

# Thoughts and experience with LXe\* and LYSO

Jianglai Liu and Yong Yang  
Shanghai Jiao Tong University

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



# Xenon

## 元素周期表

1	I A																0	18	电子层	0 族
1	1 H 氢 1.008 1s <sup>1</sup>															2 He 氦 4.003 1s <sup>2</sup>	K	2		
2	3 Li 锂 6.941 2s <sup>1</sup>	4 Be 铍 9.012 2s <sup>2</sup>											5 B 硼 10.81 2s <sup>2</sup> 2p <sup>1</sup>	6 C 碳 12.01 2s <sup>2</sup> 2p <sup>2</sup>	7 N 氮 14.01 2s <sup>2</sup> 2p <sup>3</sup>	8 O 氧 16.00 2s <sup>2</sup> 2p <sup>4</sup>	9 F 氟 19.00 2s <sup>2</sup> 2p <sup>5</sup>	10 Ne 氖 20.18 2s <sup>2</sup> 2p <sup>6</sup>	L	8
3	11 Na 钠 22.99 3s <sup>1</sup>	12 Mg 镁 24.31 3s <sup>2</sup>	III B	IV B	V B	VI B	VII B	VIII			I B	II B	13 Al 铝 26.98 3s <sup>2</sup> 3p <sup>1</sup>	14 Si 硅 28.09 3s <sup>2</sup> 3p <sup>2</sup>	15 P 磷 30.97 3s <sup>2</sup> 3p <sup>3</sup>	16 S 硫 32.06 3s <sup>2</sup> 3p <sup>4</sup>	17 Cl 氯 35.45 3s <sup>2</sup> 3p <sup>5</sup>	18 Ar 氩 39.95 3s <sup>2</sup> 3p <sup>6</sup>	M L K	8 8 2
4	19 K 钾 39.10 4s <sup>1</sup>	20 Ca 钙 40.08 4s <sup>2</sup>	21 Sc 钪 44.96 3d <sup>1</sup> 4s <sup>2</sup>	22 Ti 钛 47.87 3d <sup>2</sup> 4s <sup>2</sup>	23 V 钒 50.94 3d <sup>3</sup> 4s <sup>2</sup>	24 Cr 铬 52.00 3d <sup>5</sup> 4s <sup>1</sup>	25 Mn 锰 54.94 3d <sup>5</sup> 4s <sup>2</sup>	26 Fe 铁 55.85 3d <sup>6</sup> 4s <sup>2</sup>	27 Co 钴 58.93 3d <sup>7</sup> 4s <sup>2</sup>	28 Ni 镍 58.69 3d <sup>8</sup> 4s <sup>2</sup>	29 Cu 铜 63.55 3d <sup>10</sup> 4s <sup>1</sup>	30 Zn 锌 65.41 3d <sup>10</sup> 4s <sup>2</sup>	31 Ga 镓 69.72 4s <sup>2</sup> 4p <sup>1</sup>	32 Ge 锗 72.64 4s <sup>2</sup> 4p <sup>2</sup>	33 As 砷 74.92 4s <sup>2</sup> 4p <sup>3</sup>	34 Se 硒 78.96 4s <sup>2</sup> 4p <sup>4</sup>	35 Br 溴 79.90 4s <sup>2</sup> 4p <sup>5</sup>	36 Kr 氪 83.80 4s <sup>2</sup> 4p <sup>6</sup>	N M L K	8 18 8 2
5	37 Rb 铷 85.47 5s <sup>1</sup>	38 Sr 锶 87.62 5s <sup>2</sup>	39 Y 钇 88.91 4d <sup>1</sup> 5s <sup>2</sup>	40 Zr 锆 91.22 4d <sup>2</sup> 5s <sup>2</sup>	41 Nb 铌 92.91 4d <sup>4</sup> 5s <sup>1</sup>	42 Mo 钼 95.94 4d <sup>5</sup> 5s <sup>1</sup>	43 Tc 锝 (98) 4d <sup>5</sup> 5s <sup>2</sup>	44 Ru 钌 101.1 4d <sup>7</sup> 5s <sup>1</sup>	45 Rh 铑 102.9 4d <sup>8</sup> 5s <sup>1</sup>	46 Pd 钯 106.4 4d <sup>10</sup>	47 Ag 银 107.9 4d <sup>10</sup> 5s <sup>1</sup>	48 Cd 镉 112.4 4d <sup>10</sup> 5s <sup>2</sup>	49 In 铟 114.8 5s <sup>2</sup> 5p <sup>1</sup>	50 Sn 锡 118.7 5s <sup>2</sup> 5p <sup>2</sup>	51 Sb 锑 121.8 5s <sup>2</sup> 5p <sup>3</sup>	52 Te 碲 127.6 5s <sup>2</sup> 5p <sup>4</sup>	53 I 碘 126.9 5s <sup>2</sup> 5p <sup>5</sup>	54 Xe 氙 131.3 5s <sup>2</sup> 5p <sup>6</sup>	N M L K	8 18 18 8 2
6	55 Cs 铯 132.9 6s <sup>1</sup>	56 Ba 钡 137.3 6s <sup>2</sup>	57~71 La~Lu 镧系	72 Hf 铪 178.5 5d <sup>2</sup> 6s <sup>2</sup>	73 Ta 钽 180.9 5d <sup>3</sup> 6s <sup>2</sup>	74 W 钨 183.8 5d <sup>4</sup> 6s <sup>2</sup>	75 Re 铼 186.2 5d <sup>5</sup> 6s <sup>2</sup>	76 Os 锇 192.2 5d <sup>6</sup> 6s <sup>2</sup>	77 Ir 铱 195.1 5d <sup>7</sup> 6s <sup>2</sup>	78 Pt 铂 197.0 5d <sup>9</sup> 6s <sup>1</sup>	79 Au 金 200.6 5d <sup>10</sup> 6s <sup>1</sup>	80 Hg 汞 204.4 5d <sup>10</sup> 6s <sup>2</sup>	81 Tl 铊 207.2 6s <sup>2</sup> 6p <sup>1</sup>	82 Pb 铅 208.98 6s <sup>2</sup> 6p <sup>2</sup>	83 Bi 铋 208.98 6s <sup>2</sup> 6p <sup>3</sup>	84 Po 钋 (209) 6s <sup>2</sup> 6p <sup>4</sup>	85 At 砹 (210) 6s <sup>2</sup> 6p <sup>5</sup>	86 Rn 氡 (222) 6s <sup>2</sup> 6p <sup>6</sup>	P O N M L K	8 18 32 18 8 2
7	87 Fr 钫 (223) 7s <sup>1</sup>	88 Ra 镭 (226) 7s <sup>2</sup>	89~103 Ac~Lr 锕系	104 Rf 𨭇 (261) 6d <sup>2</sup> 7s <sup>2</sup>	105 Db 𨭉 (262) 6d <sup>3</sup> 7s <sup>2</sup>	106 Sg 𨭊 (266) 6d <sup>4</sup> 7s <sup>2</sup>	107 Bh 𨭋 (264) 6d <sup>5</sup> 7s <sup>2</sup>	108 Hs 𨭌 (277) 6d <sup>6</sup> 7s <sup>2</sup>	109 Mt 𨭍 (268) 6d <sup>7</sup> 7s <sup>2</sup>	110 Uun * (281) 6d <sup>8</sup> 7s <sup>2</sup>	111 Uuu * (272) 6d <sup>9</sup> 7s <sup>2</sup>	112 Uub * (285) 6d <sup>10</sup> 7s <sup>2</sup>								

原子序数  
元素名称  
注\*的是  
人造元素

92 U 元素符号, 红色  
指放射性元素

铀 5f<sup>14</sup>6d<sup>1</sup>7s<sup>2</sup>  
238.0 外围电子层排布, 括号  
指可能的电子层排布  
相对原子质量(加括号的数  
据为该放射性元素半衰期  
最长同位素的质量数)

