RECODE program for reactor neutrino CEvNS detection and New Physics

Yongcheng Wu/吴永成
Nanjing Normal University

第十二届新物理研讨会
Jul. 23 – Jul. 29, 2023

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Disclaimer:
I am not experimentalist.
If there is any mistake/confusion, that is my problem, it is not from my colleagues

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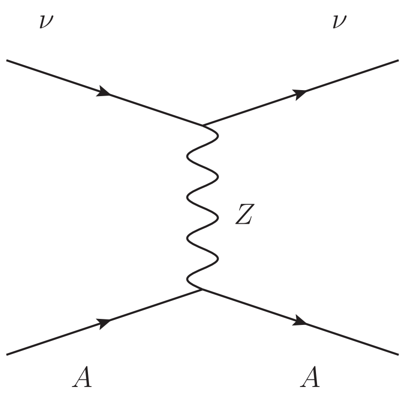
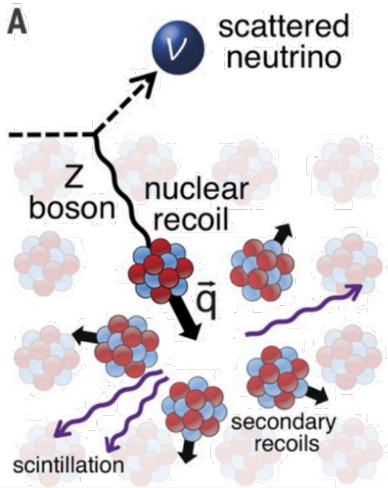
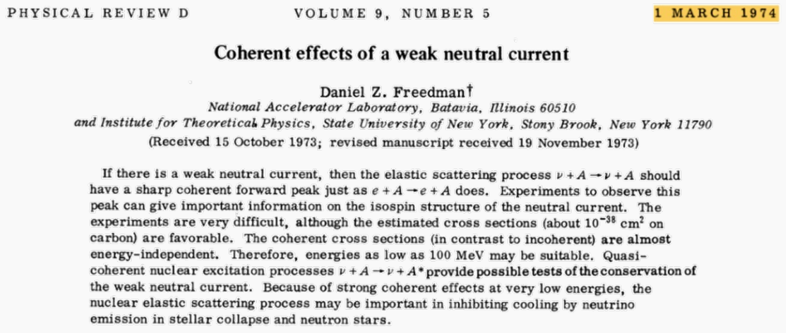
CEvNS

- Coherent Elastic Neutrino-Nucleus Scattering
  - Basic interaction between Neutrino and matter in SM
    - Weak Neutral Current
  - The nucleus scatters Neutrino as a whole





Theoretical prediction (1974)



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

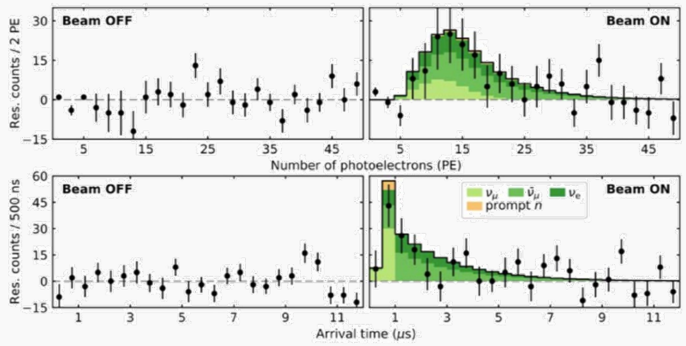
Coherent effects of a weak neutral current

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)

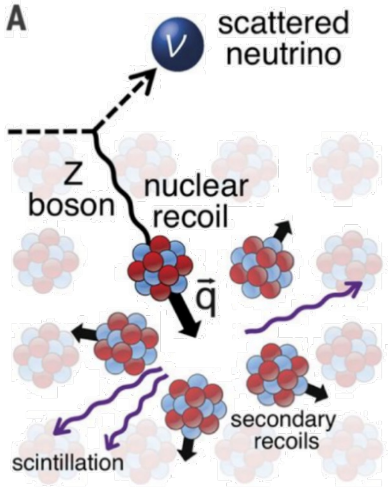
Experimental Evidence (2017)

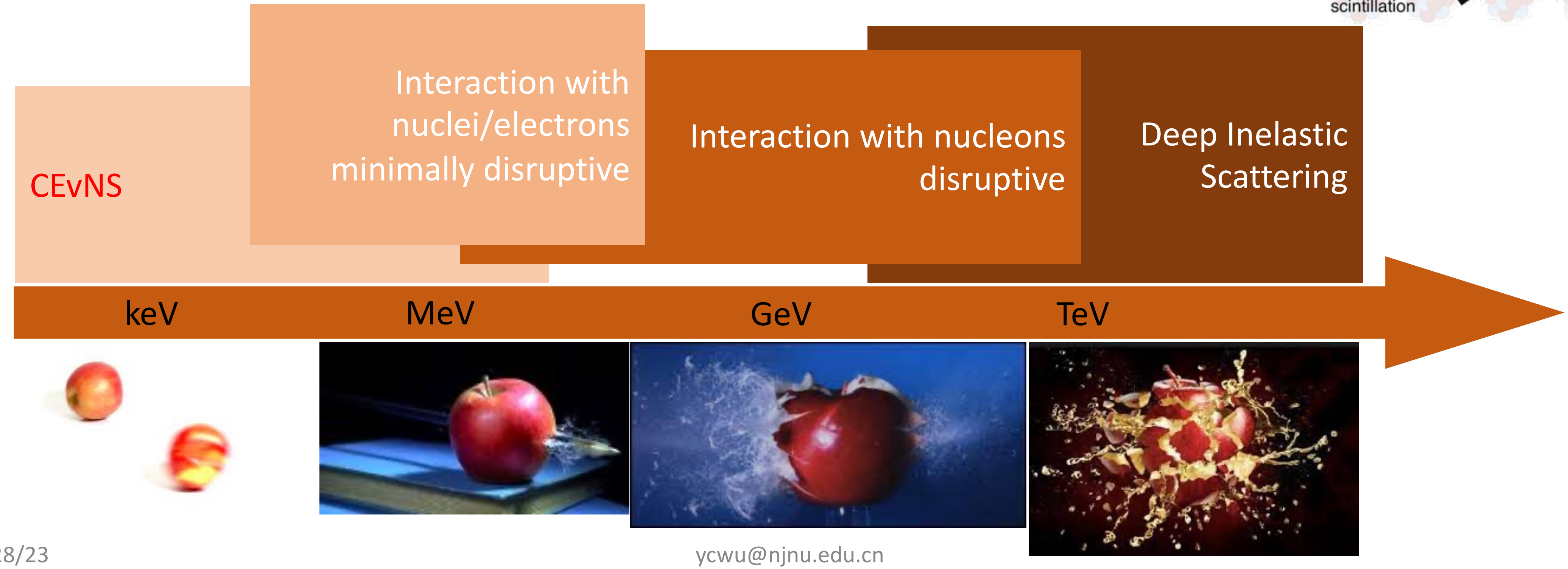


D. Akimov et al, Science 357 (2017)

CEνNS

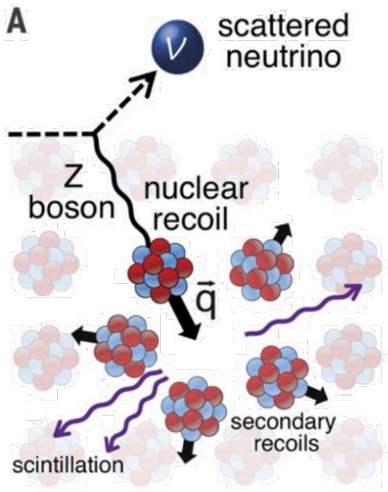
- Coherent Elastic Neutrino-Nucleus Scattering
  - Basic interaction between Neutrino and matter in SM
  - The nucleus scatters Neutrino as a whole
- Dominant for $E_\nu \lesssim 50$ MeV $\boldsymbol{q \cdot R \ll 1}$





CEvNS

- Coherent Elastic Neutrino-Nucleus Scattering
  - Basic interaction between Neutrino and matter in SM
  - The nucleus scatters Neutrino as a whole
- Dominant for $E_\nu \lesssim 50$ MeV
- Large Cross Section



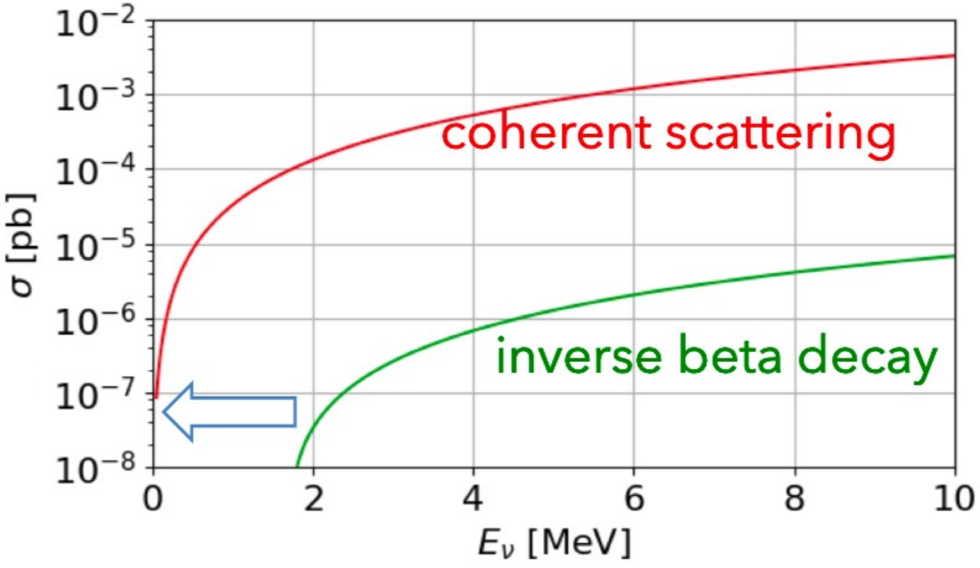
$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{8\pi} Q_W^2 |F(q)|^2 \left(2 - \frac{2E_R}{E_\nu} + \left(\frac{E_R}{E_\nu}\right)^2 - \frac{ME_R}{E_\nu^2}\right)$$

