DARK MATTER IN THE ERA OF DATA

Neal Weiner
CCPP-NYU

PANIC 2011
DARK MATTER IN THE ERA OF DATA

Cosmology can tell us about high energy physics.

Can tell us about cosmology.
THE EVOLUTION OF DARK MATTER THEORY

Pre-2008

Theory driven:
Hierarchy problem (neutralino, WIMP, KKDM),
Strong CP (axion), etc
THE EVOLUTION OF DARK MATTER THEORY

2008+

Anomaly driven:
light WIMPs, inelastic WIMPs, leptophilic WIMPs, decaying WIMPs, light mediators, CiDM, quirky DM, asymmetric DM...
THE EVOLUTION OF DARK MATTER THEORY

2011+

Data driven?
THE IMPLICATIONS OF DATA

Indirect Detection

Direct Detection
THE IMPLICATIONS OF DATA

Indirect Detection

Direct Detection
DARK MATTER IN SPACE
DARK MATTER IN SPACE

Pulsars - maybe. Dark matter?
DARK MATTER IN SPACE

Pulsars - maybe. Dark matter?
But why such a hard spectrum?
DARK MATTER IN SPACE

Pulsars - maybe. Dark matter?
But why such a hard spectrum?
Where are the anti-protons?
A LIGHT (< GEV) SECTOR

Finkbeiner+NW ’08; Arkani-Hamed, Finkbeiner, Slatyer, NW ’09; Pospelov+Ritz ’09; Nomura+Thaler ’09
A LIGHT (< GEV) SECTOR

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Finkbeiner+NW ’08; Arkani-Hamed, Finkbeiner, Slatyer, NW ’09; Pospelov+Ritz ’09; Nomura+Thaler ’09
generates hard leptons by annihilations into a light mediator, no anti-protons
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generates hard leptons by annihilations into a light mediator, no anti-protons

Realization: We are amazingly ignorant of weakly coupled GeV scale physics!
MOTIVATE IN SPACE, ANSWER ON EARTH
MOTIVATE IN SPACE, ANSWER ON EARTH

Signature: $\phi \rightarrow \eta U, U \rightarrow t^+t^-$

$\Rightarrow \phi \rightarrow \eta e^+e^- \quad \eta \rightarrow \pi^+\pi^0\pi^0$

Main bckg: $\phi \rightarrow \eta \gamma^* \rightarrow \eta e^+e^-$

Analyzed sample: 1.5 fb$^{-1}$
MOTIVATE IN SPACE, ANSWER ON EARTH

Signature: \( \phi \rightarrow \eta U, \ U \rightarrow t^+t^- \Rightarrow \phi \rightarrow e^+e^- \; \eta \rightarrow \pi^+\pi^-\pi^0 \)
Main bkg: \( \phi \rightarrow \gamma \gamma^* \rightarrow e^+e^- \)
Analyzed sample: 1.5 fb\(^{-1}\)

Upper limits (90% CL)

\[
\sigma(e^+e^- \rightarrow W_D W_D \rightarrow (\ell\ell') (\ell\ell')) < 25-60 \text{ ab}
\]
\[
g_D e^2 < 10^{-9} - 10^{-7}
\]

No evidence of dark boson found yet!

Upper limits (90% CL)

\[\alpha'/\alpha = \varepsilon^2 \]

\[1107.2531 \]

KLOE
MAMI-A1

[Plot from MAMI-A1 PRL106(2011)251802]

TALK BY FEDERICO NGUYEN

TALK BY BERTRAND ECHENARD
MOTIVATE IN SPACE, ANSWER ON EARTH

**Signature:** $\phi \rightarrow \eta U, U \rightarrow t^+t^-$

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$\sigma(e^+e^- \rightarrow W_D W_D \rightarrow (l^+l^-) (l'^+l'^-)) < 25-60$ ab

$g_0 e^2 < 10^{-9} - 10^{-7}$

**TALK BY FEDERICO NGUYEN**

**TALK BY BERTRAND ECHEMARD**

**TALKS BY BOGDAN WOJTSEKHOWSKI, REBECCA RUSSELL**
Approach: A & Production and Background Kinematics

Production diagrams analogous to photon bremsstrahlung

Nucleus

QED Backgrounds

A & products carry full beam energy!

γ*

– Distinctive kinematics
– Assists in background suppression

N~α & x branching

N~α

Best kinematics to select events for A search

O(1)

Positron beam on internal Hydrogen target

22F

JLAB

Federnico Nguyen – Caltech

PANIC 2011 - Cambridge

Talk by Federico Nguyen

Talk by Bertrand Echenard

Talks by Bogdan Wojtsekhowski, Rebecca Russell

New probes of fundamental physics at the GeV scale!
MOTIVATE IN SPACE, ANSWER IN SPACE
MOTIVATE IN SPACE, ANSWER IN SPACE

