Dark Matter Direct Detection: Recent Efforts in Reconciliation

Danielle H. Speller

University of California, Berkeley

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Physics 290E

Overview

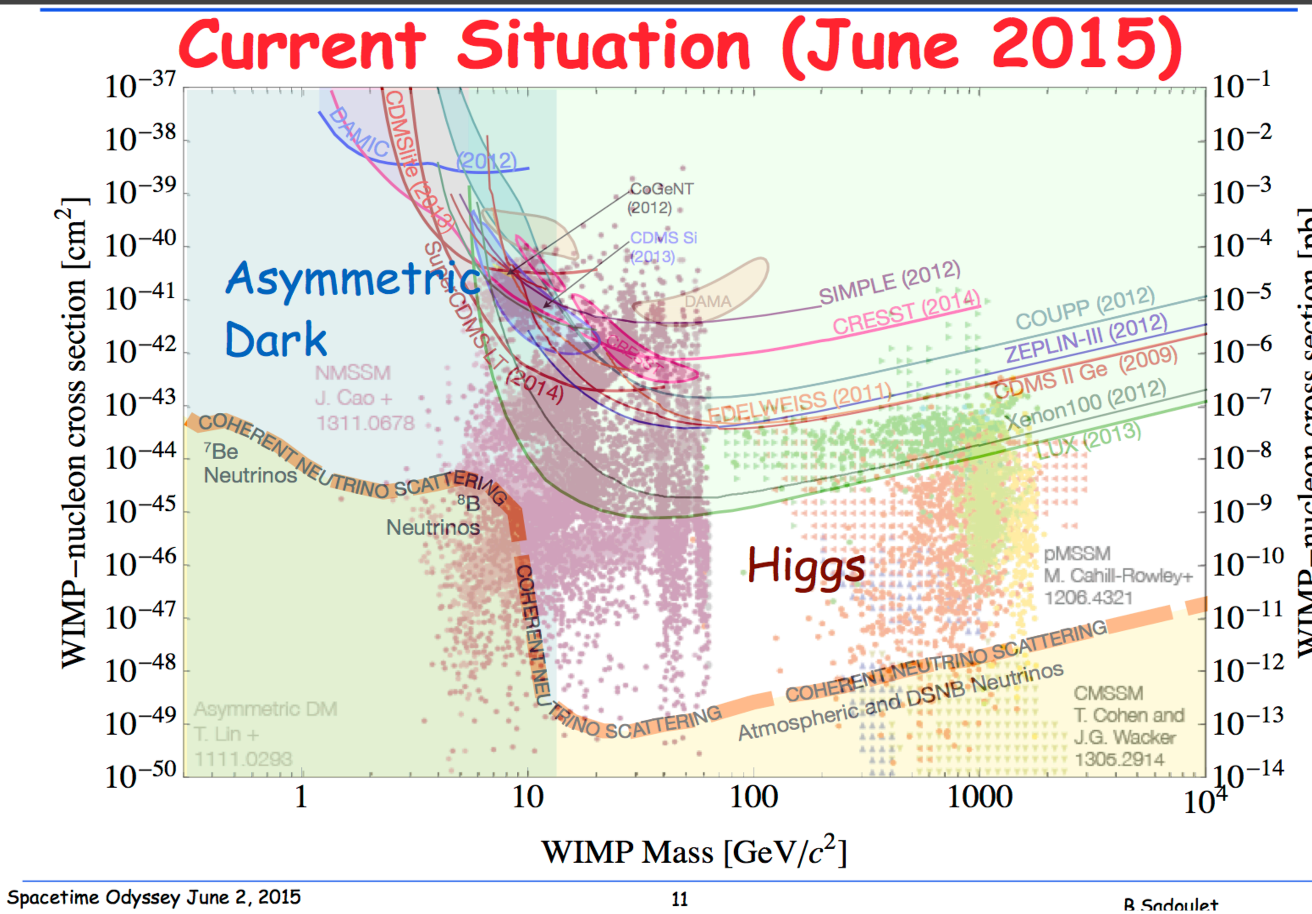
- State of the Field: Leading limits in direct searches for WIMP dark matter
- Tension between results
- Challenges of interpretation
- General reconciliation approaches
- A subset of recent studies

