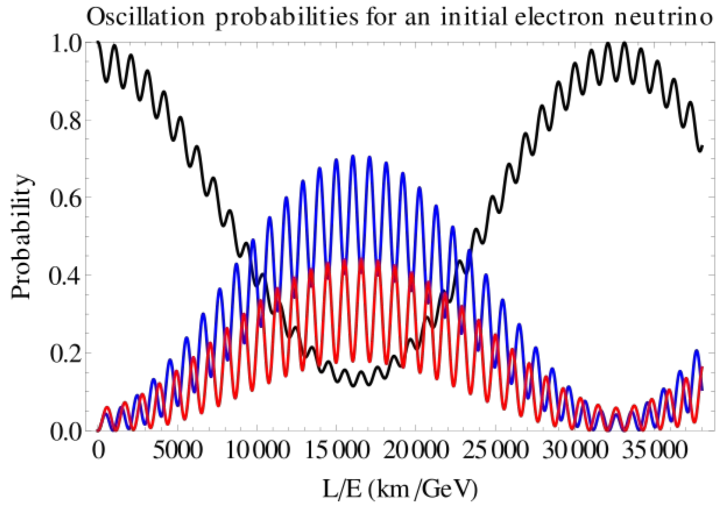
NνDEx Experiment

Hao Qiu

Institute of Modern Physics, CAS

Neutrinos



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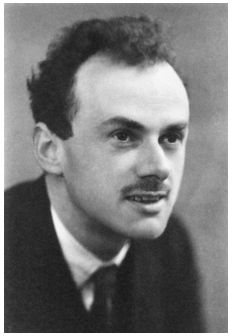

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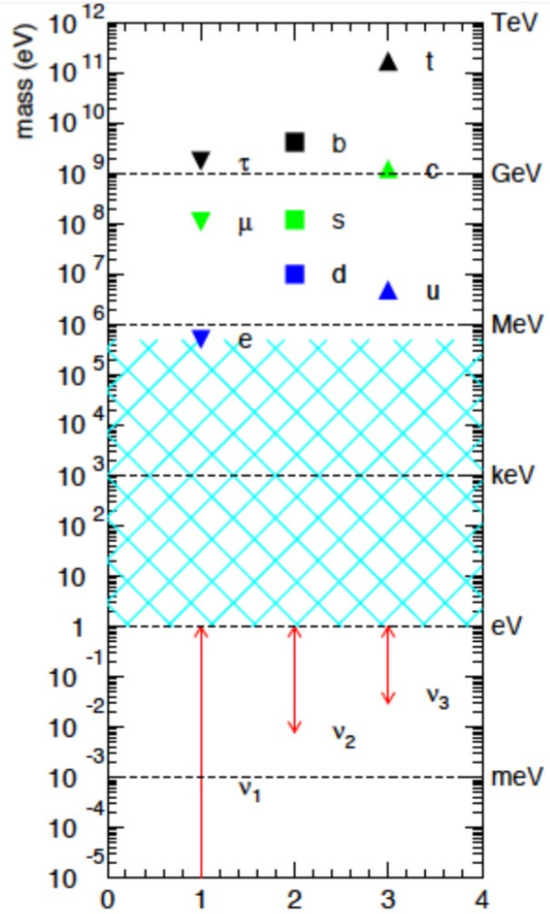
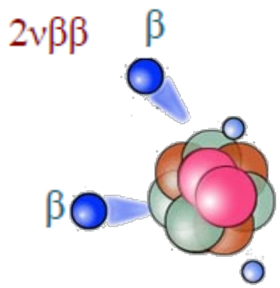
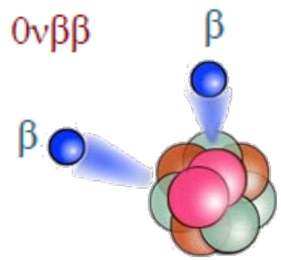


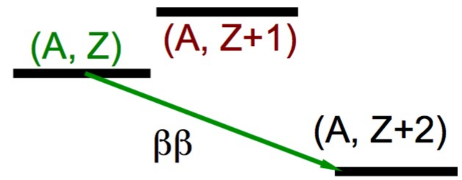
- Neutrinos oscillate ⇒ they have finite mass ⇒ beyond Standard Model
- Could be Majorana or Dirac fermions (could be their own anti-particle)
- Have "unnaturally" tiny mass

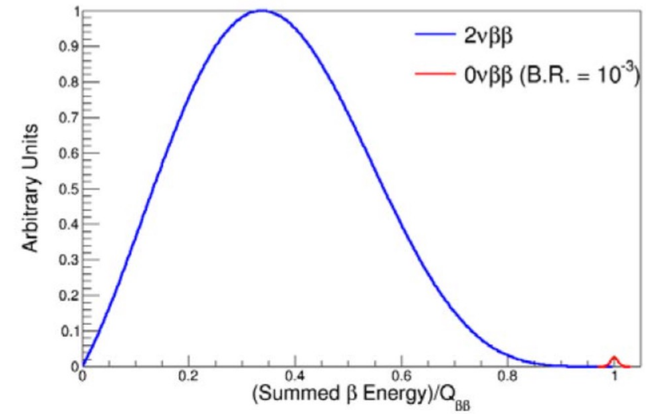
⇒ Could be a key to new physics beyond Standard Model

0νββ Decay



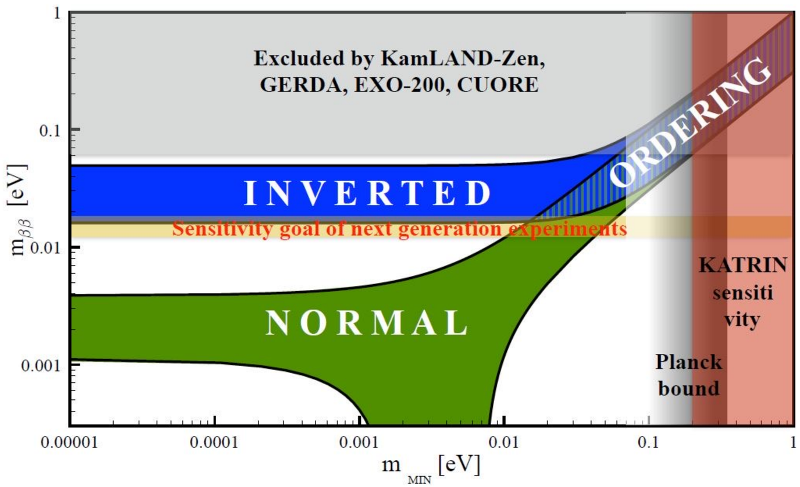


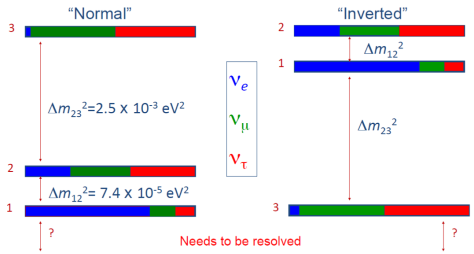


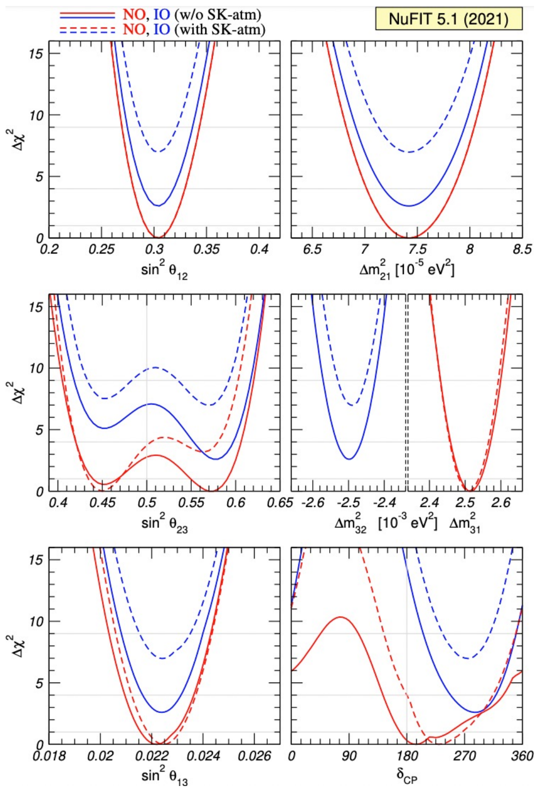


- Unstable nuclei may undergo ββ decay if single β-decay is energetically forbidden
- If 0νββ decay is observed, it
  - will prove that ν is a Majorana particle ⇒ beyond Standard Model
  - may explain the finite but tiny ν masses, by see-saw mechanism with an extended Standard Model
  - will constrain absolute ν mass, and ν mass hierarchy
  - may explain matter-antimatter asymmetry in the universe, since it violates CP symmetry and lepton number conservation

0νββ Decay Experiment Sensitivity







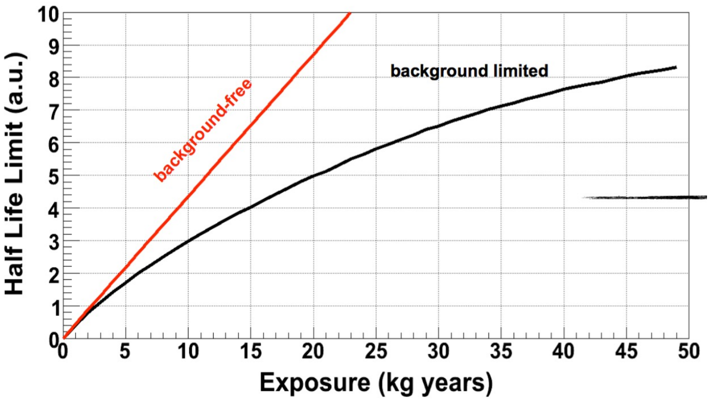
- Inverted hierarchy: $m_{\beta\beta}$ >~10 meV, goal of next generation experiments
- Normal hierarchy: $m_{\beta\beta}$ >~1 meV, 1 order of magnitude lower than inverted hierarchy
- Both current oscillation experimental results and physics naturalness slightly prefer normal hierarchy

Half Life & $m_{\beta\beta}$ sensitivity

$$\frac{1}{T^{0\nu}_{\beta\beta}} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

0 background case: $T^{0\nu}_{1/2}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{MT}{n_{CL}}$

high background case: $T^{0\nu}_{1/2}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$

