DARK MATTER AT THE WEAK SCALE

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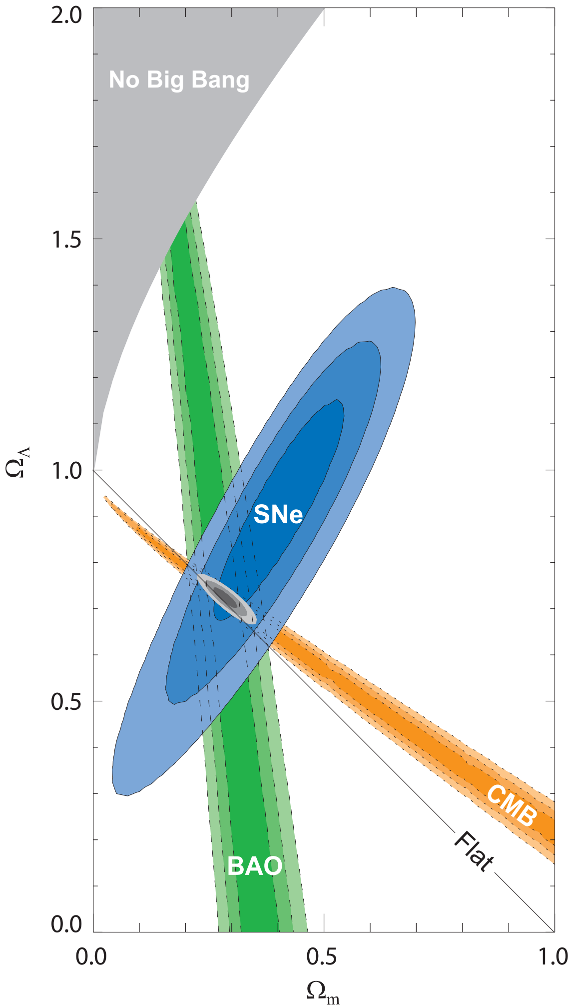
Content:

- Dark Matter: what we know
- WIMPs: earliest relics
- New physics at the EW scale?
- Burst of recent model building to account for hints of DM in Direct and Indirect searches: present hints and some models
- Summary and conclusions

Dark Matter: We know a lot!

- We know its abundance in the Universe to a percent level
- We know most is not baryonic
- We know is it NOT explained by the Standard Model of EP

Dark Matter: not baryons Fig: Kowalski et al 2008



$$\Omega = \rho/\rho_c \qquad \rho_c \simeq 5 \text{ keV/cm}^3$$

68.3%, 95.4%, 99.7%CL constraints on Ω_M and Ω_Λ obtained from Cosmic Background Radiation Anisotropy CMB (orange), Baryon Acoustic Oscillations BAO (green), and the Union Compilation of 307 Type Ia supernovae (SNe Ia) (blue); Ω_m =0.285$^{+0.020}_{-0.019}$(stat)$^{+0.011}_{-0.011}$(sys) assuming DE is a cosmological constant

WMAP7, BAO, SN1a: E. Komatsu, et al., 2010

$\Omega_\Lambda = 72.2 \pm 1.5\%$ $\Omega_m = 27.8 \pm 1.5\%$

where Ω_m is:

$\Omega_b = 4.61 \pm 0.15\%$ $\Omega_{DM} = 23.2 \pm 1.3\%$

Most of the Dark Matter: is cold or warm namely is non-relativistic or semi-relativistic at galaxy formation ($T \simeq 1\text{keV}$)

No CDM or WDM in the SM! (active-ν are HDM)

But many in extensions of the SM!

- Warm dark matter: sterile neutrino, gravitino, non-thermal WIMPs...
- Cold dark matter: WIMPs (LSP or variants LKP, LZP, LTP), axion, WIMPZILLAs, solitons (Q-balls), SuperWIMPs (get their relic density from WIMPs which decay into them)...

Here we concentrate on WIMPs.
Why WIMP's? The "WIMP" miracle....

WIMPs as Dark Matter: "Thermal WIMPs"

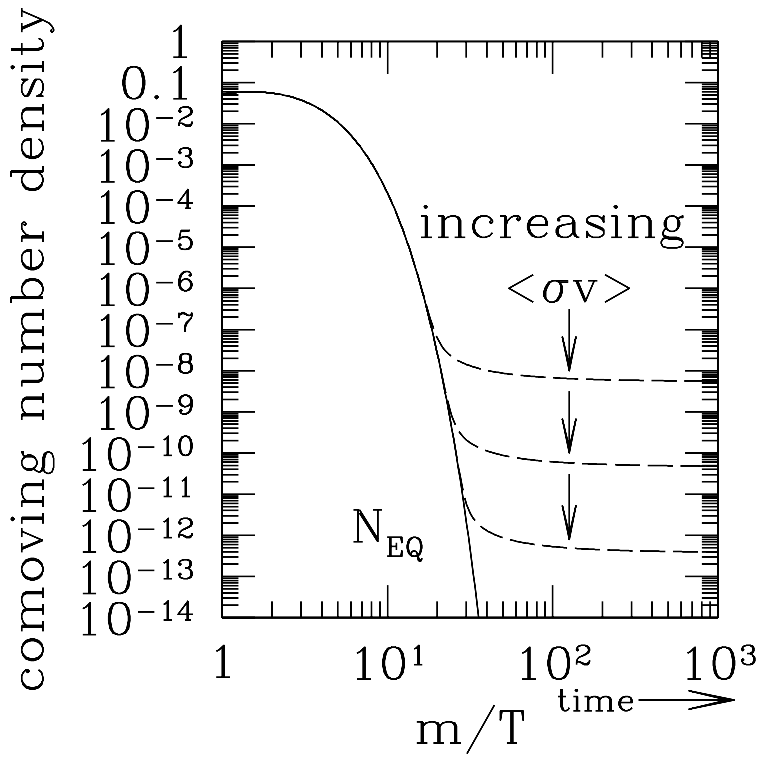
WIMPs are the earliest relics, from the pre-BBN era of the Universe, from which we have no data! So we must make assumptions...

Standard Assumptions: Universe radiation dominated at $T > T_{f.o.} \simeq m/20$

- WIMPs reach thermal equilibrium while radiation dominates
- Chemical decoupling when $\Gamma_{\rm ann} = \langle \sigma_{annih} v \rangle \, n \leq H$,
- No entropy change in matter+radiation

$$\Omega_{\rm std} h^2 \approx 0.1 \, \frac{3 \times 10^{-26} {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle}$$

Weak $\sigma_{annih} \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm s}$ for $\Omega h^2 = \Omega_{DM} h^2 \sim 0.1$!



We do not know the history of the Universe before BBN

we expect to learn about it precisely from WIMPs (or sterile neutrinos..., relics from that epoch)

- Earliest remnants: WIMPs decouple at $T_{f.o.} \simeq m_\chi/20$

- BBN (ends at $t_U \simeq$ 200 sec, $T \simeq$ MeV) is the earliest episode from which we have a trace: the abundance of light elements D, ^{4}He, ^{7}Li.

  Imposes only $T_{RH} > 4$ MeV (Hannestad, 2004)

  T_{RH}: highest T of the radiation dominated epoch before BBN

- In many viable non standard cosmological models relic densities may be very different...

Same MSSM- non standard pre-BBN cosmology: Low T_{RH} Models

MSSM with 9 parameters + μ sign + two additional parameters T_{RH} and η)

Same 1700 models

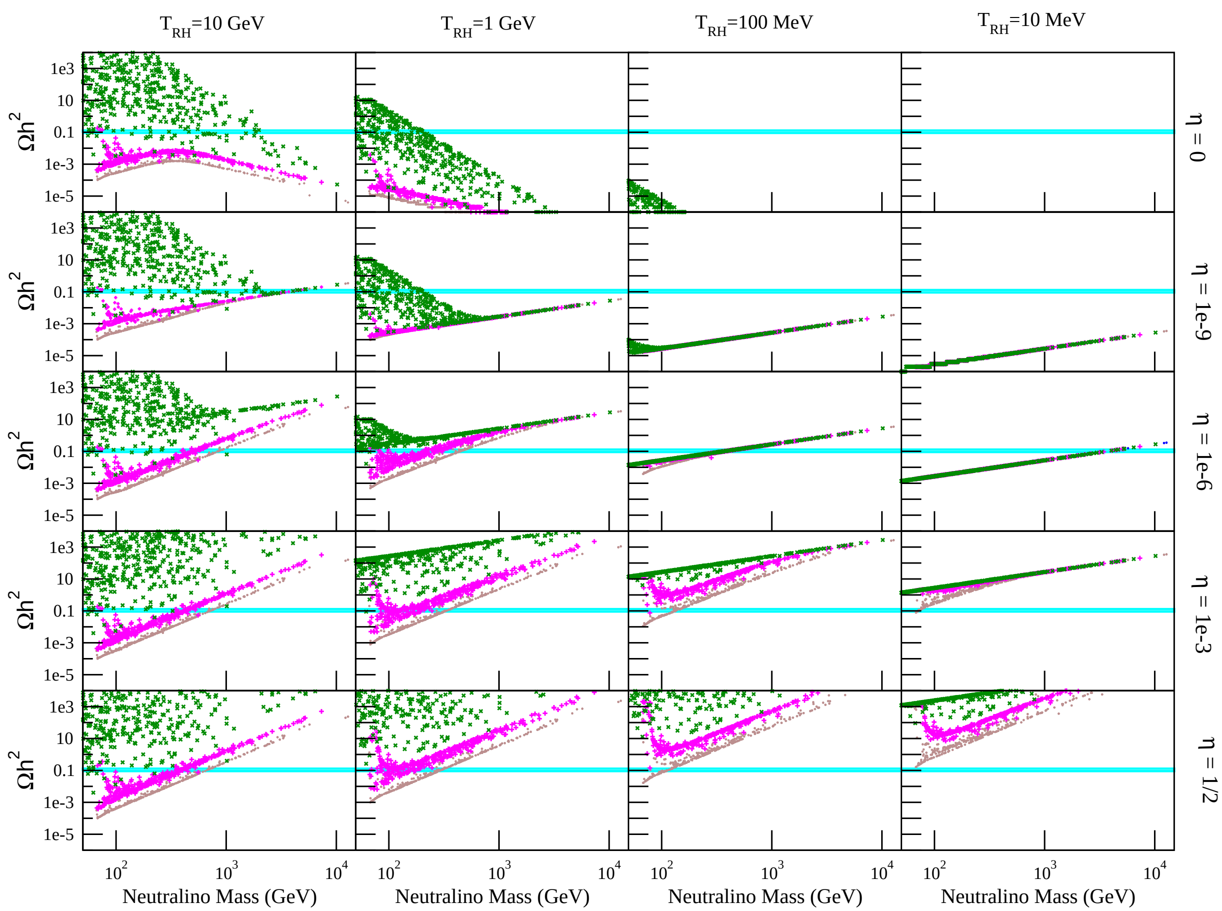
(Gelmini, Gondolo, Soldatenko &Yaguna, 2006)

All points can be brought to cross the DM cyan line with suited T_{RH}, η

bino-like

higgsino-like

wino-like



New physics at the EW scale

Expected because of Spontaneous Symmetry Breaking arguments (totally independently of the DM issue)

Naturalness implies $\Lambda_{SM} \approx \mathrm{O(TeV)}$ above which the cancellation in corrections to m_{Higgs} is due to a new theory....

- supersymmetry (with or without a composite Higgs boson)
- technicolor (walking or top assisted TC)
- large extra spatial dimension (possibly warped)
- "Little Higgs" model (Higgs is a pseudo-Goldstone boson)

which provide main potential discoveries at the LHC
and "well motivated" DM candidates...mostly WIMPs: LSP, Lightest Technibaryon, LKP (Lightest KK Particle) or LZP (in Warped SO(10) with Z3 model), LTP (the Lightest T-odd heavy photon in Little Higgs with T-parity)...

New physics to explain DM?

May be different...., for example (Arkani-Hamed, Finkbeiner, Slatyer & Weiner PRD79:015014,2009)

"A Theory of DM" WIMP, with 500-800 GeV mass, has an exited state with mass difference 0.1 to 1 MeV, is charged under a broken hidden gauge symmetry G_{dark} with a boson ϕ lighter than 1GeV, explaining:

- the DAMA signal with "inelastic" (IDM)
- the INTEGRAL data with "exciting" (XDM)
- the PAMELA data with WIMP's annihilating into light ϕ's (+ ATIC, but now Fermi!)
- the "WMAP Haze" (+ EGRET excess rejected by Fermi!)

Attests to the ingenuity of theorists to explain everything.....

Made to fit DM-not to solve the EW hierarchy.... and provides signatures for the LHC: major additions to SUSY signals, GeV-dark Higgses and gauge bosons decay into visible particles and leptons, MSSM LSP decays into the true LSP, thus many lepton jets with GeV invariant masses expected...Arkani-Hamed, Weiner JHEP0812:104,2008

Physics beyond the SM

is required by Dark Matter,

and expected at the EW scale,

and both physics may or

may not be related!

Thus LHC and DM searches are

independent and complementary.

DM searches:

Complementary to the LHC and to each other!

