Thoughts and experience with LXe* and LYSO

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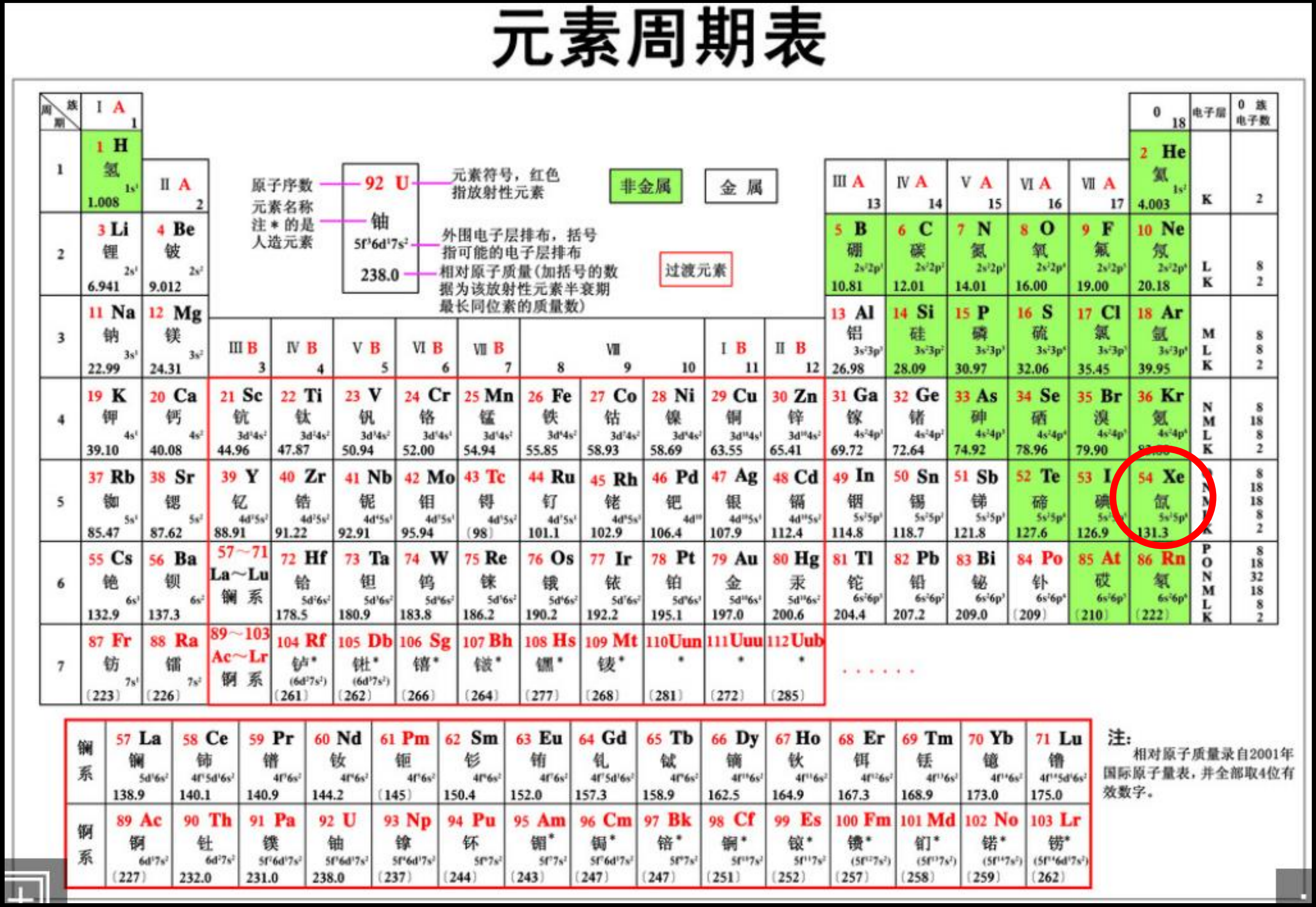
**based on PandaX experience in very low energy DM and 0vDBD experiments*

Xenon

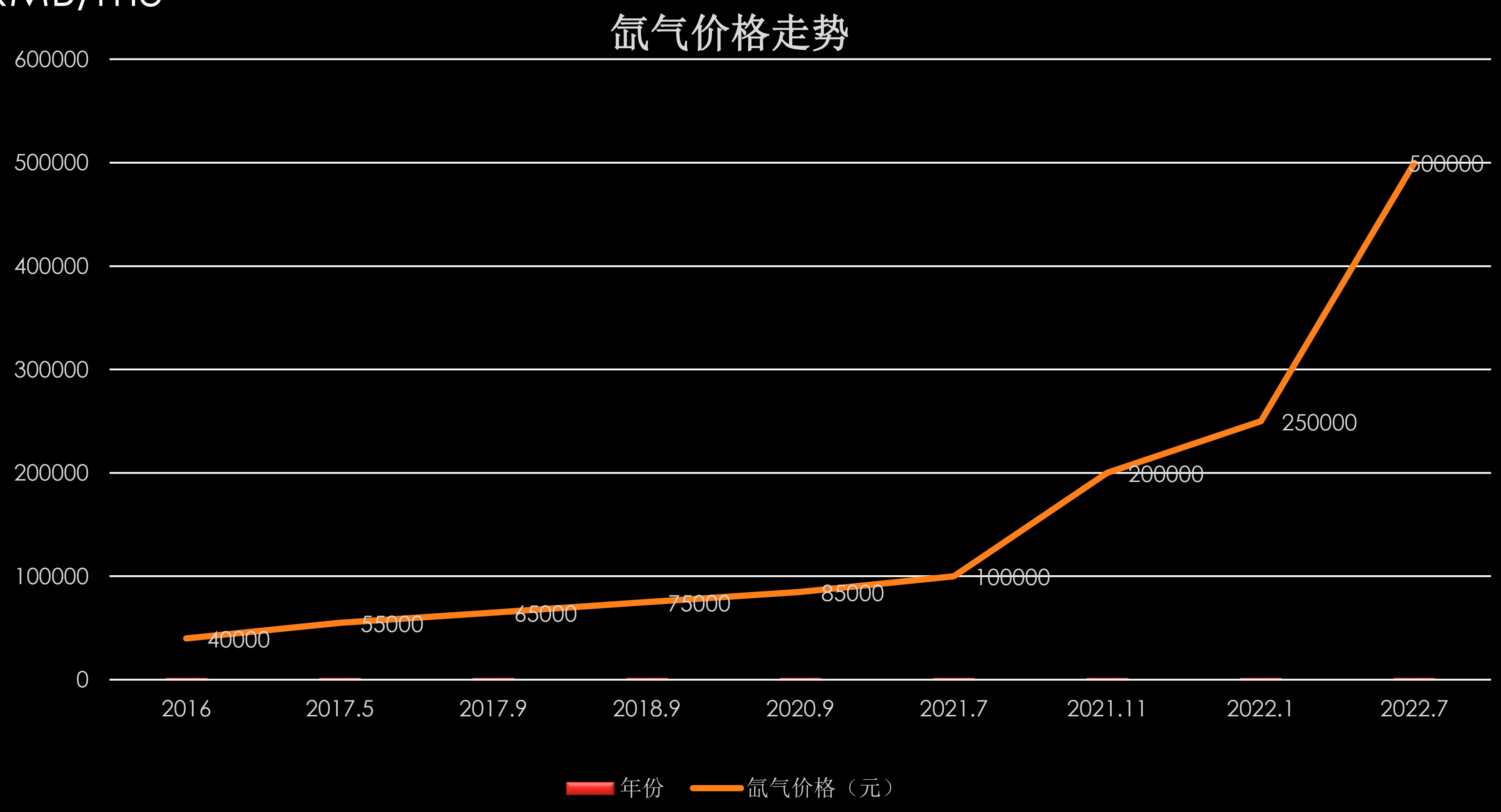


- Density: 3 g/cc (L), 6 g/l (G)
- Radiation length: 8.5 g/cm^2 or 2.9 cm (L)
- W value: 13.6 eV
- Liquid: -100 C
- Scintillation photon wavelength: 178 nm

Production & cost

- Annual production: 60-80 ton
- Usage: semi-conductor industry (etching, ion injection), satellite, lamp/medical