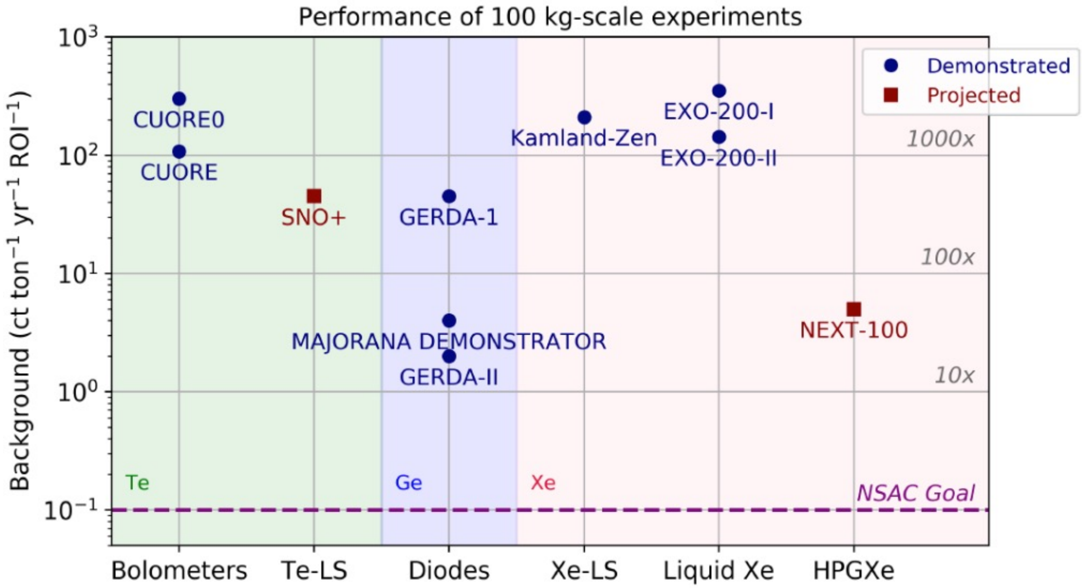


- Reducing bΔE is the key to use decay isotopes (funding) effectively and increase experiment sensitivity
- For the case of 0 background, $m_{\beta\beta}$ sensitivity ∝ $(MT)^{-1/2}$
- For the case of high background, $m_{\beta\beta}$ sensitivity ∝ $(MT)^{-1/4}$
  - 1-t for normal hierarchy → 10k t for inverted hierarchy

    same background level

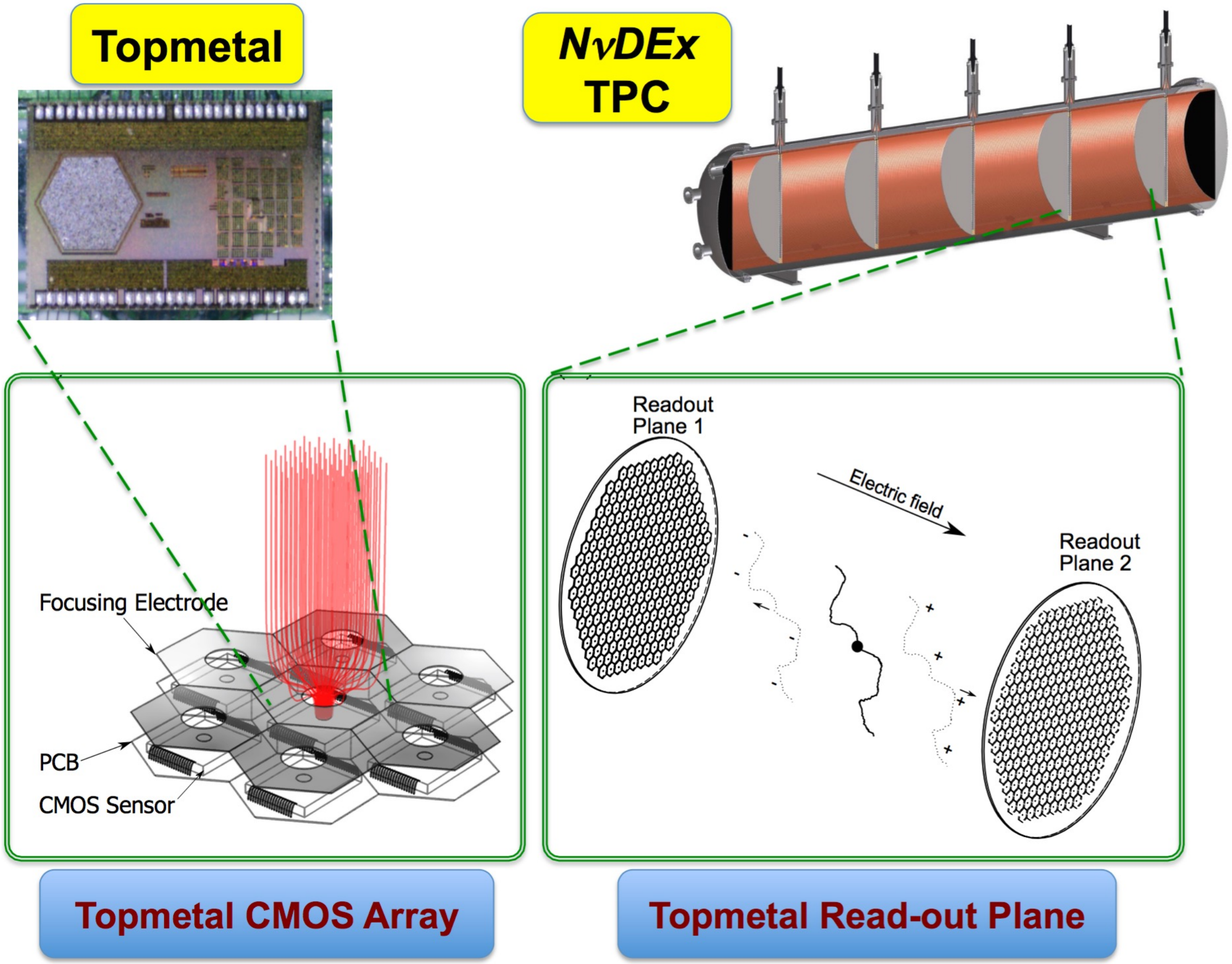
Background Level Needed
-for a Cost-effective Experiment

"100kg-class" experiments:



- For ~0 background experiments, $T_{1/2}$ ~ 10^{29} yr ⇒ ~several 10 ton yr exposure
- ⇒ In order to use the isotopes (funding) efficiently, we need background level of ~< 0.1 ct / ton yr ROI ⇒ the goal set by U.S. NSAC
- Most of current experiments are >= 1 order of magnitude away from this goal

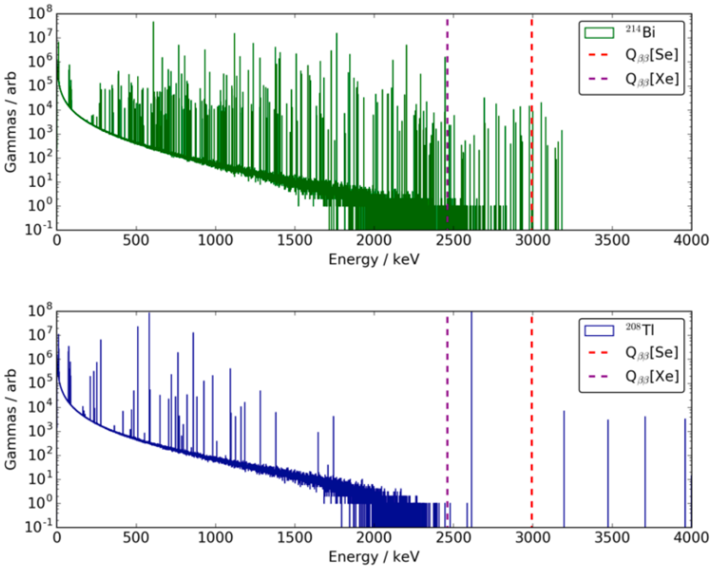
NνDEx Concept



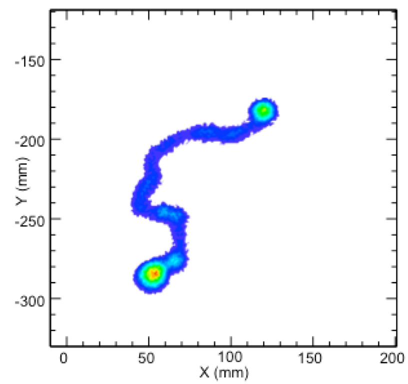
- High pressure $^{82}SeF_6$ gas TPC, with direct read-out by topmetal CMOS sensors

D.R. Nygren, Y. Mei et al 2018 JINST 13 P03015

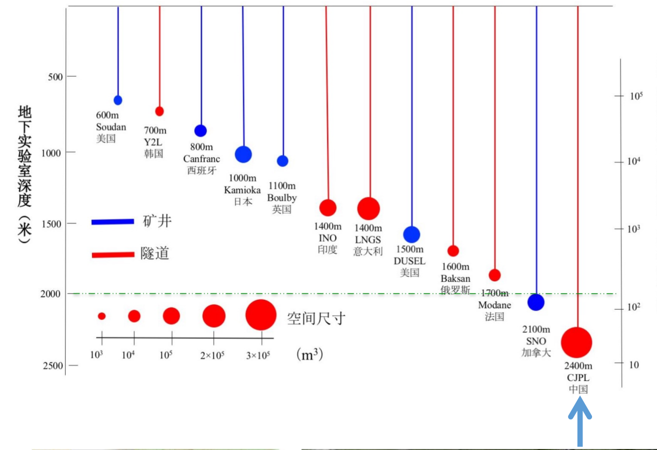
NνDEx Advantages

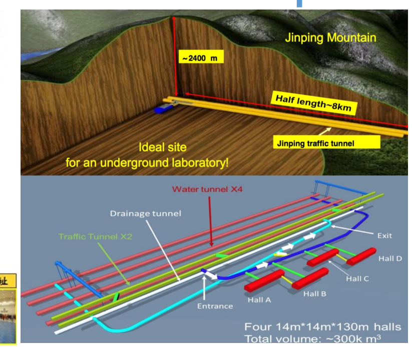


γ background energy spectra from natural radiations



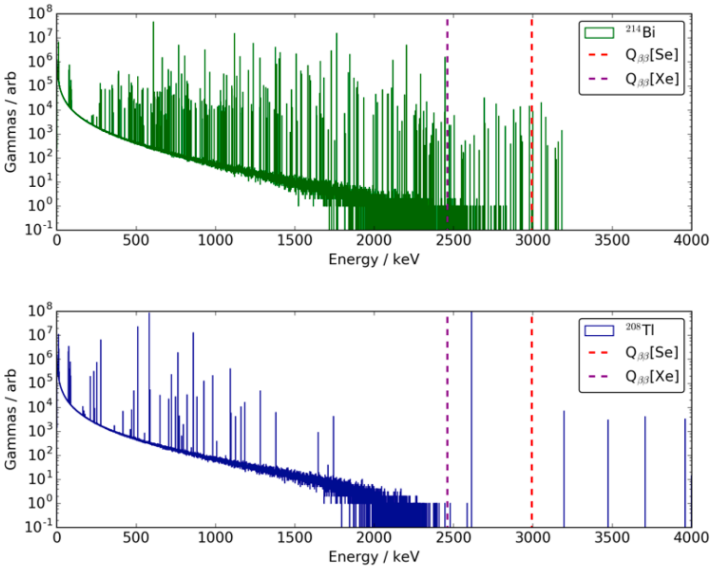
energy deposition for a 0νββ event





- NνDEx's advantages for low background
  - High Q value of ^{82}Se (2.996 MeV) – above most natural radiation background
  - Distinguish signal and background with event topology by TPC
  - Better energy resolution without avalanche amplification (~1% FWHM)
  - CJPL - deepest underground lab

