Low-Energy Scattering with COHERENT

Artwork by Sandbox Studio, Chicago with Ana Kova

Kate Scholberg, Duke University

ACFI Workshop

April 25, 2019

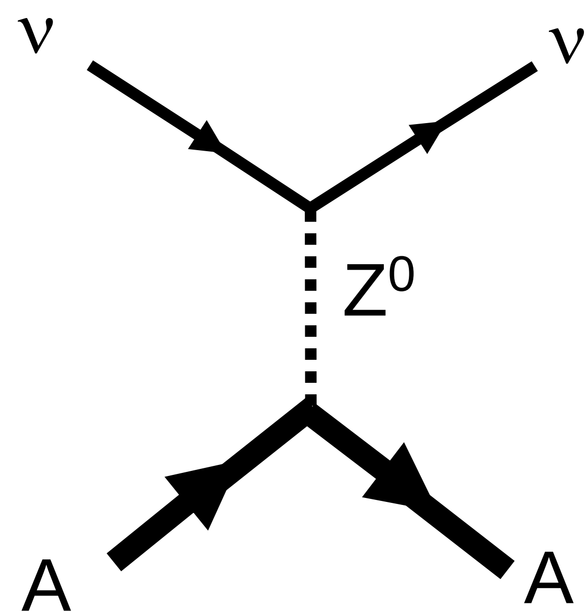
OUTLINE

- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Physics motivations
- How to measure CEvNS
- The COHERENT experiment at the SNS
- COHERENT results
  - CsI[Na] measurement and interpretation
  - New: LAr engineering run
- Future prospects
  - Notes on neutrino magnetic moment,

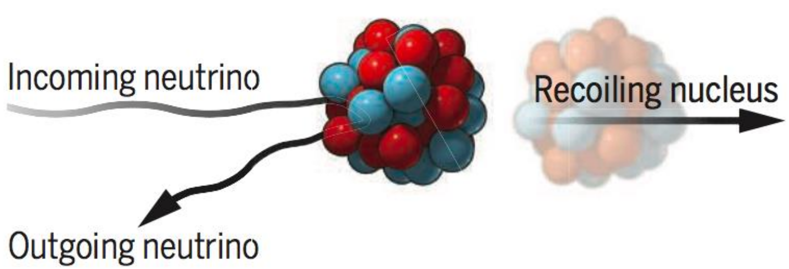
    ES vs CEvNS

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]

Image: J. Link *Science* Perspectives

Standard Model prediction for differential cross section

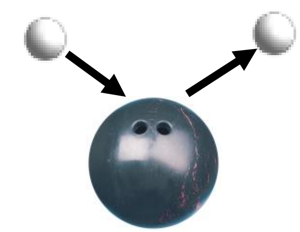
(probability of kicking a nucleus with recoil energy T)

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
$Q = \sqrt{(2 M T)}$: momentum transfer

Fermi constant (SM parameter)

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

kinematics:
ping-pong ball hits bowling ball



weak nuclear charge

Form factor: F=1 ➔ full coherence

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

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weak nuclear charge

No. of neutrons

No. of protons

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

$\sin^2\theta_W = 0.231$, so protons unimportant $\Longrightarrow Q_W \propto N$

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

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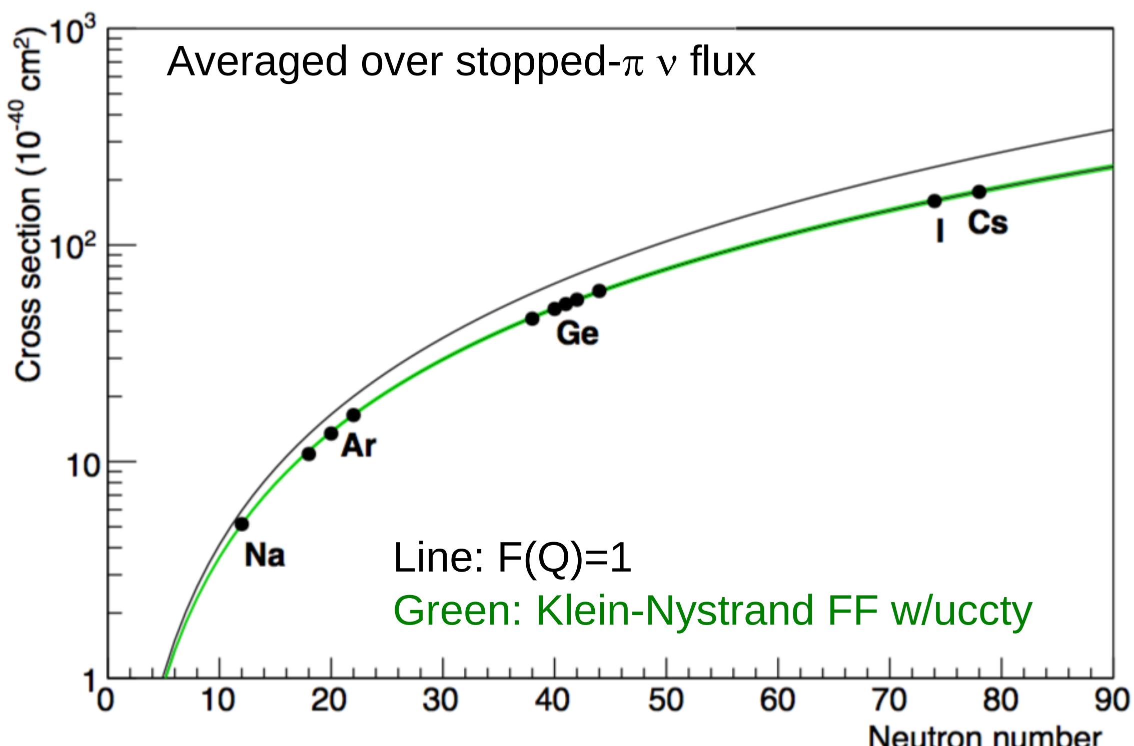
$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

$$\Rightarrow \boxed{\frac{d\sigma}{dT} \propto N^2}$$



In a bit more detail: vector and axial contributions

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

E_ν: neutrino energy
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G_V, G_A: SM weak parameters

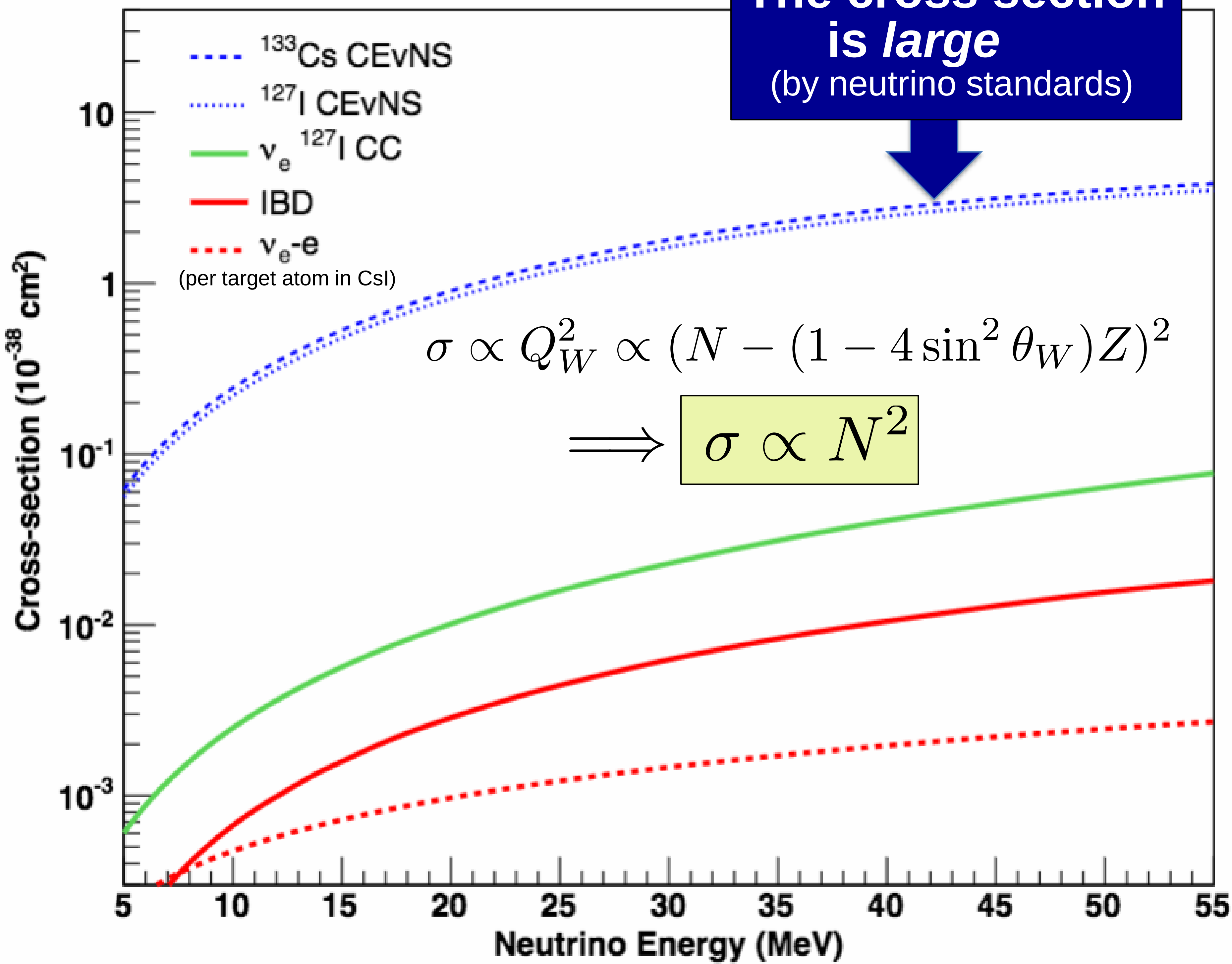
vector $G_V = g_V^p Z + g_V^n N,$ dominates

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

$$\begin{aligned} g_V^p &= 0.0298 \\ g_V^n &= -0.5117 \\ g_A^p &= 0.4955 \\ g_A^n &= -0.5121. \end{aligned}$$

For the moment, mostly ignoring axial contributions

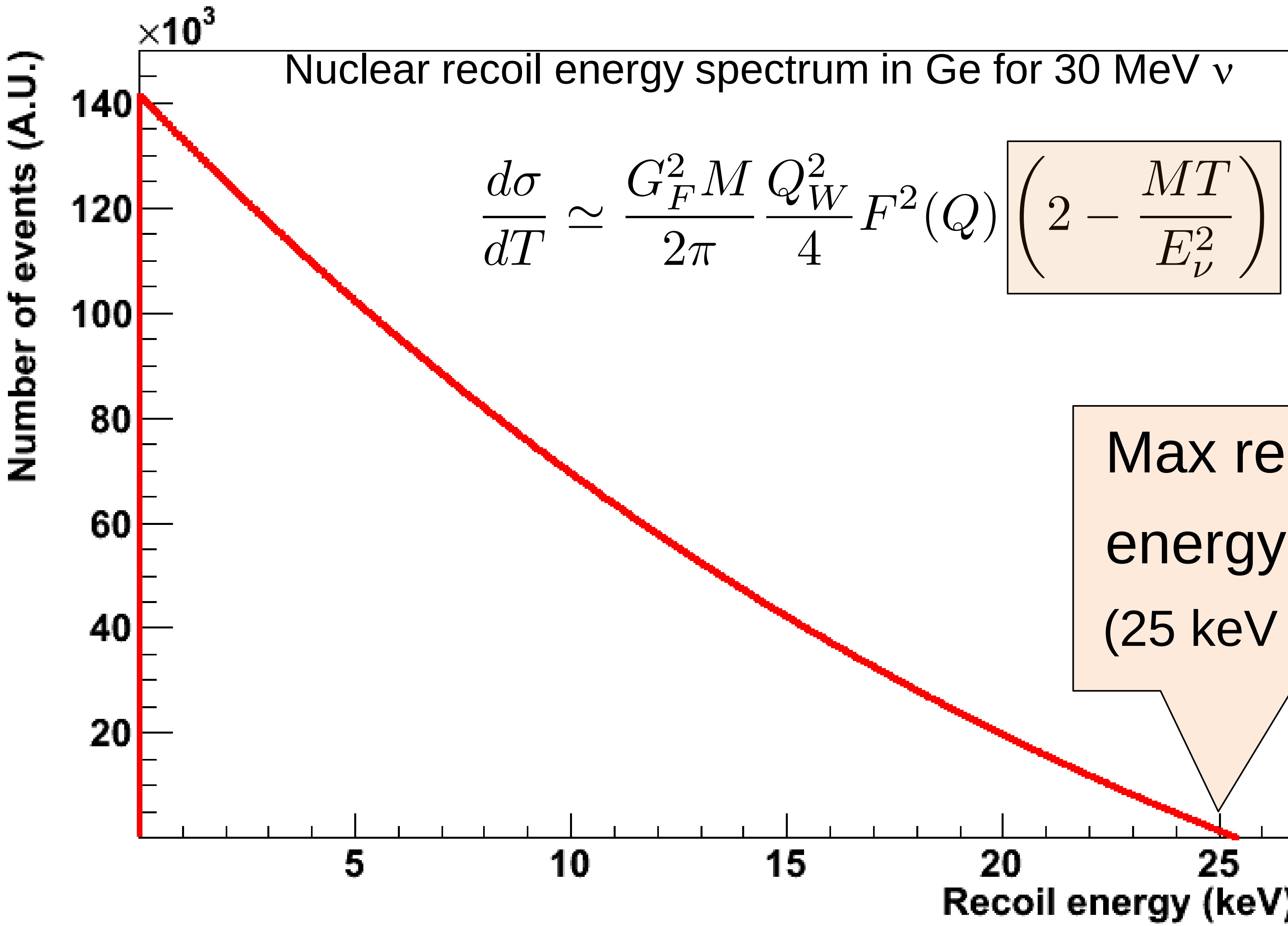
The cross section is *large*
(by neutrino standards)



$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

$$\Longrightarrow \boxed{\sigma \propto N^2}$$

Large cross section (by neutrino standards) but hard to observe due to **tiny nuclear recoil energies:**

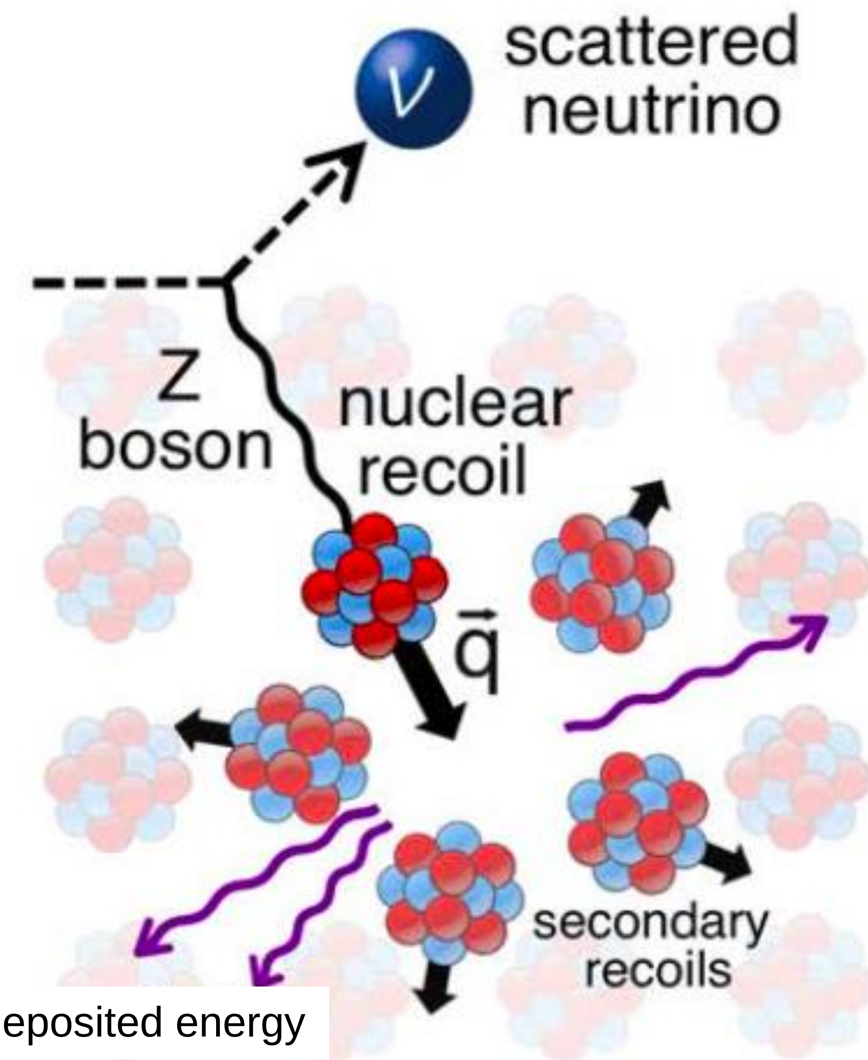


Max recoil energy is $\sim 2E_\nu^2/M$

(25 keV for Ge)

The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



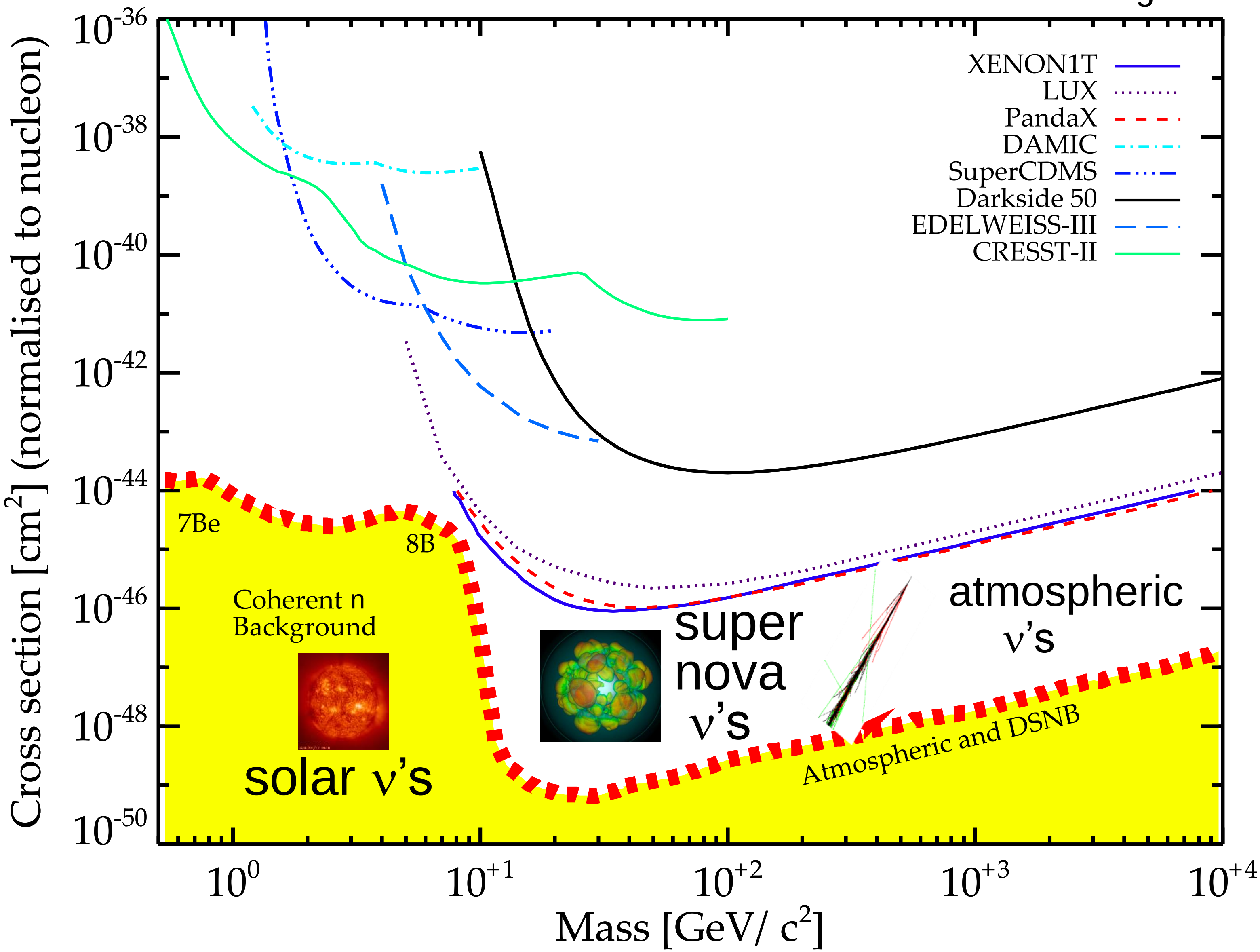
➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10’s of keV recoils

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

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

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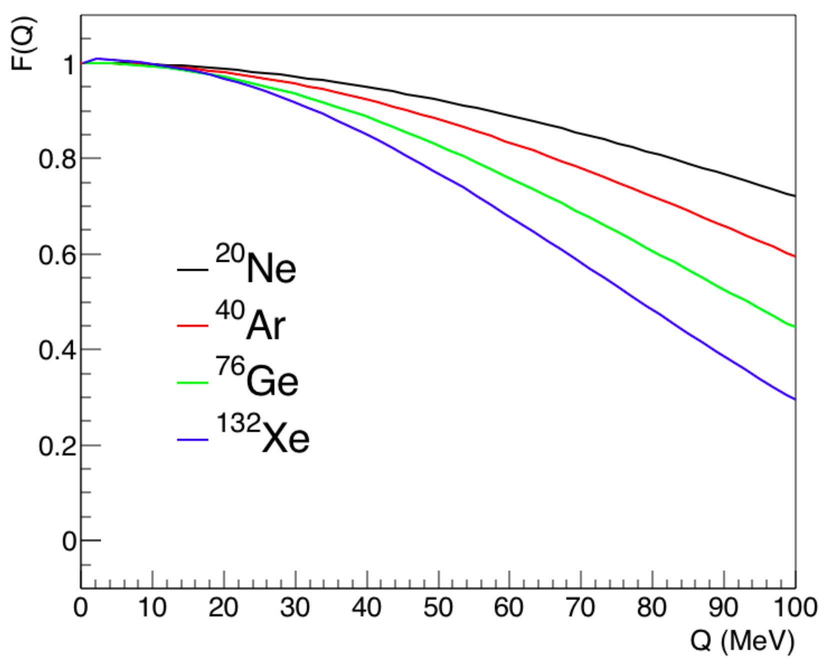
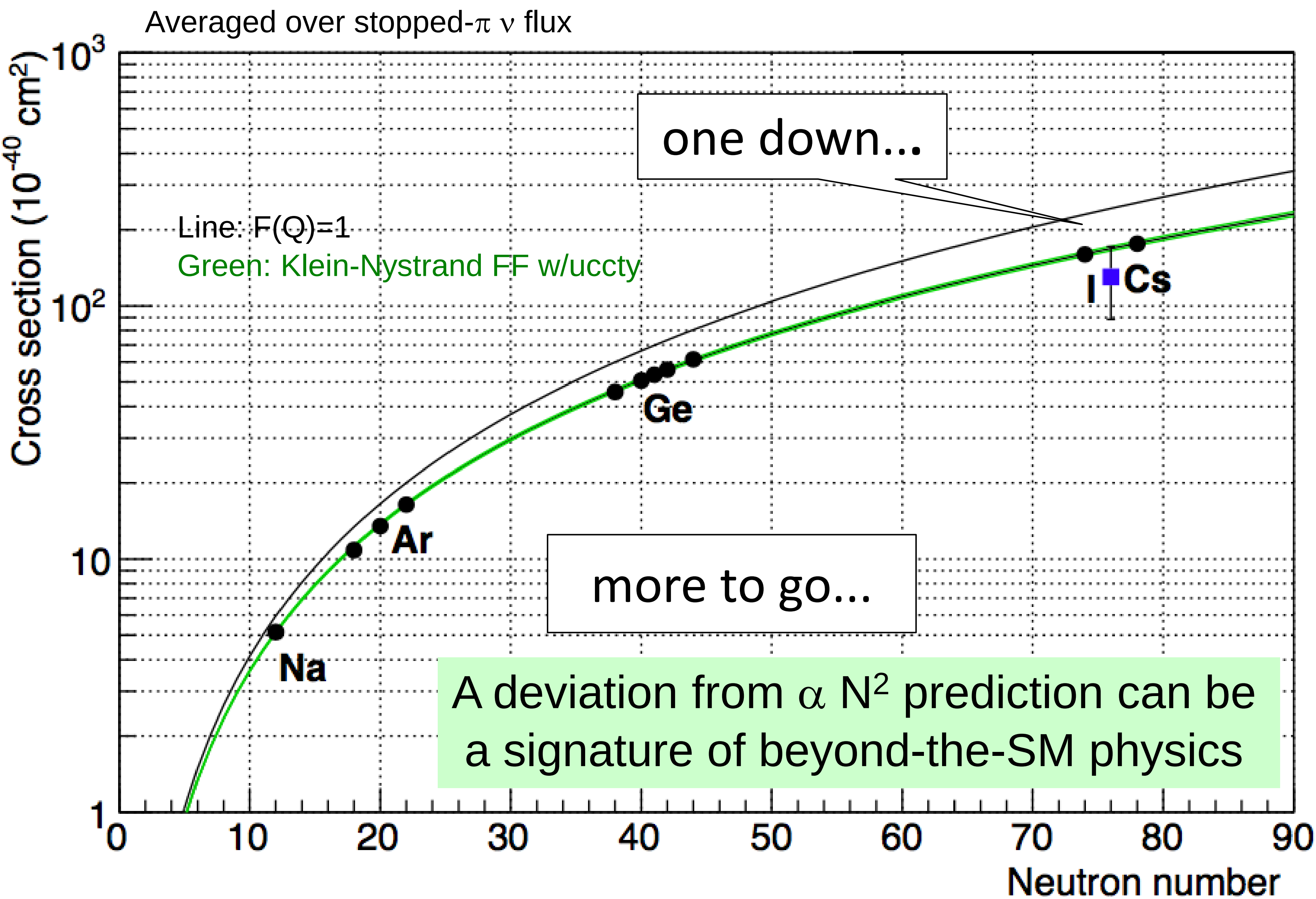
$Q = \sqrt{(2\,M\,T)}$: momentum transfer

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

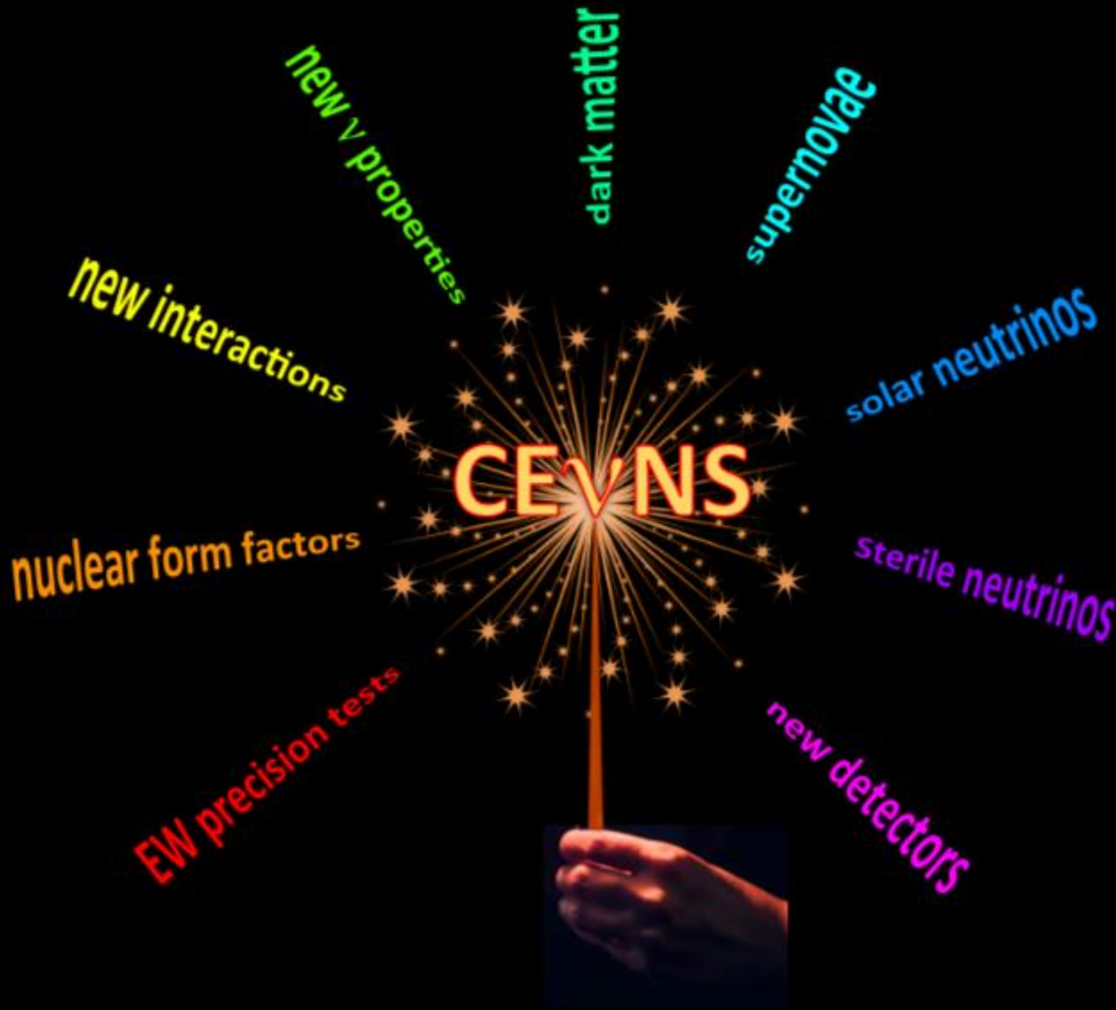


form factor suppresses cross section at large Q

Need to measure **N^2 dependence** of the CEvNS xscn



Why measure CEvNS?



E. Lisi
Neutrino 2018

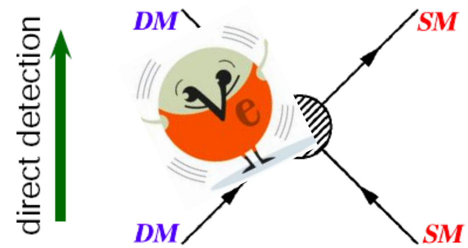
A few examples...

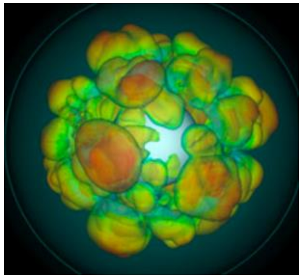
CEvNS: what's it good for?

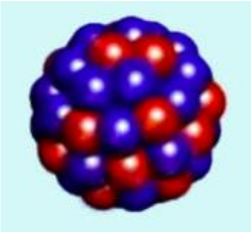
1. So
2. Many
3. Things

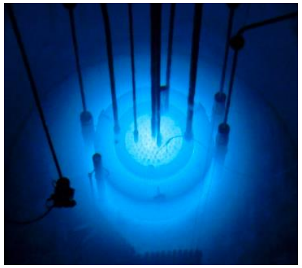
! (not a complete list!)