非金属 金属

过渡元素

镧系	57 La 镧 138.9 5d <sup>1</sup> 6s <sup>2</sup>	58 Ce 铈 140.1 4f <sup>1</sup> 5d <sup>1</sup> 6s <sup>2</sup>	59 Pr 镨 140.9 4f <sup>3</sup> 6s <sup>2</sup>	60 Nd 钕 144.2 4f <sup>4</sup> 6s <sup>2</sup>	61 Pm 钷 (145) 4f <sup>5</sup> 6s <sup>2</sup>	62 Sm 钐 150.4 4f <sup>6</sup> 6s <sup>2</sup>	63 Eu 铕 152.0 4f <sup>7</sup> 6s <sup>2</sup>	64 Gd 钆 157.3 4f <sup>7</sup> 5d <sup>1</sup> 6s <sup>2</sup>	65 Tb 铽 158.9 4f <sup>9</sup> 6s <sup>2</sup>	66 Dy 镝 162.5 4f <sup>10</sup> 6s <sup>2</sup>	67 Ho 铈 164.9 4f <sup>11</sup> 6s <sup>2</sup>	68 Er 铒 167.3 4f <sup>12</sup> 6s <sup>2</sup>	69 Tm 铥 168.9 4f <sup>13</sup> 6s <sup>2</sup>	70 Yb 镱 173.0 4f <sup>14</sup> 6s <sup>2</sup>	71 Lu 镱 175.0 4f <sup>14</sup> 5d <sup>1</sup> 6s <sup>2</sup>
锕系	89 Ac 锕 (227) 6d <sup>1</sup> 7s <sup>2</sup>	90 Th 钍 232.0 6d <sup>2</sup> 7s <sup>2</sup>	91 Pa 镤 231.0 5f <sup>2</sup> 6d <sup>1</sup> 7s <sup>2</sup>	92 U 铀 238.0 5f <sup>3</sup> 6d <sup>1</sup> 7s <sup>2</sup>	93 Np 镎 (237) 5f <sup>4</sup> 6d <sup>1</sup> 7s <sup>2</sup>	94 Pu 钚 (244) 5f <sup>6</sup> 7s <sup>2</sup>	95 Am 镅 (243) 5f <sup>7</sup> 7s <sup>2</sup>	96 Cm 锔 (247) 5f <sup>7</sup> 6d <sup>1</sup> 7s <sup>2</sup>	97 Bk 锫 (247) 5f <sup>9</sup> 7s <sup>2</sup>	98 Cf 锿 (251) 5f <sup>10</sup> 7s <sup>2</sup>	99 Es 镱 (252) 5f <sup>11</sup> 7s <sup>2</sup>	100 Fm 镆 (257) 5f <sup>12</sup> 7s <sup>2</sup>	101 Md 镎 (258) 5f <sup>13</sup> 7s <sup>2</sup>	102 No 镎 (259) 5f <sup>14</sup> 7s <sup>2</sup>	103 Lr 铷 (262) 5f <sup>14</sup> 6d <sup>1</sup> 7s <sup>2</sup>

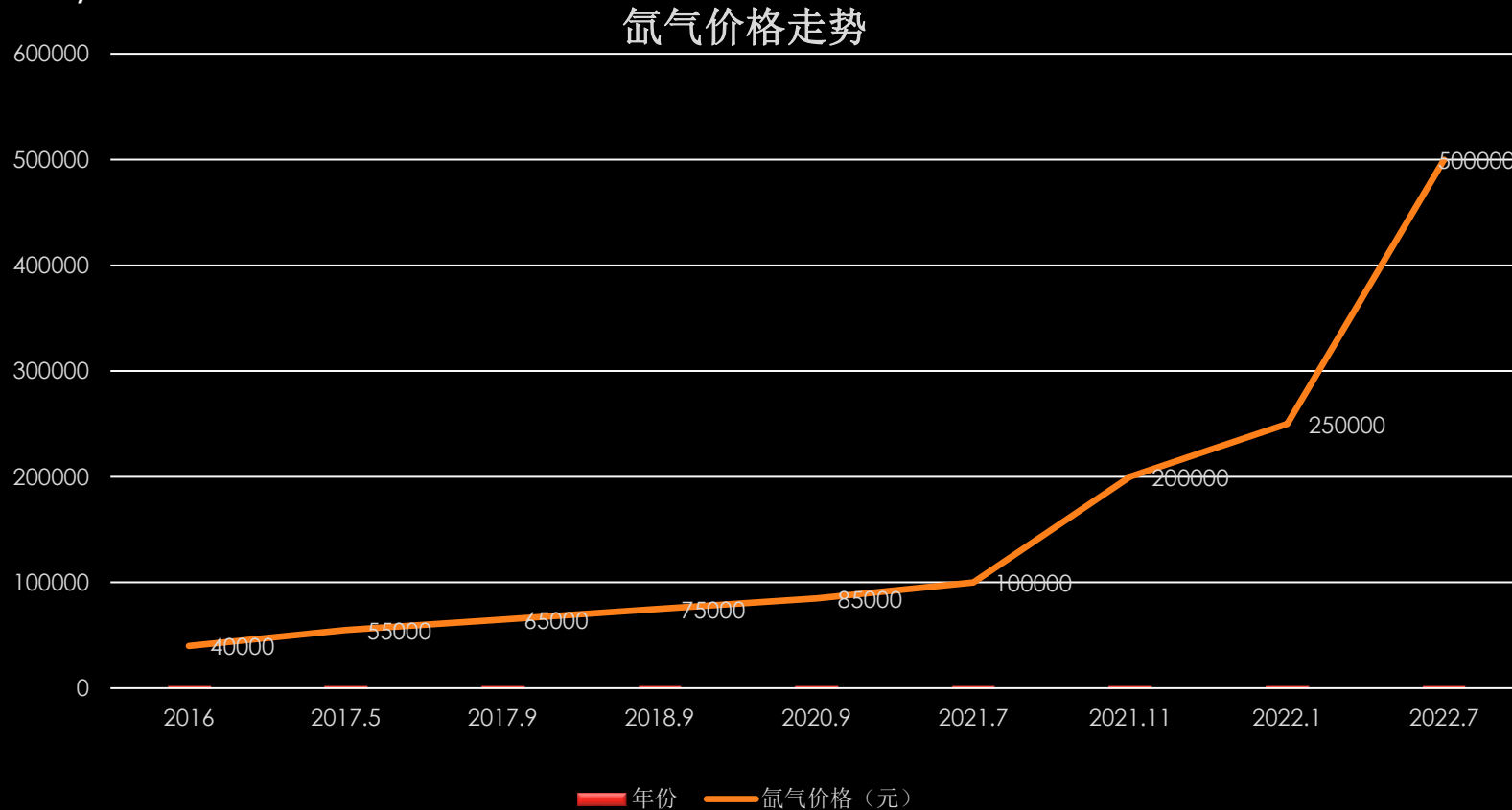
注: 相对原子质量录自2001年  
国际原子量表, 并全部取4位有  
效数字。

- Density: 3 g/cc (L), 6 g/l (G)
- Radiation length: 8.5 g/cm<sup>2</sup> 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

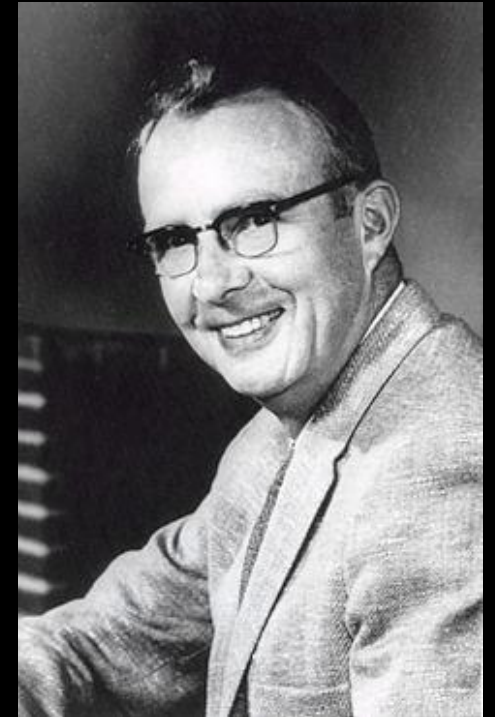
Unit: RMB/m<sup>3</sup>



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, ...)



