COHERENT Elastic Neutrino-Nucleus Scattering Experiments

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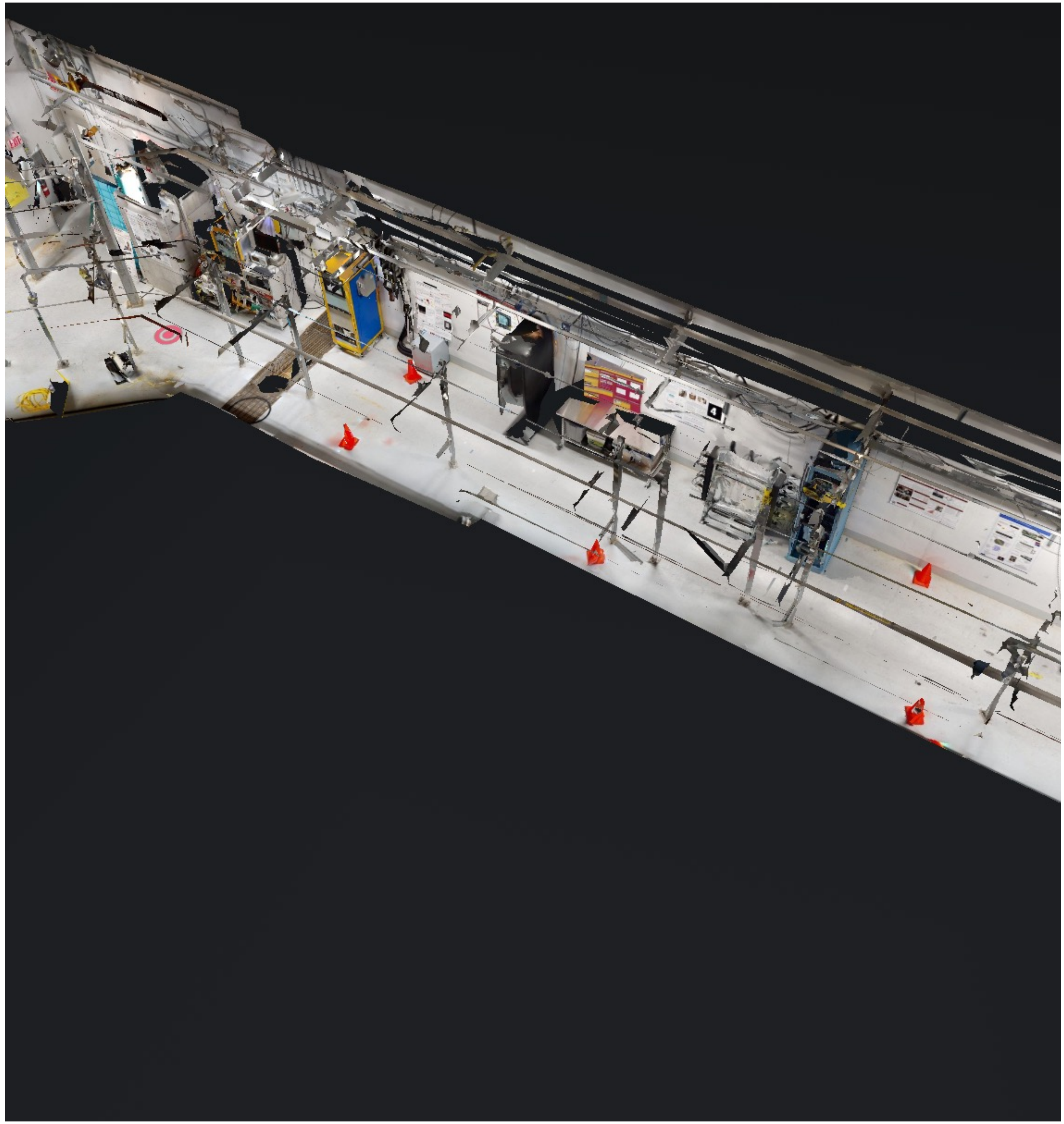
Duke University

Bormio
January 24, 2024



Neutrino interactions with Nuclei

Deep Inelastic Scattering

keV MeV GeV TeV PeV

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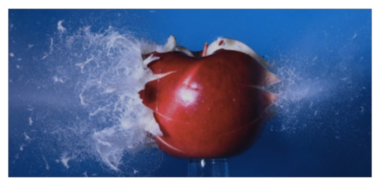

Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Neutrino interactions with Nuclei

Interactions with nuclei and electrons, minimally disruptive of the nucleus

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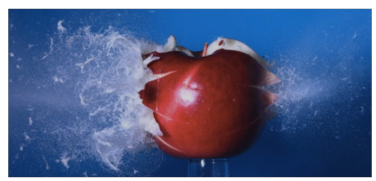



Interactions with nucleons inside nuclei, often disruptive, hadroproduction

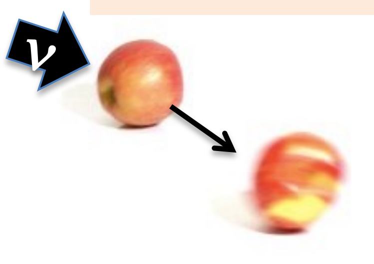
We are considering the low-energy regime and the ***gentlest*** interaction with nuclei

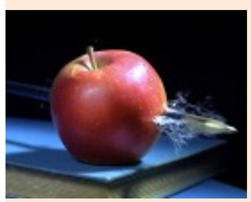
Coherent elastic neutrino-nucleus scattering

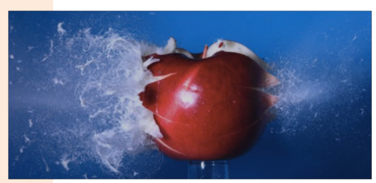
Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV



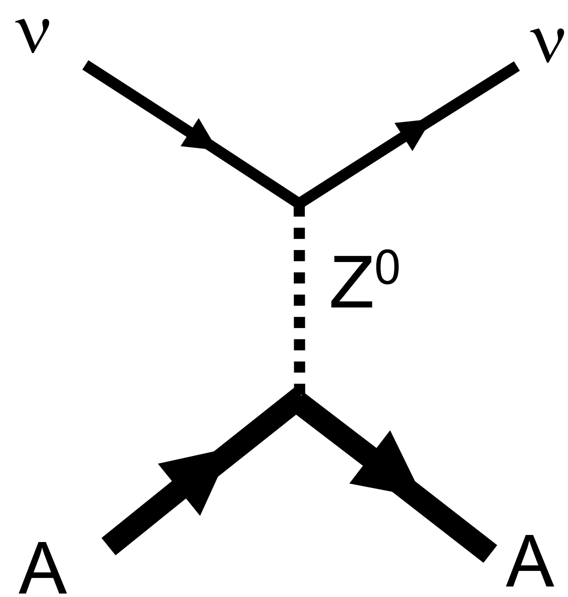




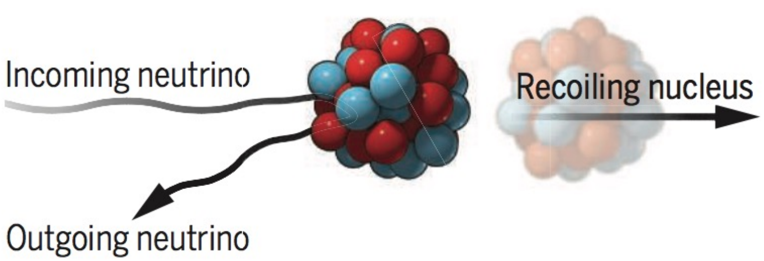
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

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

Standard Model prediction for CEvNS differential cross section

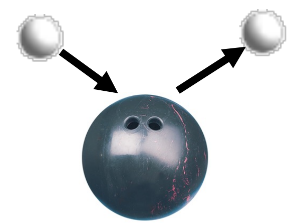
(probability of kicking a nucleus with recoil energy T)

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

Fermi constant (SM parameter)

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

kinematics:
ping-pong ball hits bowling ball



Form factor: F=1 ➔ full coherence

weak nuclear charge

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

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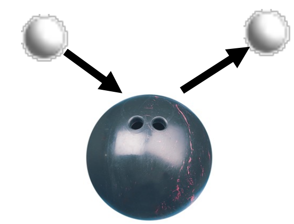

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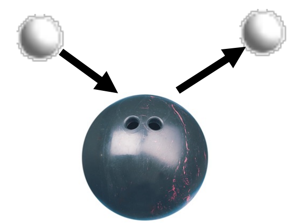

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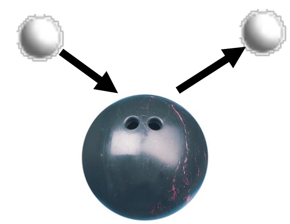

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weak nuclear charge

No. of protons

No. of neutrons

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

$\sin^2\theta_W = 0.231$, so protons unimportant

$$\Longrightarrow \quad Q_W \propto N$$

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

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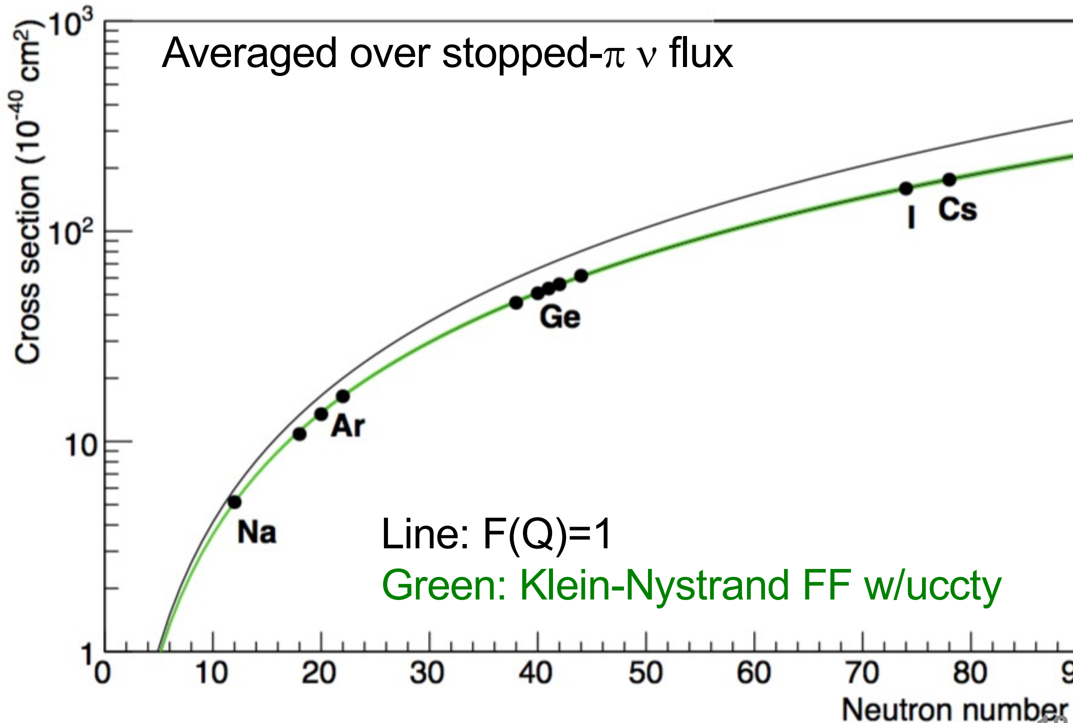
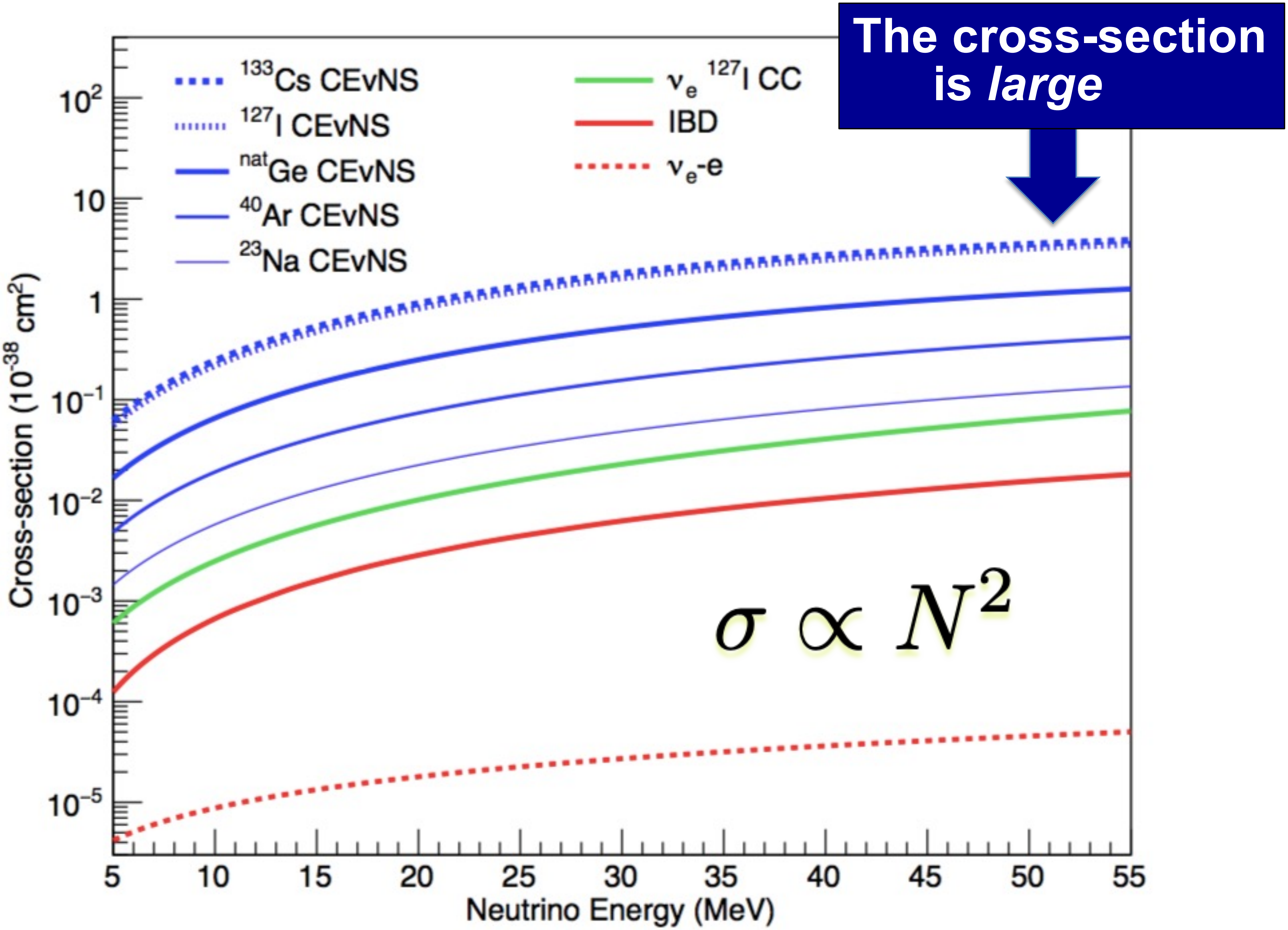
$$Q_W = (1 - 4\sin^2\theta_W)Z - N$$

