



Status and prospects of RECODE program with PPC Germanium detector

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Neutrino Scattering: Theory, Experiment, Phenomenology (vSTEP 2025)

Oct 24 - 27, 2025 @ Beijing

OUTLINE



- 1、 RECODE Program**
- 2、 Ground test at Sanmen NPP**
- 3、 Prospects and summary**

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

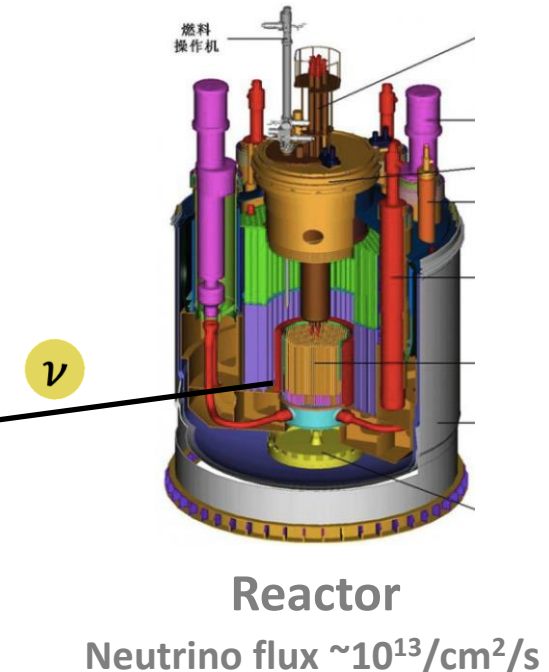
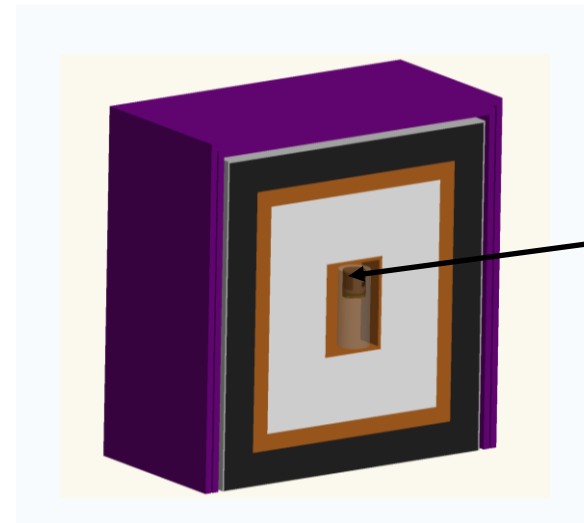
■ **Joint measurement (Far Site + Near Site)** and analysis can reduce systematical uncertainty, but requires well bkg understanding

■ Project goals:

- Two Ge arrays (Far Site + Near Site /Very Near Site, ~10kg in total)
- Energy threshold **~1 keVnr (~160eVee)**



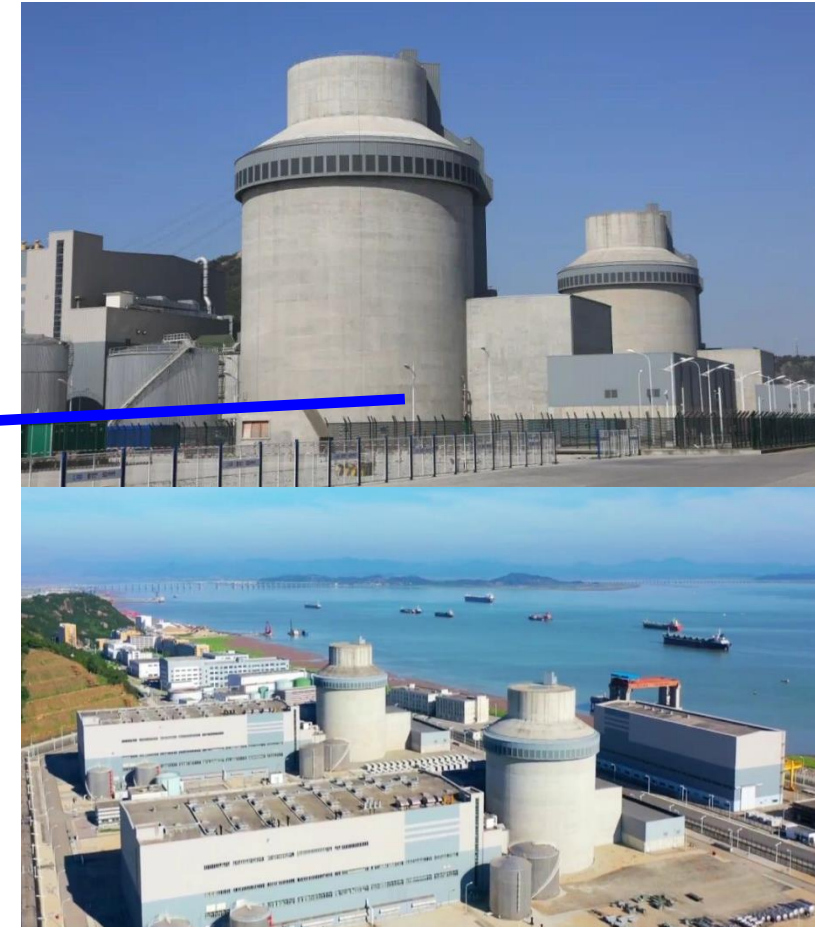
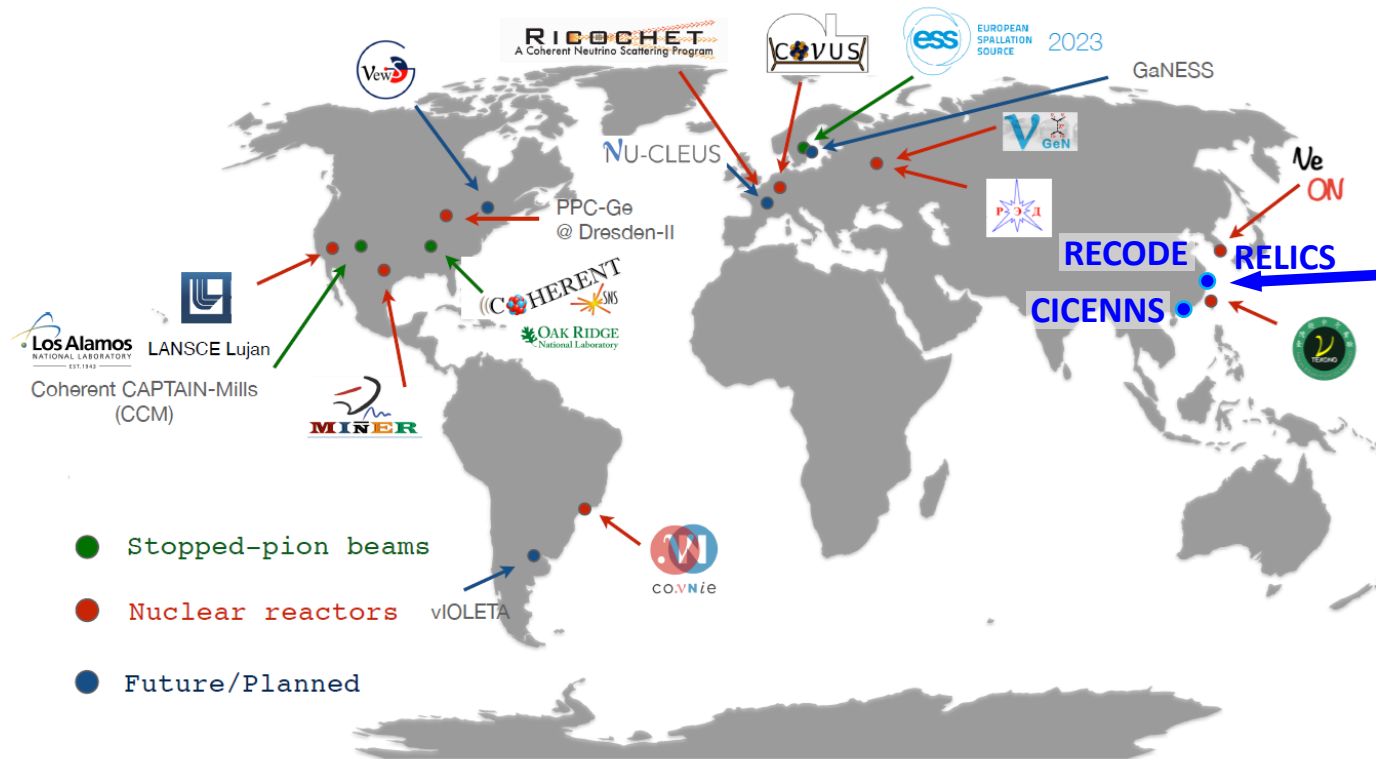
三门核电有限公司
Sanmen Nuclear Power Co., Ltd.



