A Dark Matter Puzzle

Clues from the LHC and Direct Detection Experiments

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Dark Matter Searches

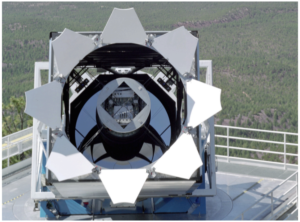
WIMP miracle drives a lot of the thinking on dark matter

Weakly interacting, $\mathcal{O}$(100 GeV) particle

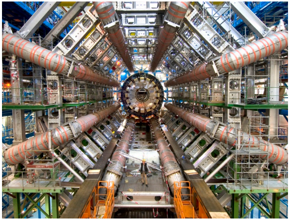
Many experiments are currently testing the WIMP paradigm

A Multifaceted Approach for Discovery

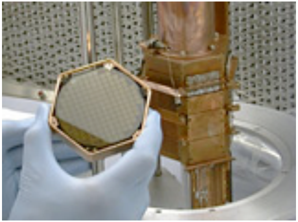
Observe it in the sky



Create it in the lab

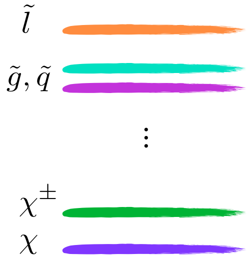


Observe it in the lab



A Minimal Model

SUSY-inspired



Dark matter is a Majorana fermion and SM singlet

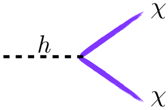
$$\chi = c_1 \widetilde{B} + c_2 \widetilde{W} + c_3 \widetilde{H}_u^0 + c_4 \widetilde{H}_d^0$$

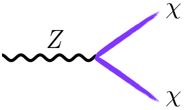
gauginos (marking $\widetilde{B}$ and $\widetilde{W}$) · higgsinos (marking $\widetilde{H}_u^0$ and $\widetilde{H}_d^0$)

Also include an additional SM triplet

$$\chi^{\pm} = a_1 \widetilde{W}^{\pm} + a_2 \widetilde{H}^{\pm}$$

Dark matter couples to the SM through Higgs and Z bosons

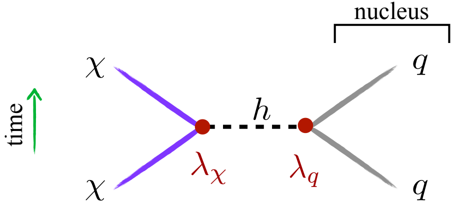




Direct Detection

Dark matter scatters off of nuclei in detector

Spin-independent interaction due to Higgs exchange

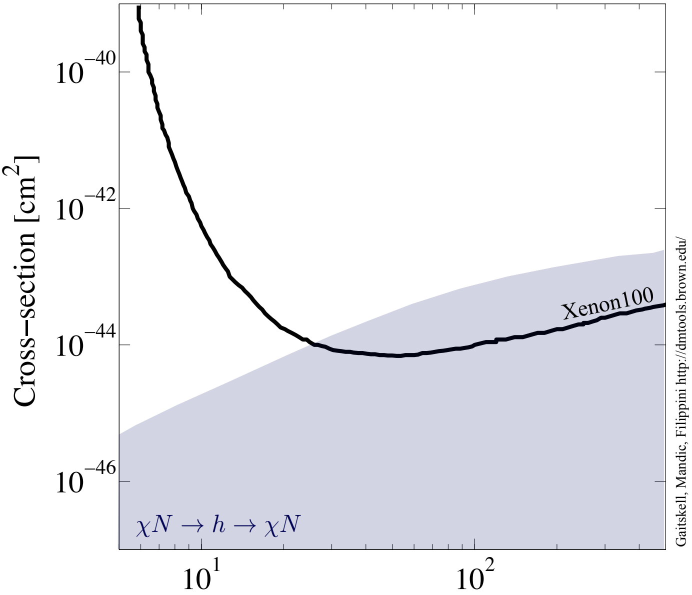


$$\sigma_{\chi N \to \chi N} \simeq \frac{\lambda_\chi^2 \lambda_q^2}{4 m_h^4} \cdot \mu_{\chi N}^2$$

