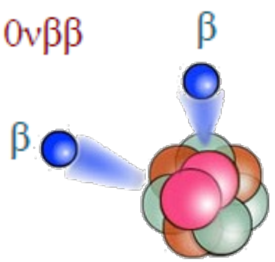
Status of NνDEx

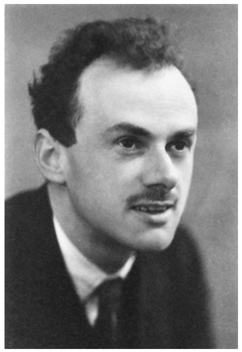
Hao Qiu

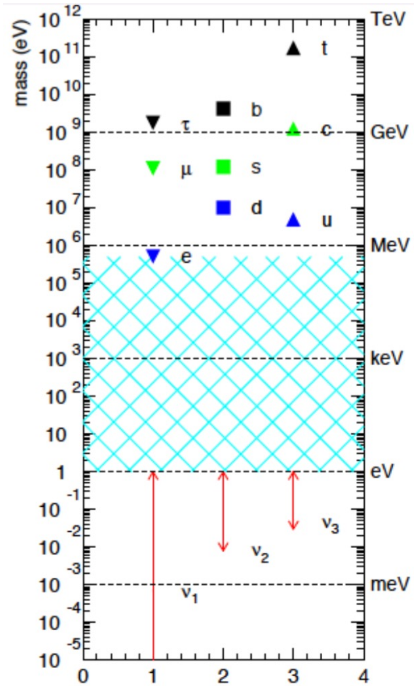
Institute of Modern Physics, CAS

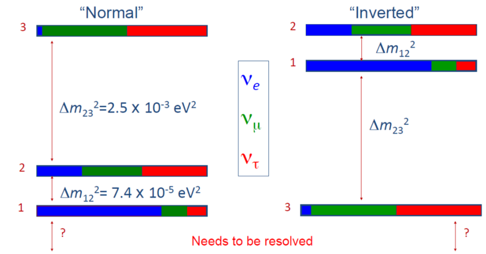
for the NνDEx Collaboration

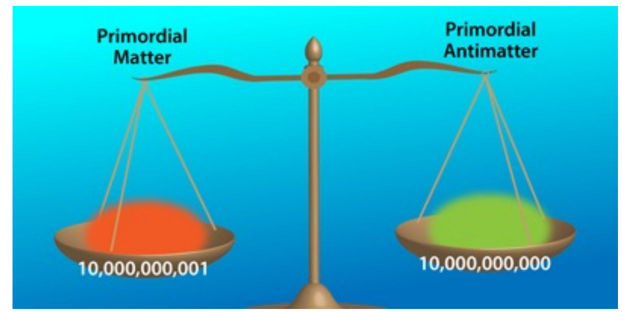
0νββ Decay





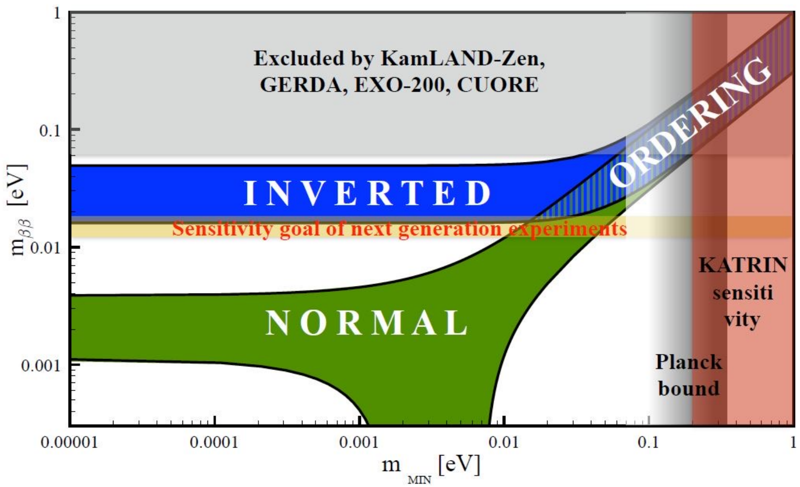


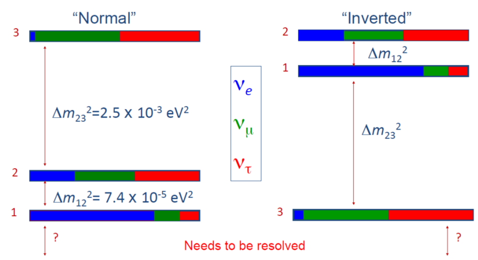


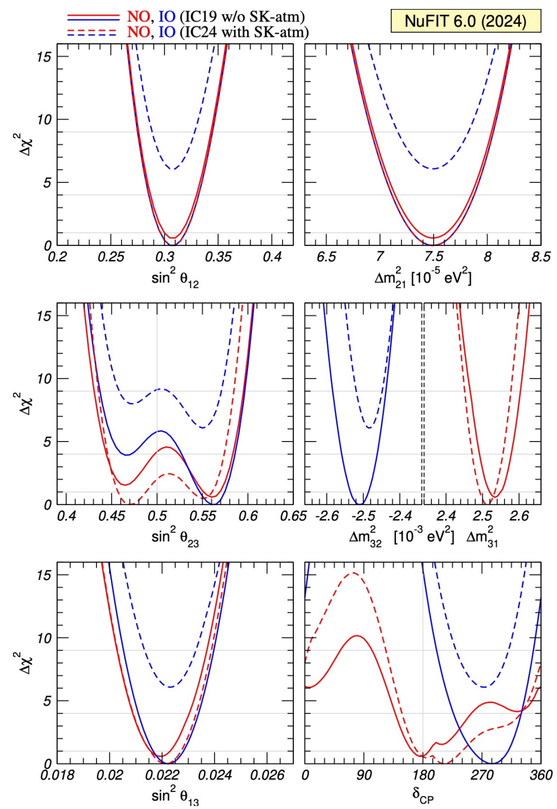


- Observation of 0νββ decay will be very important ⇒
  - ν is a Majorana particle ⇒ beyond Standard Model
  - explain the finite but tiny ν masses
  - constrain absolute ν mass & mass hierarchy
  - explain matter-antimatter asymmetry in the universe via CP and lepton number violation

0νββ Decay Experiment Sensitivity







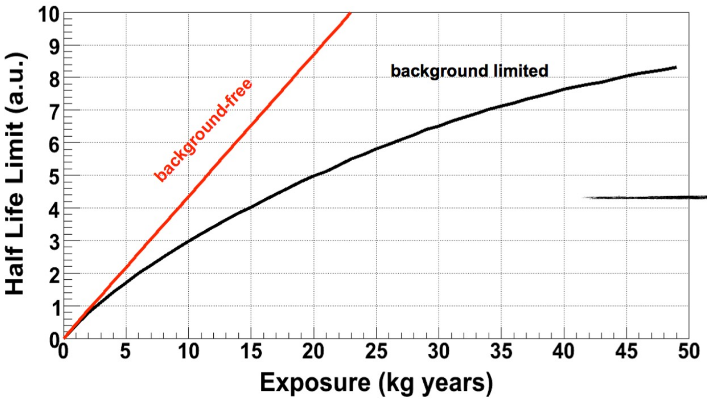
- Inverted hierarchy: $m_{\beta\beta}$ >~10 meV, goal of next generation experiments
- Normal hierarchy: $m_{\beta\beta}$ >~1 meV
- Both current oscillation experimental results and physics naturalness slightly prefer normal hierarchy

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

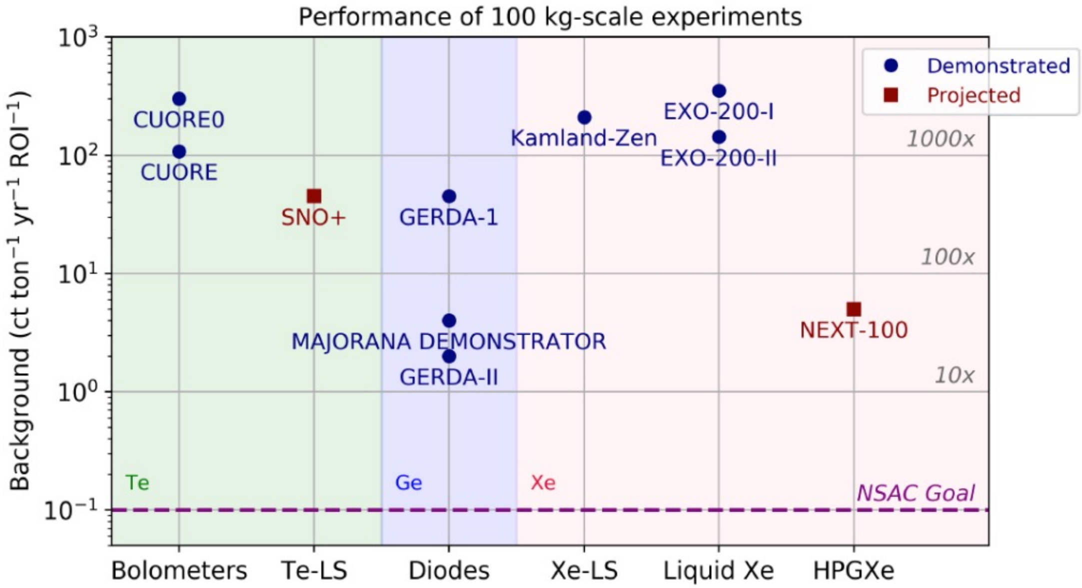


- Reducing bΔE is the key to increase experiment sensitivity
- 0 background： $m_{\beta\beta}$ sensitivity ∝ $(MT)^{-1/2}$
- High background: $m_{\beta\beta}$ sensitivity ∝ $(MT)^{-1/4}$
  - 1-t for normal hierarchy → 10k t for inverted hierarchy