RECODE Location

Sanmen Nuclear Power Plant (AP1000) @ Taizhou, Zhejiang, China

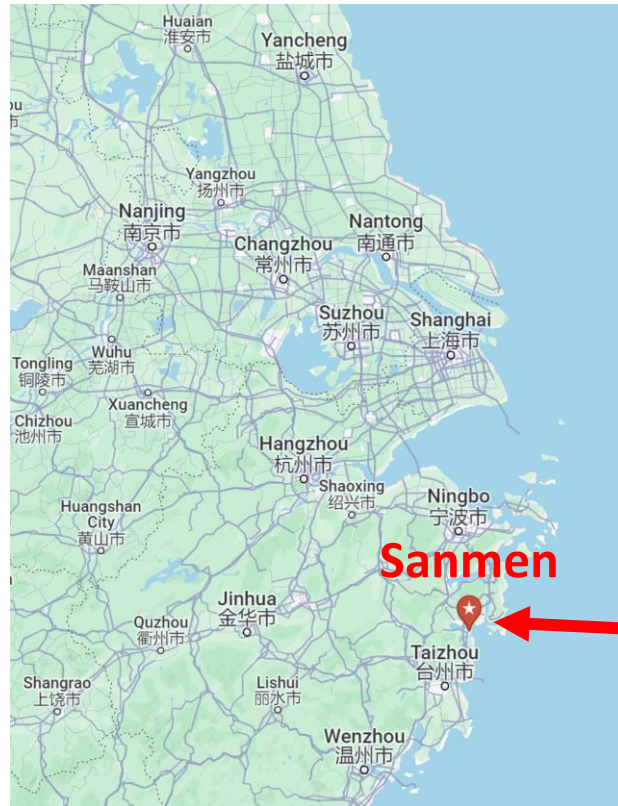
- Thermal power 3.4 GWth, ~22m /11m /7m from the core
- Neutrino flux $> 1.4 \times 10^{13} \text{ cm}^{-2}\text{s}^{-1}$



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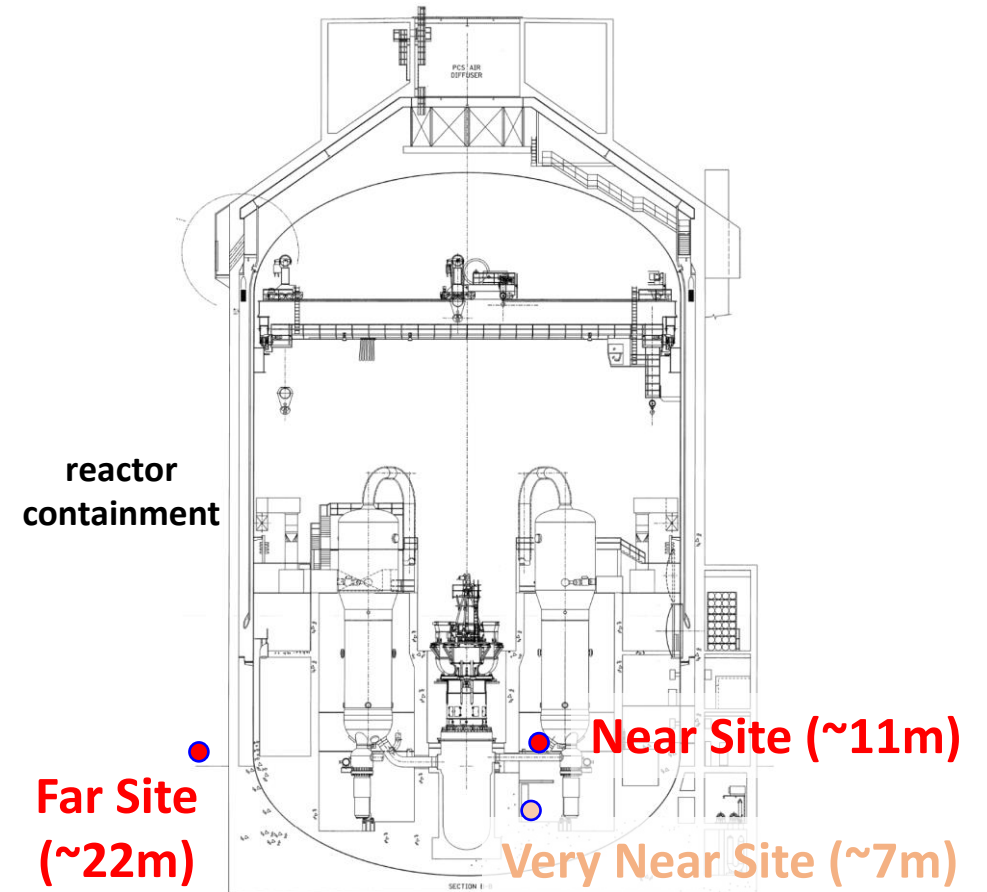
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RECODE Location

- 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;

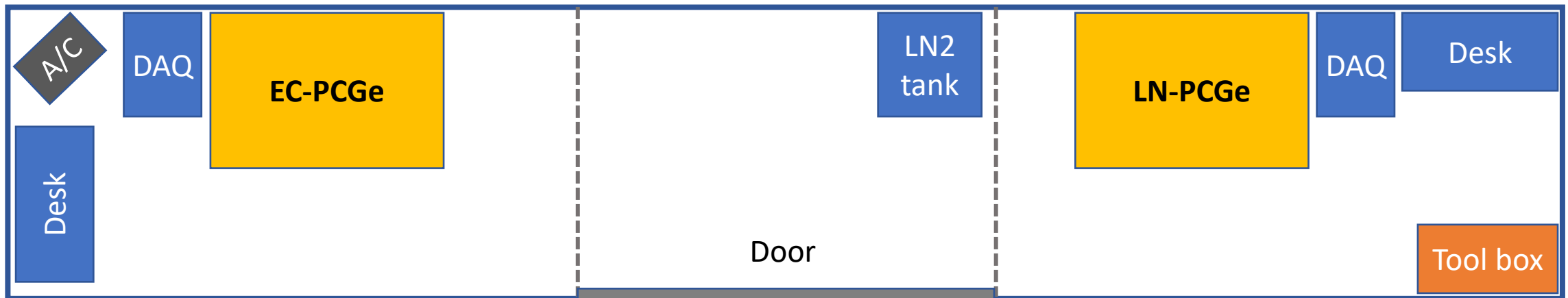
Distance to core	Thermal power	Neutrino Flux
FS ~ 22m	3.4GWth	$1.4 \cdot 10^{13}$ v/cm ² /s
NS ~ 11m	3.4GWth	$5.6 \cdot 10^{13}$ v/cm ² /s
VNS ~ 7m	3.4GWth	$1.4 \cdot 10^{14}$ v/cm ² /s



