Unlocking the mysteries of dark matter and neutrinos with PandaX

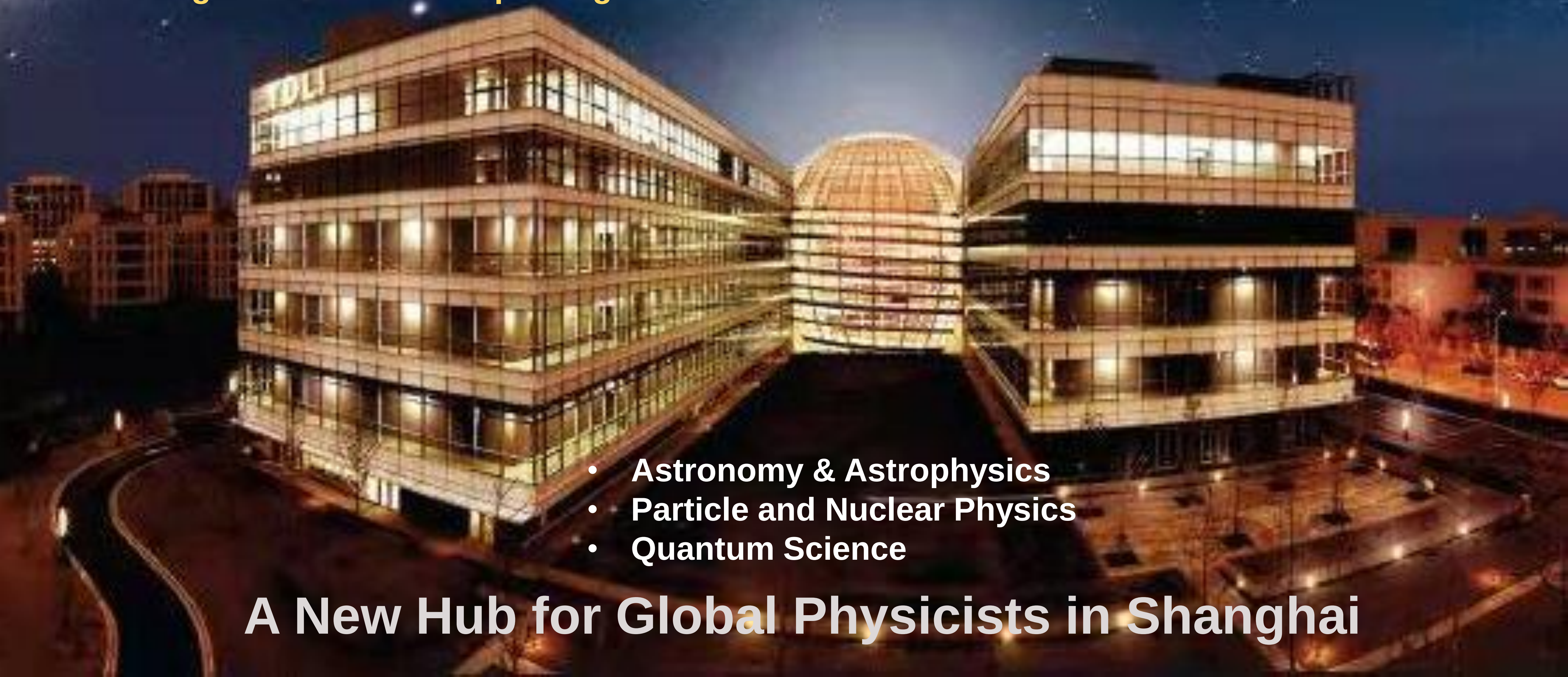
Jianglai Liu

Tsung-Dao Lee Institute and School of Physics and Astronomy

Shanghai Jiao Tong University

Proposed by T. D. Lee and founded in 2016, Tsung-Dao Lee Institute (TDLI) is a fundamental research institute in physics dedicated to

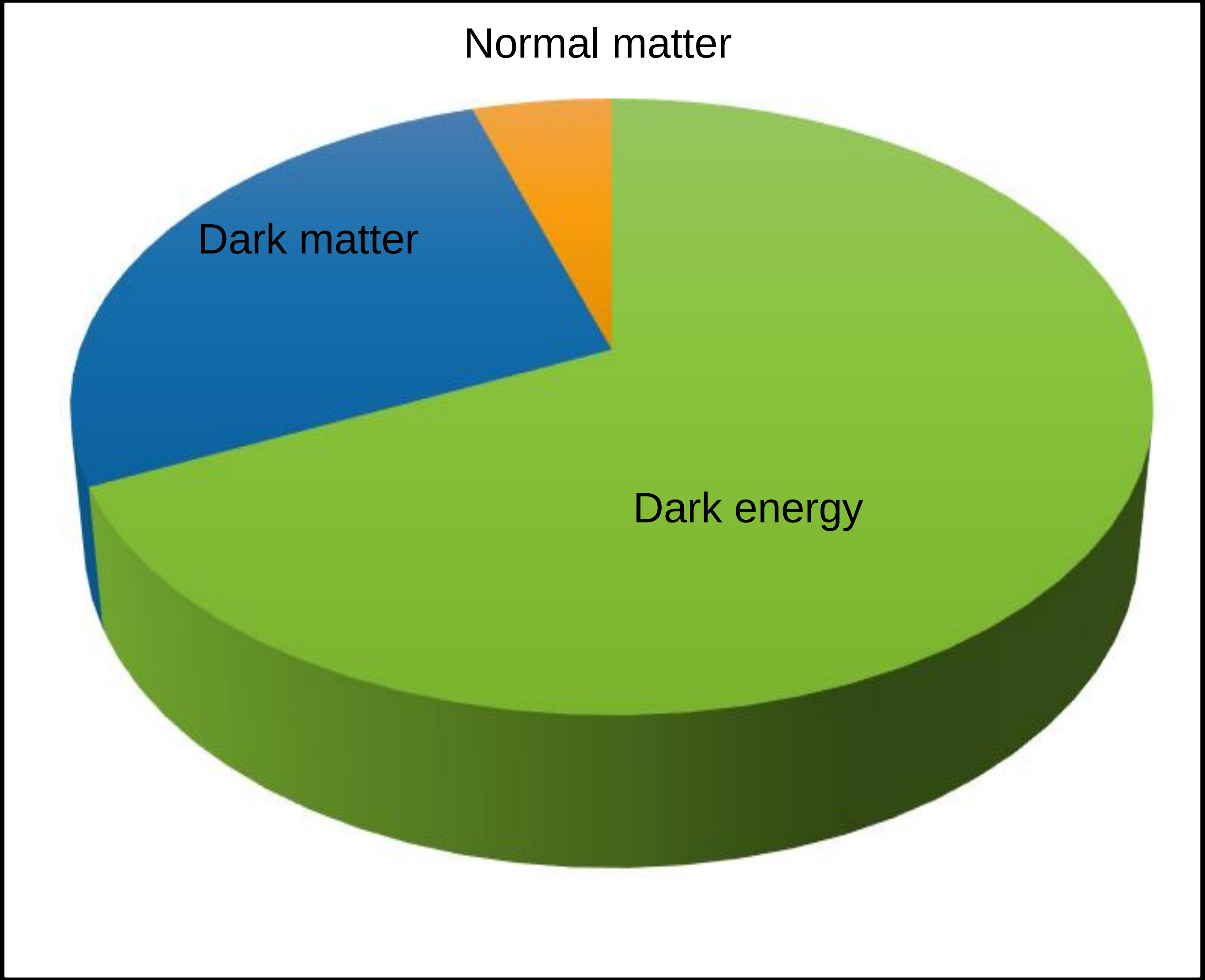
- elucidating the origin, evolution, and structure formation of matters, and unraveling its governing law,
- via big science research paradigm.



- Astronomy & Astrophysics
- Particle and Nuclear Physics
- Quantum Science

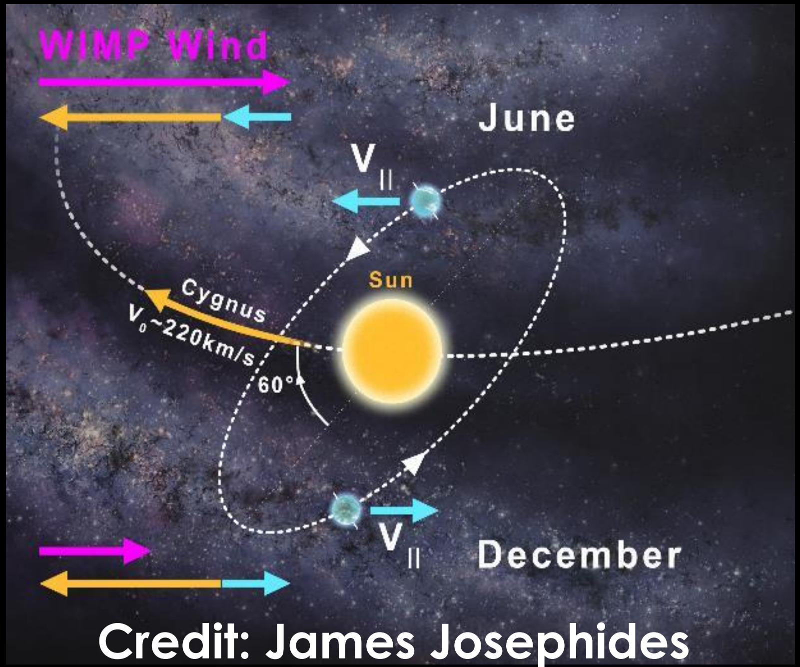
A New Hub for Global Physicists in Shanghai

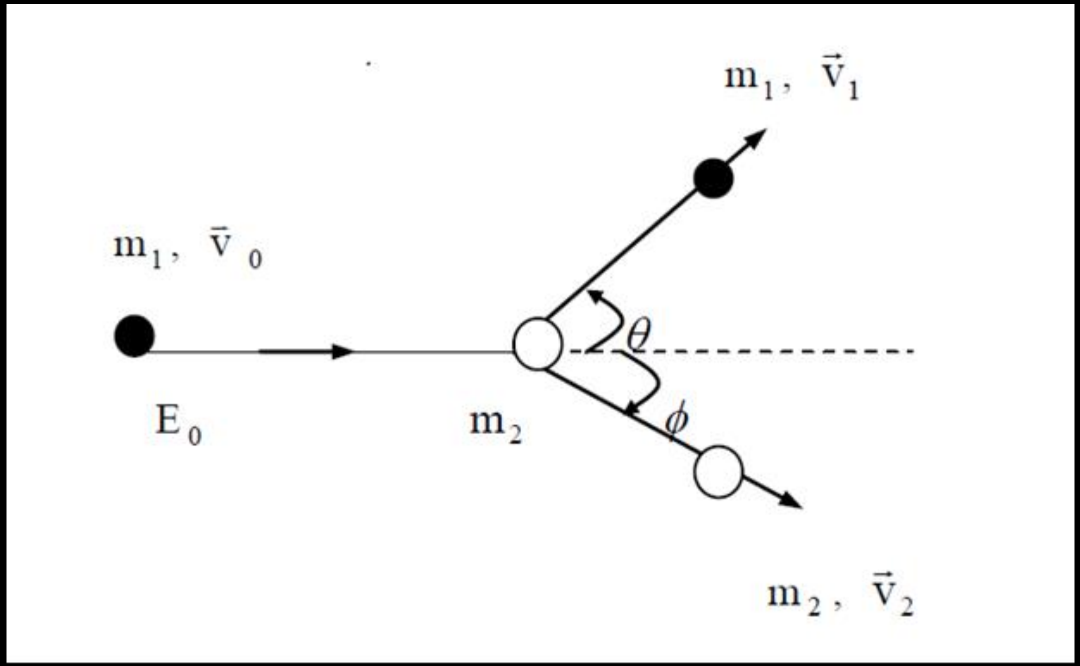
Mysterious Content of the Universe



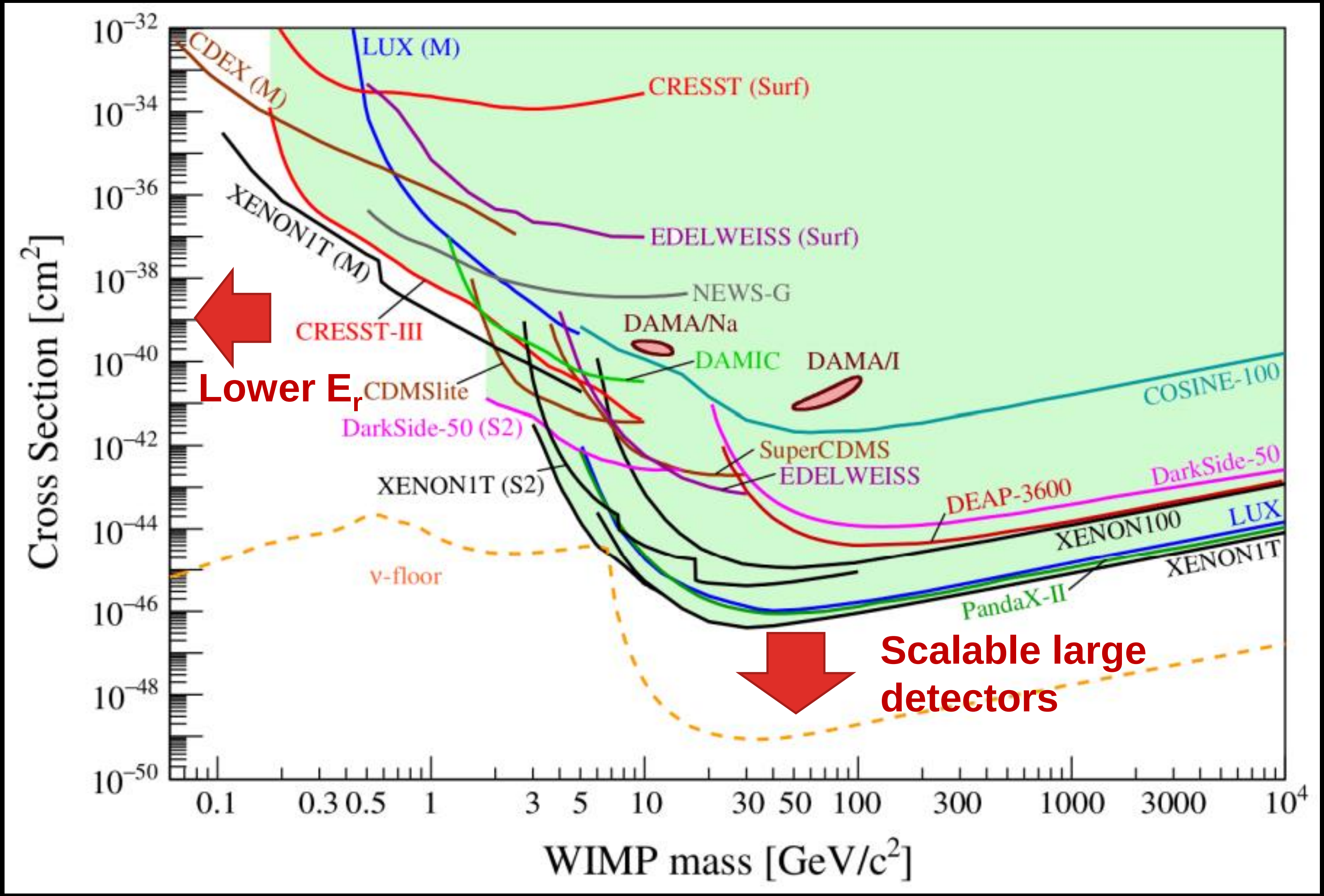
Particle Dark Matter: seeded by Gershtein and Zeldovich, JETP Lett. 4, 120 (1966), who first discussed relic neutrinos

Dark matter direct detection: classical Chadwick experiment

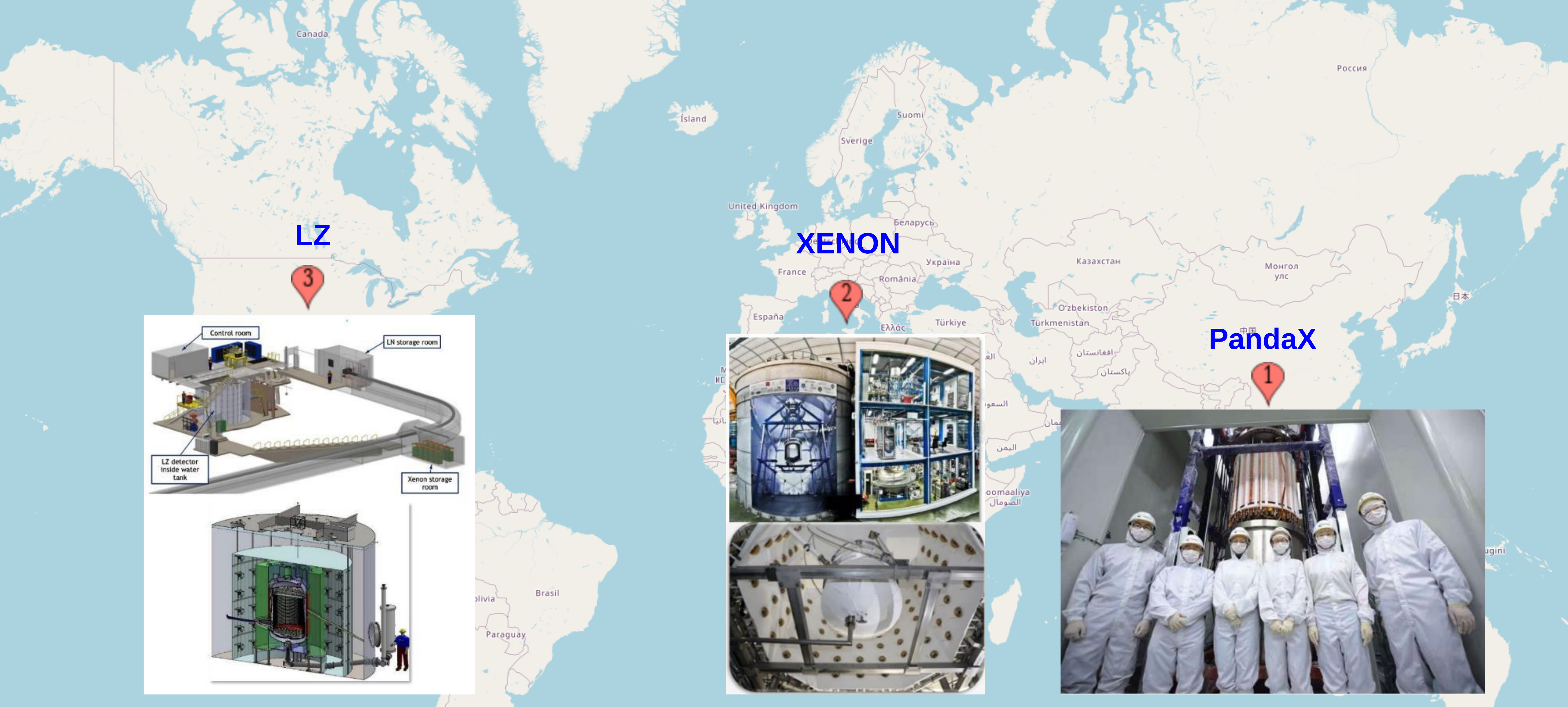




DM landscape:
"Too many" exclusions



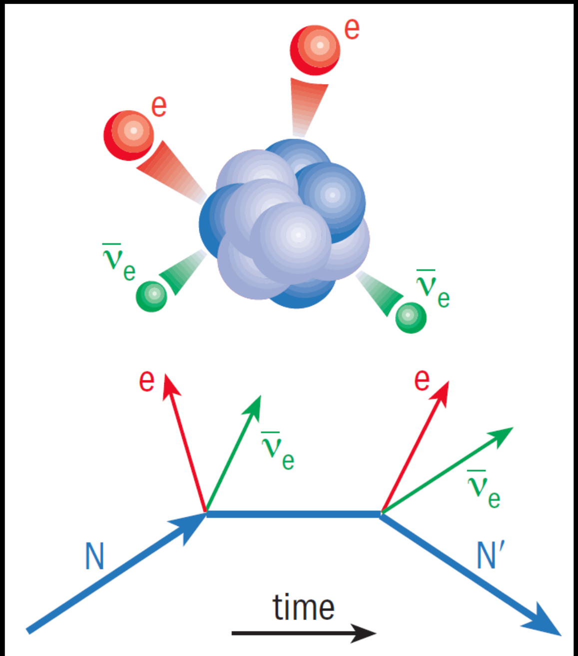
The big three xenon DM experiments

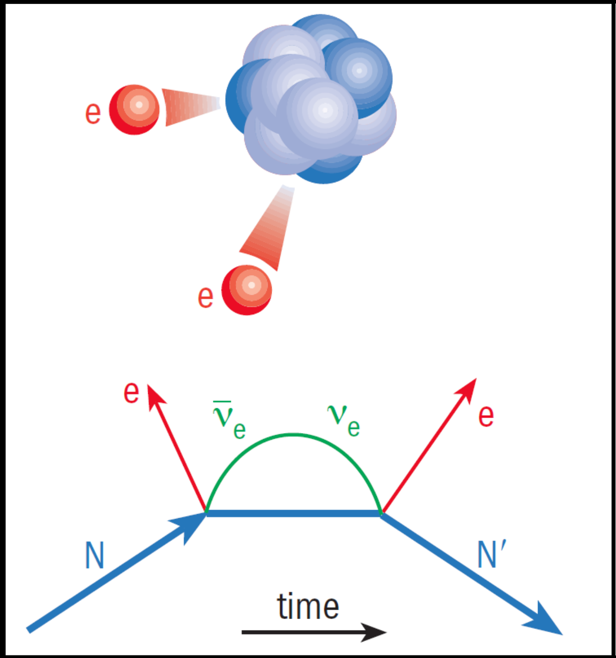


Neutrinos are Dirac or Majorana?

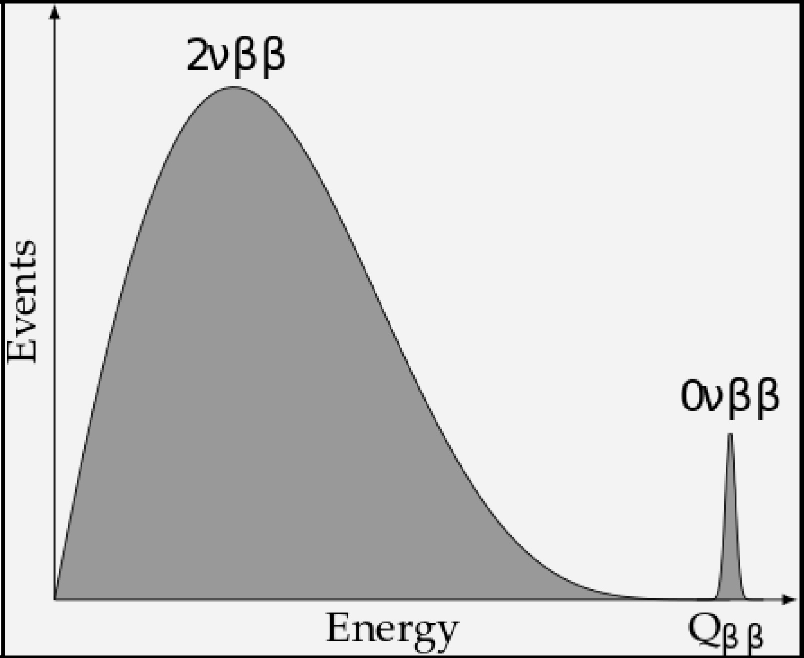
$\bar{\nu} = \nu ?$

Neutrinoless double-β decay





From Physics World



Majorana neutrino may be an important link in connecting to matter-antimatter asymmetry in our universe.

