Recent PandaX-II Results on Dark Matter Search and Status of PandaX-4T

Yong Yang

Shanghai Jiao Tong University

On behalf of  **PANDA X Collaboration**

12th IDM conference, Brown University

Outline

- Introduction to PandaX experiment and China Jinping Underground Laboratory
- Recent results from PandaX-II
- PandaX Future

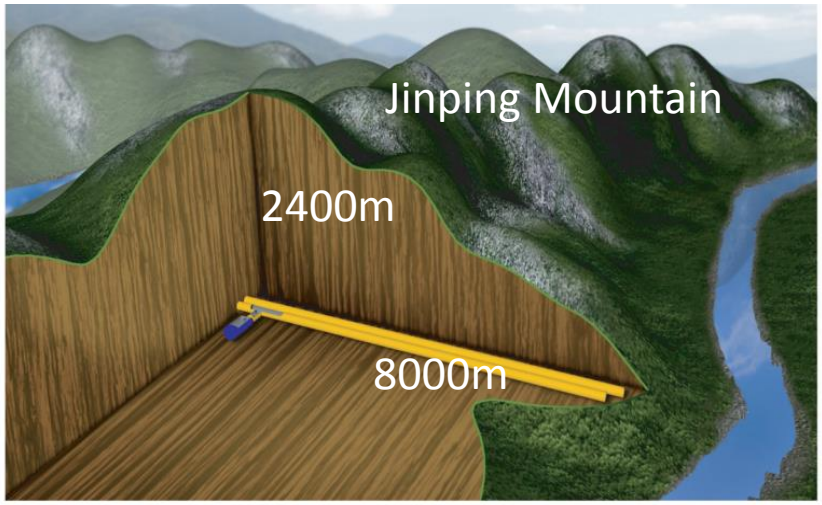
PandaX Collaboration

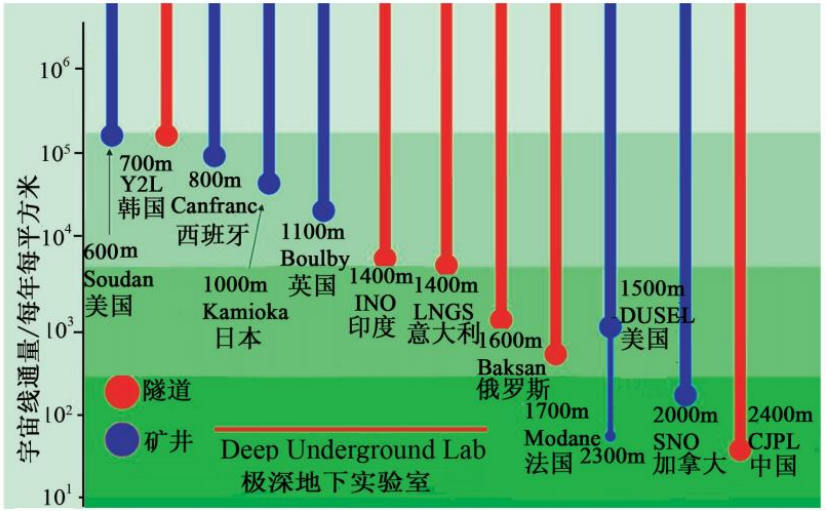
Formed in 2009, ~50 people

- 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

China JingPing Underground Lab

- Deepest (6800 m.w.e), **1μ/week/m²**
- Horizontal access!



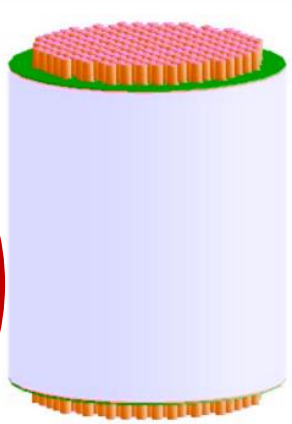


PandaX experiments

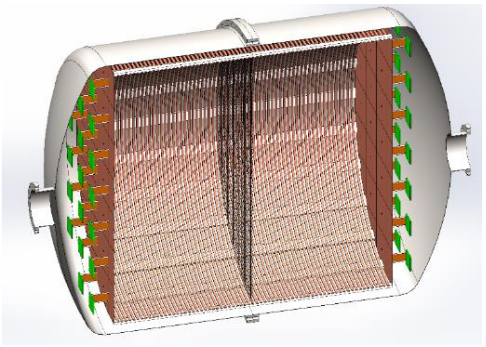
PandaX = Particle and Astrophysical Xenon Experiments

Phase I:
120 kg DM
2009-2014

Phase II:
500 kg DM
2014-2017



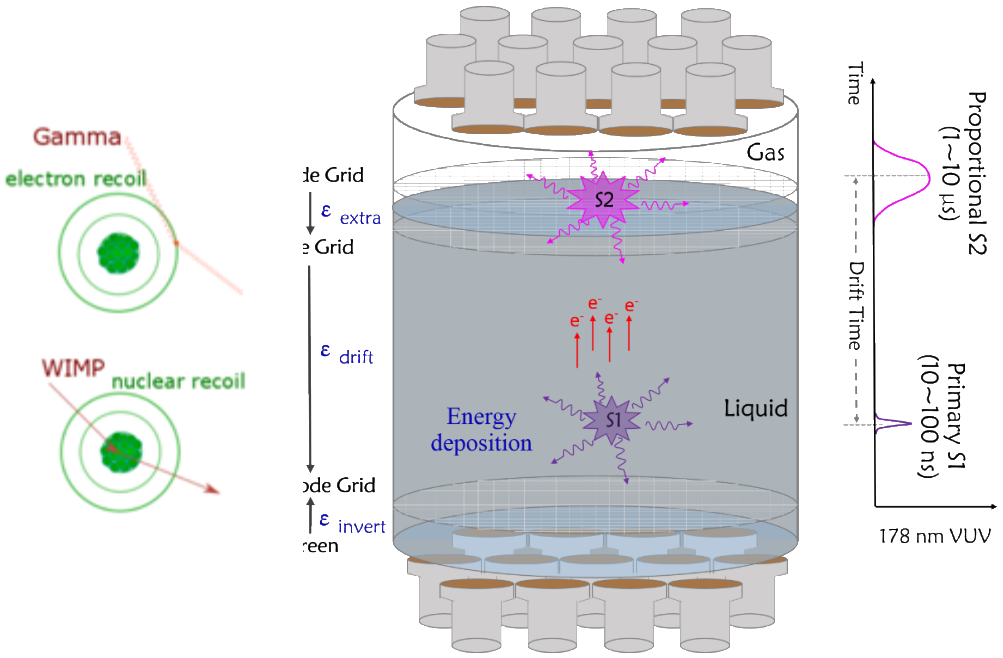
PandaX-xT:
multi-ton DM
future

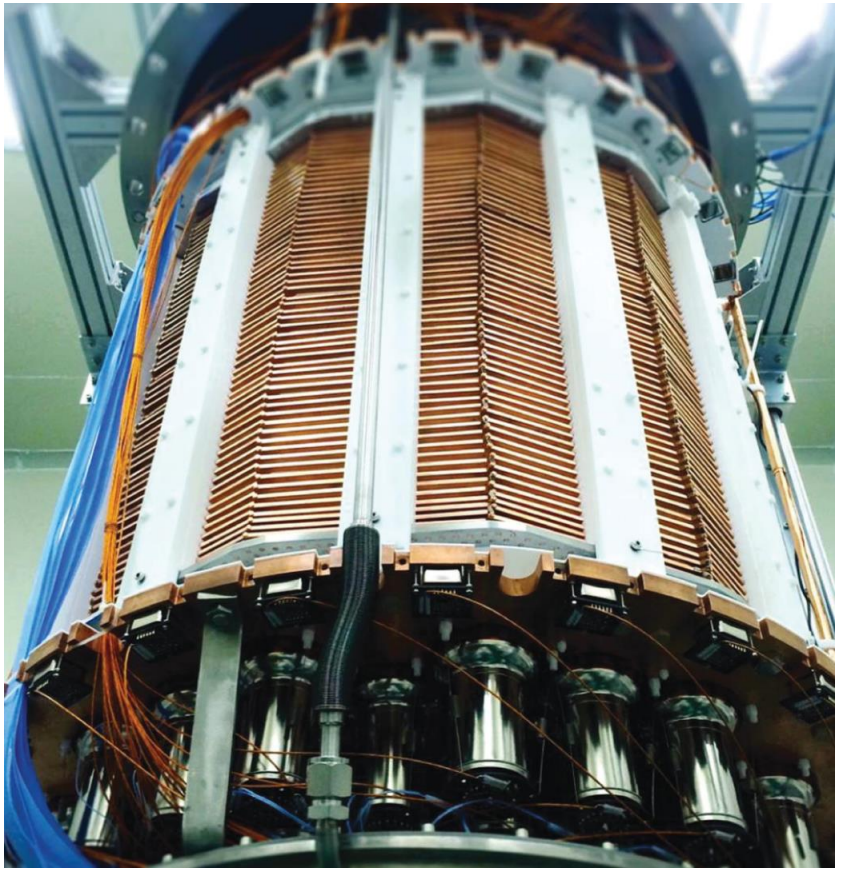


PandaX-III:
200 kg to 1 ton
^{136}Xe 0vDBD
future

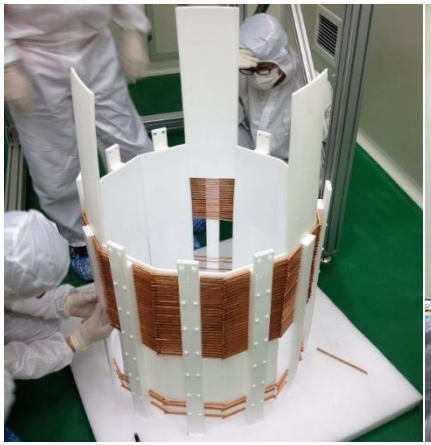
PandaX-II dual-phase TPC

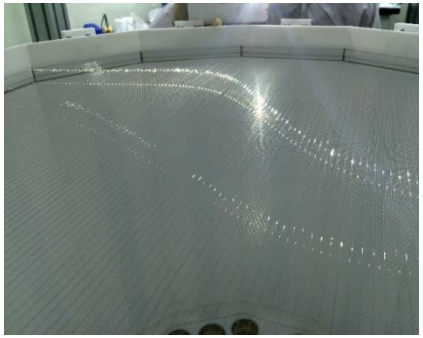
- 60 cm x 60 cm dual-phase xenon Time Projection Chamber
- Measure both scintillation (S1) and delayed charge (S2) signal
- 3-D vertexing
- Excellent background rejection

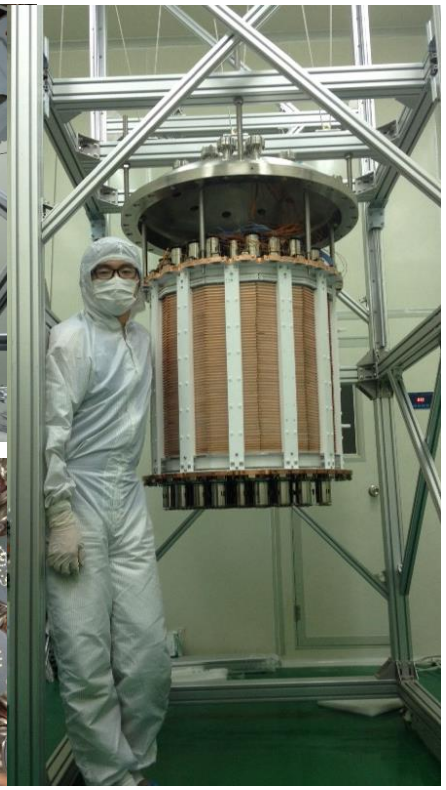
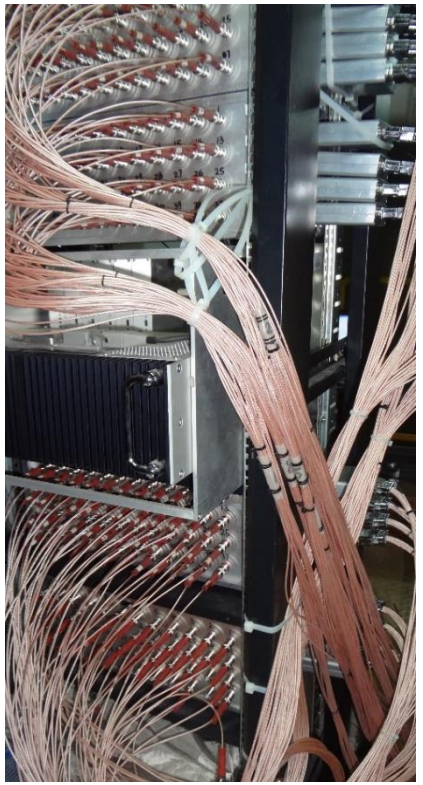




