PandaX: Status and Prospects

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State key Laboratory of Dark Matter Physics

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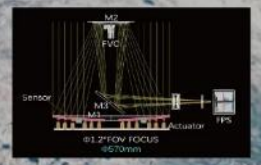
Shanghai Jiao Tong University

Tsung-Dao Lee Institute, headquarter of PandaX

科研版图 EXPERIMENTAL PLATFORMS AND REMOTE OBSERVATION SITES

青海冷湖 JUST光谱望远镜
JUST Spectroscopic Telescope
Lenghu, Qinghai

- 4300米海拔，4.4米口径双焦点
  4.4m diameter, dual focus located 4300m above sea level
- 国际最优视宁度条件，中位值0.75角秒
  One of the best sites with clean, photometric conditions
- 探索黑暗和动态的宇宙
  Explore dark and dynamic universe



2800km

2000km

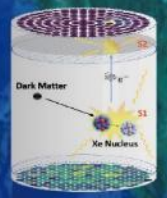
2000km

上海张江 大本营实验平台
Research Platforms
Shanghai

- 实验室天体物理实验平台，瞬间磁场10^{10}G,电场10^{13}V/cm
  Platform for Laboratory Astrophysics
- 拓扑材料研究实验平台，STM实空间分辨率高于0.5纳米
  Platform for Topological Materials
- 大规模科学计算平台，总算力6PFLOPS
  Platform for High-Performance Computing

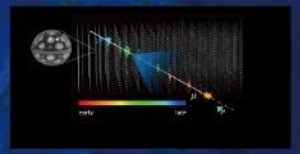
四川锦屏 PANDAX暗物质与中微子探测装置
PandaX Dark Matter and Neutrino Detector
Jinping, Sichuan

- 数十吨级PandaX液氙探测器
  Tens of Tonnes scale PandaX liquid xenon detector
- 2400米岩石覆盖，国际最深，缪子通量<10^{-10}/秒/厘米^2
  The deepest underground lab with a depth of 2400m
- 以极低的本底探测暗物质和中微子信号
  Dark matter and neutrino detection at extremely low background



海南南海 TRIDENT中微子望远镜
TRIDENT Neutrino Telescope
West Pacific Ocean

- 3500米深海下4km*4km*0.5km的切伦科夫光探测阵列
  4km*4km*0.5 km Cherenkov Telescope Array at 3500m depth
- 探测能量、指向能力、角分辨率、灵敏度较第一代中微子望远镜提高一个数量级
  Capture high-energy cosmic neutrinos
- 探索极端天体环境下的宇宙射线起源及基本物理规律
  Explore the origin and fundamental laws of cosmic rays under extreme astronomical environments

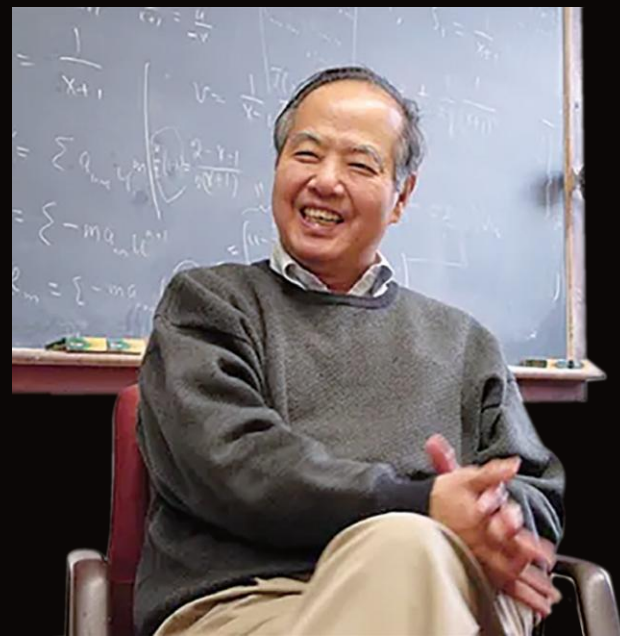


永兴岛
Yongxing Island

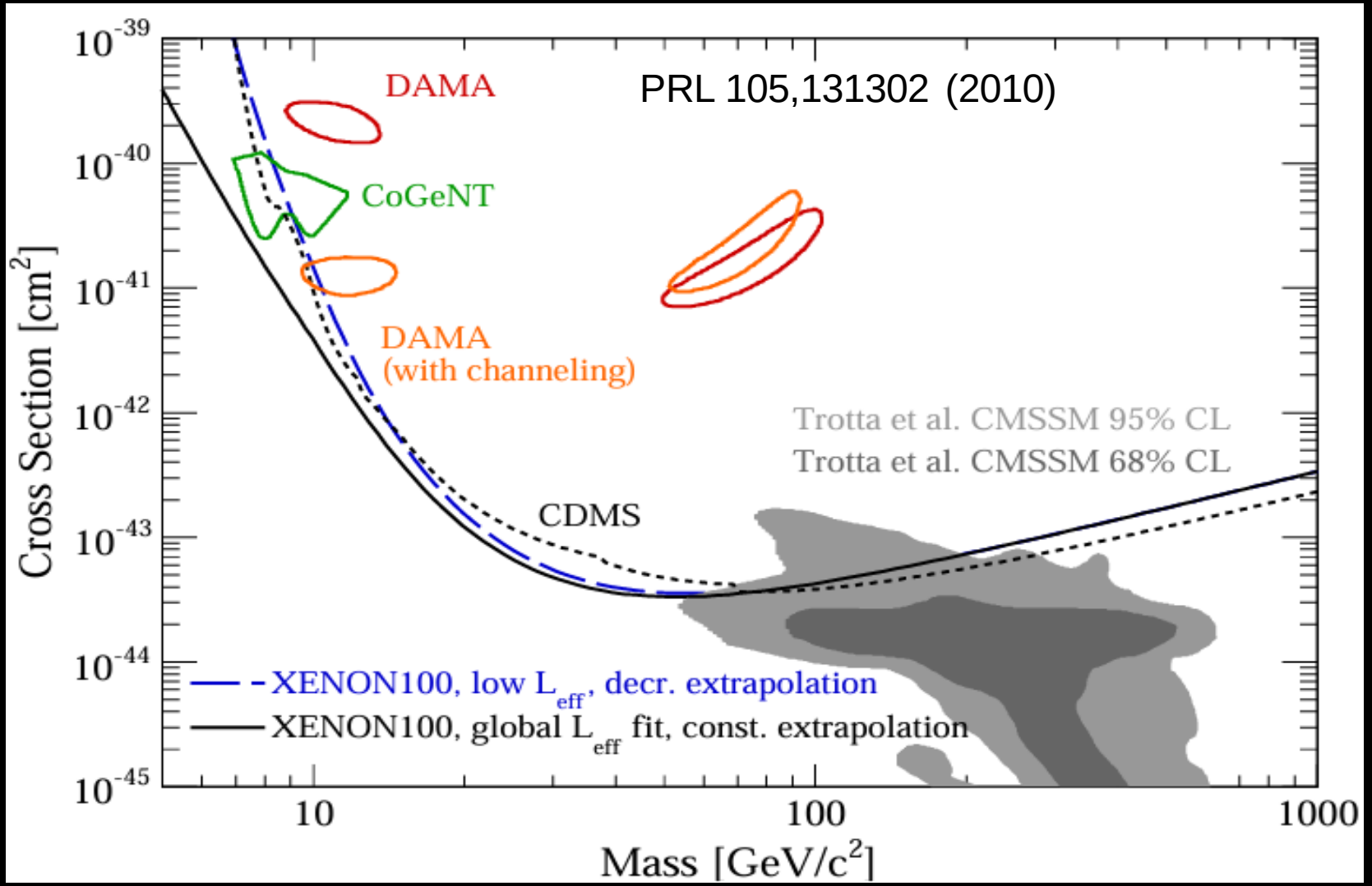
挑战根本性科学问题
Address the most fundamental science challenge

- 极端宇宙条件下物质的起源与演化
  The origin and evolution of matter under extreme cosmic conditions

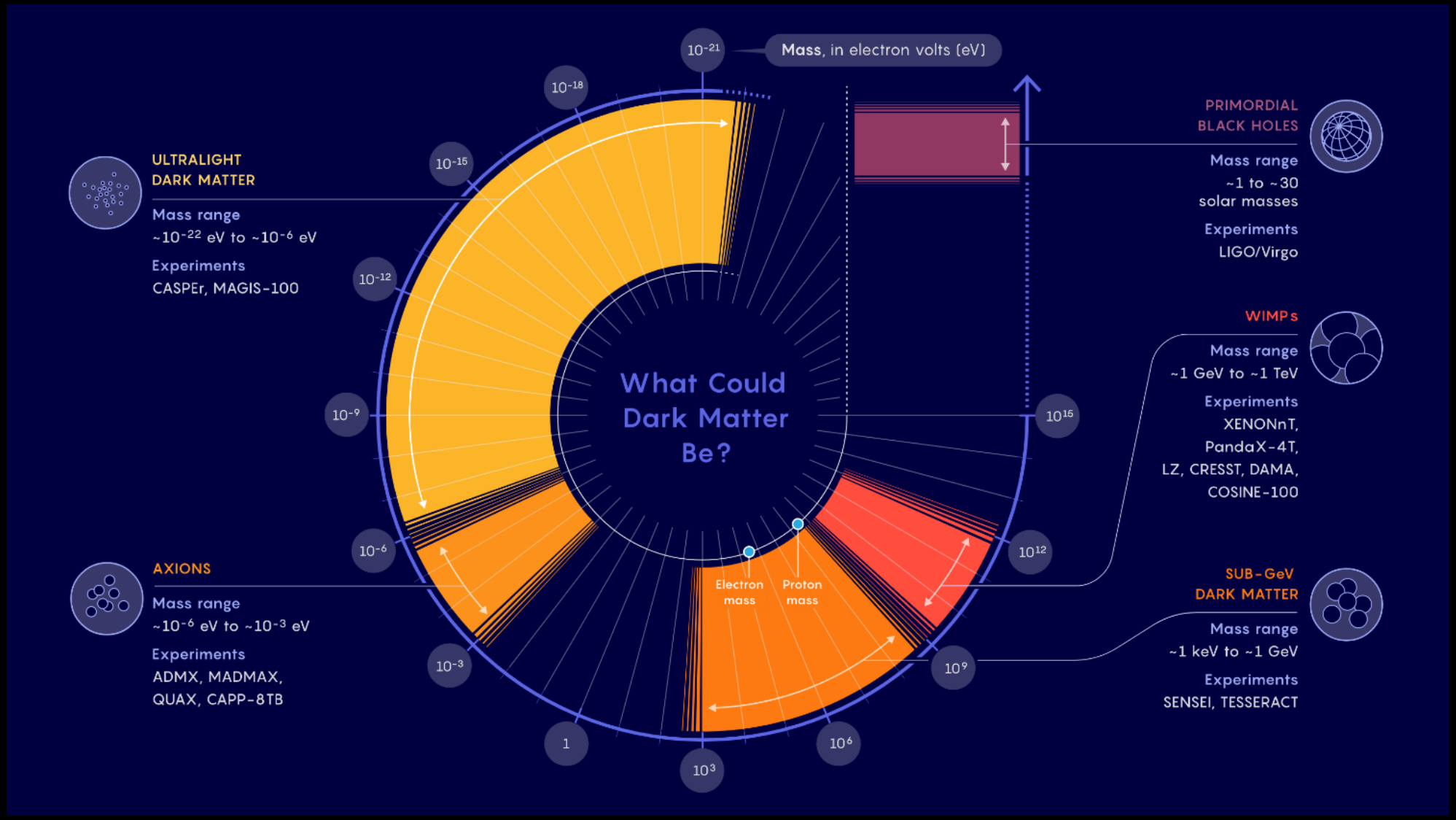
利用专用科学装置群的极端探测能力 发挥有组织科学研究的优势
Coordinated research with experts from different research areas utilizing our state-of-the-art facilities



DM: low hanging fruit?



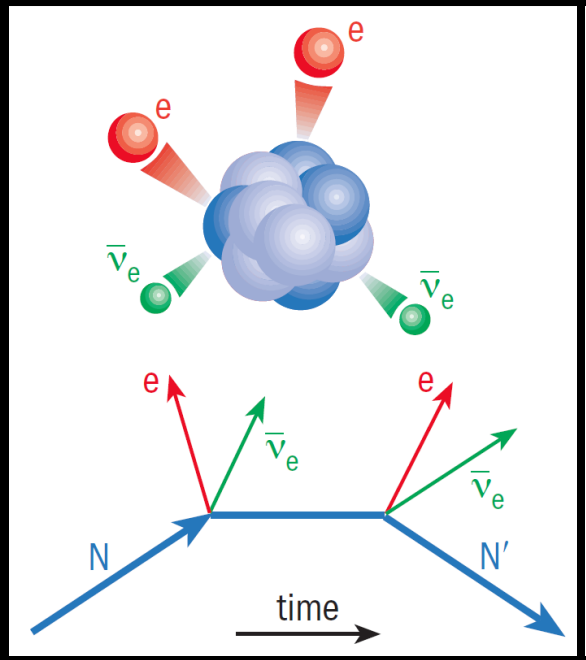
DM: low hanging fruit?

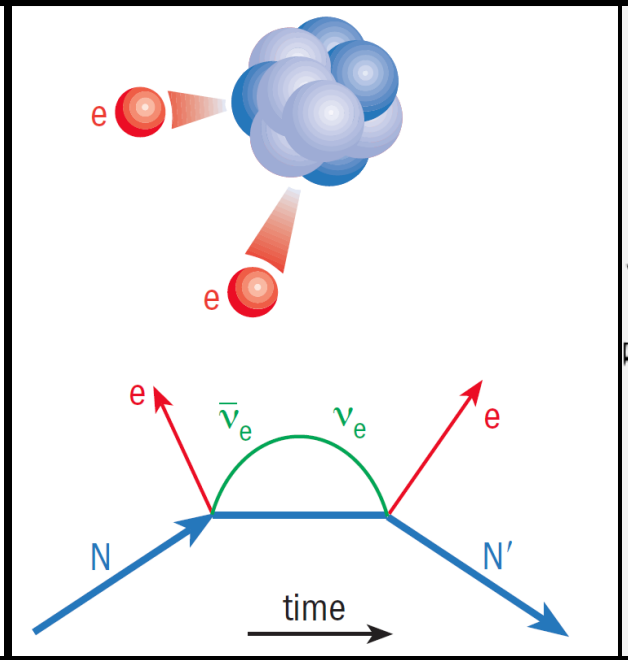


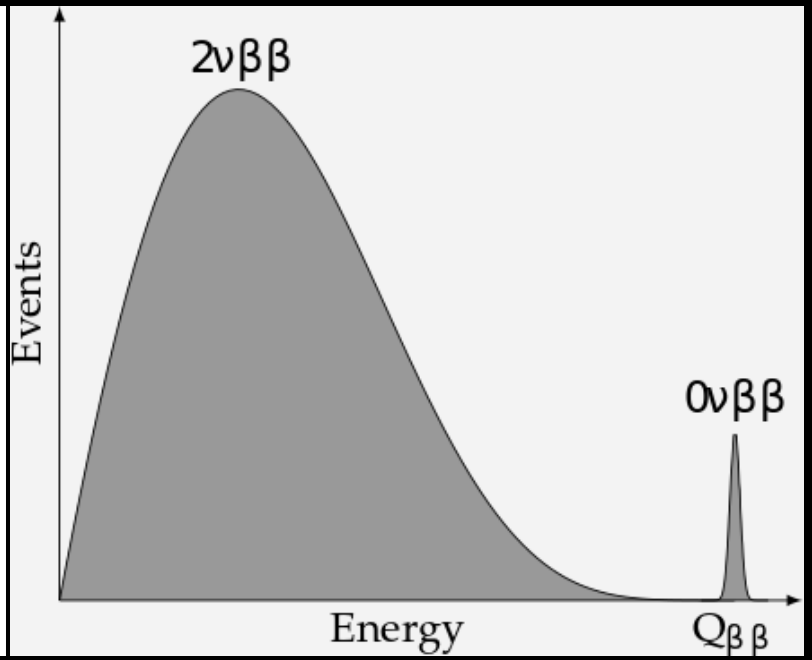
Neutrinos are Dirac or Majorana?

