Fits to Light WIMPs

Graciela Gelmini - UCLA

UCLA DM Conference - Feb 22 to 24, 2012

WIMP 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.

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

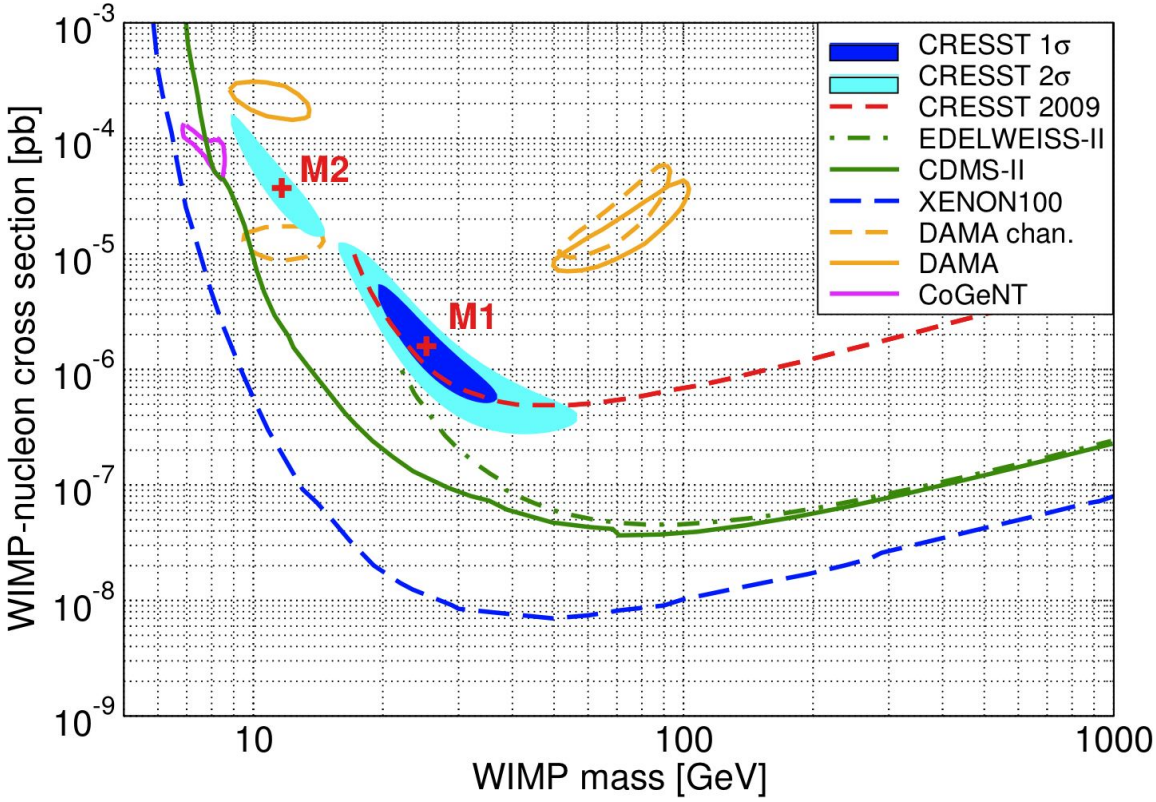
CDMS (Ge, Si), XENON 10 (Xe), XENON 100 (Xe), SIMPLE (C_2ClF_5).... have upper bounds...
Can all signals and bounds be reconciled? Some of them?

- Indirect Detection- looks for DM annihilation (or decay) products

Signals of Light WIMPs in Fermi ST data too? from the Galactic Center (D.Hooper 1201.1303) and from galaxy clusters (Han, Frenk, Eke, Gao & White 1112.2220)

I will concentrate on Direct Searches

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-

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....

- for spin-independent (SI) $\sigma(q) = \sigma_0 F^2(q)$ where
$\sigma_0 = \Big[Z + (A-Z)(f_n/f_p)\Big]^2(\mu^2/\mu_{\rm p}^2)\sigma_{\rm p} = A^2(\mu^2/\mu_{\rm p}^2)\sigma_{\rm p}$ for $f_p = f_n$

Thus the plots are in the $m, \sigma_{\rm p}$ plane.

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

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

Signal in Direct Searches: WIMPs interact with nuclei.

In crystals: most of the recoil energy goes usually to phonons,

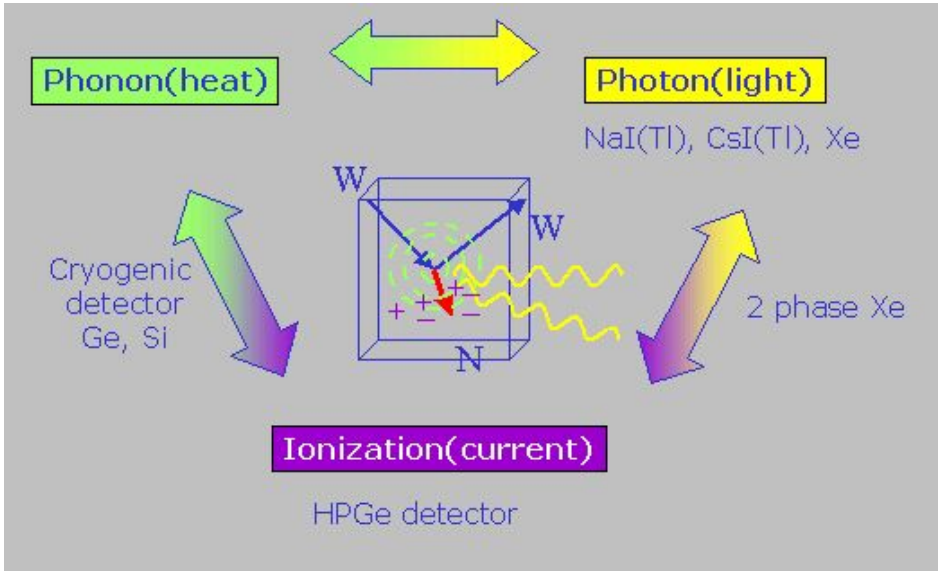
but a fraction Q goes into ionization/ scintillation, $Q_{\rm Na} = 0.3$, $Q_{\rm I} = 0.09$...

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.

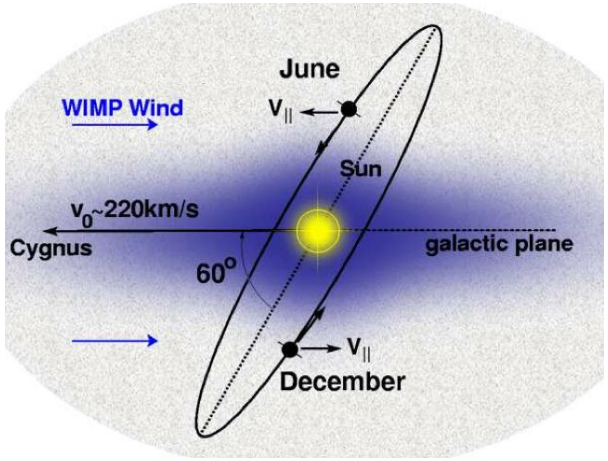
Fig. from KIMS



Signature in Direct Searches: Annual modulation of the signal

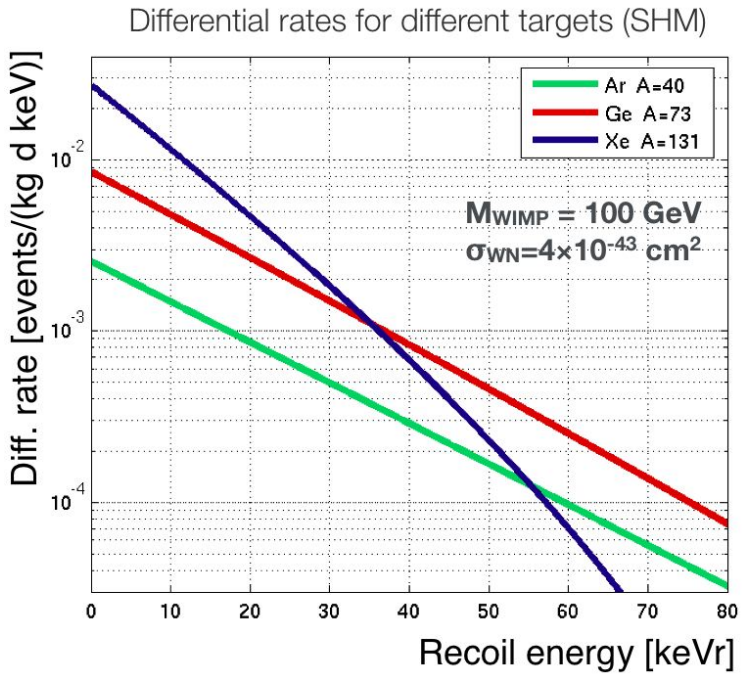
Standard Halo Model (SHM)

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

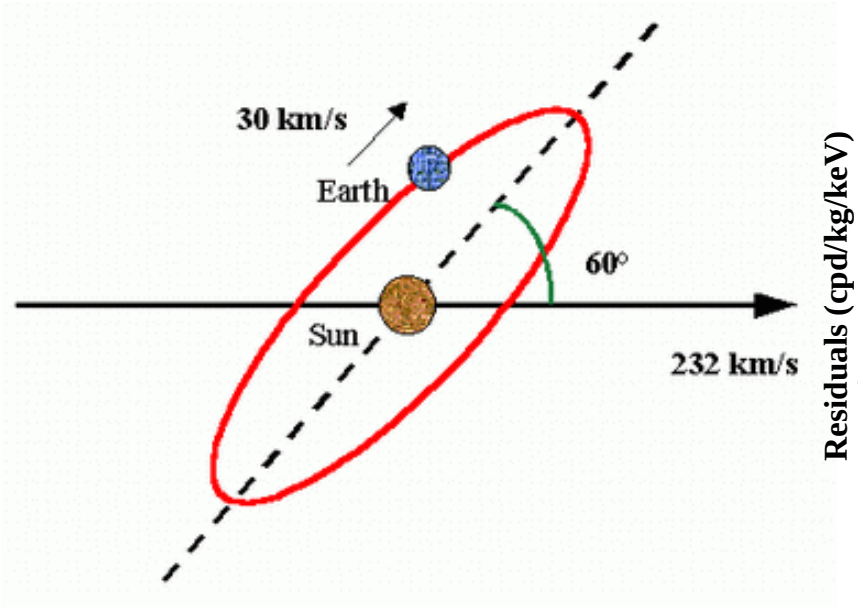


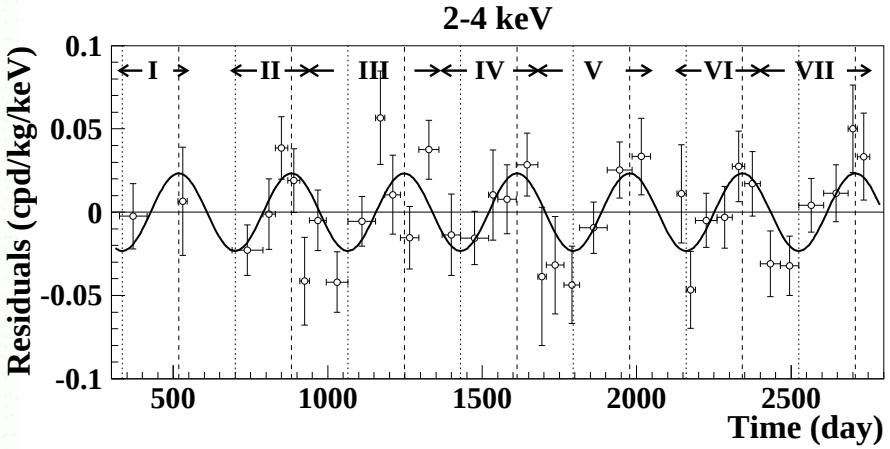
ANNUAL MODULATION: max in May, min in Dec. (Drukier, Freese, Spergel 1986)

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...

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

Old DAMA/NaI: DM signal?



