Probing new physics with CEvNS: an overview

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Corpus Christi, Texas

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Quick PSA:

GWEN PEARSON SCIENCE 09.11.14 10:00 AM

NEVER TOUCH ANYTHING THAT LOOKS LIKE DONALD TRUMP'S HAIR

Megalopyge opercularis
(southern flannel moth)

Dangers and treatment of stings [edit]

The caterpillar is regarded as a dangerous insect because of its venomous spines. Exposure to the caterpillar's fur-like spines leads to an immediate skin irritation characterized by a "grid-like hemorrhagic papular eruption with severe radiating pain." Victims describe the pain as similar to a broken bone or blunt-force trauma.[3] The reactions are sometimes localized to the affected area, but are often very severe, radiating up a limb and causing burning, swelling, nausea, headache, abdominal distress, rashes, blisters, and sometimes chest pain, numbness, or difficulty breathing.[6][7] Additionally, sweating from the welts or hives at the site of the sting are not unusual.

What is CEvNS?

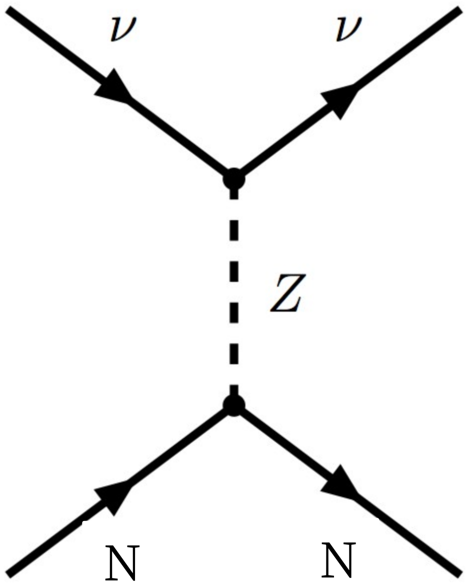
Coherent

Elastic

v (neutrino)

Nucleus

Scattering



...a brief history

1959
-1967
Glashow-Weinberg-Salam formulate electroweak theory

1973
Gargamelle observes weak neutral currents (neutrino-hadronic)

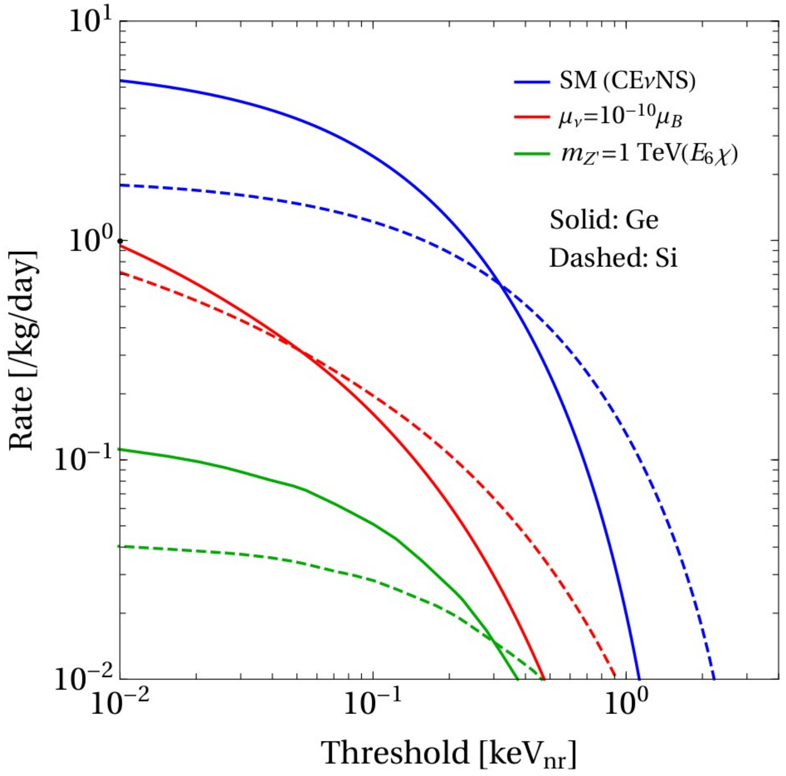
1977
Freedman

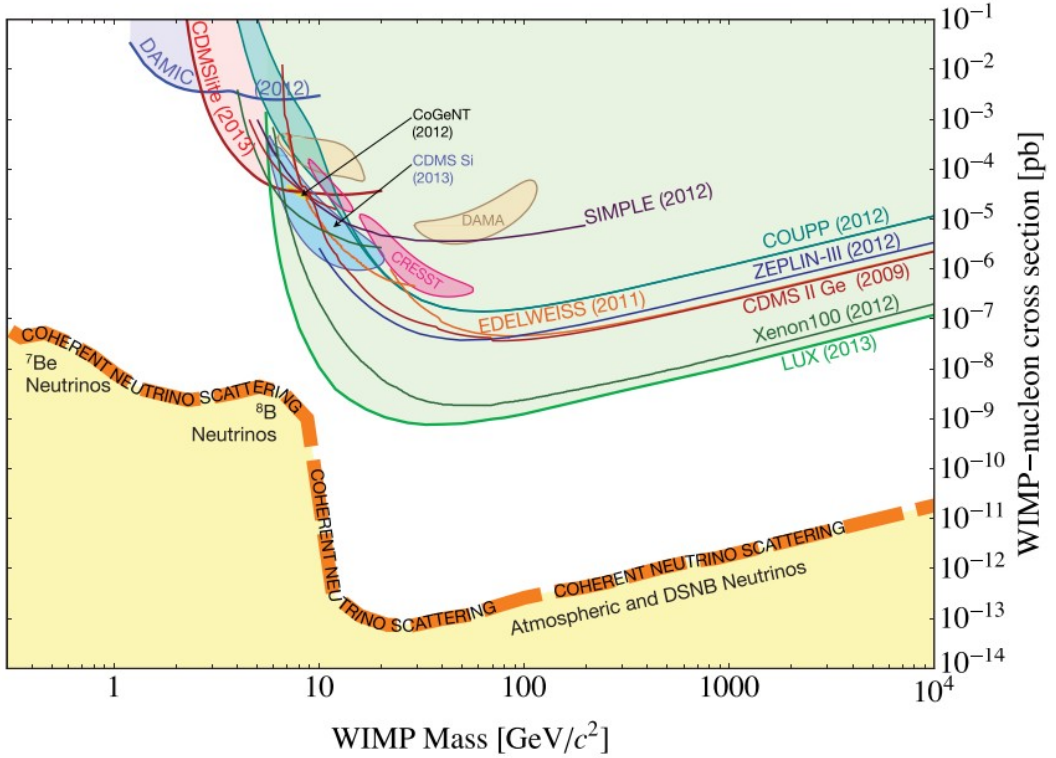
1983
Discovery of the Z-boson

2017
First observation by COHERENT

Why do we care?

- CEvNS provides a novel probe of new physics
- Confirm the normalization of the neutrino floor





CEvNS as a probe

Standard Model

- Low energy sinΘ_W
- Nuclear form factors
- g_A quenching
- Reactor flux
- Astrophysical processes

..and beyond

- Sterile neutrinos
- Accessing high-scale physics
- Nu magnetic moment
- Light mediators
- CP violation (see Diego’s talk)

Observing CEvNS

The cross section for CEvNS is large:

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

Where charge is:

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

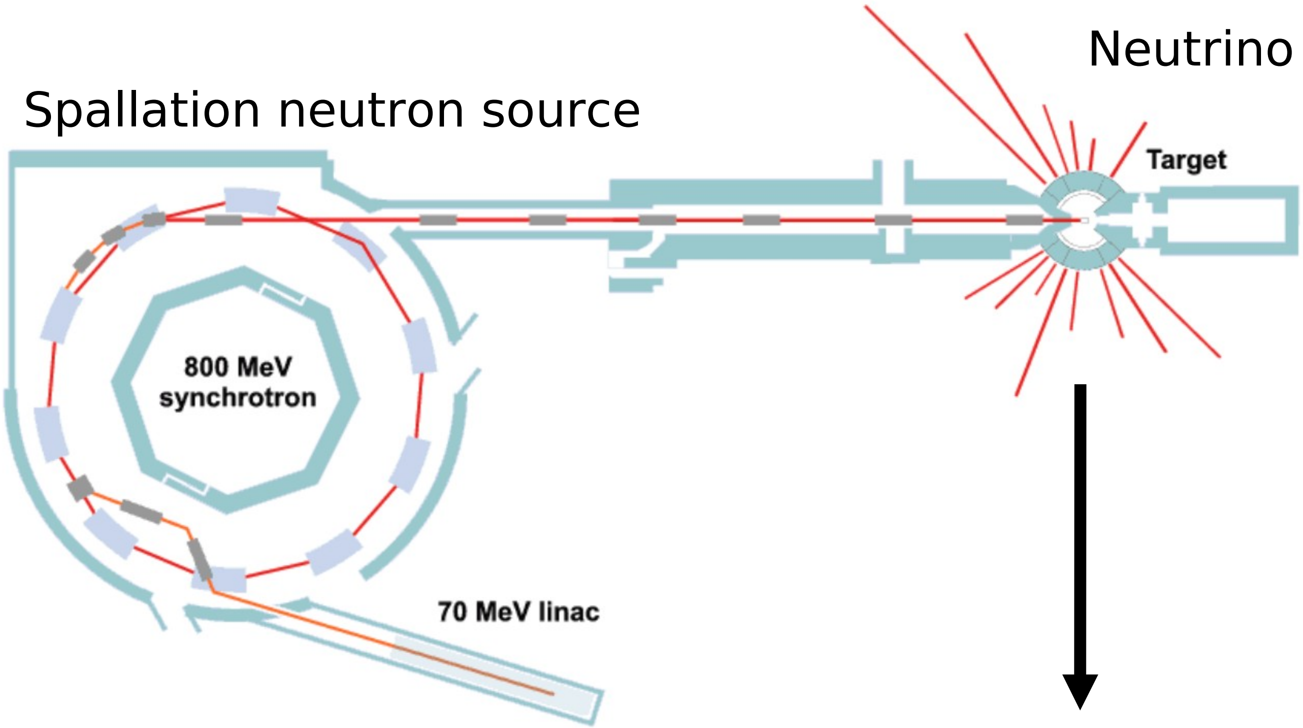
...but the recoil energy is small:

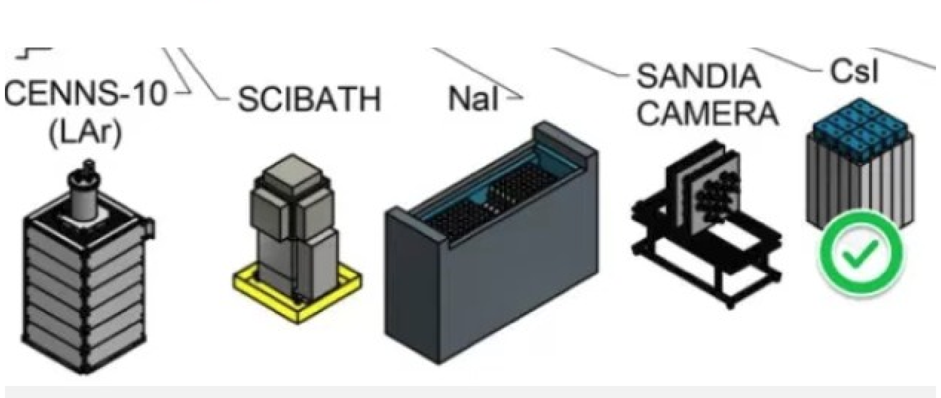
$$E_\mathrm{R}^{\mathrm{max}} = 2E_\nu^2/(M + 2E_\nu)$$

- Choose a neutrino source:
  e.g. stopped pion (a la SNS) or nuclear reactor

The COHERENT experiment

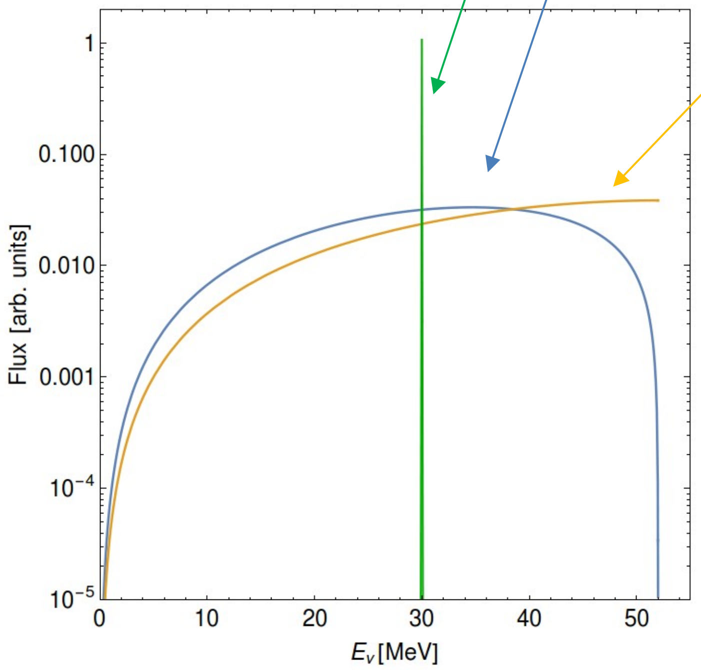
Spallation neutron source





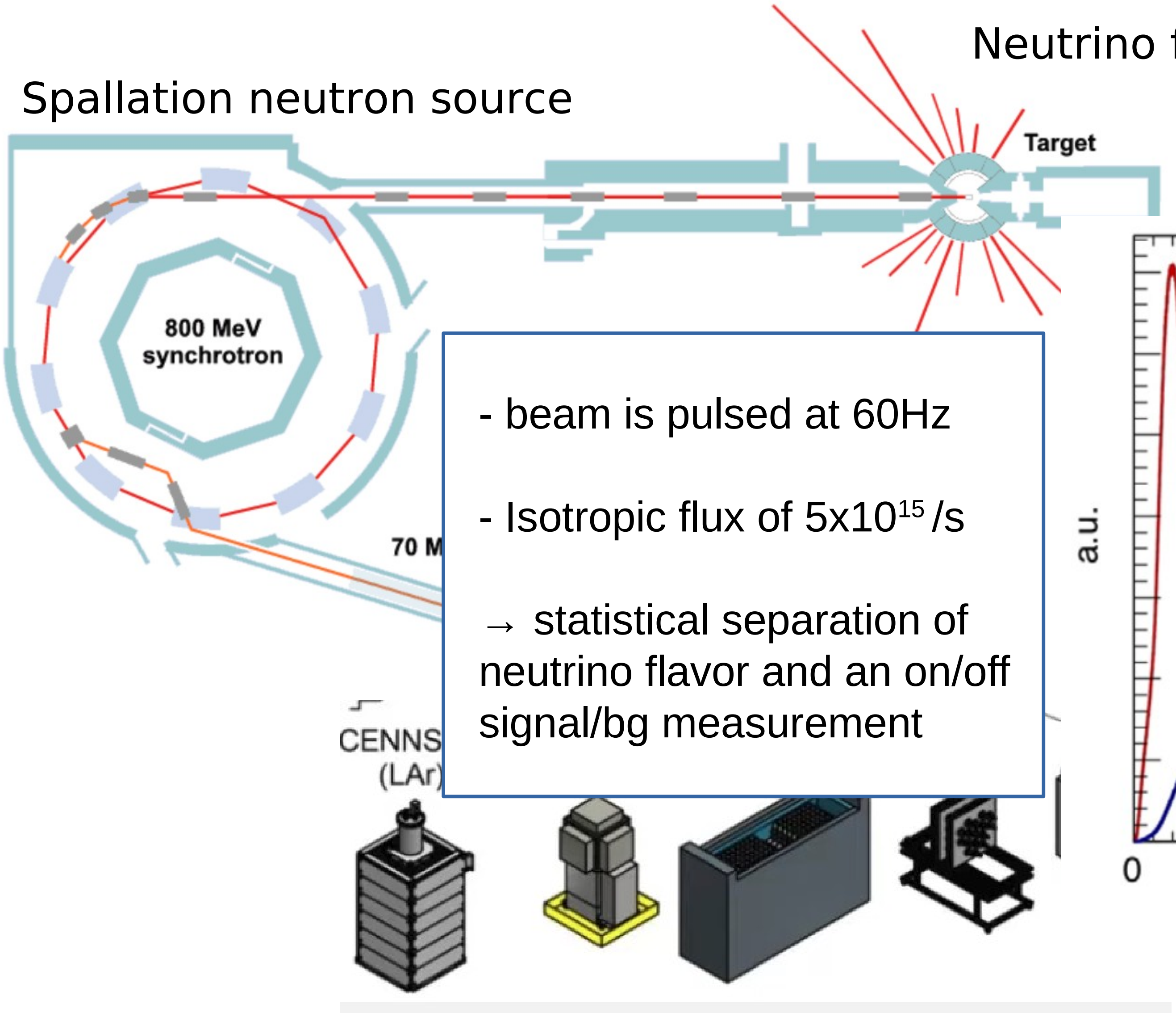
Neutrino flux from stopped pions → muons → neutrinos:

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



The COHERENT experiment

Spallation neutron source

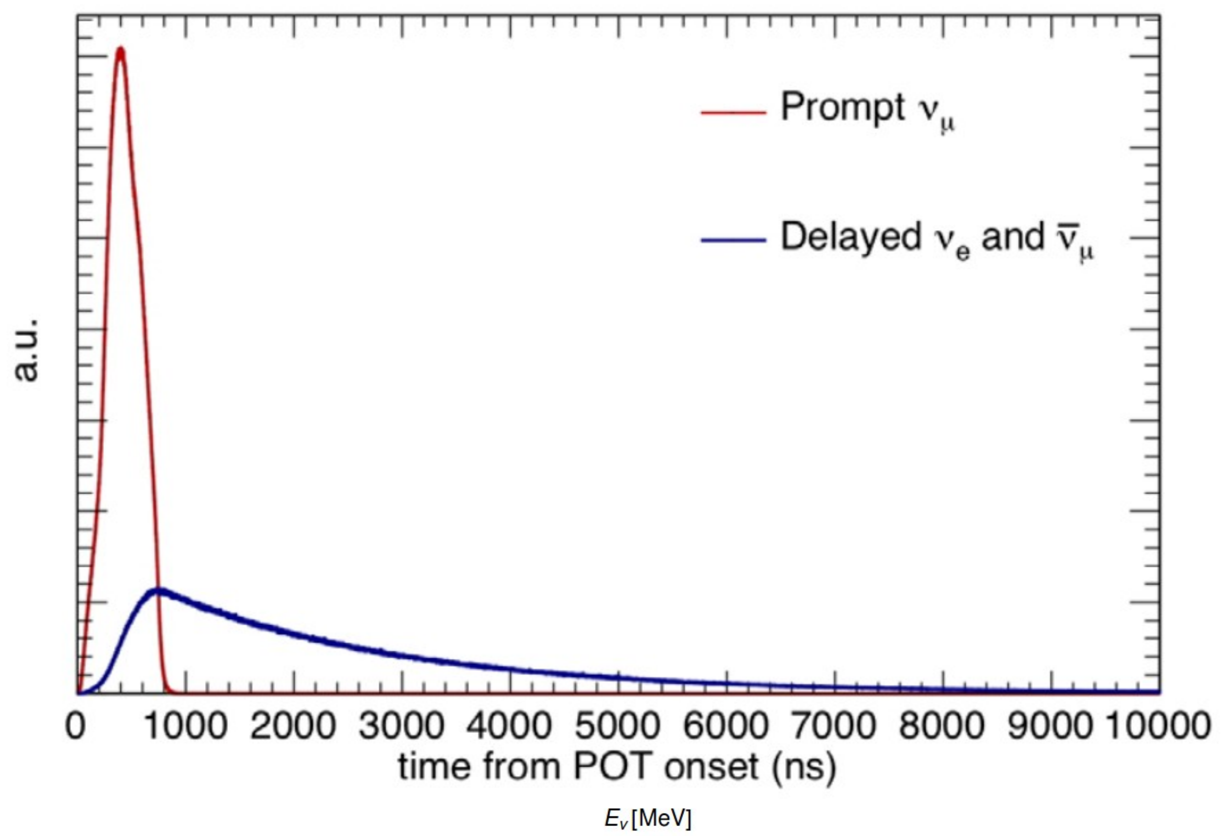


- beam is pulsed at 60Hz
- Isotropic flux of $5x10^{15}$ /s

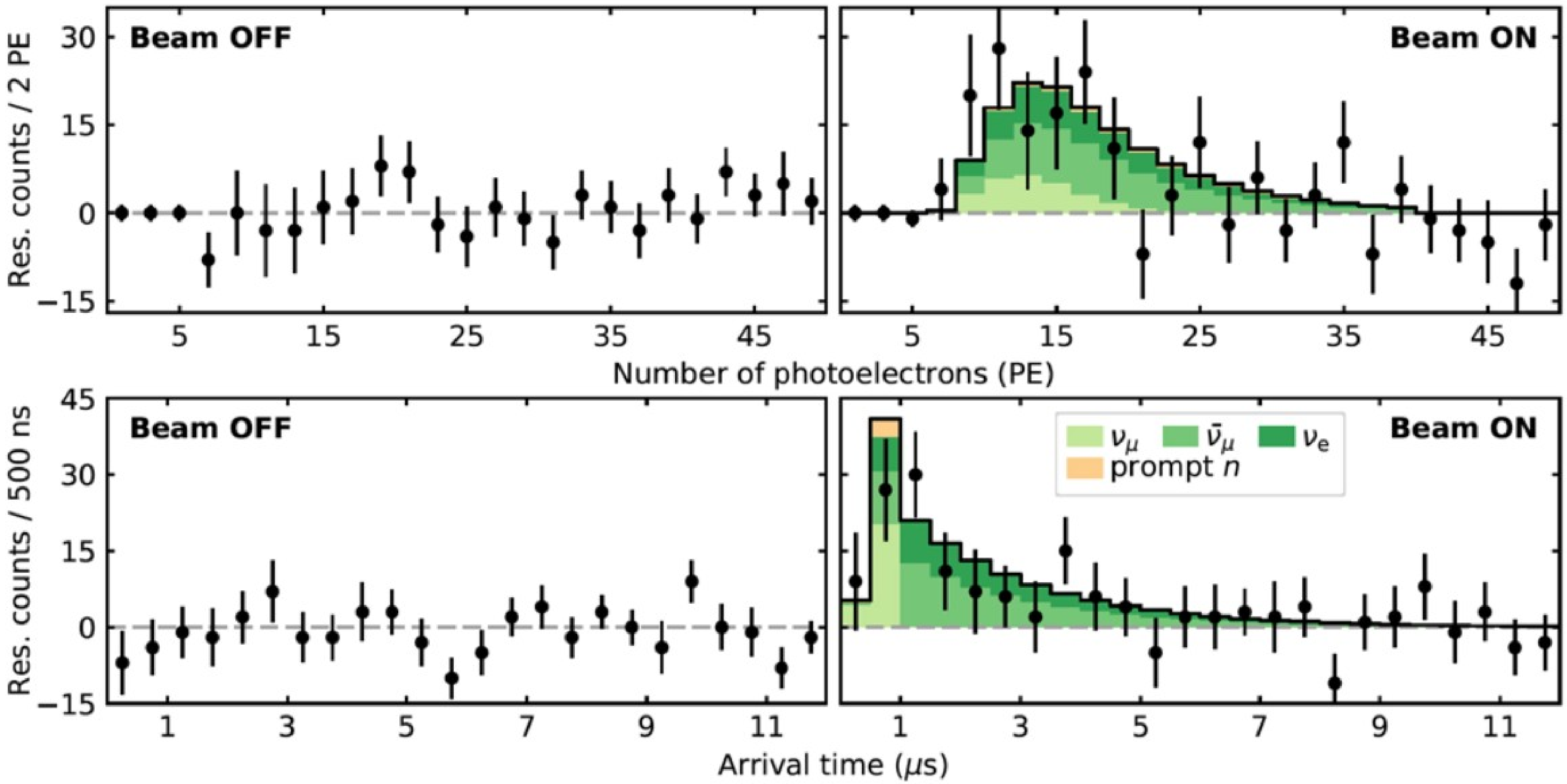
→ statistical separation of neutrino flavor and an on/off signal/bg measurement

Neutrino flux from stopped pions → muons → neutrinos:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$



COHERENT's observation of CEvNS



Akimov et al.
Science Vol. 357, 6356 (2017)

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

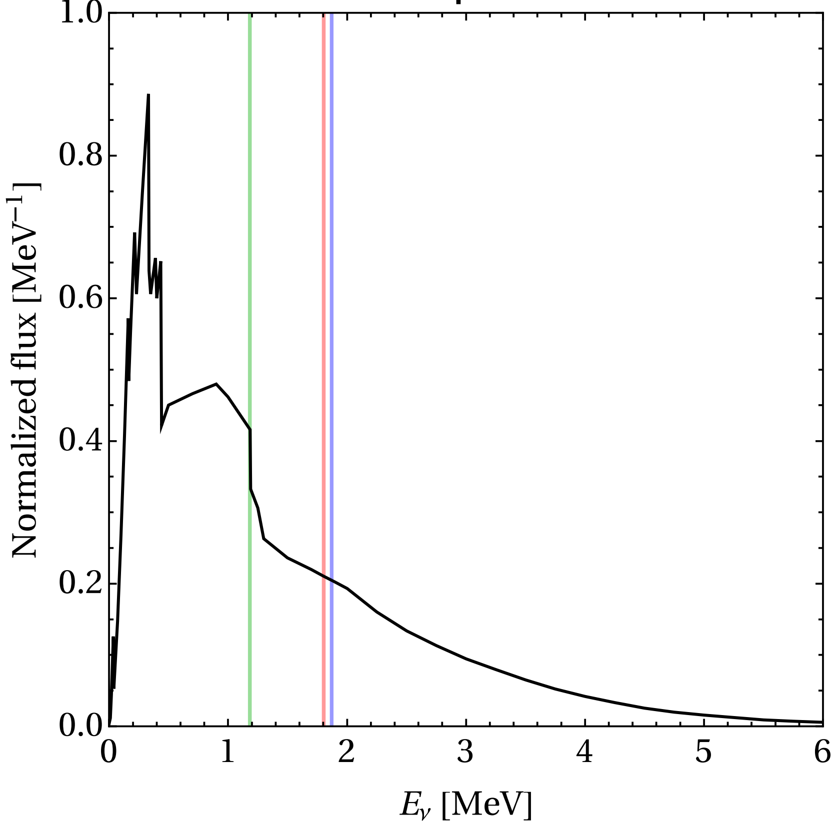
Summary of CEvNS experiments

Experiment	Source	Detector	Status
Coherent	SNS (Oakridge NL)	CsI, LAr (NaI and Ge soon)	Running
TEXONO	Reactor ~2GW (Taiwan)	Ge (P-type point contact)	Running (?)
CONNIE	Reactor ~2GW (Brazil)	Si (CCD)	Running/upgrading
MINER	Reactor ~1MW (Texas A&M)	Ge (cryogenic)	Prototype running
CONUS	Reactor ~4GW (Germany)	Ge (SAGe)	Running
Ricochet	Reactor (planned)	CryoCube (Ge-Zn)	R&D
NU-CLEUS	Reactor (CHOOZ, France)	CaWO4 (a la CRESST)	R&D
Xenon-nT/LZ	supernova/solar	LXe	Building

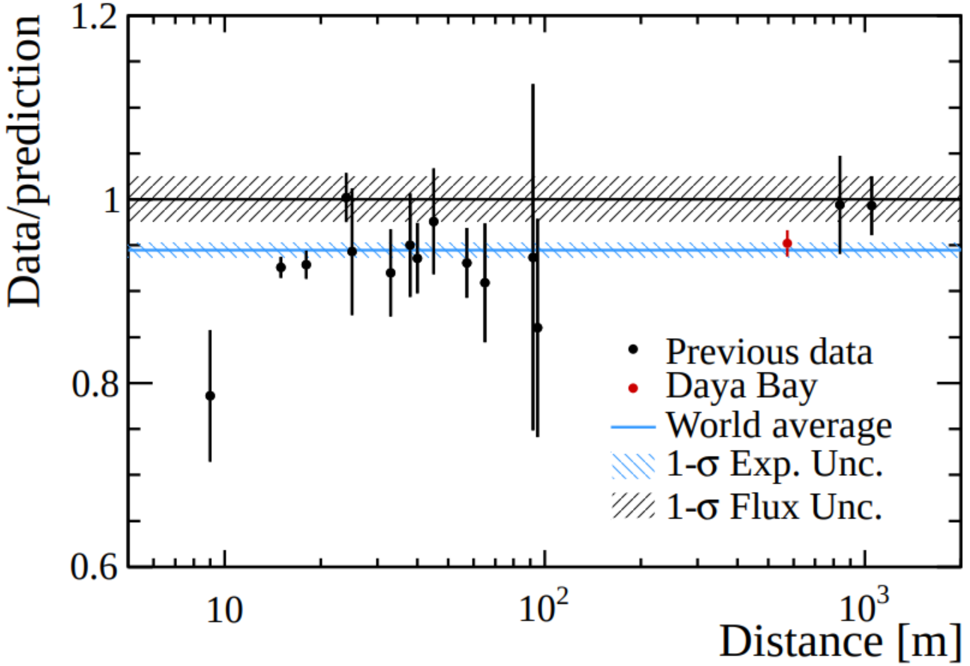
Physics with CEvNS

Reactor neutrino fluxes

Flux from Kopeikin 2012



Daya Bay flux measurement
Adey et al. arXiv: 1808.10836



- 72% of the flux is below the IBD threshold

	Percent flux above $100eV_{nr}$	Percent flux above $70eV_{nr}$
Germanium	27%	33%
Silicon	44%	52%

0.952±0.014±0.023 (1.001±0.015±0.027) for the Huber-Mueller (ILL-Vogel) model

Neutrino charge Radii

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E,T) \simeq \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E^2}\right) \times \left\{ \left[\left(g_V^p - \tilde{Q}_{\ell\ell}\right) Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2) \right]^2 + Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell' \neq \ell} |\tilde{Q}_{\ell'\ell}|^2 \right\},$$

