WIMP-Nucleon effective interactions study from PandaX-II Experiment

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On behalf of PandaX Collaboration

Outline

- PandaX-II introduction
- Effective field theory
- Results
- Summary

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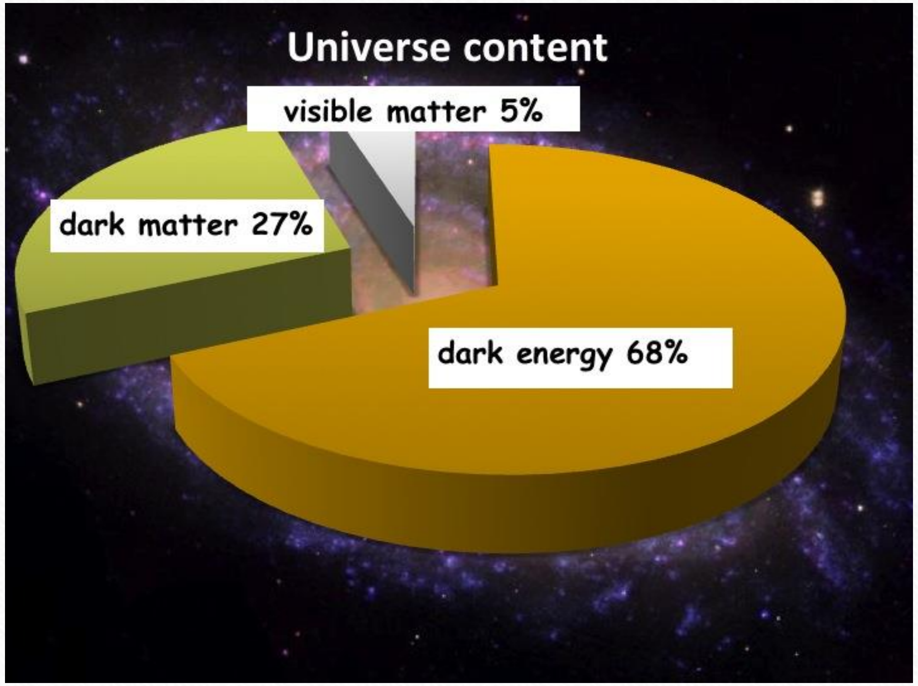
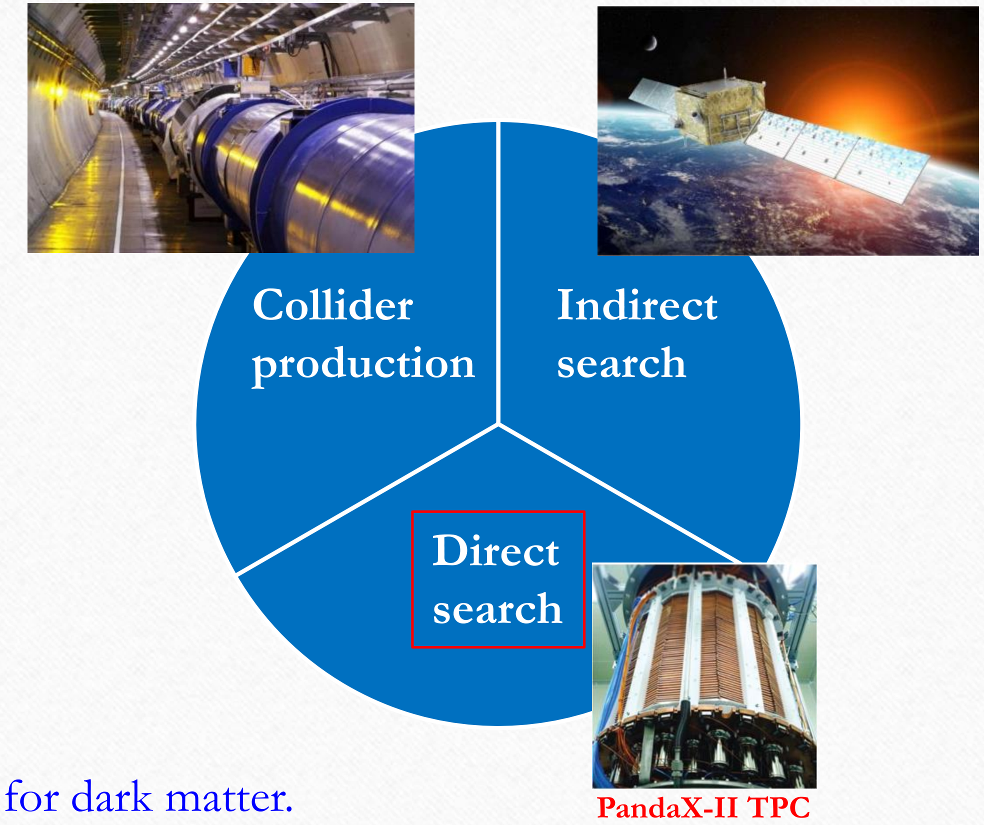
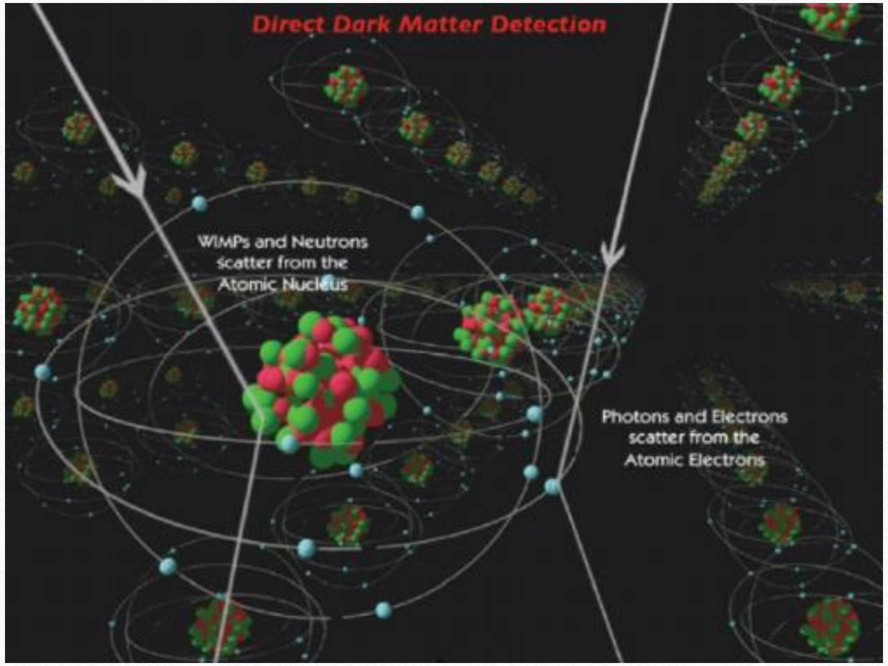
Dark Matter(DM) in the universe





