RECODE program for reactor neutrino CEvNS detection and Dark Matter

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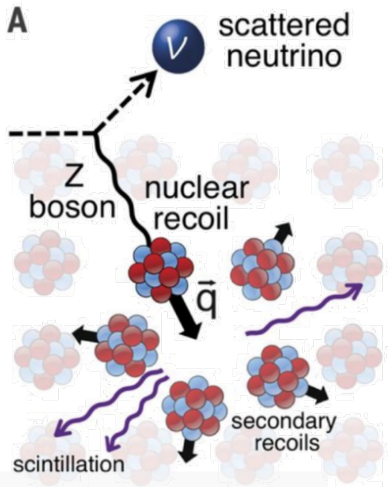
Nanjing Normal University

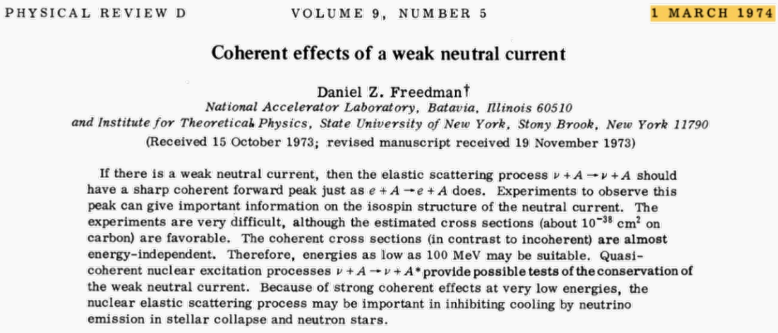
Dark Matter and Neutrino Focus Week @ TDLI
Aug. 22 – Aug. 24, 2025

CEvNS

- Coherent Elastic Neutrino-Nucleus Scattering
  - Basic interaction between Neutrino and matter in SM
    - Weak Neutral Current



Theoretical prediction (1974)


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

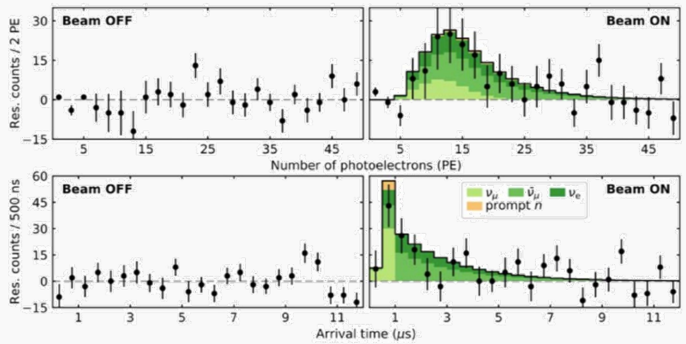
Coherent effects of a weak neutral current

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 $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ 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 $\nu + A \rightarrow \nu + A^*$ 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)

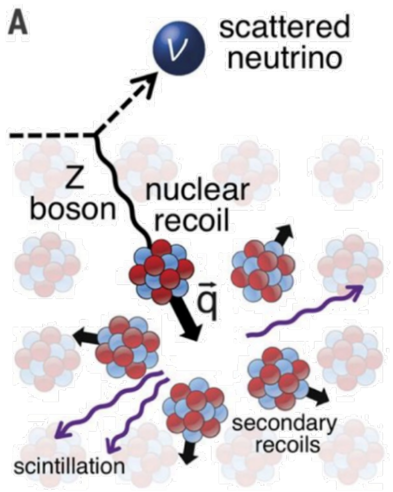
Experimental Evidence (2017)

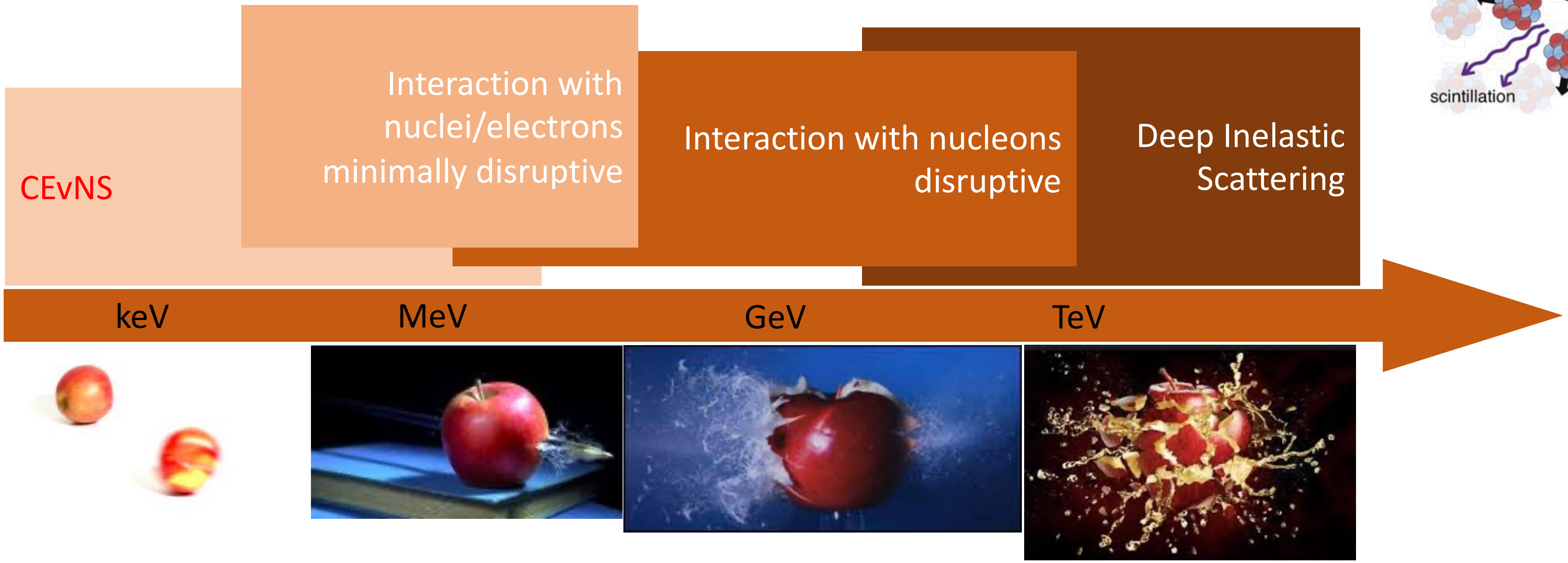


D. Akimov et al, Science 357 (2017)

CEvNS

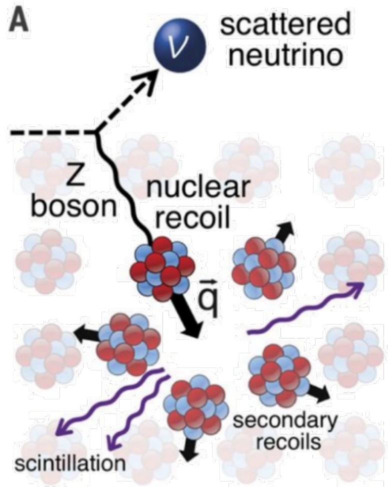
- Coherent Elastic Neutrino-Nucleus Scattering
  - Basic interaction between Neutrino and matter in SM
- Dominant for $E_\nu \lesssim 50$ MeV $\boldsymbol{q \cdot R \ll 1}$

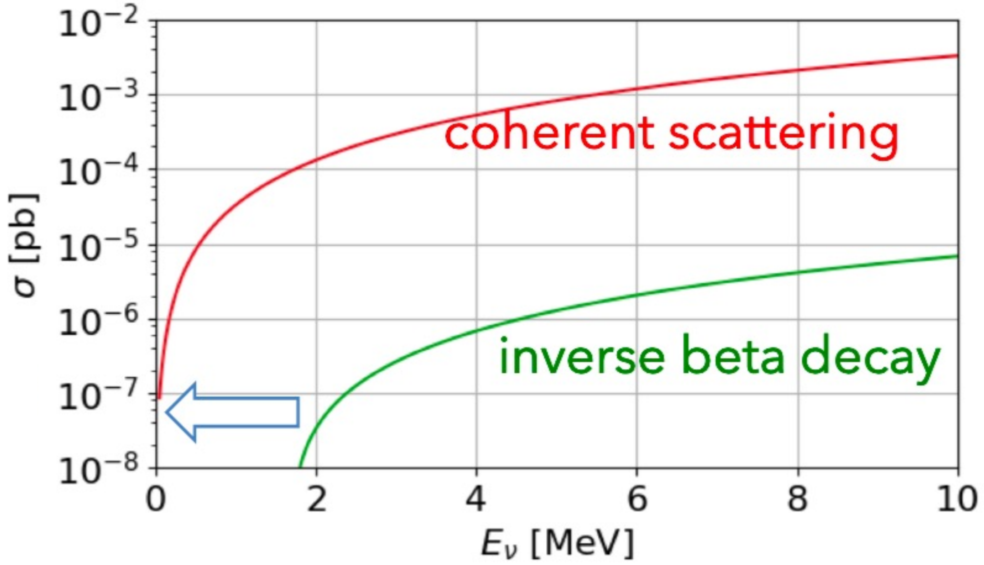




CEvNS

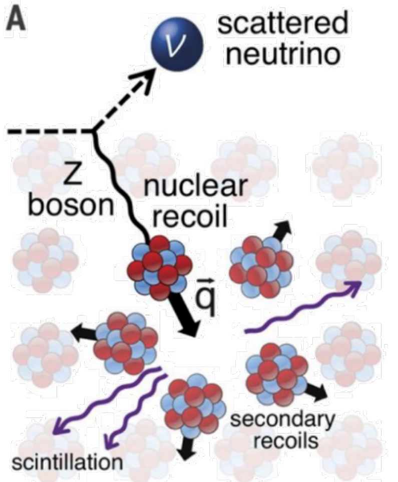
- Coherent Elastic Neutrino-Nucleus Scattering
  - Basic interaction between Neutrino and matter in SM
- Dominant for $E_\nu \lesssim 50$ MeV
- Elastic – No threshold in principle





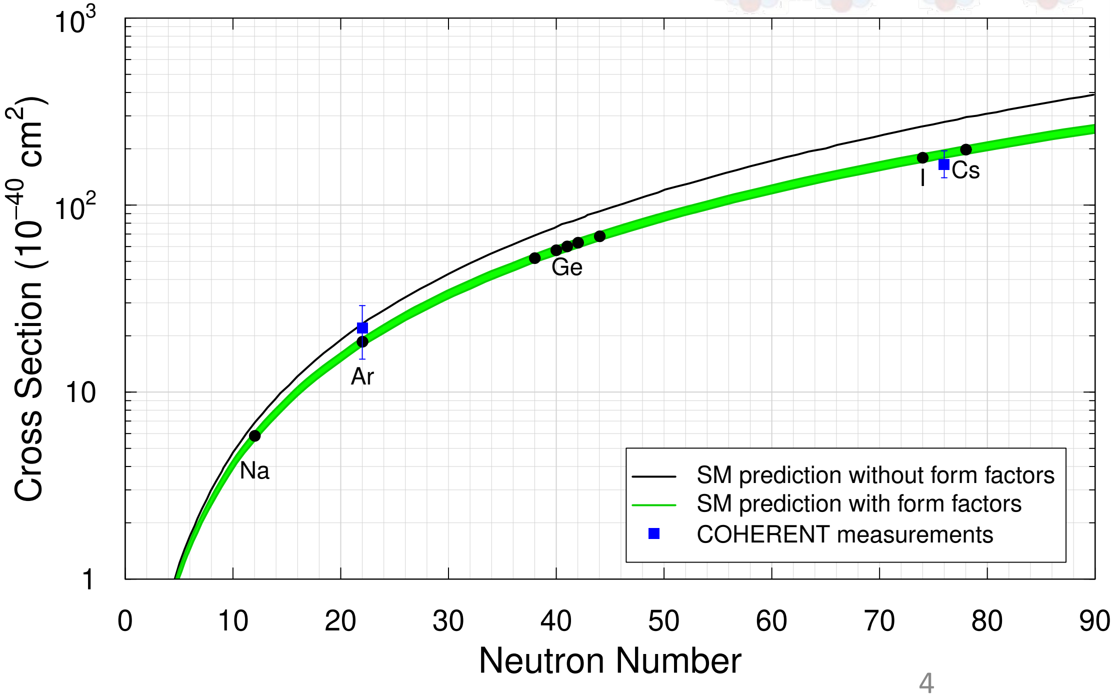
CEvNS

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



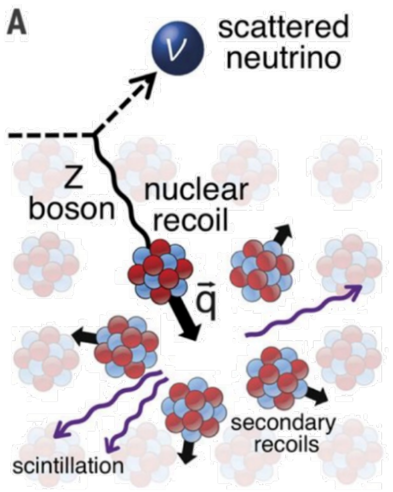
$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{8\pi} Q_W^2 |F(q)|^2 \left(2 - \frac{2E_R}{E_\nu} + \left(\frac{E_R}{E_\nu}\right)^2 - \frac{ME_R}{E_\nu^2}\right)$$

$$\left.\begin{array}{l} Q_W = N - (1 - 4\sin^2\theta_W)Z \\ \sin^2\theta_W \approx 0.23 \end{array}\right\} \sigma \propto N^2 \qquad q \cdot R \ll 1$$

