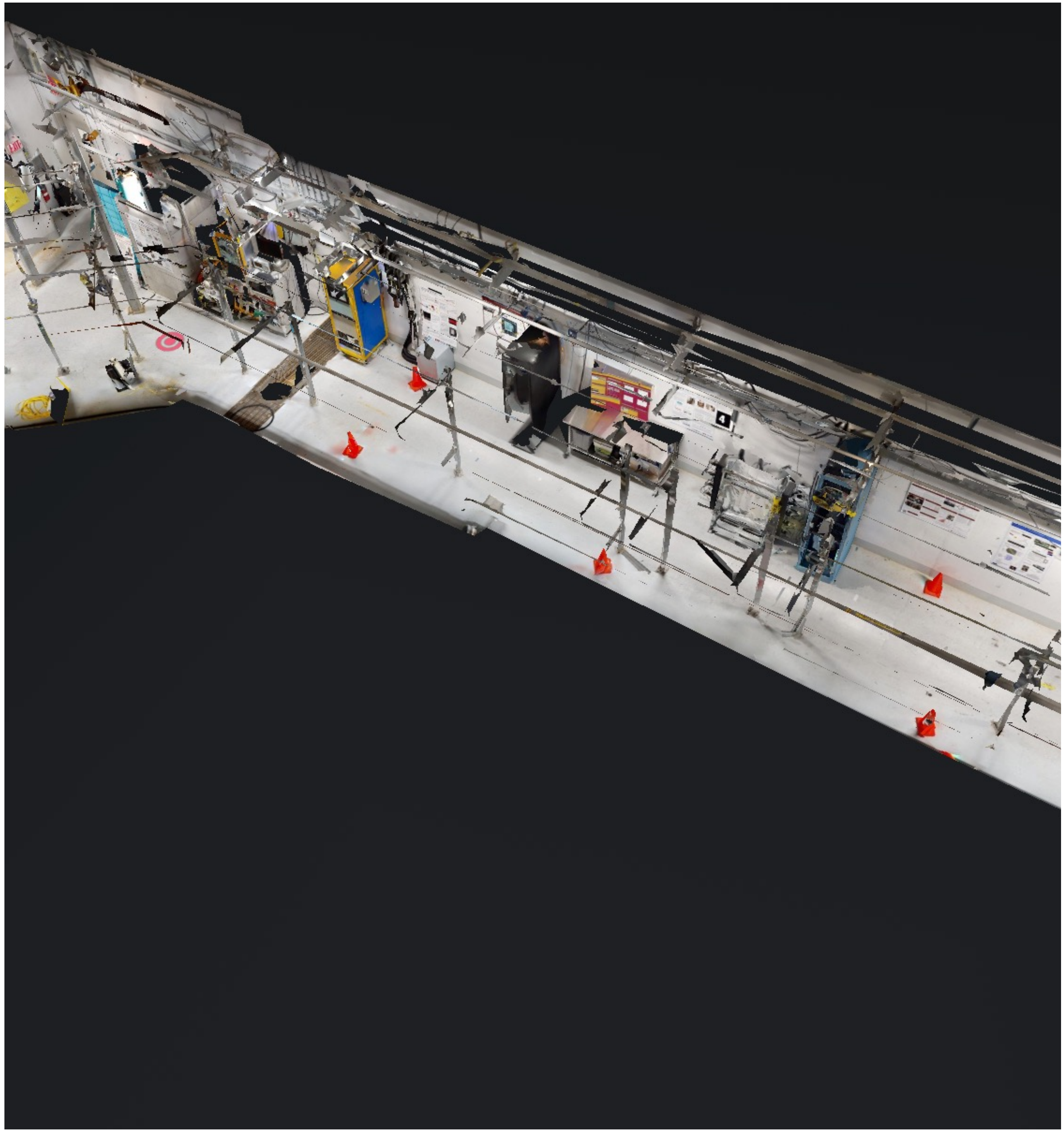
Coherent elastic neutrino nucleus scattering

Kate Scholberg,

Duke University

Precision Tests with Neutral-Current Coherent Interactions
MITP
May 26, 2022



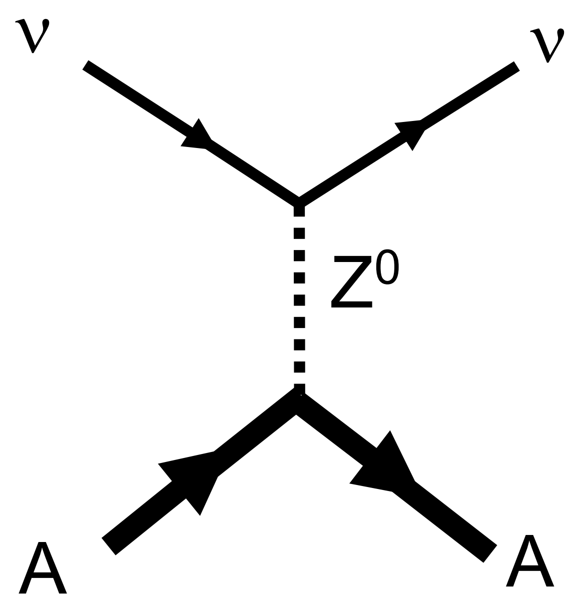
OUTLINE

-Coherent elastic neutrino-nucleus scattering
(CEvNS)

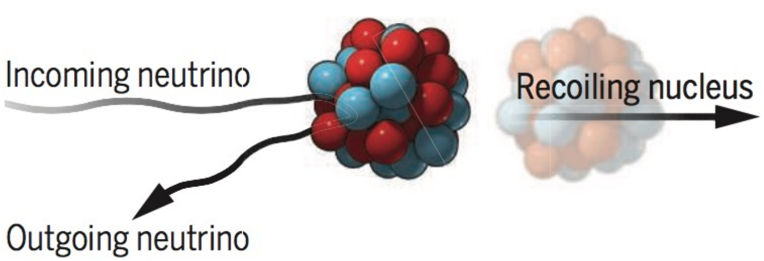
- Why measure it? Physics motivations
  (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
  - First light with CsI[Na]
  - Second measurement in Ar
  - And more data from CsI[Na]!
- Status and prospects for COHERENT
  - Opportunities at the STS
- Status and prospects for CEvNS worldwide

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

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

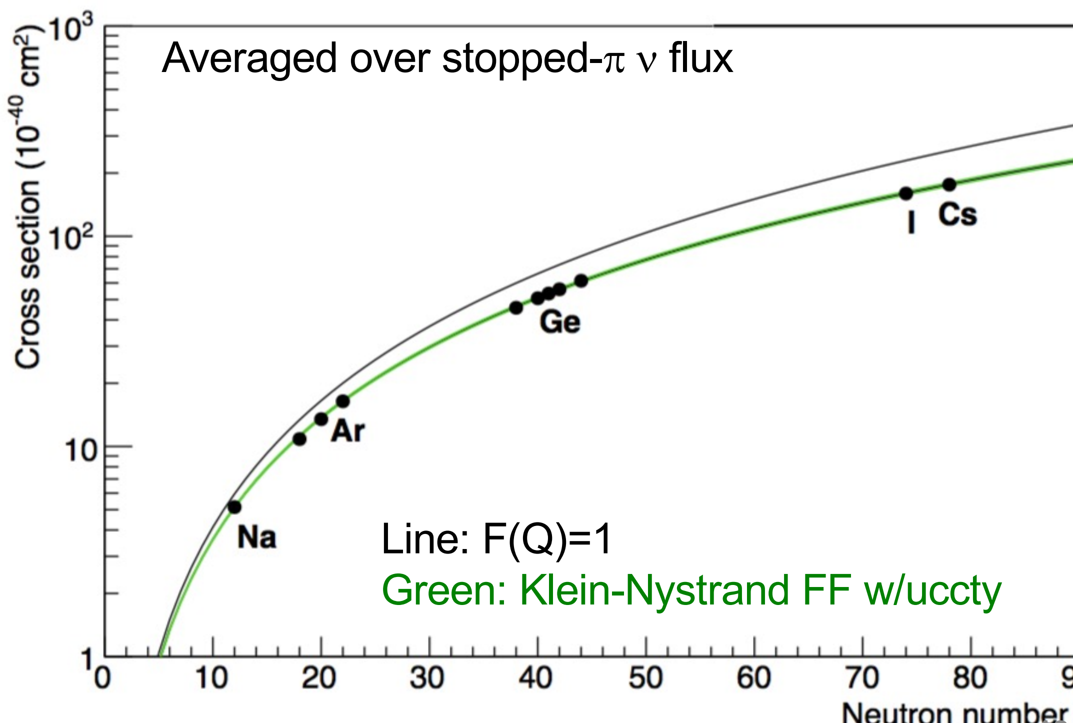
E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

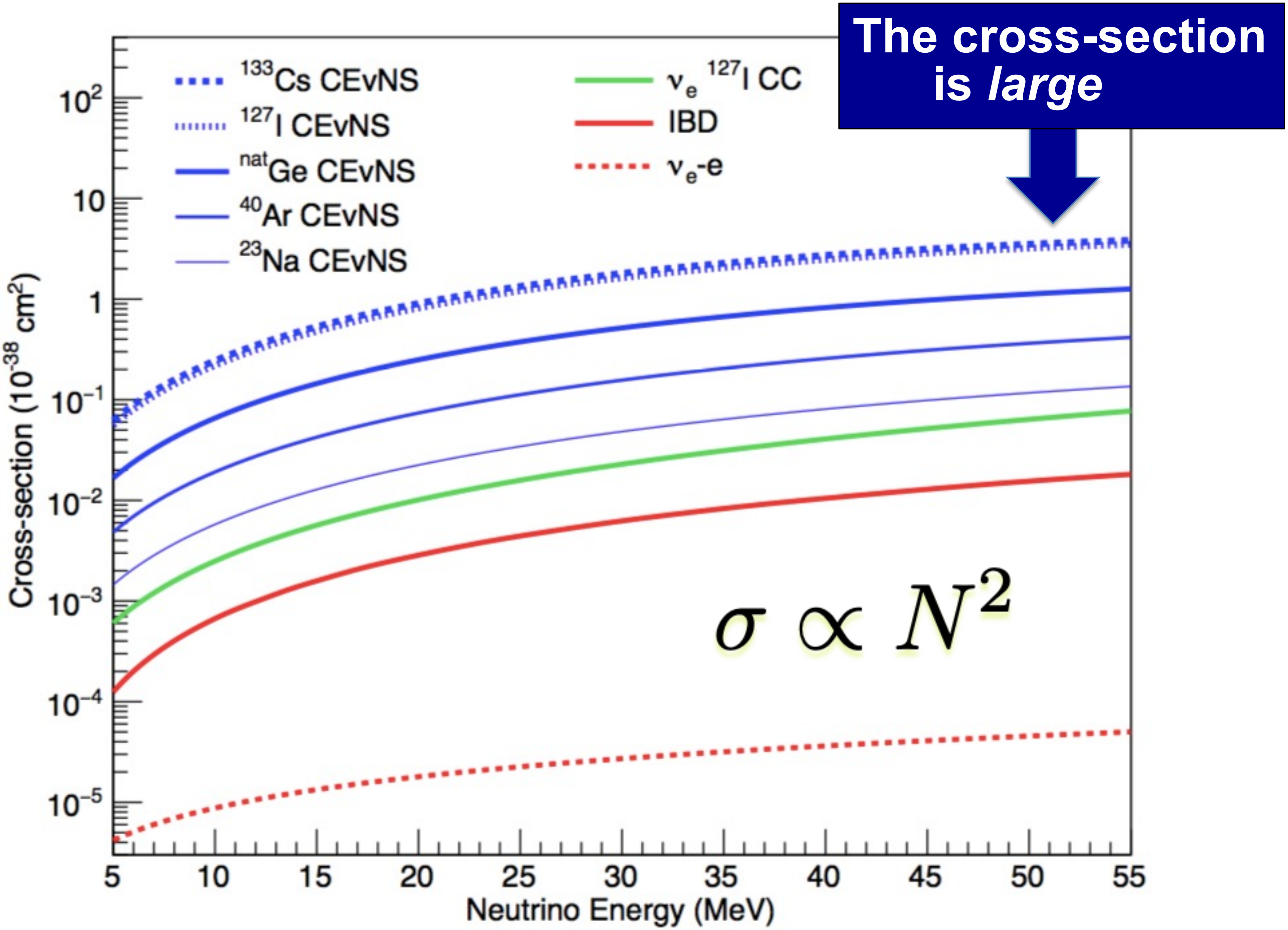
weak nuclear charge

Form factor: F=1 ➔ full coherence

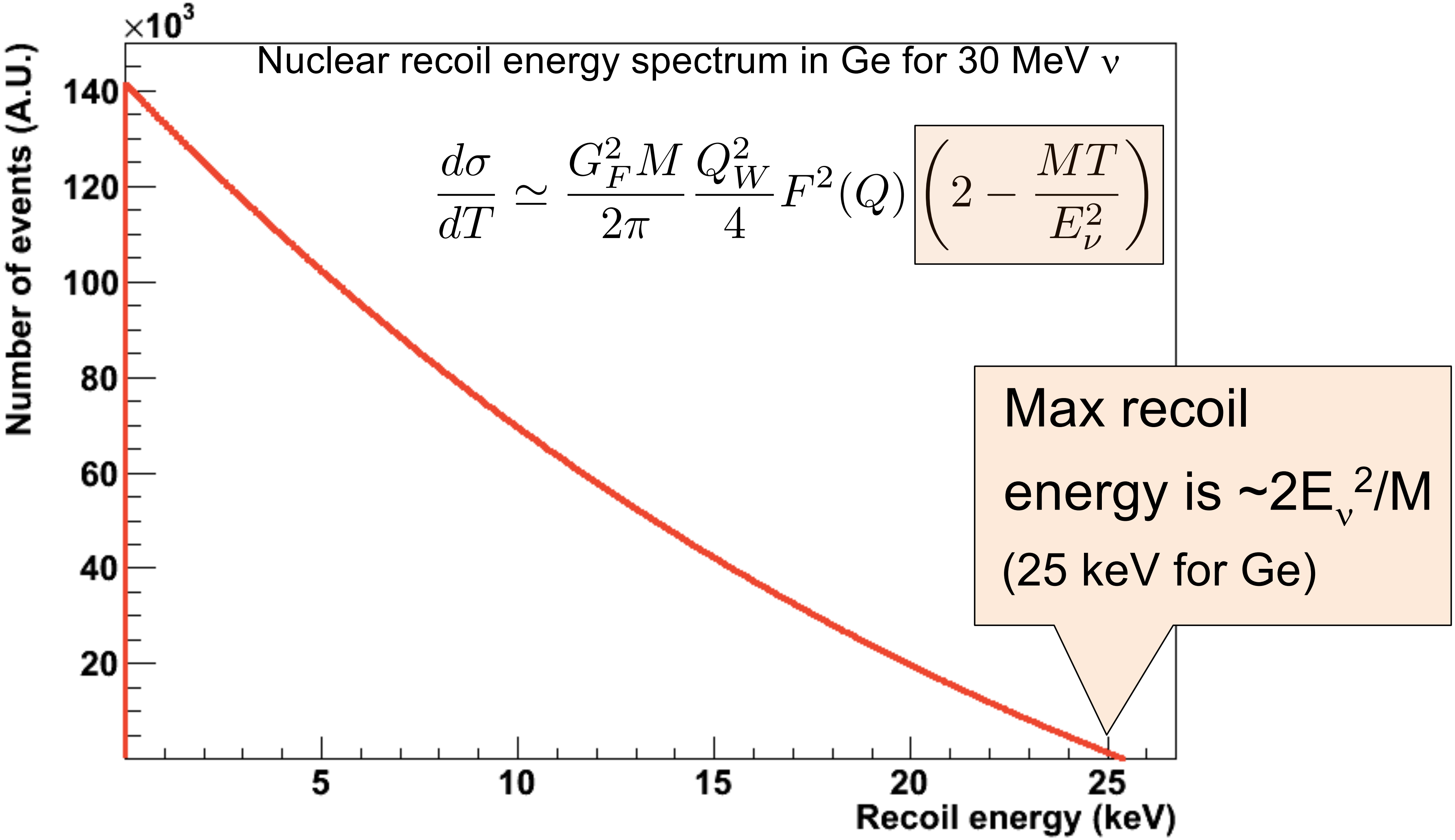
$$Q_W = (1 - 4\sin^2\theta_W)Z - N$$

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



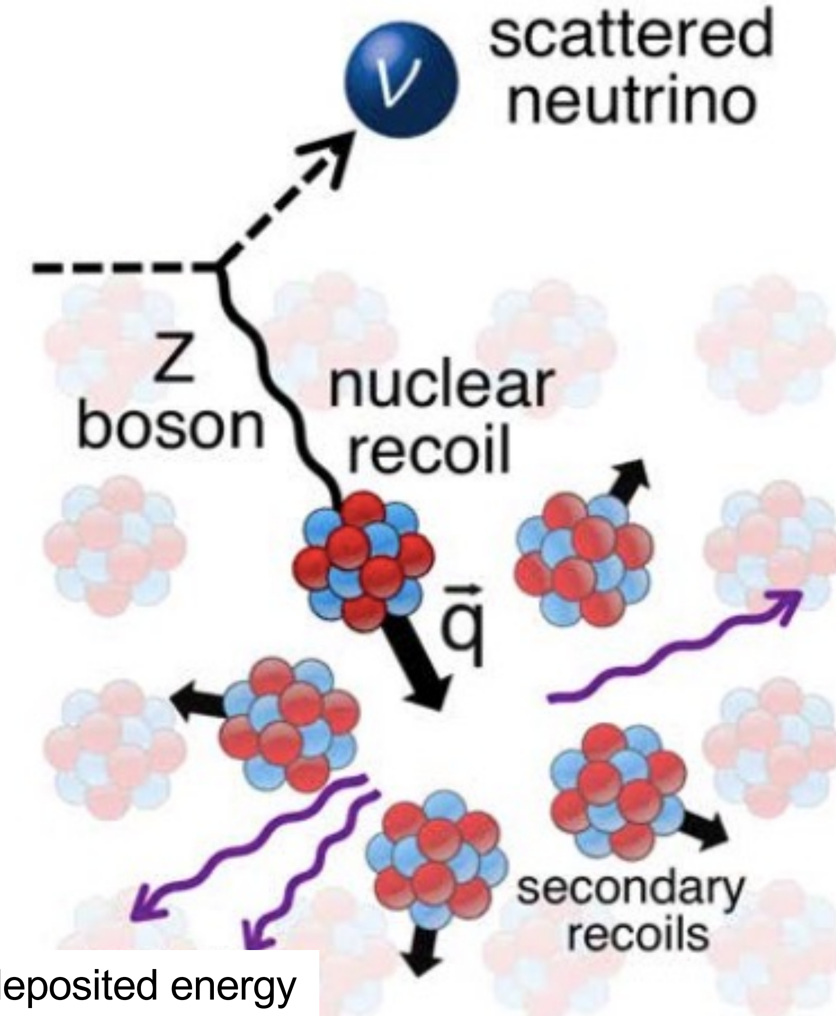

The cross-section is *large*
^{133}Cs CEvNS
^{127}I CEvNS
^{nat}Ge CEvNS
^{40}Ar CEvNS
^{23}Na CEvNS
ν_e ^{127}I CC
IBD
ν_e-e
$\sigma \propto N^2$
Cross-section (10^{-38} cm^2)
Neutrino Energy (MeV)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
5
10
15
20
25
30
35
40
45
50
55

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



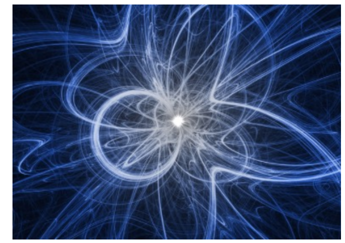
➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10’s of keV recoils

CEvNS: what's it good for?

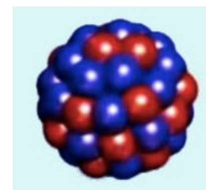
① So
② Many
③ Things
!

(not a complete list!)

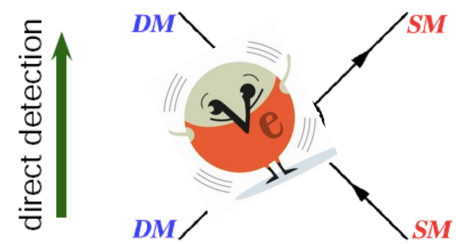
CEvNS as a **signal**
for signatures of *new physics*



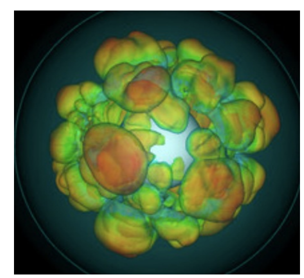
CEvNS as a **signal**
for understanding of "old" physics



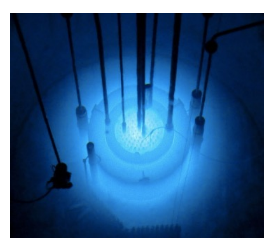
CEvNS as a **background**
for signatures of new physics



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



CEvNS as a **practical tool**



CEvNS: what's it good for?

! (not a complete list!)

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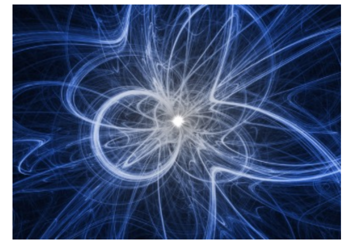

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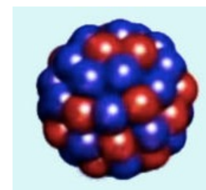

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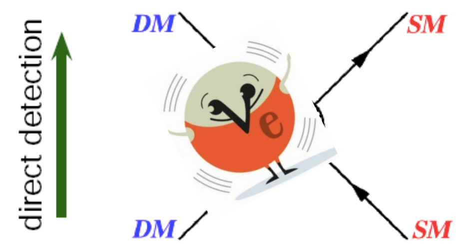

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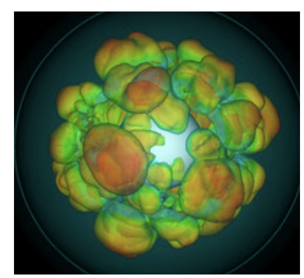
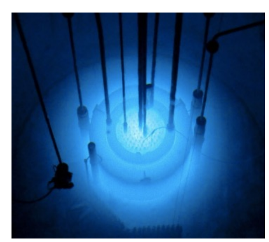


CEvNS as a **practical tool**



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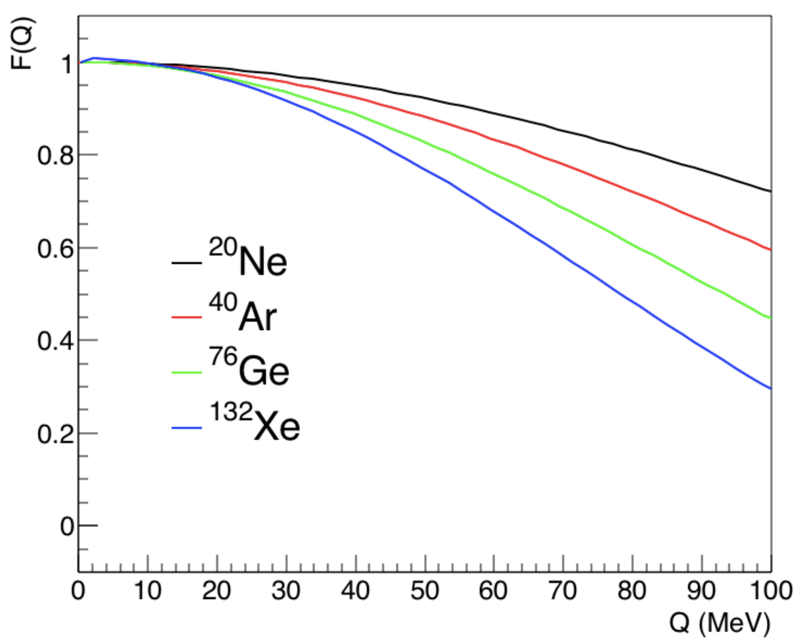
F(Q): nuclear **form factor**, <~5% uncertainty on event rate

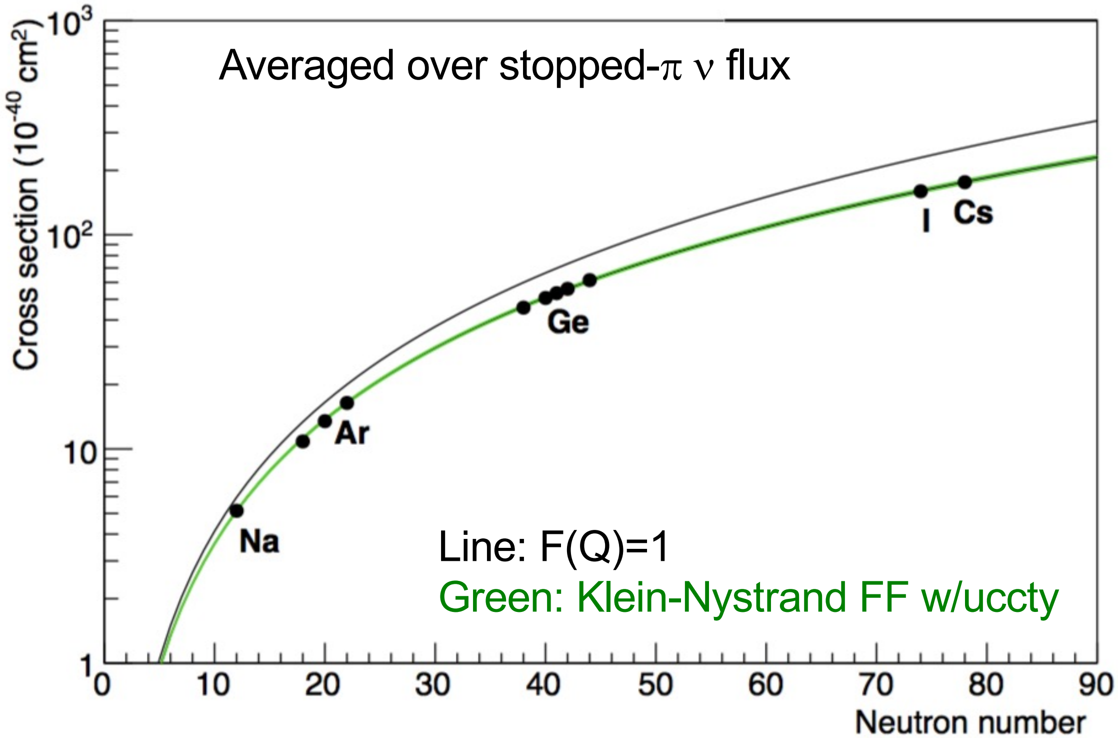


form factor suppresses cross section at large Q

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

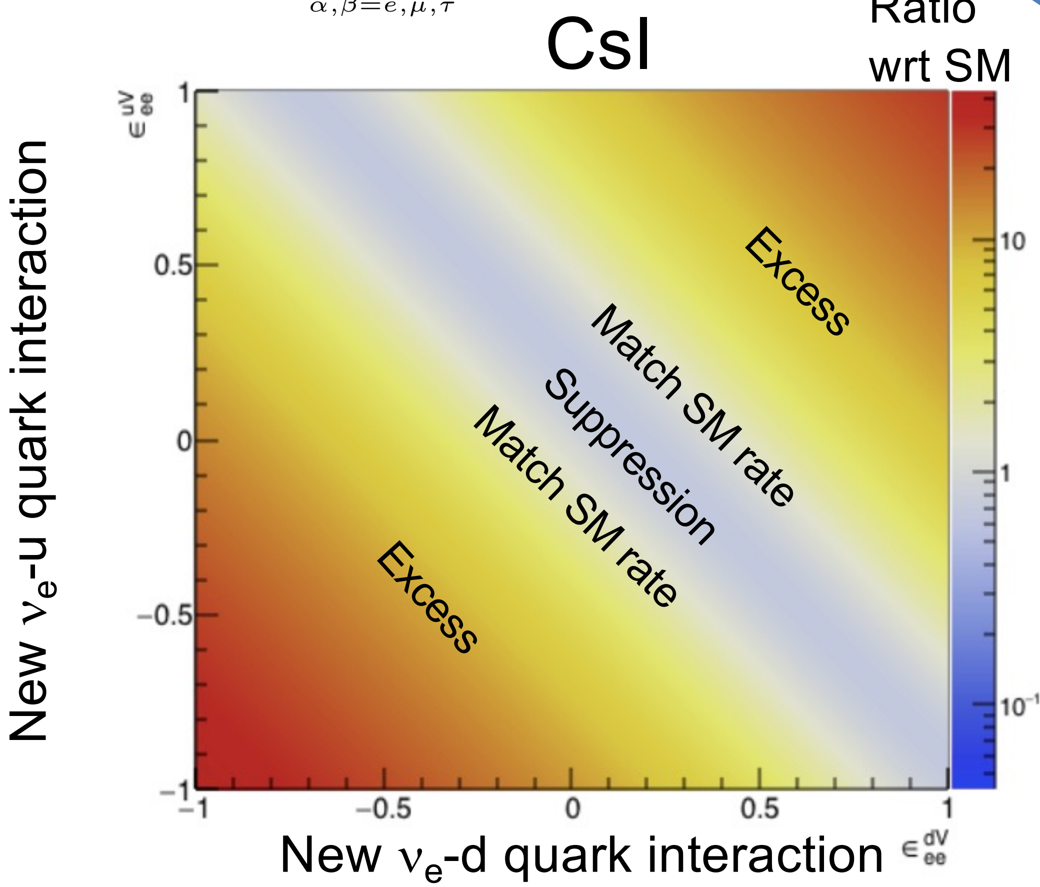


A deviation from α N^2 prediction can be a signature of beyond-the-SM physics

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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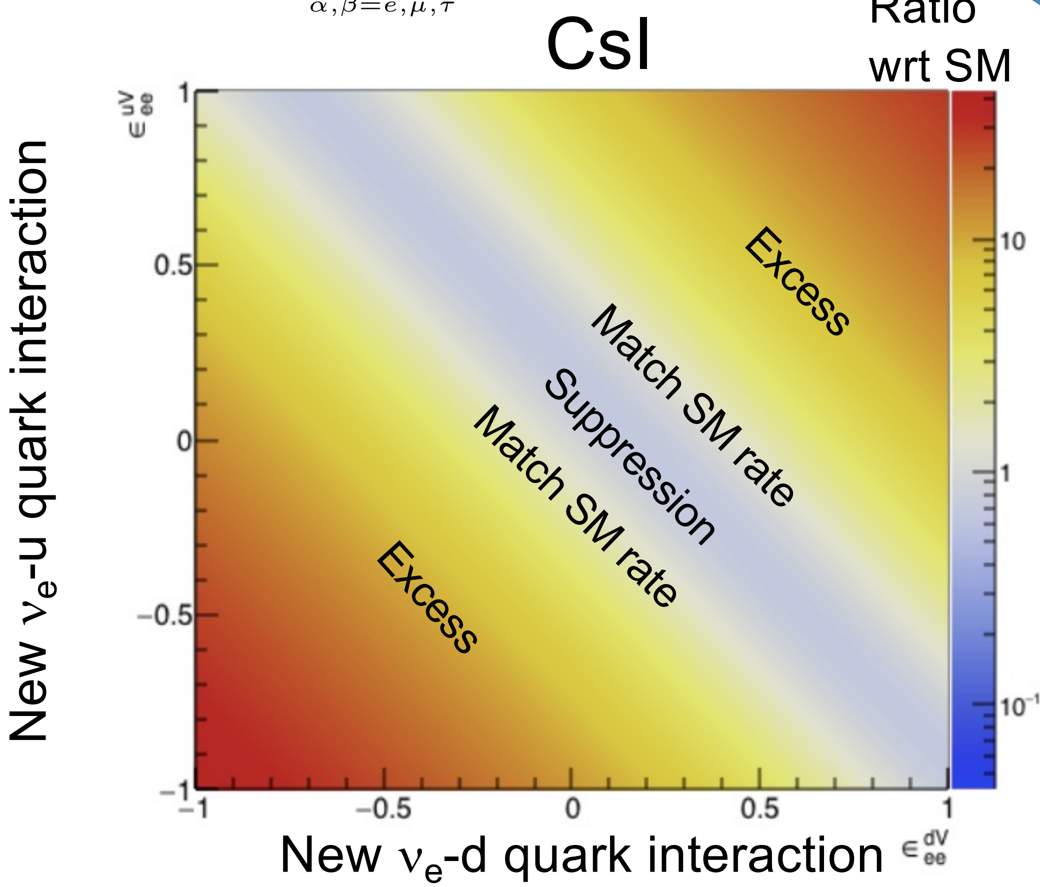

If these ε's are ~unity, there is a new interaction of ~Standard-model size... many not currently well constrained

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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

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

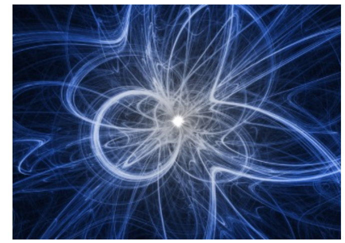
"True" disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

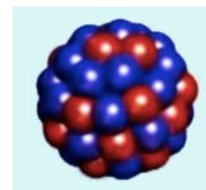
CEvNS: what's it good for?

