Recent Results from Dark Matter Direct Detection Experiments

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Many recent results, the most recent one from XENON1T

arXiv:1805.12562

This talk: WIMPs (> GeV)
Next talk (Tongyan Lin): light (sub-GeV) and ultra-light DM
Competitive field, rapid progress

Detector sensitivity improved by ~5 orders of magnitude in the last 20 years

Kaixuan Ni  Recent Results from Dark Matter Direction Detection  CIPANP 2018, 5/29-6/3/2018, Palm Springs, CA
Standard Assumptions for Dark Matter Direct Detection

- DM mass range: GeV~TeV
- local WIMP density: 0.3 GeV/cm³
- Isothermal velocity distribution: \( v_0 \sim 220 \text{ km/s} \)
- WIMP escape velocity \( \sim 544 \text{ km/s} \)
- Standard channels: SI and SD

\[
\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} \frac{d\sigma_{\chi N}}{dE_R}(v, E_R) v f(v) dv
\]

\[
\frac{d\sigma_{\chi N}}{dE_R} = \frac{m_N}{2 \mu_N^2 v^2} (\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R))
\]
Experimental signature: falling nuclear recoil energy spectrum

\[ M_\chi = 50 \text{ GeV}/c^2, \sigma_{\chi n} = 1 \times 10^{-46} \text{ cm}^2 \]

\[ M_\chi = 4 \text{ GeV}, \sigma_{\chi p} = 1 \times 10^{-40} \text{ cm}^2 \]

15 evt/ton/year > 10 keV

Heavy WIMPs

Low-mass WIMPs
Direct Detection Techniques

- Liquid argon
- Liquid xenon
- Directional detectors
- Low-threshold
- Bubble chambers
- Cryogenic bolometers
- Scintillating crystals

**Charge**
- CoGeNT
- CDEX
- DAMIC
- SENSEI
- NEWS-G
- DRIFT
- MIMAC
- DMTPC
- LUX/LZ
- PandaX
- XENON

**Light**
- SIMPLE
- PICASSO
- COUPP
- PICO
- CRESST
- COSINUS
- SuperCDMS
- EDELWEISS
- CRESST
- CRESST
- SuperCDMS
- EDELWEISS
- CRESST
- CRESST
- SuperCDMS
- EDELWEISS

**Heat**
- SIMPLE
- PICASSO
- COUPP
- PICO
- CRESST
- COSINUS
- SuperCDMS
- EDELWEISS
- CRESST
- CRESST
- SuperCDMS
- EDELWEISS

**Nuclear Recoils**
- DAMA
- DM-Ice
- COSINE
- SABRE
- ANAIS
- PICO-LON
- DEAP
- XMASS

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DAMA: so far the only experiment detected “dark matter” with $>>5$ sigma C.L.

from R. Bernabei talk, Mar. 26, 2018, LNGS

DAMA/LIBRA-phase2 (1.13 ton × yr) arXiv:1805.10486

- certainly not compatible with experiments with other targets

- could be unidentified background, e.g. Dan McKinsey, Is DAMA bathing in a sea of radioactive argon? (arXiv:1803.10110)

- need other NaI experiments:
  - COSINE/ANAIS/SABRE/PICO-LON
  - COSINUS

see talk by Reina Maruyama on COSINE-100 at DM session this afternoon
SD WIMP-proton constraints: F-target leads

- bubble chamber: 52 kg C$_3$F$_8$
- excellent electron recoil and alpha rejection
- 1167-kg-day exposure
- 3.3 keV threshold
- no single-scatter NR candidate
- best SD WIMP-proton limit: 3.4e-41 cm$^2$ at 30 GeV/c$^2$

see talk by Anthony Noble on PICO at DM session this afternoon
**SD WIMP-neutron constraints: Xe-target leads, Ge-target good at low-mass**

**Xe-target (LUX, PandaX, XENON)**
- Xe129 (29.5%), Xe131 (23.7%)
- best published SD-neutron limit: $1.6 \times 10^{-41} \text{ cm}^2$ at 35 GeV/c$^2$
- new lower-bkg data from PandaX-II, XENON1T should give stronger constraints

**Ge-target (CDMS, CDEX)**
- Ge73 (7.73%)
- best SD-neutron limit below 3 GeV/c$^2$

Model-independent Effective field theory (EFT), e.g. XENON100, Phys.Rev. D96 (2017) no.4, 042004

see also talk by Nicole Larsen on LUX EFT searches at DM session this afternoon
Low-mass (1-10 GeV) dark matter: cryogenic bolometers

**battle between low-threshold and low-background**


**CDMSlite: HV operation**
- no ER/NR discrimination: higher bkg
- but lowering the threshold: <100 eVee
- gain sensitivity for low-mass WIMPs

**CRESST–III result from arXiv:1711.07692**
Low-mass (1-10 GeV) dark matter: low-threshold counting

battle between low-threshold and low-background

CDEX-10 at CJPL

- 10kg Ge detector in liquid nitrogen
- 102.8 kg-days exposure
- analysis threshold: 160 eVee
- residual bkg rate: ~2.5 evt/keVee/kg/day
- improved SI & SD-n limits at 5 GeV/c²

CDEX, arXiv:1802.09016

see talk by Qian Yue on CDEX at DM session this afternoon
Low-mass (1-10 GeV) dark matter: liquid argon

big improvement with S2-only search in DarkSide-50

DarkSide-50 S2-only search
• no ER/NR discrimination
• low threshold: ~100 eVee
• bkg: ~1.5 event/keVee/kg/d at 0.5 keVee
• spectrum consistent with known background
• Liquid argon now gives the best limits for low-mass DM between 2-5 GeV/c²

see talk by Luca Pagani on DarkSide at DM session this afternoon
Low-mass dark matter search status