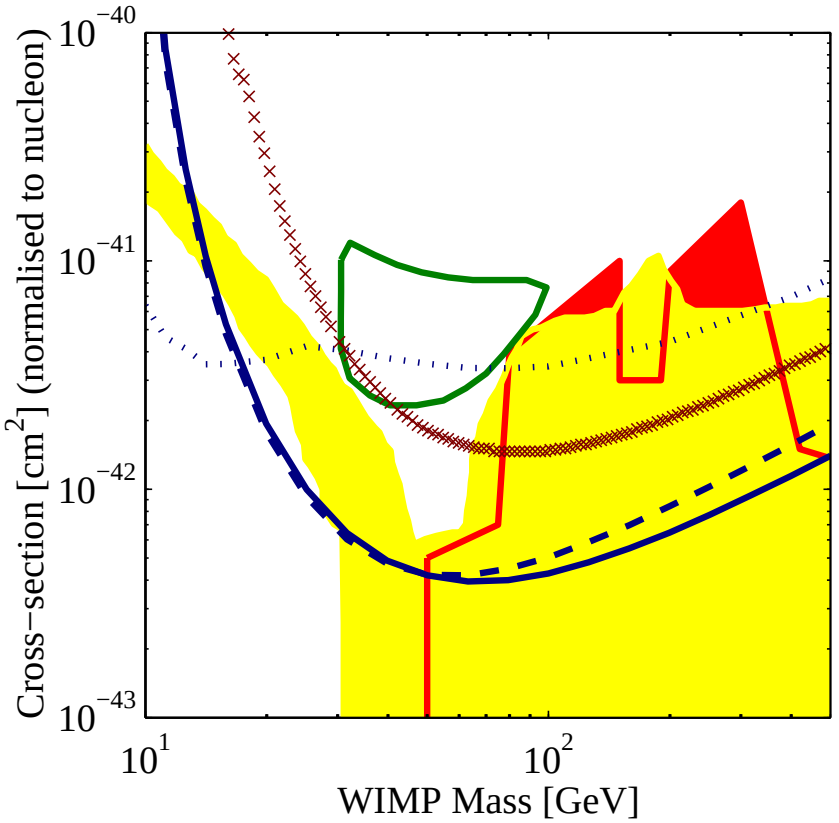


By 2002: 7 years of DAMA/NaI showed a 6σ modulation signal compatible with the Standard Halo Model.

Old DAMA/NaI SI WIMPs?

Theoretical prejudice in early DAMA analysis: DAMA region for SI WIMPs in the SHM was cut at 30GeV

which was excluded in 2002 by Edelweiss (brown crosses) and in 2004 by CDMS-Soudan (blue).



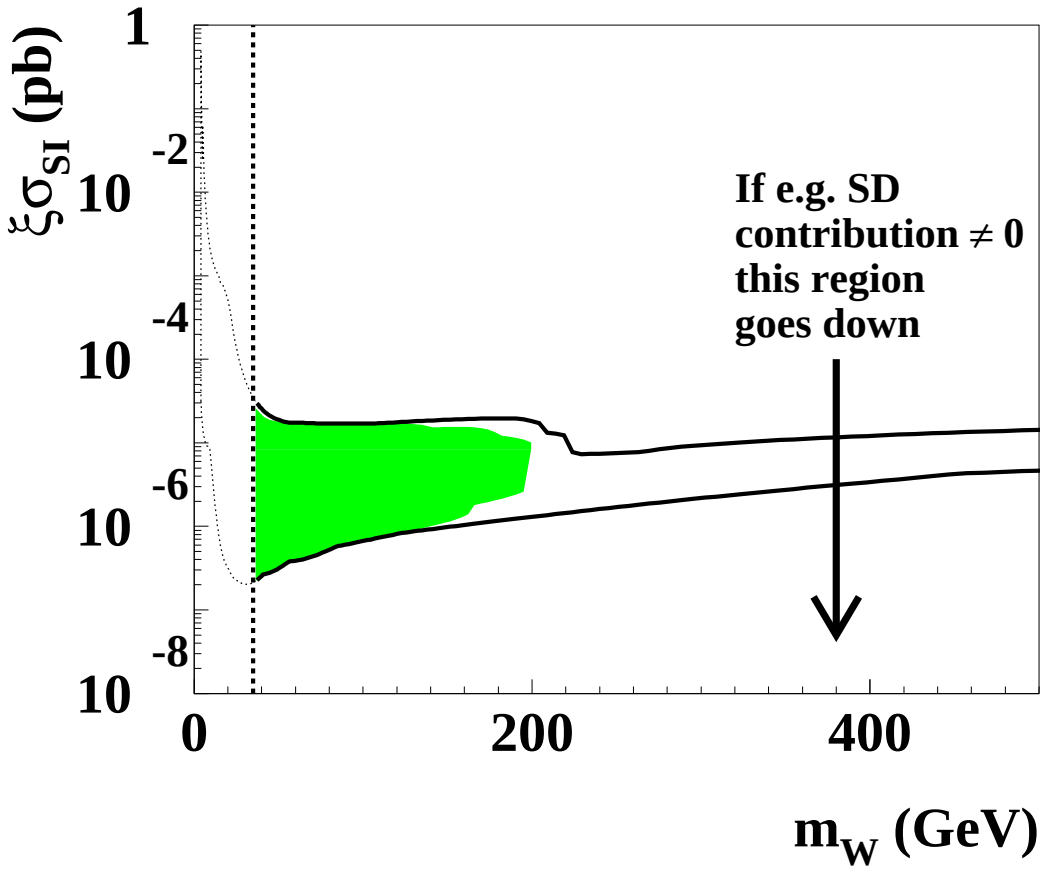
Bottino et al. light neutralinos m >6 GeV

Baltz et al.

Old DAMA SI WIMPs? "Light WIMP" DAMA region

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

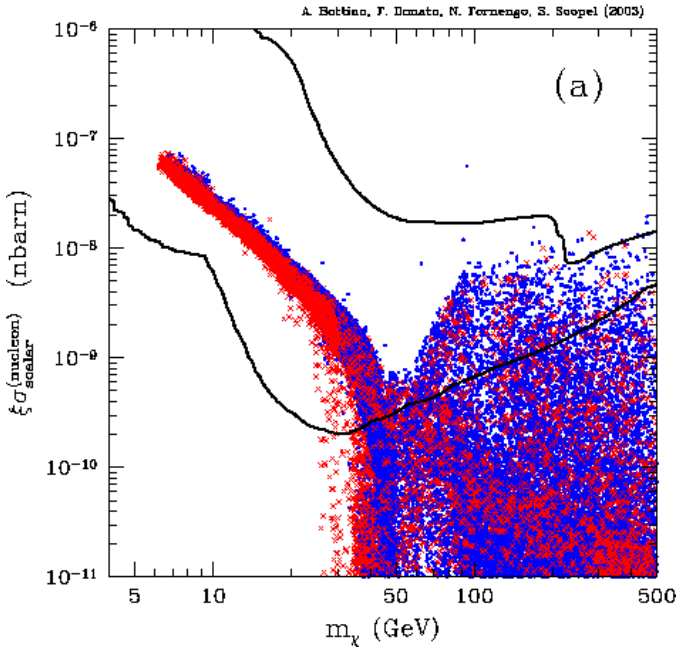
Corner of the possible region found by DAMA coll. with a large variety of halo models-joint 4σ region from the no-modulation hypothesis (astro-ph/0307403; Riv. N. Cim. 26, n.1 (2003), 1-73; Fig.28).

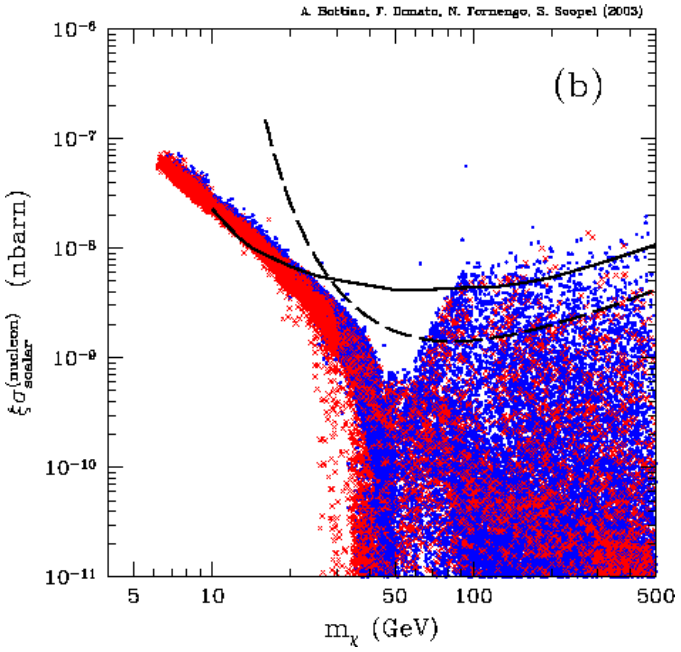


Old DAMA SI WIMPs? "Light WIMP" DAMA region

Same 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),





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)

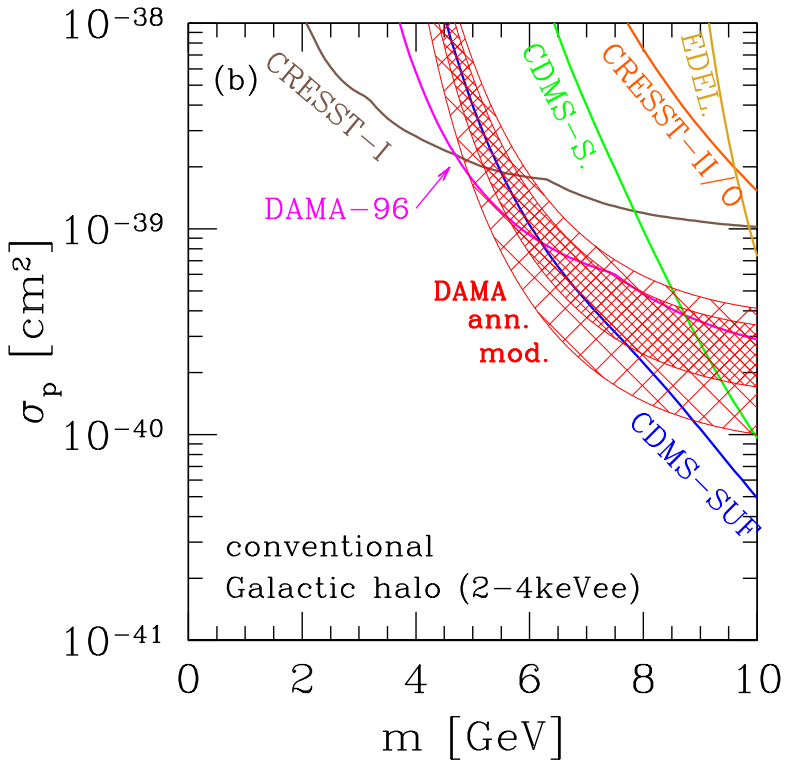
Gelmini, "Los muertos que vos matais gozan de buena salud" TAUP2005, Zaragoza

In 2004 we computed the bounds for low m and found the DAMA signal allowed in the SHM for 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...