Basic Assumptions

- Spin-Independent Elastic Scattering
- Isospin-conserving
- Standard Halo Model (SHM)
- Truncated Maxwellian Distribution
  - v_{esc} = 544 km/s
  - v_0 = 220 km/s
  - v_{sun} = 232 km/s
  - v_{orb} = 30 km/s
  - ρ_{DM} = 0.3 GeV/[$c^2 cm^3$]

Assumptions as summarized in arXiv:1311.2082v2

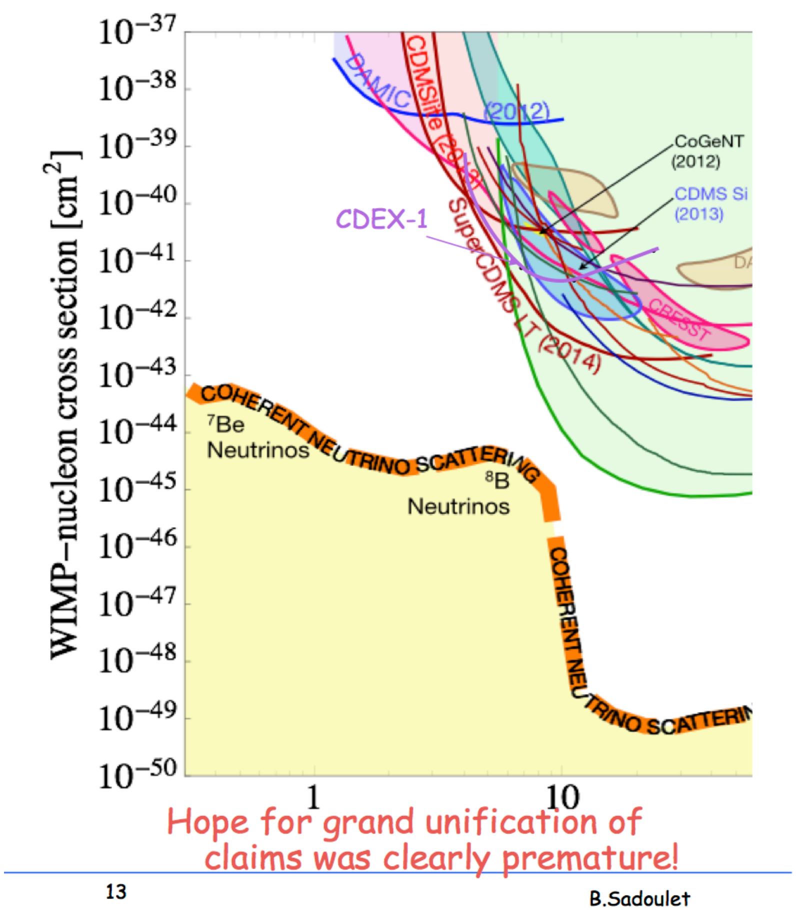
State of the Field



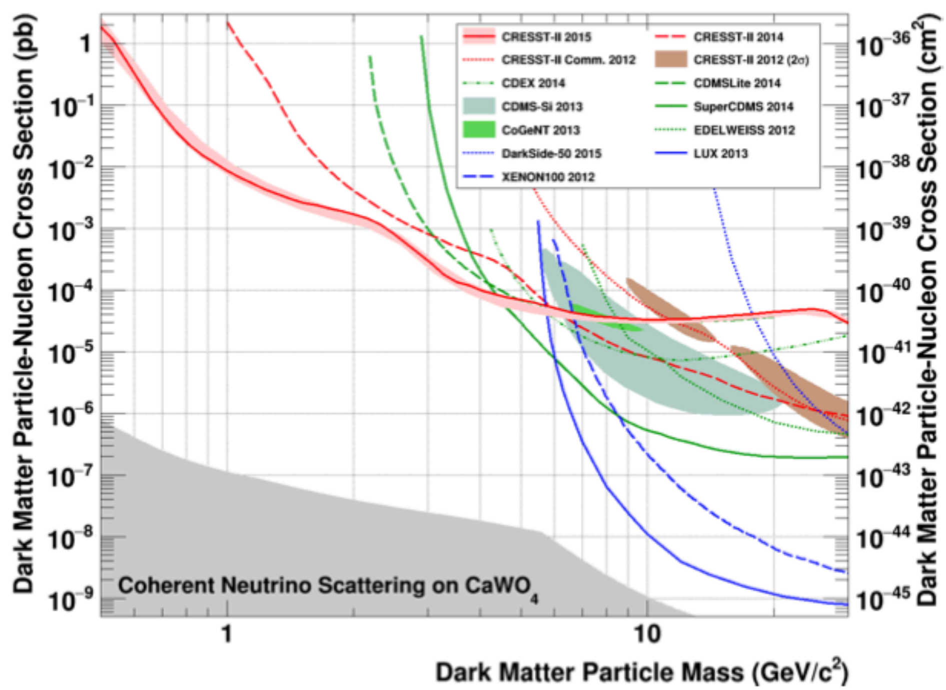
- "High-mass" region predominantly in agreement, with the notable exception of DAMA/LIBRA.
- "Low-mass" region (~10 GeV/c^2) gives rise to apparent tension between several experiments.