RECODE Location

Ground test outside the reactor containment

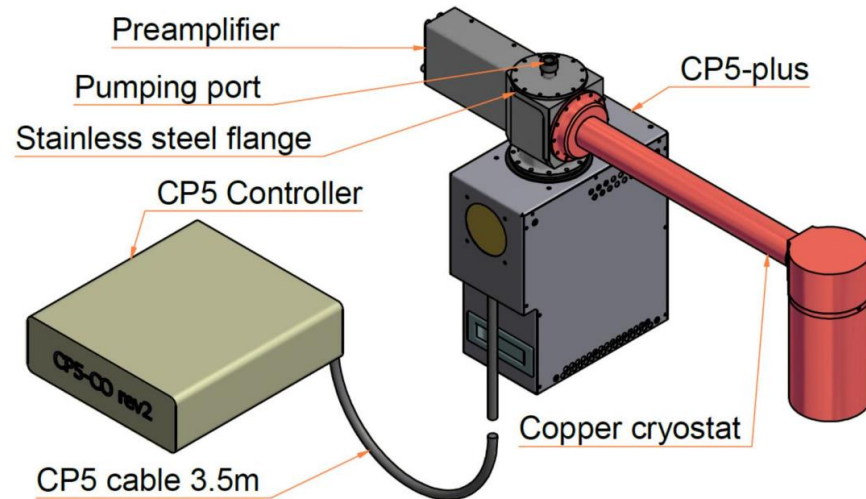
- Ground test for shielding performance and the muon veto system, in a 40-ft container outside the containment of Sanmen NPP;
- Ground test was conducted on an open space within the Sanmen NPP, approximately 35 meters away from the reactor containment;
- Two sets of detectors were simultaneously tested and cross-checking;
 - ✓ EC-PCGe (0.5 kg), will be moved to Near-Site
 - ✓ LN-PCGe (1 kg, CDEX-1B), will be moved to Far-Site when the platform is ready



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

EC PCGe for Near Site

From HT Wong



Electric cooled HPGe

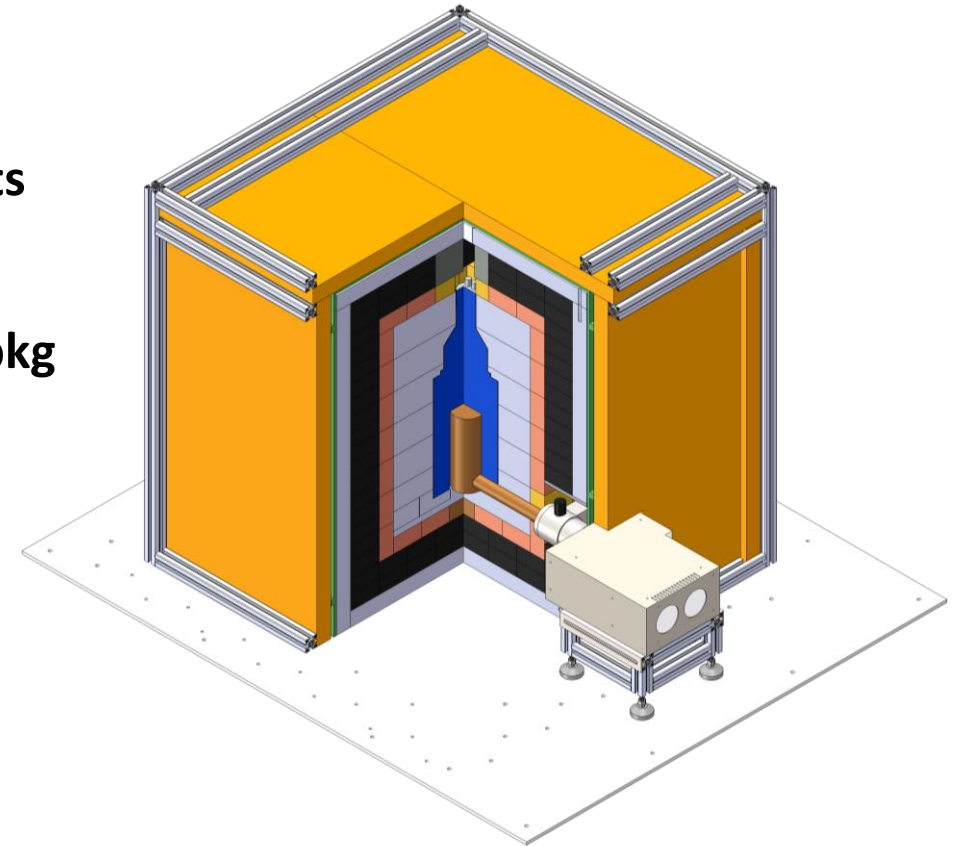
Mass (g)	Pulsar FWHM (eV _{ee})	Threshold (eV _{ee})
500	70	200
900	70	~230
1430	~60	~160
1430	70	200

Advantages of electrical cooled HPGe:

- ✓ No need to regularly replenish liquid nitrogen
- ✓ Controllable crystal temperature
- ✓ Real-time monitoring of Refrigerator performance
- ✓ Good long-term stability

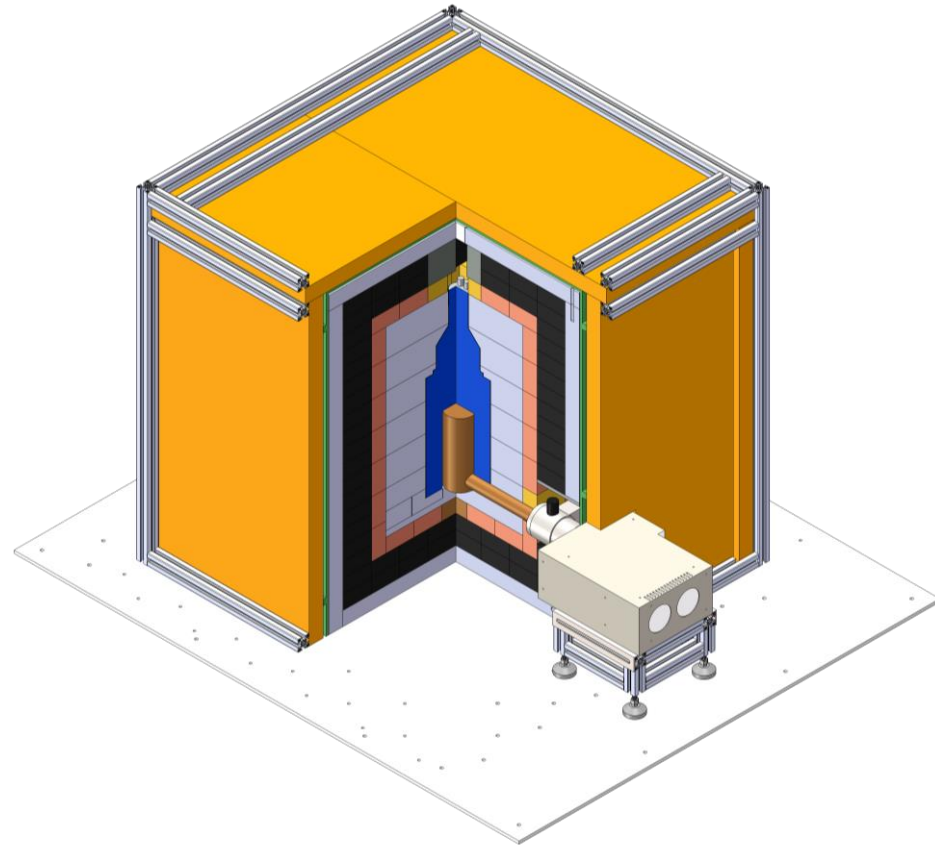
EC PCGe for Near Site

- Shielding size: 1m(W)*1m(L)*1.1m(H)
- From outer to inner:
 - ✓ Plastic scintillator muon veto (3 cm), **CRV/CRT events**
 - ✓ Aluminum Structure (4 cm)
 - ✓ Acrylic box (0.8 cm), **N₂ purging to suppress radon bkg**
 - ✓ Polyethylene (5 cm)
 - ✓ Lead (10 cm)
 - ✓ Copper (5 cm)
 - ✓ Polyethylene (~15 cm)
 - ✓ NaI anti-Compton Detector (5 cm), **ACV/ACT events**
- DAQ based on **CAEN V1725 (14 bit, 250 MS/s)**

