李政道研究所
TSUNG-DAO LEE INSTITUTE

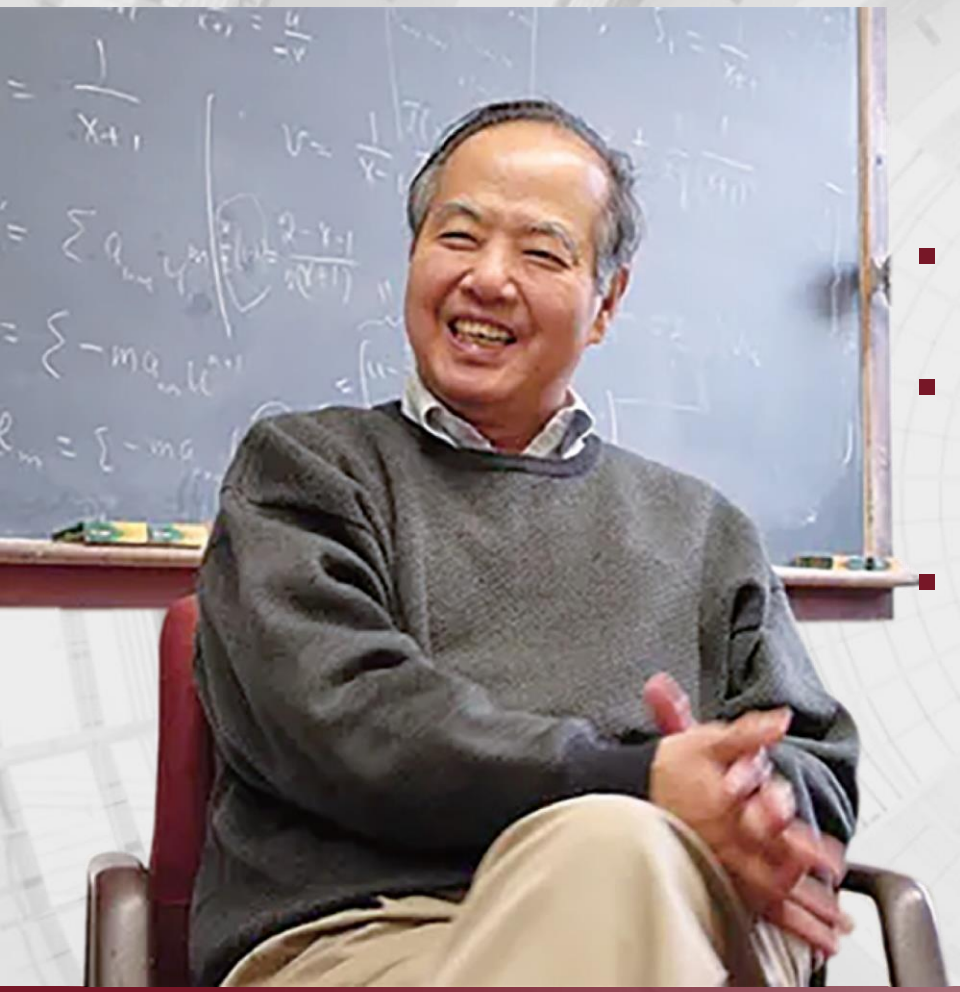
Quest for Infinity via Dark Matter and Neutrinos

— the underground physics program at Tsung-Dao Lee Institute

Jianglai Liu
Shanghai Jiao Tong University

探索·拓展
自然极限 认知疆域

Oct 2023



- What are the natures of dark matter and dark energy?
- What is the relationship between the largest infinity and the smallest infinity in the universe?
- What are the deepest laws of nature and the universe?

"...a world-top fundamental research institute..."

李政道研究所
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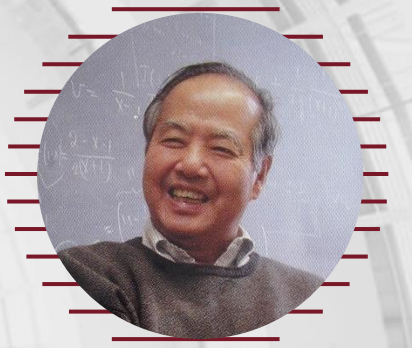
The establishment of the institute

2016.11.28



Tsung-Dao Lee

Honorary Director

Frank Wilczek

Founding Director (2016-2021)
Chief Scientist & T. D. Lee Chair Professor

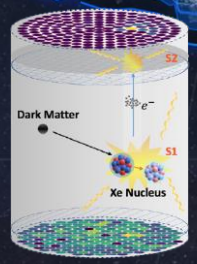
Jie Zhang

Director (2021-) &
T. D. Lee Chair Professor

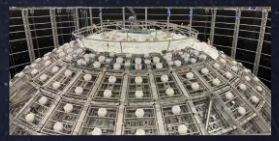
研究所
STITUTE

TDLI Shanghai Headquarter

PandaX Dark Matter and Neutrino Observatory



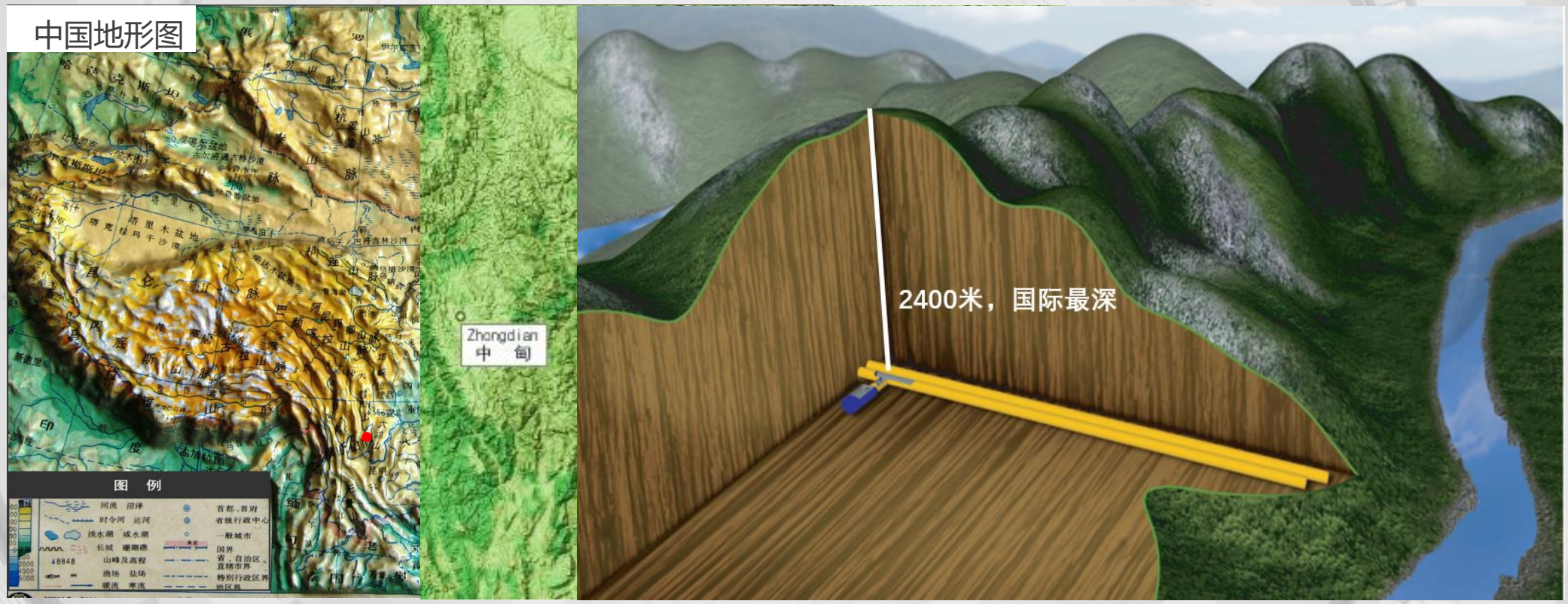
JUNO neutrino observatory



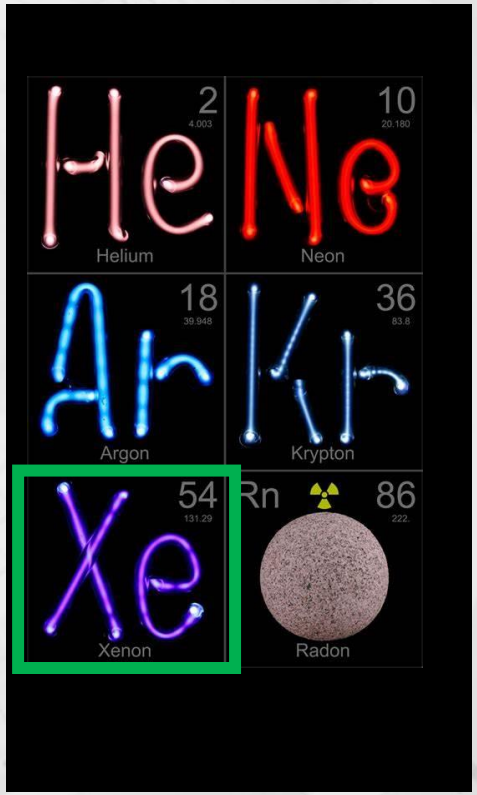
Yongxing Island

TRIDENT neutrino telescope

PandaX Observatory @ China Jinping Lab



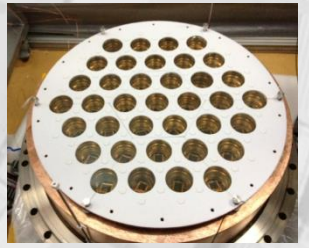
PandaX



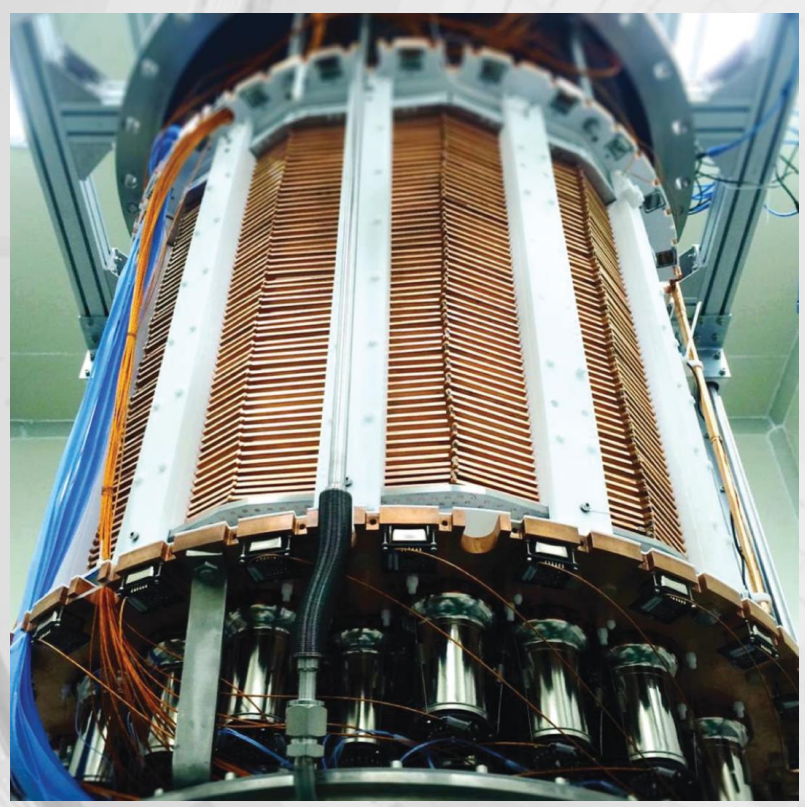
PANDA X

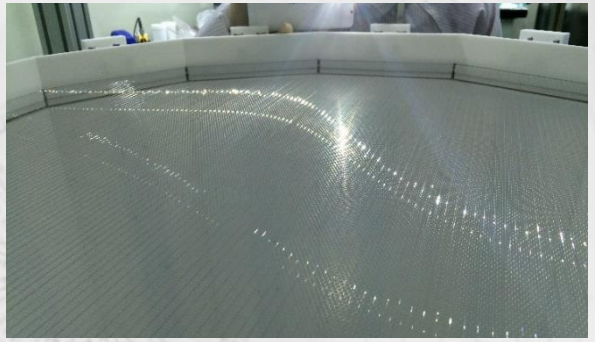
Particle **and**
Astrophysical
Xenon
Experiment

PandaX-I (2009-2014)



PandaX-II (2015-2019)