Unit: RMB/m3



Current price: $13k/kg

Xenon detectors

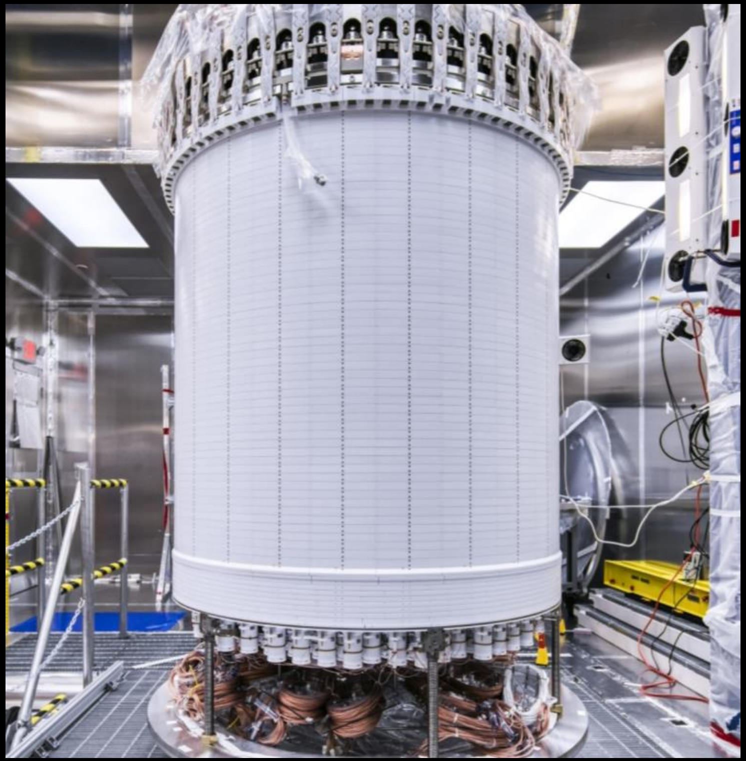
- Shortly after receiving Nobel, Alvarez developed liquid xenon detectors, 1968
- Nobel gas transparent to its own excitation photon and electron!
- Before 90s', Russia, Japan, and US
- >Late 90s', xenon TPC in dark matter and 0vDBD search (XENON, LUX, …)

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 51, NO. 5, OCTOBER 2004

Proportional Light in a Dual-Phase Xenon Chamber

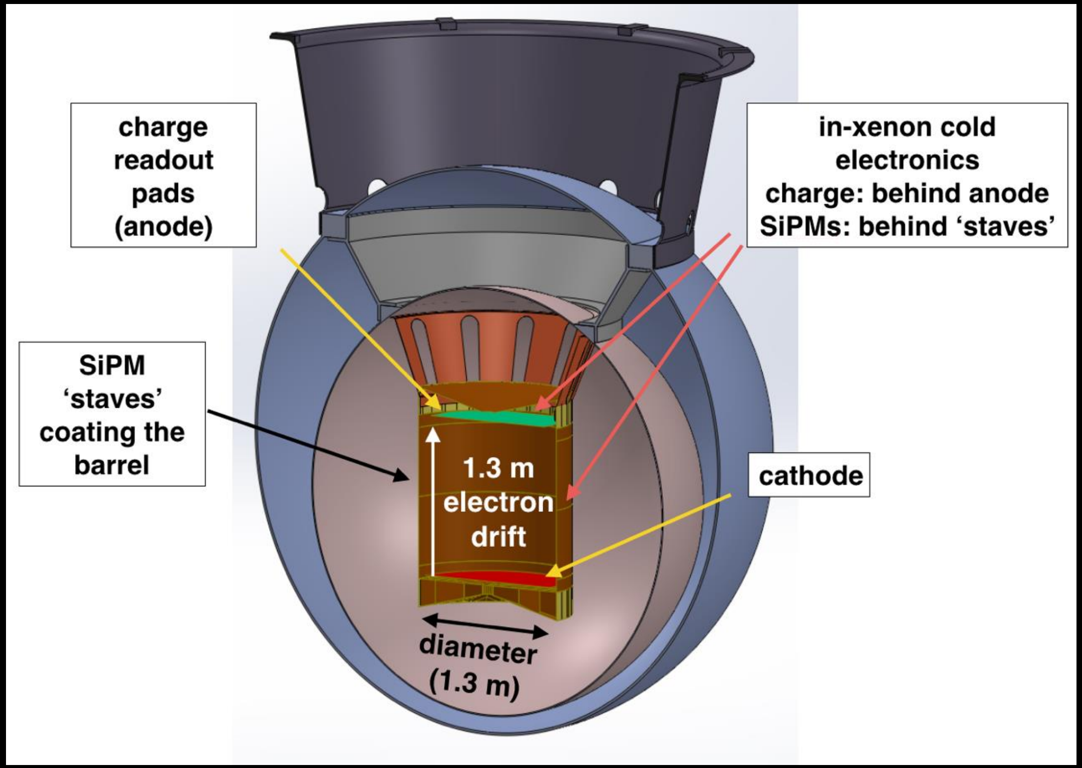
Elena Aprile, Karl L. Giboni, Pawel Majewski, Kaixuan Ni, and Masaki Yamashita