NνDEx Advantages



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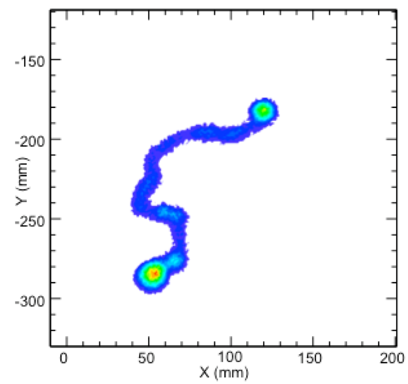
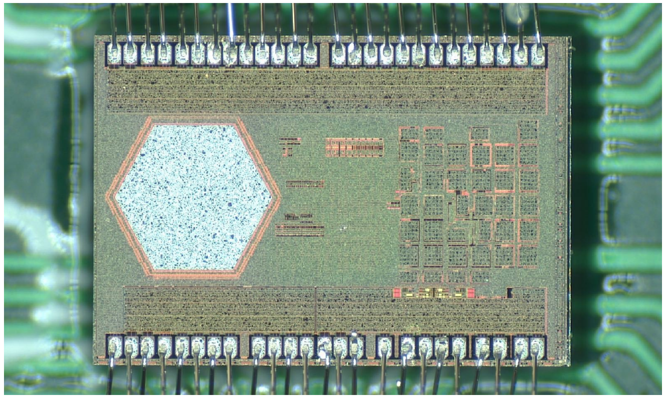


energy deposition for a 0νββ event

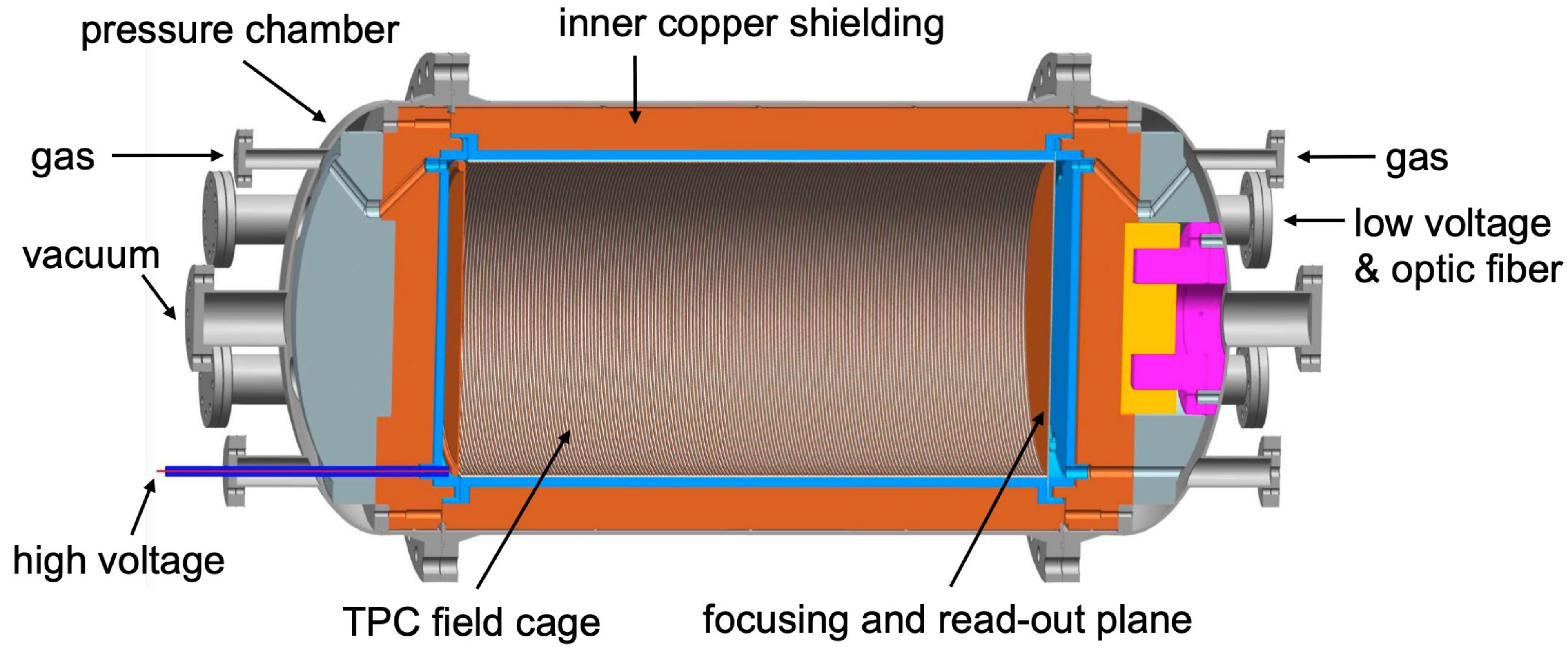


Topmetal-S silicon sensor

PLAC Pixel Laboratory at CCNU

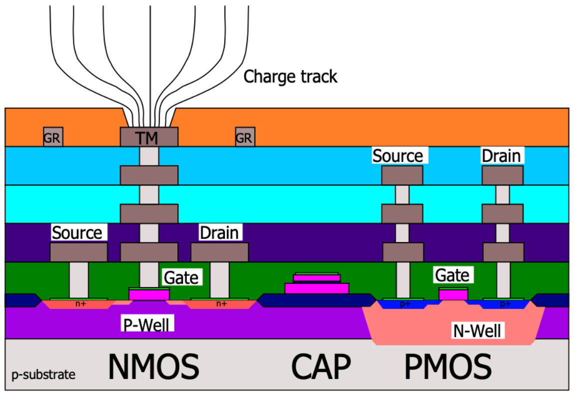
- SeF_6 is electronegative. Amplification by electron avalanche is not possible with it.
- The combination of advantages from the high Q value of ^{82}Se and TPC's ability to see event topology, is only possible with low-noise direct charge read-out.
- Topmetal-S sensor, specifically for 0νββ detection, is made by Pixel Lab of CCNU.

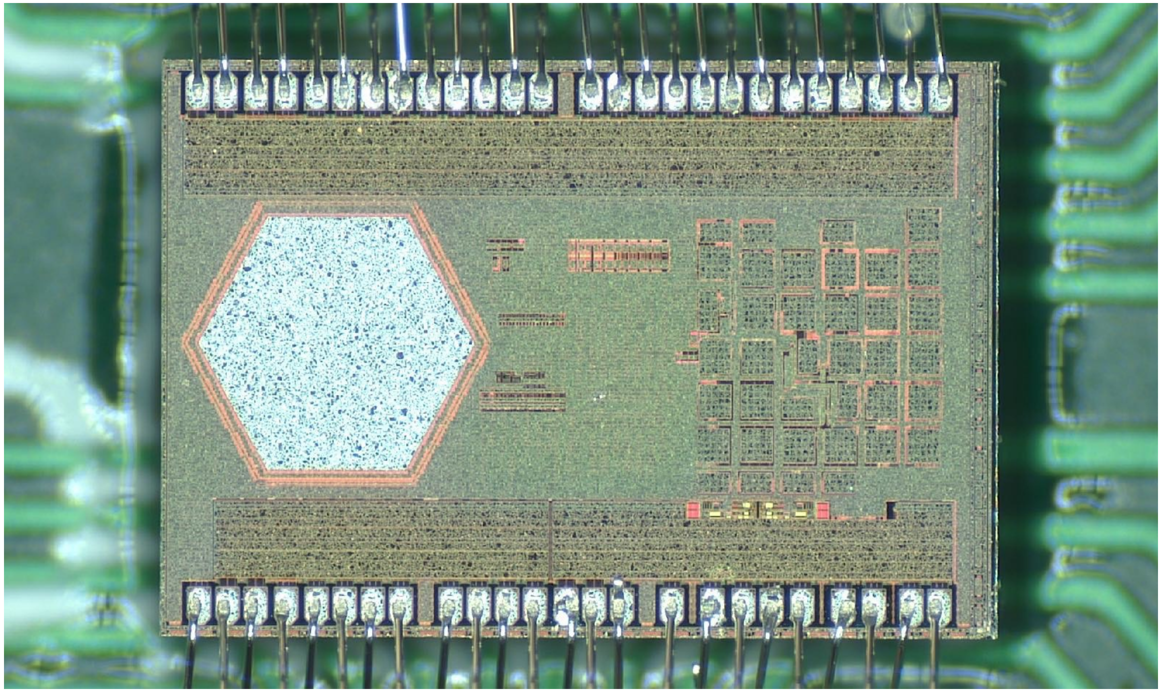
NνDEx-100



- NνDEx-100 is being built, with 100kg SeF_6 gas at 10 atm in the sensitive volume
- CDR finished, accepted for publication by NST arXiv:2304.08362
- Chinese version of CDR submitted to CJPL

Topmetal-S Sensor

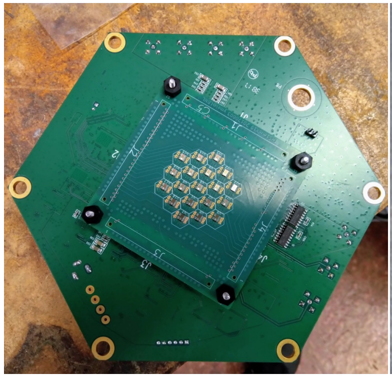
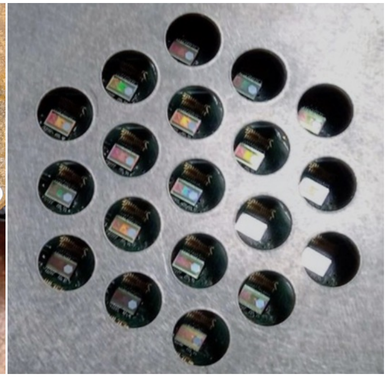
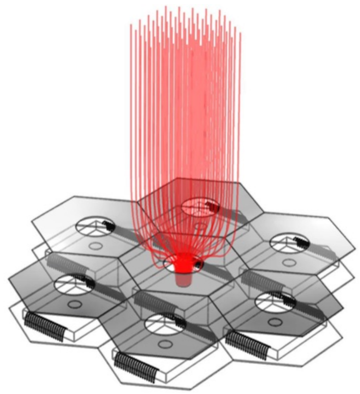


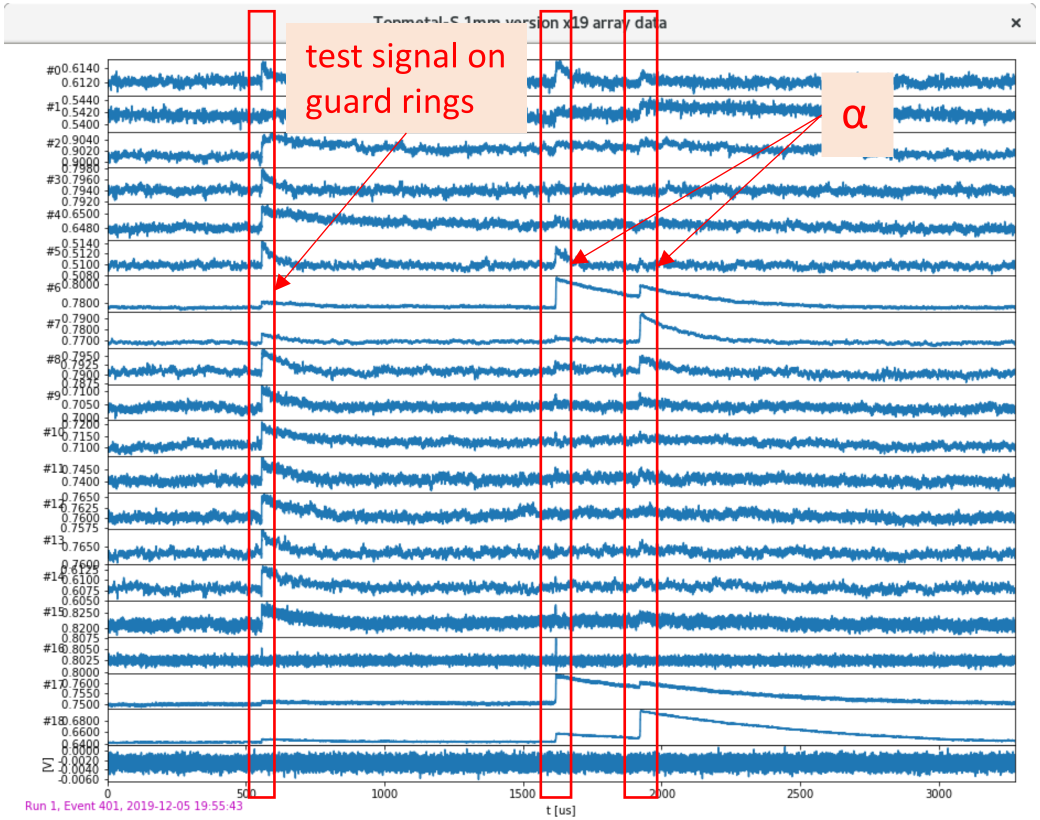


2mm × 3mm

- The key technology for NνDEx to come true
- Noise ~<45e⁻ expected, important to achieve ~1% FWHM energy resolution
- Two tapeouts have been conducted, the 3rd tapeout is being produced

