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

Ning Zhou
Shanghai Jiao Tong University
On behalf of PandaX Collaboration
ICHÉP 2018, 2018-07-07
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
PandaX Collaboration

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

  ![PandaX Collaboration](image)

- 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

Ning Zhou, ICHEP 2018
China Jinping Underground Laboratory

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

- Nov. 22 – Dec. 14, Physics commission (Run8, 19.1 days, stopped due to high Krypton background)

- Jul – Oct, ER calibration & tritium removal

- Apr.22 – July15, dark matter data taking (Run10, 77.1 days)
Highlights of PandaX-II Results

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

• new 54 ton-day: general EFT and spin-dependent search, arXiv:1807.01936
• new PandaX-4T sensitivity study, arXiv:1806.02229
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} \approx \frac{1}{m_\phi^2} \\

m_\phi < q
g N

\text{Ning Zhou, ICHEP 2018}
New Constraints on DM-nucleon

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

Ning Zhou, ICHEP 2018
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 $\alpha$

*Phys.Rept. 730 (2018) 1-57*

Ning Zhou, ICHEP 2018
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

  \[ \mathcal{O}_1 = 1 \chi \chi N \]
  \[ \mathcal{O}_3 = i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \]
  \[ \mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N \]
  \[ \mathcal{O}_5 = i \vec{S}_\chi \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \]
  \[ \mathcal{O}_9 = i \vec{S}_\chi \cdot \left( \vec{S}_N \times \frac{\vec{q}}{m_N} \right) \]
  \[ \mathcal{O}_{10} = i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \right) \]
  \[ \mathcal{O}_{11} = i \vec{S}_\chi \cdot \left( \frac{\vec{q}}{m_N} \right) \]
  \[ \mathcal{O}_{12} = \vec{S}_\chi \cdot \left( \vec{S}_N \times \vec{v}^\perp \right) \]
  \[ \mathcal{O}_{13} = i \left( \vec{S}_\chi \cdot \vec{v}^\perp \right) \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) \]
  \[ \mathcal{O}_{14} = i \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{S}_N \cdot \vec{v}^\perp \right) \]

  - Spin independent / Spin dependent: 2 EFT operators
    - SI: $\mathcal{O}_1$, SD: $\mathcal{O}_4$

*Phys. Rev. C89, 065501 (2014)*

Ning Zhou, ICHEP 2018
Relativistic EFT Operators

• 7 typical relativistic operators

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

\[ \mathcal{L}_{\text{int}}^{17} \equiv i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi \bar{N} \gamma_5 \gamma_\mu N \rightarrow \frac{2m_N}{m_M} \mathcal{O}_{11} \]

\[ \mathcal{L}_{\text{int}}^{10} \equiv i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi \bar{N} i \sigma_\mu \sigma_\alpha \frac{q_\alpha}{m_M} N \rightarrow 4 \left( \frac{\vec{q}^2}{m_N^2} \mathcal{O}_4 - \frac{m_N^2}{m_M^2} \mathcal{O}_6 \right) \]

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

Ning Zhou, ICHEP 2018
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

Ning Zhou, ICHEP 2018
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

\[
O_4 = \vec{S}_X \cdot \vec{S}_N
\]

\[
\sigma_{p,n}^{SD}(v) = \left( \frac{c_4}{m_V^2} \right)^2 \frac{\mu_{p,n}^2}{\pi} J_X(J_X + 1) \frac{1}{4}
\]
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-III: 200 kg to 1 ton HP gas $^{136}$Xe 0vDBD experiment Future

PandaX-xT: multi-ton (~4-T) DM experiment Future

CJPL-I

CJPL-II

Ning Zhou, ICHEP 2018
PandaX-4T Large Scale TPC

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

Ning Zhou, ICHEP 2018
New Experiment Hall at CJPL-II

- B2 Hall
- 14m(H) x 14m(W) x 65m(L)
- Water Shielding
  - 5000 Ton pure water
  - U/Th < 10^{-14} g/g
Current Status and Schedule

• R&D work-in-progress
• 2019-2020: assembly and commissioning
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>$0.0210 \pm 0.0042$</td>
<td>$2.0 \pm 0.3 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>$0.0114 \pm 0.0012$</td>
<td>-</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>$0.0053 \pm 0.0011$</td>
<td>-</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$0.0023 \pm 0.0003$</td>
<td>-</td>
</tr>
<tr>
<td>Neutrino</td>
<td>$0.0090 \pm 0.0002$</td>
<td>$0.8 \pm 0.4 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Sum</td>
<td>$0.049 \pm 0.005$</td>
<td>$2.8 \pm 0.5 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>

2-year yield (evts) | 1001.6 ± 102.2 | 5.7 ± 1.0
after selection (evts) | 2.5 ± 0.3 | 2.3 ± 0.4

Ning Zhou, ICHEP 2018
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: $10^{-42}\text{cm}^2$

Ning Zhou, ICHEP 2018
PandaX-III: in preparation

Looking for $^{136}\text{Xe}$ $0\nu\beta\beta$ 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!**
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
    \[ \sigma_{p,n}^{SD}(\nu) = \left( \frac{c_4}{m_W^2} \right)^2 \frac{\mu_{p,n}}{\pi} \frac{J_X(J_X+1)}{4} \]
- “Standard” SD calculation:
  - chiral EFT
  - $O_4 + O_6 +$ two nucleon pion-exchange

Ning Zhou, ICHEP 2018