0vDBD, if found

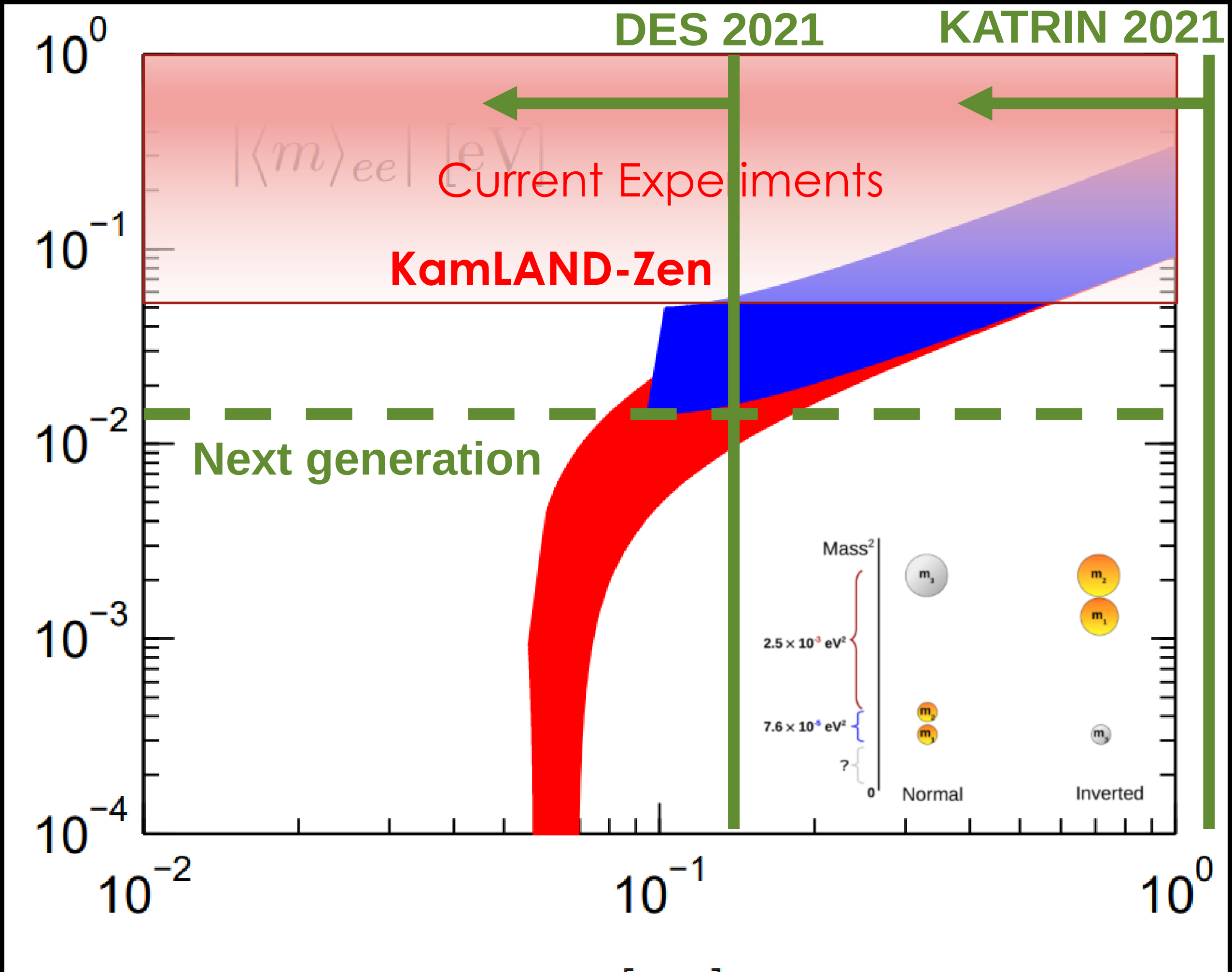
- Majorana or Dirac
- Lepton number violation
- Measures effective Majorana mass: relate 0vββ to absolute neutrino mass

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor

Nuclear matrix element

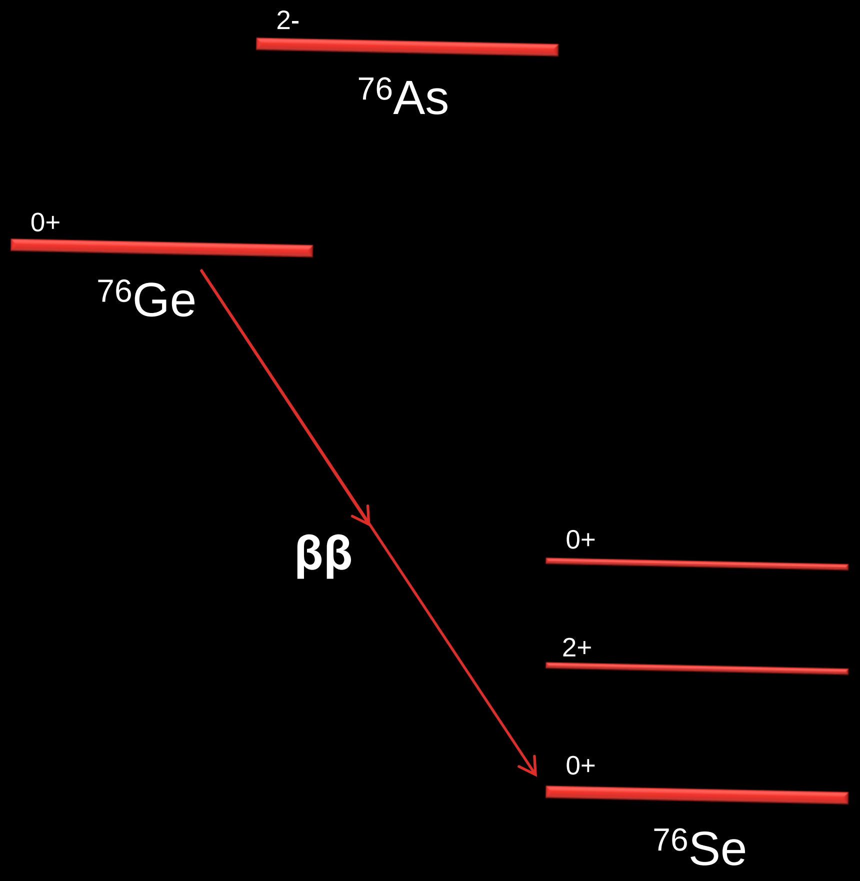
Effective Majorana neutrino mass: $|\langle m_{\beta\beta}\rangle| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$



JPG 43 030401 (2016)

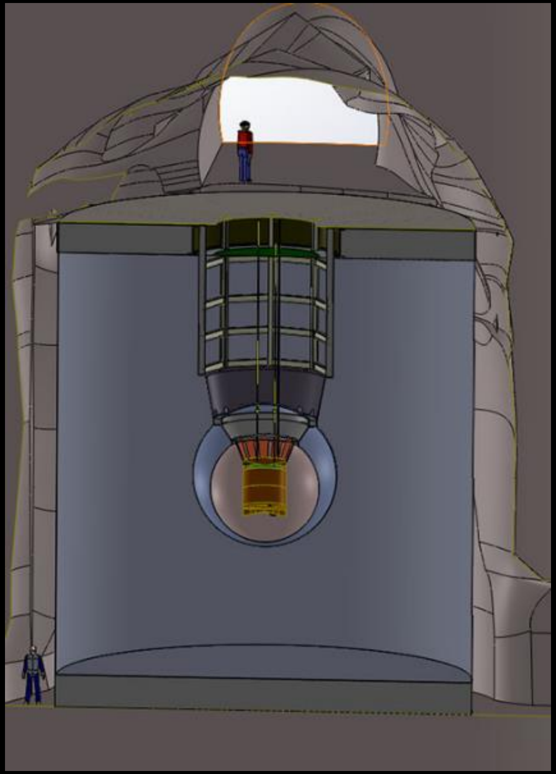
ββ isotopes

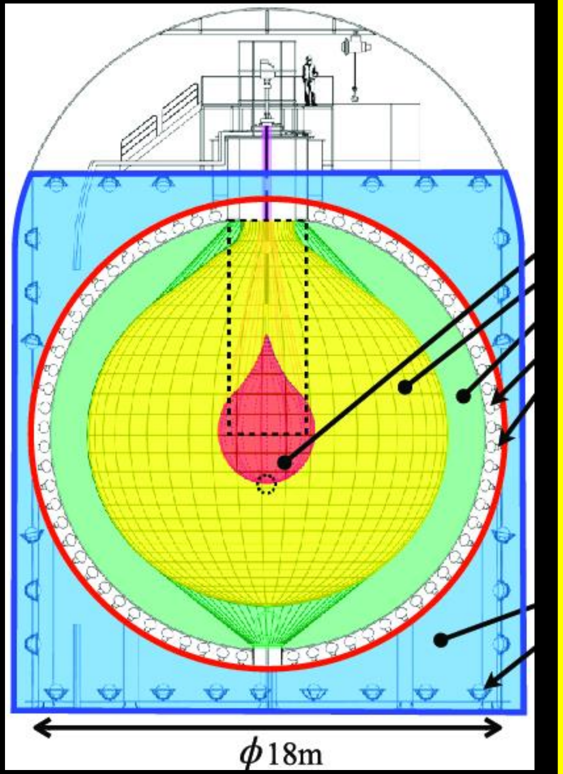
Isotope	Q-value [MeV]	Natural abudance [%]
^{48}Ca	4.27	0.187
^{150}Nd	3.37	5.6
^{96}Zr	3.35	2.8
^{100}Mo	3.03	9.8
^{82}Se	3.00	8.7
^{116}Cd	2.81	7.5
^{130}Te	2.53	34.1
^{136}Xe	2.46	8.86
^{124}Sn	2.29	5.8
^{76}Ge	2.04	7.73
^{110}Pd	2.02	11.7

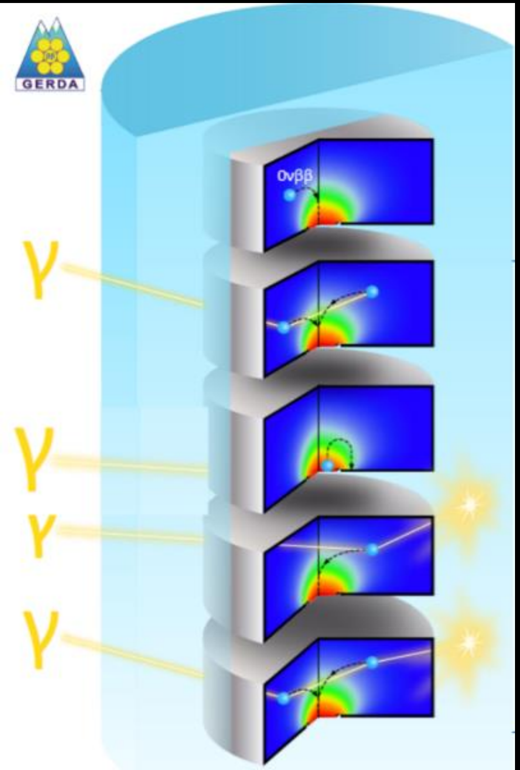


The big four

^{136}Xe







CUORE/CUPID

Bolometer

EXO/nEXO

LXe TPC

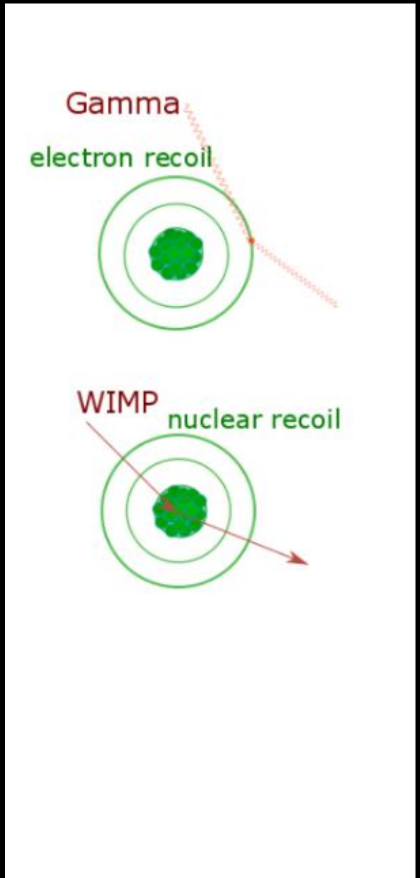
KamLAND-ZEN

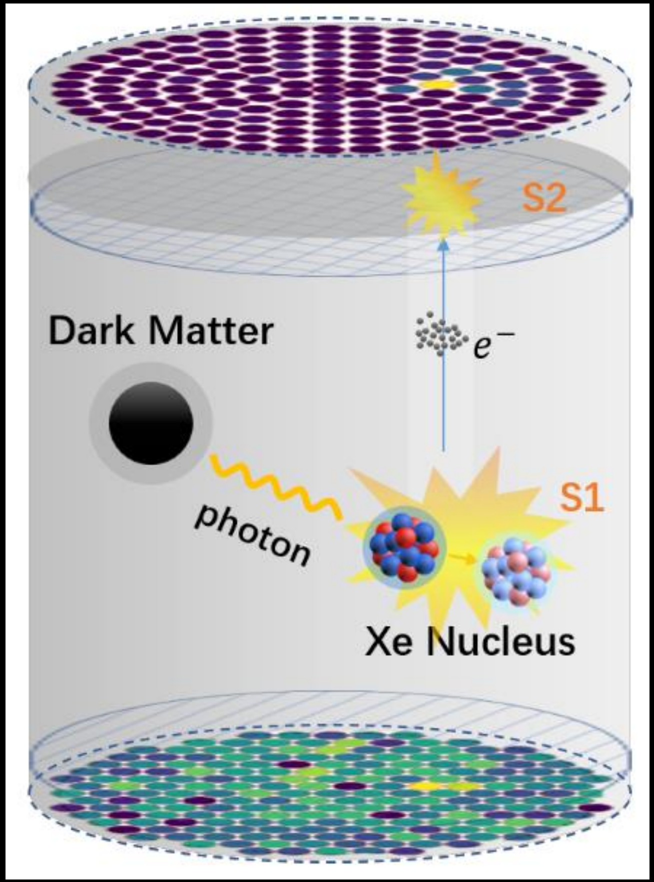
Doped LS

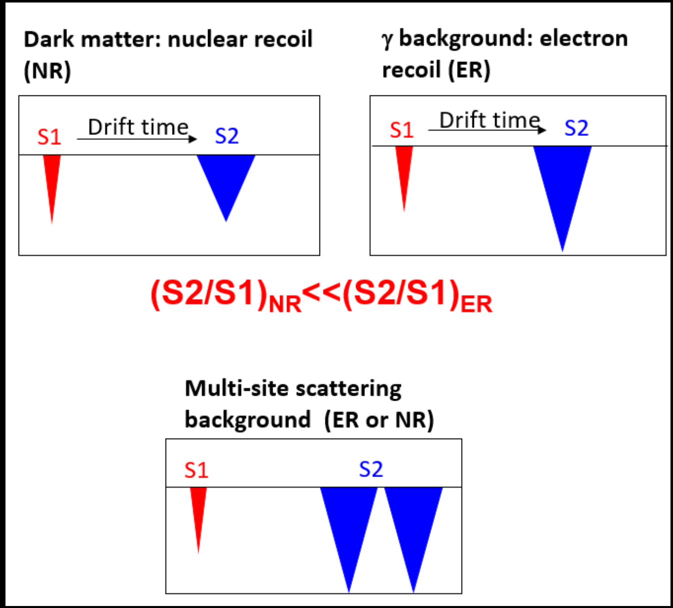
LEGEND family

HPGe

Dual-phase xenon time projection chamber (TPC)







Detector capability:

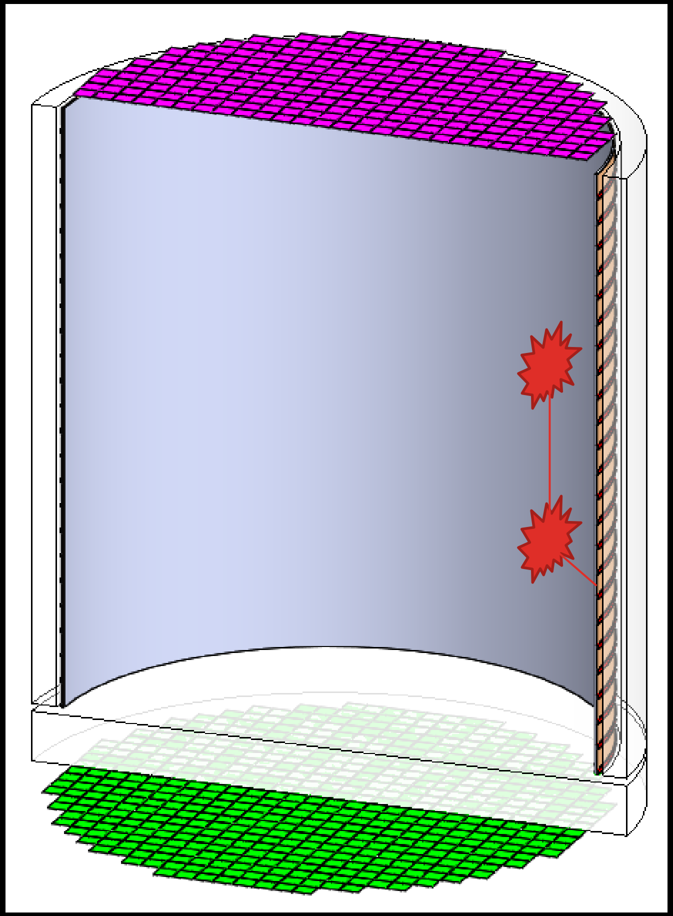
- 3D reconstruction and fiducialization
- Good ER/NR rejection
- Calorimeter capable of seeing a couple of photons/electrons

Magic of self-shielding

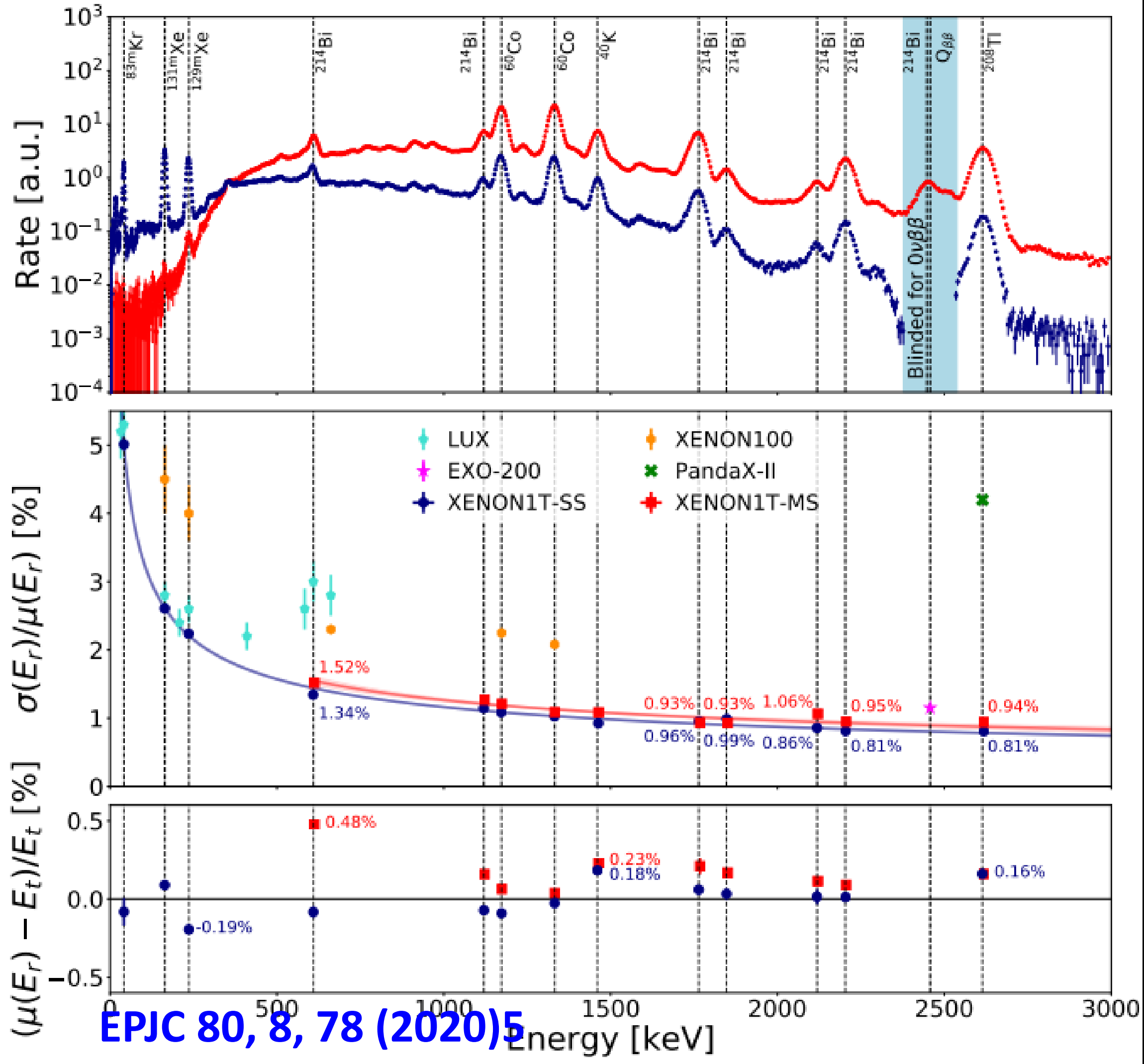
Material background (gammas/neutrons)

- Cluster @ boundary
- Multi-site
- Energy deep in target without high E cascade in the outskirt further suppressed

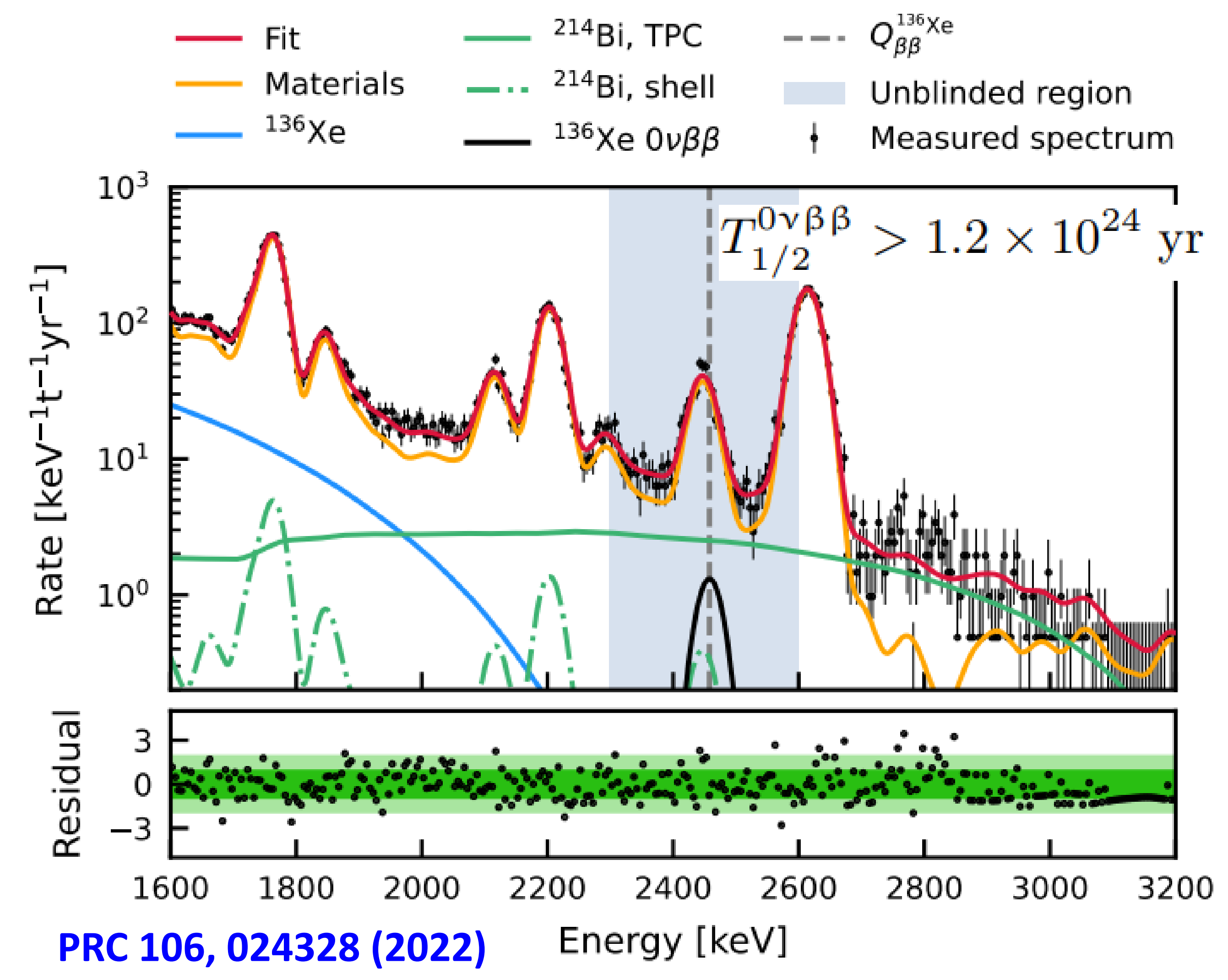
$\Rightarrow$ “self-shielding” if reconstruct vertex



XENON1T demonstrated physics @ MeV



EPJC 80, 8, 78 (2020)



PRC 106, 024328 (2022)

