**RECODE**

**REactor neutrino COherent scattering Detection Experiment**

# RECODE program for reactor neutrino CEvNS detection with PPC Germanium detector

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# OUTLINE

1、 **CEvNS**

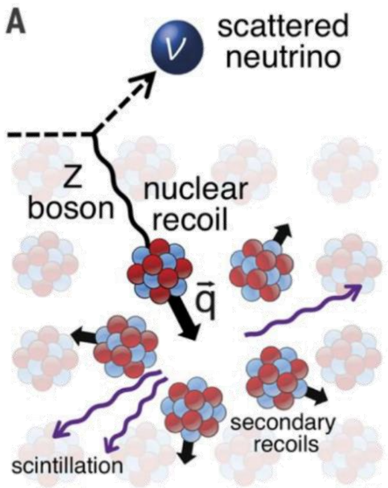
2、 RECODE Program

3、 Key technologies R&D

4、 Prospects and summary

# Coherent Elastic Neutrino Nucleus Scattering

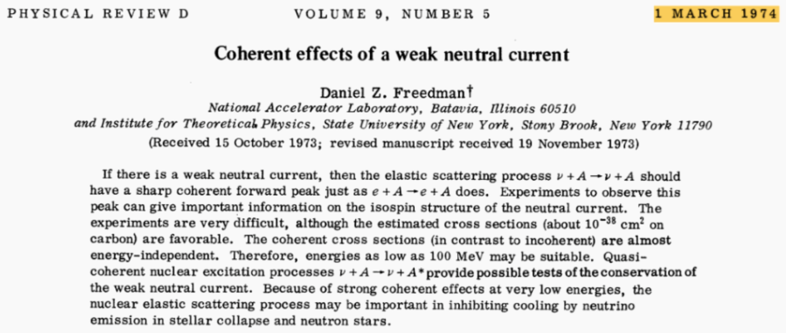
- A basic interaction between Neutrino and matter in SM
- Important way to study the properties of Neutrino
- As a whole, the nucleus scatters Neutrino




$$\sigma \propto Q_W^2 \propto \left(N - \left(1 - 4\sin^2\theta_W\right)Z\right)^2$$

$$\Rightarrow \boxed{\sigma \propto N^2}$$

## Theoretical prediction (1974)



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

**Coherent effects of a weak neutral current**

Daniel Z. Freedman†

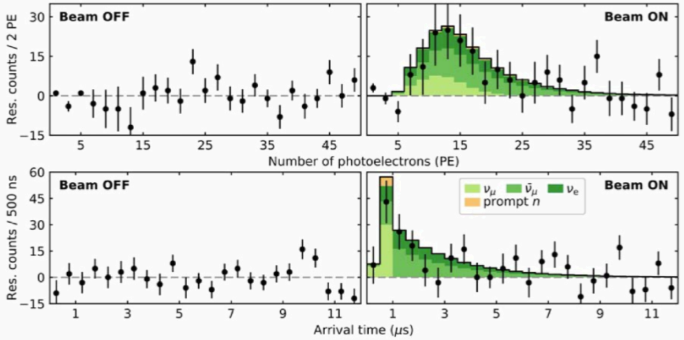
*National Accelerator Laboratory, Batavia, Illinois 60510*
*and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790*

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about $10^{-38}$ cm$^2$ on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

D. Freedman, PRD 9 1389 (1974)

## Experimental Evidence (2017)



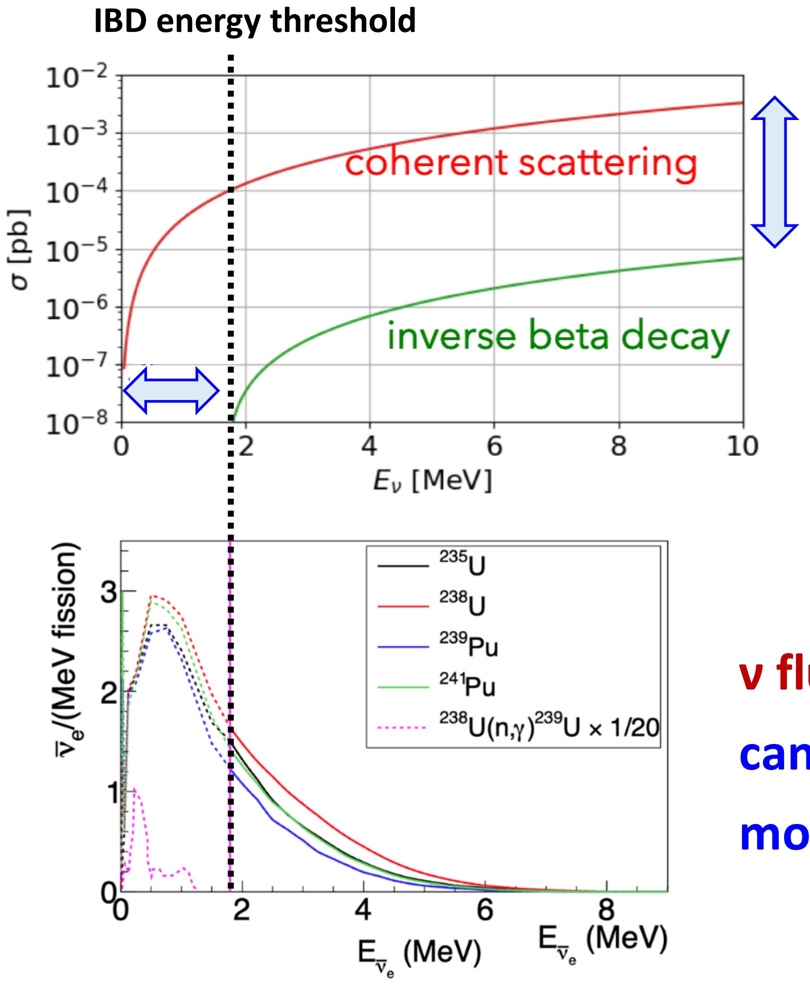


D. Akimov et al, Science 357 (2017)

# CEvNS: Experimental Features

- Larger cross section (than traditional IBD), realize the miniaturization of the detector
- No Neutrino energy threshold limit

