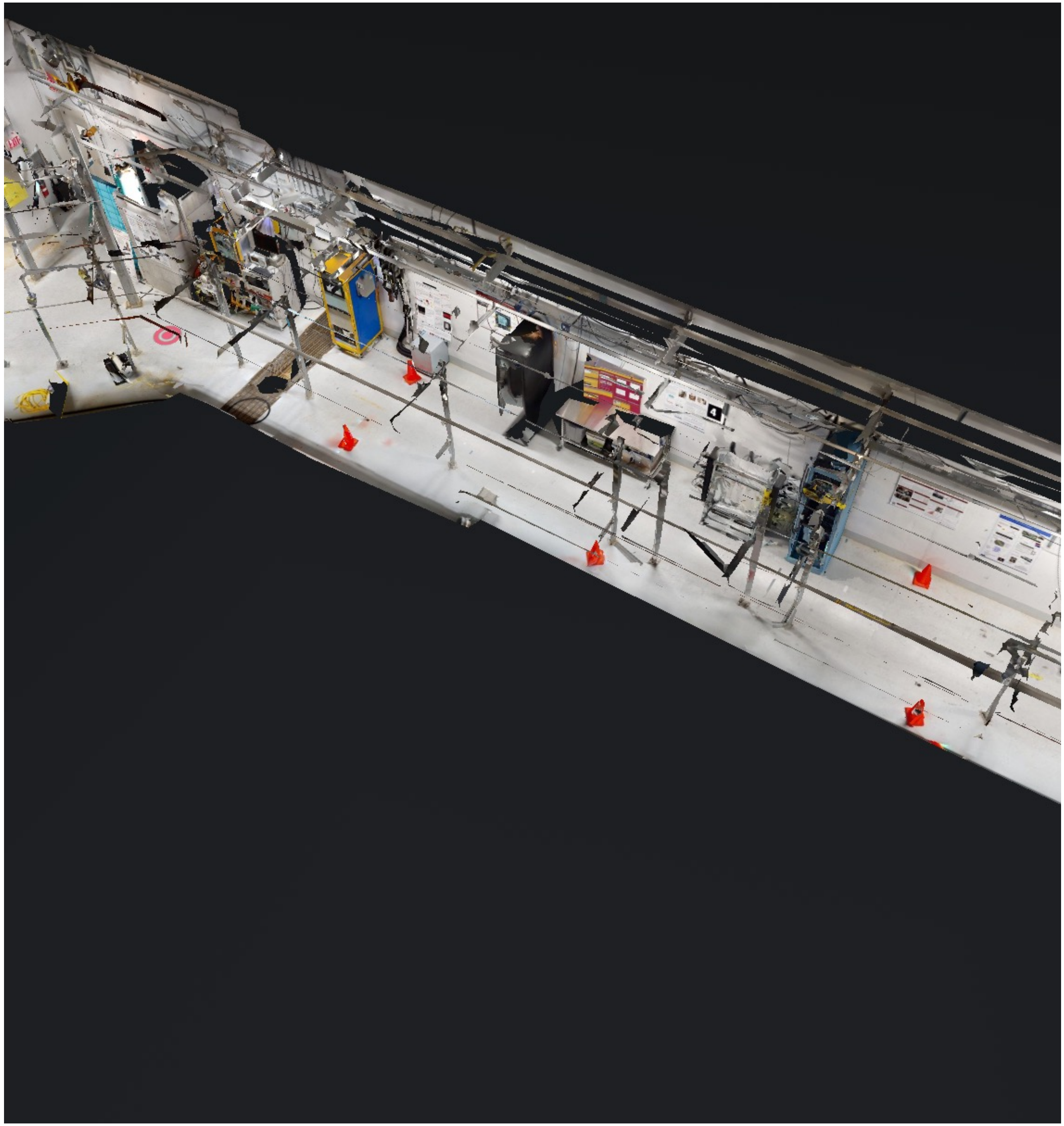
The COHERENT Experimental Program

Kate Scholberg,

Duke University

2022 KPS
Spring Pioneer Symposium
April 22, 2022



OUTLINE

-Coherent elastic neutrino-nucleus scattering
(CEvNS)

- Why measure it? Physics motivations
(short and long term)

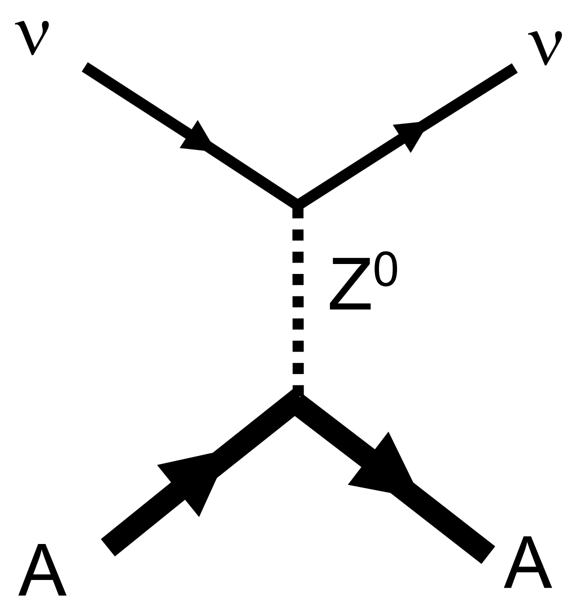
- How to measure CEvNS

- The COHERENT experiment at the SNS
  - First light with CsI[Na]
  - Second measurement in Ar
  - And more data from CsI[Na]!

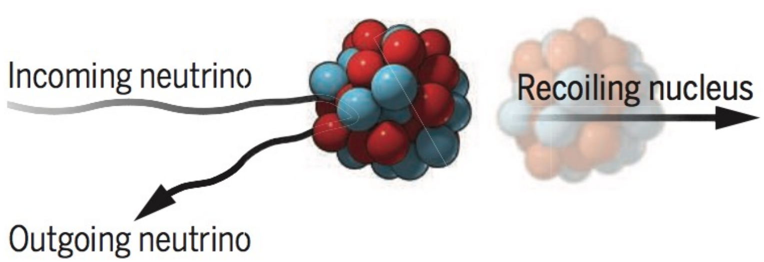
- Status and prospects for COHERENT
  - **Opportunities at the STS**

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

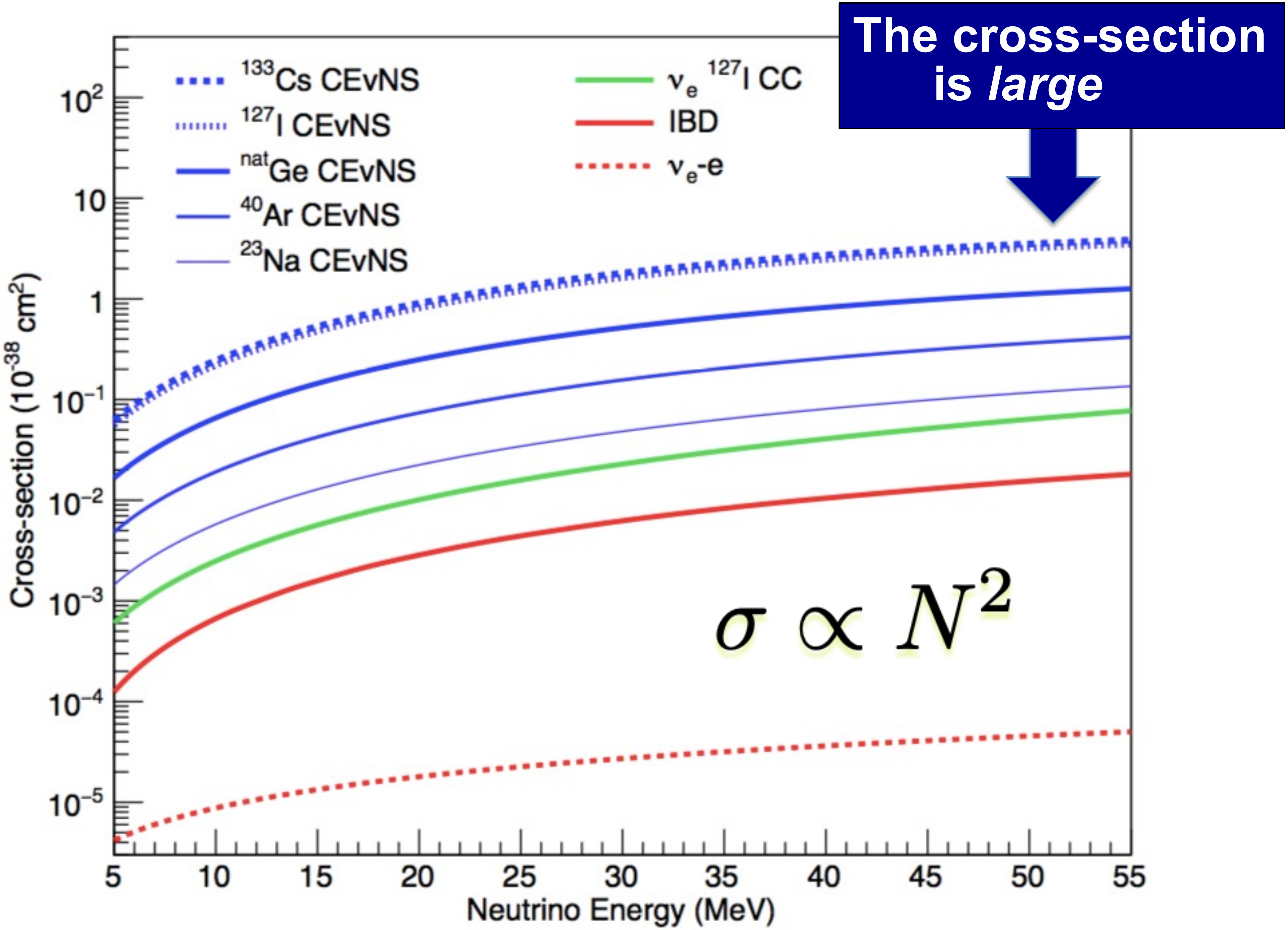


Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

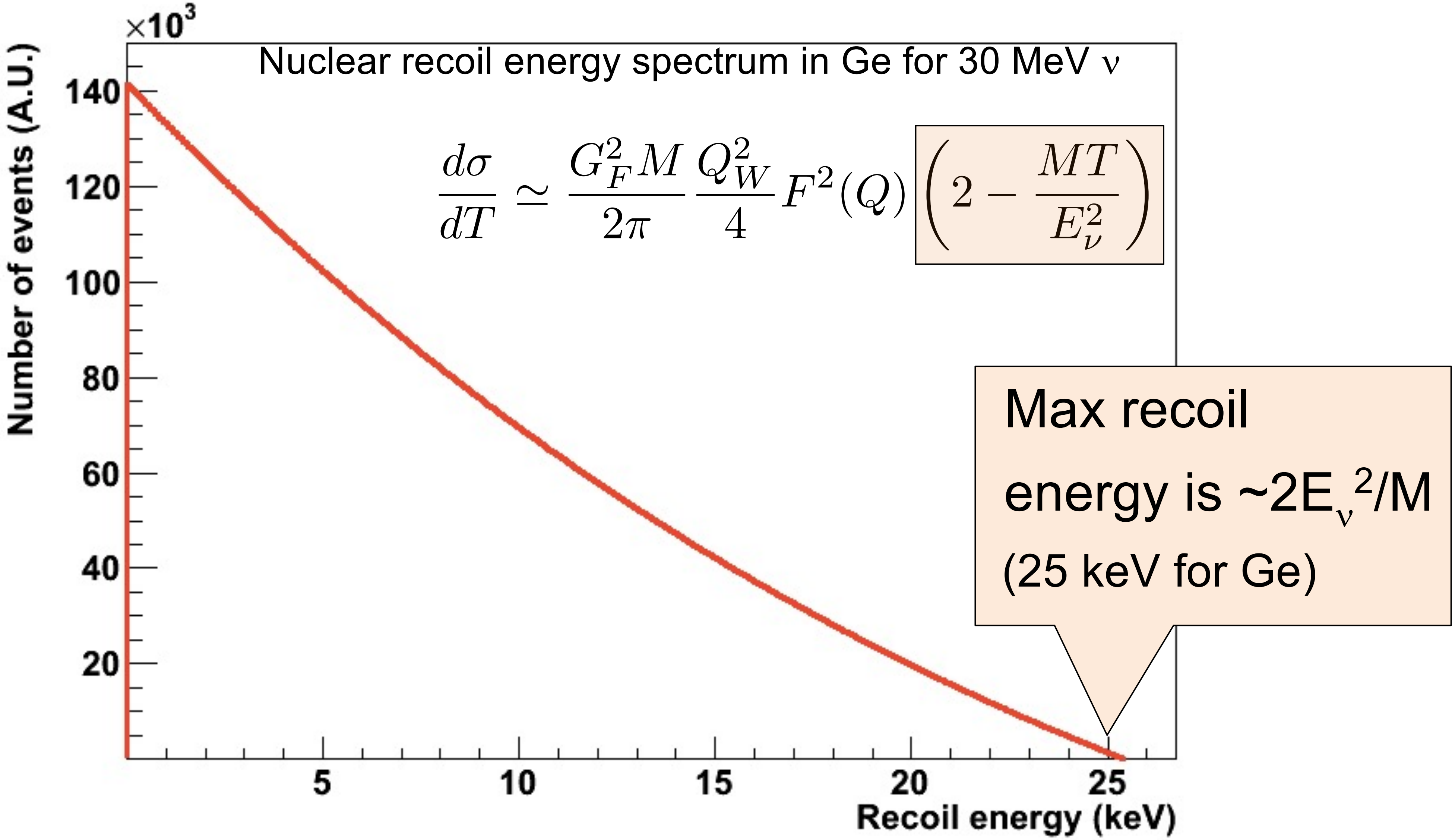
For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

A: no. of constituents

Image: J. Link *Science* Perspectives

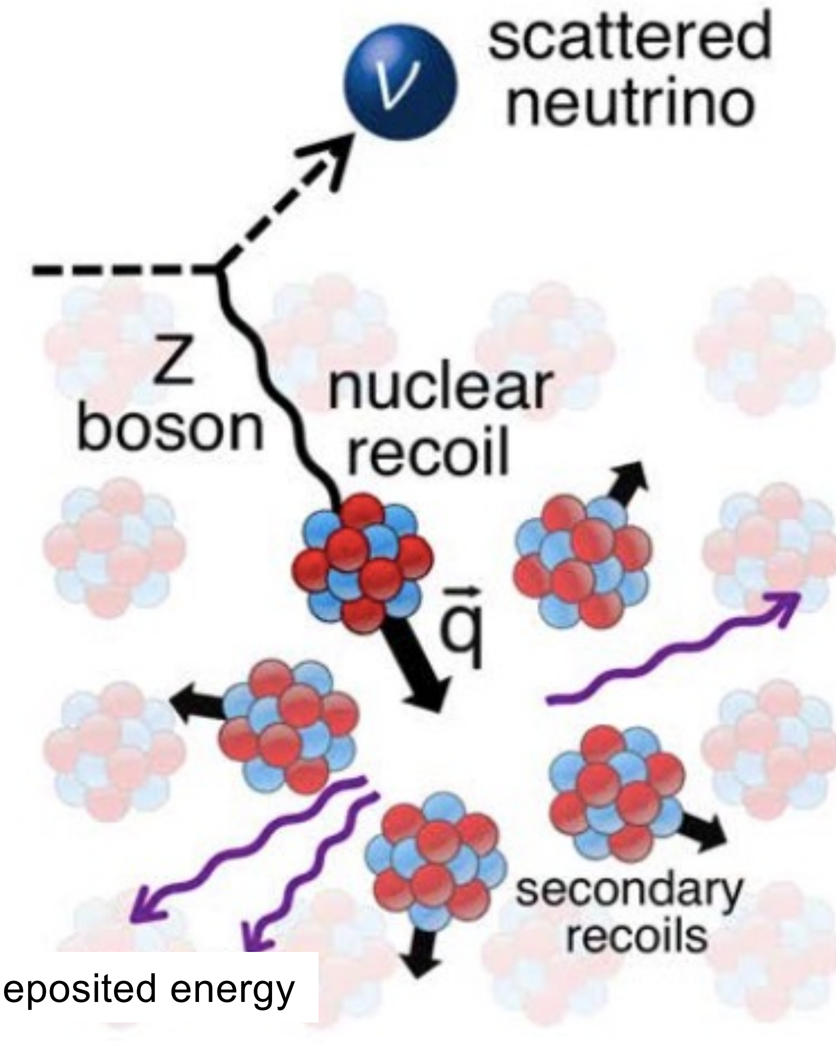

The cross-section is *large*
^{133}Cs CEvNS
^{127}I CEvNS
^{nat}Ge CEvNS
^{40}Ar CEvNS
^{23}Na CEvNS
ν_e ^{127}I CC
IBD
ν_e-e
$\sigma \propto N^2$
Cross-section (10^{-38} cm^2)
Neutrino Energy (MeV)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
5
10
15
20
25
30
35
40
45
50
55

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



The only experimental signature:

tiny energy deposited by nuclear recoils in the target material

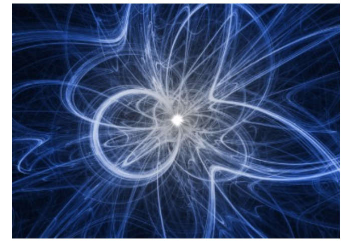


➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

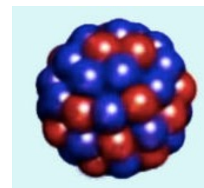
CEvNS: what's it good for?

① So ② Many ③ Things **!** (not a complete list!)

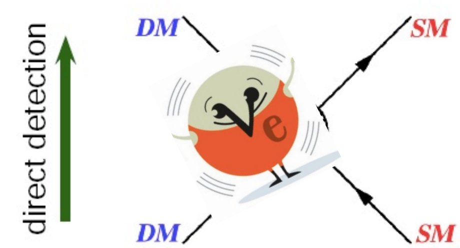
CEvNS as a **signal**
for signatures of *new physics*



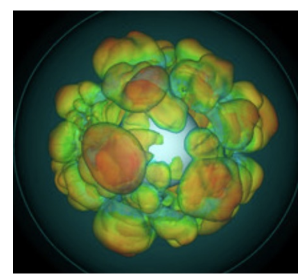
CEvNS as a **signal**
for understanding of "old" physics



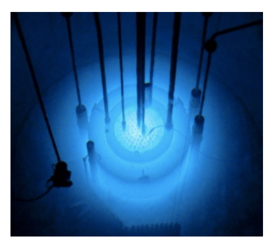
CEvNS as a **background**
for signatures of new physics



CEvNS as a **signal** for *astrophysics*



CEvNS as a **practical tool**



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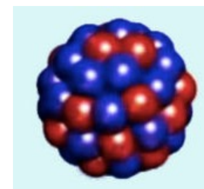

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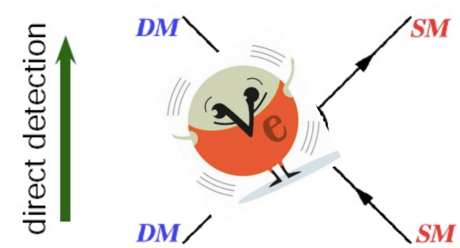

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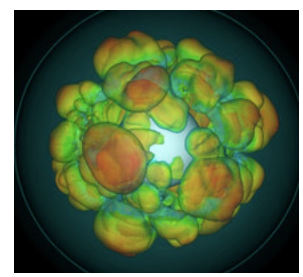

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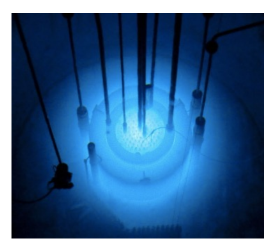

The cross section is cleanly predicted in the Standard Model

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

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

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

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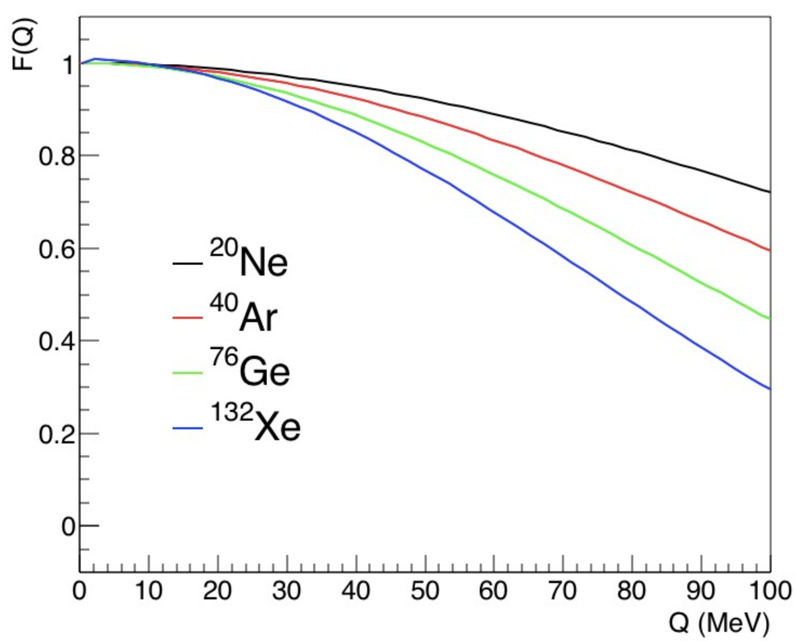
F(Q): nuclear **form factor**, <~5% uncertainty on event rate

