The saga of Light WIMPs in direct DM searches

Graciela Gelmini - UCLA

GGI- Florence- June 25 - 29, 2012

WIMP DM searches: Complementary to the LHC and to each other!

- **Indirect Detection-** looks for DM annihilation (or decay) products
- **Direct Detection-** looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way.

  Last week: "DM direct detection Silver Jubilee"- 25 years of first direct bounds:

  "Limits on CDM Candidates from an Ultralow Background Germanium Spectrometer"

  Ahlen, Avignone, Brodzinski, Drukier, Gelmini, Spergel, PLB**195**, 603 (1987).

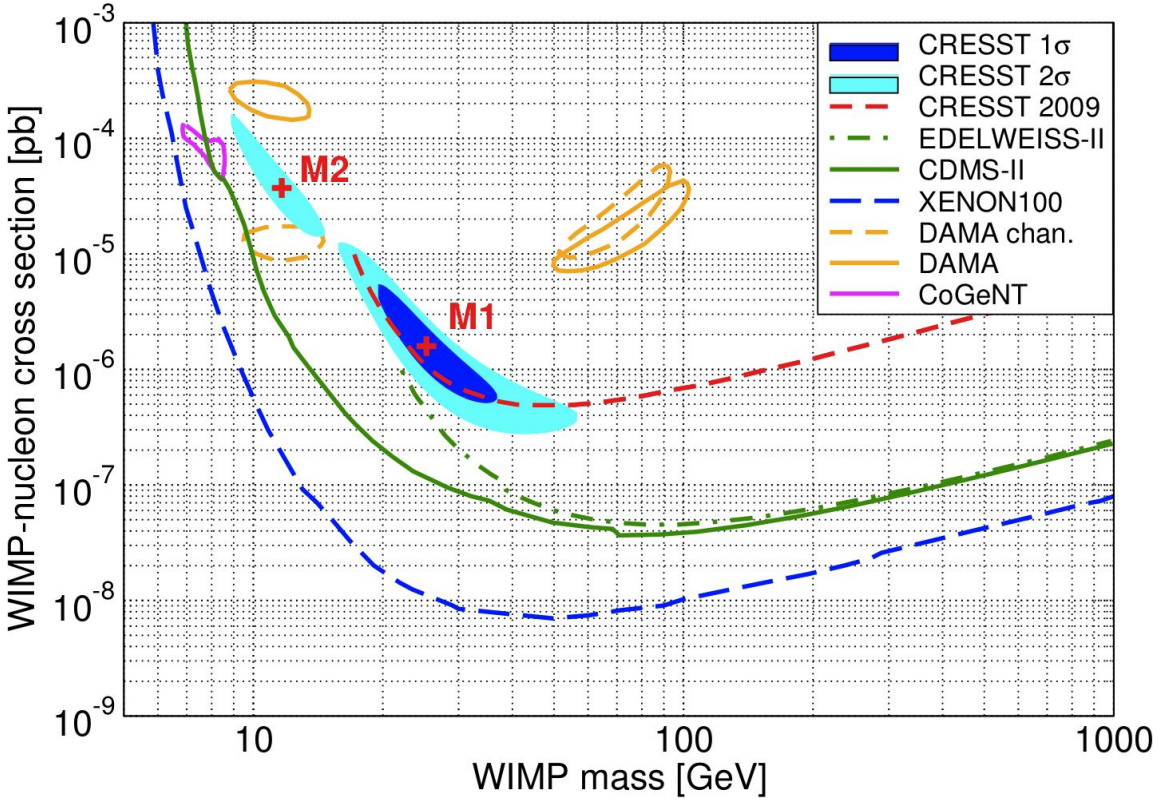
Many DM "hints" in both.... I will concentrate on Direct Searches:

DAMA (NaI), CoGeNT (Ge), CRESST II ($CaWO_4$) have detection claims.... point to WIMPs with m< 10 GeV. Are they DM signals or backgrounds?

CDMS (Ge, Si), XENON 10 (Xe), XENON 100 (Xe), SIMPLE (C_2ClF_5).... have upper bounds...

Can all signals and bounds be reconciled? Some of them?

Light WIMPs DAMA, CoGeNT, CRESST II, DM or backgrounds?



(figure from CREST II, Angloher et al. 1109.0702)

Regions disjoint and already rejected?- The devil is in the details-

(disclamer about citations!! Almost 400 for the CoGeNT Feb 2010 paper alone!)

Recall event rate: events/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nvf(\mathbf{v},t)d^3v$$

$$= \frac{\sigma(q)\rho}{2m\mu^2}\int_{v>v_{\rm min}} \frac{f(\mathbf{v},t)}{v}d^3v = \frac{\sigma(q)}{2m\mu^2}\,\rho\eta(v_{\rm min})$$

- $\frac{N_T}{M_T}$ = Avogadro's number per mol = Number of atoms per gram; $\mu = mM/(m+M)$
- For elastic scattering: $v_{\rm min} = \sqrt{ME/2\mu^2}$ and E is the ion recoil energy....

- $\rho = nm$, $f(\mathbf{v},t)$: local DM density and $\mathbf{v}$ distribution depend on halo model

Notice $\rho\eta(v_{\rm min})$ encodes all the Dark Halo dependence of the rate.

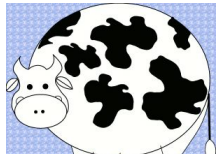
"Halo model independent analysis": compares predictions of $(\sigma_p\rho\eta/m)$ for fixed m.

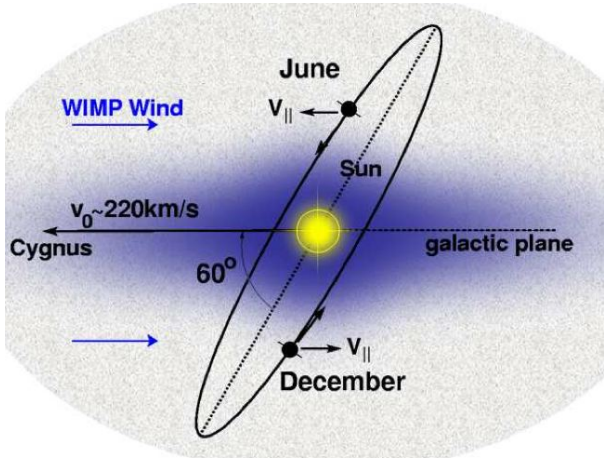
- for spin-independent (SI) $\sigma(q) = \sigma_0 F^2(q)$ where

$\sigma_0 = \Big[\langle Z f_p + (A-Z) f_n\Big]^2 (\mu^2/\mu_{\rm p}^2)\sigma_{\rm p} = A^2(\mu^2/\mu_{\rm p}^2)\sigma_{\rm p}$ for $f_p = f_n$

Thus, for a given halo model the plots are in the $m, \sigma_{\rm p}$ plane.

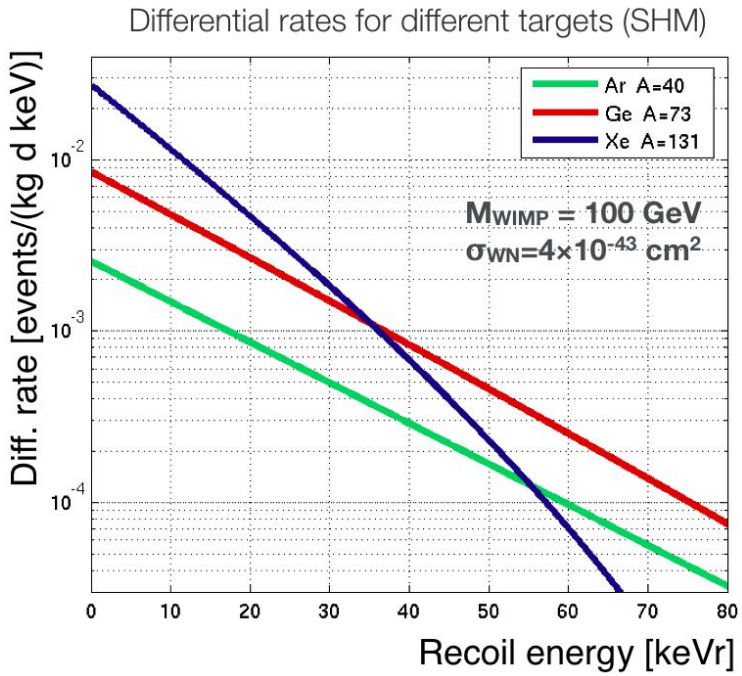
Standard Halo Model (SHM)

The  of halo models



- $\rho_{SHM} = 0.3^{+0.2}_{-0.1}$ GeV/cm^3
- $f(\mathbf{v}, t)$: Maxwellian $\vec{v}$ distribution

at rest with the Galaxy $v_\odot \simeq$220km/s (190 to 320km/s), $v_{esc} \simeq$500-650km/s



ANNUAL MODULATION: max in May, min in Dec. (Drukier, Freese, Spergel 1986)

Local ρ, $\mathbf{v}$, modulation phase and amplitude could be very different if Earth is within a DM clump or stream or if there is a "Dark Disk". Other: anisotropic models, velocity tails...

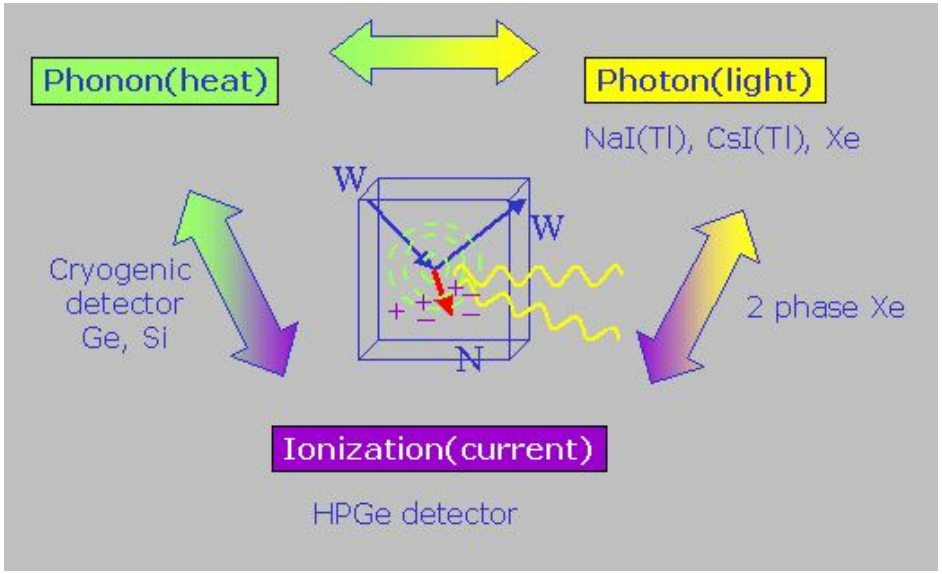
Signal in Direct Searches:

WIMPs interact with nuclei. In crystals: most of the recoil energy goes usually to phonons, but a fraction Q goes into ionization/ scintillation, $Q_{\rm Na} = 0.3$, $Q_{\rm I} = 0.09$...

