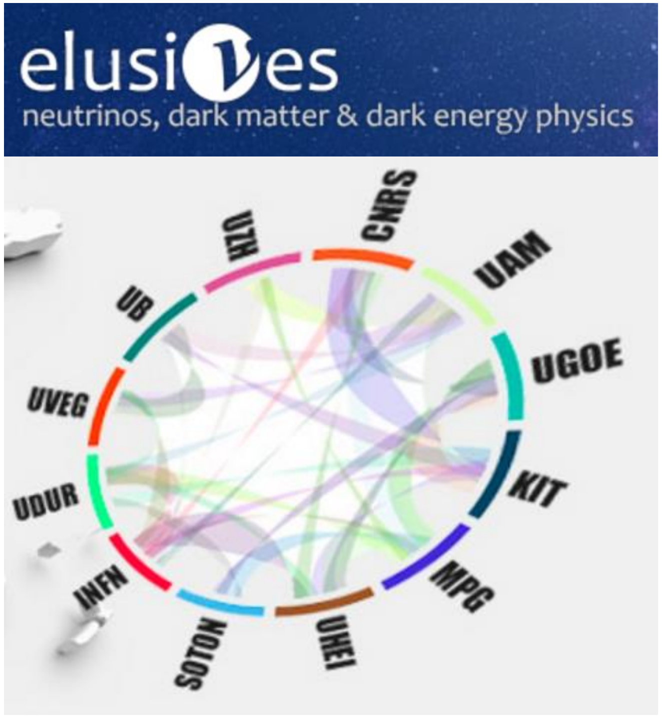
Exploring the Invisible Universe from Deep Underground

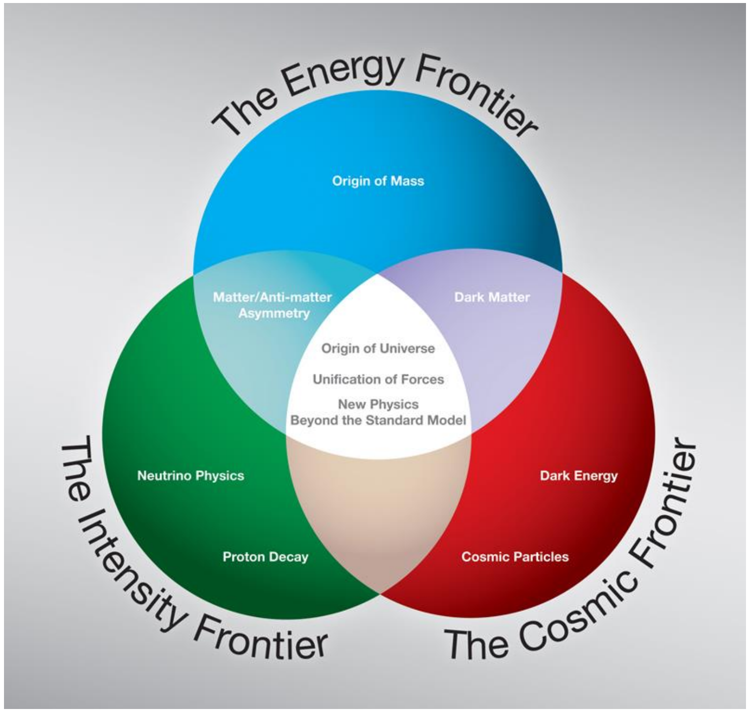
Ke Han
September 6, 2017
Shanghai Jiao Tong University

Dark Matter and neutrino physics

- Physics beyond the Standard Model.
- Interconnects particle physics, nuclear physics, cosmology, and astrophysics.



European ITN project



US HEP

Dark Matter and neutrino physics at SJTU

- PandaX
    - Dark Matter (WIMP) direct detection with Xenon TPC
- JUNO and Daya Bay
    - Neutrino oscillation physics
- PandaX-III and CUORE
    - Neutrinoless double beta decay

Members:

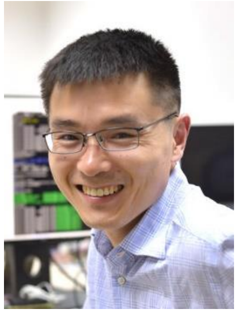
- 7 faculty; 6 engineers; 6 postdocs; 14 students


Xiangdong Ji


Jianglai Liu


Karl Giboni

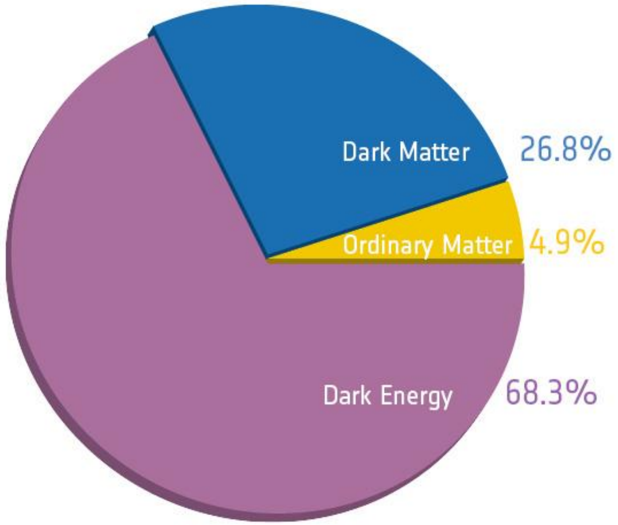

Changbo Fu

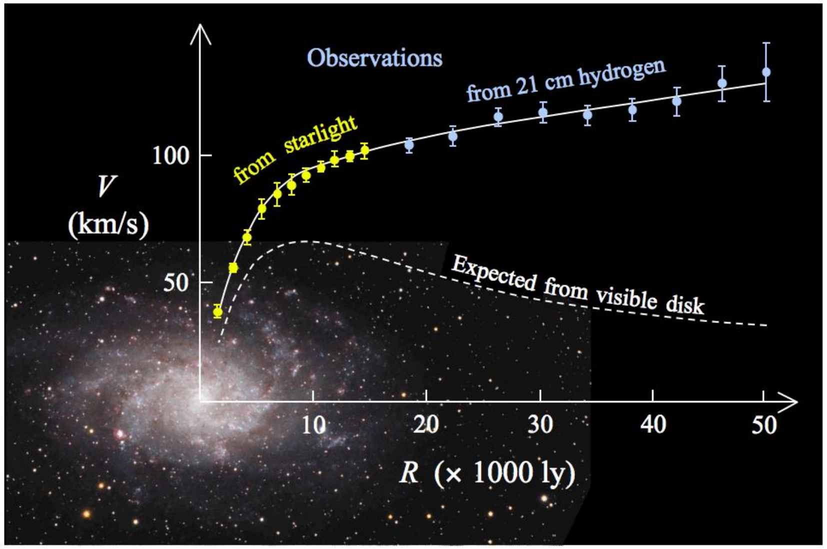

Ke Han

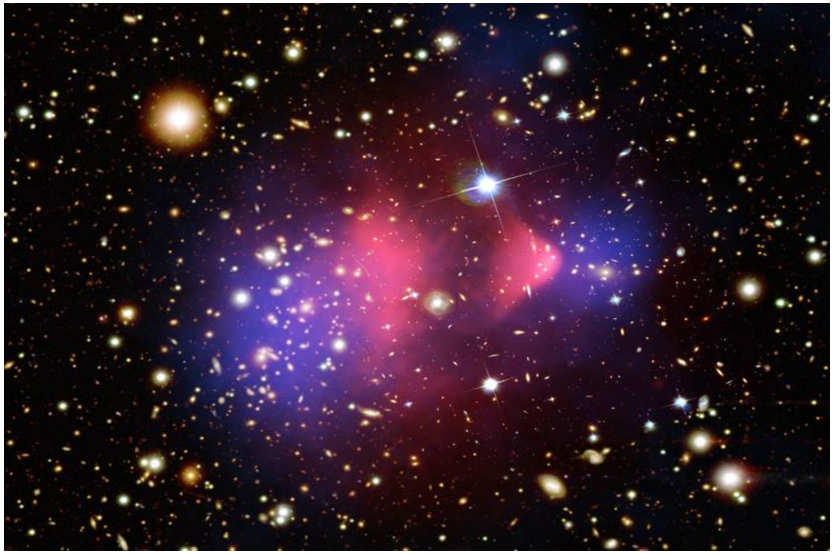

Yong Yang


Ning Zhou

Dark Matter

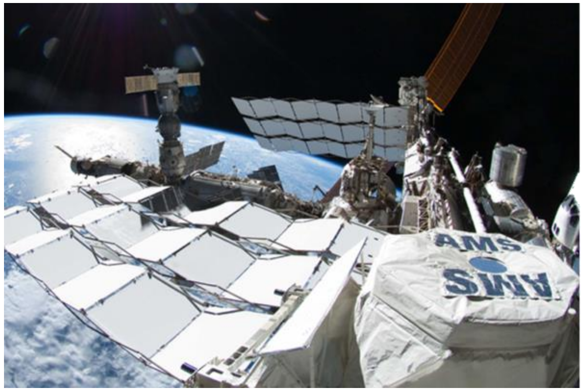


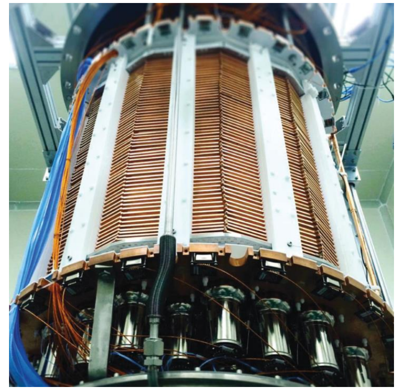


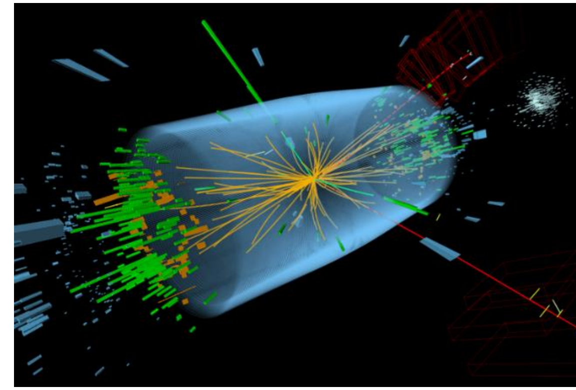


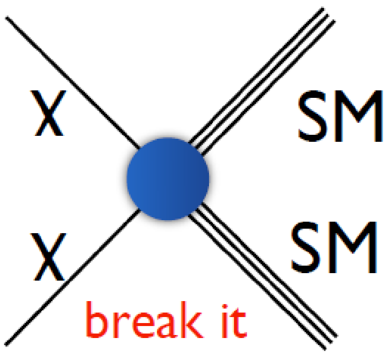
- Existence of dark matter is firmly established
- Particle nature of dark matter?
    - WIMP?

