Recent PandaX-II Results on Dark Matter Search and PandaX-4T Upgrade Plan

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On behalf of PandaX Collaboration
COSMO18, 2018-07-27
Outline

• WIMP direct detection
• PandaX experiment
• PandaX-II operation and results
• PandaX-4T upgrade plan
• Summary
Dark Matter

- Strong evidences for the existence of dark matter

DM search methods
- **Direct detection**
- Indirection detection
- Collider search

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PandaX Collaboration

- **Particle and Astrophysical Xenon Experiments**
  - Formed in 2009, ~50 people

  - Shanghai Jiao Tong University
  - Peking University
  - Shandong University
  - Nankai University
  - Shanghai Institute of Applied Physics
  - Yalong Hydropower Company
  - University of Maryland
  - University of Science & Technology of China
  - China Institute of Atomic Energy
  - Sun Yat-Sen University
  - Lawrence Berkeley National Lab
  - Alternative Energies & Atomic Energy Commission
  - University of Zaragoza
  - Suranaree University of Technology

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China Jinping Underground Laboratory

- China Jinping underground laboratory (CJPL)
  - Deepest (6800 m.w.e )!
  - Horizontal access!

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PandaX Experiment

• Dark matter direct detection through xenon
• **PandaX-I:** 2009-2014
• **PandaX-II:** 2014-2018
  – 60 cm x 60 cm dual-phase xenon TPC
  – 580 kg LXe in sensitive volume
PandaX-II On-Site

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PandaX-II Run Status

- Run9 = 79.6 days, exposure: 26.2 ton-day
- Run10 = 77.1 days, exposure: 27.9 ton-day

Mar. 9 – June 30, low background with 10-fold reduction of Kr (Run9, 79.6 days)

Nov. 2016 – Mar. 2017, 2nd distillation campaign and recommissioning

Jul. 2017 – Now, a few months $^{220}$Rn/AmBe runs, followed by DM data taking, 3x stat of Run10

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Highlights of PandaX Results

• 33 ton-day: spin independent search, \textit{PRL 117, 21303 (2016)}
• 33 ton-day: spin dependent search, \textit{PRL 118, 071301 (2017)}
• 27 ton-day: inelastic scattering search, \textit{PRD 96, 102007 (2017)}
• 27 ton-day: axion and ALP search, \textit{PRL 119, 181806 (2017)}
• 54 ton-day: spin independent search, \textit{PRL 119, 181302 (2017)}

• [new] 54 ton-day: light mediator search, \textit{PRL 121, 021304 (2018)}


Spin-independent WIMP-nucleon Scattering

- Improved from PandaX-II 2016 limit about x2.5 at high masses
- Lowest exclusion at $8.6 \times 10^{-47}$ cm$^2$ at 40 GeV, most stringent for $m_\chi > 100$ GeV when published
Light Mediator DM-SM Interaction

- Heavy mediator \( \Rightarrow \) EFT contact interaction
  - Foundation of “main” SI/SD results in direct detection
- Light mediator: mediator \( m_\phi \) is compared to or smaller than \( q \)
  - Different signal spectrum

\[
\frac{1}{m_\phi^2 + q^2} \xrightarrow{m_\phi \gg q} \frac{1}{m_\phi^2}
\]

\[m_\phi < q ??\]
New Constraints on DM-nucleon

- From 54-ton-day exposure data
- Constraints on DM-n cross section are significantly weakened for light mediator interaction

\[ \sigma(q^2)_{\chi N} = \sigma_{q^2=0} A^2 \left( \frac{\mu}{\mu_p} \right)^2 \frac{m_\phi^4}{(m_\phi^2 + q^2)^2} F^2(q^2) \]
Constraints on Self-Interacting DM

- Self-interacting DM model can have light mediator mixing with SM particles
  - Mixing parameter $\varepsilon$
  - Fine structure in dark sector $\alpha$

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General EFT DM-SM Interaction

- 14 non-relativistic EFT operators constructed with four basic variables
  - Relative perpendicular velocity between the WIMP and the nucleon ($\vec{v}^\perp$)
  - Momentum transfer ($\vec{q}$)
  - Spin of WIMP ($\vec{S}_\chi$)
  - Spin of nucleon ($\vec{S}_N$)

