# Halo Independent Analysis of direct DM detection data

**(and remark on present annihilation rate of asymmetric DM)**

Graciela Gelmini - UCLA

Light WIMPs Conference - Ann Arbor-April 15 to 18, 2013

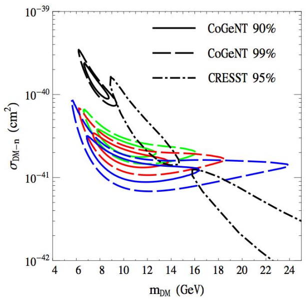
**WIMP DM searches:** Complementary to the LHC and to each other!

Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way.

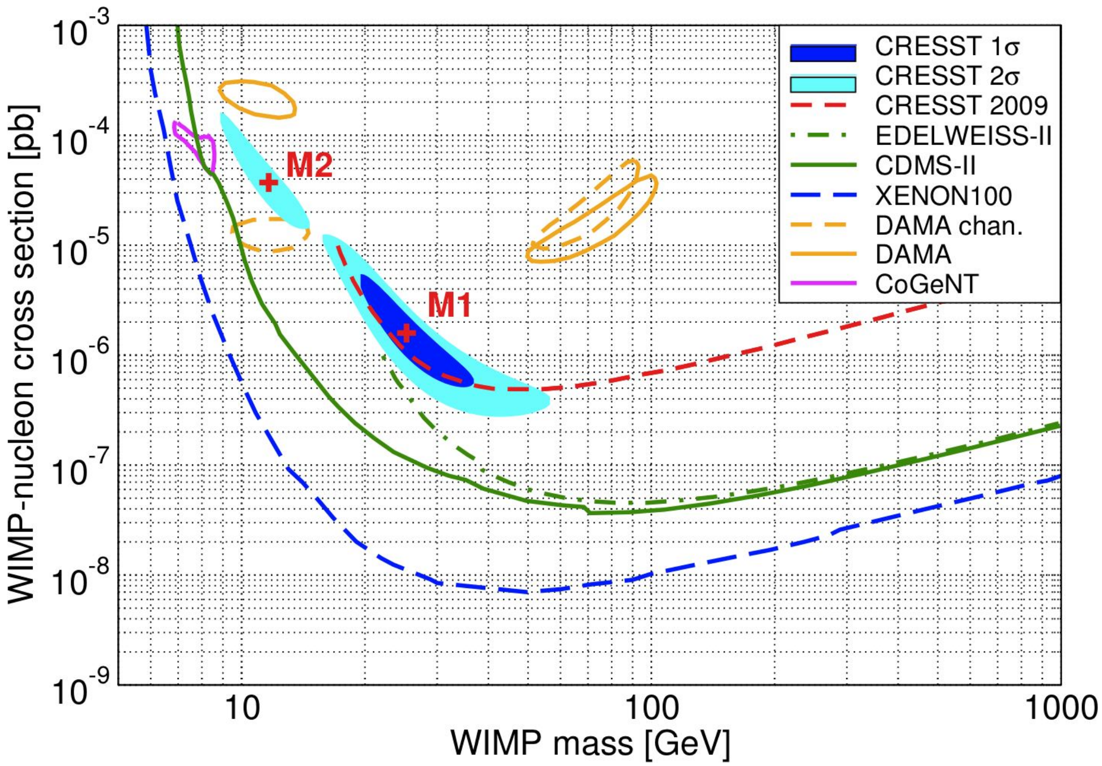
DAMA (NaI), CoGeNT (Ge), CRESST II ($CaWO_4$) AND NOW CDMS (Si)!
have potential detection claims....
point to WIMPs with m$< 10$ GeV. Are they DM signals or backgrounds?

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?




Kelso, Hooper, Buckley, 1110.5338

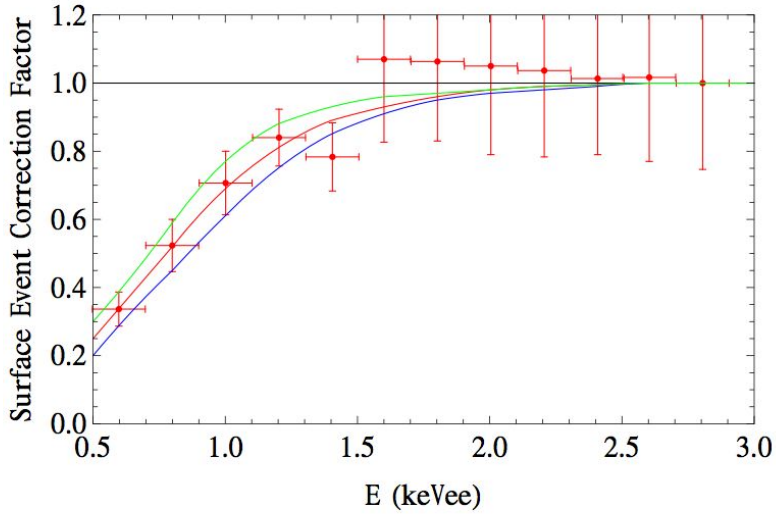


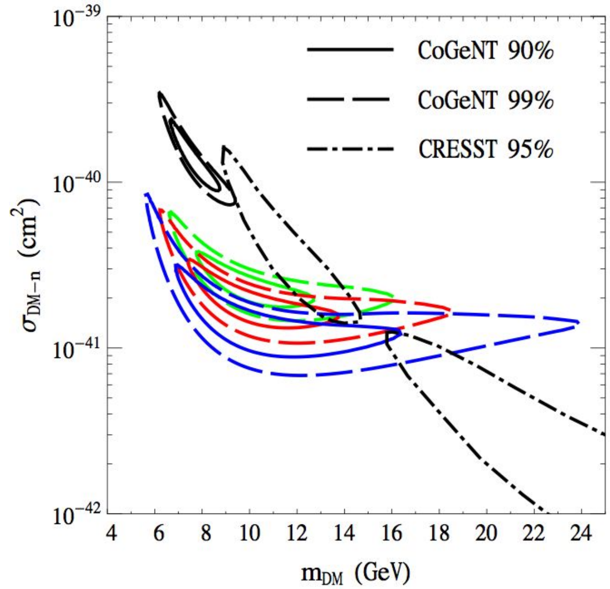

(figures from Kelso, Hooper, Buckley 1110.5338 and CREST II, Angloher et al. 1109.0702)

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

# Revised CoGeNT rate Kelso, Hooper, Buckley, 1110.5338

$\sigma$ is smaller- region more similar to CRESST II, lower than DAMA?

