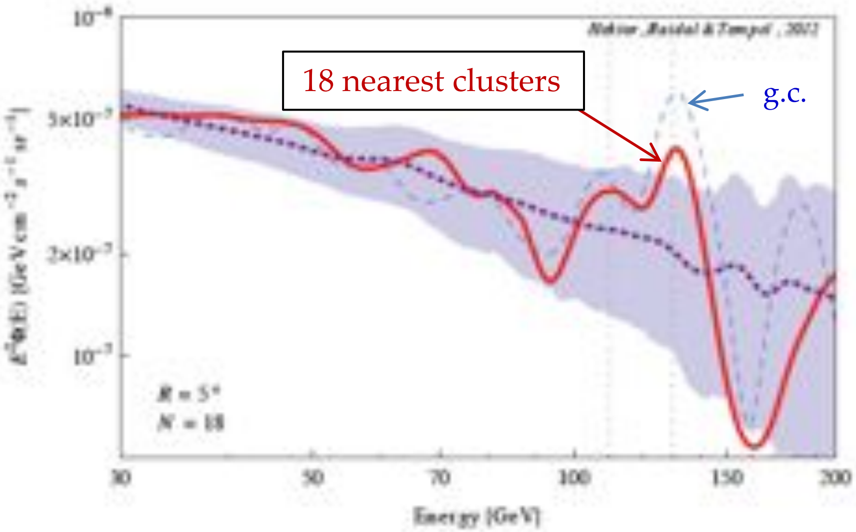
E. Tempel, A. Hektor and M. Raidal, May 2012: Independent confirmation of the existence of the excess, and that it is not correlated with Fermi bubbles.

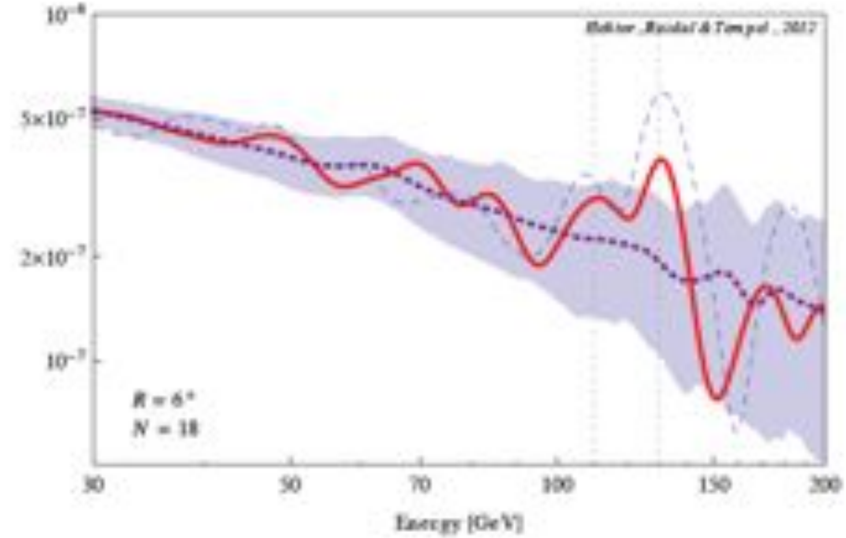
Best fit: γγ line, mass m_χ = 130 GeV



Another independent verification, M. Su and D. Finkbeiner, June 2012 (template fitting). They note: maybe a second line; flux maximum is offset by 1.5 deg from g.c.