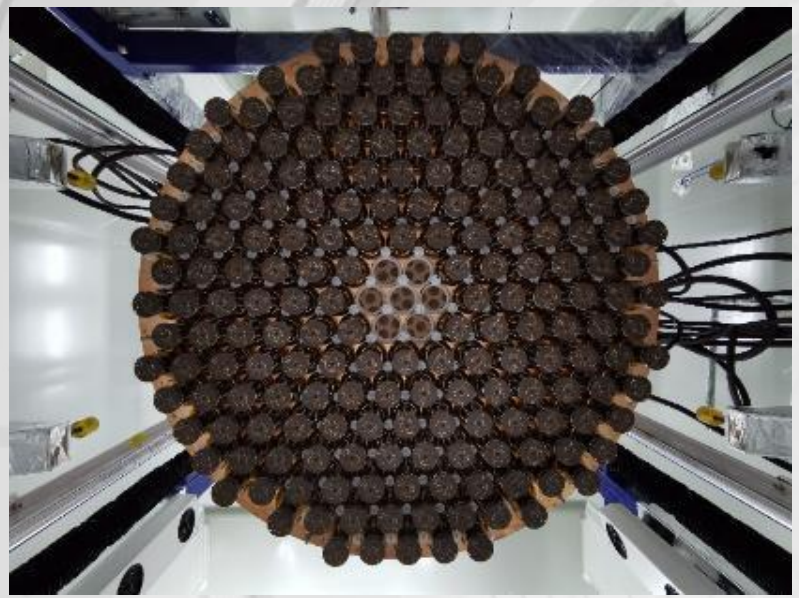




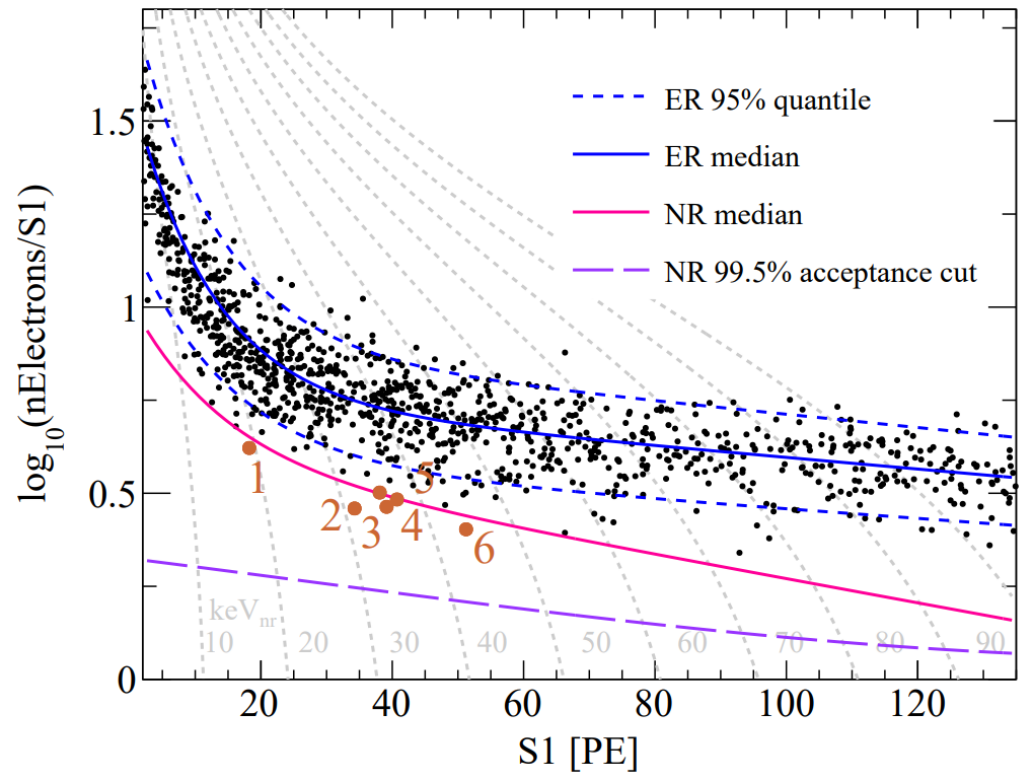
580kg

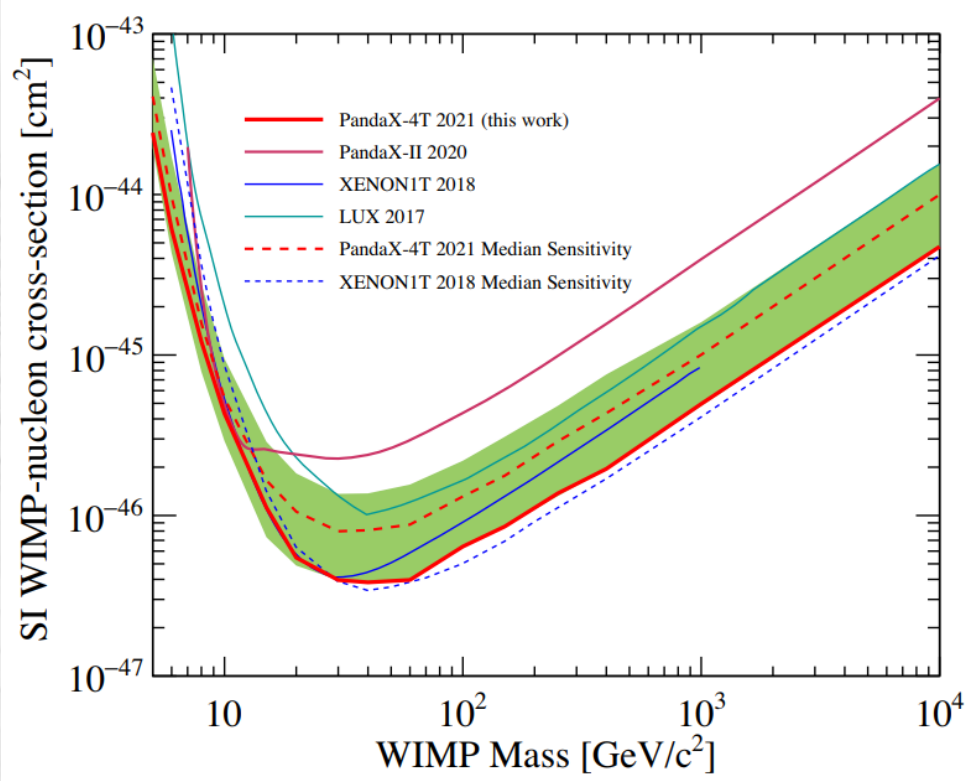
120kg

PandaX-4T (2019-Now)



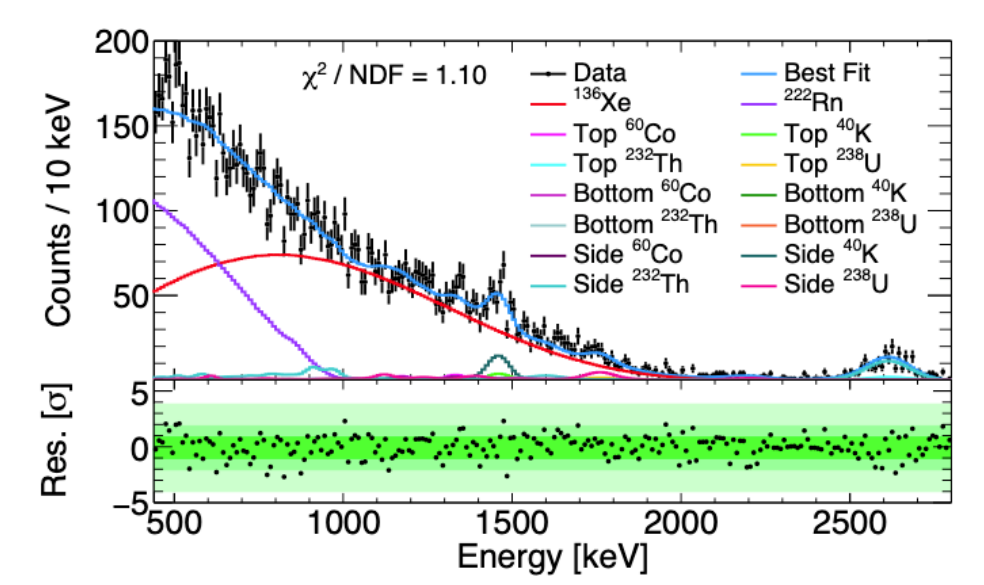
First results from PandaX-4T commissioning

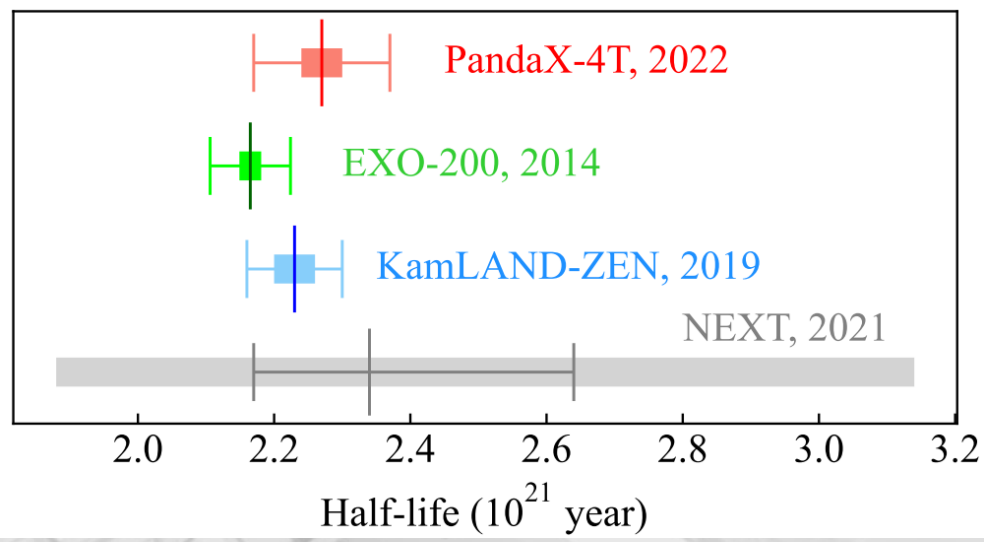




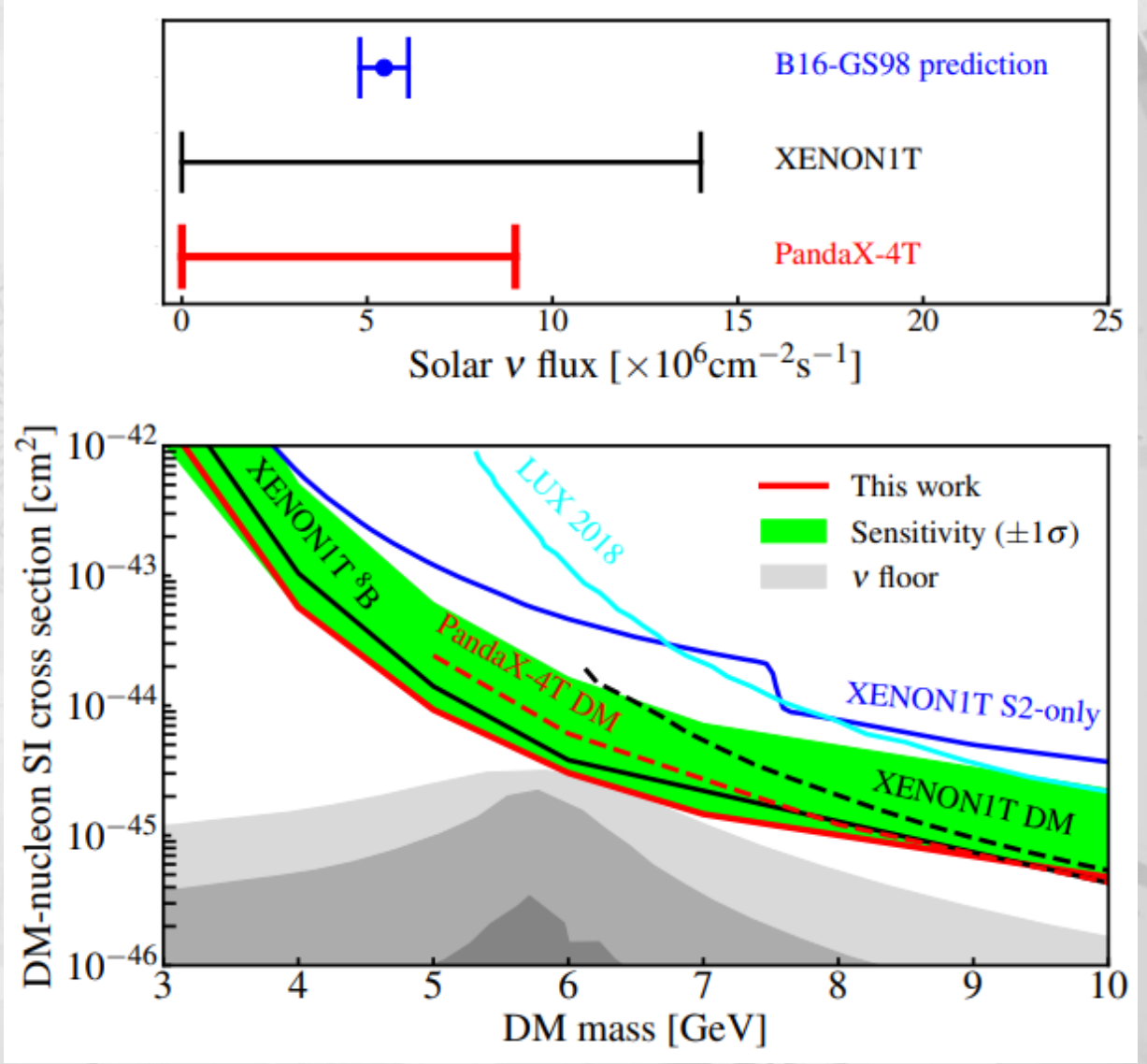
PRL 127, 261802 (2021)