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

Neutrinoless double-β decay (0vDBD)







From Physics World

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

Particle and Astrophysical Xenon observatory

2009.3 Collaboration formed

2012.7 PandaX-I started

2014.3 PandaX-I apparatus moved to Jinping

2014.5-10 PandaX-I, 120 kg operation

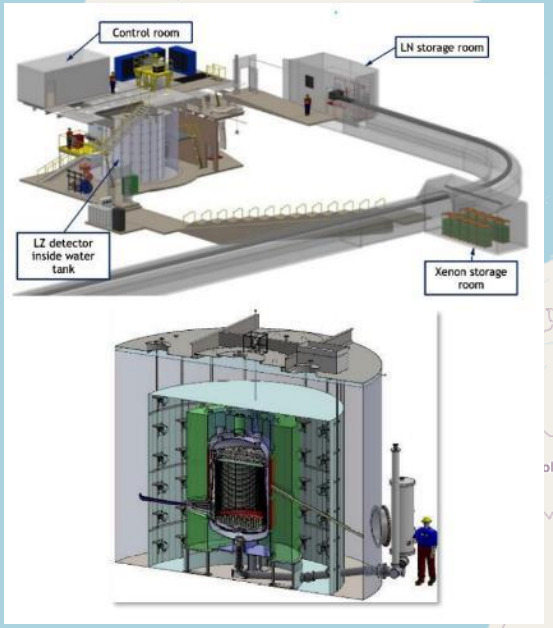
2016.7-2019.7 PandaX-II, 580 kg operation

2019.8- PandaX-4T moved to CJPL-II

PandaX Collaboration

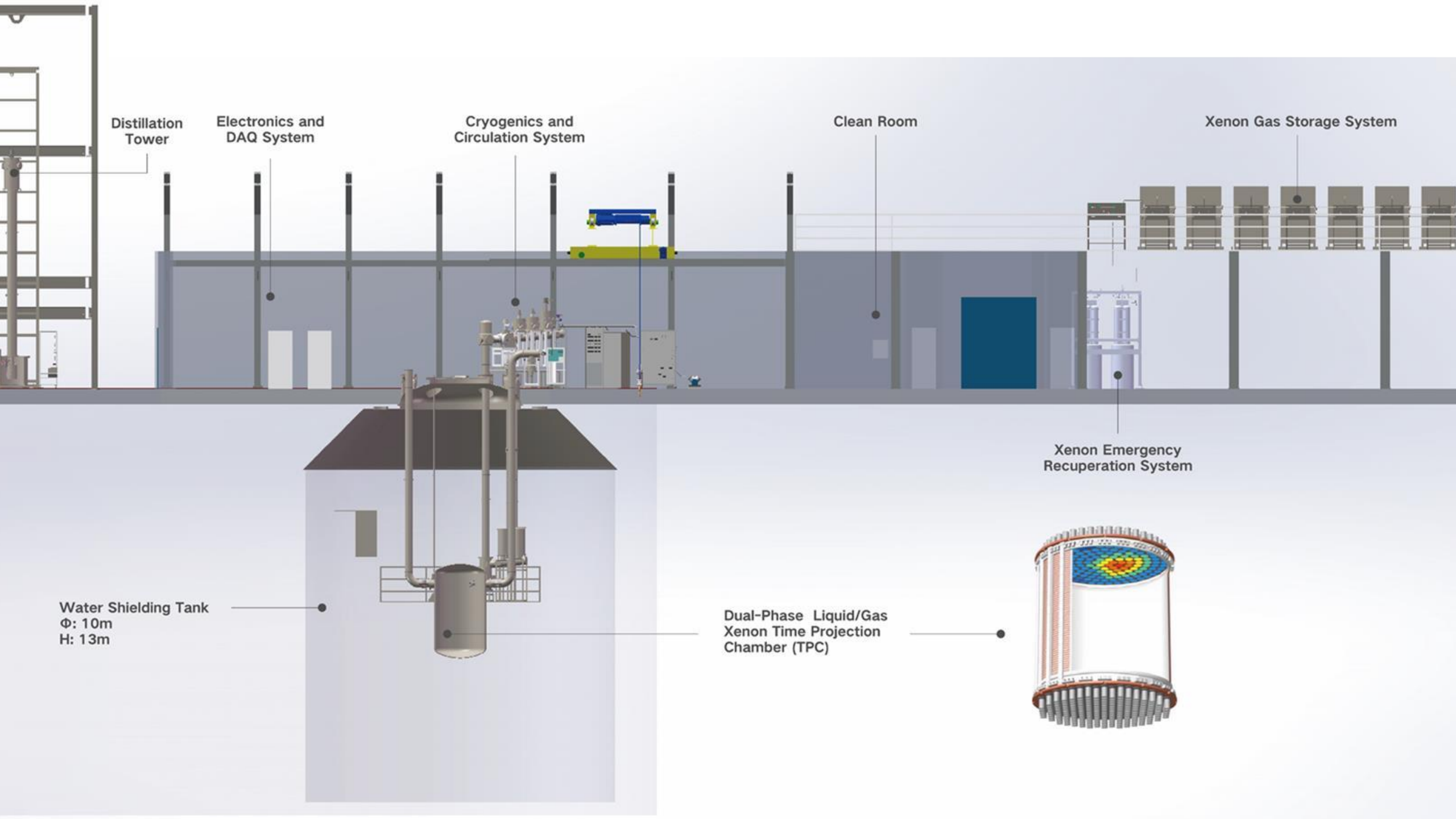
Global context

LZ



XENON

PandaX

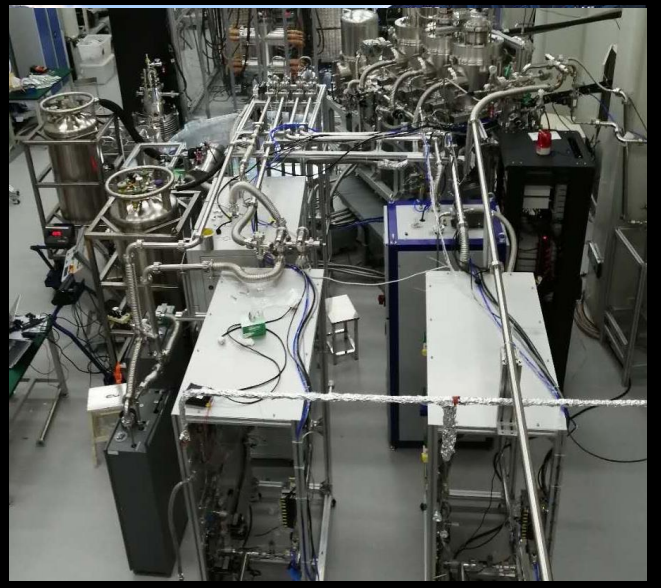

Distillation Tower
Electronics and DAQ System
Cryogenics and Circulation System
Clean Room
Xenon Gas Storage System
Xenon Emergency Recuperation System
Water Shielding Tank
Φ: 10m
H: 13m
Dual-Phase Liquid/Gas Xenon Time Projection Chamber (TPC)

2018.4 water tank construction

2019.8 PandaX-4T instllation

2020.5 liquid xenon filling

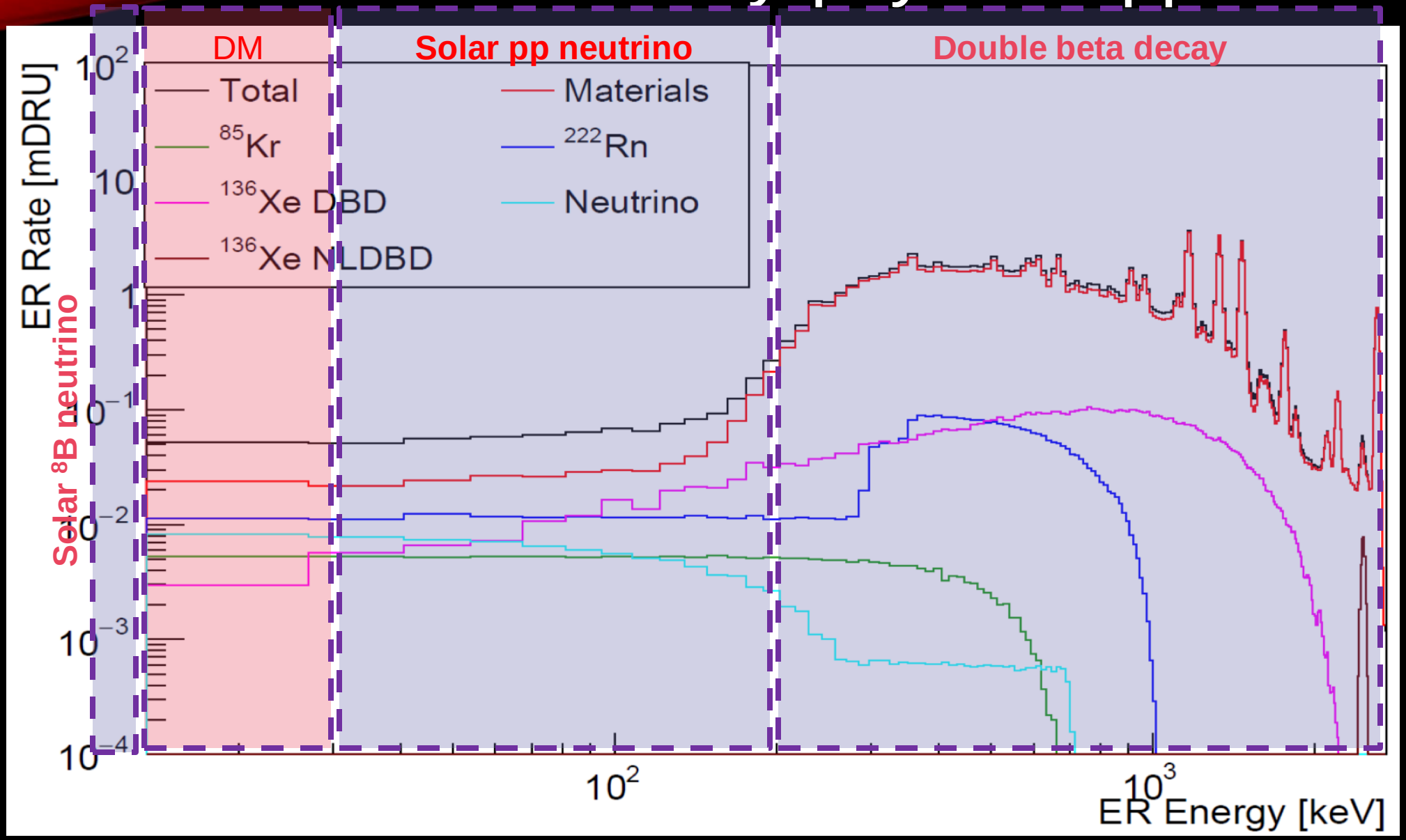
2020/6-2020/11 integration tests

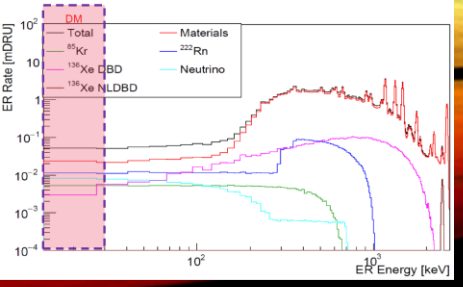


Data taking interleaved with surgeries and lab construction

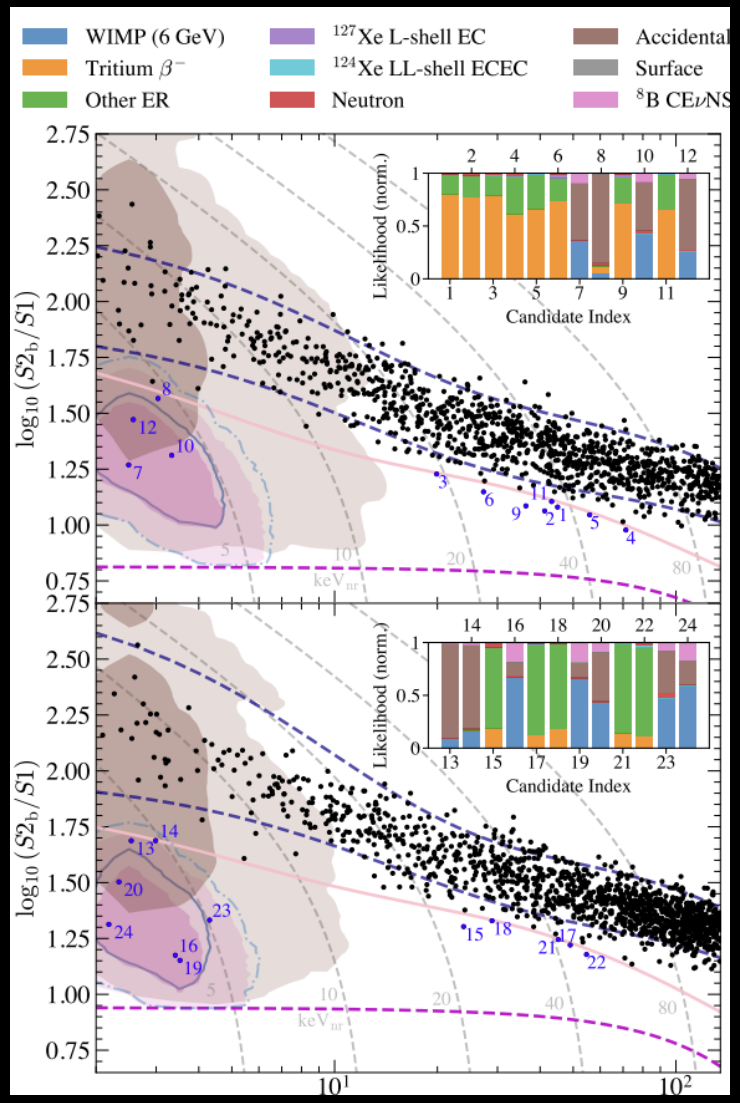
Time	Activity
2020/11-2021/04	commissioning (Run0) 95 days
2021/07-2021/10	tritium removal xenon distillation, gas flushing, etc.
2021/11-2022/05	physics run (Run1) 164 days
2022/09-2023/12	CJPL B2 hall renovation xenon recuperation, detector upgrade
2024/01-2024/07	resuming operation
Current status	physics data taking (Run2)