WIMP searches

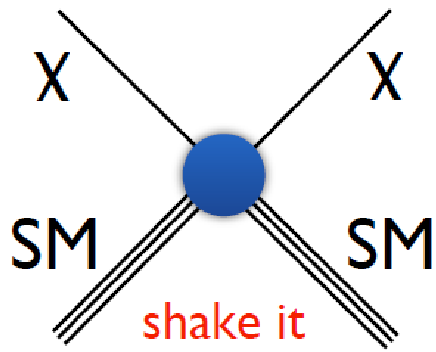




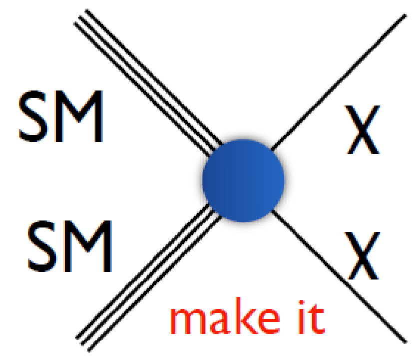




Indirect detection



Direct detection

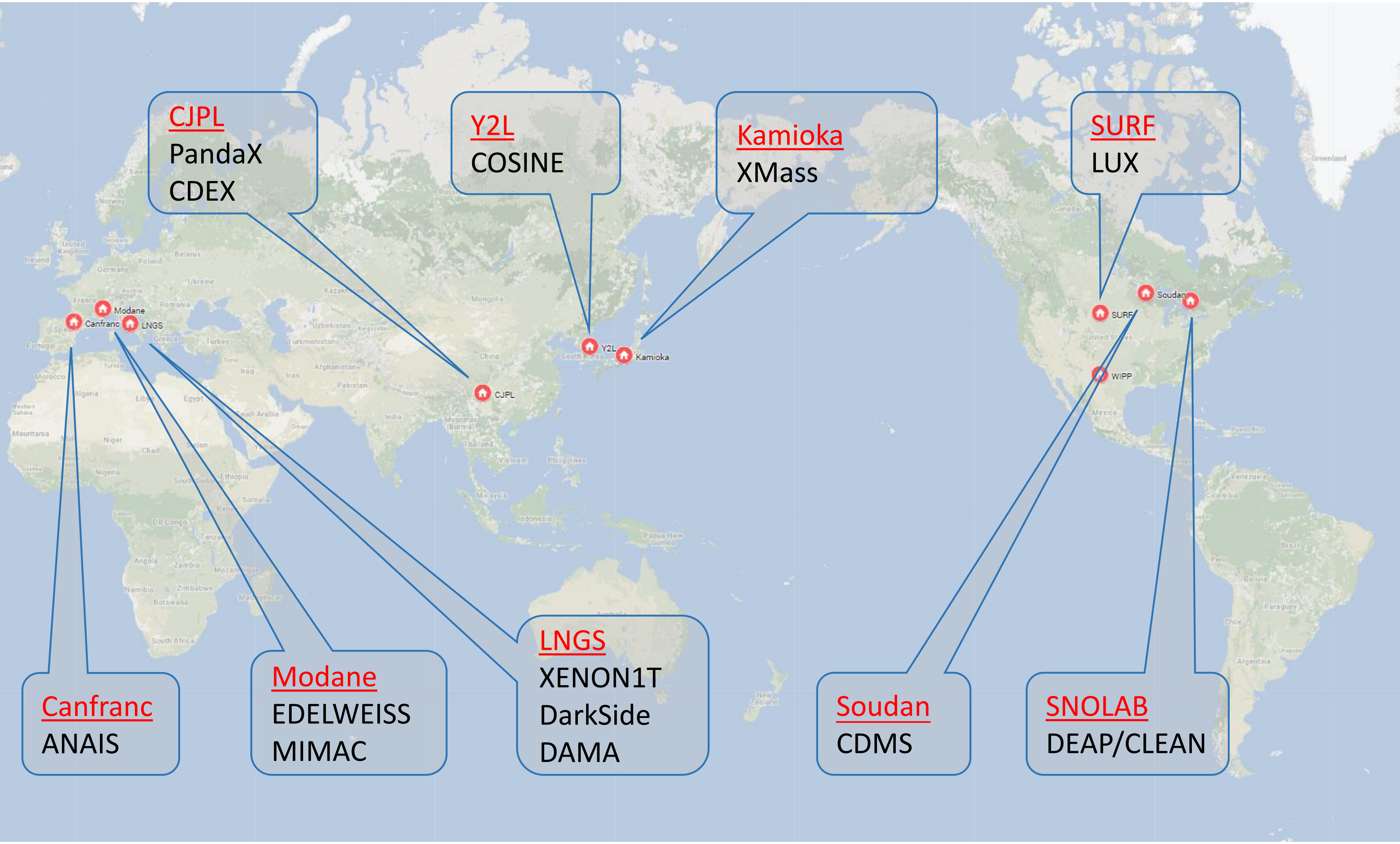


Collider

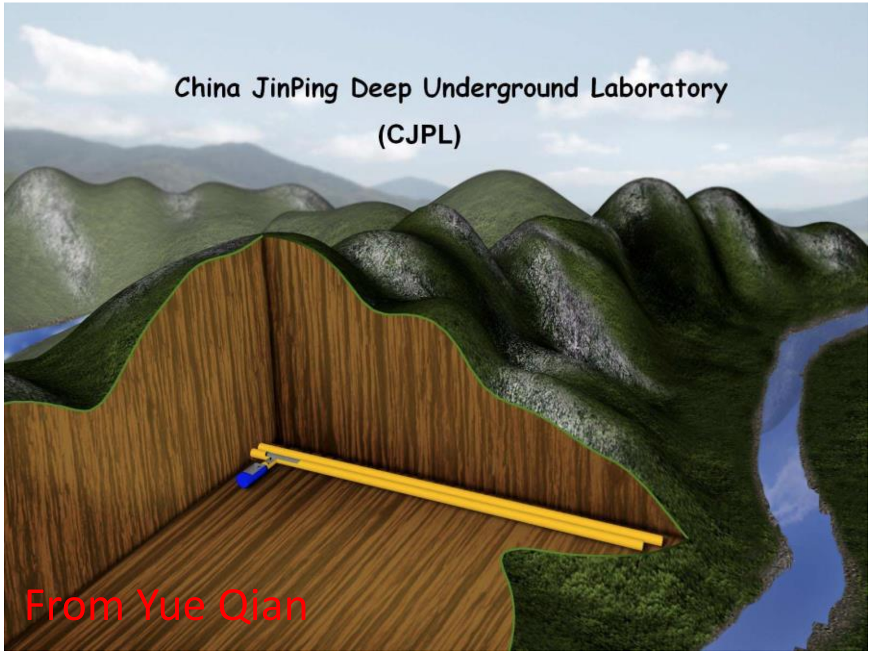
Tracy Slatyer

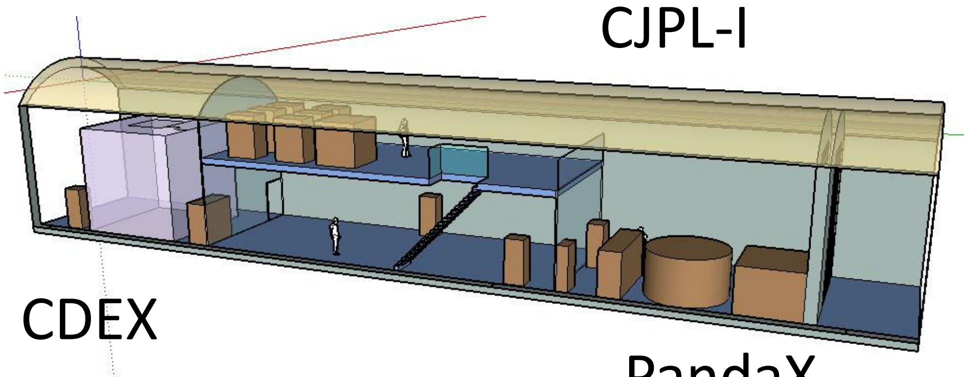
→ Time

“Dark matter rush” around the world

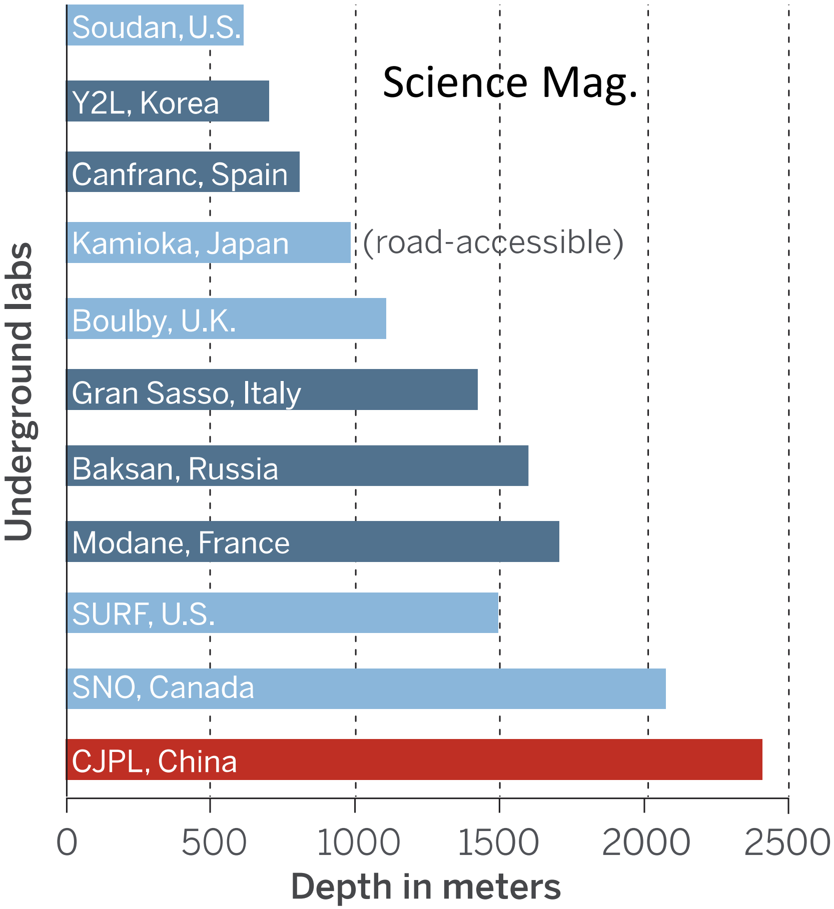


CJPL – Deepest underground physics lab in the world

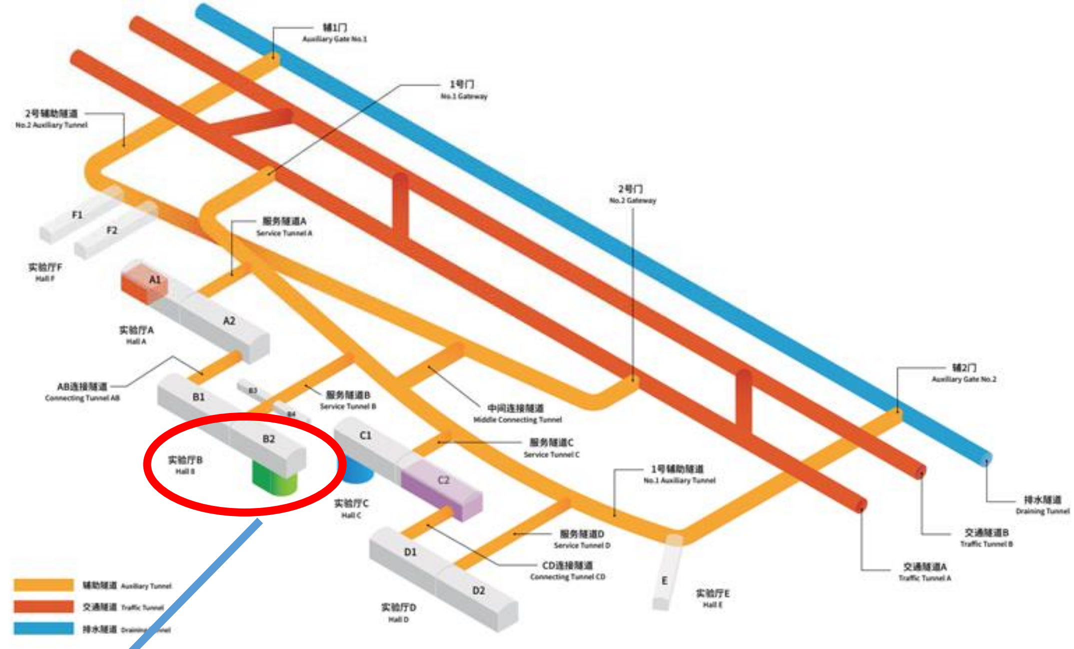




Labs are built in mines (light blue) and tunnels (dark blue and red).

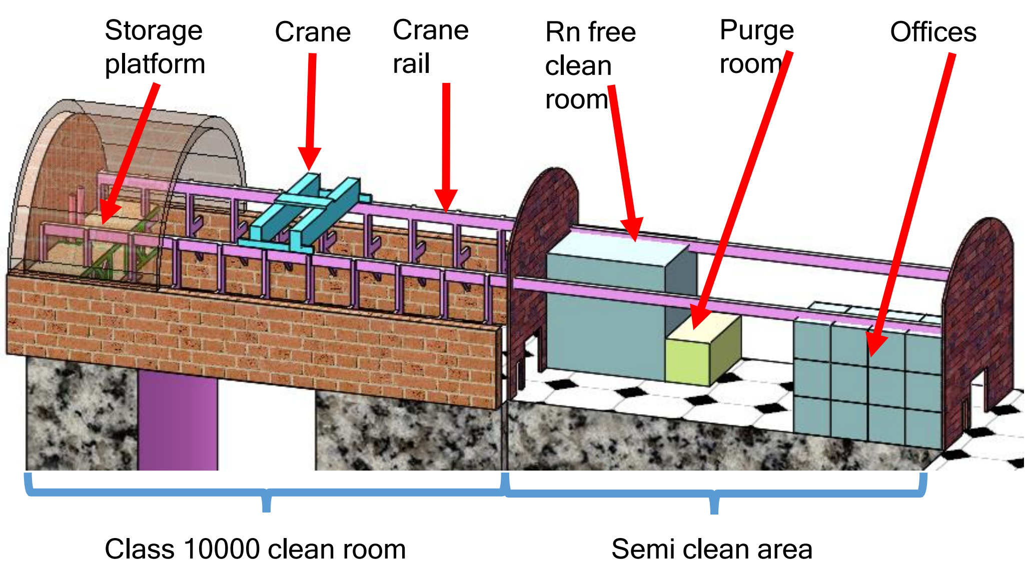


PandaX hall at CJPL-II



Experiments at CJPL-II

- PandaX projects
- CDEX
- JUNA (accelerator)
- Jinping neutrino experiment (LS)
- …



