Robust
Signals of
DARK MATTER

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Dark Attack
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Unknown unknowns and DM

• We have enough uncertainties about DM

• What kinds of signals or constraints can we make that do not depend on so many things?
Plan

• Robust signals of DM (what is the DM is not “the” DM?)

• Robust limits on DM (removing astrophysics)
Robust signals

• Why should we care about a WIMP that is not “the” DM?

• (Anthropic multiverse landscape discussion here)

• Already know 5 stable fundamental particles that are not “the” DM

• Know 253+34 composite particles that are cosmologically stable
what about stable particles here?

\[ \rho \propto \frac{1}{\sigma v} = \frac{1}{M_{\text{ann}}^2} \]
what can we learn from simple scaling arguments?
Scaling relationships:

\[ R \propto n_x M_{\text{scatt}}^2 \]

\[ \rho \propto \frac{1}{\sigma V} \frac{1}{M_{\text{ann}}^2} \]

\[ \Rightarrow R \propto \frac{1}{M_{\text{ann}}^2} \times M_{\text{scatt}}^2 \sim \text{const} \]

Scattering rate is approximately invariant.

\[ \exists \]

e.g. Duda & Gelmini

0102200
Even subdominant WIMPs are plausibly detectable.

Weak coupling
- more DM
- rate = constant

Strong coupling
- less DM
How true is this?

Consider vector exchange

\[
\Sigma = \frac{G_f^2}{2\pi} \frac{M_{\pi n}^2}{A^2} \frac{1}{\Lambda} \left( (1 - 4\sin^2 \theta_W)^2 - (A - Z)^2 \right) \sim 10^{-39} \text{ cm}^2 \sim \text{const}
\]

Scaling is for dimensionless couplings
\[ \frac{g_x^2 g_f^2 m_x^2}{m_{\nu}^4} \quad \text{parametrically related} \]

\[ \frac{g_x^4}{m_x^2} \quad \text{parametrically distinct} \]

\[ \frac{g_x^2 g_f^2 \mu^2}{m_{\nu}^4} \]
The heuristic argument that subdominant WIMPs have the same scattering rate as dominant WIMPs is limited. That said, the failure of the argument goes both ways (up or down) so the qualitative point that subdominant WIMPs are detectable seems robust.
What about indirect detection?

\[ \rho \sim \frac{1}{\sigma_{\text{ann}}} \]

\[ R \sim \rho^2 \sigma_{\text{ann}} \sim \frac{1}{\sigma_{\text{ann}}} \]

\[ \Rightarrow \text{ Seems to prefer low } \sigma \]

\[ \text{i.e. ”the” DM} \]
Or does it...?

\[ \Gamma_{\text{ann}} \sim \frac{\alpha^2}{m^2} \]

\[ \rho - \frac{1}{\sigma} - m^2 \Rightarrow \eta = \frac{\rho - m}{m} \]

\[ R = \eta^2 \sigma - \frac{m^2 \rho}{m^2} = \text{const} \]

\[ \Rightarrow \text{if a WIMP annhilates into a dark force, it can show up even if it is not "the" DM} \]
An interesting example

Consider DM with a magnetic dipole

$$\mu_0 \overline{X} \sigma^{\mu\nu} X F_{\mu\nu}$$

NB: this operator is off-diagonal i.e.

$$\chi_1 \sigma^{\mu\nu} \chi_2 F_{\mu\nu}$$
If $m_{\chi_1} = m_{\chi_2}$ (i.e., it’s Dirac), bad news.
If it is inelastic, good now.

“magnetic inelastic” DM

Xenon spectrum

Rate (cpd/kg/keV)

keV

0.008
0.006
0.004
0.002

20 40 60 80

Atomic mass

0 50 100 150 200

F
Na
I
Cs
Xe

W

\[
\mu = \frac{\mu_0}{2} \left( 2L + S \right)
\]
\[ \rho = \frac{1}{m_x^2} \]

\[ \sim \mu x x n - \mu y x \frac{1}{m_x^2} \sim \text{constant} \]
Indirect signals

\[ \chi \rightarrow \gamma \gamma \]

\[ R \sim \rho^2 \sigma_{\gamma \gamma} - \left( \frac{1}{m^2_{\chi}} \right) M_{\chi}^4 \sim \text{const} \]

\[ \Sigma_{\gamma \gamma} \lesssim 3 \times 10^{-29} \text{ cm}^3/15 \]