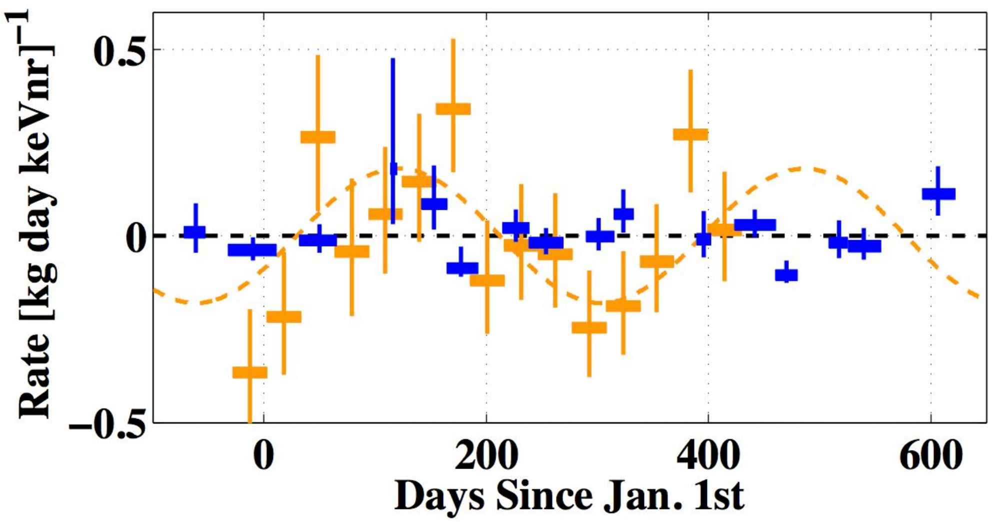



is the modulation amplitude too large for the rate?

# 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.

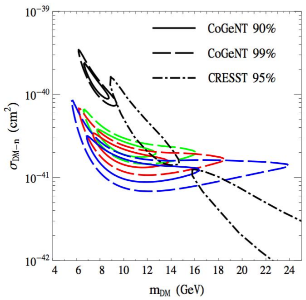



CoGeNT rate (orange)

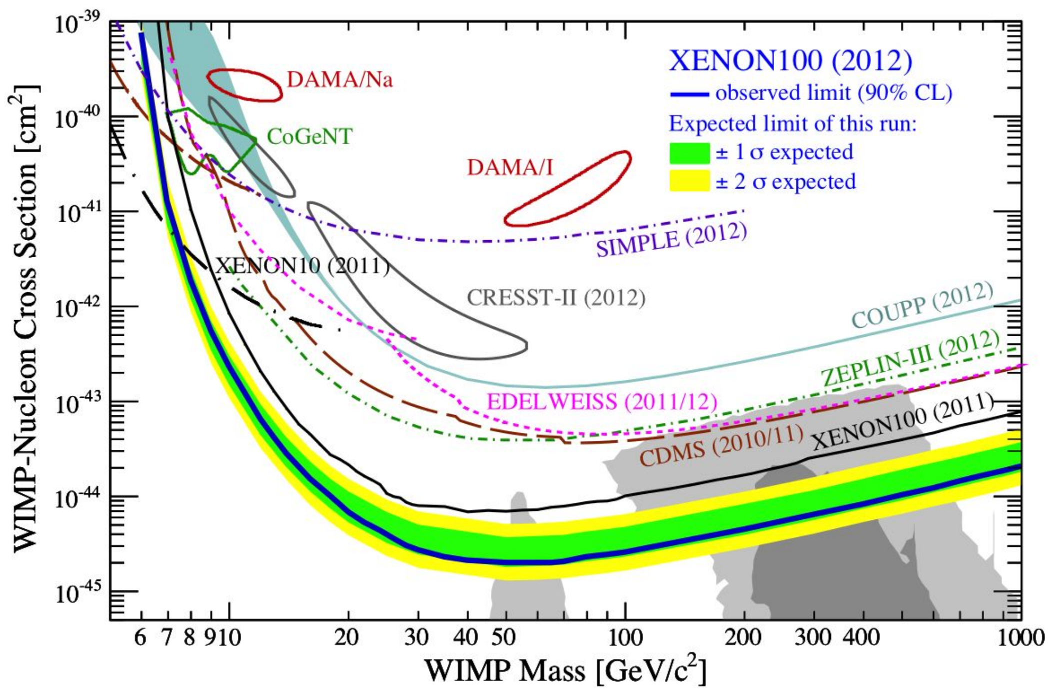
CDMS rate (blue)