- Dark matter direct-detection background
- Well-calculable cross-section in SM:
  - $\sin^2\theta_{Weff}$ at low Q
  - **Probe of BSM physics**
    - Non-standard interactions of neutrinos
    - New NC mediators
    - Neutrino magnetic moment
- New tool for sterile neutrino oscillations
- Astrophysical signals (solar & SN)
- Supernova processes
- Nuclear physics:
  - Neutron form factors
  - g_A quenching
- Possible applications (reactor monitoring)





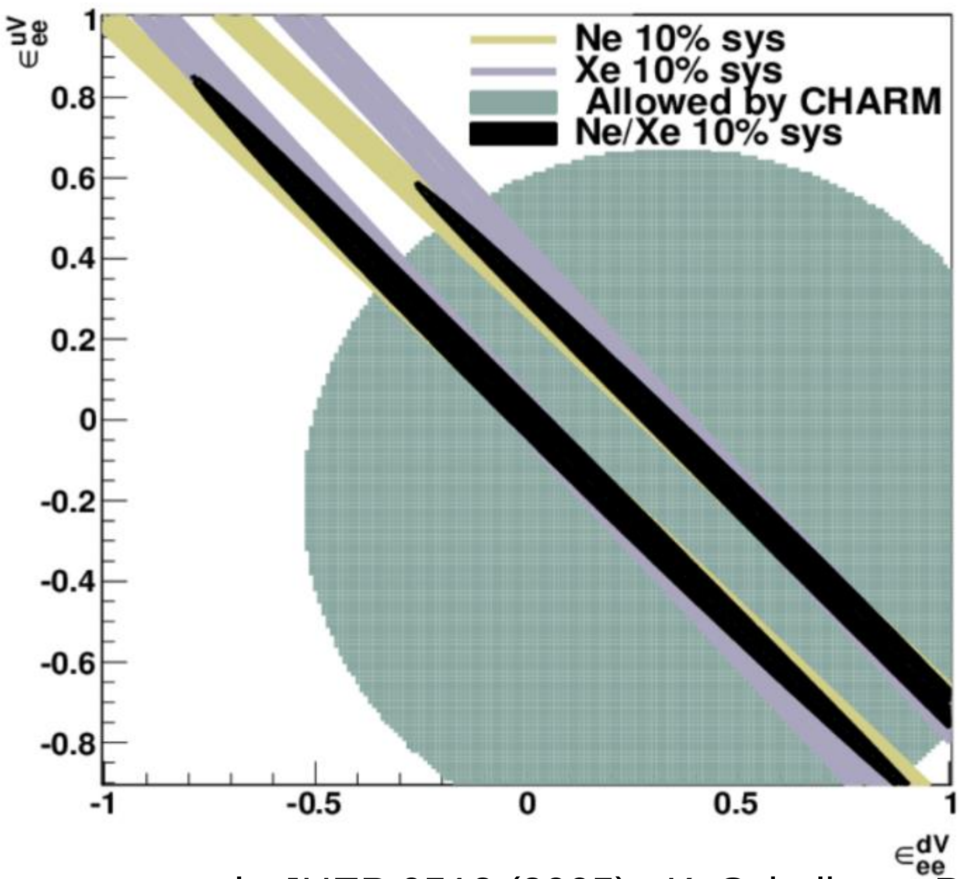




Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

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



If these ε's are ~unity, there is a new interaction of ~Standard-model size... many not currently well constrained

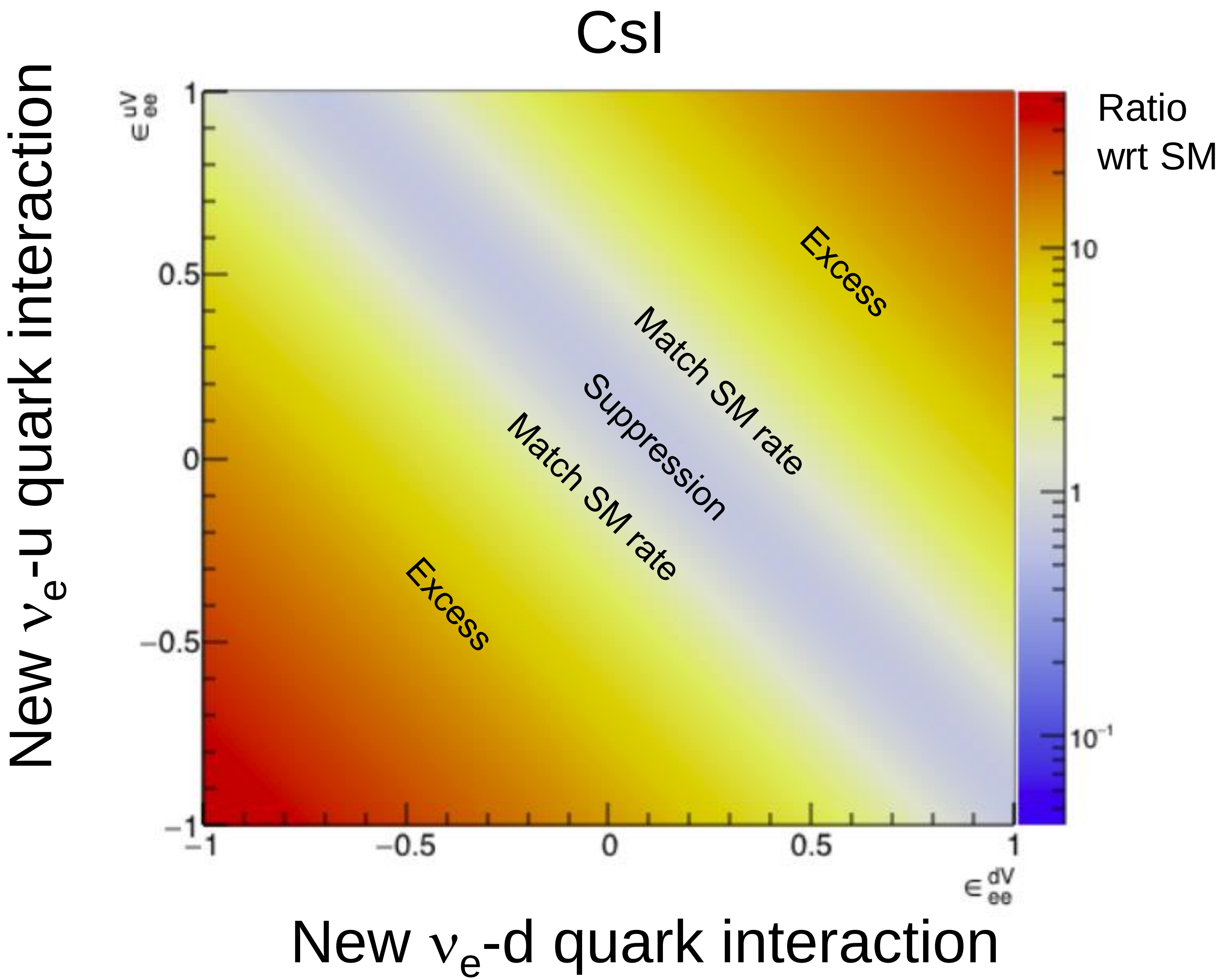
J. Barranco et al., JHEP 0512 (2005), K. Scholberg, PRD73, 033005 (2006), 021

Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment (for best sensitivity, want ***multiple targets***)

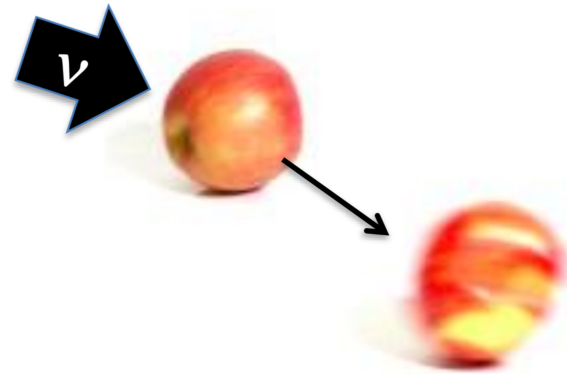
More studies: see https://sites.duke.edu/nueclipse/files/2017/04/Dent-James-NuEclipse-August-2017.pdf

Signatures of **Beyond-the-Standard-Model Physics**

Look for a CEvNS **excess** or **deficit** wrt SM expectation



How to detect CEvNS?

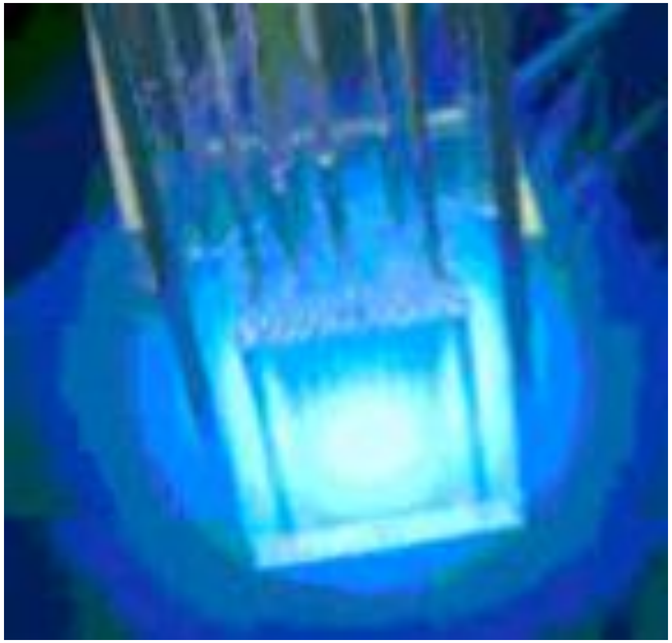


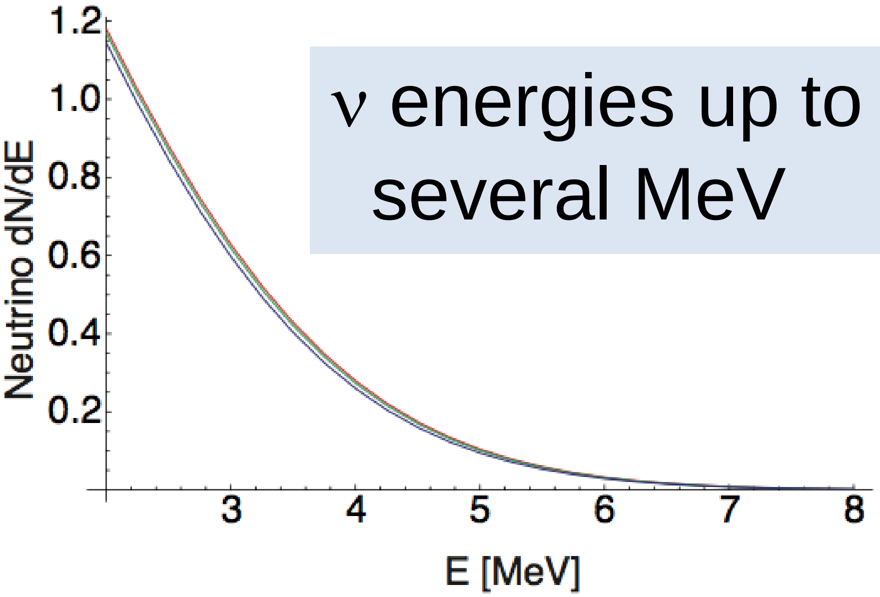
You need a neutrino source and a detector

What do you want for your ν source?

- ✓ High flux
- ✓ Well understood spectrum
- ✓ Multiple flavors (physics sensitivity)
- ✓ Pulsed source if possible, for background rejection
- ✓ Ability to get close
- ✓ Practical things: access, control, ...

Neutrinos from nuclear reactors

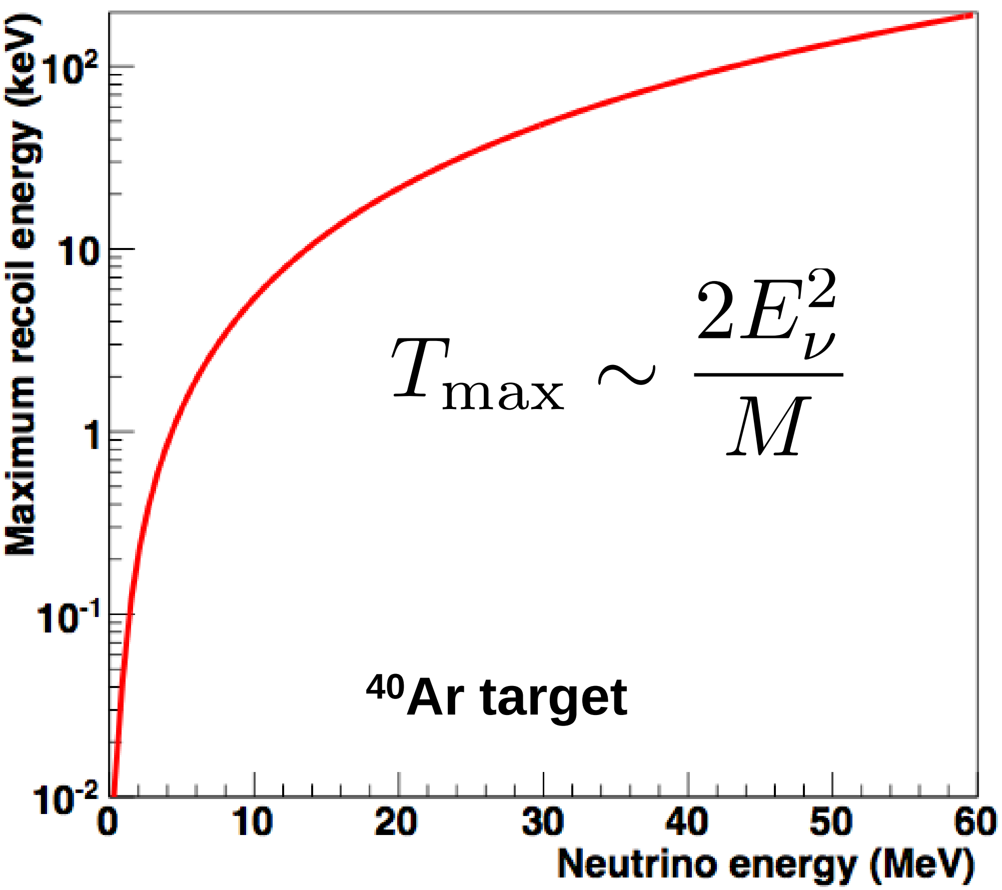


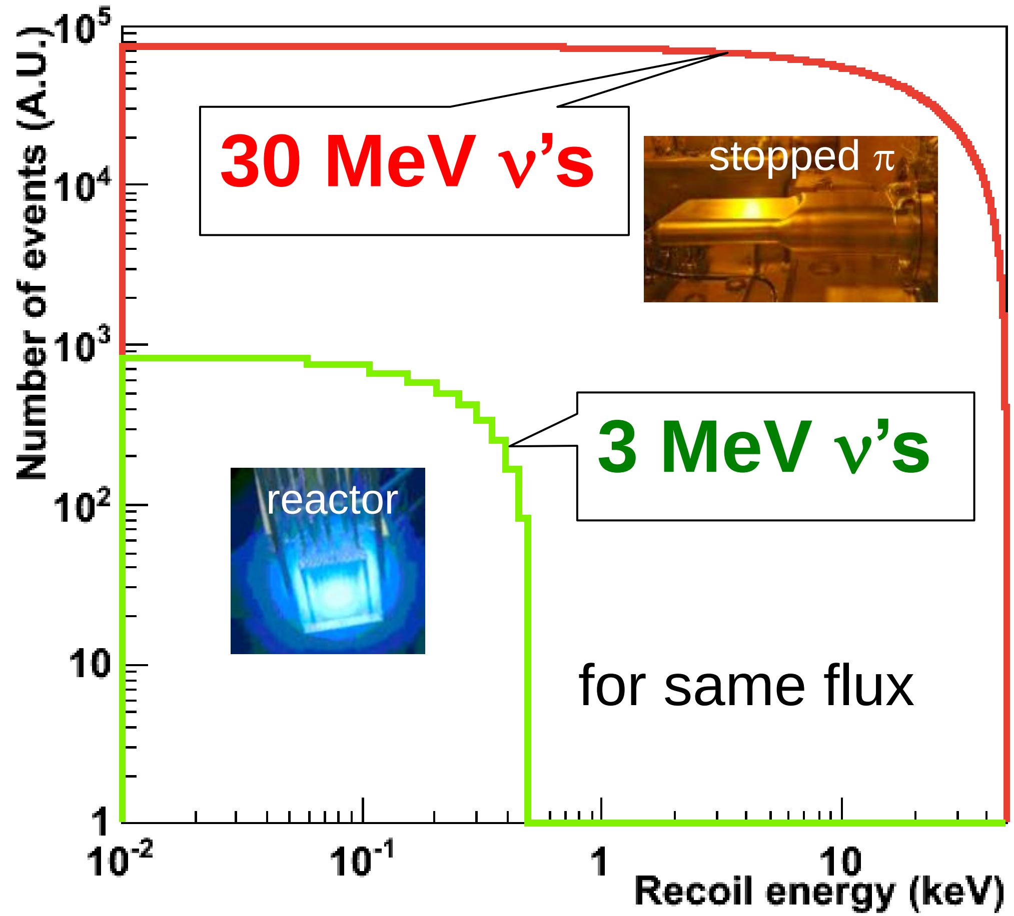


ν energies up to several MeV

- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2x10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

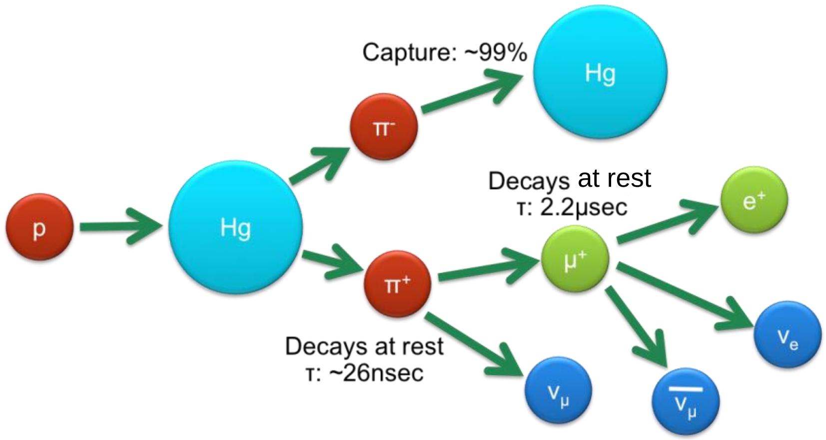
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

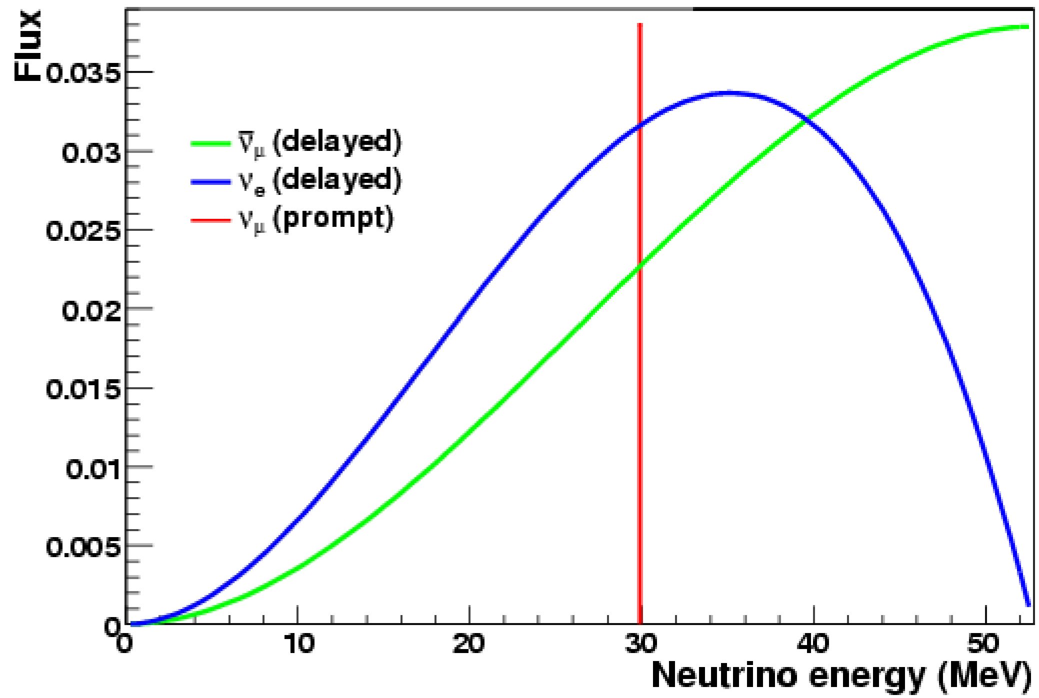




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

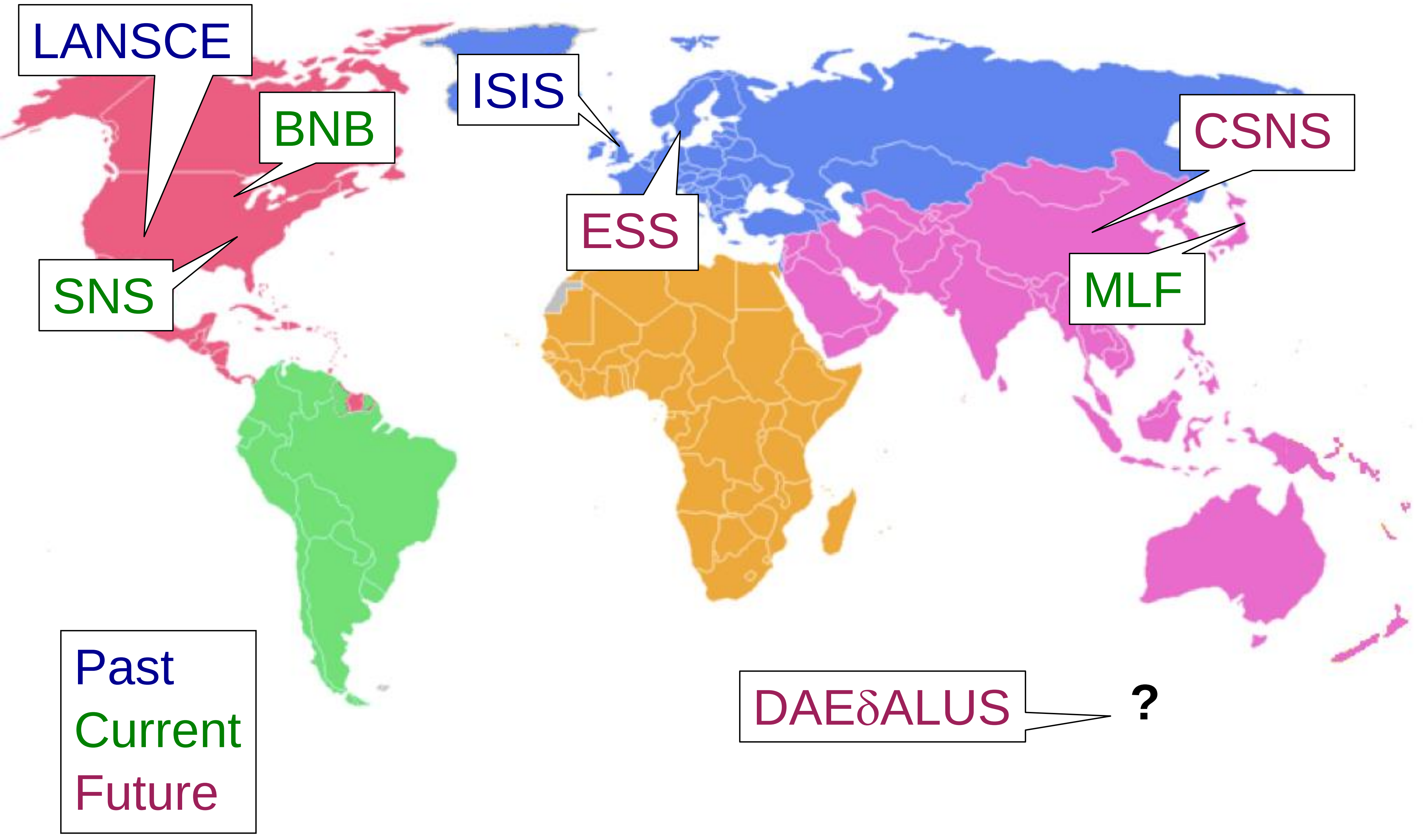
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

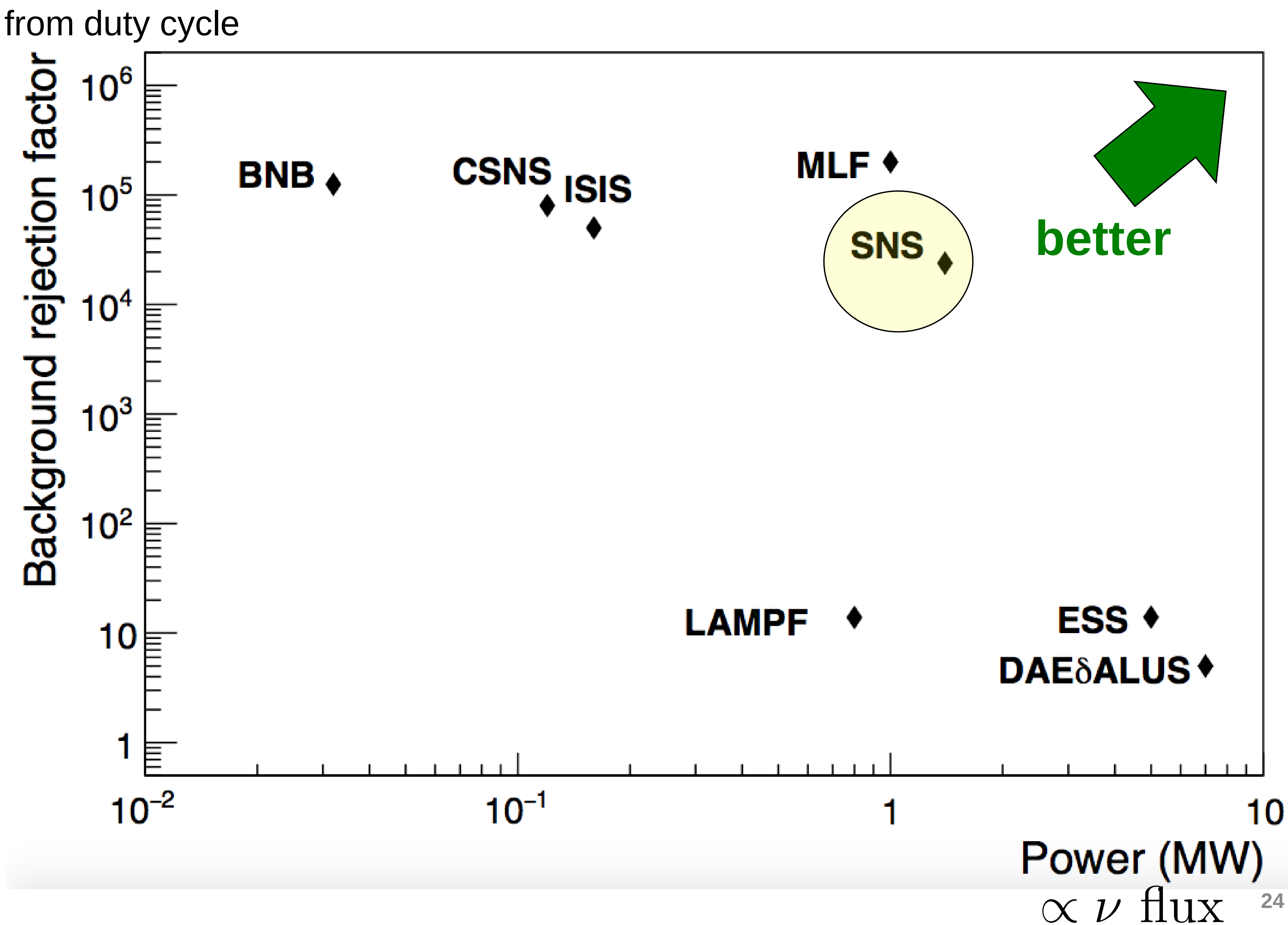
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies
between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Stopped-Pion Neutrino Sources Worldwide

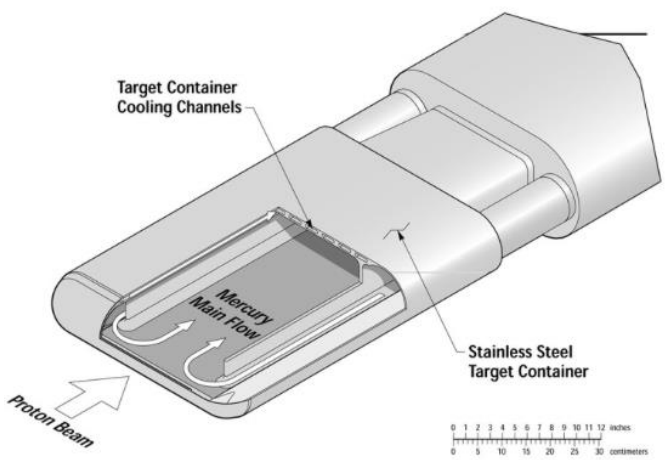


Comparison of pion decay-at-rest ν sources



Spallation Neutron Source

Oak Ridge National Laboratory, TN

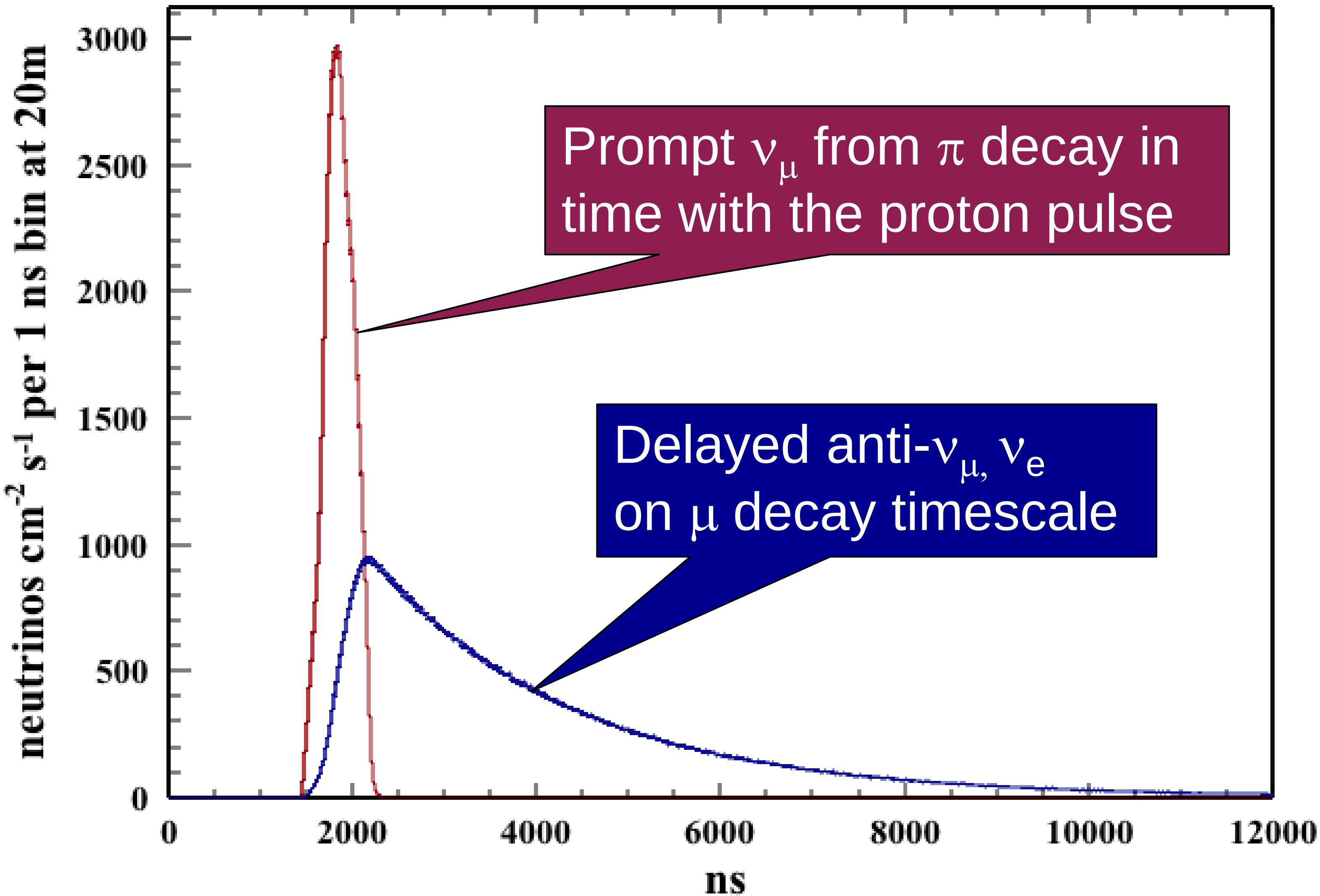


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Time structure of the SNS source

