Progress of Experiments in China's Underground Laboratories

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2024/10/15

Outline

China Jinping Underground Laboratory

- PandaX-4T
- CDEX
- PandaX-III

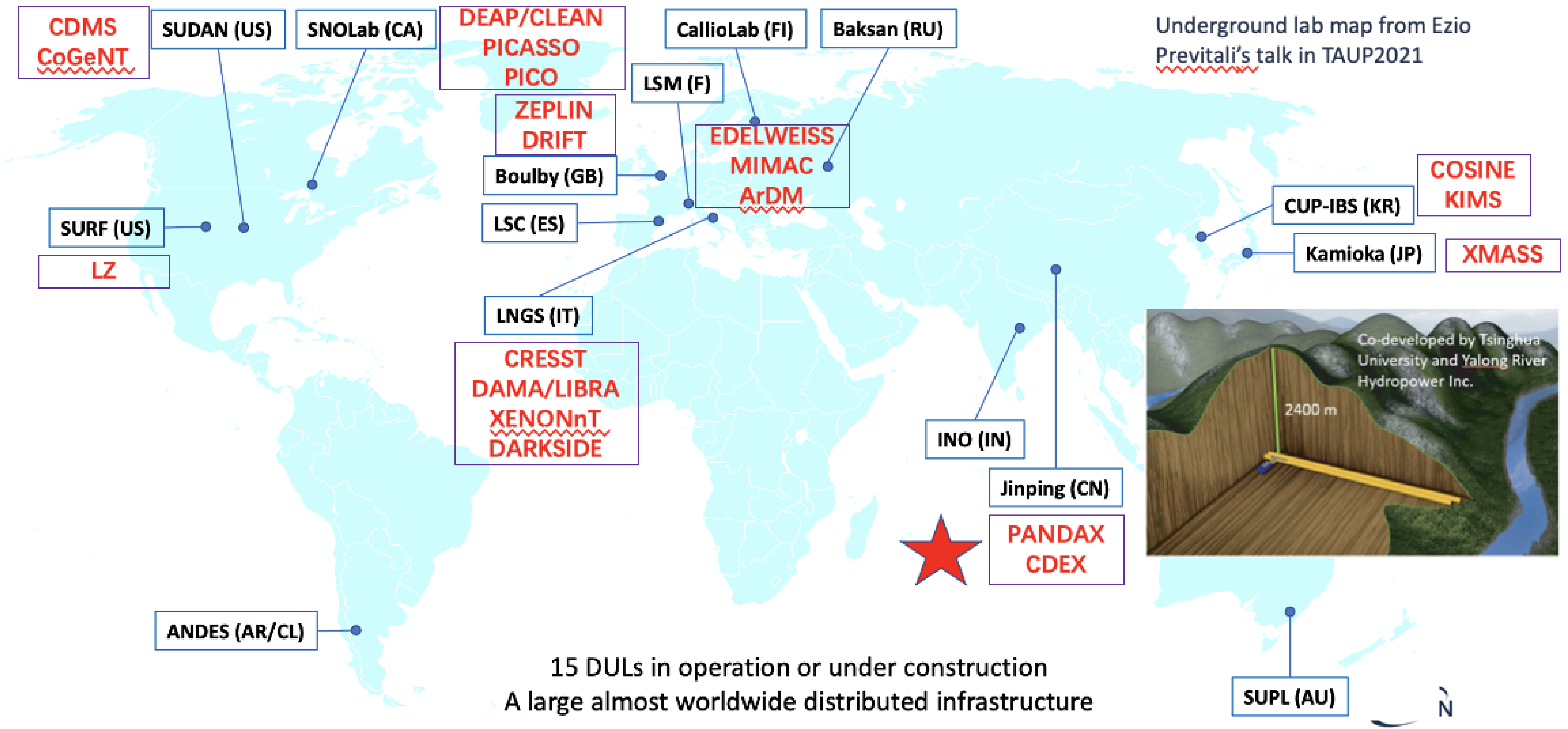
Jiangmen Underground Laboratory

- JUNO

Summary and Outlooks

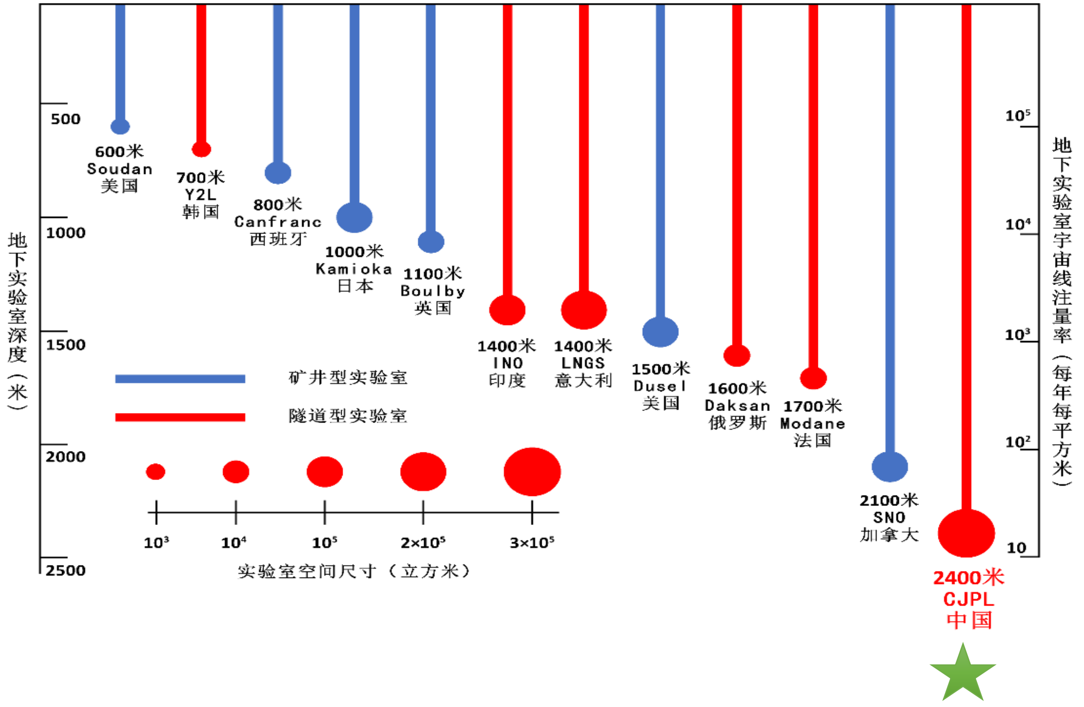
Jinping Underground Laboratory

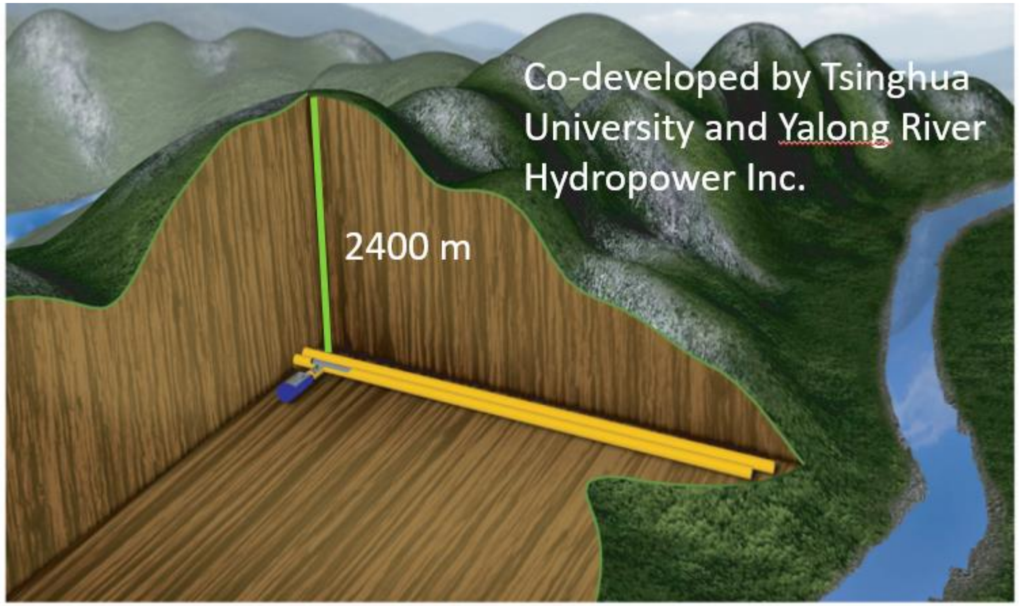
- China Jinping Underground Laboratory (CJPL) is located in Sichuan Province, China

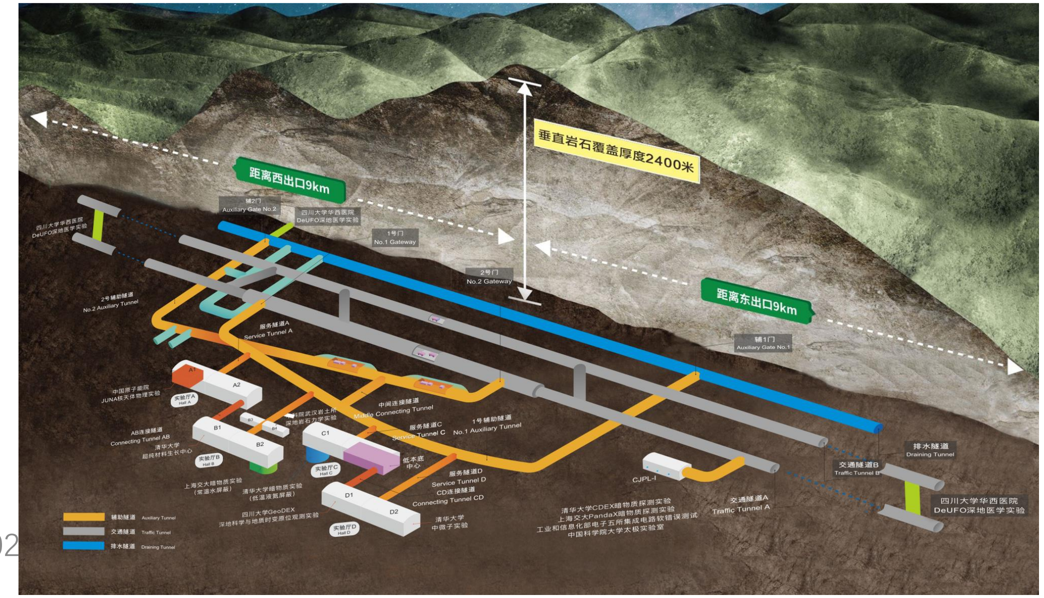


Jinping Underground Laboratory

- **Ideal site for rare decay experiments**
  - Deepest (6800 m.w.e)
  - Muon rate: ~ 1 count/week/m^2
  - Horizontal access

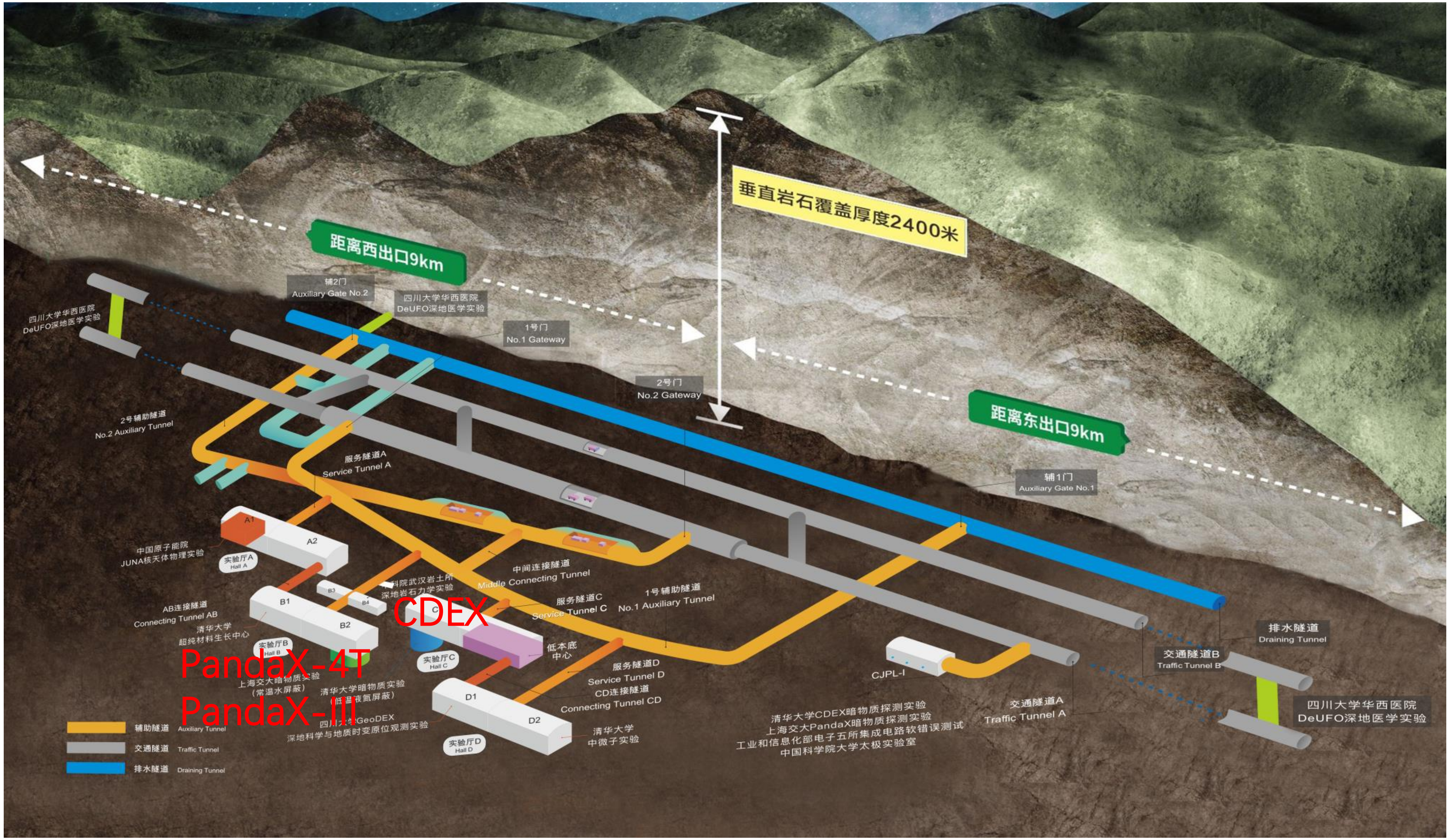






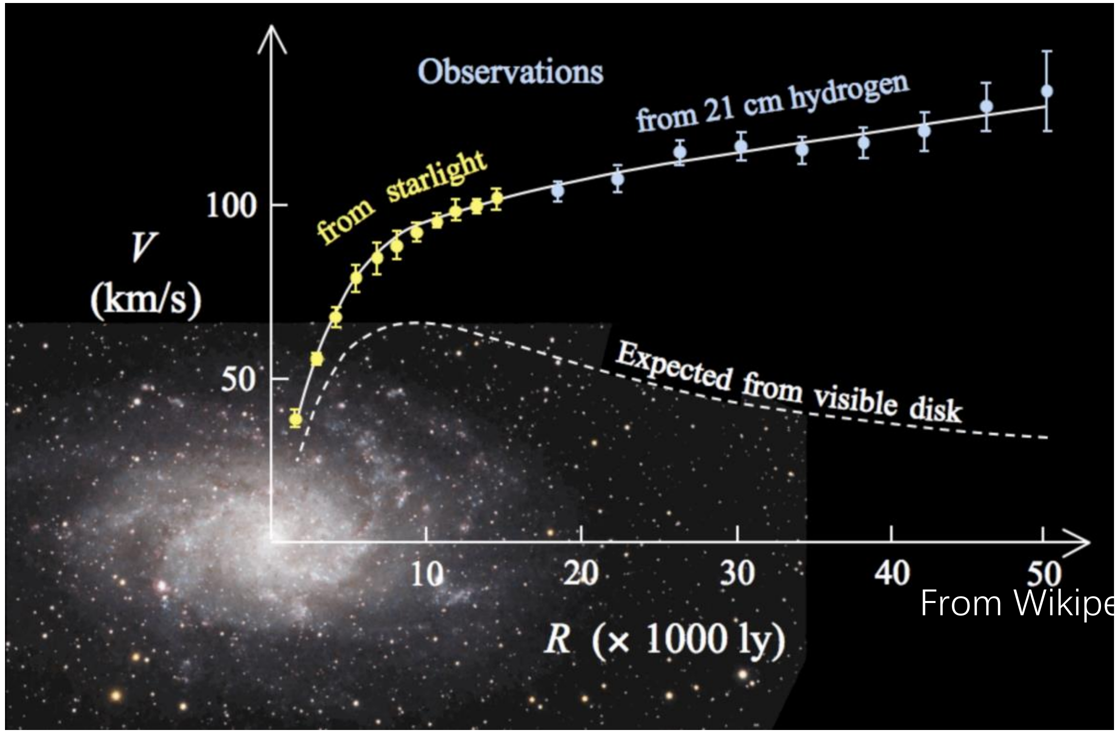
Jinping Underground Laboratory

中国锦屏地下实验室
China Jinping Underground Laboratory
CJPL
清华大学 · 雅砻江流域水电开发有限公司



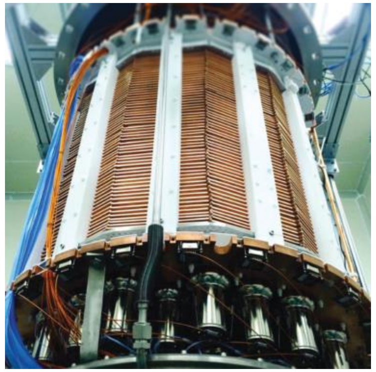
Dark matter evidence and detection method