A bit small for the 130 GeV line, but can have O(1) corrections
\[ R_{DD} \propto n_\chi \mu_\chi^2 = \frac{\rho_0}{m_\chi} \frac{\mu^2_{\text{thermal}}}{\mu_\chi^2} \times \mu_\chi^2 = \frac{\rho_0}{m_\chi} \mu^2_{\text{thermal}} \]

\[ R_{\gamma\gamma} \propto n_\chi^2 \mu_\chi^4 = \frac{\rho_0^2}{m_\chi^2} \frac{\mu^4_{\text{thermal}}}{\mu_\chi^4} \times \mu_\chi^4 = \frac{\rho_0^2}{m_\chi^2} \mu^4_{\text{thermal}} \]

if an MiDM-like model exists, its signal sizes are pretty robust
• Searches for DM are more robust than you’d have guessed
• DD signals pretty generic for stable WIMPs
• Sometimes ID signals (esp gamma gamma) are robust
robust constraints on DM
no shortage of signals
the problem with our approach

Standard halo model

$\sigma$-m plot

experiment 1

experiment 2
Fig. 12. (Color online) Light yield distribution of the accepted events, together with the expected contributions of the backgrounds and the possible signal. The solid and dashed lines correspond to the parameter values in M1 and M2, respectively.

6.2 Significance of a Signal
As described in Section 5.1, the likelihood function can be used to infer whether our observation can be statistically explained by the assumed backgrounds alone. To this end, we employ the likelihood ratio test. The result of this test naturally depends on the best fit point in parameter space, and we thus perform the test for both likelihood maxima discussed above. The resulting statistical significances, at which we can reject the background-only hypothesis, are for M1: 4.7, for M2: 4.2.

In the light of this result it seems unlikely that the backgrounds which have been considered can explain the data, and an additional source of events is indicated. Dark Matter particles, in the form of coherently scatter- 

6.3 WIMP Parameter Space
In spite of this uncertainty, it is interesting to study the WIMP parameter space which would be compatible with our observations. Fig. 13 shows the location of the two likelihood maxima in the \( (m, \sigma)_W \)-plane, together with the 1 and 2 confidence regions derived as described in Section 5.1. The contours have been calculated with respect to the global likelihood maximum M1. We note that the parameters compatible with our observation are consistent with the CRESST exclusion limit obtained in an earlier run [1], but in considerable tension with the limits published by the CDMS-II [12] and XENON100 [13] experiments. The parameter regions compatible with the observation of DAMA/LIBRA (regions taken from [16]) and CoGeNT [15] are located somewhat outside the CRESST region.

7 Future Developments
Several detector improvements aimed at a reduction of the overall background level are currently being implemented. The most important one addresses the reduction of the alpha and lead recoil backgrounds. The bronze clamps holding the target crystal were identified as the source of these two types of backgrounds. They will be replaced by clamps with a substantially lower level of contamination. A significant reduction of this background would evidently reduce the overall uncertainties of our background models and allow for a much more reliable identification of the properties of a possible signal.

Another modification addresses the neutron background. An additional layer of polyethylene shielding (PE), installed inside the vacuum can of the cryostat, will complement the present neutron PE shielding which is located outside the lead and copper shieldings.

The last background discussed in this work is the leakage from the \( e^-/ \beta^- \)-band. Most of these background events are due to internal contaminations of the target crystals so that the search for alternative, cleaner materials and/or production procedures is of high importance. The material ZnWO\(_4\), already tested in this run, is a promising candidate in this respect.
Want model independent constraints

Figure 2: Velocity distribution functions: the left panels are in the host halo's rest frame, the right panels in the rest frame of the Earth on June 21st, and the peak of the Earth's velocity relative to Galactic DM halos. The solid red line is the distribution for all particles in a 0.0 kpc wide shell centered at 8.0 kpc. The light and dark green shaded regions denote the ±1σ scatter around the median and the minimum and maximum values over the V uu sample spheres. The dotted line represents the best-fitting Maxwell-Boltzmann distributions.