! (not a complete list!)

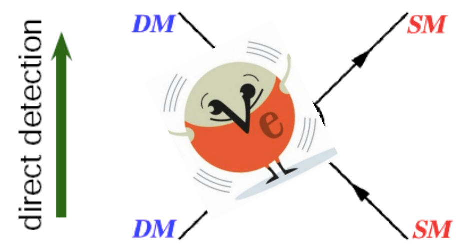
CEvNS as a **signal**
for signatures of *new physics*

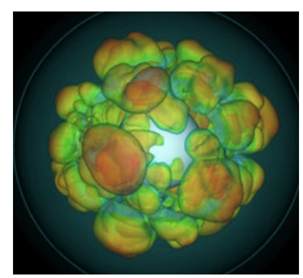


CEvNS as a **signal**
for understanding of "old" physics



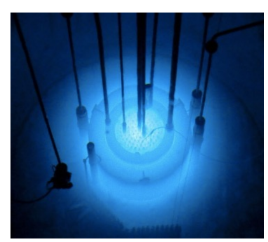
CEvNS as a **background**
for signatures of new physics



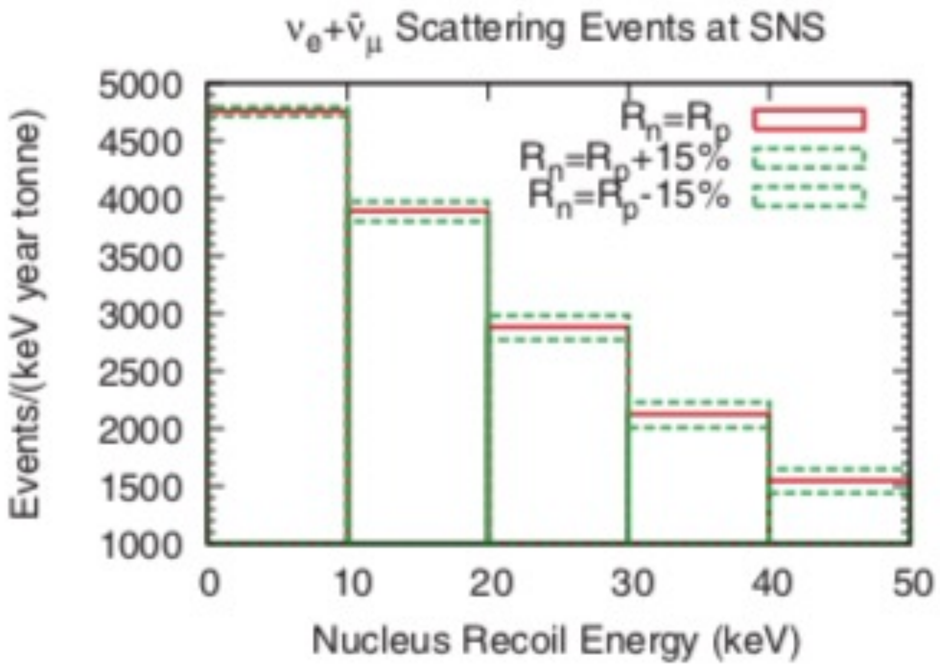


CEvNS as a **signal** for *astrophysics*

CEvNS as a **practical tool**



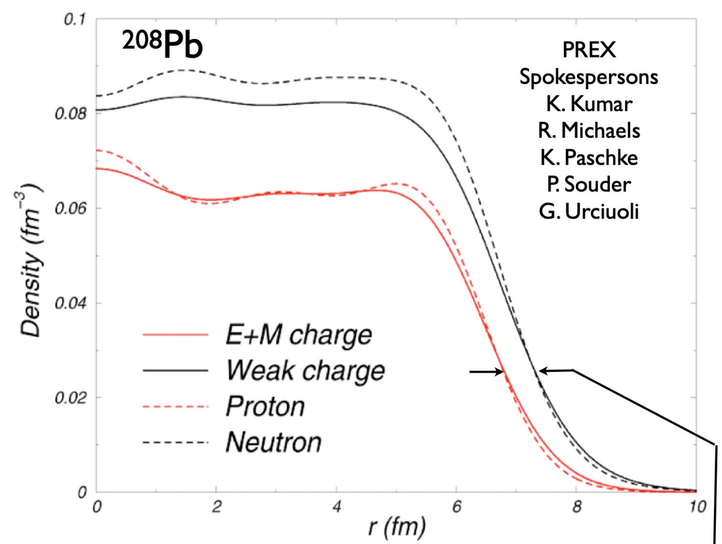
What can we learn about **nuclear physics** with CEvNS**?**



Amanik & McLaughlin, *J.Phys.G* 36 (2009) 015105

Observable is **recoil spectrum shape**

Neutron radius and skin (R_n-R_p) relevant for understanding of neutron stars, and more...



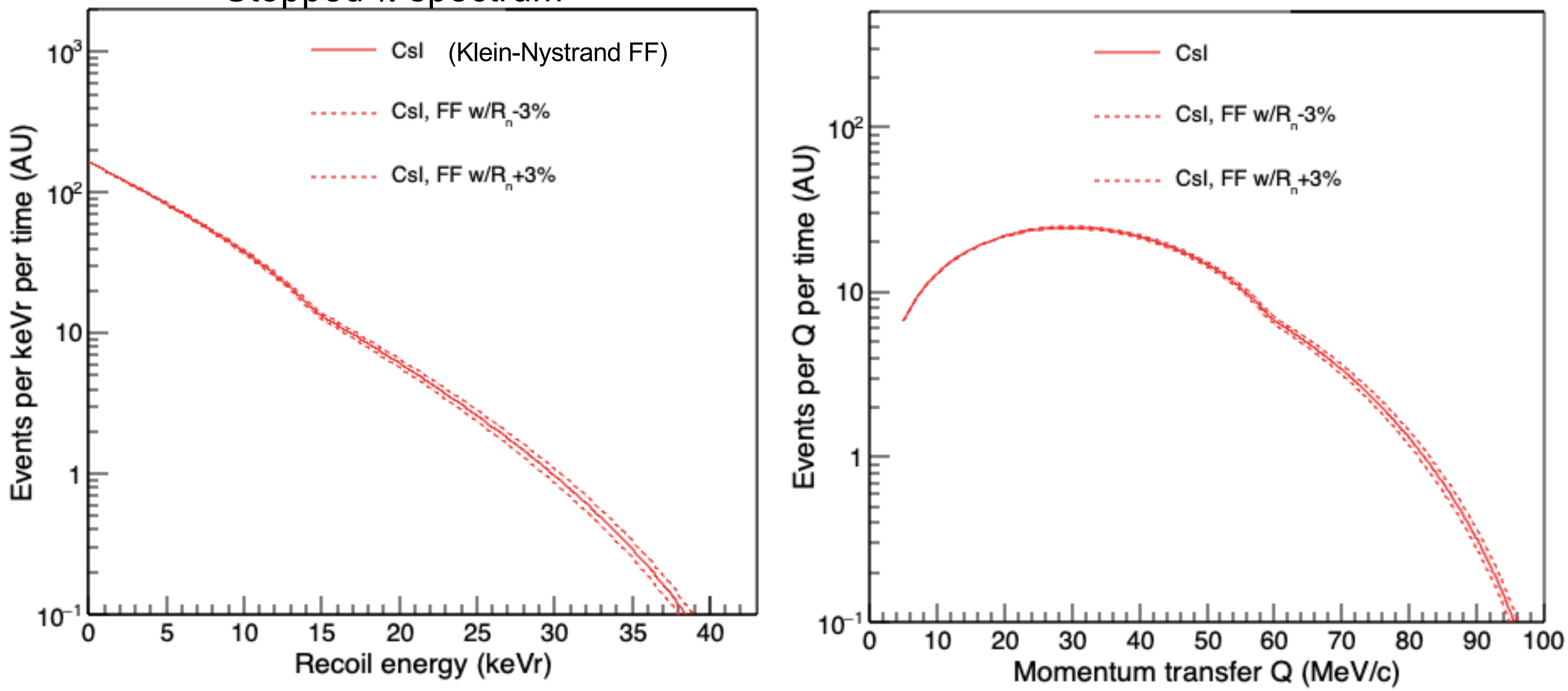
- PREX measures how much neutrons stick out past protons (neutron skin).

C. Horowitz

Effect of form-factor *theoretical uncertainty* on the recoil spectrum: estimate as R_n +/- 3%

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

Stopped-π spectrum



At current level of experimental precision, form factor uncertainty is small effect

So: if you are hunting for BSM physics
as a distortion of the recoil spectrum
… **uncertainties in the form factor are a nuisance!**

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

↔

and "new" physics

Currently experimental uncertainty > form factor uncertainty
... but we will need to think carefully about how to
disentangle these effects and understand uncertainties,
for the longer term

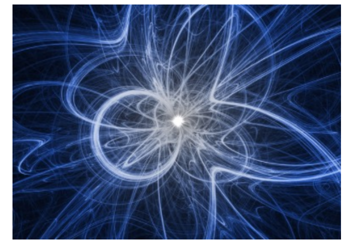
[See e.g.: D. Aristizabal Sierra et al. arXiv:1902.07398]

CEvNS: what's it good for?

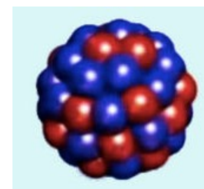
!

(not a complete list!)

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

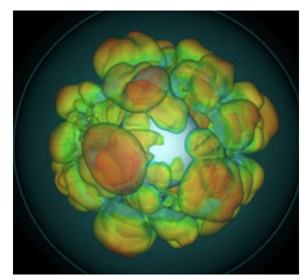


CEvNS as a **signal**
for understanding of "old" physics

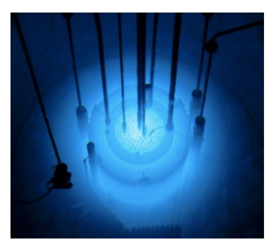


CEvNS as a **background**
for signatures of new physics (DM)

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



CEvNS as a **practical tool**



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

(CEvNS is *background*)

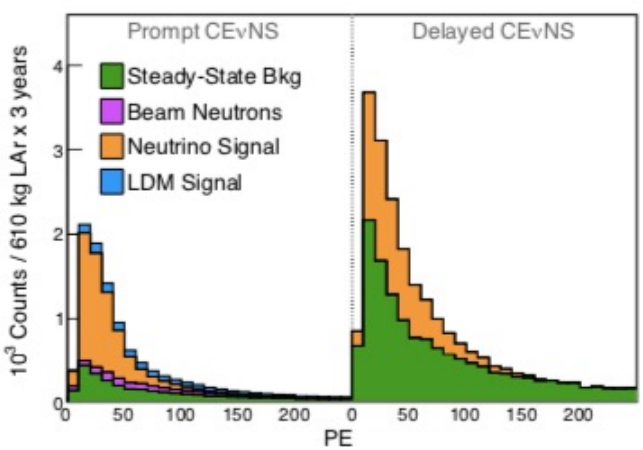
- "Vector portal": mixing of vector mediator with photons in π^0/η^0 decays
- "Leptophobic portal": new mediator coupling to baryons

} 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

Summary of what we can get at experimentally

Observables:

Event rate

Recoil spectrum ($T=Q^2/2M$)

[In principle: scattering angle... hard]

Spectral shape systematics are hard!

Knowable/controllable parameters:

Neutrino flavor, via source, and timing

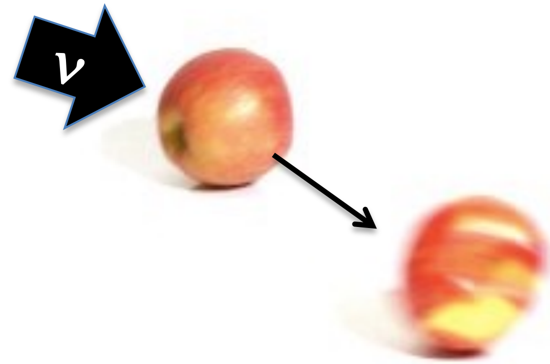
(reactor: ν_e-bar, stopped-π: ν_e, ν_μ-bar, ν_μ)

N, Z via nuclear target type

Baseline

Direction with respect to source

How to detect CEvNS?

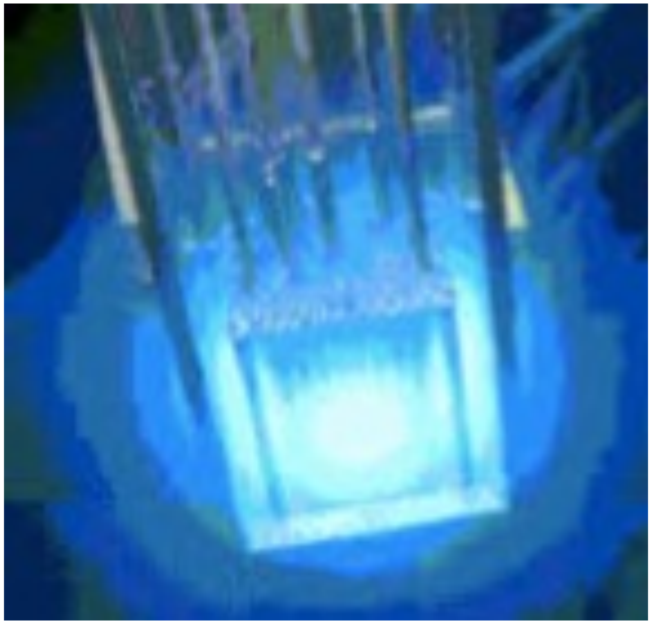


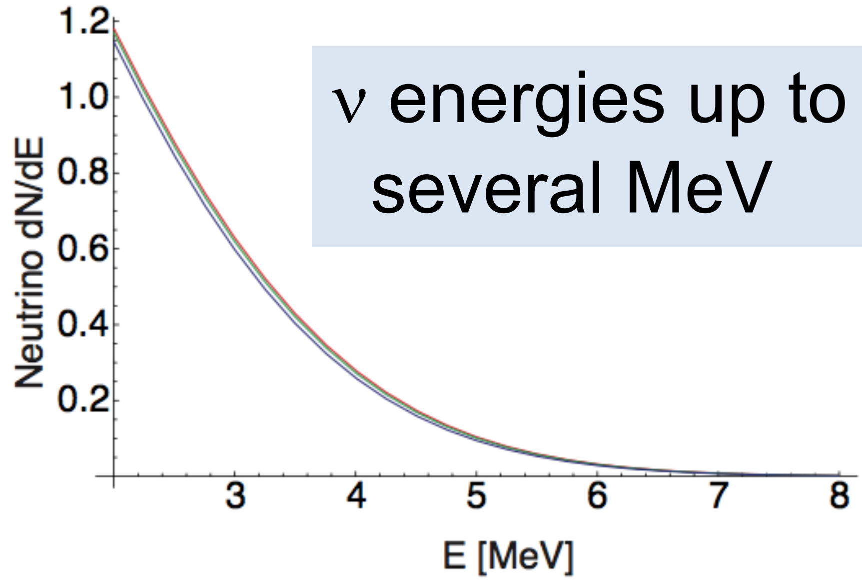
You need a neutrino source
and a detector

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

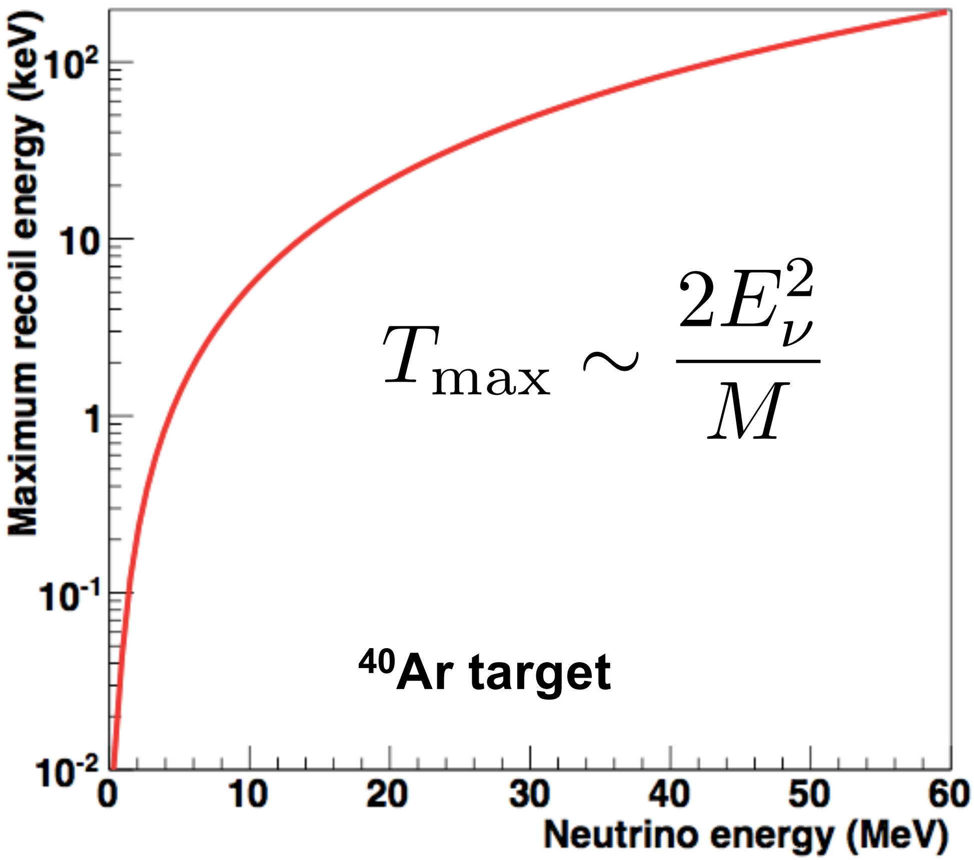


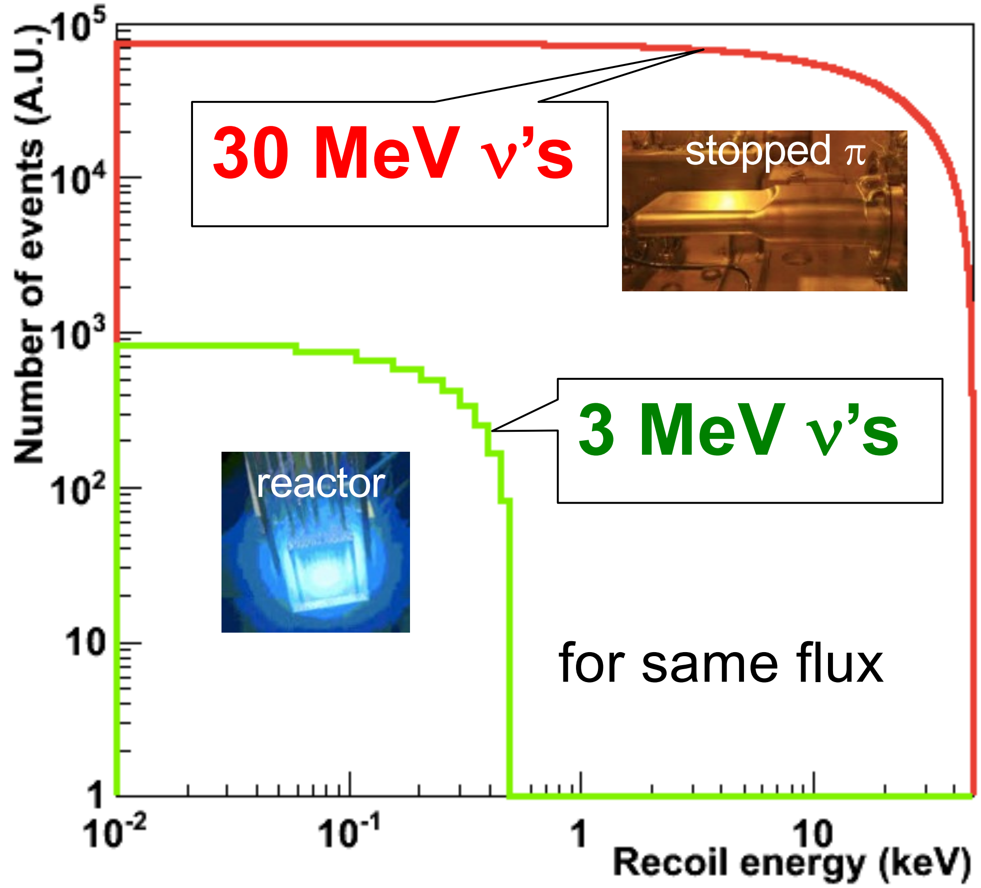


ν energies up to several MeV

- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2×10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

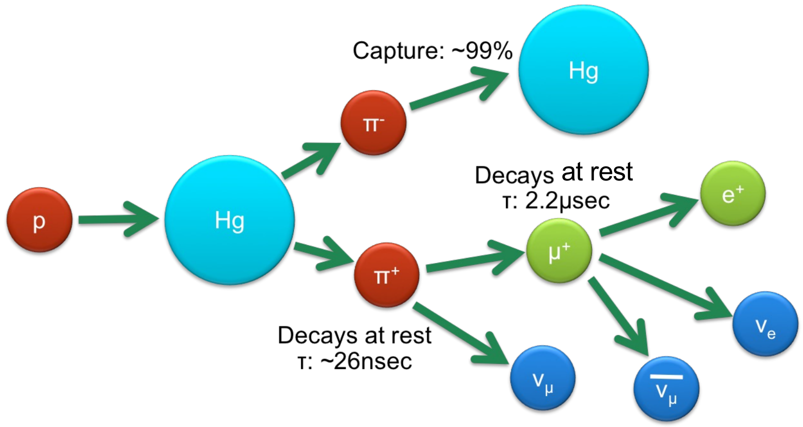
Both **cross-section** and **maximum recoil energy** **increase with neutrino energy**:

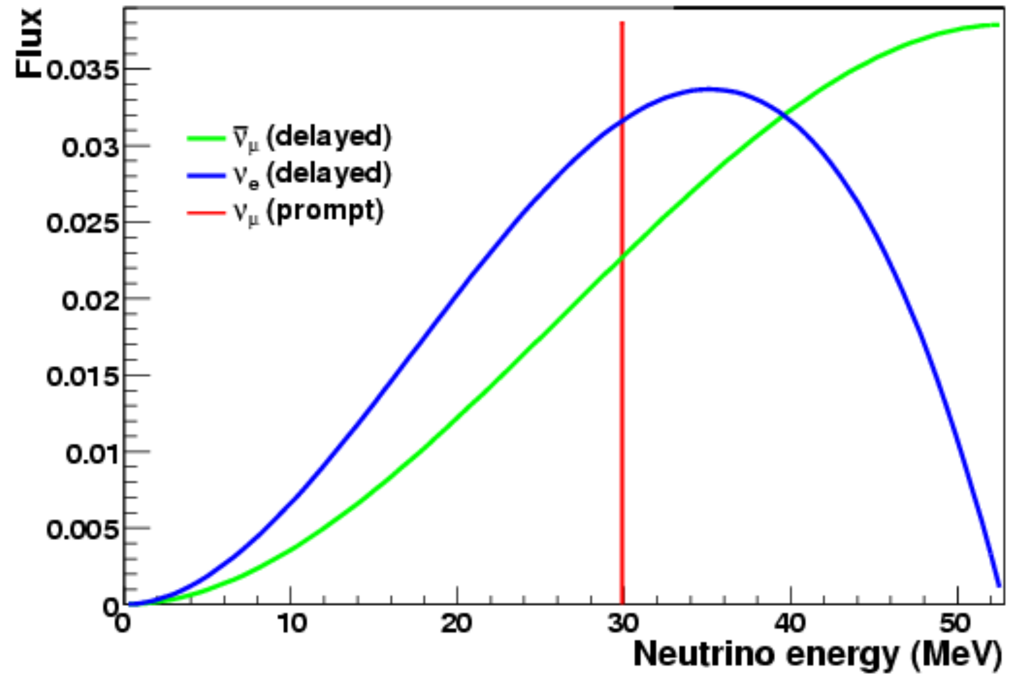




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





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

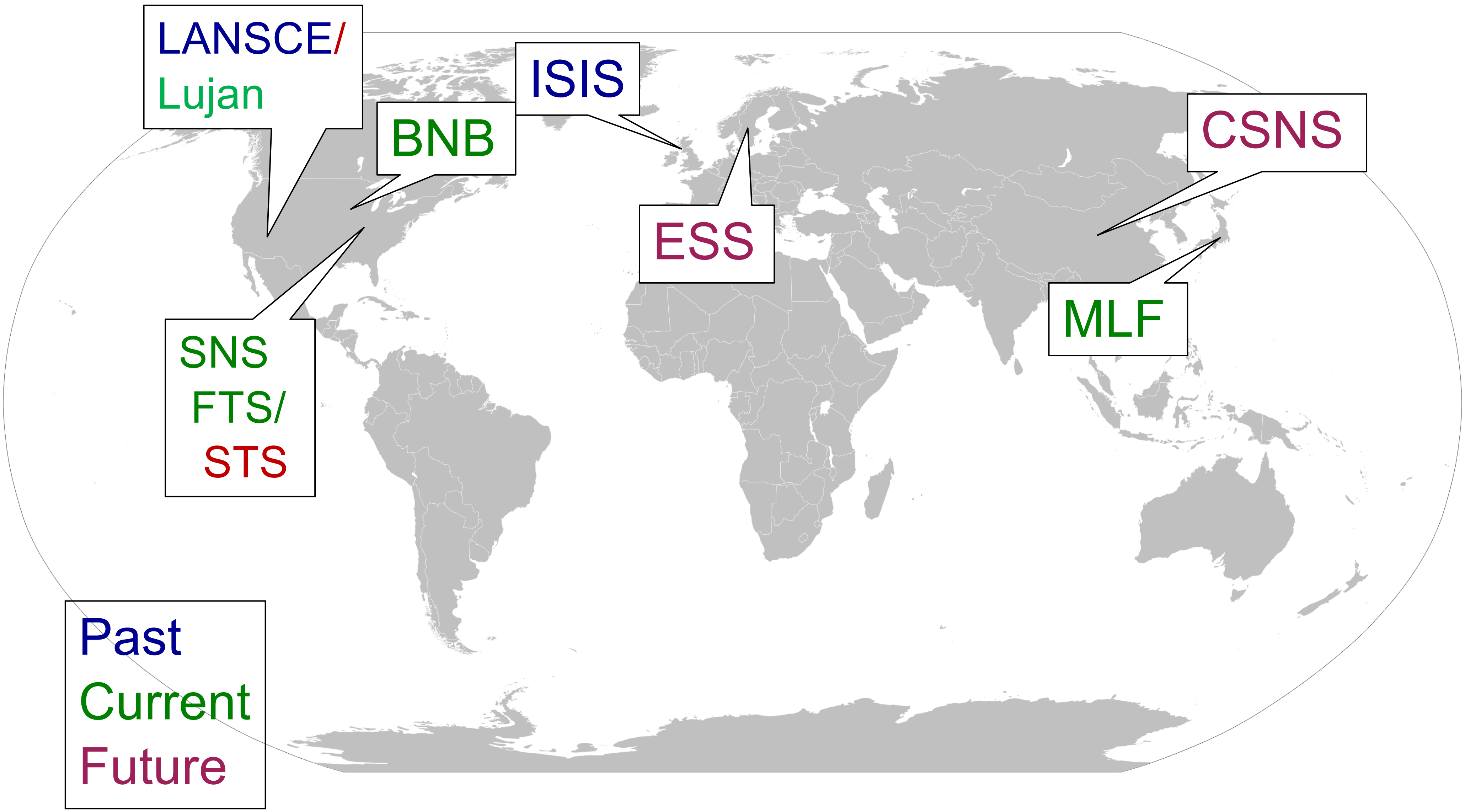
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