downarrow

downarrow

downarrow

downarrow

PAMELA
today
MOTIVATE IN SPACE, ANSWER IN SPACE

early universe

PAMENA

today

Friday, July 29, 11
**FIG. 5:** CMB power spectra for three different scenarios: no DM annihilation, 1 GeV $\gamma$-$\gamma$, and 2500 GeV XDM $\mu$-$\mu$. The plots show the variation of $L_{(\ell+1)\ell}/2/\mu K^2$ as a function of $L$ for different models. The spectra are normalized to the WMAP5 fiducial cosmology.
Bertone, Iocco, Melchiori, '09; Slatyer, WIMP with thermal relic cross section and ATIC, by a factor of
ments from local substructure could also contribute an
ing the total power in electrons (at least when the power
measures of the high-energy spectrum of the annihilation
trons – but these annihilation products also do not con-
by annihilation products other than photons and elec-
out by WMAP5 even without taking into account astro-
small mass splittings among the dark sector particles,
plest example of the Sommerfeld enhancement with a
potential to act as an especially sensitive probe of DM mod-
one parameter, the average power injected around recombina
similar results for the TT (As described in the Introduction, the CMB has the po-
K
6000
0
500
1000
10000

no DM annihilation
1 GeV e' e
1000 GeV W+W
2500 GeV XDM µ+

L(L+1) C
π
L
1000 GeV
2500 GeV XDM µ+

−
1/2

planck

S
max

CVL

Ruled out by WMAP5

Slatyer, Padmanabhan, Finkbeiner, '09

Planck forecast

Padmanabhan + Finkbeiner, '05; Galli, Bertone, Iocco, Melchiori, '09; Slatyer, Padmanabhan, Finkbeiner, '09

1 XDM µ+µ− 2500 GeV, BF = 2300
2 µ+µ− 1500 GeV, BF = 1100
3 XDM µ+µ− 2500 GeV, BF = 1000
4 XDM e+e− 1000 GeV, BF = 300
5 XDM 4:4:1 1000 GeV, BF = 420
6 e+e− 700 GeV, BF = 220
7 µ+µ− 1500 GeV, BF = 560
8 XDM 1:1:2 1500 GeV, BF = 400
9 XDM µ+µ− 400 GeV, BF = 110
10 µ+µ− 250 GeV, BF = 81
11 W+W 200 GeV, BF = 66
12 XDM e+e− 150 GeV, BF = 16
13 e+e− 100 GeV, BF = 10

f (σv) [cm³ s⁻¹]

10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
10⁻²⁷

DM Mass [GeV]

1
10
100
1000
known to within a factor of $WIMP$ with thermal relic cross section and

FIG. 5: CMB power spectra for three different models of dark matter. The degree of uniformity between the models should have definitive result in 2012–2013!

Padmanabhan + Finkbeiner, '05; Galli, Bertone, Iocco, Melchiori, '09; Slatyer, Padmanabhan, Finkbeiner, '09

should have definitive result in 2012–2013!
tell us about cosmology.
THE IMPLICATIONS OF DATA

Indirect Detection

Direct Detection

see talk by Laura Baudis
COSMOLOGY UNDERGROUND

Why now?
The standard candles of WIMPs
The standard candles of WIMPs

Z-exchange
The standard candles of WIMPs

Z-exchange

Higgs-exchange
This result excludes a large fraction of previously unaccepted exposure weighted with the standard analysis which calculates the limit from the WIMP search region with an energy resolution governed by Poisson fluctuations. Uncertainties in the energy scale are indicated in the figure.

The impact of the level limit is shown in Figure 1. The energy resolution is shown as the thick blue line together with the best fit with all relevant systematic uncertainties. Detections from vMSSM are indicated at gP and kP vL Tshaded greenV. The sensitivity of this run Tshaded blue bandV is indicated at a WIMP mass of 20 kg GeV. The energy resolution is also shown as the thick blue line together with the best fit with all relevant systematic uncertainties.

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This result excludes a large fraction of previously unexplored parameter space of a WIMP. A weighted exposure, based only on events in the WIMP search region with an acceptance rate corrected for detection efficiency, is used. This limit is consistent with the absence of a signal above background and is also shown in the absence of a signal above background. The impact of systematic uncertainties is taken into account, and uncertainties in the energy scale as indicated in the analysis, governed by Poisson fluctuations, are also considered.

The sensitivity of this run is shown as the thick blue line together with the best limits from other experiments. The limits from XENON100 (2010) and CDMS are indicated at 95% confidence level. The new result challenges these sensitivities, and has a minimum significance at a WIMP mass of around 9 GeV/c^2. Moreover, the new result challenges these sensitivities, and has a minimum significance at a WIMP mass of 9 GeV/c^2.
$\sigma_{SI} = \left( \frac{\lambda}{0.1} \right)^2 \left( \frac{f}{0.3} \right)^2 \left( \frac{100\,\text{GeV}}{M_{\chi\chi}} \right)^2 \left( \frac{115\,\text{GeV}}{m_n} \right)^4 \times 5 \times 10^{-44}\,\text{cm}^2$

$\sim 2^2$ uncertainty

The impact of $\sigma_{SI}$ limit is shown in Figure 1. The sensitivity of this run is indicated at $\chi$ and $\theta$ $T_{\text{light red}}$. Without channeling, the limits from DAMA and EDELWEISS are also shown as the thick $T_{\text{blue}}$ line. The $T_{\text{green}}$ area is favored by $\chi T_{\text{gray}} V$ as derived with the Profile Likelihood method.

Porting XENON-I, we are grateful to LNGS for hosting and support. We gratefully acknowledge support from NSF, DOE, and the Volkswagen Foundation. This work was supported in part by the Weizmann Institute of Science, SNF, STSMc, DFG, and the Weizmann Institute of Science, and has a minimum energy resolution of $35\,\text{keV}$.