Extrema of the subsample distributions, however, exhibit numerous distinctive narrow spikes at certain velocities and these are due to just such discrete structures. Note that although only a small fraction of sample spheres exhibit such spikes, they are clearly present in some spheres in all three simulations. The Galilean transform into the Earth's rest frame washes out most of the broad bumps but the spikes remain visible, especially in the high velocity tail, where they can profoundly affect the scattering rates for inelastic and light DM models (see Section y).

Kuhlen, et al.
The goal

• What can we say about direct detection experiments without making any appeal to halo models?

• Find Dark Matter / test claims

• Determine DM mass

• Determine DM interaction strength
The goal

- What can we say about direct detection experiments without making any appeal to halo models?

- Find Dark Matter / test claims
- Determine DM mass
- Determine DM interaction strength
compare target to target

DAMA [NaI(Tl)]  KIMS [CsI(Tl)]
compare target to target

DAMA [NaI(Tl)] ↔ KIMS [CsI(Tl)]

DAMA [NaI(Tl)] ↔ COUPP [CF₃I]
compare target to target

DAMA [NaI(Tl)] ↔ KIMS [CsI(Tl)]

DAMA [NaI(Tl)] ↔ COUPP [CF₃I]

CoGeNT [Ge] ↔ CDMS [Ge]
could DAMA come from Iodine?

Experiments with iodine: KIMS, COUPP
KIMS

KIMS Nuclear recoil event rate

Counts/day/kg/keV vs Energy (keV)
NB: This line totally made up
KIMS

• KIMS potentially interesting constraints

• But concern about calibration/energy resolution/quenching factor - is this a limit on the fitting model or on a WIMP signal?

• Modulation analysis should be instructive
COUPP at SNOLAB

- 17.4 live-days at 7 keV threshold
- 21.9 live-days at 10 keV threshold
- 97.3 live-days at 15 keV threshold ended June 16
- 79% acceptance for nuclear recoils after all cuts (including fiducial and acoustic)

~8 1 bubble event
0.026 ± 0.015 (90% est) cpd/kg (no bubble efficiency corr)

For 100% DAMA modulation expect .
0.037±.007 (90% )
DAMA-I

• Iodine rate from DAMA is marginal, but consistent for \( \sim O(1) \) modulated signal.

• Improvements in COUPP can definitively exclude the I interpretation
Could CoGeNT be dark matter?

Experiments with Ge and low threshold: CDMS
CoGent->CDMS

With surface event subtraction no a priori conflict
CoGeNT modulation

**FIG. 1:** Time-binned data in various energy ranges. Specifically (left) [0.5–1.5] keVee, (right) [1.5–3.1] keVee. Overlaid are the best-fit to the modulation, as derived using the binned analysis, with free phase (solid red curve) and peak set at 152 days (dashed blue). The best-fit points correspond to $A_0 = 7.4(7.5)$ events/day/kg/keVee, $A_1 = 0.14(0.09)$ and $t_0 = 107(152)$ days for the lower bin and $A_0 = 2.7(2.7)$ events/day/kg/keVee, $A_1 = 0.18(0.14)$ and $t_0 = 116(152)$ days for the higher.

A simple algorithm is used to merge any bin that contains fewer than ten events with the next highest bin. This procedure is repeated until no bin has fewer than ten events. In addition, the centers of the bins are shifted to take into account any deadtime in the experiment. Finally, the bin contents are efficiency-adjusted, the L-shell background in every bin is subtracted off, and the contents of the bin are converted to units of events/day/keVee. The error is based on the total (pre-subtraction) bin contents. This error is important for determining the weighting factors $W_i$. The power observed in the frequency $\nu = 2\pi / \text{year}$ can be converted to a significance for an oscillating signal. The probability of observing power $P$ at any particular frequency in data that do not contain an oscillating signal is $e^{-P}$, whereas the probability for observing power $P$ at any frequency (including the appropriate trial factor) is approximately $1/(1 + e^{P}N)$, where $N$ is the number of time bins [28].

