CEvNS Detection with Ricochet

Joe Johnston

MIT

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Outline

1. Ricochet
   - Superconducting Bolometers
   - Temperature Readout
   - Experimental Site
   - Current Status
2. BSM Searches at Reactors
   - Neutrino Magnetic Moment
   - NSI Couplings
   - Massive Mediators
3. Summary

Ricochet

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

- $\approx N^2$ scaling gives large cross section
- Requires low energy recoil detection (hundreds of eV)

Ricochet will achieve this via:

- Zn (superconducting) and Ge bolometers
- Phase 1: 100 eV threshold, 1 kg
- Phase 2: 10 eV threshold, 10 kg

Bolometric Detectors

Heat capacity dominated by lattice contributions at ultra-low temperatures

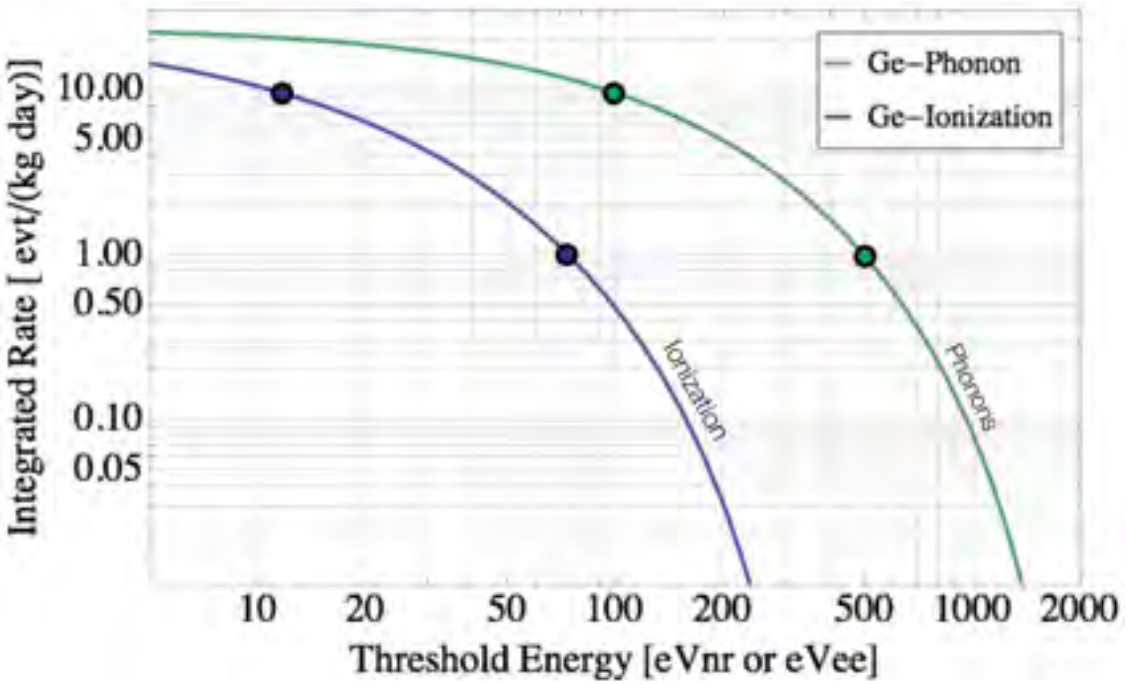
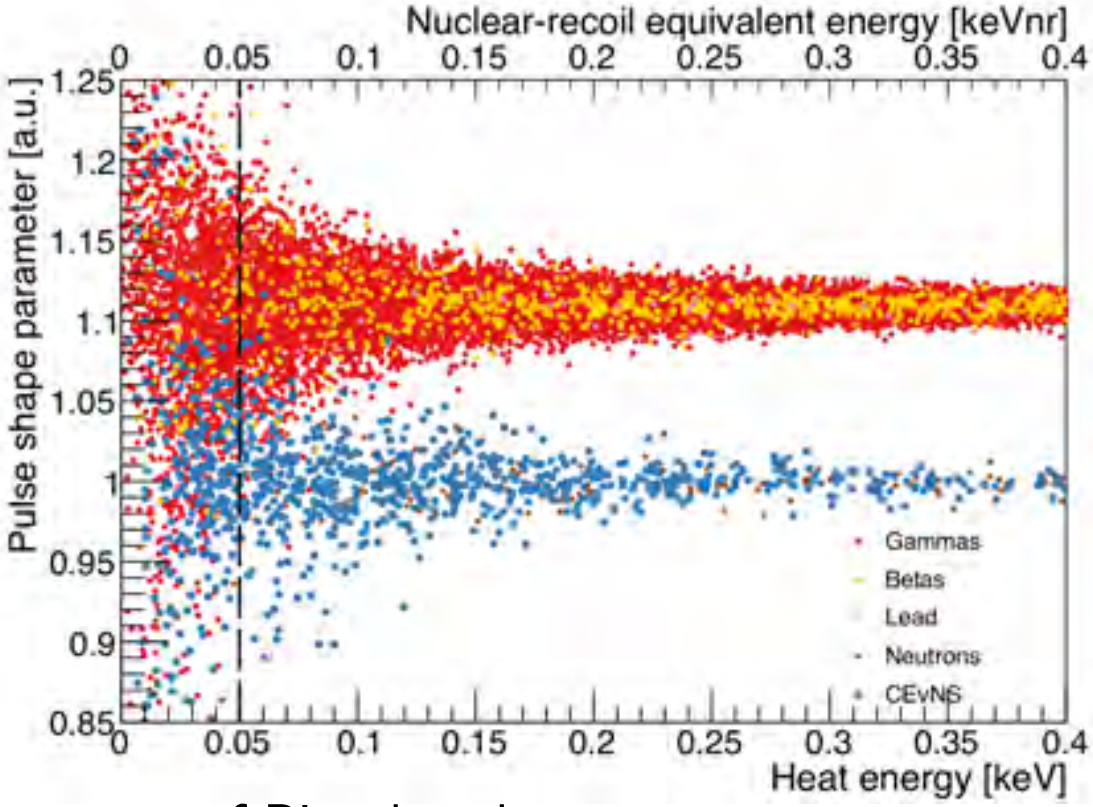


Figure from J Formaggio

Used in direct detection of dark matter

Superconducting Bolometers

- Energy deposited via quasiparticles or phonons
- EM events will create more quasiparticles
- Quasiparticles have long recombination times

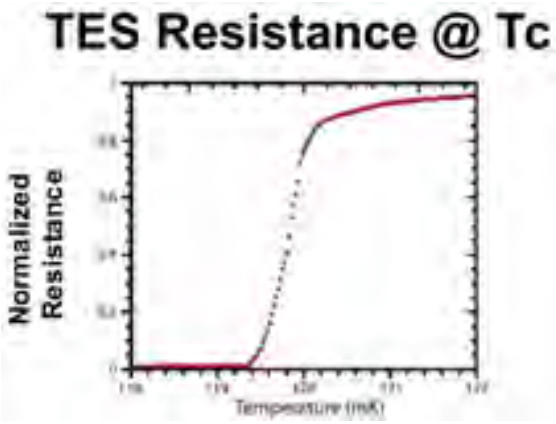


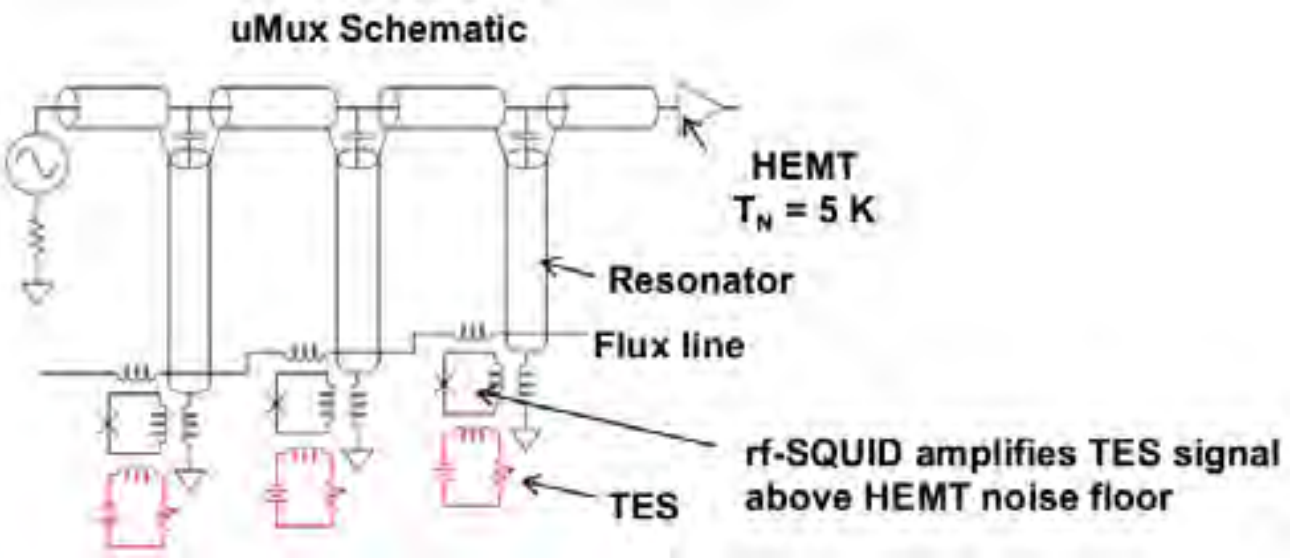
Simulation of three years of Ricochet data