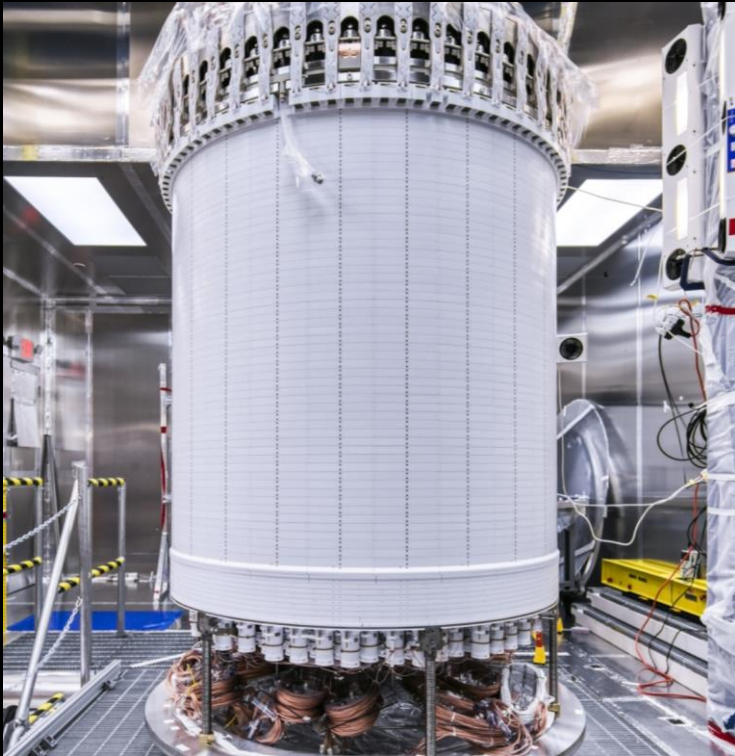
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 51, NO. 5, OCTOBER 2004

## Proportional Light in a Dual-Phase Xenon Chamber

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



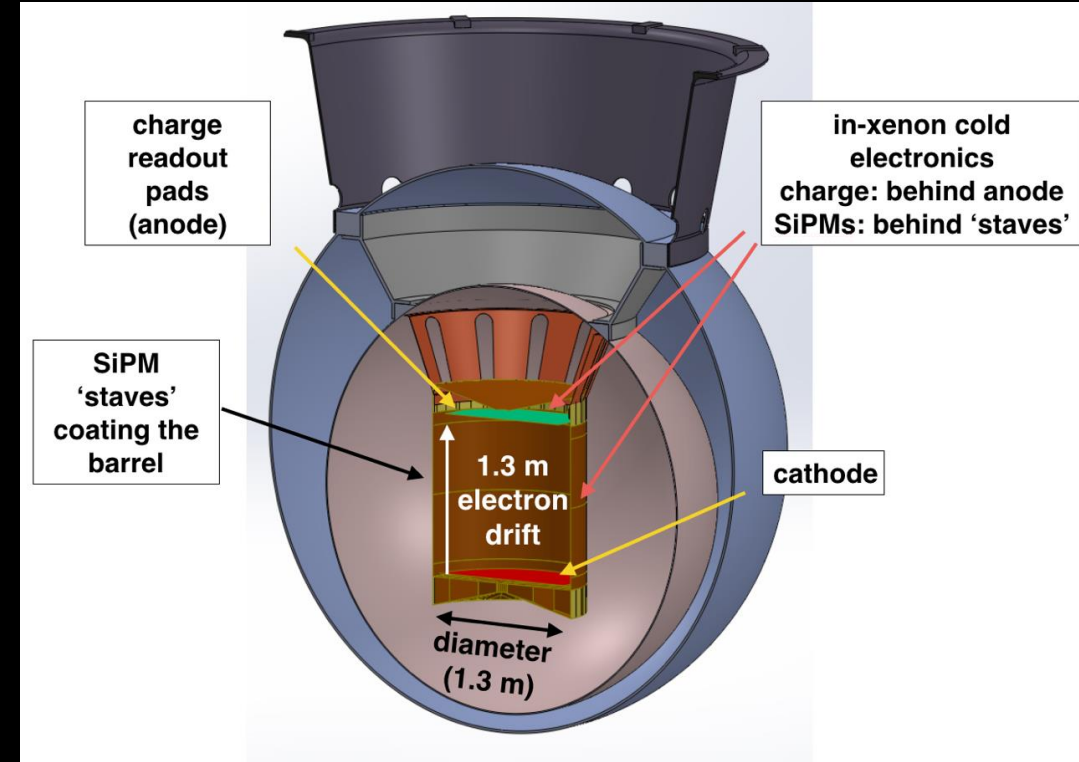
# Variety of xenon detectors in DM and 0νDBD experiments



LZ, 7-ton, Sanford Lab, 2020

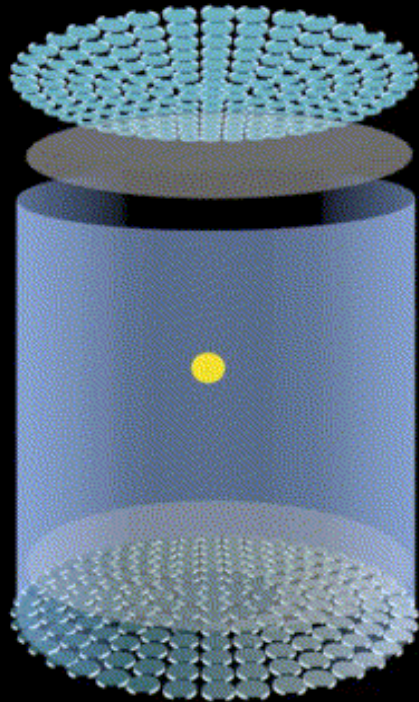
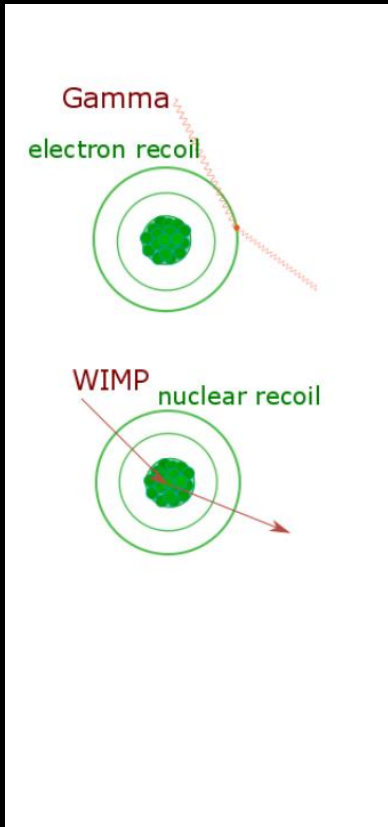


XMASS, 800 kg, Kamioka, joined XENON

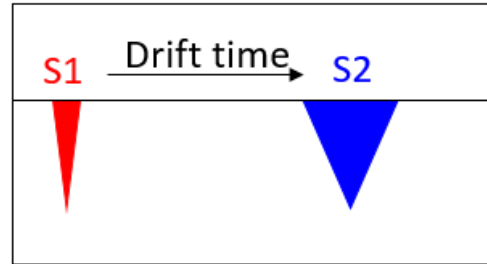


nEXO, 5 ton enriched  $^{136}\text{Xe}$ , liquid TPC

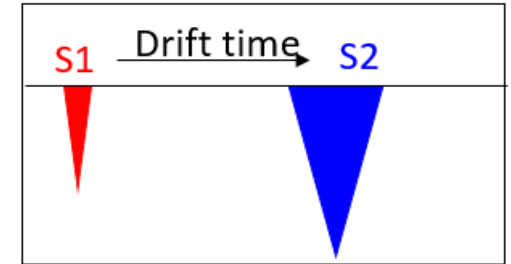
# Dual phase Xe TPC



Dark matter: nuclear recoil  
(NR)

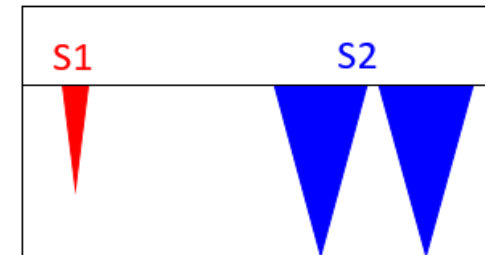


$\gamma$  background: electron recoil  
(ER)



$$(S2/S1)_{NR} \ll (S2/S1)_{ER}$$

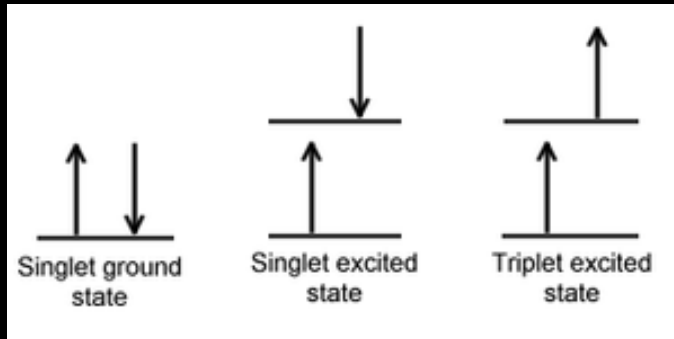
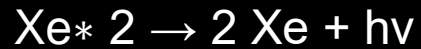
Multi-site scattering  
background (ER or NR)



