BSM Searches with COHERENT

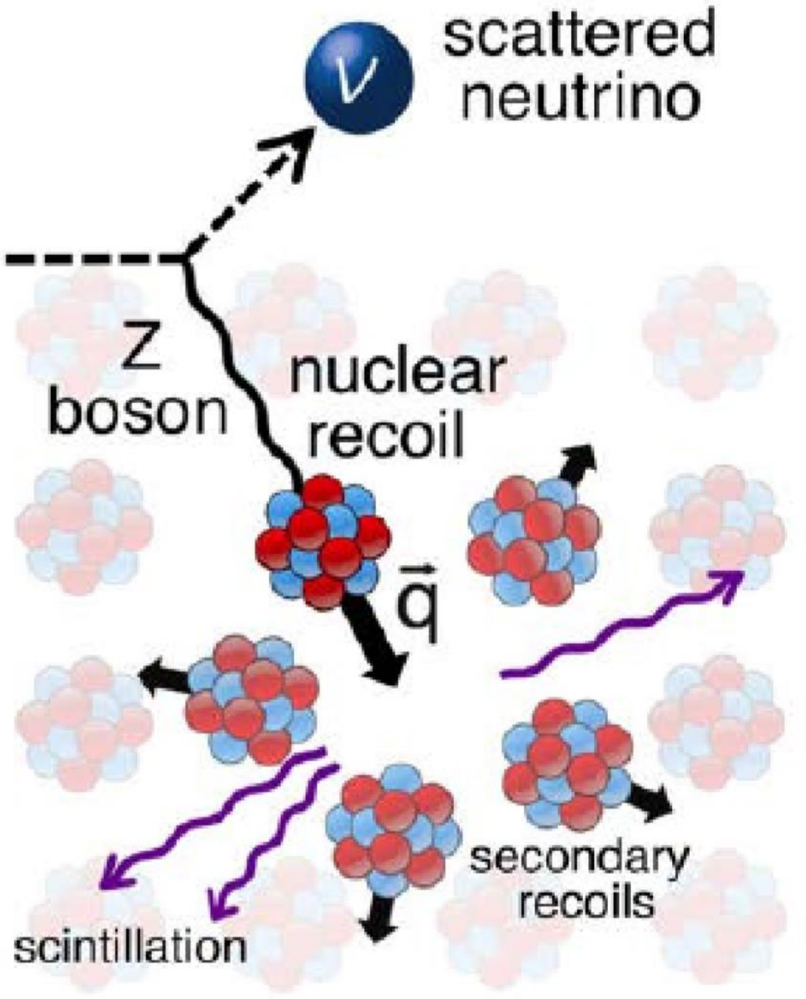
Gleb Sinev for the COHERENT collaboration

New Opportunities at the Next Generation Neutrino Experiments

April 13, 2019

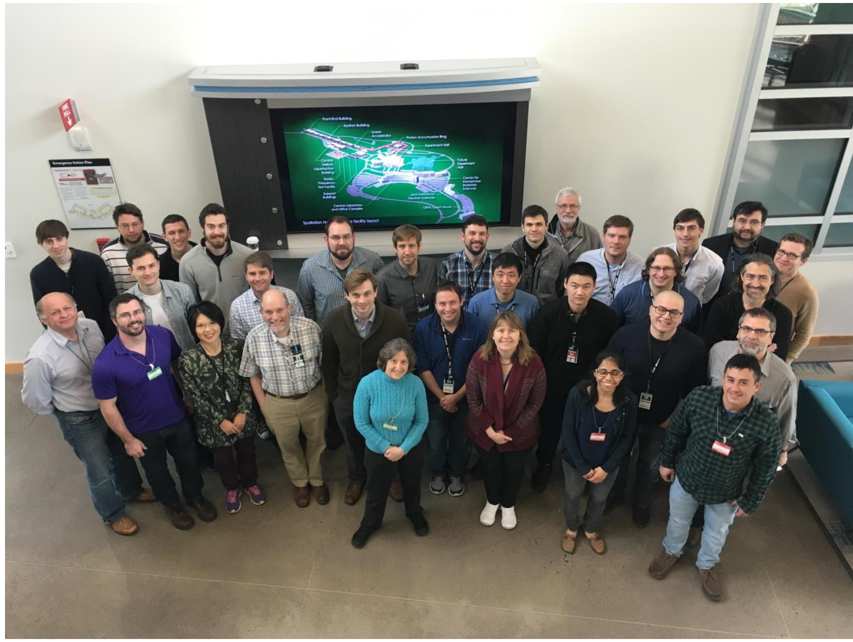
Outline

- COHERENT
  - SNS
  - Current and planned detectors
  - First CEvNS measurement
- BSM physics
  - NSI
  - Dark matter
  - Sterile neutrinos
- Conclusions



~80 members
~20 institutions
4 countries

COHERENT

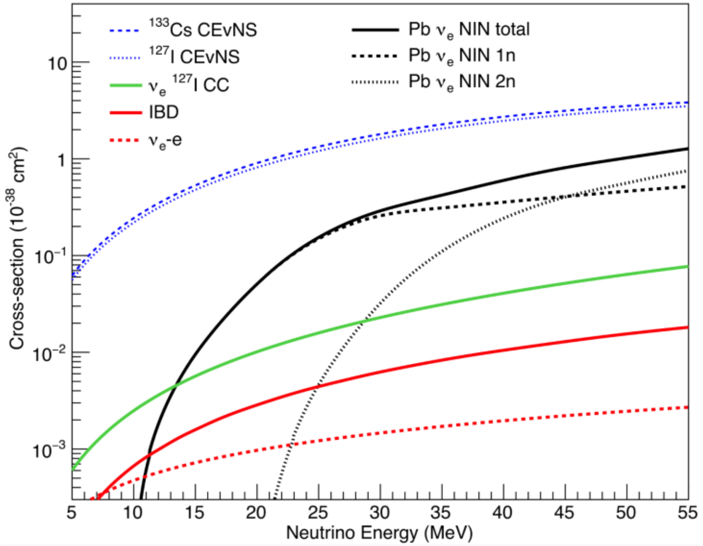


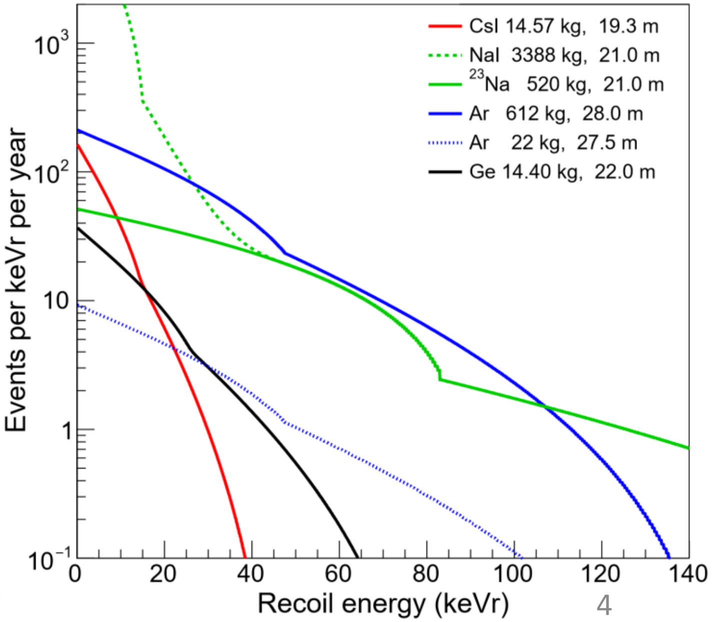
- Rich experimental program
  - Searching for and characterizing coherent elastic neutrino-nucleus scattering (CEvNS)
  - Using CEvNS for nuclear-physics measurements
  - Measuring poorly known cross sections
    - Inelastic neutrino interactions on target nuclei (Ar, I, O)
    - Neutrino-induced neutrons
  - Reducing systematic uncertainties
    - Backgrounds
    - Quenching factors
    - Neutrino flux
  - **Studying BSM physics**

Carnegie Mellon University
THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
VIRGINIA TECH.
UF UNIVERSITY of FLORIDA
KAIST
LaurentianUniversity UniversitéLaurentienne
Los Alamos NATIONAL LABORATORY EST.1943
MEPhI
UNIVERSITY OF SOUTH DAKOTA
NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910
NC STATE UNIVERSITY
NM STATE UNIVERSITY
OAK RIDGE National Laboratory
Sandia National Laboratories
THE UNIVERSITY of TENNESSEE UT KNOXVILLE
TUNL
W UNIVERSITY of WASHINGTON
CNEC Consortium for Nonproliferation Enabling Capabilities
KICP
NNSA National Nuclear Security Administration
NSF
U.S. DEPARTMENT OF ENERGY

Coherent elastic neutrino-nucleus scattering (CEνNS)

- ν can scatter coherently on whole nuclei
  - E_ν < ~50 MeV needed
  - Cross section enhanced by ~A^2 (actually ~N^2)
  - Large rates
- Elastic: ν A -> ν A
  - Detecting only through nuclear recoil energy
  - Combining with E_ν < ~50 MeV, get E_r < ~100 keV
  - Independent of ν flavor
- Very challenging but promising channel

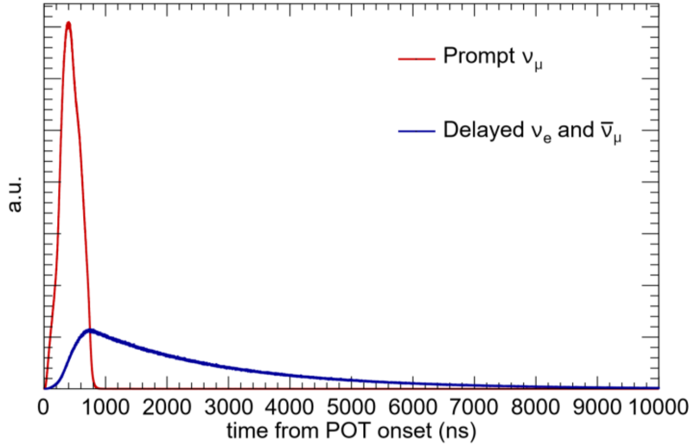


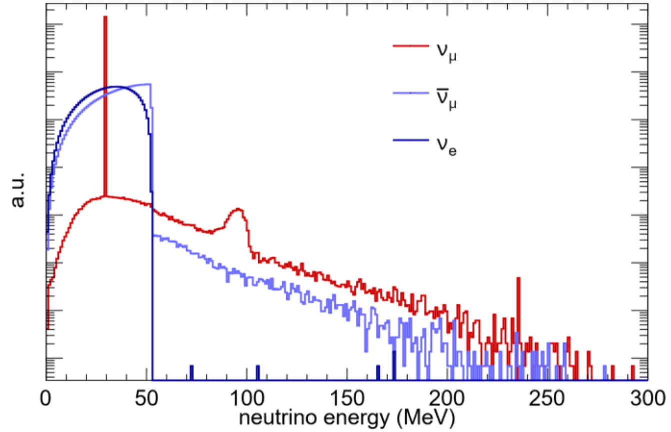


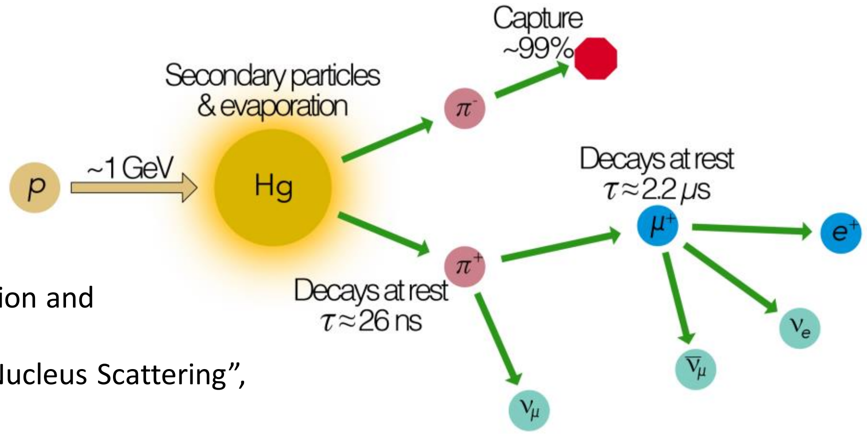
SNS

- Spallation Neutron Source at ORNL
  - Very expensive facility for physics with neutrons
  - 1.4 MW: p (1 GeV) + Hg
- πDAR source
  - ν's from π decays at rest several orders of magnitude over other ν's