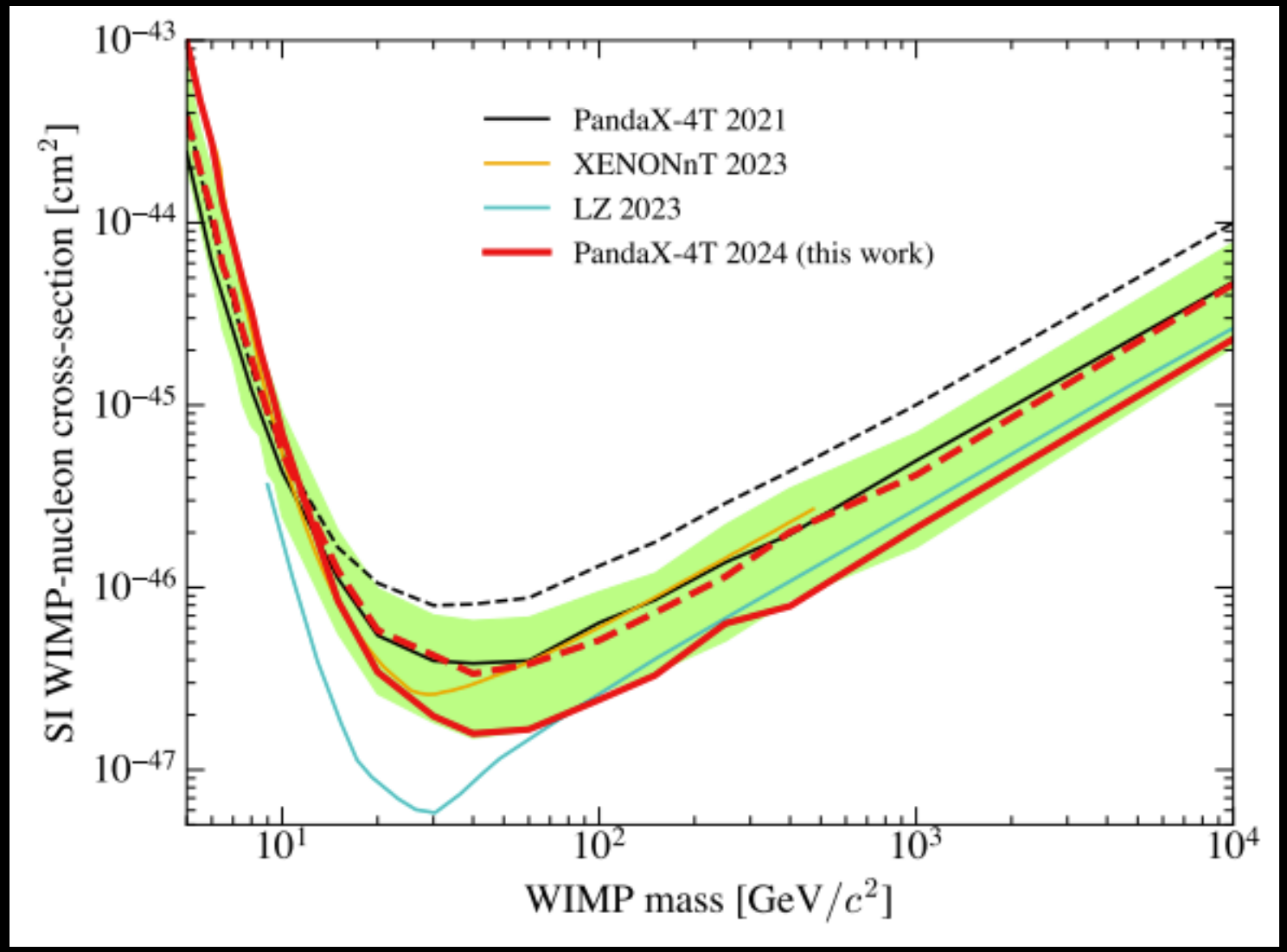
Many physics opportunities



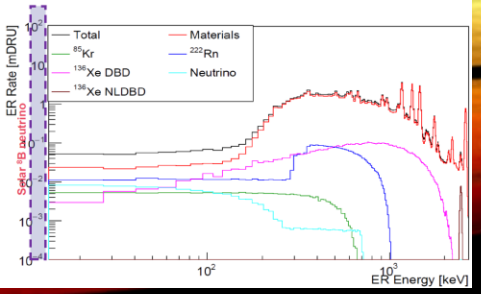


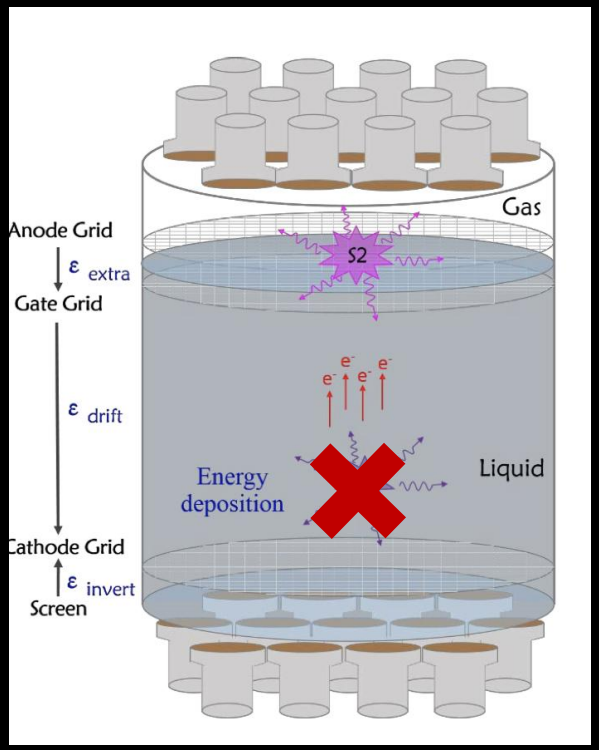
1.5 tonne*year, blinded analysis, Run0+1

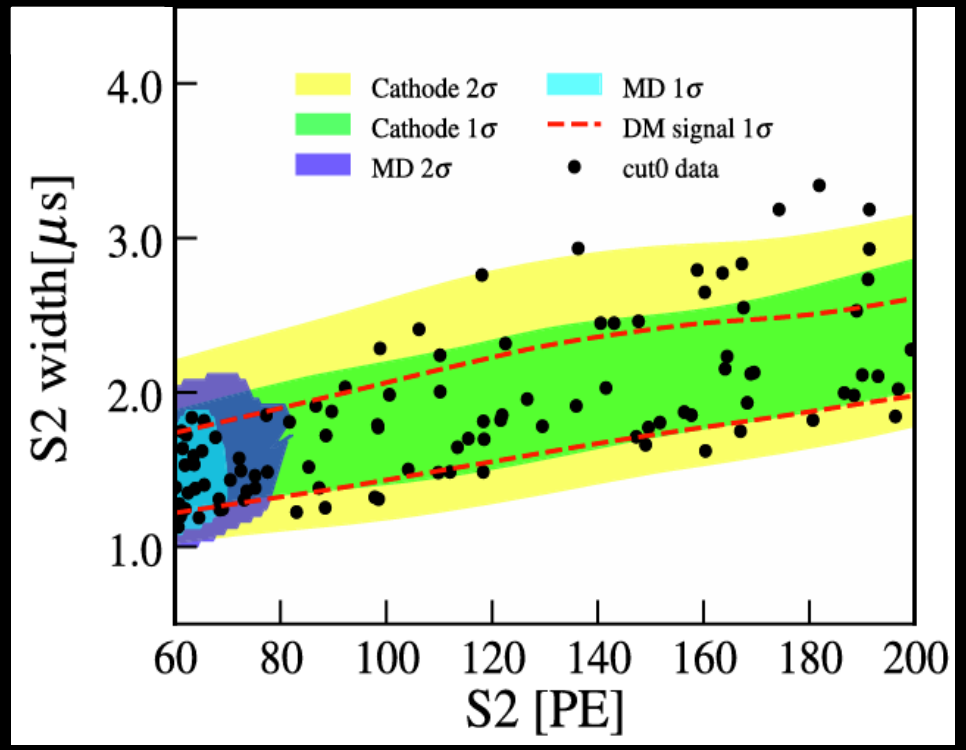


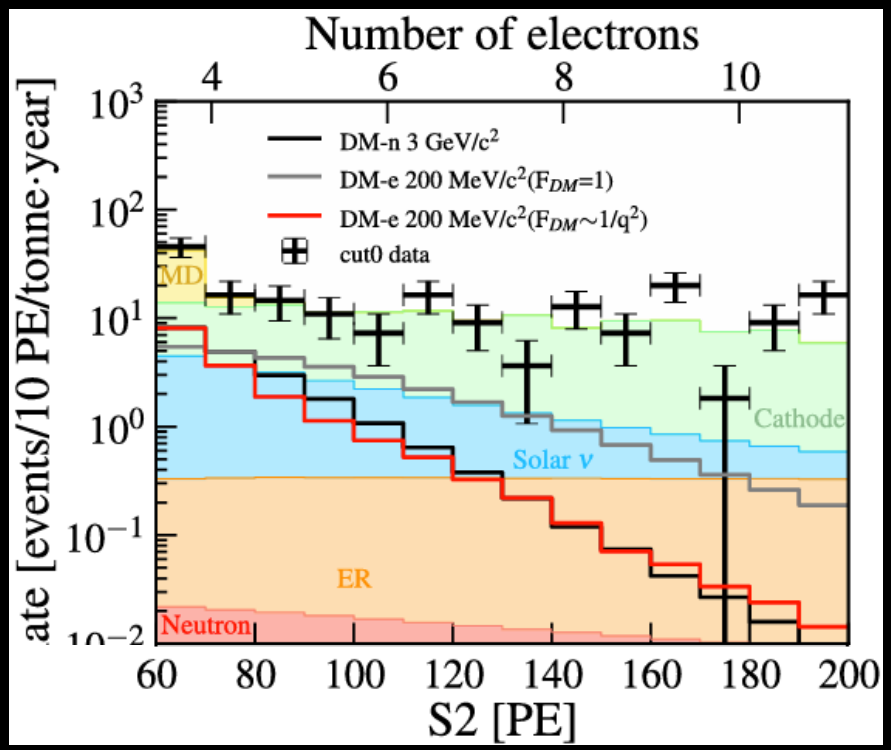


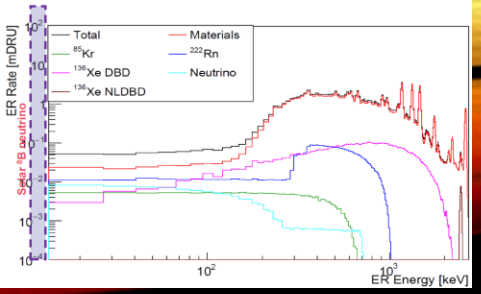
S2-only approach





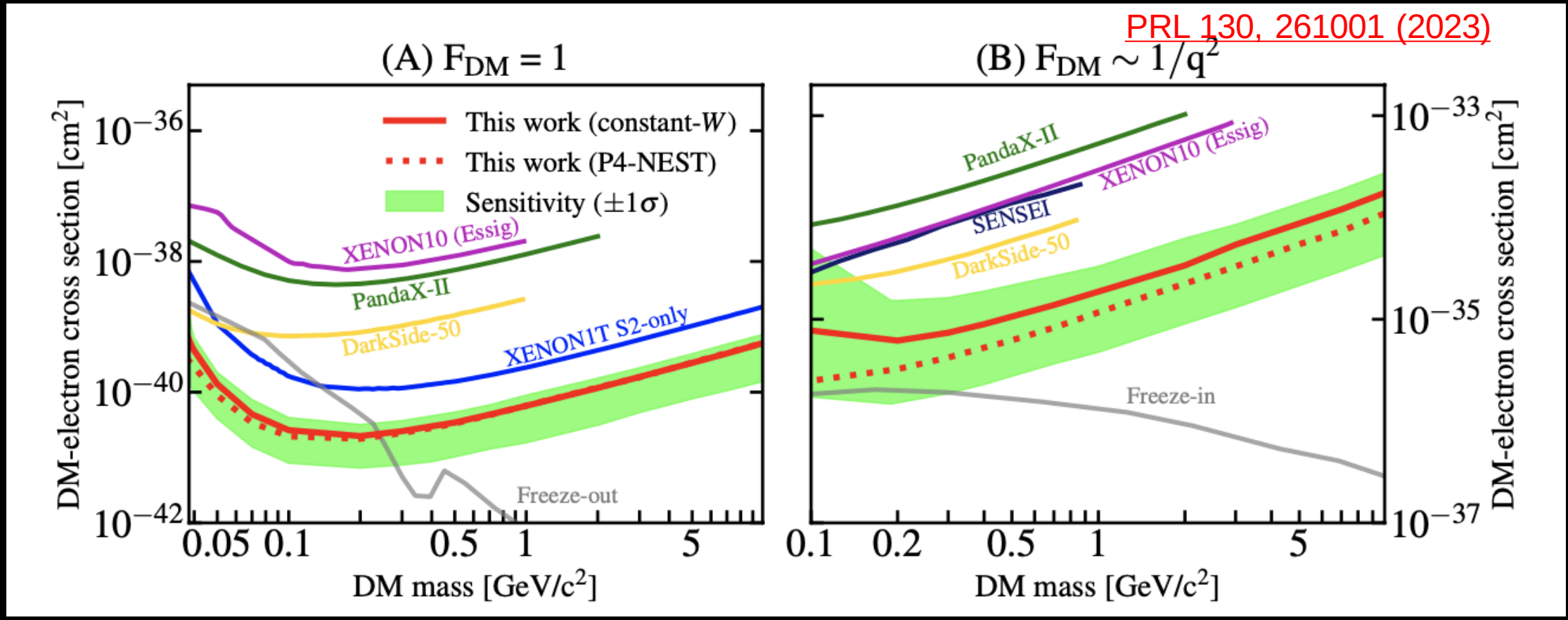




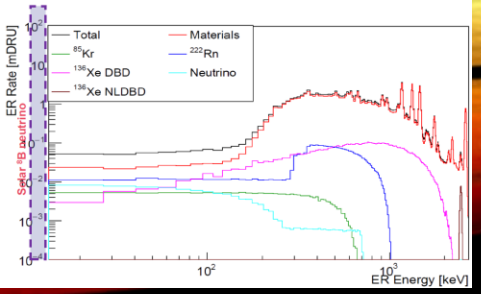


Tight limits on DM-e scattering with S2-only analysis

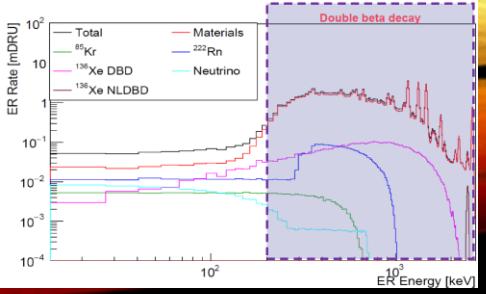
PRL 130, 261001 (2023)