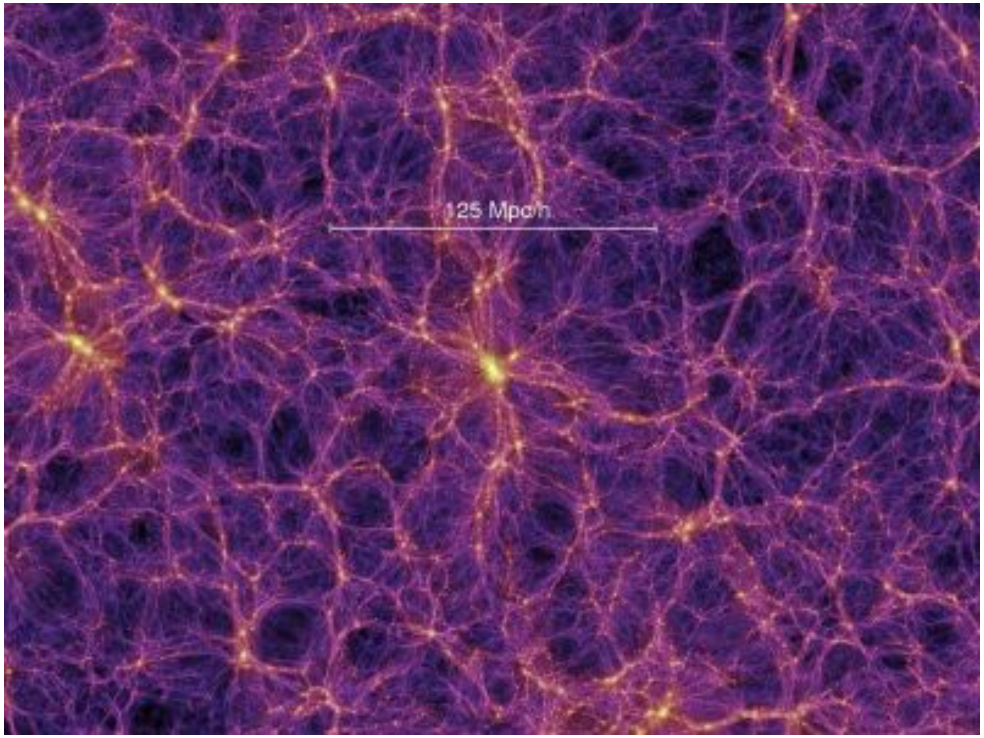
Fermi-LAT public data





Additional support: Identical (double) line signal from stacking of 18 nearest clusters for large (5 – 6 deg) angular regions (A. Hektor, M. Raidal and E. Tempel, July & Oct., 2012; see also X.-Y. Huang & al., Aug. 2012). **Should be verified, e.g. by Fermi-LAT collab.** Is this the first signal from the "cosmic web" of DM?

Cluster	l (deg)	b (deg)	M_{200} ($10^{14} M_{\odot}$)	D (Mpc)	r_{200} (deg)	J (Mpc ρ_c^2)
Virgo	-76.2	74.5	6.9	17.2	5.6	1465
Fornax	-123.3	-53.6	2.4	19.77	3.7	793
M49	-73.1	70.2	1.4	18.91	3.24	549
NGC4636	-62.3	65.5	0.5	15.89	2.74	325
A3526 (Centaurus)	-57.6	21.6	5.3	44.46	2.15	315
Ophiuchus	0.6	9.3	40.5	122.51	1.53	242
A1060 (Hydra)	-90.4	26.5	4.1	49.25	1.78	205
NGC5813	-0.8	49.8	1.	27.55	1.97	191
A3627 (Norma)	-34.7	-7.3	7.2	70.69	1.49	160
Perseus	150.4	-13.4	8.6	79.48	1.41	147
AWM7	146.3	-15.6	7.2	74.64	1.41	144
ANTLIA	-87.1	19.2	2.8	50.13	1.54	143
Coma	58.1	88.	12.9	101.14	1.27	131
A1367	-125.2	73.	10.1	94.05	1.25	121
NGC5846	0.4	48.8	0.5	26.25	1.66	120
NGC5044	-48.8	46.1	1.1	38.81	1.46	108
A2877	-66.9	-70.9	9.5	105.13	1.1	92
3C129	160.4	0.1	7.8	97.15	1.11	91