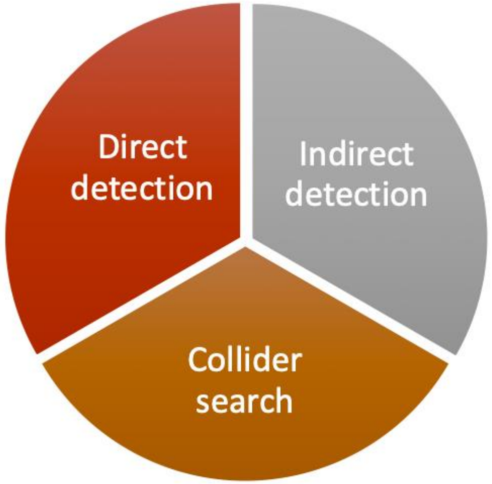
- Gravitational evidences suggest dark matter is the dominant form of matter in Universe!



Rotation curve of spiral galaxy M33

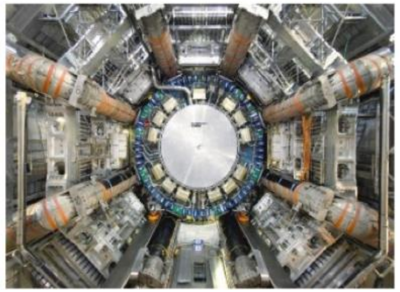
$\chi + SM \longrightarrow \chi' + SM'$



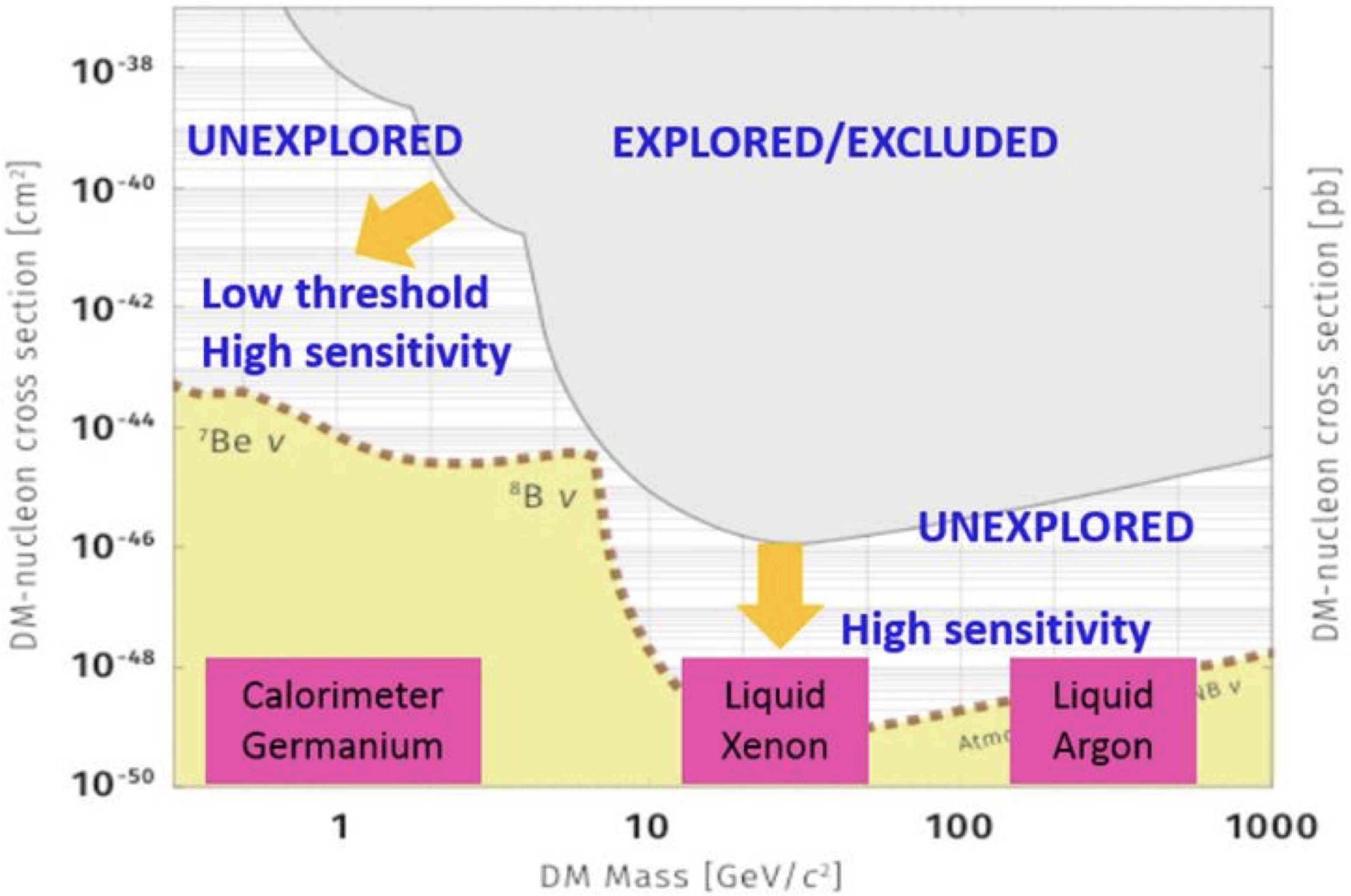


$\chi + \bar{\chi} \longrightarrow SMs$

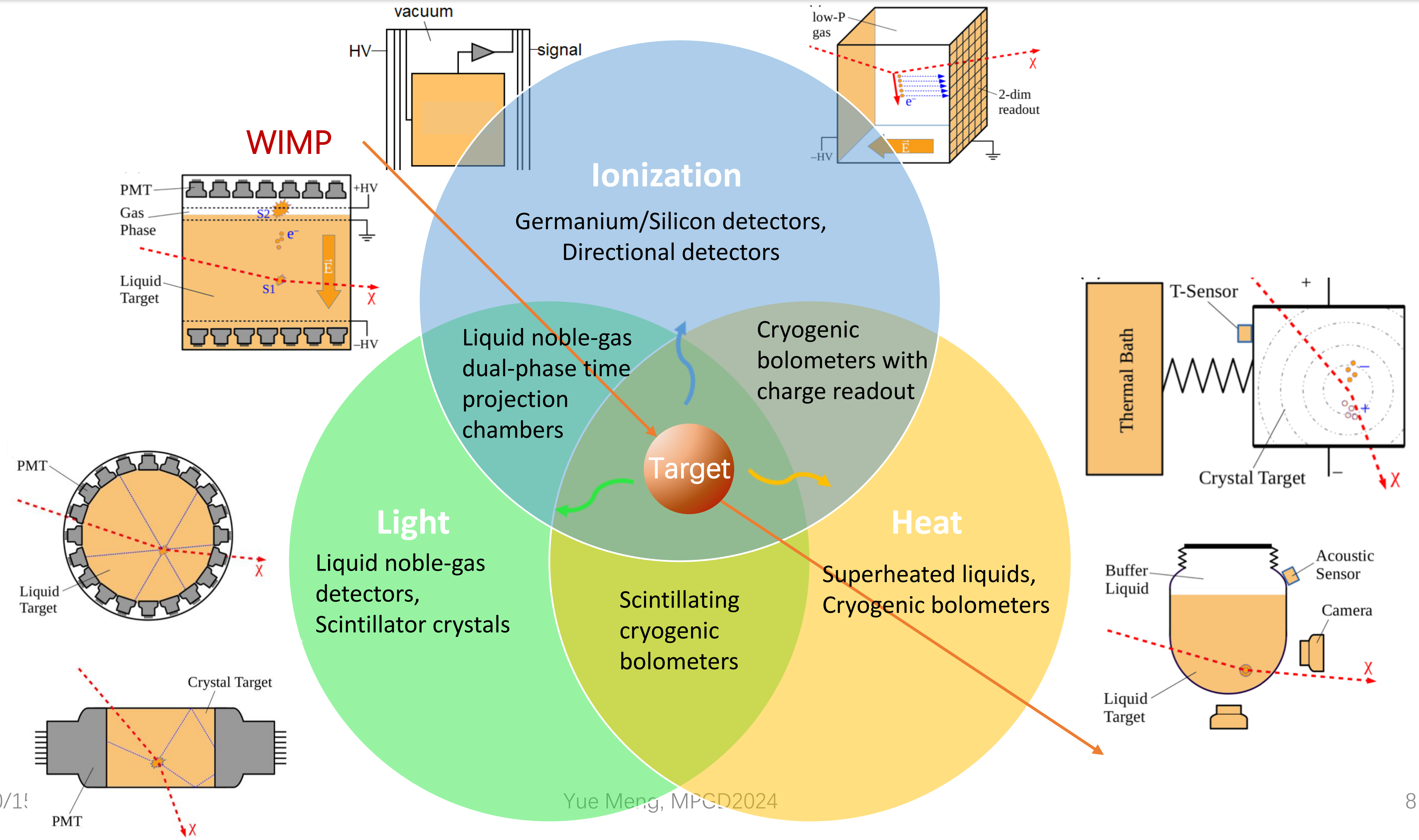
$SMs \longrightarrow \chi$(s)+(SMs)



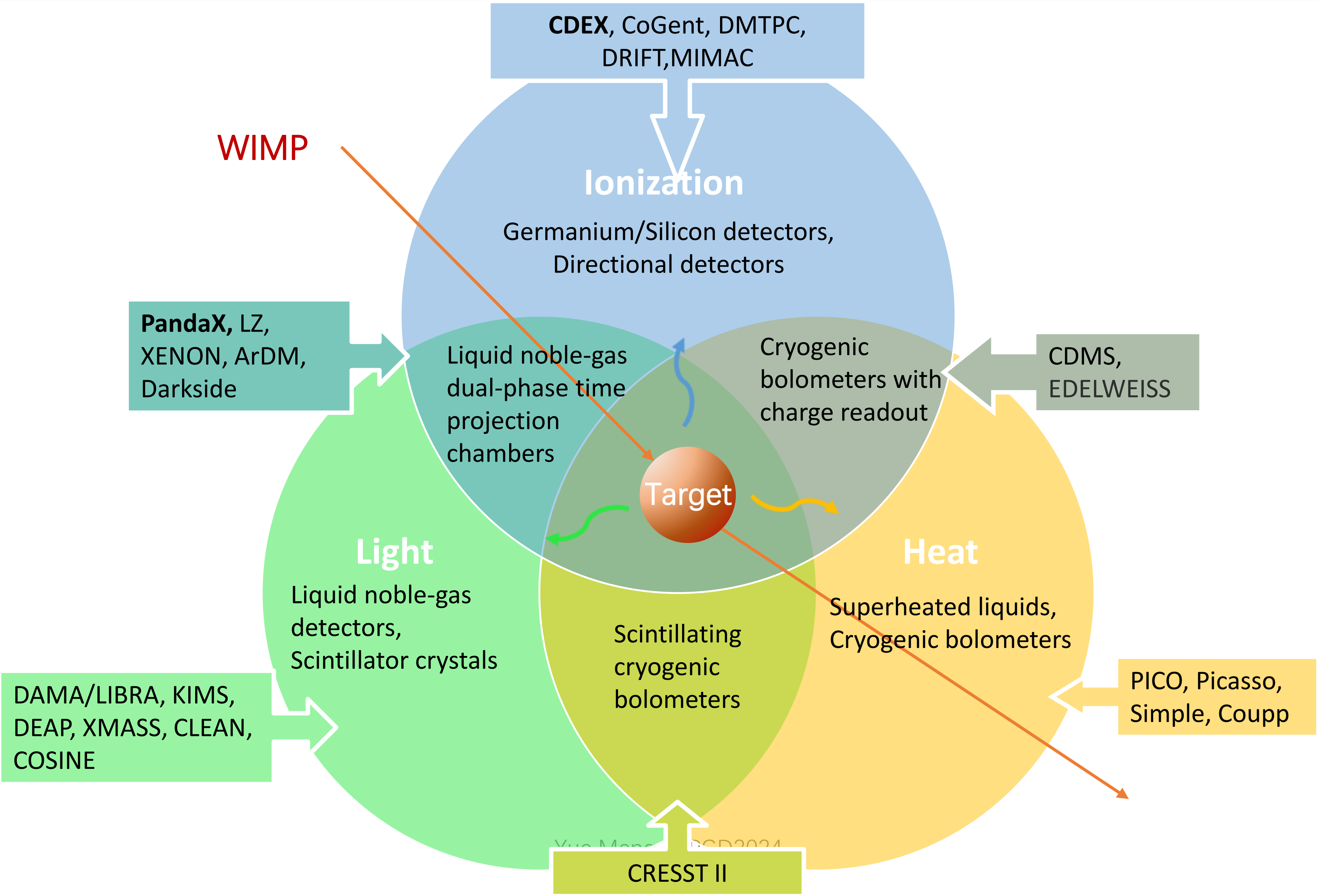
The dark matter landscape



Dark matter detection technologies



Dark matter detection technologies



PandaX-4T experiment

PandaX Roadmap

Particle and Astrophysical Xenon Experiments

Collaboration formed

2009.3

2014.5-10

PandaX-I, 120 kg operation

PandaX-II, 580 kg operation

2016.7-2019.7

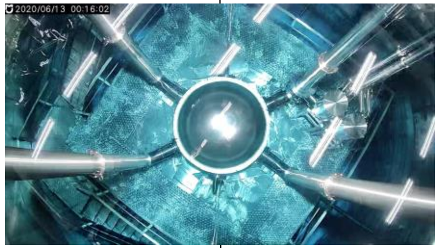
2019.8

PandaX-4T moved to CJPL-II

PandaX-4T Commissioning (Run0)