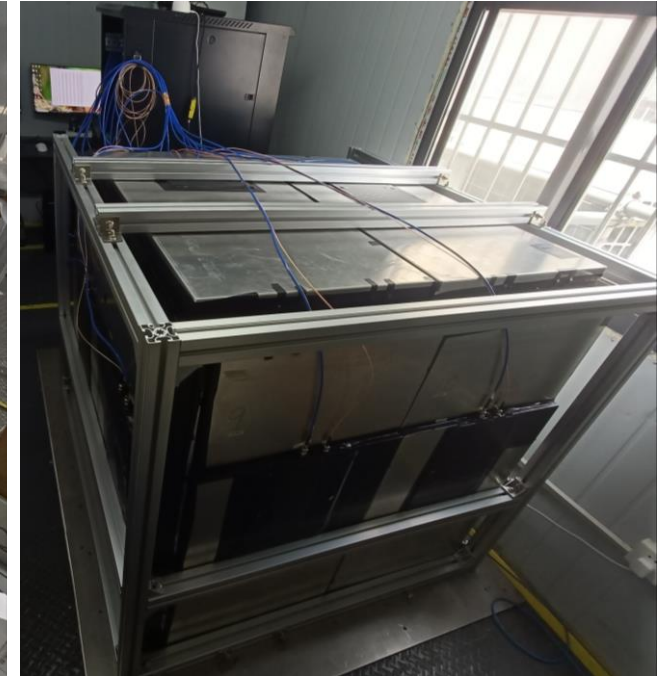


EC PCGe

EC PCGe for Near Site



EC PCGe

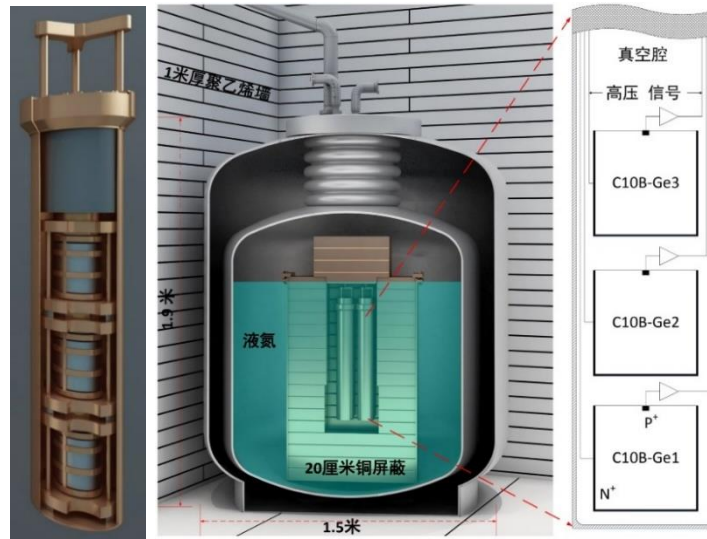


**Muon detector installed, before covering light-shielding cloth
@in the container outside the containment of Sanmen NPP**

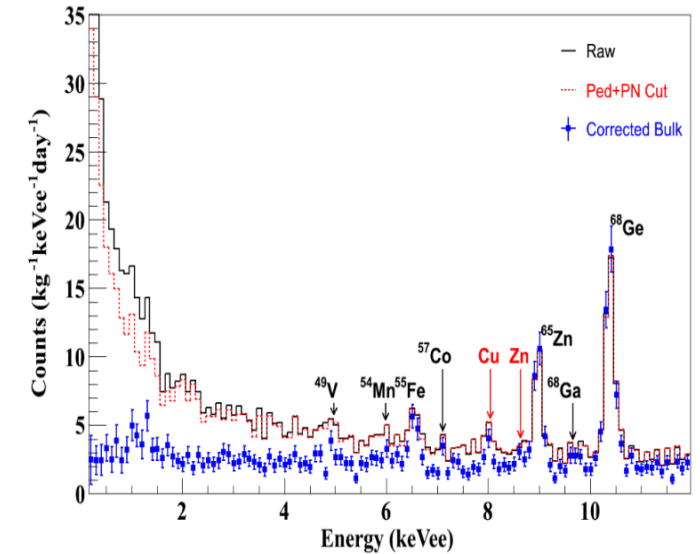
LN PCGe for Far Site (based on CDEX-1B/10)



CDEX-1B (1kg PPCGe),
cooled with the cooling finger
and LN2 Dewar



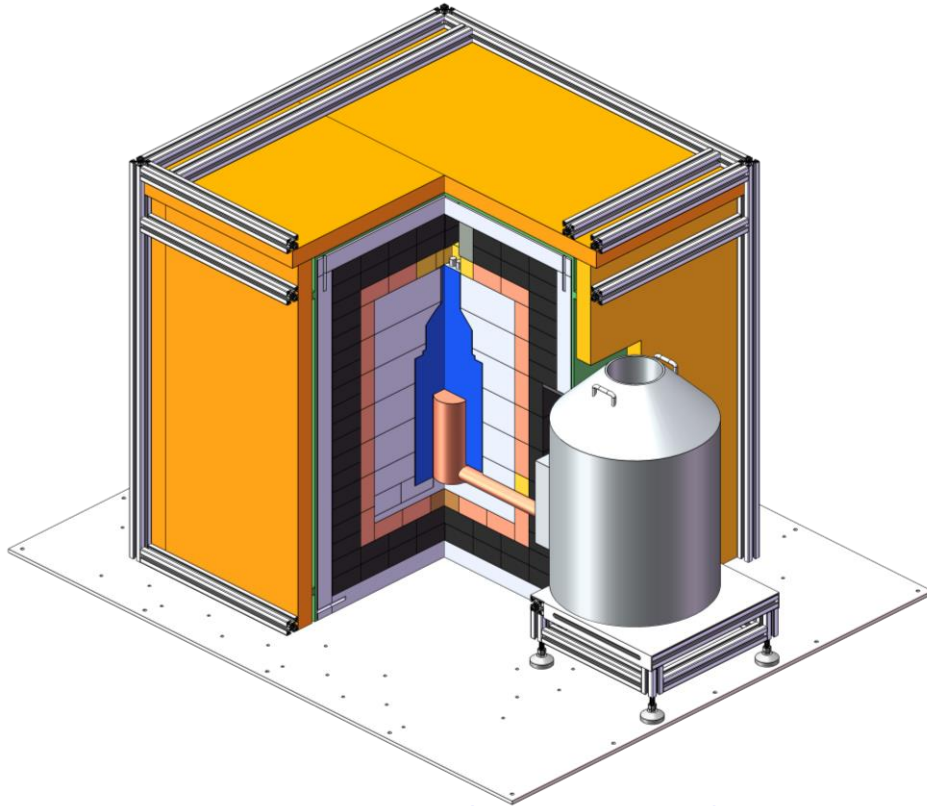
CDEX-10 (9*1kg PPCGe),
cooled with the vacuum cryos
tat directly immersed into LN2



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

PRL 120,241301 (2018)

LN PCGe for Far Site



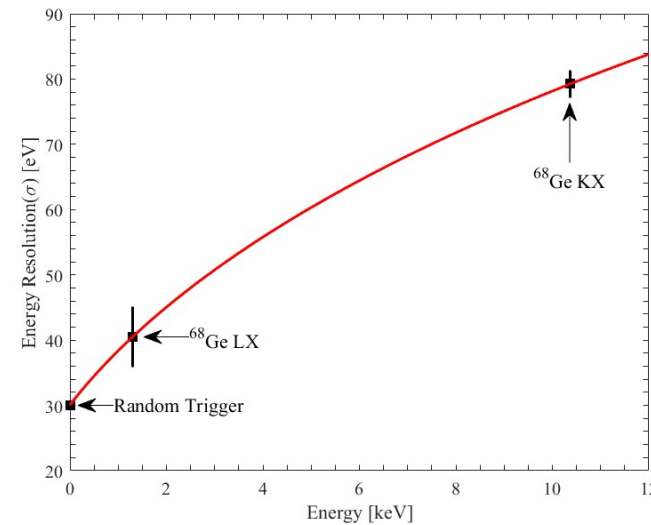
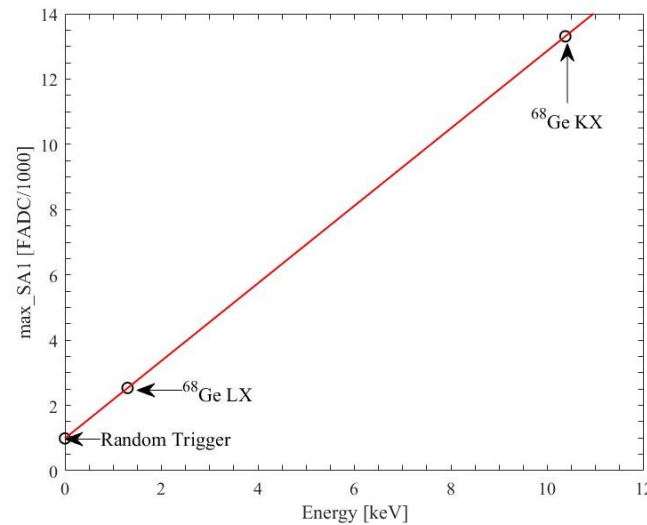
LN2 PCGe (CDEX-1B)