$q \cdot R \ll 1$

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

$$\sin^2\theta_W \approx 0.23$$

$\sigma \propto N^2$



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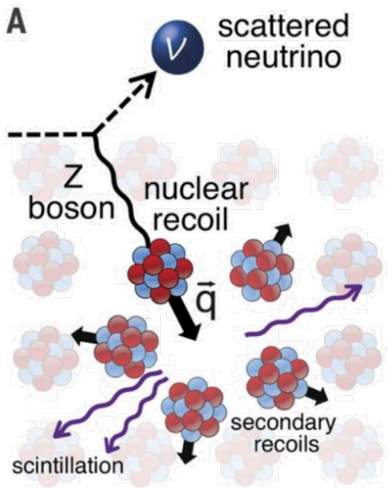

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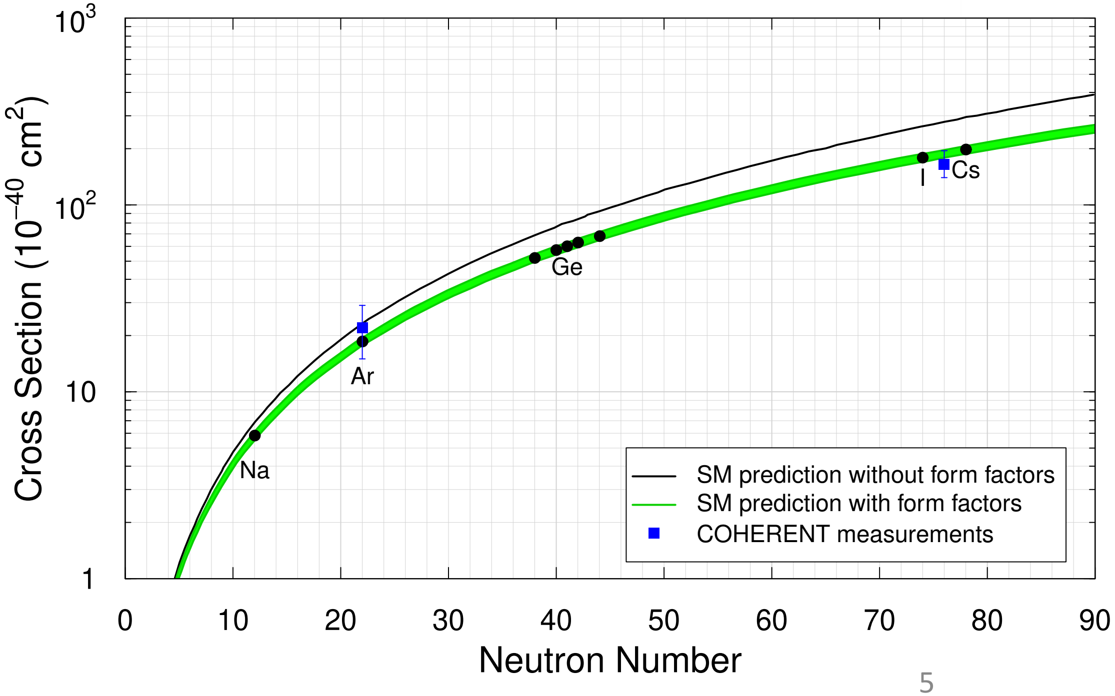
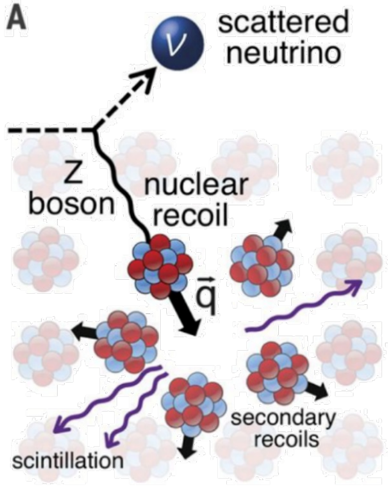
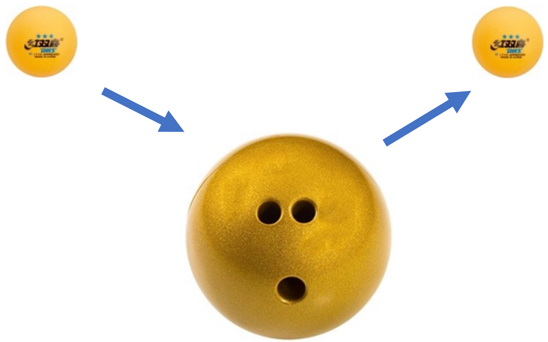


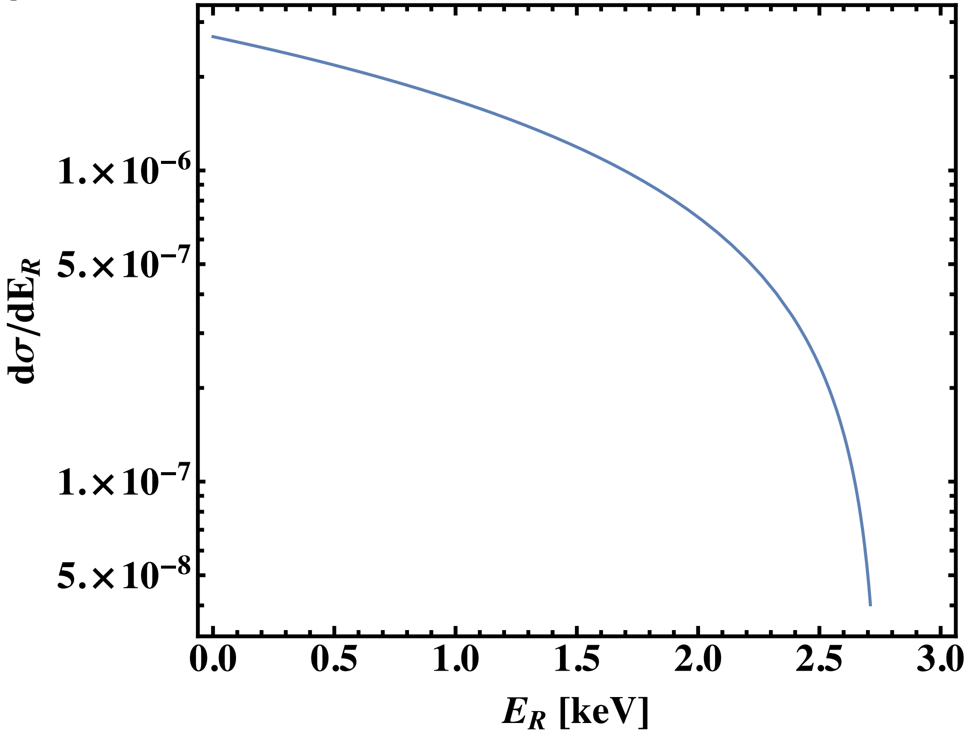
CEvNS

- Coherent Elastic Neutrino-Nucleus Scattering
  - Basic interaction between Neutrino and matter in SM
  - The nucleus scatters Neutrino as a whole
- Dominant for $E_\nu \lesssim 50$ MeV
- Large Cross Section
- Recoil Energy is Small



$$E_R \sim \frac{E_\nu^2}{M} = \frac{(E_\nu/MeV)^2}{A}\ keV$$

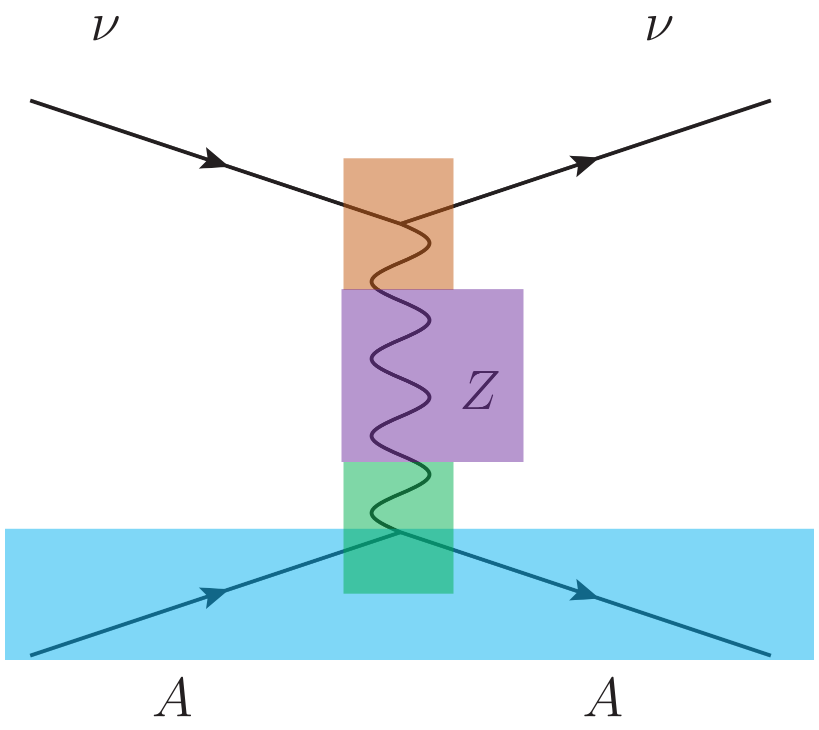




CEvNS: Physics Motivation

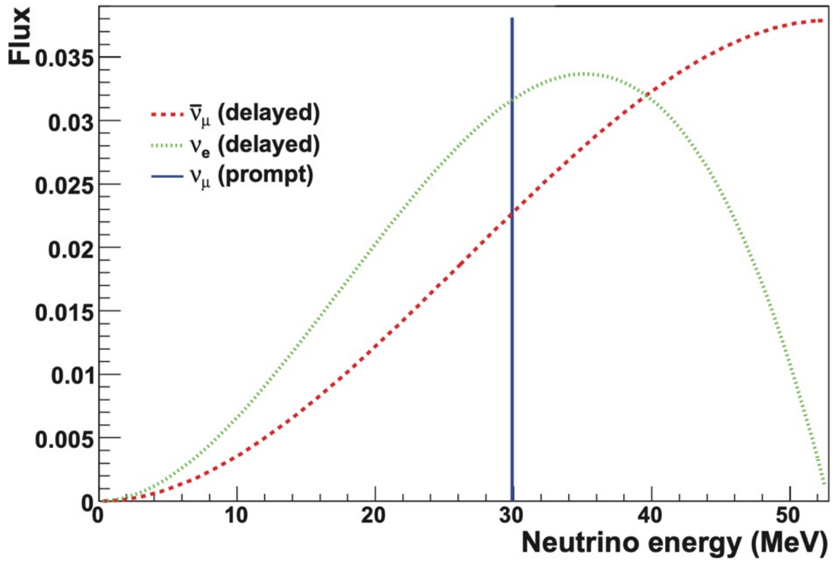
- For "Old" Physics
  - Testing Standard Model
  - Nuclear Form Factor
  - Neutron Distribution Radius
- For "New" Physics
  - Neutrino Interaction/Properties
  - Light Mediator/DM
  - etc.
- As Background for DM Detection
- Practical Tool
  - Monitoring