**III. A STUDY OF MODULATION**

The central goal of this work is to understand the properties of a potential modulation in the CoGeNT data. Therefore, we begin by applying the statistical techniques presented above to analyze the properties of the modulation, without any assumptions of its origin. We reproduce the results in [2], where a time-binned analysis is done in the energy ranges 0.5–0.9 keVee and 0.5–3 keVee. If the last bin has fewer than ten events, it is merged with the penultimate bin.
Modulation Spectra: Nuclear-Recoil Singles

FIG. 9. Amplitude of modulation vs. energy, showing maximum-likelihood fits where the phase has been fixed and the modulated rates $M$ have been determined for both CoGeNT (light orange circles, vertical bars denoting the 68% confidence intervals) and CDMS (dark blue rectangles, with vertical height denoting the 68% confidence intervals). The phase that best fits CoGeNT (106 days) over the full CoGeNT energy range is shown on the left; the phase expected from interactions with a generic WIMP halo (152.5 days) is shown on the right. The upper horizontal scales show the electron-recoil-equivalent energy scale for CoGeNT events. The 5–11.9 keV$_{nr}$ energy range over which this analysis overlaps with the low-energy channel of CoGeNT has been divided into 3 equal-sized bins (CDMS) and 6 equal-sized bins (CoGeNT). In the right plot, we also show the DAMA modulation spectrum (small grey circles), following the method of Fox et al. [29], for which we must assume both a WIMP mass (here, $m = 10$ GeV/c$^2$) and a Na quenching factor (here, $q_{Na} = 0.3$). Lower WIMP masses or higher quenching factors can push the DAMA modulated spectrum towards significantly lower energies. No attempt has been made to adjust for varying energy resolutions between the experiments.

CoGeNT Mod

CDMS Mod
DAMA - Iodine should be tested in the near future by COUPP+KIMS - already tense

CoGeNT - Modulation tested by CDMS (none in higher energy range)
but can we go between experiments?

- If we see light WIMPs/WIMPs sensitive to the tail of velocity distribution, how do we compare experiments?
a comparable mass target: XENON
Three algorithms are used to reconstruct the (S1-S2) and S2-S1 coincidence signal from the three PMT arrays. The spatial dependence of the S1 signal due to the light collection, and placed above in the gas phase. The positions are corrected for non-uniform light collection is corrected for using a map.

The spatial dependence of the S1 signal due to the light collection, and placed above in the gas phase. The positions are corrected for non-uniform light collection is corrected for using a map.
Leff=0.19, q=0.08

Leff=0.27, q=0.06

important to view whole energy range
• simple kinematics can only take you so far
WANT MODEL INDEPENDENT CONSTRAINTS

Usual: make assumptions on this set limits on this

$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \left[ \sigma(E_R) \int_{v_{min}(E_R)}^{\infty} \frac{f(v)}{v} d^3v \right]$$

Alternative: set limits on this

Fox, Liu, NW
Two key points

\[ \frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \sigma(E_R) g(v_{min}) \]

1) all the energy dependence is in two functions

\[ g(v_{min}) = \int_{v_{min}}^{\infty} d^3 v \frac{f(v, t)}{v} \quad \sigma_{SI}(E_R) = \sigma_p \frac{\mu^2}{\mu_{n\chi}^2} \left( \frac{f_p Z + f_n (A - Z)}{f_p^2} \right)^2 F^2(E_R) \]

\[ v_{min} = \sqrt{\frac{M_T E_R}{2 \mu^2}} \] 2) there is a 1-1 mapping between velocity and energy
Suppose you want to compare two experiments, 1 and 2

\[ [E_1^{\text{low}}, E_1^{\text{high}}] \Rightarrow [v_1^{\text{low min}}, v_1^{\text{high min}}] \]

map the energy range studied in experiment 1 to a velocity space range

map velocity space range back to energy space for experiment 2

\[ [v_1^{\text{low min}}, v_1^{\text{high min}}] \Rightarrow [E_2^{\text{low}}, E_2^{\text{high}}] \]

we now have an energy range where the experiments are studying the same particles

\[ [E_1^{\text{low}}, E_1^{\text{high}}] \Leftrightarrow [E_2^{\text{low}}, E_2^{\text{high}}] \]
Signals, some without. The possible comparisons between these various experiments will be the subject of the subsequent sections. Using (11) scattering rates can be compared between experiments. However, to compare to actual experimental data the relative exposures, efficiencies and other detector-specific factors must be correctly taken into account. In the next section we describe in detail the experimental parameters necessary for the comparisons in the rest of the paper.