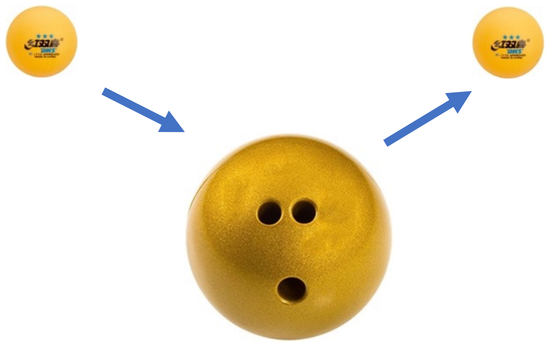


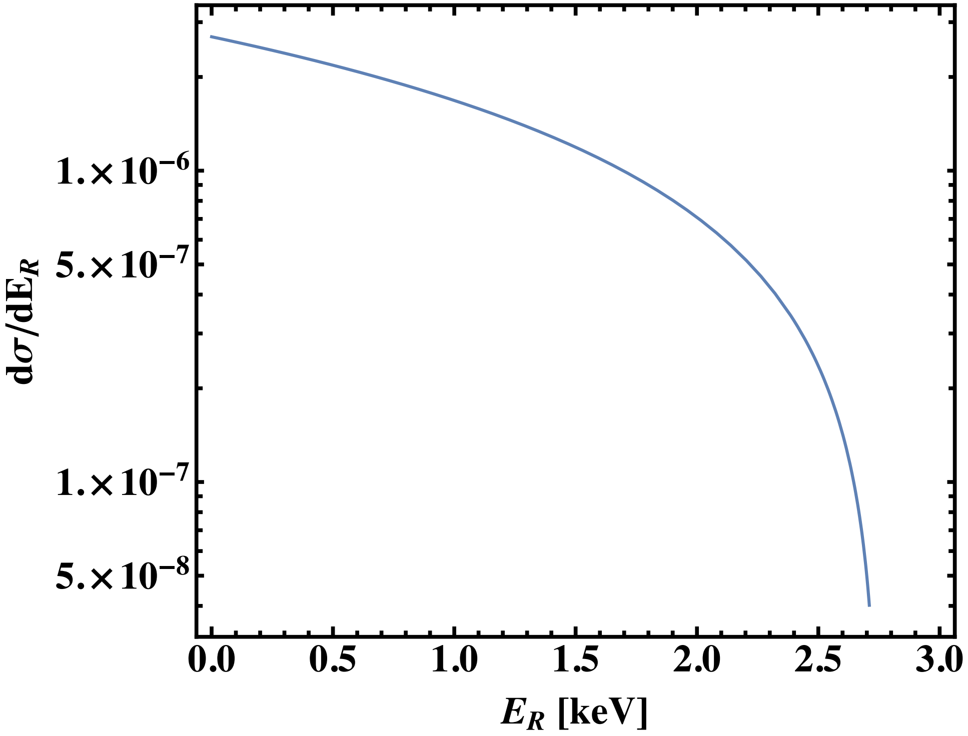
CEvNS

- Coherent Elastic Neutrino-Nucleus Scattering
  - Basic interaction between Neutrino and matter in SM
- Dominant for $E_\nu \lesssim 50$ MeV
- Recoil Energy is Small



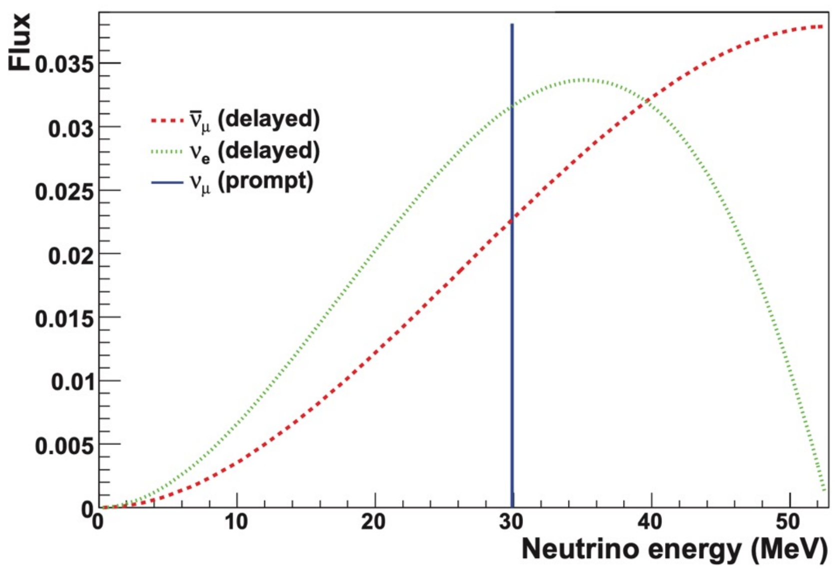
$$E_R \sim \frac{E_\nu^2}{M} = \frac{(E_\nu/MeV)^2}{A}\ keV$$

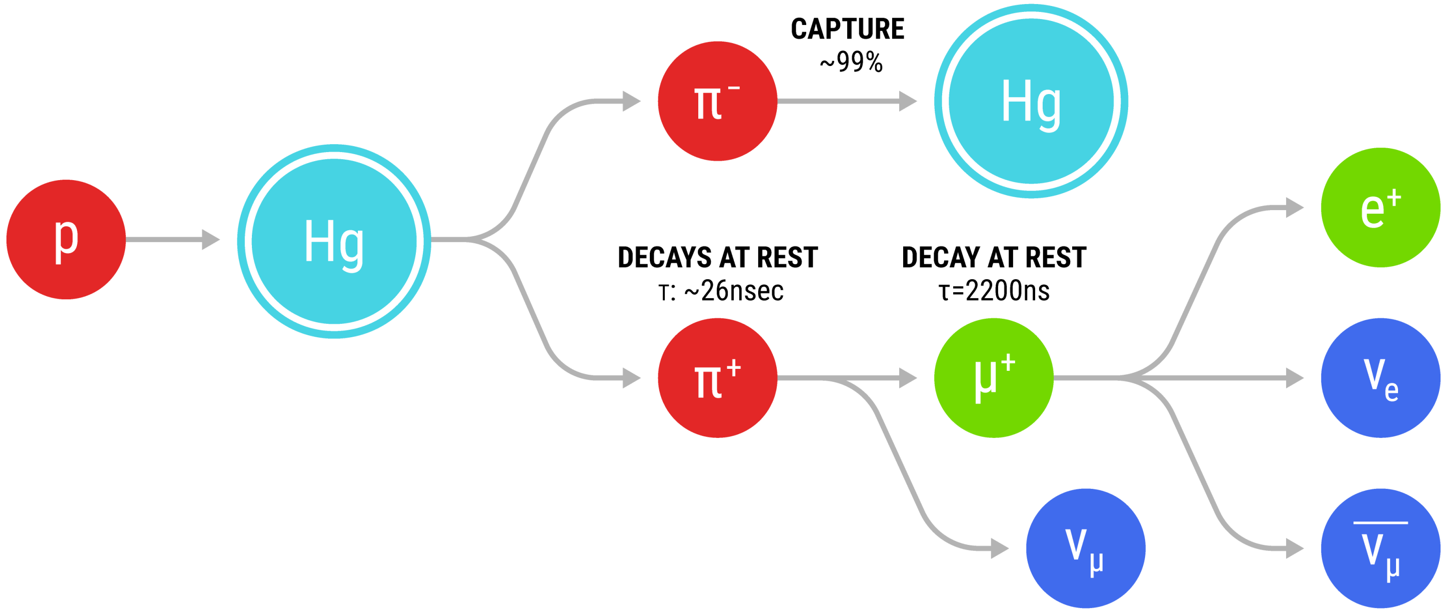




CEvNS: Neutrino Sources

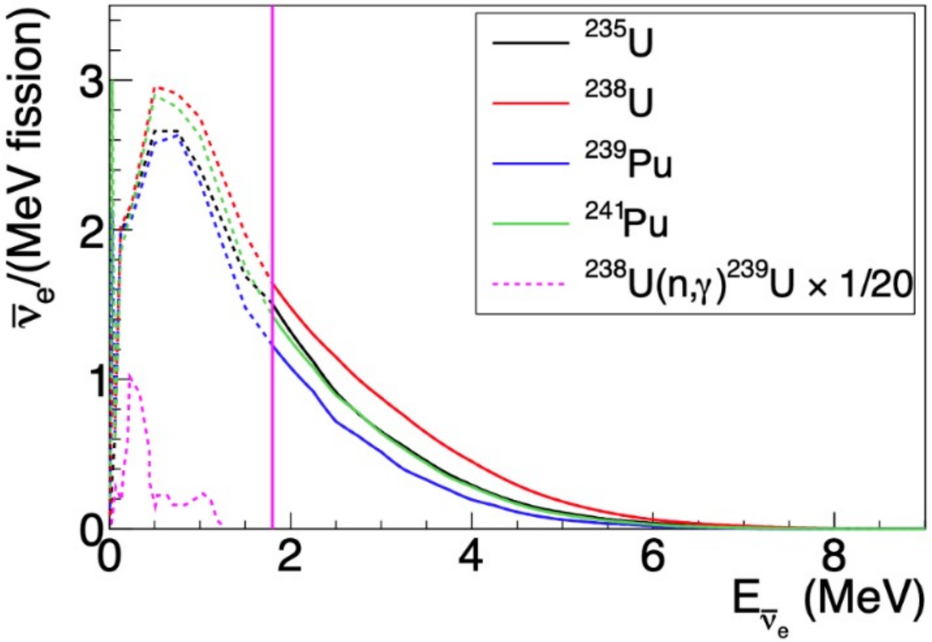
- Stopped-Pion Decay: π-DAR
  - Several 10s MeV
  - Pulsed beam
    - Good for Background rejection
  - $\sim 4.3\times10^{7}\ cm^{-2}s^{-1}$ at 20m
  - $\nu_\mu, \bar{\nu}_\mu, \nu_e$