Weakly interacting massive particles (WIMPs):
a class of theoretically well-motivated candidates for dark matter.

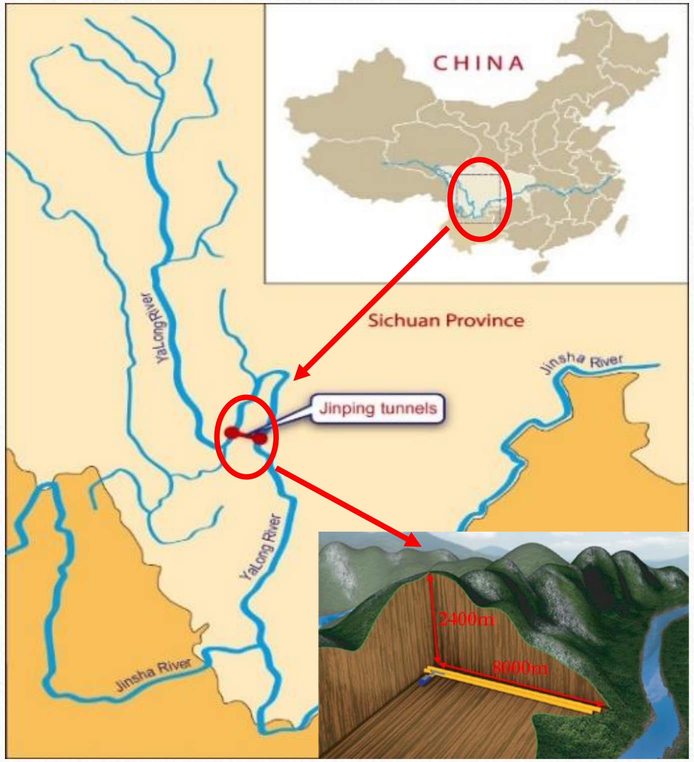
DM direct detection

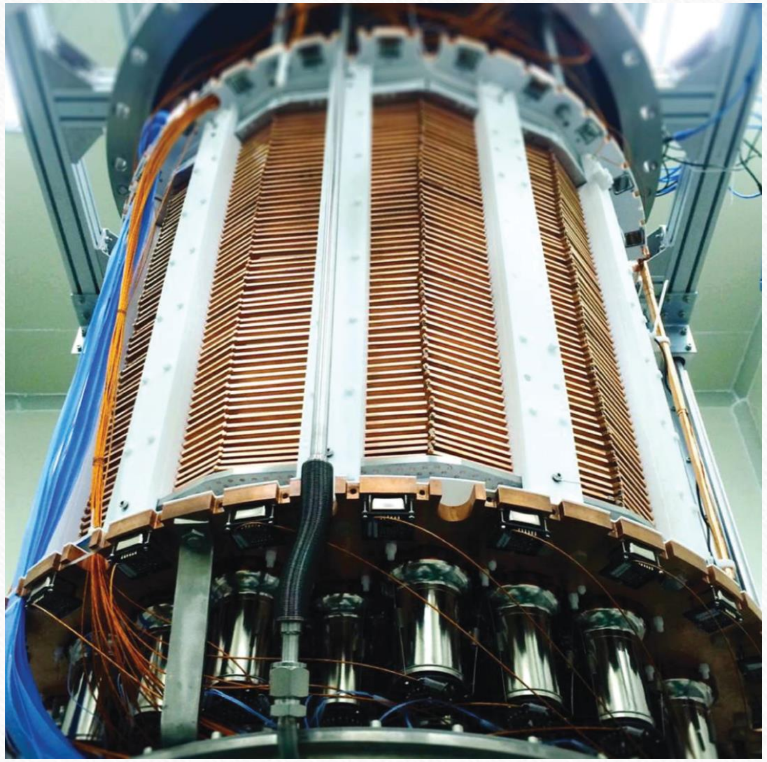


Direct detection: searching for WIMP-nuclear recoils in terrestrial detectors

- **Spin-independent (SI)** interaction: coherent scattering on all nucleons
- **Spin-dependent (SD)** interaction: can be viewed as scattering with outer unpaired nucleon

PandaX-II experiment





PandaX-II detector:

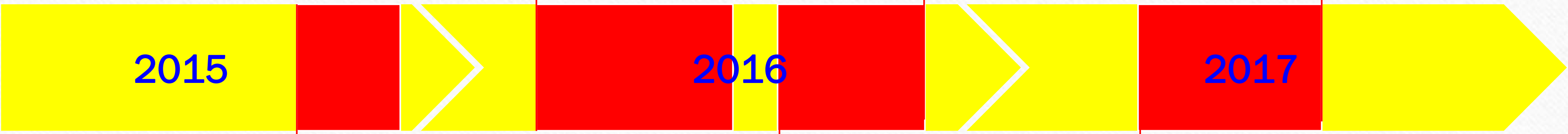
- 60 cm * 60 cm cylindrical TPC
- **580-kg** of LXe in sensitive region