In Xe: $L_{\rm eff}$ measures scintillation efficiency of a WIMP (which is S1)

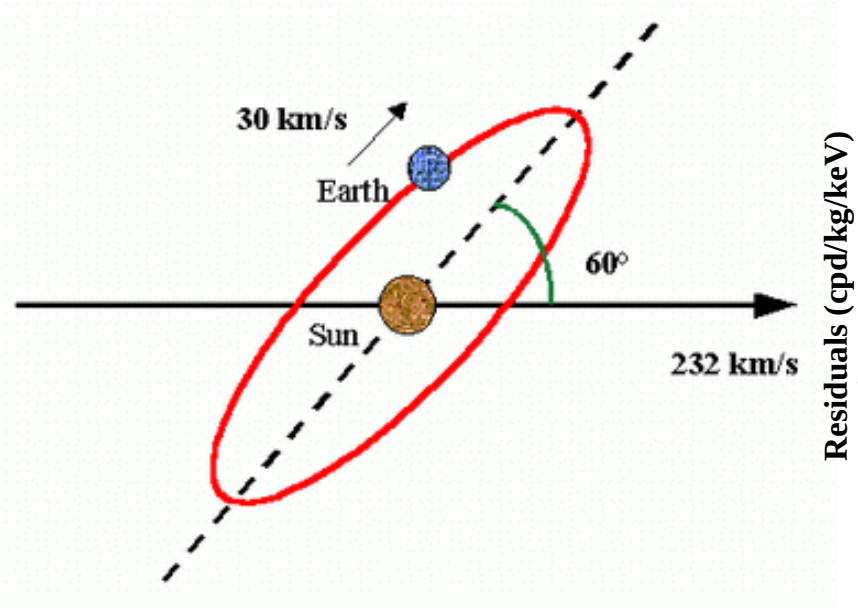
there is also delayed ionization (S2).

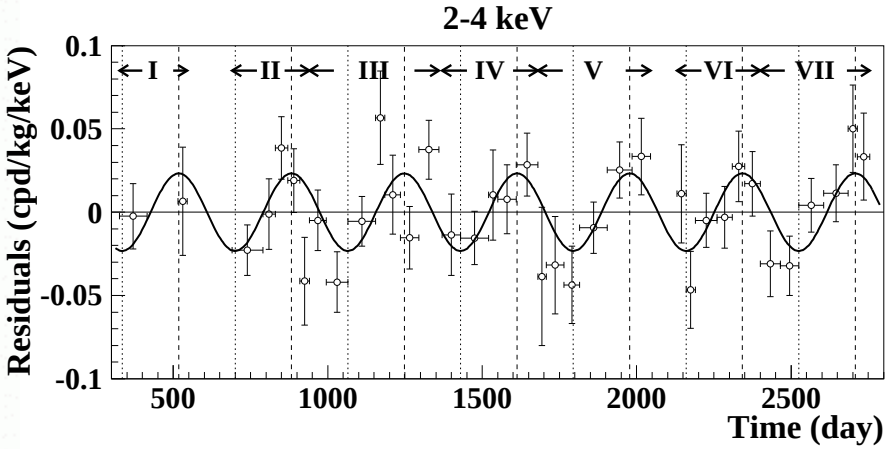
Q and $L_{\rm eff}$ have large uncertainties at low E.



Let us review the DM signals: DAMA, CoGeNT and CRESST II

Old DAMA/NaI: DM signal?

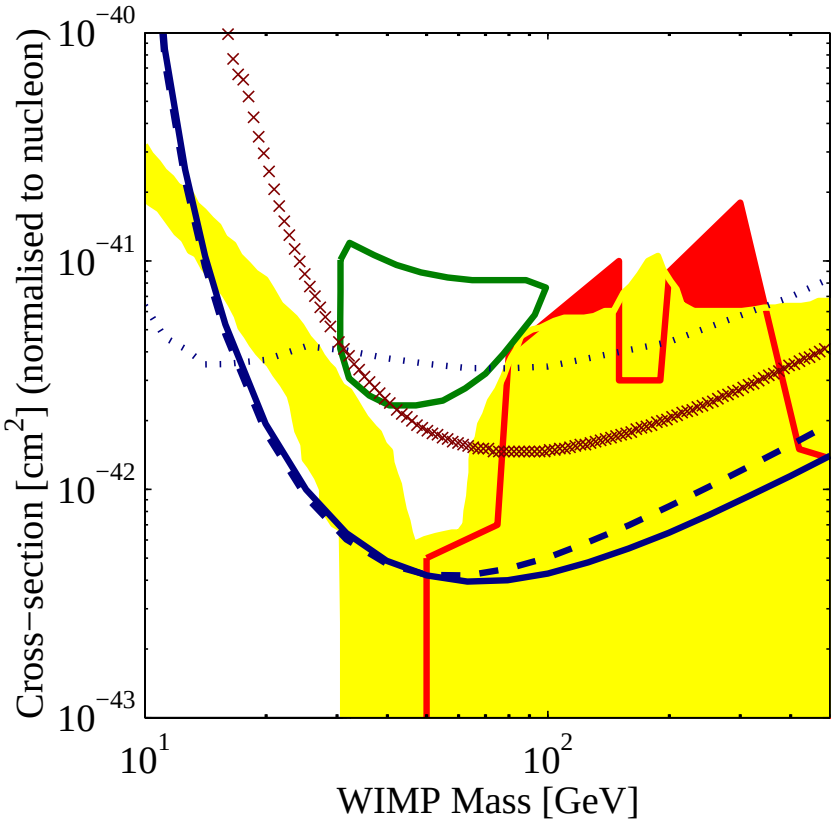




By 2002: 7 years of DAMA/NaI showed a 6σ modulation signal compatible with the Standard Halo Model.

Old DAMA/NaI SI WIMPs?

Theoretical prejudice in early DAMA analysis: DAMA region for SI WIMPs in the SHM was cut at 25GeV (from 1997 until 2003) which was excluded in 2002 by Edelweiss (brown crosses) and in 2004 by CDMS-Soudan (blue).



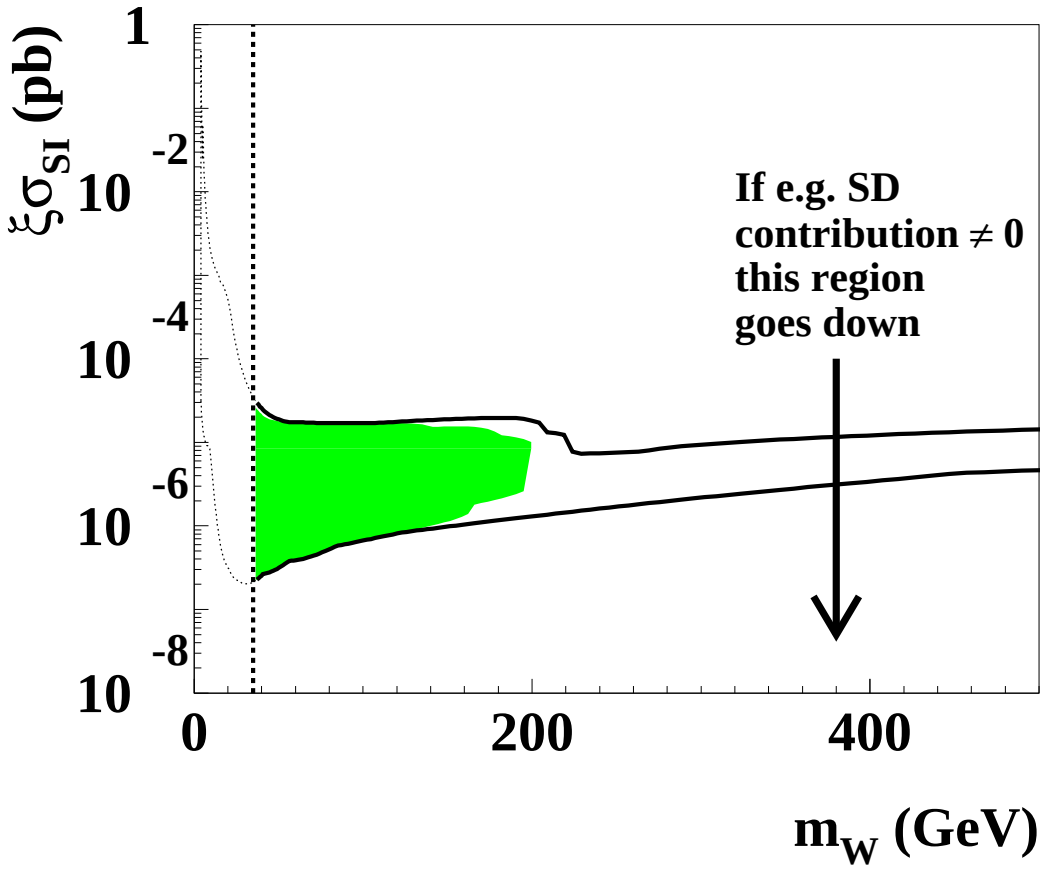
Bottino et al. light neutralinos m >6 GeV

Baltz et al.

Old DAMA SI WIMPs? "Light WIMP" DAMA region

Region < 37 GeV, first shown in 2003 by the DAMA coll. (difficult to see in the figure)

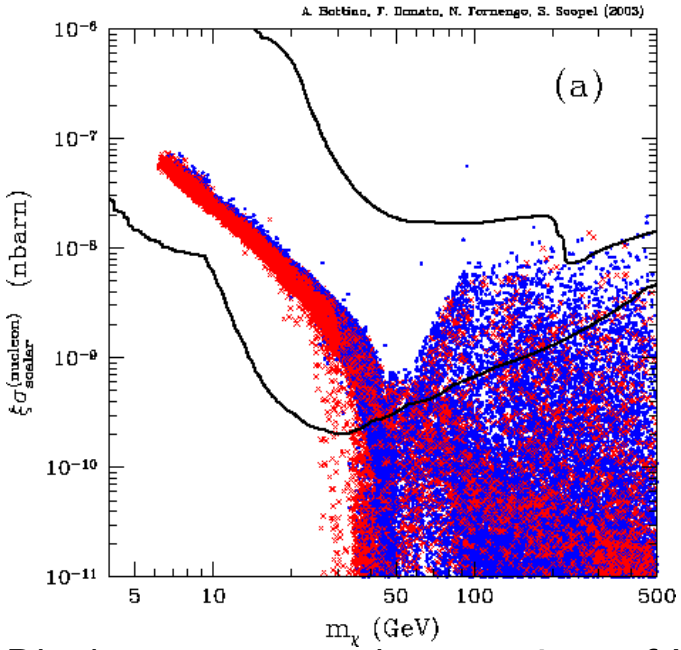
Corner of the possible region found by DAMA coll. with a large variety of halo models- joint 4σ region from the no-modulation hypothesis (astro-ph/0307403; Riv. N. Cim. 26, n.1 (2003), 1-73; Fig.28).



