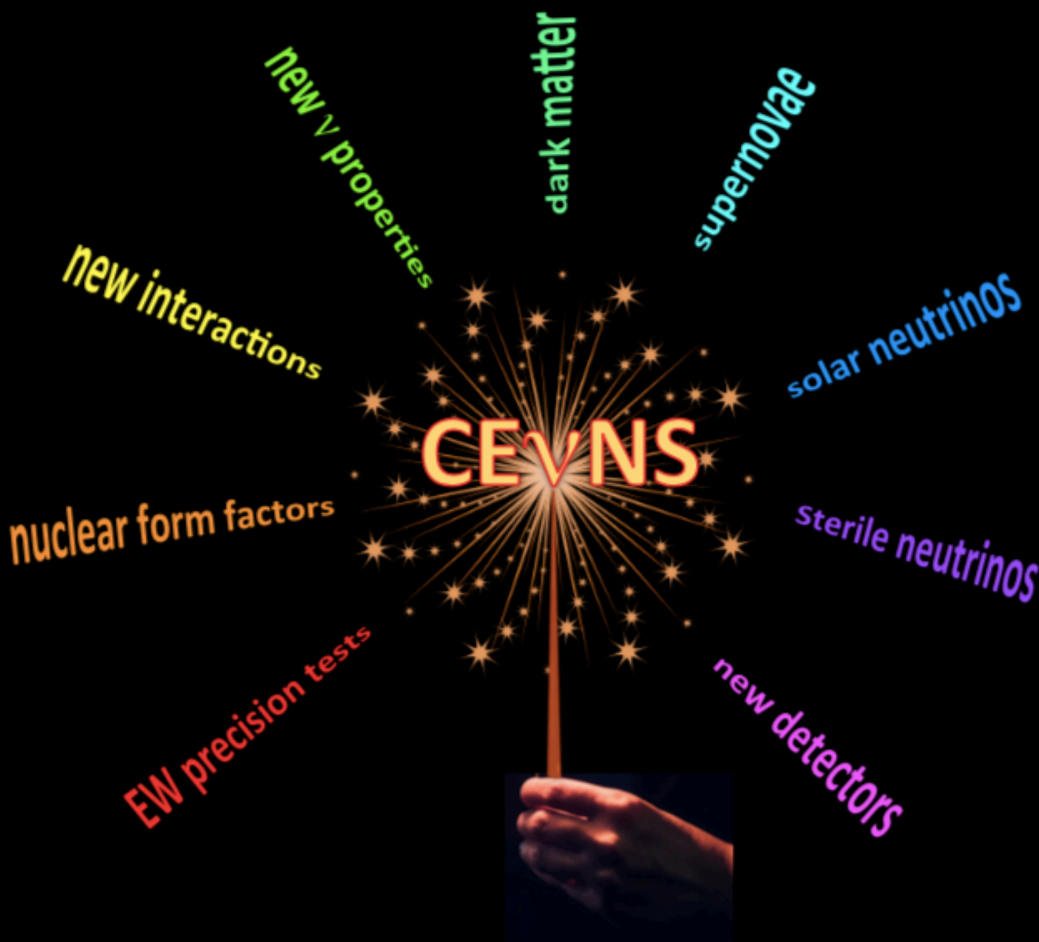
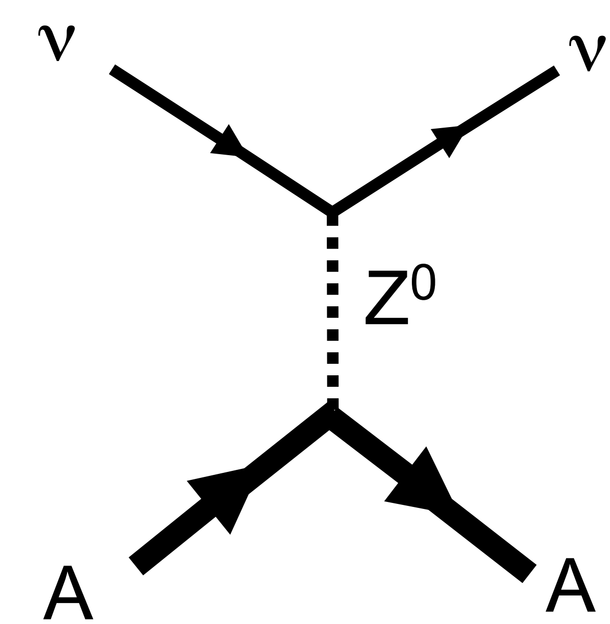
COHERENT Physics Program



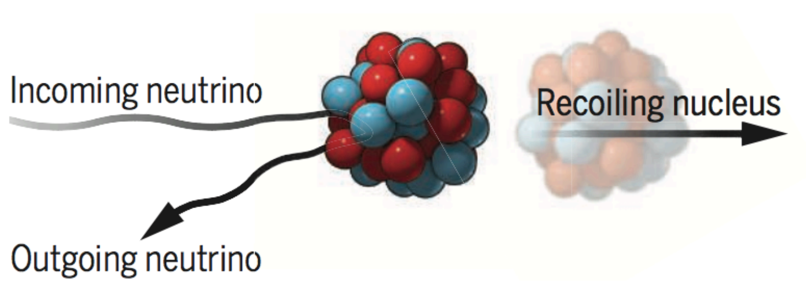
K. Scholberg
COHERENT Review
August 15, 2018

Coherent elastic neutrino-nucleus scattering (CEvNS)

$$\nu + A \rightarrow \nu + A$$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

A: no. of constituents

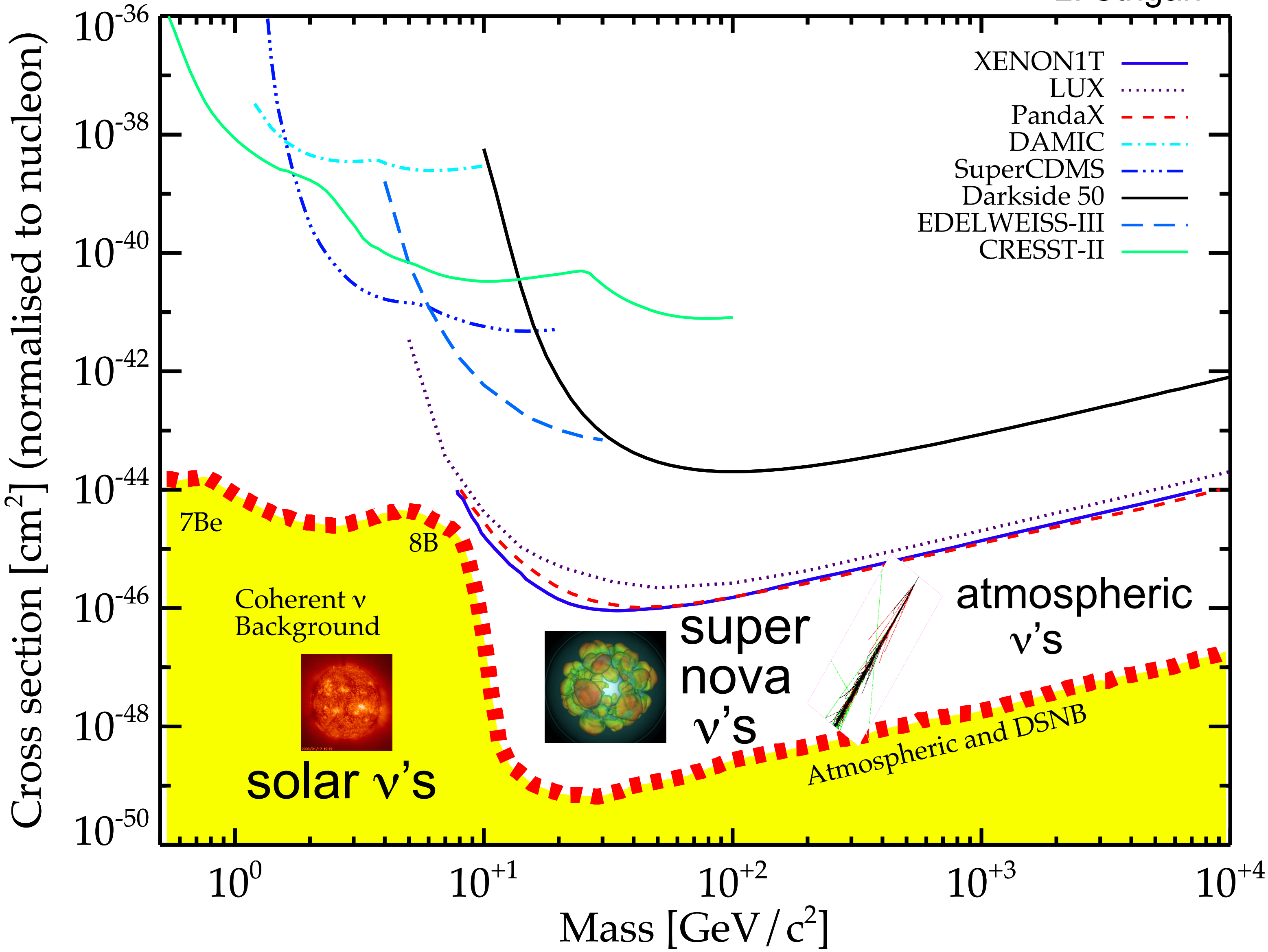
Image: J. Link *Science* Perspectives

The so-called "neutrino floor" (**signal!**) for DM experiments

J. Monroe & P. Fisher, 2007

J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari



Measure CEvNS to understand nature of background/astro signal
(& detector response, DM interaction)

The cross section is cleanly predicted in the Standard Model

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

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

G_V, G_A: SM weak parameters

vector $G_V = g_V^p Z + g_V^n N,$ ← dominates

axial $G_A = g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)$ ← small for most nuclei, zero for spin-zero

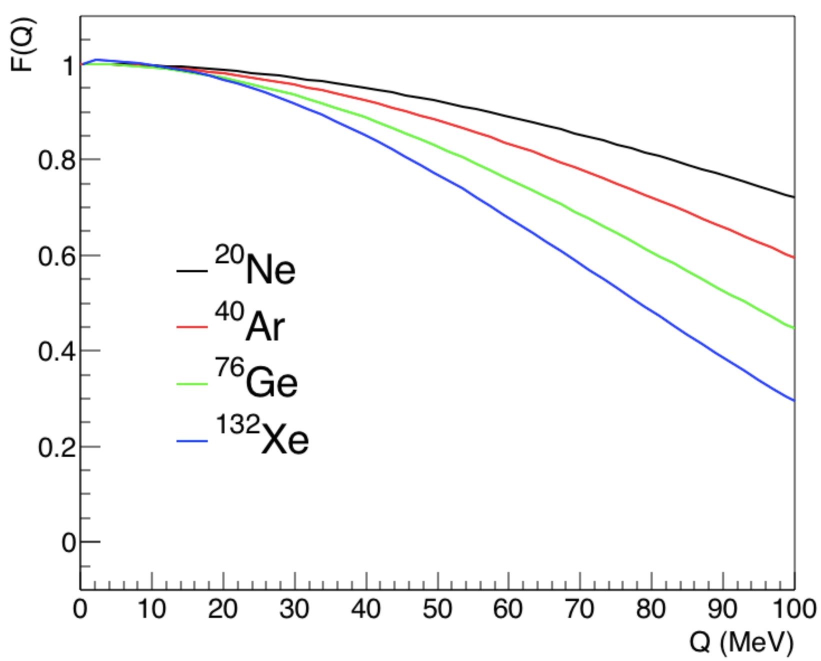
$$g_V^p = 0.0298$$
$$g_V^n = -0.5117$$
$$g_A^p = 0.4955$$
$$g_A^n = -0.5121.$$