- Considering all interactions through NNLO

\[ \begin{align*}
O_1 &= 1_x 1_N \\
O_3 &= i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \\
O_4 &= \vec{S}_\chi \cdot \vec{S}_N \\
O_5 &= i \vec{S}_\chi \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \\
O_6 &= \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) \\
O_7 &= \vec{S}_N \cdot \vec{v}^\perp \\
O_8 &= \vec{S}_\chi \cdot \vec{v}^\perp \\
O_9 &= i \vec{S}_\chi \cdot \left( \vec{S}_N \times \frac{\vec{q}}{m_N} \right) \\
O_{10} &= i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \right) \\
O_{11} &= i \vec{S}_\chi \cdot \left( \frac{\vec{q}}{m_N} \right) \\
O_{12} &= \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp) \\
O_{13} &= i (\vec{S}_\chi \cdot \vec{v}^\perp) \left( \frac{\vec{q}}{m_N} \right) \\
O_{14} &= i \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{S}_N \cdot \vec{v}^\perp \right) \\
O_{15} &= - \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left[ \vec{S}_N \times \vec{v}^\perp \right) \cdot \frac{\vec{q}}{m_N} \right]
\end{align*} \]

- Spin independent / Spin dependent: 2 EFT operators
  - SI: $O_1$  SD: $O_4$


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Relativistic EFT Operators

- 7 typical relativistic operators

\[ \mathcal{L}^9_{\text{int}} \equiv i \bar{\chi} \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi \bar{N} \gamma_\mu N \]
\[ \rightarrow -\frac{q^2}{2m_\chi m_M} \mathcal{O}_1 + \frac{2m_N}{m_M} \mathcal{O}_5 - \frac{2m_N}{m_M} \left( \frac{q^2}{m_N^2} \mathcal{O}_4 - \mathcal{O}_6 \right) \]
\[ \mathcal{L}^{17}_{\text{int}} \equiv i \bar{\chi} \sigma^{\mu\nu} \frac{q_\nu}{m_M} \gamma^5 \chi \bar{N} \gamma_\mu N \rightarrow \frac{2m_N}{m_M} \mathcal{O}_{11} \]
\[ \mathcal{L}^{10}_{\text{int}} \equiv i \bar{\chi} \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi \bar{N} \sigma^{\mu\nu} \frac{q_\alpha}{m_M} N \rightarrow 4 \left( \frac{q^2}{m_N^2} \mathcal{O}_4 - \frac{m_N^2}{m_M^2} \mathcal{O}_6 \right) \]

- Dramatically different spectra
  - \( q \) and \( v \) dependence
  - Isospin scalar vs isospin vector

\[ \mathcal{L}^5_{\text{int}} \equiv \bar{\chi} \gamma^\mu \chi \bar{N} \gamma_\mu N \rightarrow \mathcal{O}_1 \]
\[ \mathcal{L}^7_{\text{int}} \equiv \bar{\chi} \gamma^\mu \chi \bar{N} \gamma_\mu \gamma^5 N \rightarrow -2\mathcal{O}_7 + 2 \frac{m_N}{m_\chi} \mathcal{O}_9 \]
\[ \mathcal{L}^{13}_{\text{int}} \equiv \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{N} \gamma_\mu N \rightarrow 2\mathcal{O}_8 + 2 \mathcal{O}_9 \]
\[ \mathcal{L}^{15}_{\text{int}} \equiv \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{N} \gamma_\mu \gamma^5 N \rightarrow -4\mathcal{O}_4 \]
Constraints on EFT Couplings

- 54-ton-day exposure data
- Signal window selection same as SI
  - To be further optimized for various EFT in the future
- Constraints strongly depending on the operator/isospin
Constraints on Spin-Dependent Interaction

- $O_4$ SD EFT operator
  - Full basis shell-model GCN5082

- For proton-only coupling in Xe nucleus
  - $O_4$ SD EFT interaction largely suppressed

\begin{align*}
O_4 &= \vec{S}_X \cdot \vec{S}_N \\
\sigma_{p,n}^{SD}(\nu) &= \left( \frac{c_4}{m_V^2} \right)^2 \frac{\mu_{p,n}^2}{\pi} J_X(J_X + 1) \left( \frac{4}{\pi} \right)
\end{align*}
PandaX – in Future