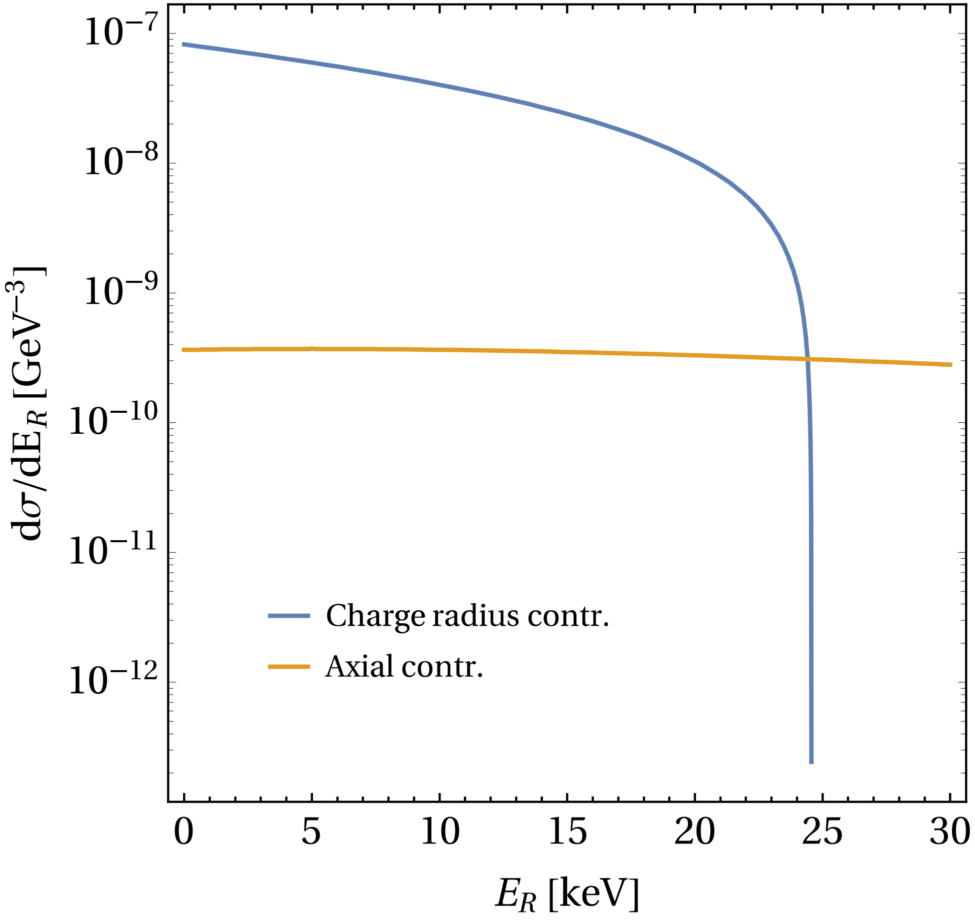
$$\tilde{Q}_{\ell\ell'} = \frac{2}{3} m_W^2 \sin^2\vartheta_W \langle r^2_{\nu_{\ell\ell'}} \rangle$$

~0.02

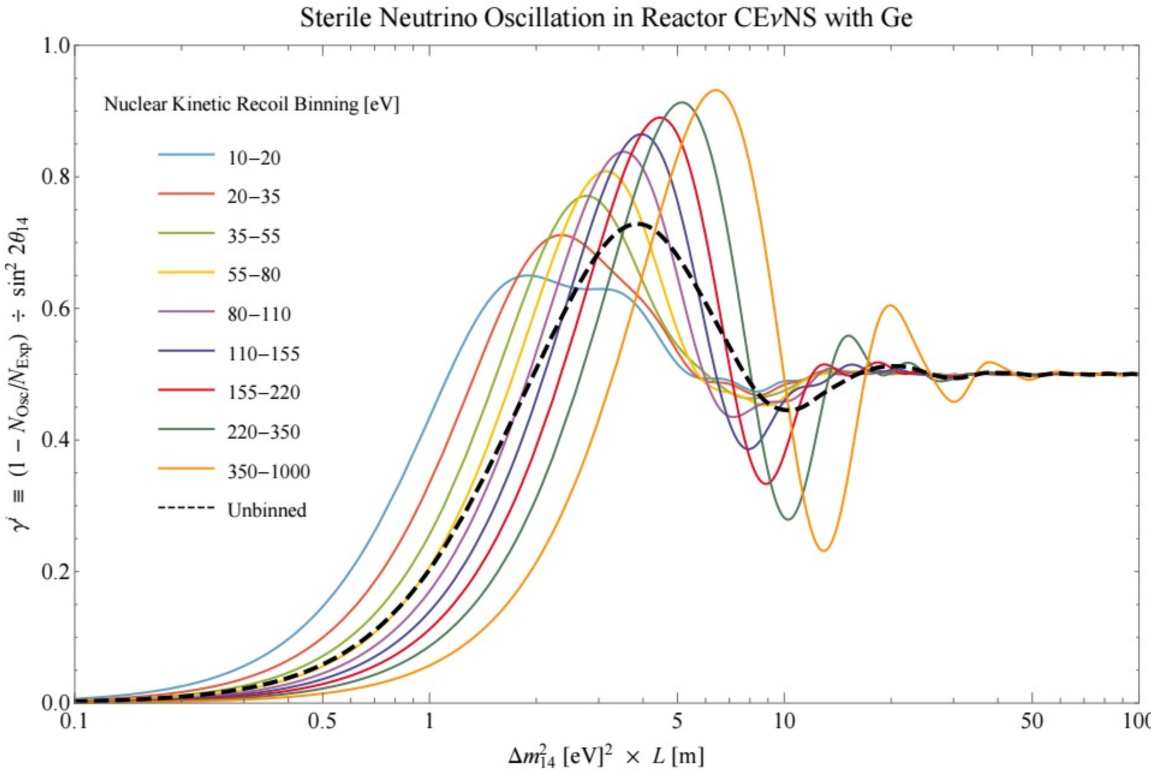
$$-8 \times 10^{-32} < \langle r^2_{\nu_\mu} \rangle < 11 \times 10^{-32}\,\mathrm{cm}^2$$

Cadeddu et al. arXiv:1810.05606

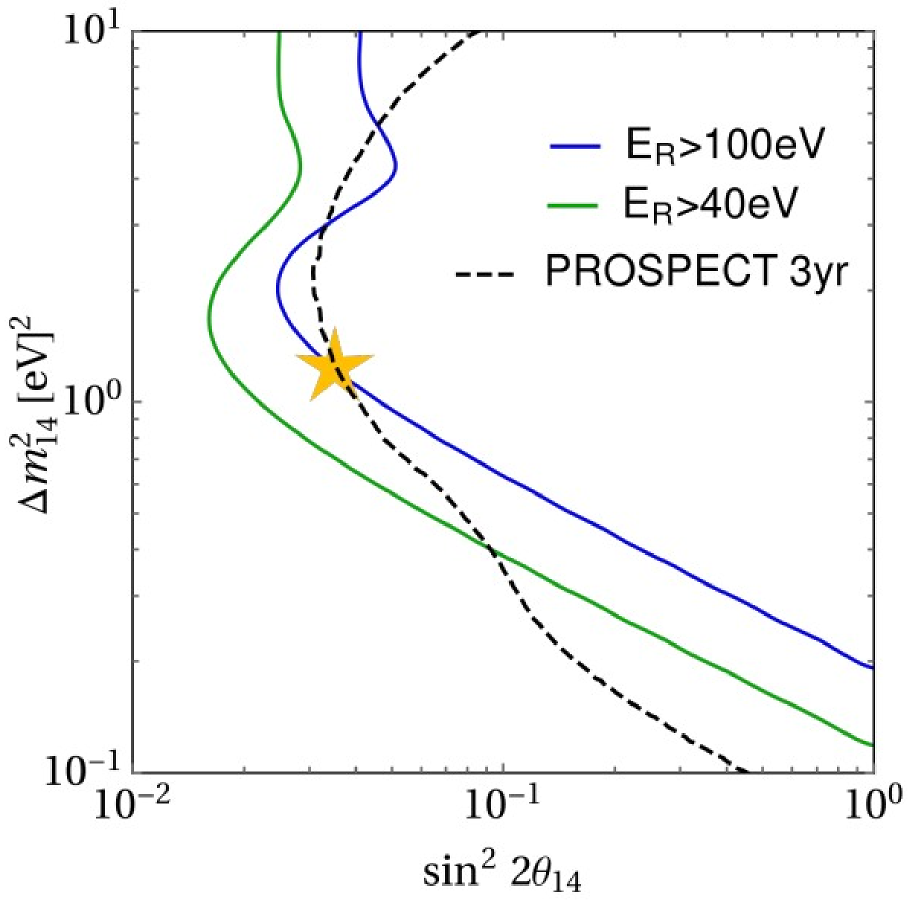
Germanium-73, E_{nu}=30 MeV



Beyond SM physics reach:
sterile neutrino



Dutta, Gao, Kubik, Mahapatra, Mirabolfath, Strigari, Walker arXiv:1511.02834



Expected reach for MINER with 10,000 kg.days, star represents world avg.

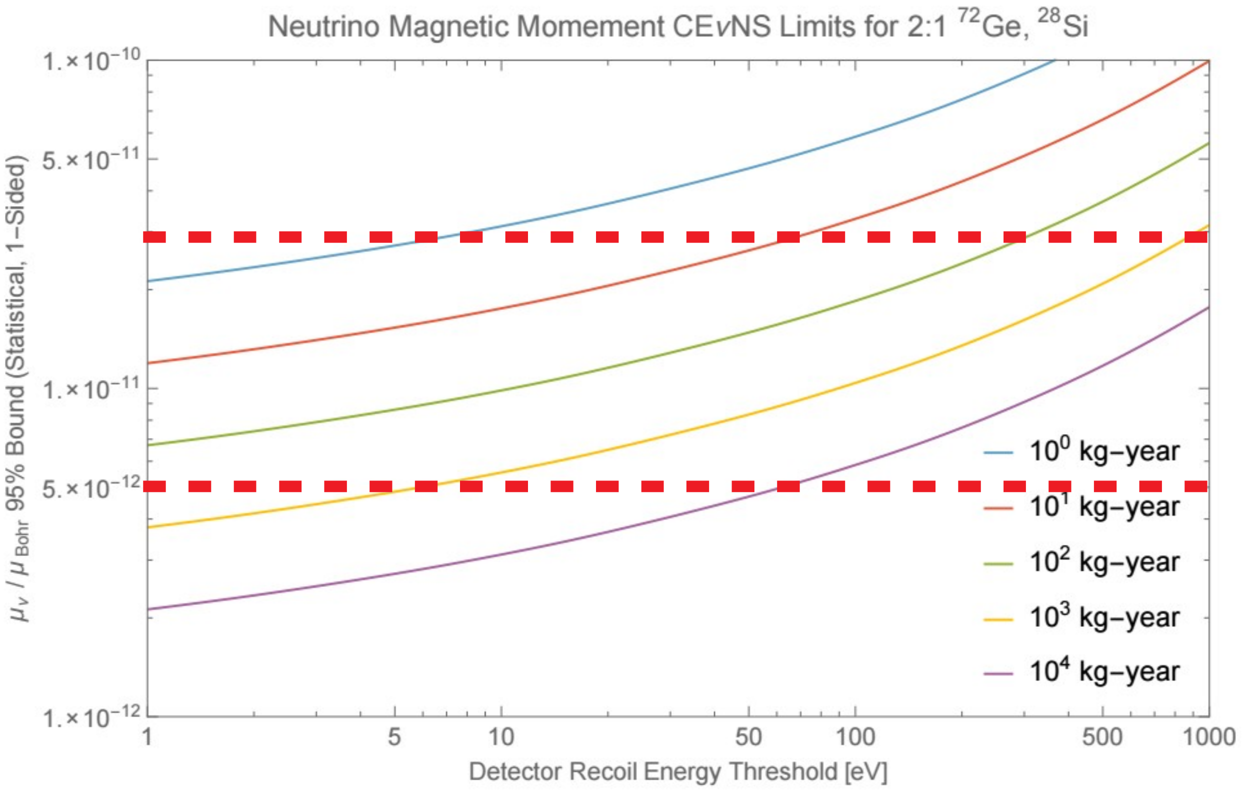
Beyond SM physics reach:
neutrino magnetic moment

$$\mu_\nu = \frac{3G_F m_e m_\nu}{4\sqrt{2}\pi^2} = 3.2\times 10^{-19}\left[\frac{m_\nu}{1\ \text{eV}}\right]$$