PandaX at Hall B2

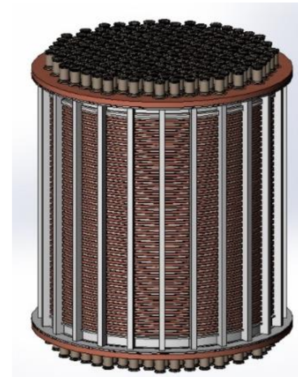
- Extra excavation for the water shielding pool (finished)
- Shared facility of DM and 0νββ searches
- Beneficial occupancy by the beginning of 2018

PandaX Projects

PARTICLE AND ASTROPHYSICAL XENON TPC

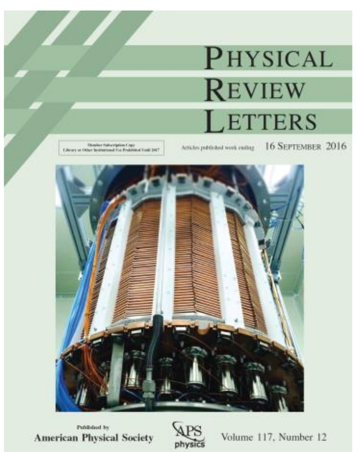
PandaX-I: 120kg LXe
(2009 – 2014)

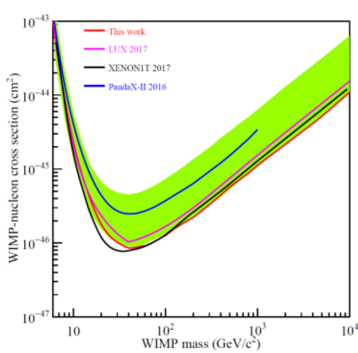
PandaX-II: 500kg LXe
(2014 – 2018)

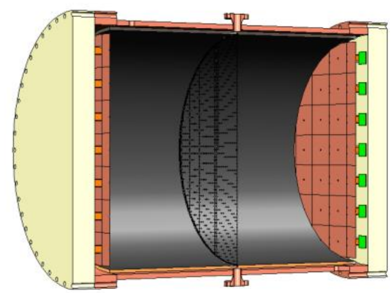


PandaX-xT LXe
(Future)

Dark matter WIMP searches







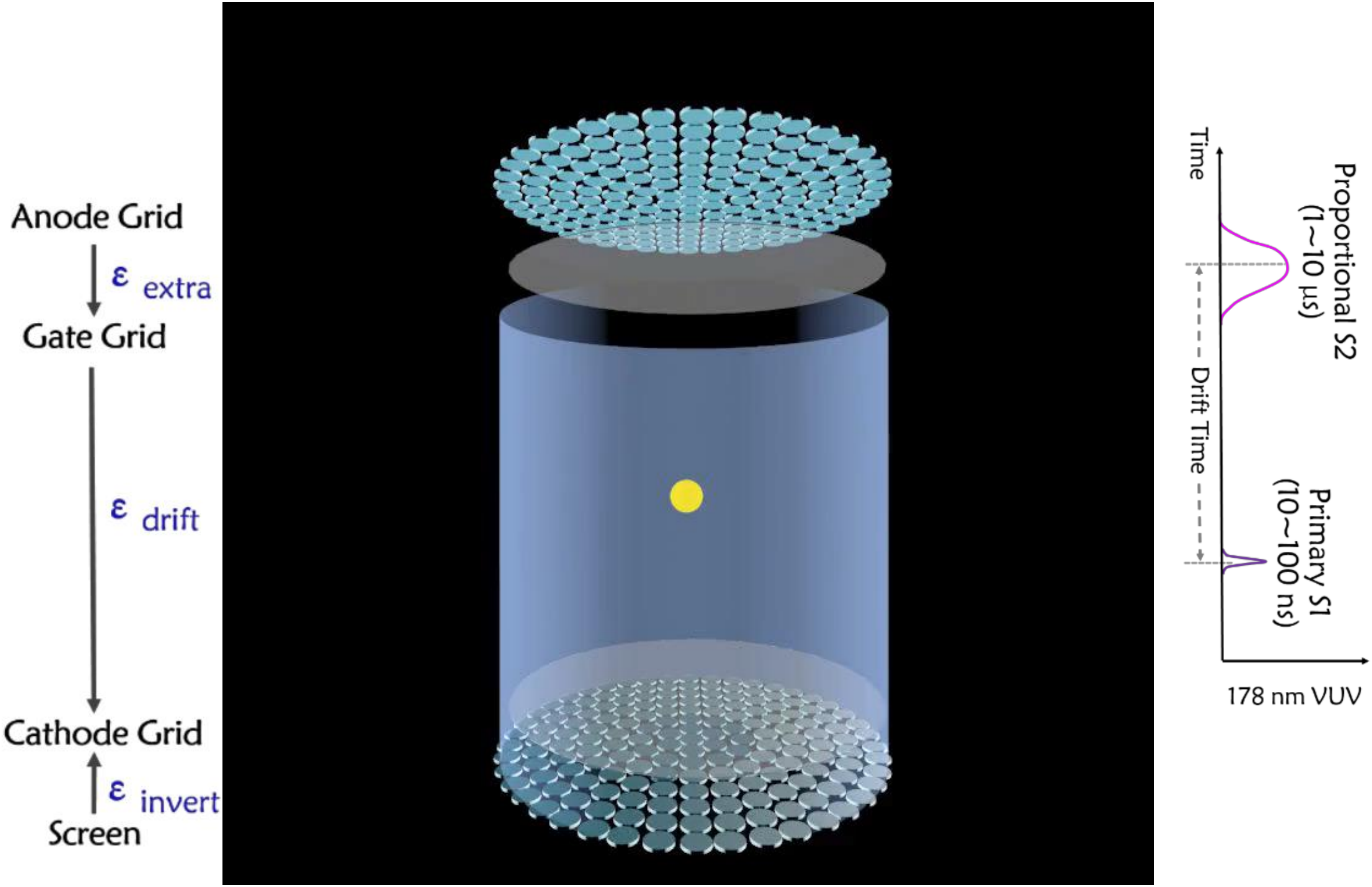
0νββ searches

PandaX-III:
200kg - 1 ton HPXe (Future)

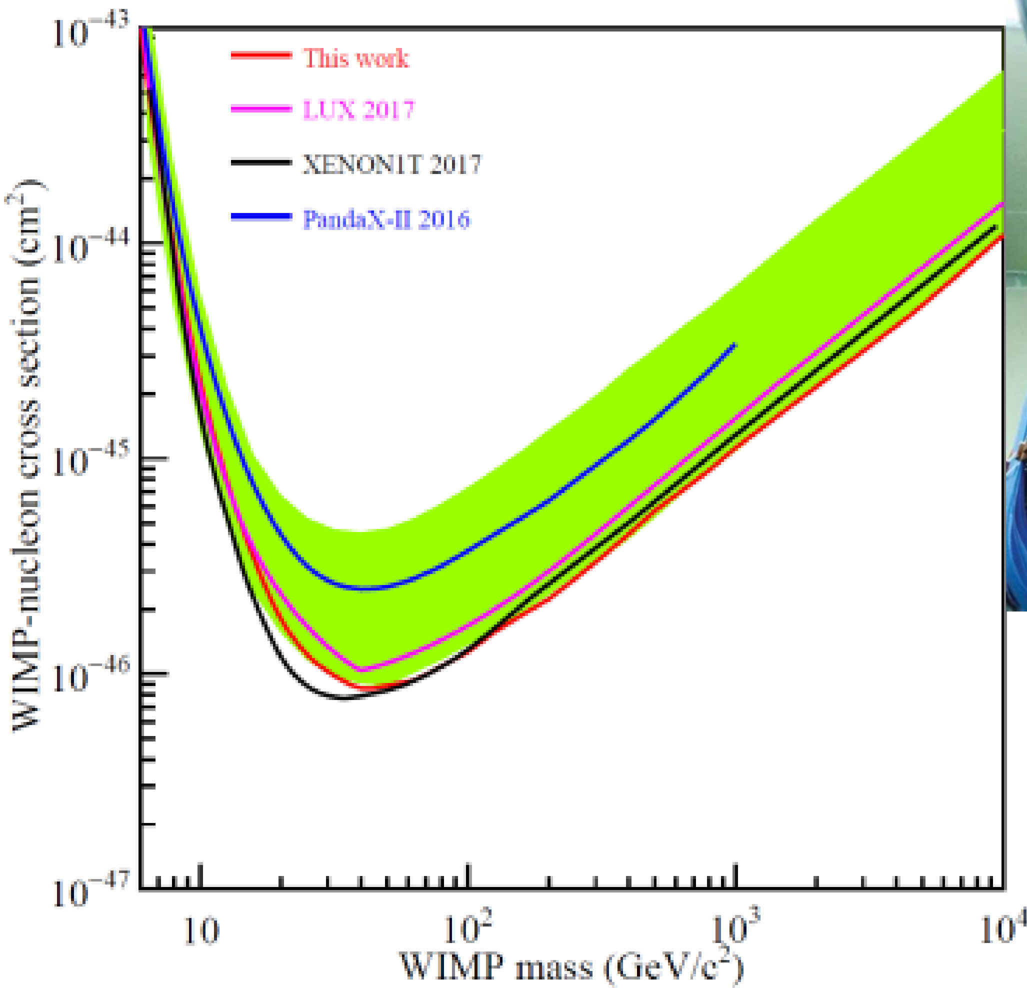
PandaX collaboration

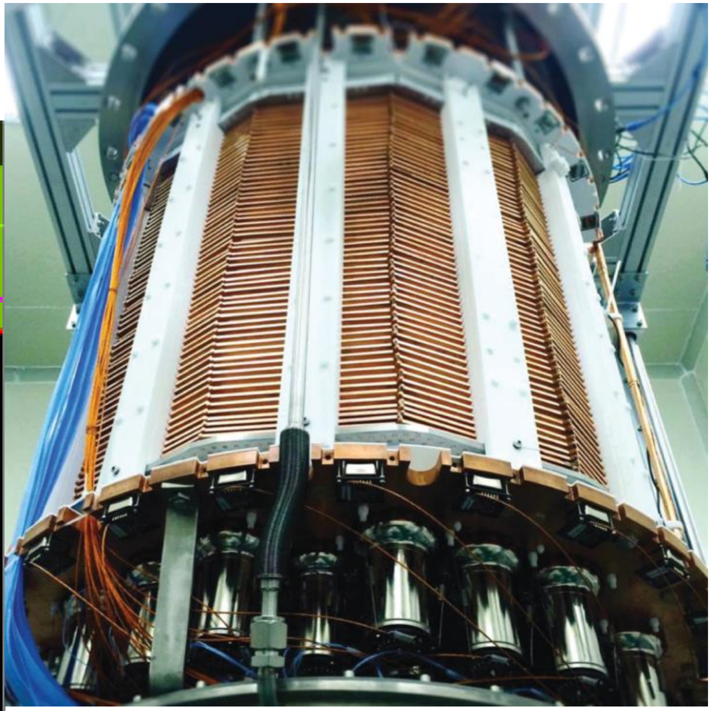
- Shanghai Jiao Tong University
- Peking University
- Shandong University
- Shanghai Institute of Applied Physics
- University of Science and Technology of China
- China Institute of Atomic Energy
- Sun Yat-Sen University
- Central China Normal University
- Yalong Hydropower Company
- University of Maryland, USA
- Lawrence Berkeley National Lab, USA
- CEA Saclay, France
- University of Zaragoza, Spain
- Suranaree University of Technology, Thailand

Dual phrase Xe TPC for dark matter



Best limit achieved

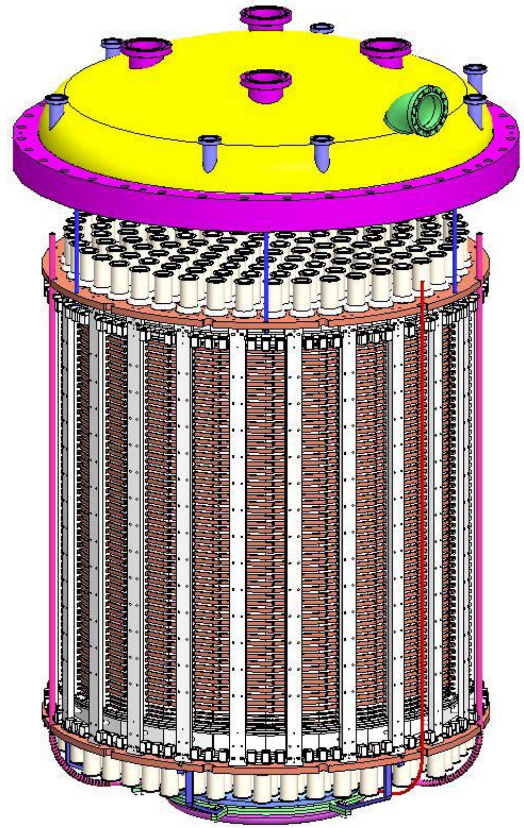


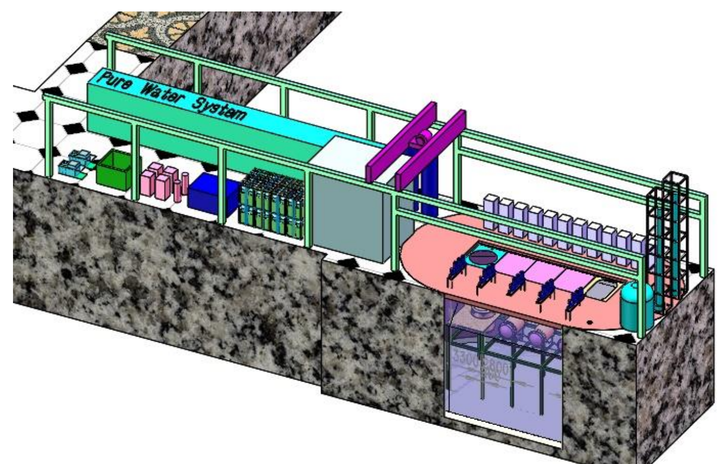


Details at Xiangyi's talk

PandaX-xT

- Preparing new experiments in CJPL-II, hall #B2
- Intermediate stage:
    - PandaX-4T (4-ton target) with SI sensitivity ~10^{-47} cm^2
    - On-site assembly and commissioning: 2019-2020
- Eventual goal: G3 xenon dark matter detector (~30T) in CJPL to “neutrino floor” sensitivity