Variety of xenon detectors in DM and 0vDBD experiments



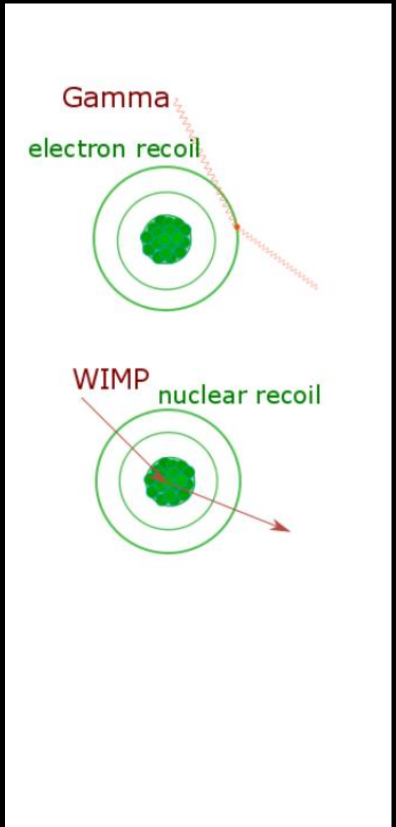
LZ, 7-ton, Sanford Lab, 2020

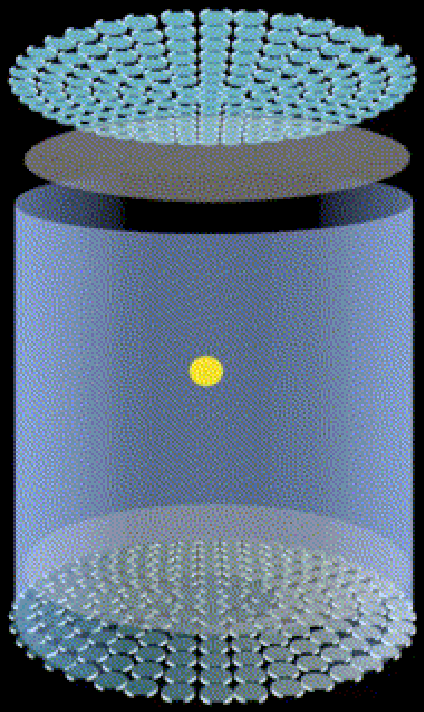
XMASS, 800 kg, Kamioka, joined XENON

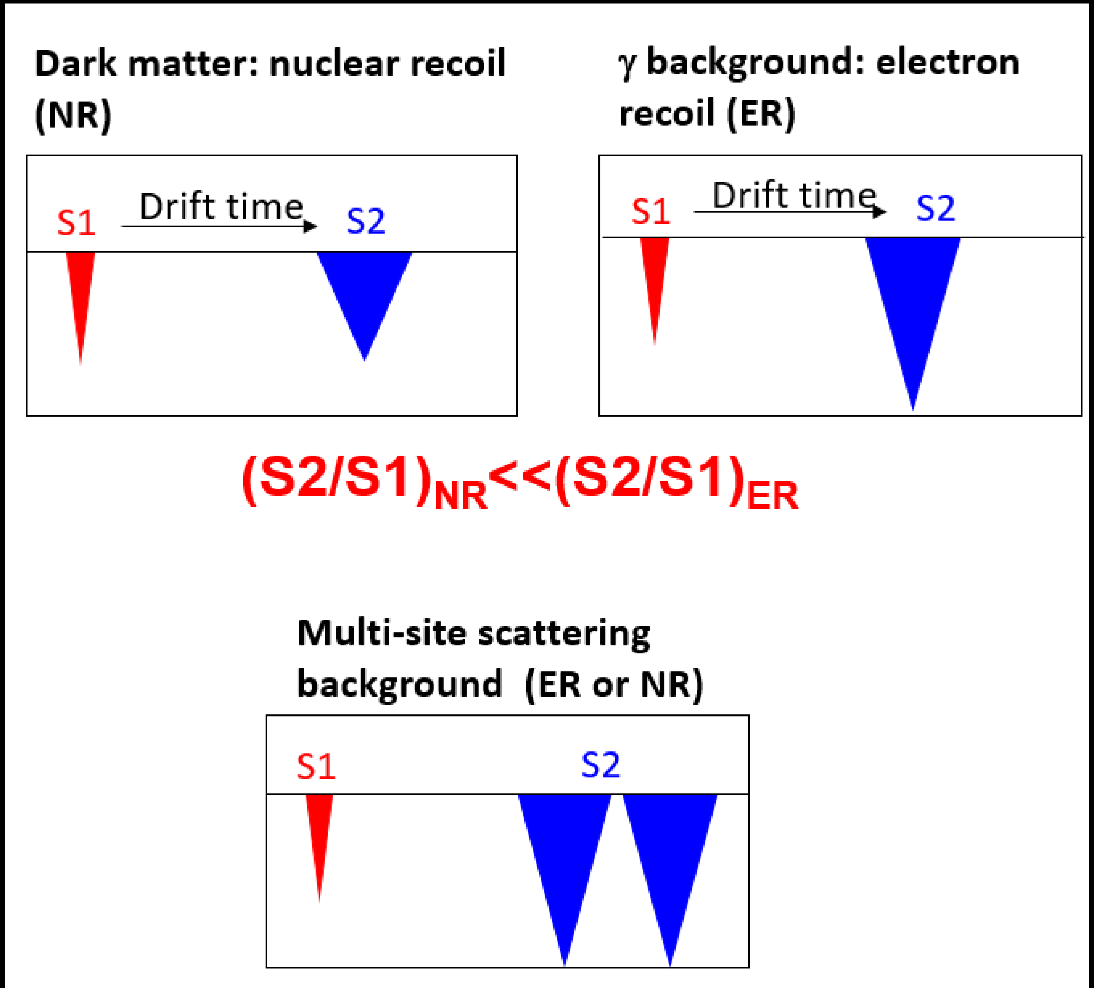


nEXO, 5 ton enriched 136Xe, liquid TPC

Dual phase Xe TPC



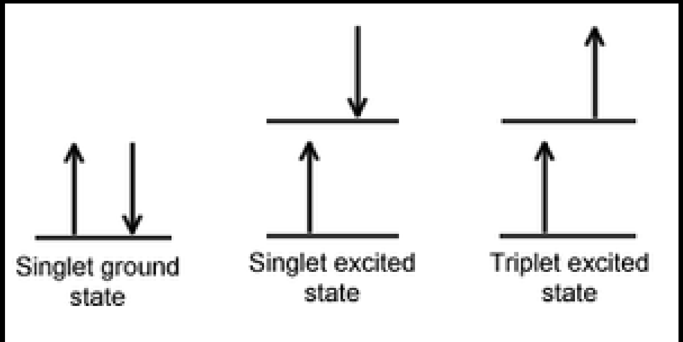




Scintillation signals

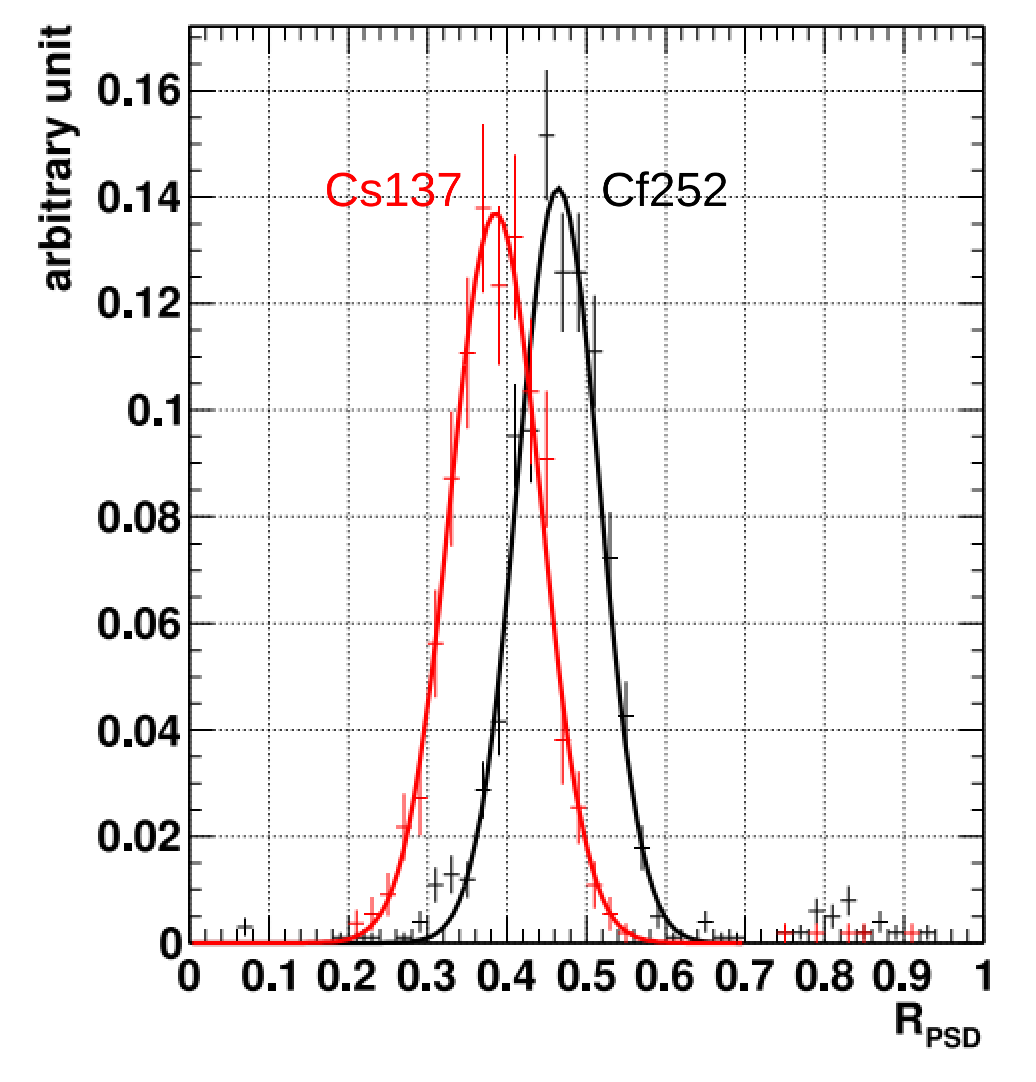
3 ns/22 ns for the single/triplet states

$Xe*_2 \rightarrow 2\,Xe + h\nu$



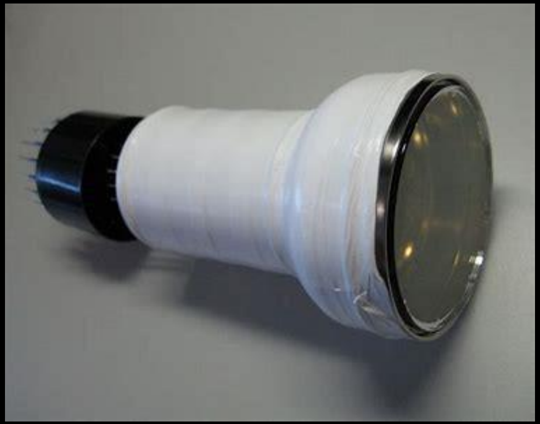
Some particle ID capability, but gets smeared by TTS, ToF, bandwidth, electronics resolution, etc.