SNS simulation

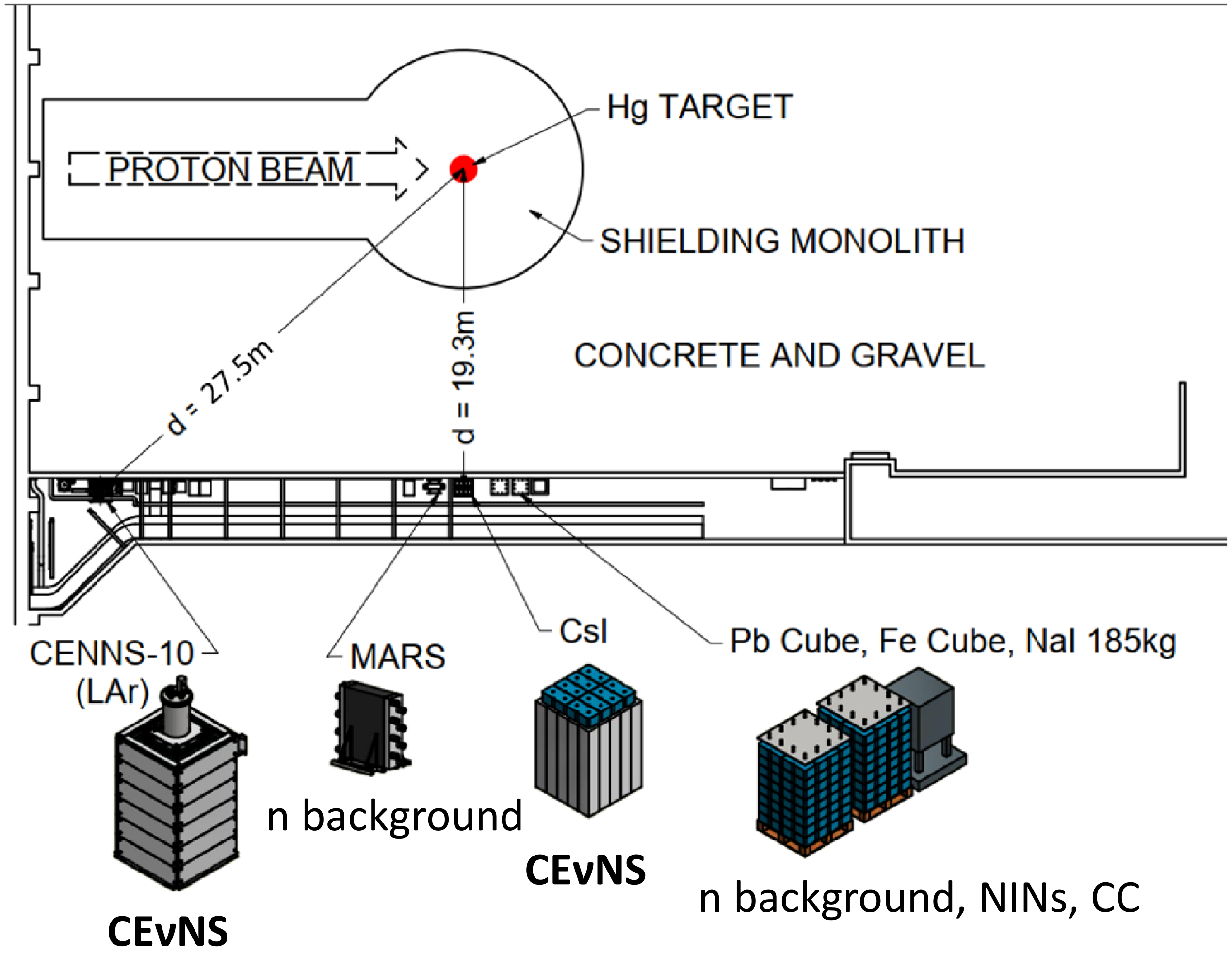






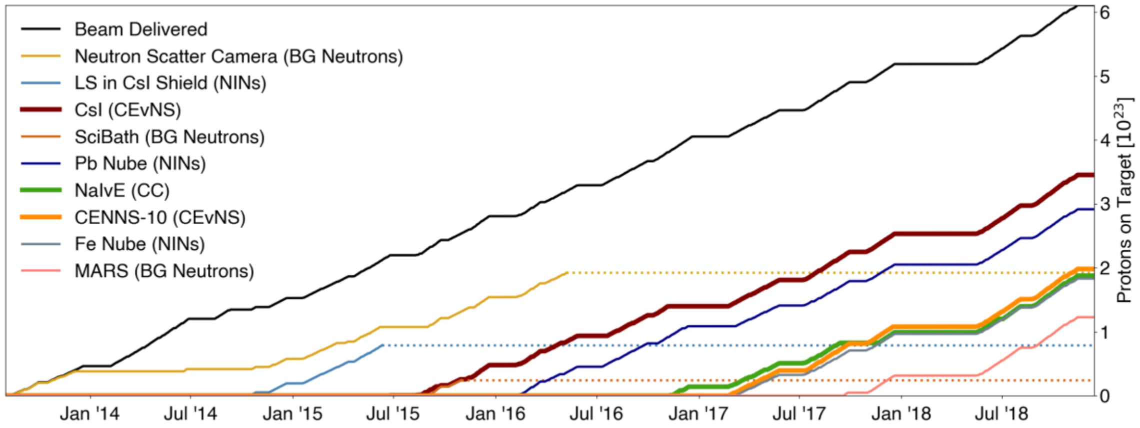
G. Rich,
"The COHERENT Collaboration and
the First Observation of
Coherent Elastic Neutrino-Nucleus Scattering",
Neutrino 2018

Current detectors



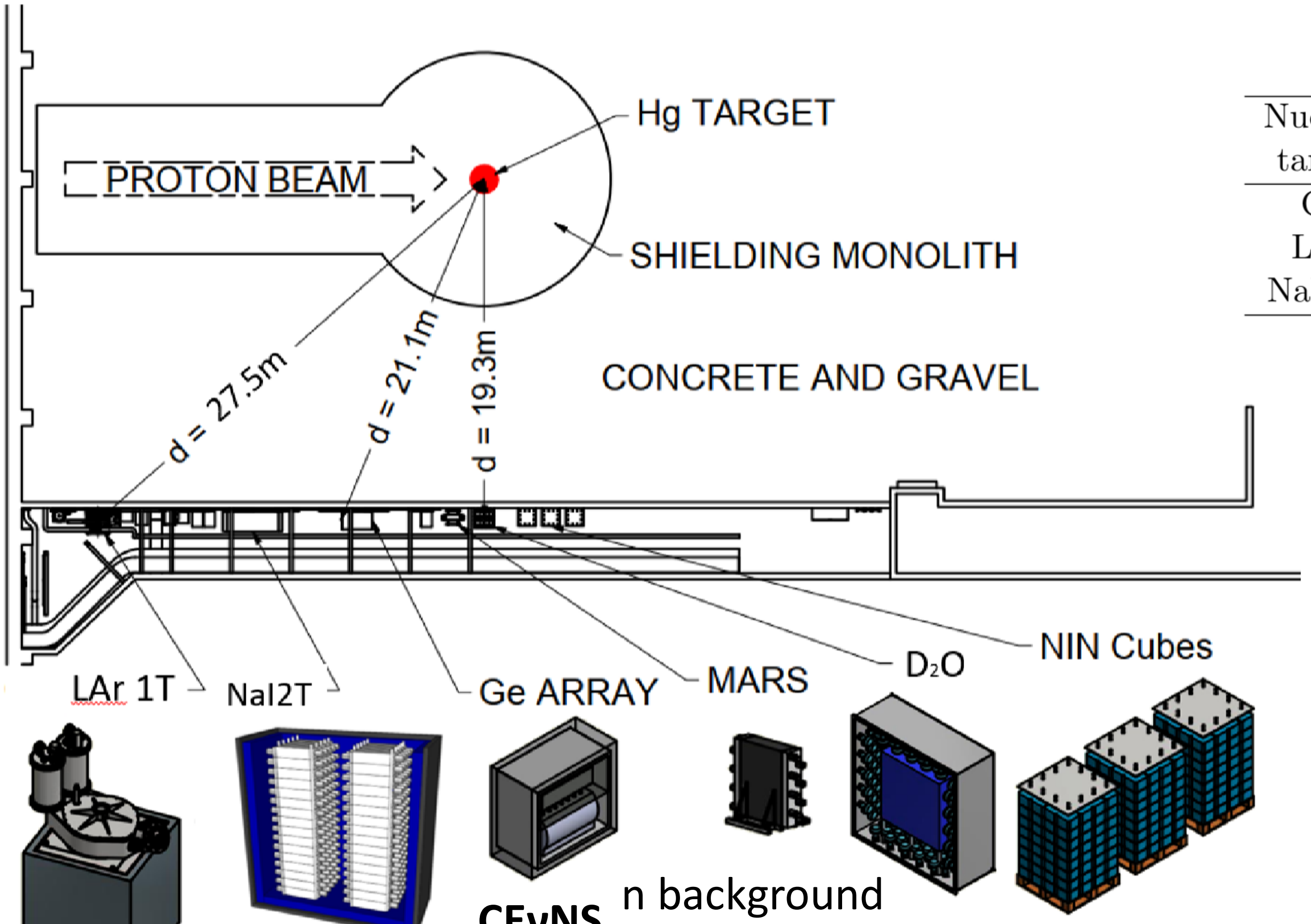
Nuclear target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVnr)
CsI[Na]	Scintillating crystal	14.6	19.3	9
LAr	Single-phase	22	27.5	20
NaI[Tl]	Scintillating crystal	185	21	13 (target)