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)

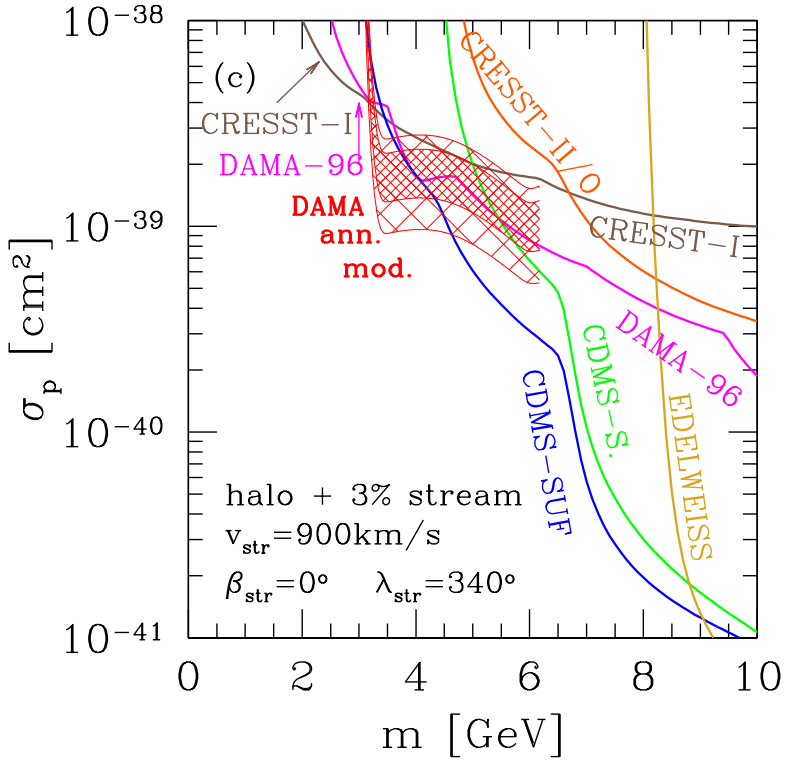
Gelmini, "Los muertos que vos matais gozan de buena salud" TAUP2005, Zaragoza

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

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

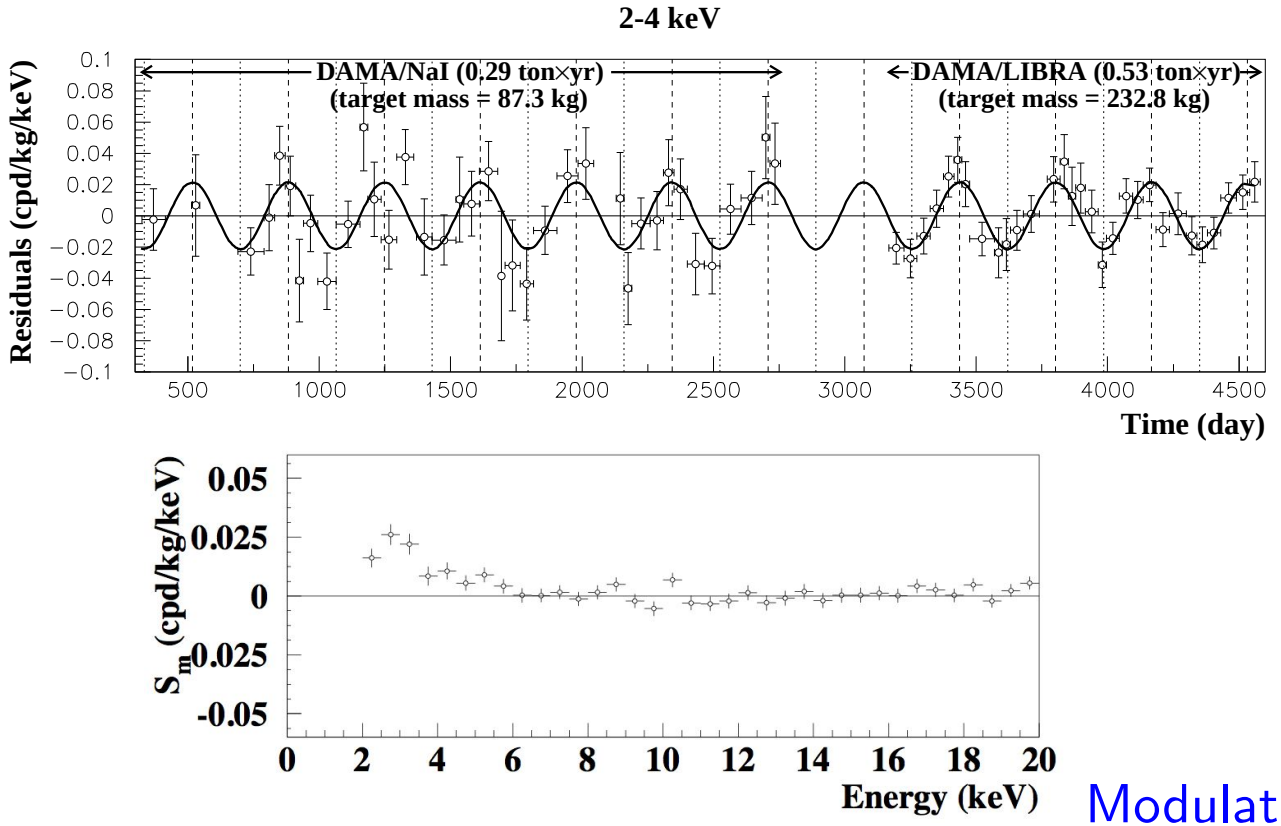
(Example: uses 2-4 and 6-14 keVee DAMA bins)

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



2008 DAMA/LIBRA

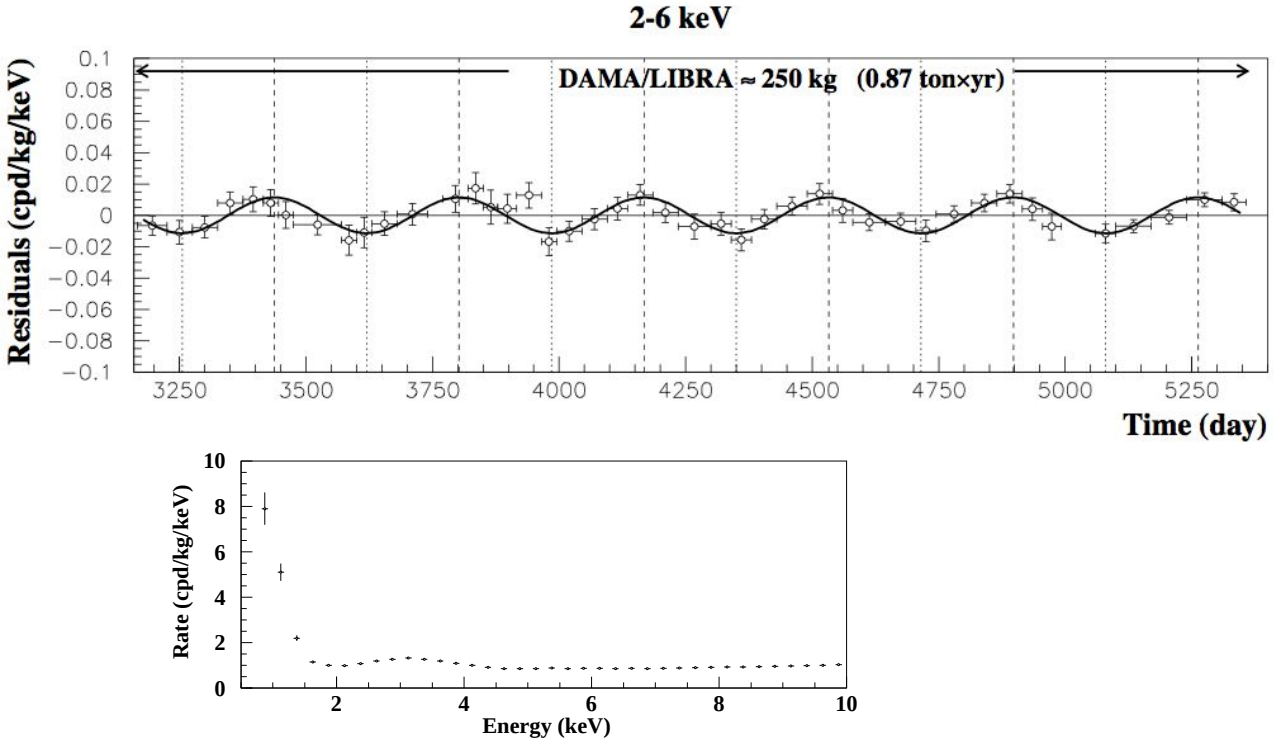
25 NaI (Tl) crystals of 9.5 kg each, 4y in LIBRA (11 years total), 0.83 ton $\times$ year, 8.2σ modulation signal. (Bernabei et al 0804.2741)



Modulation:36 bins

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)

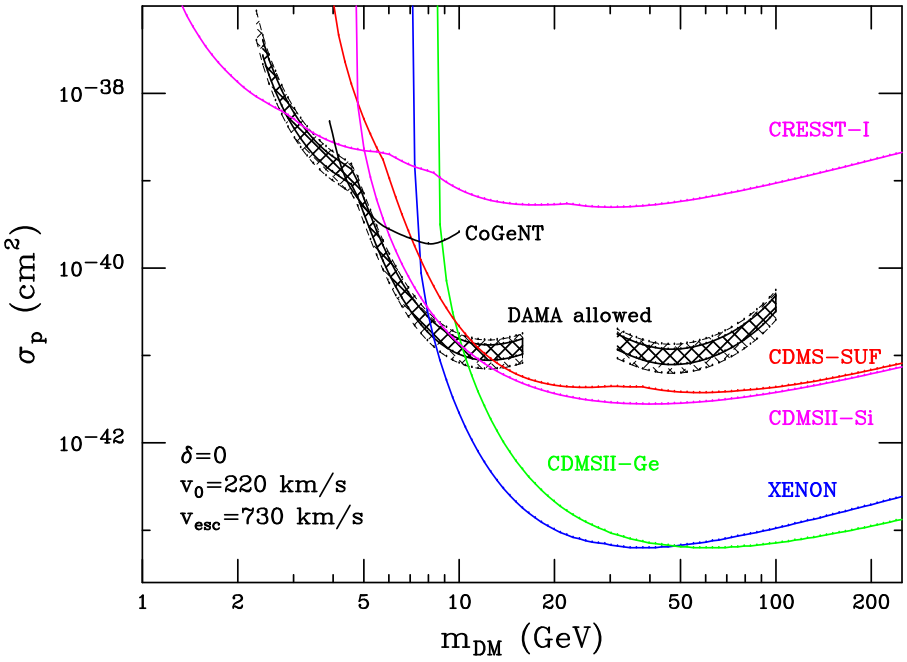


DAMA/LIBRA Light WIMPs?

Soon after 2008 data release, Petriello and Zurek repeated Gondolo-Gelmini-2005 method with new data

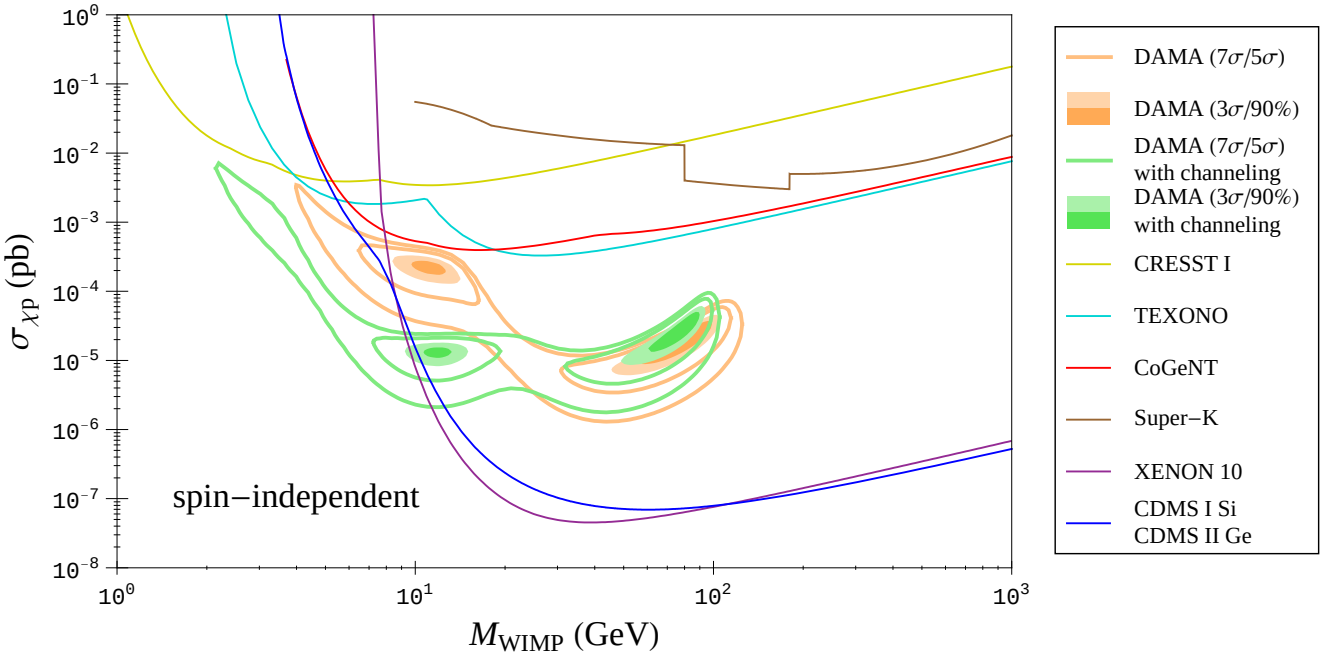
they concluded that with channeled I recoils still region allowed!

But now 36 data bins, so "raster scan" was not justified...