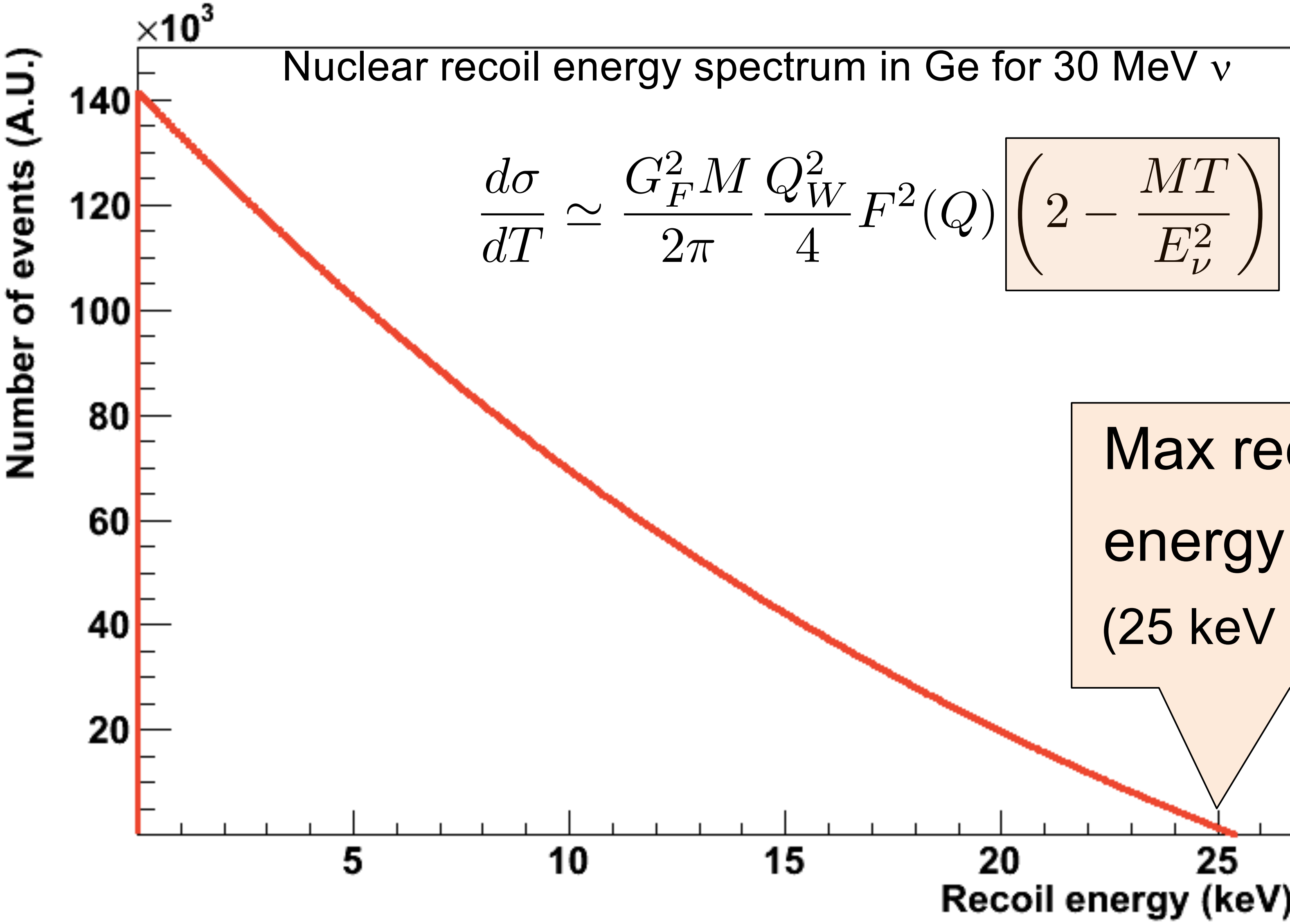
$$\Rightarrow \frac{d\sigma}{dT} \propto N^2$$





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

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

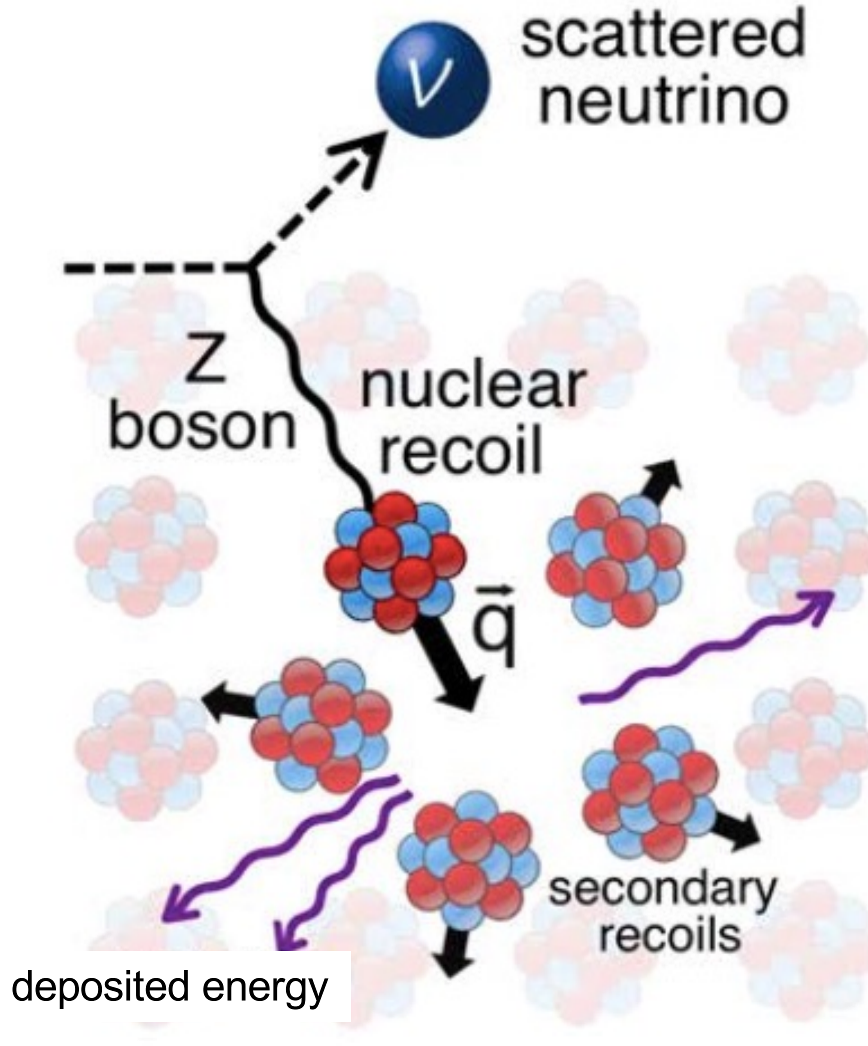


$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

Max recoil energy is ~$2E_\nu^2/M$ (25 keV for Ge)

The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



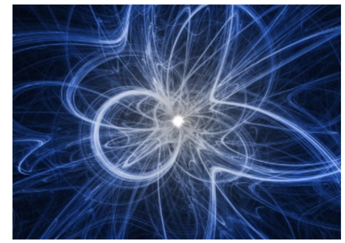
➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

CEvNS: what's it good for?

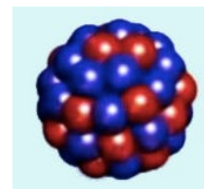
(1) So (2) Many (3) Things !

(not a complete list!)

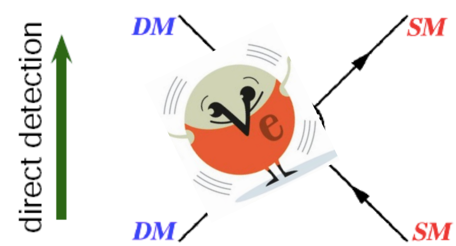
CEvNS as a **signal**
for signatures of *new physics*



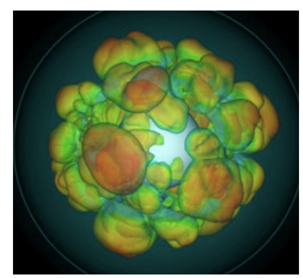
CEvNS as a **signal**
for understanding of "old" physics



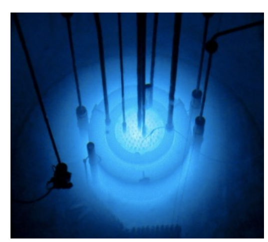
CEvNS as a **background**
for signatures of new physics



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



CEvNS as a **practical tool**



CEvNS: what's it good for?

! (not a complete list!)

CEvNS as a **signal**
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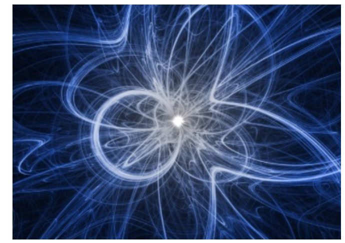

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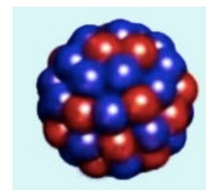

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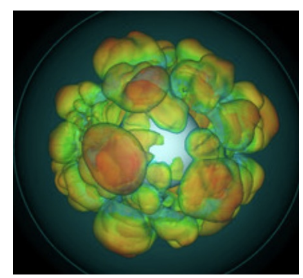

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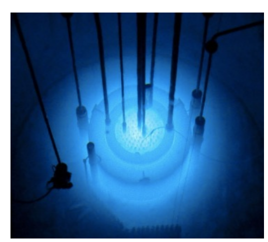

The cross section is cleanly predicted in the Standard Model

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

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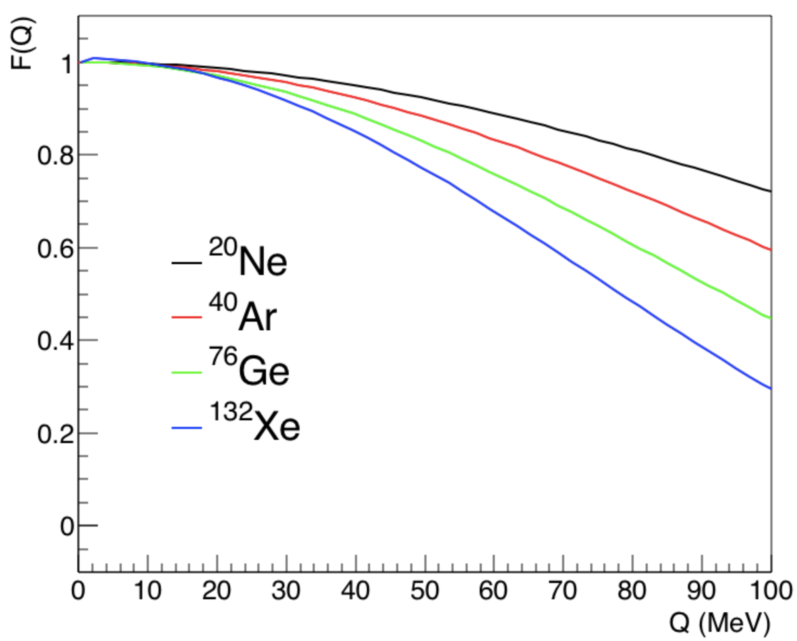
F(Q): nuclear **form factor**, <~5% uncertainty on event rate