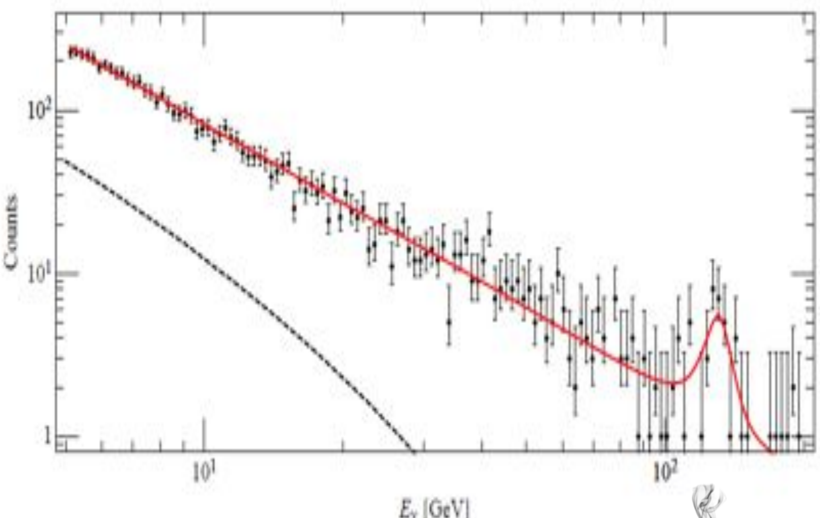
V. Springel & al., VIRGO Consortium

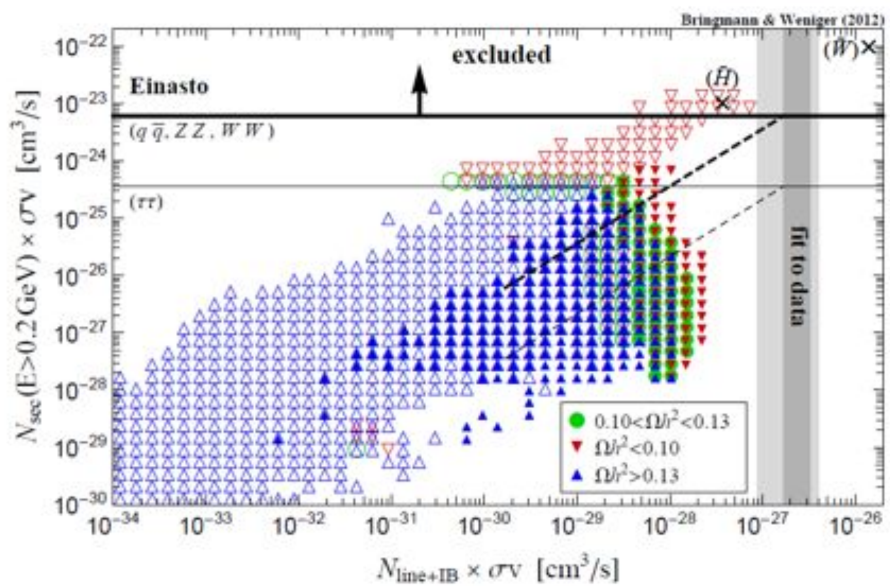
T. Bringmann & al. arXiv:1203.1312; M. Buckley and D. Hooper, 1205.6811; W. Buchmuller & M. Garny, 1206.7056; T. Cohen, M. Lisanti, T. Slatyer & J. Wacker, 1207.0800; I. Cholis, M. Tavakoli & P. Ullio, 1207.1468:

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

So what is this?	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, agrees with 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, maybe by factor of 10 (but see later). Cluster analysis has to be independently checked.	More data. Change observation strategy to optimize viewing of g.c. Use other detectors and/or other targets (clusters, dwarf galaxies, halo with galactic centre excluded,…).
2. A systematic error (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. E.Bloom (Tuesday): *"The LAT Collaboration does not have a consistent interpretation of the GC […] structure originating from a systematic error at this time"*	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.

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:**

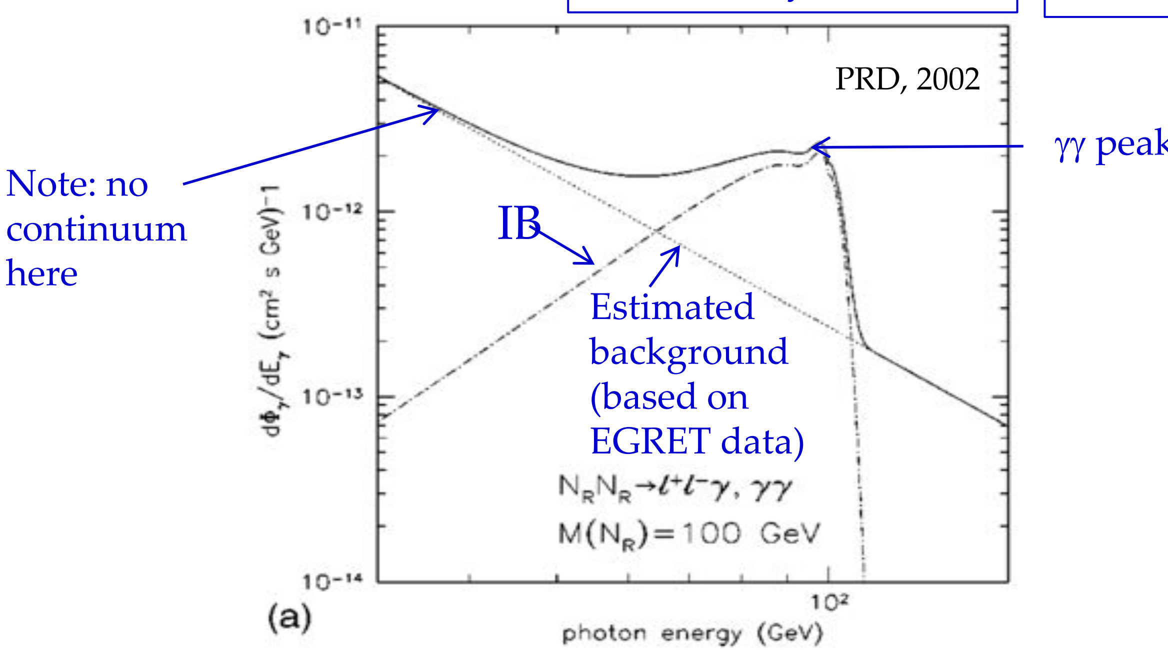
The right-handed neutrino N_R (in ”radiative see-saw” models) as the dark matter candidate – May explain observed ~ 0.1 eV neutrino masses, also muon g-2 anomaly & baryon asymmetry of universe. Internal bremsstrahlung plus γγ annihilation will give a peculiar spectrum:

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

s wave part determines the lowest order cross section today

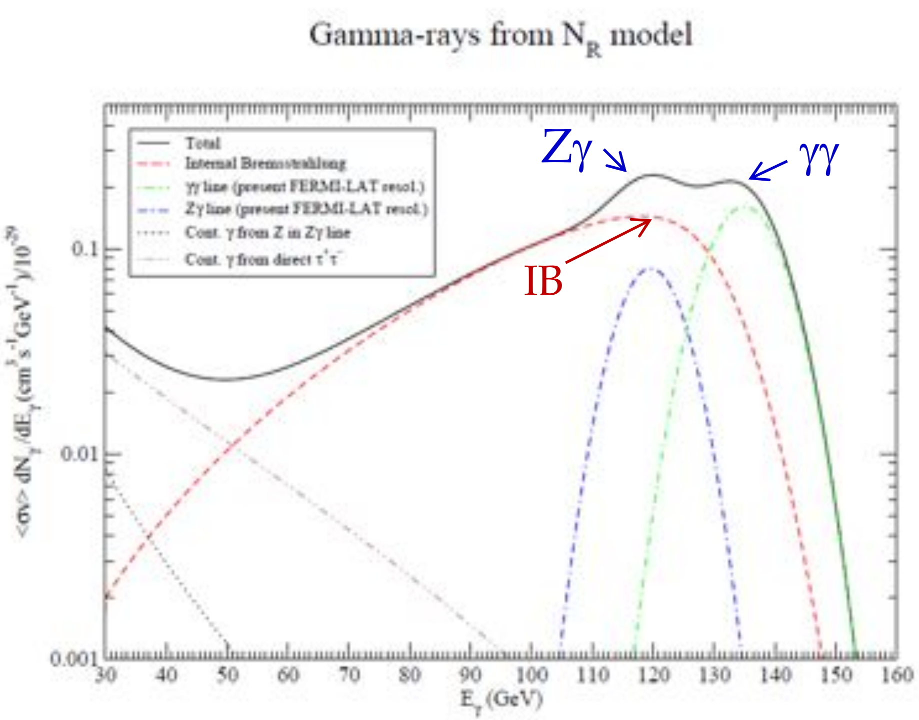
p wave part sets relic WIMP density in early universe