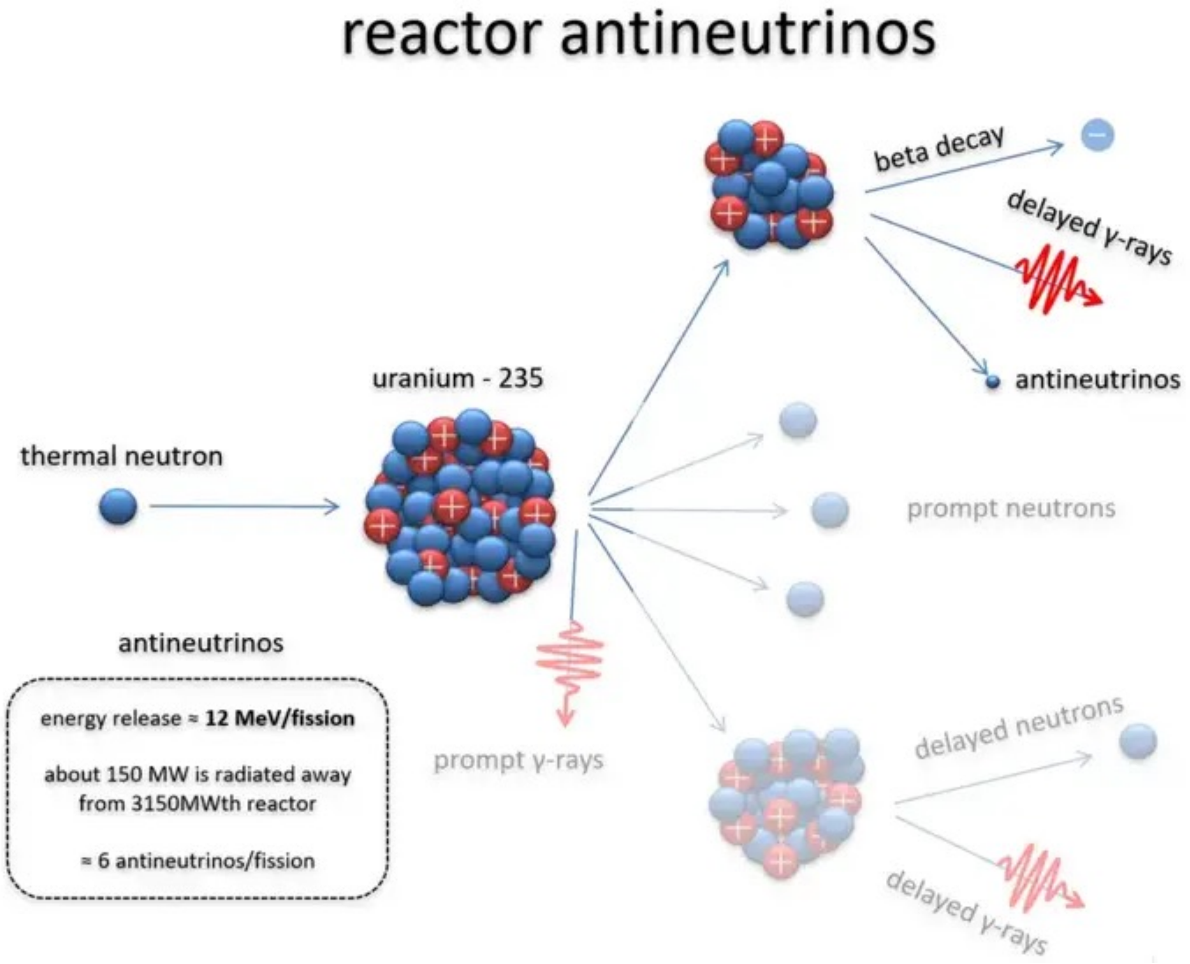




CEvNS: Neutrino Sources

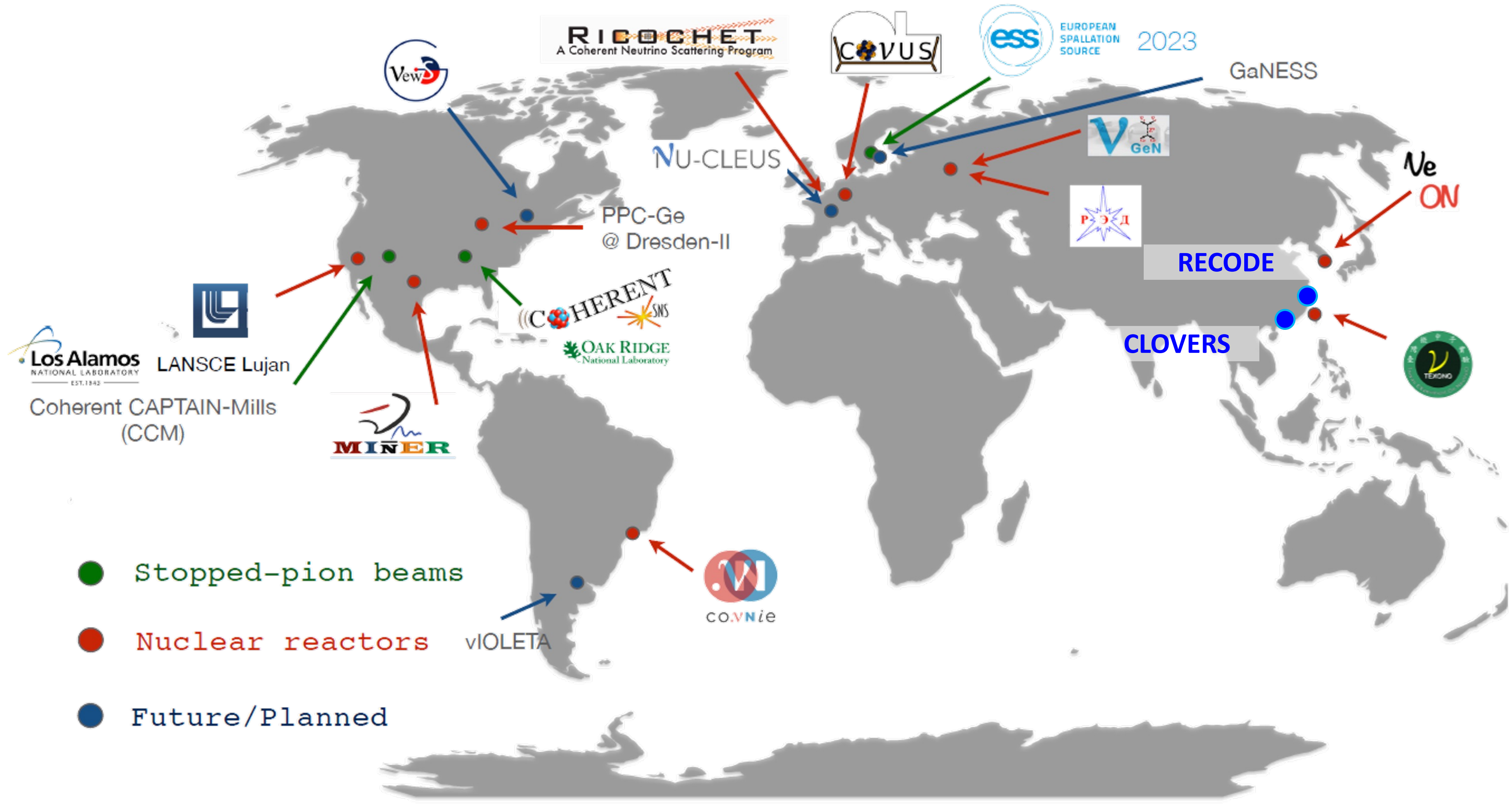
- Reactor Neutrinos
  - High flux
    - $10^{12} - 10^{13}\ cm^{-2}s^{-1}$ at 15m
  - Low energy, up to 8/10 MeV
    - Low threshold for detector
  - Mainly $\bar{\nu}_e$





Rept. Prog. Phys. 82 (2019) 036201

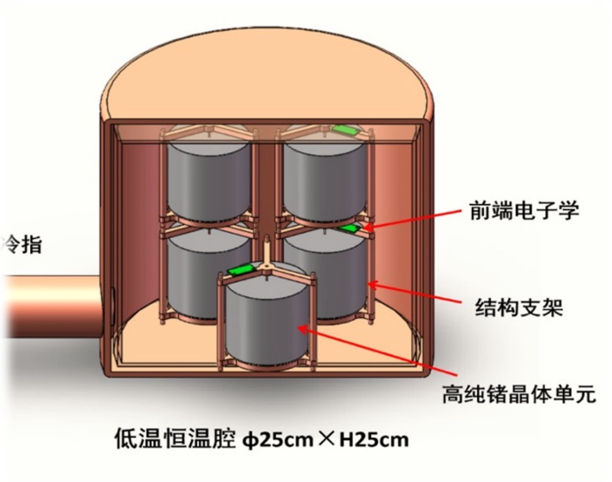
CEvNS: Experiments



RECODE Program

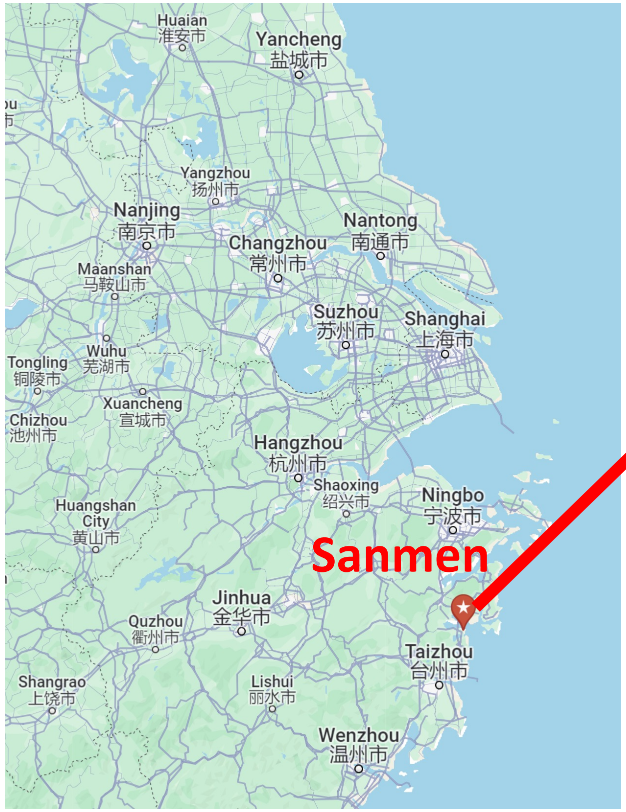
- RECODE
  - REactor neutrino COherent scattering Detection Experiment
  - Low threshold Ge detectors

- 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 Plant (AP1000)
  - @Taizhou, Zhejiang
  - Thermal power: 3.4 GW

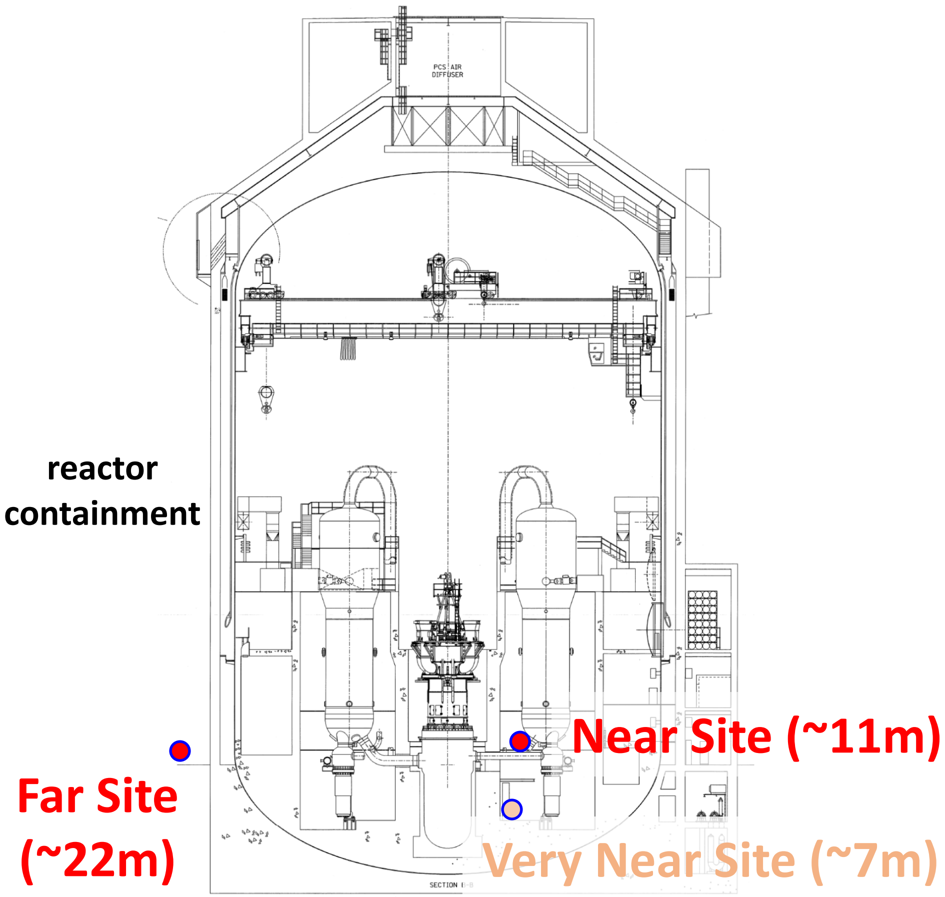


RECODE Detector Location

- First phase:
  - Far site (~22m) + Near Site (~11m)
- Future Option
  - Very Near Site (~7m)