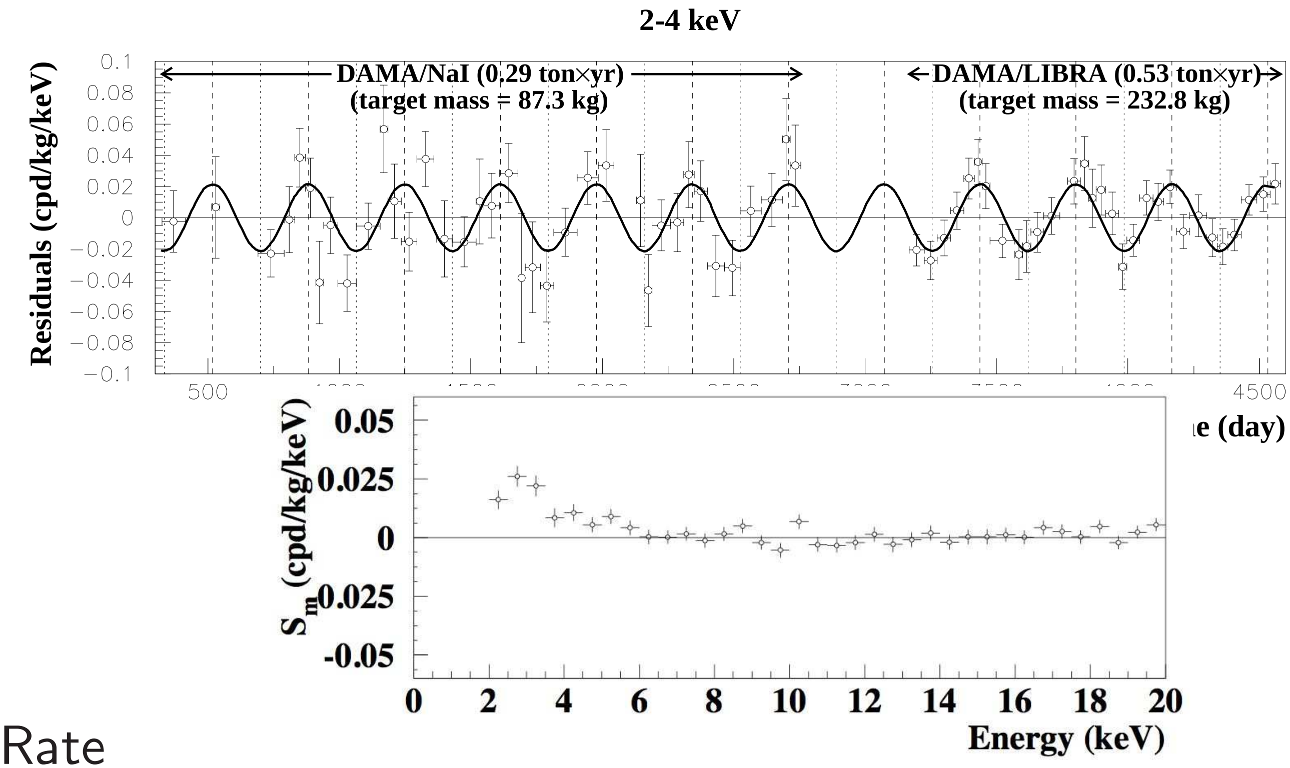
- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way
  (Many: DAMA, XENON, CDMS, CoGent, Cresst, Edelweiss, Zeplin, LUX...)

- Indirect Detection- looks for DM annihilation (or decay) products
  - neutrinos from Sun/Earth or the GC (AMANDA-Icecube, Antares-KM3NeT)
  - γ-rays and anomalous cosmic rays from Galactic Halo(s), and the Galactic Center (FST, HESS, VERITAS, PAMELA, AMS...)

Many DM "hints" in both....

Direct DM Searches: DAMA/LIBRA

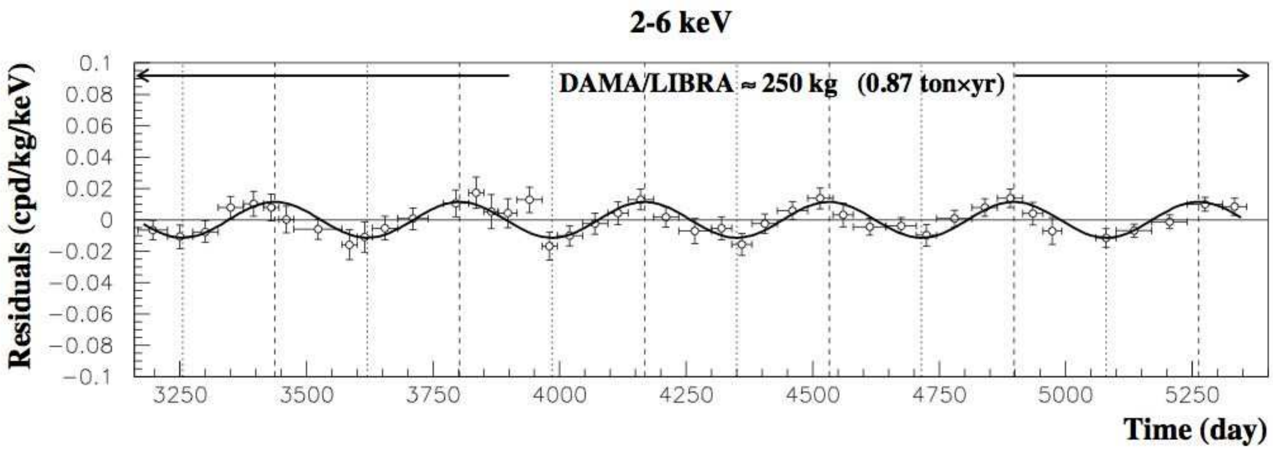
25 NaI (TI) crystals of 9.5 kg each, 4y in LIBRA (11 years total), 0.83 ton × year, 8.2σ modulation signal. (Bernabei et al 0804.2741)

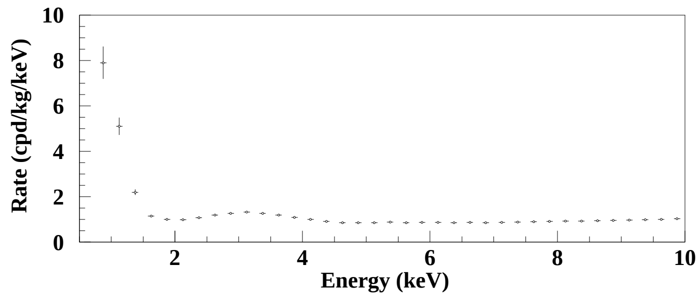


Rate

Direct DM Searches: New DAMA/LIBRA

25 NaI (Tl) crystals of 9.5 kg each, 6y in LIBRA (13 years total), 1.17 ton $\times$ year, 8.9σ modulation signal.(Bernabei et al 1002.1028)





Rate

Direct DM Searches: is the DAMA/LIBRA annual modulation signal compatible with all other searches?: maybe for light (elastically scattering) WIMP's and inelastically scattering DM (IDM) among others...

Light m <10 GeV WIMP's

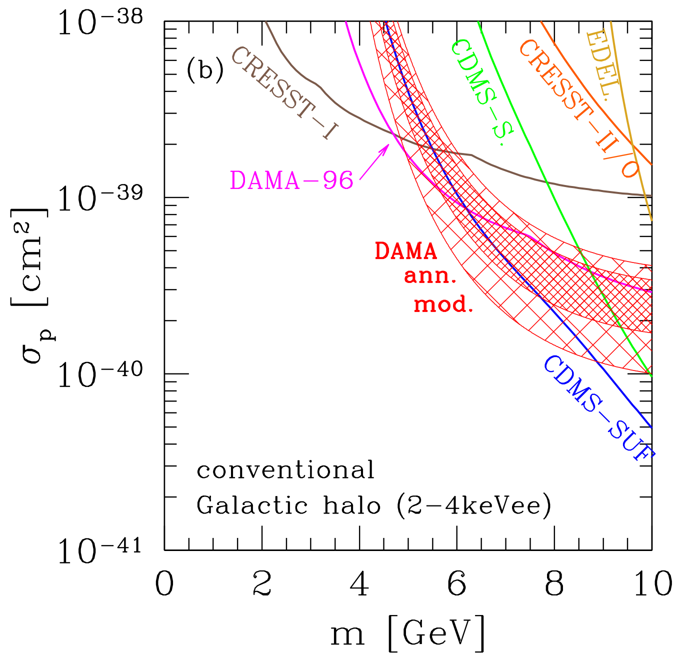
2004: DAMA signal allowed for light WIMP $m \sim 4 - 10$ GeV (SI + conventional halo)

(Gelmini, Gondolo 2004, 2005)

For SD too (Freese, Gondolo, Savage 2005)

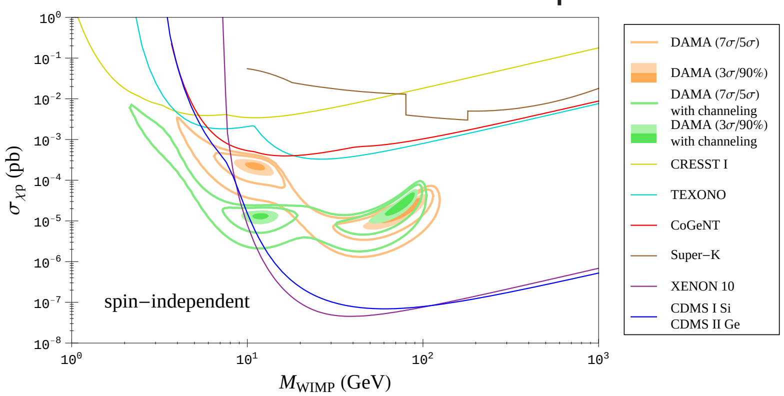
Here "raster scan" in m because only 2 data bins given (Example: 2-4, 6-14 keVee bins)

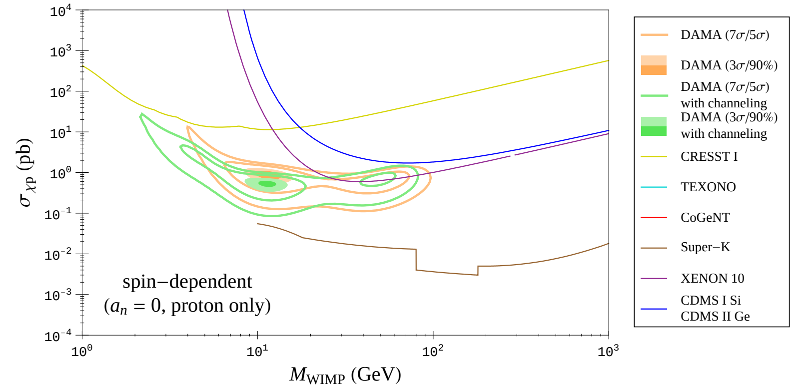
This was then... after DAMA/LIBRA 36 data bins given



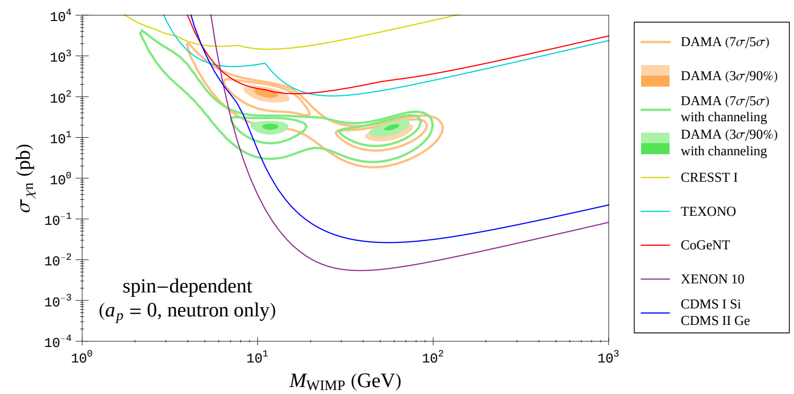
Light m <10 GeV WIMP's: (e.g. Savage, Gelmini, Gondolo, Freese JCAP 0904:010,2009)

36 bins likelihood ratio 4 param. fits





With the large channeling fraction DAMA estimated, light usual WIMPs, $m \simeq 7$ to 10 GeV were a possible explanation (in conflict with CDMS and XENON at the 2-3σ level)



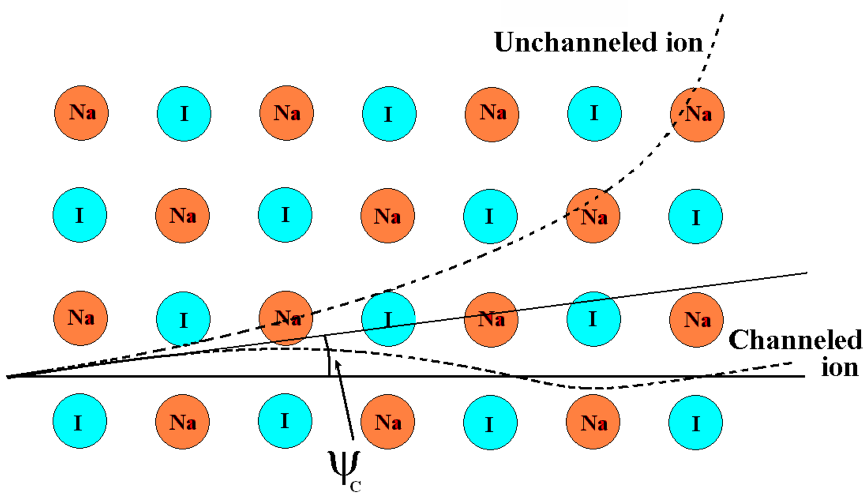
Recent revaluation of channeling: it is not important at less than 5σ. This makes it more difficult for light WIMPs (Bozorgnia, Gelmini, Gondolo 1006.3110; Savage et al. 1006.0972)