Collected POT as of Dec 2018



Started taking (non-CEvNS) data 5-6 years ago

Planned detectors



CEvNS, CC

CEvNS, CC

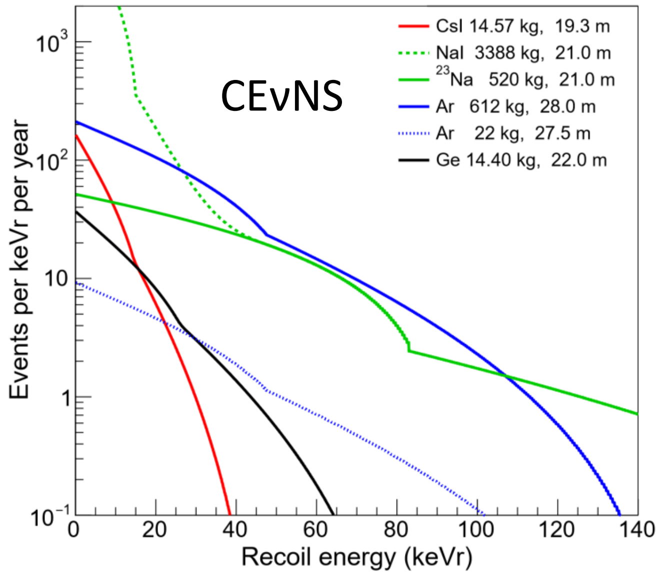
CEvNS

n background

ν flux, CC

n background, NINs

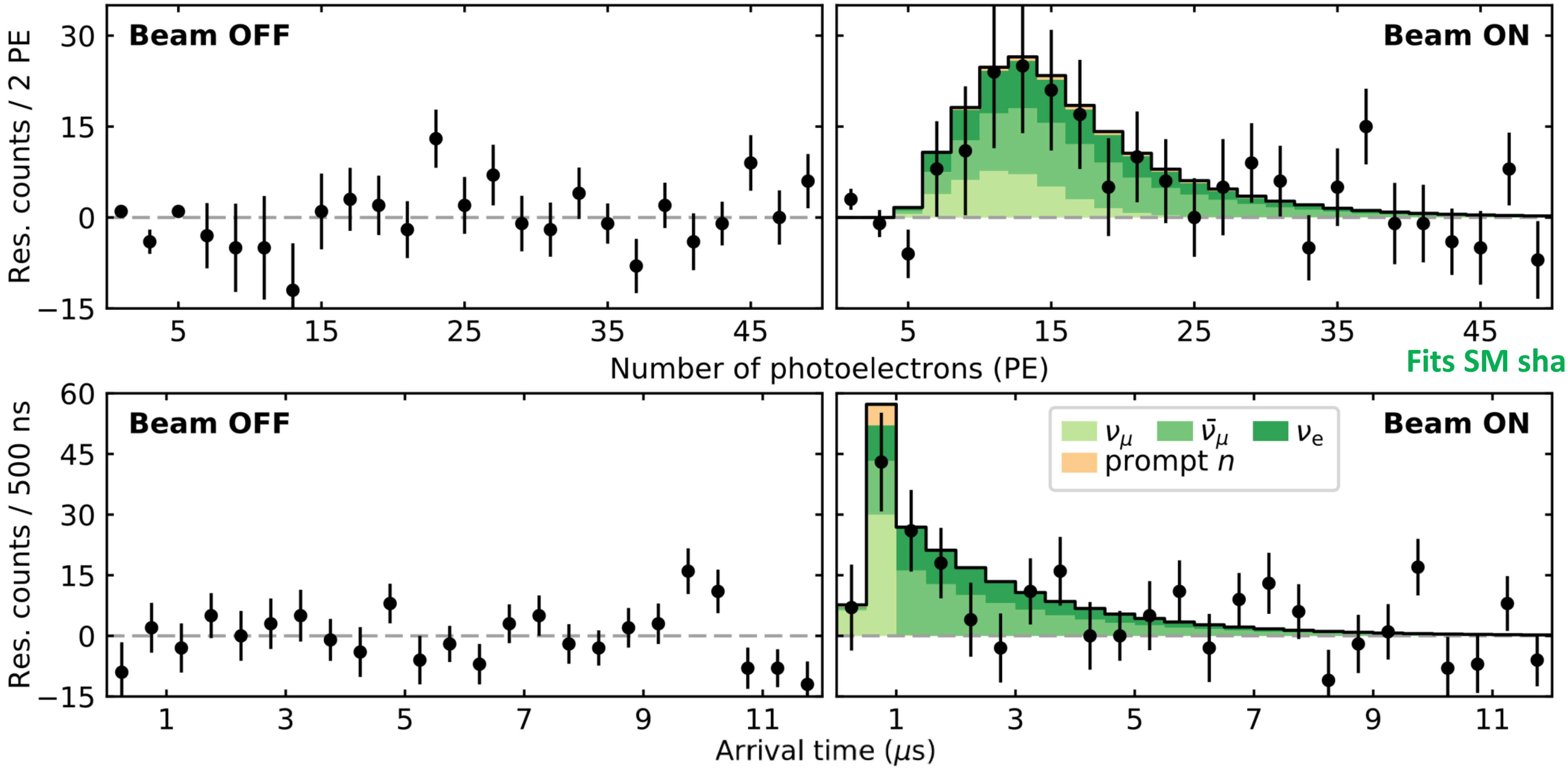
Nuclear target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVnr)
Ge	HPGe PPC	16	21	2.5
LAr	Single-phase	612	27.5	20
NaI[Tl]	Scintillating crystal	3388	22	13



D. Akimov *et al.* (COHERENT). "Observation of Coherent Elastic Neutrino-Nucleus Scattering." *Science* (2017). 1708.01294.

First CEvNS measurement

14.6-kg CsI
6.7-σ observation
134 CEvNS events



Fits SM shape well

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First CEvNS measurement

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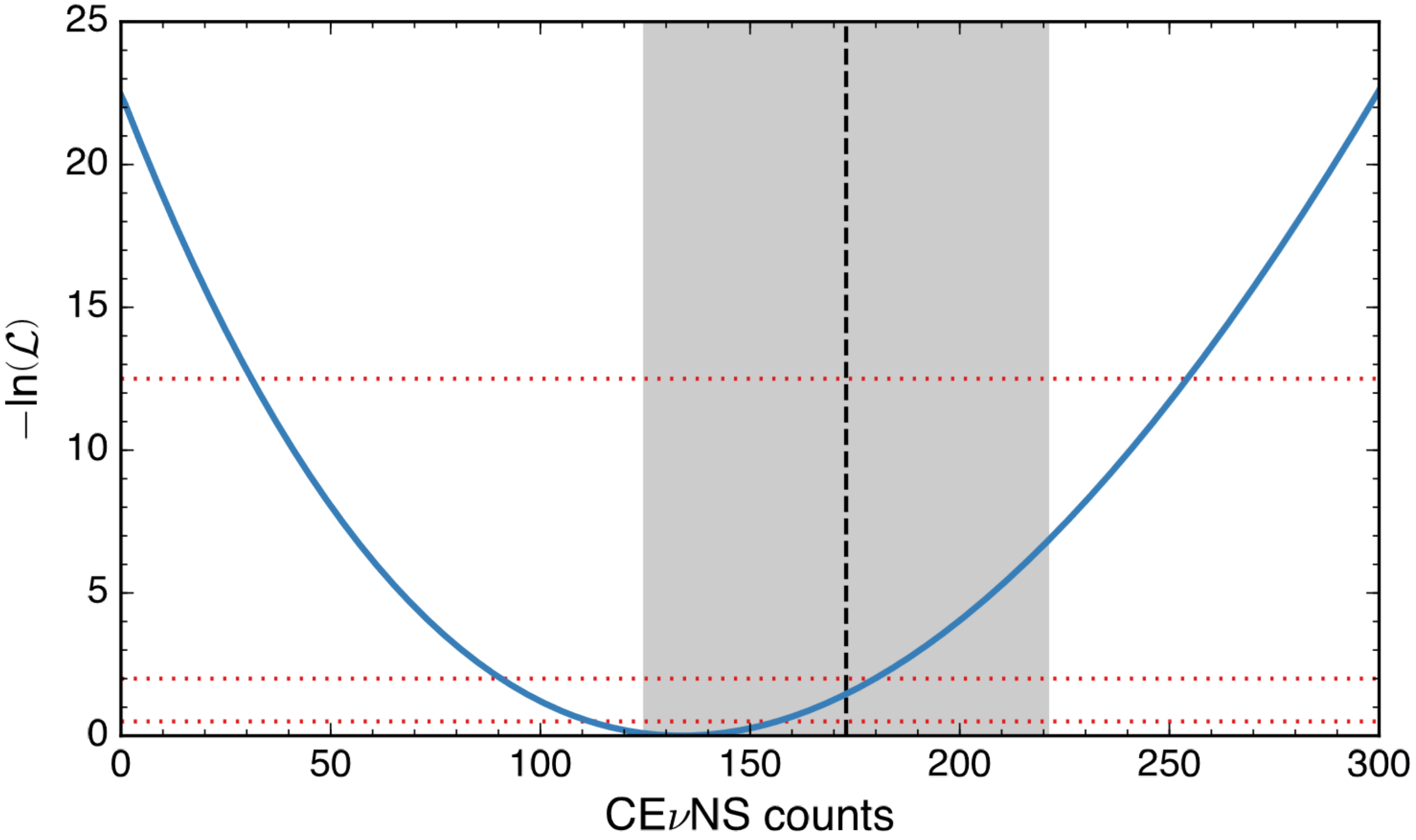


Within 1σ of SM rate

Data is available: see arXiv:1804.09459
COHERENT Collaboration data release from first observation of coherent elastic neutrino-nucleus scattering

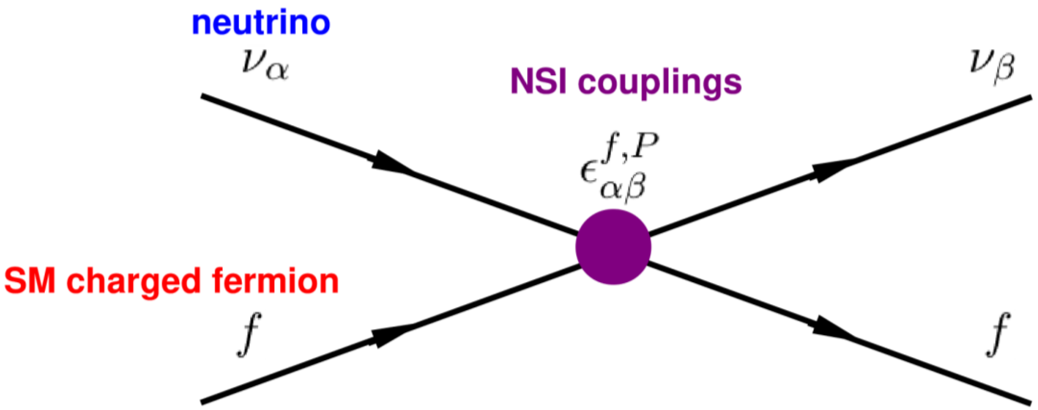
BSM physics

- Very-high-intensity protons + varied suite of sensitive detectors
- Primarily studying once-observed well-modeled SM interaction
- Great opportunity for BSM searches!

NSI: heavy mediators

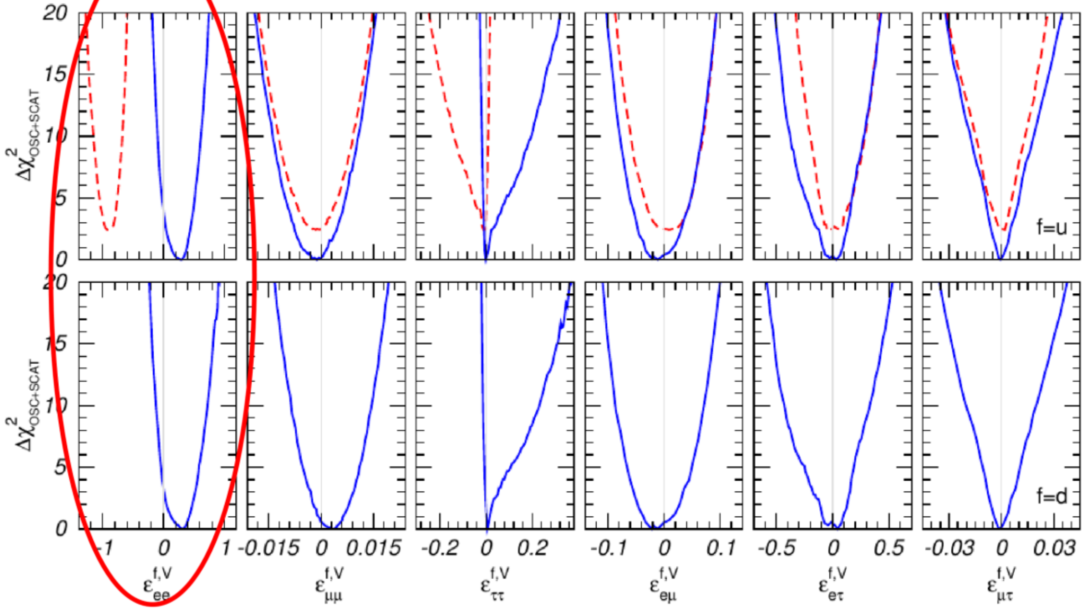
P. Coloma. P.B. Denton, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, "Curtailing the Dark Side in Non-Standard Neutrino Interactions", arXiv:1701.04828

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$



Pre-COHERENT NSI limits

From oscillation experiments + CHARM + NuTeV



P. Coloma. P.B. Denton, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, "Curtailing the Dark Side in Non-Standard Neutrino Interactions", arXiv:1701.04828

Considering these couplings (values ~1 still allowed), setting rest to 0

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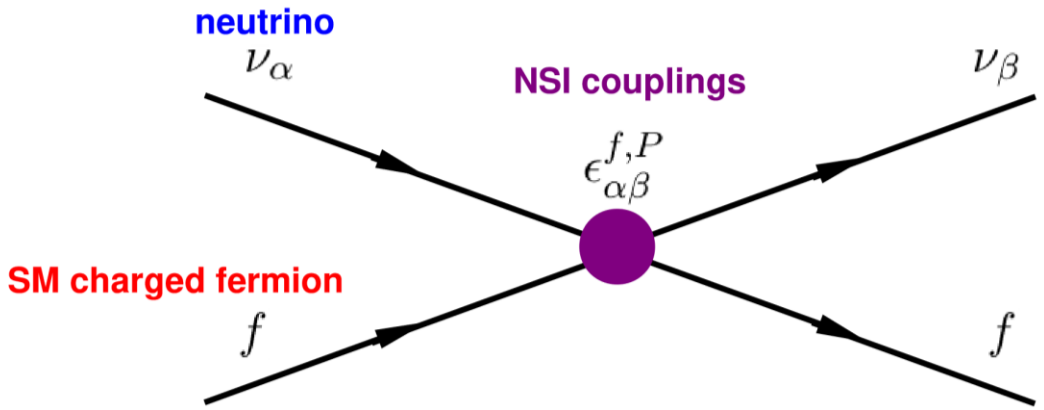


CEvNS

J. Barranco, O.G. Miranda, T.I. Rashba, "Probing new physics with coherent neutrino scattering off nuclei", arXiv:hep-ph/0508299

