Prospects for Exploring New Physics in Coherent Elastic Neutrino-Nucleus Scattering

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Abstract

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) was detected by the COHERENT experiment at the Spallation Neutron Source.[1]

$$\frac{d\sigma}{d(cos\theta)} = \frac{G_F}{8\pi} {Q_W}^2 E^2 (1 + cos\theta)$$

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

We study the possibility of probing new physics at a reactor source. Bolometers at a reactor source probe lower energy portions of the CEvNS spectrum:

Target	T_{Max}	
Nucleus	$E_\nu = 3$ MeV	$E_\nu = 30$ MeV
Ar	484 eV	48.3 keV
Zn	296 eV	29.5 keV
Ge	266 eV	26.6 keV
	(Reactor)	(Spallation)

This enables stronger bounds on:

- Neutrino Magnetic Moment
- Massive Scalar Mediator Model
- Massive Vector Mediator Model
- Non-Standard Interactions

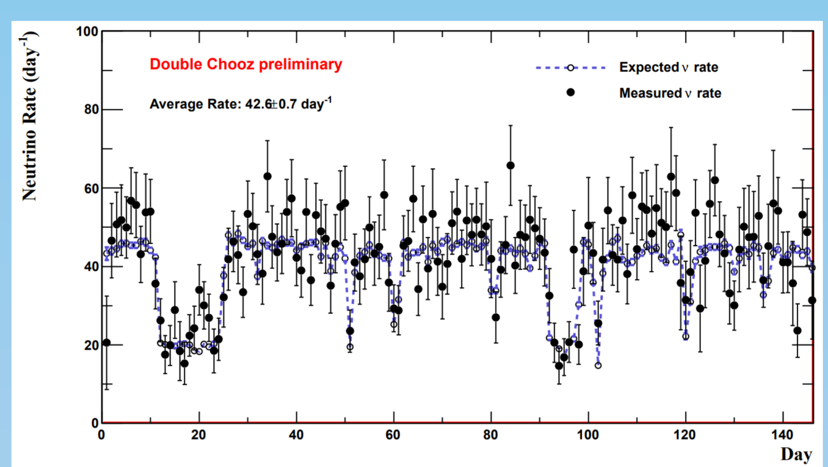
Methods

Current and planned CEvNS Projects:

- MINER: 10 kg Si+Ge at a 1 MW research reactor. Projected threshold 200 eV.
- NUCLEUS: Several grams CaWO4 + Al2O3. 10 eV energy threshold and strong external background rejection with surrounding vetos.
- Ricochet: Several kg of Zn, Ge, Si, or Os, with a 50 eV threshold.

Double Chooz Reactor:

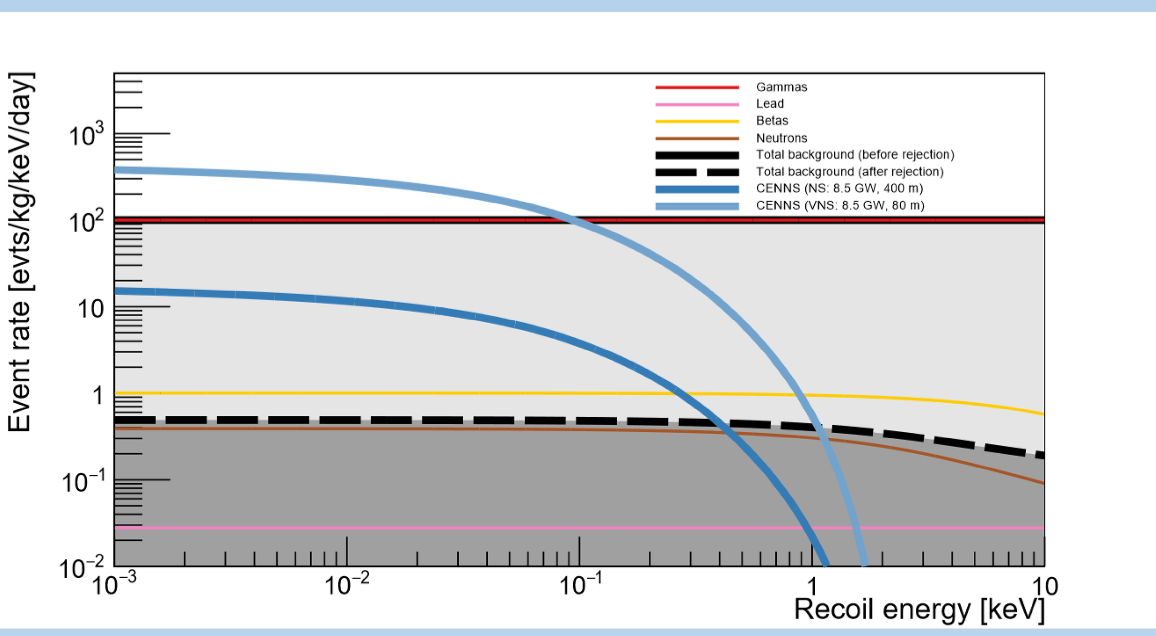
- Two cores, 8.5 GW power combined
- Two possible sites, 400 m (Near Site) and 80 m (Very Near Site)
- Both cores on 60% of the time, one core 40%