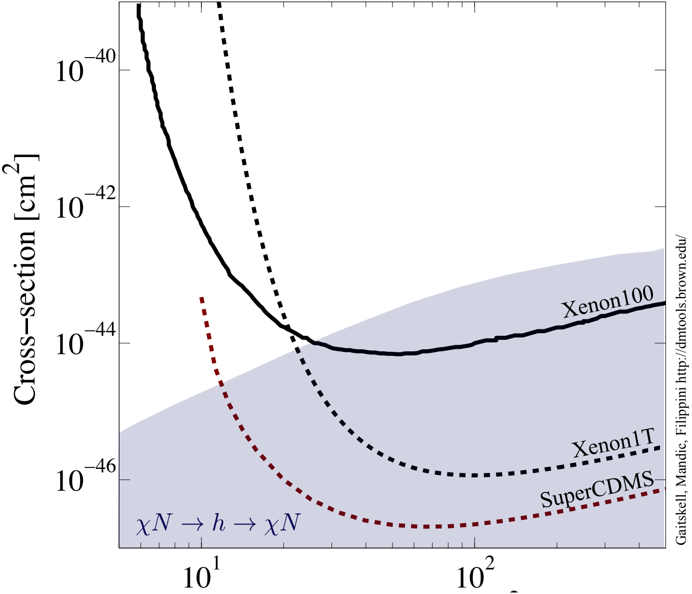
$$\sim (7 \times 10^{-44}\ \mathrm{cm}^2) \cdot \lambda_\chi^2$$

for Xe target, 125 GeV Higgs,
100 GeV DM

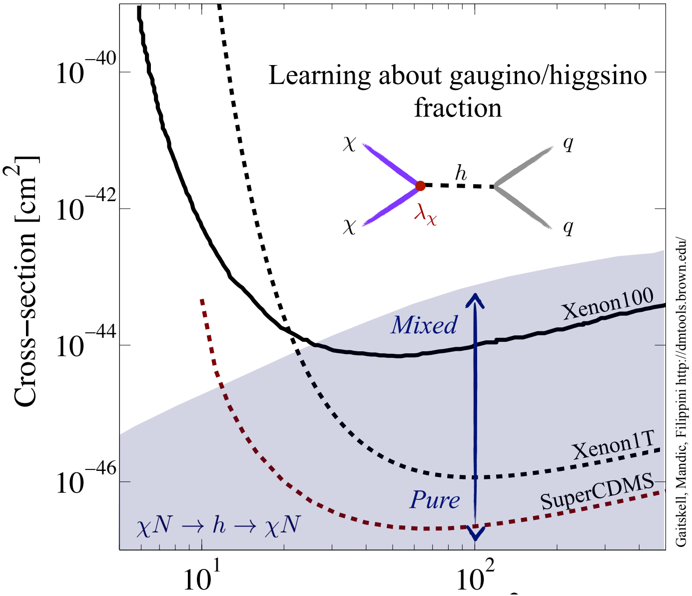
Spin-Independent Limit



Spin-Independent Limit



Spin-Independent Limit

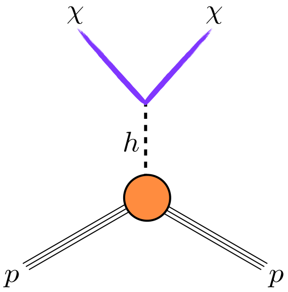


M. Perelstein and B. Shakya [1107.5048]

LHC Tests

LHC is simultaneously setting constraints on this minimal scenario

Three classes of searches are particularly relevant:



(1) Invisible branching fraction of the Higgs

Y. Bai, P. Draper, and J. Shelton [1112.4496]

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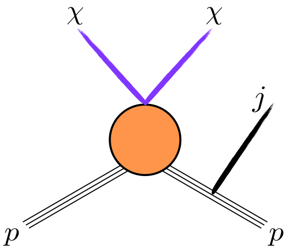

(1) Invisible branching fraction of the Higgs

Y. Bai, P. Draper, and J. Shelton [1112.4496]

(2) Direct production of electroweak states

(a) monojet searches

P. Fox, R. Harnik, J. Kopp, Y. Tsai [1109.4398]

A. Rajaraman, W. Shepherd, T. Tait, A. Wijangco [1108.1196]

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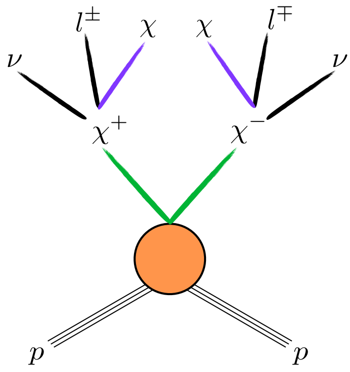