Distance	Power	Neutrino Flux	Photon Flux
FS ~ 22m	3.4GWth	$1.4*10^{13}$ v/cm^2/s	$9.4*10^{12}$/cm^2/s
NS ~ 11m	3.4GWth	$5.6*10^{13}$ v/cm^2/s	$3.8*10^{13}$/cm^2/s
VNS ~ 7m	3.4GWth	$1.4*10^{14}$ v/cm^2/s	$9.3*10^{13}$/cm^2/s

  - Movable Far site (~20 to 30 m)
- Joint analysis:
  - Far + Near (very near)
  - On + Off (18:1) - Background Analysis
  - Reduce systematical uncertainties



RECODE

- Comparison with other Exps.

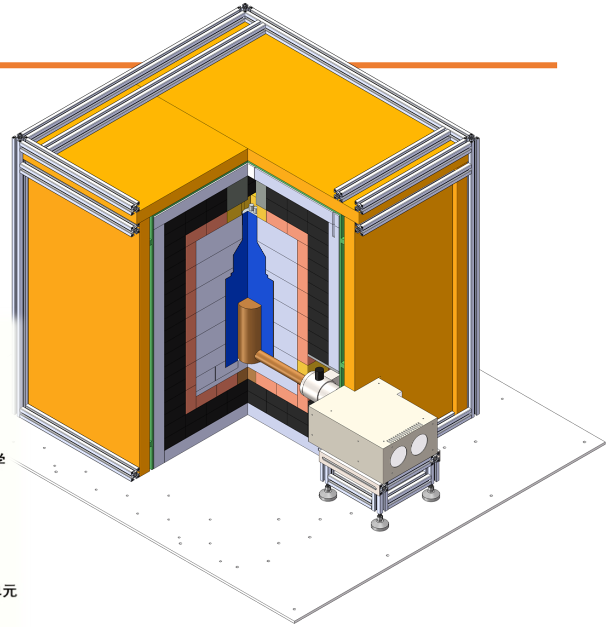
Experiment	Target	Mass	Threshold	Reactor	Distance to reactor core	Thermal power	Neutrino Flux	Location
CONNIE	Si CCDs	50 g	~ 40 eVee	Angra 2 reactor	30 m	3.8 GWth	$7.8*10^{12}$ ν/cm²/s	Brazil
MINER	Ge/Si	4 kg	~ 100 eVnr	TRIGA reactor	2~10m	1 MWth	$\sim 10^{12}$ ν/cm²/s	USA
RICOCHET	Ge & Zinc	32 g (Ge)	55 eVee	ILL reactor	8 m	58 MWth	$1.6*10^{12}$ ν/cm²/s	France
CONUS	HPGe	3.74 kg	~ 210 eVee	Brokdorf (KBR)	17 m	3.9 GWth	$2.3*10^{13}$ ν/cm²/s	Germany
COUNS+	HPGe	3.74 kg	~150 eVee	Leibstadt (KKL)	20.7m	3.6 GWth	$1.5*10^{13}$ ν/cm²/s	Switzerland
Nu-Gen	HPGe	1.6 kg	350 eVee	Kalinin NPP	11.1-12.5 m	3.1 GWth	3.4 -$4.4*10^{13}$ ν/cm²/s	Russia
TEXONO	HPGe	1 kg	~200 eVee	Kuo-Sheng NPP	28m	2.9 GWth	$6.4*10^{12}$ ν/cm²/s	Taiwan, China
RECODE	**HPGe**	**1-5kg**	**~160 eVee**	**Sanmen NPP**	**NS ~ 11m**	**3.4GWth**	**$5.6*10^{13}$ ν/cm²/s**	**China**
	HPGe	**10kg**	**~160 eVee**		**FS ~ 22m**	**3.4GWth**	**$1.4*10^{13}$ ν/cm²/s**	**China**
RELICS	LXe	50kg	~1 keVnr	Sanmen NPP	22m	3.4GWth	$1.4*10^{13}$ ν/cm²/s	China

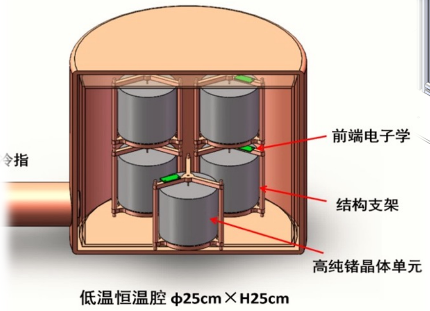
RECODE Detectors

- 5kg EC PCGe for Near Site/Very Near Site
- 5kg LN PCGe for Far Site

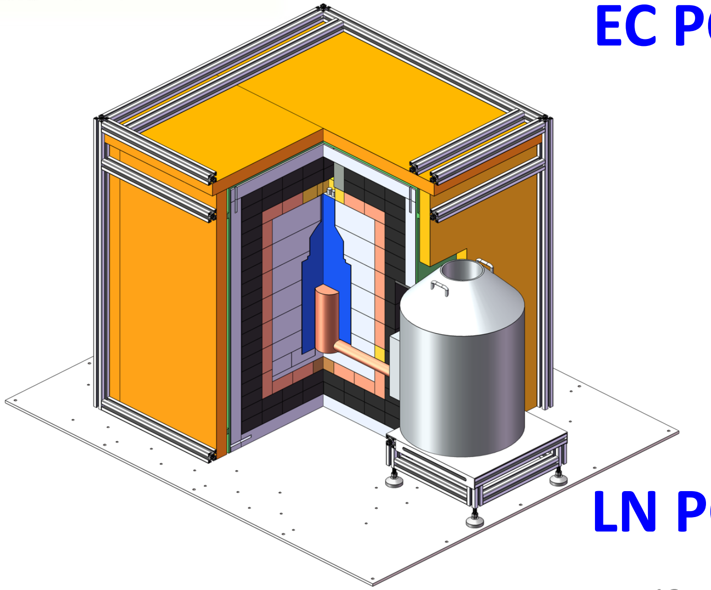
■ **Shielding size: 1m(W)*1m(L)*1.1m(H)**
  - Anti coincidence efficiency for cosmic ray: > 99%
  - Gamma flux: reduce by 5 orders of magnitude
  - Neutron flux: reduce by 3 orders of magnitude

■ **From outer to inner:**
  - ✓ Plastic scintillator muon veto (3 cm), **CRV/CRT events**
  - ✓ Aluminum 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), **ACV/ACT events**





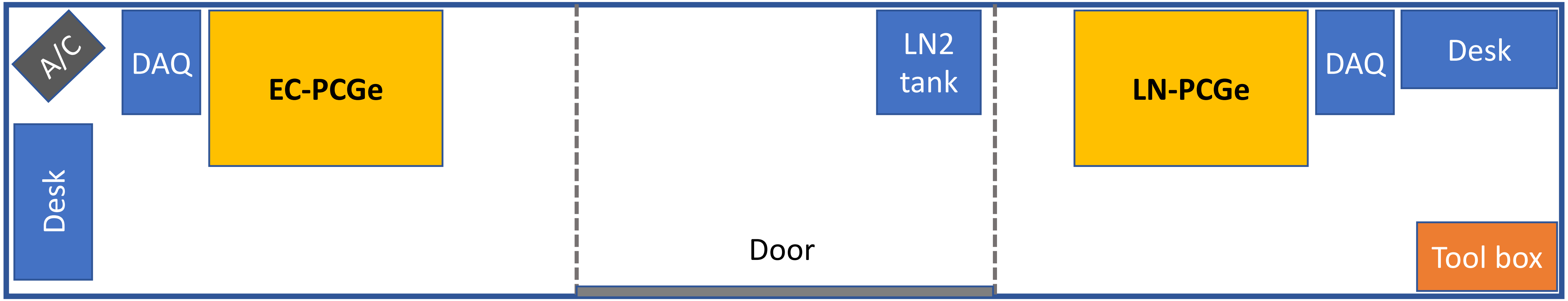
EC PCGe



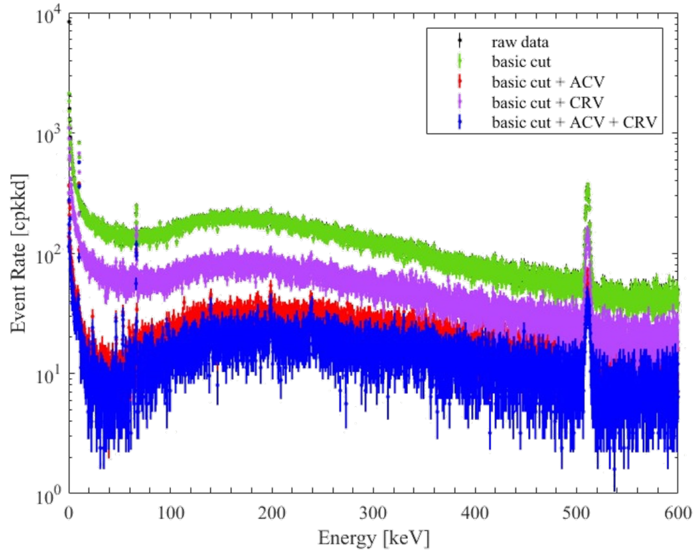
LN PCGe

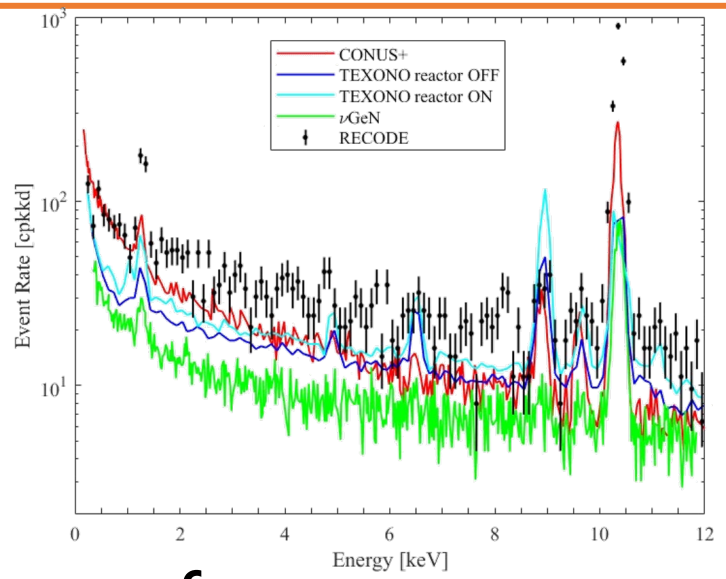
RECODE Detectors

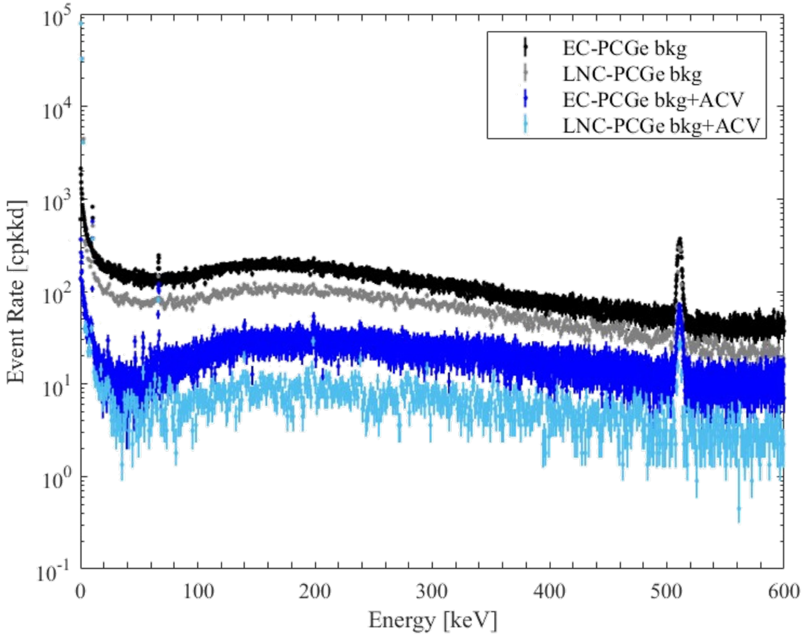
- Ground Testing Container - Outside the containment of Sanmen NPP