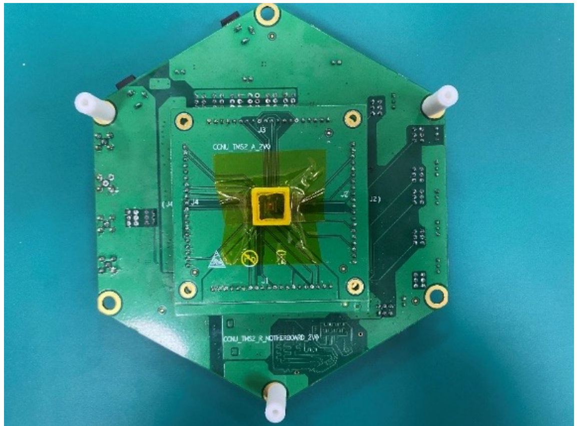
Array of 19 Topmetal-S Sensors (1st)

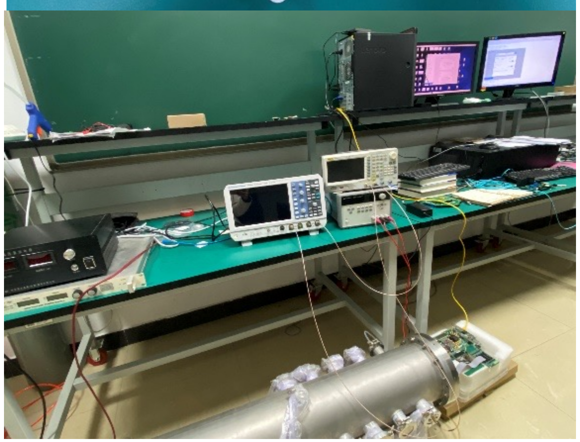




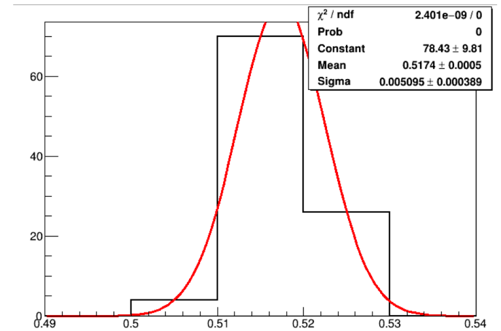


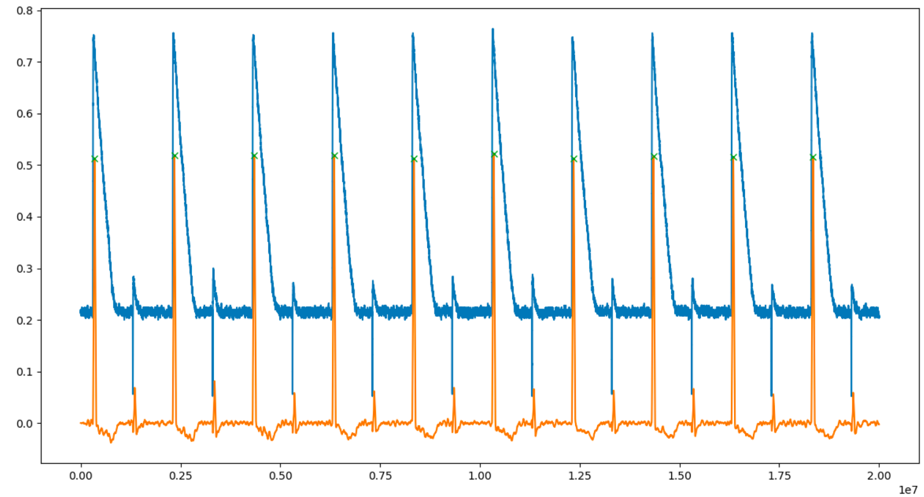
- An array of 19 Topmetal-S sensors (1st tapeout) was tested with ^{241}Am α source
- Signals from the α source observed, but the magnitude is only 5% of expected value
- The magnification in the CSA is not high enough, because the bias voltage cannot work stably when the magnification is increased

Electrical Test of Topmetal-S Sensors (2st)



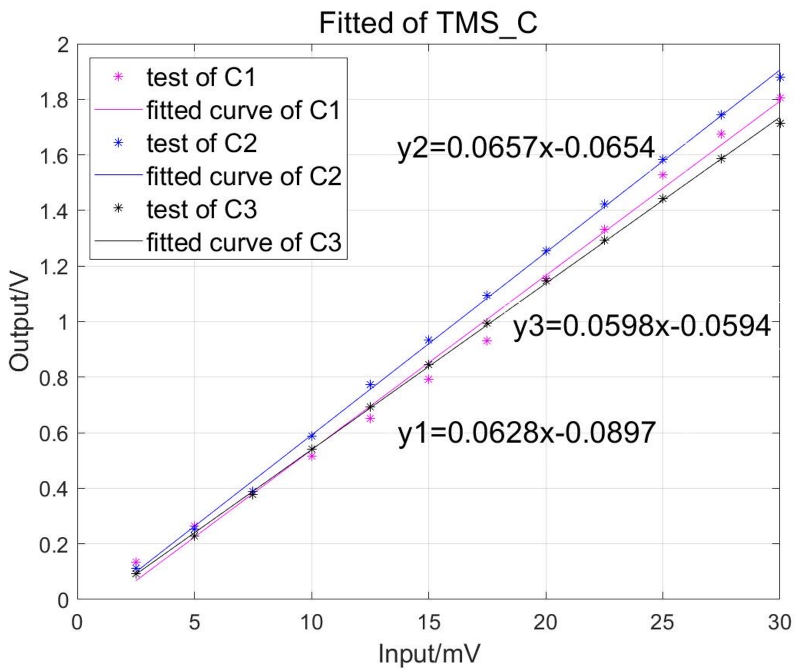


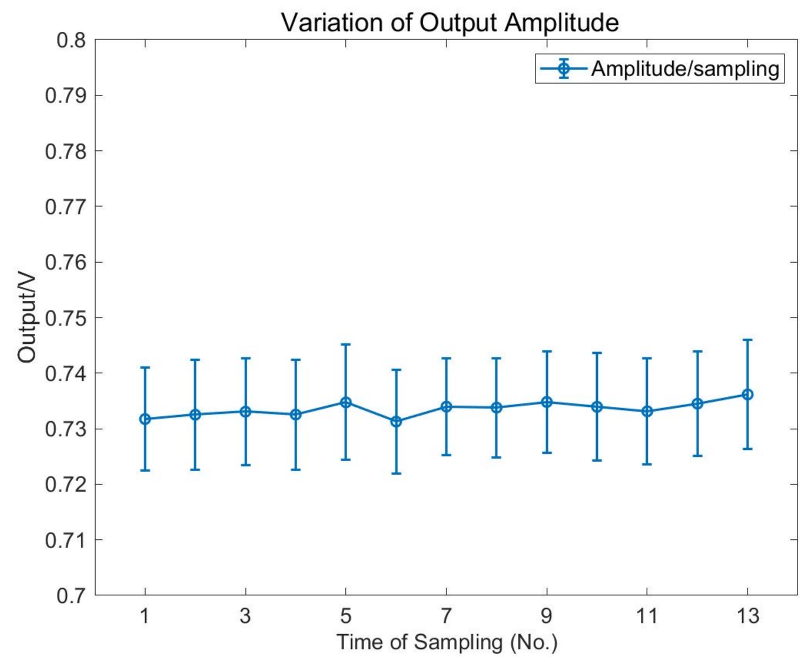




- All sensors respond the signal source correctly
- The magnification issue in the CSA of the 1st version sensors is resolved
- An equivalent input noise <130e- has been achieved so far (NνDEx goal: 45e-)

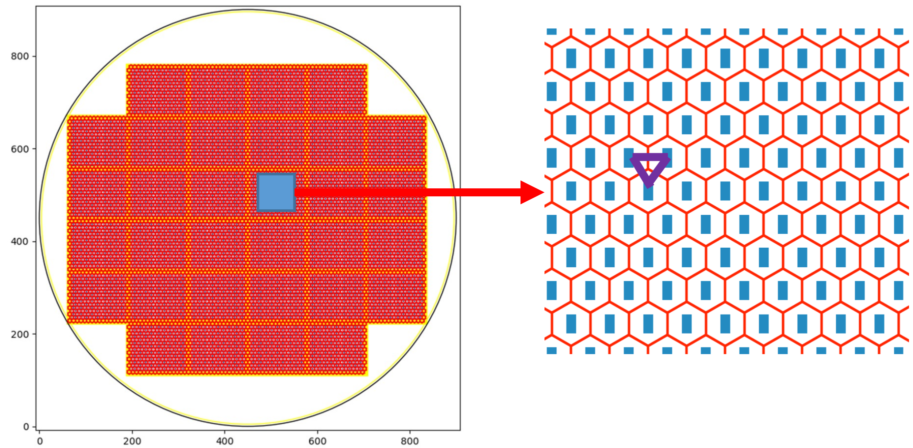
Electrical Test of Topmetal-S Sensors (2st)

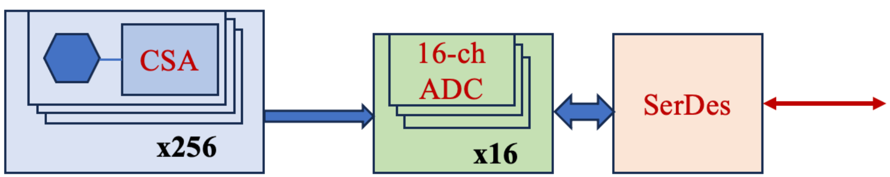


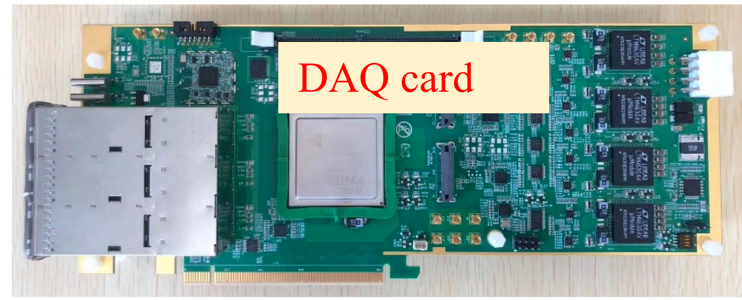


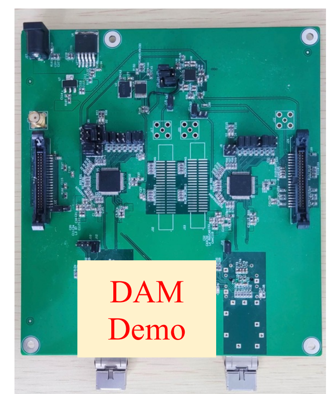
- The linearity and stability are acceptable
- Signals from the α source – being tested