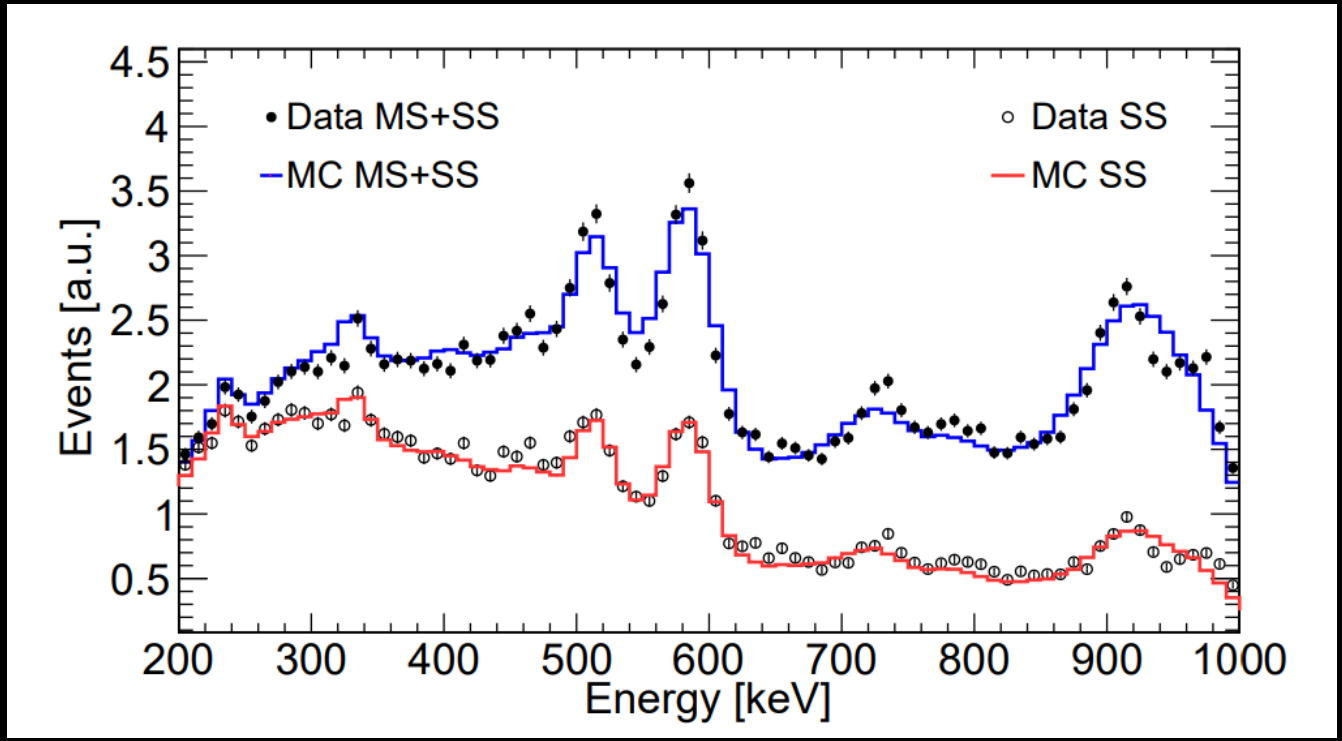
B8 neutrino CEvNS



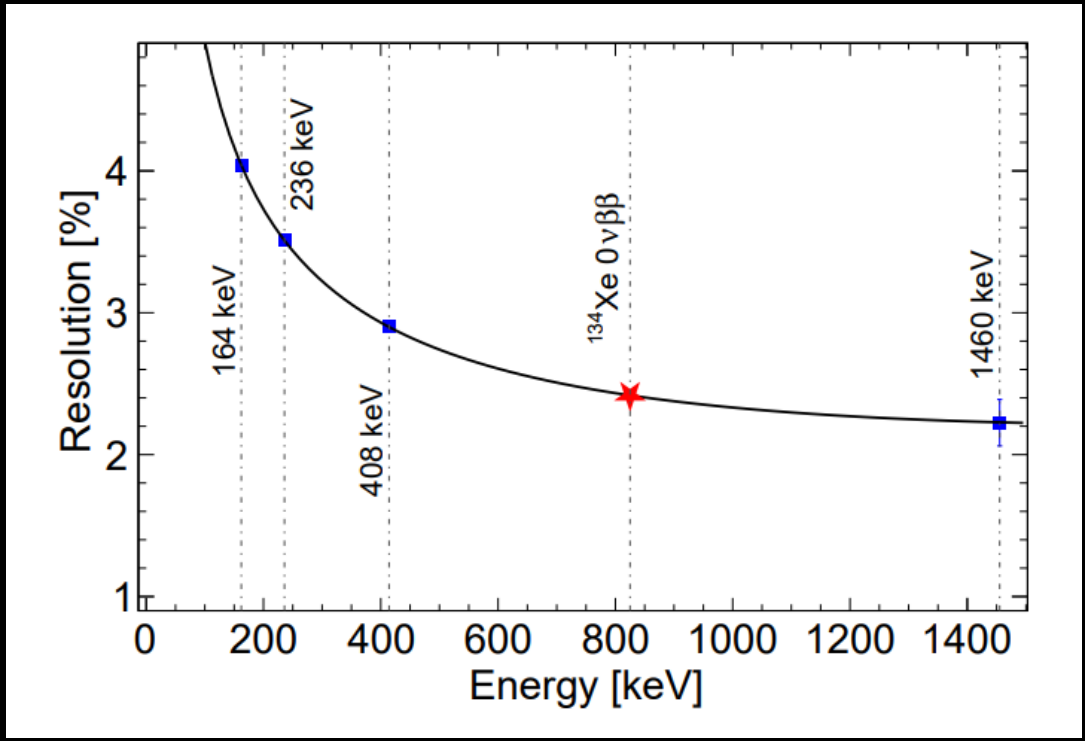
- Greatly benefit from S2-only data (~ton×year)
- Best-fit B8 events: 75±28 (S2 only) and 3.5±1.3 (S1+S2 paired)
- Reject ba
- PRL 133,
- XENONn



