Status and prospects of REactor neutrino COherent scattering Detection Experiment (RECODE)

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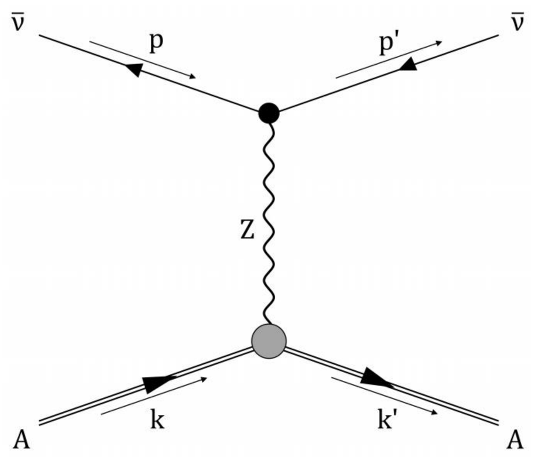
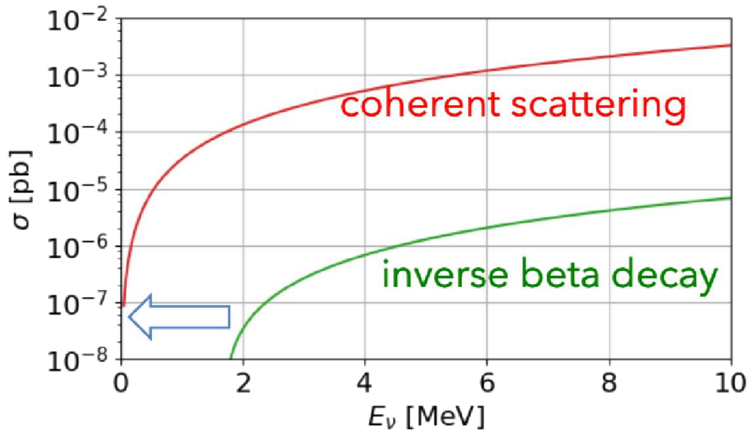
Coherent Elastic Neutrino-Nucleus Sacttering (CEvNS)

Neutrinos interact with nucleus as a single particle

- Dominant process for $E_\nu \lesssim 50\text{MeV}$
- Large cross section (10^{-16} barn) and low recoil energy (keV)



$$\frac{d\sigma}{dE_R} = \frac{G_f^2}{4\pi}\left[N - (1 - 4sin^2\theta_W)Z\right]^2 F^2(q) m_N \left(1 - \frac{m_N E_R}{E_\nu^2}\right)$$



Significance of CEvNS

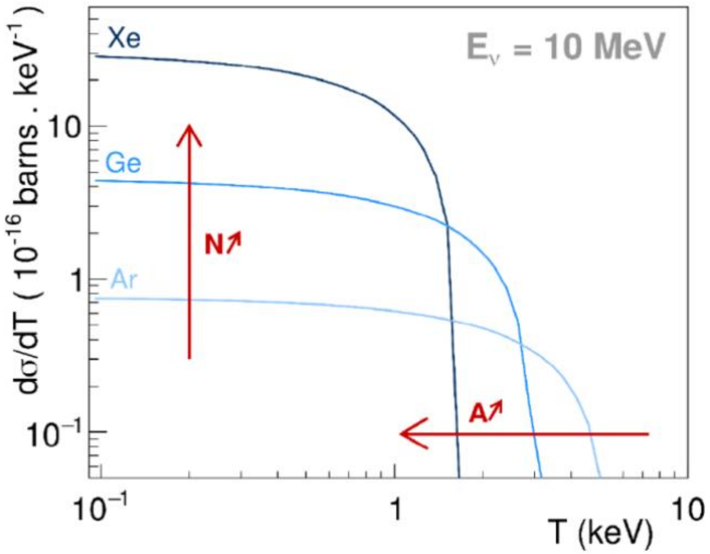
- Verification of Parameters in the Standard Model
  (e.g. Weinberg angle θ_W)
- Physics Contributions Beyond Standard-Model (BSM)

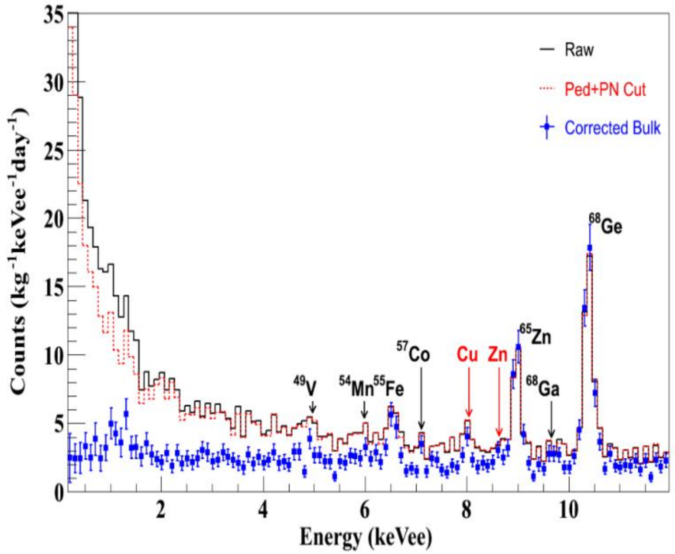
CEvNS detection by Germanium

■ Advantage of Germanium detector in CEvNS detection

- ➢ Relavant m_N and R_N for CEvNS interaction
- ➢ Low energy threshold and better resolution

$$\frac{d\sigma}{dE_R} = \frac{G_f^2}{4\pi}\left[N - (1 - 4sin^2\theta_W)Z\right]^2 F^2(q) m_N \left(1 - \frac{m_N E_R}{E_\nu^2}\right)$$





CDEX: using PPC-Ge Detectors for Dark Matter Detection

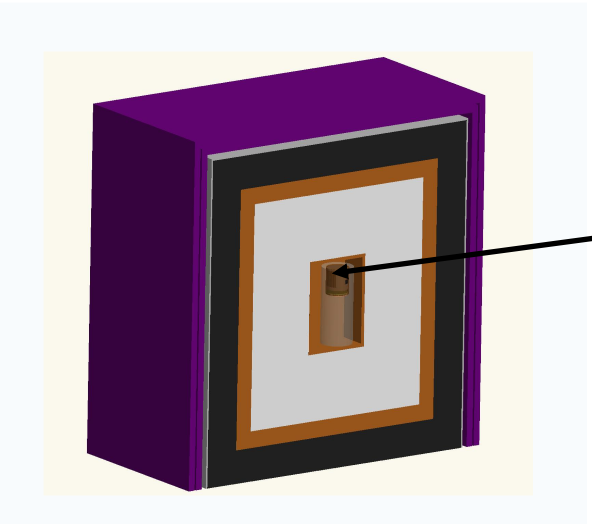
CDEX-10 bkg spectrum@CJPL, ~2 cpkkd@2keV, threshold 160 eVee

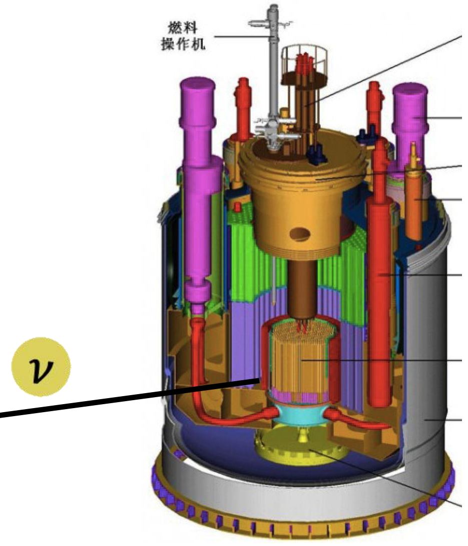
PRL 120,241301 (2018)