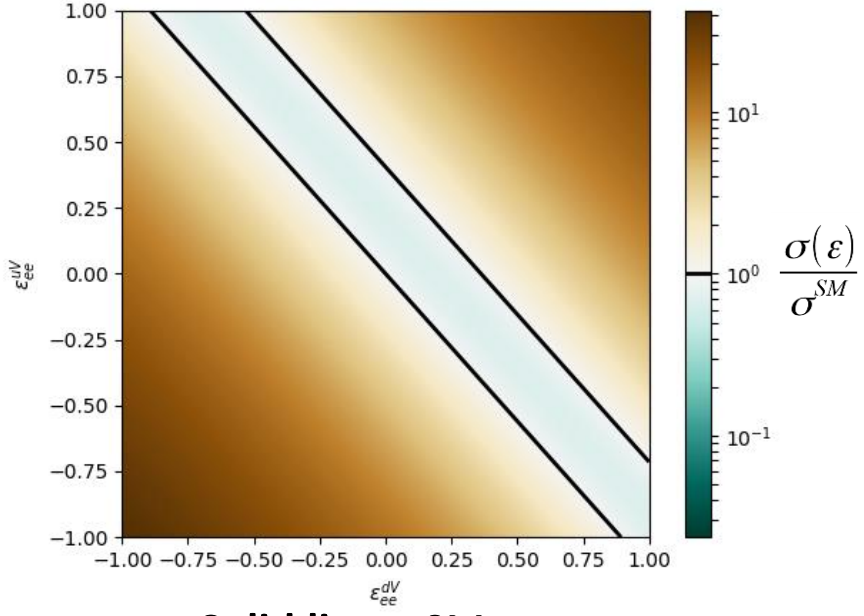
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

$$G_V = (g_V^p + \boxed{2\varepsilon^{uV}_{ee} + \varepsilon^{dV}_{ee}})Z + (g_V^n + \boxed{\varepsilon^{uV}_{ee} + 2\varepsilon^{dV}_{ee}})N$$

NSI terms

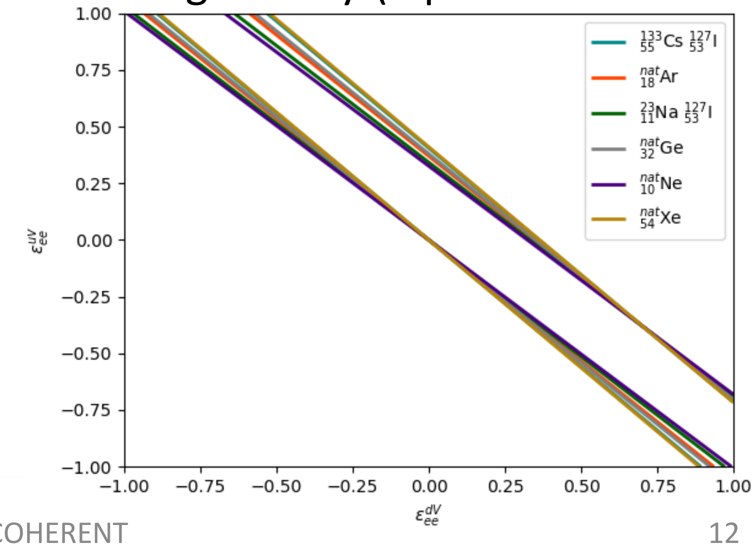
$$G_A = (g_A^p + 2\varepsilon^{uA}_{ee} + \varepsilon^{dA}_{ee})(Z_+ - Z_-) + (g_A^n + \varepsilon^{uA}_{ee} + 2\varepsilon^{dA}_{ee})(N_+ - N_-) \approx 0$$

CsI



Solid lines: SM rate

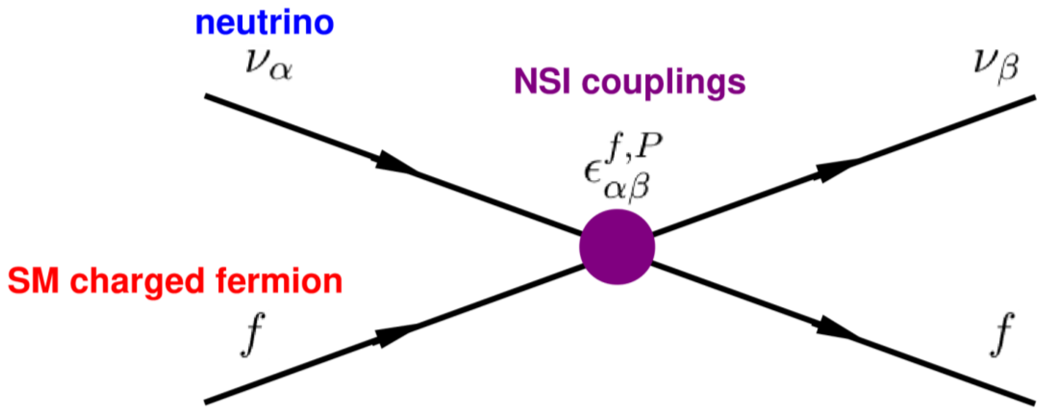
Can plot SM rates for different detectors to reduce degeneracy (2 points instead of 2 lines):



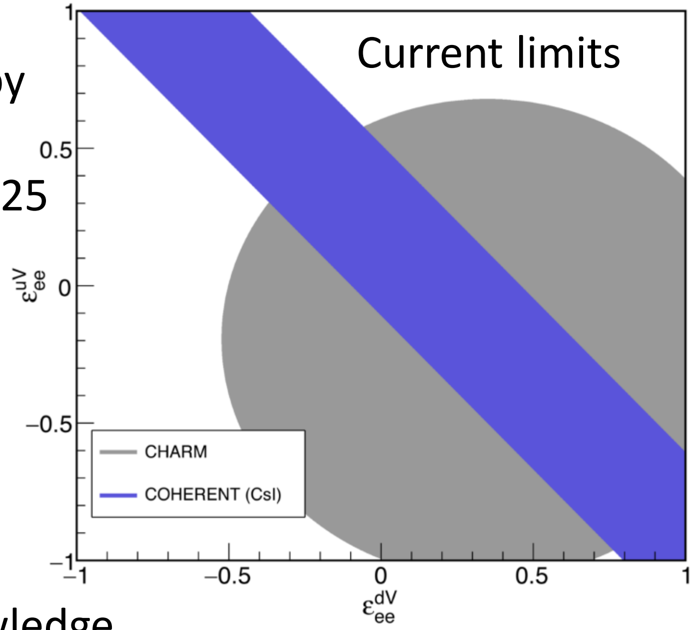
NSI: heavy mediators

P. Coloma. P.B. Denton, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, "Curtailing the Dark Side in Non-Standard Neutrino Interactions", arXiv:1701.04828

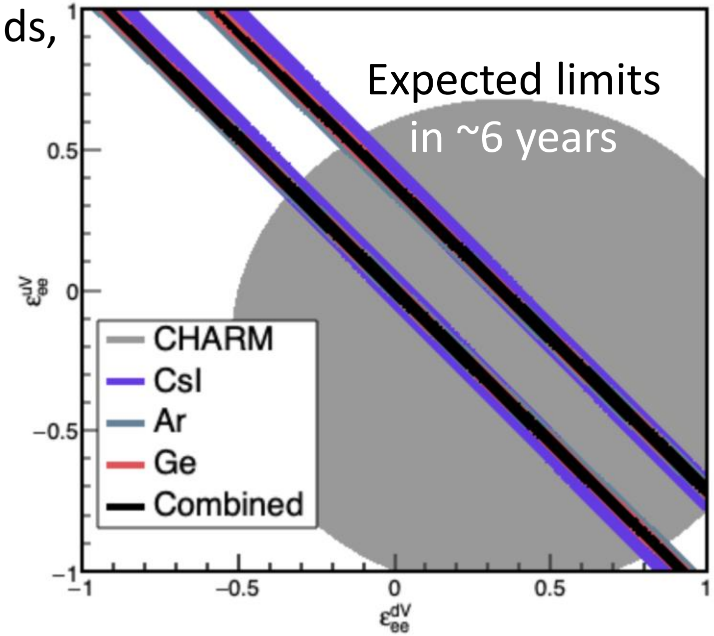
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$



Dominated by
σ_{QF} = 0.22
$\sigma_{\text{beam-on n}}$ = 0.25



Improved knowledge of n backgrounds, SNS ν flux, QFs



CEvNS

J. Barranco, O.G. Miranda, T.I. Rashba, "Probing new physics with coherent neutrino scattering off nuclei", arXiv:hep-ph/0508299

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$$G_V = (g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV})Z + (g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})N$$

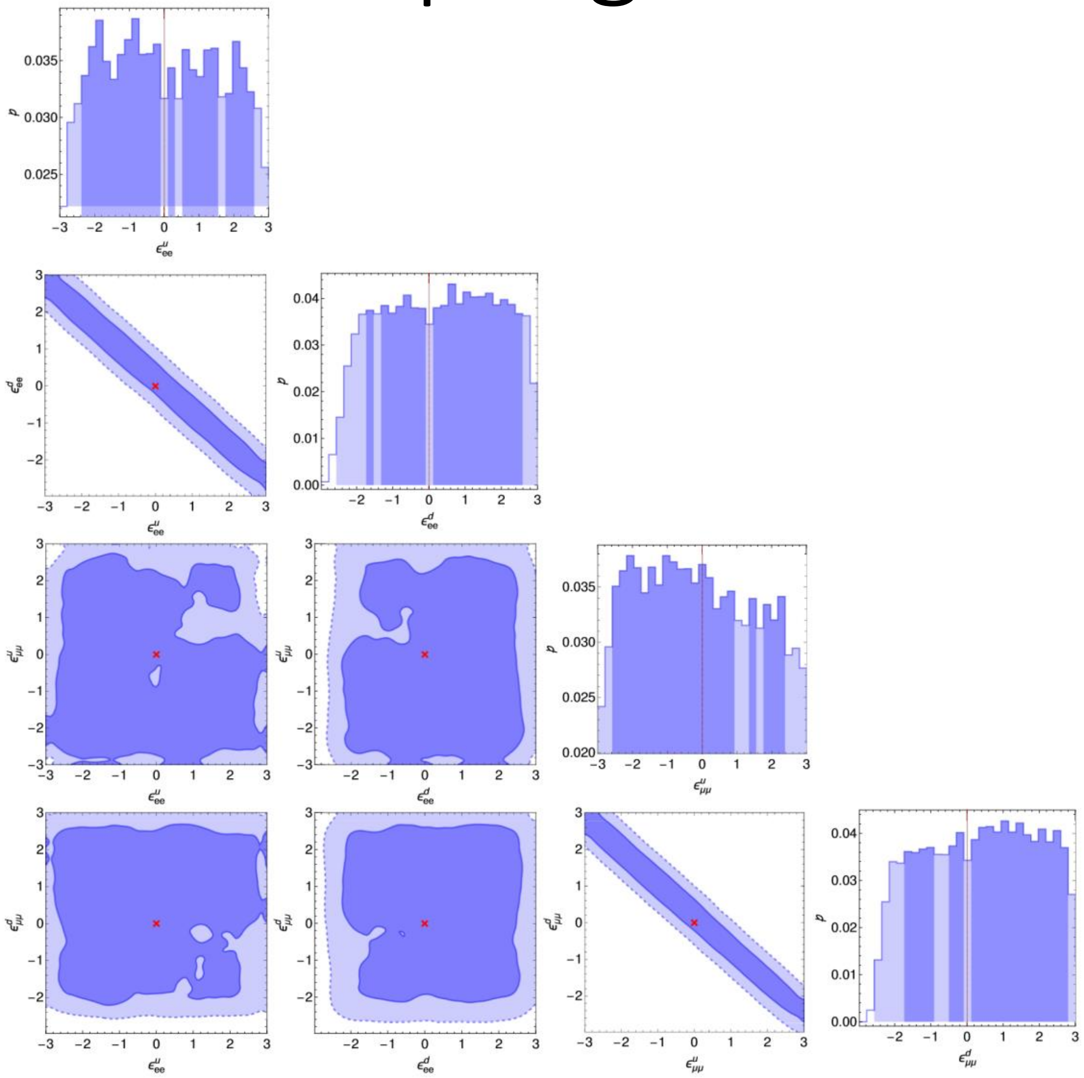
NSI terms

$$G_A = (g_A^p + 2\varepsilon_{ee}^{uA} + \varepsilon_{ee}^{dA})(Z_+ - Z_-) + (g_A^n + \varepsilon_{ee}^{uA} + 2\varepsilon_{ee}^{dA})(N_+ - N_-) \approx 0$$

J.B. Dent, B. Dutta, S. Liao, J.L. Newstead, L.E. Strigari, and J.W. Walker,
“Accelerator and reactor complementarity in coherent neutrino scattering”, arXiv:1711.03521

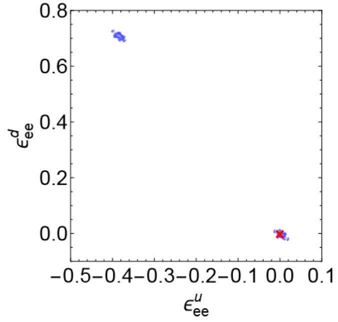
Considering 4 non-zero NSI couplings

- Published COHERENT CsI data
- Bayesian analysis
  - MultiNest package
- Adding $\epsilon_{\mu\mu}^{u}$ and $\epsilon_{\mu\mu}^{d}$
- ϵ priors (and scale) [-3, 3]
- 68% and 95% contours
- Much weaker constraints