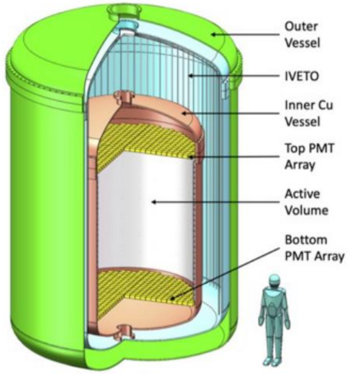
2020.11-2021.5

2021.11



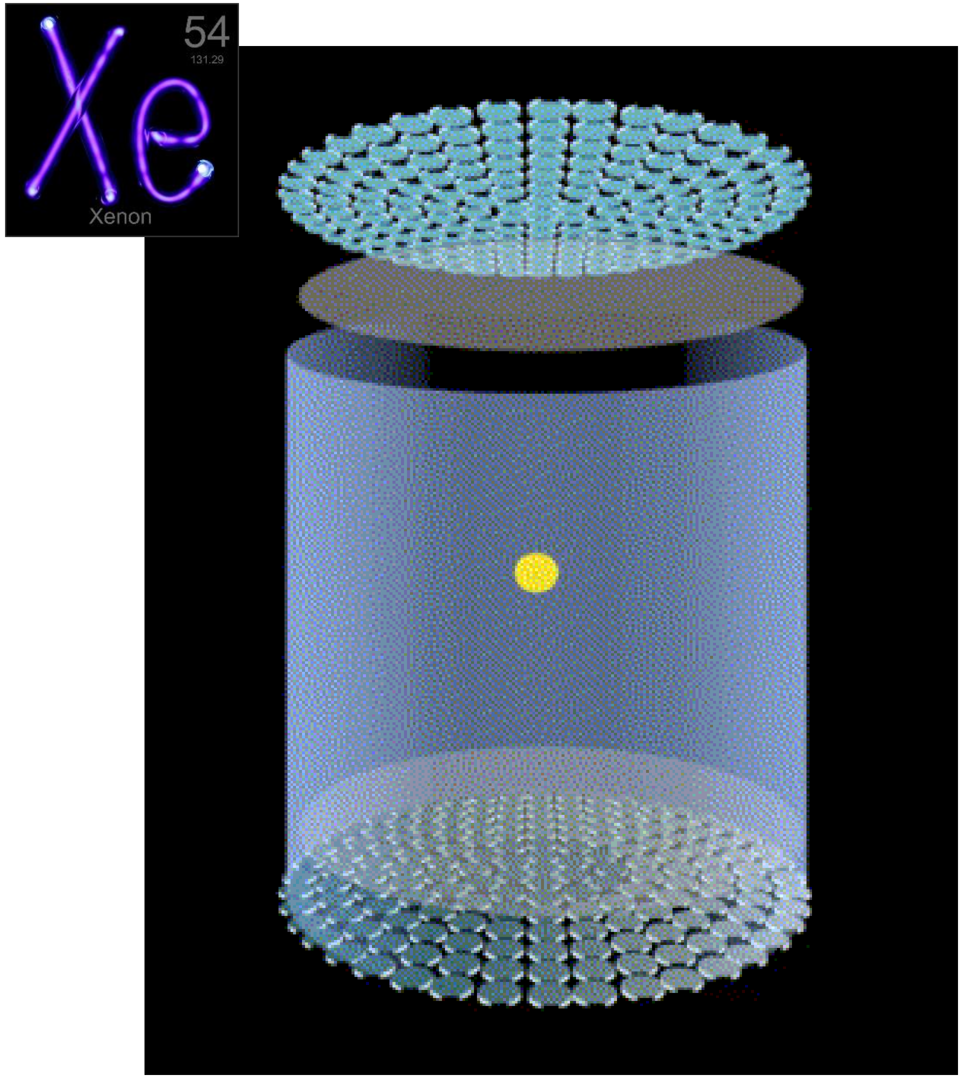
PandaX-4T Run1

Ongoing



PandaX-xT

Dual Phase Liquid-Gas Xenon TPC

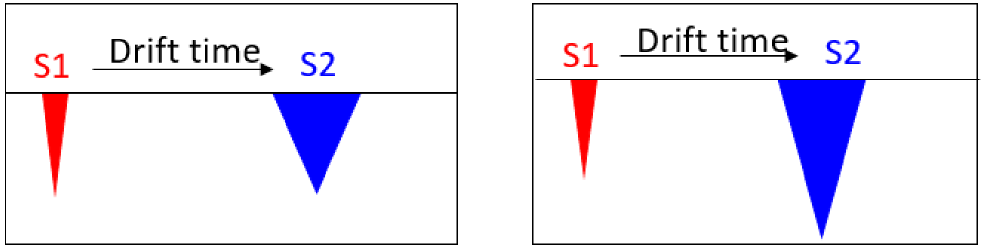


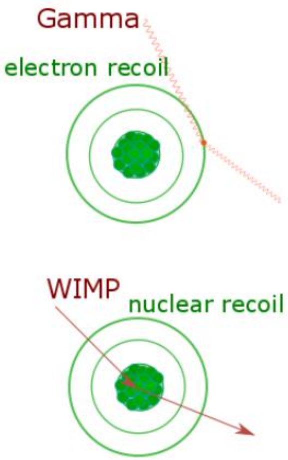
- Purity liquid xenon target, enhanced DM signals, achievable liquefication temperature, high light & charge yield

- Good ER/NR discrimination by S2/S1 ratio

Dark matter: nuclear recoil (NR)

γ background: electron recoil (ER)



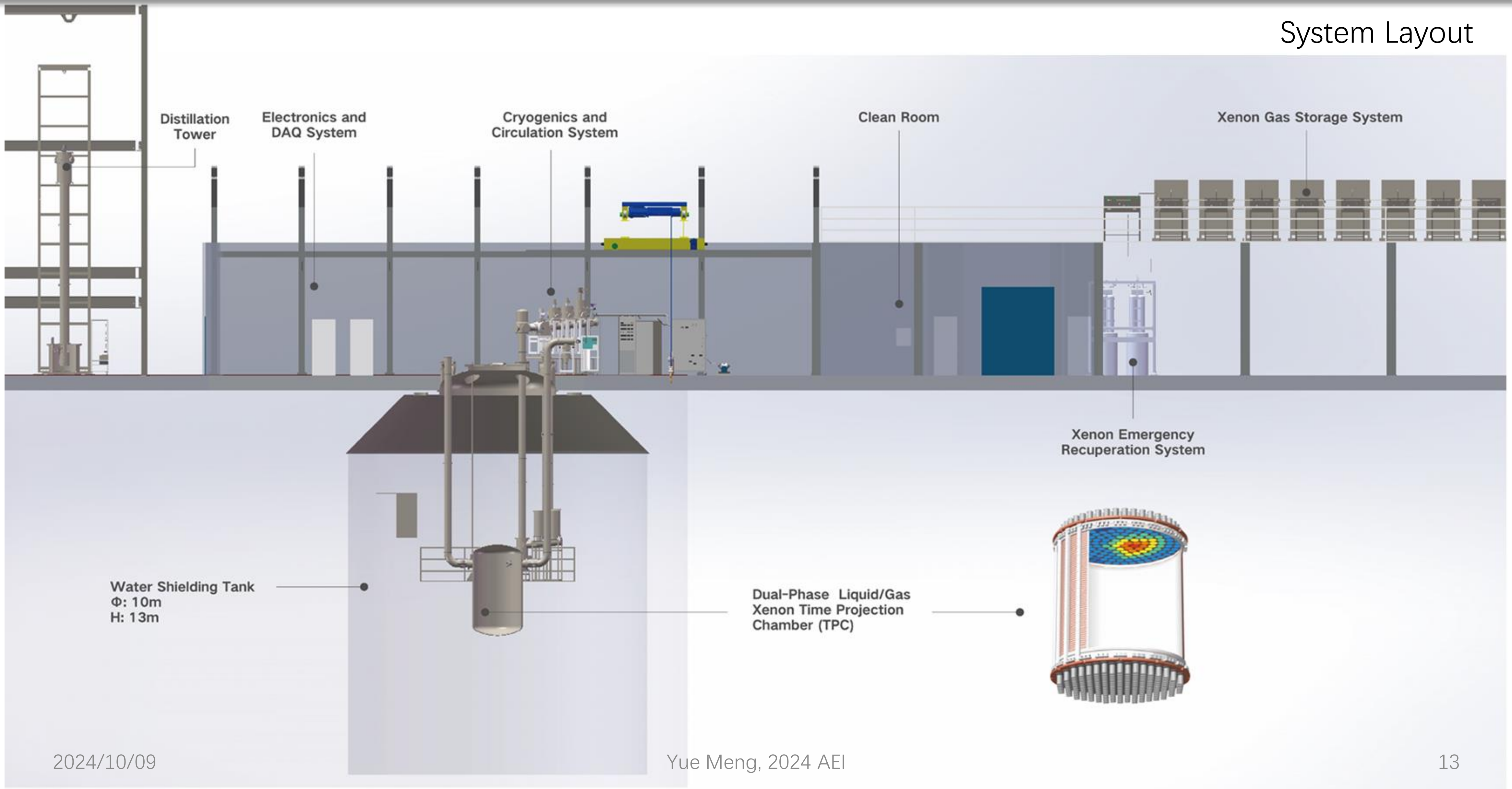


$(S2/S1)_{NR} << (S2/S1)_{ER}$

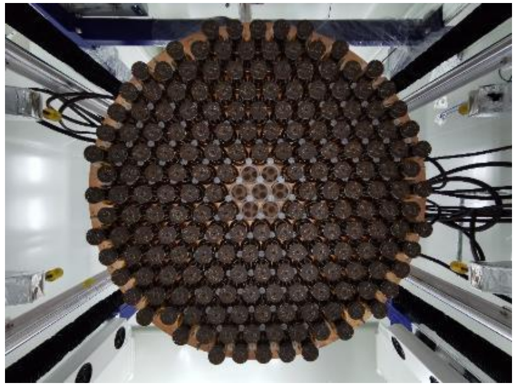
- 3D reconstruction rejects external background

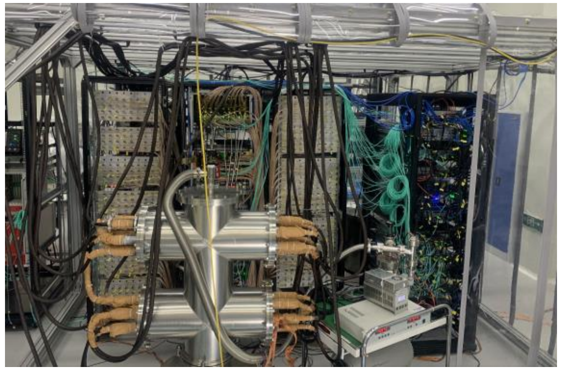
PandaX-4T Layout

System Layout



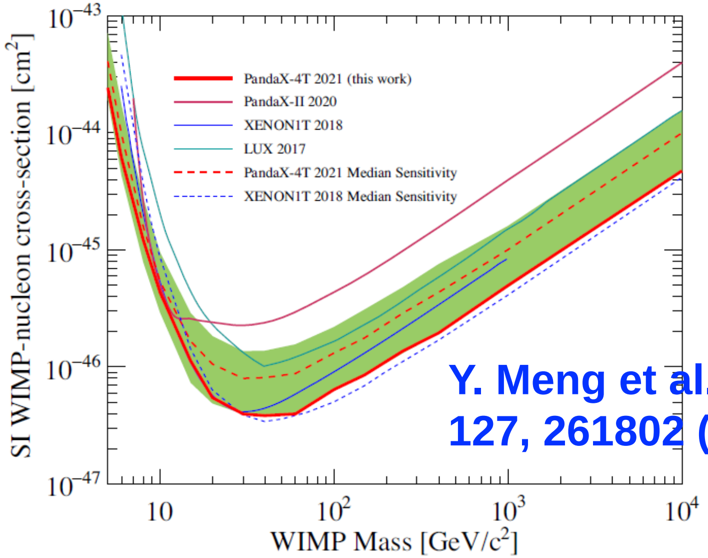
PandaX-4T Detector





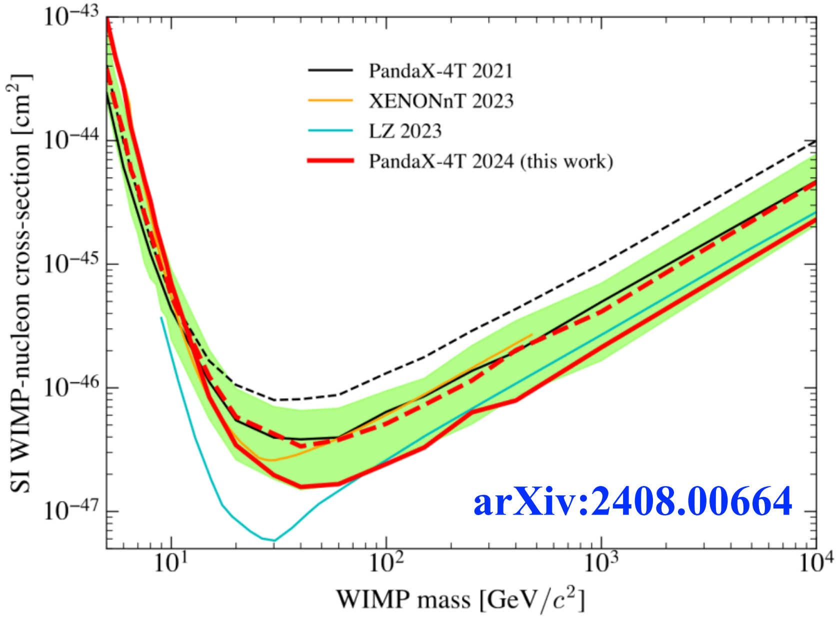
PandaX-4T WIMPs Searching

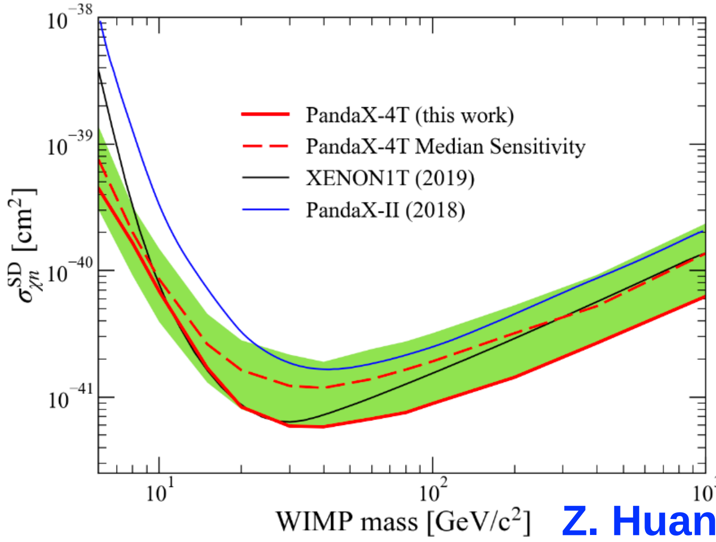
Run0

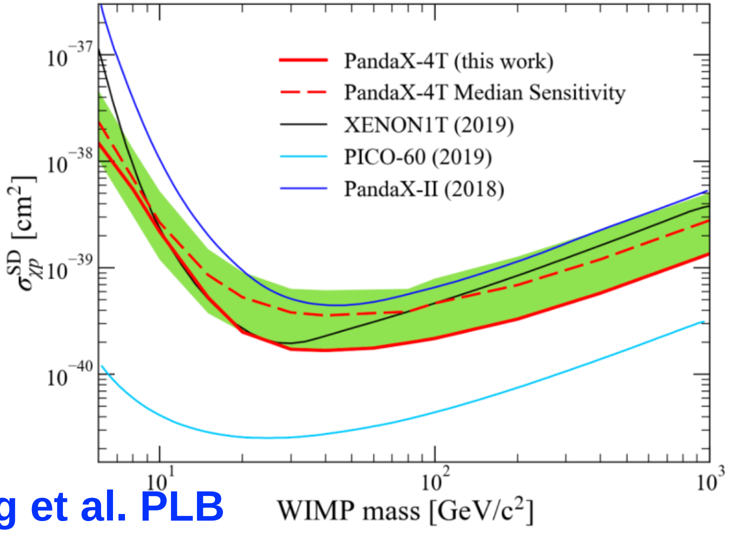


Y. Meng et al. PRL 127, 261802 (2021)

Run0+Run1







Z. Huang et al. PLB 834, 137487 (2022)

- Combined analysis using Run0+1, total exposure = 1.54 tonne-year;
- 1σ upward fluctuation with <8 GeV, while downward fluctuation in high-mass region;
- 1.6e-47 cm^2 @ 40GeV;