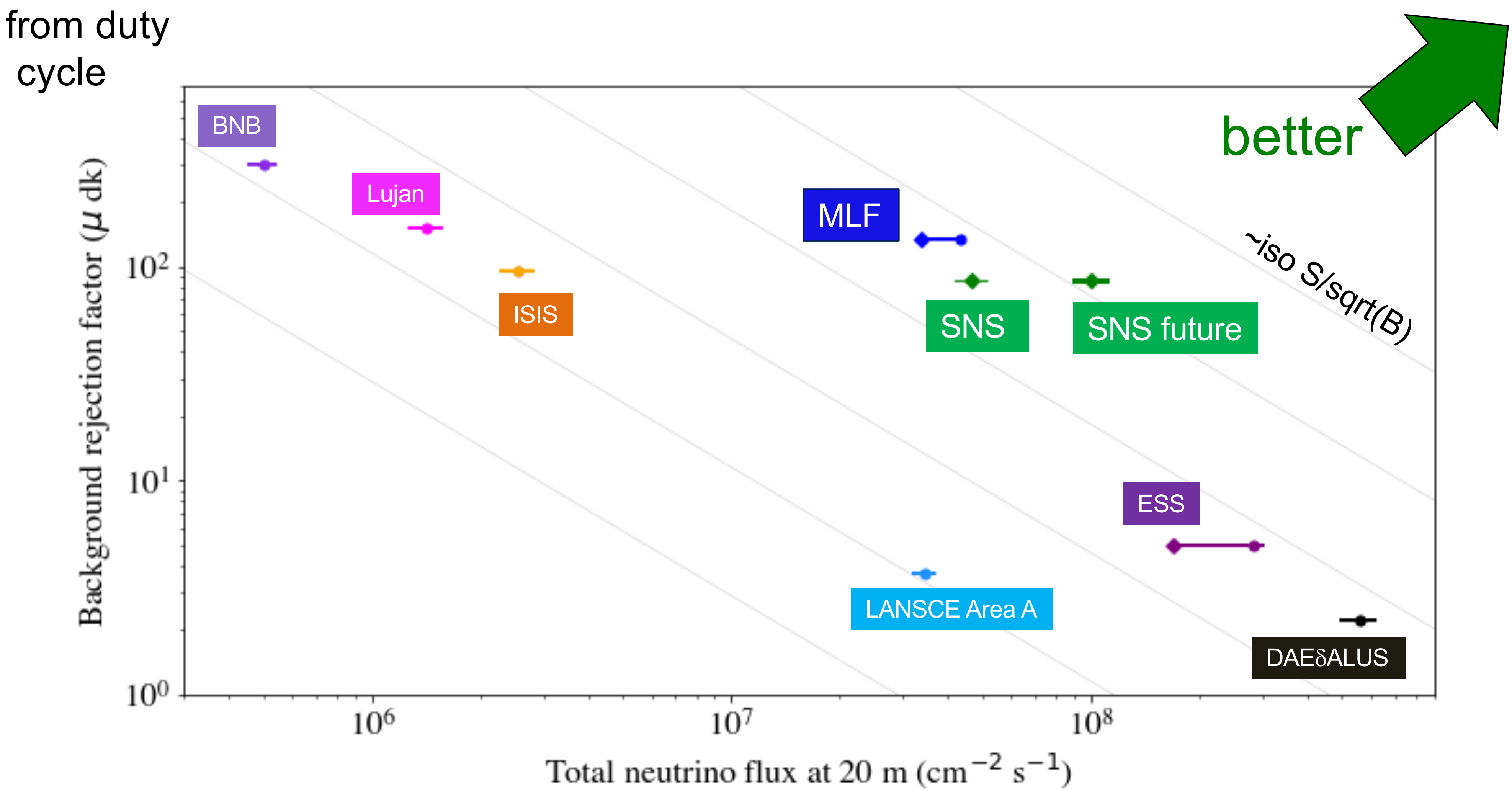
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

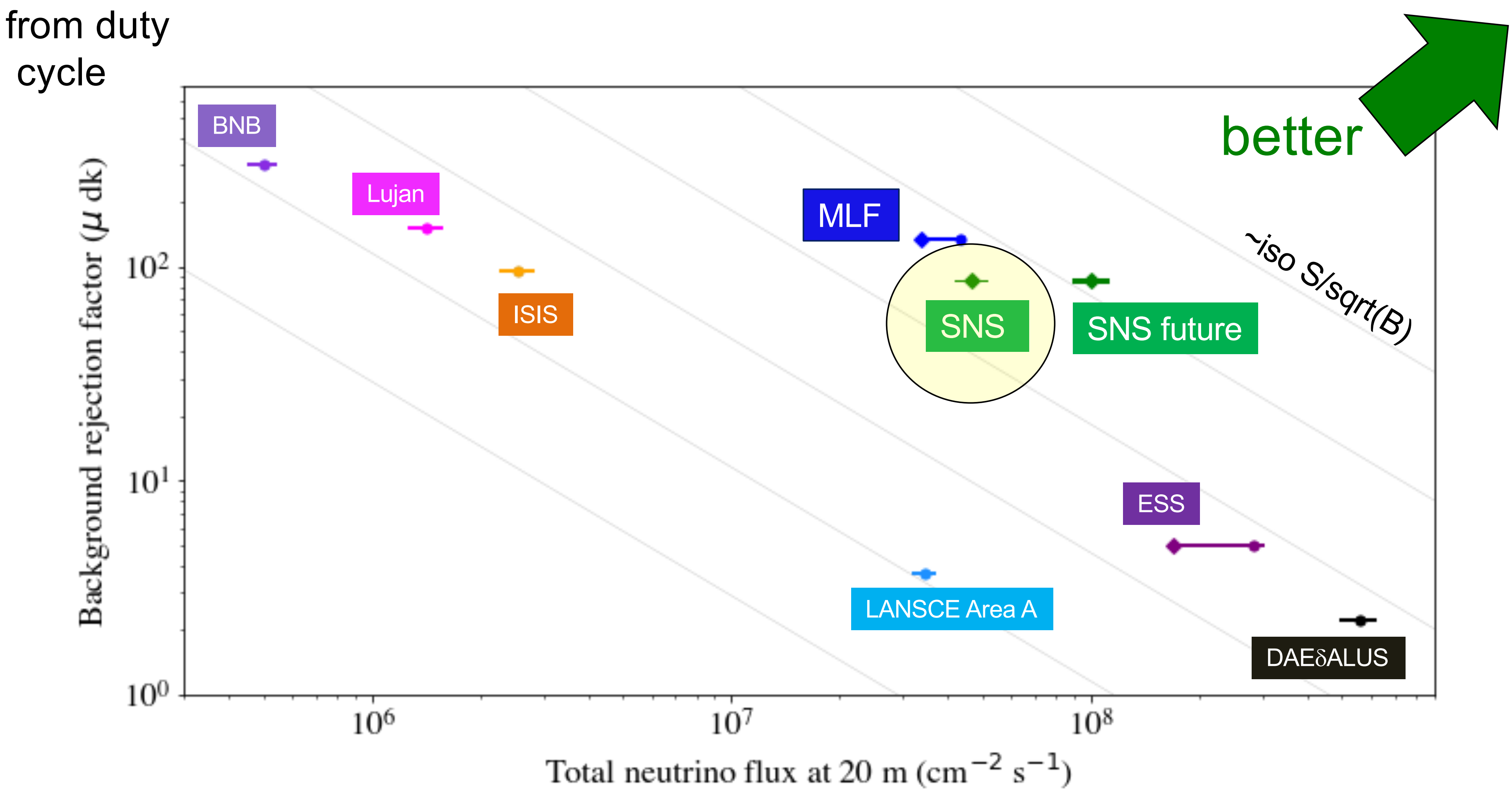
Stopped-Pion Neutrino Sources Worldwide

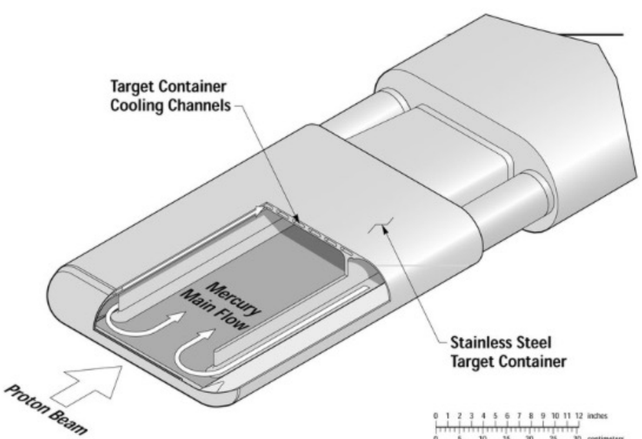


Comparison of pion decay-at-rest ν sources



Comparison of pion decay-at-rest ν sources



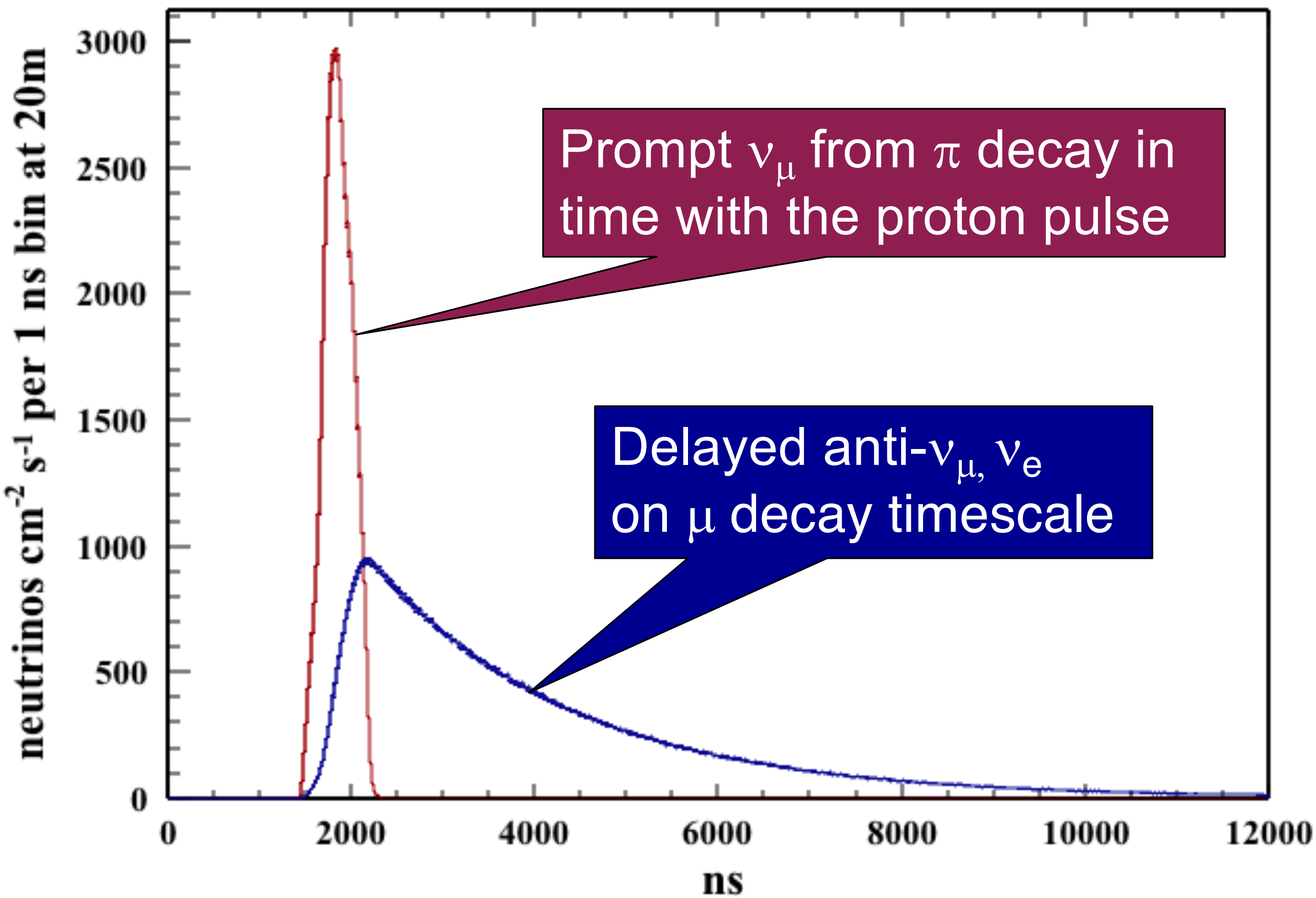


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Time structure of the SNS source

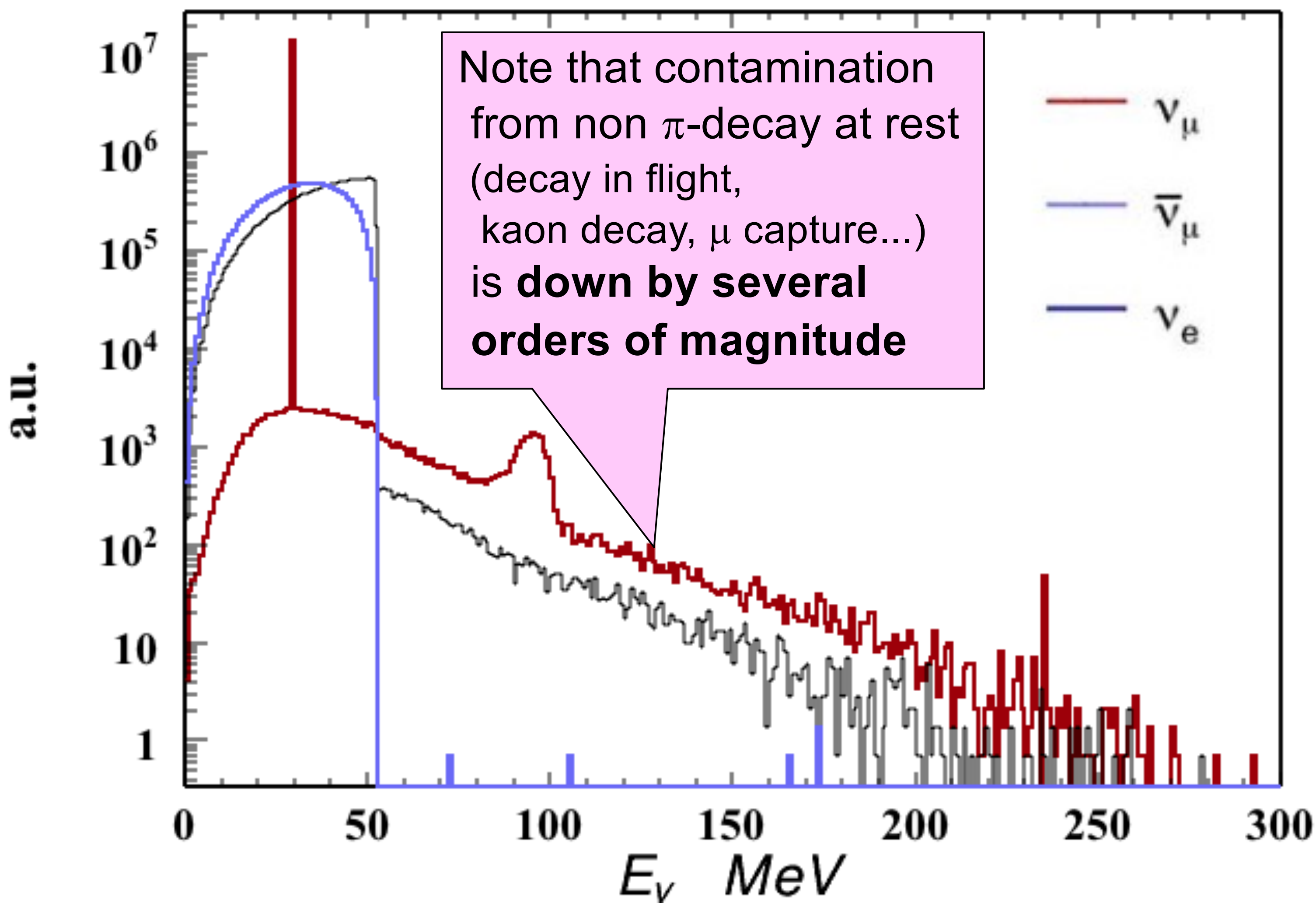
60 Hz *pulsed* source



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

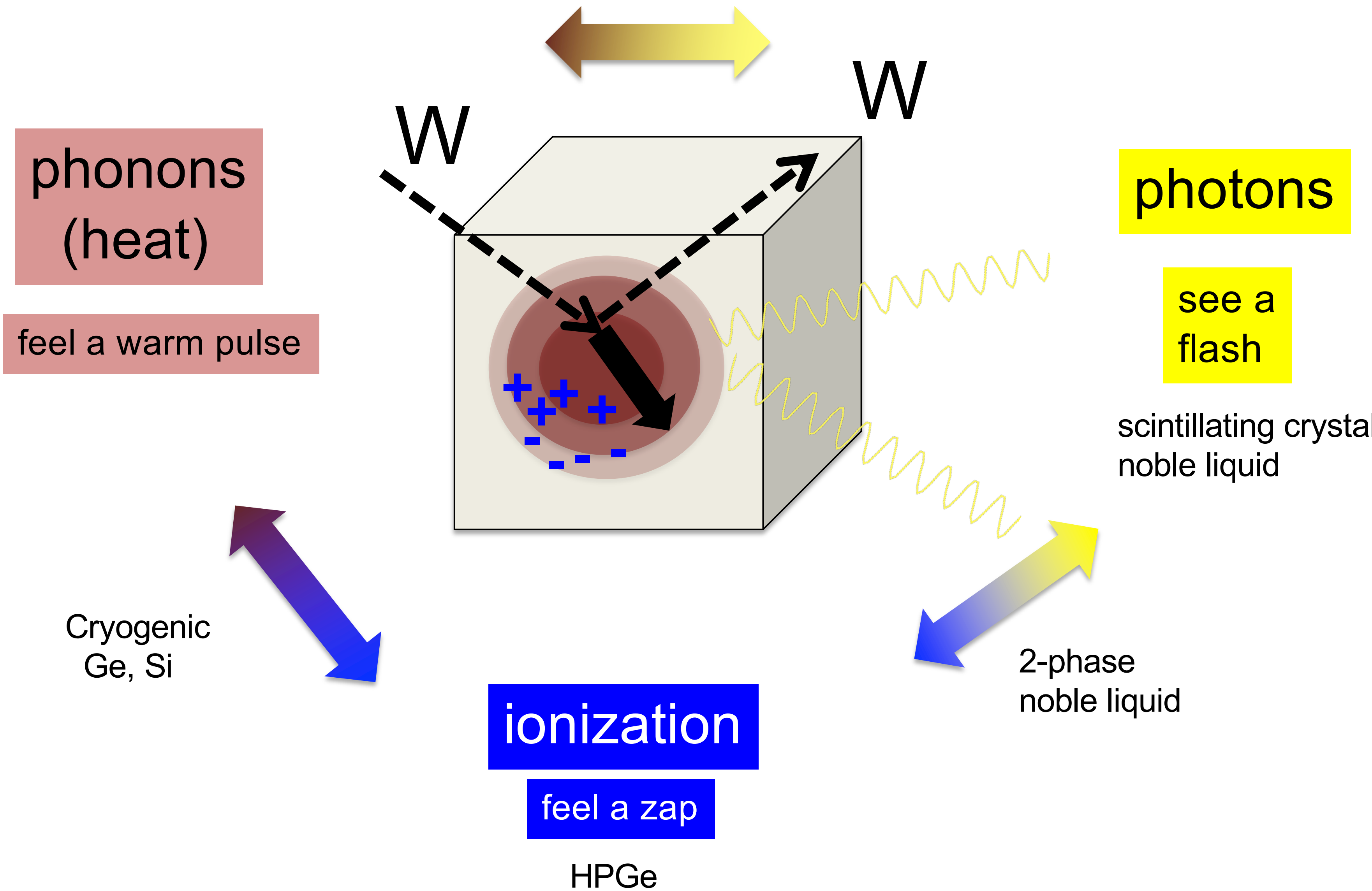
The SNS has **large, extremely clean** stopped-pion ν flux

0.08 neutrinos per flavor per proton on target



SNS flux (1.4 MW):
430 x 10^5 ν/cm²/s
@ 20 m

Low-energy nuclear recoil detection strategies



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

The COHERENT collaboration

http://sites.duke.edu/coherent

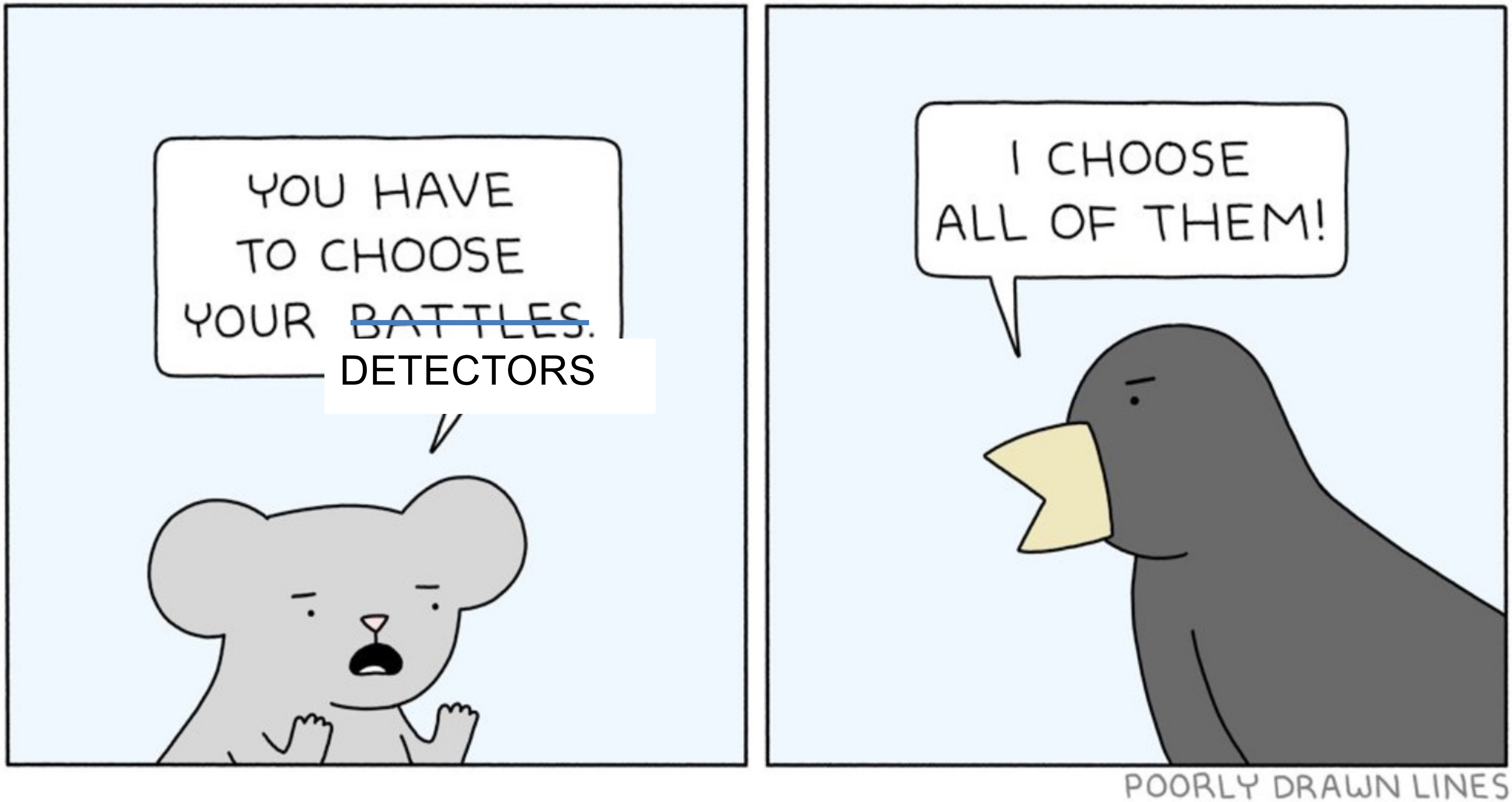
~90 members,
20 institutions
4 countries

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 UT Knoxville
Tufts University
TUNL Triangle Universities Nuclear Laboratory
Virginia Tech
W University of Washington

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

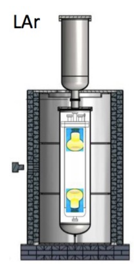
The COHERENT Spirit (so far)

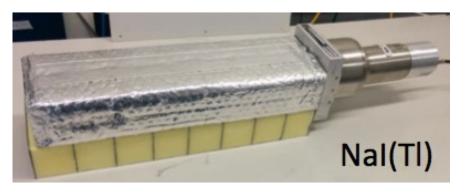


COHERENT CEvNS Detectors

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	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

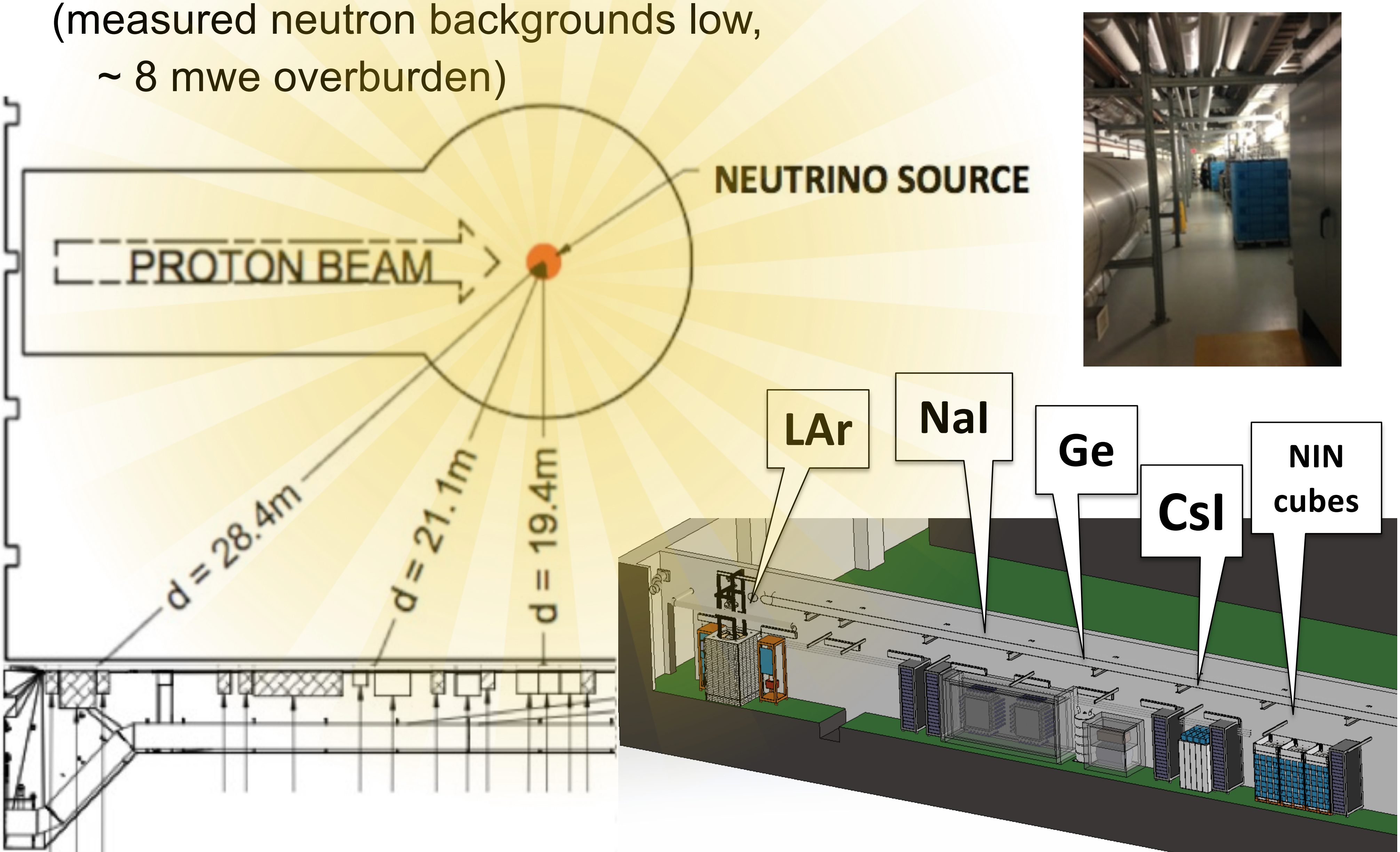




Siting for deployment in SNS basement

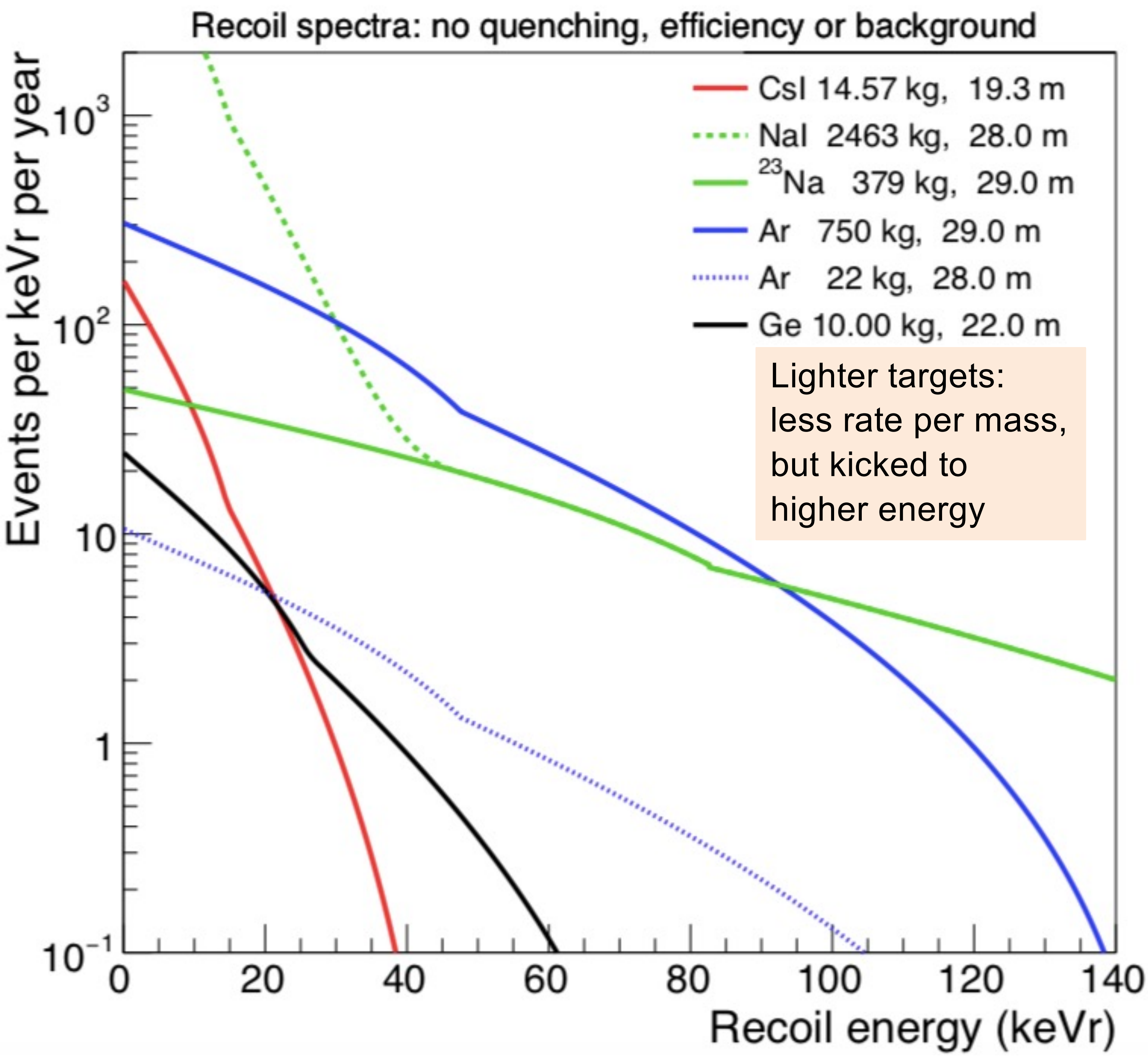
(measured neutron backgrounds low,
~ 8 mwe overburden)