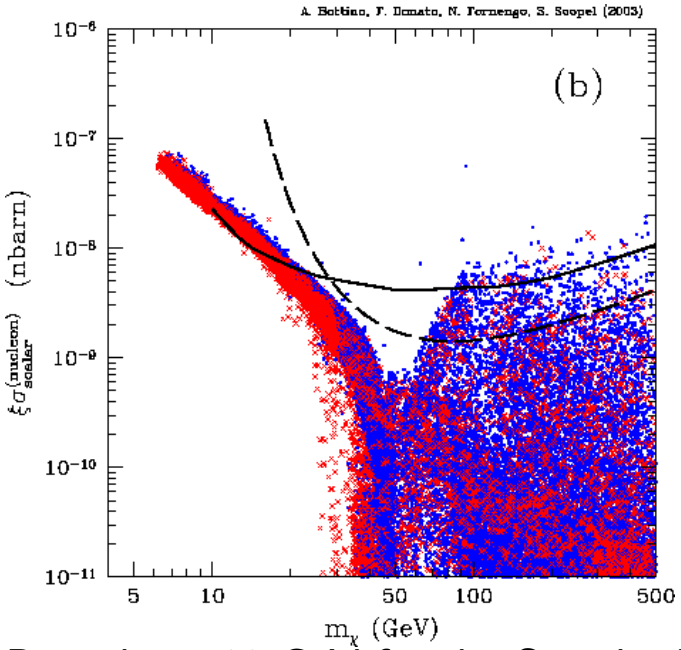
Old DAMA SI WIMPs? "Light WIMP" DAMA region

Similar region < 37 GeV shown clearly in Bottino et al.: EDELWEISS and CDMS bounds exclude $m > 10$ GeV with SHM- advice CDMS to get bounds with other halo models

Bottino, Donato, Fornengo, Scopel, "Light neutralinos and WIMP direct searches," hep-ph/0307303; PRD 69, 037302 (2004),



Black contour: 4σ large variety of HM



Bounds > 10 GeV for the Standard HM only

Old DAMA SI WIMPs? "Light WIMP" compatible

"DAMA dark matter detection compatible with other searches," Gelmini, Gondolo hep-ph/0405278; Gondolo Gelmini hep-ph/0504010; PRD 71 123520 (2005)

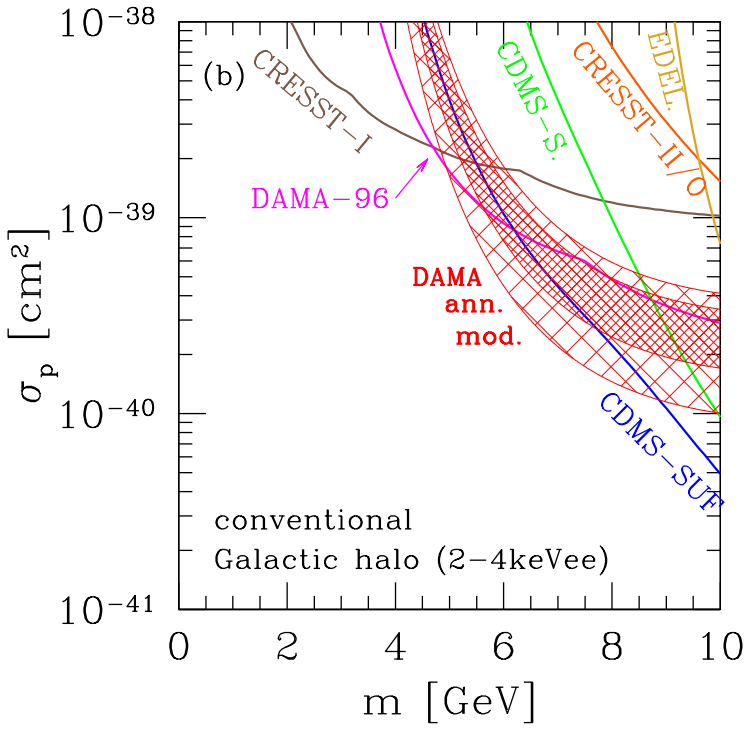
"Los muertos que vos matais gozan de buena salud" Gelmini, TAUP2005, Zaragoza

May 2004: for the 1st time computed the bounds for low m and found the DAMA signal allowed in the SHM for **"Light WIMP"** with $m < 10$ GeV, $\sigma \simeq 10^{-40}$ cm^2

Due to its Na, DAMA could see a signal that was under threshold for Ge in CDMS and EDELWEISS

(Example: uses 2-4 and 6-14 keVee DAMA bins)

Only two data bins, so we used a "raster scan" in m...



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We also considered the SHM plus a stream (bounds change with halo model)

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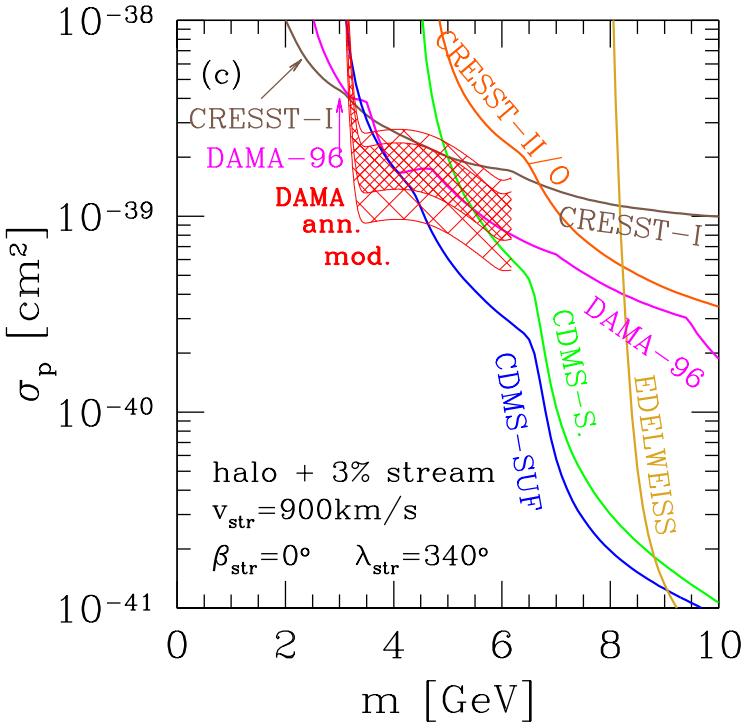
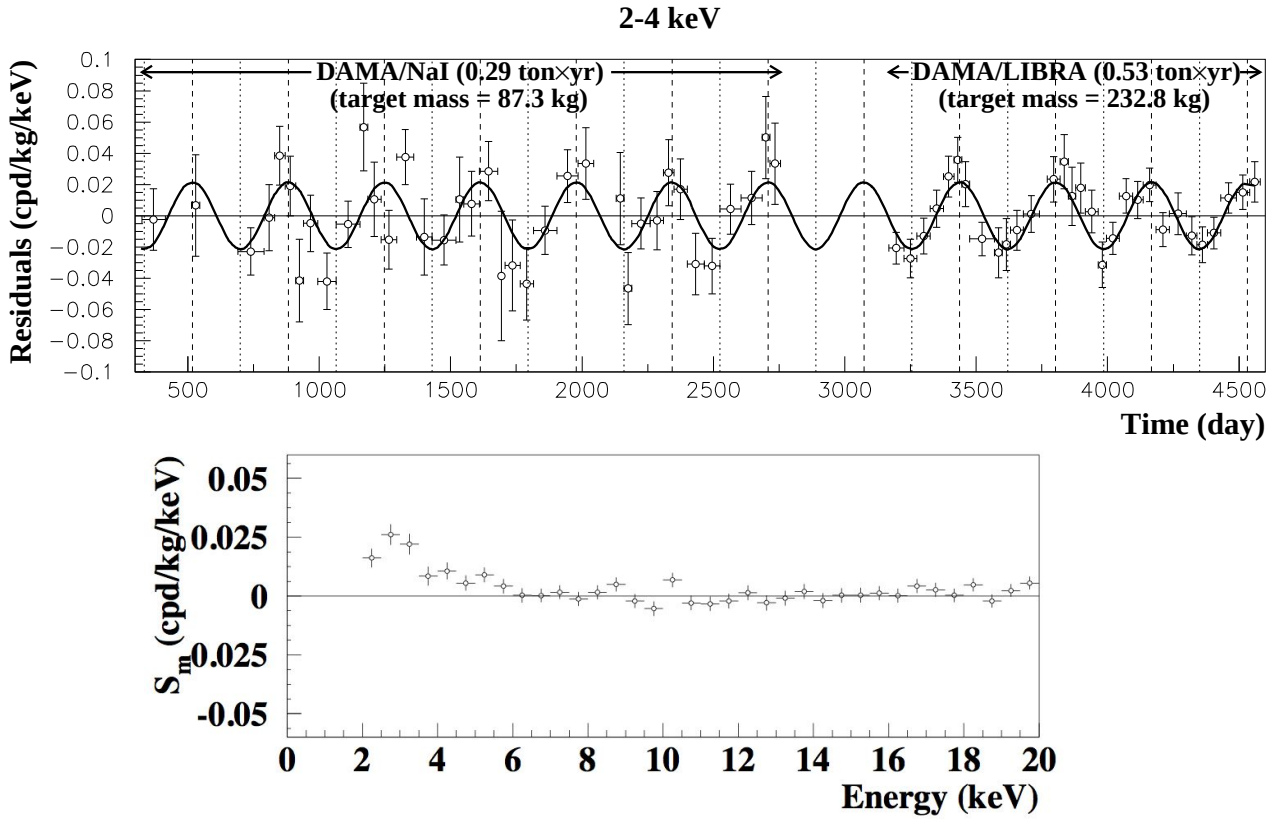