The cross section is cleanly predicted in the Standard Model

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

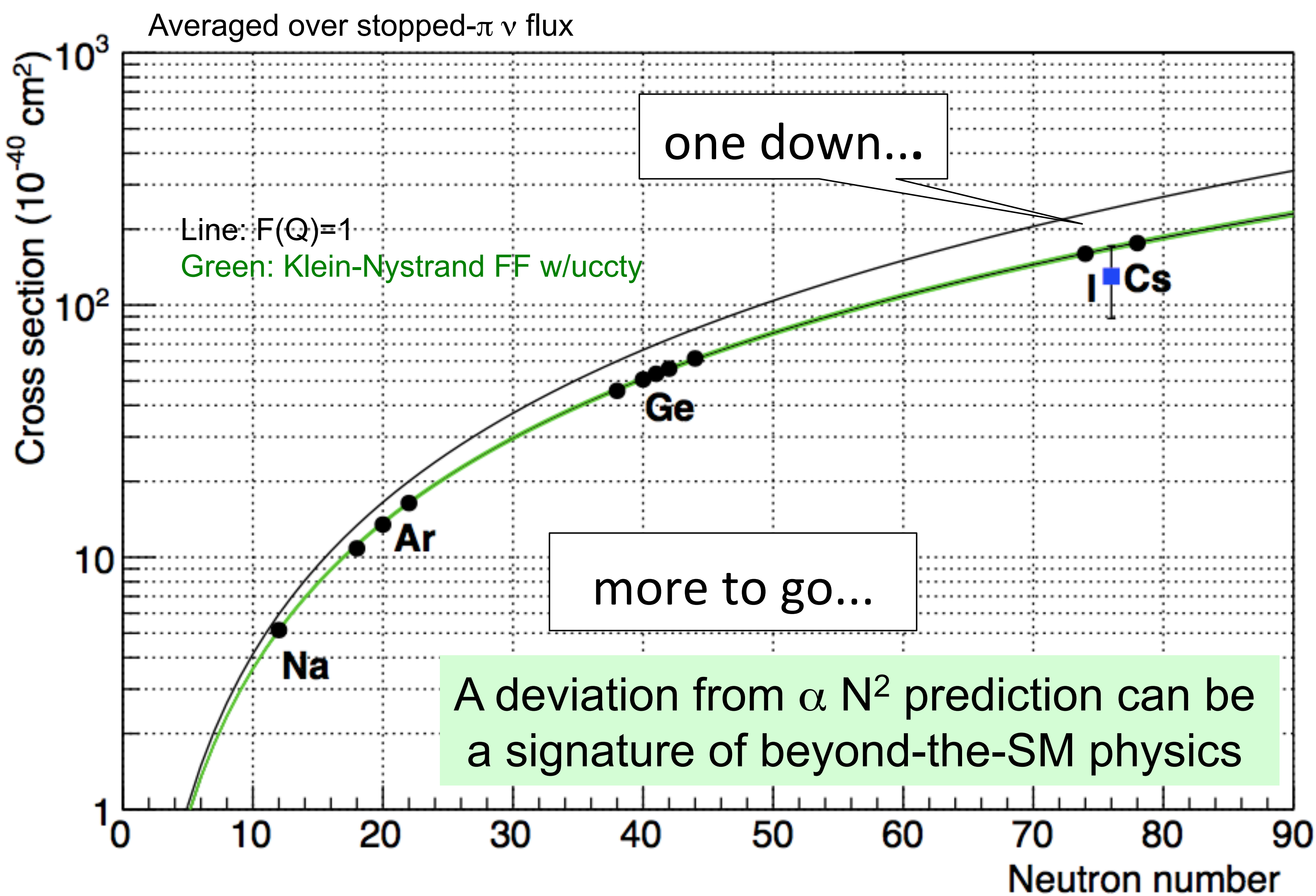
E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

F(Q): nuclear **form factor**, <~5% uncertainty on event rate



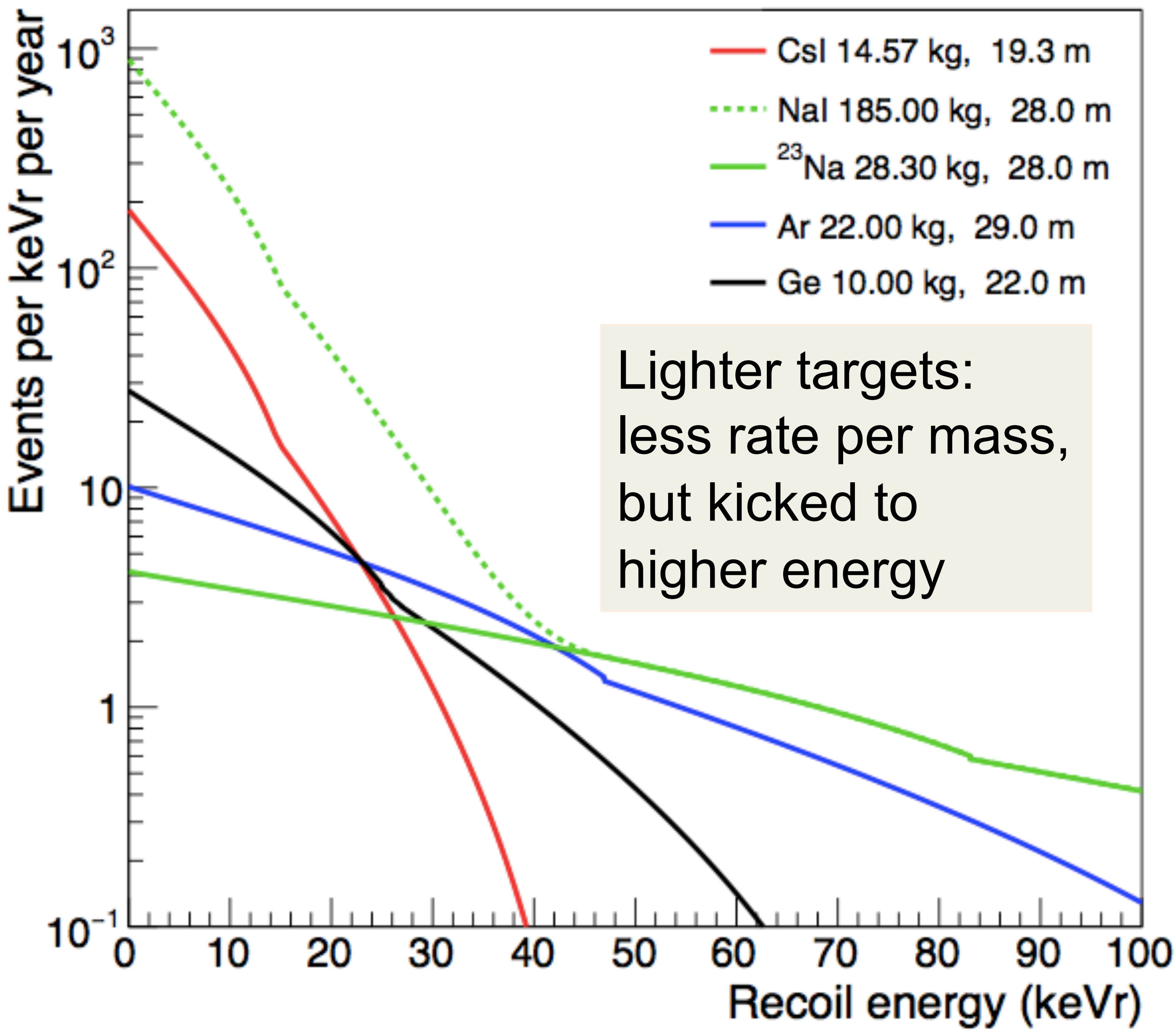
form factor suppresses cross section at large Q

Need to measure **N² dependence** of the CEvNS xscn



A deviation from α N² prediction can be a signature of beyond-the-SM physics

COHERENT's targets: expected recoil energy distributions



COHERENT Physics Topics

Topic	Experimental Signature
Non-standard-interactions/new mediators	Deviation from N^2, deviation from SM recoil spectrum shape
Weak mixing angle measurement	Event rate scaling
Neutrino **magnetic moment**	Excess at low recoil energy
Accelerator-produced **DM**	Event rate scaling
Sterile oscillations	Event rate and spectrum at multiple baselines
Nuclear **form factors**	Recoil spectrum shape
Inelastic CC/NC xscn for **supernova**	High-energy (MeV) electrons, deex γ's
Inelastic CC/NC xscn for **weak coupling parameters**	High-energy (MeV) electrons, deex γ's

COHERENT Physics Topics

Topic	Experimental Signature	Detector Requirements
Non-standard-interactions/new mediators	Deviation from N^2, deviation from SM recoil spectrum shape	Multiple targets, energy resolution, QF
Weak mixing angle measurement	Event rate scaling	Multiple targets, QF
Neutrino **magnetic moment**	Excess at low recoil energy	Low energy threshold and resolution, QF
Accelerator-produced **DM**	Event rate scaling	Energy resolution, QF
Sterile oscillations	Event rate and spectrum at multiple baselines	Similar/movable detectors at multiple baselines
Nuclear **form factors**	Recoil spectrum shape	Energy resolution, QF
Inelastic CC/NC xscn for **supernova**	High-energy (MeV) electrons,deex γ's	Large target mass
Inelastic CC/NC xscn for **weak coupling parameters**	High-energy (MeV) electrons, deex γ's	Large target mass

Physics topics by detector subsystem

	CsI	Ar	NaI	Ge	Nubes	D_2O
Non-standard-interactions/ new mediators	✔	✔	✔	✔		
Weak mixing angle measurement	✔	✔	✔	✔		
Neutrino **magnetic moment**				✔		
Accelerator-produced **DM**	✔	✔	✔	✔		
Sterile oscillations	✔	✔	✔	✔		
Nuclear **form factors**	✔	✔	✔	✔		
Inelastic CC/NC xscn for **supernova**		✔			✔	✔
Inelastic CC/NC xscn for **weak coupling parameters**		✔	✔		✔	

Grey texture: ***combination* important** (N^2, systematics cancellation)
D_2O important for all
Quenching factor measurements critical for all

Searching for BSM Physics with CEvNS

A first example: simple counting to constrain **non-standard interactions (NSI)** of neutrinos with quarks

Davidson et al., JHEP 0303:011 (2004)
Barranco et al., JHEP 0512:021 (2005)