1106.2209, XMASS

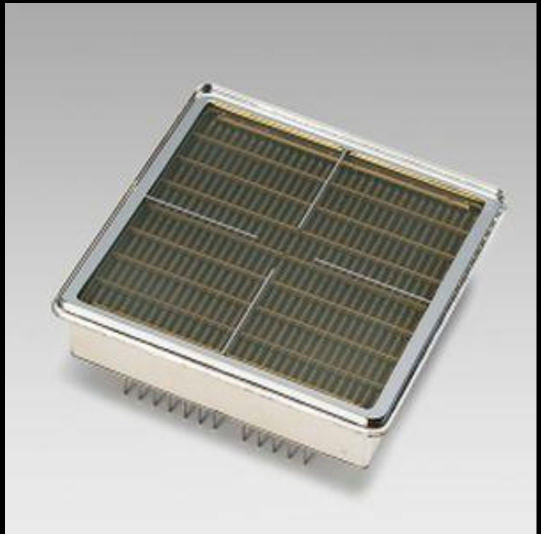


Possible photosensor options

- PMTs
  - R11410 (DM, 3” round-headed, 30% QE, 20 Hz DR @ -100 C, ultralow bkg) $6000/piece
  - R12699 (DM, 2” square with 4 independent anode, 30% QE, 20 Hz DR @ -100 C, ultralow bkg), $6000/piece
  - R9869 2” used by MEG
- VUV SiPM option from Hamamatsu (MEG-II)



TTS ~ 3.5 ns

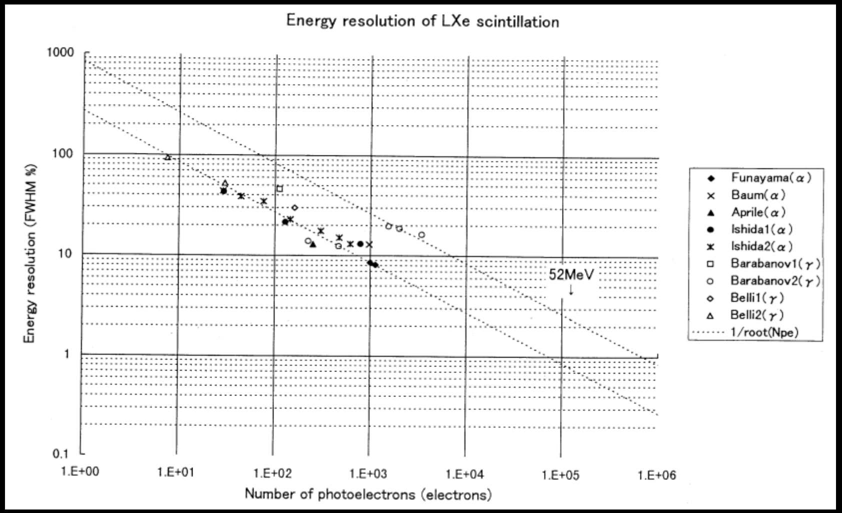


TTS ~ ns

Liquid TPC vs. spherical in DM and 0vDBD

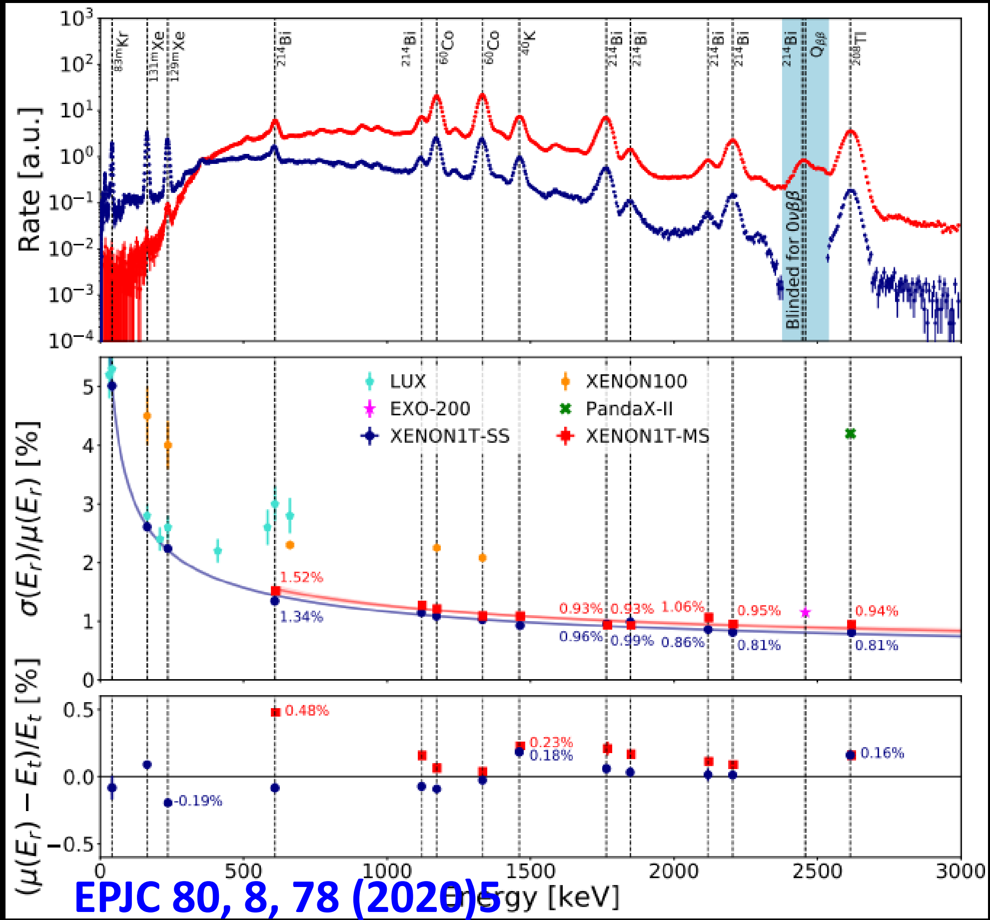
	TPC	Spherical
Scaling up	Challenging	Easy
DM position reconstruction	Good (cm)	Bad, leakages into FV
DM background	Good (99.5% rejection of ER background)	Bad, some pulse shape discrimination for ER
Light yield	~5 PE/keV but with ionization electrons	14 PE/keV （XMASS)
Energy resolution (2.5 MeV)	1% (XENON1T)	4.6% (Doke & Masuda)
NLDBD position reconstruction	Good	Good
NLDBD background	Good	Good