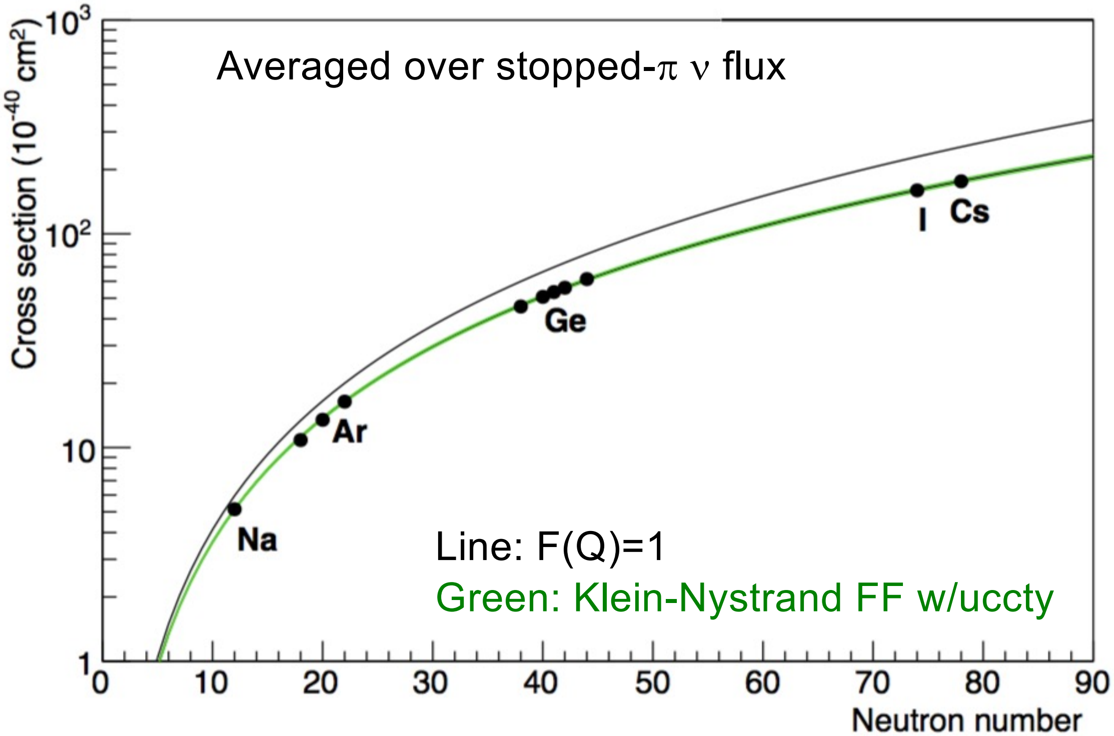


form factor suppresses cross section at large Q

The CEvNS rate is a clean Standard Model prediction

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

small nuclear uncertainties

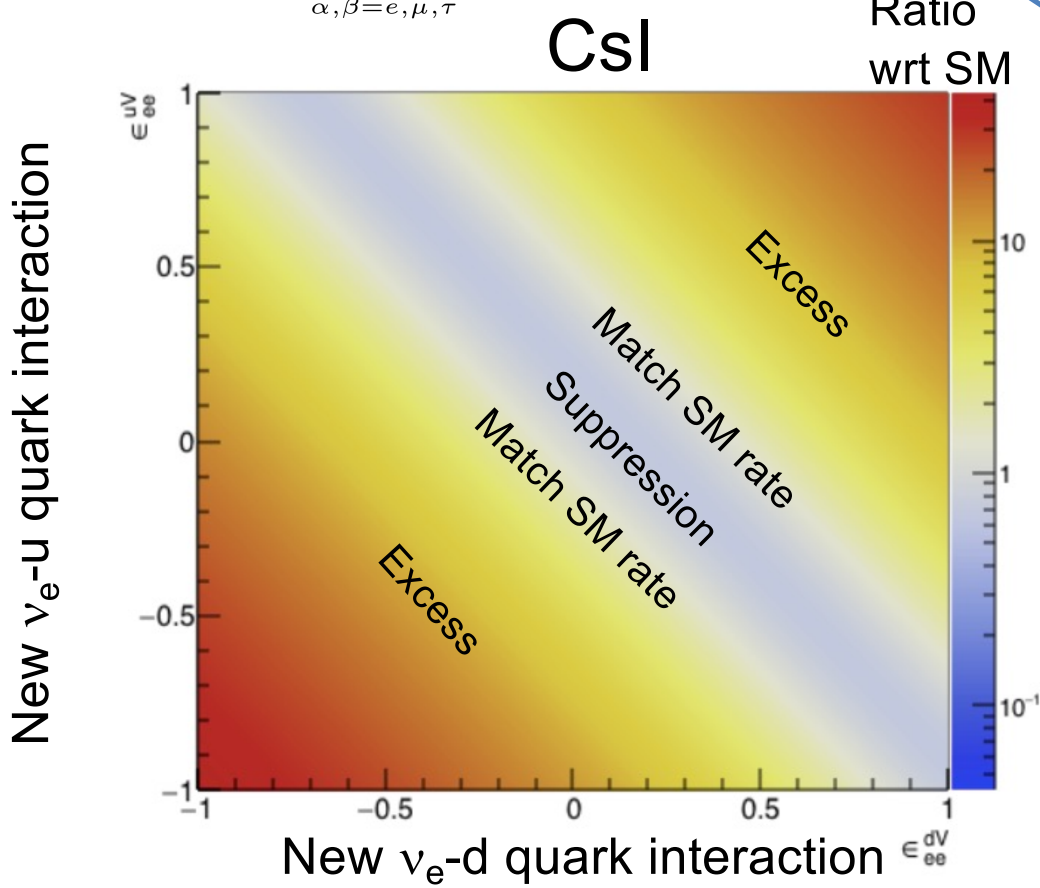


A deviation from α N^2 prediction can be a signature of beyond-the-SM physics

Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

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



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

For heavy mediators, expect ***overall scaling*** of CEvNS event rate, depending on N, Z

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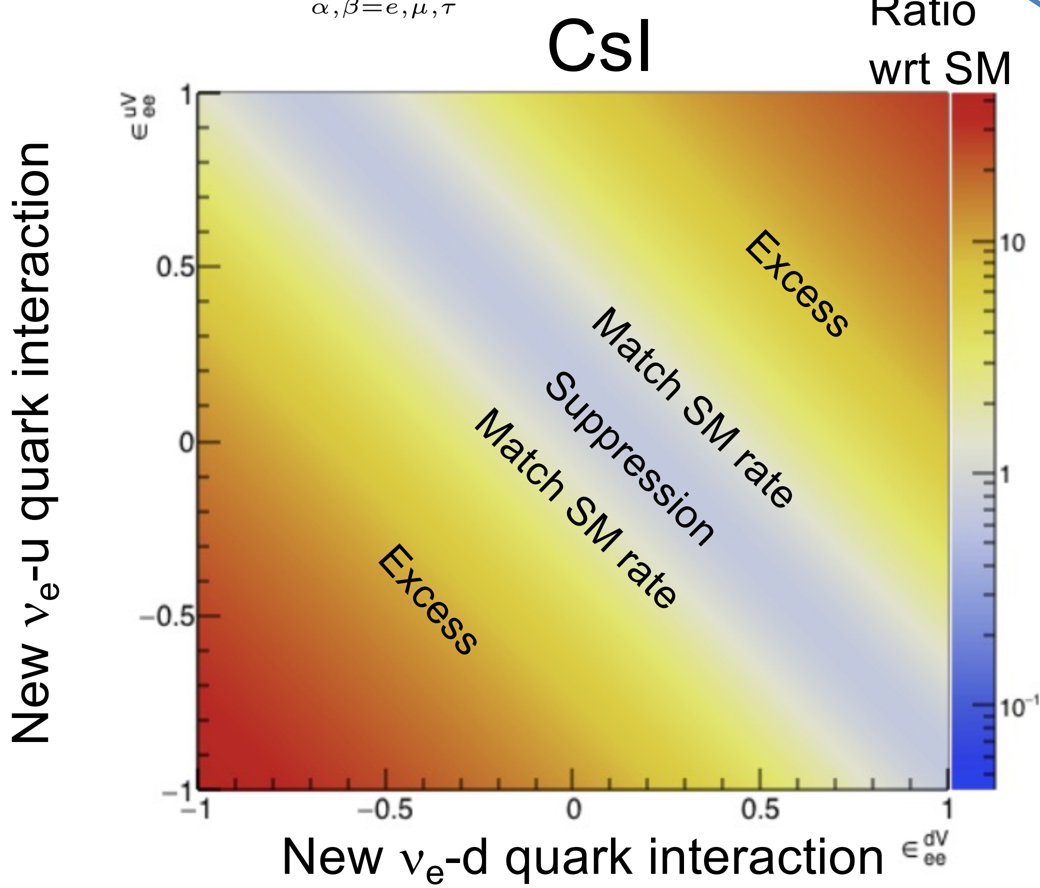

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Observe less or more CEvNS than expected?
...could be beyond-the-SM physics!

Other new physics results in a

distortion of the recoil spectrum (Q dependence)

BSM Light Mediators

SM weak charge

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

Effective weak charge in presence of light vector mediator Z'

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

specific to neutrinos and quarks

e.g. arXiv:1708.04255

Neutrino (Anomalous) Magnetic Moment

e.g. arXiv:1505.03202, 1711.09773

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

Specific ~1/T upturn at low recoil energy

Sterile Neutrino Oscillations

$$P^{\mathrm{SBL}}_{\nu_\alpha\to\nu_\alpha}(E_\nu) = 1 - \sin^2 2\theta_{\alpha\alpha}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

"True" disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

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(3) Things !

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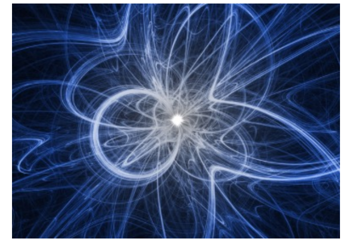

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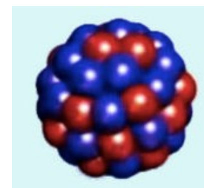
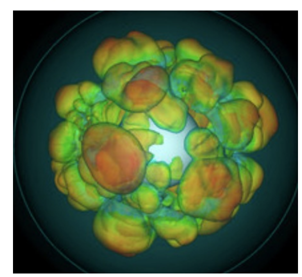


CEvNS as a **background**
for signatures of new physics (DM)

CEvNS as a **signal** for *astrophysics*



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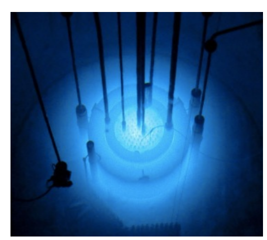


Light **accelerator-produced DM** direct detection possibilities

(CEvNS is *background*)

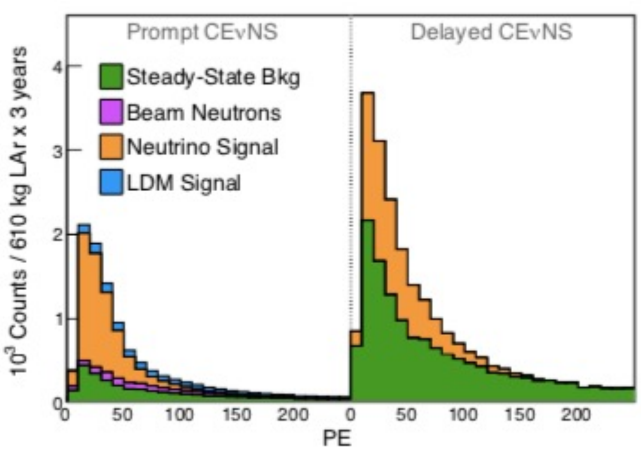
- “Vector portal”: mixing of vector mediator with photons in π^0/η^0 decays
- “Leptophobic portal“: new mediator coupling to baryons

} decay product χ then makes nuclear recoil

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

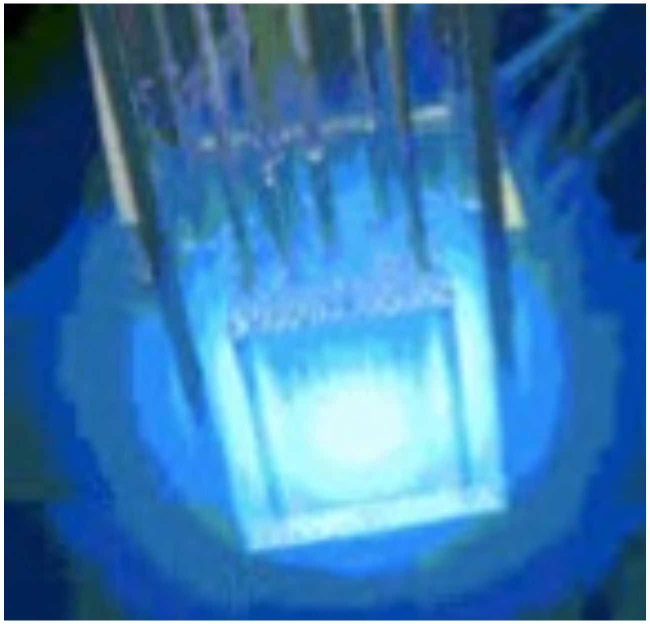
$$\pi^- + p \longrightarrow n + V^{(*)} \longrightarrow n + \chi^\dagger + \chi$$

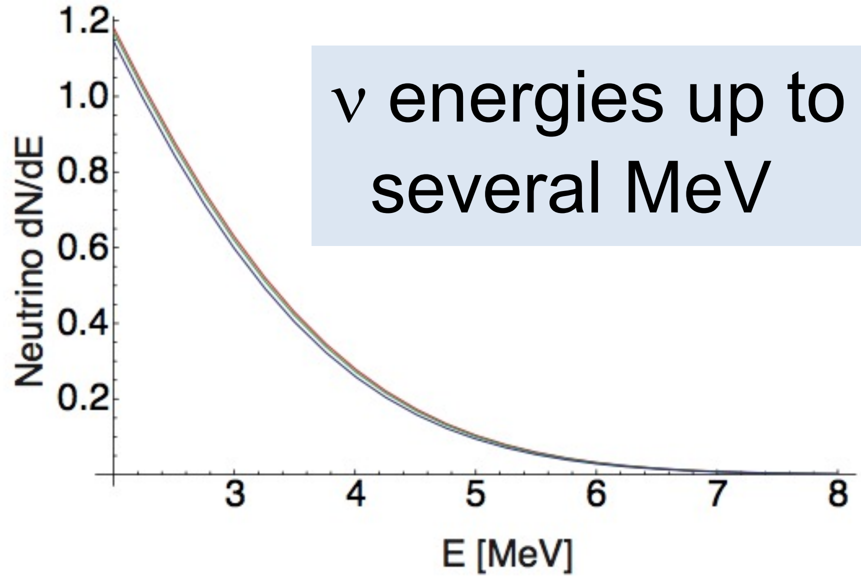
B. Batell et al., PRD 90 (2014)
P. de Niverville et al., PRD 95 (2017)
B. Dutta et al., arXiv:1906.10745
COHERENT, arXiv:1911.6422



Expect *characteristic time, recoil energy, angle distribution* for DM vs CEvNS

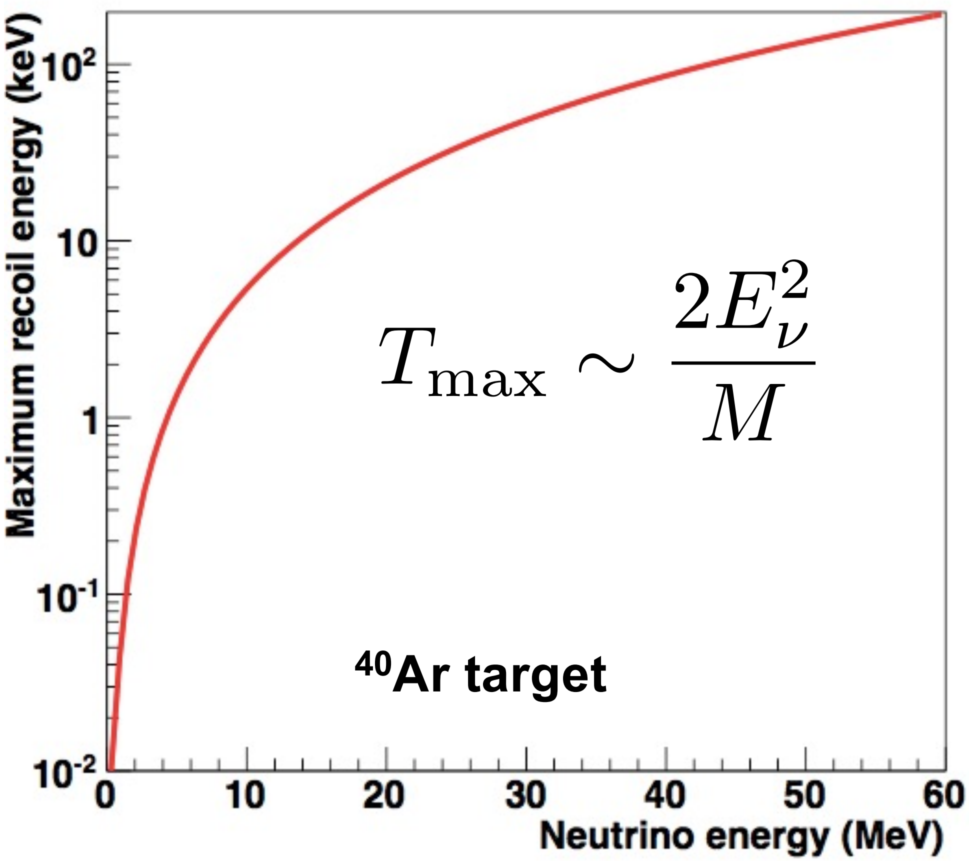
Neutrinos from nuclear reactors

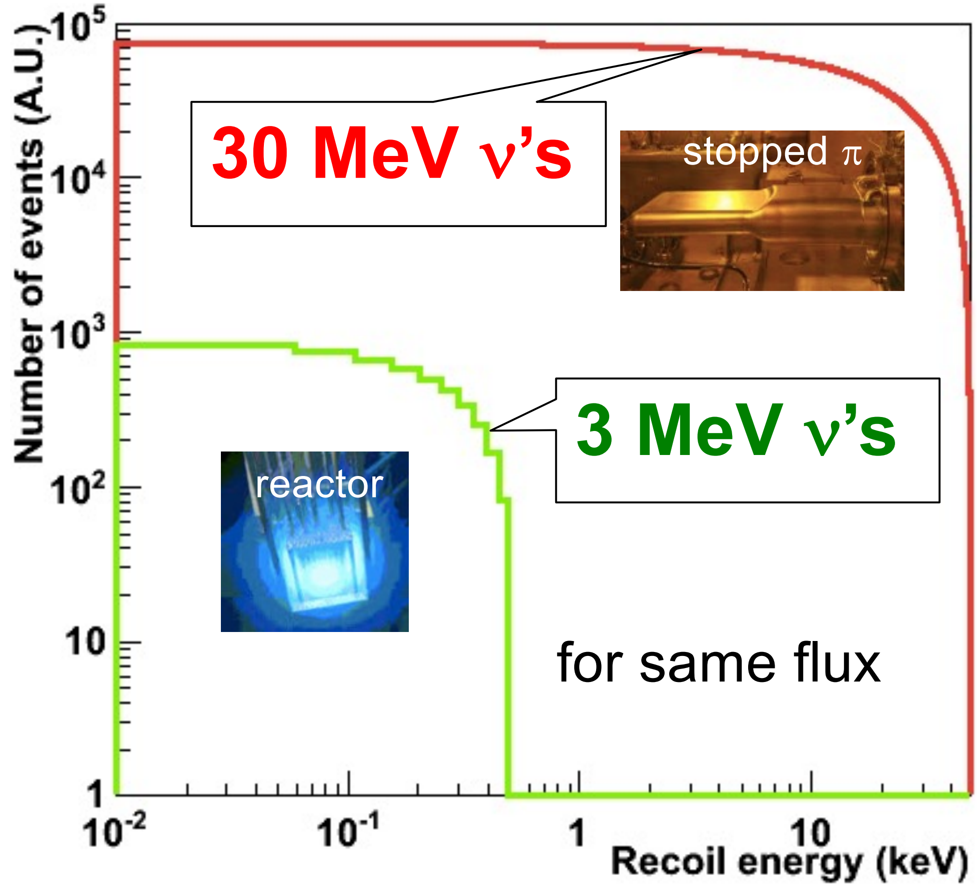




- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~$2x10^{20}$ s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

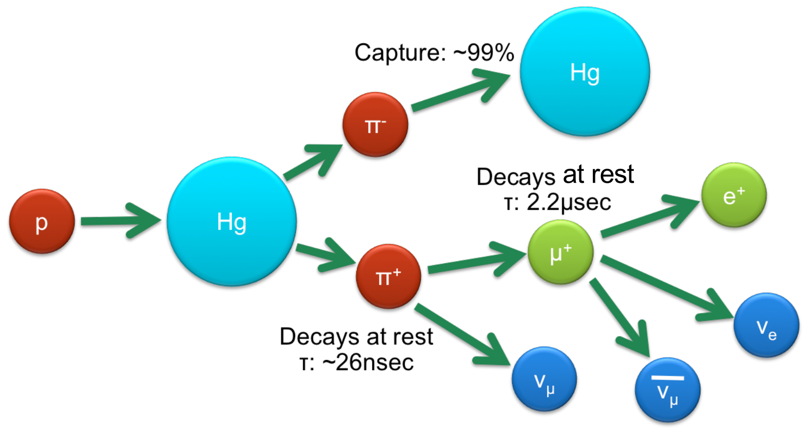
Both **cross-section** and **maximum recoil energy** **increase with neutrino energy**:

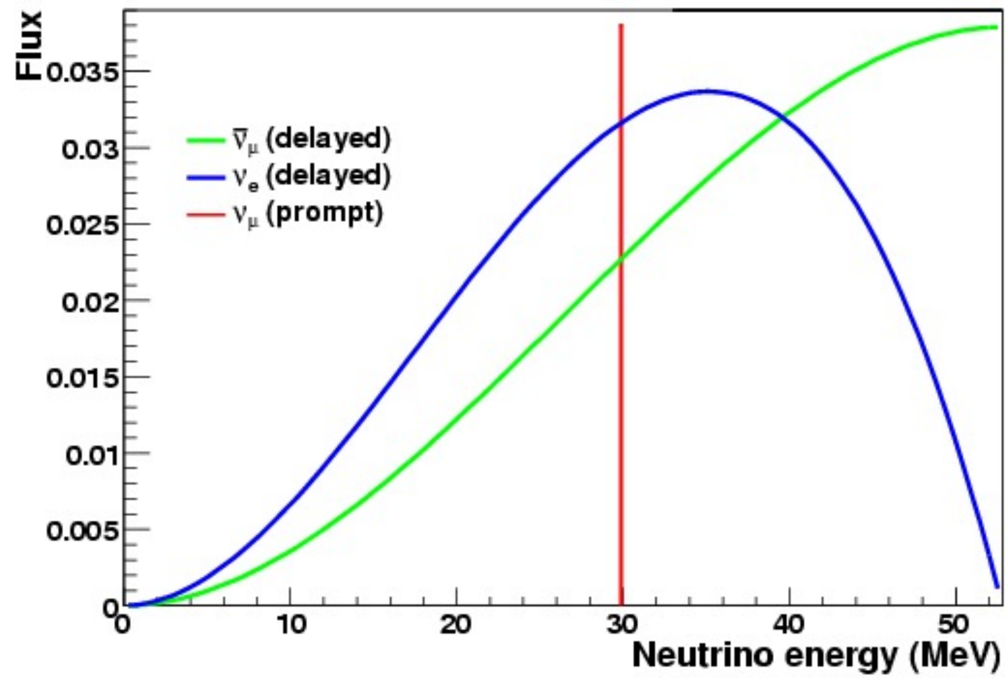




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





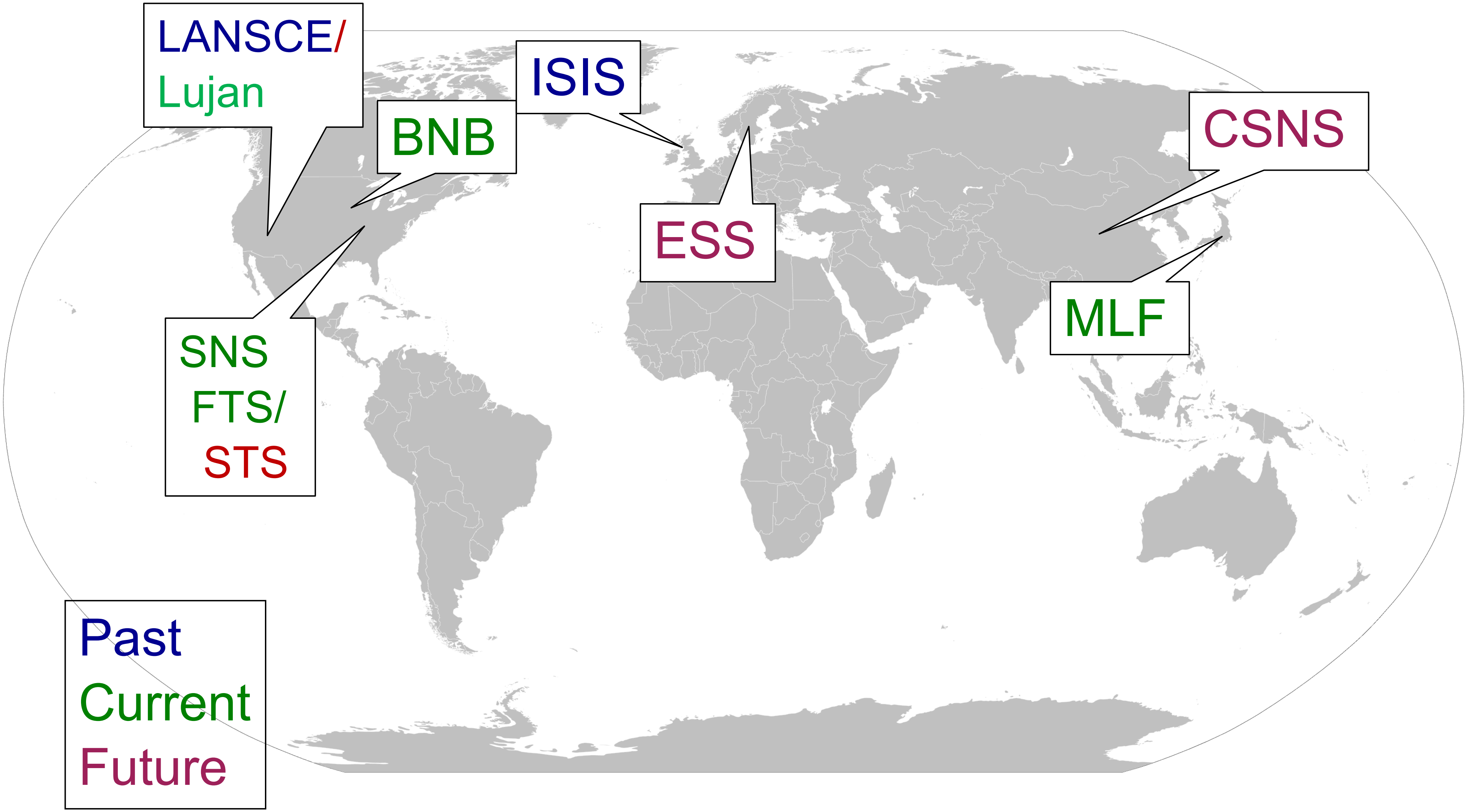
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

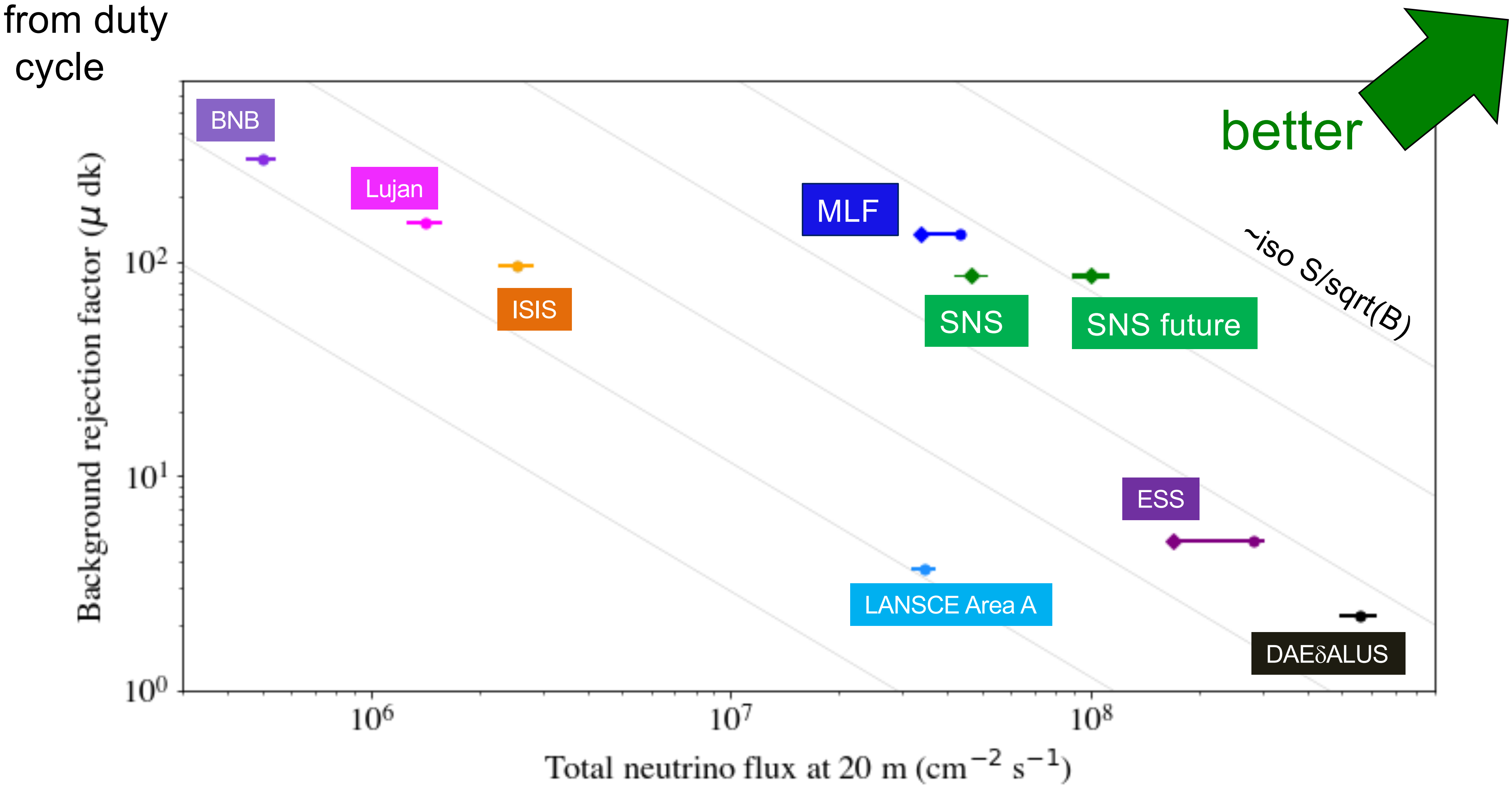
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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



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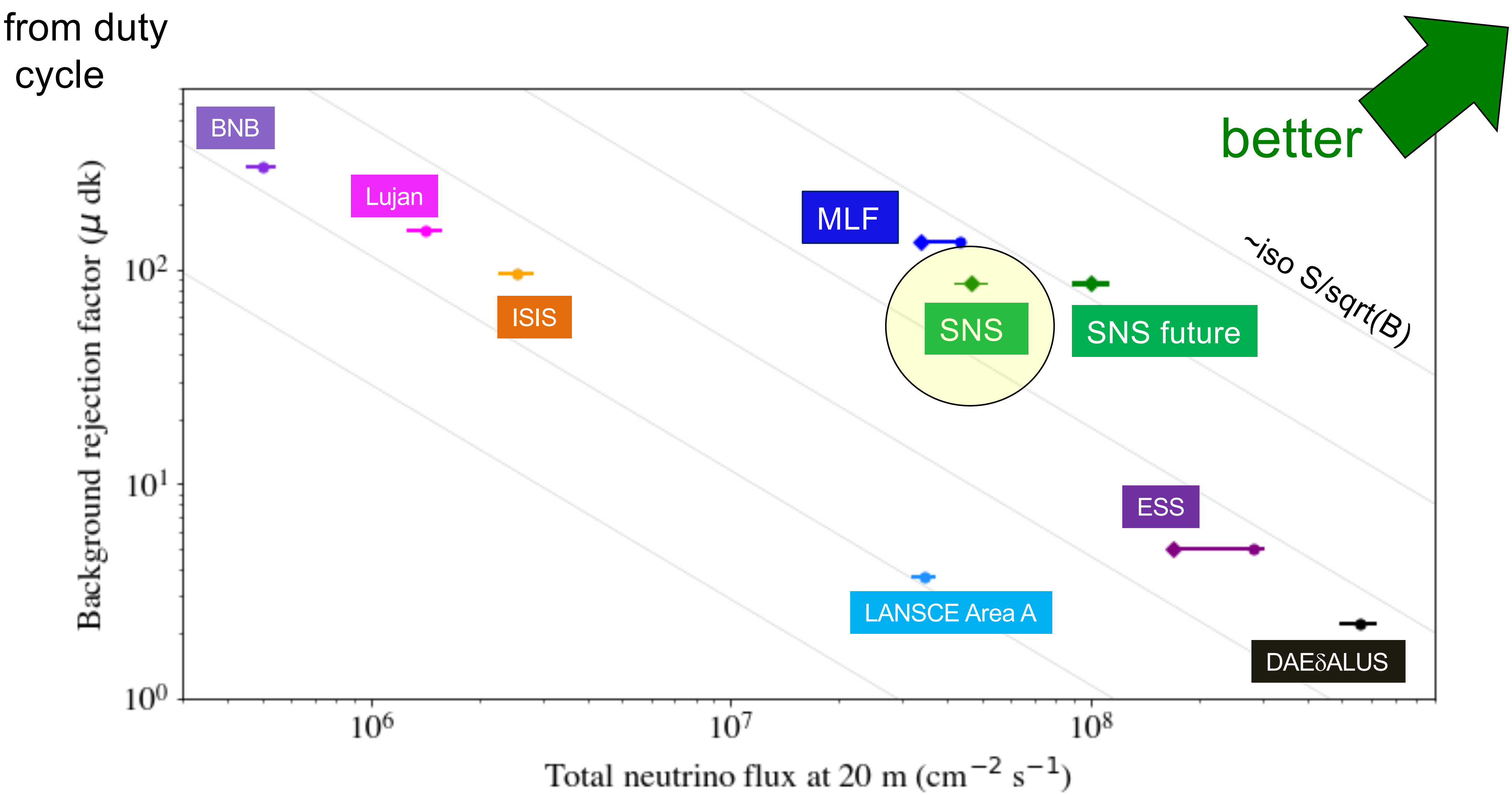
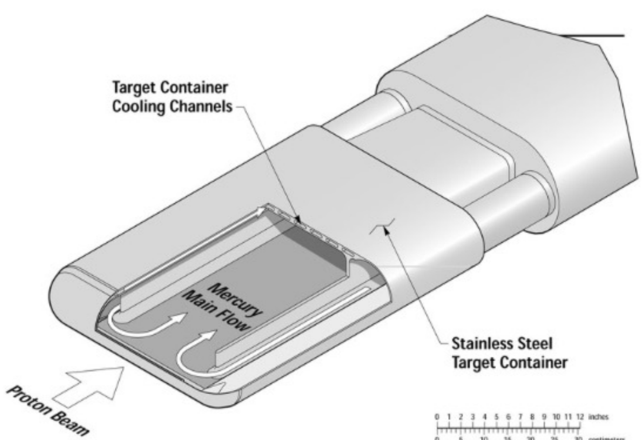


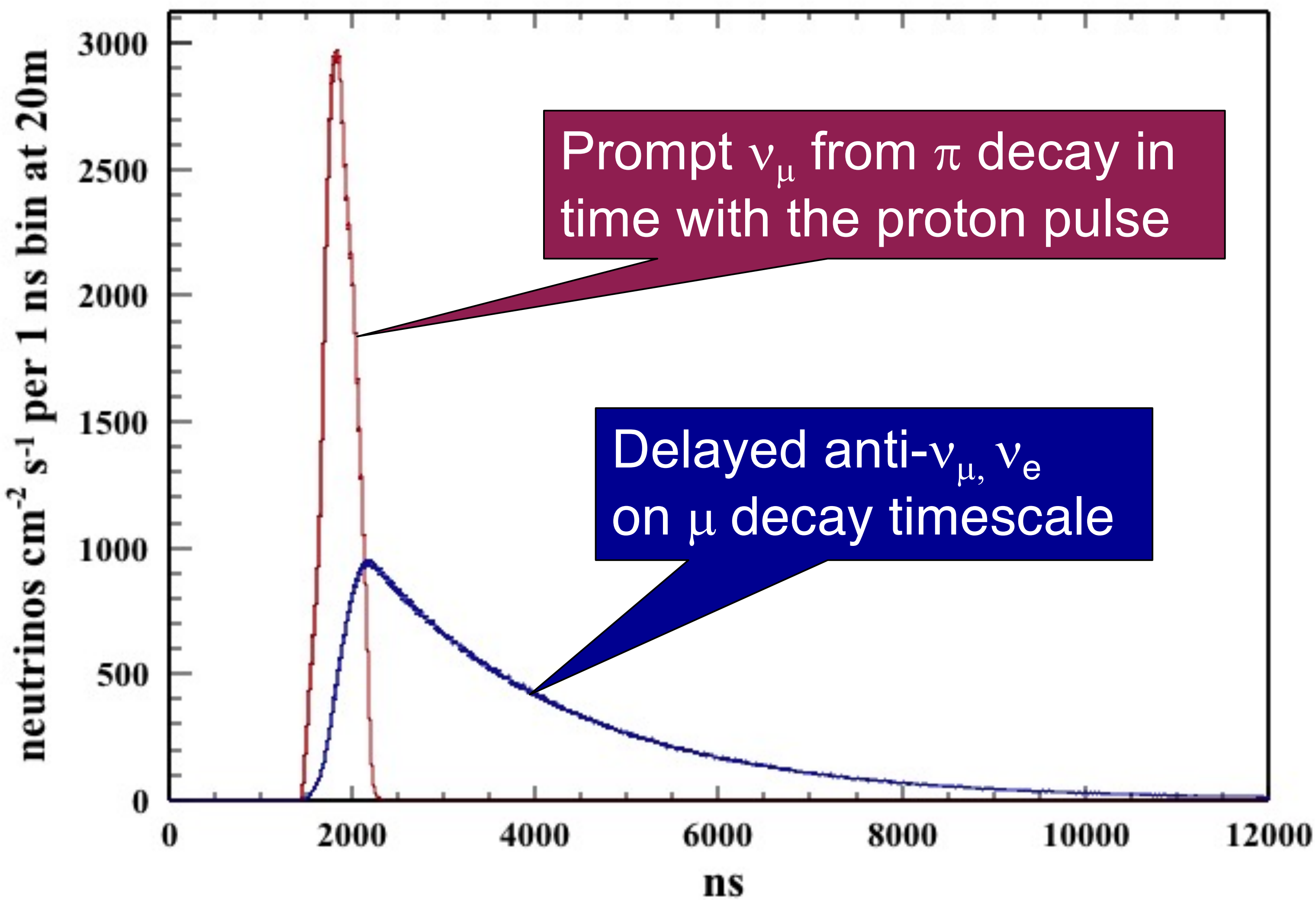


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Time structure of the SNS source

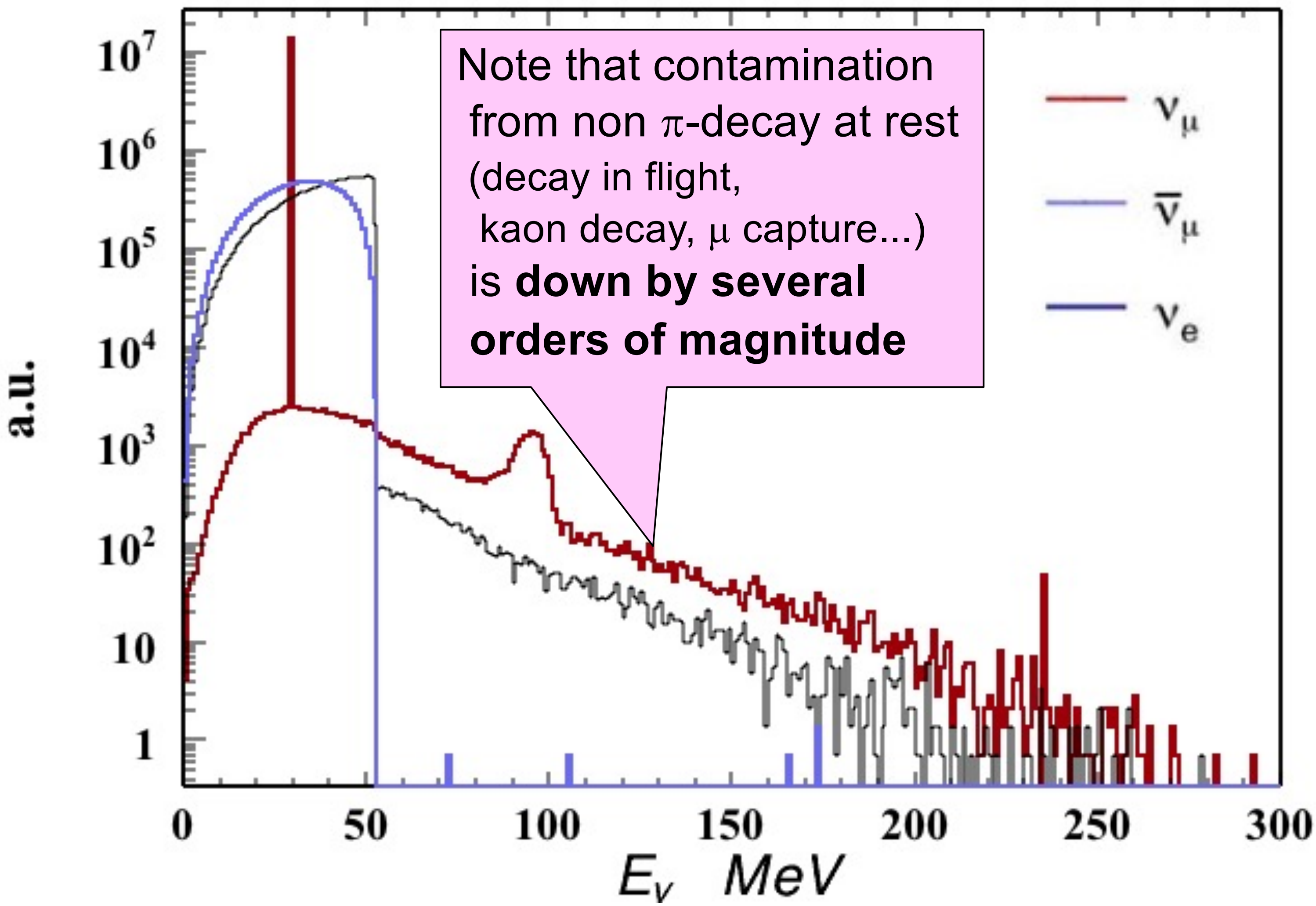
60 Hz *pulsed* source



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/cm²/s
@ 20 m

The COHERENT collaboration

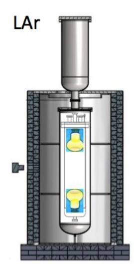
http://sites.duke.edu/coherent

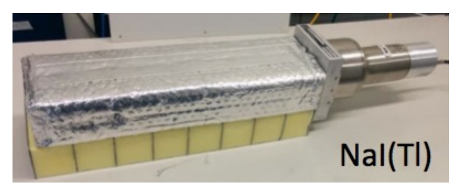
~90 members,
20 institutions
4 countries

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	19	22	<few
LAr	Single-phase flash	24	27.5	20
NaI[Tl]	Scintillating crystal flash	185*/3338	25	13

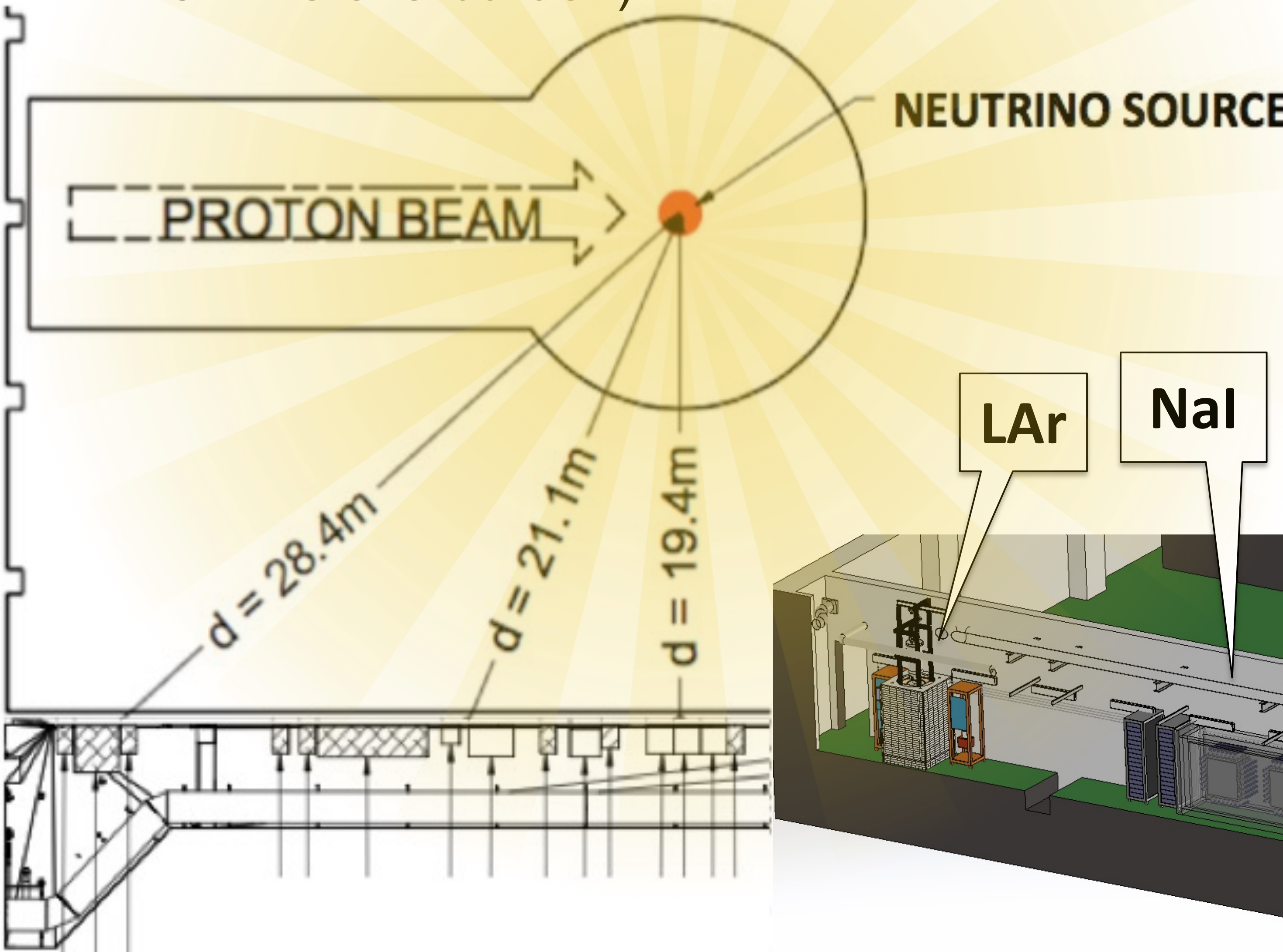
Multiple detectors for N^2 dependence of the cross section