CDMS II 1203.1309

# Latest XENON100 bounds July 2012:1207.5988



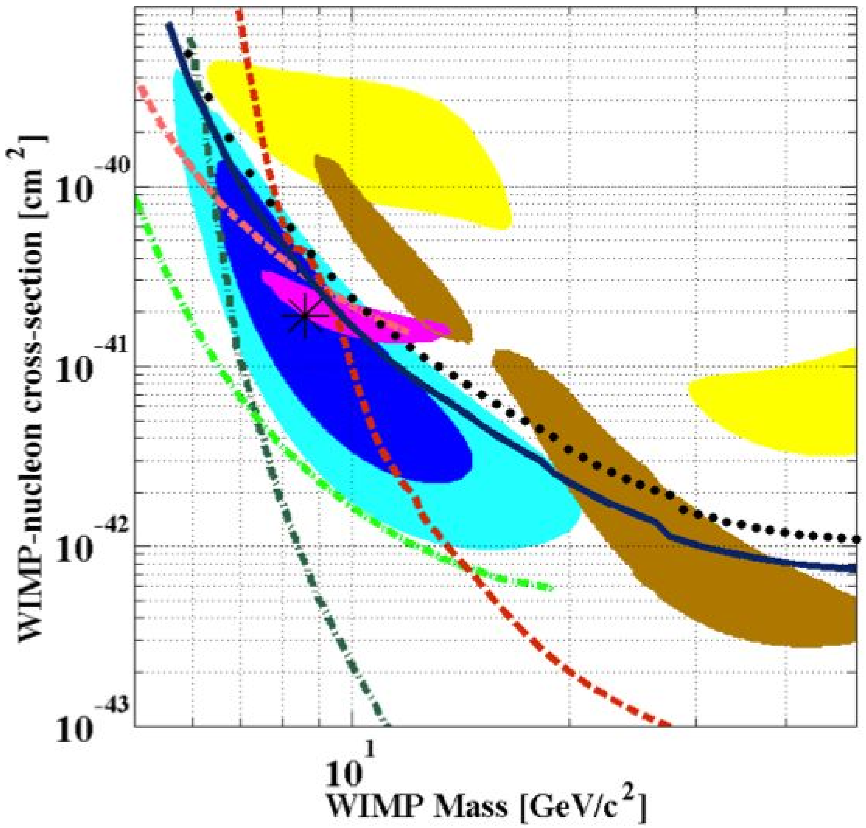

Kelso, Hooper, Buckley, 1110.5338



# New CDMS three events in Si TODAY!

We report results of a search for Weakly Interacting Massive Particles (WIMPs) with the silicon (Si) detectors of the CDMS II experiment. A blind analysis of data from eight Si detectors, with a total raw exposure of 140.2 kg-days, revealed three WIMP-candidate events with a final surface-event background estimate of $0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$. Other known backgrounds from neutrons and $^{206}$Pb are limited to $< 0.13$ and $< 0.08$ events at the 90% confidence level, respectively. These data place a 90% upper confidence limit on the WIMP-nucleon cross section of $2.4 \times 10^{-41}$ cm$^2$ at a WIMP mass of 10 GeV/$c^2$. Simulations indicate a 5.4% probability that a statistical fluctuation of the known backgrounds would produce three or more events in the signal region. A profile likelihood ratio test that includes the measured recoil energies of the three events gives a 0.19% probability for the known-background-only hypothesis when tested against the alternative WIMP+background hypothesis. The highest likelihood was found for a WIMP mass of 8.6 GeV/$c^2$ and WIMP-nucleon cross section of $1.9\times10^{-41}$ cm$^2$.

# New CDMS three events in Si TODAY!

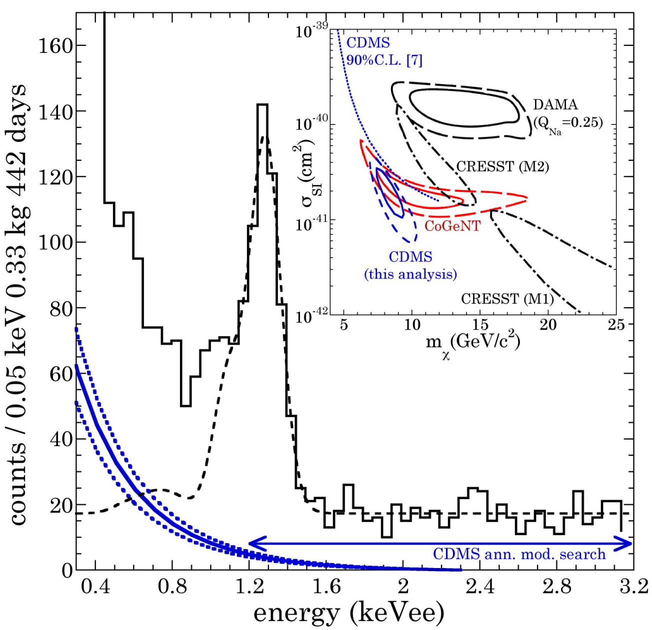



Not yet included in the plots that follow.

Not unlike the region identified by Collar and Fieds in the CDMS Ge data

# 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)

# Uncertainties in regions and bounds

- Signals: Detector response model (e.g. energy resolution, fraction of energy deposited which is detectable) has large uncertainties at low E. (e.g. Collar 1010.5187, 1106.0653)

- Characteristics of the Dark Halo: Xe is heavy, thus only sensitive to high v WIMP tail, which may be missing: make a "halo independent analysis" when possible (Fox, Liu, Weiner 1011.1915; Frandsen et al 1111.0292; Gondolo, Gelmini 1202.6359)

- Type of DM interaction: spin-independent (SI)? spin-dependent (SD)? With different couplings with p and n (i.e isospin violating-IV)? Inelastic (iDM)? Magnetic moment interaction? Milli-charged DM? Elastic or inelastic DM?
  - for Xe and SI interactions $\left[\langle Z + (A - Z)(f_n/f_p)\right] \simeq 0$?
  
  i.e. $f_n/f_p = -0.7$ is such that WIMP-Xe coupling $\sim 0$.

- Backgrounds: some, or part, or all of the possible DM signals may be actually due to backgrounds?

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

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

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

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

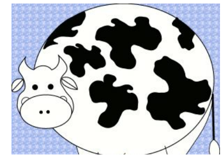
- for spin-independent (SI) $\sigma(q) = \sigma_0 F^2(q)$ where

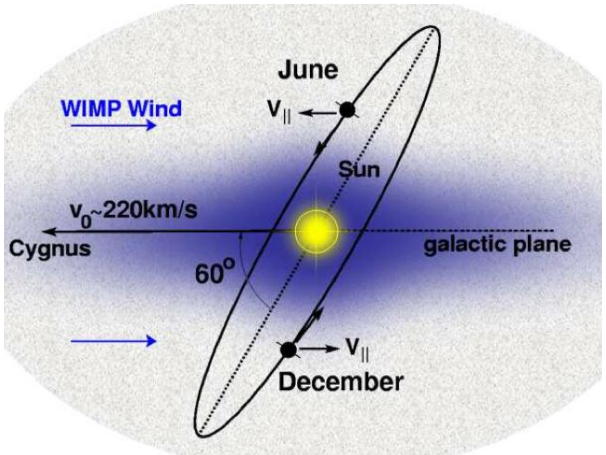
$\sigma_0 = \left[Z + (A-Z)(f_n/f_p)\right]^2 (\mu^2/\mu_{\rm p}^2)\sigma_{\rm p} = A^2(\mu^2/\mu_{\rm p}^2)\sigma_{\rm p}$ for $f_p = f_n$

