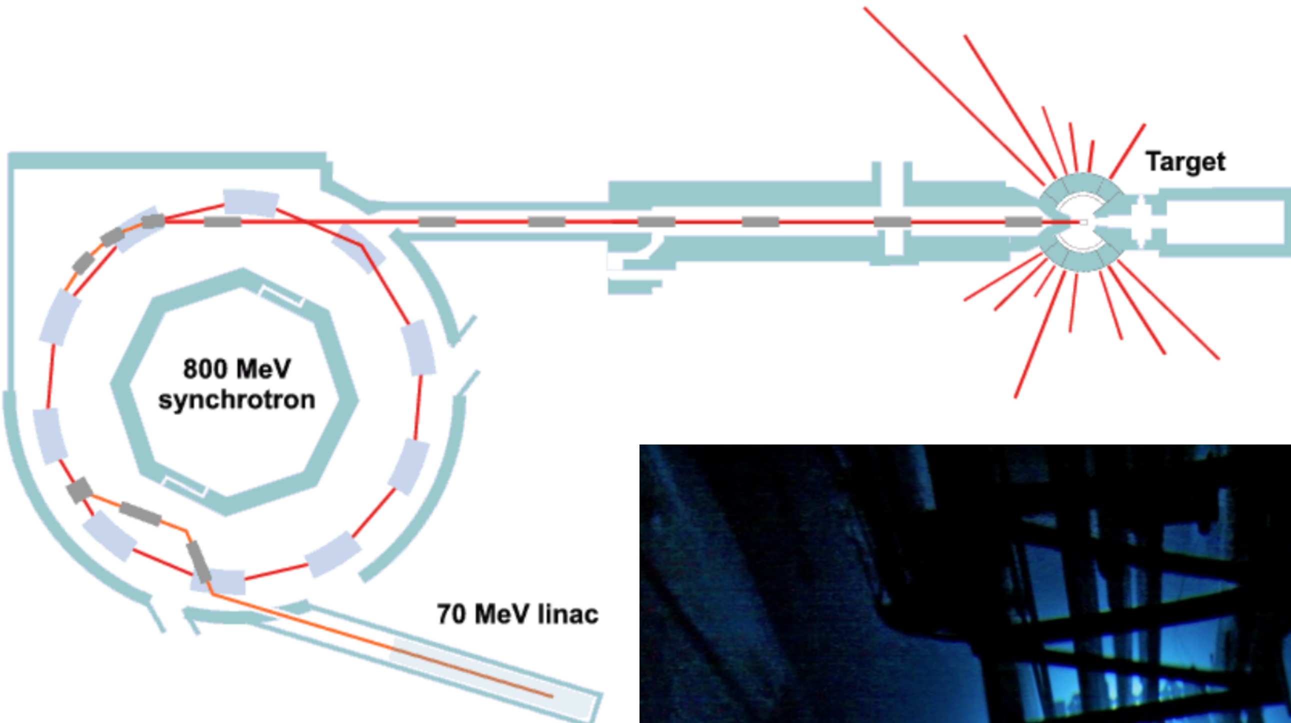
# Accelerator and reactor complementarity in coherent neutrino-nucleus scattering





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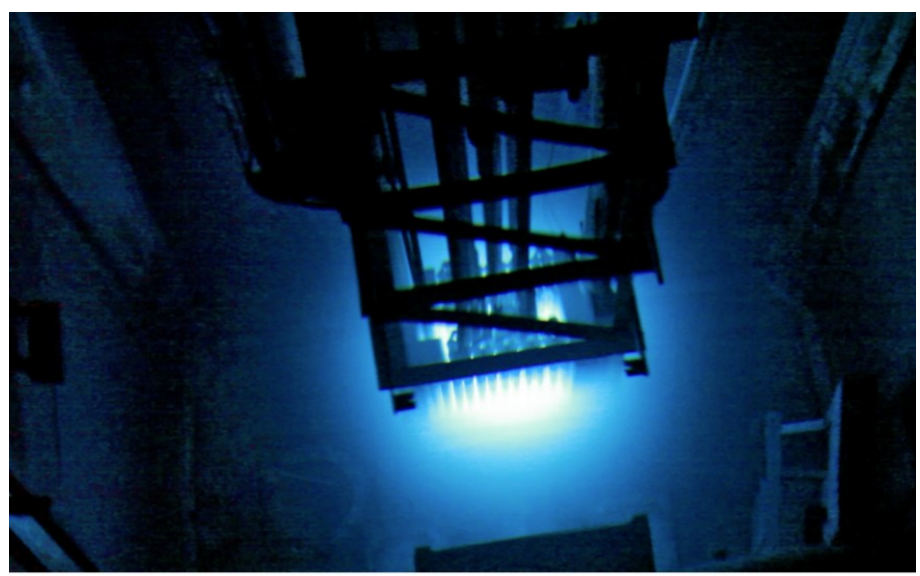



Based on:
arXiv:1711.03521

# Outline

I. Introduction to CNS

II. The COHERENT experiment

III. The MINER experiment

IV. Complementarity

V. Summary

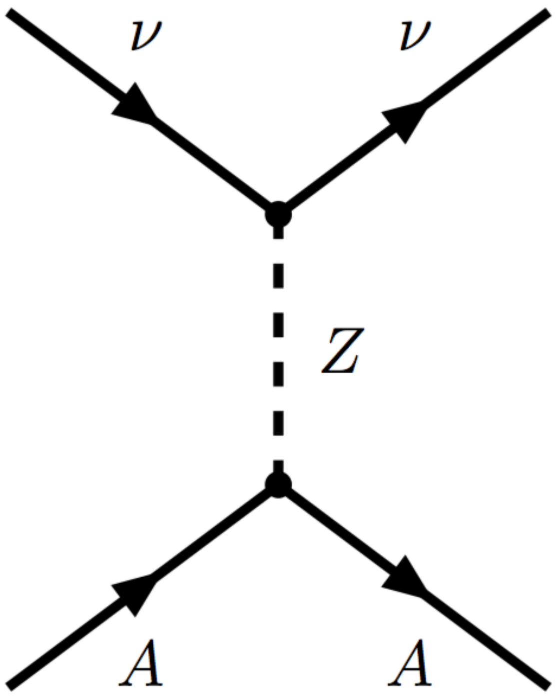
# I. Introduction to coherent elastic neutrino-nucleus scattering (CNS, CNNS, CENNS, CEvNS etc)

# Coherent neutrino neutral currents

Brief history:

**D.Z. Freedman (1974) and**
**V.B. Kopeliovich & L.L. Frankfurt (1974)**
- first suggested (10 years before Z disc)

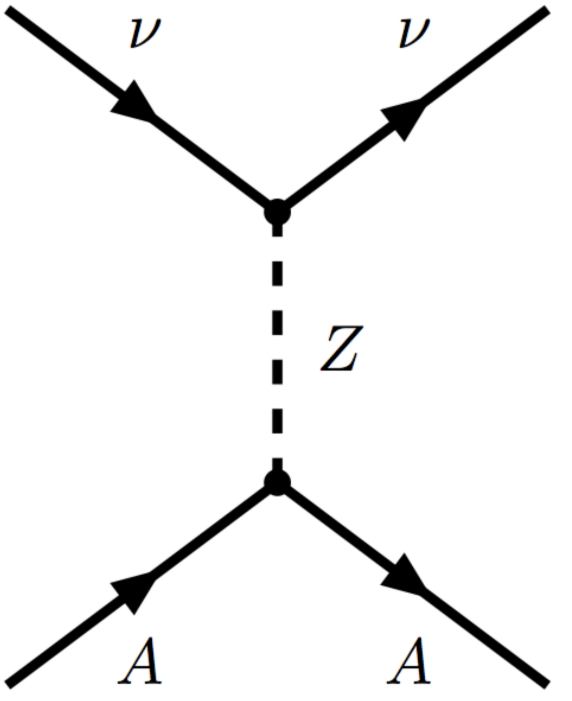
**Drukier and Stodolsky (1984)**
- superconducting grains
**Cabrera, Krauss and Wilczek (1985)**
- bolometric detection