"Model-independent" parameterization

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

ε's parameterize new interactions

"Non-Universal": ε_{ee}, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$

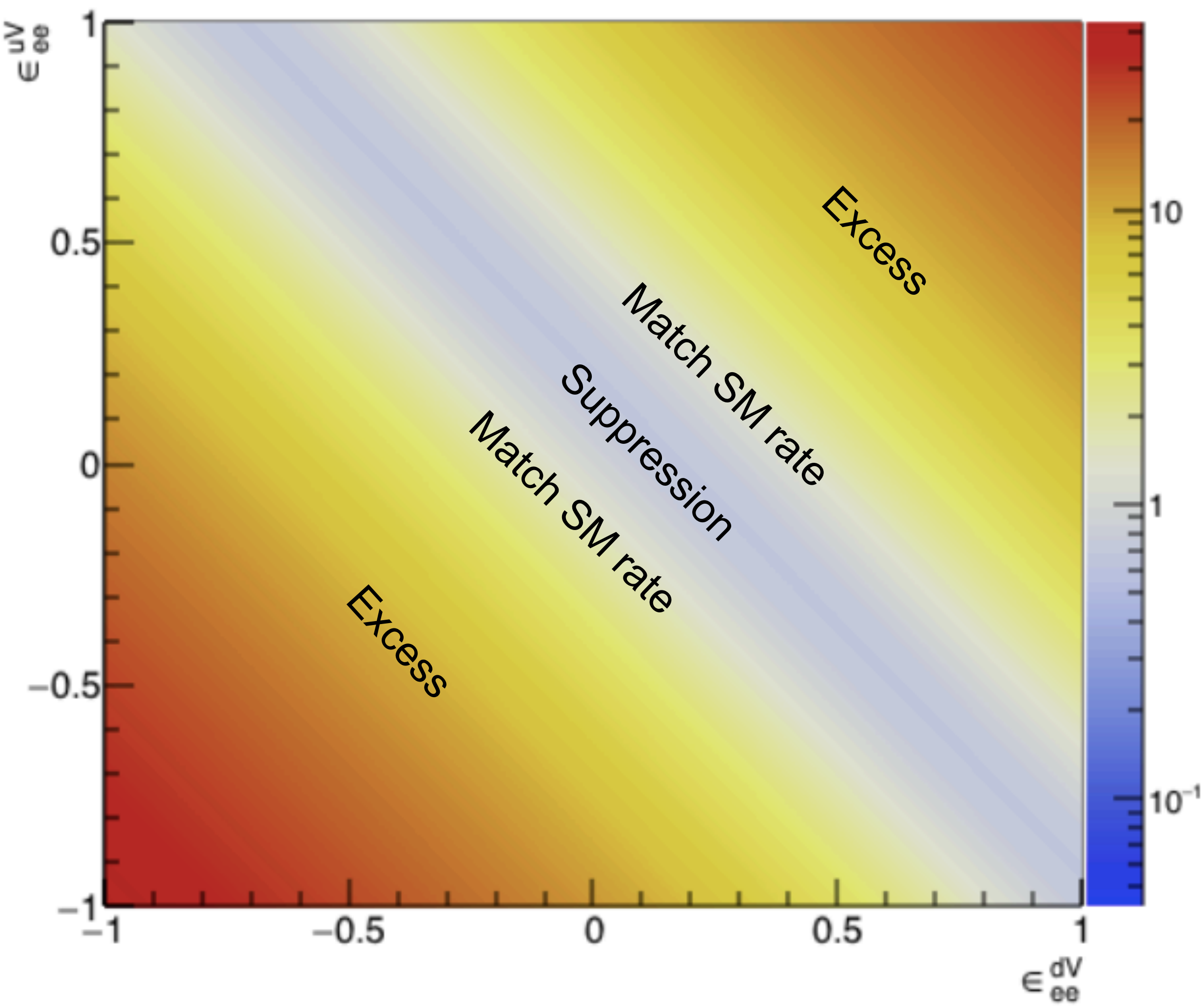
Flavor-changing: $\varepsilon_{\alpha\beta}$, where $\alpha \neq \beta$

$\Rightarrow$ some are quite poorly constrained (~unity allowed)

Ratio of rate with NSI to SM rate (all flavors in stopped-pion beam)

ε_{ee}^{uV} vs ε_{ee}^{dV} parameters (assume others zero)

CsI



Note that for

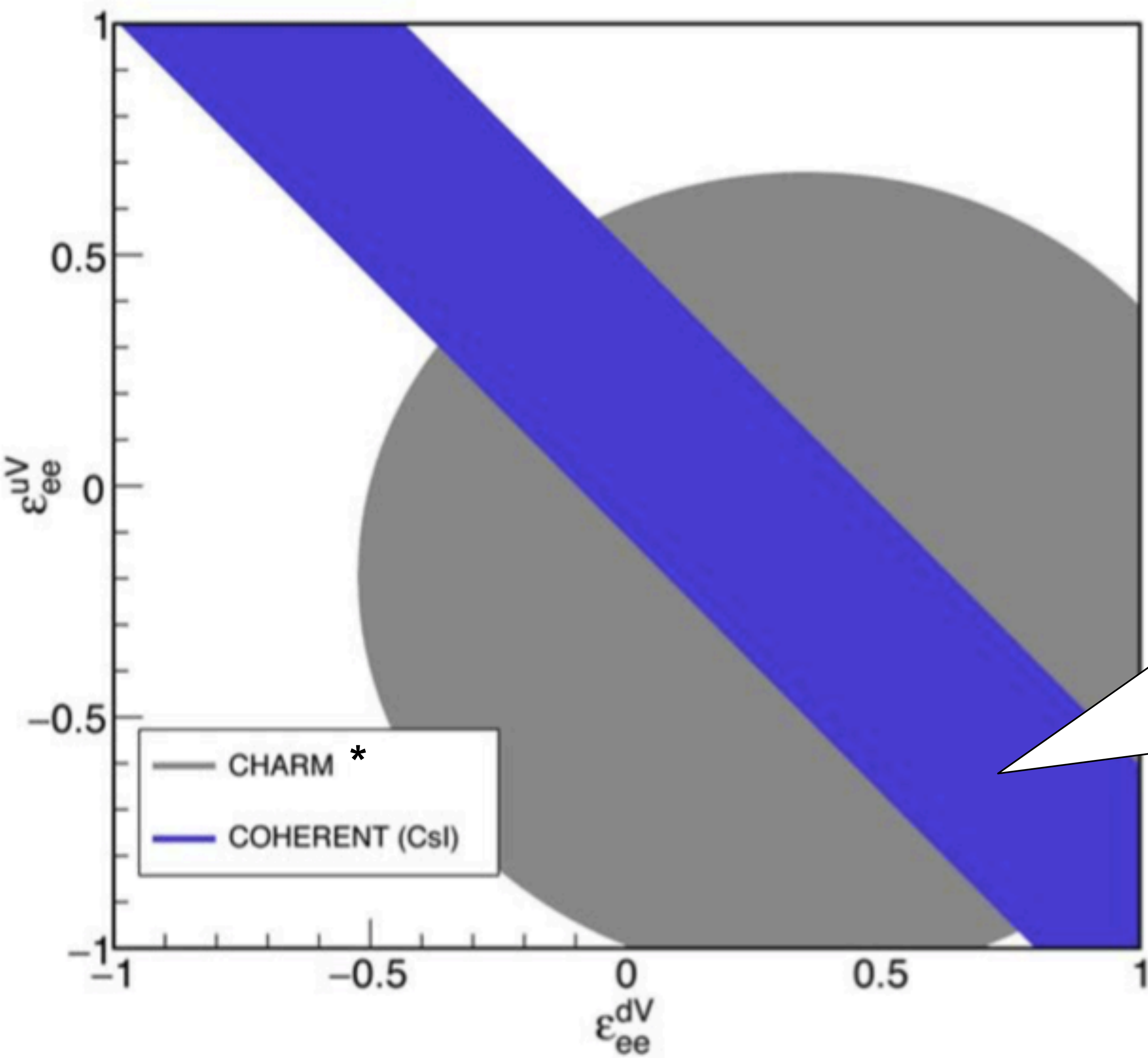
$$Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) = \pm(Zg_V^p + Ng_V^n),$$

the rate is the same as for the SM, so parameters will be allowed

Get slightly different slope for different targets

Example: **Neutrino non-standard interactions**

Constraints for current CsI data set:



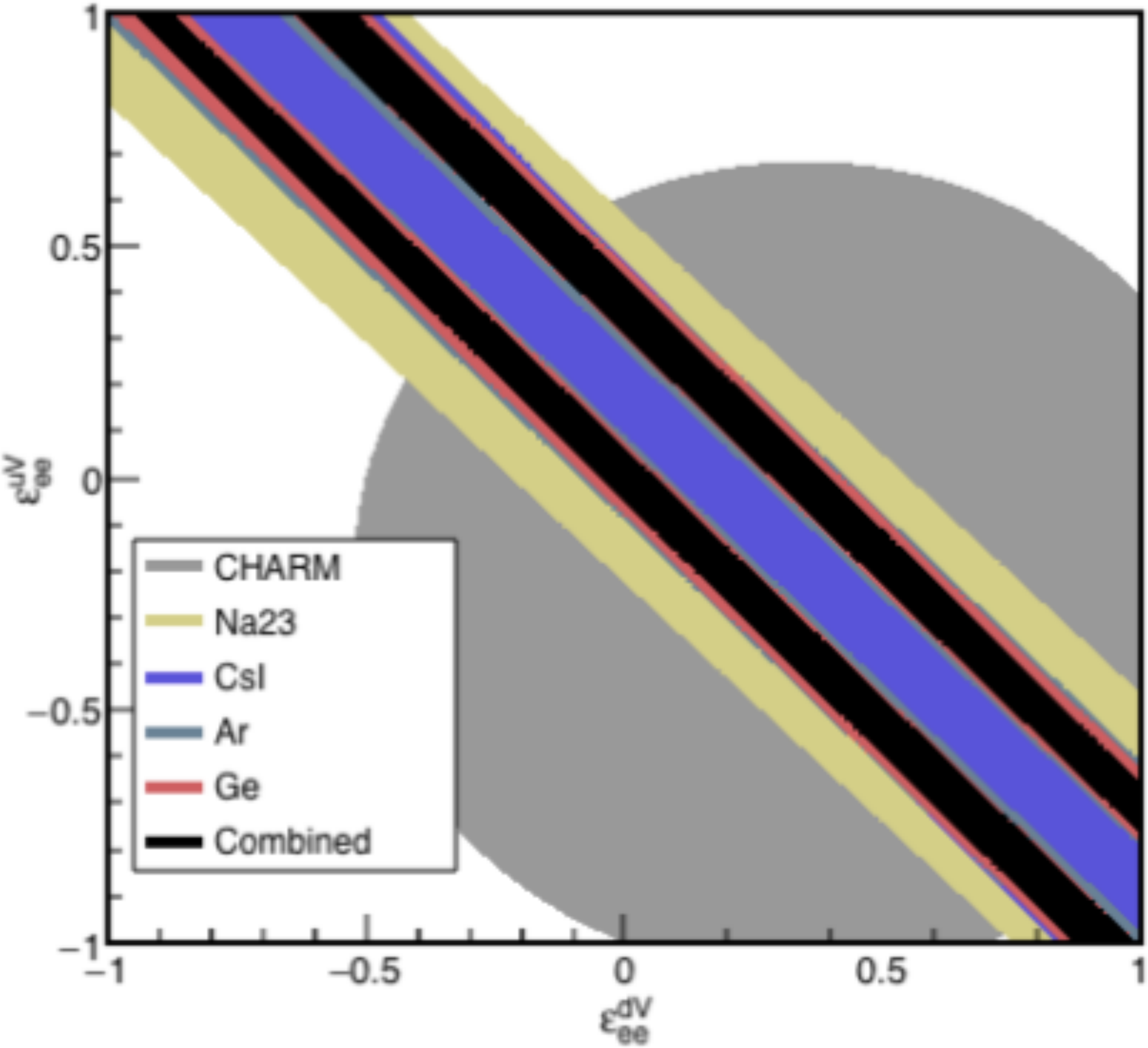
- Assume all other ε's zero

Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

See also Coloma et al., arXiv:1708.02899

*CHARM constraints apply only to heavy mediators

Projected future sensitivities for NSI

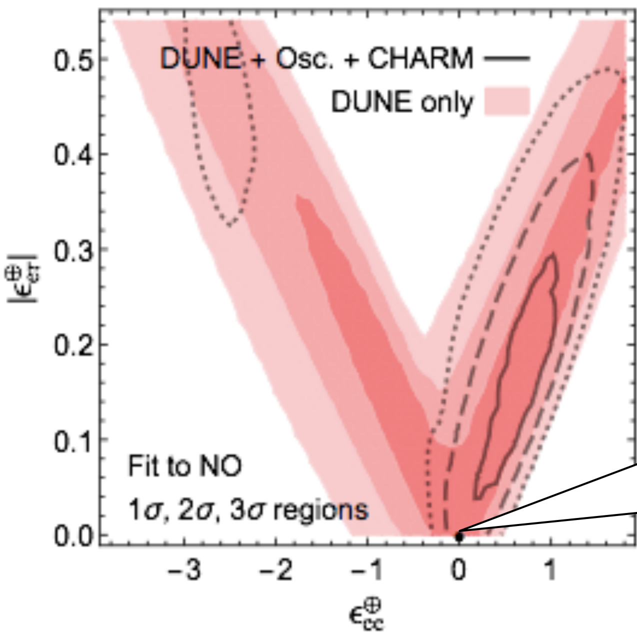


Combination of targets improves sensitivity

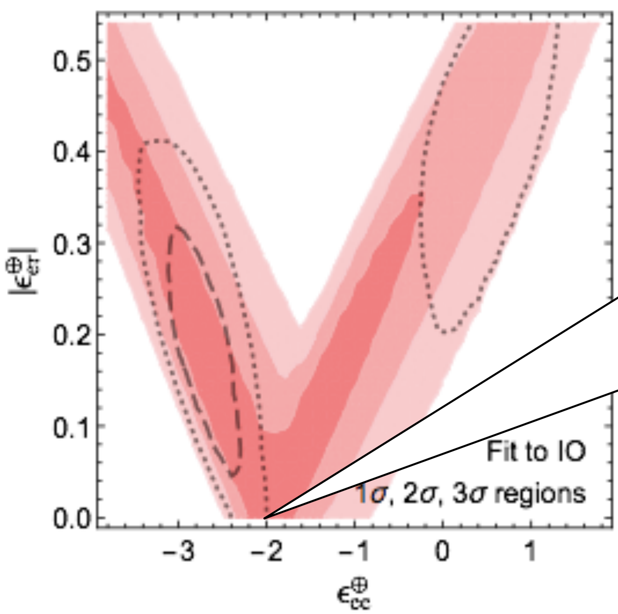
Generalized mass ordering degeneracy in neutrino oscillation experiments

Pilar Coloma[1] and Thomas Schwetz[2]

Phys.Rev. D94 (2016) no.5, 055005,
Erratum: Phys.Rev. D95 (2017) no.7, 079903
P. Coloma et al., JHEP 1704 (2017) 116



Normal ordering w/no NSI...



...looks just like inverted ordering w/NSI

If you allow for NSI, an ambiguity exists in determining mass ordering w/ LBL experiments: **"LMA-Dark"**

Same answer for

$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21} = -\Delta m^2_{32}\,,$$
$$\sin\theta_{12} \to \cos\theta_{12}\,,$$
$$\delta \to \pi - \delta\,,$$
$$(\epsilon_{ee} - \epsilon_{\mu\mu}) \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2\,,$$
$$(\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\,,$$
$$\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha \neq \beta)$$

Generalized mass ordering degeneracy in neutrino oscillation experiments

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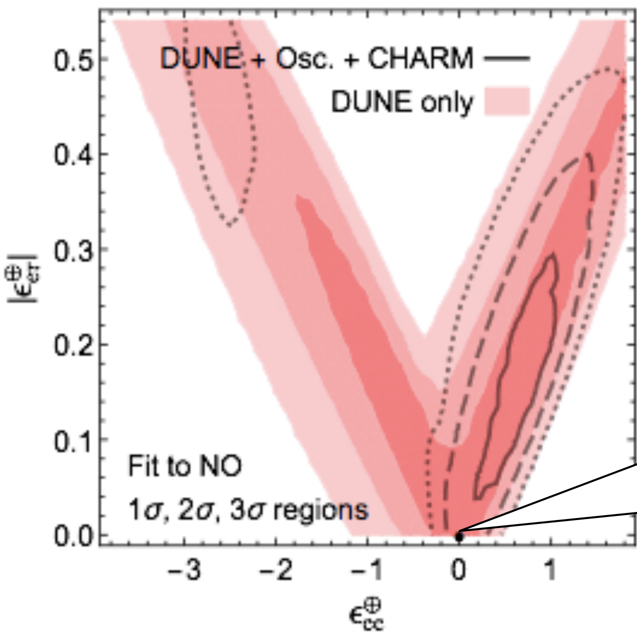
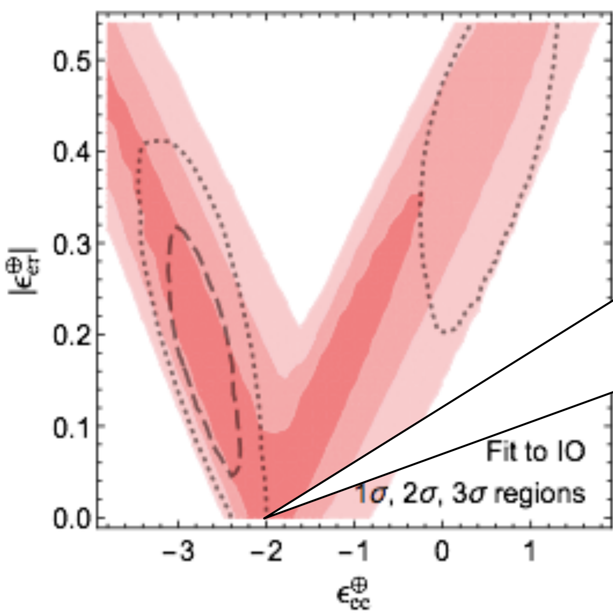


Normal ordering w/no NSI...



...looks just like inverted ordering w/NSI

CEvNS measurements can place significant constraints to **resolve the LMA-D ambiguity** if SM rate is measured

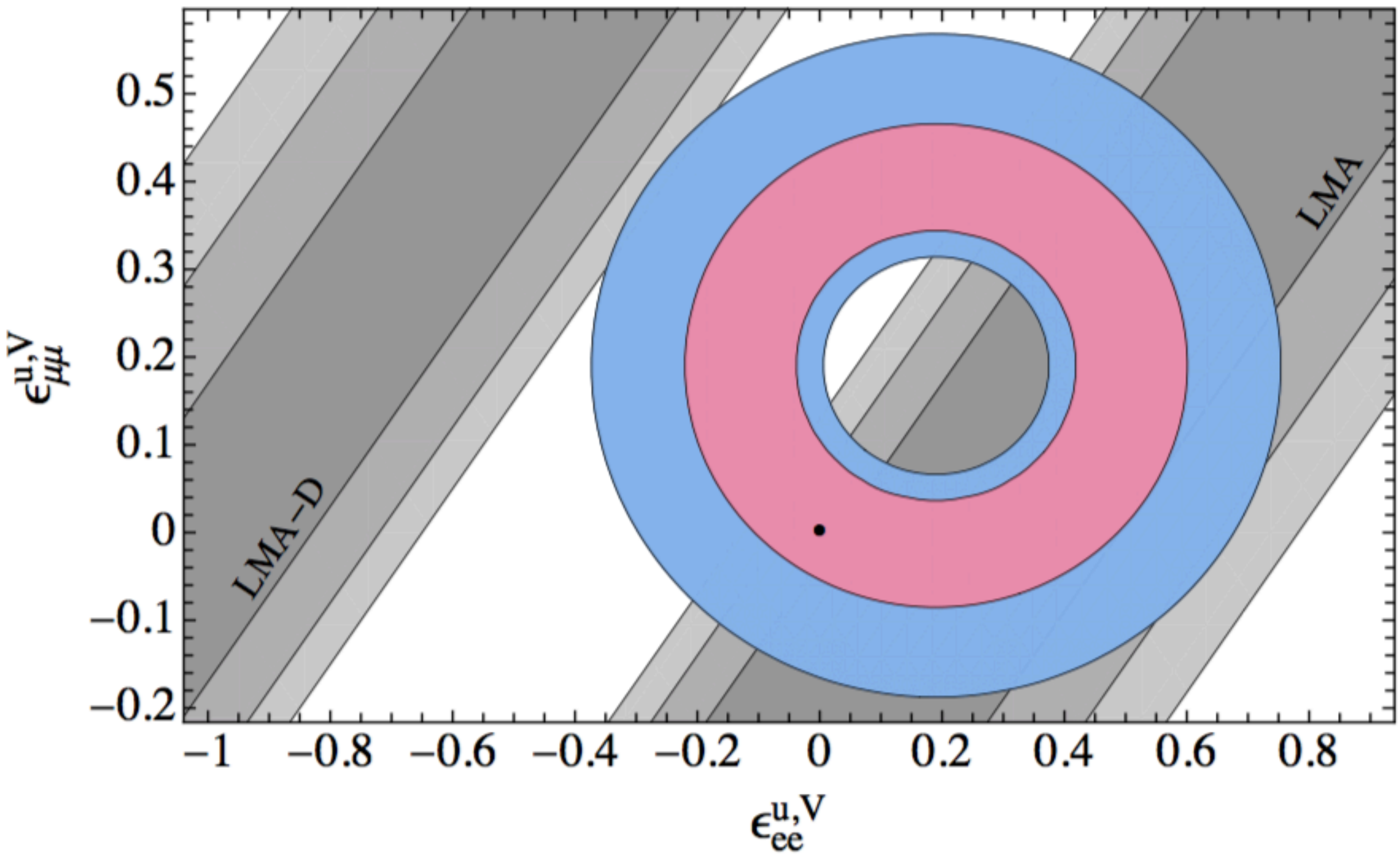
OR, could *confirm an NSI signature* observed by DUNE

A COHERENT enlightenment of the neutrino Dark Side

Pilar Coloma,[1,*] M. C. Gonzalez-Garcia,,[2,3,4,†] Michele Maltoni,,[5,‡] and Thomas Schwetz[6,§]