- 2~3 orders of magnitude above the “neutrino floor”
- challenges: background reduction/discrimination at the lowest threshold
“the battlefield”: heavy WIMPs search

![Graph showing the search for heavy WIMPs with different experiments like XENON100, PandaX-II, PICO, DEAP-3600, Edelweiss-III, DarkSide, LUX, and SuperCDMS.](image-url)
SuperCDMS at Soudan

• iZIP detectors
• 1690 kg days exposure
• single candidate observed, consistent with bkg
• best limits for WIMP-germanium-nucleus interaction > 12 GeV/c²

see talk by Francisco Ponce on SuperCDMS at DM session this afternoon

Phys.Rev.Lett. 120 (2018) no.6, 061802
Liquid Argon results: DarkSide-50 & DEAP-3600

DEAP-3600, arXiv:1707.08042

DarkSide-50, arXiv:1802.07198

DarkSide-50, PSD-only

37 kg x 532 live-days

see more by Luca Pagani (DarkSide) and Yu Chen (DEAP-3600)
at DM session this afternoon
Impressive evolution of LXeTPCs as WIMP detectors

Fiducial mass [kg]

- XENON10: 5 kg
- XENON100: 34 kg
- LUX: 118 kg
- PandaX: 306 kg
- XENON1T: 1300 kg

Low-energy ER background [events / (tonne keV day)]

- XENON10: 1000
- XENON100: 5.3
- LUX: 2.6
- PandaX: 0.8
- XENON1T: 0.2
Hunting for WIMPs with Liquid Xenon

WIMPs/Neutrons

- nuclear recoil

Gammas

- electron recoil

WIMP interaction with Liquid Xe:

- Proportional gas Xe
- Liquid Xe
- PMT Array

Electromagnetic responses:

- Nuclear recoil
- Electron recoil
- Gammas

Energy responses:

- S1
- S2

WIMP signal distinction:

- (S2/S1)_{wimp} << (S2/S1)_{gamma}
WIMP detectors from the XENON-series

<table>
<thead>
<tr>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T</th>
<th>XENONnT</th>
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</thead>
<tbody>
<tr>
<td><img src="XENON10.jpg" alt="Image" /></td>
<td><img src="XENON100.jpg" alt="Image" /></td>
<td><img src="XENON1T.jpg" alt="Image" /></td>
<td><img src="XENONnT.jpg" alt="Image" /></td>
</tr>
<tr>
<td>25 kg - 15cm drift</td>
<td>161 kg - 30 cm drift</td>
<td>3.2 ton - 1 m drift</td>
<td>8 ton - 1.5 m drift</td>
</tr>
<tr>
<td>~10^{-43} cm^2</td>
<td>~10^{-45} cm^2</td>
<td>~10^{-47} cm^2</td>
<td>~10^{-48} cm^2</td>
</tr>
</tbody>
</table>
The frontline detectors using the LXeTPC

**LUX**
Active Target: ~250 kg
completed

**PandaX-II**
Active Target: ~580 kg
Status: running

**XENON1T**
Active Target: 2000 kg
Status: running
XENON1T Data taking

XENON1T: search for dark matter and other rare events

ROI for WIMP search up to 11 keV
Surface background: from reduced-S2 events from Rn-daughters on the PTFE surface
Accidental Coincidence (AC) and Radiogenic neutron background

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate $[t^{-1} y^{-1}]$</th>
<th>Fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiogenic n</td>
<td>$0.6 \pm 0.1$</td>
<td>96.5</td>
</tr>
<tr>
<td>CEνNS</td>
<td>0.012</td>
<td>2.0</td>
</tr>
<tr>
<td>Cosmogenic n</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 2.0$</td>
</tr>
</tbody>
</table>

(Expectations in 4-50 keV search window, 1t FV, single scatters)

JCAP04 (2016) 027
ER and NR modeling from in-situ calibration data

ER rejection: ~99.7% in the reference region with NR acceptance [-2σ, median]
Fiducial volume optimization

- new surface background model allowed inclusion of radius, $R$, in statistical inference to maximize useful volume. Analysis space became $cS1$, $cS2b$, $R$ and $Z$.

Event reconstruction and data selections were fixed before unblinding.
Dark Matter Search Results

- Results interpreted with unbinned profile likelihood analysis in cS1, cS2, R space
- Piecharts indicate the relative PDF from the best fit (assuming 200 GeV/c² WIMPs at cross-section of $4.7 \times 10^{-47}$ cm²)
Event spatial distribution

- ER
- Surface
- Neutron
- AC
- WIMP
- TPC edge
- 1.3 t
- 0.9 t
- 0.65 t

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Statistical Interpretation

- No significant (>3 sigma) excess at any scanned WIMP mass
- p-value for background-only hypothesis: ~0.2 at high WIMP mass
- Rate plot shows best-fit cross-section of $4.7 \times 10^{-47}$ cm$^2$ assuming 200 GeV/c$^2$ WIMPs
Direct Detection of WIMPs by 2025?

- Neutrino Coherent Scattering
- DarkSide-20k (100t-y)
- PandaX-4T (6t-y)
- XENONnT (20t-y)
- LZ (15t-y)
- DARWIN (200t-y)

**SI WIMP-nucleon cross section [cm²]**

**SI WIMP-nucleon cross section [pb]**

- WIMP Mass [GeV/c²]