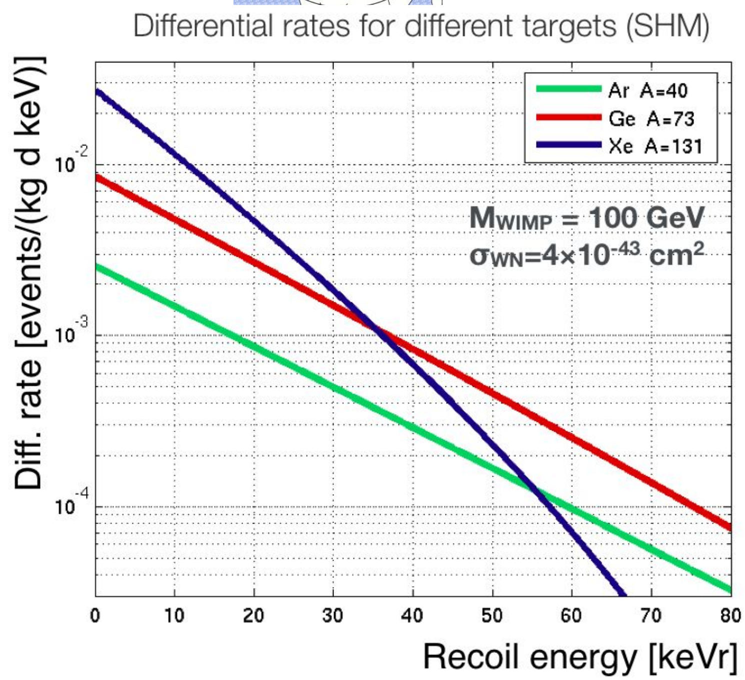
Thus the plots are in the $m, \sigma_{\rm p}$ plane.

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

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

# 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 $\rho$, $\mathbf{v}$, 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...

# Halo independent analysis Fox, Liu, Weiner 1011.1915

Rate in events/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE_R} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE_R} \times nvf(\mathbf{v},t)d^3v$$
$$= \frac{\sigma(q)\rho}{2m\mu^2} \int_{v>v_{\min}} \frac{f(\mathbf{v},t)}{v} d^3v = \frac{\sigma(q)}{2m\mu^2}\ \rho\eta(v_{\min})$$

- $\frac{N_T}{M_T}$ = Avogadro's number per mol = Number of atoms per gram; $\mu = mM/(m+M)$
- WIMP-nucleus differential cross section $d\sigma/dE_R = \sigma(E_R)\ M2\mu^2 v^2$
- For elastic scattering: $v_{\min} = \sqrt{ME/2\mu^2}$ and $E$ is the ion recoil energy.
- $\sigma^{SI}(q) = \left[Z + (A-Z)(f_n/f_p)\right]^2 (\mu^2/\mu_{\rm p}^2)\sigma_{\rm p} F^2(q)$

$\eta(v_{\min}, t) = \eta_0(v_{\min}) + \eta_1(v_{\min}) \cos\omega(t - t_0)$; $\quad R_i(t) = R_{0i} + R_{1i}\cos[\omega(t - t_0)]$

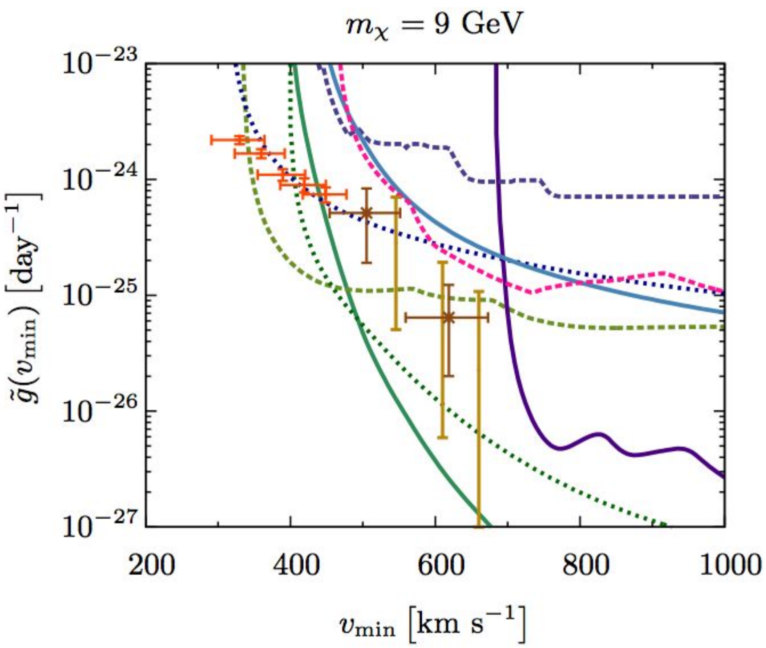
$\tilde{\eta}(v_{\min}) = \sigma_p(\rho/m)\eta(v_{\min})$ factor common to all direct detection experiments- data at energy $E$ can be mapped into $v_{min}$-$\tilde{\eta}$ space at $v_{\min}(E)$ for fixed WIMP mass $m$.

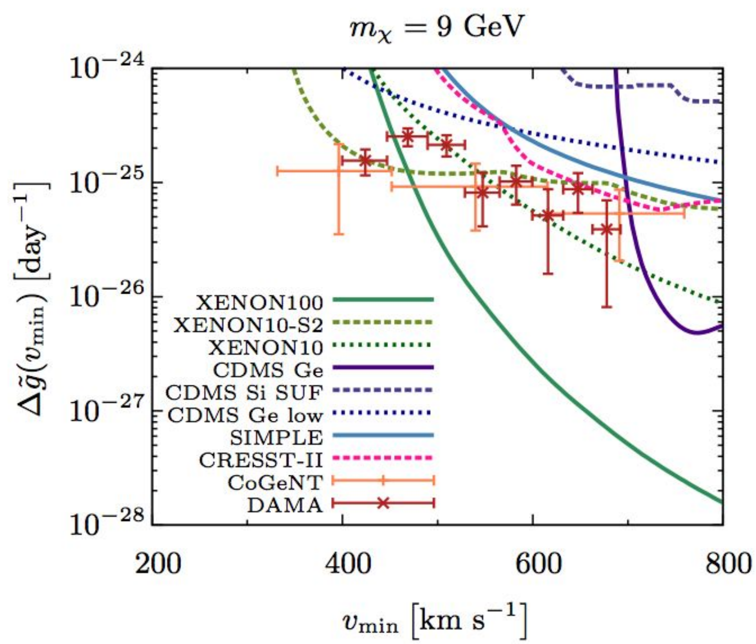
# Light WIMPs "halo independent analysis"

