Hunting for WIMPs in Panda Land

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Outline

- Why do we believe there is dark matter?
- What is dark matter? and how do we detect them?
- Jinping lab and PandaX experiment
- Recent results
- PandaX future

Why do we believe there is dark matter?

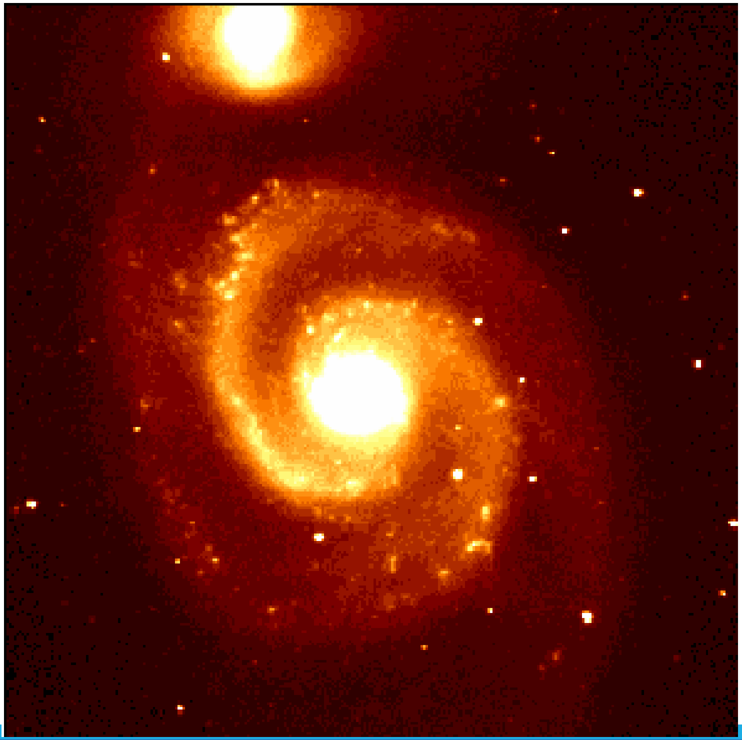
There is more gravity in the universe than meets the eye!

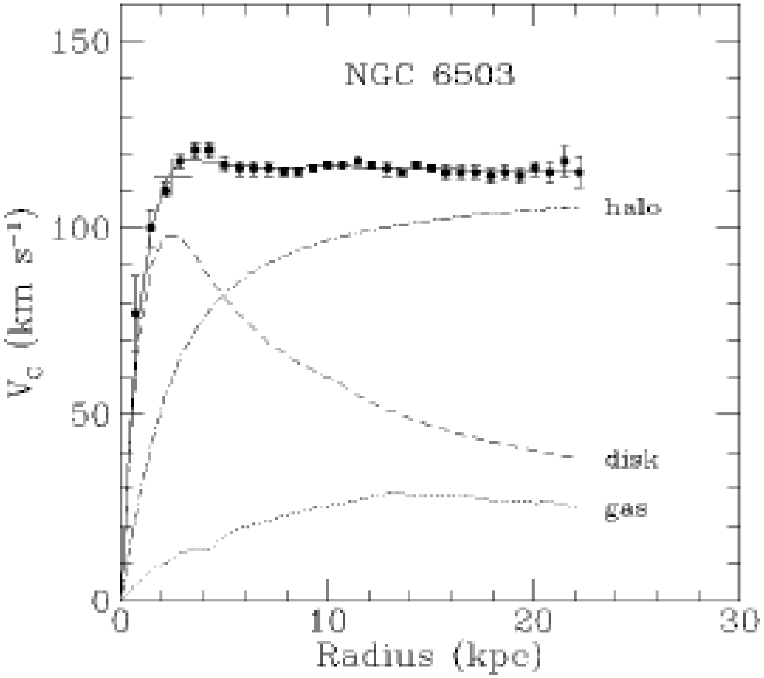
- Galaxy Rotational Curve
- Gravitational Lensing
- Cosmic Microwave Background (CMB) fluctuation
- Galaxy Distributions in the Universe
- ……

All evidences point to the existence of a new type of matter in the universe!

Rotational Curve (Ford & Rubin, 70s')

- In a galaxy, the rotational speed of stars as a function of distance forms the rotational curve.

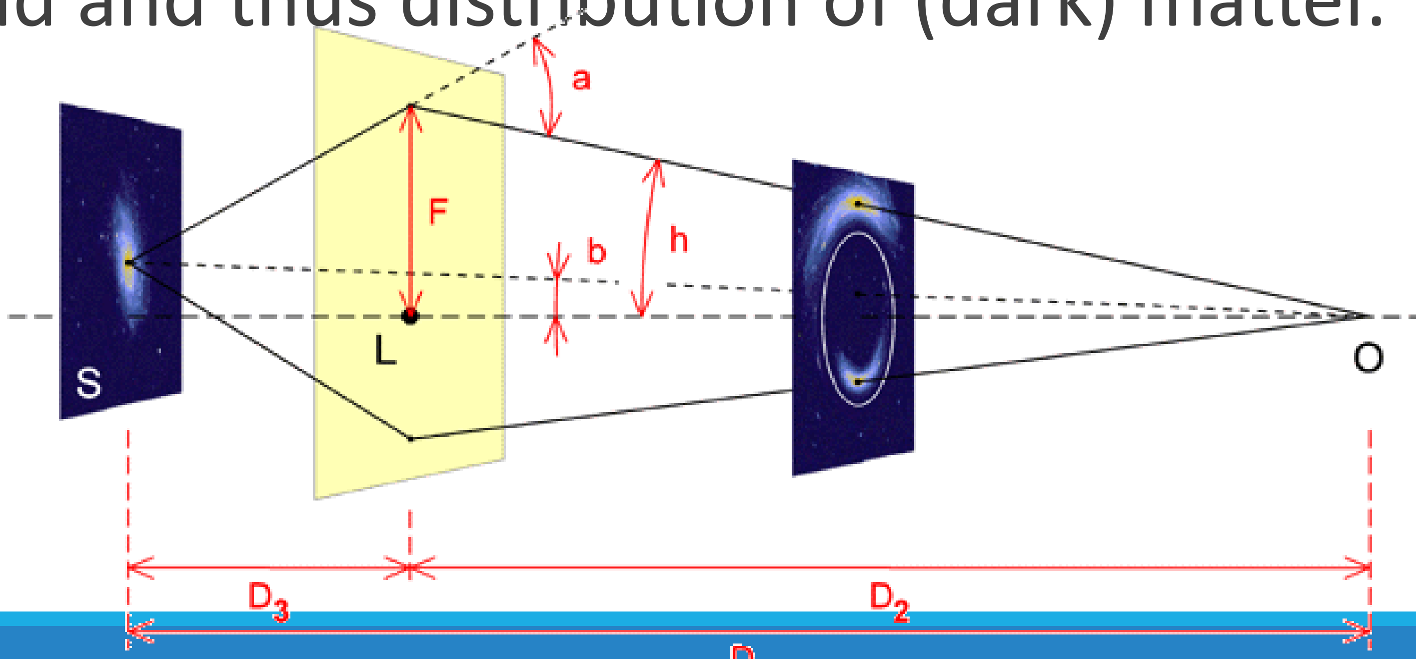




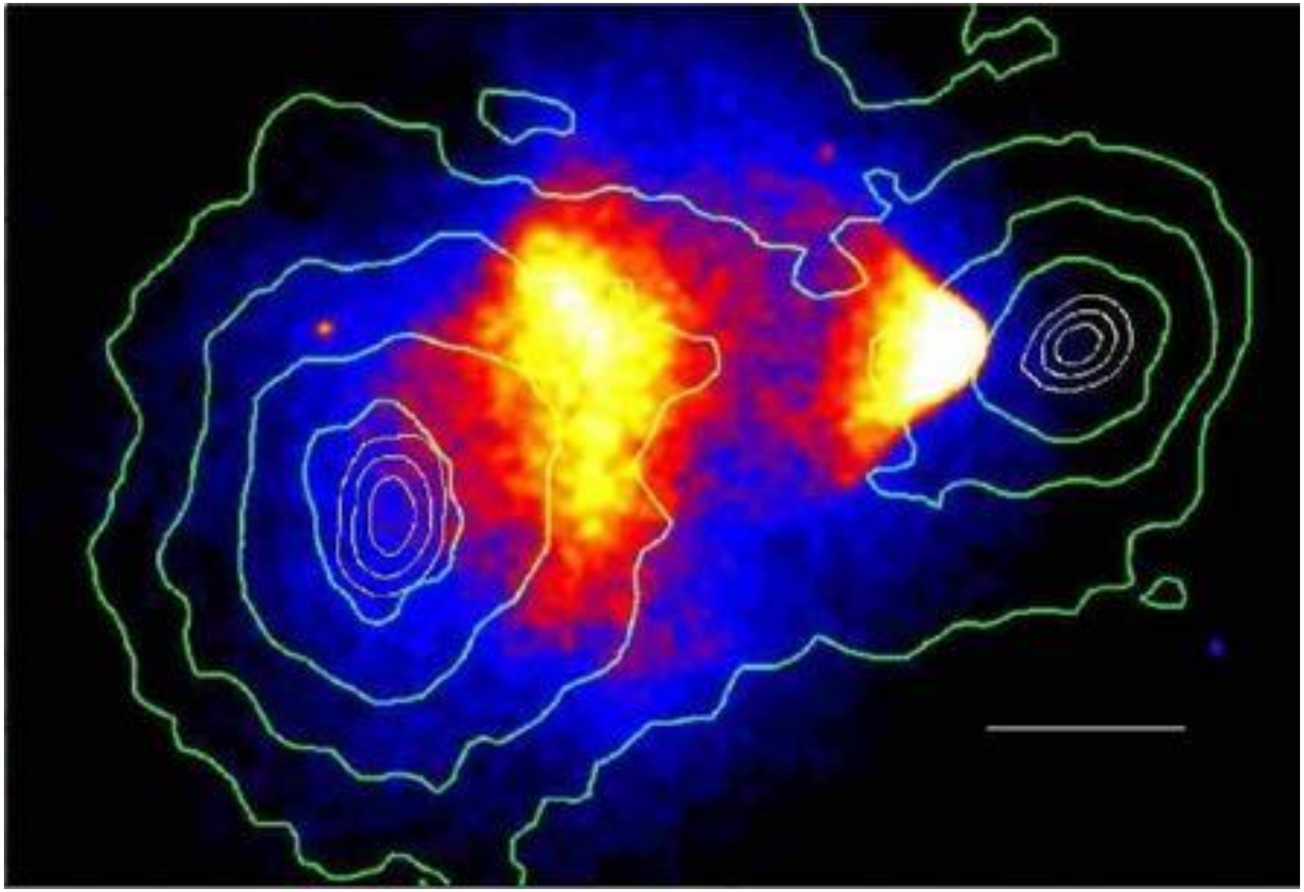
95% mass from dark matter!

Gravitational lensing

- When light passes through a gravitational field, it refracts. From the magnitude of deflection, we can calculate the gravitational field and thus distribution of (dark) matter.



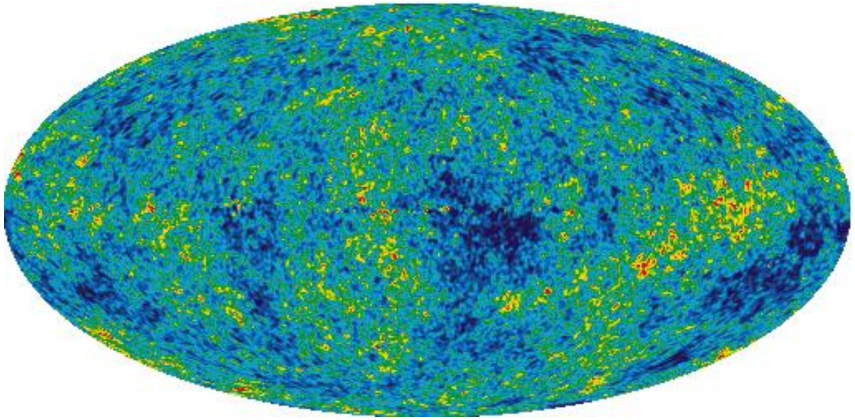
Bullet Cluster

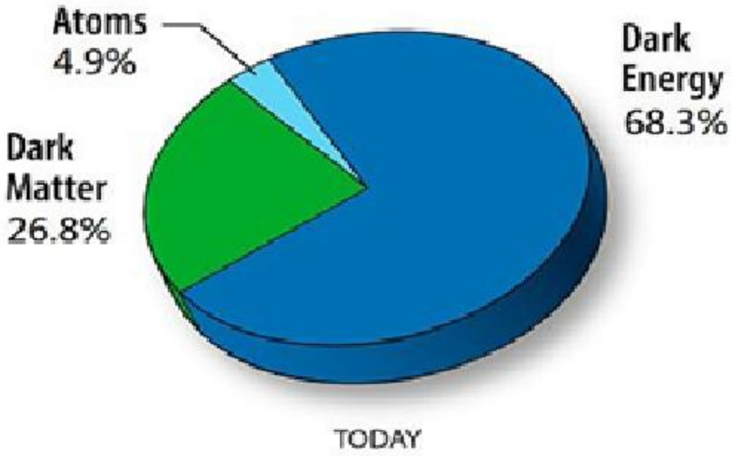


Fluctuations of CMB

- In 1992， Smoot discovered 10^{-5} level temperature fluctuation at different directions (COBE)

CMB fluctuation map



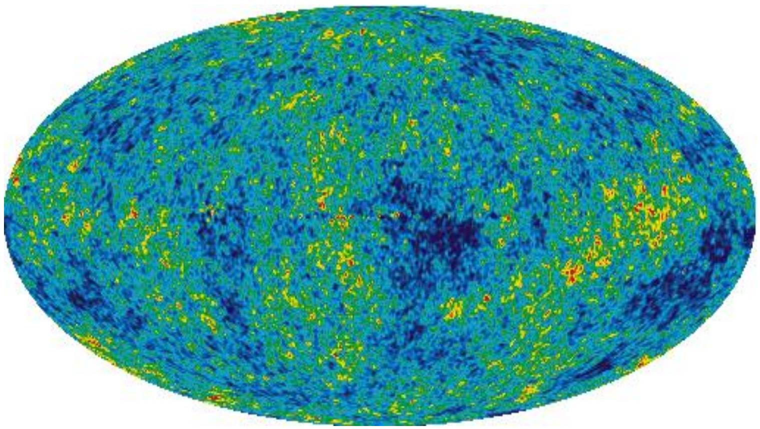


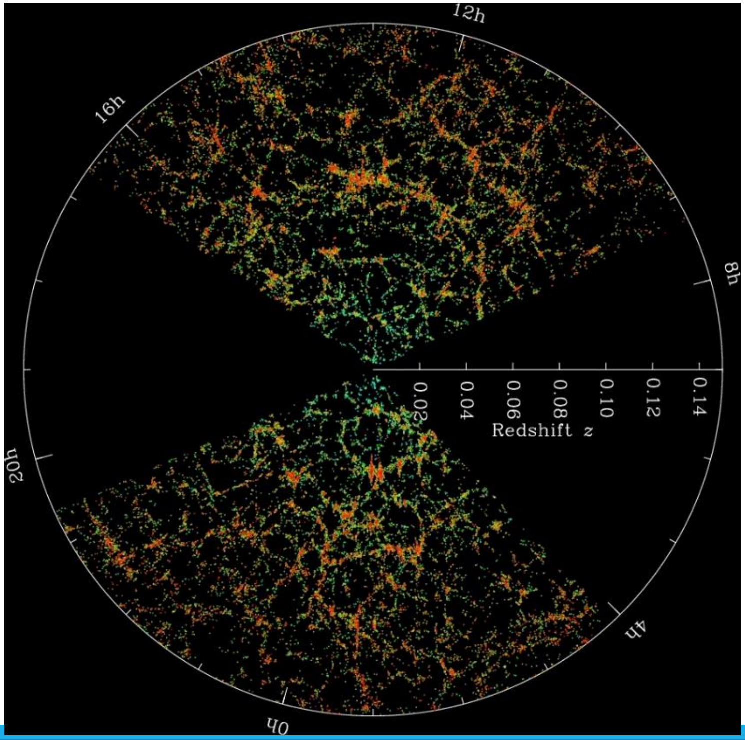
- The fluctuation can be explained by inflation model with 27% cold dark matter!

Large scale structure of the universe

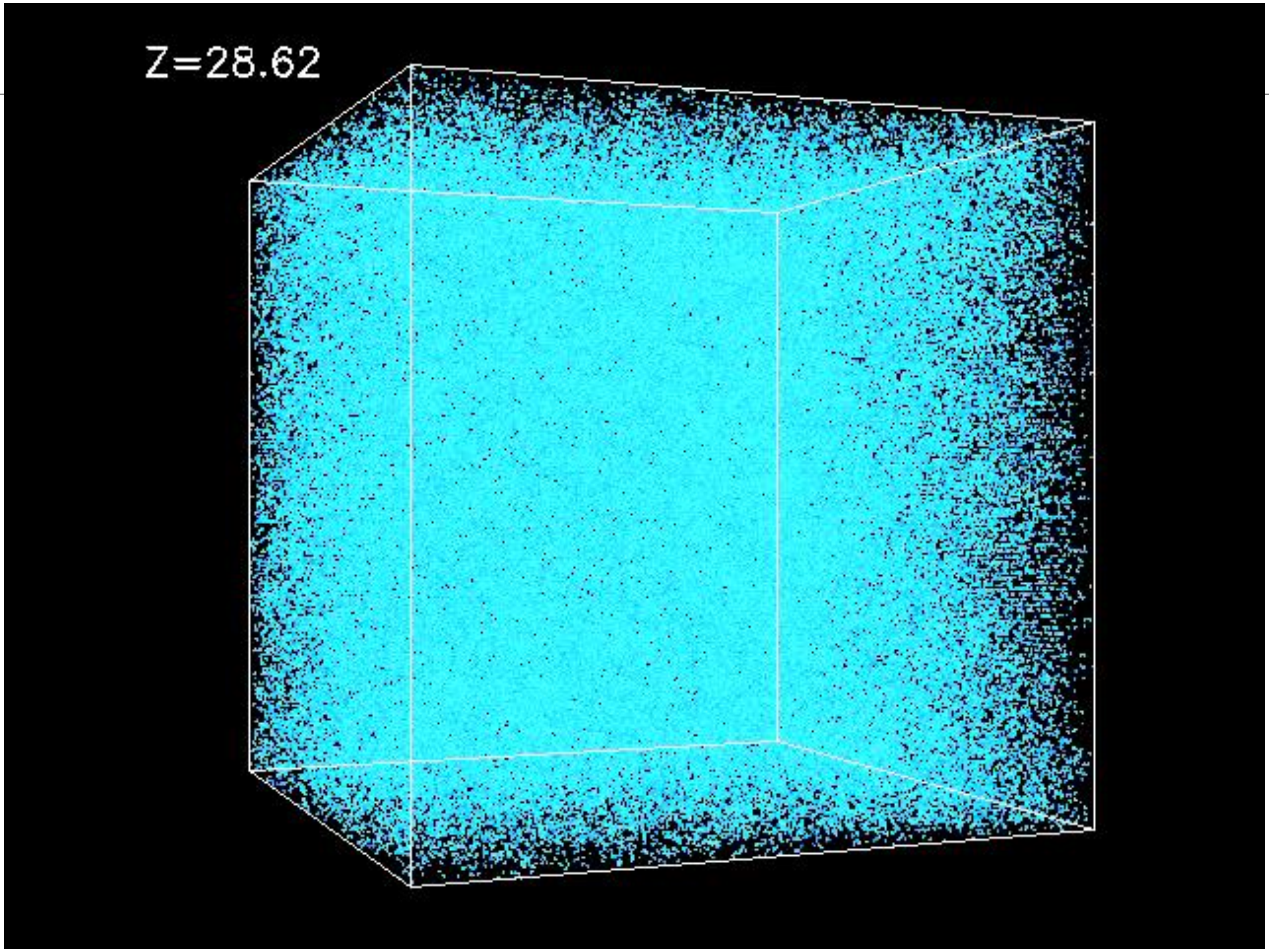
- Today's universe is quite lumpy and this lumpiness has been generated from this 10^{-5} level CMB fluctuation.