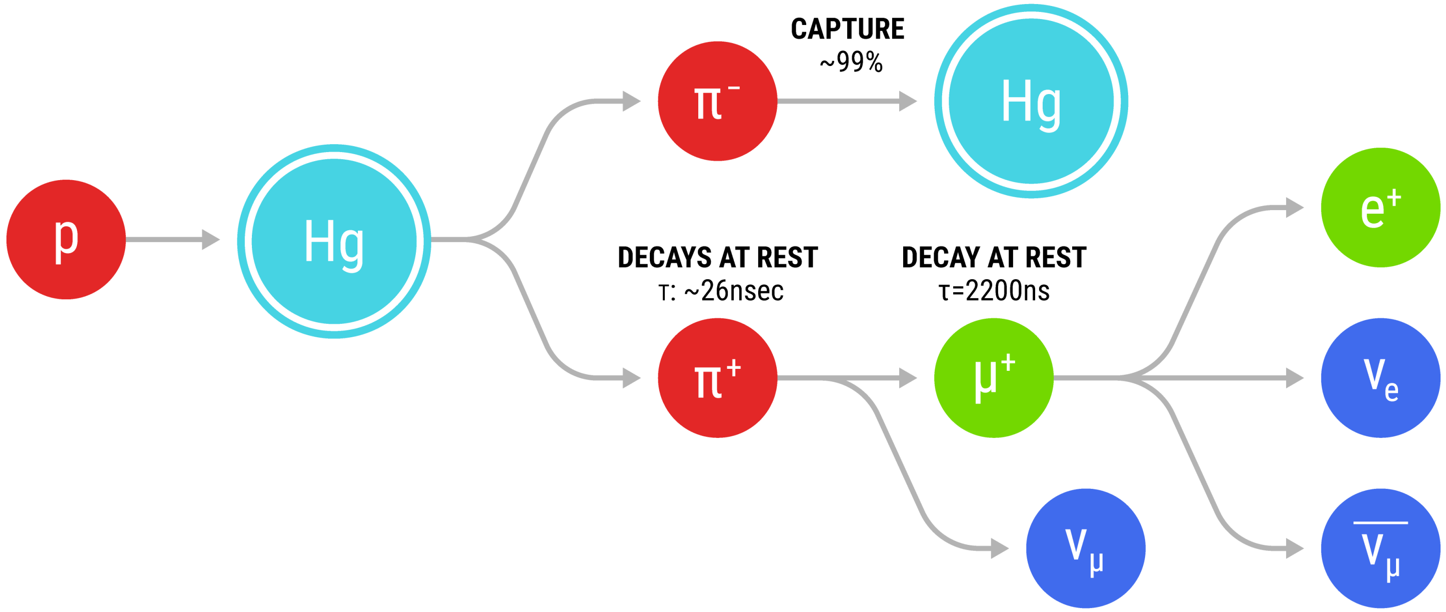
$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{8\pi} Q_W^2 |F(q)|^2 \left(2 - \frac{2E_R}{E_\nu} + \left(\frac{E_R}{E_\nu}\right)^2 - \frac{ME_R}{E_\nu^2}\right)$$



CEvNS: Neutrino Sources

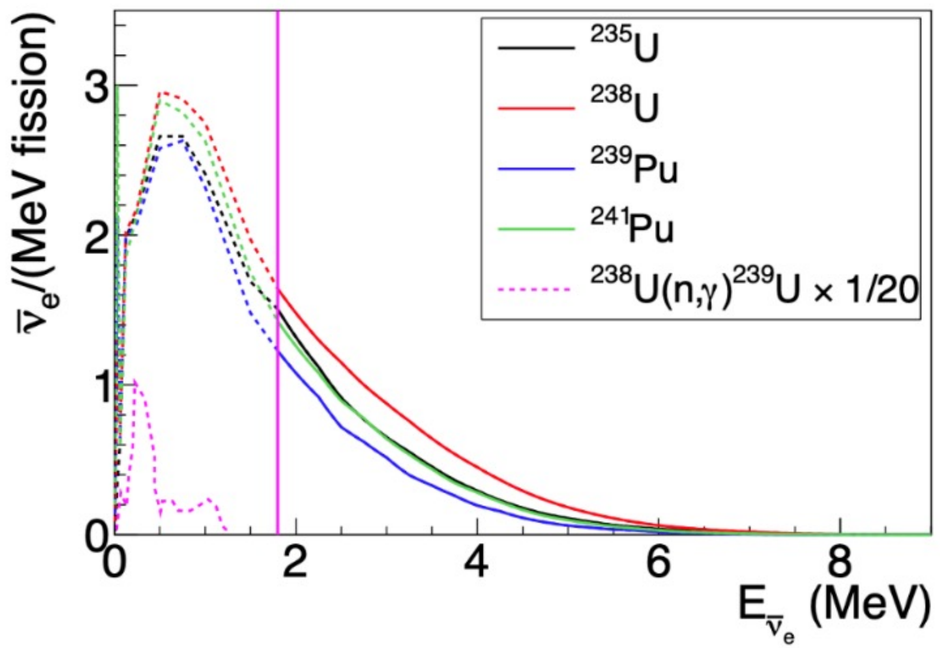
- Stopped-Pion Decay: π-DAR
  - Several 10s MeV
  - Pulsed beam
    - Good for Background rejection
  - $\sim 4.3\times10^{7}\ cm^{-2}s^{-1}$ at 20m