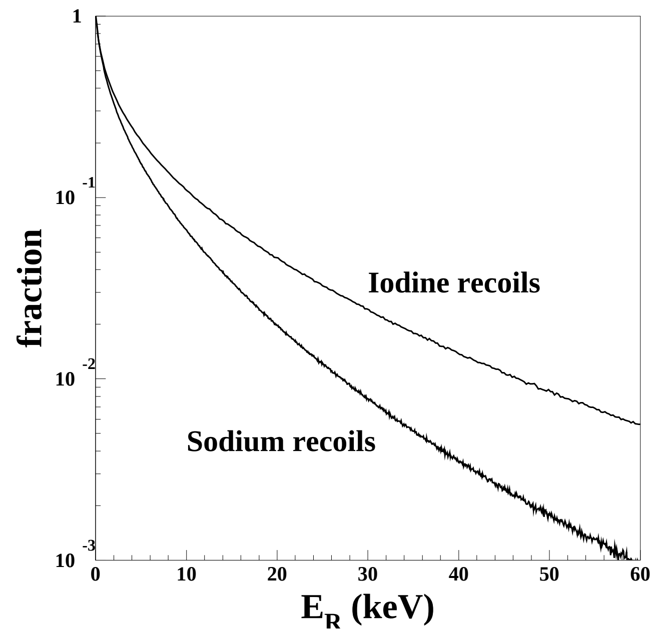
DAMA channeling fraction:

When ions recoiling after a collision with a WIMP move along crystal axes and planes, they give their energy to electrons, so $Q = 1$ instead of $Q_I = 0.09$ and $Q_{Na} = 0.3$

Calculated as if ions are incident on the crystal, i.e. start in the middle of the channel

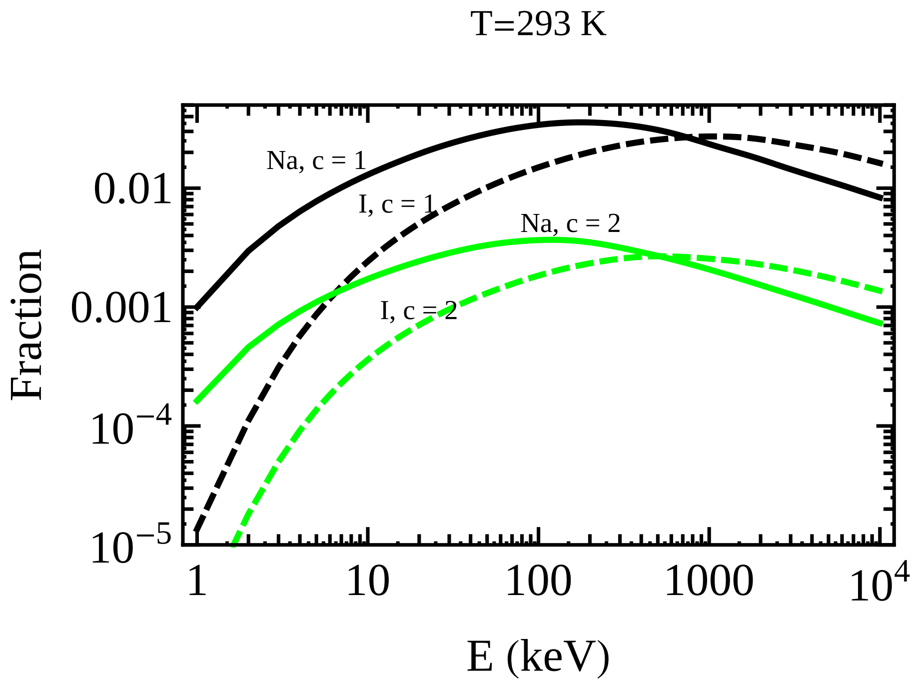
(DAMA, 2008)





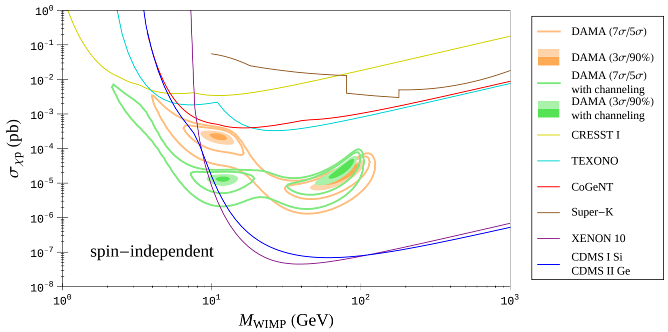
DAMA channeling fraction: When colliding with WIMPs ions are ejected from lattice sites, "blocking" is important and channeling is reduced- A generous upper bound on the fraction (using analytic channeling models) is given by $c = 1$ curve

(Bozorgnia, Gelmini, Gondolo 1006.3110)

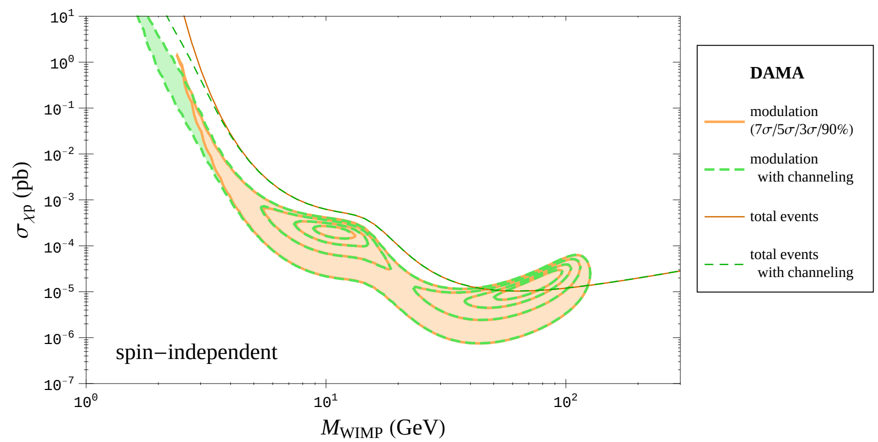


Compatibility of DAMA/LIBRA with other experiments

Then (Savage, Gelmini, Gondolo, Freese JCAP 0904:010,2009)



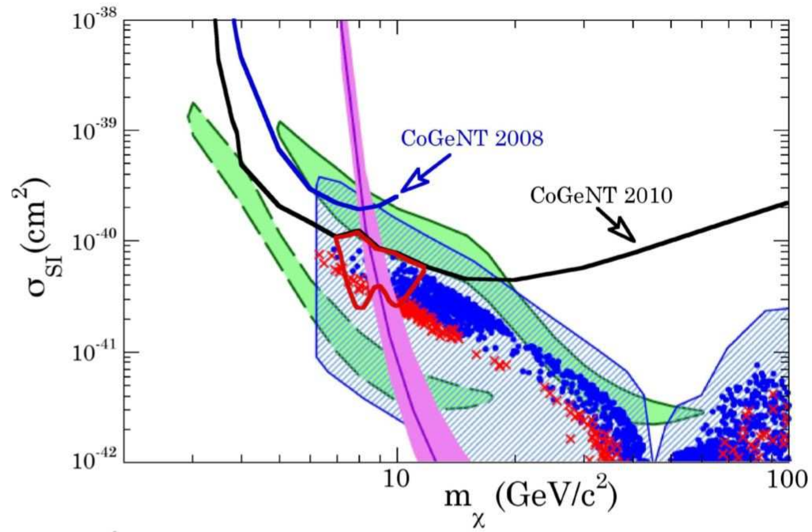
and now (difference at 7σ)(Savage, Gelmini, Gondolo Freese, 1006.0972)



Higher region due to Na, lower due to I

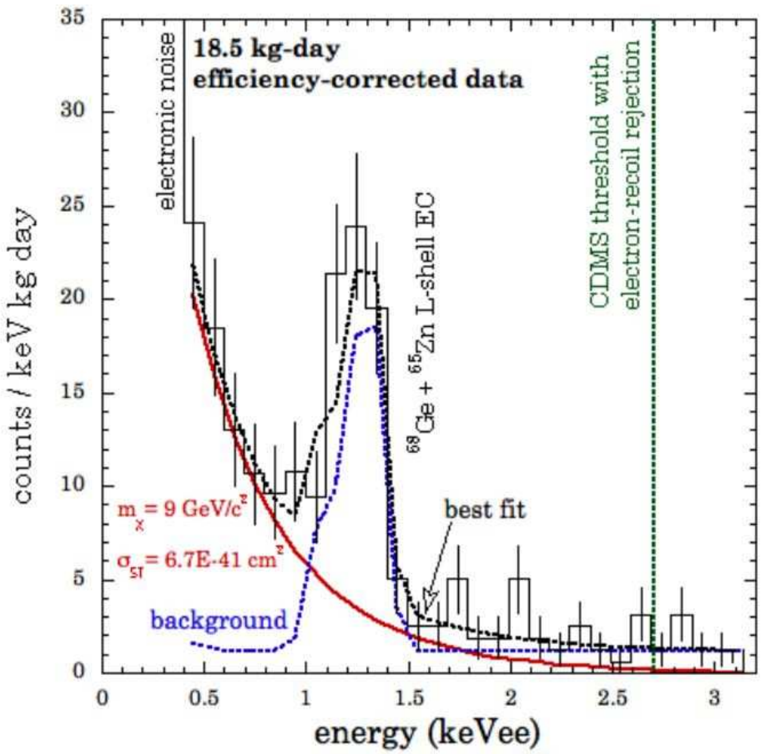
Light m <10 GeV WIMP's: CoGeNT is a 440g Ge detector with extremely low threshold, 0.4 keVee, 56 days of data, has excess "compatible" with the red-outlined irregular region for WIMPs with SI interactions

(C. E. Aalseth et al. [CoGeNT collaboration], arXiv:1002.4703 [astro-ph.CO])



DAMA+ recent excess of events by the CoGeNT collaboration (maybe also also hints in CRESST) generated a new bust of models, most need light bosons with GeV mass scale ... (e.g. Chang, Liu, Pierce, Weiner &Yavin 10, Kufflic, Pierce & Zurek, 10; Essig, Schuster, Toro & Wojtsekhowski, 10...) but neutralinos with no gaugino-unification are OK too...(Bottino, Donato, Fornengo, Scopel 2003-2008)

Light m <10 GeV WIMP's: CoGeNT



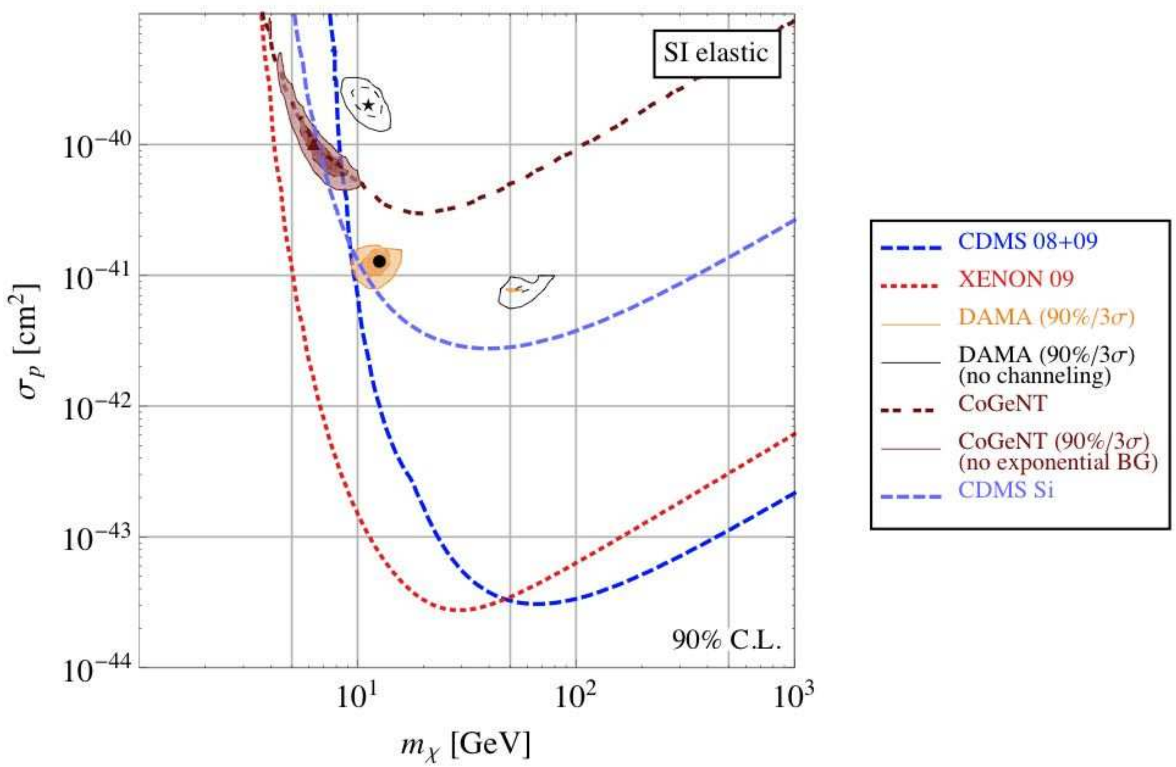
(Juan Collar DM-Marina del Rey, 2010):

Quotable: The excess of irreducible <u>bulk-like</u> events in CoGeNT is compatible with the WIMP hypothesis in a region where CDMS, DAMA and (several) phenomenological models (good thermal relics) can coexist. It is also equally compatible with any exponential background.