Luminance of Dark Matter

- Possible residual weak EM properties
- Coupling with photons

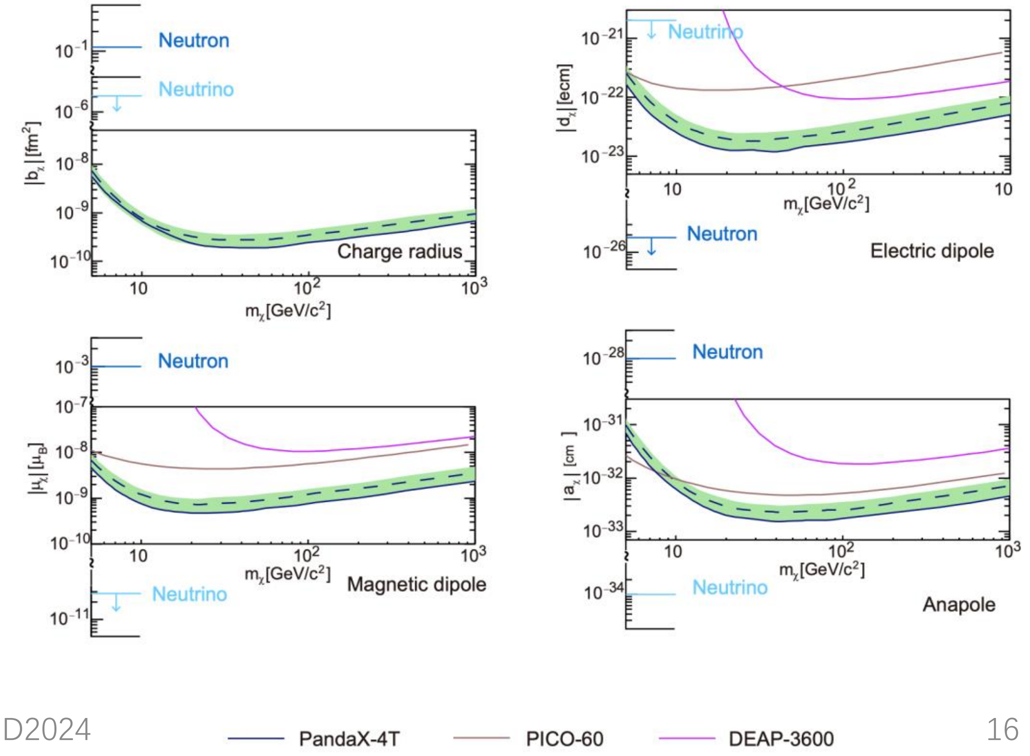
$$\mathcal{L} = Qe\bar{\chi}\gamma^{\mu}\chi A_{\mu} + \frac{\mu_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + i\frac{d_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu} + b_{\chi}\bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu} + a_{\chi}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$$

millicharge | magnetic dipole | electric dipole | charge radius | anapole

tree-level | higher-order loop-level

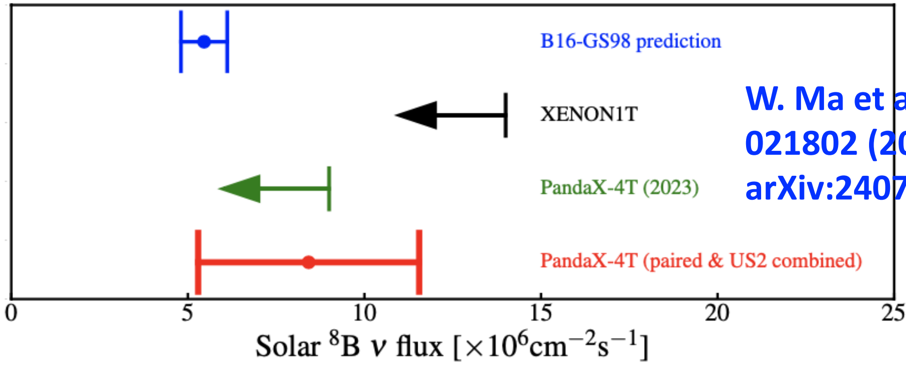
- **First experimental constraints on DM charge radius**
  - 4 orders of magnitude smaller than neutrino
- **Other EM properties**
  - Up to 3 – 10 times improvement

X. Ning et al. Nature 618 (2023) 7963, 47-50



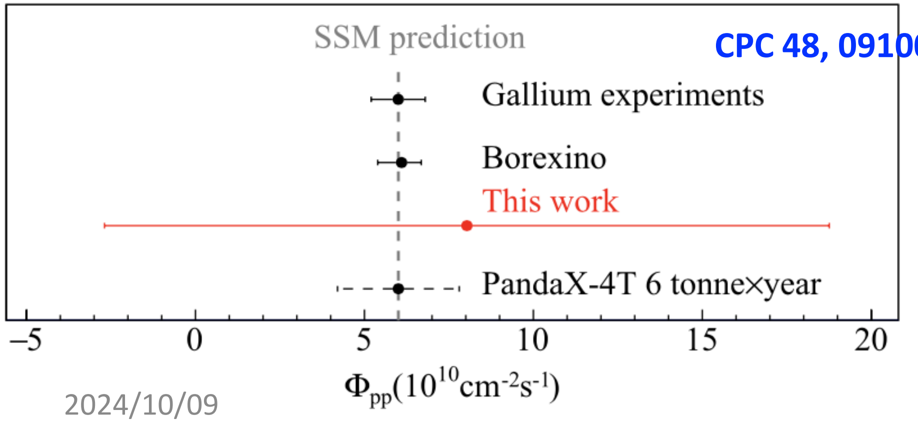
PandaX-4T Search for Neutrinos

- PandaX-4T measures solar ^{8}B neutrino flux by CEvNS channel



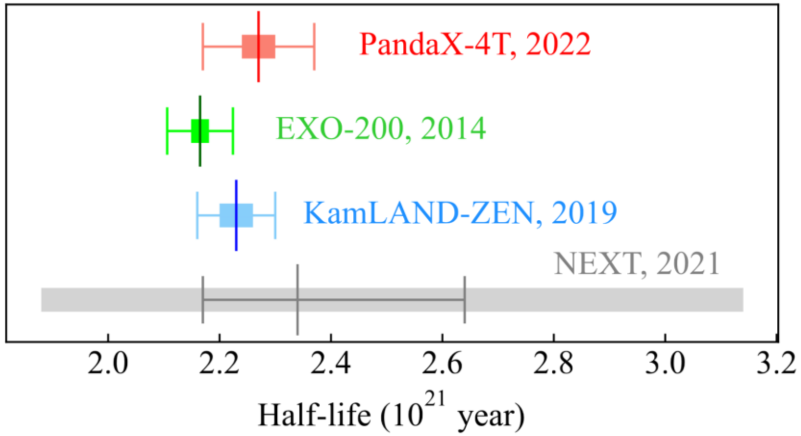
W. Ma et al. PRL 130, 021802 (2023)
arXiv:2407.10892v3

- PandaX-4T measures pp neutrino by neutrino-electron elastic scatterings



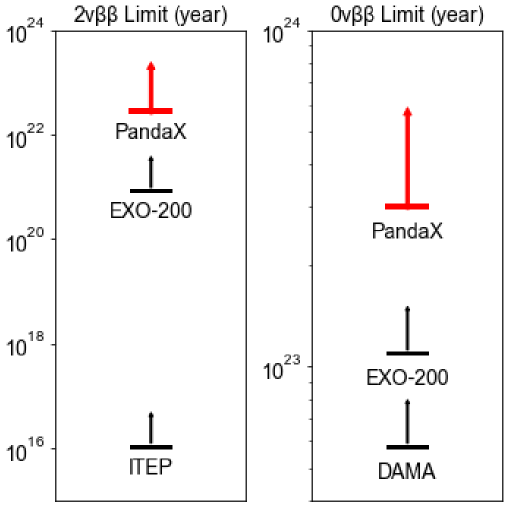
CPC 48, 091001 (2024)

- First ^{136}Xe 2υDBD half-life measurement with natural xenon detector



Research Vol 2022, 9798721 (2022)

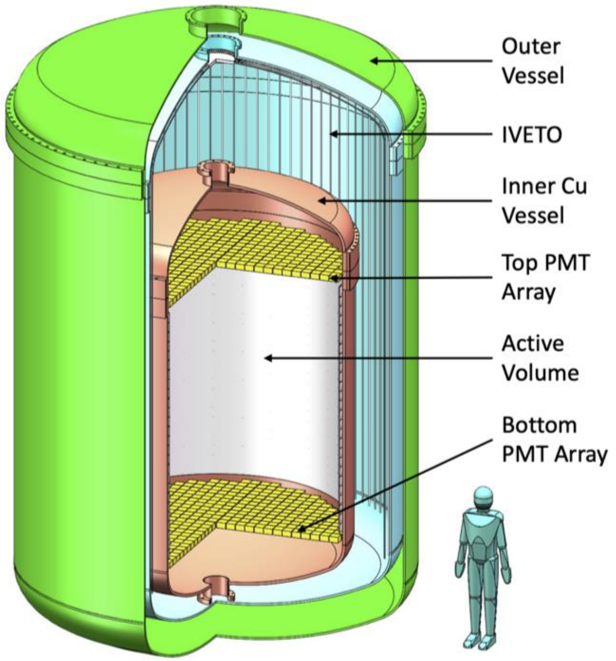
- ^{134}Xe $2/0\upsilon$DBD half-life measurements

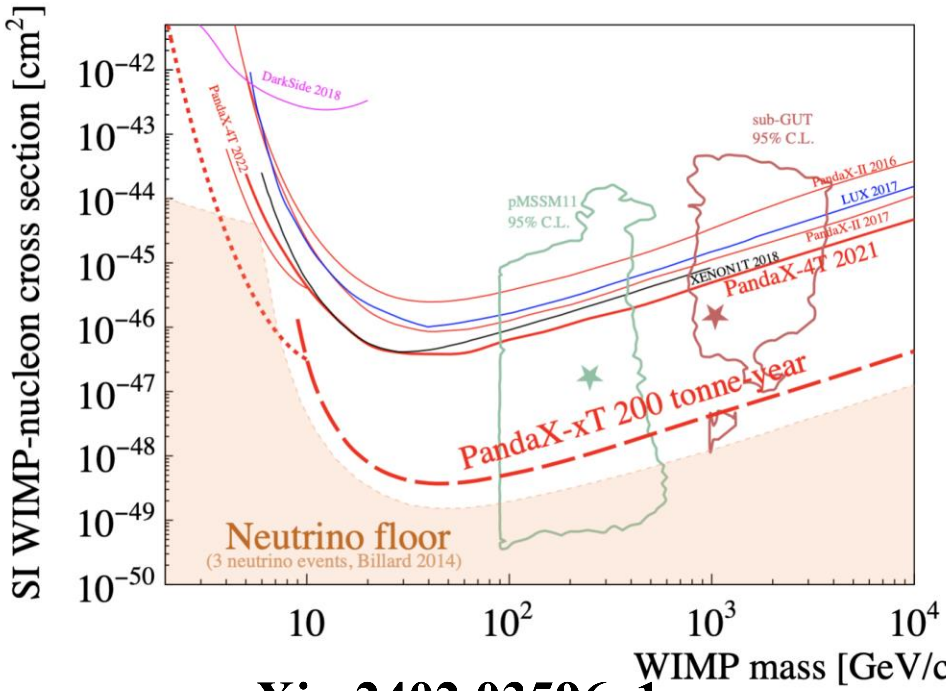


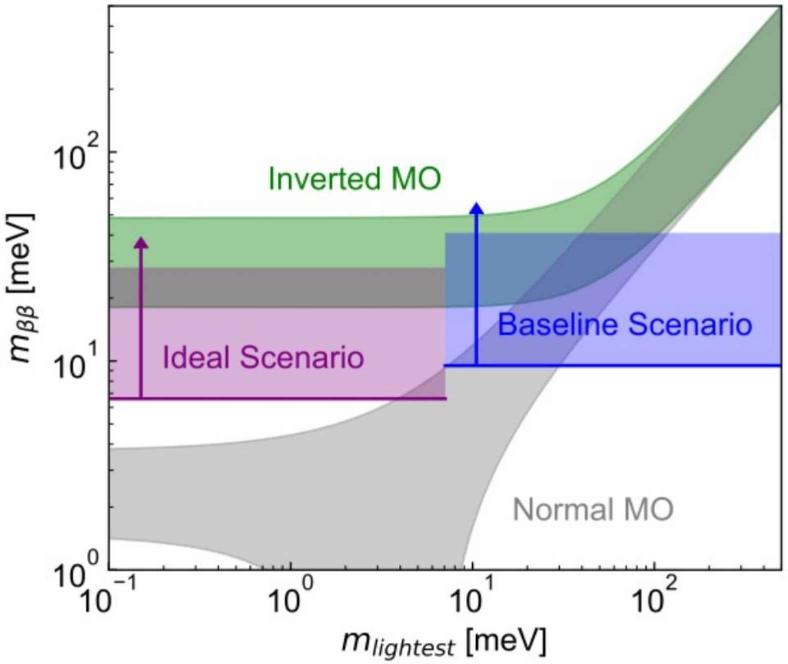
PRL 132, 152502 (2024)

Future plan: PandaX-xT

- **Next-generation liquid xenon experiment**
  - with >30 tonne liquid xenon in the sensitive volume
  - decisive test on WIMP and key test on Dirac/Majorana neutrino







arXiv:2402.03596v1

CDEX experiment

From Litao Yang, Tsinghua University

China Dark matter Experiment (CDEX)

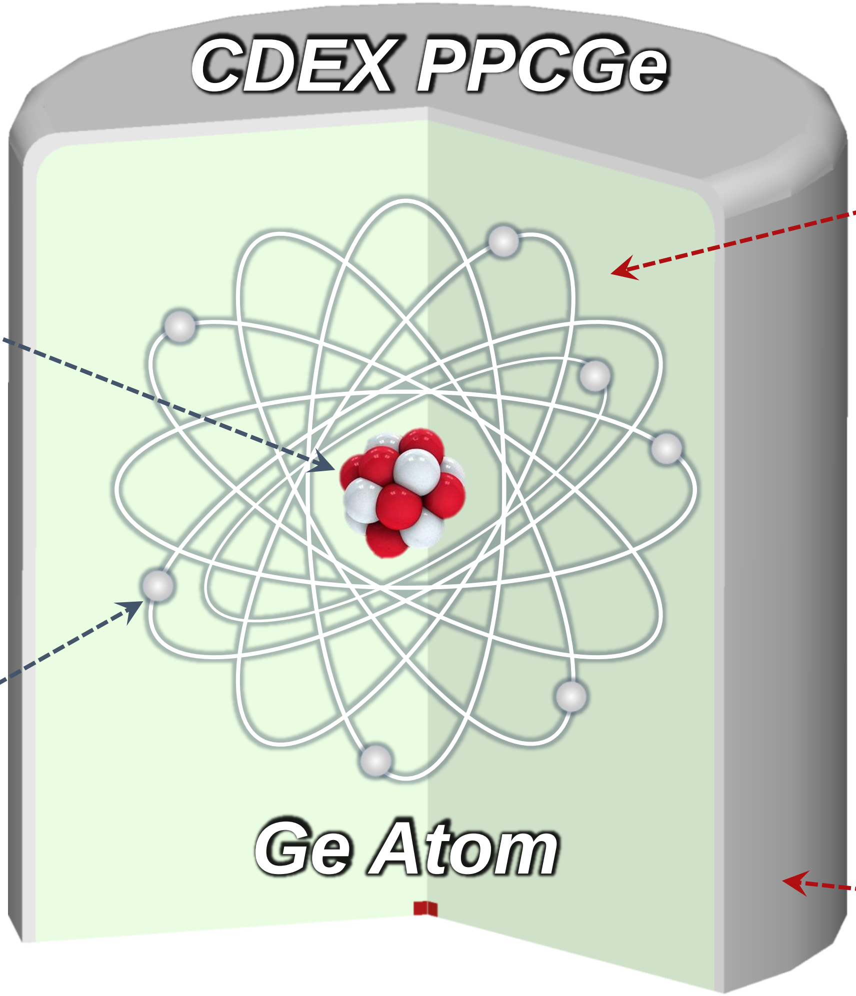
- **CDEX operates low energy threshold PPCGe to search for Light Dark Matter in CJPL**

DM Signal

Dark Matter Interaction with Nucleus

WIMPs,
Bosonic DM,
Fermionic DM,
Boosted DM,
Evaporating PHBs
DM Modulation
…

Dark Matter Interaction with Electrons



Background

Interaction with bulk sensitive volume

Ge cosmogenic isotopes
(Ge-68, Mn-54, …, H-3)