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



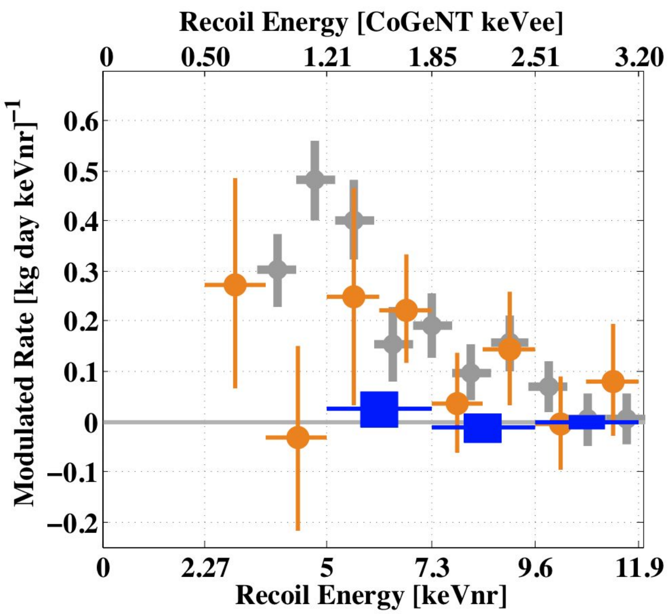




Halo modifications alone cannot save the signal regions from Xe bounds (here variations of $Q$, $L_{eff}$ and reduced CoGeNT rate not considered- CRESST oversimplified).

Method of Fox, Liu, Weiner used by CDMS in its modulation bound paper.

# 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:




Modulation amplitudes for $m = 10$ GeV

(energy resolutions not taken into account)

CoGeNT

DAMA $(Q = 0.3)$

CDMS-modulation

Difficult to take into account efficiencies and energy resolutions with the original method

# Halo Independent analysis

Fox, Liu, Weiner 1011.1915 and Frandsen et al 1111.0292 took efficiencies and form factors constant, either over the bin when integrating rates over bins, or at energies which minimize/maximize the ratio total rates to be compared for a putative signal or a constraint- $\epsilon(E_R)$ an an energy-dependent efficiency. $\bar{E}_2 = \bar{E}_1 \mu_2^2 M_T^{(1)} / \mu_1^2 M_T^{(2)}$

$$R = \left( \frac{2 N_A \rho \, \sigma_p m_p}{m_\chi \, \mu_{n\chi}^2 \, f_p^2} \right) \left( \frac{\mu^2 C_T}{M_T} \right) \int_{v_{low}}^{v_{high}} dv \, \epsilon(E_R) F^2(E_R(v)) v g(v)$$

$$R_2 \leq \frac{\epsilon_2(\bar{E}_2) F_2^2(\bar{E}_2)}{\epsilon_1(\bar{E}_1) F_1^2(\bar{E}_1)} \frac{C_T^{(2)}}{C_T^{(1)}} \frac{M_T^{(1)}}{M_T^{(2)}} \frac{\mu_2^2}{\mu_1^2} R_1$$

This forced Frandsen et al to consider small enough bins (particularly limiting for CRESST-II data due to the onset of detector module thresholds).

Gondolo-Gelmini 1202.6359 extended the method of Fox, Liu, and Weiner to include energy resolution and efficiency with arbitrary energy dependence, making it more suitable for experiments to use in presenting their results.

# Halo Independent analysis Gondolo-Gelmini 1202.6359

Start with the differential rate

$$\frac{dR}{dE'} = \epsilon(E') \int_0^\infty dE_R \sum_{A,Z} C_{A,Z}\, G_{A,Z}(E_R, E')\, \frac{dR_{A,Z}}{dE_R}$$

- $C_{A,Z}$: mass fraction in nuclide $A$, $Z$; $E'$: detected energy
- $\epsilon(E')$: counting efficiency or cut acceptance
- $G_{A,Z}(E_R, E')$: energy response function (includes the energy resolution $\sigma_E(E')$ and the mean value $\langle E' \rangle = E\, Q_{A,Z}(E_R)$)

$$\frac{dR_{A,Z}}{dE_R} = \frac{\sigma_{A,Z}(E)}{2m\mu^2_{A,Z}}\, \rho\, \eta(v_{\rm min}, t) \sim \tilde{\eta}(v_{\rm min})$$

$\sigma_{A,Z}(E) \sim \sigma_p$ thus $\tilde{\eta}(v_{\rm min}) = \sigma_p(\rho/m)\eta(v_{\rm min})$

and changing variable to $v_{\rm min}$, $dE_R = (4\mu^2_{A,Z}/m_{A,Z})v_{\rm min} dv_{\rm min}$

# Halo Independent analysis Gondolo-Gelmini 1202.6359

Expected rate over a detected energy interval $[E'_1, E'_2]$

$$R_{[E'_1,E'_2]} = \int_0^\infty dv_{\rm min}\ \mathcal{R}^{SI}_{[E'_1,E'_2]}(v_{\rm min})\ \tilde{\eta}(v_{\rm min}) = \overline{\tilde{\eta}_{[E'_1,E'_2]}} \int_0^\infty dv_{\rm min}\ \mathcal{R}^{SI}_{[E'_1,E'_2]}(v_{\rm min})$$