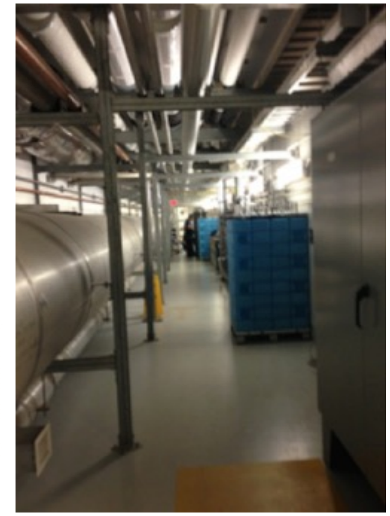
Siting for deployment in SNS basement

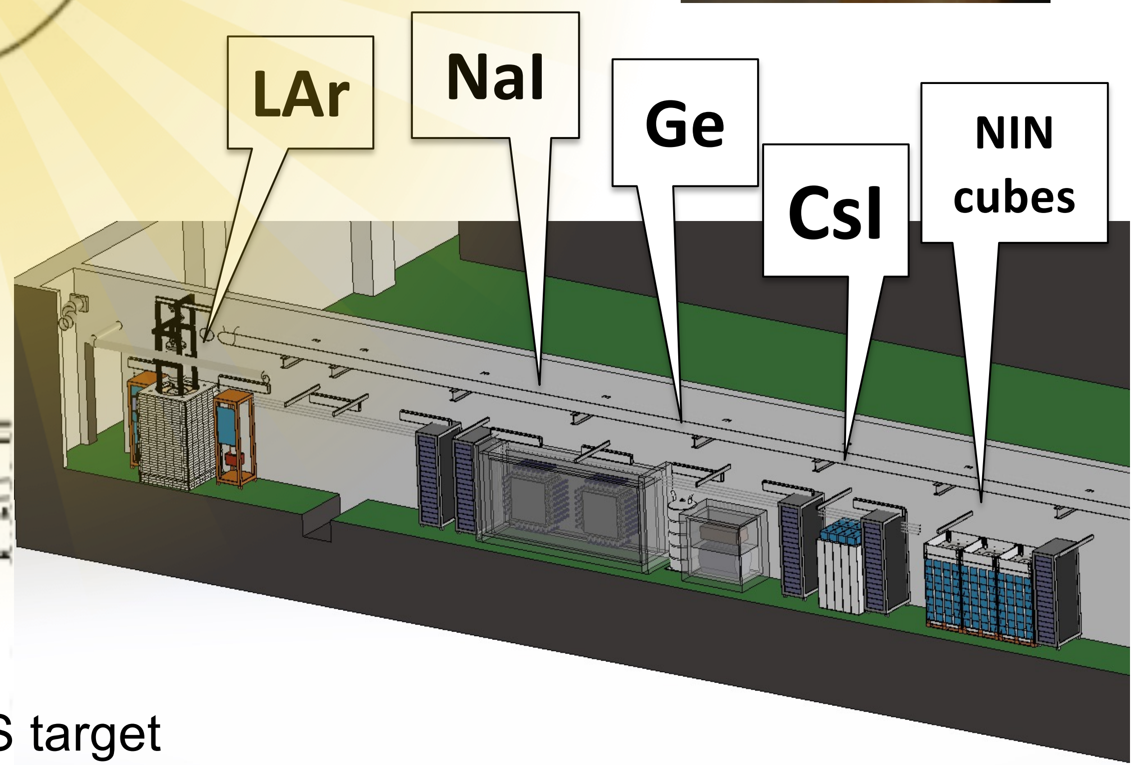
(measured neutron backgrounds low, ~ 8 mwe overburden)



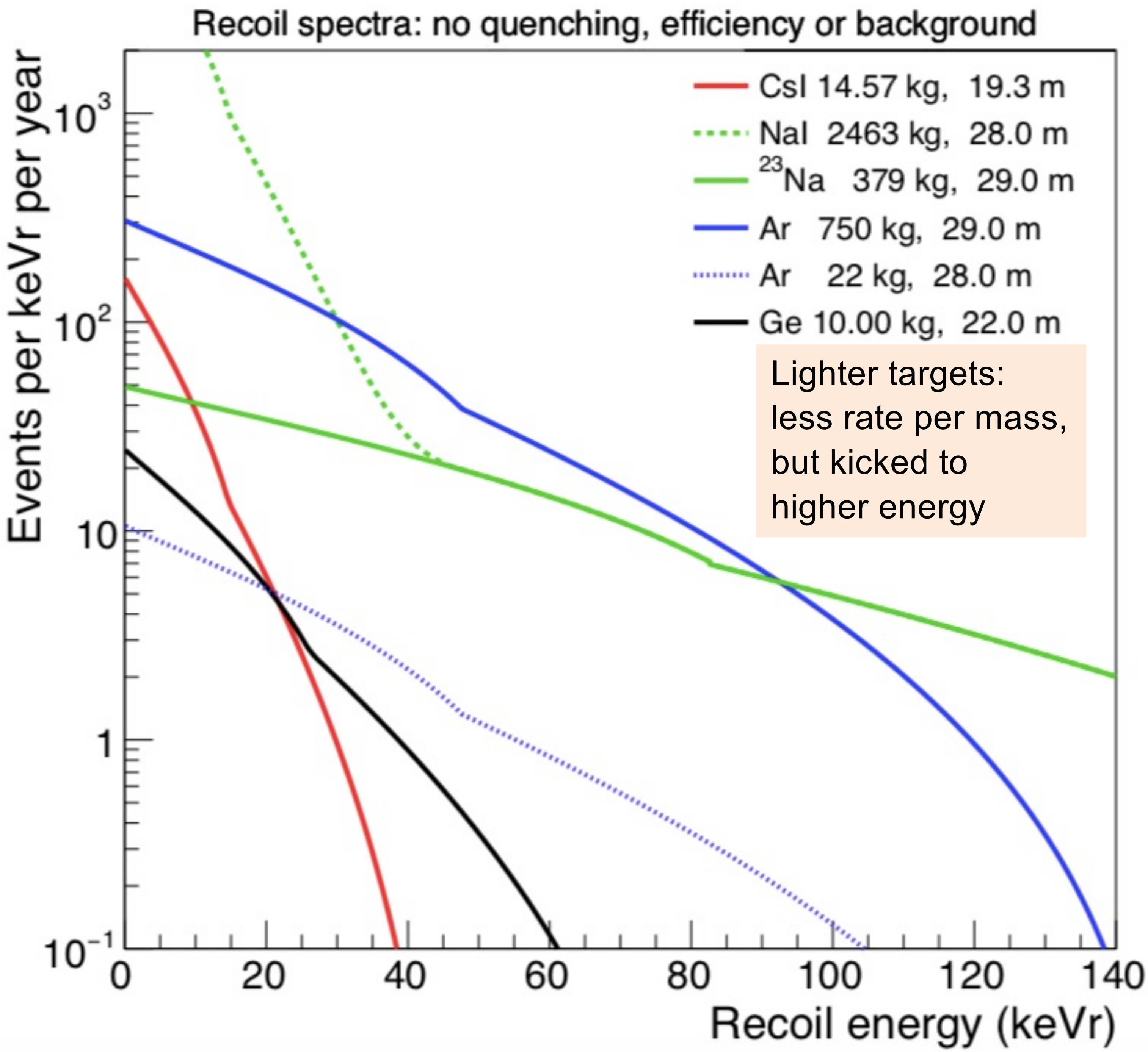
Isotropic ν glow from Hg SNS target

View looking down “Neutrino Alley”





Expected recoil energy distribution

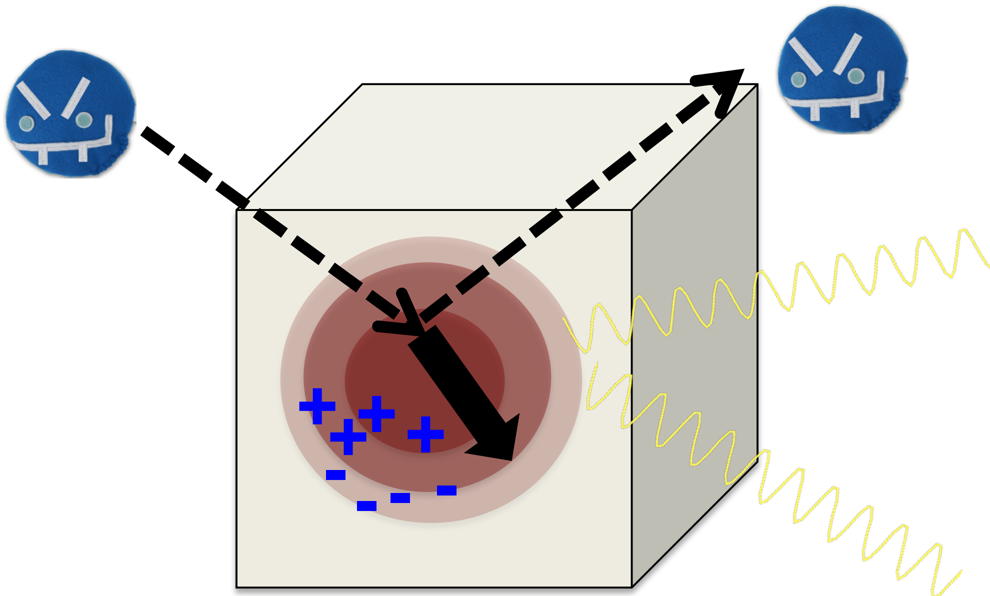


Backgrounds

Usual suspects:

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

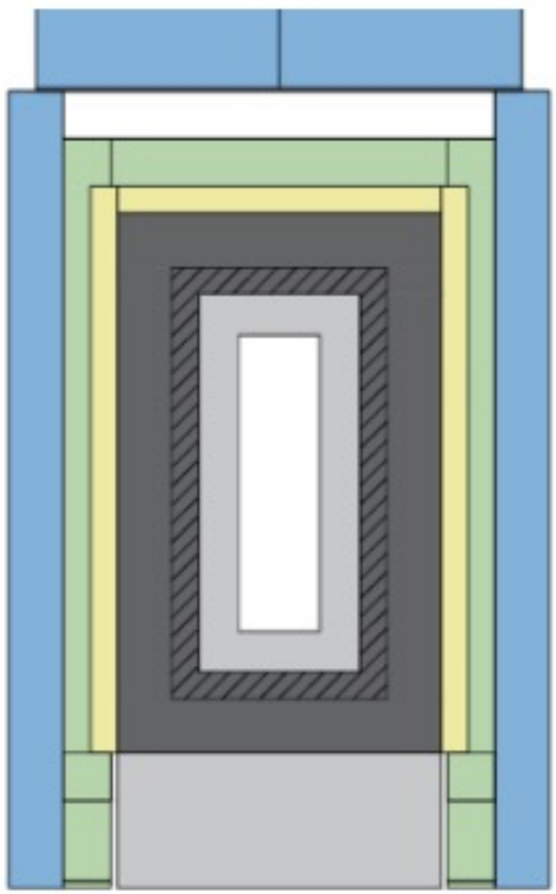
Neutrons are especially not your friends*

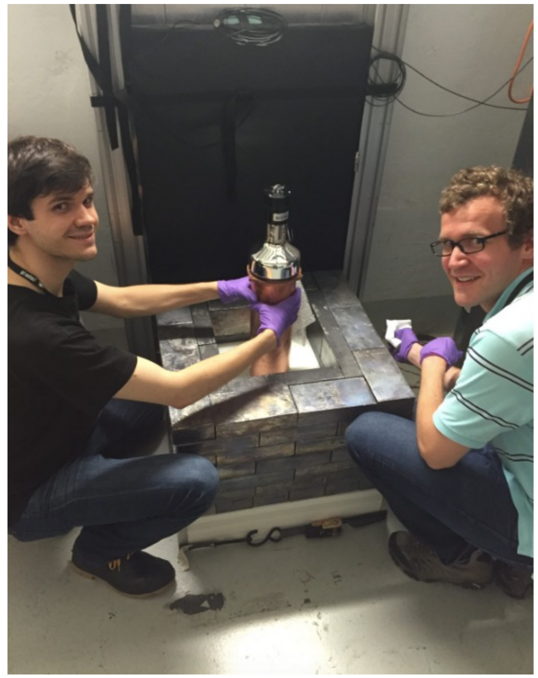


Steady-state backgrounds can be *measured* off-beam-pulse
... in-time backgrounds must be carefully characterized

*Thanks to Robert Cooper for the "mean neutron"

The CsI Detector in Shielding in Neutrino Alley at the SNS



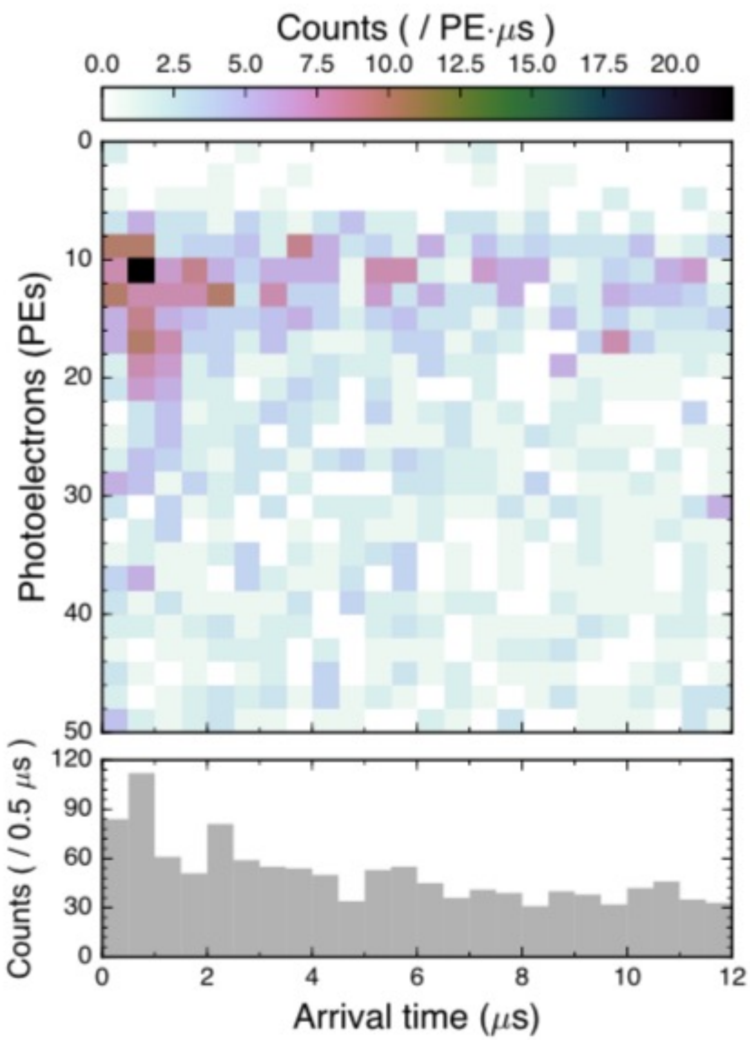


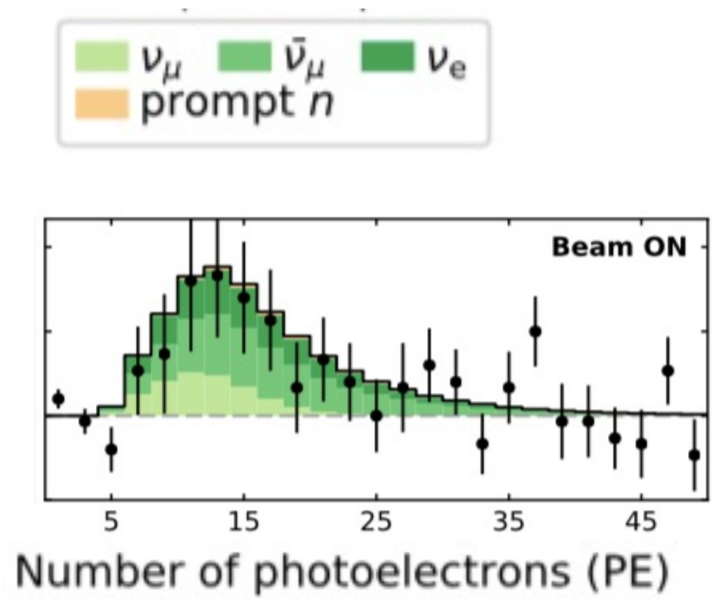
A hand-held detector!

Almost wrapped up...

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

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





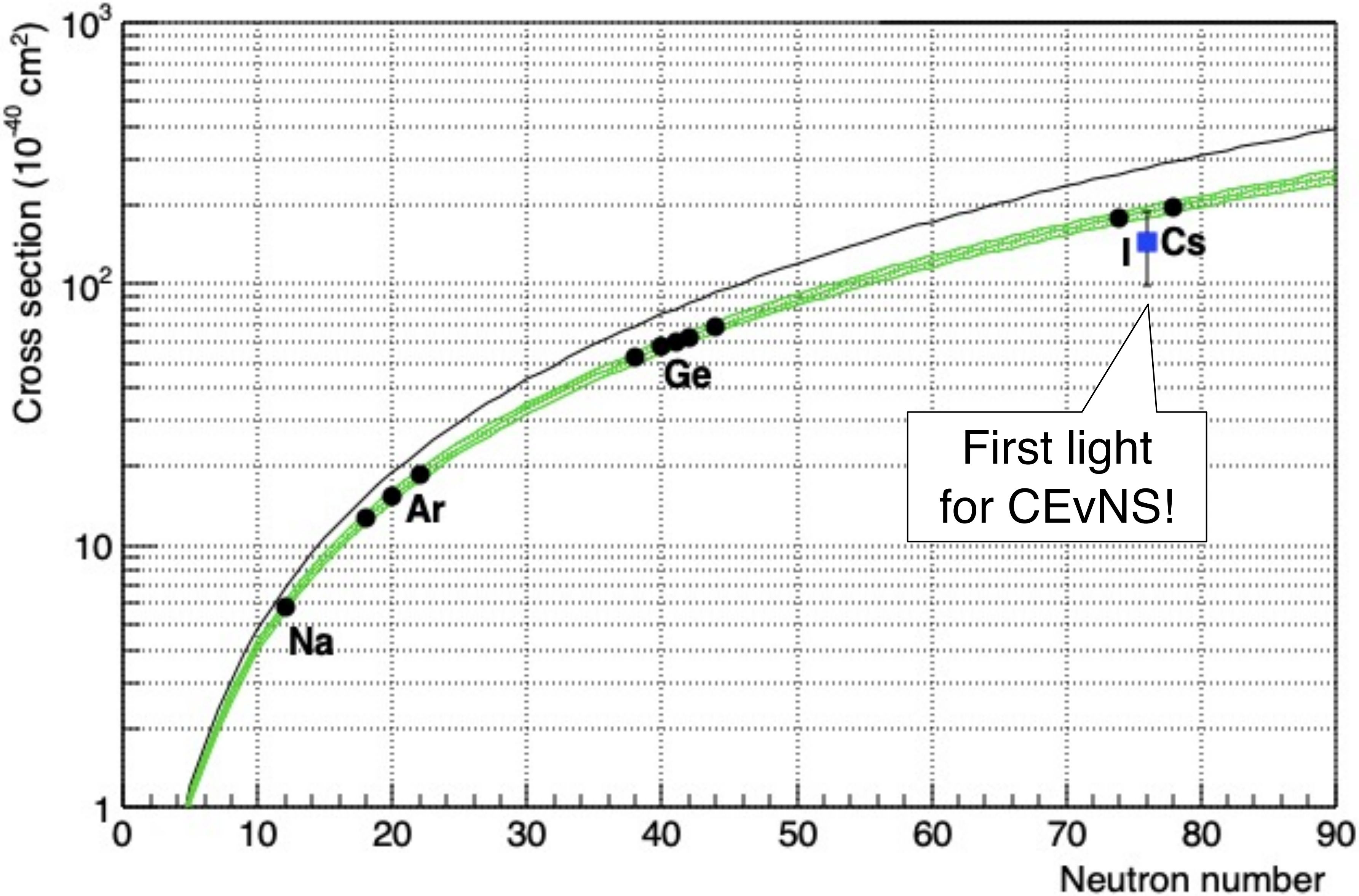
Background-subtracted and integrated over time

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

→ measure of the Q spectrum

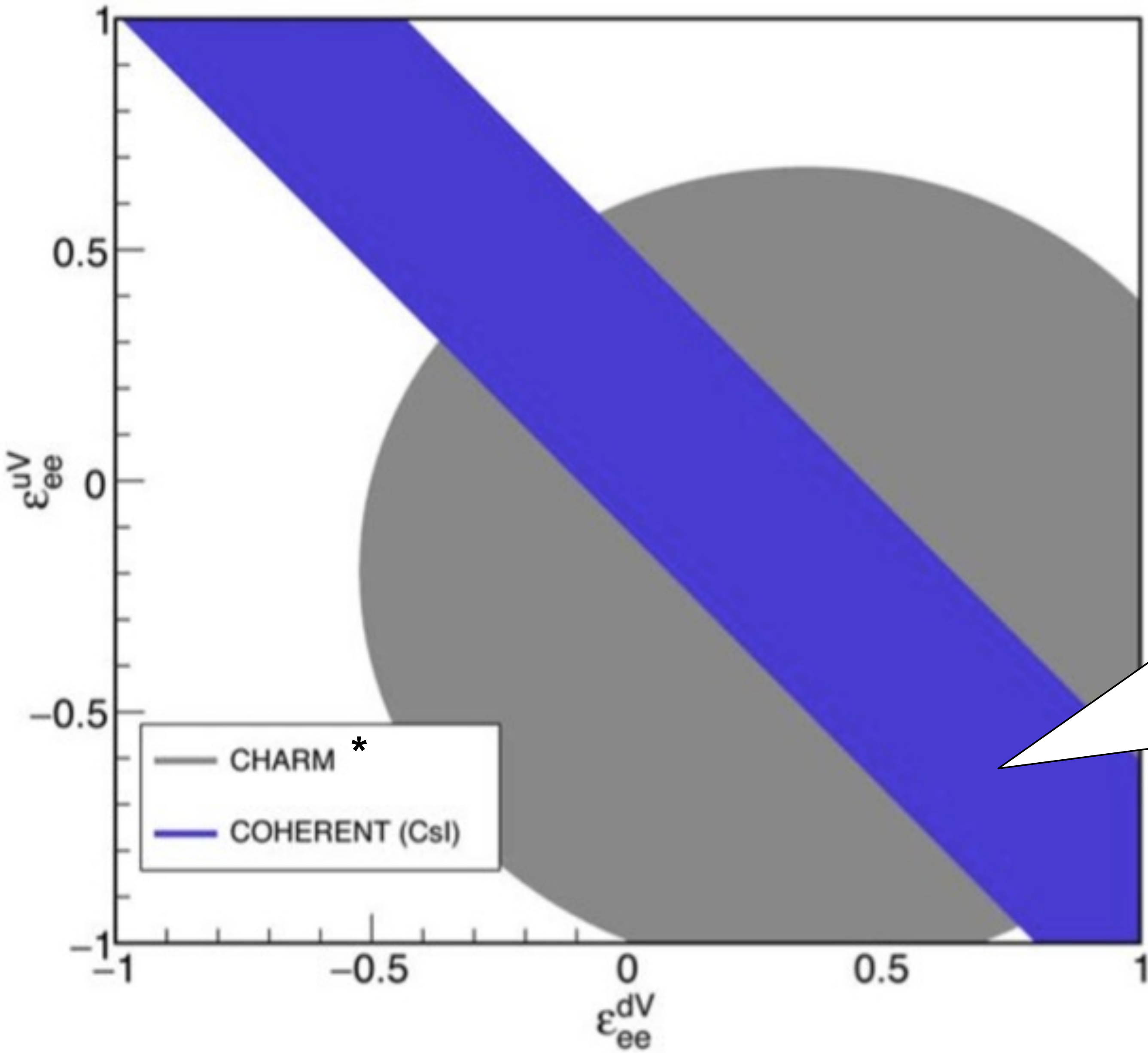
DOI: 10.5281/zenodo.1228631

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



Cross section (10^{-40} cm^2)
Neutron number
Na
Ar
Ge
I
Cs
First light for CEvNS!