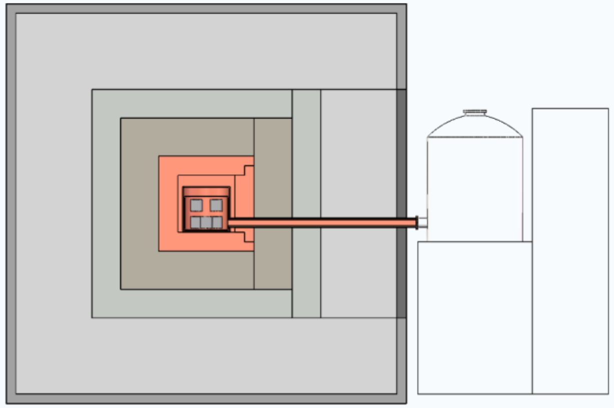
CEvNS：
No energy threshold



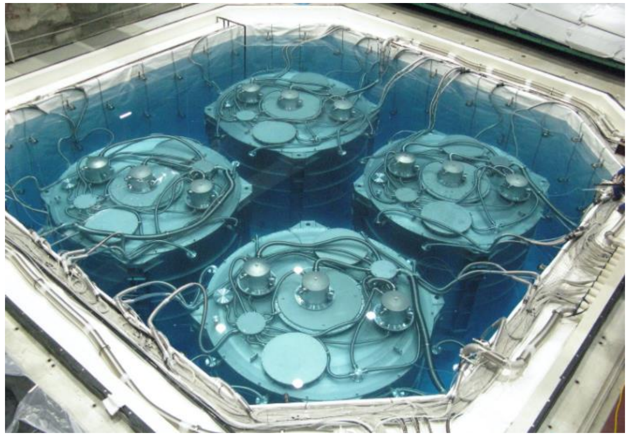

Large cross-sections helps achieve miniaturization of detectors

ν flux ∝ core power can be used for reactor monitoring

CEvNS: tens of kilograms

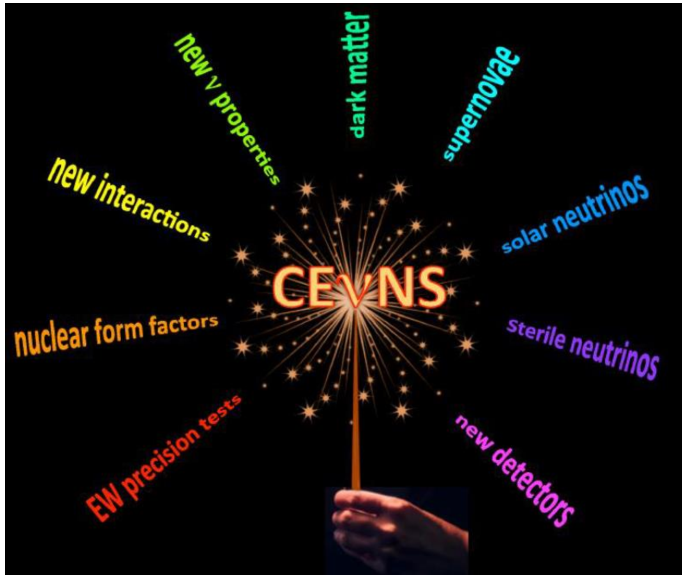


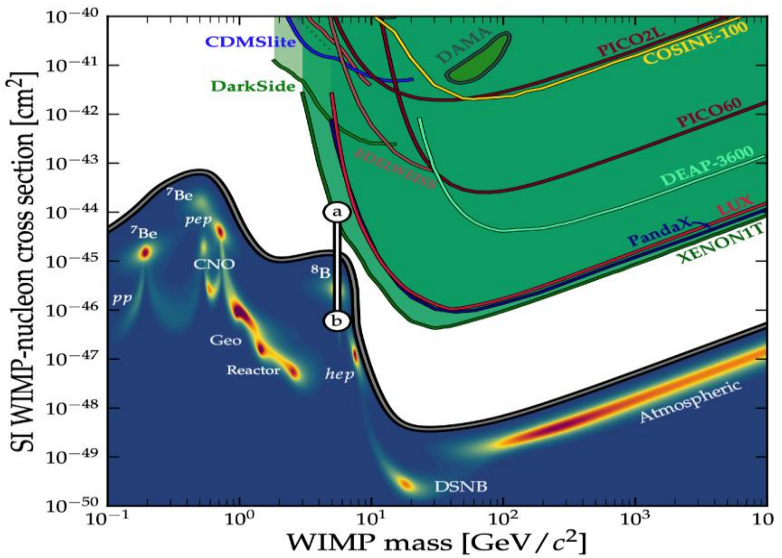
IBD: hundred tons level



# CEvNS: Research Significance

- **As signals, test the Standard Model and explore new physics**
  - Scattering cross-section
  - Weak Mixing Angle under low momentum transfer
  - Neutrino Interactions beyond SM
  - Anomalous Neutrino magnetic moment
- **As a tool, develop monitoring technologies**
  - Reactor monitoring
  - Spent fuel monitoring
  - Military nuclear verification
- **As a probe, develop multi-messenger astronomy**
  - New ways to detect Solar ν and Supernova ν
  - Understand "Neutrino Floor“, important bkg in DM Exp.

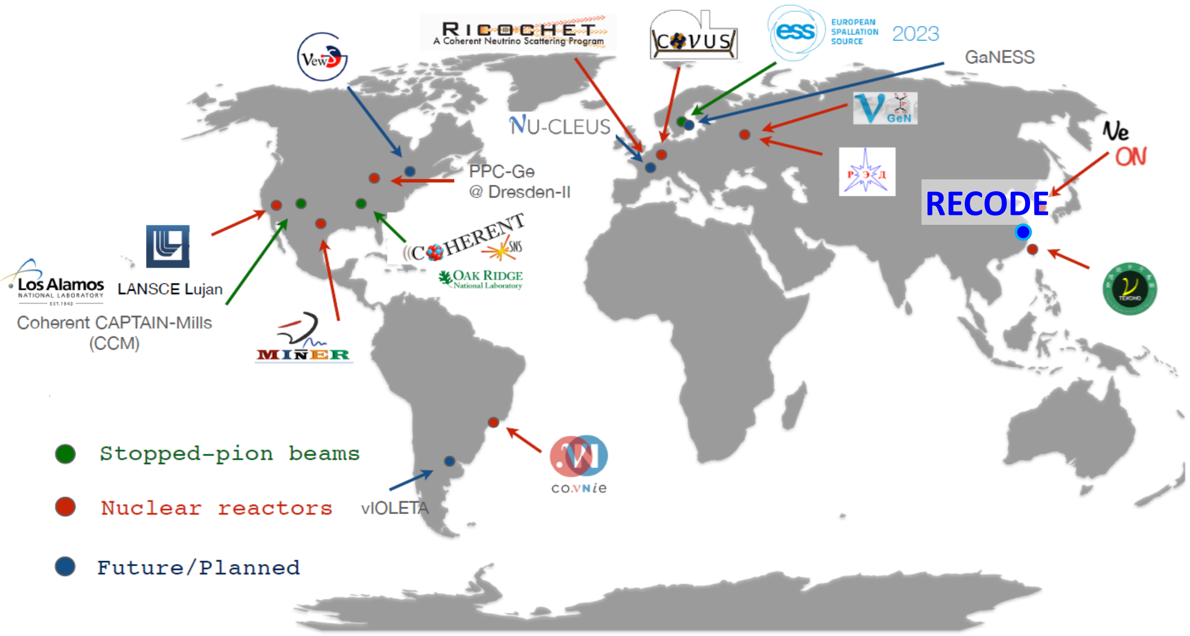


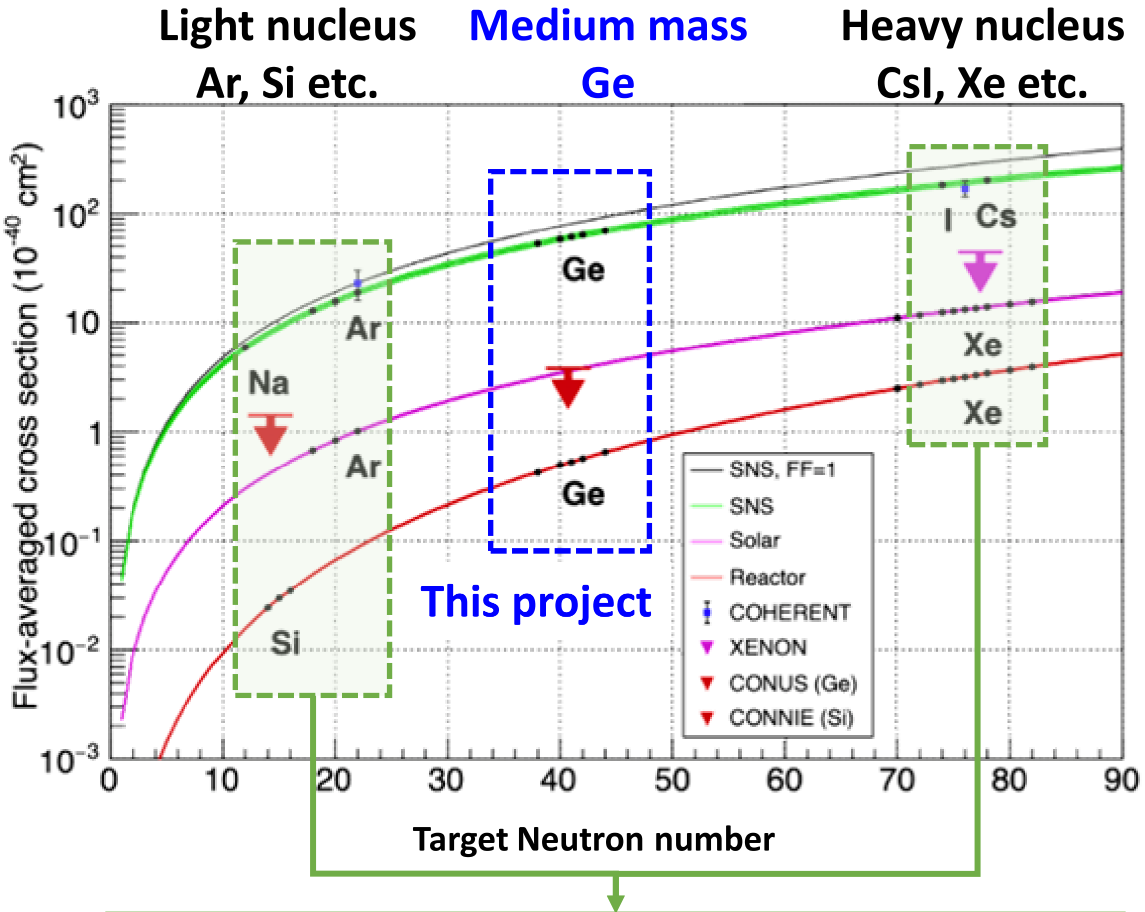



# CEvNS measurement with HPGe: physical needs

$$\sigma \propto N^2$$

- Both Ar (light nucleus) and CsI (heavy nucleus) results are from the high-energy neutrino beam of accelerator;
- Reactor neutrino CEvNS has not been successfully mea sured in experiments to date;
- Ge (middle mass region) has advantages in measuring reactor neutrino CEvNS;




| | |
|---|---|
| Light region, Ar | PRL 126, 012002 (2021) , 3.5σ |
| Heavy region, CsI | Science 357, 1123 (2017) , 6.7σ<br>PRL 129, 081801 (2022), 11.6σ |

# CEvNS measurement with HPGe: technical features

- Reactor neutrino beam: high intensity ($10^{12}/cm^2/s$), but low energy (several MeV);
- Detector requirements: low energy threshold, low background, long-term stability and grou nd operation;

## CEvNS Technical Challenges

| | |
|---|---|
| Rare event rate | Low background |
| Low energy transfer | Low  threshold |
| ON/OFF measurements | stability |

| | |
|---|---|
| Near Reactor core | Ground operation |

Considering the influence of high flux Cosmic ray

Obtained long-term verification in DM exp.

