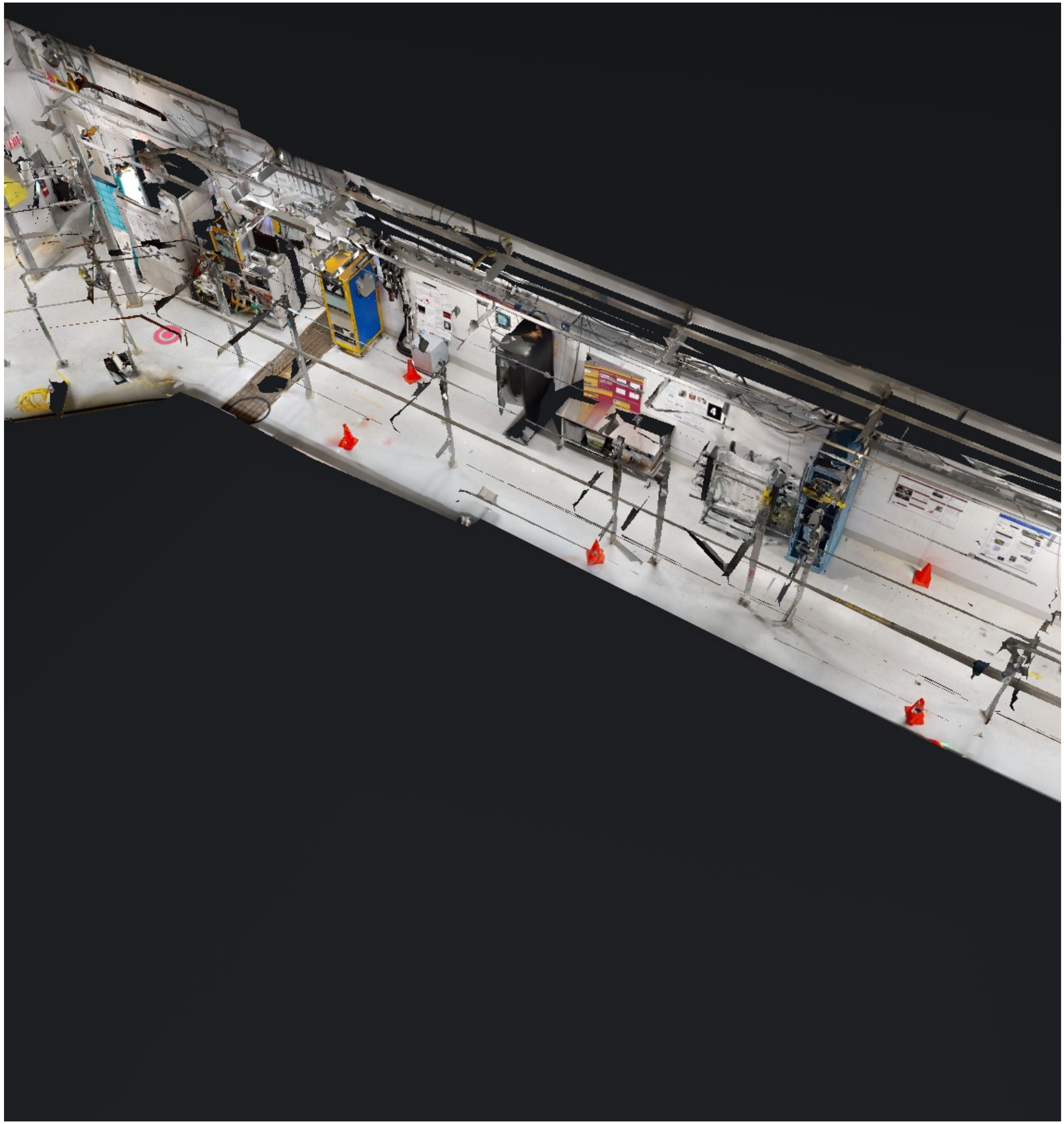
COHERENT Elastic Neutrino-Nucleus Scattering

Kate Scholberg,

Duke University

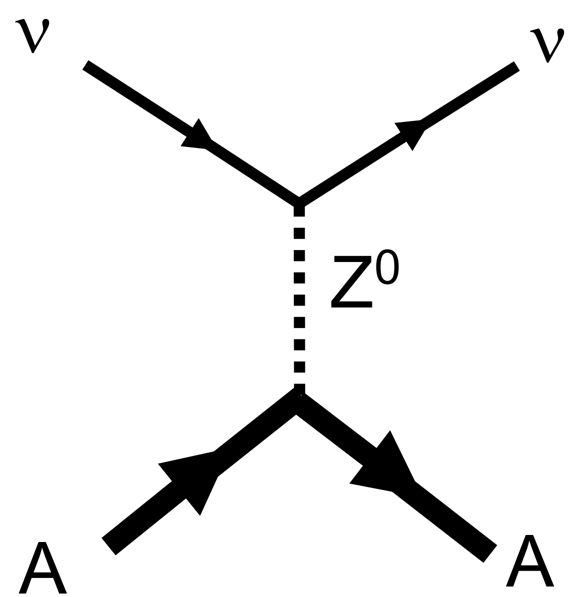
EDSU 2022
November 8, 2022

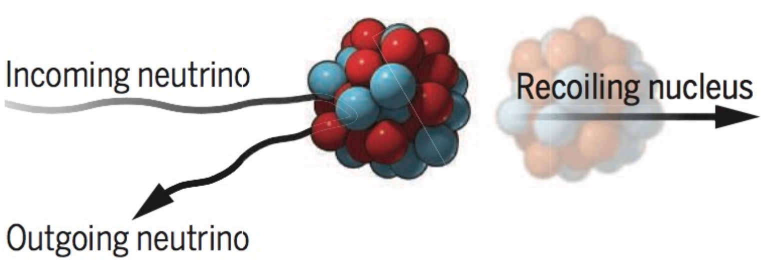


Coherent elastic neutrino-nucleus scattering (CEvNS)

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

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



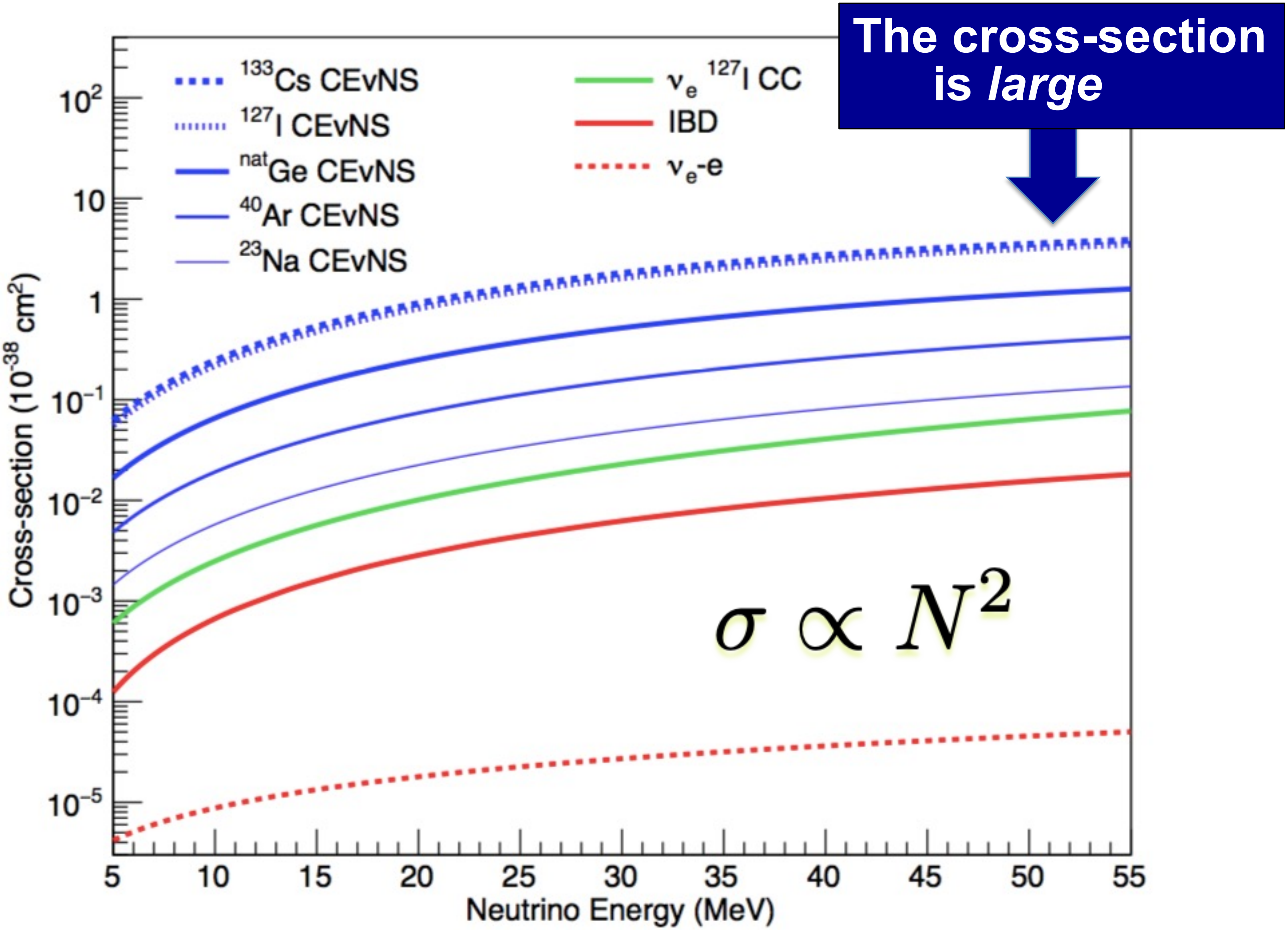


Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

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

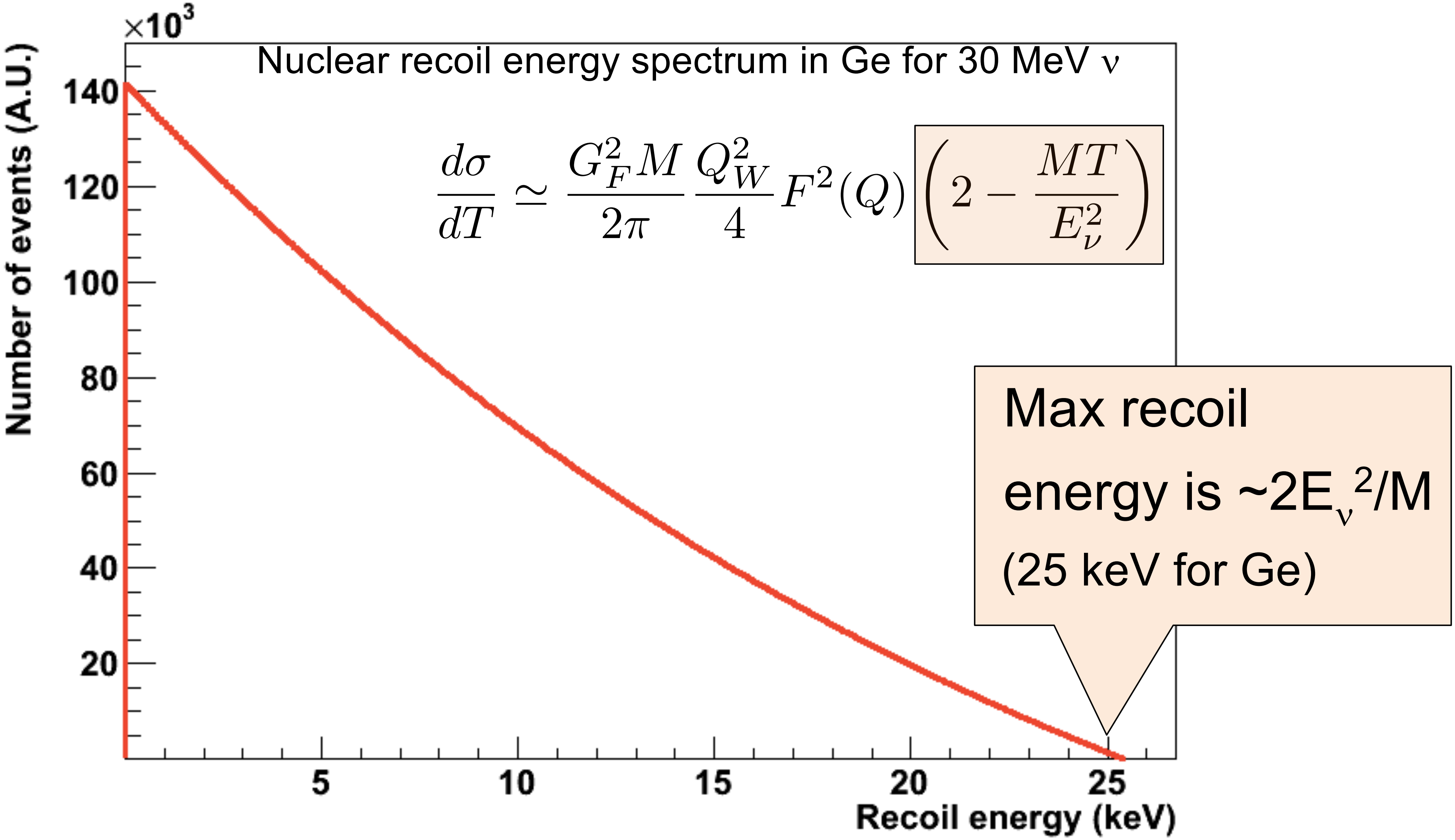
A: no. of constituents

Image: J. Link *Science* Perspectives



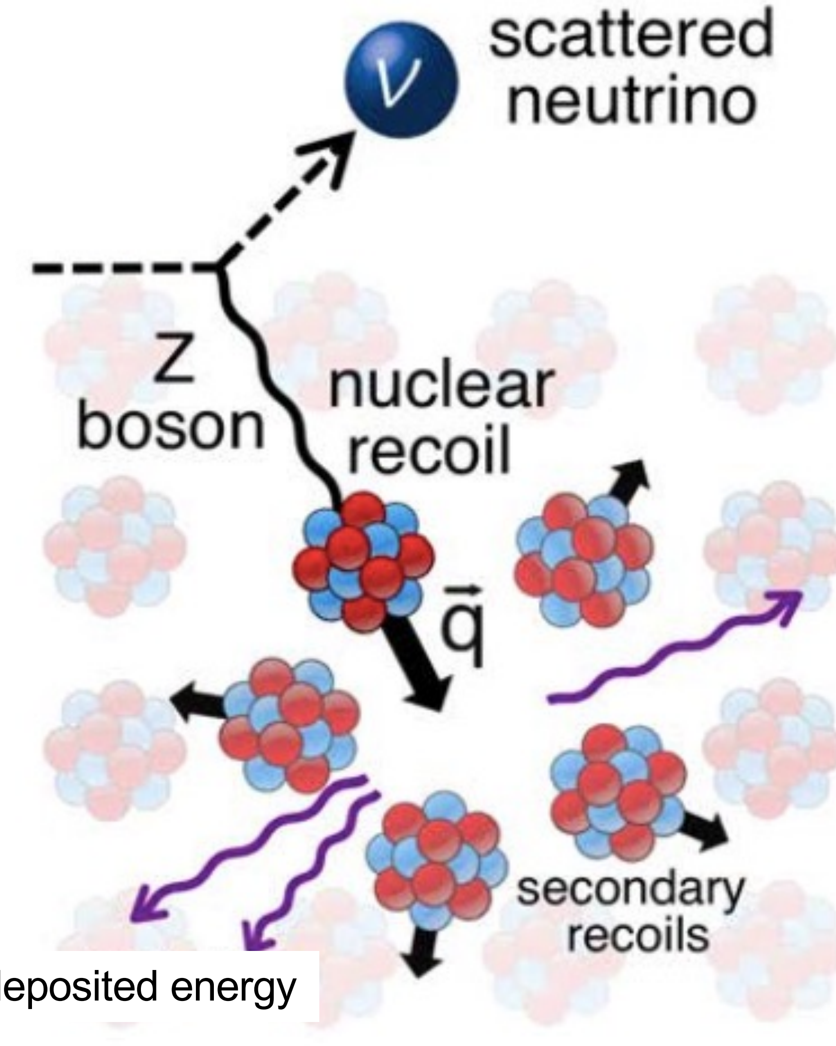
The cross-section is *large*
^{133}Cs CEvNS
^{127}I CEvNS
^{nat}Ge CEvNS
^{40}Ar CEvNS
^{23}Na CEvNS
ν_e ^{127}I CC
IBD
ν_e-e
Cross-section (10^{-38} cm^2)
Neutrino Energy (MeV)
$\sigma \propto N^2$

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



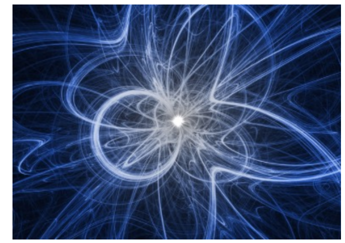
➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

CEvNS: what's it good for?

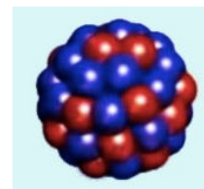
!

(not a complete list!)

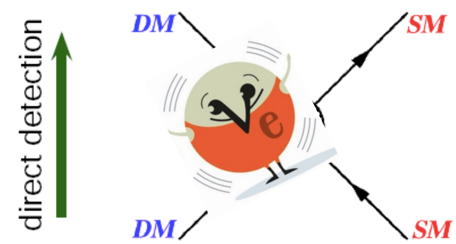
CEvNS as a **signal**
for signatures of *new physics*



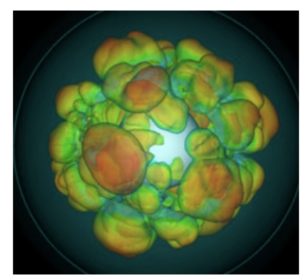
CEvNS as a **signal**
for understanding of "old" physics



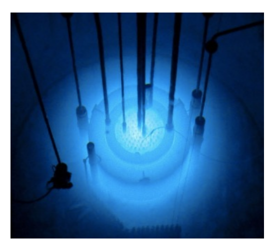
CEvNS as a **background**
for signatures of new physics



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



CEvNS as a **practical tool**



CEvNS: what's it good for?