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(b) multilepton searches

ML and N. Weiner [1112.4834]

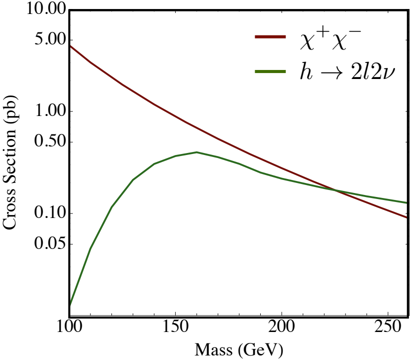
E. Contreras-Campana *et al.* [1112.2298]

Direct Production at LHC

ML and N. Weiner [1112.4834]

Higgs searches are already sensitive to light electroweakino states

e.g., $pp \to h \to W^+W^- \to l^+\nu\ l^-\nu$



Higgs analyses are inclusive because they require minimal missing energy:

$$\not{E}_T \gtrsim 25\text{–}40\ \text{GeV}$$

*catches light electroweakinos

Many SUSY multilepton analyses require

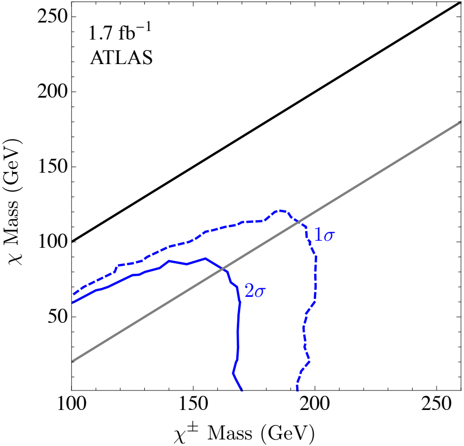
$$\not{E}_T \gtrsim 80\text{–}100\ \text{GeV}$$

Direct Production at LHC

ML and N. Weiner [1112.4834]

Higgs searches provide the tightest limits, extending LEP bound

$$pp \to \chi^+\chi^- \to 2l + \not{E}_T$$

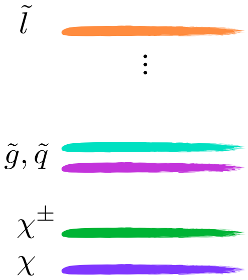


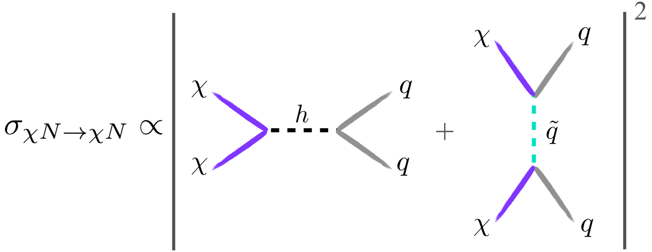
New Colored States

Introduce colored states such as squarks or gluinos in the spectrum

Additional contributions to scattering cross section

May weaken direct detection constraints on mixing fraction of neutralino

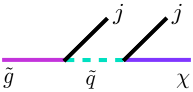




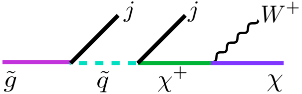
Cascade Decays

Dark matter produced in decays of colored particles

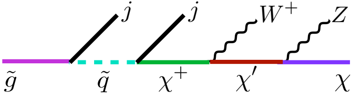
For longer cascades, more energy in visible final states, reducing missing energy



4 jets



4-8 jets, 0-2 leptons



4-12 jets, 0-6 leptons

Longer cascades are weakly constrained by current searches

Searches with minimal missing energy requirements necessary to catch models with several states near dark matter