$\mathcal{R}^{SI}$: response function for SI WIMP interactions

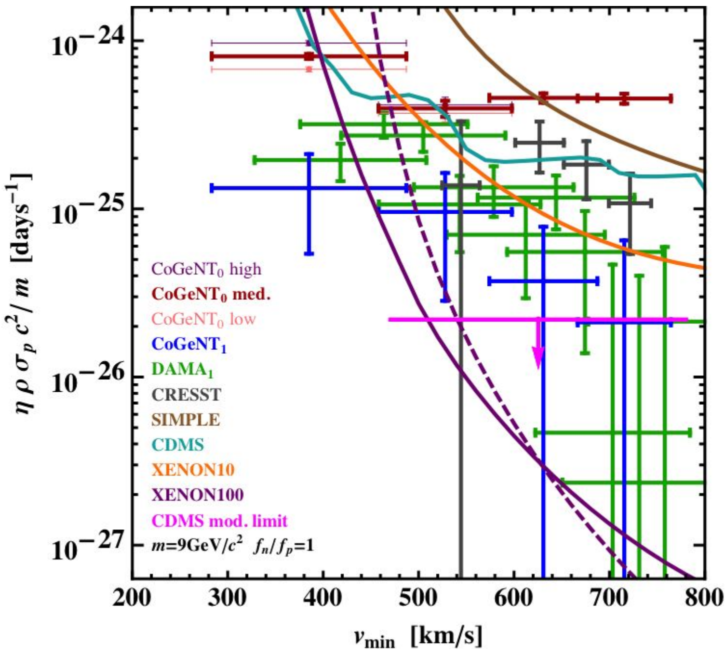
$$\mathcal{R}^{SI}_{[E'_1,E'_2]}(v_{\rm min}) = \sum_{A,Z} \frac{2\, v_{\rm min}\, C_{A,Z}\, \sigma^{SI}_{A,Z}(E_{A,Z})}{m_{A,Z}\, \sigma_p\, (E'_2 - E'_1)} \int_{E'_1}^{E'_2} dE'\, G_{A,Z}(E_{A,Z}, E')\, \epsilon(E')$$

is non zero only for an interval in $(v_{\rm min})$ [in as simplified approach $\mathcal{R}^{SI}_{[E'_1,E'_2]}(v_{\rm min})$ is significantly different from zero only in the interval $[v_{\rm min,1}, v_{\rm min,2}]$ with $v_{\rm min,1} = v_{\rm min}(E'_1 - \sigma_E(E'_1))$ and $v_{\rm min,2} = v_{\rm min}(E'_2 + \sigma_E(E'_2))$].

# Light WIMPs “halo independent analysis”

$\rho\eta(v_{\min}, t) = \rho[\eta_0 + \eta_1 \cos\omega(t - t_0)]$ due to annual modulation

$\rho\eta_0$ and $\rho\eta_1$ should be the same for all experiments! and $\eta_1 < \eta_0$. Relation $v_{\min}$ with $E$ depends on $m$, so we need to fix $m$ here 9 GeV. Same conclusions for other light $m$.




Gondolo, Gelmini 1202.6359

$f_n/f_p = 1$, $Q_{Na}$=0.3

CoGeNT (brown) and CRESST (gray) rates,

CoGeNT modulation (blue) compatible with DAMA modulation (green) but $>$ 25 % of CoGeNT rate,

CDMS modulat. bound 1203.1309 (purple)

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

# Light WIMPs-SI "halo independent analysis"

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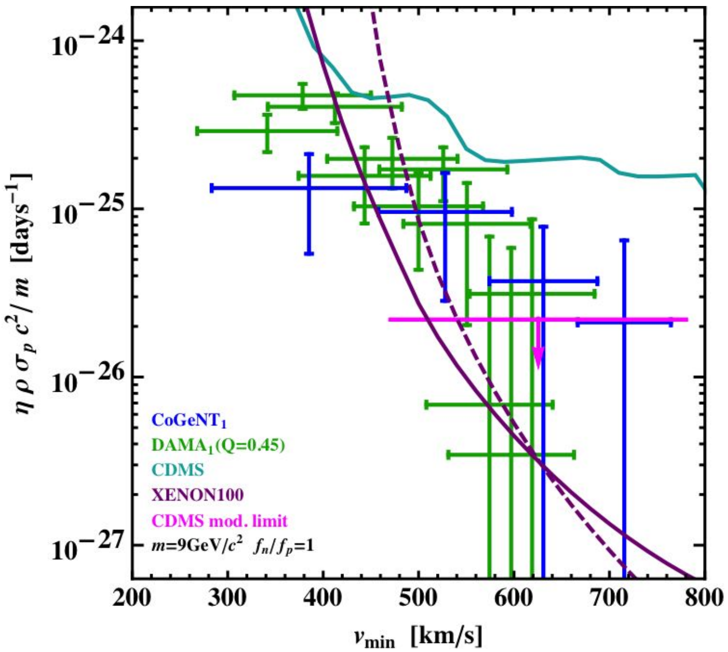



Gondolo, Gelmini 1202.6359

$f_n/f_p = 1$, Q$_{Na}$=0.45

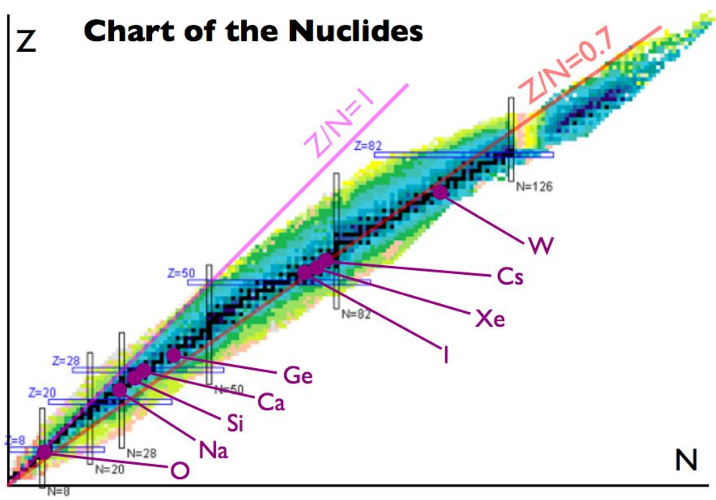
CoGeNT (brown) and CRESST (gray) rates, CoGeNT modulation (blue) compatible with DAMA modulation (green) but $> 25$ % of CoGeNT rate,