CMB fluctuation





Simulating the large-scale structure

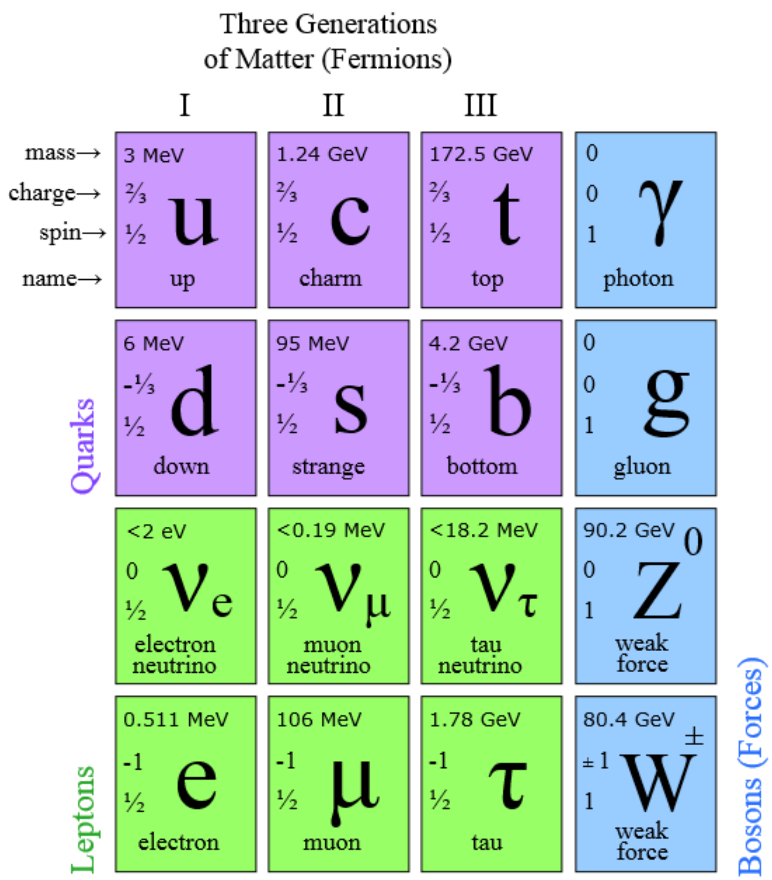


What is dark matter? how to detect them?

What do we know about DM?

- It has a long life time, probably much longer than that of the universe (>10^{17} sec).
- It has no electromagnetic and strong interactions.
- It is not in the standard model of particle physics. (neutrino only accounts for less than 0.1% of the energy).

Standard model of particles



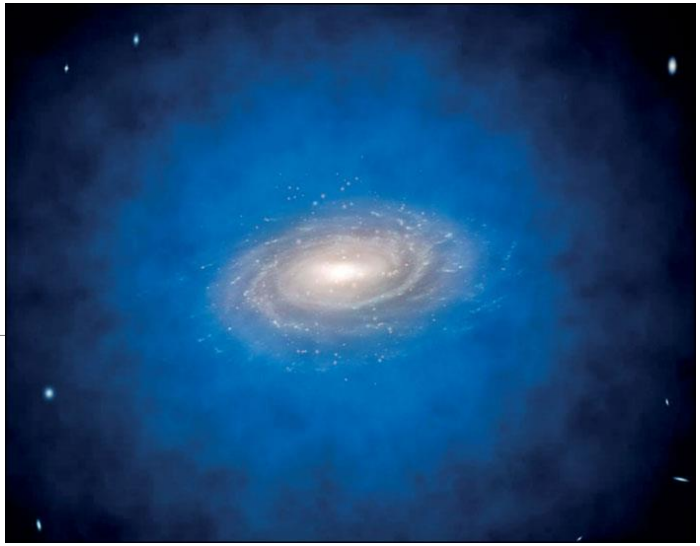
What is dark matter?

- Know unknown and unknown unknowns…
  - Primordial black holes
  - Axions
  - Sterile neutrinos, SM singlet scalars,
  - Weak-interacting massive particles (WIMPs)
    - stable particles from the extension of the SM's weak interaction sector.

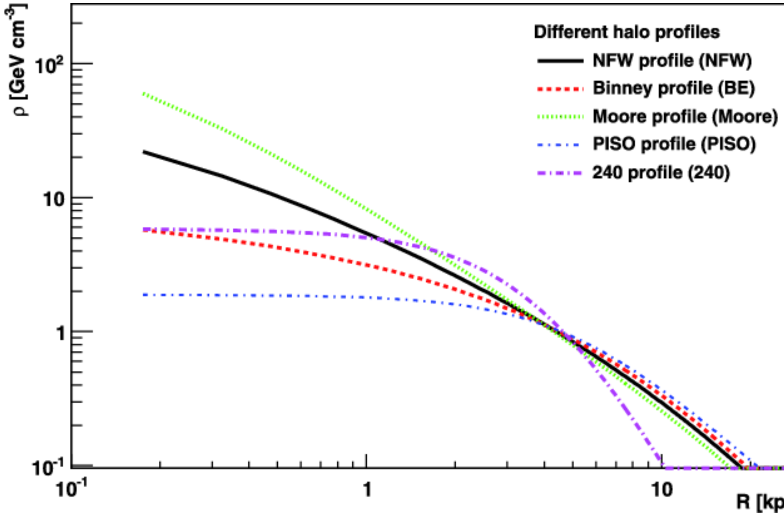
Why WIMPs are popular

- Naturally exist in SUSY or extra dimensional theories with masses of GeV-TeV.
- WIMP Miracle
  - If the universe history is thermal, the particles of EW mass scale and weak interactions can produce the right amount of DM in the present universe!
- We can study them using particle/nuclear experiments.

DM in Milky Way



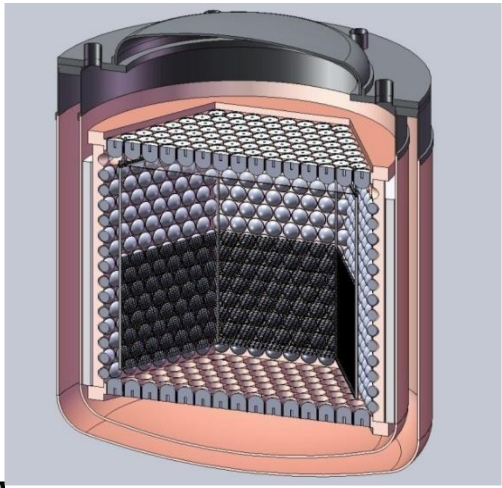
- Our Milky Way has dark matter halo, which accounts for more than 95% of the Wilky Way mass.
- The halo density profile: Simulations + Galaxy Rotation Curve →



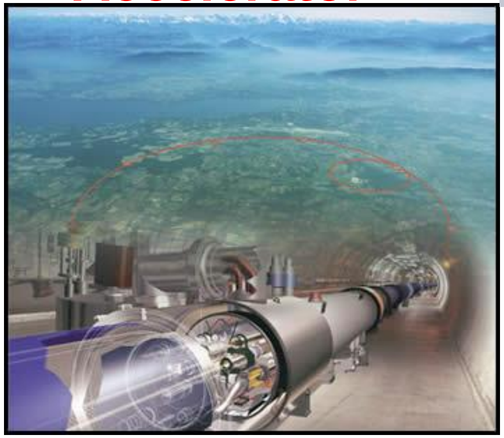
- Near the solar orbit, the DM density is about $0.3GeV/cm^3$.

WIMPs Detection

Direct Detection



Accelerator

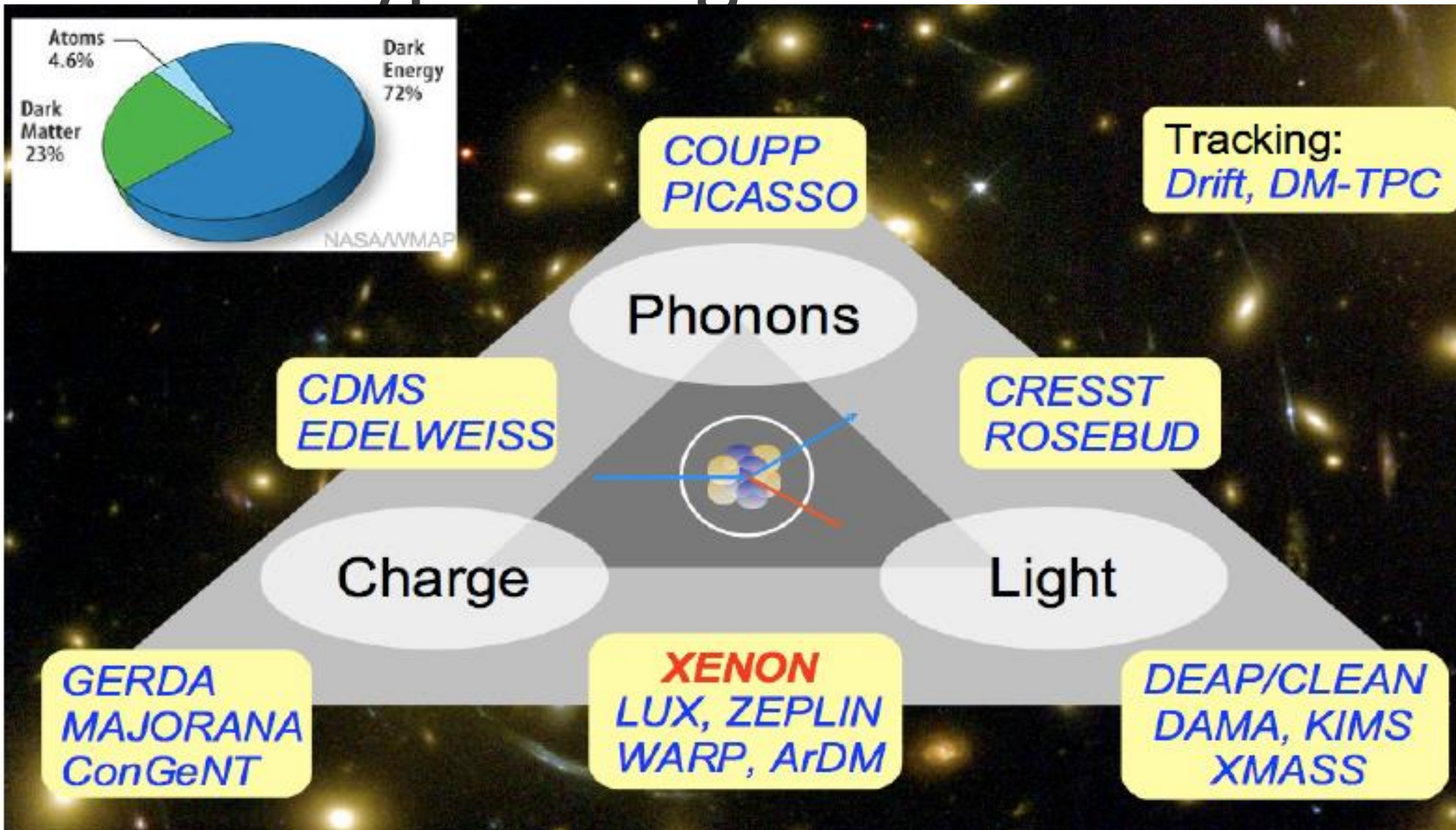


Indirect Detection

Direct Search

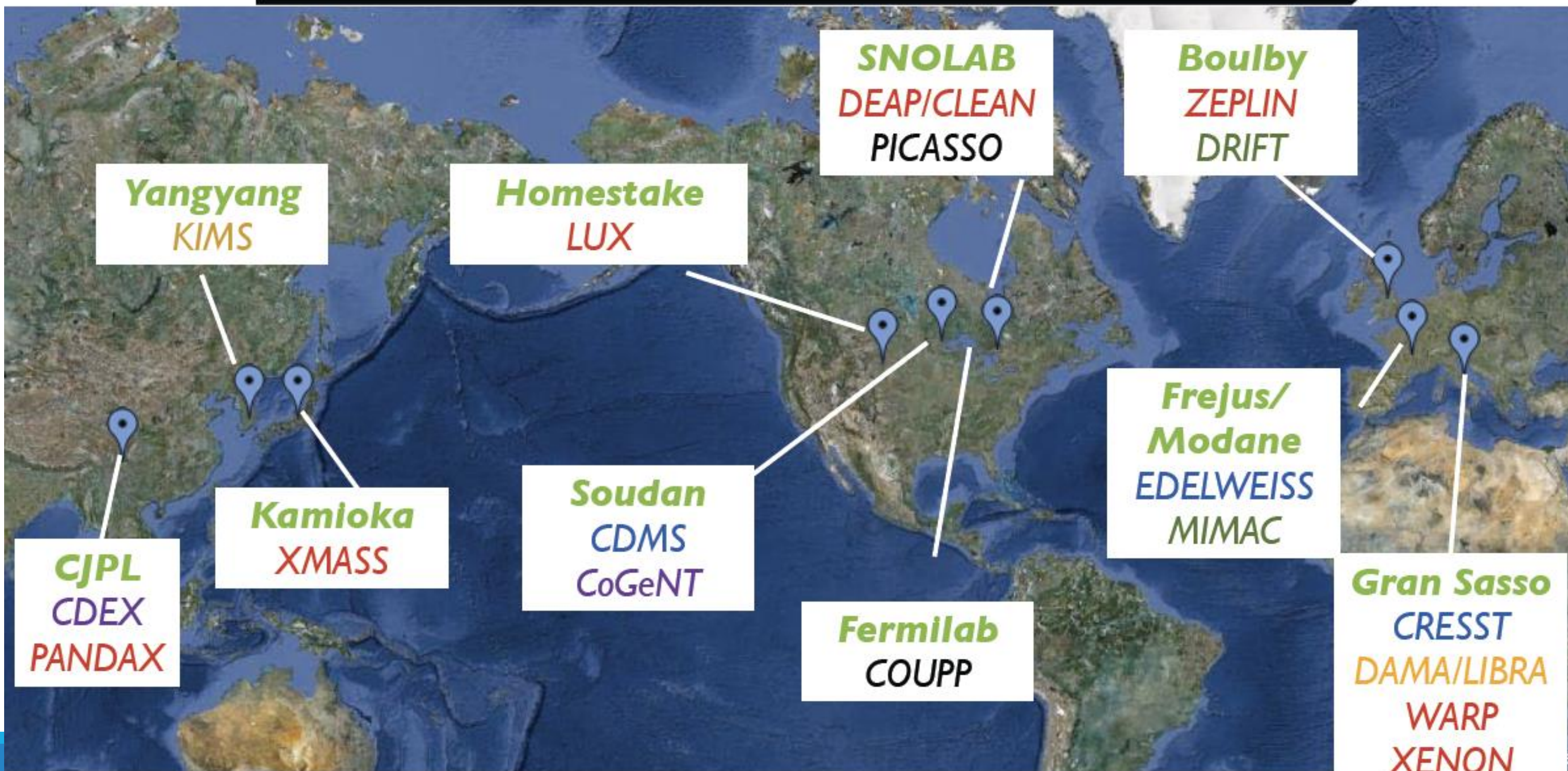
- The solar system is moving at ~230km/s around the galactic center.
- Everything on the Earth is like a small fish, swimming against the DM current. The WIMPs have a small probability hitting the atomic nuclei through weak interactions producing nuclei recoils (<1 time/ 300kg day).
- Direct detection is to detect the medium reaction due to nuclear recoil.

Three types of signals

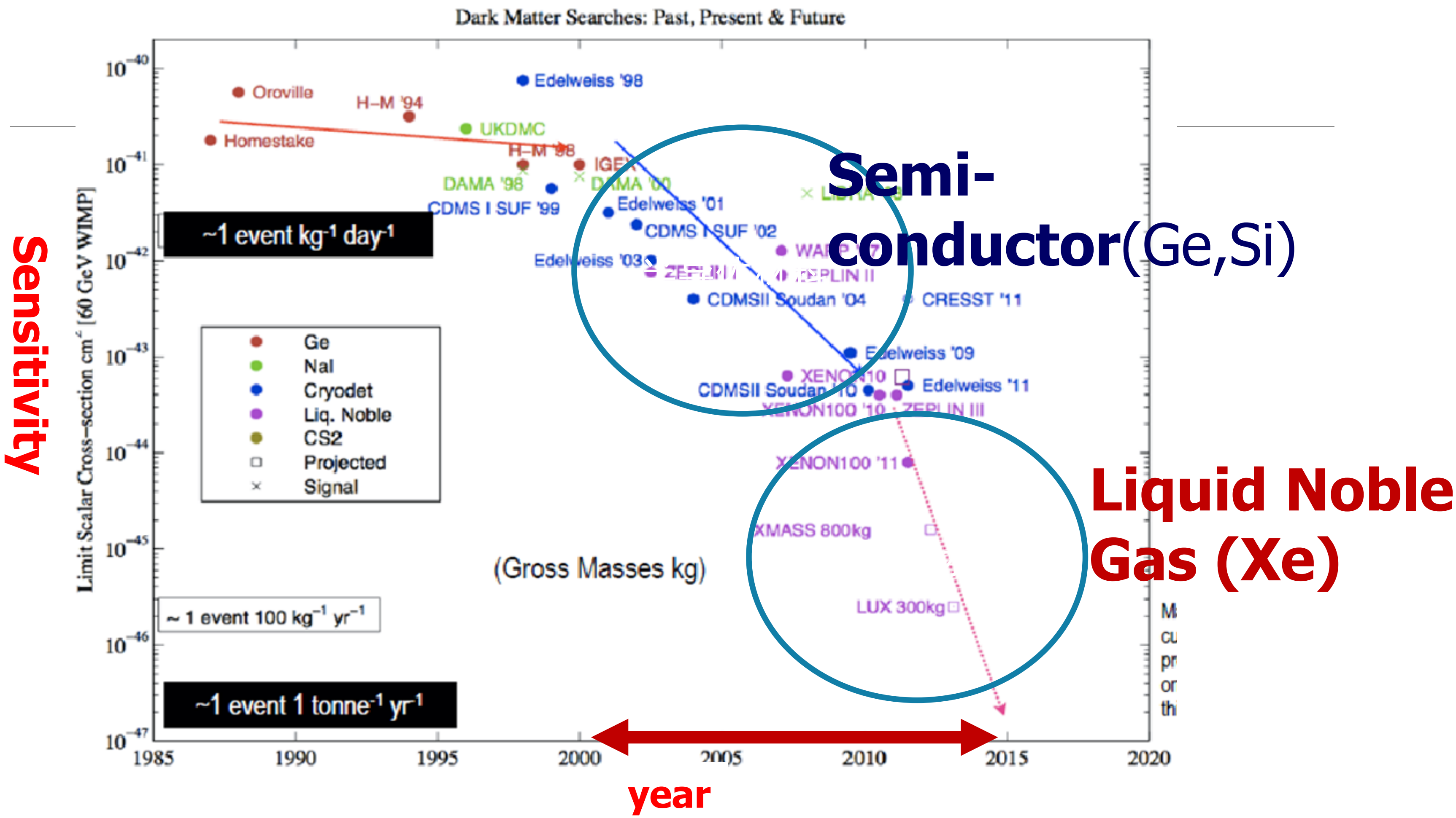


Direct detection experiments around the world

Cryogenic Bolometer (Ge, Si etc.)
Solid Scintillator (NaI, CsI)
Noble Liquids (LXe, LAr)
Directional / Ultra-low threshold / Bubble chamber



DM Detection Sensitivity



➢Dual Phase-Liquid Noble gas detector produced quicker exponential growth in sensitivity

Jinping Underground Lab and PandaX experiment

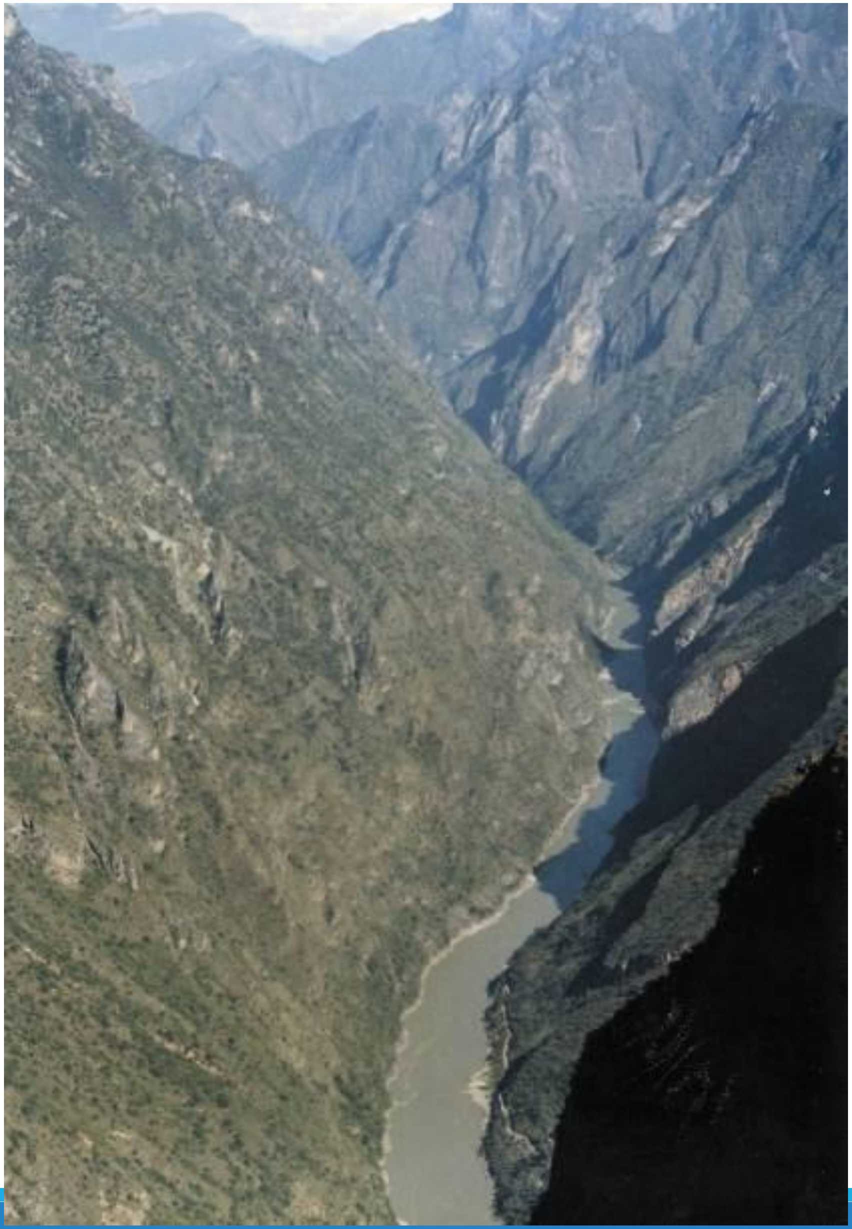
Yalong River and Jinping Hydropower Plant

Yalong river is located at the western part of Sichuan, with length of 1571km and drop height of 4420m. Twenty-one hydropower plants are planned, with total hydropower of 30GW.