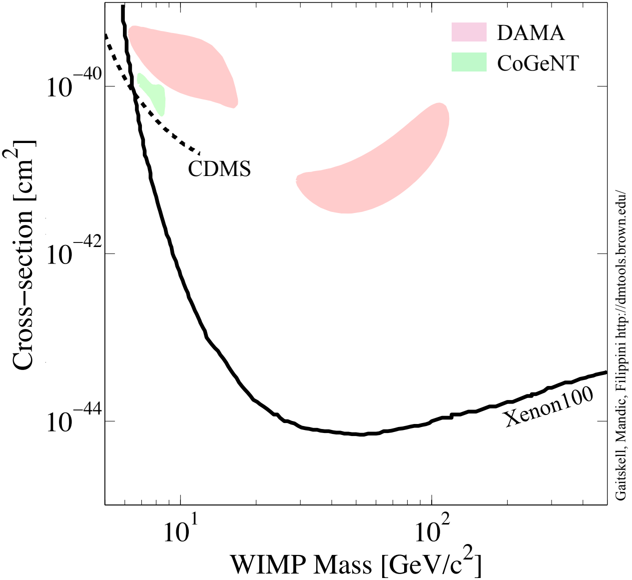
Summary

Xenon100 starting to probe Higgs-exchange region

LHC searches starting to constrain direct electroweakino production and short cascade topologies

Low MET searches critical for disentangling spectrum of dark matter theory

Dark Matter Anomalies

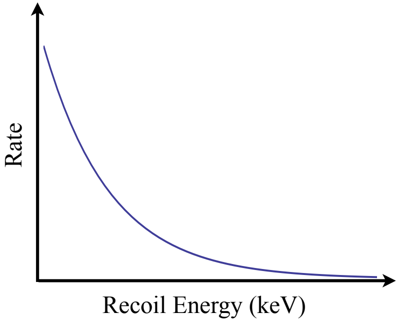


Recoil Spectrum

Average over all possible DM velocities in the galactic halo

$$\frac{dR}{dE_R} = n_{\rm dm}\left\langle v\frac{d\sigma}{dE_R}\right\rangle \propto \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \; \frac{d\sigma}{dE_R} \; v\, f(v) \sim e^{-E_R/E_0}$$

$$v_{\rm min} = \sqrt{\frac{m_N E_R}{2\mu^2}} \qquad f(v) = e^{-v^2/v_0^2}$$



For standard assumptions, recoil spectrum is exponential

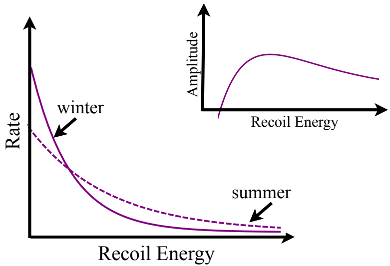
Signal dominates at low E_R

Annual Modulation

Direct detection experiments measure scattering rate and (if possible) modulation amplitude

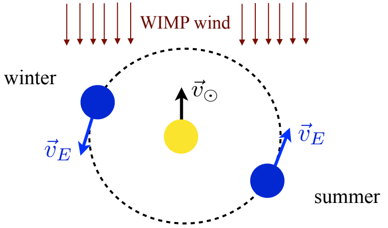
Recoil energy spectrum

$$R \propto \int \frac{f(v)}{v} dv$$



Modulation Amplitude

$$\text{Amplitude} = \frac{1}{2}(R_{\max} - R_{\min})$$



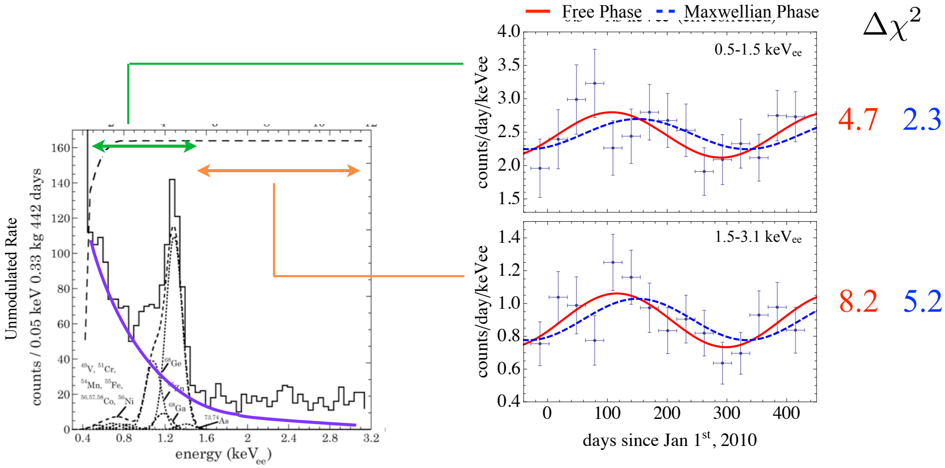
$v \leq v_{\rm esc} + |\vec{v}_E - \vec{v}_\odot|$ $\quad$ $v \leq v_{\rm esc} + |\vec{v}_E + \vec{v}_\odot|$