same background level

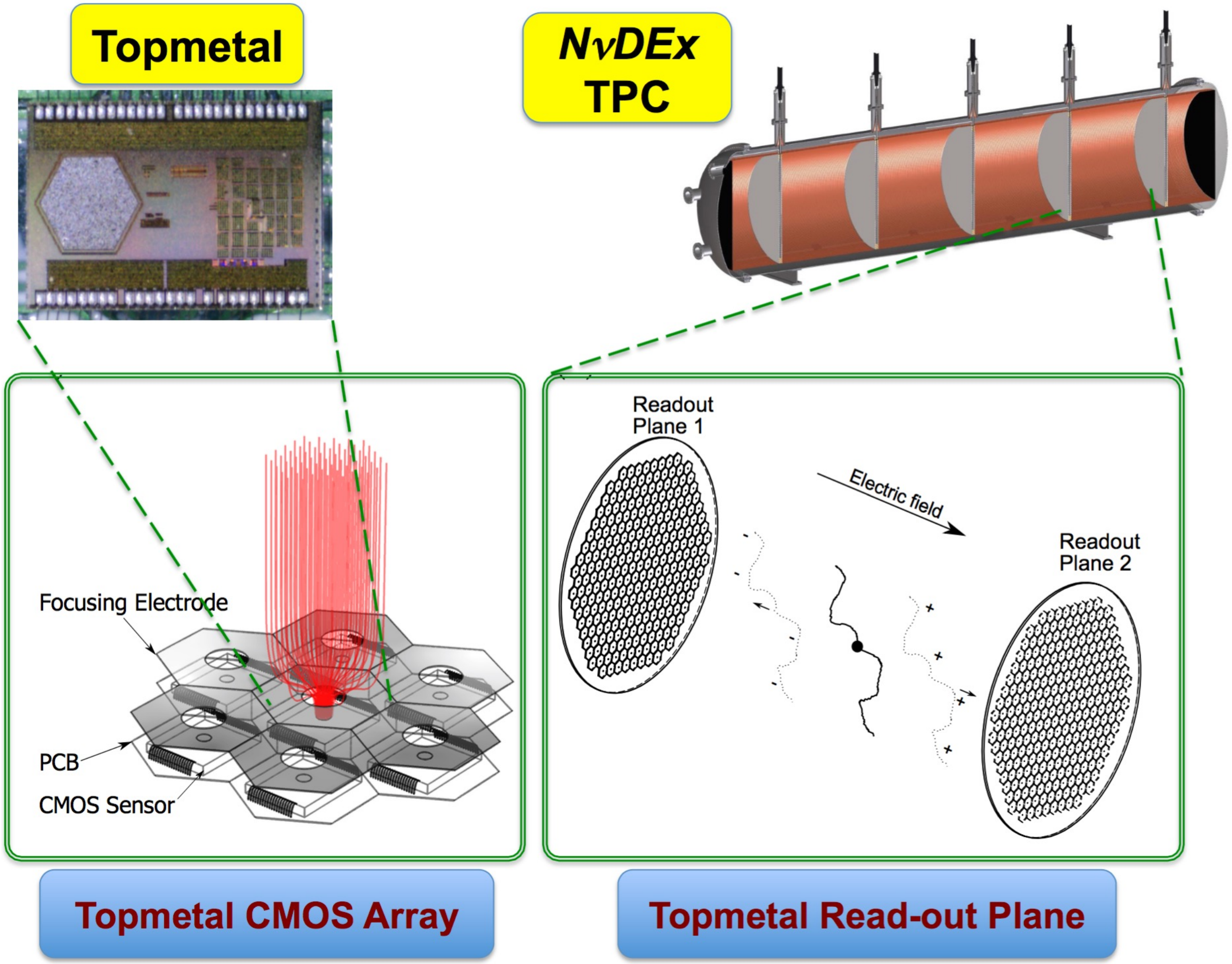
Background Level Needed
-for a Cost-effective Experiment

"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
- Most of current experiments are >= 1 order of magnitude away from this goal

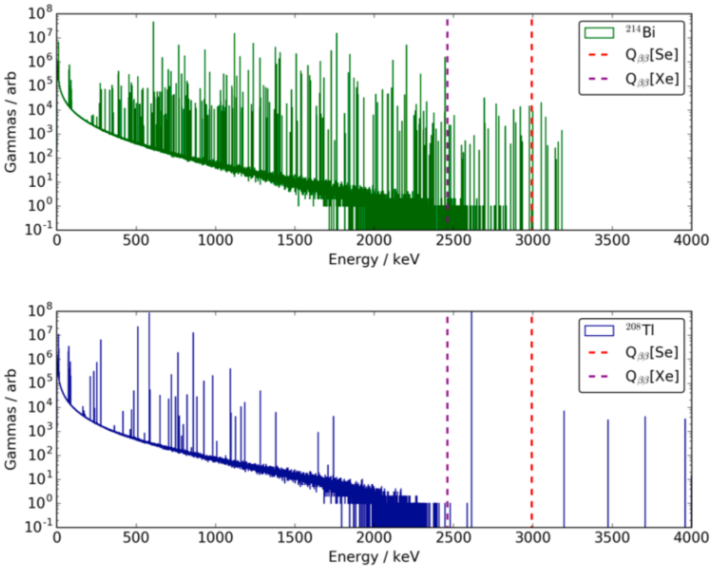
NνDEx Concept



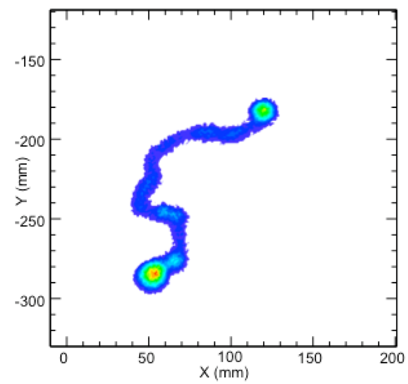
- High pressure $^{82}SeF_6$ gas TPC, with direct read-out by CMOS sensors

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

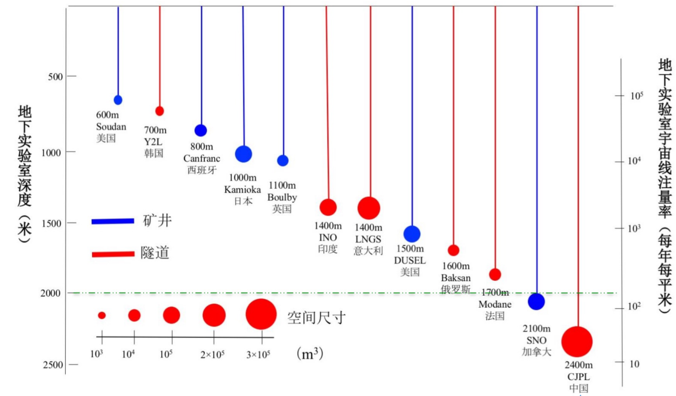
NνDEx Advantages

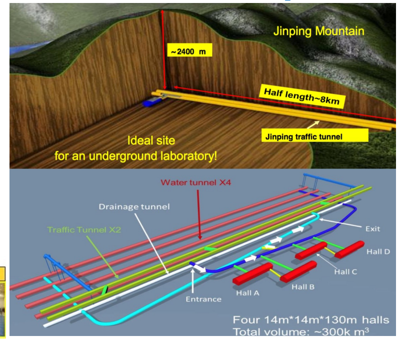


γ background energy spectra from natural radiations



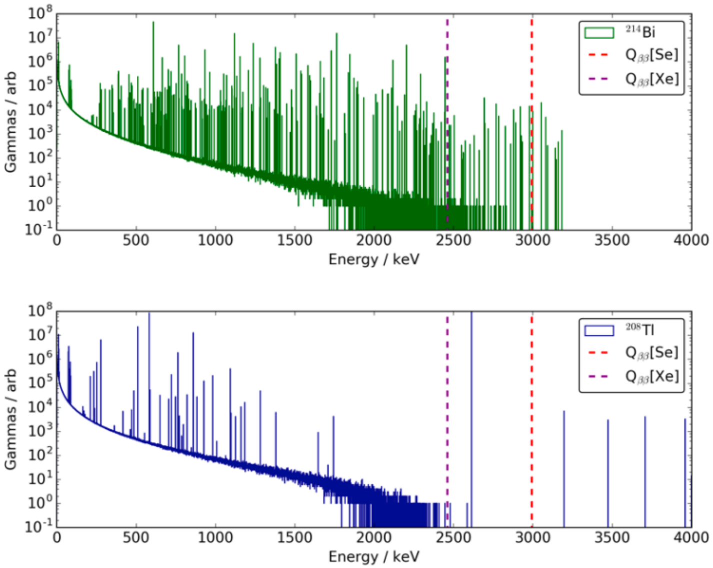
energy deposition for a 0νββ event



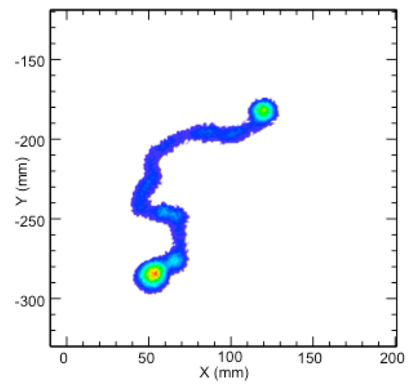


- NνDEx's advantages for low background
  - High Q value of ^{82}Se (2.996 MeV) – above most natural radiation background
  - Distinguish signal and background with event topology by TPC
  - Better energy resolution without avalanche amplification (~1% FWHM)
  - CJPL - deepest underground lab