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;)

Drobyshevski, 0706.3095 suggested "channeling" in DM detection; DAMA coll. followed

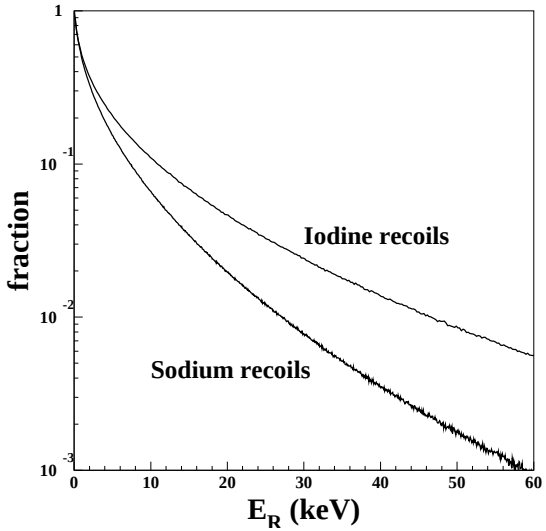


With the channeling fractions DAMA estimated in 2008, new distinct region of light WIMPS $m \simeq$ 7-10 GeV with Na or channeled I recoils were a possible explanation

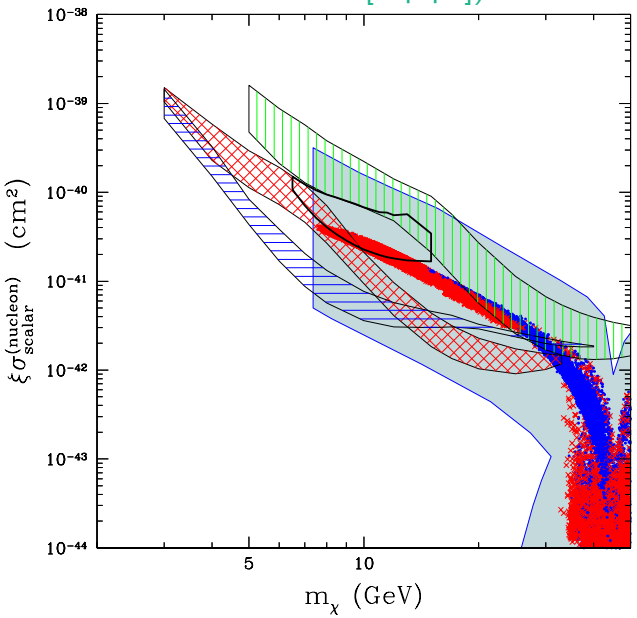
Channeling effect in DM detection:

Large 2008 DAMA fraction estimate affects region of Light WIMPs

(DAMA Eur. Phys. J. C **53**, 205, 2008)



(Belli et al. arXiv:1106.4667 [hep-ph])



Right: DAMA regions (red changing Q_{Na}-blue with DAMA channeling), CoGeNT (outline), flag-like region of neutralino candidates from Bottino, Donato,Fornengo,Scopel 2003-2011. Now $m < 18$ GeV rejected by LHC bounds (Bottino, Fornengo, Scopel arXiv:1112.5666 [hep-ph])

Channeling and Blocking Effects in Crystals refer to the orientation dependence of ion penetration in crystals.

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

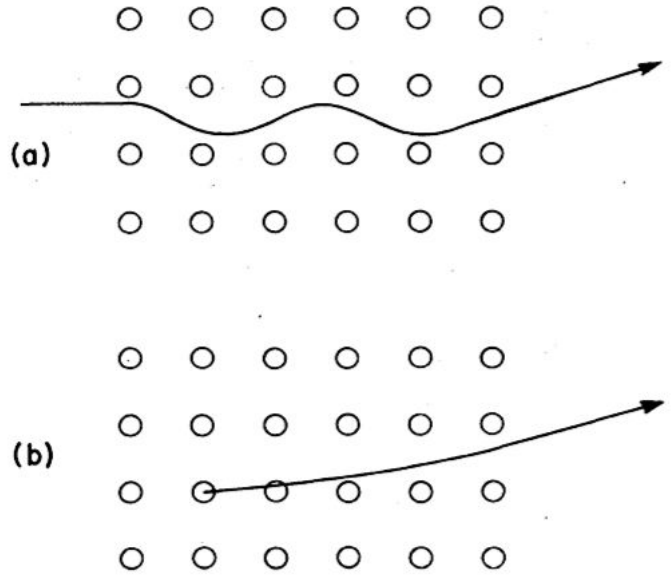


FIG. 1. Schematic illustration of (a) channeling and (b) blocking effects. The drawings are highly exaggerated. In reality, the oscillations of channeled trajectories occur with wavelengths typically several hundreds or thousands of lattice spacings.

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

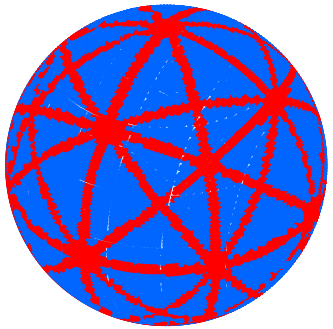
Channeling in DM detectors (Bozorgnia, Gelmini, Gondolo 2010)

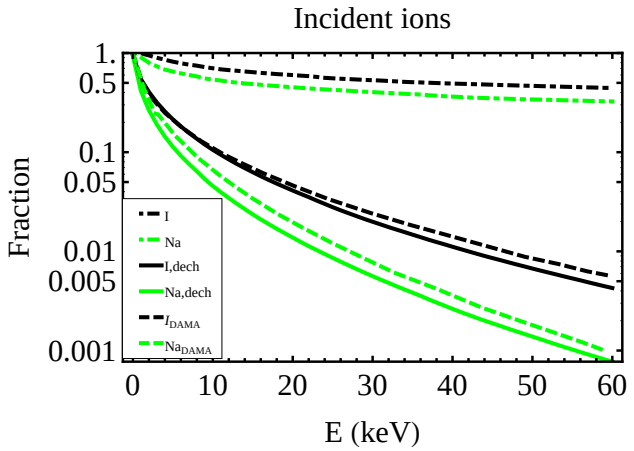
The DAMA channeling fractions can be reproduced with analytic methods (Lindhard et al. 60's). Calculated as if ions start from the middle of the channel

Prob. $\chi_{\rm channel} = 1$ for $\psi < \psi_c^{\rm channel}$

Zero otherwise

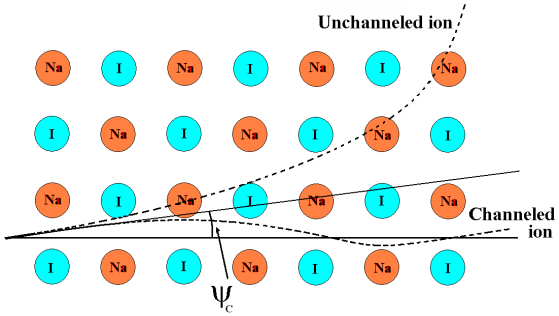
$$P_{\rm geometric}(E_R) = \frac{1}{4\pi}\int \chi(E_R, \hat{\mathbf{q}}) d\Omega_q$$



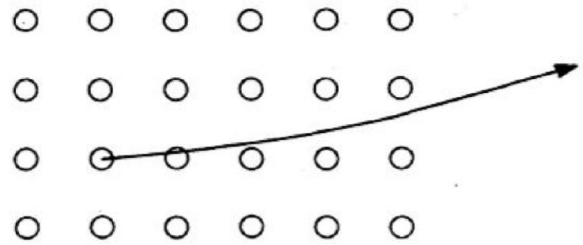


But recoiling ions are ejected from lattice sites! Blocking is important

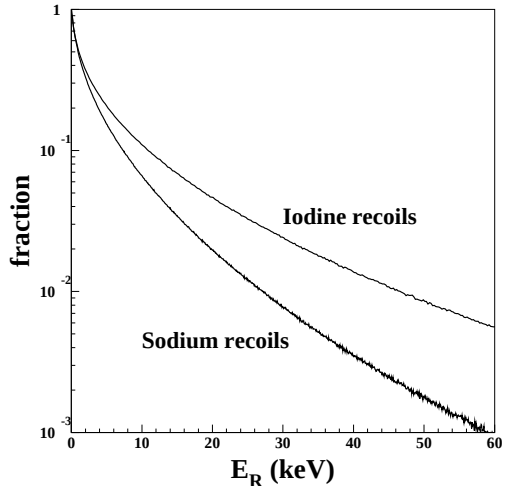
Channeling is much less than in the DAMA estimates



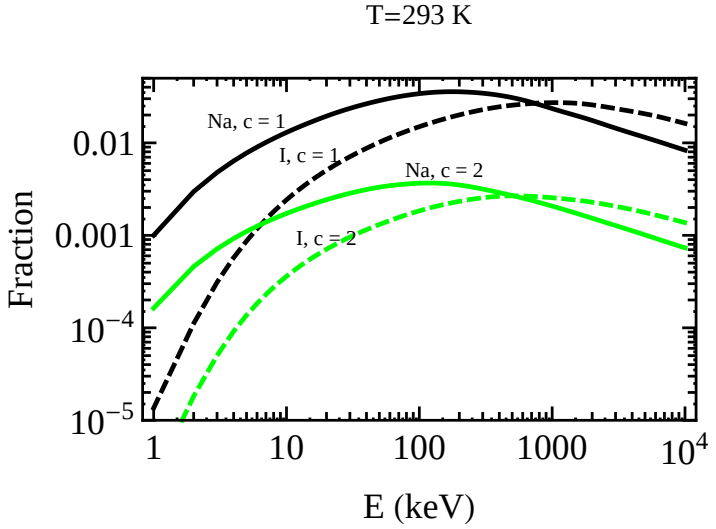
Bernabei et al Eur.Phys.J.C53 2008



Bozorgnia, Gelmini, Gondolo, JCAP1011 2010



40% at 2 keV

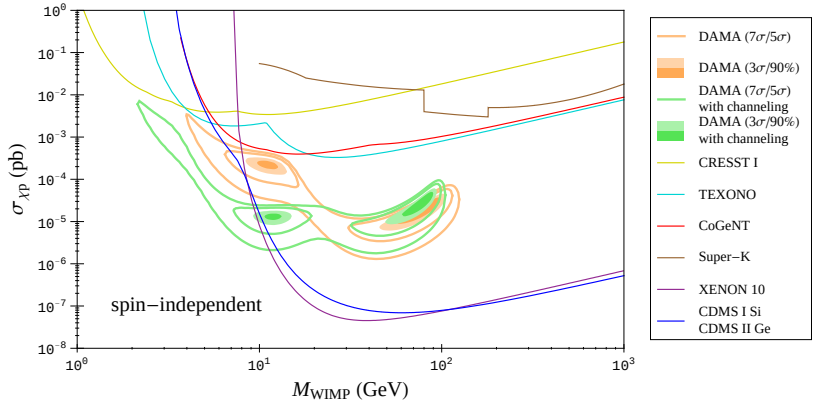


0.4% at 2 keV

DAMA/LIBRA WIMP region does not change with channeling

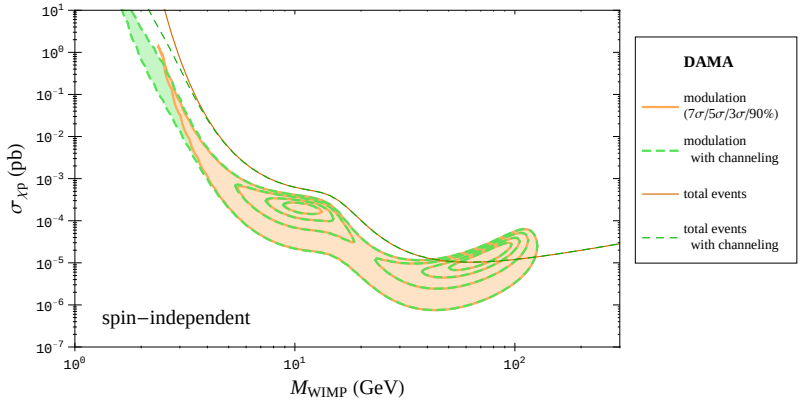
With the DAMA fractions

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



and ours (difference at 7σ)

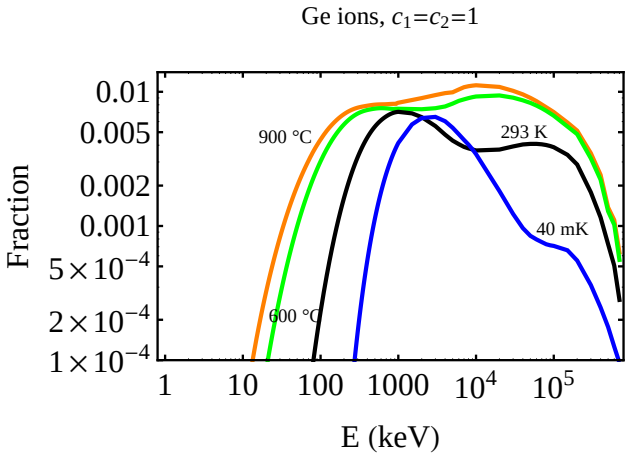
Savage, Gelmini, Gondolo Freese, PRD83, 055002 (2011)