CoGeNT 2011

Aalseth *et al.* [1106.0650]

Ge target, 15 months of data taking

Claim 2.8σ evidence for annual modulation

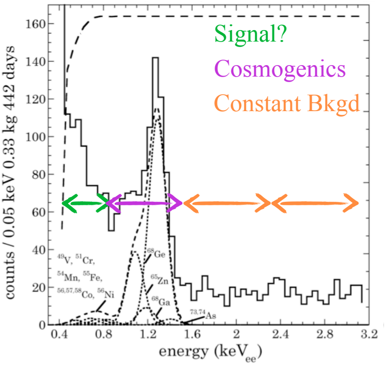


P. Fox, J. Kopp, ML, N. Weiner [1107.0717]

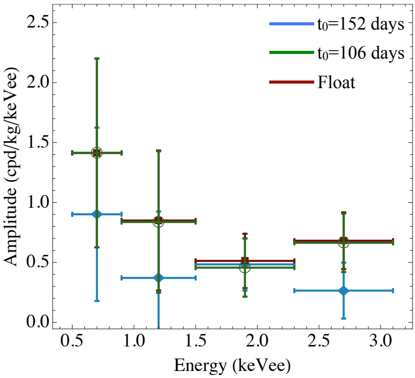
Modulation Amplitude

Most significant annual modulation above 1.5 keV_{ee}

Unmodulated Rate



Modulation Amplitude



(Unbinned Max Likelihood)

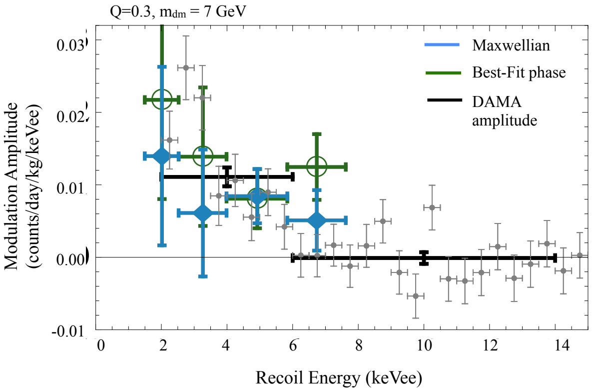
DAMA

Bernabei *et al.* [0804.2741]

NaI target, 11 years of data taking

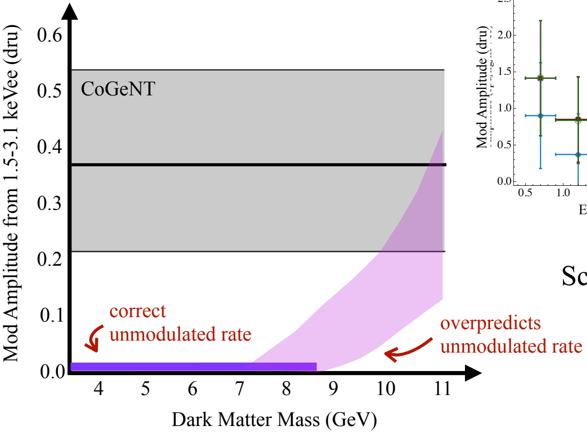
Claim 8.9σ evidence for annual modulation

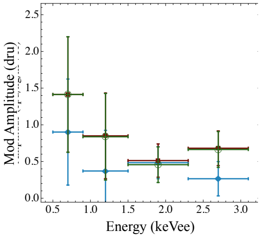
Can be consistent with CoGeNT modulation

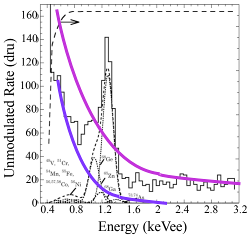


Inconsistency

Explaining modulation at high energies with standard assumptions overpredicts unmodulated rate