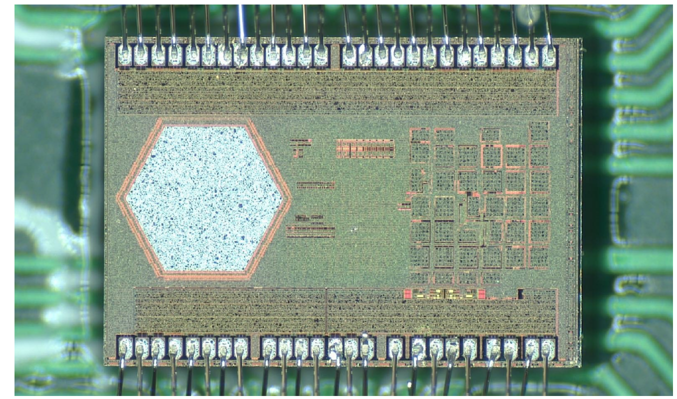
NνDEx Advantages



γ background energy spectra from natural radiations



energy deposition for a 0νββ event

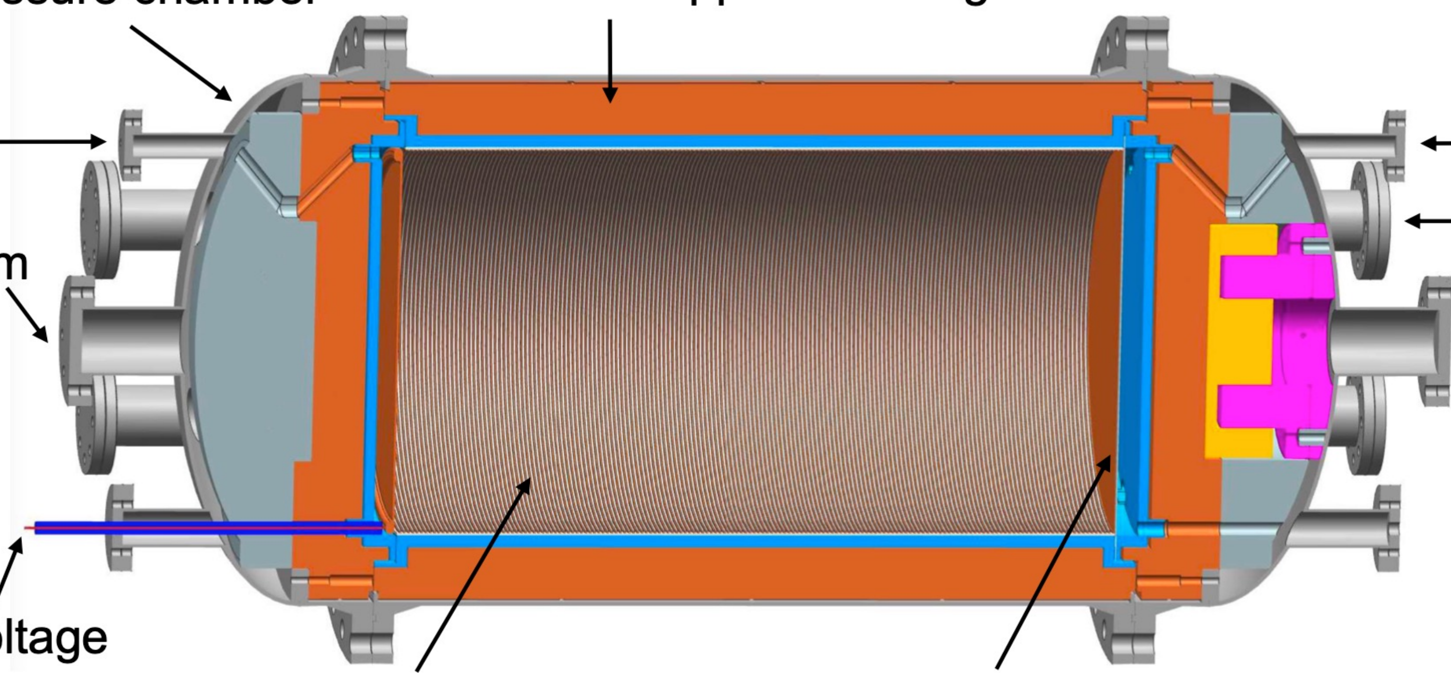


CMOS sensor for NνDEx

PLAC Pixel Laboratory at CCNU

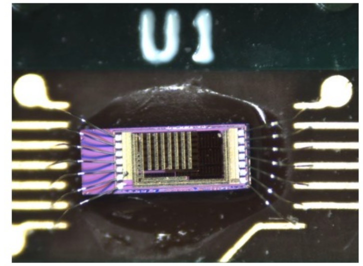
- SeF_6 is electronegative, amplification by electron avalanche is not possible with it
  - ⇒ low-noise direct charge read-out
- CMOS sensors specifically for 0νββ detection are developed by Pixel Lab of CCNU

NνDEx-100

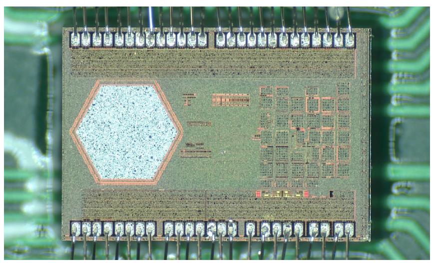


- NνDEx-100 is being built, with 100kg SeF_6 gas at 10 atm in the sensitive volume

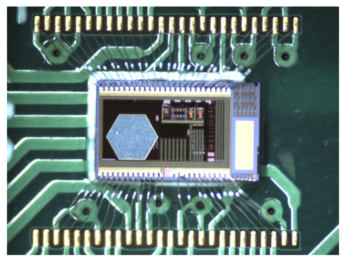
Sensor Chips



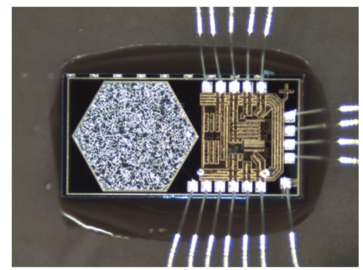
V2·GB, ENC~119e-



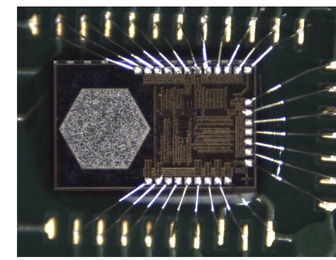
v0, signal<<expectation



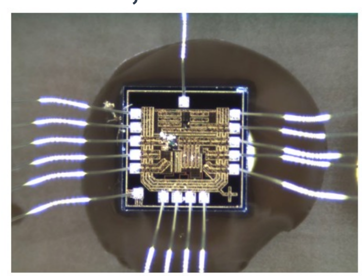
v1.B, ENC~130e-



V2·TA , ENC~58e-



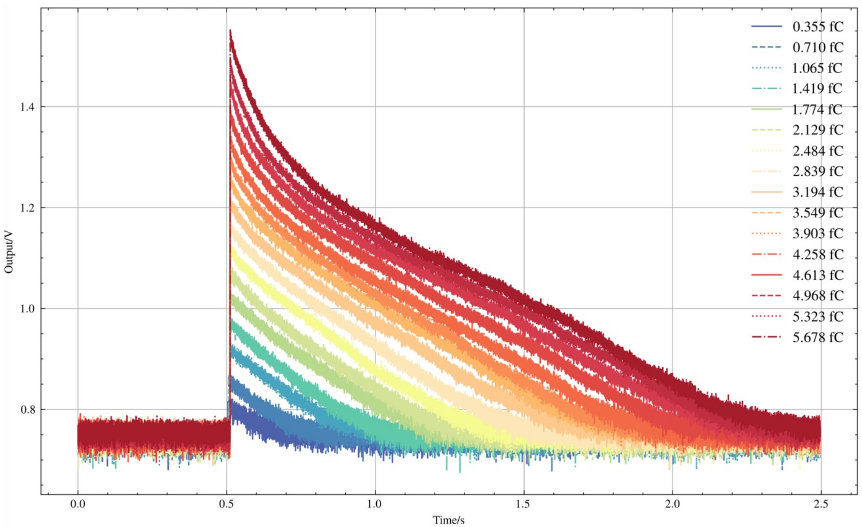
V3·TA
being tested



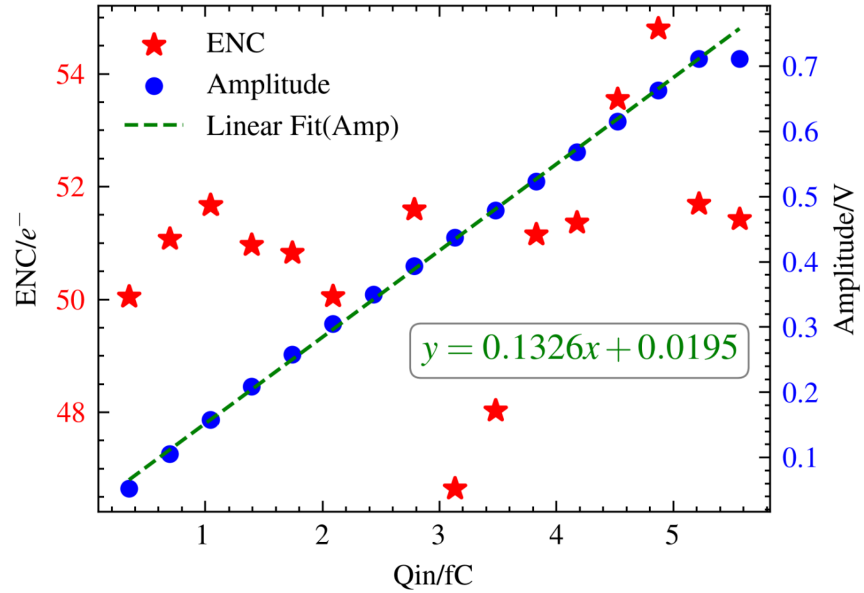
V2·TB , ENC~50e-

- Key technology for NνDEx to come true
- Equivalent Noise Charge (ENC) ~<45e^- required for good energy resolution
- 4 tapeouts have been produced
- ENC~50e^- achieved by V2·TB – getting close to the requirement of 45e^-