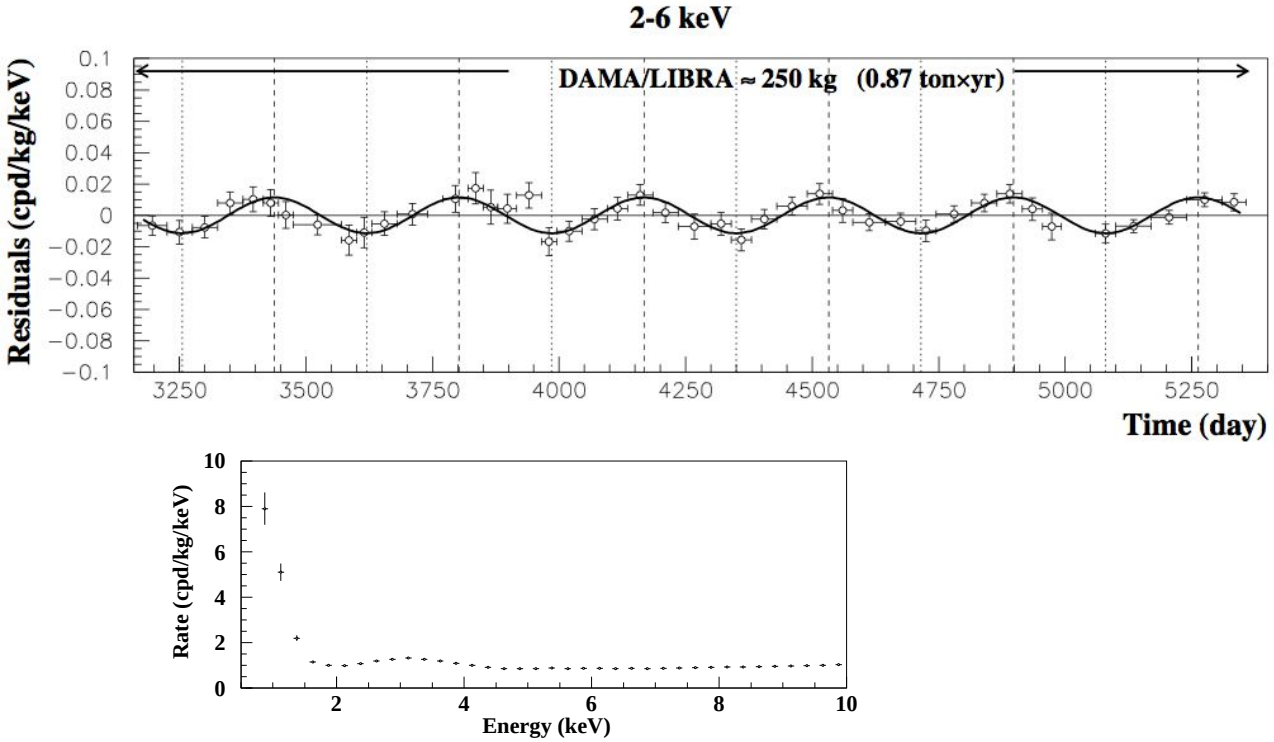
2008 DAMA/LIBRA

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



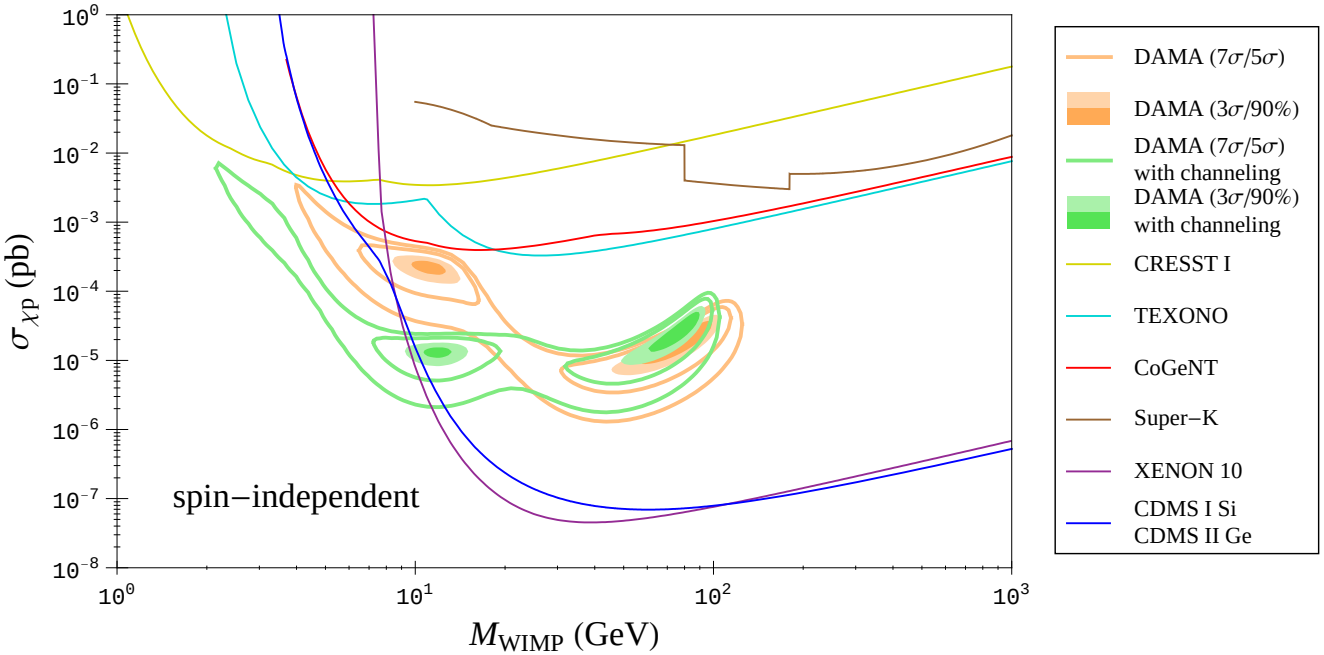
2010 DAMA/LIBRA

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)



SI, 36 bins (likelihood ratio 4param. fit)

Savage, Gelmini, Gondolo and Freese, arXiv:0808.3607, JCAP 0904:010,2009 (Many others reached similar conclusions...Petriello, Zurek; Bottino Donato,Fornengo, Scopel; Chang, Pierce Weiner; Fairbairn Schwetz; Hooper, Petriello, Zurek, Kamionkowski;)

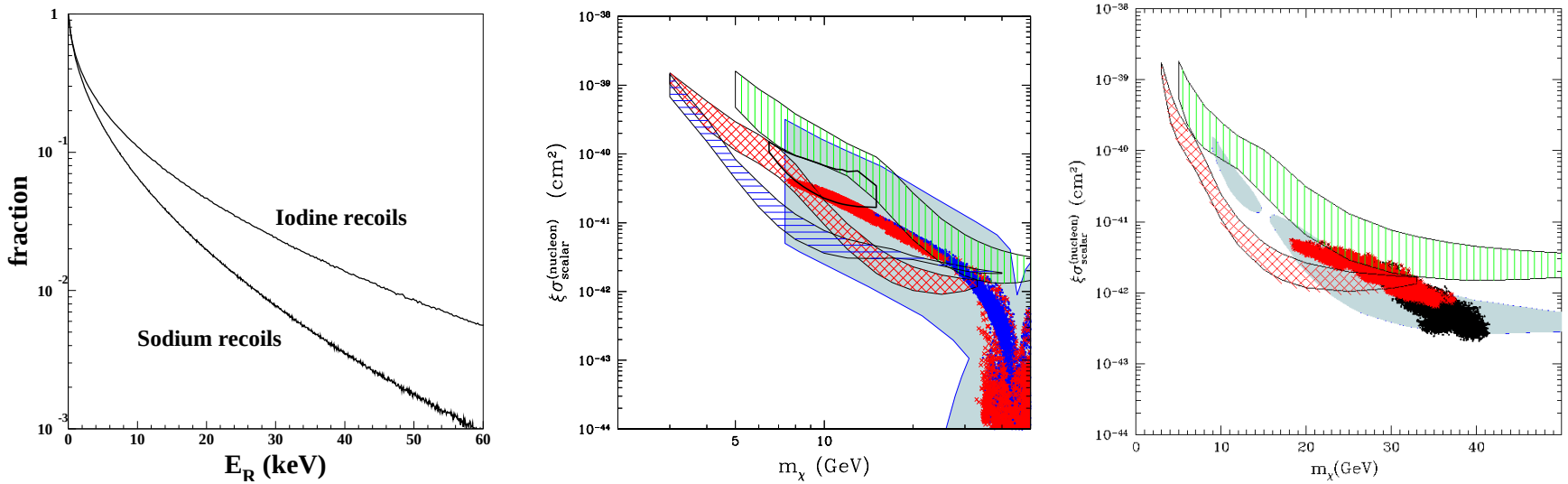


With the channeling fractions DAMA estimated in 2008, new distinct region of light WIMPS $m \simeq$ 7-10 GeV with Na or channeled I recoils were a possible explanation Drobyshevski, 0706.3095 suggested "channeling" in DM detection; DAMA coll. followed

Channeling effect in DM detection:

LEFT:Large 2008 DAMA fraction estimate affects region of Light WIMPs

(DAMA Eur.PJC53 205, 2008) (Belli et al. arXiv:1106.4667 [hep-ph]) (Bottino, Fornengo, Scopel arXiv:1112.5666 [hep-ph])



MIDDLE: DAMA regions (green Q_{Na}=0.3, red changing Q_{Na},blue with DAMA channeling), 2010 CoGeNT (black outline), flag-like region of Light Neutralino Model from Bottino, Donato,Fornengo,Scopel 2003-2011,
RIGHT: model now rejected by LHC for $m < 18$ GeV

Channeling and Blocking Effects in Crystals depend on the initial position of the ion and the angle of incidence with respect to a lattice row or wall.

Channeling:

Ions moving in the crystal along symmetry axes and planes suffer a series of small-angle scattering that maintain them in the open "channels", and give all their energy to electrons so $Q = 1$(ions do not get close to lattice sites)

Blocking:

Reduction of the flux of ions **originating in lattice sites** along symmetry axis and planes

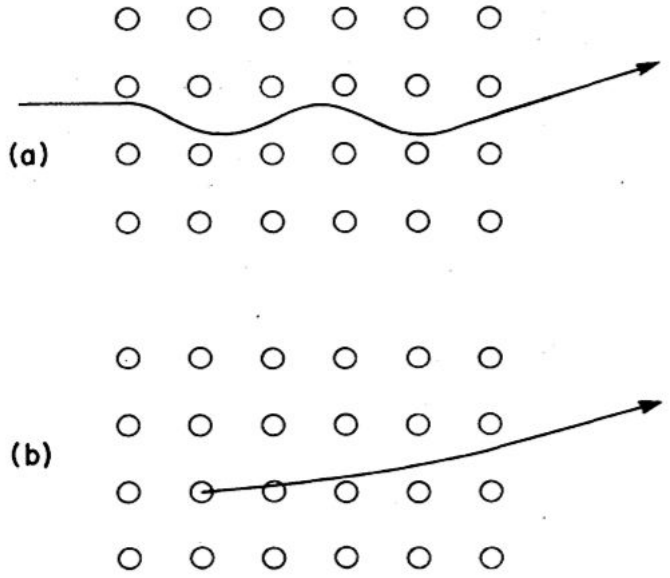
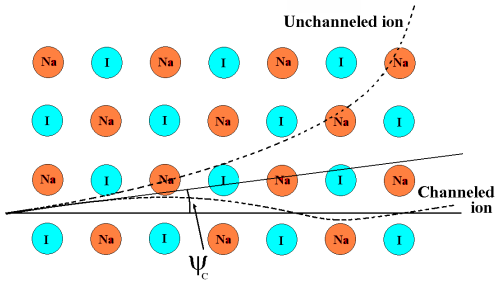


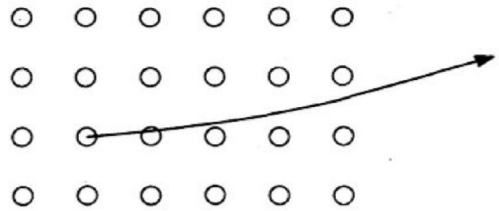
FIG. 1. Schematic illustration of (a) channeling and (b) blocking effects. The drawings are highly exaggerated. In reality, the oscillations of channeled trajectories occur with wavelengths typically several hundreds or thousands of lattice spacings.