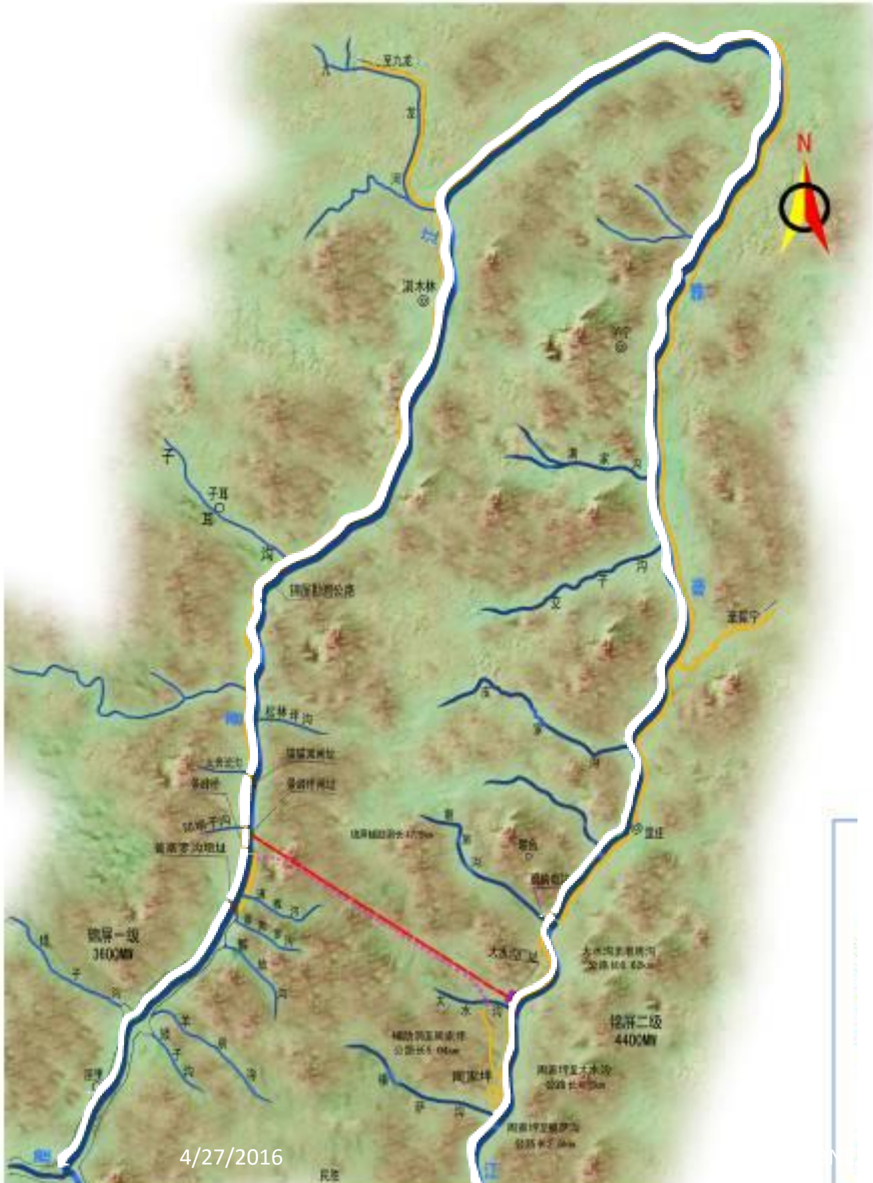
Yalong River and Jinping Hydropower Plant

Yalong river is located at the western part of Sichuan, with length of 1571km and drop height of 4420m.

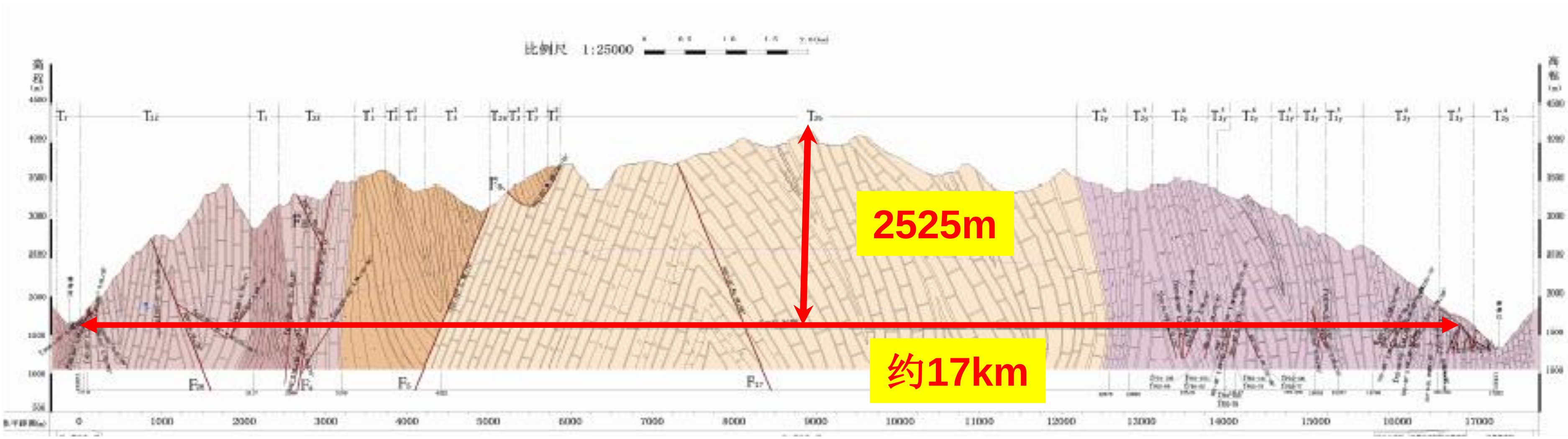
High Mountain and great canyon

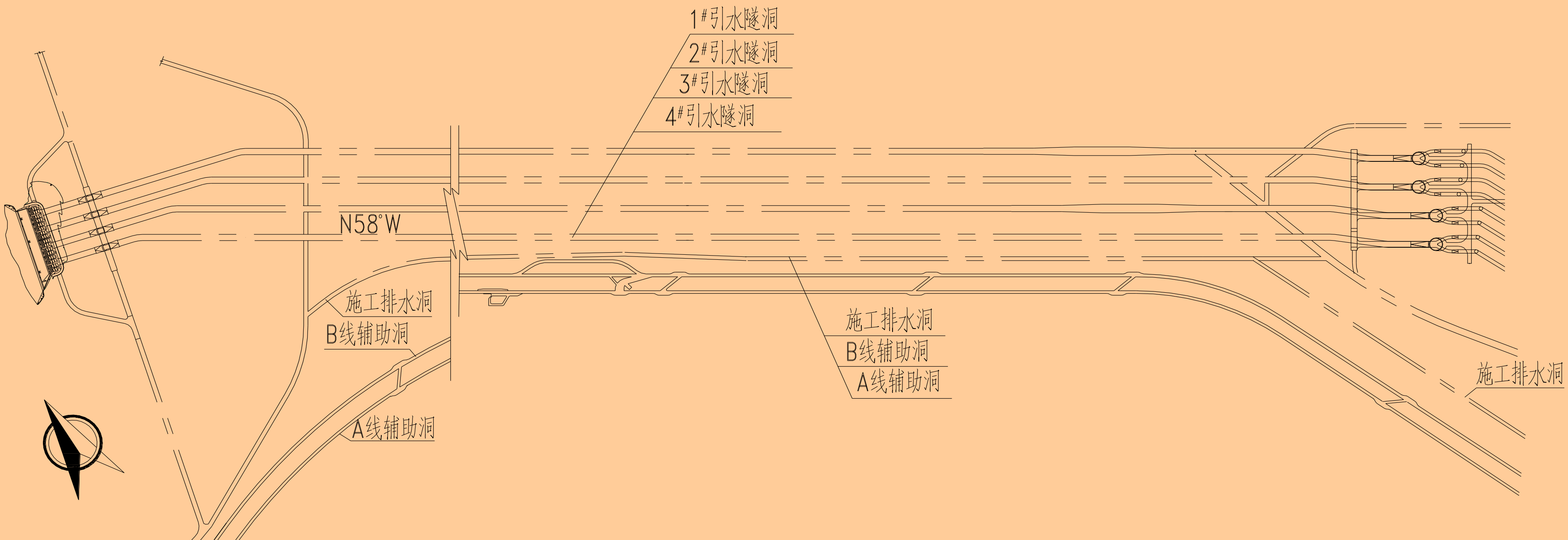


Sharp U-turn around the Jinping mountain



Tunnels at Jingpin Mountain



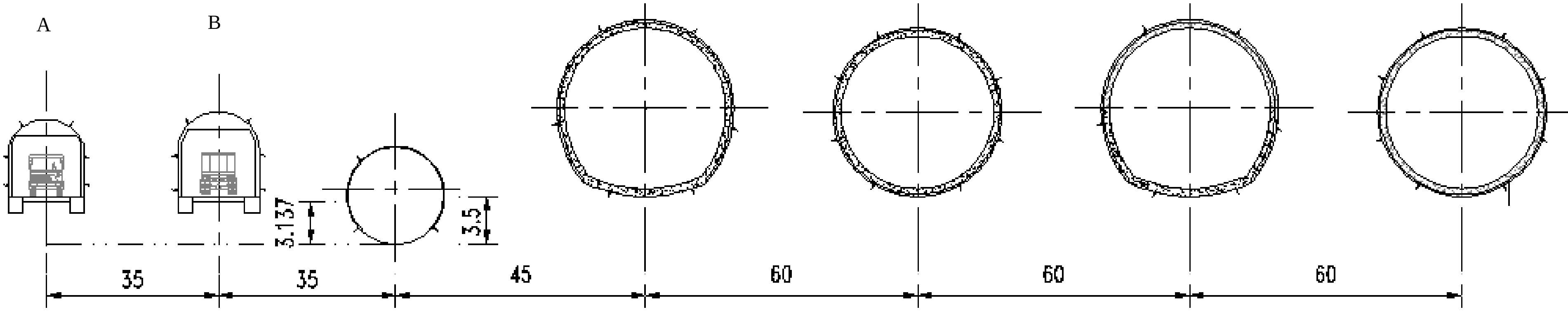


Tunnels at Jingpin Mountain

- Four water tunnels: length of 16.67 km
  - two of diameter of 12.4 m: TBM
  - two of diameter of 13m: drilling and blasting,
- Two traffic tunnels: 5.5×5.7m、6×6.25m, length of 17.5km
- One drain tunnel with diameter of 7.2m, length of 17.5km

(only used during construction, and could be used for super big volume experiment!)

- maximum Overburden 2525m



TBM for water tunnels

Both traffic tunnels were run-through Aug. 2008, opened in the end of 2009

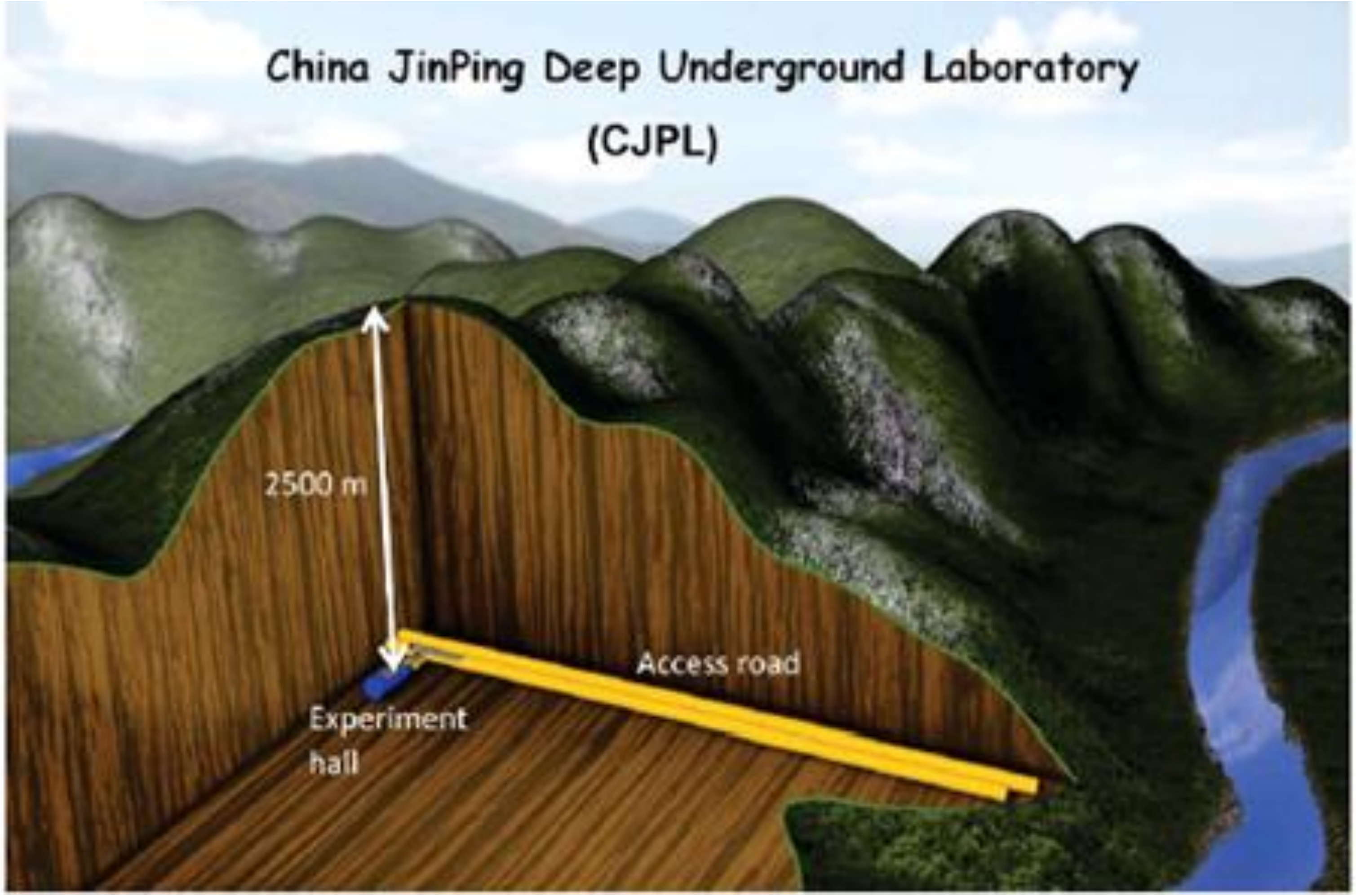
March, 2009 (四川凉山彝族自治州）

A small experimental hall

- In 2009, Tsinghua University and Yalong company decided to dig a small exp. hall for dark matter research
- The hall was excavated early 2010 with size $6x6x40m^3$.
- The hall can accommodate two experiments.

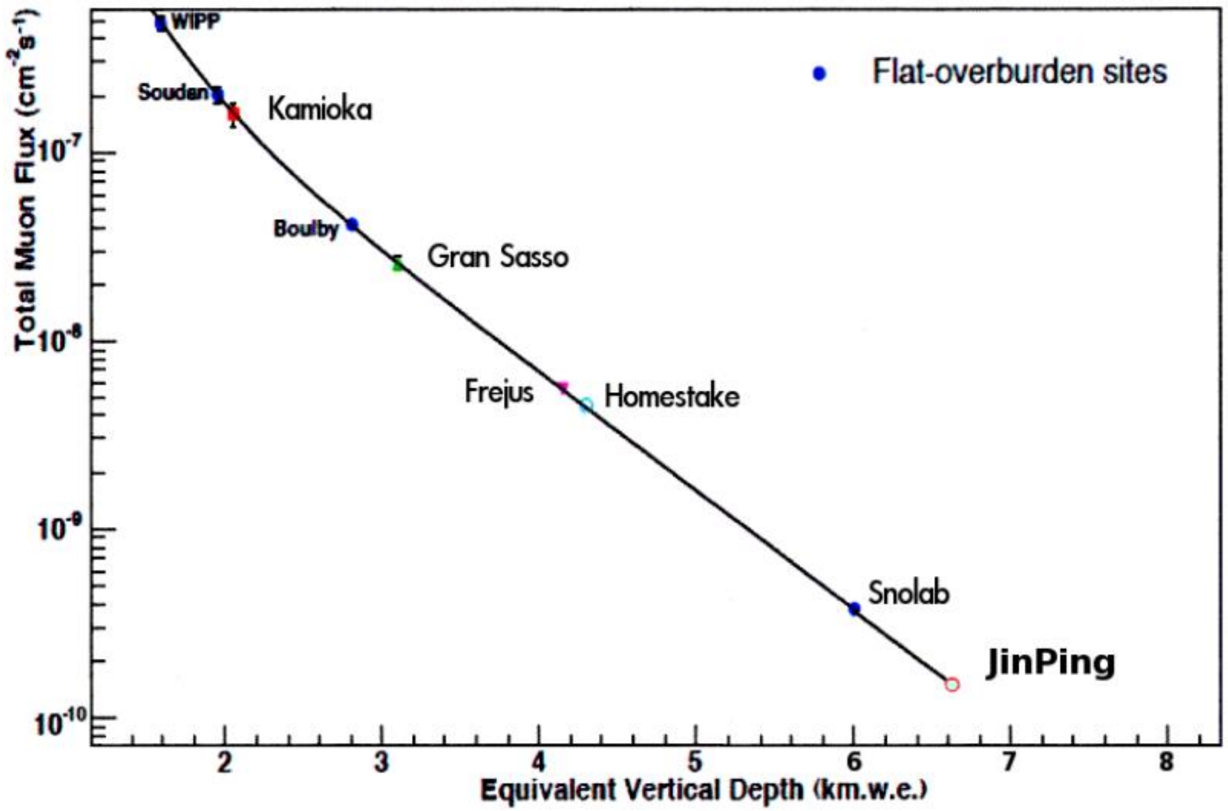
In the process of excavation

A deep underground lab?