Doke & Masuda



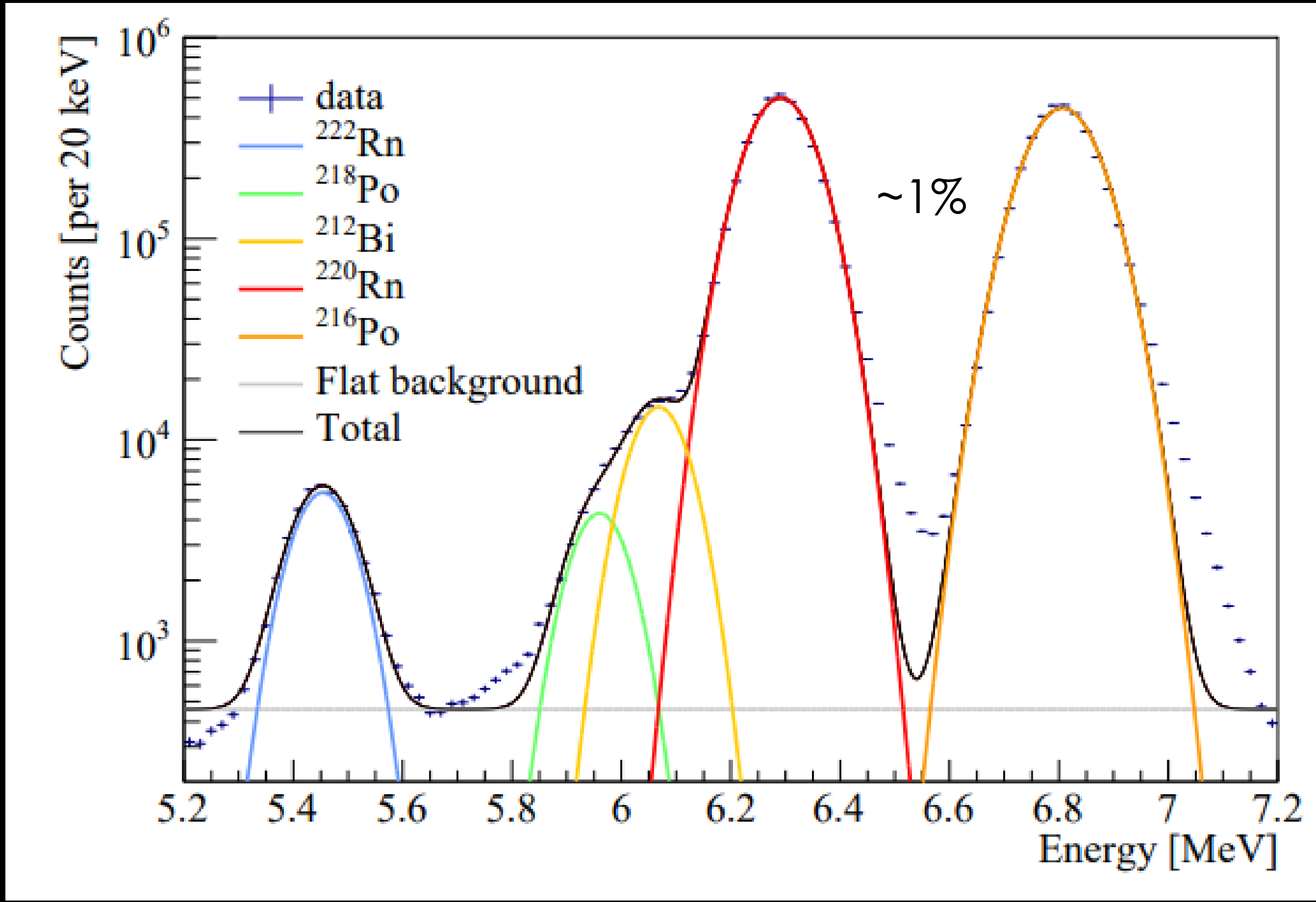
Energy resolution in PandaX

XENON1T



EPJC 80, 8, 78 (2020)5

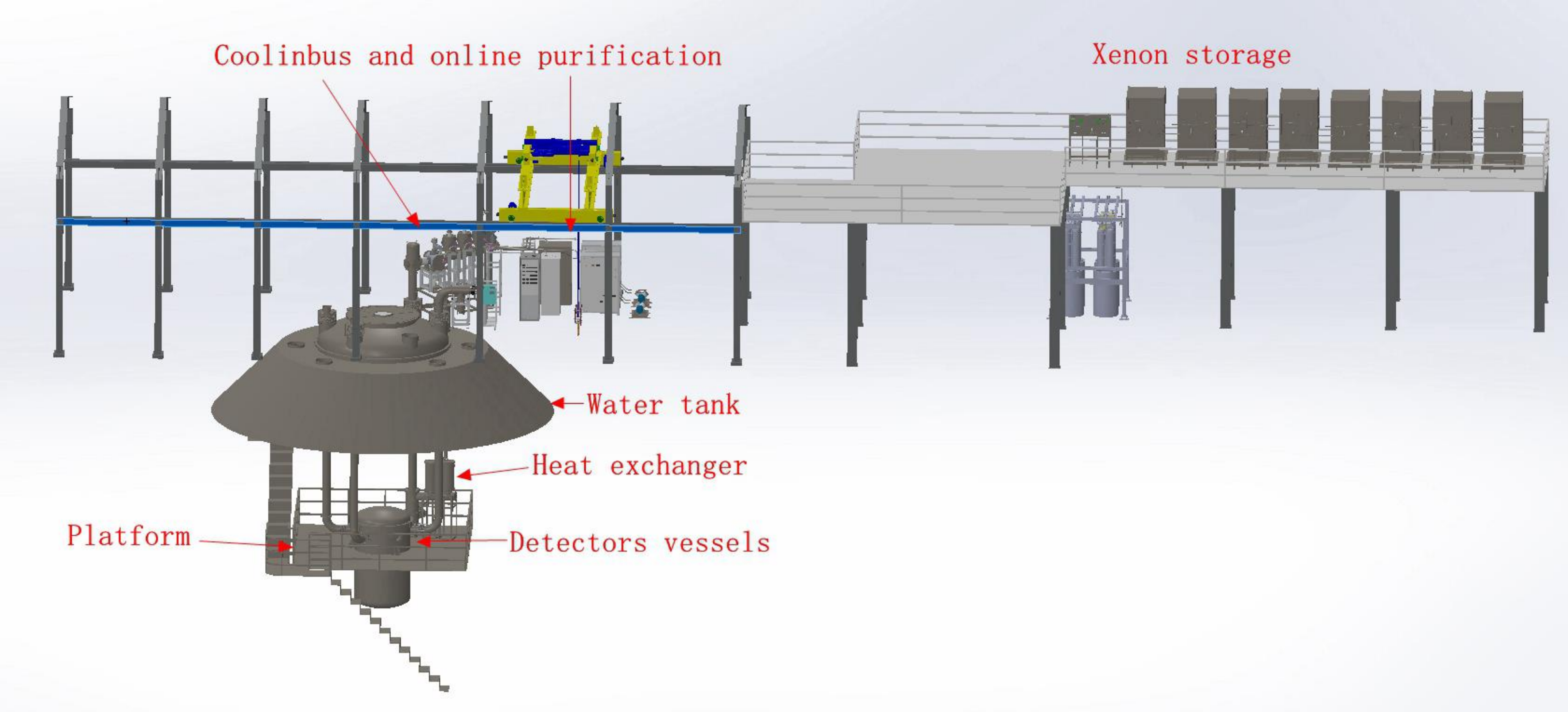
PandaX-II, 2006.09311



- Uniformity calibration achieved via internal Rn222 & Rn220 decays
- De-saturation correction important (for position reconstruction, then energy correction)