- 55 top + 55 bottom R11410 3" target PMTs
- 24 top + 24 bottom R8520 1" VETO PMTs

PandaX-II run history

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

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

July 2017 – Now, ^{220}Rn/AmBe runs, followed by blinded DM search



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)

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

} **54 ton-day**

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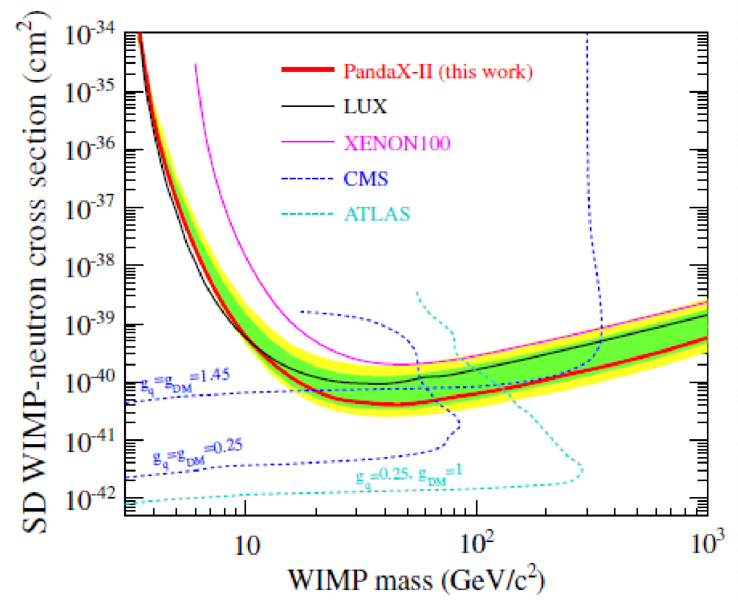
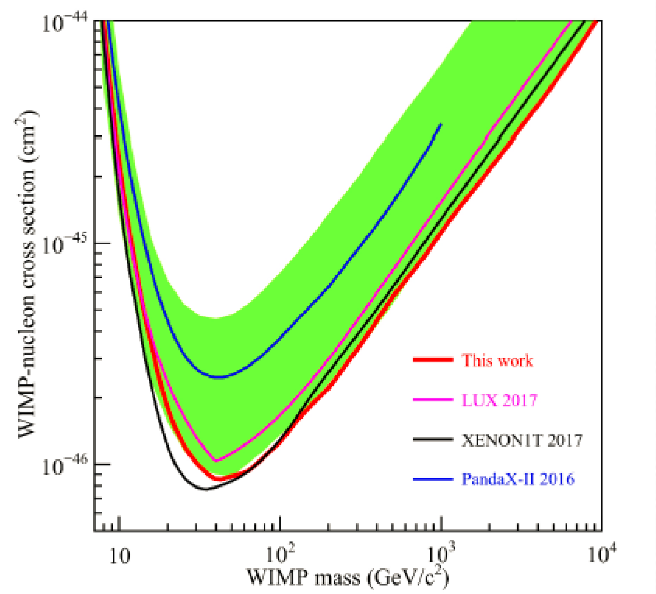
Previous SI and SD results

Run8+9(33 t-day) SD Results
PRL 118, 071301 (2017)