Solid state det. flexibility

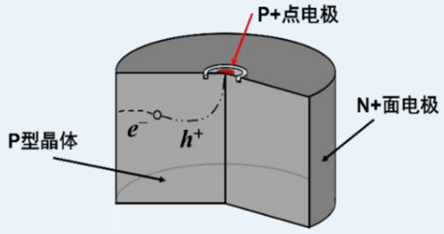
## Technical advantages of HPGe

Excellent resolution （< 0.12%）

Low threshold （< 200 eV）

Low internal bkg （纯度~13个9）

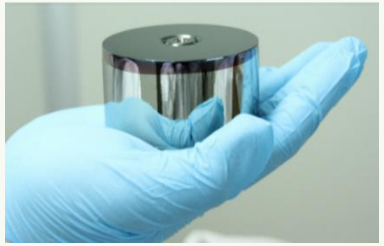
Long-term stability （数十年）




High density,

small volume （ϕ6cm*H6cm）

Bkg control in confined spaces

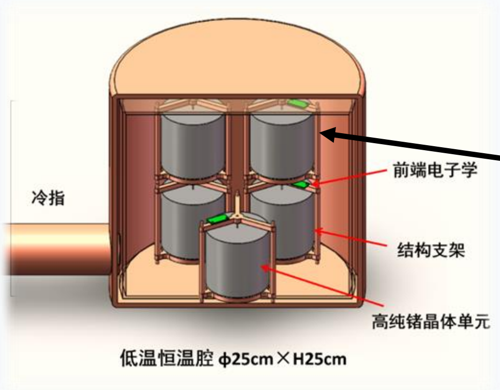


# RECODE

- RECODE（REactor neutrino COherent scattering Detection Experiment）
- CEvNS measurements based on low threshold PPCGe detectors

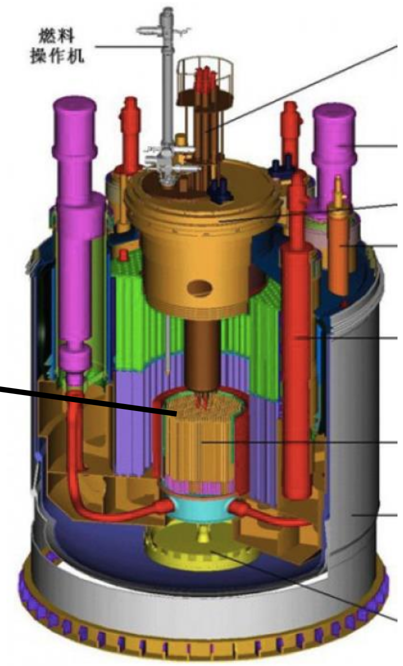
**Project goals：**

- **Two Ge arrays（10kg in total）**
  - ✓ Energy threshold ~1 keVnr（~160eVee）
  - ✓ Background level <2 counts/kg/keV/day
- **Joint measurement（collinear, equidistant）to reduce systematical uncertainty**
  - ✓ Two Ge arrays with adjustable distance
  - ✓ Joint measurement, Conjoint analysis




**Low threshold, low bkg Ge array**

**volume： ϕ25cm*H25cm**




**Reactor**

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

# RECODE roadmap

**Two key parameters for detectors in CEvNS exp.**

- low energy threshold
- low background

**RECODE roadmap:**

- (1) Development of HPGe Array
- (2) Design and construction of the shielding
- (3) Joint measurement of two detector arrays
- (4) Data analysis, physical analysis

# (1) Development of HPGe Array

**Design features**

- Two HPGe arrays, 10kg in total
- Threshold 160eVee
- Background 2 cpkkd

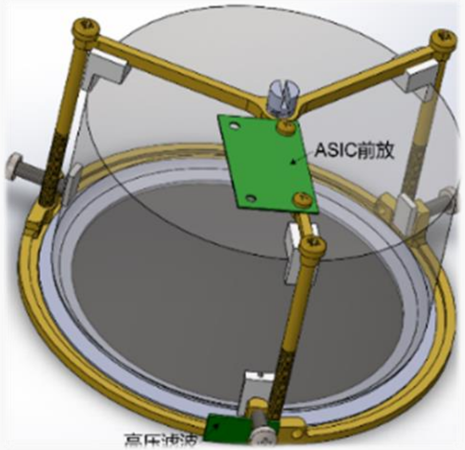
**CDEX-10 det.**

- ✓ Threshold 160 eVee
- ✓ Background 2 cpkkd

**Low bkg update**

**Detector unit**

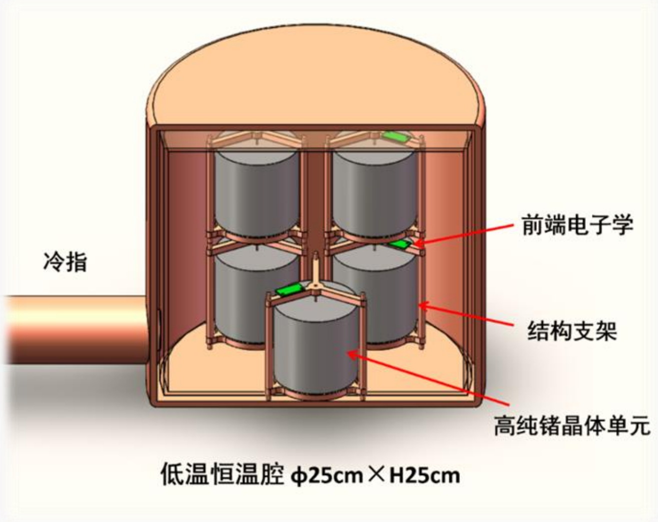
- ✓ Lightweight design, ϕ6cm × H 6cm
- ✓ Low bkg Copper/PTFE structure
- ✓ low bkg, low noise electronics




**Array update**

**Detector array**

- ✓ Liquid N2, cooling fingers
- ✓ Cryostat ϕ25cm × H 25cm



# (2) Design and construction of the shielding

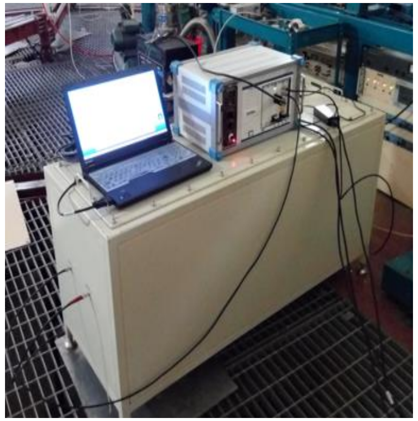
- **Shielding design and optimization**

- Anti coincidence efficiency of Cosmic ray:>99%
- Gamma current strength: reduced by 5 orders of magnitude
- Neutron current intensity: reduced by 3 orders of magnitude

- Environmental background measurement

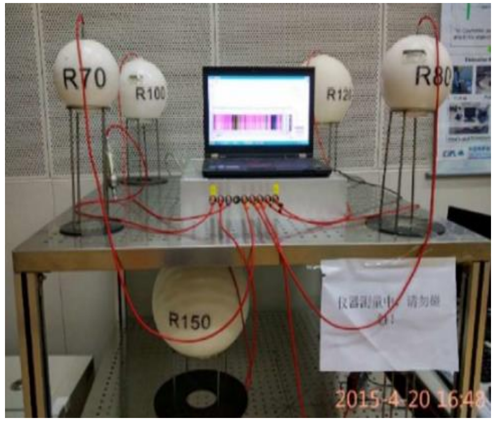
Muon detector

*CPC 37, 086001 (2013)*



Ga-dopted liquid scintillation detector

*NIMA 889, 105 (2018)*




Multi sphere neutron spectrometer

*NIMA 859, 37 (2017)*


Thermal neutron detector

*NIMA 804, 108 (2015)*

Gamma spectrometer

*Astro. Phys. 128, 102560 (2021)*

# (2) Design and construction of the shielding

■ **Shielding design and optimization**

➢ Anti coincidence efficiency of Cosmic ray:>99%

➢ Gamma current strength: reduced by 5 orders of magnitude

➢ Neutron current intensity: reduced by 3 orders of magnitude

■ **From outer to inner (Preliminary):**

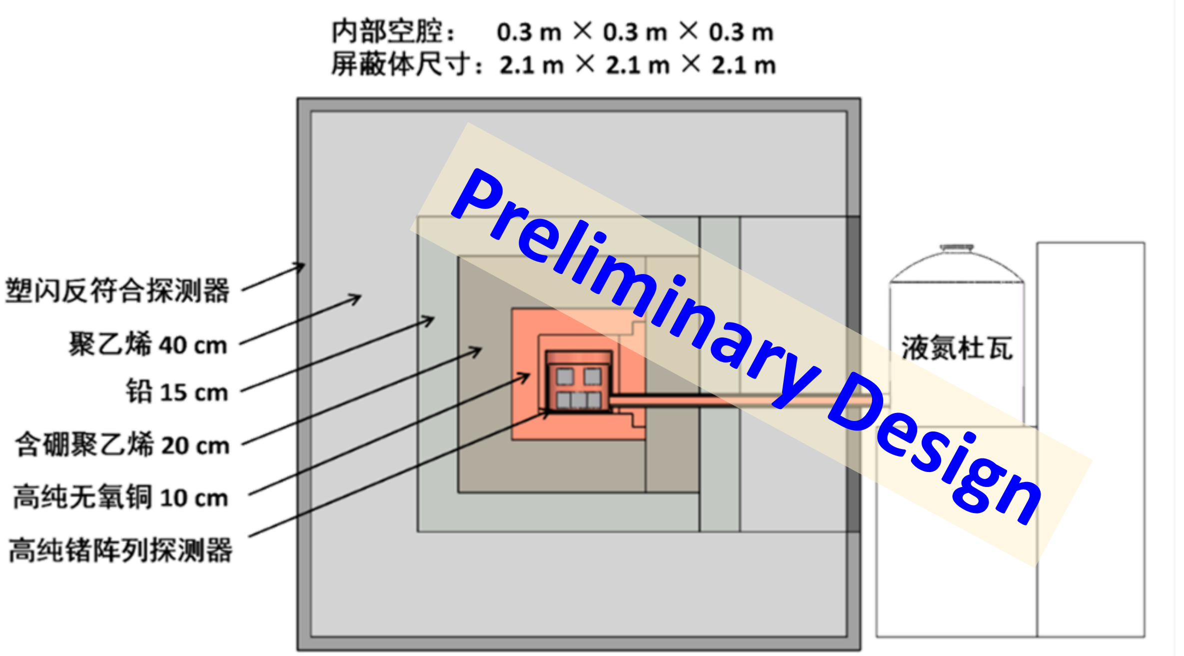
✓ Muon veto detector

✓ Polyethylene (PE)