Neutrino results from PandaX-4T commissioning



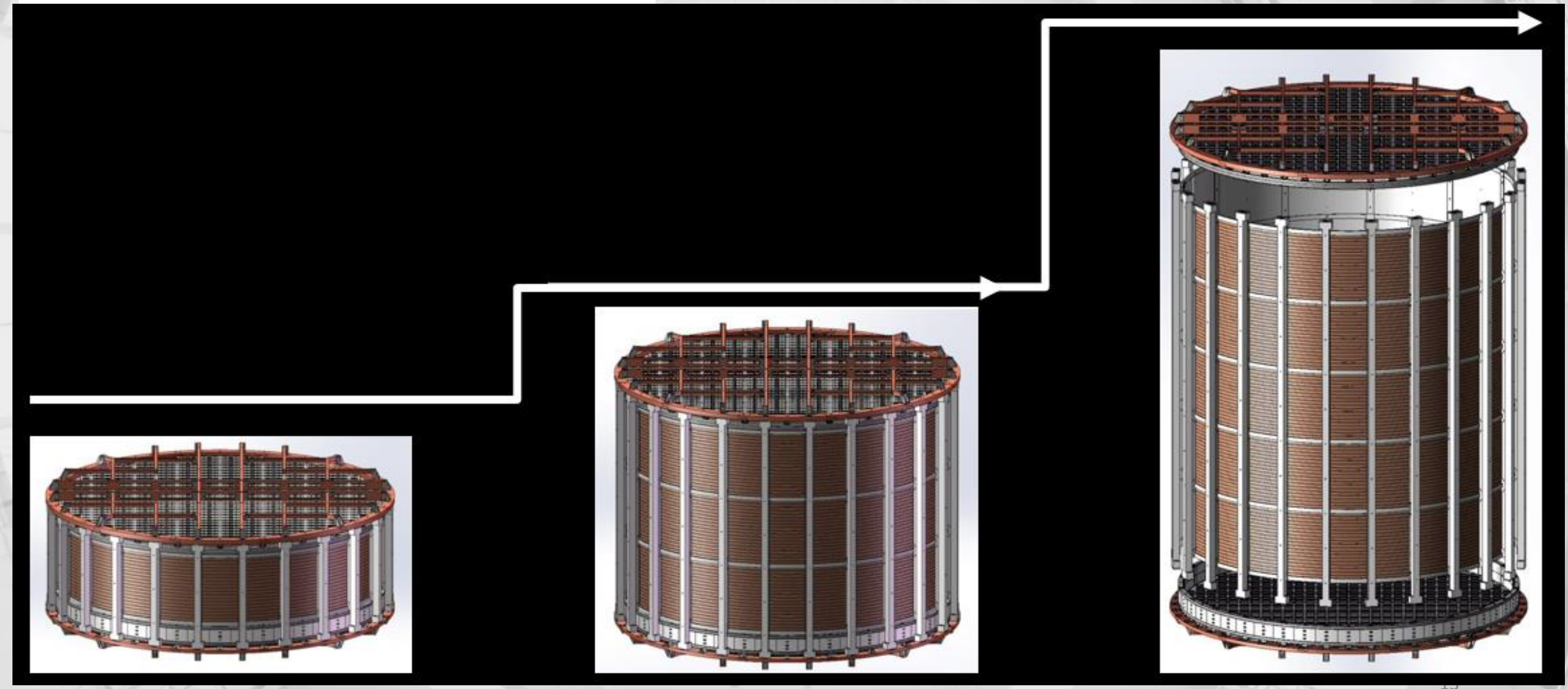


Research 9798721 (2022)

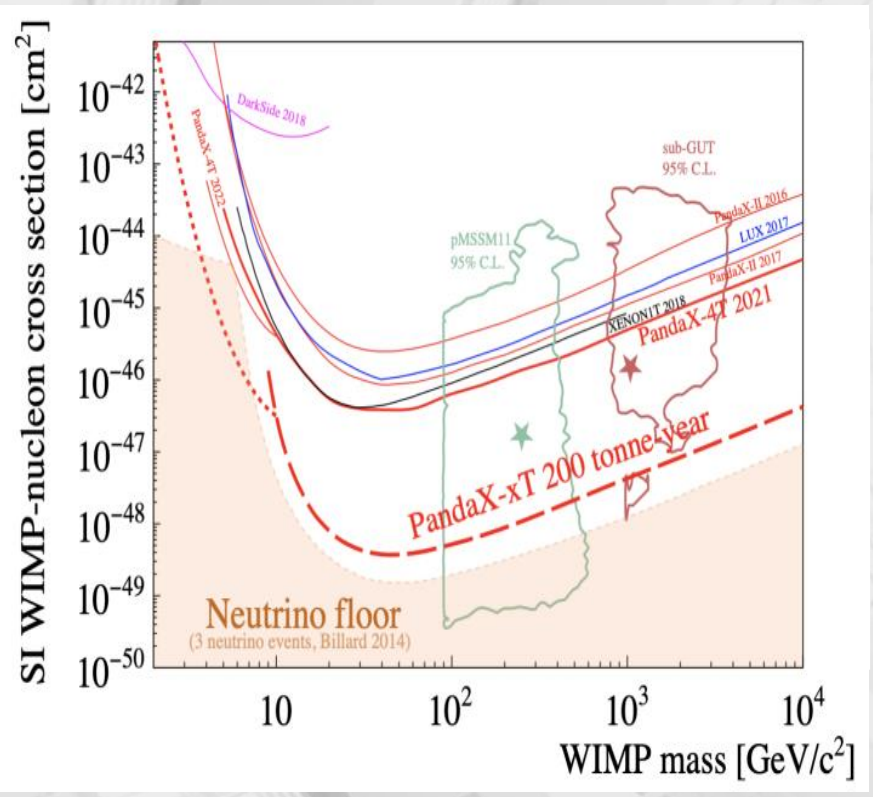


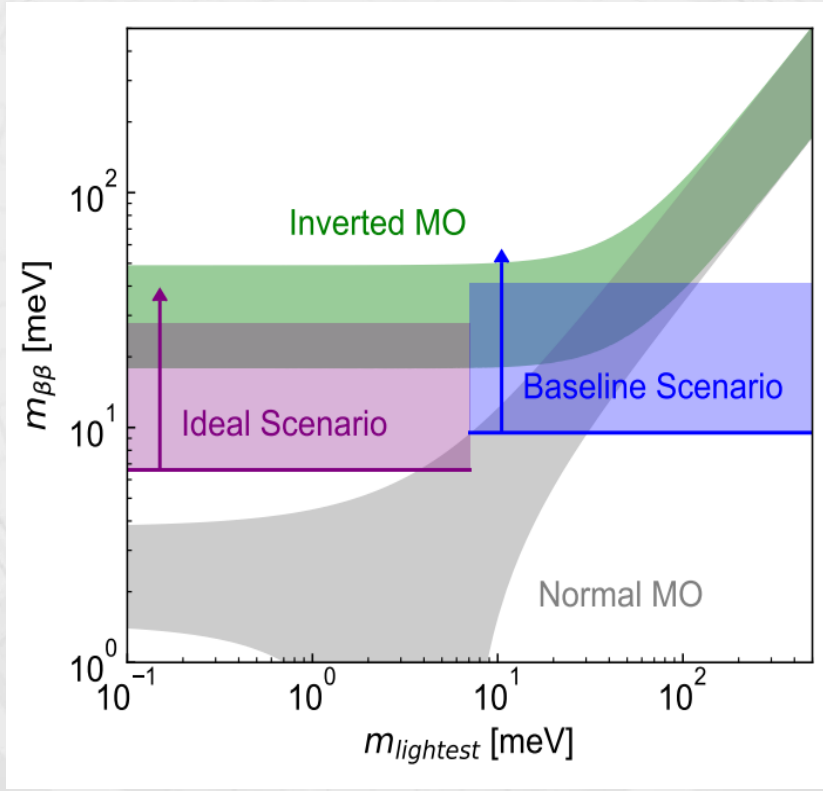
PRL 130, 021802 (2023)