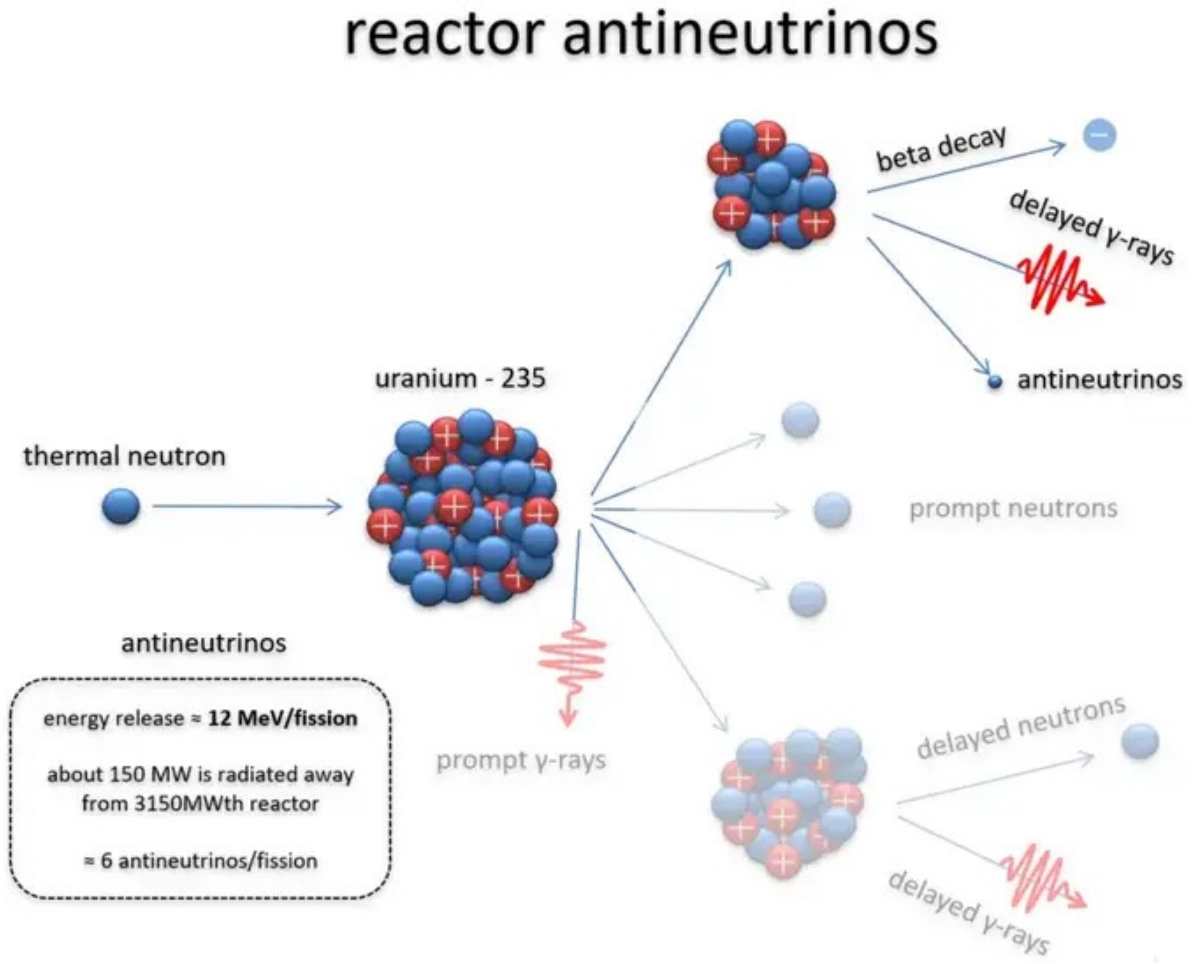




CEvNS: Neutrino Sources

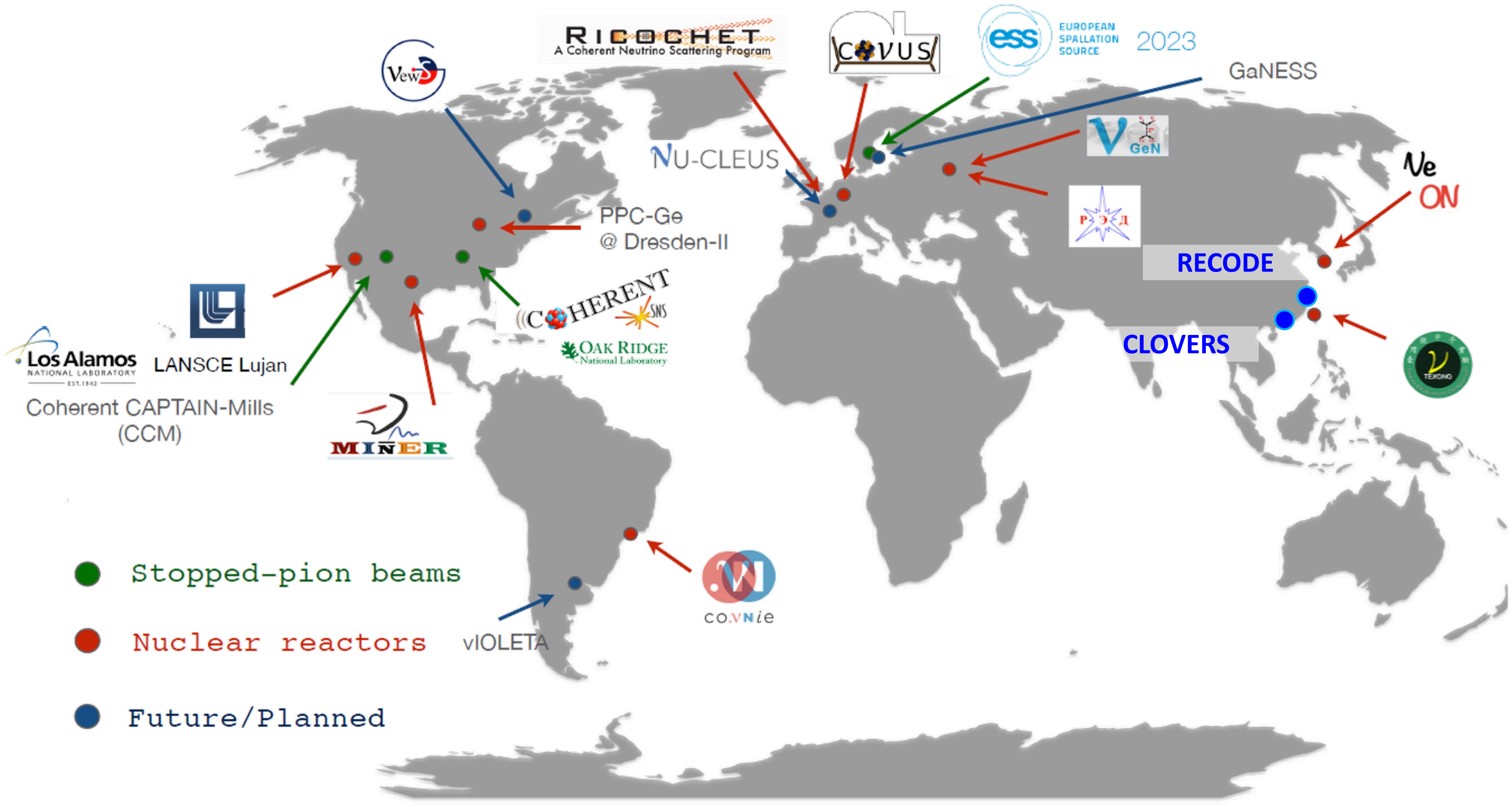
- Reactor Neutrinos
  - High flux
    - $10^{12} - 10^{13}\ cm^{-2}s^{-1}$ at 15m
  - Low energy, up to 8/10 MeV
    - Low threshold for detector
  - Mainly $\bar{\nu}_e$





Rept. Prog. Phys. 82 (2019) 036201

CEvNS: Experiments



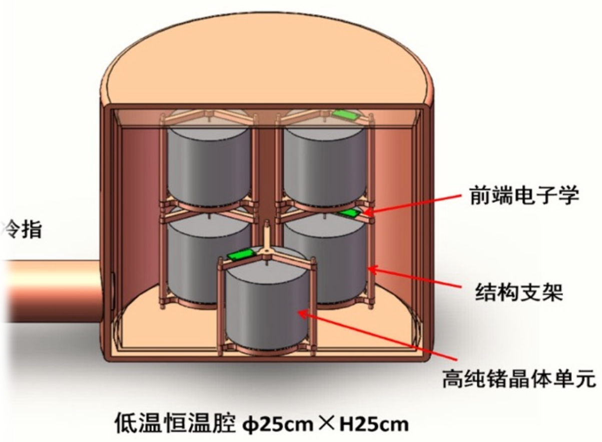
RECODE Program

- RECODE

  REactor neutrino COherent scattering Detection Experiment

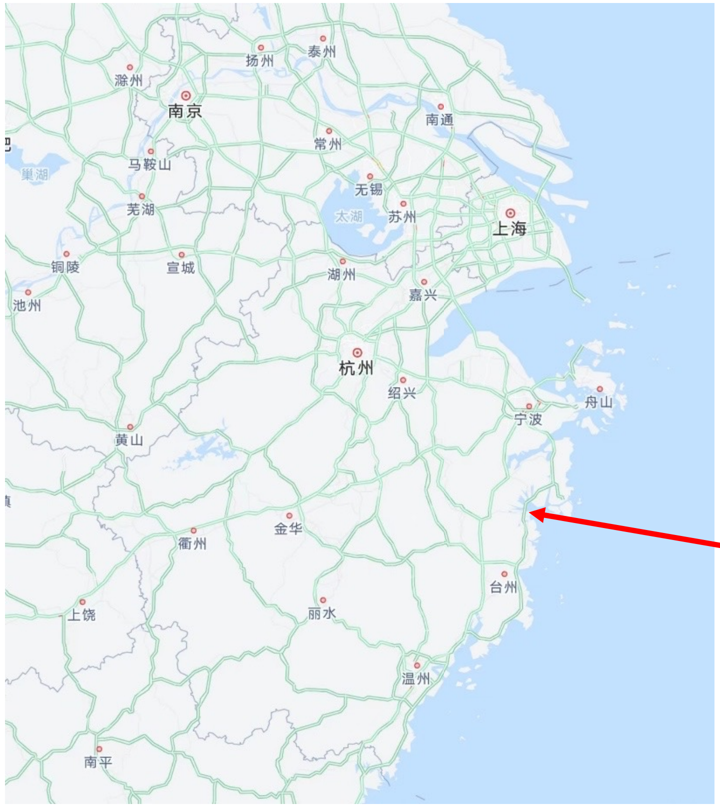
  - Low threshold Ge detectors
  - Reactor neutrinos

- Project Goals:
  - Two Ge arrays (10kg in total)
    - Energy threshold ~ 1 keVnr (~160eVee)
    - ~ 500 CEvNS events/kg/year
    - Background level < 2 counts/kg/keV/day



RECODE Location

- **Sanmen Nuclear Power station @ Taizhou, Zhejiang**
  - Thermal power ~ 3.4 GW
  - 25 meters from the core
  - Neutrino flux ~ $10^{13}\ cm^{-2}s^{-1}$



RECODE Roadmap & Schedule

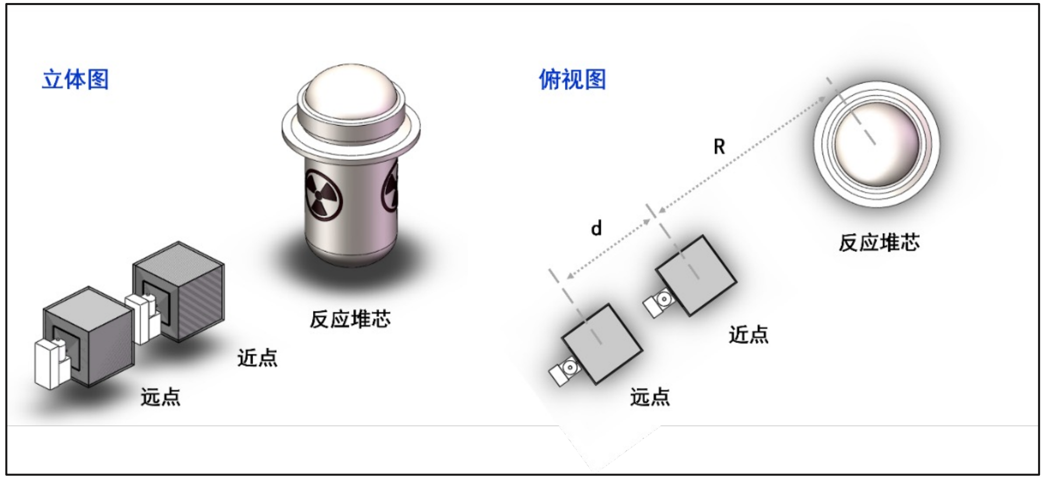
2023 → 2024 → 2025 → 2026 → 2027

Subsystems testing @CJPL and ground

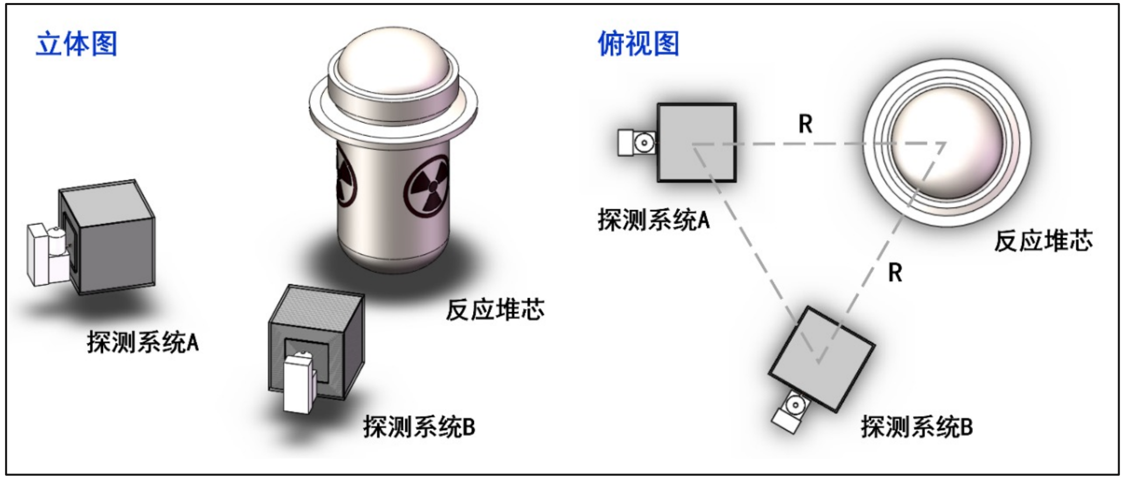
- Bkg Measurement
- Design Subsystem
- Proposal
- Individual Test
- Joint Test

Physics Run @nuclear power plant

- Installation Test
- Run-I
- Run-II
- Run-III
- Data Analysis, Physical Analysis