JinPing Lab: A Low Background Facility

Low cosmic muon background



Low radioactivity from rock

Facility	Depth [m.w.e.]	μ Flux [events / (m^2·year)]	Rock	^{238}U [Bq / kg]	^{232}Th [Bq / kg]	^{40}K [Bq / kg]
Jinping (PandaX)	6,600	66	marble	1.8 ± 0.2	< 0.27	< 1.1
Homestake	4,500	950	rhyolite	100	45	900
Grand Sasso – Hall B	3,500	8,030	dolomite	5.2	0.25	4.9

The 66 muons/m^2/year is an estimate based on 33 days of measurement, less uncertainty soon

PandaX collaboration

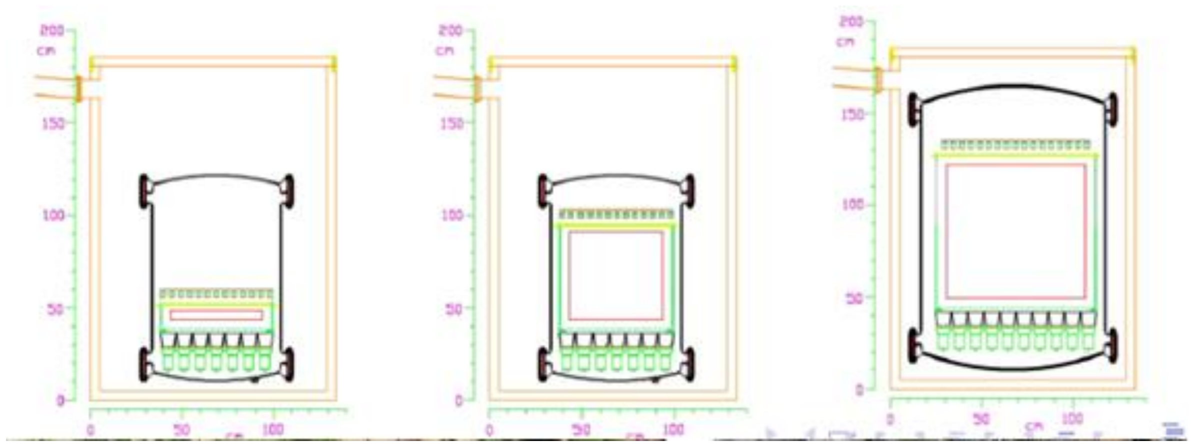
~40 people

Started in 2009

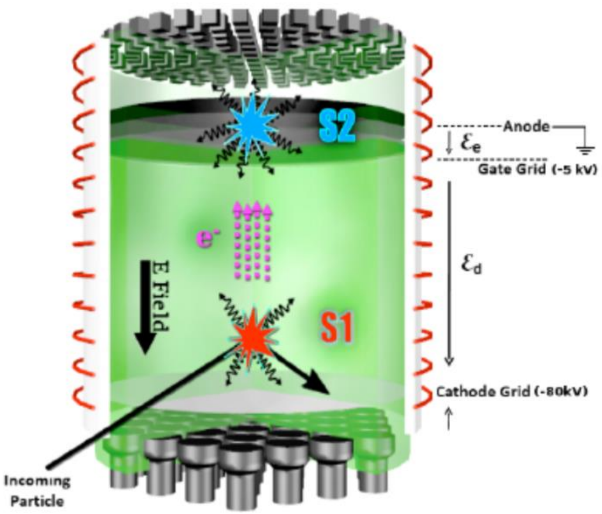
- Shanghai Jiao Tong University (2009-)
- Peking University (2009-)
- Shandong University (2009-)
- Shanghai Institute of Applied Physics, CAS (2009-)
- University of Science & Technology (2015-)
- China Institute of Atomic Energy (2015-)
- Sun Yat-Sen University (2015-）
- Yalong Hydropower (2009-)
- University of Maryland (2009-)
- University of Michigan (2011-2015)

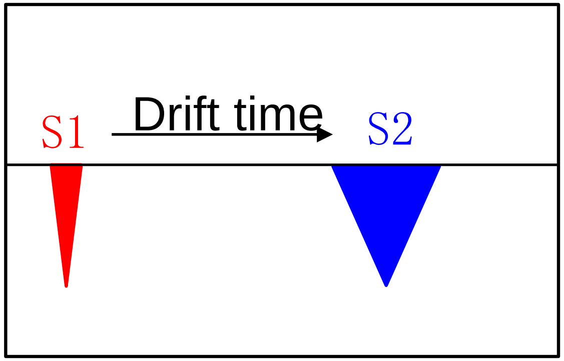
PandaX road map

- PandaX = Particle AND Astrophysical Xenon Detector
- Goal: develop a ton-scale Xenon dark matter detector in stages, and use Xe136 to search for neutrinoless double beta decay



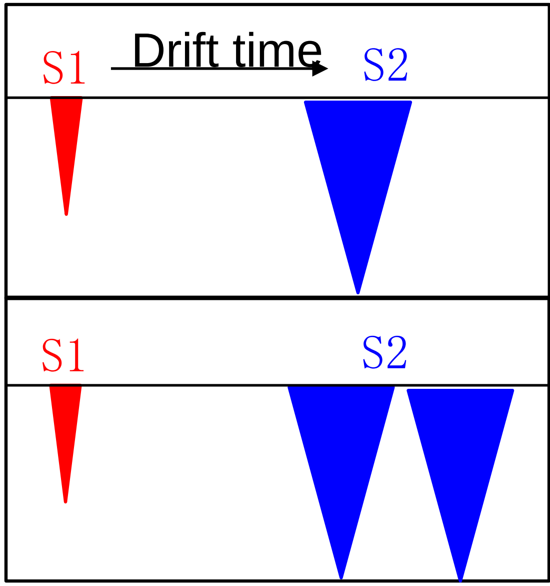
Dual phase xenon detector





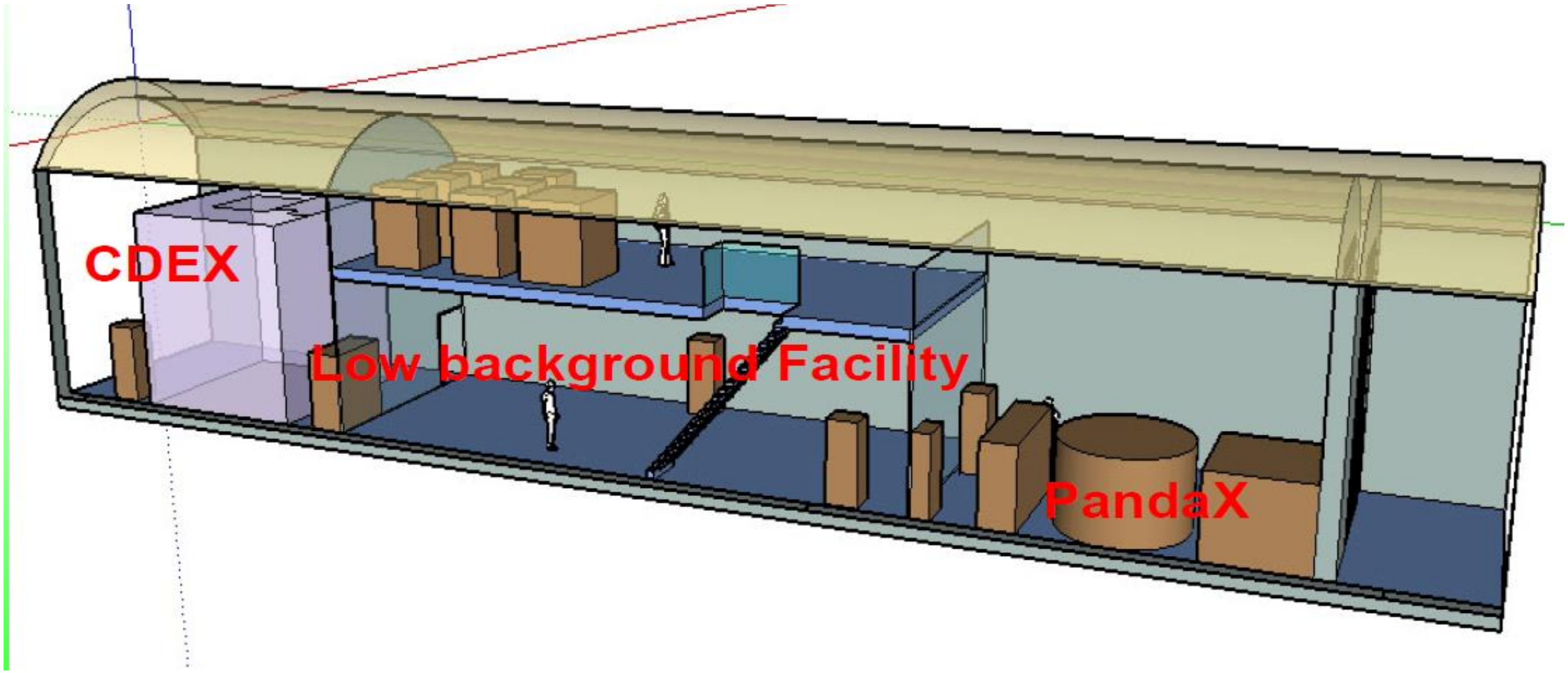
Dark matter: nuclear recoil (NR)

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



Gamma background: electron recoil (ER)

Layout of the exp in Jinping lab



Before moving in

- Early, 2012


2012 04 16


2012 03 11

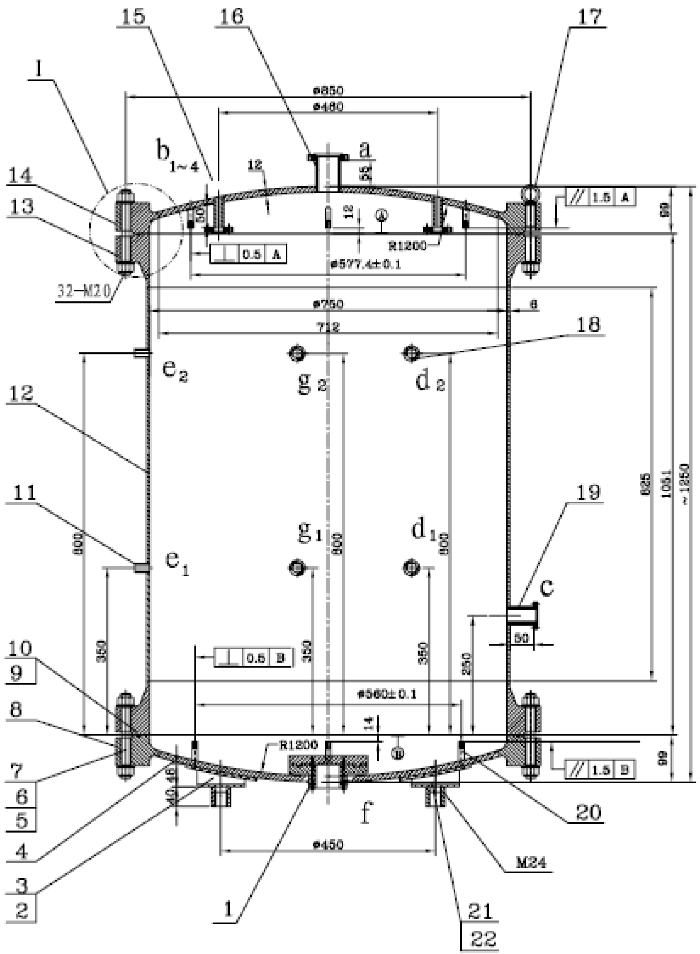

2012 04 20

Cooling bus

with Heat Exchanger , with speed up to 100 SLPM.

PandaX-I 120 kg detector

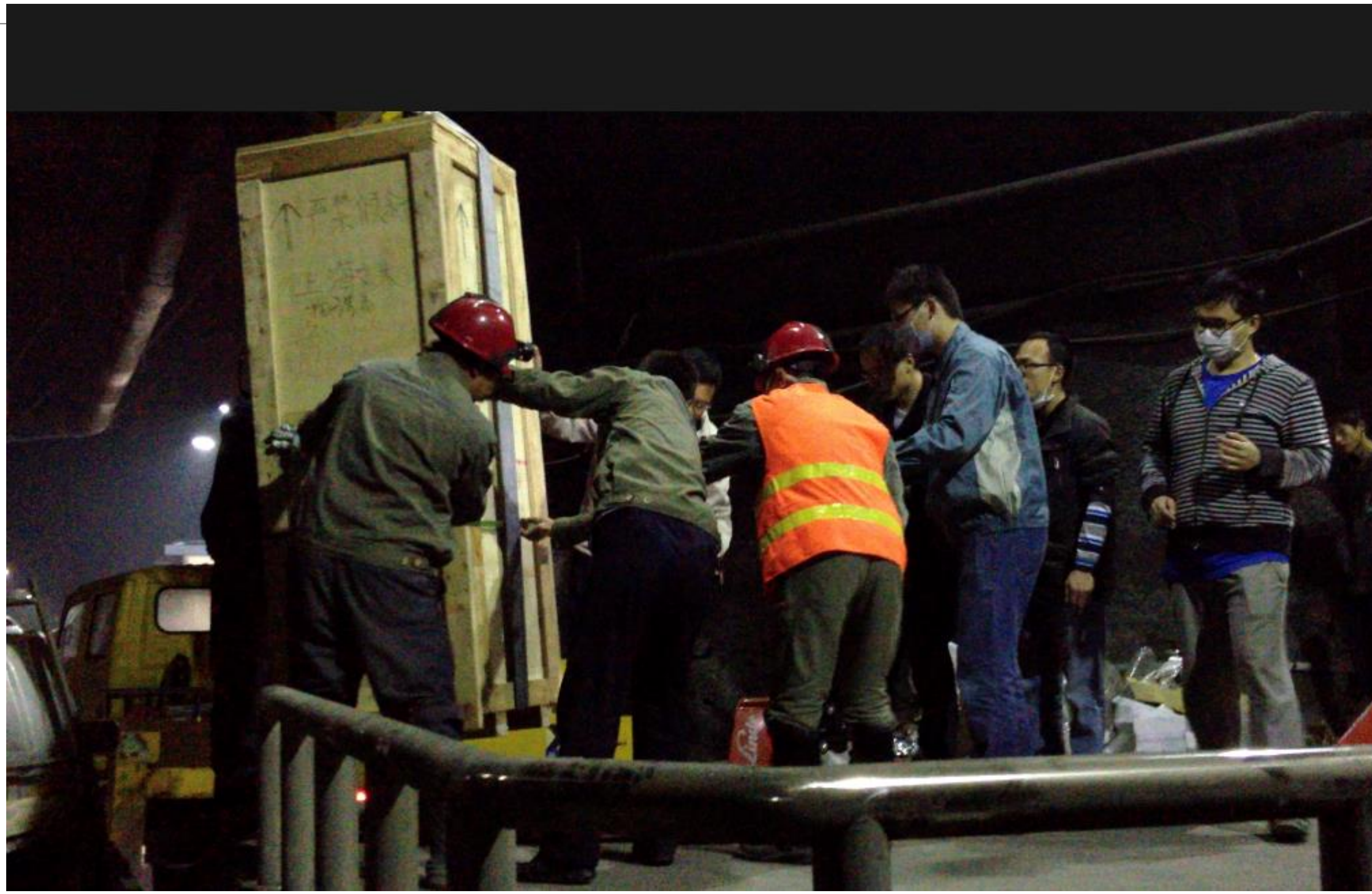
InnerVessel



el

Kr removal

PandaX equipment were moved to Jinping lab on Aug. 16, 2012



PHYSICS

Dark-matter hunt gets deep

China launches world's deepest particle-physics experiment — but it joins a crowded field.

BY EUGENIE SAMUEL REICH

More than 1,000 metres underground, physicists have set traps of liquid xenon to catch their prey: hypothetical particles of dark matter that might very rarely interact with ordinary matter as they drift through Earth. With construction costs on the order of US$10 million each, such experiments are a relatively cheap way to work out the composition of 85% of the matter in the Universe. But does the world really need four of them?

Ongoing experiments in Italy, the United States and Japan are now being joined by a fourth in China, called PandaX (see 'Dark and deep'). Installed in the deepest laboratory in the world, 2,500 metres under the marble mountain of JinPing in Sichuan province, PandaX will this year begin monitoring 120 kilograms of xenon. The team hopes to scale the tank up to 1 tonne by 2016, which would mean that the experiment had developed more quickly than any other dark-matter search. "We want to demonstrate that world-class research in dark matter is possible in China," says Xiangdong Ji, a physicist at Shanghai Jiao Tong University in China and a spokesman for PandaX.


WOLFGANG LORENZON

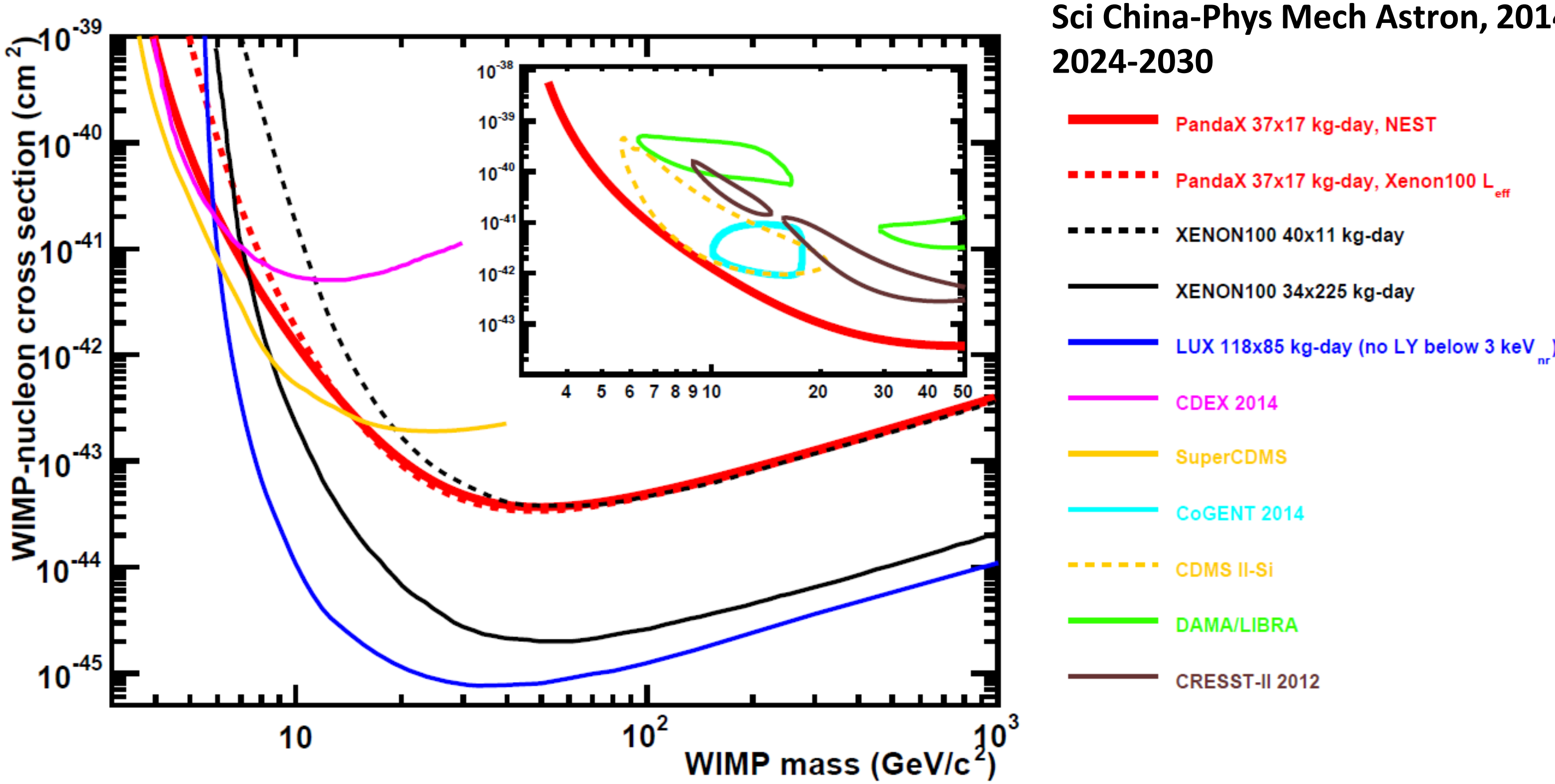
A conveyor belt removes rock from JinPing laboratory, a 2,500-metre-deep dark-matter experiment site.

Dark-matter researchers in the West are excited by the ambition of the project, but some question the duplication of effort. "Spending all our money on different direct-detection ▶

First data-taking ceremony, March, 2014

PandaX-I first results

Sci China-Phys Mech Astron, 2014, 57(11): 2024-2030



- **Our results disfavor previously reported signals**
- **At low mass region, our results significantly better than XENON100 first results with similar exposure**

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News > Physics > Chinese team is catching up in hunt for dark matter

LATEST NEWS

MENGJIAO XIAO/SHANGHAI JIAO TONG UNIVERSITY

Researchers will quadruple the amount of liquid xenon in the PandaX detector just by making it taller and pouring in more liquid.