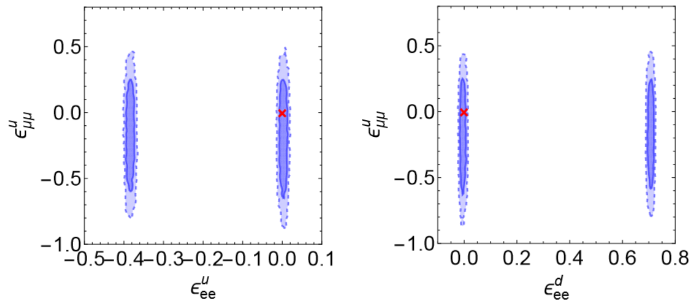


J.B. Dent, B. Dutta, S. Liao, J.L. Newstead, L.E. Strigari, and J.W. Walker,
“Accelerator and reactor complementarity in coherent neutrino scattering”, arXiv:1711.03521

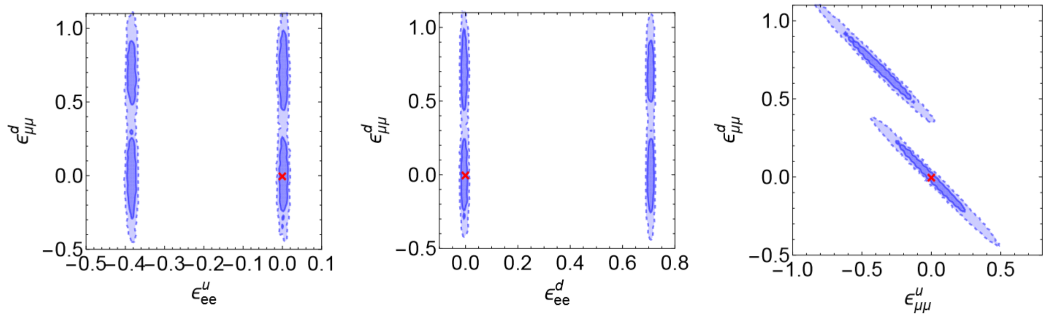
Considering 4 non-zero NSI couplings

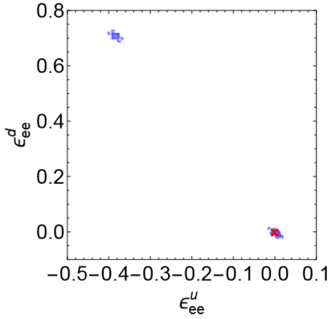


Future COHERENT + reactor data
Binned in energy

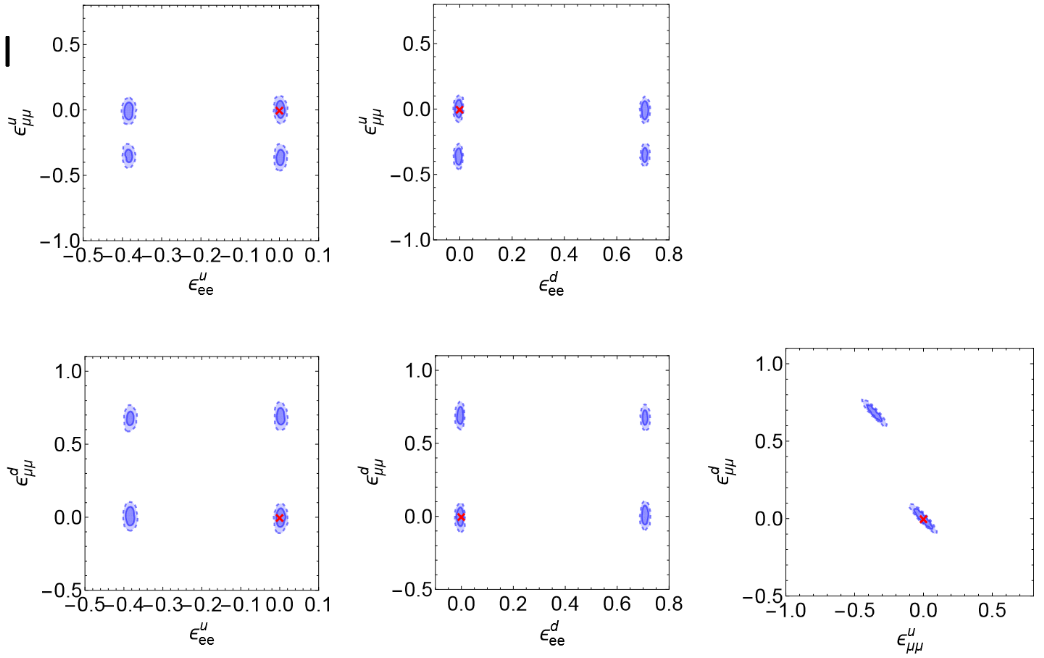


Reactors (ee)
better constrain NSI





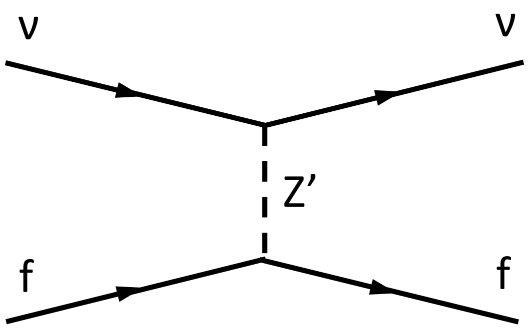
Future COHERENT + reactor data
Binned in energy
0 background for COHERENT



J. Liao and D. Marfatia, "COHERENT constraints on nonstandard neutrino interactions", arXiv:1708.04255

NSI: light mediators

- Adding Z' propagator



CEvNS

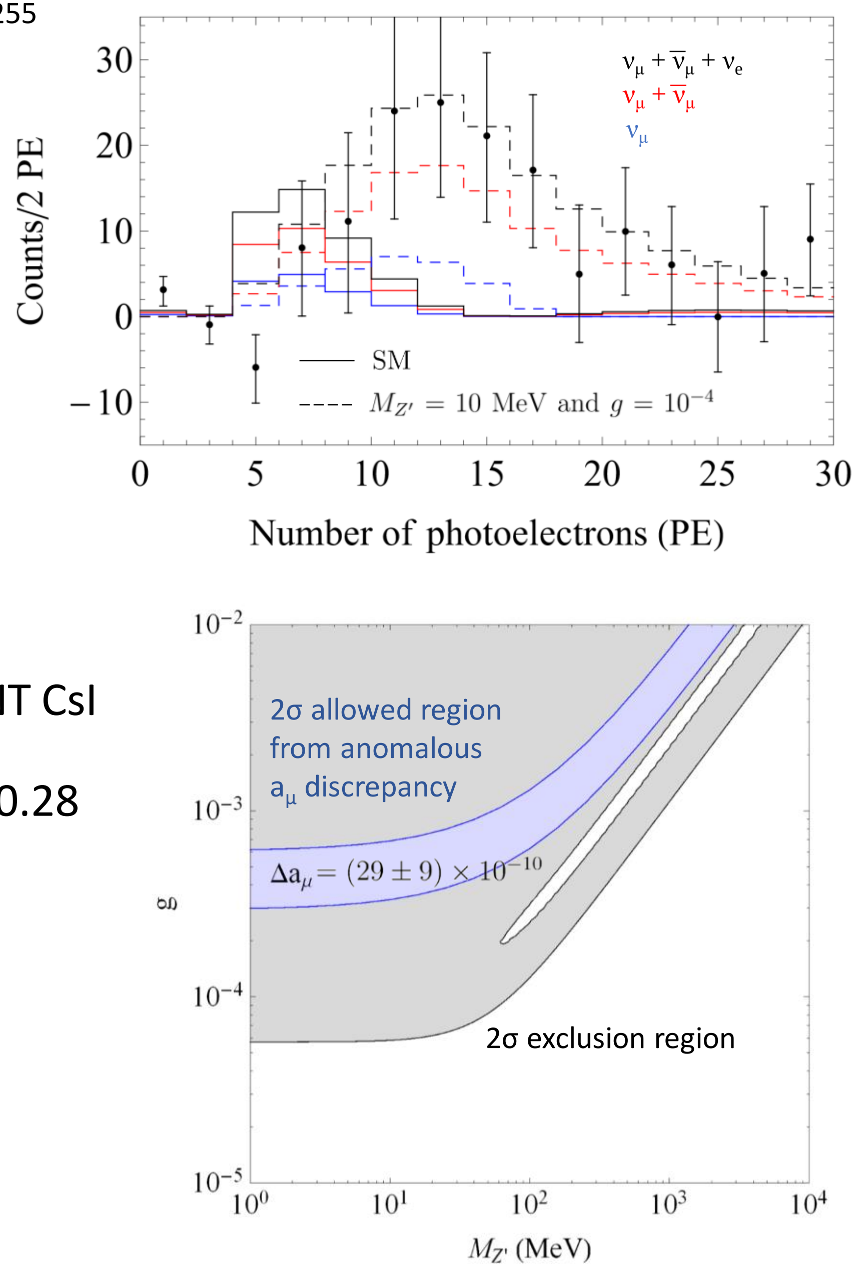
$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi} Q_\alpha^2 F^2(2ME_r) M \left(2 - \frac{ME_r}{E_\nu^2}\right)$$

$$Q^2_{\alpha,\mathrm{SM}} = \left(Z g_p^V + N g_n^V\right)^2$$

$$Q^2_{\alpha,\mathrm{NSI}} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right)\right]^2$$

COHERENT CsI

$\sigma_{syst} = 0.28$

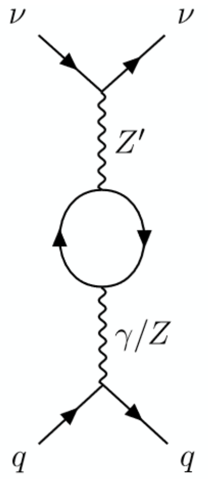


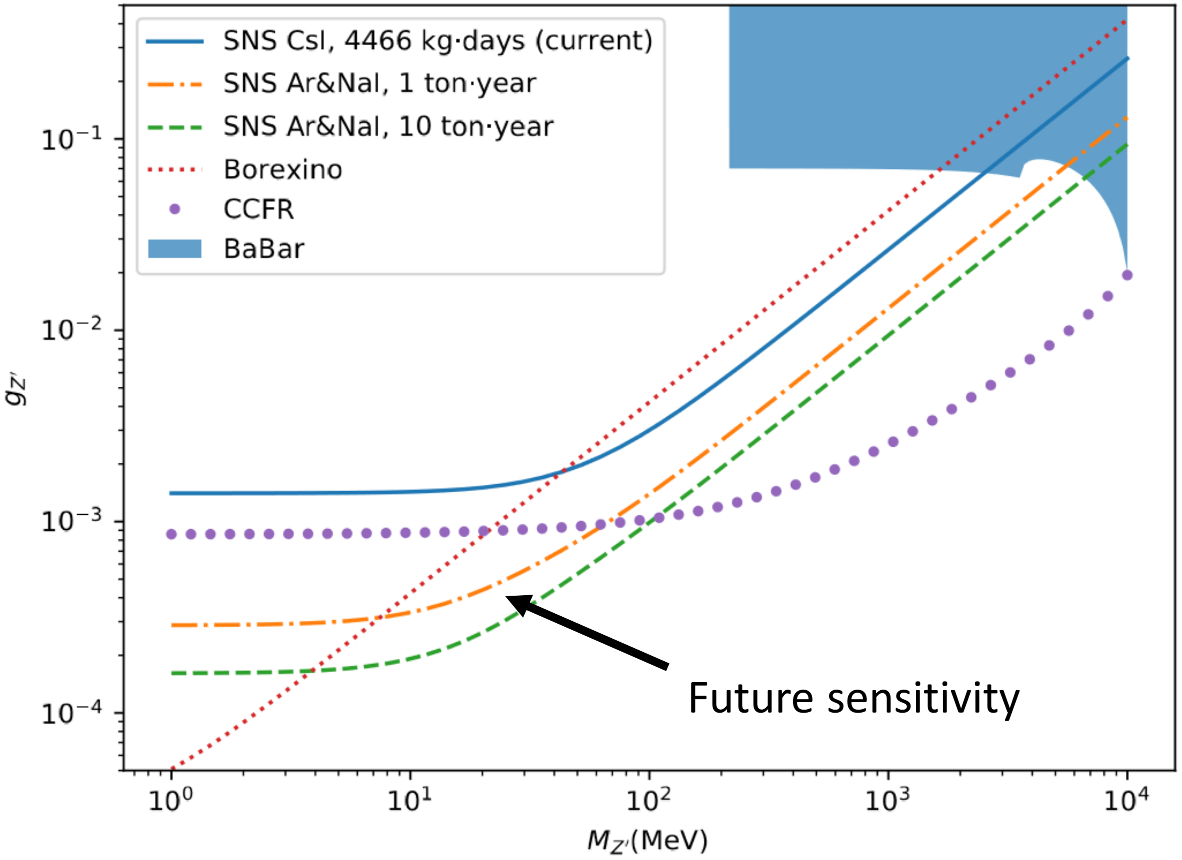
M. Abdullah, J.B. Dent, B. Dutta, G. Kane, S. Liao, and L.E. Strigari, "Coherent Elastic Neutrino Nucleus Scattering (CEvNS) as a probe of Z' through kinetic and mass mixing effects", arXiv:1803.01224