(Vogel and Engel, PRD, 1989)

- Sensitive to Dirac/Majorana nature (Bell et al. hep-ph/0606248) and right-handed currents

- CEvNS is competitive with existing limit from Beda et al. arXiv:1005.2736

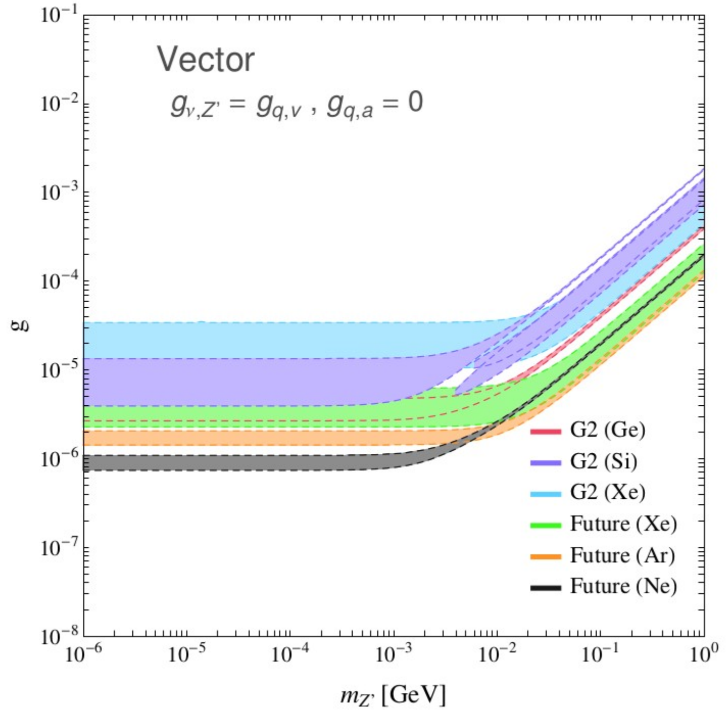


Dutta, Mahapatra, Strigari, Walker, 1508.07981

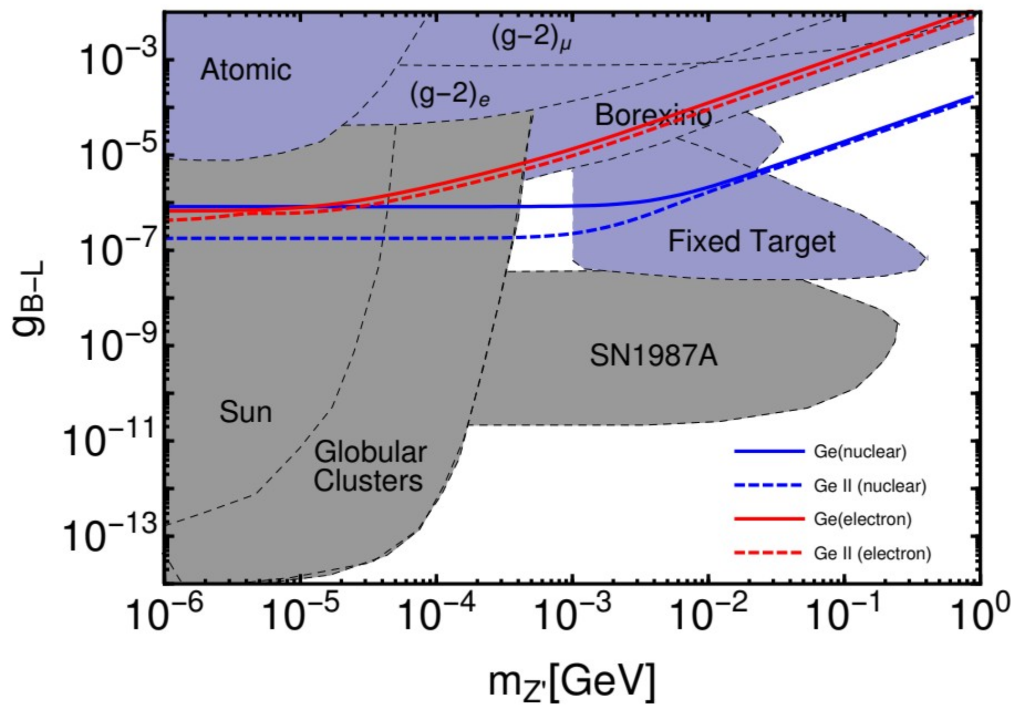
Beyond SM physics reach:
light mediators

- CEvNS can constrain new light mediators (scalar, pseudo-scalar, vector and axial-vector)

Using solar neutrinos:
Cerdeno et al. arXiv:1604.01025



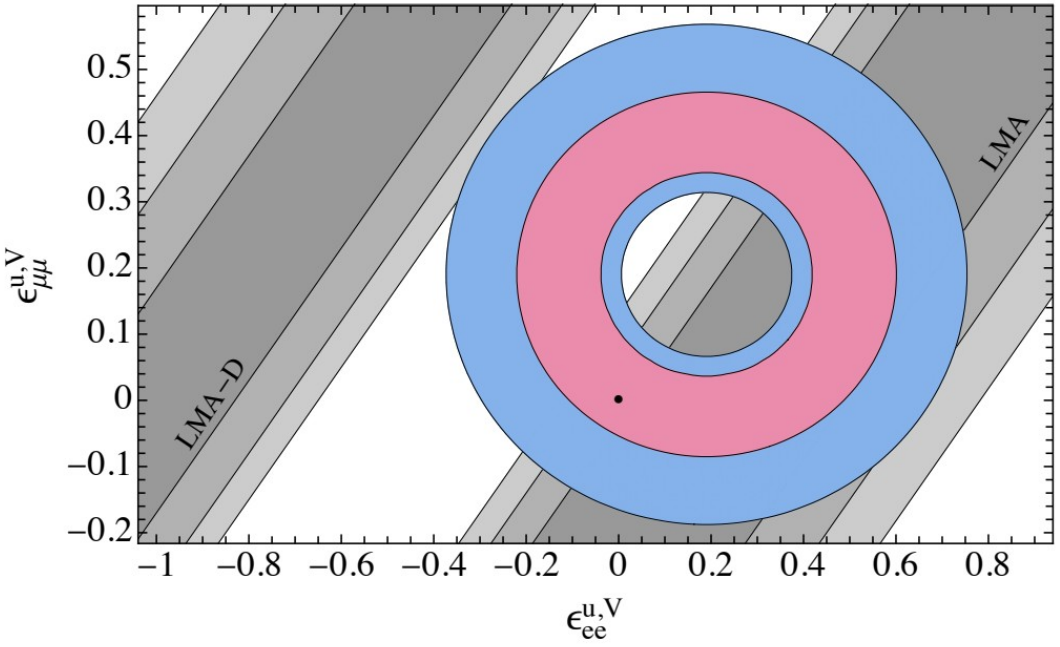
Using reactor/SNS neutrinos:
Dutta et al. arXiv:1612.06350



Beyond SM physics reach:

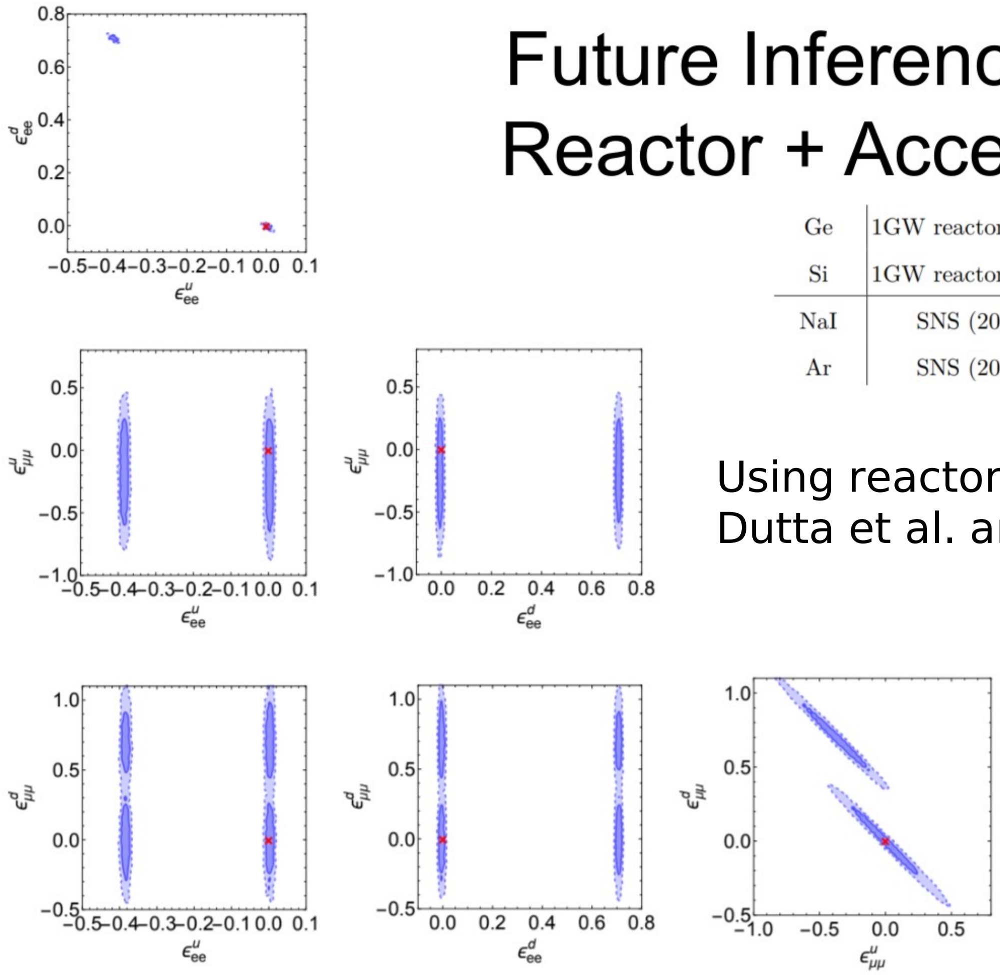
Non-standard interactions

- Large degeneracies in NSI parameter space require multiple detectors/sources to constrain