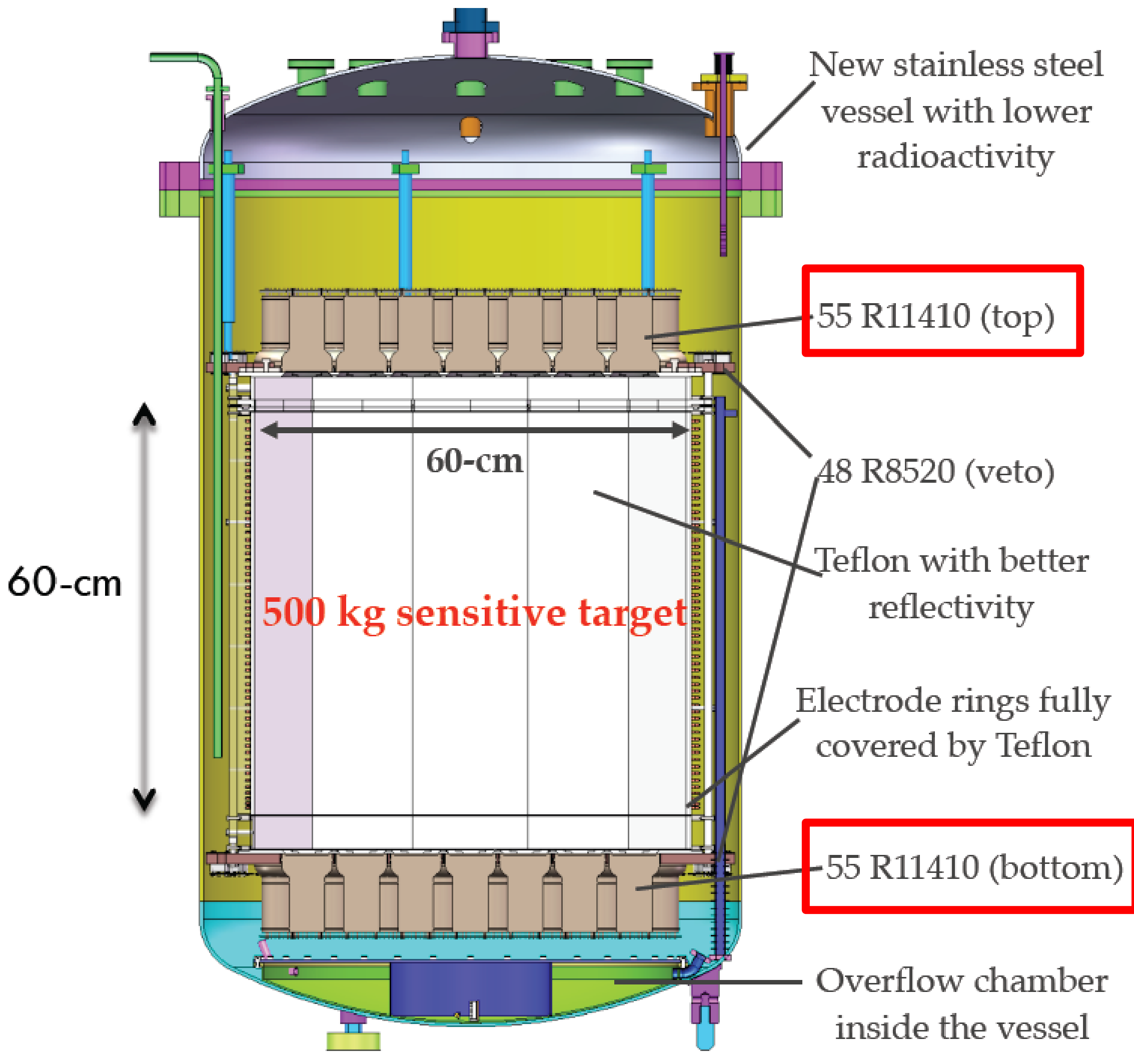
PandaX started from nothing at 2010 when XENON100 had their first results. We are catching up!

PandaX I decommissioned

- We took 75 more days of data for PandaX I from July to Nov.
- We stopped PandaX I running on Nov. 15, 2014 and the detector was de-assembled.
- The final data for PandaX-I has been published in 2015 in PRD.

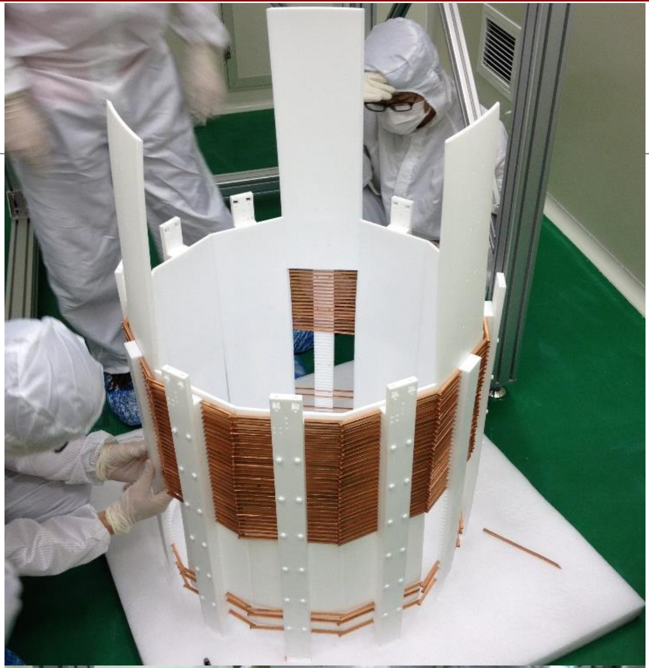
500 kg detector and recent results

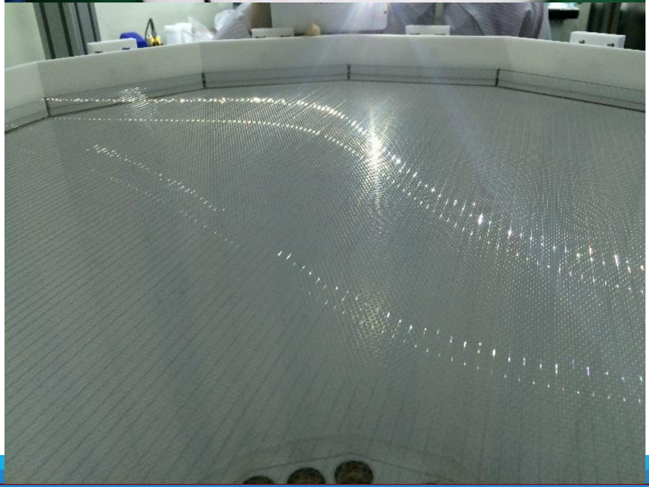
PandaX-II



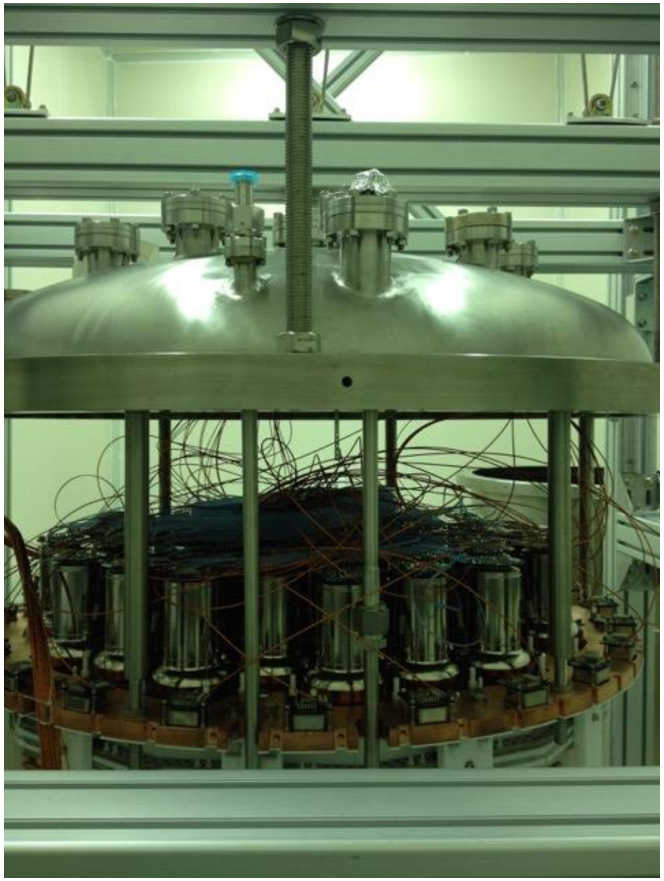
- New inner vessel with clean SS
- New and taller TPC with brand-new electrodes
- More 3" PMTs and improved base design
- New separate skin veto region
- New overflow chamber

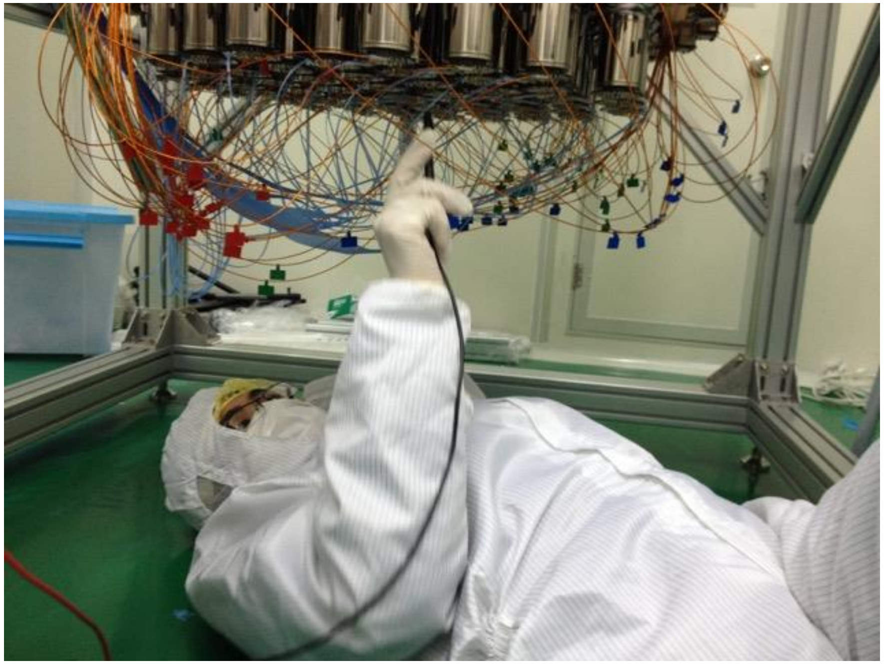
Assembling the detector

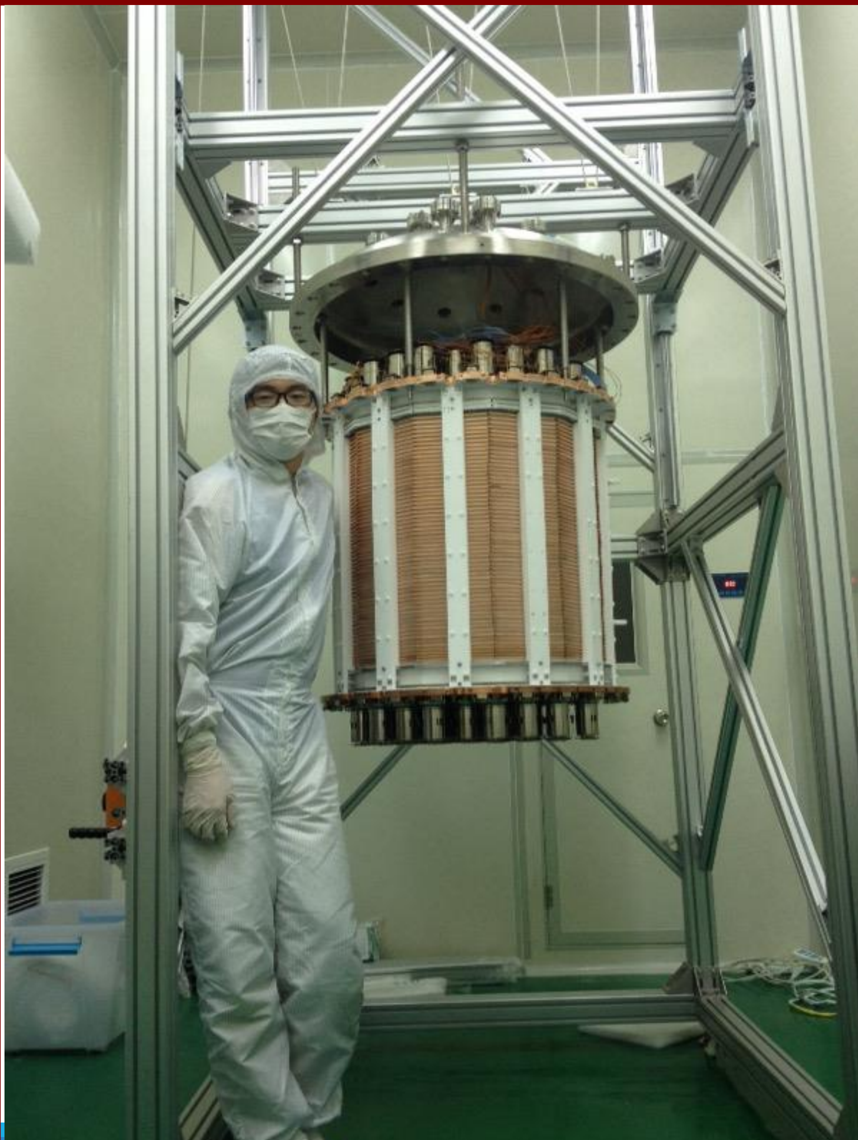


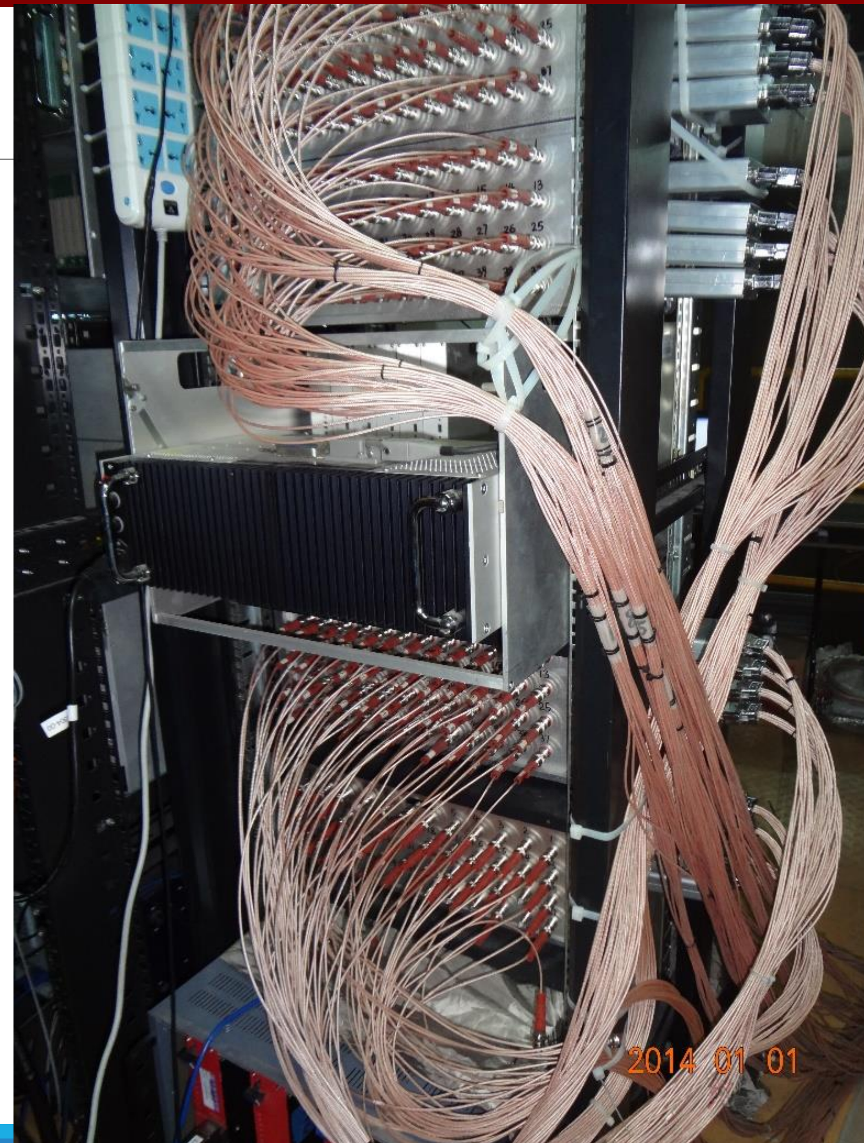


World largest LXe TPC in making… Dec. 16, 2014

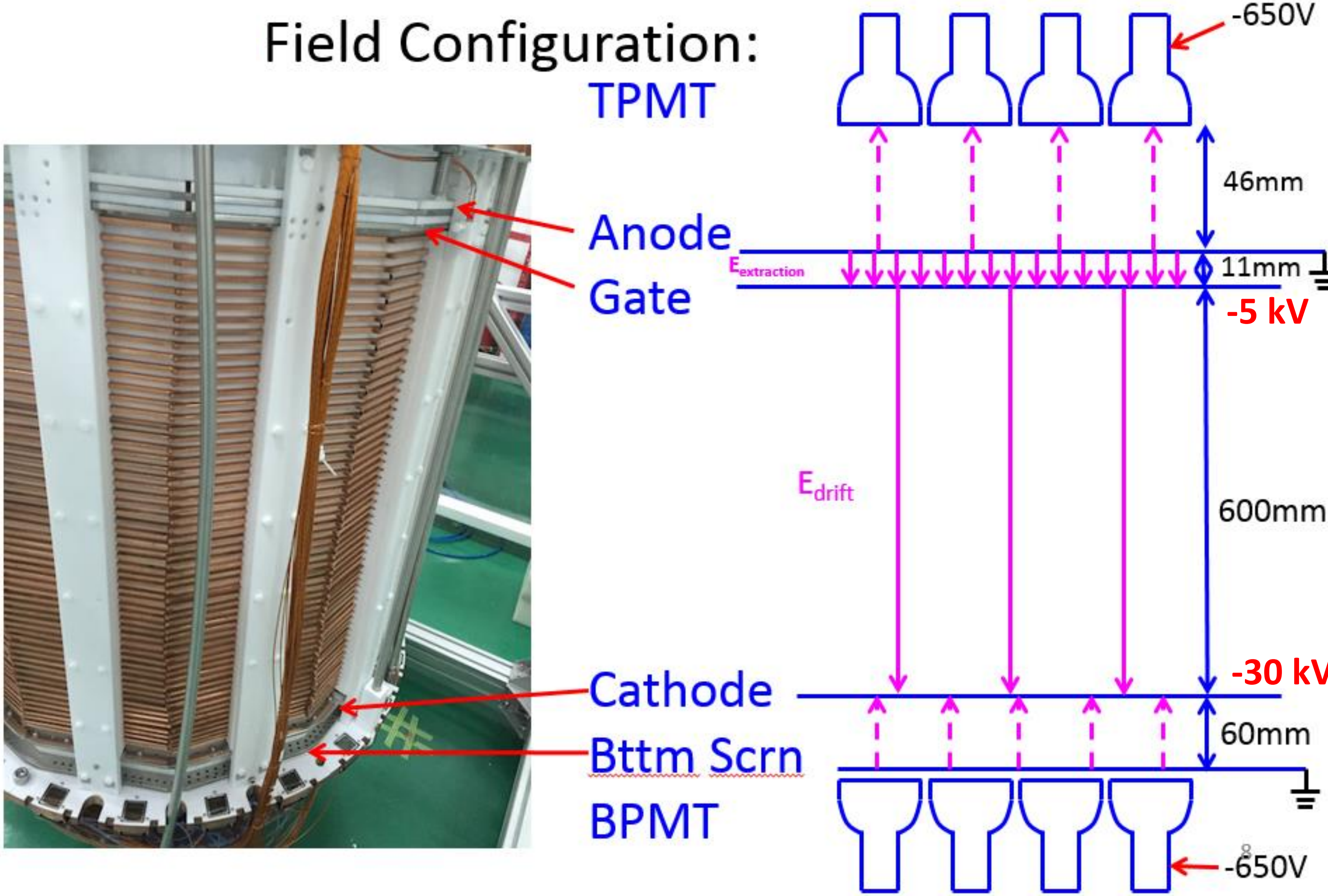







2014 01 01

Configuration of fields

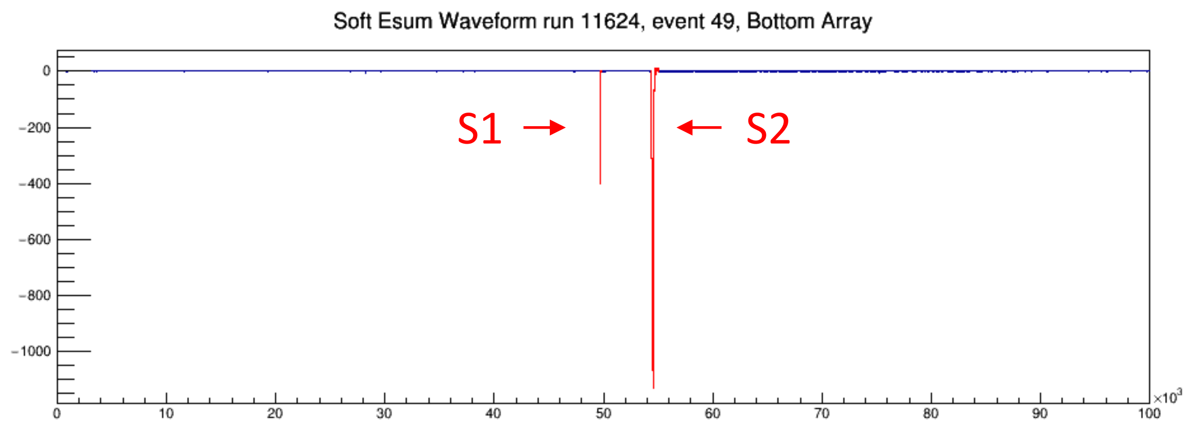


Run history

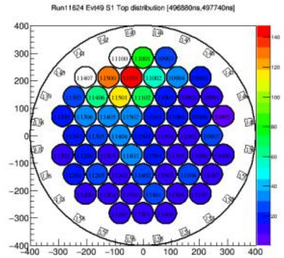
- We had a series of engineering runs in 2015, fixing various problems as we were testing all the components of the setup.