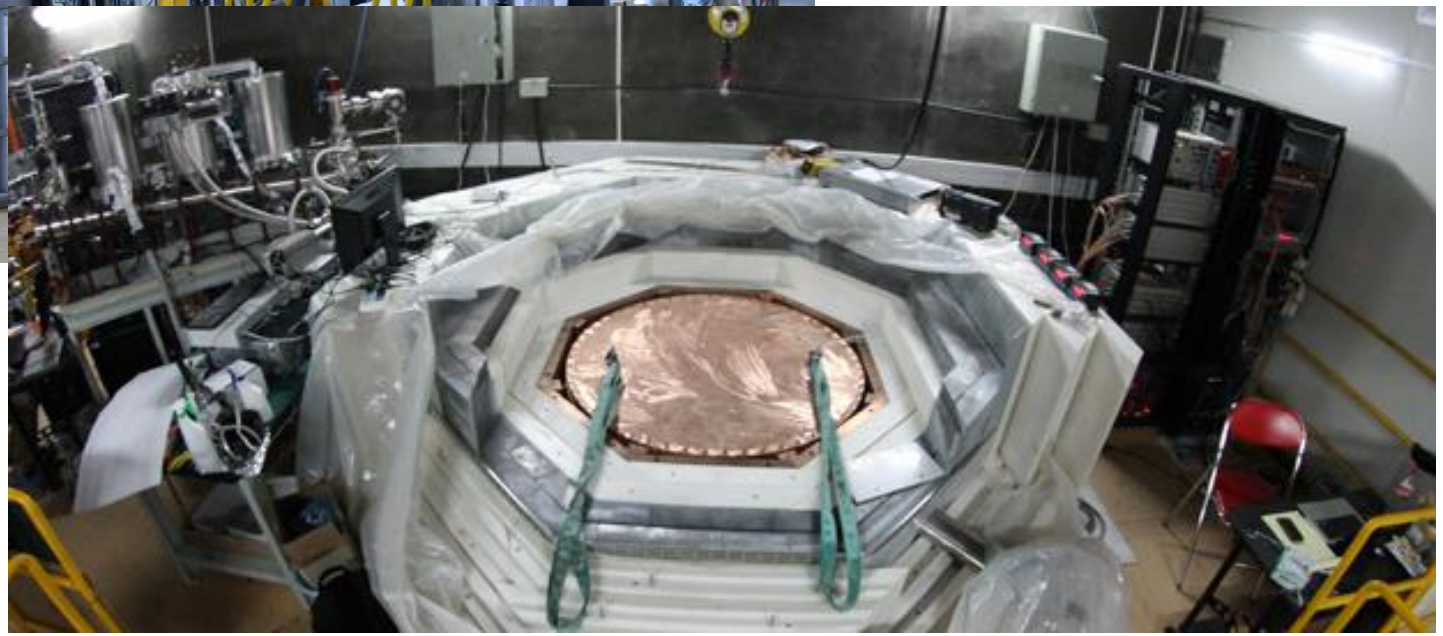
Assembling the detector





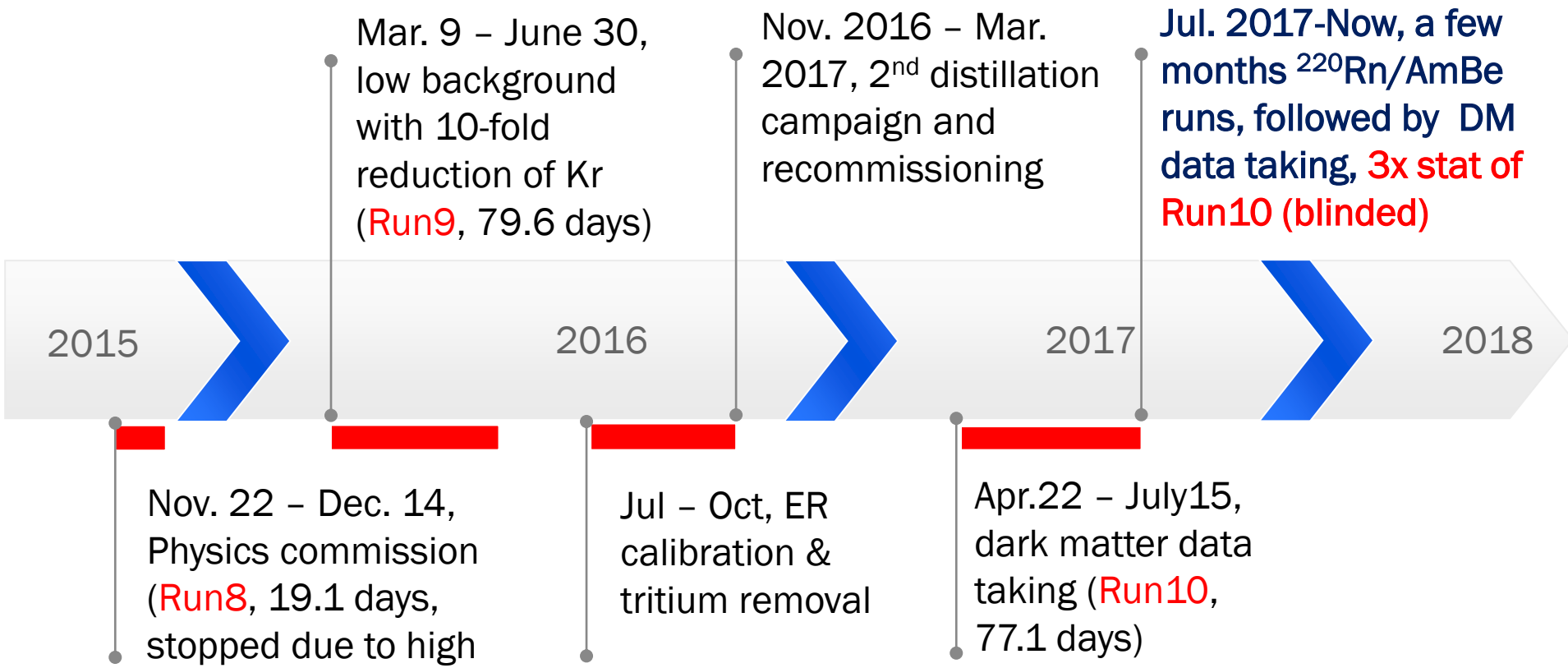



PandaX-II Site



PandaX-II Run History

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

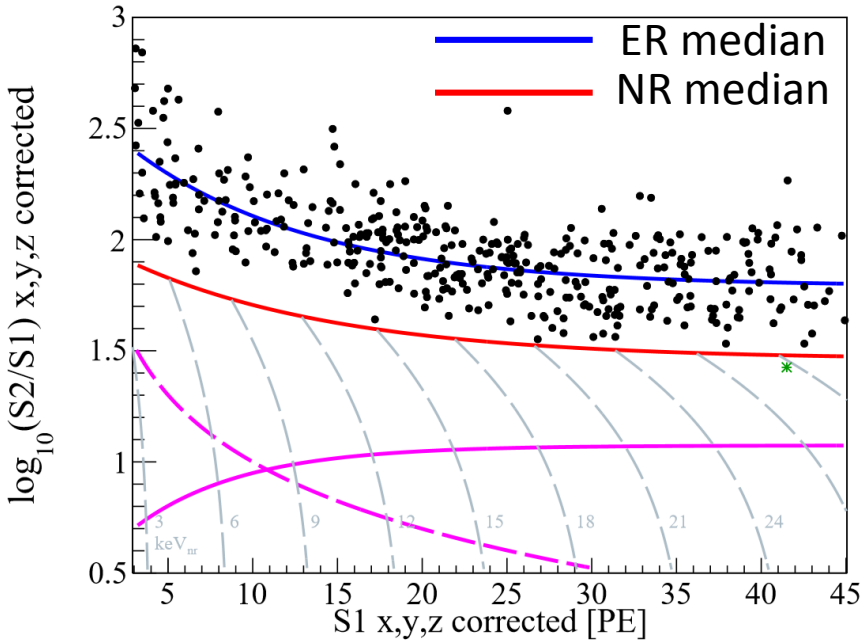


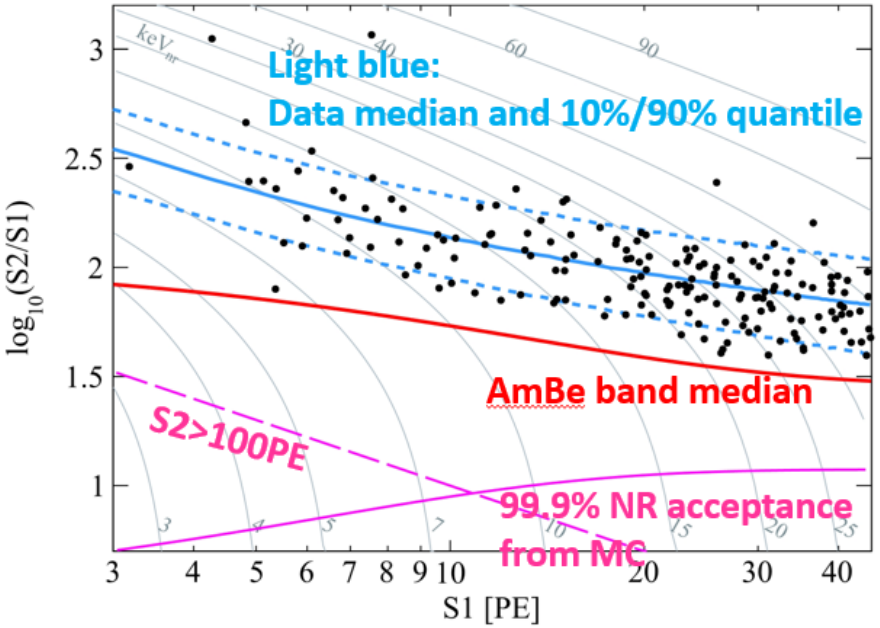
PandaX-II Results

Physics Topics	Exposure (ton-day)	Publication
WIMP spin-independent	33	**PRL 117, 21303 (2016)**
WIMP spin-dependent	33	**PRL 118, 071301 (2017)**
Inelastic scattering	27	**PRD 96, 102007 (2017)**
Axion and Axion-Like-Particle	27	**PRL 119, 181806 (2017)**
WIMP spin-independent	54	PRL 119, 181302 (2017)
Light mediator and Self-Interacting Dark Matter(*)	54	PRL 121, 021304 (2018)
General EFT and spin dependent(*)	54	arXiv:1807.01936

Results from 54 ton-day are presented in this talk.
(*) Very recent results from collaborating with theorists: Hai-bo Yu (UCI) and Wick C. Haxton (UCB&LBNL)