✓ Lead (Pb)

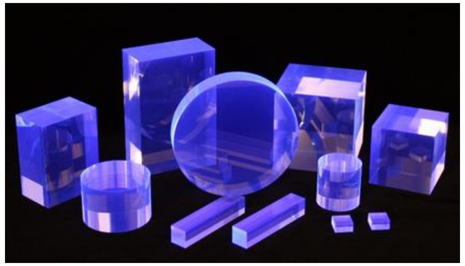
✓ Boron dopted polyethylene (PE(B))

✓ High purity oxygen free copper



# Muon veto system

- **Plastic scintillator anti coincidence detector**
  - ✓ Large area modular Muon veto detector based on plastic scintillator and optical fiber
    - Muon anti coincidence efficiency ≥ 99%
    - Optimize the size of the module, based on the shielding size
  - ✓ Preliminary Model selection
    - Plastic scitillator： EJ-200
    - Wavelength shifted fiber： BCF-92
    - Signal readout： CR125



Conceptual design of detector unit

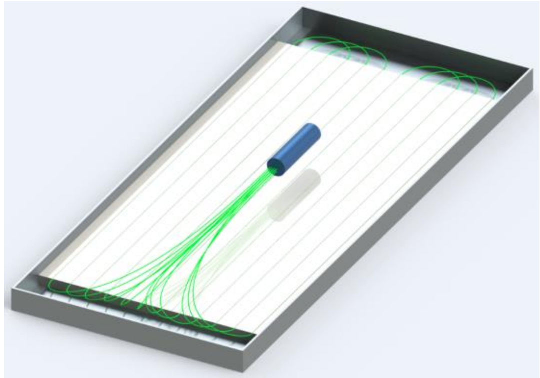


Diagram of Muon veto system

# Reactor neutrinos

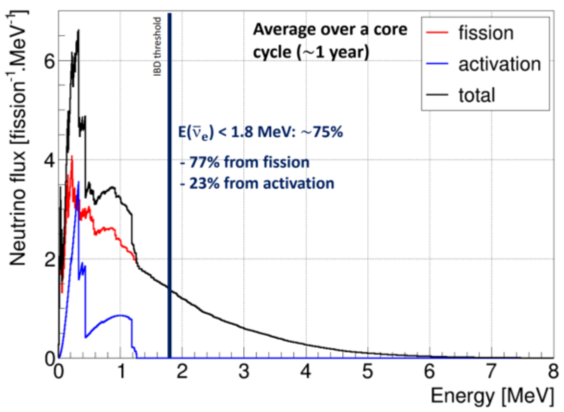
- **Mainly comes from the fission of $^{235}U$, $^{239}Pu$, $^{238}U$ and $^{241}Pu$, and the activation;**
- **Different neutrino spectrum for different reactor types;**
- **During whole fuel cycle, the proportion of each nuclide and the neutrino flux contributed will change. This will leads to 3-5% uncertainty of Neutrino flux;**

$$\phi_{\bar{\nu}_e} = \underbrace{\phi_{fission}}_{\sim 0\text{-}10\ MeV} + \underbrace{\phi_{activation} + \phi_{spent\ fuel}}_{\sim 0\text{-}3\ MeV}$$

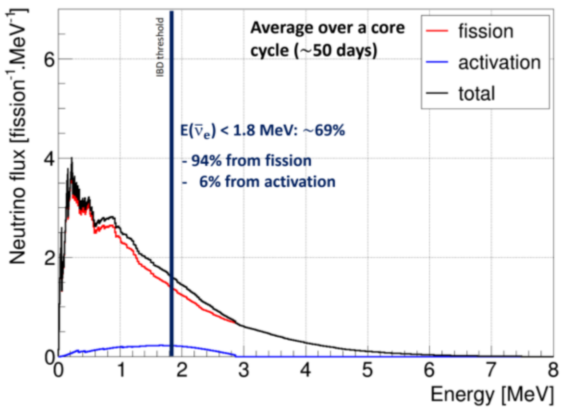
*PWR @Chooz*
*($E_{235U} \sim 4\%$)*
*- NUCLEUS*

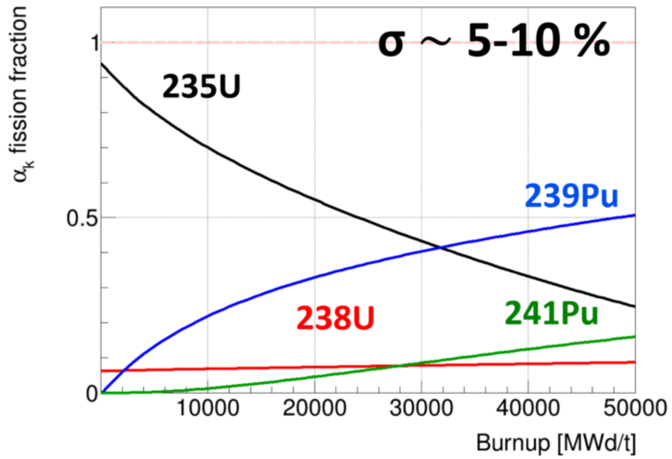
| | | Flux [$\bar{\nu}_e$.fiss$^{-1}$] | Rel. Contrib. [%] | |
|---|---|---|---|---|
| Fission | $^{235}U$ | 3.3 | 46.3 | ~83% |
| | $^{239}Pu$ | 1.7 | 24.1 | |
| | $^{238}U$ | 0.5 | 7.3 | |
| | $^{241}Pu$ | 0.4 | 5.1 | |
| Activation | $^{239}U$ | 0.6 | 8.6 | ~17% |
| | $^{239}Np$ | 0.6 | 8.6 | |
| Total | | 7.2 | | |

Commercial PWR, LEU
- N4 type Chooz like -




Research reactor, HEU
- HFR @ILL-




- CEvNS: thresholdless process ⇒ sensitive to low energy $\bar{\nu}_e$ (fission & activation) below the 1.8 MeV IBD threshold
  ↳ but material + recoil energy threshold dependency

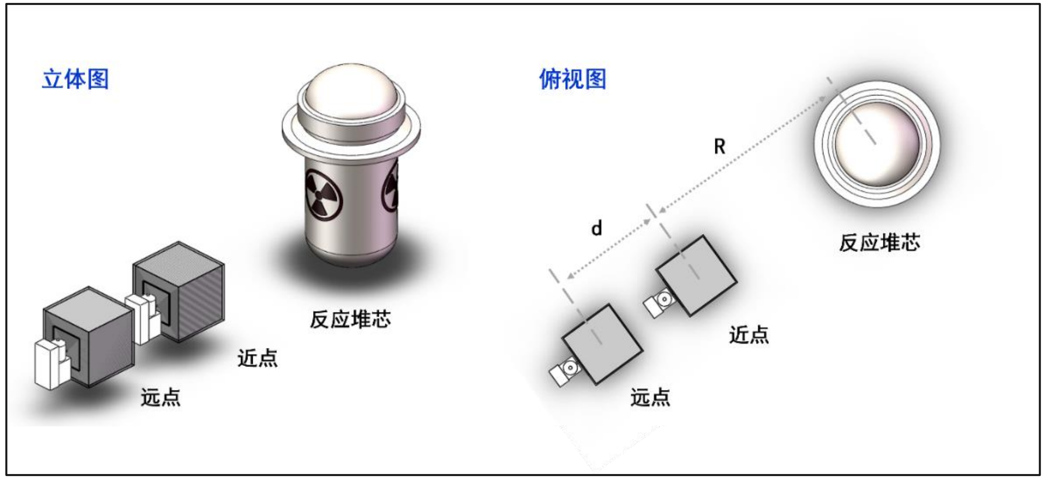
# (3) Joint measurement of two detector arrays

■ **joint measurements (such as collinear, equidistant) to reduce system errors**