Minimum **χ-n SD** cross section limit:
4.1×10^{-41} cm^2 at 40 GeV/c^2

Run9+10(54 t-day) SI Results
PRL 119, 181302 (2017)



Minimum elastic **SI** cross section limit:
8.6×10^{-47} cm^2 @ 40 GeV/c^2

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- PandaX-II introduction
- **Effective field theory**
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Effective field theory (EFT)

- The traditional SI/SD approach:
  - take only leading-order terms in a WIMP-nucleon interaction
  - present a simple treatment on nuclear structure
- A more sophisticated EFT approach for WIMP scattering was developed:
  - Consider all leading-order and next-to-leading order operators.
  - Combination of four basic terms:
    - ✓ Relative perpendicular velocity between the WIMP and the nucleon ($\vec{v}^{\perp}$)
    - ✓ Momentum transfer ($\vec{q}$)
    - ✓ Spins of WIMP ($\vec{S}_{\chi}$)
    - ✓ Spins of nucleon ($\vec{S}_{N}$)

EFT operators

- Parametrizing the WIMP-nucleus interaction in terms of 14 operators, O_i :

$$\mathcal{O}_1 = 1_\chi 1_N \qquad \mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right) \qquad \mathcal{O}_{10} = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N \qquad \mathcal{O}_{11} = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right) \qquad \mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$$

$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right) \qquad \mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp \qquad \mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)(\vec{S}_N \cdot \vec{v}^\perp)$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp \qquad \mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left[(\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right]$$

Following the convention from N. Anand et al, Phys. Rev. C89, 065501 (2014).

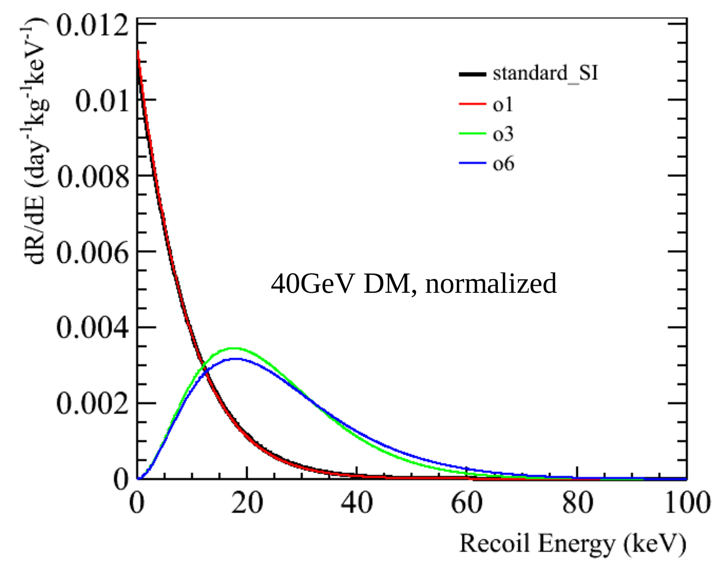
The EFT interaction would take the form:

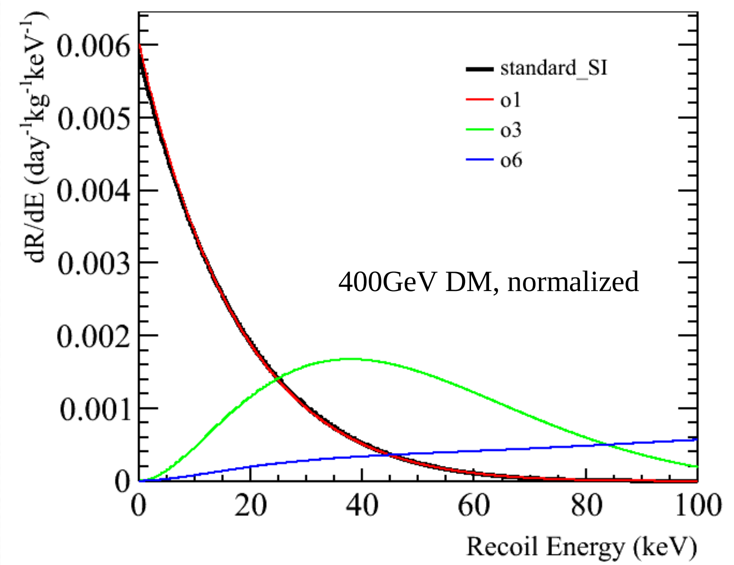
$$\sum_{\alpha=n,p} \sum_{i=1}^{15} c_i^\alpha \mathcal{O}_i^\alpha, \qquad c_2^\alpha \equiv 0.$$

- Each EFT operator has independent couplings to protons and neutrons,
- The framework allows interference between certain operators.