Run9+Run10 WIMP Search Results





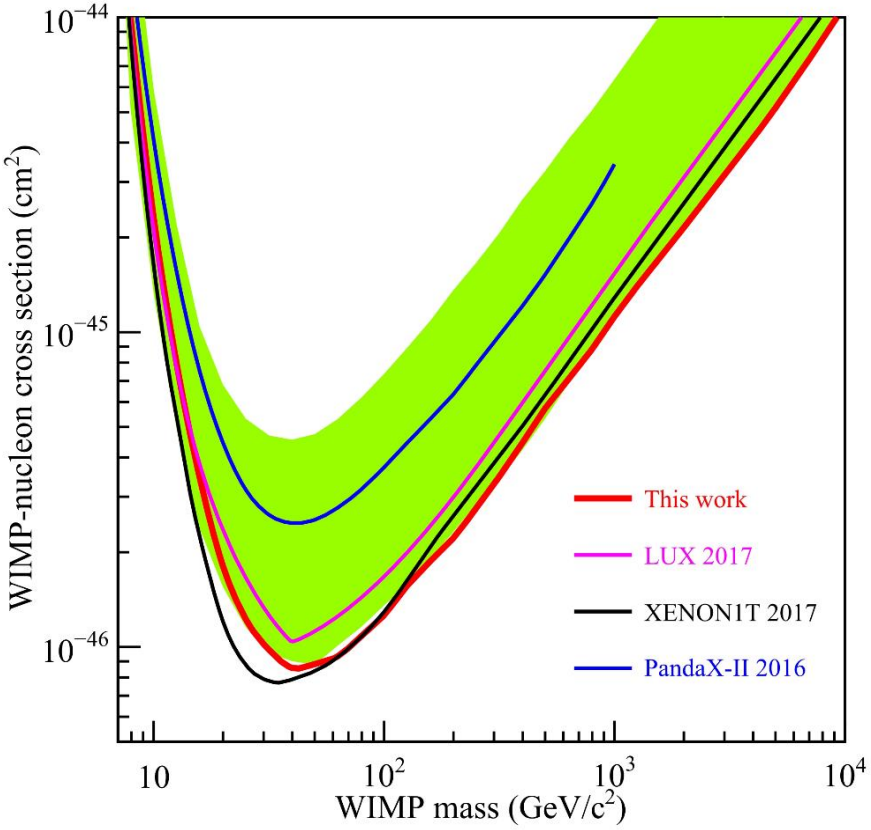
	ER	Accidental	Neutron	Total Fitted	Total Observed
Run 9	376.1	13.5	0.85	390 ± 50	389
Below NR median	2.0	0.9	0.35	3.2 ± 0.9	1
Run 10	172.2	3.9	0.83	177 ± 33	177
Below NR median	0.9	0.6	0.33	1.8 ± 0.5	0

Item	Run 9 (mDRU)	Run 10 (mDRU)
^{85}Kr	1.19±0.20	0.20±0.07
^{127}Xe	0.42±0.10	0.021±0.005
^{3}H	0	0.27±0.08
^{222}Rn	0.13±0.07	0.12±0.06
^{220}Rn	0.01±0.01	0.02±0.01
ER (material)	0.20±0.10	0.20±0.10
Solar ν	0.01	0.01
^{136}Xe	0.0022	0.0022
Total	1.96±0.25	0.79±0.16

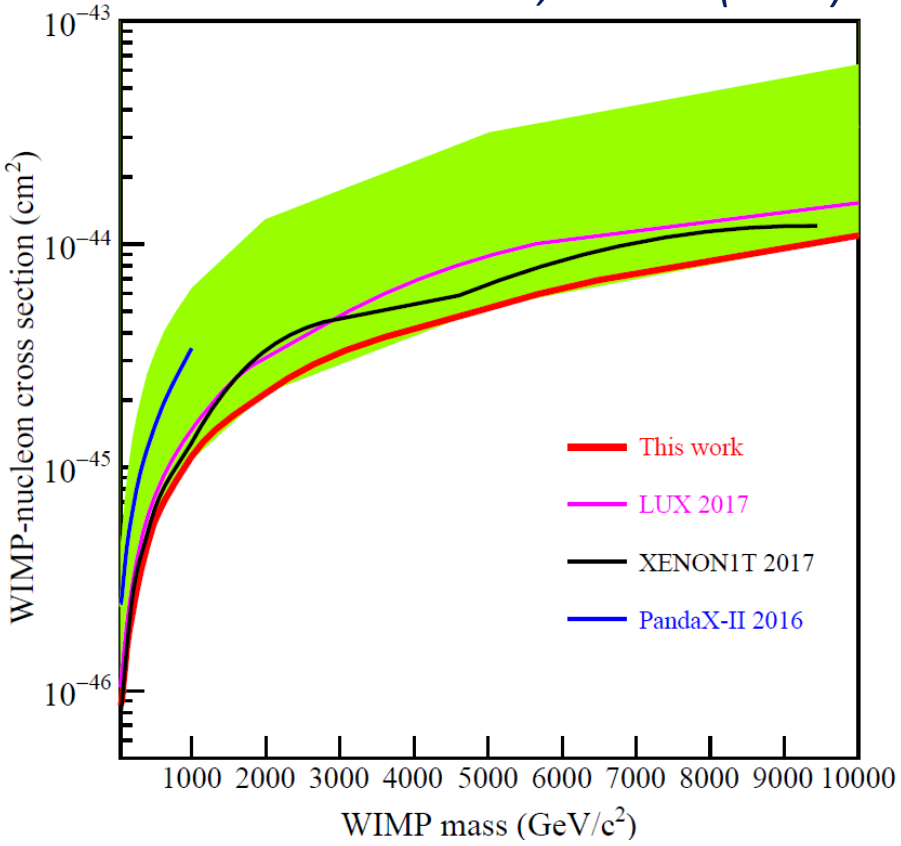
ER background in mDRU
(10^{-3} evts/kg/day/keV)

WIMP-nucleon SI cross section limits

PandaX-II 54 ton-day



PRL 119, 181302 (2017)



- Lowest exclusion at 8.6×10^{-47}cm^2 at 40GeV, most stringent for m_χ > 100 GeV when published
- Improved from PandaX-II 2016 limit about 2.5 time at high masses

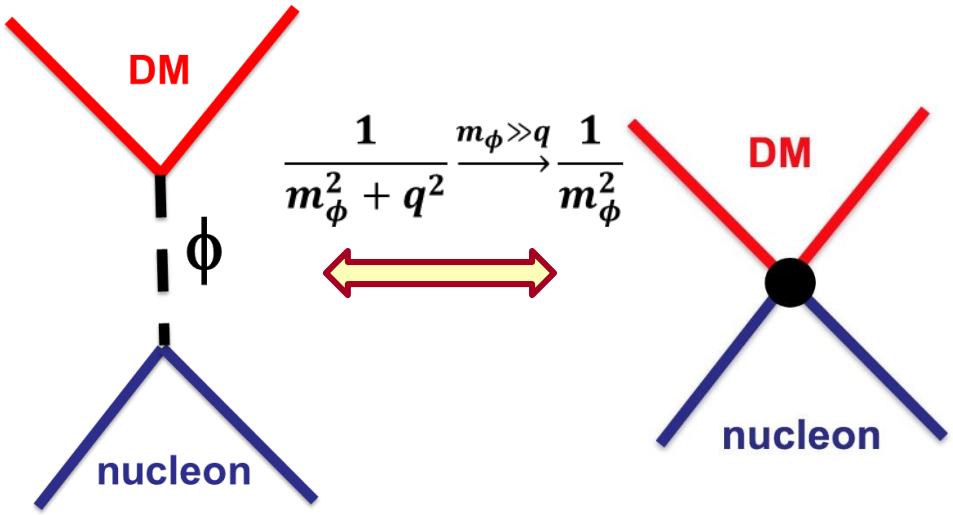
PHYSICAL REVIEW LETTERS

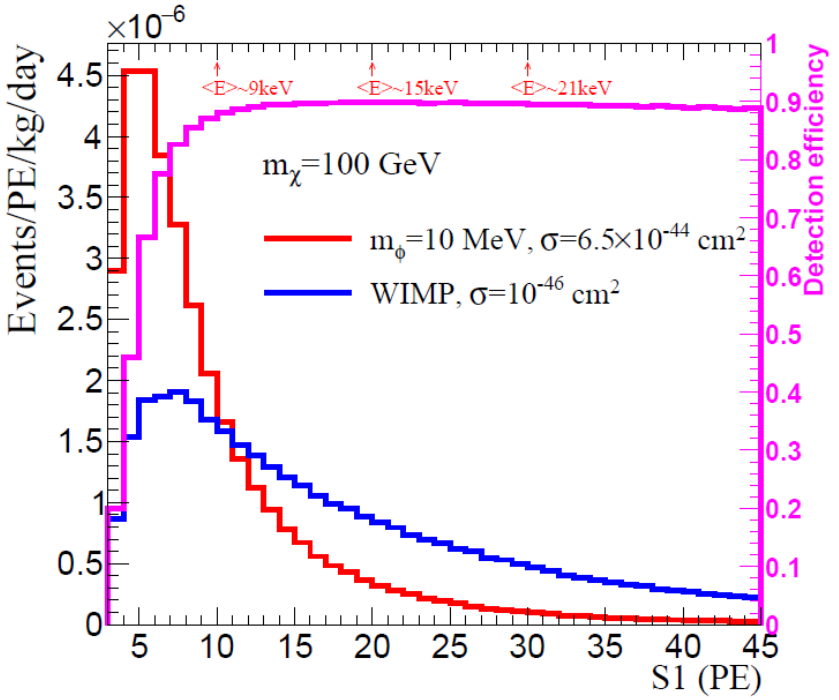
Editors' Suggestion Open Access

Constraining Dark Matter Models with a Light Mediator at the PandaX-II Experiment

Xiangxiang Ren *et al.* (PandaX-II Collaboration)
Phys. Rev. Lett. **121**, 021304 – Published 12 July 2018

Light-mediator DM





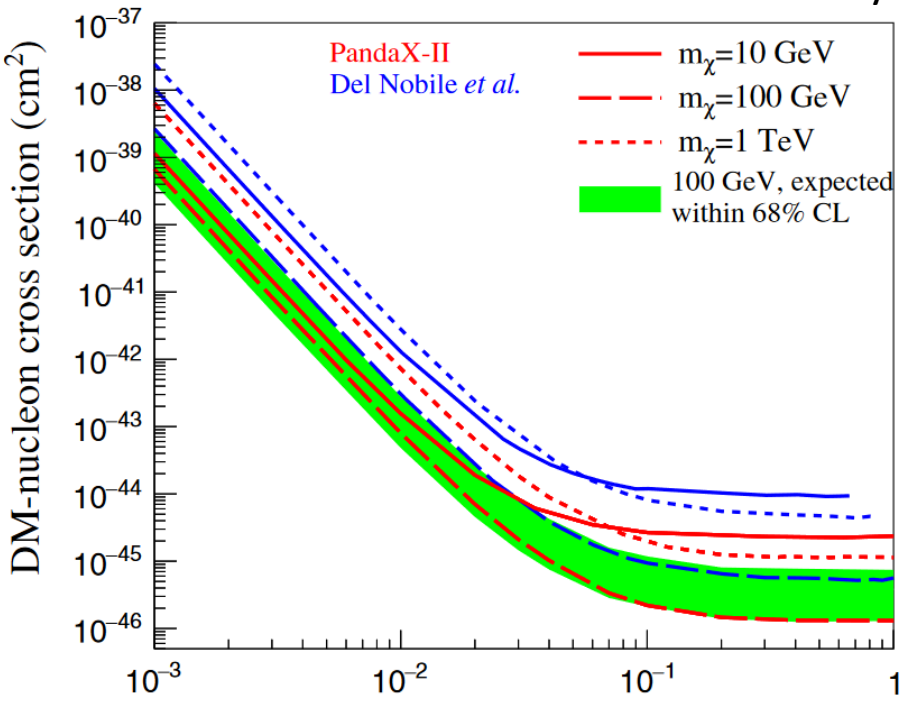
- Heavy mediator ➔ EFT contact interaction
  - Foundation of "main" SI/SD results in direct detection
  - typical q ~ 10-50 MeV for 10GeV-1TeV DM