①/② collinear measurement modes



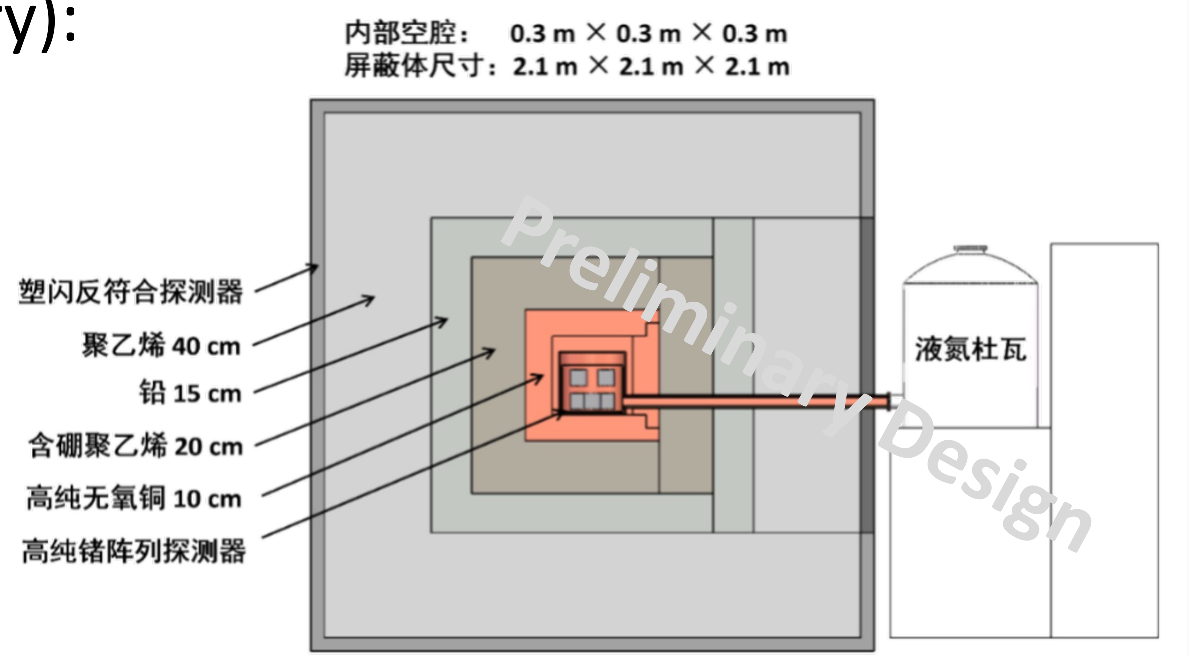
③ equidistance measurement mode

ycwu@njnu.edu.cn

RECODE: Detector Shielding

- Shielding design and optimization
  - Anti coincidence efficiency for cosmic ray: > 99%
  - Gamma flux: reduce by 5 orders of magnitude
  - Neutron flux: reduce by 3 orders of magnitude

- From outer to inner layers (Preliminary):
  - Muon veto detector
  - Polyethylene
  - Lead
  - Boron-doped polyethylene
  - High purity oxygen free copper



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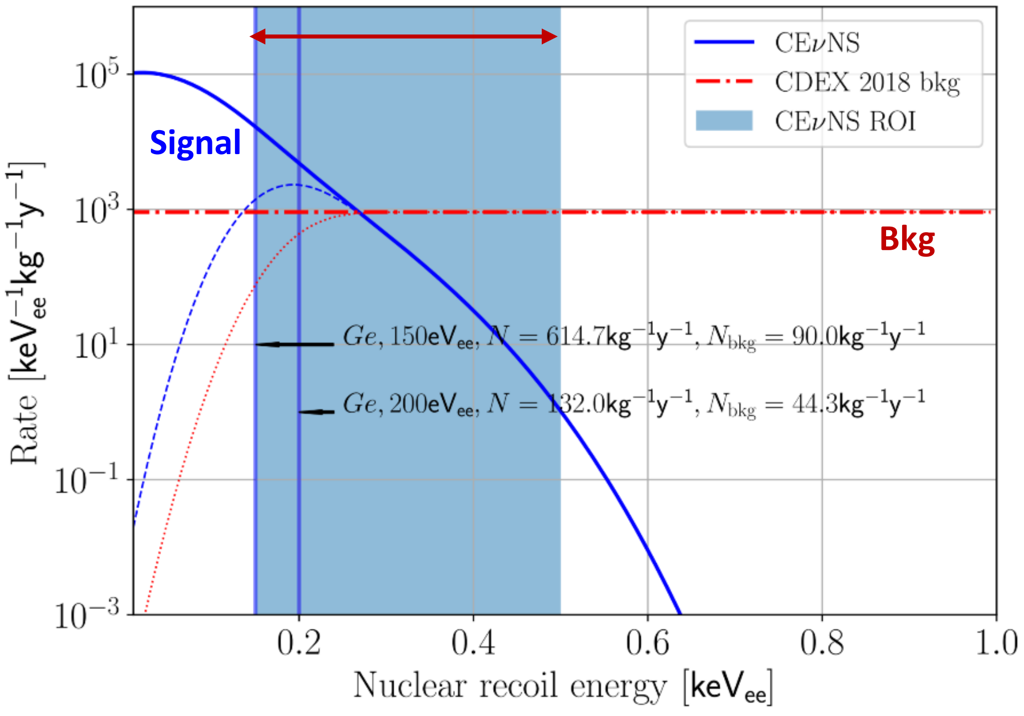
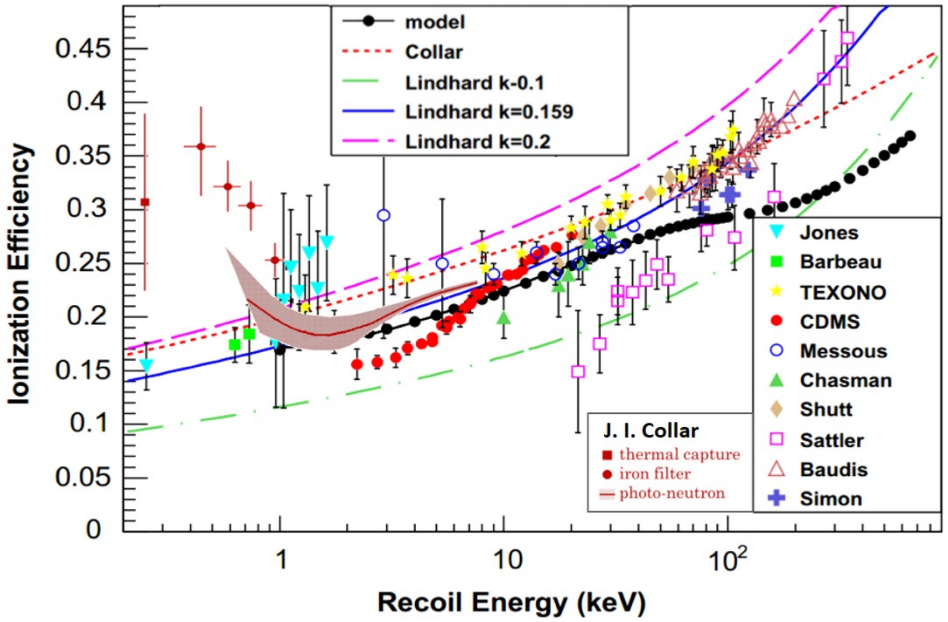
RECODE: Uncertainties

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



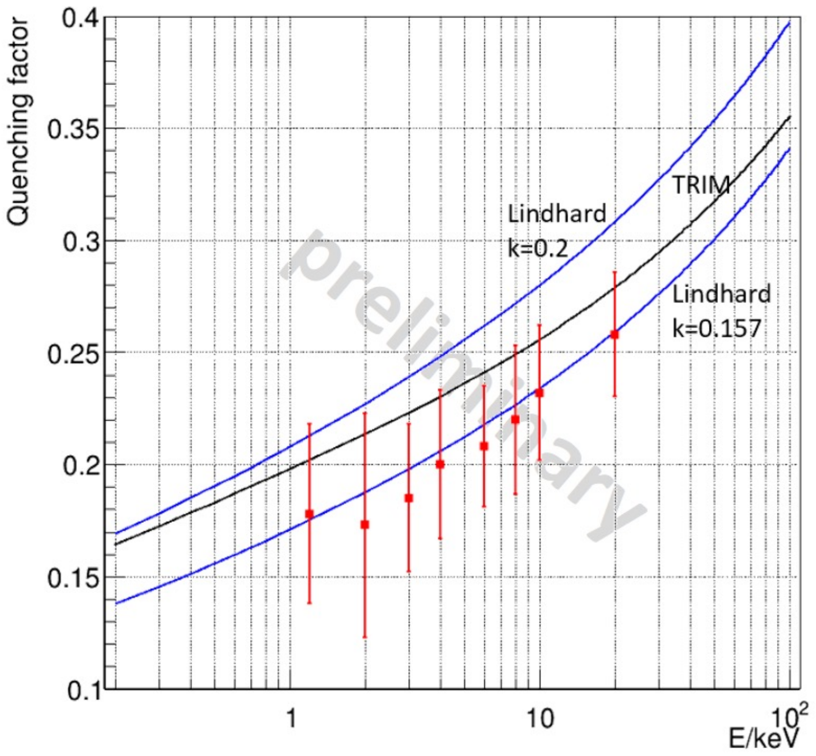
Expected CEvNS spectrum in Ge

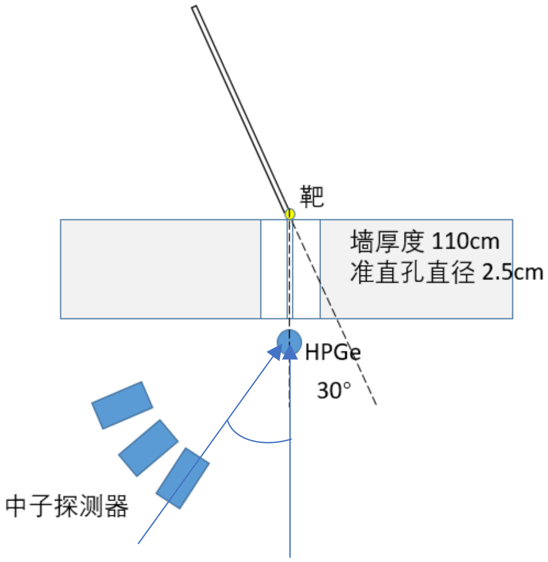
- Systematics:
  - Quenching factor: 10%-20%
  - Reactor neutrino intensity: 3%
    - Reduced through joint measurement
  - Background modeling:
    - ON/OFF measurement



RECODE: Quenching factor measurement

- Measurement of Ge QF @ 1-10 keV
  - 10g ultra-low threshold high-purity germanium detector