(From D. Gemmell 1974, Rev. Mod. Phys. 46, 129)

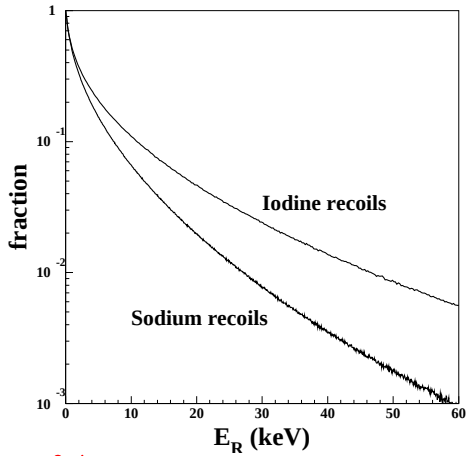
Channeling is much less than in the DAMA estimates



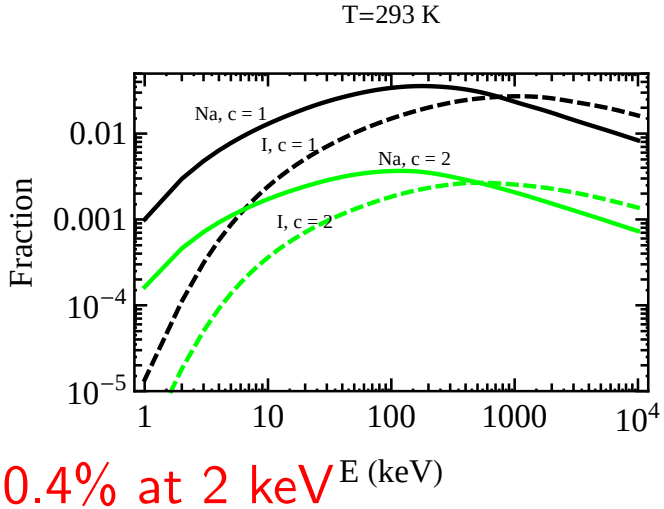
Bernabei et al 2008



Bozorgnia, Gelmini, Gondolo, 2010



40% at 2 keV



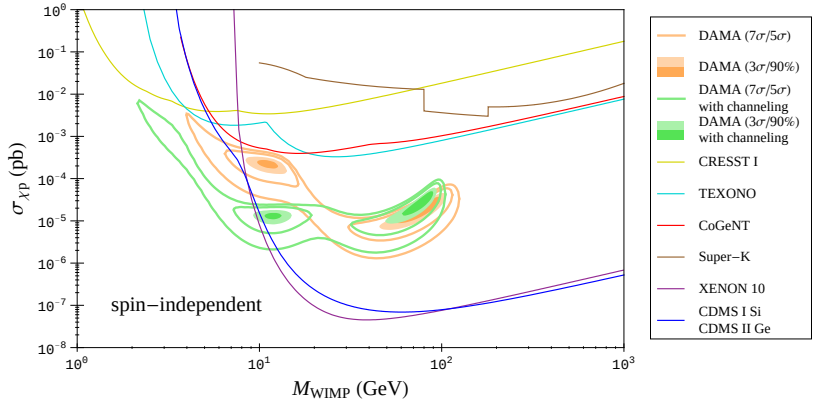
0.4% at 2 keV

Now channeling tested experimentally by Collar et al. in Ge and the KIMS coll. in CsI: preliminary results compatible with BGG estimates

DAMA/LIBRA WIMP region does not change with channeling

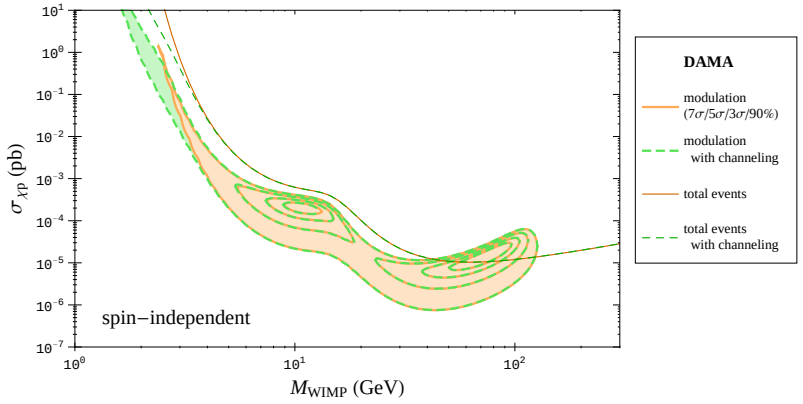
With the DAMA fractions

Savage, Gelmini, Gondolo, Freese JCAP 0904:010,2009



and ours (difference at 7σ)

Savage, Gelmini, Gondolo Freese, PRD83, 055002 (2011)

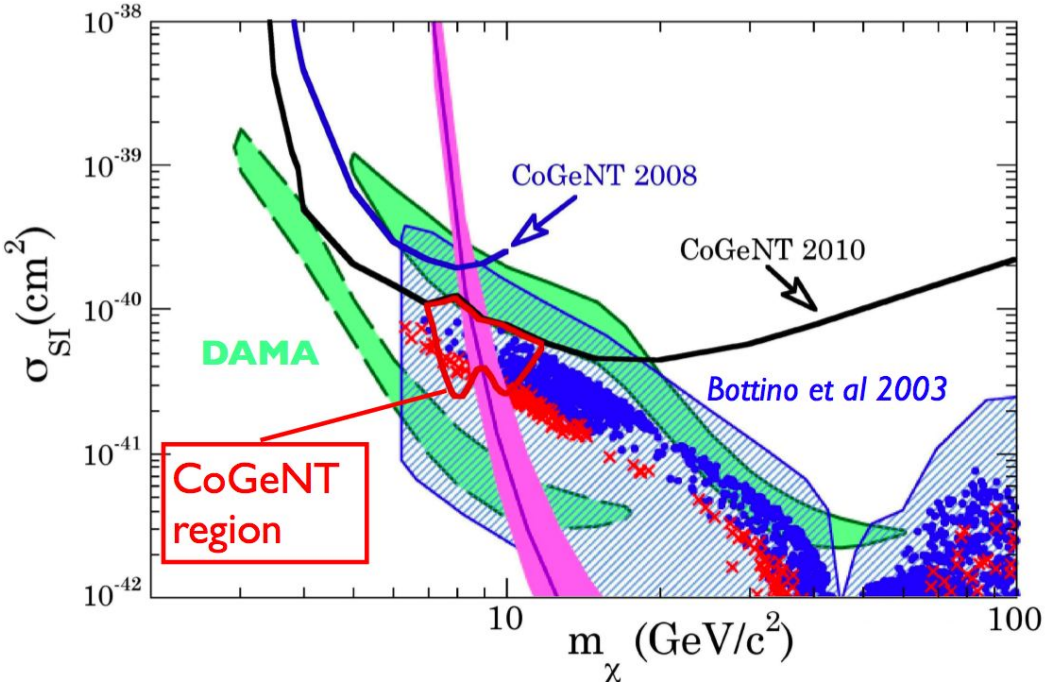


Only higher region due to Na survives - Lower due to I, rejected by at least 2 orders of magnitude by bounds (in particular CsI)

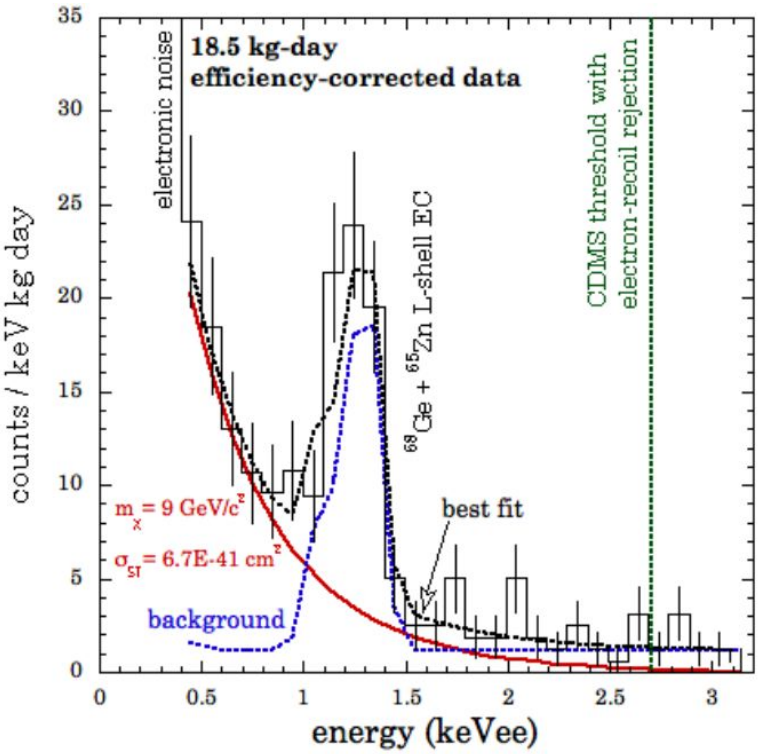
CoGeNT "irreducible excess"

CoGeNT is a 440g Ge detector in the Soudan Mine 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

Feb. 2010: Aalseth et al. [CoGeNT collaboration], arXiv:1002.4703 [astro-ph.CO]



Light WIMP or just background? CoGeNT data



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

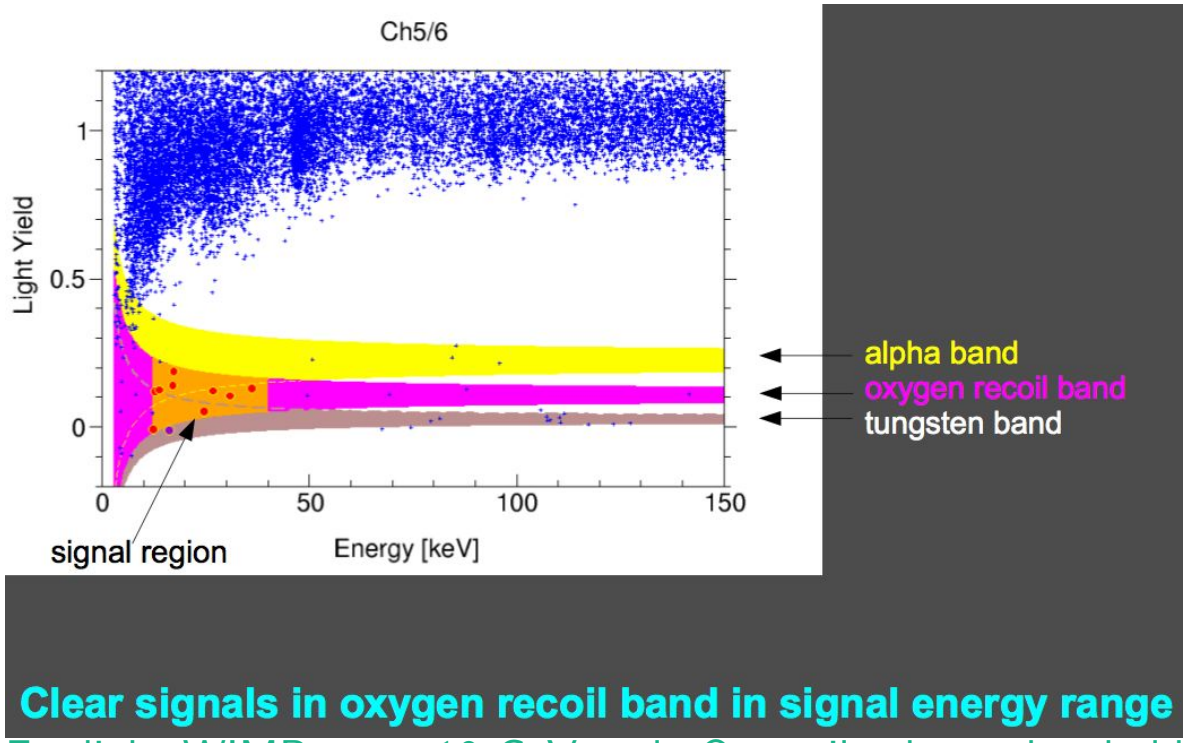
Quotable: The excess of irreducible bulk-like events in CoGeNT is compatible with the WIMP hypothesis in a region where CDMS, DAMA and (several) phenomenological models (good thermal relics) can coexist. It is also equally compatible with any exponential background.