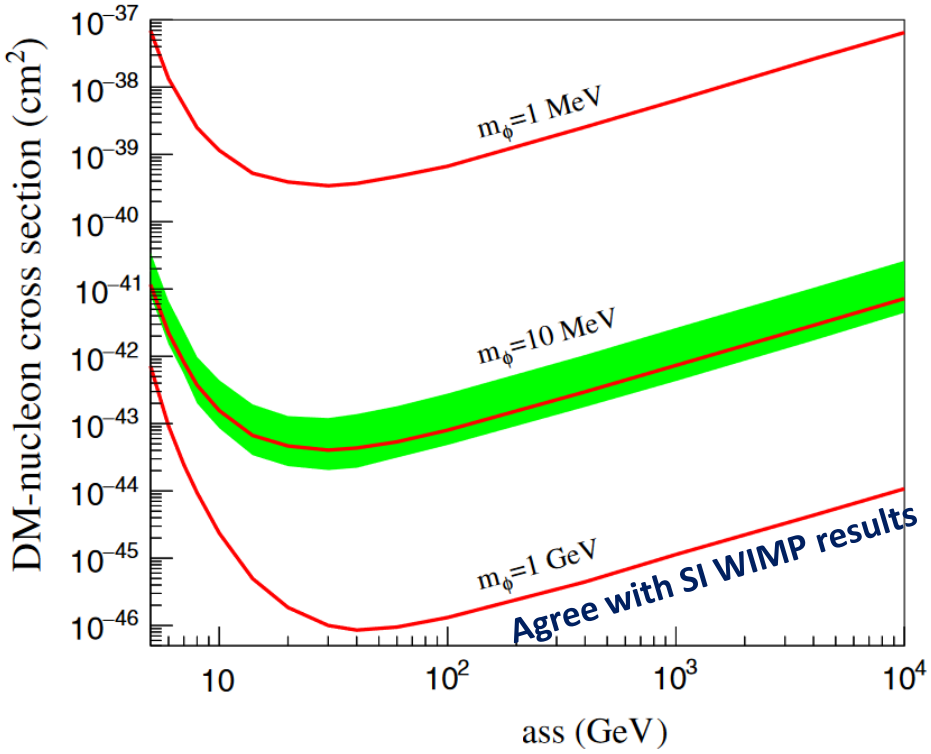
- Light mediator: mediator m_ϕ is compared to or smaller than q
  - Signal spectrum more peaked towards to low-energy
  - q can not be simply ignored

New constraints on σ (DM-nucleon)

PandaX-II 54 ton-day

PRL 121, 021304 (2018)





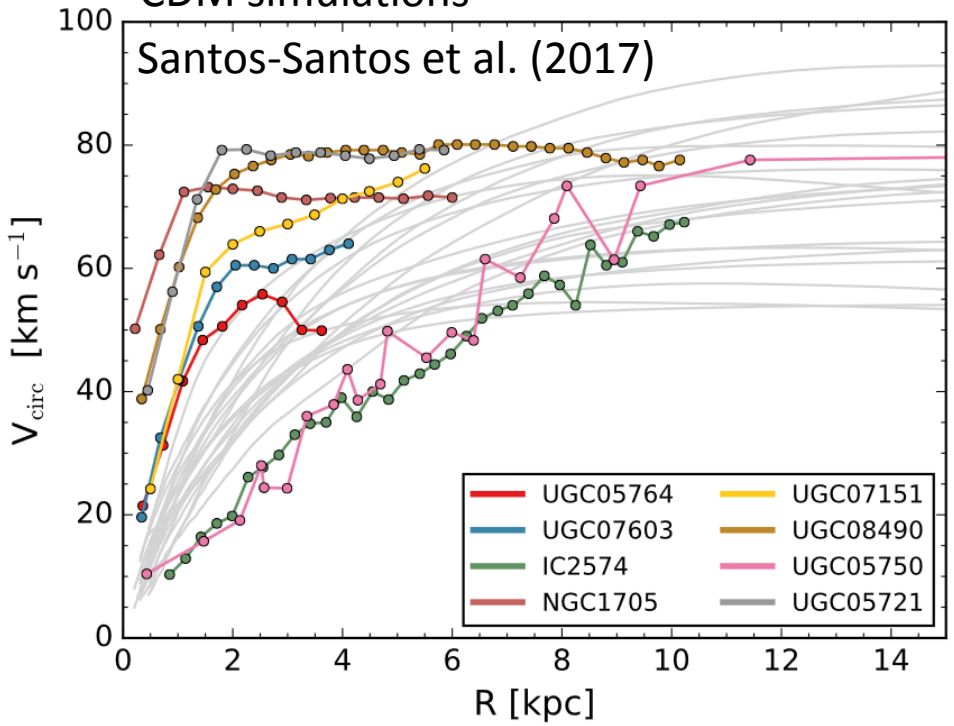
$$\sigma(q^2)_{\chi N} = \sigma|_{q^2=0} A^2 \left(\frac{\mu}{\mu_p}\right)^2 \frac{m_\phi^4}{(m_\phi^2 + q^2)^2} F^2(q^2)$$

Our Limits

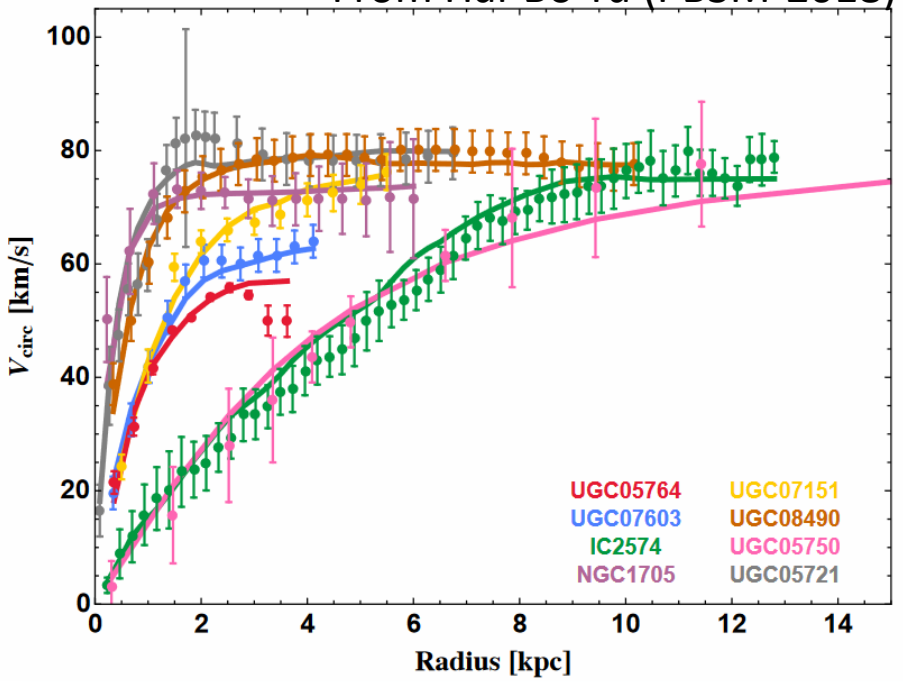
For light-mediator (scalar/vector) DM models

Self-Interacting DM with a light mediator

State-of-art hydrodynamical CDM simulations



From Hai-Bo Yu (PBSM-2018)



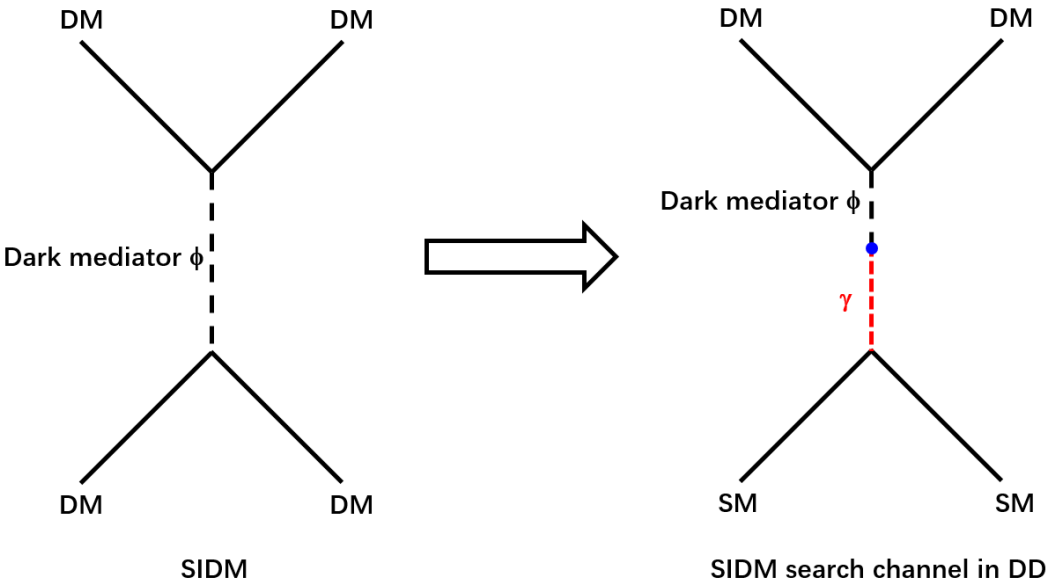
Points : Observed galaxy rotation curves

Solid Lines: SIDM Fits

Gray lines : CDM Simulated

Self-Interacting DM with light-mediator

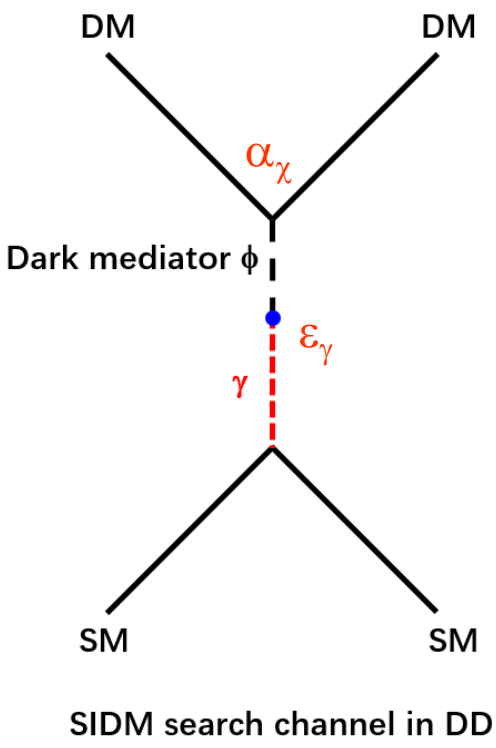
"Direct Detection Portals for Self-interacting Dark Matter", M. Kaplingha *et. al*, PRD 89,035009(2014)
"Direct Detection Signatures of Self-Interacting Dark Matter with a Light Mediator", E. Del. Nobile, JCAP1510, 055 (2015)



- If the mediator mixes with SM particles (through g/Z/H mixing), SIDM could be detected at direct detection experiments.