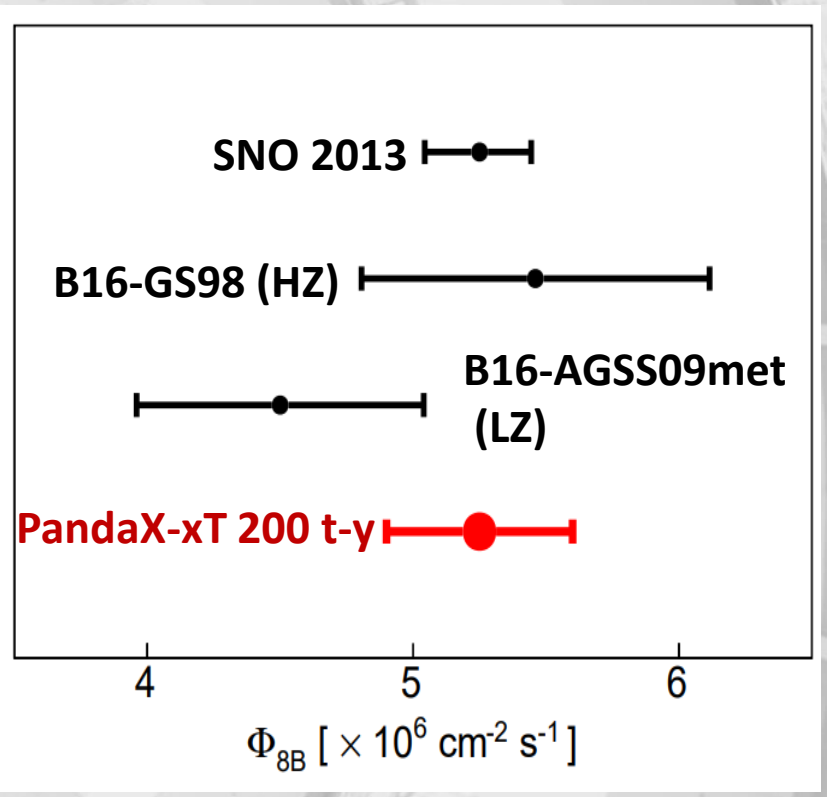
PandaX-xT



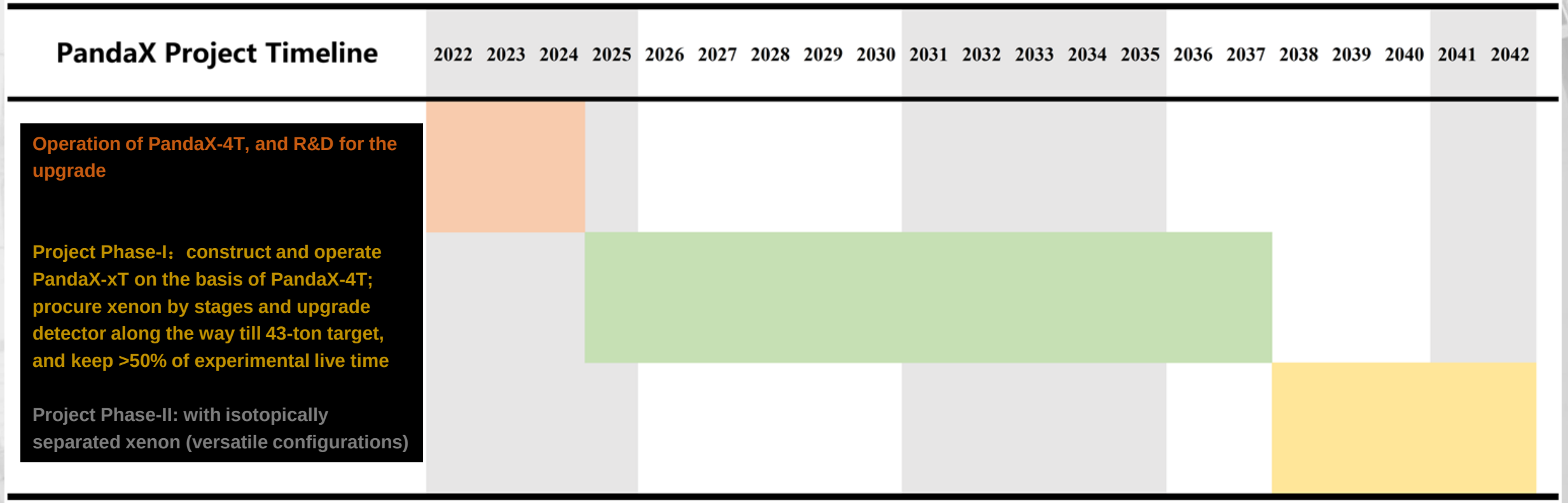
PandaX-xT: scientific potentials



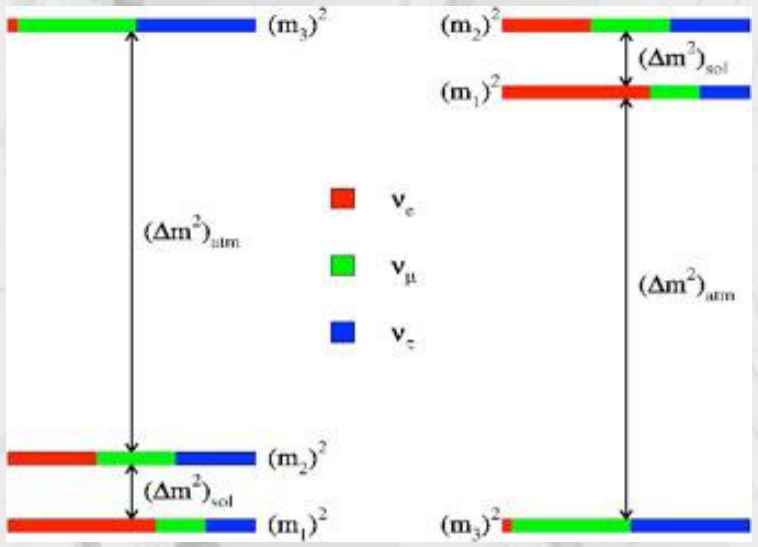




PandaX-xT: staged development



Unresolved neutrino mass ordering and JUNO



$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

$$\approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

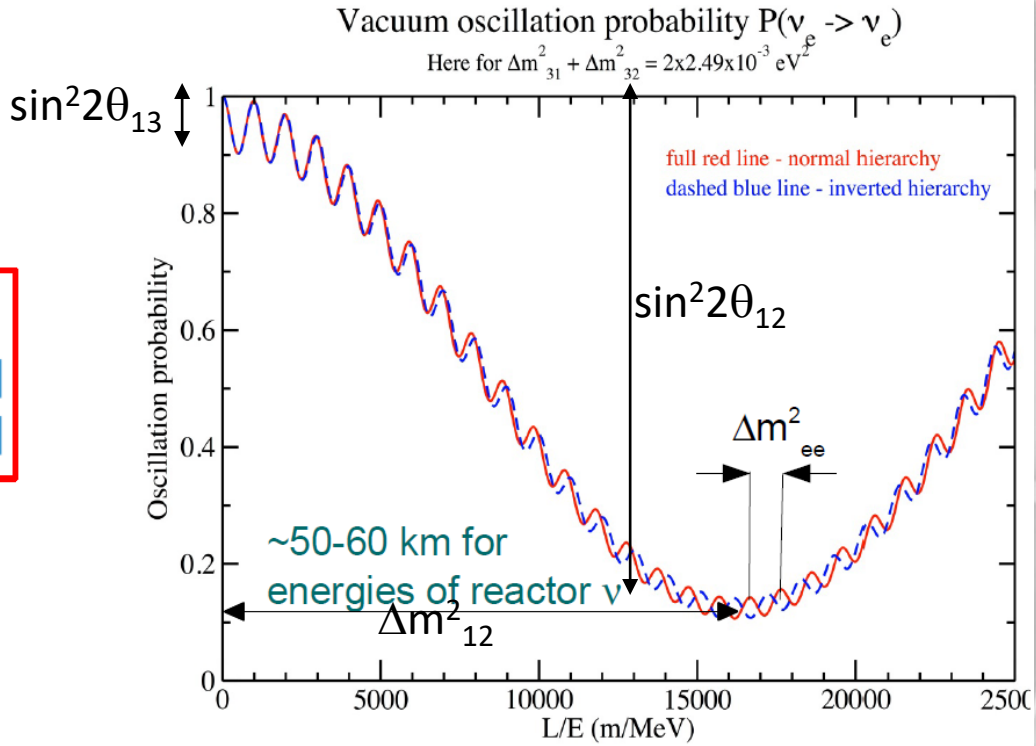
$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$

Δm^2_{ee} = effective neutrino mass-squared difference (beat frequency)

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \text{NH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \text{IH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

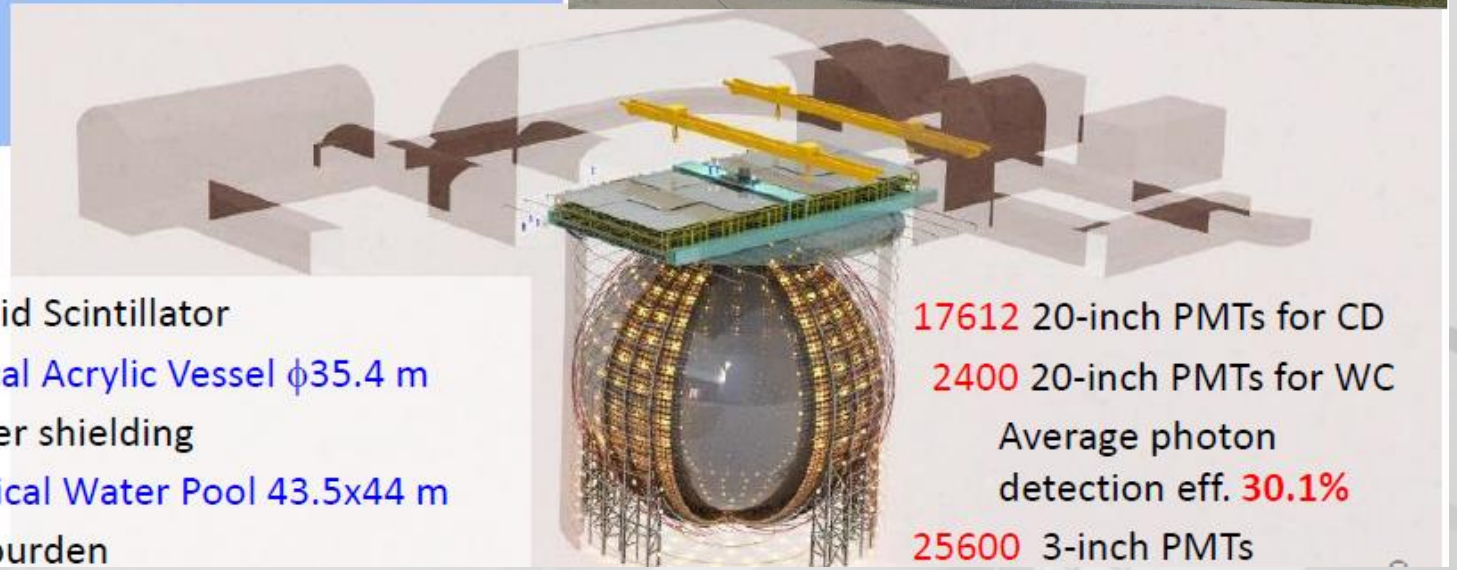
with $\Delta m^2_{12} << \Delta m^2_{32}$

→ different beat frequency (Δm^2_{ee}) for both hierarchies



JUNO facts

Yangjiang NPP: 2.9 GW x 6
Taishan NPP: 4.6 GW x 2
Equal baseline: 52.5 km

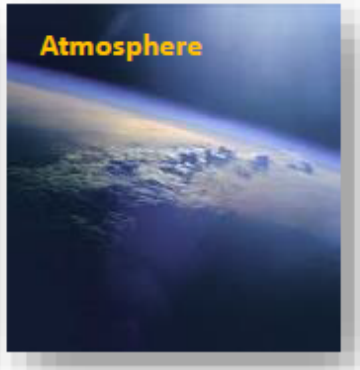


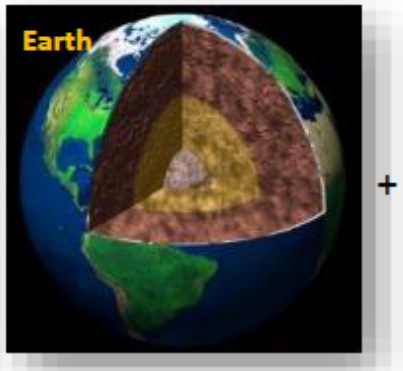
20 kton Liquid Scintillator
Spherical Acrylic Vessel ϕ35.4 m
35 kton water shielding
Cylindrical Water Pool 43.5x44 m
700 m overburden

17612 20-inch PMTs for CD
2400 20-inch PMTs for WC
Average photon detection eff. 30.1%
25600 3-inch PMTs


75% from NNVT, 25% from Hamamatsu

JUNO physics (physics data expected 2024)





+ New physics

Prog. Part. Nucl. Phys. 123, 103927 (2022)

IBD: inverse beta decay
CCSN: core-collapse supernova
DSNB: Diffused Supernova Neutrino Background

~60 IBDs per day | Several per day | Hundreds per day | ~5000 IBDs for CCSN @10 kpc | Several IBDs per day

Neutrino oscillation & properties

Neutrinos as a probe

- Energy resolution **2.95%** @ 1MeV w/ full simulation
- **ν mass ordering: 3σ (reactor only)** @ ~6 yrs (*Neutrino 2022*), atmospheric ν oscillation being improved
- **ν oscillation parameters:** precision of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}| < 0.5\%$ in 6 yrs (2204.13249)