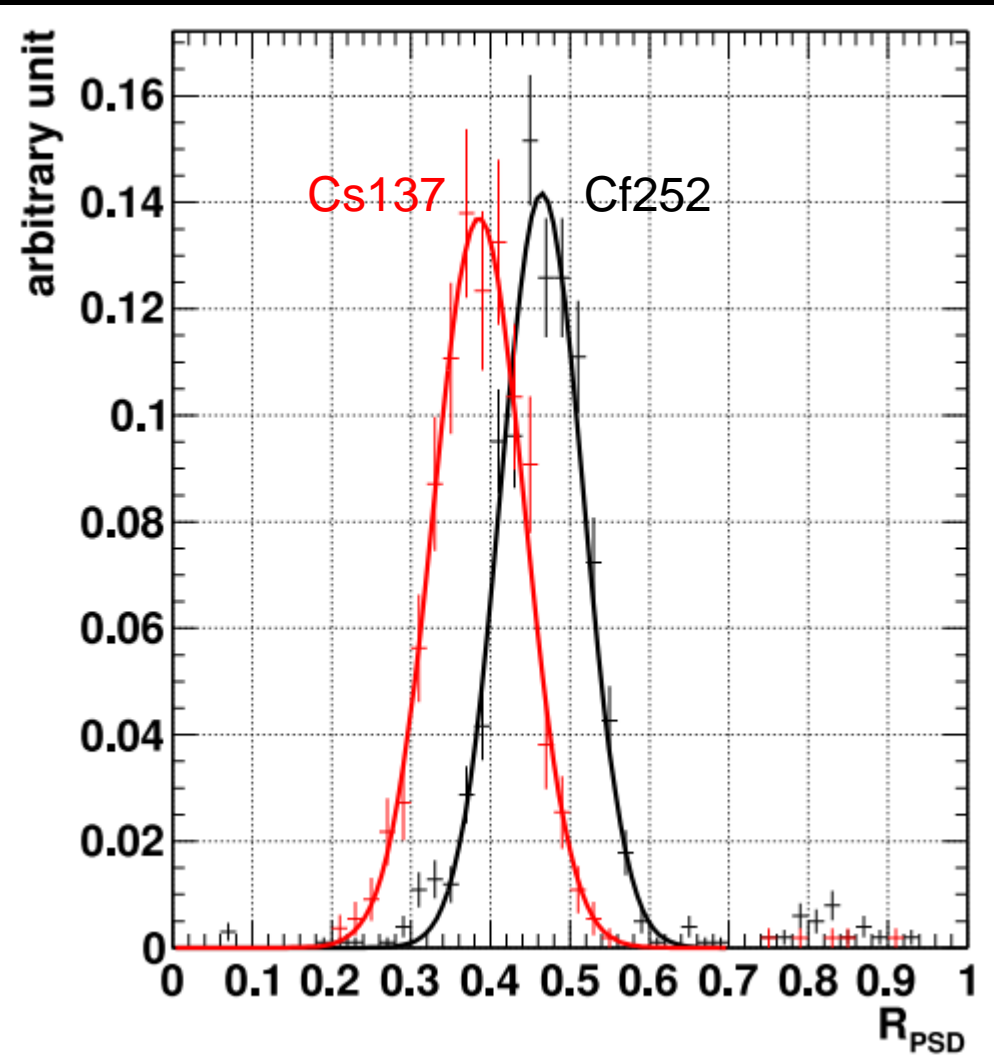
# Scintillation signals

1106.2209, XMASS

3 ns/22 ns for the single/triplet states

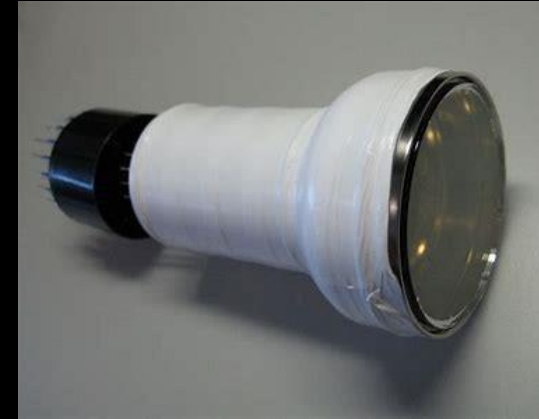


Some particle ID capability, but gets smeared by TTS, ToF, bandwidth, electronics resolution, etc.

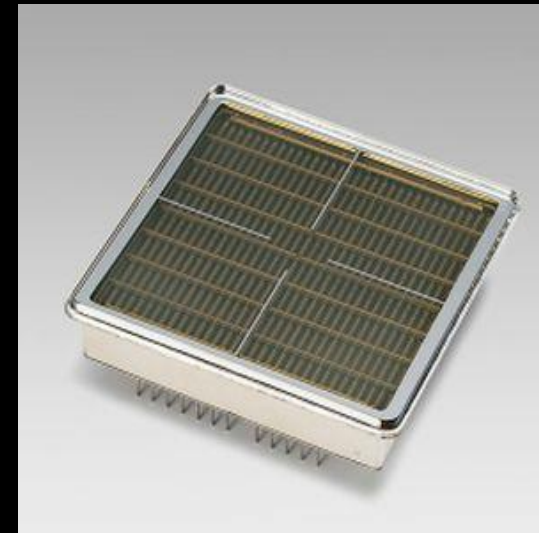


# Possible photosensor options

- 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



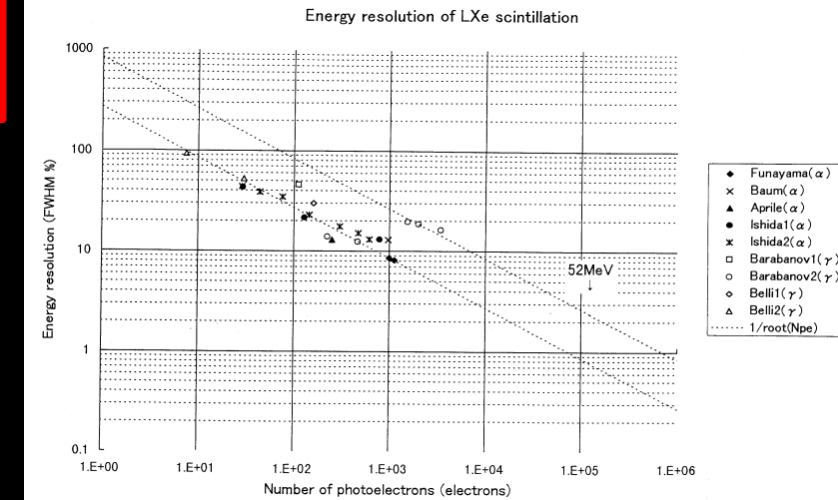
TTS ~ ns



# Liquid TPC vs. spherical in DM and 0νDBD

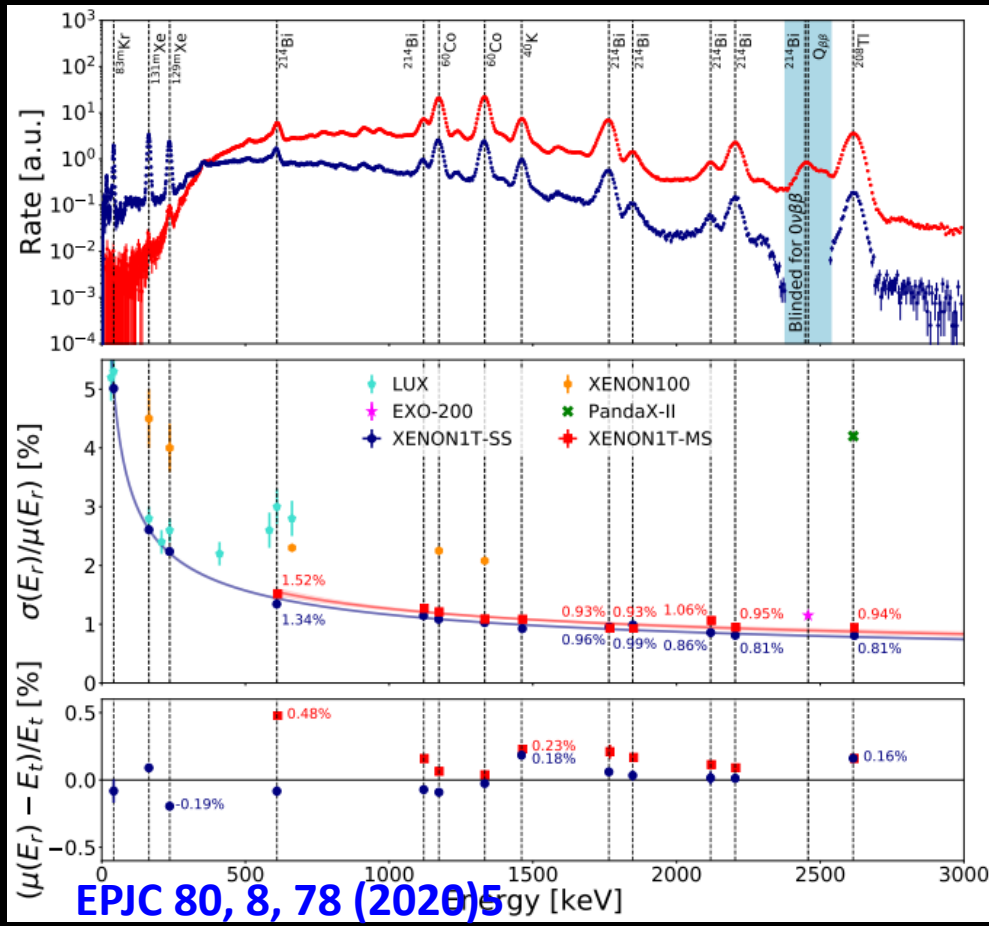
	TPC	Spherical
Scaling up	Challenging	Easy
DM position reconstruction	Good (cm)	Bad, leakages into FV
DM background	Good (99.5% rejection of ER background)	Bad, some pulse shape discrimination for ER
Light yield	~5 PE/keV but with ionization electrons	14 PE/keV (XMASS)
Energy resolution (2.5 MeV)	1% (XENON1T)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