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; Kelso Hooper 1011.3076; ... paper has 375 citations so far)

CRESST II irreducible excess with 564 kgd $CaWO_4$ at LNGS

Feb 2010 Preliminary results,W.Seidel in WONDER, LNGS; Nov. F.Probst in Princeton

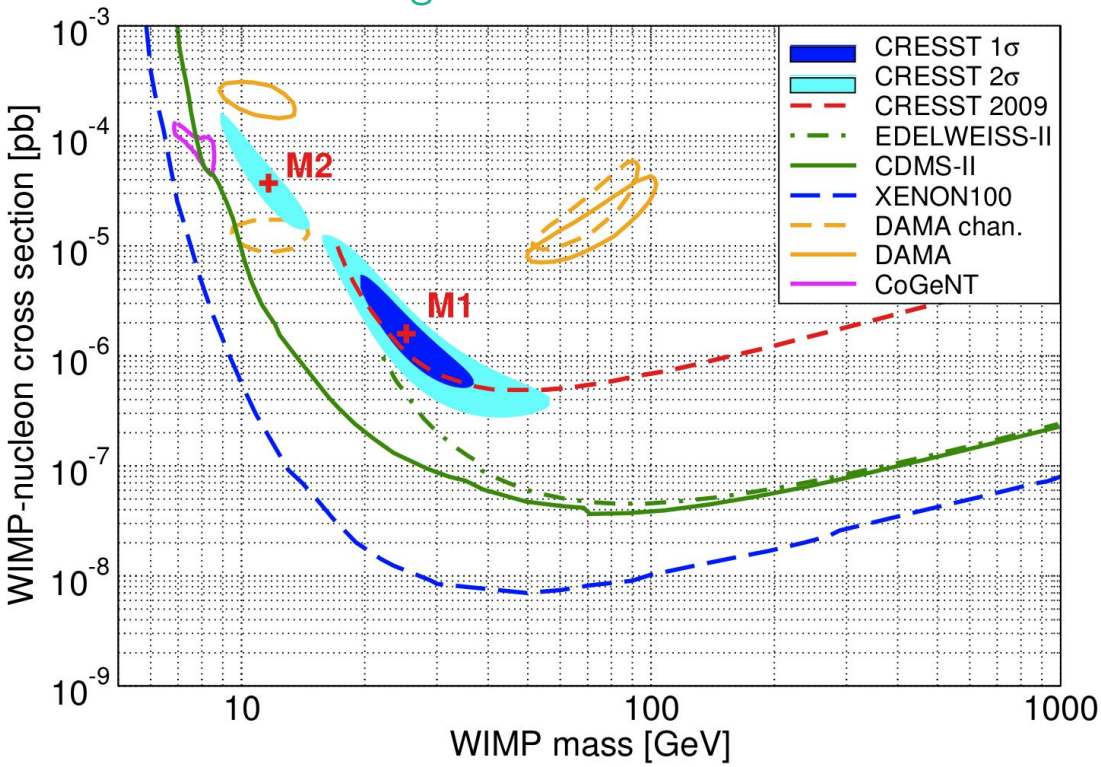


Excess of events in O band: point towards Light WIMPs!

For light WIMPs m$<$ 10 GeV, only O recoils above threshold, Ca recoils for m$\simeq$ 10 GeV and W dominates for large m

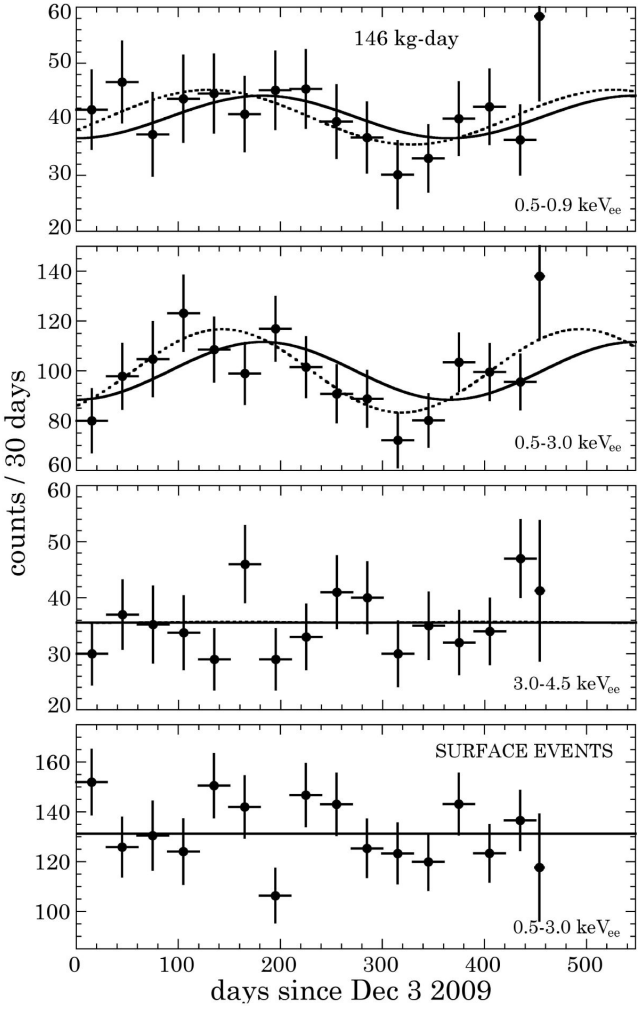
CRESST II irreducible excess

730 kg d; fit of background and WIMP signal together (best fit back. depends on signal)
Sept. 2011, confirmed excess Angloher et al. 1109.0702



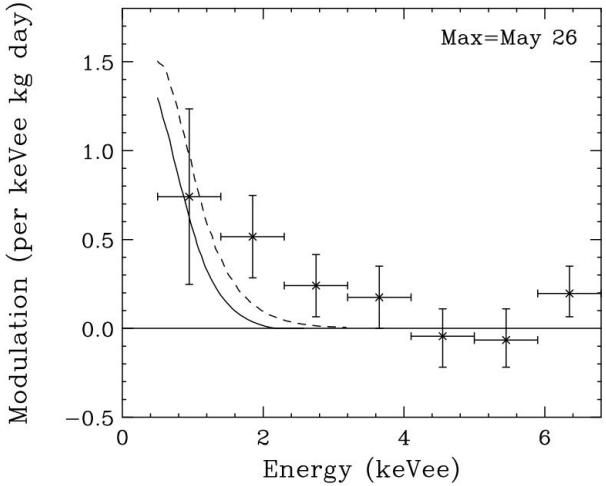
Regions disjoint? XENON and CDMS bounds reject all regions? There are uncertainties.....

CoGeNT annual modulation



June 2011: Aalseth et al. [CoGeNT coll.], arXiv:1106.0650 [astro-ph.CO]- 103 citations

15 months (442 d): events in the CoGeNT "irreducible excess" has a 16.6±3.8 % annual modulation peaking at 4/18±16 d, a phase compatible with DAMA's (5/16±7d 2-4keVee, 5/26 ±7d 2-6 keVee)



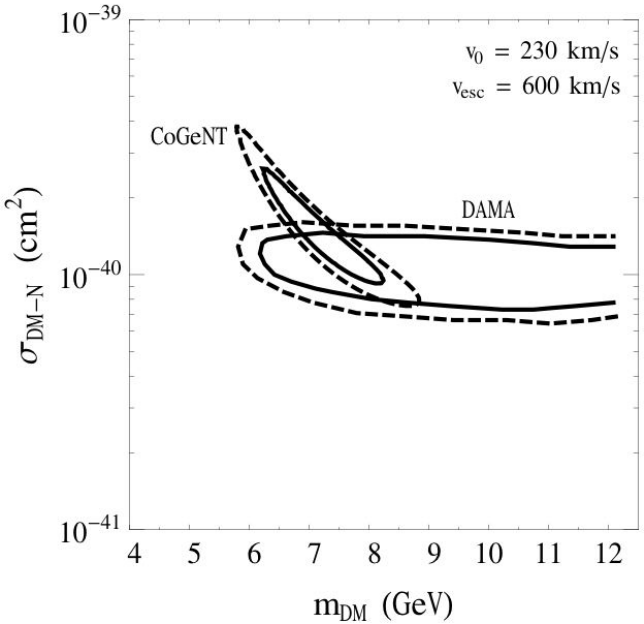
Kelso,Hooper; 1106.1066 [hep-ph]

Light WIMP CoGeNT+DAMA

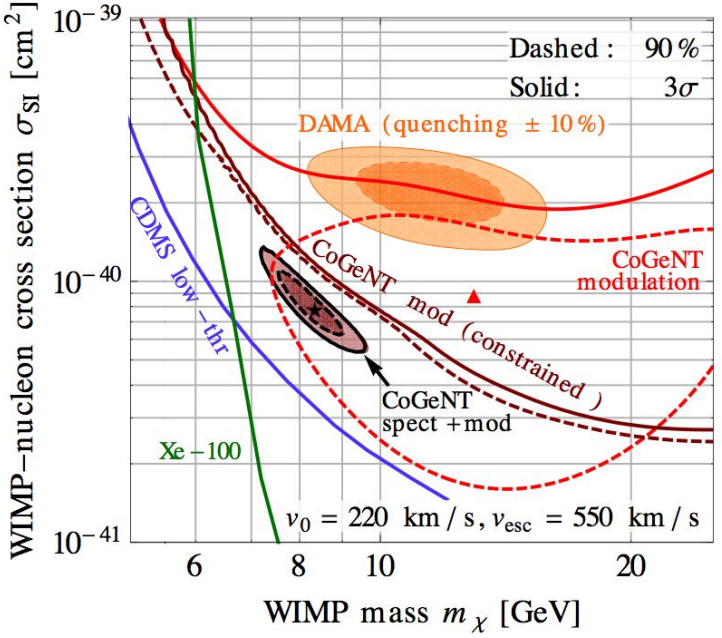
Usual value of fraction of Na recoil energy going to scintillation is Q_{Na}= 0.3, but there are large uncertainties (0.2 to 0.4)