Sensor Chips

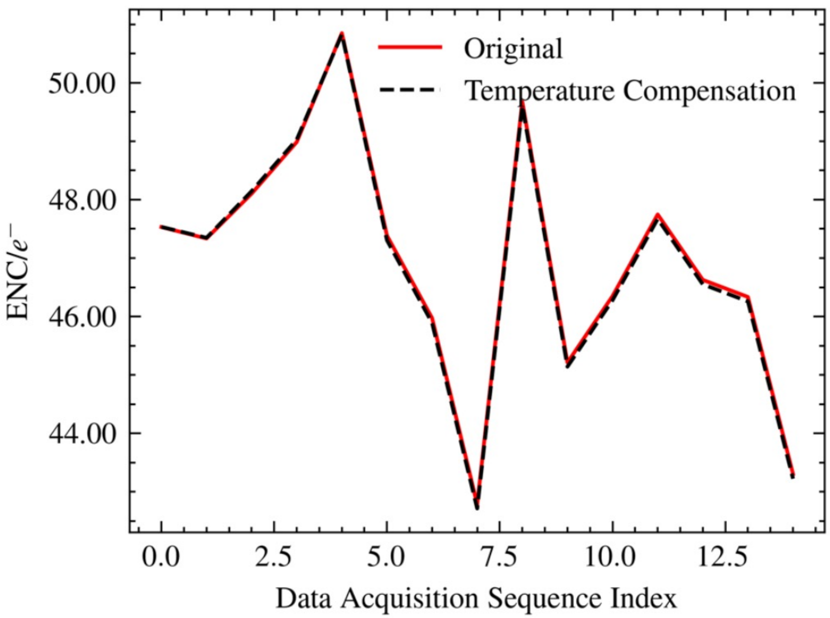


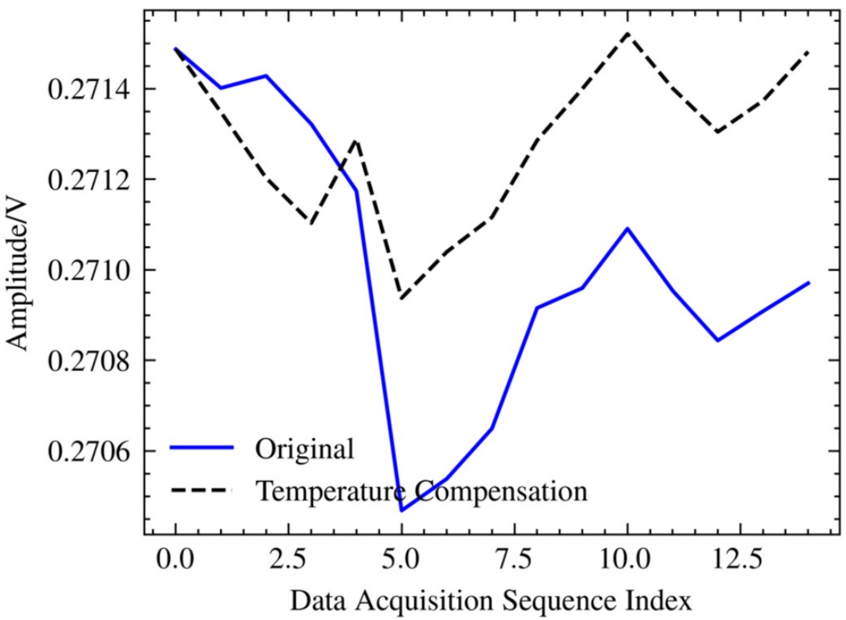
Signal shapes with different input charge (V2·TA)



ENC & output amplitude vs. input charge (V2·TB)

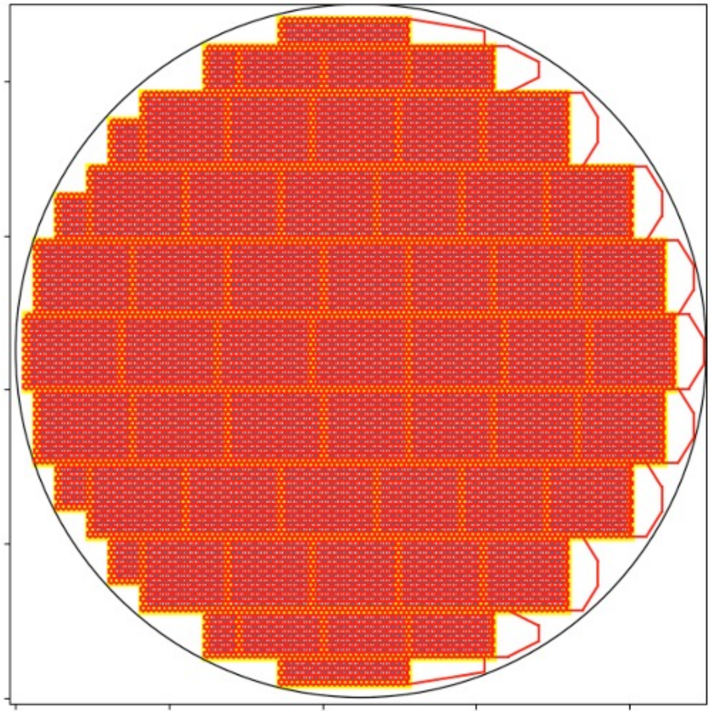
Sensor Chips

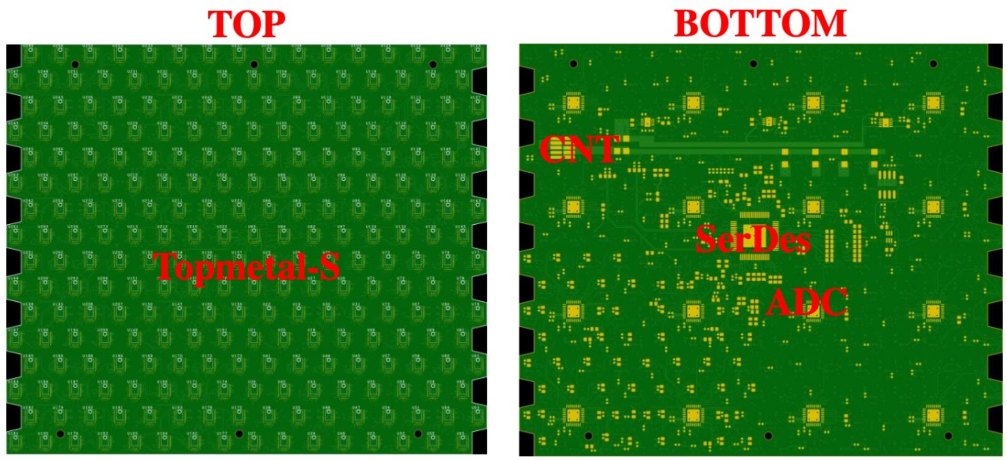




- ENC & output amplitude from 6750 samples in a 19-hour test
    - V2·TB, input charge 1.82 fC
- ENC ~< 50e$^-$
- Amplitude variation ~< 0.3%

Read-out plane & DAQ





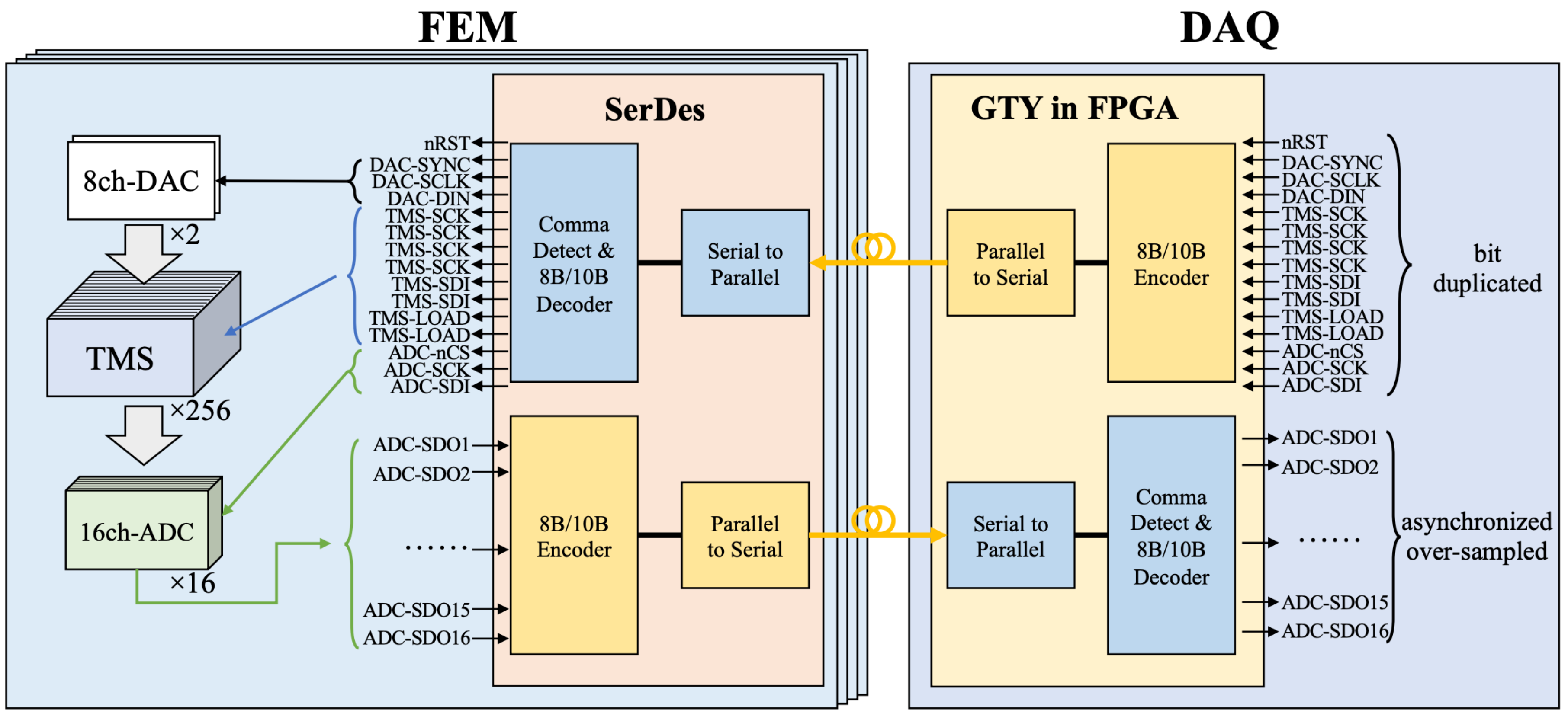
- Sensor chip pitch: 8mm
- Sampling rate: 0.5-20 kSps