Recoil spectra from EFT

- Unlike the standard SI/SD, some EFT operators depend explicitly on $\vec{q}$:
  - Scattering rate peaks at nonzero recoil energy
  - For high WIMP masses, rate may even maximize outside typical analysis windows





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Effective field theory

- Four **dimension-four** effective interactions corresponding to the possible relativistic vector/axial-vector interactions (left)

$$\mathcal{L}_{\rm int}^5 \equiv \bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu N \to \mathcal{O}_1$$

$$\mathcal{L}_{\rm int}^7 \equiv \bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu\gamma^5 N \to -2\mathcal{O}_7 + 2\frac{m_N}{m_\chi}\mathcal{O}_9$$

$$\mathcal{L}_{\rm int}^{13} \equiv \bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu N \to 2\mathcal{O}_8 + 2\mathcal{O}_9$$

$$\mathcal{L}_{\rm int}^{15} \equiv \bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N \to -4\mathcal{O}_4$$

$$\mathcal{L}_{\rm int}^9 \equiv \bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}\gamma_\mu N$$
$$\to -\frac{\vec{q}^{\,2}}{2m_\chi m_M}\mathcal{O}_1 + \frac{2m_N}{m_M}\mathcal{O}_5 - \frac{2m_N}{m_M}(\frac{\vec{q}^{\,2}}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6)$$

$$\mathcal{L}_{\rm int}^{17} \equiv i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar{N}\gamma_\mu N \to \frac{2m_N}{m_M}\mathcal{O}_{11}$$

$$\mathcal{L}_{\rm int}^{10} \equiv \bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N \to 4(\frac{\vec{q}^{\,2}}{m_M^2}\mathcal{O}_4 - \frac{m_N^2}{m_M^2}\mathcal{O}_6)$$

- **Dimension-five** operators coupling the WIMP **magnetic moment or electric dipole moment** with the nucleon's vector current (first two in right)
- **Dimension-six** operator coupling WIMP and nucleon **magnetic moments** (last in right)

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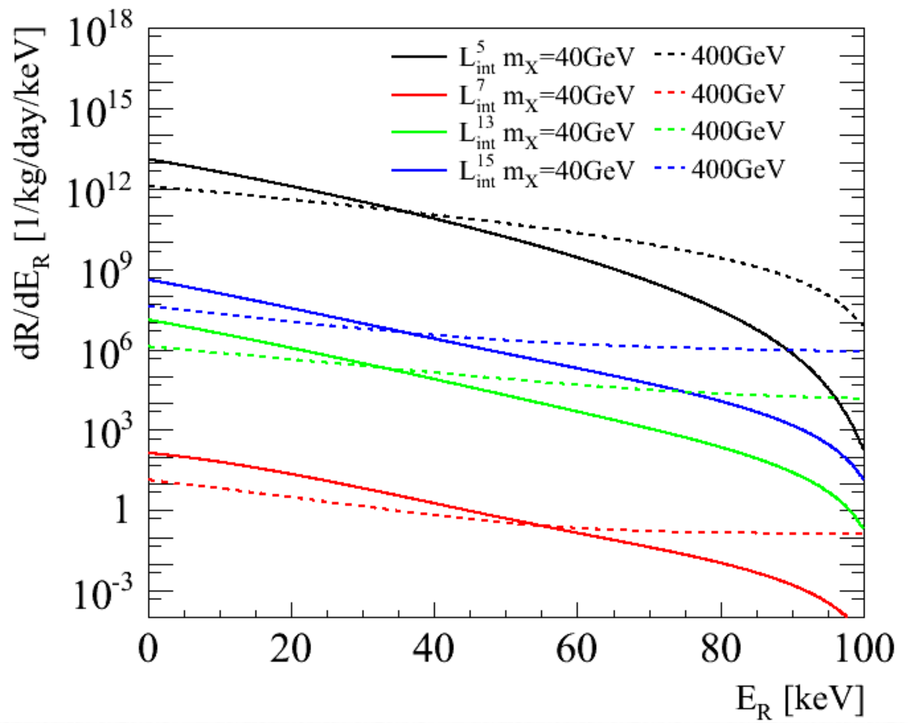
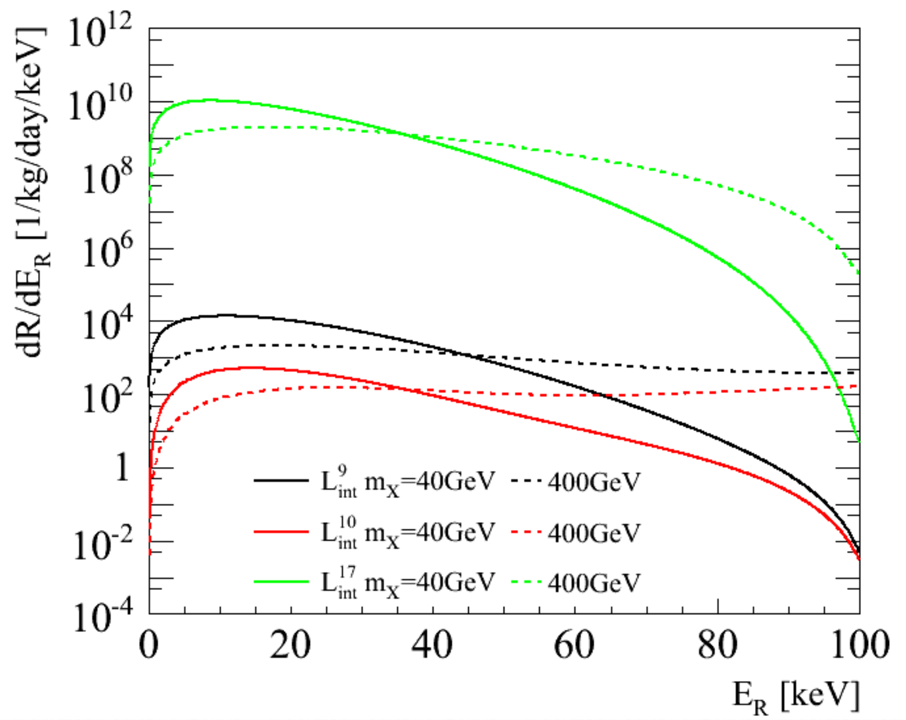
Numerical work assumptions