**Muon detector units waiting for installation
@in the container outside the containment of Sanmen NPP**

Ground test: EC PCGe

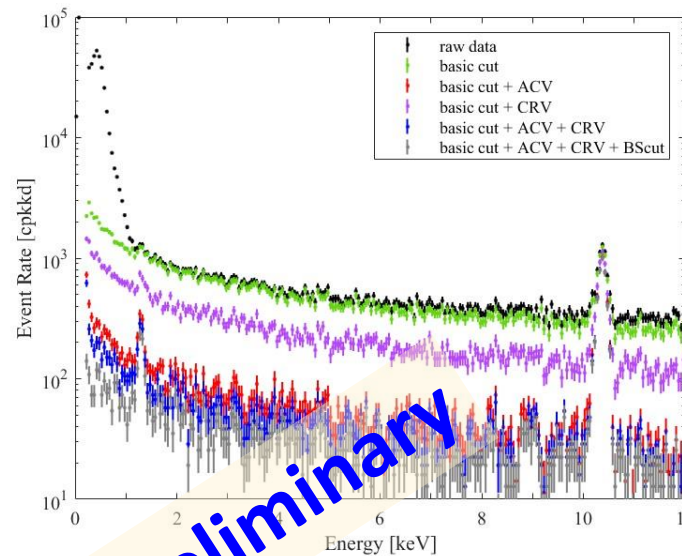
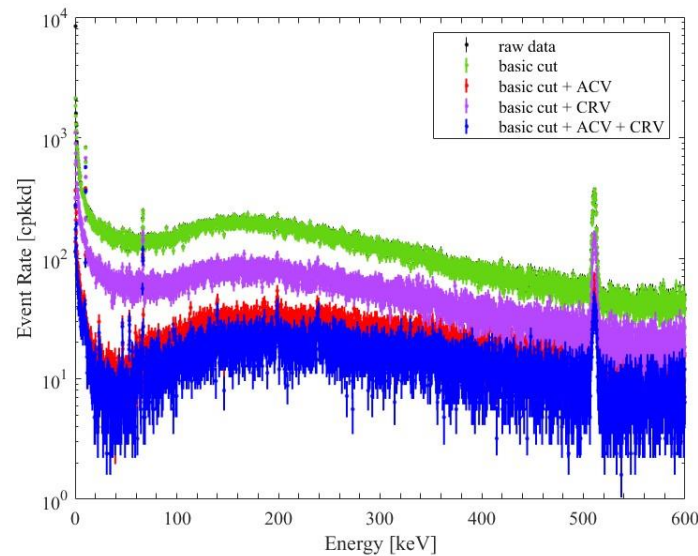
- Energy calibration is performed using characteristic X-rays from internal cosmogenic radioactivity, showing excellent energy linearity and an energy resolution of 80 eV @ 10.37 keV;
- Preliminary data analysis shows that the energy threshold is lower than 220 eV, and further detailed analysis is still in progress.



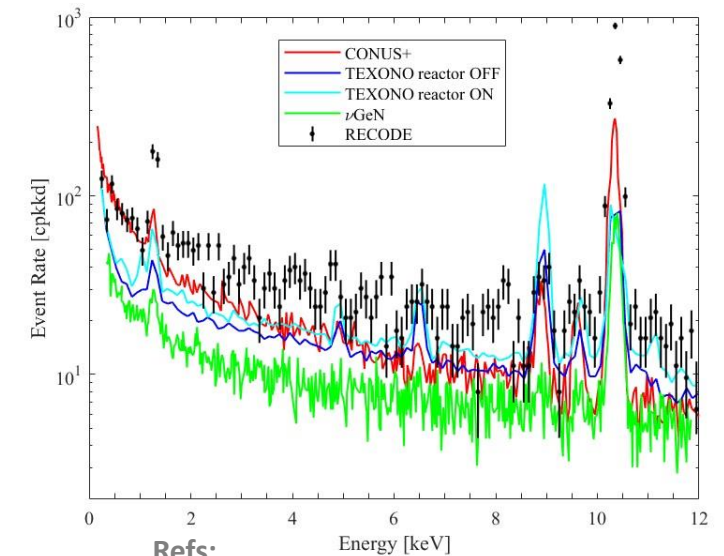
Peak used	Ture E (keV)	Calibrated E (keV)	Delta E (keV)	FWHM (eV)
RT	0	-0.002	-0.002	30.08 ± 0.08
LX_Ge	1.298	$1.300 \pm 5.45\text{E-}3$	+0.002	40.49 ± 4.64
KX_Ge	10.373	$10.372 \pm 3.05\text{E-}3$	-0.001	79.25 ± 2.12

Ground test: EC PCGe

- Ground test data shows that the anti-coincidence capability of NaI detectors outperforms that of plastic scintillator (CR-veto) detectors, suppressing the bkg by an order of magnitude;
- In addition to CR-veto detectors, NaI is also necessary to further reduce the bkg level;
- Comparisons with other experiments show that the shielding performance met expectations without additional concrete coverage. After moving into the reactor containment, the cosmic-ray-induced background can be further reduced.



Preliminary



Refs:

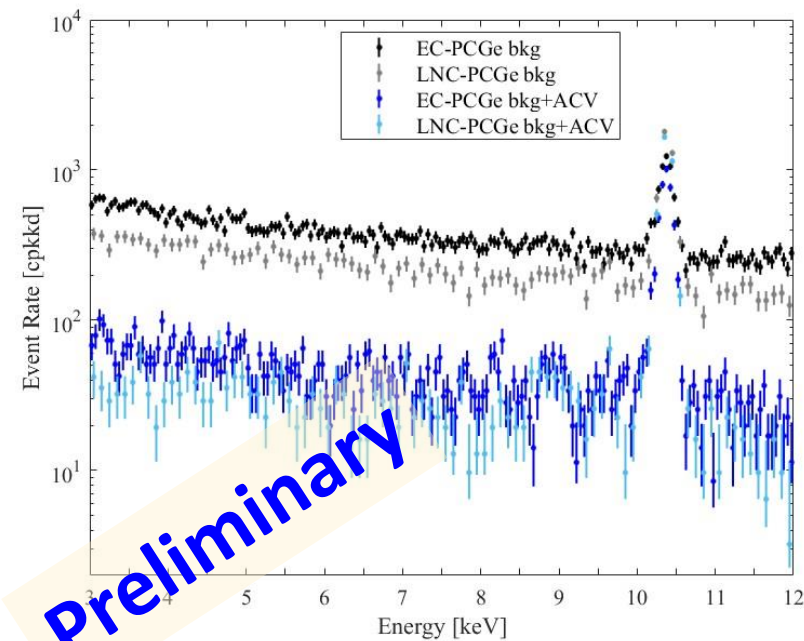
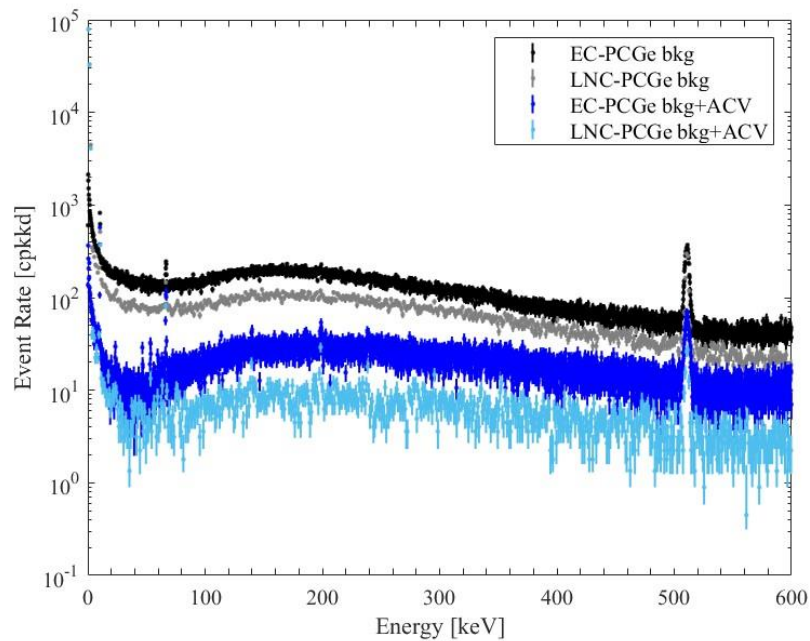
CONUS+: 2501.05206