Phys.Rev. D96 (2017) no.11, 115007

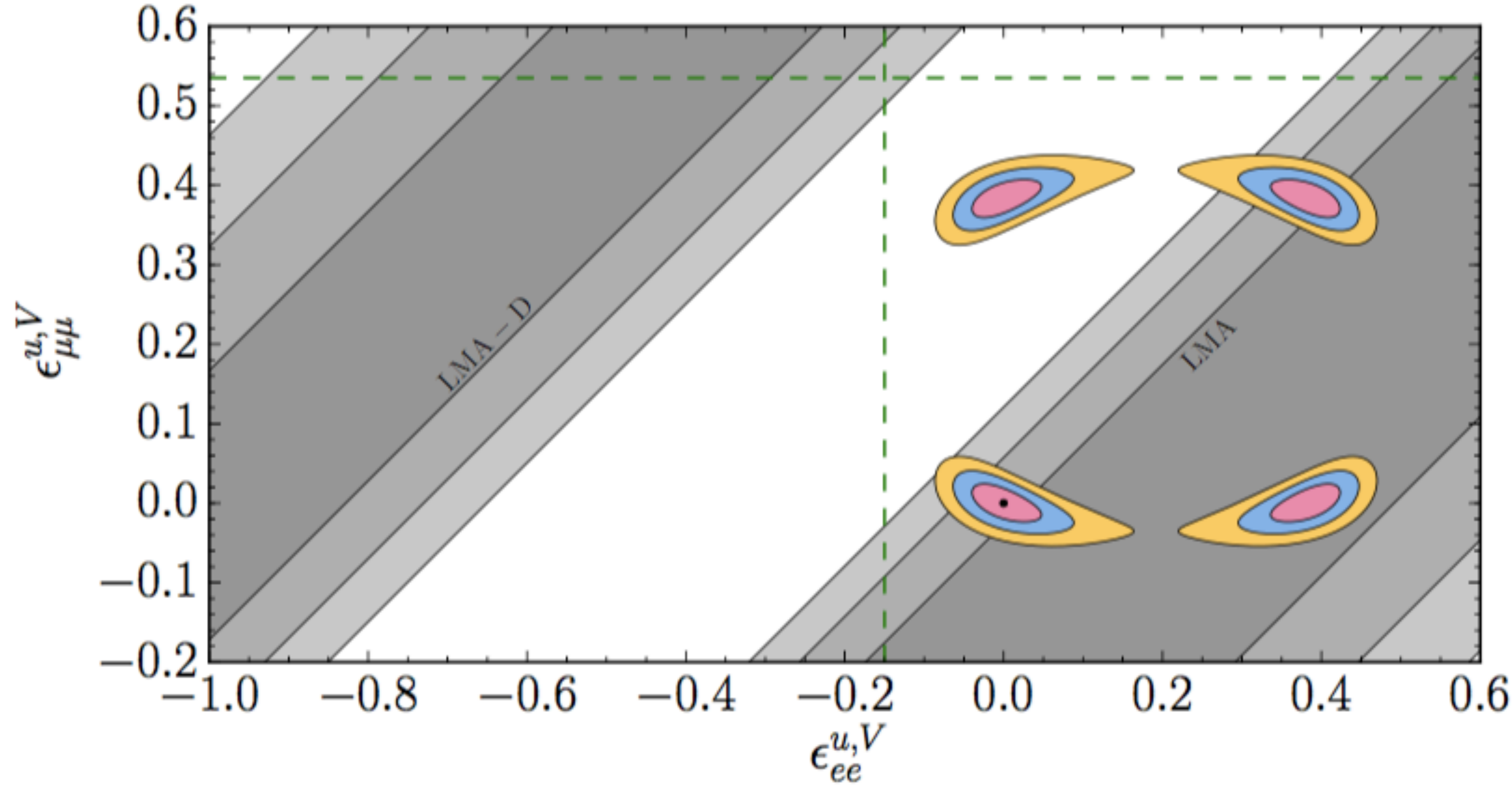
1σ, 2σ allowed regions projected in (ε_{ee}^{uV}, $\varepsilon_{\mu\mu}^{uV}$) plane



First COHERENT results are already disfavoring LMA-D

P. Coloma et al., JHEP 1704 (2017) 116

Future COHERENT results will fully exclude LMA-D



Another phenomenological analysis, making use of spectral fit:

COHERENT constraints on nonstandard neutrino interactions

Jiajun Liao and Danny Marfatia

arXiv:1708.04255

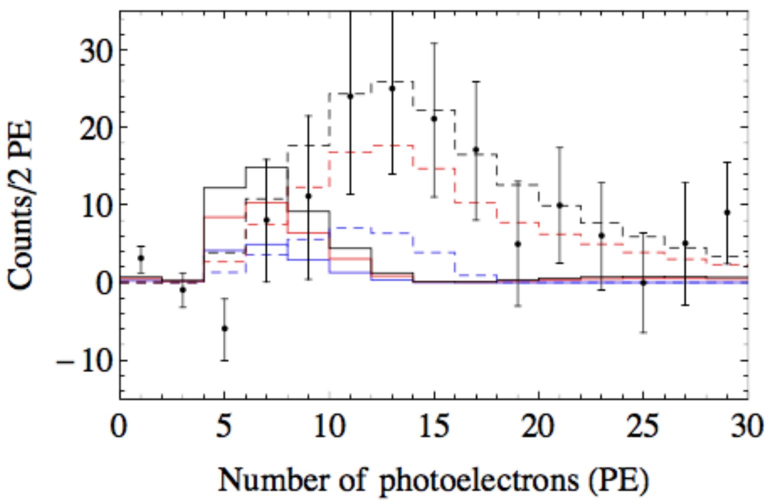
SM weak charge

$$Q^2_{\alpha,\mathrm{SM}} = \left(Zg_p^V + Ng_n^V\right)^2$$

Effective weak charge in presence of light vector mediator Z'

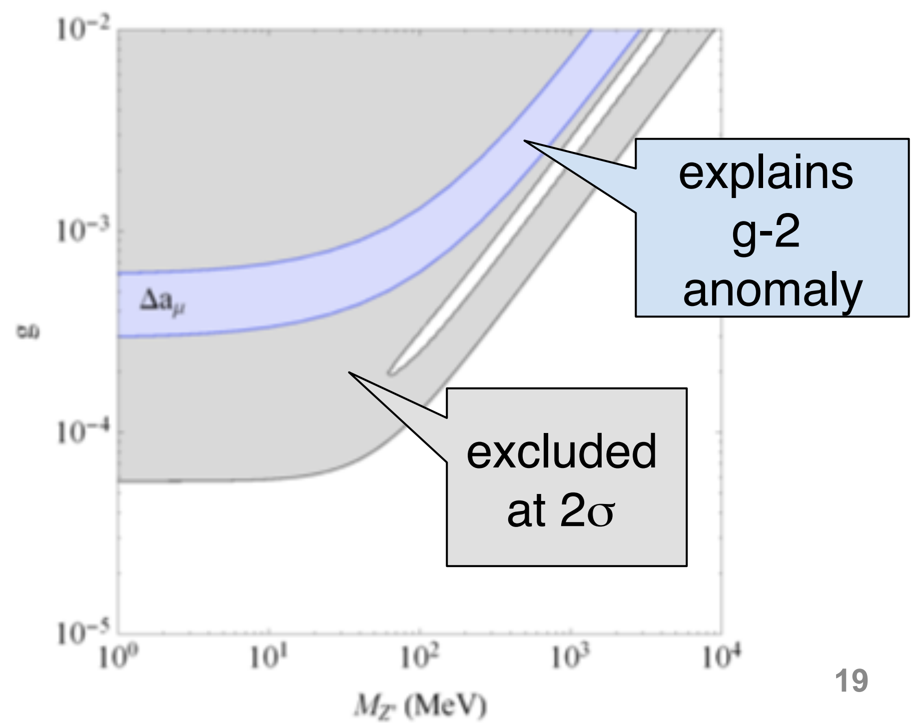
$$Q^2_{\alpha,\mathrm{NSI}} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right)\right]^2$$

- Q^2-dependence ➔ *affects recoil spectrum*
- 2 parameters: g, $M_{Z'}$



Dashed: SM
Solid: NSI w/ $M_{Z'}$= 10 MeV, g=10^{-4}

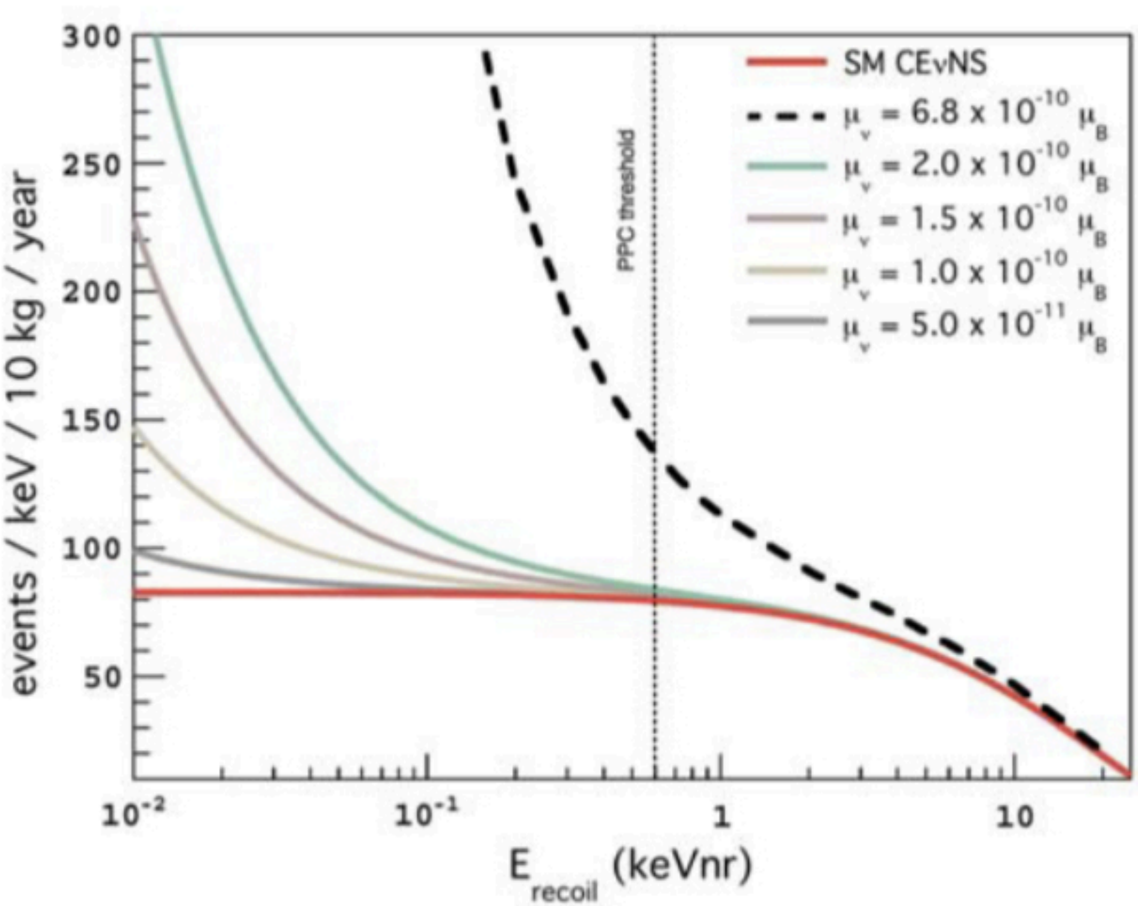
Blue: ν_μ
Red: ν_μ + ν_μ_bar
Black: ν_μ + ν_μ_bar + ν_e



Neutrino magnetic moment

Signature is **distortion at low recoil energy E**

$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-T/E_\nu}{T} + \frac{T}{4E_\nu^2}\right)$$



➔requires very low energy threshold (i.e., Ge)

See also Kosmas et al., arXiv:1505.03202

More in Juan's talk

Nuclear physics with CEvNS

If systematics can be reduced to ~ few % level,
we can start to explore nuclear form factors