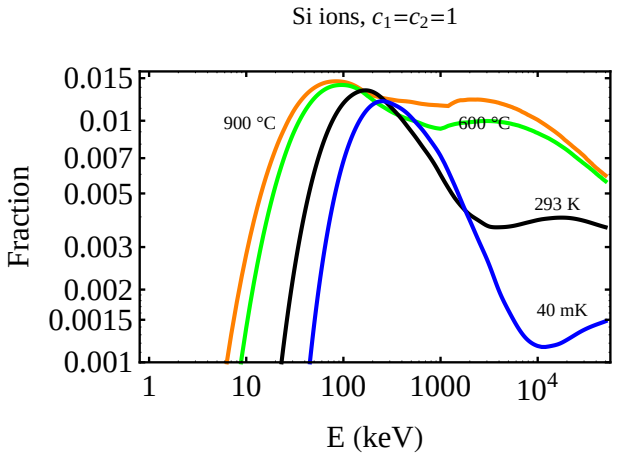


Higher region due to Na - Lower due to I rejected by at least 2 orders of magnitude

Channeling probability of ions ejected from lattice sites: Si, Ge

These are upper bounds (Bozorgnia, Gelmini, Gondolo, JCAP **1011**, 019 (2010))





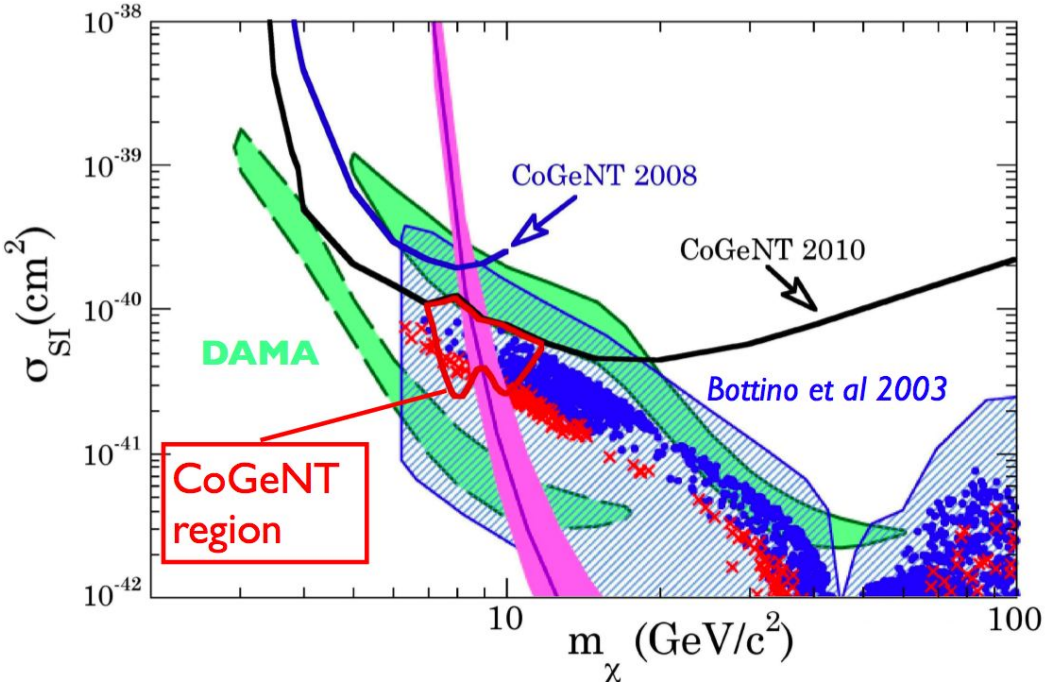
We computed channeling fractions for NaI, Si, Ge, CsI and solid Xe, Ar and Ne and they are all very small, a few percent at most

(Farina et al. arXiv1107.0715 considered 10%, 20% channeling fractions in Ge and NaI!)

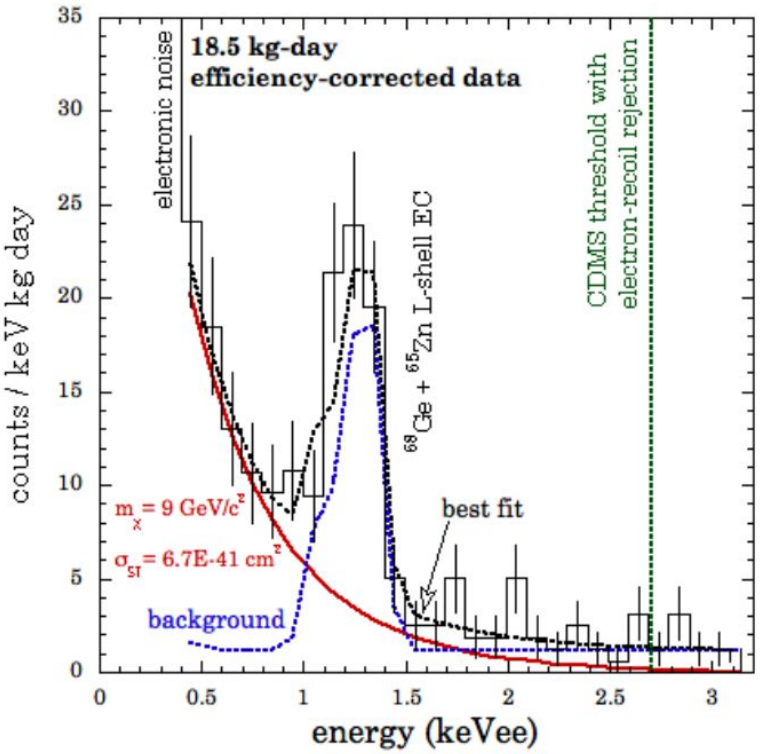
CoGeNT "irreducible excess"

CoGeNT is a 440g Ge detector in the Soudan Mine with extremely low threshold, 0.4 keVee. With 56 days of data, announced an excess of irreducible background "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

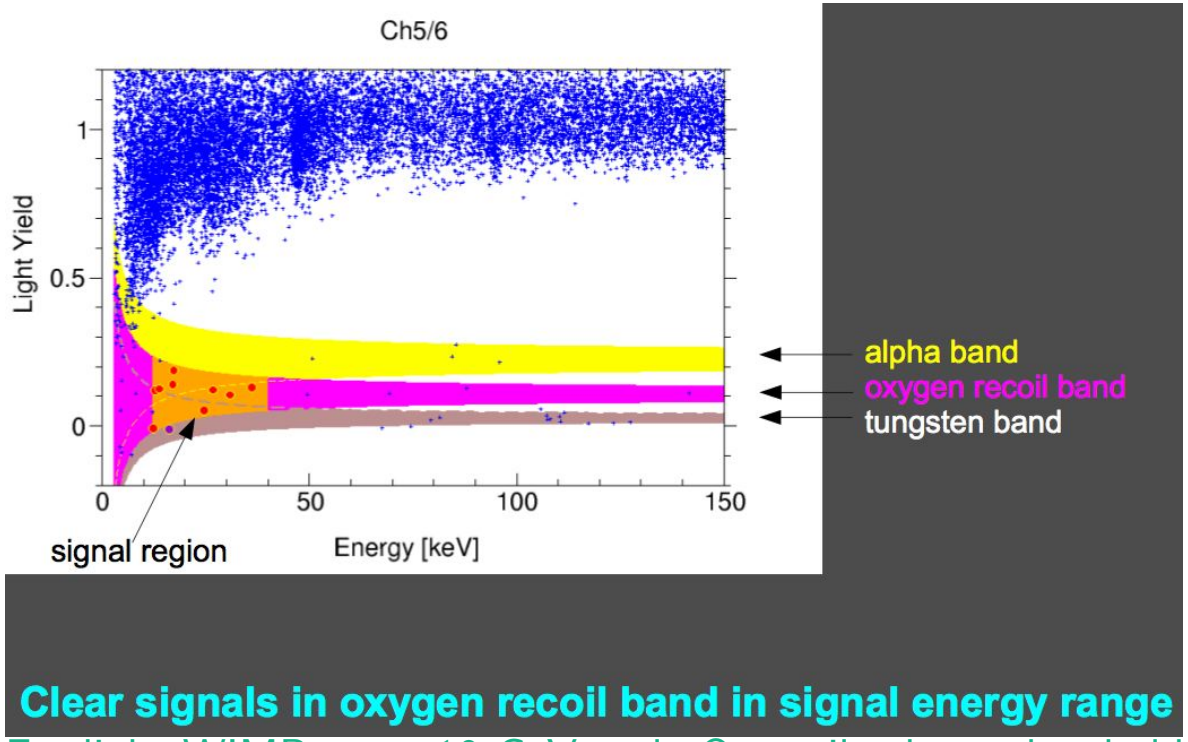


(Juan Collar DM-Marina del Rey, 2010):

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 302 citations so far)

CRESST II irreducible excess with 564 kgd $CaWO_4$ Feb 2010 Preliminary results,W.Seidel in WONDER, LNGS; Nov. F.Probst in Princeton

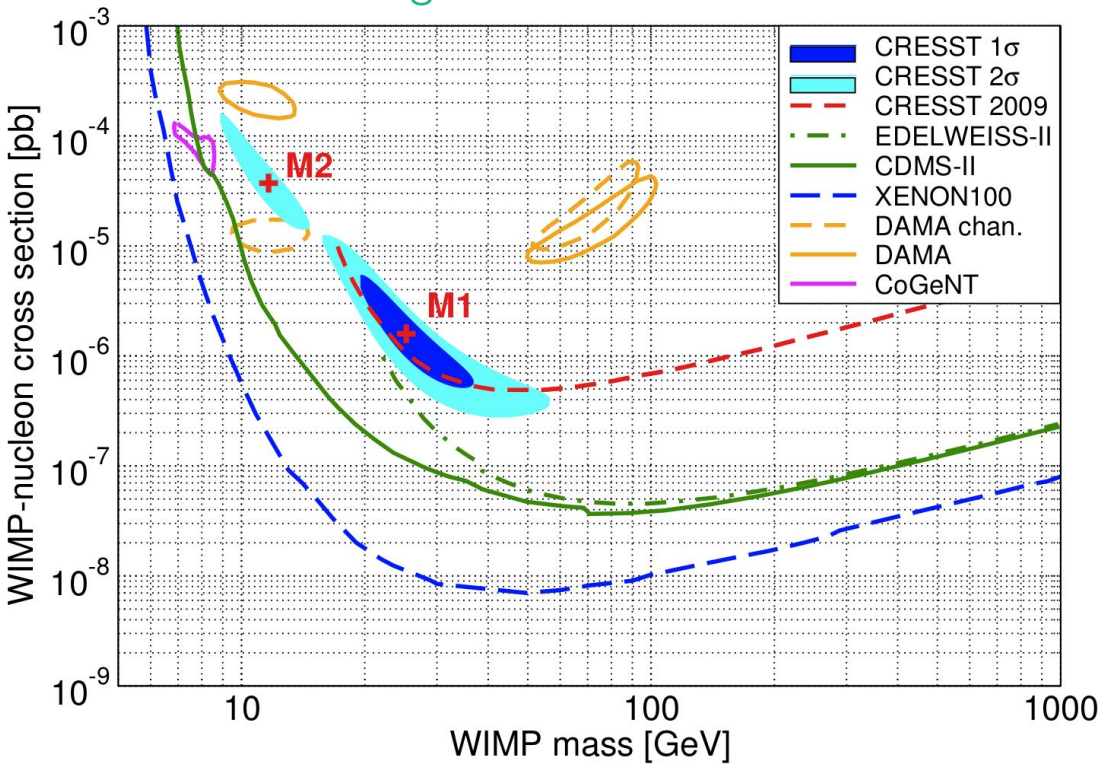


Excess of events in O band: point towards Light WIMPs!