$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m}{2\pi}\left((g_v + g_a)^2 + (g_v - g_a)^2\left(1 - \frac{E_R}{E_\nu}\right)^2 + (g_a^2 - g_v^2)\frac{mE_R}{E_{\nu^2}}\right)$$

# Coherent neutrino-nucleus scattering

- Relatively large cross sections, but low energy (coherence is lost at higher energies)
- ~MeV neutrinos have ~keV recoil
- All neutrino flavors contribute equally




$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}(E_r, E_\nu) = \frac{G_F^2}{4\pi} Q_W^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

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

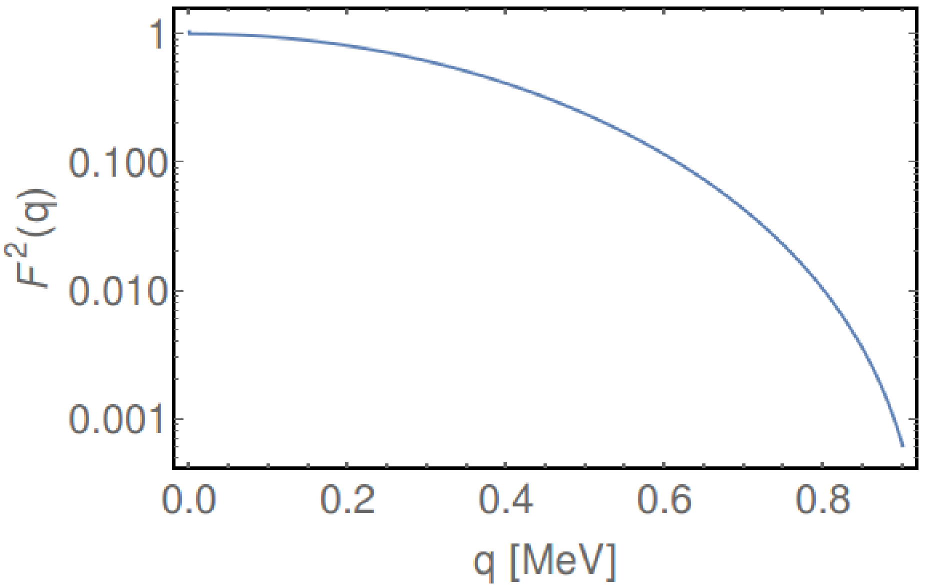
# CEvNS: nuclear form factor

Analogous to Rutherford scattering, but instead of the charge distribution we take the Fourier transform of the neutron distribution:

$$F(q) = \int_0^\infty \rho(r) \frac{\sin(qr)}{qr} 4\pi r^2 dr,$$

Helm form factor: models a spherical nucleus with a ‘fuzzy’ skin

$$F(q) = 3 \frac{\sin(qr_n) - qr_n \cos(qr_n)}{(qr_n)^3} \exp\left[\frac{-(qs)^2}{2}\right],$$




q < 0.2 MeV required to maintain coherency in germanium

# Neutrino sources

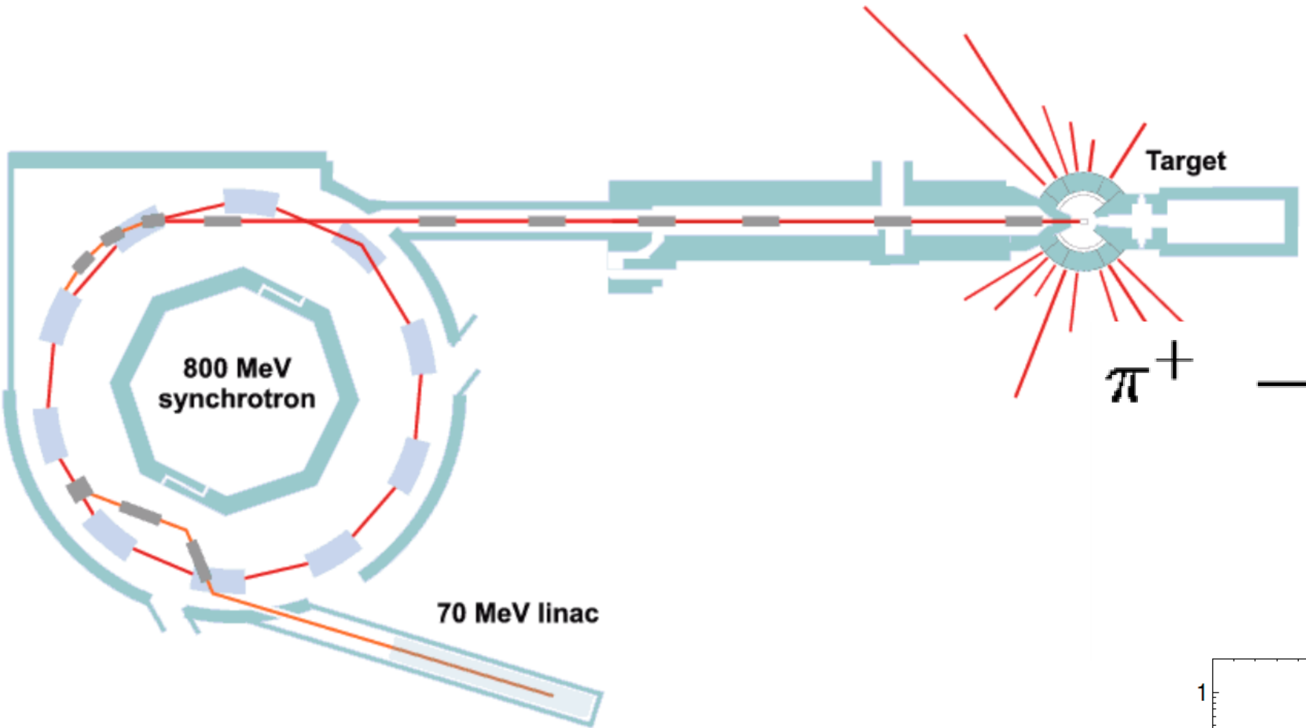
1. Solar
2. Atmospheric (produced by cosmic rays)
3. Supernovae
4. Nuclear reactors
5. Reactor/Stopped pion (e.g. SNS)