WIMP region only if exponential background is constrained (Kopp, Schwetz, Zupan addition to 0912.4264; Fitzpatrick, Hooper, Zurek 1003.0014; Chang, Liu, Pierce, Weiner, Yavin 1004.0697; Hooper, Collar, Hall, McKinsey 1007.1005)

Light m <10 GeV WIMP's: CoGeNT close to DAMA-no channelling Na region for SI- WIMP CoGeNT region only if exponential background is constrained

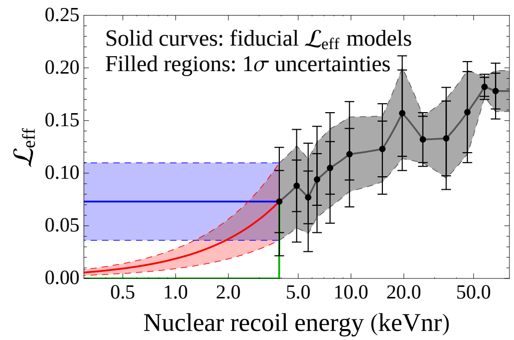
(Example: Kopp, Schwetz, Zupan addition to 0912.4264)

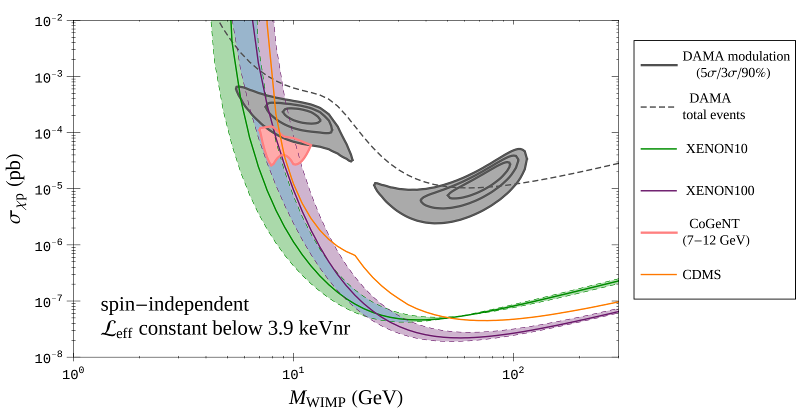


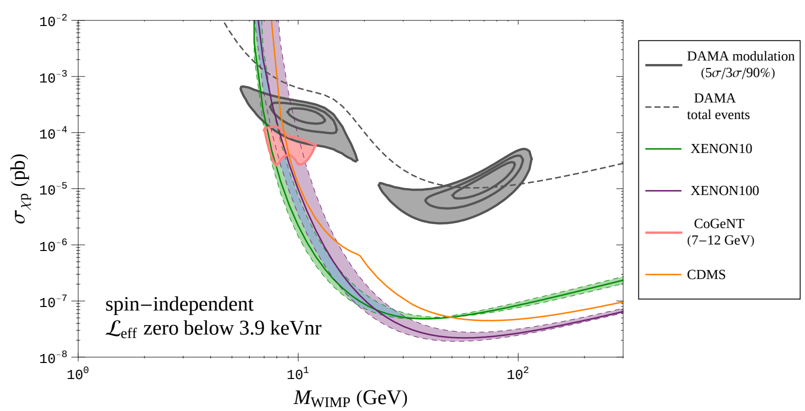
But XENON bound depends on L_{eff} (see talks of T. Marrodan Undagoitia and A. Ferella)

Light m <10 GeV WIMP's:DAMA/LIBRA +CoGeNT vs XENON bounds

L_{eff} measures how much scintillation light is produced a certain Xe nuclear recoil energy. Data of Manzur et.al 09 extrapolated below 4 keVnr. Band: changes in 90%CL bound with 1σ in L_{eff}. Green: XENON10. Purple: ZENON100(Savage,Gelmini, Gondolo, Freese 2010)



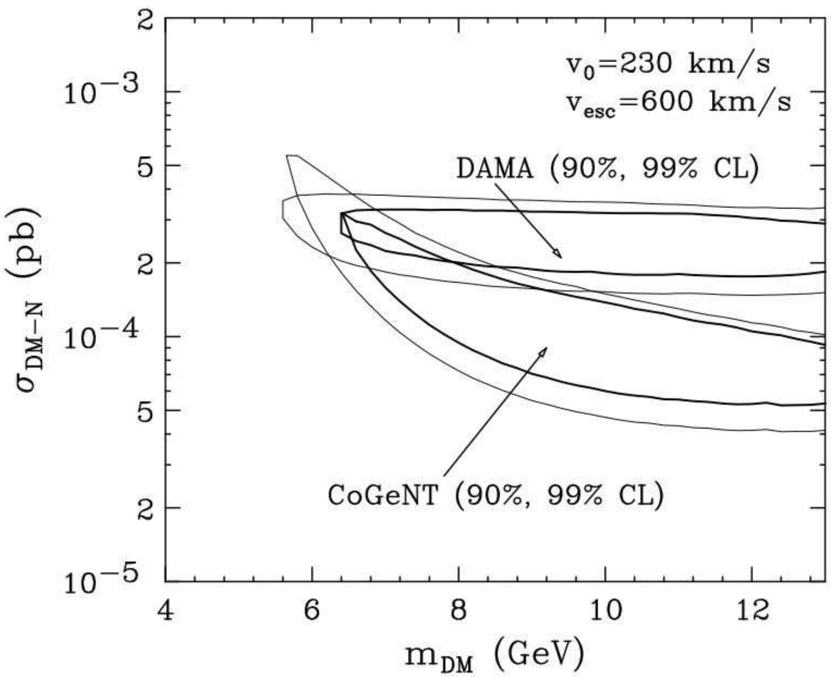


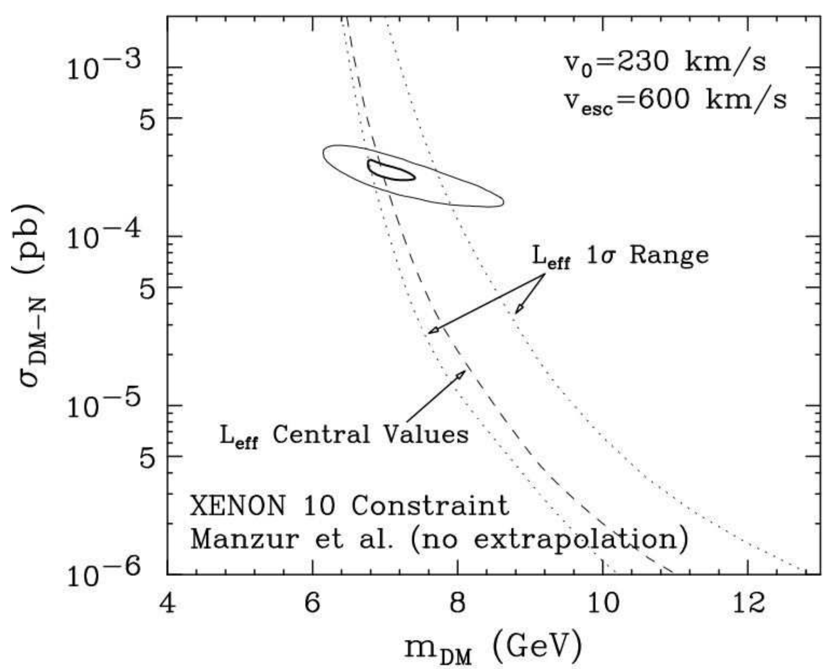


Light m <10 GeV WIMP's: CoGeNT+ DAMA vs XENON bounds

No exp. background in CoGeNT+ $Q_{\rm Na} = 0.2$ to 0.4 (instead of usual 0.3) regions overlap

(Hooper, Collar, Hall, McKinsey 1007.1005 - XENON bounds taken from Savage,Gelmini, Gondolo, Freese 2010



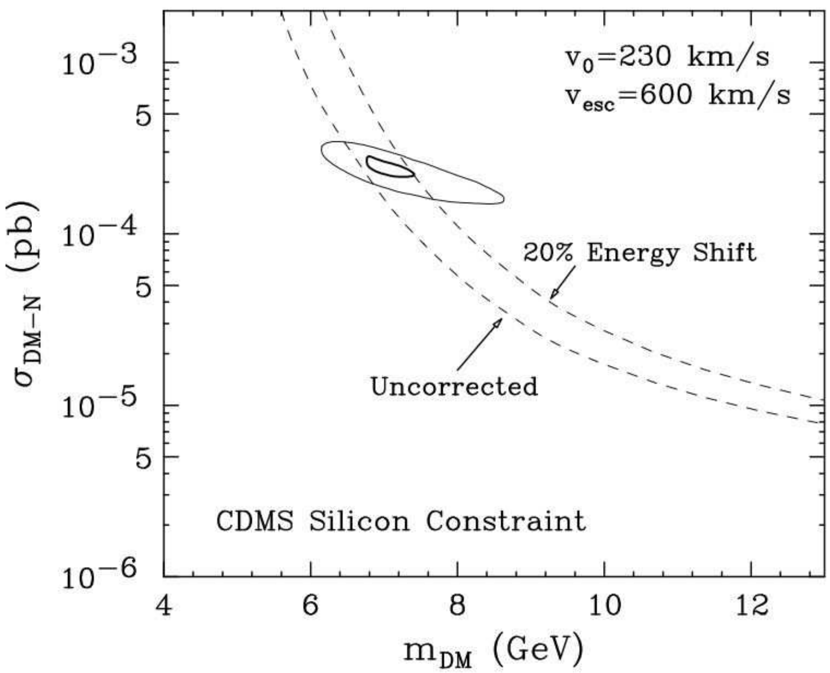


(m$_{DM}$ = 7.2 GeV and $\sigma_{DM-N} = 2.25 \times 10^{-4}$ pb good to fit CRESS hint too!)

Light m <10 GeV WIMP's: CoGeNT+ DAMA vs CDMS-Si bounds

No exp. background in CoGeNT+ $Q_{\rm Na} = 0.2$ to 0.4 (instead of usual 0.3) regions overlap-

CDMS Si limit is very important (see talk of Lauren Hsu) (Hooper, Collar, Hall, McKinsey 1007.1005)



To weaken CDMS-Si bound: Hooper et al assume 20% energy shift in E calibration of Si.

Other way proposed: Ge and NaI are more n rich than Si thus $f_p = -f_n$ weakens Si limits (but not yet a model for this) (Chang, Liu, Pierce, Weiner, Yavin 1004.0697)

If CoGeNT region is there (exp. background is constrained) something should be at play to weaken the XENON and CDMS Si bounds!

Inelastic DM (IDM):

(Tucker-Smith, Weiner 01 and 04; Chang, Kribs, Tucker-Smith, Weiner 08; March-Russel, McCabe, McCullough 08; Cui, Morrisey, Poland, Randall 09; Arina, Ling, Tytgat 09; chmidt-Hoberg, Winkler 09; Shu, Yin, Zhu 10; McCullough, Fairbairn 10; Alves, Lisanti, Wacker 1005.5421)

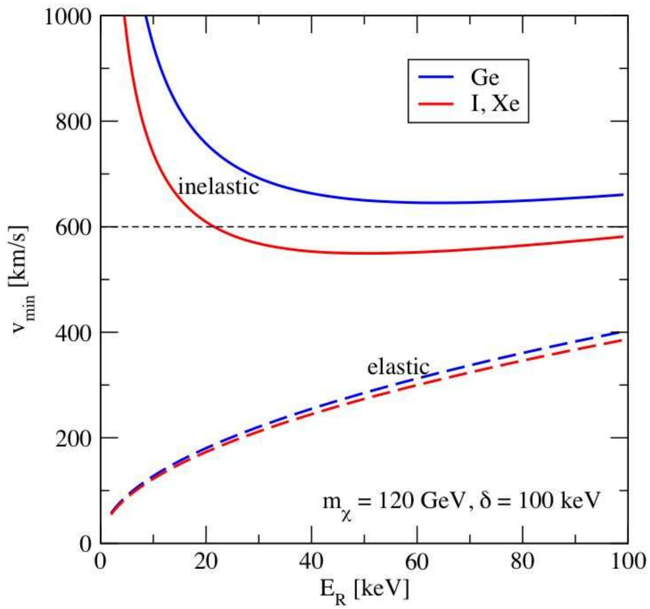
In addition to the DM state χ with mass m_χ there is an excited state χ^*

$$m^*_\chi - m_\chi = \delta \simeq 100 \text{ keV}$$

Inelastic scattering $\chi + N \to \chi^* + N$ dominates over elastic.