Primordial radionuclides
(U-chain, Th-chain, Rn-222)
(shielded by Cu, Pb)

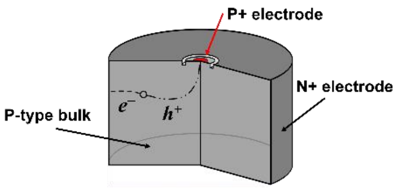
Environmental Neutron
(shielded by 1 m PE and BPE)

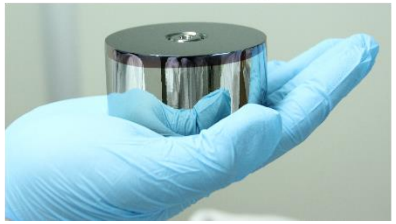
Cosmic-ray muon
(shielded by 2400 m rock of CJPL)

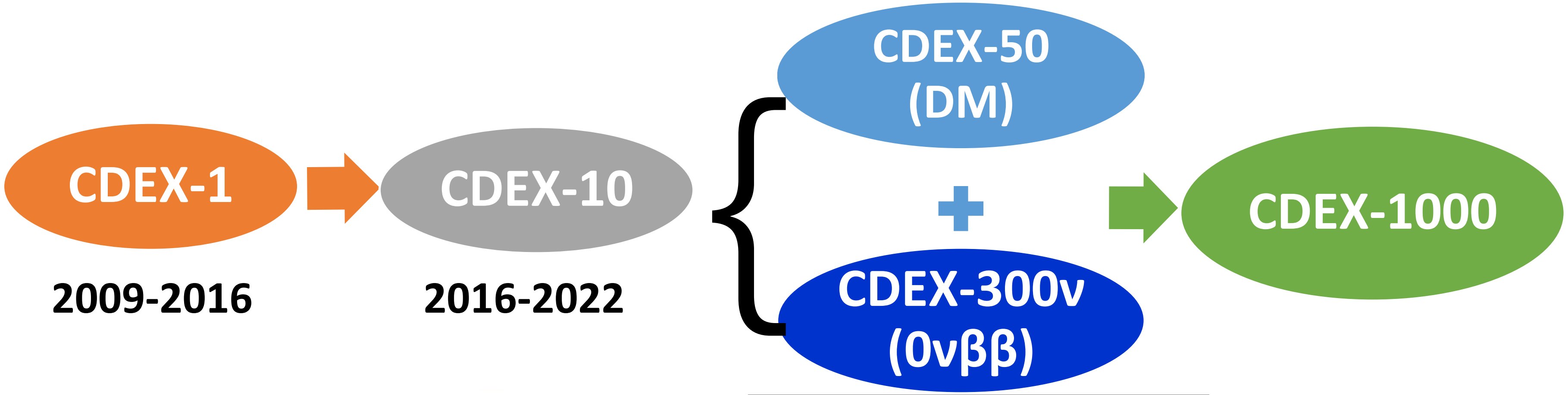
Interaction with surface inactive volume

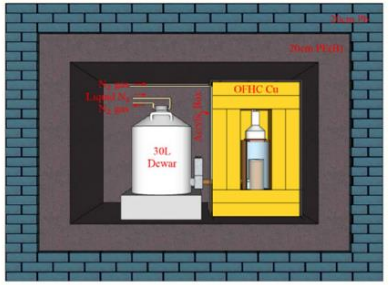
CDEX Roadmap

- **CDEX-1 (2009-2016):** Development of PPC Ge detector, bkg understanding
- **CDEX-10 (2016-2022):** Performances of Ge array detector immersed in LN_2
- **CDEX-50 (2021-202X):** 50kg Ge detector arrays for DM searches
- **CDEX-300ν (2021-202X):** 300kg enriched Ge detector arrays for 0νββ Exp.

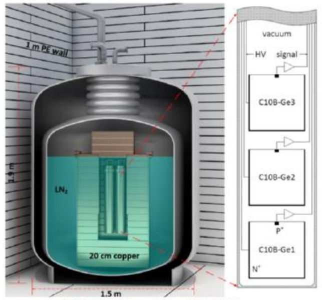




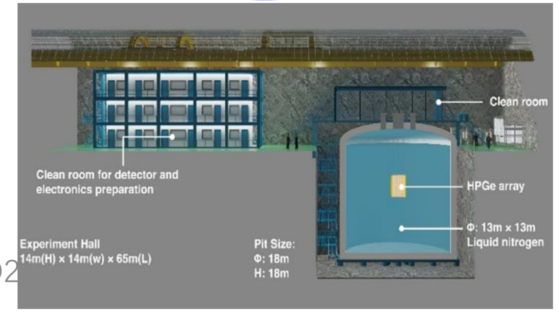




CDEX-1A&B: 1kg PPC Ge×2

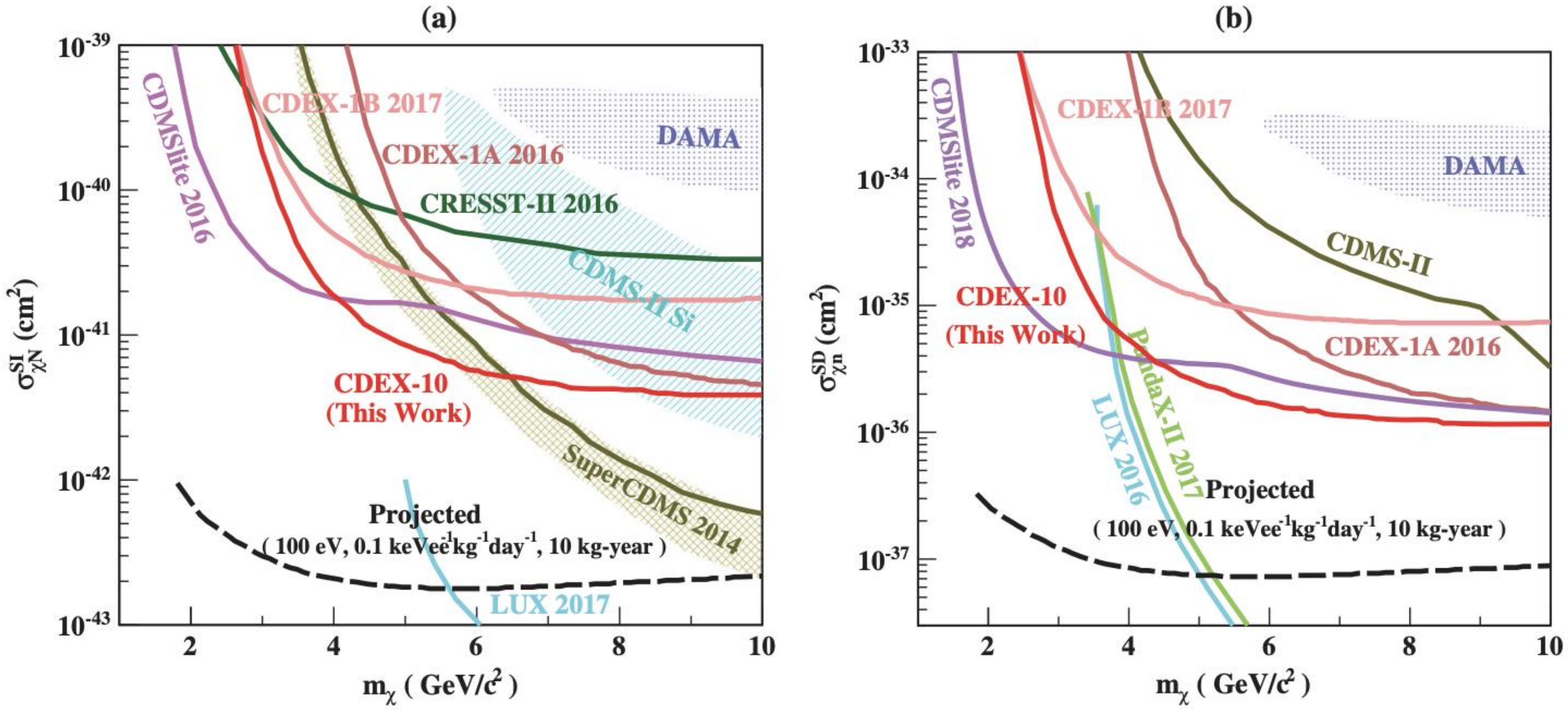


CDEX-10: ~10kg PPC Ge array

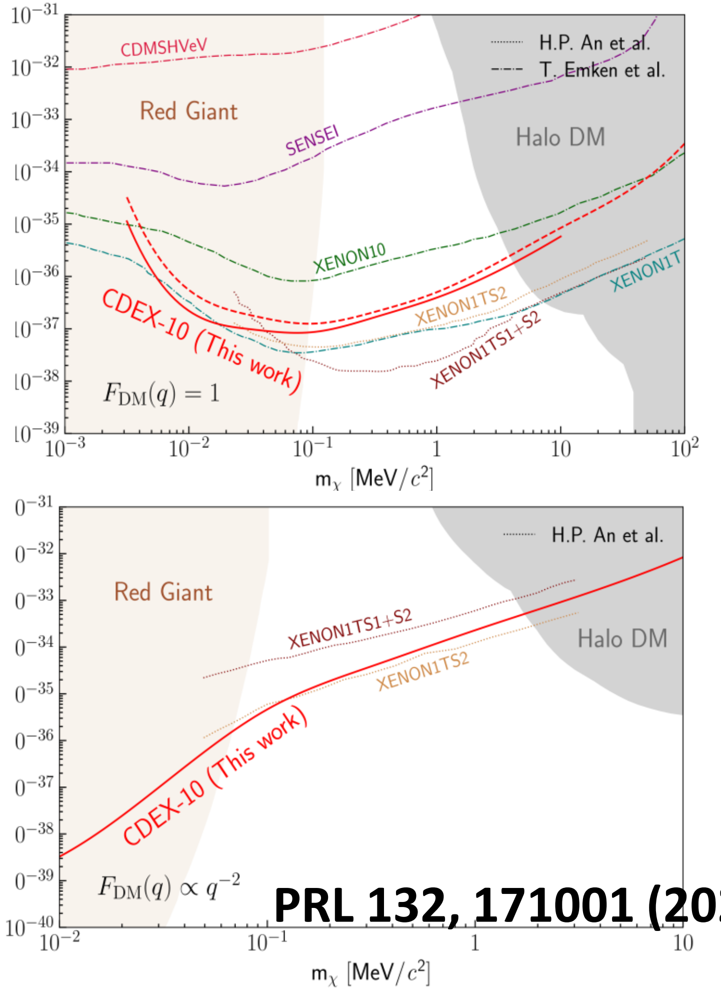


Dark matter Searching

- **CDEX-10 WIMP search results**



PRL 120, 241301 (2018)



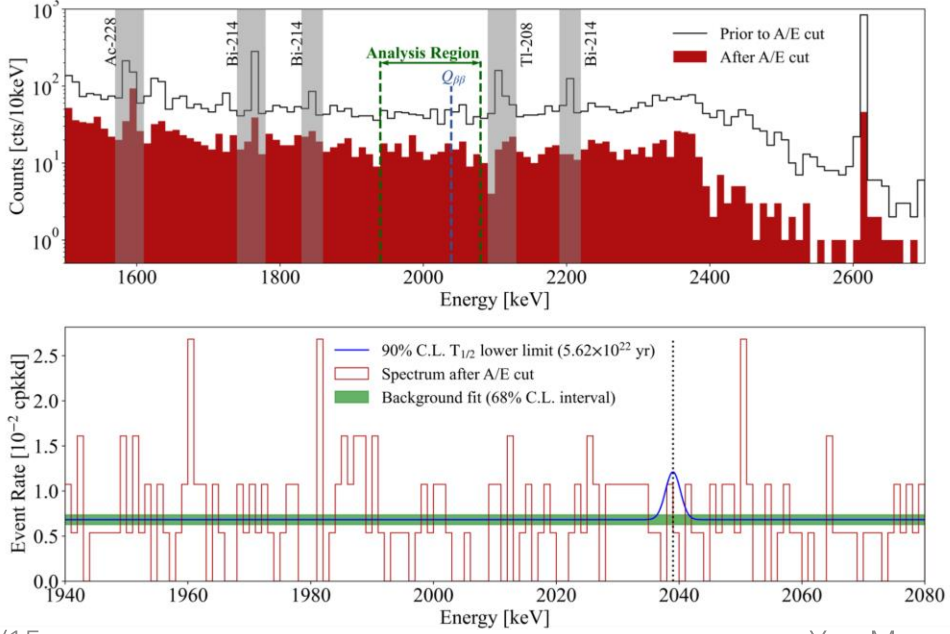
PRL 132, 171001 (2024)

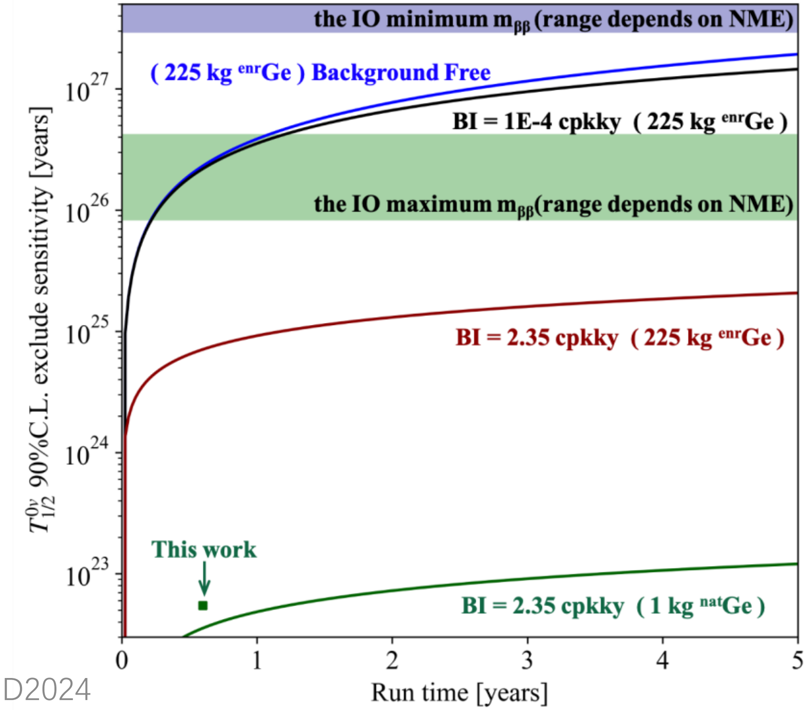
CDEX-10 SRDM results

New 0νββ result from CDEX

- Natural BEGe, 1.1kg, 186.4 kg·day exposure
- Establish data analysis procedure and PSD method, 50% reduction of background in ROI than CDEX-1
- First CDEX result from BEGe, $T_{1/2}^{0\nu} \geq 5.6 \times 10^{22}$ yr, 90% C. L.