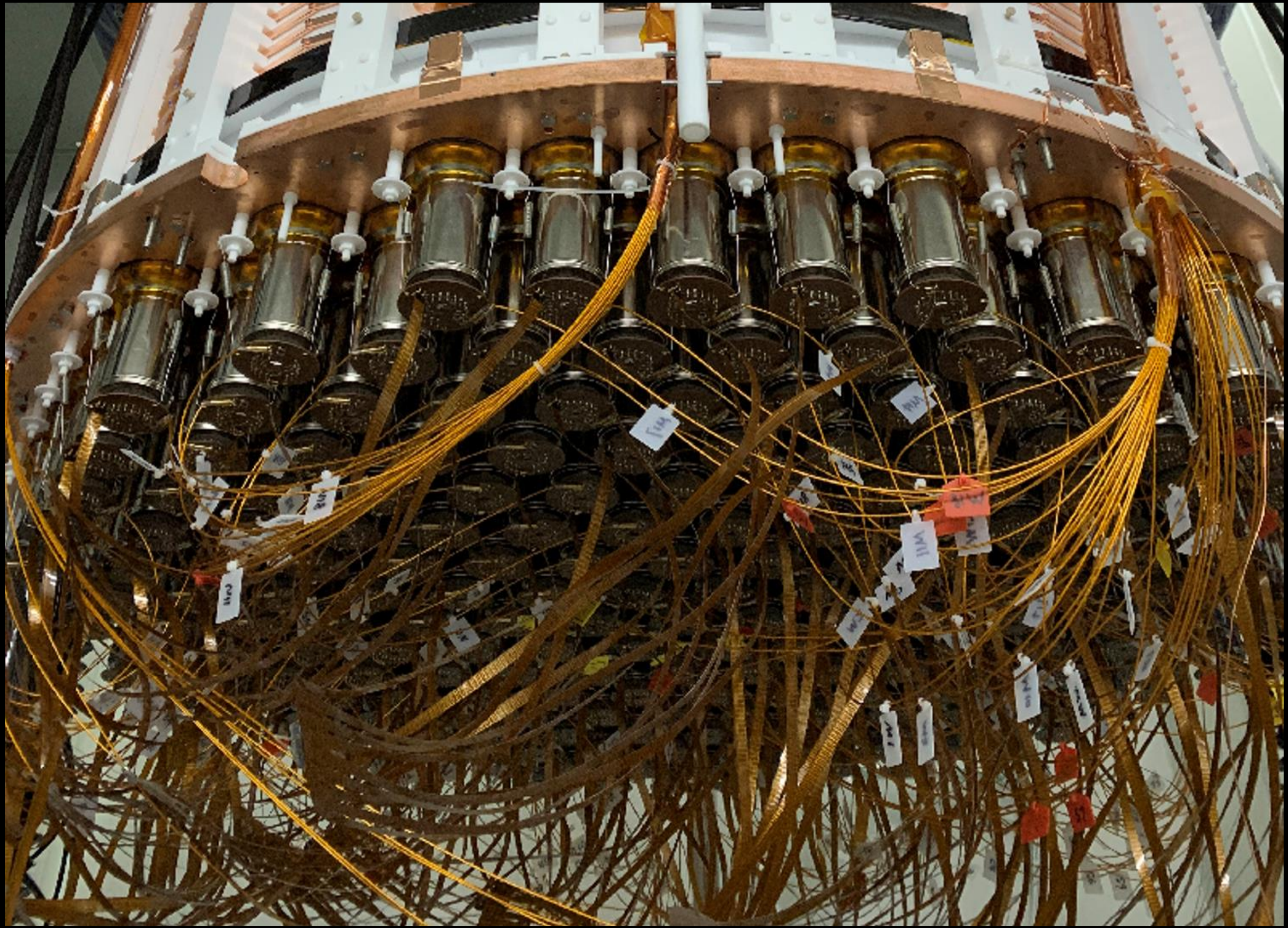
Key ingredient

arXiv:2012.10583

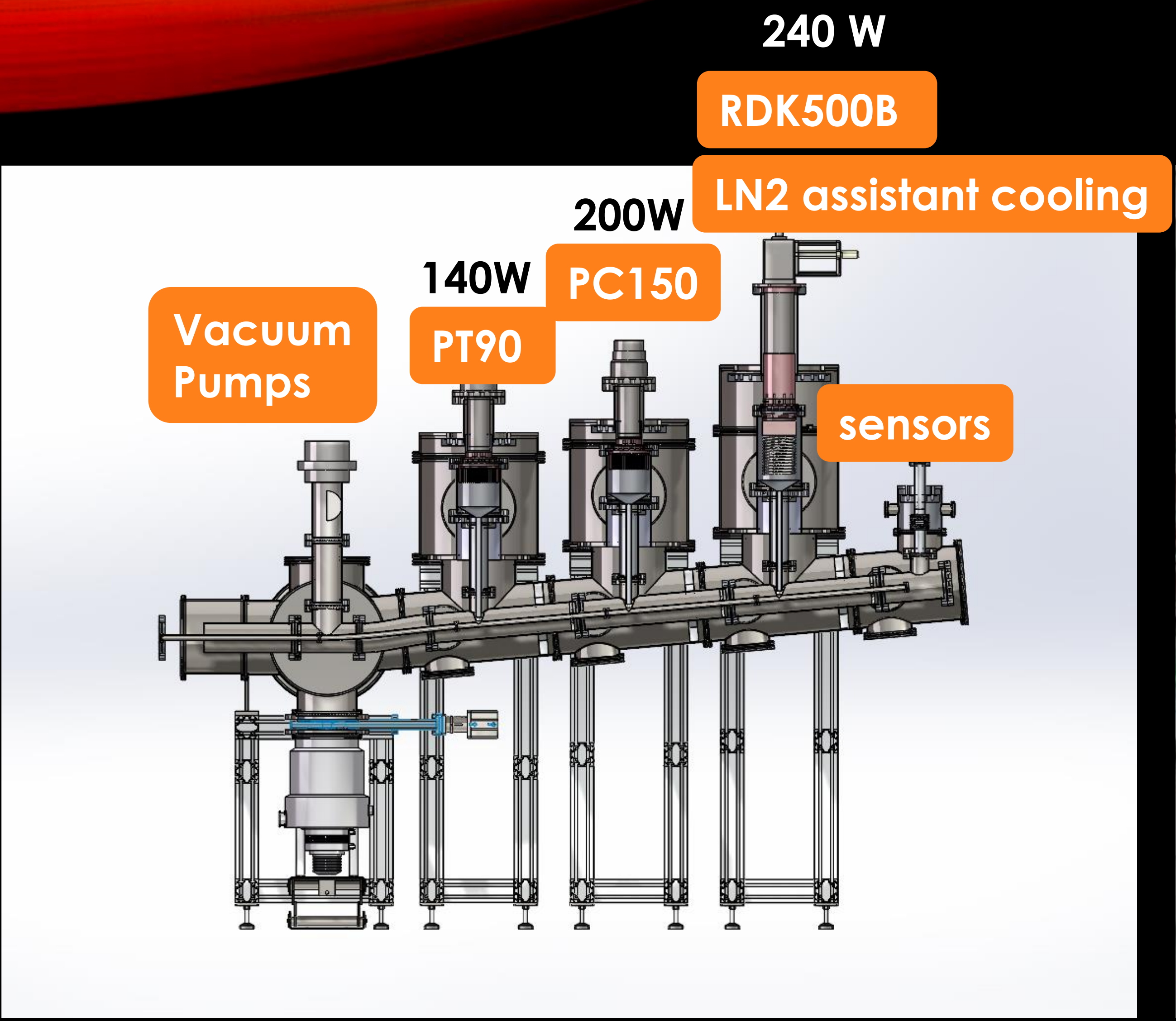


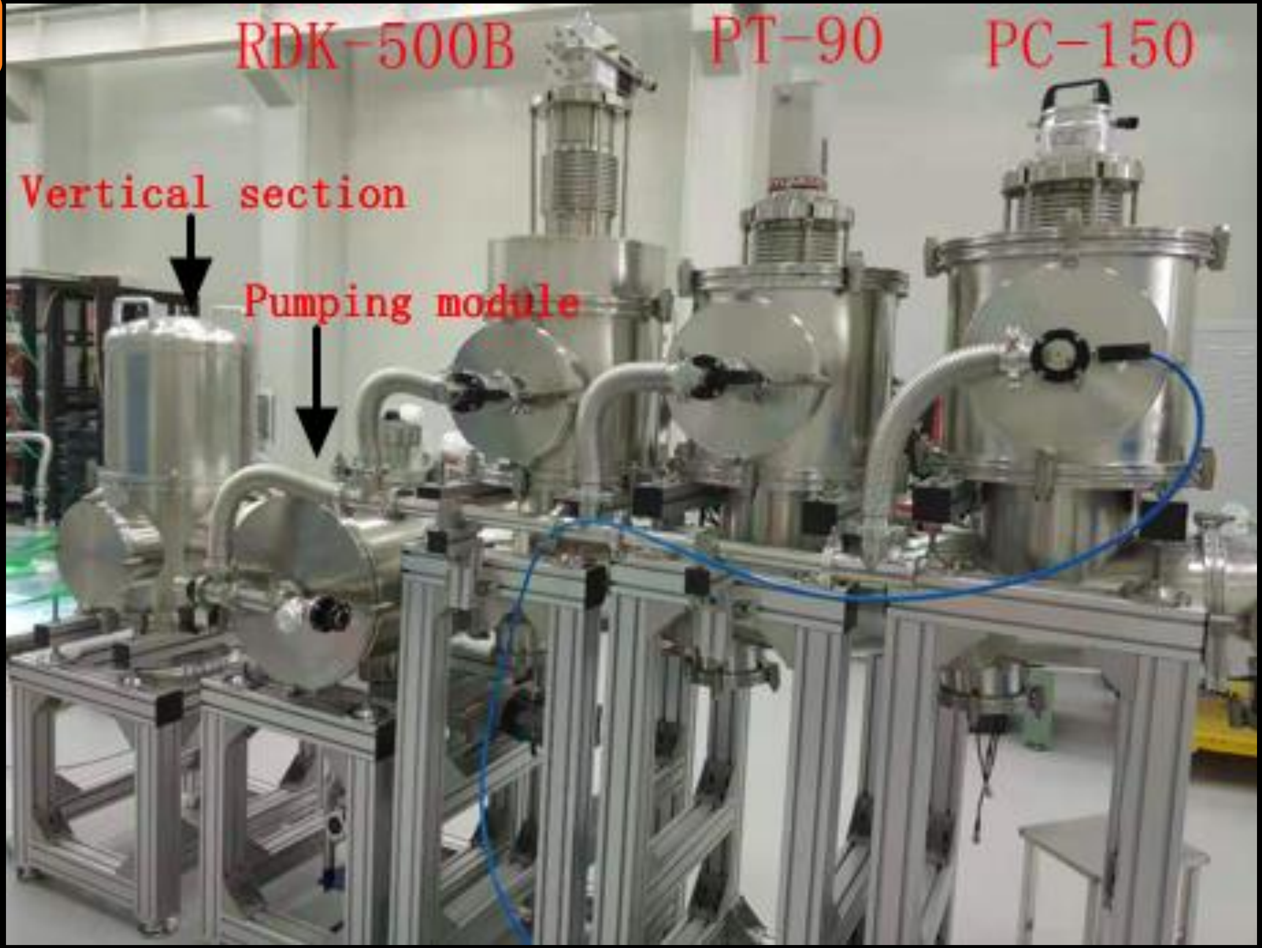
- A cryogenic system providing cooling power all the time (580 W)
- A circulation and purification system to remove outgassing from LXe (130 slpm: ~1 ton/day)
- Filling (LN2 assisted, 1 ton/day), recuperation by high pressure pump (1.5 ton/day)