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



- Assume all other ε's zero

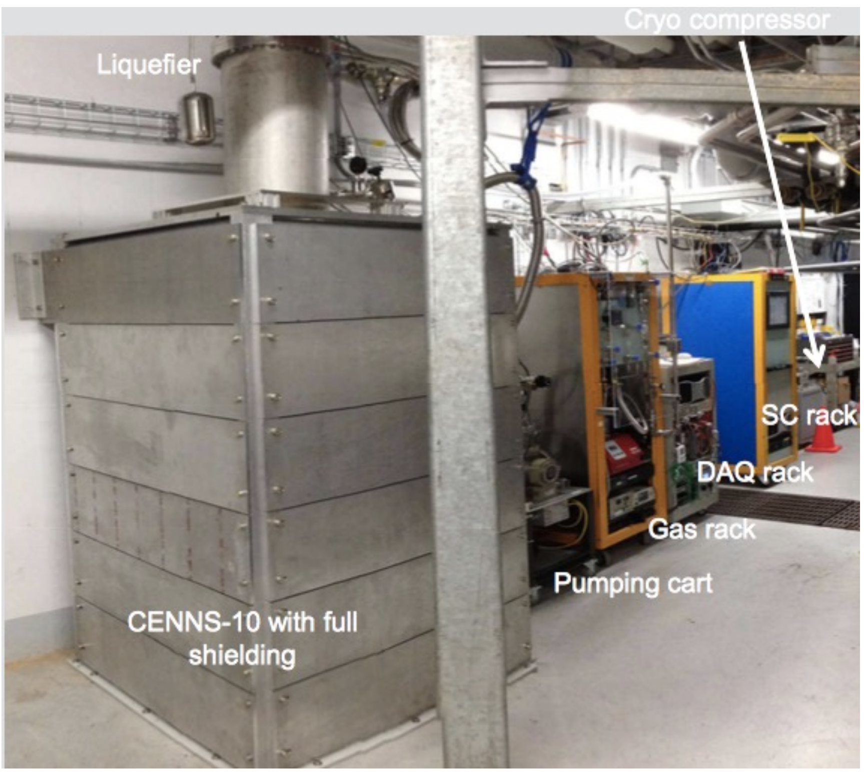
Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

See also Coloma et al., arXiv:1708.02899, many more!

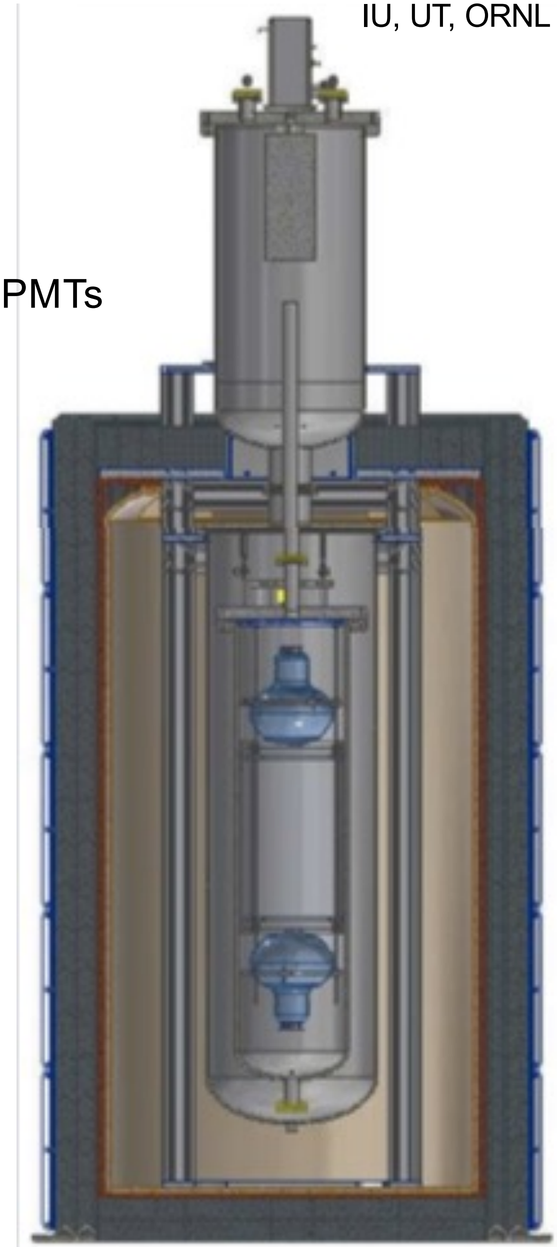
*CHARM constraints apply only to heavy mediators

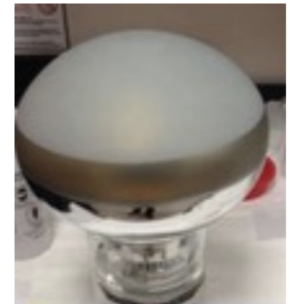
Single-Phase Liquid Argon

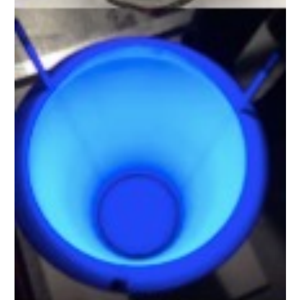
- ~24 kg active mass
- 2 x Hamamatsu 5912-02-MOD 8” PMTs
  - 8” borosilicate glass window
  - 14 dynodes
  - QE: 18%@ 400 nm
- Wavelength shifter: TPB-coated Teflon walls and PMTs
- Cryomech cryocooler – 90 Wt
  - PT90 single-state pulse-tube cold head

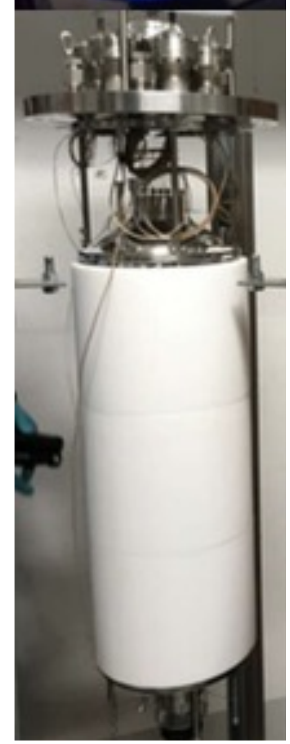


IU, UT, ORNL







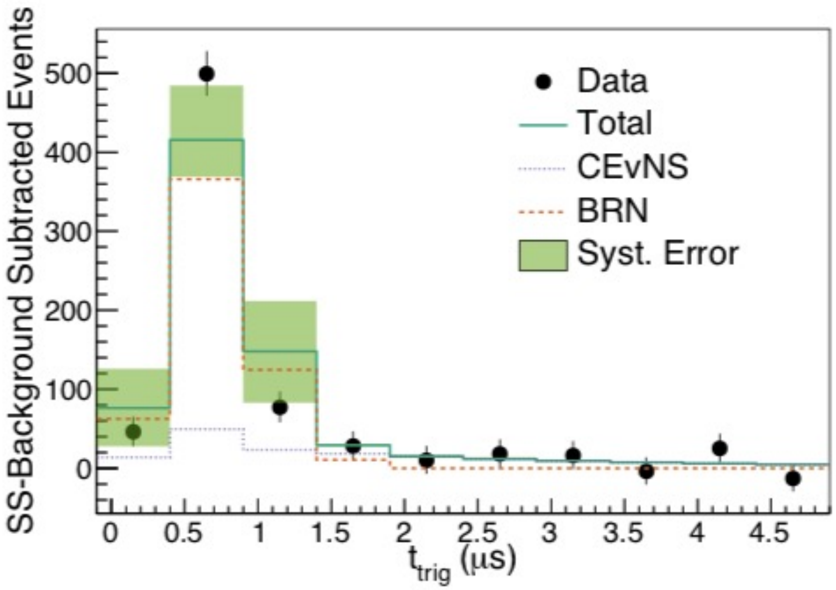


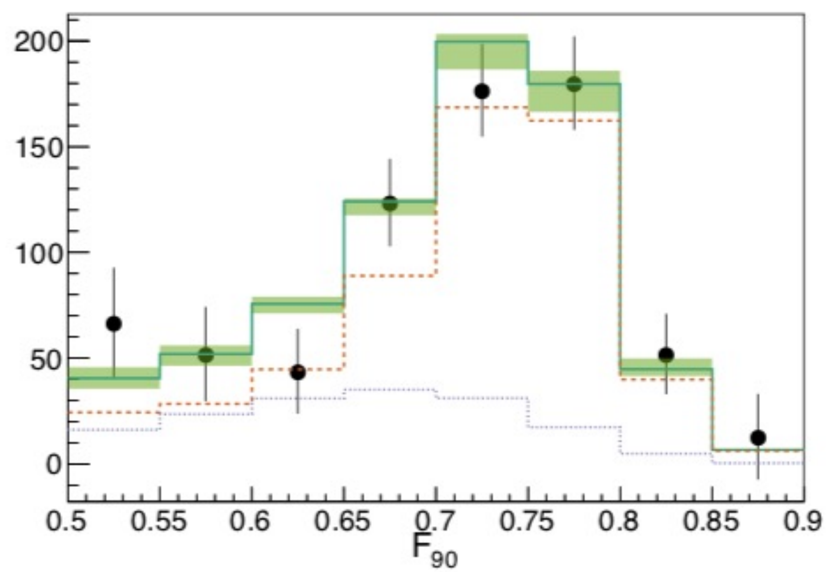
Detector from FNAL, previously built (Jonghee Yoo et al.) for CENNS@BNB

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

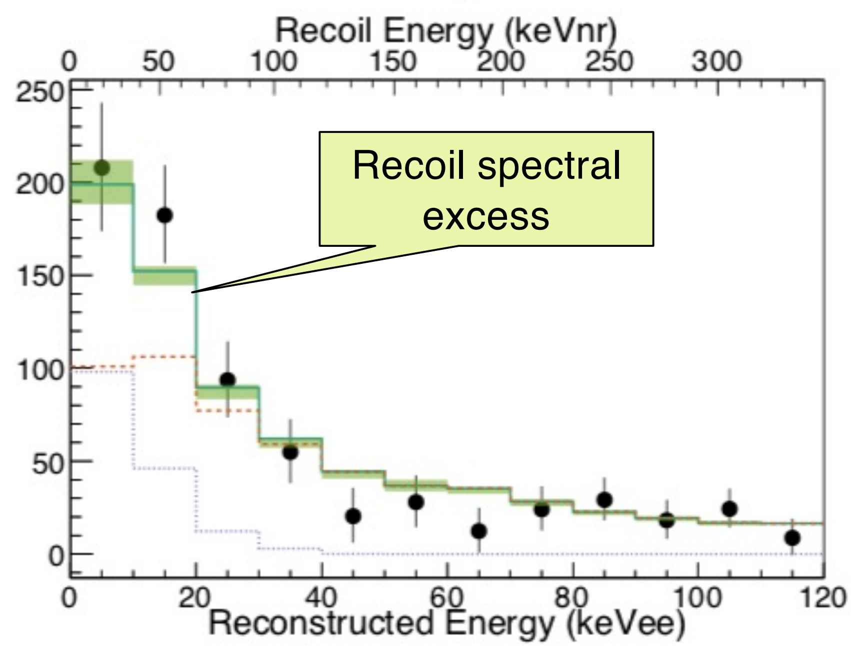
Likelihood fit in time, recoil energy, PSD parameter

Beam-unrelated-background-subtracted projections of 3D likelihood fit

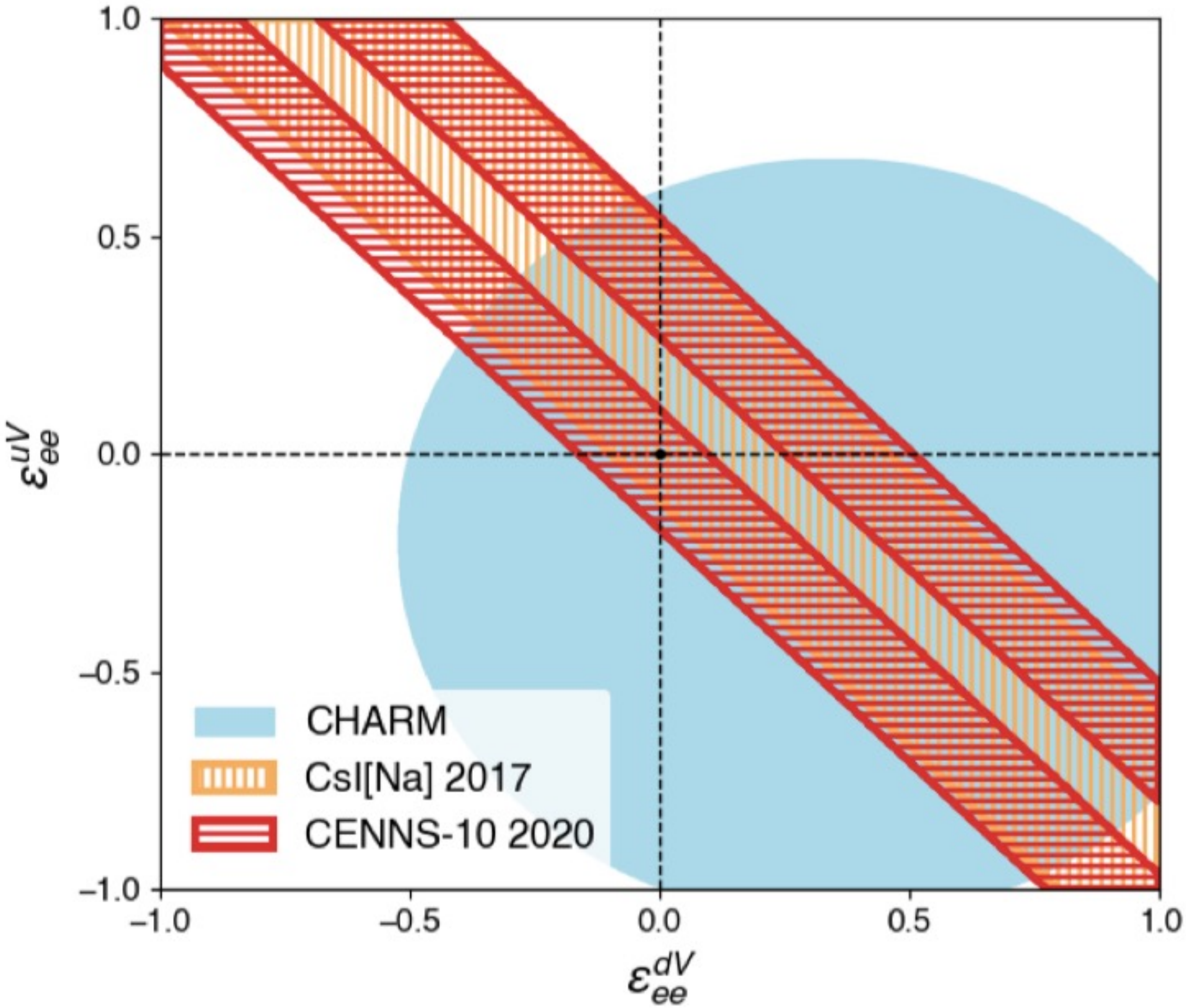




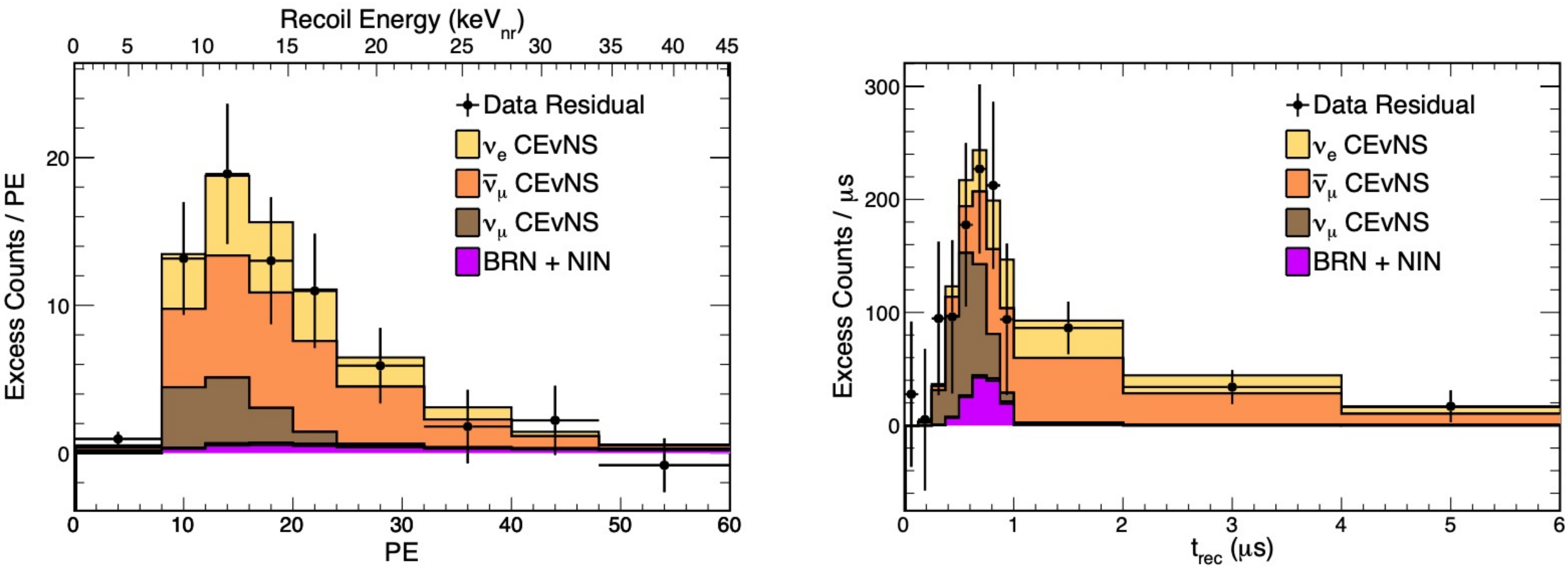
- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the "A" analysis)



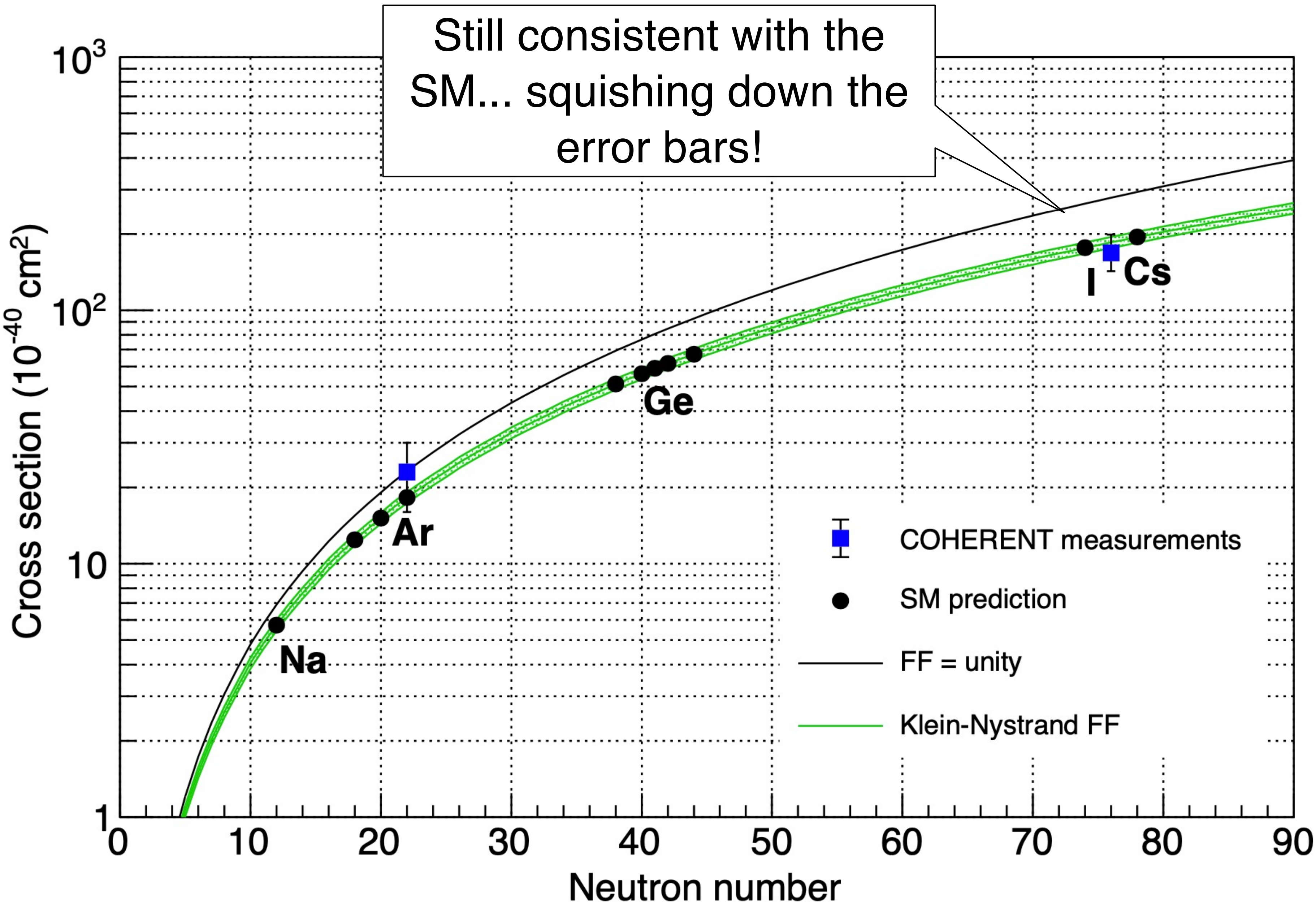
New Constraints on NSI parameters



Remaining CsI[Na] dataset,
with >2 x statistics
+ improved detector response understanding
+ improved analysis