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

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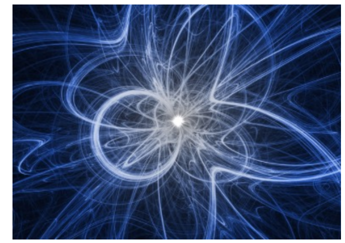

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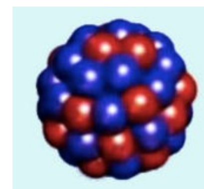

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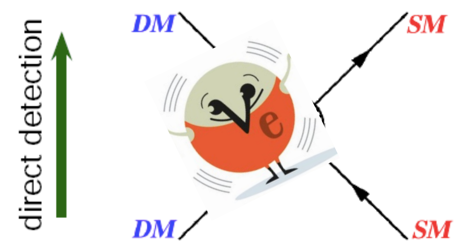

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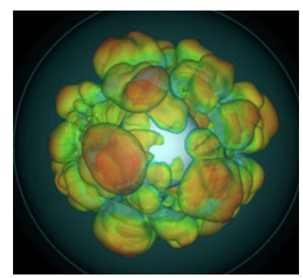

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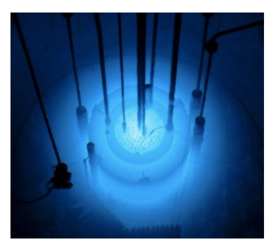
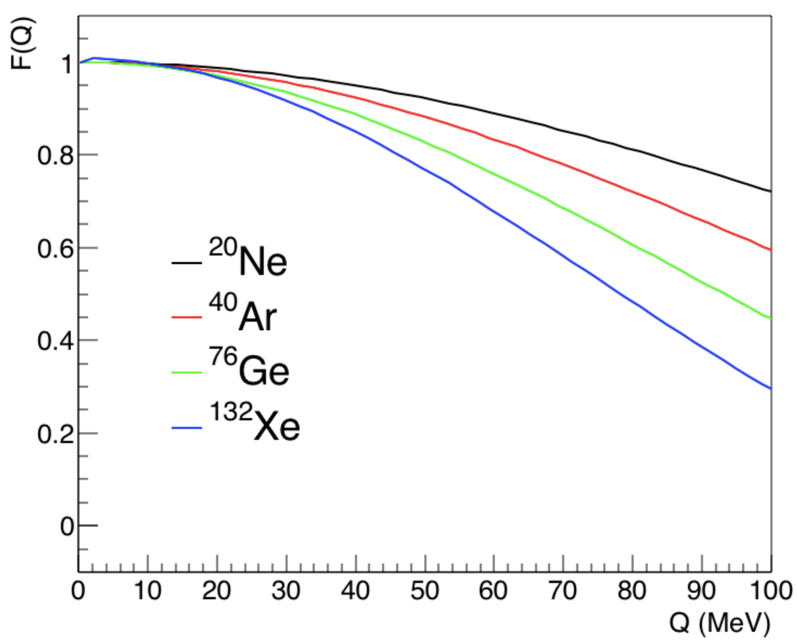


The cross section is cleanly predicted in the Standard Model

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

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

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

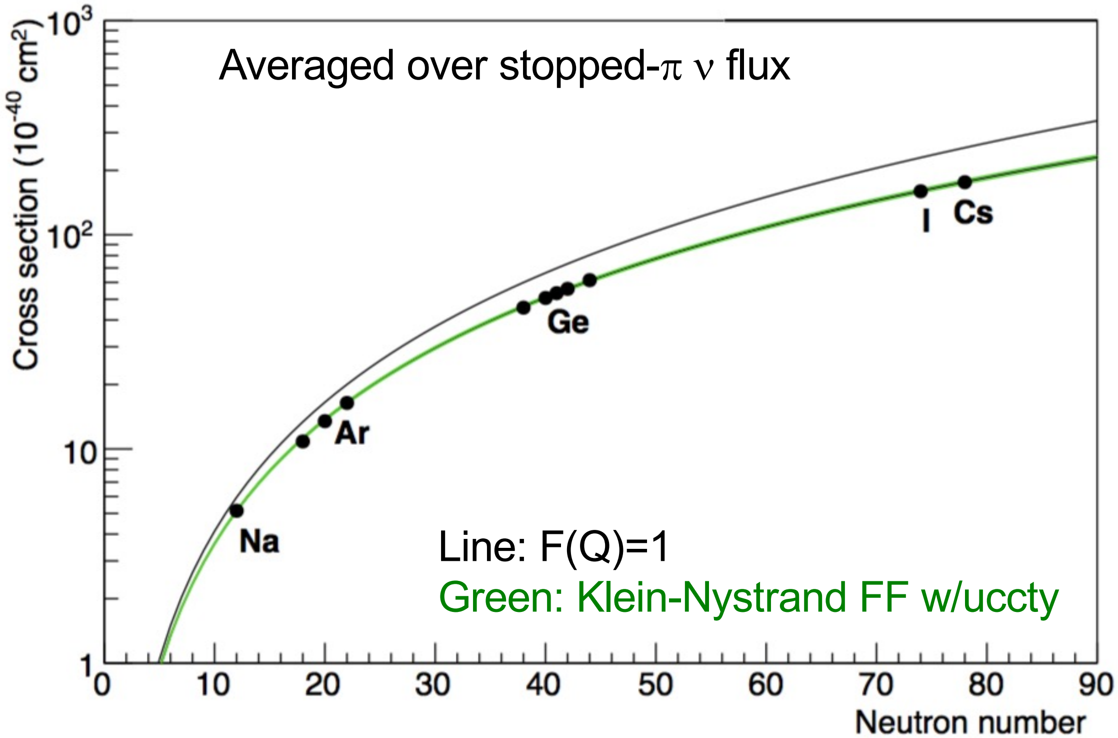


form factor suppresses cross section at large Q

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

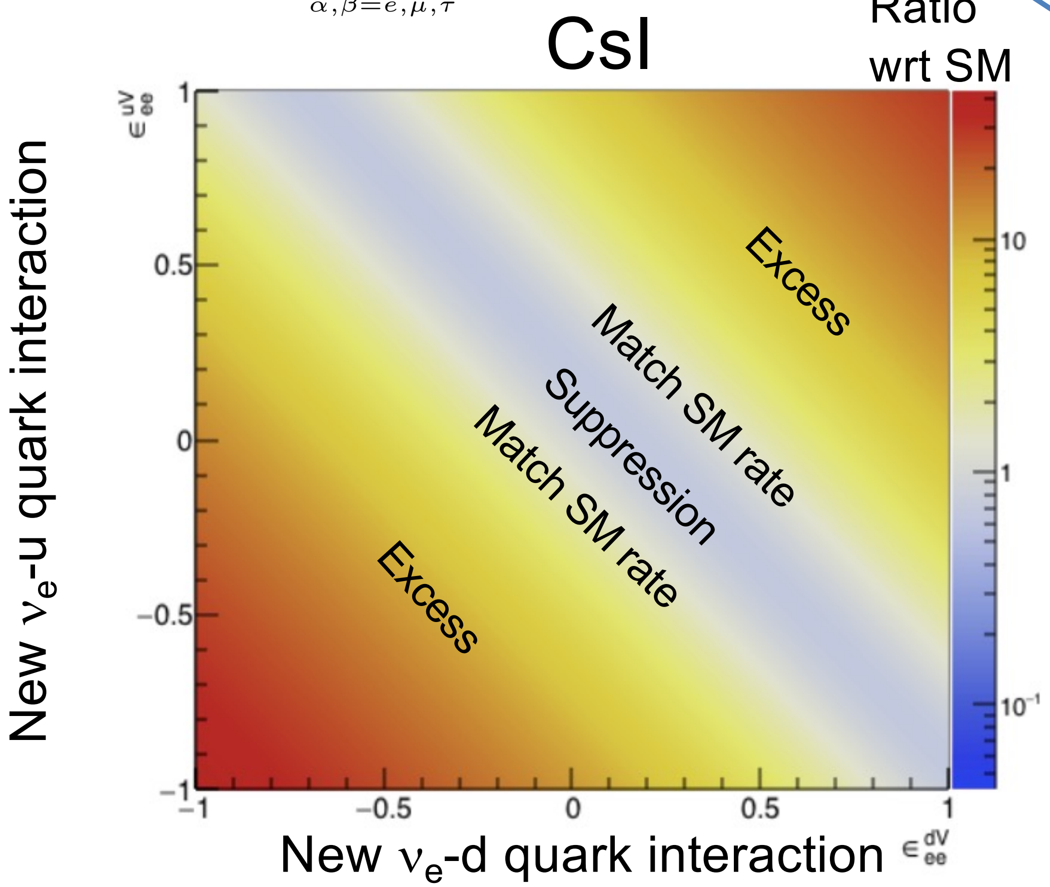


A deviation from α N^2 prediction can be a signature of beyond-the-SM physics

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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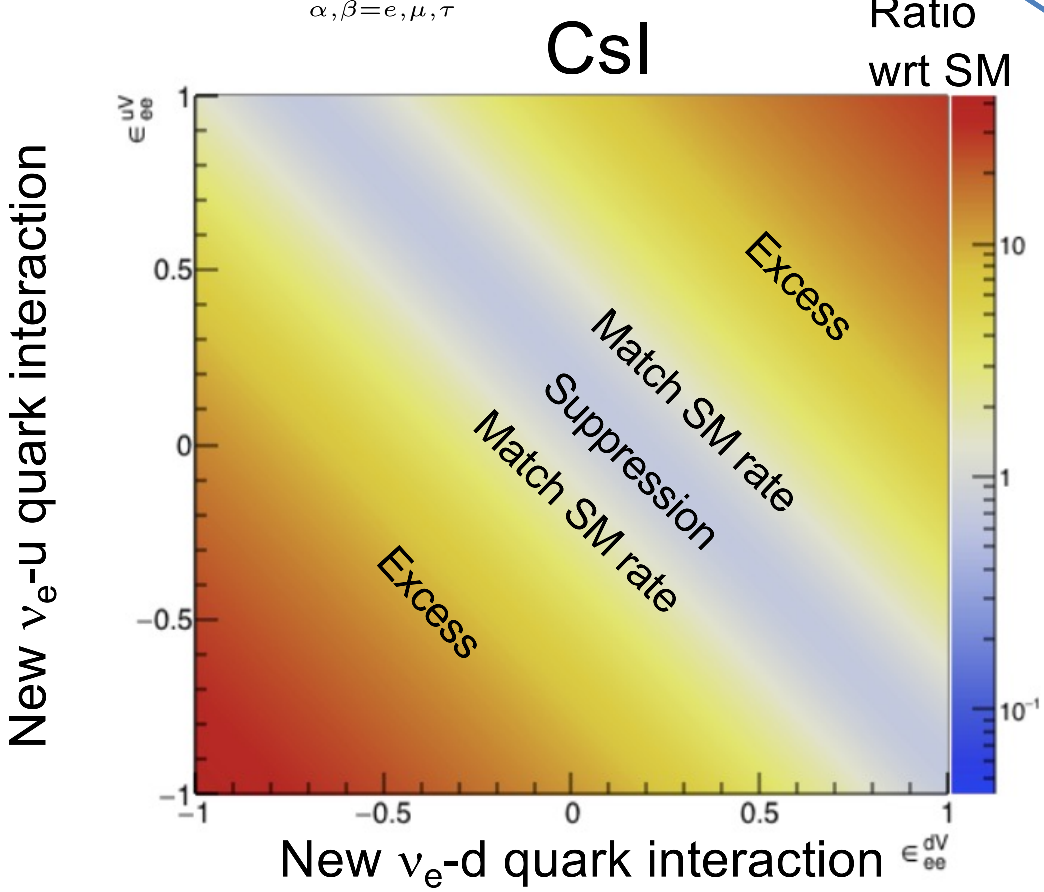

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Observe less or more CEvNS than expected?
...could be beyond-the-SM physics!

Other new physics results in a *distortion of the recoil spectrum* (Q dependence)

BSM Light Mediators

SM weak charge

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

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

CEvNS: what's it good for?

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③ Things
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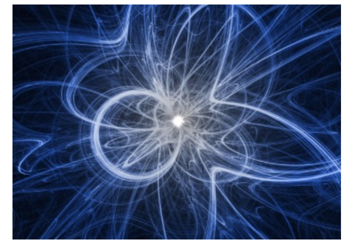
(not a complete list!)

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



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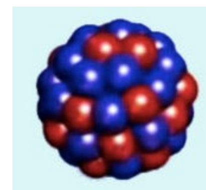
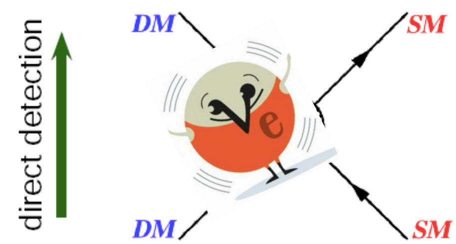
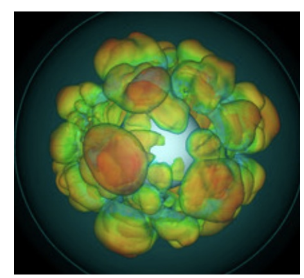


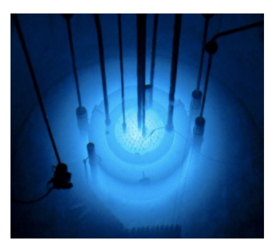
CEvNS as a **background**
for signatures of new physics (DM)



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



CEvNS as a **practical tool**



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

(CEvNS is *background*)

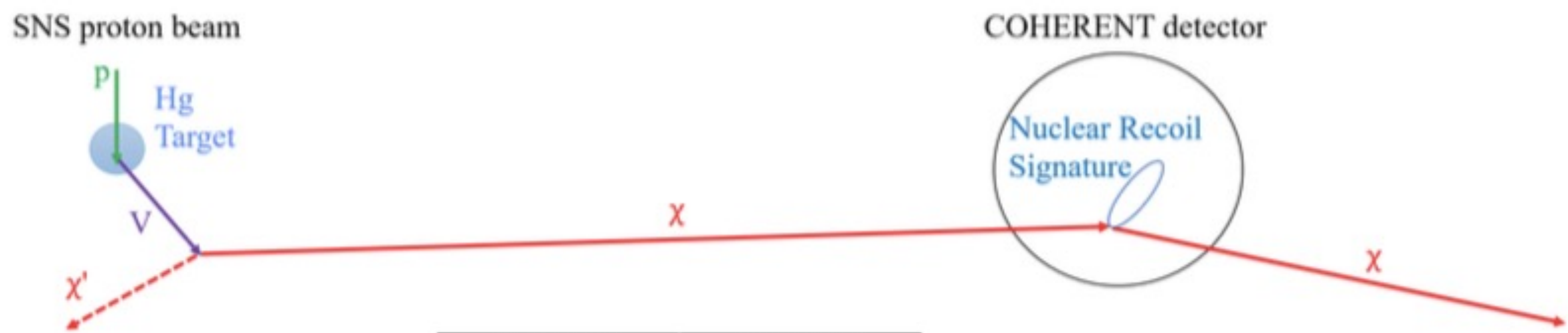
- "Vector portal": mixing of vector mediator with photons in π^0/η^0 decays
- "Leptophobic portal": new mediator coupling to baryons

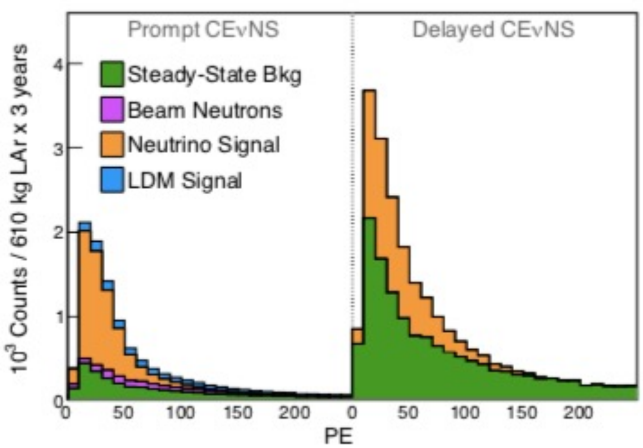
} decay product χ then makes nuclear recoil

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

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

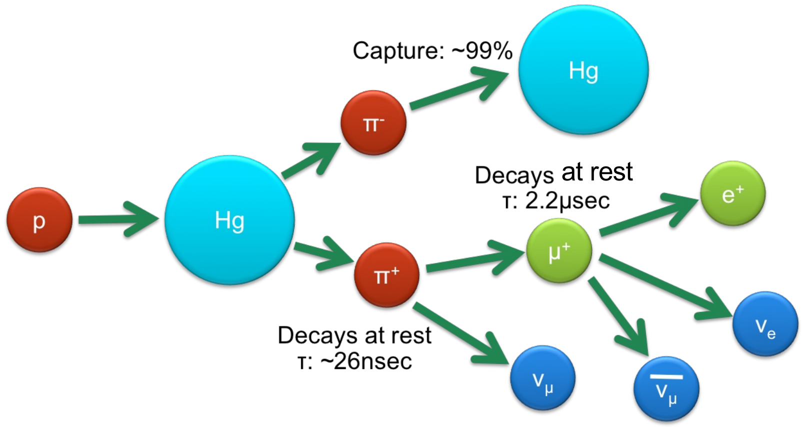
B. Batell et al., PRD 90 (2014)
P. de Niverville et al., PRD 95 (2017)
B. Dutta et al., arXiv:1906.10745
COHERENT, arXiv:1911.6422

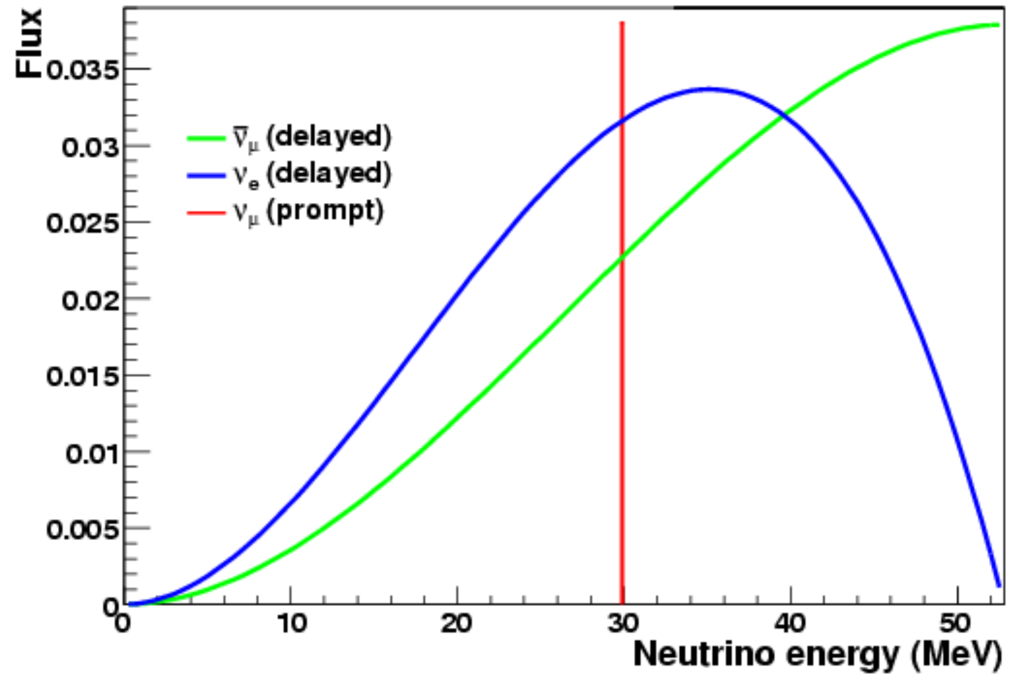




Expect *characteristic time, recoil energy, angle distribution* for DM vs CEvNS

Stopped-Pion (πDAR) Neutrinos





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

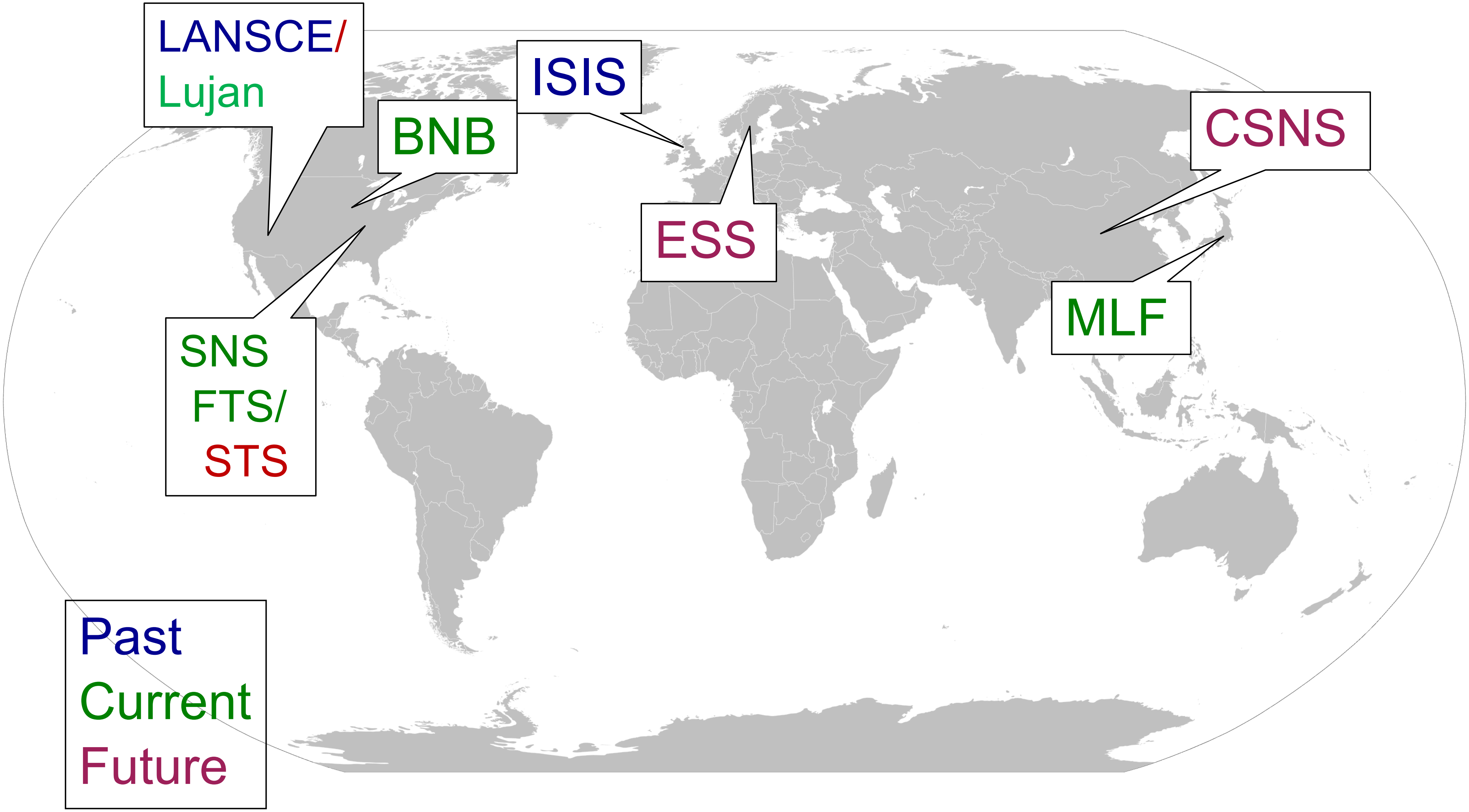
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