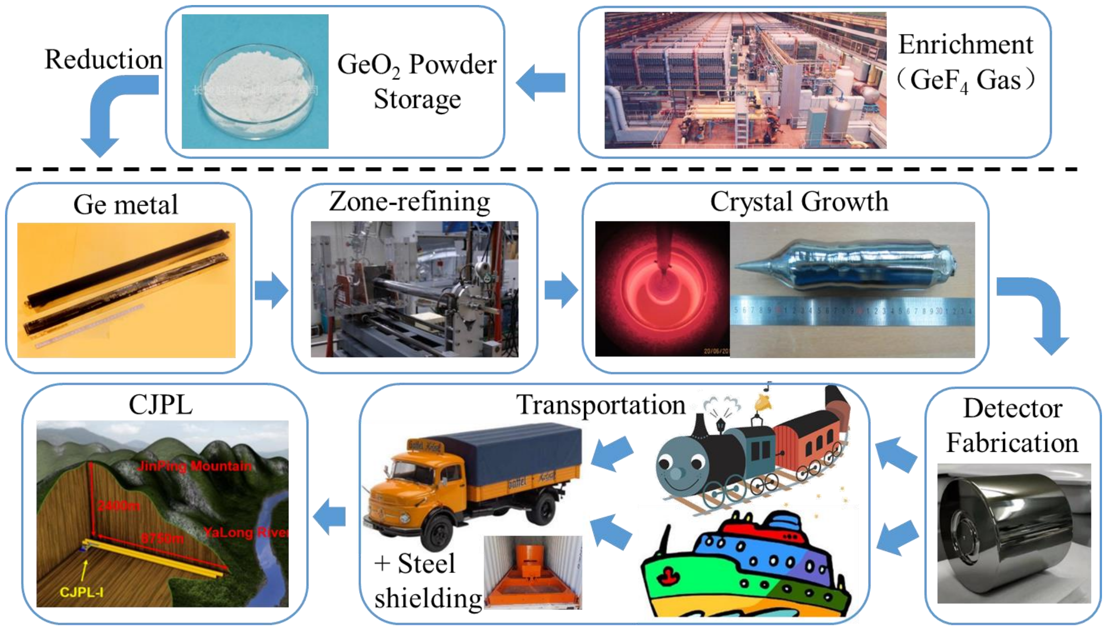
PRD 106, 032012 (2022)





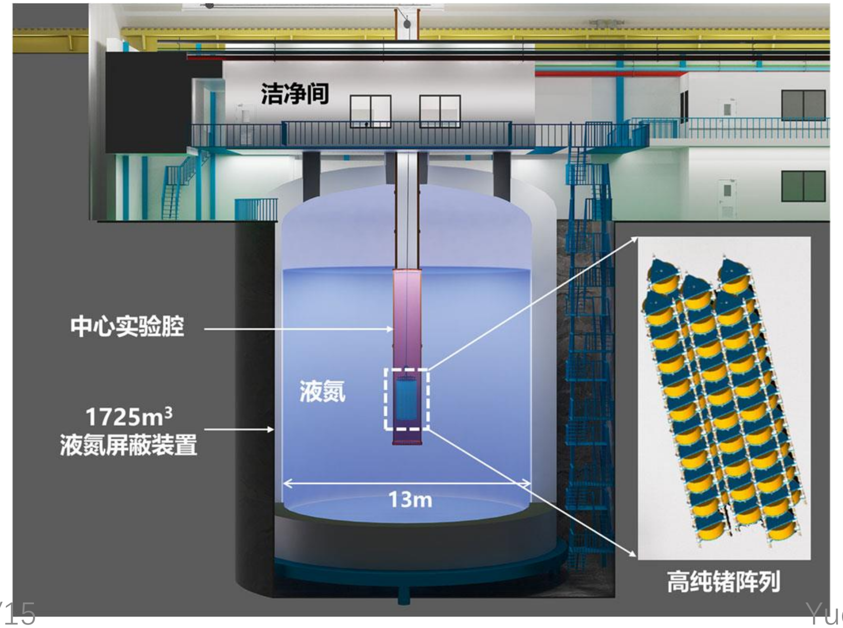
Enriched Ge material

- 200kg ^{76}Ge (>86%) arrived, half from Russia and half from China
- Whole technical chain established
- The mass production power (hundreds of kg per year) of enriched ^{76}Ge material has been setup in China

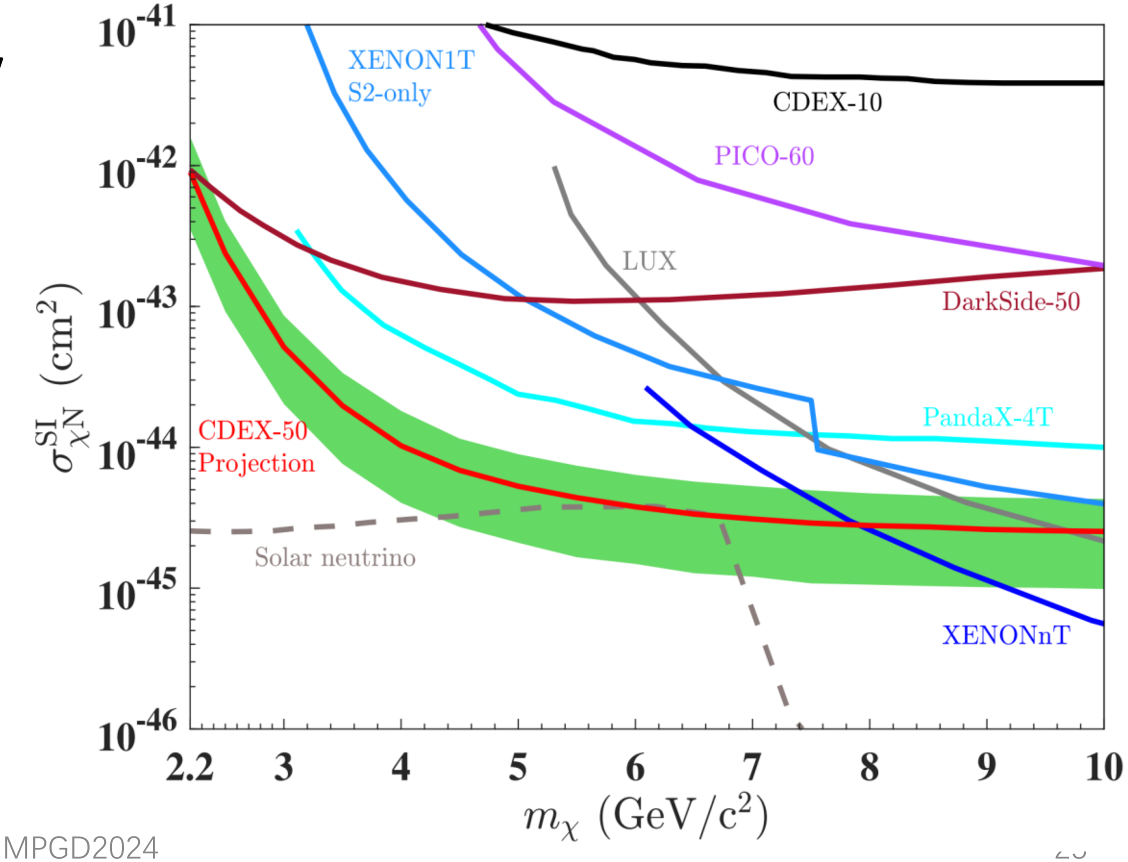


CDEX-50

- **Ge detectors** array directly immerse into **LN_2** for cooling and shielding
- target mass (Ge) reaches ~50kg
- Bkg level: **<0.01 cts/(keV·kg·day) @1 keV**
- Energy threshold for data analysis: **160 eV**
- WIMP SI sensitivity reaches **10^{-44} cm^2**

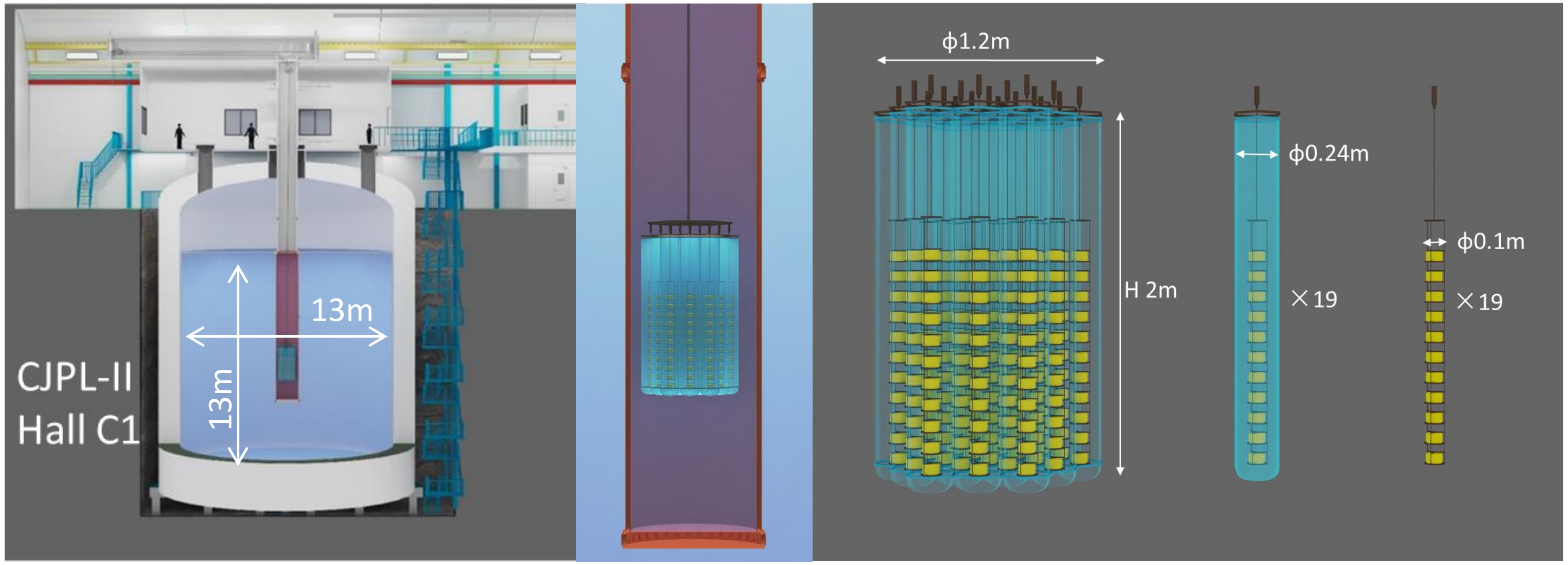


JCAP 07 (2024) 009



CDEX-300ν Overview

- LN_2 tank shared with CDEX-50, in Hall C @ CJPL-II
- Reentrant tube containing LAr submerged in LN_2
- Ge detector array immersed in LAr (veto) tube
- Ge array divided into 19 strings (10-11 det/string, 200 det. in total ~225kg)
- An exposure for ^{76}Ge 0νββ: >1t·y, $T_{1/2} > 10^{27}$y



1725 m^3 Liquid Nitrogen

Parameter	CDEX-300
^{76}Ge mass	>225 kg
BI@2039keV	10^{-4} cpkky
E_R@2039keV	2.5 keV (FWHM)
Run time	5 y (2027-2031)
Exposure	1.125 t·y
$T_{1/2}$	$>1\times10^{27}$y
$m_{\beta\beta}$	28.5~68.0 meV

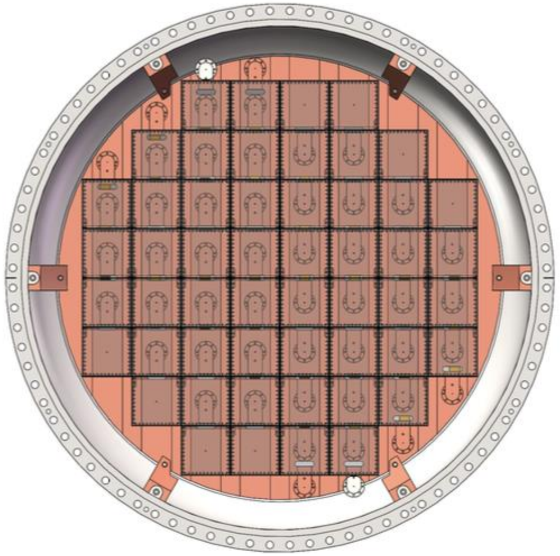
PandaX-III experiment

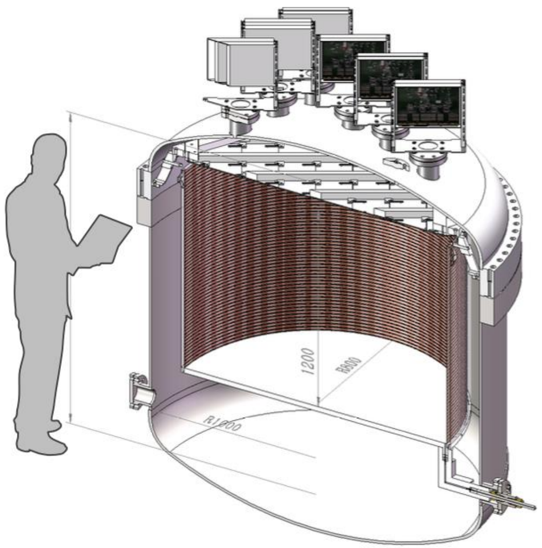
From Ke Han, Shanghai Jiao Tong University

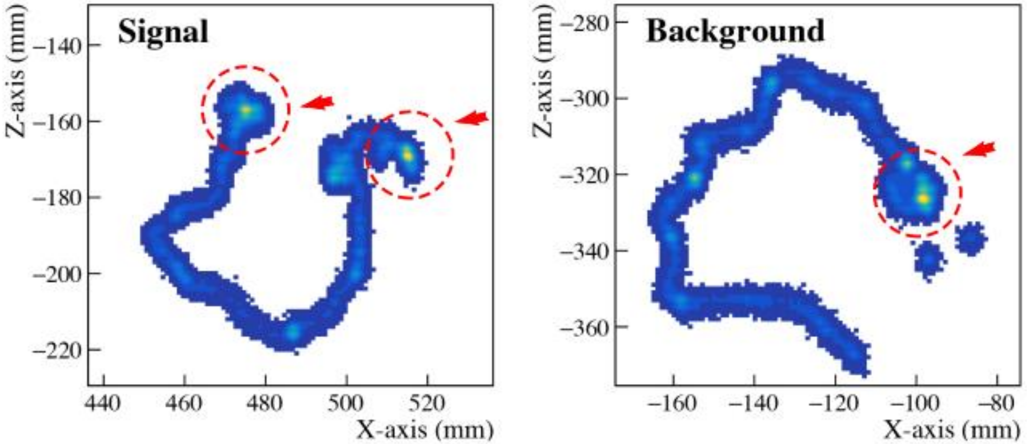
PandaX-III experiment

PandaX-III: high pressure gas TPC for 0νββ of ^{136}Xe

- TPC: 100 kg scale high pressure TPC at 10 bar operating pressure
- Micromegas strip readout for millimeter level spatial resolution
- Good energy resolution and tracking capability for signal-background discrimination



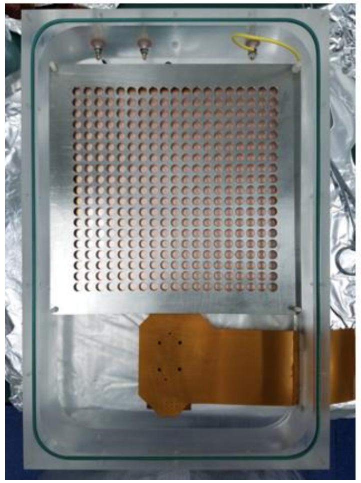




PandaX-III Detector

- Test setups, prototype, and full vessel at SJTU

1 MM,
flow gas



MiniTPC:
1 MM,
16 bar

Prototype TPC:
7 MM, 10 bar

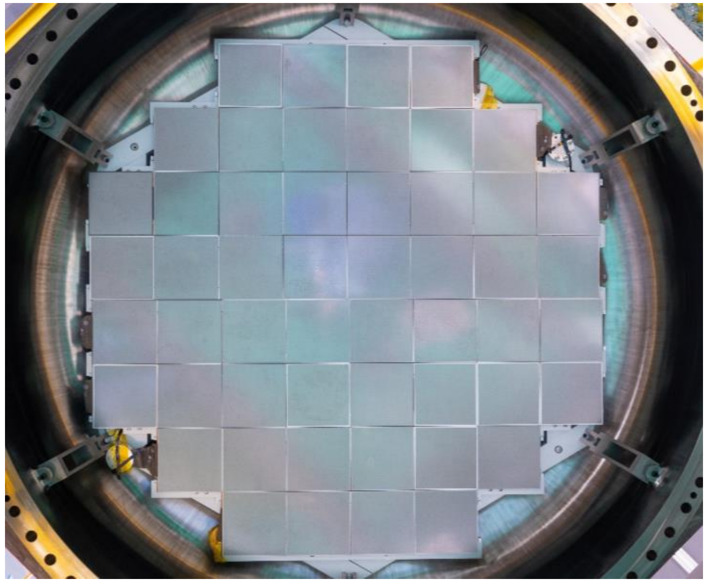
Full vessel: low background
SS, 4 m^3 inner volume

PandaX-III Detector Commissioning

- Thermal bonding Micromegas from USTC were applied
- Best energy resolution at 6 keV (^{55}Fe) is 15% in 1 bar argon/CO_2
- Low background field cage with acrylic and kapton flexible PCB
- Convolutional Neural network (CNN) for track classification (Sci. China Phys. Mech. Astron. 61 (2018) 101007)
- Kalman filter based track reconstruction to improve 0νββ search sensitivity by 3 times to 2.7×10^{26} years (JHEP 06 (2021) 106)

Readout PCB

Thermal bonding MM

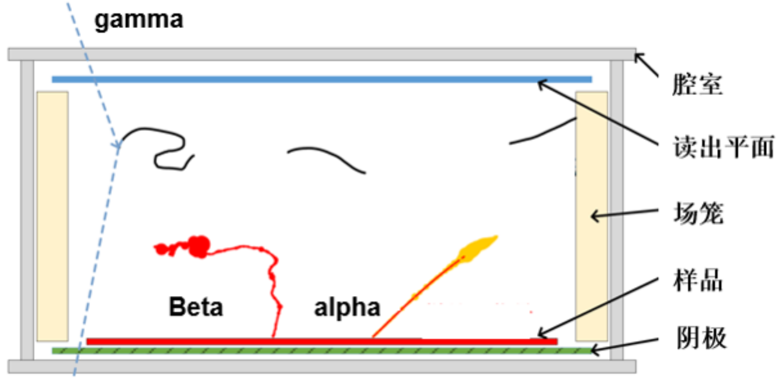


Readout plane

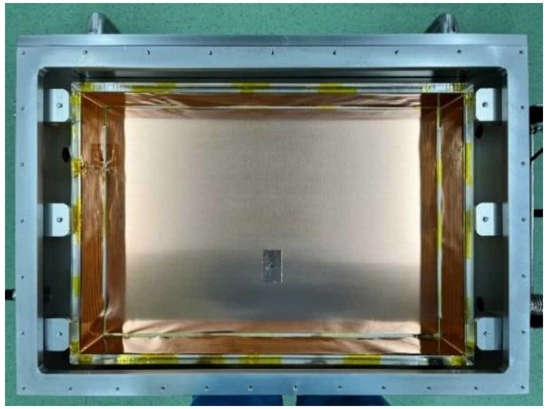
Field cage

Ultra-Low Background Charged Particle

- Combining gas TPC and thermal-bonding Micromegas.