View looking
down “Neutrino Alley”



Isotropic ν glow from Hg SNS target

Expected recoil energy distribution

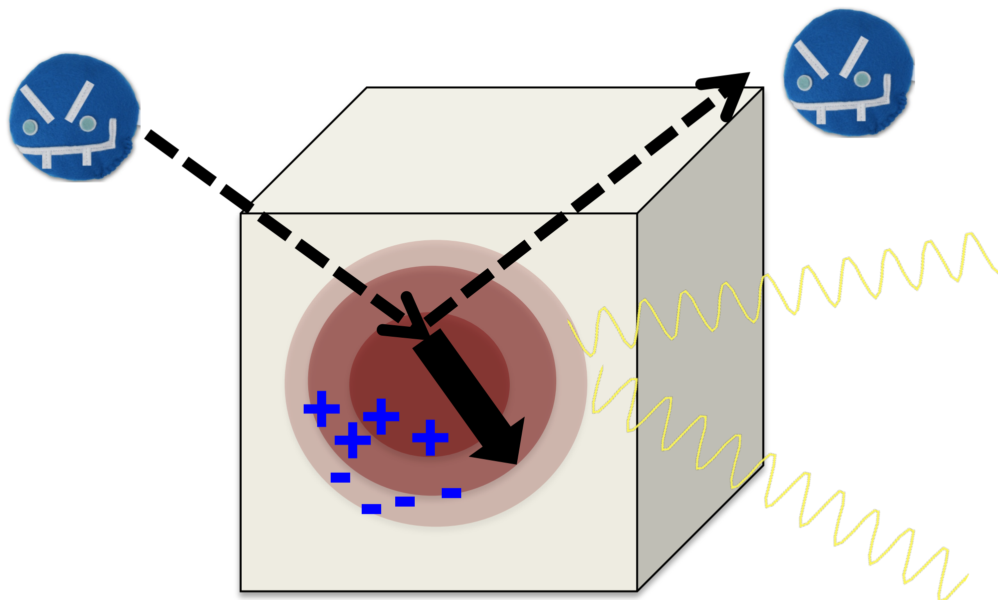


Backgrounds

Usual suspects:

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

Neutrons are especially not your friends*

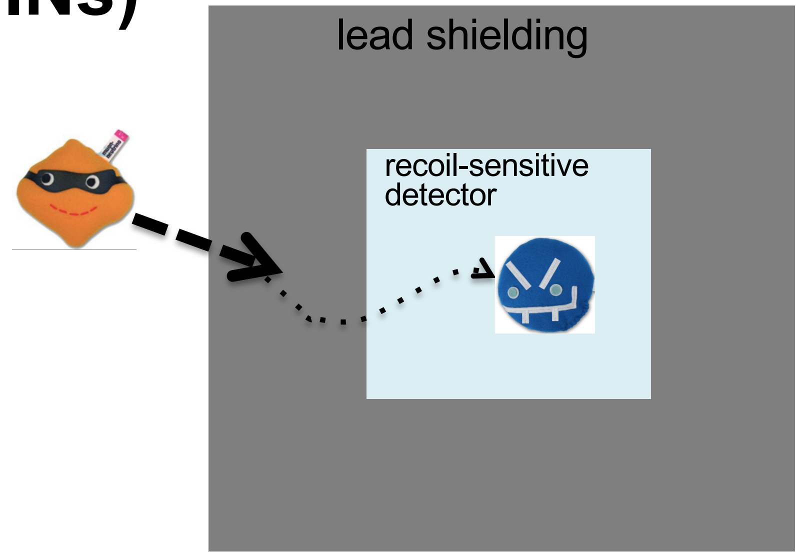


Steady-state backgrounds can be *measured* off-beam-pulse
... in-time backgrounds must be carefully characterized

*Thanks to Robert Cooper for the “mean neutron”

A "friendly fire" in-time background:

Neutrino Induced Neutrons (NINs)



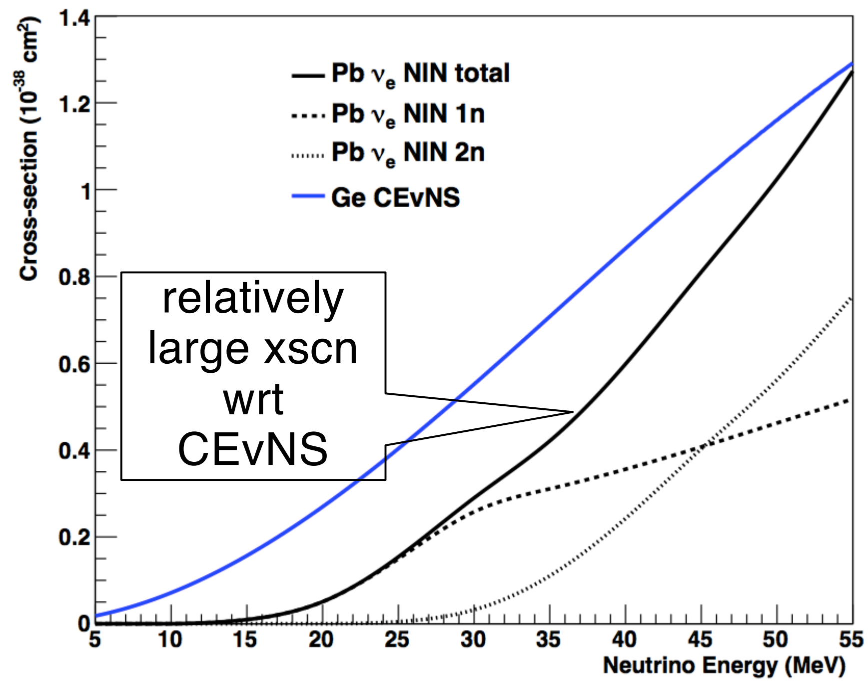
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

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

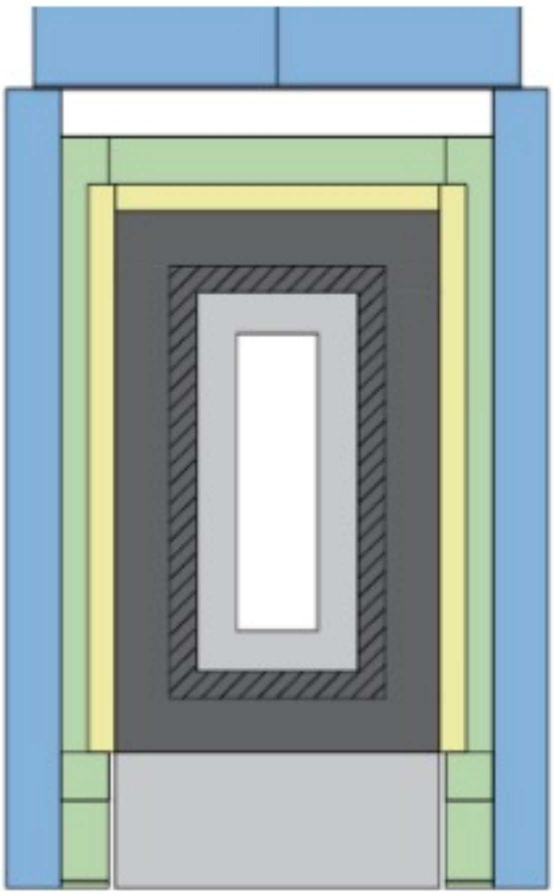
↘ 1n, 2n, γ emission

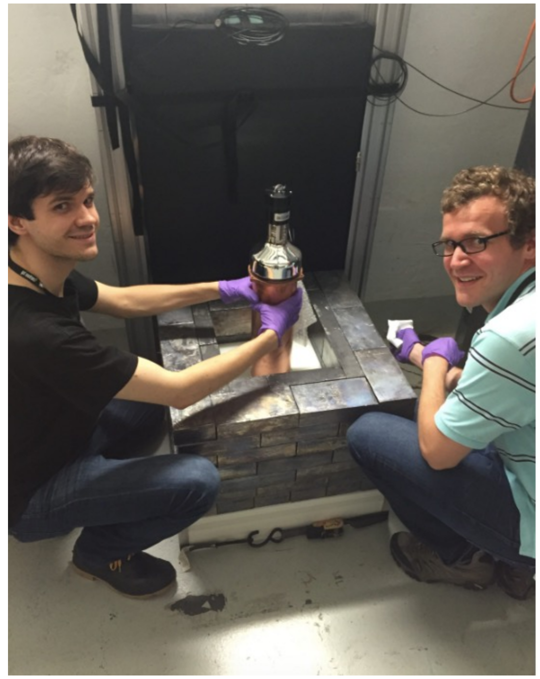
- potentially non-negligible background from shielding
- requires careful shielding design
- large uncertainties (factor of few) in xscn calculation
- [Also: a signal in itself, e.g, HALO SN detector]



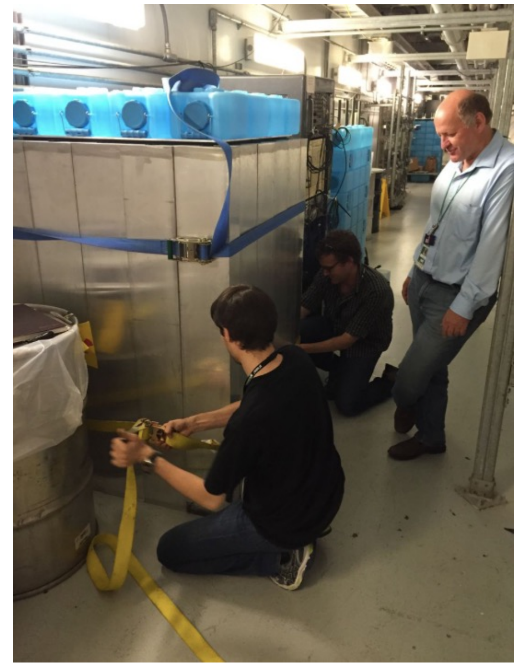
Results of dedicated measurement @Nu2022

The CsI Detector in Shielding in Neutrino Alley at the SNS





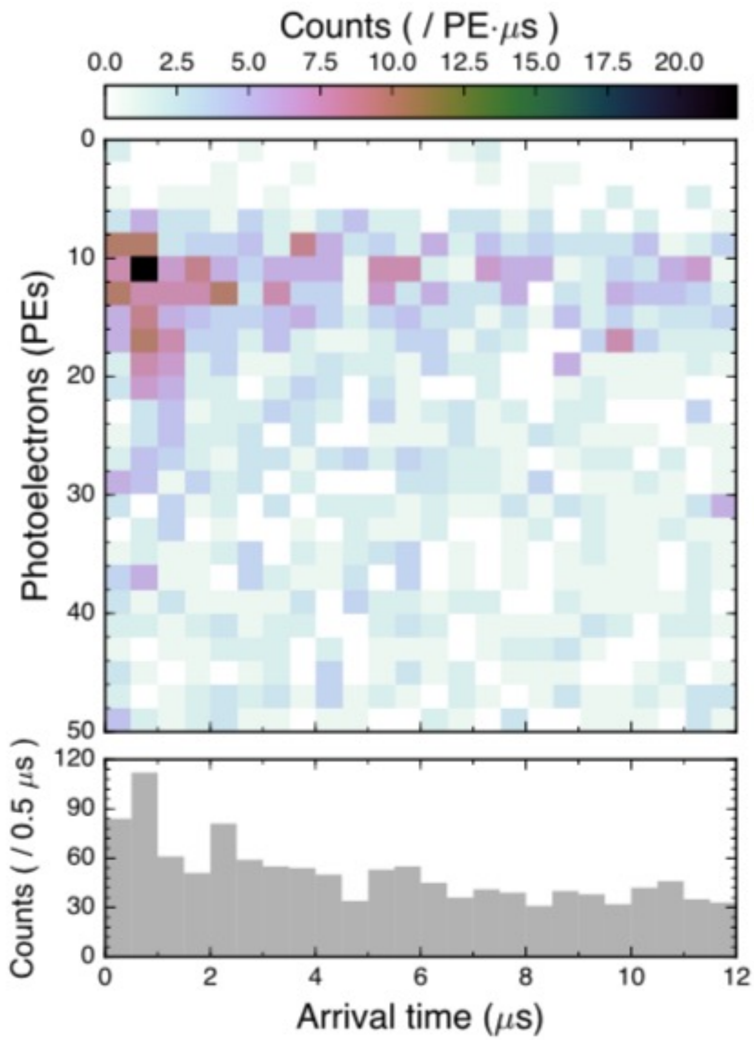
A hand-held detector!

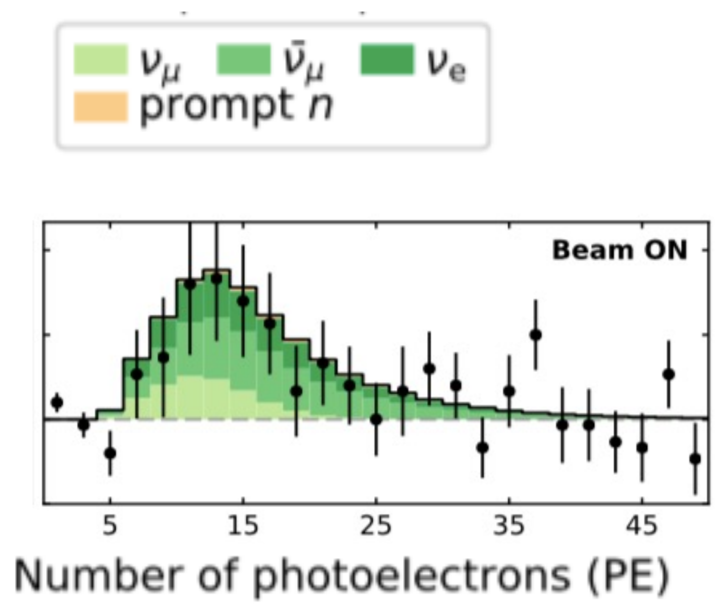


Almost wrapped up...

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





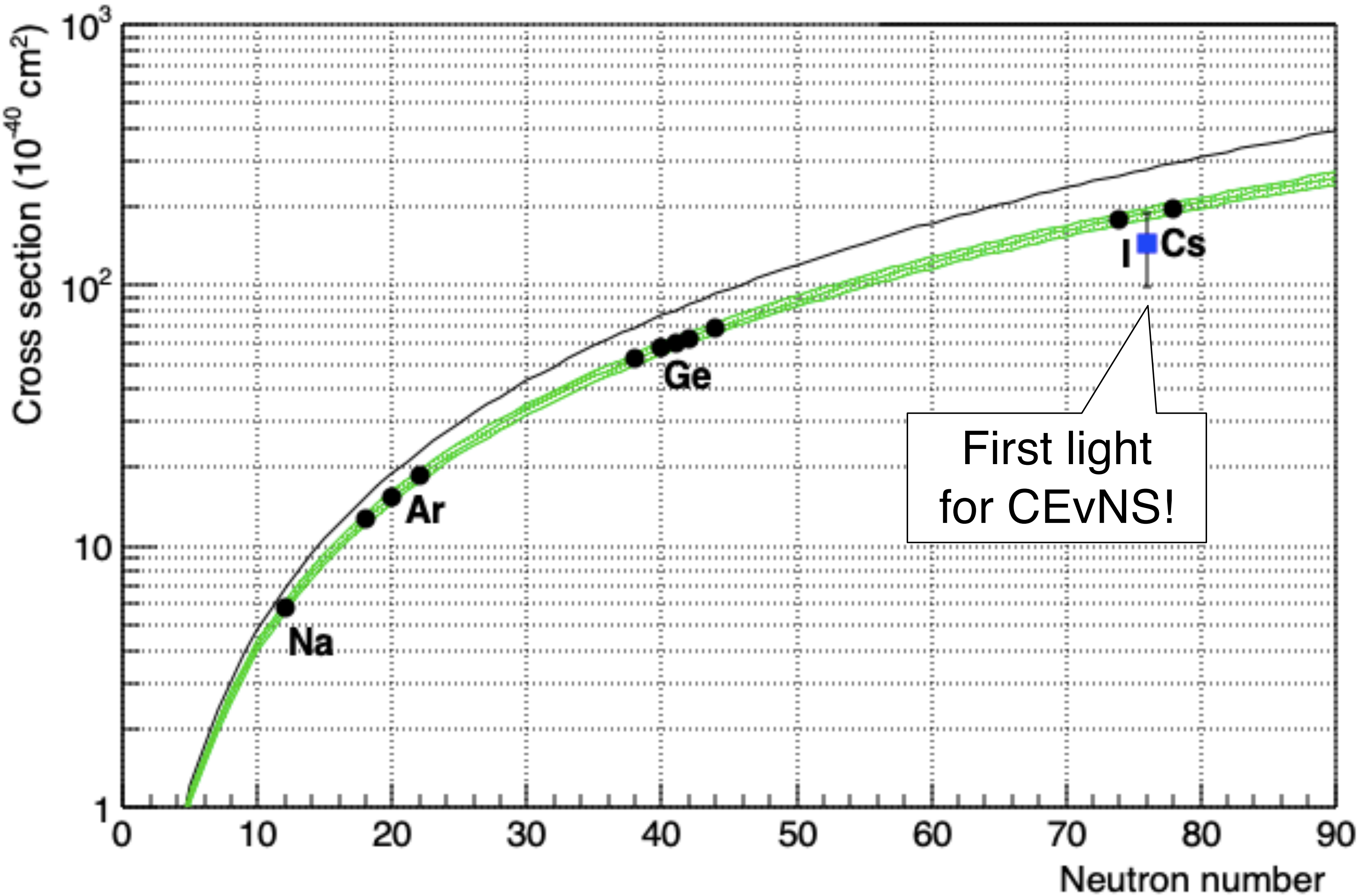
Background-subtracted and integrated over time

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

→ measure of the Q spectrum

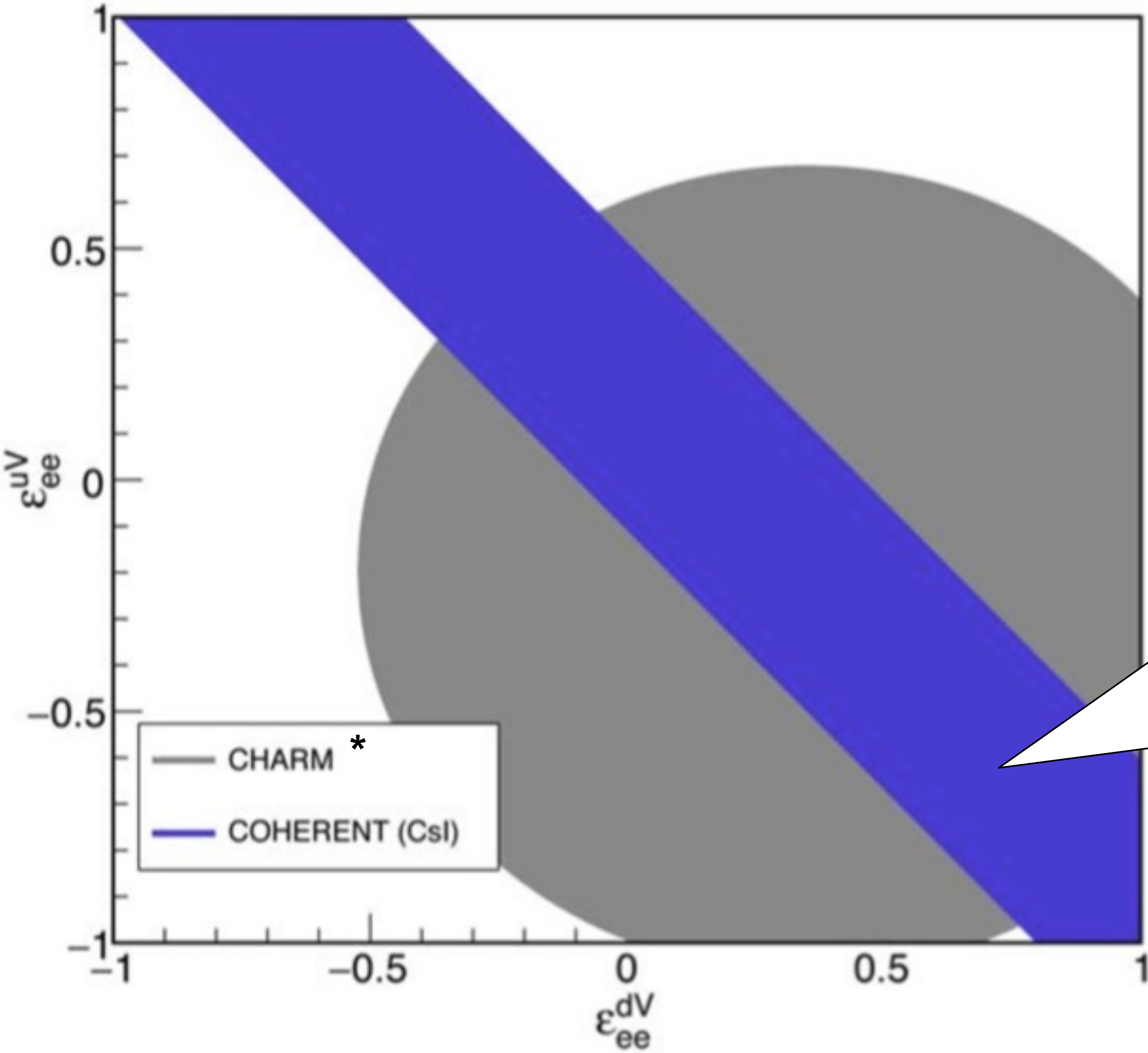
DOI: 10.5281/zenodo.1228631

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%

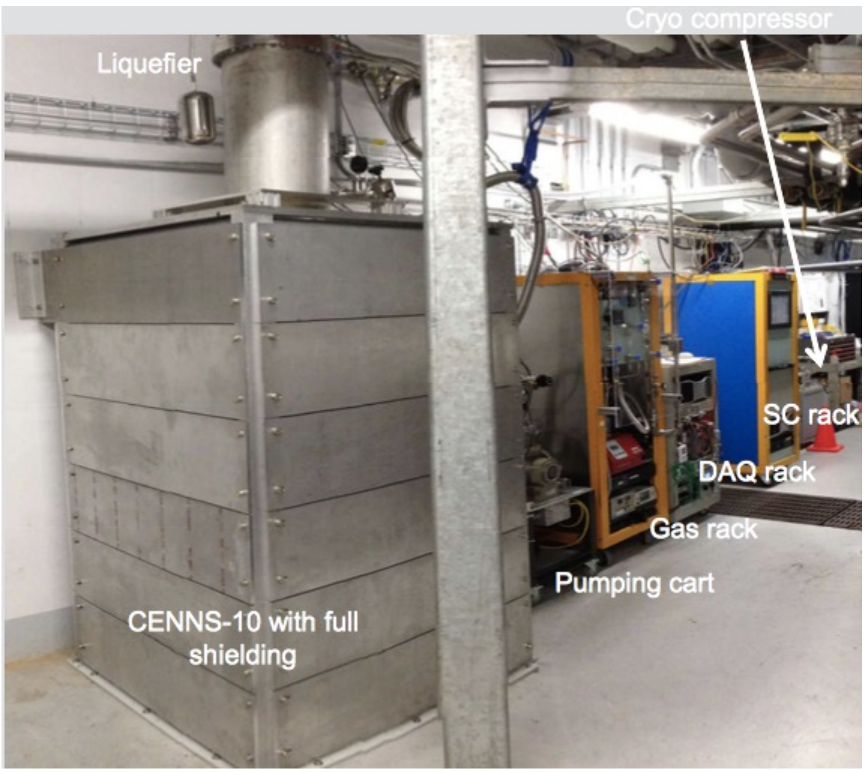
See also Coloma et al., arXiv:1708.02899, many more!