Coloma et al.
arXiv:1708.02899

Future Inference with Reactor + Accelerator



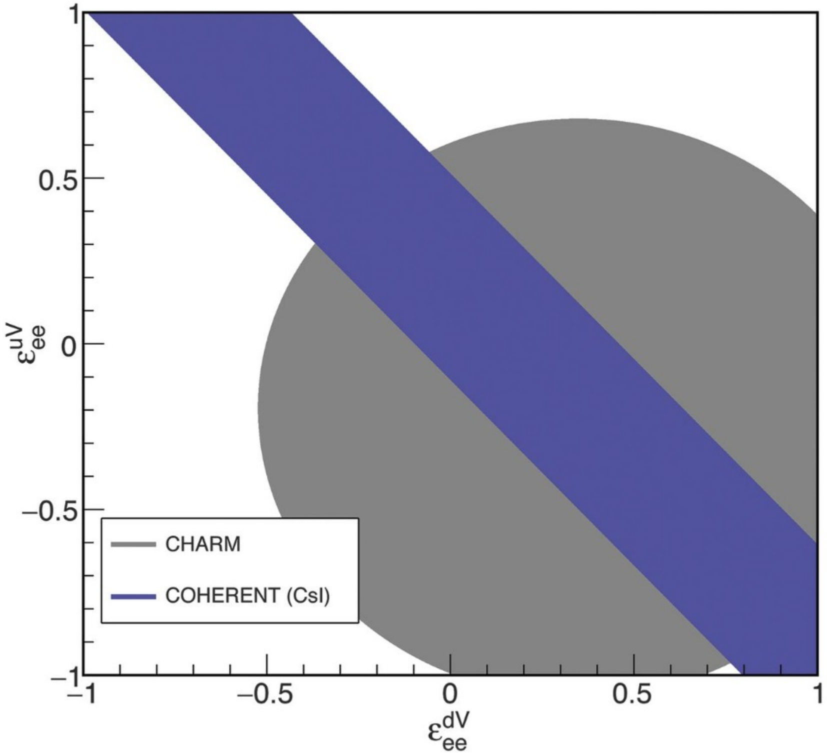
Ge	1GW reactor (20m)	10^4 kg.days
Si	1GW reactor (20m)	10^4 kg.days
NaI	SNS (20m)	1 tonne.year
Ar	SNS (20m)	1 tonne.year

Using reactor/SNS neutrinos:
Dutta et al. arXiv:1711.03521

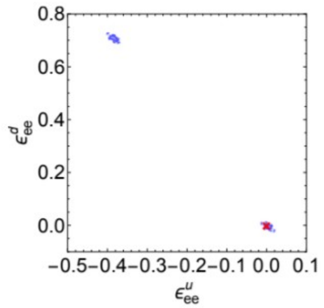
Beyond SM physics reach:

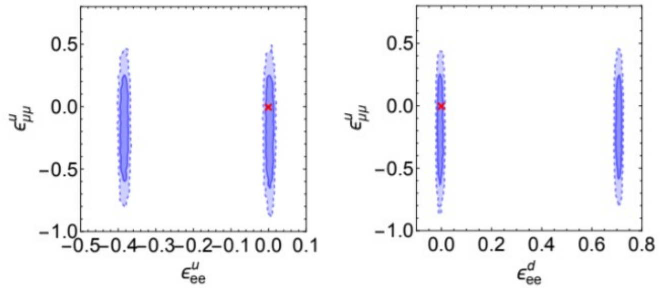
Non-standard interactions

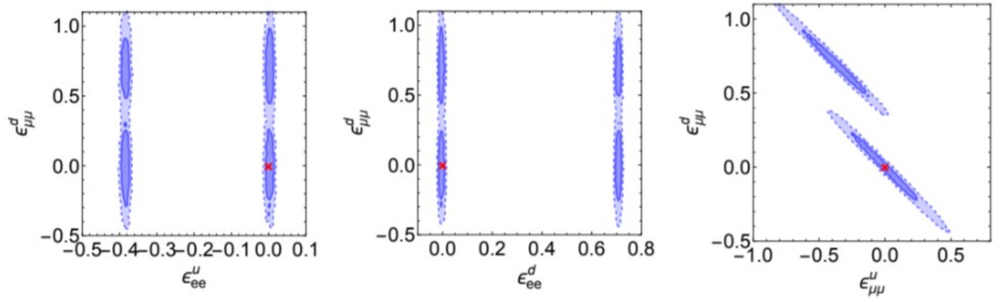
- NSI simply parameterizes discrepancy from the SM, providing a (somewhat) model independent space to constrain



Akimov et al.
Science Vol. 357, 6356 (2017)







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Using reactor/SNS neutrinos:
Dutta et al. arXiv:

COHERENT axial contribution

Total predicted:

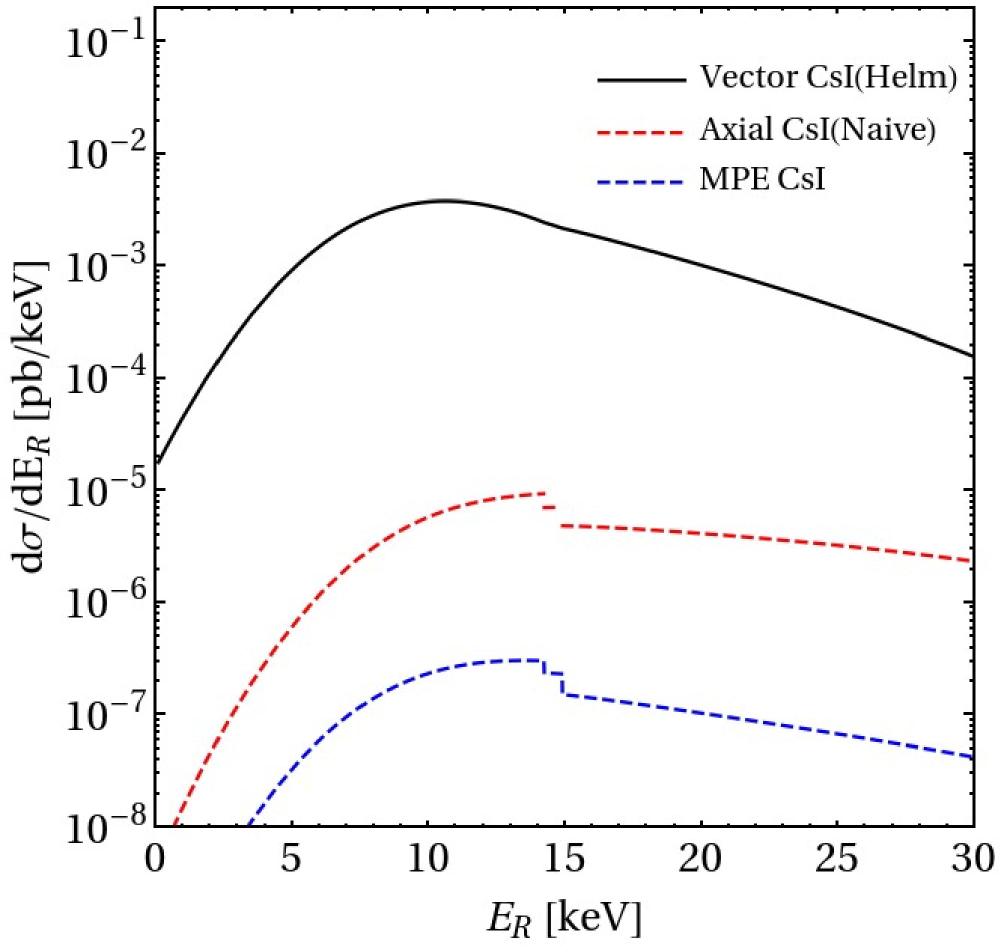
Helm: 182
MPE: 177

Axial contribution: 0.014

COHERENT expected: 174

Observed: 134+/-22

COHERENT CsI rates



Summary

- CEvNS is a new probe in the toolbox of the phenomenologist, being sensitive to a variety of new physics channels
- Lots of experiments will be providing new insights into neutrino-hadron interactions in the coming years
- A multi-messenger approach will be vital to break degeneracies and interpret experimental results

CEvNS cross sections

- It is desirable to have a consistent formalism for calculating CEvNS cross sections across different detector targets (including isotopes)

- The commonly used form, valid for point (fermionic) particles:

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

J. Barranco et al. (2005)

- The formalism of semi-leptonic electroweak nuclear scattering developed by Walecka (1975), Donnelly & Peccei (1978) is suitable for our purposes

The fundamentals

- The effective NC interaction lagrangian, where the currents sum over all fermions with the V-A structure:

$$\mathscr{L}_{\text{eff}}^{(\text{NC})} = -\frac{G_{\text{F}}}{\sqrt{2}}\, j_Z^{\mu} j_{Z\mu}$$

- We want the matrix elements for leptonic-hadronic currents:

$$\langle f|\hat{H}_W|i\rangle = \frac{G_F}{\sqrt{2}} \int d^3x \langle f| j_{\mu}^{lep} \hat{\mathcal{J}}^{\mu}(\vec{x})|i\rangle$$

The cross section

Summing over the spins and averaging over nuclear spins (only):