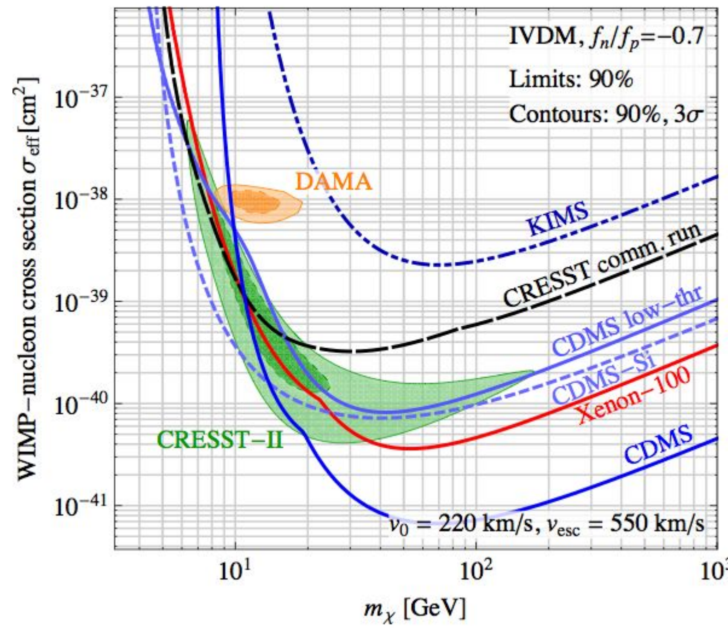
CDMS modulat. bound 1203.1309 (purple)

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

**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!

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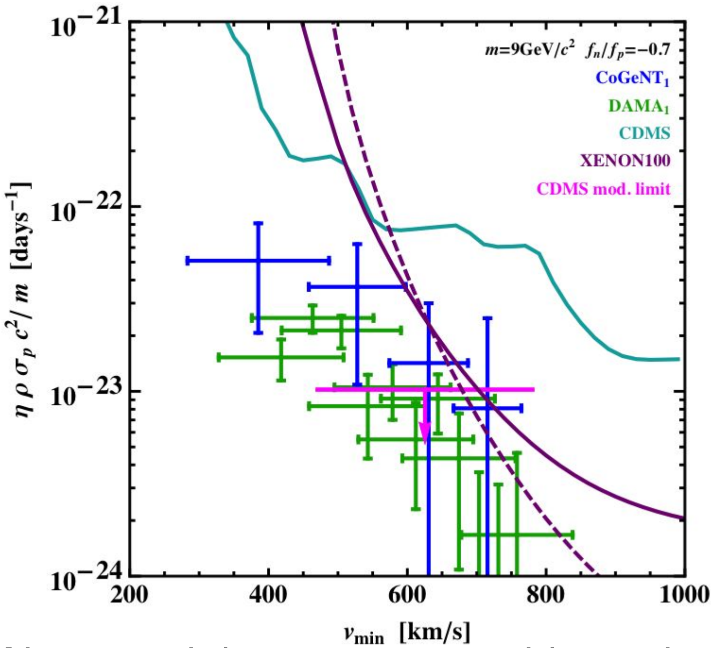


Gondolo, Gelmini 1202.6359

$f_n/f_p = -0.7$, $Q_{Na}$=0.3, $m$ = 9GeV

CoGeNT rates (brown) and CRESST rate

CoGeNT modulation (blue) compatible with DAMA modulation (green) but on top of CRESST unmodulated rate (gray) (they are incompatible)

CDMS modulation bound 1203.1309 is the most constraining for 5 -11.9 keV Ge recoil energy- Allowed region below it

Now modulations compatible with all bounds except CDMS-modulation bound. But CRESST unmodulated is on top of CoGeNT modulation.

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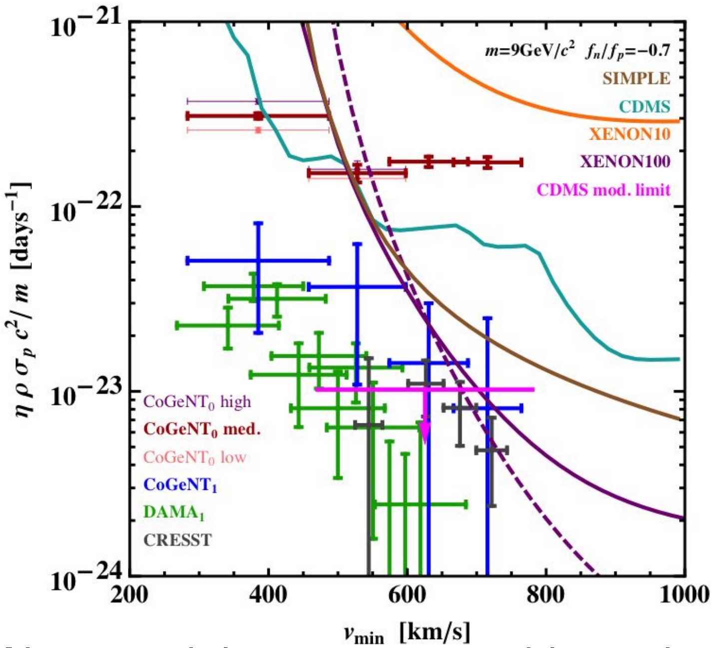


Gondolo, Gelmini 1202.6359

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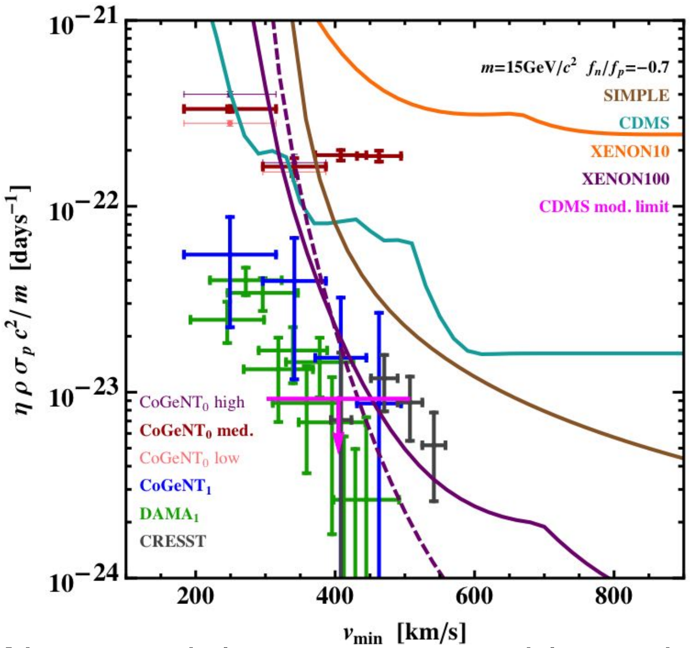



Gondolo, Gelmini 1202.6359

$f_n/f_p = -0.7$, Q$_{Na}$=0.45, $m$ = 15GeV

CoGeNT rates and CRESST rate

CoGeNT modulation (blue) compatible with DAMA modulation (green) but on top of CRESST unmodulated rate (gray) (they are incompatible)

CDMS modulation bound 1203.1309 is the most constraining for 5 -11.9 keV Ge recoil energy- Allowed region below it

Now modulations compatible with all bounds except CDMS-modulation bound. But CRESST unmodulated is on top of CoGeNT modulation.