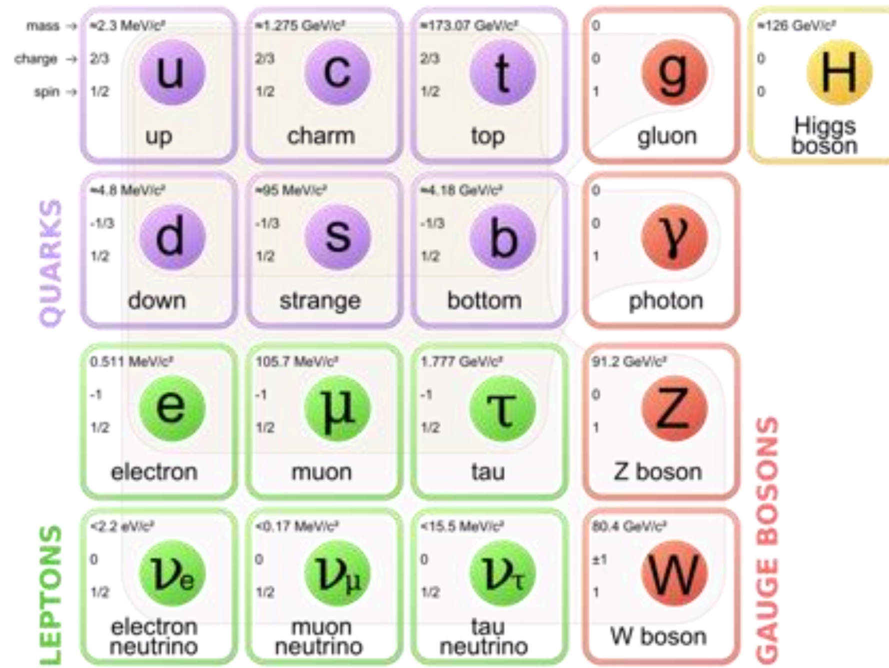


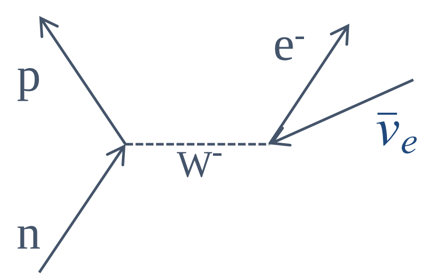


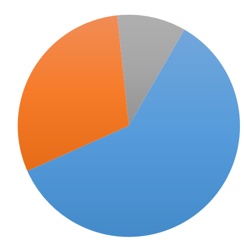
Neutrinos: what do we know

- We know three generations of neutrinos:
  - Electron
  - Muon
  - Tau
- Neutral
- Weakly interacting

- Neutrino Flavor transitions and mixing of massive neutrinos
- Two hierarchical mass scales Δm^2.
- Three mixing angles

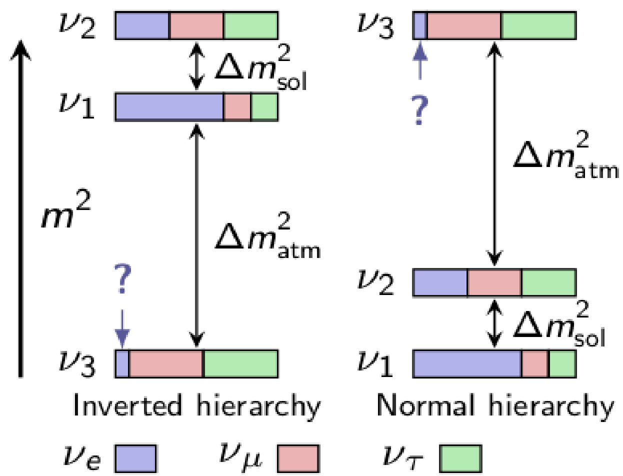


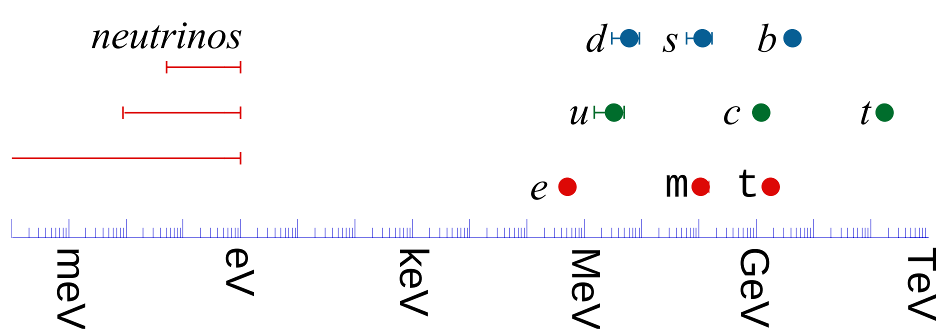




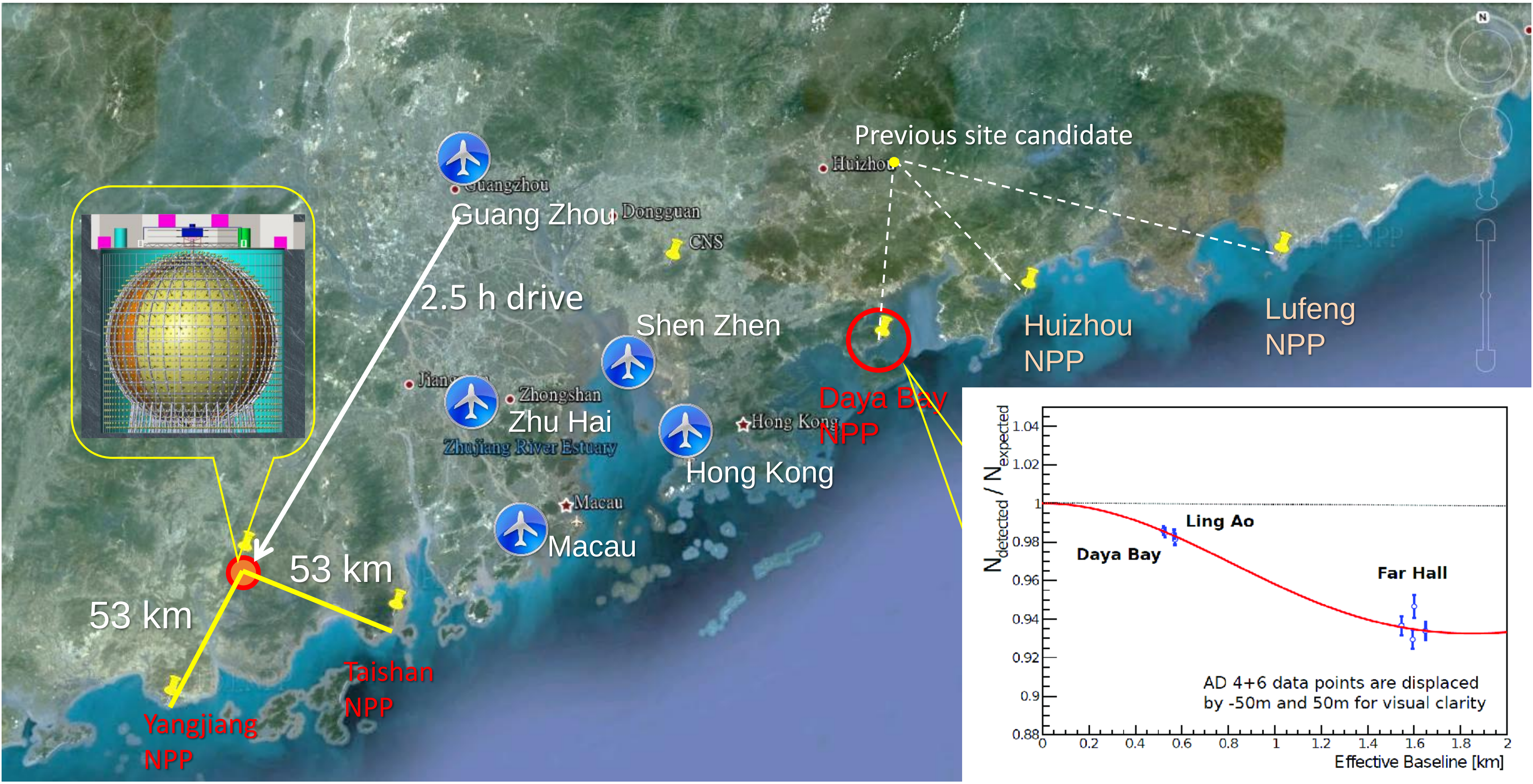
What are some open questions?

- Mass hierarchy: the sign of $\Delta m_{23}{}^2$
  - Mid-baseline reactor antineutrino experiment
- The nature of the massive neutrinos – Dirac or Majorana?
  - Double beta decay experiment
- The absolute mass scale
  - Beta decay end-point measurement
- CP violating phase δ.
  - Long baseline accelerator neutrino experiment
- The existence of sterile neutrinos
  - Short baseline reactor antineutrino experiment
  - Source experiments



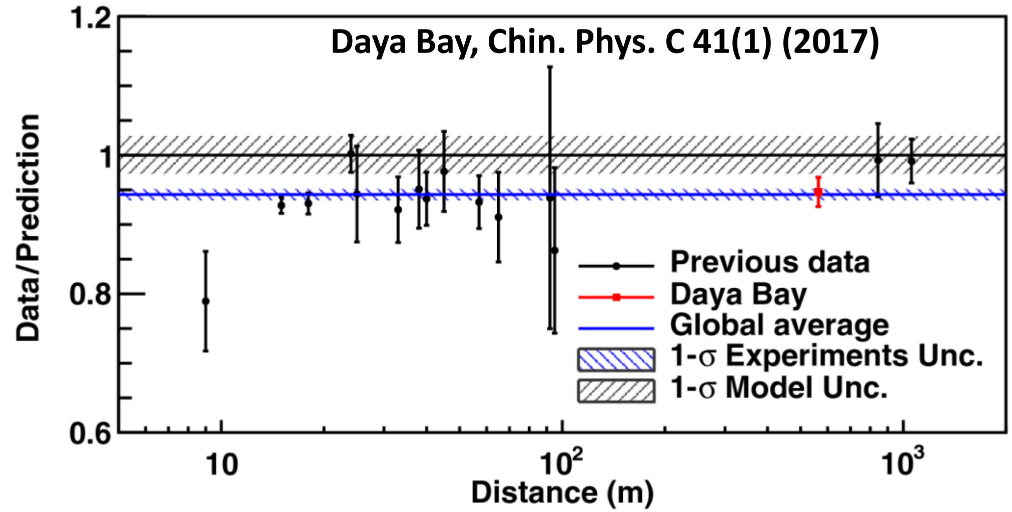


Daya Bay and JUNO

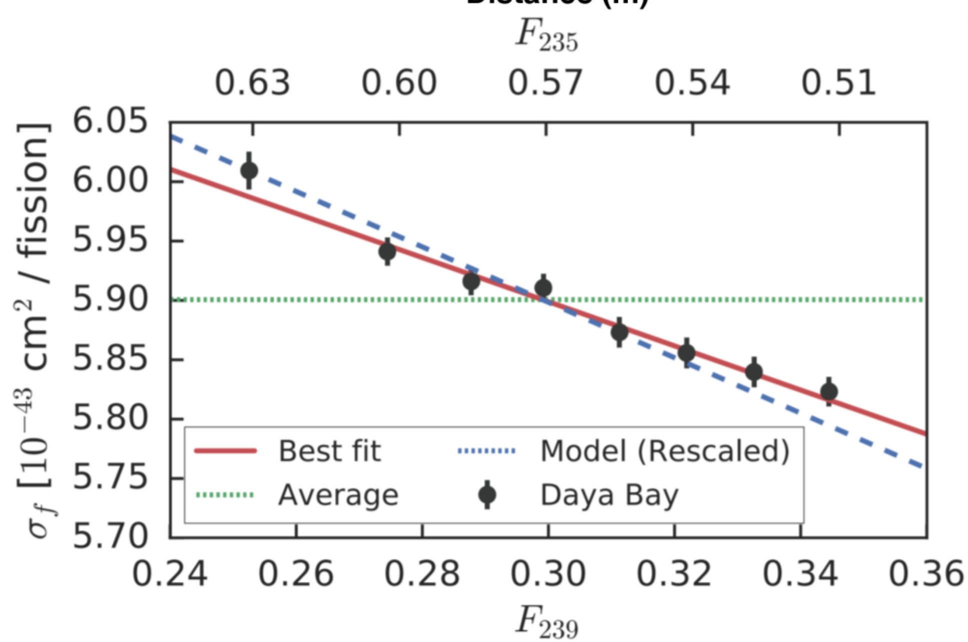


Reactor Antineutrino Anomaly: ^{235}U or sterile neutrino?