- A physics commissioning run:
  Nov. 22 – Dec. 14 (19.1 live-day x 306 kg FV)
  not everything in perfect conditions:
  no gamma calibration (-) * large Kr contamination (-)
  = some physics result (+)

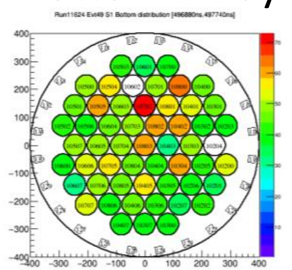
Typical single-scatter waveform

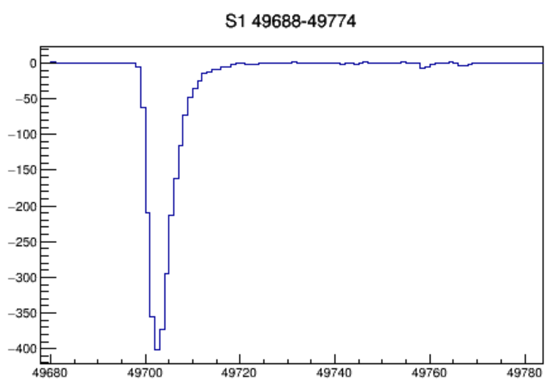


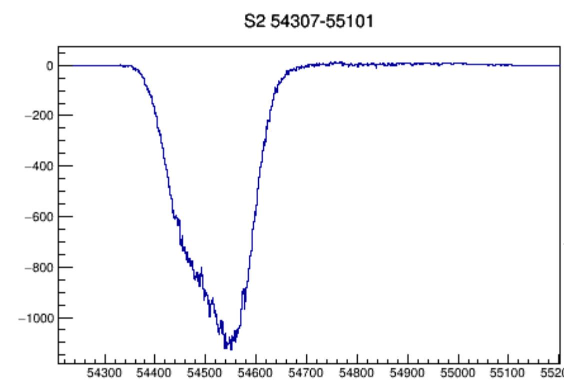
Top Array



Bottom Array







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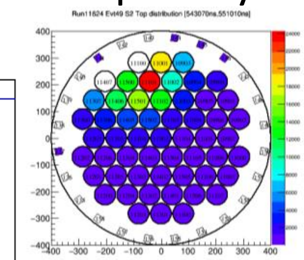
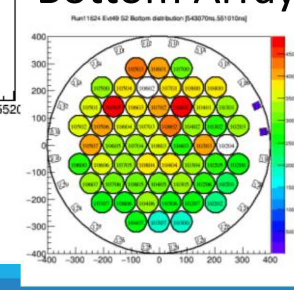


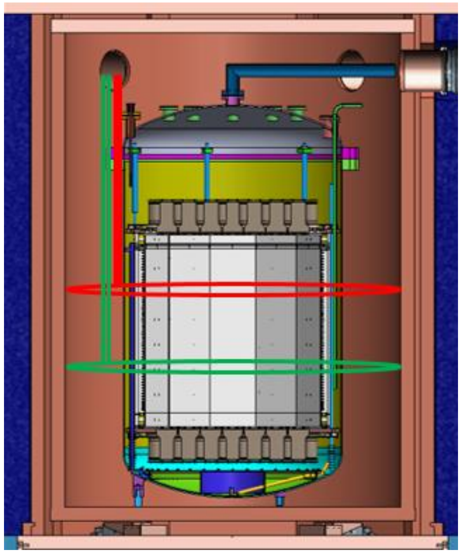
Bottom Array



Calibrating the detector responses

- **Detector uniformity correction**

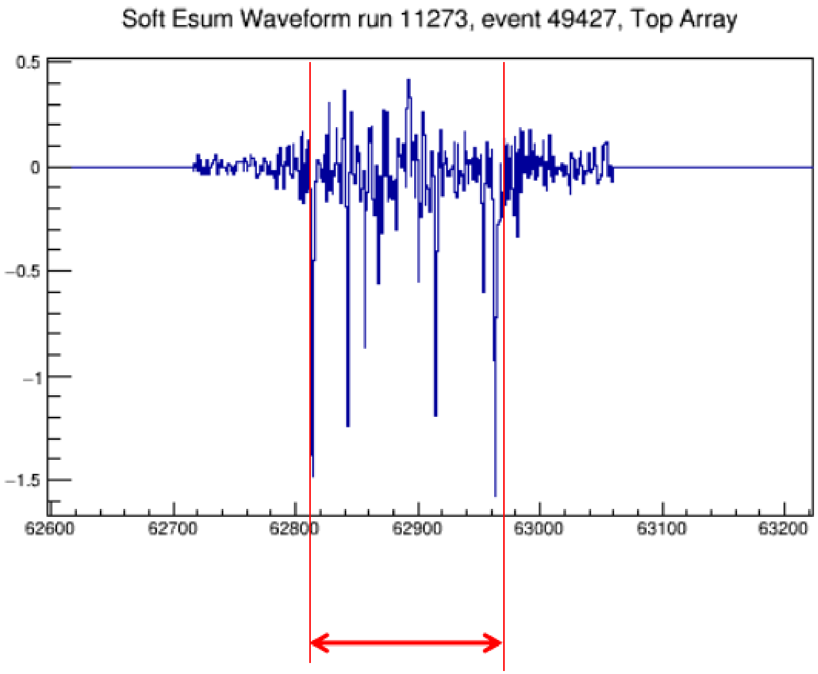
- **Light/charge collection parameters in energy reconstruction**

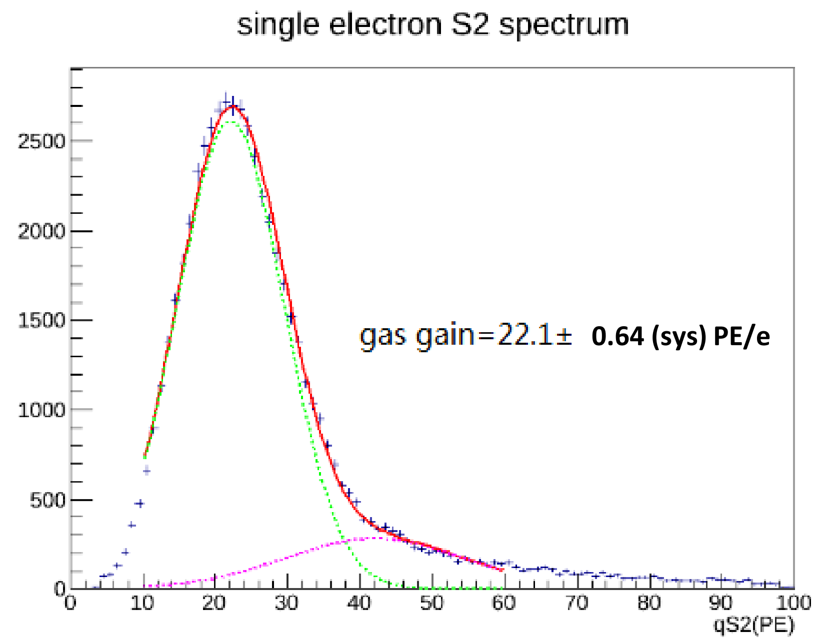


$$E_{ee} = W \times \left(\frac{\mathrm{S1}}{\mathrm{PDE}} + \frac{\mathrm{S2}}{\mathrm{EEE} \times \mathrm{SEG}}\right)$$

- **Compare the low energy NR response between neutron calibration data and MC (NEST-based + measured parameters)**

Single electron gain

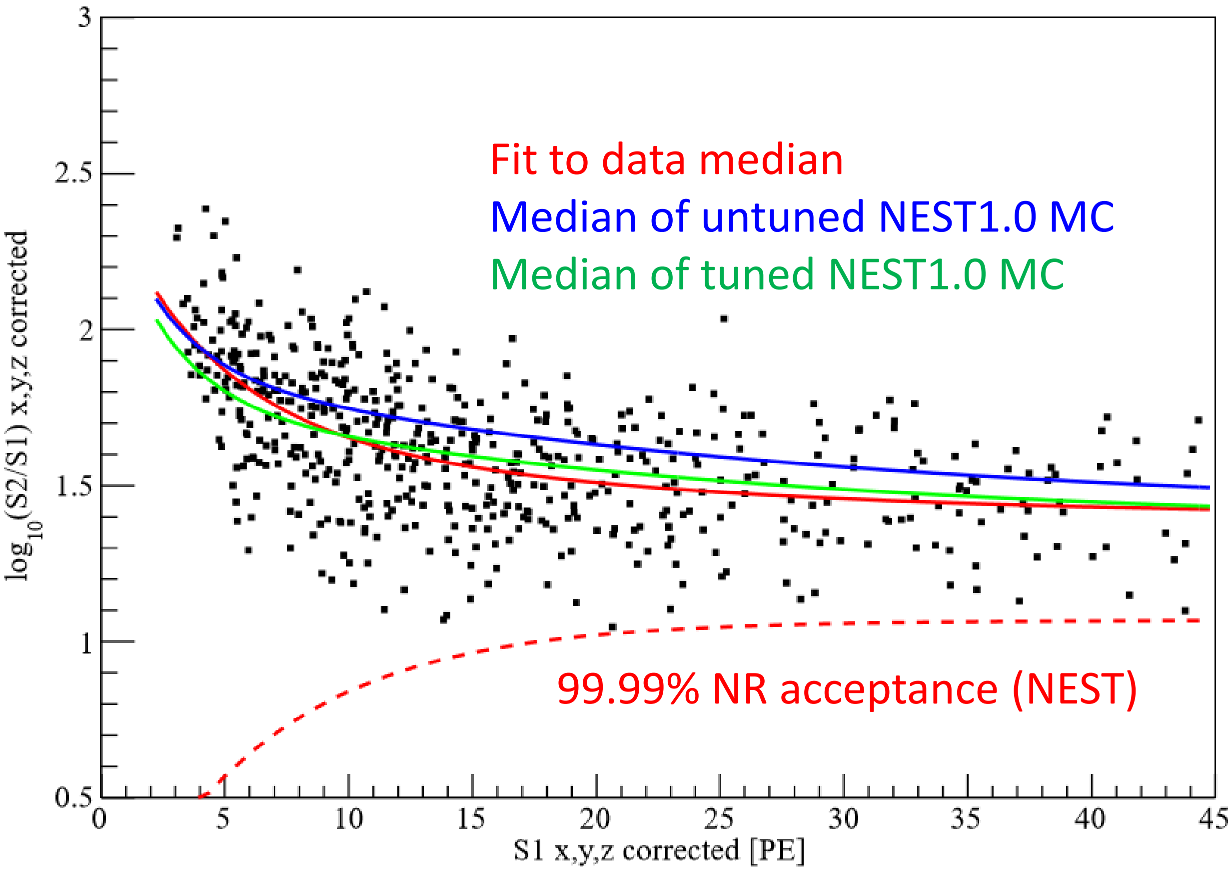




- **Identifying smallest S2 in the data**
- **Varying selection method and fits to study systematics**

  $\Rightarrow$ **22.1 ± 0.7 PE/e,**

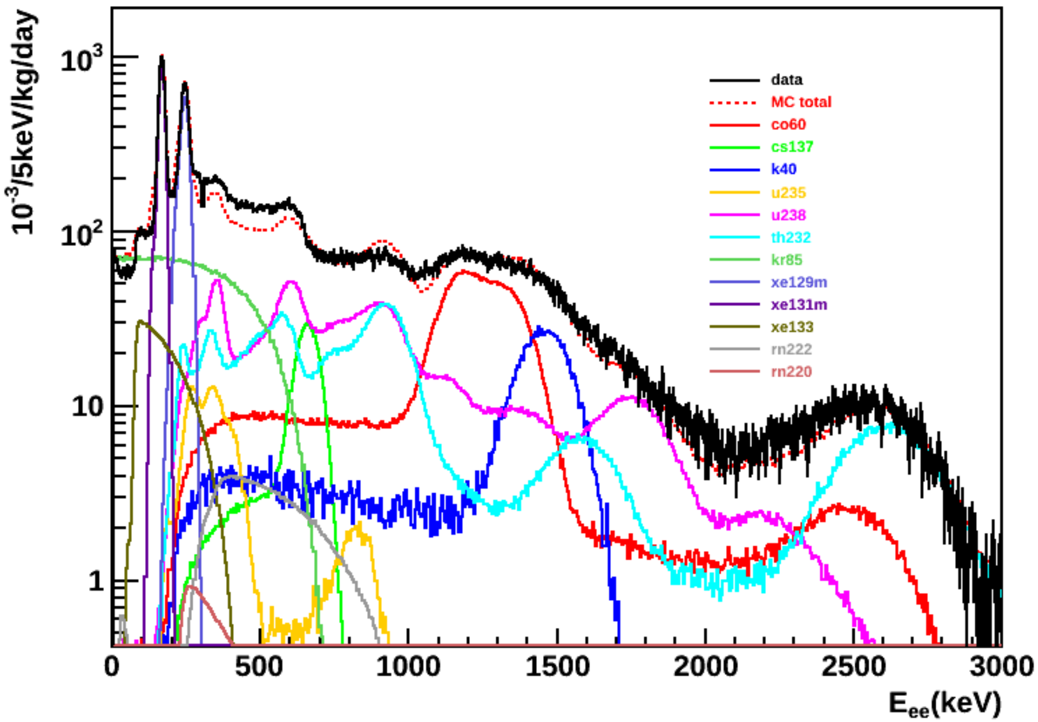
NR calibration



- Geant4 energy spectrum
- NEST 1.0 photons/electrons
- PDE/EEE/SEG from calibration
- Double PE emission from R11410 from Faham et al. (JINST 10, P09010)

Tuned NEST 1.0:
N_{ex}/N_i ratio scaled up by **1.5**

ER background summary

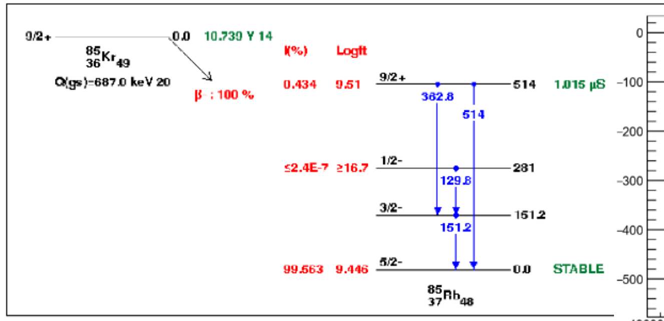


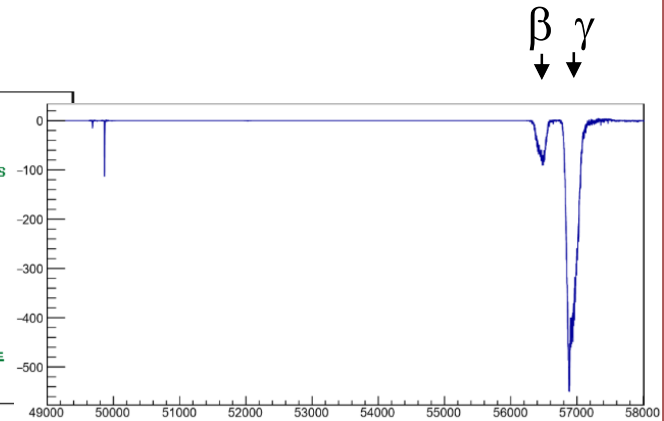
Item	Background (mDRU)
Total	15.33
^{85}Kr	15.04
^{222}Rn	0.075
^{220}Rn	0.021
^{129m}Xe, ^{131m}Xe, ^{133}Xe	~0
PMT arrays & bases	0.097
PTFE wall	0.021
Inner vessel	0.045
Others IV components	0.026
Cu outer vessel	0.016

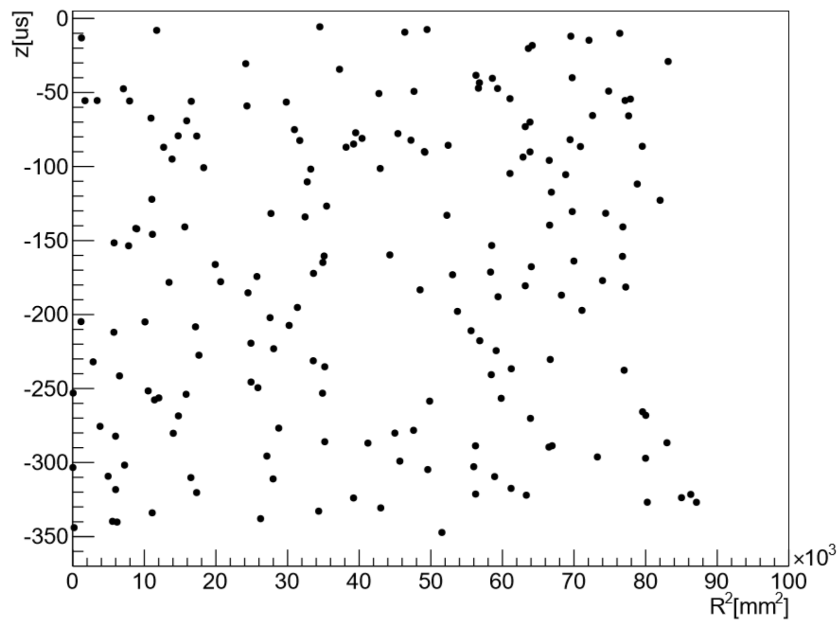
- Shape in reasonable agreement with MC
- Low energy agreement also within 17%

Kryton background

- **Significant uniformly distributed ER background observed in the data**
- (β,γ) analysis confirmed that it is due to ^{85}Kr, Kr/Xe = (437 ± 70) ppt
- Due to an accidental air leak in the previous recuperation

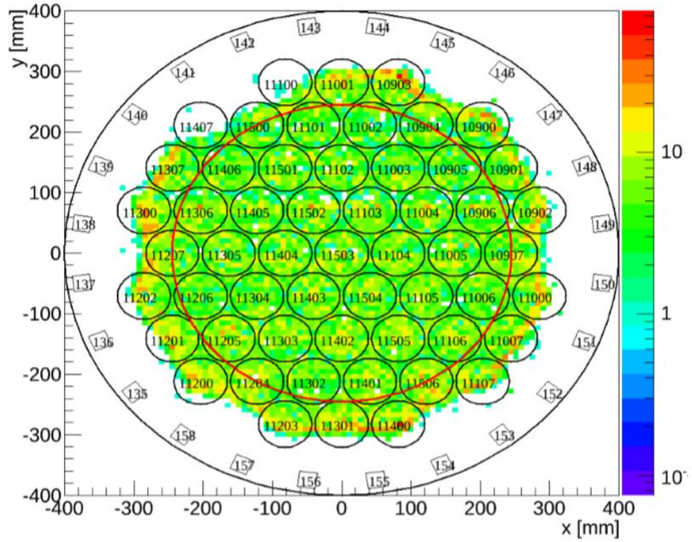


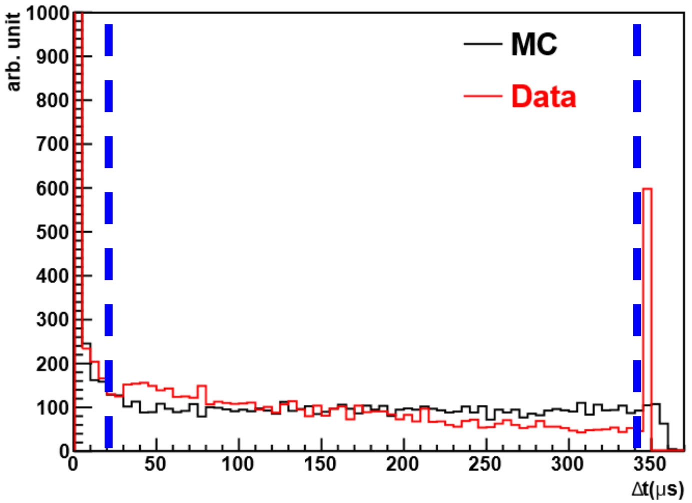




Distribution of β vertices

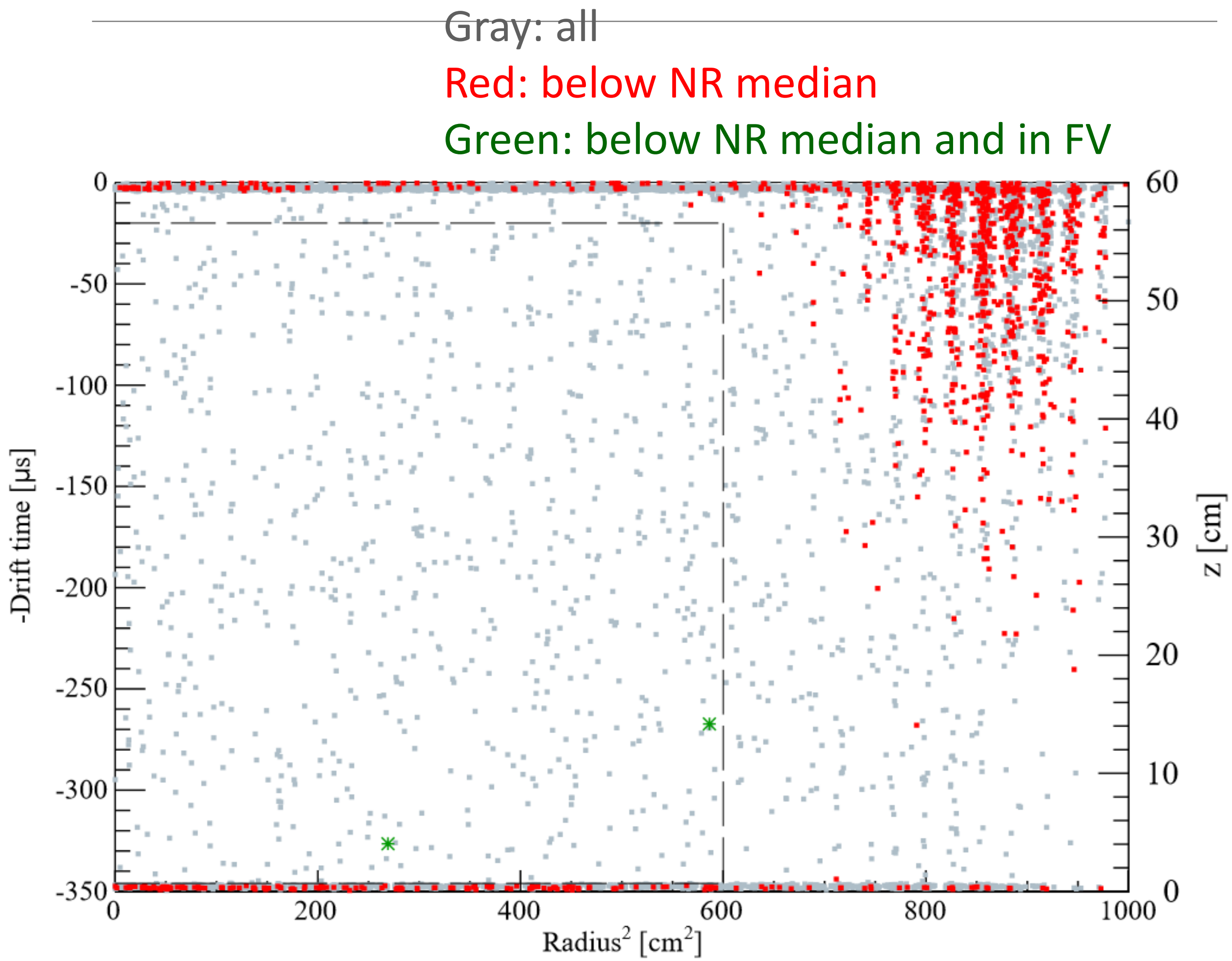
Final selection cuts





- Horizontal cut determined by reconstruction quality (removing the last ring of PMT)
- Vertical cut determined by choosing the flat region in non-DM-window for both data and MC (excess at cathode likely due to Rn daughters accumulation)
- S1 cut: [3, 45] PE by optimizing the median sensitivity using **expected background only**