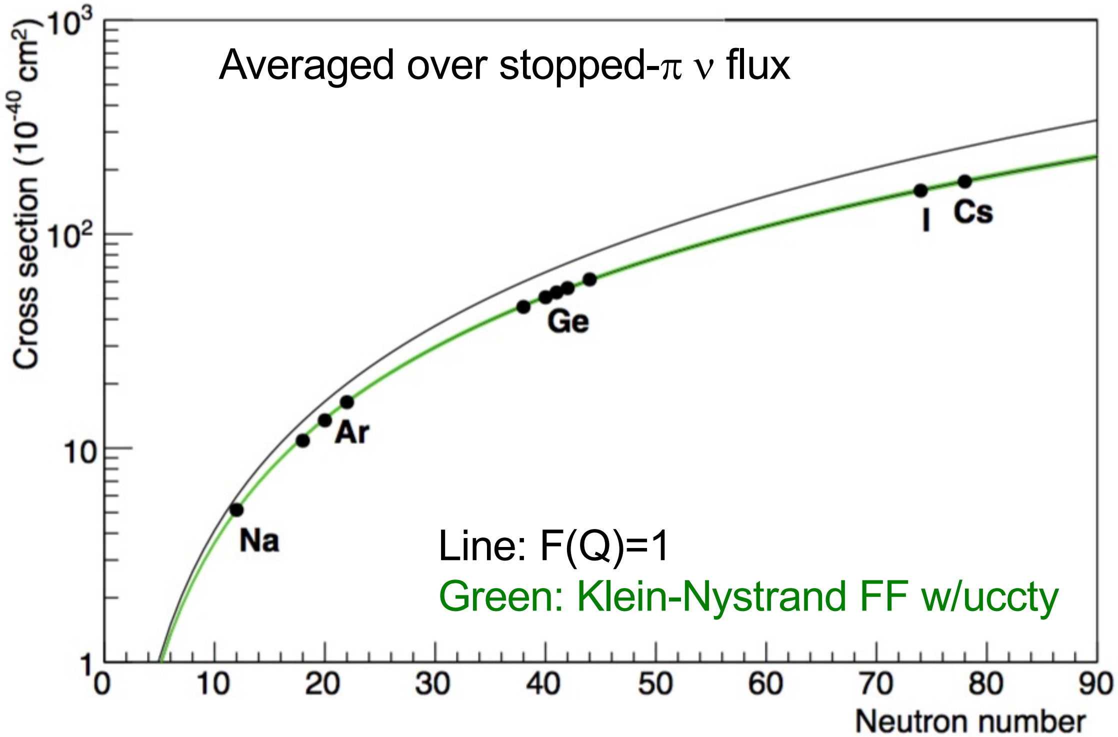


form factor suppresses cross section at large Q

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

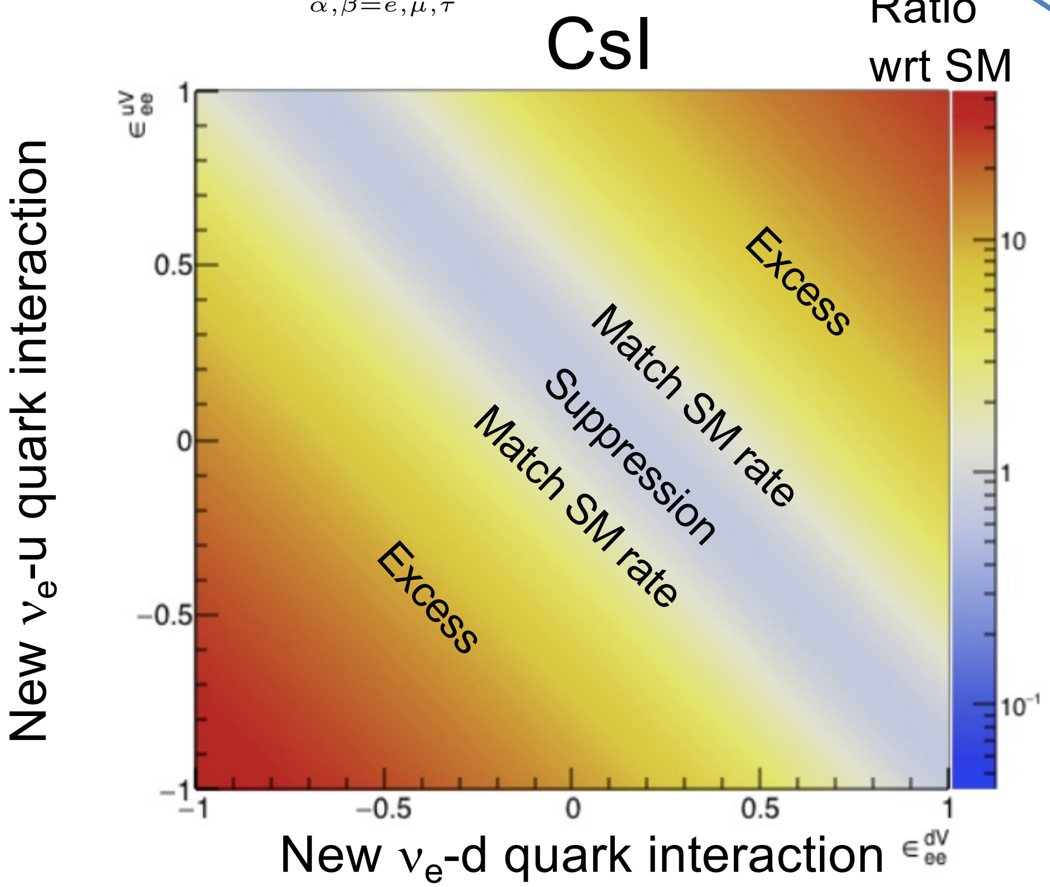


A deviation from α N^2 prediction can be a signature of beyond-the-SM physics

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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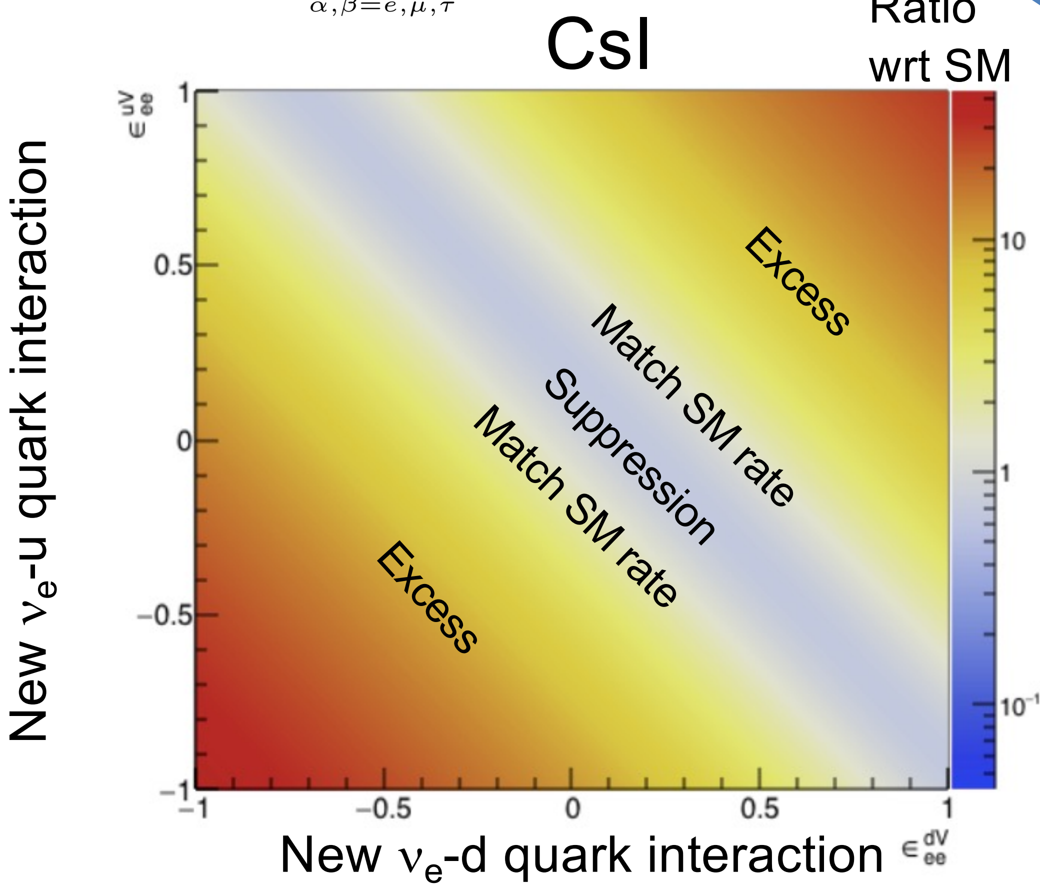

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Observe less or more CEvNS than expected?
...could be beyond-the-SM physics!

Other new physics results in a

distortion of the recoil spectrum (Q dependence)

BSM Light Mediators

SM weak charge

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

Effective weak charge in presence of light vector mediator Z'

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

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

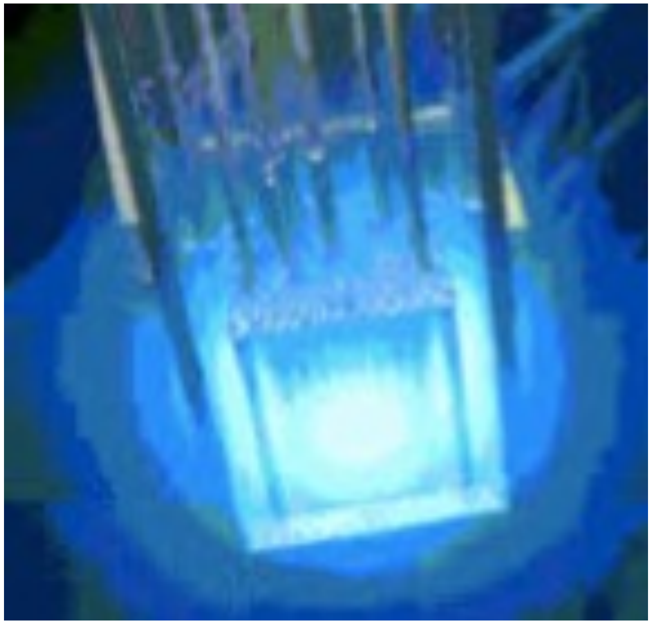
Sterile Neutrino Oscillations

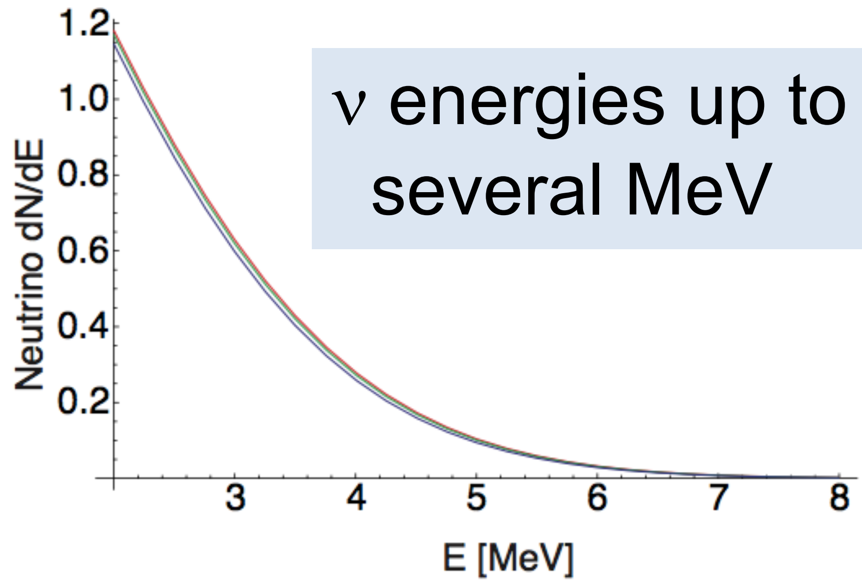
$$P^{\mathrm{SBL}}_{\nu_\alpha\to\nu_\alpha}(E_\nu) = 1 - \sin^2 2\theta_{\alpha\alpha}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

"True" disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

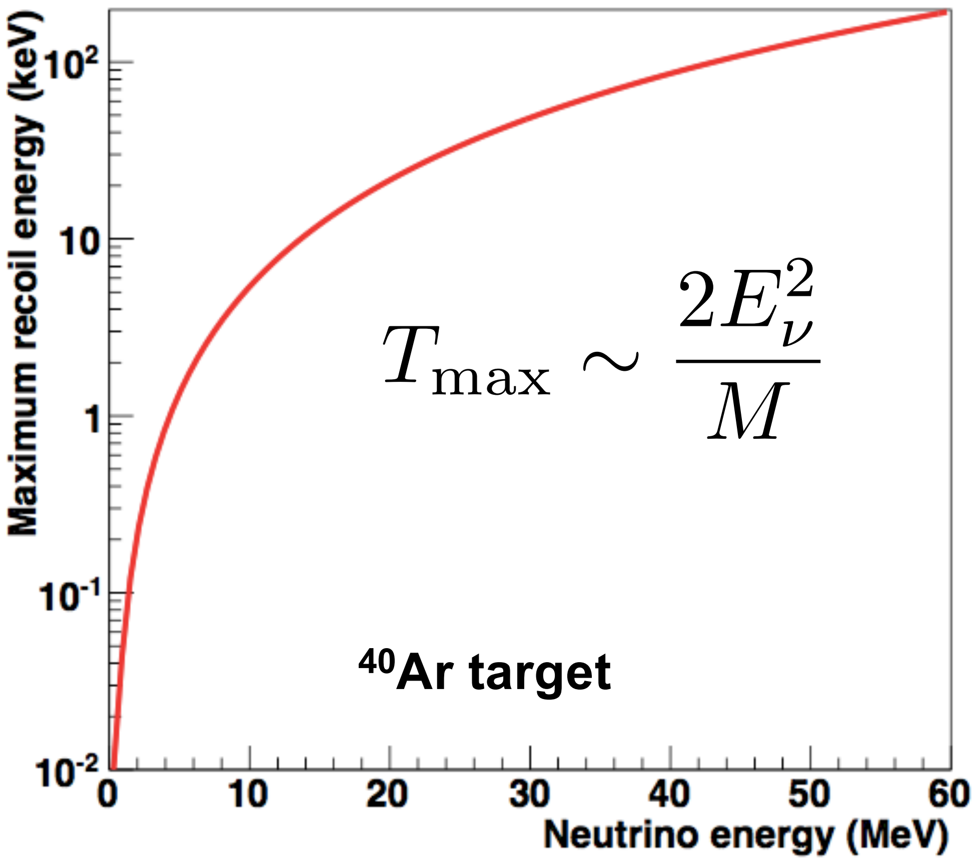
Neutrinos from nuclear reactors

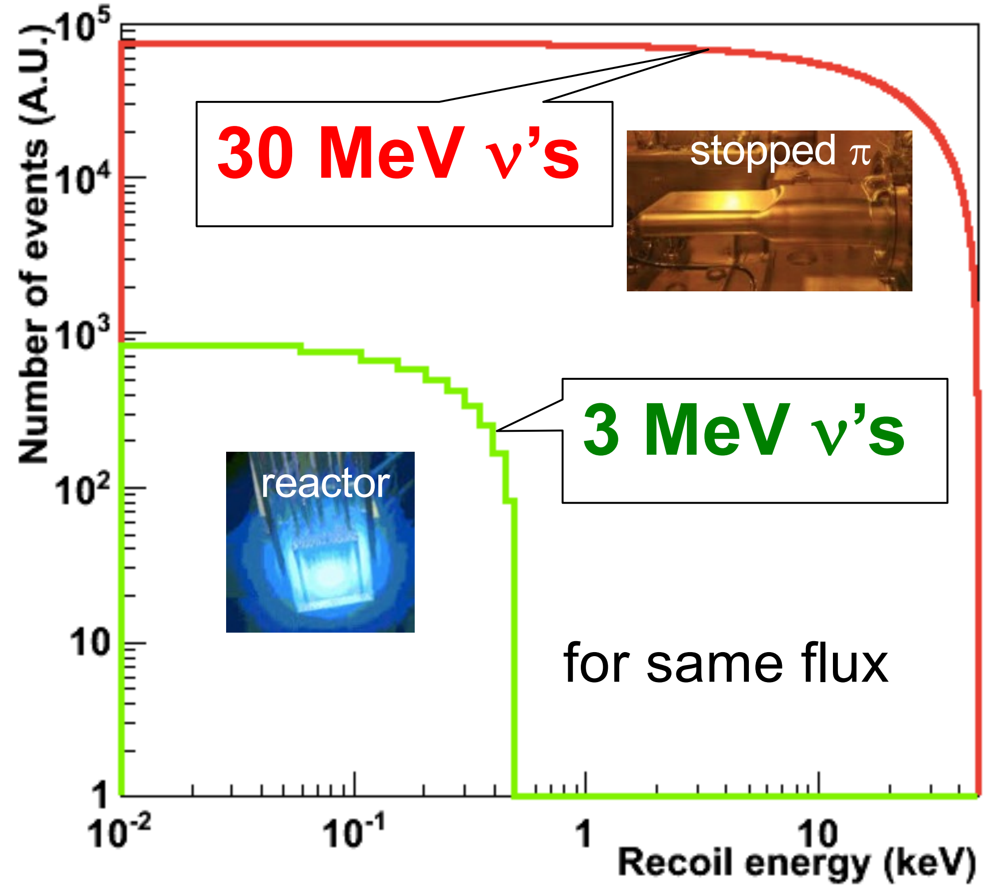




- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2x10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

