A Review on Direct Dark Matter Searches

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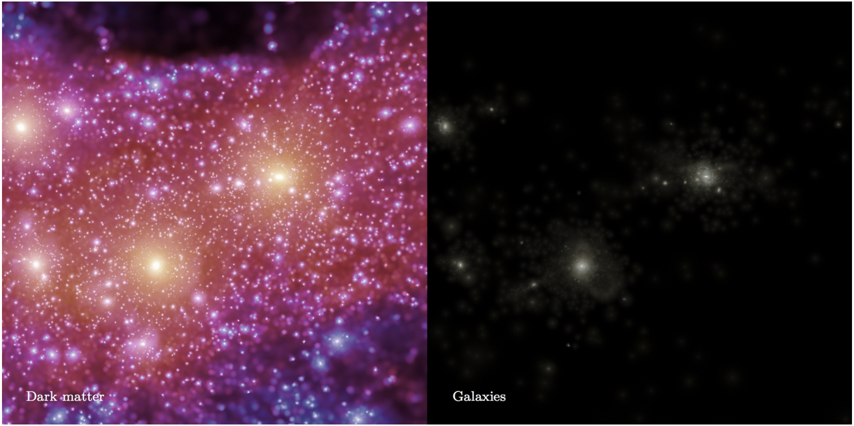
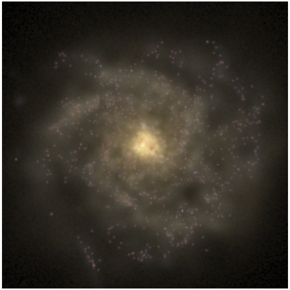
Dark matter haloes



APOSTLE Simulations, 1511.01098

Local dark matter distribution

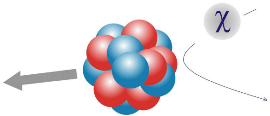


Dark matter (DM) halo in the local neighborhood most likely dominated by a smooth component.

- **"Standard Halo Model"**: isothermal sphere with an isotropic Maxwell-Boltzmann velocity distribution.
  - local DM density: $\rho_\chi \sim 0.3$ GeV cm^{-3}
  - typical DM velocity: $\bar{v} \simeq 220$ km/s
- Local DM flux: $\sim 100,000$ particles/cm^2/s for a 100 GeV WIMP.

Direct detection principles

- Look for energy deposited in low-background detectors by the scattering of WIMPs in the dark halo of our galaxy.
- WIMP-nucleus collision:



- Elastic recoil energy:

$$E_R = \frac{2\mu_{\chi A}^2 v^2}{m_A} \cos^2\theta_{\rm lab}$$

$\theta_{\rm lab}$: angle of the nuclear recoil relative to the initial WIMP direction

- Minimum WIMP speed required to produce a recoil energy E_R:

$$\boxed{v_m = \sqrt{\frac{m_A E_R}{2\mu_{\chi A}^2}}}$$

The differential event rate

- The differential event rate (event/keV/kg/day):

$$R(E_R, t) = \frac{\rho_\chi}{m_\chi} \frac{1}{m_A} \int_{v > v_m} d^3 v \frac{d\sigma_A}{dE_R} \ v \ f_{\rm det}(\mathbf{v}, t)$$

- For the standard spin-independent and spin-dependent scattering:

$$\frac{d\sigma_A}{dE_R} = \frac{m_A}{2\mu_{\chi A}^2 v^2} \sigma_0 F^2(E_R)$$

$$R(E_R, t) = \underbrace{\frac{\sigma_0 F^2(E_R)}{2 m_\chi \mu_{\chi A}^2}}_{\text{particle physics}} \ \underbrace{\rho_\chi \eta(v_m, t)}_{\text{astrophysics}}$$

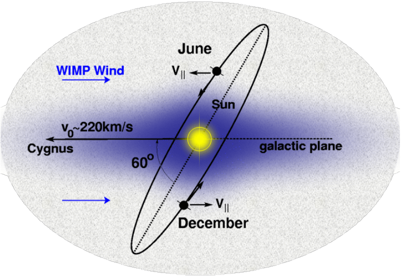
where

$$\eta(v_m, t) \equiv \int_{v > v_m} d^3 v \ \frac{f_{\rm det}(\mathbf{v}, t)}{v} \qquad \text{halo integral}$$

Annual modulation

- Due to the motion of the Earth around the Sun, the velocity distribution in the Earth's frame changes in a year.