The cross-section is governed by Poisson fluctuations, and a density of $T_{\text{green}} V$ $[\text{V}]$ $T_{\text{gray}} V$ $[\text{V}]$ $T_{\text{green}}$ $[\text{V}]$ $T_{\text{gray}} V$. The results from vMSSM are indicated at $\chi$ and $k$. $T_{\text{light red}}$ $V$ $[\text{V}]$ $T_{\text{green}} V$ $[\text{V}]$ $T_{\text{gray}} V$. The limits from XENON100 (2011) shown as the thick $T_{\text{blue}}$ line together with the $\chi$ $T_{\text{green}}$ $V$ $[\text{V}]$ $T_{\text{gray}} V$. The interpretation of the DZm result as being due to light mass WIMPse is negligible at $k$ $k_{\text{light red}}$. $V$ $[\text{V}]$ $T_{\text{green}} V$ $[\text{V}]$ $T_{\text{gray}} V$. Without channeling, the limits from DAMA/I and CoGeNT are also shown.

The absence of a signal above background and is also shown.

This result excludes a large fraction of previously unexd of a $T_{\text{green}} V$ $[\text{V}]$ $T_{\text{gray}} V$. This limit is consistent with the two events around $k_{\text{keV}}$.

The cross-section is governed by Poisson fluctuations, and a density of $T_{\text{green}} V$ $[\text{V}]$ $T_{\text{gray}} V$ $[\text{V}]$ $T_{\text{green}} V$. The limits from XENON100 (2010) shown as the thick $T_{\text{blue}}$ line together with the $\chi$ $T_{\text{green}} V$ $[\text{V}]$ $T_{\text{gray}} V$. The interpretation of the DZm result as being due to light mass WIMPse is negligible at $k$ $k_{\text{light red}}$. $V$ $[\text{V}]$ $T_{\text{green}} V$ $[\text{V}]$ $T_{\text{gray}} V$. Without channeling, the limits from DAMA/I and CoGeNT are also shown.
This result excludes a large fraction of previously unexplored parameter space based only on events in the WIMP search region with an improved analysis which calculates the limit on the absence of a signal above background and is also shown in Figure 1. The impact of a level $[CL]$ limit is shown in Figure 1.

Uncertainties in the energy scale as indicated in Figure 2 are taken into account. The resulting 95% confidence interval (C.L.) limits are shown in Figure 3 at a WIMP mass of 10 GeV.

The energy resolution, governed by Poisson fluctuations, is taken into account. Figure 4 shows the sensitivity of this run. The limits from taking into account all relevant systematic uncertainties is also shown. As derived with the Profile Likelihood method, the new XENON100 (2011) result is the expected limit in the interpretation of the DAMA/Na and CoGeNT results as being due to light mass WIMPs.

We gratefully acknowledge support from the National Science Foundation (NSF), the DOE, and the following sponsors of XENON Science. We are grateful to LNGS for hosting and supporting XENON Science. We are grateful to LNGS for hosting and supporting XENON Science. We are grateful to LNGS for hosting and supporting XENON Science.

The figure shows the WIMP-nucleon cross section as a function of WIMP mass. The cross section is calculated using the formula:

$$\sigma_{SI} = \left(\frac{\lambda}{0.1}\right)^2 \left(\frac{\phi}{0.3}\right)^2 \left(\frac{100 \text{ GeV}}{M_{WIMP}}\right)^2 \left(\frac{115 \text{ GeV}}{m_n}\right)^4 \times 5 \times 10^{-44} \text{ cm}^2$$

The uncertainty is marked with a blue arrow, indicating a 2\sigma uncertainty.
HIGGS ↔ DM

Pinning down the Higgs mass pinpoints the Higgs-candle
This result excludes a large fraction of previously unaccepted events weighted with the standard analysis which calculates the limit weaker than expected. This limit is consistent with the two events around kg keV in Fig. 1.

The impact of the $C.L.$ limit is shown in Fig. 2. Incorporation of $\sigma_{\text{sens}}$ into the limit results in a confidence region $V$.

Uncertainties in the energy scale as indicated in the resolution governed by Poisson fluctuations is taken into account.

atyIz $[fl]$ Spin-independent elastic WIMP-nucleon cross-section as function of WIMP mass.

The limits from XENON100 shown as the thick blue line together with the $V$ band taking into account all relevant systematic uncertainties are

$$\sigma_{5\%} = \left( \frac{\Lambda}{0.1} \right)^2 \left( \frac{\ell}{0.3} \right)^2 \left( \frac{100 \text{GeV}}{m_\Omega m} \right)^2 \left( \frac{115 \text{GeV}}{m_n} \right)^4 \times 5 \times 10^{-44} \text{ cm}^2$$