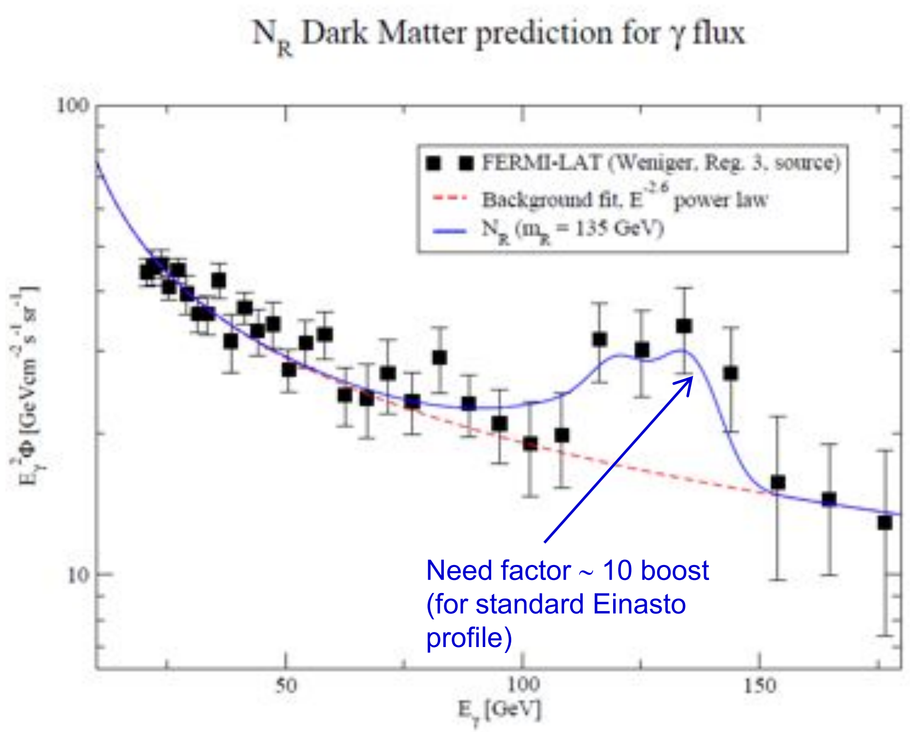
$f = m_S/m_N$



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

- 2γ line at 135 GeV, internal brems with broad peak at ~ 120 GeV, add Zγ line at 119 GeV (neglected in paper with Baltz)
- Adjust absolute rate, compare with data
- N.B.: This model is very similar to supersymmetric models with light sleptons (cf. Bringmann & Weniger, arXiv 1208.5481)
- Other attempts which circumvent the problem of no continuum: N. Weiner and I. Yavin, arXiv:1209.1093 (magnetic and Rayleigh dipole); B. Shakya, arXiv:1209.2427 ("fine-tuned" SUSY bino + small wino admixture),…