Details in the poster by

Lei Lang, Kai Chen, Chaosong Gao

Wednesday 18:00

Read-out plane & DAQ



- PCIe-based data acquisition system:

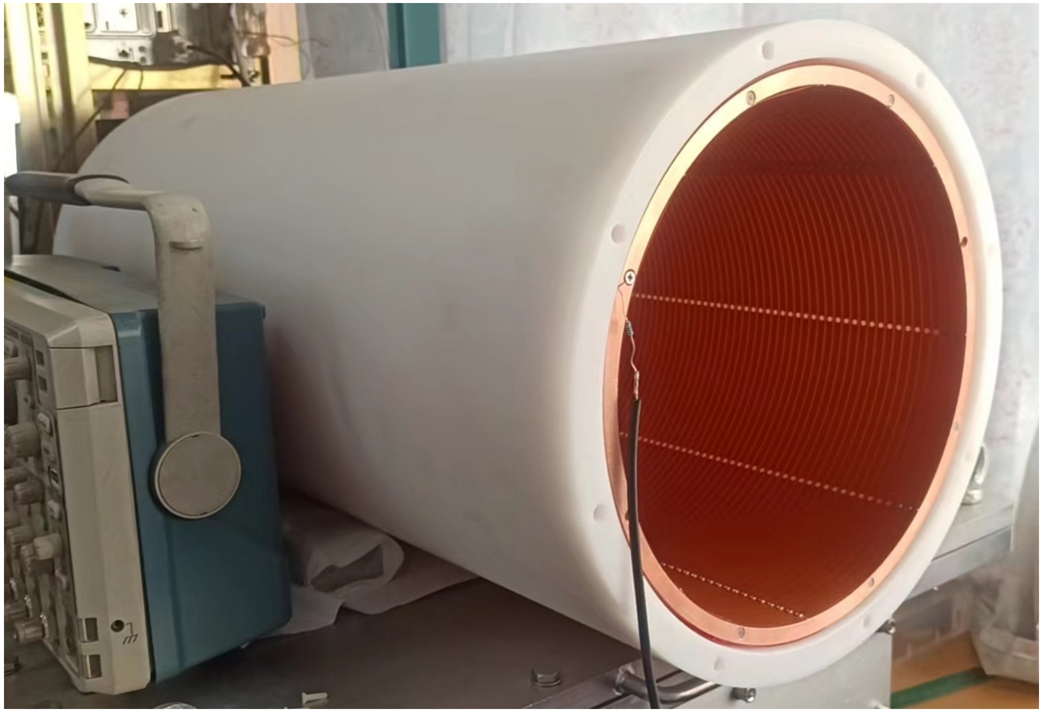
FELIX

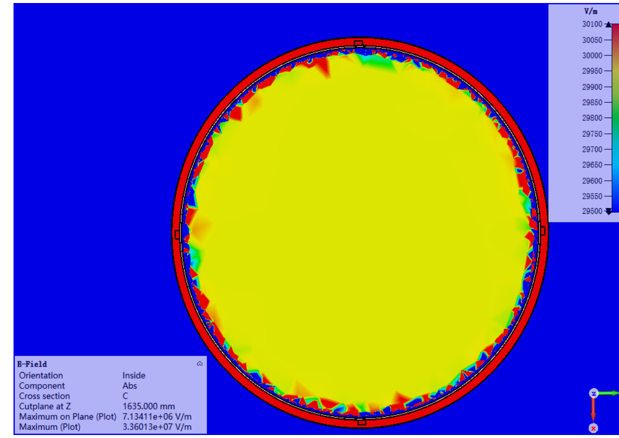
Details in the poster by

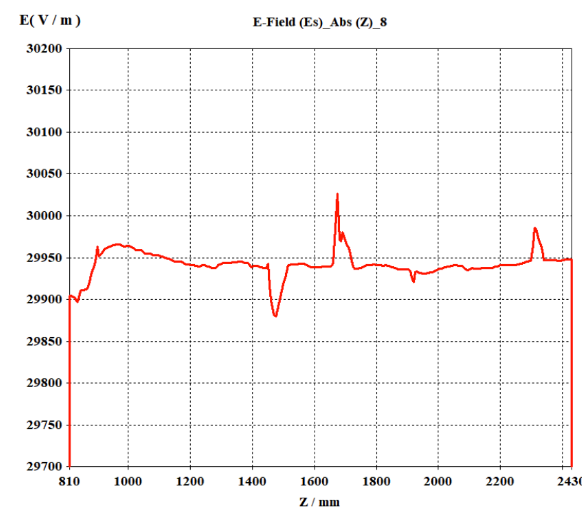
Lei Lang, Kai Chen, Chaosong Gao

Wednesday 18:00

TPC field cage

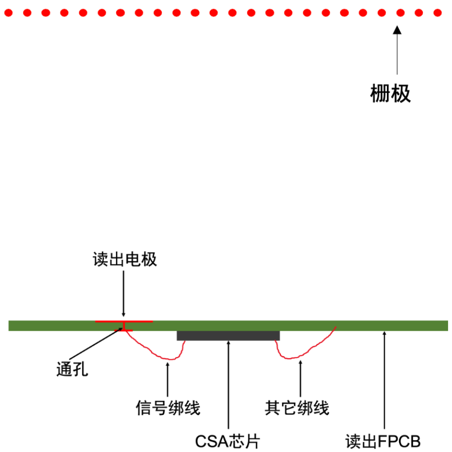


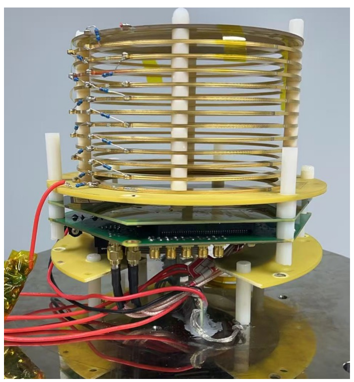


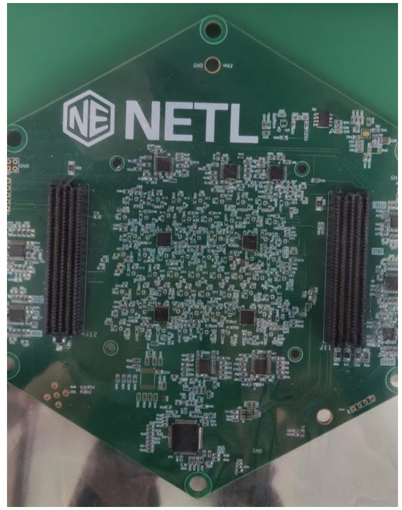


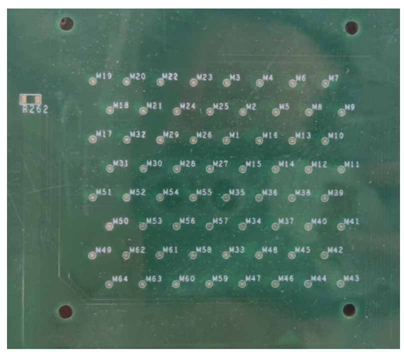
- Polyoxymethylene (POM) insulation layer & support structure + flexible PCB
- Preliminary design completed
- A 30 cm diameter prototype was fabricated.