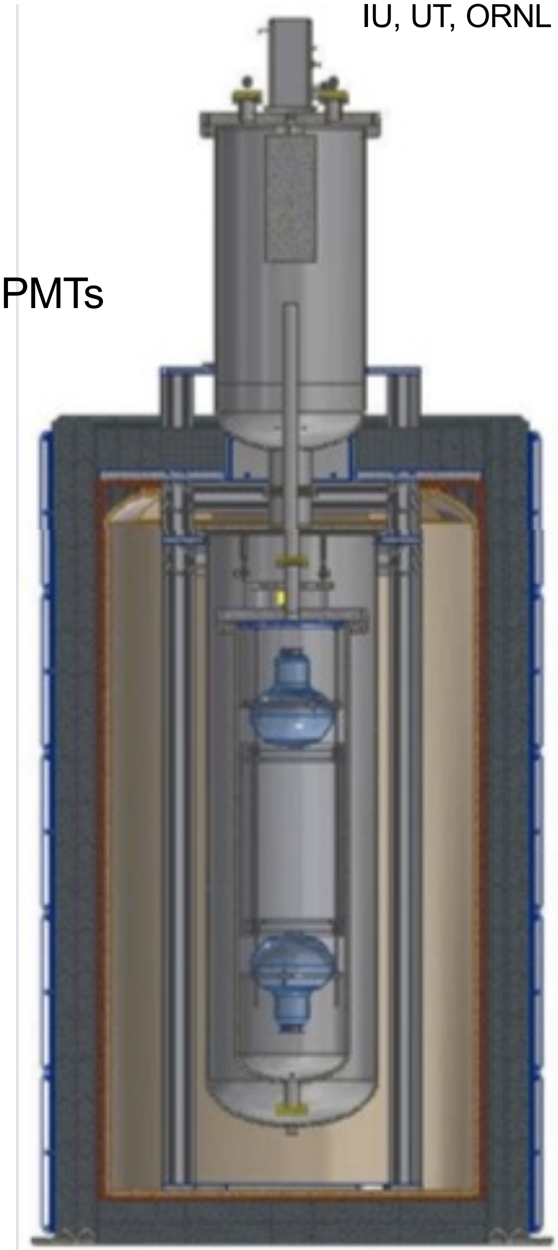
*CHARM constraints apply only to heavy mediators

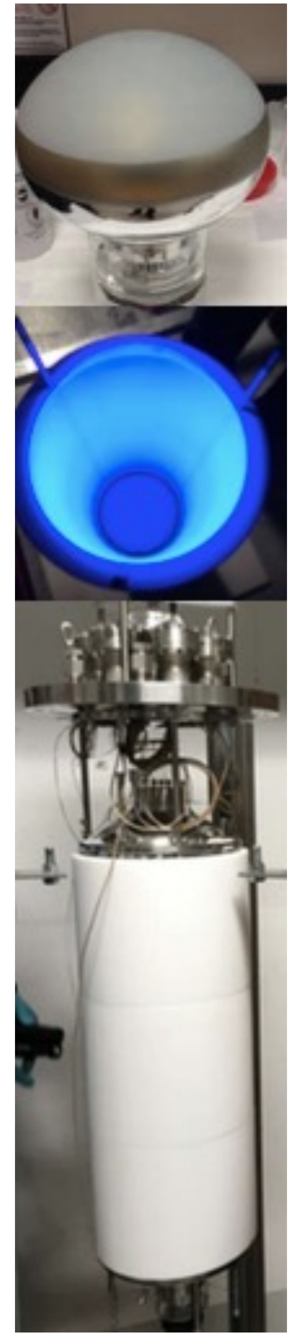
Single-Phase Liquid Argon

- ~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



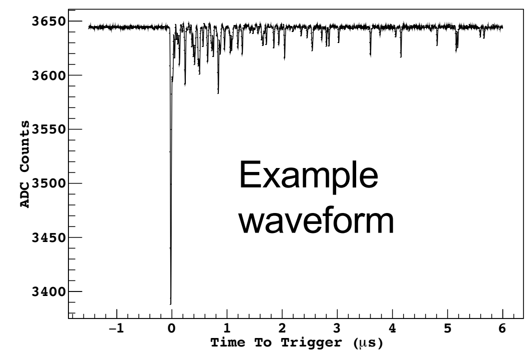




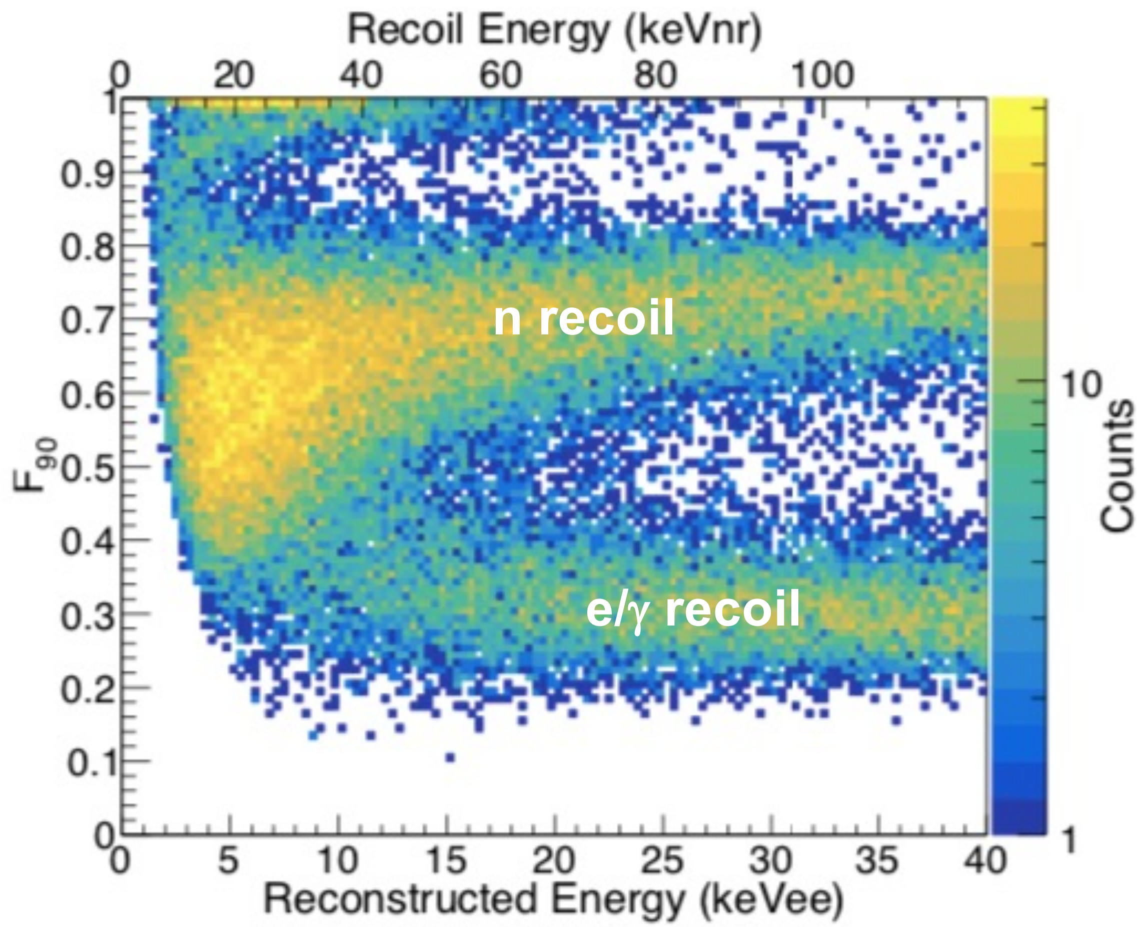
Detector from FNAL, previously built (Jonghee Yoo et al.) for CENNS@BNB

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

Use **pulse-shape discrimination** to select recoils

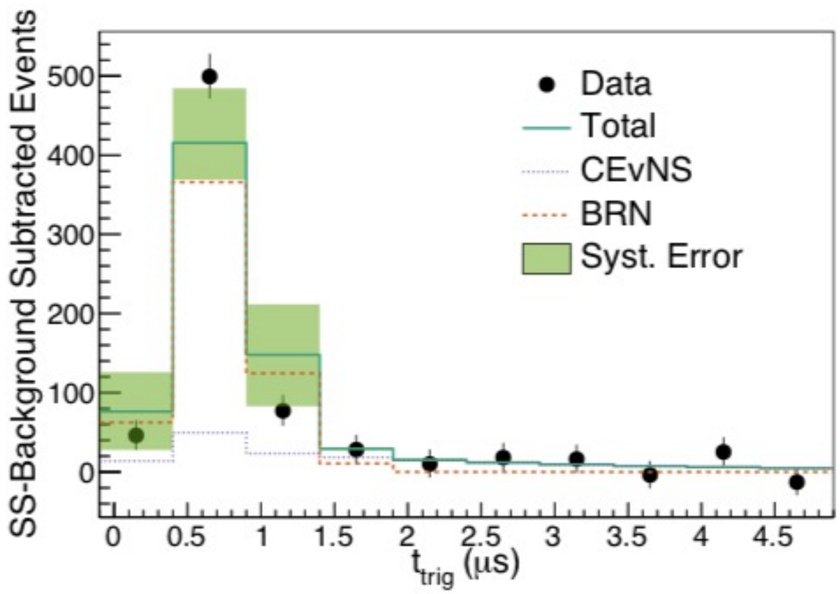


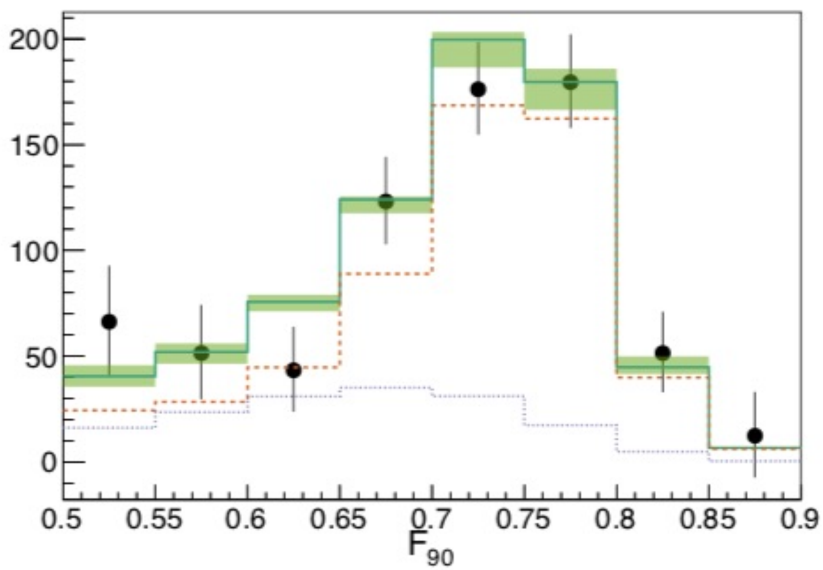
F90: fraction of light in first 90 ns



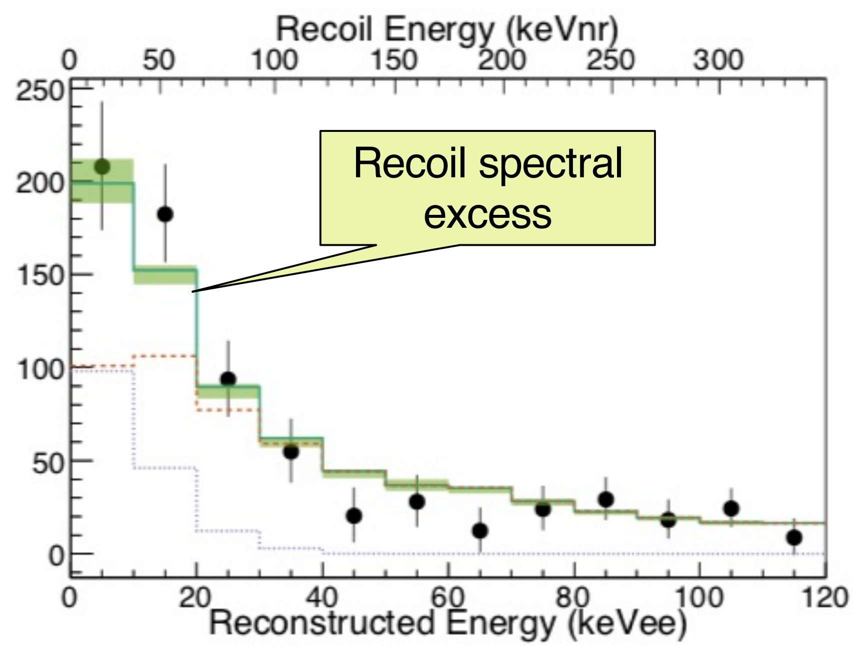
Likelihood fit in time, recoil energy, PSD parameter

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

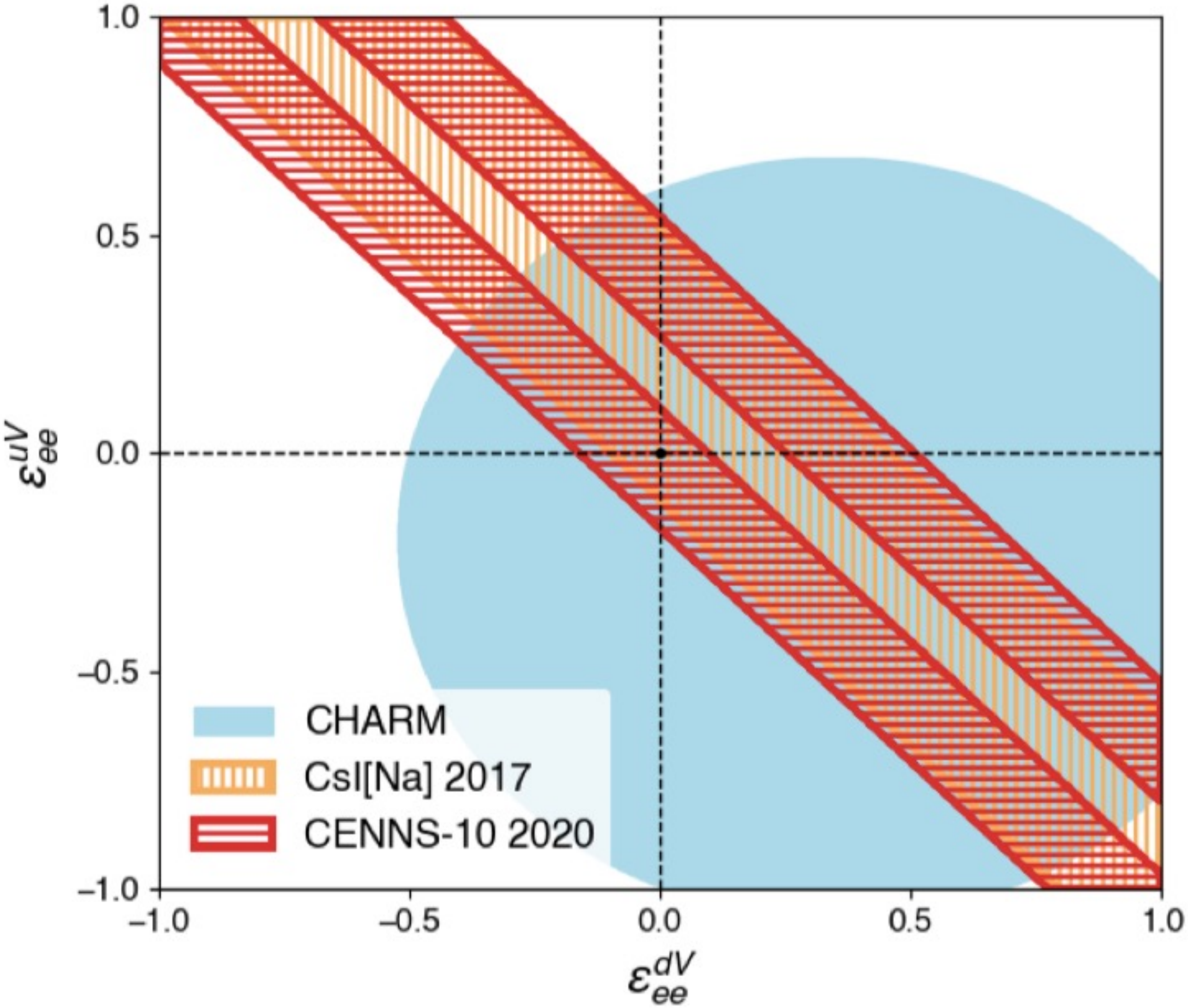




- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the “A” analysis)

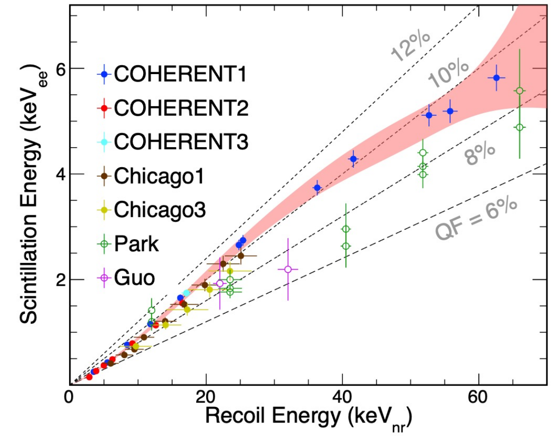


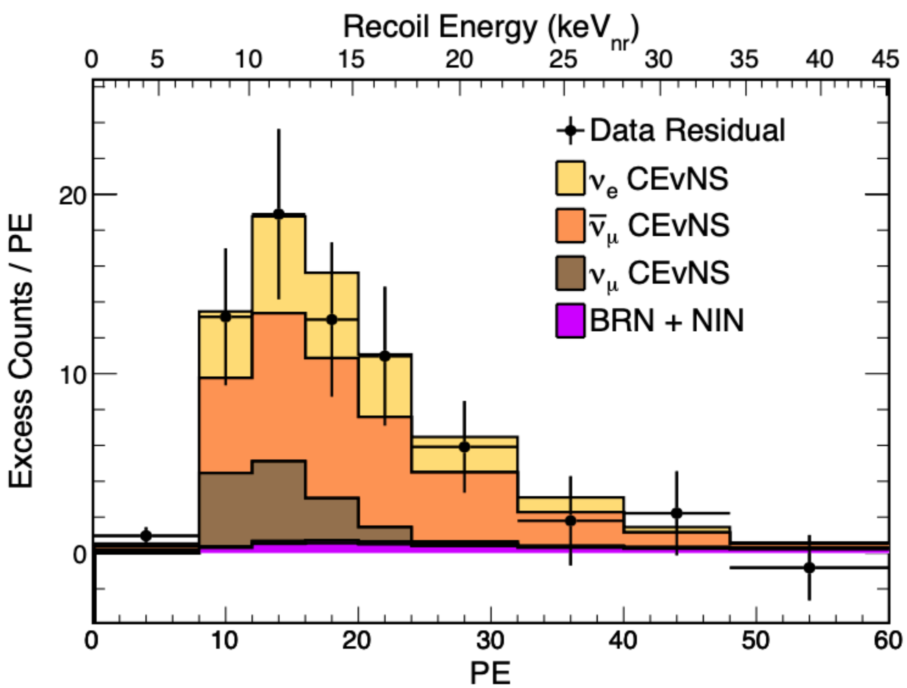
New Constraints on NSI parameters

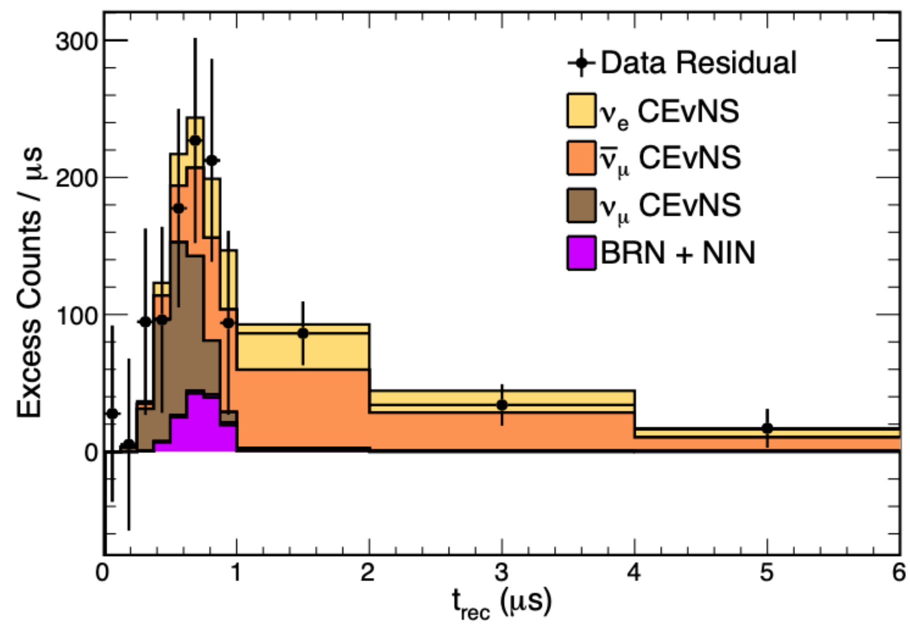


Full CsI Dataset Results

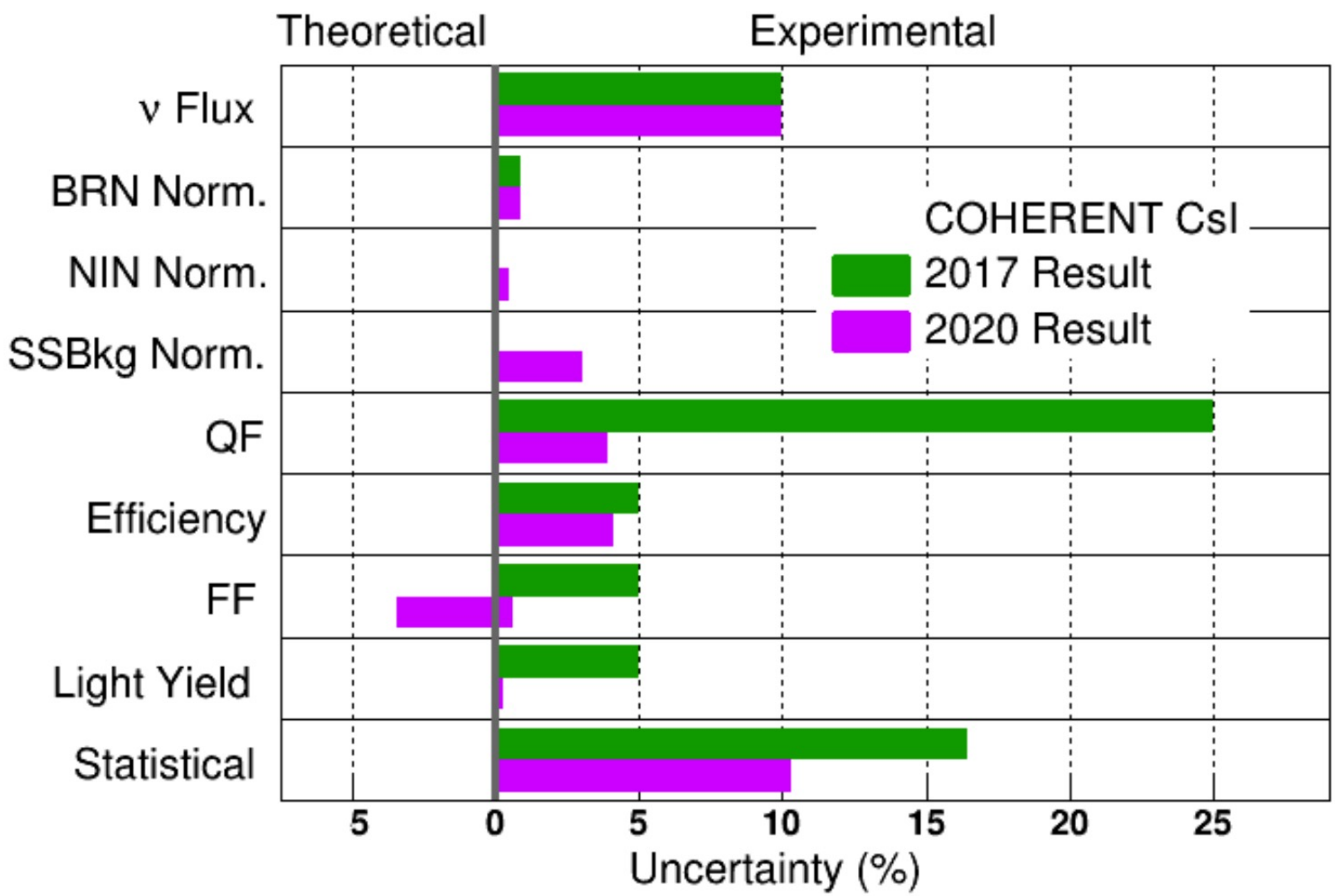
with >2 x statistics
 + improved detector response understanding
 + improved analysis



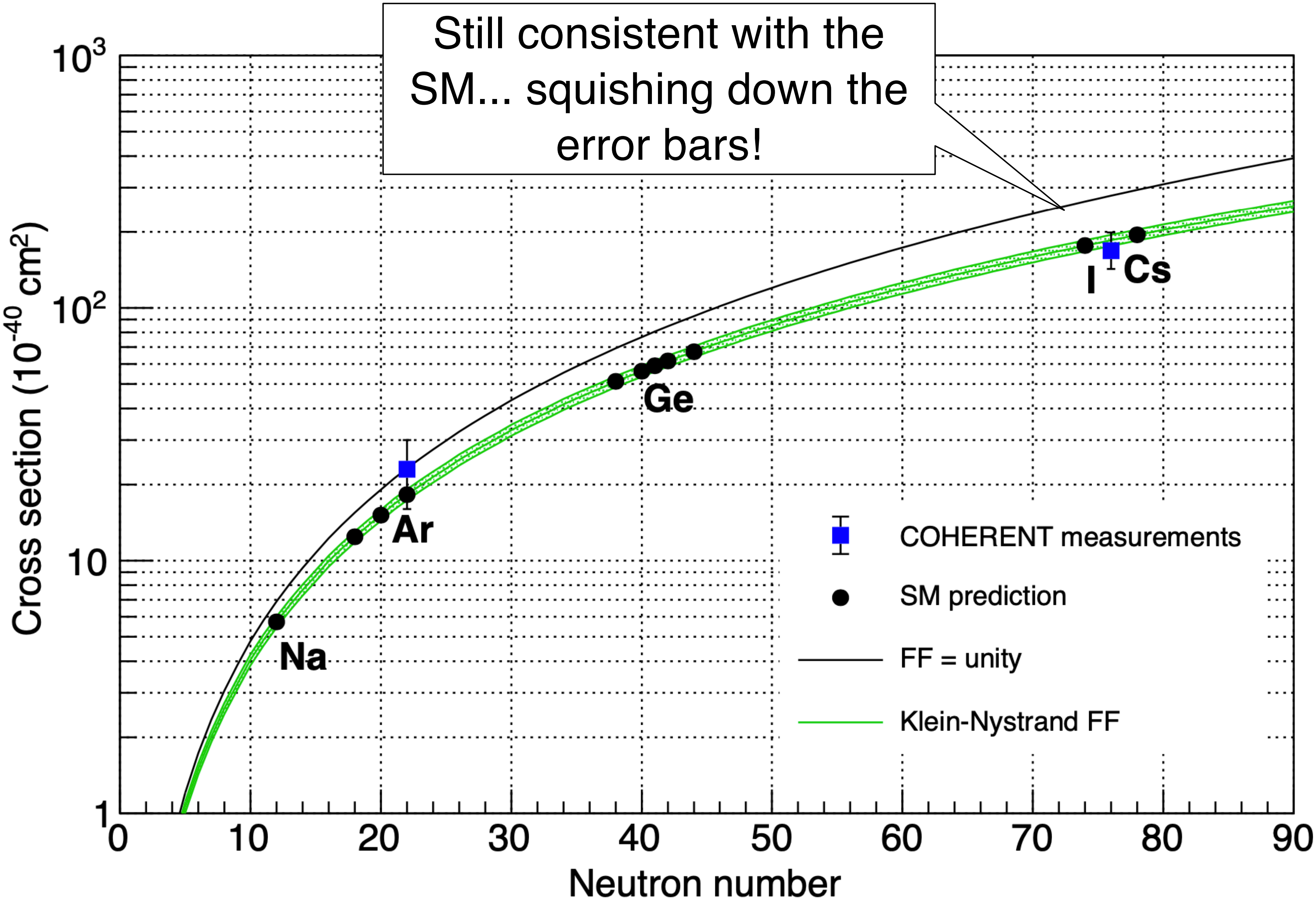




Quenching factor (detector response vs recoil energy): arXiv:2111.02477
Full CsI dataset: arXiv:2110.07730



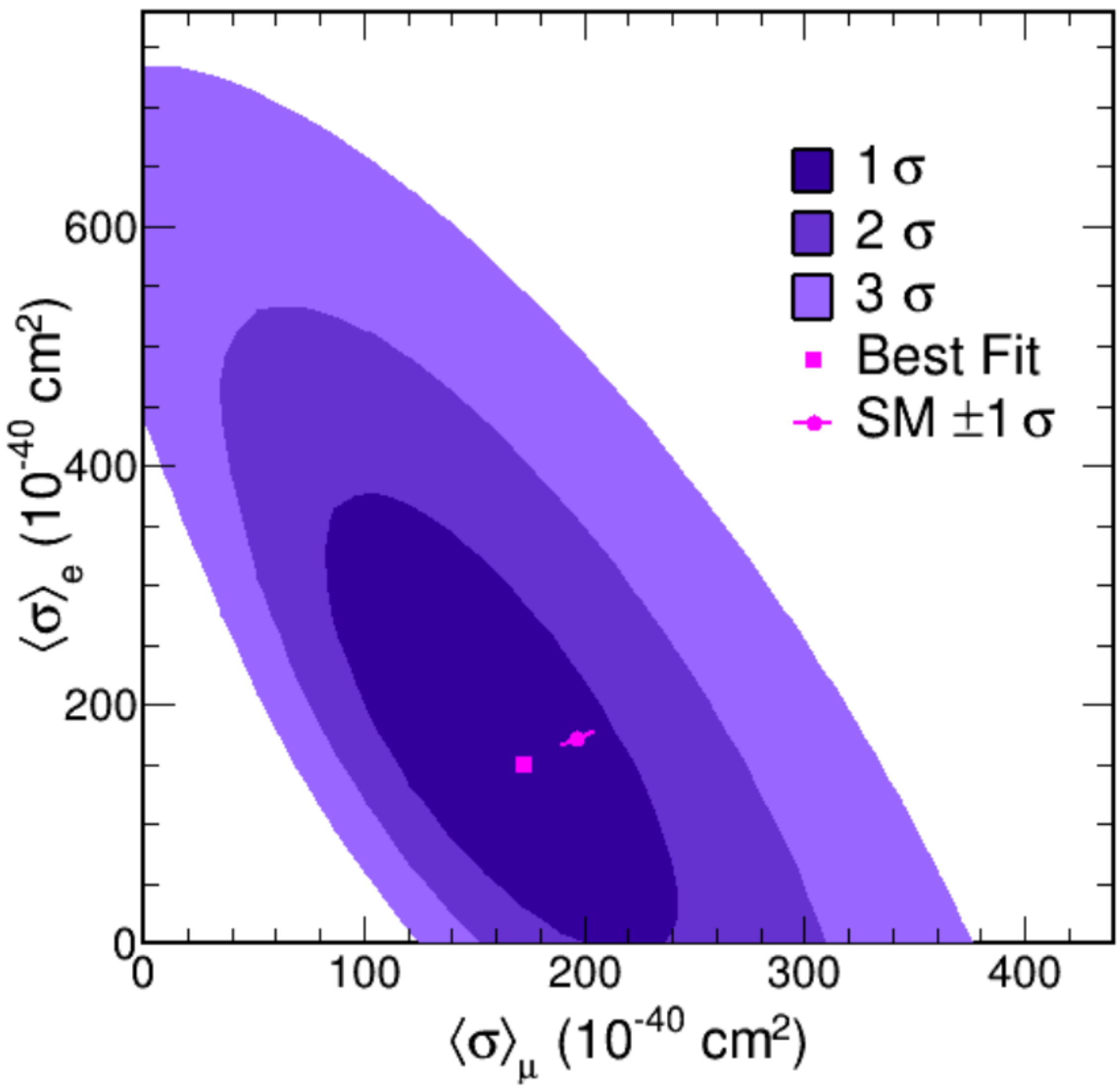
- overall uncertainty now about ~18% for CsI
- neither stat nor sys uncertainty dominates
- dominant systematic is flux normalization