TPC & inner vessel

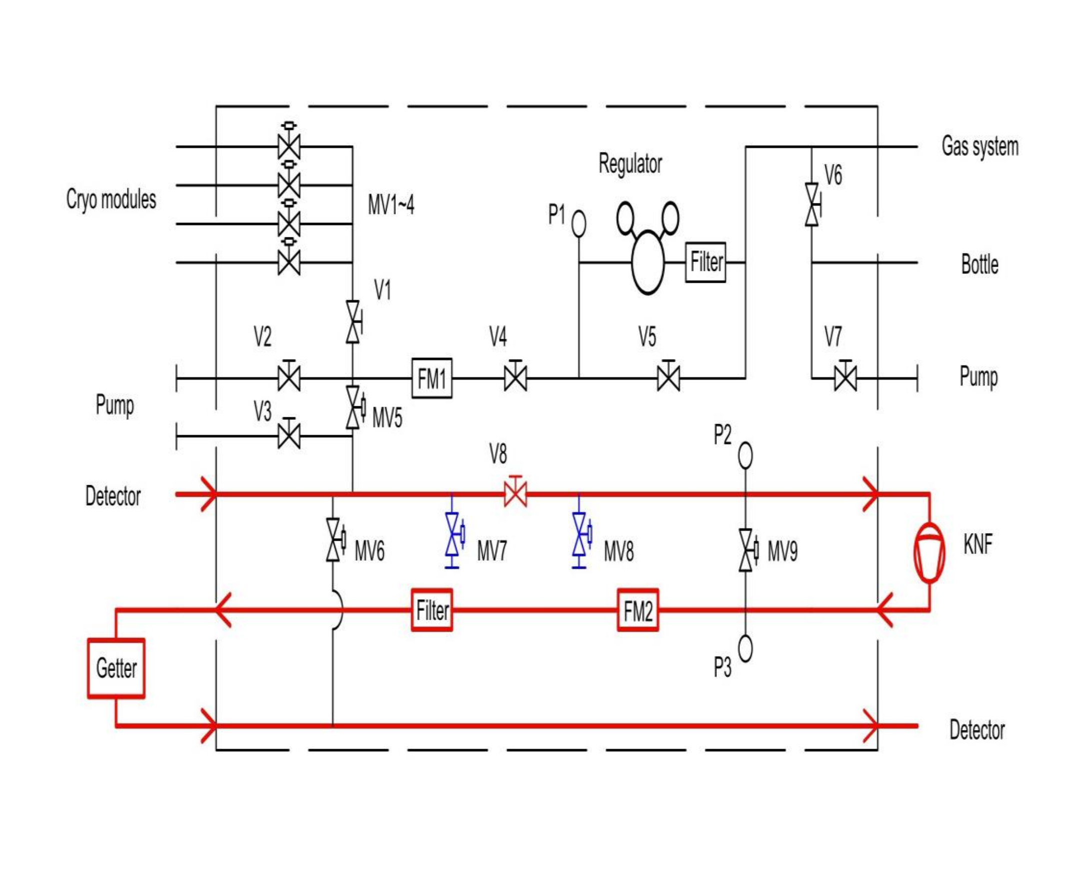


"Cooling bus"