Models: a quasi Dirac fermion (Dirac mass $>>$ Majorana mass, leads to a splitting and a gauge boson coupled to two different mass eigenstates), or similar to the p and n and their coupling to the W (but in a hidden sector)

Inelastic DM (fig from T. Schwetz)



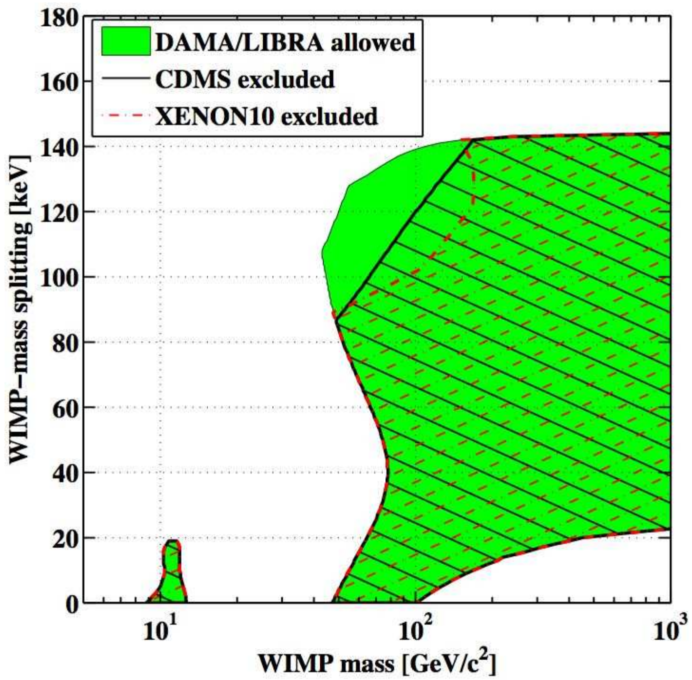
$$v_{min}^{inel} = \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}}$$

$$v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$$

Only high-velocity DM particles have enough energy to up-scatter, and v_{min}^{inel} decreases with increasing target mass M, thus targets with high mass are favored (better I in DAMA than Ge in CDMS, but Xe and W are heavy too...). Notice no low E_R events.

Leads to very different spectrum (no low E_R events) The modulation of the signal is enhanced (the number of WIMPs changes more rapidly at high v)

IDM: for SI recent bound from CDMS leave very small room for compatibility



New XENON100 soon... this is for Spin Independent (SI) interactions

But IDM with Spin Dependent coupling to p only would survive (although not realistic model for it)(Kopp, Schwetz, Zupan, JCAP1002:014,2010; Chang, Liu, Pierce, Weiner &Yavin 1004.0697)

- SD coupling with p,

eliminates XENON, CDMS and CRESST bounds

- Inelasticity,

eliminates PICASSO and COUPP (light targets)

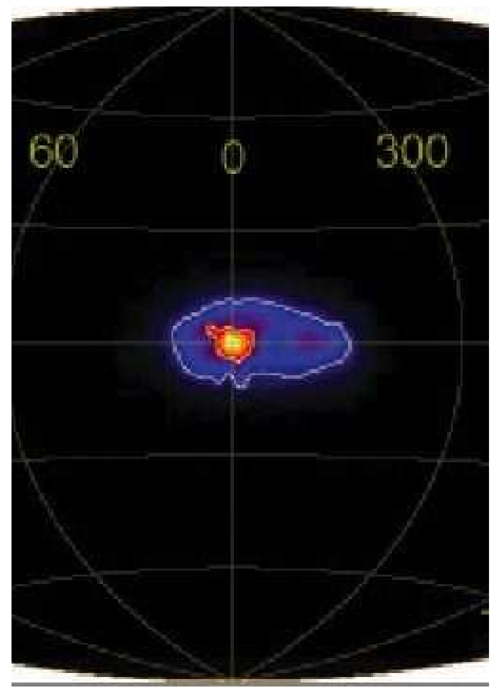
(For SD,coupling with nucleus is mainly with an unpaired nucleon:

- DAMA, KIMS , COUPP, PICASSO and SIMPLE have unpaired p,
- XENON, ZEPLIN,CDMS and CoGeNT have unpaired n)

Indirect DM Searches: INTEGRAL: satellite launched in 2002

511 keV line from the GC, observed first with balloons (30 y old signal) until recently region was seen as spherical pointing towards DM

Jan 2008: region not spherical but with a disk around Low Mass X-ray Binaries, which are possible sources of e! so no DM after all?



Still DM could explain the spherical component of the signal

Tuned DM candidates were proposed to produce e^+e^- pairs at rest...

Models for INTEGRAL 511 keV line from the GC: Tuned DM particles were proposed. The positrons need to annihilate almost at rest to produce a line with $E = m_e$.

-MeV mass Light DM (LDM)(Boehm et al 04, Beacom et al 04)
The MeV scale is the mass of the annihilating DM particles, which annihilated into e^+e^-

- eXciting DM (XDM): (D. Finkbeiner 2007)
500 GeV mass χ with a excited state χ^* very close in energy

Similar to "Inelastic DM" proposed to explain DAMA/LIBRA, but
$\delta = m_{\chi^*} - m_\chi \sim$ MeV must be larger (not 100 keV but MeV)
so that e^+e^- are produced at rest via de-excitation of the excited state: $\chi^* \to \chi e^+ e^-$.

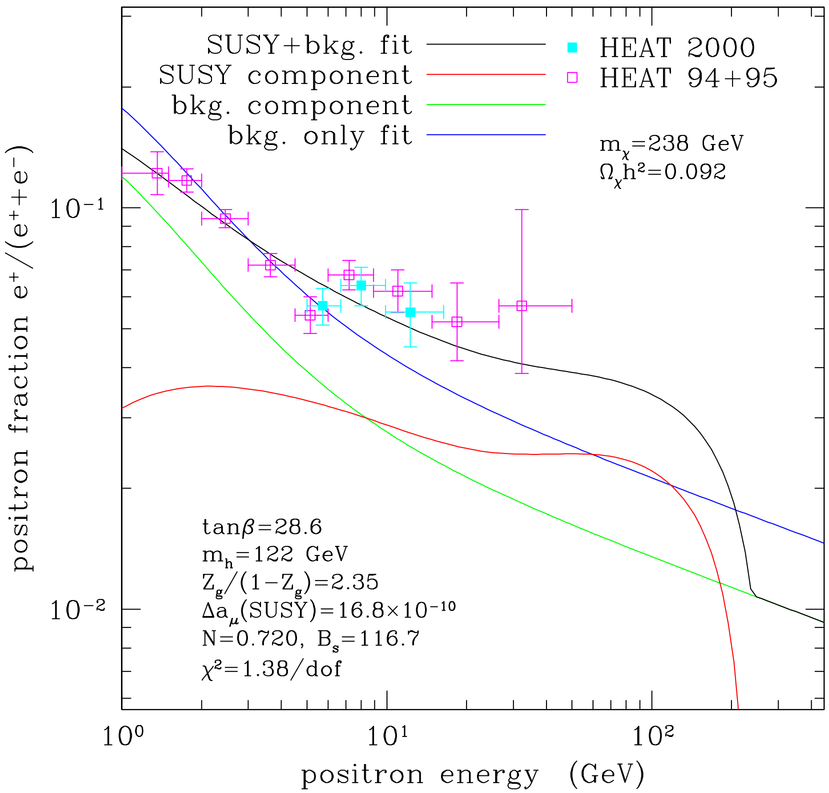
The excitation of the high energy state is due to collisions, which fixes the particle mass, given the characteristic $v \simeq 10^{-3}c$:

$$E_{colllision} \simeq m_{\chi^*} - m_\chi \simeq (1/2) m_\chi 10^{-6} \simeq 1 \text{ MeV}$$

which works if $m_\chi \simeq 500$ GeV.

Indirect DM Searches: The old "HEAT positron excess"

(Baltz et al 2002)



Two explanations:

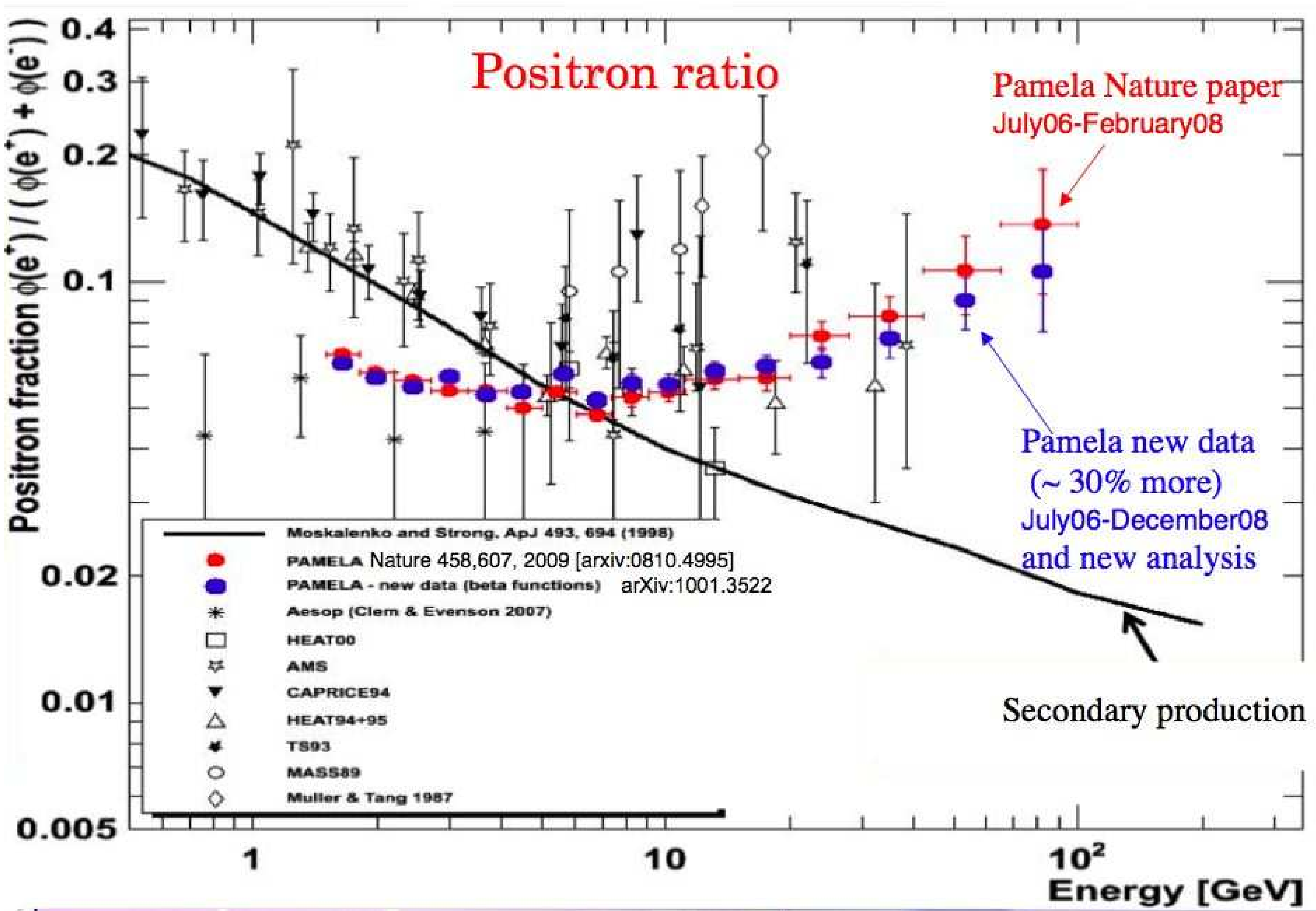
1) DM annihilation, with boost factor $B > 30$

NOTICE: needed "Boost Factor" B

$$B = \frac{\text{Annihilation Rate Needed}}{\text{Naive Annihilation Rate}}$$

2) astrophysical sources

PAMELA: Positron fraction excess 10-100 GeV



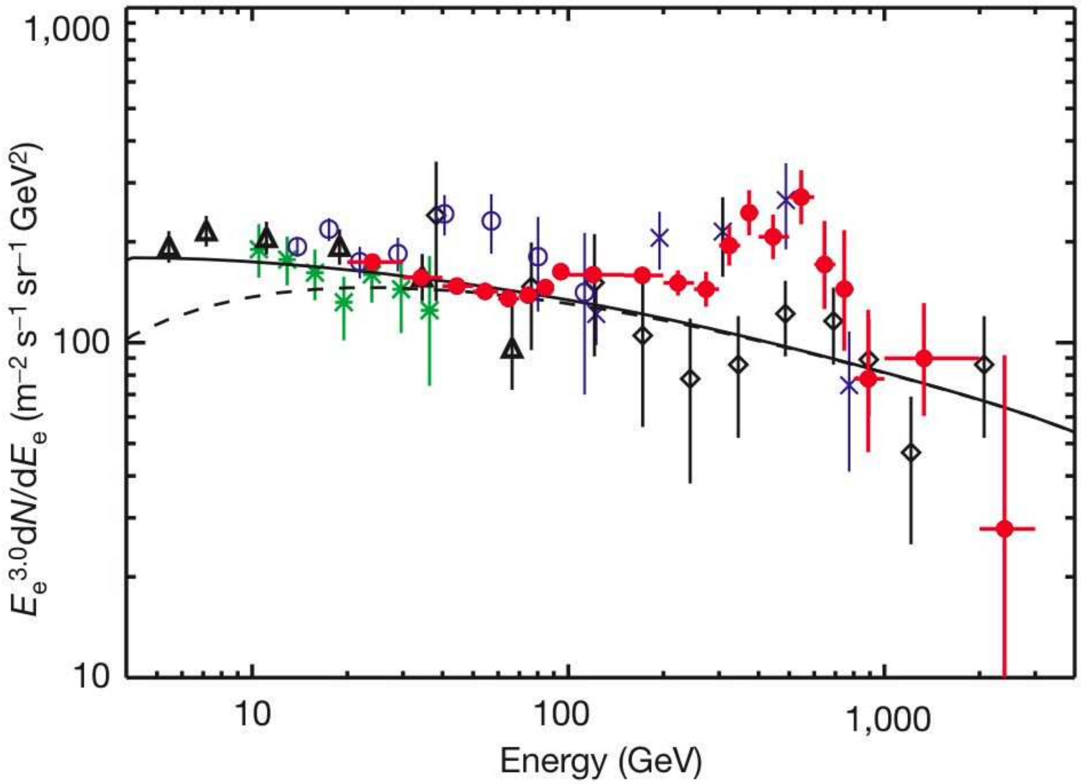
Also ATIC:

Balloon-born calorimeter launched

from McMurdo, Antarctica.