III. APPLICATIONS: A COMPARISON OF EXISTING EXPERIMENTS

The important consequences of (10) are immediately obvious. In principle, one can compare a positive signal at one experiment with one at another, or test the compatibility of a null result with a positive one. Unfortunately, ideal circumstances will rarely present themselves: additional backgrounds can complicate the extraction of $g(v)$, resolution can smear signals, or uncertainties in atomic physics (such as quenching factors) can complicate issues, making a precise extraction of the true $E_{NR}$ and hence $v_{\min}$ impossible. Furthermore, the signal may appear as a modulation (as in DAMA) limiting access to $g(v)$ to as summer/winter.

Finally, we see that the CRESST results are completely tested by the low-threshold XENON10 analysis, CDMS-Si (even with a 10 keV) threshold. While the nominal threshold, depending on the details of $L_{eff}$, of XENON10 ($\ll 5$ keV) and XENON100 ($\ll 6$ keV) is too high, both experiments can probe down to 4 keV with moderately reduced sensitivity, and energy smearing will give XENON sensitivity to the CRESST signal.

With these ranges in hand, we can proceed to compare the experiments directly. We shall see that if the potential signal is large enough, $g(v)$ can be extracted directly, even if $f(v)$ cannot be extracted with a reliability. In such cases, we can make slight stronger statements involving the spectra. However, even if $g(v)$ cannot be reconstructed, we can still make significant statements by integrating over the relevant velocity range.

A. Application I: Employing Spectra in Near-Ideal Situations (CoGeNT)

We consider first the situation when there is sufficient data to be able to extract a recoil spectrum, CoGeNT is an example of such an experiment, because the putative signal is quite large. We concentrate on the events below 3.2 keVee where the DM signal should be largest and there are few cosmogenic backgrounds. In this range, in addition to the possible DM signal at low energies, the data contains several clear cosmogenic peaks and a constant background above the peaks. We average the $[1.62-3.16$ keVee$]$ bins as an estimate of the constant background and subtract this from the bins in the $[0.42-0.92$ keVee$]$ range, which we then consider as the DM signal, after this subtraction there are 92 signal events before efficiency correction. This allows us to determine $g(v)$ or, equivalently, predict the rate at any other experiment in the equivalent energy range. One can easily observe from its definition that $g(v)$ is monotonically decreasing as a function of $v$ (see, for instance the XENON10 thresholds).

<table>
<thead>
<tr>
<th>Approx. range</th>
<th>O</th>
<th>Na</th>
<th>Si</th>
<th>Ar</th>
<th>Ge</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoGeNT (Ge): 2 - 4</td>
<td>4.3 - 8.6</td>
<td>3.9 - 7.8</td>
<td>3.6 - 7.2</td>
<td>3.0 - 6.0</td>
<td>2 - 4</td>
<td>1.3 - 2.5</td>
</tr>
<tr>
<td>DAMA (Na): 6 - 13</td>
<td>6.6 - 14</td>
<td>6 - 13</td>
<td>5.5 - 12</td>
<td>4.6 - 10</td>
<td>3.1 - 6.7</td>
<td>1.9 - 4.2</td>
</tr>
<tr>
<td>CRESST (O): 15 - 40</td>
<td>15 - 40</td>
<td>14 - 36</td>
<td>12 - 33</td>
<td>10 - 28</td>
<td>6.9 - 19</td>
<td>4.3 - 12</td>
</tr>
</tbody>
</table>

TABLE I: Conversion of energy ranges (all in keV) between various experiments/targets for a 10 GeV DM particle, using the expression in (7).
step 2