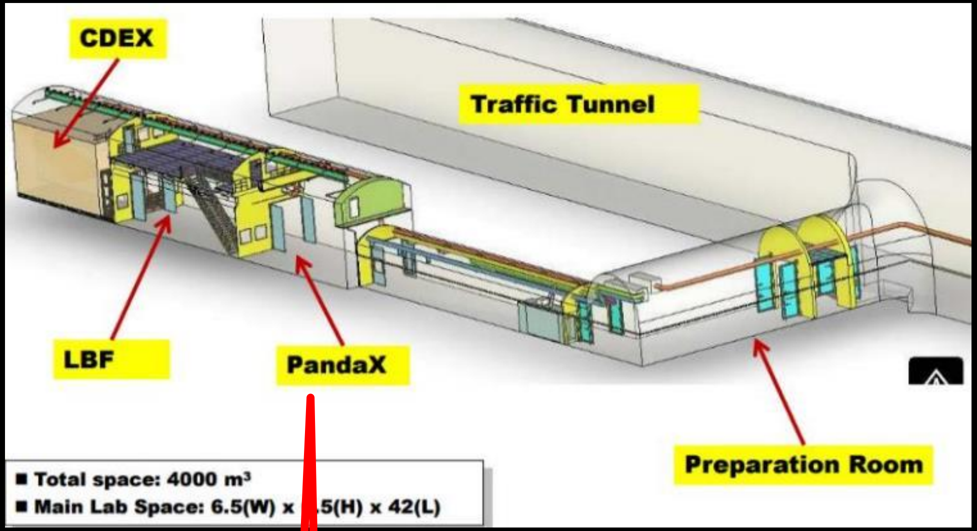
PANDA X

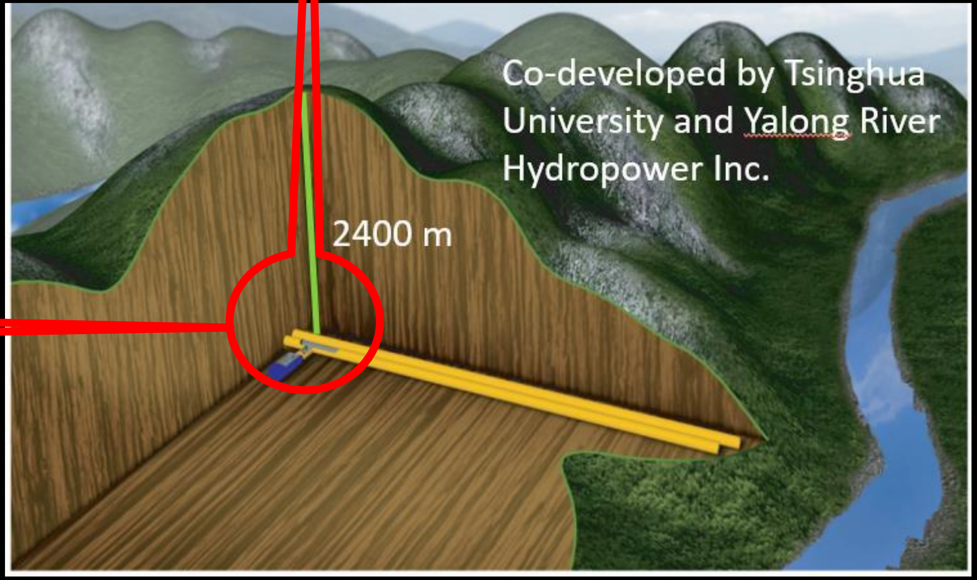
Particle and Astrophysical Xenon observatory

Coll

SINAP CNNC 雅砻江水电 Universidad Zaragoza

China Jinping underground Laboratory





CJPL-II Project (2014-)

PHYSICS

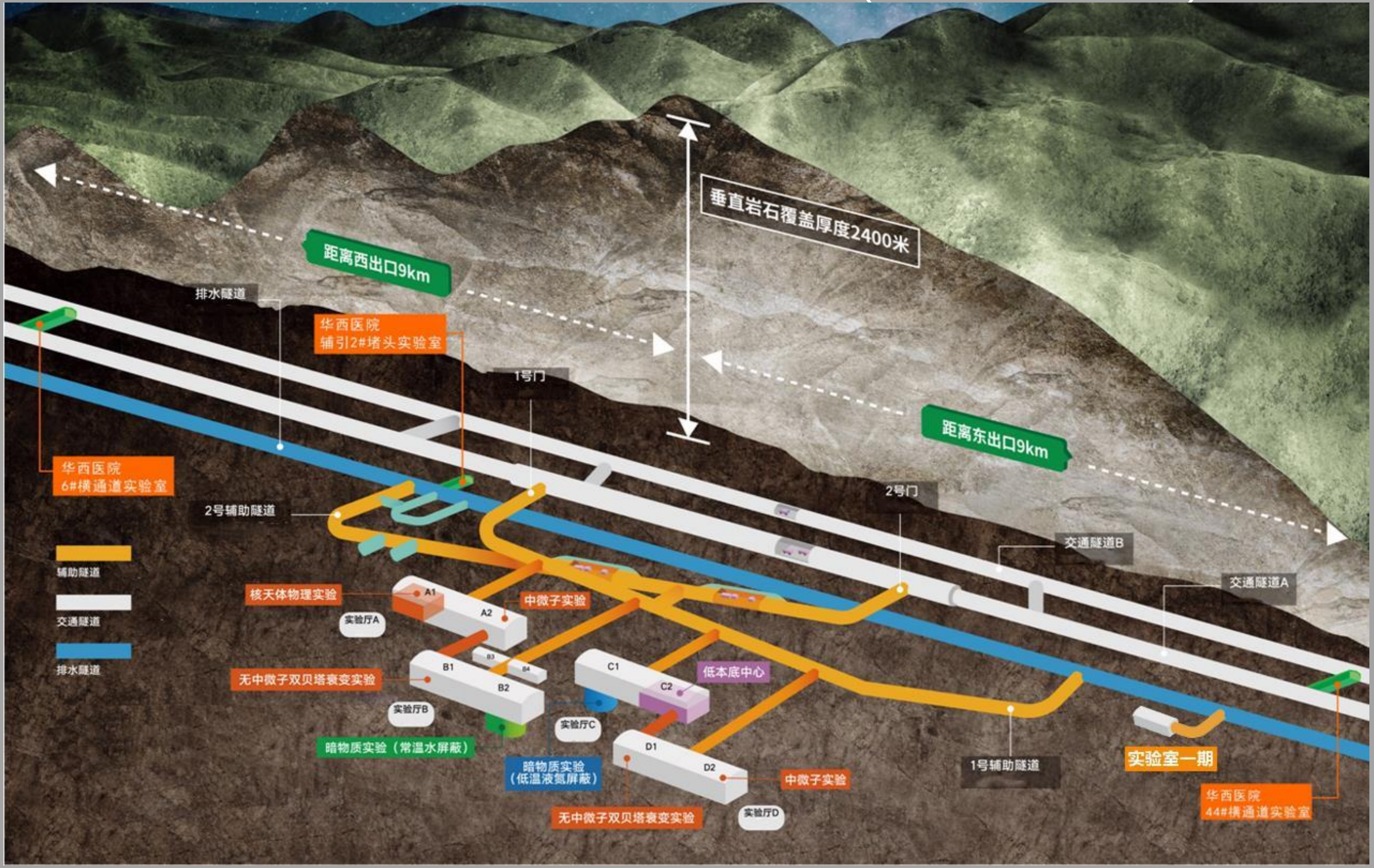
China supersizes its underground physics lab

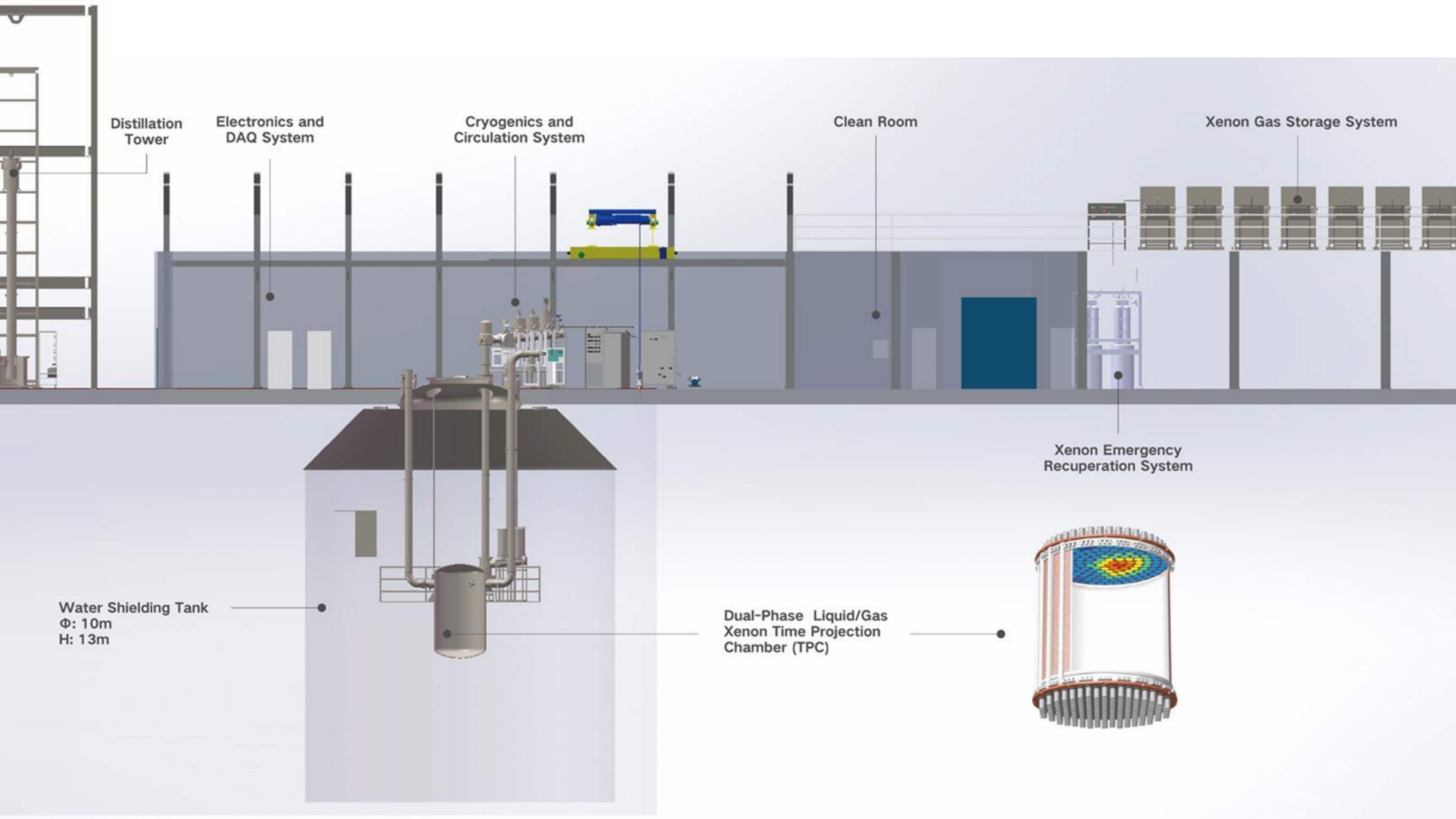
Planned expansion could pave way for “ultimate dark matter experiment”

The world’s deepest physics laboratory is about to become one of its largest. Early next year, workers will start carving four cavernous experiment halls along a tunnel through Jinping Mountain in China’s Sichuan province. Once the science at the China Jinping Underground Laboratory (CJPL) is scaled up as well, “it will be a milestone for Chinese physics,” says Nigel Smith, director of the underground SNOLAB in Sudbury, Canada.

Science, Nov. 30, 2014

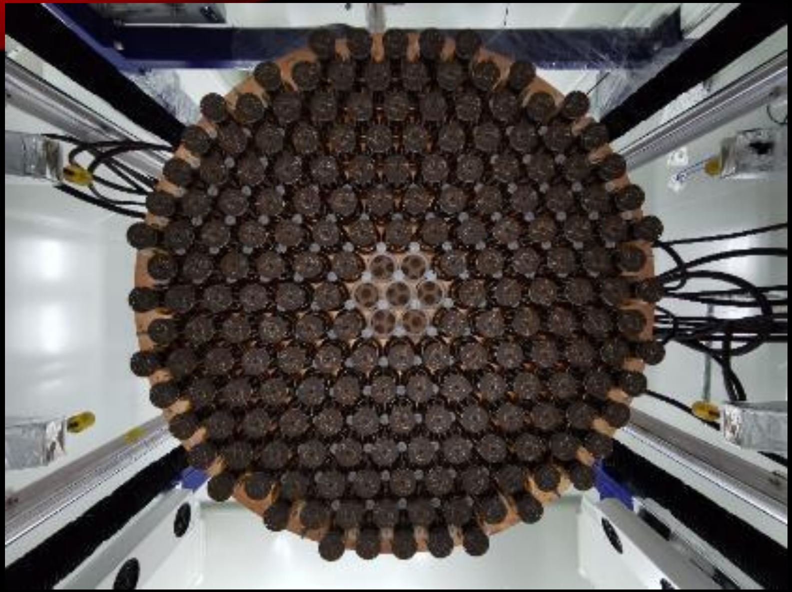
300k m^3 with 8 main halls of 14x14x65 m (4000m^3 of CJPL-I).



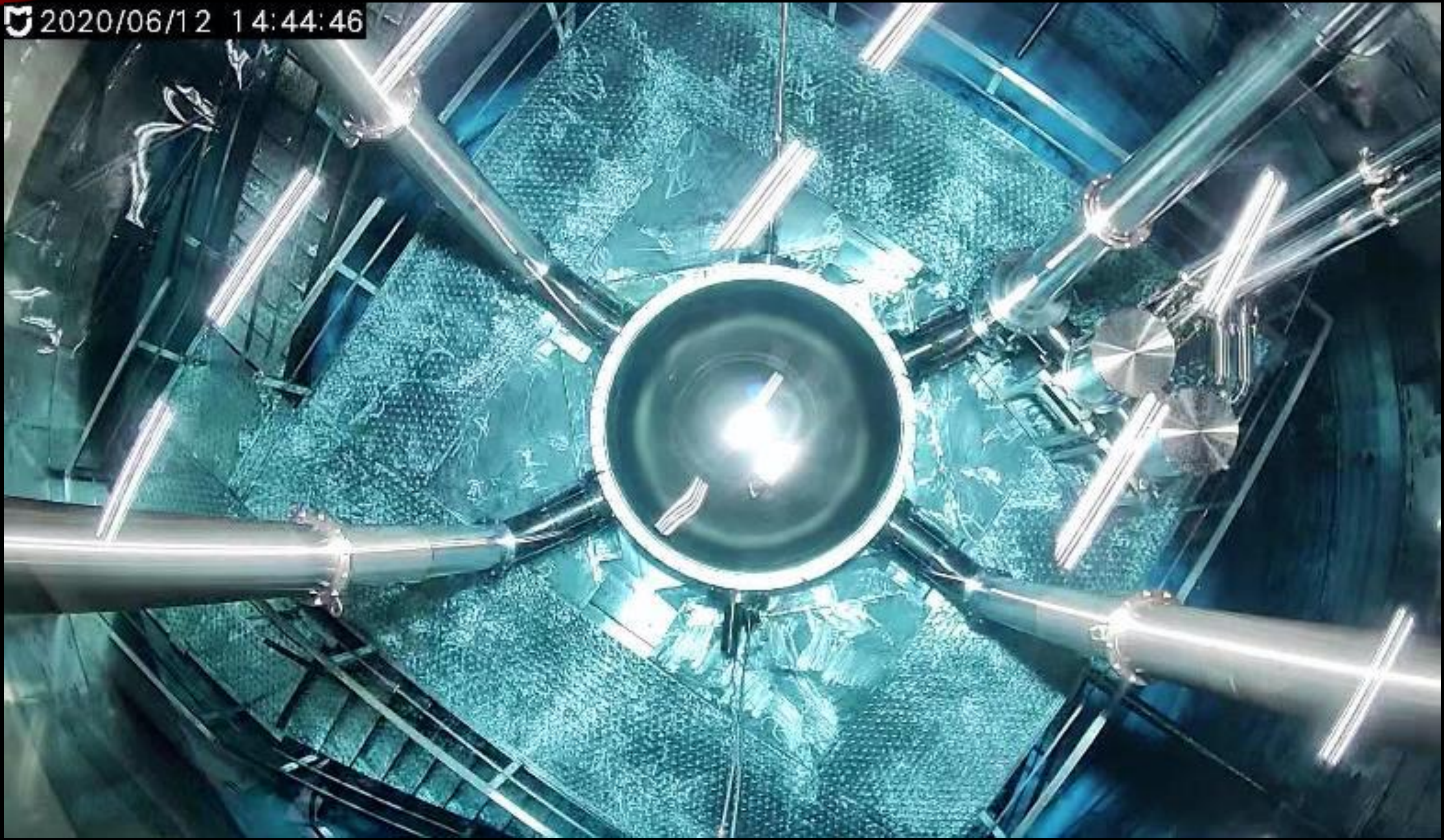

Distillation Tower
Electronics and DAQ System
Cryogenics and Circulation System
Clean Room
Xenon Gas Storage System
Xenon Emergency Recuperation System
Water Shielding Tank
Φ: 10m
H: 13m
Dual-Phase Liquid/Gas Xenon Time Projection Chamber (TPC)


上海交通大学PandaX暗物质与中微子实验平台

TPC installation



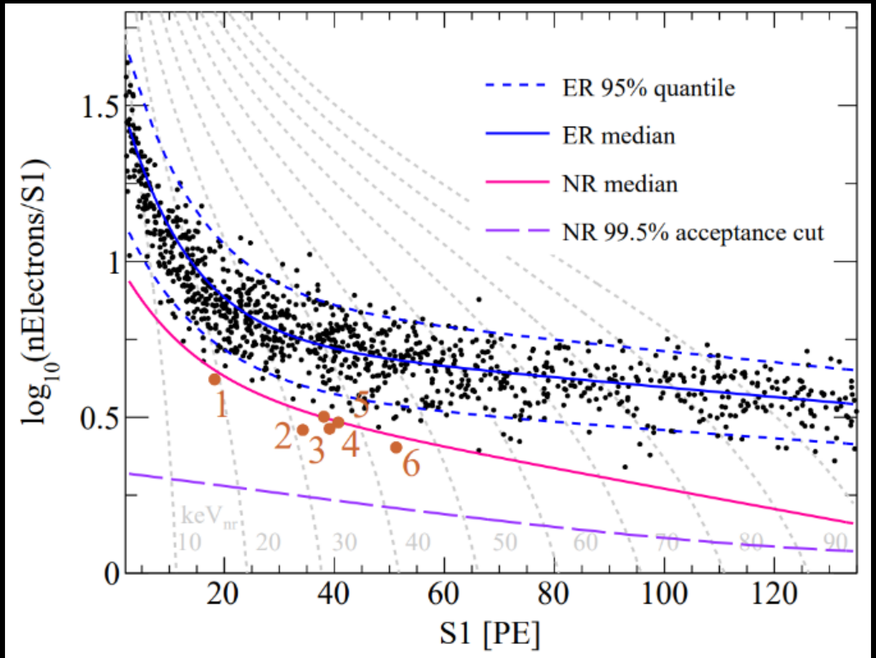
Ultrapure water filling

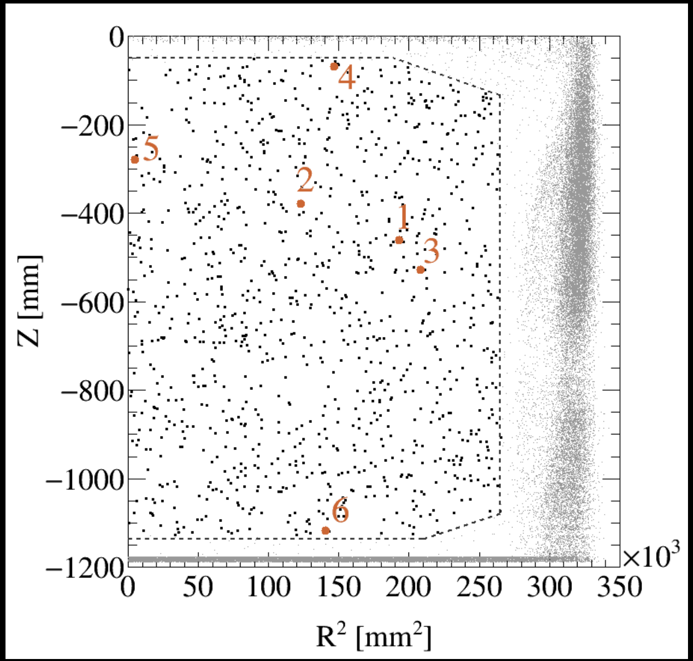


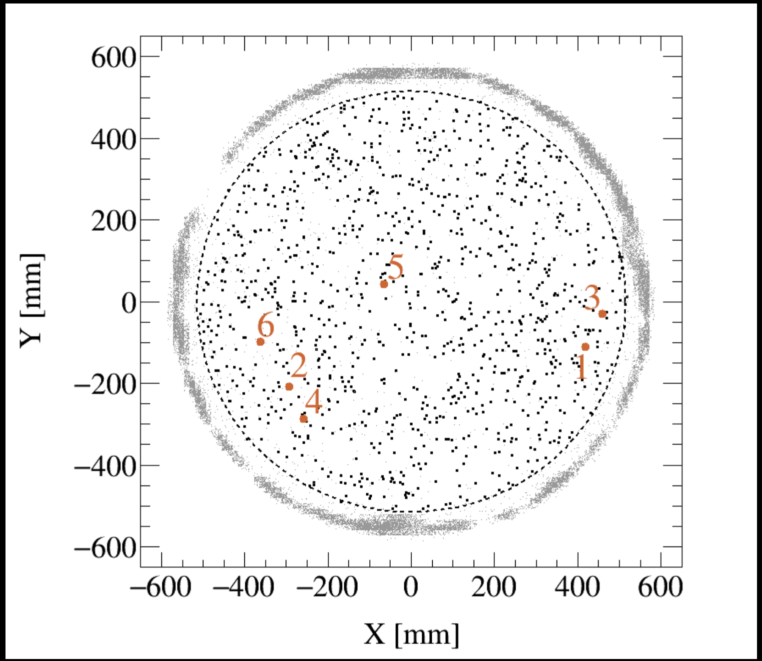
Timeline of the commissioning run

- Apr. 2, 2018, permission from CJPL management to start construction in B2 hall
- Aug. 19, 2019, infrastructure completed, detector installation in CJPL-II started
- Mar 6, 2020, offline distillation of xenon completed
- May 28, 2020, installation completed
- Nov. 28, 2020 – Apr. 16, 2021, commissioning run

Dark matter candidates



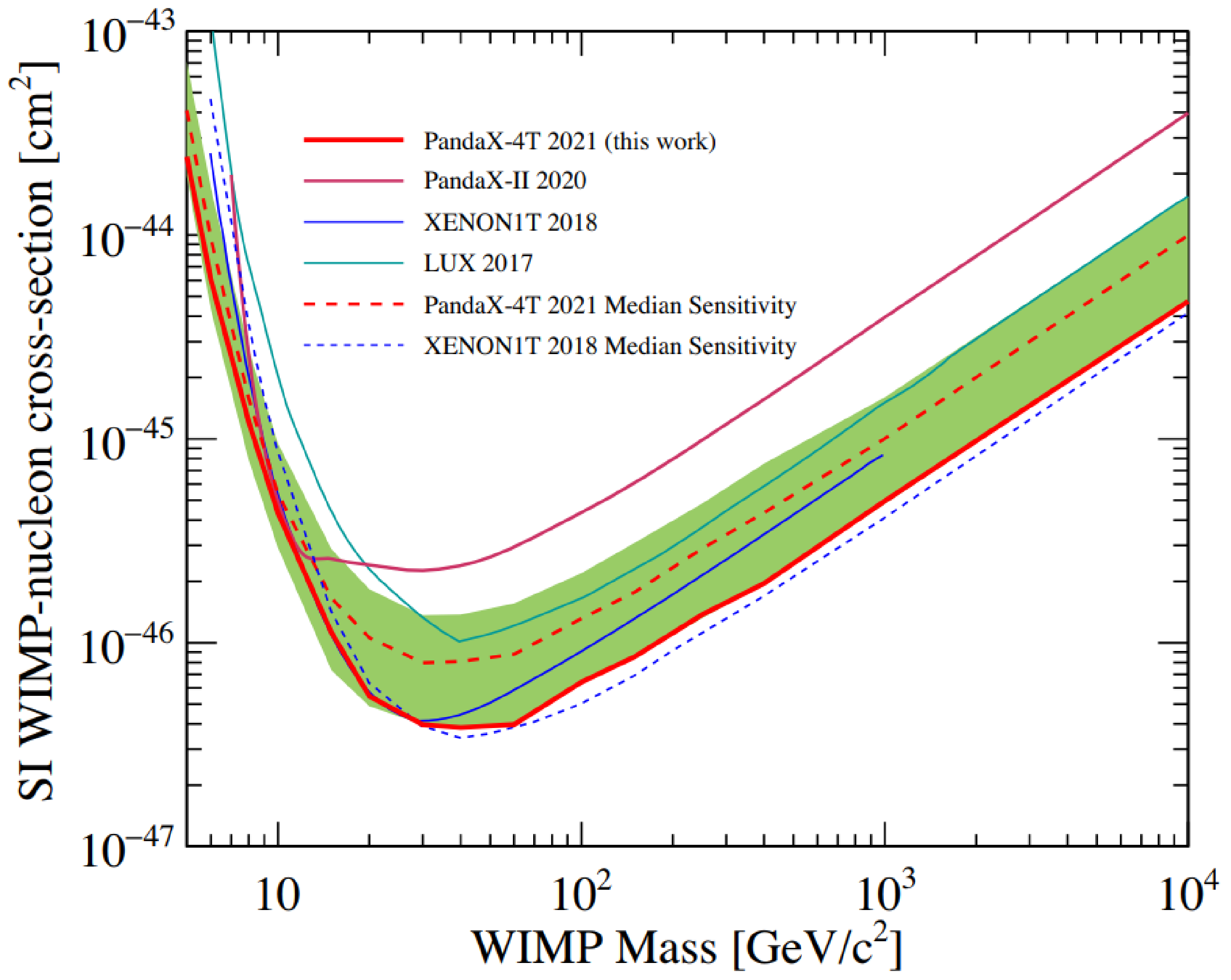




- Events uniformly distributed in the FV, expected if dominated by tritium and radon.
- In FV, 1058 candidates, 6 below NR median line (~-1σ downward fluctuation from expected 9.8 evts)