# CEvNS experiments

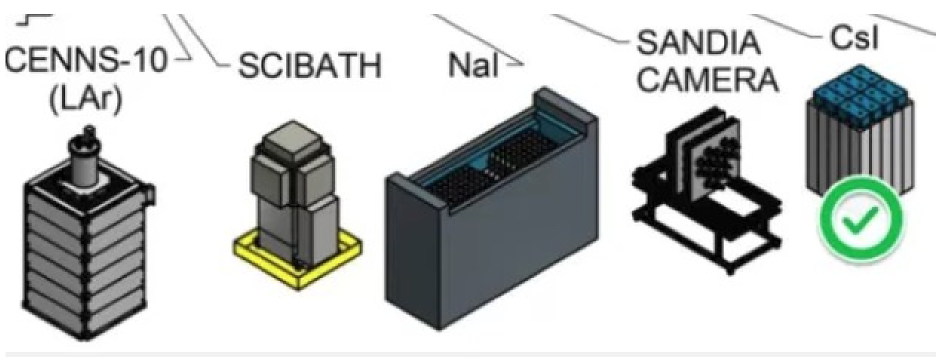
| Experiment | Source | Detector | Status |
|---|---|---|---|
| Coherent | Collider (Spallation neutron source) | Caesium-Iodide scintillators, Argon TPC and more | Running/adding new detectors |
| MIvER | Reactor | Germanium (cryogenic iZip) | Building prototype |
| CONUS | Reactor | Germanium (P-type point contact) | Running |
| CONNIE | Reactor | Silicon CCD | Running/upgrading |
| LZ | Sun | Xenon TPC | Building |

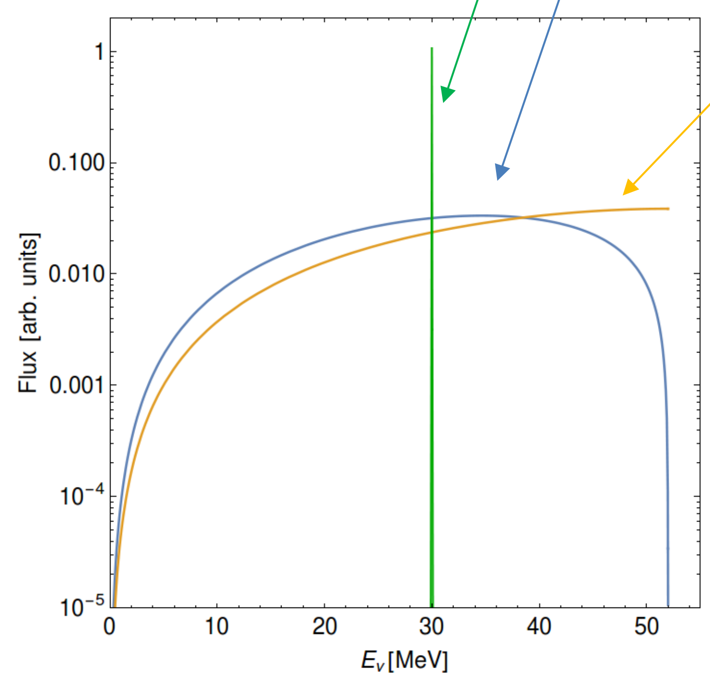
# II. The COHERENT experiment

# COHERENT at the SNS




$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



# The SNS Beam

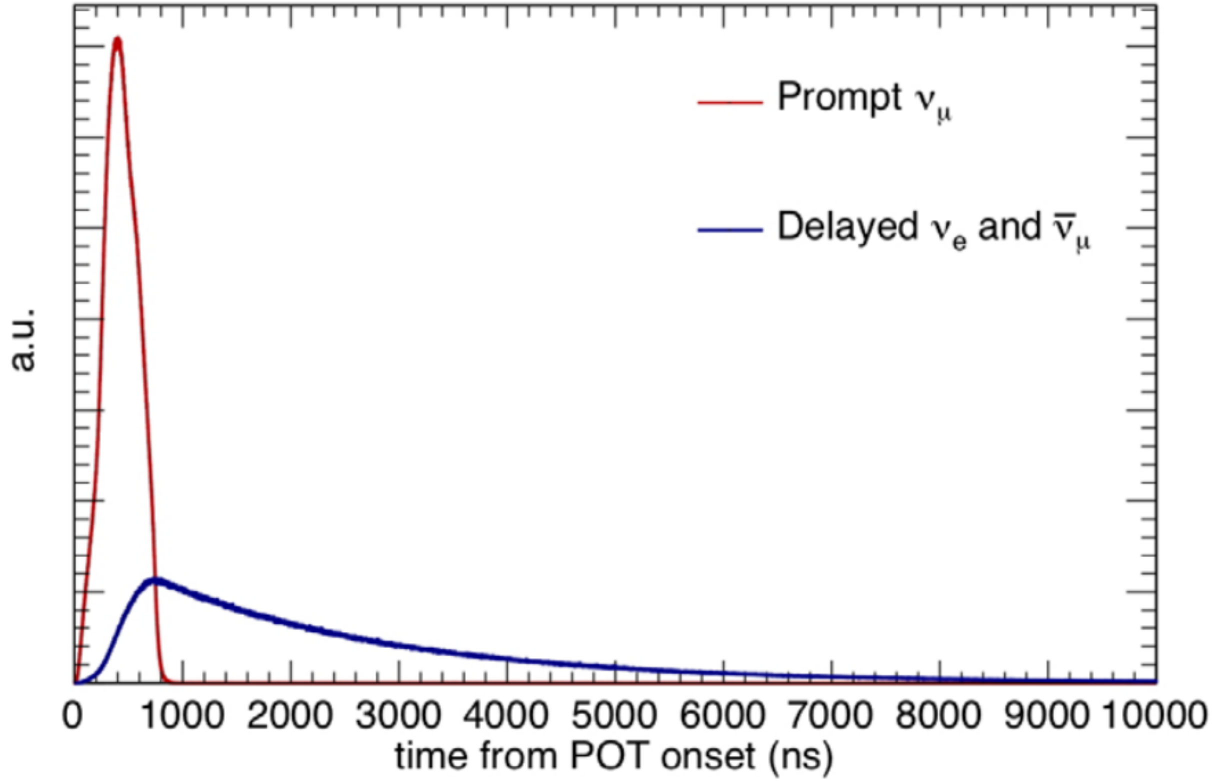
- the proton beam is made of 700 ns bunches