L_μ - L_τ Z' bozon

- Extend SM with non-universal gauge symmetry U(1) L_μ - L_τ

$$\mathcal{L}_{int} \supset g_{Z'} Q_{\alpha\beta}(\bar{l}_\alpha \gamma^\mu l_\beta + \bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta}) Z'_\mu$$





B. Dutta, S. Liao, S. Sinha, and L.E. Strigari,
“Searching for Beyond the Standard Model Physics
with COHERENT Energy and Timing Data”, arXiv:1903.10666

Adding time information

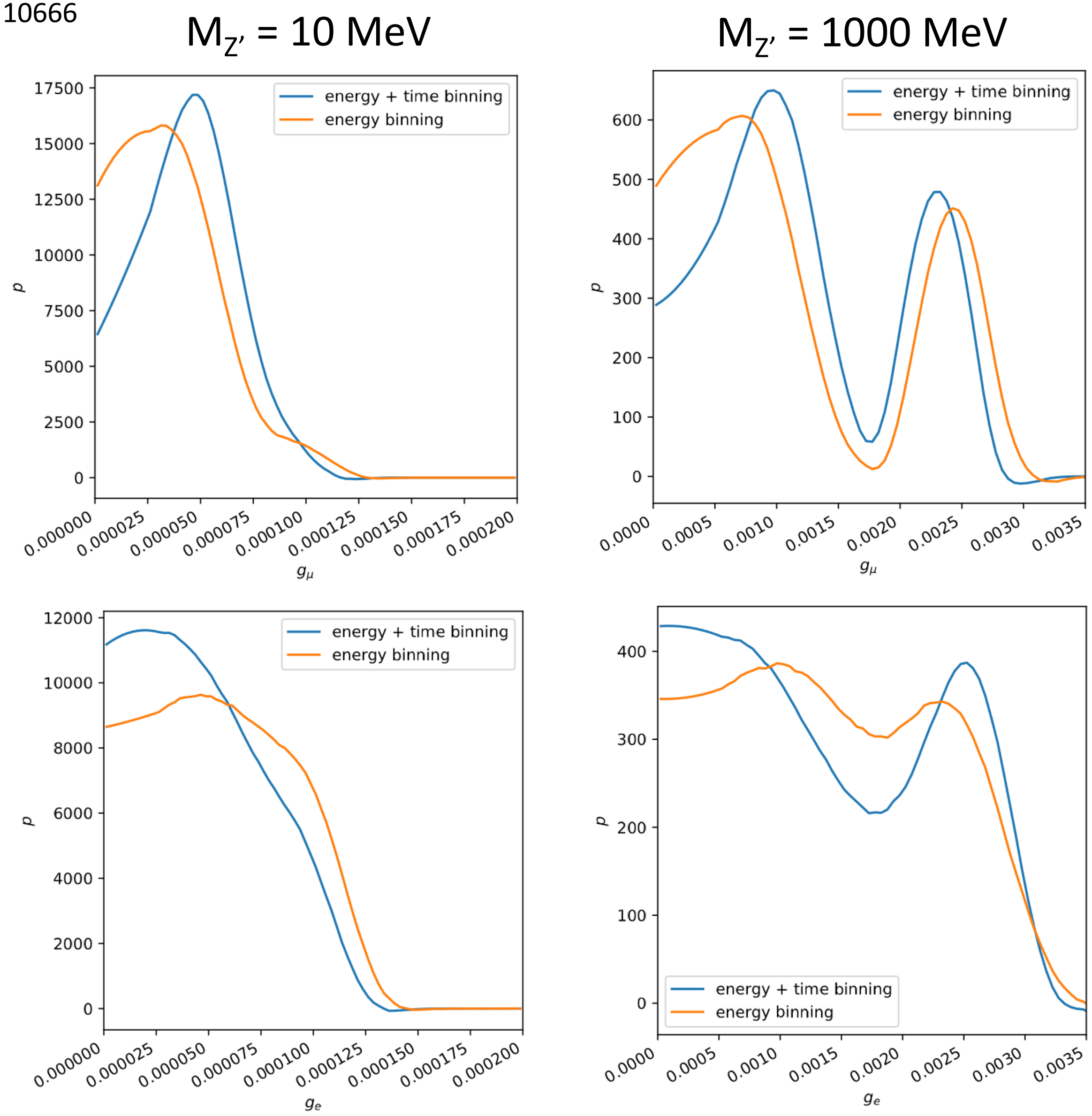
$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m}{2\pi}\left((g_v+g_a)^2 + (g_v-g_a)^2\left(1-\frac{E_R}{E_\nu}\right)^2 + (g_a^2-g_v^2)\frac{mE_R}{E_\nu^2}\right)$$

$$\mathcal{L} \supset Z'_\mu(g'_\nu \bar{\nu}_L\gamma^\mu\nu_L + g'_{f,v}\bar{f}\gamma^\mu f + g'_{f,a}\bar{f}\gamma^\mu\gamma^5 f)$$

$$(g_v, g_a) \Rightarrow (g_v, g_a) + \frac{g'_\nu\,(g'_{f,v}, \pm g'_{f,a})}{\sqrt{2}G_F\,(q^2 + M_{Z'}^2)})$$

$$g_u = g_d = g_\nu = g$$

Adding ν time information improves NSI constraints



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$$\mathcal{L} \supset Z'_\mu(g'_\nu \bar{\nu}_L \gamma^\mu \nu_L + g'_{f,v}\bar{f}\gamma^\mu f + g'_{f,a}\bar{f}\gamma^\mu\gamma^5 f)$$

$$(g_v, g_a) \Rightarrow (g_v, g_a) + \frac{g'_\nu\,(g'_{f,v}, \pm g'_{f,a})}{\sqrt{2}G_F\,(q^2 + M_{Z'}^2)})$$

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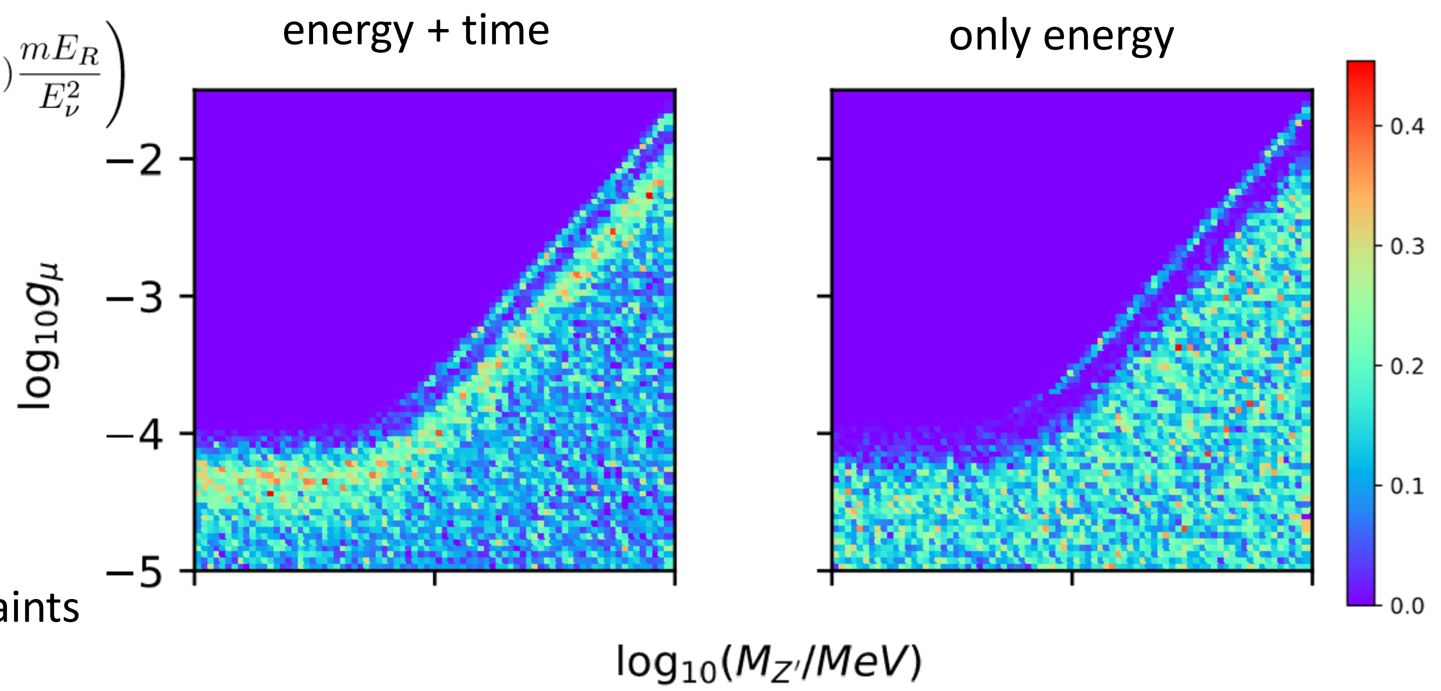
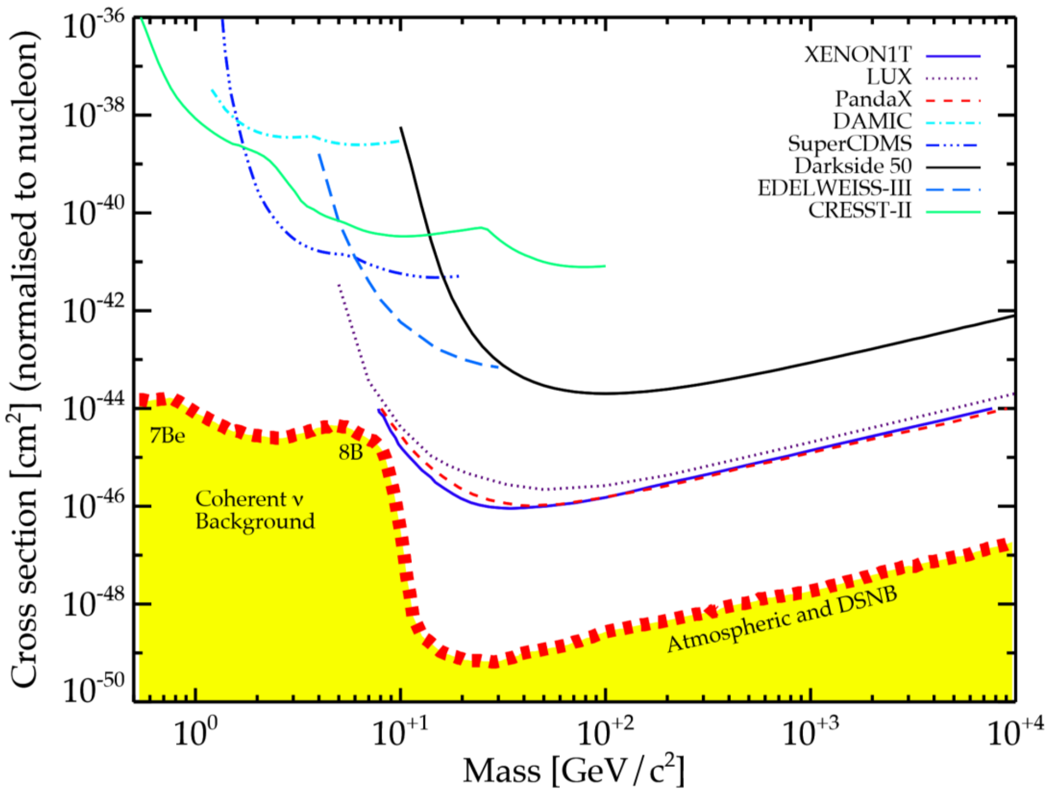


Adding ν time information improves NSI constraints

In this case, NSI is favored by ~2σ

Dark matter: background for DM searches

- Future (next-gen) DM experiments will eventually observe signal
- May be produced by coherently scattering astrophysical ν's instead of DM
- Need to characterize both ν flux and CEνNS to understand this background