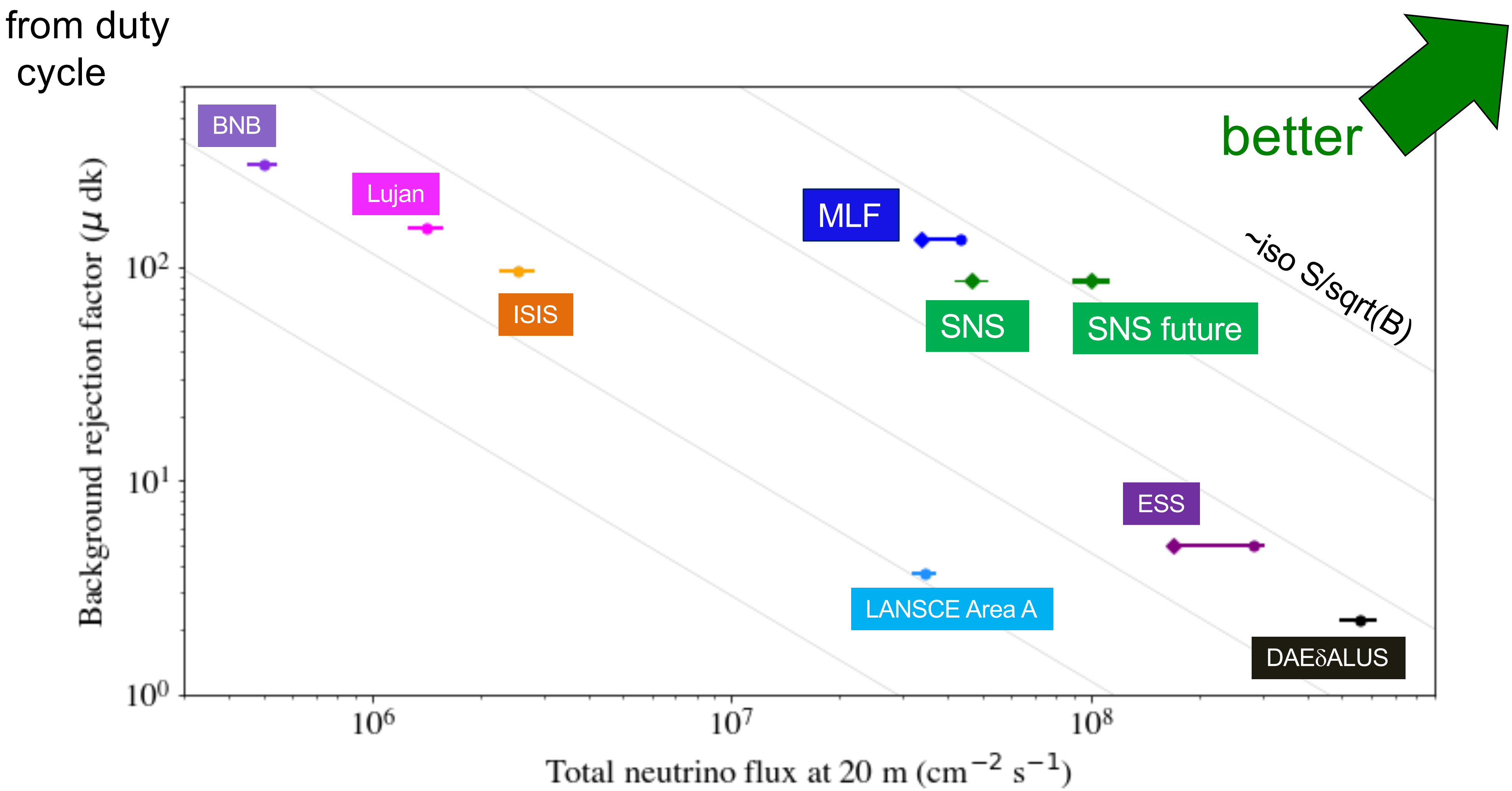
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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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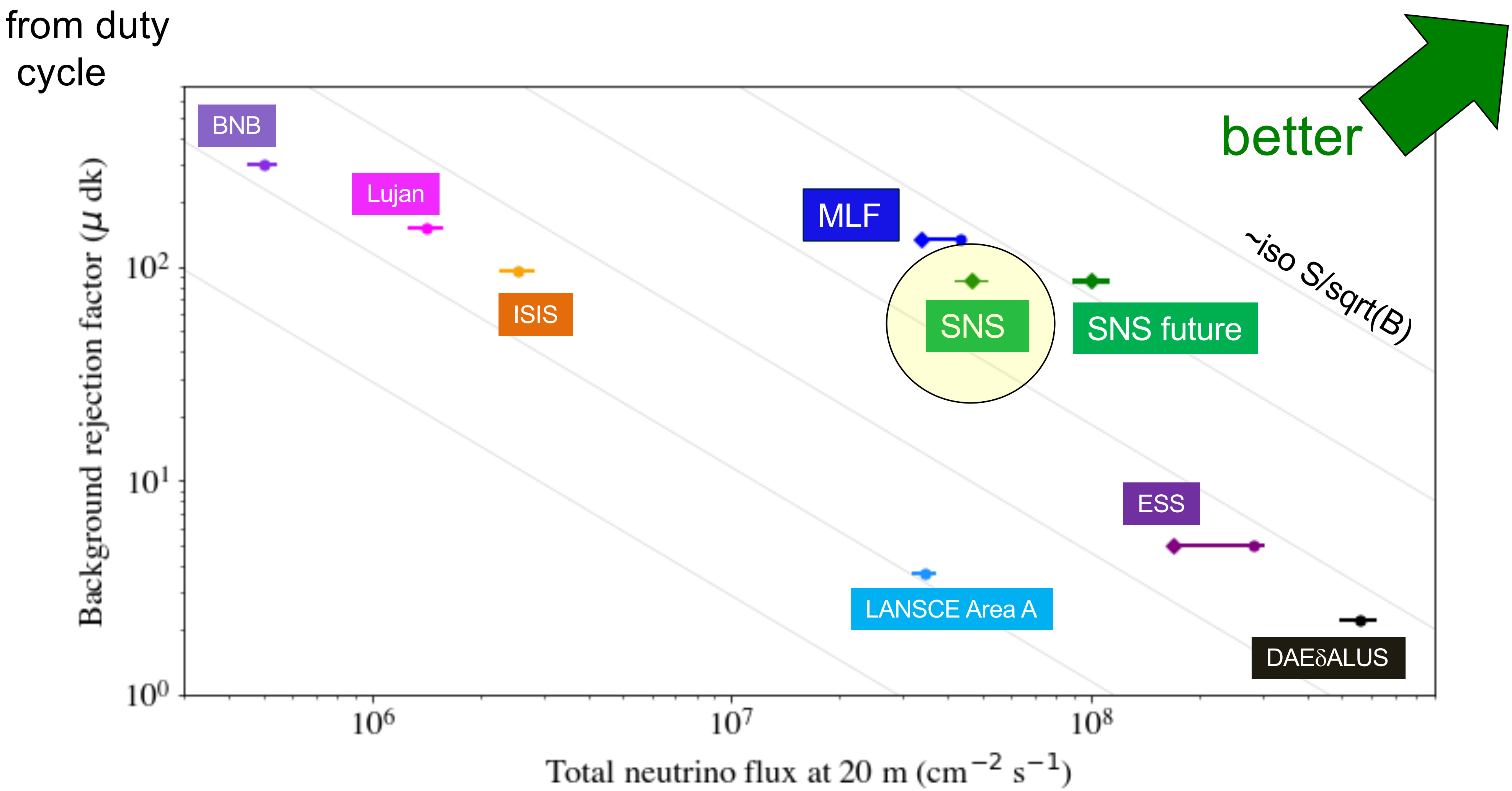
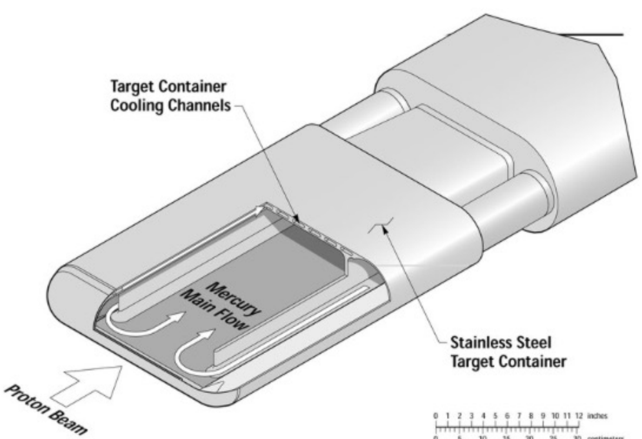


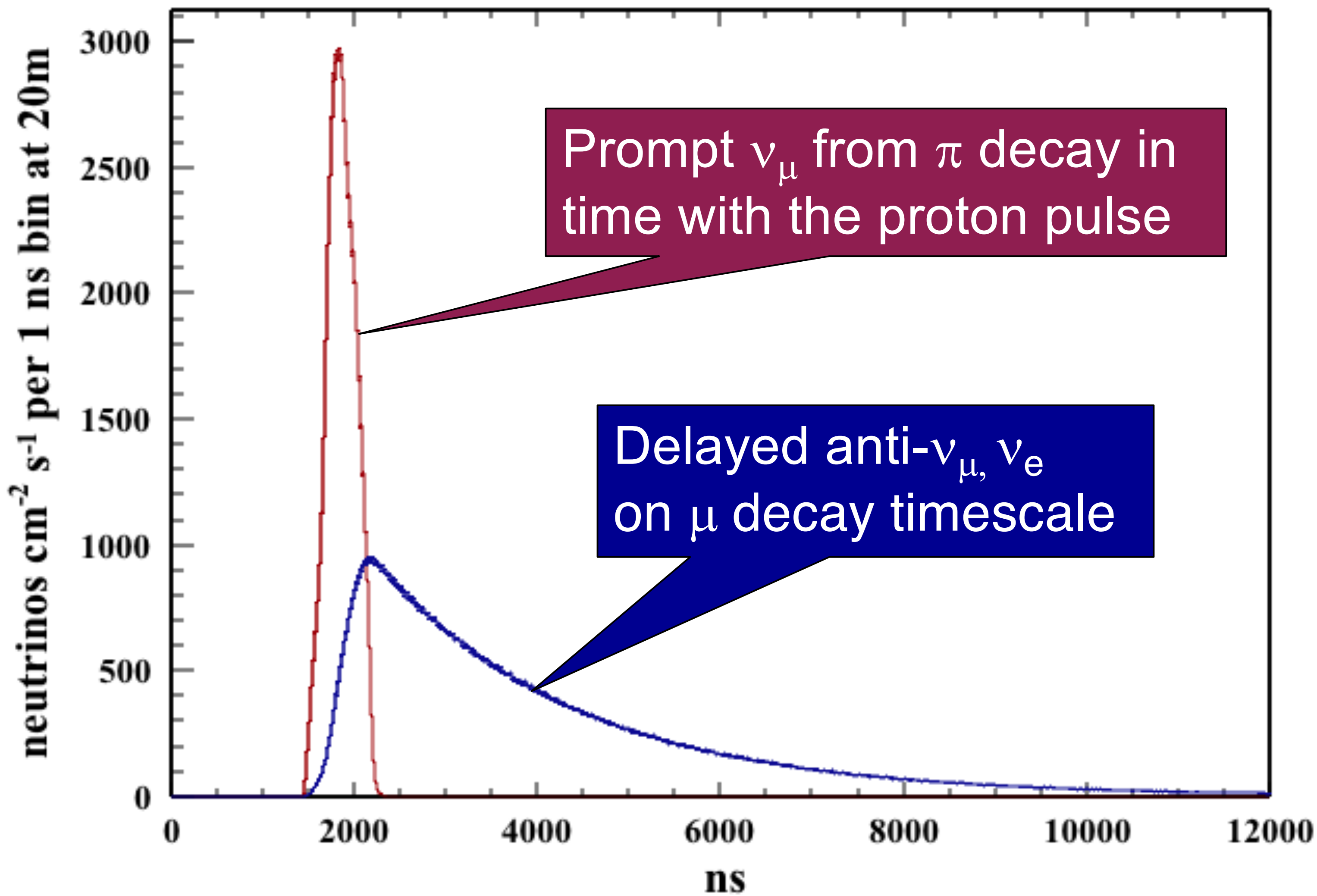


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

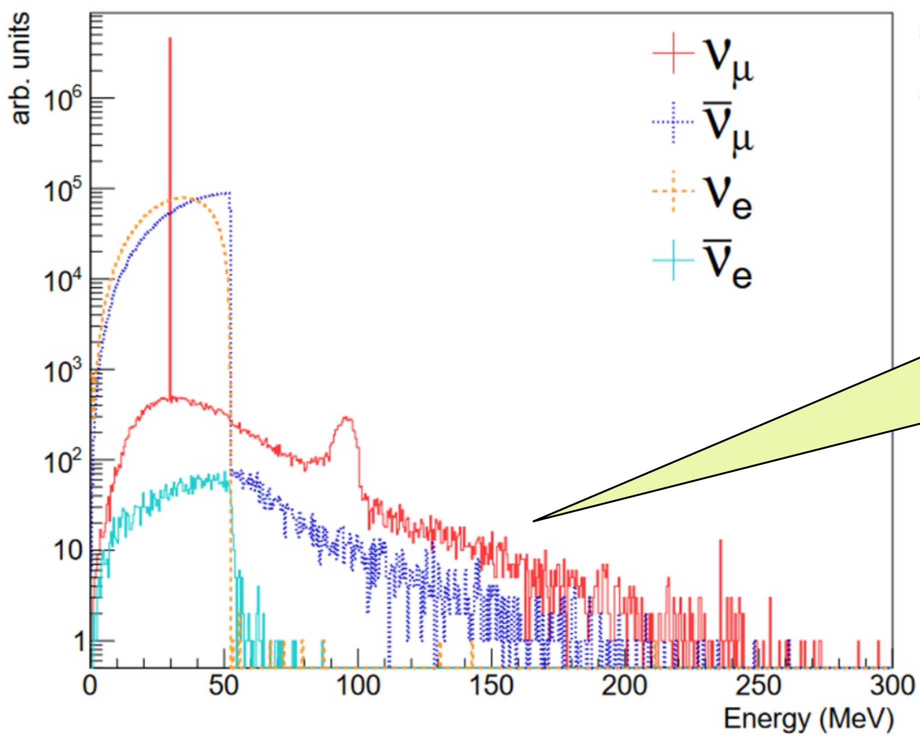
Time structure of the SNS source

60 Hz *pulsed* source

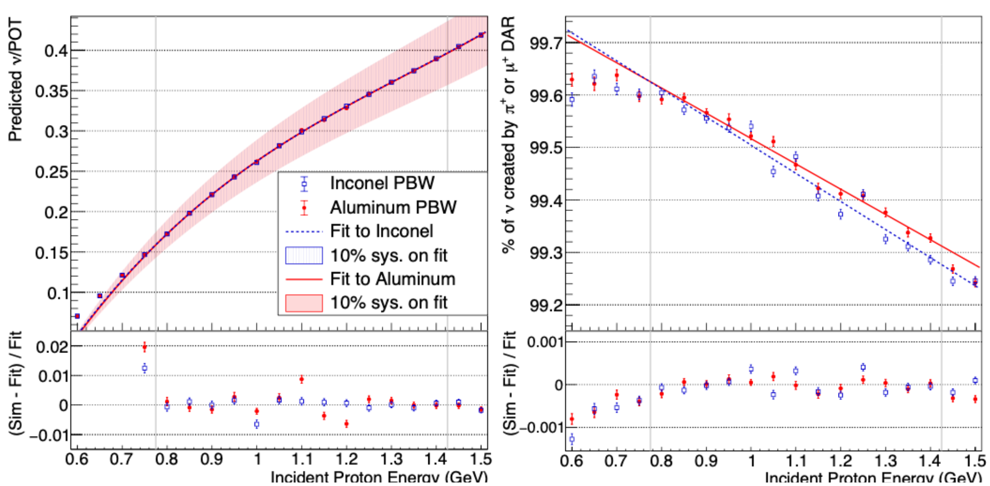


Background rejection factor ~few x 10^{-4}

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



Note that contamination from non π-decay at rest (decay in flight, kaon decay, μ capture...) is **down by several orders of magnitude**



Phys.Rev.D 106 (2022) 3, 032003 • e-Print: 2109.11049 [hep-ex]

SNS flux (1.4 MW):
470 x 10^5 ν/cm^2/s @ 20 m
>99% pure decay at rest

The COHERENT collaboration

http://sites.duke.edu/coherent

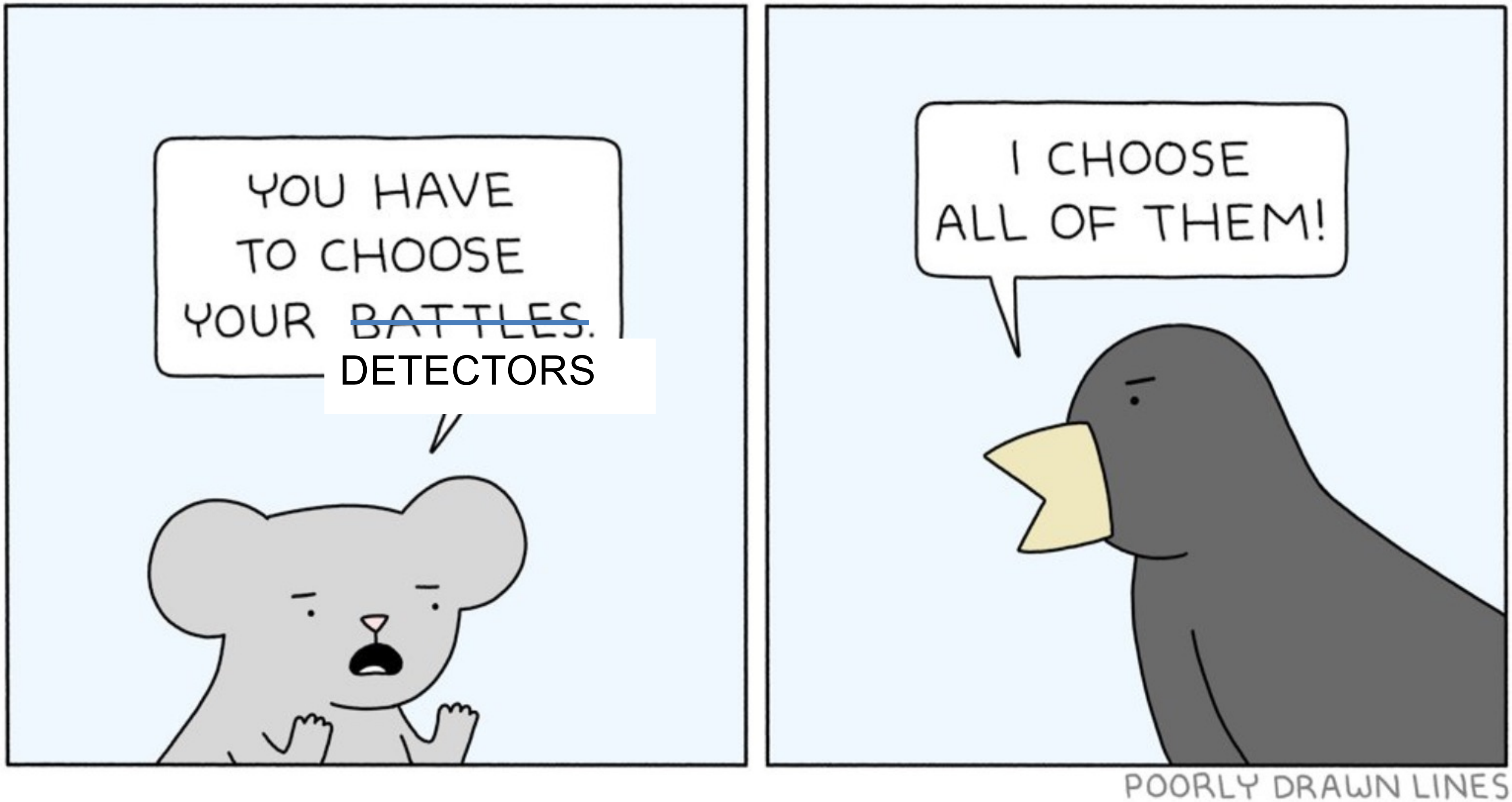
~90 members,
20 institutions
4 countries

COHERENT
SNS
SPALLATION NEUTRON SOURCE

Carnegie Mellon University
Duke University
UF University of Florida
Laurentian University Université Laurentienne
Los Alamos National Laboratory EST. 1943
MEPhI
NC Central University
NC State University
Oak Ridge National Laboratory
Sandia National Laboratories
서울대학교 Seoul National University
SLAC National Accelerator Laboratory
University of South Dakota
The University of Tennessee Knoxville
Tufts University
TUNL Triangle Universities Nuclear Laboratory
Virginia Tech
University of Washington

U.S. Department of Energy
Office of Science
NSF
NNSA National Nuclear Security Administration
Consortium for Monitoring, Technology and Verification
NRF 한국연구재단

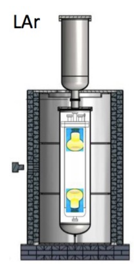
The COHERENT Spirit (so far)

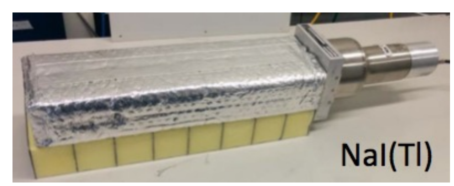


COHERENT CEvNS Detectors

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	18	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