Drukier, Freese, Spergel, 1986



$$f_{\rm det}(\mathbf{v},t) = f_{\rm sun}(\mathbf{v}+\mathbf{v}_e(t)) = f_{\rm gal}(\mathbf{v}+\mathbf{v}_s+\mathbf{v}_e(t))$$

Sun's velocity wrt the Galaxy: $\mathbf{v}_s \approx (0, 220, 0) + (11, 12, 7)$ km/s

Earth's velocity: $v_e \approx 30$ km/s

Velocity distribution $f_{\rm gal}(\mathbf{v})$?

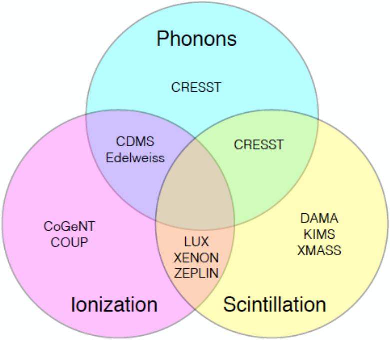
- The velocity distribution depends on the halo model.
- In the SHM, a truncated Maxwellian velocity distribution is assumed

$$f_{\rm gal}(\mathbf{v}) \approx \begin{cases} N \exp(-\mathbf{v}^2/\bar{v}^2) & v < v_{\rm esc} \\ 0 & v \geq v_{\rm esc} \end{cases}$$

  with $\bar{v} \simeq 220$ km/s, $v_{\rm esc} \simeq 550$ km/s.

- DM distribution could be very different from Maxwellian:
  - Most likely both smooth and un-virialized components.
  - the smooth component may not be Maxwellian.

Hints for a signal



- Few experiments have reported "hints" for a signal:
  - **DAMA:** scintillation (NaI)
  - **CDMS-Si:** ionization + phonons (Si)
  - **CoGeNT:** ionization (Ge)
  - **CRESST:** scintillation + phonons ($CaWO_4$)
- Other experiments have found no evidence for DM.

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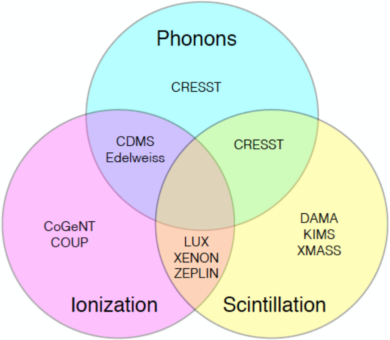

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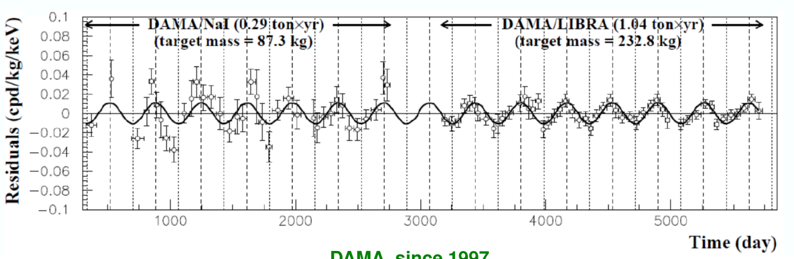
DAMA annual modulation signal

- NaI detectors; 9.3σ modulation signal; 1.33 ton yr (14 yrs)



DAMA, since 1997

- Two possible WIMP masses: $m_\chi \sim 10$ GeV, $m_\chi \sim 80$ GeV.

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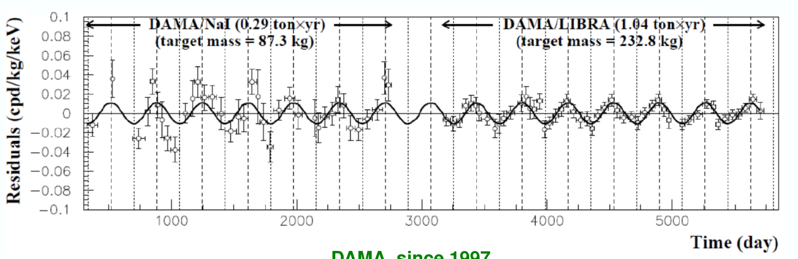
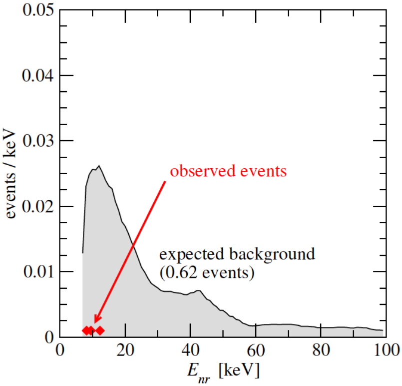