- pulsed at 60Hz

- Pion efficiency ~8%

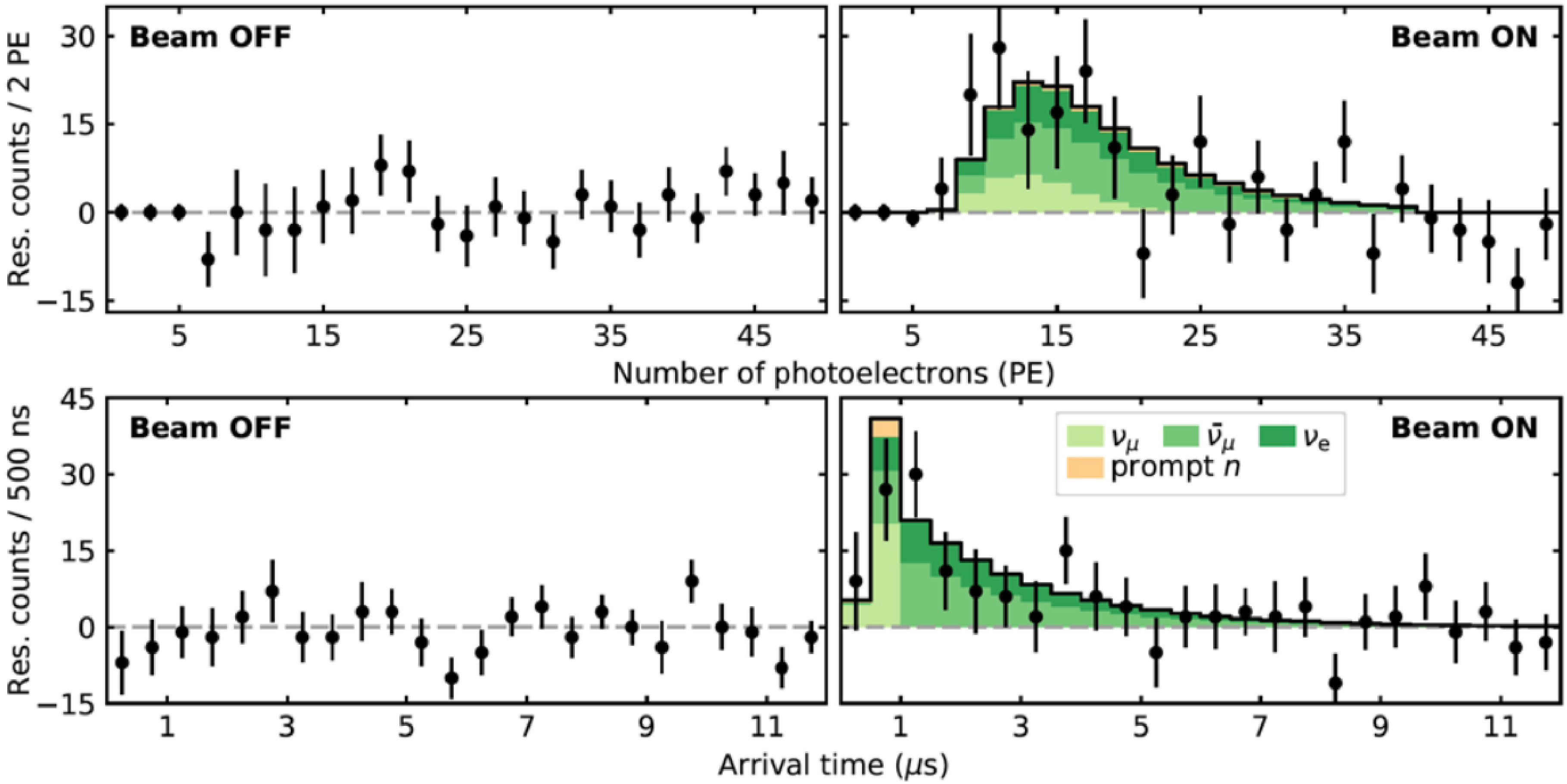
- Isotropic flux of $5x10^{15}$ /s

- allows for statistical separation of neutrino flavor



# First observation of CEvNS

See Kate Scholberg's talk tomorrow!