RECODE

- RECODE (**RE**actor neutrino **CO**herent scattering **D**etection **E**xperiment) with PPCGe detectors
- For commercial NPP, operation cycle (ON) >> maintenance period (OFF), resulting in large statistical uncertainty in OFF data
- **Joint measurement (Far Site + Near Site)** and analysis can reduce systematical uncertainty, but requires well bkg understanding

- Project goals：
  - Two Ge arrays（Far Site_22m + Near Site_11m /Very Near Site_7m, ~10kg in total）
  - Energy threshold ~1 keVnr (~160eVee)





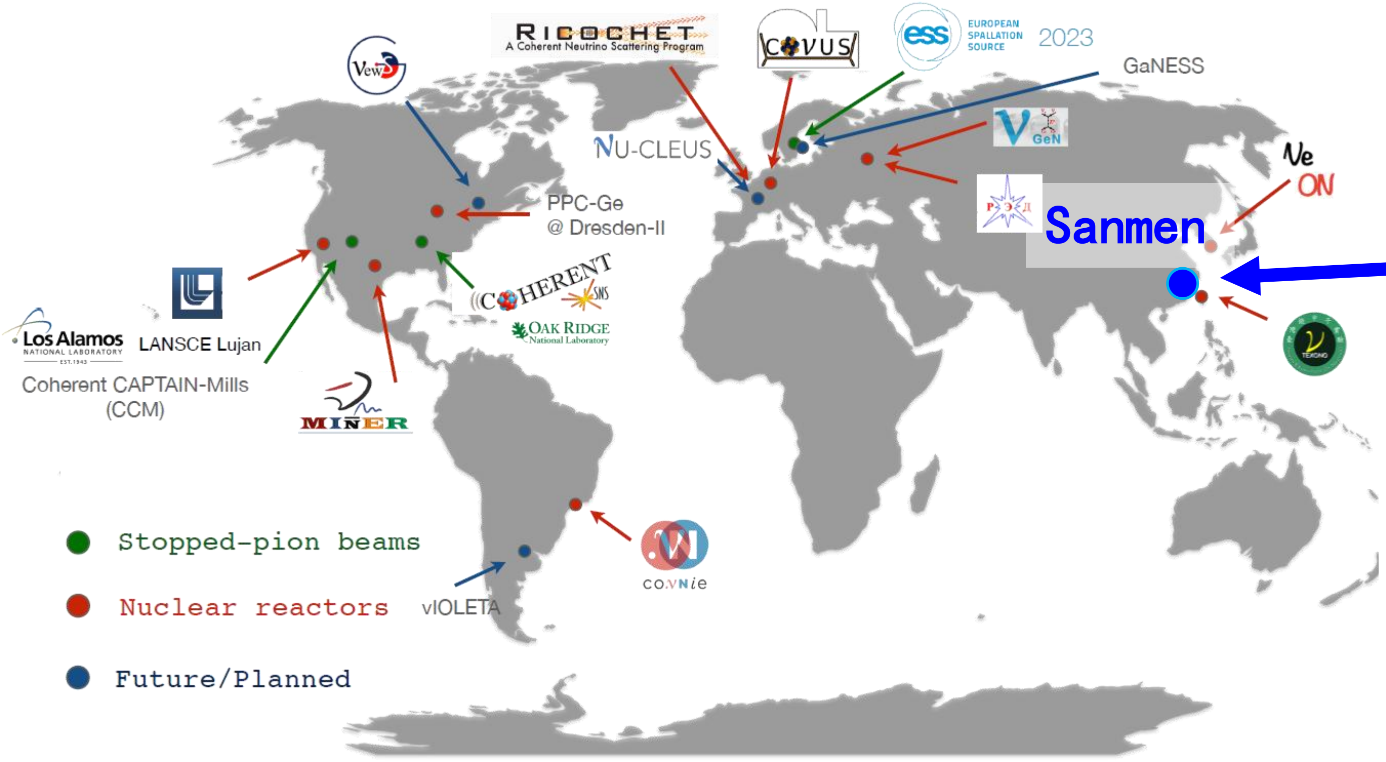
Reactor

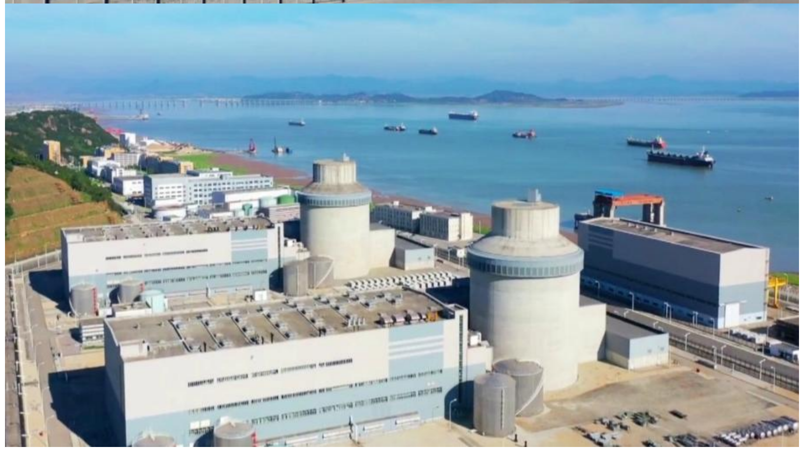
Neutrino flux ~$10^{13}/cm^2/s$

RECODE Location

Sanmen Nuclear Power Plant (AP1000) @ Zhejiang, China

- Thermal power 3.4 GWth, ~22m /11m /7m from the core
- Neutrino flux > 1.4 × 10^{13} $cm^{-2}s^{-1}$



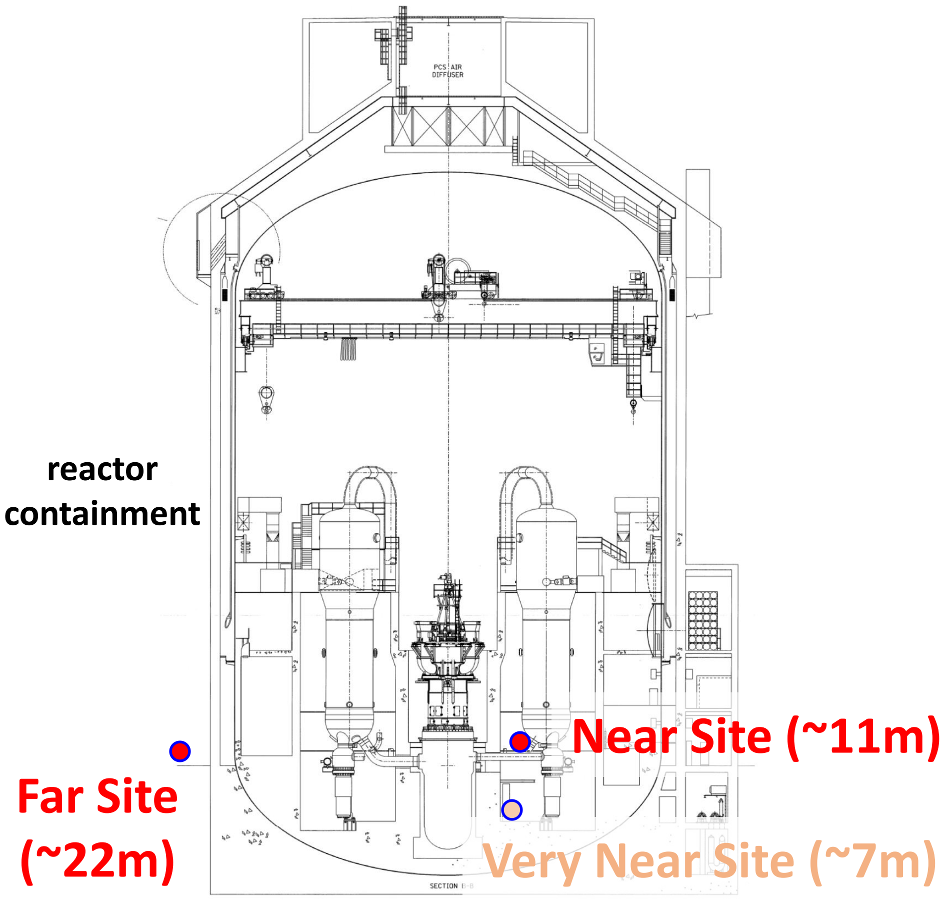


Carla Bonifazi, TAUP 2021

RECODE Location

- In the first phase, it will be carried out at the Far Site (~22m) and Near Site (~11m);
- The Very Near Site (~7m) serve as an option for future detector debugging after long-term stable operation;
- No entry is allowed during the 18-month operation period, and reactor neutron background needs to be considered;
- The equivalent water depth coverage thickness at each site is being evaluated;