Neutrino rate vs time for the Double Chooz experiment[2]

Backgrounds:

- Compton: 100 evts/kg/day in Ge
- Neutrons: 10 times larger at very near site
- Other backgrounds are negligible



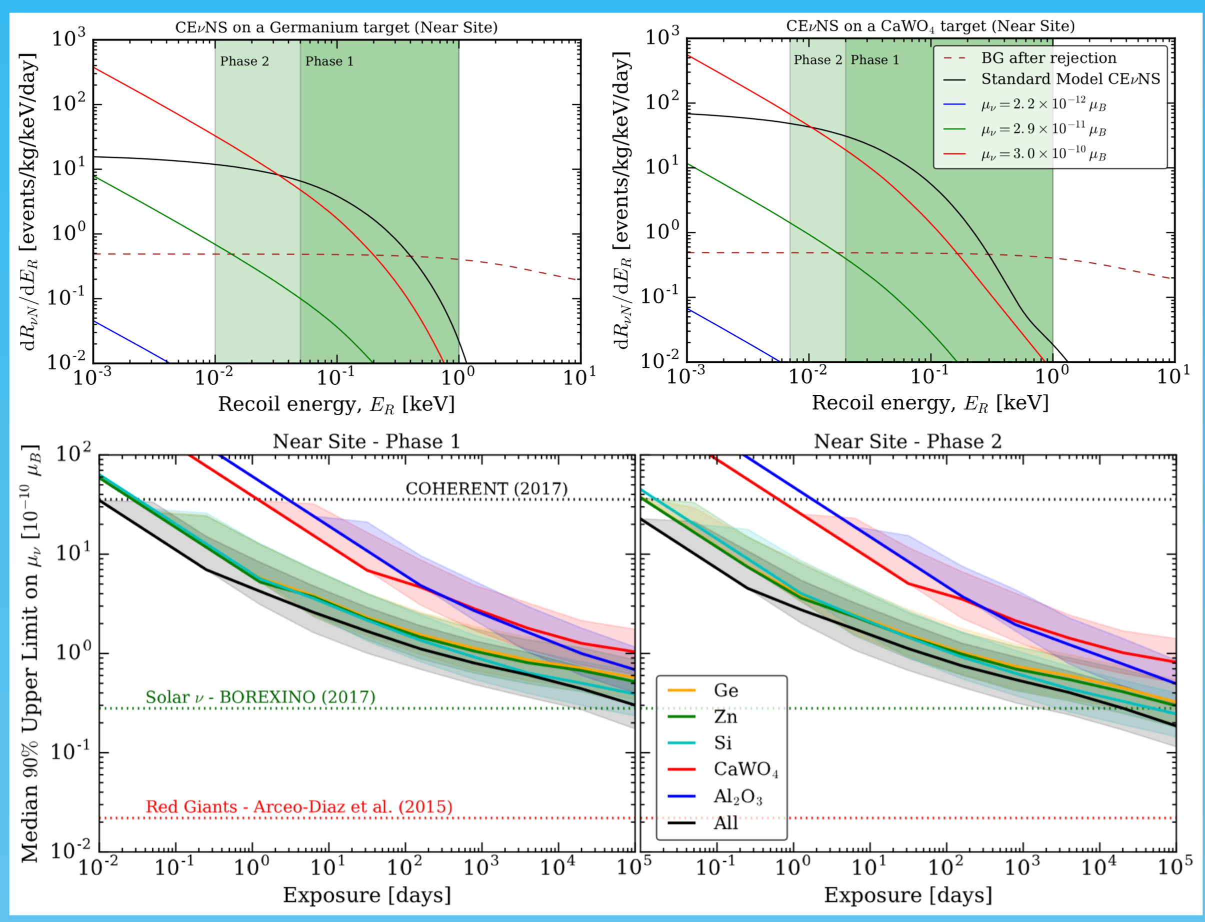
Target	Phase 1 E_{th} [eV]	Phase 1 Mass [g]	Phase 2 E_{th} [eV]	Phase 2 Mass [g]	Background reduction gamma	Background reduction neutron
Zn	50	500	10	5000	1000	1
Ge	50	500	10	5000	1000	1
Si	50	500	10	5000	1000	1
$CaWO_4$	20	6.84	7	68.4	1000	10
Al_2O_3	20	4.41	4	44.1	1000	10