Figure from talk by B. Sadoulet, UC Berkeley Physics 290E, Fall 2015

State of the Field, continued



More limits have since been added…



Figures from talk by B. Sadoulet, UC Berkeley Physics 290E, Fall 2015 (left) and arXiv:1509.01515 (right)

Limits in Tension

Exclusions

- CDEX-1
- CDMS II – Ge, low threshold
- CDMSLite
- COUPP
- CRESST II (2015)
- LUX
- SuperCDMS-LT
- Xenon10 (S2)

vs.

*Regions of Interest**

- CDMS II – Si
- CoGeNT
- CRESST II (2012)
- DAMA/LIBRA

Furthermore, some "Regions of interest" (ROI) are in tension with one another

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Germanium
Silicon
$CaWO_4$
L. Xenon
NaI (Tl)
CF_3I

Limits in Tension, continued

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vs.

Regions of Interest

- CDMS II – Si
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- CRESST II (2012)
- DAMA/LIBRA

Solid Crystal
Liquid Noble
Bubble Chamber

Limits in Tension, continued

Exclusions

- CDEX-1 I
- CDMS II – Ge, low thresh. I H
- CDMSLite* I
- COUPP I H S
- CRESST II (2015) H S
- LUX I S
- SuperCDMS-LT I H
- Xenon10 (S2) I S

vs.

Regions of Interest

- CDMS II – Si I H
- CoGeNT I
- CRESST II (2012) H S
- DAMA/LIBRA S

I - Ionization
H – Heat/Phonons
S – Scintillation/Light

Note: Many experiments also use additional discrimination techniques (e.g. pulse shape, timing)

* with Luke-Neganov Amplification

Limits in Tension, continued

Exclusions

- CDEX-1
- CDMS II – Ge, low threshold
- CDMSLite
- COUPP
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- **LUX**
- SuperCDMS-LT
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vs.