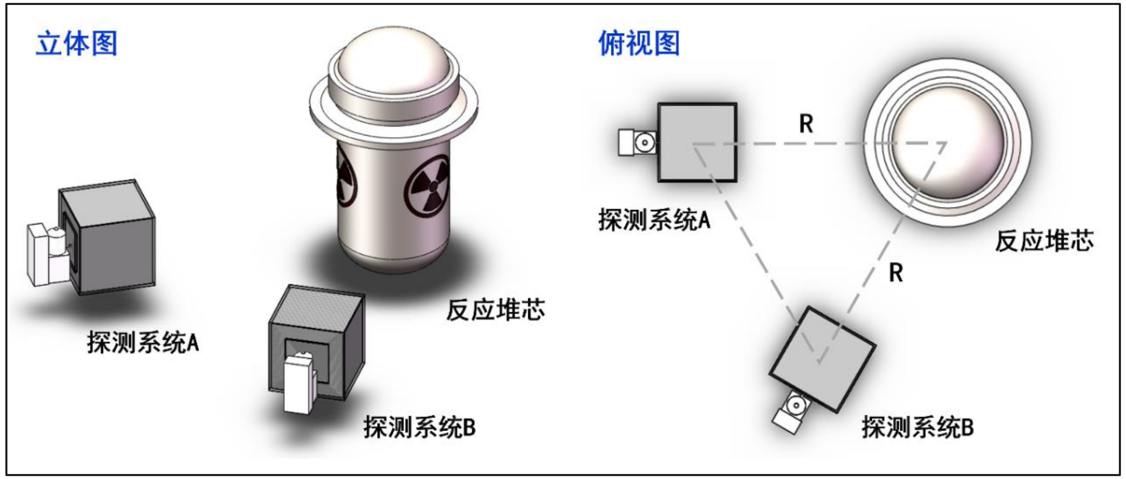
$$\boldsymbol{Count\ rates} \propto \frac{\boldsymbol{total\ Neutrino\ number}}{\boldsymbol{Distance^2}} + \boldsymbol{background}$$

- Systematic uncertainty: Neutrino flux (∝reactor thermal power), background of detector system
- Joint measurement: reduce systematic error and improve the sensitivity

| Measurement mode | Experimental set-up |
|---|---|
| ①、② **Collinear**<br>（Array A、B and reactor are collinear） | ① A far、B near |
| | ② B far、A near |
| ③ **equidistant** | A、B have same distance to the reactor |




①/② collinear measurement modes



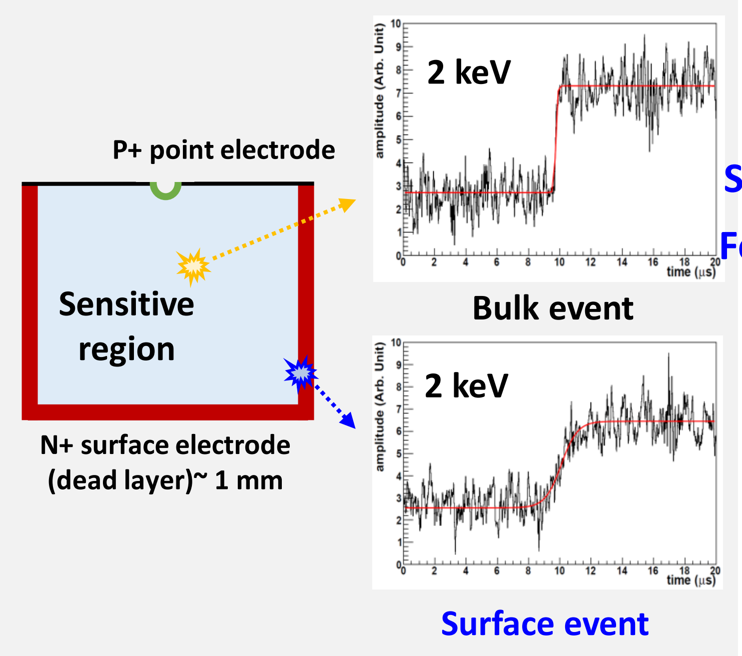

③ isometric measurement mode

# (4) Data analysis

- ➢Development of **bulk/surface events discrimination method**: achieving a significant reduction in background levels near the threshold;
- ➢Establish the **energy calibration at keV region** under low background environment: internal cosmogenic radioactive X-rays to calibrate;

*NIM-A* 886, 13–23 (2018)

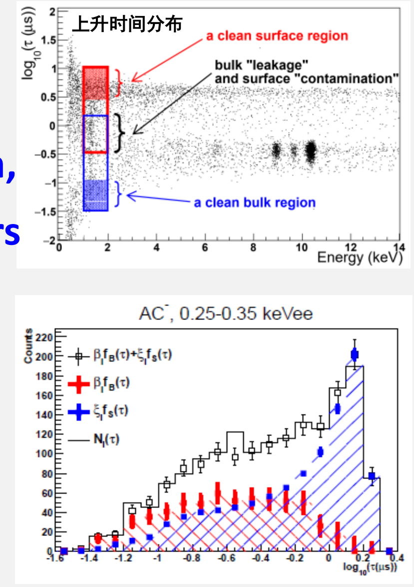
*Science China-PMA* 62, 031012 (2019)




Surface “noise” from “deadlayer”