- Daya Bay observed a flux deficit in comparison to the model calculation flux.
  - Hint of sterile neutrino?

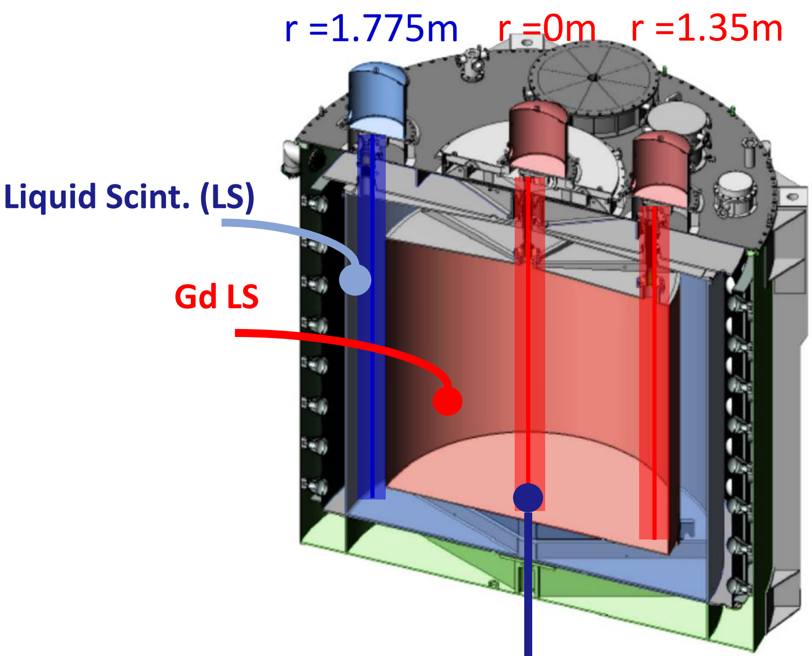


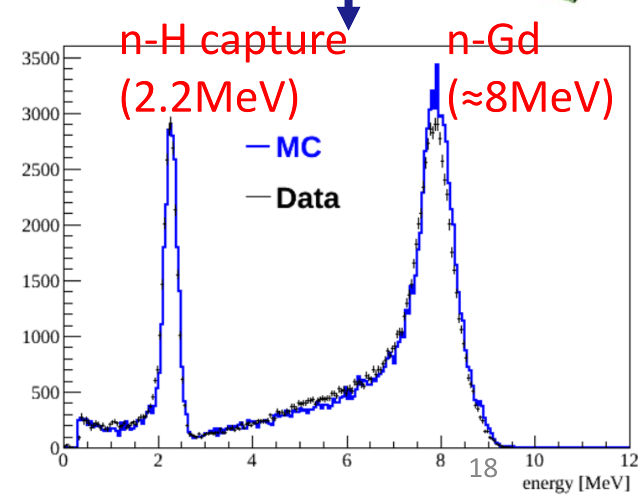
- More recently, observed correlations between reactor core fuel evolution and changes in the reactor antineutrino flux and energy spectrum
  - ^{235}U flux calculation problem or Sterile neutrino?



Neutron Calibration Campaign

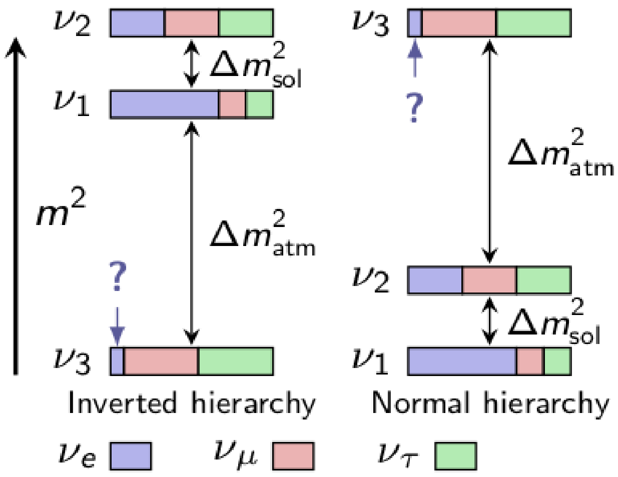
- At Daya Bay, inverse beta decay (IBD) to detect antineutrinos
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
- Dominant systematic uncertainty for antineutrino detection is the efficiency for IBD neutron
- Extensive neutron calibration campaign at the end of 2016
  - AmC and AmBe (few MeV) sources along three z-axes of the automated calibration units (ACU)
- Target: improve the IBD detection efficiency (x2) ⇒ more precise reactor flux measurement





MH determination with reactor neutrinos

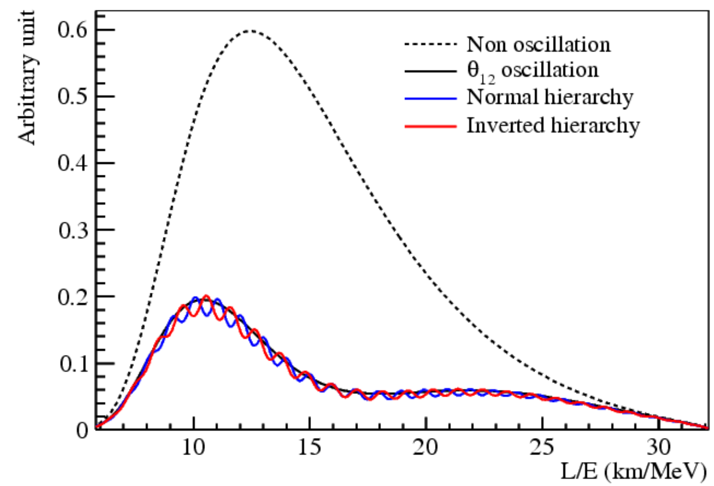
- Determine MH with reactors: oscillation probability independent of CP phase and θ_{23} .



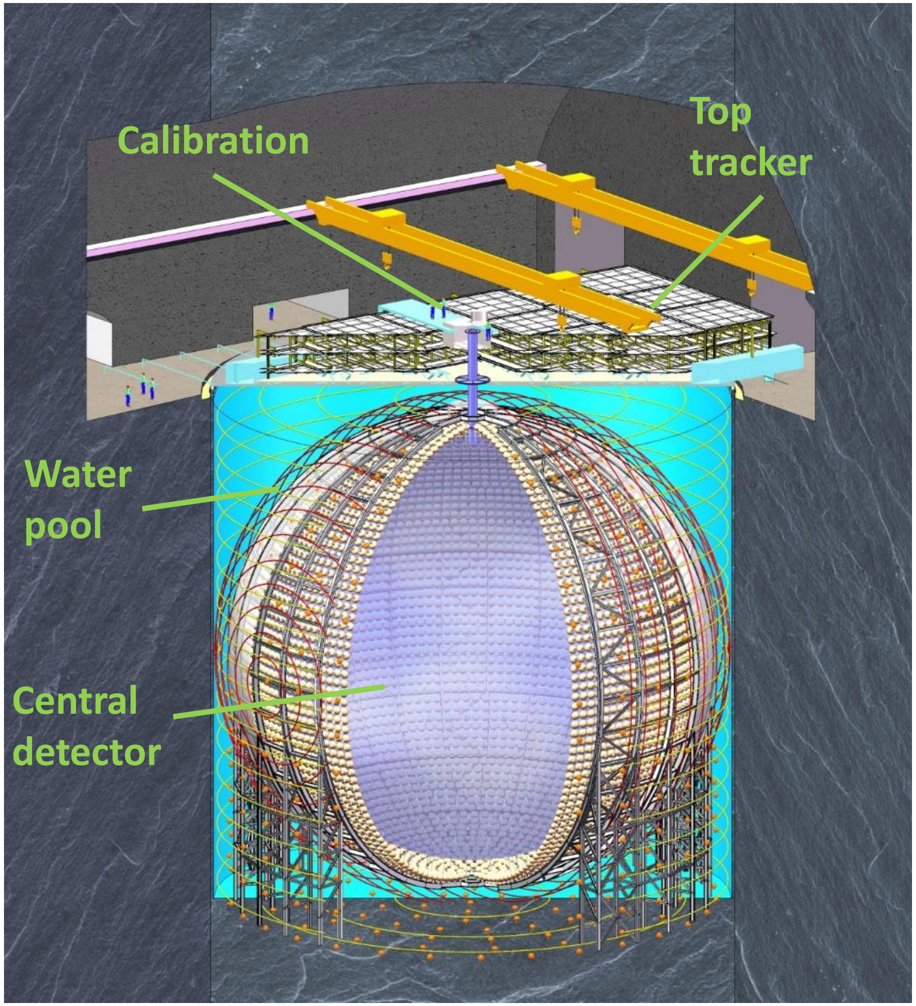
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\end{aligned}
$$

$$
\begin{aligned}
P_{ee} = 1 &- \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta_{21}) \\
&- \sin^2 2\theta_{13} \sin^2(|\Delta_{31}|) \\
&- \sin^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{21}) \cos(2|\Delta_{31}|) \\
&\pm \frac{\sin^2\theta_{12}}{2} \sin^2 2\theta_{13} \sin(2\Delta_{21}) \sin(2|\Delta_{31}|)
\end{aligned}
$$