Regions of Interest

- **CDMS II – Si**
- **CoGeNT (2012)**
- **CRESST II (2012)**
- **DAMA/LIBRA**

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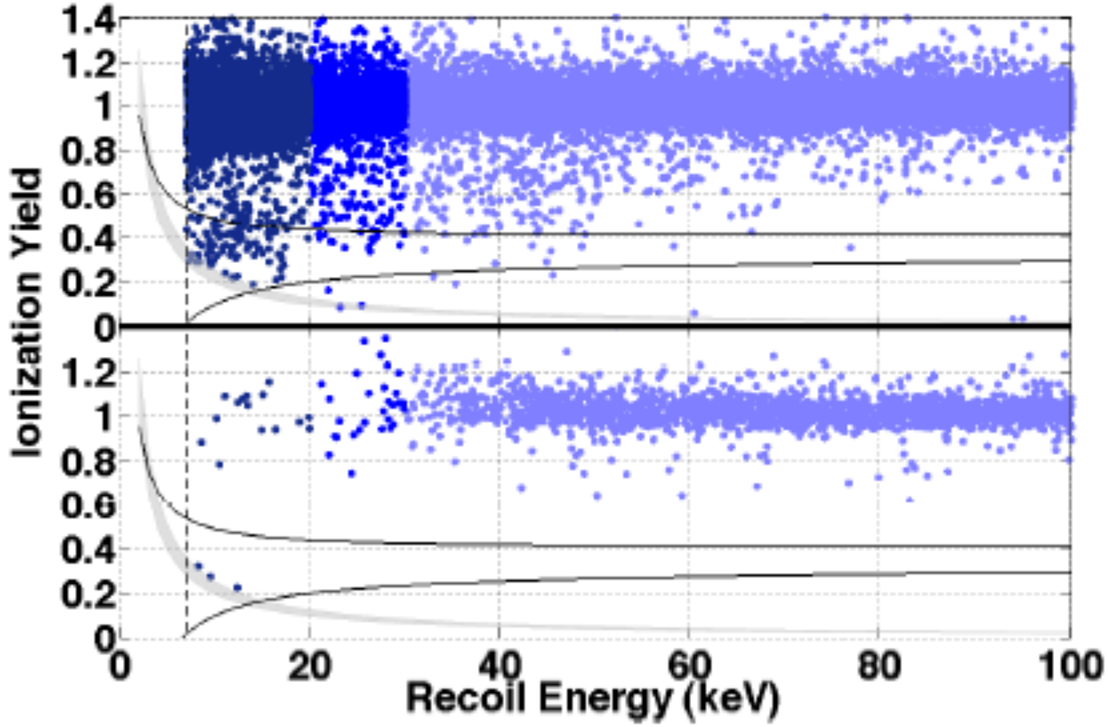
Challenges to Dark Matter Interpretations

- Particle event backgrounds (Surface contamination/radon, other radiogenics, cosmogenics)?
- Noise near low-energy thresholds?
- Experimental uncertainties & detector response (e.g. L_{eff}, nuclear recoil energy scale)?
- Sensitivity of target nuclei to specific interactions/kinematic scenarios?
- Over-reduction of backgrounds (i.e., throwing out the baby with the bathwater?)

Challenges, continued

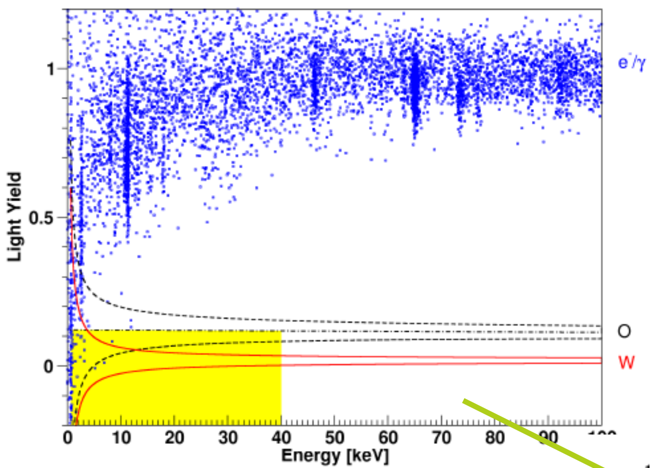
- CDMS II – Si – events fairly close to threshold energies
- CRESST II - known backgrounds; rate excess from first results not confirmed with upgraded detector and continued search
- CoGeNT – unexpected surface contamination, acknowledged by collaboration; however, rate excess and modulation persist with reanalysis
- DAMA/LIBRA – excluded by most other technologies, backgrounds hypothesized by other researchers; but clear, persistent, highly significant, modulating signal

