WIMP Searches

Alvaro E. Chavarria
University of Washington
Happy to be here again!

<table>
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<tr>
<td>9:00 AM - 9:30 AM</td>
<td><strong>BREAKFAST</strong></td>
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<td>9:15 AM - 9:30 AM</td>
<td><strong>WORKSHOP OPENING</strong> Rocky Kolb</td>
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<td>9:30 AM - 10:00 AM</td>
<td><strong>MORNING SESSION</strong></td>
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<tr>
<td>10:00 AM - 10:30 AM</td>
<td><strong>Alvaro Chavarria</strong>, Kavli Institute for Cosmological Physics</td>
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<td><strong>DAMIC and low mass WIMP searches</strong> [PDF, 34.04 MB]</td>
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Outline

- Direct detection (DD) of “WIMP” dark matter.
- Extending the DD sensitivity to the scattering of lighter WIMPs.
- Technology overview.
- Results from different experiments (focus on leading and recent 2018-19 results).
- Outlook for the coming years.
Galactic dark matter

Local density in $\sim 0.3$ GeV $c^2$ cm$^{-3}$.

Interaction cross-section is small.

Dark matter is cold, kinetic energy is $\sim 10^{-6}$ $Mc^2$.

Dark matter particle can deposit at most its kinetic energy (if fermion) or its rest energy (if boson).

Need detector with low energy threshold, largest possible exposure and correspondingly low backgrounds.
WIMP-nucleus ES

Traditional mechanism for WIMP searches:

Maximum energy transfer when $M \sim A$

For low-mass WIMP:

$$M_T \gg M_\chi \quad E_T < 4 \frac{M_\chi}{M_T} E_\chi$$

Recoil spectrum in Si target

Lower recoil energies for smaller WIMP masses

Coherent enhancement:

$$\sigma_N \propto A^2$$
Lighter WIMPs

Elastic scattering limited:
\[ E_T < \frac{4 M_X}{M_T} E_X \]

Find process that can extract most (all!) kinetic energy from the DM particle.

- If the energy is deposited by an electron, can probe \( E_X \) down to ionization threshold!

Noble liquids \( \sim 10 \) eV
Semiconductors \( \sim 1 \) eV!

Can probe scattering of WIMPs as light as MeV/c².

Warm DM

Will not make it to lab
Rapid loss in sensitivity

Low-mass search
(DAMIC)

High-mass search
(LUX)

Solar neutrinos
ADM models
SUSY models
DSNB + Atmospheric

\( \sigma_n \) [pb]

WIMP mass [GeV]

WIMP mass [GeV]
Processes

Three-body final state:

- An additional $e^-$ or $\gamma$ in the final state.
- **Migdal effect** (atomic $e^-$) or **Bremsstrahlung** ($\gamma$).
- $E$ and $p$ can be conserved even when $e^-$ or $\gamma$ take most of the WIMP kinetic energy.
- Probability of $e^-$ or $\gamma$ emission $<10^{-6}$. Rare.
- Never observed for recoils with keV energies. **Uncalibrated**.

DM-e scattering:

- Electrons are a lighter target.
- Electrons bound with some momentum; there is a region of phase-space where the electron carries most of the WIMP kinetic energy.
- Phase-space ‘penalty,’ no coherent enhancement and probing DM-e interaction cross-section.
Direct detection

Although there are new ideas motivated by a broader theoretical perspective and enabled by new technologies, the game remains the same

- **Low threshold** (toward the ionization limit and below with heat sensors) to access smaller WIMP masses.

- **Scalable technologies** to increase the number of interactions in the target.

- **Low and controlled backgrounds** to identify the rarest signals and probe the smallest cross sections.

- **(Maybe someday) directionality** to confirm the discovery and WIMP astronomy.
Technologies

Target Materials
- Xe, Ar, Ne, He
- Ge, Si, He
- C₃F₈, CF₃I
- Ge, Si, CaWO₄, NaI
- NaI, CsI
- CS₂, CF₄, CHF₃

SIMPLE
PICASSO
COUPP
PICO

Techniques
- Noble liquids
- Low-threshold
- Bubble chambers
- Cryogenic bolometers
- Scintillating crystals
- Directional detectors

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Charge
- CoGeNT
- CDEX
- DAMIC
- SENSEI
- NEWS-G
- DRIFT
- MIMAC
- DMTPC
- NEWAGE

Heat
- SuperCDMS
- EDELWEISS

Light
- LUX/LZ
- PandaX
- XENON

DAMA
- DM-Ice
- COSINE
- SABRE
- ANAIS
- DEAP
- XMASS

Technologies
- K. Ni PDF 2019
Annual modulation (9.5 $\sigma$) of total low-energy signal rate in array of NaI scintillating crystals.

“Smoking gun” evidence for dark matter

Phase 2 results 2011-2017 confirmed and extended modulation to 1 keV

Note: Modulation amplitude is larger than total recoil rates in iodine and electron targets.

No proposed DM explanation is consistent with DAMA and other experiments:
100-kg NaI arrays in Korea and Spain released first annual modulation results in 2019: Observed modulation amplitudes consistent with both DAMA and no modulation.