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

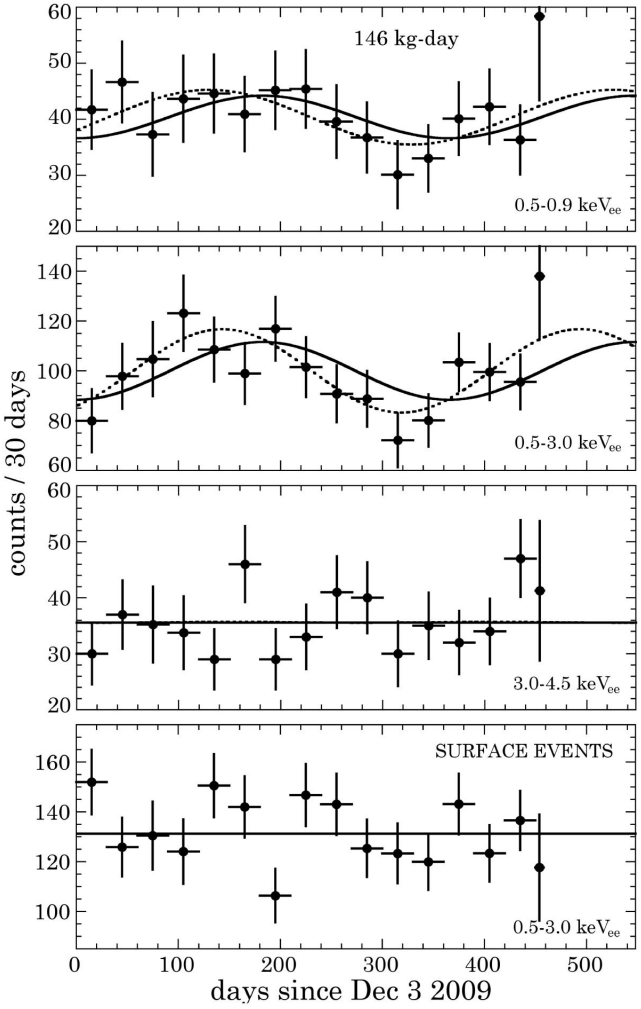
CRESST II irreducible background

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



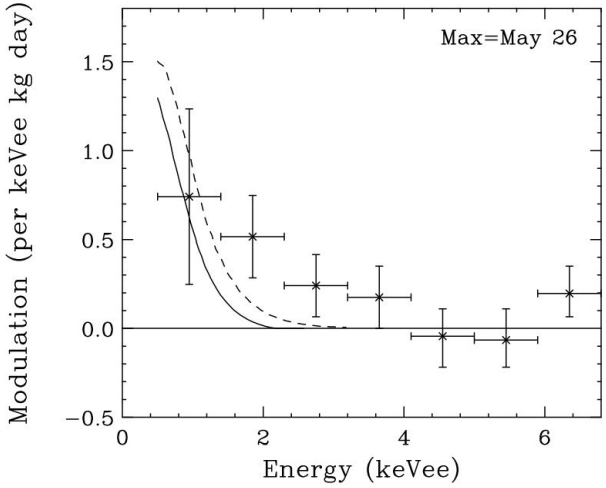
Regions disjoint? XENON and CDMS bounds reject all regions? There are uncertainties.....

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" have a 16.6±3.8 % annual modulation peaking at April 18 ±16 d, a phase compatible with DAMA's (5/16±7d 2-4keVee, 5/26 ±7d 2-6 keVee)

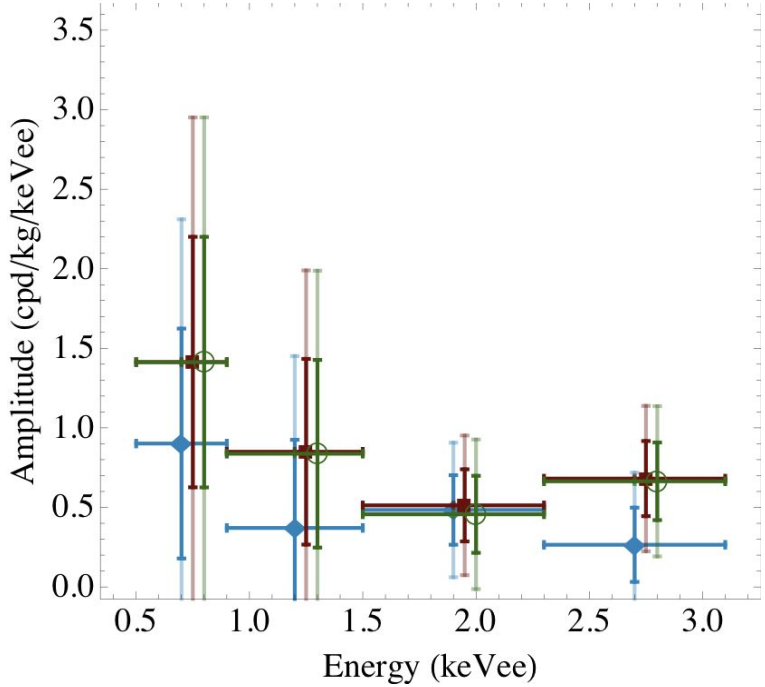


Kelso,Hooper; 1106.1066 [hep-ph]

CoGeNT annual modulation

Has been extensively studied in many papers-

Exemplary: the CoGeNT collaboration released all their time-tagged raw data



Fox, Kopp, Lisanti, Weiner, arXiv:1107.0717

These bins: below radioactive peaks, in the subtracted peaks region, and two above-

Modulation non-zero and with larger significance above the radioactive peaks regions, not where the exponential rate is (1st bin).

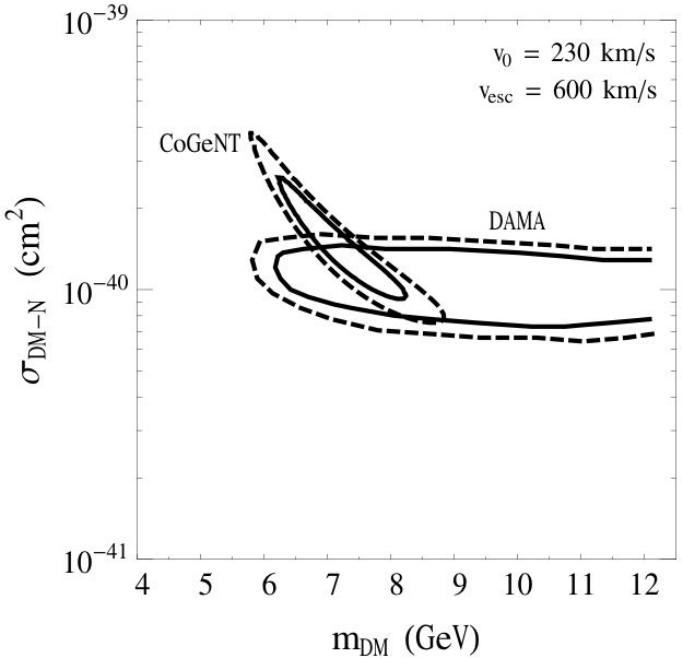
Goes to zero at still larger energies.

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

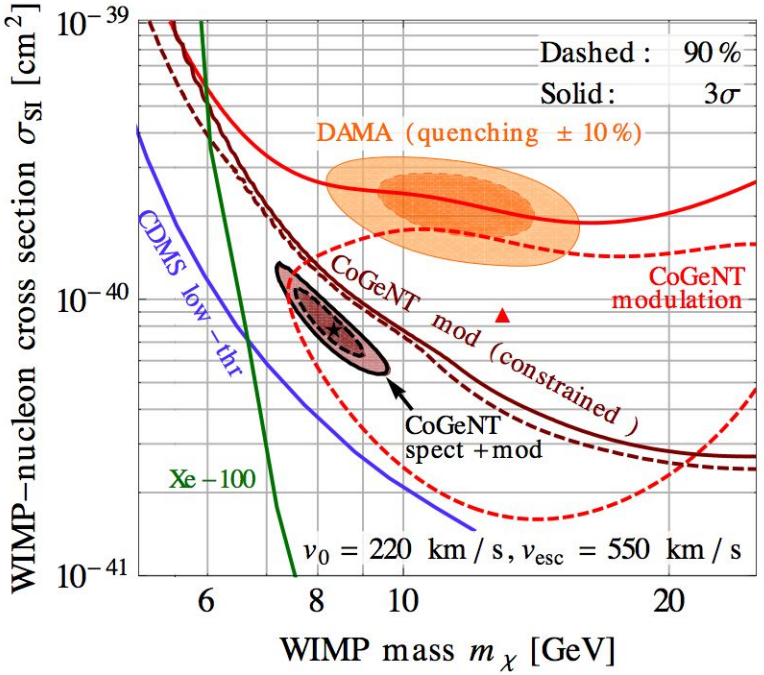
Compatible if Q_{Na}= 0.40 - 0.45



Fox, Kopp, Lisanti, Weiner, arXiv:1107.0717

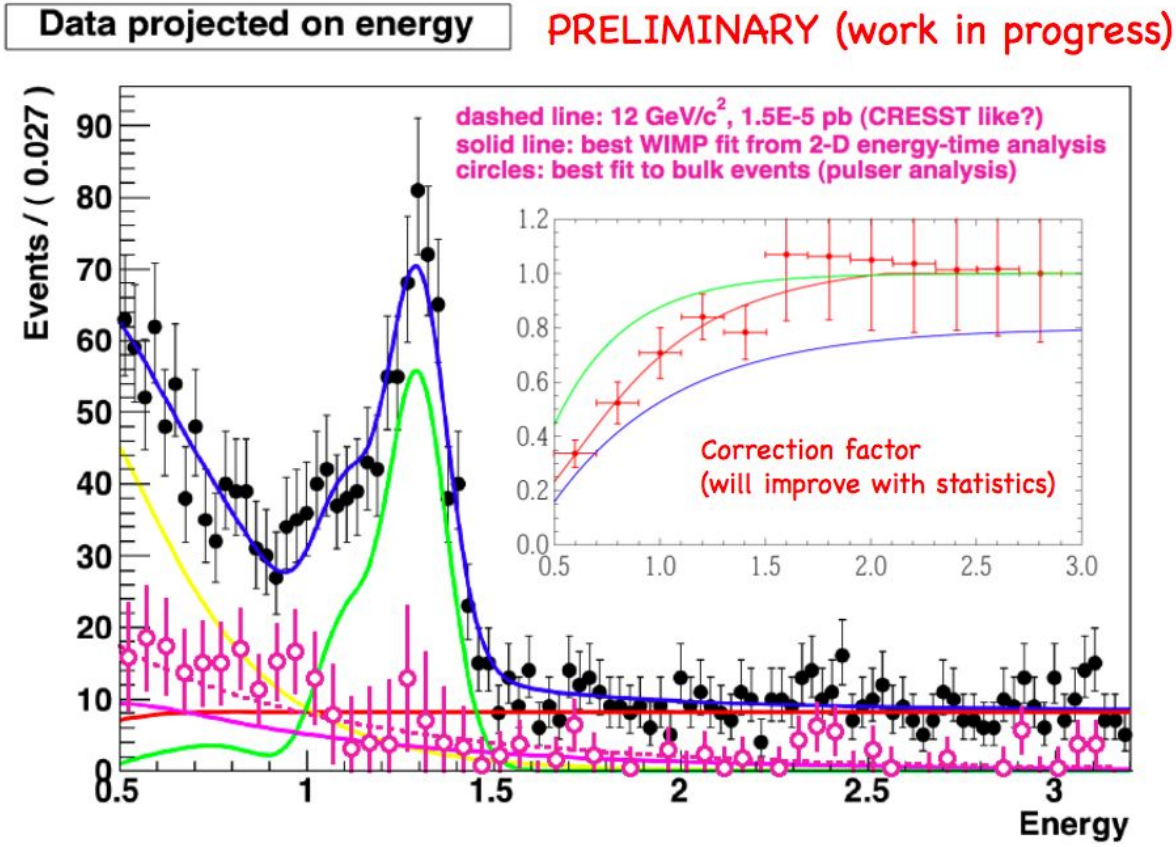
not otherwise,

and XENON and CDMS bounds?