Kelso,Hooper; 1106.1066

Compatible if Q_{Na}= 0.40 - 0.45



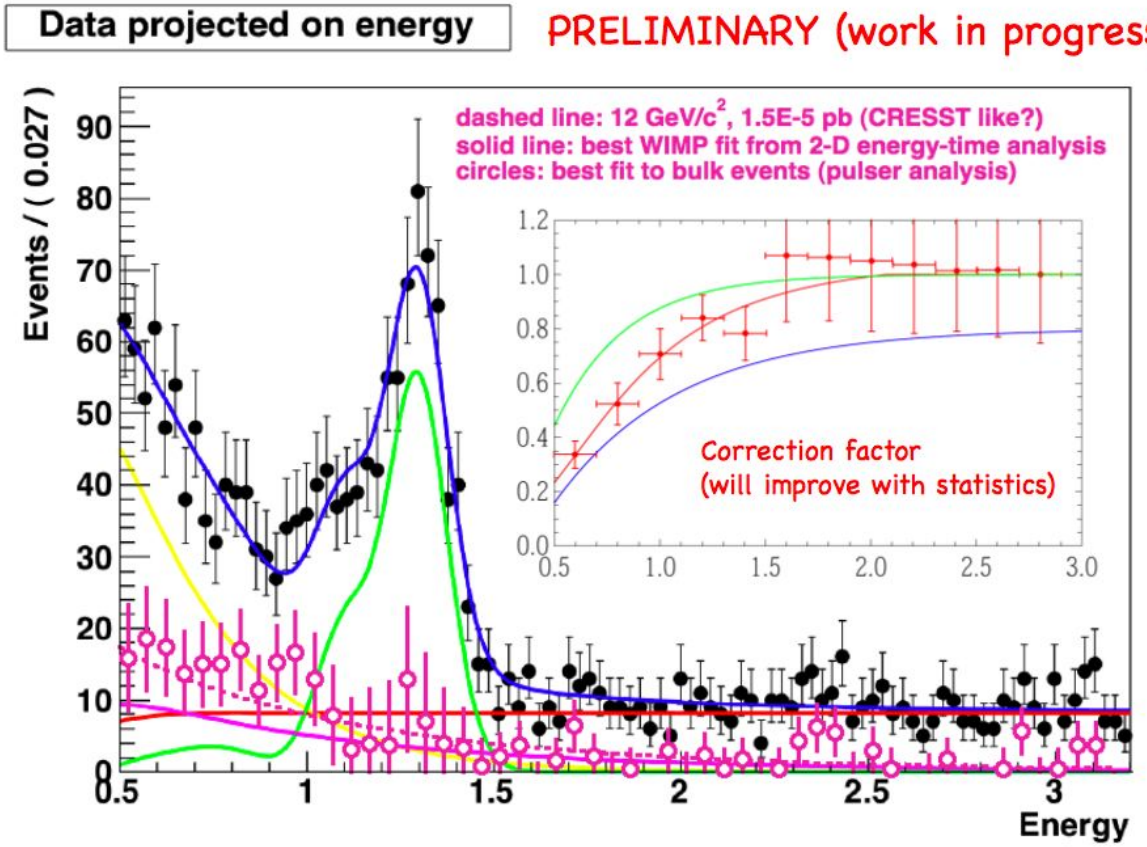
Fox, Kopp, Lisante, Weiner 1107.0717 not otherwise, and XENON and CDMS bounds?



Best bounds: CDMS (Ge) low thr (2 keVnr) for larger σ and XENON100 1104.2549 (S2/S1 8.4 keV thr), and XENON10 1104.3088 (S2, 1.4 keV thr) for lower σ

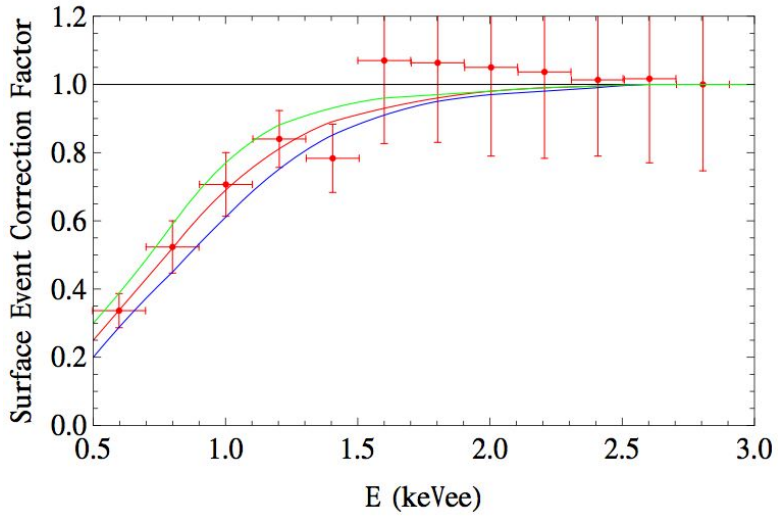
THESE FITS ARE OBSOLETE, because...

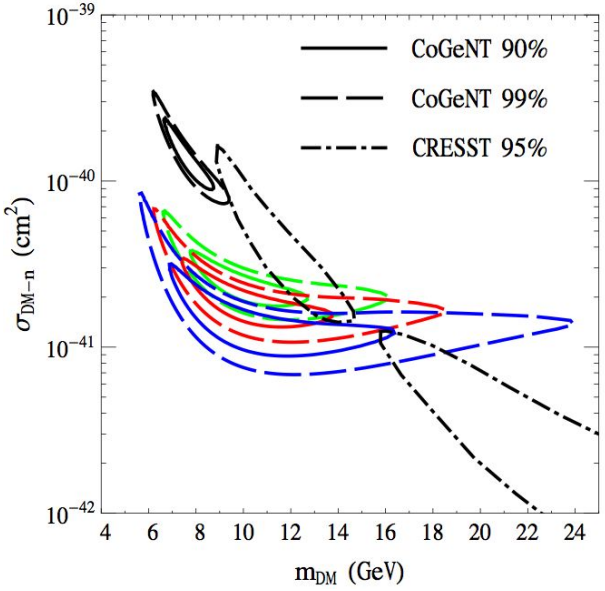
CoGeNT rate revised Collar talk at TAUP 2011-Sept. 2011



Revised CoGeNT rate Kelso, Hooper, Buckley, 1110.5338

σ is smaller- region more similar to CRESST II, lower than DAMA?





Is now the modulation amplitude too large for the rate?

With these lower σ the CDMS rate bounds can be avoided, but XENON100 and XENON10 bounds?
Could Xe bounds be relaxed?

Light WIMP region: can XENON bounds be relaxed?

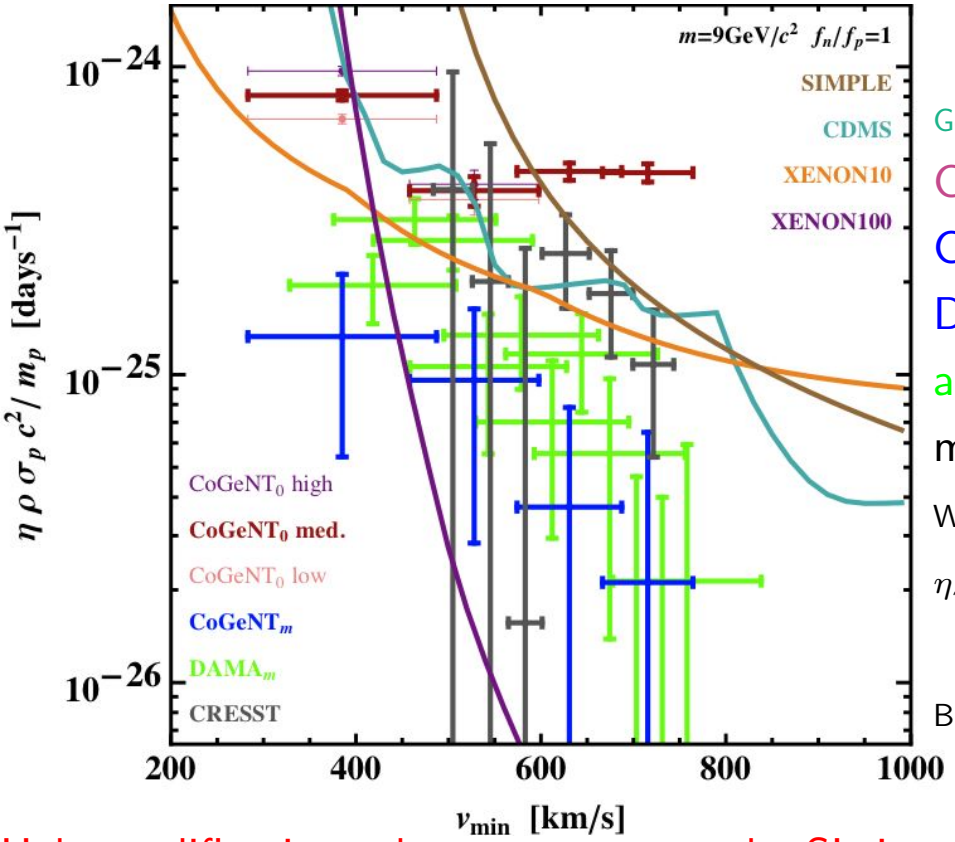
- L_{eff} and ionization yield smaller? Collar objects to L_{eff} and ionization yield, 1106.0653v3. Experimental issue... (efficiencies and energy resolution near threshold are essential- paradoxically a worse energy resolution produces stronger bounds...) and/or

- large dependence on Halo Model? Should not affect CDMS, which has Ge as CoGeNT, but Xe heavier, thus only sensitive to high v WIMP tail, which may be missing: make a "halo independent analysis" (Fox, Liu, Weiner 1011.1915; Frandsen et al 1111.0292; Gondolo, Gelmini 1202.6359) and/or

- for Xe $\left[\langle Z + (A - Z)(f_n/f_p)\right] \simeq 0$?
i.e. $f_n/f_p = -0.7$ is such that WIMP-Xe coupling~ 0 and/or

- Other? inelastic DM, p or v-dependent DM form factor, spin dependent...

Revised CoGeNT rate-"halo independent comparison"



Gondolo, Gelmini 1202.6359

CoGeNT rates and CRESST rate

CoGeNT modulation compatible with DAMA but $>$ 25 % of rate!

and DAMA modulation

mapped into v_{min}-space

We plot weighted average η_{i0}, η_{im}

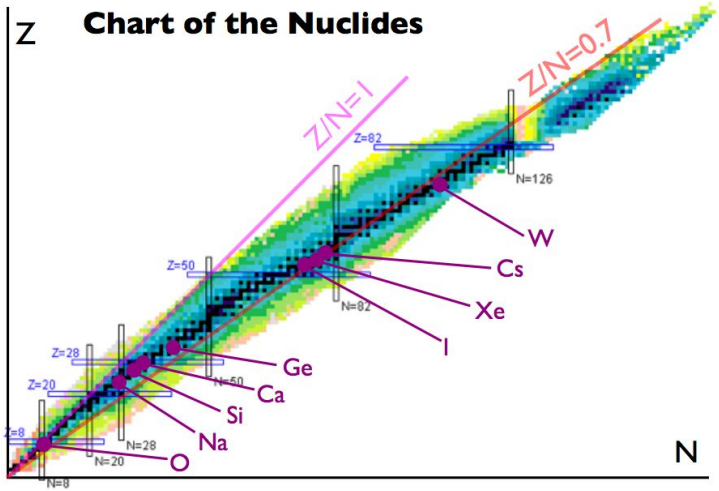
$$\eta_i = \eta_{i0} + \eta_{im}\cos(\omega t - t_0)$$

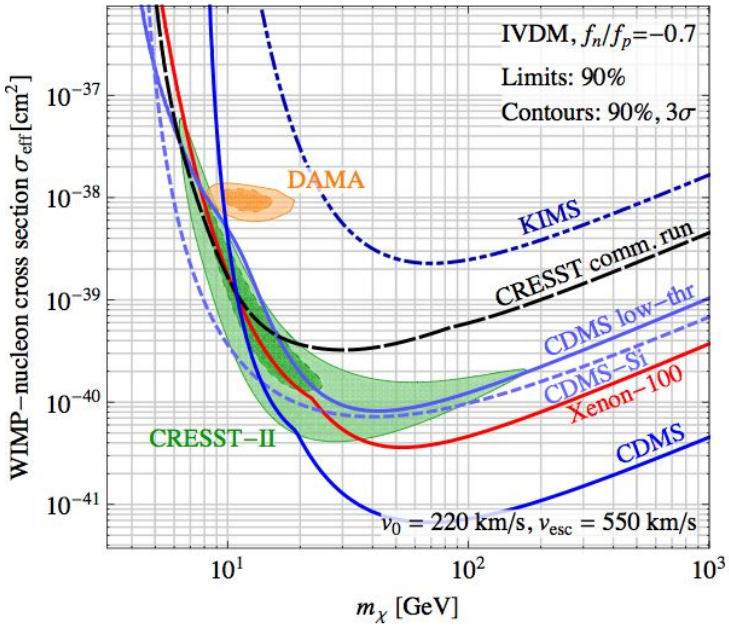
Bins extended by E-resolution ΔE on both sides

Halo modifications alone cannot save the SI signal regions from Xe bounds

Isospin violating (IV) light WIMP? Kurilov, Kamionkowski 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010, Feng et al 2011...