$\uparrow \sim 2^2$ uncertainty
This result excludes a large fraction of previously unexcluded events from a typical exposure corrected to account for the impact of not including channeling. Uncertainties in the energy scale, as indicated in the figure, are taken into account. As a result, limits are consistent with the two events around 9 keV in Fig. 1. The sensitivity of this run is shown as the thick, shaded blue band. The limits from XENON100 (2010) are indicated at 90% C.L. for each mass point. Results from vMSSM are indicated at 95% C.L.
This result excludes a large fraction of previously unexcluded acceptance-corrected exposure weighted with the specified ones from the standard analysis which calculates the limit two events around kg keV in the WIMP search region with an absence of a signal above background and is also shown in the absence of a signal above background and is also shown in the presence of e ek m. The impact of a level [CL] limit is shown in the absence of a signal above background and is also shown in the presence of e ek m as well as uncertainties in. The sensitivity of this run is shaded blue band [CL] limit is shown in the absence of a signal above background and is also shown in the presence of e ek m as well as uncertainties in.
Figure 1: Experimental model-independent residual rate of the single-hit scintillation events, measured by DAMA/LIBRA, in the (2 – 4), (2 – 5) and (2 – 6) keV energy intervals as a function of the time. The zero of the time scale is January 1st of the first year of data taking of the former DAMA/NaI experiment [15]. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves are the sinusoidal functions $A \cos(\omega(t-t_0))$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, with a phase $t_0 = 152.5$ days (June 2nd), and with modulation amplitudes, $A$, equal to the central values obtained by best fit over the whole data including also the exposure previously collected by the former DAMA/NaI experiment: cumulative exposure is 1.17 ton × yr (see also ref. [15] and refs. therein). The dashed vertical lines correspond to the maximum expected for the DM signal (June 2nd), while the dotted vertical lines correspond to the minimum. See text.
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What is it: annual modulation in scintillation events in 100/250 kg NaI(Tl) crystal - DM?
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• What’s to like: single hit, stable phase, low energy, no candidate “conventional” explanations
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- What’s to like: single hit, stable phase, low energy, no candidate “conventional” explanations

- What’s not to like: null results from other exps, data are still unavailable, no event discrimination
COGENT
• What is it: events in an ionization experiment, x10 larger than expected background - DM?
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• What’s to like: excellent energy resolution/calibration, good statistics
• What is it: events in an ionization experiment, x10 larger than expected background - DM?

• What's to like: excellent energy resolution/calibration, good statistics

• What's not to like: no discrimination, hasn't been mercilessly beaten for a decade, no clear corroborating features [yet] (modulation), null results from other exps
CRESST

Signal region

Light Yield

Energy [keV]
• What is it: an excess of events in a CaWO₄ detector, consistent with Oxygen scattering (~10-40 keV)
• What is it: an excess of events in a CaWO₄ detector, consistent with Oxygen scattering (~10-40 keV)

• What’s to like: good discrimination vs electron recoil, not muon induced neutrons
• What is it: an excess of events in a CaWO$_4$ detector, consistent with Oxygen scattering (~10-40 keV)

• What’s to like: good discrimination vs electron recoil, not muon induced neutrons

• What’s not to like: lots of events at high (15 keV+ energy, should have been seen elsewhere), signal lies left, right, above and below clear background sources, still have only seen 2 of 9 detectors, naively low energy looks too clean to be WIMP
• The same beast?

don’t really line up, but within spitting distance
Light neutralinos with large scattering cross sections in the minimal supersymmetric standard model

Eric Kuflik, Aaron Pierce, and Kathryn M. Zurek
Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109
(Dated: July 20, 2010)

Motivated by recent data from CoGeNT and the DAMA annual modulation signal, we discuss collider constraints on minimal supersymmetric standard model neutralino dark matter with mass in the 5-15 GeV range. The lightest superpartner (LSP) would be a bino with a small Higgsino admixture. Maximization of the dark matter-nucleon scattering cross section for such a weakly interacting massive particle requires a light Higgs boson with $\tan \beta$ enhanced couplings. Limits on the invisible width of the $Z$ boson, combined with the rare decays $B^\pm \to \tau \nu$, and the ratio $B \to D\tau\nu/B \to D\ell\nu$, constrain cross sections to be below $\sigma_n \lesssim 5 \times 10^{-42}$ cm$^2$. This indicates a higher local Dark Matter density than is usually assumed by a factor of roughly six would be necessary to explain the CoGeNT excess. This scenario also requires a light charged Higgs boson, which can give substantial contributions to rare decays such as $b \to s\gamma$ and $t \to bH^+$. We also discuss the impact of Tevatron searches for Higgs bosons at large $\tan \beta$. 
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interaction through a light sector?
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WHAT WOULD IT BE?

interaction through a light sector?
cue GeV searches again...
One recent plot...

![WIMP-Nucleon Cross Section vs. WIMP Mass graph]

- **DAMA/Na**
- **CoGeNT**
- **CDMS**
- **EDELWEISS**
- **XENON100 (2010)**
- **XENON100 (2011)**
- **Buchmueller et al.**

The plot shows the WIMP-Nucleon Cross Section [cm$^2$] as a function of WIMP Mass [GeV/c$^2$]. Different experiments like DAMA/Na, CoGeNT, CDMS, EDELWEISS, XENON100 (2010), XENON100 (2011), and Buchmueller et al. are plotted, each with a specific sensitivity region. The graph includes uncertainties in the energy scale as indicated in the solution, governed by Poisson fluctuations, and has a minimum sensitivity of this run.
<table>
<thead>
<tr>
<th>Number</th>
<th>Title</th>
<th>Authors</th>
<th>Date</th>
<th>Temporary entry</th>
<th>Reference Details</th>
</tr>
</thead>
</table>
WHAT ARE THE NEW KEY RESULTS?
TENSIONS? EXCLUSIONS?

**Graphs and Data Visualization**

1. **Graph 1**: Counts (keV·kg⁻¹·d⁻¹) vs. Ionization energy (keVee)
   - Data points for different sources are shown, with error bars.
   - Axes: Ionization energy (keVee) on the x-axis, Counts (keV·kg⁻¹·d⁻¹) on the y-axis.