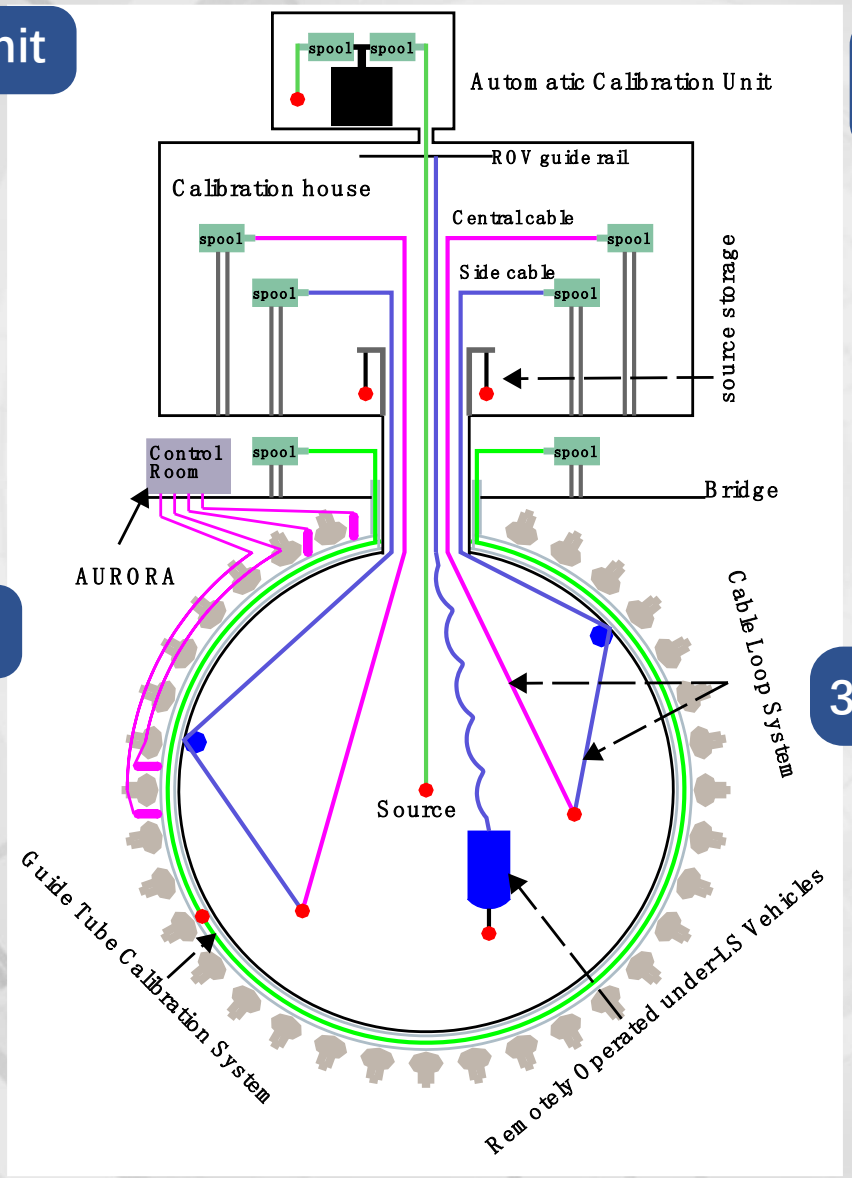
- **Supernova** ν: ~7300 of all-flavor neutrinos @ 10 kpc
- **DSNB**: **3σ** in 3 yrs (2205.08830)
- **Solar** ν:
  - ^{7}Be, pep, CNO (2303.03910)
  - ^{8}B flux (2210.08437)
- **Geo** ν: ~400 per year, 5% precision in 10 yrs

- **Nucleon Decays**: $p \to \bar{\nu}K^+$ 9.6×10^{33} yrs (90% C.L.) in 10 yrs (2212.08502), neutron invisible decay (ongoing)
- **Indirect DM search:** ~good sensitivity in 15-100 MeV region (2306.09567)
- **Future upgrade (2030s) : searching for 0νββ**

SJTU contribution: calibration

1D Automatic Calibration Unit

2D Cable Loop System



Calibration system layout

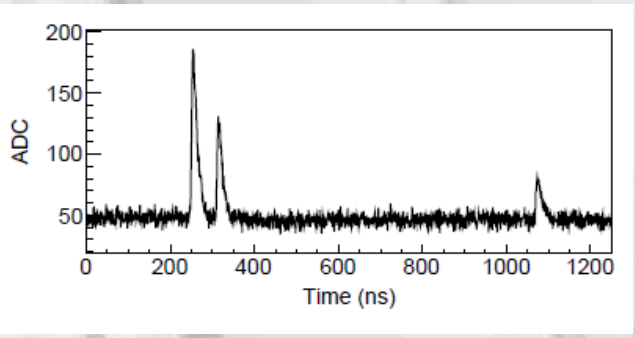
Calibration house with all control systems

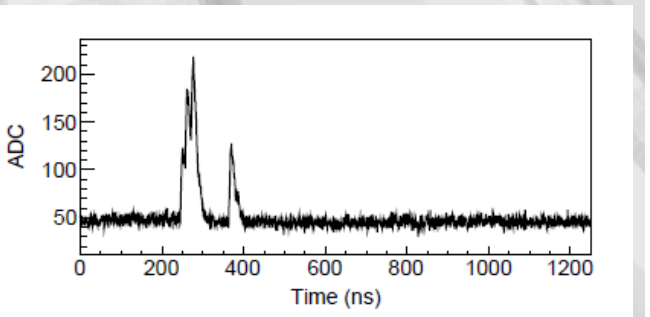
3D Remotely operated vehicles

Yue Meng

E.g. Calibration Data-Driven Waveform Recon

Reassemble single-hit waveform data into fake data to train the photoelectron reconstruction neural network





E.g. Calibration Data-Driven E-reso Model

- $\mathrm{d}E_e$ and $\mathrm{d}x$ distributions from Geant4, distinguish e^+ and e^-
- liquid scintillator non-linearity

$$\mathrm{d}E_e^{vis,s} = \frac{Y\mathrm{d}E_e}{1 + k_B\,\mathrm{d}E_e/\mathrm{d}x} \tag{9}$$

- Cherenkov non-linearity, Frank-Tamm formula and an effective refraction index n

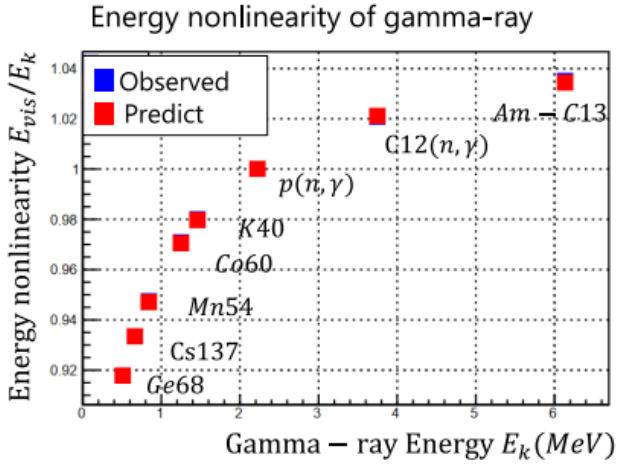
$$\mathrm{d}E_e^{vis,c} = p\left(1 - 1/n^2\beta^2\right)\mathrm{d}x \tag{10}$$

- total visible energy

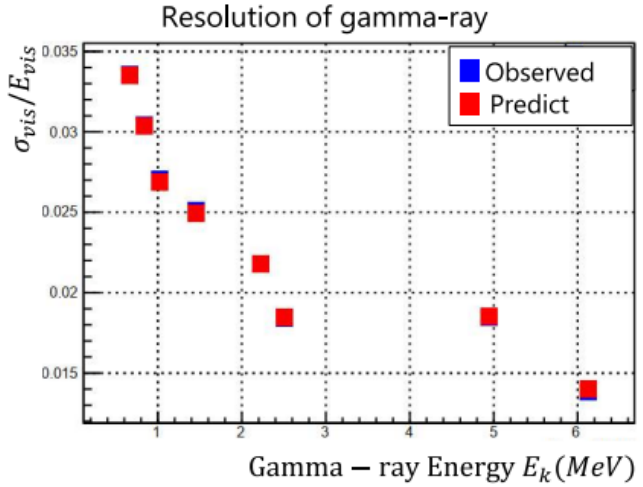
$$E_\gamma^{vis} = \sum_{steps}\left(\mathrm{d}E_e^{vis,s} + \mathrm{d}E_e^{vis,c}\right) \tag{11}$$

- stochastic smearing: $a\sqrt{N}$
- fit parameters Y, k_B, p, n, a to gamma calibration data