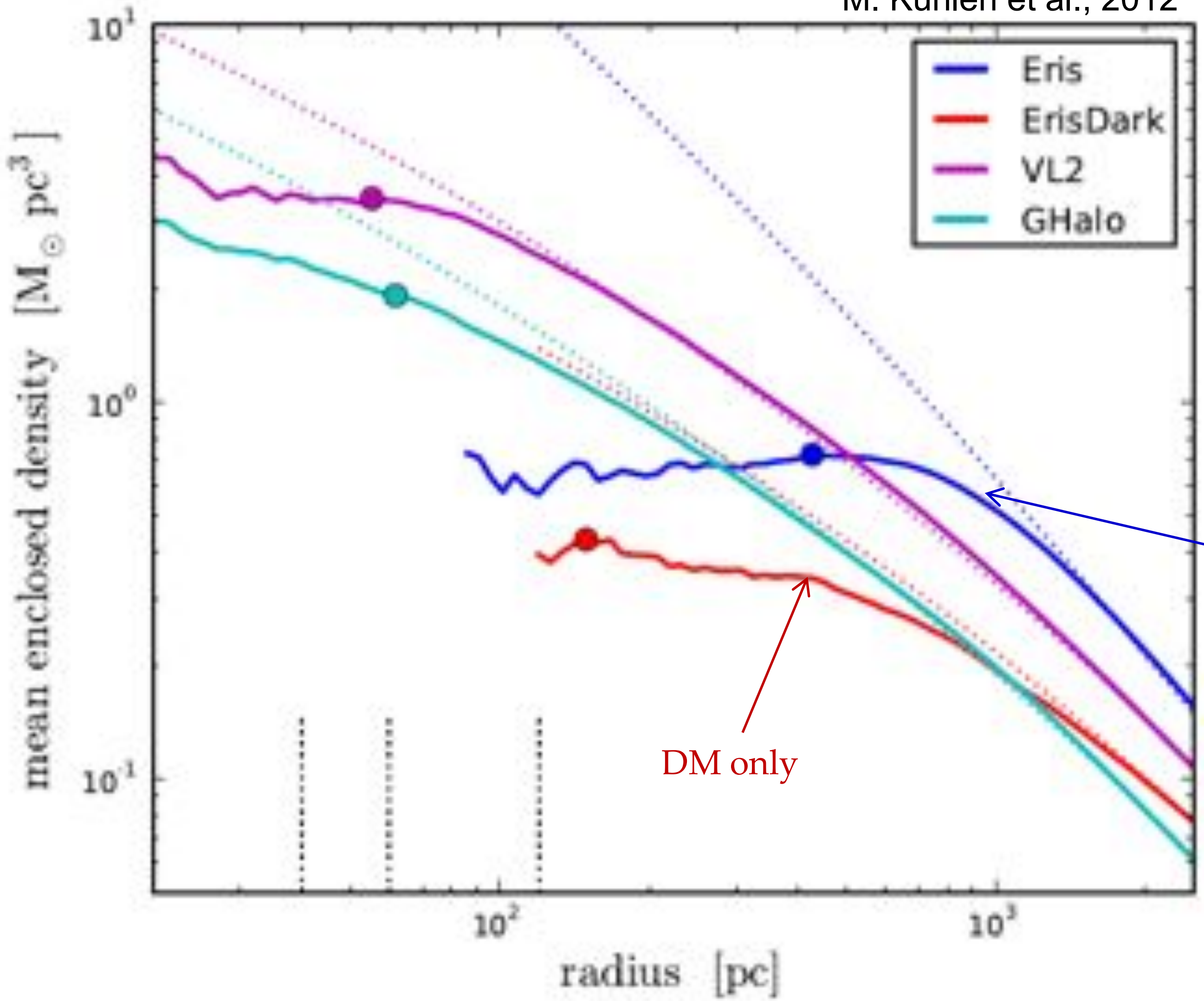




Assume present Fermi-LAT energy resolution, ~ 10 %

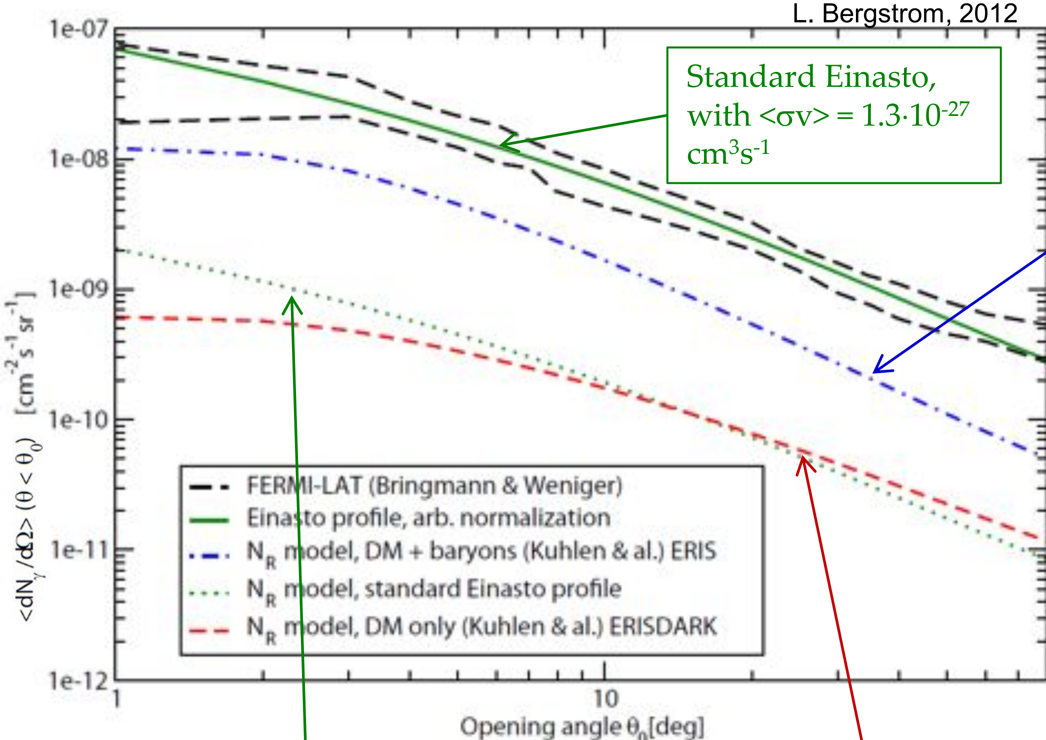
How the presence of baryons changes the DM density near the g.c.:
New DM simulations including baryons (M. Kuhlen & al,. 2012). The presence of the bar changes both the angular and radial distribution of DM over several Gyr:

M. Kuhlen et al., 2012



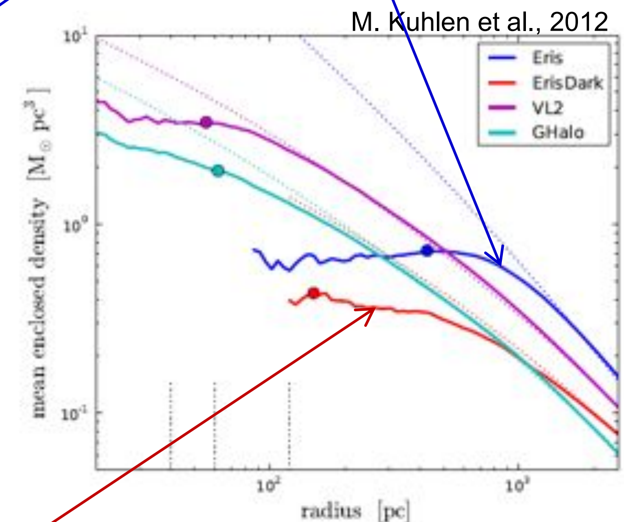
DM + baryons gives ”adiabatic contraction” of DM, and causes a core. Also a displacement of centre of DM from g.c. (although low density contrast)

Gives factor 6-8 enhancement of rate:



Standard Einasto, with <σv> = $1.3 \cdot 10^{-27}$ cm^3s^{-1}

N_R prediction, <σv> = $1.0 \cdot 10^{-28}$ cm^3s^{-1} Using ERIS DM plus baryons halo distribution