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{4\pi^2} \frac{4\pi}{2J_i + 1} \left(\langle l_0 \rangle \langle l_0 \rangle^* \sum_{J=0}^{\infty} |\langle J_i || \hat{\mathcal{M}}_J || J_i \rangle|^2 + \frac{1}{2} \langle \vec{l} \rangle \cdot \langle \vec{l} \rangle^* \sum_{J=1}^{\infty} |\langle J_i || \hat{\mathcal{T}}_J^{\mathrm{el}} || J_i \rangle|^2 \right)$$

Evaluating the neutrino traces and putting this in terms of the recoil energy:

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m_T}{\pi} \frac{4\pi}{2j+1} \left[\left(1 - \frac{m_T E_R}{2E_\nu^2}\right) \sum_{J=0,2..}^{\infty} |\langle j || \hat{\mathcal{M}}_J || j \rangle|^2 \right.$$
$$\left. + \frac{1}{2} \left(1 + \frac{E_R m_T}{2E_\nu^2}\right) \sum_{J=1,3..}^{\infty} |\langle j || \hat{\mathcal{T}}_J^{\mathrm{el}} || j \rangle|^2 \right]$$

(leading order in Er/Enu)

Form factors

Define form factors as:

$$F_M^{(N,N')}(q^2) = \frac{4\pi}{2j+1} \sum_{J=0,2,\ldots} \langle j||M_J^{(N)}||j\rangle\langle j||M_J^{(N')}||j\rangle$$

$$F_{\Sigma'}^{(N,N')}(q^2) = \frac{4\pi}{2j+1} \sum_{J=1,3,\ldots} \langle j||\Sigma_J^{'(N)}||j\rangle\langle j||\Sigma_J^{'(N')}||j\rangle$$

Then the cross section can be written:

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m_T}{\pi}\left[\left(1-\frac{m_T E_R}{2E_\nu^2}\right)\left({g_V^n}^2 F_M^{nn}(q^2) + 2g_V^p g_V^n F_M^{pn}(q^2) + {g_V^p}^2 F_M^{pp}(q^2)\right)\right.$$

$$\left.+\frac{1}{2}\left(1+\frac{m_T E_R}{2E_\nu^2}\right)\left({g_A^n}^2 F_{\Sigma'}^{nn}(q^2) + 2g_A^p g_A^n F_{\Sigma'}^{pn}(q^2) + {g_A^p}^2 F_{\Sigma'}^{pp}(q^2)\right)\right]$$

Cross section comparison

This work:

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m_T}{\pi}\left[\left(1-\frac{m_T E_R}{2E_\nu^2}\right)\left({g_V^n}^2 F_M^{nn}(q^2) + 2g_V^p g_V^n F_M^{pn}(q^2) + {g_V^p}^2 F_M^{pp}(q^2)\right)\right.$$
$$\left. + \frac{1}{2}\left(1+\frac{m_T E_R}{2E_\nu^2}\right)\left({g_A^n}^2 F_{\Sigma'}^{nn}(q^2) + 2g_A^p g_A^n F_{\Sigma'}^{pn}(q^2) + {g_A^p}^2 F_{\Sigma'}^{pp}(q^2)\right)\right]$$

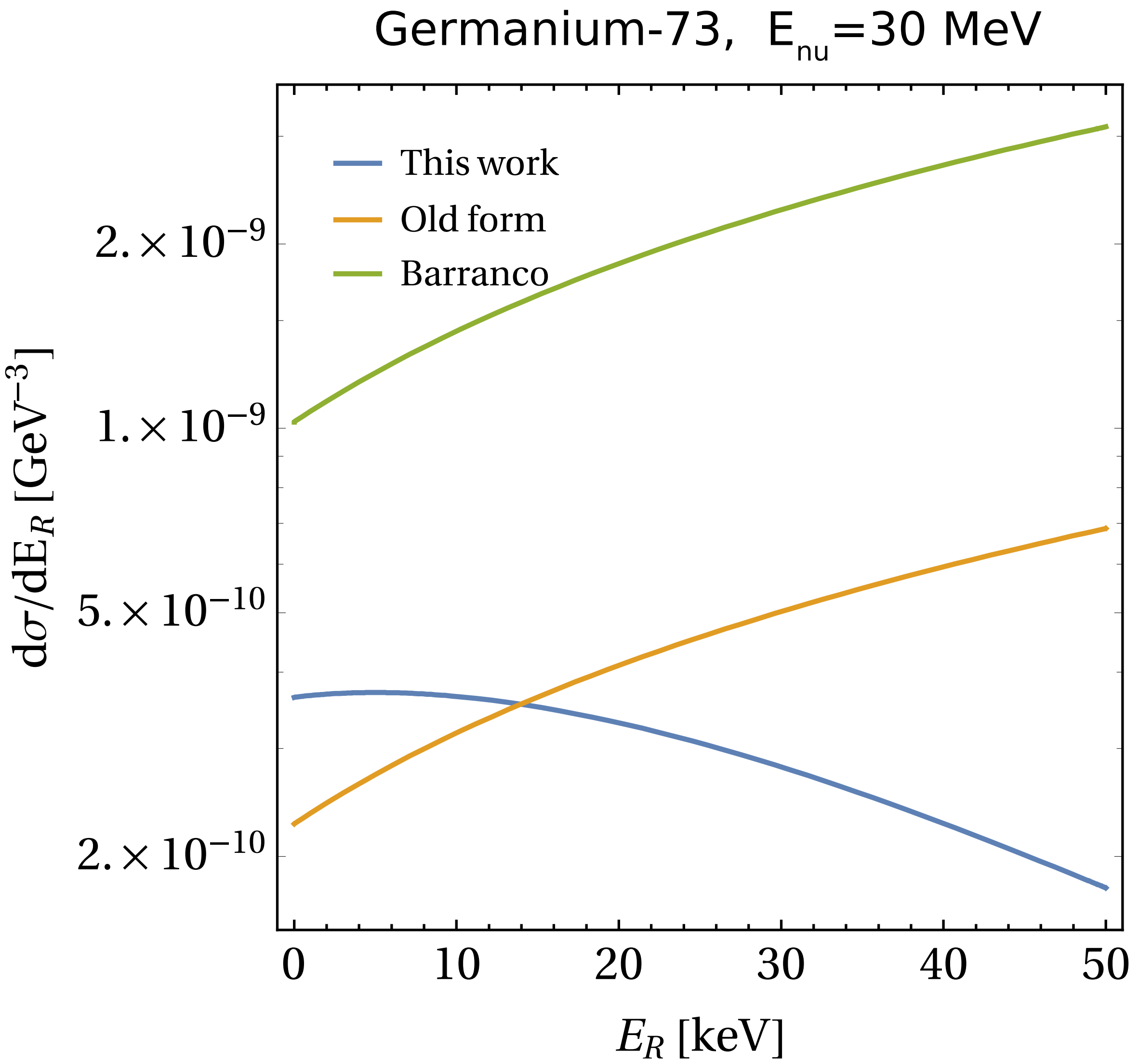
Our past work:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}(E_r, E_\nu) = \frac{G_F^2 m_N}{\pi}\left[\left(1-\frac{m_N E_r}{2E_\nu^2}\right) Q_v^2 F^2(E_r) + \left(1+\frac{m_N E_r}{2E_\nu^2}\right) Q_a^2 \frac{4(J_N+1)}{3J_N}\right]$$

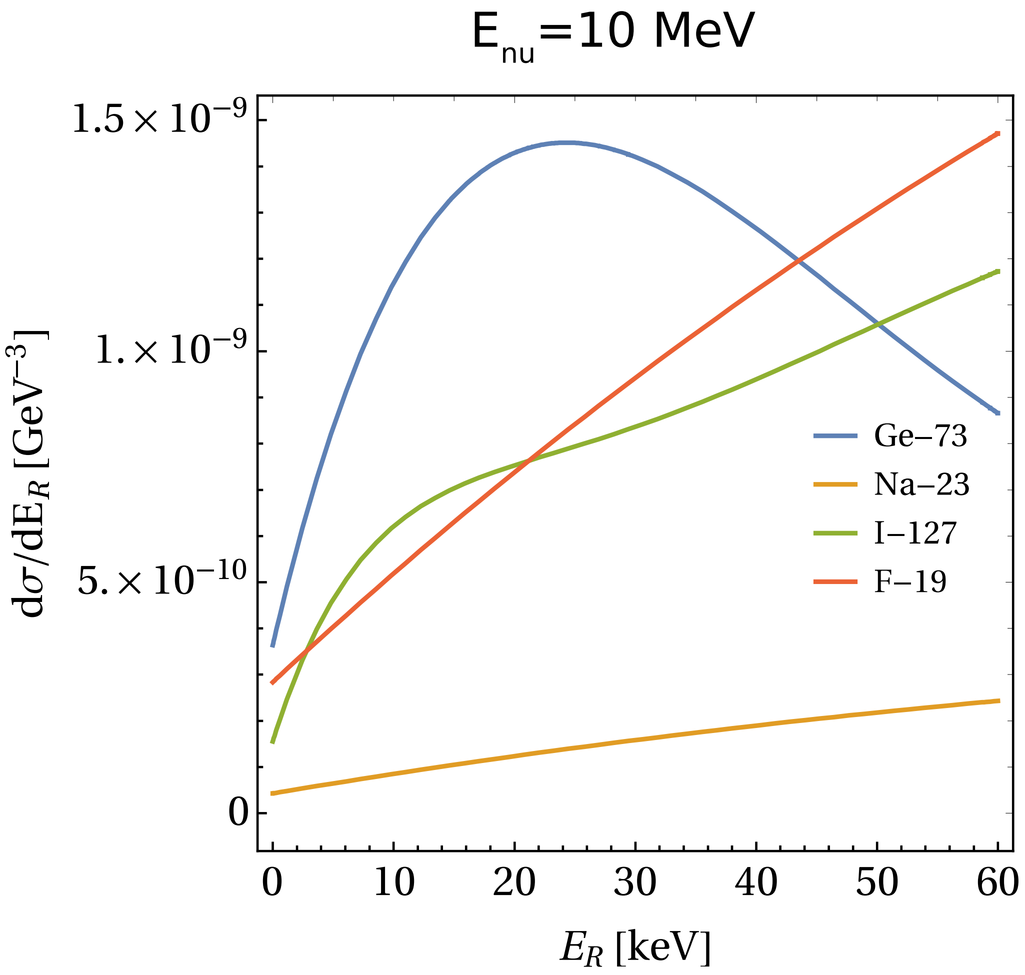
Barranco (to Er/Enu):