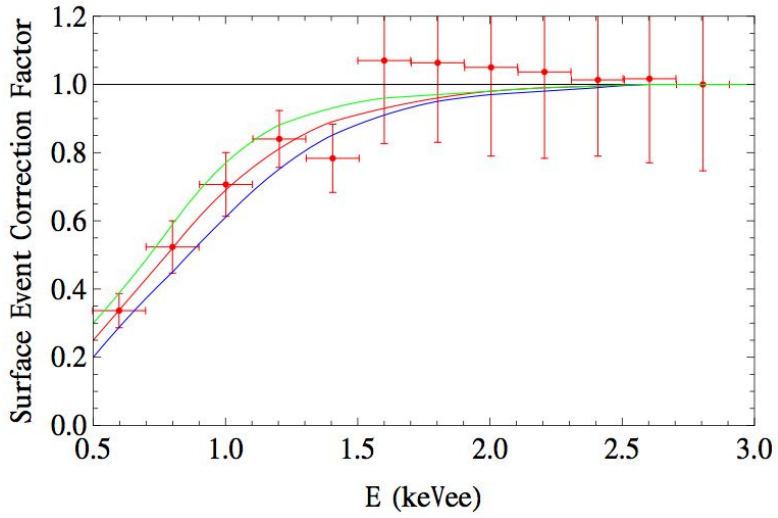
THESE FITS ARE ALREADY OBSOLETE, because...

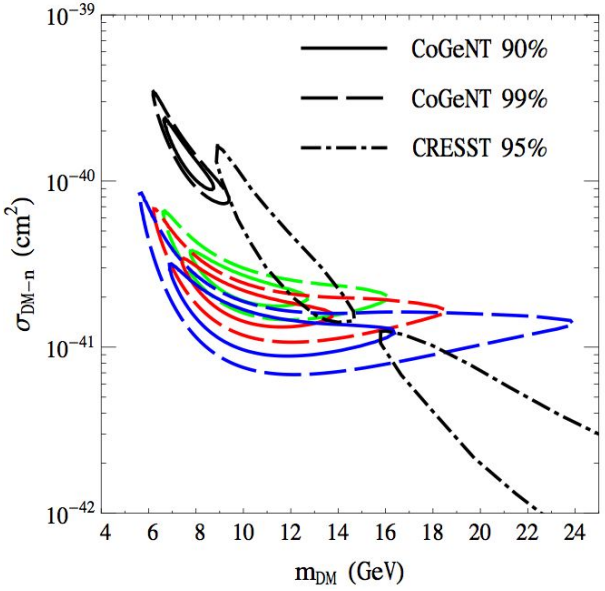
CoGeNT background revised Collar talk at TAUP 2011-Sept. 2011



Revised CoGeNT rate Kelso, Hooper, Buckley, 1110.5338

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





Is the background annually modulated?

If not, is the modulation amplitude too large for the rate?

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? Xe heavier, thus only sensitive to high v WIMP tail, which may be missing- 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

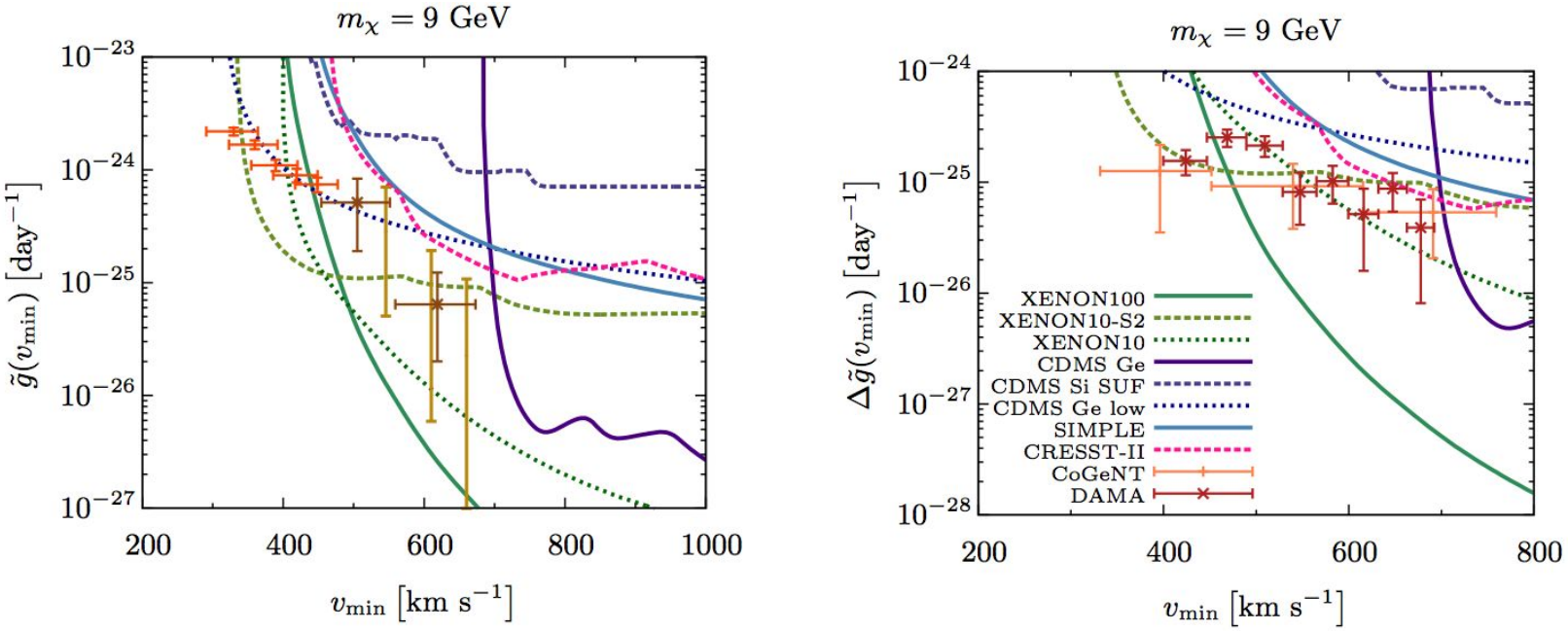
- Other? inelastic DM, p or v-dependent DM form factor, spin dependent...

Light WIMPs "halo independent analysis"

Fox, Liu, Weiner 1011.1915; Frandsen et al 1111.0292

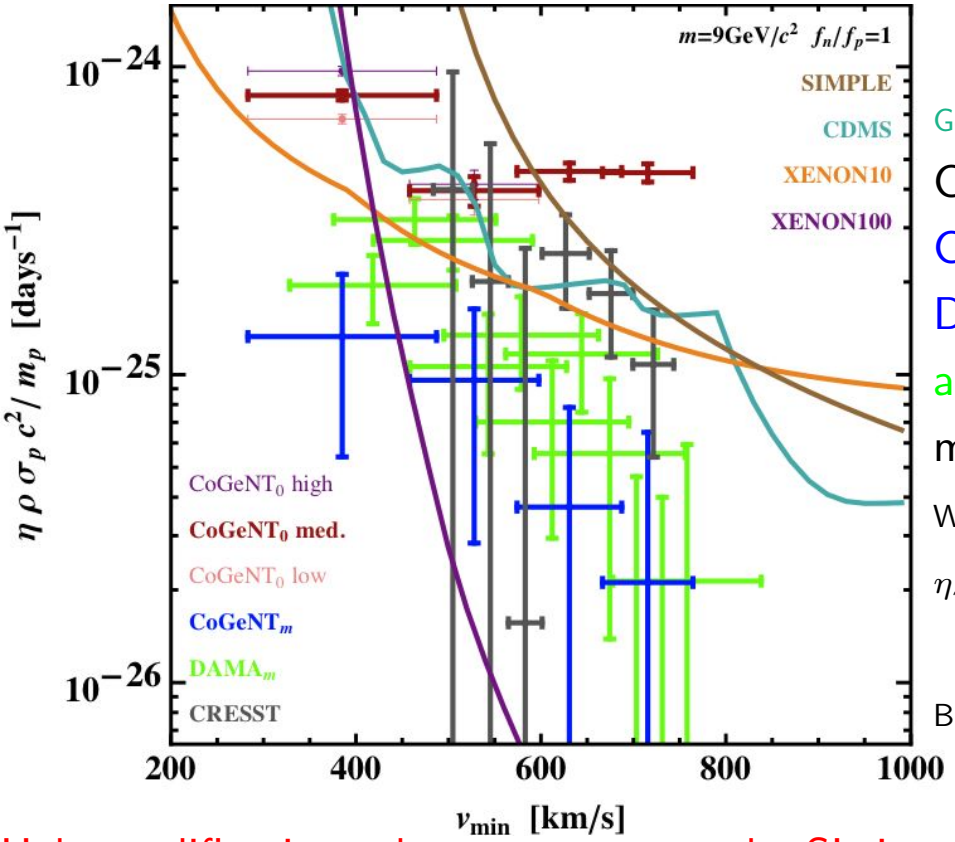
$\rho\eta(v_{\rm min})$ should be the same for all experiments !

Here $\bar{g}(v_{\rm min}) = \rho\eta(v_{\rm min})\sigma_p/m$, $\Delta\bar{g}(v_{\rm min})$ =annual mod. amp. of $\bar{g}$ Frandsen et al 1111.0292



Halo modifications alone cannot save the signal regions from Xe bounds (here variations of Q, L_{eff} and reduced CoGeNT rate not considered- CRESST oversimplified).

Revised CoGeNT rate-"halo independent comparison"



Gondolo Gelmini in preparation

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 $\eta_i 0$, $\eta_i m$

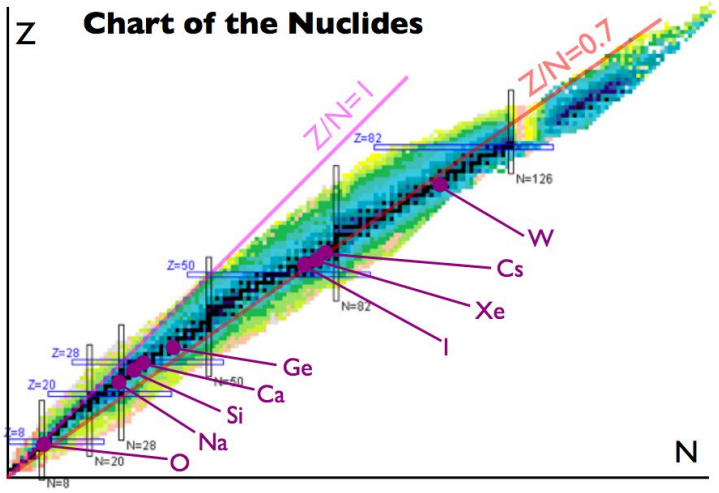
$$\eta_i = \eta_i 0 + \eta_i m \cos(\omega t - t_0)$$

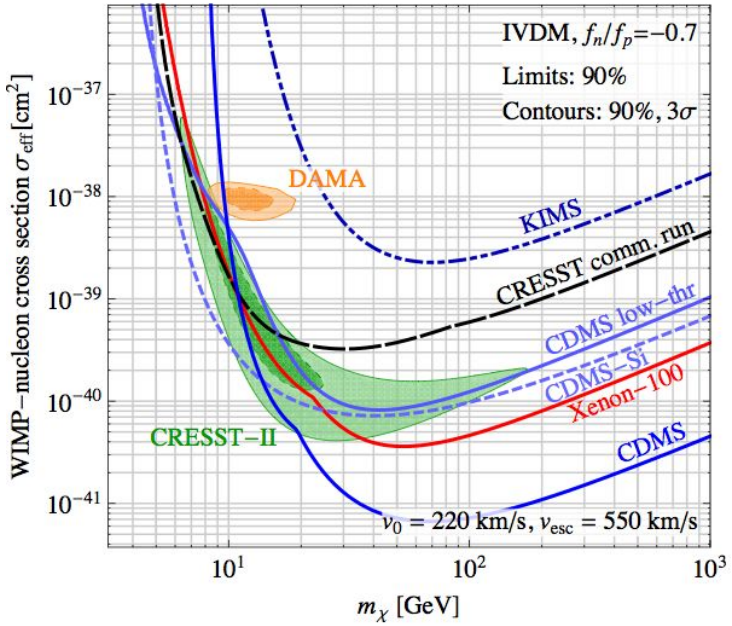
Bins extended by E-resolution ΔE on both sides