CDMS II-Si events

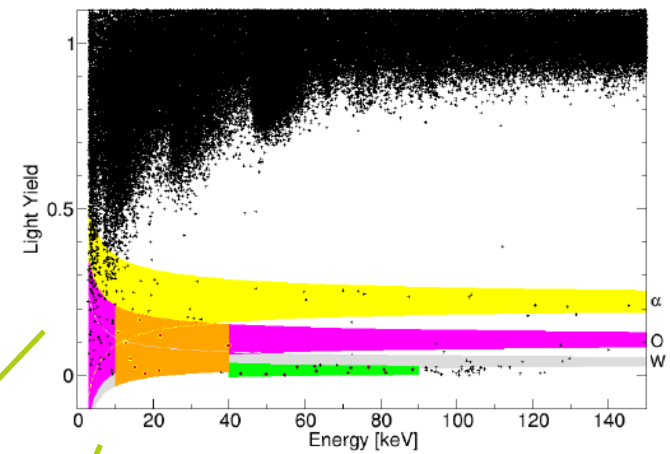


arXiv:1304.4279

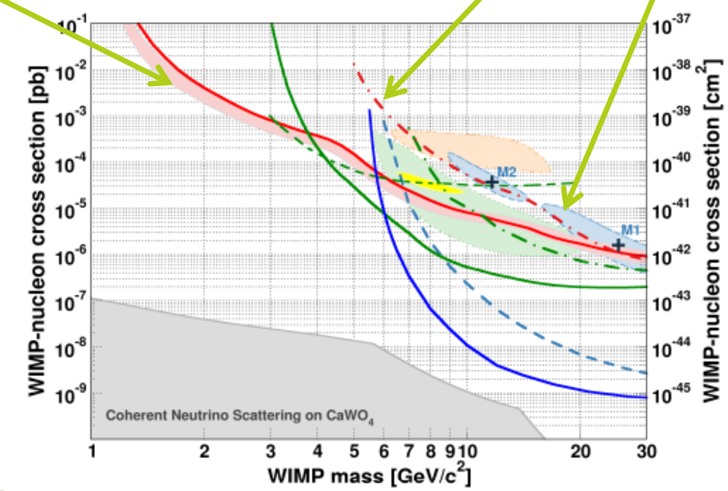
CRESST-II (2011)



Upgrade, 2014



CH51, 2011



arXiv: 1407.3146v2

Challenges, continued

- Example counter-challenges
  - Difficulty of comparing different targets (e.g. NaI with other materials)
  - Low energy scintillation light yield uncertainties (e.g. LXe)
  - Uncertainties on the nuclear recoil energy scale in crystals (e.g. Ge)

General Reconciliation Approaches

Assuming the dark matter interpretation is viable, what can we do?

$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{R}}} = \frac{\rho}{m_{\mathrm{N}} m_{\chi}} \int_{v_{\min}}^{\infty} v f(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{E}}(t)) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}} F^2(E_{\mathrm{R}})\, \mathrm{d}^3 v$$

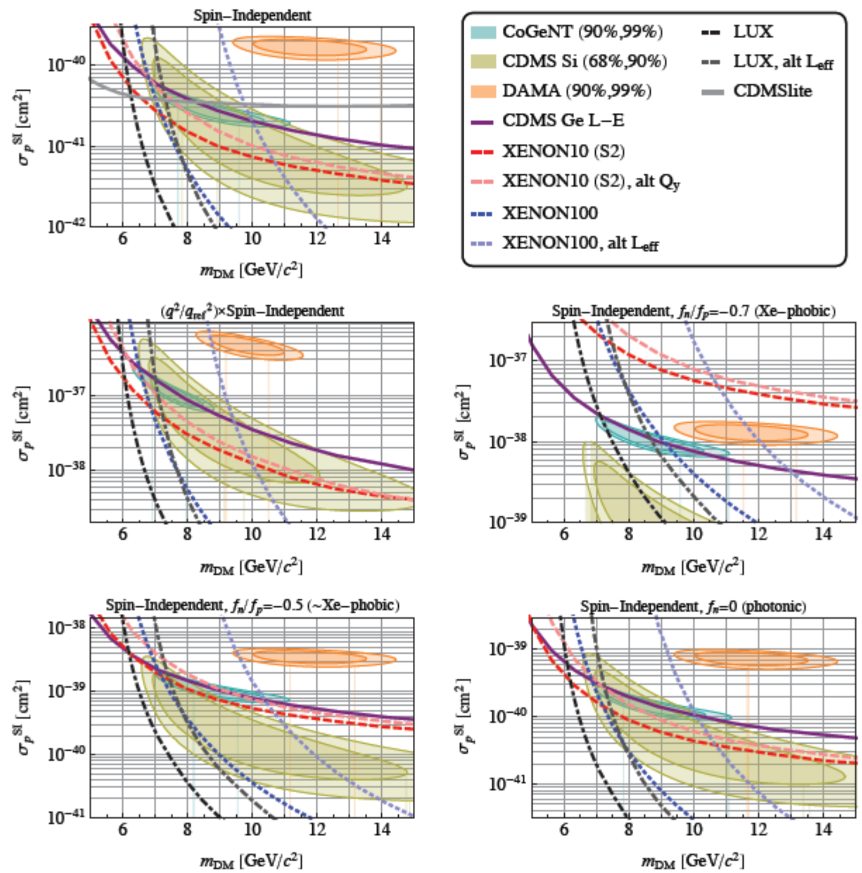
- Nuclear/Particle Physics
- Astrophysics
- Model Independence
- Other comparisons