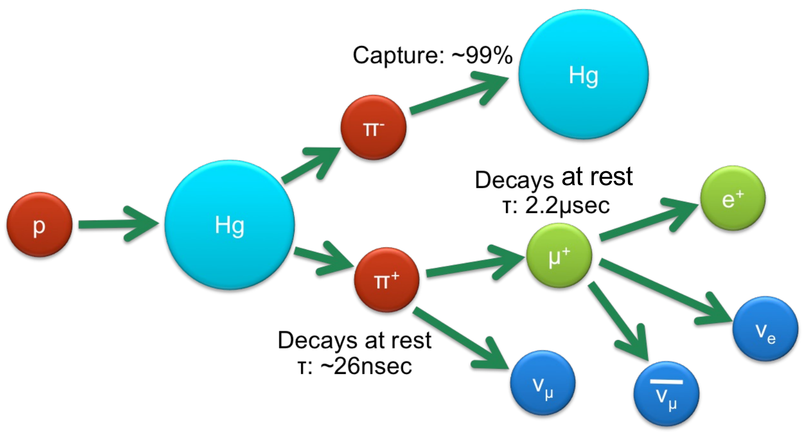
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

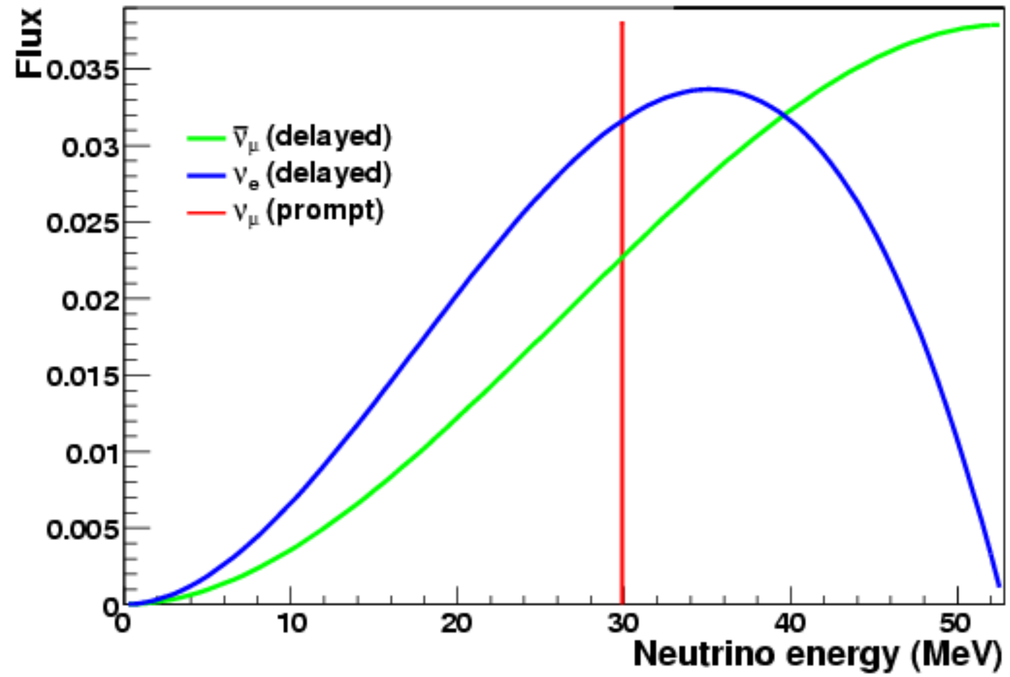




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





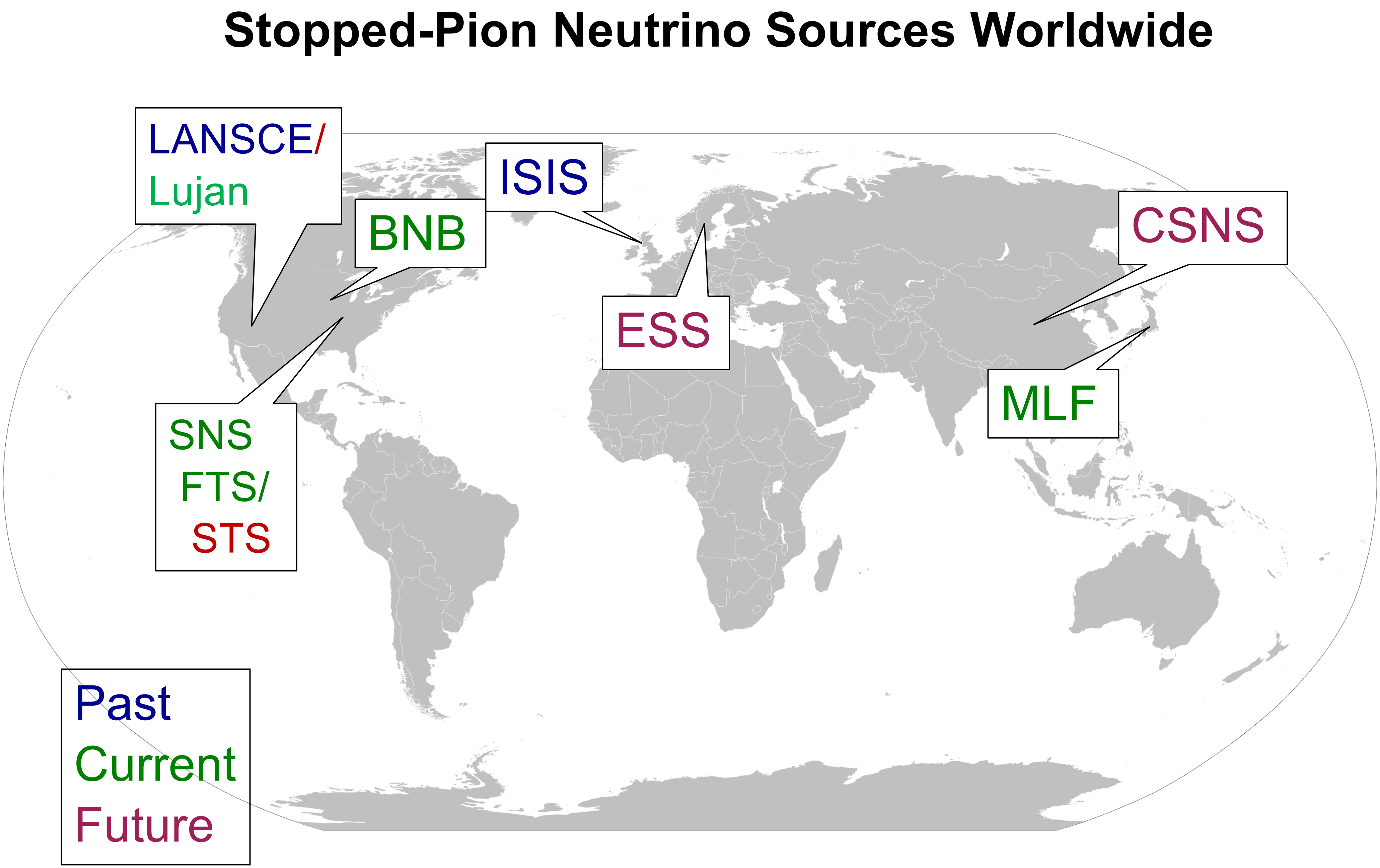
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

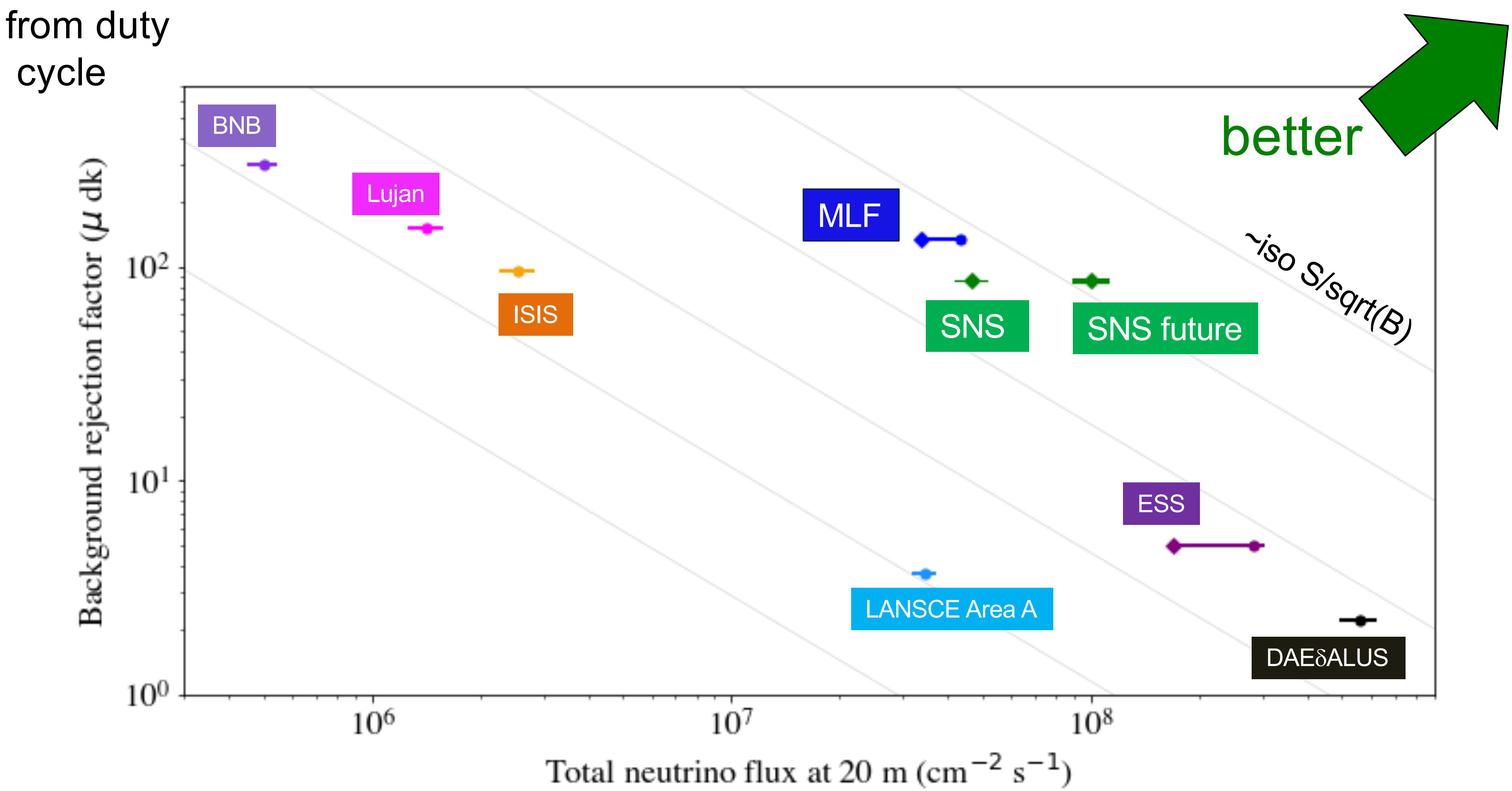
$$\downarrow$$

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

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


Stopped-Pion Neutrino Sources Worldwide
LANSCE/
Lujan
ISIS
BNB
CSNS
ESS
MLF
SNS
FTS/
STS
Past
Current
Future