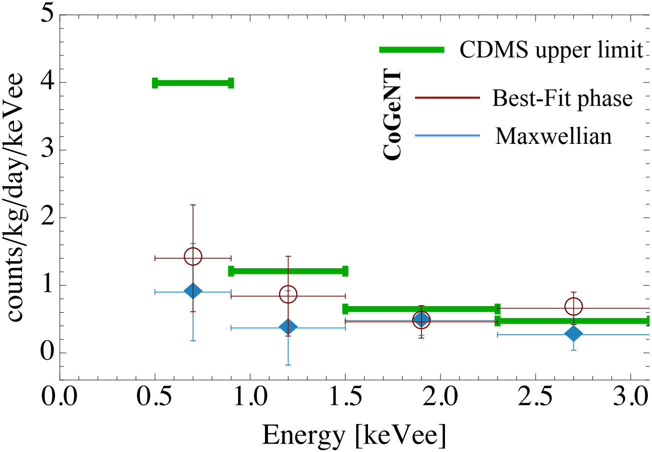
Scan over well-motivated halos:

$$f(v) \sim e^{-v^2/v_0^2}$$

[vary v_0, v_{esc}]

CDMS

CDMS should see nearly 100% modulation between 1.5-3.0 keVee



Conclusions

A diverse set of experiments are testing the WIMP paradigm

Experimental results providing hints as to what the dark sector is like

Anomalies suggest that dark matter may be ~10 GeV

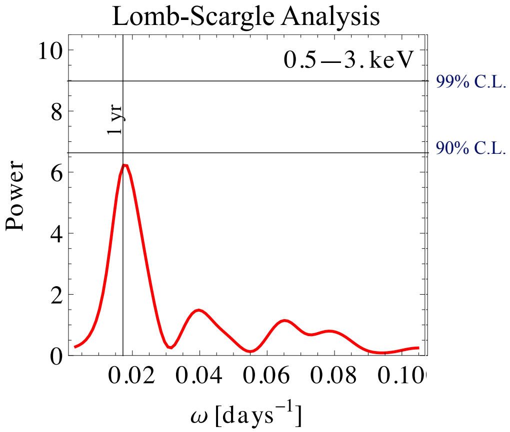
CoGeNT modulation inconsistent with standard DM assumptions

If correct, CDMS should see strong modulation signal

Additional Slides

Modulation Amplitude

Most significant annual modulation above 1.5 keV_{ee}



Daily Modulation

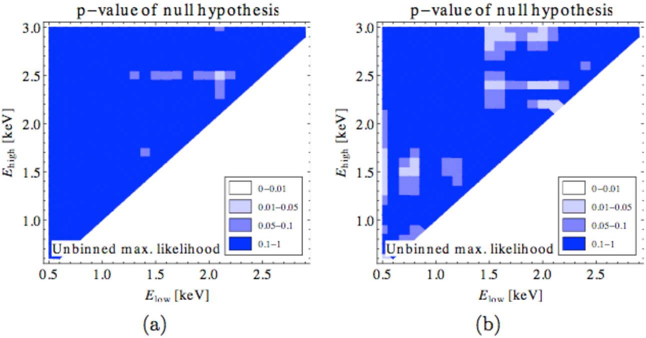


Figure 2: Significance of daily modulation in CoGeNT, as measured by the probability for the null (no modulation) hypothesis to give the observed amount of modulation. We have fitted a model of the form (2.1) to the data after subtracting backgrounds and correcting for detection efficiencies and shutdown periods. In the fit, we have kept the oscillation period ω fixed at (a) one solar day (24 hrs) and (b) one sidereal day (23.93 hrs), and we have treated the average rate A_0, the modulation fraction A_1, and the phase t_0 as free parameters.

Modulation Fraction

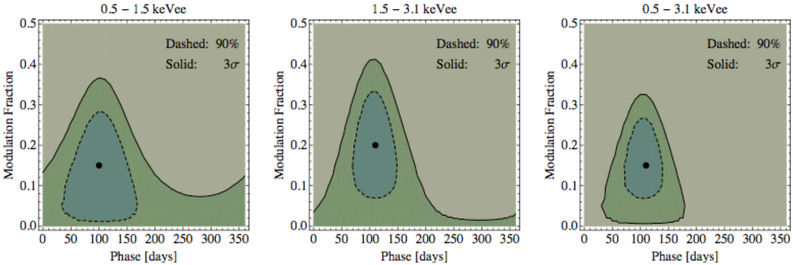


Figure 4: Likelihood analysis of the allowed regions in modulation and phase for different energy ranges: in [0.5–1.5] keVee (*left*), [1.5–3.1] keVee (*middle*), and [0.5–3.1] keVee (*right*). The contours are of $\Delta\chi^2$ from the best fit point, shown as •.