- fit to source non-linearity



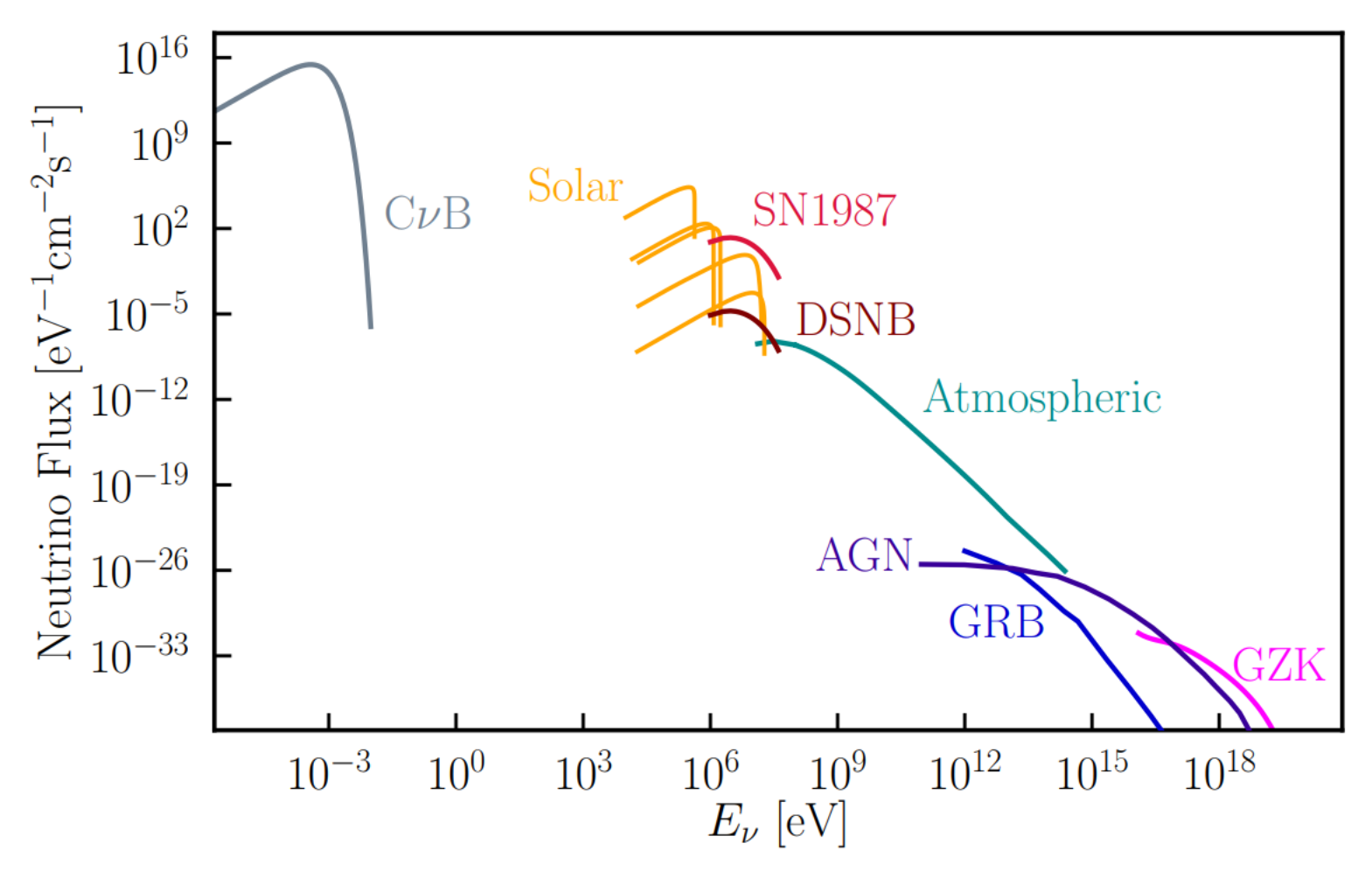
- fit to source resolution

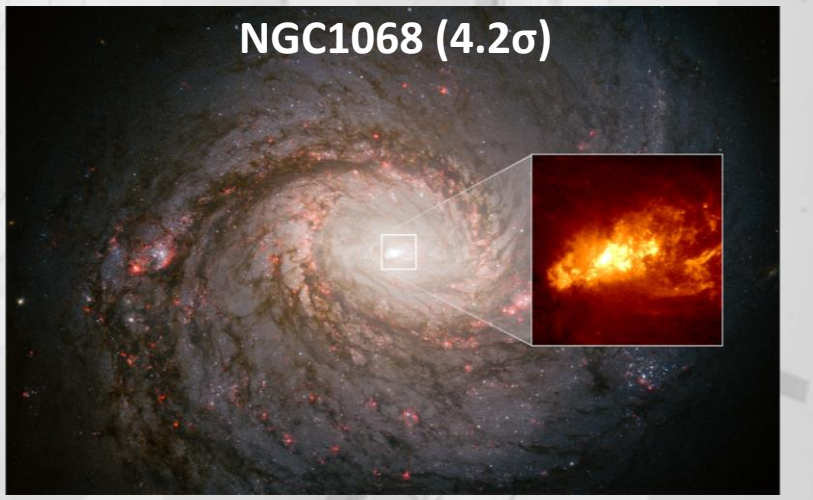


Other analysis effort from SJTU

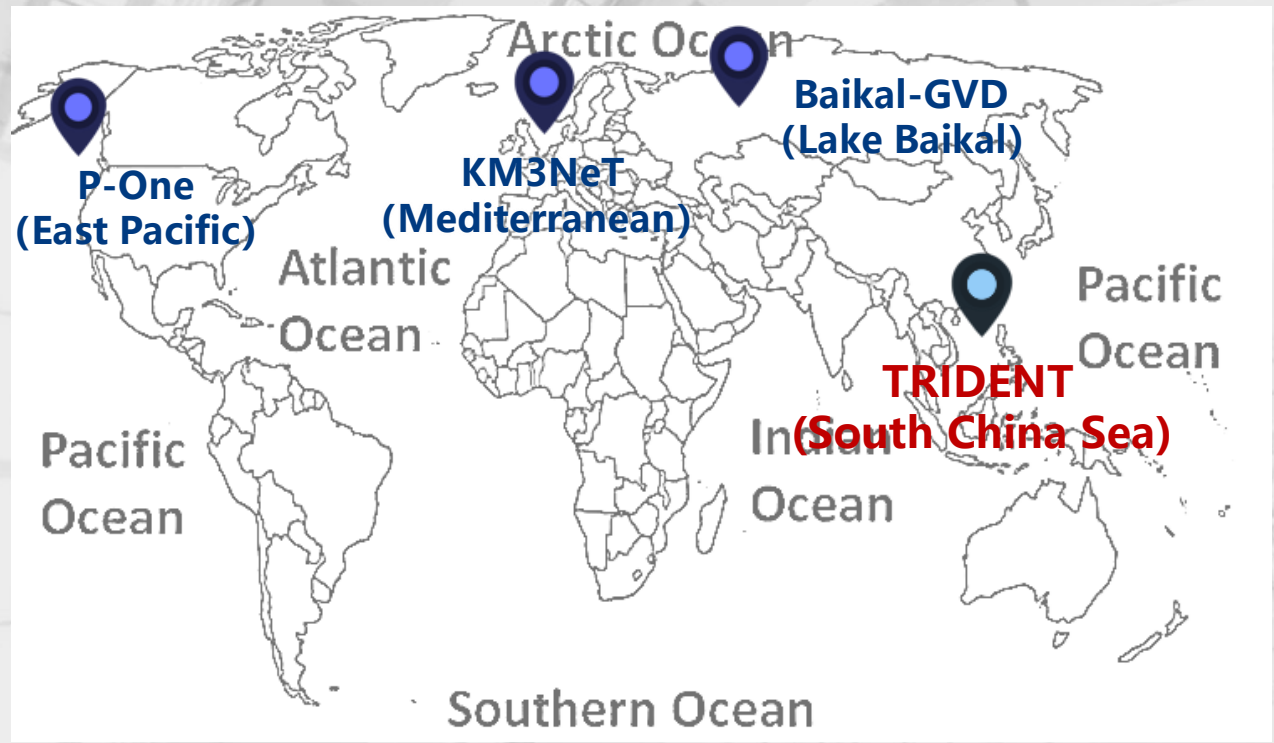
- accidental background (1 / day)
- Li9 and He8 (1 / day)
- Geoneutrino (1 / day)
- alpha-n fast neutrons (0.1 / day)
- particle identification
- cut optimization
- systematics
- event binning

Neutrinos as cosmic messengers

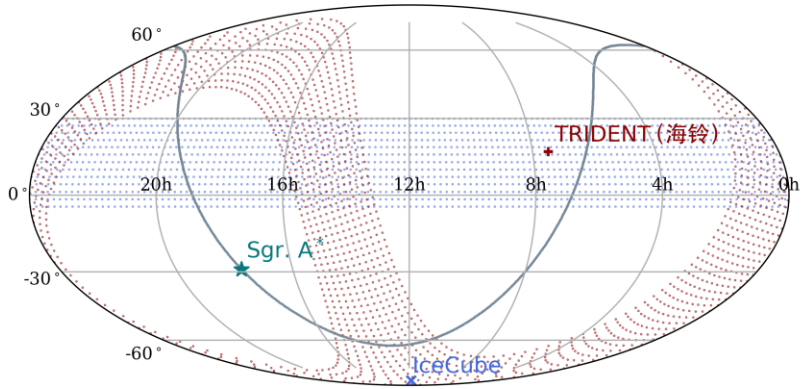




Next-gen neutrino telescopes in planning



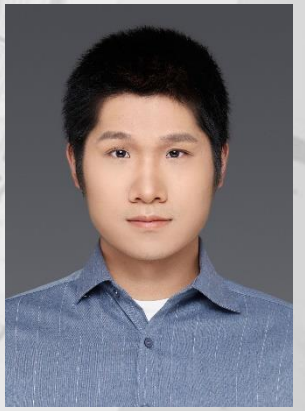
TRopIcal DEep-sea Neutrino Telescope



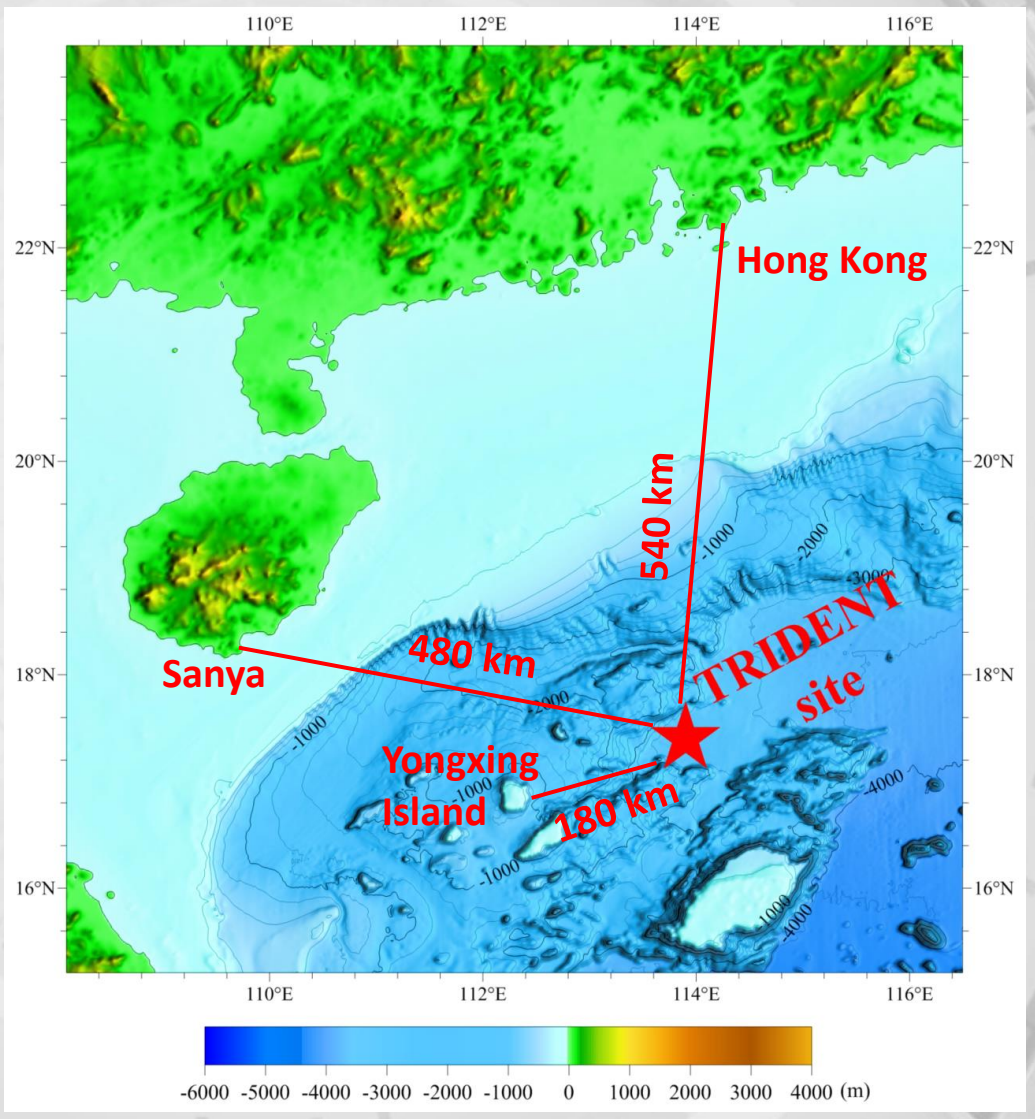
Donglian Xu

Xin Xiang

Hualin Mei



TRIDENT Explorer



Pre-selected site conditions

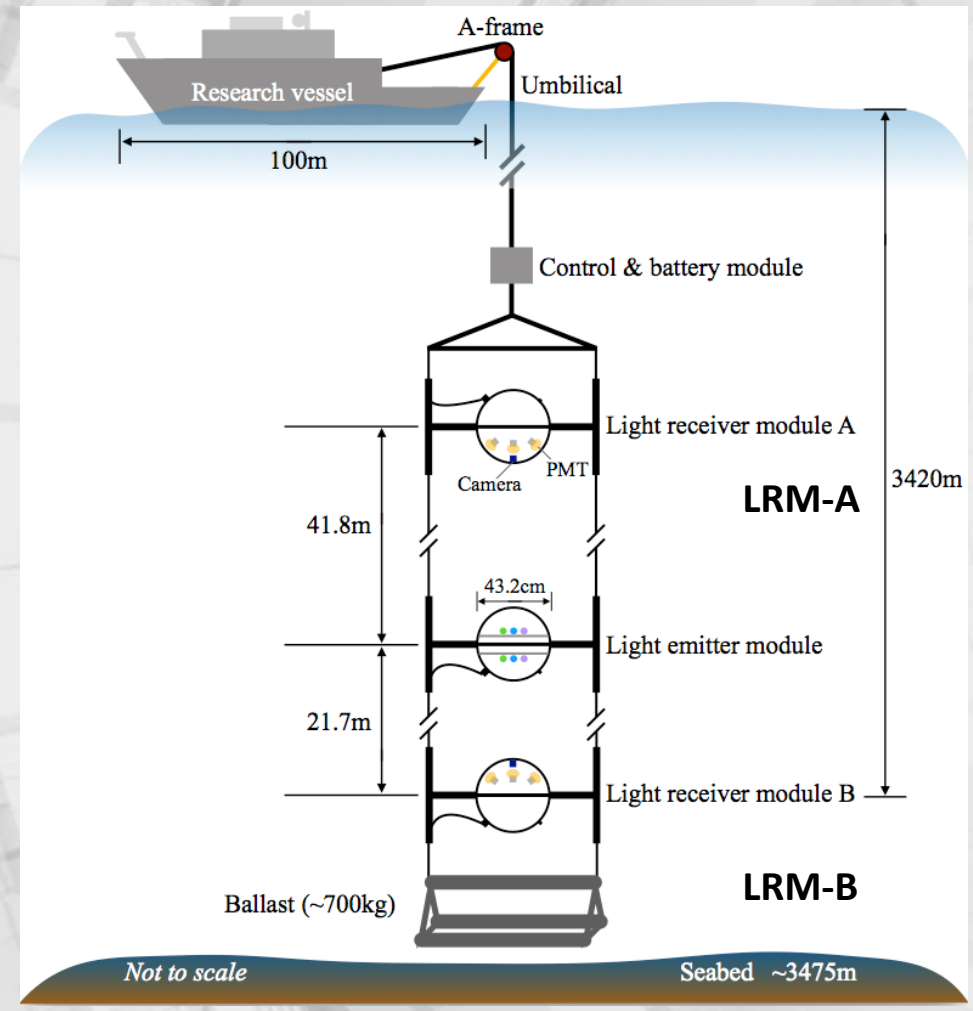
- Flat seabed
- No nearby high rises or deep trenches
- Depth >3km
- Close proximity to a shore