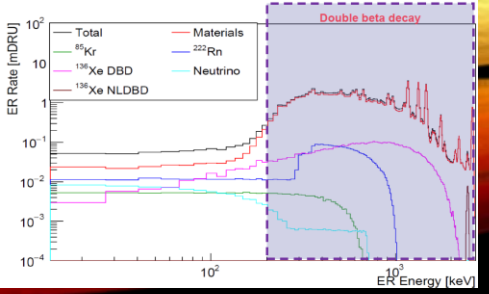
Calibrating PandaX at MeV



Th232 gamma calibration data

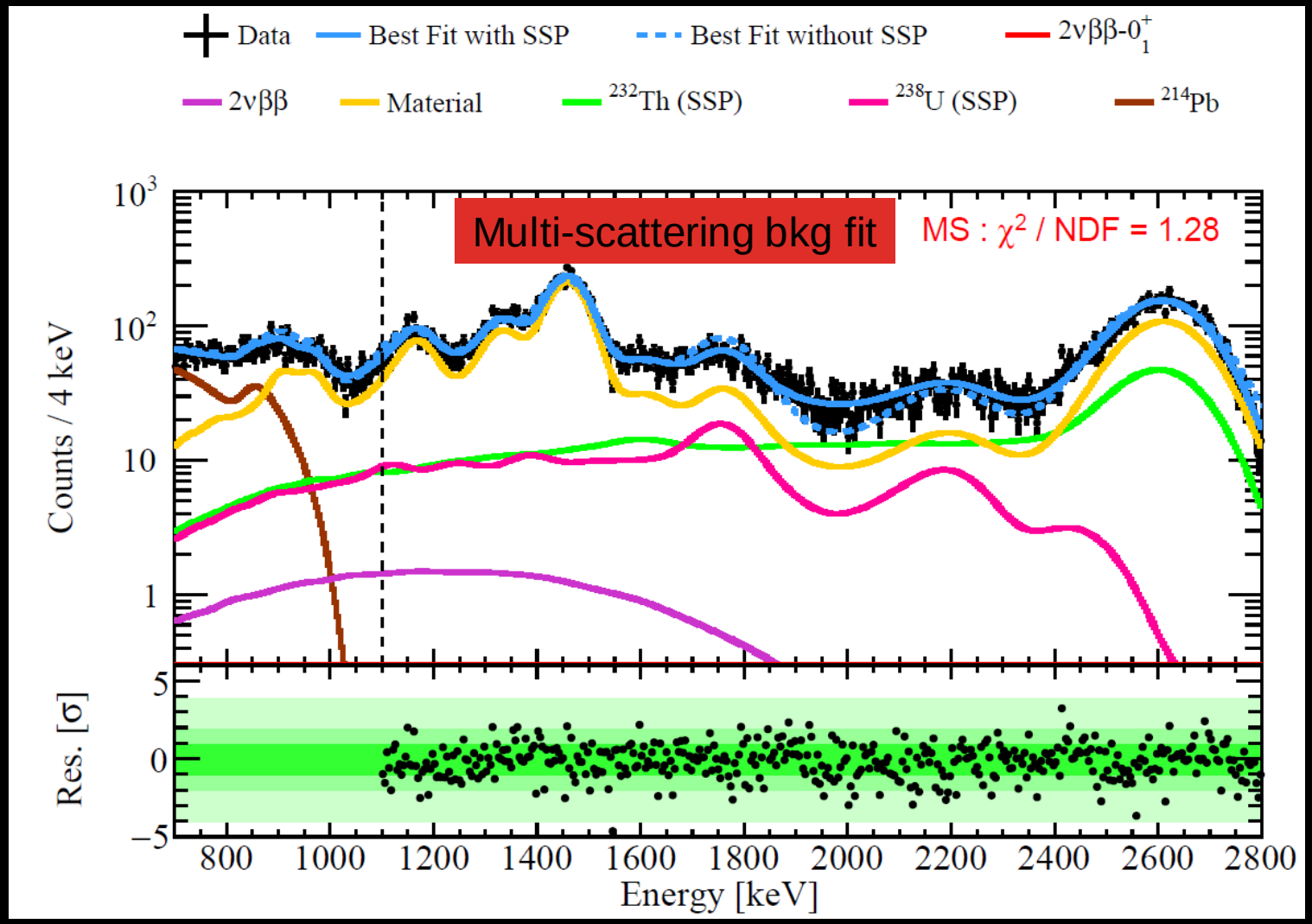


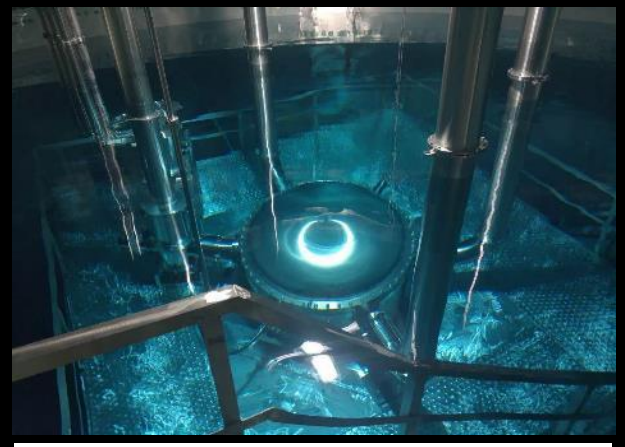
Internal gamma peaks



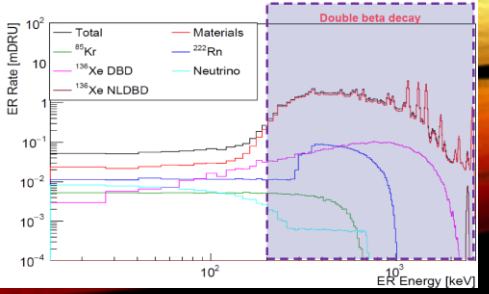
Understanding background at MeV

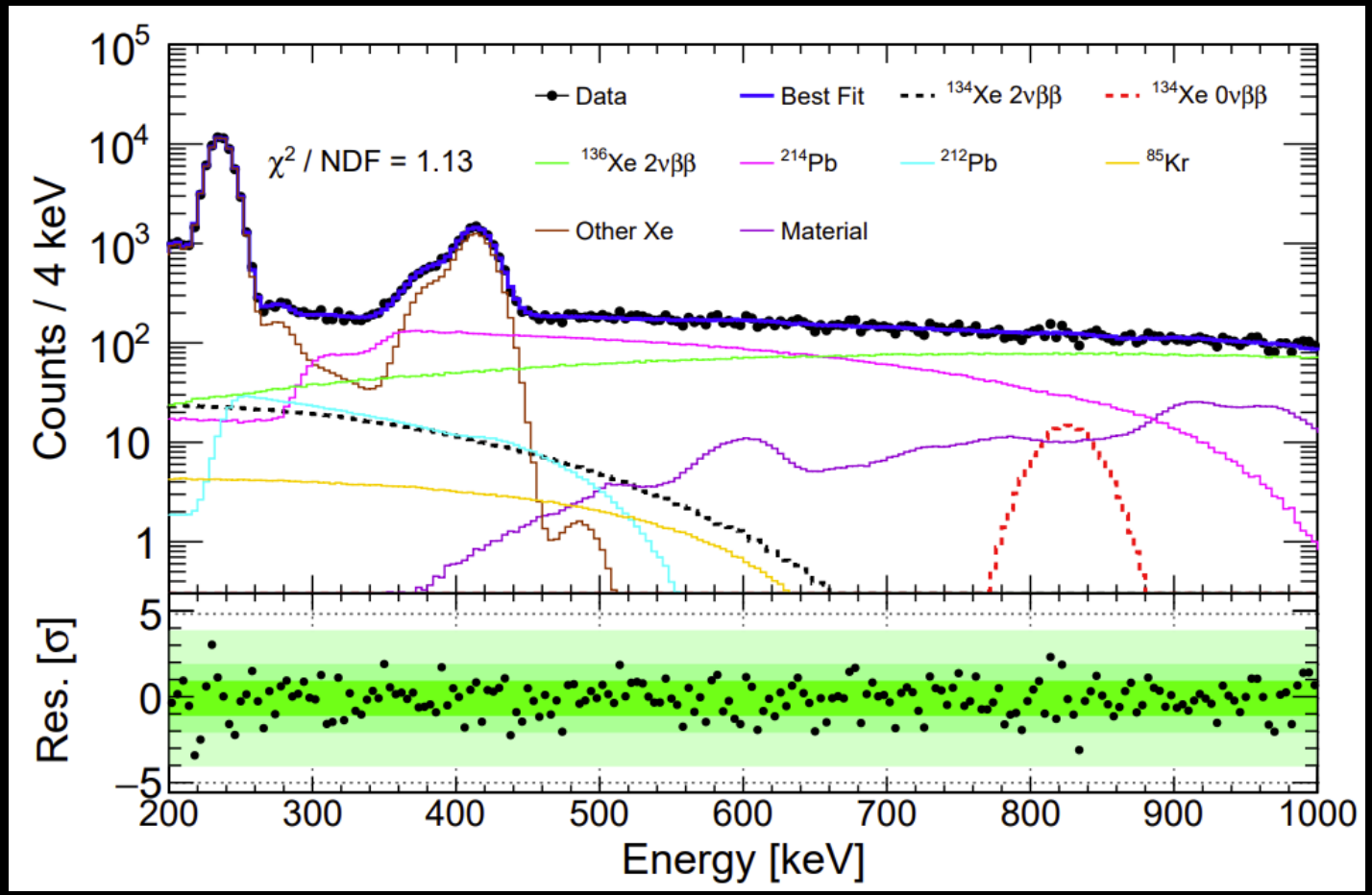
JHEP 05 (2025) 089, arXiv:2502.03017

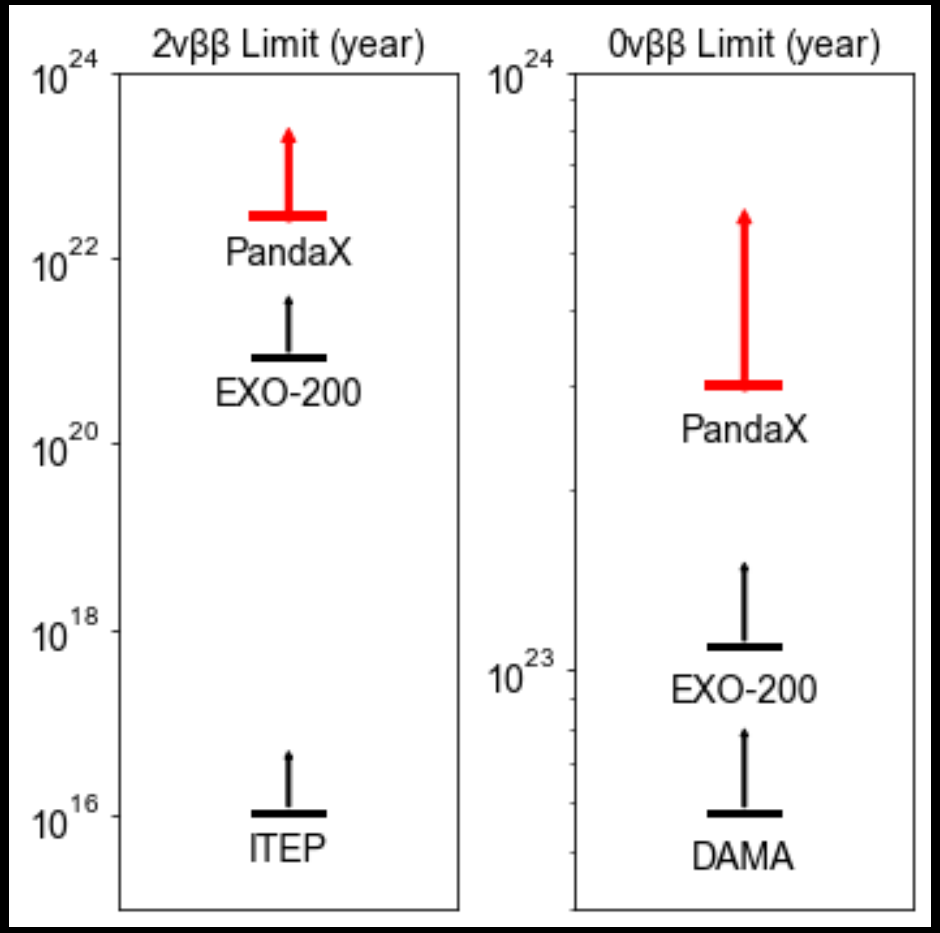




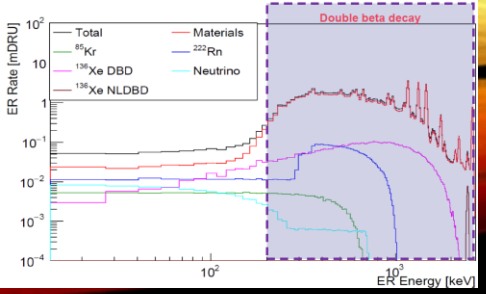
^{134}Xe: a unique blessing

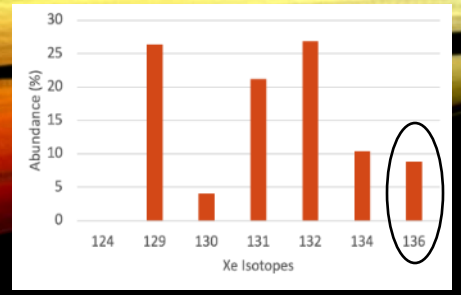




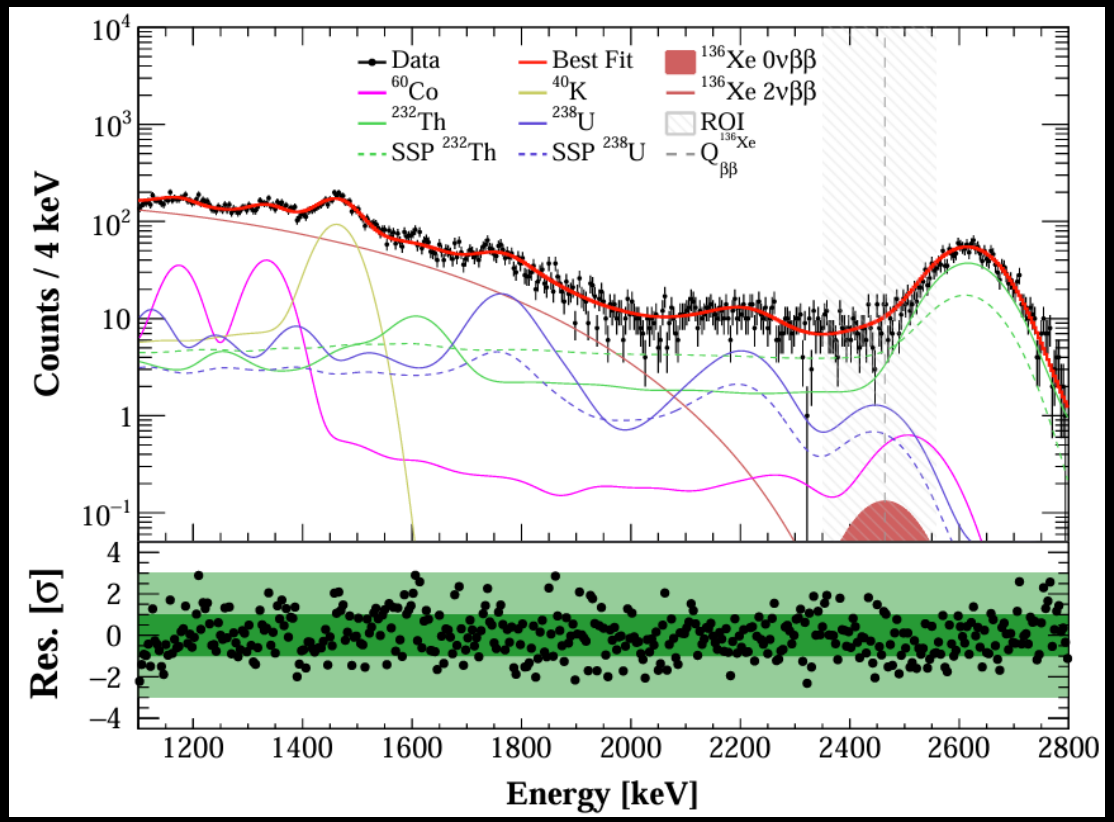


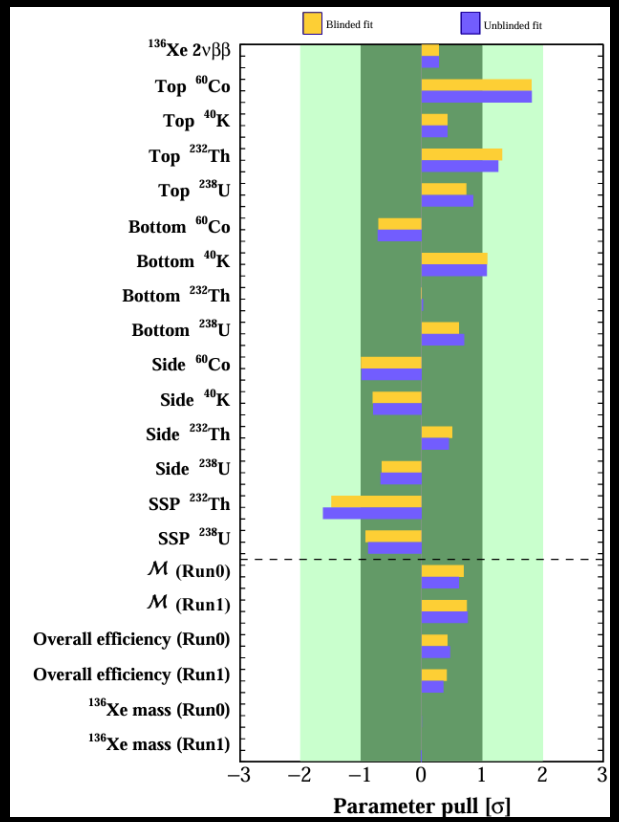
PRL 132, 152502 (2024)





Search for Xe136 0vDBD

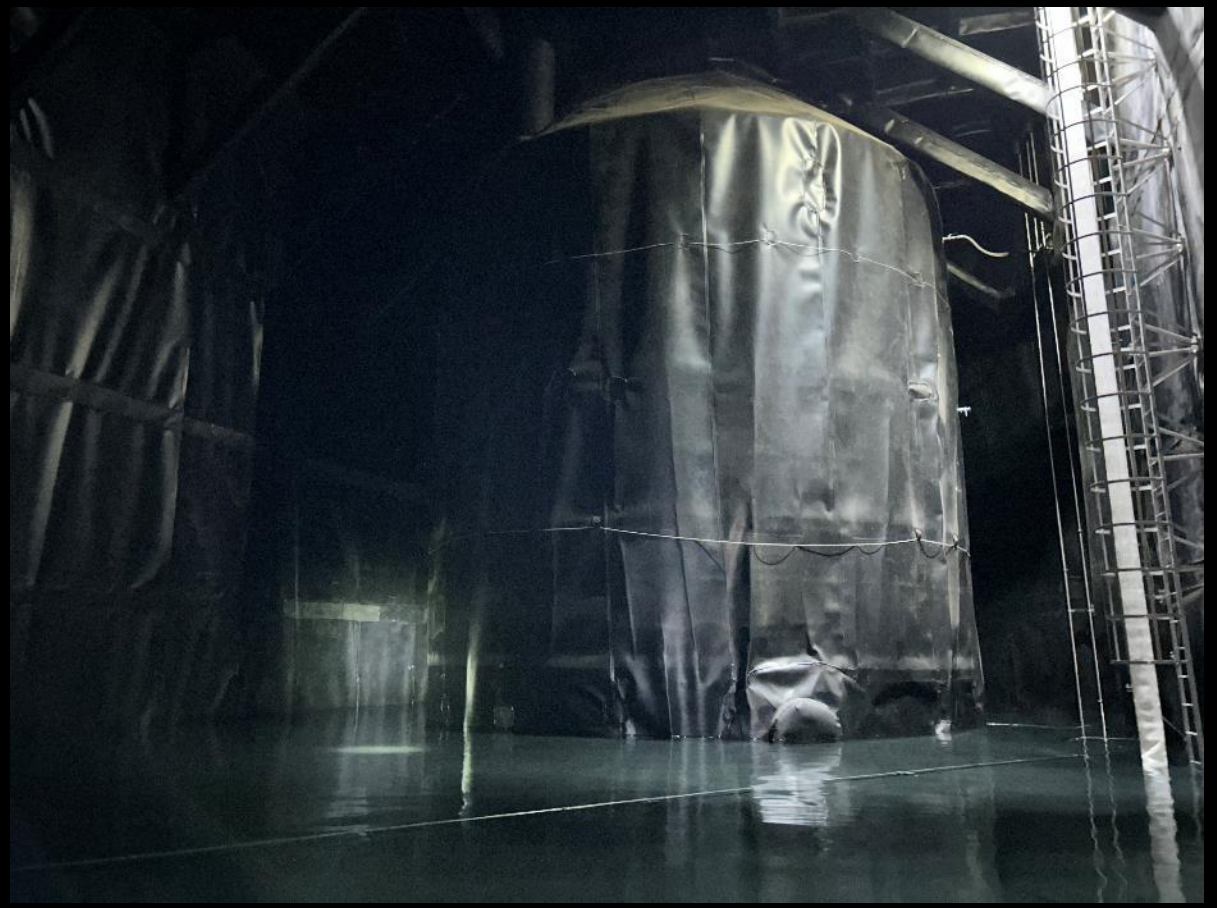




Science Bulletin Vol. 70,11 (2025)
arXiv:2412.13979

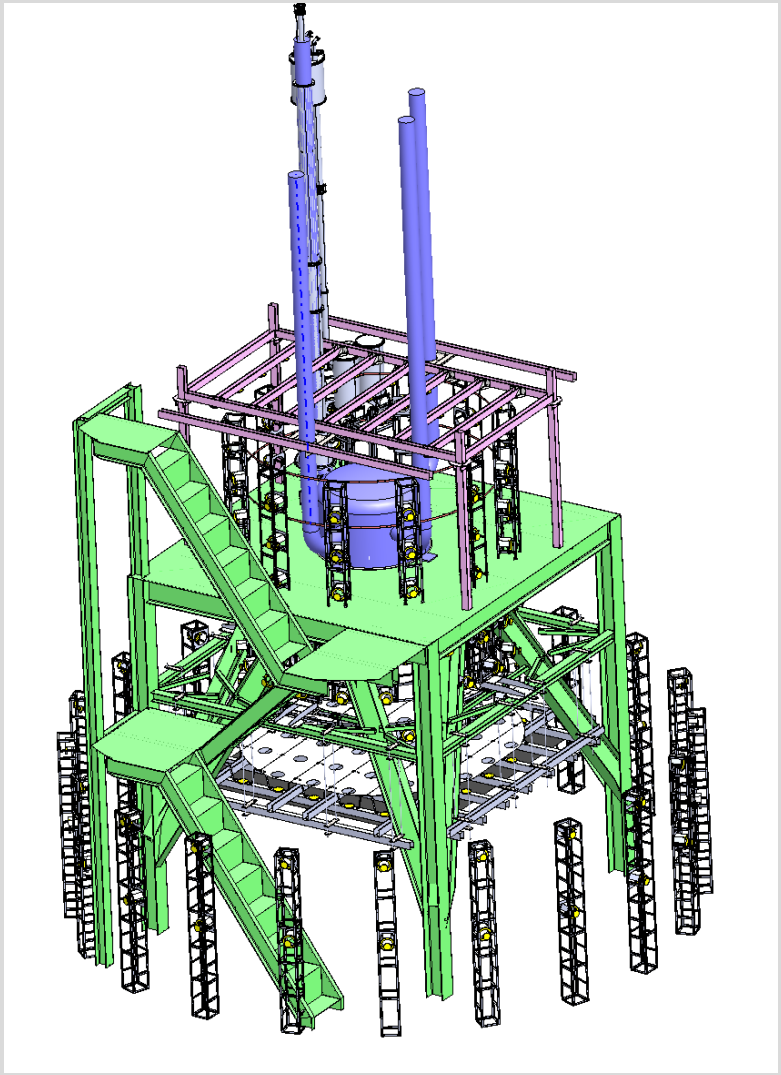
Lifetime
$> 2.1 \times 10^{24}$year
90% CL
$m_{ββ}$<0.6-1.4 eV

2024: Shiny again!