P. S. Amanik and G. C. McLaughlin, J. Phys. G 36:015105

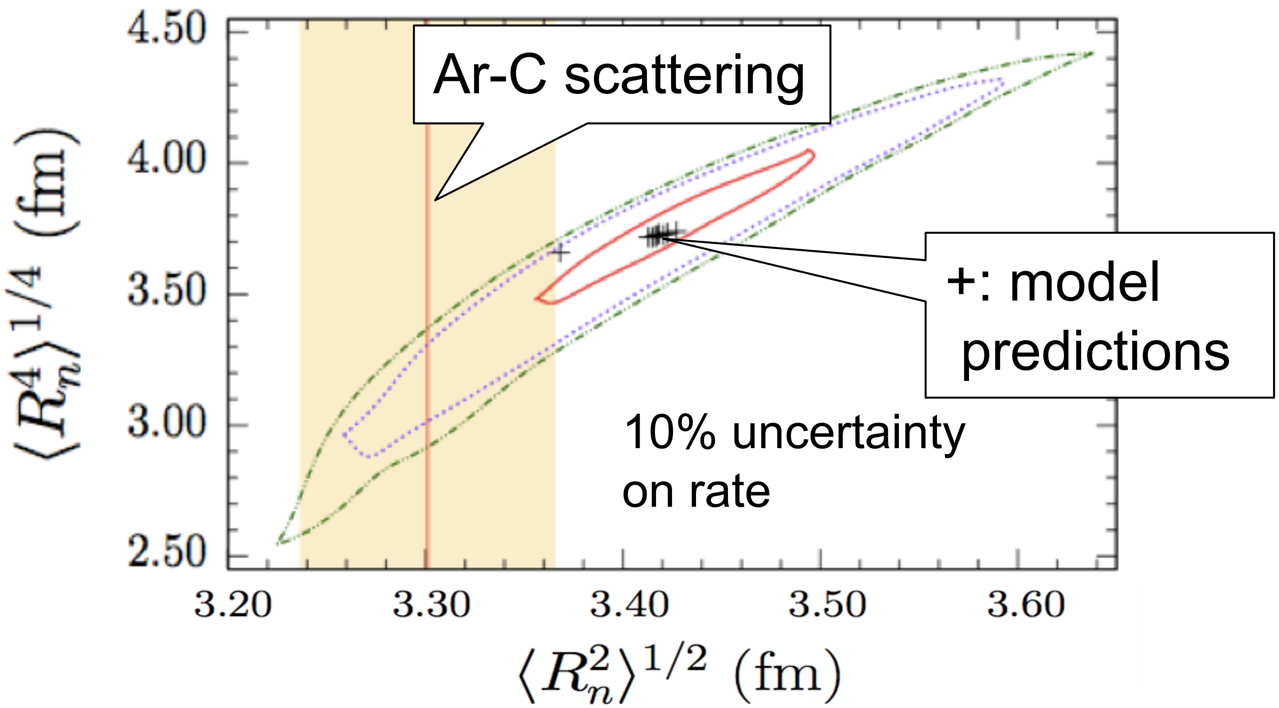
K. Patton et al., PRC86 (2012) 024612

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

Form factor: encodes information about nuclear (primarily neutron) distributions

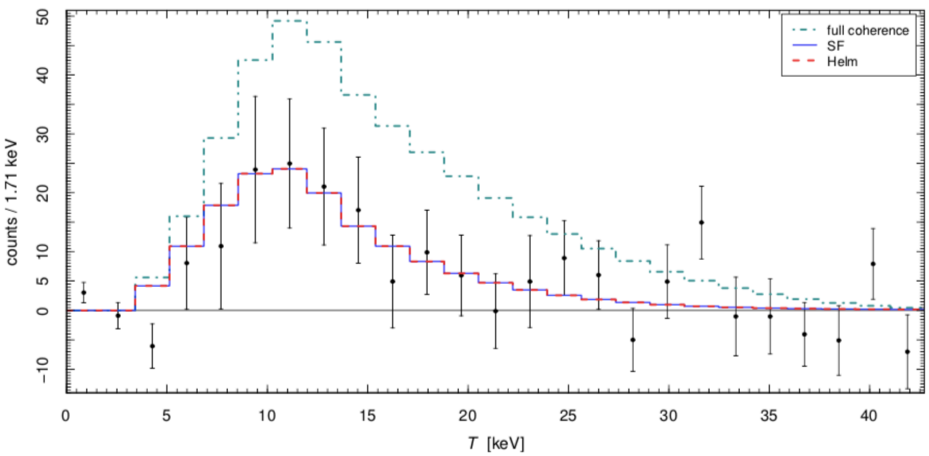
Fit recoil ***spectral shape*** to determine the $F^2(Q)$ moments
(requires very good energy resolution,good systematics control)

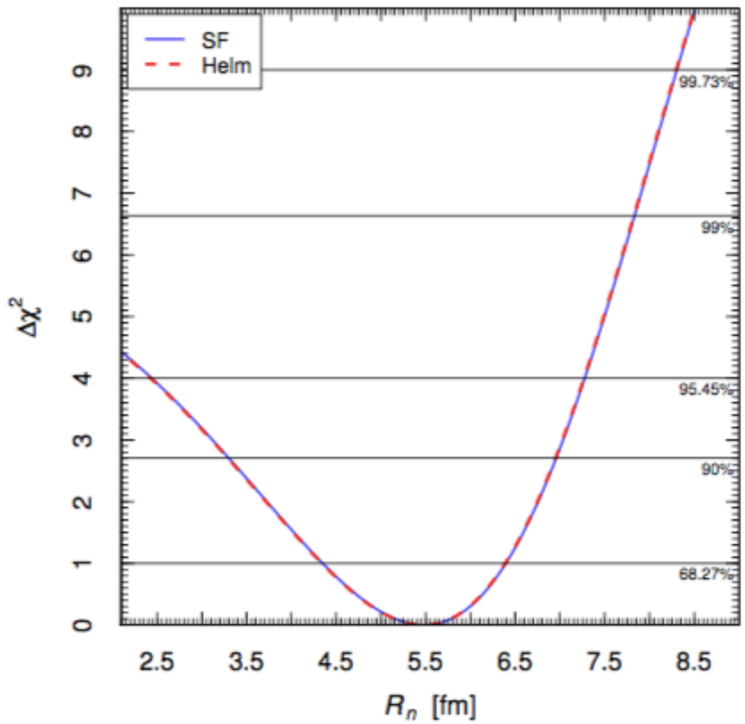
Example:
tonne-scale experiment at πDAR source



Sensitivity to R_n in the recoil spectrum shape

M. Cadeddu, C. Giunti, Y. F. Li, and Y. Y. Zhang. "Average CsI neutron density distribution from COHERENT data." (2017). 1710.02730.





$$F_N^{\mathrm{Helm}}(q^2) = 3\,\frac{j_1(qR_0)}{qR_0}\,e^{-q^2 s^2/2},$$

$$R_n = 5.5^{+0.9}_{-1.1}\ \mathrm{fm}. \qquad \Delta R_{np} \simeq 0.7^{+0.9}_{-1.1}\ \mathrm{fm}.$$

- Fit to neutron radius w/ ~18% uncertainty, but does not handle bin-by-bin correlation of systematics
- Also some info on neutron skin

More in Rex's talk

Light DM direct detection possibilities

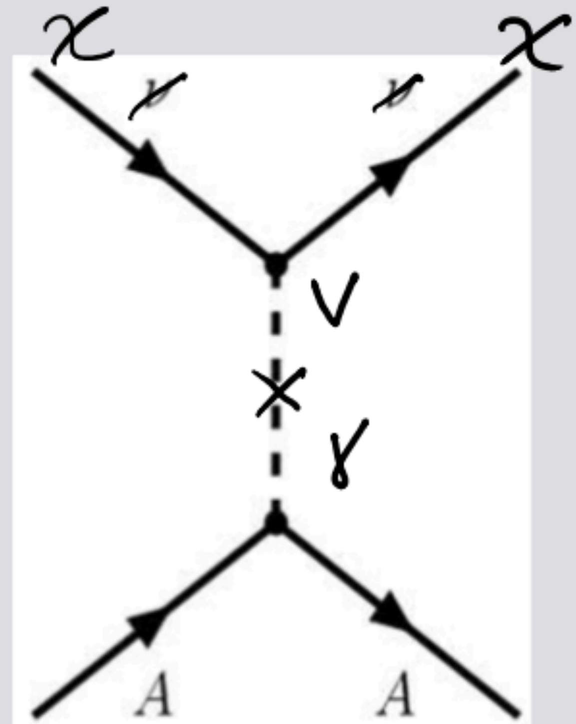
Light new physics in coherent neutrino-nucleus scattering experiments

Patrick deNiverville,[1] Maxim Pospelov,[1,2] and Adam Ritz[1]

[1] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*

(Dated: May 2015)

detection:



production:

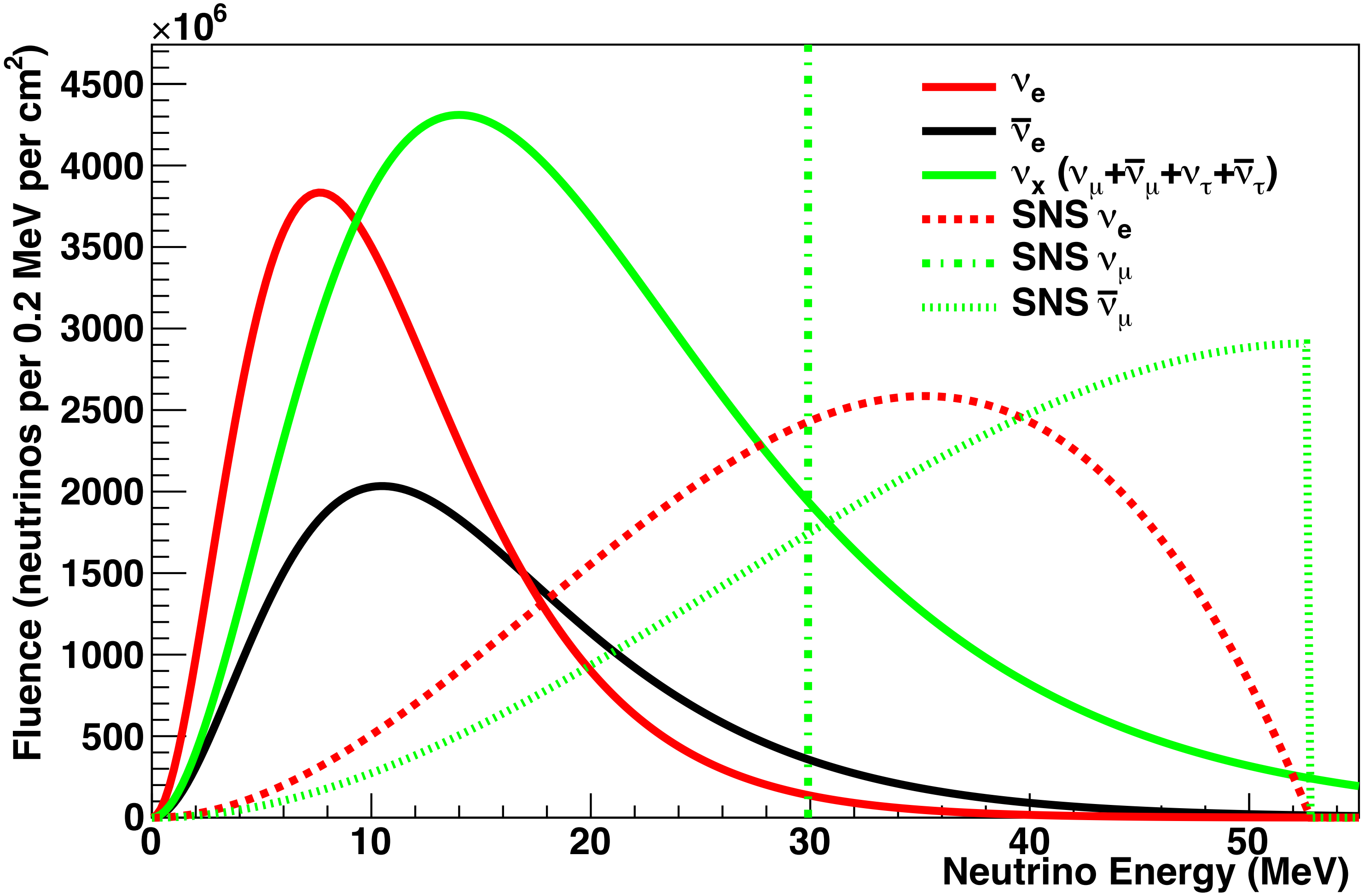
proton → target → $\pi^{0,\pm}$ →

$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

$$\pi^- + p \longrightarrow n + V^{(*)} \longrightarrow n + \chi^\dagger + \chi$$