Neutrino Magnetic Moment

In minimal extensions of the Standard Model, a Dirac neutrino can obtain a magnetic moment as high as $\mu_\nu \approx 10^{-15}\,\mu_B$, while a Majorana Neutrino could allow $\mu_\nu \approx 10^{-12}\,\mu_B$ or higher.

A neutrino magnetic moment adds a term to CEvNS:

$$\frac{d\sigma_{\nu-N}^{mag.}}{d(E_R)} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1}{E_R} - \frac{1}{E_\nu} + \frac{E_R}{4E_\nu^2}\right)F^2(E_R)$$



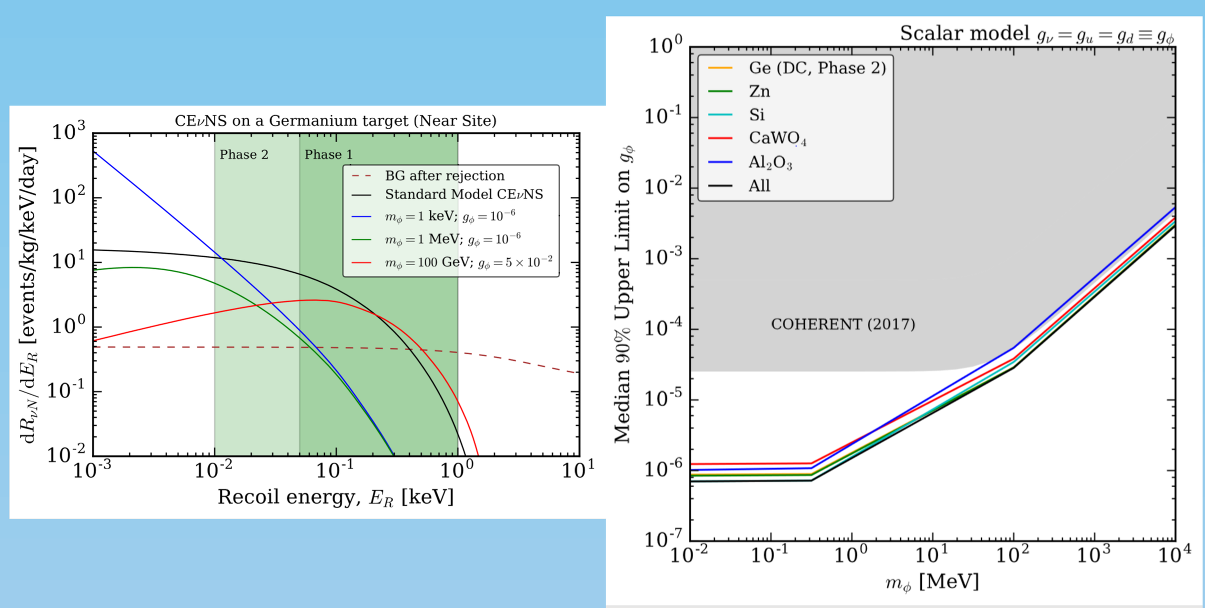
Bounds become competitive with terrestrial bounds after several years runtime

Massive Scalar Mediator

Adds a term to CEvNS:

$$\frac{d\sigma_\phi}{d(E_R)} = \frac{g_\nu^2 Q_\phi^2}{4\pi}\frac{E_R m_N^2}{E_\nu^2(q^2+m_\phi^2)^2}F^2(E_R)$$