Comparison of pion decay-at-rest ν sources



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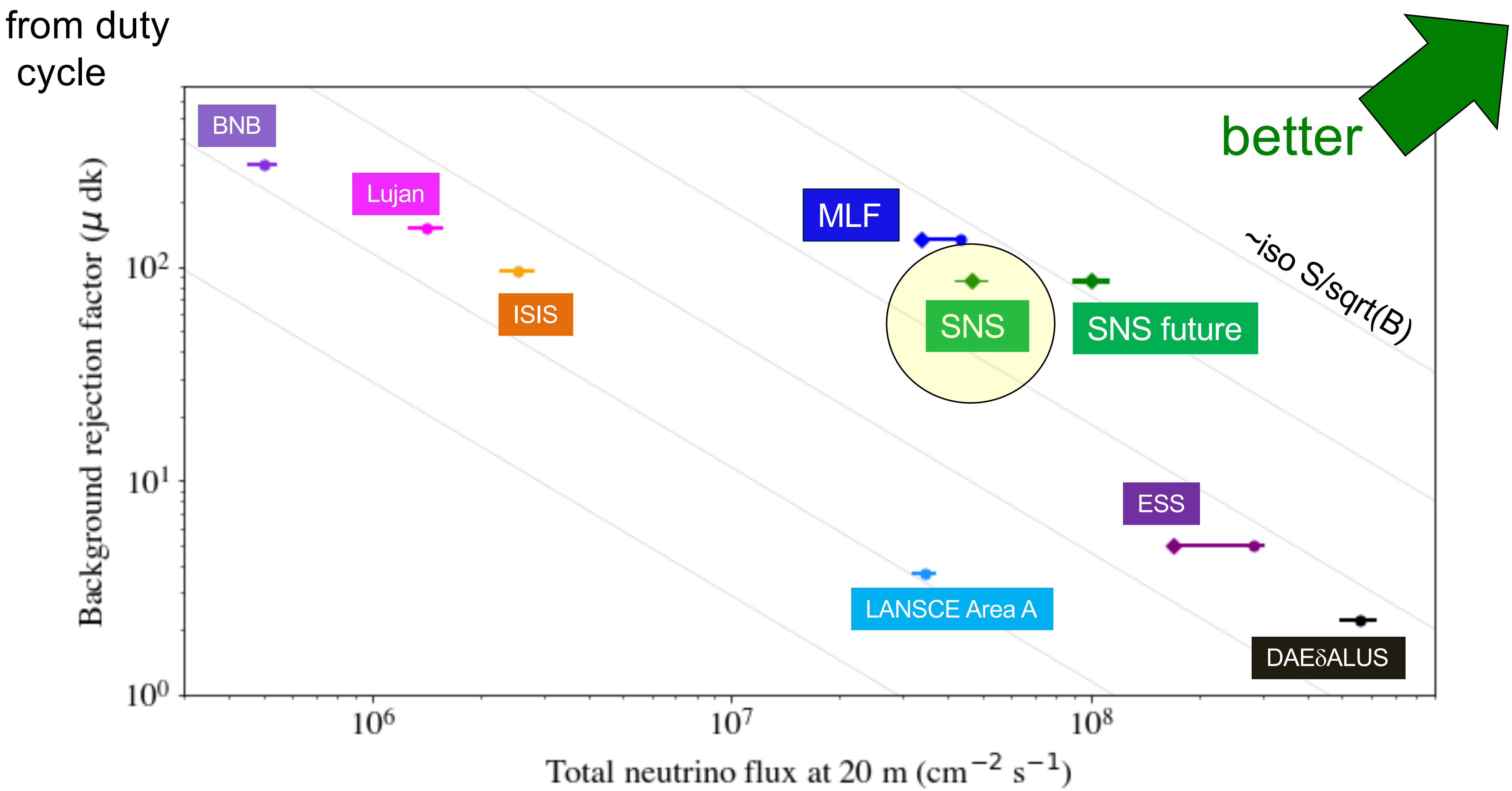
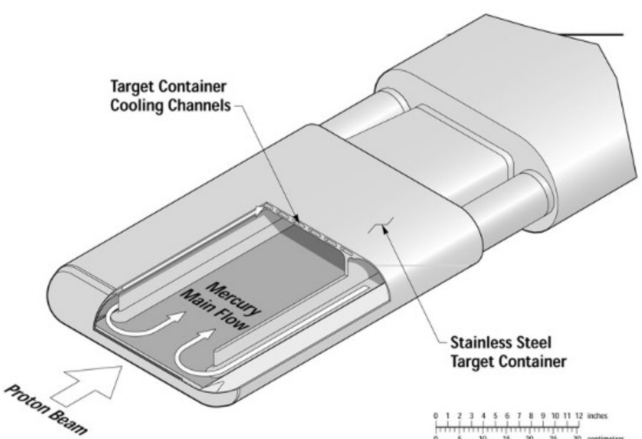


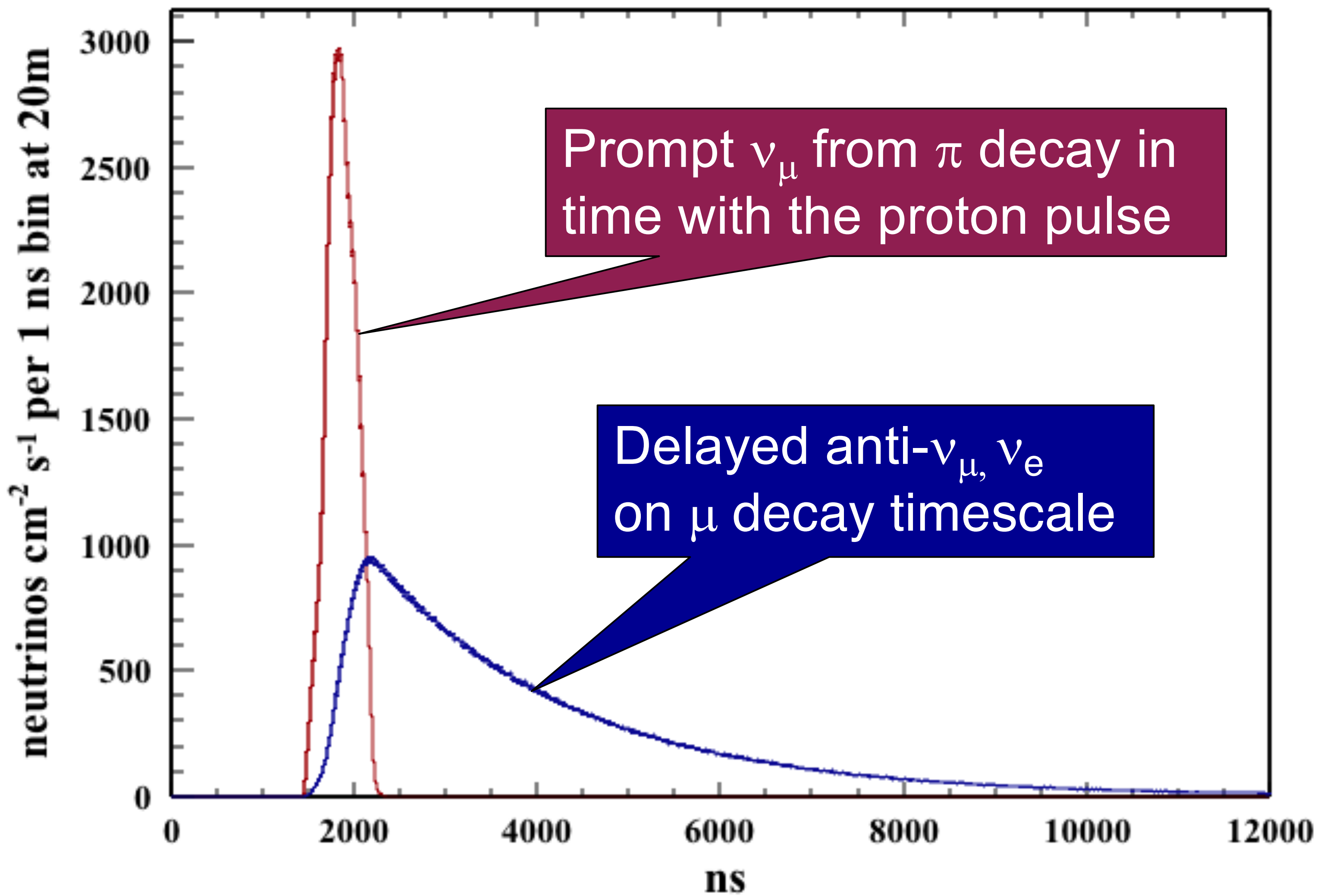


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

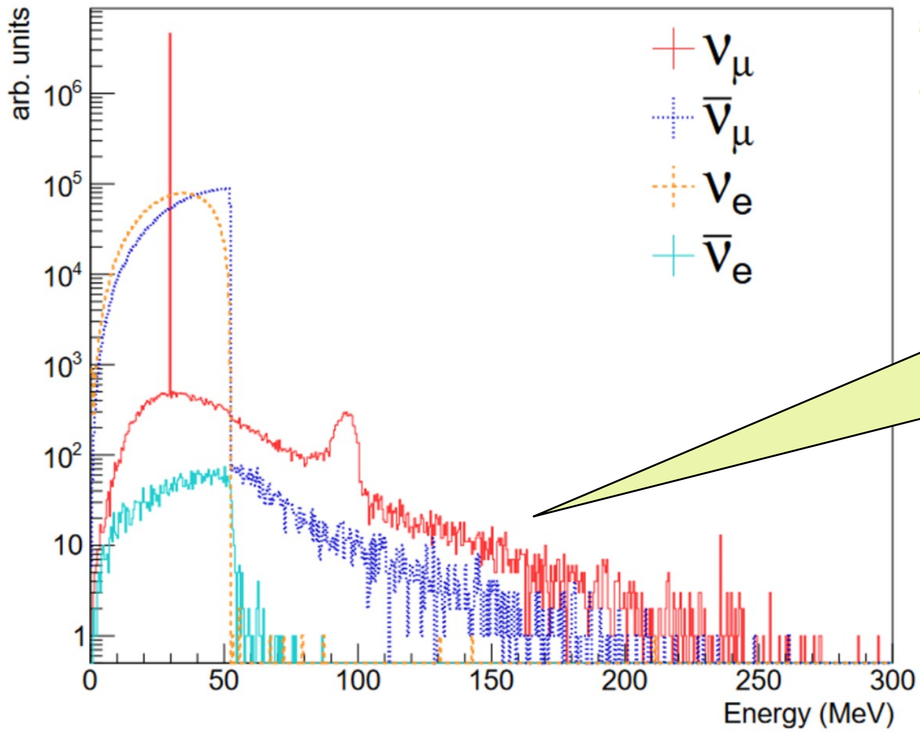
Time structure of the SNS source

60 Hz *pulsed* source

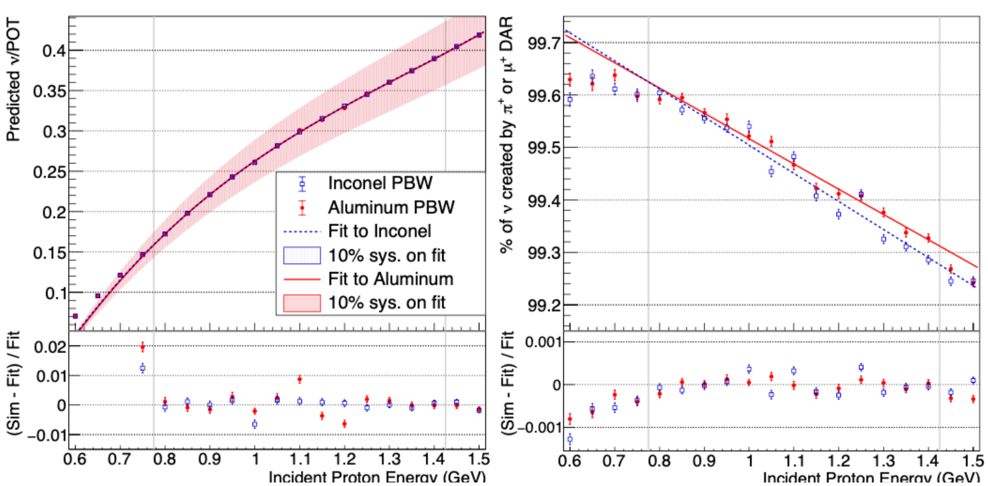


Background rejection factor ~few x 10^{-4}

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/cm²/s @ 20 m
>99% pure decay at rest

The COHERENT collaboration

http://sites.duke.edu/coherent

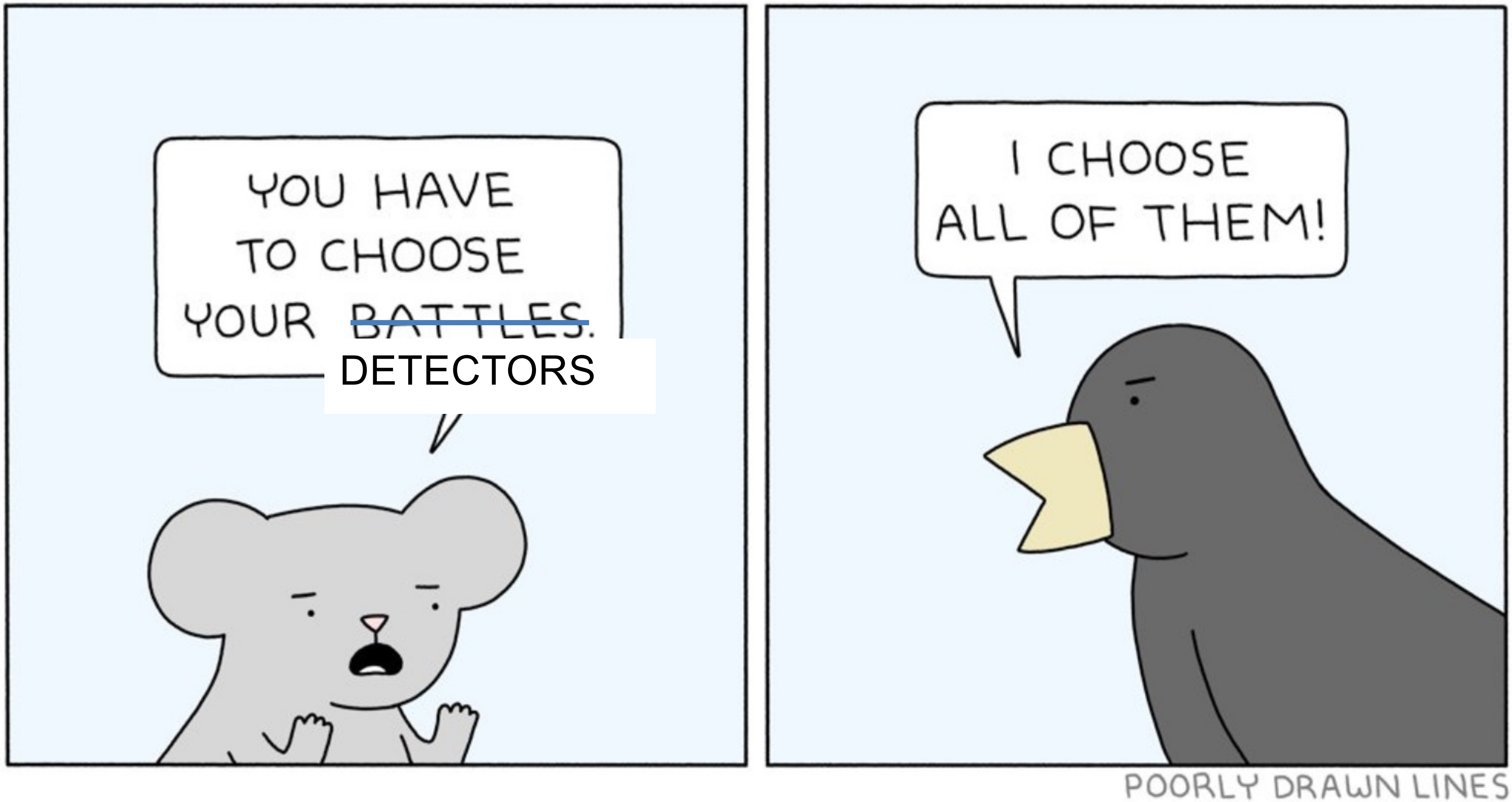
~100 members,
20 institutions
4 countries