Figure from J Billard

Multiplexing TES Readouts

- Thermalize a transition edge sensor (TES) to each detector
- RF SQUID inductance depends on external flux
- Each detector readout is tuned to a specific frequency
- GHz input allows scanning over frequencies



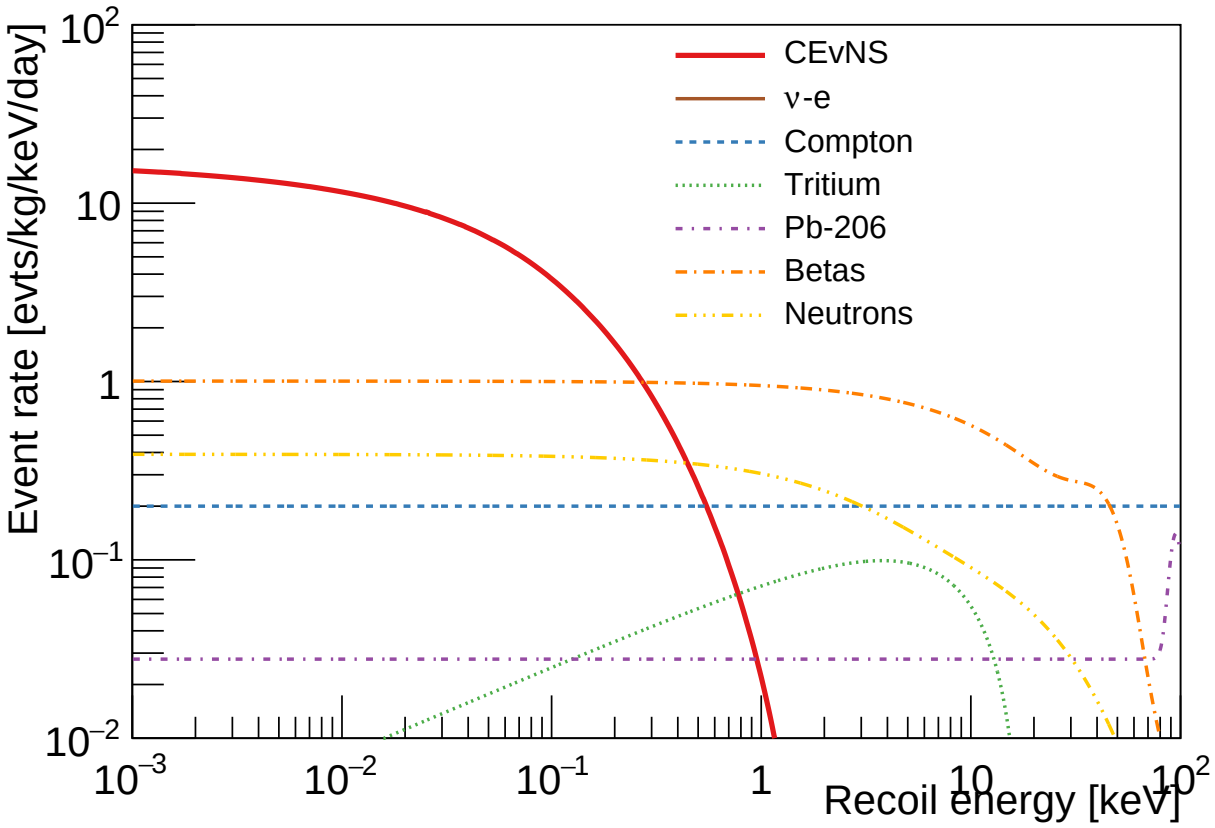


Slide from J Formaggio

Ricochet will likely be at the Chooz Reactor Complex

- Two cores
- 8.5 GW power combined
- Both cores on 60% of the time, one core 40%
- Near Site (NS): 400 m from cores, 120 m.w.e
- Very Near Site (VNS): 80 m from cores, $\approx$ 10 m.w.e expected

Near Site Backgrounds



- Neutron rate from simulation
  Internal backgrounds from EDELWEISS
- 1.5 evts/kg/day background, 0.5 evts/kg/day signal (0.1-1 keV ROI)

- Currently have several Zn crystals
- Initial calibration pulses taken at IPNL Lyon
- Future crystals will be cubes for easier polishing

(J. Billard, J. Johnston, B. Kavanagh. arxiv:1805.01798 [hep-ph]. Under review by JCAP.)

- Reactor detection probes lower energy neutrinos (3 vs 30 MeV)

Assumptions:

- Isotopes Si, Ge, Zn, $CaWO_4$, and Al_2O_3 (Sapphire).

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

Backgrounds:

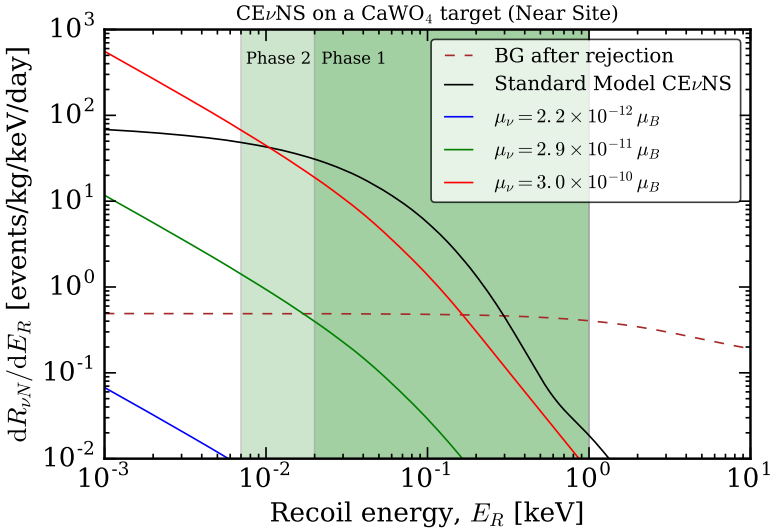
- Compton: 10^{-3} discrimination power
- Neutrons: 0.1 discrimination power in $CaWO_4$ and Al_2O_3