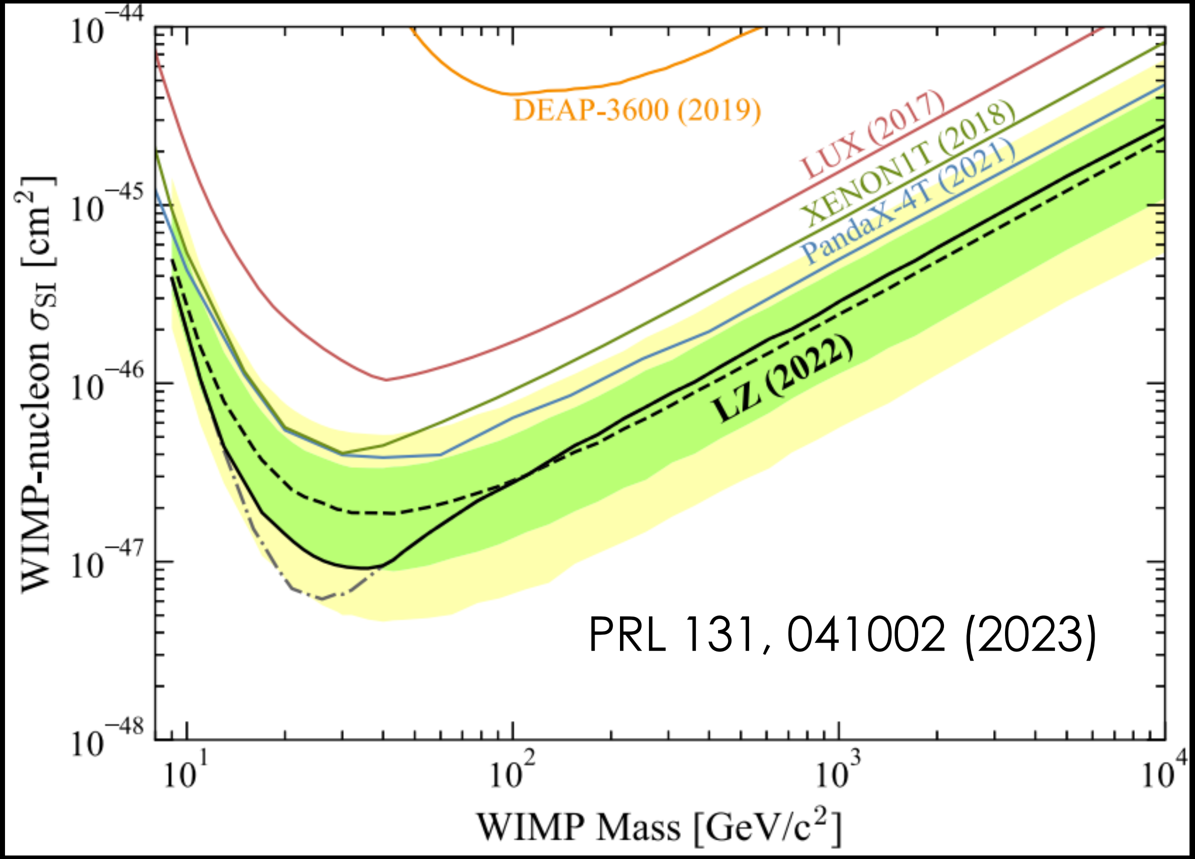
WIMP-nucleon SI exclusion limits

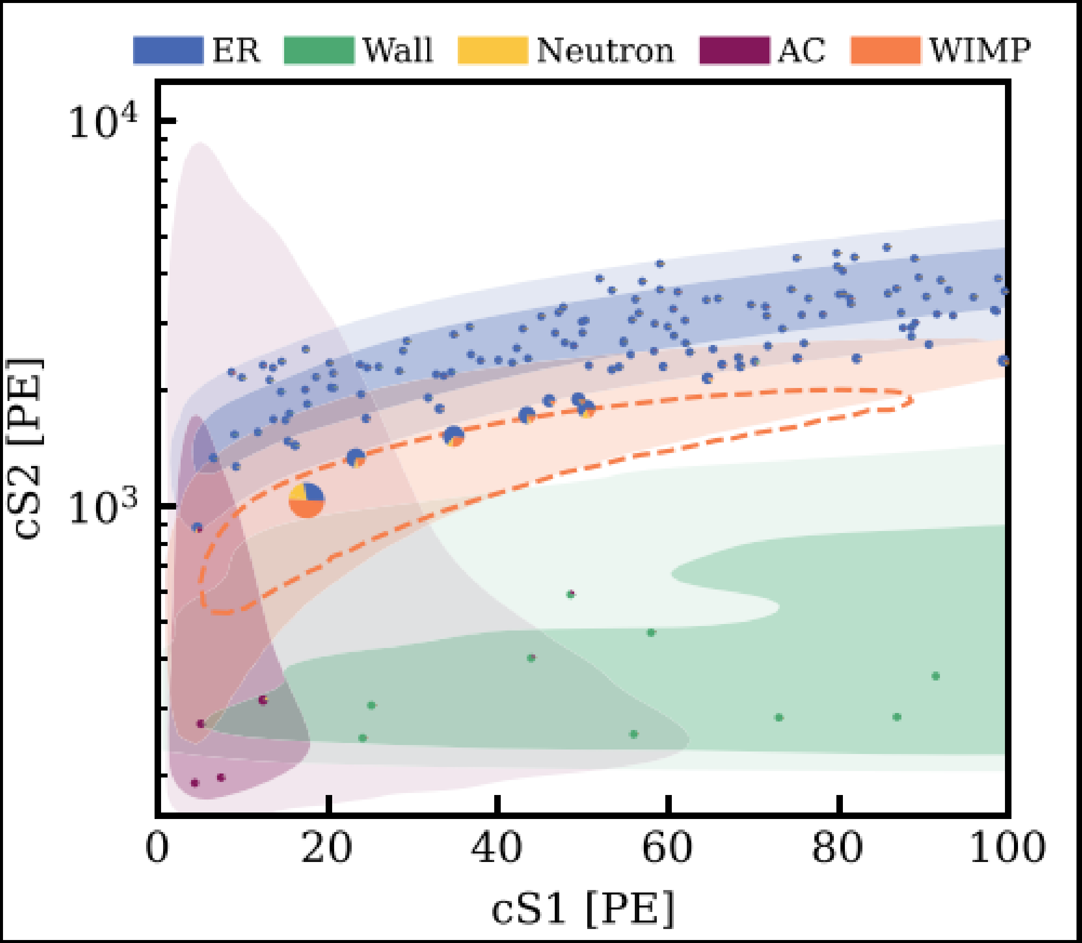
PRL 127, 261802 (2021)



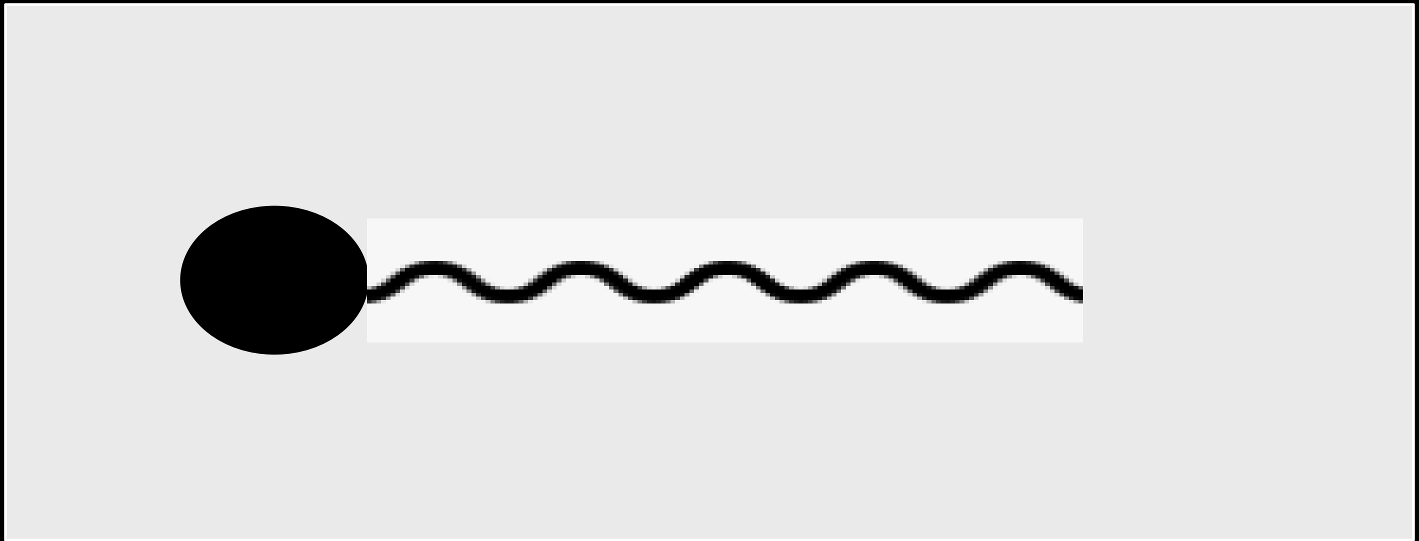
- Exposure: 0.63 tonne•year
- Sensitivity improved from PandaX-II final analysis by 2.6 times (40 GeV/c^2)

LZ and XENONnT first results





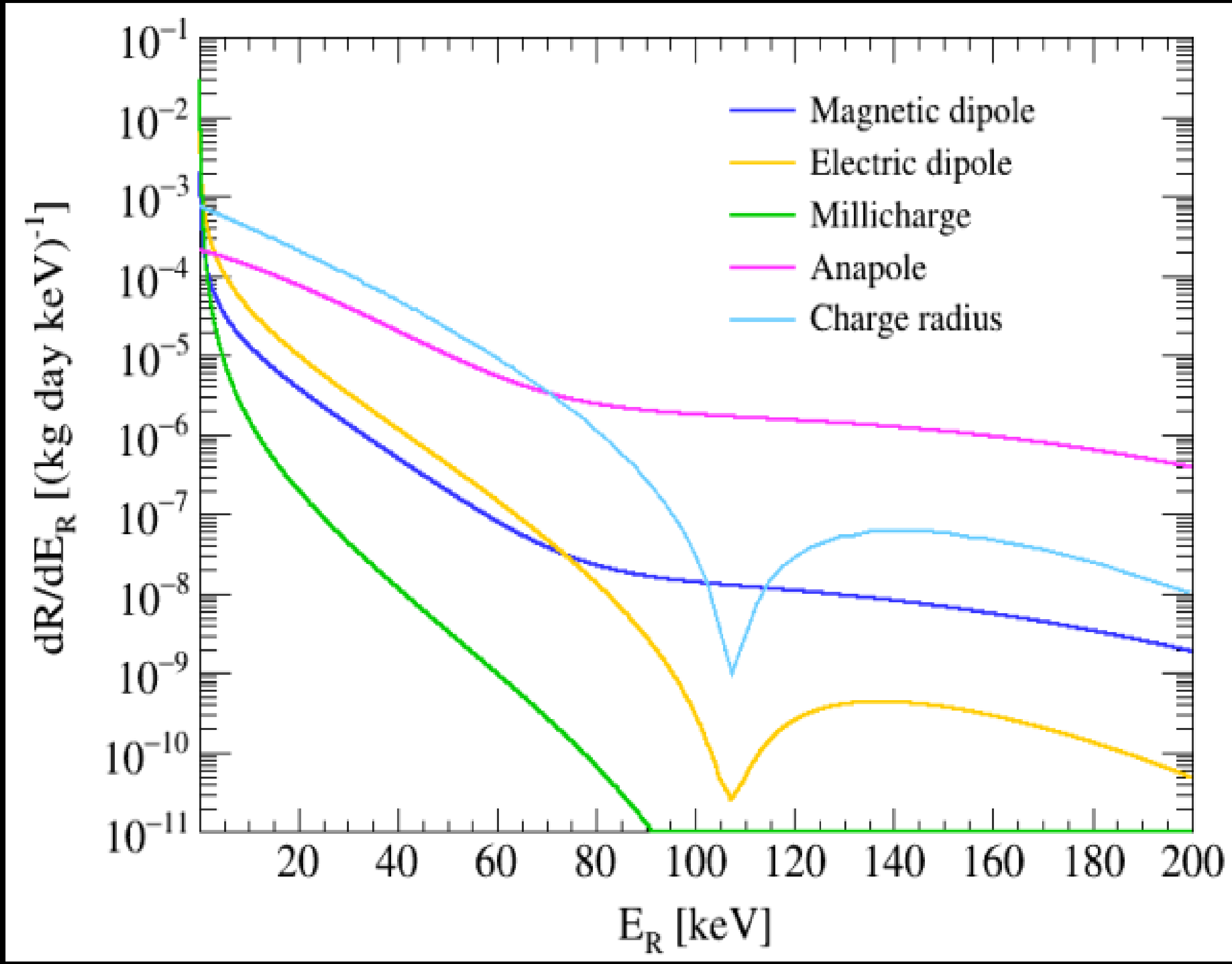
How dark is dark matter?

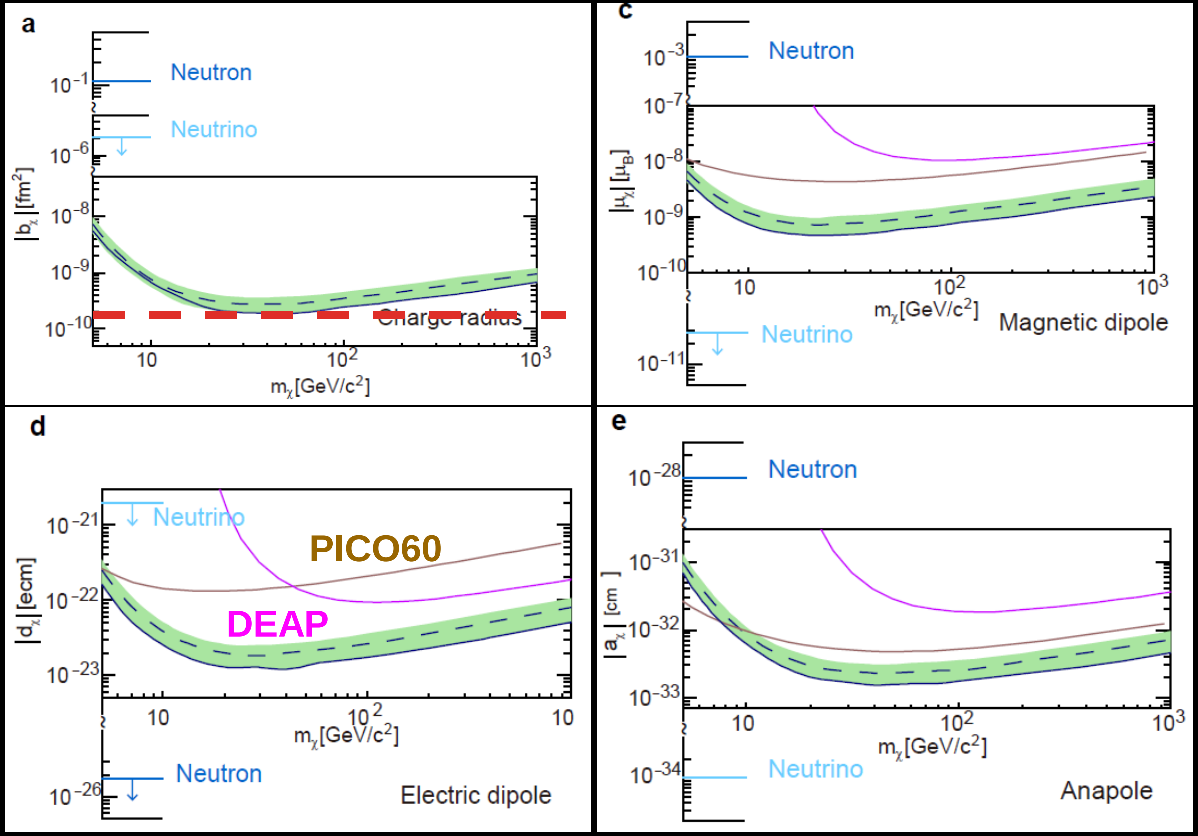


$$\mathcal{L} = Qe\bar{\chi}\gamma^{\mu}\chi A_{\mu} + \frac{\mu_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + i\frac{d_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu} + b_{\chi}\bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu} + a_{\chi}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$$

State-of-the-art Constraints to the DM EM properties

Spectra with DMFormFactor, Fitzpatrick et al, 2013



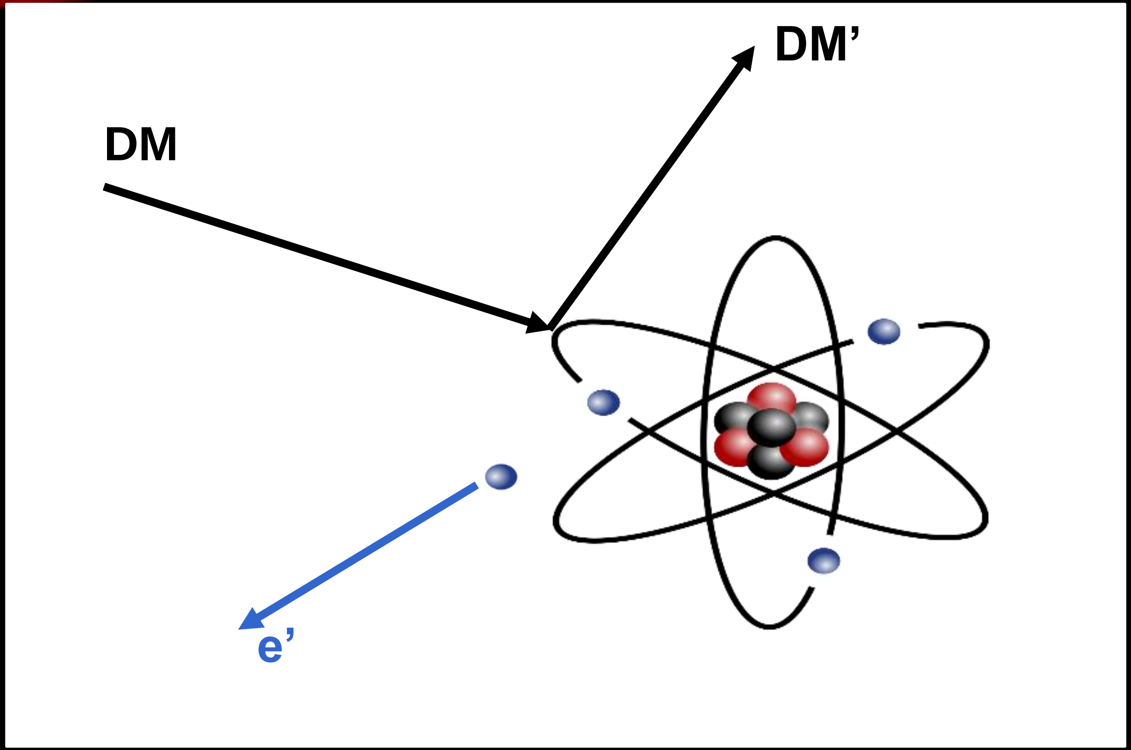


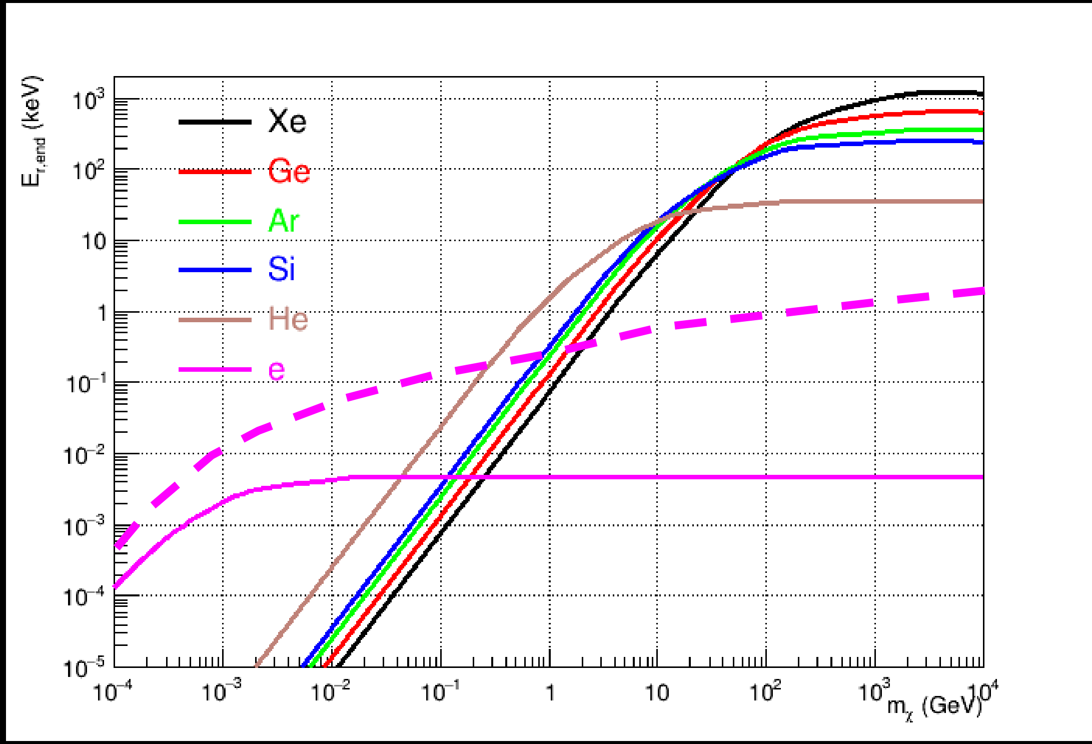
nature

Article | Published: 17 May 2023

Limits on the luminance of dark matter from xenon recoil data

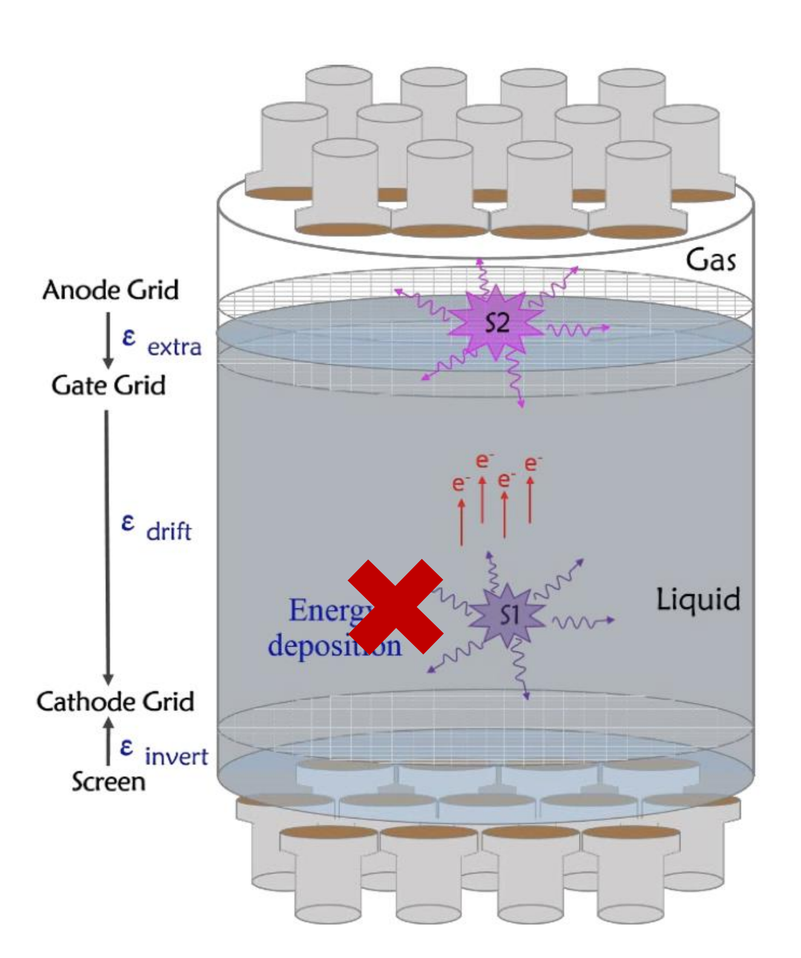
Going after electrons

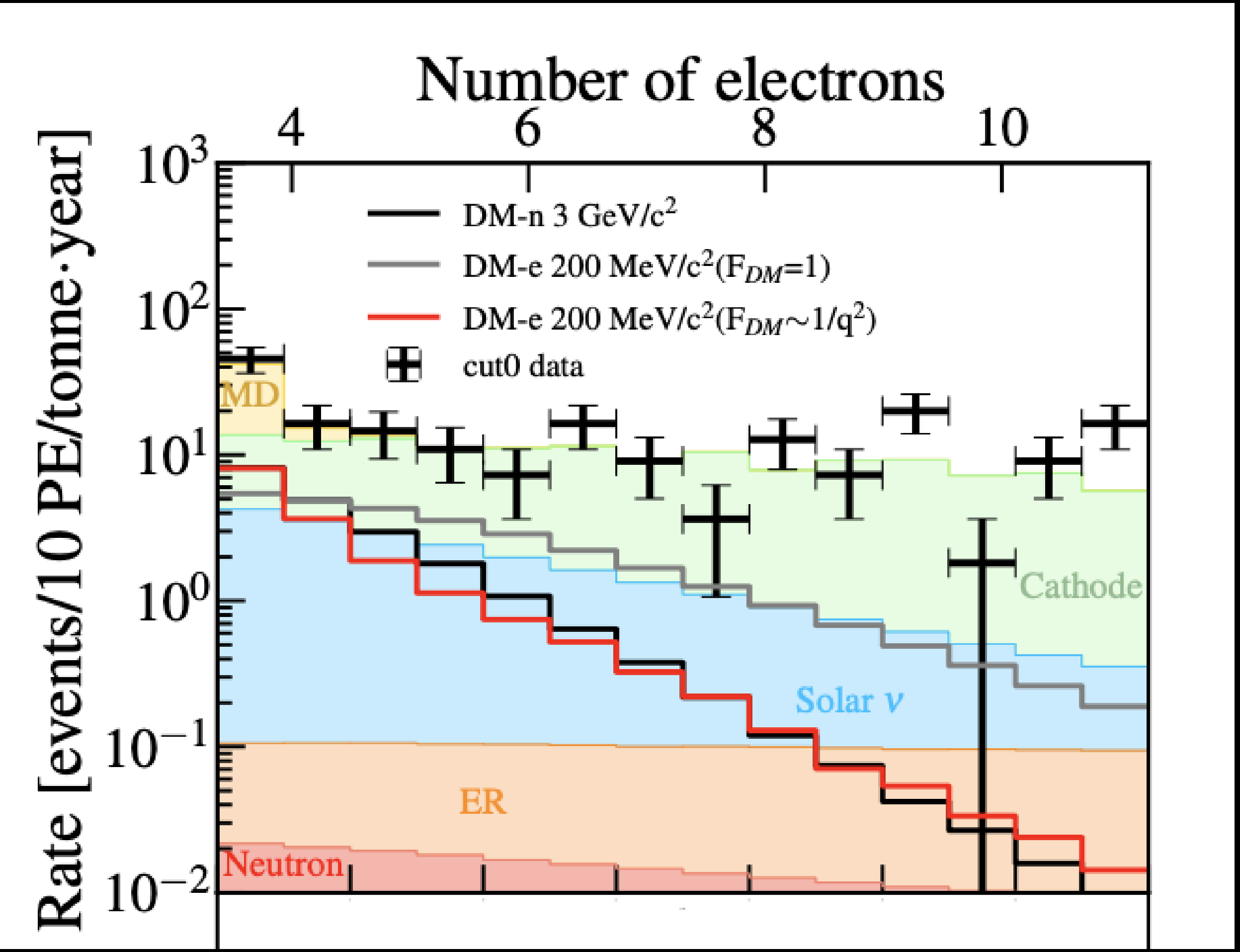




- DM could certainly interact directly with electrons
- Bound electrons in the atomic, leading to sizable energy deposition from electron ionization. Essig, Mardon, Volansky, PRD 85, 076007 (2012)