More in Rex's talk

Non-CEvNS measurements for supernova neutrinos



SNS spectrum overlaps well...

opportunities for measuring CC and NC

A “friendly fire” in-time background:

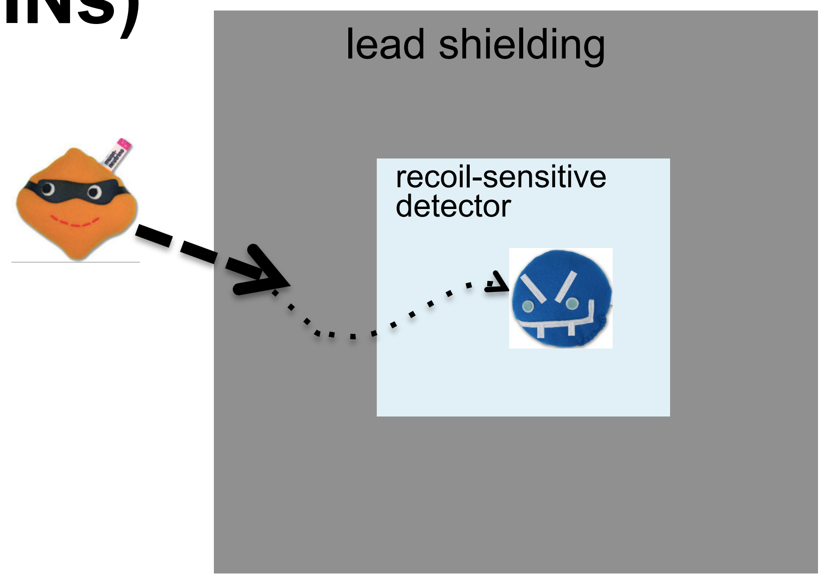
Neutrino Induced Neutrons (NINs)

$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^-$ CC

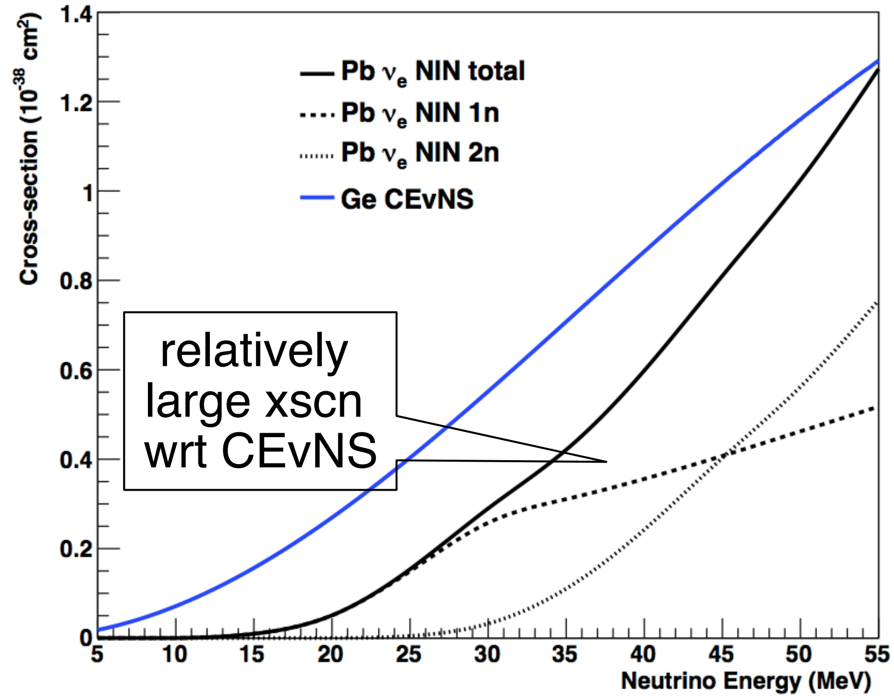
↘ 1n, 2n emission

$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x$ NC

↘ 1n, 2n, γ emission



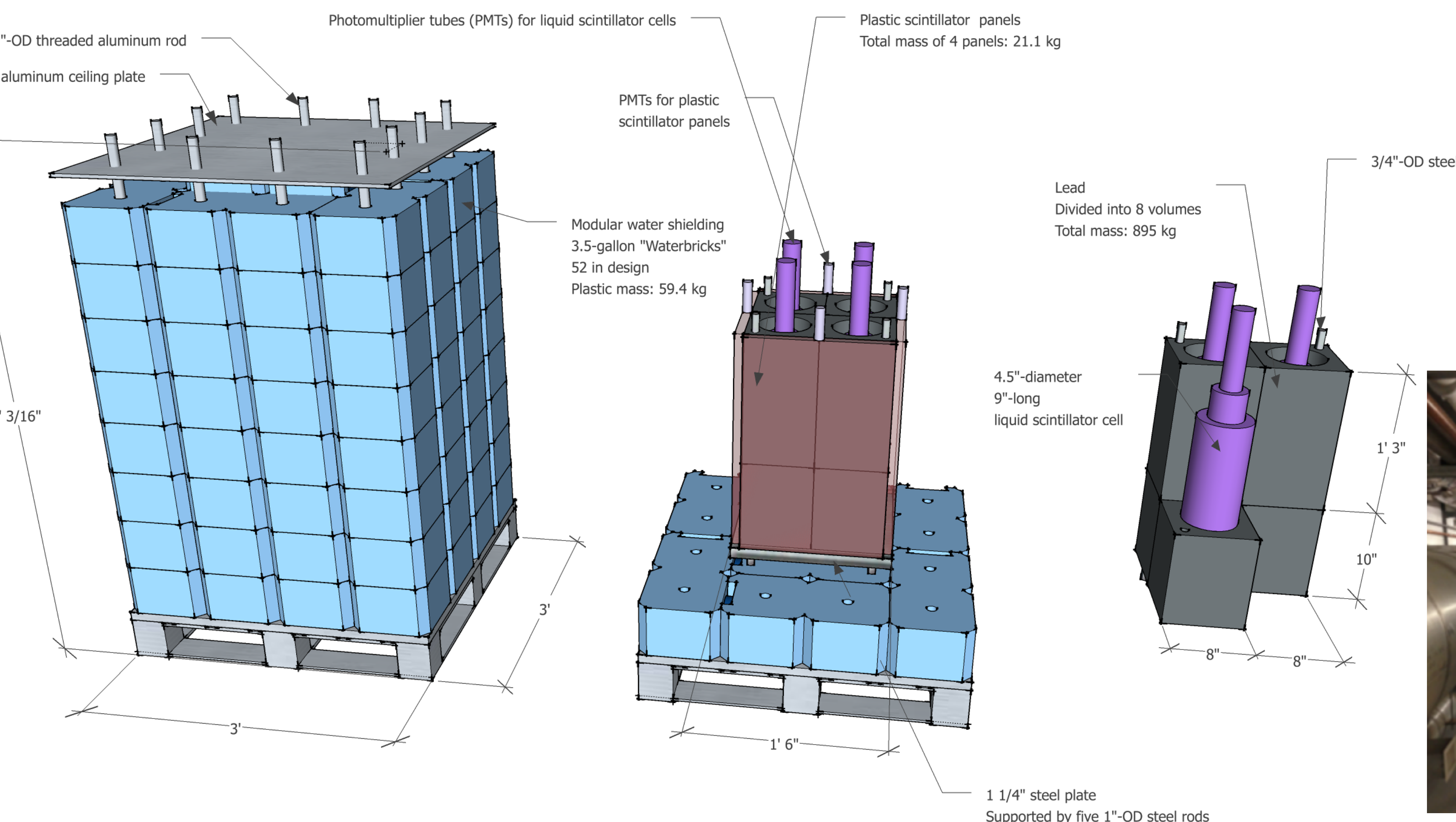
- potentially non-negligible background from shielding
- requires careful shielding design
- large uncertainties (factor of few) in xscn calculation
- [Also: a signal in itself, e.g, HALO SN detector]



NIN measurement in SNS basement with Nubes

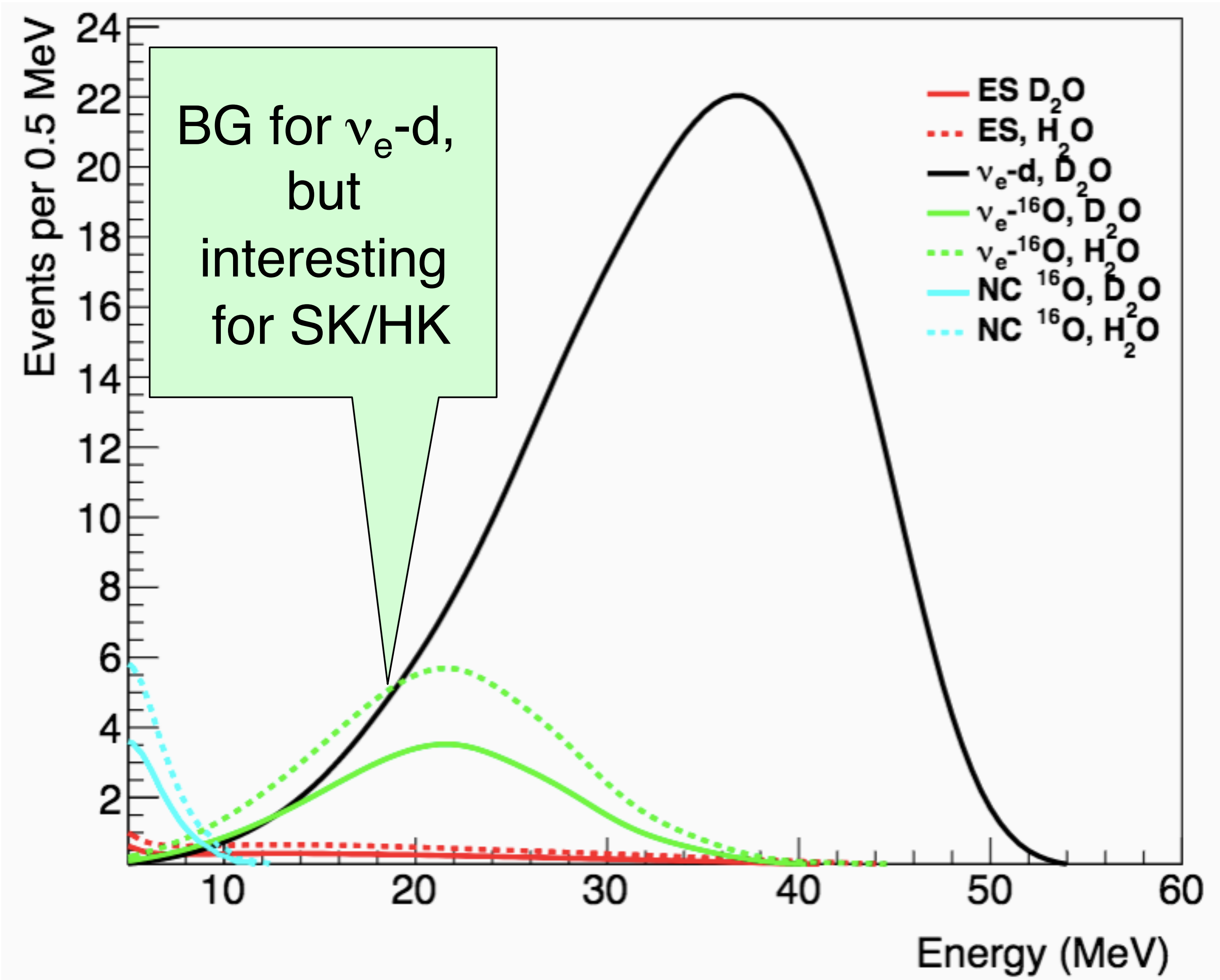
Liquid scintillator surrounded by Pb, Fe (swappable for other NIN targets) inside water shield