SIDM particle-physics model

M. Kaplingha *et. al,* PRD 89,035009(2014)



SIDM search channel in DD

New Parameter	Description
α_χ	Fine structure in DM sector
ε_γ	Mixing parameter between mediator and photon

- For Symmetric SIDM models, where DM and anti-DM are equally populated in early Universe, α_χ can be fixed by the observed DM relic density.

$$\sim 0.2 \times \left(\frac{\alpha_X}{10^{-2}}\right)^{-2} \times \begin{cases} (m_X/300\ \mathrm{GeV})^2 & \text{vector} \\ (m_X/100\ \mathrm{GeV})^2 & \text{scalar} \end{cases}$$

$\alpha_\chi \approx 4 \times 10^{-5} \times (m_\chi/\mathrm{GeV})$, γ/Z mixing

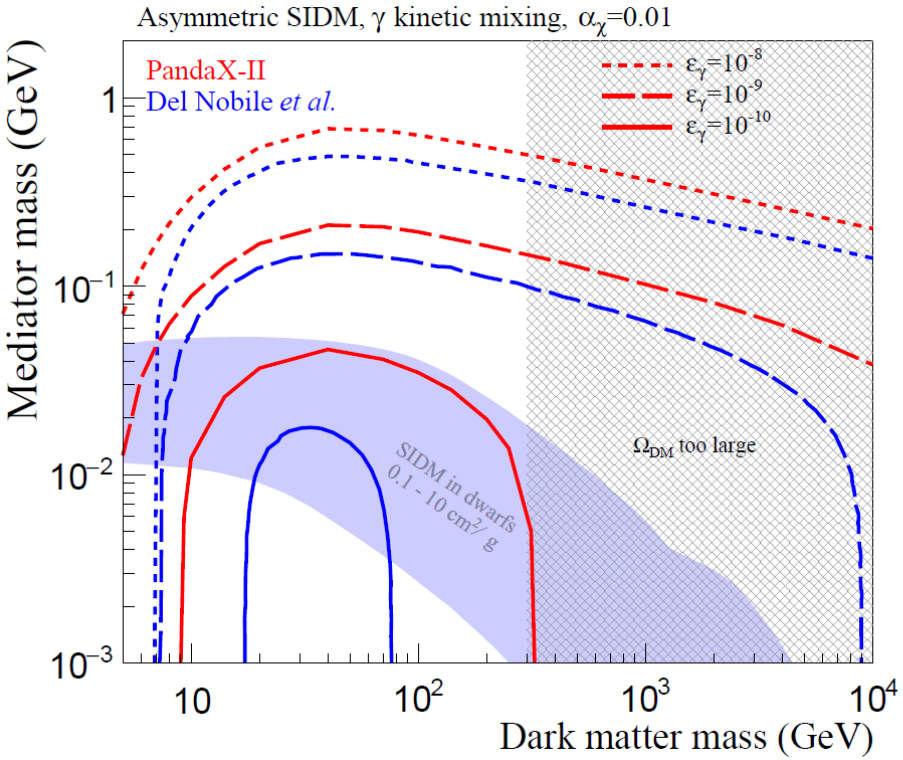
$\alpha_\chi \approx 10^{-4} \times (m_\chi/\mathrm{GeV})$, H mixing

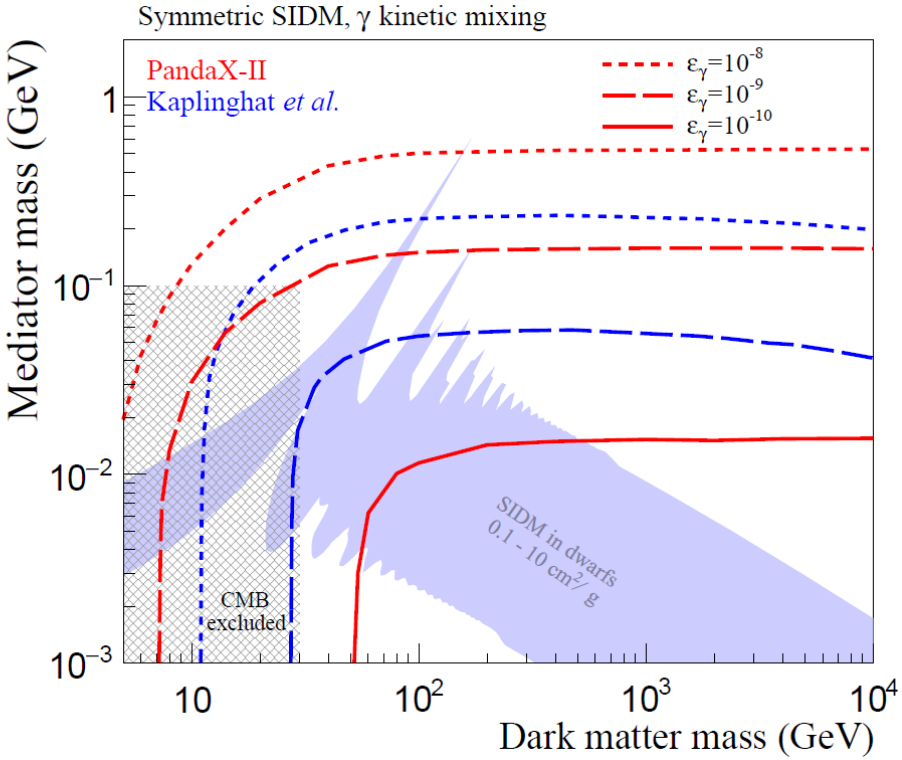
- For Asymmetric SIDM models, α_χ = 0.01 is assumed
- Very recently, H. Ran *et. al.* PLB783(2018) 76-81, derive best-fit value of m_ϕ and α_χ

Constraining Self-Interacting Dark Matter

PandaX-II 54 ton-day

PRL 121, 021304 (2018)





- Lower limits on mediator mass vs DM mass for Asymmetric (left) and Symmetric SIDM with photon kinetic mixing.
- In the favored SIDM parameter space, PandaX-II is sensitive for as small as 10^{-10} mixing parameter

arXiv.org > hep-ex > arXiv:1807.01936

High Energy Physics - Experiment

Constraining WIMP-Nucleon Effective Interactions from PandaX-II Experiment

General EFT DM-SM interaction

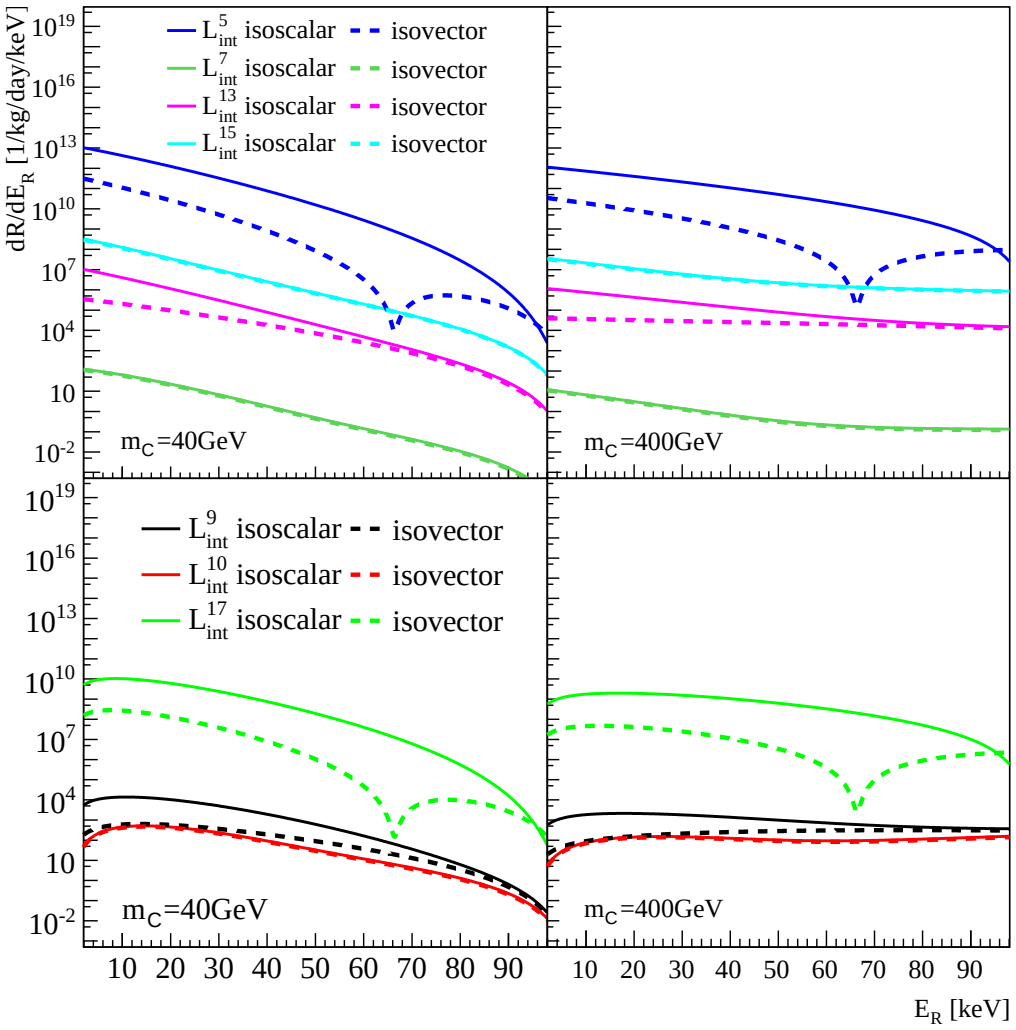
7 typical relativistic operators studied, complete list in
Phys. Rev. C89, 065501 (2014)

Dimension	Operator	Interactions
4	$\mathcal{L}^{5}_{\rm int} \equiv \bar{\chi}\gamma^{\mu}\chi\bar{N}\gamma_{\mu}N$ $\mathcal{L}^{7}_{\rm int} \equiv \bar{\chi}\gamma^{\mu}\chi\bar{N}\gamma_{\mu}\gamma^{5}N$ $\mathcal{L}^{13}_{\rm int} \equiv \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{N}\gamma_{\mu}N$ $\mathcal{L}^{15}_{\rm int} \equiv \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{N}\gamma_{\mu}\gamma^{5}N$	vector/axial- vector interactions (L5/15: standard SI/SD)
5	$\mathcal{L}^{9}_{\rm int} \equiv \bar{\chi}i\sigma^{\mu\nu}\frac{q_{\nu}}{m_M}\chi\bar{N}\gamma_{\mu}N$ $\mathcal{L}^{17}_{\rm int} \equiv i\bar{\chi}i\sigma^{\mu\nu}\frac{q_{\nu}}{m_M}\gamma^{5}\chi\bar{N}\gamma_{\mu}N$	coupling the WIMP magnetic moment or electric dipole moment with the nucleon's vector current
6	$\mathcal{L}^{10}_{\rm int} \equiv \bar{\chi}i\sigma^{\mu\nu}\frac{q_{\nu}}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^{\alpha}}{m_M}N$	coupling WIMP and nucleon magnetic moments

A unit dimensionless coupling is assumed here,
this will be constrained by PandaX-II data.

Energy spectra for EFT operators

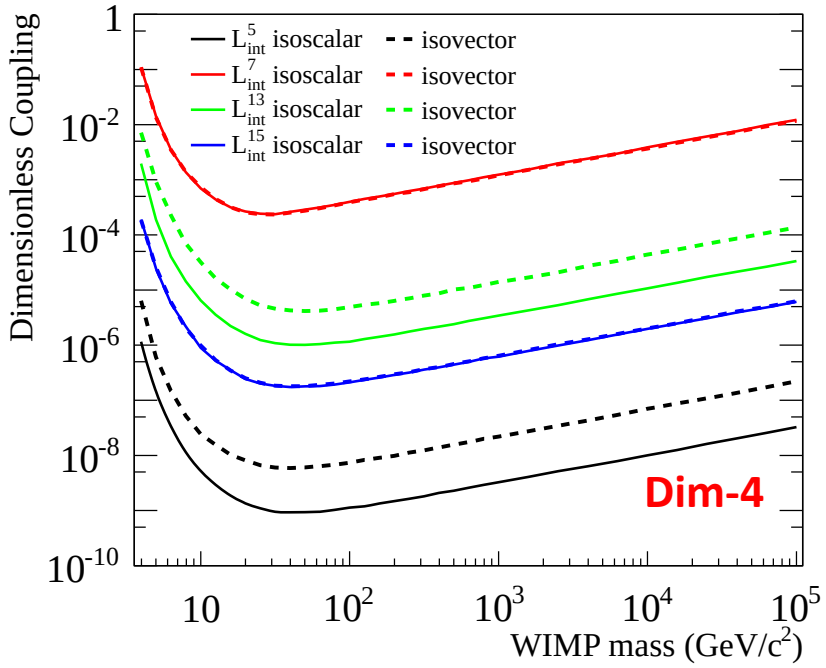
- 7 typical relativistic operator, leading to dramatically different spectra
  - ***q*** and ***v*** dependence
  - Isospin scalar (coupling to proton and neutron with same sign)
  - isospin vector (p,n opposite sign)