Invert:

\[
\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2m_\chi \mu^2} \sigma(E_R) g(\nu_{\text{min}}) \quad \Rightarrow \quad g(\nu) = \frac{2m_\chi \mu^2}{N_T M_T \rho \sigma(E_R)} \frac{dR_1}{dE_1}
\]

\[
\frac{dR_2}{dE_R}(E_2) = \frac{C_T^{(2)}}{C_T^{(1)}} \frac{F_2^2(E_2)}{F_1^2} \left( \frac{\mu_1^2 M_T^{(2)}}{\mu_2^2 M_T^{(1)}} E_2 \right) \frac{dR_1}{dE_R} \left( \frac{\mu_1^2 M_T^{(2)}}{\mu_2^2 M_T^{(1)}} E_2 \right)
\]

A direct prediction of the rate at experiment 2 from experiment 1
FIG. 2: The extracted CoGeNT signal (left and bottom axes) and the rate it is mapped to on a Xenon target (top and right axes) for $m = 10$ GeV (rescaled by form factors at the corresponding energies). The dashed line is the lower bound on the rate at low energies, using the monotonically falling nature of $\gamma (v_{\text{min}})$. This is not especially relevant for our analysis here, but would be likely relevant in situations where the other experiments could probe lower energies as well.

Since we will compare this with the XENON10 experiment, we choose $f_p = 1$ and $f_n = 0$, which is motivated from light mediators mixing with the photon, since it will give the most lenient bounds. Using (11) we can map the CoGeNT signal onto a Xenon target, and study the signal that would arise at XENON10. We show this in figure 2.
FIG. 9. Amplitude of modulation vs. energy, showing maximum-likelihood fits where the phase has been fixed and the modulated rates $M$ have been determined for both CoGeNT (light orange circles, vertical bars denoting the 68% confidence intervals) and CDMS (dark blue rectangles, with vertical height denoting the 68% confidence intervals). The phase that best fits CoGeNT (106 days) over the full CoGeNT energy range is shown on the left; the phase expected from interactions with a generic WIMP halo (152.5 days) is shown on the right. The upper horizontal scales show the electron-recoil-equivalent energy scale for CoGeNT events. The 5–11.9 keV$_{nr}$ energy range over which this analysis overlaps with the low-energy channel of CoGeNT has been divided into 3 equal-sized bins (CDMS) and 6 equal-sized bins (CoGeNT). In the right plot, we also show the DAMA modulation spectrum (small grey circles), following the method of Fox et al. [29], for which we must assume both a WIMP mass (here, $m = 10$ GeV/$c^2$) and a Na quenching factor (here, $q_{Na} = 0.3$). Lower WIMP masses or higher quenching factors can push the DAMA modulated spectrum towards significantly lower energies. No attempt has been made to adjust for varying energy resolutions between the experiments.
Modulation Spectra: Nuclear-Recoil Singles

Recoil Energy [keVnr] vs. Modulated Rate [kg day keVnr]

FIG. 9. Amplitude of modulation vs. energy, showing maximum-likelihood fits where the phase has been fixed and the modulated rates $M$ have been determined for both CoGeNT (light orange circles, vertical bars denoting the 68% confidence intervals) and CDMS (dark blue rectangles, with vertical height denoting the 68% confidence intervals). The phase that best fits CoGeNT (106 days) over the full CoGeNT energy range is shown on the left; the phase expected from interactions with a generic WIMP halo (152.5 days) is shown on the right. The upper horizontal scales show the electron-recoil-equivalent energy scale for CoGeNT events. The 5–11.9 keV$_{nr}$ energy range over which this analysis overlaps with the low-energy channel of CoGeNT has been divided into 3 equal-sized bins (CDMS) and 6 equal-sized bins (CoGeNT). In the right plot, we also show the DAMA modulation spectrum (small grey circles), following the method of Fox et al. [29], for which we must assume both a WIMP mass (here, $m$ = 10 GeV/c$^2$) and a Na quenching factor (here, $q_{Na}$ = 0.3). Lower WIMP masses or higher quenching factors can push the DAMA modulated spectrum towards significantly lower energies. No attempt has been made to adjust for varying energy resolutions between the experiments.

10 GeV
Table 2: Predicted modulation amplitudes for example nuclear targets, given the best-fit values for CoGeNT assuming a Maxwellian phase. The units are in counts/day/kg/keVnr for all columns, except that labelled CoGeNT where they are counts/day/kg/keVee. The equivalent energy ranges and rates for other targets are shown, assuming $m = 7$ GeV and spin-independent scattering proportional to $A^2$. Note that we have not included detector efficiencies or mass fractions in any of the predicted rates.