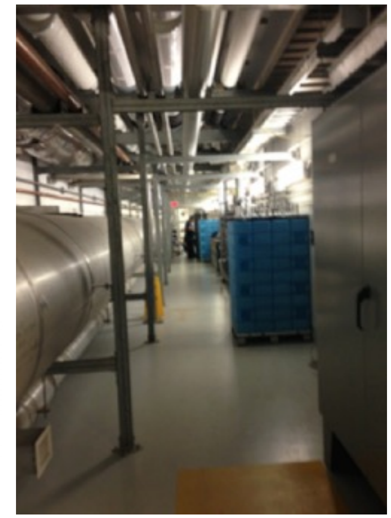


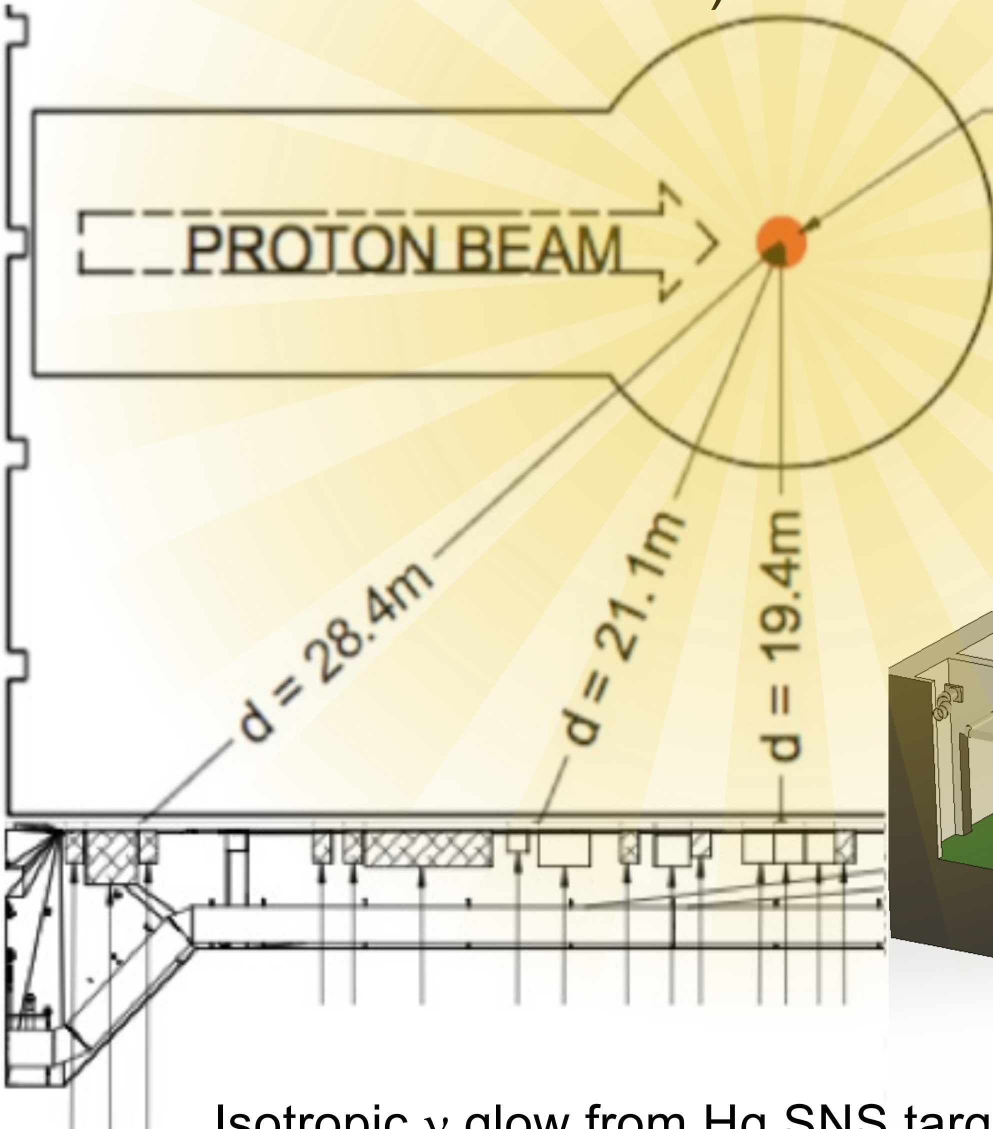


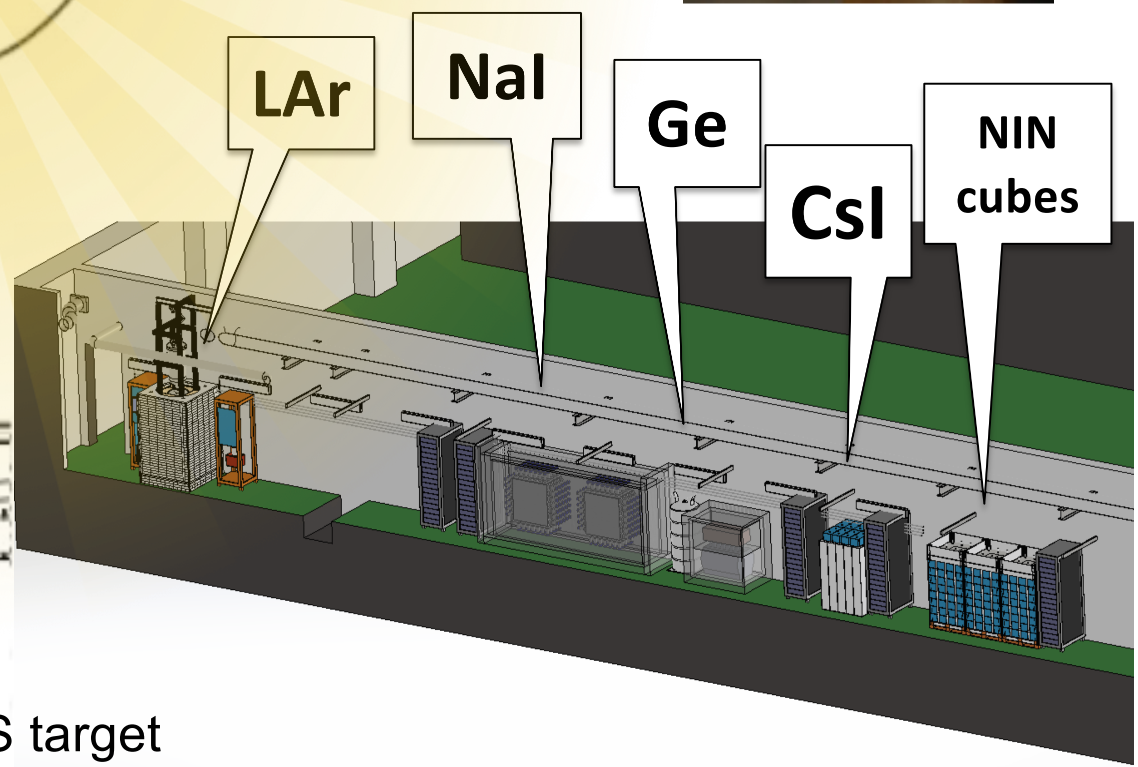
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

View looking
down “Neutrino Alley”

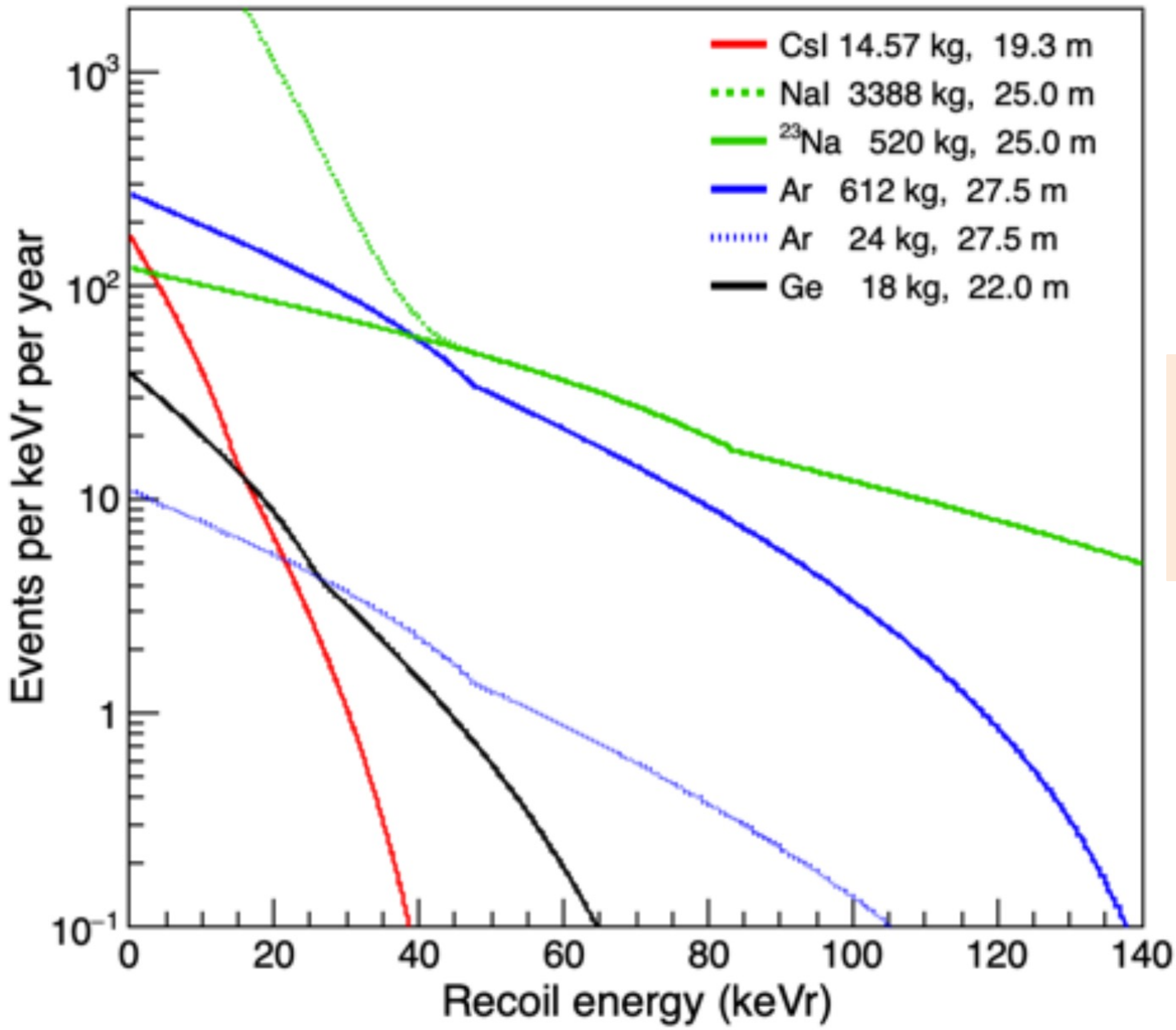






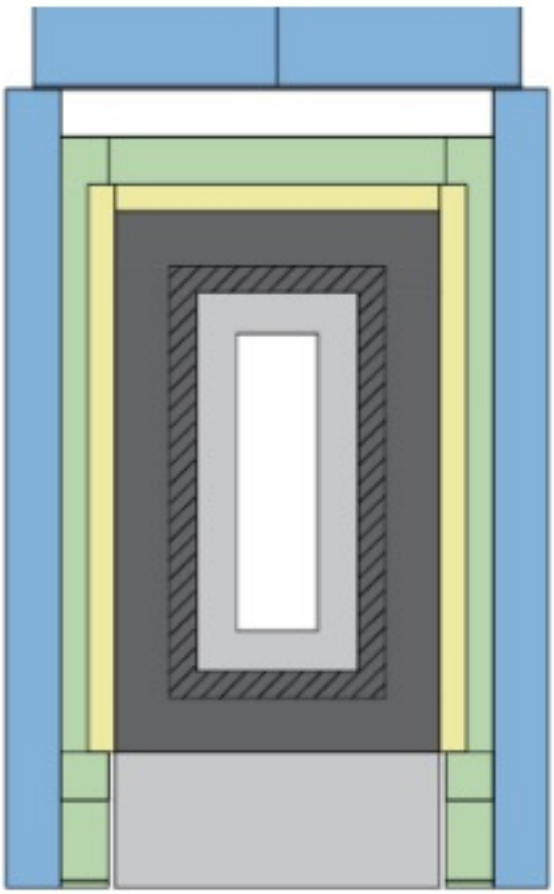
Isotropic ν glow from Hg SNS target

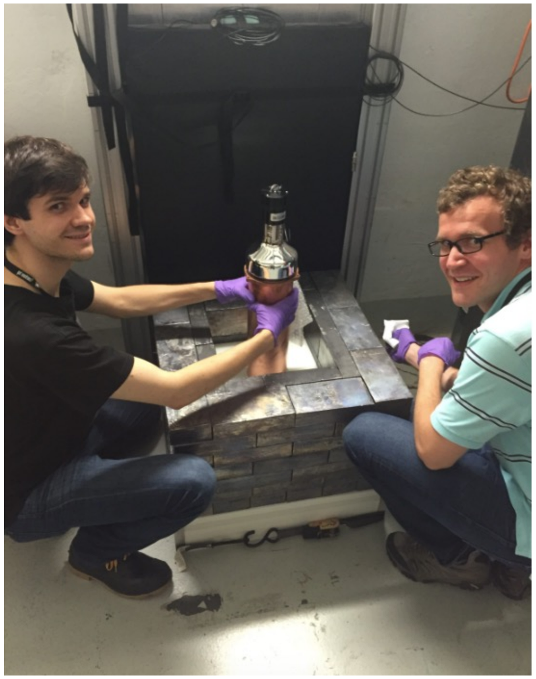
Expected recoil energy distribution



Lighter targets:
less rate per mass,
but kicked to
higher energy

The CsI Detector in Shielding in Neutrino Alley at the SNS





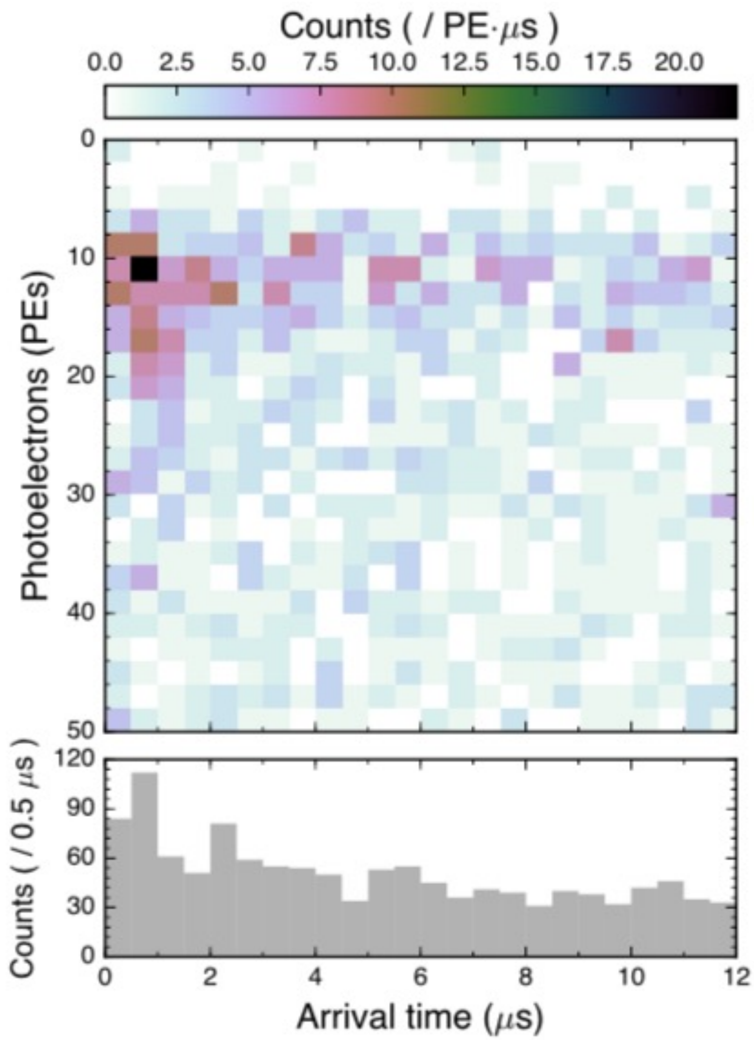
A hand-held detector!

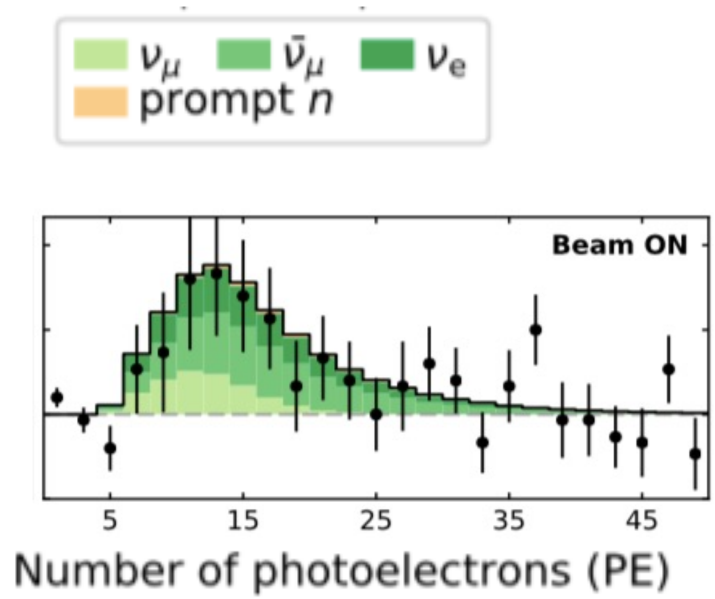
Almost wrapped up...

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

KICP

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





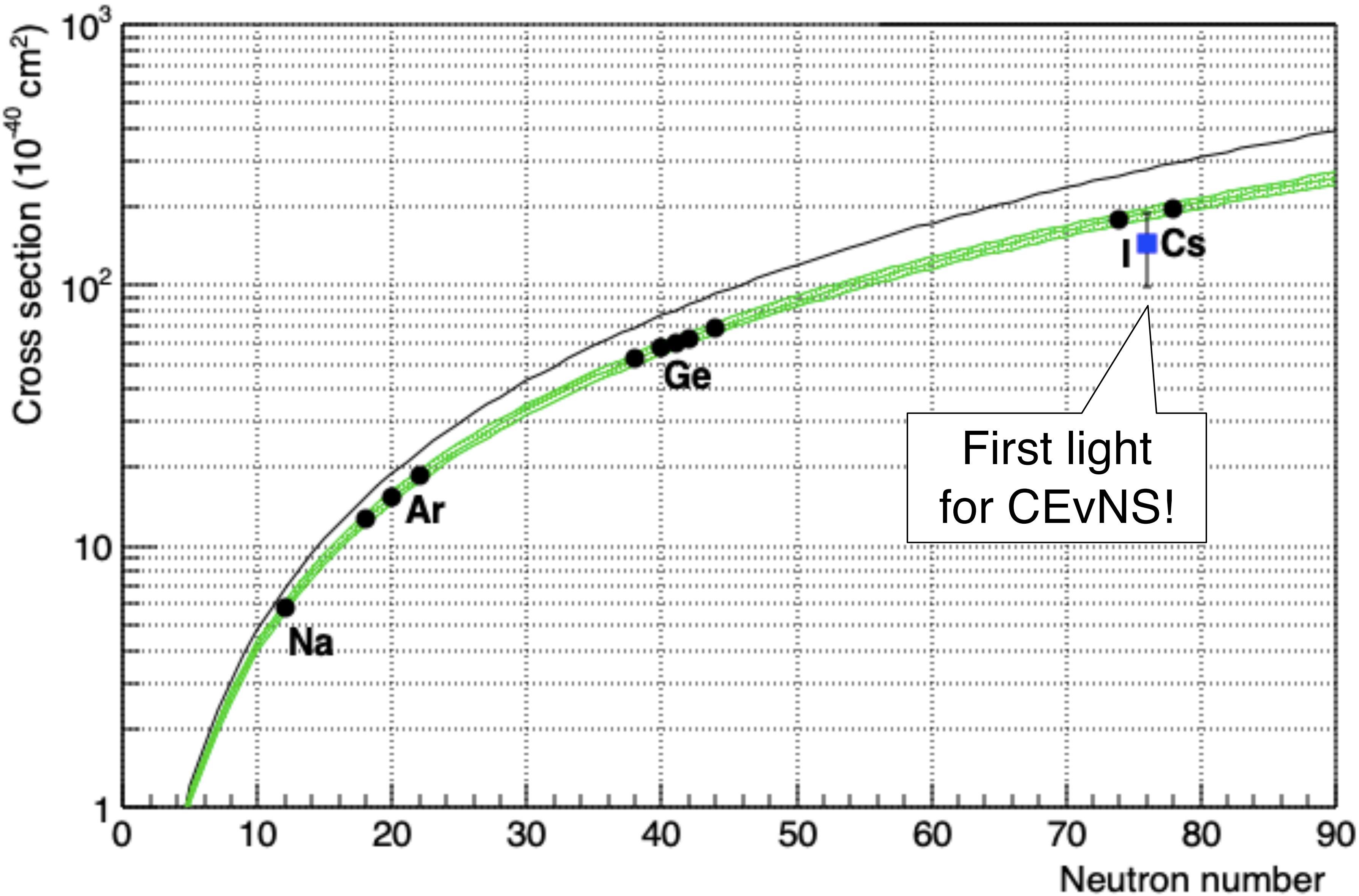
Background-subtracted and integrated over time