COHERENT
SNS
SPALLATION NEUTRON SOURCE

Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
Carnegie Mellon University
CONCORD U
Duke University
UF University of Florida
Florida State University 1851
Laurentian University / Université Laurentienne
Los Alamos National Laboratory
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
Washington & Jefferson College

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

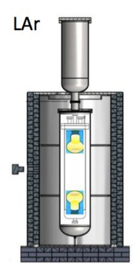
The COHERENT Spirit (so far)

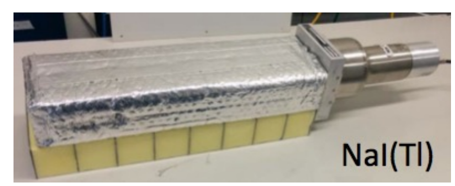


COHERENT CEvNS Detectors

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal — flash	14.6	19.3	5
Ge	HPGe PPC — zap	18	19.1	7.5
LAr	Single-phase — flash	24	27.5	20
NaI[Tl]	Scintillating crystal — flash	185*/3338	25	13

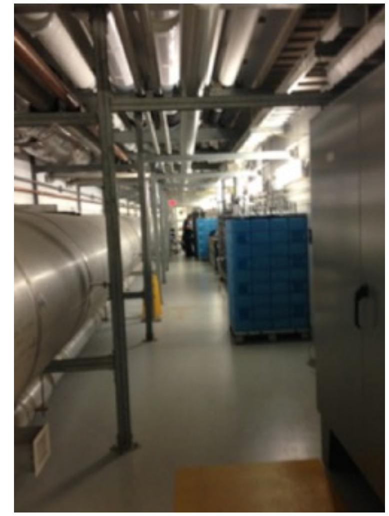
Multiple detectors for N^2 dependence of the cross section

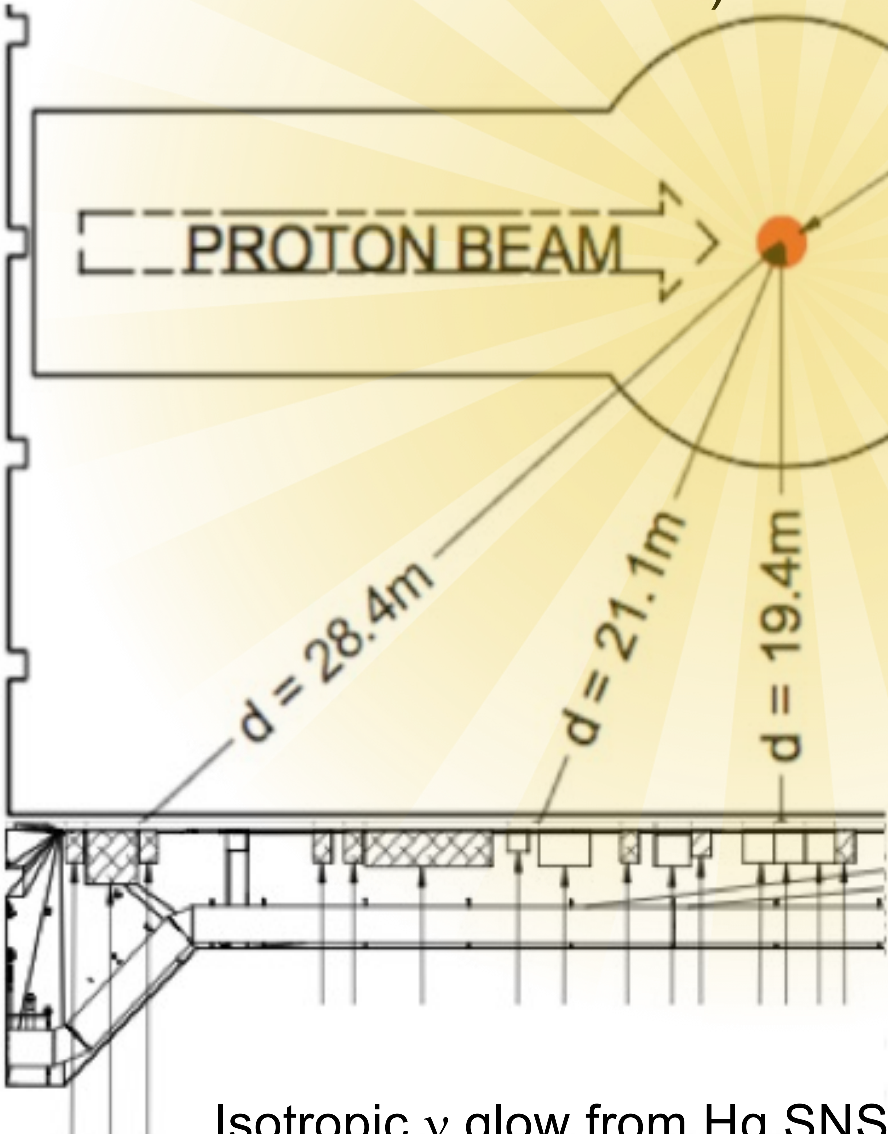


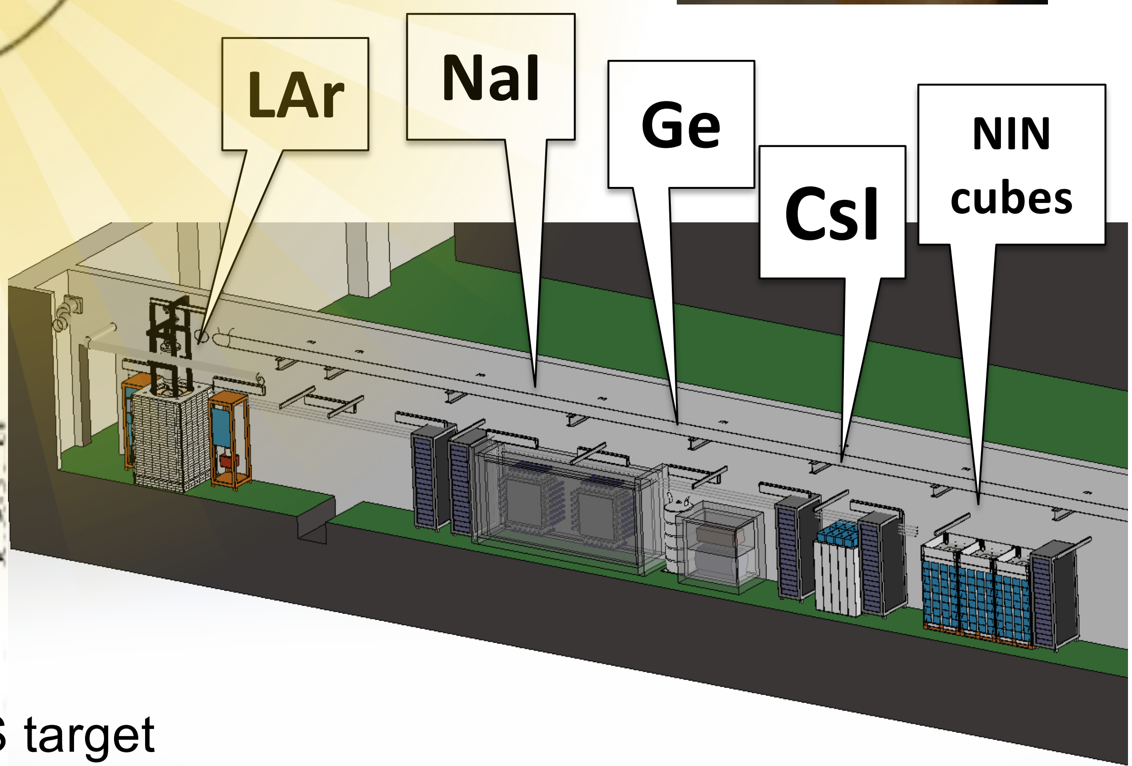


Siting for deployment in SNS basement
(measured neutron backgrounds low, ~ 8 mwe overburden)

View looking down "Neutrino Alley"

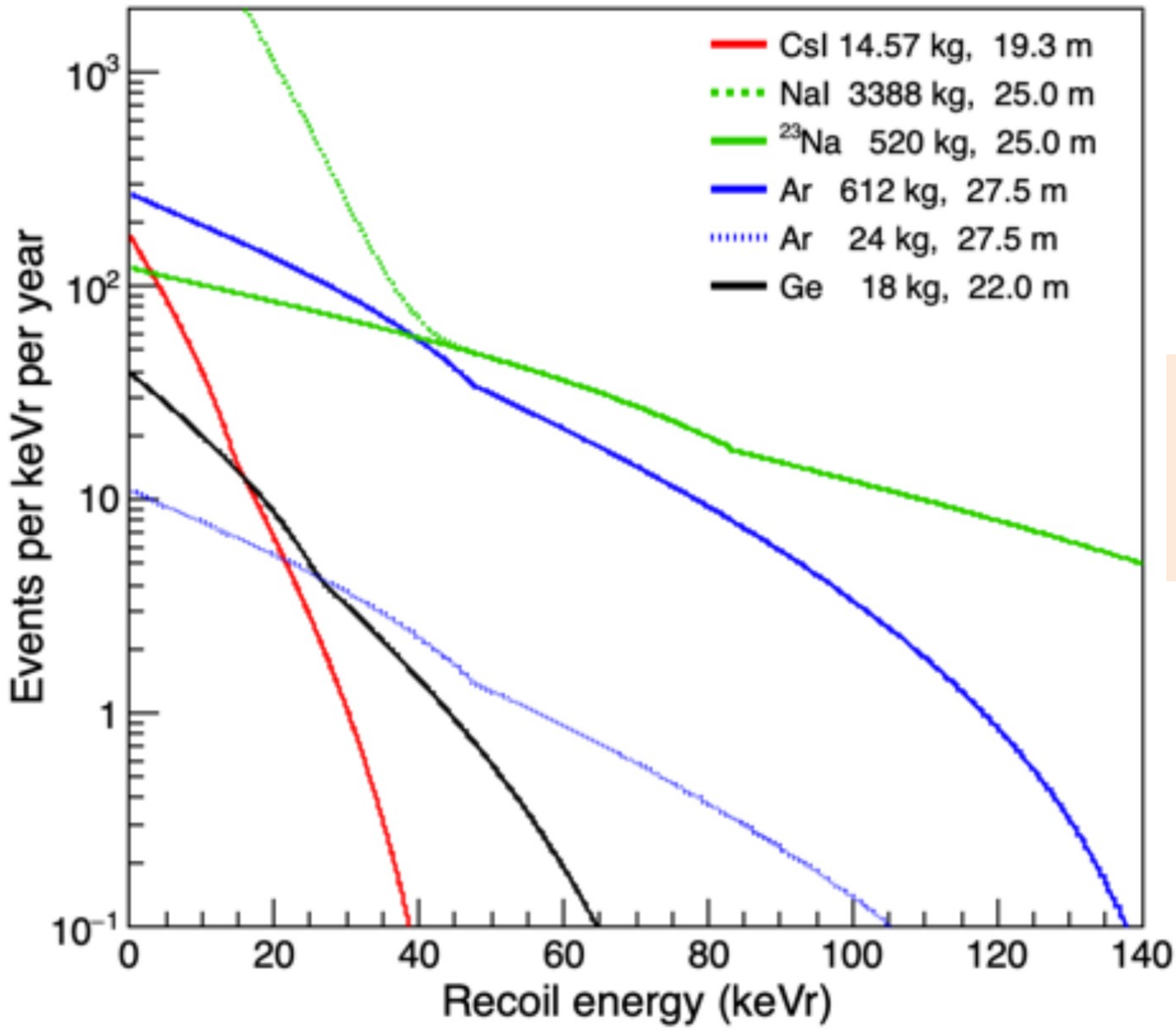






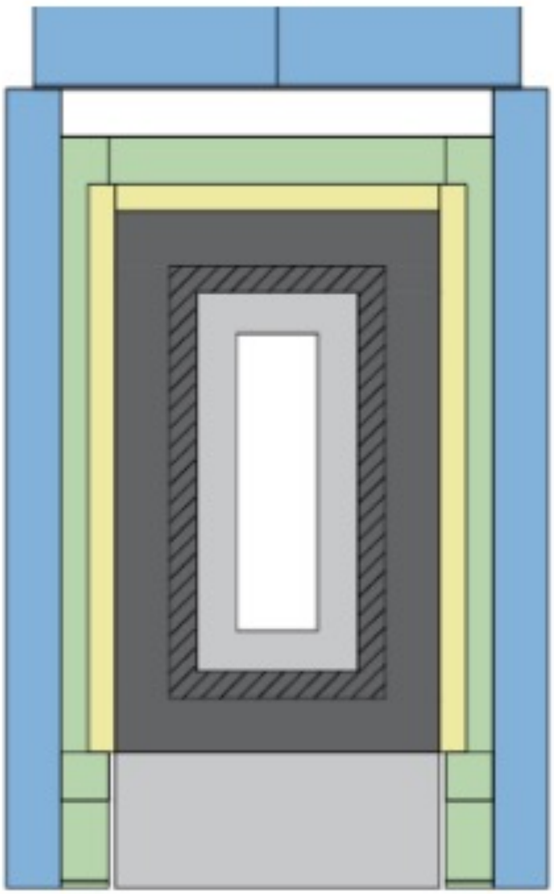
Isotropic ν glow from Hg SNS target

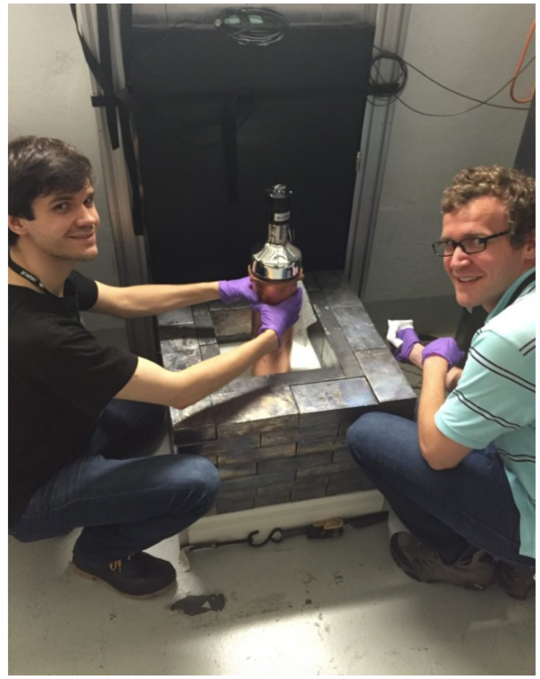
Expected recoil energy distribution



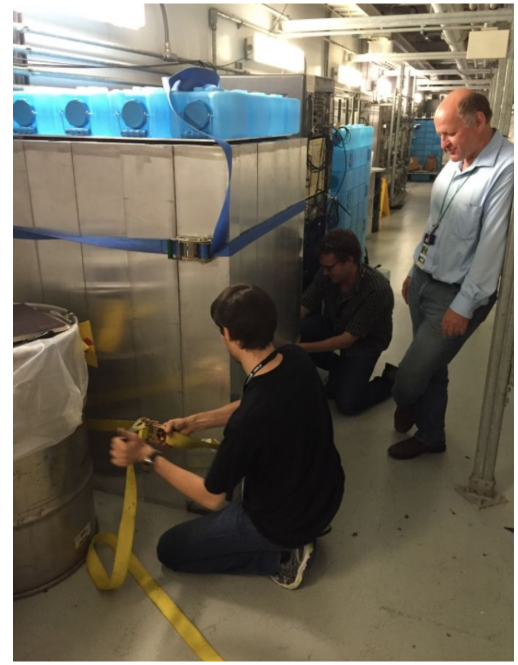
Lighter targets:
less rate per mass,
but kicked to
higher energy