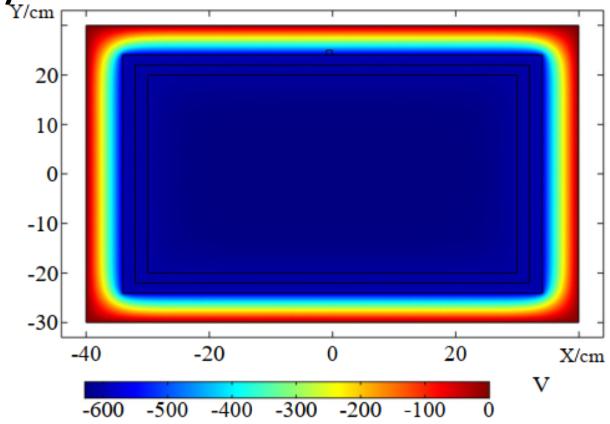


Readout plane - Micromegas



Internal detector

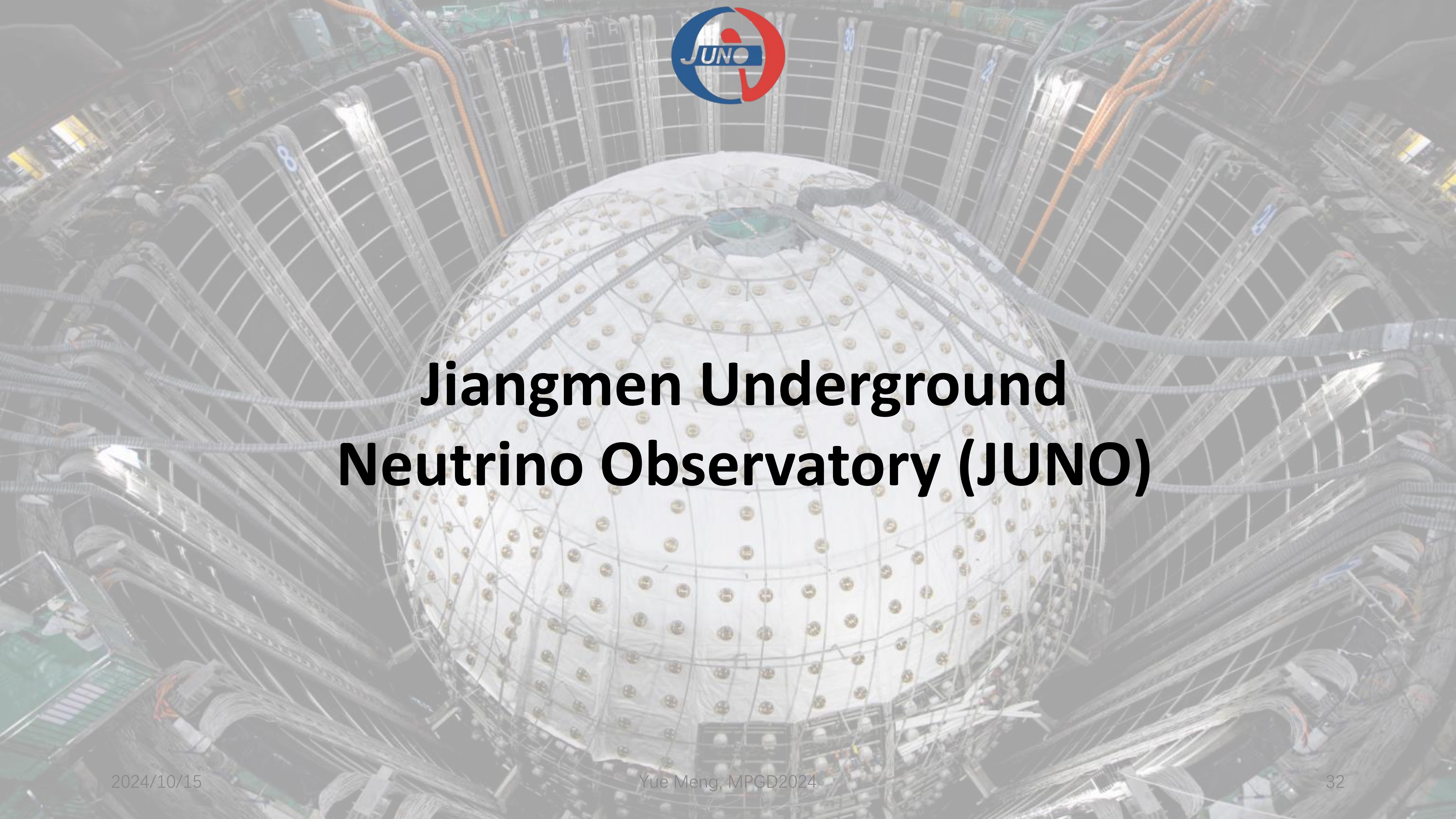
- Particle track discrimination to reduce backgrounds.
- Large area, high detection efficiency, high sensitivity.
  - Time Projection Chamber (0.5-1.5 bar Argon/Xenon)
  - Readout plane： 2400 cm^2 （2×3 Micromegas）
  - Drift distance： 10 cm (Volume: 24 L)
  - Flexible PCB field cage
  - Samples are placed directly on the cathode to ensure complete deposition of alpha energy.



E-field distribution in the X-Y plane

Readout electronics

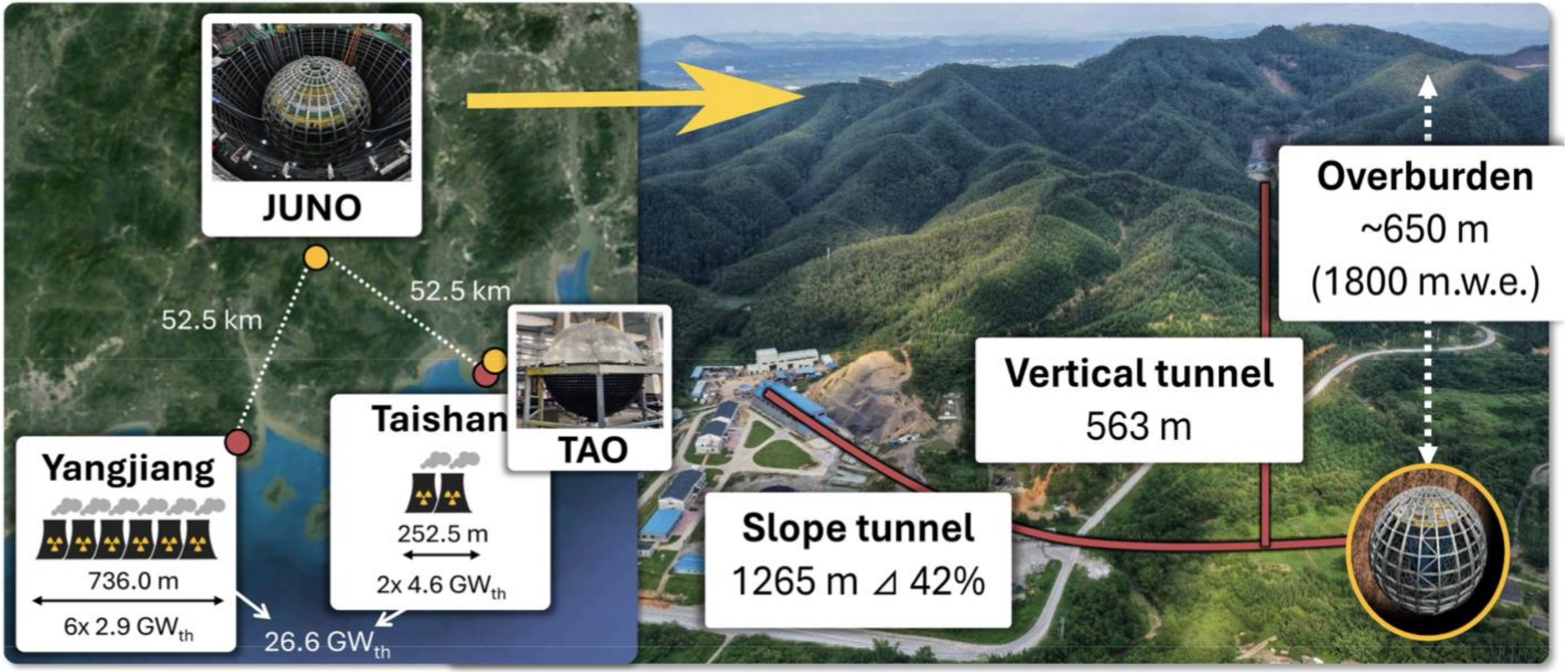
- Alpha background (Copper cathode + Gas): $(0.14 \pm 0.02)\times10^{-6}$ Bq/cm^2



Jiangmen Underground Neutrino Observatory (JUNO)

JUNO experiment

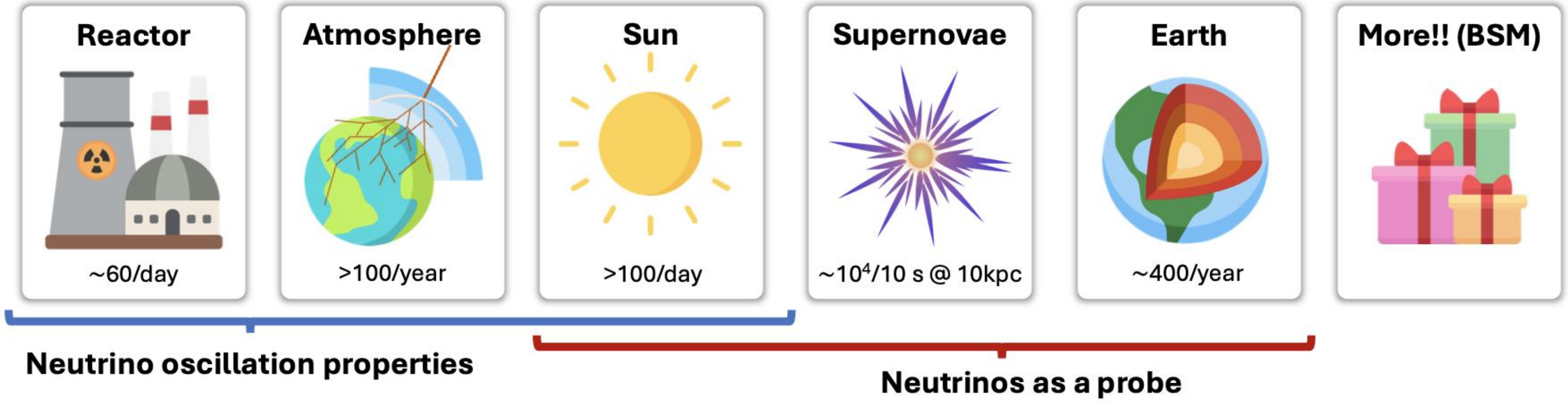
- JUNO is located in Guangdong Province, China



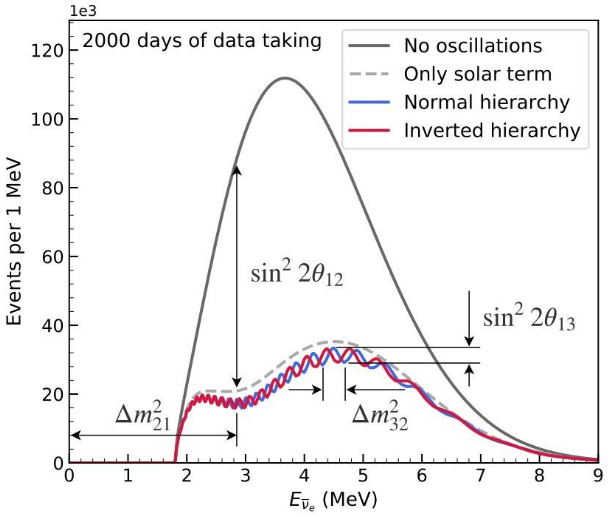
From Andrea Serafini and Benda Xu

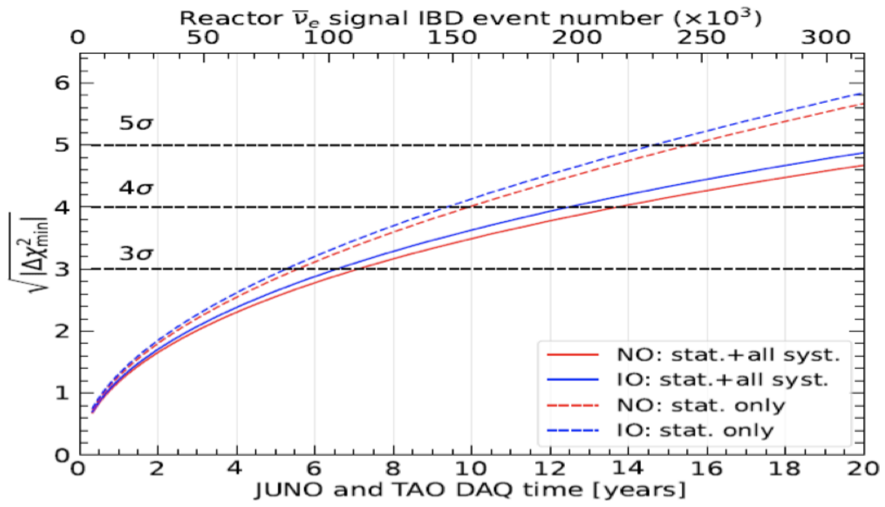
JUNO Physics Prospects

- **JUNO has a rich program in neutrino physics and astrophysics**



- **Neutrino mass ordering: 3σ (reactors only) @ ~6 years * 26.6 GW_{th} exposure**