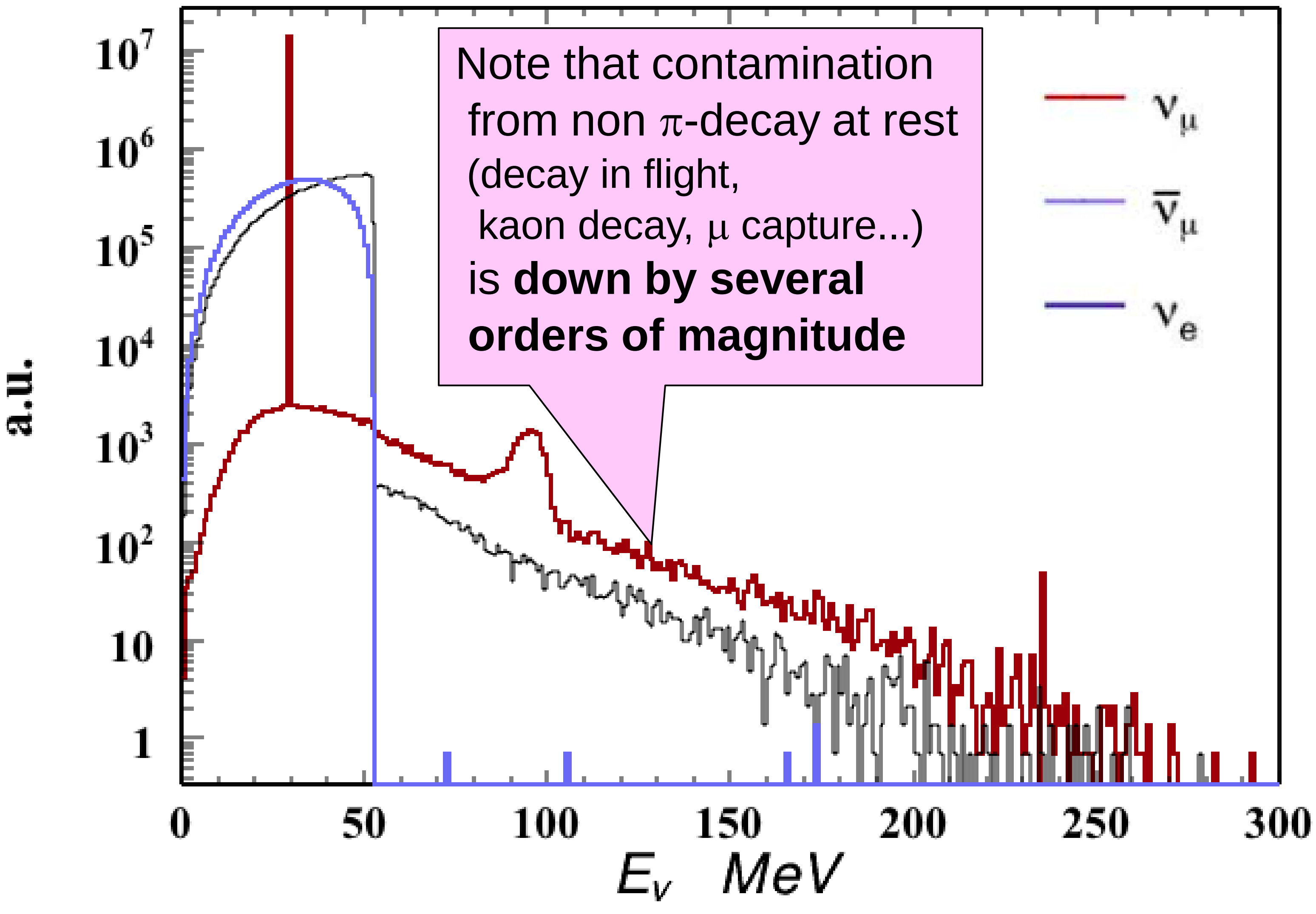
60 Hz *pulsed* source



Background rejection factor ~few x 10^{-4}

The SNS has **large, extremely clean** stopped-pion ν flux

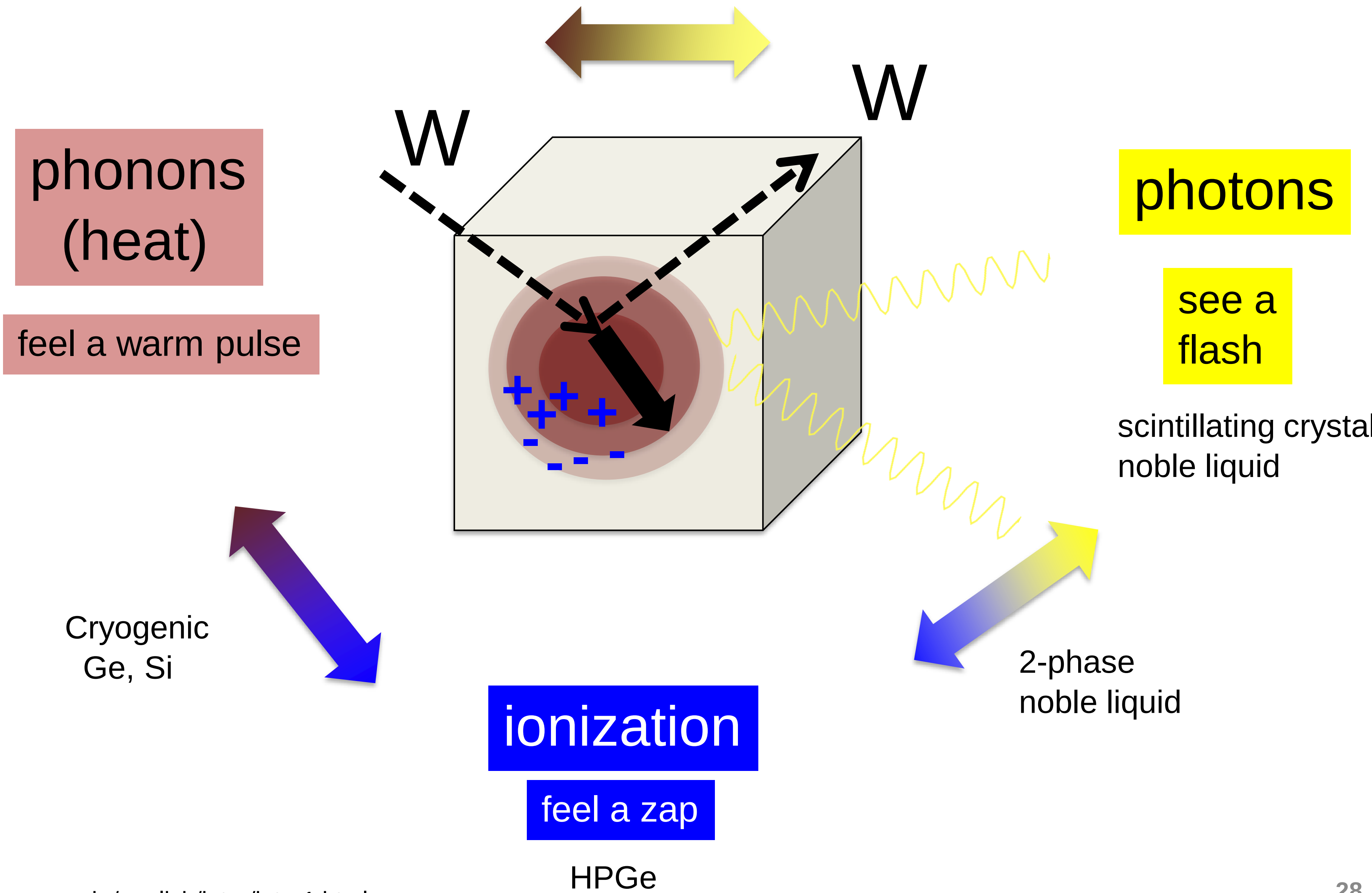
0.08 neutrinos per flavor per proton on target



SNS flux (1.4 MW):
430 x 10^5 ν/cm^2/s
@ 20 m

Now, ***detecting*** the tiny kick of the neutrino...

This is just like the tiny thump of a WIMP;
we benefit from the last few decades of low-energy nuclear recoil detectors



http://dmrc.snu.ac.kr/english/intro/intro1.html

The COHERENT collaboration

http://sites.duke.edu/coherent

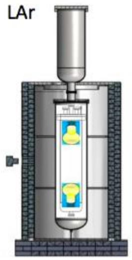
~90 members,
20 institutions
4 countries

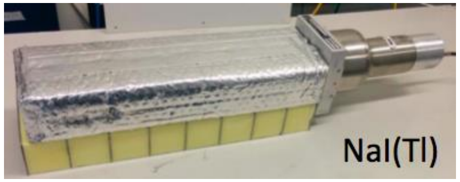
arXiv:1509.08702

COHERENT CEvNS Detectors

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal flash	14.6	19.3	6.5
Ge	HPGe PPC zap	16	22	<few
LAr	Single-phase flash	22	29	20
NaI[Tl]	Scintillating crystal flash	185*/3338	28	13

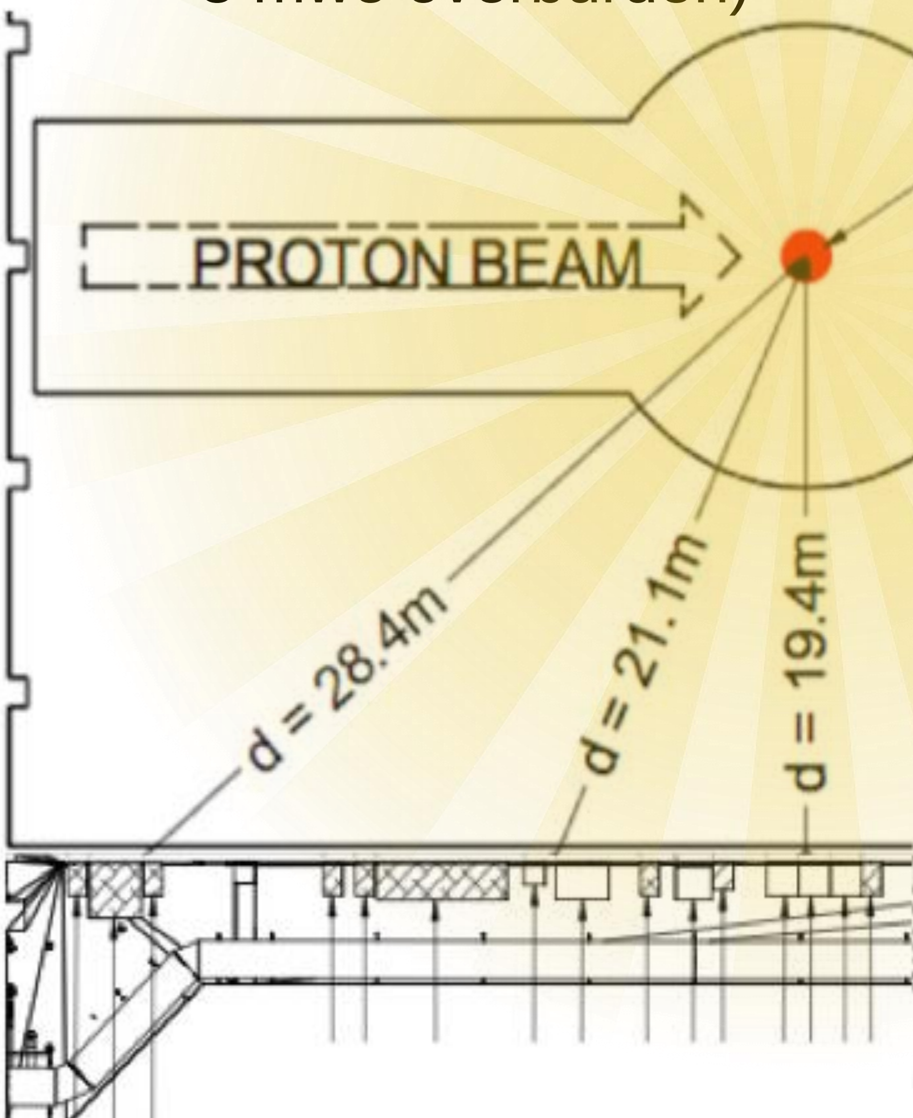
Multiple detectors for N^2 dependence of the cross section



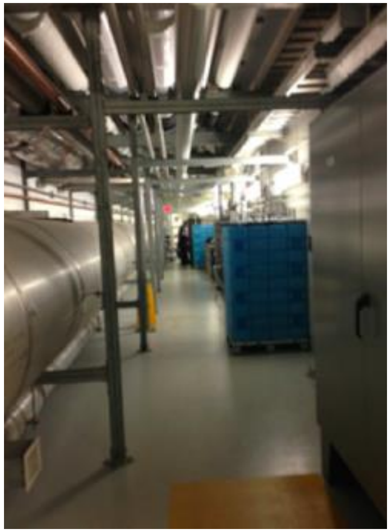


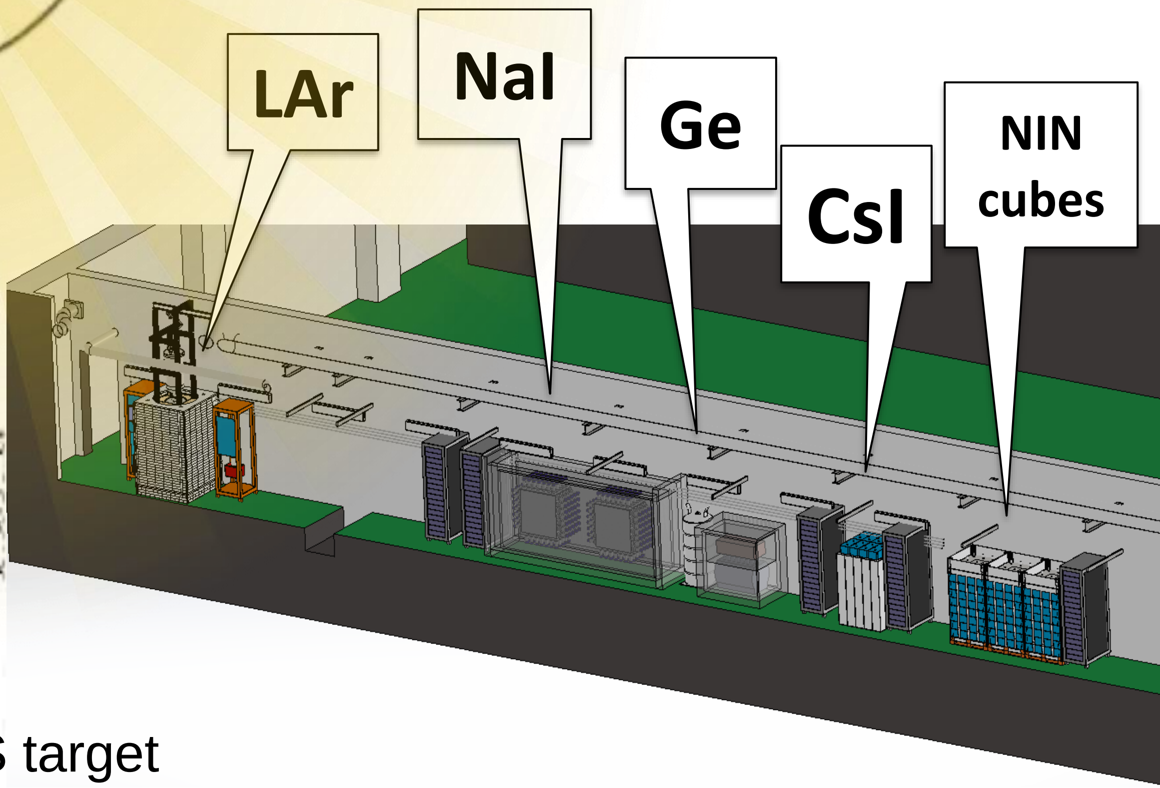
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)



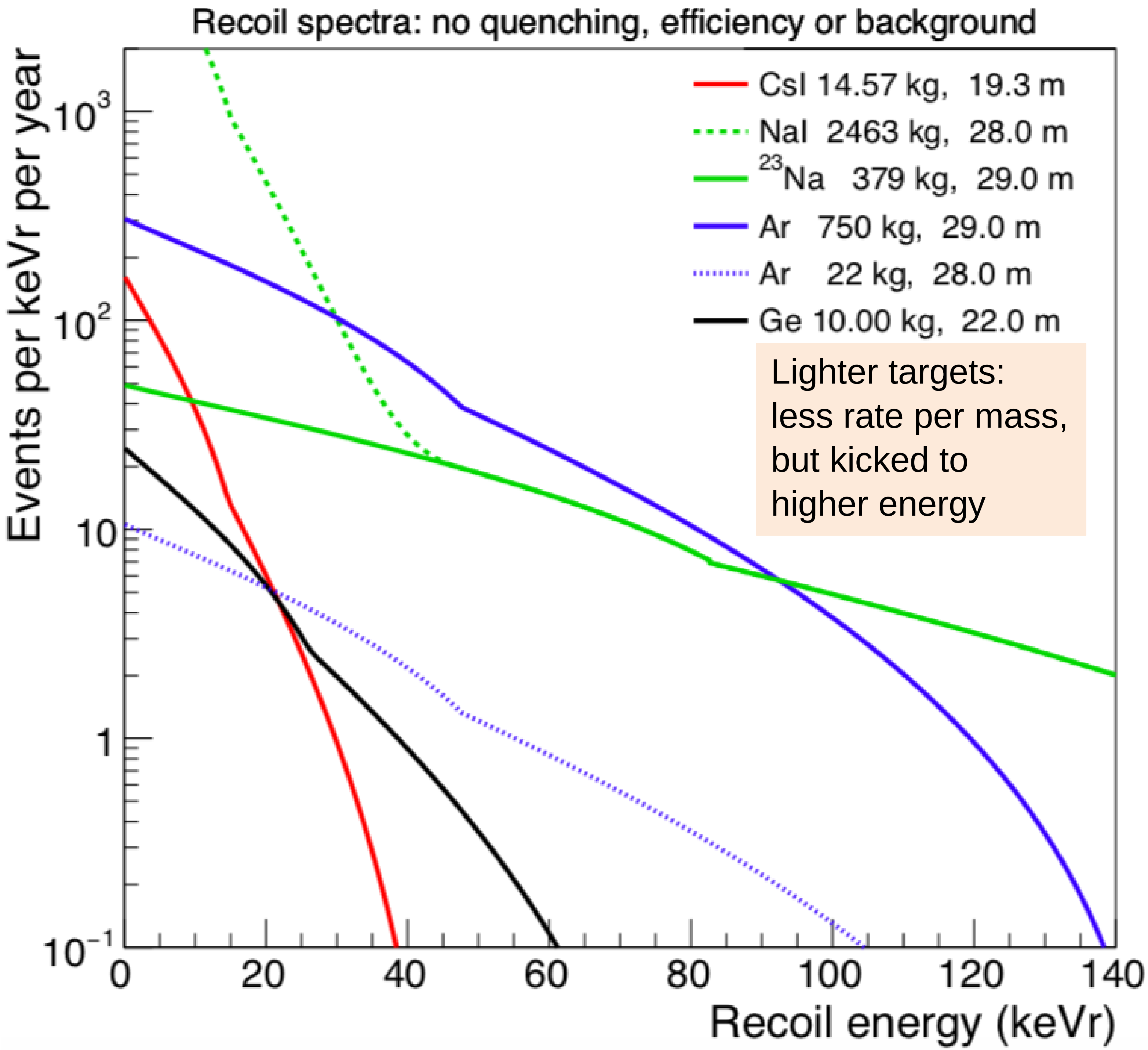
View looking down "Neutrino Alley"





Isotropic ν glow from Hg SNS target

Expected recoil energy distribution

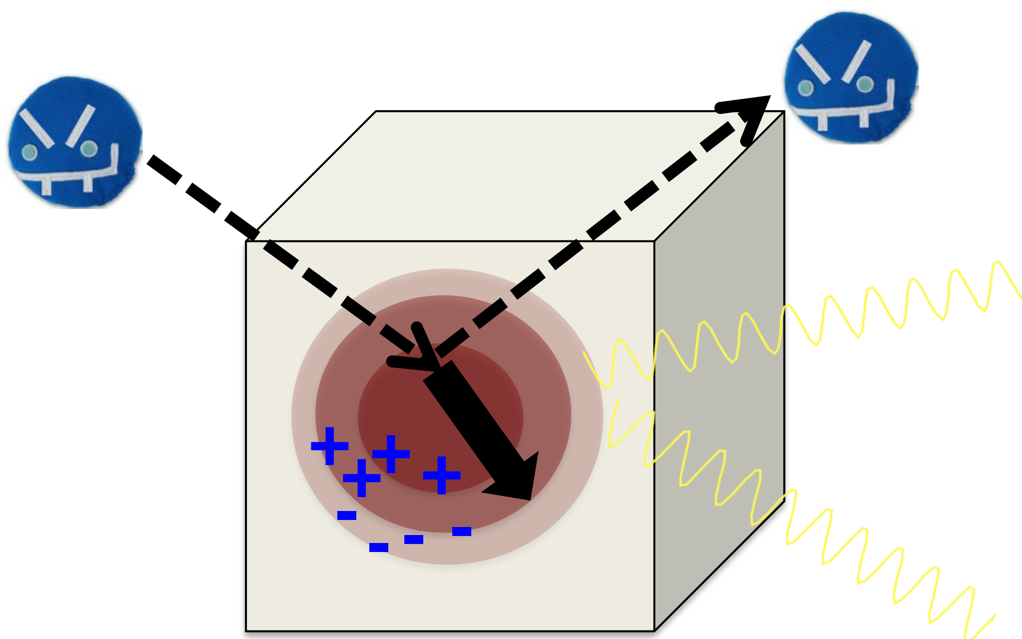


Backgrounds

Usual suspects:

- cosmogenics
- ambient and intrinsic radioactivity
- detector-specific noise and dark rate

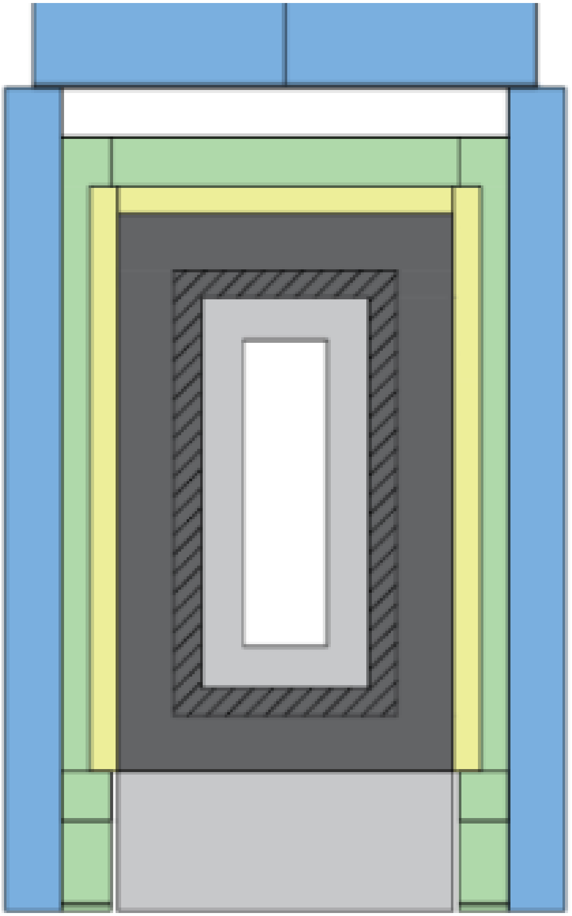
Neutrons are especially not our friends*

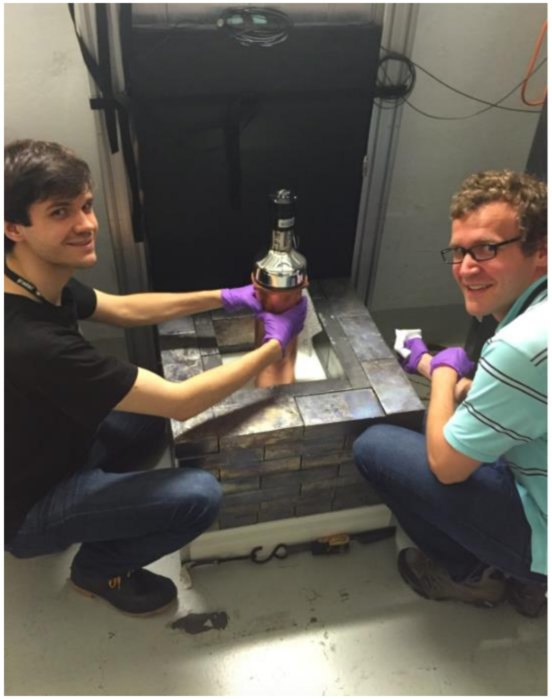


Steady-state backgrounds can be *measured* off-beam-pulse
... in-time backgrounds must be carefully characterized

*Thanks to Robert Cooper for the "mean neutron"

The CsI Detector in Shielding in Neutrino Alley at the SNS





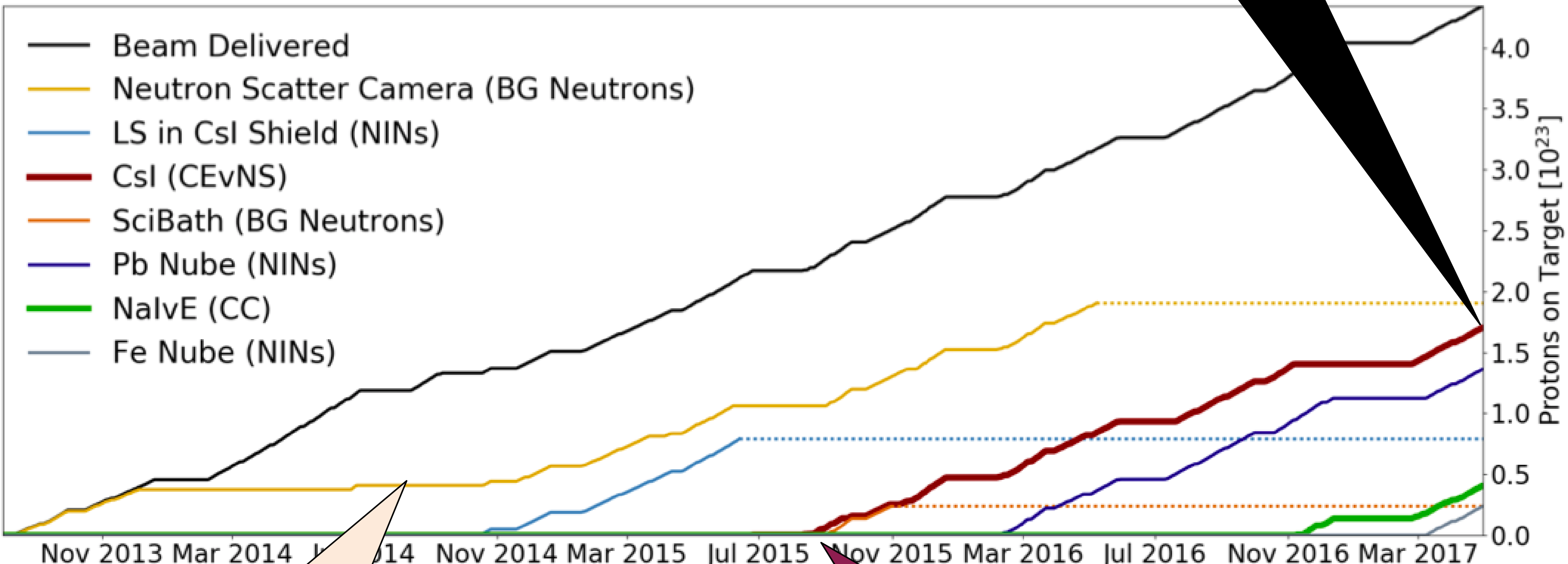
A hand-held detector!

Almost wrapped up...

Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3”	2”	4”	2”	4”
Colour					

COHERENT data taking

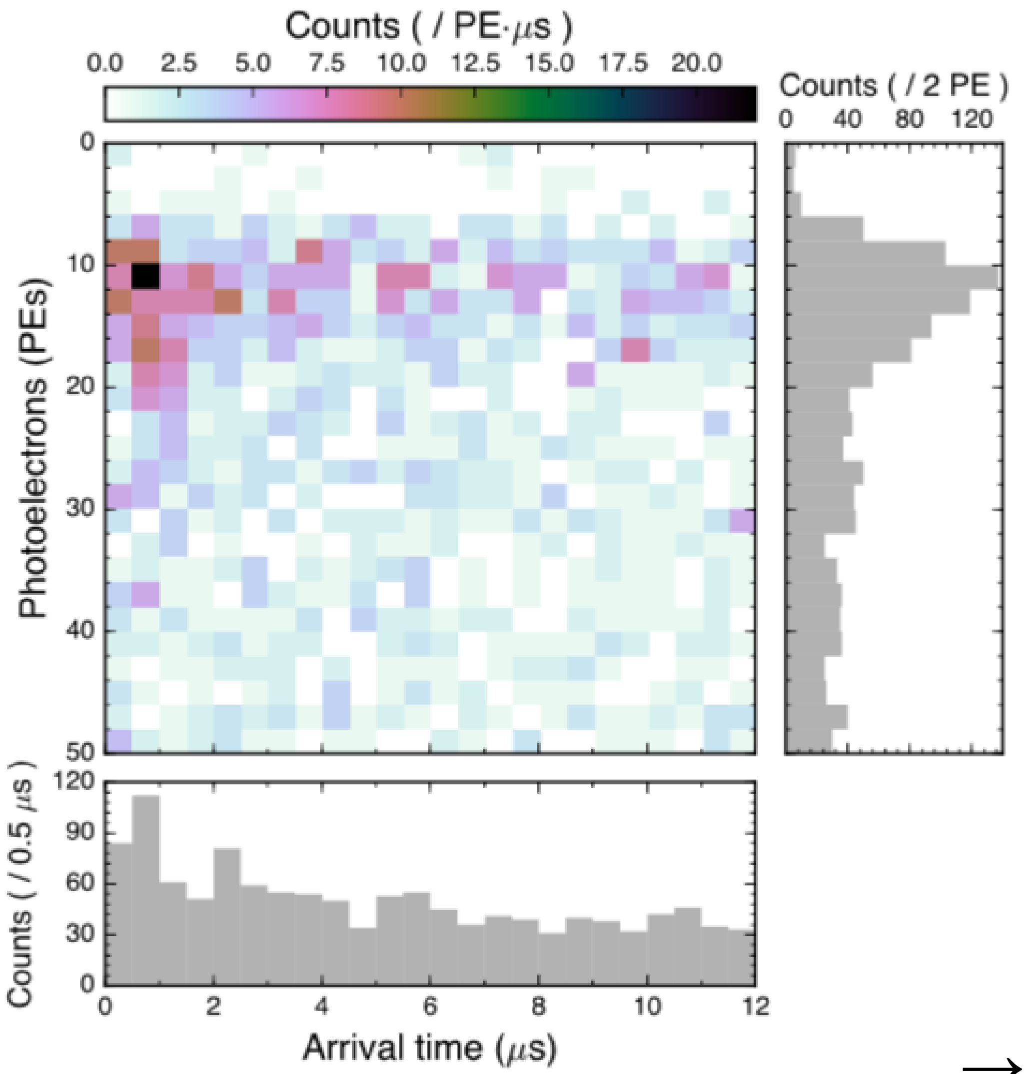
1.76 $\times 10^{23}$ POT delivered to CsI (7.48 GWhr)

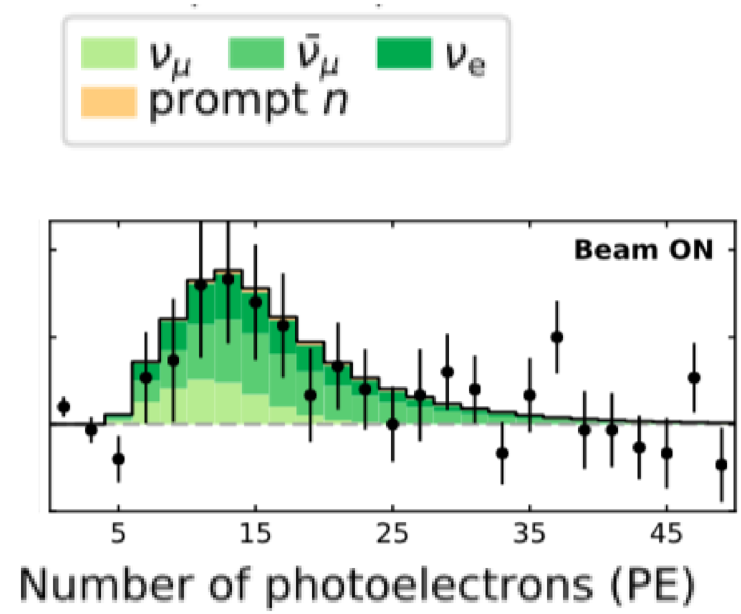


Neutron background data-taking for ~2 years before first CEvNS detectors

CsI data-taking starting summer 2015

First light at the SNS (stopped-pion neutrinos) with 14.6-kg CsI[Na] detector





Background-subtracted and integrated over time

$$\mathrm{PE} \propto T \propto Q^2$$

→ measure of the Q spectrum

DOI: 10.5281/zenodo.1228631

D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

Signal, background, and uncertainty summary numbers

$6 \leq \text{PE} \leq 30$, $0 \leq t \leq 6000$ ns

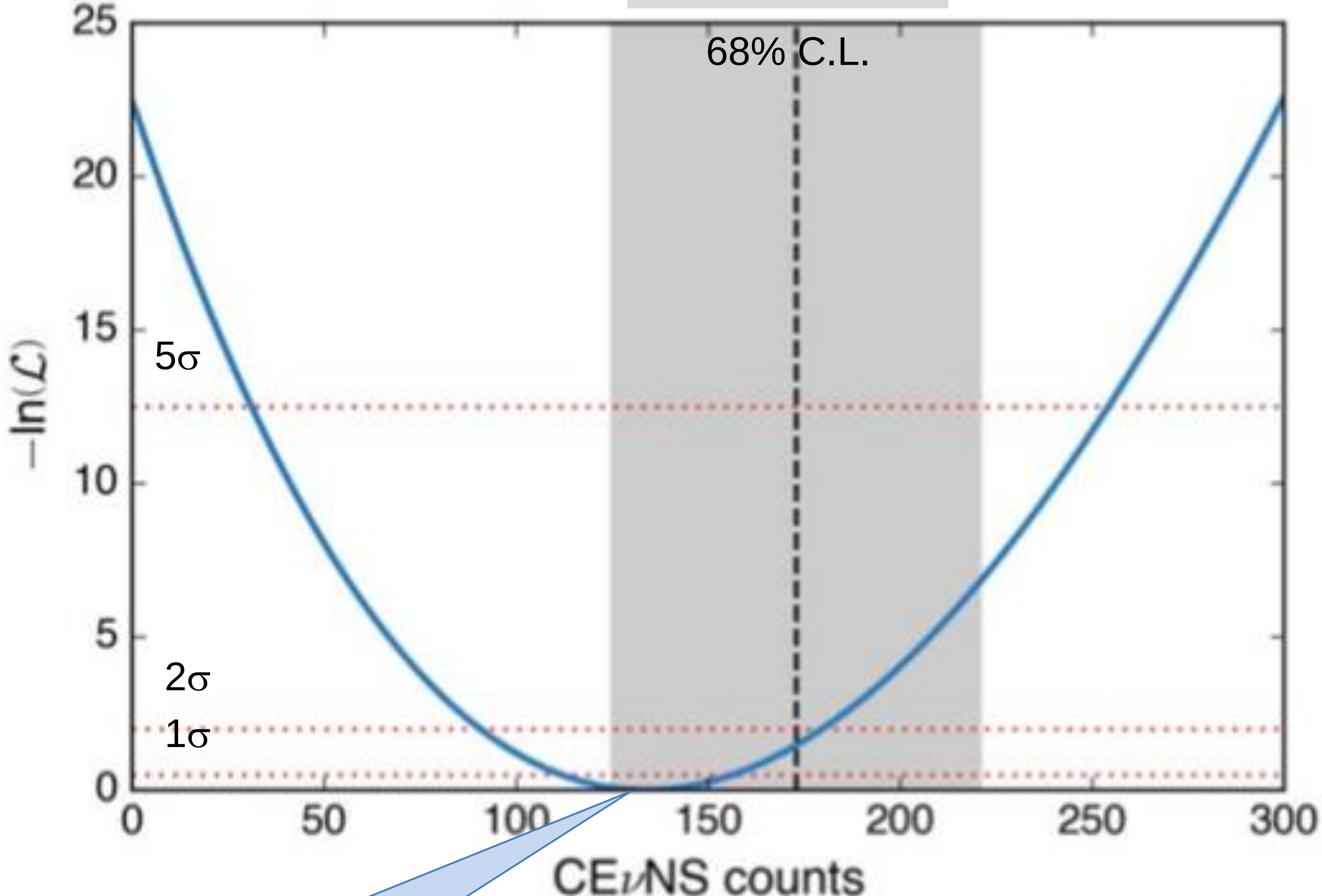
Beam ON coincidence window	547 counts
Anticoincidence window	405 counts
Beam-on bg: prompt beam neutrons	7.0 ± 1.7
Beam-on bg: NINs (neglected)	4.0 ± 1.3
Signal counts, single-bin counting	136 ± 31
Signal counts, 2D likelihood fit	**134 ± 22**
Predicted SM signal counts	**173 ± 48**

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

Dominant uncertainty

Results of 2D energy, time fit

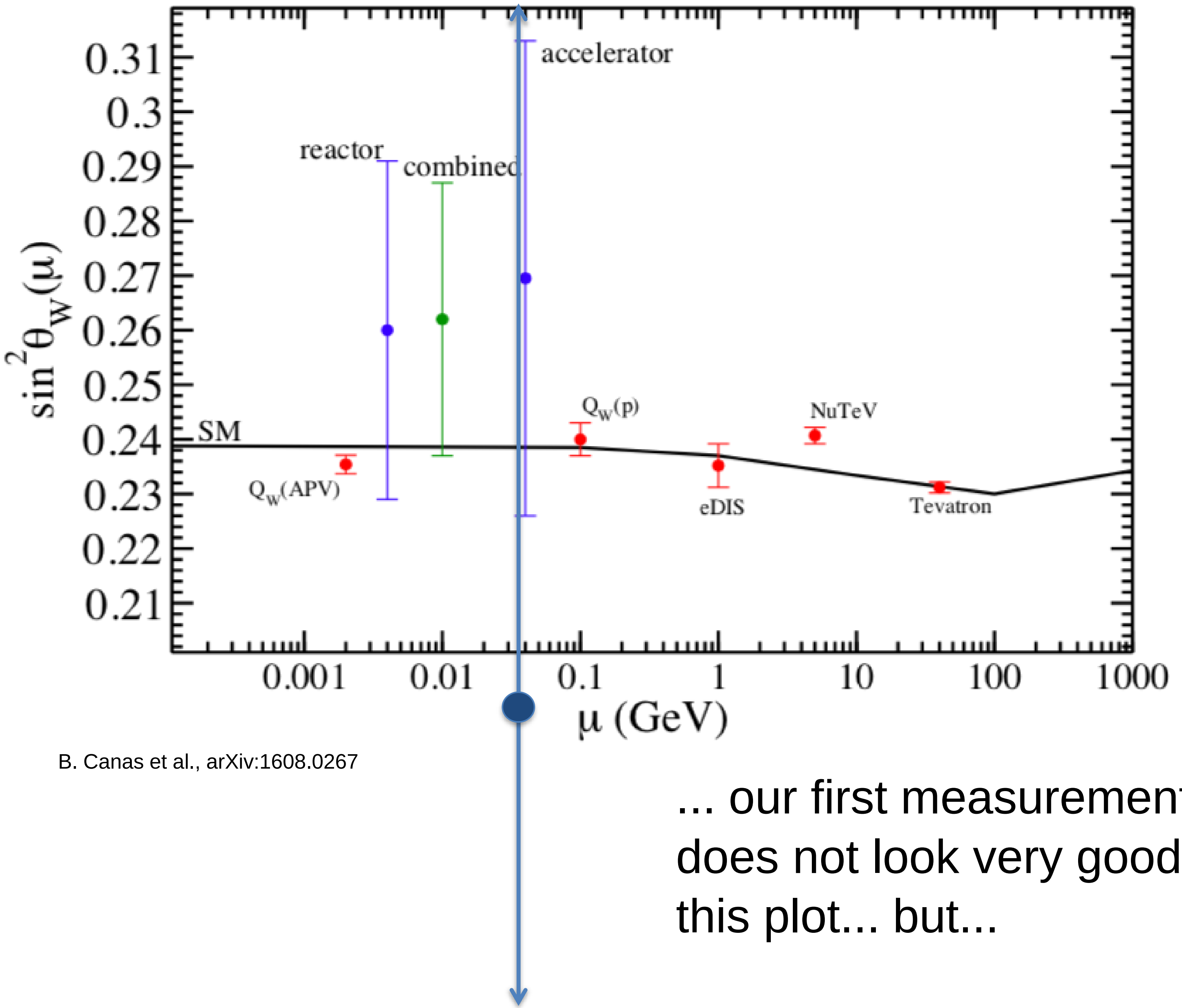
SM prediction, 173 events



Best fit: **134 ± 22** observed events

No CEvNS rejected at 6.7σ, consistent w/SM within 1σ

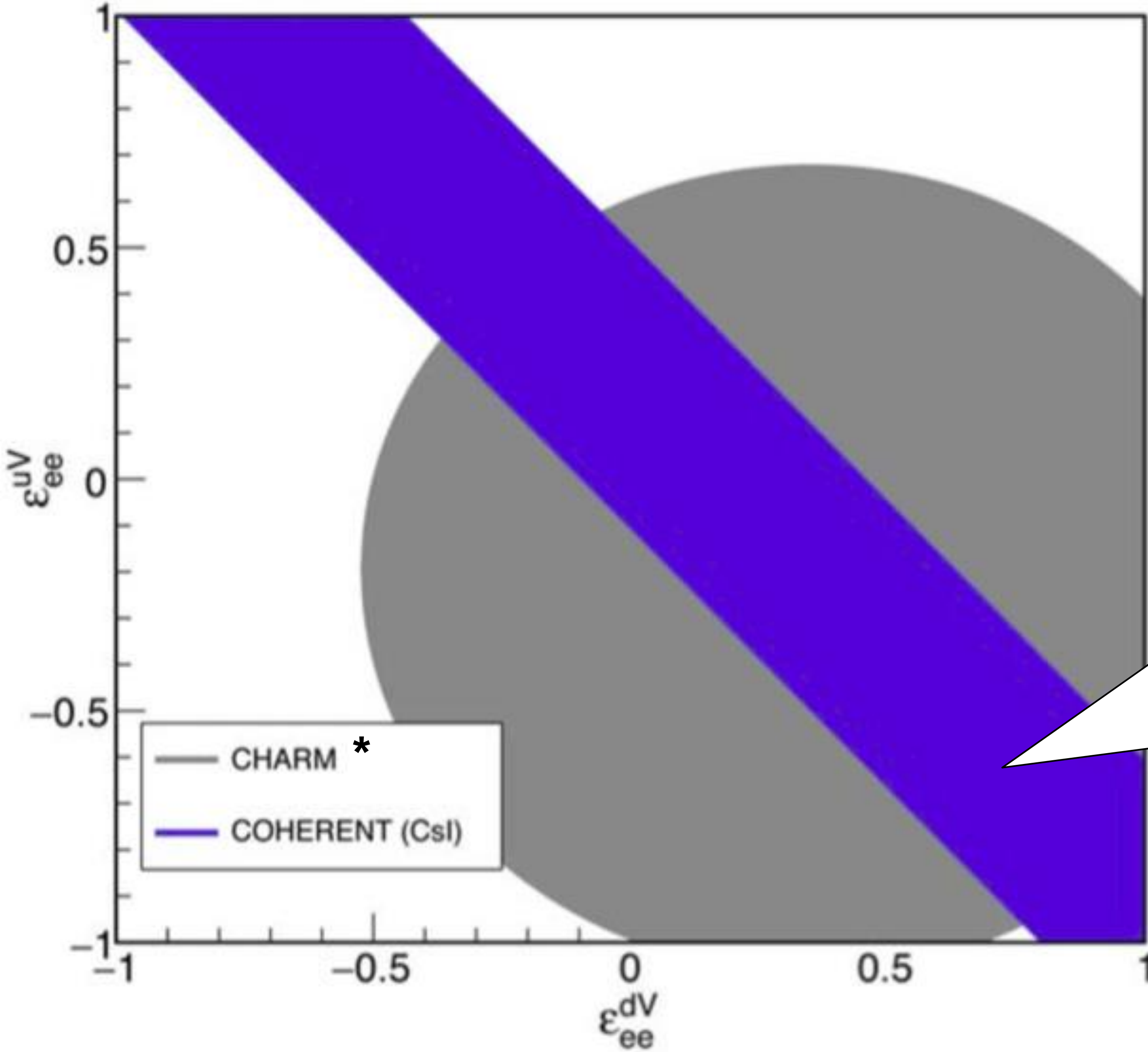
Interpreting the rate in the context of SM parameters



B. Canas et al., arXiv:1608.0267

... our first measurement does not look very good on this plot... but...

Neutrino non-standard interaction constraints for current CsI data set:



- Assume all other ε's zero

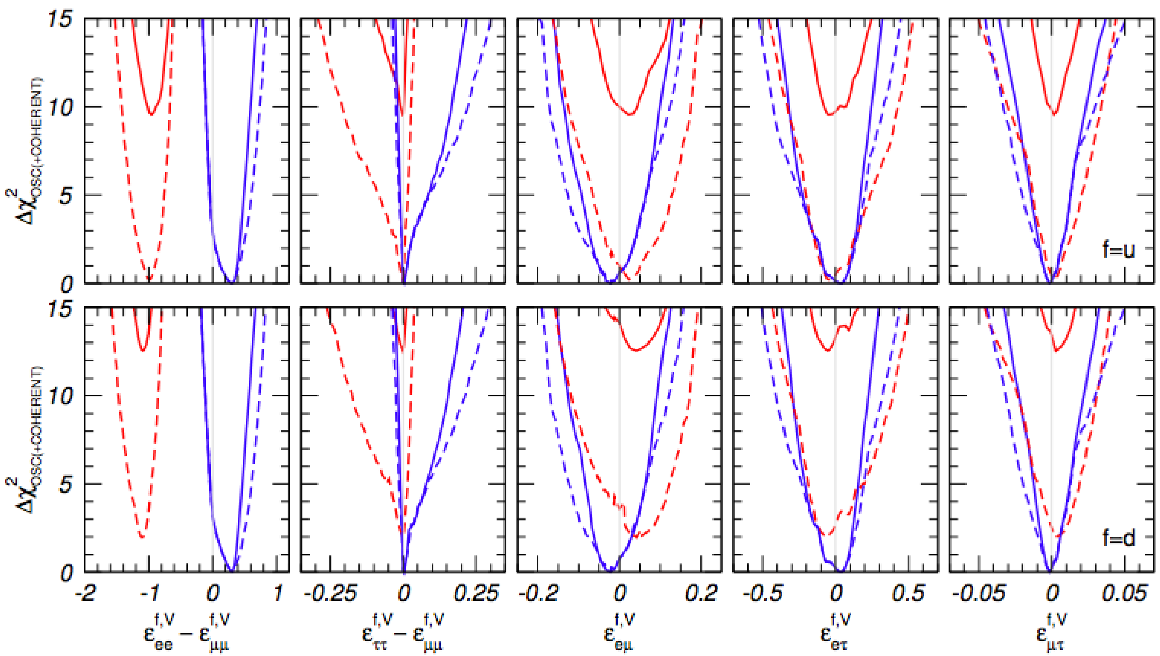
Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

See also Coloma et al., arXiv:1708.02899

*CHARM constraints apply only to heavy mediators

A COHERENT enlightenment of the neutrino Dark Side

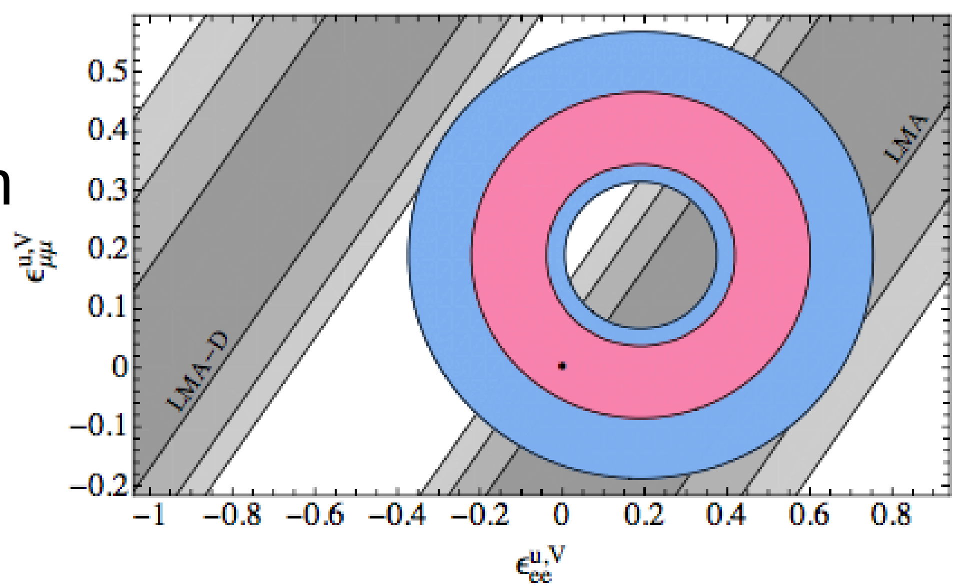
Pilar Coloma,[1,*] M. C. Gonzalez-Garcia,,[2,3,4,†] Michele Maltoni,,[5,‡] and Thomas Schwetz[6,§]



Global fits to COHERENT + oscillation experiments

Solid: COHERENT
Dashed: COHERENT + osc
Blue: LMA ($\theta_{12} < \pi/4$)
Red: LMA-D ($\theta_{12} > \pi/4$)
("dark side", still allowed with NSI)

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

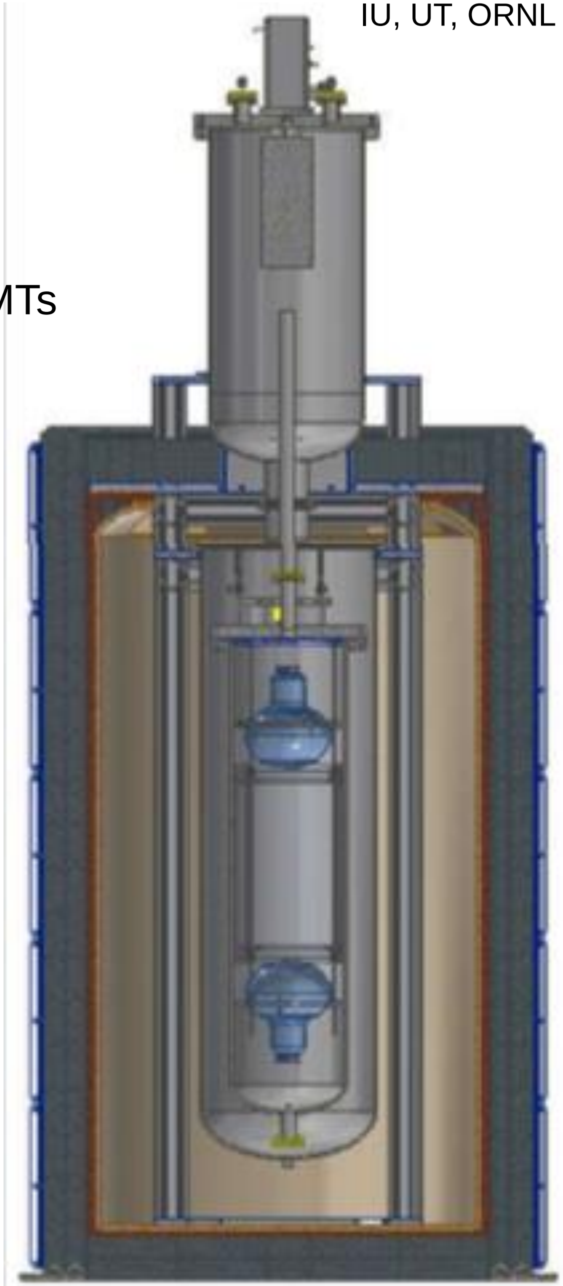


Already meaningful constraints!

Single-Phase Liquid Argon

- ~22 kg fiducial mass
- 2 x Hamamatsu 5912-02-MOD 8” PMTs
  - 8” borosilicate glass windown
  - 14 dynodes
  - QE: 18%@ 400 nm
- Wavelength shifter: TB-coated teflon walls and PMTs
- Cryomech cryocooler – 90 Wt
  - PT90 single-state pulse-tube cold head

IU, UT, ORNL



Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB

(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

Matt Heath, APS April meeting

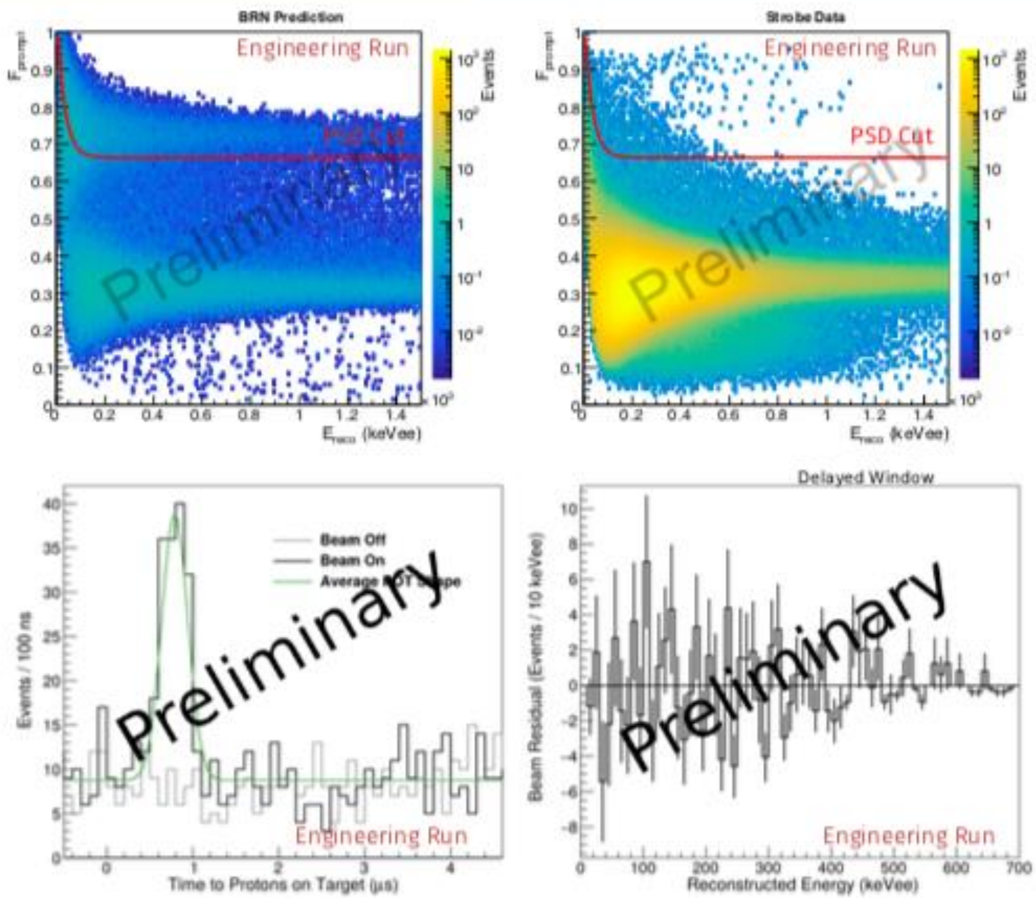
Engineering Run

Full Shielding Analysis

- Addition of 20.3 cm H_2O and 1.27 cm Cu
- 2 analysis methods:
  1. Counting exp't: cut in PSD/energy/time and count events
     - No indication of neutrons/CEvNS in delayed window
     - Cross section limit: $\sigma^{\mathrm{Ar}}_{CEvNS} < 150 \times 10^{-40}\ \mathrm{cm}^2$ ~8.6 x SM prediction

	Steady-State Backgrounds	Beam-Related Neutrons	CEvNS
Neutron Count. Exp't	88	123	0.2
CEvNS Count. Exp't	10.3	< 1	0.5
Likelihood	5200	143	3.9

Engineering Run Event Rate Predictions

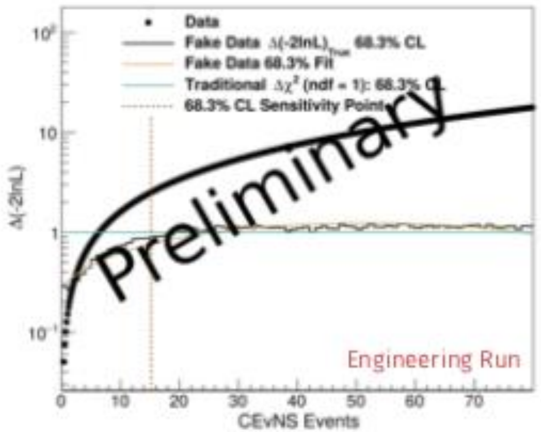


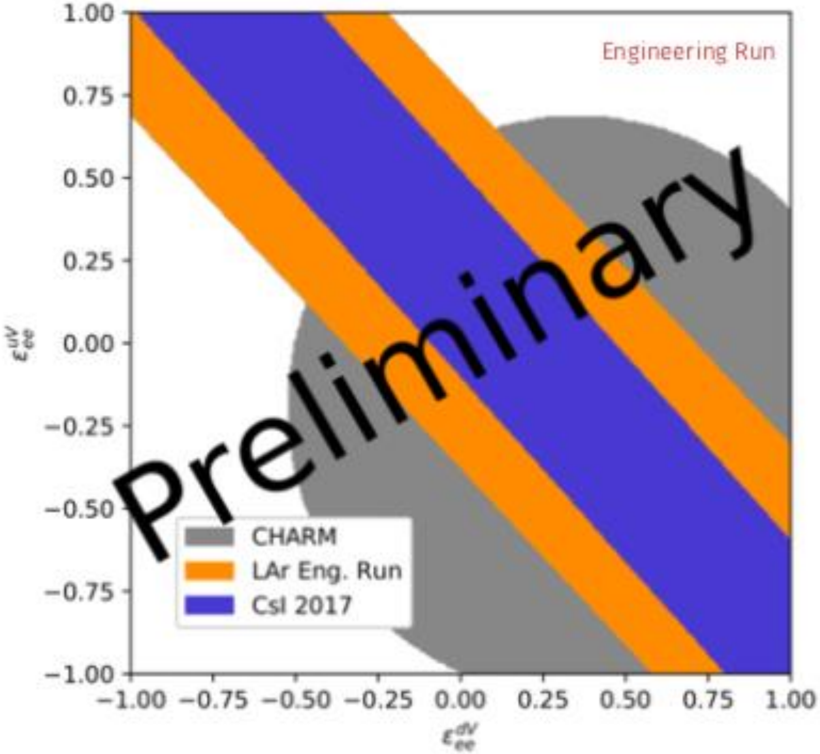
9

Engineering Run

Full Shielding Analysis

- 2 analysis methods:
    1. Counting exp't
    2. Full likelihood analysis
        - Full 3D likelihood fit in energy/time/PSD with wider cuts
        - No CEvNS excess: $\sigma^{\mathrm{Ar}}_{CEvNS} < 24 \times 10^{-40}\ \mathrm{cm}^2 (68.3\,\%\ CL)$ following Feldman-Cousins
        - Non-standard interactions constraints[1]



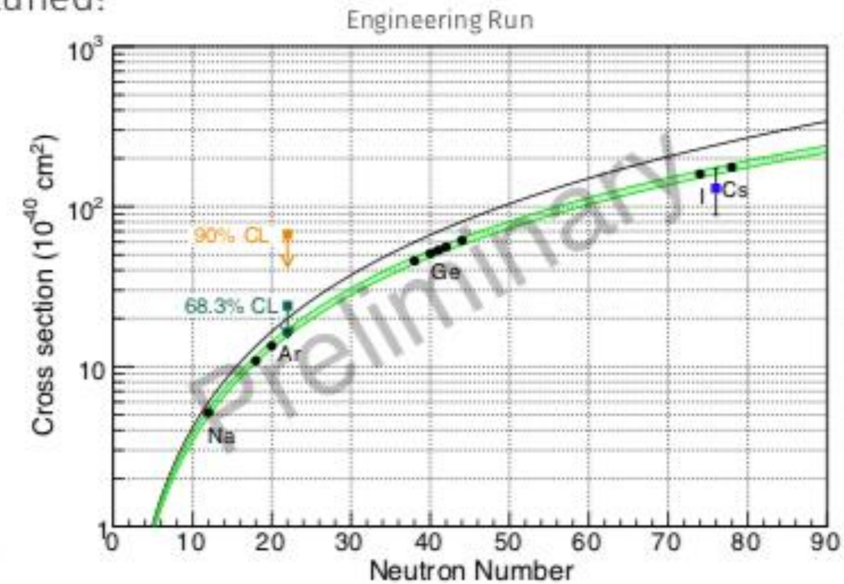


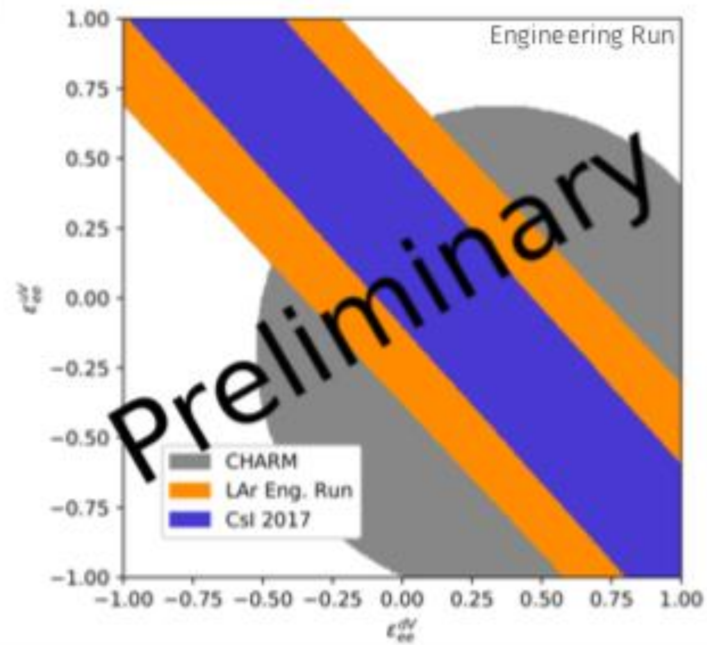
[1] To appear in M. R. Heath, IU Thesis

Matt Heath, APS April meeting

Summary

- Results from LAr detector Engineering Run![2]
  - Confirm all beam-related neutrons prompt and can be predicted
  - CEvNS limit from likelihood analysis
    - Confirm CsI NSI results even with high threshold, high bkg rate, and short run time
- CENNS-10 taking data
  - Production Run results soon!
    - Lower threshold, lower bkg rates, longer exposure time!
  - Stay tuned!