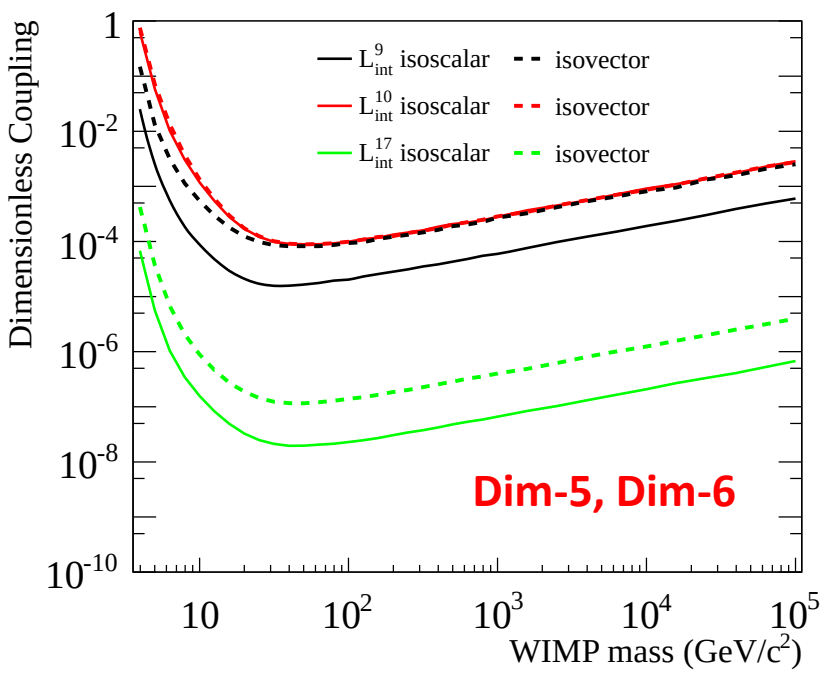


Upper limits on coupling

PandaX-II 54 ton-day

arXiv:1807.01936

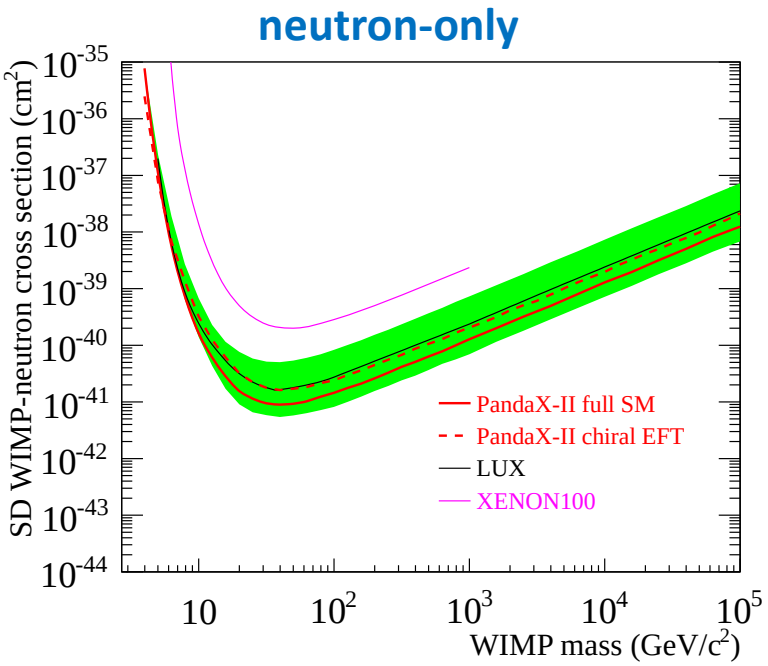


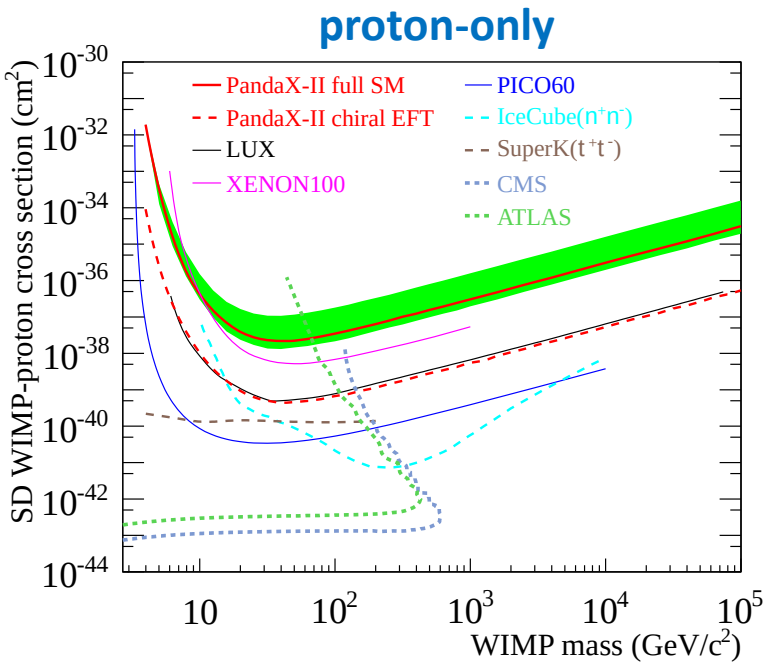


Constraints strongly depending on the operator/isospin

L5/15: standard SI/SD

Constraints on Spin-dependent Interaction

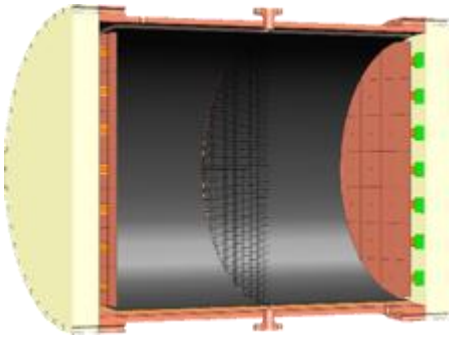




- Two "nuclear matrix element" calculations:
  - Full basis shell-model GCN5082, J. Mendende et al., Nucl. Phys. A818, 139 (2009)
  - Chiral EFT matrix element, P. Klos, Phys. Rev. D 88, 083516 (2013)
  - Proton-only interaction more sensitive to the calculation
- Most stringent limits on neutron-only SD cross section for $m_\chi > 40$ GeV

PandaX Future

- PandaX-xT 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

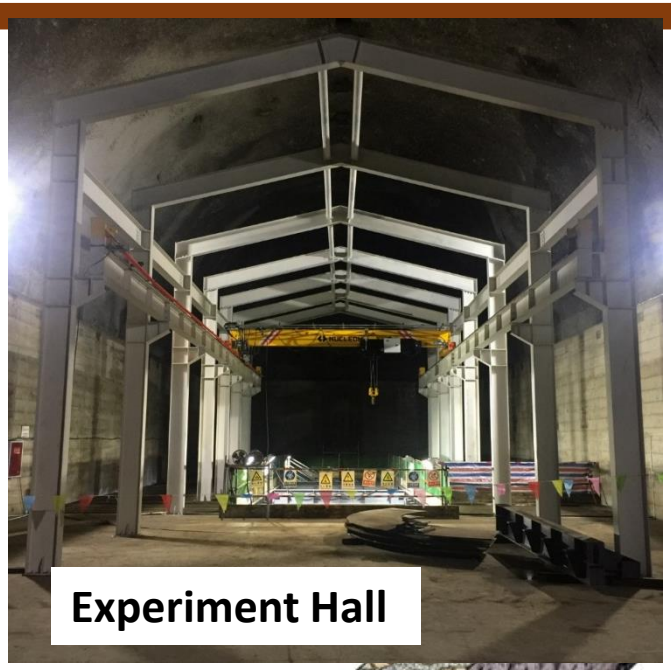
PandaX-III: 200 kg to 1 ton HP gas ^{136}Xe 0vDBD experiment Future