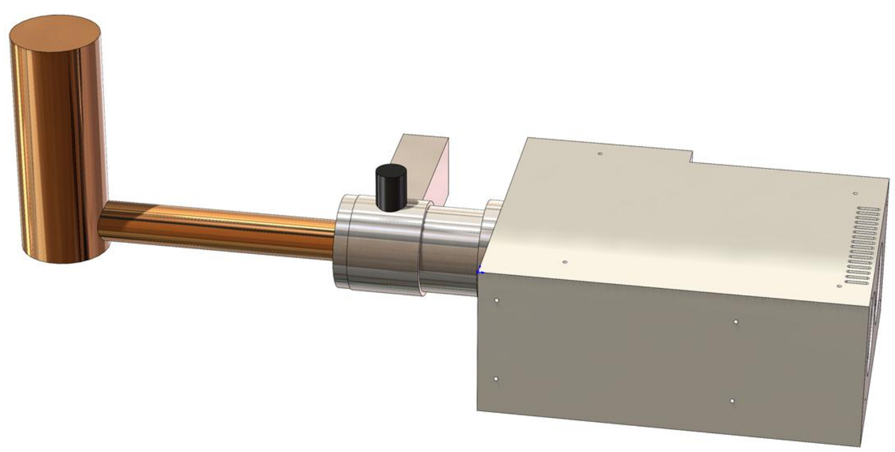
Distance to core	Thermal power	Neutrino Flux
FS ~ 22m	3.4GWth	$1.4*10^{13}$ ν/cm²/s
NS ~ 11m	3.4GWth	$5.6*10^{13}$ ν/cm²/s
VNS ~ 7m	3.4GWth	$1.4*10^{14}$ ν/cm²/s



RECODE Location

RECODE Detector

Near Site: EC-PCGe



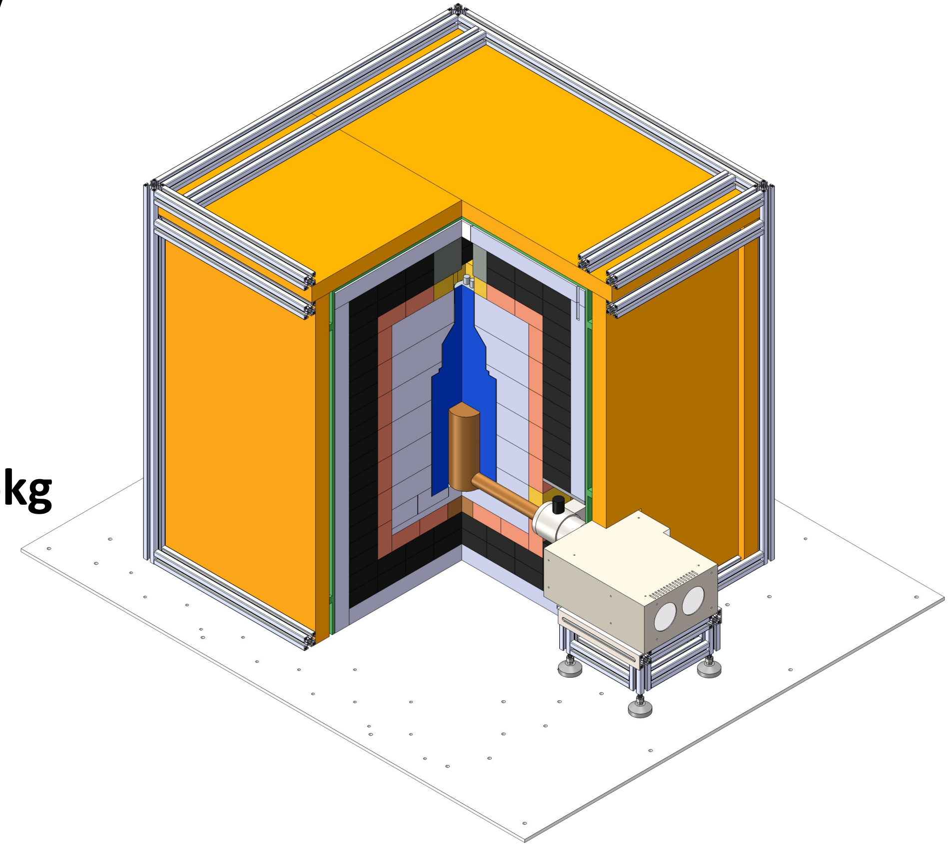
- Electrical cooled HPGe (E1)
- Crystal mass: 500g
- No need to regularly replenish liquid nitrogen
- Good long-term stability

Far Site: LNC-PCGe

- Liquid nitrogen cooled cold-tip detector (CDEX-1B)
- Crystal mass: 1008g
- Further understanding to the detector response
- Good long-term stability

Shielding Design

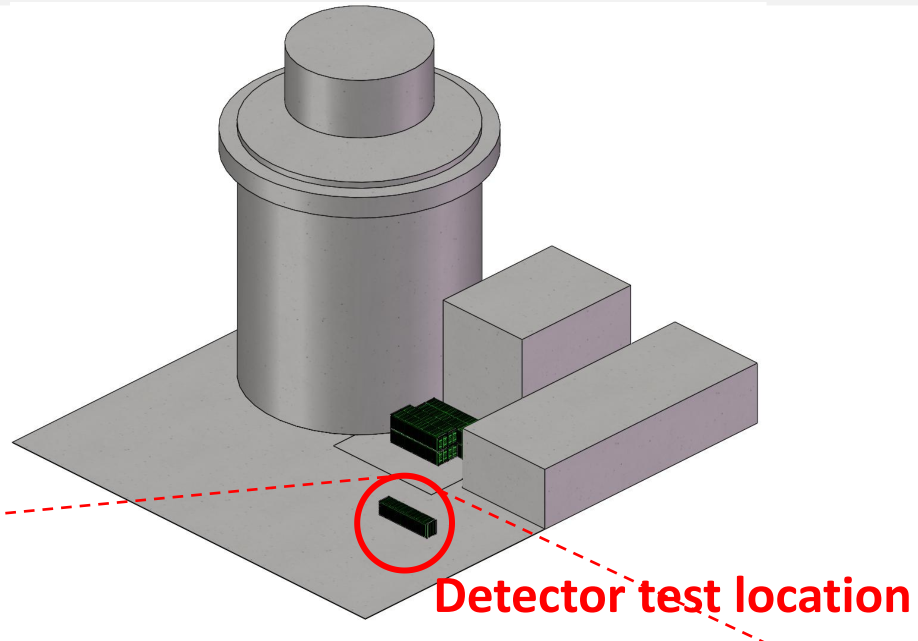
- **Shielding material and geometric optimized by Geant4 simulation**
- **Shielding size: 1m(W)*1m(L)*1.1m(H)**
- **From outer to inner:**
  - ✓ Plastic scintillator muon veto (3 cm)
  - ✓ Aluminium Structure (4 cm)
  - ✓ Acrylic box (0.8 cm), **N_2 purging to suppress radon bkg**
  - ✓ Polyethylene (5 cm)
  - ✓ Lead (10 cm)
  - ✓ Copper (5 cm)
  - ✓ Polyethylene (~15 cm)
  - ✓ NaI anti-Compton Detector (5 cm)