ATIC-1 in 2000-01
ATIC-2 in 2002-03.

Nature, Nov. 19, 2008
($e^+ + e^-$) 6σ excess in the
300-800 GeV range!

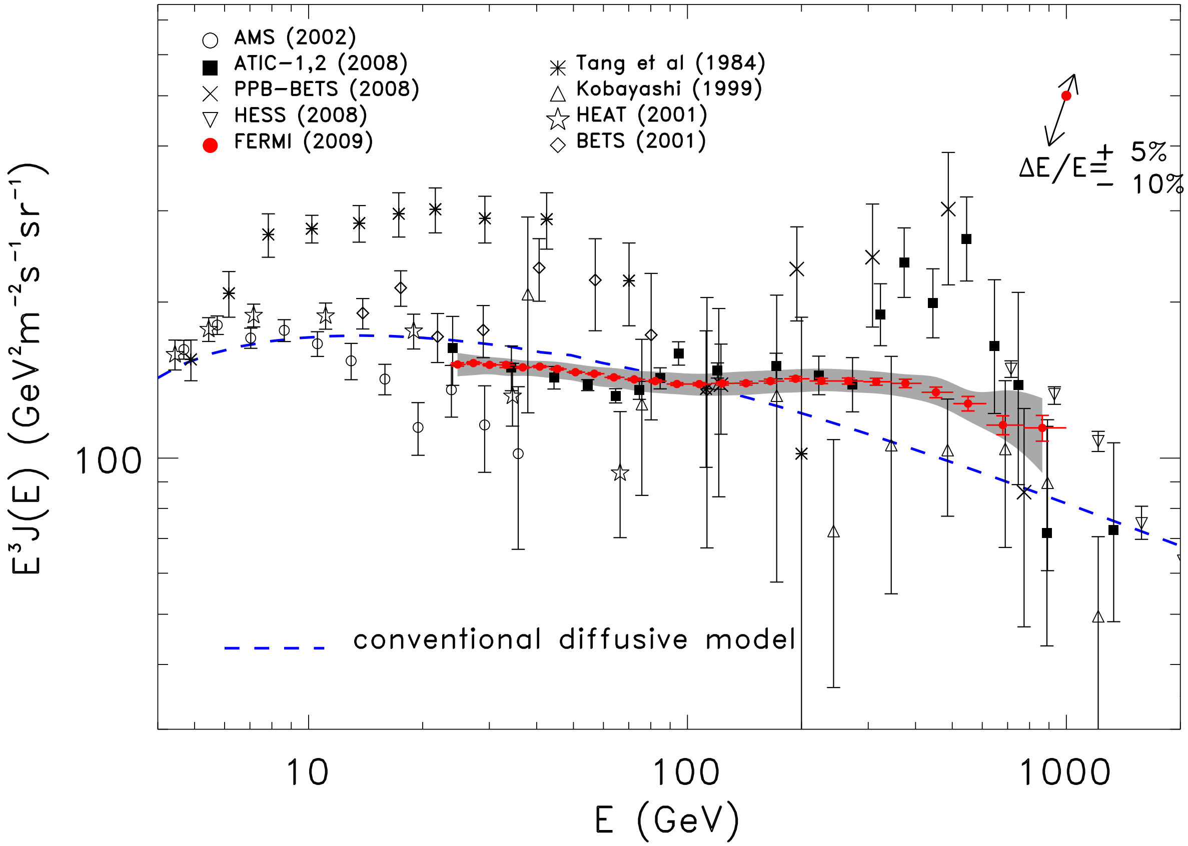


Confirmed by ATIC-4 (2007-08) but rejected by HESS and FERMI.

FERMI: $e^+ + e^-$ spectrum 20 GeV to 1 TeV

FERMI -LAT
measured the spectrum
with better accuracy:
first $e^+ + e^-$ results
in the April APS Meeting
(May 4 2009)

Shows an excess over the conventional diffusive model of propagation GALPROP (in blue).



$$J_{e^\pm} = (175.40 \pm 6.09) \left(\frac{E}{1 \text{ GeV}}\right)^{-(3.045 \pm 0.008)} \text{GeV}^{-1}\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

Sources? (already explained by S. Sarkar)

- **e^+ e^- come from $<$ 1 kpc so must be produced locally**

- **what produces e^+ could produce $\bar{p}$ (PAMELA) and γ (FST-ACT's)!**

  But not signal has been seen in $\bar{p}$ or γ!

  PAMELA $\bar{p}/p$ ratio (Feb/08 and May/09) and $\bar{p}$ flux (July/10) results are compatible with secondary cosmic rays

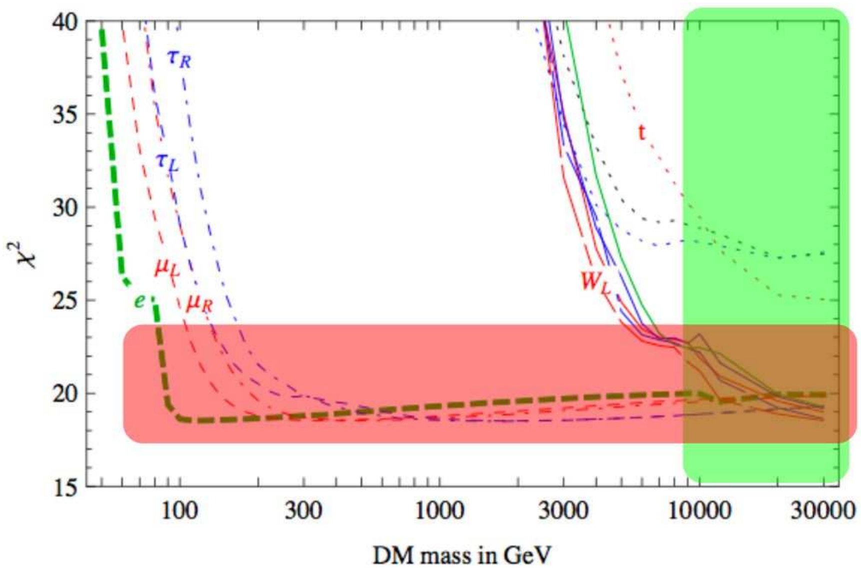
Sources: astrophysical? Dark matter? More than 500 papers!

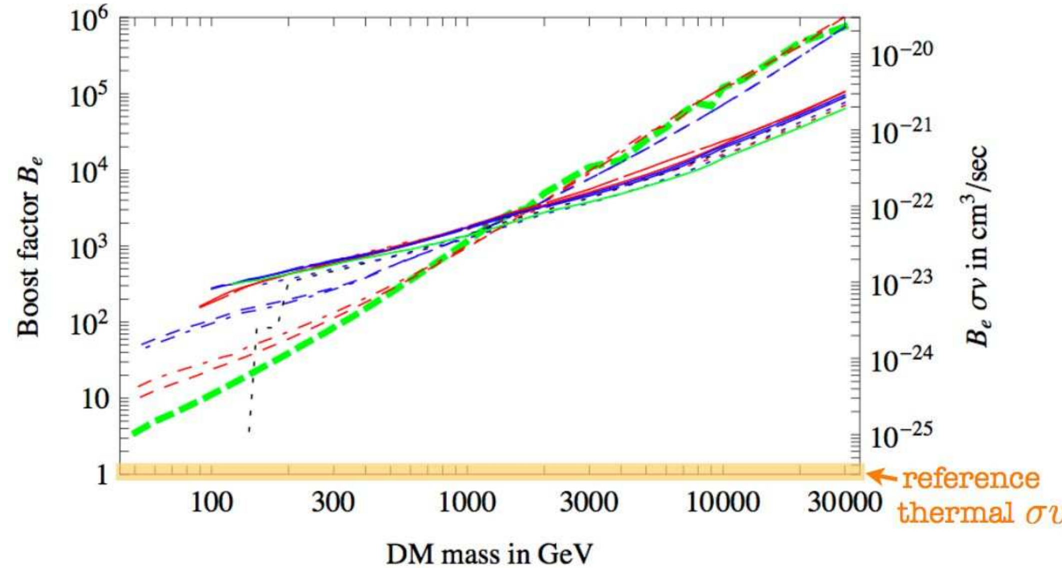
- Is a source of primary e^+ necessary?
  Secondary CR accelerated at the galactic sources (Blasi 09, Blasi & Serpico 09, Mertsch & Sarkar 09) but other secondary/primary ratios should rise too (Boron/Calcium by PAMELA before AMS2?) (talk of S. Sarkar)

- Known possible astrophysical sources?
  Pulsars or other supernova remnants nearby A good solution, although sources are not well understood (Aharonian, Atoyan and Volk, 95; Hooper, Blasi, Serpico 08; Yuksel, Kistler, Stanev 08; Profumo 08...) (talk of S. Sarkar)

- DM annihilation or decay?
  Thermally produced DM annihilation requires large enhancement of rate. Must produce almost exclusively leptons. Only tuned models survive all bounds (not your usual-straightforward-vanilla-flavor favorite WIMP)

“Thermal” DM annihilations: fit to e^+ and $\bar{p}$ PAMELA data with DM annihilating into single channels- BEFORE FERMI DATA (Cirelli, Kadastik, Raidal, Strumia NPB813, 2009; Bertone, Cirelli, Strumia, Taoso, JCAP03, 2009; Figs from M. Cirelli)



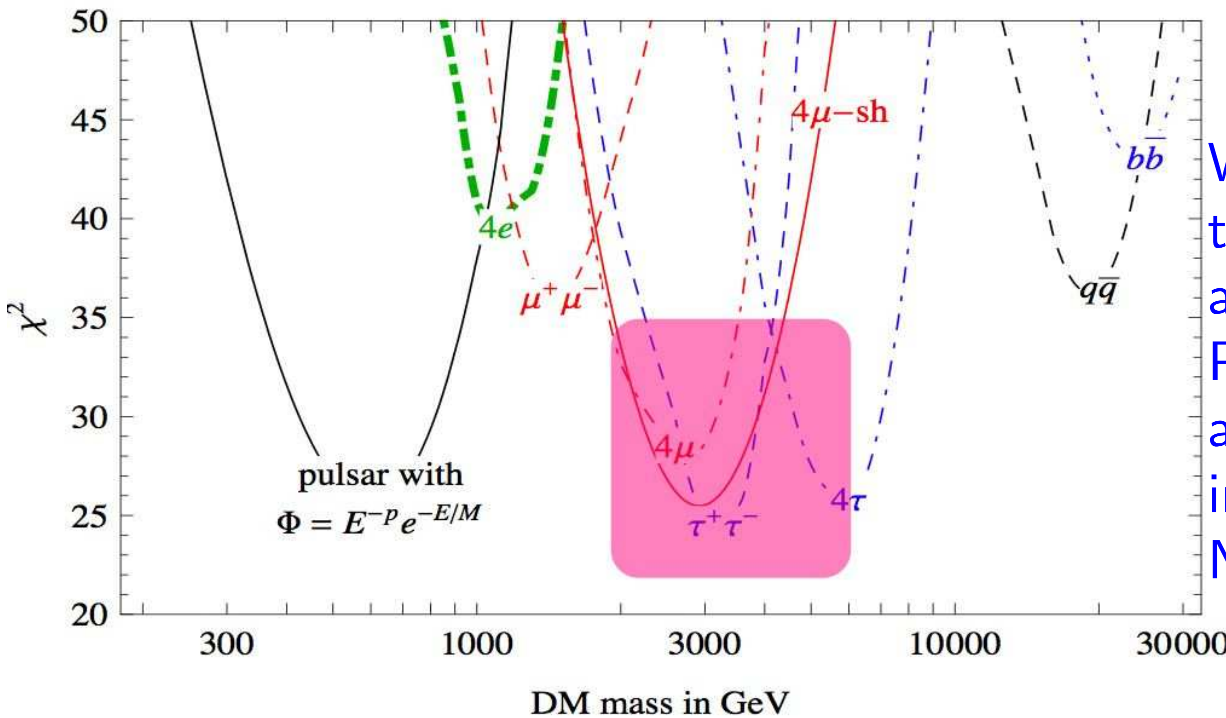


-Either annihilate into leptons, $B >$ few, or into W's for m$_\chi >$ TeV, $B > 10^2$

-Cross sections needed are $\sigma_{annih} \simeq$10 to 10^3 $\times\, 10^{-26}\mathrm{cm}^3/\mathrm{s}$ or $B \simeq$10 to 10^3

"Thermal" DM annihilation adding FERMI and HESS

(Meade, Papucci, Strumia, Volansky, 0905.0480 - Figs from M. Cirelli)



WW and e^+e^- do not fit the data well any longer and only $m > 1$ TeV OK. Preferred model: DM annihilates mostly into $\tau^+\tau^-$ or 4μ or 4τ NOT EASY!