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

→ measure of the Q spectrum

DOI: 10.5281/zenodo.1228631

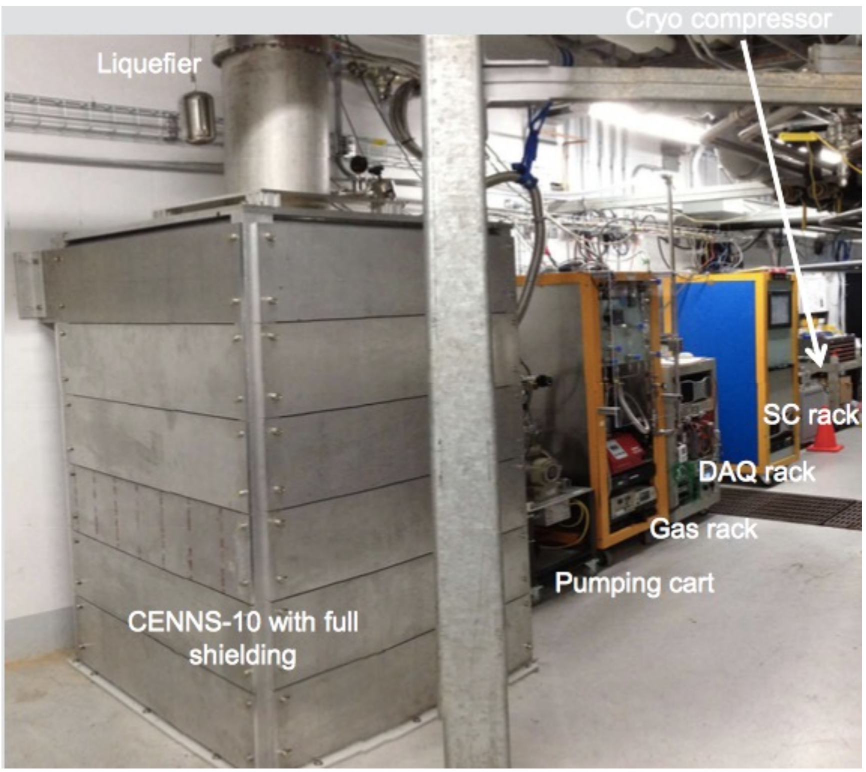
D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990



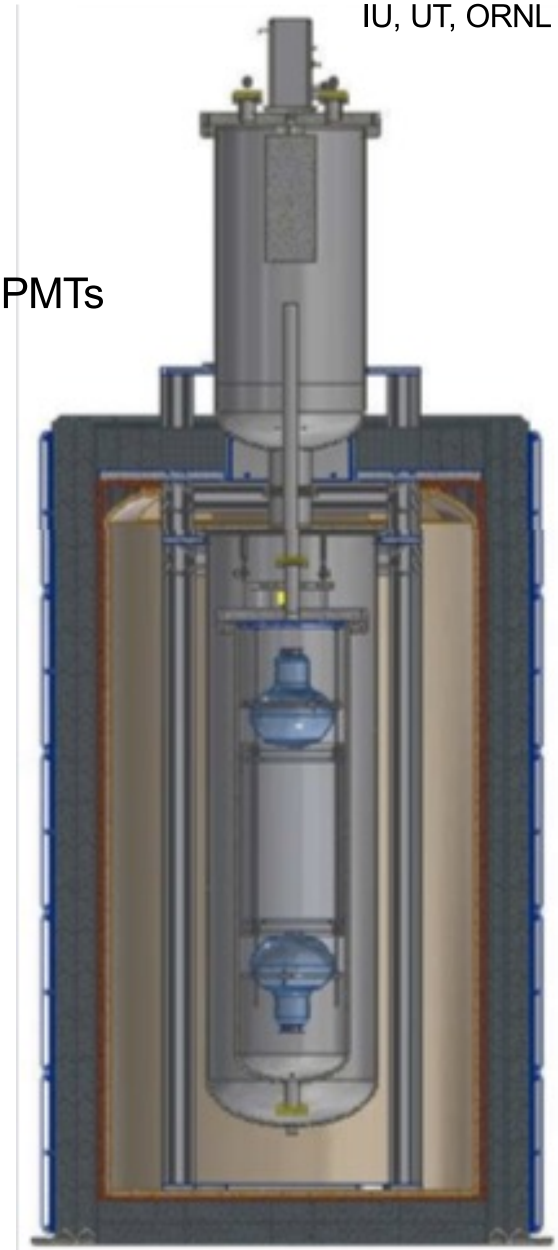
Cross section (10^{-40} cm^2)
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
90
Neutron number
Na
Ar
Ge
I
Cs
First light
for CEvNS!

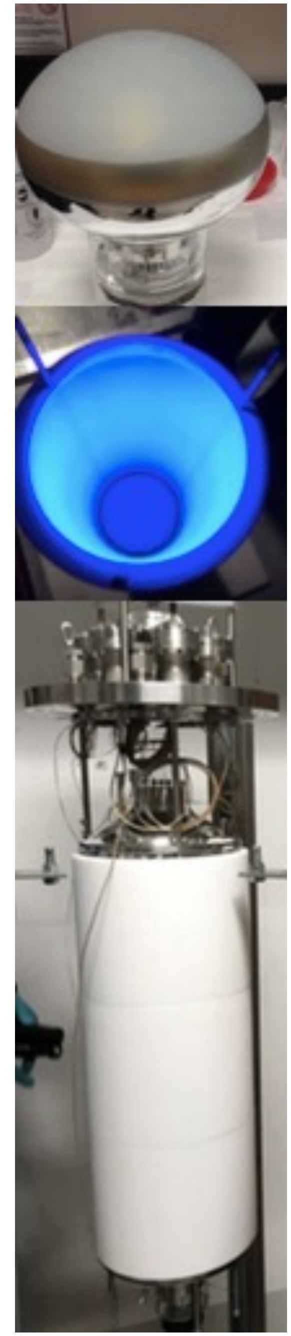
Single-Phase Liquid Argon

- ~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



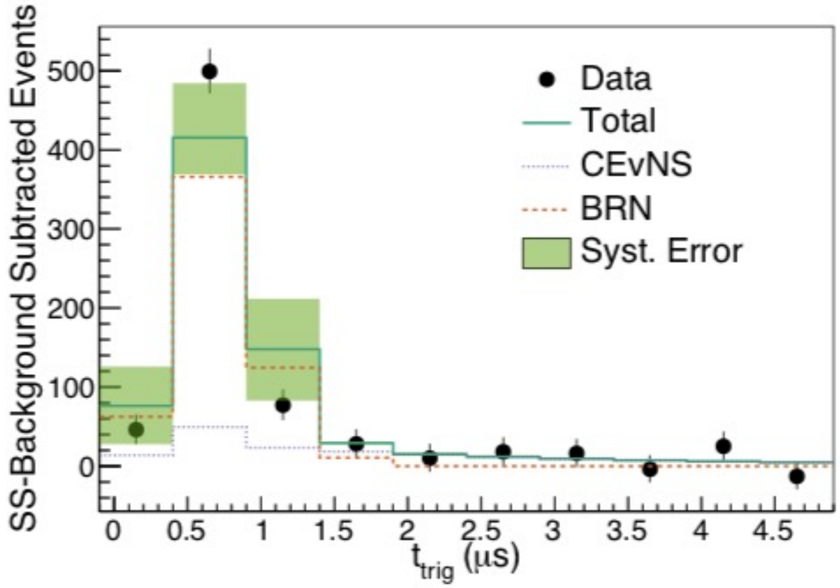


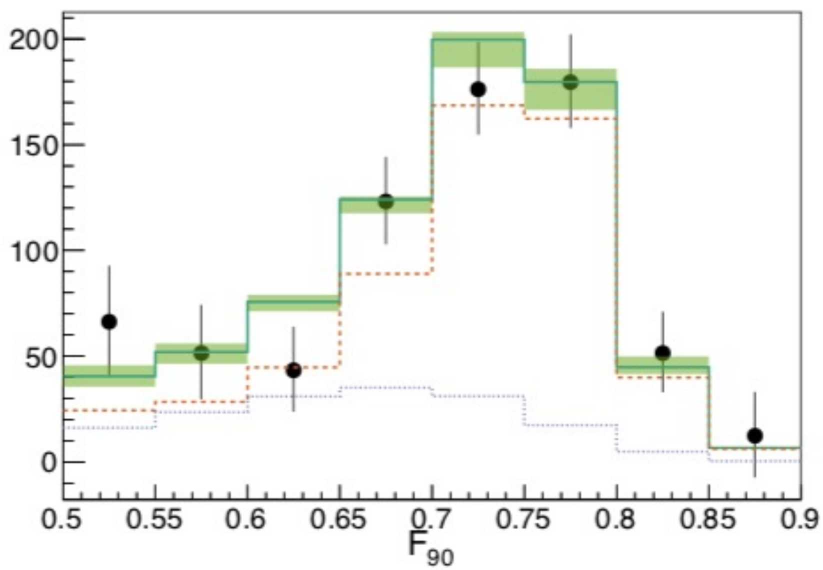
Detector from FNAL, previously built (Jonghee Yoo et al.) for CENNS@BNB

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

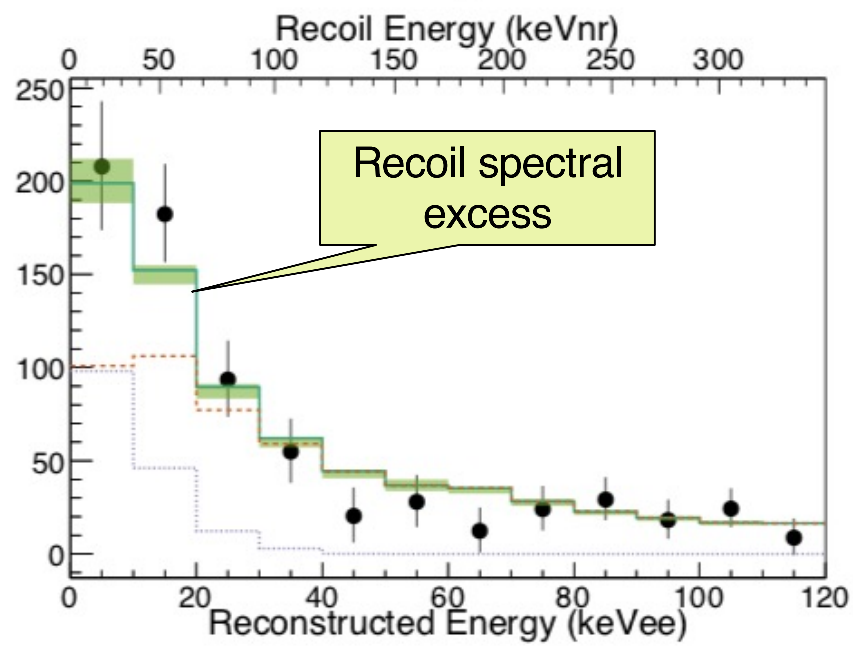
Likelihood fit in time, recoil energy, PSD parameter

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

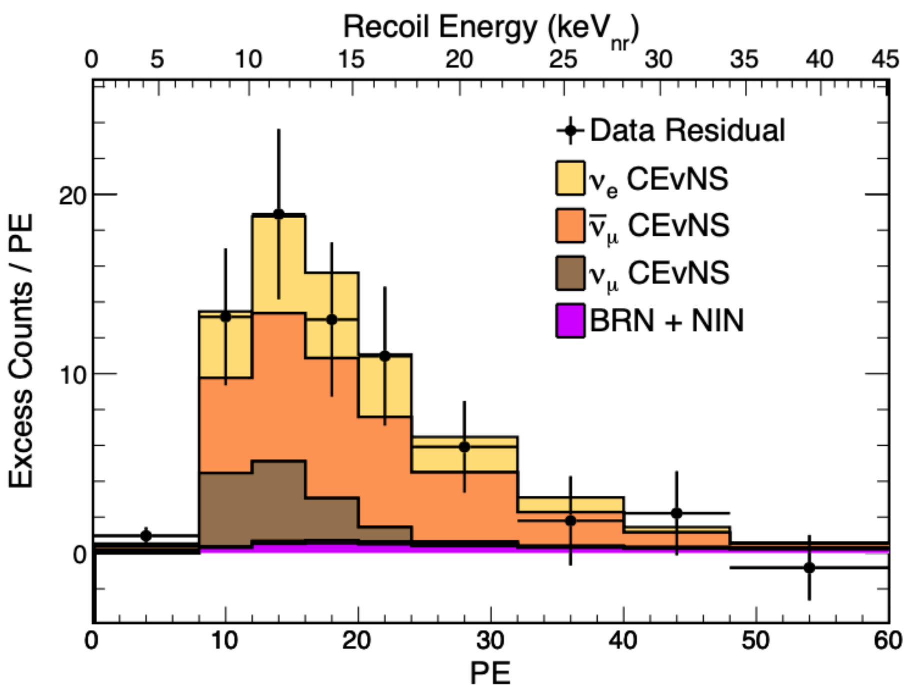


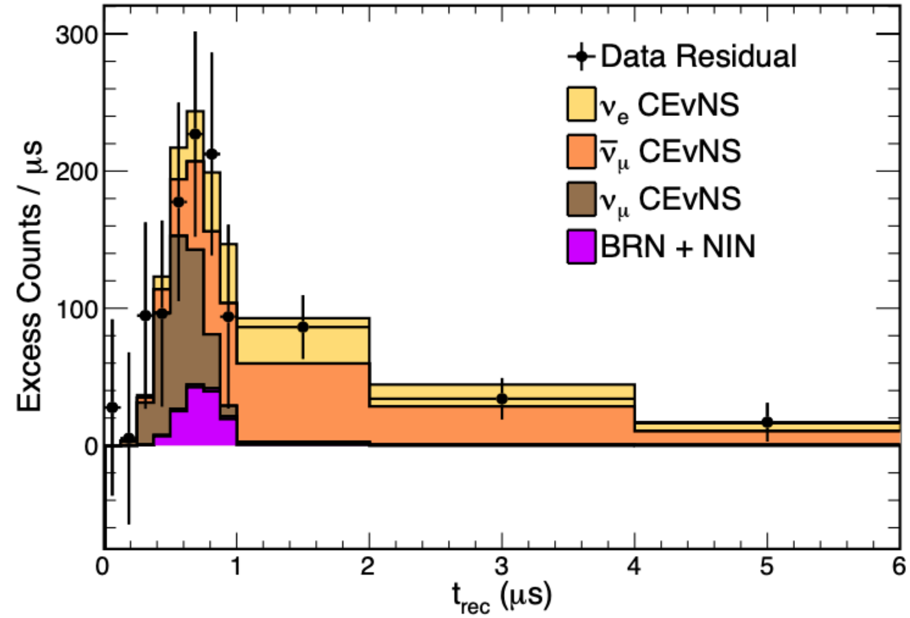


- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the "A" analysis)

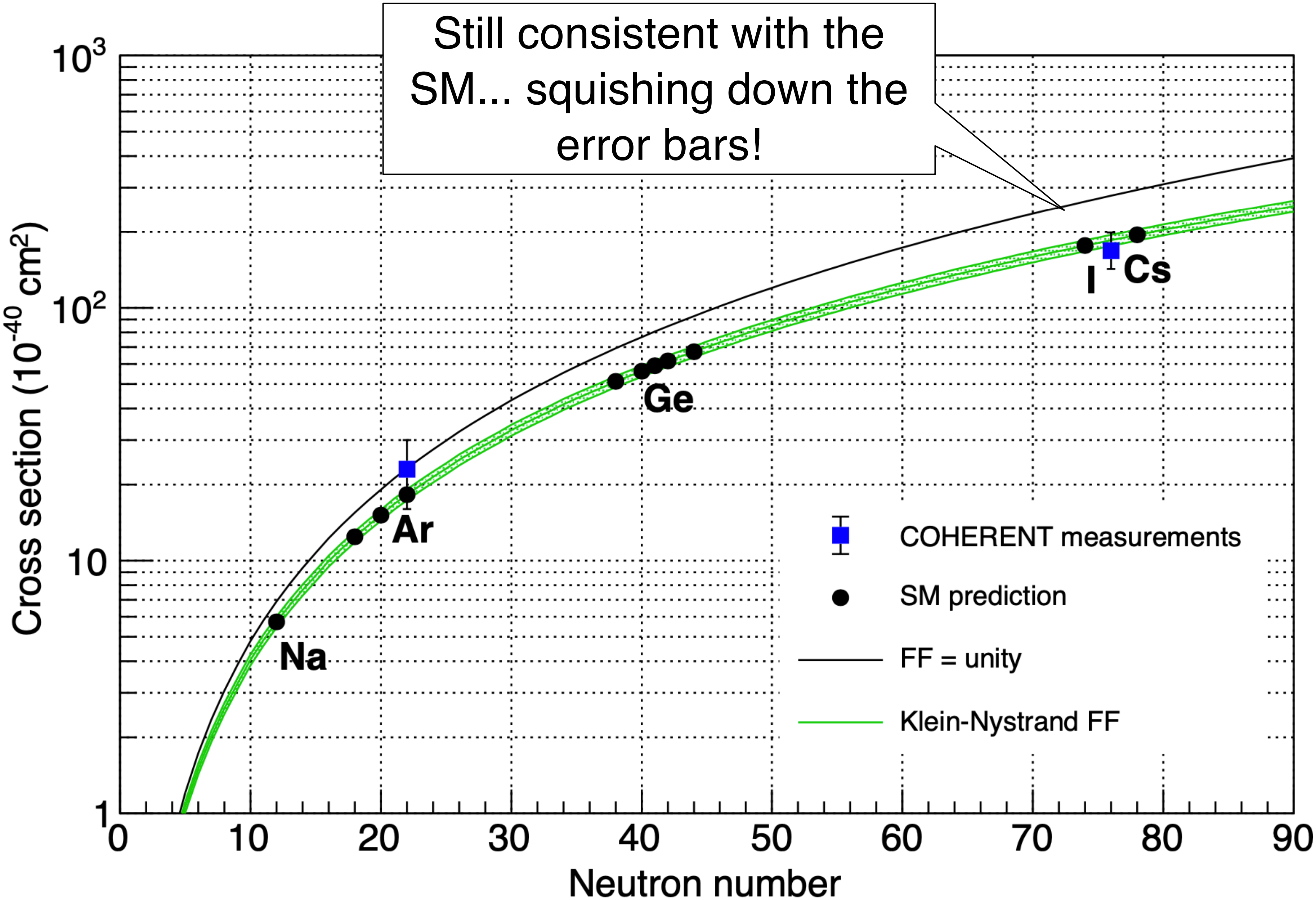


Remaining CsI[Na] dataset,
with >2 x statistics
+ improved detector response understanding
+ improved analysis