TEXONO: PRL 134,121802 (2025)

vGeN: CPC 49, 053004 (2025)

Ground test: LN PCGe (CDEX-1B)

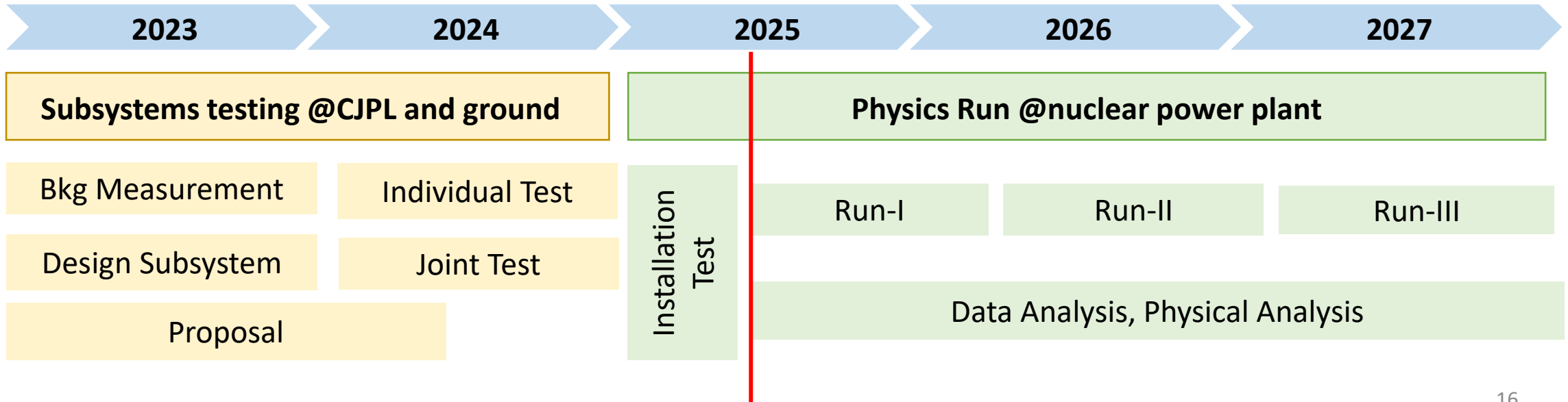
- The experimental data from two detectors (with different crystal sizes) were compared;
- It was found that larger crystal sizes lead to lower background event rates. This is due to the reduction in the number of muon events per unit mass/crystal volume;
- According to Geant4 simulation, cosmic-ray neutrons primarily contribute significantly to the background below 5 keV, and the anti-coincidence capabilities of NaI and plastic scintillator detectors for neutrons are less pronounced than those for muons.



Preliminary

RECODE: Status & Schedule

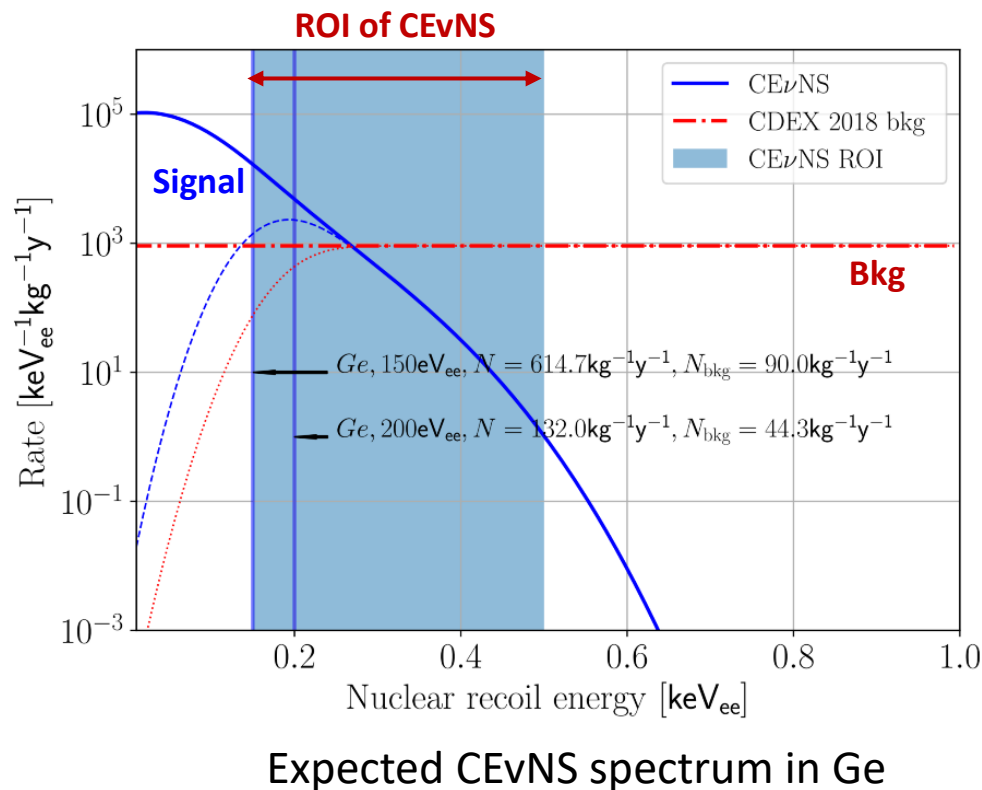
- **Test the shielding performance outside the containment of Sanmen NPP**
 - **Met the expectations w/o additional concrete coverage**
 - Cosmic ray induced background will be further reduced when the detectors are placed at experimental sites
 - Additional reactor neutron background needs to be considered
 - **Equivalent water depth coverage thickness is being evaluated**
- **Formal Operation starts soon – Stay tuned!**



RECODE: Uncertainties

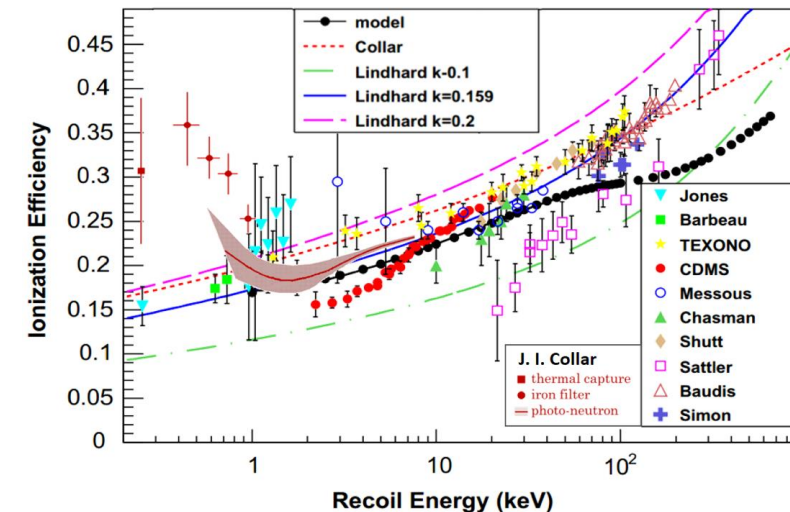
- Statistical:

- Signal/Noise > 5:1
- ~ 500 CEvNS events/kg/year
- 1.5% statistical



- Systematics:

- Quenching factor: 10%-20%
 - Measurement of Ge QF
- Reactor neutrino intensity: 3%
 - Reduced through joint measurement
- Background modeling:
 - Ground Testing
 - ON/OFF measurement

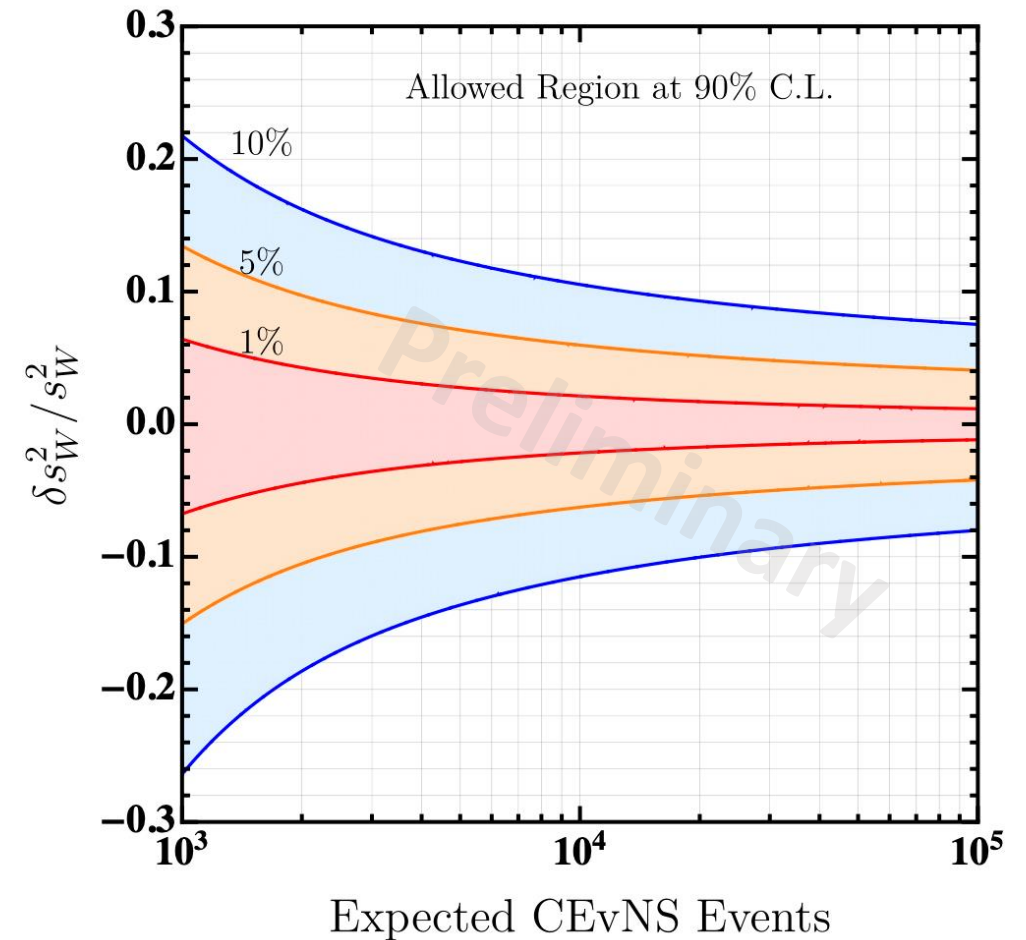
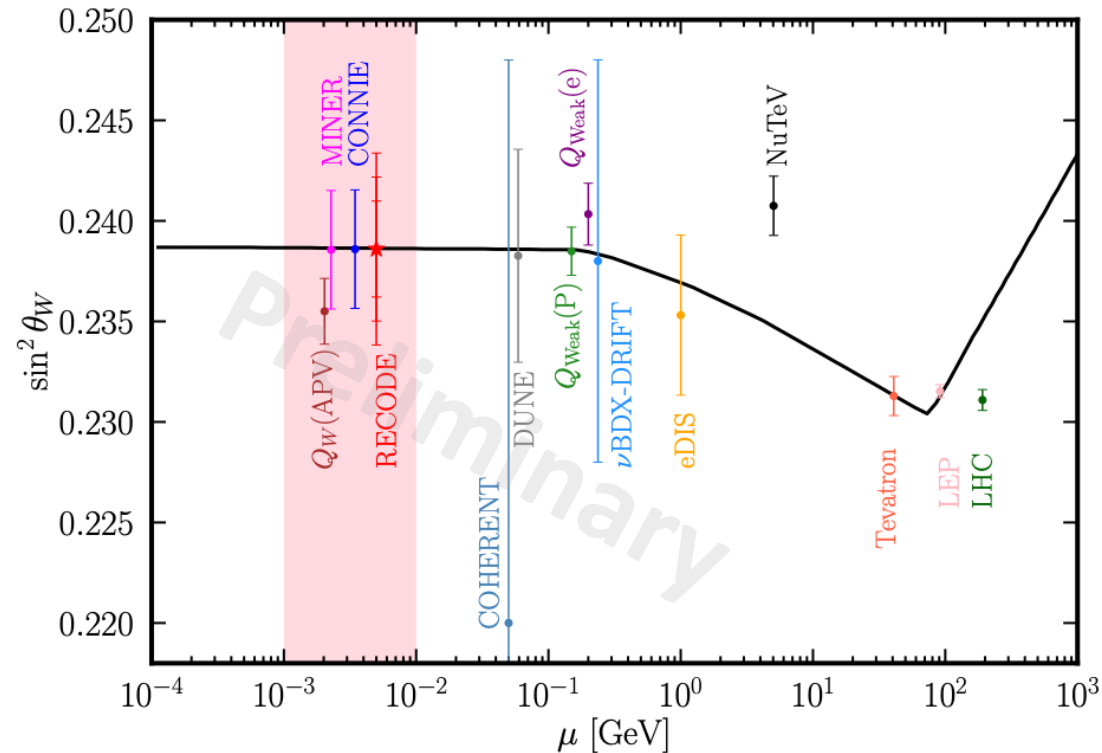


RECODE: Prospects

- Weak Mixing Angle

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{8\pi} Q_W^2 |F(q)|^2 \left(2 - \frac{2E_R}{E_\nu} + \left(\frac{E_R}{E_\nu} \right)^2 - \frac{ME_R}{E_\nu^2} \right)$$