[2] To appear in M. R. Heath, IU Thesis

Another phenomenological analysis, making use of spectral fit:

COHERENT constraints on nonstandard neutrino interactions

Jiajun Liao and Danny Marfatia

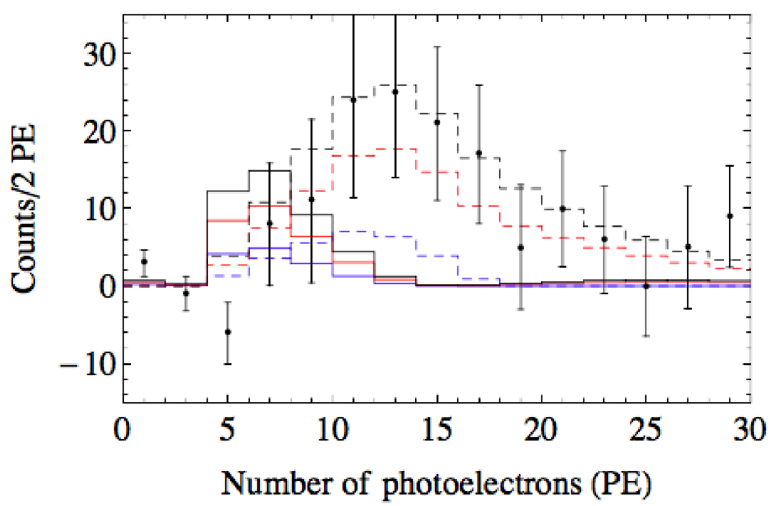
arXiv:1708.04255

SM weak charge

Effective weak charge in presence of light vector mediator Z'

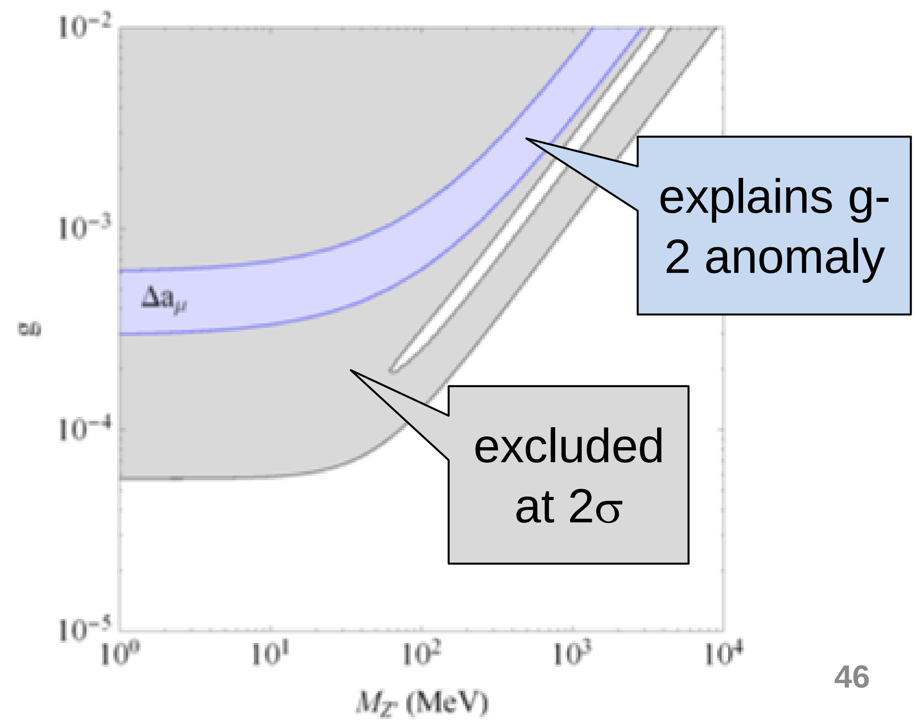
$$Q^2_{\alpha,\mathrm{SM}} = (Z g_p^V + N g_n^V)^2 \quad \Rightarrow \quad Q^2_{\alpha,\mathrm{NSI}} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M_{Z'}^2)} \right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M_{Z'}^2)} \right) \right]^2$$

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

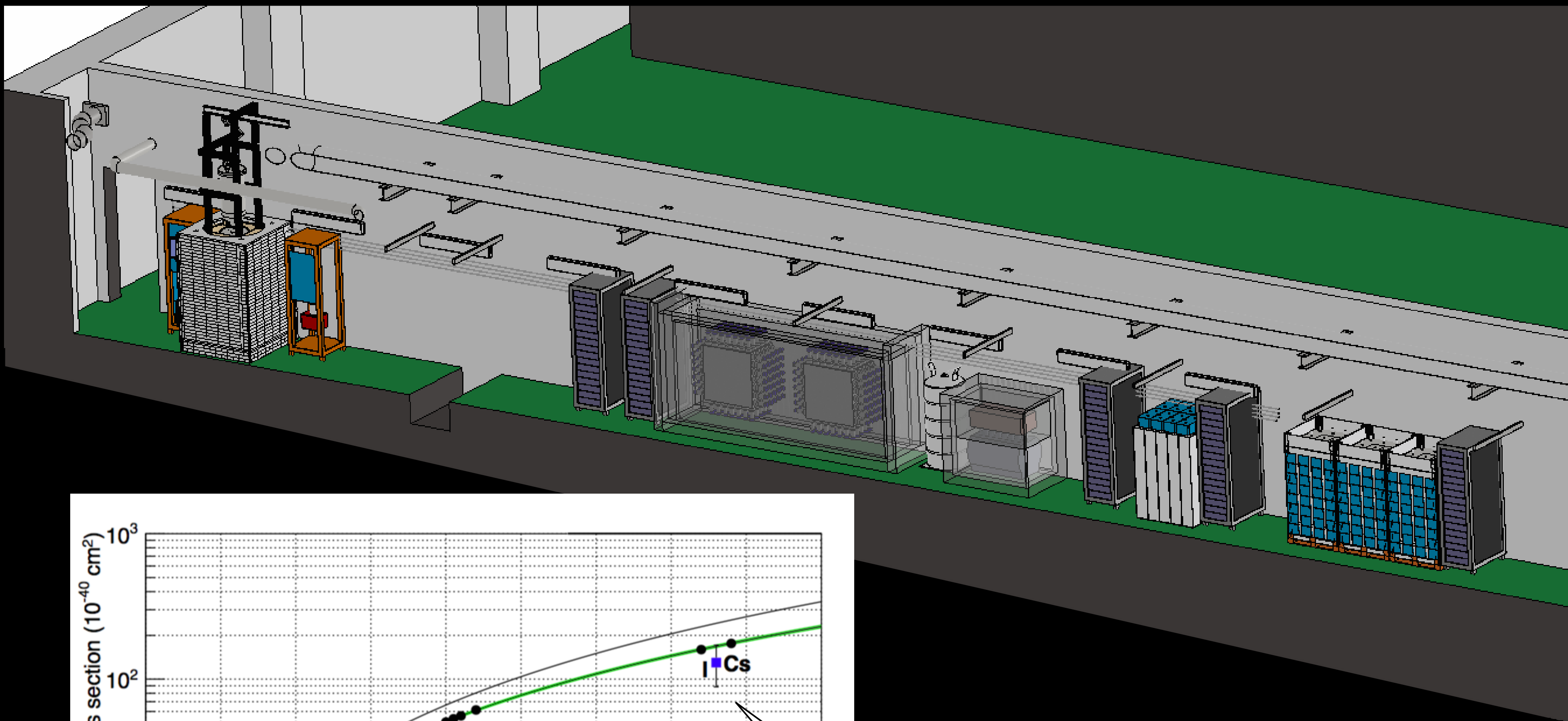


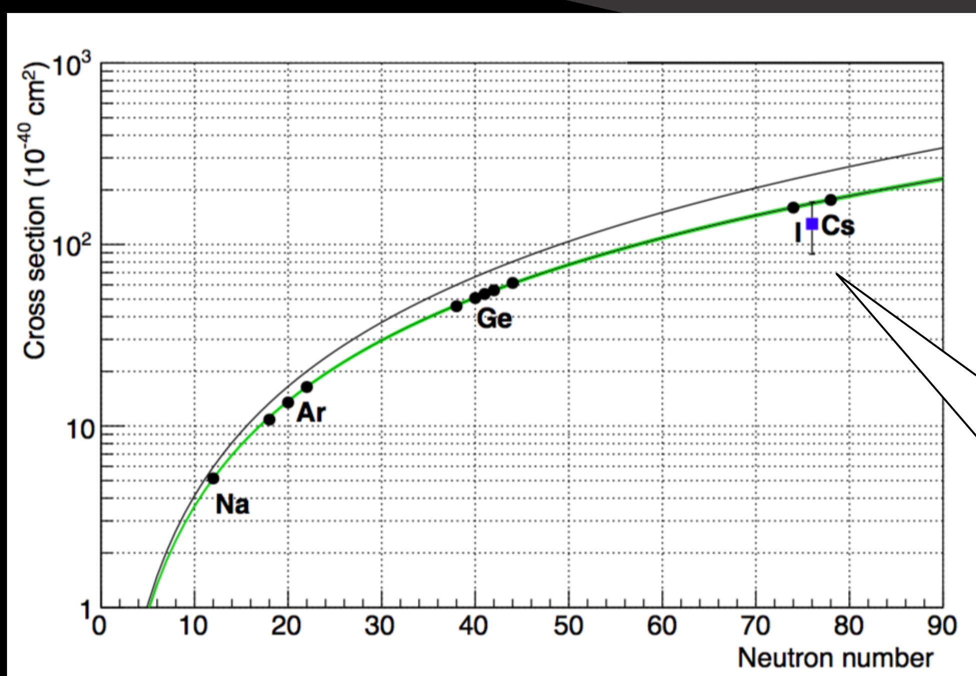
Dashed: SM
Solid: NSI w/ $M_{z'}$= 10 MeV, g=10^{-4}

Blue: ν_μ
Red: ν_μ + $\nu_\mu$bar
Black: $\nu_\mu + \nu_\mu$bar + ν_e



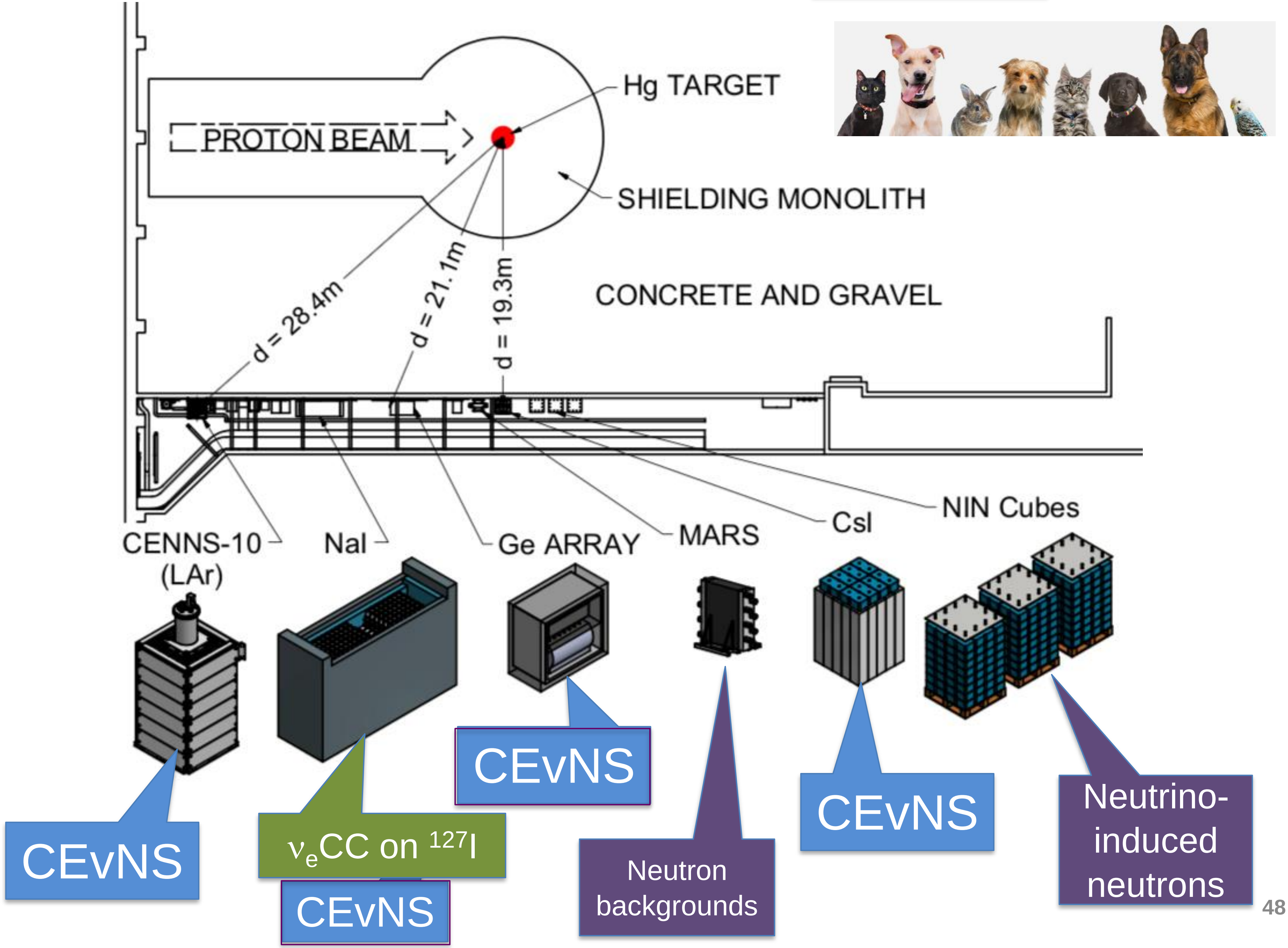
What's Next for COHERENT?



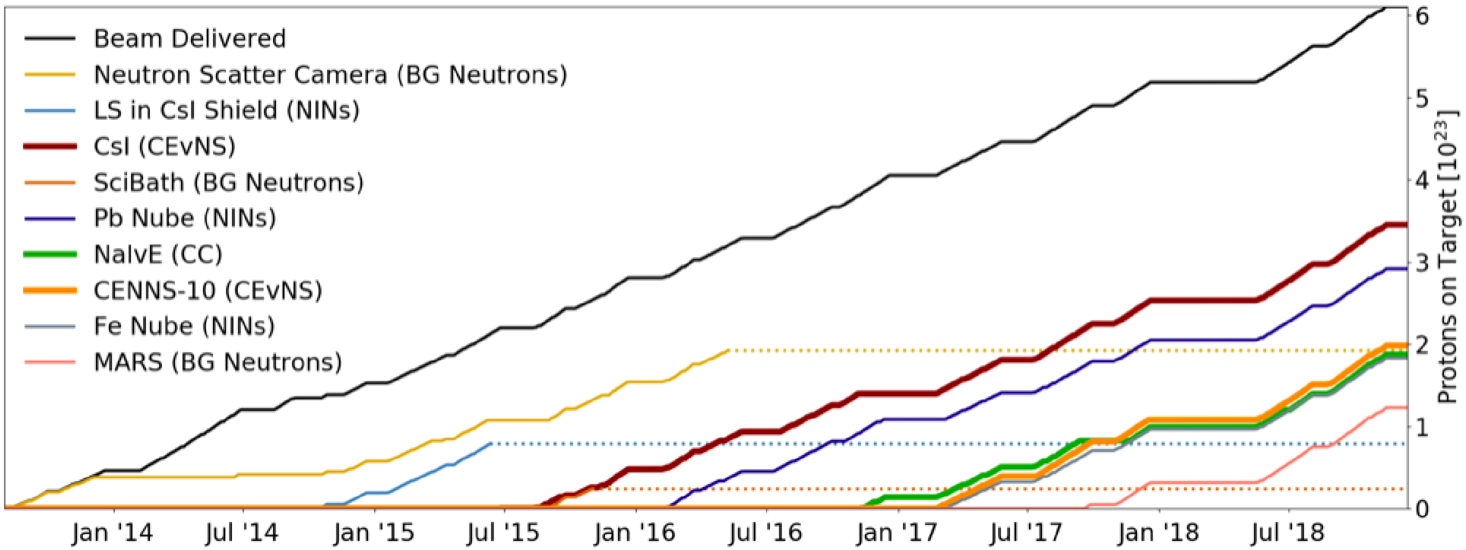


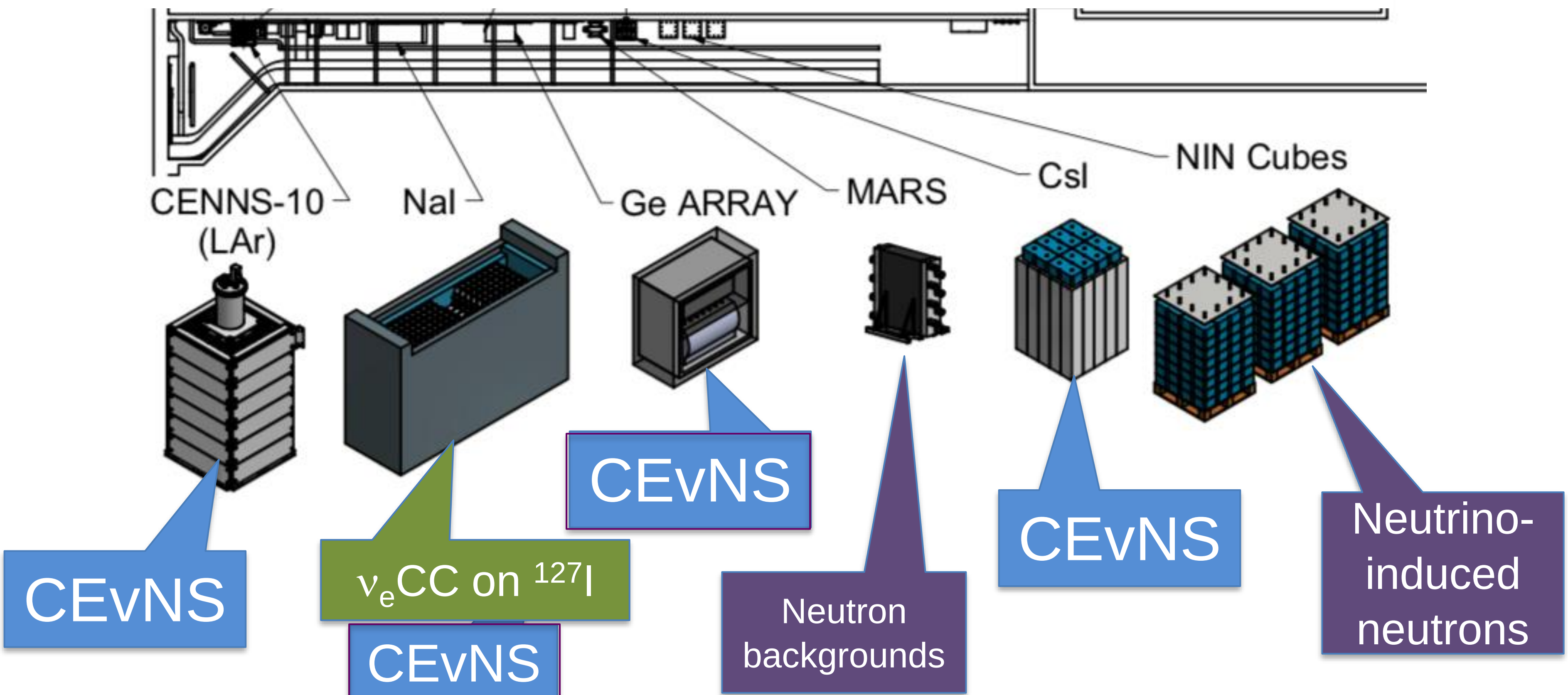
One measurement so far! Want to map out N^2 dependence

Neutrino Alley Deployments: current & near future



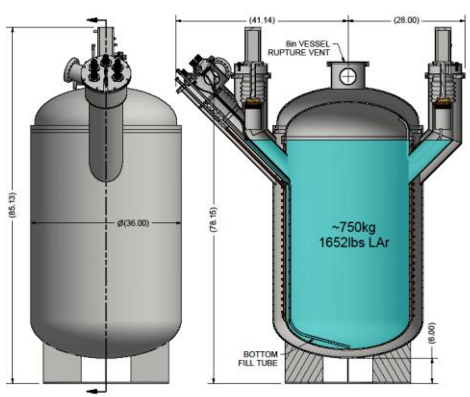
Lots more data in the can!

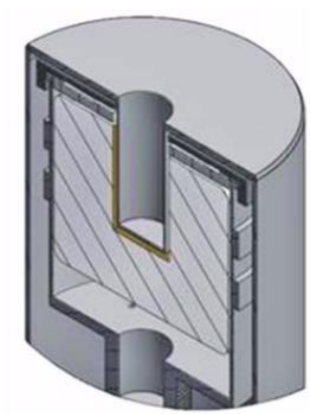


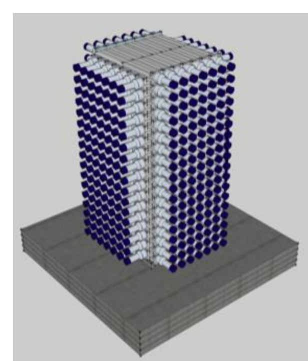


COHERENT **CEvNS** Detector Status and **Farther Future**

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	20	6.5	9/2015	Finishing data-taking
Ge	HPGe PPC	16	22	<few	2019	
LAr	Single-phase	22	29	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	28	13	*high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes

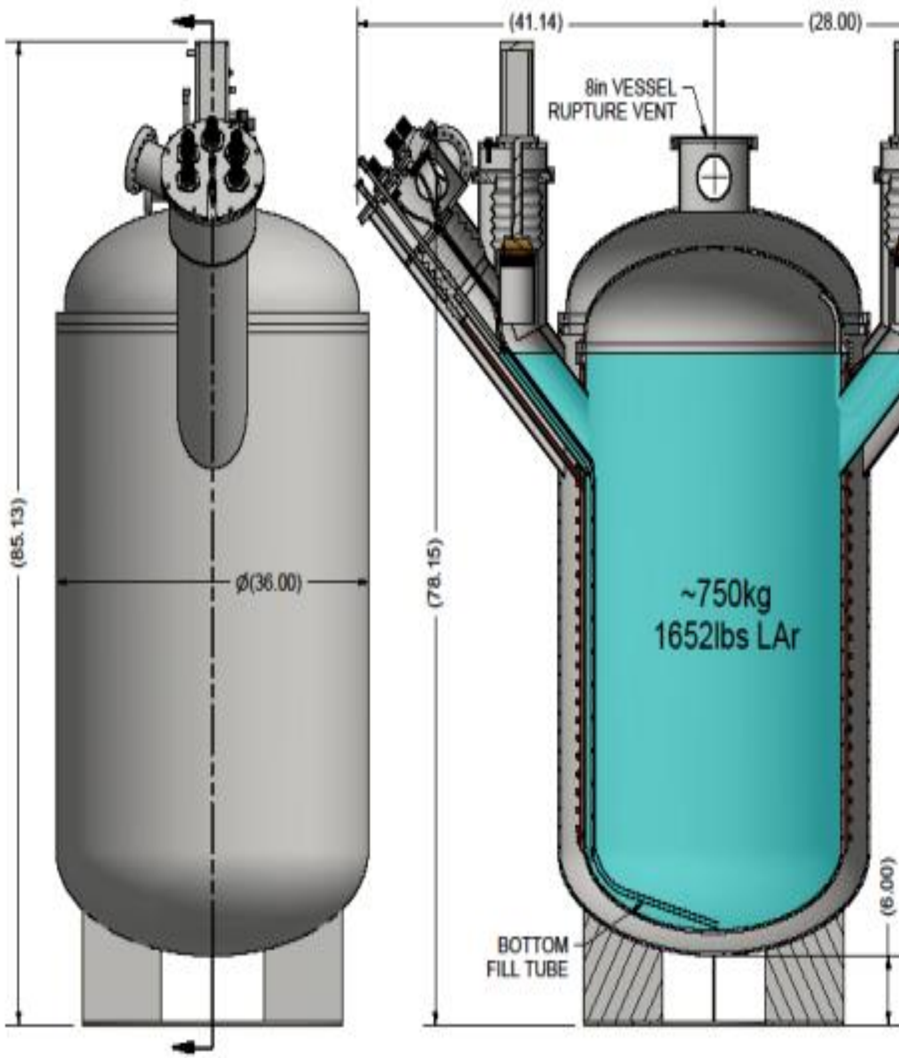




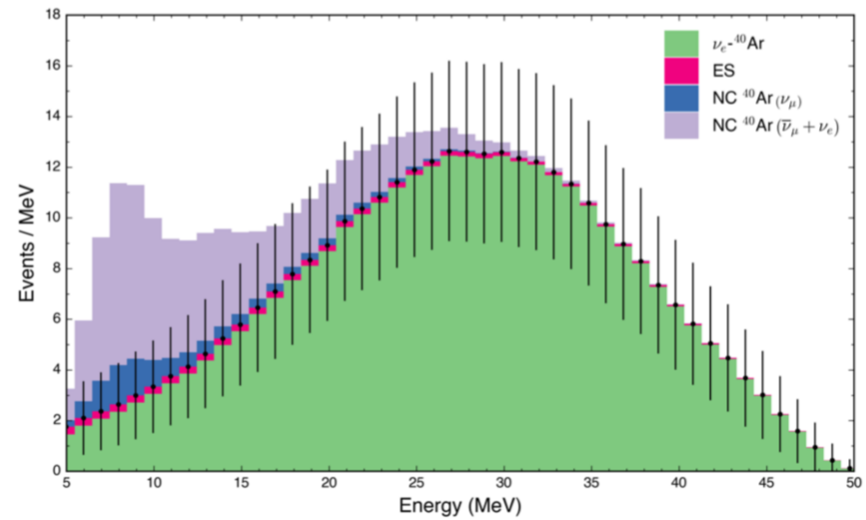


+ concepts for other targets

Tonne-scale LAr Detector



- 750-kg LAr will fit in the same place, will reuse part of existing infrastructure
- Could potentially use depleted argon



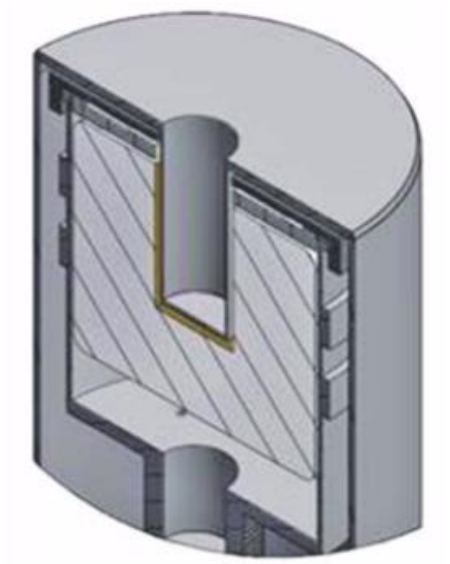
CC/NC **inelastic** in argon of interest for supernova neutrinos