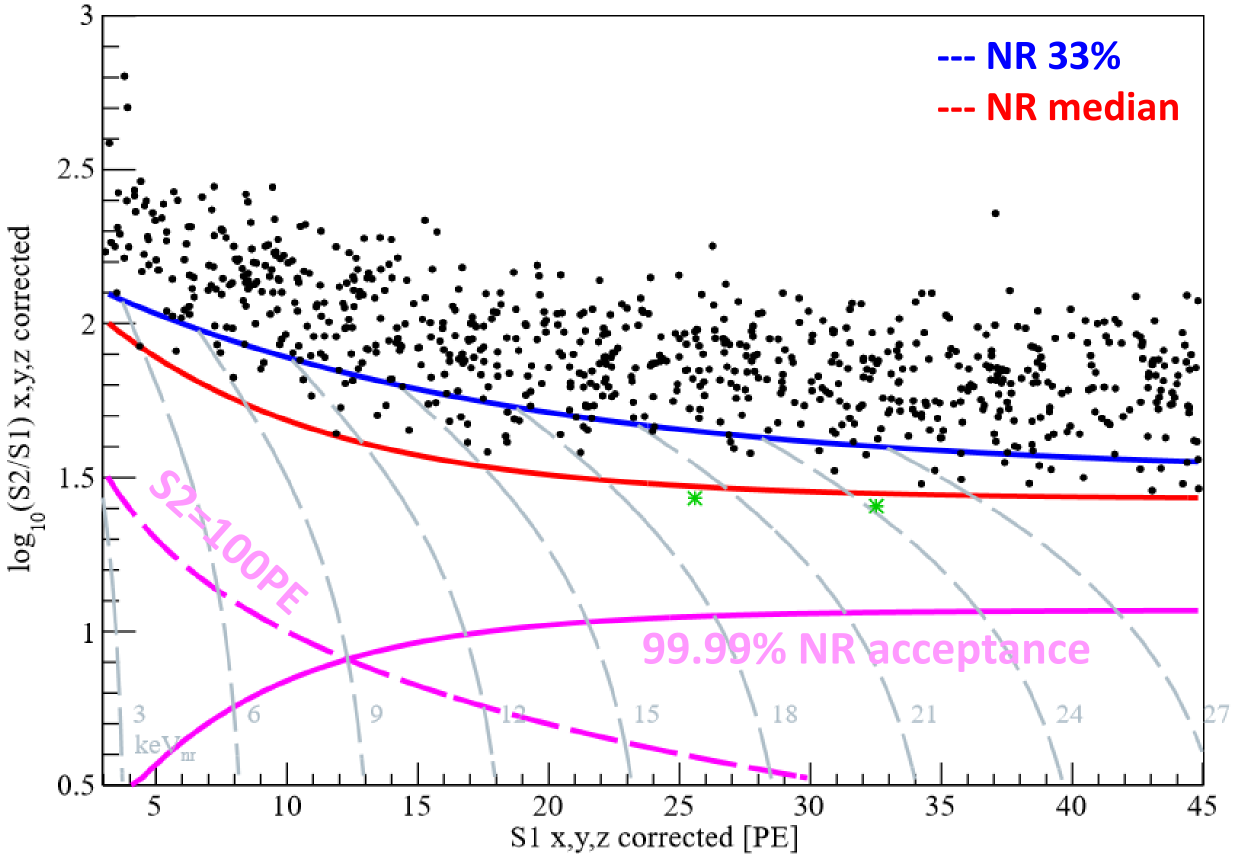
Final candidates

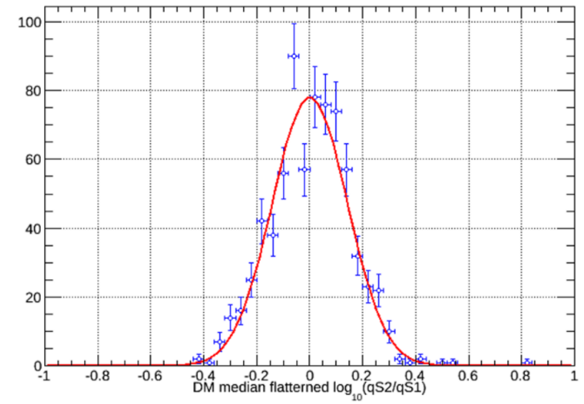


Cut	#Events	Rate (Hz)
All triggers	4779083	2.89
Single S2 cut	1833756	1.11
Quality cut	1262906	0.76
Skin veto cut	1081044	0.65
S1 range	45883	2.77×10^{-2}
S2 range	29755	1.80×10^{-2}
Fiducial volume	728	4.40×10^{-4}

- 728 total candidates found in the FV
- **2** below NR median
- Outside FV, edge events more likely to lose electrons, leading to S2 suppression

Final candidates





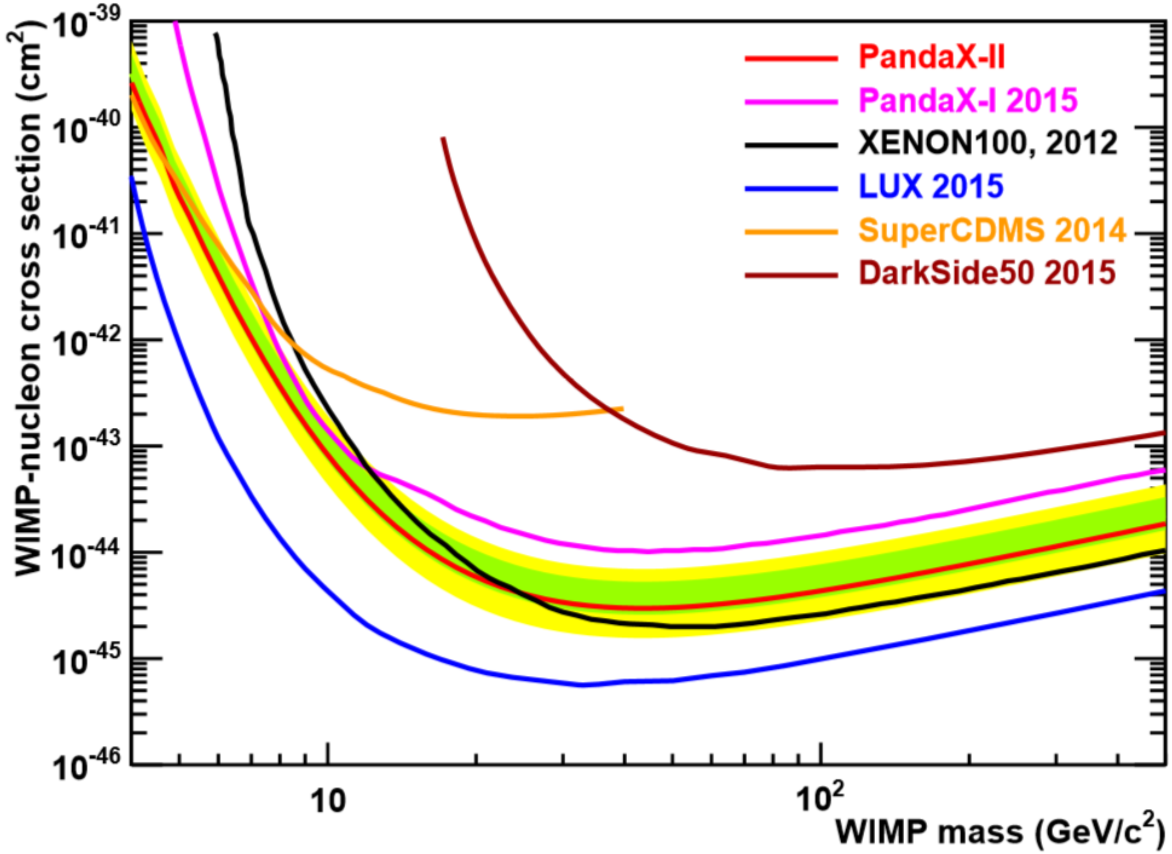
Two events below NR median appear consistent with Gaussian background leakage

Total expected background

	ER	Accidental	Neutron	Total Expected	Total observed
All	611	5.9	0.13	617±104	728
Below NR median	2.5	0.7	0.06	3.2±0.71	2

- Accidental background statistically determined from data using isolated S2 and S1 from the data
- Neutron background dominated by the (α, n) from PTFE reflector
- Background systematics dominated by the ER leakage fraction (0.4%±0.2%) and Kr rate (17%) uncertainty

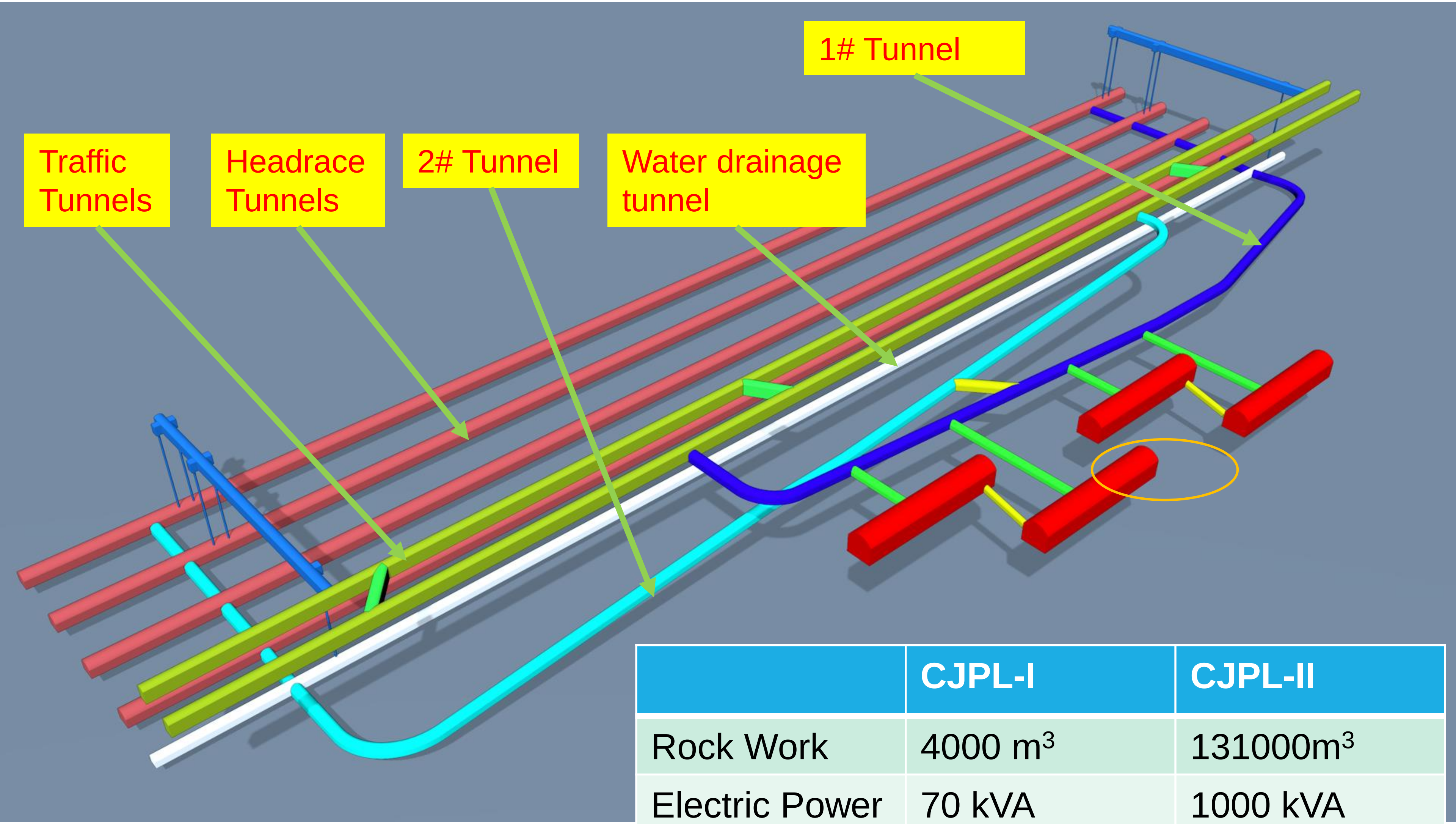
Exclusion limits



- ~~Simple counting analysis~~ based on an expected background of 3.2(0.7) evts and 2 observed evts
- Sizable (x2) difference of using original NEST or tuned NEST to predict DM distribution due to DM acceptance, but within 1σ band
- Low mass: competitive with SuperCDMS; high mass: similar exclusion limit as XENON100 225-day

PandaX future

Preliminary Design of CJPL-II



	CJPL-I	CJPL-II
Rock Work	4000 m^3	131000m^3
Electric Power	70 kVA	1000 kVA
Fresh Air	2400 m^3/h	40000 m^3/h

Experimental Hall and Steel

钢材估量表

编 号	规 格	单 重 Kg/m或Kg/m²	长度/面积 m或m²	总 重 Kg
1	H350X250X10X16	87.8	2815	247160
2	H550X350X10X16	128.6	9	1160
3	H400X300X10X16	104.2	5	520
4	H500X350X10X16	124.6	242	30150
5	H600X500X10X16	170.2	16.5	2810
6	HN100X50X5X7	8.9	610	5430
7	HN200X100X5.5X8	20.5	260	5330
8	2L63X6	11.5	610	7015
9	2L50X6	9	105	945
10	2L90X6	16.7	5	85
11	L63X6	5.8	14500	84100
12	吊车轨道	43	260	11180
13	节点板			47505
	总重			443390

注：1. 钢丝网用量不包括在总重内

2. 钢丝网采用丝径为4mm，孔径为30mm，面积约4736m²

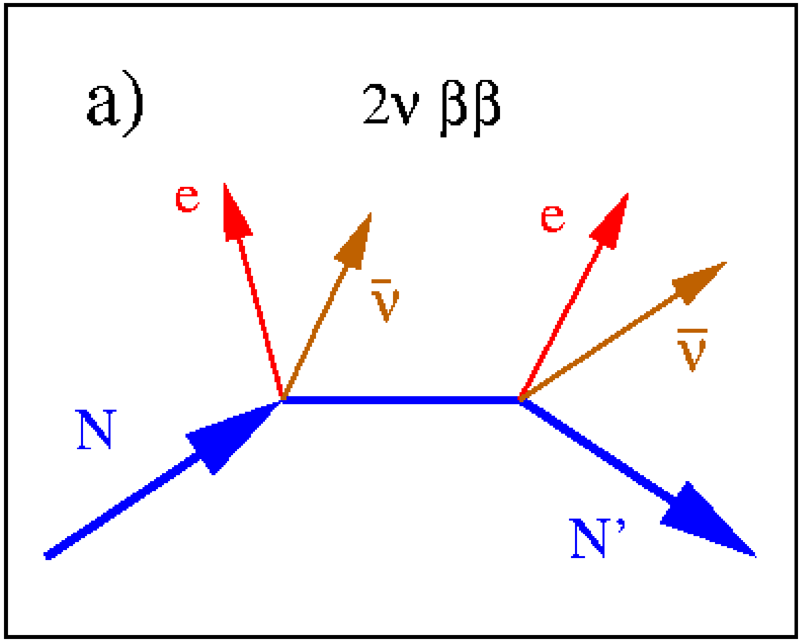
Two plans

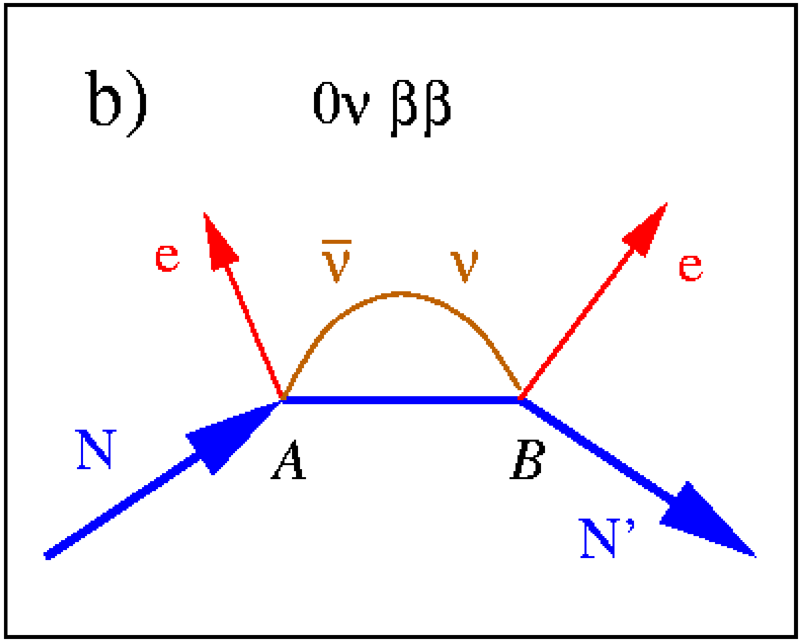
- Searching for neutrino-antineutrino oscillation through Xe136 double beta decay
- Ultimate LXe dark matter experiment:

  upgrade to 3 ton and then 20-30 ton

  low-energy solar neutrino

Two Types of Double Beta Decay

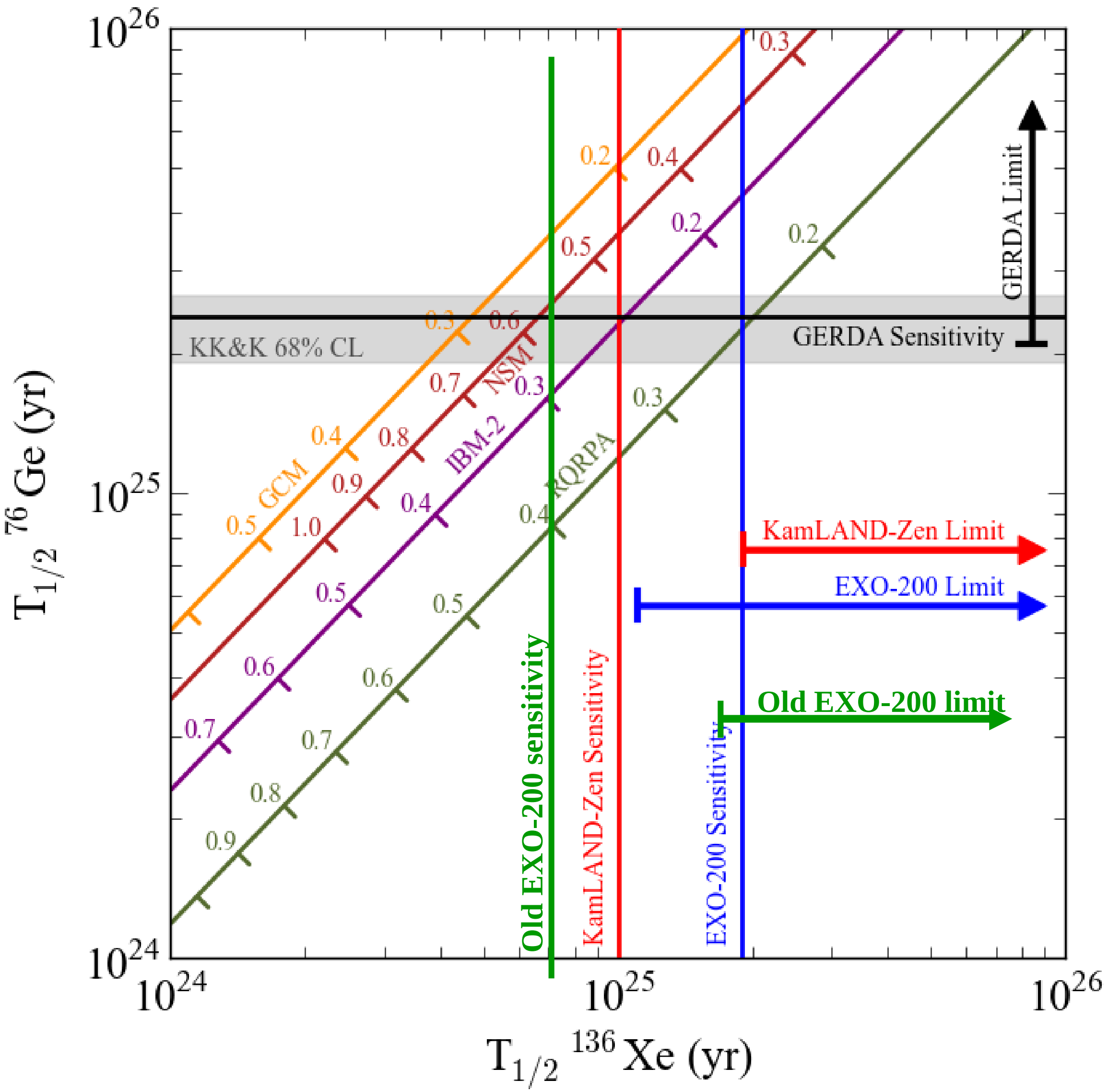




2νββ mode:
a conventional
2nd order process
in Standard Model

Observation of 0νββ:
- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

Comparison of 0νββ Measurements



$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$yr (90%CL)