Coupling $\left[\langle Z f_p + (A-Z) f_n\right] \simeq 0$ for $f_n/f_p \simeq -Z/N$, not all because of isotopes



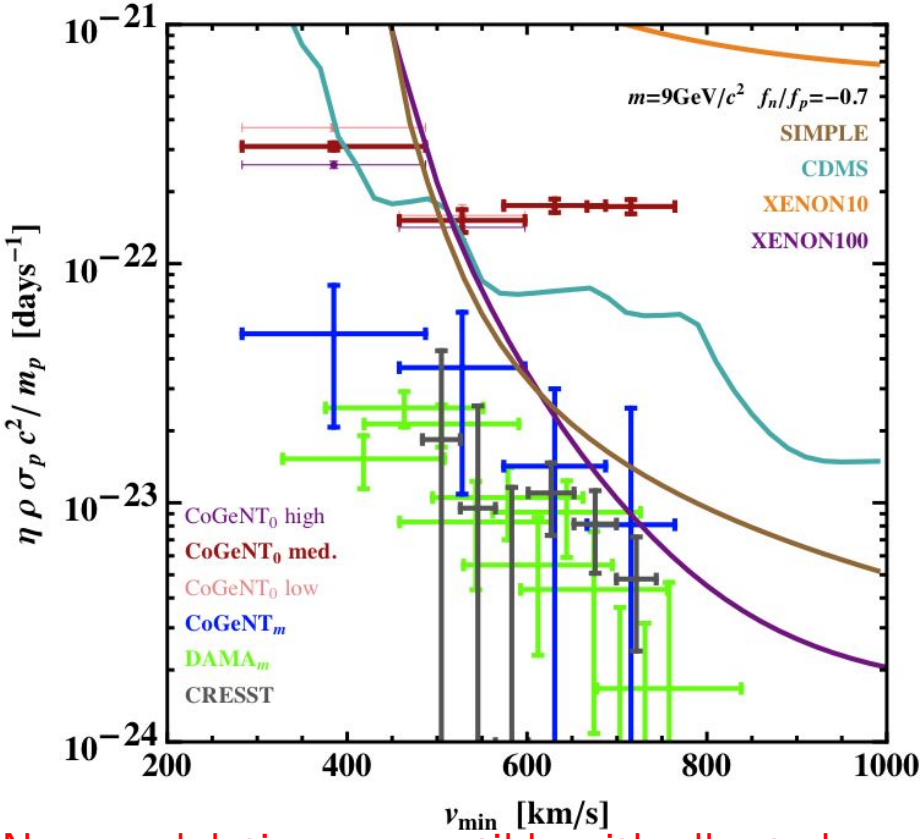


Kopp, Schwetz, Zupan 1110.2721

Best bounds from CDMS now, Ge and Si similar to Na and O!

IV light WIMPs "halo independent analysis"

Gondolo Gelmini 1202.6359



Gondolo Gelmini 1202.6359

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Bins extended by E-resolution ΔE on both sides

Now modulations compatible with all rate bounds! - Problems:

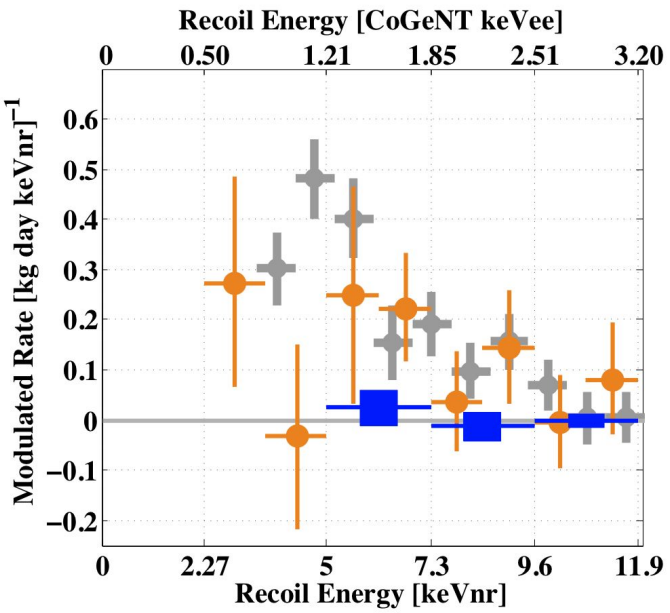
- CoGeNT rate could be lowered but then modulation too high;

-CRESST unmodulated is on top of CoGeNT modulation! so they are incompatible

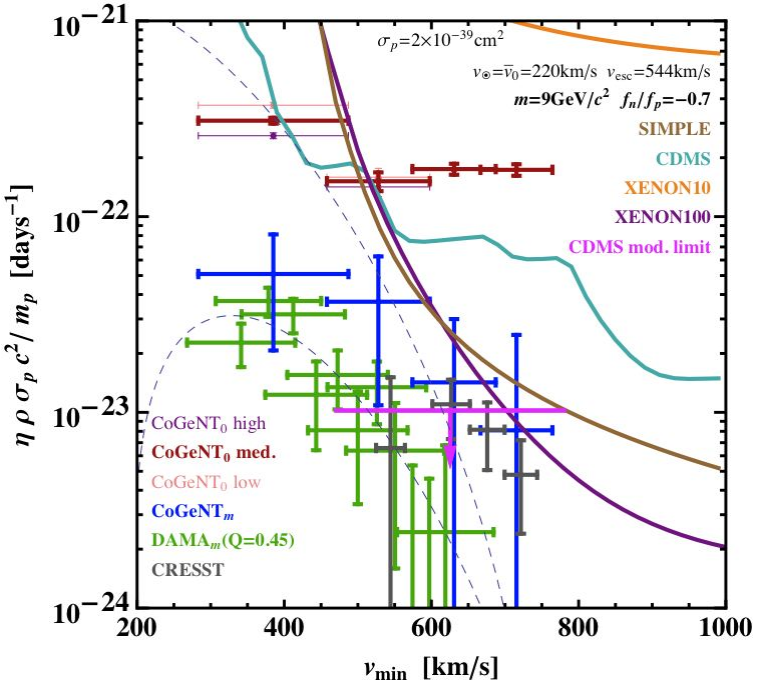
Before last act in the saga so far...

CDMS negative annual modulation search

March 2012: 1203.1309 CDMS (Ge): no modulation $>$ 0.06 ev./keVnr kg day in 5 to 11.9 keVnr (CoGeNT thres. 0.4 keVee $\simeq$ 1.6 keVnr) to 99%CL. Halo independent comparison:



CDMS II 1203.1309

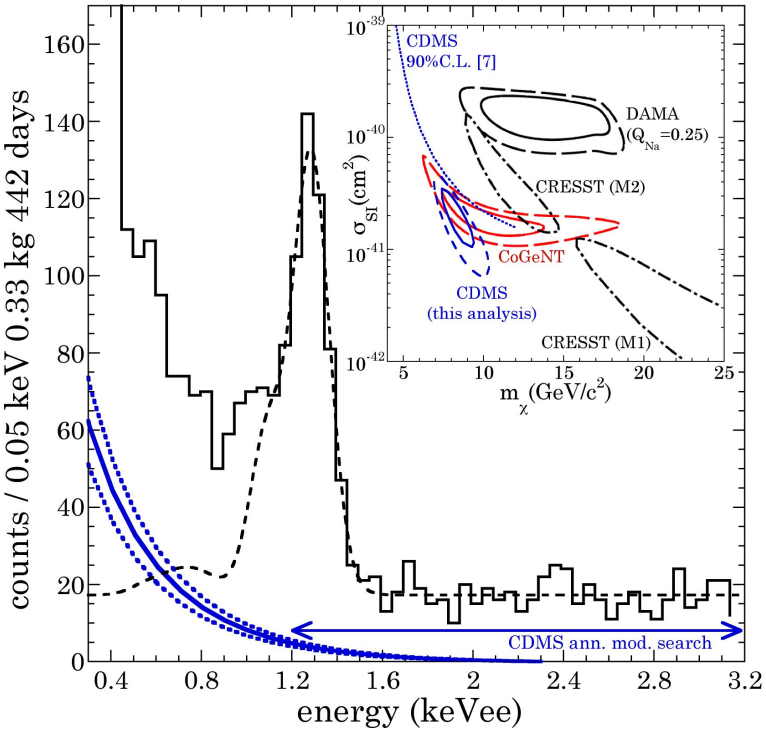


Gondolo Gelmini 1202.6359

Last act in the saga so far...

Signal of Light WIMPs in CDMS??

April 2012: 1204.3559 Collar and Fields read off CDMS data from figure in their March 2012 paper (published for the first time), reanalyzed CDMS Ge data
AND CLAIM FIT TO DATA IS MUCH BETTER ADDING A LIGHT WIMP SIGNAL!



"CDMS signal" shown overlapped to CoGeNT rate- CDMS and CoGeNT $\sigma - m$ regions would overlap!!!

The modulation of this signal would be below the negative modulation CDMS search limit (0.06 events/keVnr kg day)

Light WIMPs or Backgrounds? At this point the situation is confusing and exciting.... Light WIMP's are promising candidates- however its signal would be close to threshold where background is difficult to understand.

DAMA/LIBRA lowered their threshold to 1 keVee and results will be very important for light WIMPs, but if the DAMA modulation is due to DM, a DM signal must be found by another experiment. There have been many objections to the DAMA result over the years, now extended to CoGeNT, none conclusive...

"DM-Ice" 250 kg NaI in the South Pole could check the annual modulation in NaI either with opposite in phase (e.g. muon rate) or absent (e.g. temperature, neutrons) background annual variation; DM-Ice 17(kg) already deployed (Cherwinka et al 1106.1156)
A better alternative: **ANDES**, the only underground laboratory in the southern hemisphere!

In the near future: CRESST II and CoGeNT will understand better their backgrounds

In the longer run: XENON-1Ton, PandaX, DarkSide, SuperCDMS...

DM searches are advancing fast... Lots of data necessarily lead to many hints... hopefully at some point several of them will point to the same DM candidate!