CC $\nu_e + {}^{40}Ar$ ❼ $e^- + {}^{40}K^*$

NC $\nu_x + {}^{40}Ar$ ❼ $\nu_x + {}^{40}Ar^*$

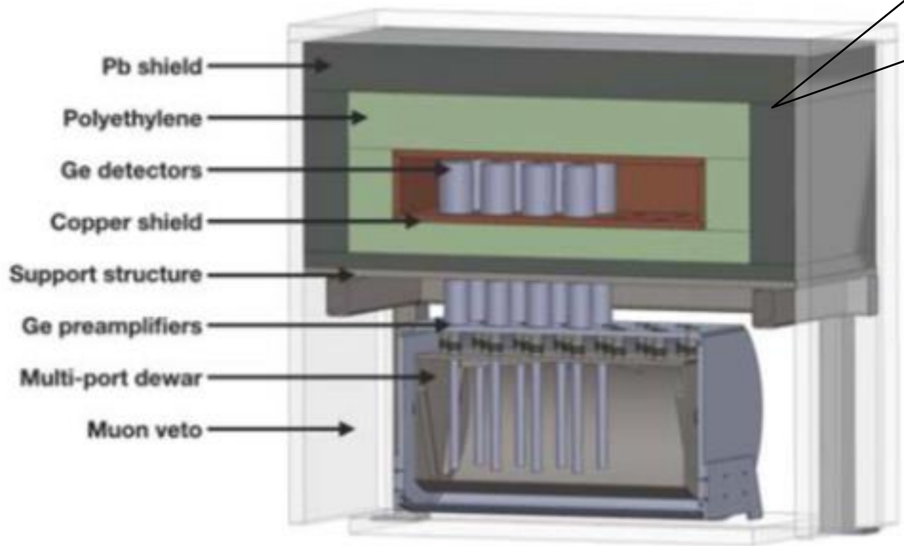
High-Purity Germanium Detectors

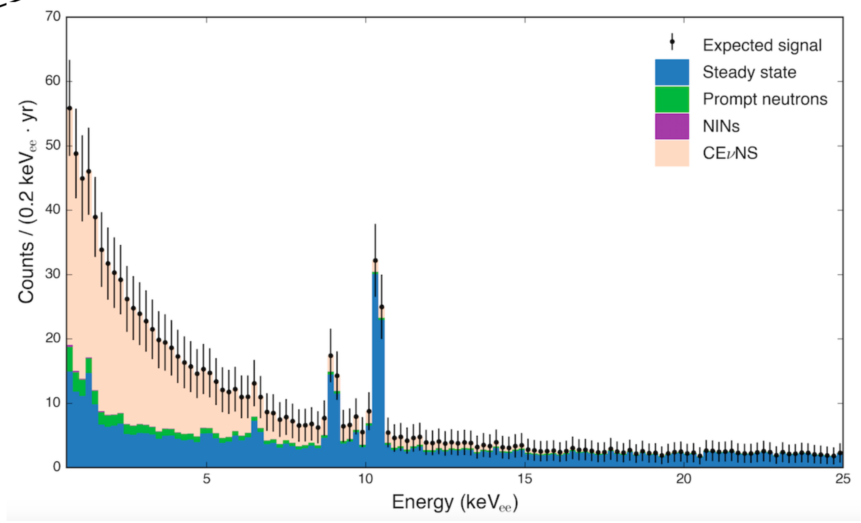
P-type Point Contact



- Excellent low-energy resolution
- Well-measured quenching factor
- Reasonable timing

- 8 Canberra/Mirion 2 kg detectors in multi-port dewar
- Compact poly+Cu+Pb shield
- Muon veto
- Designed to enable additional detectors

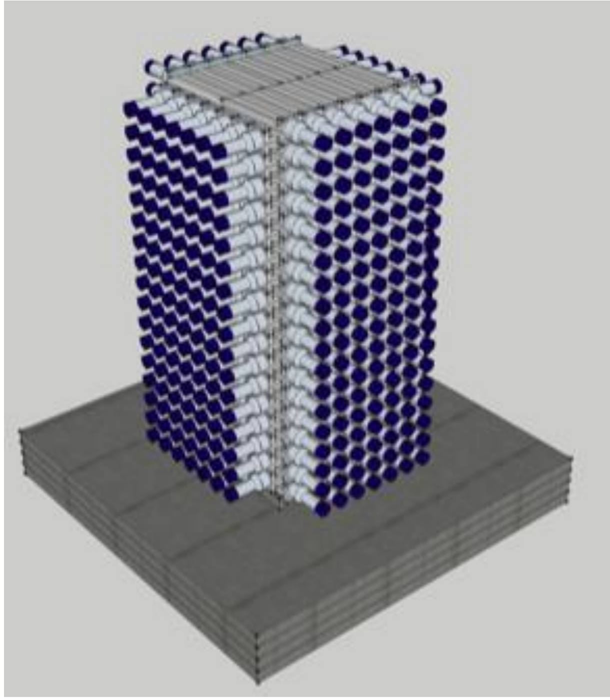




Sodium Iodide (NaI[Tl]) Detectors (NaIvE)

- up to 9 tons available, 2 tons in hand
- QF measured
- require PMT base refurbishment (dual gain) to enable low threshold for CEvNS on Na measurement
- development and instrumentation tests underway at UW, Duke

Multi-ton concept

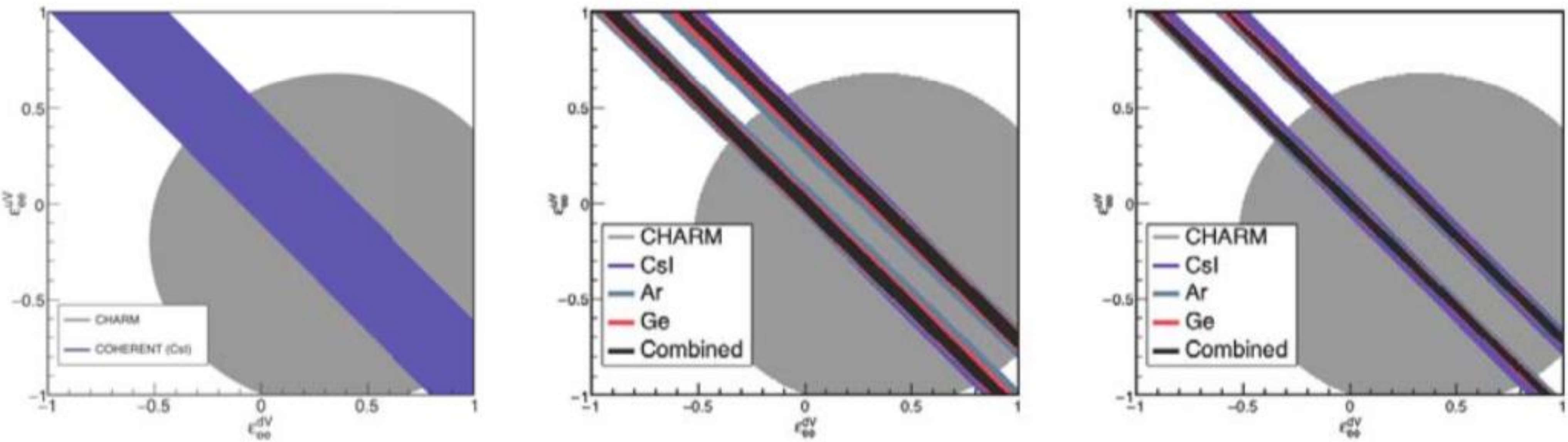


In the meantime: **185 kg deployed at SNS** to go after ν_e**CC on ^{127}I**

Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{127}I	$^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$	Stopped π/μ	LSND	$284 \pm 91(\mathrm{stat}) \pm 25(\mathrm{sys})$	210-310 [Quasi-particle] (Engel *et al.*, 1994)

J.A. Formaggio and G. Zeller, RMP 84 (2012) 1307-1341

Estimated future sensitivities for NSI

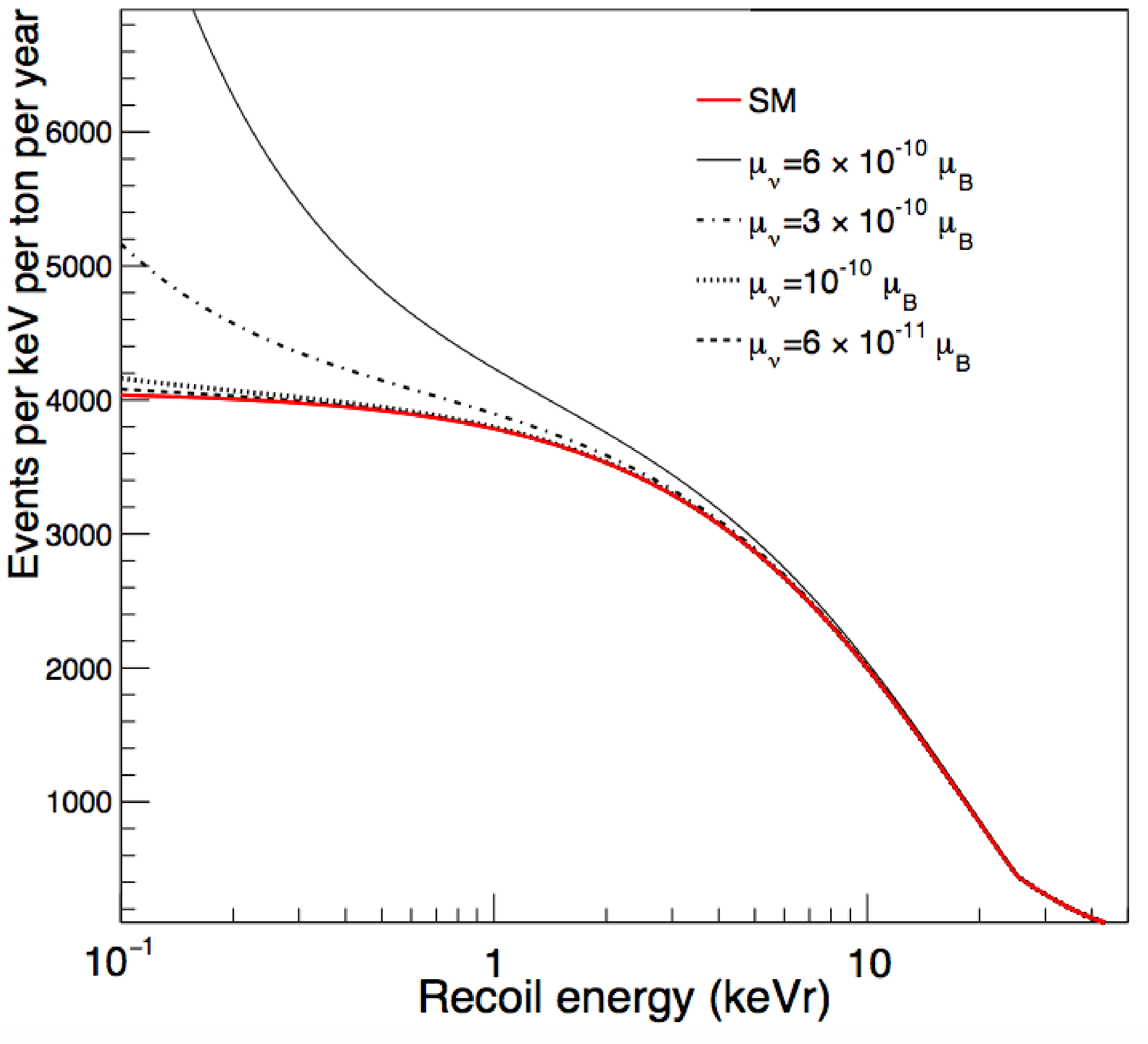


Combination
of targets
improves
sensitivity

Neutrino magnetic moment

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

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



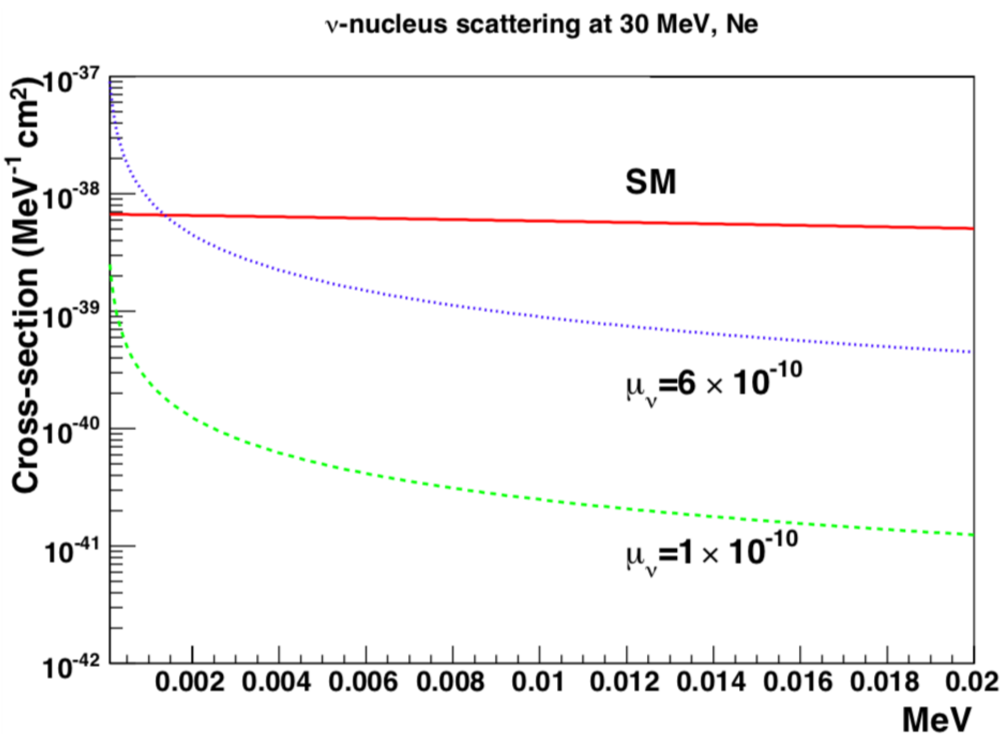
➔ very low energy threshold is desirable (i.e., Ge)

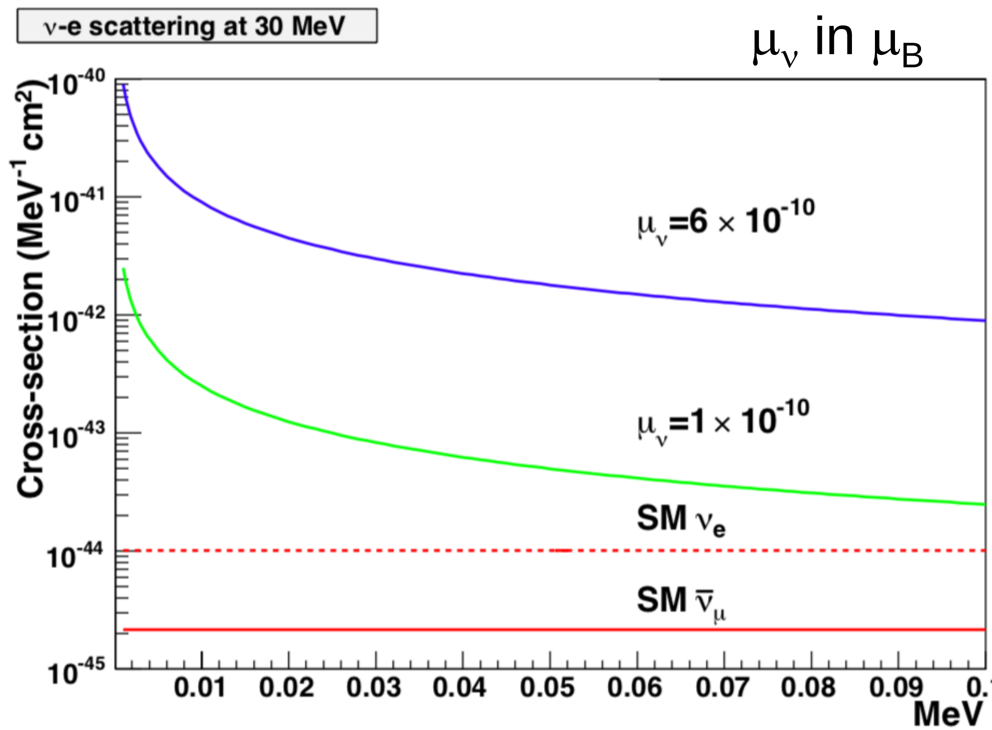
Note **muon flavor** content @ stopped-π source

CEvNS vs ν-e Elastic Scattering

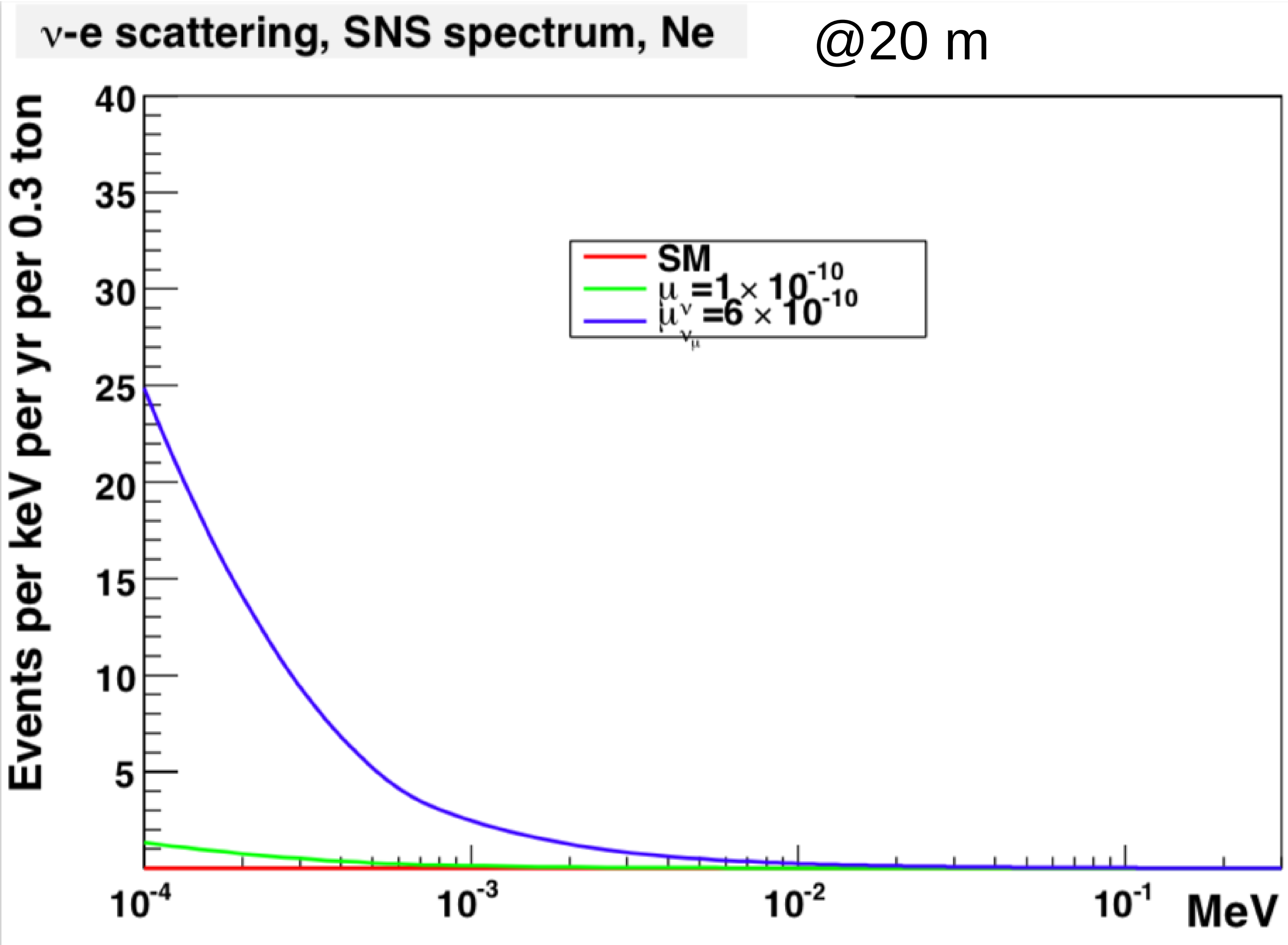
$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-T/E_\nu}{T}+\frac{T}{4E_\nu^2}\right)$$

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





- CEvNS xscn larger by Z^2 than ES
- But Z more electrons per target for ES, so xscn ~Z bigger
- CEvNS magnetic scattering has higher rate, but more SM bg



@20 m

quite hard @ SNS...

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%

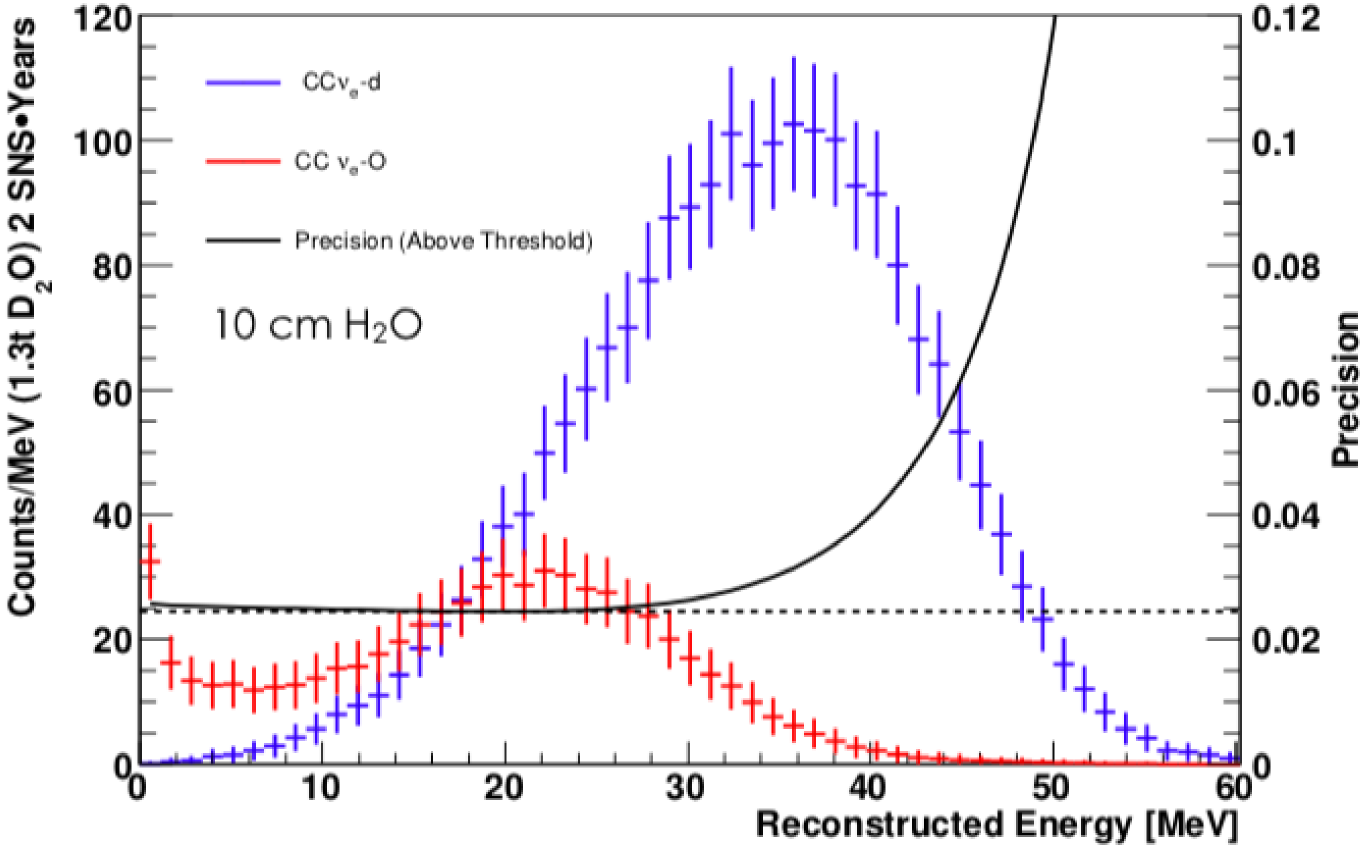
Dominant uncertainty (detector-dependent)

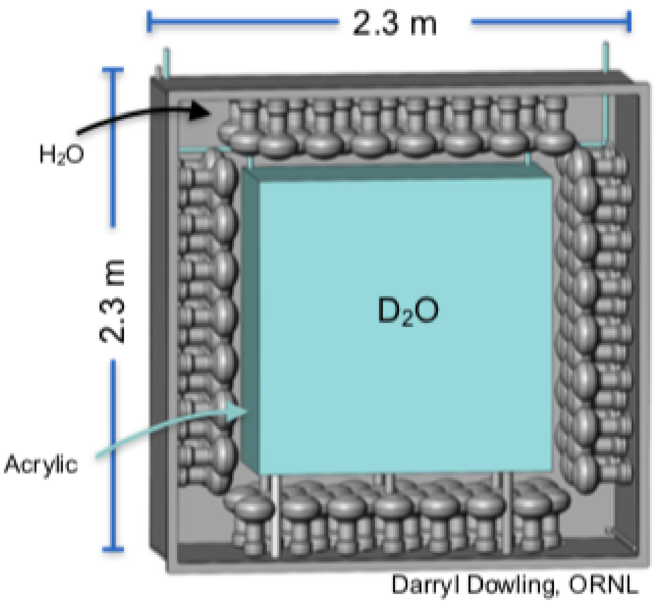
Next largest uncertainty (affects all detectors)

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

Heavy water detector in Neutrino Alley

Measurement Precision with 2 SNS years at 1.4 MW



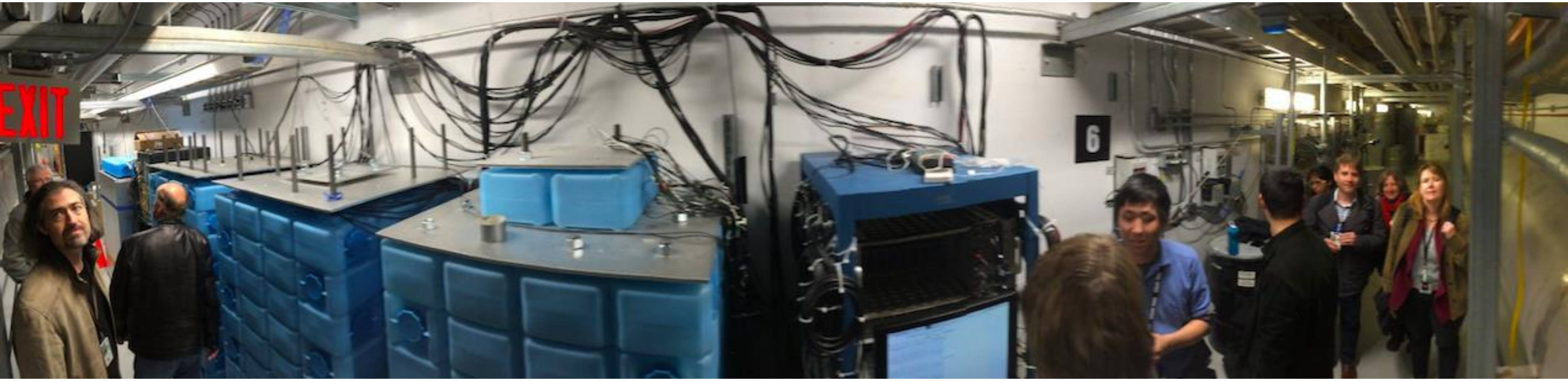


- 1.3 tons D_2O within acrylic inner vessel
- 10 cm H_2O "tail catcher" for high energy e-
- 112 8" bialkali photomultipliers

➔ ~few percent precision on flux normalization

Summary

- **CEvNS:**
  - large cross section, but tiny recoils, α N^2
  - accessible w/low-energy threshold detectors, plus extra oomph of stopped-pion neutrino source
- **First measurement** by COHERENT CsI[Na] at the SNS
- **Meaningful bounds on beyond-the-SM physics**

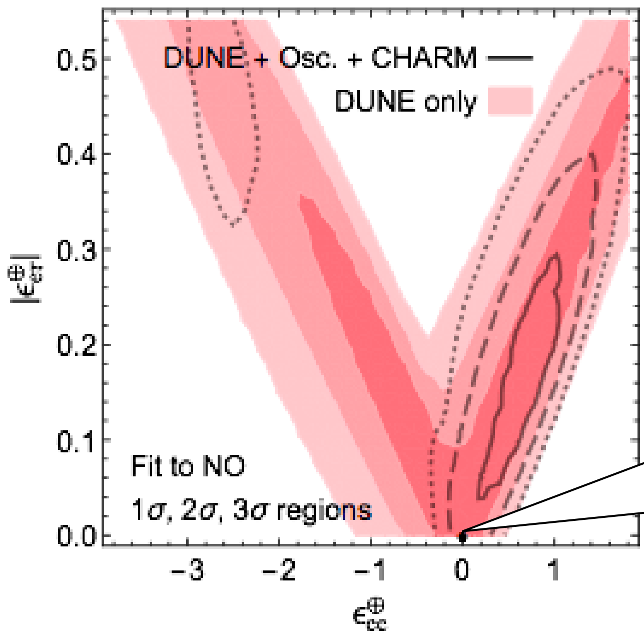


- **It's just the beginning....**
- Multiple targets, upgrades and new ideas in the works!
- Other CEvNS experiments at reactors are joining the fun (CONUS, CONNIE, MINER, RED, Ricochet, Nu-cleus...)

Generalized mass ordering degeneracy in neutrino oscillation experiments

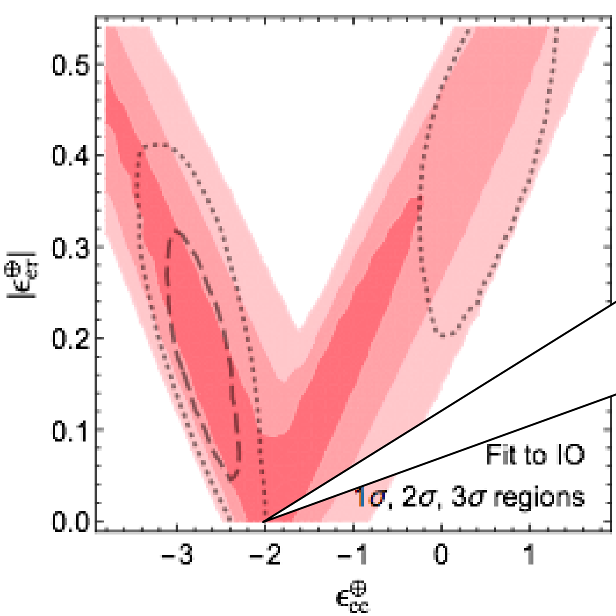
Pilar Coloma[1] and Thomas Schwetz[2]

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...

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



...looks just like inverted ordering w/NSI

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

Pilar Coloma[1] and Thomas Schwetz[2]

Phys.Rev. D94 (2016) no.5, 055005,
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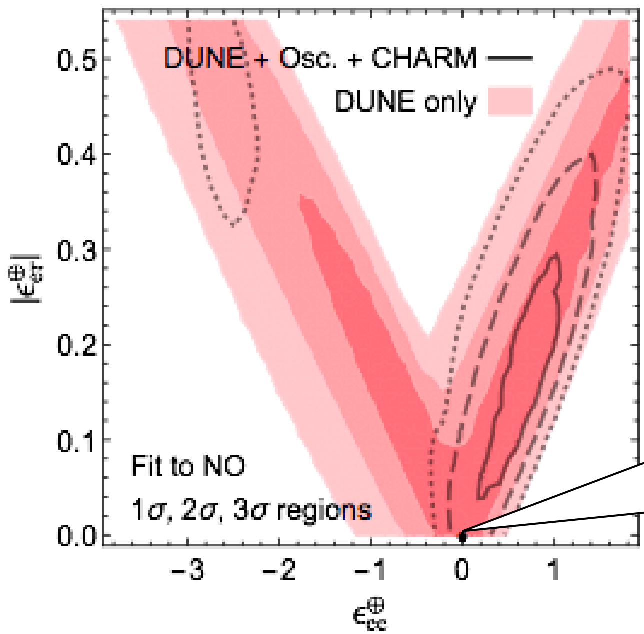
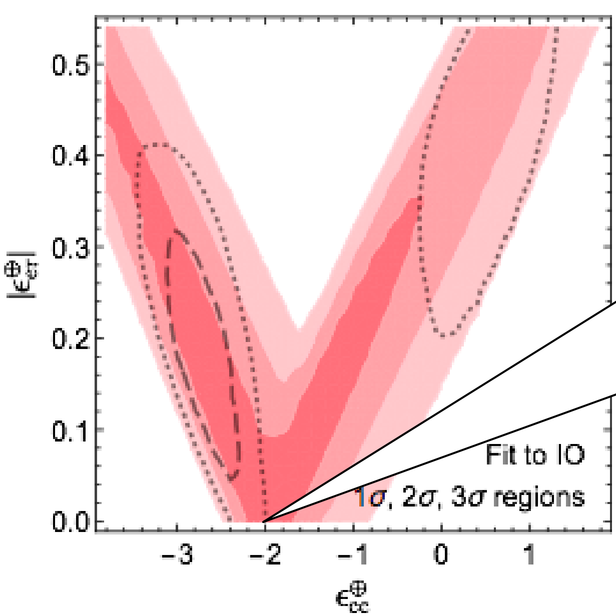


Normal ordering w/no NSI...