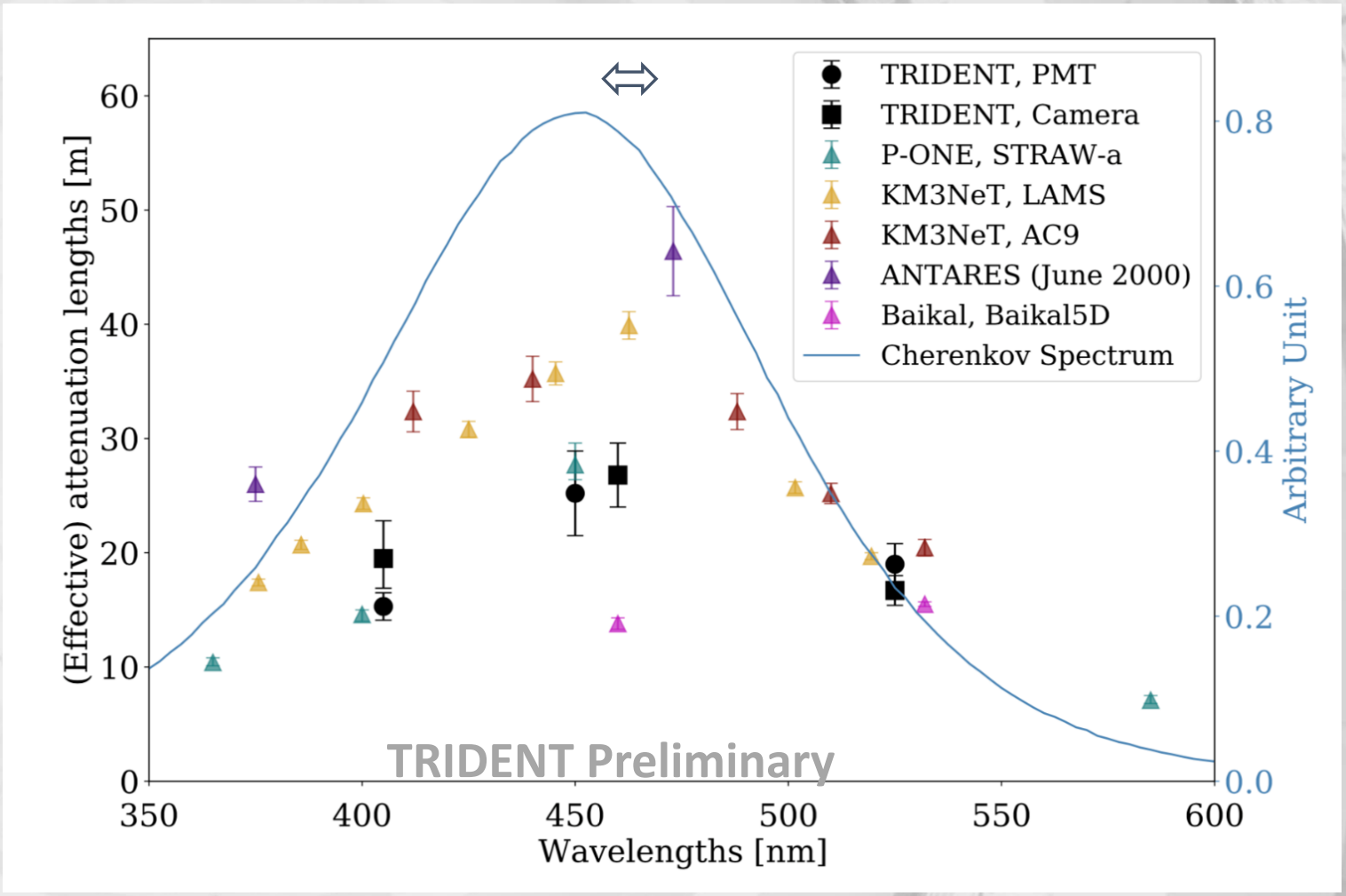
Measured params

- Current field
- Optical properties
- Radioactivity

https://trident.sjtu.edu.cn/en

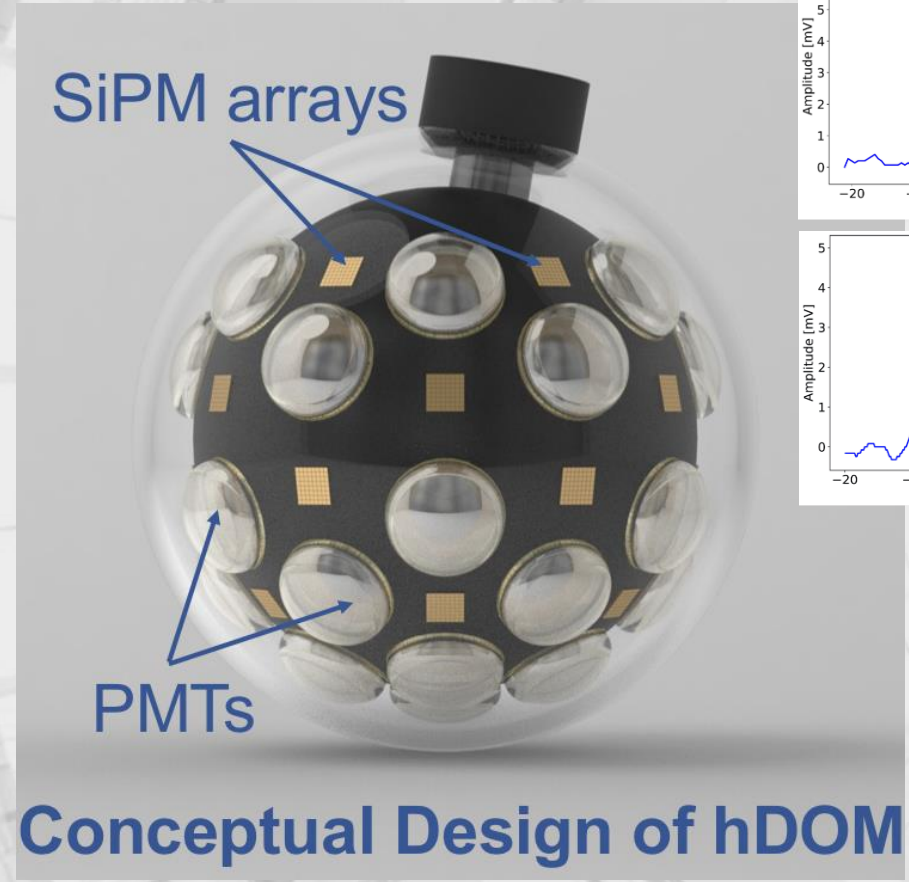
TRIDENT Explorer



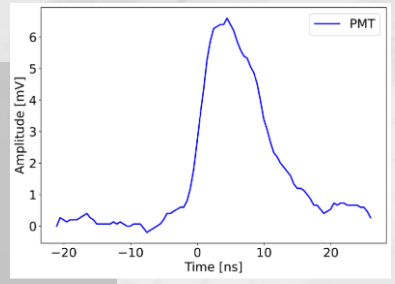


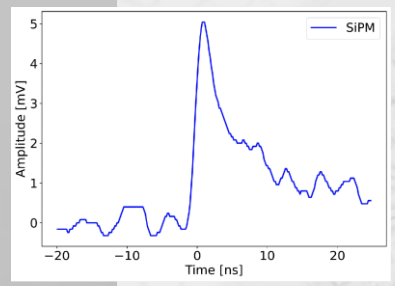
TRIDENT Collaboration, arXiv:2207.04519v1

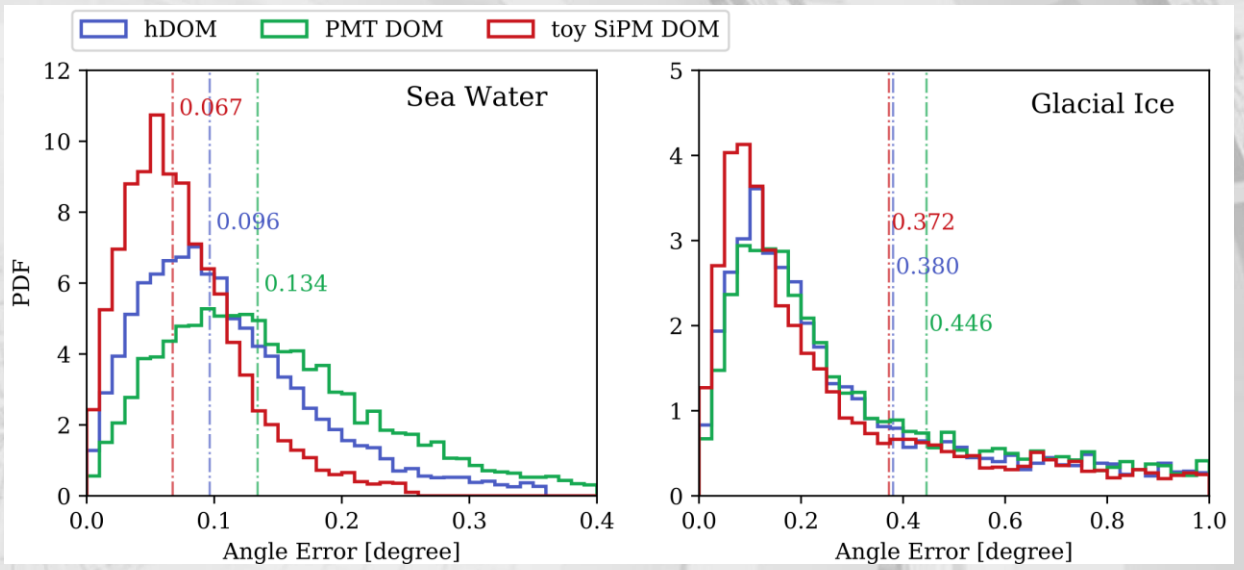
Hybrid Digital Optical Module



Conceptual Design of hDOM







- Better than 0.1° @ E_ν > 100 TeV
- **>40% improvement** (cf mDOM) in angular resolution, assuming PMT TTS ~5ns

Updated:

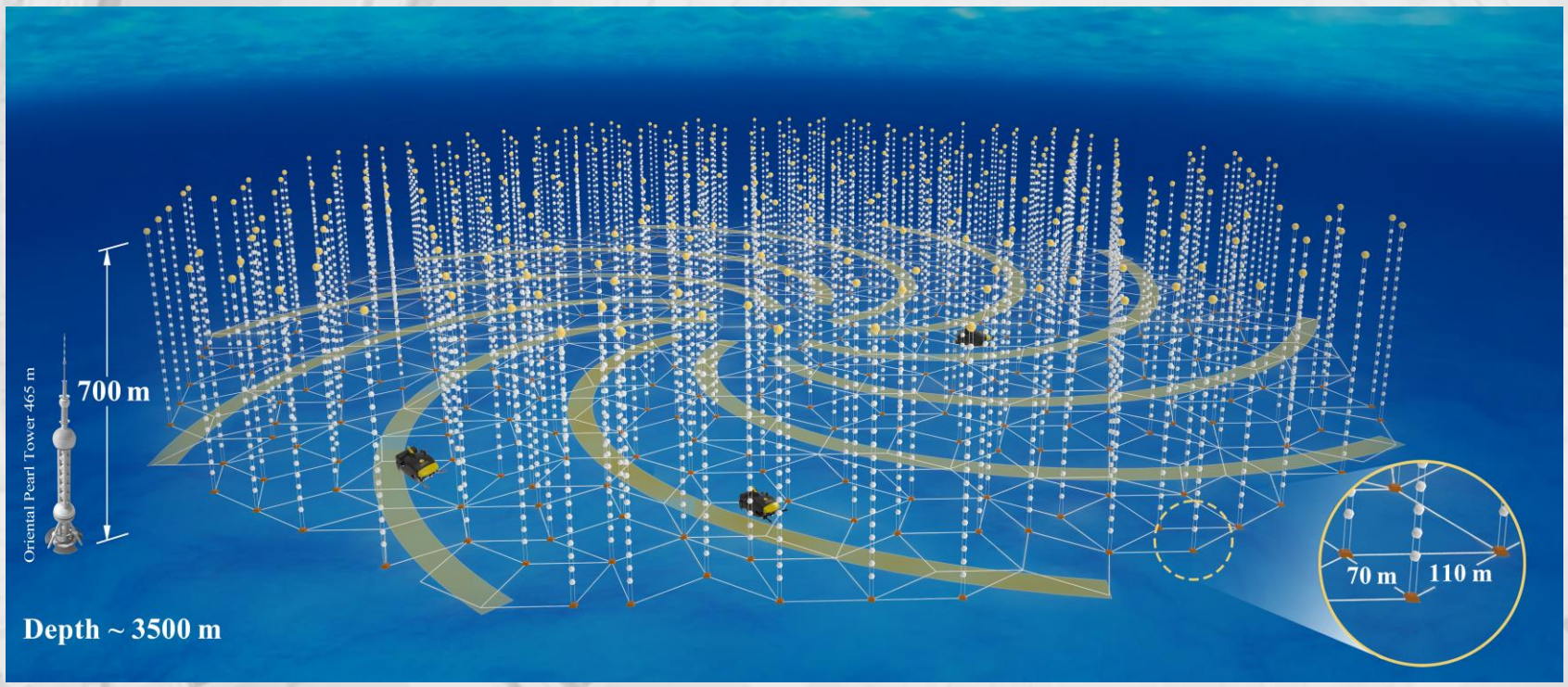
PMT TTS ~3ns + 10cm hDOM position smearing: 40% → 30%