Table 3 shows the ranges of energies at other experiments that correspond to the CoGeNT energy bins: [0.5, 0.9], [0.9, 1.5], [1.5, 2.3], and [2.3, 3.1] keVee. Note that these energies are given in “electron equivalent” and correspond to [2.3, 3.8], [3.8, 6.1], [6.1, 8.9], and [8.9, 11.6] in nuclear recoil energies. These tables also show how the CoGeNT modulation amplitude in each energy bin translates to other experiments, assuming a 7 GeV WIMP with spin-independent scattering proportional to $A^2$. (Note that we have not included detector efficiencies or mass fractions in any of the predicted rates.) Let us consider each experiment in turn.

CDMS-Ge: A direct comparison can be made between the CoGeNT and CDMS count rates because they both have germanium targets. Using the results of the low-energy analysis of the CDMS experiment [16], we calculate an upper limit for the rate in each detector such that it has a 1.3% probability of having a lower rate. This gives a probability of 10% that any one of CDMS’s eight detectors has a lower rate than is observed. In each of the five energy bins, the strongest limit from all the detectors is chosen and we treat this as a 90% confidence limit.

Figure 13 shows that the count rates at CDMS are not low enough to constrain the CoGeNT modulation. However, the count rates are low enough that there should be modulation at a very high level in CDMS. Thus, even weak modulation constraints

The probability that the particular detector that sets the limit has a strong downward fluctuation is small, and so the confidence is actually better than 90%, but we treat it as a 90% C.L. to be conservative.

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### Table 2: Predicted Modulation Amplitudes

<table>
<thead>
<tr>
<th>Bin</th>
<th>CoGeNT</th>
<th>Ge</th>
<th>Na (Q=0.3)</th>
<th>Si</th>
<th>O</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[0.5,0.9]</td>
<td>[2.3,3.8]</td>
<td>[1.5,2.5]</td>
<td>[4.5,7.6]</td>
<td>[5.8,9.9]</td>
<td>[1.4,2.3]</td>
</tr>
<tr>
<td></td>
<td>0.90 ± 0.72</td>
<td>0.23 ± 0.18</td>
<td>0.078 ± 0.062</td>
<td>0.035 ± 0.028</td>
<td>0.011 ± 0.009</td>
<td>0.72 ± 0.58</td>
</tr>
</tbody>
</table>
if 15 events at CRESST above 15 keV...

A side comment: don’t forget CDMS-Si...
Constraints?

What if your experiment

a) doesn’t probe the same $v_{\text{min}}$ space?
b) doesn’t see anything?

Make a limit on $g(v)$
limiting $g(v)$

Note: $g(v)$ is monotonic!

$$g(v_{min}) = \int_{v_{min}}^{\infty} d^3v \frac{f(v, t)}{v}$$

also Fox, Kribs, Tait 1011.1910; McCabe 1107.0741; Frandsen et al 1111.0292; Herrero-Garcia, Schwetz, Zupan 1112.1627, 1205.1345; Gelmini + Gondolo 1202.6539

Lack of events Gives constraints at low E at high E
limiting \( g(v) \)

Most conservative assumption is theta function

\[
g(v; v_1) = g_1 \Theta(v_1 - v)
\]

i.e., do not assume velocity extends to known but exponentially suppressed values at high velocity

\[
\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \sigma(E_R) g_1 \Theta(v_1 - v_{\text{min}}(E_R))
\]
- (1) Pick some energy (velocity) upper bound
- (2) set a limit using your favorite technique (Poisson, Yellin...) for that velocity range on $\rho \sigma g_1 / m_\chi$
  - (i.e., just replace the usual $g(v)$ with a theta function)
constraining $g(v)$

$m_\chi = 10$ GeV

FIG. 7: A comparison of measurements and constraints of the astrophysical observable $g(v)$ [see relevant expressions in (1),(2),(8)] for $m_\chi = 10$ GeV: CoGeNT (blue), CDMS-Si (red, solid), CDMS-Ge (green, dot-dashed), XENON10 - MIN $L_{\text{eff}}$ (purple, dashed), and XENON10 - MED $L_{\text{eff}}$ (gray, dotted). CoGeNT values assume the events arise from elastically scattering dark matter, while for other experiments, regions above and to the right of the lines are excluded at 90% confidence. The jagged features of the CDMS-Ge curve arise from the presence of the two detected events.