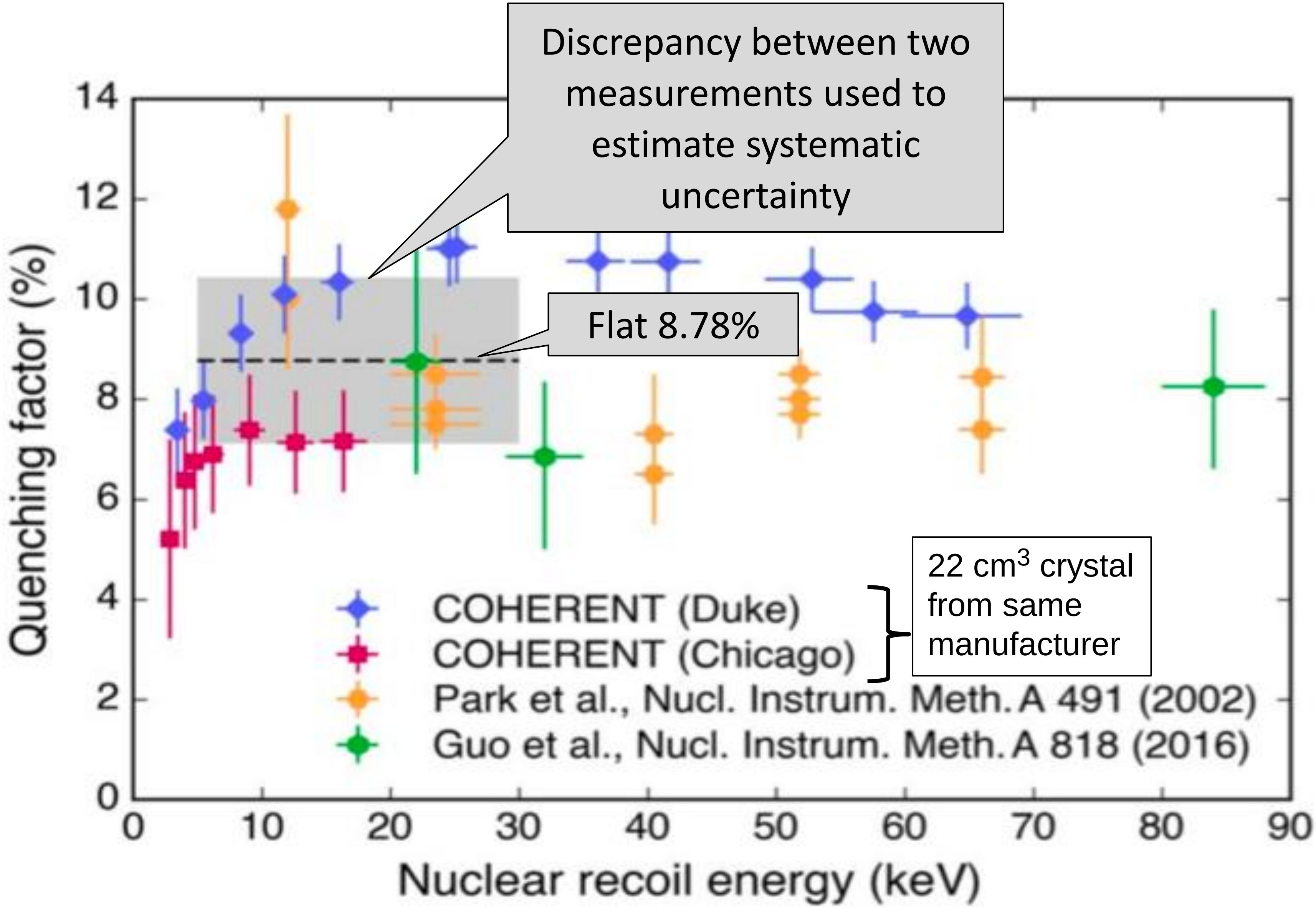


...looks just like inverted ordering w/NSI

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

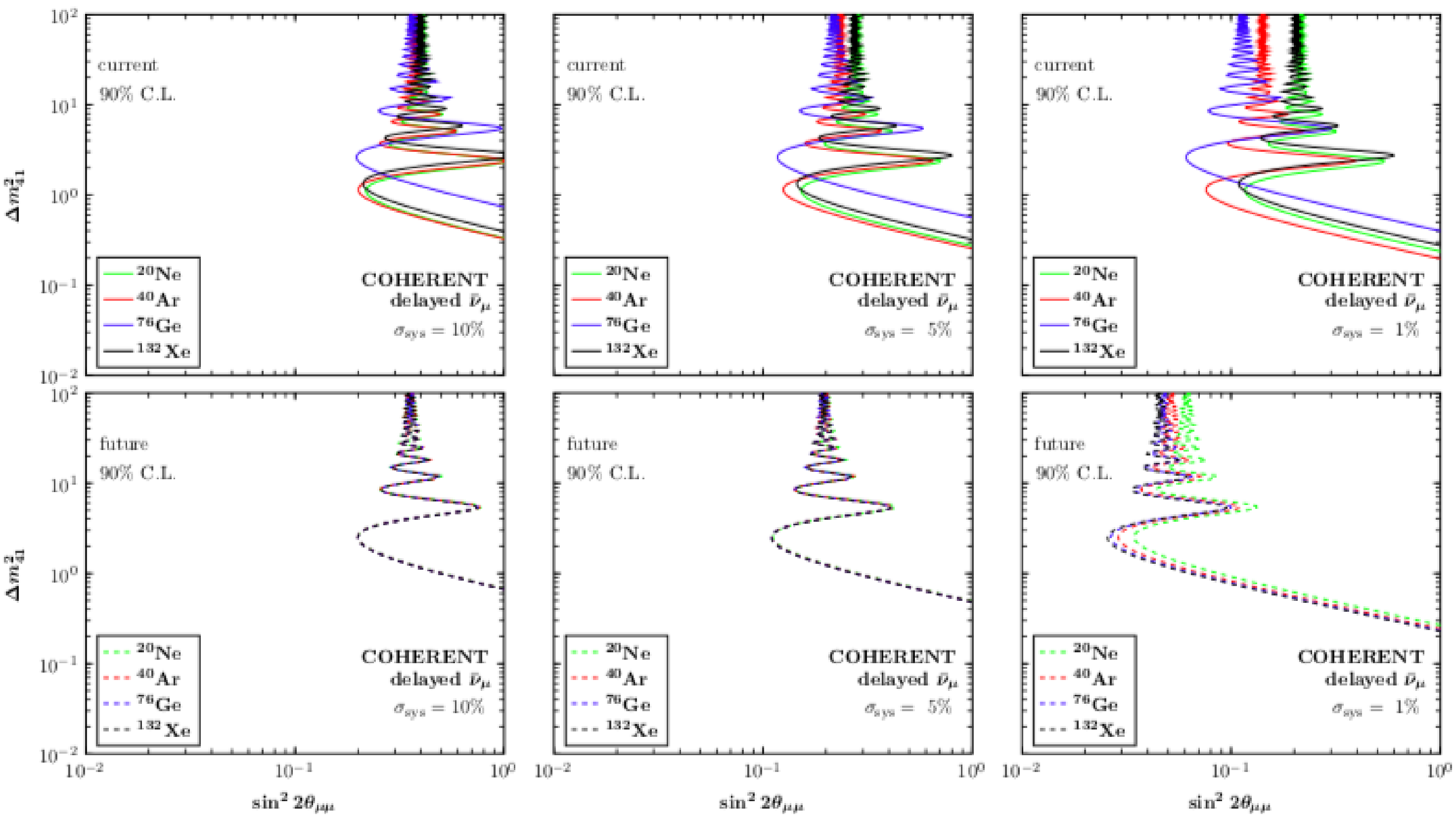
CsI quenching factor measurements at TUNL w/ neutrons



$$\underbrace{13.348 \text{ pe/keVee}}_{\text{ee light yield}} * \underbrace{0.0878 \text{ keVee/keVr}}_{\text{QF}} = \mathbf{1.2\ pe/keVr}$$

Another example: **sterile neutrino oscillations**

- CEvNS is NC and doesn't care about the flavor;
  disappearance is "true" disappearance
- Some neutrino spectral info in the recoil spectrum
- Can cancel some systematics with multiple identical, or movable detectors

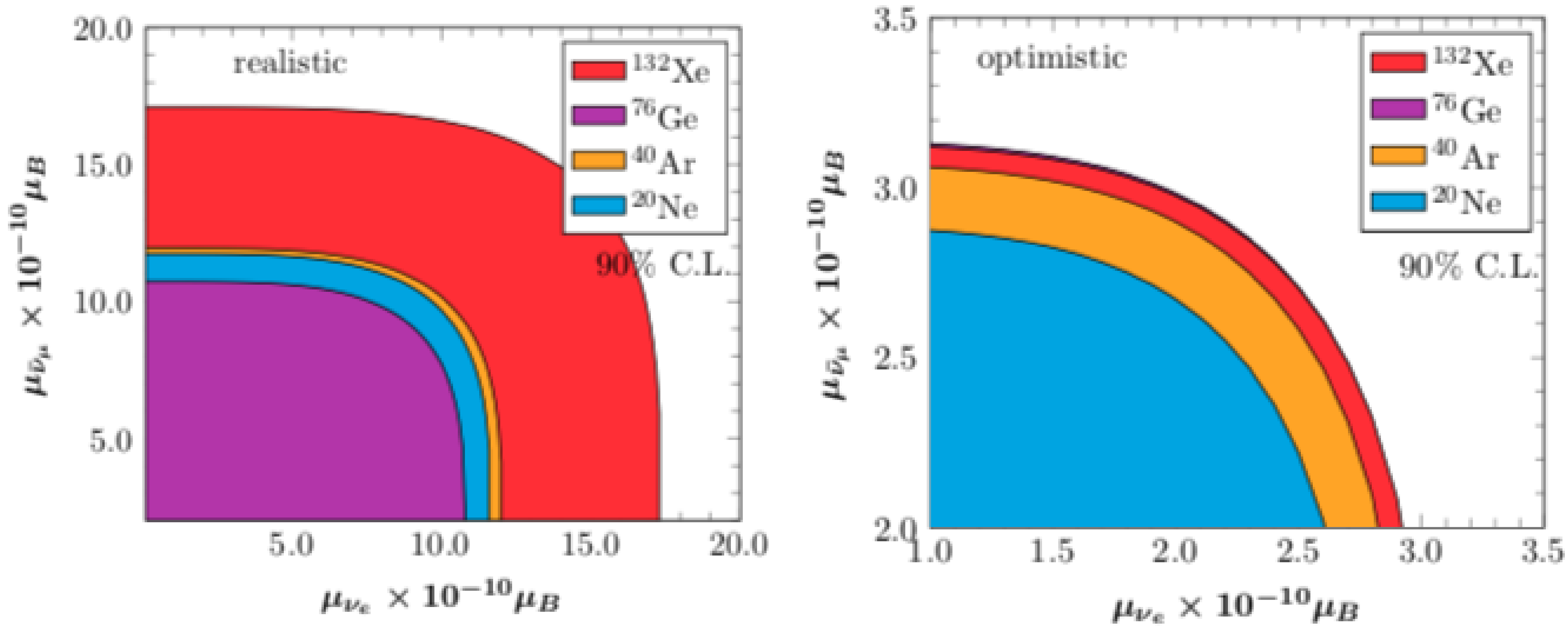


In this work, the calculation is performed for two cases corresponding to (i) the "current" configuration: a (^{20}Ne, ^{40}Ar, ^{76}Ge, ^{132}Xe) target with mass (391, 456, 100, 100) kg located at (46, 46, 20, 40) m from the source with energy threshold of (30, 20, 10, 8) keV$_{nr}$ and a running time of 2.4×10^7s, and (ii) the "future" configuration: 1 ton of detector mass located at 20 m from the source with energy threshold 1 keV$_{nr}$ and 1 year of data taking time (see e.g Ref. [7]).

Even 100 kg of Ge is expensive/challenging, but multitons of noble liquid is entirely thinkable

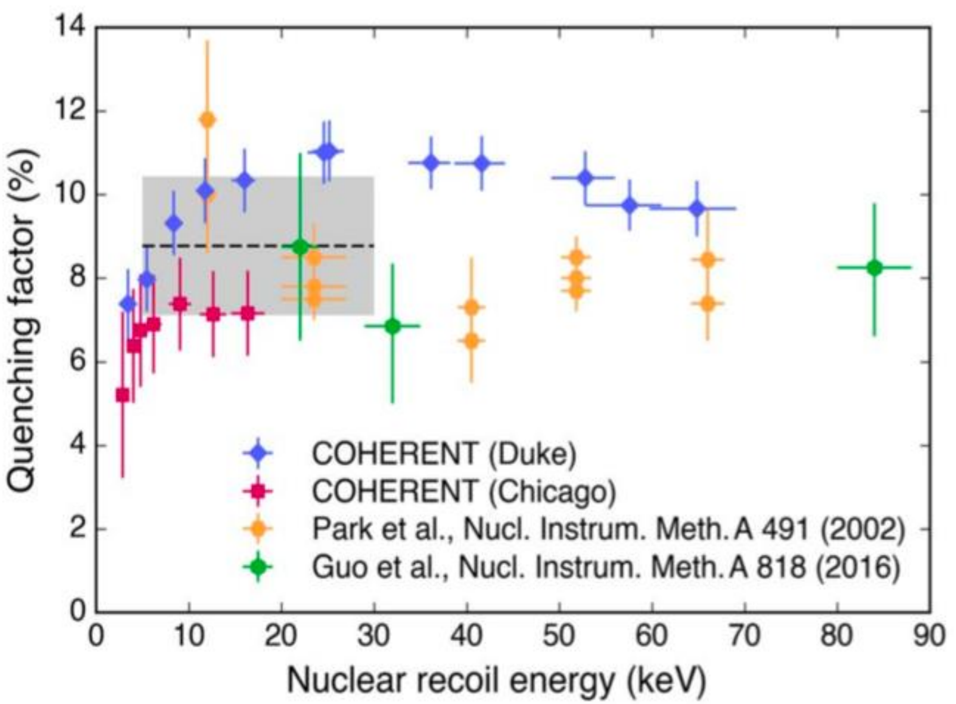
Kosmas et al., Phys.Rev. D96 (2017) no.6, 063013

Projections: Kosmas et al., arXiv:1505.03202, 1711.09773



Some experimental issues to keep in mind

- Efficiency is a function of T, and has shape uncertainties
- Low energy thresholds are hard to achieve
- "Quenching factor" (observable recoil energy compared to electron energy deposition) and other detector response has T shape uncertainties
- T shape uncertainties **have correlations**
- Energy resolution matters
- Backgrounds matter (a lot)
- There are flux normalization and shape uncertainties*
- All of these are **very target- and detector-dependent**
- It's very hard work to get a handle on these parameters and their (correlated) uncertainties



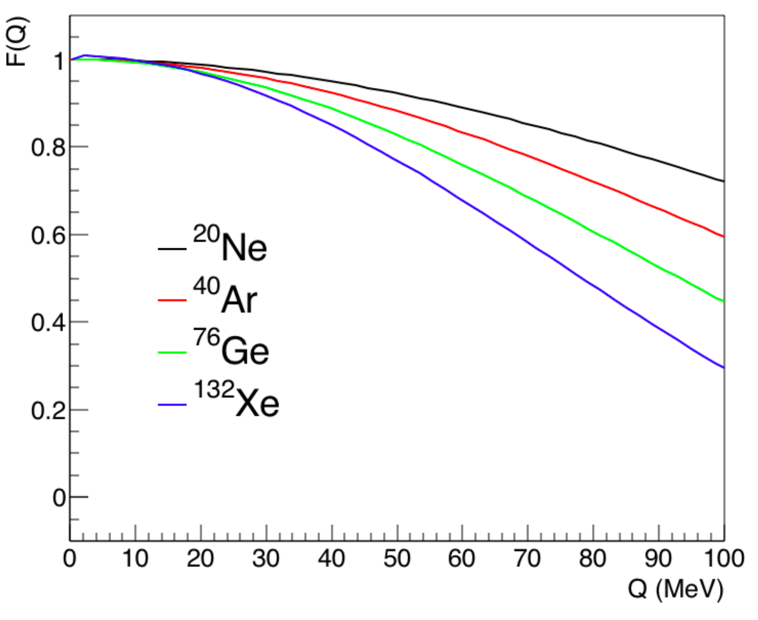
*Little flux shape uncertainty at SNS

Now, zoom in on the **form factor(s)**

- Fourier transform of the nucleon distributions
- encapsulates information about non-point-like-ness of the nucleus

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

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
$Q = \sqrt{(2MT)}$: momentum transfer



form factor suppresses cross section at large Q ➡ larger effect for **stopped-π**, SN, atmν than solar, reactor

One should write separate

$F_n^V(Q)$, $F_n^A(Q)$, $F_p^V(Q)$, $F_p^A(Q)$ form factors

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

$$G_V = g_V^p F_V^p(Q) Z + g_V^n F_V^n(Q) N$$

$$G_A = g_A^p F_A^p(Q)(Z_+ - Z_-) + g_A^n F_A^n(Q)(N_+ - N_-)$$

Currently, assuming these are **all the same**,

except for extra neutron skin for $F_n^V(Q)$

- axial contributions are pretty tiny
- proton contributions also quite unimportant

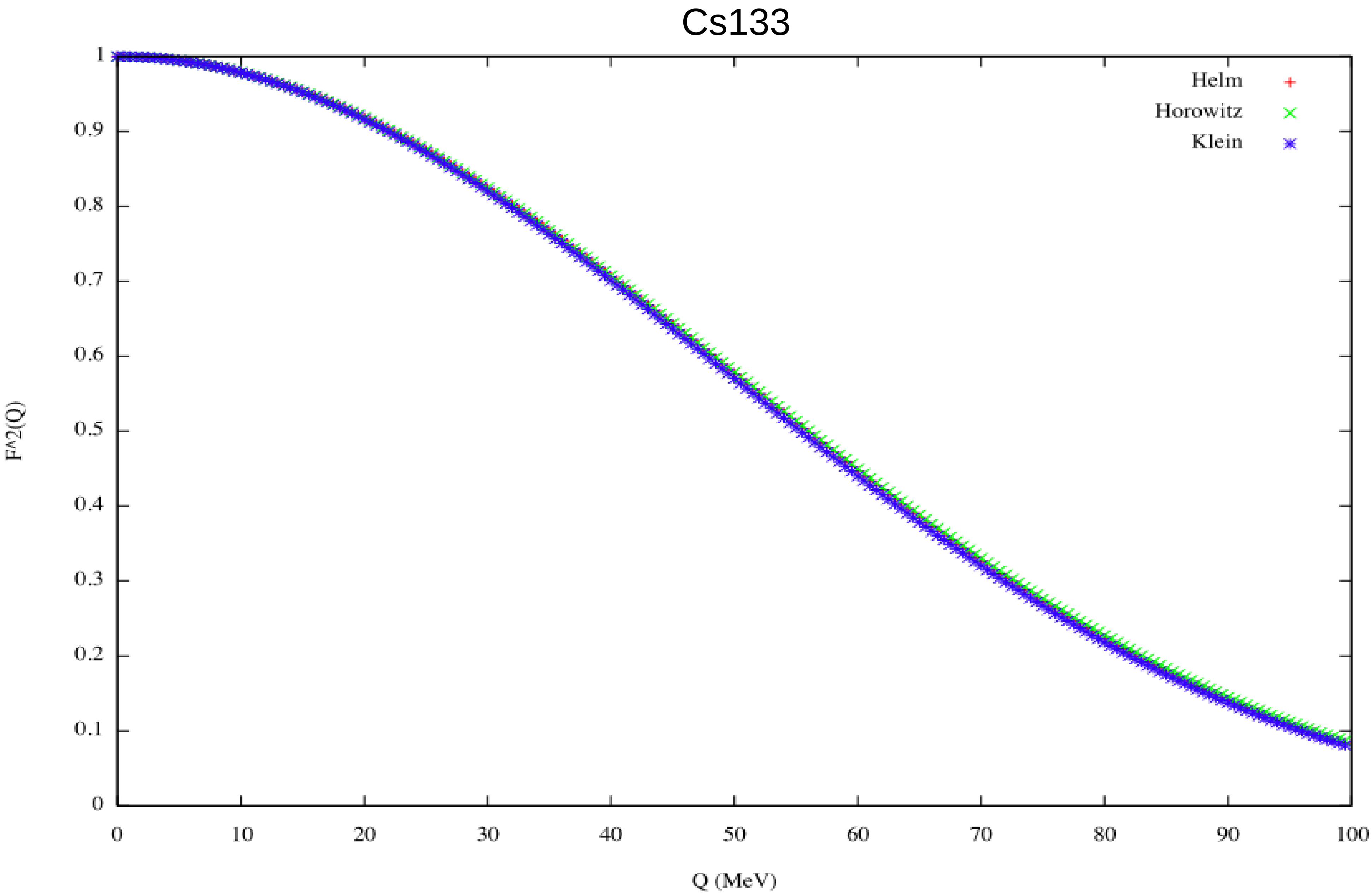
Three form-factor functional forms studied in detail for COHERENT:

“Helm”	$F(Q) = \frac{3}{QR_0}\left(\frac{\sin(QR_0)}{(QR_0)^2} - \frac{\cos(QR_0)}{QR_0}\right) e^{-Q^2 s^2/2}$ $R = 1.2A^{1/3} \quad s = 0.9$
“Klein-Nystrand”	$F(Q) = \frac{3(\sin(QR) - QR\cos(QR_n))}{(QR)^3(1 + a_k^2 Q^2)}$ $R = 1.2A^{1/3} \qquad a_k = 0.7$
“Horowitz”	Numerical files from Chuck Horowitz, “based on relativistic mean field interaction FSUgold that does a good job reproducing the binding energy and charge radii of many nuclei”

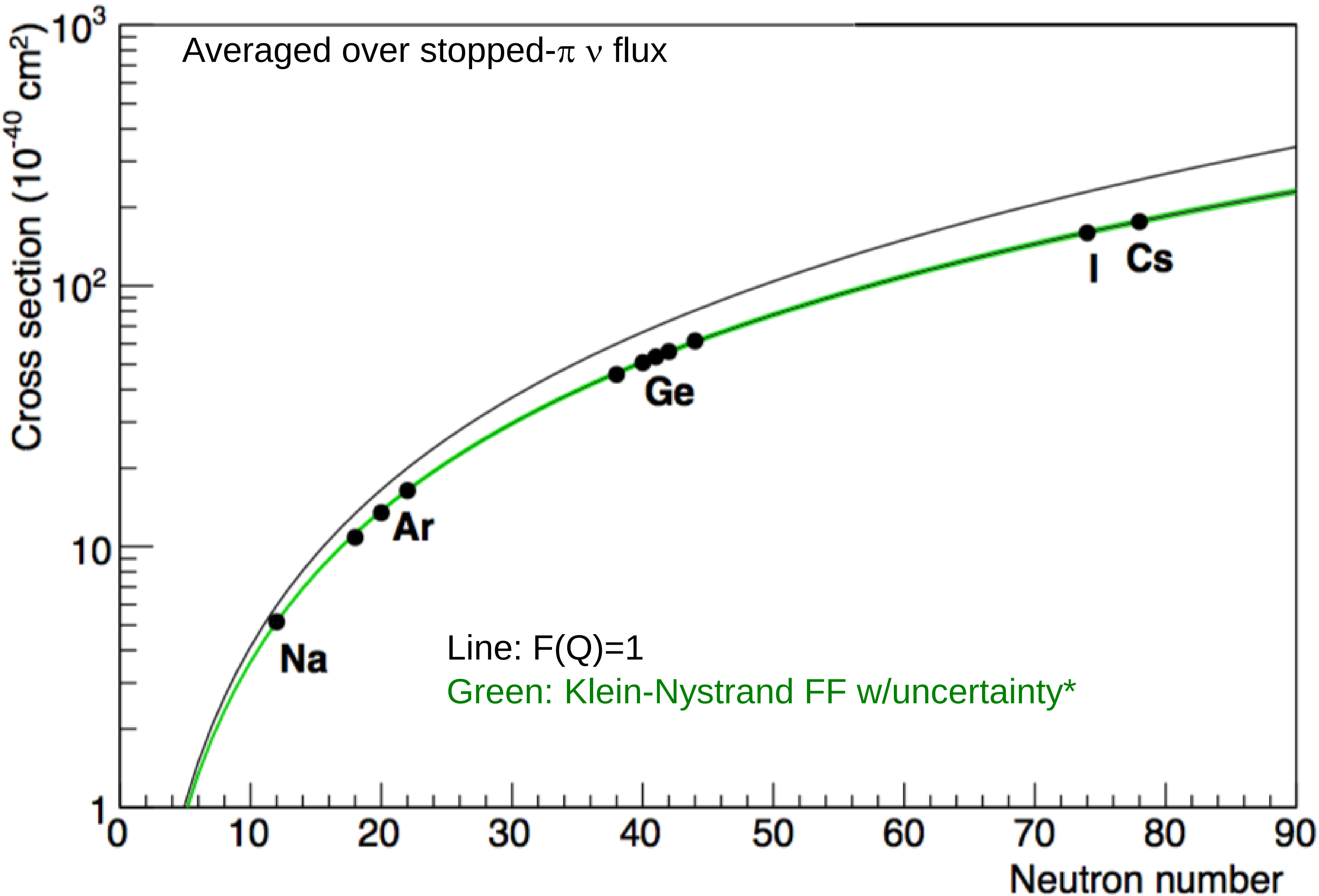
Neutron skin adjustment $R = 1.2A^{1/3} + 1.01\frac{A - 2Z}{A}$

also looked at: “solid sphere”, Lewin-Smith;
did not look at “symmetrized Fermi function”

Different parameterizations give very similar shapes

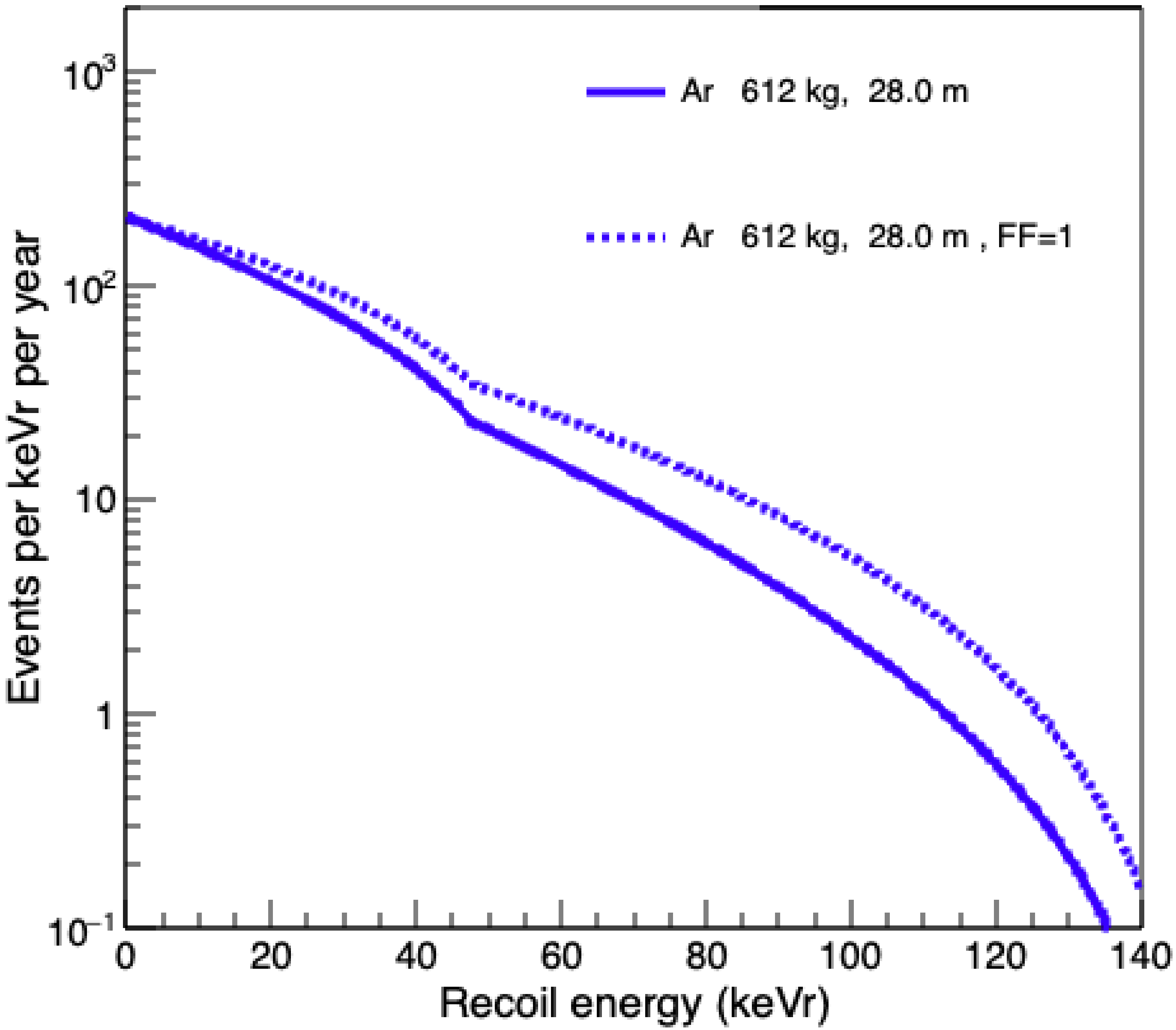


Effect of the form factor on the flux-averaged xscns



*will come back to this

Effect of the form factor on the recoil spectra



Approaching the form factor as **something to *measure* using CEvNS**…

assume the SM is true, **learn about the nucleus (and astrophysics!)**

Nuclear neutron form factor from neutrino–nucleus coherent elastic scattering

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Received 19 June 2008
Published 30 October 2008
Online at stacks.iop.org/JPhysG/36/015105

Abstract
We point out that there is potential to study the nuclear neutron form factor through neutrino nucleus coherent elastic scattering. We determine numbers of events for various scenarios in a liquid noble nuclear recoil detector at a stopped pion neutrino source

Neutrino-nucleus coherent scattering as a probe of neutron density distributions

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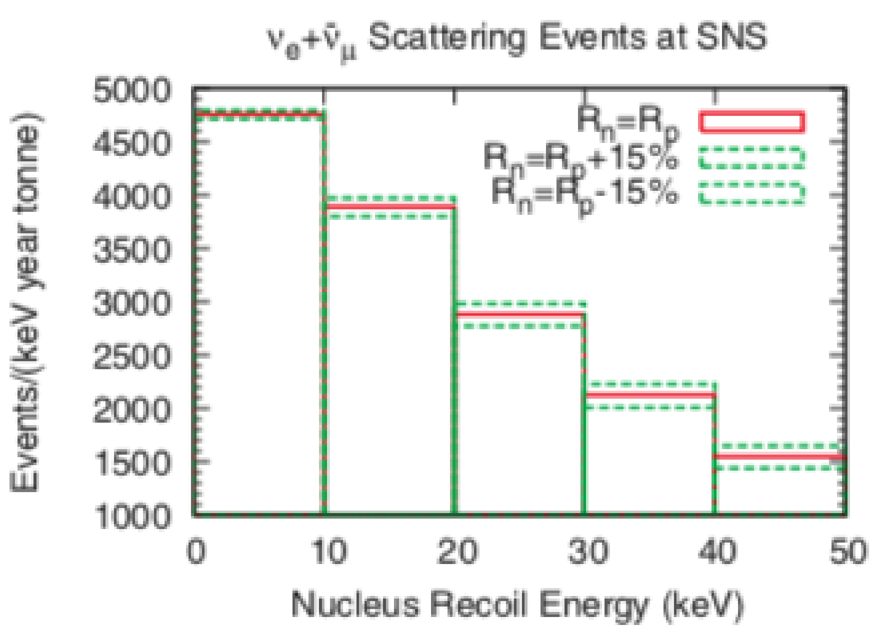
(Dated: July 4, 2012)

Neutrino-nucleus coherent elastic scattering provides a theoretically appealing way to measure the neutron part of nuclear form factors. Using an expansion of form factors into moments, we show that neutrinos from stopped pions can probe not only the second moment of the form factor (the neutron radius) but also the fourth moment. Using simple Monte Carlo techniques for argon, germanium, and xenon detectors of 3.5 tonnes, 1.5 tonnes, and 300 kg, respectively, we show that the neutron radii can be found with an uncertainty of a few percent when near a neutrino flux of 3×10^7 neutrinos/cm^2/s. If the normalization of the neutrino flux is known independently, one can determine the moments accurately enough to discriminate among the predictions of various nuclear energy functionals.