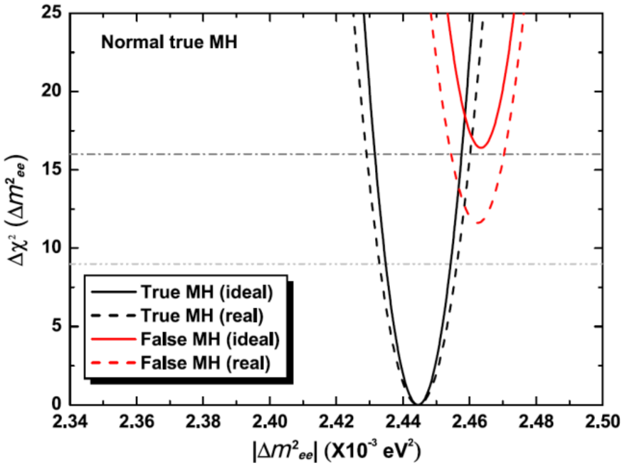
+ NH
- IH



JUNO: Jiangmen Underground Neutrino Observatory



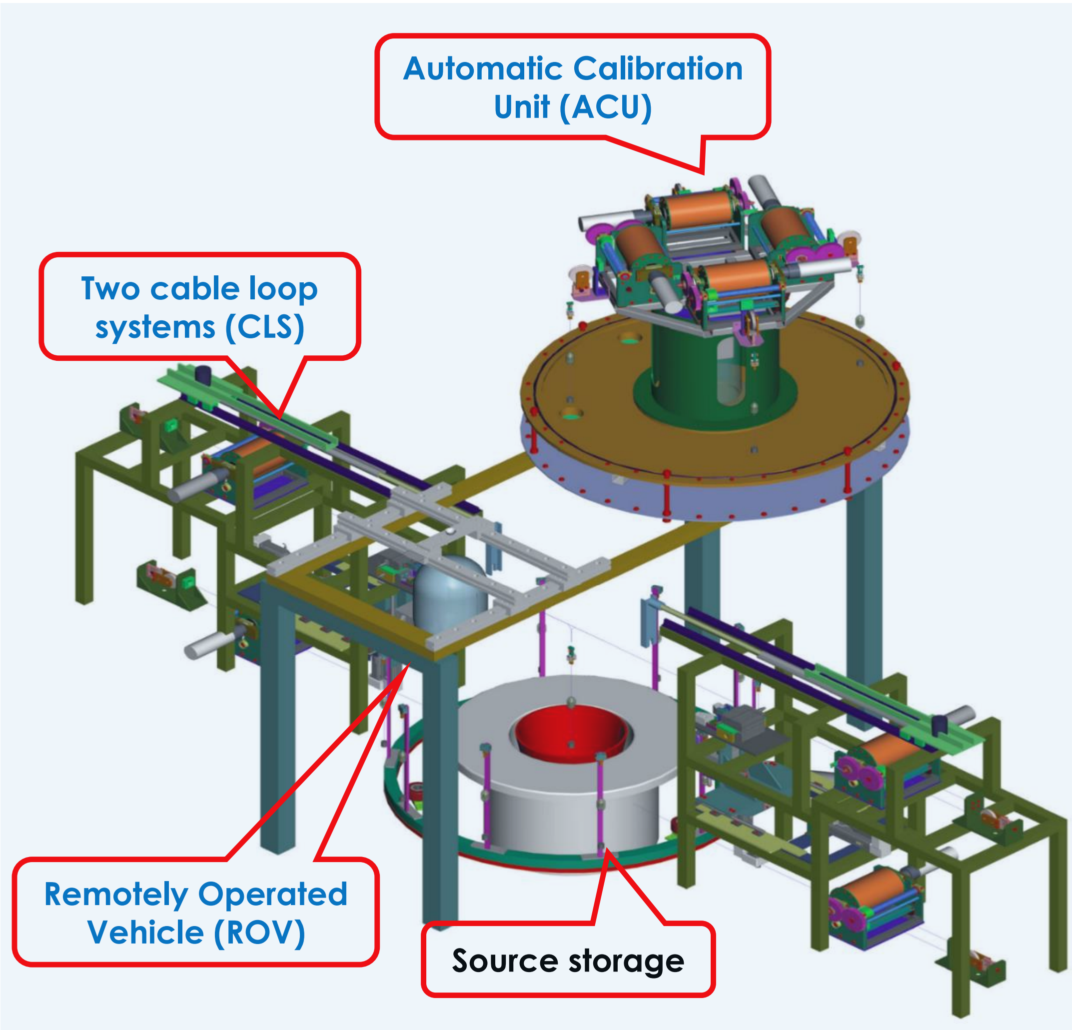
- **Central Detector:**
  - Acrylic sphere (**Φ=35.4m**) +
  - Stainless steel latticed shell (Φ=40.1m).
- **Liquid scintillator: 20 kton**
- **PMTs:**
  - ~17,000 20" PMTs + ~25,000 3" PMTs
  - photocathode coverage **>75%.**
- **Water Cherenkov:**
  - 35 kton pure water + 2,000 20" veto PMTs

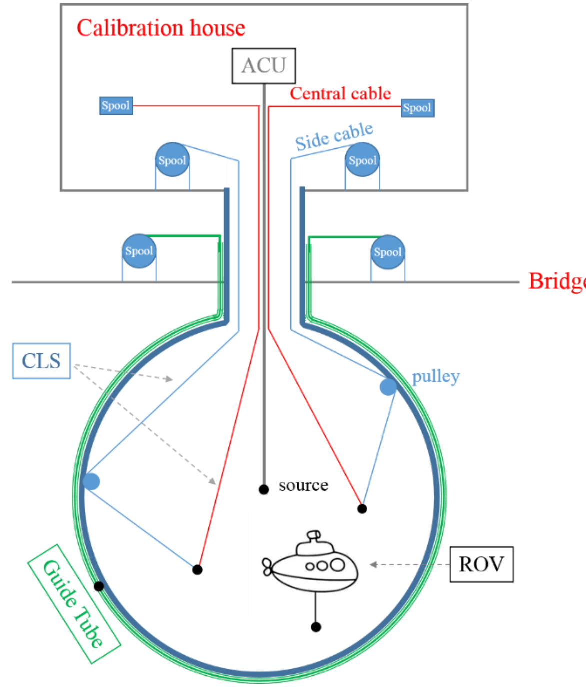


- With 6-years, determine MH at **>3σ (4σ)** for JUNO-alone (JUNO + accelerator experiments) with the energy resolution **$< 3\%/\sqrt{E(MeV)}$**

JUNO calibration system

- **Goal: <3%/$\sqrt{E(MeV)}$** energy resolution, **<1%** energy scale uncertainty





- **ACU:** Scan the central axis (1D)
- **CLS:** Scan one vertical plane (2D)
- **ROV:** Scan "everywhere" (3D)
- **Guide Tube:** Scan boundary

Neutrinoless double beta decay

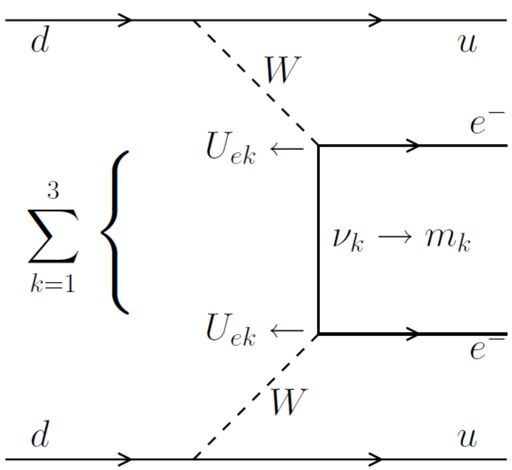
- Explores the Majorana nature of neutrinos
- Tests lepton number conservation
  - ΔL = +2
  - 0νββ is not just a neutrino experiment!
- Connects to broad neutrino oscillation physics picture

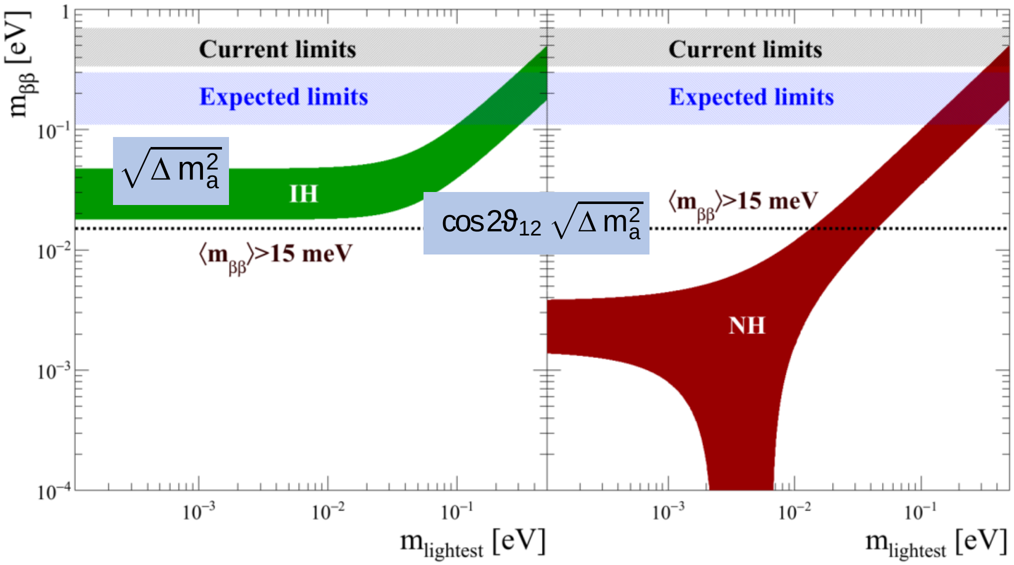
Majorana Neutrino

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

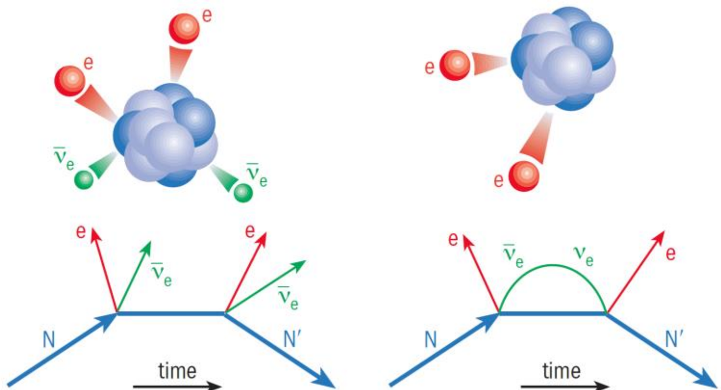
Example:

$$^{136}Xe \rightarrow {}^{136}Ba + 2e^{-} + (2\bar{\nu}_e)$$



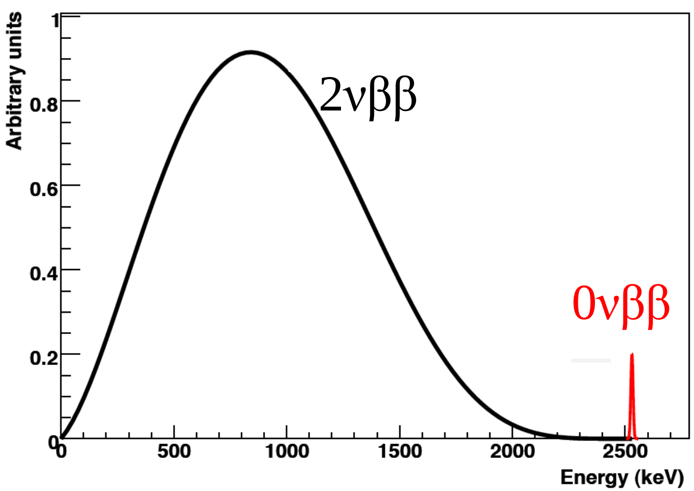


Neutrinoless double beta decay

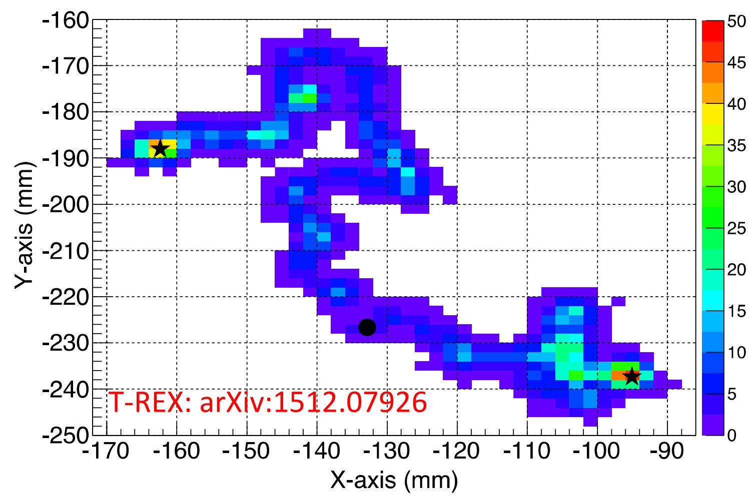


From Physics World

- Measure energies of emitted e$^-$ (universal approach)
- Electron tracks are a huge plus (unique feature of certain experiments)
- Daughter nuclei identification (ultimate dream?)