RECODE Ground test



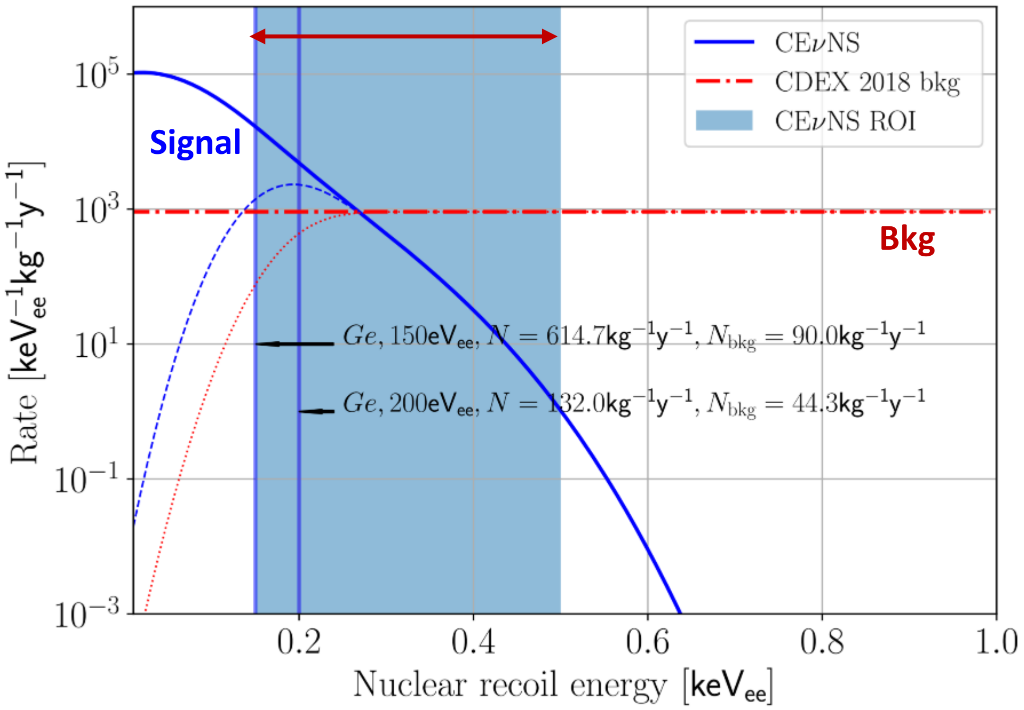




- Test the shielding performance
  - Met the expectations w/o additional concrete coverage
    - Cosmic ray induced background will be further reduced when the detectors are placed at experimental sites
    - Additional reactor neutron background needs to be considered
  - Equivalent water depth coverage thickness is being evaluated
- Formal Operation starting this October

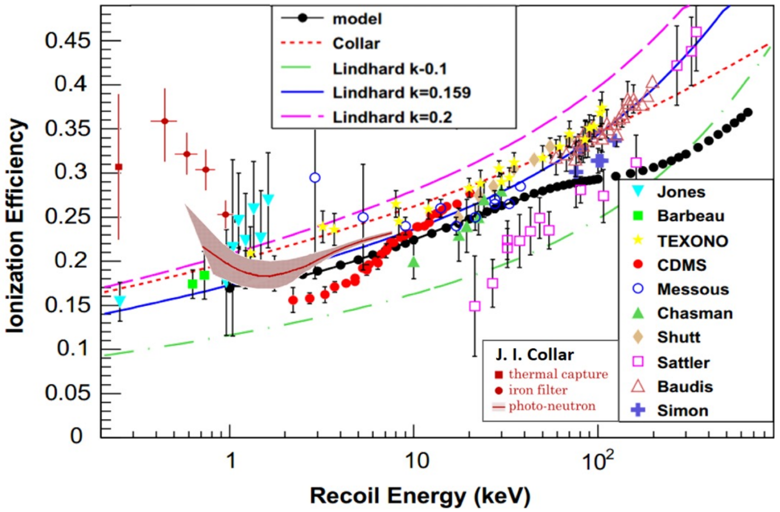
RECODE: Uncertainties

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



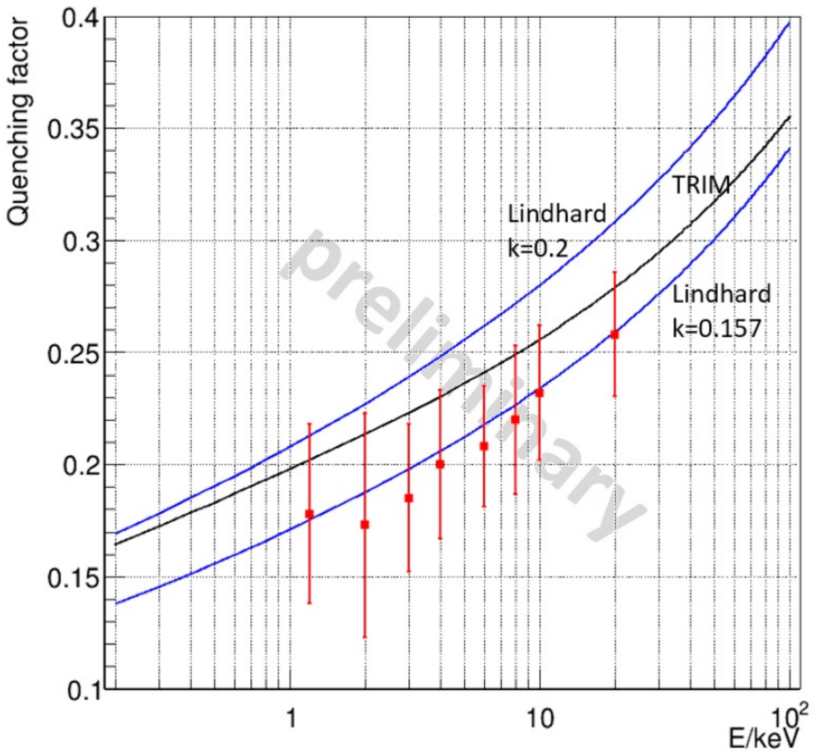
Expected CEvNS spectrum in Ge

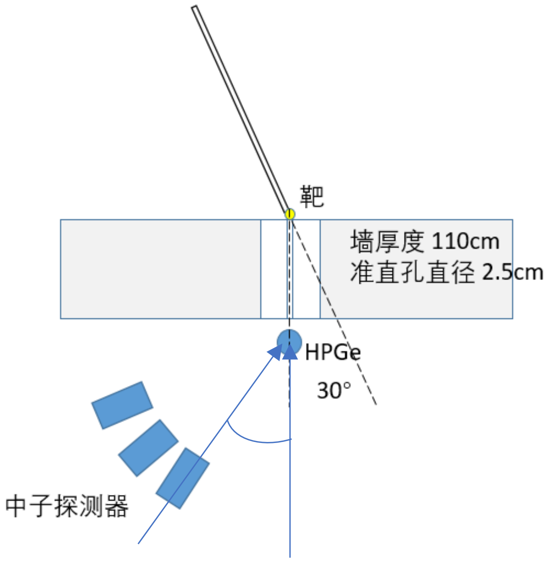
- Systematics:
  - Quenching factor: 10%-20%
  - Reactor neutrino intensity: 3%
    - Reduced through joint measurement
  - Background modeling:
    - Ground Testing
    - ON/OFF measurement



RECODE: Quenching factor measurement

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

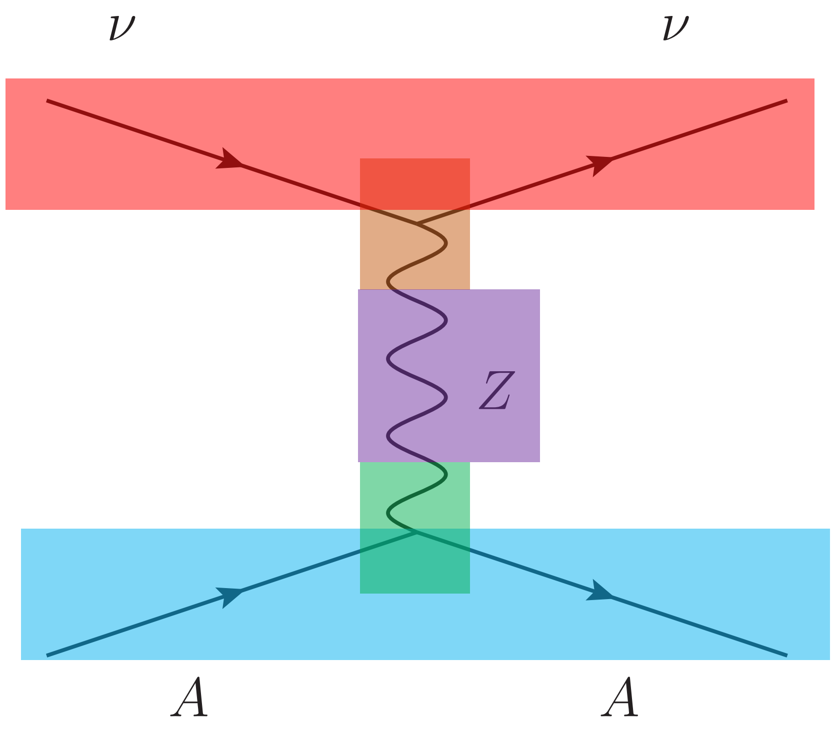




CEvNS: Physics Motivation

- DM Detection
  - Neutrino Fog
  - DM Detector
- For "Old" Physics
  - Testing Standard Model
  - Nuclear Form Factor
  - Neutron Distribution Radius
- For "New" Physics
  - Neutrino Interaction/Properties
  - Light Mediator/DM
  - Different in-coming particles:
    - ALP, Sterile Neutrino
- Practical Tool
  - Monitoring