2. **Graph 2**: Log of (S2/S1) vs. Energy [keVnr]
   - Data points and a fitted line are displayed.
   - Axes: Energy [keVnr] on the x-axis, Log of (S2/S1) on the y-axis.

3. **Graph 3**: Left vs. Energy [keVnr]
   - Data points from various sources are plotted.
   - Axes: Energy [keVnr] on the x-axis, Left on the y-axis.
TENSIONS? EXCLUSIONS?

modulation?
CDMS LOW THRESHOLD
CDMS LOW THRESHOLD

![Graphs showing ionization yield versus recoil energy and WIMP mass versus WIMP-neutron cross-section]
CDMS LOW THRESHOLD

![Graphs and data plots showing the results of CDMS low threshold experiments.](image)

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**Figure 1.** (Color online). Comparison of the energy spectra for different detectors and experiments. The inset shows the measured nuclear-recoil acceptance, which does not include a correction for the nuclear-recoil band (solid) compared to the ground estimate (dashed), surface events (+), and bulk ground model involving significant backgrounds.

**Figure 2.** (Color online). Events in the ionization-yield versus recoil-energy plane for T1Z5. A band of events with ionization yield below the bulk electron recoils, with an efficiency, averaged over all detectors. The limits do not depend strongly on the extrapolation that systemic errors are di.

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**Results and Analysis:**

- Identified above 10 keV implies that 10–20% of the candidates are nuclear recoils but below the bulk electron recoils, with an efficiency, averaged over all detectors.
- Event rate (keV day$^{-1}$) for neutron-only scattering [20]. An escape velocity of 544 km/s was used for the CDMS and XENON100 exclusion limits.
- The limits do not depend strongly on the extrapolation of spin-independent elastic scattering of low-mass WIMPs.

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**References:**

CDMS LOW THRESHOLD

Same target. Appears to exclude CoGeNT...
WHERE ARE WE W/ COGENT

- Limits from CDMS, SIMPLE, XENON (ionization+scintillation, ionization only) seem strong

- Current: already 458 days recorded (vs 56); CoGeNT-4 installation this summer. Modulation?
modulation?
Exponential “DM” signal

modulation?
Exponential “DM” signal

Search for modulation

modulation?
LOOK IN FULL DATA

provided by CoGeNT collaboration
0.5 – 1.5 keVee (eff. corrected)

1.5 – 3.1 keVee (eff. corrected)
SHM predicts ~few %

87% (90%)

97.7% (98.3%)

0.5 – 1.5 keVee (eff. corrected)

1.5 – 3.1 keVee (eff. corrected)
modulation appears at low energies
• No significant diurnal modulation either
ARE THERE UNCERTAINTIES?

\[
\frac{dR}{dE_R} = N_T M_N \frac{\rho_\chi \sigma_n}{2m_\chi \mu_{ne}^2} \frac{(f_p Z + f_n (A - Z))^2}{f_n^2} F^2[E_R] \int_{\beta_{\text{min}}}^{\infty} \frac{f(v)}{v} dv.
\]
ARE THERE UNCERTAINTIES?

\[
\frac{dR}{dE_R} = N_T M_N \frac{\rho \sigma_n}{2m_\chi \mu_{ne}^2} \left( f_p Z + f_n (A - Z) \right)^2 F^2[E_R] \int_{\beta_{\text{min}}}^{\infty} \frac{f(v)}{v} dv.
\]

particle physics

PP: Type of interaction, mediator
ARE THERE UNCERTAINTIES?

**nuclear physics**

\[
\frac{dR}{dE_R} = N_T M_N \frac{\rho \sigma_n (f_p Z + f_n (A - Z))^2}{2m_\chi \mu_{ne}^2} \frac{f^2}{f_n^2} F^2[E_R] \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv.
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**particle physics**

PP: Type of interaction, mediator

NP: Form factor - when de Broglie wavelength of interaction is comparable to nuclear size - resolve that it is not a point particle \((q^2 \sim 2 M_N E_R \Rightarrow E_R \sim 100 \text{ keV})\) *(Duda, Gondolo+Kemper 0608035)*
ARE THERE UNCERTAINTIES?

\[
\frac{dR}{dE_R} = N_T M_N \frac{\rho \sigma_n (f_p Z + f_n (A-Z))^2}{2m_\chi \mu_{\chi n}^2} \frac{F^2 (E_R)}{f_n^2} \int_{f_n \beta_{\min}}^{\infty} \frac{f(v)}{v} dv.
\]

**nuclear physics**

**particle physics**

**astrophysics**

PP: Type of interaction, mediator

NP: Form factor - when de Broglie wavelength of interaction is comparable to nuclear size - resolve that it is not a point particle \(q^2 \sim 2 M_N E_R \Rightarrow E_R \sim 100 \text{ keV}\) (Duda, Gondolo+Kemper 0608035)

AP: How many particles are there at a given velocity *in the Earth frame*
WIMP–nucleon cross section $\sigma_{SI} [\text{cm}^2]$

- Dashed: $90\%$
- Solid: $3\sigma$

DAMA (quenching $\pm 10\%$)

$\nu_0 = 220 \text{ km/s}, \nu_{\text{esc}} = 550 \text{ km/s}$
$\sigma_{\text{SI}}$ WIMP-nucleon cross section [cm$^2$]