Structure model: EC-PCGe

Detector test: outside the reactor containment

- Test for detector stability, shielding performance and the muon veto system
- Open space within the Sanmen NPP, >60 meters away from the reactor core;
- Two detectors： Same situation & cross-checking;



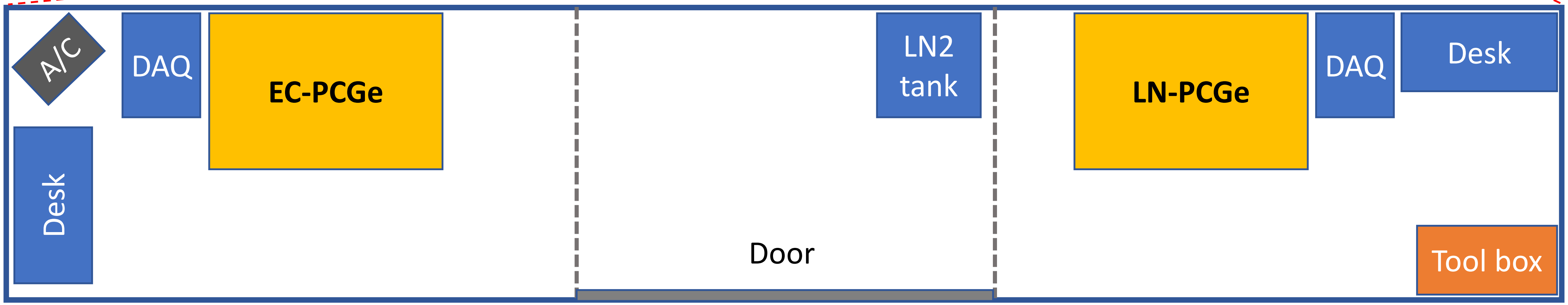


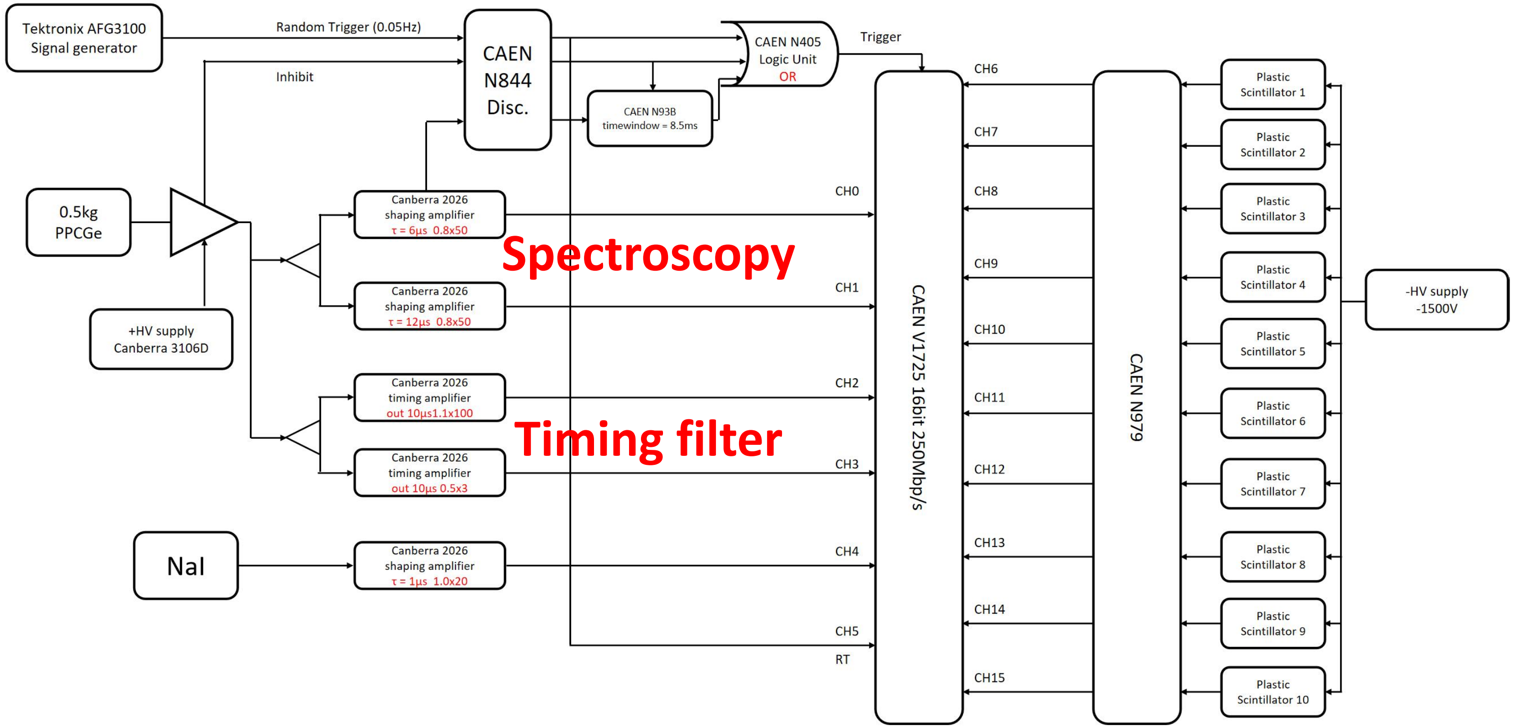
Diagram of the 40-ft container outside the containment of Sanmen NPP

Detector test: EC-PCGe

- Construction: 2025.04
- Stable Run: 2025.04-2025.06 (25 kg•day exposure)
- CAEN V1725 for digitalization (16 channel used)