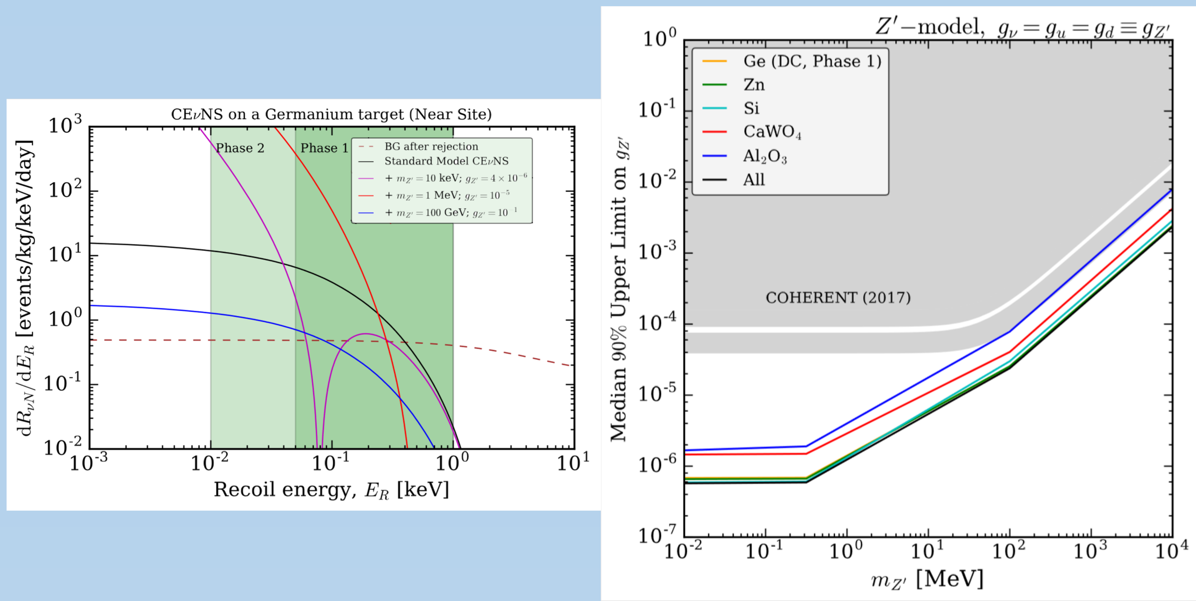
$$Q_\phi = (15.1\,Z + 14\,N)g_q$$



Massive Vector Mediator

Interferes with SM CEvNS:

$$Q_W \rightarrow Q_{SM+NP} = Q_W - \frac{\sqrt{2}}{G_F}\frac{Q_{Z'}}{q^2 + m_{Z'}^2}$$



A monolithic target allows for fully destructive interference, giving a stronger bound.

For both the scalar and vector mediator, a low mediator mass strongly deforms the spectrum at low energies, allowing a bolometer at a reactor to place strong bounds on mediator strength.