Doke & Masuda

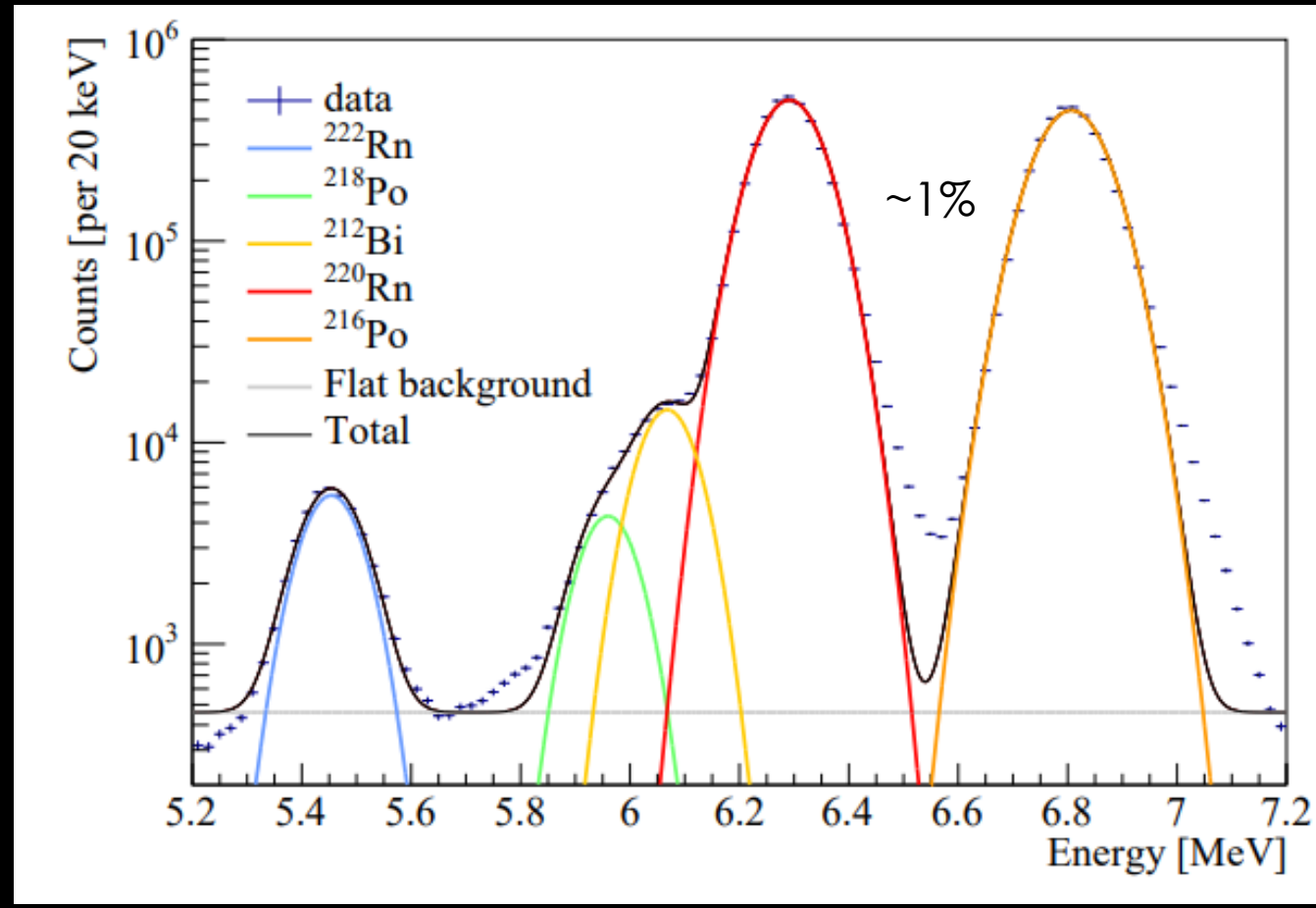


# Energy resolution in PandaX

XENON1T

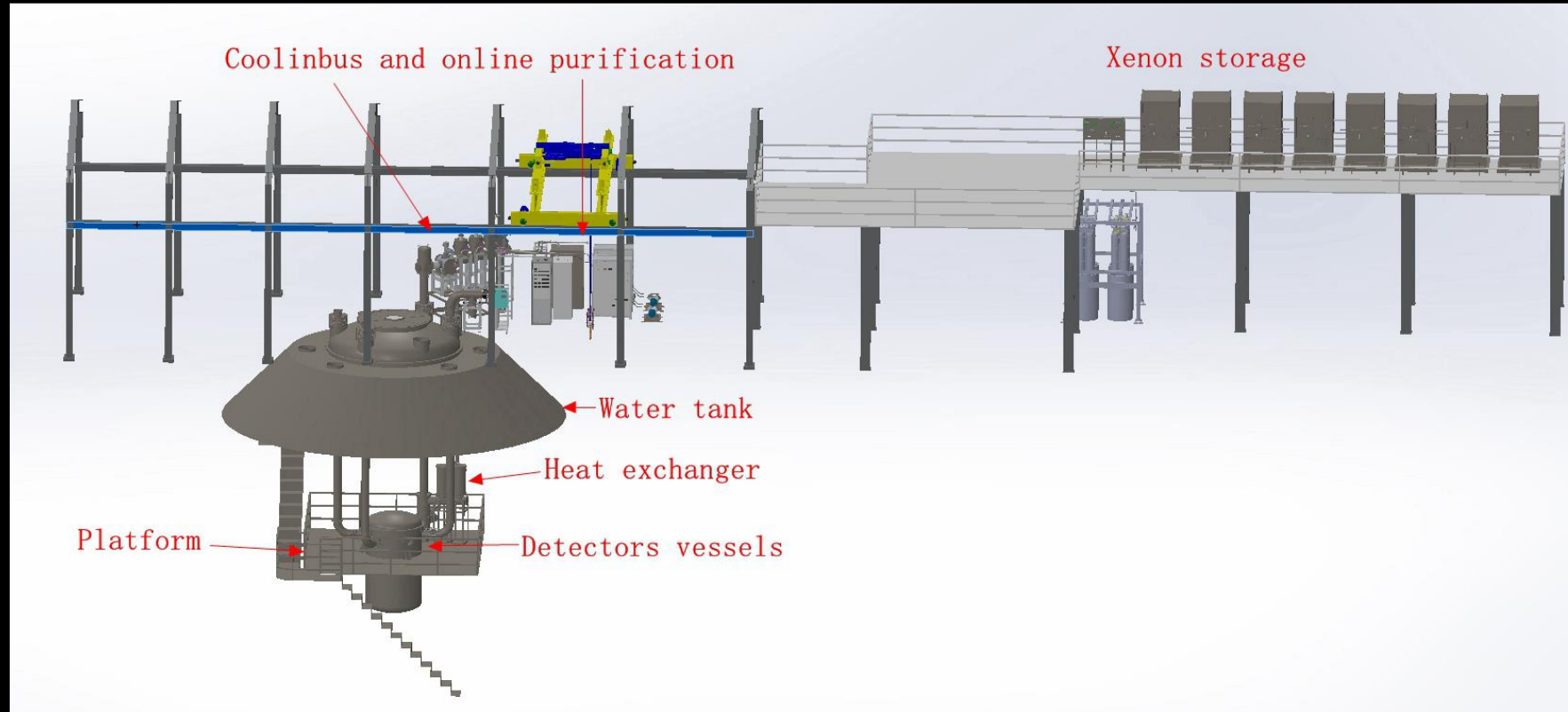


PandaX-II, 2006.09311



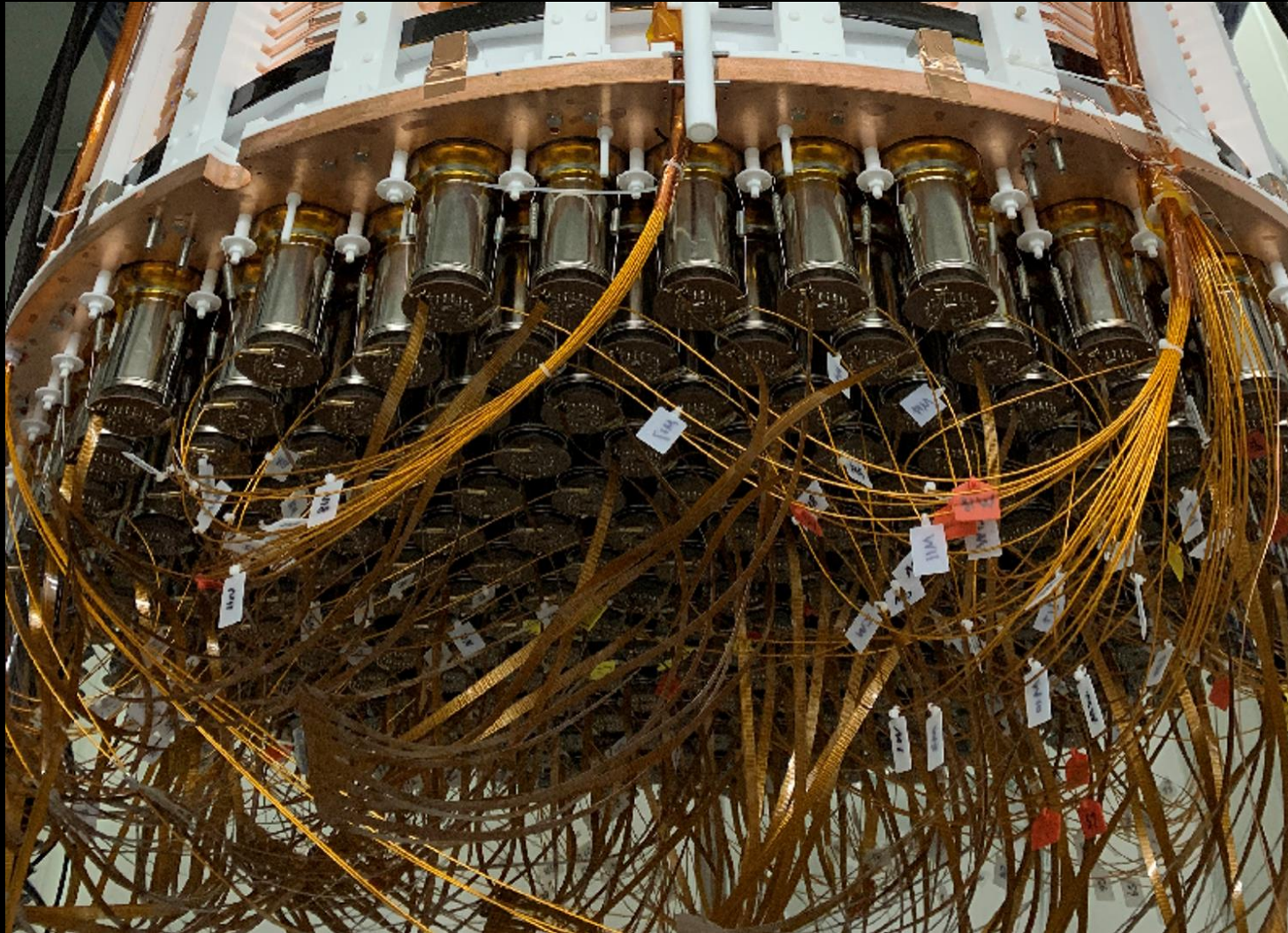
- Uniformity calibration achieved via internal Rn222 & Rn220 decays