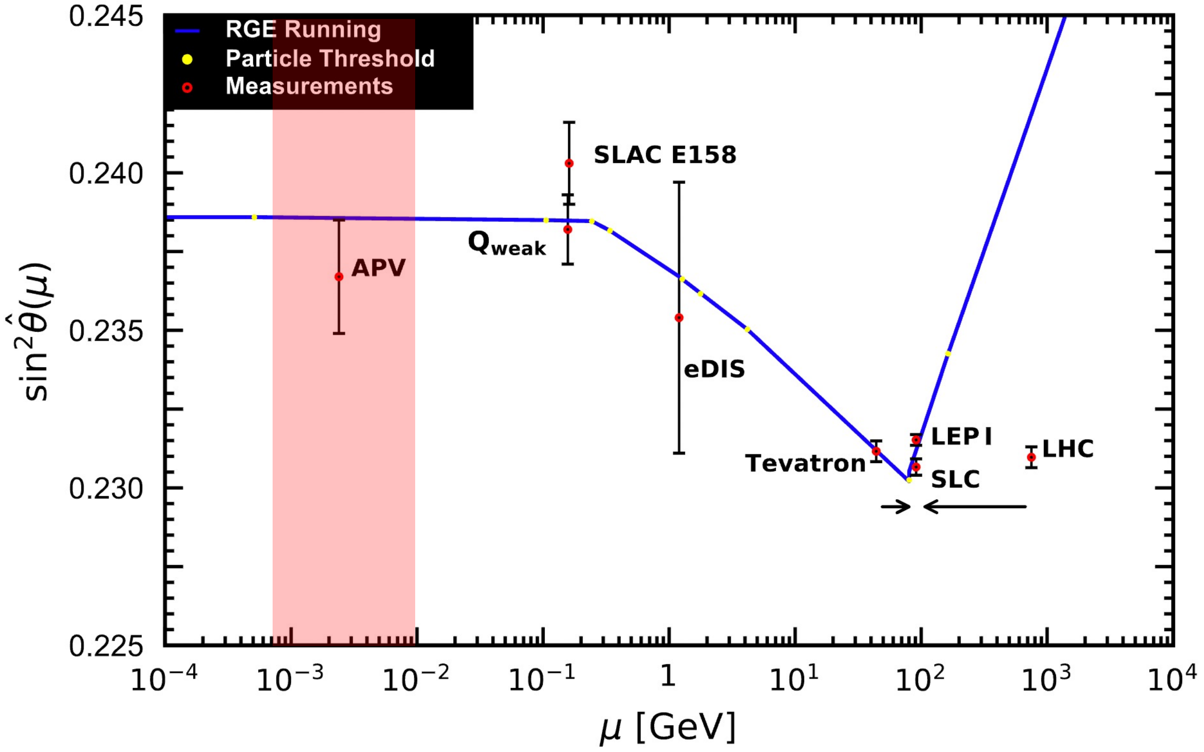


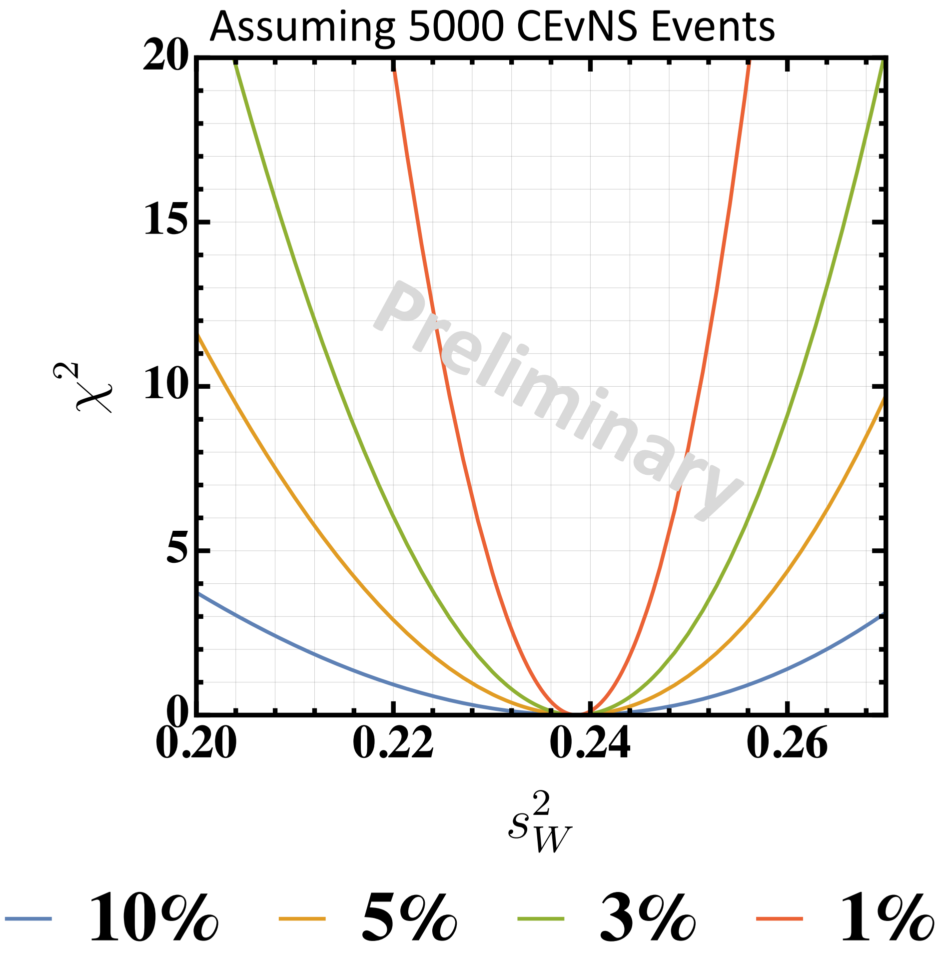
RECODE: Prospects

- Weak Mixing Angle

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

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





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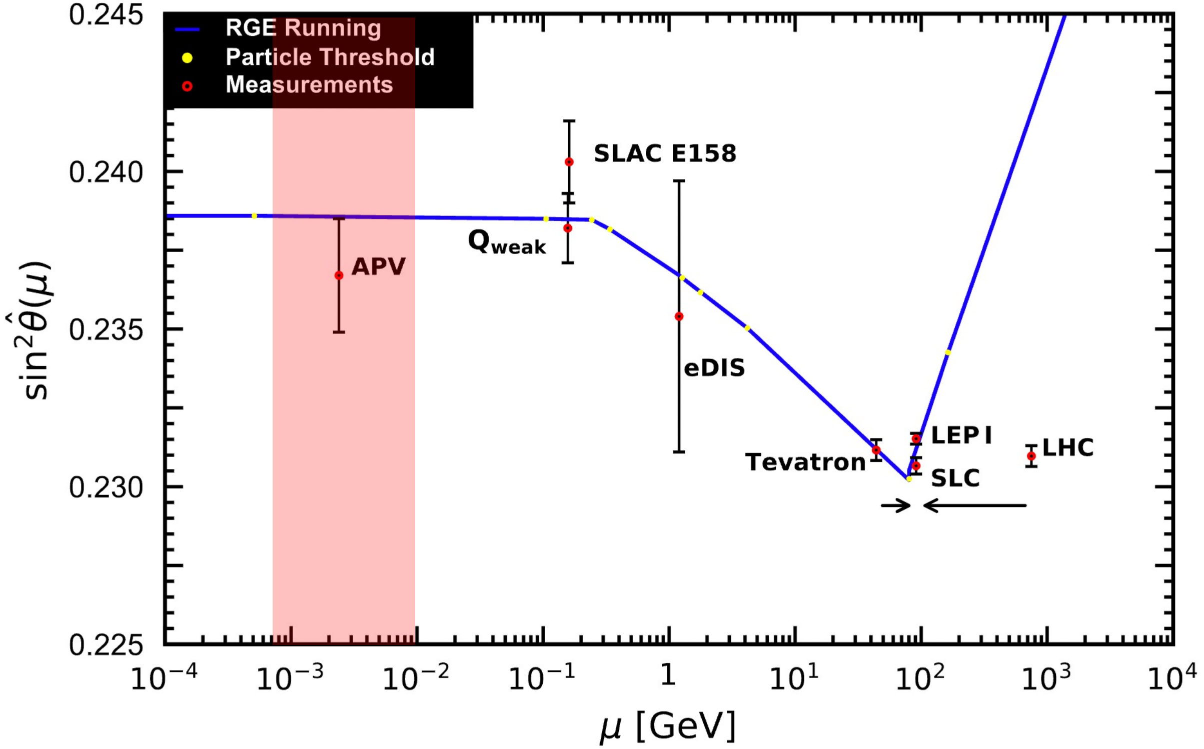
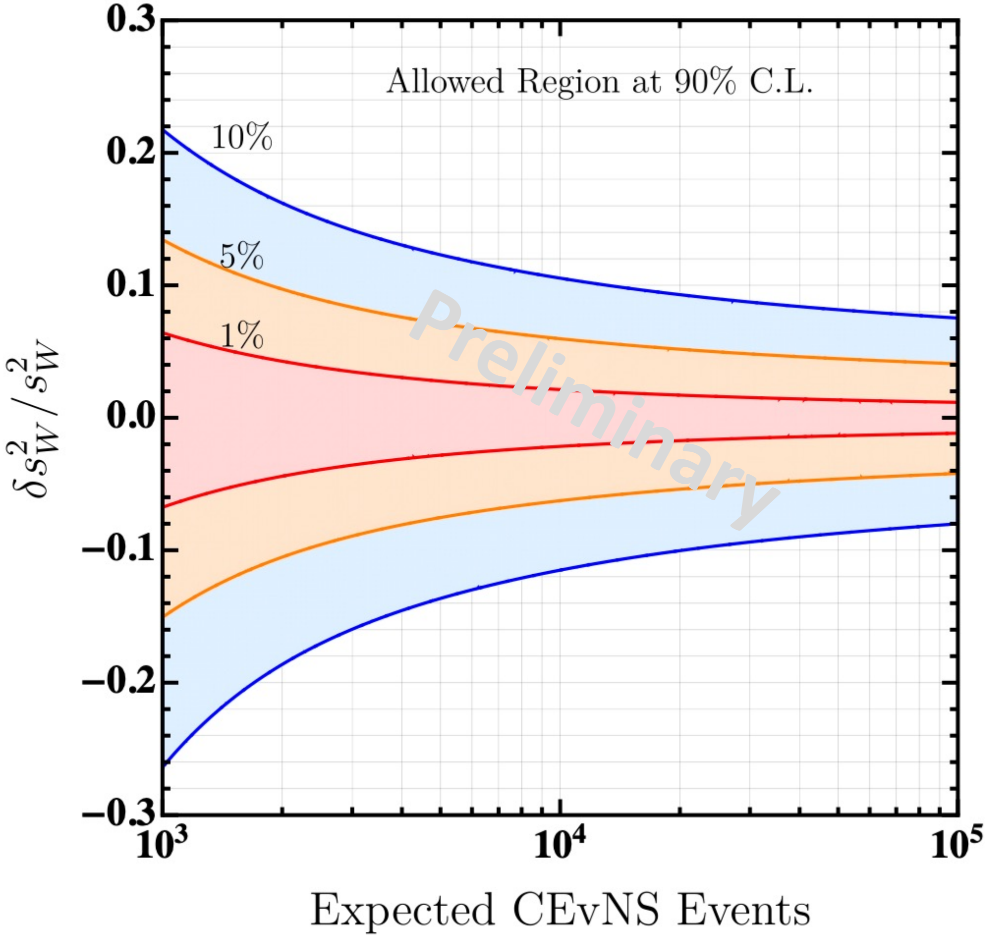