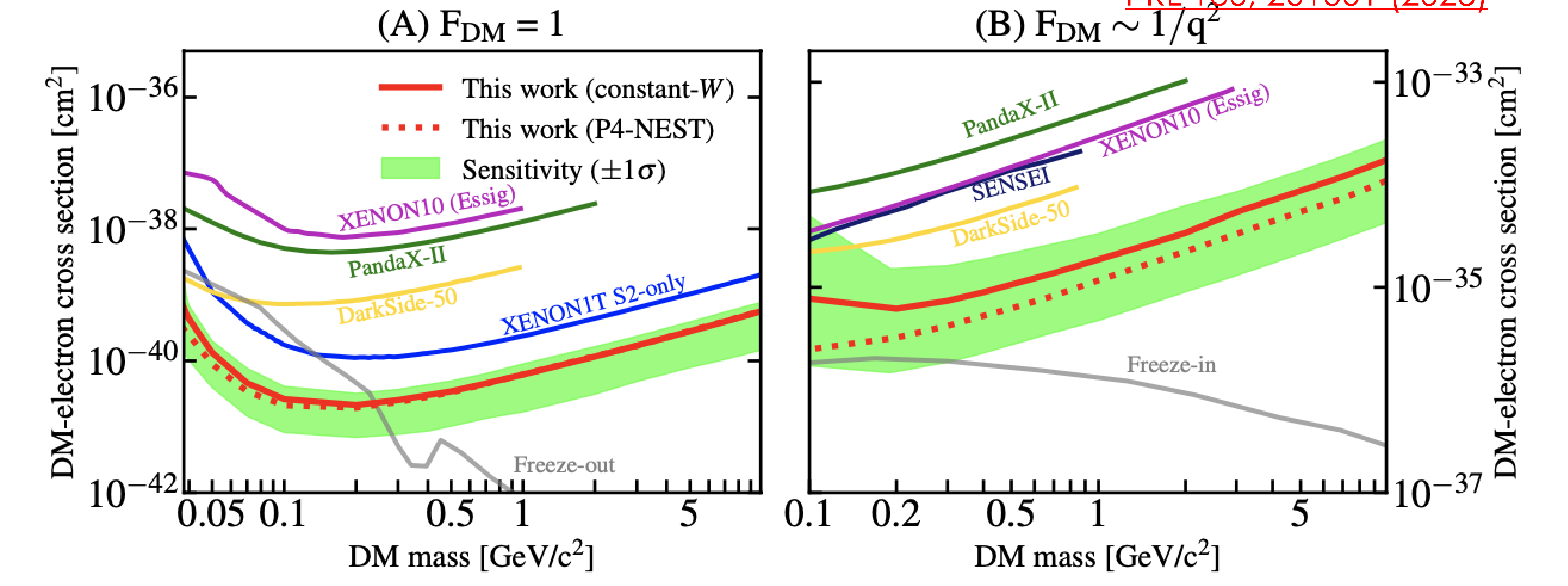
S2-only approach



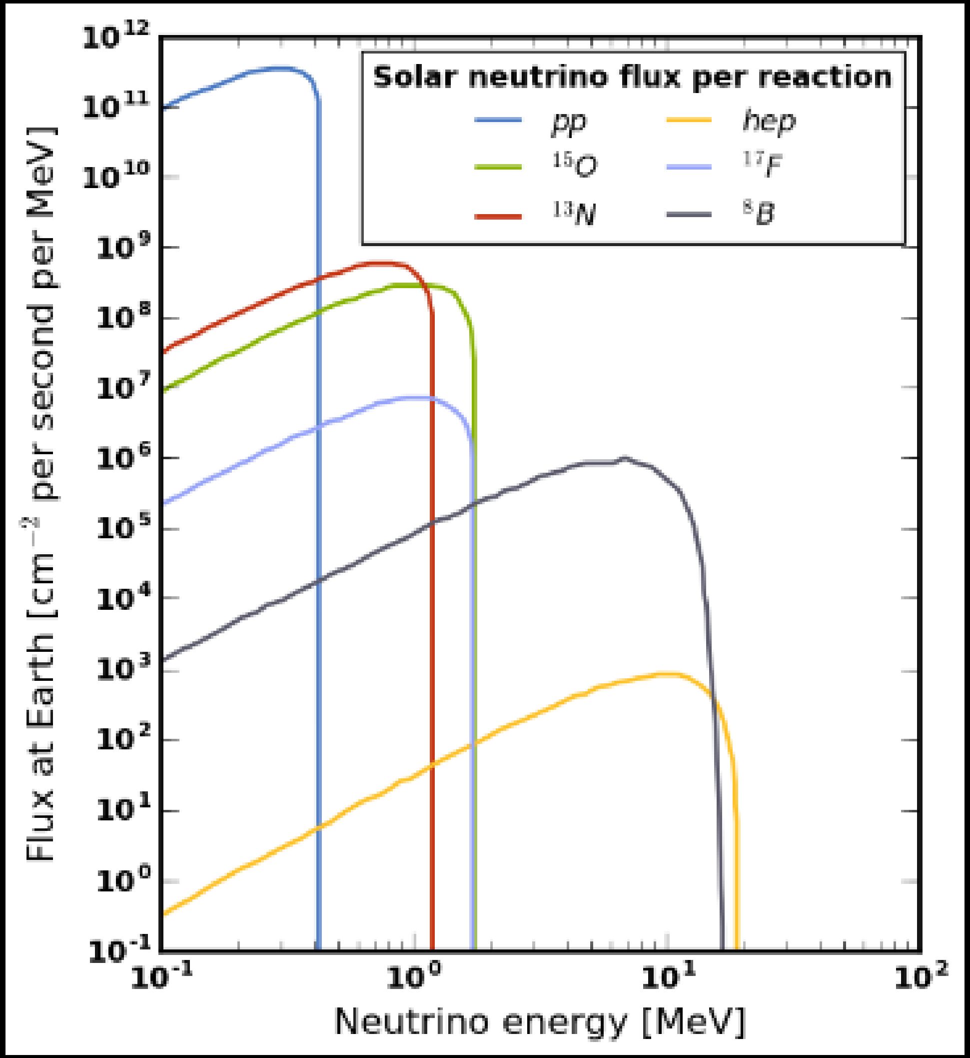


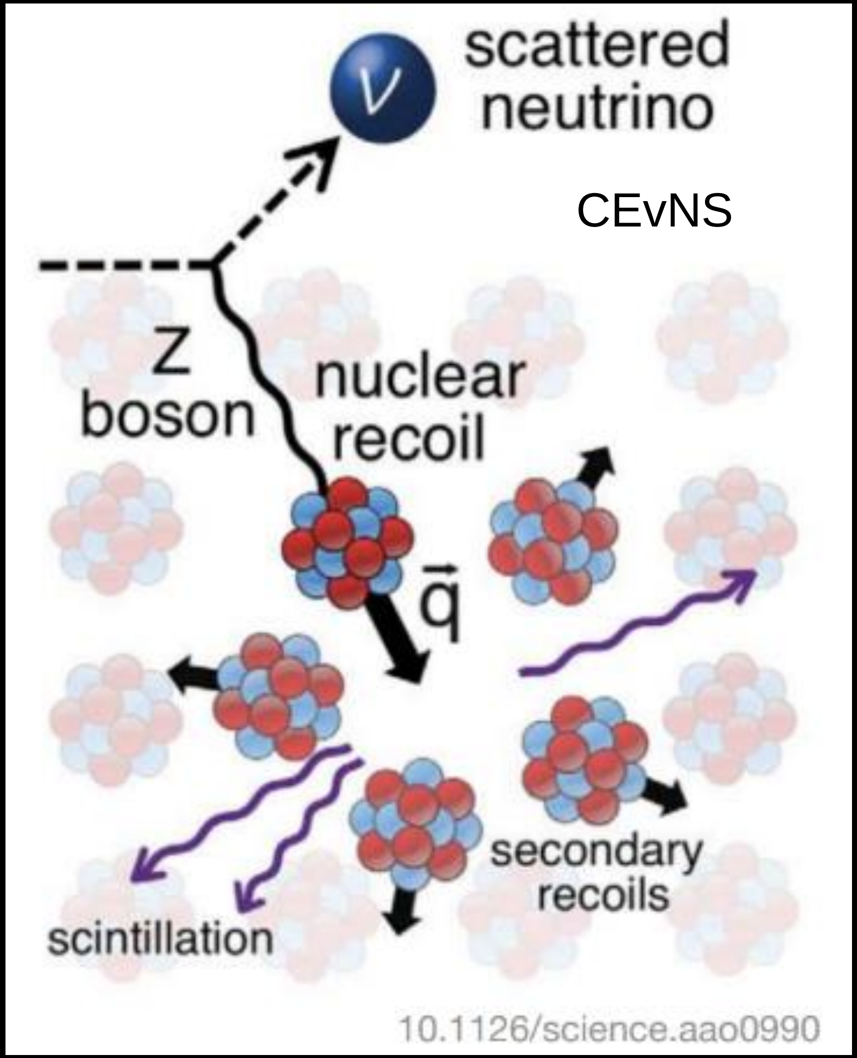
Tight limits on DM-e scattering

PRL 130, 261001 (2023)



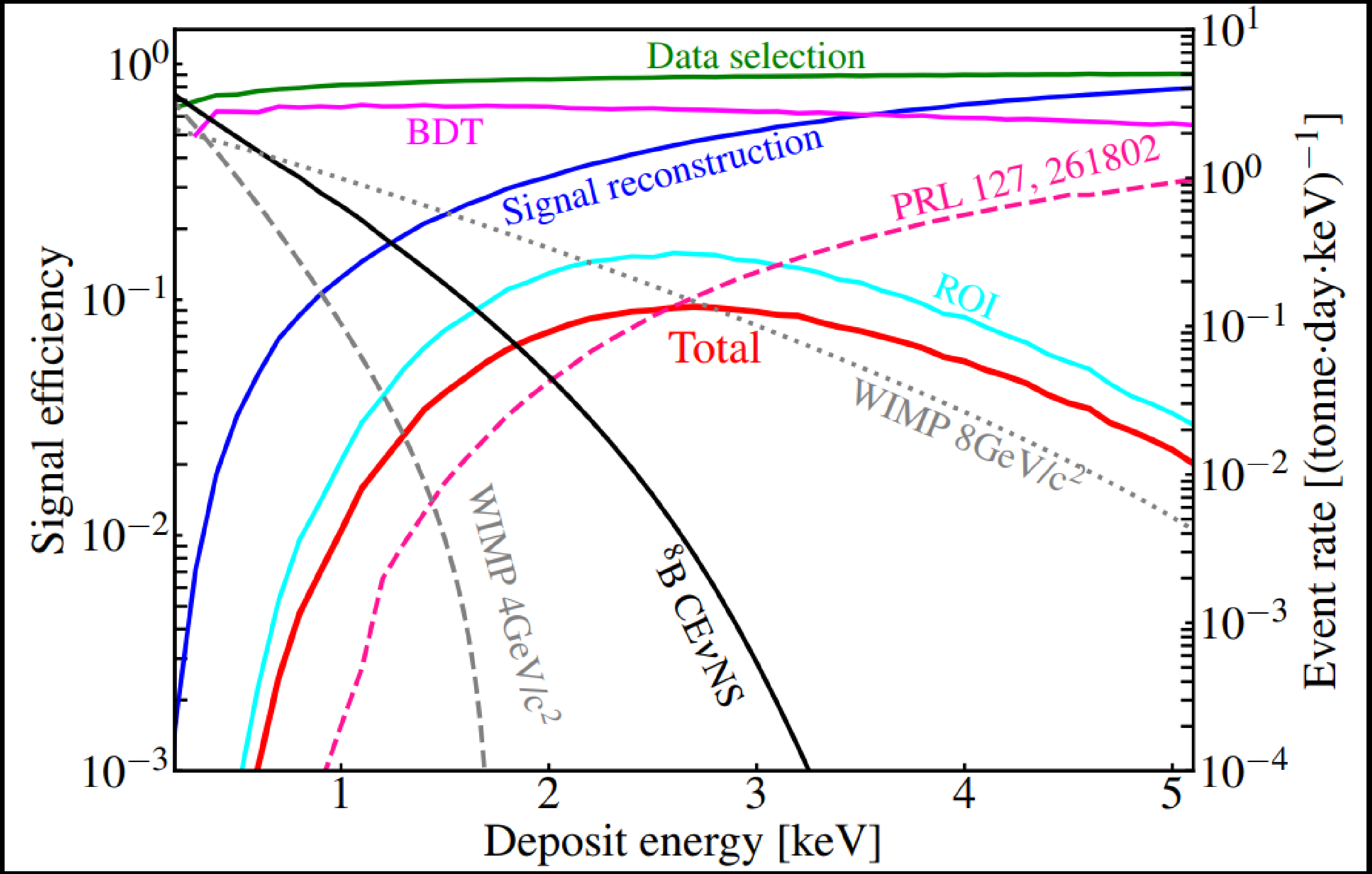
^{8}B neutrino floor?





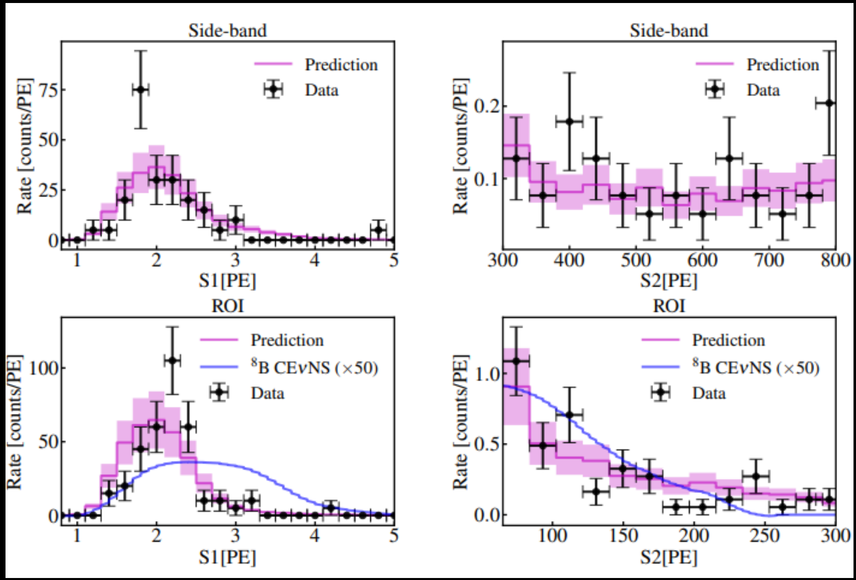
PandaX-4T Search on B8 CEvNS

- To enhance sensitivity ^{8}B, need to lower the selection threshold (S1↓, S2 ↓)
- Key difficulty: accidental background ↑
- Blind analysis: with 0.48 ton-year data, excluding period when we see an increase of noises rates (micro-discharge)



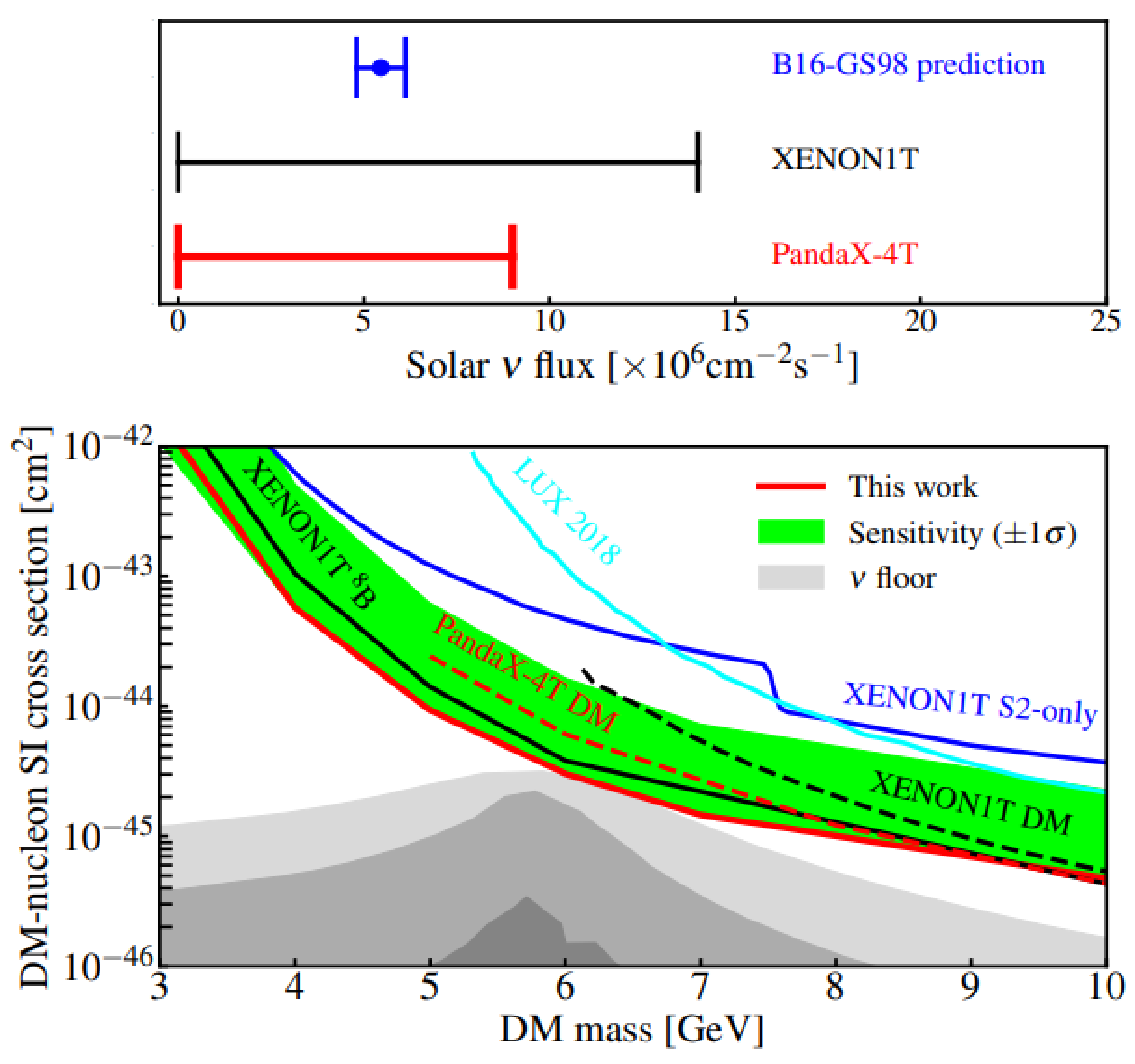
Control of accidental background

- Use "scrambled" real data to predict accidental background
- B8 signal model built on snippets of S1 and S2 from calibration data
- BDT training/selection is entirely blinded
- 17% probability (with ^{8}B CEvNS and no WIMP)



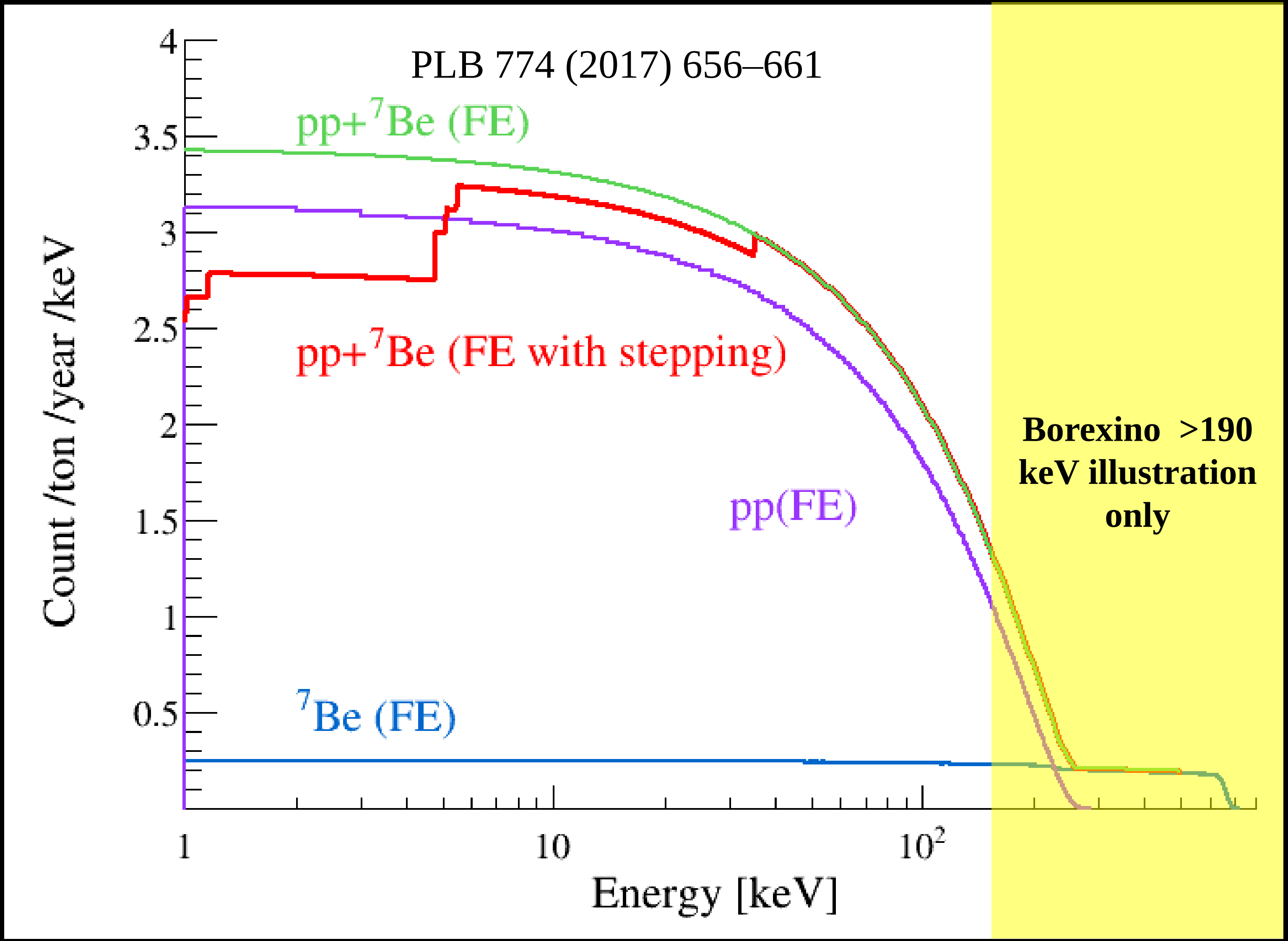
Nhit requirement on S1	BDT	Expected BKG (evt)	Expected 8B (evt)	Observed (evt)
2	Before	62.7	2.3	59
	After	1.5	1.4	1
3	Before	0.9	0.4	2
	After	0.07	0.3	0