Modulation Analysis

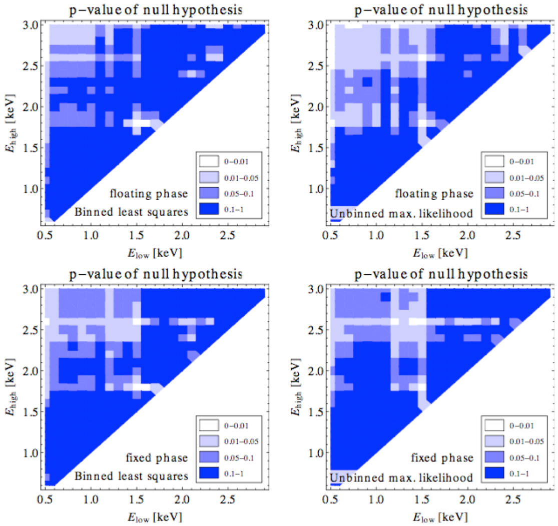


Figure 5: Results of modulation fit with $\omega = \omega_0 = 2\pi/1$ year, using both the binned and unbinned approaches. The upper plots allow the phase to float and the lower plots fix it at the value expected by the SHM ($t_0 = 152$ days). The probability of the null (no modulation) hypothesis to fluctuate to the observed best fit values is calculated from the $\Delta\chi^2$ between the two best fits, assuming 2 degrees of freedom for the upper plots and 1 for the lower.

Modulation Analysis

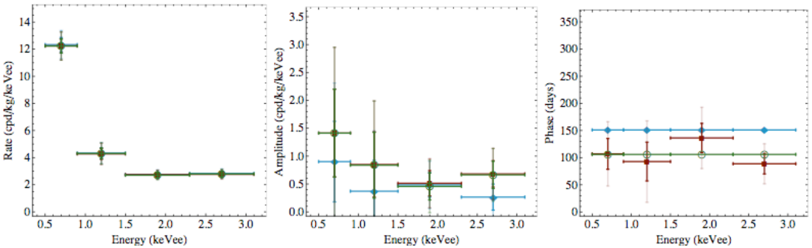


Figure 6: Spectra for three different scenarios: (red square) the phase is allowed to float in the fit, (blue diamond) the phase is fixed to Maxwellian (152 days), and (green open circle) the phase is fixed to the best fit phase (106 days) for a fit to the full data range 0.5-3.1 keVee. The spectra represent: total rate (left), modulation amplitude (middle) and phase (right).

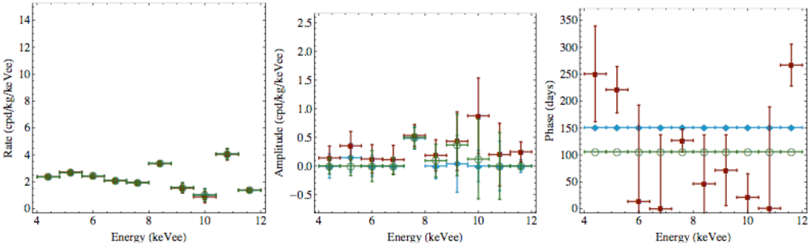


Figure 7: Same as Fig. 6, except for data from the high energy channel.