ycwu@njnu.edu.cn

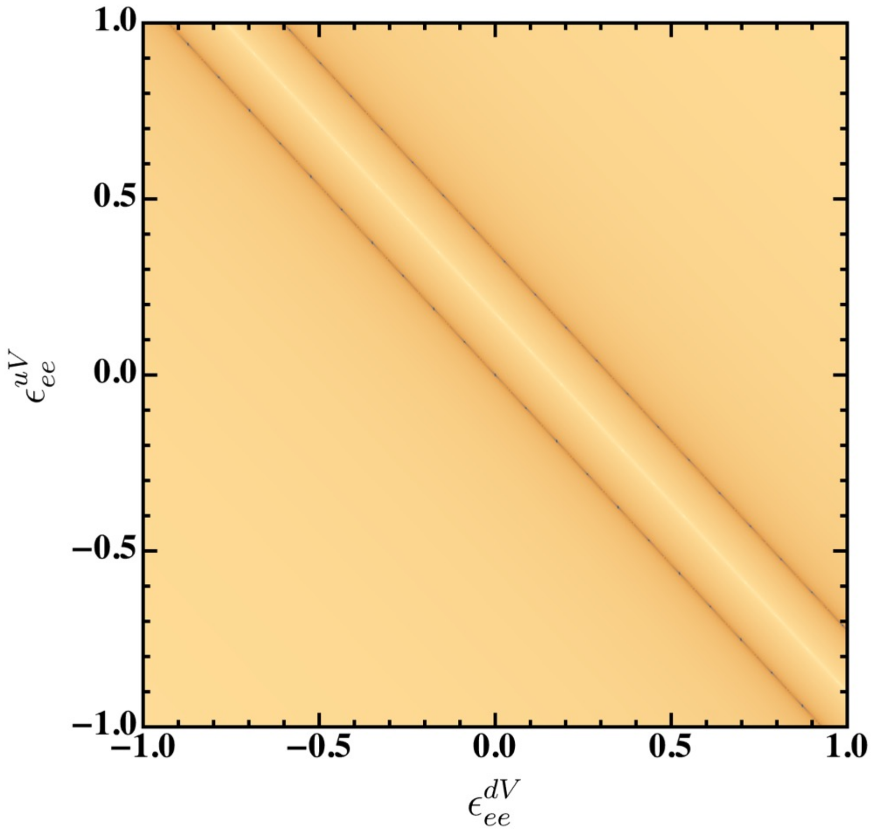
RECODE: Prospects

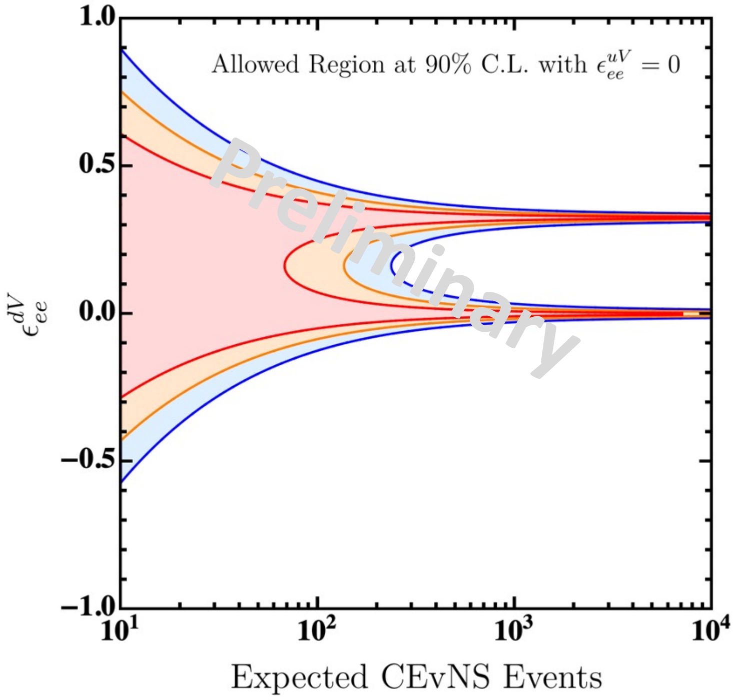
- Neutrino NSI

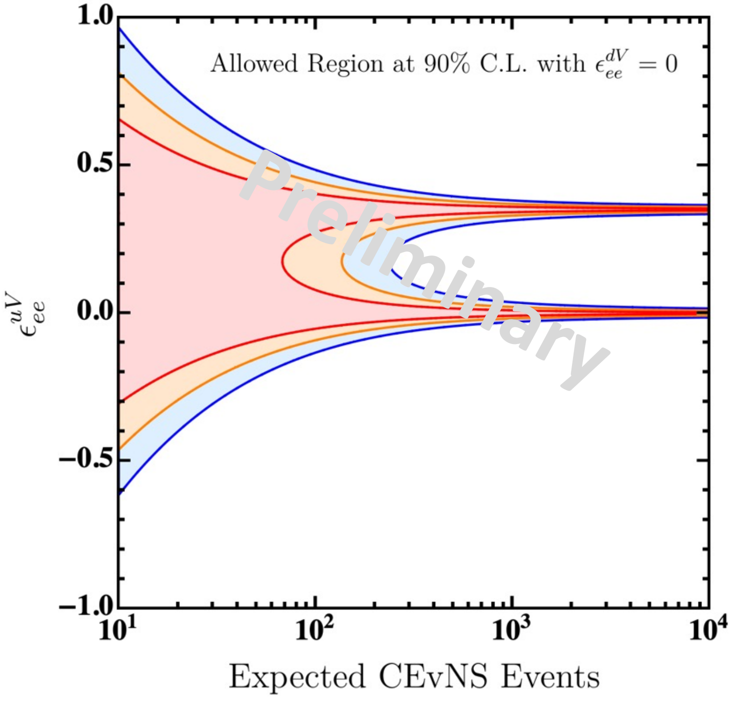
$$\mathcal{L}^{NSI} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{f,V}(\bar{\nu}_{\alpha L}\gamma^{\mu}\nu_{\beta L})(\bar{f}\gamma_{\mu}f)$$

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

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







RECODE: Prospects

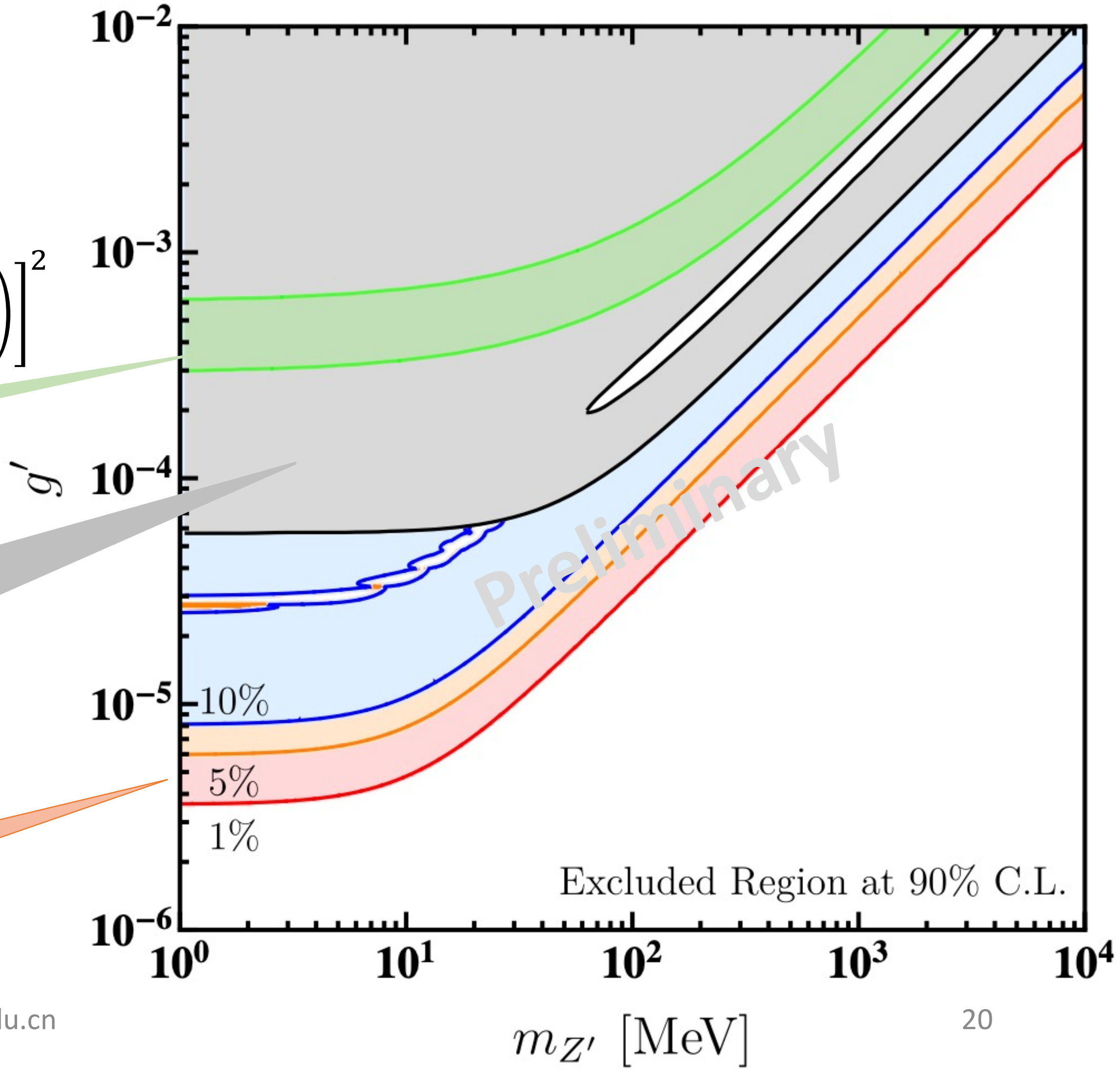
- Light Mediator

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

$$Q_{SM}^2 = \left(Z\, g_p^V + N\, g_n^V\right)^2$$

$$Q_{BSM}^2 = \left[Z\left(g_p^V + \frac{3g'^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)}\right) + N\left(g_n^V + \frac{3g'^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)}\right)\right]^2$$