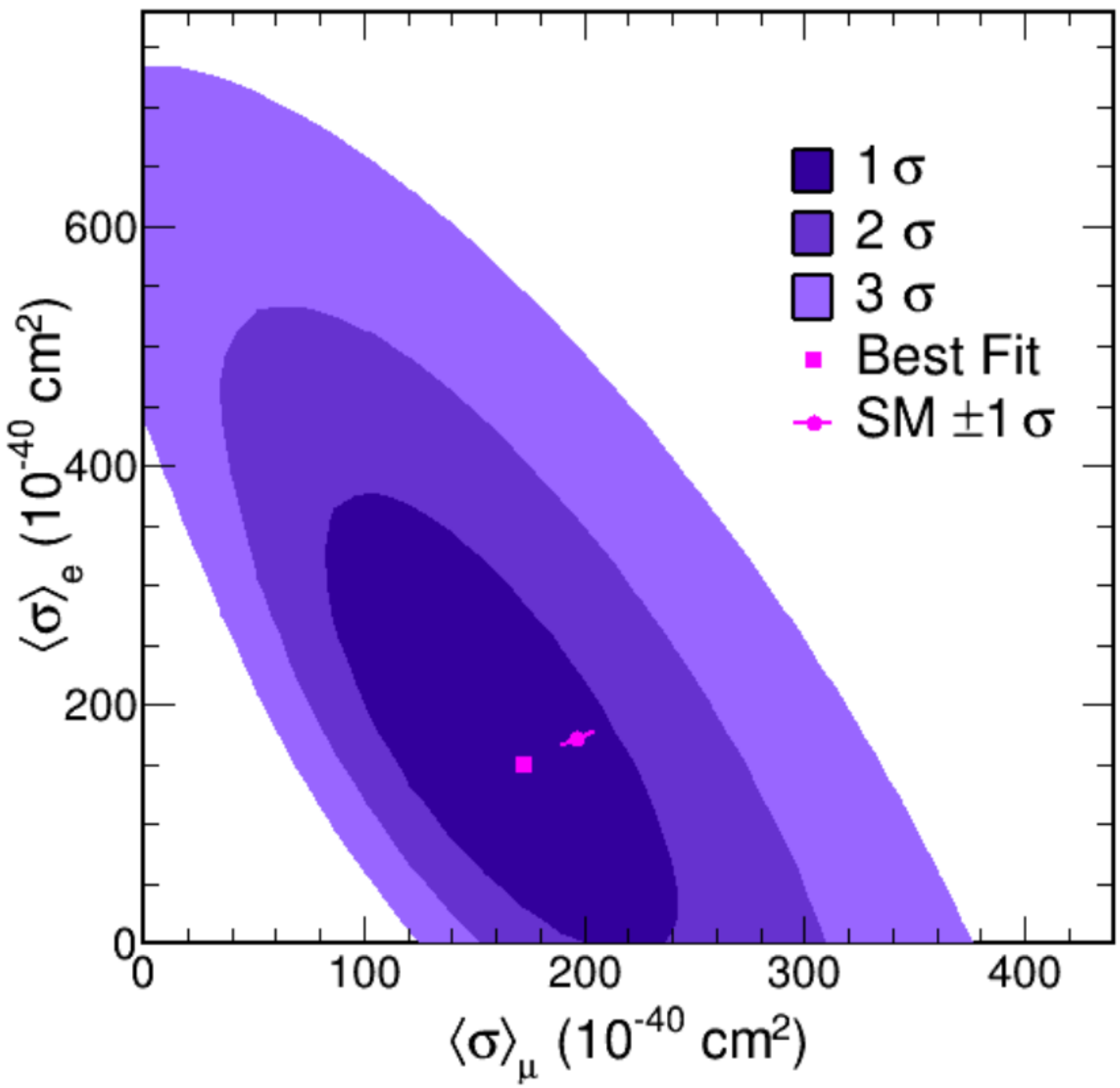


arXiv: 2110.07730

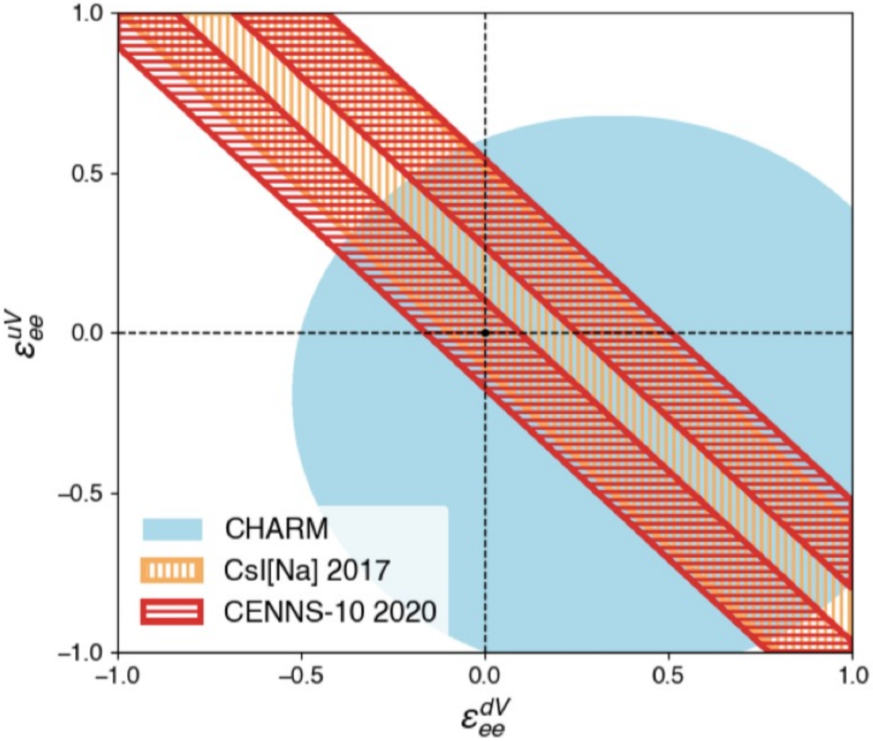

Still consistent with the SM... squishing down the error bars!
Cross section (10^{-40} cm^2)
Neutron number
Na
Ar
Ge
I
Cs
COHERENT measurements
SM prediction
FF = unity
Klein-Nystrand FF

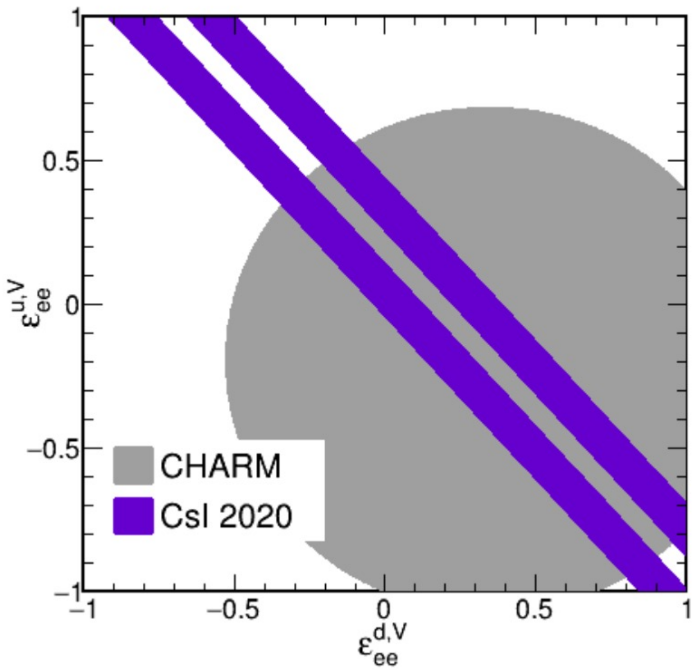
Flavored CEvNS cross sections

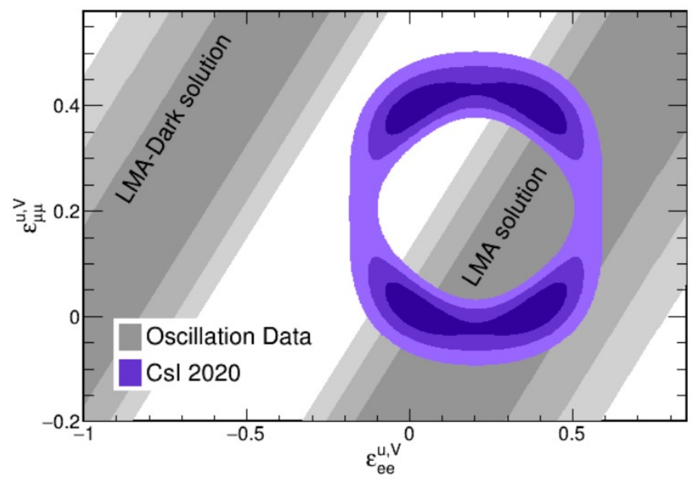
Separate electron and muon flavors by timing



And squeezing down the possibilities for new physics...

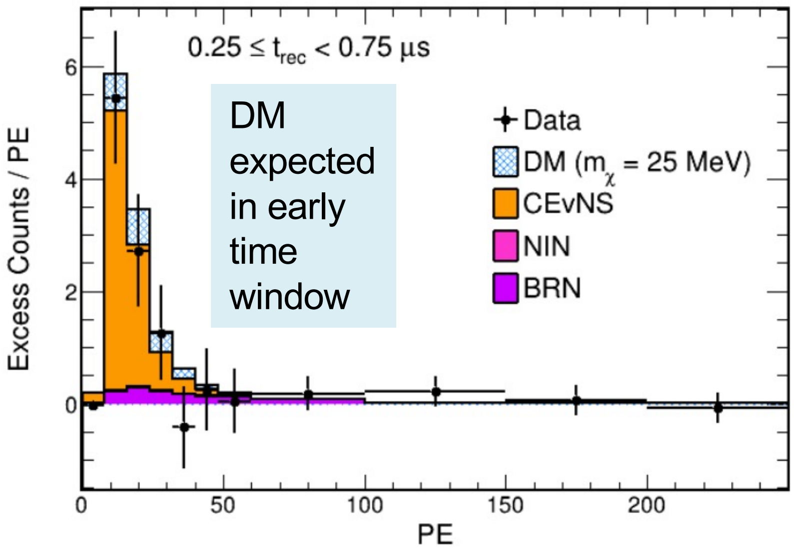


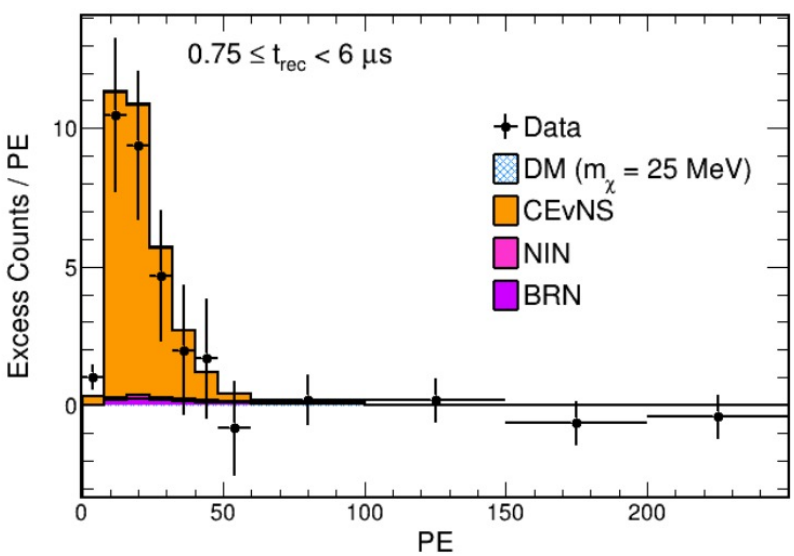


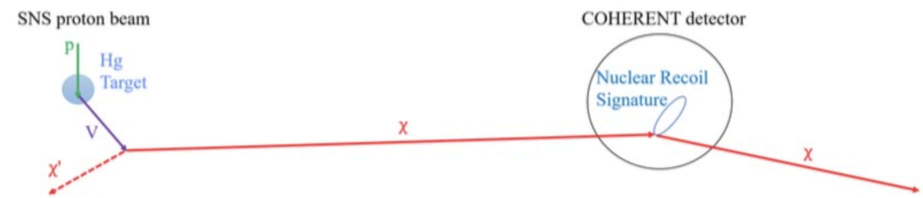


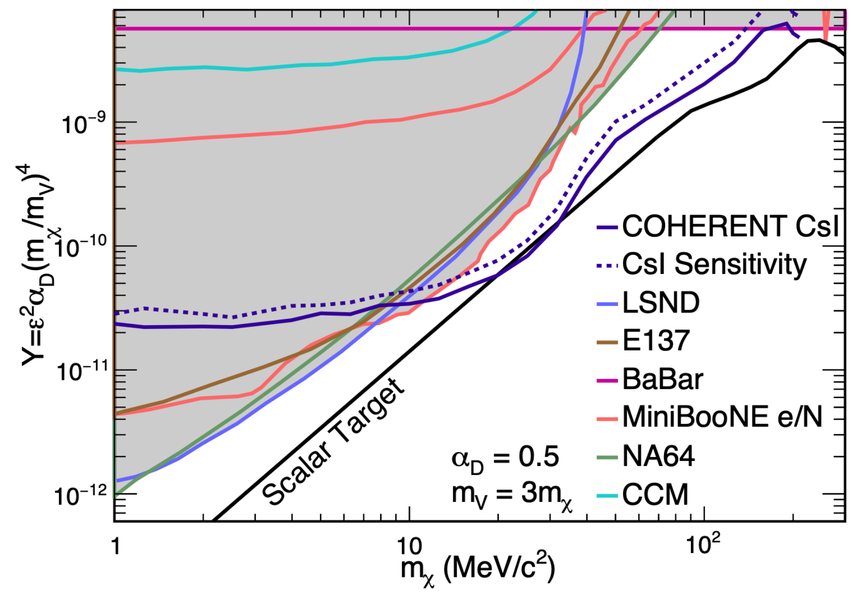
Accelerator-produced DM search

https://indico.phy.ornl.gov/event/126/
arXiv:2110.11453





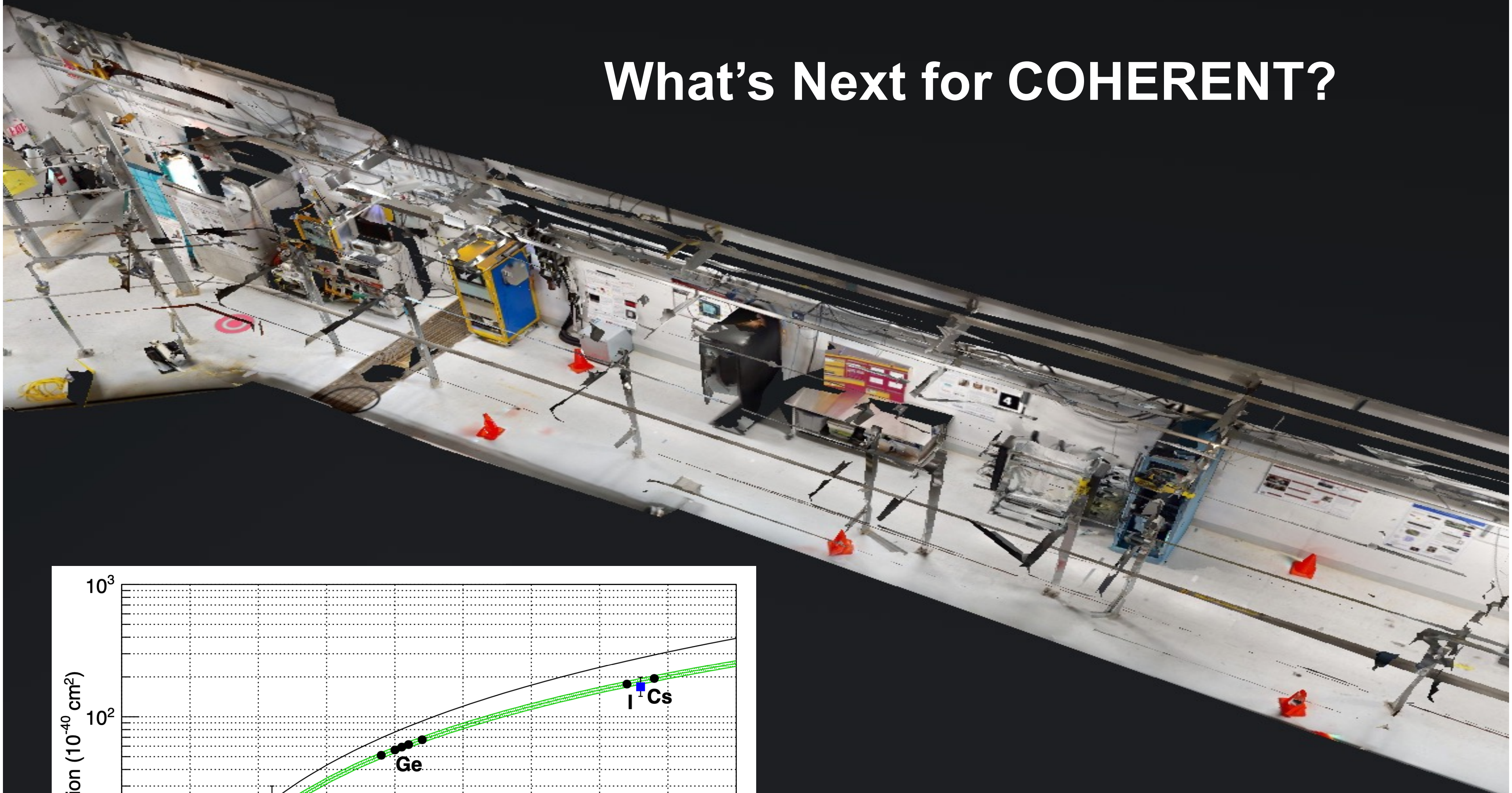


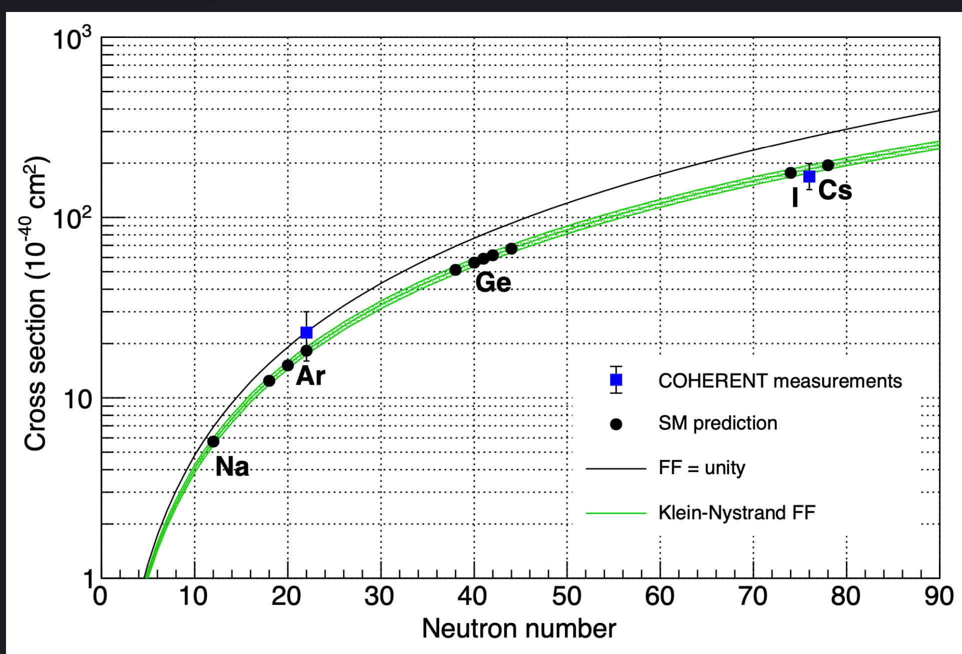


Limits down to cosmological expectation for scalar DM particle

arXiv:2110.11453
+ arXiv:2205.12414 leptophobic DM

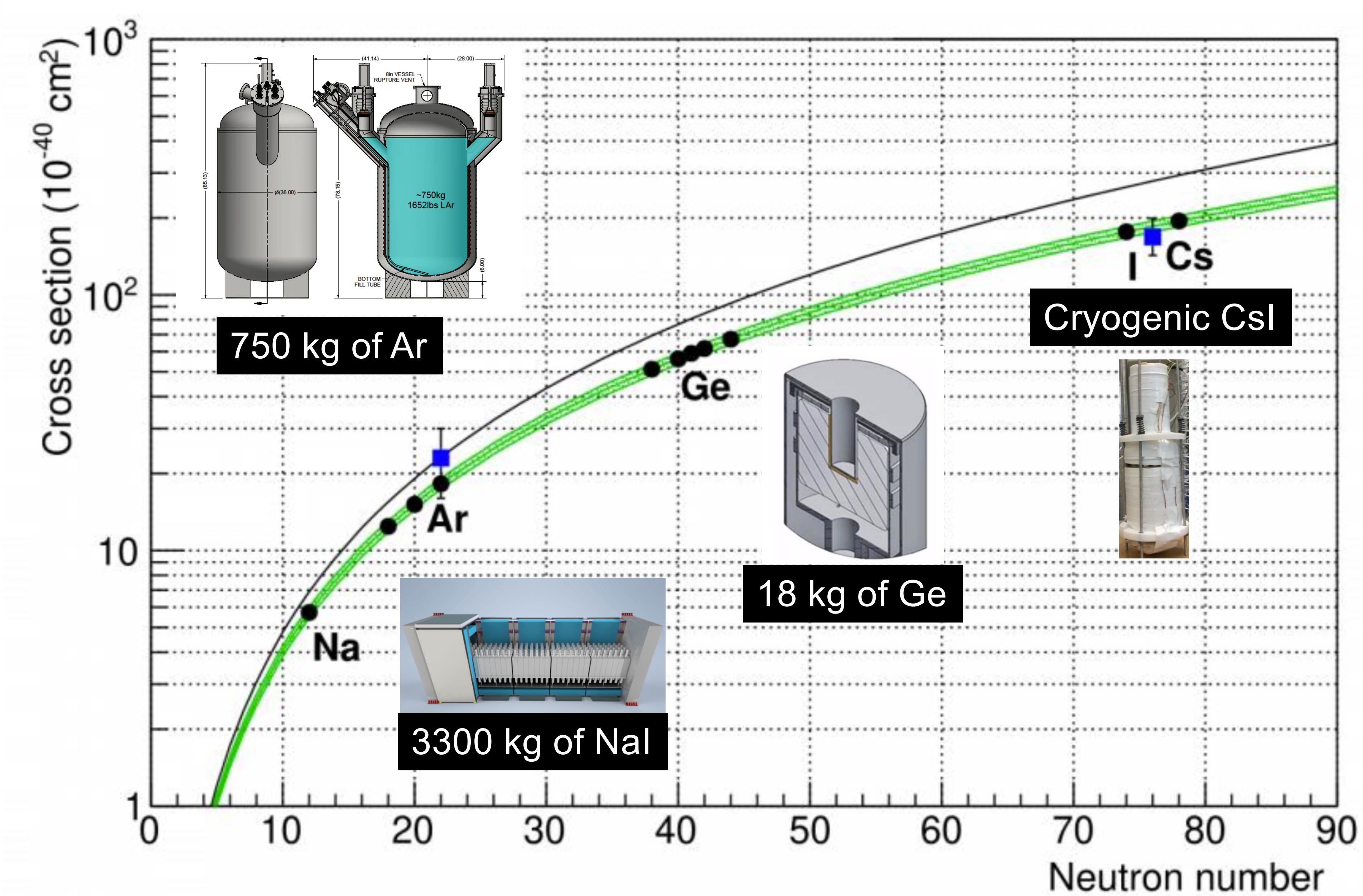
What's Next for COHERENT?