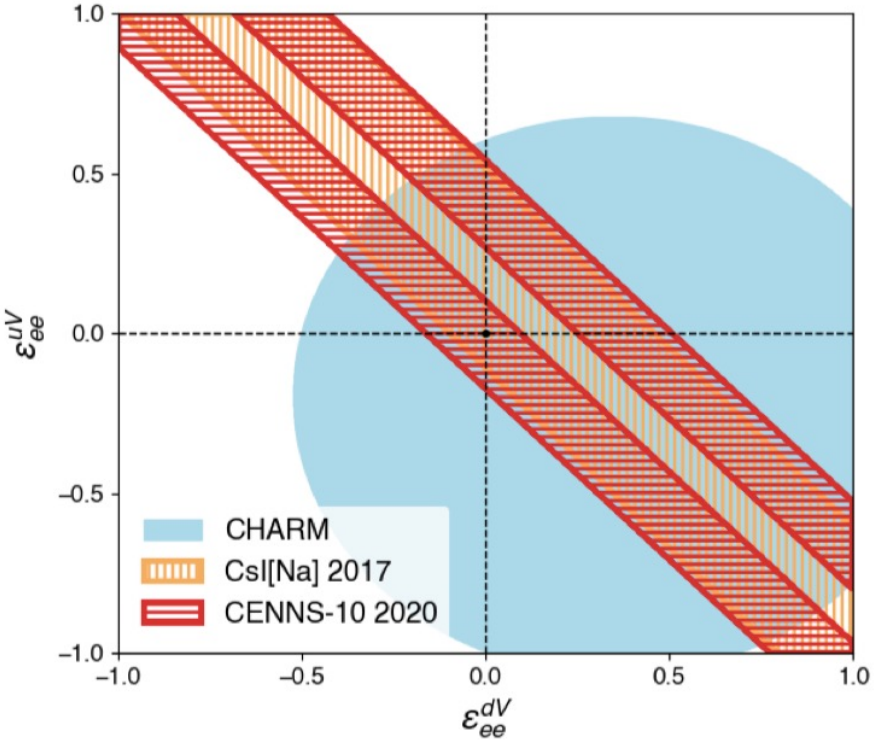
Still consistent with the SM... squishing down the error bars!
Cross section (10^{-40} cm^2)
Neutron number
COHERENT measurements
SM prediction
FF = unity
Klein-Nystrand FF
Na
Ar
Ge
I
Cs

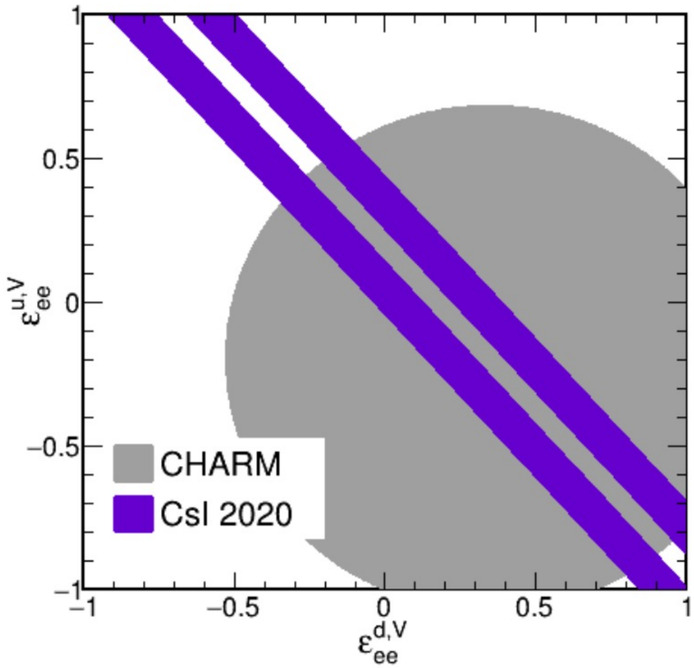
Flavored CEvNS cross sections

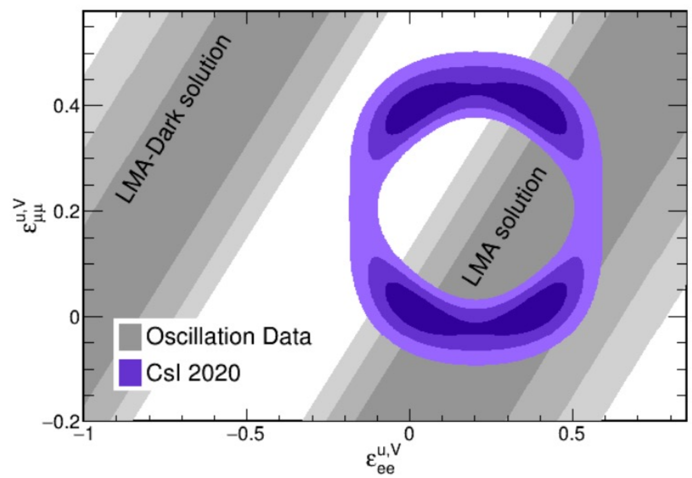
Separate electron and muon flavors by timing



And squeezing down the possibilities for new physics...

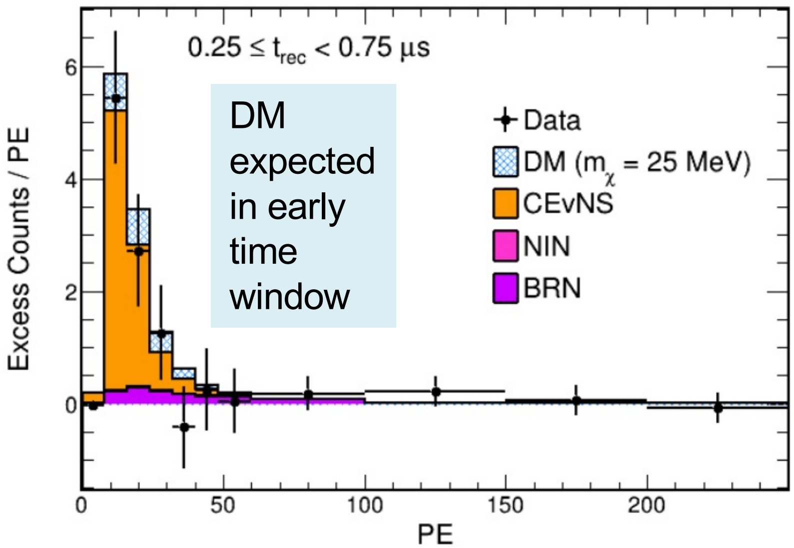


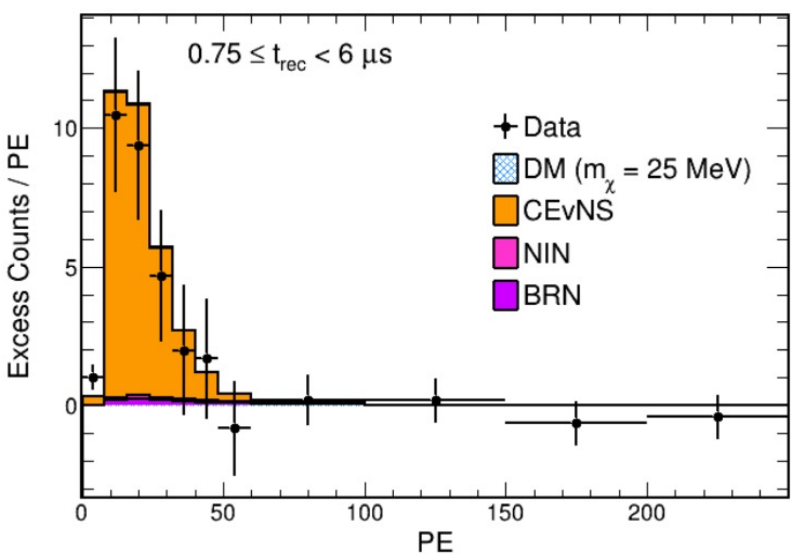


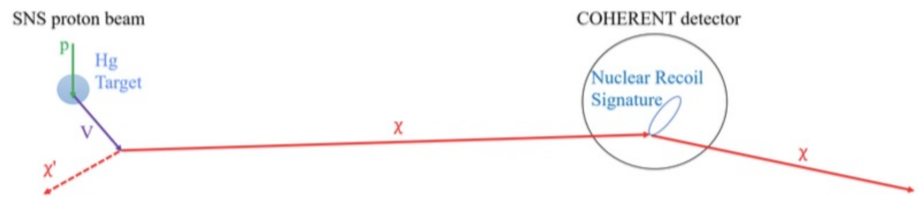


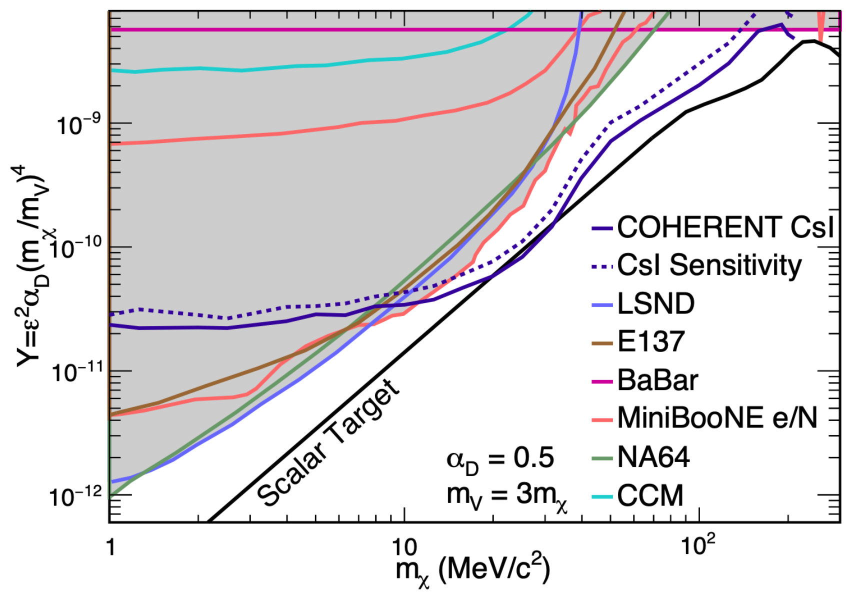
Accelerator-produced DM search

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







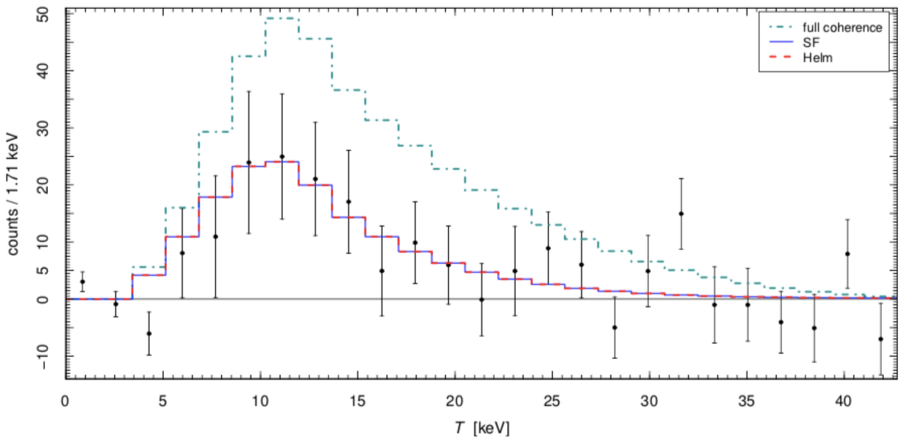


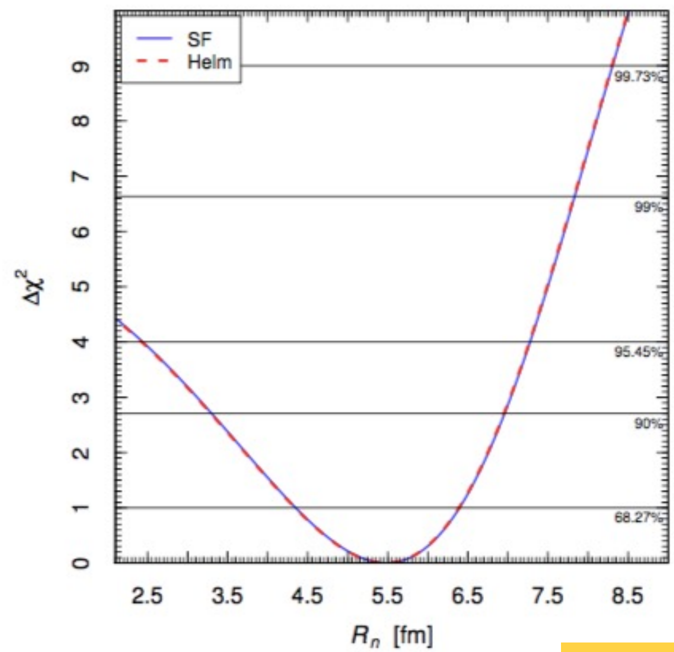
Limits down to cosmological expectation for scalar DM particle
arXiv:2110.11453

... and more results @Nu2022!

What can we learn about form factors?

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

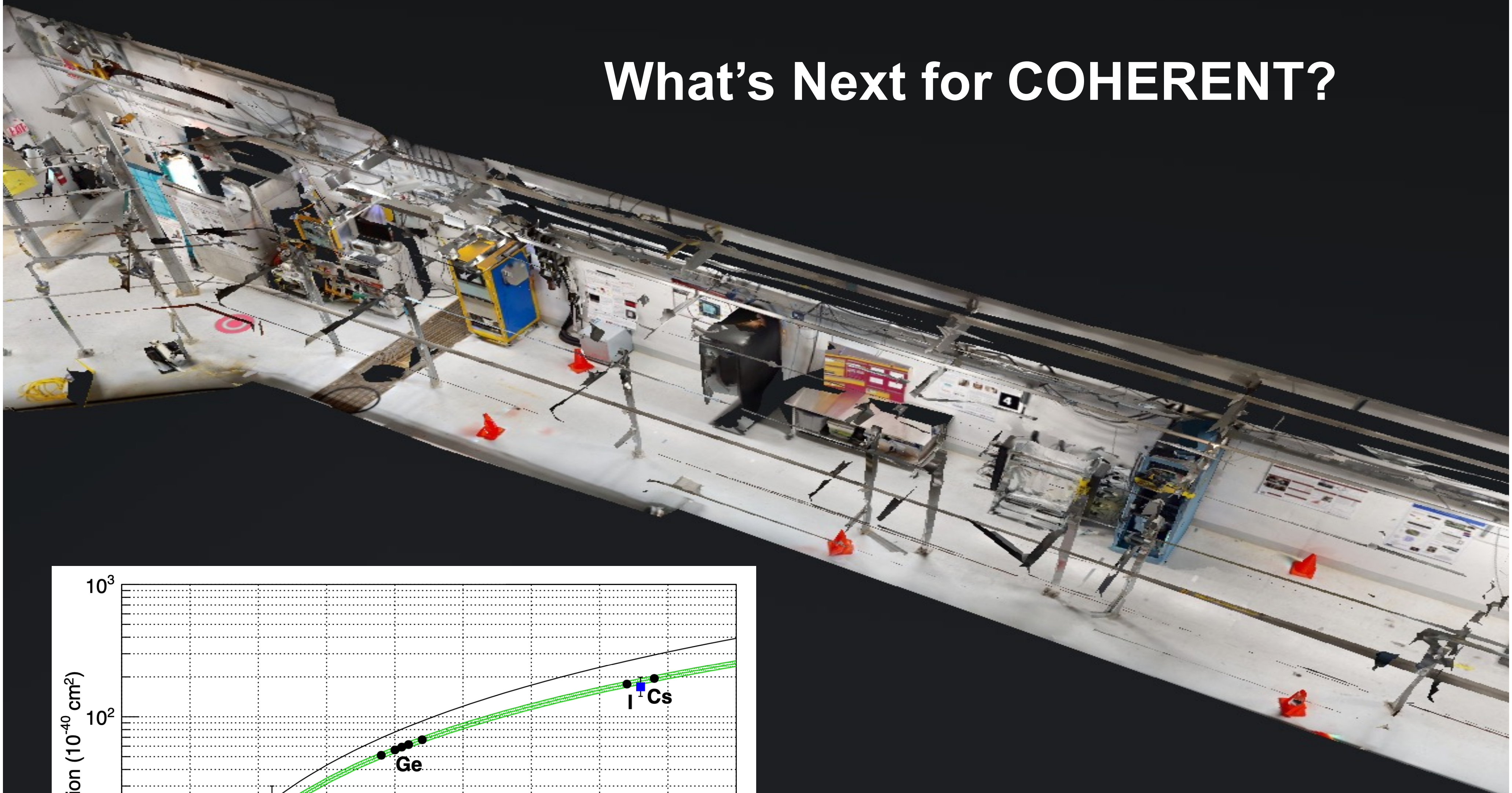
$$F_N^{\text{Helm}}(q^2) = 3\,\frac{j_1(qR_0)}{qR_0}\,e^{-q^2 s^2/2},$$

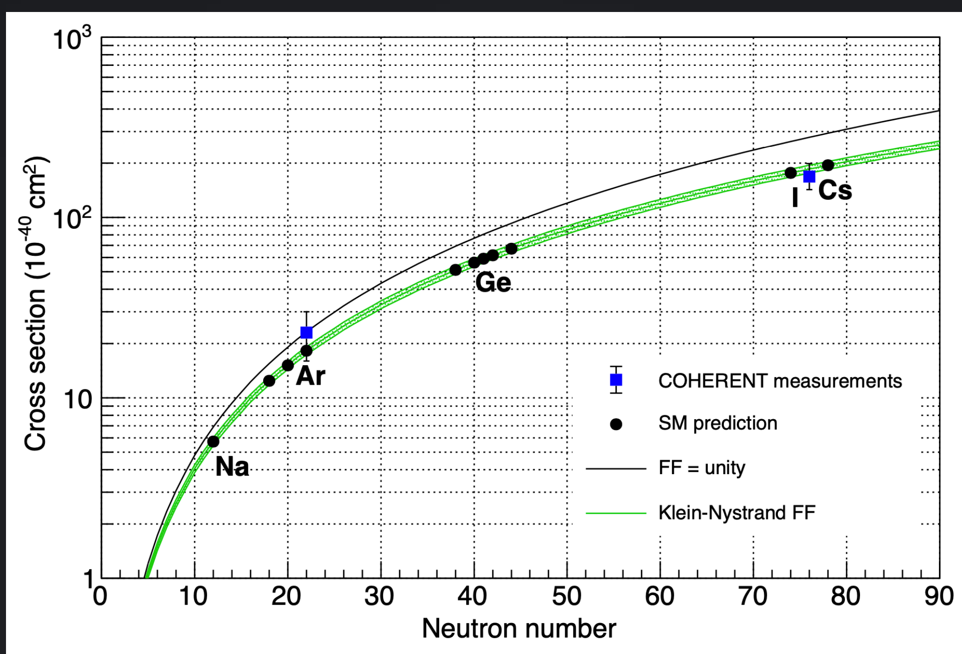
$$R_n = 5.5^{+0.9}_{-1.1}\ \text{fm}. \qquad \Delta R_{np} \simeq 0.7^{+0.9}_{-1.1}\ \text{fm}.$$

Spectral shape systematics are hard!

- Fit to neutron radius resulting in ~18% uncertainty, as well as neutron skin measurement
- We now have good quenching factor information w/uncertainties (arXiv:2111.02477)

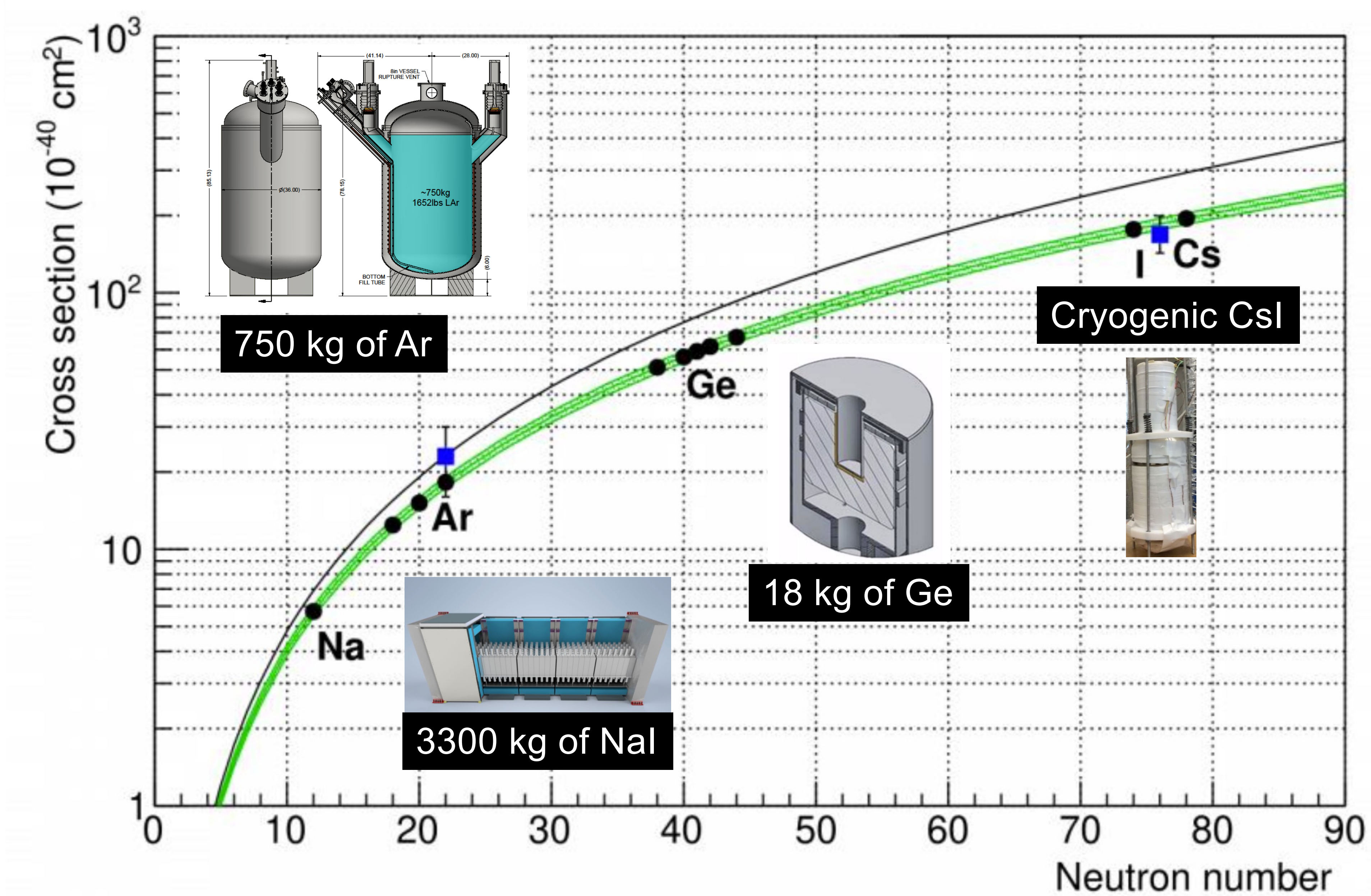
What’s Next for COHERENT?





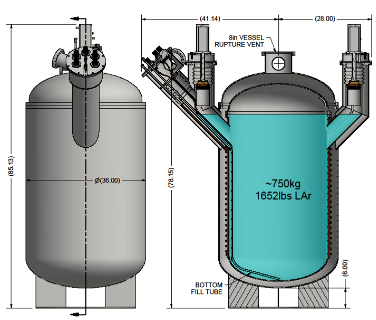
Two down!
But still more
to go!

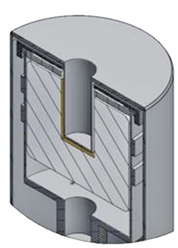
COHERENT future deployments

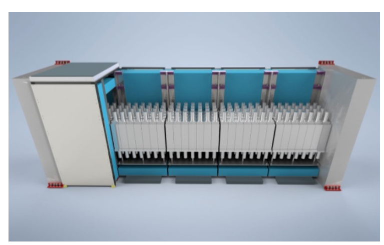


COHERENT **CEvNS** Detector Status and **Farther Future**

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





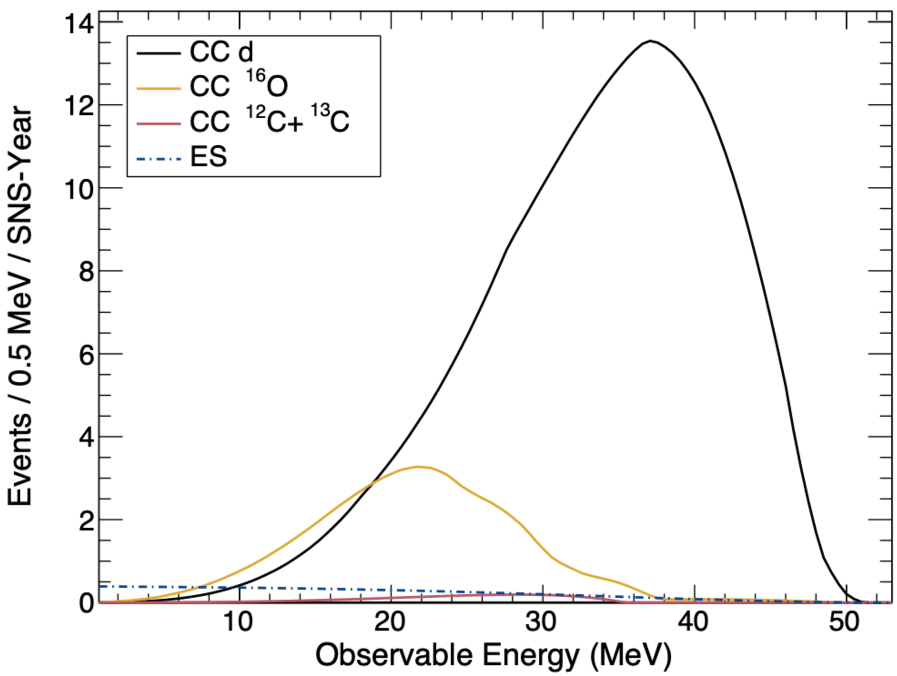


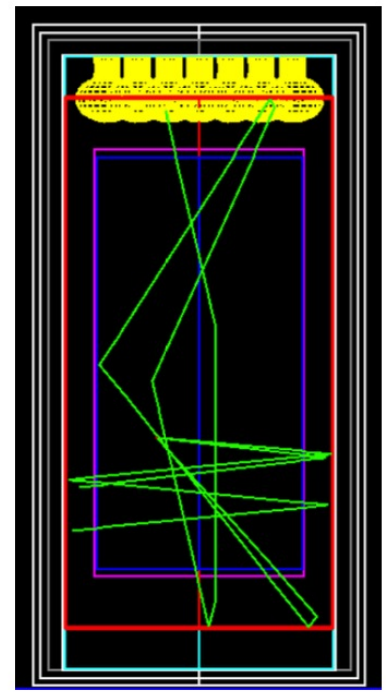
+D_2O for flux normalization
+ CryoCsI
+ thorium
+ LArTPC
+ concepts for other targets...

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%

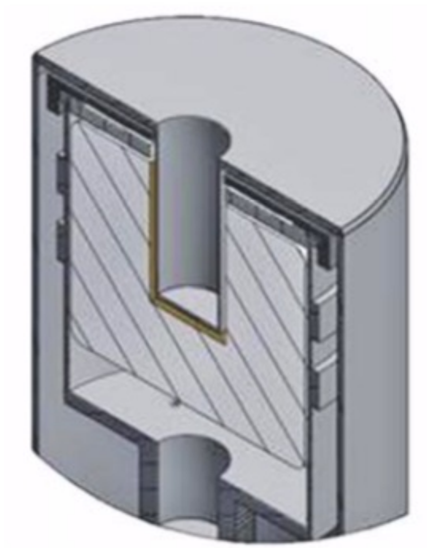




Measure electrons to determine flux normalization

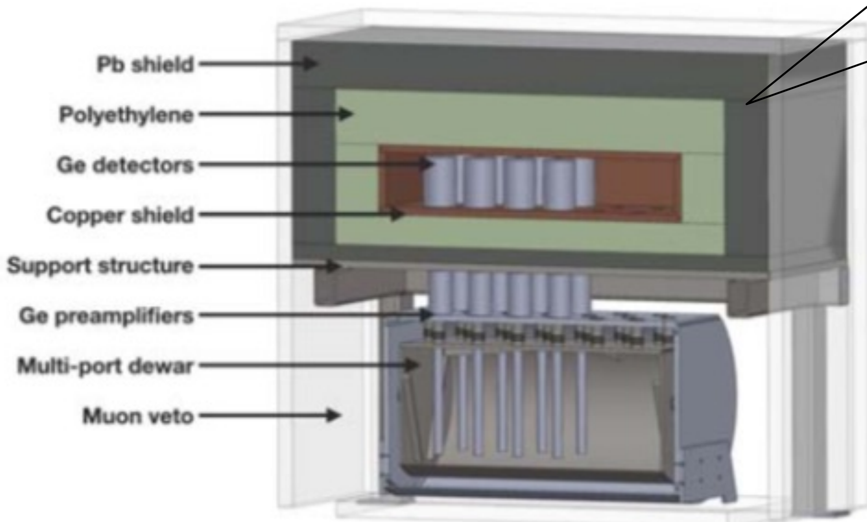
High-Purity Germanium Detectors

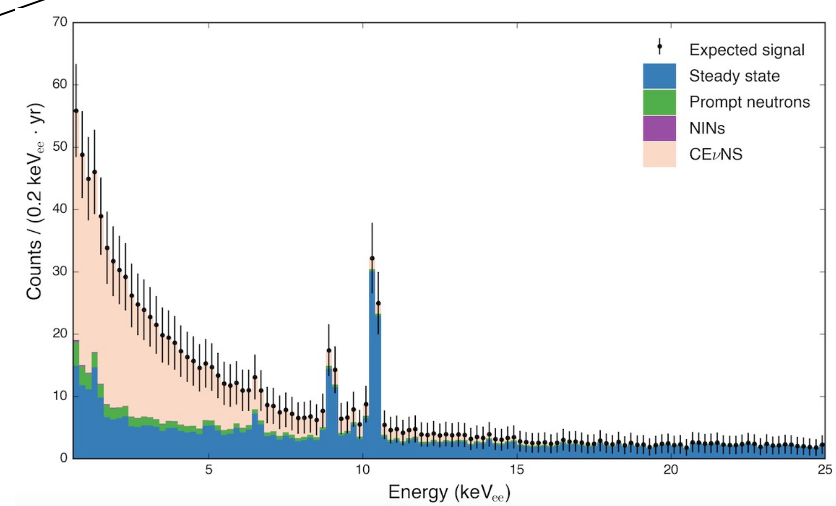
P-type Point Contact



- 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

yesterday in Neutrino Alley!