The CsI Detector in Shielding in Neutrino Alley at the SNS





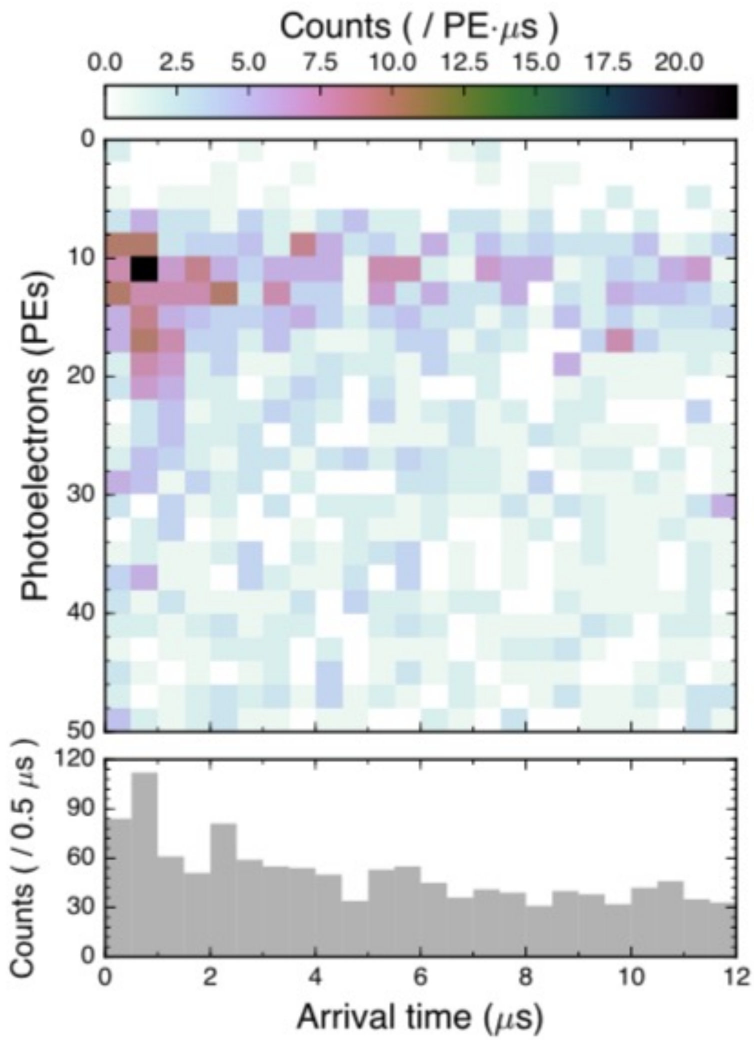
A hand-held detector!

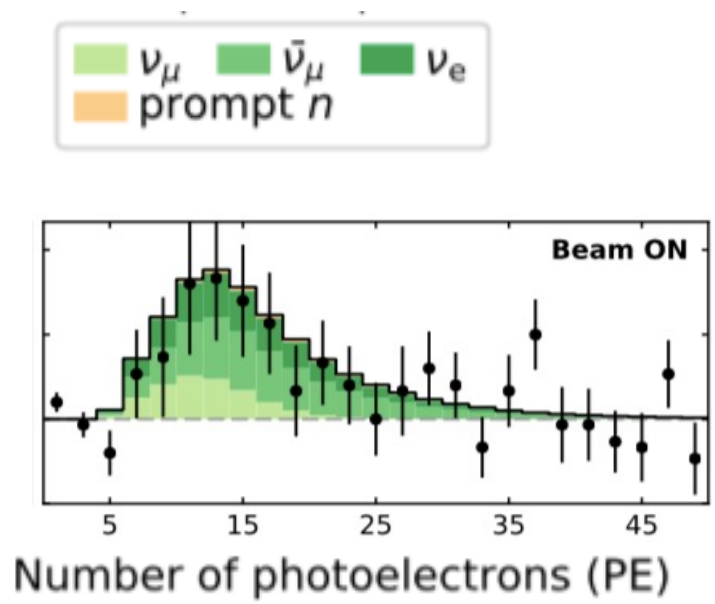


Almost wrapped up...

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

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





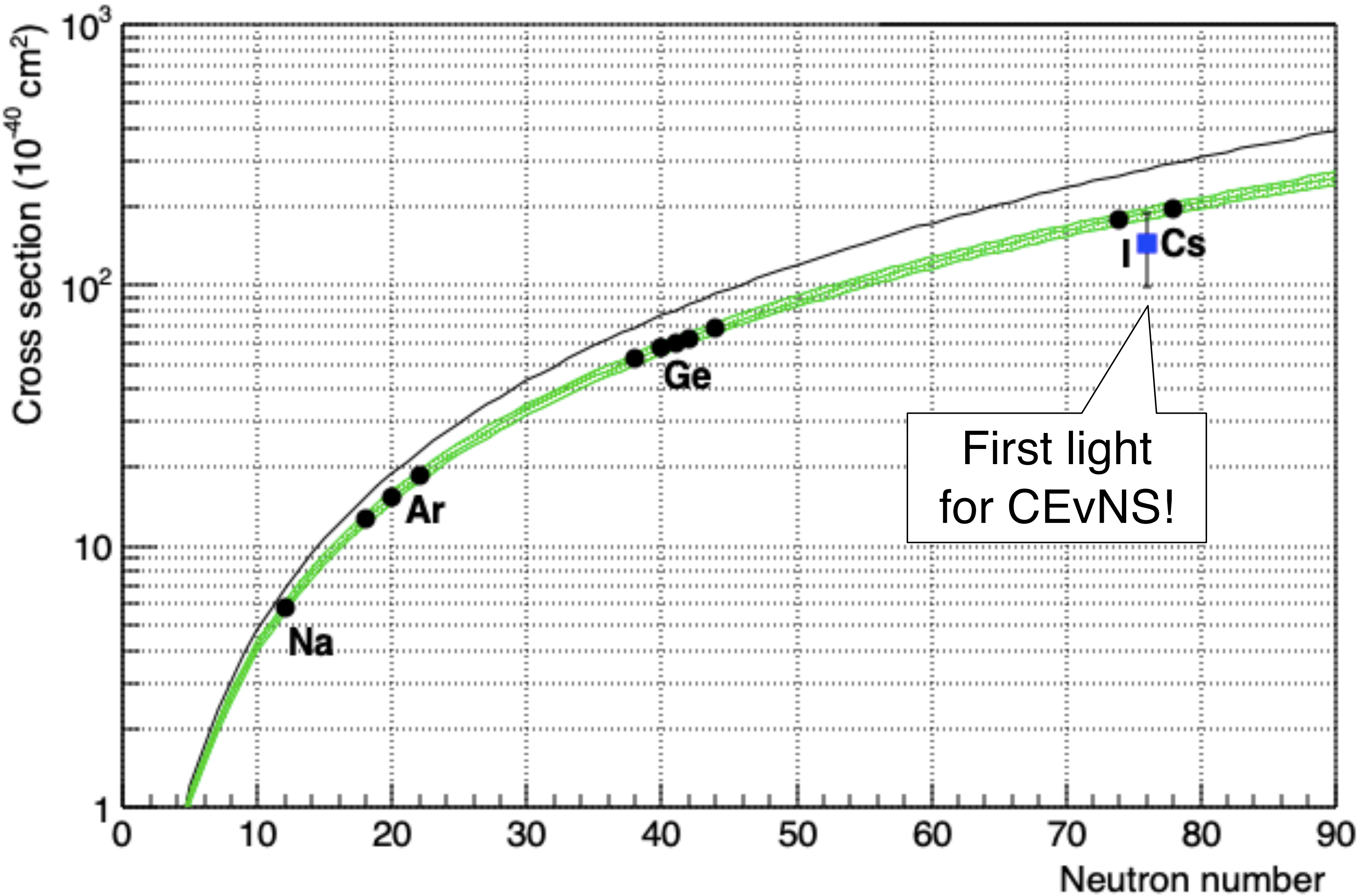
Background-subtracted and integrated over time

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

→ measure of the Q spectrum

DOI: 10.5281/zenodo.1228631

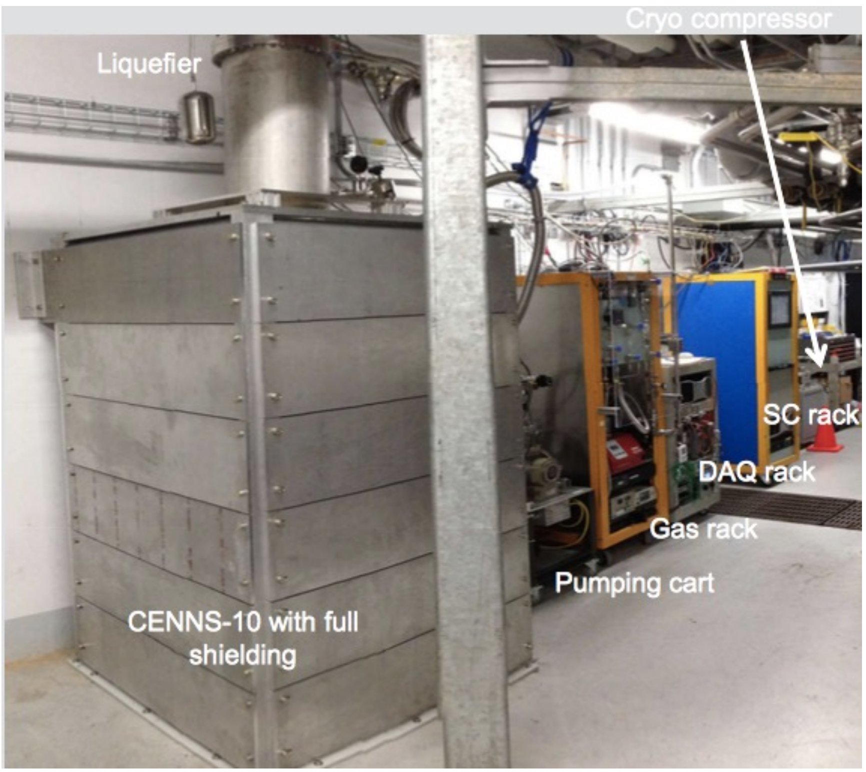
D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990



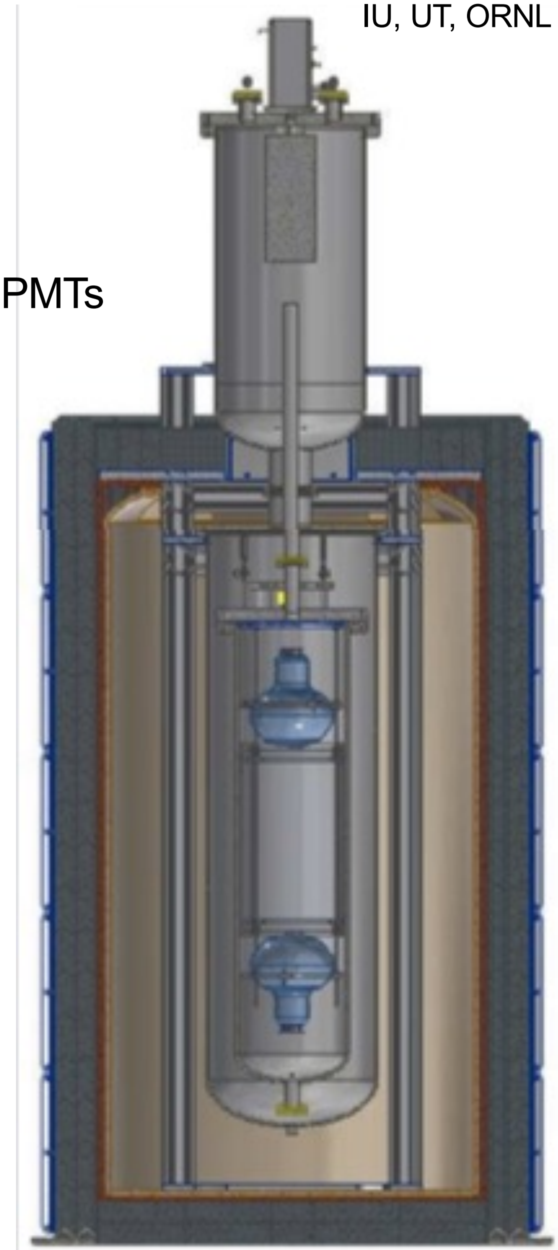
Cross section (10^{-40} cm^2)
Neutron number
Na
Ar
Ge
I
Cs
First light for CEvNS!