- Only consider a single individual operator at a time
- For general consideration, apply the coupling in **isoscalar** case, in which the operator is equally coupled to protons and neutrons
- In the spin-dependent analysis, similar as the standard approach, set the couplings **only to protons** and **only to neutrons**.

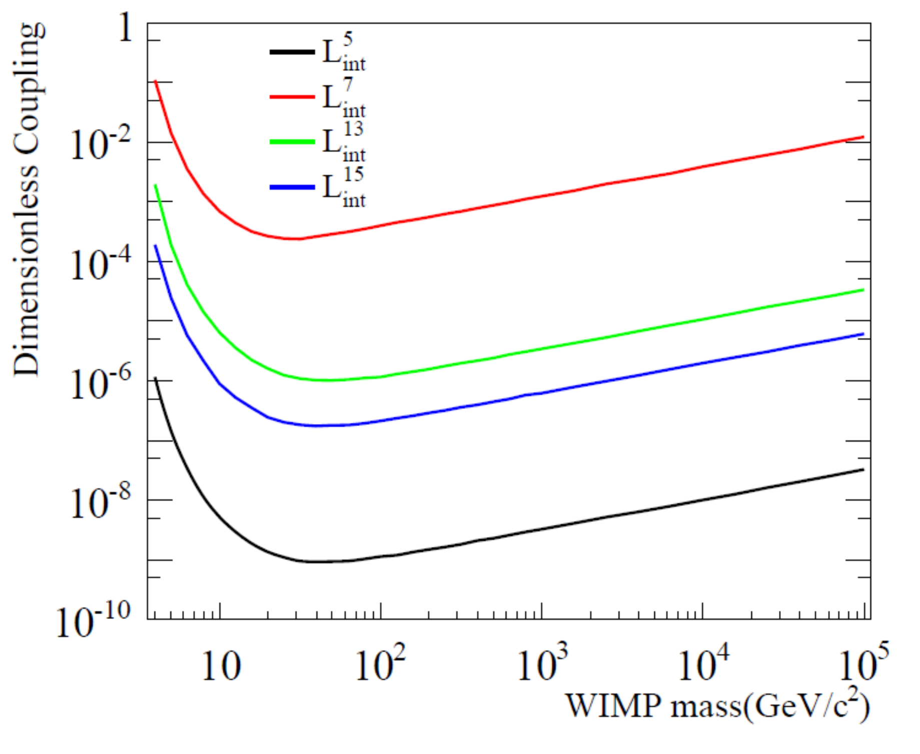
Recoil energy spectra

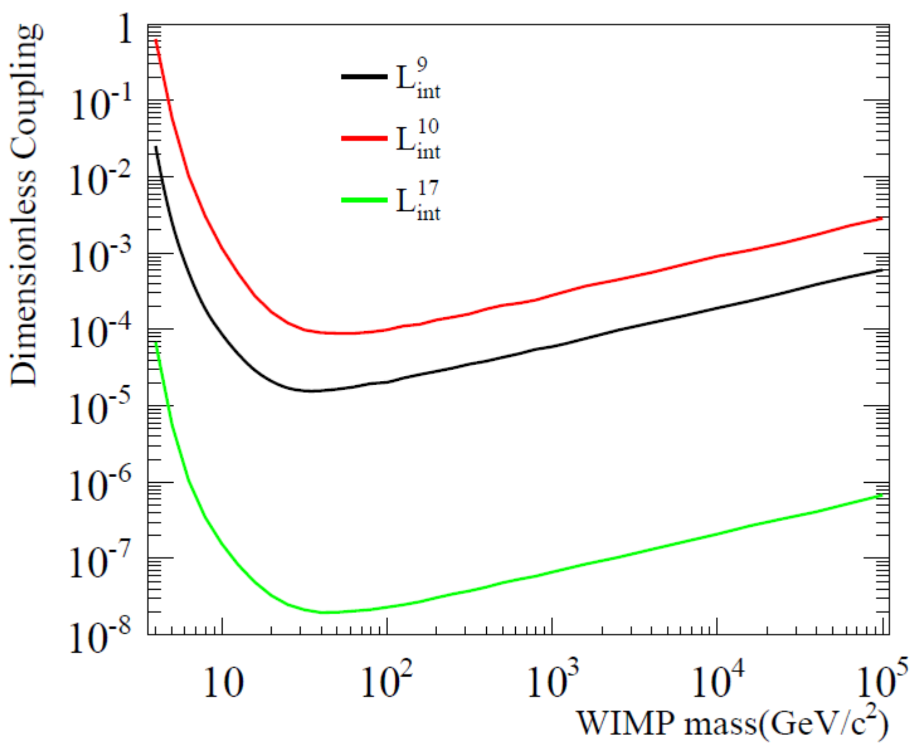
- In isoscalar case, $c^{neutron}=c^{proton}$