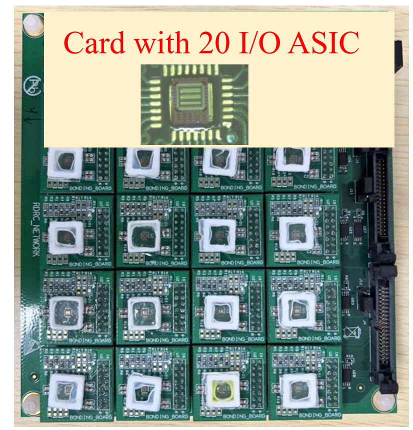
Readout & DAQ

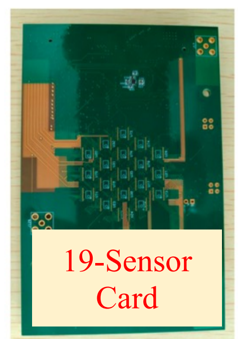


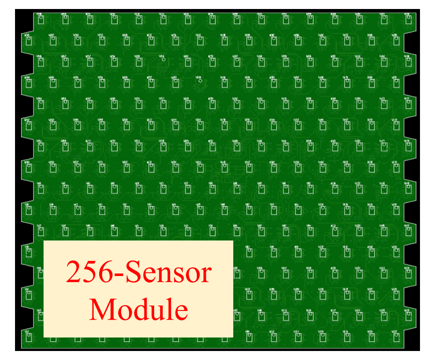






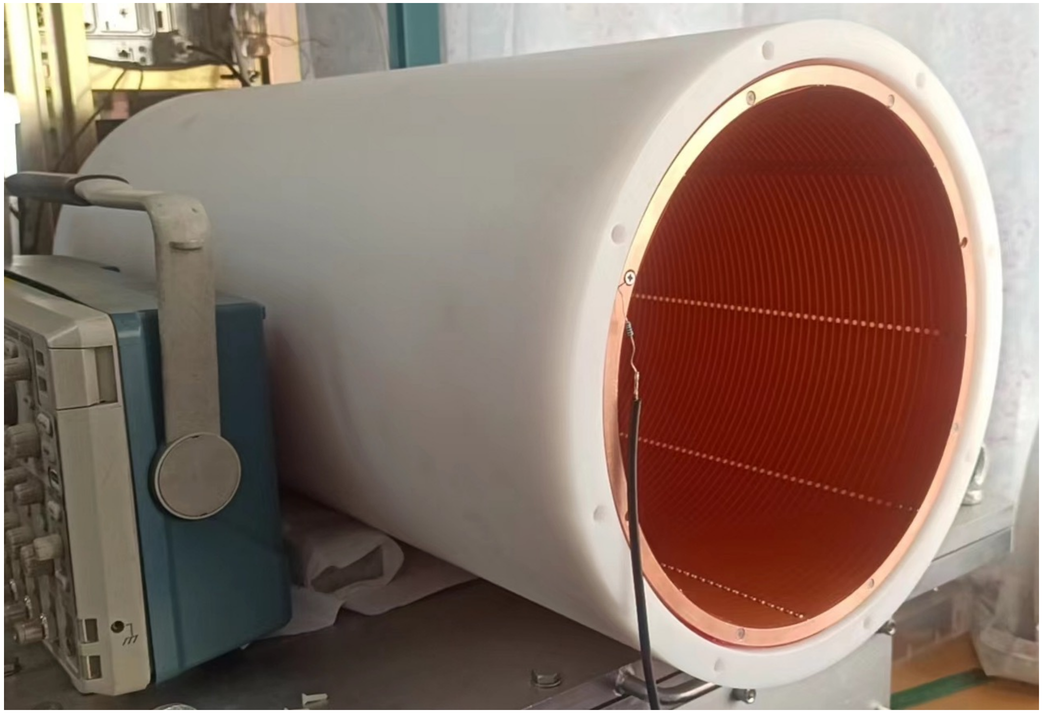


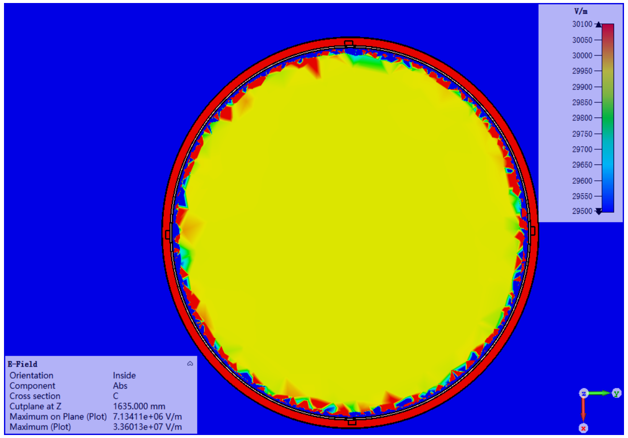


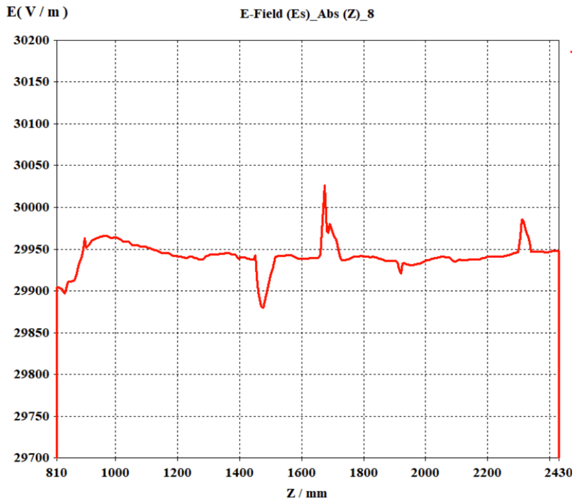


- Sensor pitch: 8mm
- Sampling rate: 0.5~20 kSps
- 256 Sensor array module: under design
- DAM module: functions evaluated
- DAQ system: the first prototype finished, software design ongoing

TPC Field Cage

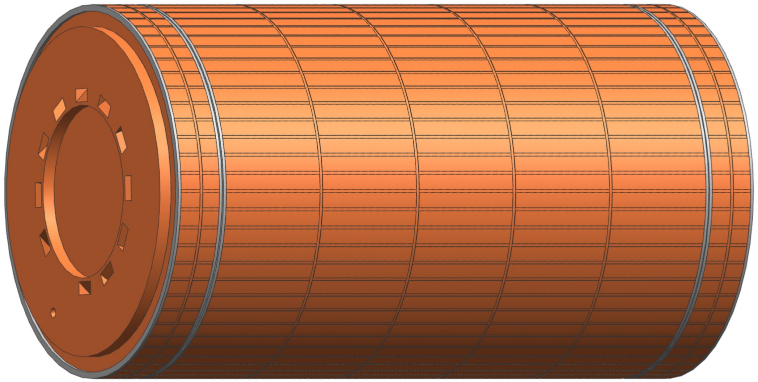


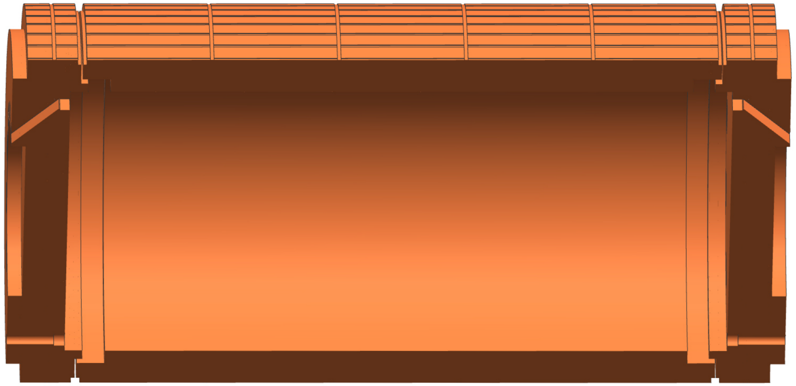




- 2.5cm thick Polyoxymethylene (POM) insulator + POM supporting structure + FPCB
- Finished with an initial design, a 30cm-diameter prototype is made and being tested