- **Dashed**: 90 %
- **Solid**: 3$\sigma$

**DAMA** (quenching $\pm$ 10 %)

$v_0 = 220$ km / s, $v_{\text{esc}} = 550$ km

**CDMS low-thr**

**CoGeNT mod (constrained)**

**CoGeNT spect + mod**

**LCoGeNT mod**

**H constrained**

**LCoGeNT spect**

**Mod Amplitude from 1.5–3.1 keVee (dru)**

Mass (GeV)

Friday, July 29, 11
If the modulation is from a WIMP it’s not from a Maxwellian halo.
If the modulation is from a WIMP it’s not from a Maxwellian halo

IMHO you should (judiciously) ignore plots that look like this
many models sensitive to highest velocities
COMPARING EXPERIMENTS IN THE ERA OF DATA

- WIMP searches have historically been measured by how well they find nothing
- With events, need new approaches to compare experiments
III. APPLICATIONS: A COMPARISON OF EXISTING EXPERIMENTS

The important consequences of $t_{10}$ 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 $v_{\text{min}}$, resolution can smear signals, or uncertainties in atomic physics such as quenching factors can complicate issues making a precise extraction of the true $E_{\text{NR}}$ and hence $v_{\text{min}}$ impossible. Furthermore, the signal may appear as a modulation as in DAMA limiting access to $v_{\text{ut}}$ as summer/winter.

FIG. 1: $v_{\text{min}}$ thresholds for various experiments. Solid bands are CRESST Oxygen band, 15-40 keV (red, top), DAMA Na band 6.7-13.3 keV (green, middle), CoGeNT Ge 1.9-3.9 keV (blue, bottom). Constraints are Xenon 1, 2 and 5 keV (dashed, dotted, and dot-dashed, thick blue), and CDMS-Si 7 and 10 keV, (dot-dashed and dashed, thin red).
INTEGRATING OUT ASTROPHYSICS

\[ g(\nu_{\text{min}}, t) = \int_{\nu_{\text{min}}}^{\infty} d\nu \frac{f(\nu, t)}{\nu} \]

\[ [E_{\text{low}}^{(1)}, E_{\text{low}}^{(1)}] \leftrightarrow [\nu_{\text{min}}^{\text{low}}, \nu_{\text{min}}^{\text{high}}] \leftrightarrow [E_{\text{low}}^{(2)}, E_{\text{high}}^{(2)}], \]

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

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

A direct prediction of the rate at experiment 2 from experiment 1

Liu, Fox, NW '10
Related: Fox, Kribs, Tait '10
FIG. 3: The number of events predicted at XENON10 by the possible DM signal at CoGeNT for 3 cases of $L_{\text{eff}}$: MIN, MED, and MAX. The black line is the 90% C.L. upper limit on the number of events allowed by XENON10 data.

Since there were no events at XENON10 in the energy range corresponding to the CoGeNT range, we see that independent of all astrophysical assumptions, only for $L_{\text{MIN}}$ are CoGeNT and XENON10 consistent at the 90% C.L. In the MIN case, $m < 1$ GeV allows CoGeNT to evade XENON10. For MED and MAX cases, the predicted signal at XENON10 would be too large by a significant amount, excluding the elastic SI WIMP scattering interpretation by more than an order of magnitude.

Because of the uncertainties associated with extracting the value of $L_{\text{eff}}$ at low energies, additional attempts have been made to probe the low energy region with Xenon experiments. In particular, we examined data from XENON10 and used only the ionization signal, which is typically larger than S1 and can allow a more reliable signal at low energies.

The value of the charge yield, drift electrons per keV, was extracted from Monte Carlo results. Using the values there, the equivalent energy range for CoGeNT is approximately 6 to 16 m GeV for electrons above the q electron threshold. Assuming a value of $Q_y = 7$ electrons/keV for instance, the threshold of q electrons at XENON10 only captures a portion of the signal predicted by CoGeNT.

While the q electron cut corresponds to a particular value of energy in principle, Poisson fluctuations smear this. Nonetheless, an interesting question is the expected rate on the target used by CoGeNT with kg d of exposure. This is most easily phrased in terms of the question of what charge yield can make these experiments consistent. Assuming a constant charge yield over the energy question now, we can calculate the likelihood based on Poisson fluctuations of events appearing in the XENON10 experiment, which we show. One sees that one would require a charge yield of roughly $Q_y < 0.1$ electrons/keV for consistency, much lower than the value of $Q_y = 7$ extracted by CoGeNT. Whether such a significant difference is reasonable will no doubt be subject to a great deal of discussion.

B. Application II: Total Rate Comparisons in Sub-Optimal Situations (CRESST)
The above situation with CoGeNT is close to ideal: low background, high statistics, good energy resolution, and calibration. In contrast, there are often situations with significantly less ideal characteristics. In particular, it may be that not enough is known about the background or the data itself to be able to extract a recoil spectrum for DM, but we shall see it is nonetheless possible to say something about the total number of DM scatters. This is...
agreement is surprisingly good...
Table 2: Modulation amplitudes, for all columns except that labelled CoGeNT the units are counts/day/kg/keVnr, in the CoGeNT column the units are counts/day/kg/keVee, for four bins assuming a Maxwellian phase, the equivalent energy ranges and rates for other targets, assuming $m_X = 7$ GeV and spin-independent scattering cross sections proportional to $A^2$. Note that we have not included detector efficiencies or mass fractions in any of the predicted rates.
Halo-independent:

CDMS-Si, CDMS-Ge ~ 100% modulation

XENON100 ~ 10-30+ events (unless Leff < 0.4)

Tensions from light targets (Si) and heavy (Xe) so neutron-proton interference doesn’t help
AN EYE TOWARDS CRESST...