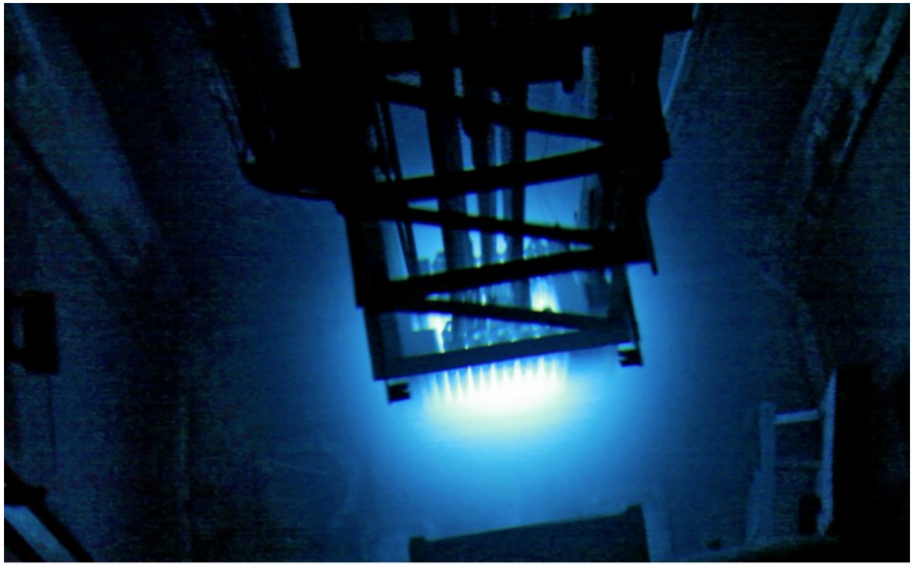



**Best fit of: 134±22 CNS events**
**Implying: 77±16% of SM cross section**

# III. The MIvER experiment

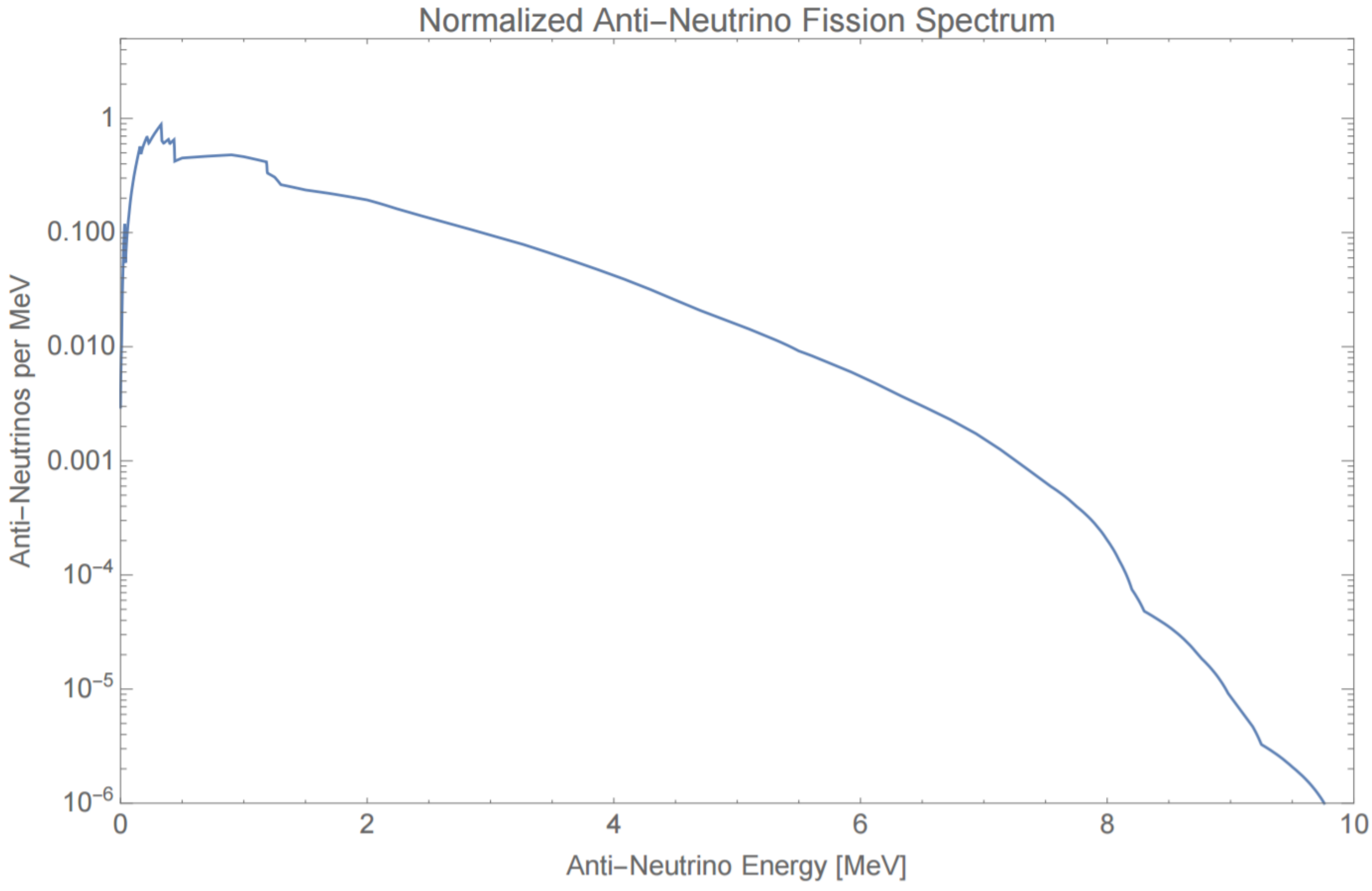
# Texas A&M Nuclear Science Center

- 1 MW TRIGA Reactor (from 1961)
- Provides training to students and emergency responders
- Materials/biomaterial science research
- Isotope production
- Now fundamental research!



# Reactor Flux

Total flux = $1.5 \times 10^{12}$ $cm^{-2}s^{-1}$ (at 1m)




K. Schreckenbach et al. PLB 160 (1985)
Update: Daya Bay arXiv:1607.05378

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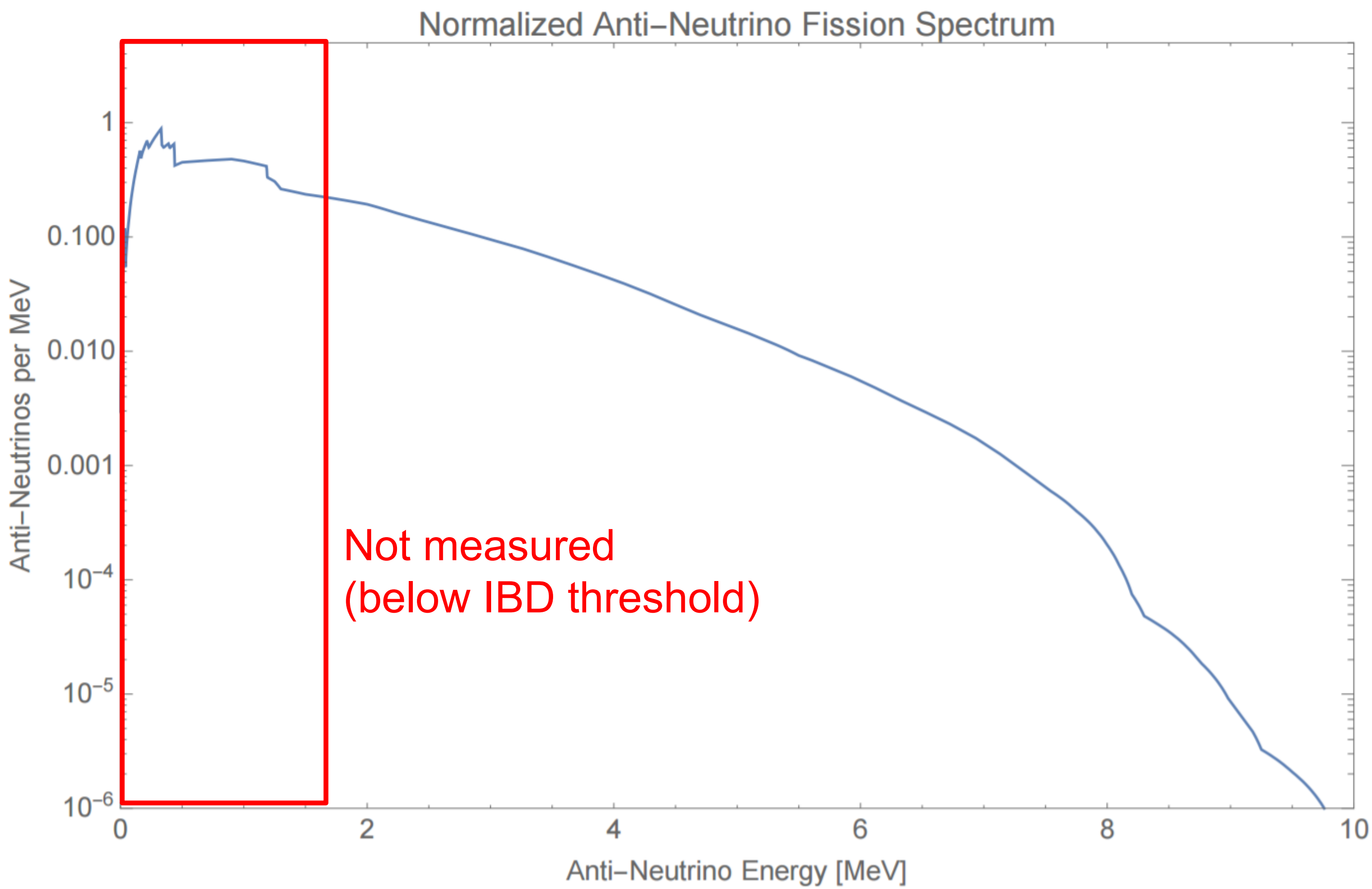


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# Detectors

- SuperCDMS detectors
  - Germanium and silicon
  - iZIP and high voltage
  - sub keV thresholds
- Detector configurations:

| Ge/Si (baseline) | Ge/Si (goal) |
|---|---|
| 100eV threshold<br>100dru background | 10eV/20eV threshold<br>10dru background |

- Experimental timeline:
- ~4kg Ge + 1kg Si this year, then scale up 20kg Ge + 10kg Si

# Beyond SM physics reach

- Sterile neutrino
- Non-standard interactions (NSI)
- Magnetic moment of neutrino
- NSI with light mediators

# IV. Complementarity

# Non-standard interactions

A simple way to parameterize BSM physics in the neutrino sector:

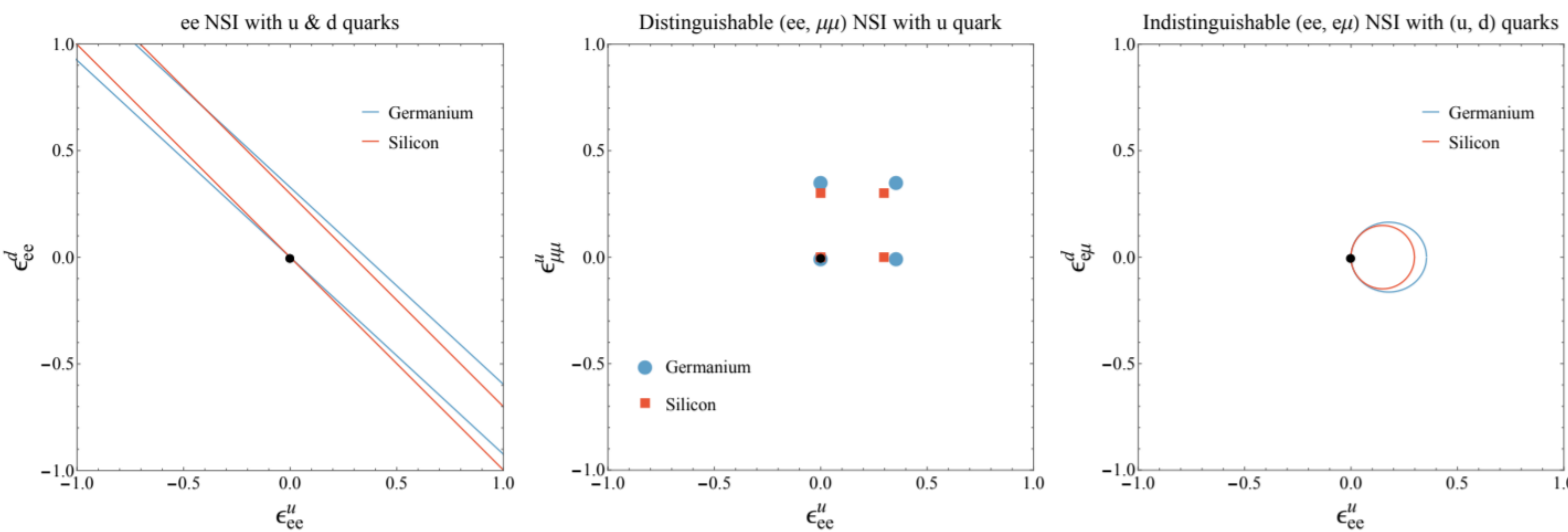
$$\frac{d\sigma}{dE_R} = \frac{G_F^2 Q_V^2}{2\pi} m_N \left(1 - \left(\frac{m_N E_R}{E_\nu^2}\right) + \left(1 - \frac{E_R}{E_\nu}\right)^2\right) F(q^2)$$

$$\begin{aligned} Q_V^2 \equiv & \left[Z(g_p^V + 2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{d}) + N(g_n^V + \epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{d})\right]^2 \\ & + \sum_{\alpha\neq\beta} \left[Z(2\epsilon_{\alpha\beta}^{uV} + \epsilon_{\alpha\beta}^{d} V) + N(\epsilon_{\alpha\beta}^{uV} + 2\epsilon_{\alpha\beta}^{dV})\right]^2 \end{aligned}$$

# NSI and Degeneracies

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 Q_V^2}{2\pi} m_N \left(1 - \left(\frac{m_N E_R}{E_\nu^2}\right) + \left(1 - \frac{E_R}{E_\nu}\right)^2\right) F(q^2)$$

$$Q_V^2 \equiv \left[Z(g_p^V + 2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{d}) + N(g_n^V + \epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{d})\right]^2$$
$$+ \sum_{\alpha\neq\beta} \left[Z(2\epsilon_{\alpha\beta}^{uV} + \epsilon_{\alpha\beta}^{d} V) + N(\epsilon_{\alpha\beta}^{uV} + 2\epsilon_{\alpha\beta}^{dV})\right]^2$$



# Bayesian inference

- A method for reconstructing model parameters

- Bayes' theorem:

$$\mathcal{P}(\theta, D|I) = \frac{\mathcal{L}(D|\theta, I)\pi(\theta, I)}{\epsilon(D, I)},$$

- Likelihood function (poisson):

$$\mathcal{L}(\sigma, \theta) = \prod_{i=1}^{N} P(E_i(\sigma, \theta), A_i)$$

# Bayesian inference

- Bayesian priors:

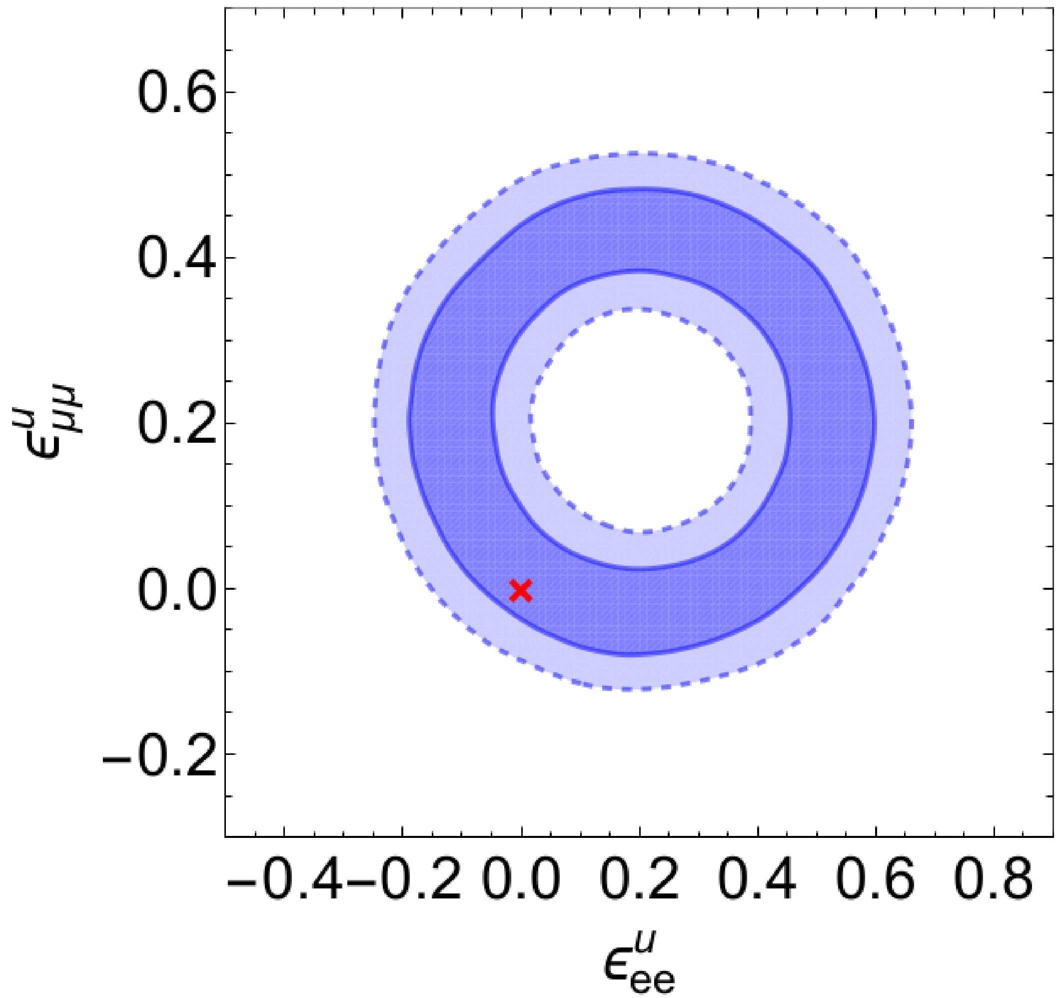
| Parameter | Prior range | Scale |
|---|---|---|
| $\epsilon^{f}_{\alpha\alpha}$ | (-1.5, 1.5) | linear |
| SNS flux | $(4.29 \pm 0.43) \times 10^{9}$ | Gaussian |
| Reactor flux | $(1.50 \pm 0.03) \times 10^{12}$ | Gaussian |
| SNS background | $(5 \pm 0.25) \times 10^{-3}$ | Gaussian |
| Reactor background | $(1 \pm 0.1)$ | Gaussian |

- Experimental configurations:

| Name | Detector | Source | Exposure | Threshold |
|---|---|---|---|---|
| Current (COHERENT) | CsI | SNS (20m) | 4466 kg.days | 4.25 keV |
| Future (reactor) | Ge | 1GW reactor (20m) | $10^{4}$ kg.days | 100 eV |
| | Si | 1GW reactor (20m) | $10^{4}$ kg.days | 100 eV |
| Future (accelerator) | NaI | SNS (20m) | 1 tonne.year | 2 keV |
| | Ar | SNS (20m) | 1 tonne.year | 30 keV |