^{8}B & low mass WIMP results

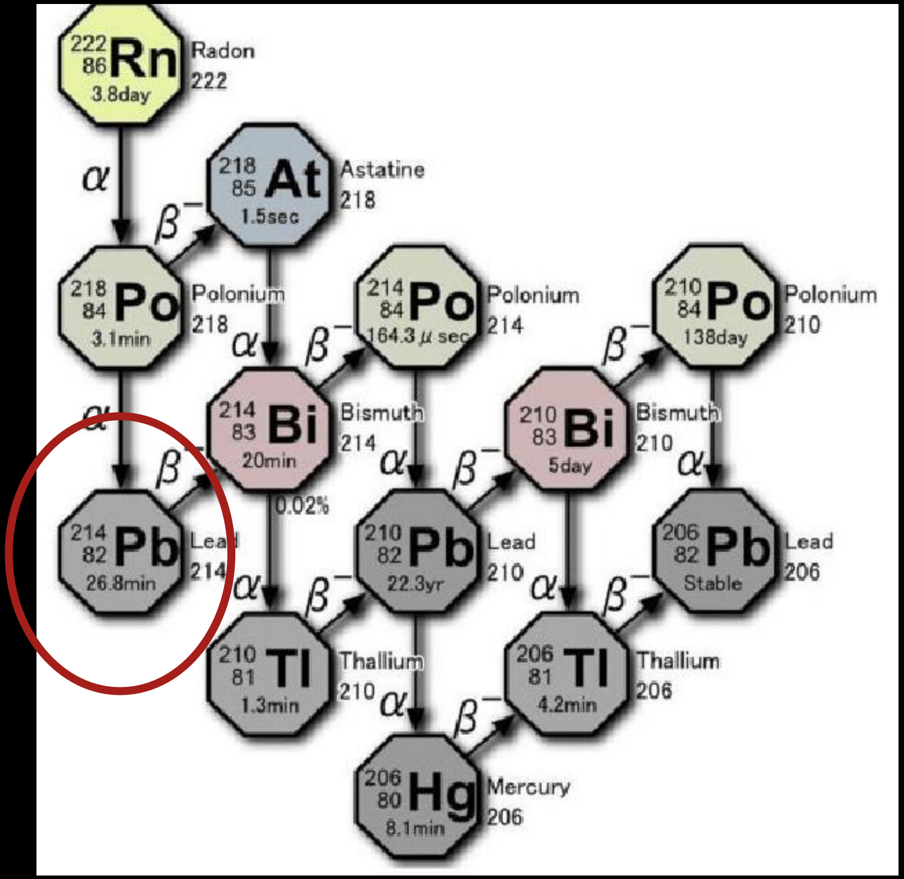


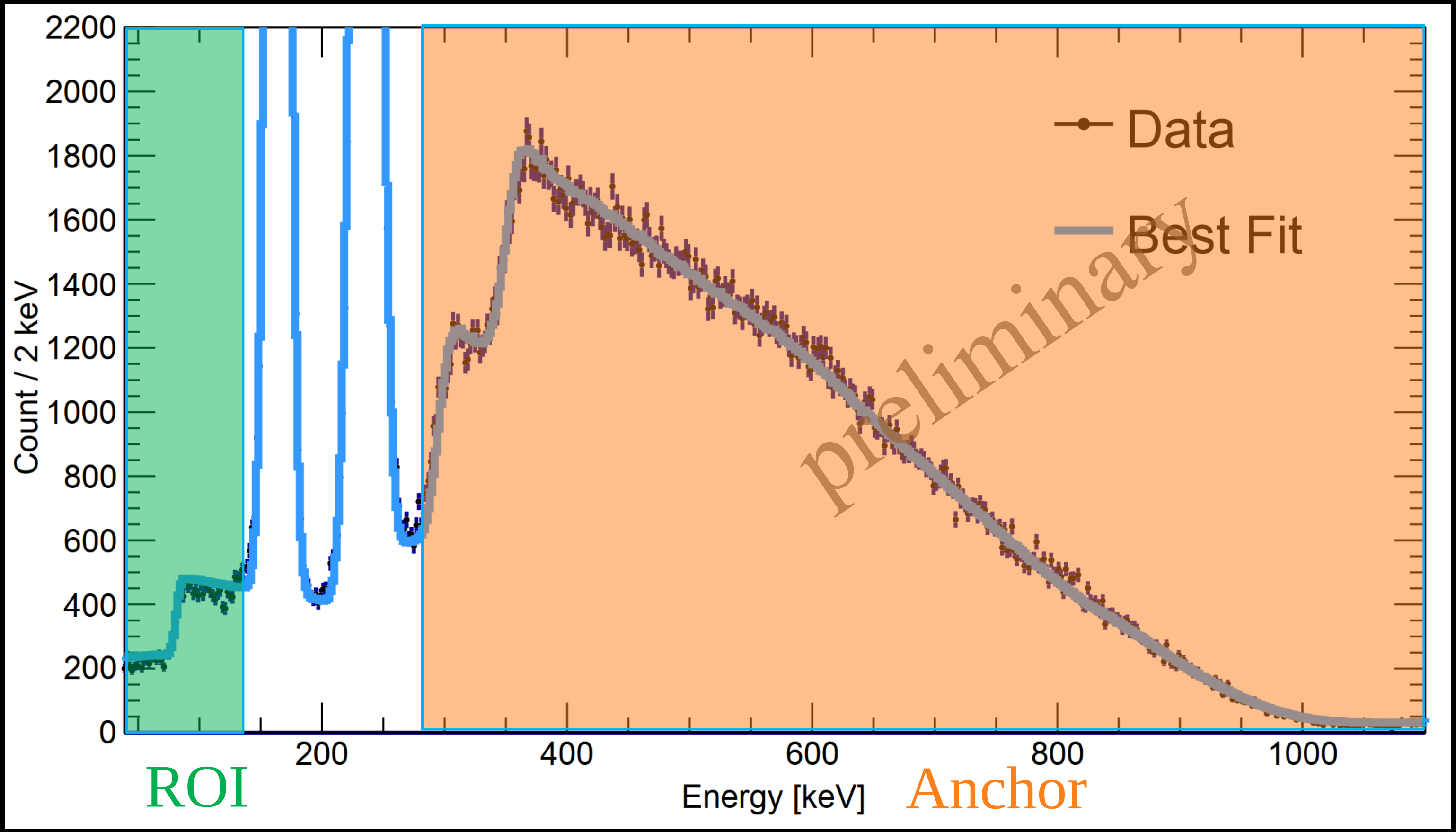
- Leading constraint on ^{8}B flux using CEvNS
- Can cast constraint on neutrino-nucleus interactions
- Assuming nominal ^{8}B background, also set tightest low mass WIMP-nucleon SI interaction limit between 5 and 10 GeV/c^2
- PRL 130, 021802 (2023)

Going after low energy pp neutrino



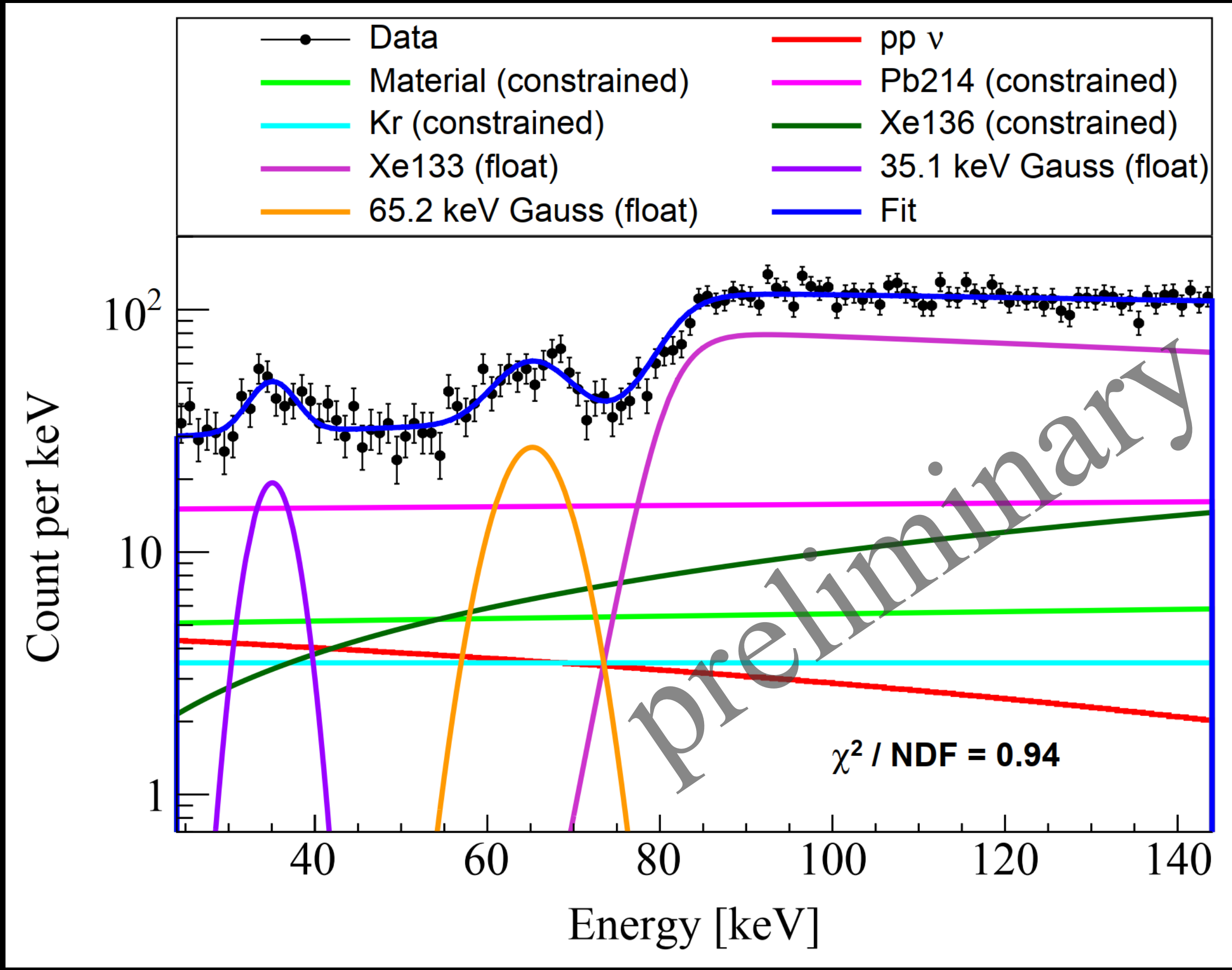
Direct measurement of Pb214 shape





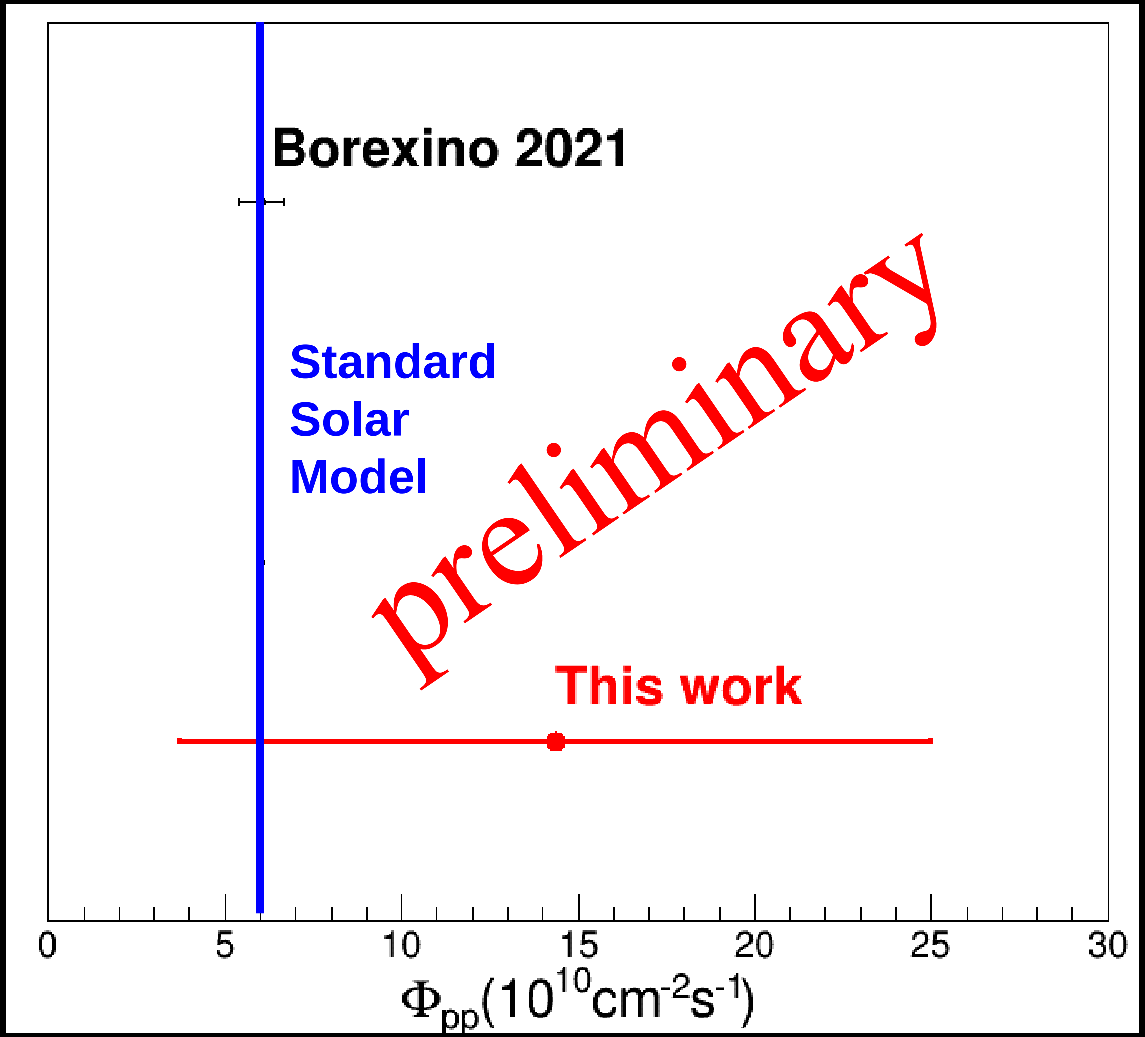
Preliminary solar pp + ^{7}Be neutrinos

ROI chosen as [24, 144] keV



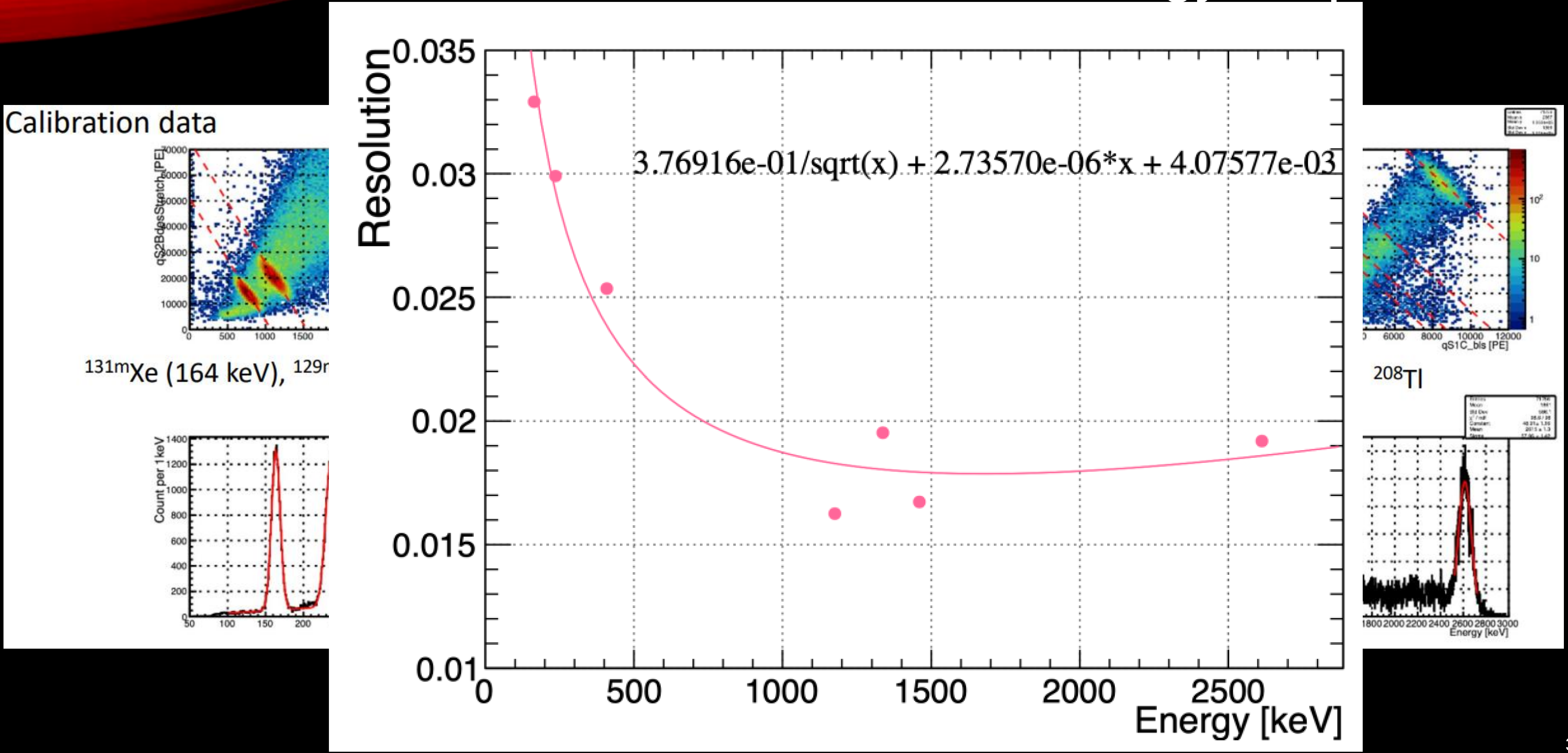
- Constrained from higher energy fits or dedicated studies:
  - Pb214 (10% constraint)
  - Material (12.5% constraint)
  - ^{136}Xe 2nbb (4.6% constraint)
  - ^{85}Kr (51% constraint)
- Float:
  - 35 keV single gaussian peak (^{127}Xe + ^{124}Xe + ^{125}I)
  - 65 keV single gaussian peak (^{124}Xe + ^{125}I)
  - ^{133}Xe (simulated spectrum)

First pp neutrino measurement below 190 keV!