DAMA, since 1997

- Two possible WIMP masses: $m_\chi \sim 10$ GeV, $m_\chi \sim 80$ GeV.
- Steps forward:
  - DAMA/LIBRA-phase 2 running with lower energy threshold.
  - Other NaI detectors: **ANAIS, DM-Ice, KIMS-NaI, SABRE, . . .**

CDMS-Si excess of events

- 140.2 kg day in 8 Si detectors. Observed 3 events against expected background of 0.62 events.
- WIMP $+$ background hypothesis favored over the known background estimate at $\sim 3\sigma$.

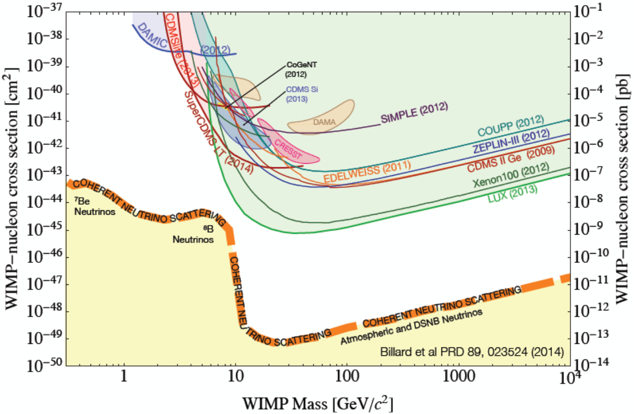


- Maximum likelihood at $m_\chi = 8.6$ GeV

Constraints from other experiments

Spin-independent scattering:

- Strong tension between hints for a signal and exclusion limits:



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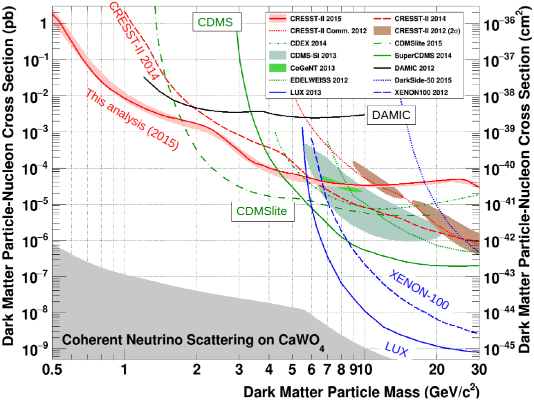


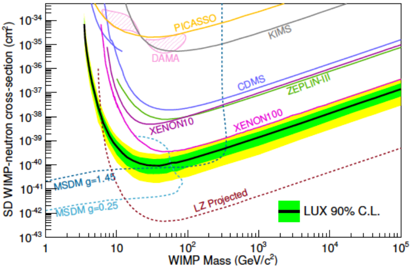
CRESST, 1509.01515

Constraints from other experiments

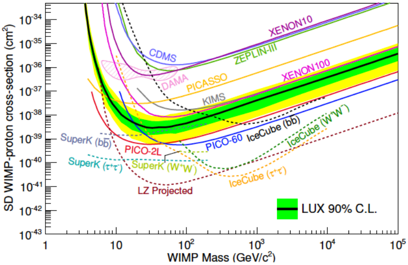
Spin-dependent scattering:

- Happens only in detector nuclei with an odd number of protons and/or neutrons.

Neutron cross section



Proton cross section



LUX, 1602.03489

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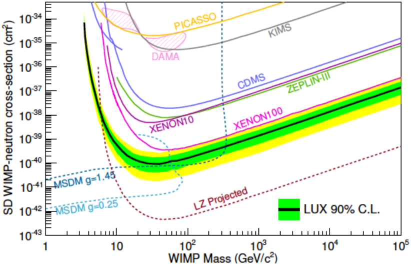