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



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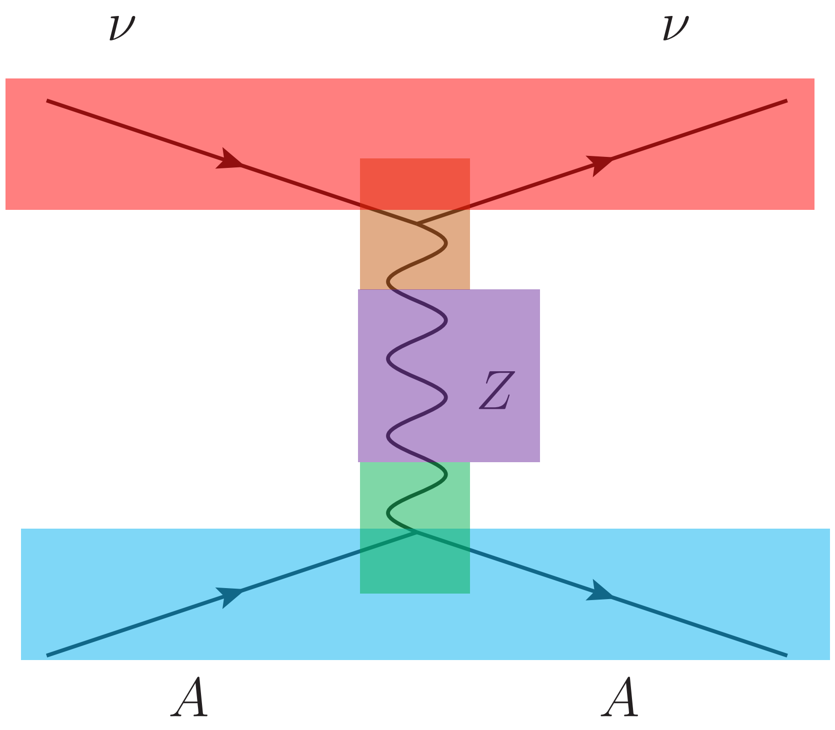
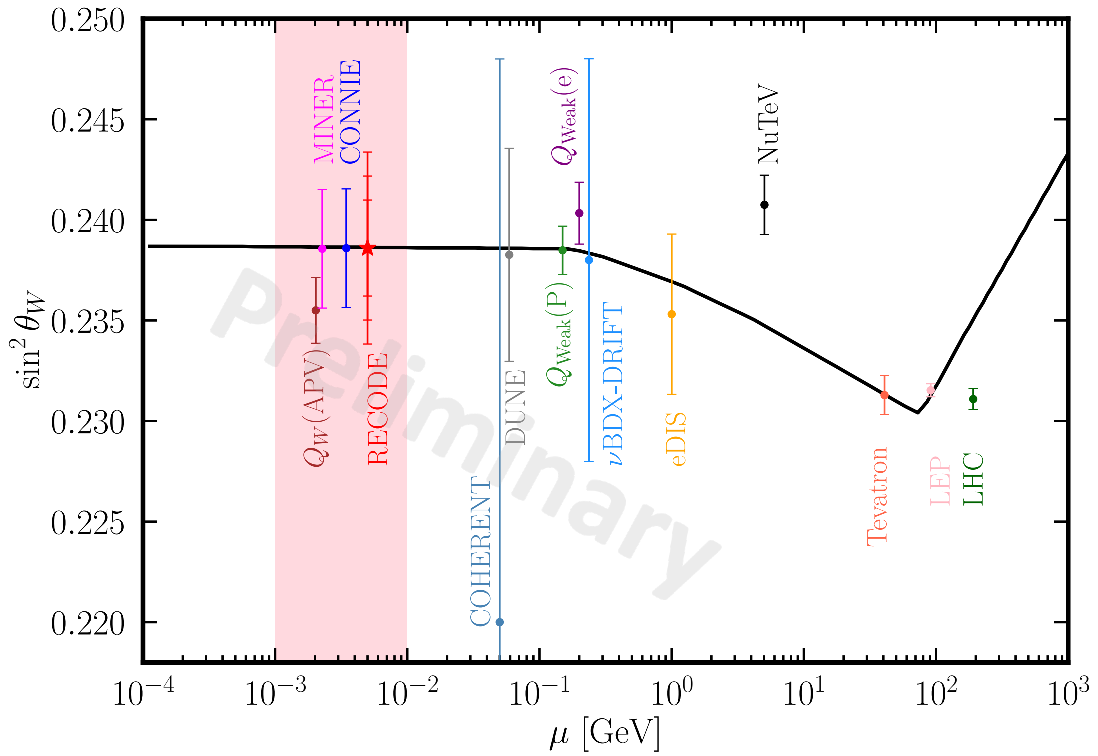


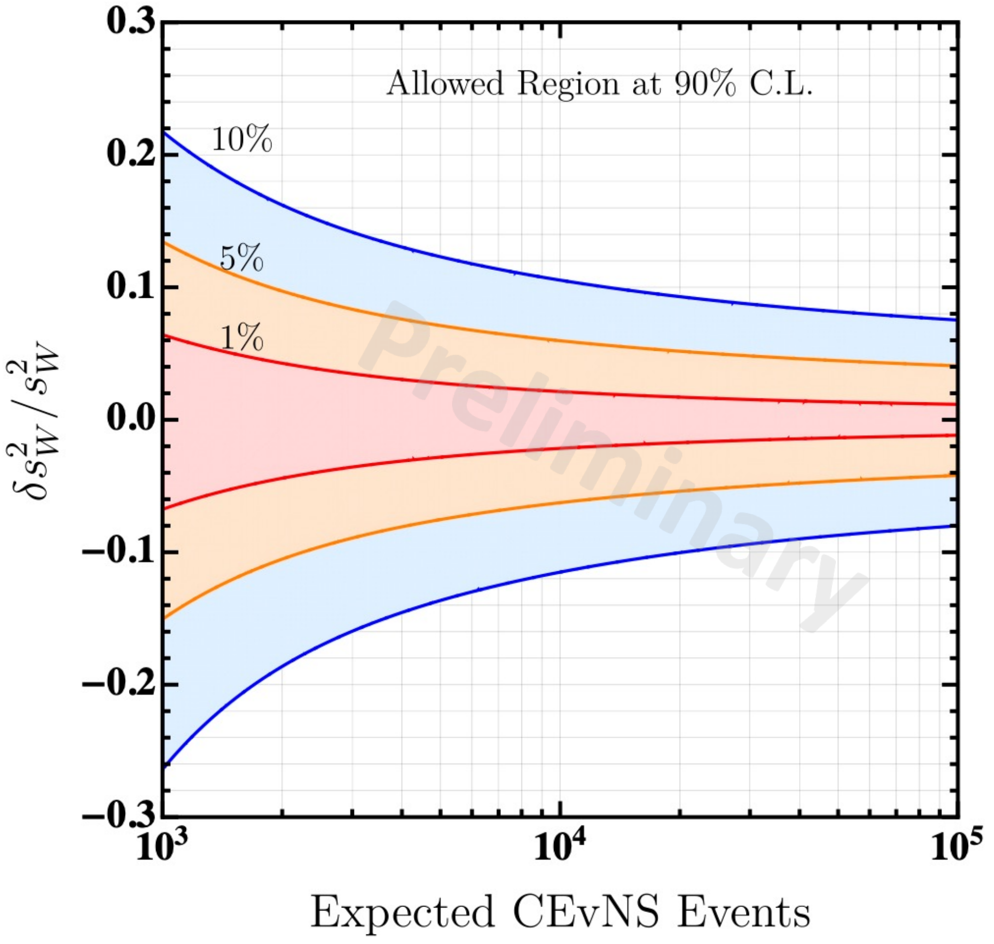
RECODE: Prospects

- 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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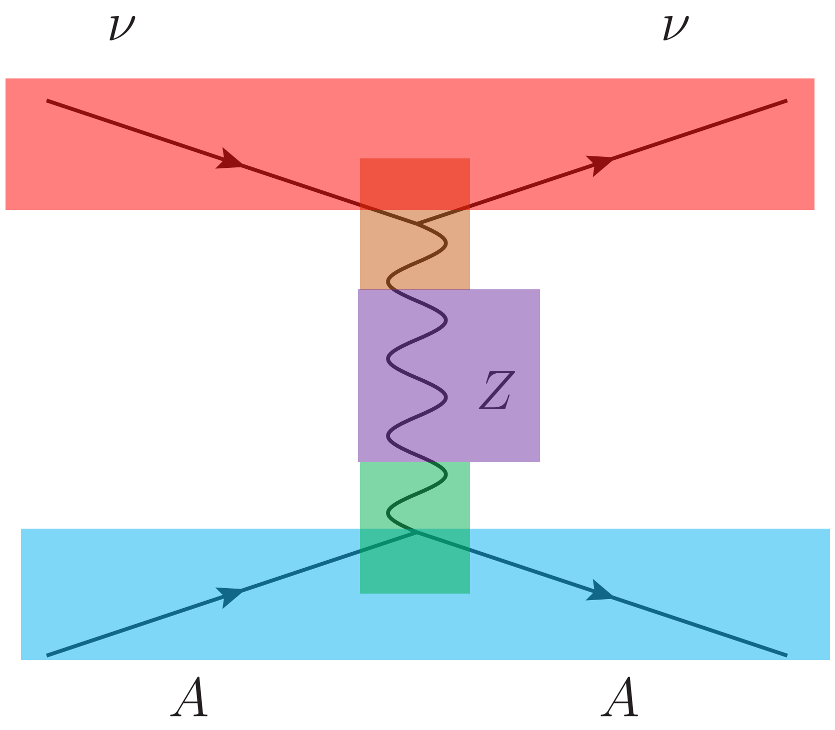