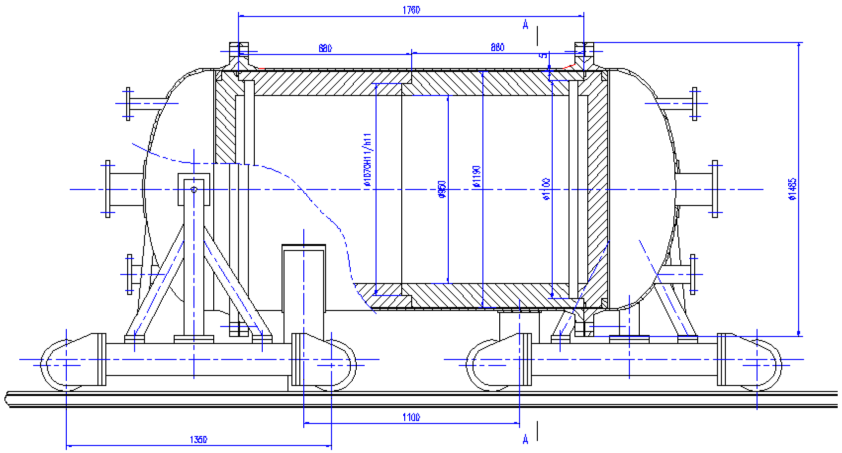
Inner Copper Shielding

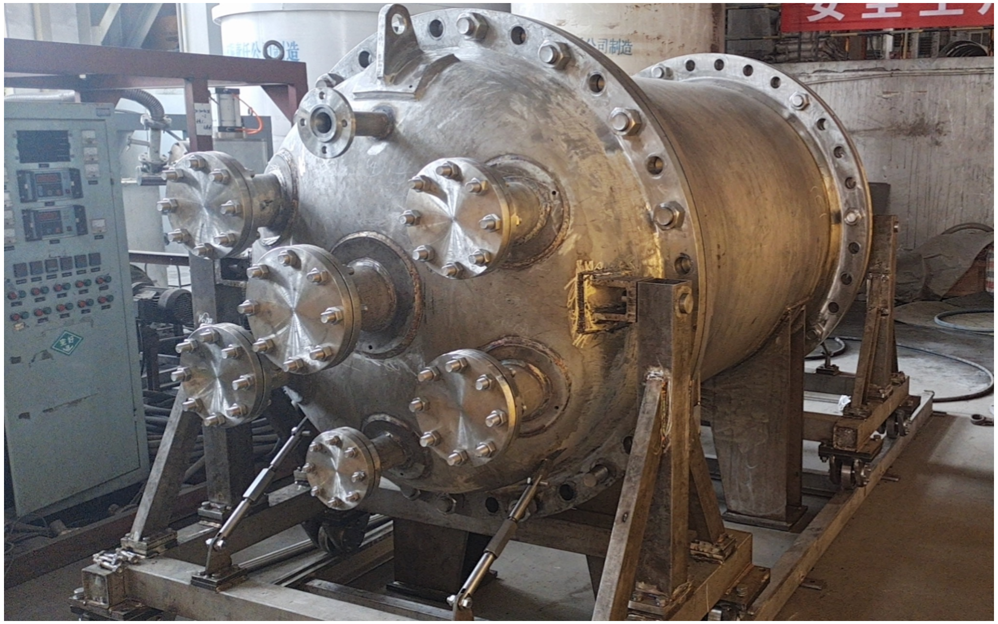




- Low-radiation oxygen-free copper
- 12 cm thick
- Finished with manufacture

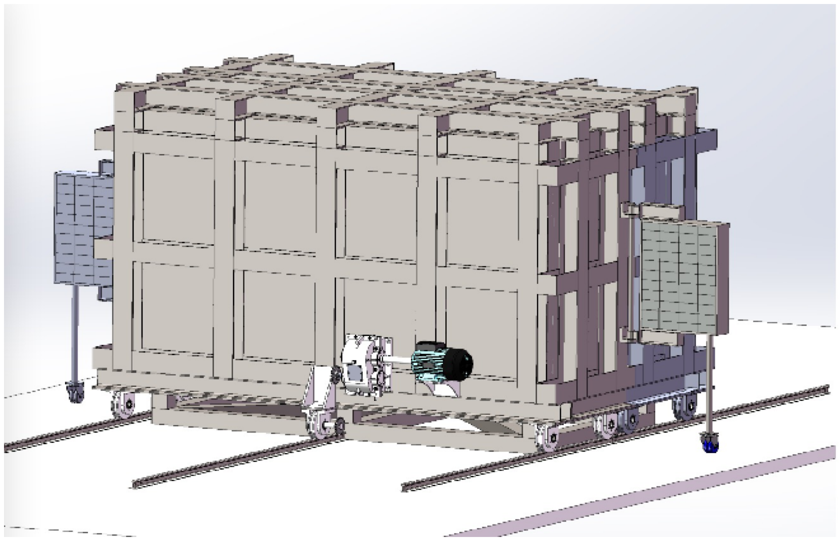
Pressure Vessel

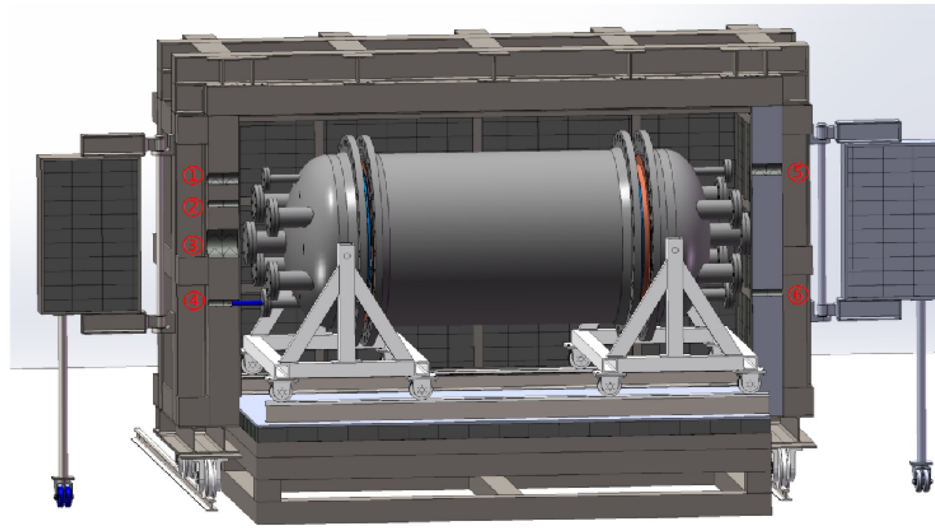




- 316L alloy
- Maximum pressure: 15 atm
- Manufactured, to be assembled with inner copper shielding

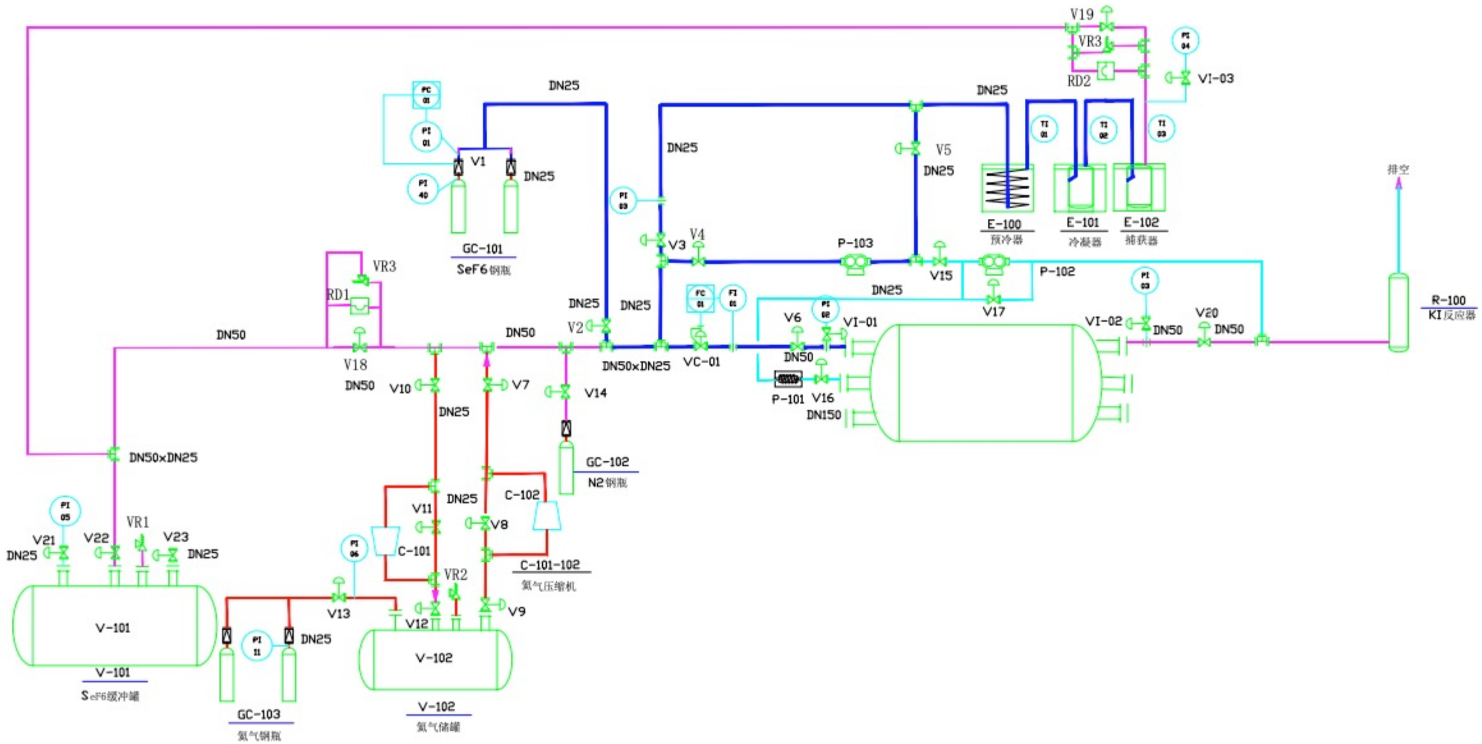
External Shielding





- 20 cm thick of Pb to stop γ
- High density polyethylene to stop neutrons
    - between the Pb layer and pressure chamber
    - 30 cm thick outside Pb layer
- Finished with design

Gas System & Gas Safety



- SeF_6 is poisonous: < 0.05 ppm in environment ⇒ multi-layer safety measures
- A cold trap for SeF_6 storing
- An emergency tank for emergent SeF_6 releasing
- After SeF_6 is condensed and the system evacuated, a trace amount of residual gas is purged into a reactor containing potassium iodide (KI)
- Test with non-poisonous SF_6 for gas tightness before filling SeF_6 each time

Gas System & Gas Safty

pre-cooler

condenser

chiller

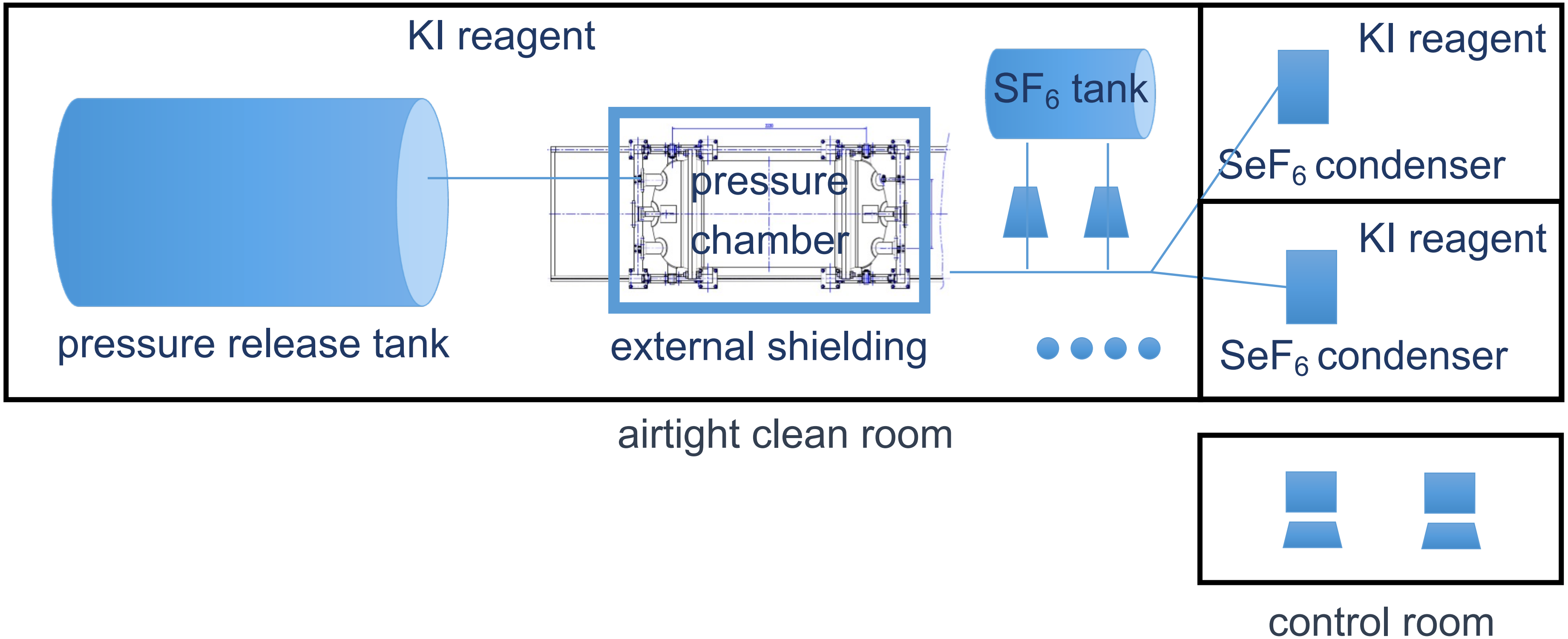
vacuum pump

emergent release tank

SF_6 storage tank

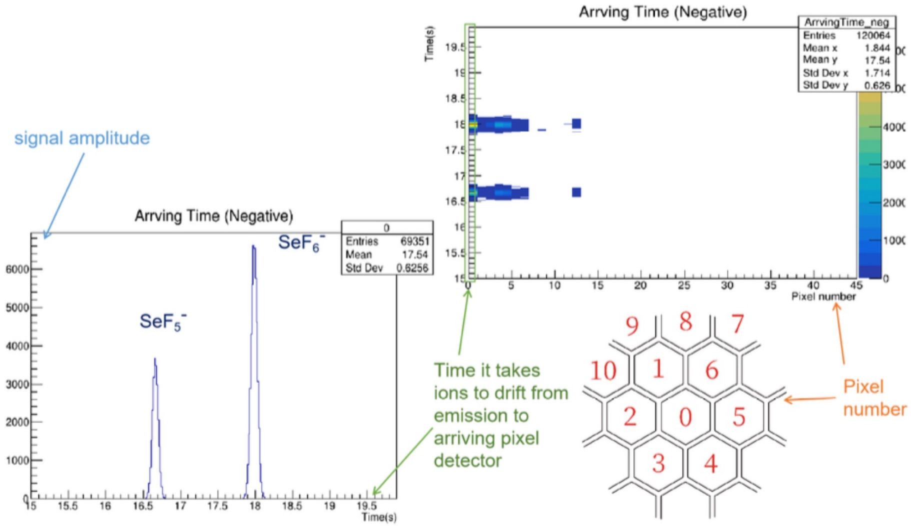
- Most parts of the gas system have been manufactured
- Waiting to be assembled with the pressure chamber
- Will be tested with SF_6 for a long time and many operation cycles, before using SeF_6