- De-saturation correction important (for position reconstruction, then energy correction)

# Key ingredient



- 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

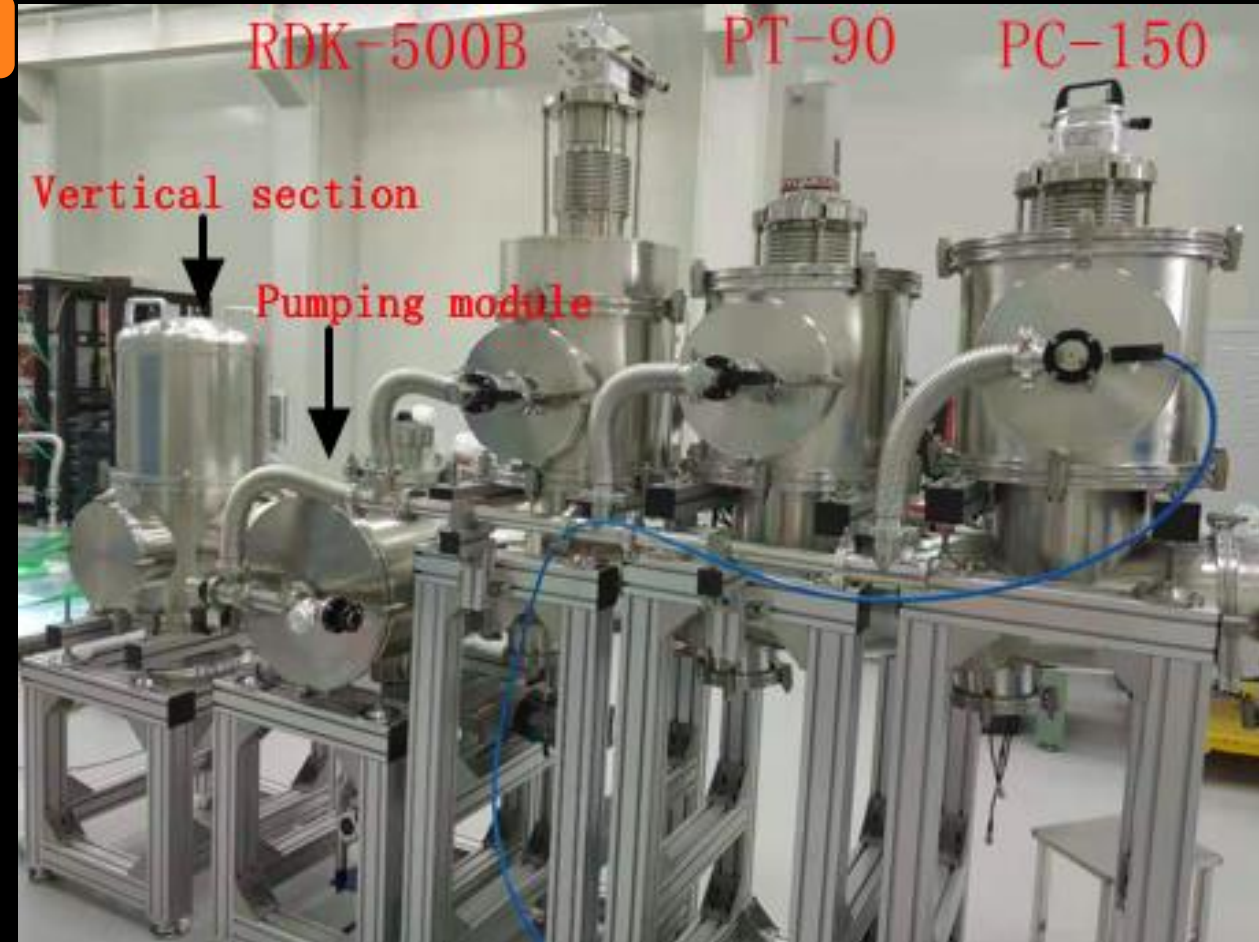
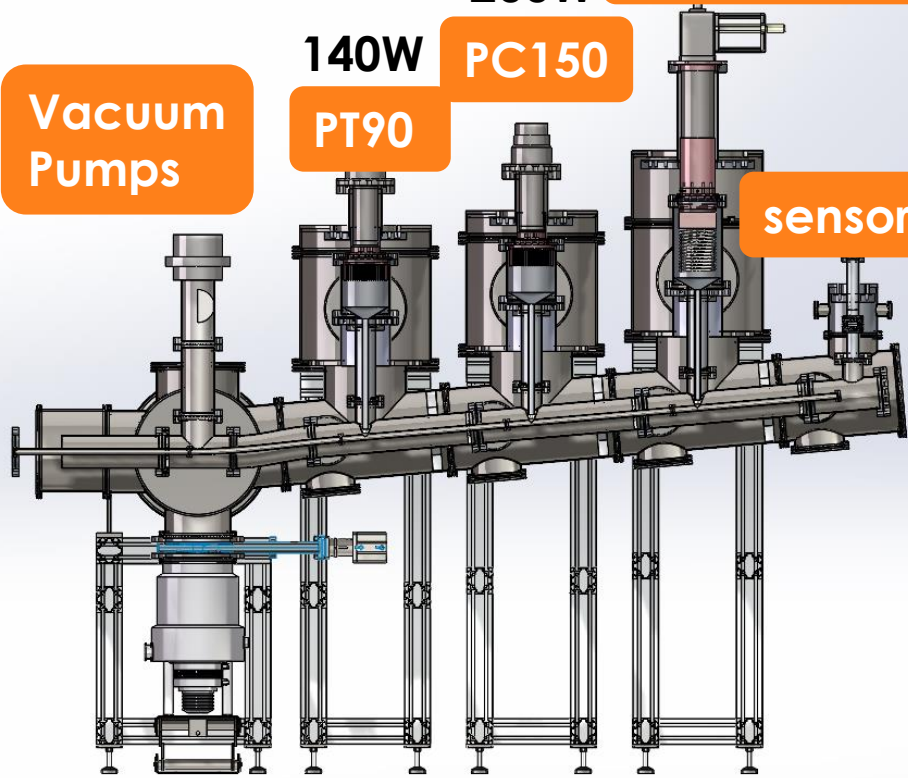
PC150