Smooth waveform,

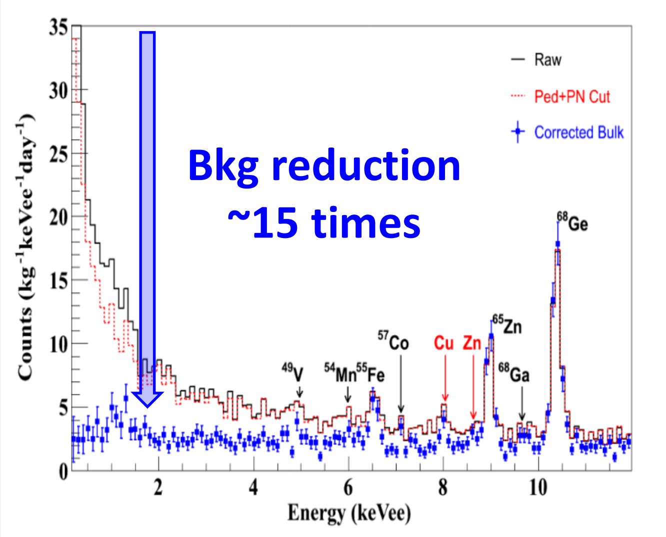
Feature parameters extraction




$$N_i(E,\tau) = \beta_i f_B(E,\tau) + \xi_i f_S(E,\tau)$$

Ratio Method based on the risetime PDF

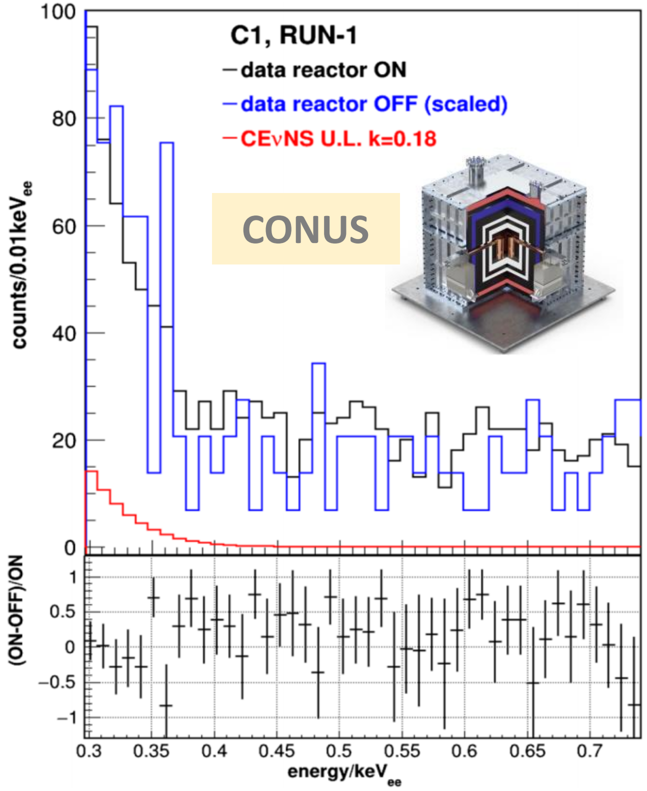
Significantly lower bkg



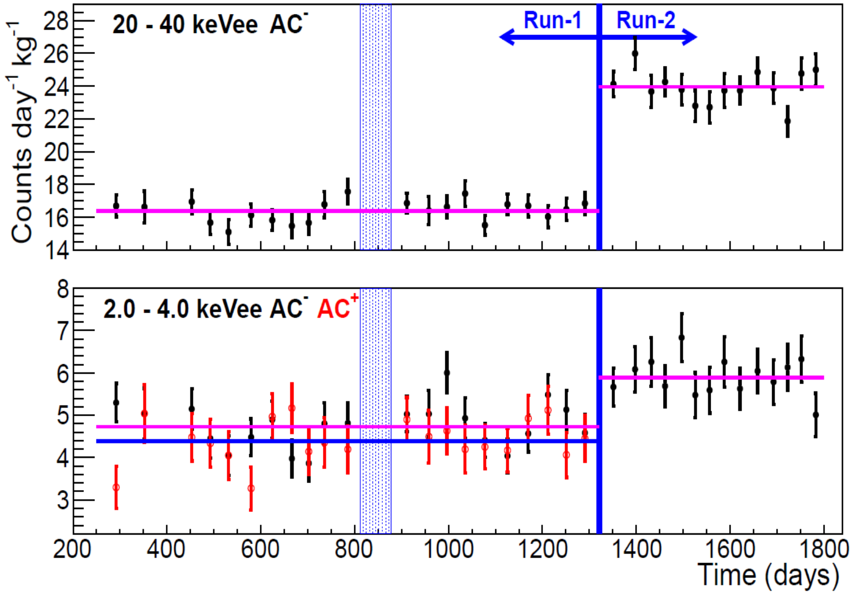

CDEX-10 experimental data

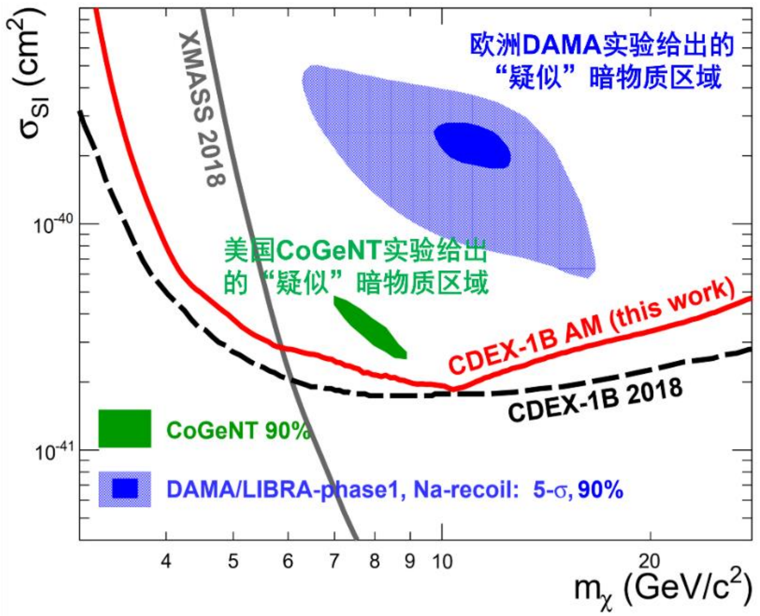
# Long term stability

- ■ON-OFF analysis is **independent of bkg model,** can provide conclusive evidence for CEvNS;
- ■ON-OFF analysis requires long-term stable operation (shutdown for examine/repair~1 m/yr);
- ■Based on >4 years' data from CDEX, we have demonstrate the stable operation of Ge detector, and an annual modulation study on DM-nucleus scattering has been conducted.




*CONUS, PRL 126 (2021) 041804




***PRL*** 123, 221301 (2019)

# (4) Physical Analysis

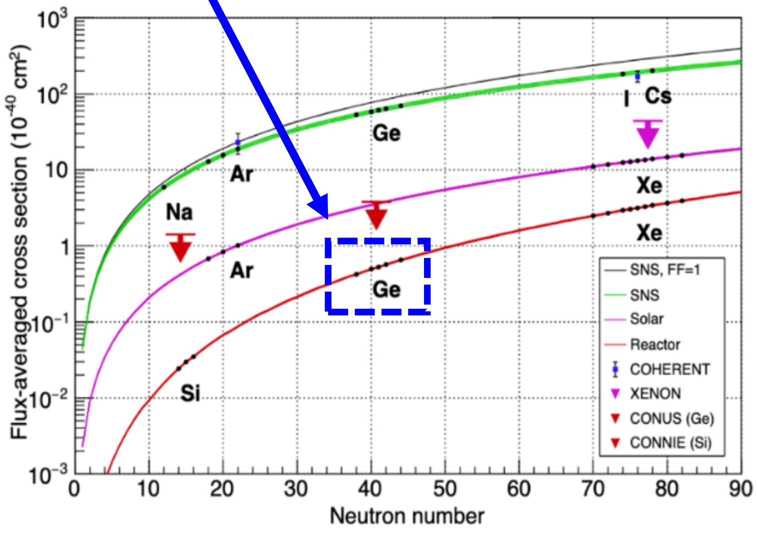
## ■ Accurate Testing of SM

- ✓ Measurement of CEvNS scattering cross-section;
- ✓ weak mixing angle under low momentum transfer…

## ■ Explore new physics beyond SM

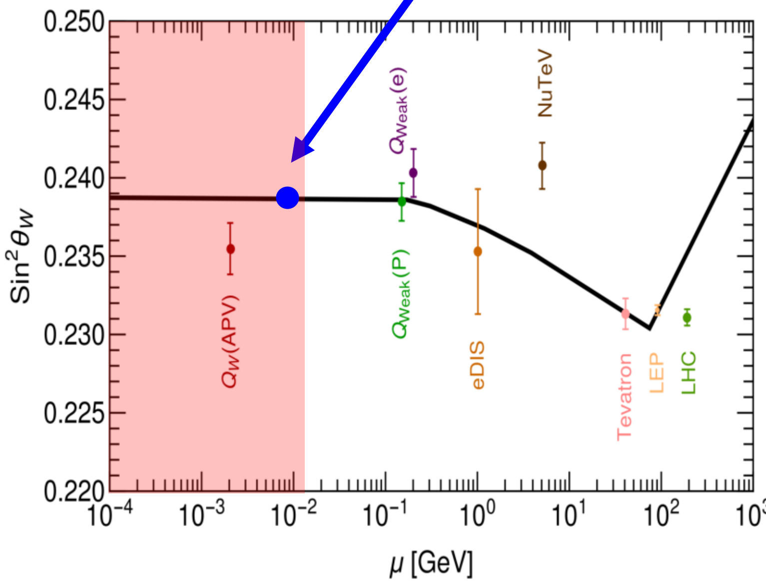
- ✓ Neutrino Non-standard interaction;
- ✓ Neutrino anomalous magnetic moment…

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2-\frac{MT}{E_\nu^2}\right)$$




CEvNS scattering cross-section

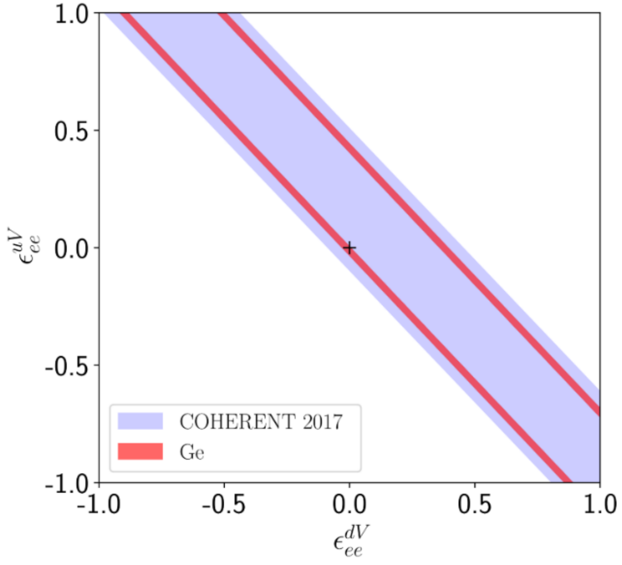
$$Q_W = N - \left(1-4\sin^2\theta_W\right)Z$$




Weinberg angle under low momentum transfer

$$\frac{d\sigma(E_\nu)}{dT} = \frac{G_F^2 M}{2\pi} G_V^2\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{MT}{E_\nu^2}\right]$$

$$G_V = \left(\left(g_V^p+2\epsilon_{ee}^{uV}+\epsilon_{ee}^{dV}\right)Z+\left(g_V^n+\epsilon_{ee}^{uV}+2\epsilon_{ee}^{dV}\right)N\right)F^V(Q^2)$$

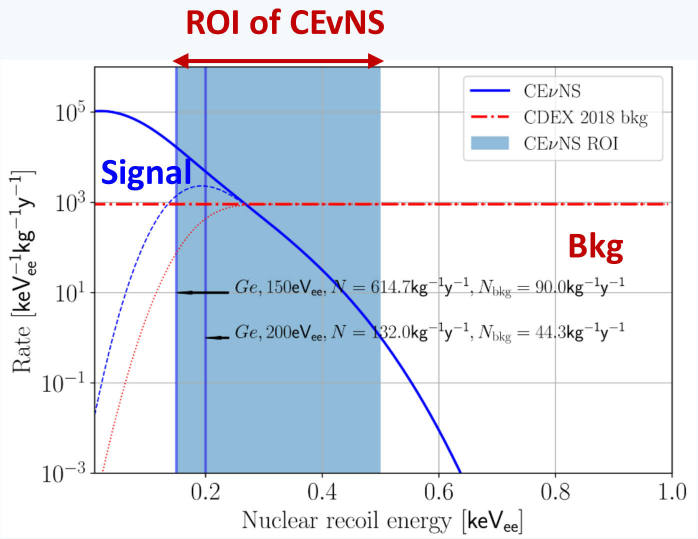



Neutrino NSI

# Expected Physical Results

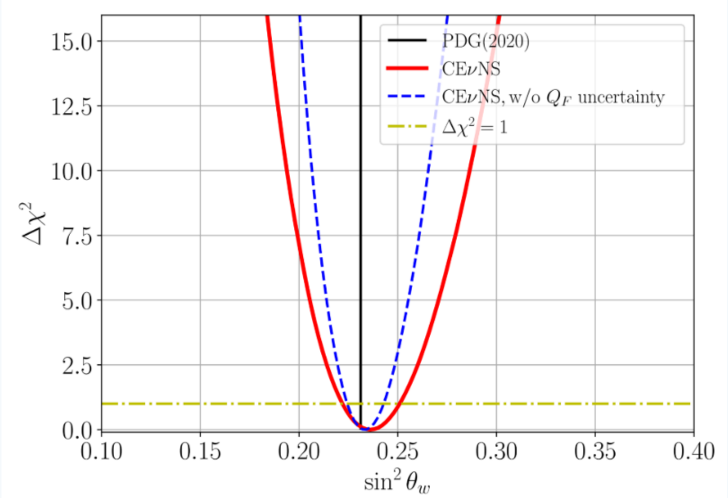
## ■ Accurate measurement of reactor CEvNS