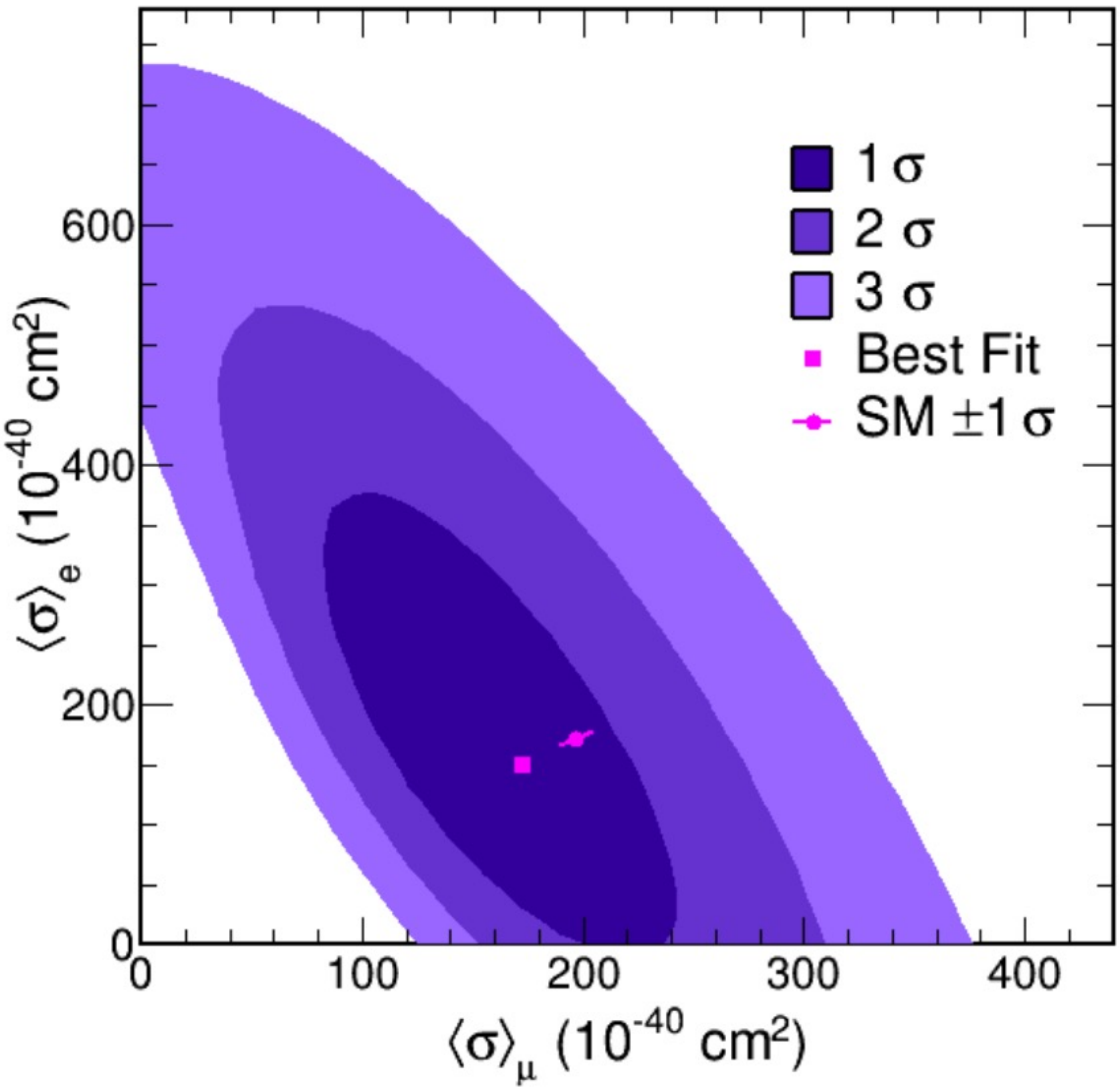
arXiv: 2110.07730



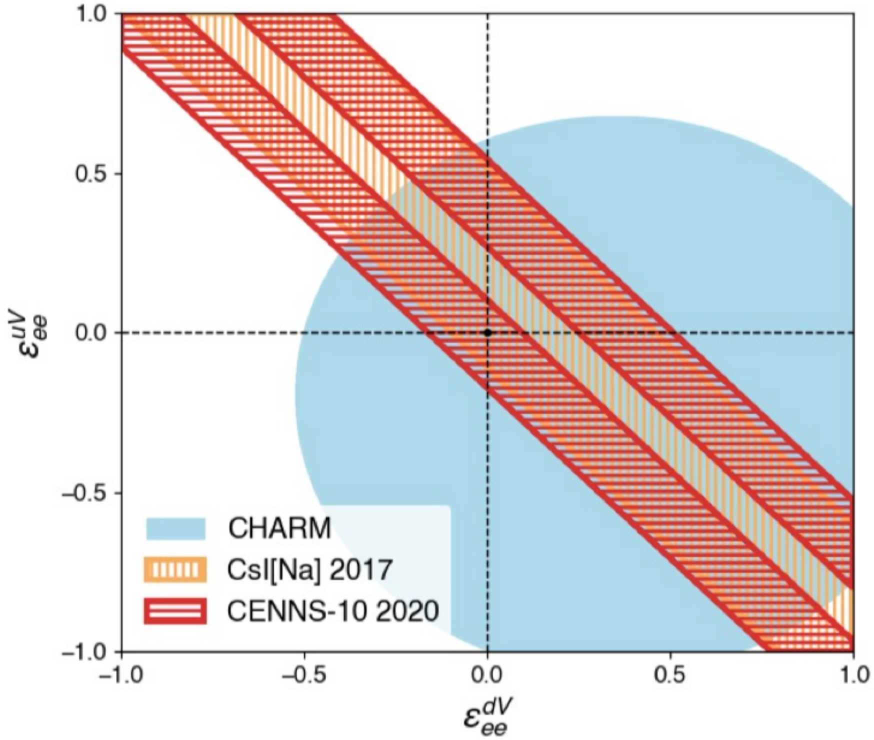
Still consistent with the SM... squishing down the error bars!
Cross section (10^{-40} cm^2)
Neutron number
COHERENT measurements
SM prediction
FF = unity
Klein-Nystrand FF
Na
Ar
Ge
I
Cs

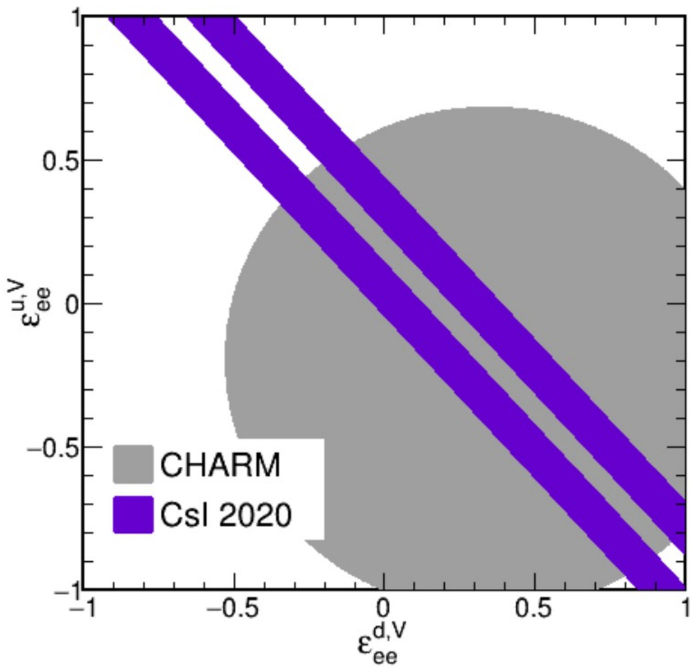
Flavored CEvNS cross sections

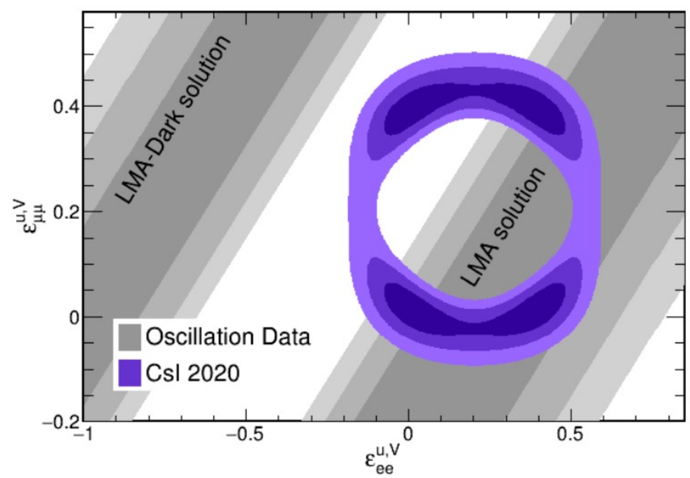
Separate electron and muon flavors by timing



And squeezing down the possibilities for new physics...



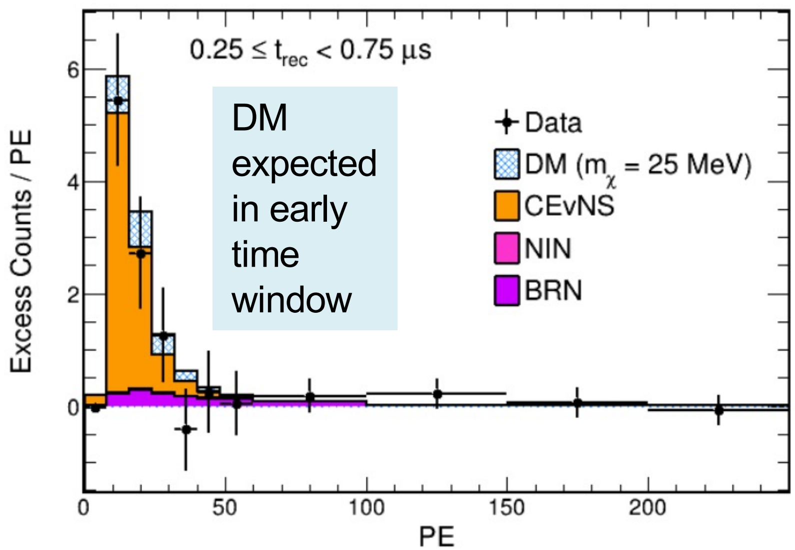


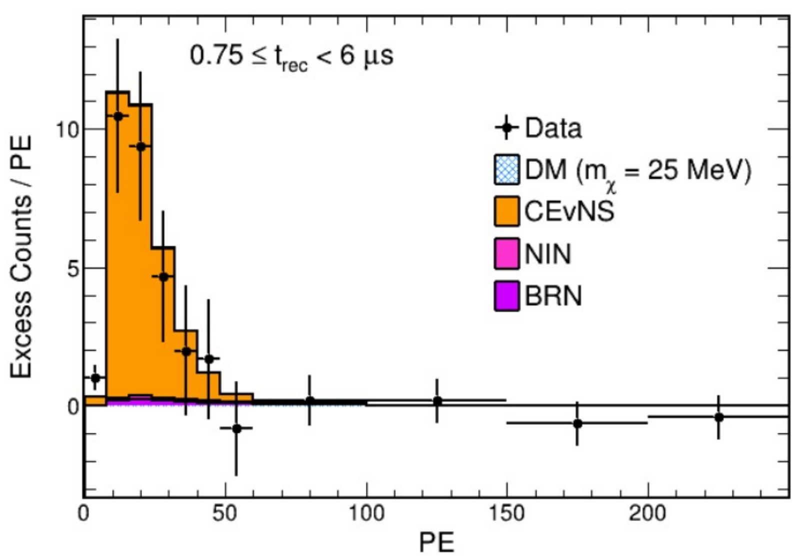


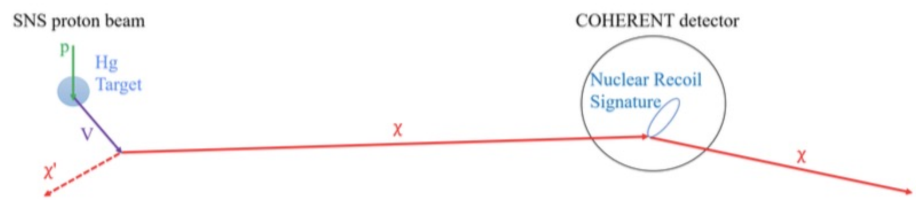
Accelerator-produced DM search

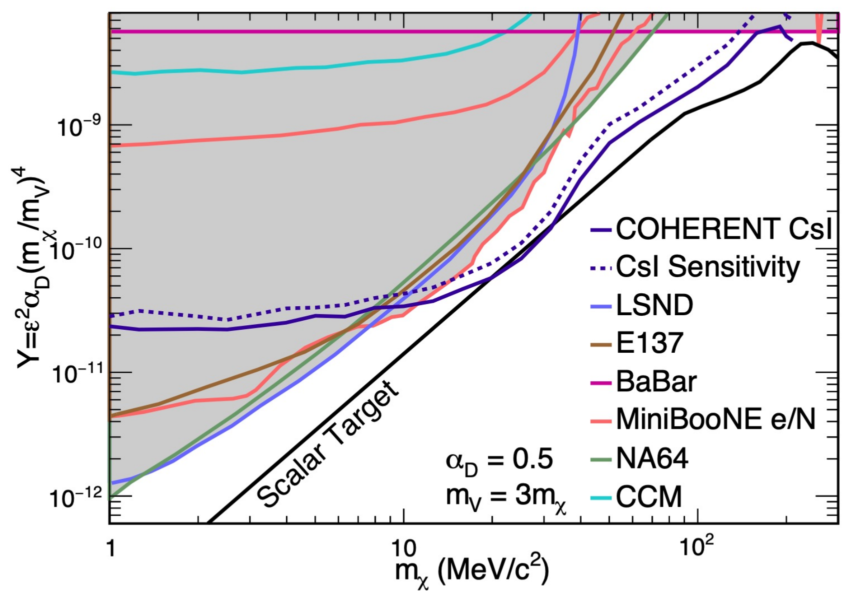
https://indico.phy.ornl.gov/event/126/

arXiv:2110.11453





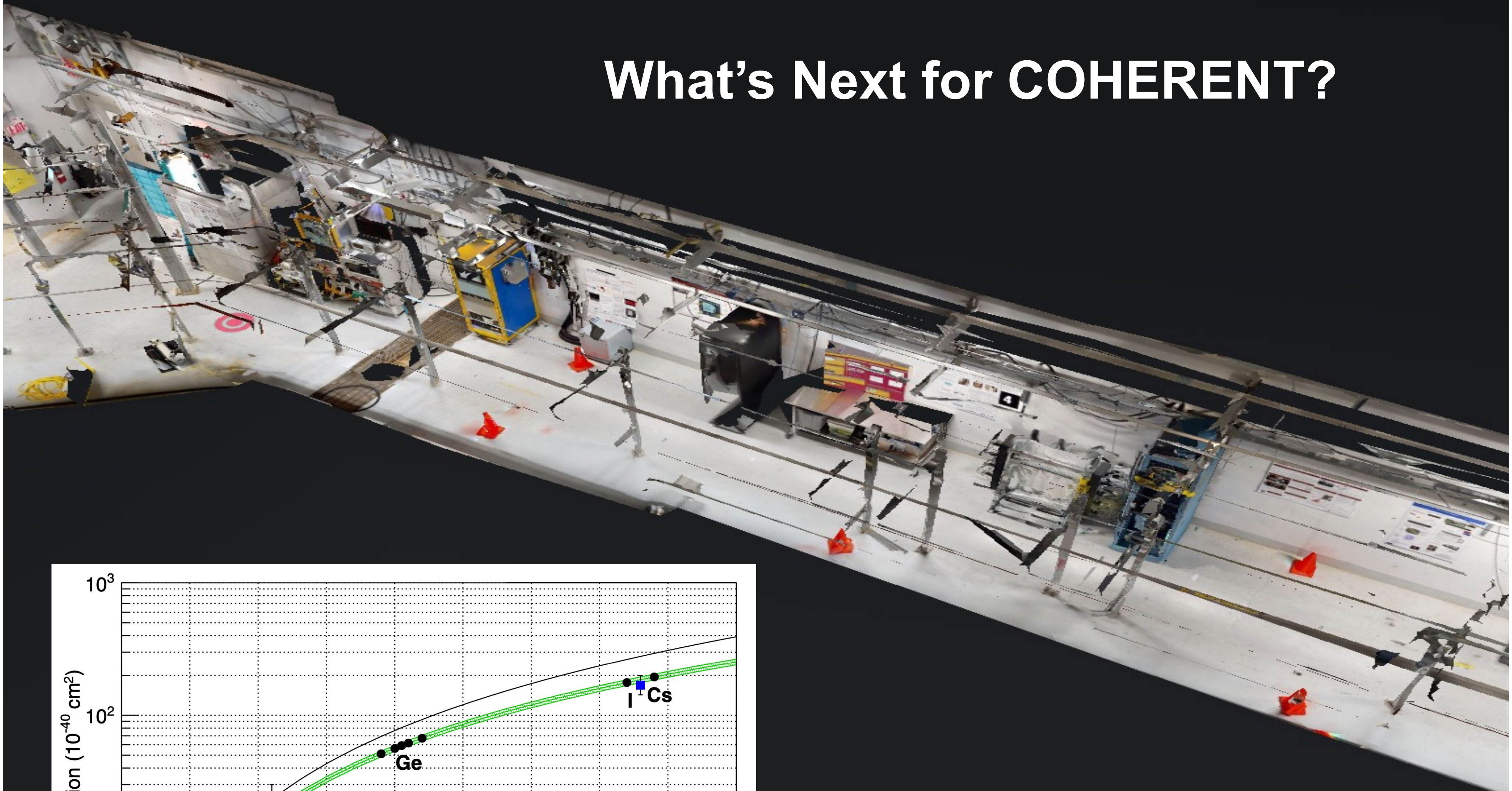


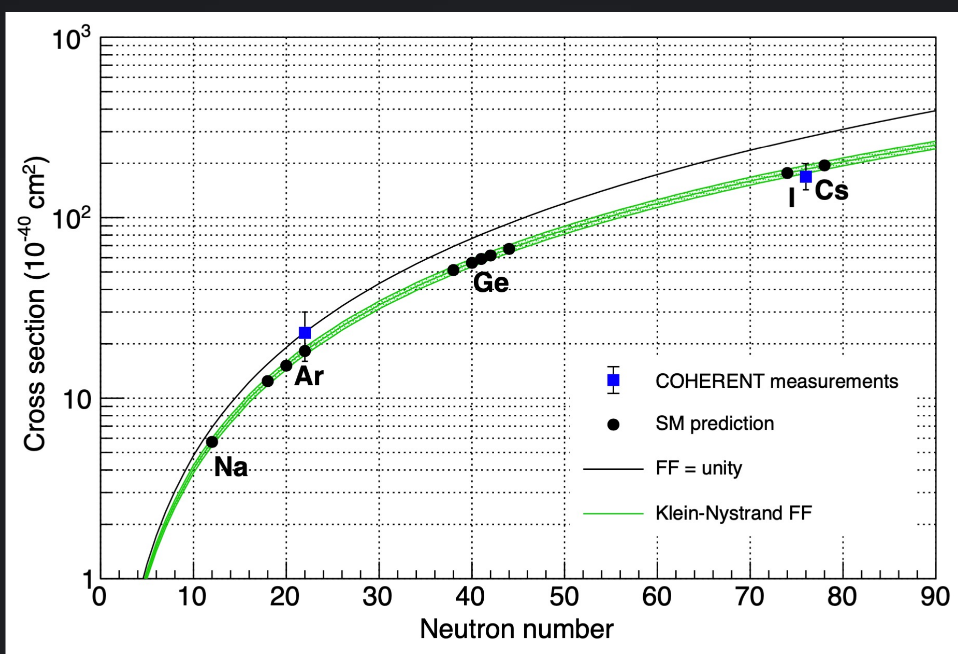


Limits down to cosmological expectation for scalar DM particle

arXiv:2110.11453

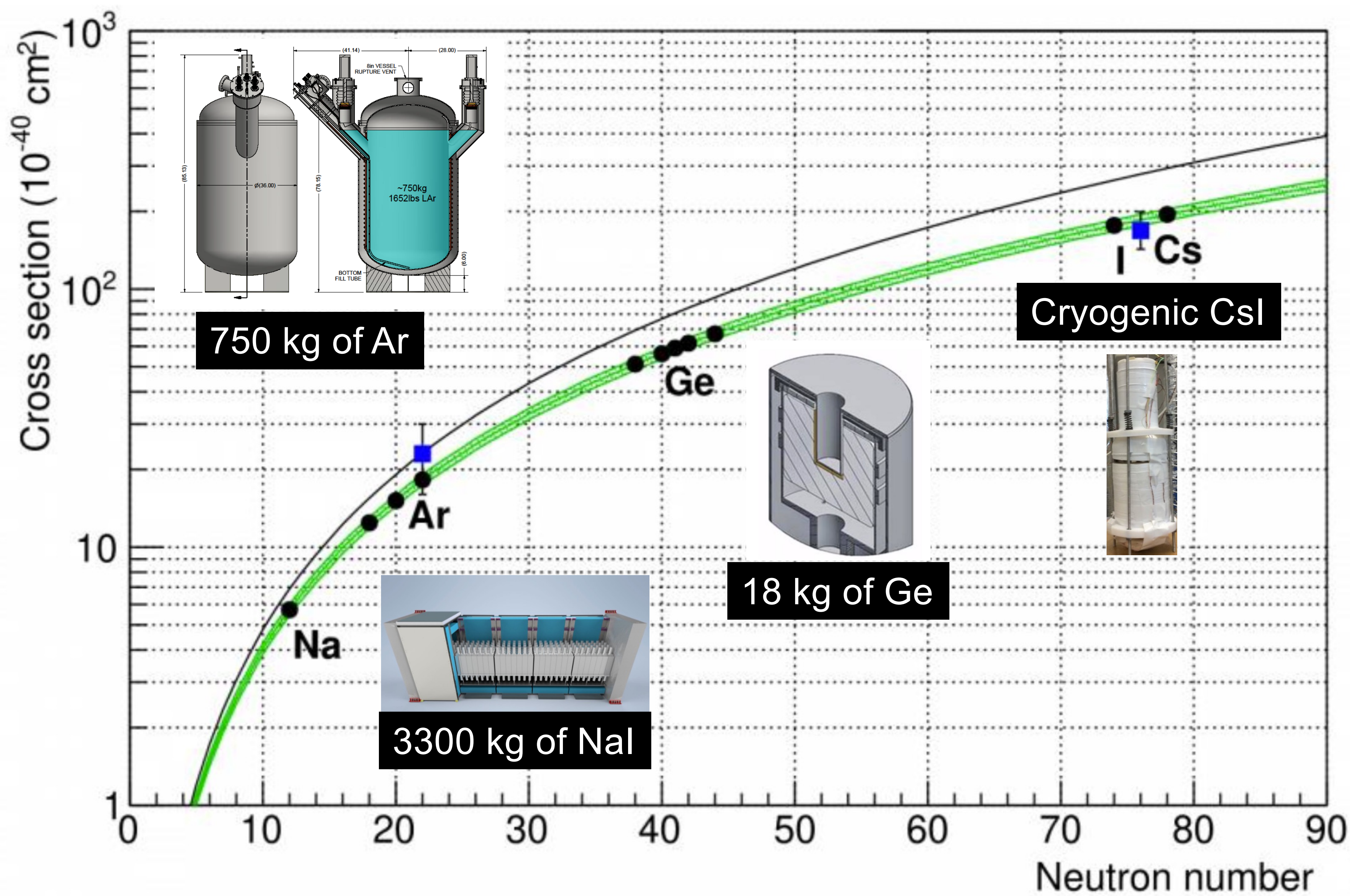
What’s Next for COHERENT?