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



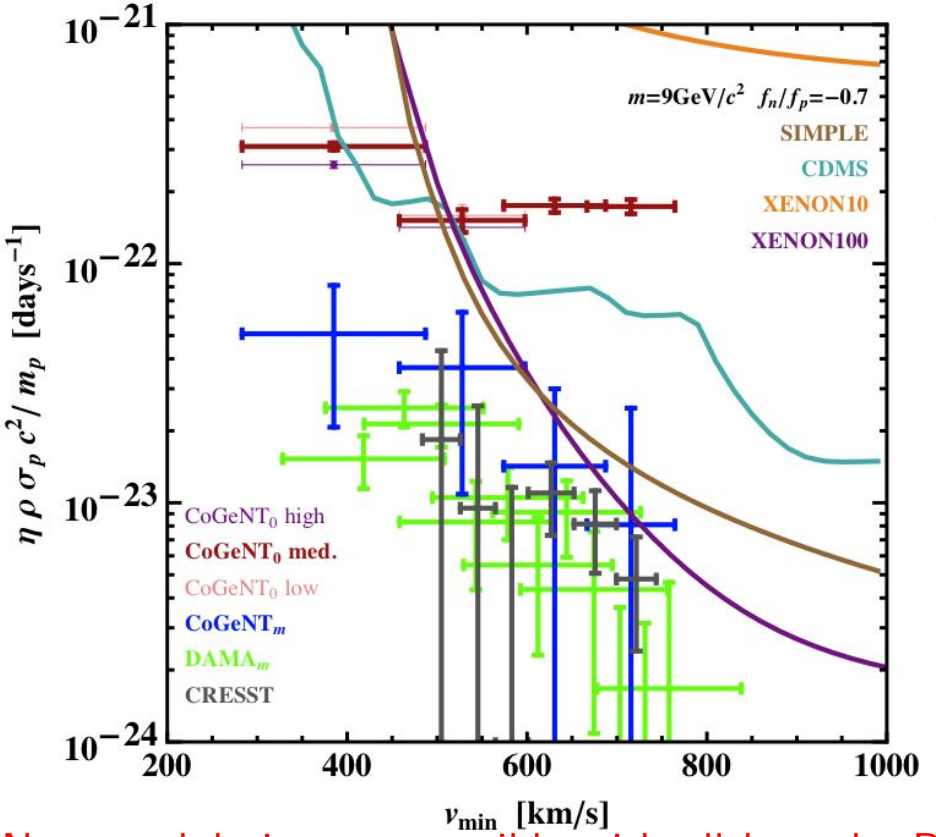


Kopp, Schwetz, Zupan 1110.2721

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

IV light WIMPs "halo independent analysis"

Gondolo Gelmini 2012



Gondolo Gelmini in preparation

CoGeNT rates and CRESST rate

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

and DAMA modulation

mapped into v_{min}-space

Now modulations compatible with all bounds- Problem: CoGeNT rate could be lowered- but t modulation too high; CRESST unmodulated is on top of CoGeNT modulation!

Other possibilities for Light WIMPs?

do not lead to compatibility, unless combined with Isospin Violation

Spin Dependent Interactions see e.g. Schwetz and Zupan 1106.6241

For SD,coupling with nucleus is mainly with an unpaired nucleon: in DAMA (Na and I) is a p (rejected by Fluorine-COUPP, PICASSO , SIMPLE) but in CoGeNT (Ge) is n (as in Xe too). CDMS+CoGeNT required couplings n/p = 7 (rejected by CDMS and Xe100.

Inelasticity see e.g. Schwetz and Zupan 1106.6241, Farina et al. 1107.0715

$\delta = M'_{DM} - M_{DM}$ can be >0 (iDM), favors heavy targets,

Tucker-Smith, Weiner 01 and 04; Chang, Kribs, Tucker-Smith, Weiner 08.....

or <0 exoDM, favors lighter target Esig et al. 1004.0937

neither leads to compatibility of all results.

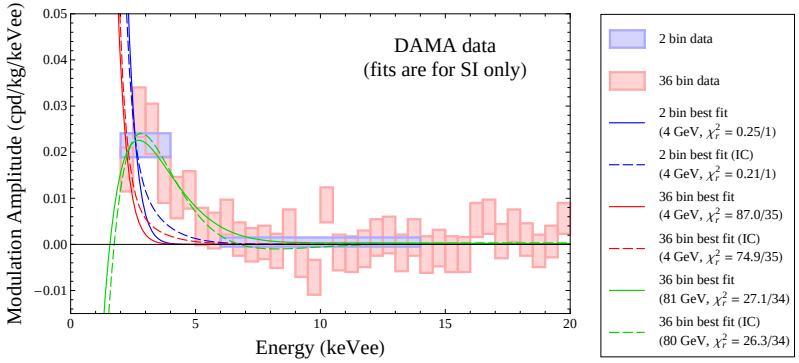
Cross sections with other q and v dependence and DM form factors several q and v dependences have been studied and some are promising

We may not have found the right model yet....

Light WIMPs Outlook

At this point there is a big confusion.... many possibilities changing all the time. 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 the results will be very important for light WIMPs the modulation below 2 keVee will favor light or heavy WIMPs



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

Light WIMPs Outlook

There have been many objections to the DAMA result over the years (now extended to CoGeNT too) none of them conclusive, but if the DAMA modulation is due to DM, a DM signal must be found by another experiment. May be CoGeNT and/or CRESST II!

In the near future: CRESST II and CoGeNT will eventually understand better their background and annual modulation.

In the longer run: XENON-1Ton, LUX, 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!

Light WIMPs or Backgrounds?

There have been many objections to the DAMA result over the years, none conclusive... now extended to CoGeNT too... Most frequent,
could they be observing annually modulated backgrounds?

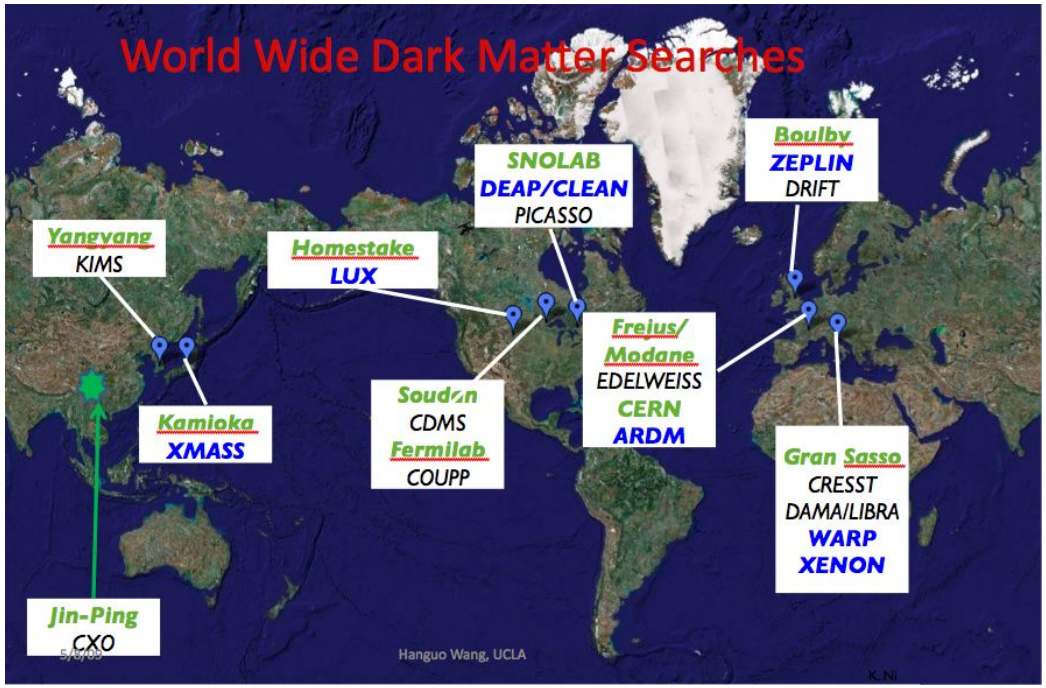
- O(10 MeV) ambient neutrons at the LNGS or Soudan Mine (via scattering or neutron capture and activation- Auger electrons) J. P. Ralston arXiv1006.5255

- $>$TeV cosmic ray μ's which reach the LNGS or Soudan Mine underground facility and
  -either produce secondary neutrons via spallation in the detector or surrounding rock J. P Ralston arXiv1006.5255, K. Blum arXiv1110.0857
  -or deposit their energy directly into the detector D, Nygren arXiv1102.0815 (2011)

- - correlation does not mean causation DAMA refuted each claim...technical issue...
  -is the temporal correlation strong enough? theoretical issue... Recently addressed question: Can including the stochastic nature of muon induced neutron production and interaction lead to agreement in phase with DAMA and CoGeNT modulation?
  K. Blum 1110.0857: YES, S. Chang, J. Pradler and I. Yavin arXiv:1111.4222: No

Light WIMPs or Backgrounds?

A definitive way to eliminate the doubt that the annual modulation in a direct DM detector is due to seasonal backgrounds: make the experiments in the Southern Hemisphere. Problem is, all underground laboratories are in the North



"DM-ICE" in the South Pole Proposal to deploy NaI crystals 2 km under-ice and use IceCube as a cosmic-ray veto. 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; so far "DM-ICE17" (17 kg NaI) already deployed two crystals (final aim to get to 250 kg NaI) (Cherwinka et al 1106.1156)

However given the choice where would you rather work, Antarctica or the wine country of Argentina and Chile?

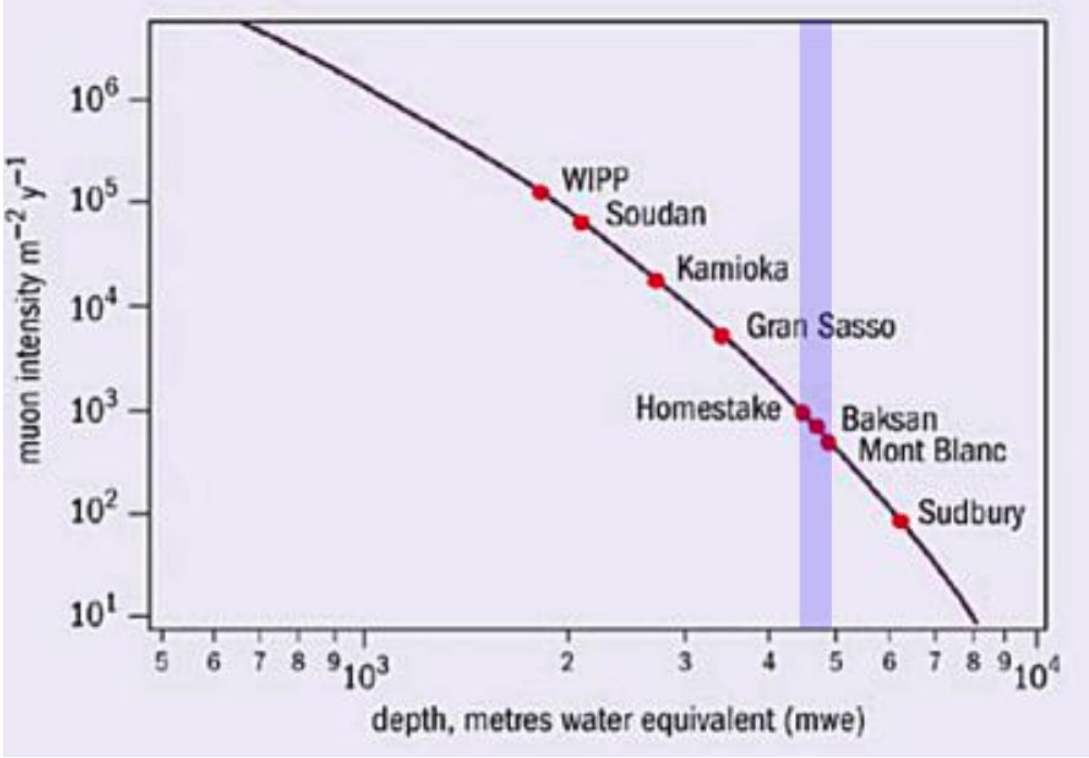
Opportunity to build ANDES at the Agua Negra Tunnel

ANDES Laboratory concept

ANDES, an underground laboratory in the Agua Negra tunnel

- 2 tunnels, 12 m diameter, separated 60 m, 14 km long
- Argentinian side at about 400 km N of Pierre Auger
- Entry in Argentina (close to the city of San Juan) at altitude 4085m, in Chile at 3600 m (close to La Serena)
- Cavities at $\simeq$ 3700m altitude
- Deepest point from surface at $\simeq$4800 mwe
- Rock: andesite, basalt, rhyolite; density $\simeq$ 2.7 g/cm^3
- Low radioactivity: 10^{-5} neutrons/kg s (Gran Sasso-10^{-4}, Modane 10^{-5}); 1.08 $\times 10^{-5}$ μ's/ m^2 sec; T$\simeq$ 30-40^o C

ANDES, an underground laboratory in the Agua Negra tunnel



More information: http://andeslab.org/
or talk: www.fis.utfsm.cl/HEP-2012/martes/Dib.pptx
or contact: osvaldo.civitarese@fisica.unlp.edu.ar