Limits on the couplings





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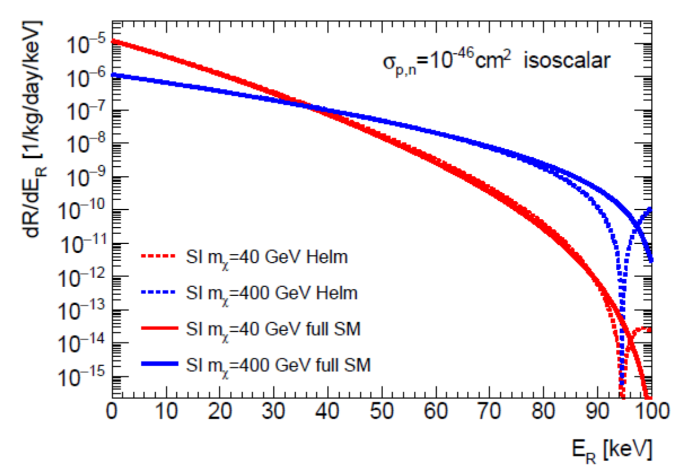
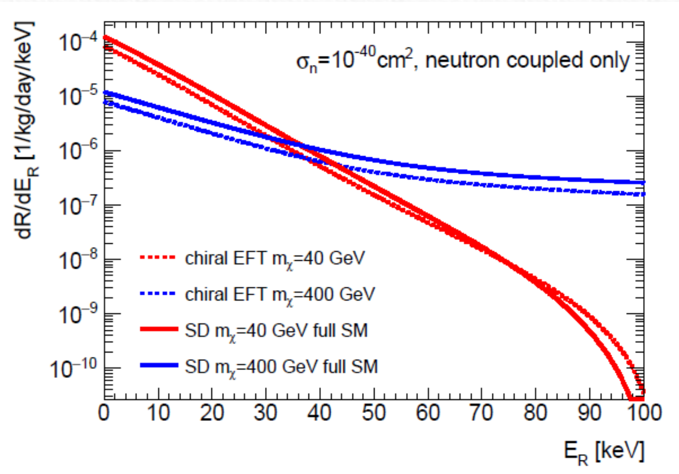
Updated SD recoil spectra

- Comparison between different treatments of SI/SD scattering
- Consider spin-1/2 WIMPs