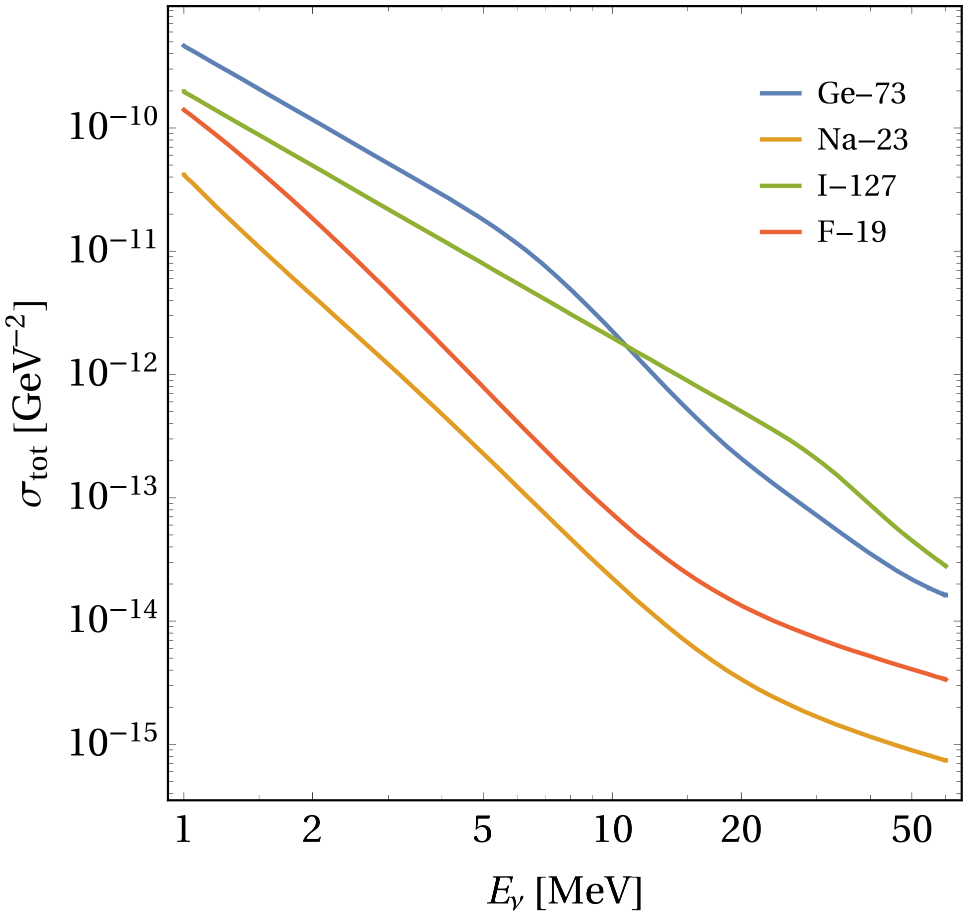
$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m_T}{\pi}\left[\left(1-\frac{m_T E_R}{2E_\nu^2}\right)\left(g_V^p Z + g_V^n N\right)^2 F_V(q^2)^2\right.$$
$$\left. + \left(1+\frac{m_T E_R}{2E_\nu^2}\right)\left(g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)\right)^2 F_A^2(q^2)\right]$$

Axial cross section comparison



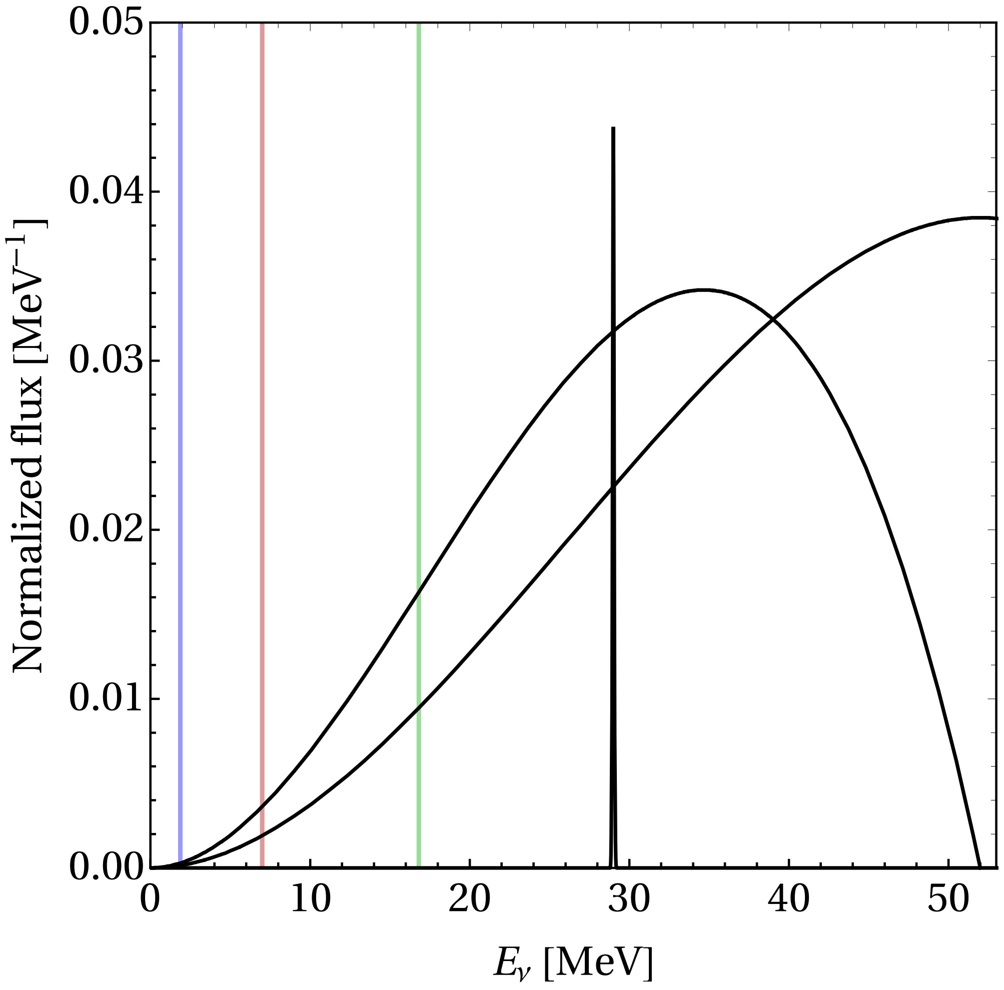
Axial cross section





Neutrino fluxes

SNS flux due to decay of stopped pions → muons → neutrinos:

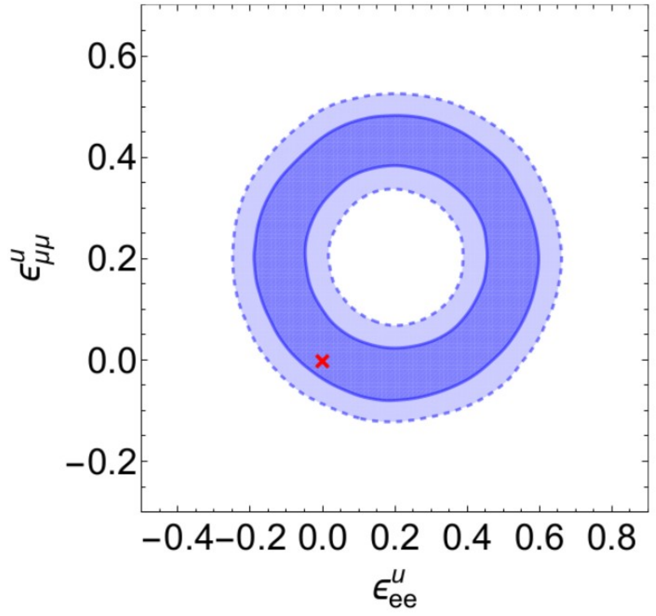


	Percent flux above thresh.
Germanium 100 eV_{nr}	~100%
Sodium 4.25 keV_{nr}	>99%
Caesium 4.25 keV_{nr}	95%

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 ± 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

Nucleon currents and their form factors

- In the low-q limit $F_1^{(N)}$ is electric charge (no isoscalar contributions)

$$F_1^{Z(N)}(q^2) = I_3^N(F_1^p - F_1^n) - 2\sin^2(\theta_w)F_1^N - \frac{1}{2}F_1^{s(N)}$$
$$G_A^{Z(N)}(q^2) = I_3^N(G_A^p - G_A^n) - \frac{1}{2}G_A^{s(N)}$$

- The form factors become:

$$F_1^{Z(N)}(q^2 \to 0) = I_3^N - 2\sin^2(\theta_w)Q^N \equiv g_V^N$$
$$G_A^{Z(N)}(q^2 \to 0) = I_3^N g_A - \frac{1}{2}g_A^{s(N)} \equiv g_A^N$$

- Our nucleon currents are thus (in low-q limit):

$$\mathcal{J}_Z^\mu = \bar{N}\gamma^\mu\left(g_V^N - g_A^N\gamma^5\right)N$$

- Where the charges are:

$$g_V^p = 0.015 \quad g_V^n = -0.51$$
$$g_A^p = 0.63 \quad g_A^n = -0.59$$

The nuclear responses

$$\sum_{J=0,2..}^{\infty} |\langle j||\hat{\mathcal{M}}_J||j\rangle|^2 \qquad \sum_{J=1,3..}^{\infty} |\langle j||\hat{\mathcal{T}}_J^{\rm el}||j\rangle|^2$$

Where the nuclear responses in first quantization are:

$$\hat{\mathcal{M}}_{JM}(q) = \sum_{i=1}^{A} g_V^N(i)\, M_{JM}(q\vec{x}_i) \qquad \hat{\mathcal{T}}^{el}_{JM}(q) = i\sum_{i=1}^{A} g_A^N(i)\, \Sigma'_{JM}(q\vec{x}_i)$$

Single particle operator	Operator	P/CP	Long wave limit
$M_{JM}(q\vec{x}_i) \equiv j_J(qx_i)Y_{JM}(\Omega_{x_i})$	Vector charge	even/even	1
$\Sigma'_{JM}(q\vec{x}_i) \equiv -i\left\{\frac{1}{q}\vec{\nabla}_i \times \vec{M}^M_{JJ}(q\vec{x}_i)\right\}\cdot\vec{\sigma}(i)$	Transverse spin current	odd/odd	σ