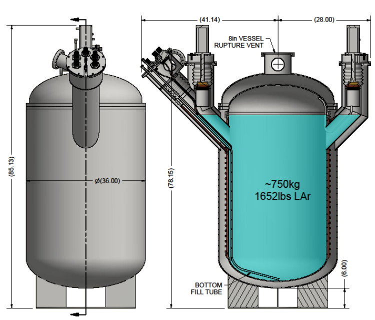
Two down!
But still more
to go!

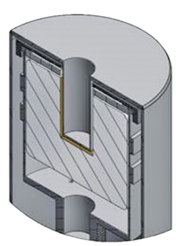
COHERENT future deployments

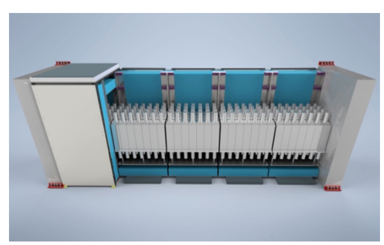


COHERENT **CEvNS** Detector Status and **Farther Future**

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	19.3	6.5	9/2015	Decommissioned
Ge	HPGe PPC	18	22	<few	2022	Funded by NSF MRI, in progress
LAr	Single-phase	24	27.5	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	25	13	2022 *high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes







+D_2O for flux normalization

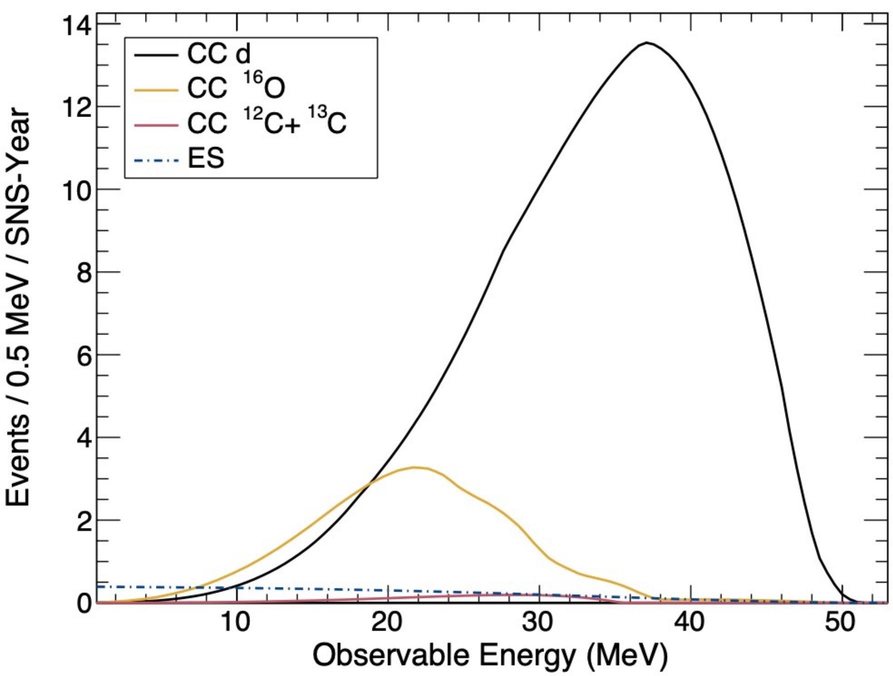
+ CryoCsI

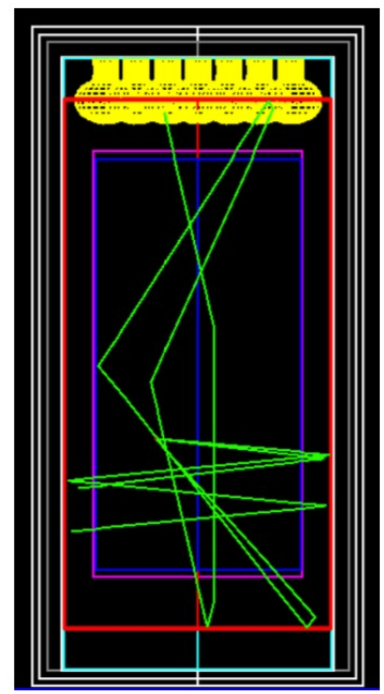
+ concepts for other targets...

Heavy water detector in Neutrino Alley

Dominant current uncertainty is ~10%, on neutrino flux from SNS

$\nu_e + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$ cross section known to ~1-2%

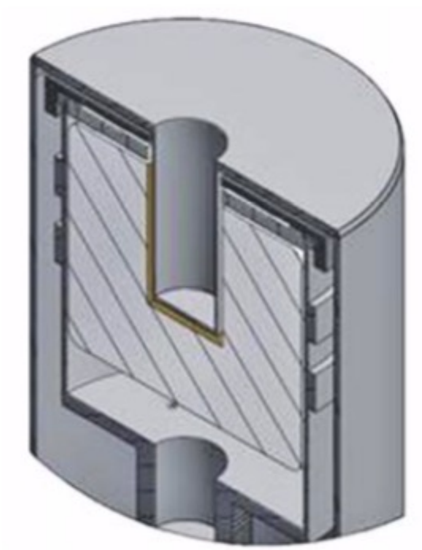




Measure electrons to determine flux normalization

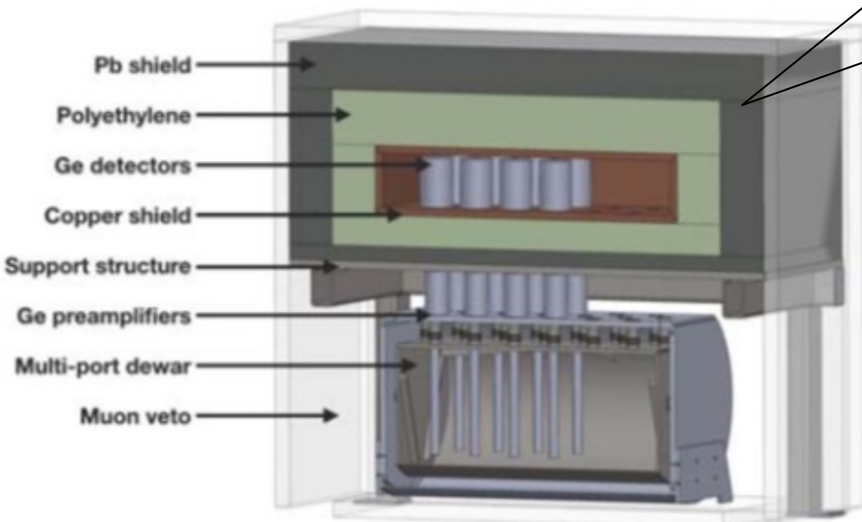
High-Purity Germanium Detectors

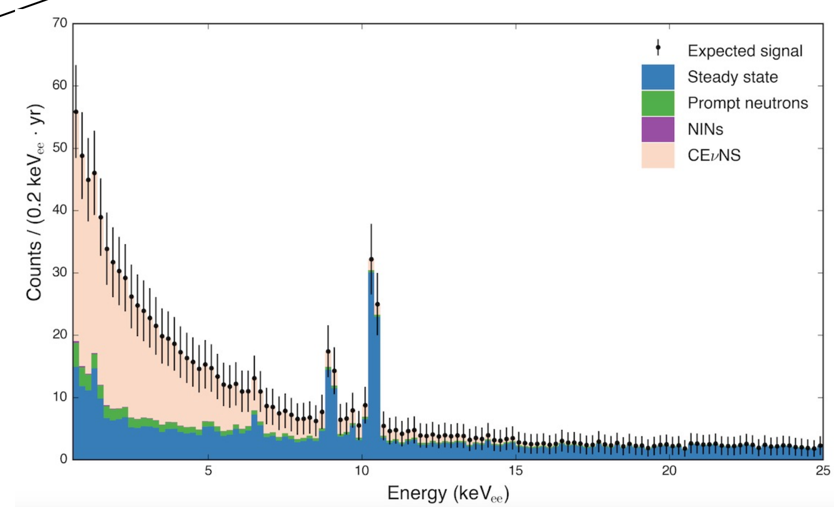
P-type Point Contact



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

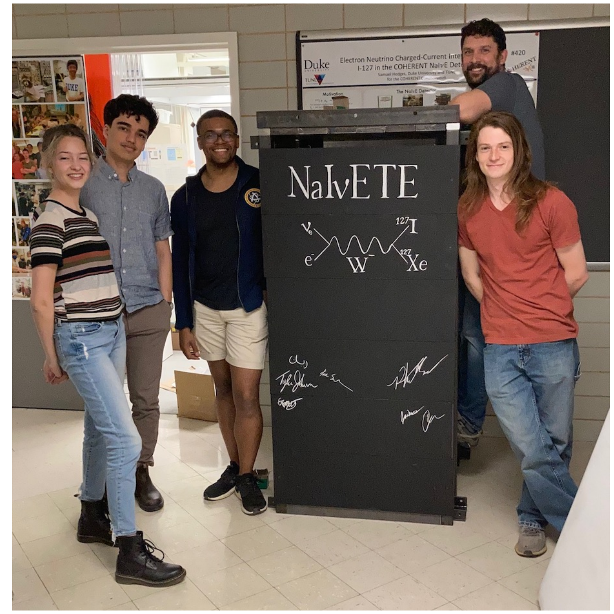
- 8 Canberra/Mirion 2 kg detectors in multi-port dewar
- Compact poly+Cu+Pb shield
- Muon veto
- Designed to enable additional detectors





Sodium Iodide (NaI[Tl]) Detectors

- up to 9 tons available, 3.3 tons in hand
- QF measured
- PMT base refurbishment (dual gain) to enable low threshold for CEvNS on Na measurement



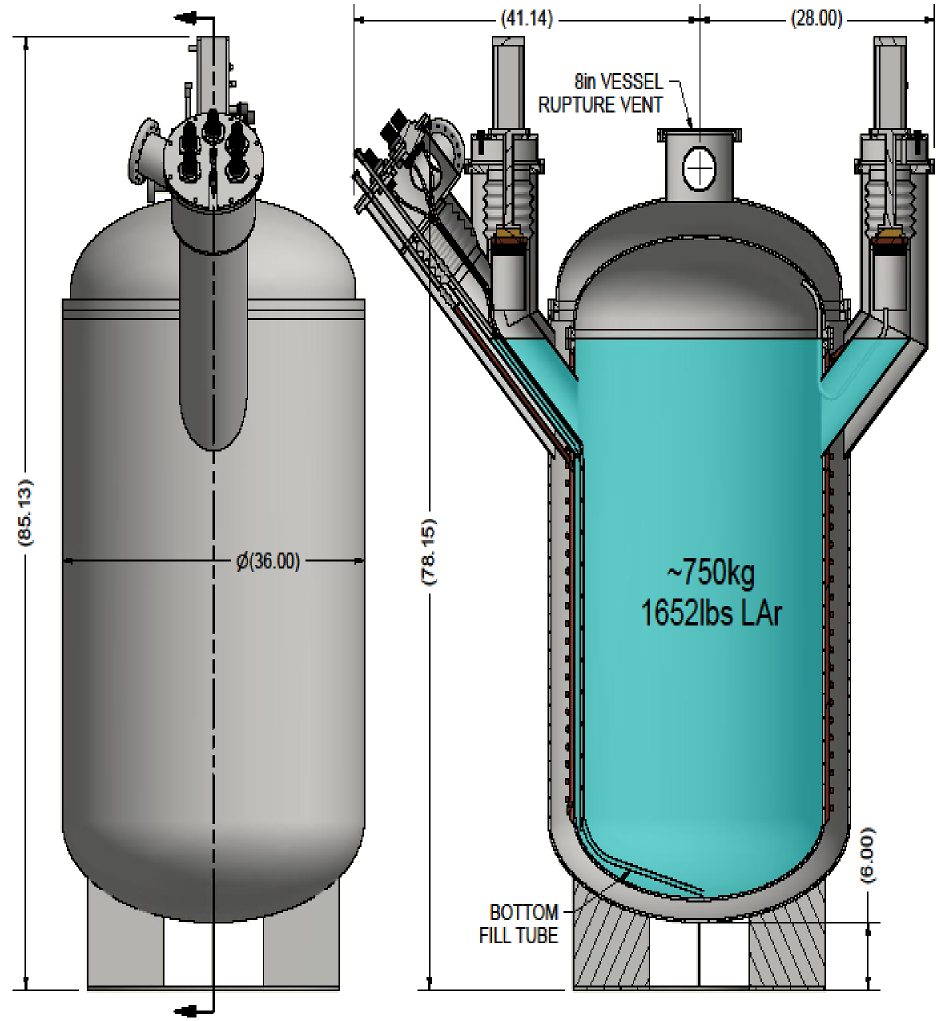
NaIvE: 185 kg deployed at SNS to go after ν_eCC on ^{127}I

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

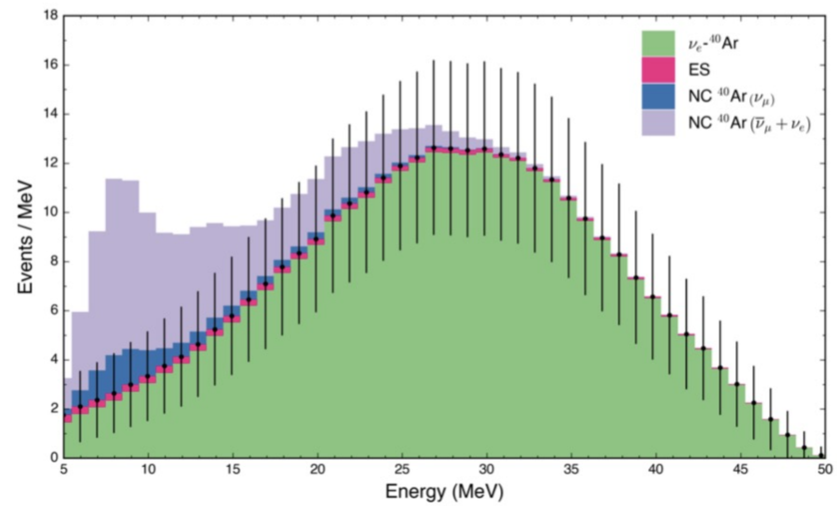
J.A. Formaggio and G. Zeller, RMP 84 (2012) 1307-1341

NaIVETE: 3.3 tonnes for CEvNS + ν_eCC on ^{127}I

Tonne-scale LAr Detector



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

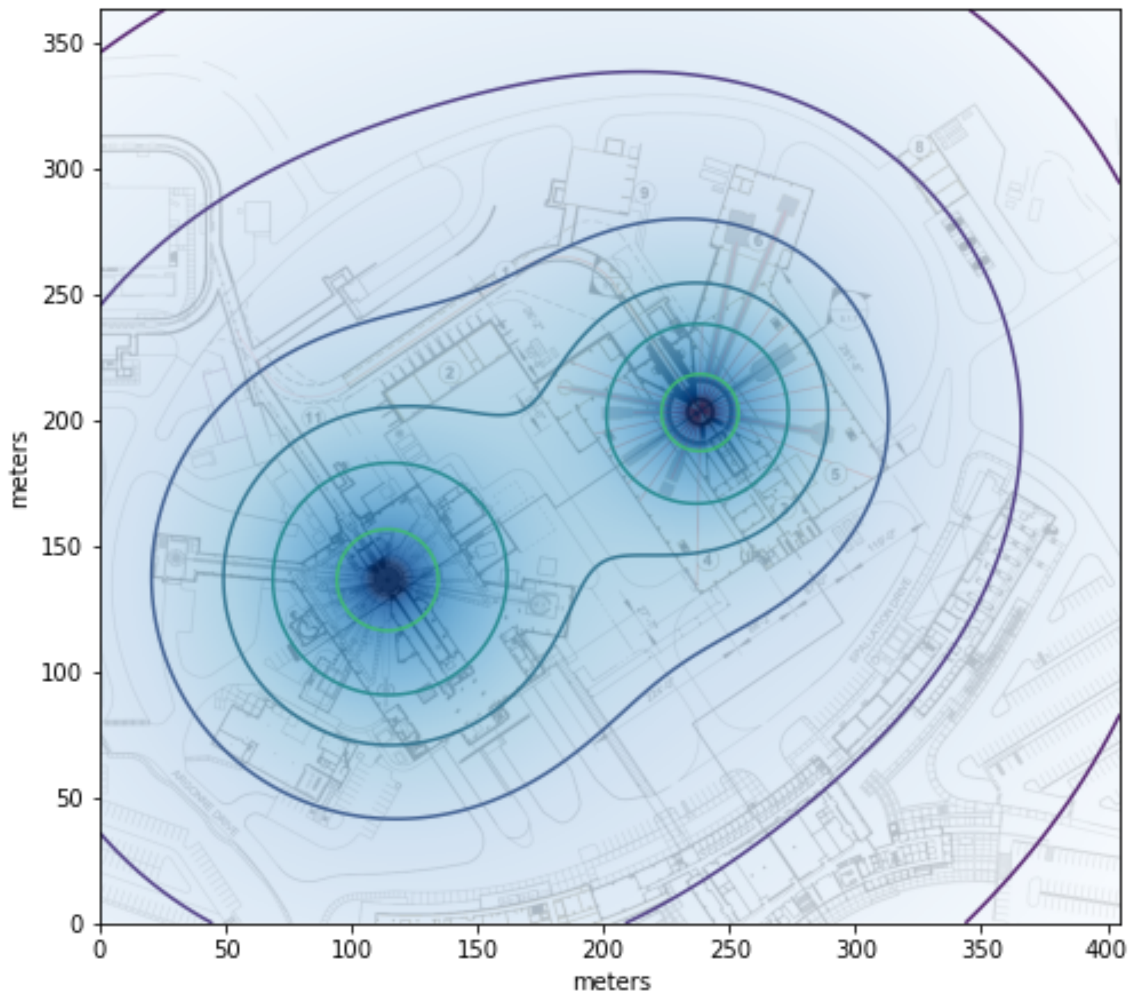


CC/NC **inelastic** in argon of interest for supernova neutrinos

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

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

SNS power upgrade to 2 MW in 2023,
Second Target Station upgrade to 2.8 MW ~2030



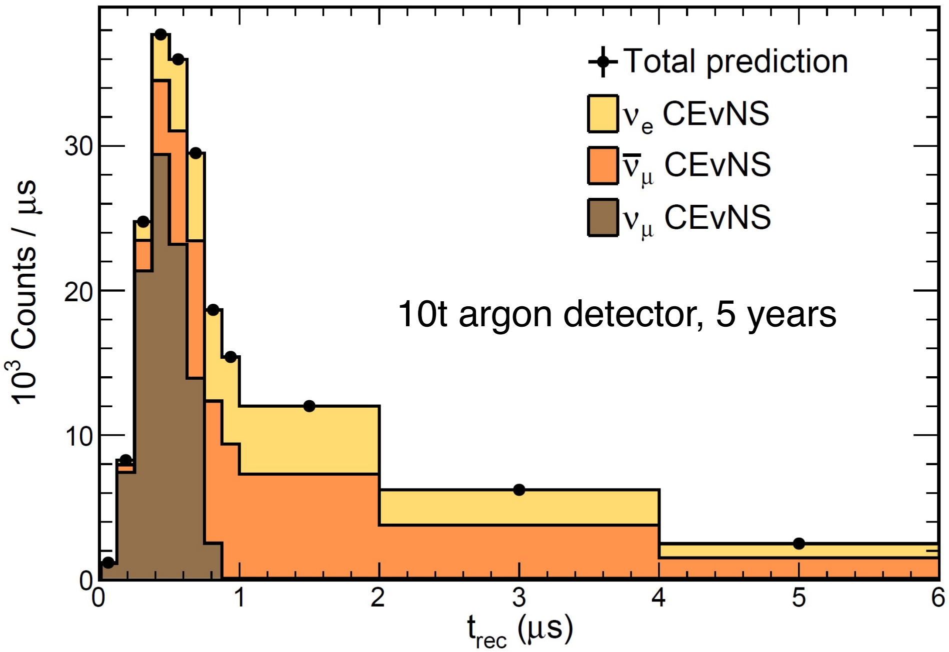
¾ bunches to FTS
¼ bunches to STS

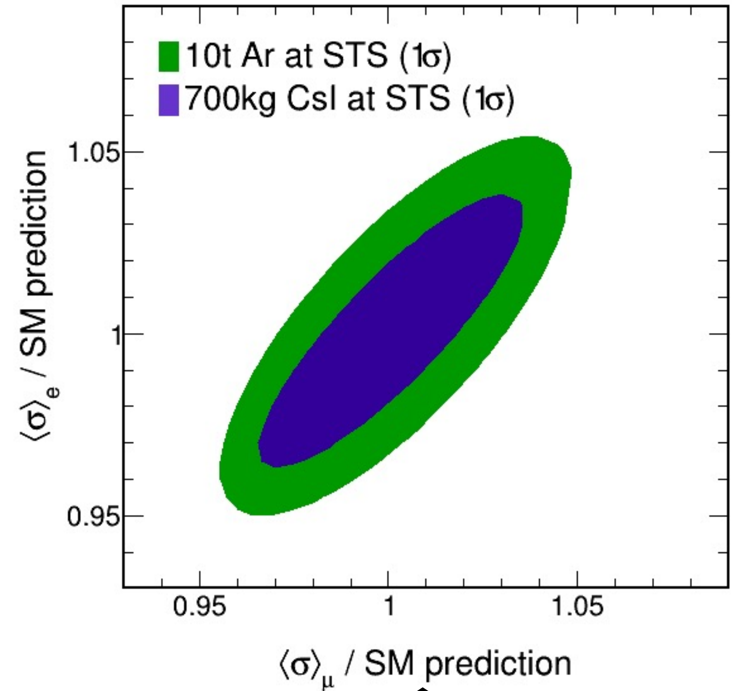
Promising new space available for **~10-tonne scale detectors**

Many exciting possibilities for ν's + DM!