240 W
RDK500B
LN2 assistant cooling
200W
PC150
140W
PT90
Vacuum Pumps
sensors


RDK-500B
PT-90
PC-150
Vertical section
Pumping module

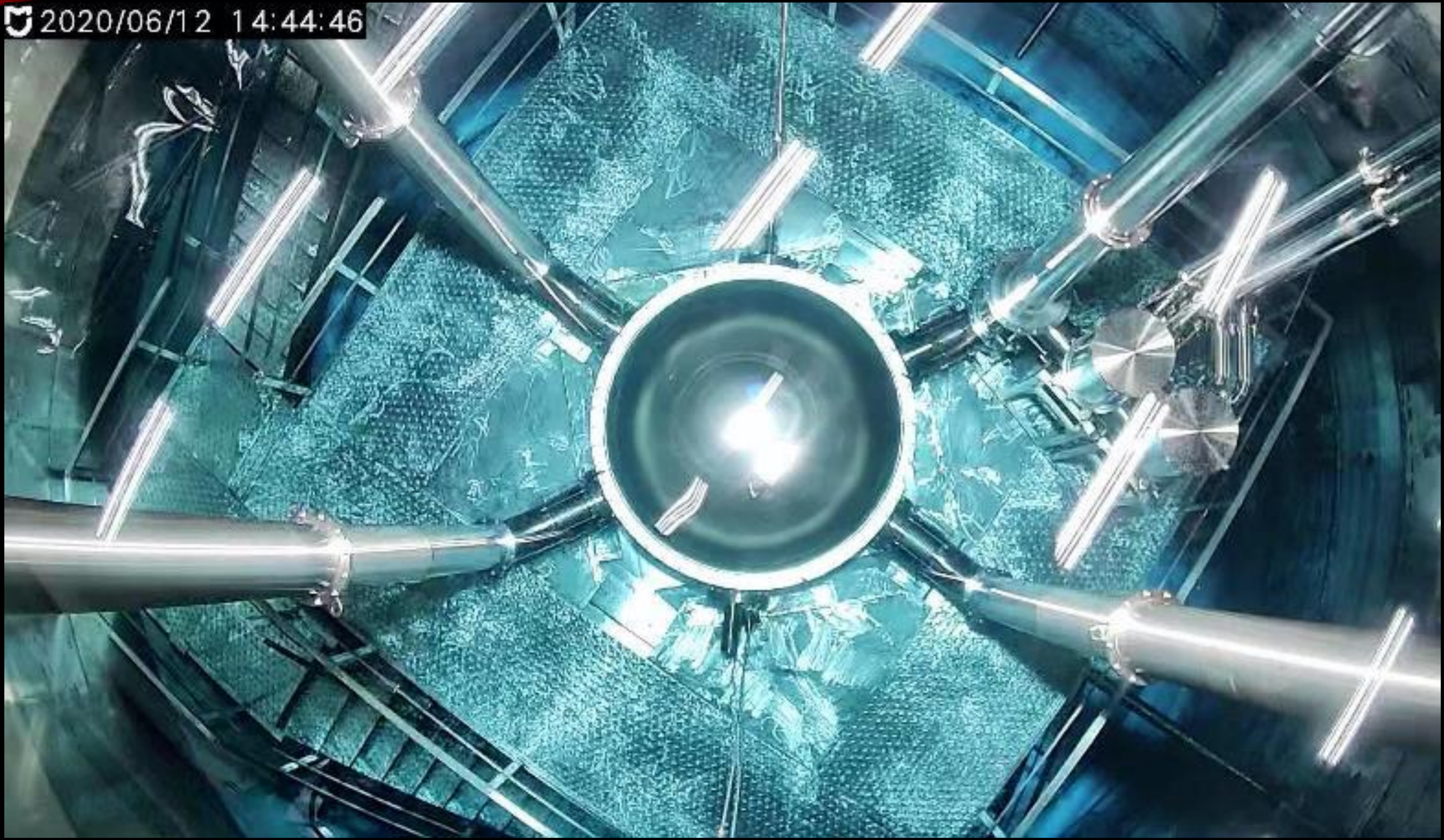
Re-circulation and purification



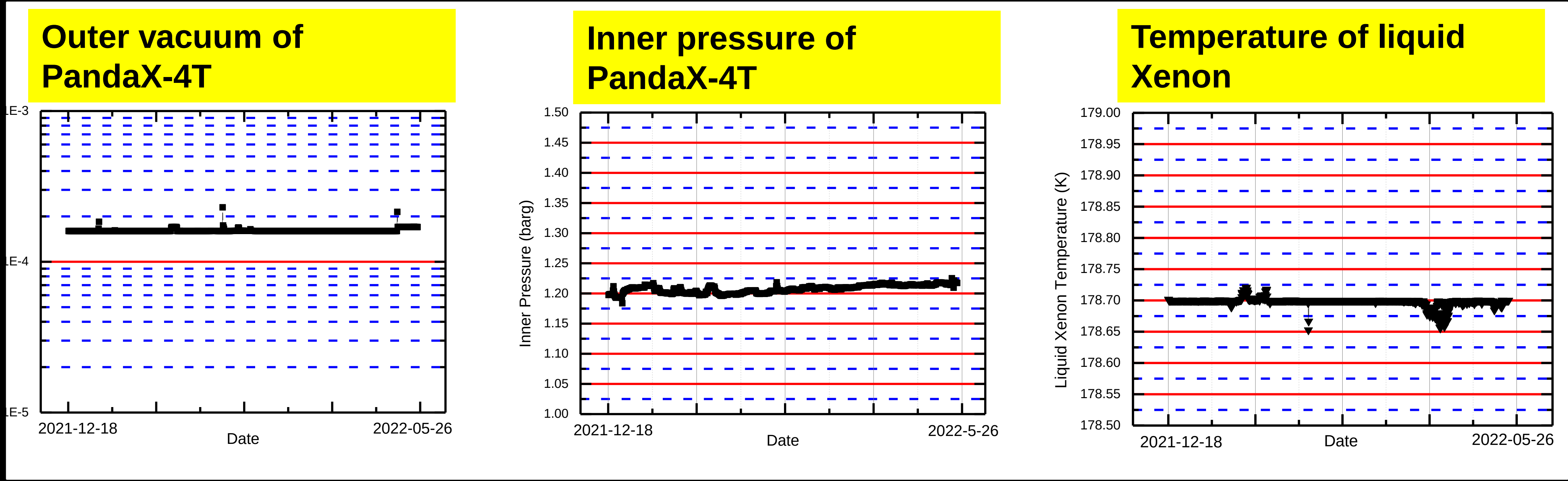
- Circulation speed achieved, 100 slpm (loop 1, SAES PS5-MGT50-R-909), 30 slpm (loop 2, Simpure 9N300-R), ~1 ton/day
- Heat exchanger efficiency: 97.5%

Overall system

Detector in operation



Performance



Parameters	Static Heat	Outer vacuum	Fluctuation of P_Xe	Fluctuation of T_Xe
Value	~90 W	<3.0E-4 Pa	< 0.05 bar	< 0.1 K

Photon/electron transparency

- Pumping for 2 weeks before filling
- Filling the detector (LN2 assistant cooling)
- Two kinds of outgassing impurities

1. H_2O: photon transparency
    - MEG: 100 ppb ~ 1 m
    - Normally we achieve good photon transparency in 1-2 weeks after recirculation
2. N_2/O_2: electron transparency

- Electron lifetime of 1 ms ~O_2-equivalent concentration of ~ppb (takes months purification)

Maximum e_lifetime: 2200 us

2021.11~2022.05

Personnel

- PandaX cryogenic system was developed by a few people (~4). Over years much experience has been gained
- The system can be designed robust so things can be manned remotely
- Emergencies:
  - vacuum pump failure (hot backup, sorption pump using LN2)
  - power failure (backup power, diesel generator)
  - Leak => regular xenon sniffing (weekly)
  - Getter saturated => timed maintanenece
  - etc.
- Stay vigilant
- Regular in-person on-site shift

LYSO advantages (R. Zhu's talk, 2021)

- Bright (200 times of PWO), fast (40 ns) and radiation hard.
- Longitudinal light response non-uniformity issue caused by self-absorption, cerium segregation and tapered geometry can be addressed by roughening crystal's side surface

Crystals with Mass Production Capability

Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	CeF_3	PbF_2	BGO	BSO	$PbWO_4$	LYSO:Ce	AFO Glasses	Sapphire:Ti
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.77	7.13	6.8	8.3	7.40	4.6	3.98
Melting points (°C)	651	621	621	1280	1460	824	1050	1030	1123	2050	\	2040
X_0 (cm)	2.59	1.86	1.86	2.03	1.65	0.94	1.12	1.15	0.89	1.14	2.96	7.02
R_M (cm)	4.13	3.57	3.57	3.10	2.39	2.18	2.23	2.33	2.00	2.07	2.89	2.88
λ_I (cm)	42.9	39.3	39.3	30.7	23.2	22.4	22.7	23.4	20.7	20.9	26.4	24.2
Z_{eff}	50.1	54.0	54.0	51.6	51.7	77.4	72.9	75.3	74.5	64.8	42.8	11.2
dE/dX (MeV/cm)	4.79	5.56	5.56	6.52	8.40	9.42	8.99	8.59	10.1	9.55	6.84	6.75
λ_{peak} [a] (nm)	410	560	420 310	300 220	340 300	\	480	470	425 420	420	365	750
Refractive Index[b]	1.85	1.79	1.95	1.50	1.62	1.82	2.15	2.68	2.20	1.82	\	1.76
Normalized Light Yield[a,c]	120	190	4.2 1.3	42 4.8	8.6	\	25	5	0.4 0.1	100	1.5	\
Total Light yield (ph/MeV)	35,000	58,000	1700	13,000	2,600	\	7,400	1,500	130	30,000	450	\
Decay time[a] (ns)	245	1220	30 6	600 0.5	30	\	300	100	30 10	40	40	3200
Hygroscopic	Yes	Slight	Slight	No	No	No	No	No	No	No	No	No
Experiment	Crystal Ball	CLEO BaBar BELLE BES III	KTeV Mu2e S. BELLE	TAPS Mu2e-II	\	A4 g-2	L3 BELLE CalVision	\	CMS ALICE PrimEx Panda	COMET HERD CMS BTL RADiCAL	HHCAL	HHCAL

October 12, 2021

Presentation by Ren-Yuan Zhu, Caltech, in the PIENUX Group meeting, at University of Washington

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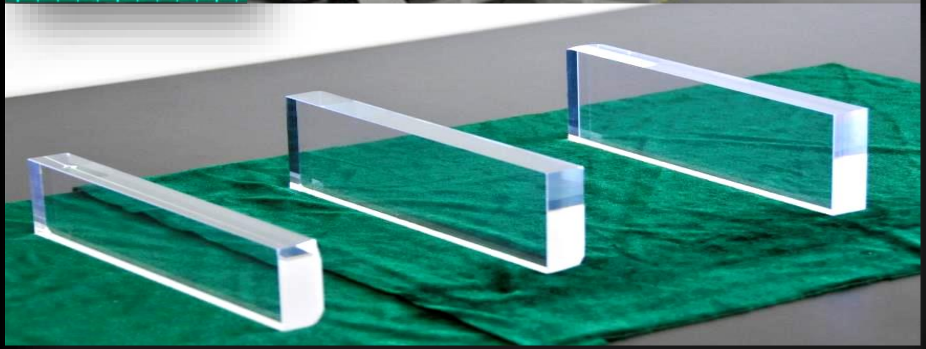
LYSO@ Shanghai Institute of Ceramics



- SIC is the most comprehensive institute in China for inorganic material researches and applications.
- Dr. Dongzhou Ding, leader of the rare earth oxide scintillator group at SIC, is keen for collaborative R&D with physicists.
- They have provided LYSO crystals for HERD experiment (250 pcs) at IHEP, CAS, and KLOE2 experiment (96 pcs) at INFN.
- SIC's production capability: 2×10^4 cc / month using Iradium oven and crystal pulling method

Price driver

Biggest driver is the price of Iradium

- 2019.12.15 1450 USD/oz
- 2021.7.2 5740 USD/oz
- 2022.9.30 4040 USD/oz

Second is the cost of Lu_2O_3

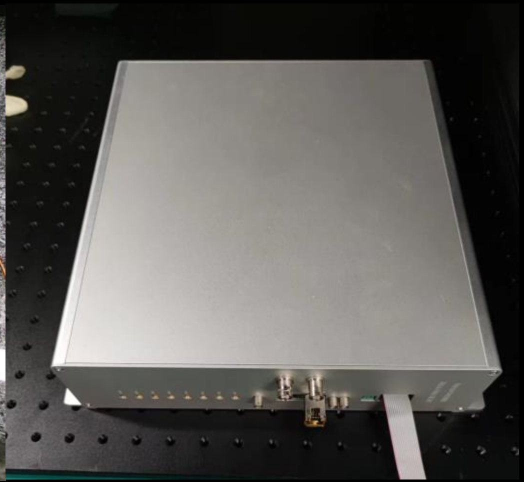
Price in Aug: Hex-petagon shaped 17.5 cm $32k/piece

Other commercial companies

- United Imaging (联影) make their own LYSO crystal for PET (big production plant in Suzhou)
- They claim they are more stable in production than SIC
- However, PET LYSO is very small
- Less interested in doing R&D for physicists
- Worth exploring

Measurement started at SJTU

LYSO + PMT R7725, 1200V
(inside dark box)



500MS/s digitization
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