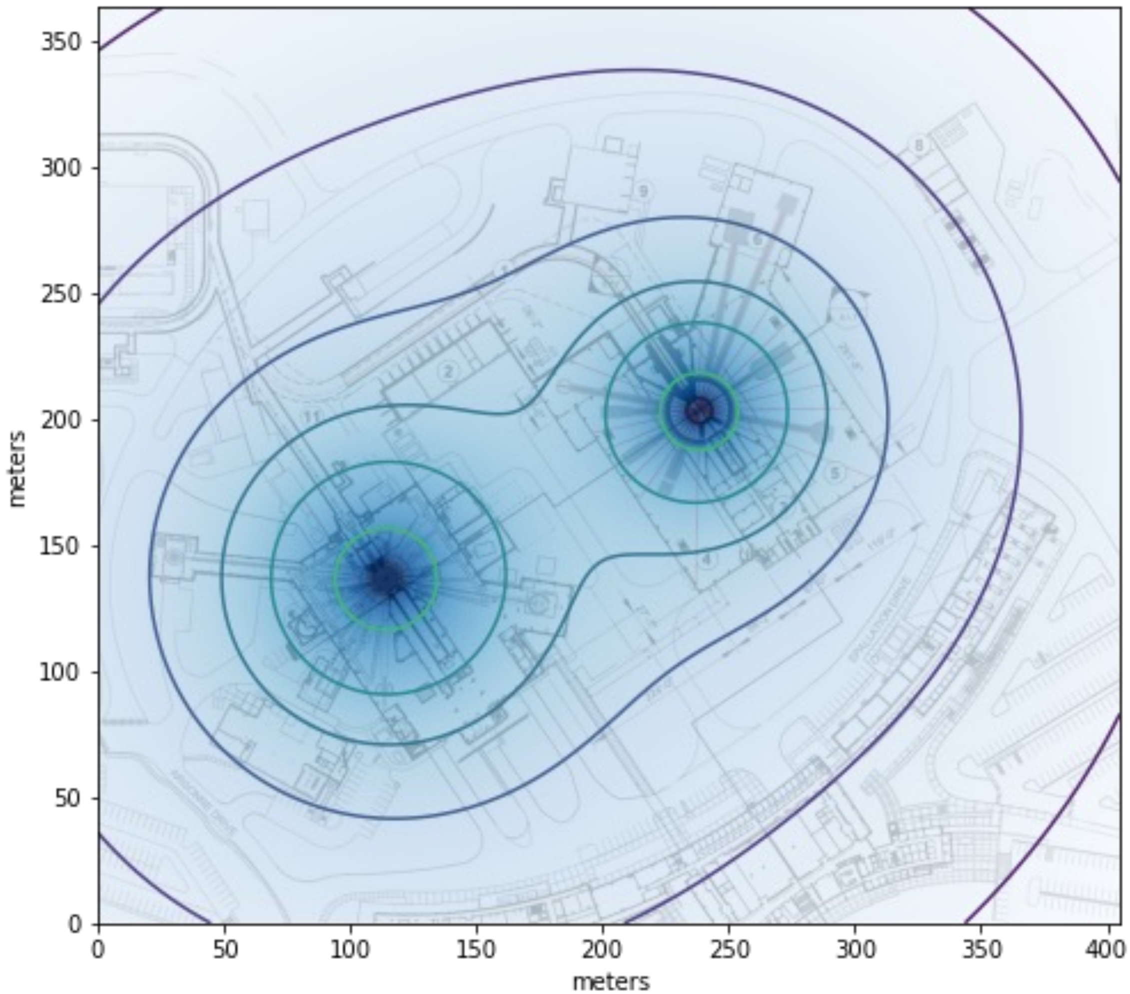


Two down!
But still more
to go!

COHERENT future deployments



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



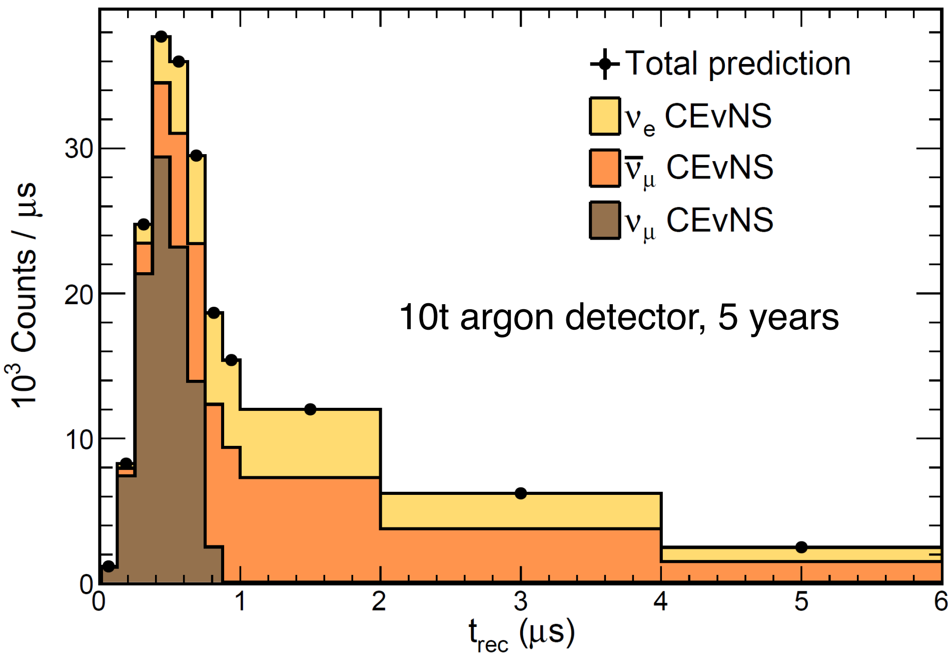
¾ bunches to FTS
¼ bunches to STS

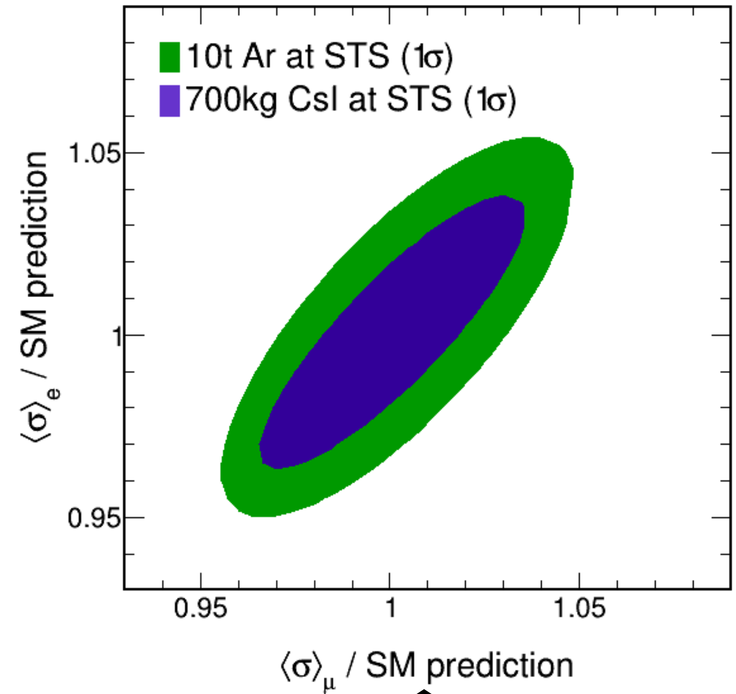
Promising new space available for **~10-tonne scale detectors**

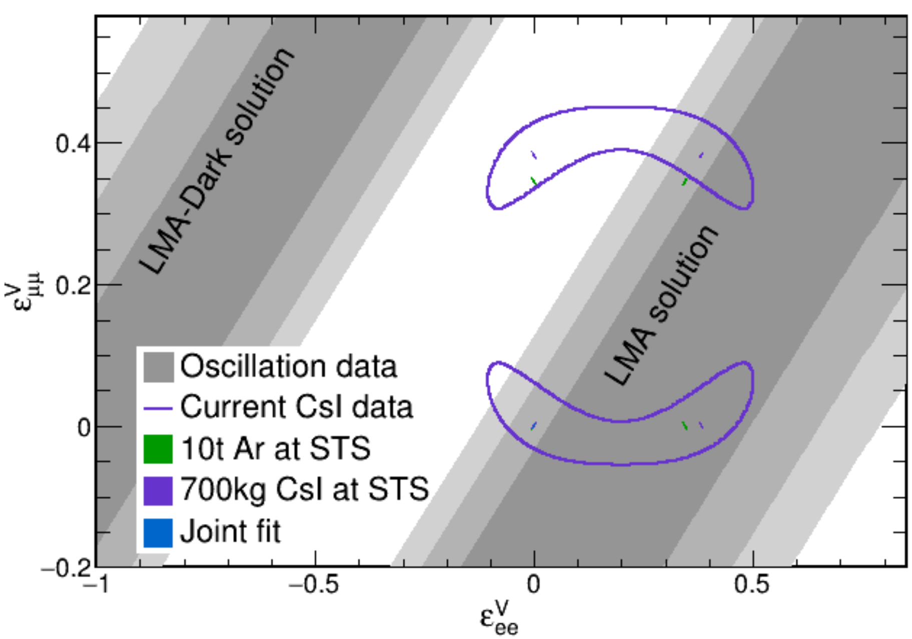
Many exciting possibilities for ν's + DM!

See D. Pershey, APS April 2022 invited talk

Future flavored CEvNS cross section measurements







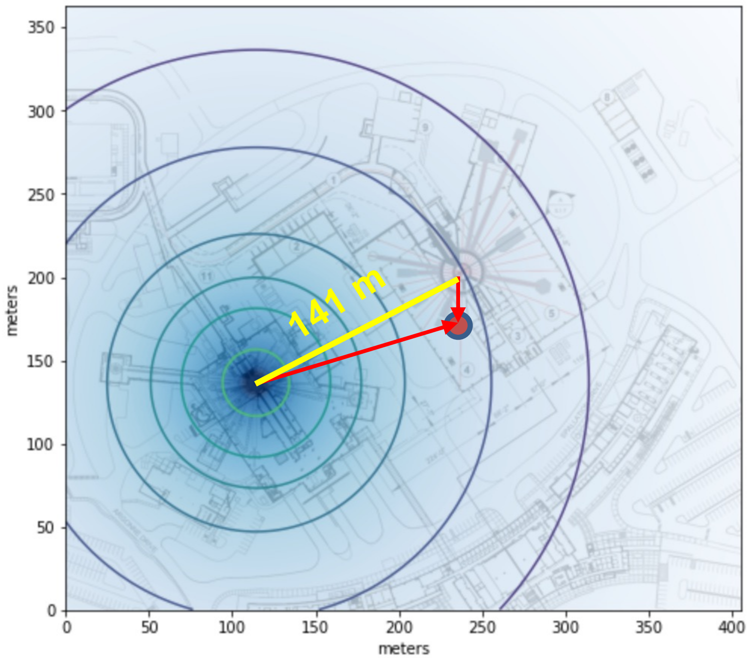
Sensitive to ~few % SM differences in μ- and e-flavor cross sections, testing lepton universality of CEvNS (at tree level)

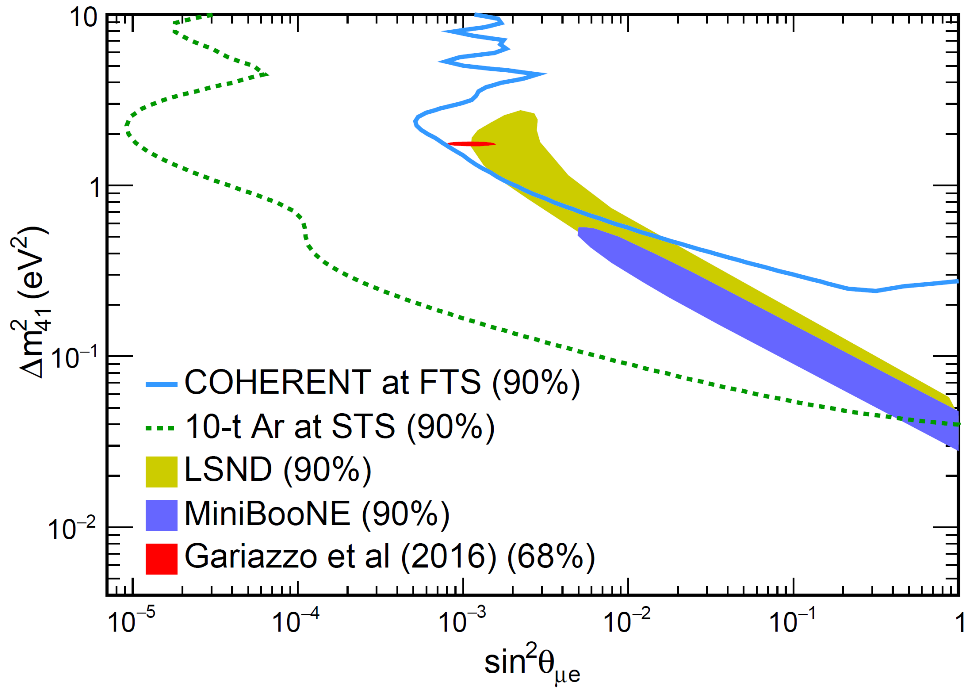
Stringent NSI parameters constraints, resolving oscillation ambiguities

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

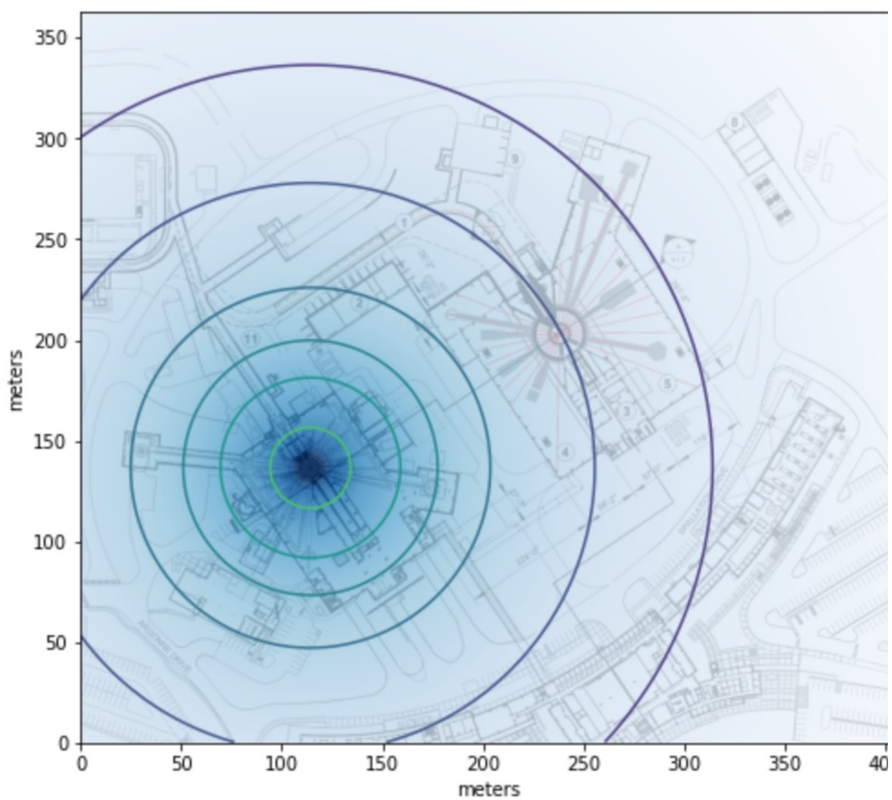
Assume L_{STS} = 20 m and L_{FTS} = 121 m, 10-t argon CEvNS detector

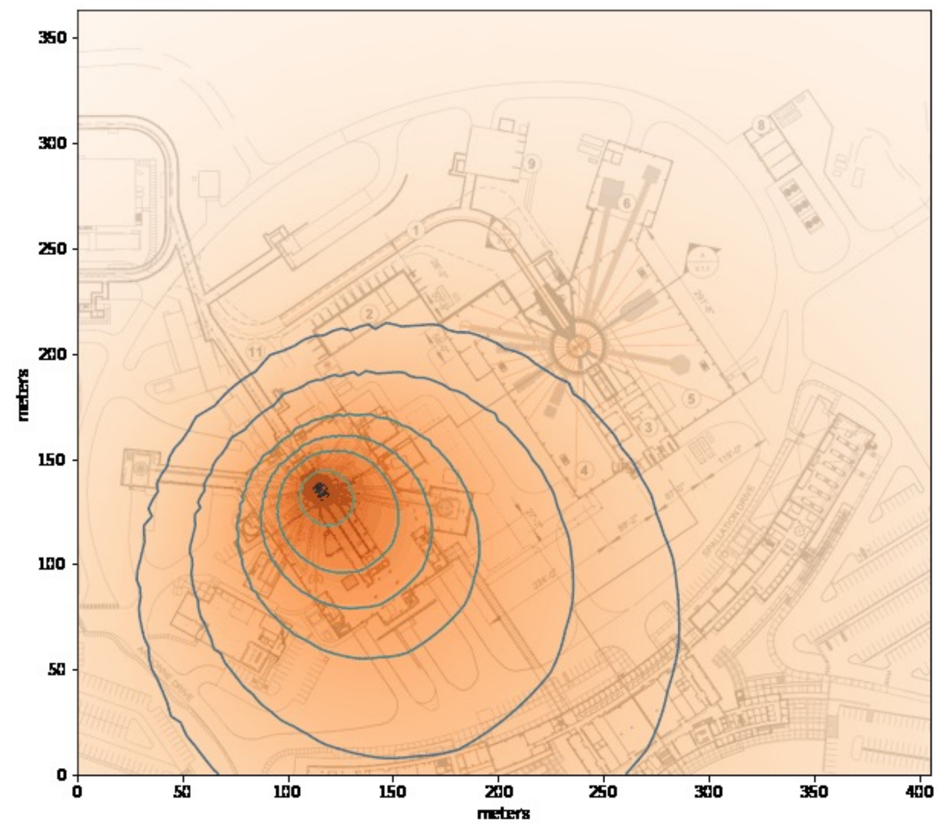
In 5 years, test ~entire parameter space allowed by LSND/MiniBooNE

Directionality of flux at the SNS

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

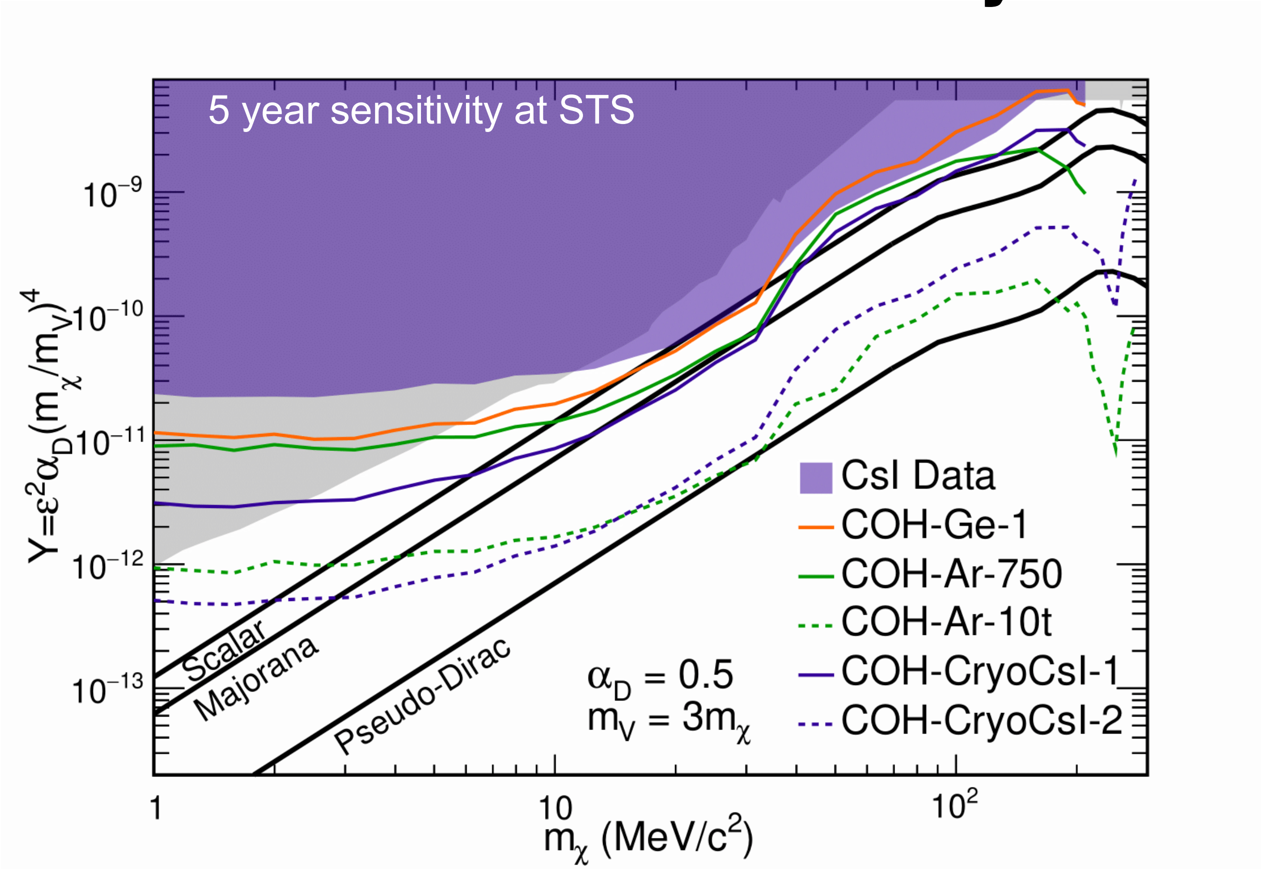
DM flux produced in-flight
is **boosted forward**