# Other possibilities for Light WIMPs?

Spin Dependent Interactions (SD)? $\sigma(q) = \frac{32\mu^2 G_F^2 (J_N+1)}{J_N} \left[ \langle S_p \rangle a_p + \langle S_n \rangle a_n \right]^2$

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) see e.g. Schwetz and Zupan 1106.6241

Cross sections with other $q$ and $v$ dependence and/or DM form factors?

several $q$ and $v$ dependences have been studied and some are promising, in particular magnetic -moment interactions

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

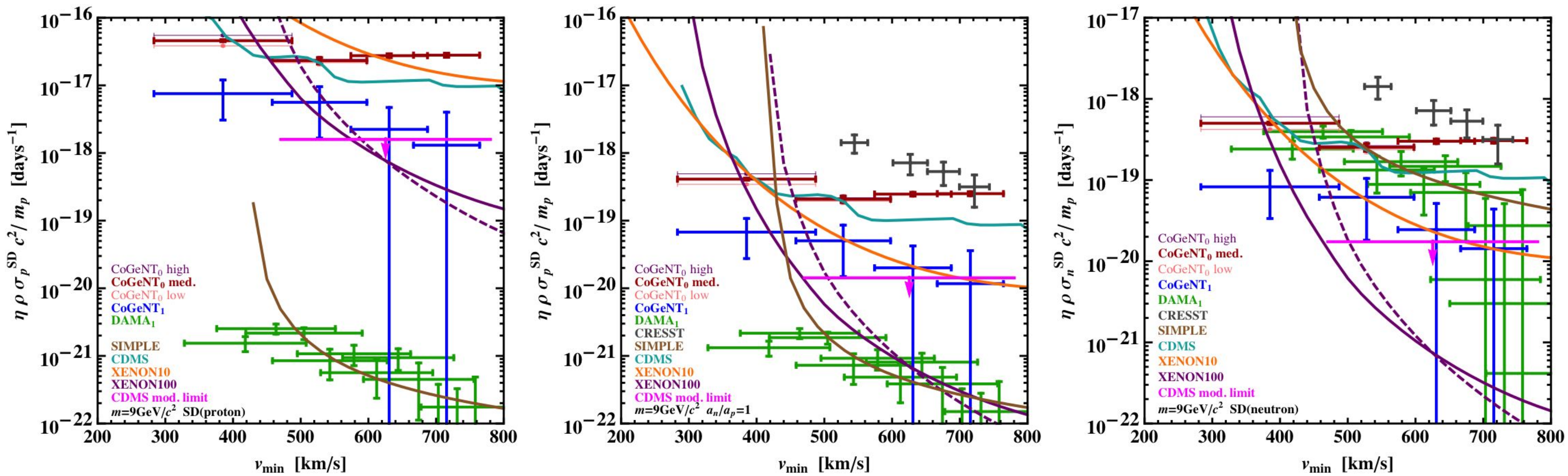
Del Nobile, Gelmini, Gondolo, Huh are extending the halo independent analysis .

# Light WIMPs-SI "halo independent analysis"

Del Nobile, Gelmini, Gondolo, Huh-in preparation

SD-p: DAMA (Na and I) rejected by Fluorine (COUPP, PICASSO , SIMPLE)

SD-n: CoGeNT (Ge), rejected by CDMS (Ge) and Xenon100 (Xe)



# Light WIMPs Outlook

I agree with the statement of Juan Collar (CoGeNT) at IDM2012 last July

> this speaker does not know how to reconcile
> DAMA, CoGeNT and CRESST:
>
> Either we are to learn something subtle about
> the halo, couplings, or detector effects, or...
>
> their observations have nothing in common.

# 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

# Opportunity to build ANDES at the Agua Negra Tunnel

## Brief remark on present annihilation rate of **Asymmetric DM:**

Idea almost as old as the "WIMP miracle" An asymmetry $Y_\chi - Y_{\bar{\chi}} = (n_\chi - n_{\bar{\chi}})/s = A$ similar to that of baryons could explain why $\Omega_{DM} \simeq \Omega_B$!

1985: Nussinov, if technibaryon and baryons have same number density then $\Omega_{DM}/\Omega_B = m_{TB}/1$ GeV (with $\Omega_{DM} \simeq 1$, $m_{TB} \simeq 100$GeV!)

1986: Gelmini, Hall and Lin, proposed a model for "cosmions" ($m_C =$ 5 to 10 GeV) with $B - C$ number conserved and the same asymmetry is produced for both (when "cosmions" were abandoned to explain the solar-neutrino problem this paper was largely forgotten!- also we could account "only" for $\Omega_{DM} \simeq 0.2$)

Barr, Chivukula and Farhi, 1990; Barr, 1991; Kaplan, 1992; Dodelson, Greene and Widrow, 1992; Fujii and Yanagida, 2002); Kitano and Low, 2005; Farrar and Zaharijas, 2006); Gudnason, Kouvaris and Sannino, 2006; Kitano, Murayama and Ratz, 2008.

...Kaplan, Luty and Zurek, 2009 [which now has 190 citations]...

Main characteristic: no annihilation rate after freeze-out. But this is a pre-BBN cosmology dependent statement-when freeze-out happens in a non standard cosmological phase the annihilation rate at present may be even larger than for symmetric DM in the standard cosmology (see Gelmini, Huh, Rehagen 1304.3697)