Still, other constraints besides PAMELA, FST and HESS $e^+ + e^-$data:

- γ from DM annihilation in the Galactic Center (HESS has measure γ emission form the GC and the Galactic Ridge)

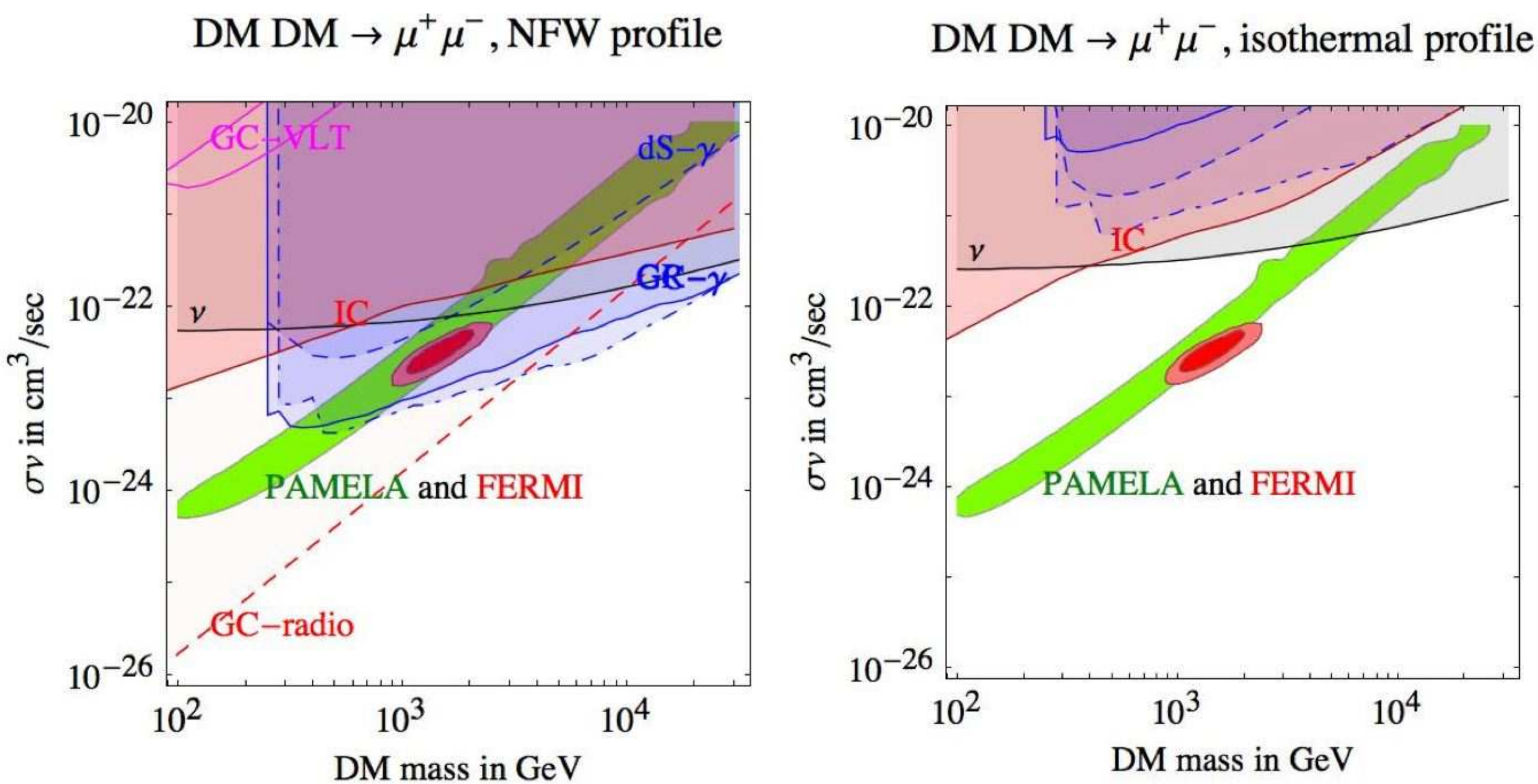
- Radio waves from synchrotron radiation of $e\pm$ (from DM annihilation) in the GC

- γ from DM annihilation in the Sg Dwarf galaxy

- EGRET and Fermi diffuseγ emission set bounds on Inverse Compton of $e\pm$ (from annhilations) on the CMB, IR and starlight γ (probes regions outside the GC)

- ν from the GC (from SuperKamiokande)

Constraints from the GC favor Isothermal Core! (not cusped halo models but cored, so astrophysical $B = 1$) (Meade, Papucci, Strumia, Volansky, 0905.0480)



Large enough local DM annihilation signal (0.1 to 1 kpc^3):

- The enhancement is astrophysical Cannot be large (at most a factor of 10 for cusped halo models)

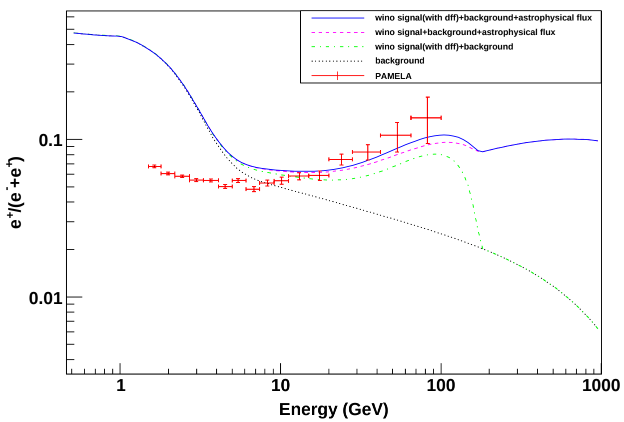
- $\sigma_{\rm annh}$ is large (also in the early Universe)

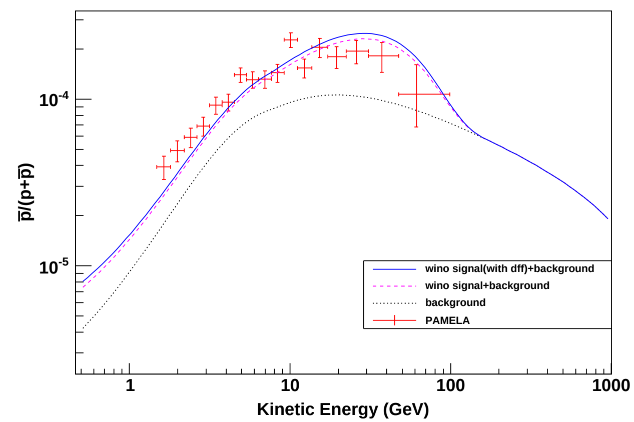
- $\sigma_{\rm annhilation}$ is enhanced in the halo (small v) with respect to that in the early Universe (larger v)

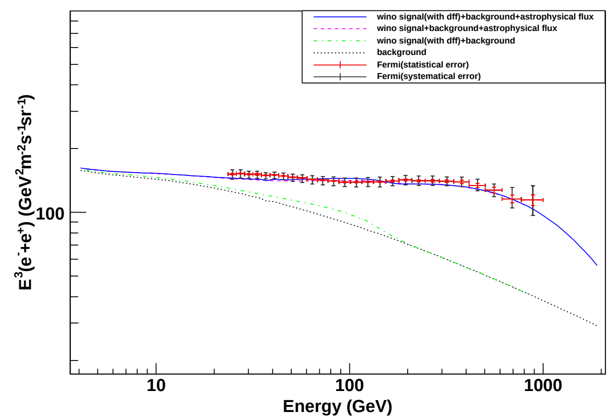
“Non-Thermal” annihilating DM:

May be WIMP has a large $\sigma_{\rm annhilation}$ and is non-thermally produced in the early universe (non-standard pre-BBN cosmology) e.g. a Wino (Kane, Lu and Watson 09)

It does not need any boost! Fit to e^+ PAMELA data is OK
but fit to Fermi data requires “conspiracy” with astrophysical source!







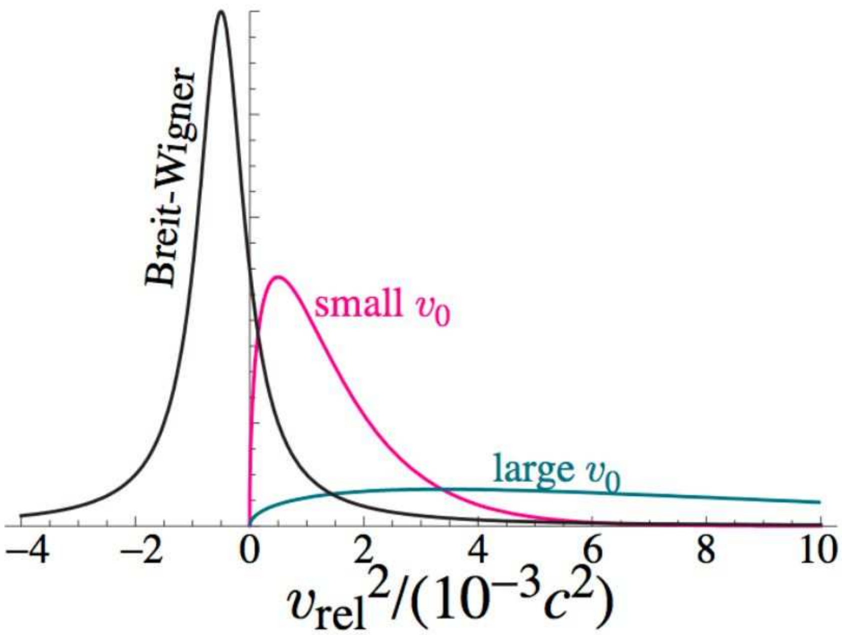
PAMELA $\bar{p}$ constraint: $m_{Wino} > 400$ (200) GeV for Einasto (Isothermal) halo

(Cholis, 1007.1160)

Particle boost-factors:

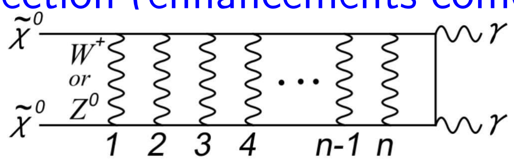
May be the $\sigma_{\mathrm{annhilation}}$ is enhanced with respect to that in the early Universe

- Resonance enhancement: DM annihilation cross section has a narrow resonance just below threshold (Cirelli et al 08; Nath et al. 08; Ibe, Murayama &Yanagida 08)



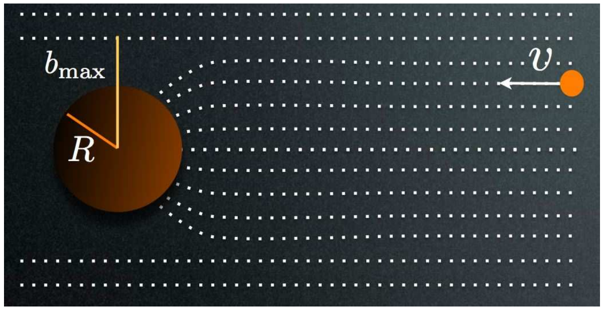
Particle boost-factors:

- **"Sommerfeld resonance"**: long distance attractive forces modify the wave function of the DM particles which enhances the annihilation cross section (enhancements come from ladder diagrams in perturbative expansion) (Iengo 08)



  - Works for heavy neutralino-chargino almost degenerate; attractive Yukawa force from multiple t-channel W and Z exchange, forms bounds states at small (galactic) velocities (no effect in the Early Universe) (Hisano, Matsumoto and Nojiri, 03; Hisano, Matsumoto and Saito 04)
  - or Yukawa potential due to the exchange of a light hidden gauge or scalar boson ϕ (Arkani-Hamed, Finkbeiner, Slatyer, Weiner 09)

  Classical analogy: in the presence of a long range attractive force (like gravity)
  $\sigma = \sigma_0(1 + v^2_{escape}/v^2) > \sigma_0 = \pi R^2$
  thus for $v << v_{escape}$, $\sigma >> \sigma_0$



Particle models:

- Annihilating DM models with minimal extensions of the SM: heavy WIMPs e.g. Inert Doublet Model (Tytgat et al 0901.2556)

- Annihilating DM models with considerable extension of the SM: complex dark and hidden sector (e.g. Pospelov et al 07, Arkani-Hamed et al 08, Nomura % Thaler 08, Baai & Han 08, Cirelli etal 08, Fox & Poppitz 08, Park &Shu 09, Phalen, Pierce & Weiner 09..).
  - $\sim$TeV mass DM,
  - new attractive forces mediated by light $\sim$ GeV bosons (attractive forces to produce the Sommerfeld enhancement)
  - leptophilic either
    -because the DM carries Lepton number
    -or because of kinematics (light mediator).

- Decaying DM (Ibarra et al 07 to 09, Nardi, Sannino & Strumia 0811.4153; Arvanitaki et al 0812)

"A Theory of DM": (Arkani-Hamed, Finkbeiner, Slatyer & Weiner PRD79:015014,2009)

(see talk of Tracy Slatyer)

- χ is a 500-800 GeV mass WIMP
- ϕ few GeV new gauge boson ("dark photon") coupled only to DM with typical strength mediates new attractive forces which produce the Sommerfeld enhancement and is "leptophilic" because it is so light that can only decay into e^+e^- or $\mu^+\mu^-$ $\chi\chi \to \phi\phi \to 4\ell$, if mostly 4μ, FERMI data OK!
- To account for DAMA and INTEGRAL,
  χ is a multiplet of states and ϕ is a non- Abelian gauge boson of a group G_{dark}
  (the mass splittings are due to loops of ϕ bosons)
  -inelastic scatterings (IDM) explain DAMA $\delta m \simeq 100$ keV
  -excited-DM (XDM) explain INTEGRAL $\chi\chi \to \chi\chi^*$ and $\chi^* \to e^+e^-$ $\delta m \simeq 1$ MeV
- Major additions to SUSY signals depend on realization: GeV-dark Higgses and gauge bosons decay into visible particles, dominantly lepton "jets", MSSM LSP decays into the true "dark" LSP, thus many lepton jets with GeV invariant masses expected...
  (Arkani-Hamed, Weiner 0810.0714 [hep-ph])

Many variations: Some are...