Newly implemented water veto detector

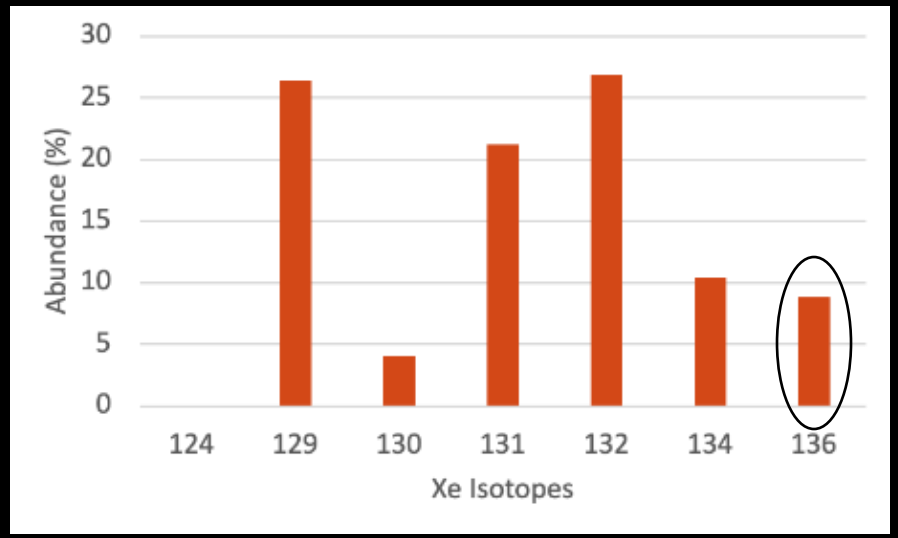
- installed 270 8-inch PMTs in late 2023
- inner layer: 2 m radius, about 1 m to the outer surface of the LXe cryostat
- outer layer: 5 m radius
- Seeing muons, seeing neutrons !
- Future: directly measure atmospheric neutrinos with 4000-ton water detectors



PandaX-xT

$$Sensitivity \propto \sqrt{\frac{B}{Mt}}$$

B = bkg rate in ROI per unit target mass



A multi-ten ton liquid xenon project at CJPL-II

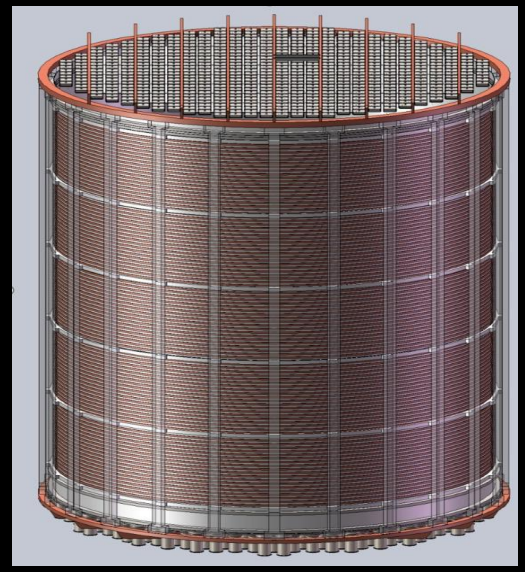
1. Searching for DM-nucleon interactions to neutrino floor, a decisive test on WIMP paradigm
2. A sensitive test on Majorana nature of neutrinos using the 0vDBD of ^{136}Xe, covering inverted neutrino MO parameter space
3. Detecting low-energy neutrinos from the Sun and other astrophysical and terrestrial origins, and exploring other ultra-rare signals.

Next Generation Xe

PandaX-xT: step-wise strategy to a 40-ton-scale LXe observatory at CJPL

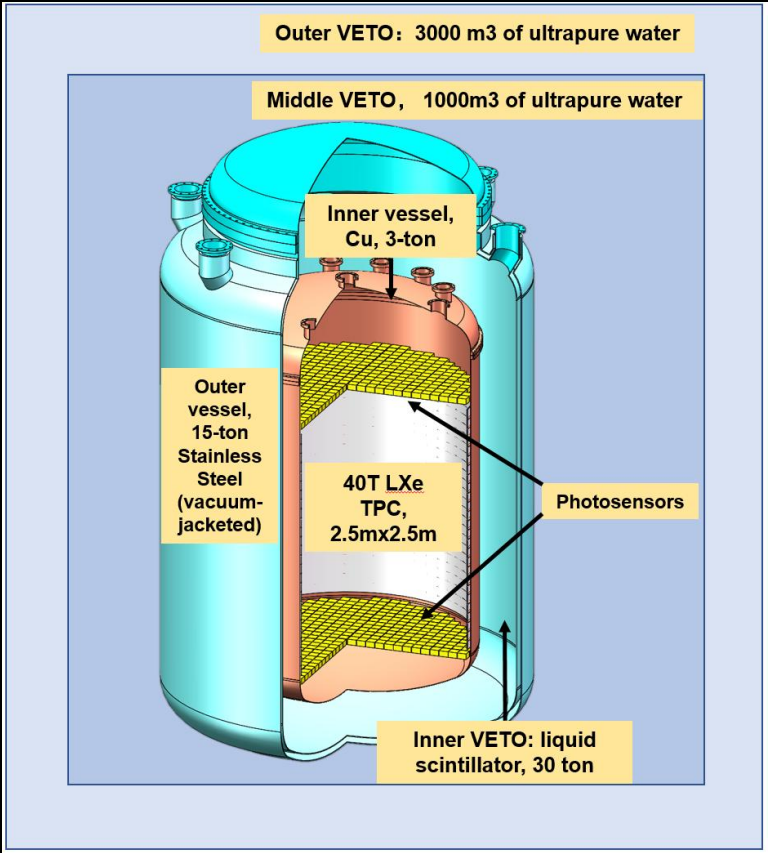
PandaX-4T

PandaX-20T (2027, mostly funded)



PandaX-40T

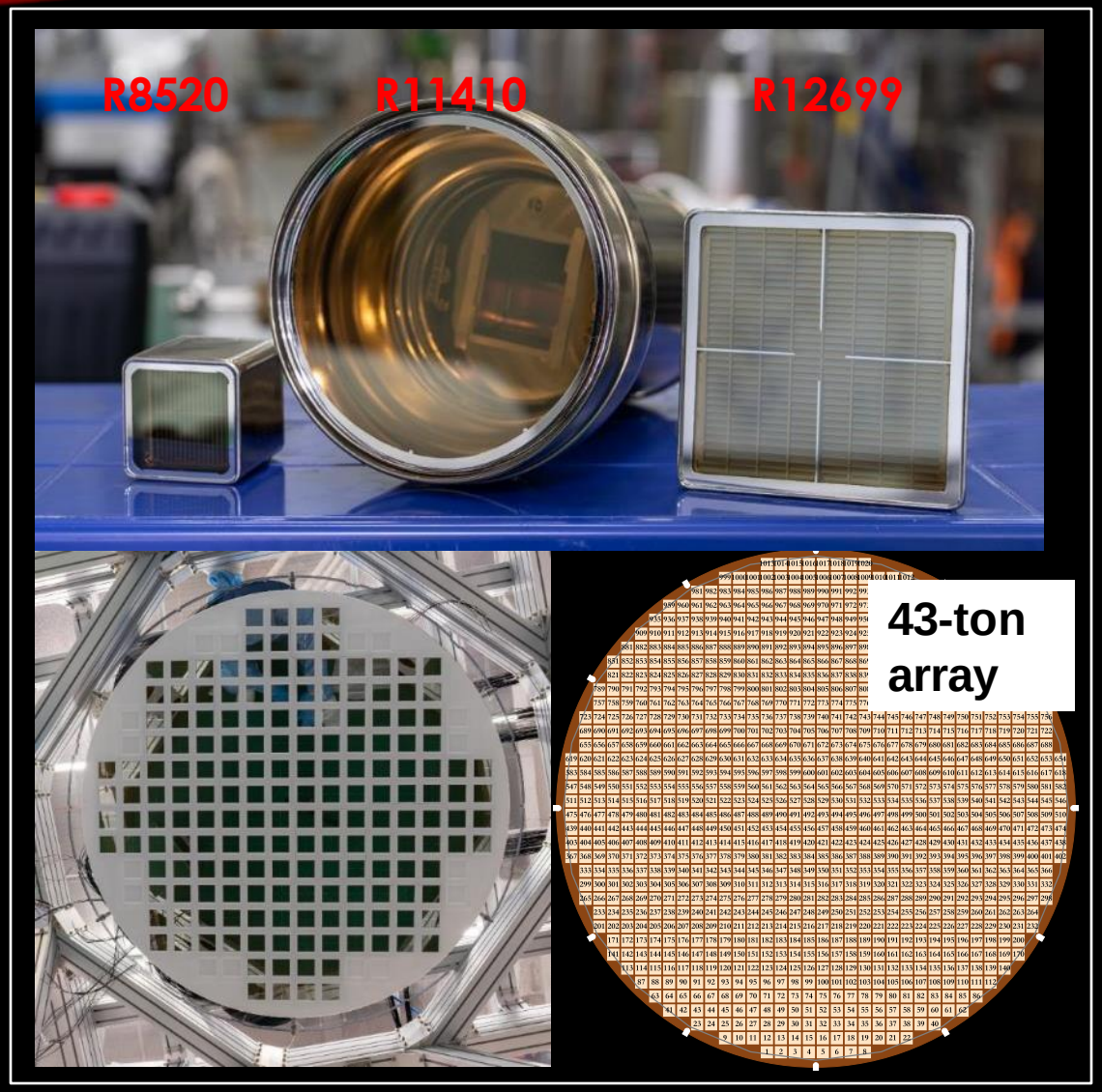
PandaX-20/40T @ CJPL



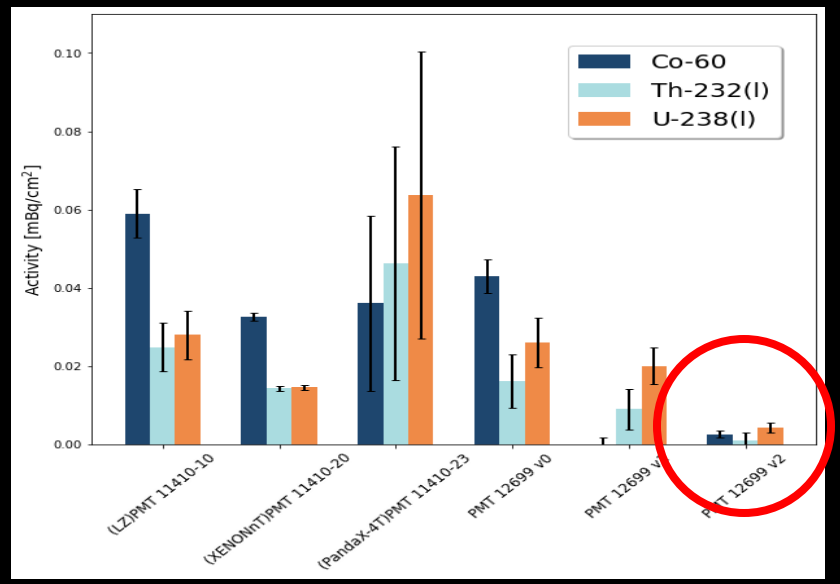
TPC development

- Field cage: Kapton film with copper embedded
- Supporting structure: low radioactivity PMMA (developed in JUNO) or PTFE
- 400 kg prototype TPC under construction @TDLI
- 2.6 m electrodes built and tested

New photosensors



- 10 m^2 top/bottom coverage
- Hamamatsu R12699 (2”x2”), iterated two versions (v1/v2)
- Dark noise <10 Hz/channel，QE @178 nm > 30%
- arXiv:2412.10830, NIMA



Liquid xenon storage and handling

Each storage tank: 6-m^3 (maximum 18 ton) of LXe

Cryogenic pump: filling/emptying detector @ 1.5 ton/hour.

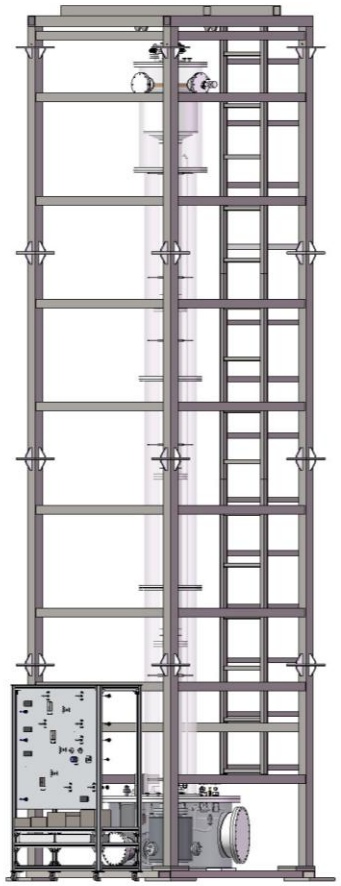
Cryogenics and recirculation

- Flexible with redundancy
- Cooling Power:

  ≥ 1500W@178K (GM cooler) + others
- Online purification speed:

3.5-ton/day for gas, 8-ton/day for liquid

Distillation towers

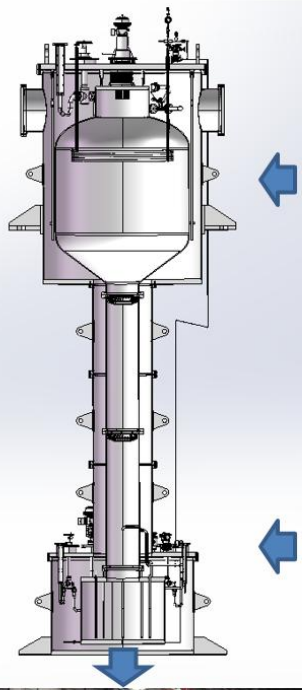


Kr distillation tower : 30 kg/hour.

Target Kr concentration in Xe: 0.01 ppt

Outer vacuum tower

Outer vacuum chamber



condenser

reboiler

Inner tower

Rn distillation tower : 850 kg/hour.