arXiv:1304.6066

Nuclear/Particle Physics

- Interaction operators
  - Often results in energy or momentum dependence of the interaction → suppression or enhancement of recoil energy spectrum at different energies
- Couplings (i.e. isospin conserving/isospin violating DM by changing the ratio of the nucleon couplings)
- Form factor (Helm generally assumed)
- Also, kinematics (e.g. inelastic dark matter – different required v_{min} changes the sensitivity of certain targets)

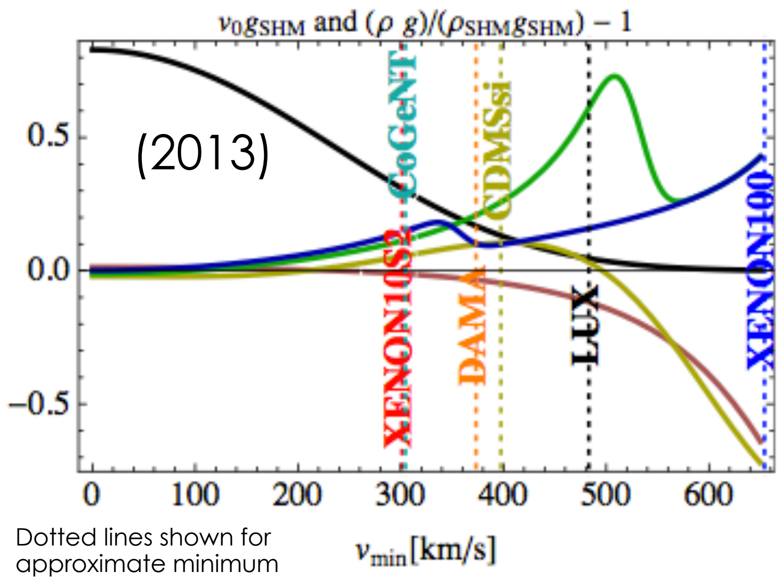
Nuclear/Particle Physics



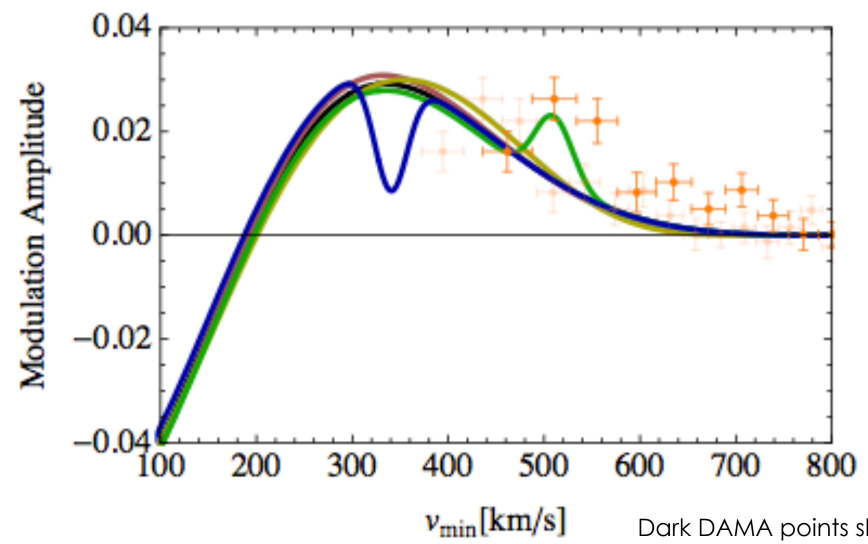
Astrophysics

- Different velocity distributions or assumptions about the escape velocity affect the expected rates between experiments.