Can test angular dependence of boosted DM flux

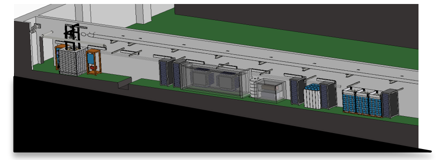
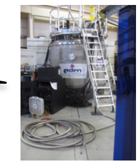
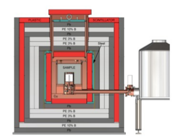
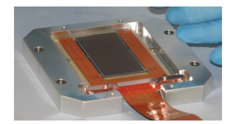
Future COHERENT sensitivity to dark matter

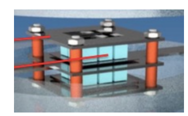


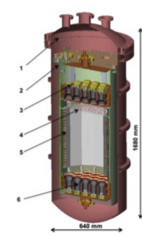
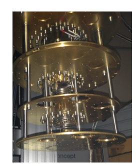
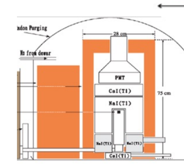
- **Short term:** Ge detector will explore scalar target at lower masses
- **Medium term**: large Ar, CsI detectors to lower DM flux sensitivity, probe of Majorana fermion target
- **Longer term:** large detectors placed forward at the STS (dashed lines) will test even pessimistic scenarios

Many CEvNS Efforts Worldwide [incomplete]

Experiment	Technology	Location	Source
COHERENT	CsI, Ar, Ge, NaI	USA	πDAR
CCM	Ar	USA	πDAR
ESS	CsI, Si, Ge, Xe	Sweden	πDAR
CONNIE	Si CCDs	Brazil	Reactor
CONUS	HPGe	Germany	Reactor
MINER	Ge/Si cryogenic	USA	Reactor
NUCLEUS	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe	Reactor
νGEN	Ge PPC	Russia	Reactor
RED-100	LXe dual phase	Russia	Reactor
Ricochet	Ge, Zn bolometers	France	Reactor
TEXONO	p-PCGe	Taiwan	Reactor

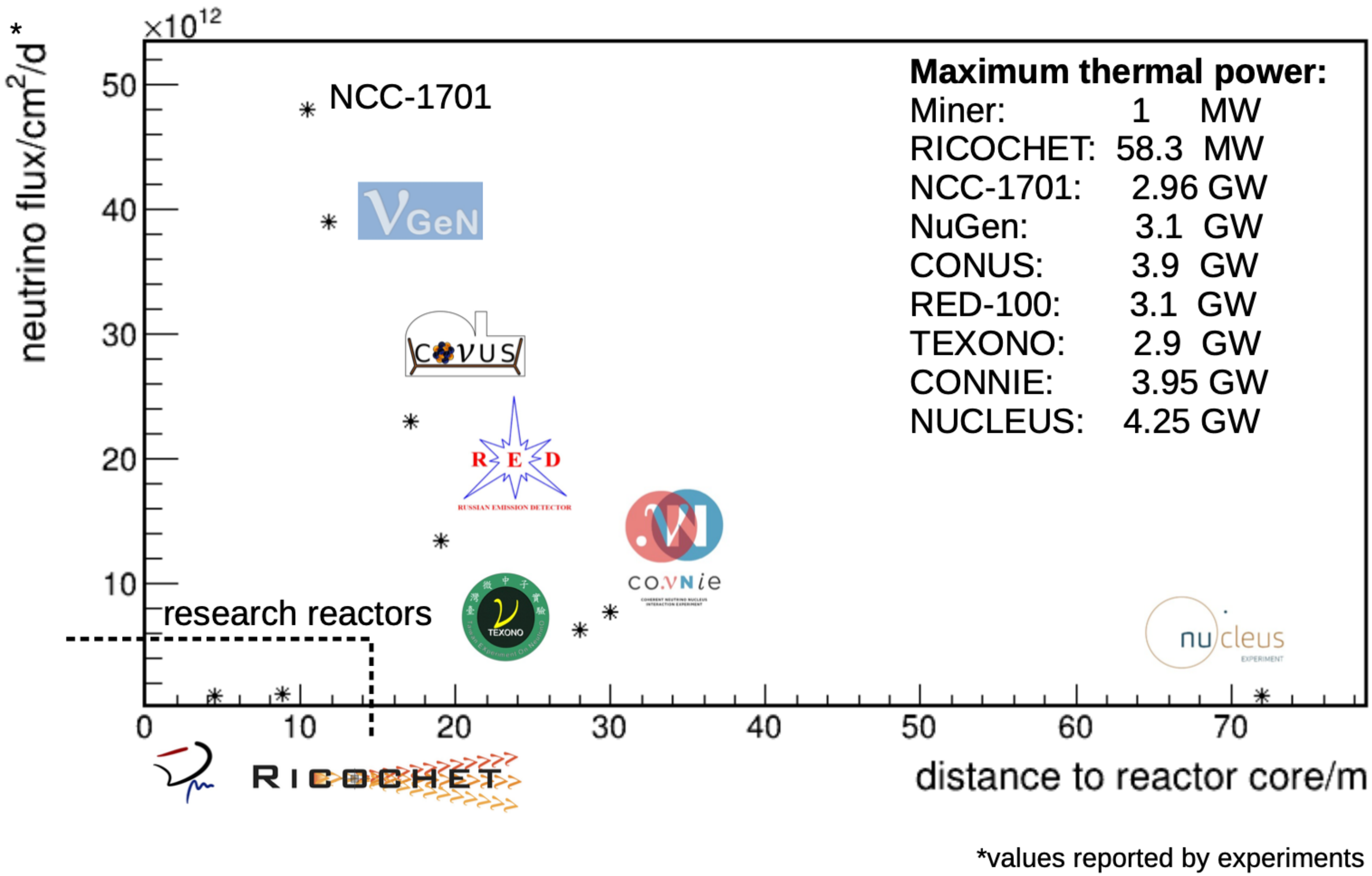


+ DM detectors, +directional detectors +more...(NEON, SBC...)

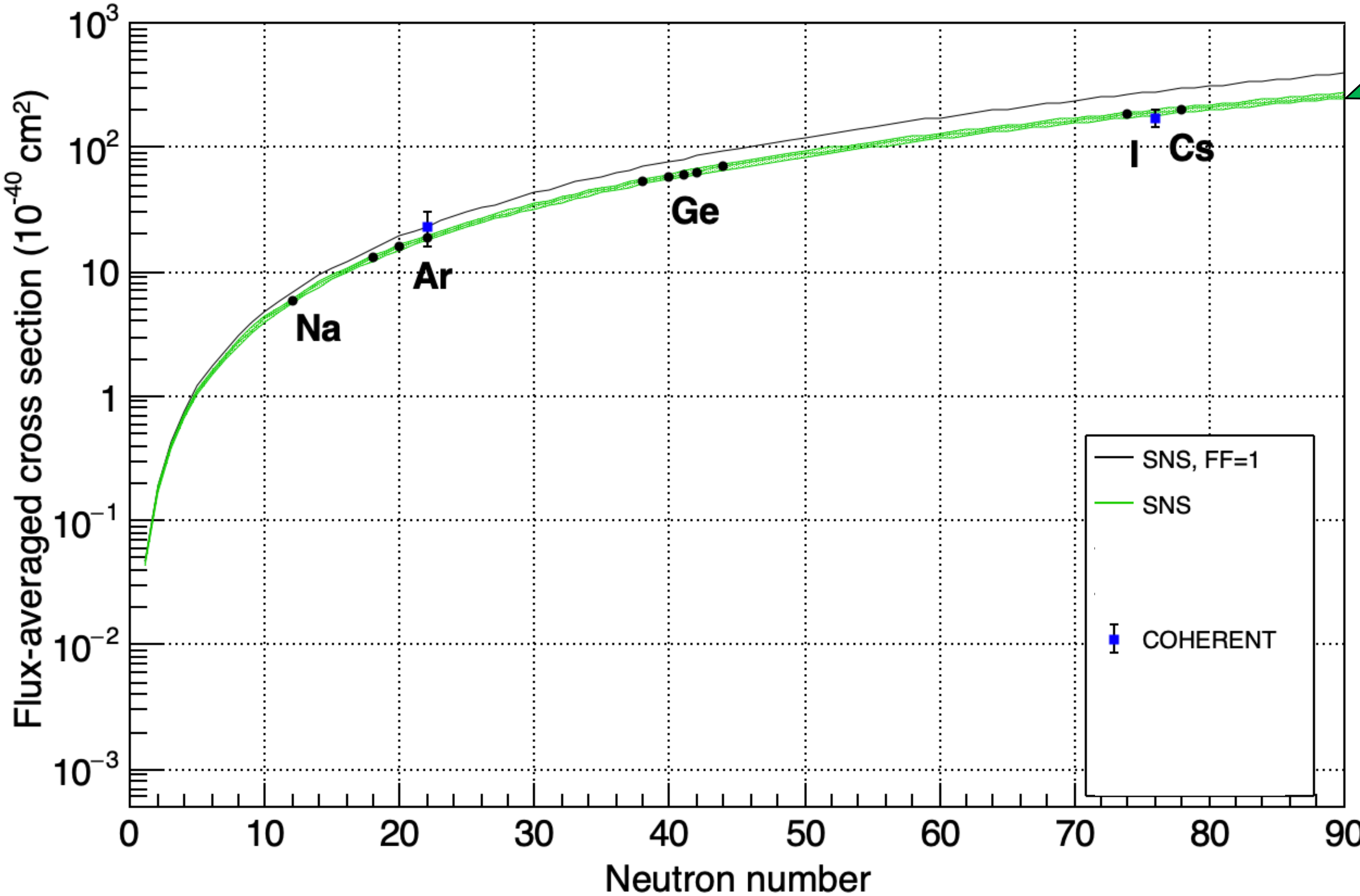
many novel low-background, low-threshold technologies!!

CEνNS detection at reactor



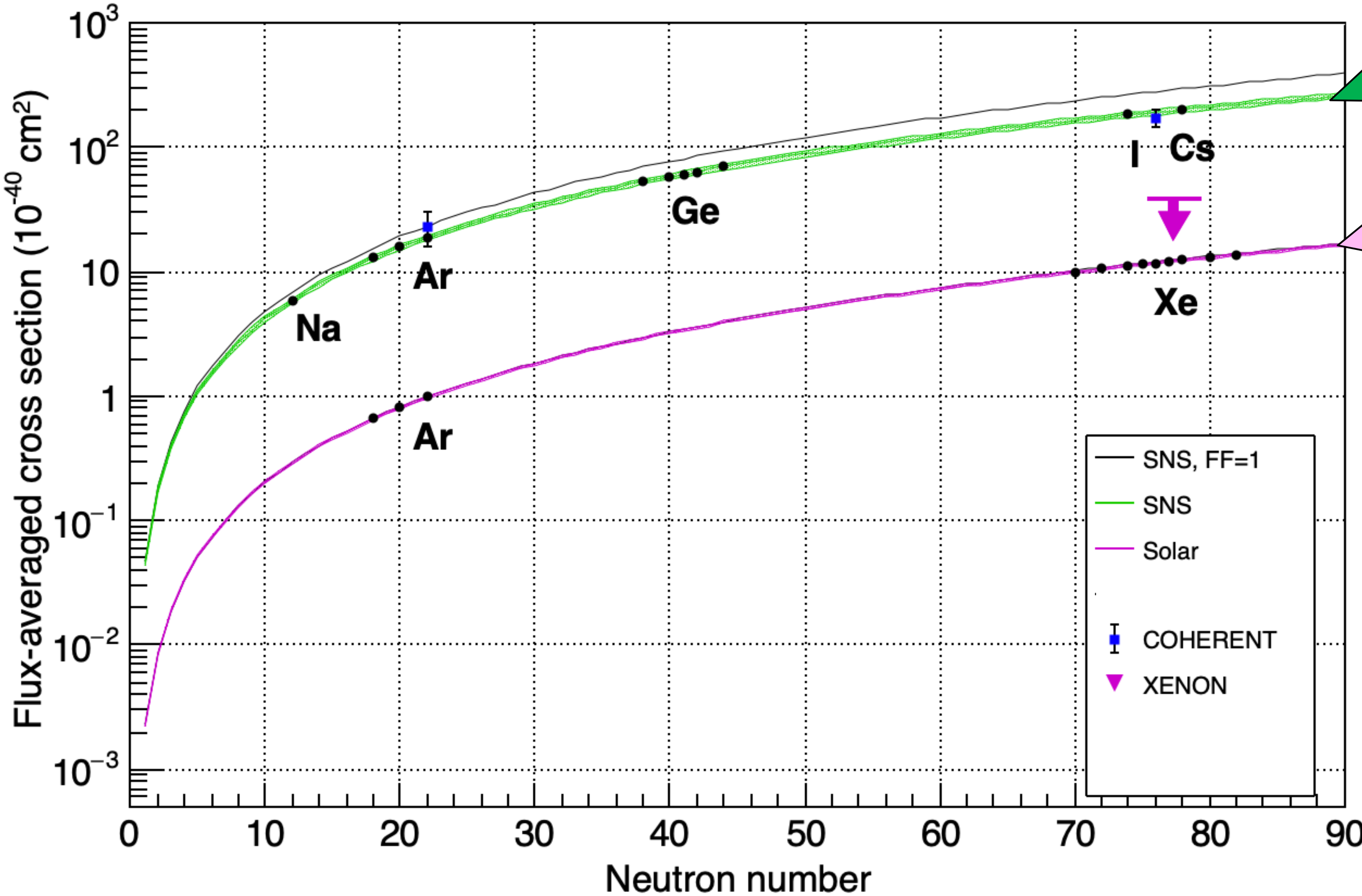
J. Hakenmuller, NDM 2022

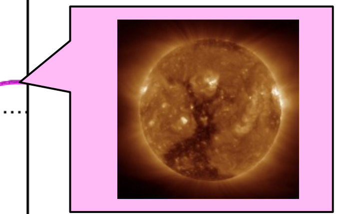
Summary of CEvNS Results



So far: measurements in CsI, Ar from COHERENT

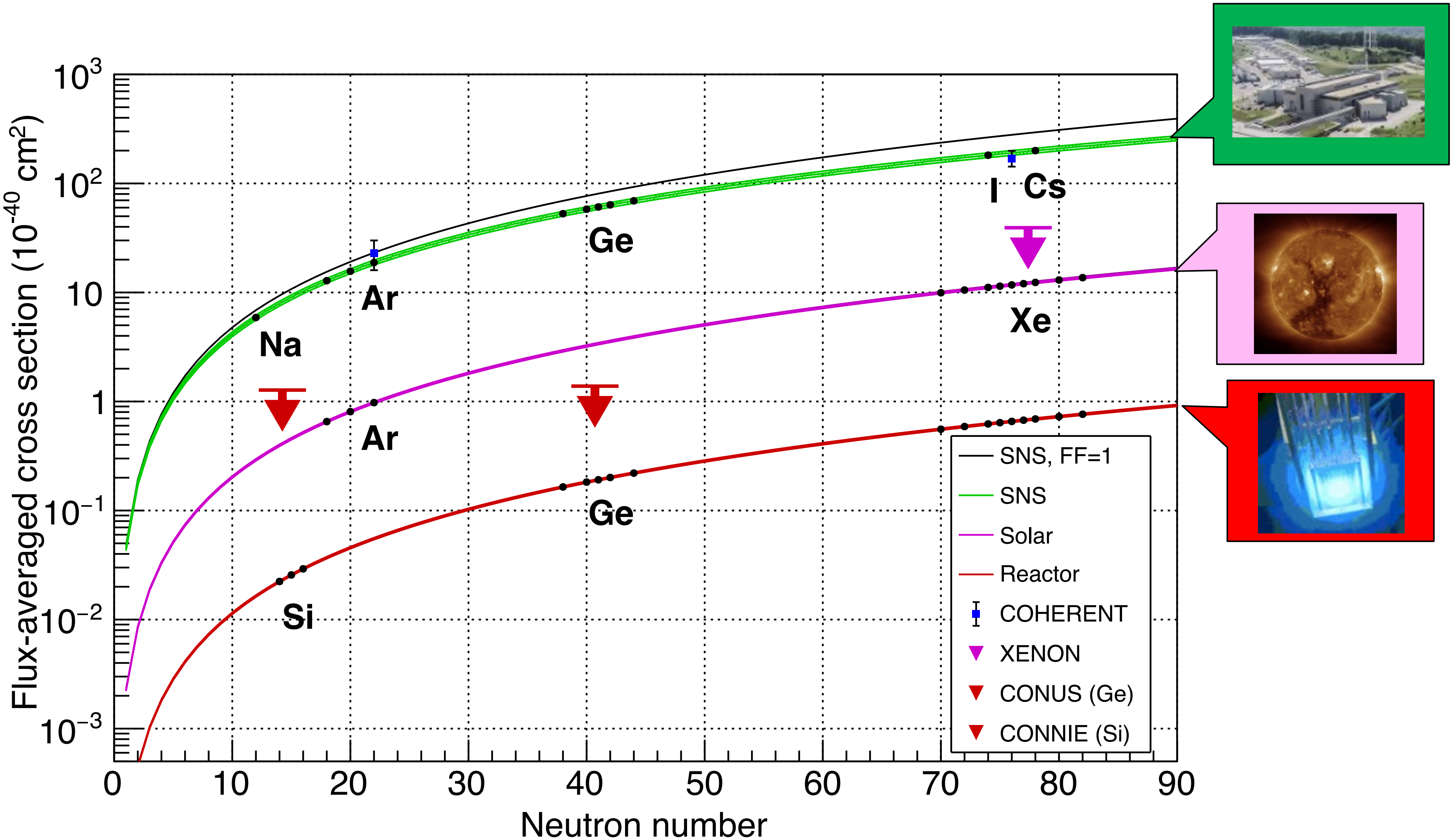
Summary of CEvNS Results





Limits from XENON on solar CEvNS

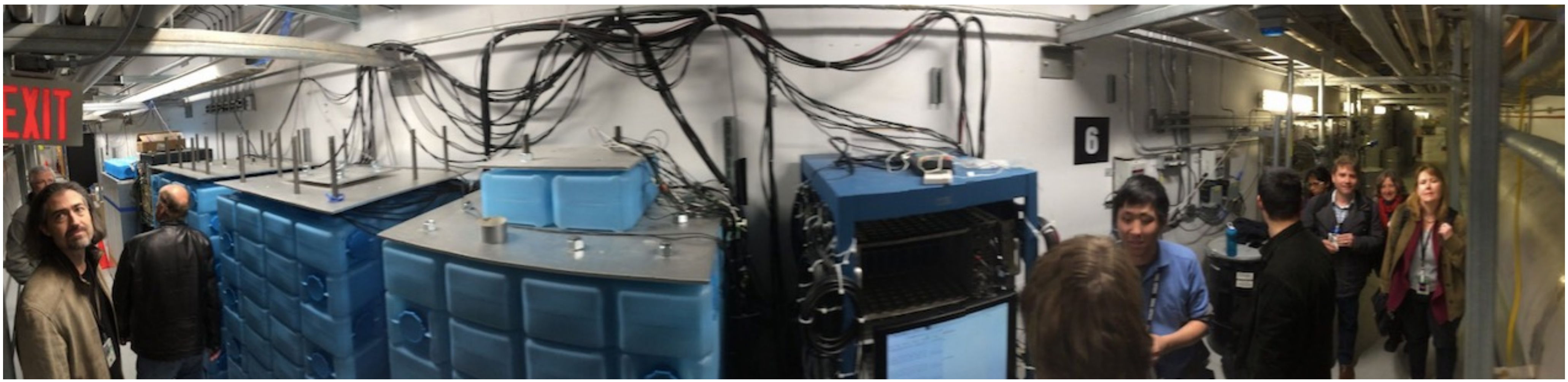
Summary of CEvNS Results



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

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, now Ar!
- **Meaningful bounds on beyond-the-SM physics**



- **It's still just the beginning....** more NaI+Ge+more 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...)