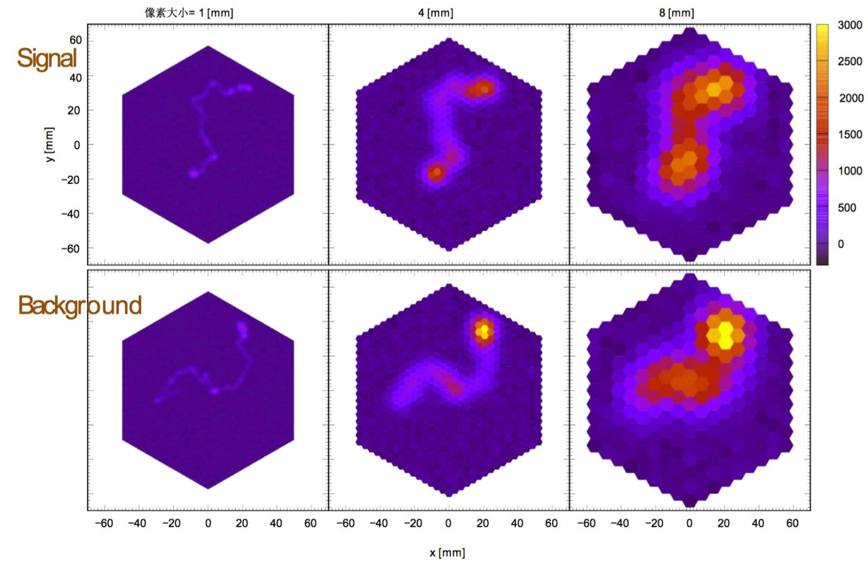
Airtight Clean Room

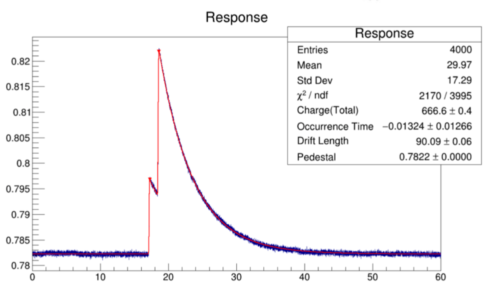


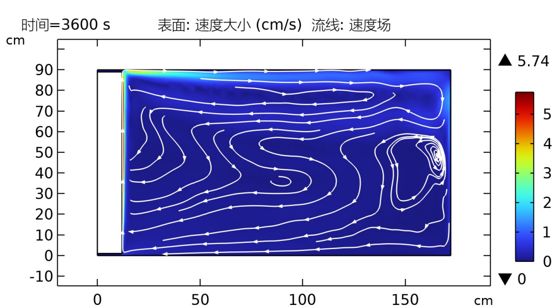
- The entire experimental set-up will be placed in an airtight clean room
- During data taking, the airtight clean room will be kept airtight, and the whole experiment will be controlled remotely
- Sufficient potassium iodide (KI) reagent placed to absorb SeF_6 in case of leakage
- When accessing the experiment, SeF_6 will be condensed in isolated airtight rooms

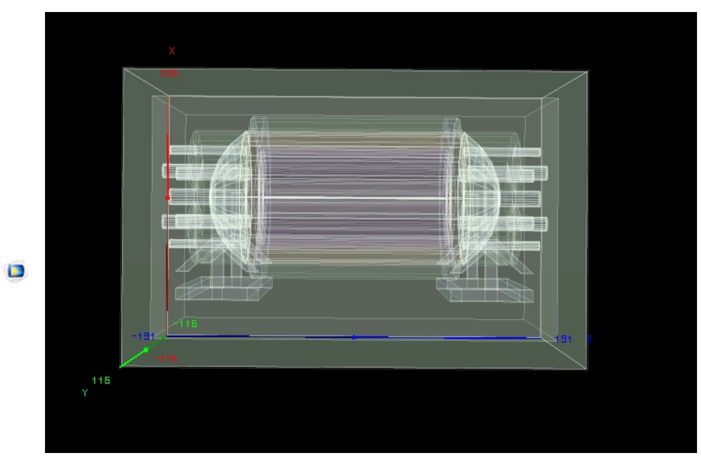
Simulations

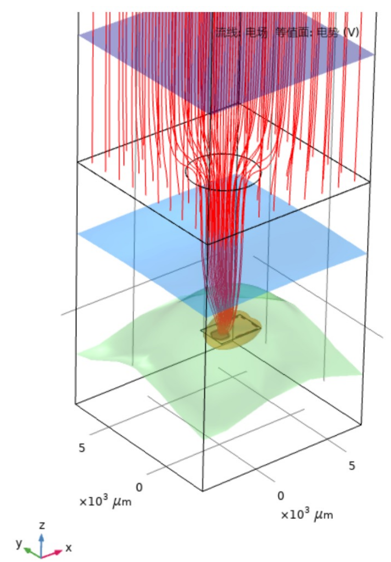












- Various simulations have been carried out

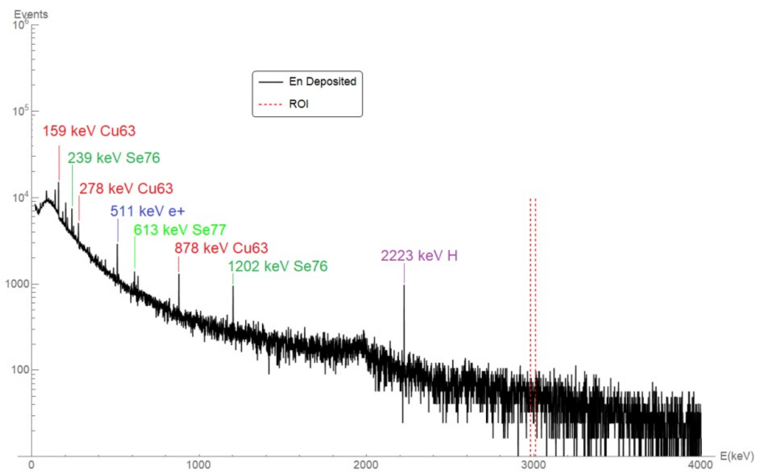
Background Estimations - γ

γ background from different sources without suppression using event topology

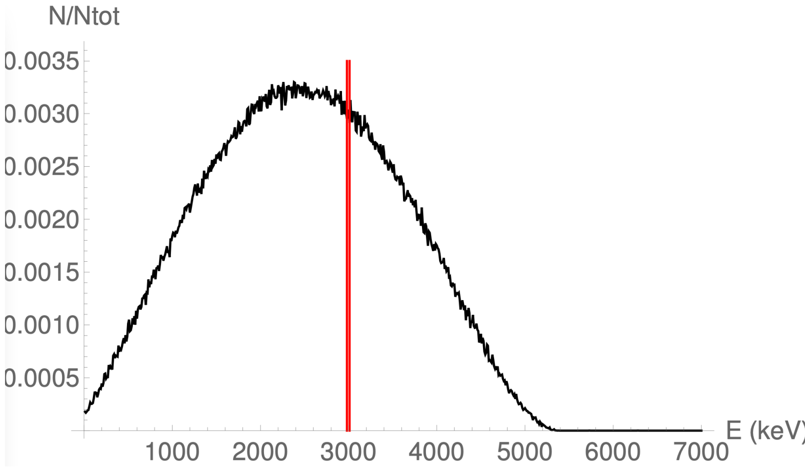
Source		Background in ROI	
Material	Subsystem	evts/yr	10^{-5}evts/(keV kg yr)
Concrete	Experimental hall	0.004	0.12
Lead	External shielding	0.003	0.09
HDPE	External shielding	0.005	0.16
Steel	Pressure vessel	0.026	0.86
Copper	Inner copper shielding	0.050	1.67
POM	Field cage	0.330	10.99
Total		0.42	13.9

- Assuming the same natural radiation contaminations as NEXT, ~0.4 counts / year in ROI for 100kg gas, without suppression using event topology
- ~< 0.04 counts / year with suppression using event topology (most conservative estimation)

Background Estimations - Neutrons



Energy deposited in the detector by neutron-induced γ's



Energy spectrum of ^{20}F β decay

- Neutrons can induce γ in Cu, Pb etc ← major contribution
- Neutrons can also interact directly with Se and F in the gas
  - $n + {}^{82}Se \rightarrow {}^{83}Se \rightarrow {}^{83}Br + e + \overline{\nu}_e \rightarrow {}^{83}Kr + e + \overline{\nu}_e$
  - $n + {}^{19}F \rightarrow {}^{20}F \rightarrow {}^{20}Ne + e + \overline{\nu}_e$
- With HDPE blocks placed in and outside the Pb shielding, the neutron induced background will be reduced to 0.03 events/year before suppression with event topology << γ background

arXiv:2307.12785

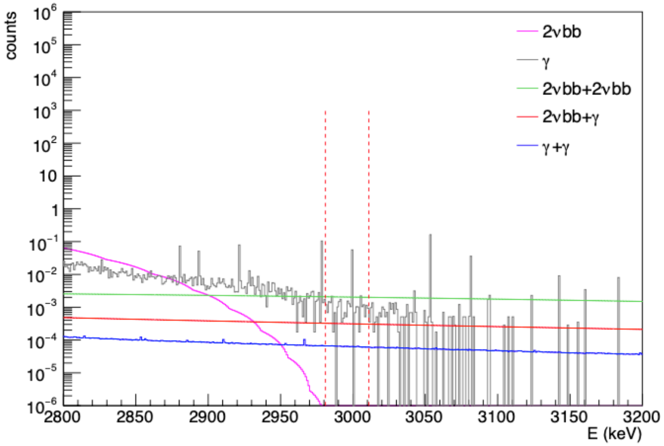
Background Estimations - Cosmic-generated

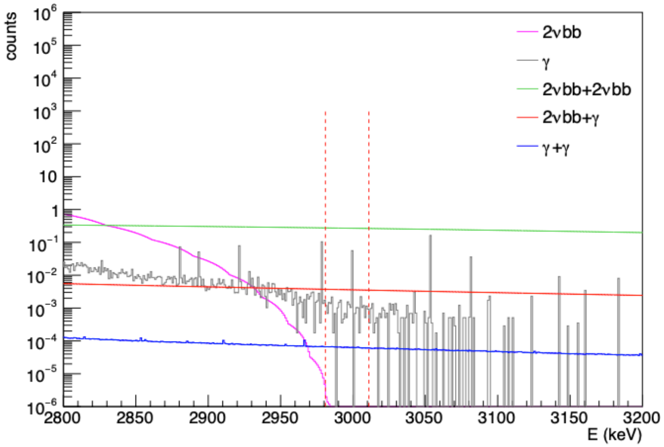
Table 4. Cosmogenic activation rate of various radio-isotopes in copper, as well as activities after exposure at sea level and cooling for certain time lengths.