- Secluded DM (precursor model to the others) (Pospelov, Ritz et al 0711.4866, Nath et al 0810,5762)
- Axion Portal: ϕ is a pseudoscalar axion-like (Nomura, Thaler 08)
- singlet-extended UED: χ is KK right handed neutrino, ϕ is an extra bulk singlet Bai, Han 08
- χ carrries Lepton number $L_\mu - L_\tau$ (Cirelli et al 08, Fox, Poppitz 08)
- χ annihilates into another particle that carries Lepton number and decays weakly (Phalen, Pierce Weiner 09)
- ...

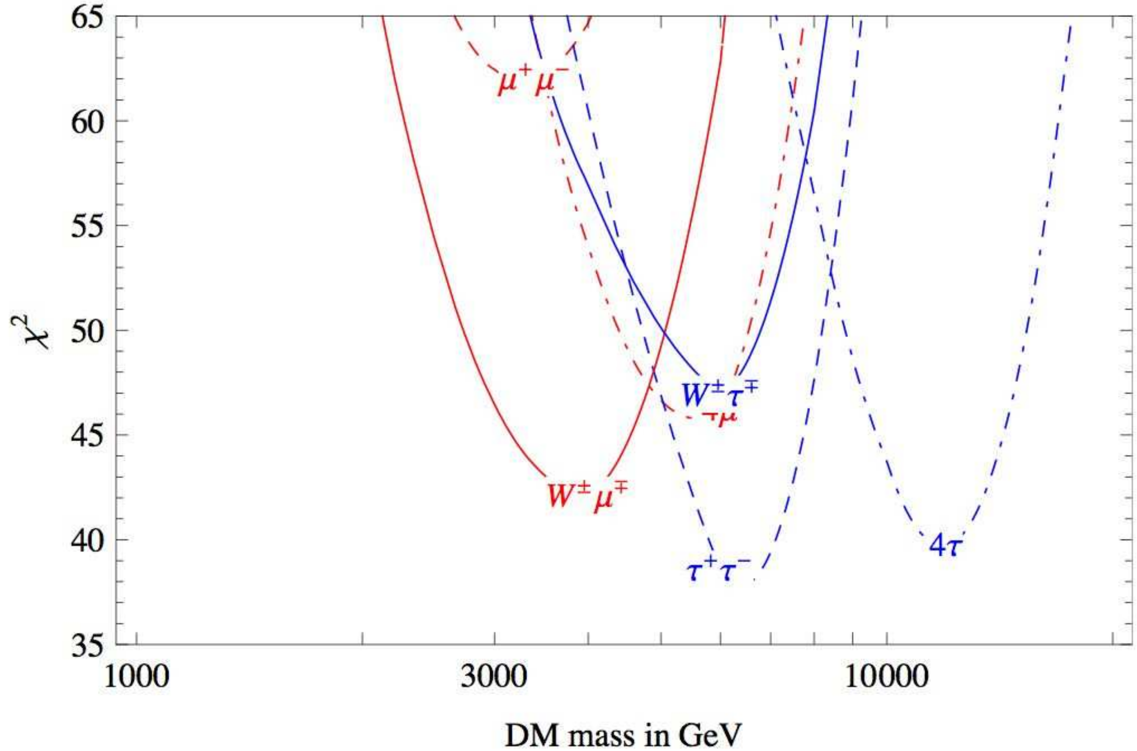
But potential problems:

CMB and Fermi gamma ray constraints: Some models found marginally compatible with PAMELA/Fermi/HESS, these constraints (annihilating DM can comprise only $< 1/4$ of DM otherwise Sommerfeld enhancement is too large!) (Cirelli,Cline 1005.1779)

Sommerfeld enhancement in the Early Universe: Potential problems with decoupling unless enhancement < 100! so may not be enough for PAMELA... (Feng, Kaplinghat, Yu 1005.4678)

Decaying DM: (With $\tau > t_U \simeq 10^{17}$ s)

PAMELA+FST+HESS require: multi-TeV mass, $\tau > 10^{26}$ s, decays mostly into 2nd or 3rd generation leptons ($\chi \to W\ell$, $\bar{\ell}\ell\nu$, 4μ) Very tuned models!



Meade et al. 0905.0480

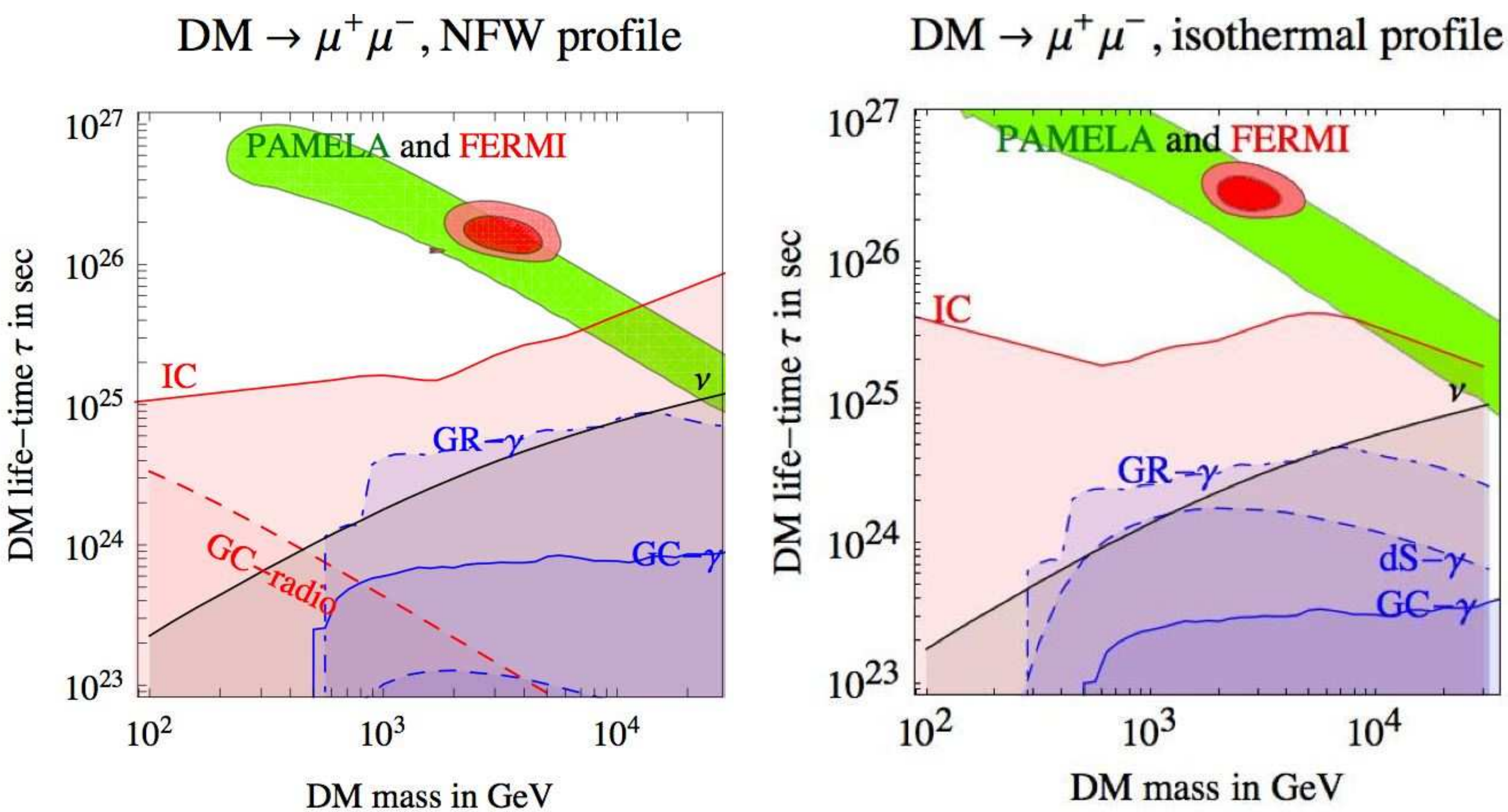
Decaying DM:

Ibarra et al 07 to 09, Nardi, Sannino & Strumia 0811.4153; Arvanitaki et al 0812.

Candidates for multi TeV mass DM decaying with $\tau > 10^{26}$ s

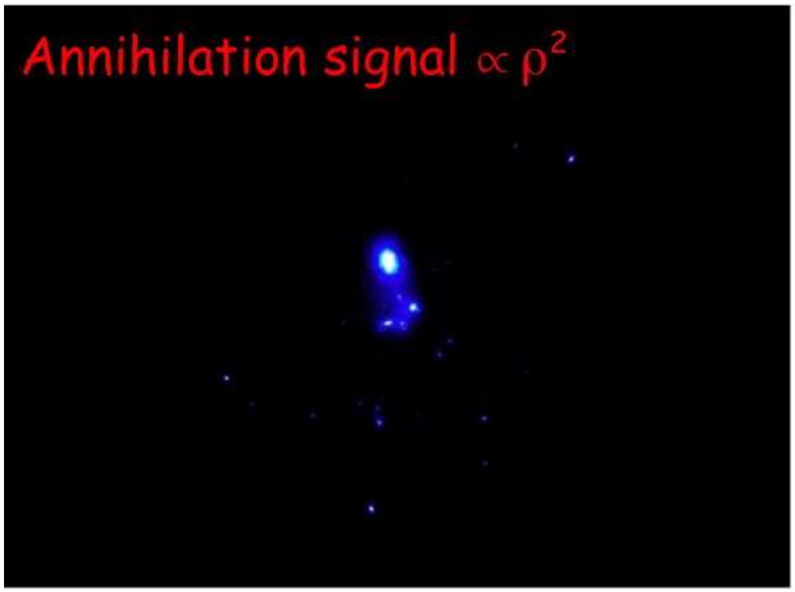
- SuperWIMPs,
- gravitinos with broken R-parity,
- right- sneutrinos in models with Dirac neutrino masses,
- hidden sector gauge bosons or gauginos,
- hidden sector fermions etc...

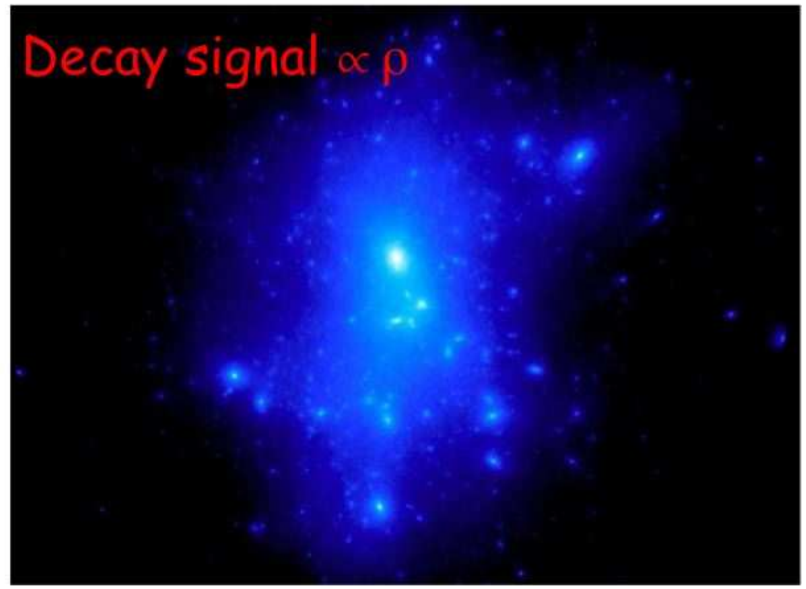
Decaying DM: any halo profile is OK PAMELA, FST, HESS and additional constraints due to $\bar{p}$, γ-rays, ν, antideuterium Example:(Meade, Papucci, Strumia, Volansky, 0905.0480)



How to distinguish decaying from annihilating DM?

Gamma-ray observations will be crucial (Fig. from B. Moore)





SUMMARY

Direct Detection: Models to make all data compatible are difficult to produce and testable with more data (IDM, light WIMPs...). New hints from CoGeNT and maybe CRESST for light WIMPs?

Indirect Detection:

PAMELA and FERMI data can be explained by nearby pulsars or SN remnant alone...

If it is Annihilating DM: not the simplest DM scenarios (goes preferentially into leptons of 2nd and 3rd generation, has large annihilation rate so either non-thermal or some boost factor B, has $\sim$TeV mass and disfavors cusped halo profiles)

If it is Decaying DM, must decay mostly into leptons of the 2nd or 3rd generation, multi-TeV mass with $\tau \sim 10^{26}$ s (very suppressed!)

We need more data and plenty coming from FERMI, PAMELA, AMS-2, ACTs:

CONCLUSIONS-OUTLOOK

DM searches are advancing fast... Lots of data lead to many hints... data driven recent burst of model building due to difficulty in accommodating all hints...

So far, no firm DM signature found but models opened our imagination and expectations for things to come... the physics of DM and the physics needed at the EW scale may be different...

In most scenarios one can think of the LHC should find at least a hint of the new physics... Besides, DM may have several components to be found in different ways...

DM particles would be our first probe of the immediate pre-BBN cosmology

All possibilities are still open.... hopefully not for long!