Ge^{68} Peak

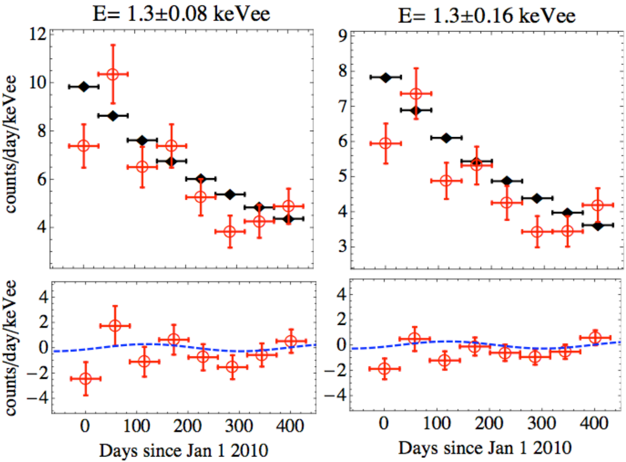


Figure 8: Time variation for data centered on the Ge^{68} L-shell peak for two different energy ranges. The top panel shows the predicted cosmogenic contribution using Eq. A.1 and the parameters given in Appendix A (black diamonds), as well as the (efficiency corrected) time-binned distribution of the data (red open circles). A constant of 1.4 counts/day/keVee (see unmodulated spectrum in Fig. 6) has been added to the background. The bottom panel shows the residuals between the data and the model (red). The dashed blue line is the best-fit modulation in the range 0.9–1.5 keVee, obtained using the log-likelihood approach as in Fig. 6.

Inelastic

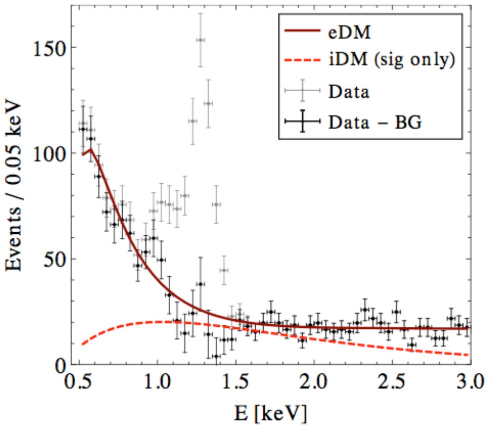


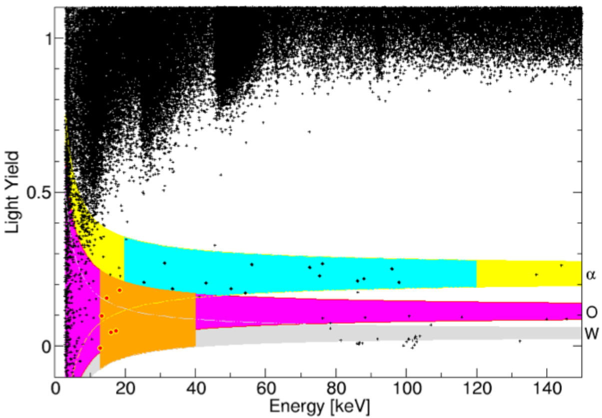
Figure 9: Comparison of the CoGeNT data to the predicted event spectrum for elastically (solid dark red) and inelastically (light red dashed) scattering dark matter. In both cases, results for the best fit dark matter parameter are shown. In the elastic case, the fit was done using the unbinned maximum likelihood approach including energy and timing information for each event as well as a constant background, whereas in the inelastic case, we have carried out the binned analysis described in the text, with 5 constant backgrounds c_i. (For iDM, only the signal is shown, but not the fitted constant background.)

CRESST

$CaWO_4$ target, 730 kg-days of data

Angloher et al., 1109.0702.

Relies on background modeling to determine signal excess



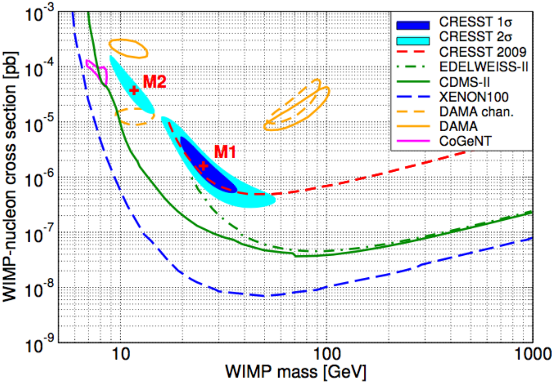
Unexplained excess above lower threshold (12-19 keV)

Naively, should see lots of events below this threshold if light WIMP

CRESST

[1.5,3.1] keVee in CoGeNT corresponds to [15.6,29.8] keVnr in CRESST O band

CoGeNT *modulation* ⇔ CRESST signal



	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$
	4.7σ	4.2σ