140W

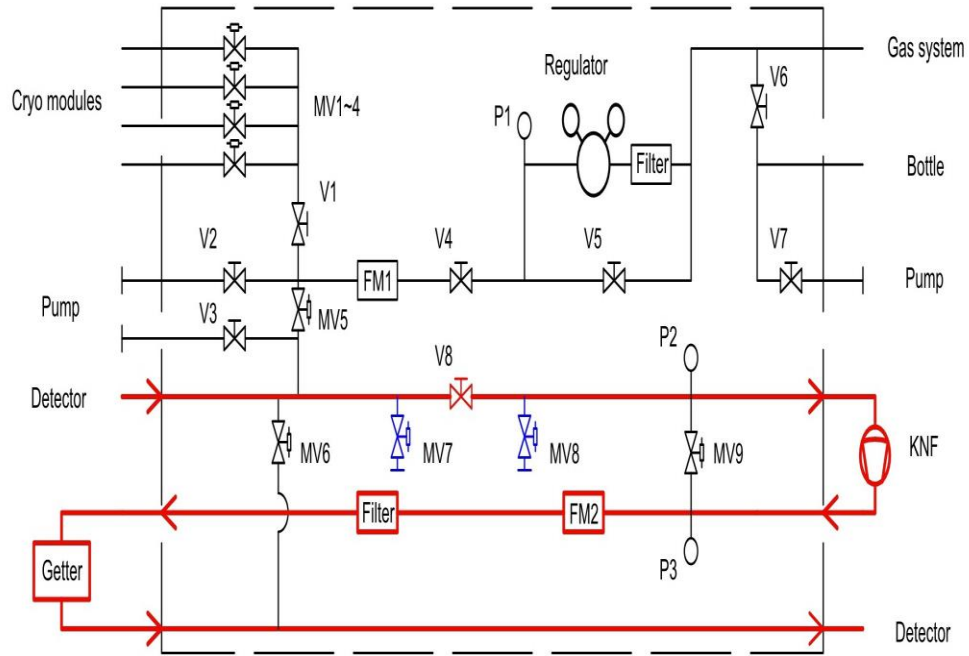
PT90

Vacuum Pumps

sensors



# Re-circulation and purification



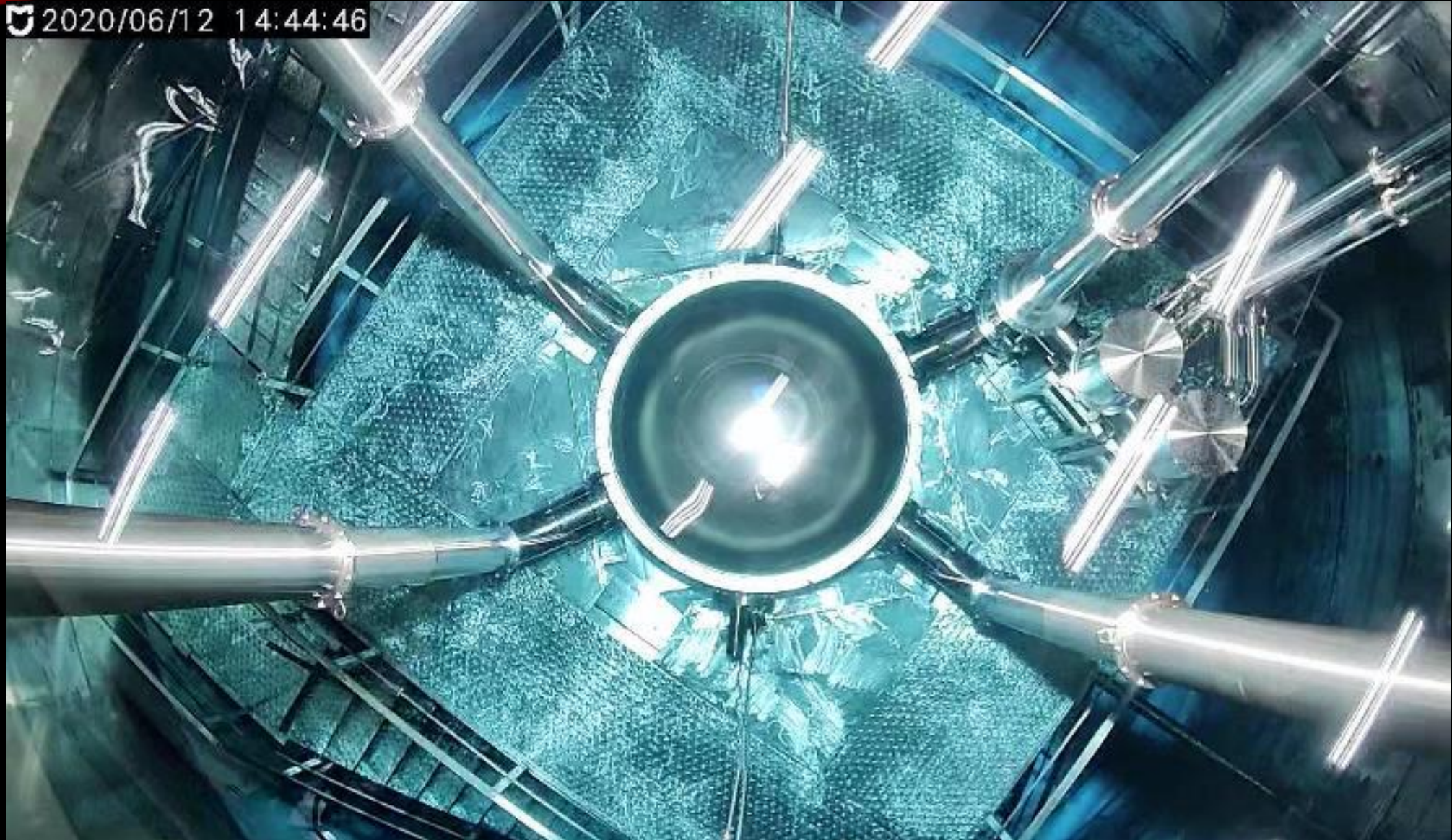
- Circulation speed achieved, 100 slpm (loop 1, SAES PS5-MGT50-R-909), 30 slpm (loop 2, Simpure 9N300-R), ~1 ton/day
- Heat exchanger efficiency: 97.5%