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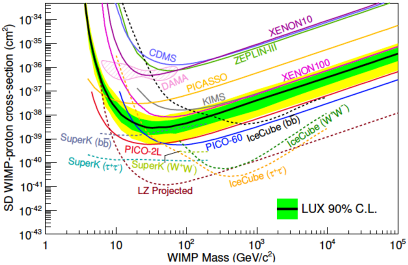
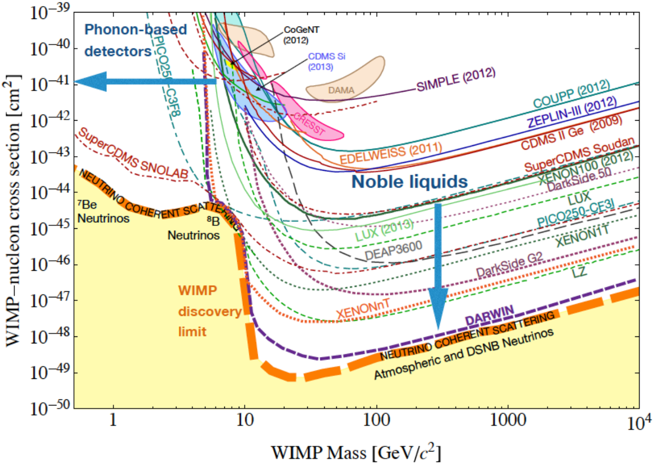


LUX, 1602.03489

- **Warning:** These kinds of plots assume the Standard Halo Model and a specific DM-nucleus interaction.

Direct detection Prospects

- Future experiments: **SuperCDMS SNOLAB, LZ, XENON1T, XENONnT, Darwin, . . .**



Directional direct detection

- Measure both the energy and direction of WIMP-induced recoils. Several experiments: **DRIFT, DMTPC, NEWAGE, MIMAC, . . .**
- Maximum WIMP flux come from one direction. $\Rightarrow$ nuclear recoils cluster around the same direction. $\Rightarrow$ **dipole feature** in the recoil rate; can be confirmed with only $\sim$10 events **[Spergel, 1988]**.
- No known backgrounds can mimic this directional signature! Smoking gun evidence for DM.

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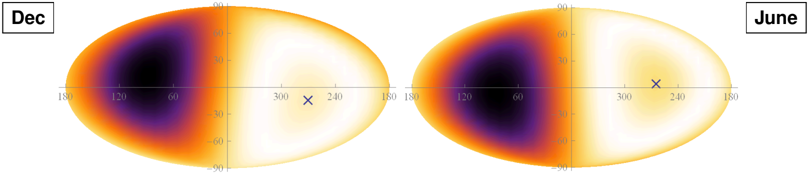
- Other directional features: **ring-like features** and **aberration**



Bozorgnia, Gelmini, Gondolo, 1205.2333

Interpretation of results

- Multiple uncertainties in the interpretation of direct detection data from:
  - **astrophysics**: local DM density and velocity distribution
  - **particle physics**: differential cross section
  - **nuclear physics**: nuclear form factors, spin content, . . .
  - **detector response**: scintillation efficiency, ionization yield, quenching factors, . . .
- Different approaches and methods have been developed to overcome these uncertainties.

Astrophysical uncertainties

- Local DM density: normalization factor in the event rate.
- DM velocity distribution: enters in the halo integral. $\Rightarrow$ Different experiments (energy threshold, target nuclei) probe different DM speed ranges, and thus their dependence on the DM velocity distribution varies.

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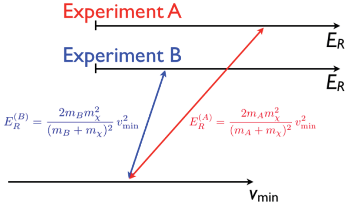
- Methods to tackle astrophysical uncertainties:
  - **Astrophysics independent methods**: compare different experiments without making assumptions about the DM distribution.
  - **Model or parametrize the DM distribution**: use information from astronomical data, and/or cosmological simulations.

Astrophysics independent methods

Comparison of experiments in v_m space: **Fox, Kribs, Tait, 1011.1910; Fox, Liu, Weiner, 1011.1915, and applied in many other works**

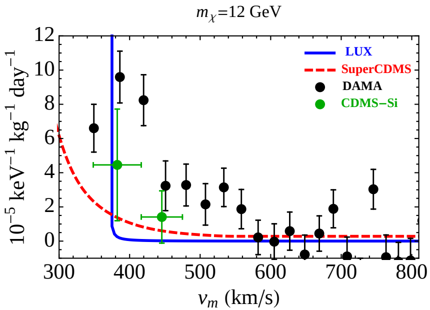
$$\underbrace{\frac{2m_\chi\mu_{\chi A}^2}{\sigma_0 F^2(E_R)}}_{\text{particle physics}} R(E_R,t) = \underbrace{\rho_\chi \eta(v_m,t)}_{\text{astrophysics}}$$

- r.h.s. is independent of experiment.
- For fixed DM mass and interaction type, transform observed spectrum into function of v_m using the l.h.s.
- compare experiments without specifying the r.h.s.