- ➢ approximately 500 CEvNS signals /kg/year, with a signal-to-noise ratio of ~5:1 near the threshold;




Expected CEvNS spectrum in Ge

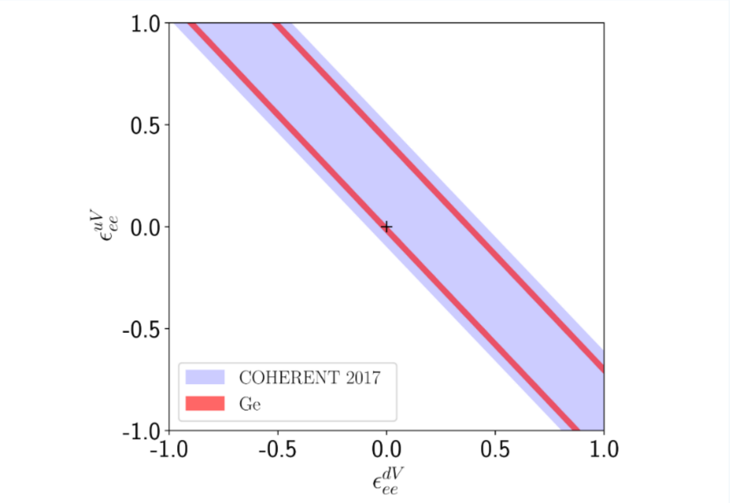
- ➢ Cross-section uncertainty within 20%, and weak mixing angle accuracy within 10% *




Limits on weak mixing angle

## ■ Limiting Neutrino NSI

- ➢ High sensitivity on NSI (red band)
- ➢ COHERENT 2017: Purple area




Limits on neutrino NSI

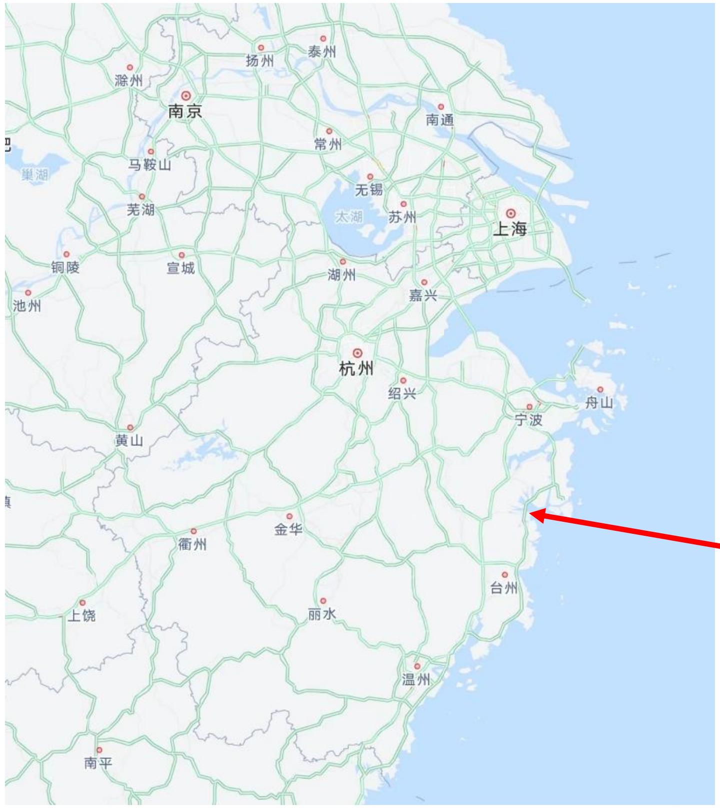
* Uncertainty mainly comes from the quenching factor of germanium

# Project site selection

## ■Sanmen Nuclear Power station@ Taizhou, Zhejiang

■Thermal power 3.4 GW, ~25 meters from the core

■Neutrino flux ~ $1.0 \times 10^{13}$ $cm^{-2}s^{-1}$

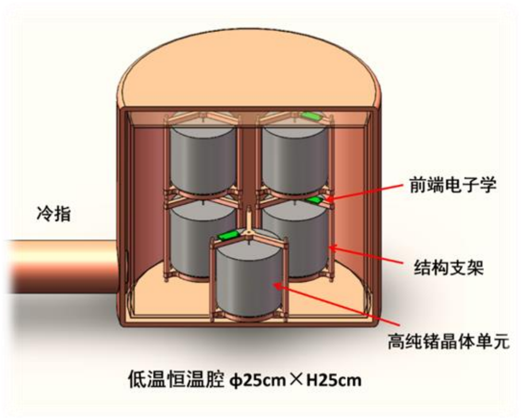


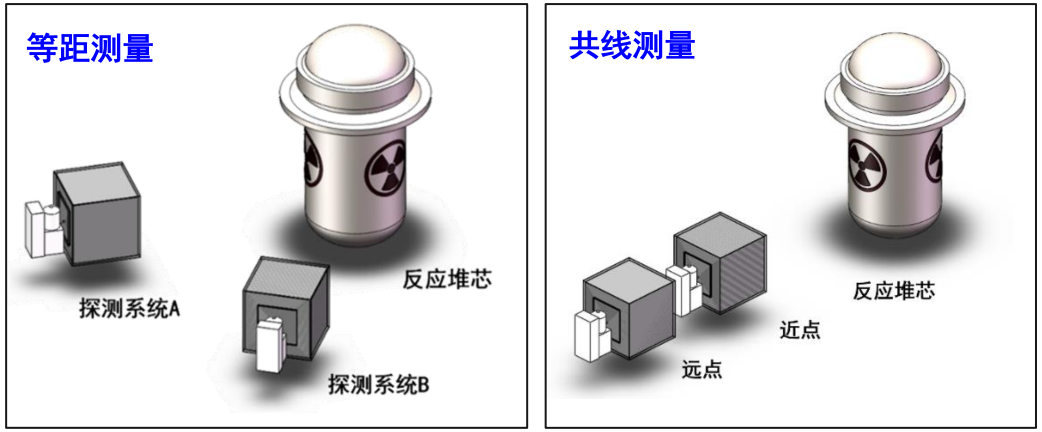

# Schedule

| 2023 | 2024 | 2025 | 2026 | 2027 |
| --- | --- | --- | --- | --- |
| ✓ On site environmental bkg measurement/estimation<br>✓ Design, production, and processing of various subsystems | ✓ Subsystem independent testing<br>✓ Joint testing work | ✓ Transport to nuclear power plant, installation, testing<br>✓ First physics run | ✓ Change working mode<br>✓ Second physics run<br>✓ Data analysis | ✓ Change working mode<br>✓ Third physics run<br>✓ Data analysis |

**Subsystems testing @CJPL and ground**

**Physics Run @nuclear power plant**



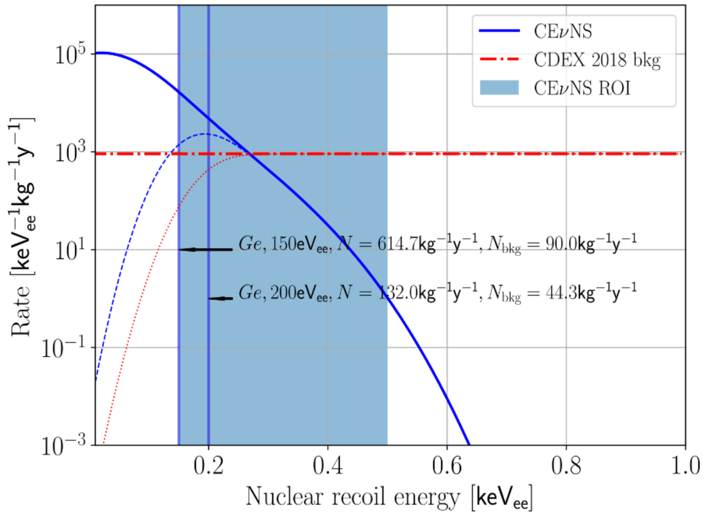
# Uncertainty analysis

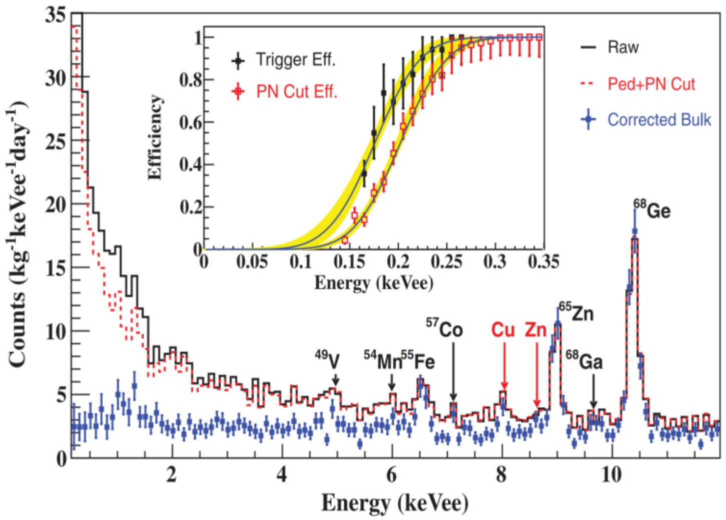
■Statistical uncertainty: not significant, increase the exposure as much as possible;