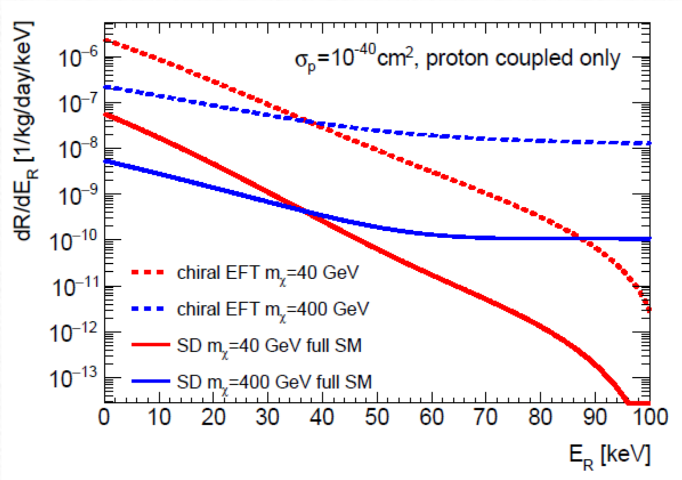
SI scattering



SD-neutron only



SD-proton only

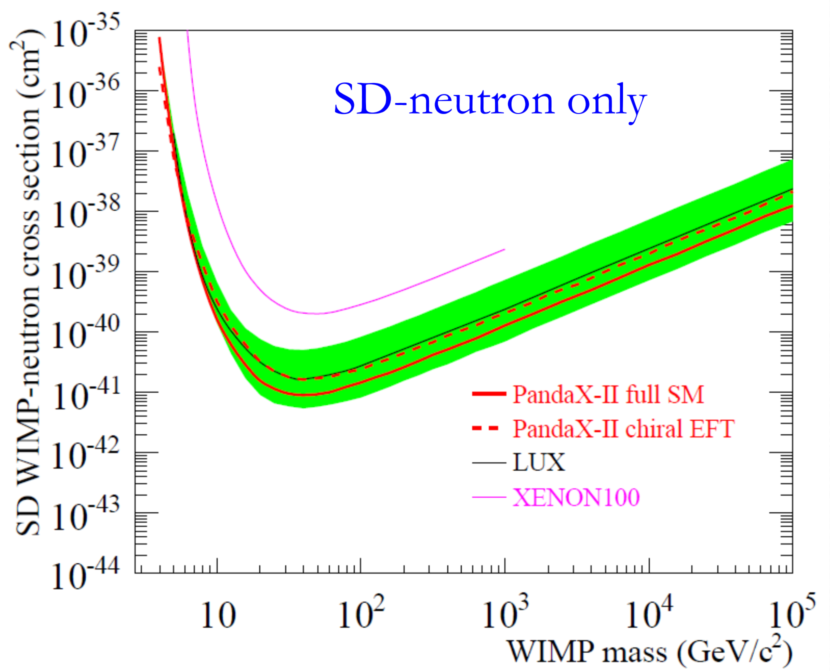


Helm: traditional treatment, structure function given by the Helm form factor,
Full SM: full-basis shell-model (SM) calculations, vector-vector interaction L^5_{int}

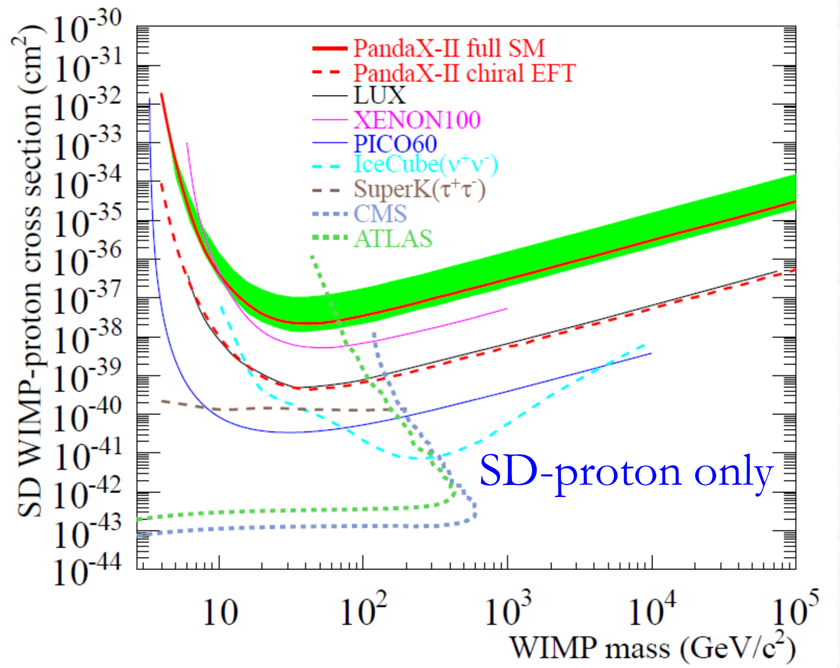
Chiral EFT: traditional treatment, with truncations on SM calculation and additional contributions from O_6 and a pion exchange current,
Full SM: full-basis shell-model (SM) calculations, axial vector-axial vector interaction L^{15}_{int}

Updated SD cross section limits

- Calculated with the 54 ton-day dataset from PandaX-II



Minimum **χ-n SD** cross section limit(EFT): 9×10^{-42} cm^2 at 40 GeV/c^2



Minimum **χ-p SD** cross section limit(EFT): 2.2×10^{-38} cm^2 at 40 GeV/c^2

Summary

- A Effective Field Theory model describing the WIMP-nucleus scattering is employed to analyze the 54 ton-day exposure data.
- Notice significant rate in high recoil energy (above 40 keV) for certain momentum-dependent EFT operators at large DM mass, leading to the idea of extending the energy window.
- New SD interaction results are presented, setting the most stringent upper limit to date on the SD WIMP-neutron cross section (9.0e-42 cm^2) above WIMP mass of 40 GeV/c^2.

Thank you!

backups

Effective field theory

- Differential cross section for elastic scattering can be expressed as:

$$\frac{d\sigma(v,E_R)}{dE_R} = 2m_T \frac{d\sigma(v,\vec{q}^{\,2})}{d\vec{q}^{\,2}} = \frac{2m_T}{4\pi v^2}\left[\frac{1}{2J_\chi+1}\frac{1}{2J_N+1}\sum_{\text{spins}}|\mathcal{M}|^2\right]$$

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi}\int \frac{d\sigma(v,E_R)}{dE_R} v f(\vec{v}) d^3v$$

- For SI and SD case, the single-nucleon cross section could be expressed as:

$$\sigma^{\text{SI}}_{p,n}(v) = \left(\frac{c_1}{m_V^2}\right)^2 \frac{\mu^2_{p,n}}{\pi}$$

$$\sigma^{\text{SD}}_{p,n}(v) = \left(\frac{c_4}{m_V^2}\right)^2 \frac{\mu^2_{p,n}}{\pi}\frac{J_\chi(J_\chi+1)}{4}$$