However, one can exploit the fact that $g$ is a monotonically decreasing function, so for our constraints, we simply assume that $g(v)$ is constant below $v$, and assume a Poisson limit on the integral of (8) from the experimental threshold to $v$.

However, other techniques could also be used, see the Appendix for more details.

This approach with a $g(v)$ plot has numerous advantages over the traditional $m_\chi$ plots. It makes manifest what the relationships between the different experiments are in terms of what $v_{\min}$-space is probed, and shows (for a given mass) whether tensions exist.

Moreover, the quantity $g(v)$ is extremely tightly linked to the data, with only a scaling by form factor as in (8). Thus, unlike $m_\chi$ plots, which have a tremendous amount of processing in them, this provides a direct comparison of experimental results on the same...
we note that \( \tilde{\sigma} \) arise from a reasonable self-consistent model of the DM halo. Therefore we look at the range for which the best-fit DM regions of CRESST-II and CoGeNT do not overlap within their observational bounds (see the left panel of Figure 4). Moreover, it is not possible to find any model for the DM halo that provides a consistent description of all experiments. This choice must be different from the SHM; indeed many alternative models and overlaps of predictions for \( \tilde{\sigma} \) from all reasonable models of the galactic halo in Figure 4.

\[ m_\chi = 6 \text{ GeV} \]

\[ m_\chi = 12 \text{ GeV} \]

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We convert the energies of the three candidate events as a function of $S_1$, and the $S_1/S_2$ discrimination accepts it would depend on the WIMP mass when expressed conservative value of 0.6 since it is unclear why in Fig. 2.

We use the light $E$ analyses [15], and try to be conservative. We use only the T1Z5 detector [9], which gives the most efficient but more transparent than the method in Appendix.

We read the modulation amplitudes from [1]. For compound detectors like SIMPLE, Eq. (13) is equivalent but more transparent than the method in Appendix.

We consider results from XENON10 [7], which uses $F$ and maximum gap upper limits coincide. For XE100, the combined Poisson probability for Stage 1 and 2. For XE100 and CDMS bounds exclude all but the lowest isospin-symmetric couplings and WIMP mass of 9 GeV, the is based on the so-called $S_2$ ionization signal which al-

Further, the exposure is 730 kg days. We assume a maximum quenching factor, which requires to make bins larger than the number and scatterings of events. We combine the 36 bins from Fig. 1 of [9] into dependent, which requires to make bins larger than the number and scatterings of events.

The exposure is 730 kg days. We assume a maximum quenching factor, which requires to make bins larger than the number and scatterings of events. We combine the 36 bins from Fig. 1 of [9] into dependent, which requires to make bins larger than the number and scatterings of events. We combine the 36 bins from Fig. 1 of [9] into dependent, which requires to make bins larger than the number and scatterings of events.
limiting $g(v)$

- you have to pick a mass
- but there is an unambiguous map between masses $m_1 \leftrightarrow m_2$
- Could easily be output as supplement to usual $\sigma$-m plots
in summary

- DM searches are more robust than we might have guessed
- Can find stable particles that are not “the” DM in both direct and indirect detection
- As a complement to standard $\sigma$-m plots, we can directly compare direct detection experiments, in maps and $g(v)$ limits
• For astrophysics independent limits

• iodine interpretations of DAMA are being squeezed

• Important to see wide range of Xe energies to constrain scenarios (i.e., I can imagine $10^{-1}$ suppression easily but not $10^{-4}$)

• CDMS may not necessarily kill the possibility of a signal at CoGeNT but does seem to kill the consistency of CoGeNT and DAMA

• Evading XENON signals pushes you into the arms of CDMS-Si
in summary

• limits on $g(v)$ are simple, clear baseline constraints

• Three final asides:
  • There is a certain intellectual honesty that is compelled by plotting things in many physical parameter spaces
  • “plots” need no longer be static things (e.g., DMtools)
  • Without these model independent constraints Subir will never pay up