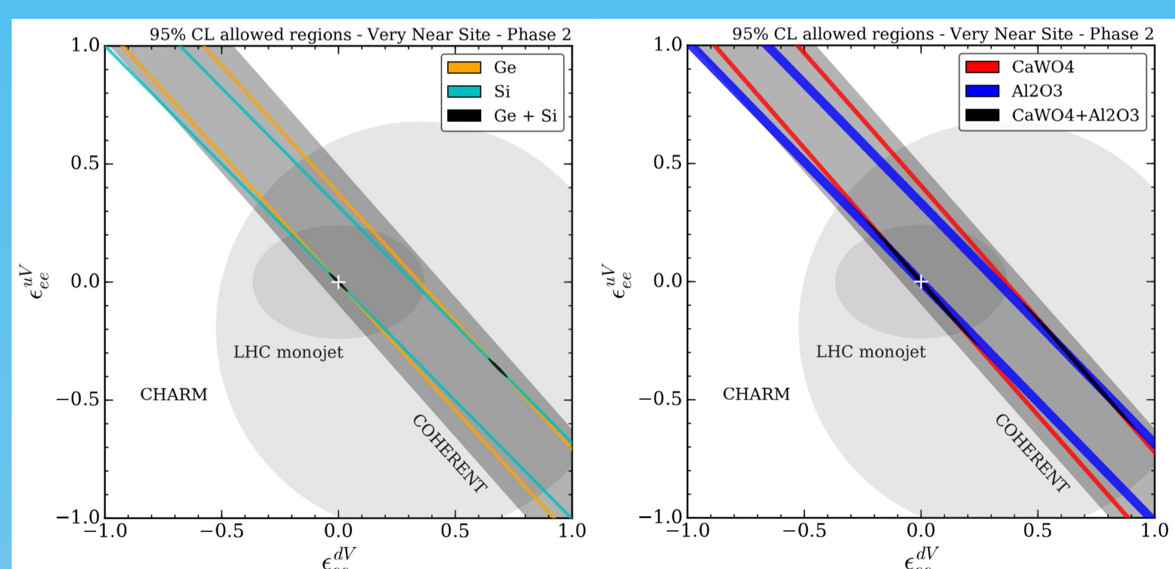
Non-Standard Interactions

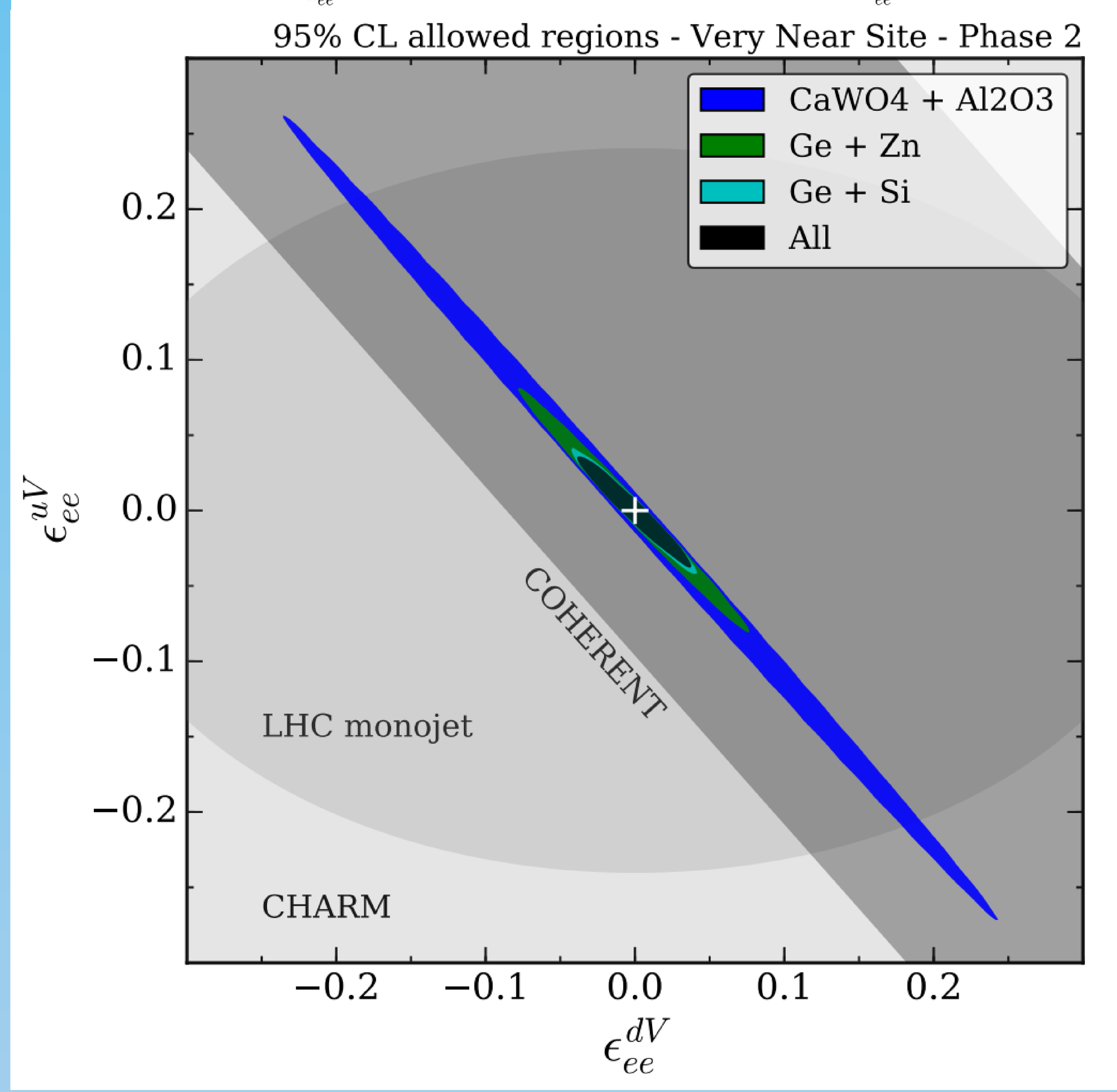
Introduce a 4-fermion coupling, focusing on vector coupling to quarks:

$$Q_W = \left[4N\left(-\frac{1}{2} + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\right) + Z\left(\frac{1}{2} - 2sin^2\theta_W + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}\right)\right]^2 + 4\left[N\left(\epsilon_{e\tau}^{uV} + 2\epsilon_{e\tau}^{dV}\right) + Z\left(2\epsilon_{e\tau}^{uV} + \epsilon_{e\tau}^{dV}\right)\right]^2$$

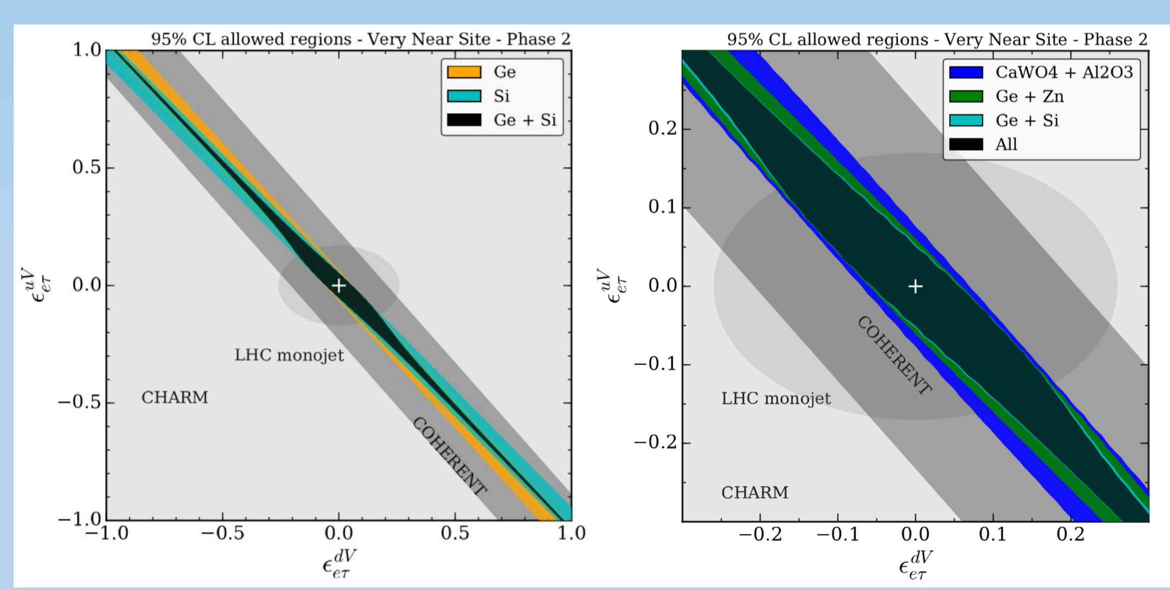
- $\epsilon_{e\mu}^{uV}$ not included because it is already strongly constrained by $\mu \rightarrow e$ conversion in nuclei
- Degeneracy between $\epsilon_{\alpha\beta}^{uV}$ and $\epsilon_{\alpha\beta}^{dV}$ can be broken by combining targets with different N/Z
- Breaking the $\epsilon_{\alpha\beta}^{uV}$ and $\epsilon_{\alpha\beta}^{dV}$ degeneracy is important for determining the mass hierarchy with DUNE[3]

Flavor Conserving





Flavor Changing



Conclusions

- Neutrino magnetic moment consistent with a Majorana neutrino can be probed
- Low threshold detectors can place strong constraints on massive mediator models, especially for mediators less than 10 MeV
- Combining multiple targets can place tight constraints on non-standard interactions

References:

1. D. Akimov, et al, "Observation of Coherent Elastic Neutrino Nucleus Scattering," Science, 2017.
2. arXiv:1205.6685 [hep-ex]
3. P. Coloma and T. Schwetz, Phys. Rev. D 95, 079903 (2017))

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