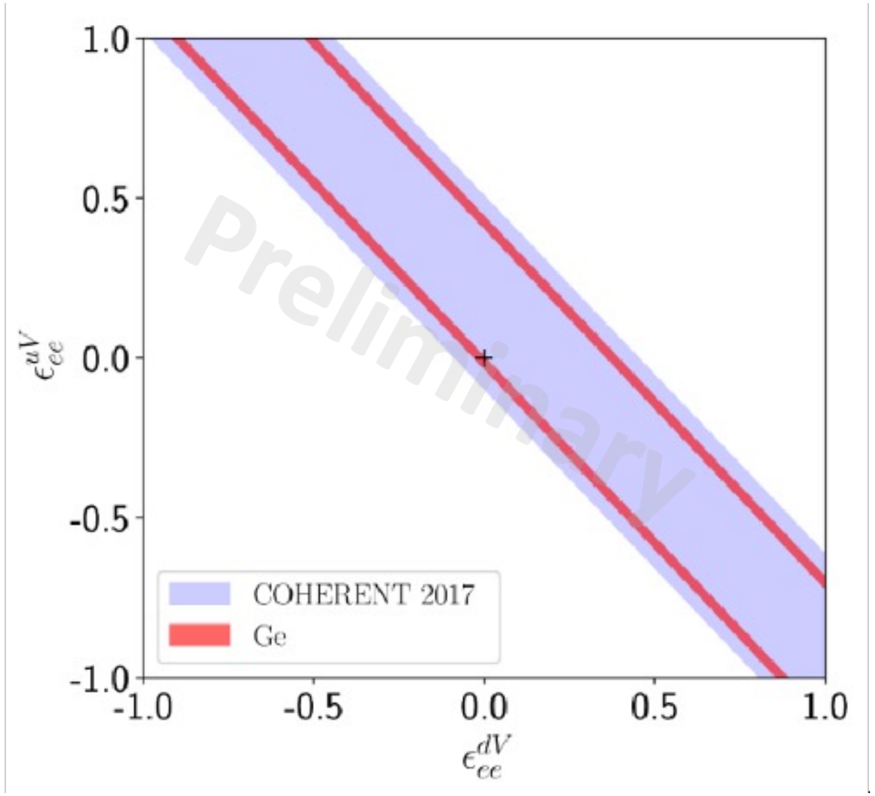
RECODE: Prospects

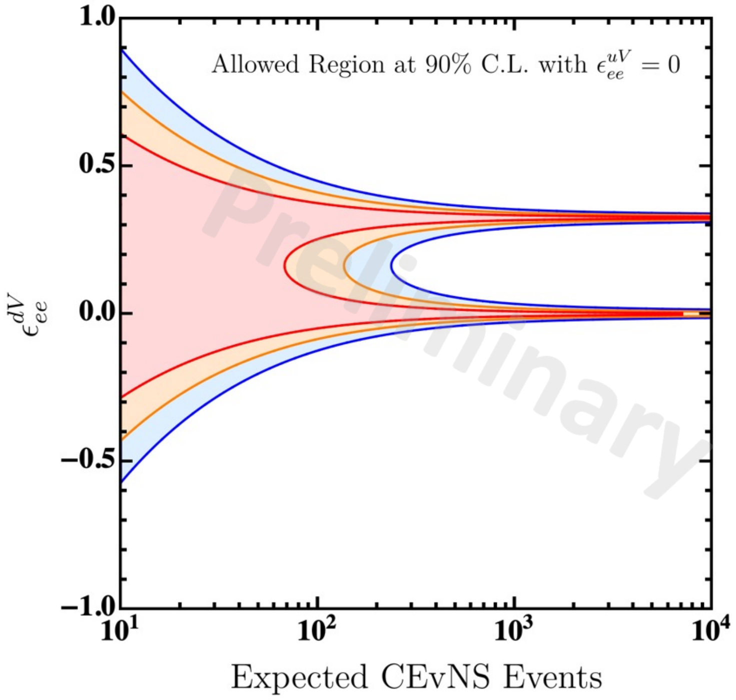
- Neutrino NSI

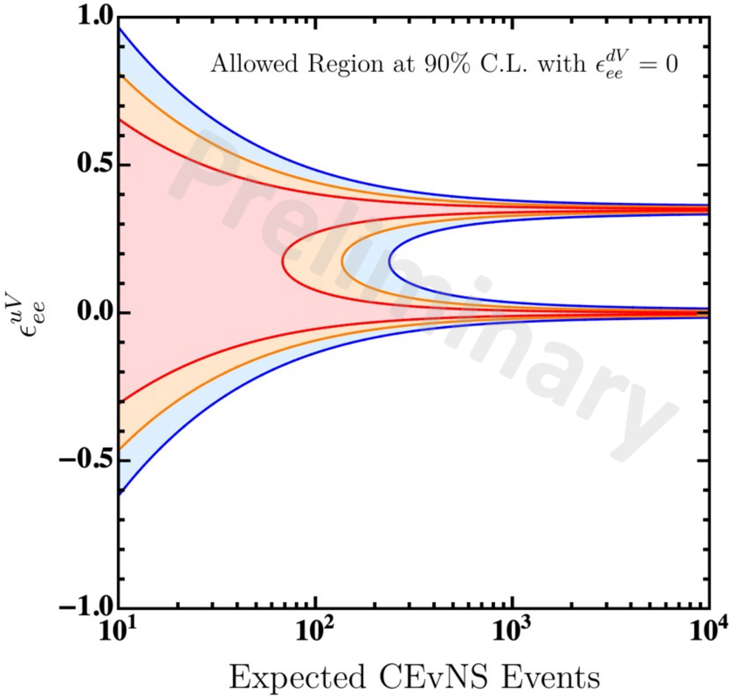
$$\mathcal{L}^{NSI} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{f,V}(\bar{\nu}_{\alpha L}\gamma^{\mu}\nu_{\beta L})(\bar{f}\gamma_{\mu}f)$$

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

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







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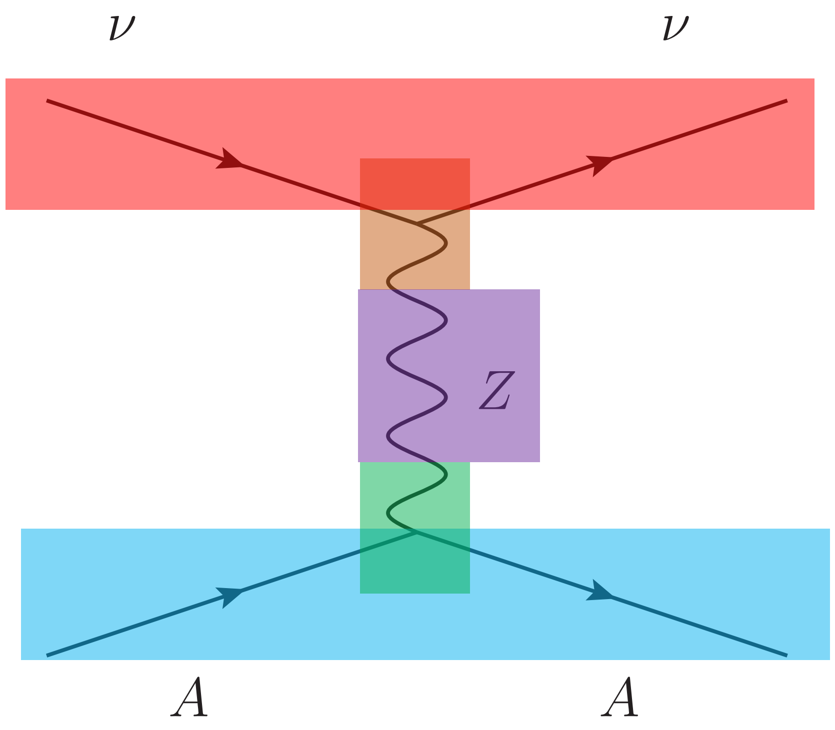


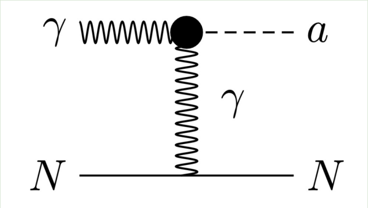
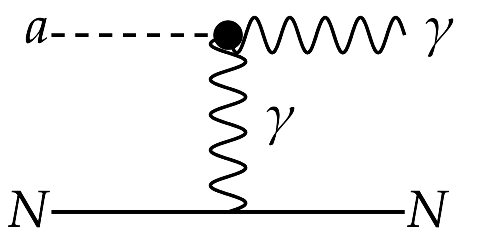
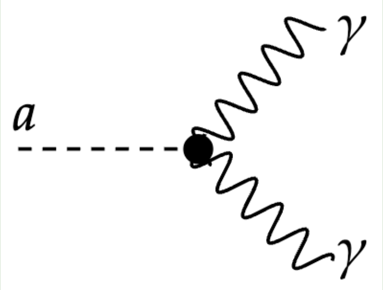
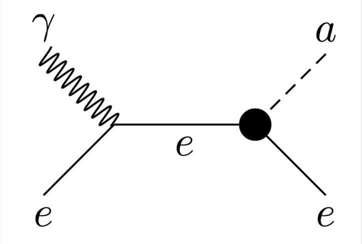
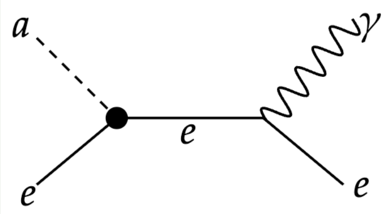
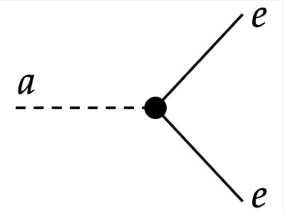
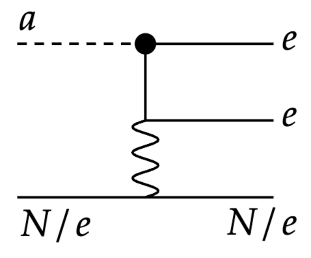
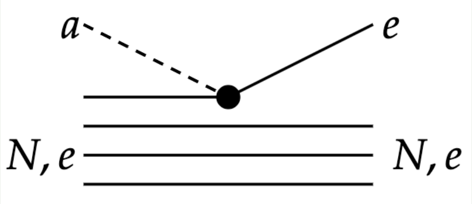
RECODE: Prospects

- ALP From Reactor
  - Photon Flux (MeV)

H. Bechteler et.al. Jul – Spez 255 (1984) 62

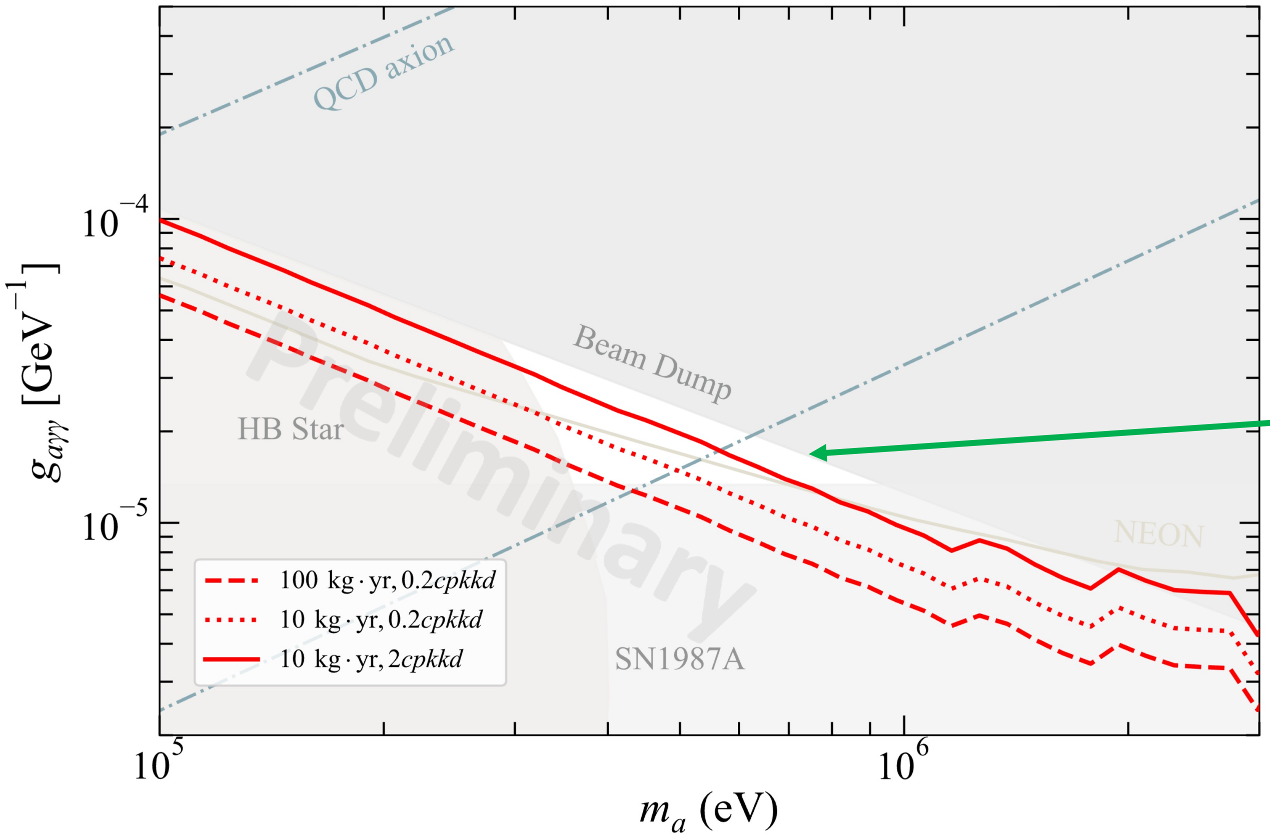
$$\frac{d\Phi}{dE_\gamma} = \frac{5.8\times10^{17}}{\mathrm{MeV}\cdot\mathrm{sec}}\left(\frac{P}{\mathrm{MW}}\right)e^{-1.1E_\gamma/\mathrm{MeV}}$$

$$\mathcal{L} \supset -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - ig_{ae}a\bar{e}\gamma_5 e$$