Wait 3-5 years for 3-σ sensitivity to test DAMA!
Noble liquids

- Xenon or argon.
- 3D position reconstruction: fiducialization.
- Discrimination between electronic and nuclear recoils.
- Large target mass (tonne scale).
- Easy to purify.
- Sensitivity to single-photon (S1) and single-electron (S2) signals.
Noble liquids

XENON1T Migdal + Brems.

For these low masses, <10^{-6} of WIMP interactions in the target produce a signal

At lower masses limits become less robust. For what WIMP mass range can XENON really discover the WIMP?
- Bubble chamber 52 kg of $\text{C}_3\text{F}_8$.
- No energy measurement; threshold detector.
- Insensitive to electronic recoils.
- Acoustic rejection of $\alpha$s.
- No unexpected backgrounds in latest run.
- New upside-down chamber design PICO-40L under installation at SNOLAB.

**FIG. 1.** The PICO-60 detector as configured for its operation with two columns of two cameras each.

**FIG. 6.** Contour plot of integrated acoustic cut used in the prior analysis.

**FIG. 7.** The 90% C.L. limit on the SD WIMP-proton cross section.
Cryogenic bolometers

CRESST-III

- ~25 g CaWO$_4$ crystals.
- Phonon + scintillation readout.
- ~30 eV phonon threshold.
- First results with a single crystal in 2019.

SuperCDMS at SNOLAB

- Demonstrated HV operation as ionization sensor.
- 1.4 kg (0.6 kg) Ge (Si) detectors.
- Previous results with <100 eV$_{ee}$ threshold.
- 24-detector tower under installation at SNOLAB.

EDELWEISS
Ionization sensors

DAMIC

- Pixelated charge readout.
- 7-CCD 40-g detector operating at SNOLAB.
- Low-threshold analysis sensitive to single charges in silicon.
- $\sim$1 eV band gap in silicon.

Scattering of 0.5-5 MeV/$c^2$ particles fundamentally out of reach for xenon TPC

‘WIMP’ kinetic energy below ionization threshold
**Skipper CCD**

**SENSEI at Fermilab**: Skipper CCDs (*LBNL design*) successfully tested with sub e\(^{-}\) noise. X-ray spectroscopy demonstrated.

Technology will allow 2 e\(^{-}\) (few eV) threshold.

**Observed \(~1/\sqrt{N}\)**

DAMIC-M will adopt LBNL skipper design tested by SENSEI
DAMIC-M

- 50 CCDs (0.7 kg target mass) at LSM (France).
- Most massive CCDs ever built (6k x 6k x 0.675 mm, mass 14 g).
- Skipper readout for ~eV threshold.
- Background reduction to a fraction of dru (improved design, materials, procedures).

Institutions:
The University of Chicago, University of Washington, Pacific Northwest National Laboratory (PNNL), SNOLAB, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Laboratoire de l'Accélérateur Linéaire (LAL), the Laboratoire Souterrain de Modane/Grenoble (LSM), University of Zurich, Niels Bohr Institute, University of Southern Denmark, University of Santander, Centro Atómico Bariloche

24 Mpix CCD at UW: 10 g!
Outlook

(consider the following plots sketches)
Prospect for heavy WIMP Searches

Major on-going G2 experiments with Noble Liquids, with Liquid Xenon/Argon
Start operational as early as 2020 and for ~5 years
Next generation (G3) experiment DARWIN is under preparation to start ~2025 and run for 10 years.
Expect another 15 years of "neutrino-background free" search for heavy WIMPs

Discovery Limits (Xe) due to CEvNS (Ruppin, Billard et al.)
Prospects for low-mass WIMP searches

![Graph showing prospects for low-mass WIMP searches](K. Ni PDF 2019)

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**Discovery Limits due to CEvNS**
(Ruppin, Billard et al.)
Prospects for DM-e scattering searches

Complementary to searches at accelerators for electron’s missing momentum (LDMX) or χ interacting directly (BDX):

\( \sigma_e > 10^{-35} \) cm\(^2\) for DAMIC-M (1 kg y)

\( \sigma_e > 10^{-36} \) cm\(^2\) for DAMIC (1 kg y)

\( \sigma_e > 10^{-37} \) cm\(^2\) for XENON10

\( \sigma_e > 10^{-38} \) cm\(^2\) for XENON1T

\( \sigma_e > 10^{-39} \) cm\(^2\) for SENSEI (100 g y)

E.g., \( M_A > 2M_X \)
Conclusions

- Direct detection field still very vibrant!

- Continued push toward lower masses: now we have ‘WIMP’ scattering lifts down to ~0.5 MeV/c^2.

- New approaches with noble liquid TPC make XENON rule.

- But also development of new technologies where noble liquids are fundamentally limited.

- Keep in mind experimental uncertainties! The difference between placing an exclusion limit over background and a discovery.

- International program to increase sensitivity by orders of magnitude in the 0.5 MeV/c^2 to TeV-scale in the next five years.

- **Note**: I only reviewed DM scattering by contact interactions! There are many other interaction mechanisms.