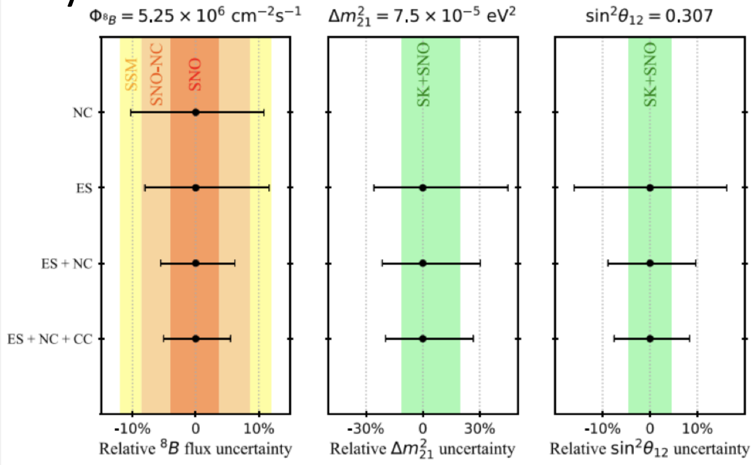


JUNO Physics Prospects

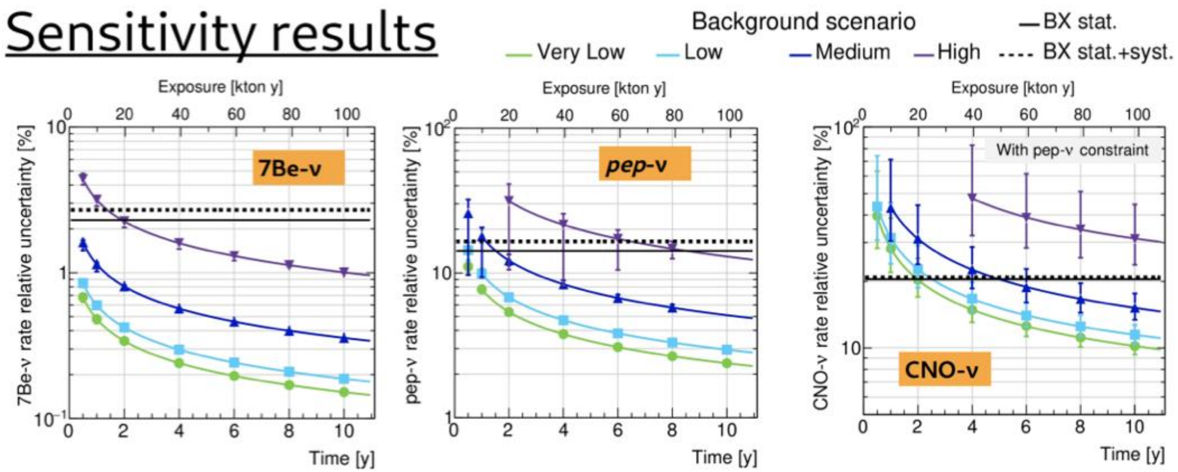
- **Precision measurement of oscillation parameters**

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2 \theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2 \theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)

- **Solar neutrinos detection**
  - The largest ^{13}C ES+NC+CC sample, ^{8}B flux can be model-independently measured to 5% in 10 years
  - JUNO will reduce the Borexino uncertainty on ^{7}Be, pep, CNO flux measurement



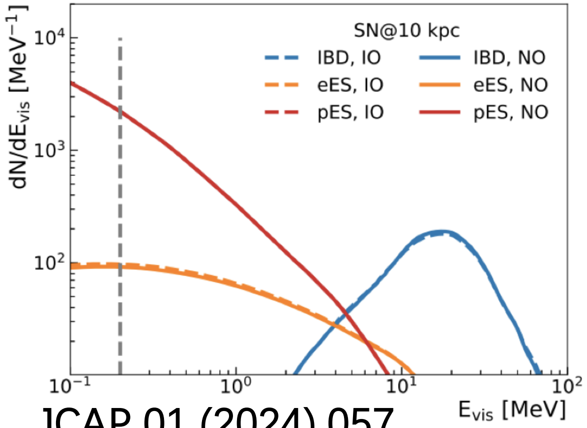
Astrophys. J 965, 122(2024)



JCAP 10, 022 (2023)

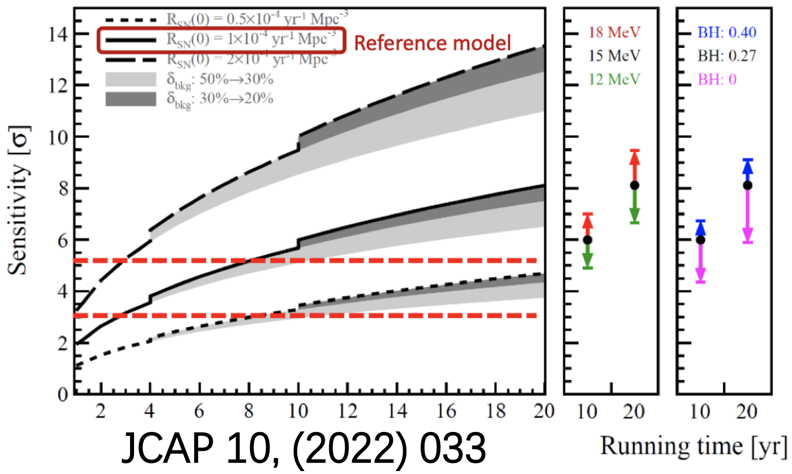
JUNO Physics Prospects

- **Supernova neutrinos**
  - Excellent capability for early warning with 3 detection channels



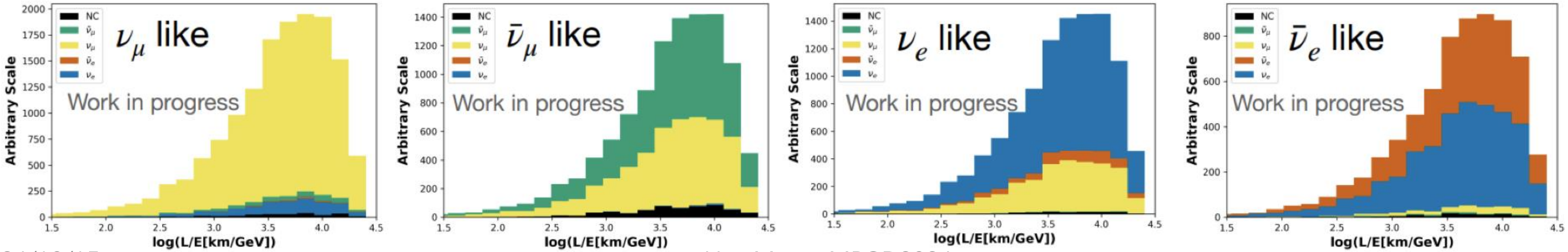
JCAP 01 (2024) 057

  - Diffuse Supernova Neutrino Background, 3 σ in 3 years



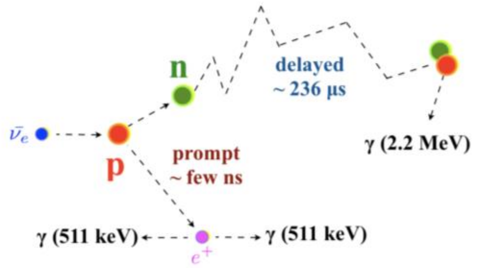
JCAP 10, (2022) 033

- **Atmospheric neutrinos**
  - JUNO will be the first to study atmospheric neutrino oscillation with liquid scintillator



Keys for the JUNO Detector

- Detection via inverse beta decay (IBD) event

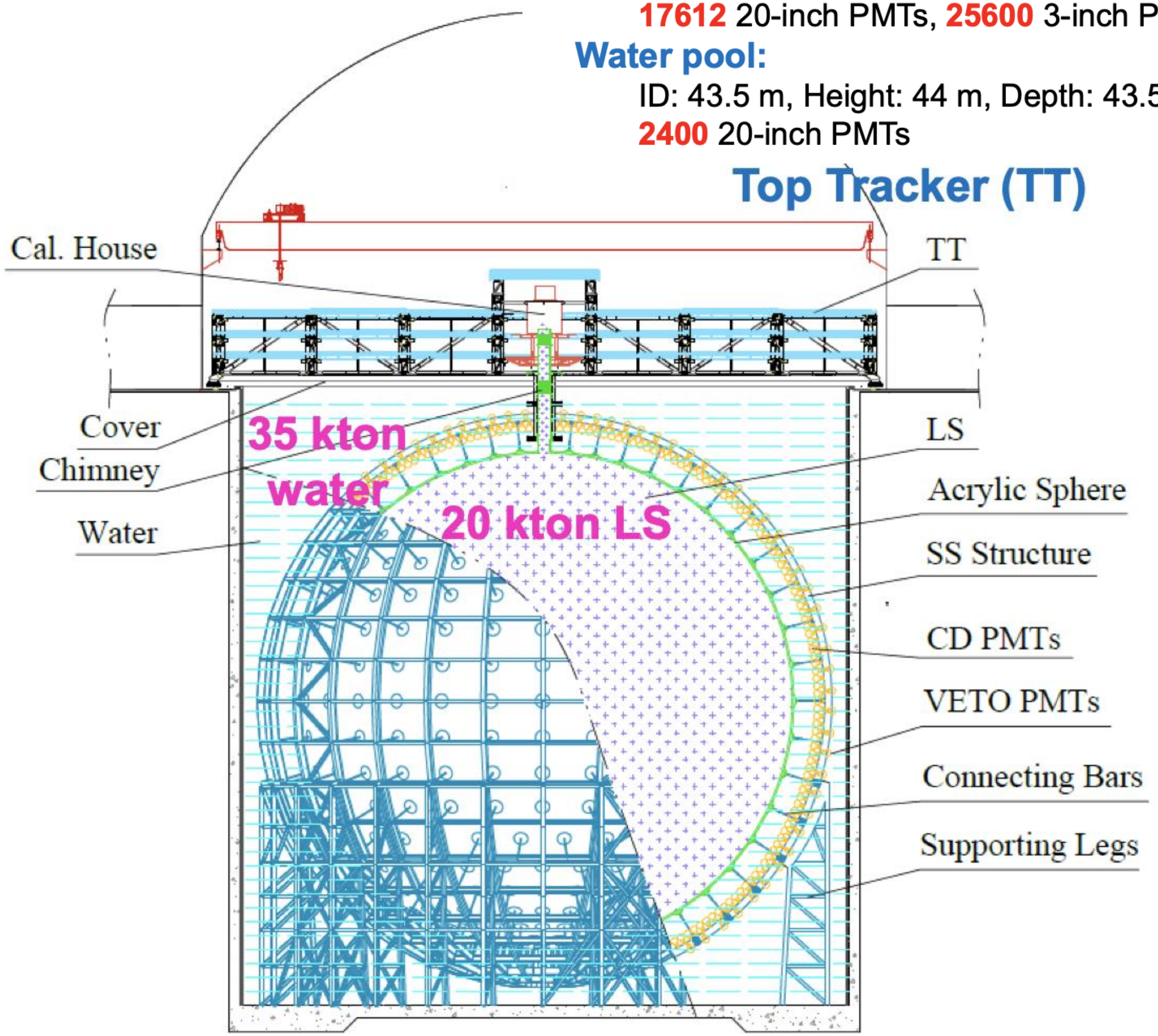


- The optimal baseline for the detector
- Large statistics
  - 26.6 GW_{th} power
  - ~60 IBD events per day
- Energy resolution < 3%/√E @1 MeV

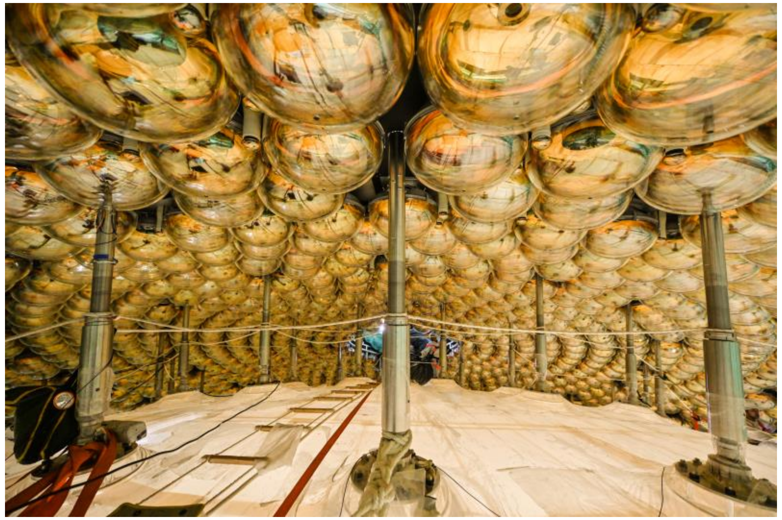
$$\frac{\sigma_{E_{\rm vis}}}{E_{\rm vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}}\right)^2}$$

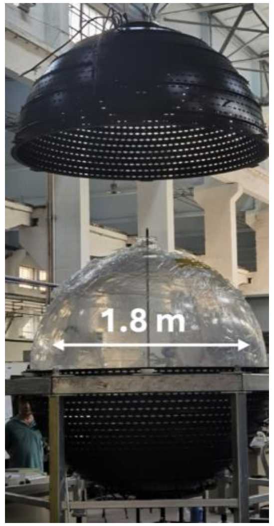
- Energy scale uncertainty < 1%
  - Comprehensive calibration strategy
- Background control

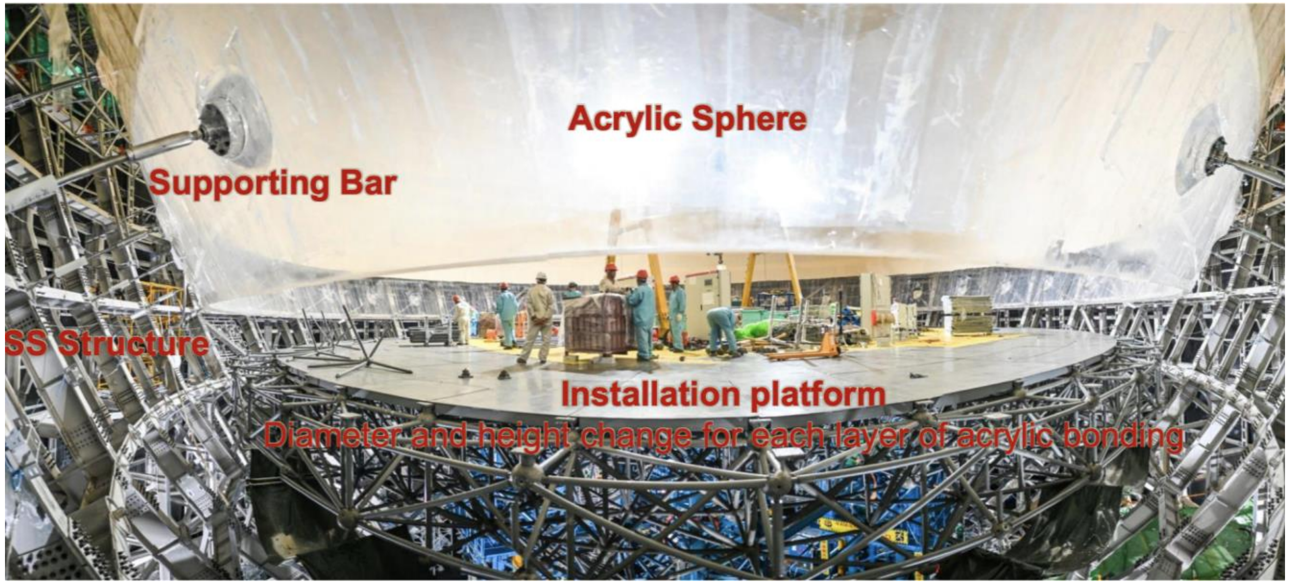
Acrylic Sphere:
Inner Diameter (ID): 35.4 m
Thickness:12 cm
Stainless Steel (SS) Structure:
ID: 40.1 m, Outer Diameter (OD): 41.1 m
17612 20-inch PMTs, 25600 3-inch PMTs
Water pool:
ID: 43.5 m, Height: 44 m, Depth: 43.5 m
2400 20-inch PMTs



JUNO Detector Construction







JUNO construction is nearing completion and will start the detector filling

Summary & Outlooks

- China’s underground laboratories offer an extremely low-background environment, ideal for rare decay and high-precision fundamental physics research.
- Significant achievements have been made in dark matter and neutrino experiments, advancing our understanding of the universe’s fundamental components and interactions.
- More experimental results are expected in the near future.

Thank You！