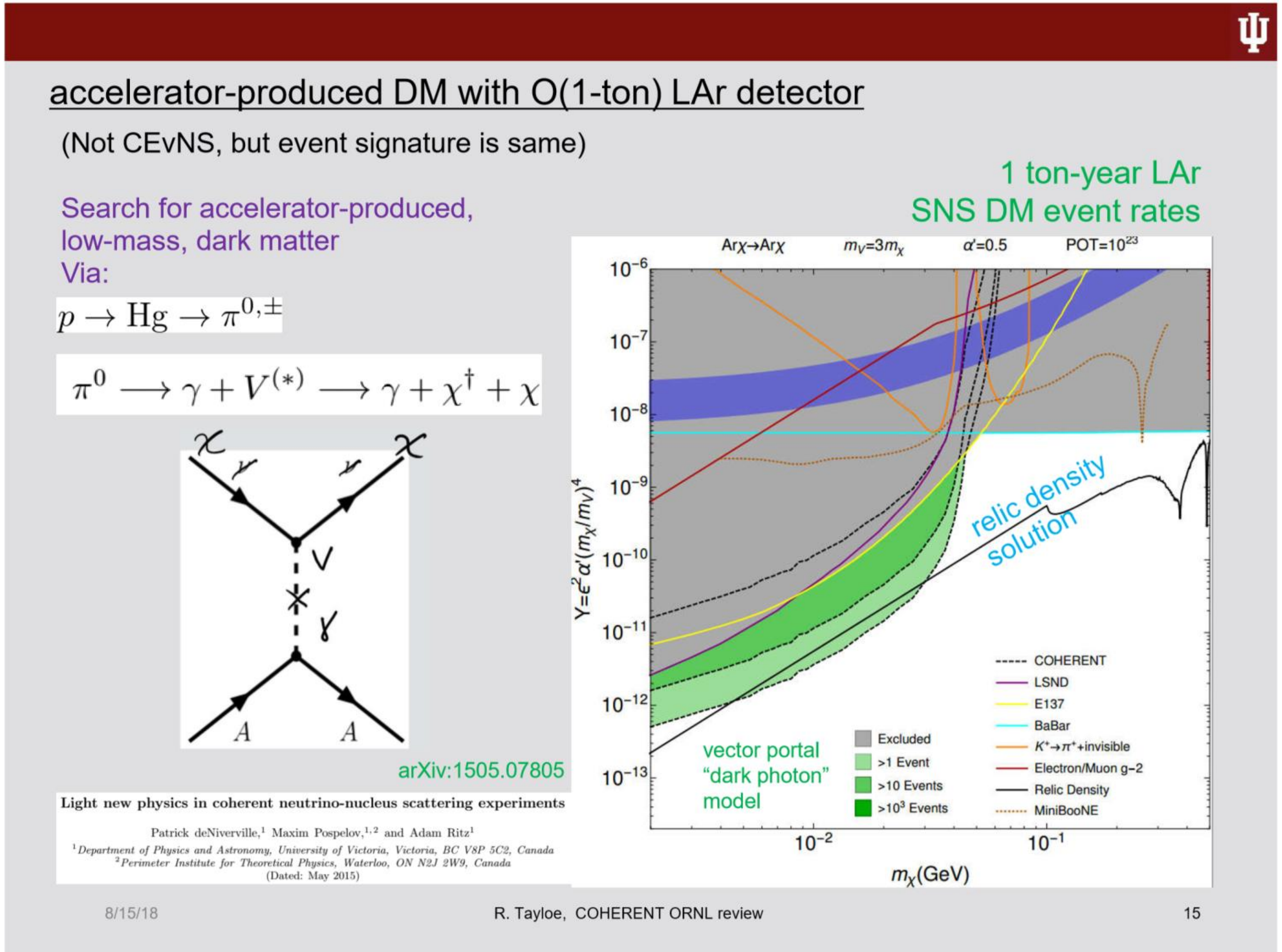


Updated by L. Strigari from

J. Billard, E. Figueroa-Feliciano, and L. Strigari. "Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments." *Phys. Rev.* **D89**, 023524 (2014).

Dark matter: direct measurement

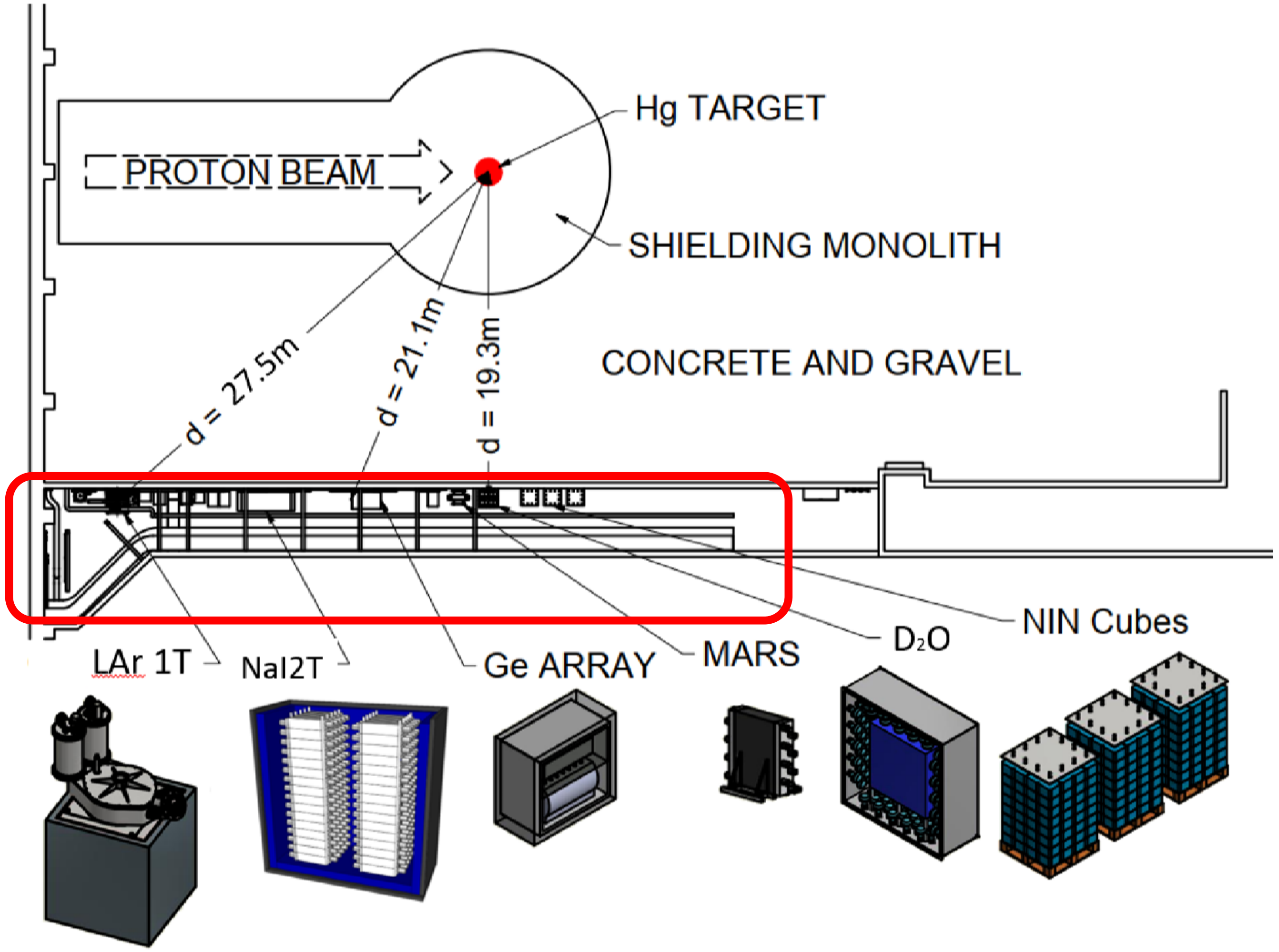
- Sub-GeV DM particles produced by SNS
- Planned studies with future ton-scale detectors



R. Tayloe, "Measurement of CEvNS with a liquid argon detector at the ORNL SNS", The Magnificent CEvNS

Sterile neutrinos

- CEvNS does not depend on ν flavor
  - Excellent way to look for disappearing (or excess) total ν flux!
- Can use available space to vary baseline
- Sensitivity studies under way



Conclusions

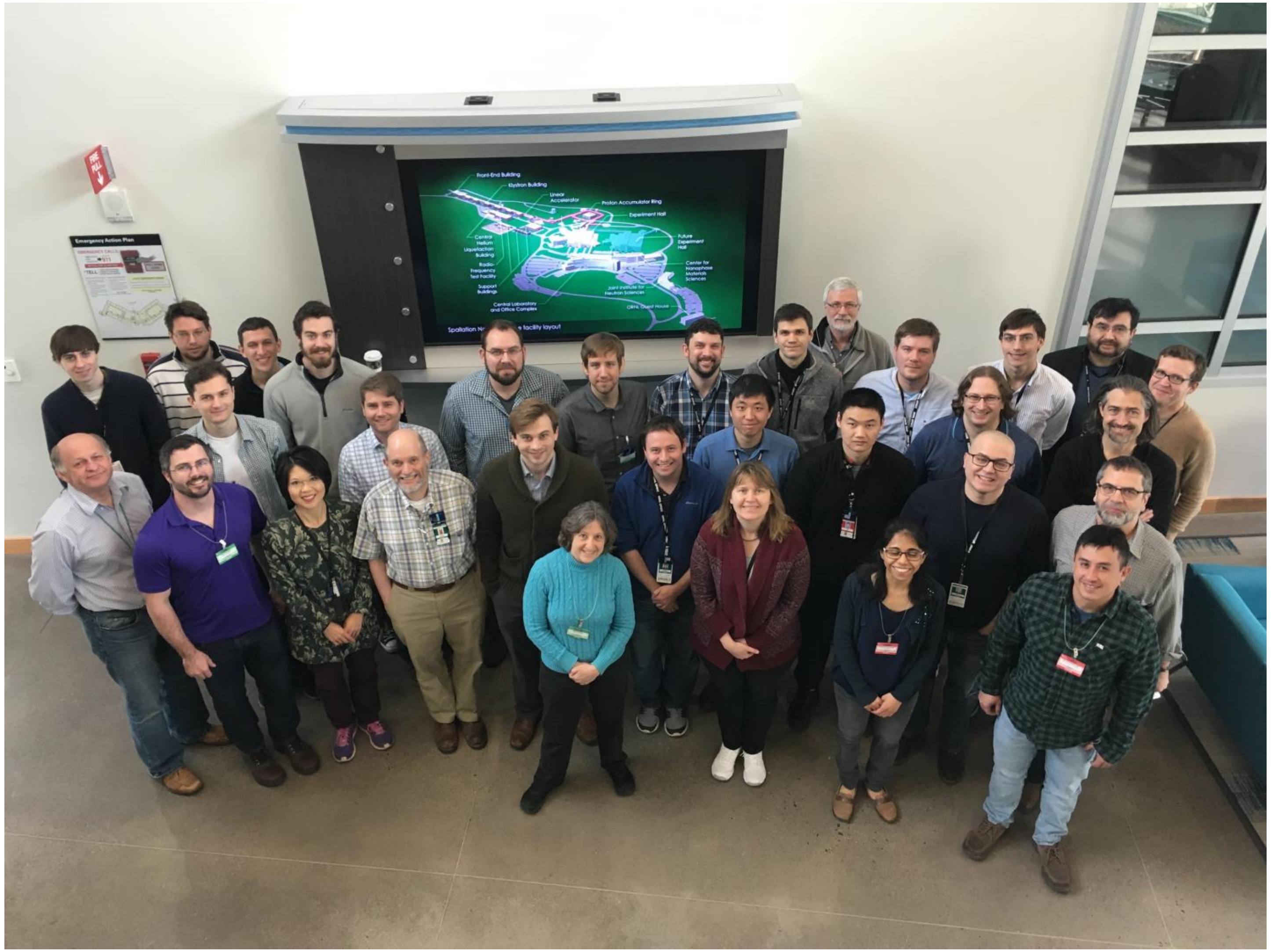
- CsI result already able to constrain BSM physics
- Potentially can do much better with currently running and soon-to-be-installed detectors
  - NSI, dark matter, sterile ν's
  - BSM in measurements of μ_ν, θ_W, …
- COHERENT results can facilitate BSM searches for other experiments
  - CEνNS background for next-gen DM experiments
  - CC ν-Ar cross section for DUNE
  - CC ν-O cross section for Super-K/Hyper-K