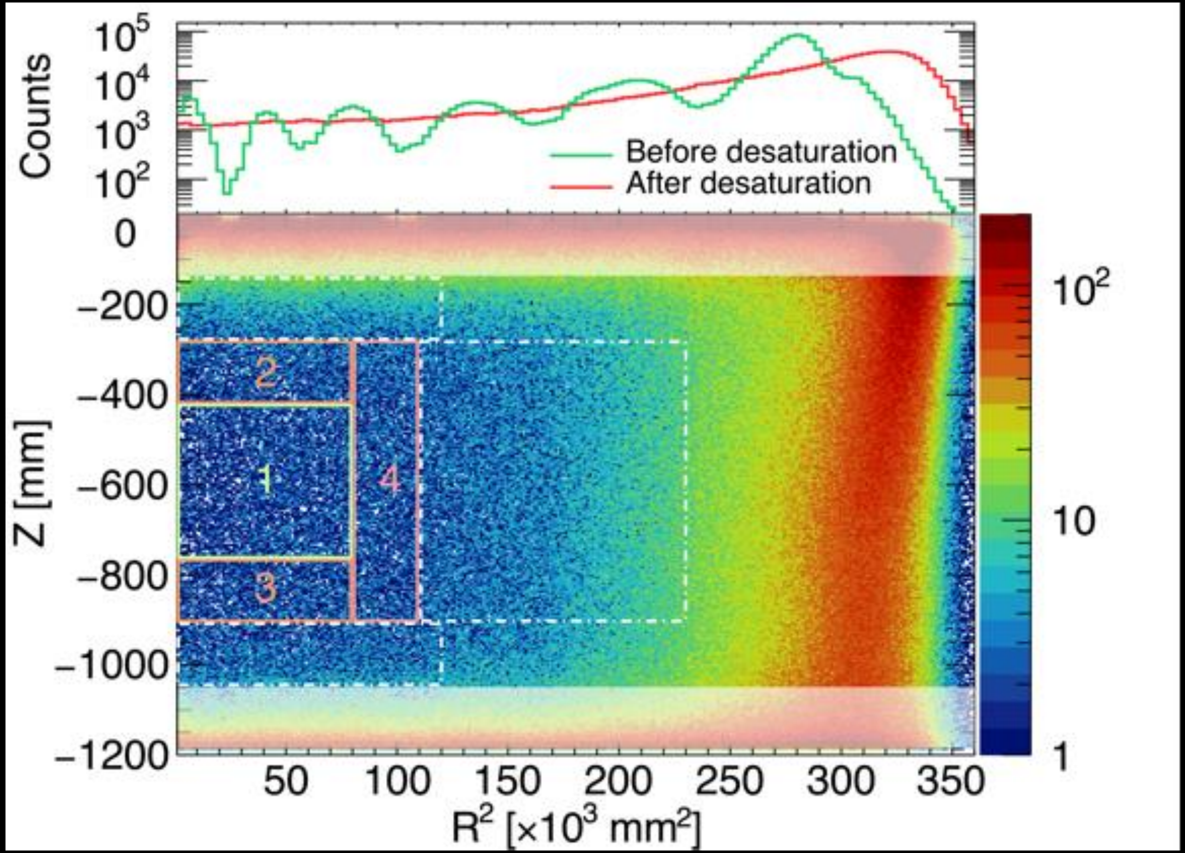


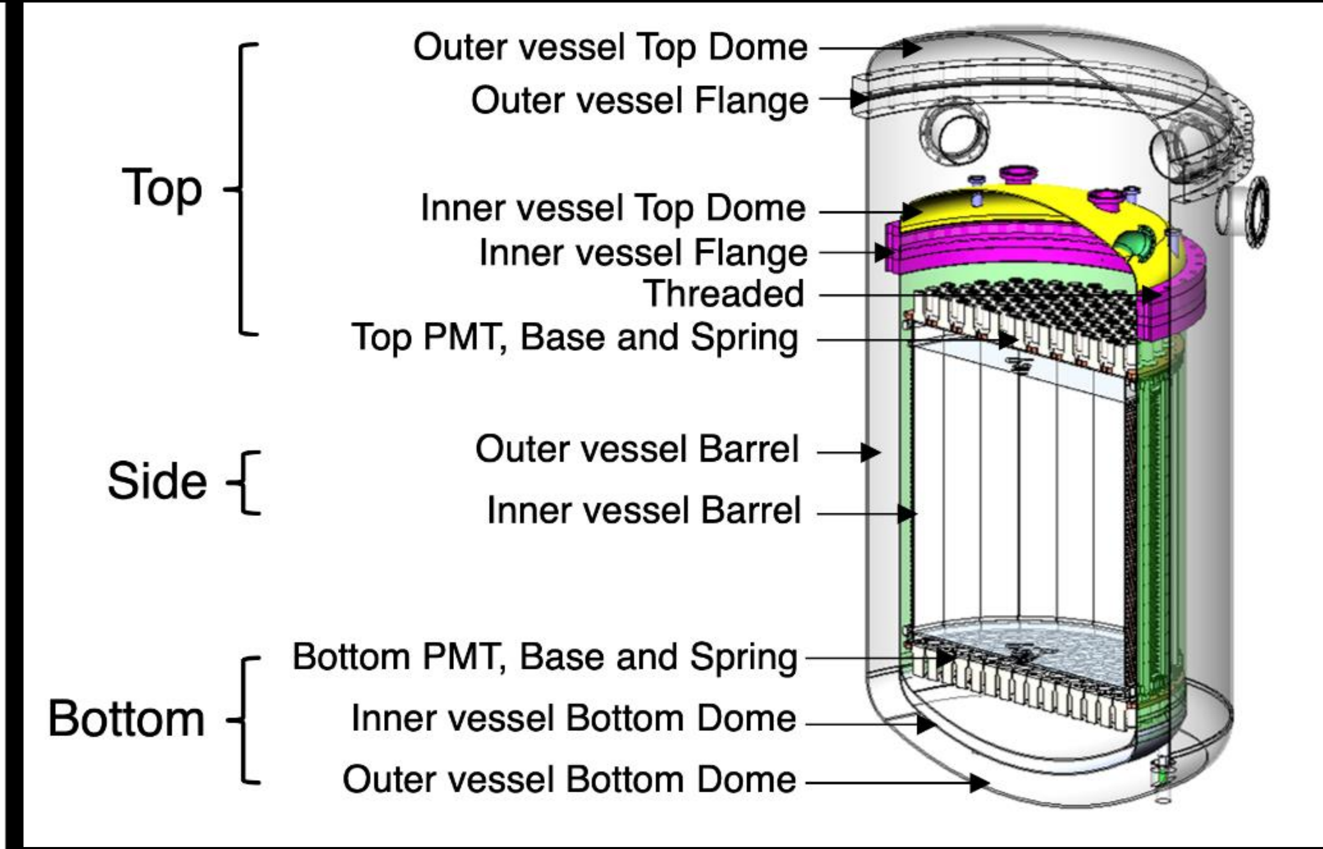
^{136}Xe double beta decay

Calibration and energy response

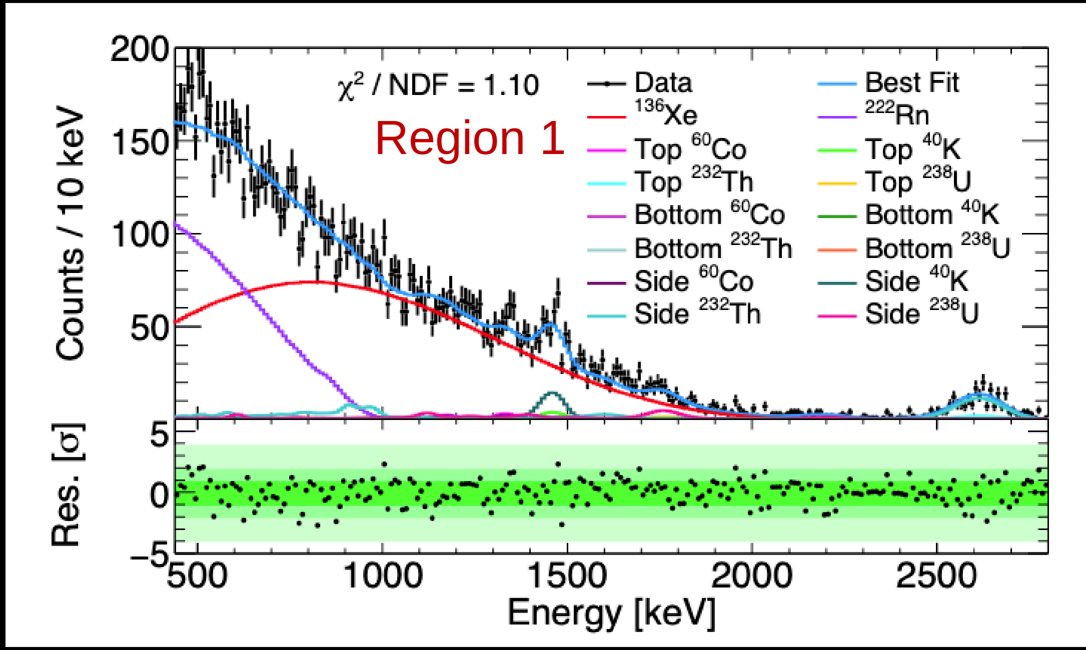


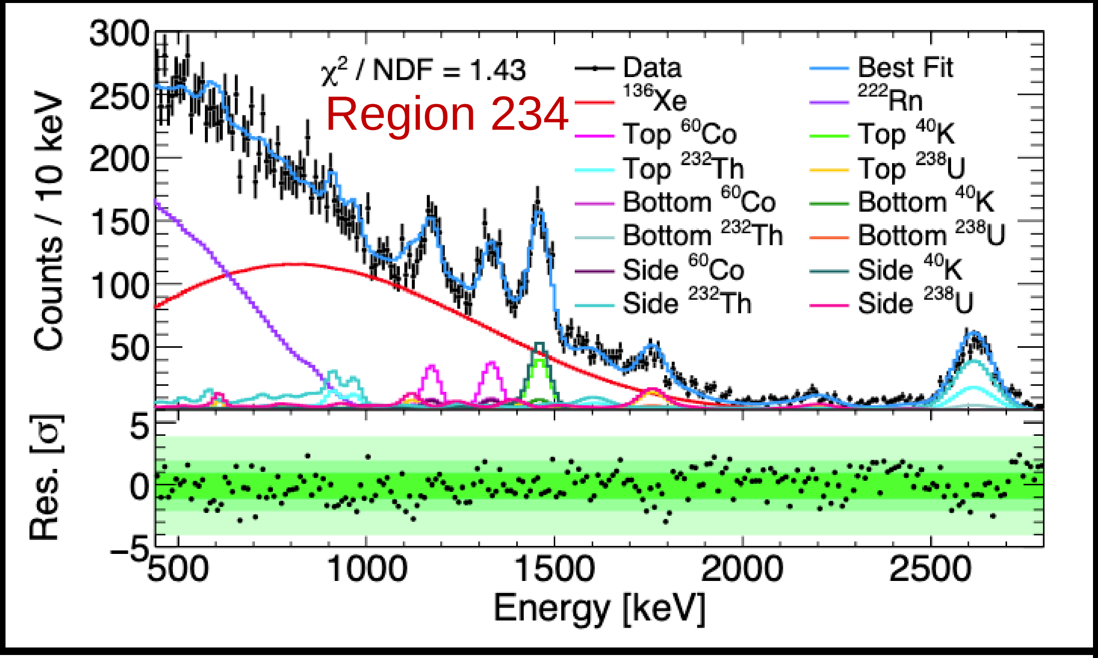
PandaX-4T, precise measurement of 2vDBD

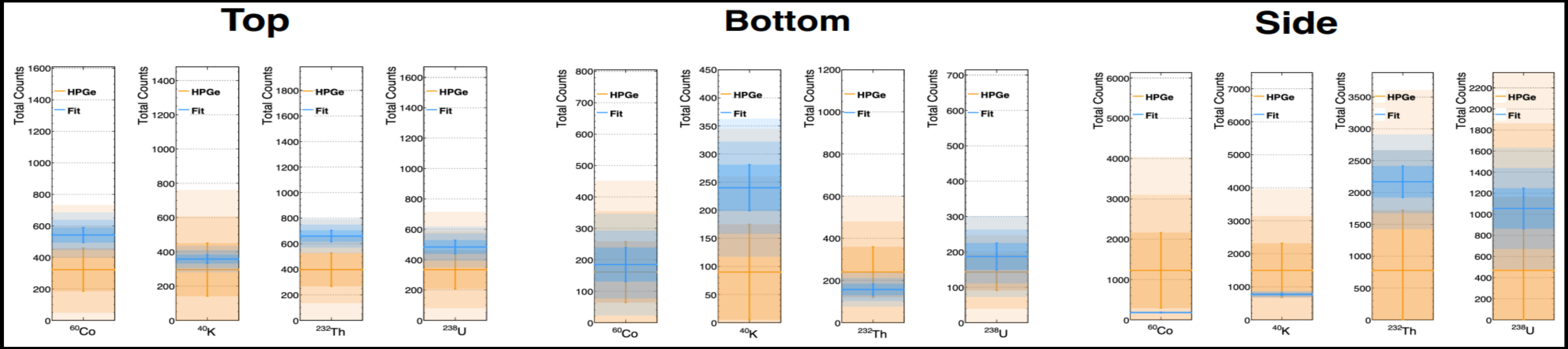




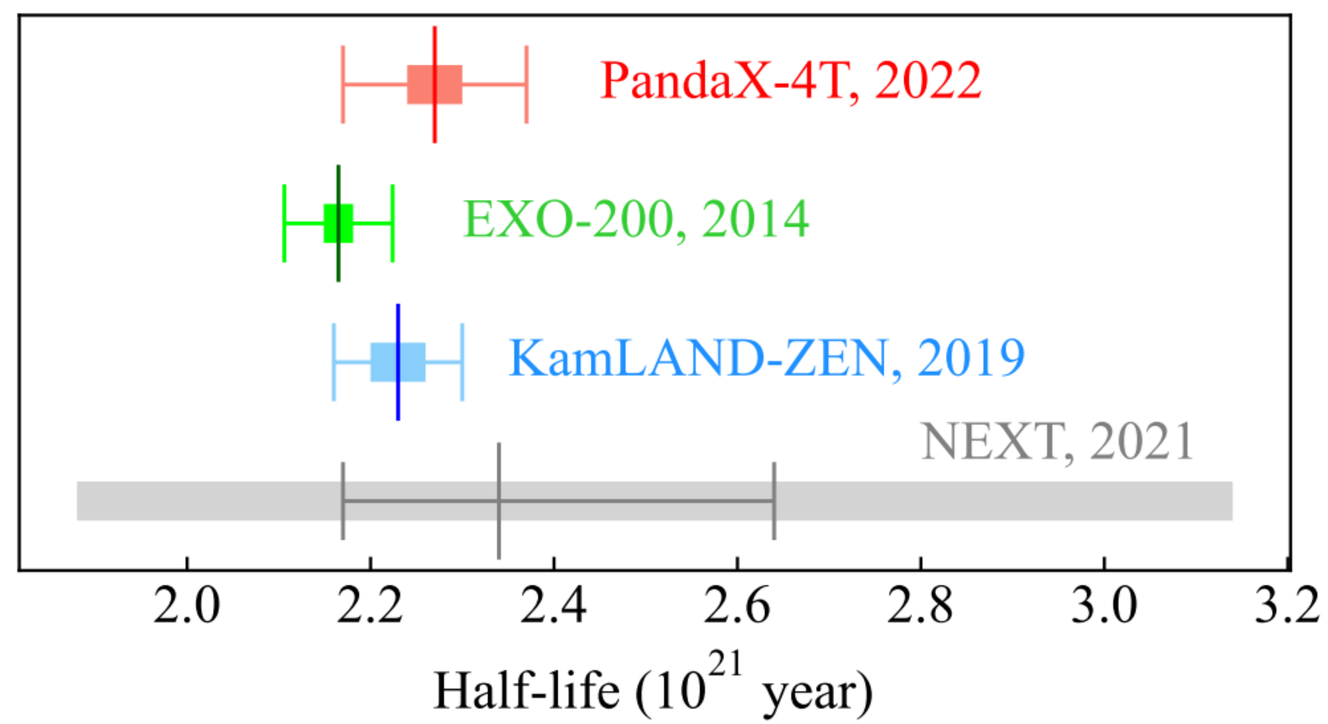
PandaX-4T, precise measurement of 2vDBD







PandaX-4T, precise measurement of 2vDBD



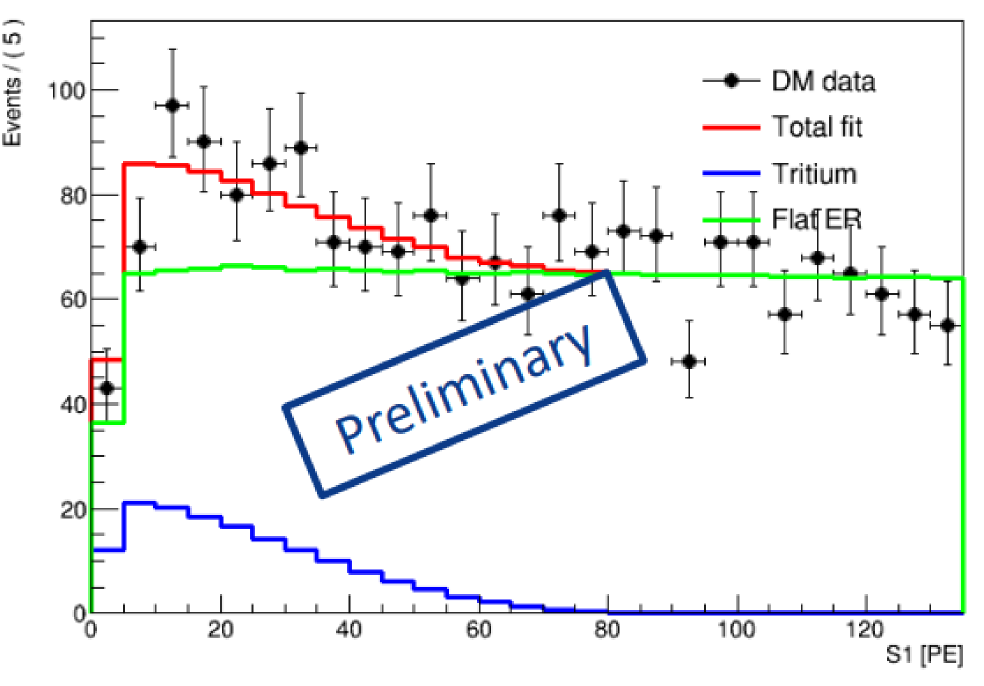
- ^{136}Xe DBD half-life: $2.27 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.}) \times 10^{21}$ year
- First such measurement with natural xenon arXiv:2205.12809, **Research** vol 2022, 9798721

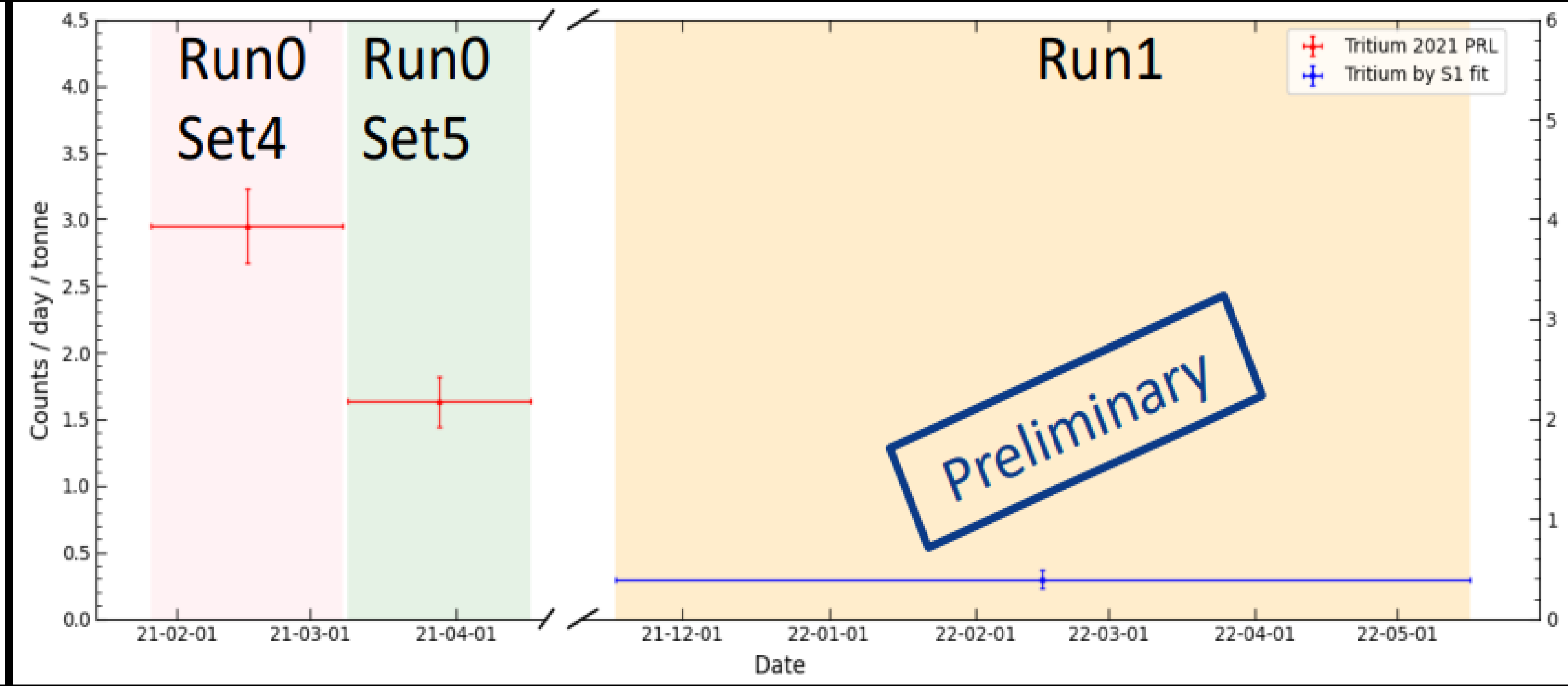
After commissioning

- Tritium removal
  - xenon distillation, gas flushing, etc
- 2021/11 – 2022/05: physics run (Run1)
  - 164 days: ~ 1 tonne-year (blinded)
- 2022/09 - 2023/08: hall construction
  - xenon recuperation
  - detector upgraded
- Expect to resume by the end of 2023

Level of tritium

- Preliminary estimation of tritium level for Run1 by fitting S1 spectrum with S2 blinded
- Extensive tritium measures planned for next run (Run 2)





Preliminary background (Run0+Run1)

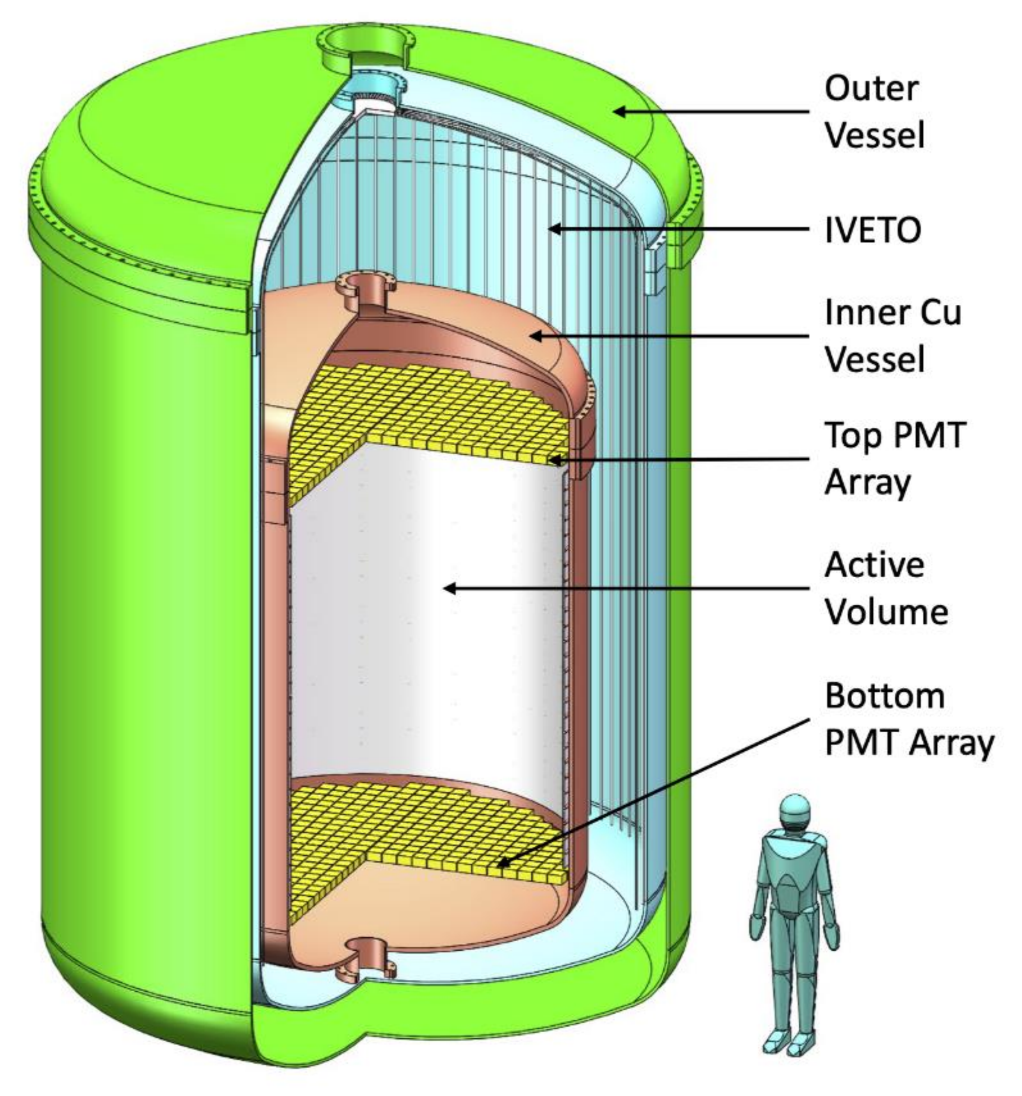
Component	Run0: 0.6 tonne-year	Run1: 1.0 tonne-year
Tritium	2.3 ± 0.2 counts/day/tonne	0.4 ± 0.1 counts/day/tonne
Rn	7.1 ± 0.2 uBq/kg	8.7 ± 0.3 uBq/kg
Kr	0.5 ± 0.3 ppt	0.9 ± 0.3 ppt
Neutron	1.0 ± 0.2 events	2.3 ± 0.4 events
Surface	0.10 ± 0.06 events	0.16 ± 0.09 events
AC	work-in-progress	work-in-progress

Future

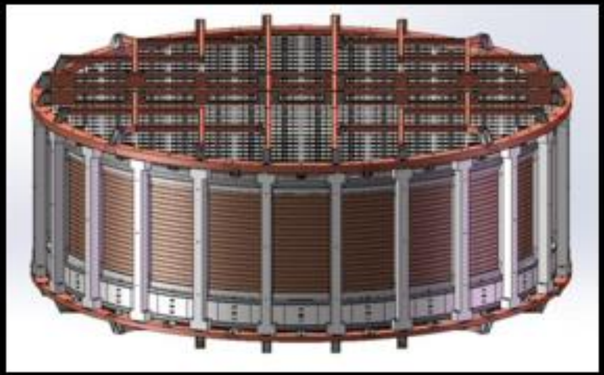
China starts to call major instrumentation proposals for the 15th 5-year

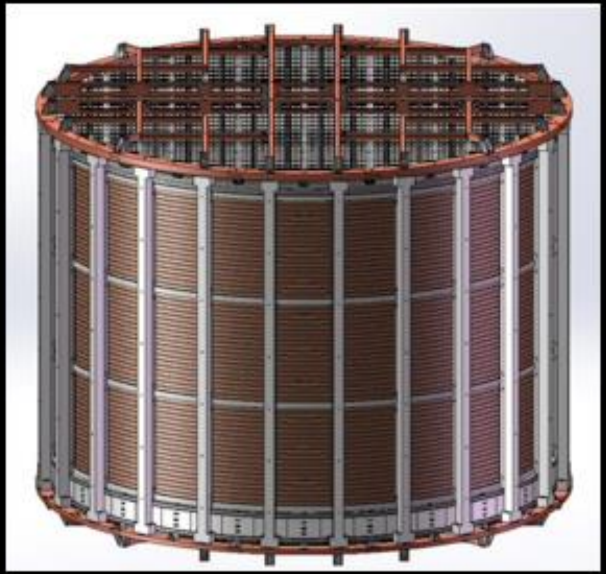
PandaX-xT

- Continue operate PandaX-4T till end of 2024
- Next: PandaX-xT, general-purpose observatory on dark matter, 0vDBD (^{136}Xe), neutrinos, other ultra-rare phenomena
- 47-ton xenon, including 43-ton sensitive volume
- CJPL advantages
  - DM: unique advantage on atmospheric neutrino background (low latitude), 50% of LNGS (PRD 105, 043001, 2022)
  - 0vDBD: Low ^{137}Xe background (depth), 1/100 of LNGS (estimated using μ rate)