# Overall system



# Detector in operation

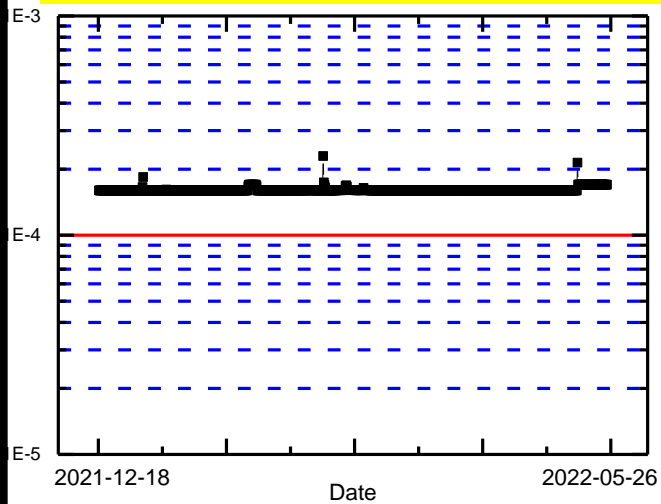
2020/06/12 14:44:46



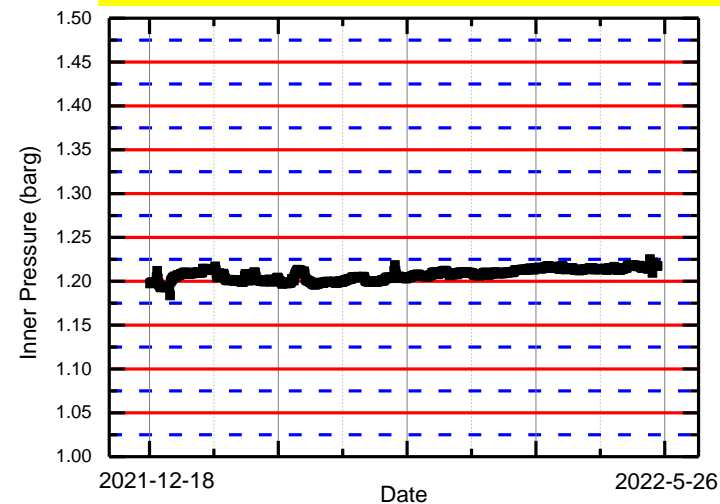


# Performance

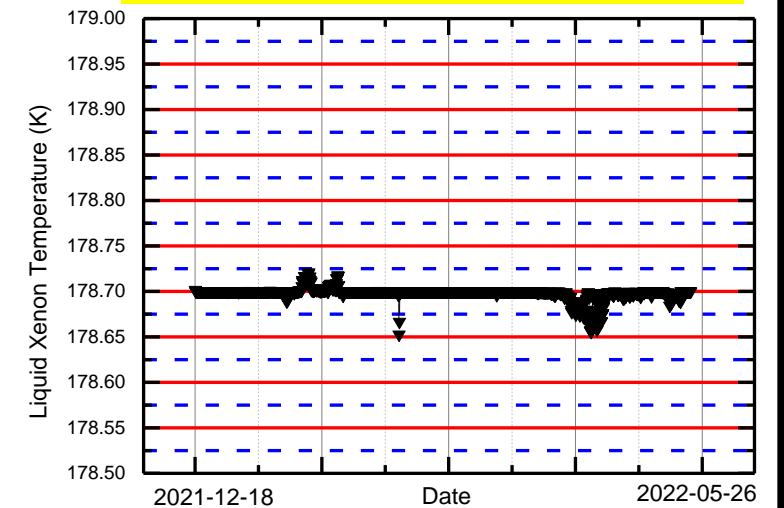
**Outer vacuum of PandaX-4T**



**Inner pressure of PandaX-4T**



**Temperature of liquid Xenon**

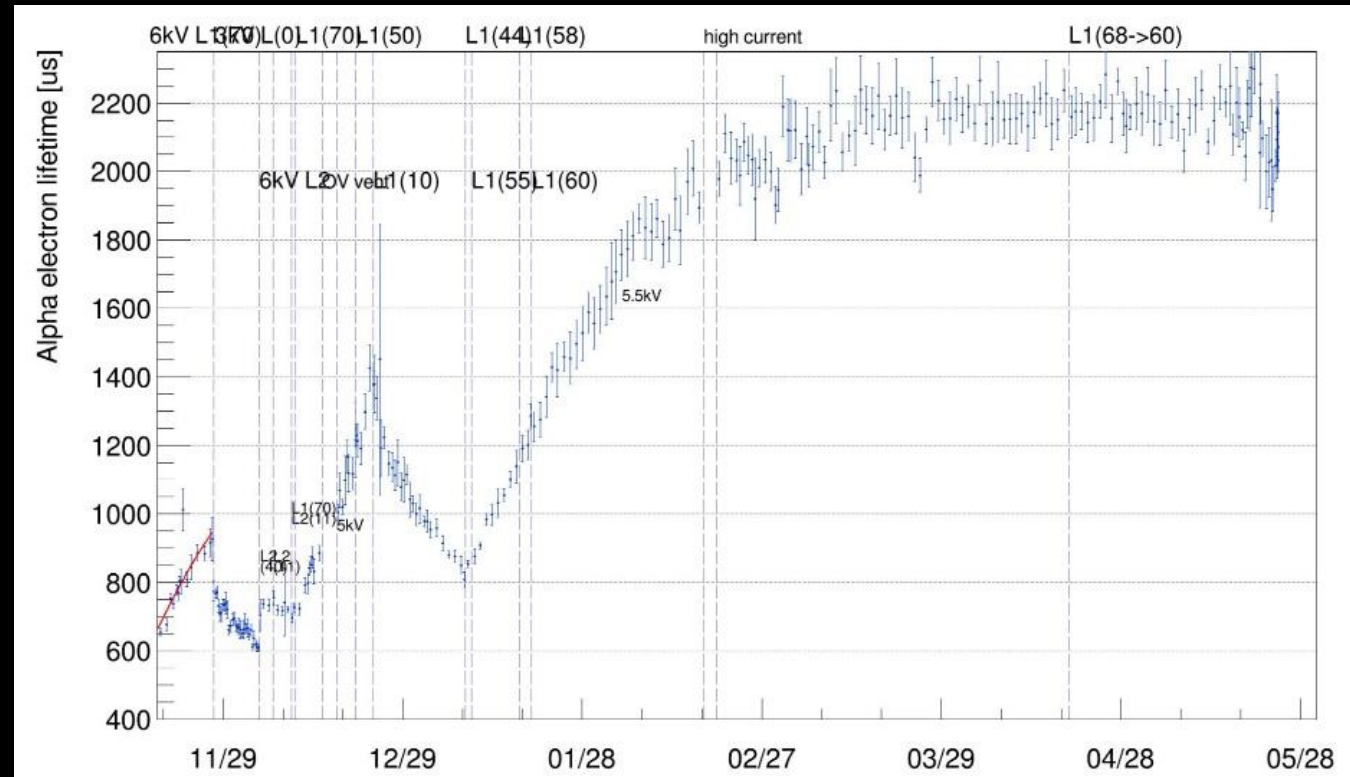


Parameters	Static Heat	Outer vacuum	Fluctuation of P_Xe	Fluctuation of T_Xe
Value	~90 W	<3.0E-4 Pa	< 0.05 bar	< 0.1 K

# Photon/electron transparency

- Pumping for 2 weeks before filling
- Filling the detector (LN2 assistant cooling)
- Two kinds of outgassing impurities
  1. H<sub>2</sub>O: photon transparency
    - MEG: 100 ppb ~ 1 m
    - Normally we achieve good photon transparency in 1-2 weeks after recirculation
  2. N<sub>2</sub>/O<sub>2</sub>: electron transparency
    - Electron lifetime of 1 ms ~O<sub>2</sub>-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 maintenance
  - 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	Nal:TI	CsI:TI	CsI	BaF <sub>2</sub>	CeF <sub>3</sub>	PbF <sub>2</sub>	BGO	BSO	PbWO <sub>4</sub>	LYSO:Ce	AFO Glasses	Sapphire:Ti
Density (g/cm <sup>3</sup> )	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 <sub>0</sub> (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 <sub>M</sub> (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 <sub>1</sub> (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 <sub>eff</sub>	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 <sub>peak</sub> <sup>a</sup> (nm)	410	560	420 310	300 220	340 300	\	480	470	425 420	420	365	750
Refractive Index <sup>b</sup>	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 <sup>a,c</sup>	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 <sup>a</sup> (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

# 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:  $2 \times 10^4$  cc / month using Iridium oven and crystal pulling method**

# Price driver

Biggest driver is the price of Iridium

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

Second is the cost of  $\text{Lu}_2\text{O}_3$

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

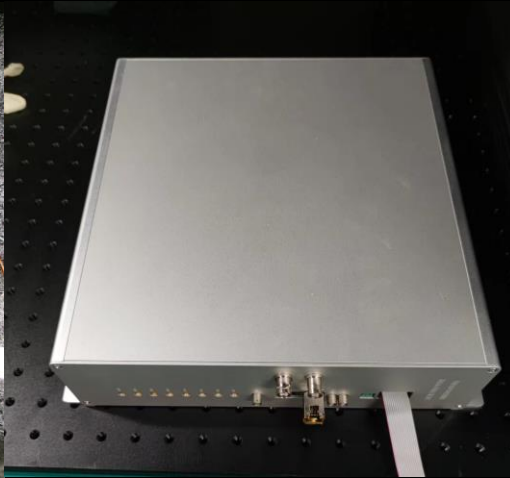
# Other commercial companies

- 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  
(2108.11804)