Couplings	Production	Detection
$g_{a\gamma}$		 
g_{ae}		   

RECODE Prospects

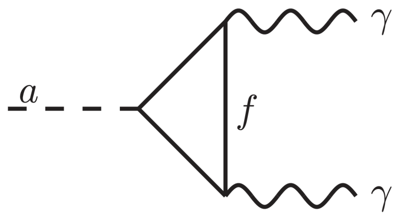
- ALP From Reactor

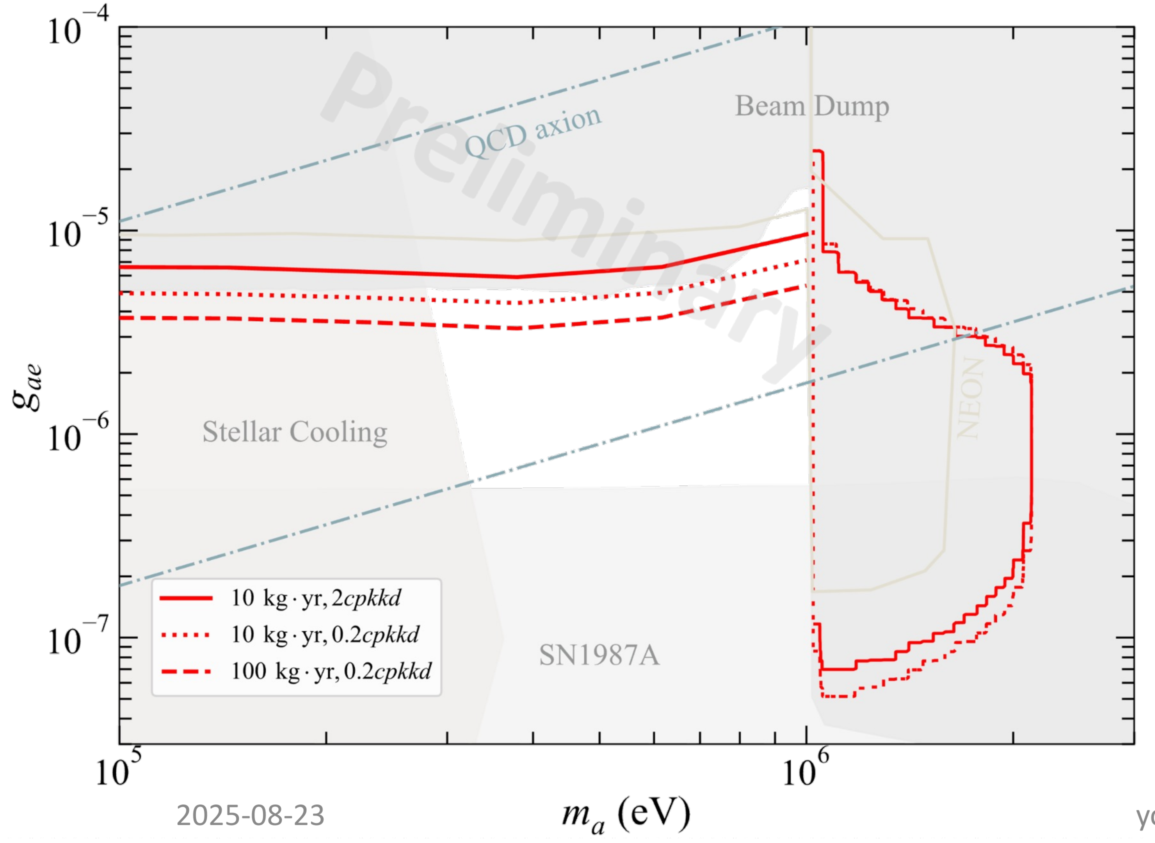


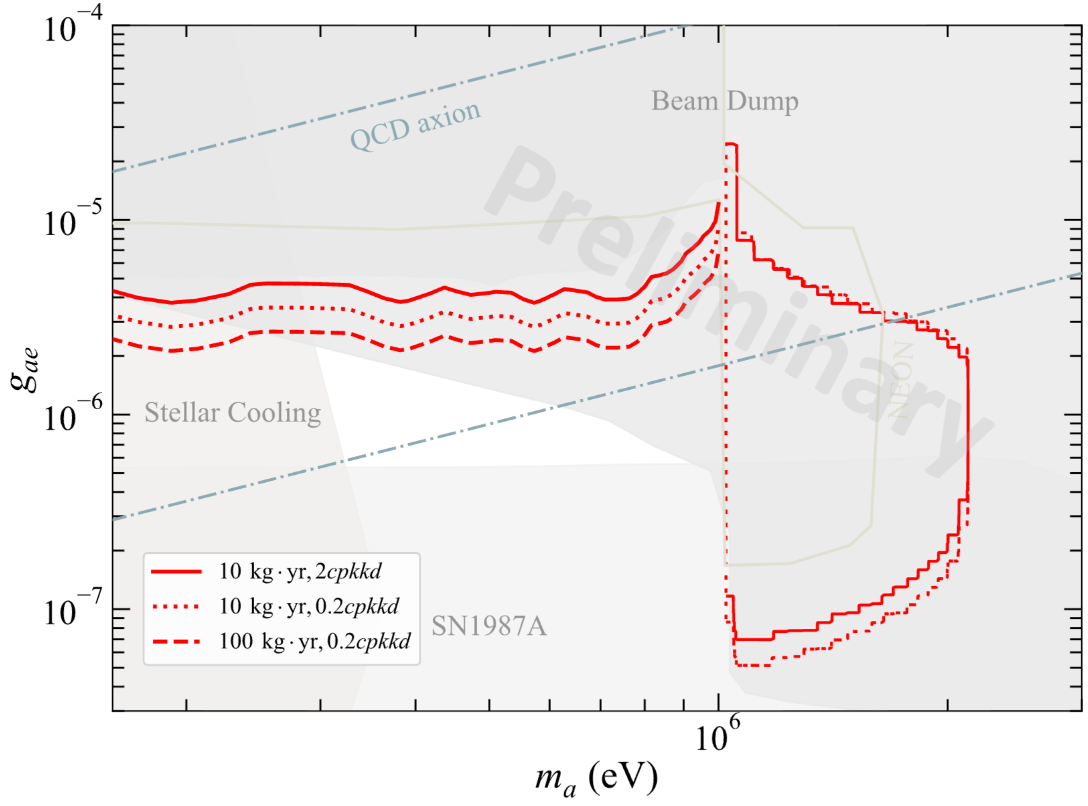
Cosmological Triangle

RECODE Prospects

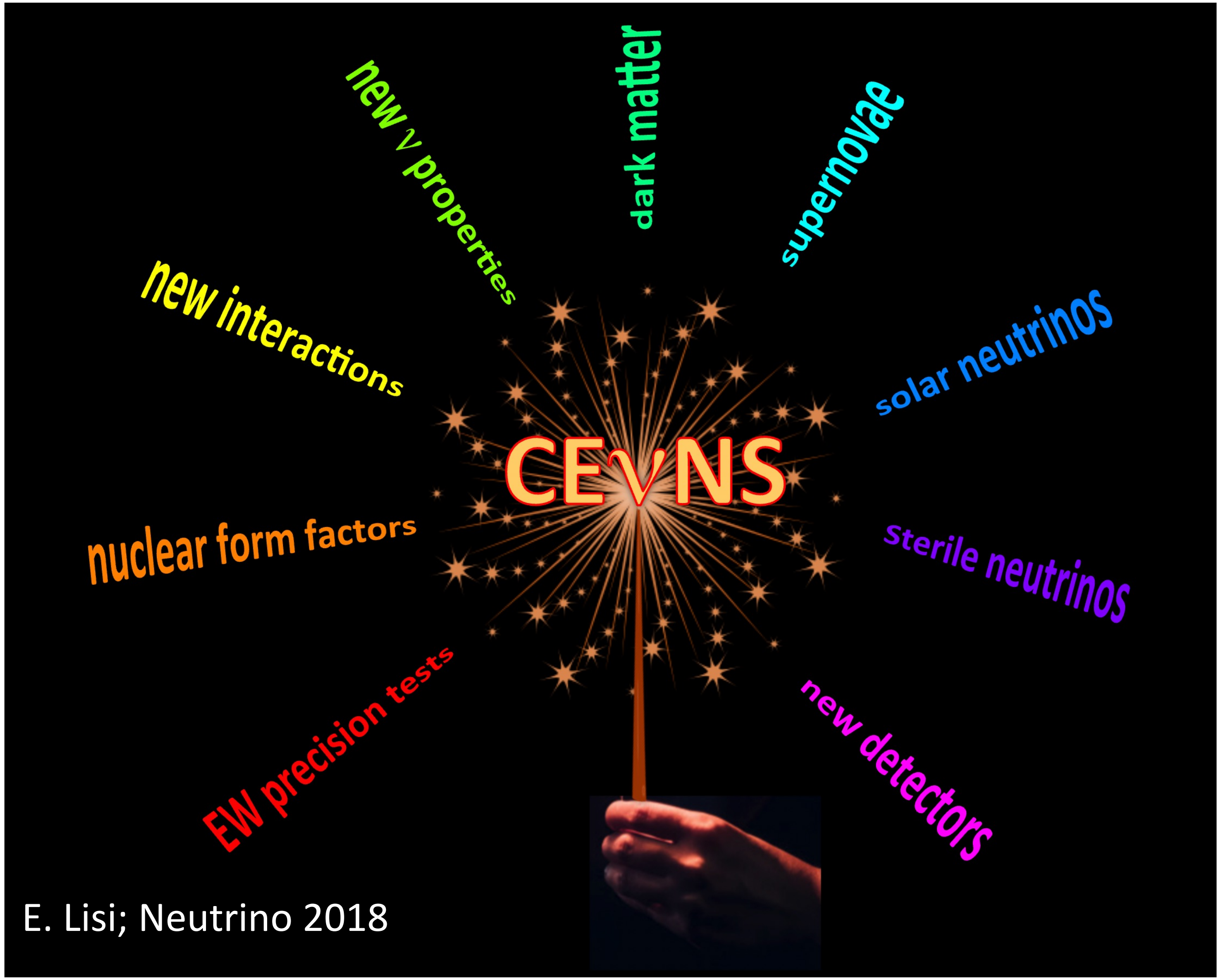
- ALP From Reactor



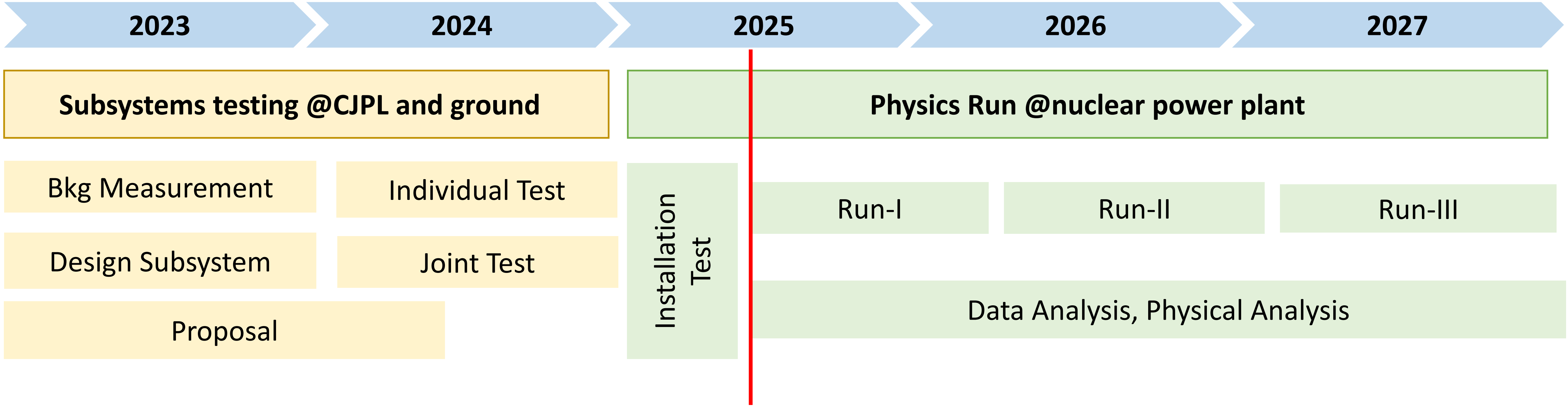




Summary


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

RECODE Roadmap & Schedule



Formal Operation starts this October – Stay tuned!