# Current Inference with COHERENT 2017 data

4466 kg.days CsI data

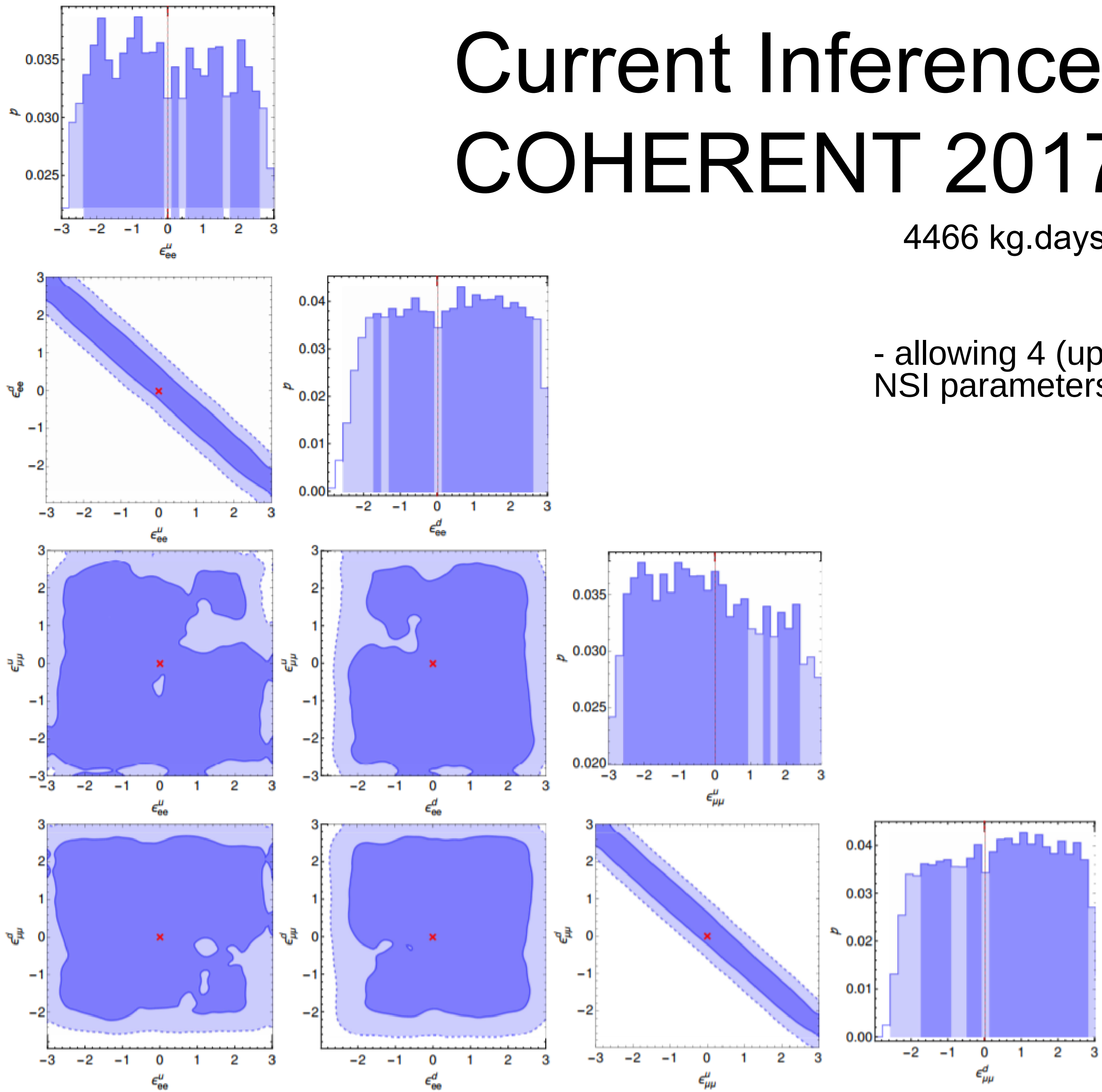



- only 2 up-type NSI parameters allowed to be non-zero

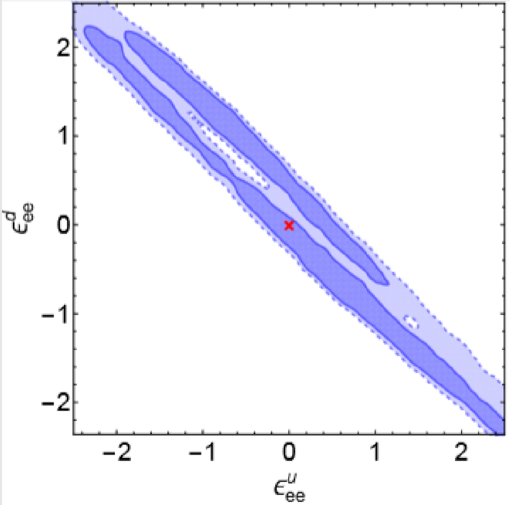
# Current Inference with COHERENT 2017 data

4466 kg.days CsI data

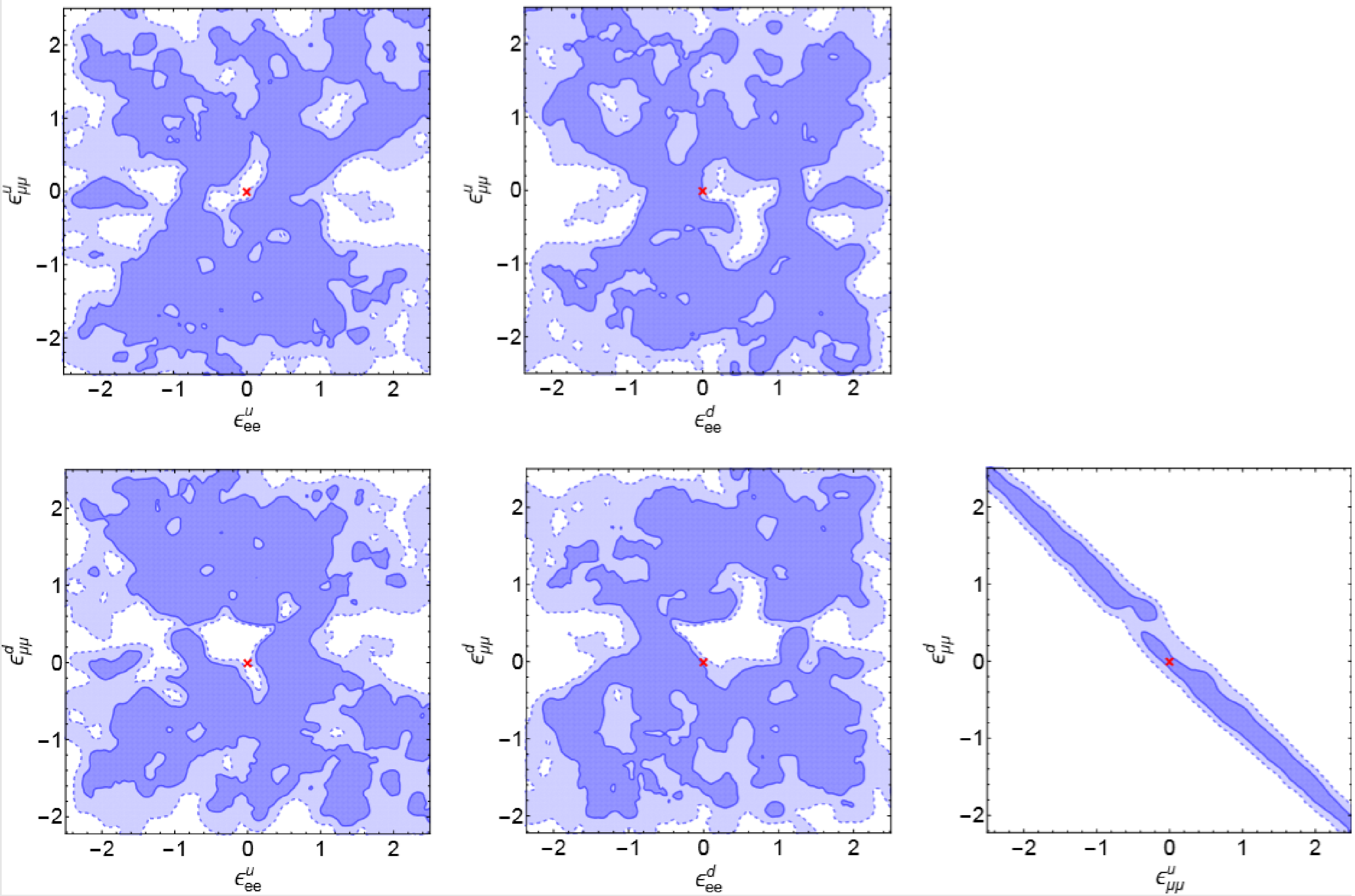
- allowing 4 (up and down) NSI parameters to be non-zero