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

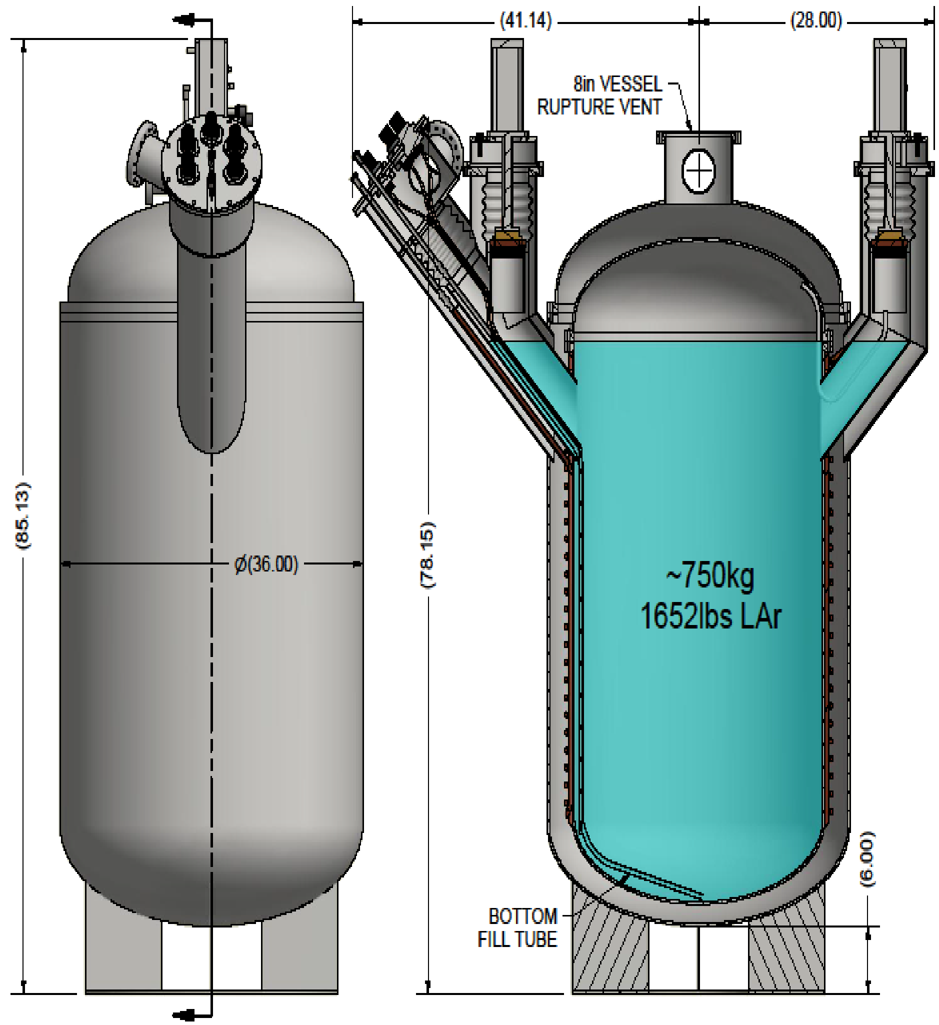
Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{127}I	$^{127}I(\nu_e, e^-)^{127}Xe$	Stopped π/μ	LSND	$284 \pm 91(stat) \pm 25(sys)$	210-310 [Quasi-particle] (Engel *et al.*, 1994)

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

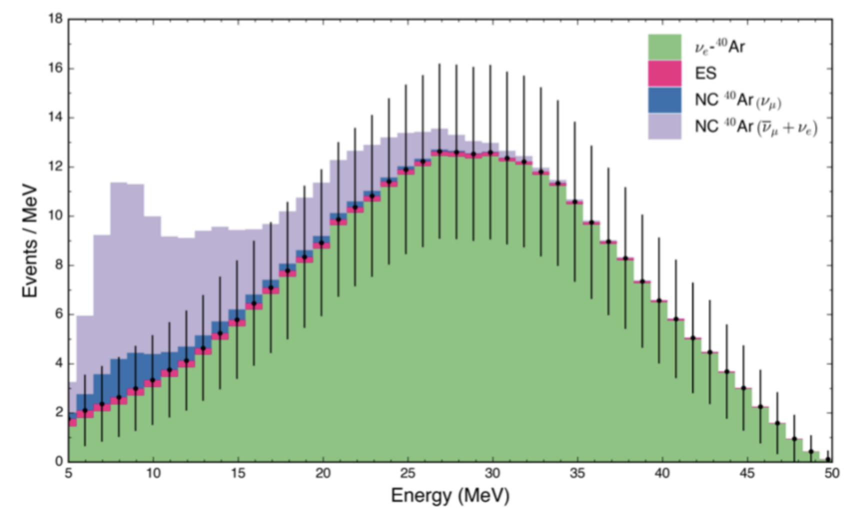
NaIVETE: 3.3 tonnes for CEvNS + ν_eCC on ^{127}I

(+ NuThor: 115 kg of 232-Th)

Tonne-scale LAr Detector



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

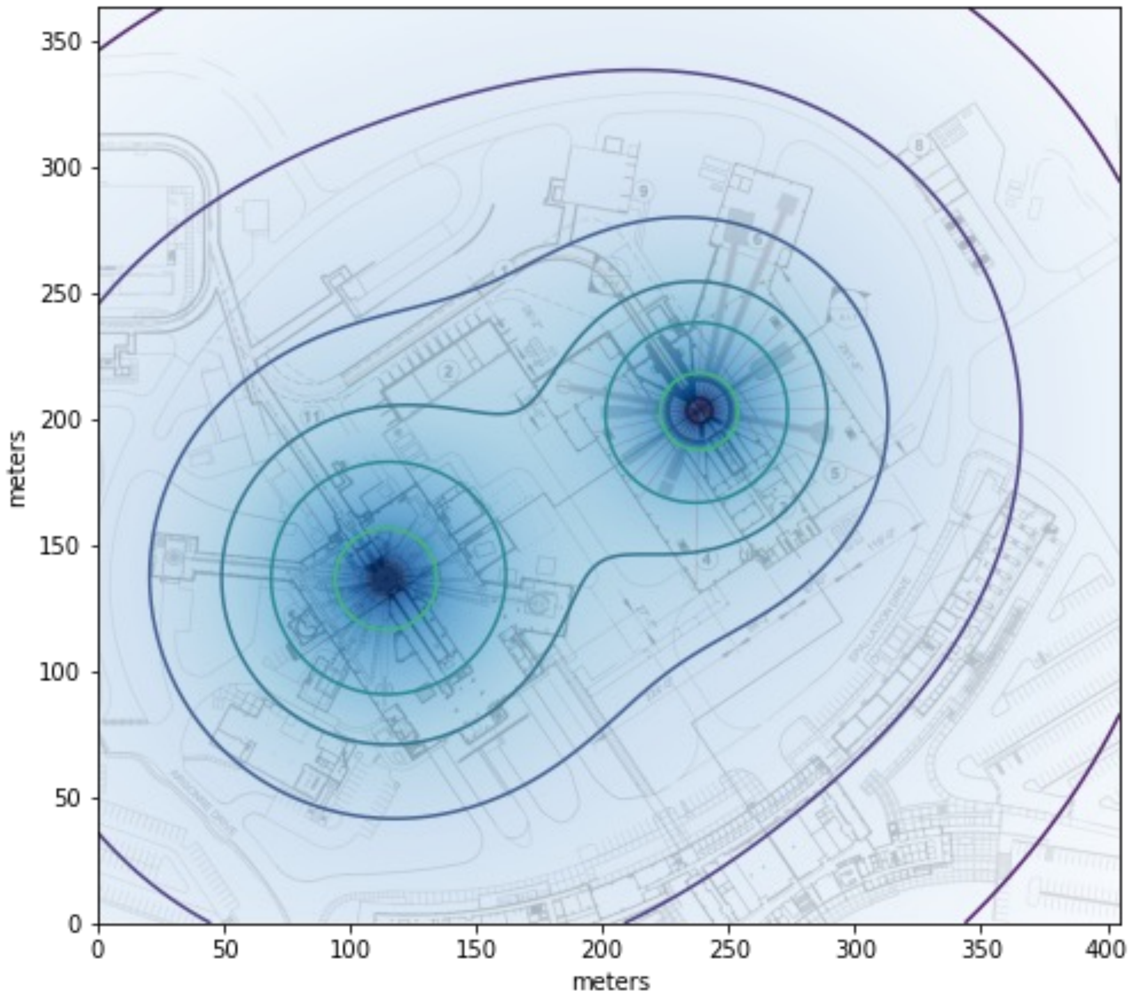


CC/NC **inelastic** in argon of interest for supernova neutrinos

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

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

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



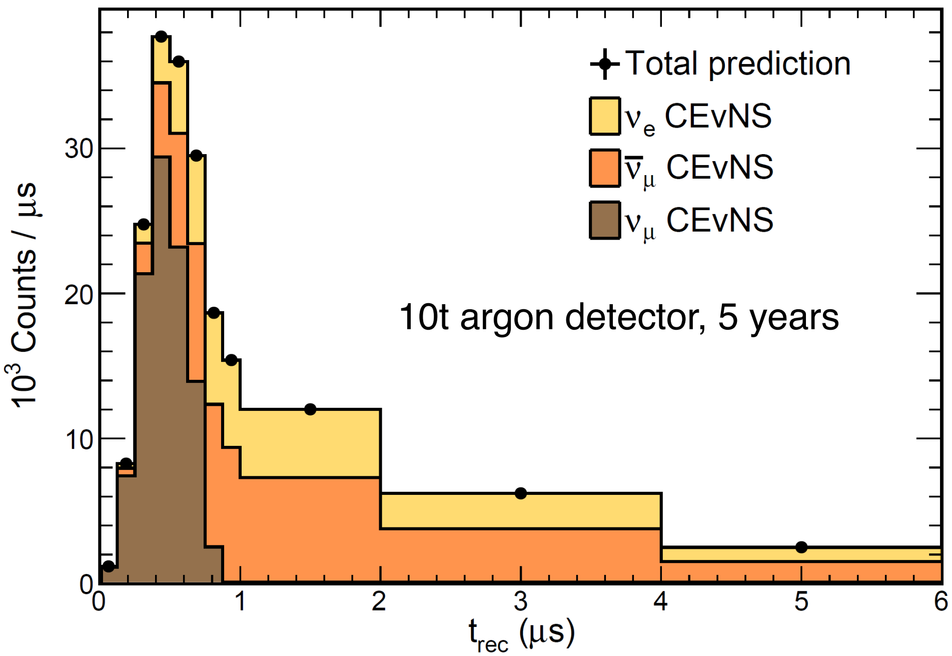
¾ bunches to FTS
¼ bunches to STS

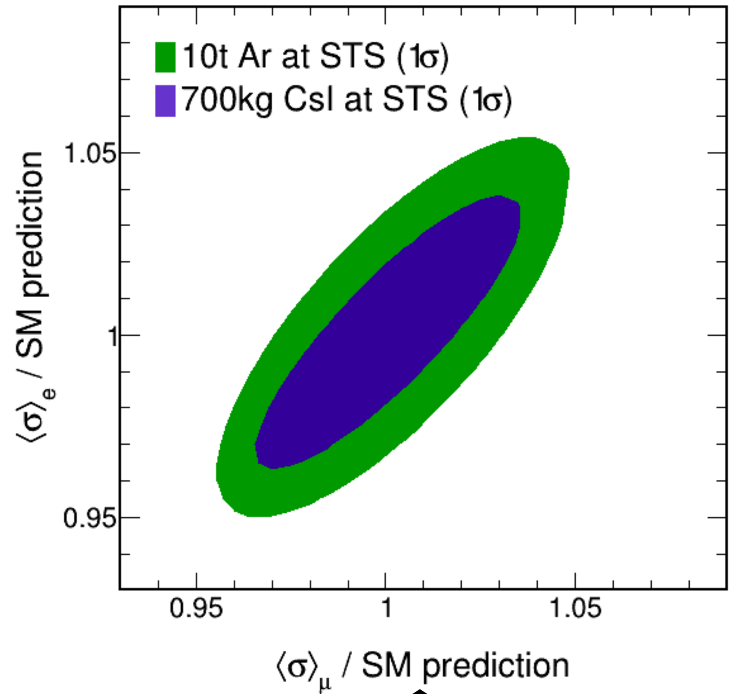
Promising new space available for **~10-tonne scale detectors**

Many exciting possibilities for ν's + DM!

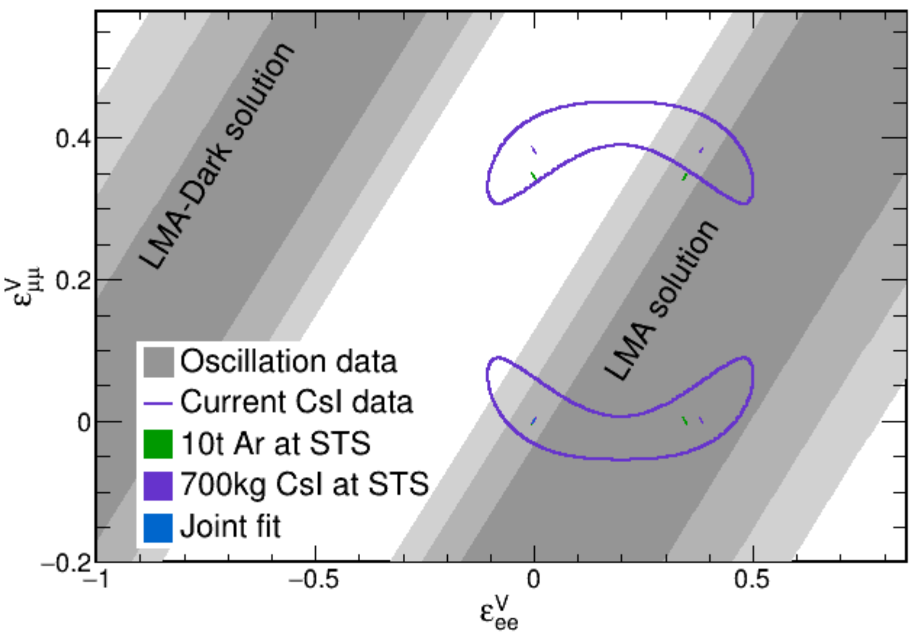
See D. Pershey, APS April 2022 invited talk

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)

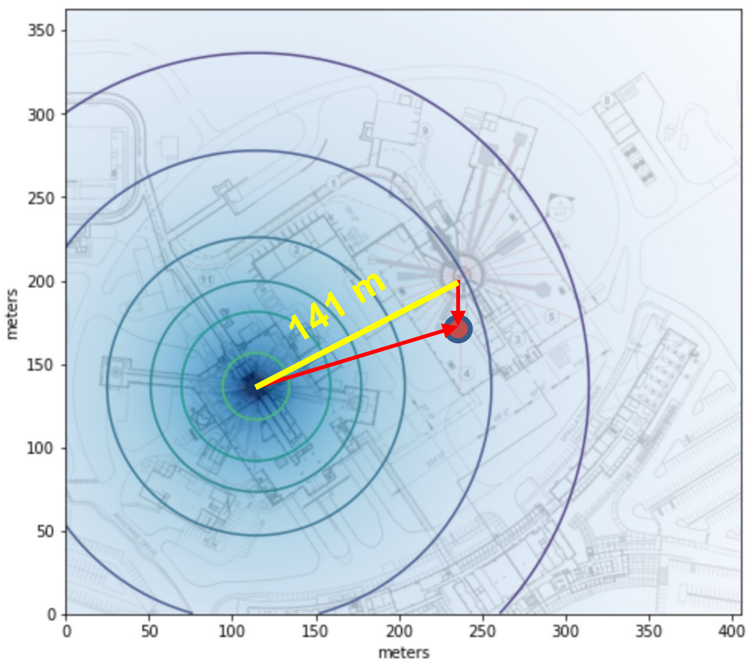


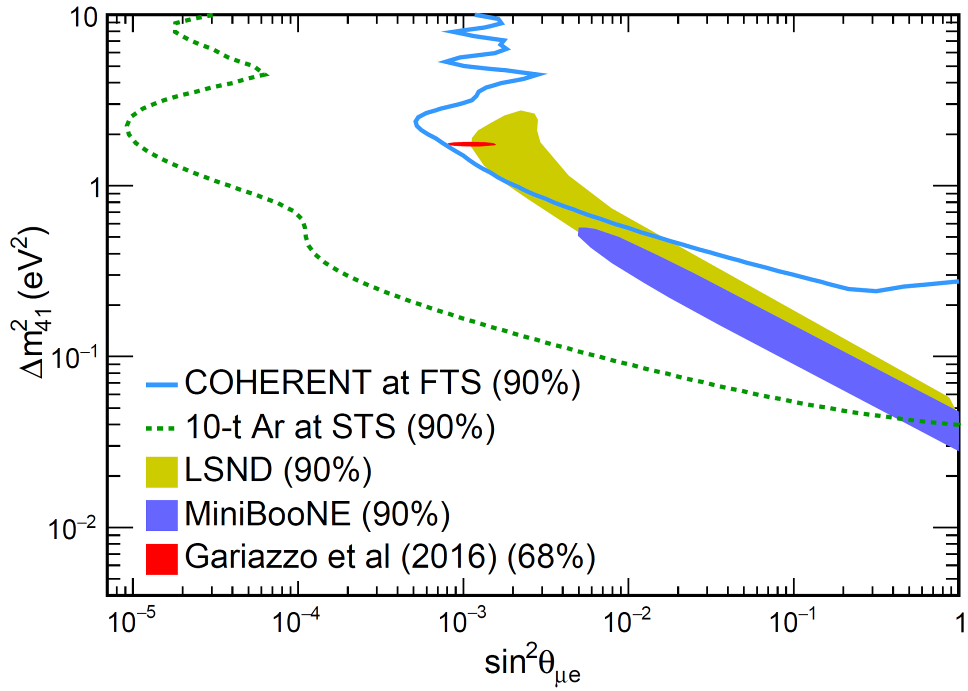
Stringent NSI parameters constraints, resolving oscillation ambiguities

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

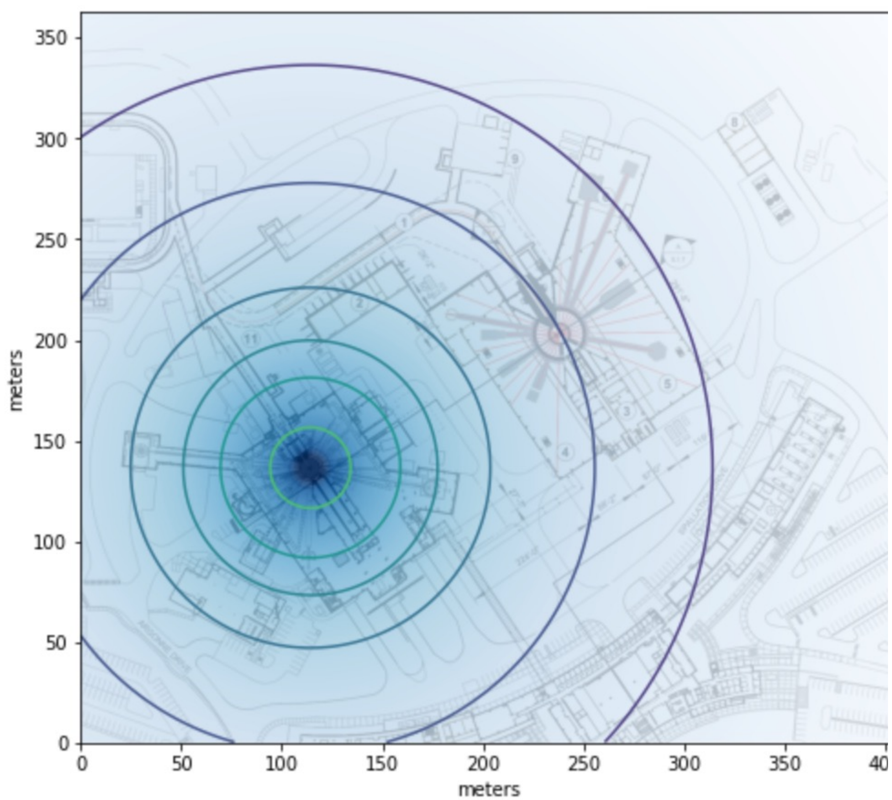
Assume L_{STS} = 20 m and L_{FTS} = 121 m, 10-t argon CEvNS detector

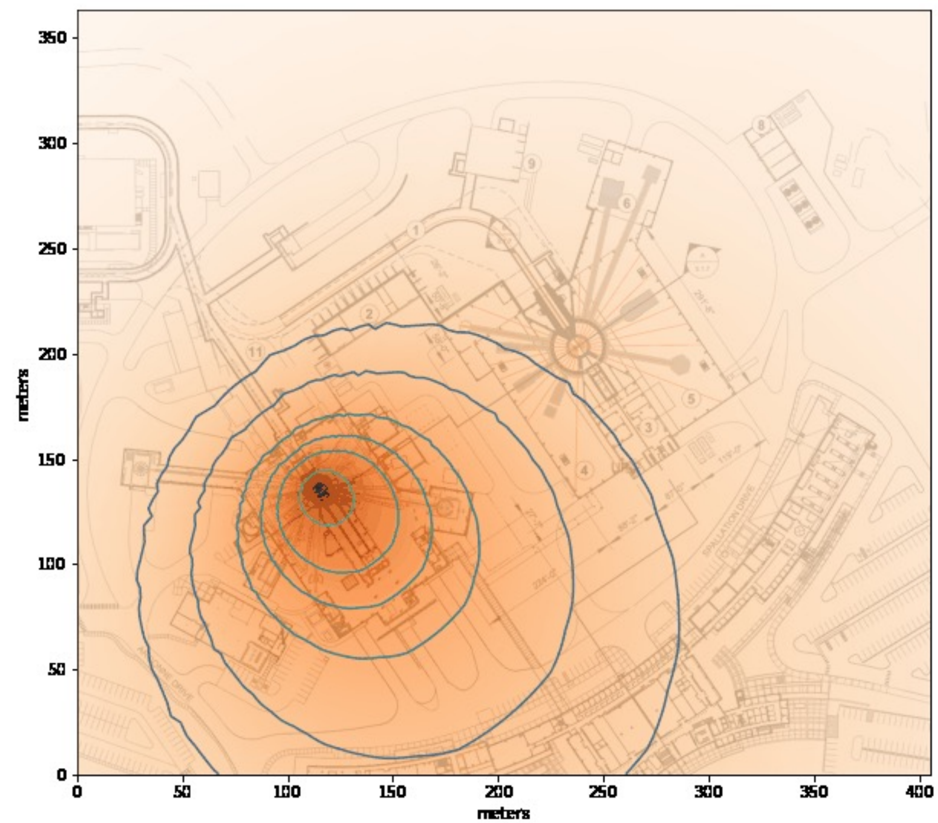
In 5 years, test ~entire parameter space allowed by LSND/MiniBooNE

Directionality of flux at the SNS

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

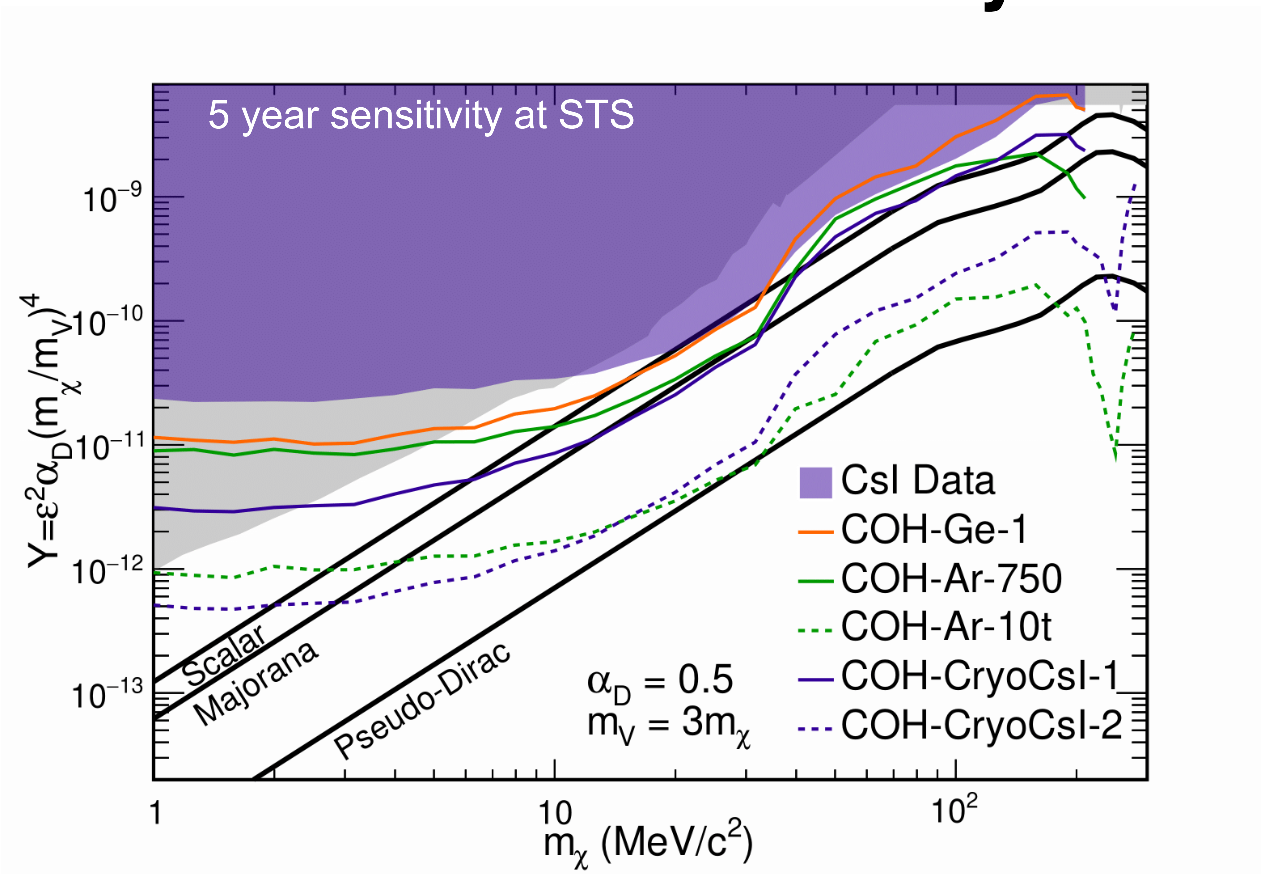
DM flux produced in-flight
is **boosted forward**





Can test angular dependence of boosted DM flux

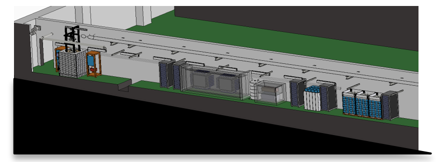
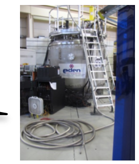
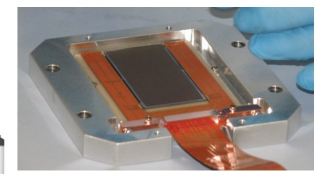
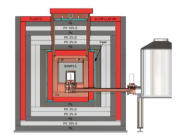
Future COHERENT sensitivity to dark matter

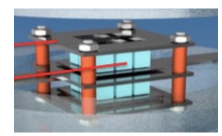


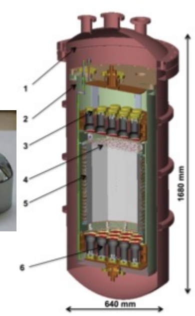
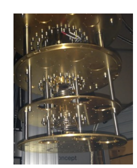
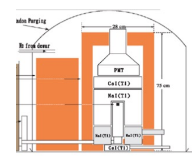
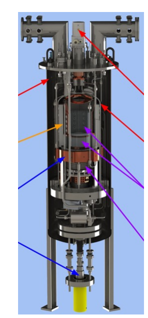
- **Short term:** Ge detector will explore scalar target at lower masses
- **Medium term**: large Ar, CsI detectors to lower DM flux sensitivity, probe of Majorana fermion target
- **Longer term:** large detectors placed forward at the STS (dashed lines) will test even pessimistic scenarios

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
SBC	Xe, Ar	USA?	Reactor
TEXONO	p-PCGe	Taiwan	Reactor

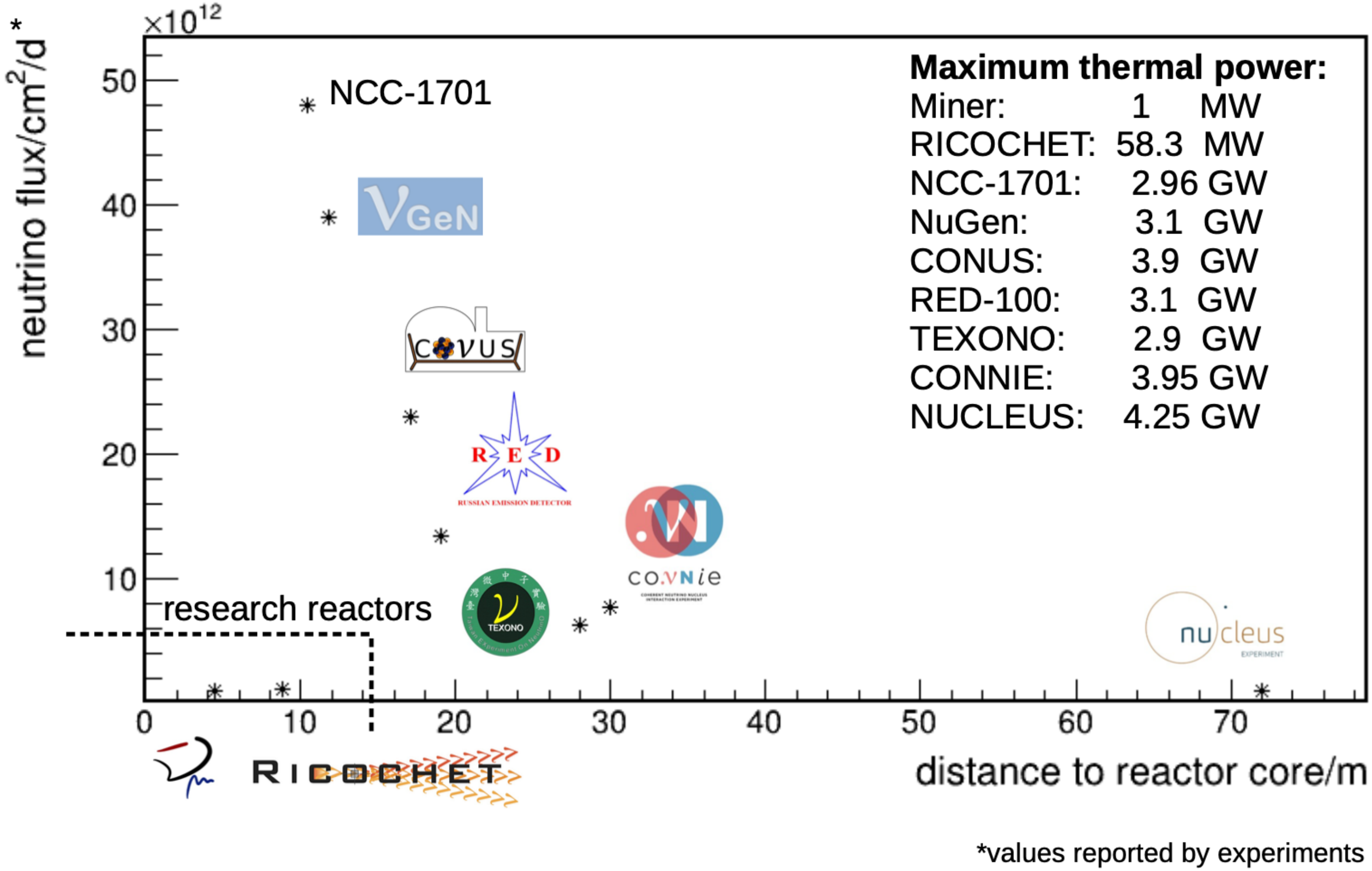


+ DM detectors, +directional detectors +more...