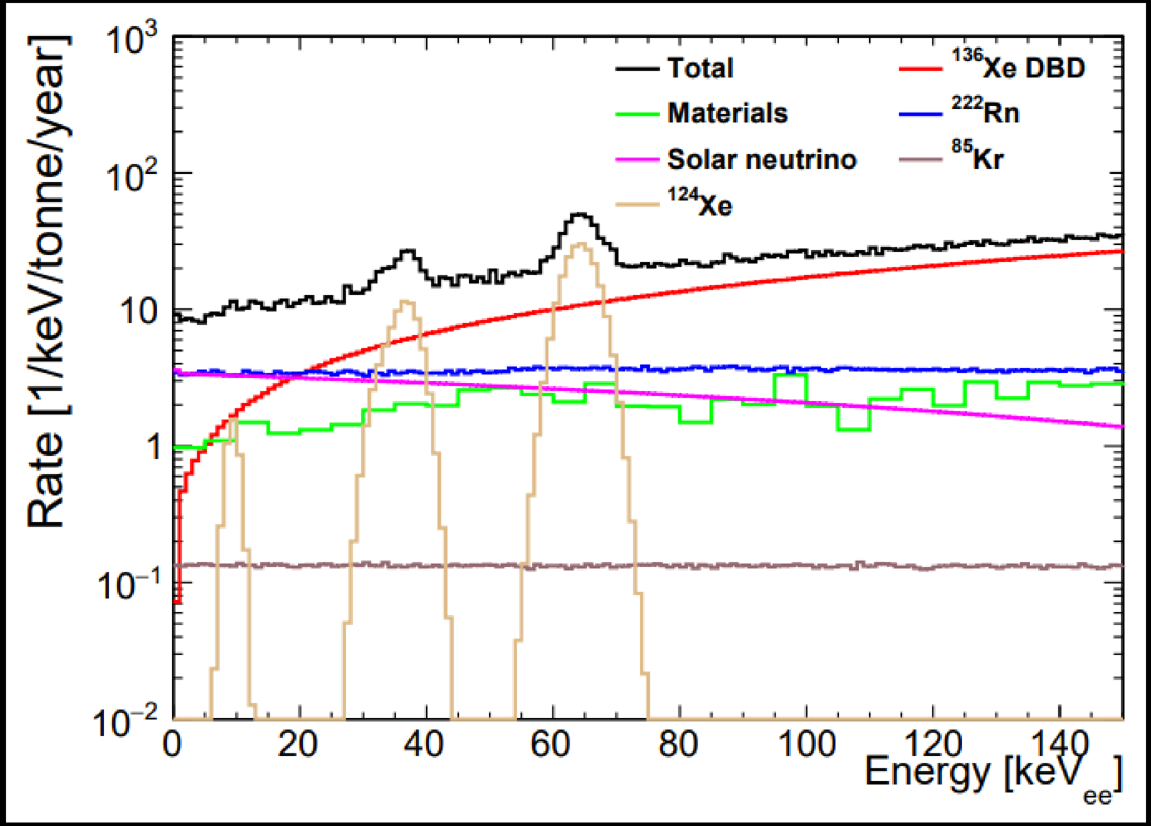


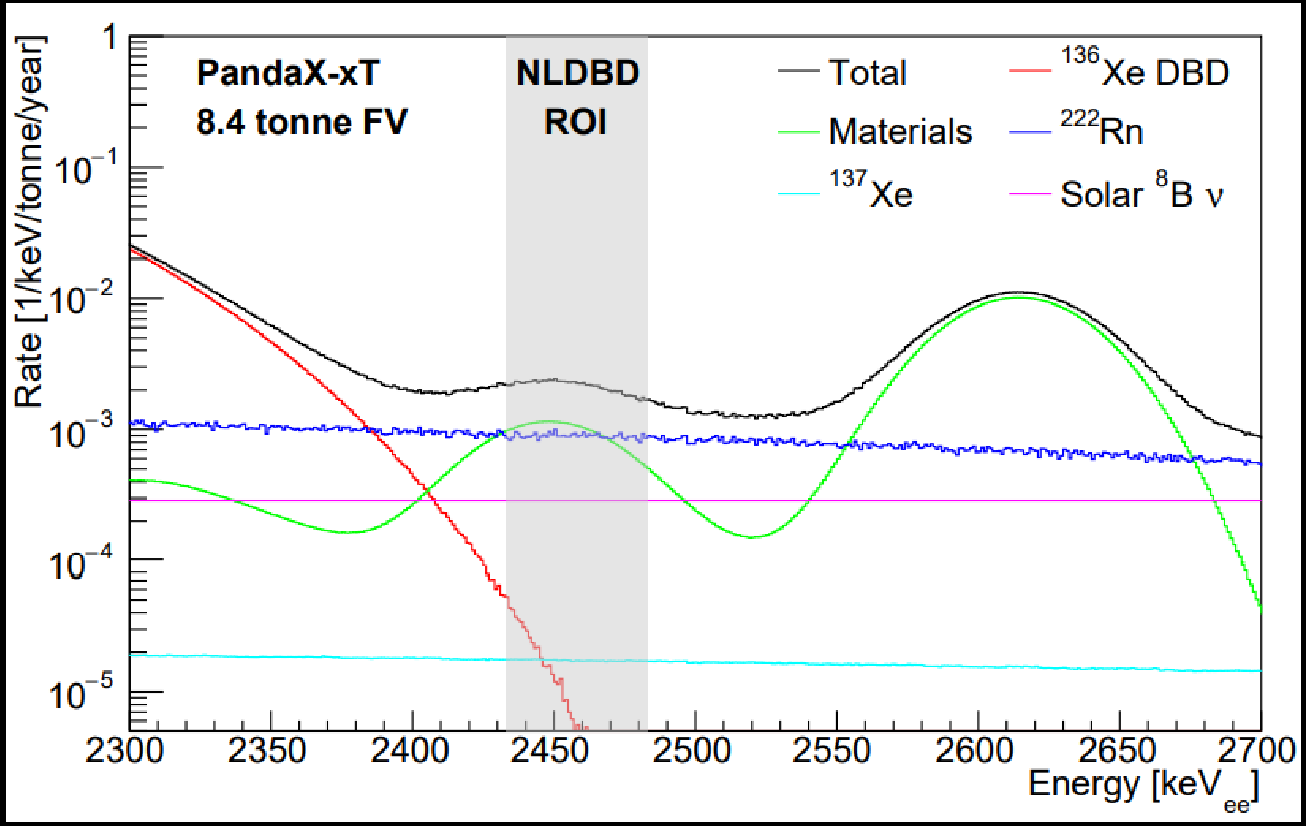
Advantage of Liquid: staged plan





Neutrino significant background

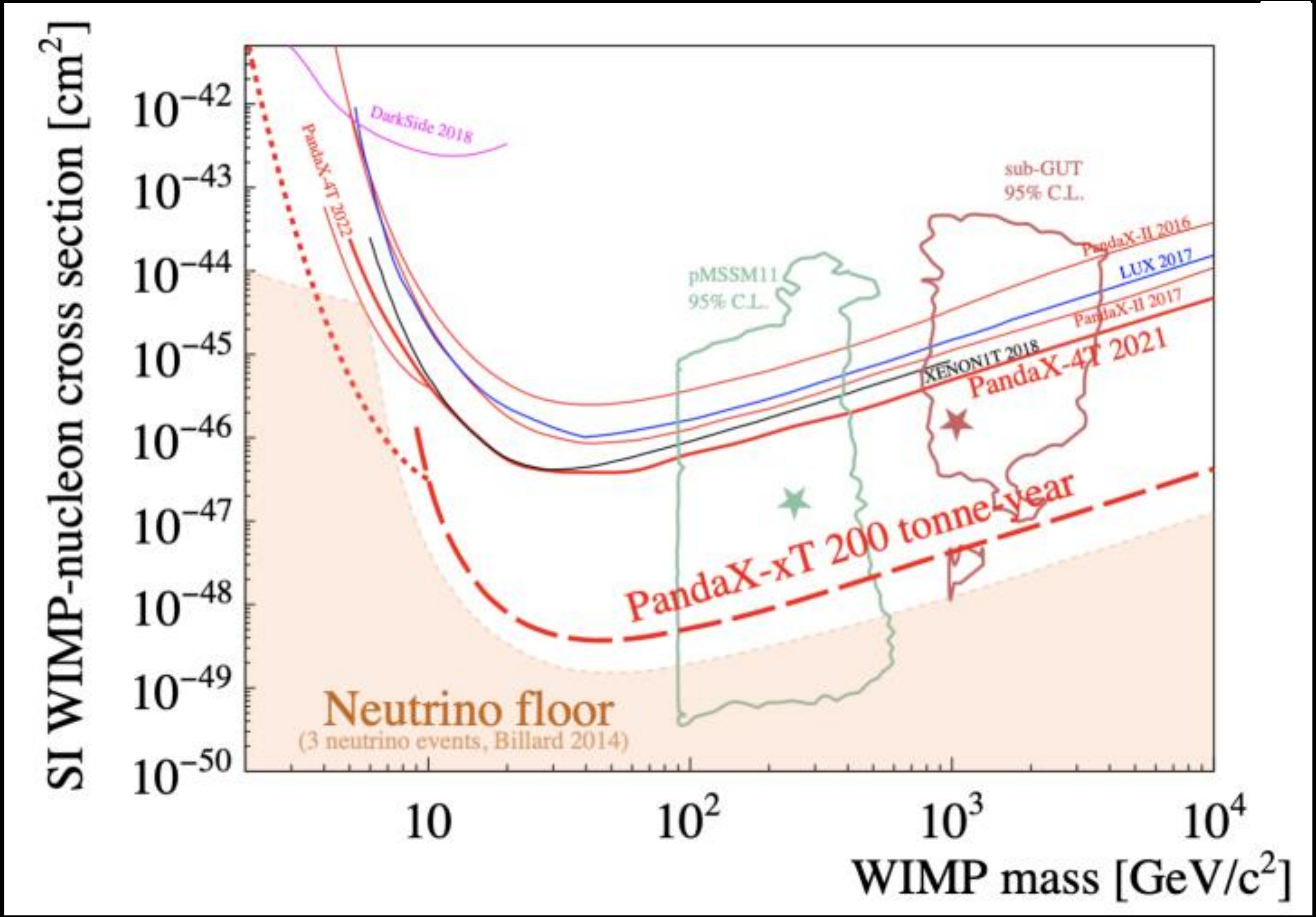




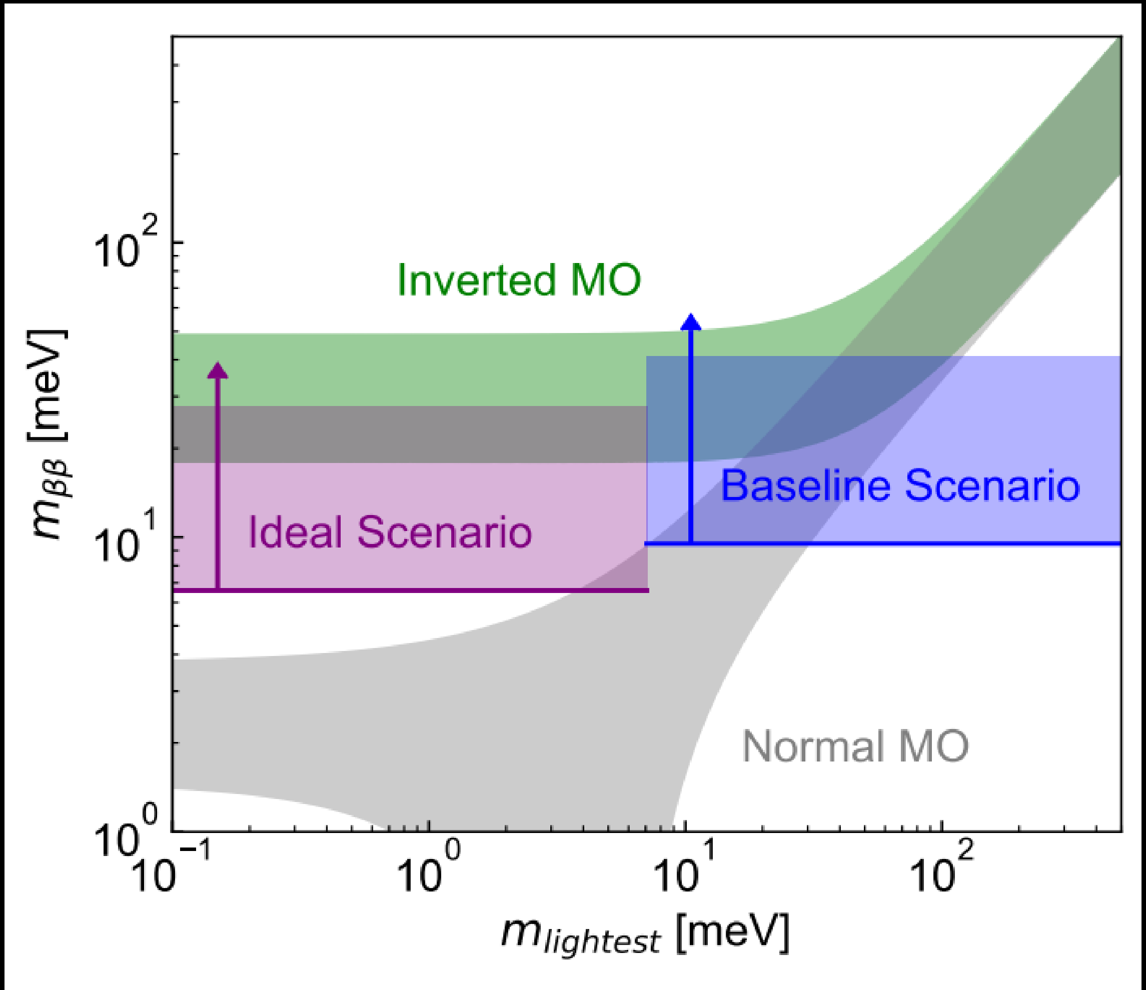
Low energy: dominated by ^{222}Rn, pp neutrino, ^{136}Xe （34.2 ton FV)

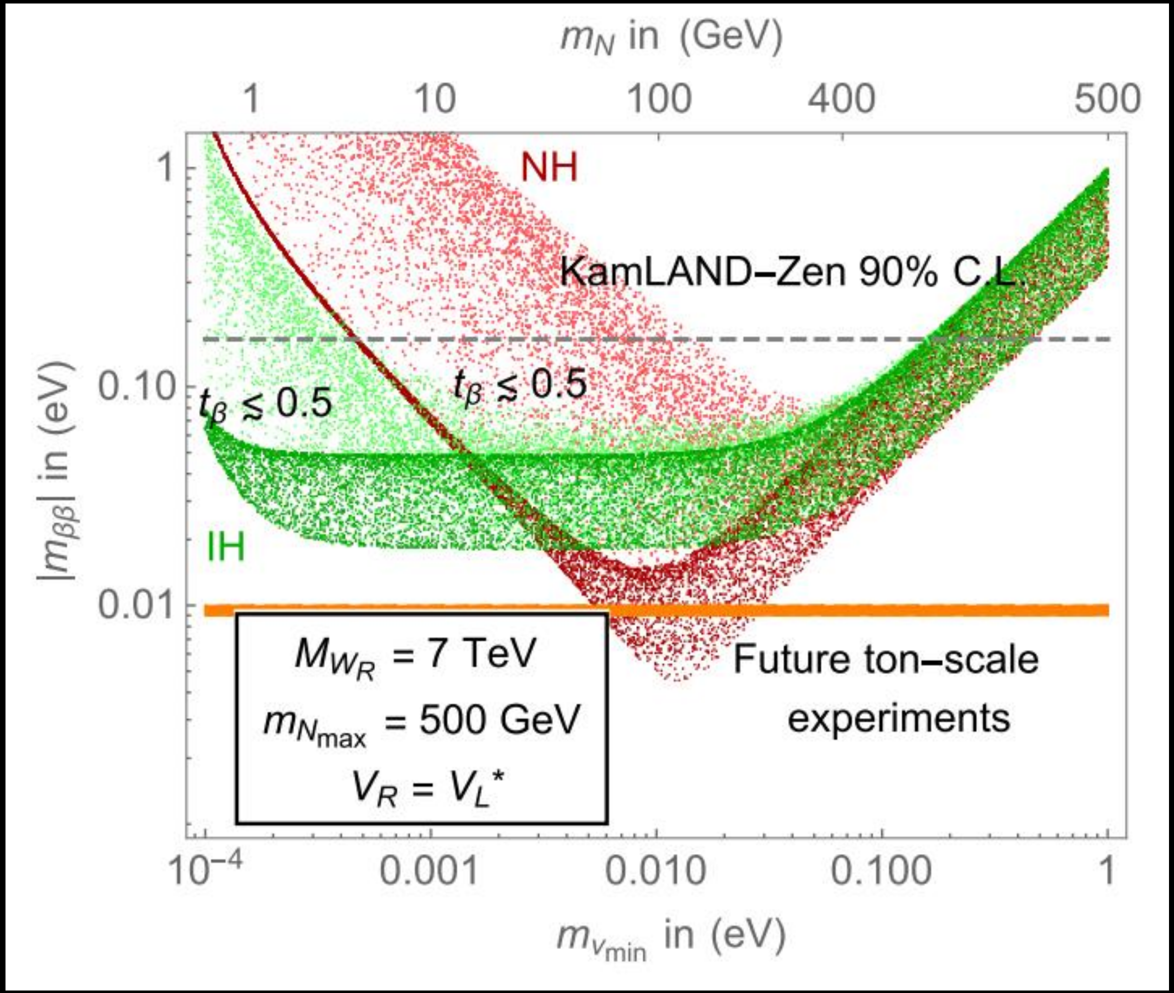
High energy: dominated by ^{222}Rn, ^{8}B neutrino, and ^{238}U in material (8.4 ton FV) Note ^{137}Xe (4 min $T_{1/2}$) after muon, key background for LNGS

Scientific potential



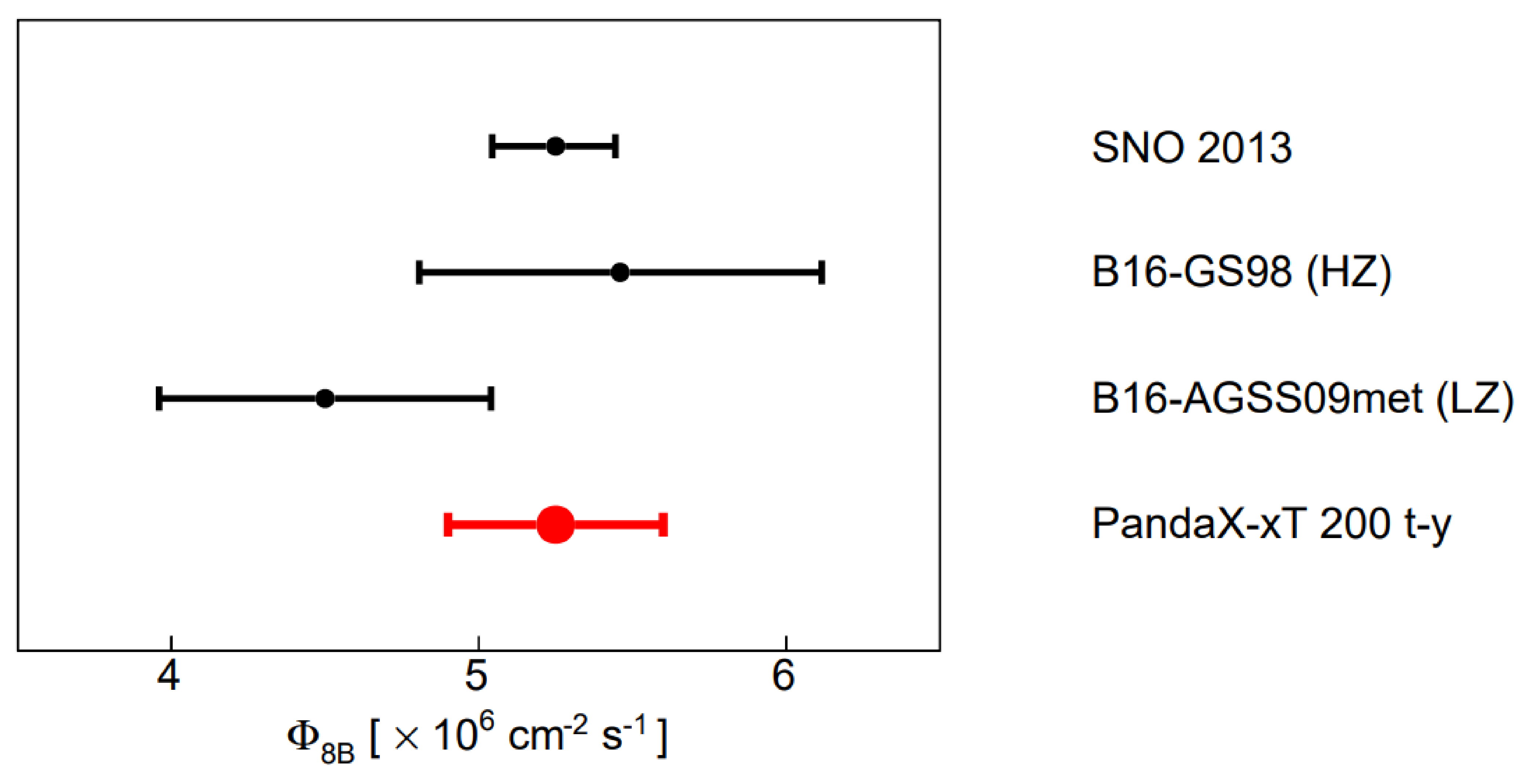
Scientific potential



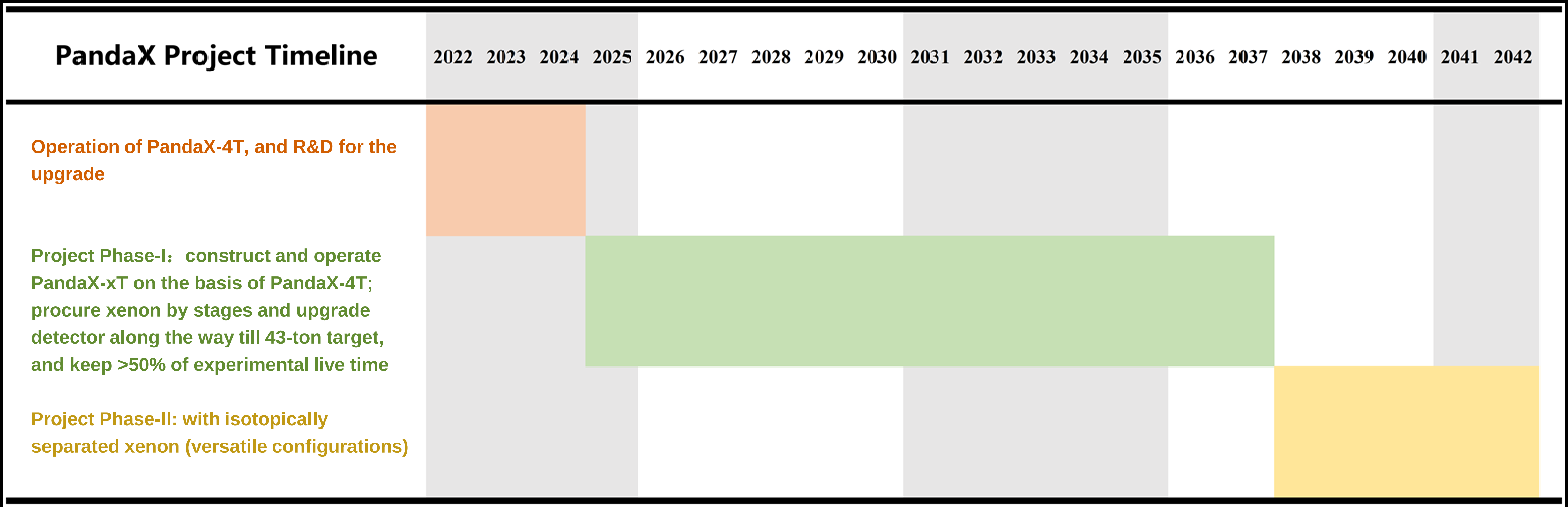


Li, Ramsey-Musolf, Vasquez, PRL 126, 151801 (2021)

Scientific potential

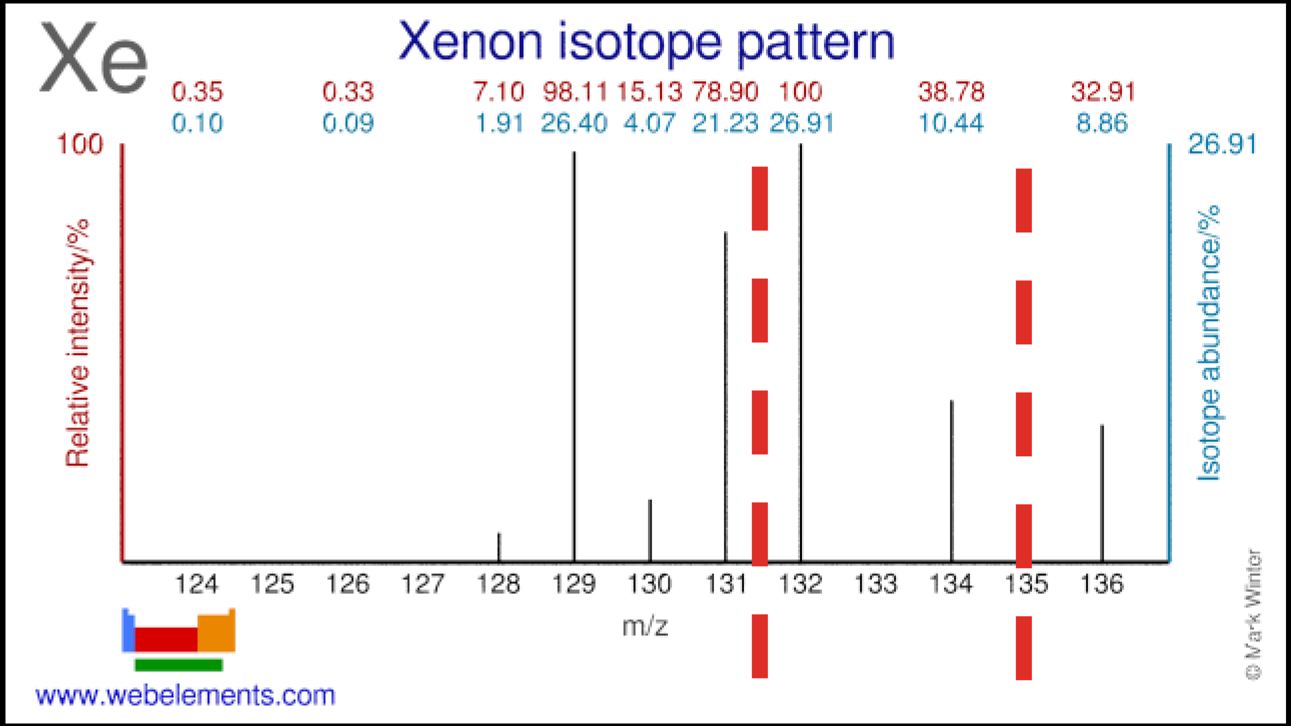


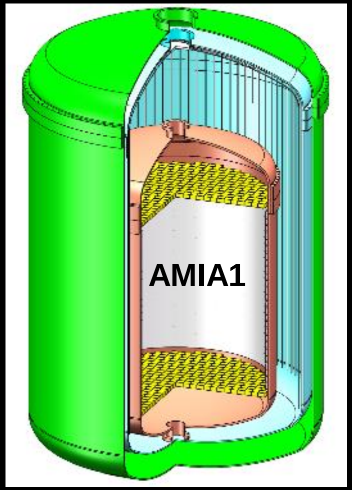
Staged development

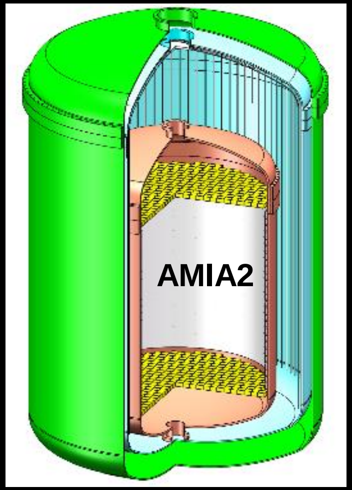


Staged development

- Stage 2: Xenon with artificially modified isotopic abundance (AMIA), either via a split of odd and even nuclei, or further enrichment of ^{136}Xe, to improve sensitivity to spin-dependence of DM-nucleon interactions and NLDBD







Discovery smoking gun！

Summary

- PandaX-4T is a cutting-edge, multi-ton liquid xenon experiment
- Very rich programs in DM and neutrinos
- Background improvement is demonstrated, and is continuing
- Future: a pragmatic approach with a stage-wise upgrade to PandaX-xT aiming for VERY exciting physics
- Highly welcome collaborators and new theoretical ideas

Thank you!