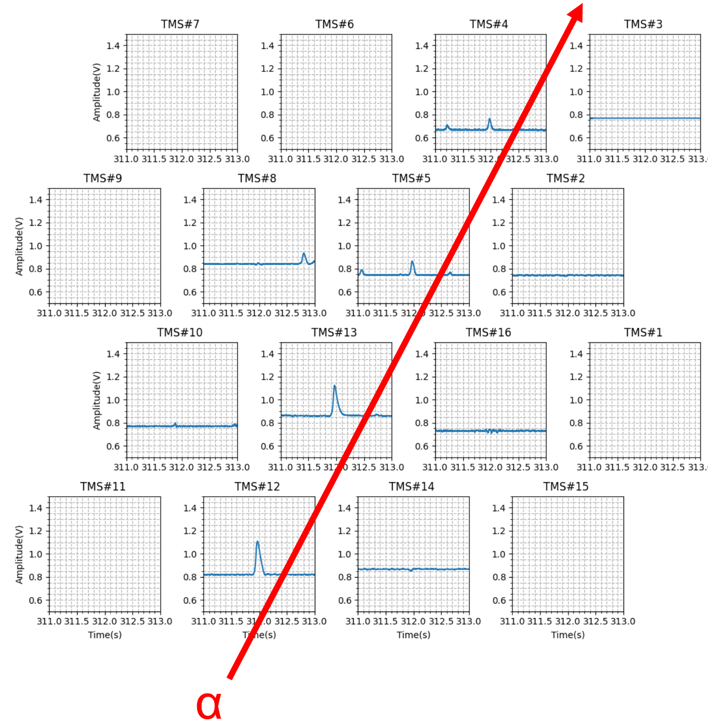
Prototype TPC

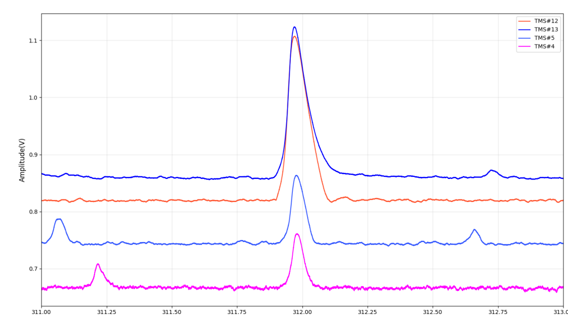






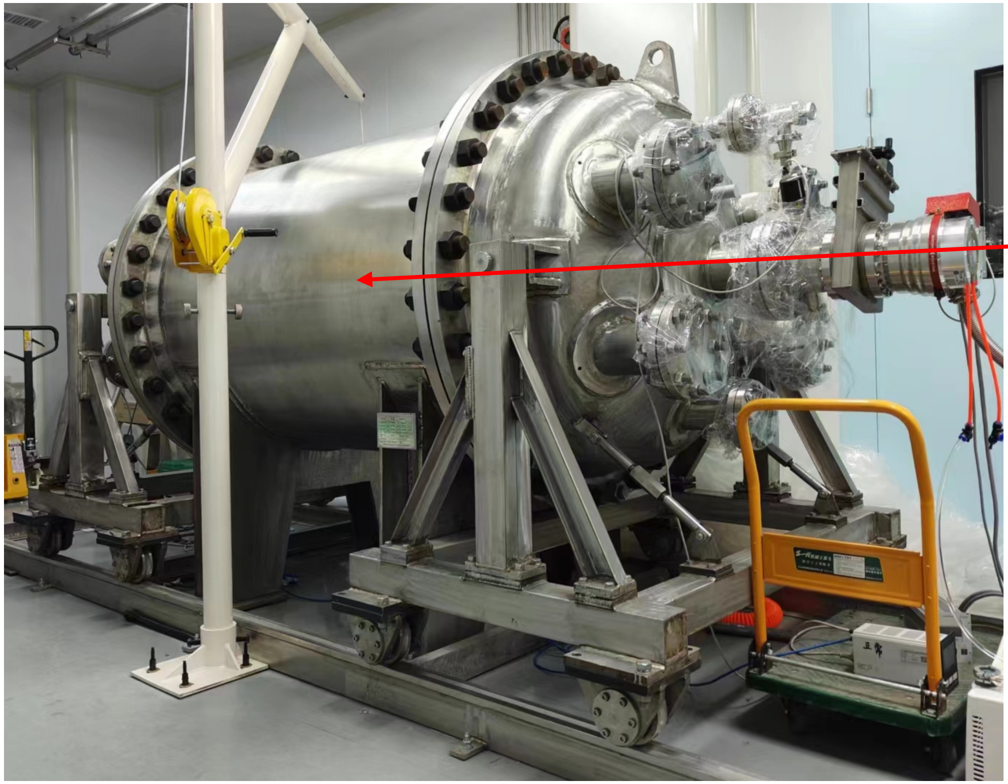






- Readout plane with V2·TB sensor chip array
- α tracks observed
- Energy resolution being measured with an X-ray source

Inner copper shielding & pressure vessel



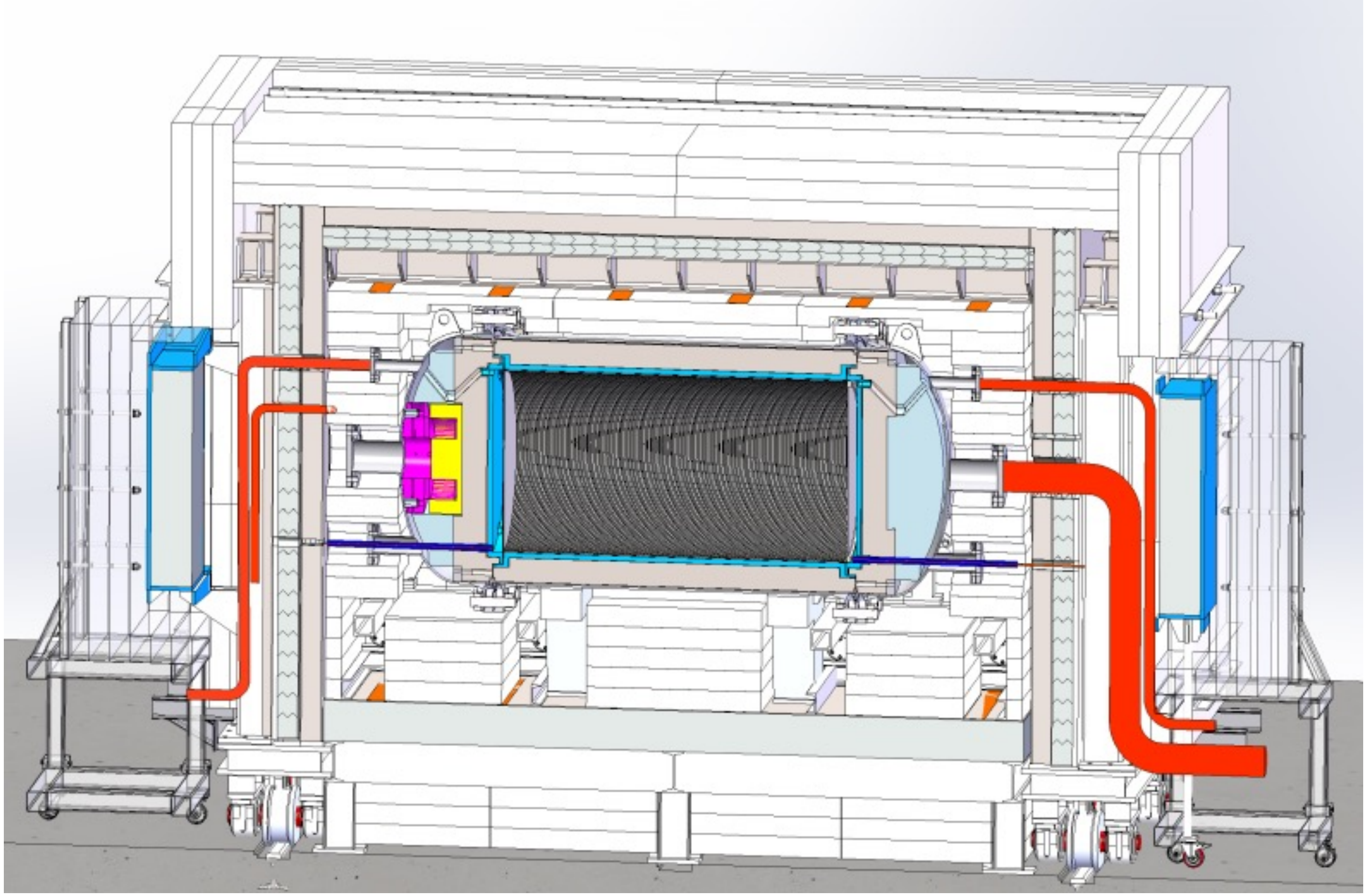
- Inner copper shielding & pressure vessel manufactured & assembled