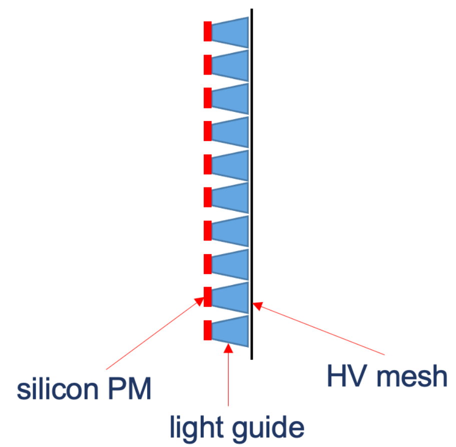
Isotope	Q-value (keV)	Half-life (d)	Production rate (atoms/kg/d) Calc.	Production rate (atoms/kg/d) Expt. [31]	Activity after 2yr exposure (μBq/kg)	Activity after 1yr cooling (μBq/kg)
^{46}Sc	2367	83.8	3.1	2.18±0.74	36	1.7
^{54}Mn	1377	312	14.3	8.85±0.86	133	59
^{59}Fe	1565	44.5	4.2	18.7±4.9	49	0.2
^{56}Co	4566	77.3	8.7	9.5±1.2	101	3.8
^{57}Co	836	272	32.5	74±17	318	125
^{58}Co	2307	70.9	56.6	67.9±3.7	655	18
^{60}Co	2824	1.92×10^{3}	26.3	86.4±7.8	71	62

- ^{56}Co from Cu is the most important isotope
  - After exposure at Lanzhou, ~323 μBq/Kg, background in ROI ~3700 evts / yr
  - Need ~3 years to cool down underground to be below γ background in ROI
- Other isotopes with long enough half life are with Q value < Q of ^{82}Se

Background Estimations – Others & Pile-up

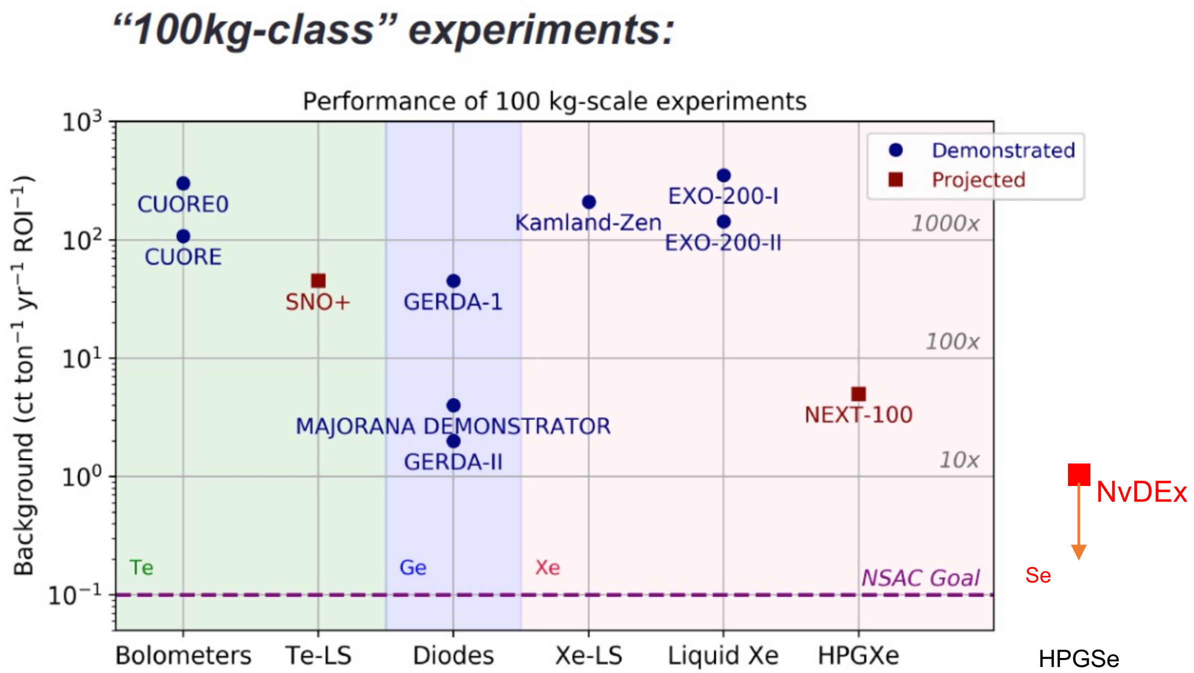






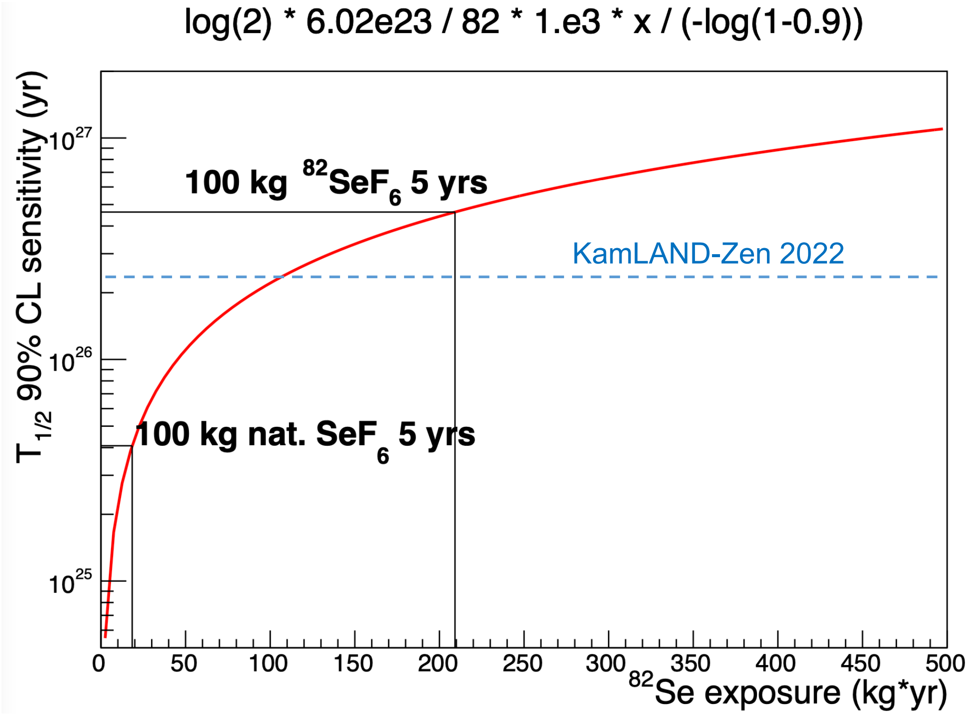
- Other background sources are estimated to be neglectable
  - Natural radioactive α & β, Radon, cosmic μ, ν, 2νββ
- Due to slow drift velocity of ions, pile-up backgrounds could be an issue
  - The drift time for 160 cm maximum drift length is ~7s
  - Estimated assuming events can be separated if they are 10cm*10cm*10cm away
  - For natural SeF_6, 2νββ + 2νββ: 0.06 evts / yr ROI < γ background
  - For $^{82}SeF_6$, 2νββ + 2νββ: 8.1 evts / yr ROI > γ background
  - Can be removed by adding scintillation light read-out with silicon PM at the HV end

Background Estimations



- Natural radiation γ is the dominant background source for NνDEx
- In total, ~<0.05 counts / year in ROI ⇒ ~<1 cts / (ton yr ROI)
- Very good potential for a future multi-ton scale experiment reaching for normal hierarchy $m_{\beta\beta}$ region

Sensitivity Estimation

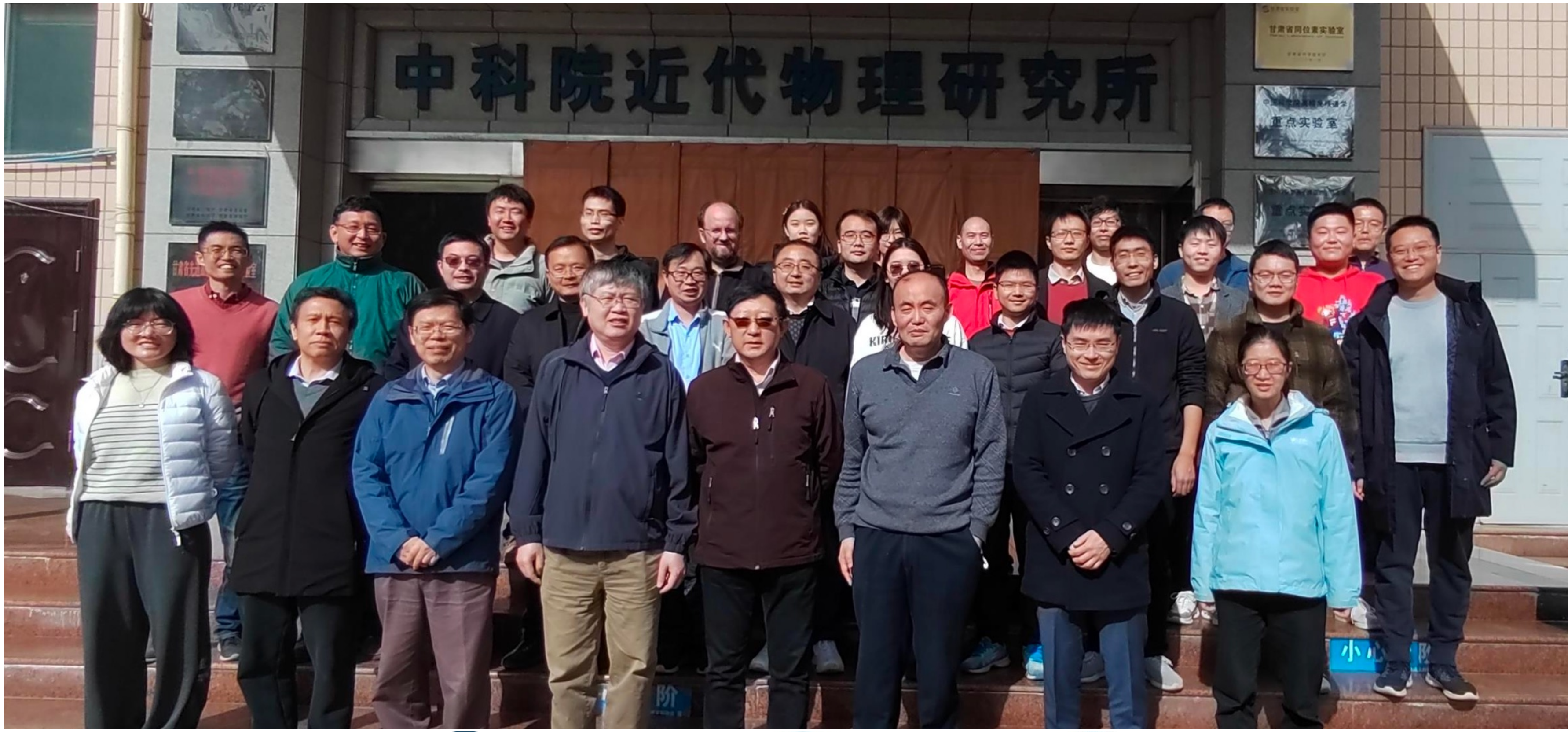


- Within 5 years the background in ROI ~< 0.25 counts, basically 0 background
- $T_{1/2} > 4 \times 10^{25}$ yr at 90% CL, with 100 kg natural SeF_6 (only 3.7kg ^{82}Se) 5 yrs
- $T_{1/2} > 4 \times 10^{26}$ yr at 90% CL, with 100 kg $^{82}SeF_6$ 5 yrs

Future Plan

- 2024:
  - Demonstrate topmetal sensor array TPC readout
  - TDR
  - Get approval to enter CJPL
- 2025:
  - Assemble the whole system
- 2026:
  - Begin data-taking, get 1st physics results

NνDEx Collaboration



- 1st NνDEx workshop in 2019
- >30 collaborators from 9 institutes now

Welcome to join

Summary

- NνDEx concept combines advantages from the high Q value of ^{82}Se and TPC's ability to see event topology, using noval topmetal sensor technology
- NνDEx-100 is being built, plan to be assembled around 2025
- 2 tapeouts of Topmetal-S sensors conducted, 3rd being produced
- Very low background level expected: ~<1 ct / (ton yr ROI)
    - Good potential for multi-ton scale experiment reaching for normal hierarchy $m_{\beta\beta}$ region
- ~ $4 \times 10^{25/26}$ yr sensitivity expected, with 100kg natural SeF_6 / $^{82}SeF_6$ gas

Thanks ☺

Welcome to join

Back-up

Budgets

子系统	所需经费（万元）
Topmetal-S 芯片	350
读出电子学及数据获取系统	120
TPC 场笼	74
高压气腔及铜屏蔽体	61
气路系统	44
外屏蔽体	260
气密洁净间	320
SeF_6 气体	350
总计	1579

表 7. 各子系统未来完成研制所需经费

项目名称	总经费（万元）	结余经费（万元）
国家重点研发计划 2022YFA1604703（支持 NνDEx 实验部分）	441.6	428.4
国家重点研发计划青年项目 2021YFA1601300（直接经费）	395	322
中国科学院从 0 到 1 原始创新计划 ZDBS-LY-SLH014	240	41.5
中国科学院国际合作伙伴计划 GJHZ2067	100	4.9
国家自然科学基金委青年科学基金项目 12105110	30	20.4
总计	1206.6	817.2

表 8. NνDEx-100 探测器研制经费来源