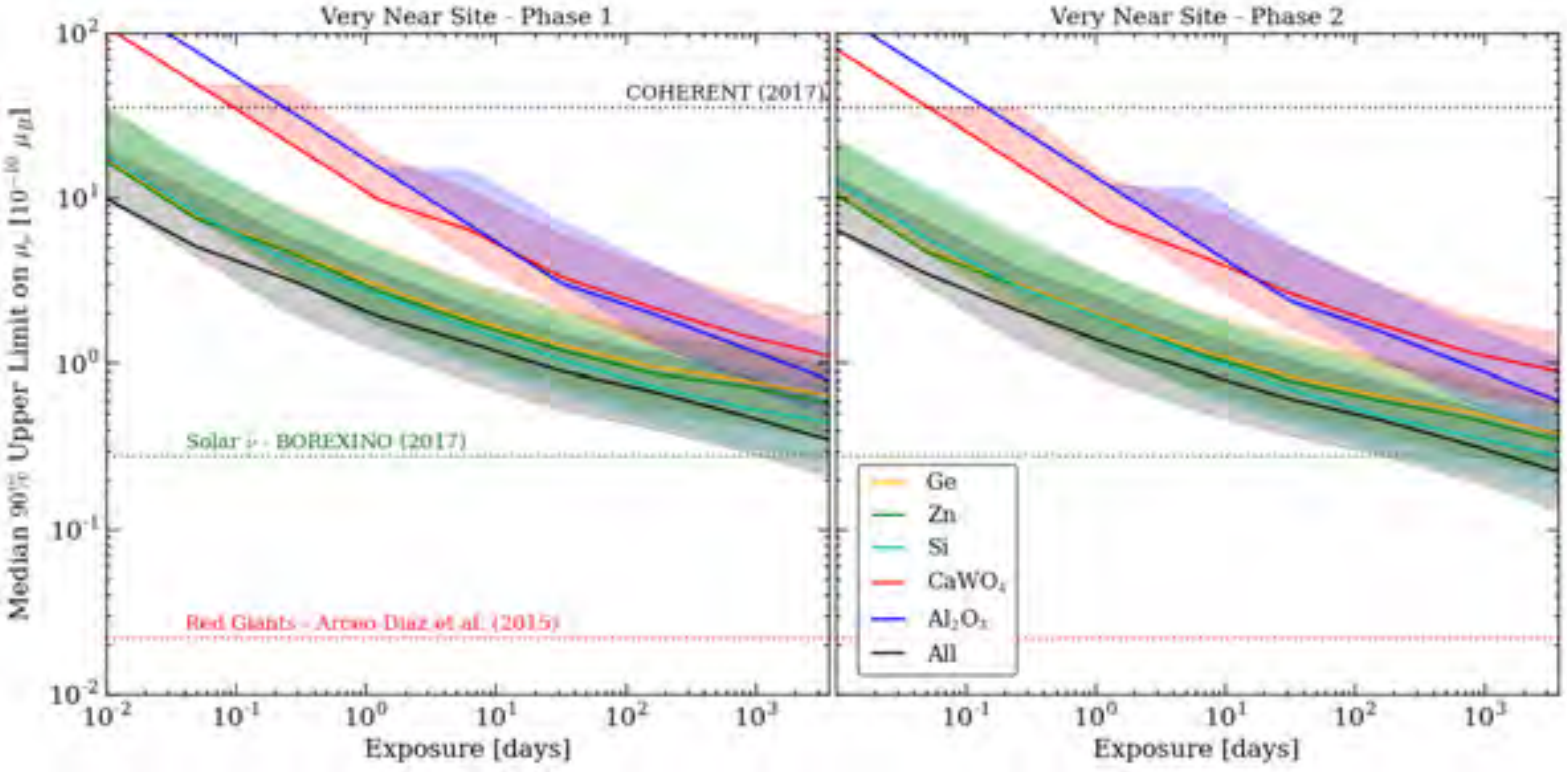
Neutrino Magnetic Moment

- Minimal SM extensions allow up to $\mu_\nu \approx 10^{-15}\mu_B$
- A Majorana Neutrino could allow $\mu_\nu \approx 10^{-12}\mu_B$ or higher

$$\frac{d\sigma^{\text{Coherent}}_{\nu-N}}{dE_R} = \frac{d\sigma^{\text{SM CEvNS}}_{\nu-N}}{dE_R} + \frac{\mathrm{d}\sigma^{\text{mag.}}_{\nu-N}}{\mathrm{d}E_R}$$

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

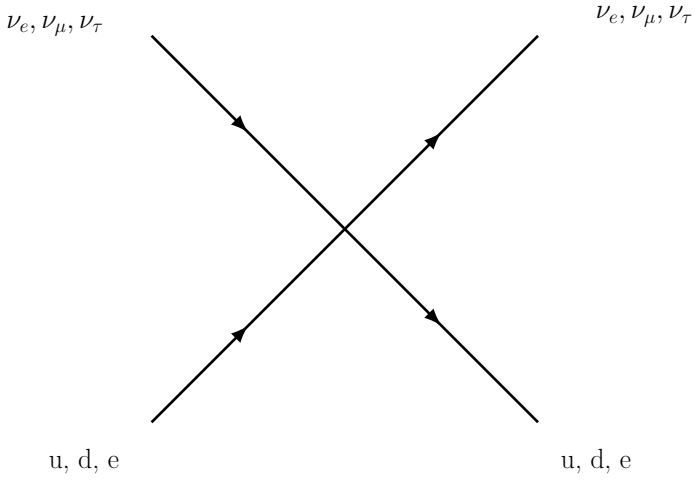




Competitive with terrestrial bounds around several years

Focus on vector couplings to quarks, $\epsilon_{ee}^{qV} = \epsilon_{ee}^{qL} + \epsilon_{ee}^{qR}$, $q = u, d$:

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



- $\epsilon_{e\mu}^{uV}$ constrained by $\mu \to e$ conversion in nuclei
- $\epsilon_{\alpha\beta}^{uV}/\epsilon_{\alpha\beta}^{dV}$ degeneracy broken by combining different N/Z ratios
- Breaking $\epsilon_{\alpha\beta}^{uV}$ / $\epsilon_{\alpha\beta}^{dV}$ degeneracy is important for DUNE

(P. Coloma and T. Schwetz, Phys. Rev. D 95, 079903 (2017))

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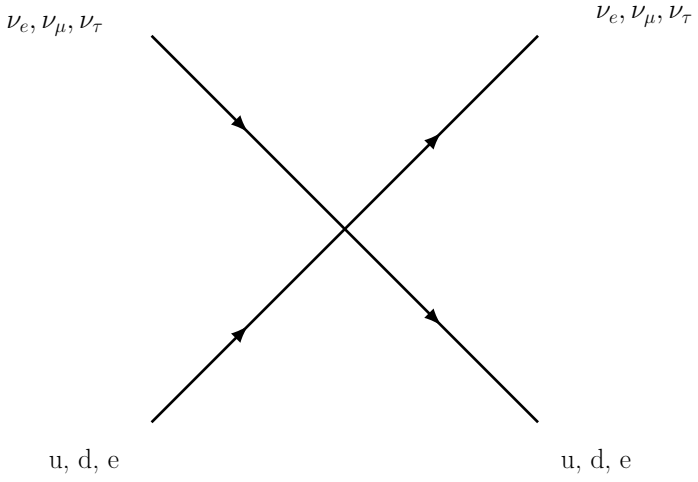
$$+4\left[N(\epsilon_{e\tau}^{uV} + 2\epsilon_{e\tau}^{dV}) + Z(2\epsilon_{e\tau}^{uV} + \epsilon_{e\tau}^{dV})\right]^2$$