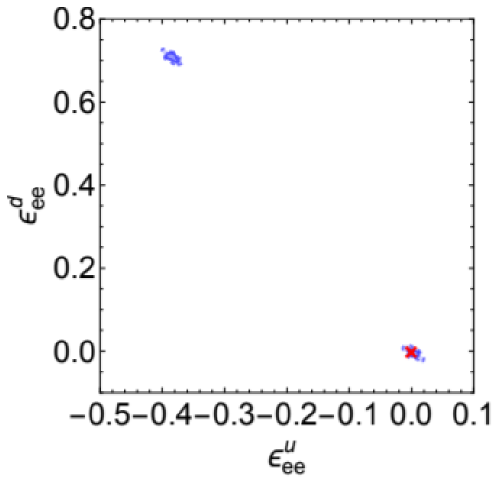
# Future Inference with Accelerator data only



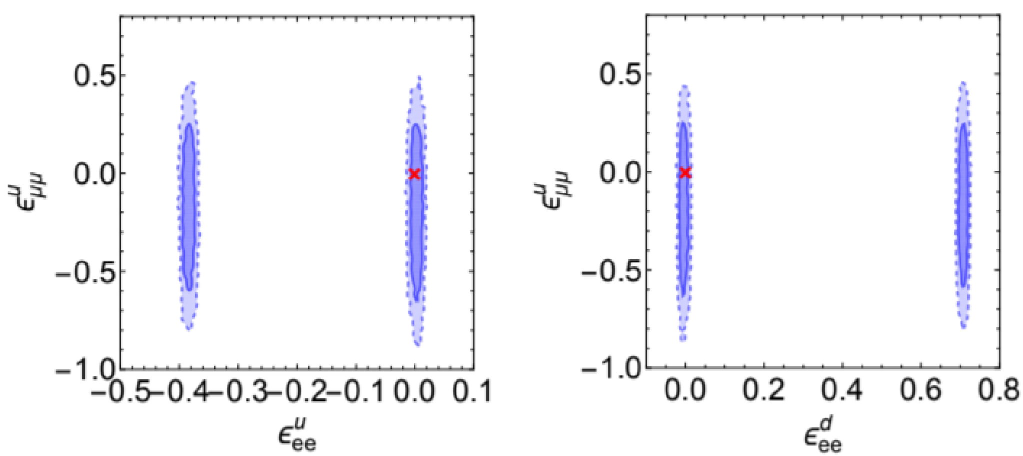

| | | |
|---|---|---|
| NaI | SNS (20m) | 1 tonne.year |
| Ar | SNS (20m) | 1 tonne.year |

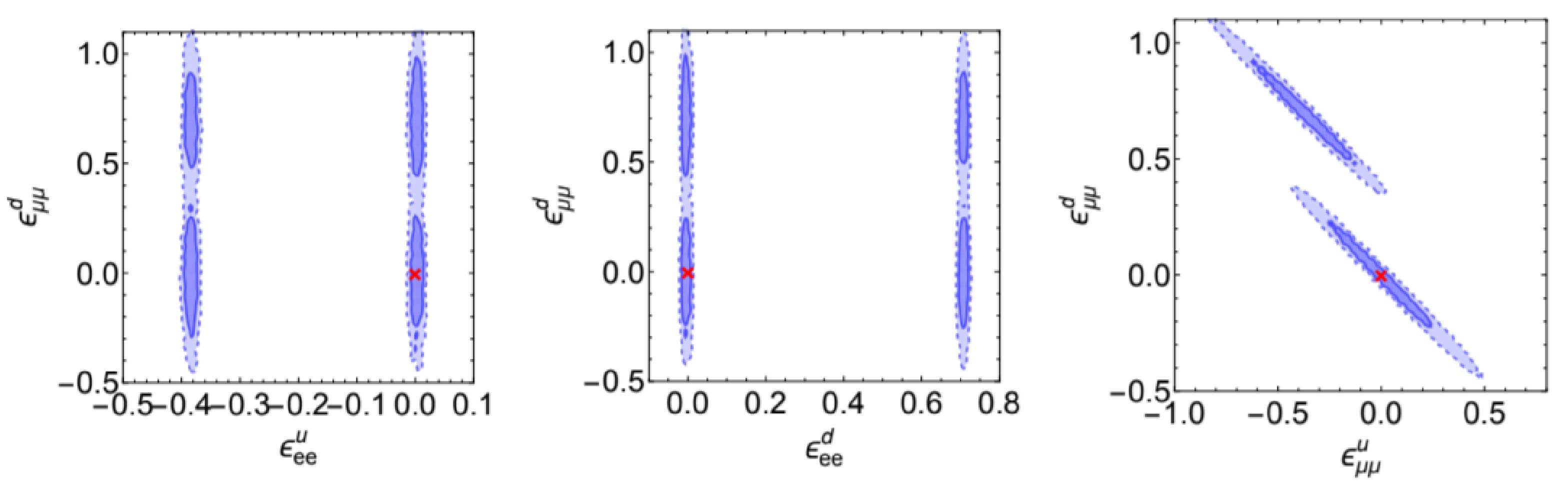


# Future Inference with Reactor + Accelerator




| | | |
|---|---|---|
| Ge | 1GW reactor (20m) | $10^4$ kg.days |
| Si | 1GW reactor (20m) | $10^4$ kg.days |
| NaI | SNS (20m) | 1 tonne.year |
| Ar | SNS (20m) | 1 tonne.year |



# IV. Summary

- CEvNS experiments are now a reality and more data is coming!
- CEvNS provides a new tool to search for and constrain BSM physics
- When constraining NSI we need different sources of neutrinos and different detectors to fully explore possible parameter space