• PandaX-4T for DM search
• PandaX-III for 0vbb search

PandaX-I: 120 kg DM experiment 2009-2014
PandaX-II: 500 kg DM experiment 2014-2018
PandaX-xt: multi-ton (~4-T) DM experiment Future
PandaX-III: 200 kg to 1 ton HP gas $^{136}$Xe 0vDBD experiment Future
PandaX-4T Large Scale TPC

- Drift region: $\Phi \sim 1.2\, \text{m}, \; H \sim 1.2\, \text{m}$
  - Xenon in sensitive region $\sim 4$ ton, drift field 400 V/cm
- Design goal:
  - High signal collection efficiency
  - Uniform $E$ field in a large volume
  - Veto facility

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New Experiment Hall at CJPL-II

- **B2 Hall**
- **14m(H)x14m(W)x65m(L)**
- **Water Shielding**
  - 5000Ton pure water
  - U/Th <10^{-14} g/g
Current Status and Schedule

- R&D work-in-progress
- 2019-2020: assembly and commissioning

- Inner vessel
- TPC prototype
- PMT test
- Cooling bus
- Krypton measurement
- DAQ board
PandaX-4T Background Simulation

- Simulate the ER and NR events
  - Detector materials: inner/outer vessels, flanges, copper plates, electrodes, PTFE materials, PMTs etc
  - Radioactivity in xenon: $^{85}$Kr, $^{222}$Rn, $^{136}$Xe
  - Neutrino

- Background in signal region
  - Total ER background: 0.05 mDRU
  - Total NR background: 1 event / ton / year

Table 4 Final background budget within the WIMP search window.

<table>
<thead>
<tr>
<th>Sources</th>
<th>ER in mDRU</th>
<th>NR in mDRU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>0.0210±0.0042</td>
<td>2.0 ± 0.3 · 10^{-4}</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>0.0114±0.0012</td>
<td>-</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>0.0053±0.0011</td>
<td>-</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>0.0023±0.0003</td>
<td>-</td>
</tr>
<tr>
<td>Neutrino</td>
<td>0.0090±0.0002</td>
<td>0.8 ± 0.4 · 10^{-4}</td>
</tr>
<tr>
<td>Sum</td>
<td>0.049 ±0.005</td>
<td>2.8 ± 0.5 · 10^{-4}</td>
</tr>
<tr>
<td>2-year yield (evts)</td>
<td>1001.6± 102.2</td>
<td>5.7±1.0</td>
</tr>
<tr>
<td>after selection (evts)</td>
<td>2.5±0.3</td>
<td>2.3±0.4</td>
</tr>
</tbody>
</table>
PandaX-4T Expected Sensitivity

- With two-year exposure, x10 improvement on sensitivity could be achieved.
- SI DM-nucleon sensitivity: $10^{-47}\text{cm}^2$
- SD DM-neutron: $10^{-42}\text{cm}^2$
PandaX-III: in preparation

- Looking for $^{136}$Xe $0\nu\beta\beta$ decay
- Lepton number violation
- 200-kg High pressure Xe detector

Prototype detector in Lab
Summary and Outlook

• PandaX experiment with 580kg Xenon has reached the world frontier of dark matter direct detection.
  – PandaX-II continues data-taking smoothly.
  – Recently, light mediator and EFT results are obtained
  – More results are expected.

• The future PandaX-4T experiment R&D is work-in-progress.
  – Expected sensitivity to SI interaction could reach $10^{-47}$ cm$^2$
  – Detector assembly and commissioning is scheduled in 2019-2020

• PandaX-III $0\nu\beta\beta$ search detector is in preparation.

• Thank you!

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Backup

•
Constraints on Spin-Dependent Interaction

- $O_4$ SD EFT operator $\mathcal{O}_4 = \vec{S}_x \cdot \vec{S}_N$
  - Full basis shell-model GCN5082
- For proton-only coupling in Xe nucleus
  - $O_4$ SD EFT interaction largely suppressed
    $$\sigma_{p,n}^{SD}(\nu) = \left(\frac{c_4}{m_V^2}\right)^2 \frac{\mu_{p,n}^2}{\pi} \frac{J_X(J_X+1)}{4}$$
- “Standard” SD calculation:
  - chiral EFT
  - $O_4 + O_6 +$ two nucleon pion-exchange

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