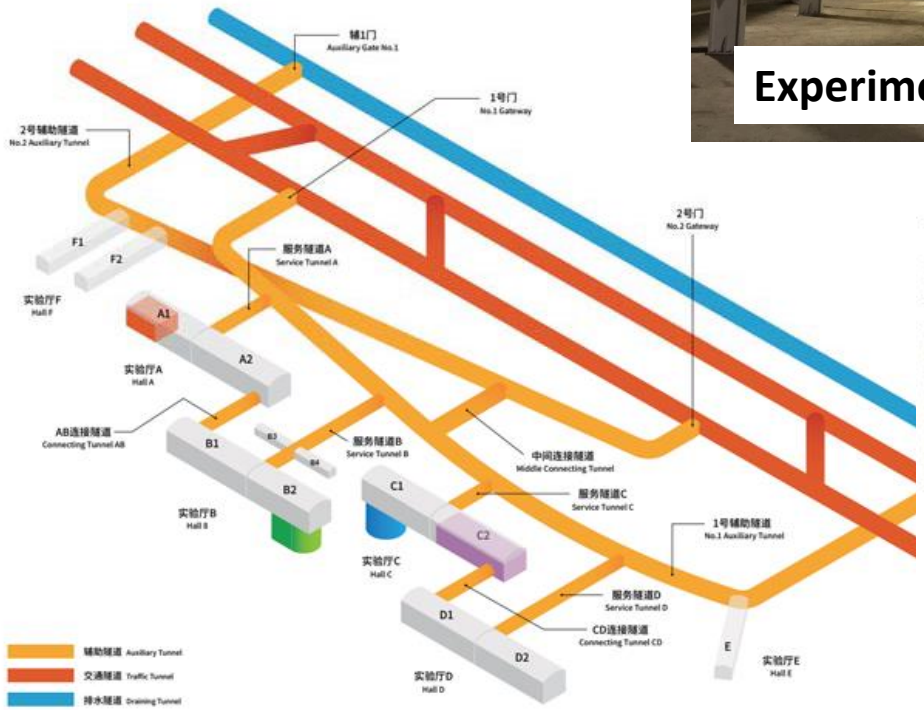
CJPL-I

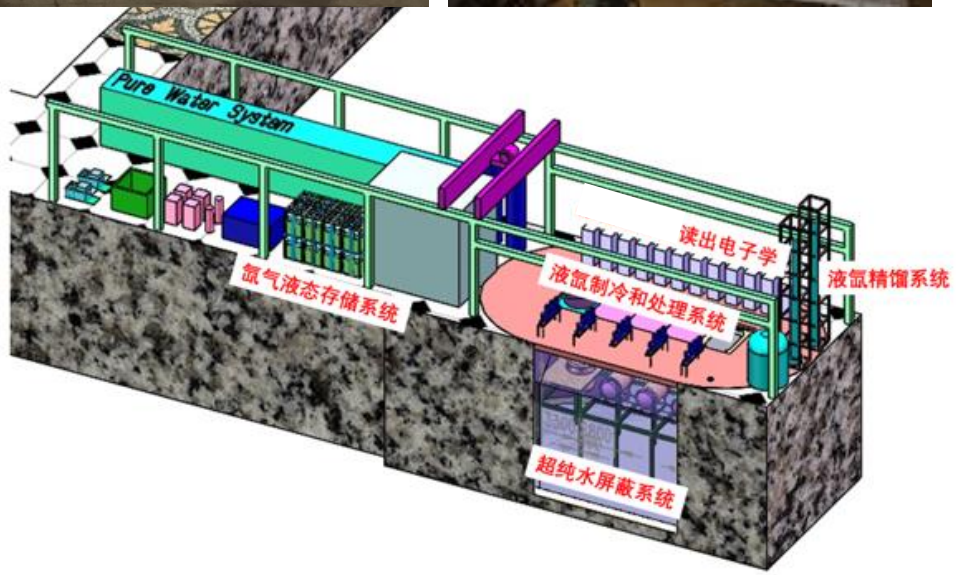
CJPL-II

New experiment hall at CJPL-II

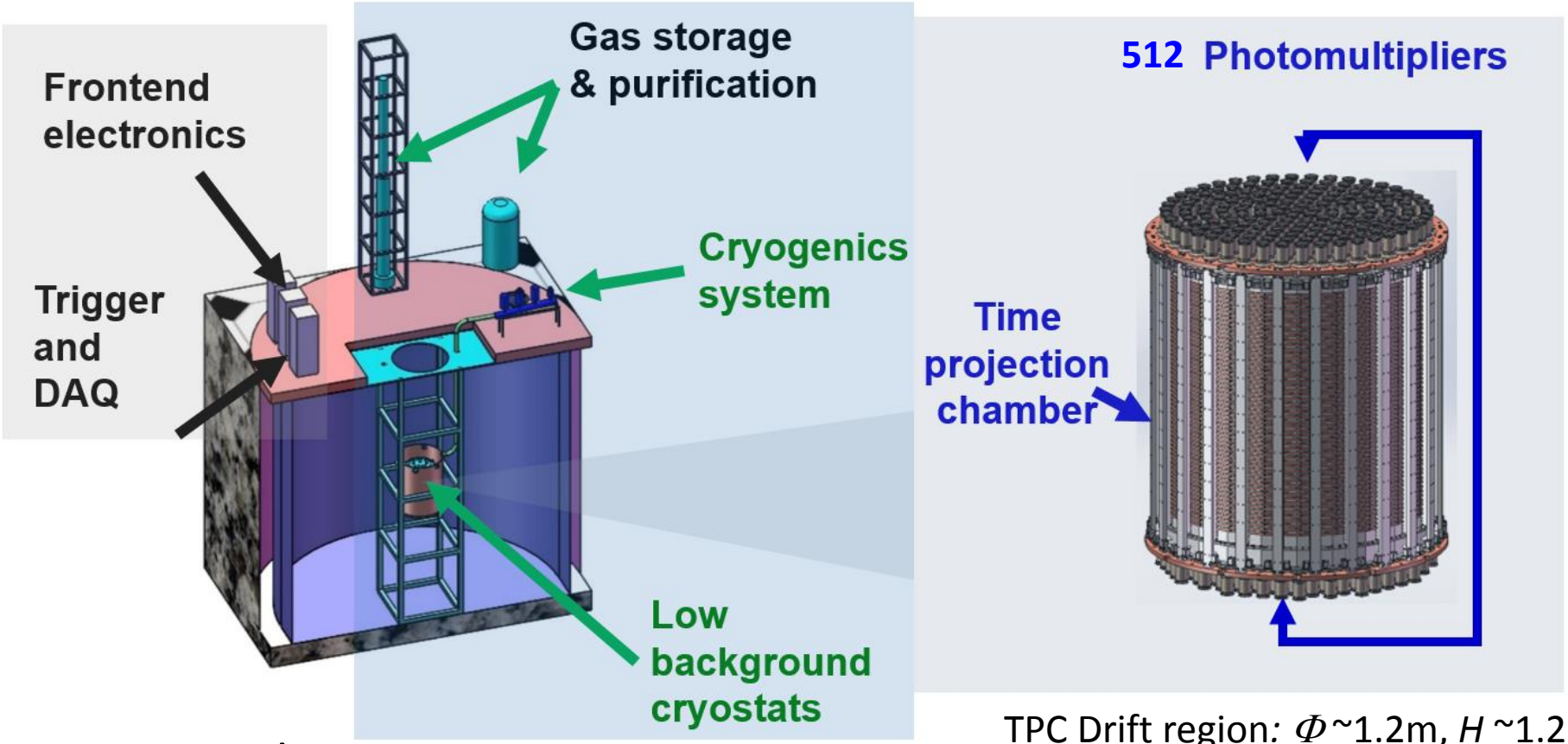
- B2 Hall
- 14m(H)x14m(W)x65m(L)
- Water Shielding
  - 5000Ton pure water
  - U/Th <10^{-14} g/g







PandaX-xT facilities

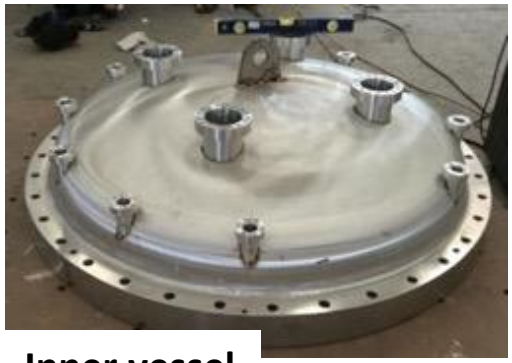


TPC Drift region: Φ ~1.2m, H ~1.2m

- Intermediate stage:
  - **PandaX-4T** (4-ton in sensitive region) with SI sensitivity ~10^{-47} cm^2
  - On-site assembly and commissioning: 2019-2020

Current Status and Schedule

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

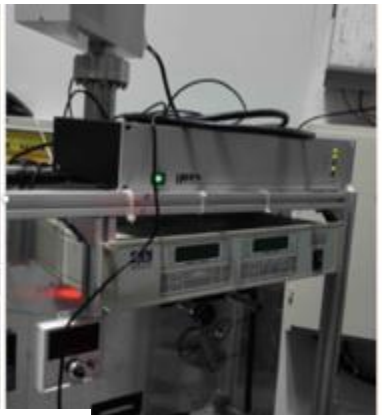


Inner vessel

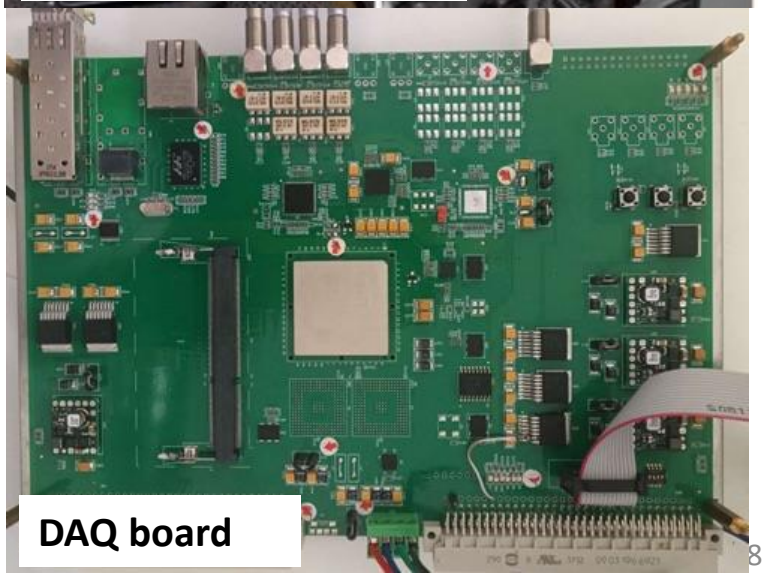
Cooling bus

TPC prototype

PMT test



Krypton measurement

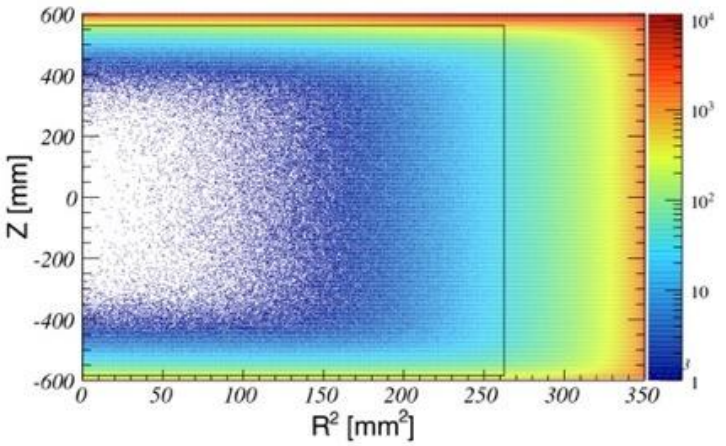


DAQ board

PandaX-4T background estimation

- **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

arXiv:1806.02229

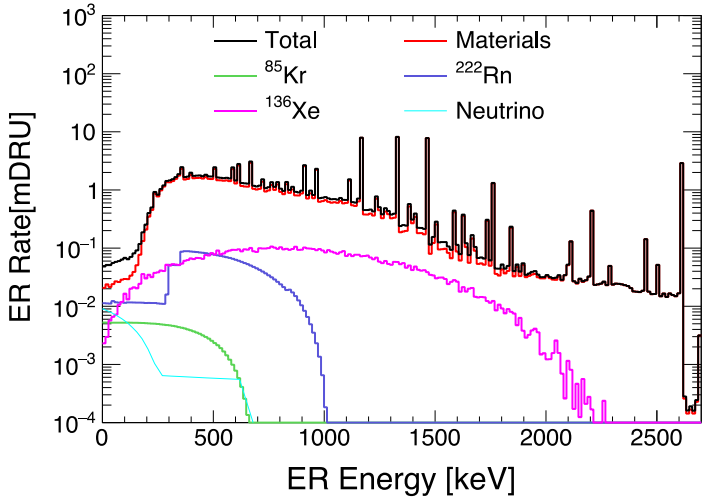


- **Below NR median:**
  - Total ER background: 0.05 mDRU
  - Total NR background: 1 event / t-y

Table 4 Final background budget within the WIMP search window.

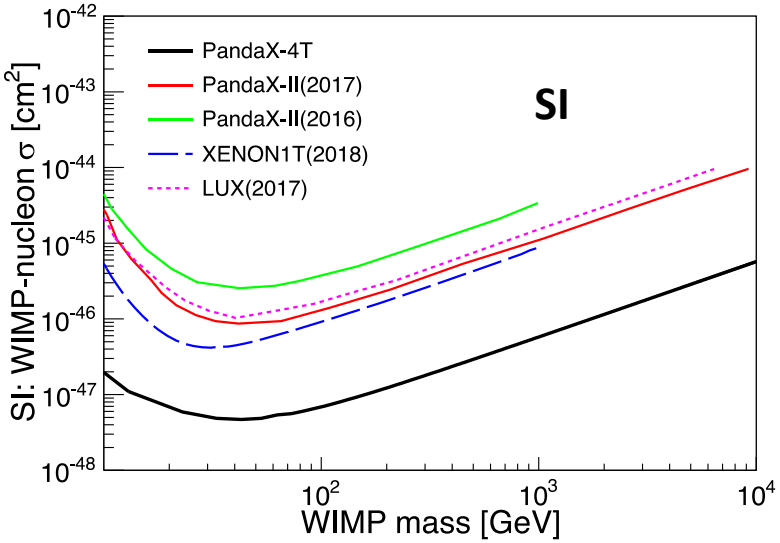
Sources	ER in mDRU	NR in mDRU
Materials	0.0210±0.0042	$2.0 \pm 0.3 \cdot 10^{-4}$
^{222}Rn	0.0114±0.0012	-
^{85}Kr	0.0053±0.0011	-
^{136}Xe	0.0023±0.0003	-
Neutrino	0.0090±0.0002	$0.8 \pm 0.4 \cdot 10^{-4}$
Sum	0.049 ±0.005	$2.8 \pm 0.5 \cdot 10^{-4}$
2-year yield (evts)	1001.6± 102.2	5.7±1.0
after selection (evts)	2.5±0.3	2.3±0.4