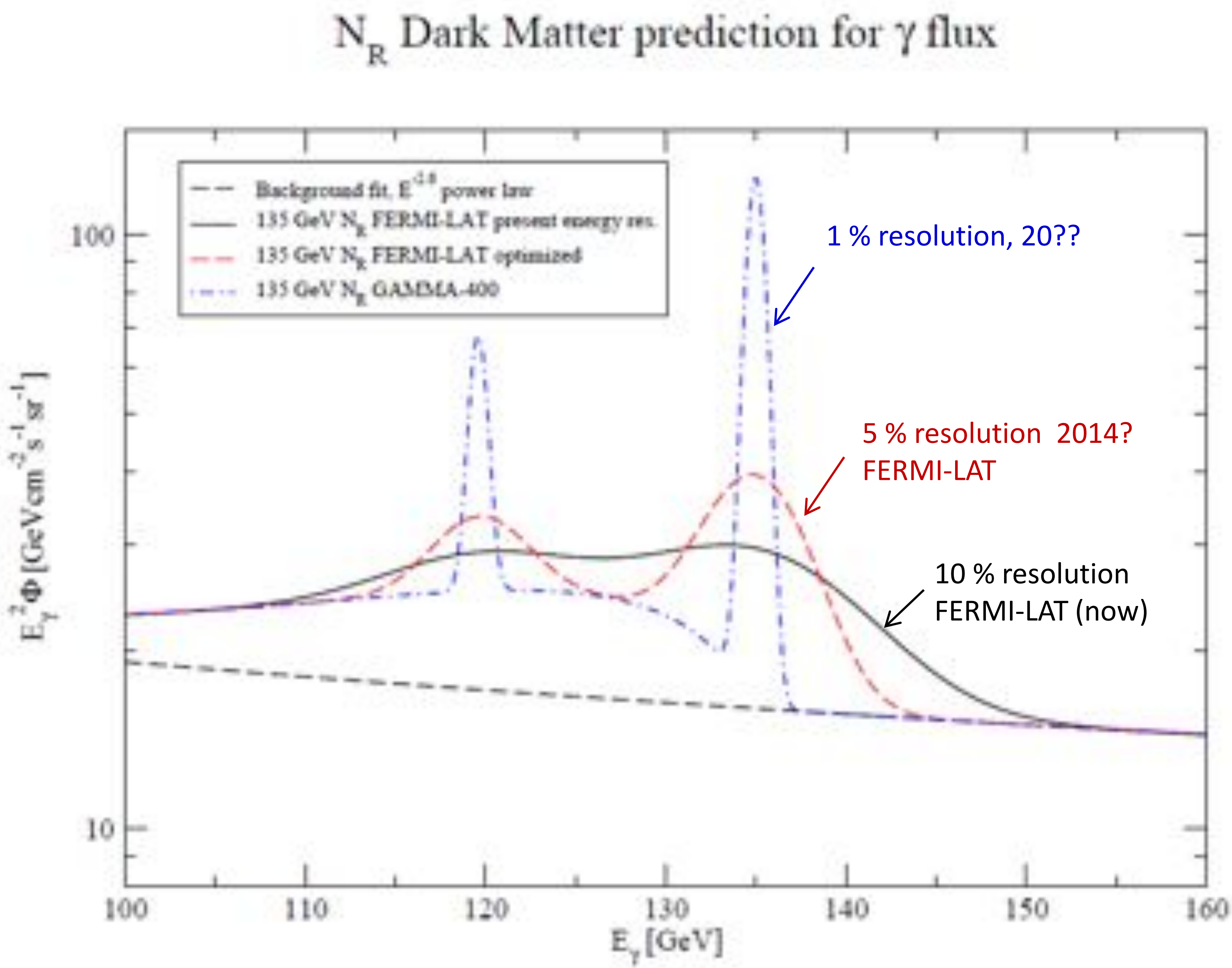


N_R prediction, <σv> = $1.0 \cdot 10^{-28}$ cm^3s^{-1} using standard Einasto DM only halo

ERISDARK, DM only halo distribution

Only factor 2-3 missing ⇒ Rate problem essentially solved!

The future:



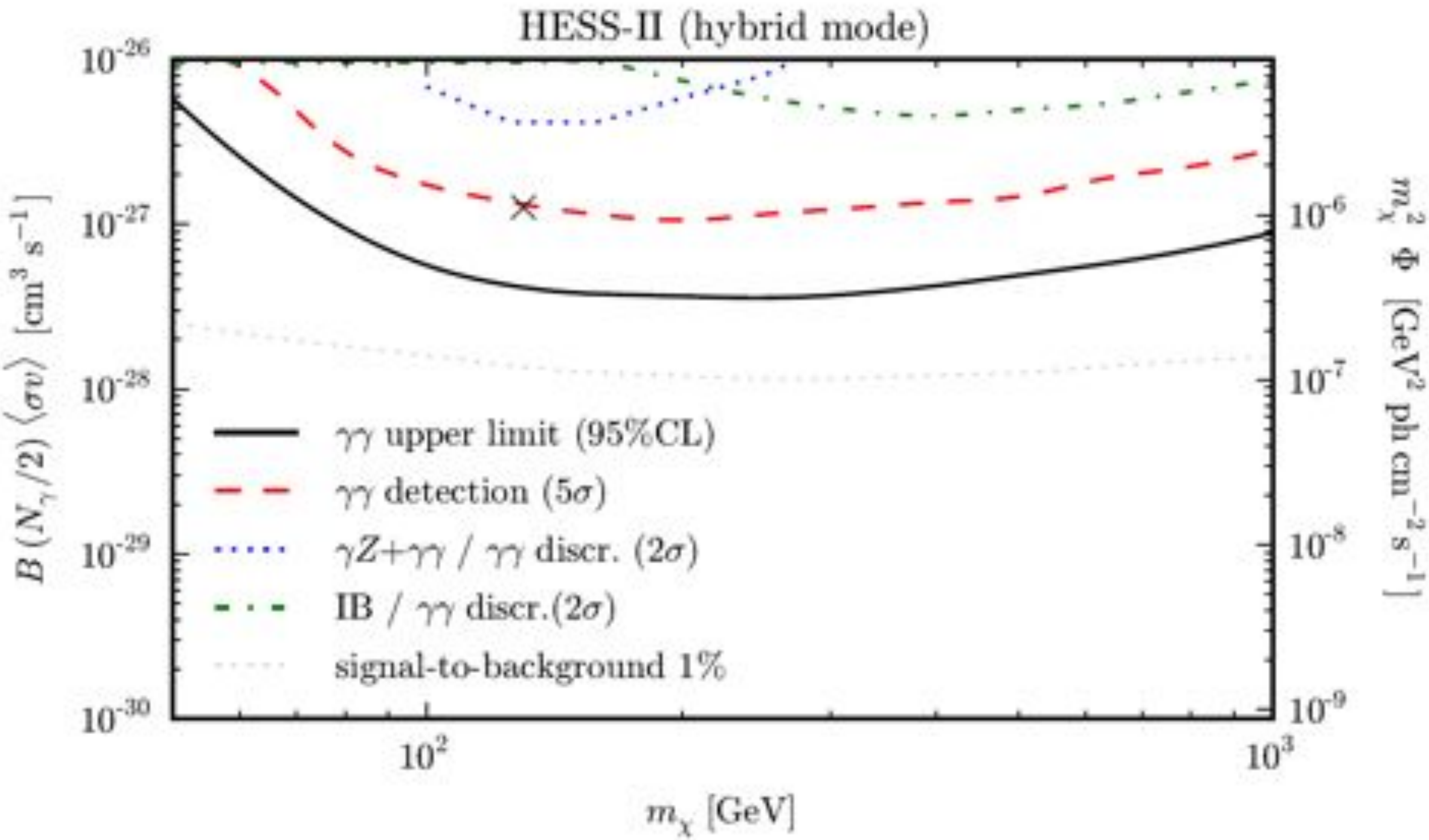
L.B., PRD, in press (2012)

A new player in the game: HESS-II in Namibia (28 m segmented mirror) – saw first light July 26th 2012.

Ideal viewing conditions for galactic centre April – August.

The dark matter analysis is presently led from Stockholm (C. Farnier & al.)

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



5 σ detection after 50 hours of observation in 2013 (or strong upper limit). With CTA (2018) need less than 5 hours (!)

Reminder! Reasons for still being skeptical:

- Statistics is relatively low, and background not well studied in this energy range.

- The Fermi-LAT collaboration has not yet confirmed the effect. The bump from the Earth's limb also at ~ 130 GeV may point to an (unknown) instrumental effect? Look forward to talk of A. Albert for the Fermi-LAT collaboration later today.

The good news is that within one or two years we will definitely know:

- Fermi-LAT has then collected more data, perhaps optimized for viewing the g.c.

- HESS-II has a golden opportunity to either conclusively make a discovery (at 5 σ) , or rule out the effect, already next year.

A bright 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 the planned Chinese Space Station. Energy resolution (100 GeV) ~ 1 %. Effective area ~ 1 - 2 m^2. Angular resolution (100 GeV) ~ 0.01°. Planned launch around 2020.

All three have detection of dark matter as one key science driver (and will build on the remarkable success of Fermi-LAT)

Ideal, e.g., for looking for spectral DM-induced features, like searching for γ-ray lines up to 1 TeV. 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, in press).

Otherwise, the parameter space of viable models will be probed with unprecedented precision – will follow the WIMP lead to the end...

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 this exciting tentative effect is real – caution is advised at present.

- The field is entering a period of rapid development: CERN LHC is 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 fully operational; Fermi-LAT will collect at least 5 more years of data; HESS-II has seen first light; CTA, Gamma-400, DAMPE and HERD may operate by around 2020, 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!