Planning upgrade using PROSPECT Li-loaded scintillator



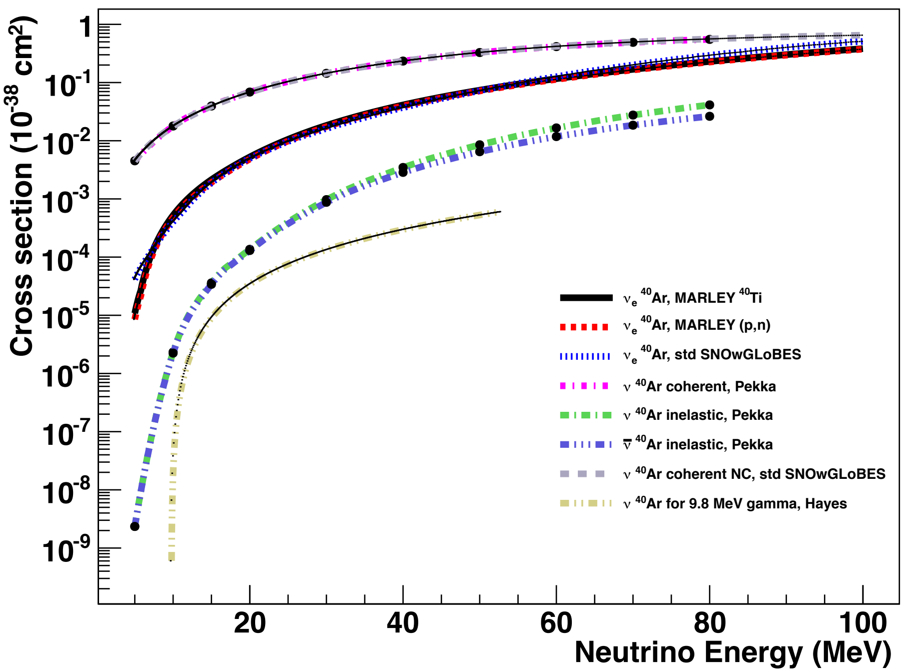
P. Barbeau

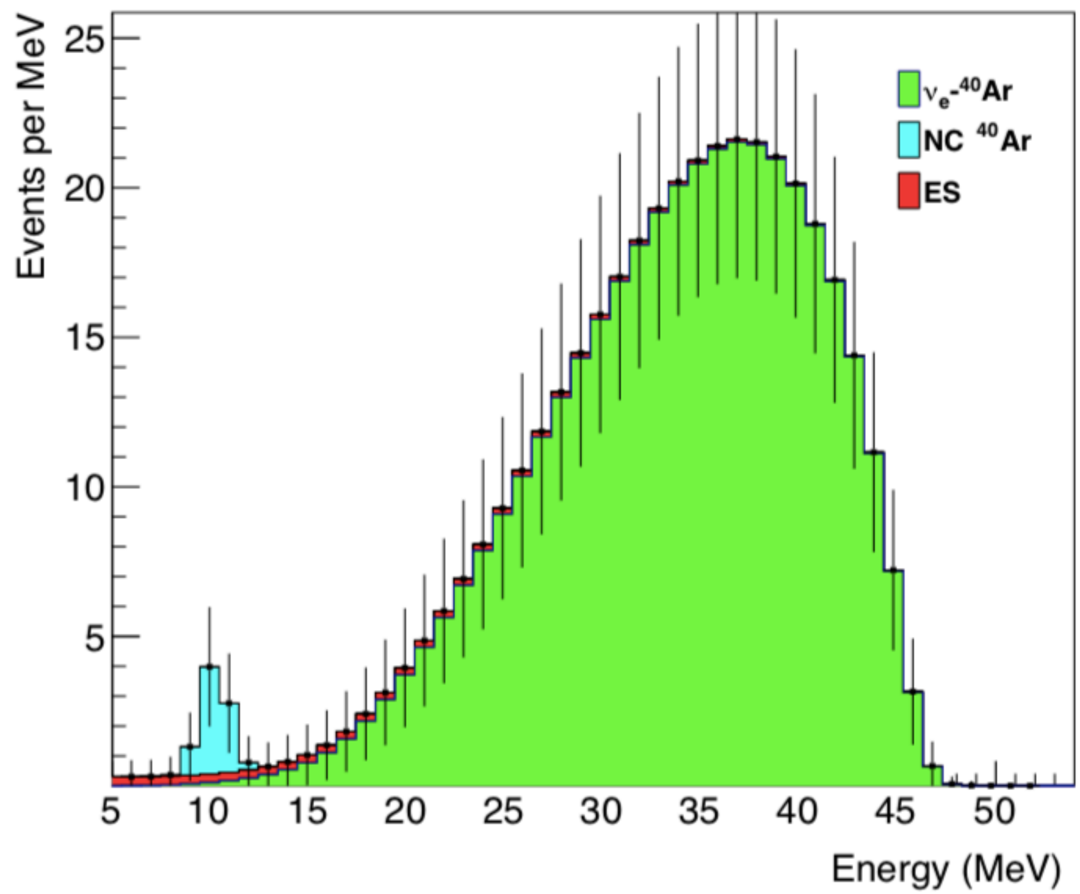
CC and NC measurements in light & heavy water



More in Jason's talk

CC & NC measurements in LAr





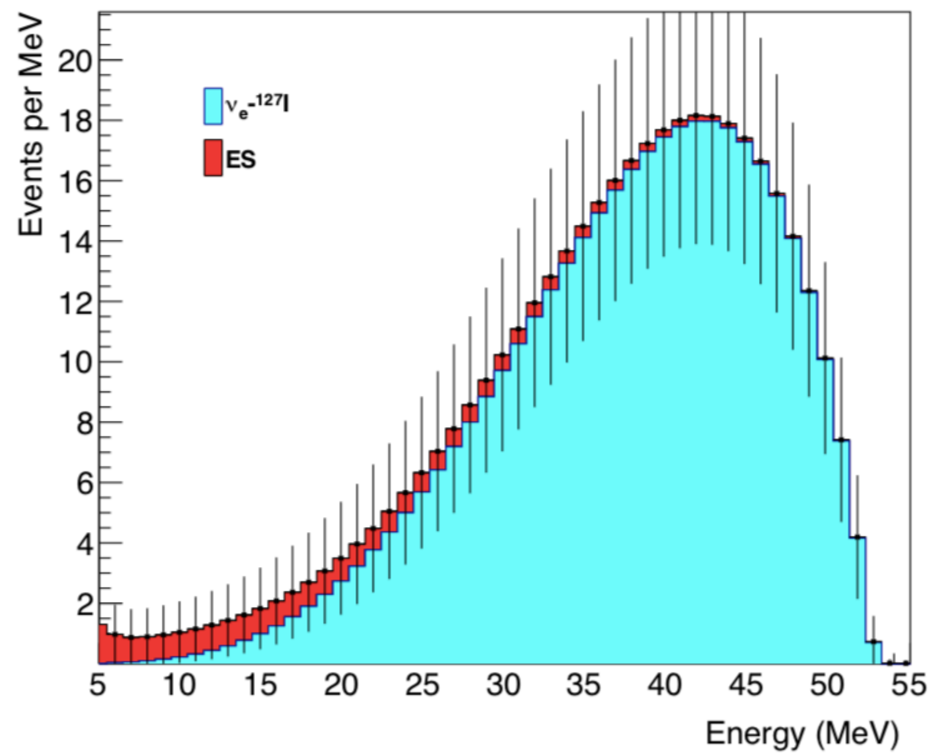
More in Rex's talk

Charged-current measurements in ^{127}I

TABLE III. Contributions of individual multipoles to the total cross section for neutrinos from muon decay, in units of 10^{-40} cm^2. The two columns correspond to quenched and free values for g_A, respectively (see text).

J^π	$g_A = -1.0$	$g_A = -1.26$
0^+	0.096	0.096
0^-	0.00001	0.00002
1^+	1.017	1.528
1^-	0.006	0.008
2^+	0.155	0.213
2^-	0.693	1.055
3^+	0.149	0.171
3^-	0.017	0.025
Total	2.098	3.096

J. Engel, 1994



Exclusive cross section to bound final states of ^{127}Xe measured @ LANL, but we can measure **inclusive CC** xscn in NaI

More in Phil's talk

Reducing systematic uncertainties

2017 CsI measurement

Uncertainties on signal and background predictions	
Event selection	5%
Quenching factor	25%
Flux	10%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

Dominant uncertainty (detector-dependent)

Next largest uncertainty (affects all detectors)

- ancillary quenching factor measurements are important for the physics program
- D_2O for flux normalization also needed

P5 Science Drivers

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass ★
- Identify the new physics of dark matter ★
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles. ★

COHERENT connects to 3/5 of these

Recommendation 4: Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects.

In addition,
it's a "small-scale"
project

zenodo

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April 25, 2018

Dataset Open Access

COHERENT Collaboration data release from the first observation of coherent elastic neutrino-nucleus scattering

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Release of COHERENT Collaboration data associated with the first observation of coherent elastic neutrino-nucleus scattering (CEvNS), as published in Science (DOI: 10.1126/science.aao0990) and also available as arXiv:1708.01294[nucl-ex].

This data set should enable researchers to extend the study of CEvNS as desired. Future COHERENT Collaboration results will have similar data releases.

Available for theorists

"pyCEvNS" collaboration

Take-Away Messages

- COHERENT will demonstrate CEvNS **N^2 dependence**
- **Multiple targets** needed for this demonstration, as well as to test for BSM physics

- Significant **NSI sensitivity improvements** expected
  - important for interpretation of LBL oscillation experiments
  - *combination* of targets helps

- Many other physics topics : CC/NC for SNB, magnetic moment, etc.
- Control of systematics will require:
  - D_2O for flux
  - ancillary QF measurements