wikimedia.org

Backup slides

COHERENT collaboration

~80 members
~20 institutions
4 countries



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Laurentian University / Université Laurentienne
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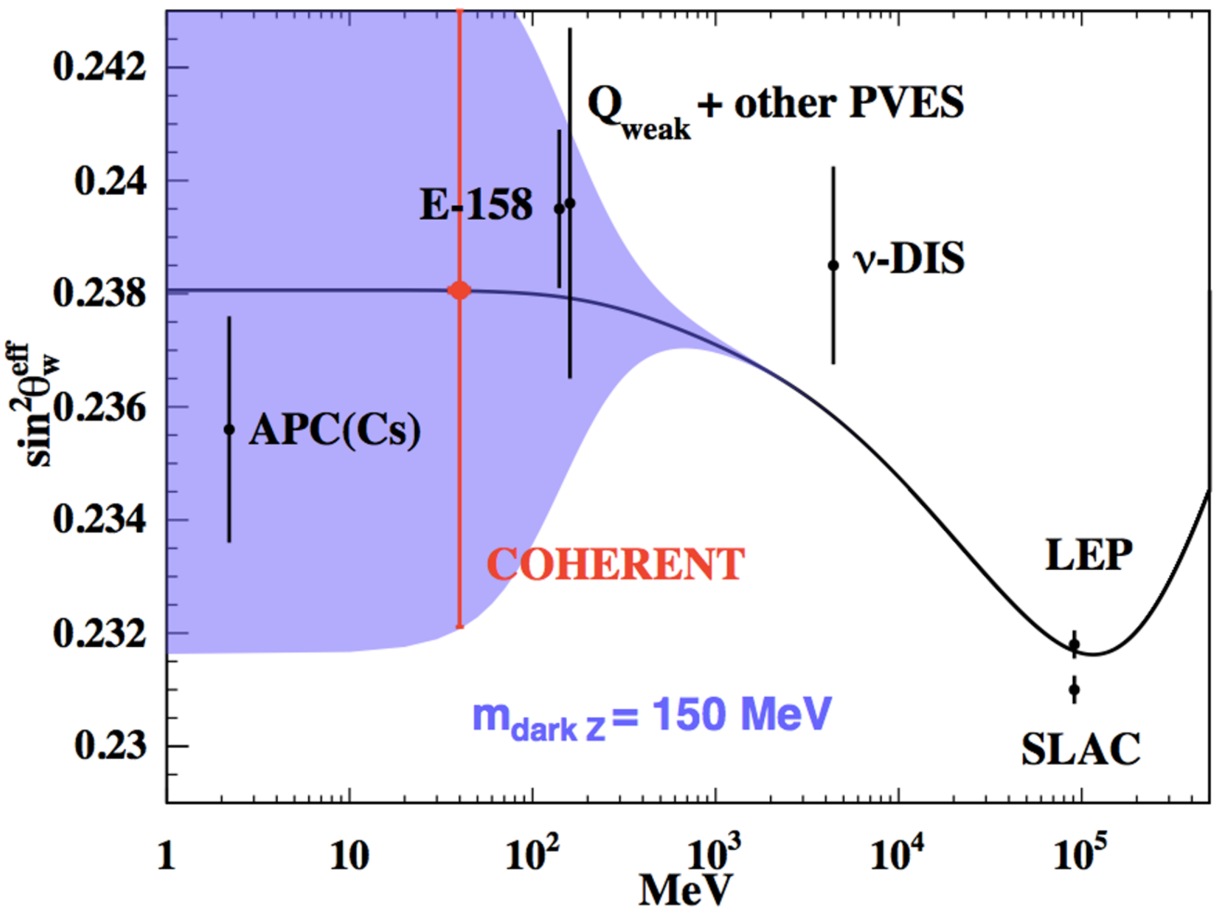
MEPhI
University of South Dakota
North Carolina Central University
NC State University
NM State University
Oak Ridge National Laboratory
Sandia National Laboratories
The University of Tennessee Knoxville
TUNL
University of Washington

CNEC Consortium for Nonproliferation Enabling Capabilities
KICP
NNSA National Nuclear Security Administration
NSF
U.S. Department of Energy

Neutrino magnetic moment

Weak mixing angle



COHERENT CsI NSI limit

- August 2017 result
- 14.6 kg CsI[Na]
- ~2 years running
  - 308.1 live-days
- Events
  - 134 ± 22 observed
  - 173 ± 48 predicted

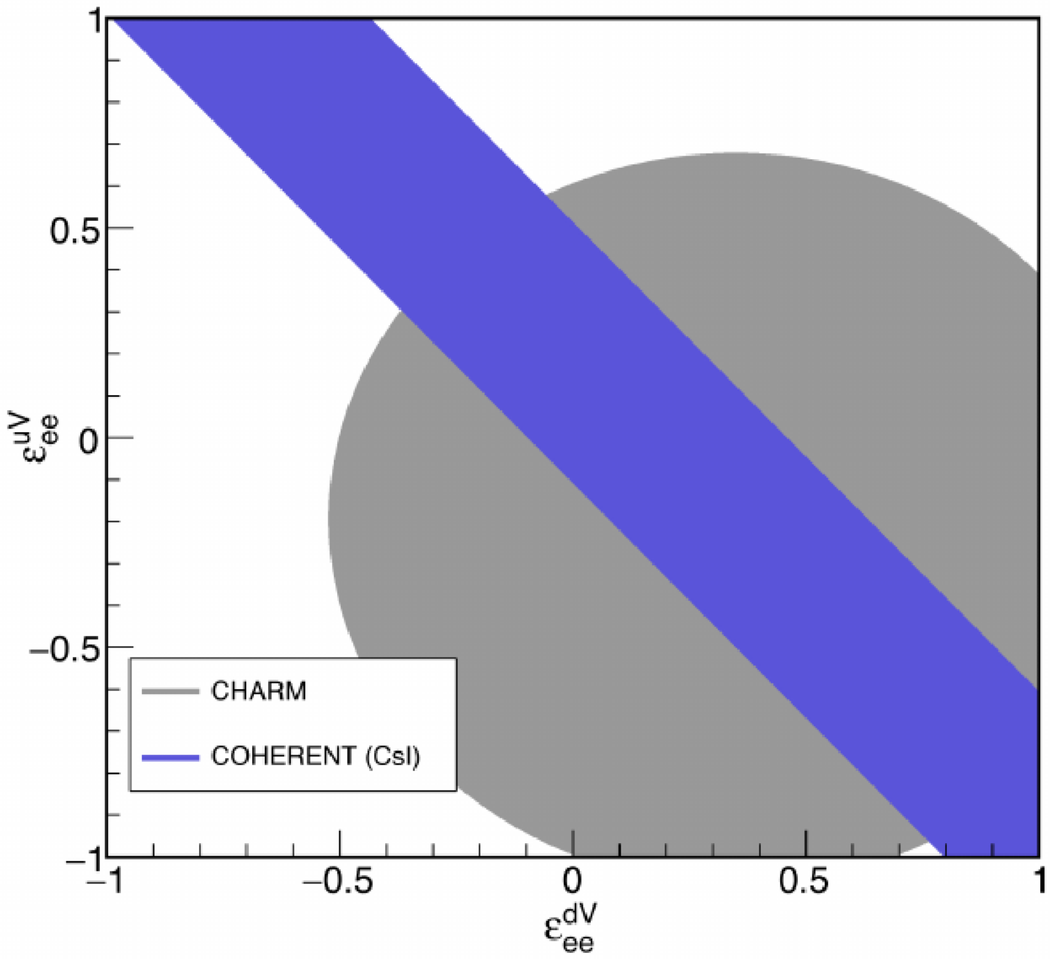


TABLE I: Baseline priors used for the NSI parameters and nuisance parameters in this analysis. Fluxes are per $cm^2 \cdot s$, and backgrounds are per kg·day·keV.

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

TABLE II: Experimental configurations used in this analysis

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

J.B. Dent, B. Dutta, S. Liao, J.L. Newstead, L.E. Strigari, and J.W. Walker, "Accelerator and reactor complementarity in coherent neutrino scattering", arXiv:1711.03521

Considering 4 non-zero NSI couplings

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M. Abdullah, J.B. Dent, B. Dutta, G. Kane, S. Liao, and L.E. Strigari, "Coherent Elastic Neutrino Nucleus Scattering (CEvNS) as a probe of Z' through kinetic and mass mixing effects", arXiv:1803.01224

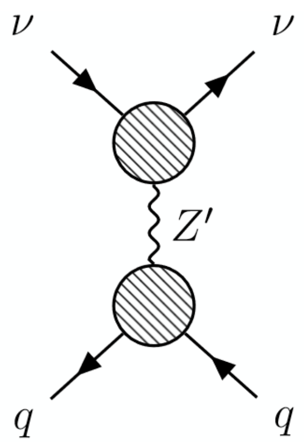
Dark hypercharge Z' bozon

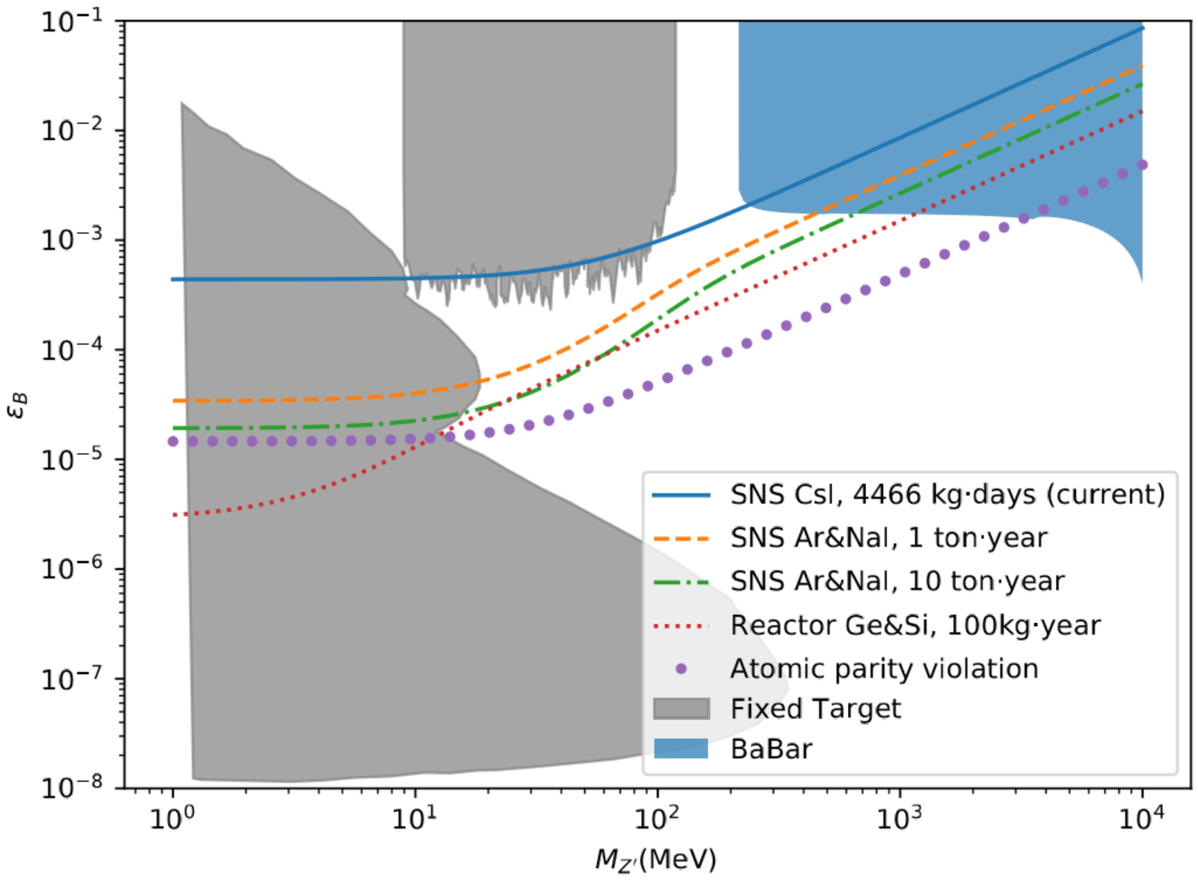
$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m}{2\pi}\left((g_v+g_a)^2 + (g_v-g_a)^2\left(1-\frac{E_R}{E_\nu}\right)^2 + (g_a^2-g_v^2)\frac{mE_R}{E_\nu^2}\right)$$

$$\mathcal{L} \supset Z'_\mu(g'_\nu \bar{\nu}_L\gamma^\mu\nu_L + g'_{f,v}\bar{f}\gamma^\mu f + g'_{f,a}\bar{f}\gamma^\mu\gamma^5 f)$$

$$(g_v, g_a) \Rightarrow (g_v, g_a) + \frac{g'_\nu\,(g'_{f,v}, \pm g'_{f,a})}{\sqrt{2}G_F\,(q^2+M_{Z'}^2)})$$

Z' coupling: $ig\tan\theta_w\,(Y_f/2)\,\epsilon_B$





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Z' coupling: $\frac{-ig}{\cos\theta_w}\epsilon_z\,[T_L^3 - \sin\theta_w^2 Q]$