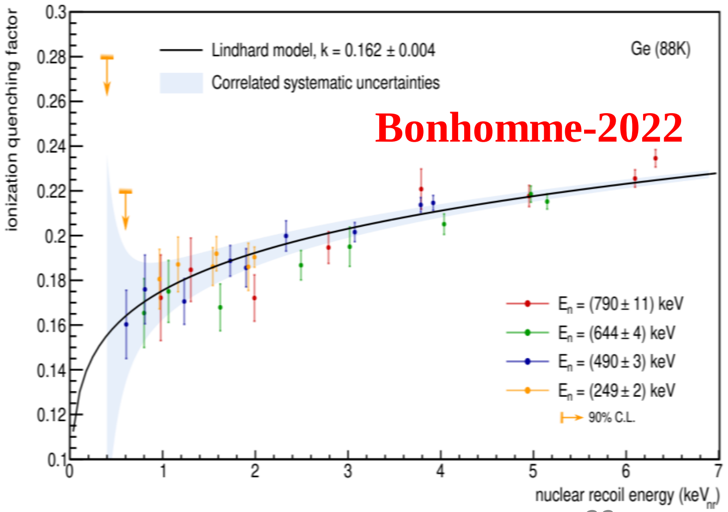
- Signal/Noise>5:1, if there are 5000 signals and 1000 background signals per year, 1.5%

■Systematic uncertainty:

- **mainly come from the uncertainty of nuclear recoil quenching factor~10% -20%;**
- Uncertainty of reactor Neutrino current intensity (~3%): eliminated through joint measurement
- Triggering efficiency and event selection efficiency (very low): high energy resolution
- Background model uncertainty: reduced through joint measurement and ON/OFF measurement



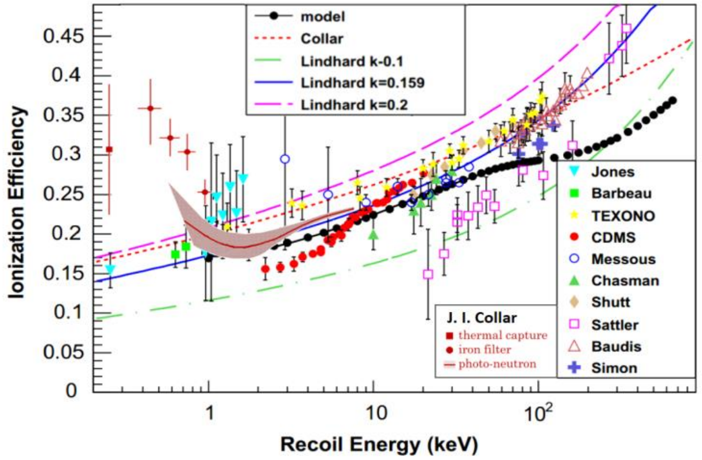



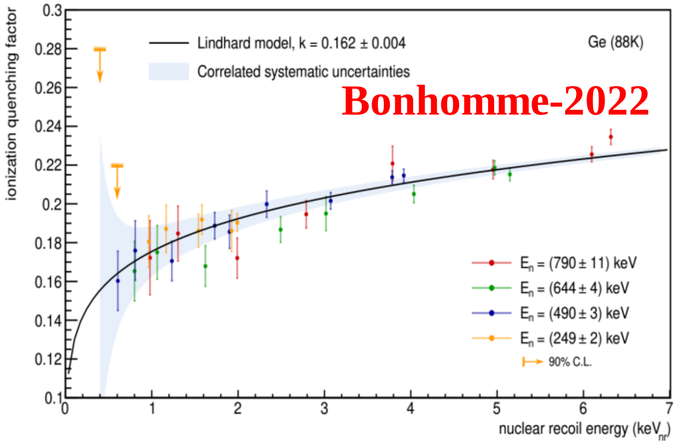
# Measurement of quenching factor

## ■Single energy nuclear recoil

- Using monoenergetic neutrons (accelerator monoenergetic proton targeting, screening mono energy neutrons through neutron coincidence detector angle)
- Specific Nuclear reaction channel (such as Inelastic scattering produced by thermal Neutron capture)

| Experiment | Neutron source | Recoil nuclear energy (keV) | Reaction |
|---|---|---|---|
| Sattler-1966 | T(p,n)He3 400 keV-6.5 MeV;<br>T(d,n)He4 >14. 1 MeV; | 21.4 ~ 997 | elastic scattering |
| Chasman-1965 | 700keV- 2.2MeV | 20 ~ 100 | 72Ge(n, n')72Ge*(691keV);<br>74Ge(n, n')74Ge*(596.3); |
| Chasman-1967 | T(p,n)He3 2.38 MeV; | 56.2, 102.9 | 72Ge(n, n')72Ge*(691keV);<br>74Ge(n, n')74Ge*(596.3); |
| Chasman-1968 | 703keV- 733keV | 10 ~ 30 | 72Ge(n, n')72Ge*(691keV); |
| Jones-1971 | **7Li(p,n)7Be** 70keV-110keV; | 0.96 ~ 1.75 | 73Ge(n, n')73Ge*(68.75keV); |
| Jones-1975 | Thermal neutron | 0.254 | 72Ge(n, γ)73Ge*(68.75keV); |
| Messous-1995 | **7Li(p,n)7Be** 1.306MeV; | 3 ~ 40 | 74Ge(n, n')74Ge*(595.9keV); |
| Baudis-1998 | **7Li(p,n)7Be** 13.77MeV;<br>65Cu(p,n)65Zn 13.75MeV;<br>63Cu(p,n)63Zn 11.78MeV; | 60 ~ 200 | elastic scattering |
| Collar-2021 | Photo-neutron source, Thermal neutron, 24 keV iron-filtered neutron | 0.254；<br>0.3 ~ 8 | elastic scattering<br>72Ge(n, γ)73Ge*(68.75keV); |
| Bonhomme-2022 | **7Li(p,n)7Be** 250keV – 800 keV; | 0.4 ~ 6 | elastic scattering |

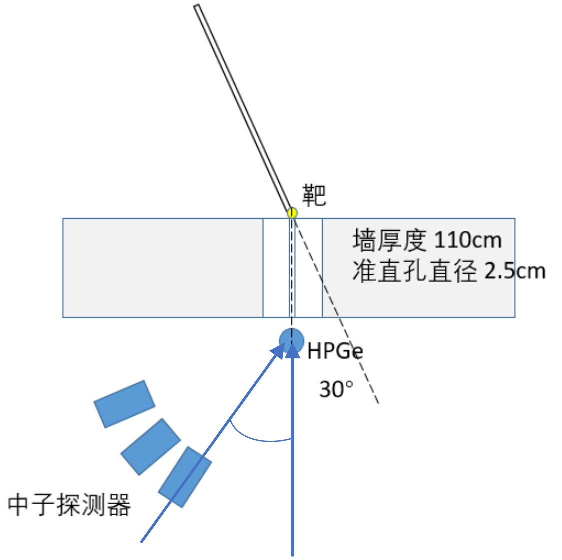


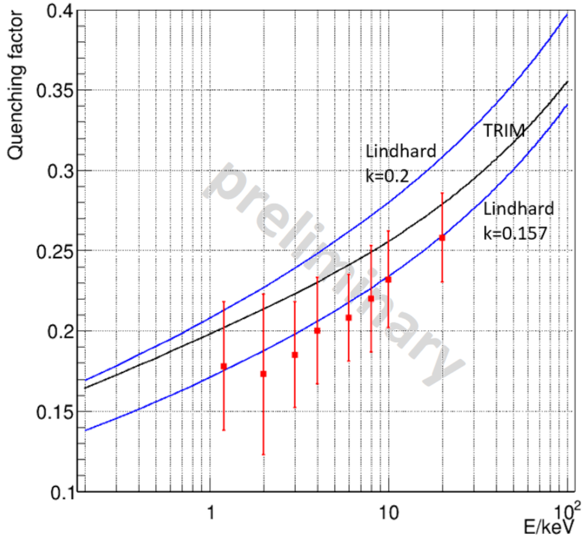



# Measurement of quenching factor

## ➢ Measurement of Ge QF @ 1-10keV

- ✓ 10g ultra-low threshold high-purity germanium detector
- ✓ High Voltage Multiplier at CIAE
- ✓ EJ-301/BC-501A liquid Scintillator
- ✓ QF measurement results @1.2keV-20keV





## ➢ Future plans

- ✓ Use californium fission chambers or tandem accelerators to conduct more accurate measurements
  - more accurate measurement @ 1-20keV
  - Conduct measurement and research below 1keV

# Summary

- **Reactor neutrino CEvNS detection has great scientific significance for the verification of SM at low energy scale and the accurate measurement of weak mixing angle;**
- **The key performance parameters of the HPGe detector, such as low energy threshold, low background, have been validated for many years in CJPL;**
- **By designing a lightweight structure and upgrading low background materials, we will developed a joint measurement system based on germanium detector array;**
- **By joint measurements, the experimental systematic uncertainty can be significantly reduced and then improve the sensitivity.**

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Thank you!

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