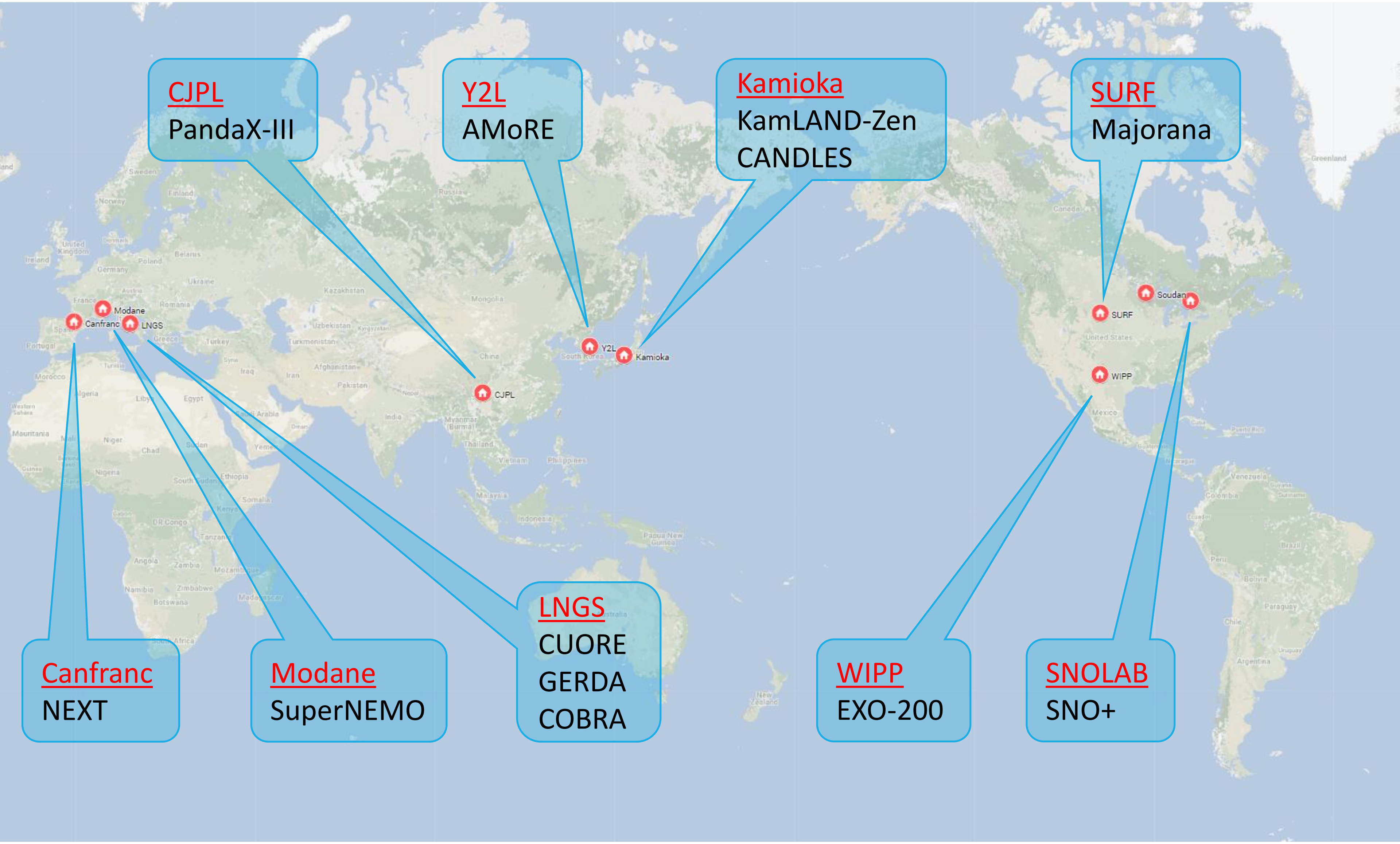


Sum of two electrons energy



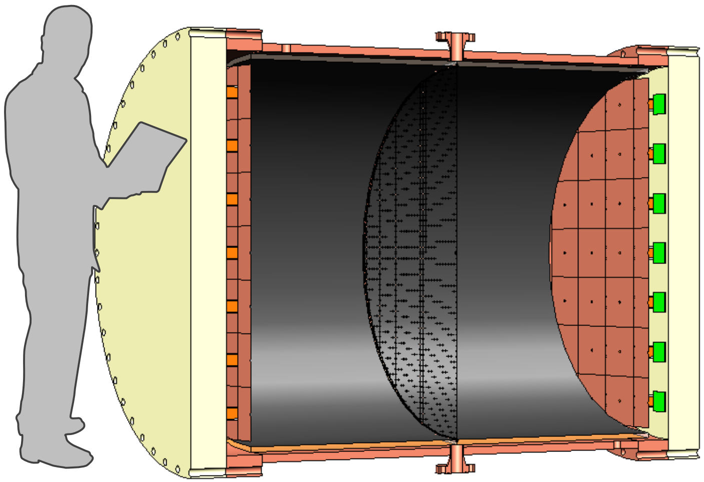
Simulated track of 0νββ in high pressure Xe

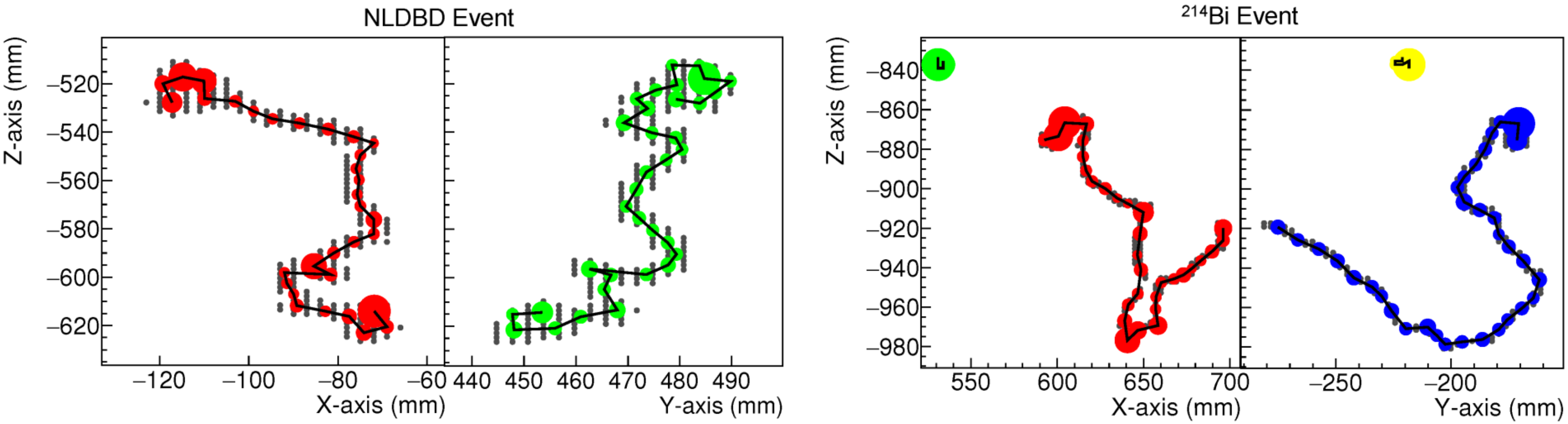
Major 0νββ experiments around the world



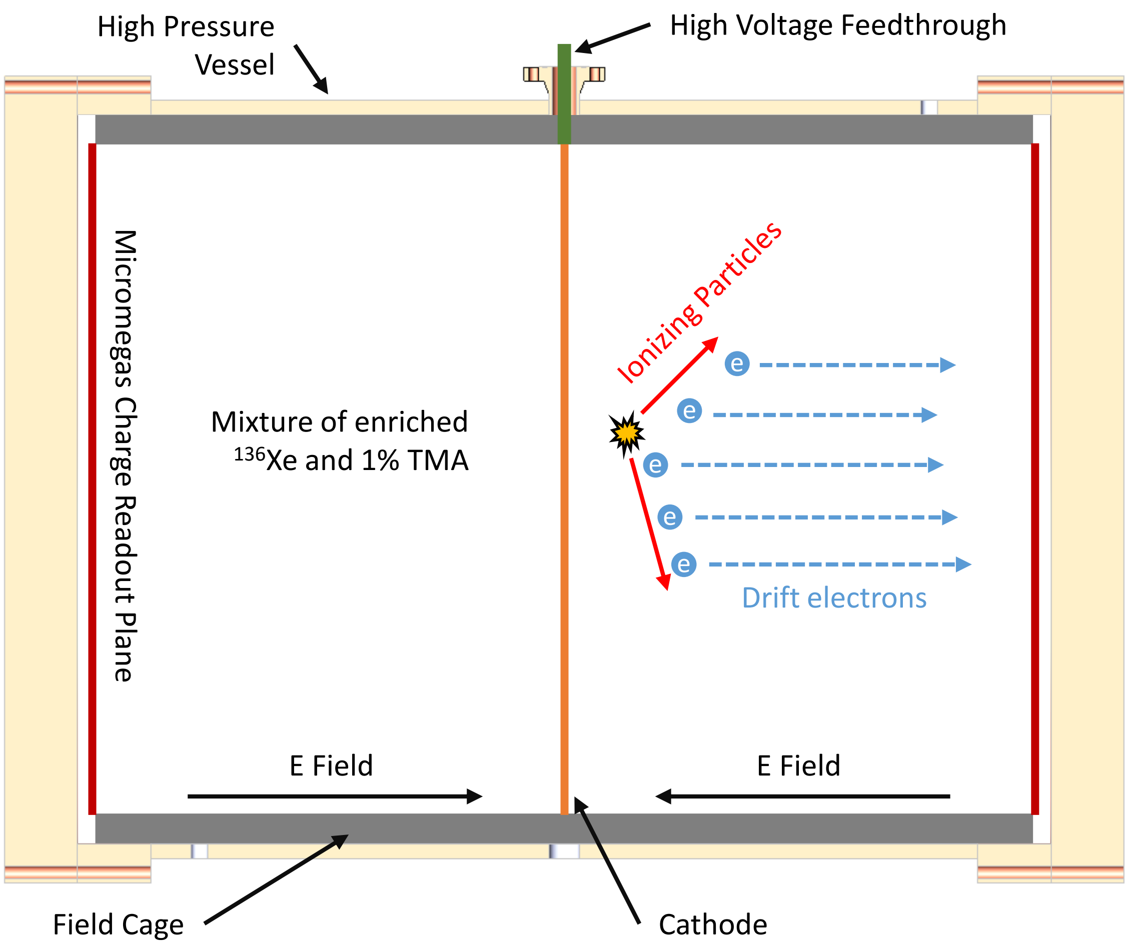
PandaX-III: high pressure gas TPC for 0νββ of ^{136}Xe

- TPC: 200 kg scale, symmetric, double-ended charge readout, with 10 bar of ^{136}Xe
- Main features: good energy resolution and background suppression with tracking

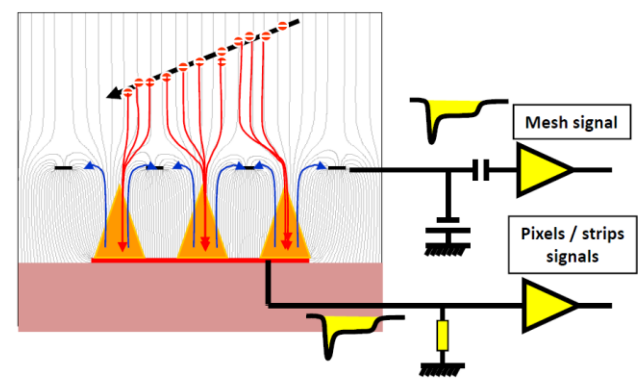




PandaX-III TPC illustrated

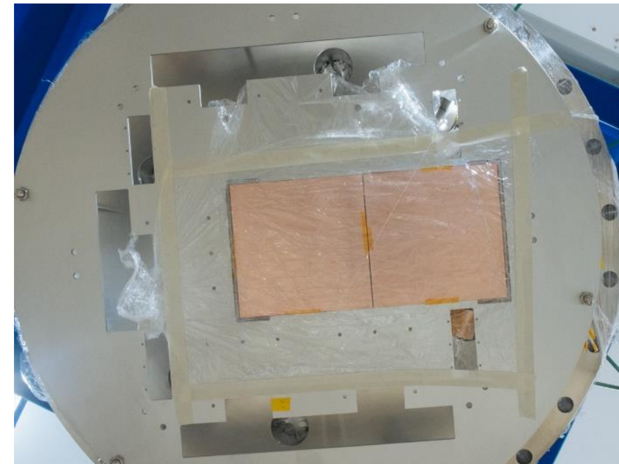


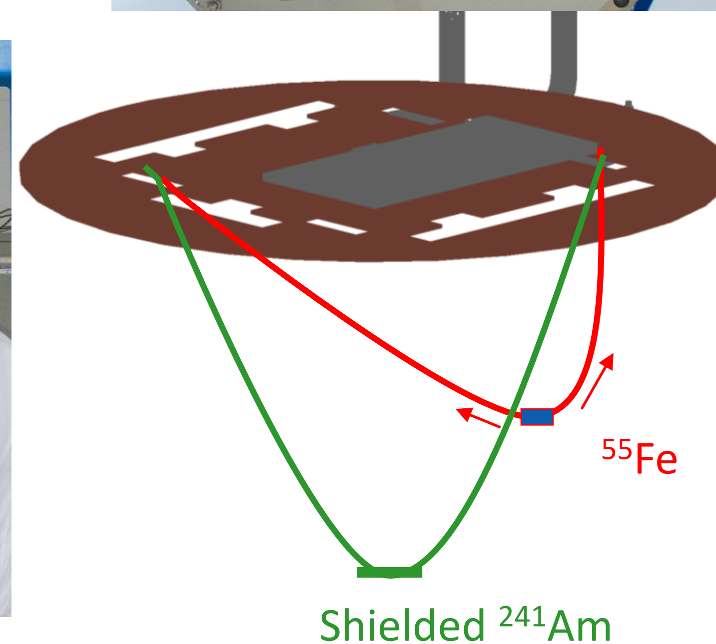
- ~4m³ active volume
- 10 bar working pressure
- ~10000 readout channels
- Xe+TMA gas mixture
- Charge-only readout with microbulk Micromegas