EC-PCGe system
Muon detector installed in the container

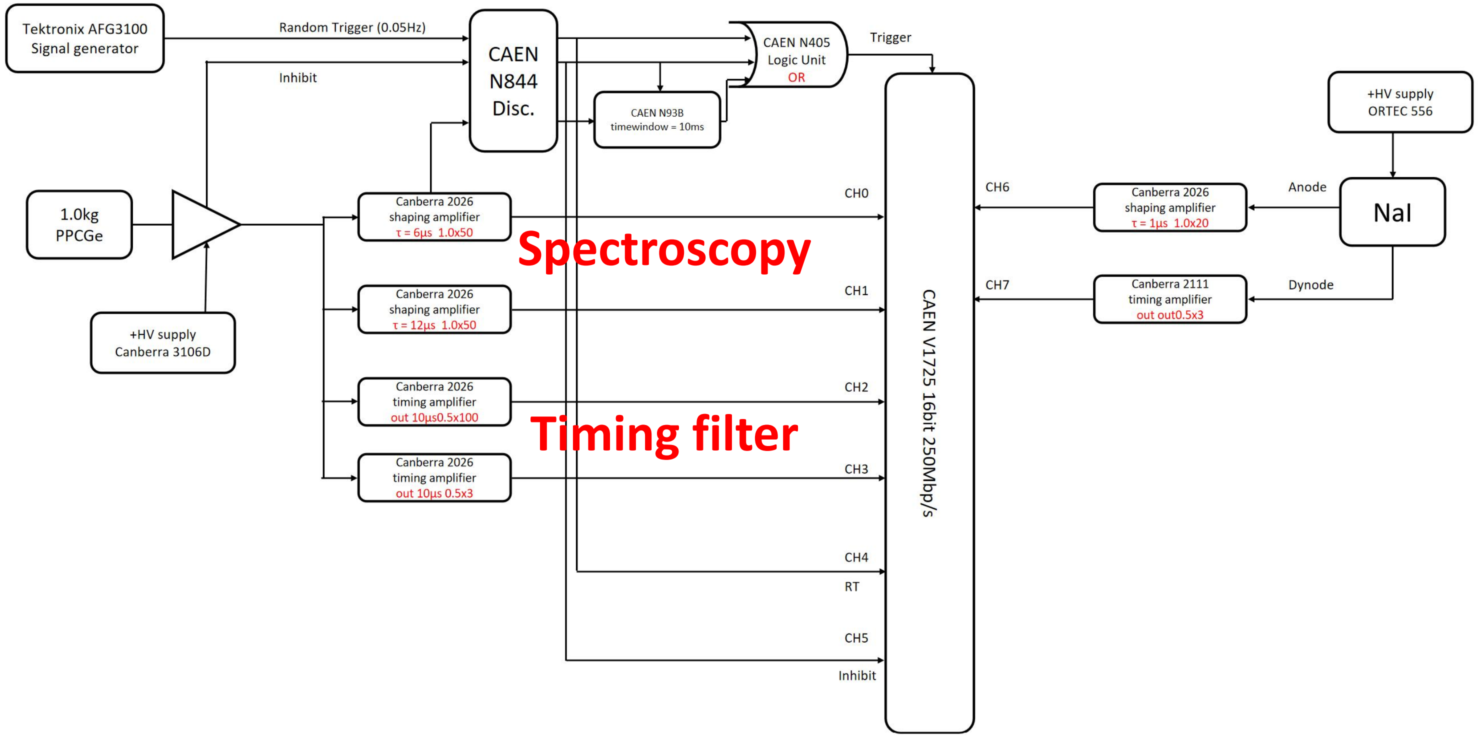
DAQ system



Detector test: LN-PCGe

- Construction: 2025.05
- Stable Run: 2025.05-2025.07 (28 kg•day exposure)
- CAEN V1725 for digitalization (8 channel used)

DAQ system



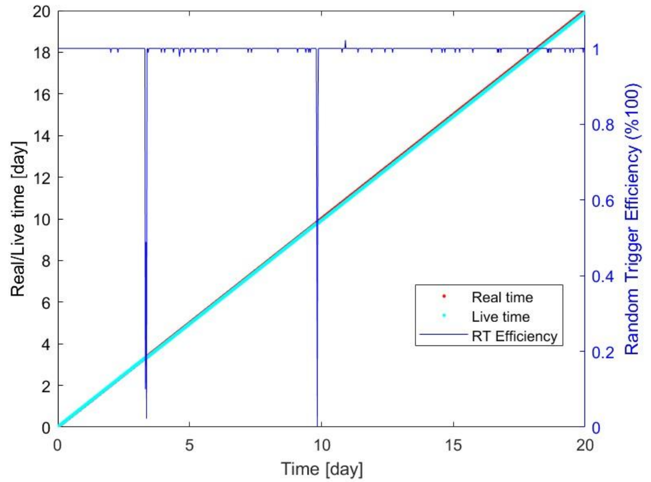
LNC-PCGe system
No Muon detector
in the container

Detector test: Trigger Rate check

- Trigger rate reveal the stablity of detector
- Random trigger efficiency: RT num detected/generated
- Inhibit trigger: reveal the leakage current level
- Germanium self trigger: Affected by environmental noise*