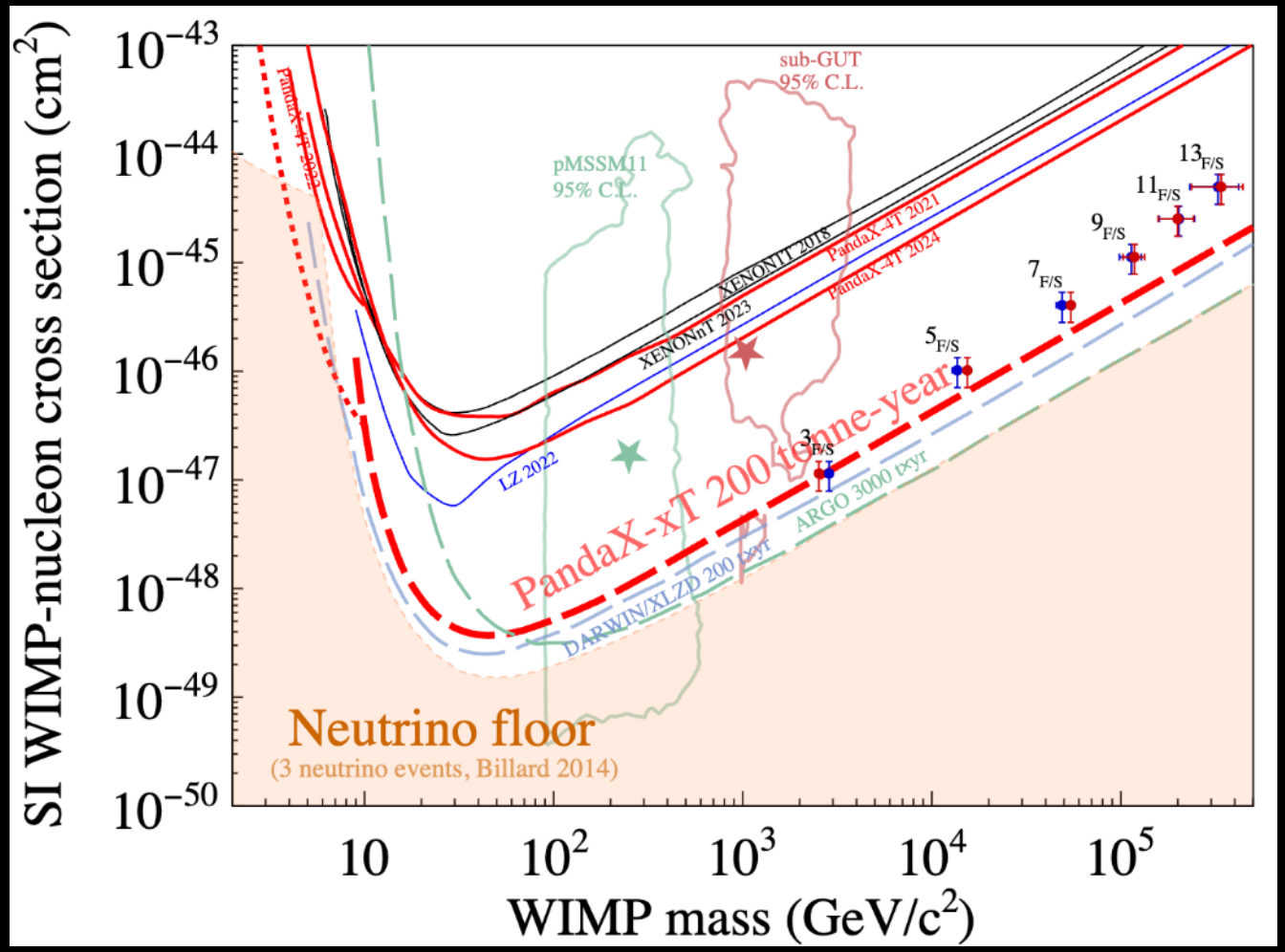
Target: 0.5 μBq/kg

“Baseline” background

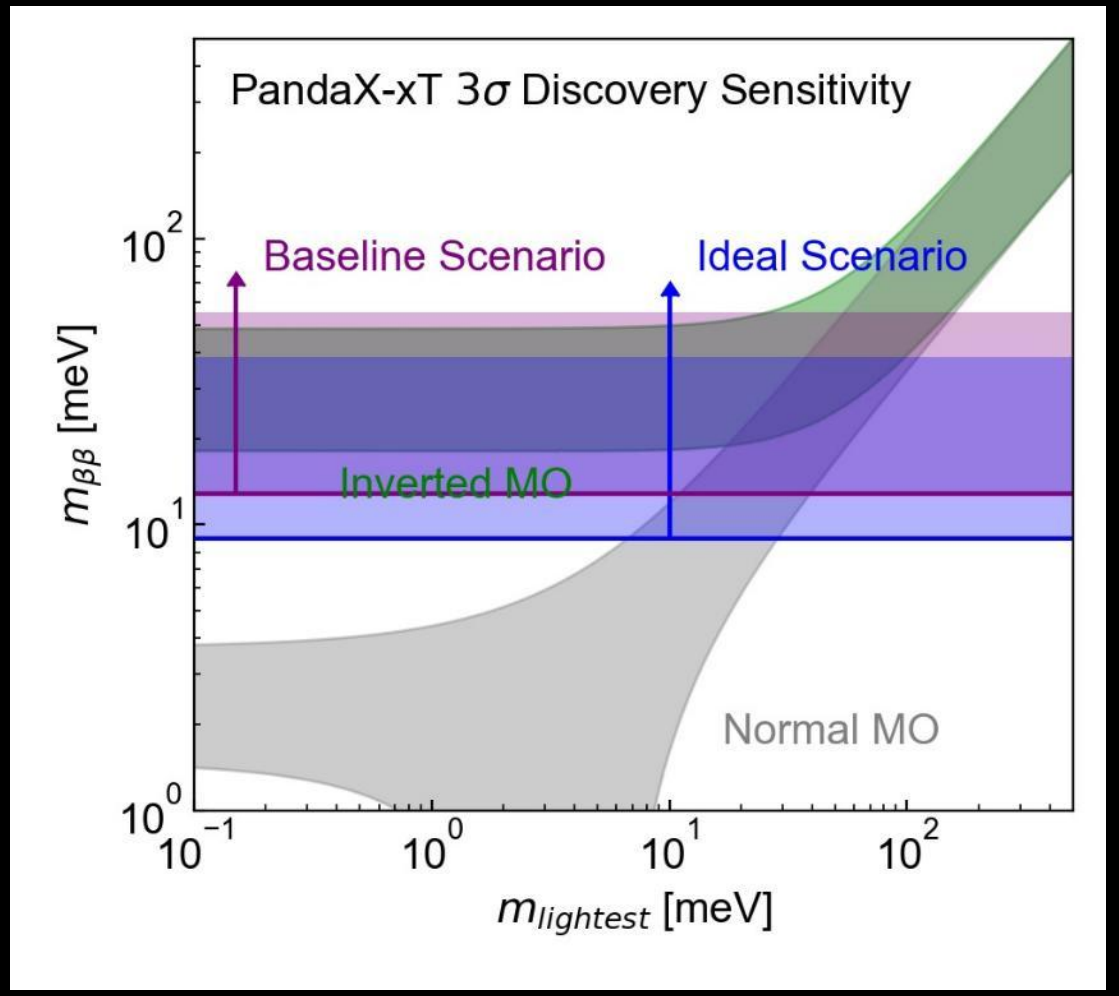
Component		Background assumption
1	Photosensors	U/Th/K = 0.02/0.01/1.5 mBq/cm^2 Hamamatsu R12699 prototype
2	Inner vessel	U/Th/K 5 ppt (g/g)
3	Kr	0.01 ppt (mol/mol)
4	Rn222	0.5 uBq/kg

Physics reach

Dark matter sensitivity



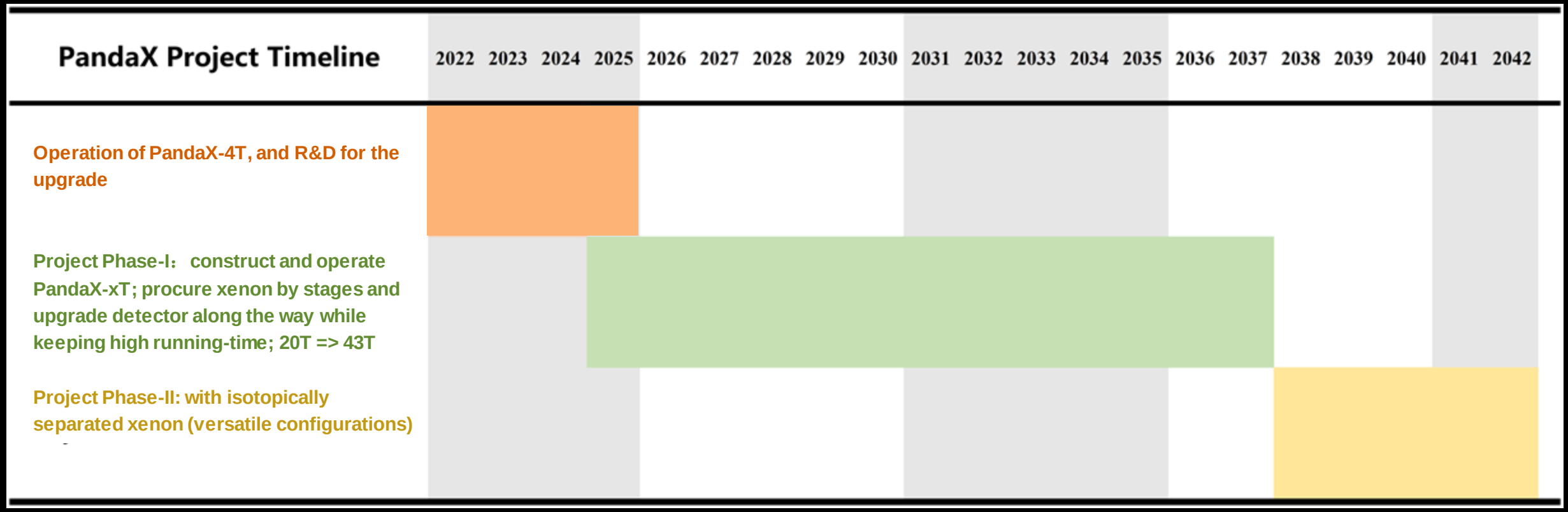
Majorana sensitivity



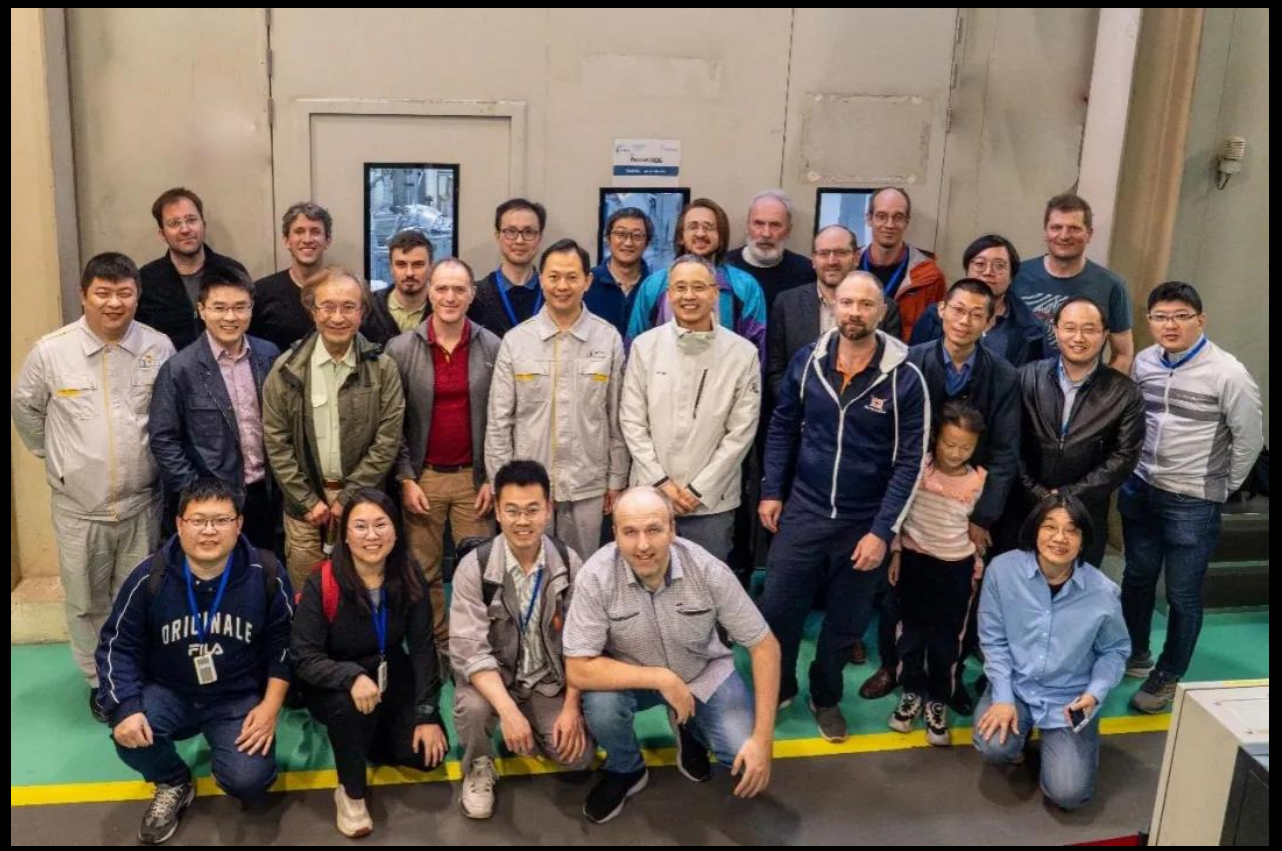
Complementarity with XLZD/ARGO

- Friendly competition good for the science
- Data taking in parallel => increase the world data for global analysis
- Different experimental sites/detector design features/background $\Rightarrow$ Cross checks
- Learn from each other's lessons and technological breakthrough
- Joint force in a general way

Schedule


PandaX Project Timeline
2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042
Operation of PandaX-4T, and R&D for the upgrade
Project Phase-I： construct and operate PandaX-xT; procure xenon by stages and upgrade detector along the way while keeping high running-time; 20T => 43T
Project Phase-II: with isotopically separated xenon (versatile configurations)

PandaX-xT first open meeting (Apr. 7-11, 2025)



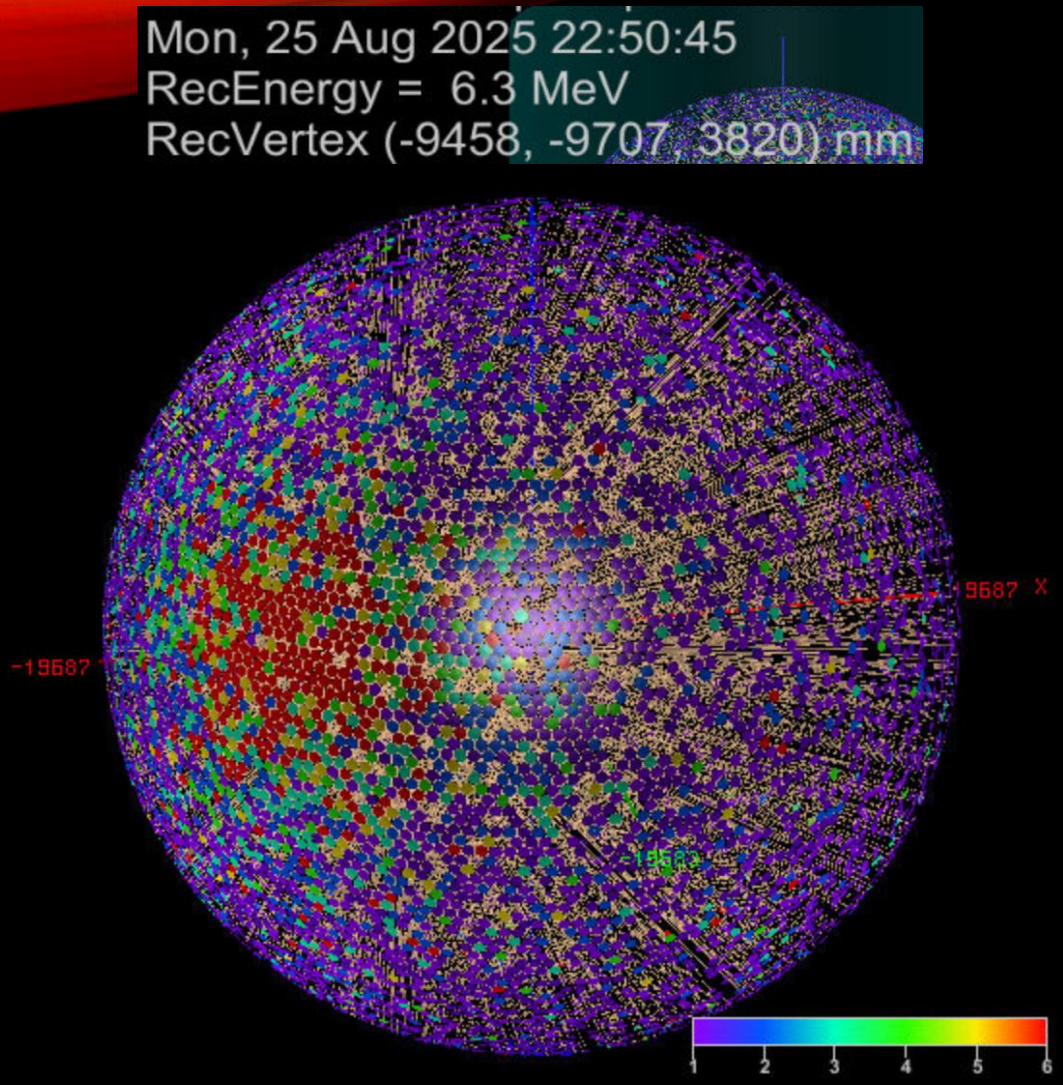
- A few groups in Russian, Japan, UK (more on the neutrino side) expressed some interest of joining force
- Applying for NSFC-CJPL international cooperation “incubator” funding