Energy spectrum of accepted events

What are these?
2011 (REMAINING)

- CRESST paper (soon? by Sept?)
- More XENON+ZEPLIN data
- COUPP?
- CDMS modulation study?
- No (obvious) WIMPs at the LHC
DARK MATTER IN THE ERA OF DATA
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• Data is rolling in for DM (indirect, direct, collider)
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• Amazingly, it’s not all negative
DARK MATTER IN THE ERA OF DATA

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• But the positive stuff is hard to interpret
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  • large modulation, strange events at high energy
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  • large modulation, strange events at high energy

• Shouldn’t compare to limits that use simple halo models
DARK MATTER IN THE ERA OF DATA

can tell us about cosmology can tell us about high energy physics

Friday, July 29, 11
DARK MATTER IN THE ERA OF DATA

• Very confusing
DARK MATTER IN THE ERA OF DATA

• Very confusing

• The era of data... needs more data...
DARK MATTER IN THE ERA OF DATA

- Very confusing
- The era of data... needs more data...
- and we’ll have it (soon)

High-energy physics can tell us about cosmology.
DARK MATTER IN THE ERA OF DATA

can tell us about cosmology can tell us about high energy physics
can tell us about cosmology can tell us about high energy physics
can tell us about cosmology can tell us about high energy physics
time to complete the circle!

Friday, July 29, 11
OTHER EXPLANATIONS OF DAMA

• What if it’s not a light WIMP?
“INELASTIC” DARK MATTER


• With dark forces, DM-nucleus scattering must be inelastic

• If dark matter can only scatter off of a nucleus by transitioning to an excited state (100 keV), the kinematics are changed dramatically

\[
\frac{\mu \chi N v^2}{2} > \delta
\]
EFFECTS ON WIMP SEARCHES

\( n(v) \): velocity distribution of WIMPs

Heavy targets

visible to DAMA

visible to DAMA and CDMS

Enhanced modulation

Modified spectrum

Xenon spectrum
Tight constraints from CDMS, XENON (shown), also ZEPLIN,

Assume Maxwellian - must be in the highly modulated regime
Inelastic Dark Matter

WIMP nucleon cross section [pb]

- CRESST (all det.)
- DAMA allowed (90%)
- DAMA allowed (3σ)

δ = 80 keV

March 2010 (WONDER)
Inelastic Dark Matter

WIMP nucleon cross section [pb]

- CRESST (all det.)
- DAMA allowed (90%)
- DAMA allowed (3σ)

δ = 80 keV

WIMP mass [GeV/c²]

March 2010 (WONDER)

July 2010 (IDM)
Currently excluded by ~1.5 assuming MB halo
XENON100+IDM
The XENON100 experiment has just reported results for 45 live days of a dark matter search. The same data are used here to constrain the iDM model. Single scatter events observed in the 12 kg liquid xenon fiducial volume are shown in figure g. Three events fall in the predefined WIMP search region for dark matter interactions, which is compatible with the background expectation described in fig. Hence, no significant signal is observed.

Energy (keV) 10 20 30 40
(S2/S1)-ER mean 10 \log -1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4
S1 [PE] 5 10 15 20 25 30 35

FIG. Events observed in the XENON100 experiment passing all analysis cuts with 21 live days of data and a fiducial mass of 12 kg. 10 events are found in the predefined WIMP search region. To extract the WIMP allowed region, the procedure described in fig has been followed, using a quenching factor of 2 for iodine and not considering ion channeling. The goodness of fit test of the data has been used for computing the lower confidence limit on the cross section. The resulting cross section can be used to predict a scatter rate in XENON100, as an example. Figure i shows the expected spectrum in XENON100, taking into account exposure and acceptance, and the lower confidence level cross section from the WIMP allowed region. The WIMP velocity has been averaged considering the data taking period to account for annual modulation effects. With this data, a limit on \( \sigma \) can be extracted for every pair of \( M \) and \( \tau \) values using both the Feldman-Cousins method or the optimum gap method. We assume a Maxwellian WIMP velocity distribution with characteristic velocity \( v_0 \) \( \approx 250 \) km/s and escape velocity \( v_{\text{esc}} \) \( \approx 600 \) km/s, a local WIMP density of \( 0.3 \) GeV/cm\(^3\), and the Helm form factors.

Figure i shows the extracted limit for \( \sigma \) keV using the Feldman-Cousins method. The WIMP allowed region is also shown in the plot.

The systematic application of the procedure described above to the data for all the points in the c-M plane space results in the gray area in figure (i) showing the allowed parameter space. Previous constraints on iDM from CDMS by RESST or EDELWEISS results involved target nuclei with different masses than iodine, which thus sample a different region of the WIMP velocity distribution. Thanks to the similar mass of xenon and iodine nuclei, constraints inferred from liquid xenon experiments are robust with respect to uncertainties in halo parameters. This has already been shown by ZEPLIN III, which however leaves a very small space.