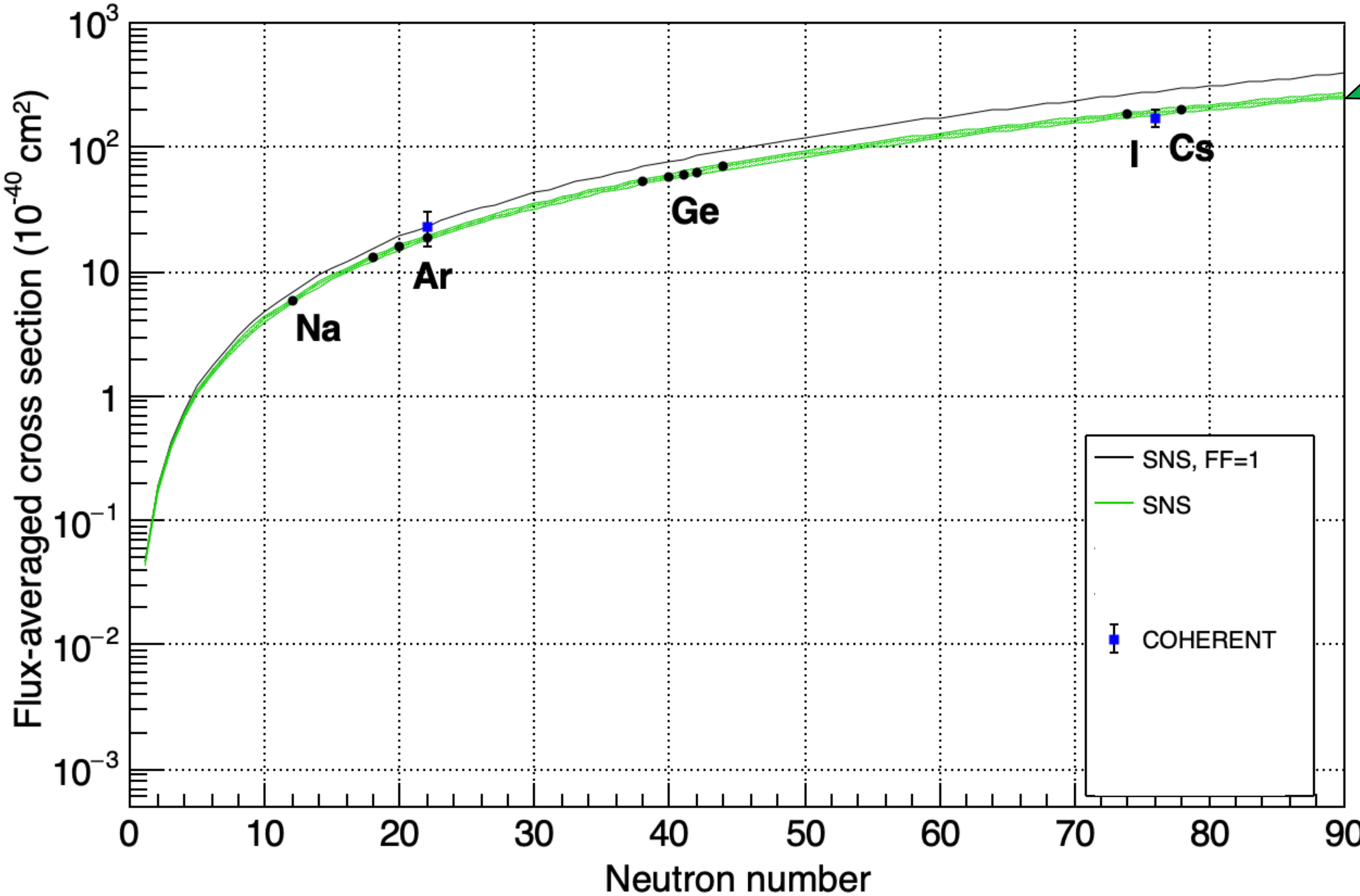
many novel low-background, low-threshold technologies!!

CEνNS detection at reactor



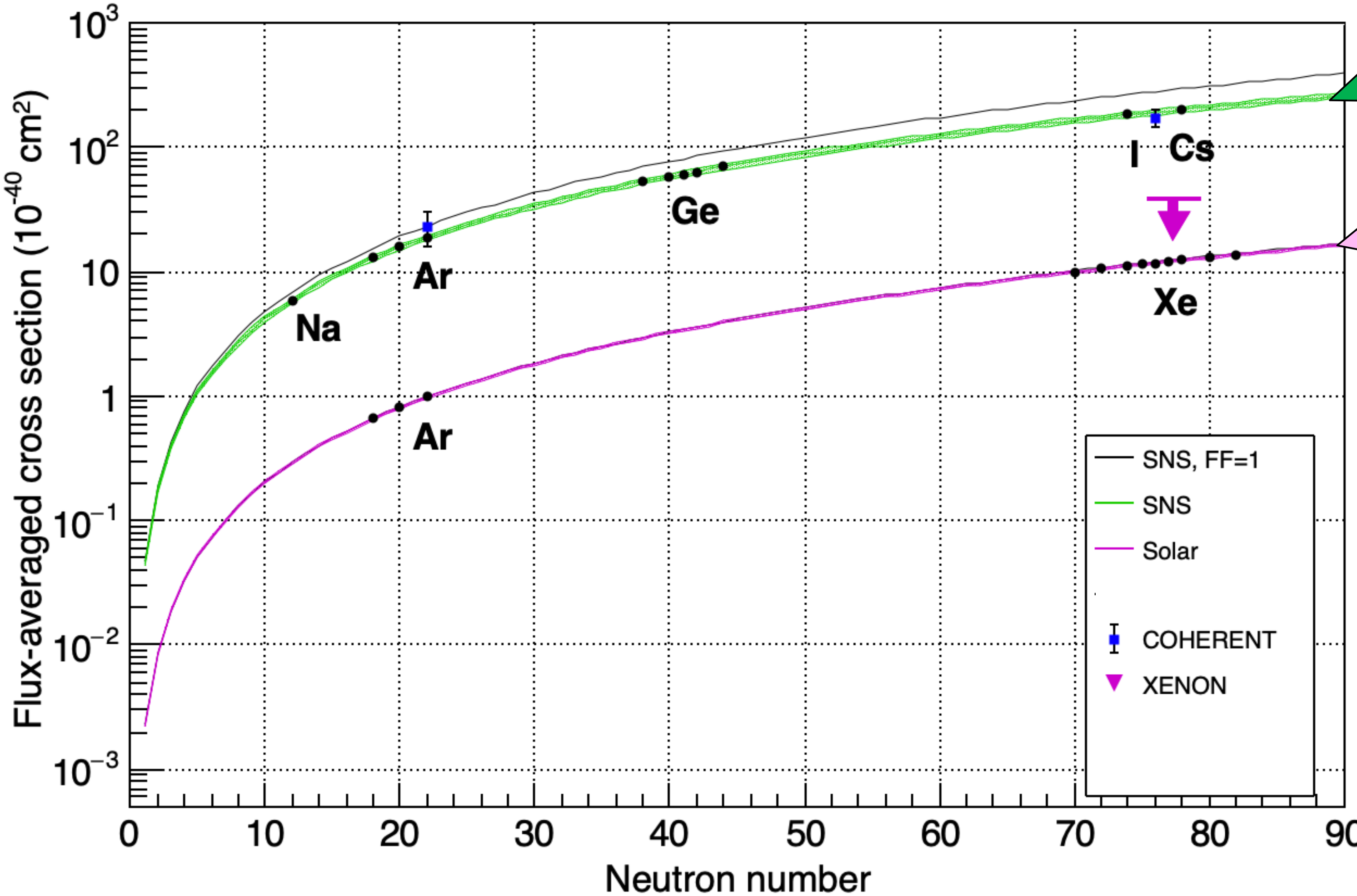
J. Hakenmuller, NDM 2022

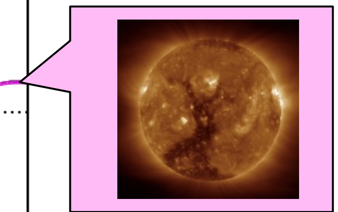
Summary of CEvNS Results



So far: measurements in CsI, Ar from COHERENT

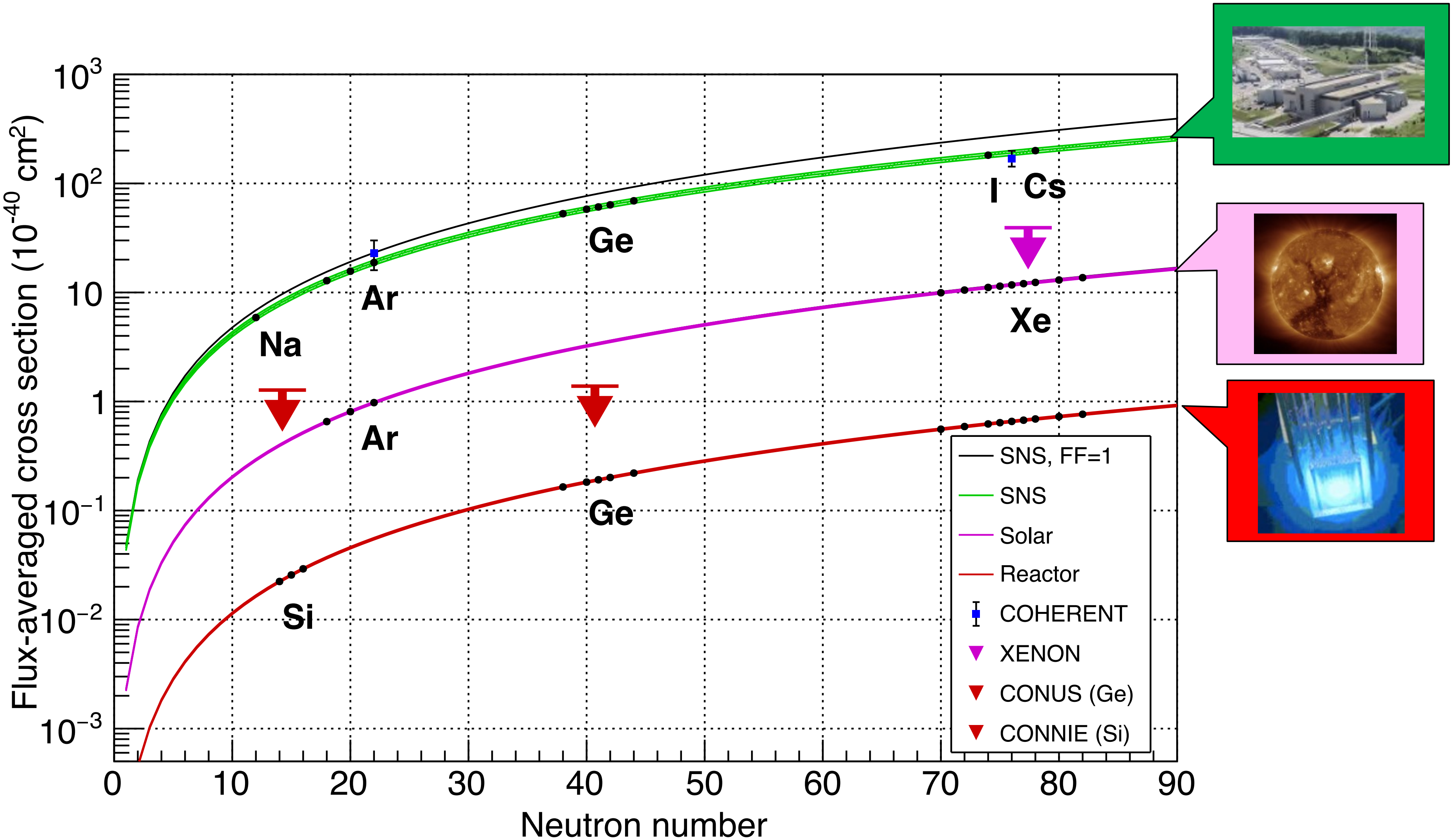
Summary of CEvNS Results





Limits from XENON on solar CEvNS

Summary of CEvNS Results



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

Comments on overall status and prospects

- **Reactor neutrinos:**
  - Backgrounds and quenching factors are hard...
  - But on the cusp! Will get there!
  - F~1, great for BSM, but electron antineutrinos only
  - Not great for nuclear structure understanding

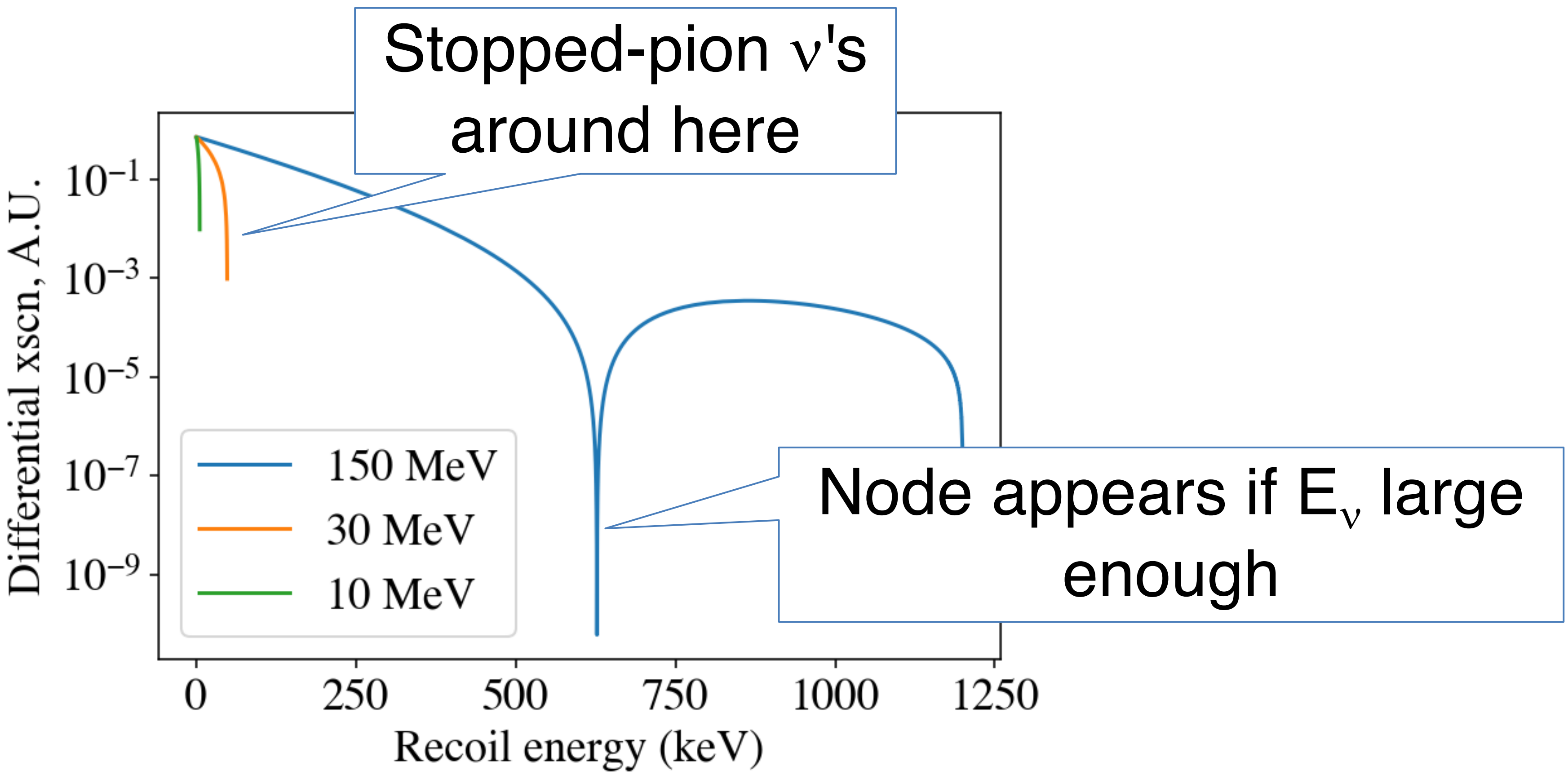
- **Stopped-pion neutrinos (up to 50 MeV):**
  - 15-20% ucty measurements now
  - 5-10% ucty in next several years (+ more targets)
  - few % ucty conceivable with tonne-scale @ ORNL STS

- **Where do we want to get to?**
  - few % level tests SM flavor-dependent radiative corrections
  - <few % w/Q dependence measures form factors

Some thoughts...how can we best measure neutron radii with neutrinos?

Possible strategy: use higher energies and kill it with stats

Argon-40, monochromatic neutrinos, same flux



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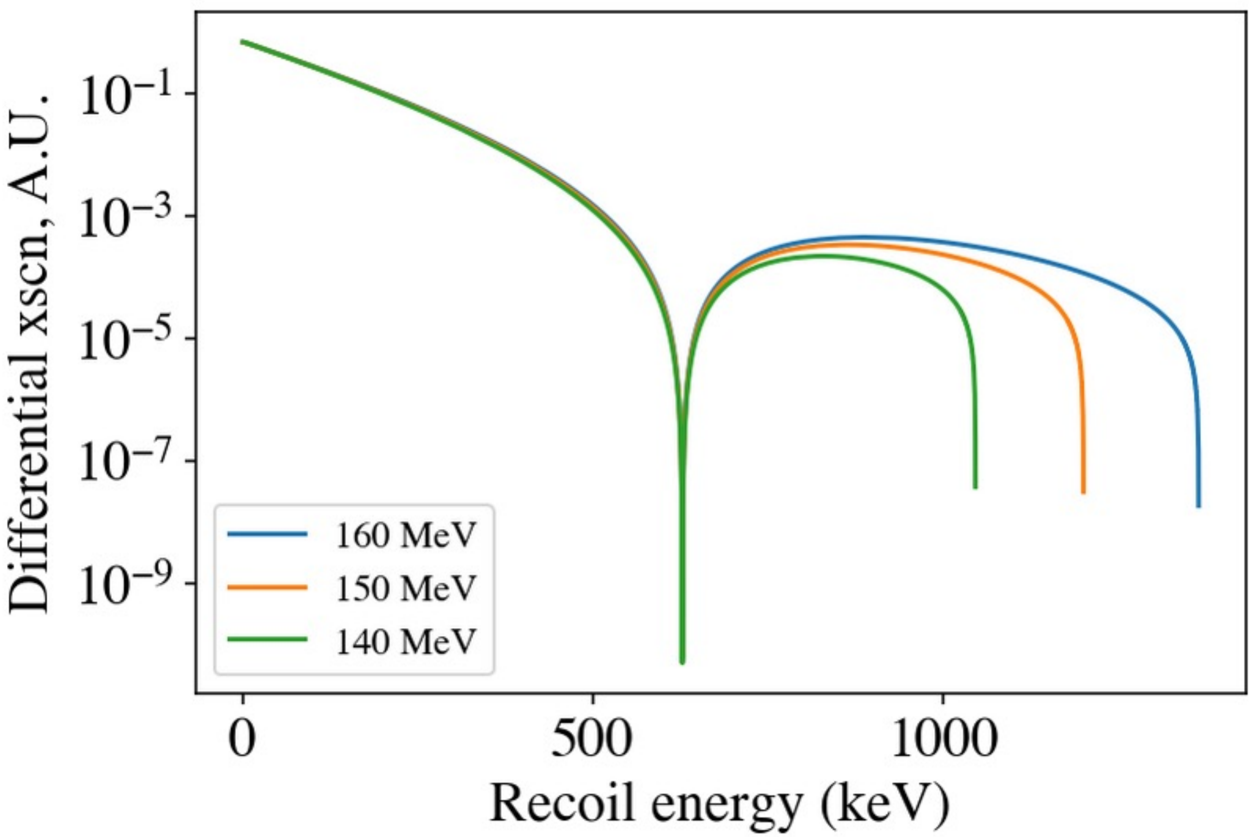

The position of the node doesn't care about the neutrino energy
(in our approximation)

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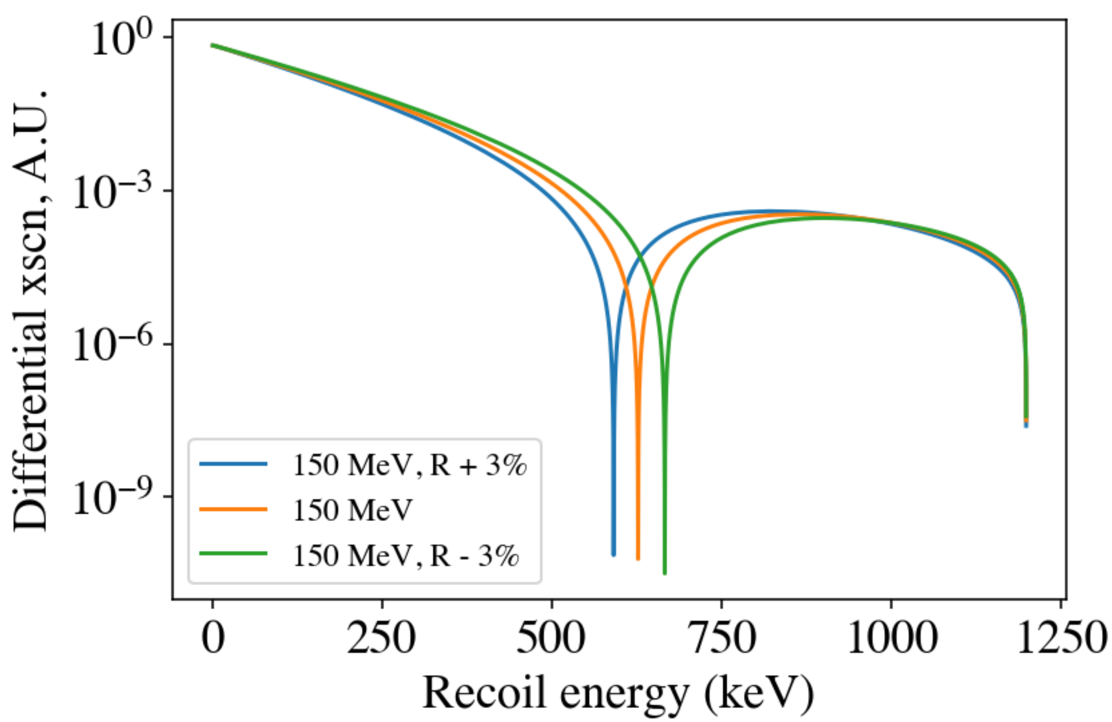
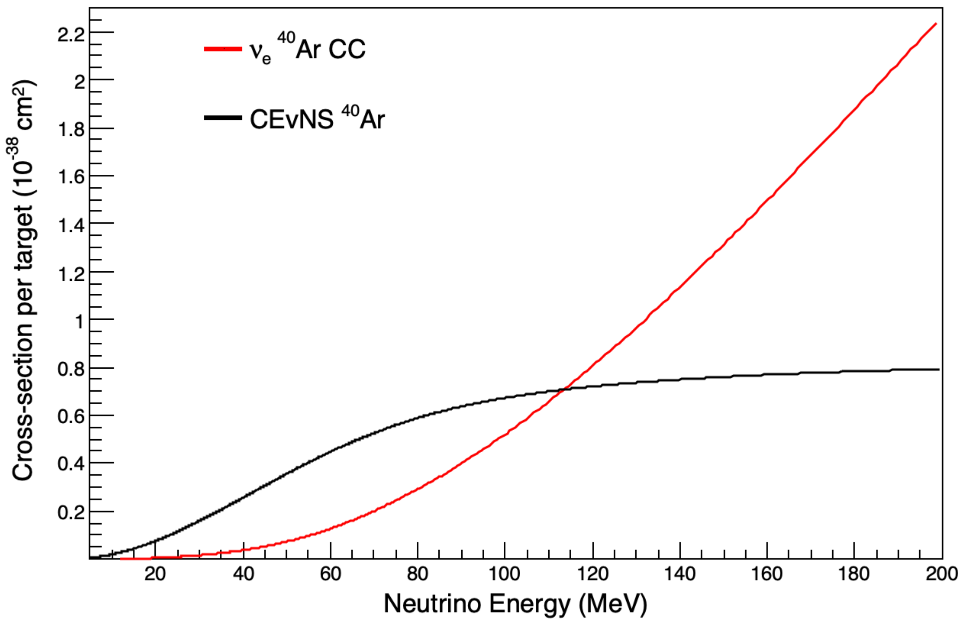


The position of the node *does* care the neutron radius...

Insensitive to neutrino spectral shape uncertainties?

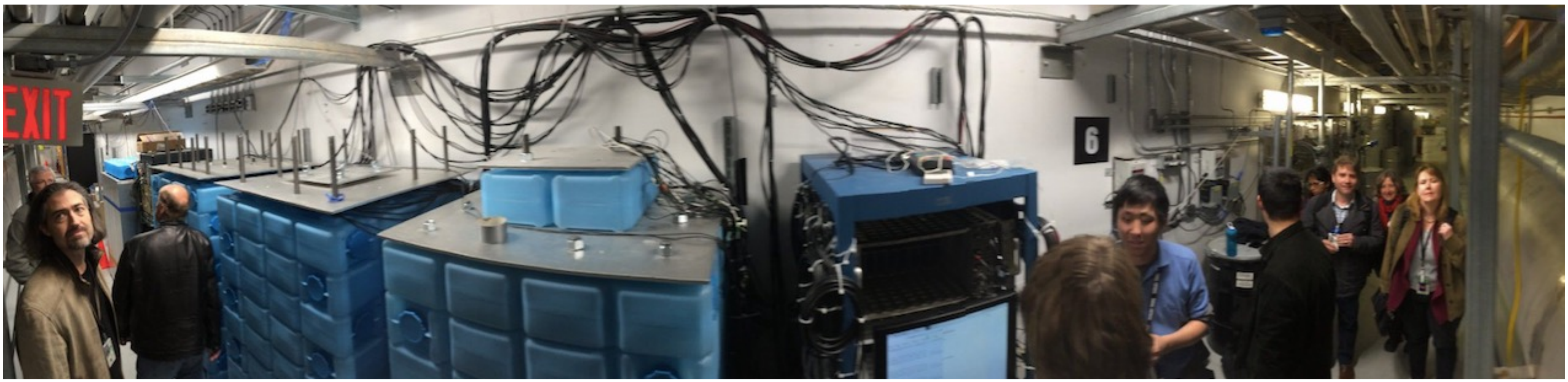
Potential issue: inelastics start to dominate,
i.e. scattering off nucleons, but these are quite experimentally distinct (bright)



- Can we find a source of ~100 MeV neutrinos?
  - Maybe... π/μDIF? Muon capture?
- Detector/flux scale-up by ~10^3 ?
  - Not insane...
    (hmmm, DUNE ND?
    ...0.5 MeV threshold hard but not impossible...)
- Need to do some quantitative studies....

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 Ar data, 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...)