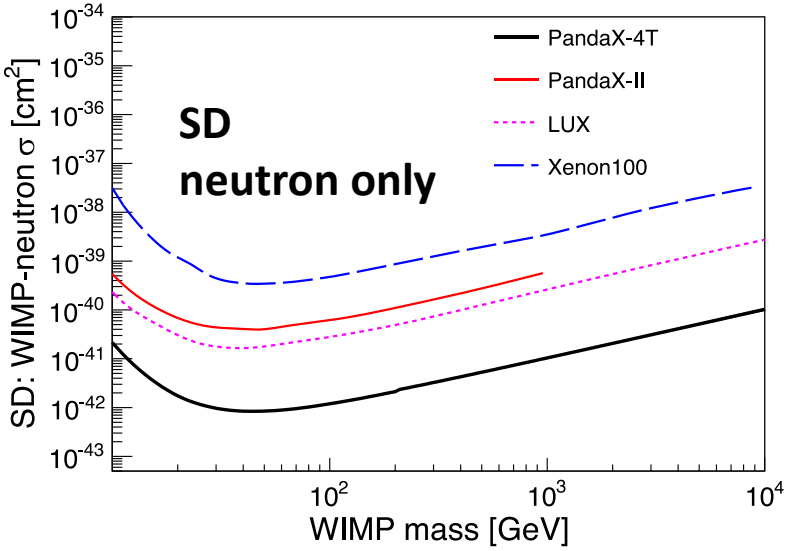
FV=2.8ton

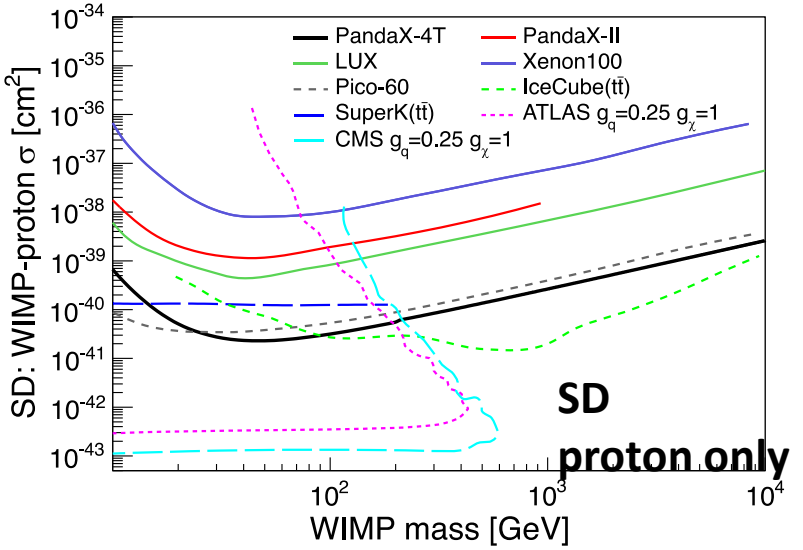


PandaX-4T projected sensitivity

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







Summary

- Most Recent results from PandaX-II are presented
  - Light-mediator and self-interacting DM model
  - Generic EFT and SD
  - Very fruitful collaborations with theorists.

- PandaX-4T is under preparation
  - Expected 10x improvement on sensitivity, for SI interaction could reach 10^{-47} cm^2
  - Detector assembly and commissioning is scheduled in 2019-2020

Thank you!

backup

backup

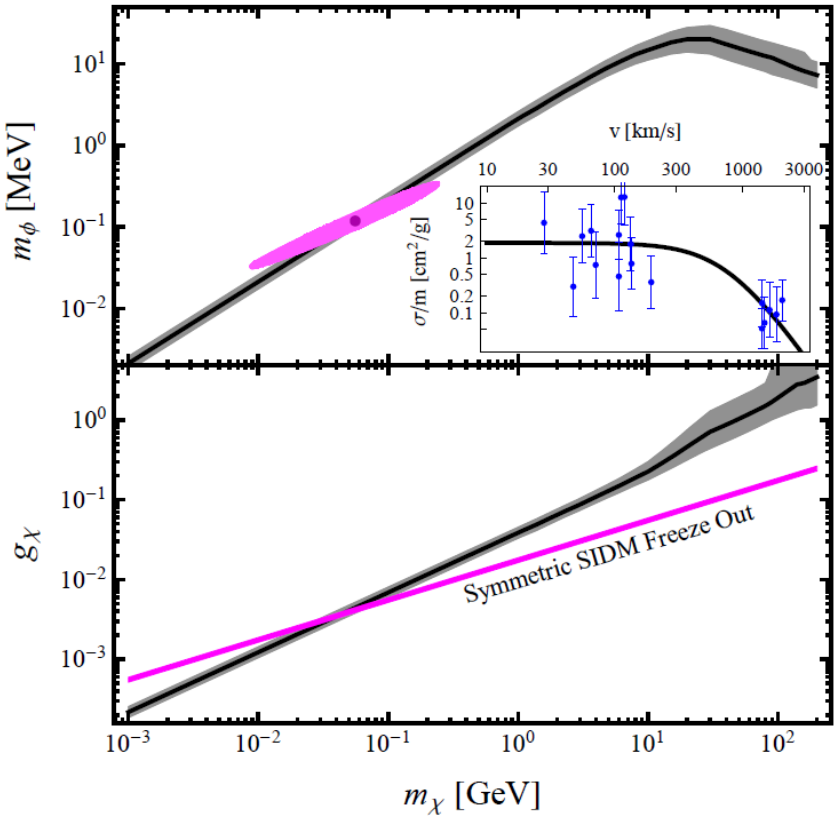


FIG. 1: SIDM parameter space (2σ CL) favored by a wide range of astrophysical data from dwarf galaxies to galaxy clusters, for both asymmetric (gray) and symmetric DM (magenta). *Inset:* the DM self-scattering cross section vs. velocity for a best fit case and the data points with error bars are from [5].

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

SI

$$\mathcal{O}_1 = 1_\chi 1_N$$

SD

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

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

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

$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^{\perp}$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^{\perp}$$

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

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N}\right)$$

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

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^{\perp})$$

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

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

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

Phys. Rev. C89, 065501 (2014)

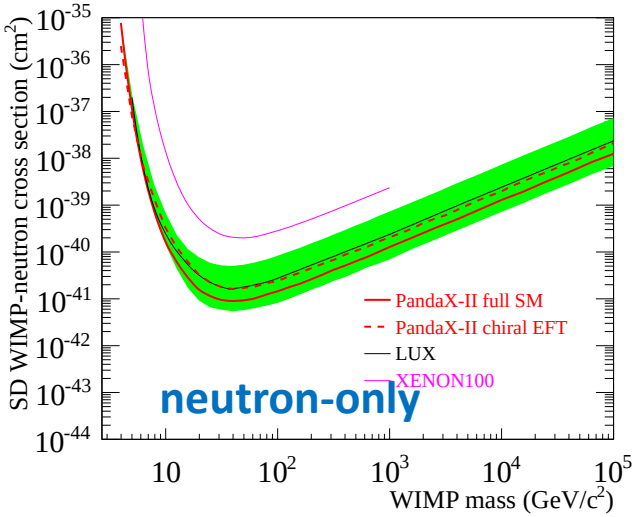
- Spin independent / Spin dependent: 2 EFT operators
  - SI: O_1 SD: O_4

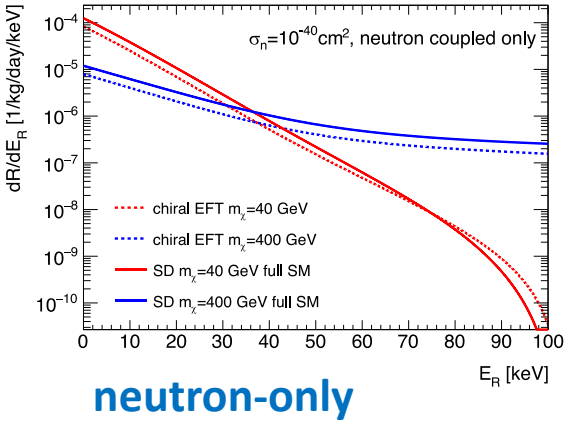
Constraints on Spin-Dependent Interaction

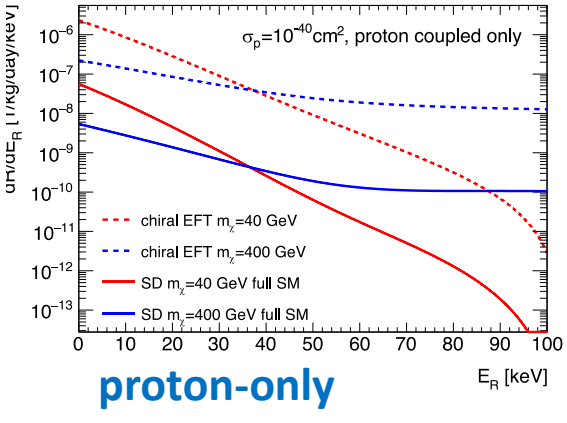
- ***O_4*** SD EFT operator $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$
  - Full basis shell-model GCN5082
- For proton-only coupling in Xe nucleus
  - O_4 SD EFT interaction largely suppressed

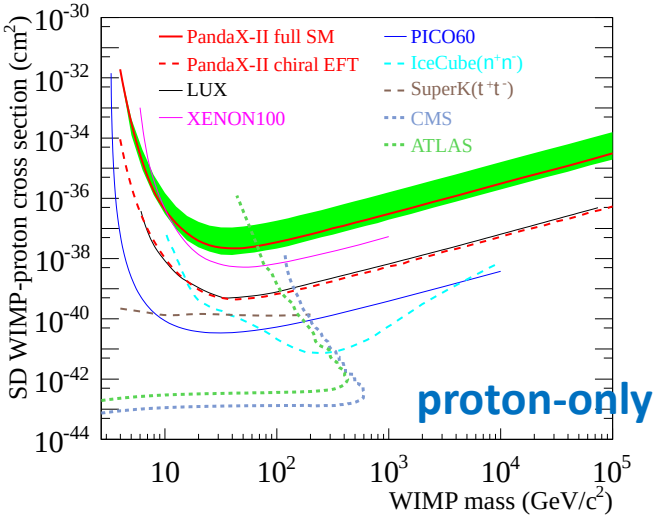
$$\sigma^{\mathrm{SD}}_{p,n}(v) = \left(\frac{c_4}{m_V^2}\right)^2 \frac{\mu^2_{p,n}}{\pi} \frac{J_\chi(J_\chi+1)}{4}$$

- "Standard" SD calculation:
  - chiral EFT
  - O4 + O6 + two nucleon pion-exchange





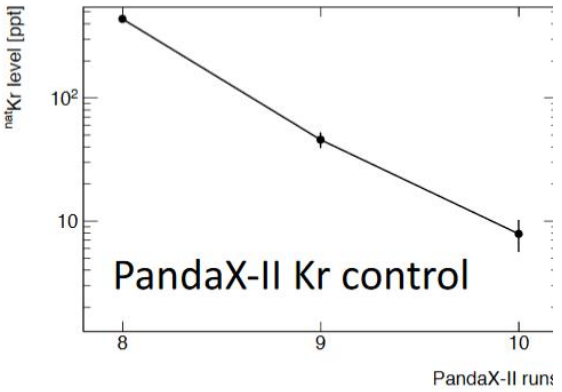




^{85}Kr Control

- ^{85}Kr could be a major background
- **Distillation is very effective in removing it**

PandaX-II	Run 8	Run 9	Run 10
Kr level	437 ± 13 ppt	44.5 ± 6.2 ppt	6.6 ± 2.2 ppt



- Distillation tower at CJPL
  - Online distillation continuously -> ^{nat}Kr below 0.1 ppt
- ^{nat}Kr measurement system
  - To reach a sensitivity of 0.1-0.01 ppt

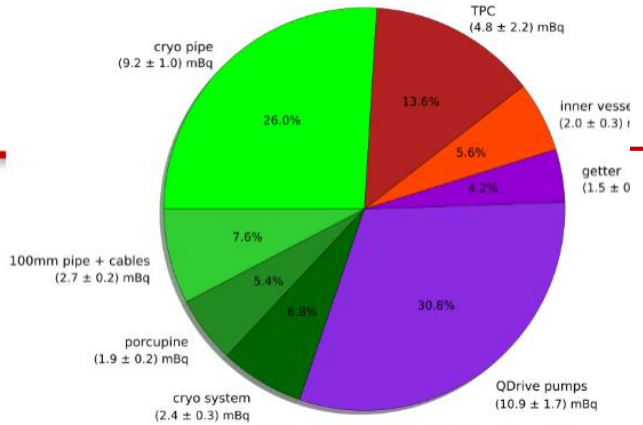
^{222}Rn Control

- Current level at PandaX-II: 8.6μBq/kg
  - Internal Rn emanation is primarily from the plumbing (warm section)
  - Consistent with findings from XENON1T

- PandaX-4T:
  - Plumbing length similar to PandaX-II
  - **The goal is to reach 1μBq/kg**

- To use Rn emanation measurement chamber to screen components

- Rn filtration/distillation plan in consideration



xenon1T Rn budget