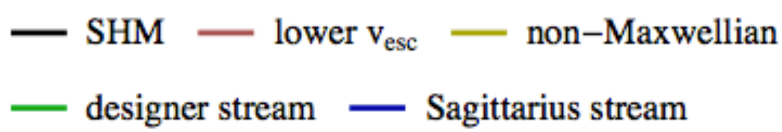
Astrophysics



Dotted lines shown for approximate minimum v_{min} for m_{DM} = 10 GeV/c^2



Dark DAMA points shown for mDM = 8 GeV/c2; lighter for 10 GeV/c2



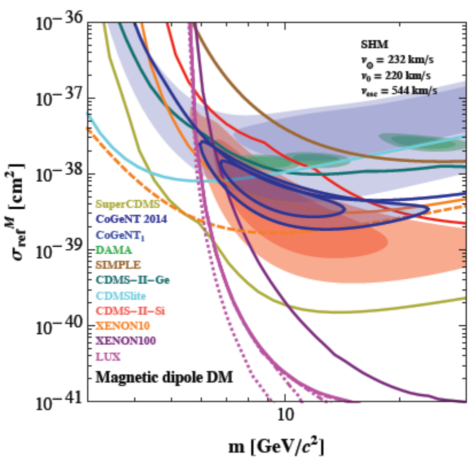
Minimum velocity: $v_{\min} = \sqrt{2m_N E_R^{\min}}/2\mu_N$

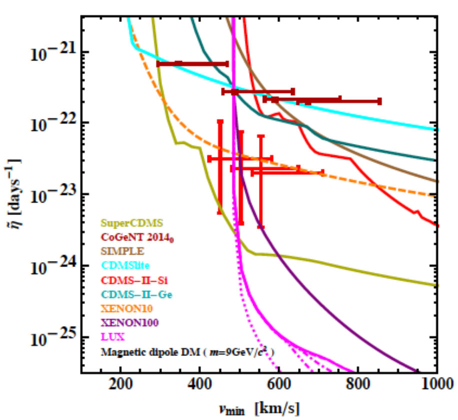
Velocity moment (shown for SHM): $g(v_{\min}) = \int_{v_{\min}}^{\infty} \frac{1}{v^2} v f(\vec{v}) d^3v$

Figure taken from arXiv: 1311.2082

Model Independence

- Remove barriers to the direct comparison of different targets and eliminating dependence upon halo assumptions
- Halo Independence (caveat – makes assumptions about the mass): Change of variables to v_{min}, rather than E_r, and integrate over the velocity distribution





arXiv: 1411.0787

- Mass & Halo Independence: Anderson, A.J. et al. arXiv:1504.03333

Other Comparisons

- Multi-experiment global maximum likelihood analyses (e.g. arXiv:1409.5446 - "Quantifying (dis)agreement between direct detection experiments in a halo-independent way")
- Compatibility studies: Joint probability of obtaining positive and negative results (e.g. arXiv:1410.6060 – "What is the probability that direct detection experiments have observed dark matter?")

Reconciliation of results? Not quite yet …

"The Unbearable Lightness of Being" (arXiv:1304.6066)
"Light dark matter anomalies after LUX " (arXiv: 1311.2082)

- Although halo effects are expected to be important, they are not entirely successful at relieving the tension between experiments
- CDMS II Si, CoGeNT, and can be brought into closer agreement by some models involving
- DAMA/LIBRA tends to remain in tension with consistent interpretations of the other regions
- LUX generally remains in tension with an elastic scattering interpretation of the favored regions for other experiments (1311.2082), although small regions remain with a relaxation of Leff

Conclusions

- Direct searches for elastically scattering WIMP dark matter interactions have returned apparently conflicting results.
- WIMP interpretations for direct detection signals below discovery significance face a number of technical challenges that must be carefully considered.
- Assuming the possibility of a WIMP interpretation, general approaches to a unified understanding of the results involves investigation of sensitivity to the astrophysical and nuclear/particle physics models and assumptions. Recently, much work has been done to develop model-independent comparisons, as well as quantitative compatibility analyses.
- Although a large number of models have attempted to simultaneously reconcile WIMP interpretations of various regions of interest, a clear resolution to this puzzle has not yet been attained.

- Gresham, M.I. and Zurek, K. "Light dark matter anomalies after LUX". arXiv:1311.2082
- Frandsen, M. T., et. al. "The Unbearable Lightness of Being: CDMS versus XENON". arXiv:1304.6066
- Gelmini, G. "Halo Independent analysis of direct dark matter detection data for any WIMP interaction". arXiv: 1411.0787