Details in Qiang Hu's talk

Thursday 16:40

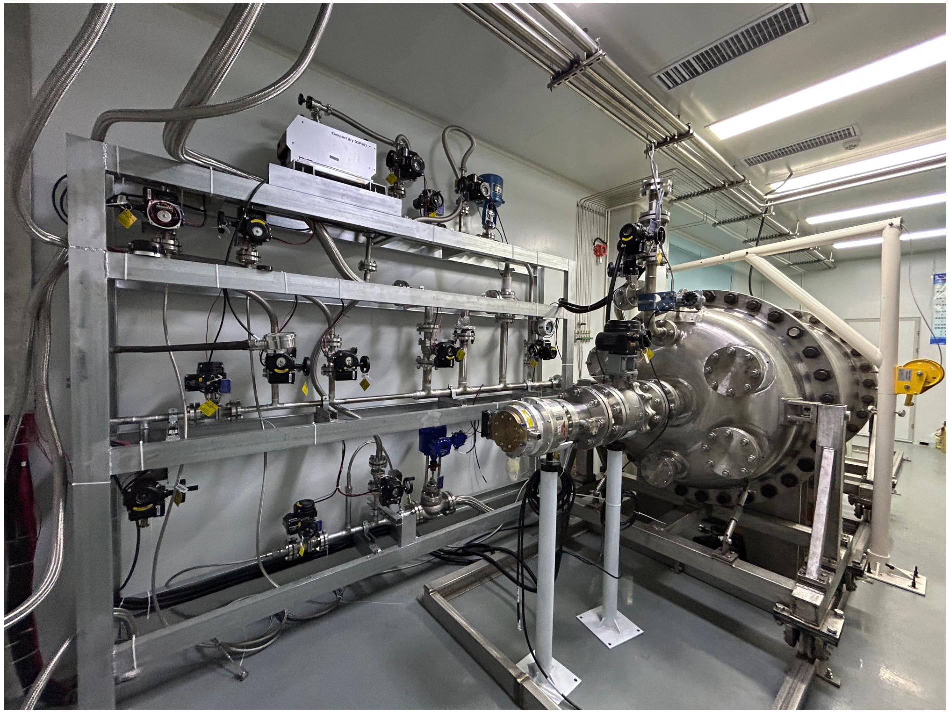
North Hall #3

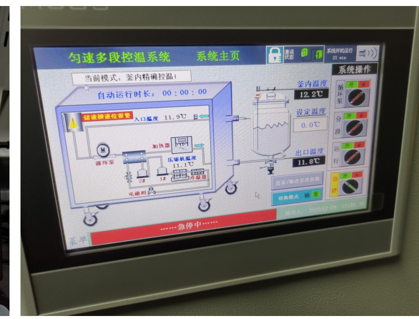
External Shielding



- Pb to stop γ
- High density polyethylene to stop neutrons

Gas System





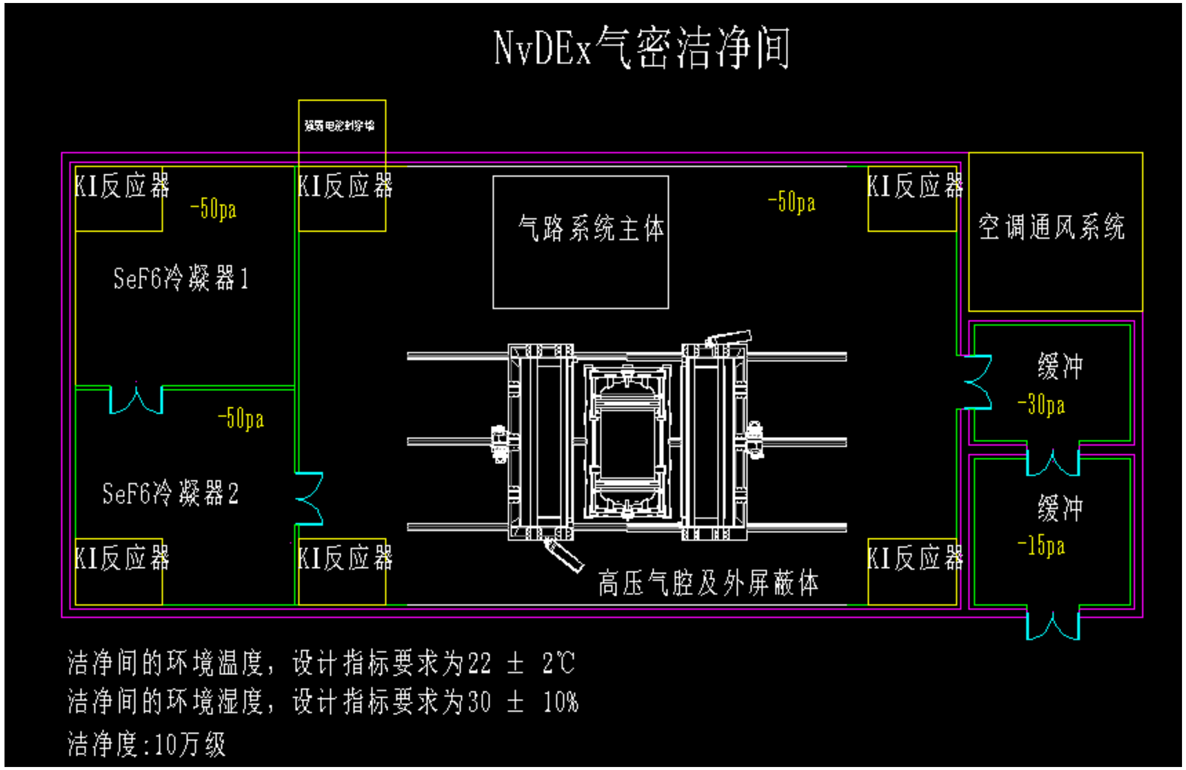
- SeF_6 is toxic: < 0.05 ppm in the environment ⇒ Multi-layered safety measures
- Gas system being assembled

Details in Qiang Hu's talk

Thursday 16:40

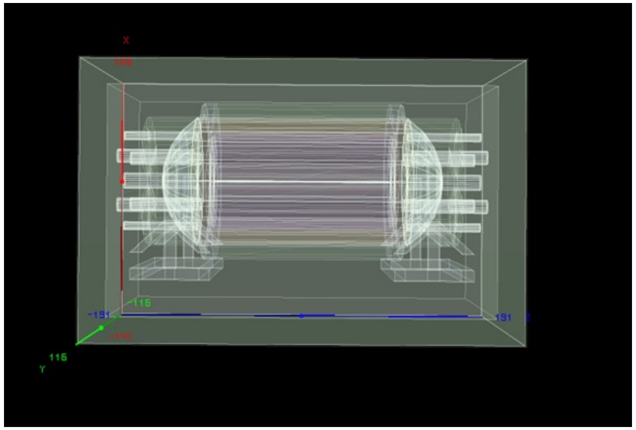
North Hall #3

Airtight Clean Room

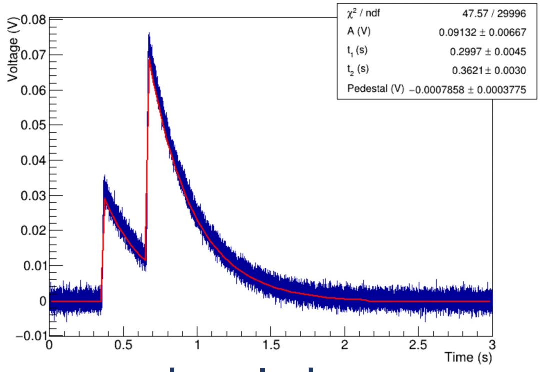


- The entire experimental set-up will be placed in an airtight clean room
- During data taking, the airtight clean room will be kept airtight, and the whole experiment will be controlled remotely
- SeF_6 gas reactor (molten NaOH) in the room to absorb any leaked gas
- When accessing the experiment, SeF_6 will be condensed in isolated airtight rooms

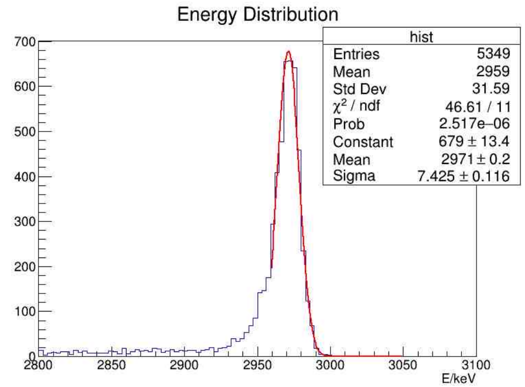
Simulations



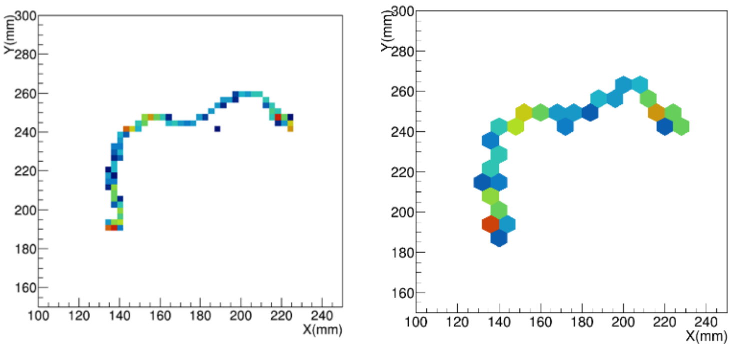
GEANT geometry model



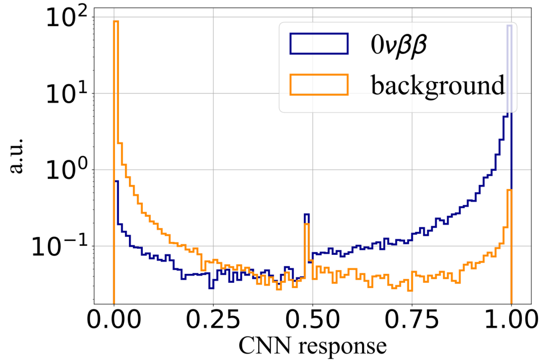
signal shape

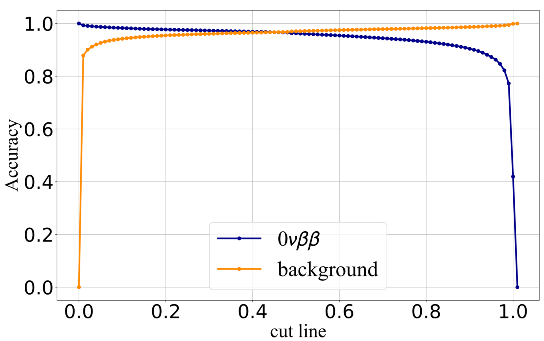


reconstructed 0νββ energy



simulated vs. reconstructed 0νββ signal





signal / background distinguish

with neural networks

- Full simulation and reconstruction software completed
- Sensor chip noise 45e$^-$ ⇒ Energy resolution 0.7%
- Background reduction by 70 times with 90% signal efficiency using neural networks

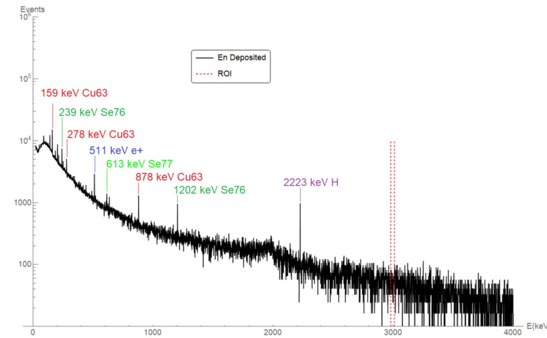
Background Estimations

Table 2 γ background from different sources without suppression using event topology

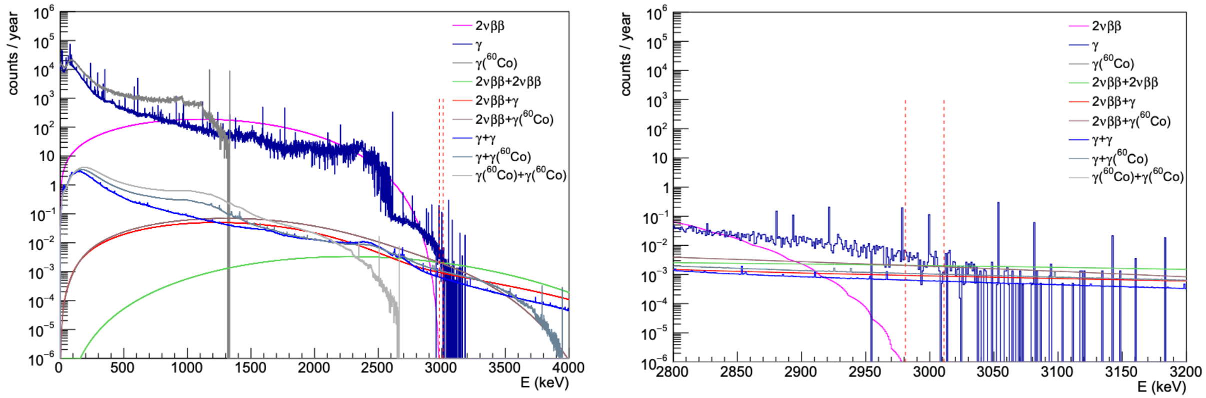
Source		Background in ROI	
Material	Subsystem	evts/yr	10^{-5}evts/(keV kg yr)
Concrete	Experimental hall	0.004	0.12
Lead	External shielding	0.003	0.09
HDPE	External shielding	0.005	0.16
Steel	Pressure vessel	0.026	0.86
Copper	Inner copper shielding	0.050	1.67
POM	Field cage	0.330	10.99
Total		0.42	13.9

Isotope	Q-value (keV)	Half-life (d)	Production rate (atoms/kg/d)		Activity after 2 yr exposure (μBq/kg)	Activity after 1 yr cooling (μBq/kg)
			Calc.	Expt. [31]		
^{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