  *Effectively rejected by data filter

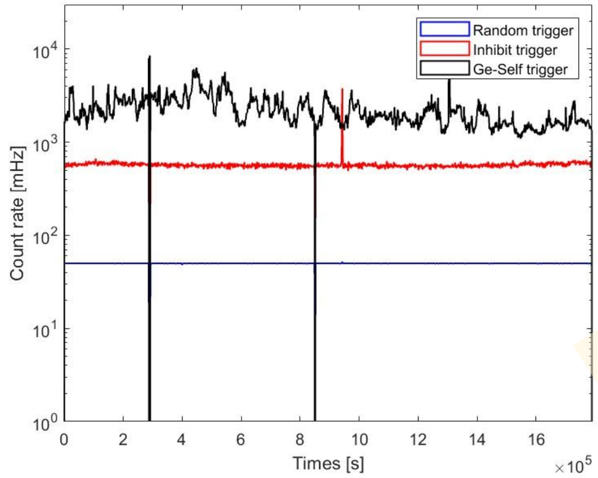
  *Time check&cut after filter

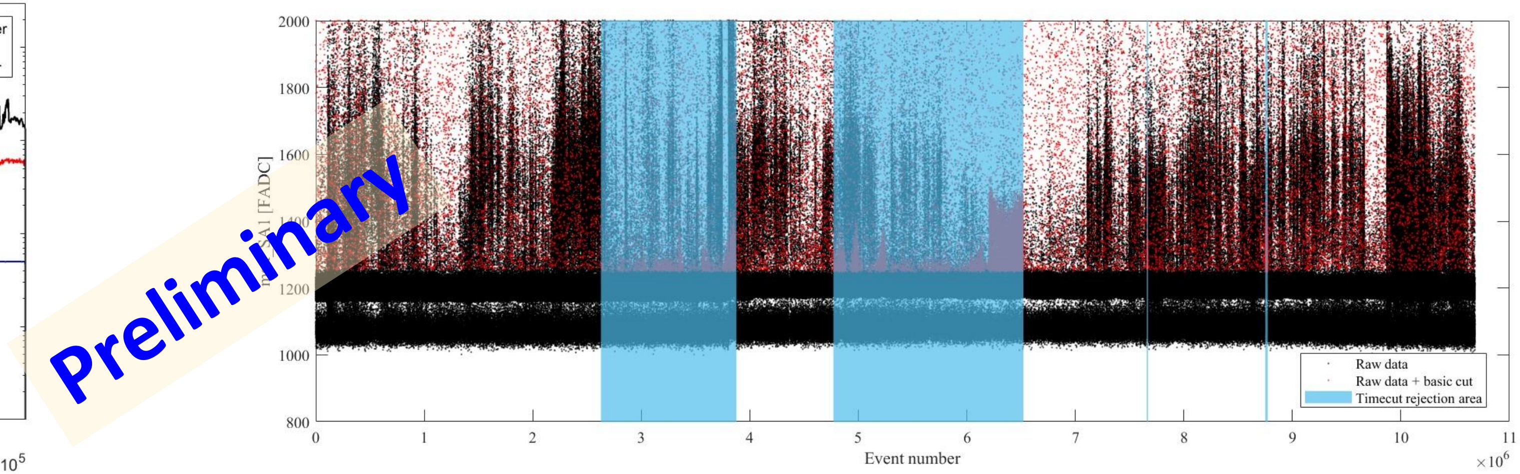


Trigger rate @EC-PCGe

Timecut after filter @EC-PCGe

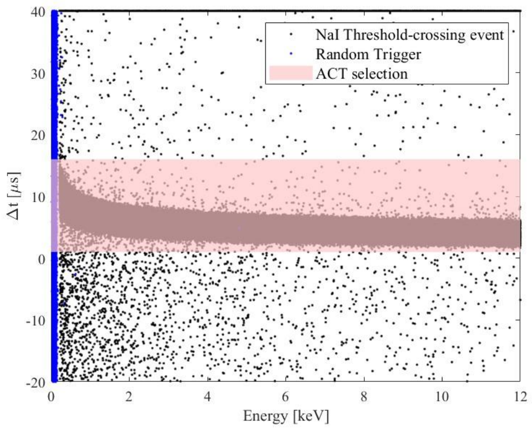
RT efficiency&Live time @EC-PCGe

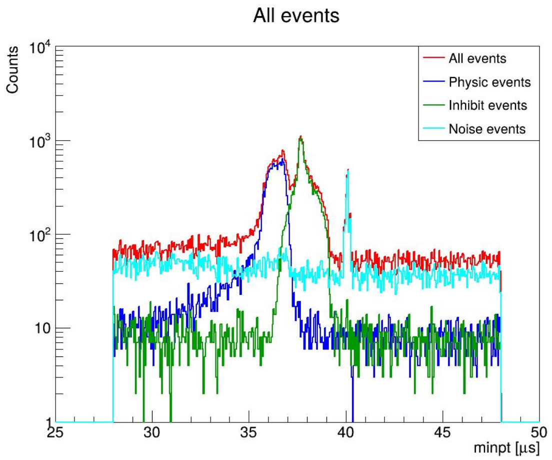




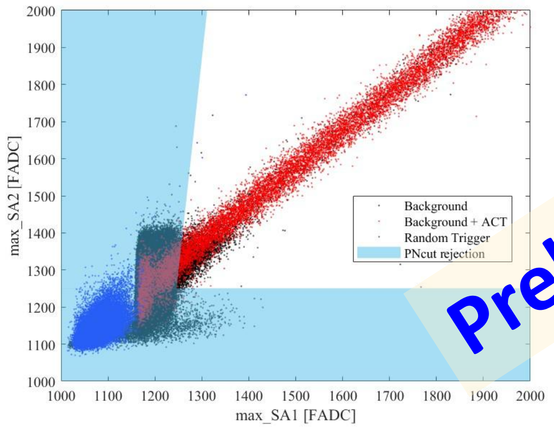
Detector test: Data Analysis

- Time Window select for coincidence event
- Accidental coincidence detemined by time window, calculated&corrected by the RT events

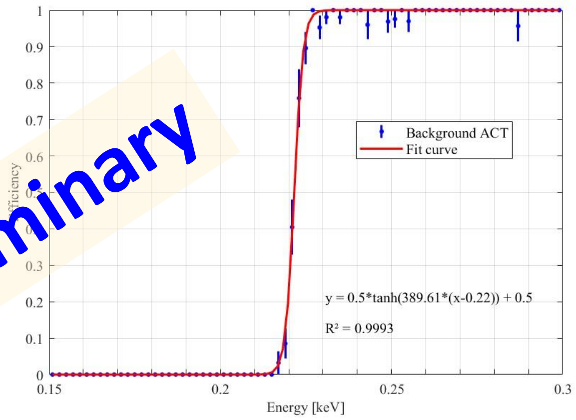




Coincidence event selection @EC-PCGe



PNcut@EC-PCGe



Energy threshold:

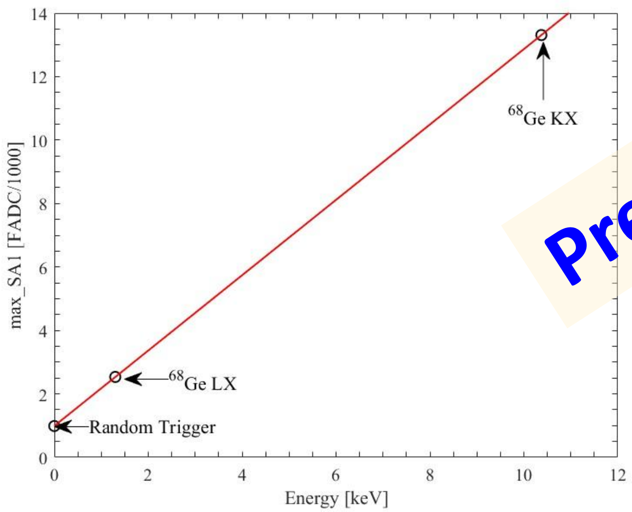
0.22 keV (50%) for EC-PCGe

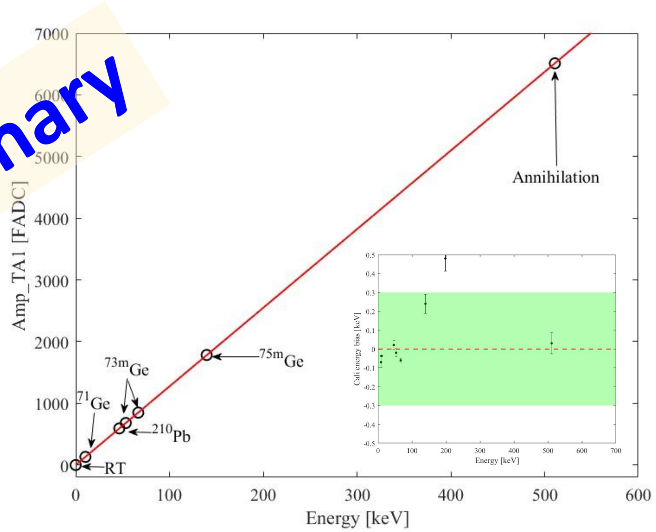
0.21 keV (50%) for LNC-PCGe

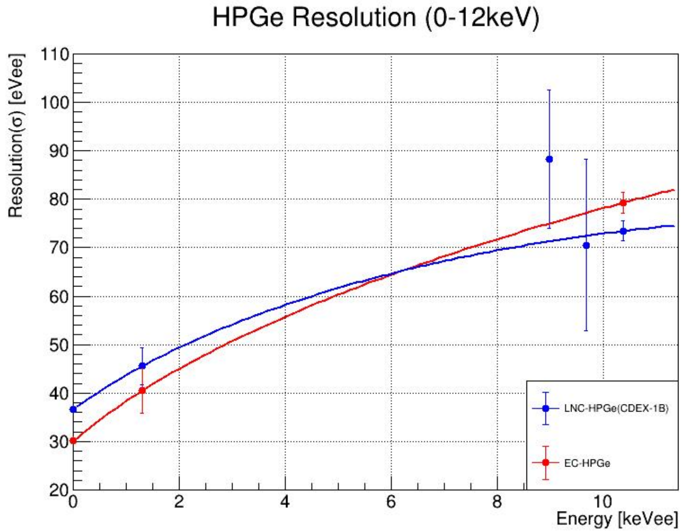
- Data filter including pedcut, mincut, energycut and PNcut
- PNcut determines the threshold, Fitted by the ACT survival rate after PNcut

Calibration & Resolution

- **Energy Calibration**
  - Low-energy region: Characteristic X-ray peaks from cosmogenic radionuclides
  - High-energy region: Full-energy peaks of gamma rays
- **Energy Resolution**
  - Gauss fit by CERN RooFit (unbinned data & Maximum likelihood)
  - Resolution (σ) at 10.37 keV: 79.2 eV (EC-PCGe) & 73.4 eV (LNC-PCGe)