Astrophysics independent methods

- Experimental ⊕ results: measurement of the halo integral.
- Experimental ⊖ results: upper bound on the halo integral.

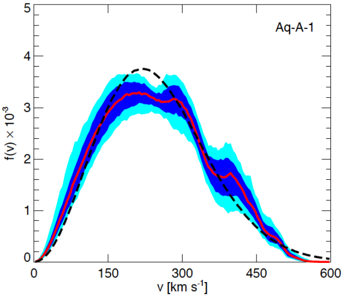


Bozorgnia, Schwetz, 1410.6160

- Conflict between hints and null results persists, independent of assumptions about the DM distribution.

DM distribution from simulations

- DM velocity distributions from cosmological N-body simulations **without baryons**, deviate substantially from a Maxwellian.

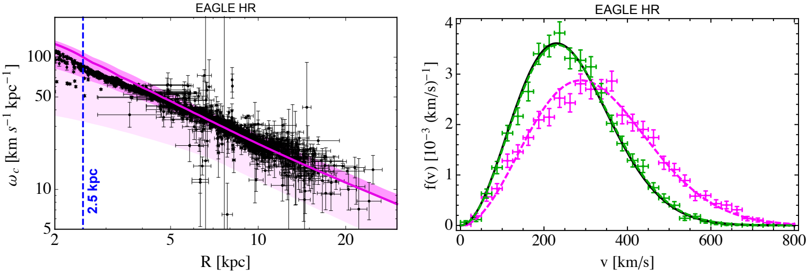


Vogelsberger et al. 0812.0362

- Significant systematic uncertainties since the impact of baryons are neglected.
- Realistic cosmological simulations **with baryons** have recently become possible!

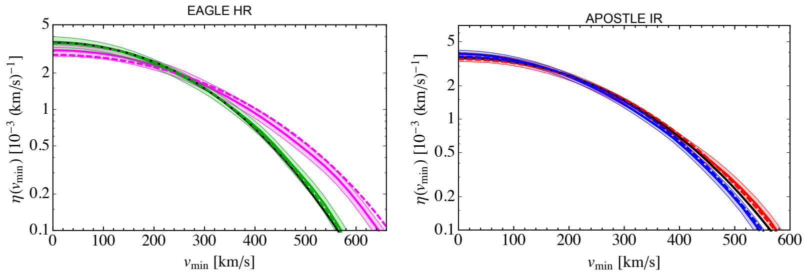
DM distribution from simulations

- Previous hydrodynamic simulations predicted velocity distributions different from a Maxwellian **[Ling et al. 2009, Eris 2013, NIHAO 2015].**
- To make more precise predictions:
  - Identify Milky Way (MW) analogues using observed MW kinematical data: rotation curves, total stellar mass.



Bozorgnia et al. 1601.04707

DM distribution from simulations



Bozorgnia et al. 1601.04707

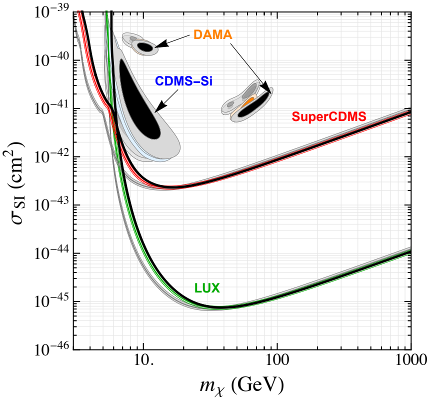
- Halo integrals and hence direct detection event rates obtained from a Maxwellian velocity distribution with a free peak speed are similar to those obtained directly from the simulated haloes **[Bozorgnia et al. 1601.04707, Kelso et al. 1601.04725, Sloane et al. 1601.05402].**

DM distribution from simulations

- Best fit peak speed of the Maxwellian: 223 – 289 km/s. ⇒ shift of allowed regions and exclusion limits by a few GeV at low DM masses compared to SHM **[Bozorgnia et al. 1601.04707].**

- Shift in the allowed regions and exclusion limits occurs in the same direction. ⇒ compatibility between different experiments is not improved.

Fix local $\rho_{\rm DM} = 0.3$ GeV cm^{-3}



Summary

- Current direct detection experiments are probing a large region of the WIMP parameter space.
- Difficult to make the remaining hints for a signal consistent with null results . . .
  even with methods to overcome astrophysical uncertainties, and for many non-standard particle physics models.
- ***Interesting times ahead . . .***
  with new data to come as experiments improve their sensitivity and become larger (multi-ton scales).