Summary

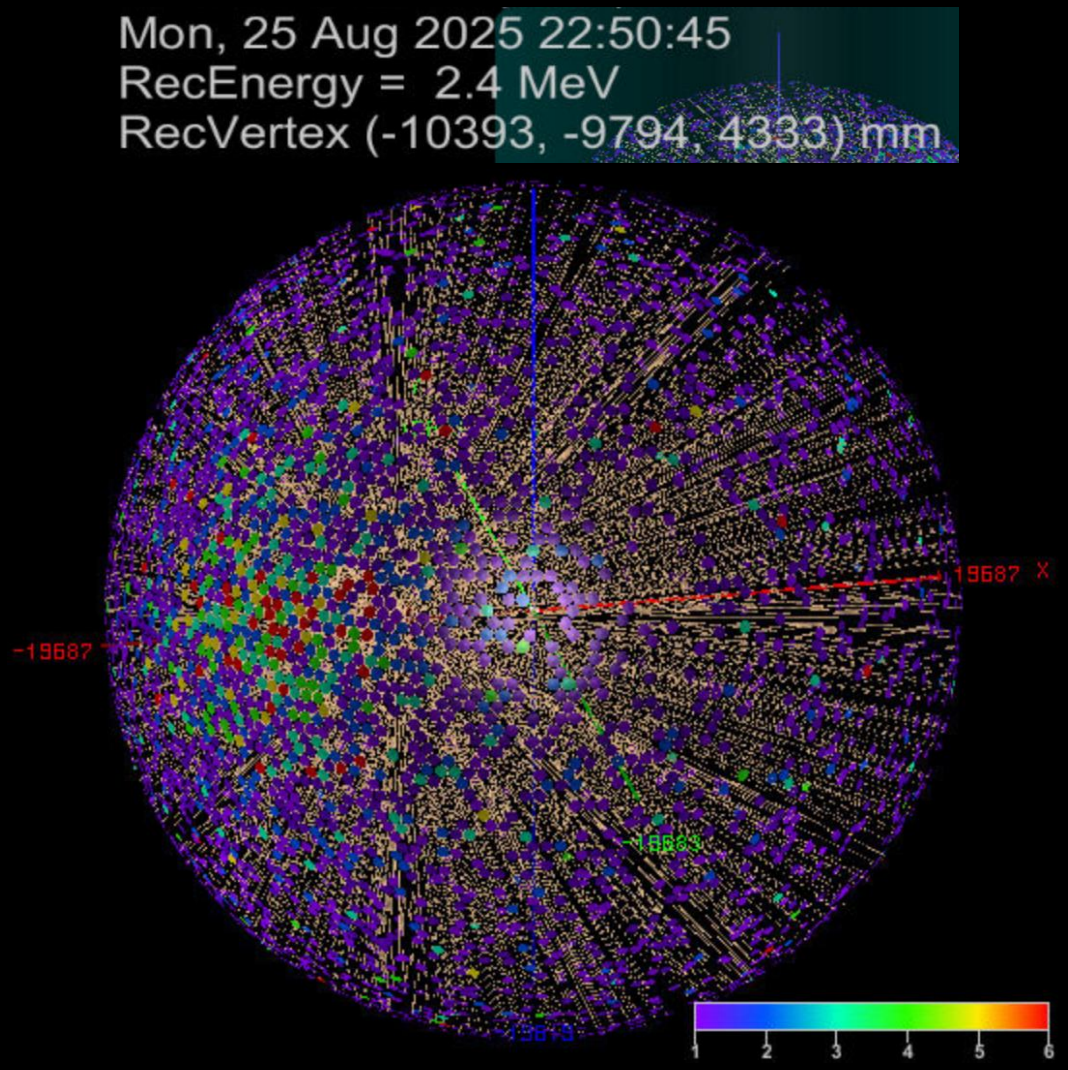
- PandaX-4T has developed a very rich physics program in DM and Neutrinos(!)
  - Technically: developing more and more sensitive detectors
  - Physics-wise: stronger connections with theorists
- A pragmatic approach with a stage-wise upgrade to PandaX-xT aiming for VERY exciting physics
  - Next stage: PandaX-20T
- Highly welcome collaborators

JUNO Experiment

A Golden Reactor Neutrino Event



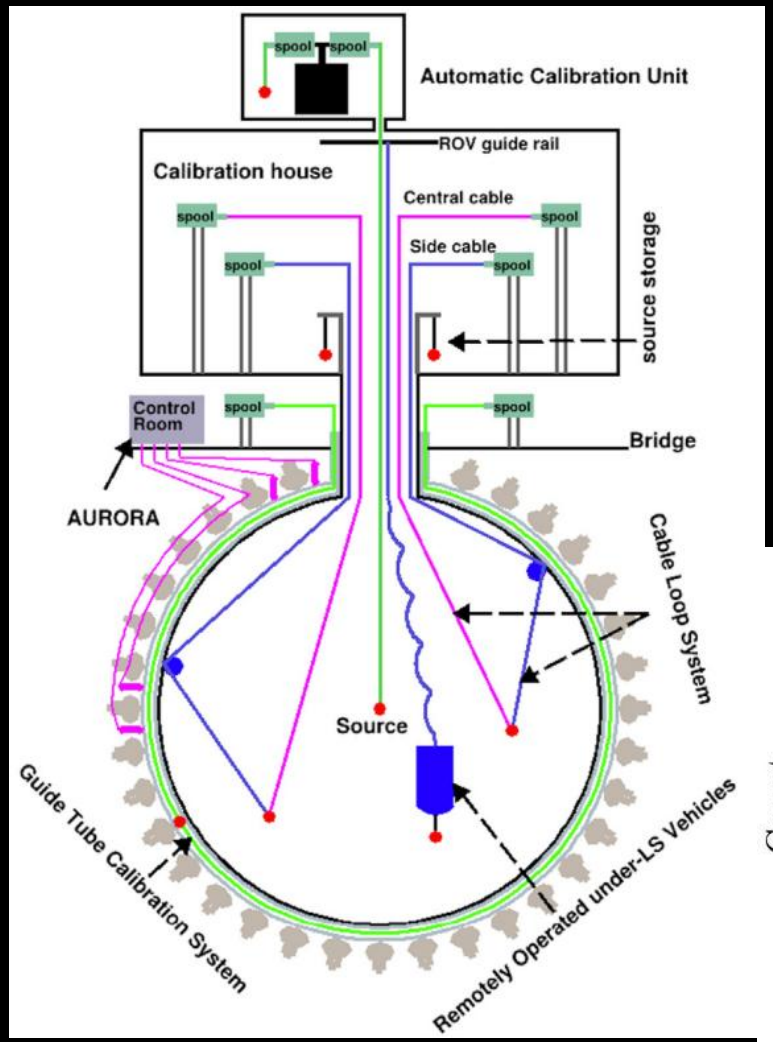
Prompt e+ signal



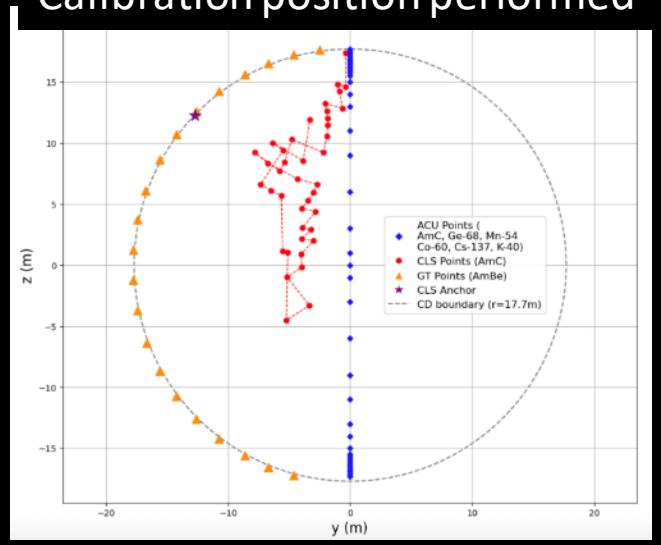
Delay neutron signal

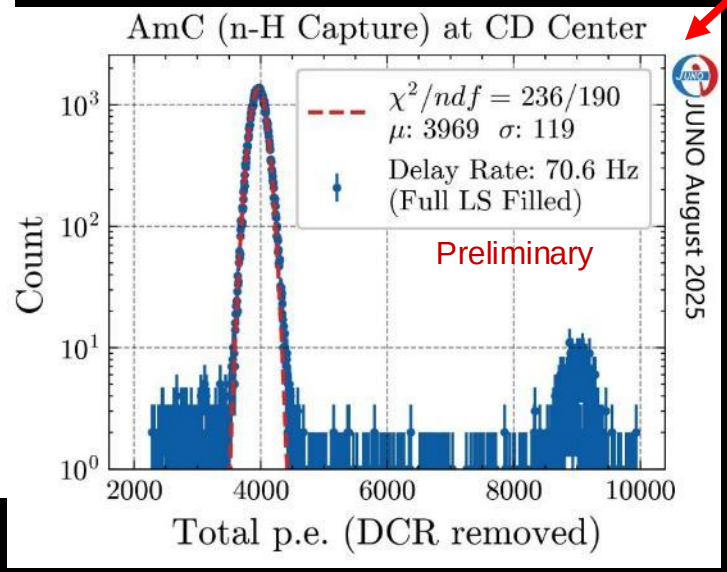
Calibration

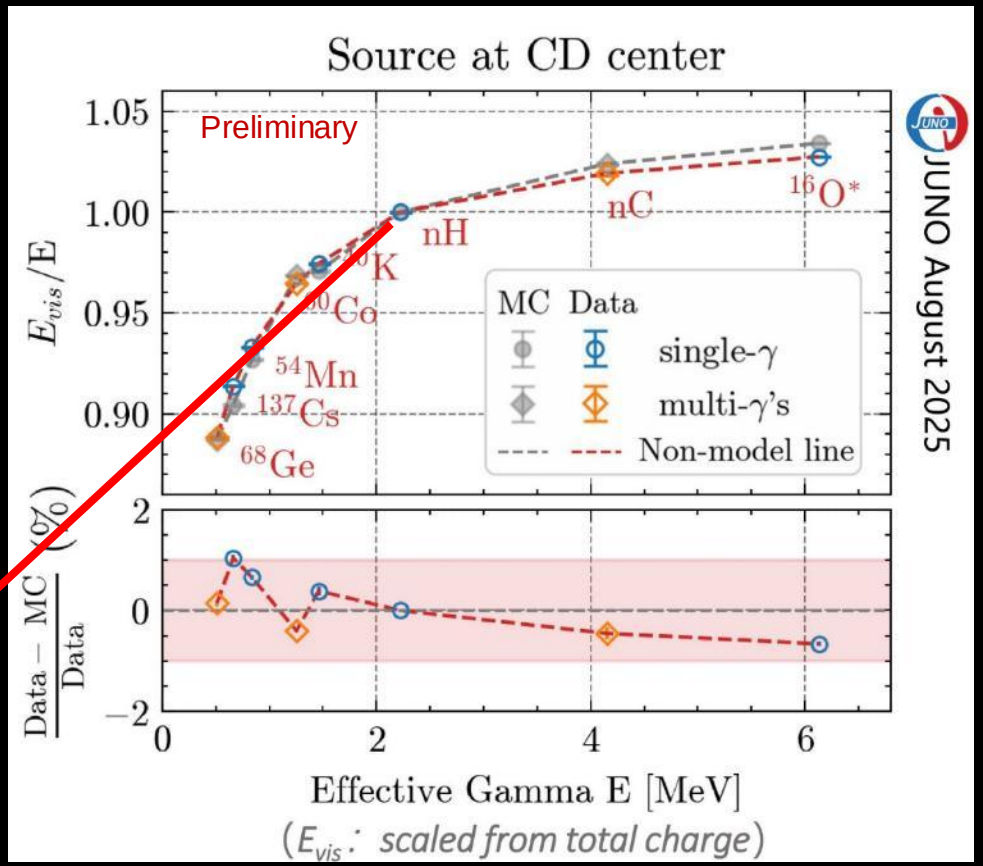
1D, 2D, 3D scan systems using laser/e^+/γ/n sources + n/α background events



Calibration position performed







Energy Non-linearity is known to < 1% !

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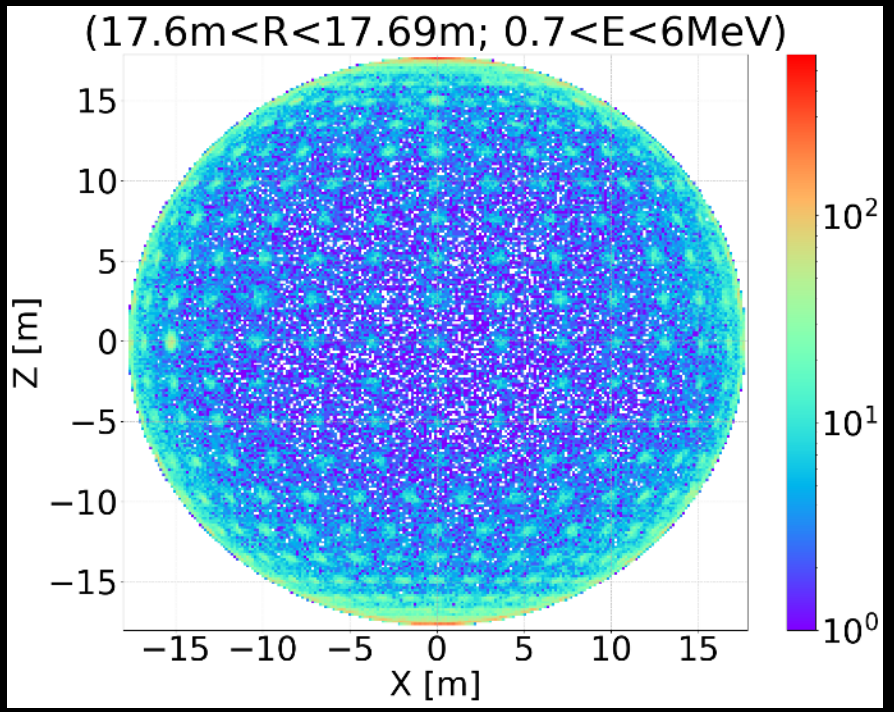
A Clean Detector

- VETO Water:
  - ⇨ U/Th<0.4×10^{-15} g/g, ^{222}Rn<10 mBq/m^3, ^{226}Ra<1 mBq/m^3
- All detector materials are clean and water shielding works:
  - ⇨ Single rate <7 Hz for R<17.2m & E>0.7MeV (design 7.2Hz)
  - ⇨ Good enough for reactor neutrinos
- LS very close to Borexino, further reduction after ^{222}Rn decays
  - ⇨ ^{238}U<3×10^{-17} g/g (low radon region)
  - ⇨ ^{232}Th<1×10^{-16} g/g (R<13m)
  - ⇨ ^{210}Po<1×10^{5} [cpd/kt]



Radiopurity control of raw material:

- ✓ Meticulous Monte Carlo Simulation for proper distribution of radioactivity budget
- ✓ Careful material screening
- ✓ Accurate detector production handling

Better than spec. by 15% ! *JHEP* 11 (2021) 102

Radiopurity control:

- ➢ Leak check of all joints (each < 10^{-8} mbar·L/s) for ^{222}Rn and ^{85}Kr √
- ➢ Cleaning and washing of all pipes & vessels to remove dust (by check water/LAB cleanness) √
- ➢ Clean room environment during installation √
- ➢ Acrylic Surface treatment and protection(Rn daughters) √
- ➢ LS filling scheme: water replacement and water washing √

Recirculation probably impossible, unlike Borexino, KamLAND, SNO+,…