Preliminary design: PNU3-09

F. Hu, Z. Li and D. L. Xu, PoS(ICRC2021)1043

Telescope geometry

Primary aim of design: to resolve point sources out of the diffuse flux rapidly



TRIDENT Collaboration, arXiv:2207.04519v1

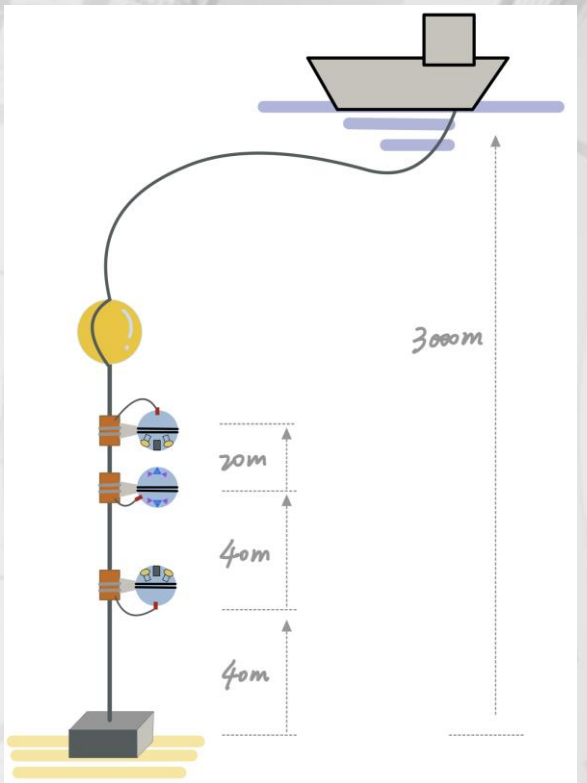
Penrose tiling

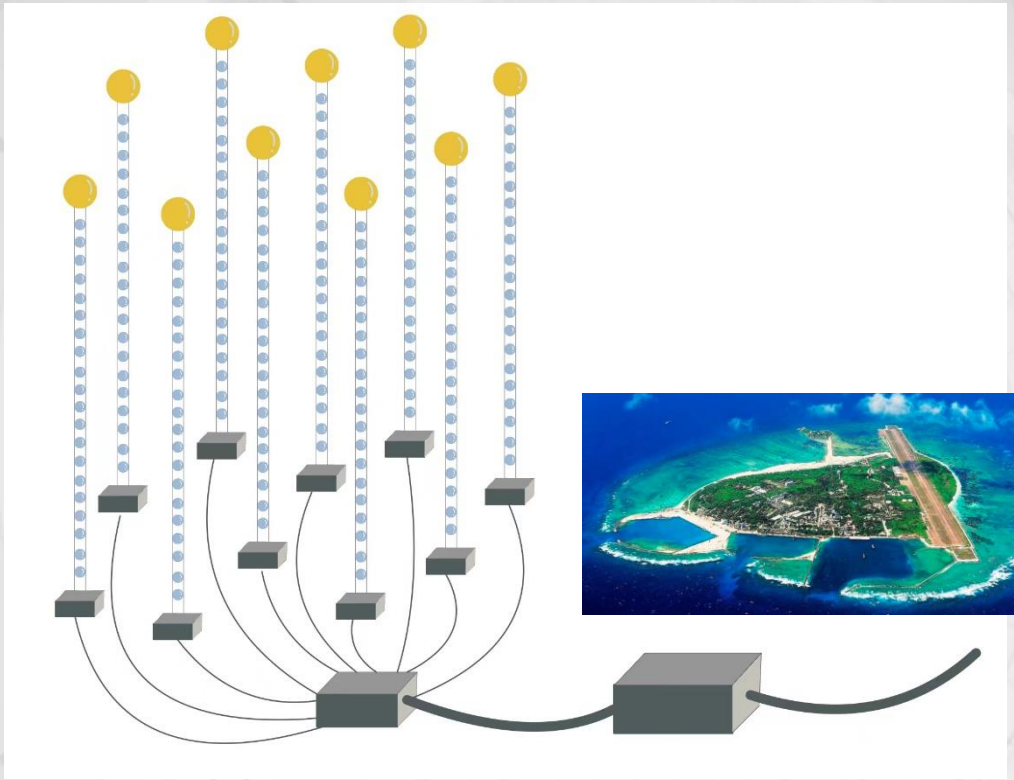
Uneven inter-string spacing **70m** and **110m**

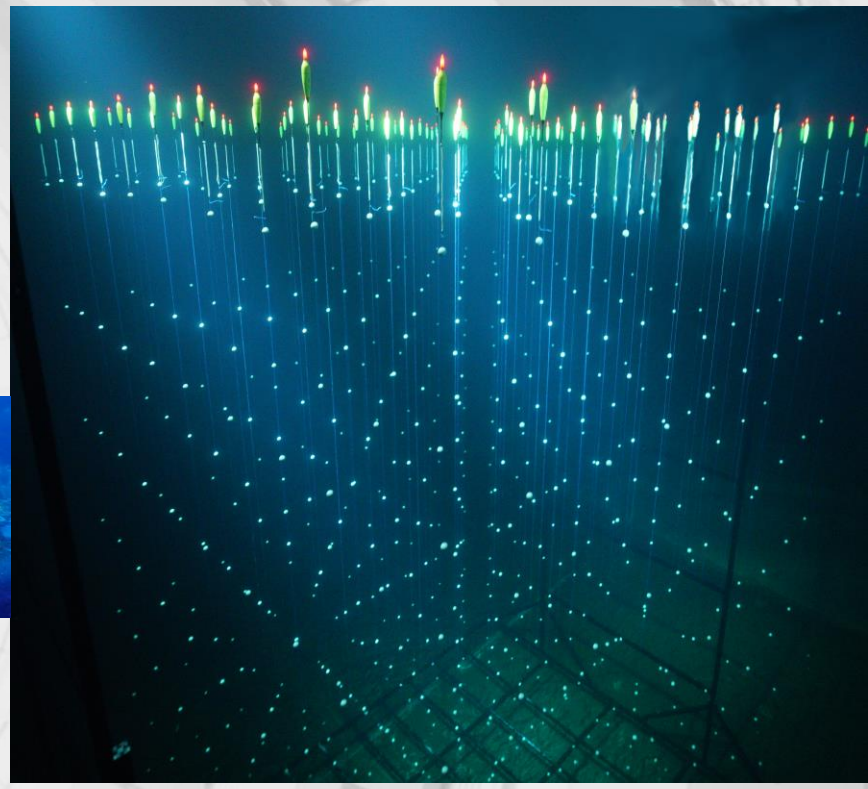
Expanded energy window of sub **TeV – EeV**

- **1200** strings
- **20** hDOMs / string
- Volume: ~ **8** km^3
- Underwater ROV for deployment & maintenance

TRIDENT Timeline





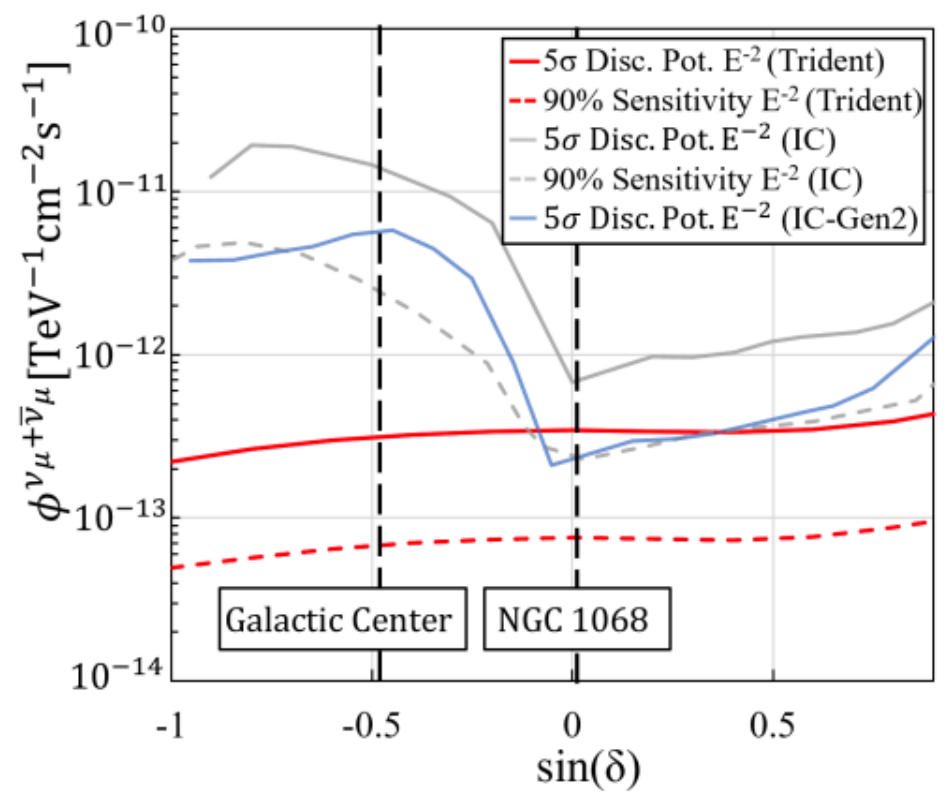


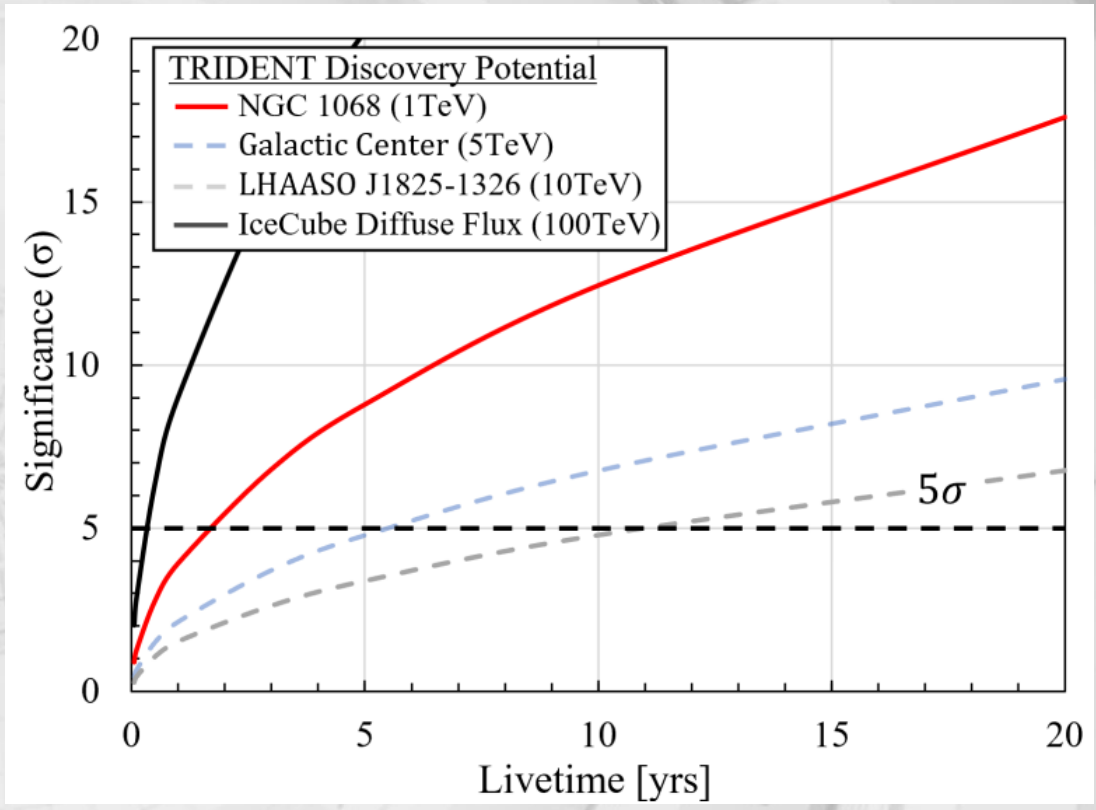
Pathfinder: 2019-2022 completed

Phase-I project: 2022-2026 in progress

Big array construction: 2026- under planning

Source sensitivities





- TRIDENT expected to detect the IceCube steady source candidate NGC1068 at 5σ level within one year of operation

TRIDENT Collaboration, arXiv:2207.04519v1

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