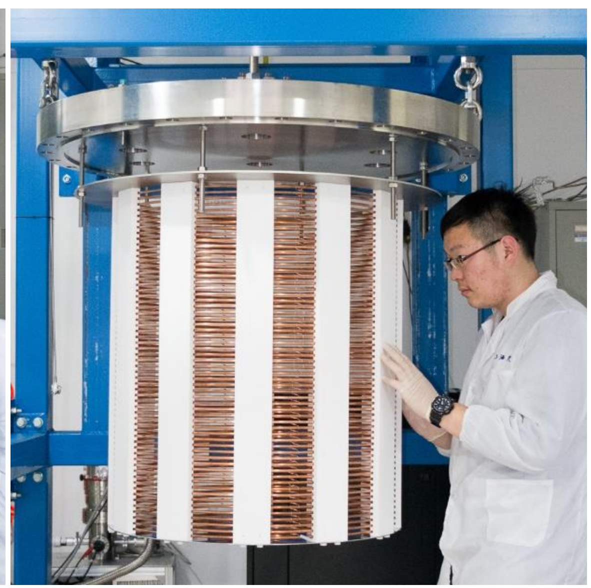


Prototype TPC at SJTU

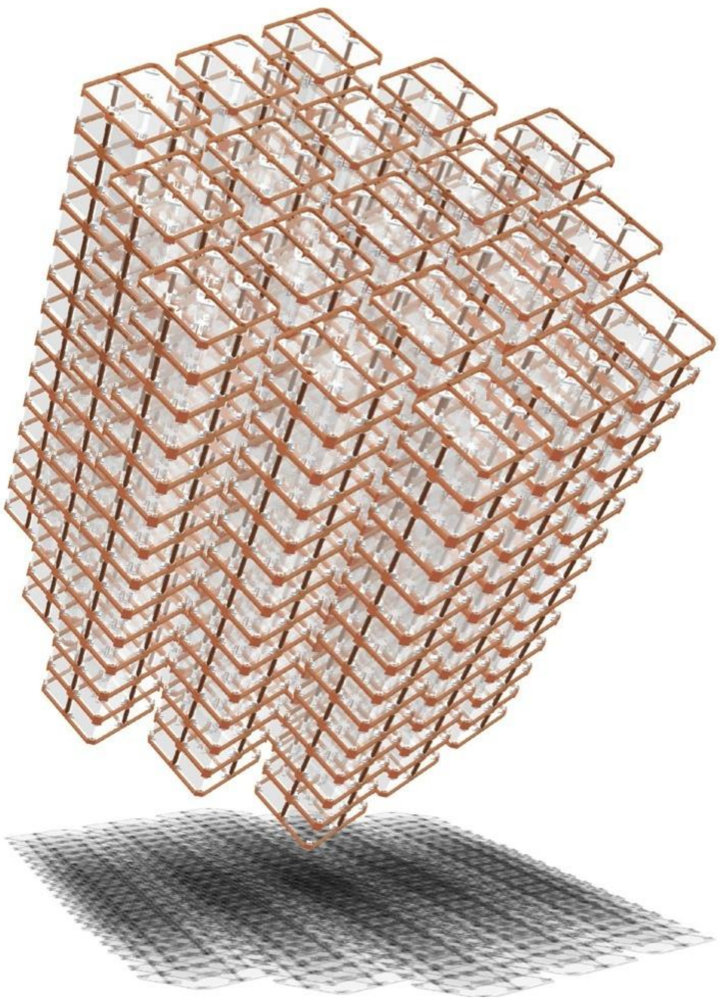
- 16 kg of xenon at 10 bar (active mass within TPC)
    - Single-ended TPC
- Data taking with Ar, Xe, Xe+TMA at different pressures
- Two Micromegas modules installed. Movable source used for calibration



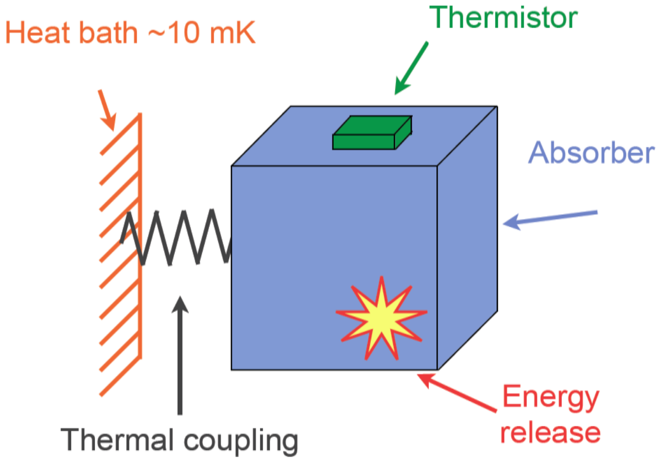




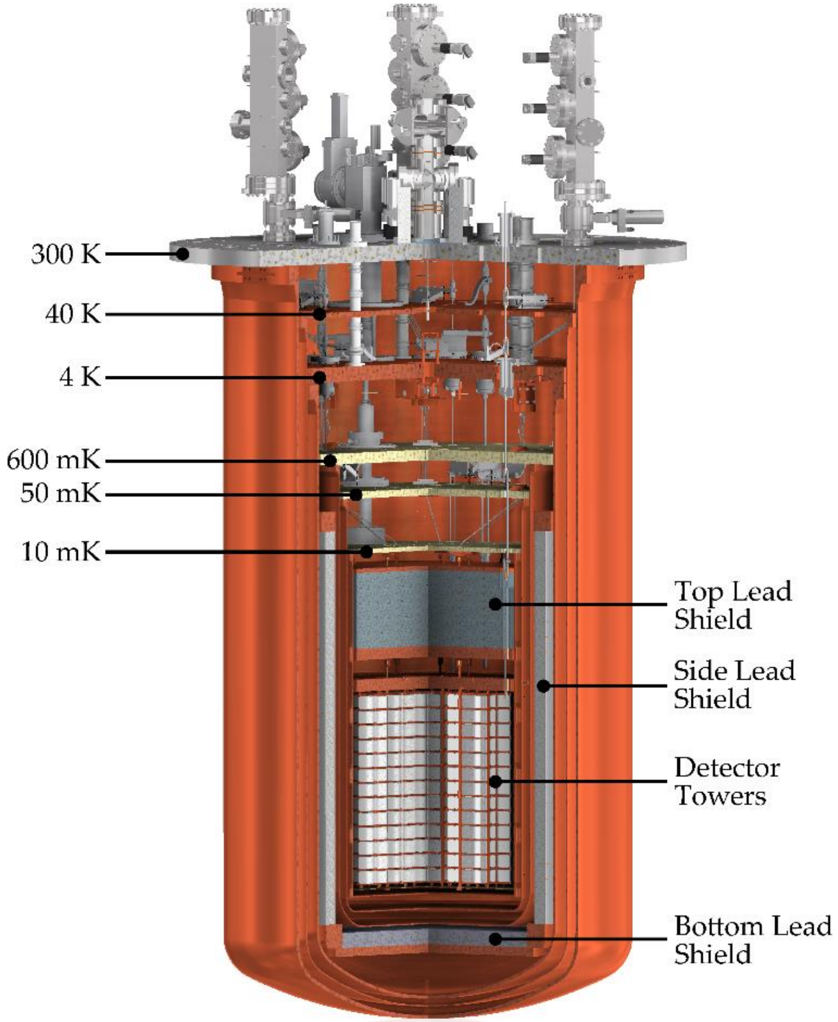
CUORE (Cryogenic Underground Observatory for Rare Events)



- Search for $0\nu\beta\beta$ of ^{130}Te and other rare events
- 988 TeO_2 crystals run as a bolometer array
  - 741 kg total; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei



CUORE (Cryogenic Underground Observatory for Rare Events)



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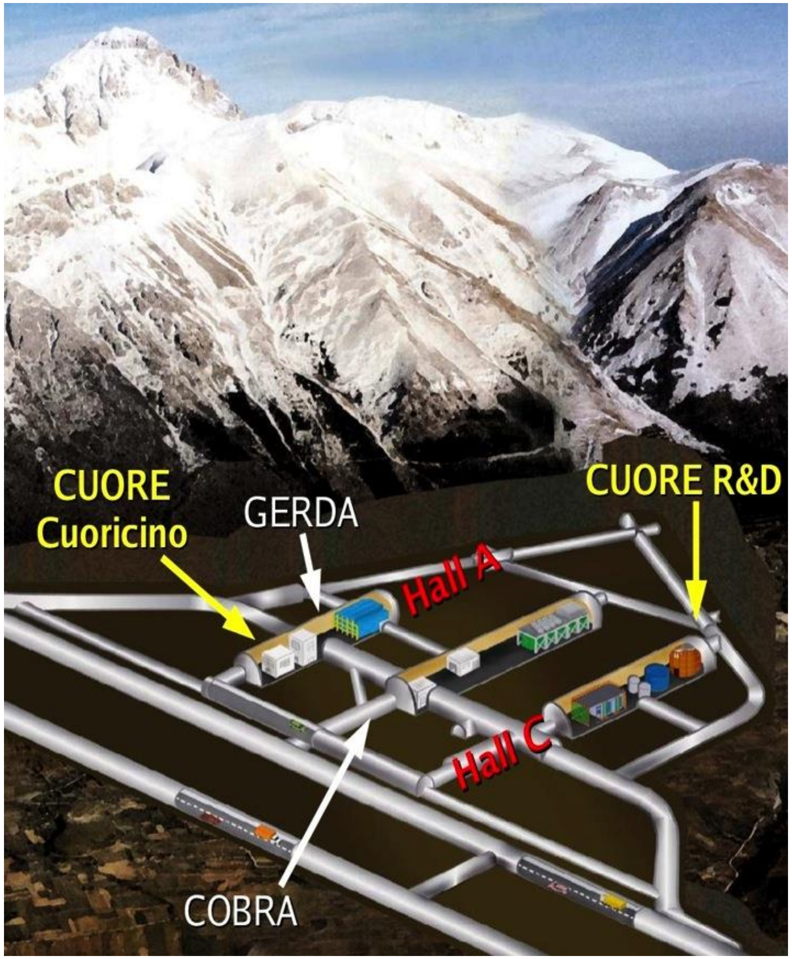

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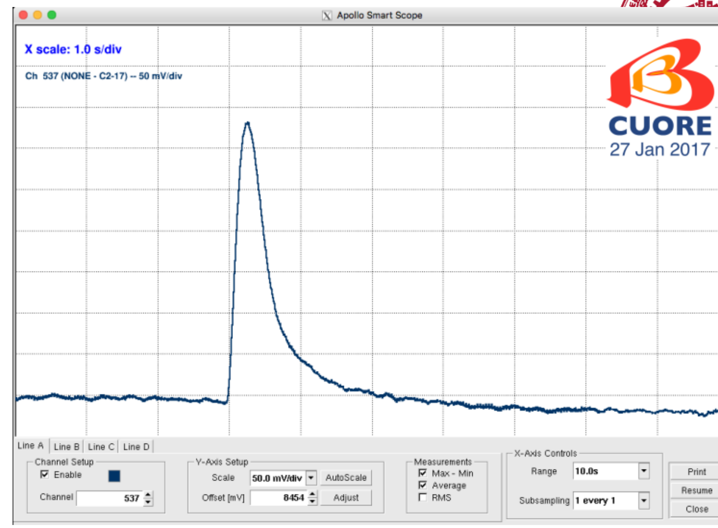
- Gran Sasso underground lab (LNGS), Italy
  - 3600 m water equivalent
  - Muon Flux at LNGS: *~3x10^{-8} μ/(s cm^2)*

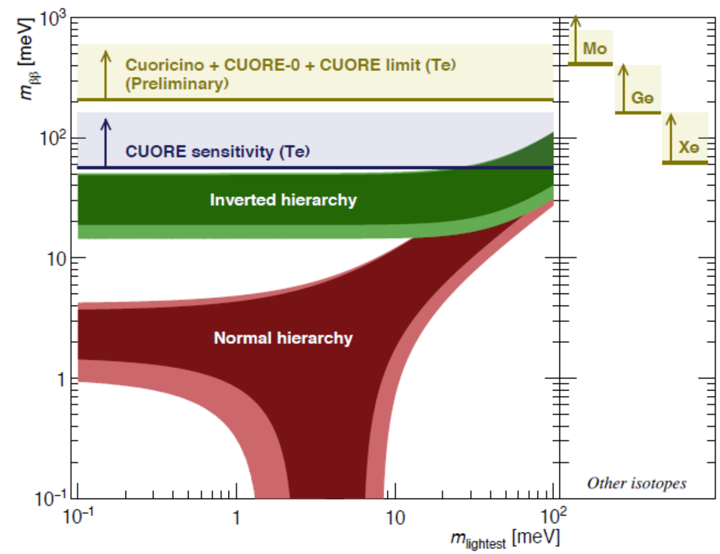
2017: a great year for CUORE

- Data taking started early this year
- First physics result in July



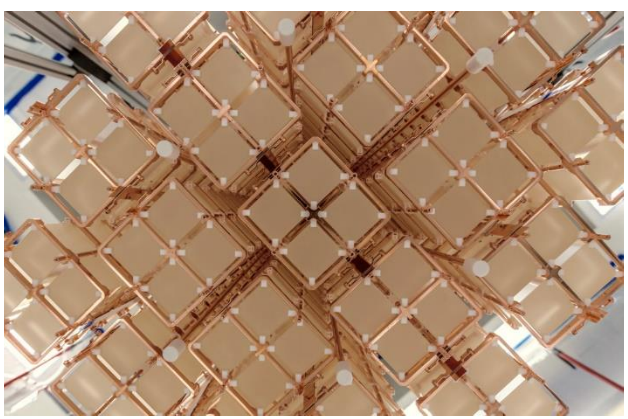
Future

- CUPID (CUORE with particle ID)
  - Enrichment
  - Phonon + photon dual readout
  - Multiple crystal choices
  - Active discussion of CUPID-China



$T_{0\nu}(^{130}Te) > 6.6 \times 10^{24}$ yr

$m_{\beta\beta} <$ 210 - 590 meV



Conclusions

- Very active mega-group on dark matter and neutrino physics
  - WIMP search
  - Neutrino oscillation
  - Neutrinoless double beta decay
- PandaX, the Flagship experiment founded and led by SJTU, has been a huge success
  - World-leading results
  - In China: pioneering effort; broad impact
- International collaboration in both directions