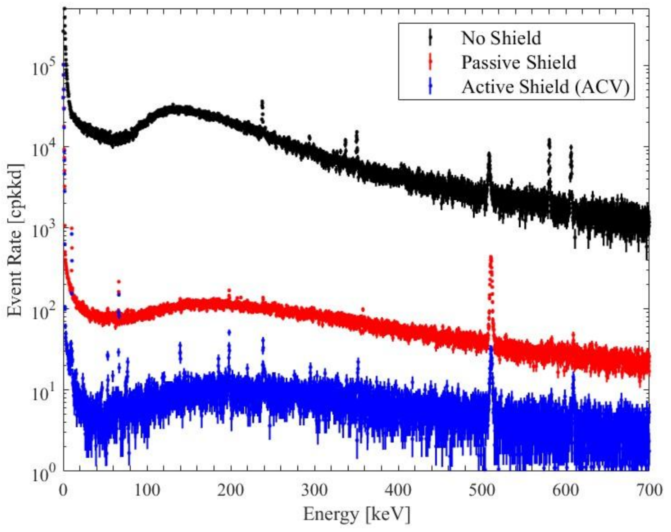
Calibration (0-12keV)
@EC-PCGe

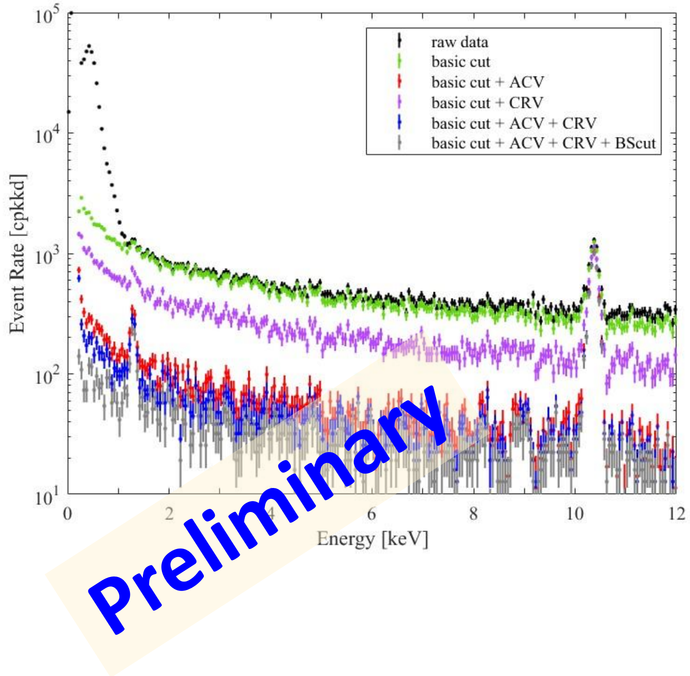
Calibration (0-700keV)
@EC-PCGe

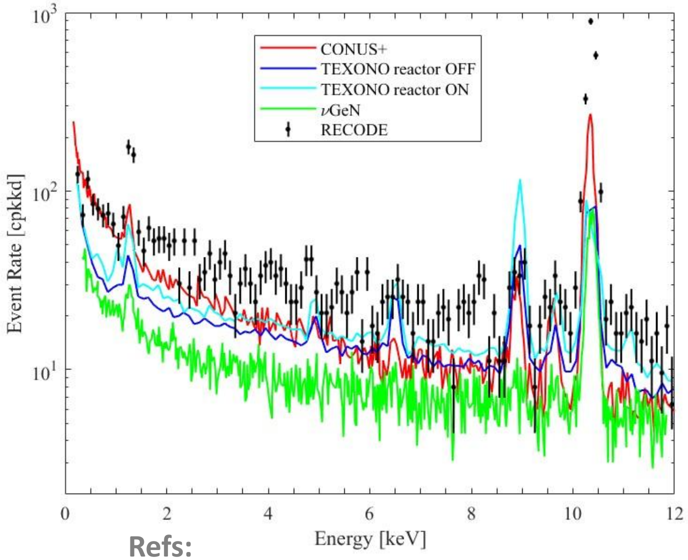
Resolution

Spectrum analyse

- Passive/Active Shielding suppress the bkg by 2/1 order of magnitude
- Anti-coincidence capability of NaI detector outperforms that of plastic scintillator (CR-veto) detectors;
- In addition to CR-veto detectors, NaI is also necessary to further reduce the bkg level;
- Comparisons with other experiments: the shielding performance met expectations without additional concrete coverage.



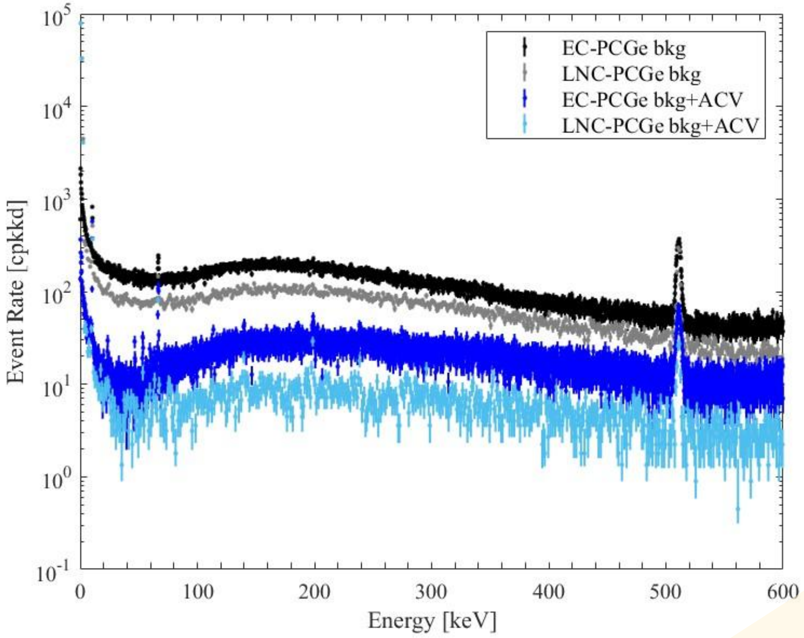


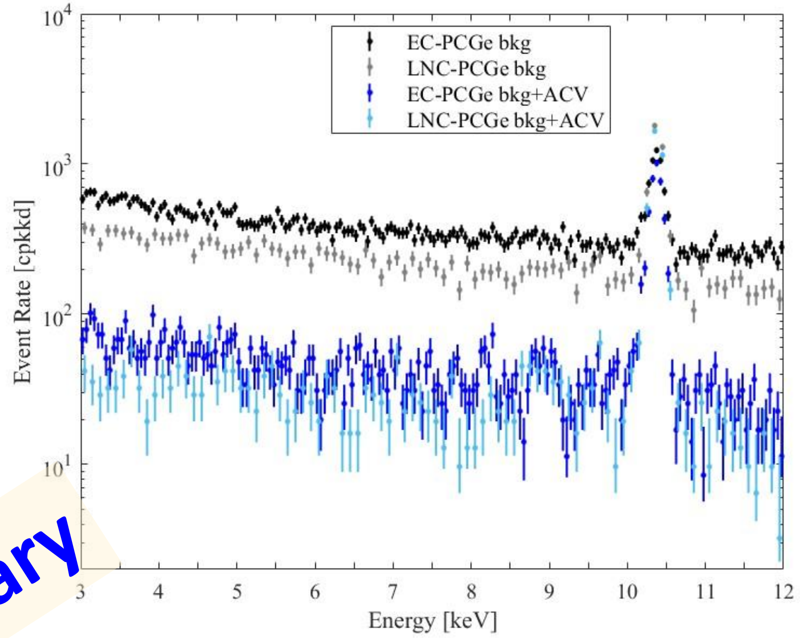


Refs:
CONUS+: 2501.05206
TEXONO: PRL 134,121802 (2025)
vGeN: CPC 49, 053004 (2025)

Spectrum analyse-2

- The experimental data from two detectors (with different crystal sizes) were compared;
- It was found that larger crystal sizes lead to lower background event rates. This is due to the reduction in the number of muon events per unit mass/crystal volume;