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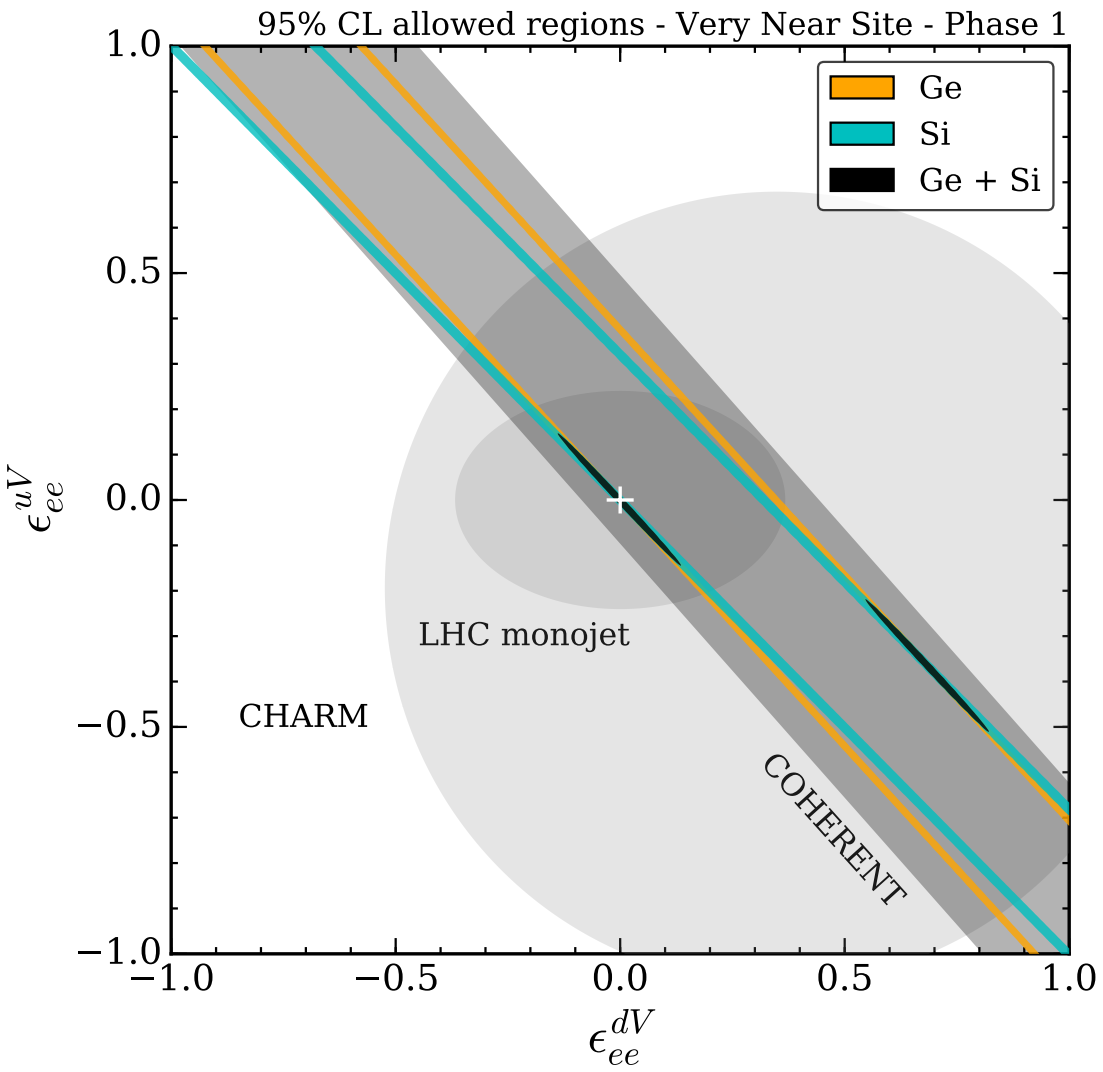
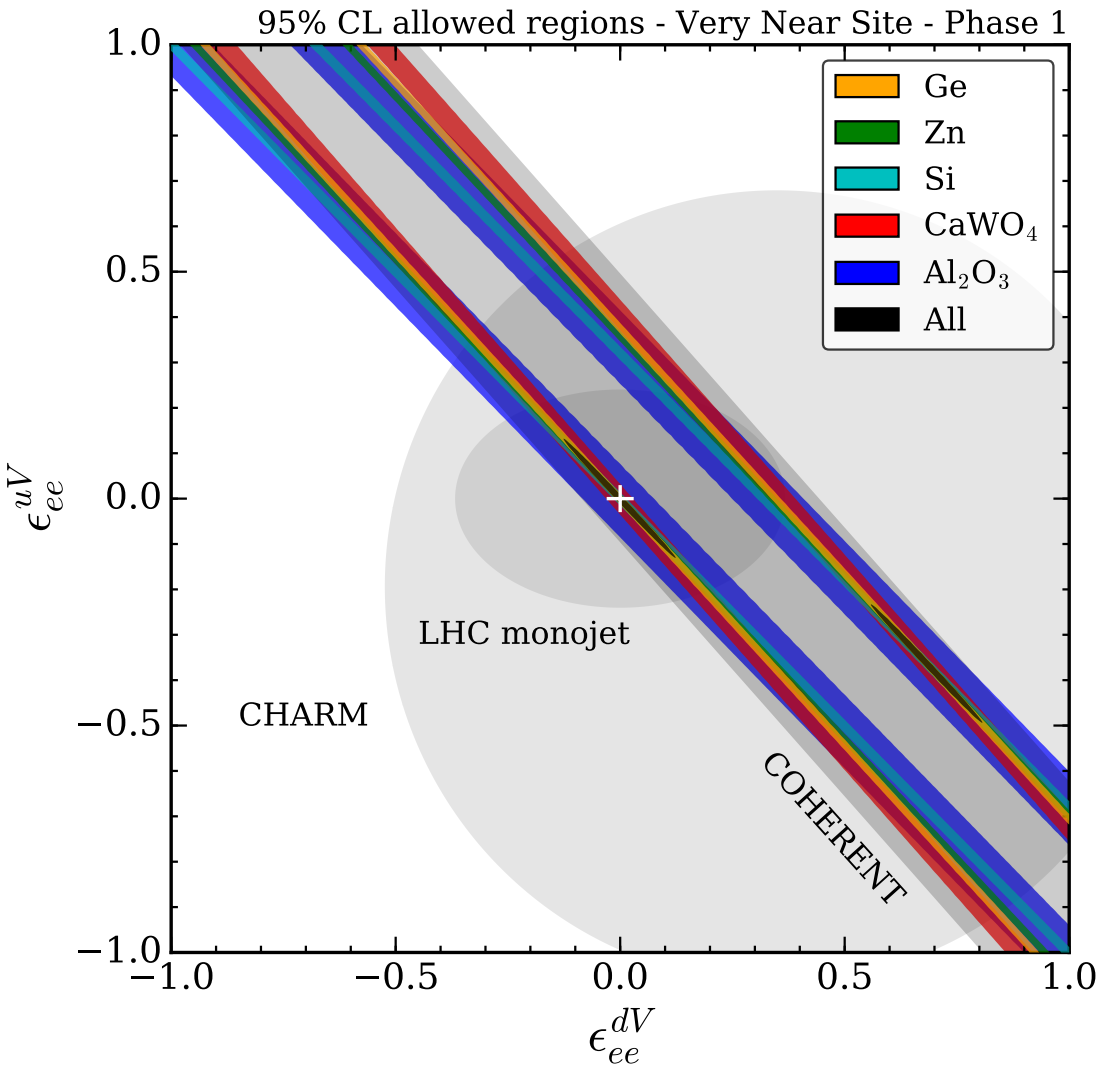
Flavor Conserving Ge+Si:



N/Z values: Ge=1.27, Zn=1.18, Si=1.01, Al=1.08, O=1.00, W=1.48

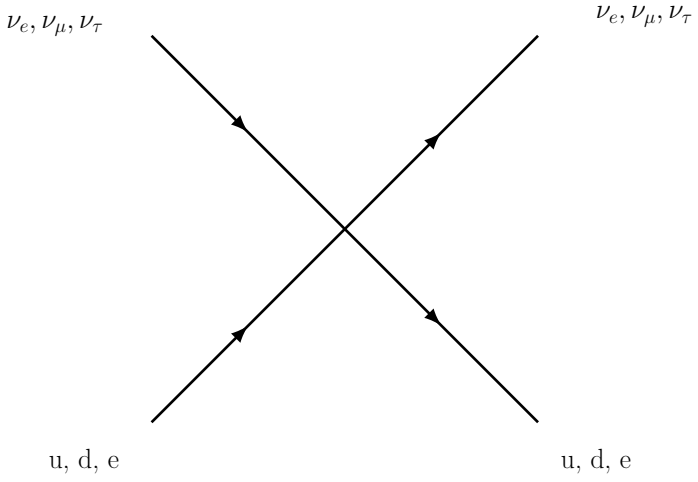
Flavor Conserving All:



A multi-target experiment can place very strong bounds

Focus on vector couplings to quarks, $\epsilon_{ee}^{qV} = \epsilon_{ee}^{qL} + \epsilon_{ee}^{qR}$, $q = u, d$:

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



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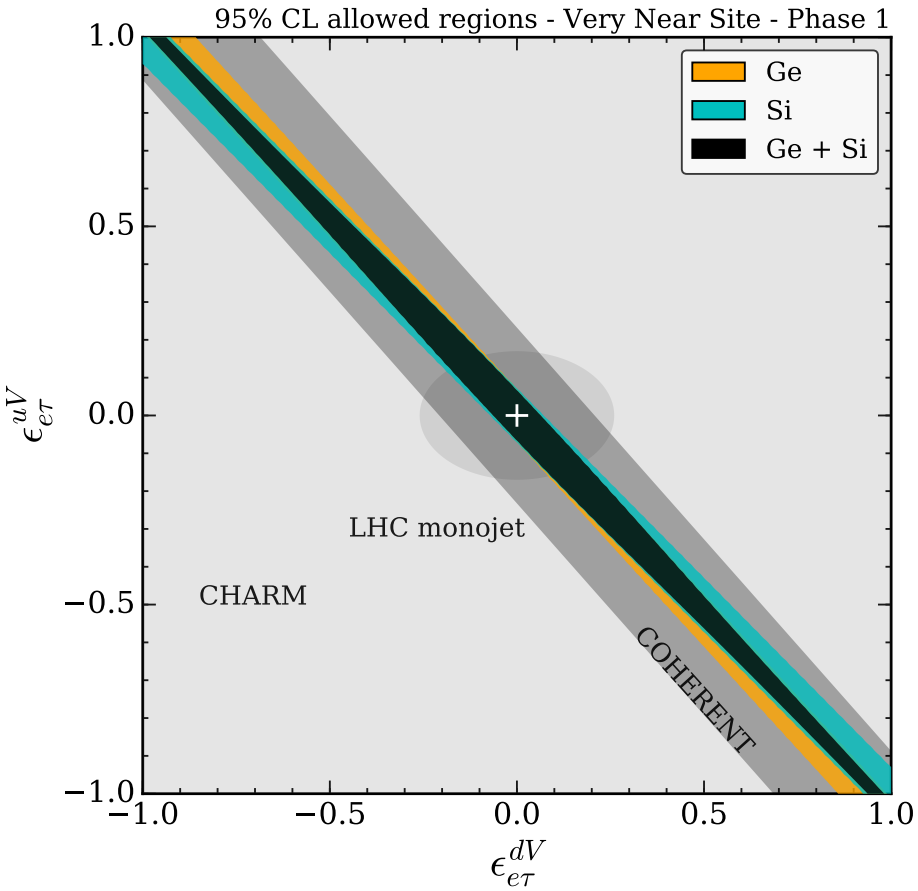
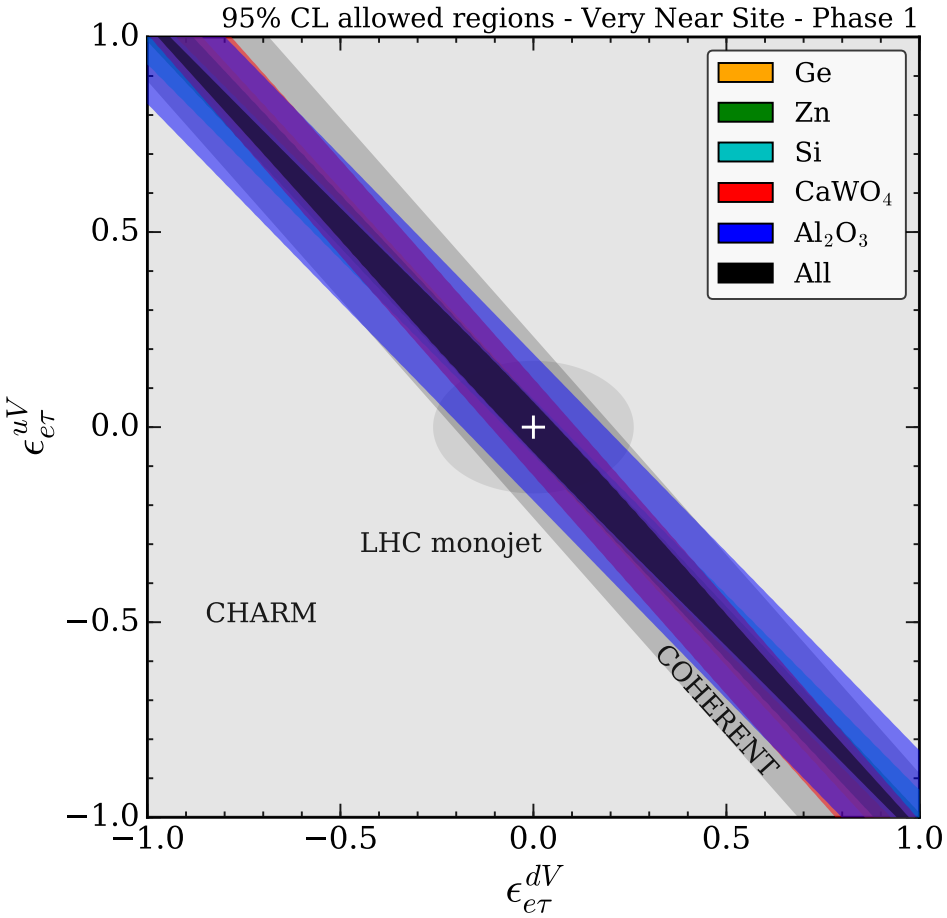
(P. Coloma and T. Schwetz, Phys. Rev. D 95, 079903 (2017))

Flavor Changing Constraints:

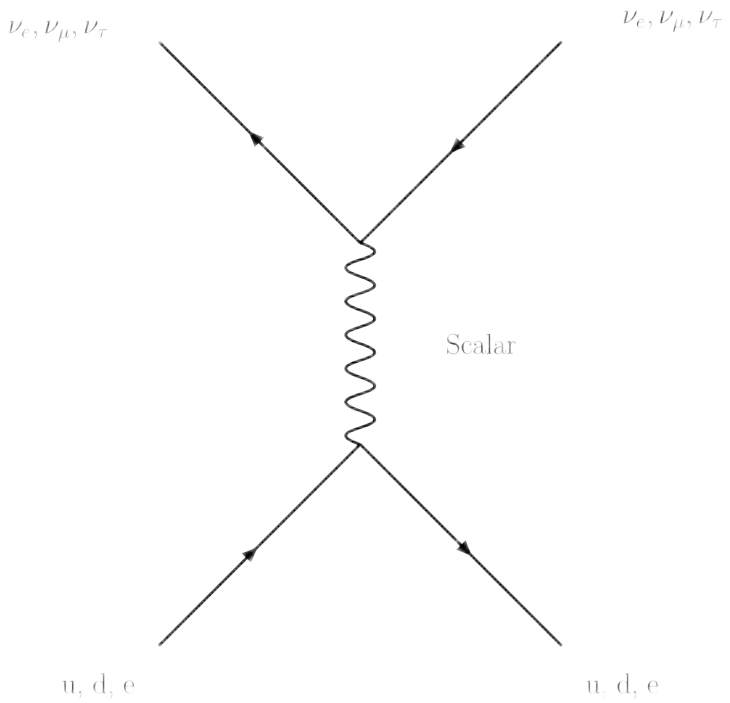


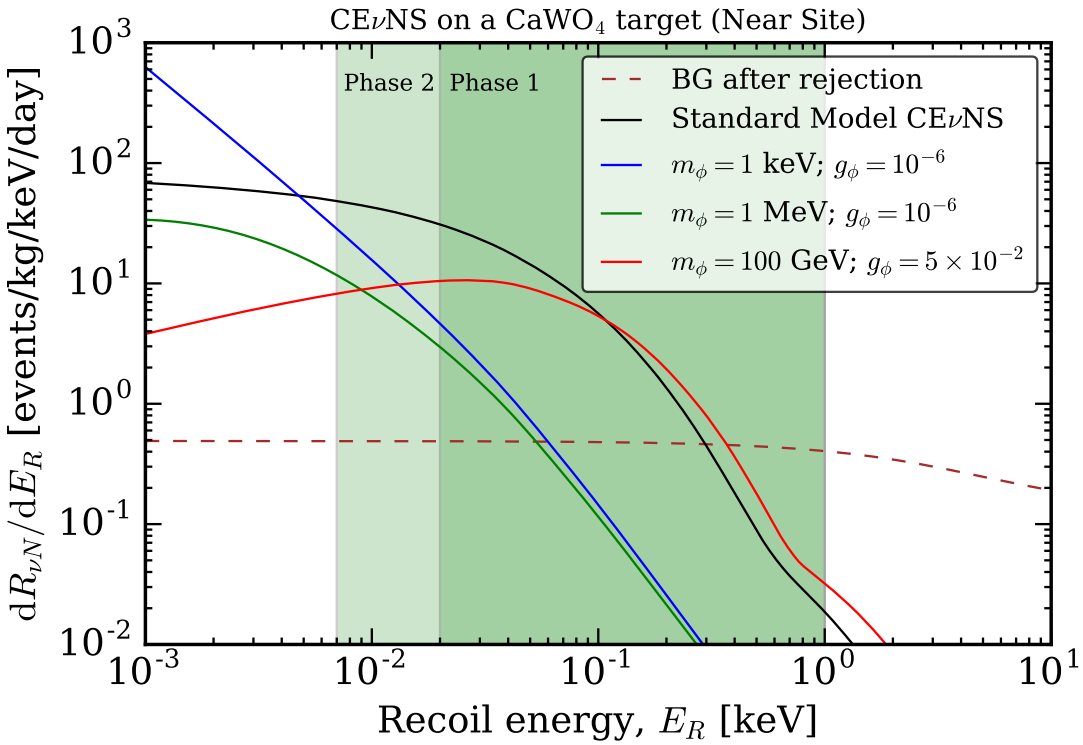


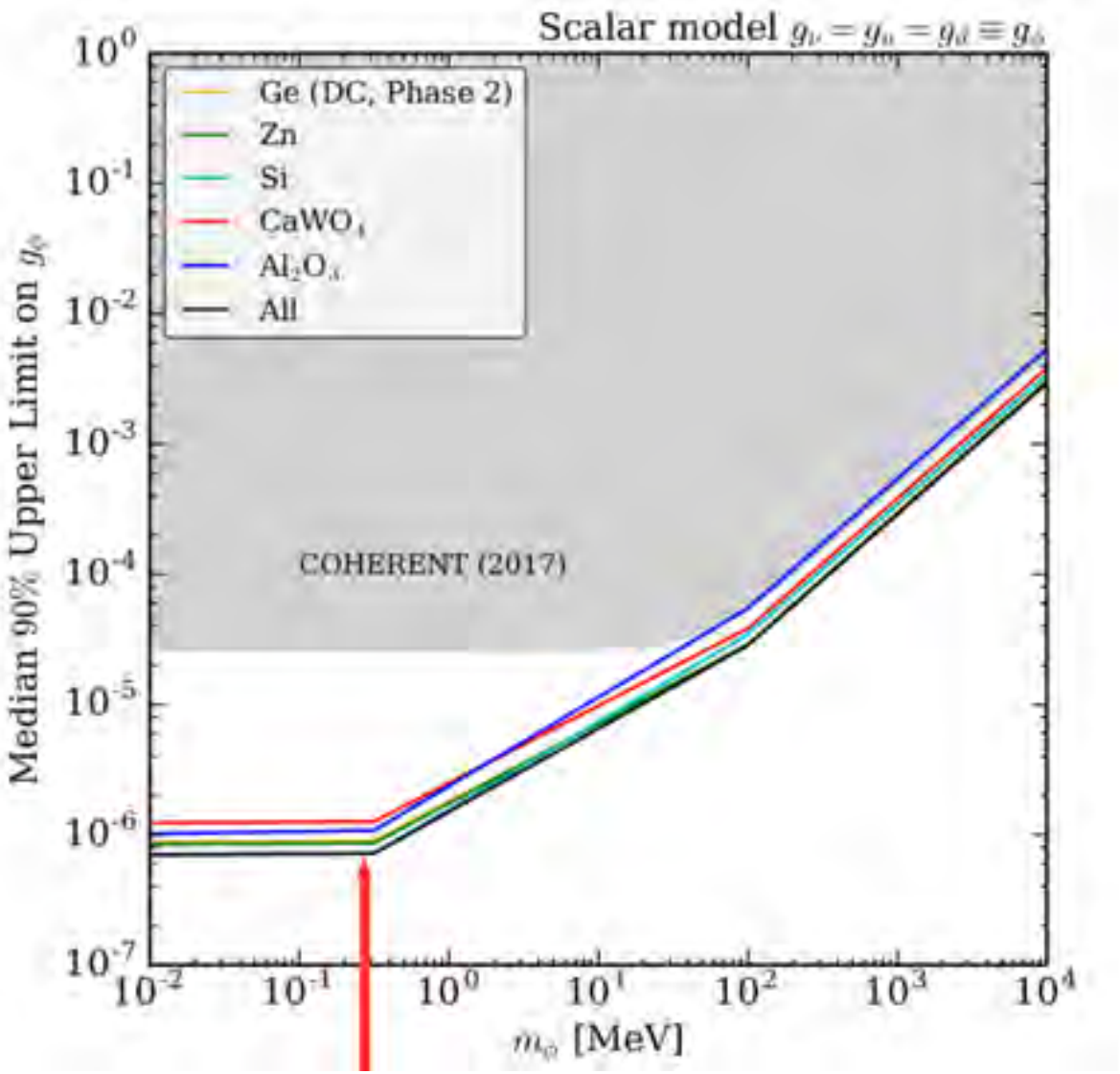
A massive scalar mediator adds a term to SM CEvNS

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

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



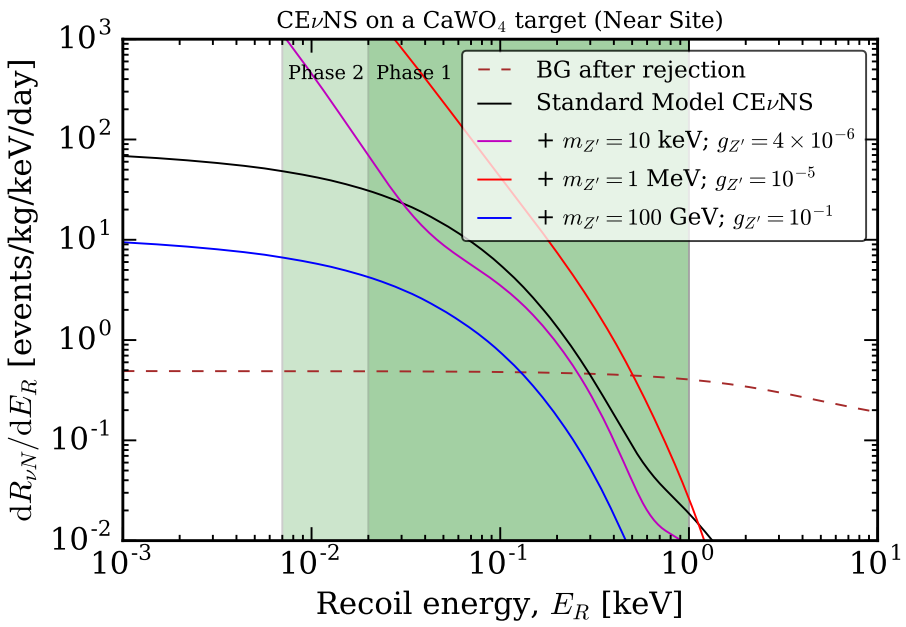


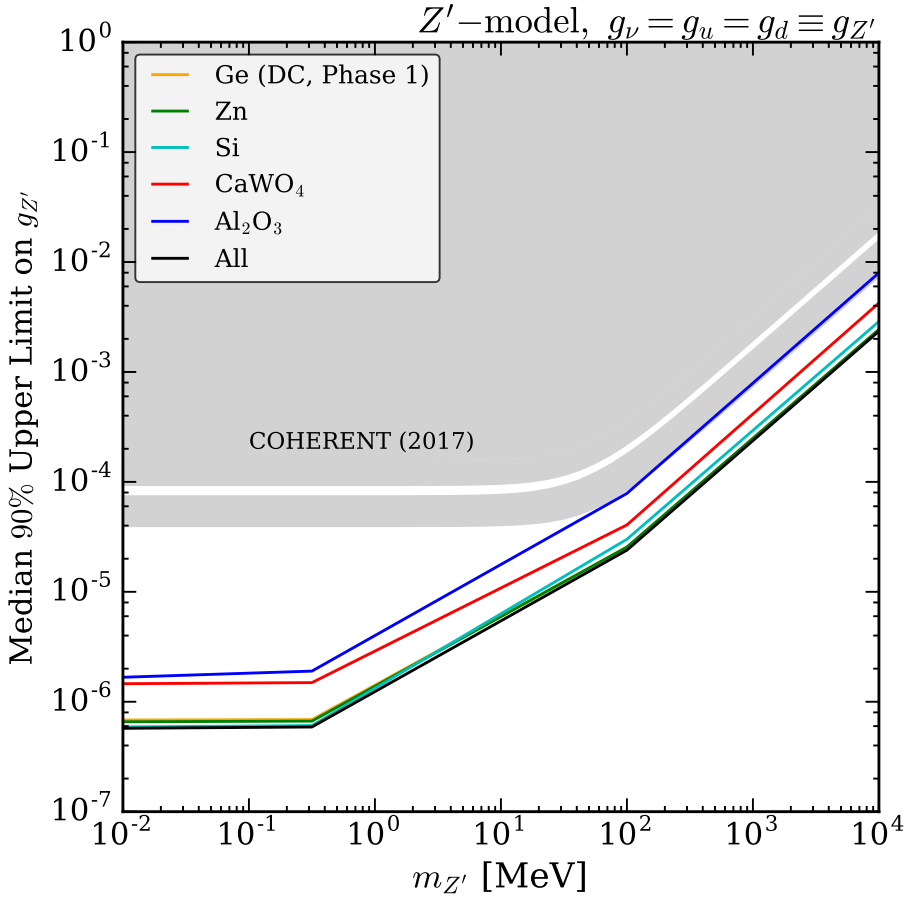


Lower mediator masses are better probed at low neutrino energies

A vector mediator interferes with SM CEvNS

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





Ricochet:

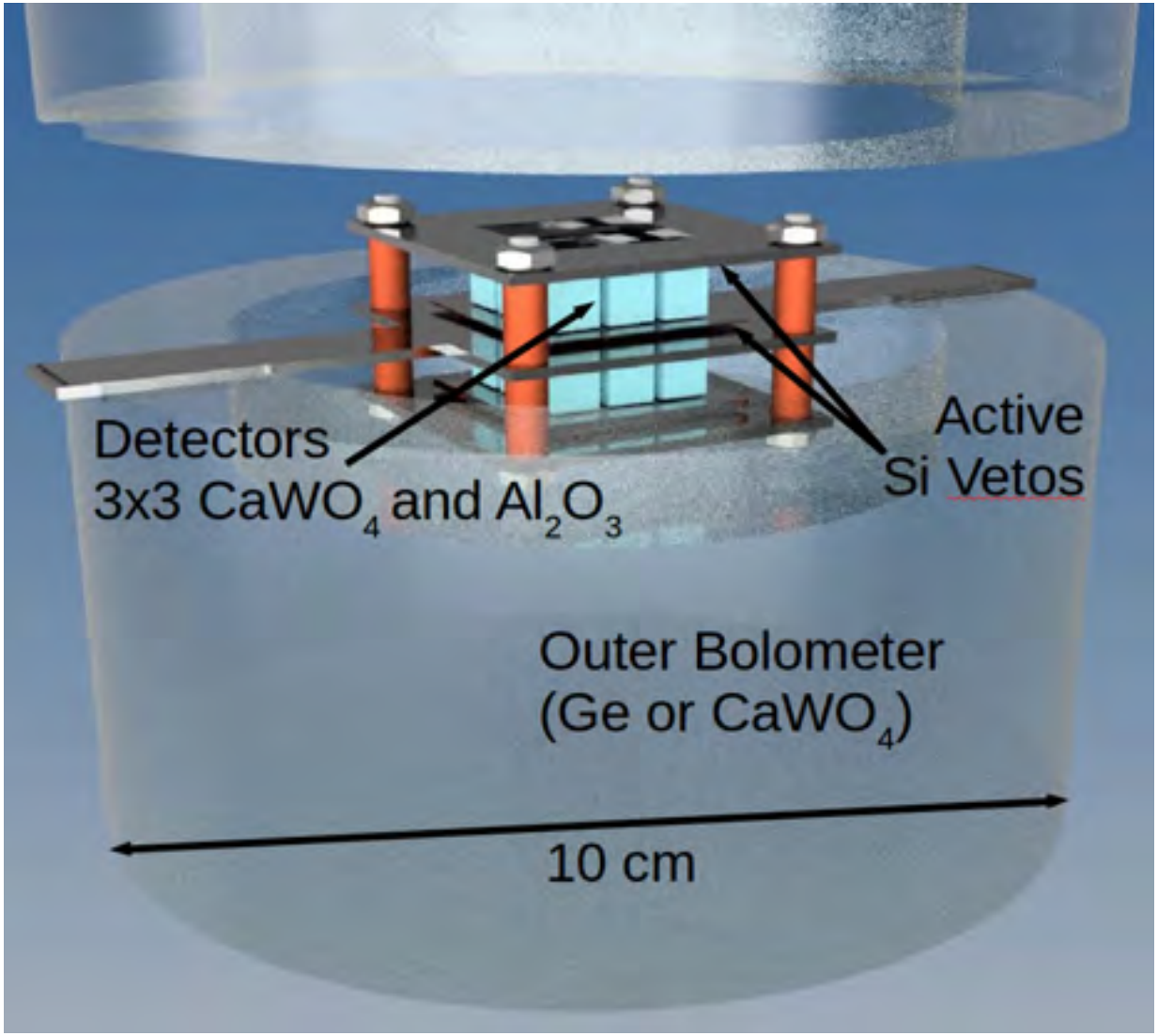
- Superconducting Zn bolometers for background rejection
- Multiplexing TES readout will allow necessary scaling
- Experimental site at Chooz reactor complex
- Zn crystals fabricated and in testing

Proposed experiments will be able to place bounds on new physics:

- Probe nuetrino magnetic moment
- Multiple targets tightly contrain NSI
- Low energy neutrinos better constrain simple mediator models

Backup Slides

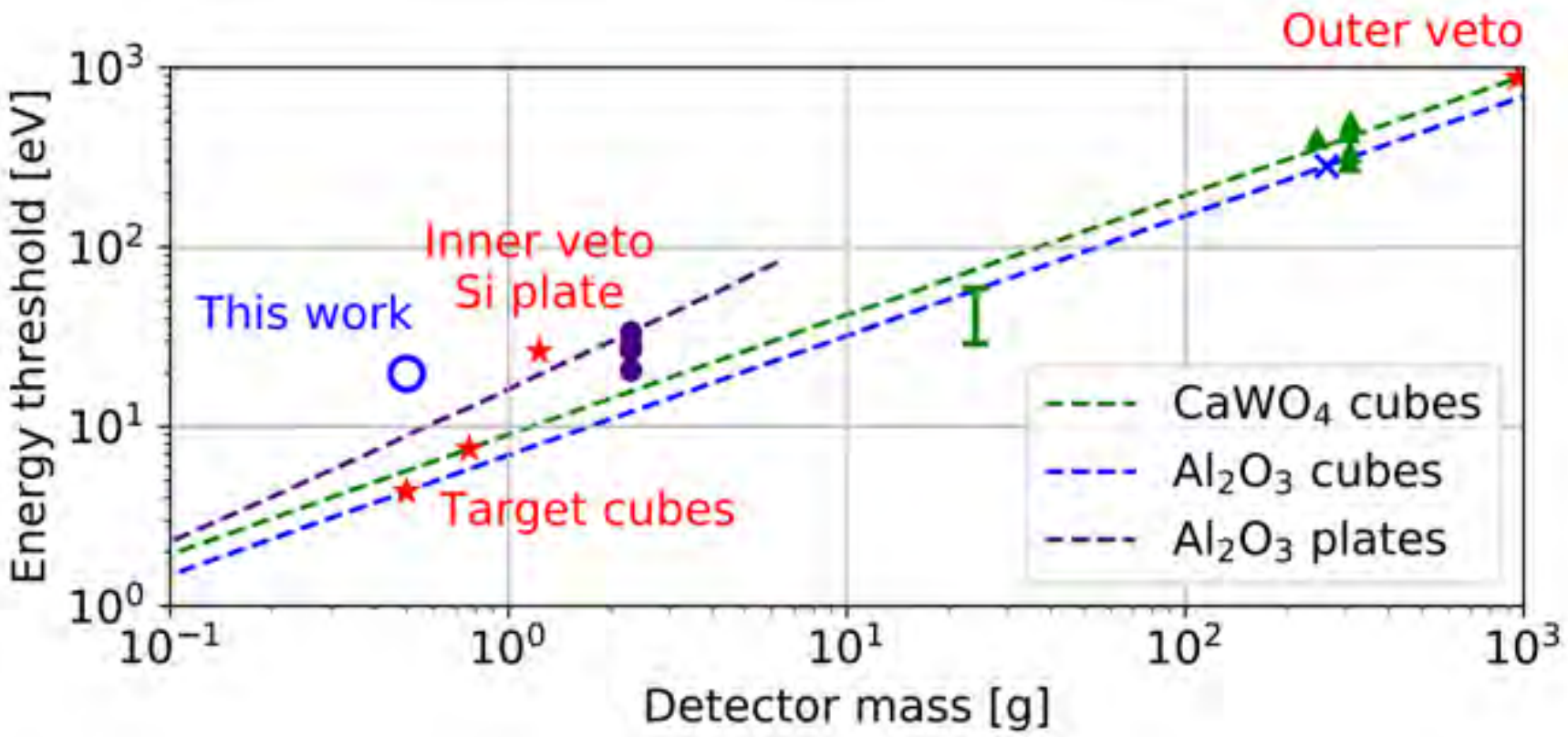
ν-cleus



Strauss et al. arXiv:1704.04320v2 [physics.ins-det] 9 Aug 2017. *(Labels added)*

ν-cleus

- Initially 11 g, 110 g at a later phase
- Threshold O($\leq$10 eV)