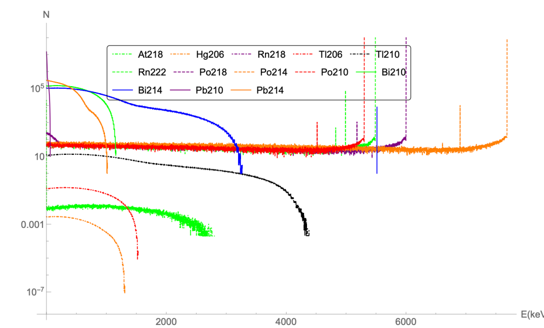
cosmogenic backgrounds in Cu



n-induced γ background spectrum



Energy spectra for various single-event and pile-up backgrounds with natural SeF_6 gas without further suppression using event topology information

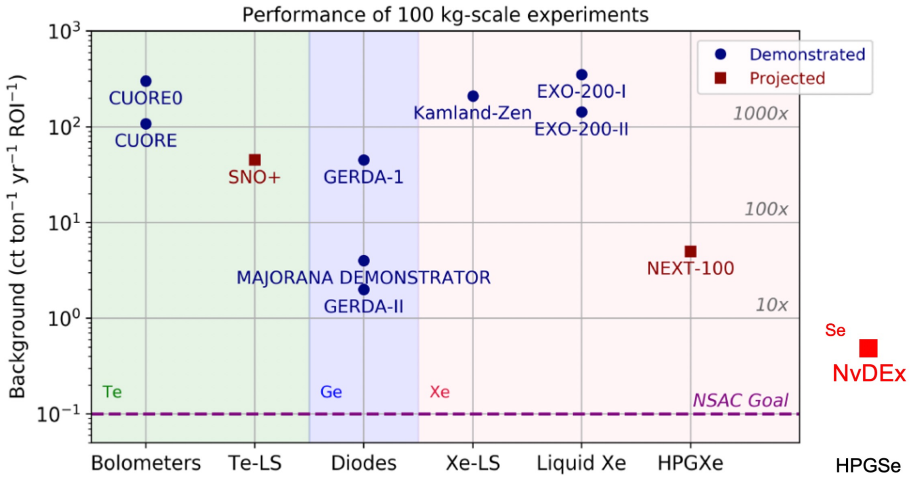


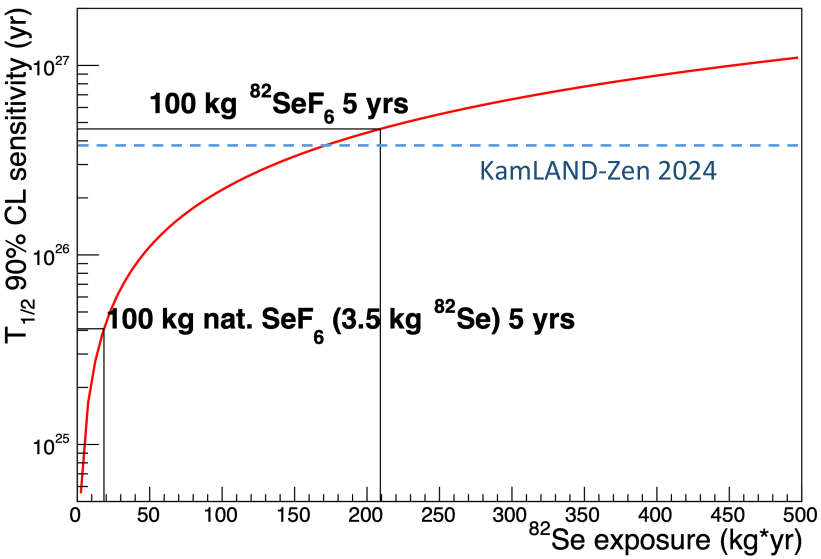
Background energy spectrum from the ^{222}Rn decay chain

- Completed preliminary simulation or upper limit estimation for various backgrounds
  - γ, neutron, cosmogenic, α, β, radon, μ, ν, $2\nu\beta\beta$

Background & sensitivity estimations

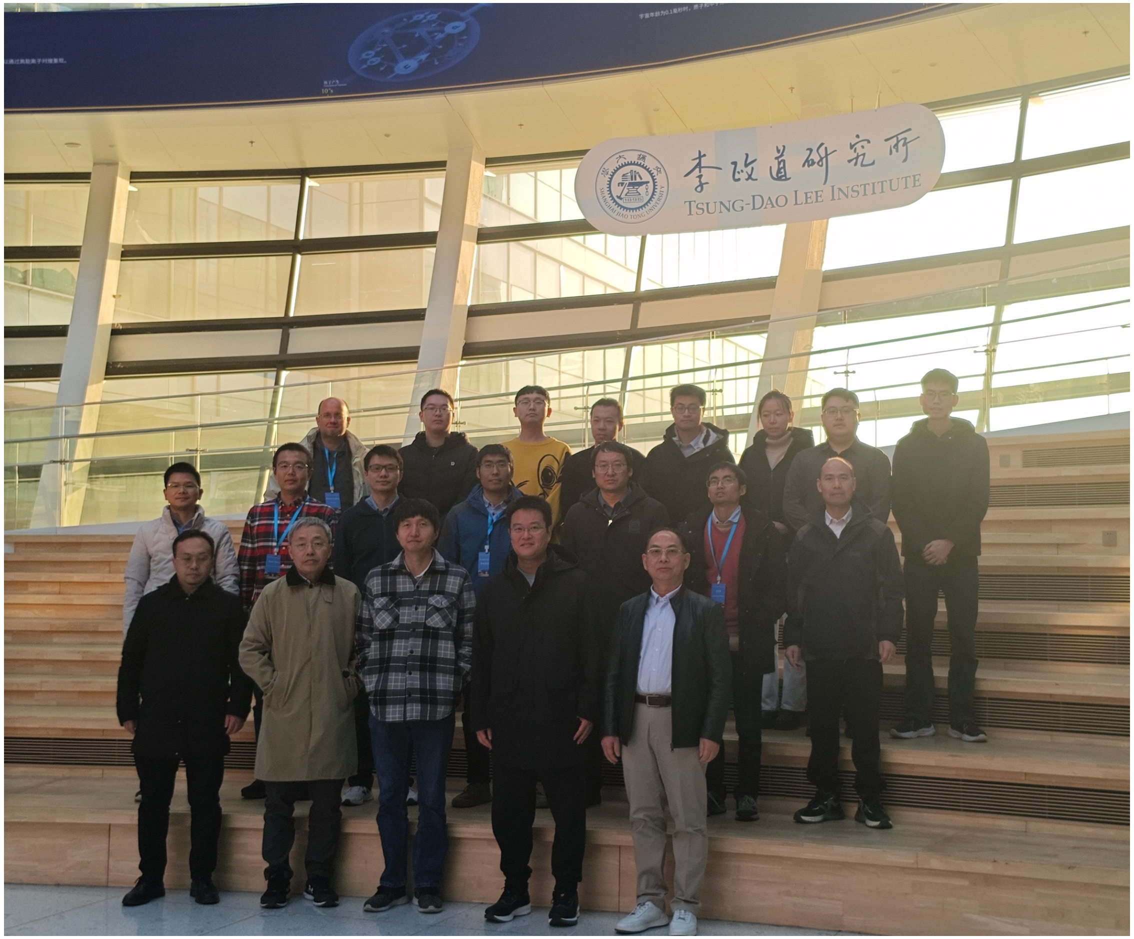
"100kg-class" experiments:





- ~<0.05 counts / year in ROI ⇒ ~0.5 cts / (ton yr ROI)
  - Below the world's major existing experiments
- $T_{1/2} > 4 \times 10^{26}$ yr at 90% CL with 100 kg $^{82}SeF_6$ 5 yrs, better than the current world record - KamLAND-Zen

NνDEx Collaboration



IMP
CENTRAL CHINA NORMAL UNIVERSITY
LANZHOU UNIVERSITY 1909
BERKELEY LAB
SHANGHAI ADVANCED RESEARCH INSTITUTE, CAS
SINAP
NORTH CHINA UNIVERSITY OF WATER RESOURCES AND ELECTRIC POWER 1951
SHANGHAI JIAO TONG UNIVERSITY 1896

- >30 collaborators from 9 institutes

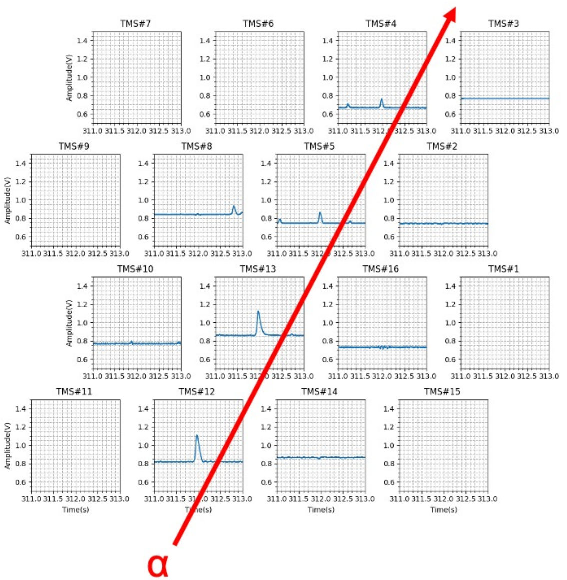
Welcome to join

Summary

- NνDEx concept combines advantages from the high Q value of ^{82}Se and TPC's ability to see event topology, using novel sensor technology
- Sensor chips reach $50e^-$ noise level (goal: $45e^-$)
- α particle track observed by a prototype TPC
- Very low background level expected: ~<1 ct / (ton yr ROI)
- ~ 4×10^{26} yr sensitivity expected with 100kg $^{82}SeF_6$ gas

Thanks ☺

Welcome to join



Future Plan

- NνDEx-100
  - 2025:
    - Verify the readout plane with self-developed sensor chips and obtain a reasonable energy resolution
    - Continue to apply for entering CJPL
  - 2026:
    - Engineering batch sensor chip tapeout
    - Complete the CJPL admission application process
  - 2027:
    - System assembly and commission, begin taking data (using SF_6 gas, w/o airtight cleanroom).
- NνDEx-100 with $^{82}SeF_6$ & NνDEx-Xt in the future