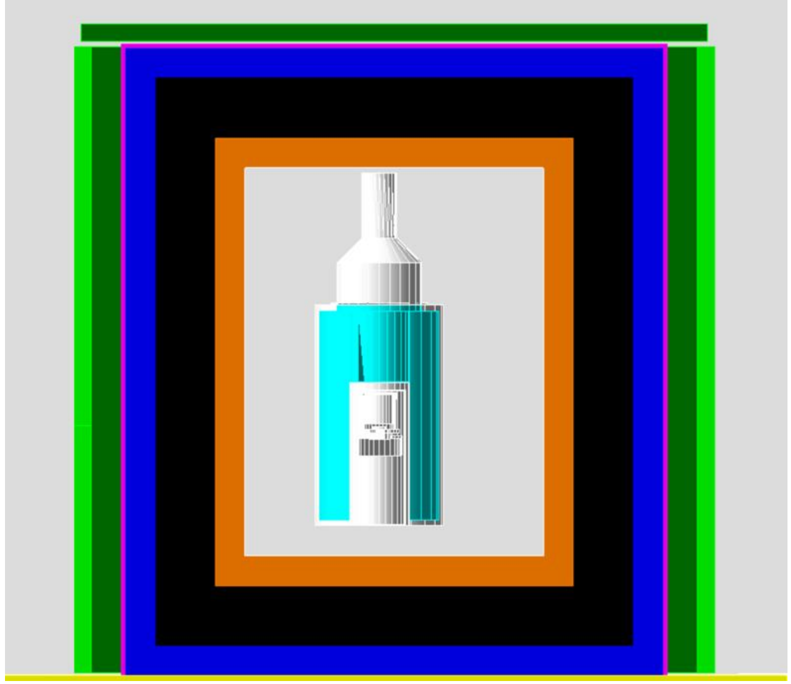


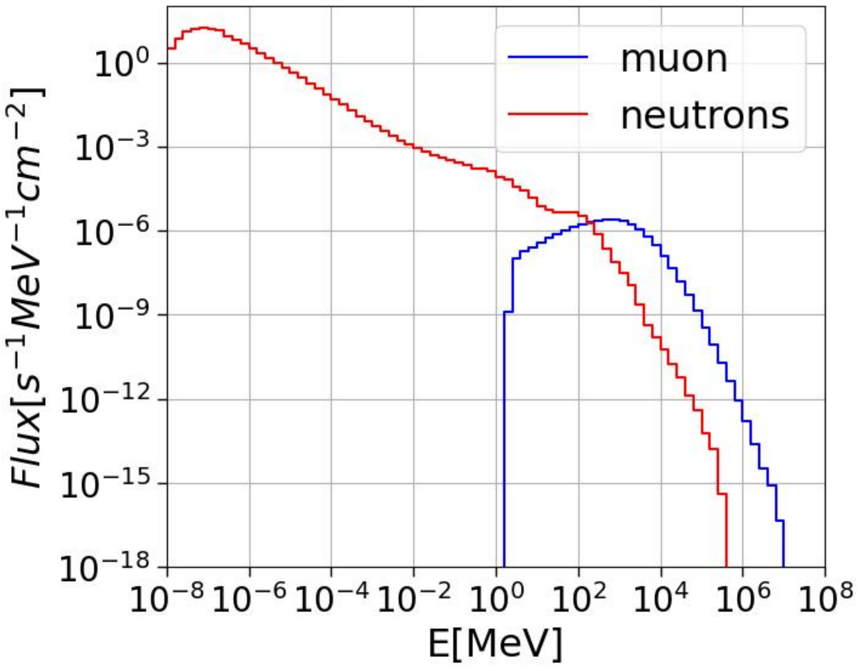


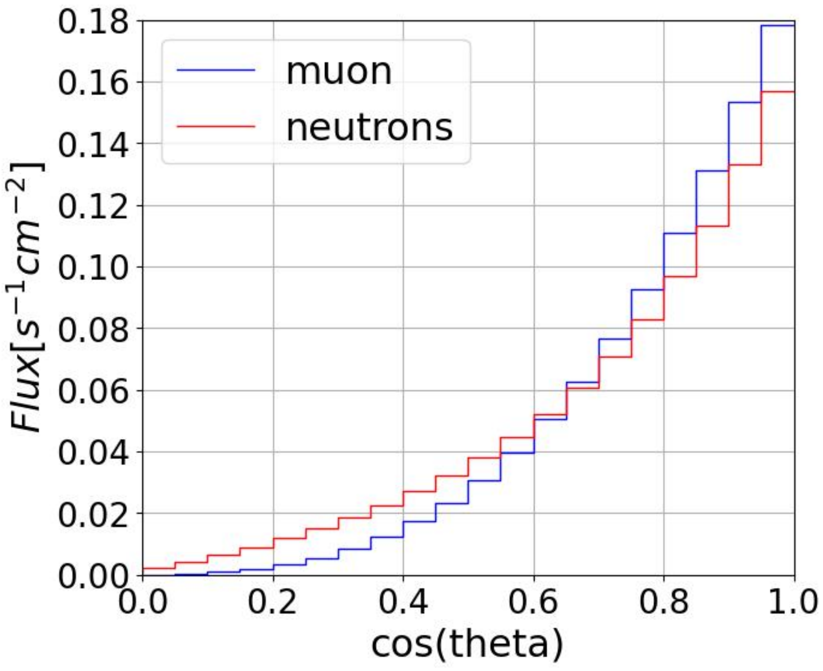
Preliminary

Background understand—Simulation

- **Geant4 Monte Carlo simulation, with detector&shield geometry established;**
- **Local cosmic ray information gained by CRY software;**
- **Flux of μ: 104.3$/s/m^2$, n:13.3$/s/m^2$, Direction mainly from the sky.**

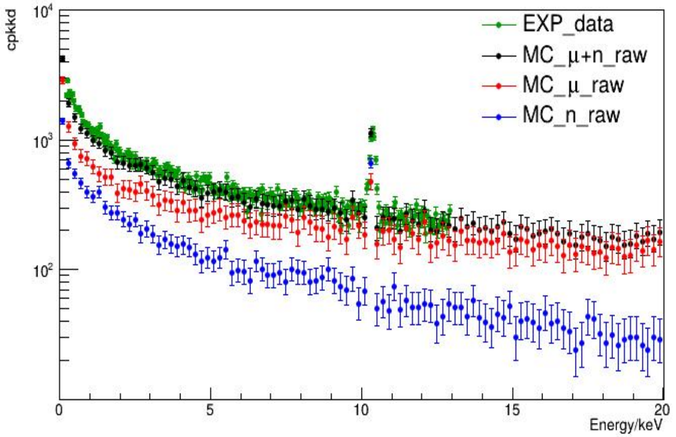




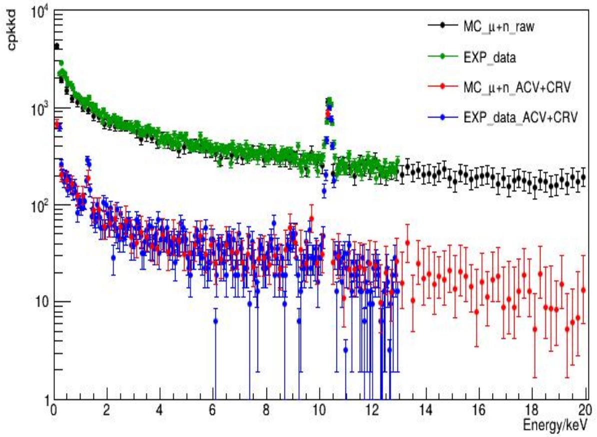


Simulation spectrum

- Simulation spectrum fits pretty well with experimental spectrum, so as the anti-coincidence events;
- In ROI ([0.16-0.5] keV), μ-induced bkg is 2 times than n-induced bkg;
- Anti-coincidence is more effective to μ-induced bkg, resulting a neutron domination in vetoed bkg



Bkg level (cpkkd) @[0.16-0.5] keV	μ-induced bkg	n-induced bkg	Total	neutron proportion
Passive shield	1230.33±84.89	674.87±39.17	1905.20±93.50	35.42%
ACV	101.08±23.24	171.92±19.48	273.00±30.32	62.97%
CRV	361.68±45.33	605.37±37.07	967.05±58.56	62.60%
ACV+CRV	63.18±18.04	160.33±18.79	223.51±26.05	71.73%



Summary

- RECODE, located at the Sanmen NPP in Zhejiang, China, uses PCGe detectors to jointly measure the reactor neutrino CEvNS at multiple experimental sites;
- RECODE has finished the first ground test, the performance of detector and shielding met our expectation;
- Simulations are proceeded at the same time, helping us understand the background;
- The EC PCGe will enter the containment in October. By then, the platform outside the containment (Far-Site) will also be in place;
- Upgrades of EC PCGe (70X70mm, 1430g) from G3 to G4 is underway (by end of year);

Thank you!