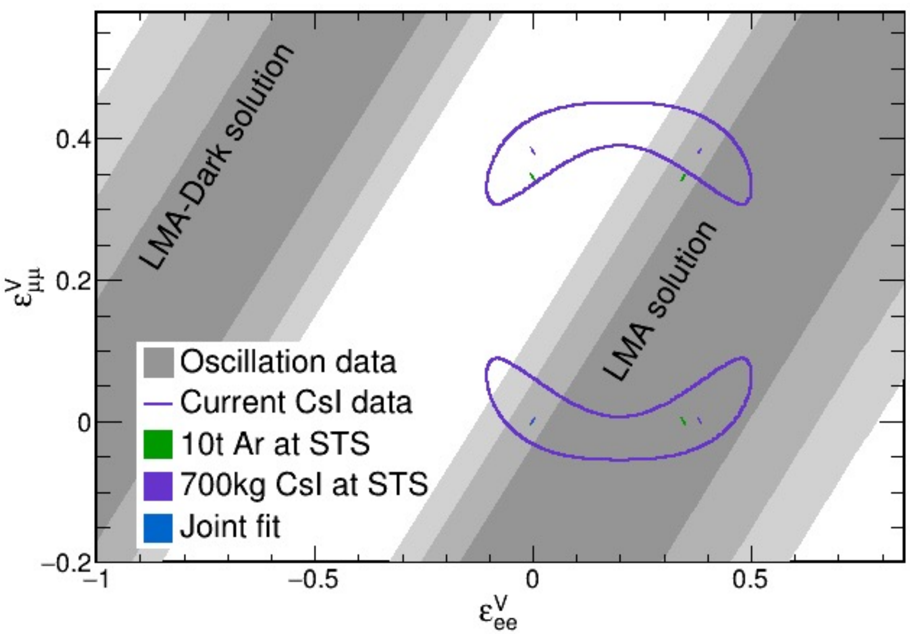
See D. Pershey, APS April 2022 invited talk

Future flavored CEvNS cross section measurements





Sensitive to ~few % SM differences in μ- and *e*-flavor cross sections, testing lepton universality of CEvNS (at tree level)

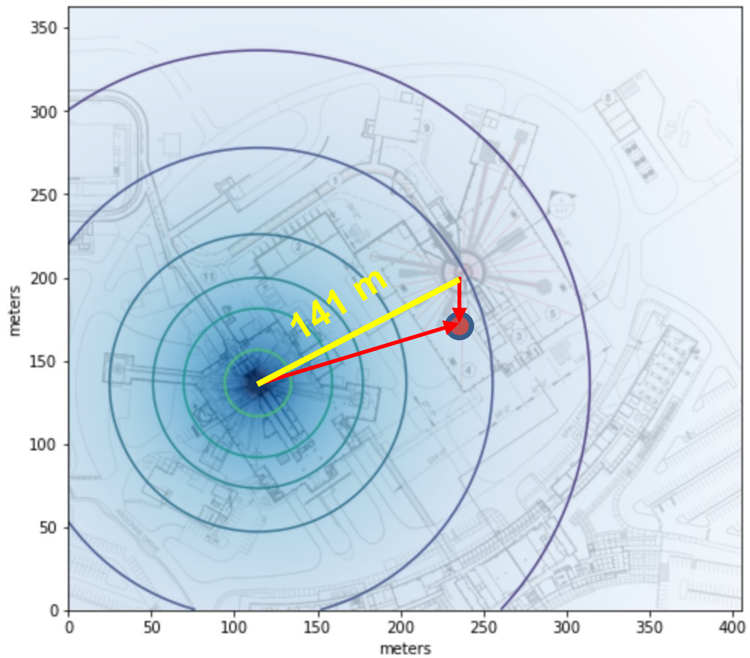


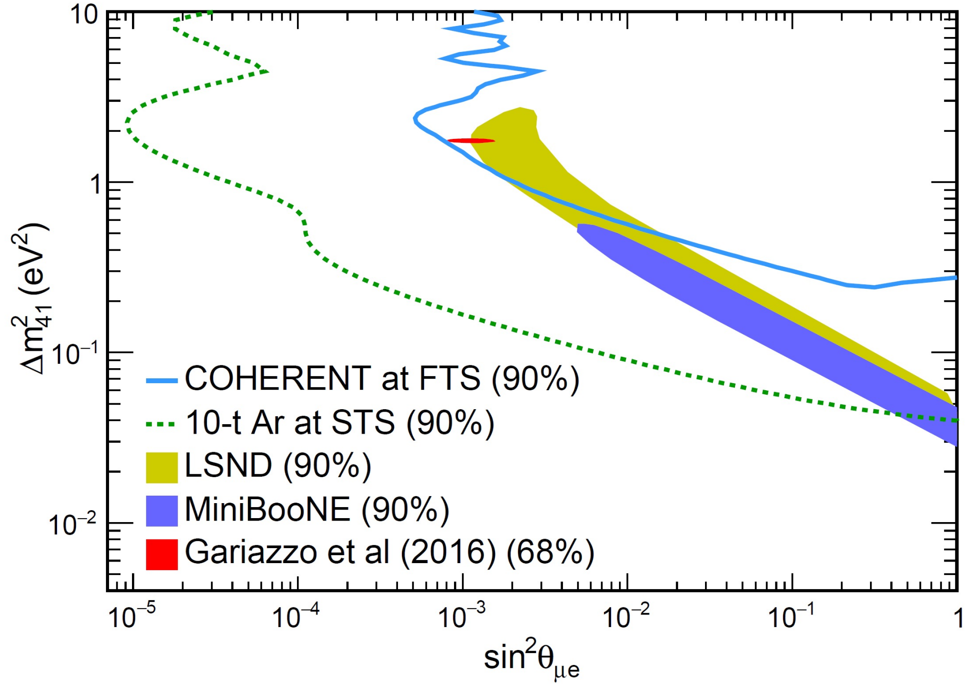
Stringent NSI parameters constraints, resolving oscillation ambiguities

Sterile neutrino sensitivity

$$1 - P(\nu_e \to \nu_s) = 1 - \sin^2 2\theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$1 - P(\nu_\mu \to \nu_s) = 1 - \cos^4 \theta_{14} \sin^2 2\theta_{24} \cos^2 \theta_{34} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$





Cancel detector-related systematic uncertainties
w/ different baselines in one CEvNS detector seeing 2 sources

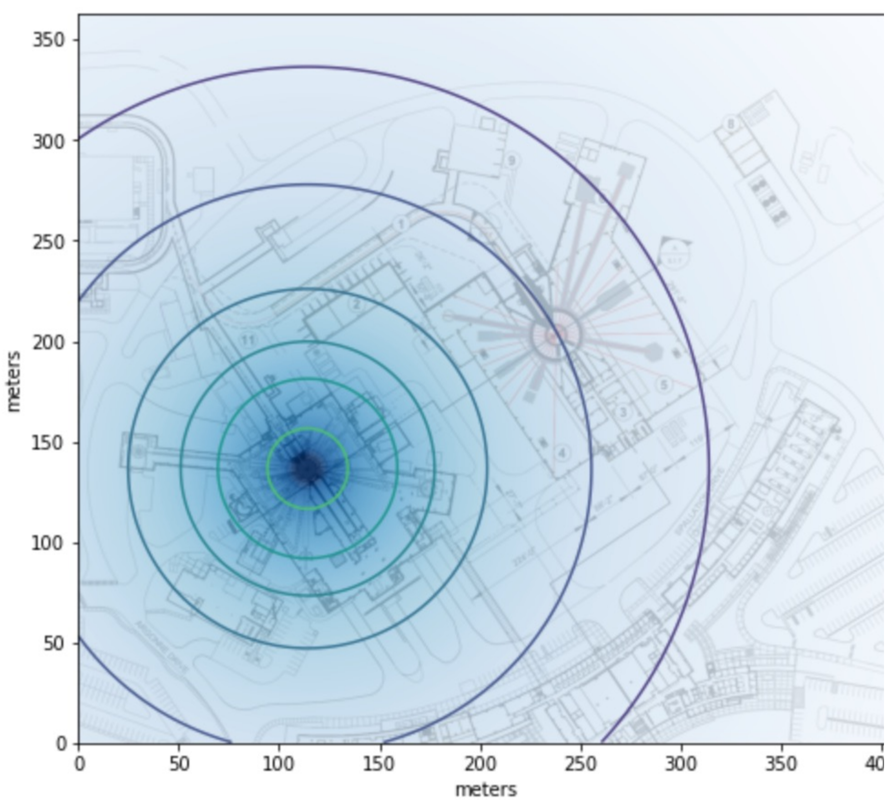
Can also exploit flavor separation by timing

Assume L_{STS} = 20 m and L_{FTS} = 121 m, 10-t argon CEvNS detector

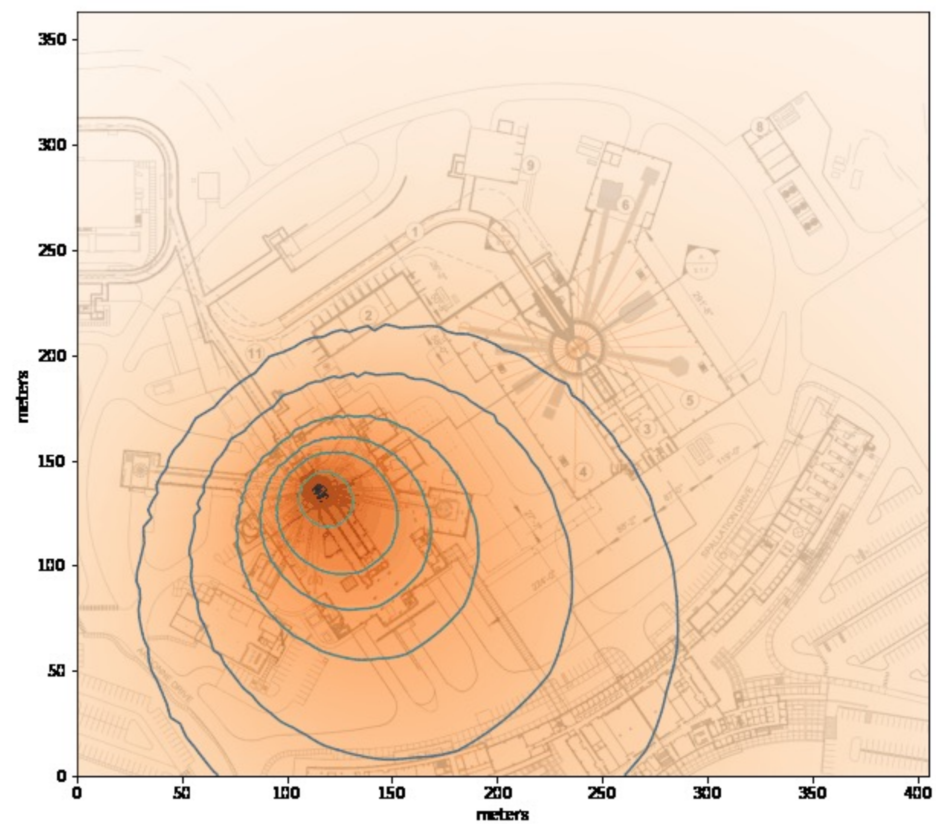
In 5 years, test ~entire parameter space allowed by LSND/MiniBooNE

Directionality of flux at the SNS

Neutrino flux
from pion decay at rest
is **isotropic**

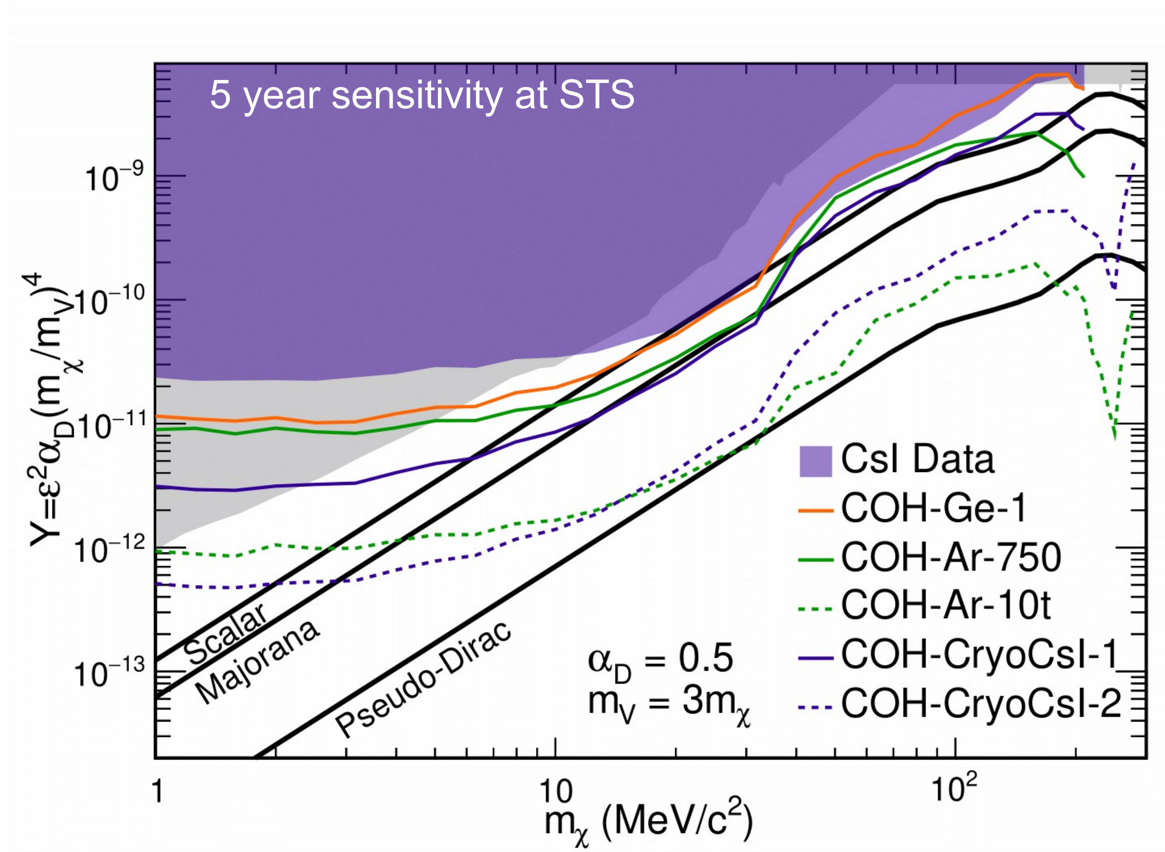


DM flux produced in-flight
is **boosted forward**



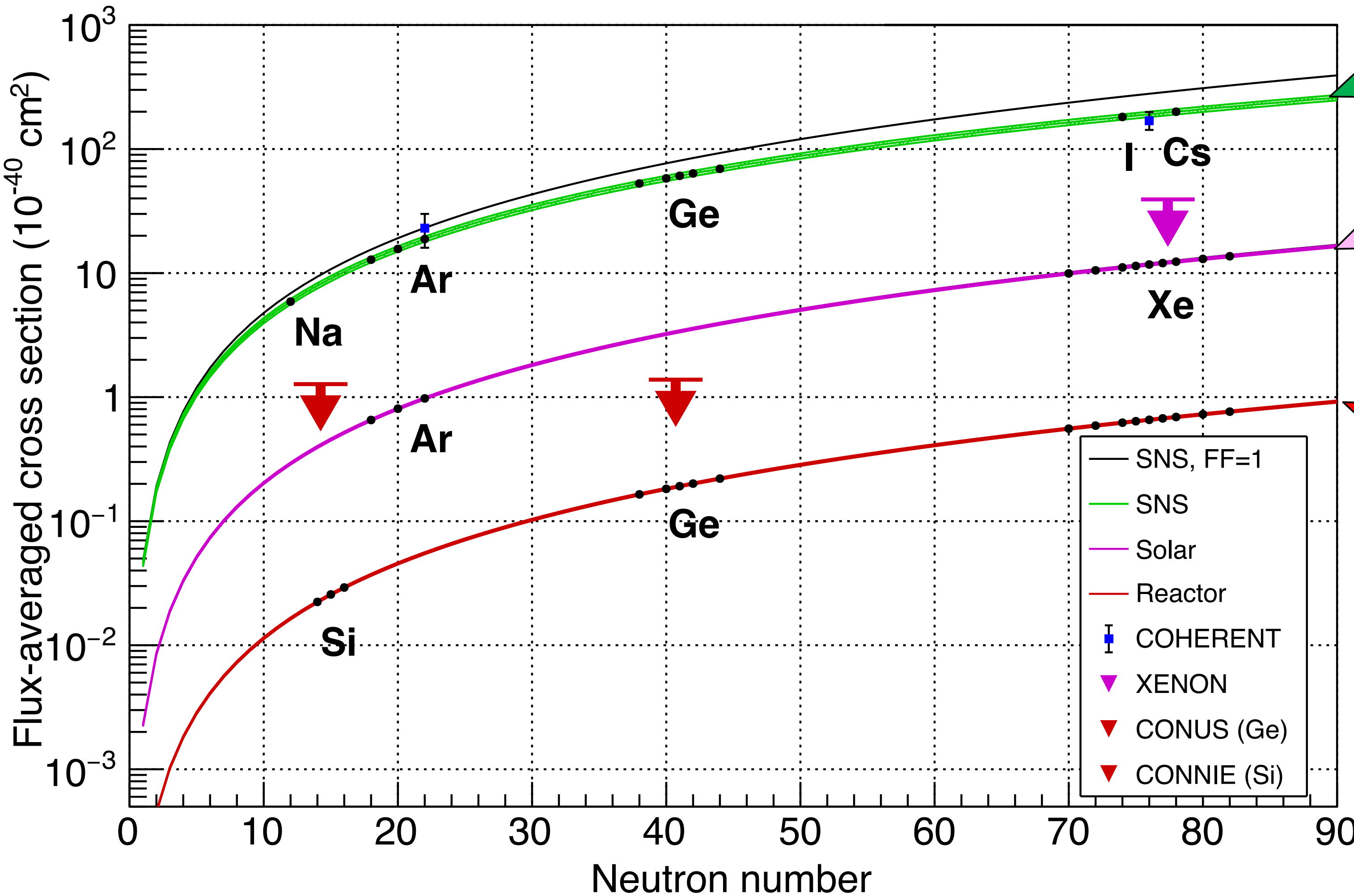
Can test angular dependence of boosted DM flux

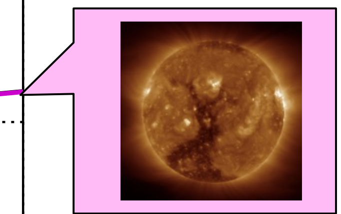
Future COHERENT sensitivity to dark matter

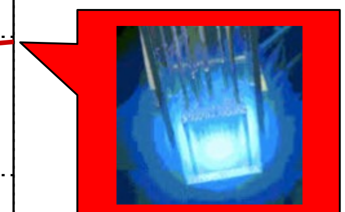


- **Short term:** Ge detector will explore scalar target at lower masses
- **Medium term**: large Ar, CsI detectors to lower DM flux sensitivity, probe of Majorana fermion target
- **Longer term:** large detectors placed forward at the STS (dashed lines) will test even pessimistic scenarios

Summary of CEvNS Results



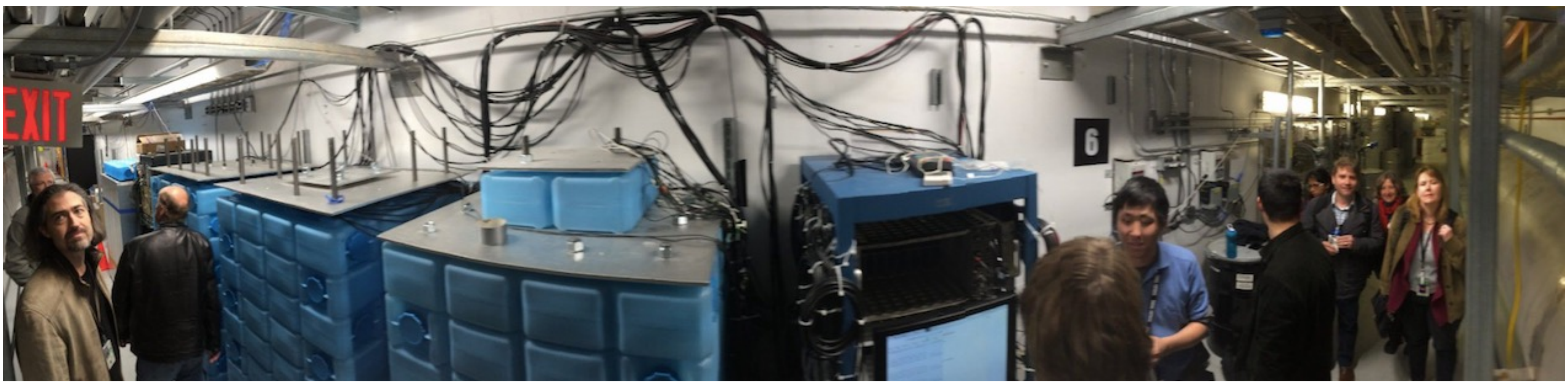




Limits on reactor CEvNS in Ge, Si... looking forward to more soon!

Summary

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



- **It's still just the beginning....** more NaI+Ge soon
- Multiple targets, upgrades and new ideas in the works!
- New exciting opportunities with more SNS power + STS!
- Other CEvNS experiments are joining the fun!
  (CCM, TEXONO, CONUS, CONNIE, MINER, RED, Ricochet, NUCLEUS, NEON, SBC...)