$$Q_W = N - (1 - 4 \sin^2 \theta_W) Z$$



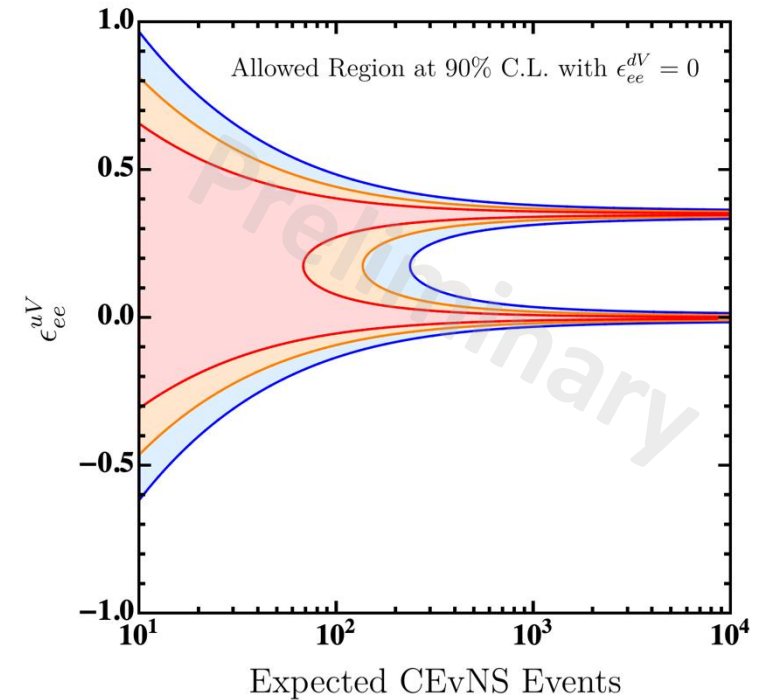
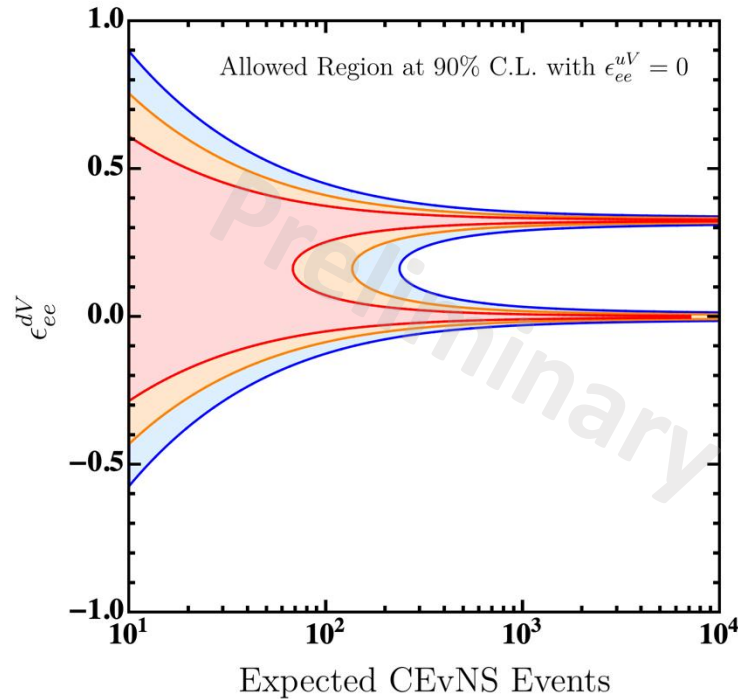
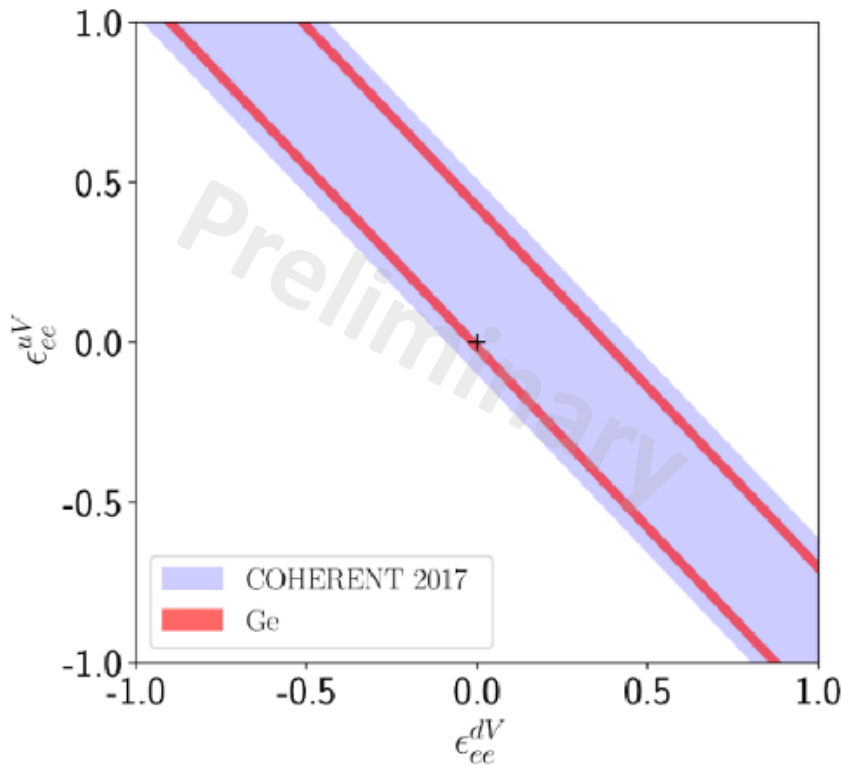
RECODE: Prospects

- Neutrino NSI

$$\mathcal{L}^{NSI} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{f,V} (\bar{\nu}_{\alpha L} \gamma^\mu \nu_{\beta L}) (\bar{f} \gamma_\mu f)$$

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{2\pi} |F(q)|^2 \left(2 - \frac{ME_R}{E_\nu^2} \right) \times \left(\left(Z(g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}) + N(g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}) \right)^2 + \dots \right)$$

$$g_V^p = \frac{1}{2} - 2 \sin^2 \theta_W, \quad g_V^n = -\frac{1}{2}$$





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 is currently under ground test. More detailed analysis is still in progress;
- The EC PCGe will enter the containment to carry out Near-Site experimental data acquisition. The platform outside the containment (Far-Site) will also be in place soon;
- Upgrades of EC PCGe (70X70mm, 1430g) from G3 to G4 is underway;
- Through combined measurements and analysis, the systematic uncertainty can be reduced, thereby improving the sensitivity.



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Thank you!

Litao YANG (杨丽桃), yanglt@mail.tsinghua.edu.cn



Key parameters comparison

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■ Thermal power 3.4 GWth, ~22m /11m /7m from the core

■ Neutrino flux $> 1.4 \times 10^{13} \text{ cm}^{-2}\text{s}^{-1}$

Experiment	Target	Mass	Threshold	Reactor	Distance to reactor core	Thermal power	Neutrino Flux	Location
RECODE	HPGe	1-2kg	~160 eVee	Sanmen NPP	NS ~ 11m	3.4GWth	$5.6 \times 10^{13} \text{ v/cm}^2/\text{s}$	China
	HPGe	10kg	~160 eVee		FS ~ 22m	3.4GWth	$1.4 \times 10^{13} \text{ v/cm}^2/\text{s}$	China
RELICS	LXe	50kg	~1 keVnr	Sanmen NPP	22m	3.4GWth	$1.4 \times 10^{13} \text{ v/cm}^2/\text{s}$	China
CONUS	HPGe	3.74 kg	~ 210 eVee	Brokdorf (KBR)	17 m	3.9 GWth	$2.3 \times 10^{13} \text{ v/cm}^2/\text{s}$	Germany
COUNS+	HPGe	3.74 kg	~150 eVee	Leibstadt (KKL)	20.7m	3.6 GWth	$1.5 \times 10^{13} \text{ v/cm}^2/\text{s}$	Switzerland
Nu-Gen	HPGe	1.6 kg	350 eVee	Kalinin NPP	11.1-12.5 m	3.1 GWth	$3.4 - 4.4 \times 10^{13} \text{ v/cm}^2/\text{s}$	Russia
TEXONO	HPGe	1 kg	~200 eVee	Kuo-Sheng NPP	28m	2.9 GWth	$6.4 \times 10^{12} \text{ v/cm}^2/\text{s}$	Taiwan, China
CONNIE	Si CCDs	50 g	~ 40 eVee	Angra 2 reactor	30 m	3.8 GWth	$7.8 \times 10^{12} \text{ v/cm}^2/\text{s}$	Brazil
MINER	Ge/Si	4 kg	~ 100 eVnr	TRIGA reactor	2~10m	1 MWth	$\sim 10^{12} \text{ v/cm}^2/\text{s}$	USA
RICOCHET	Ge & Zinc	32 g (Ge)	55 eVee	ILL reactor	8 m	58 MWth	$1.6 \times 10^{12} \text{ v/cm}^2/\text{s}$	France