$\langle m_\nu \rangle < 190 - 450$ meV

Average $T_{1/2}^{0\nu\beta\beta}$ sensitivity: $1.9 \cdot 10^{25}$ yr

J.B.Albert et al. (EXO-200) arXiv:1402.6956 (27 Feb 2014)

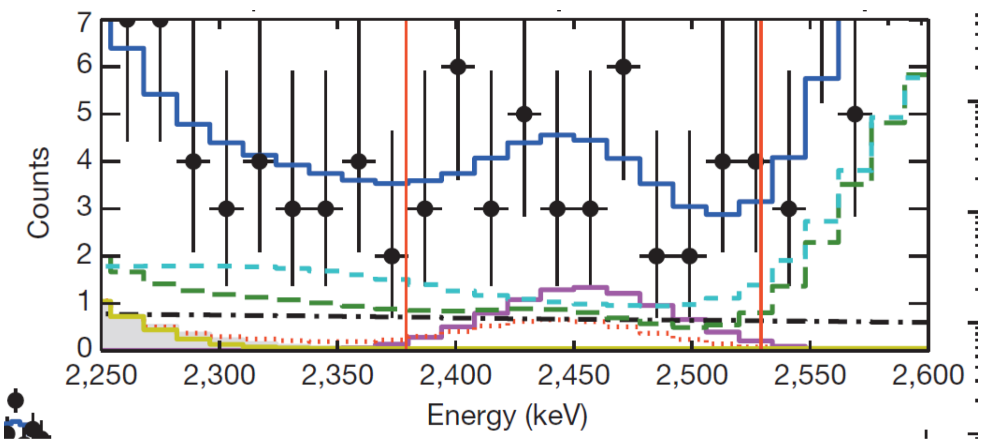
A. Gando et al. (KamLAND-ZEN) PRL 110 (2013) 062502

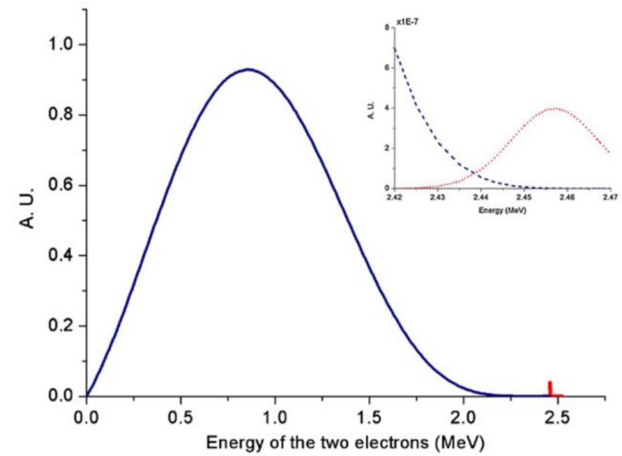
M. Agostini et al. (GERDA) PRL 111 (2013) 122503

M. Auger et al. (EXO-200) PRL 109 (2012) 032505

Key requirements for discovering 0vDBD

- Low radioactivity (more stringent requirement than for DM search)
- Good energy resolution
- Tracking detector





EXO200: Nature 2014

Advantages of High Pressure Xe Gas

- Great energy resolution

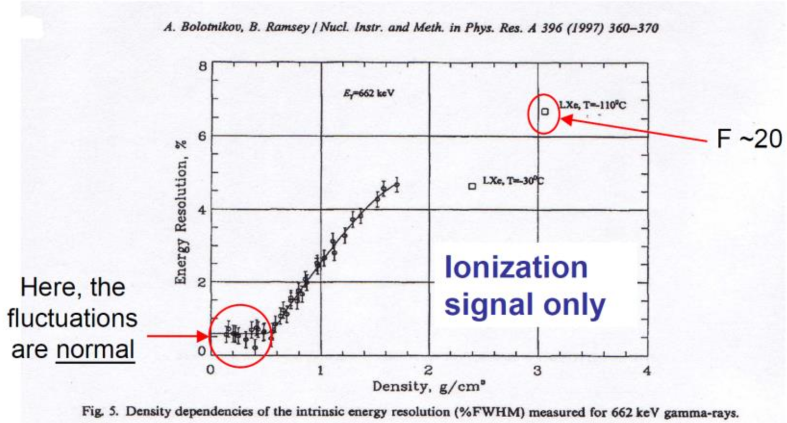
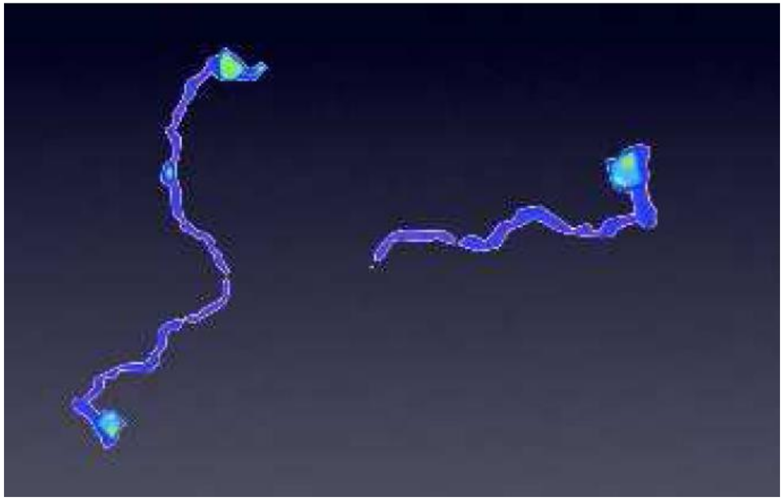


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For ρ <0.55 g/cm³, ionization energy resolution is "intrinsic"

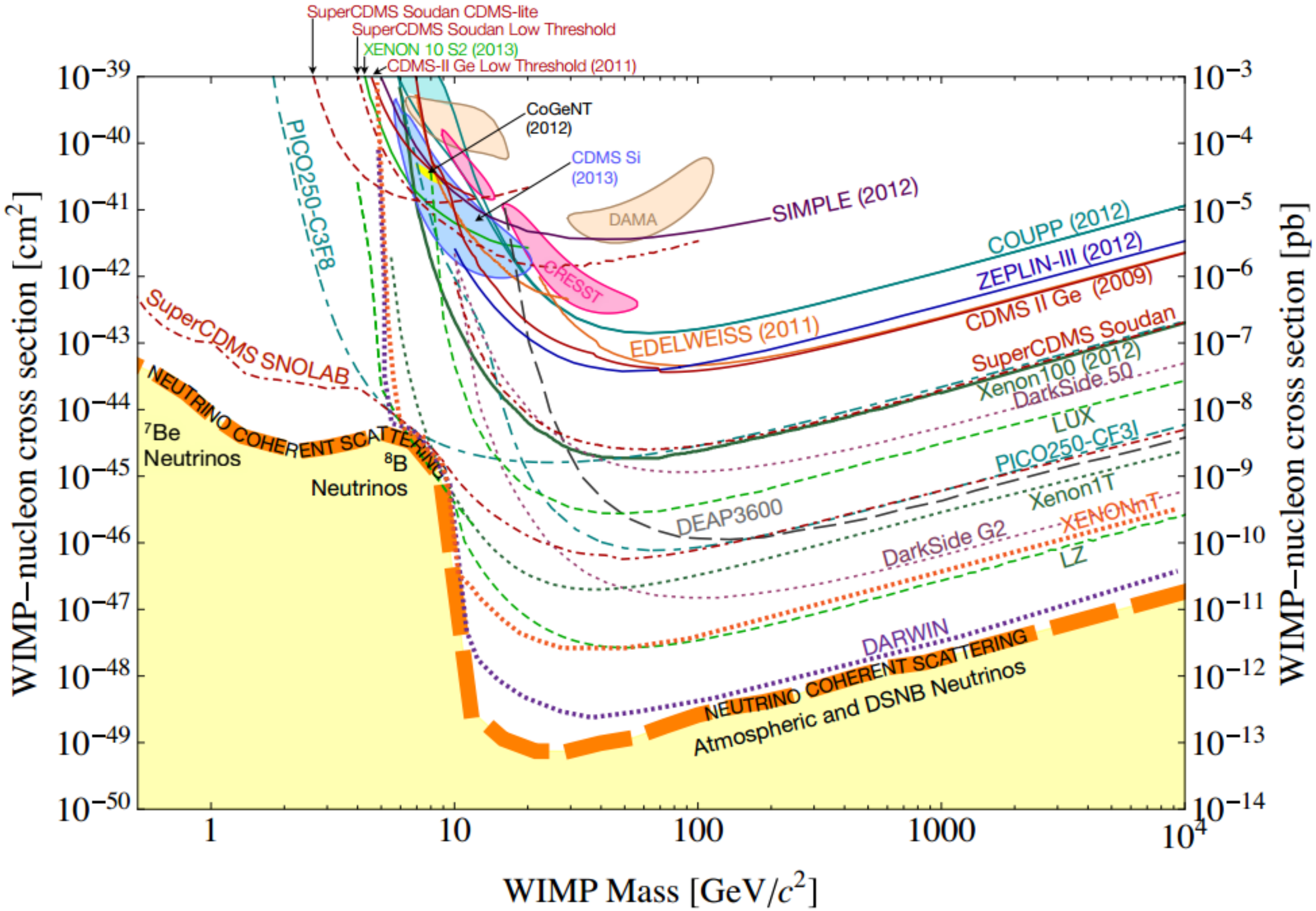
- Tracking capability



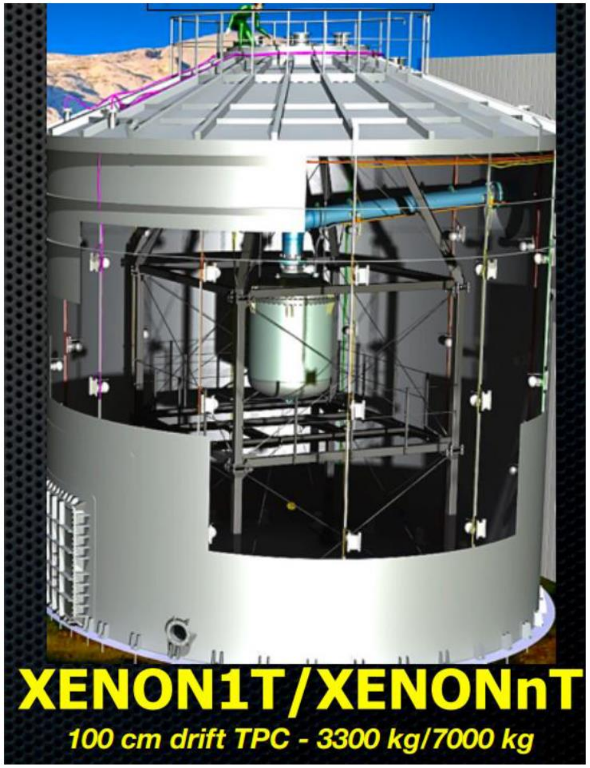
PandaX III: 200kg HP Xe136 exp

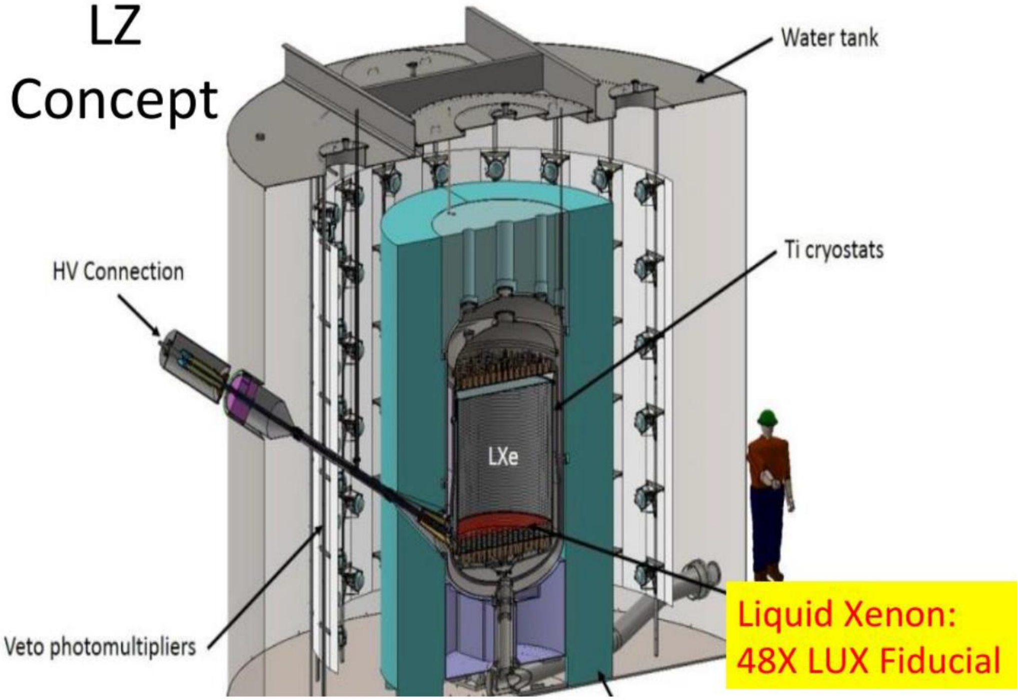
- 13x13x13 m^3 water pond for external shielding
- Kevlar-reinforced thin Cu (1-2mm) high-pressure (10-15bar) vessel, 5 m
- Symmetric TPC readout for charges
  - Mircomega, energy resolution 1%
  - TopMetal (modified CMOS), energy resolution 0.5%
  - 100K-200K channel
- Easy upgrade to 1 ton (5 modules).

Ultimate dark matter exp



Stiff competitions in DM search



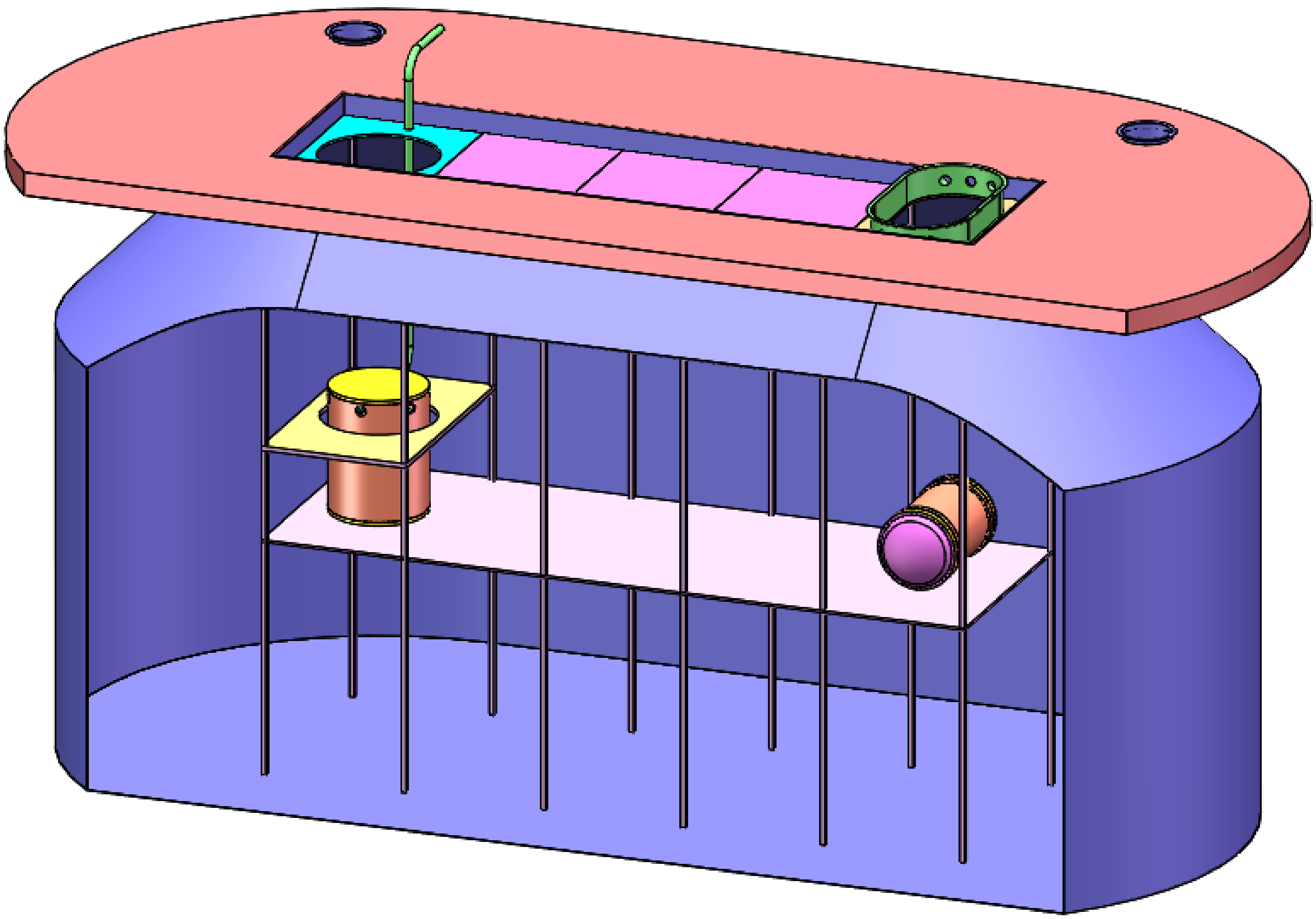


5. 6吨有效质量

Future Panda: 20-30 ton LXe DM detector

- Beyond LZ and XENONnt
- International Collaboration for the ultimate dark matter detector
- Great solar neutrino detector:

  pp neutrino, CNO neutrino, Matter-Vacuum oscillation transition region



Summary

- Jinping Underground lab in its first phase has produced interesting results in dark matter search.
- A 500kg LXe dark matter PandaX detector is running and has the sensitivity leading the world.
- Second phase expansion of the lab is under way, and more exciting physics to come in the future.