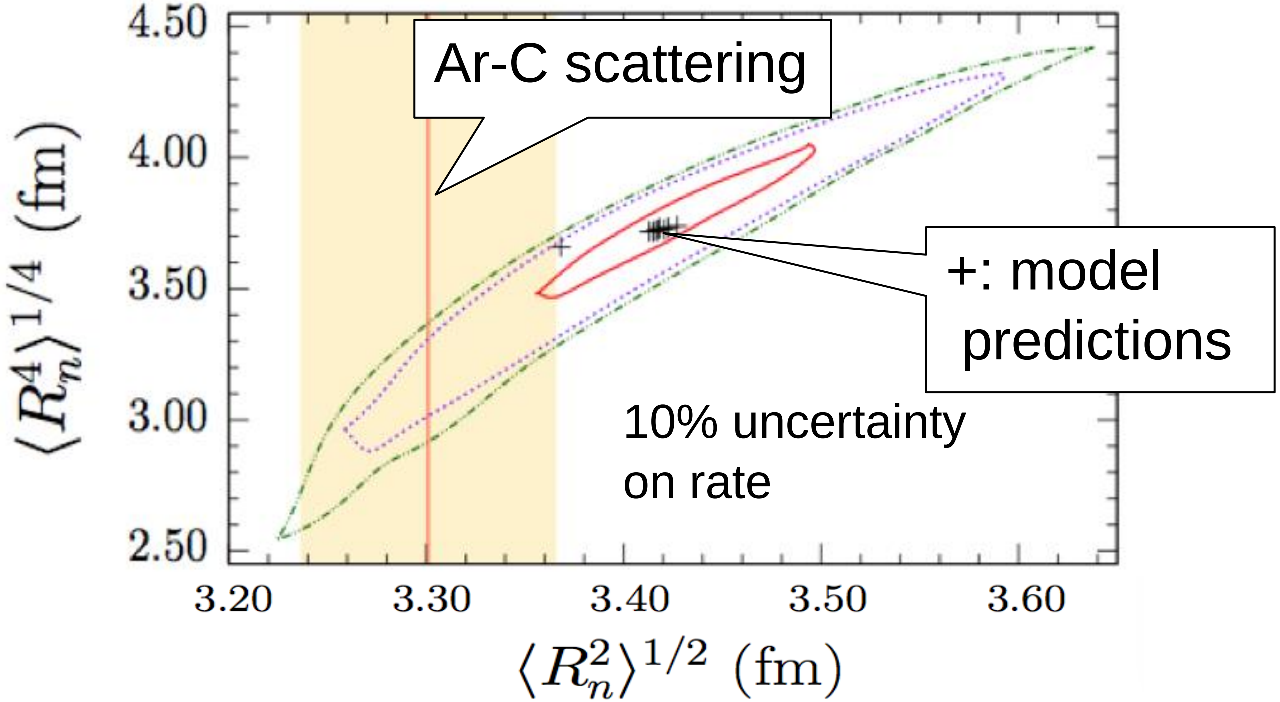
Observable is **recoil spectrum shape**

Approach: expand in moments of the neutron radius

$$F_n(Q^2) \approx \int \rho_n(r)\left(1 - \frac{Q^2}{3!}r^2 + \frac{Q^4}{5!}r^4 - \frac{Q^6}{7!}r^6 + \cdots\right) r^2 dr$$
$$\approx N\left(1 - \frac{Q^2}{3!}\langle R_n^2\rangle + \frac{Q^4}{5!}\langle R_n^4\rangle - \frac{Q^6}{7!}\langle R_n^6\rangle + \cdots\right) \quad (6)$$

$$\langle R_n^k\rangle = \frac{\int \rho_n r^k d^3r}{\int \rho_n d^3r}$$

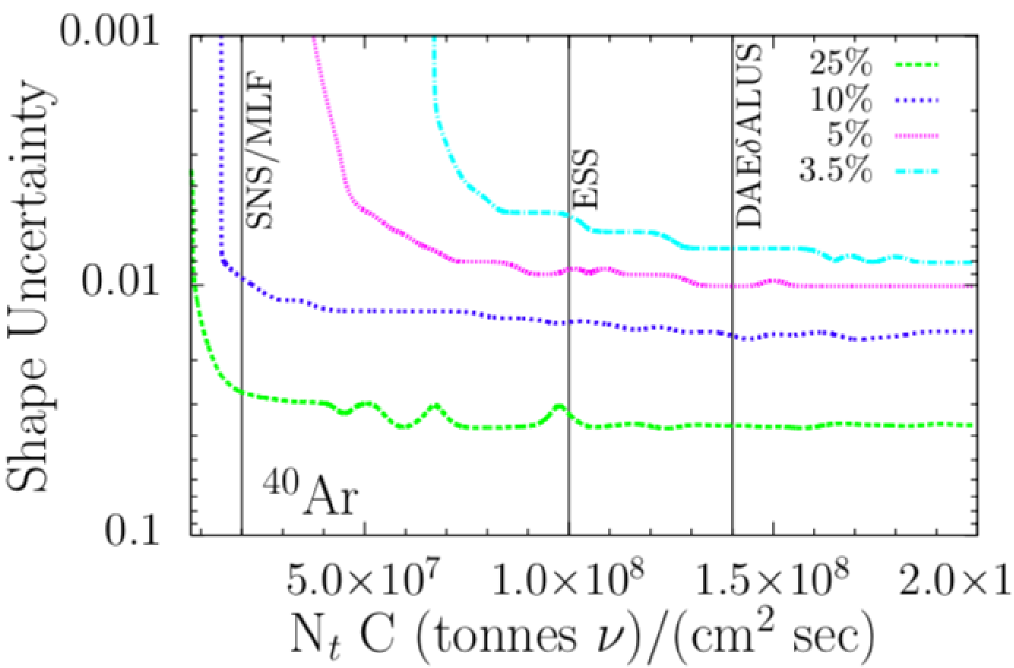
Example:
tonne-scale
experiment
at πDAR source



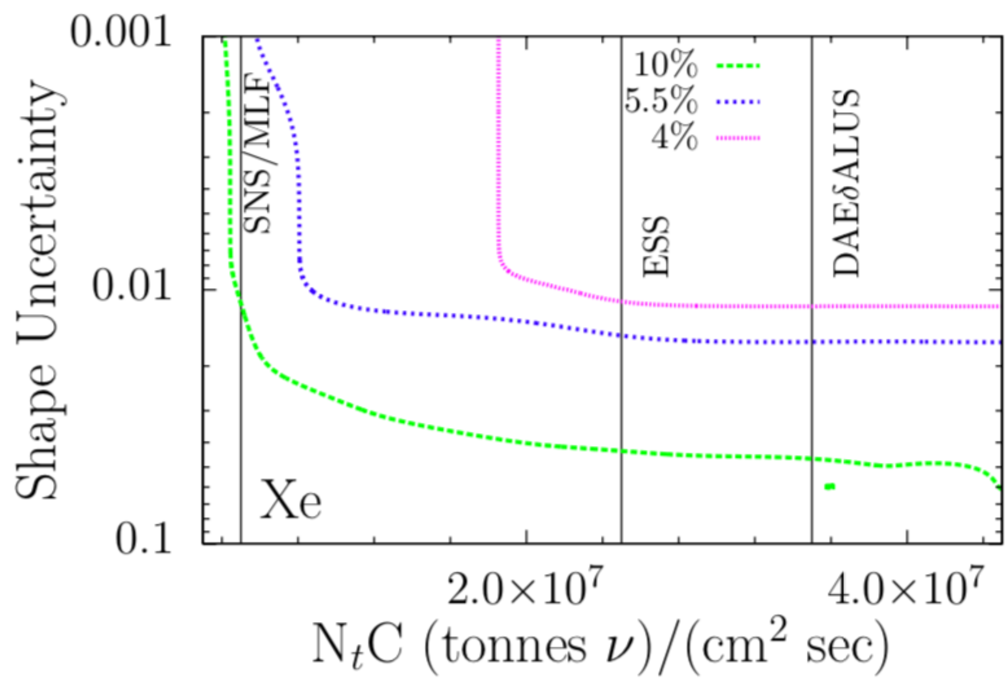
K. Patton et al., PRC86 (2012) 024612

More studies with this approach

KELLY M PATTON et al.
Int J Mod Phys E, 2013 vol. 22 (06)
p. 1330013



uncertainty in $\langle R_n^2 \rangle^{1/2}$ at the 90% confidence level



uncertainty in $\langle R_n^4 \rangle_{\mathrm{eff}}^{1/4}$ at the 90% confidence level

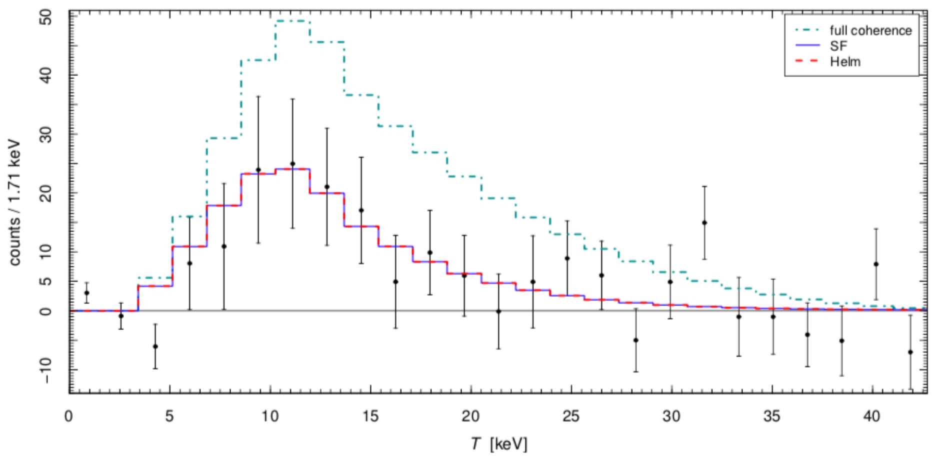
Lines: 2 tonnes @ 20 m

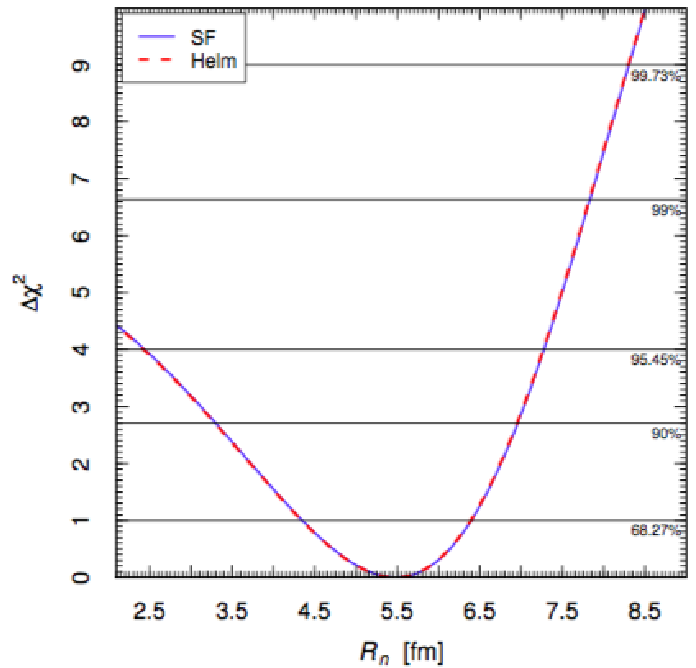
4^{th} moment

Uses uncertainties uncorrelated bin by bin,
which is probably too conservative

First fit to the COHERENT CsI data

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





Helm functional form

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

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

- Fit to neutron radius resulting in ~18% uncertainty, as well as neutron skin measurement
- Does not handle bin-by-bin correlation of systematics (e.g., from QF)

COHERENT will have better measurement soon, + handling of shape systematics w/ correlations

But now: suppose your physics goal is to

- hunt for BSM effects in the recoil spectrum
- understand an astrophysical CEvNS signal
- understand an astrophysical CEvNS background (DM floor)

then… **uncertainties in the form factor are a nuisance**!

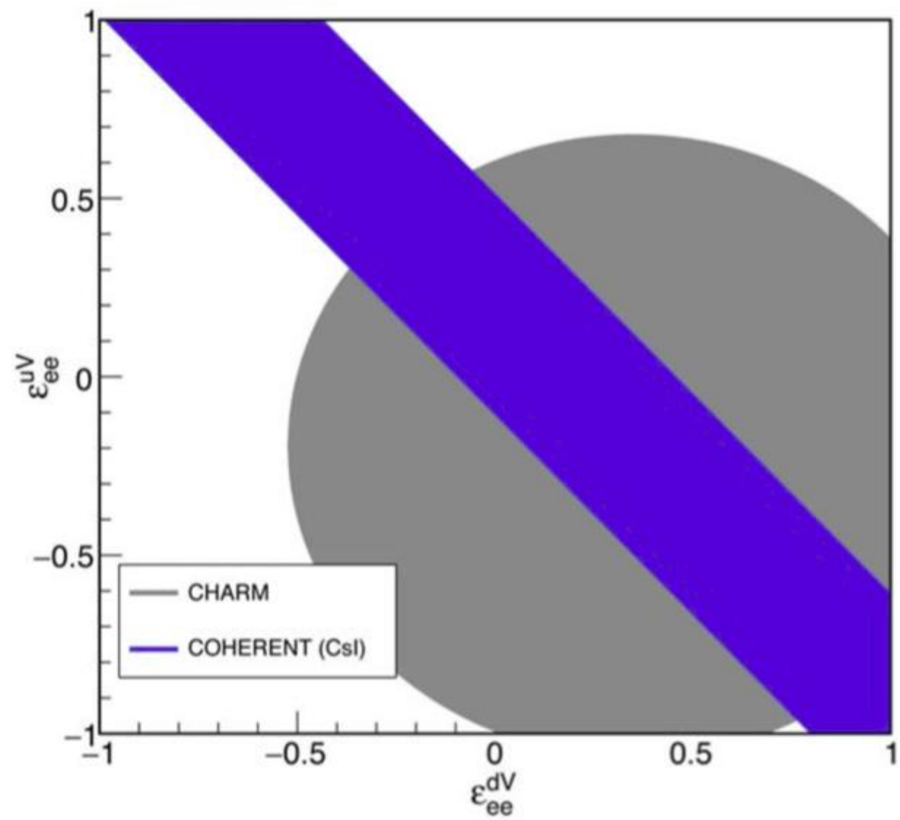
There are degeneracies in the observables between "old" (but still mysterious) physics

and "new" physics

We will need to think carefully about how to disentangle these effects and understand uncertainties

Initial COHERENT CsI result used Klein-Nystrand (no skin)

- assumed +/-**5% FF uncertainty** on counts or 1-bin NSI analysis
- conservative estimate based on variation of
  integrated counts for different parameterizations
- not the dominant uncertainty (which is QF-related, +/-25%)

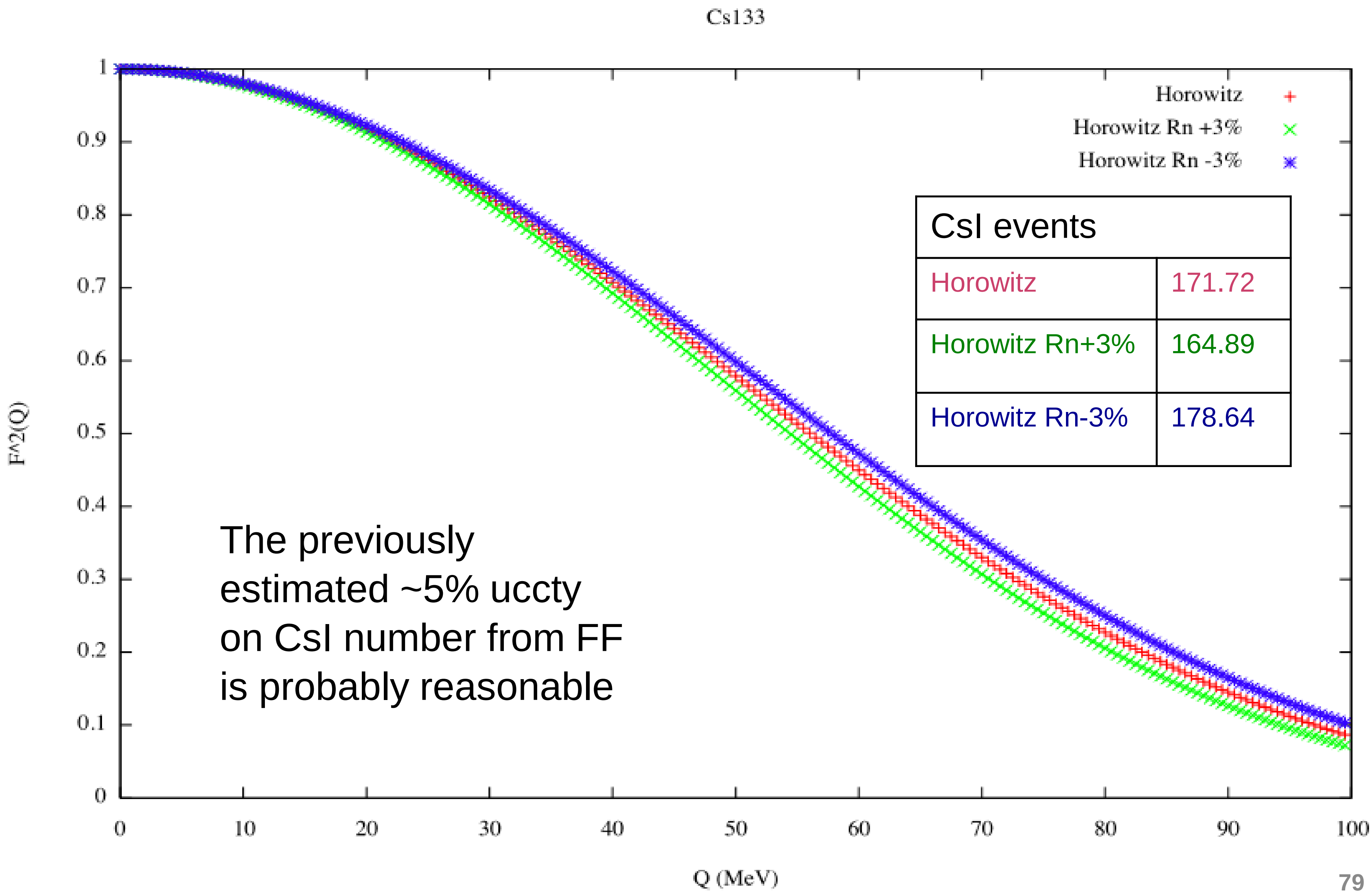


Updated estimates of integrated event rates
w/FF variation are within this uncertainty

Current method of estimating FF uncertainty:

R_n scaling (via Q) by ±3% (C. Horowitz's estimate of R_n uccty)

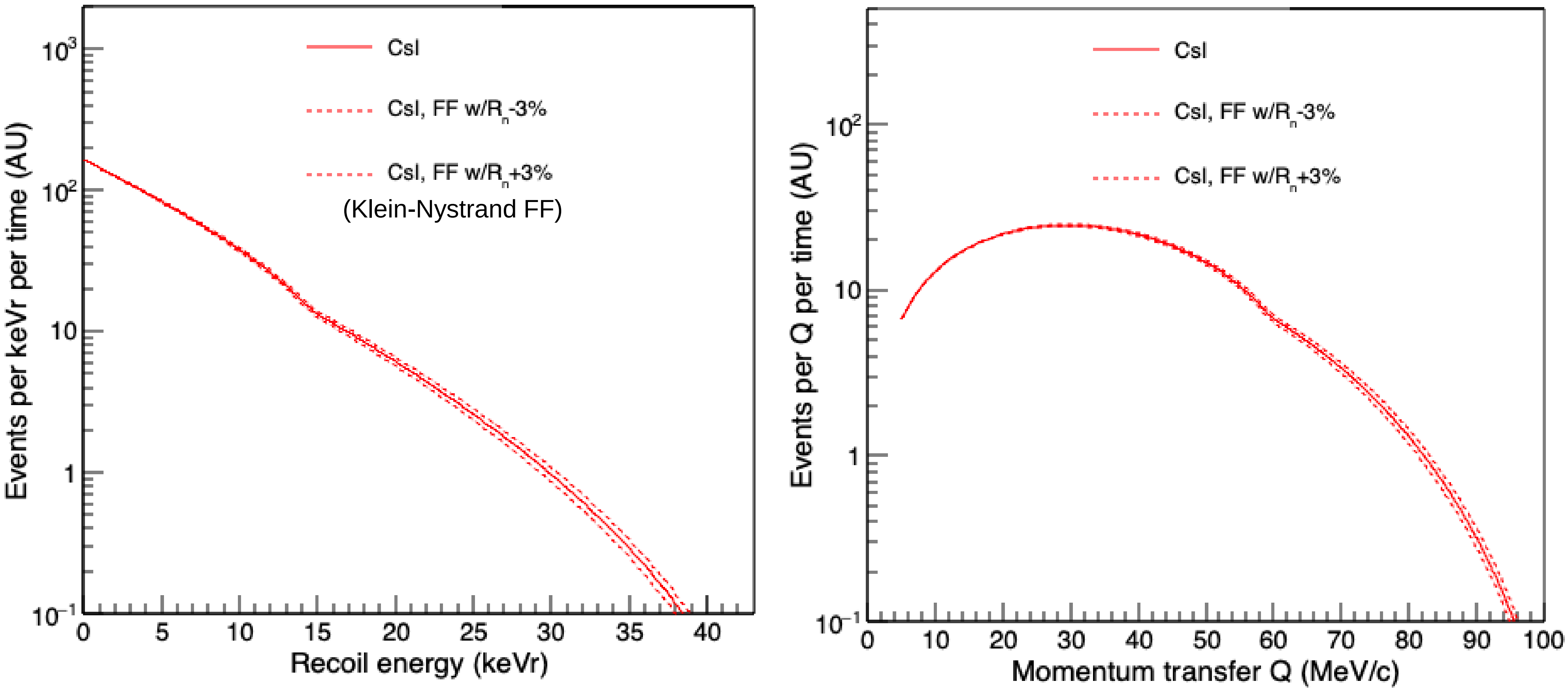
➔ ~4% effect on CsI number



CsI events	
Horowitz	171.72
Horowitz Rn+3%	164.89
Horowitz Rn-3%	178.64

The previously estimated ~5% uccty on CsI number from FF is probably reasonable

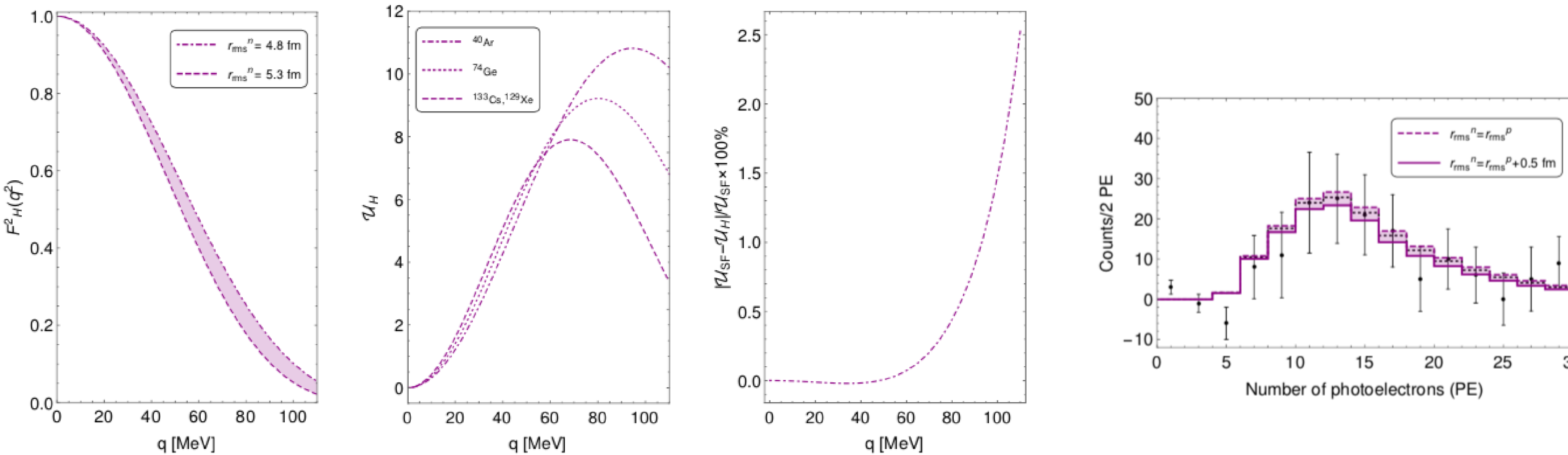
Effect of FF uncertainty on the SNS recoil spectrum



New:

Impact of form factor uncertainties on interpretations of coherent elastic neutrino-nucleus scattering data

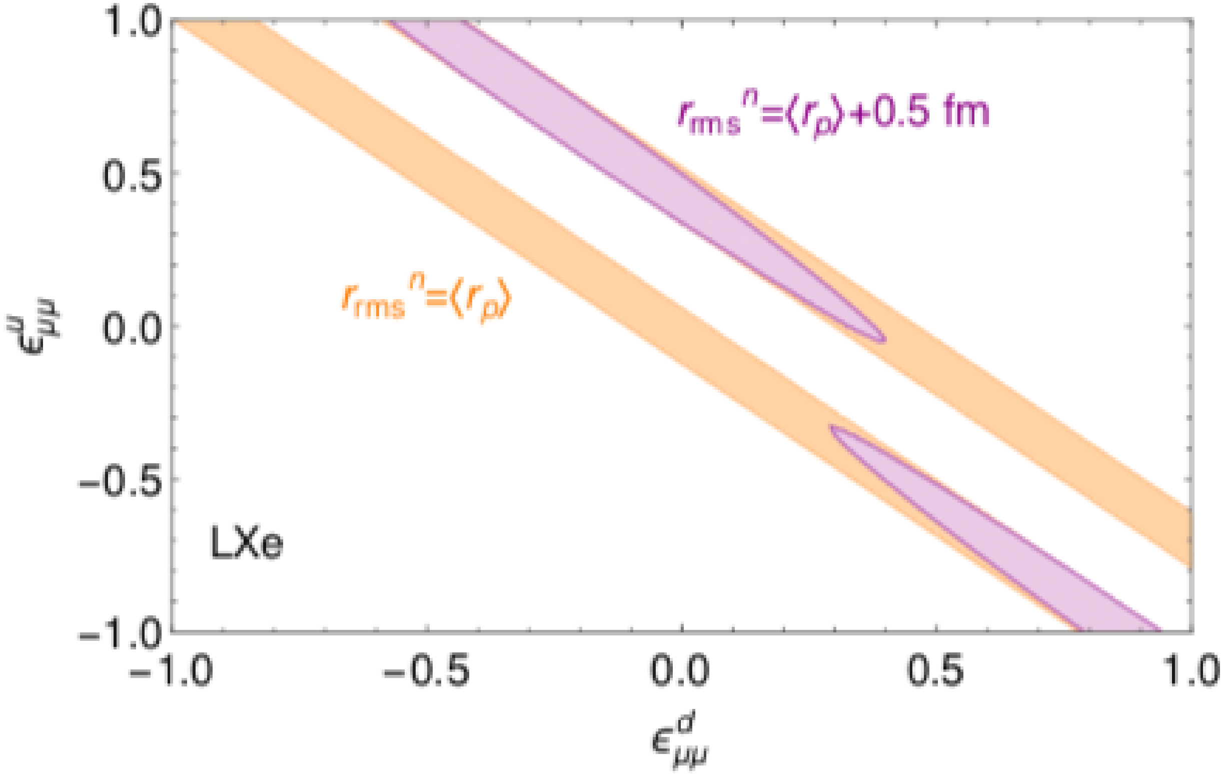
D. Aristizabal Sierra,[1,2,*] Jiajun Liao,[3,4,†] and D. Marfatia[4,‡]



$$r^n_{\rm rms}|_{\rm max} \equiv r^p_{\rm rms} + 0.5\ {\rm fm}\,. \qquad \mathcal{U}_H = \left| F_H^2(q^2)|_{r^n_{\rm rms}=r^p_{\rm rms}} - F_H^2(q^2)|_{r^n_{\rm rms}=r^p_{\rm rms}+0.5\,{\rm fm}} \right| \times 100\%\ ,$$

Helm form factor with R_n varied ~+/-9%

May make significant impact on BSM sensitivity:



- But is +/-0.5 fm on R_n the right amount of uncertainty?
- Is varying R_n even the right thing to do?
- How to incorporate known nuclear structure physics?