Strauss et al. arXiv:1704.04320v2 [physics.ins-det] 9 Aug 2017

Background Assumptions

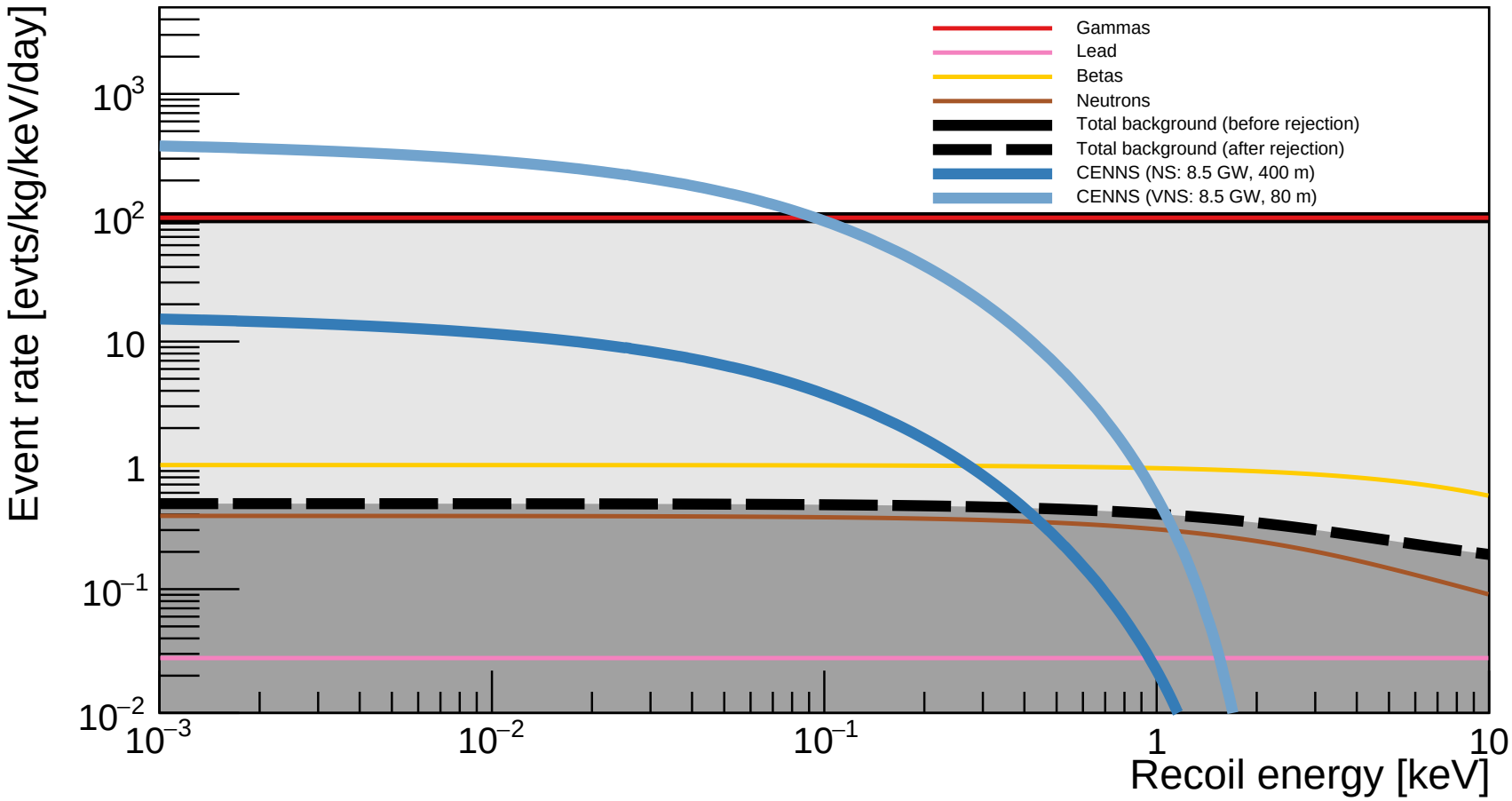
Compton Background:

- 100 events/kg/day in Ge
- Factor 10^{-3} discrimination power

Neutron Background:

- 10 times larger at VNS
- Factor of 0.1 discrimination power for $CaWO_4$ and Al_2O_3
- No reactor correlation

All other backgrounds negligible



- 10% background normalization uncertainty
- 5% CEvNS normalizations uncertainty

Likelihood:

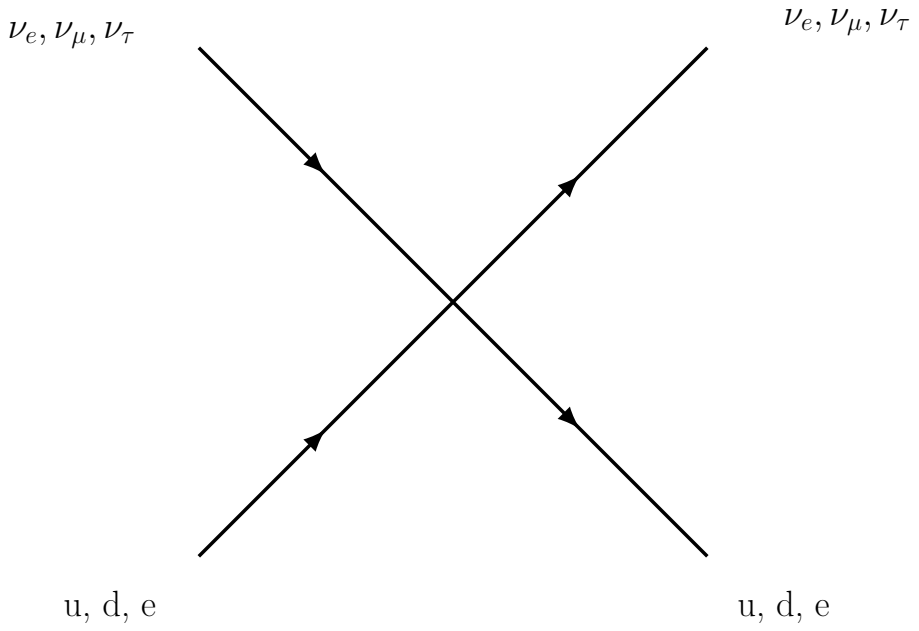
$$\mathcal{L}(\mathbf{D}|\boldsymbol{\theta},\boldsymbol{\psi}) = \mathcal{L}(\boldsymbol{\psi}) \times \prod_{i}^{N_{\rm bins}} P\left(N_{\rm obs}^{(i)} \middle| N_{\rm sig}^{(i)}(\boldsymbol{\theta}) + N_{\rm bg}^{(i)}(\boldsymbol{\psi})\right) .$$

- θ is our parameter of interest
- γ is nuisance parameters, for example constraining the backgrounds.
- A 10% uncertainty is assumed on all background normalizations
- A 5% uncertainty is assumed on the CEvNS signal
- Use profile likelihood ratio test to determine most bounds
- An asimov data set is used to determine bounds on NSI

(G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J.* C71 (2011) 1554,[1007.1727]

Introduce a 4-fermion coupling (α,β=e,μ,τ, f=e,u,d, $P = L, R$)

$$\mathcal{L}^{\mathrm{NSI}} = -\epsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F (\overline{\nu}_\alpha \gamma_\rho L \nu_\beta)(\overline{f} \gamma^\rho P f)$$



$\sin^2(\theta_W)$ and APV constraints

- It is very difficult to place bounds on new physics without assuming some constraint on $\sin^2(\theta_W)$
- We fix $\sin^2(\theta_W)$, but multiply all CEvNS signals by a 5% envelope to account for all systematic uncertainties