Friday, July 29, 11
XENON100+IDM
THE TARGETS OF DARK MATTER DETECTION

Should consider magnetically coupled iDM

Chang, NW, Yavin '10

Also: SDiDM Kopp, Schwetz, Zupan '09
<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atomic mass (m_a/u)</th>
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<tbody>
<tr>
<td>$^{127}$I</td>
<td>126.904473 (5)</td>
<td>100</td>
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\[ \mu_{Xe} \approx 0.5 \]
\[ \mu_I \approx 2.8 \]
\[ \Rightarrow \left( \frac{\mu_I}{\mu_{Xe}} \right)^2 \approx 30 \]

Requires
\[ N_X \approx 10^2 N_N \]
### Isotope Properties

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Requires

\[ \mu_X \approx 10^2 \mu_N \]

---

**NB: Charge-dipole scattering**
AN IMPURE THOUGHT

DAMA is not NaI but NaI(Tl)
• Tuned at 5% level

• Requires $10^3$ larger cross sections and larger
OTHER IDEAS
The xenon based experiments of ZEPLIN and XENON may also present strong constraints. The splitting of the appropriate energy levels in $^{122}_{55}Cs$ is $\sim 500$ keV, so it is possible that no resonance is available for these xenon experiments. However, it is difficult to be sure due to the comparable binding energies of iodine and xenon and the preponderance of different isotopes of xenon present in the detectors. For simplicity we have concentrated throughout on one of the high abundance isotopes. Furthermore, rDM has the feature of increased modulation (see Fig. 2) and the XENON data was taken between October and February, which somewhat weakens their bounds on rDM. Similar to the case II for DAMA, the spectral lines corresponding to the isotopes of cesium may be the dominant signals at the ZEPLIN and XENON. A more detailed study of the spectra and number of the predicted events in other experiments and the allowed resonance speeds for each experiment is warranted.
MOMENTUM DEPENDENT SPIN DEPENDENT SCATTERING

enormous cross sections - a model?  

Chang, Pierce NW
We propose a dark matter model in which the signal in direct detection experiments arises from electromagnetic not nuclear energy deposition. This can provide a novel explanation for DAMA while avoiding many direct detection constraints. The dark matter state is taken nearly degenerate with another state. These states are naturally connected by a dipole moment operator, which can give both the dominant scattering and decay modes between the two states. The signal at DAMA then arises from dark matter scattering in the Earth into the excited state and decaying back to the ground state through emission of a single photon in the detector. This model has unique signatures in direct detection experiments. The density and chemical composition of the detector is irrelevant, only the total volume affects the event rate. In addition, the spectrum is a monoenergetic line, which can fit the DAMA signal well. This model is readily testable at experiments such as CDMS and XENON non if they analyze their low energy electronic recoil event.

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I. Introduction and Overview

II. Luminous Dark Matter

A. Results

B. Generating Inelastic Dipole Interactions

III. Constraints

A. Upscattering

B. Excited State Decay

XENON non


Electronic signal proportional to volume of detector
ELECTRON SCATTERING

Luminous Dark Matter

Brian Feldstein,1 Peter W. Graham,2 and Surjeet Rajendran3

proportional to volume

Friday, July 29, 11
\[
\left( 0.04 \frac{cpd}{kg} \times 24 \times 9.7 \frac{kg}{\text{crystal}} \right) \times 200 \pi \text{ cm}^2 \times 30 \text{ cm}
\]

\[
(10.2 \text{ cm})^2 \times 25.4 \text{ cm} \times 24
\]

\[
\approx 2.7 \text{ counts day}^{-1}
\]
\[
\left(0.04 \frac{cpd}{kg} \times 24 \times 9.7 \frac{kg}{crystal}\right) \times 200 \pi \text{ cm}^2 \times 30 \text{ cm} \\
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\]

\[ (10.2 \text{ cm})^2 \times 25.4 \text{ cm} \times 24 \]

\[ \approx 2.7 \text{ counts/day} \]
SHIFT COUPLINGS TO HELP?

![Graph showing the relationship between $(f_p - f_n)$ and $(f_p + f_n)$ with a central value and bounds.]

Chang et al 1004.0697

Feng, Kumar, Marfatia, Sanford 1102.4311
SHIFT COUPLINGS TO HELP?

XENON vs CoGeNT
(min ~ 1/20)

XENON vs DAMA(Na)
(min ~ 1/100)
This result excludes a large fraction of previously unexplored parameter space of a WIMP of accepted corrected exposure weighted with the spectrum calculated using 1.17×10^{-6}pb/natural atom. This limit is consistent with the absence of a signal above background and is also shown for a WIMP mass of 80 GeV/c^2.

The impact of these sensitivities is incorporated into the limit on the WIMP-Nucleon Cross Section as a function of WIMP mass and has a minimum around 20 GeV/c^2. The limit at higher masses is due to the presence of CoGeNT and CDMS. Due to the presence of other experiments, the new result challenges the interpretation of the data from these experiments.

We gratefully acknowledge support from the following institutions: NSFC, DDE, Weizmann Institute of Science, STCSM, DFG, Fondazione S. Vinci, Zanasi e Righi, Volkswagen Foundation, FCT, Région des Pays de Loire, CNRS/INSU, and the Mexican National Council for Science and Technology (CONACyT).
WHERE IS THE MODULATION?
Q_{Na}=0.5 interpretations disfavored
mSUGRA Models Passing B-physics $g_\mu - 2$, LEP and $0.09 \leq \Omega h^2 \leq 0.13$, with ATLAS Constraints

ATLAS Un-constrained
ATLAS Constrained (95% CL)
Mixed Region

DAMA
CoGeNT
CDMS
Xenon-100
Xenon-1T
SuperCDMS 1000

Akula et al 2011

The LHC begins to probe...