J. Liao, D. Marfatia; Phys. Lett. B 775 (2017) 54



Explain the g-2 anomaly

Excluded at 2σ From COHERENT

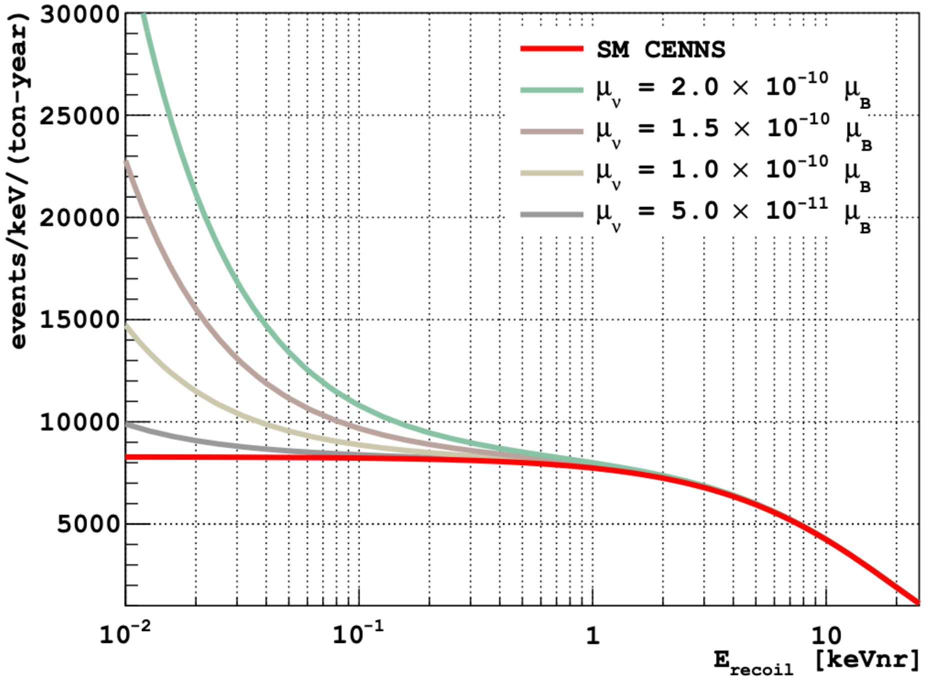
Excluded at 90% with 1-year RECODE Running

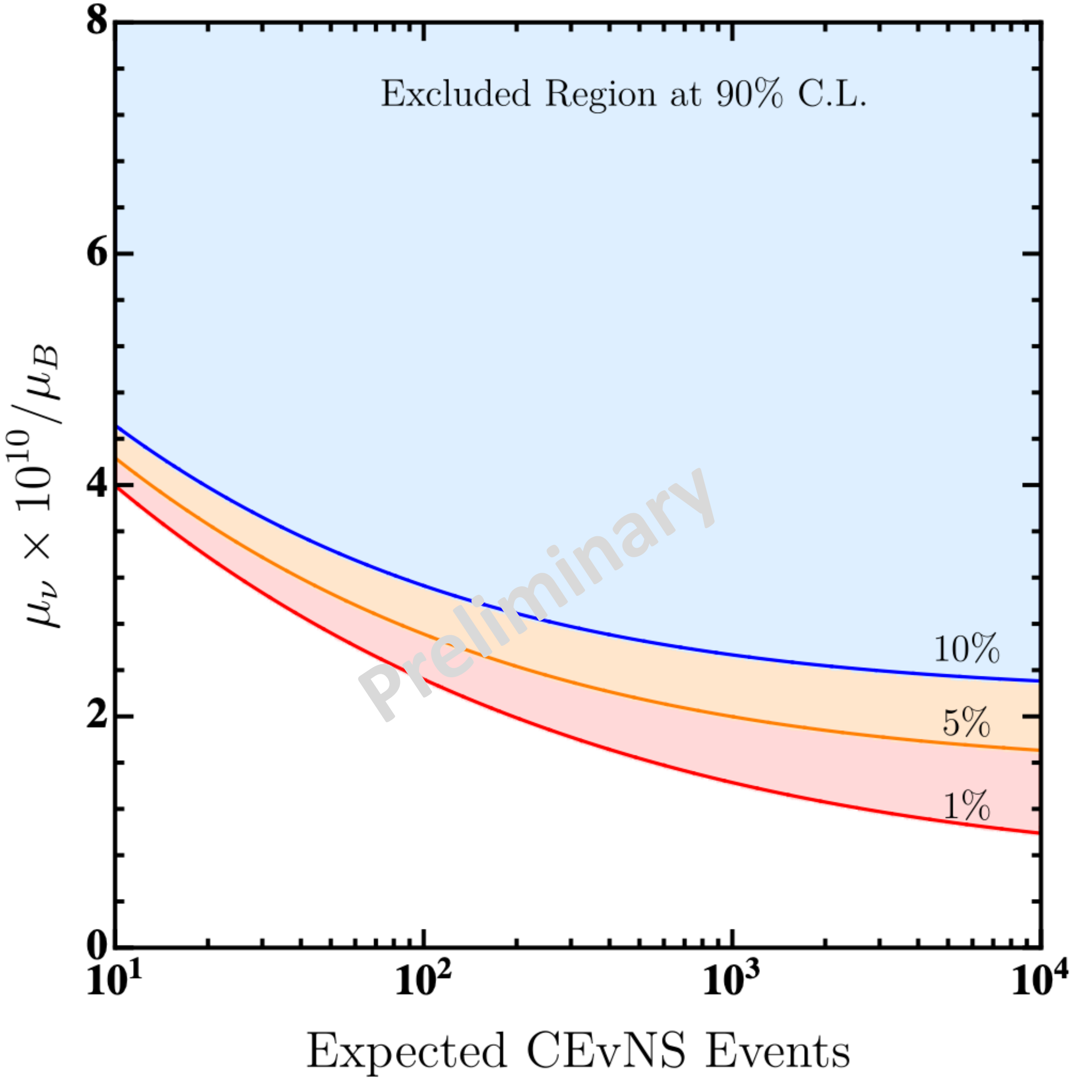
RECODE: Prospects

- Neutrino Magnetic Moment

$$\frac{d\sigma}{dE_R} = \left(\frac{d\sigma}{dE_R}\right)_{SM} + \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-\frac{E_R}{E_\nu}}{E_R} + \frac{E_R}{4E_\nu^2}\right)F_Z^2(Q)$$

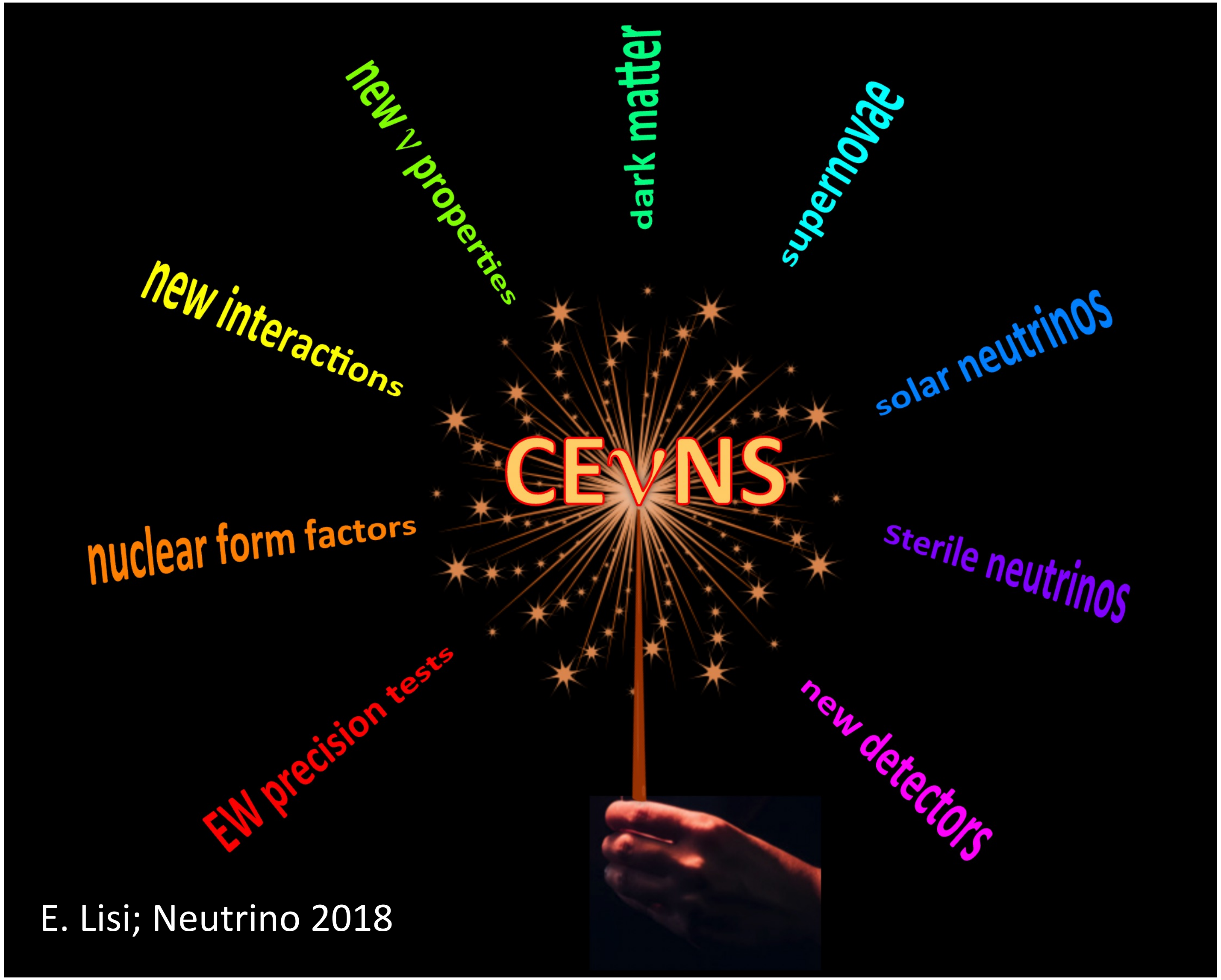
  - Lower threshold is better





S.J. Brice et. al; arXiv: 1311.5958

Summary



new ν properties
dark matter
supernovae
new interactions
solar neutrinos
CEνNS
nuclear form factors
sterile neutrinos
EW precision tests
new detectors
E. Lisi; Neutrino 2018