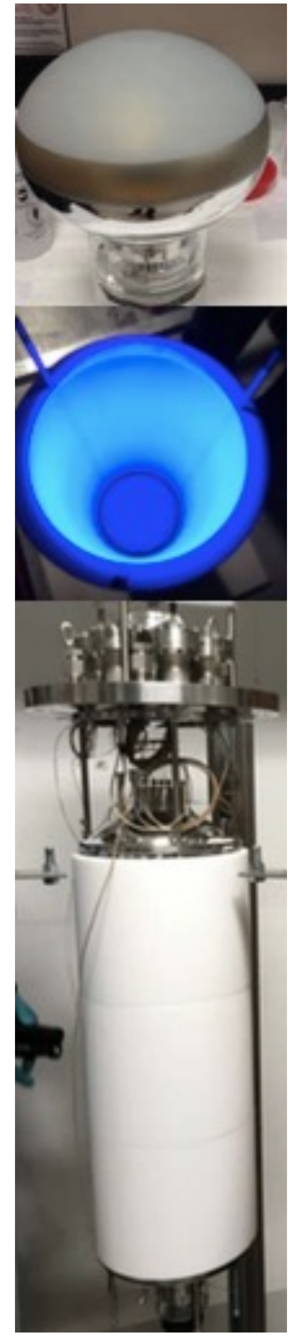
Single-Phase Liquid Argon

- ~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



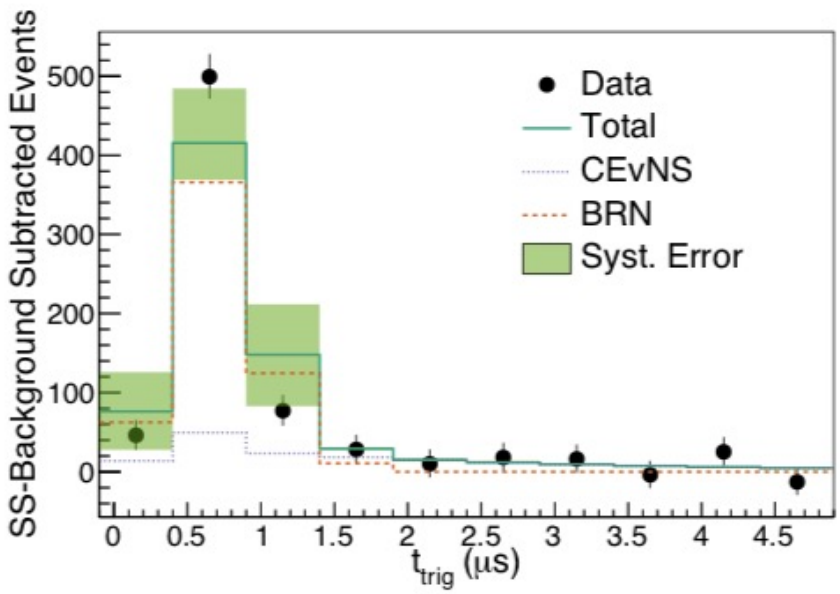


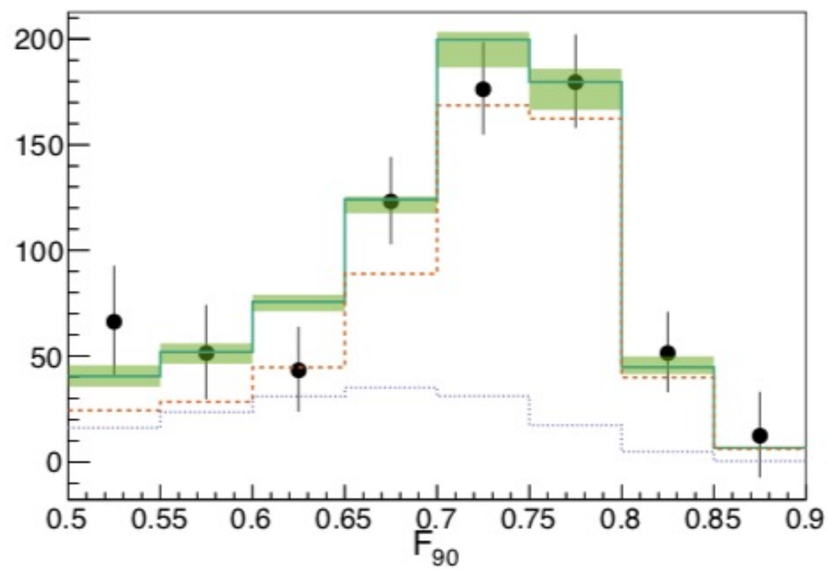
Detector from FNAL, previously built (Jonghee Yoo et al.) for CENNS@BNB

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

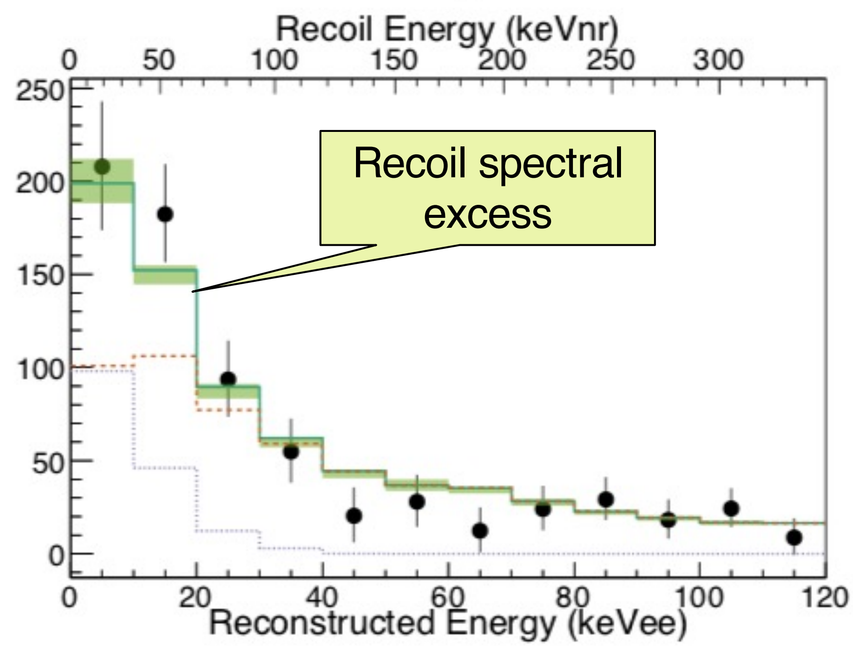
Likelihood fit in time, recoil energy, PSD parameter

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

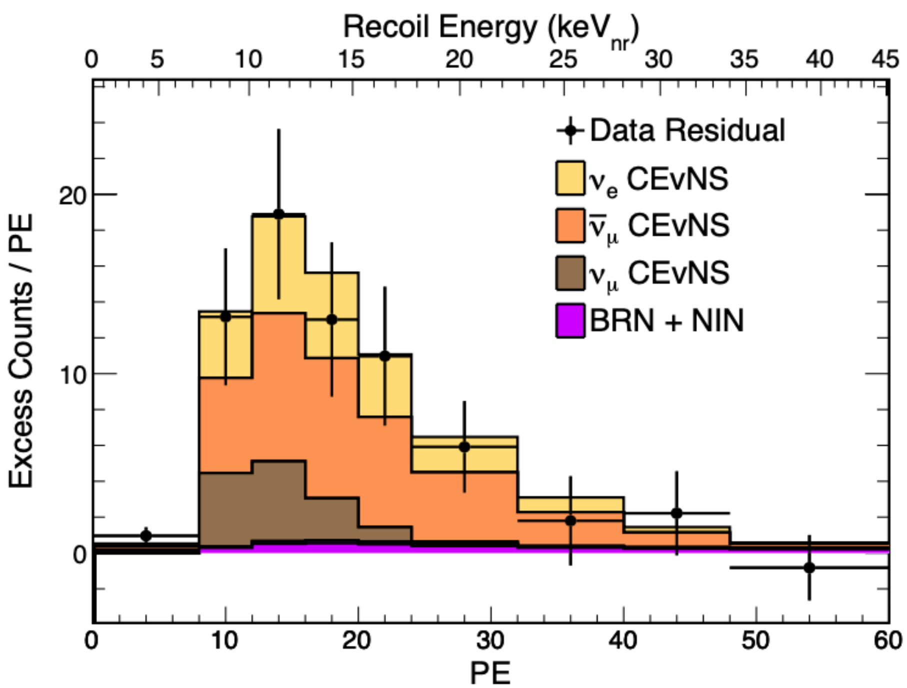


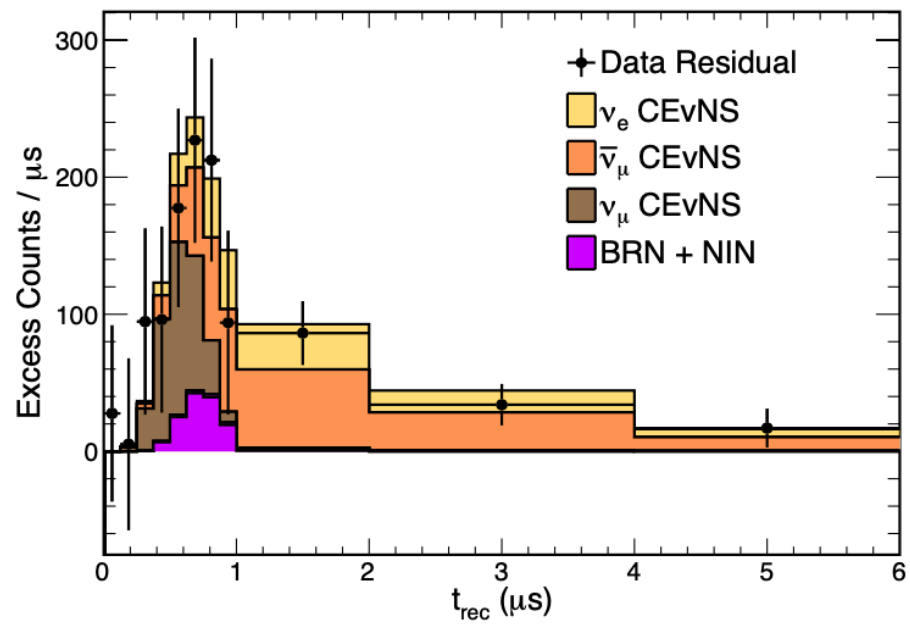


- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results (this is the "A" analysis)

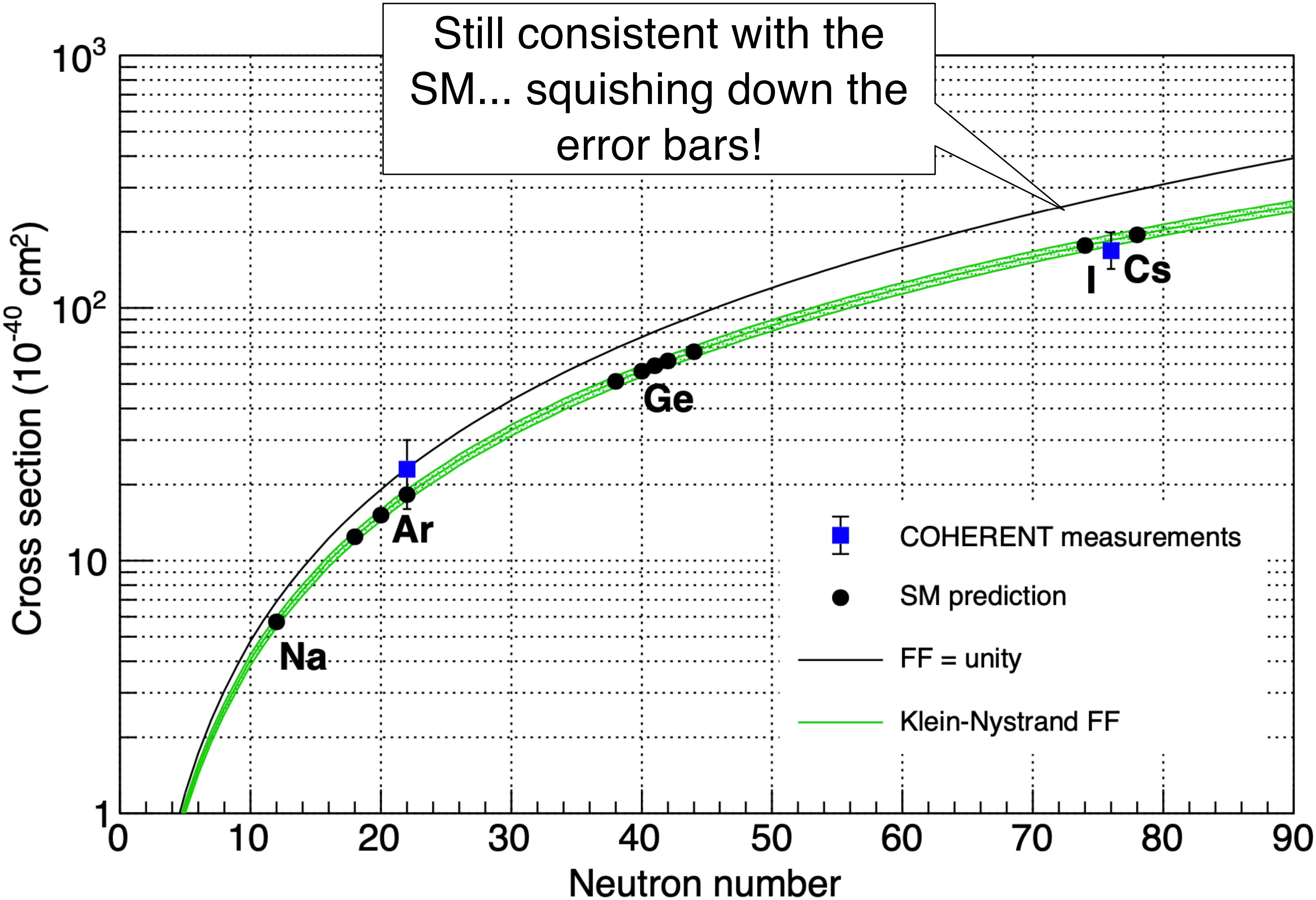


Remaining CsI[Na] dataset,
with >2 x statistics
+ improved detector response understanding
+ improved analysis





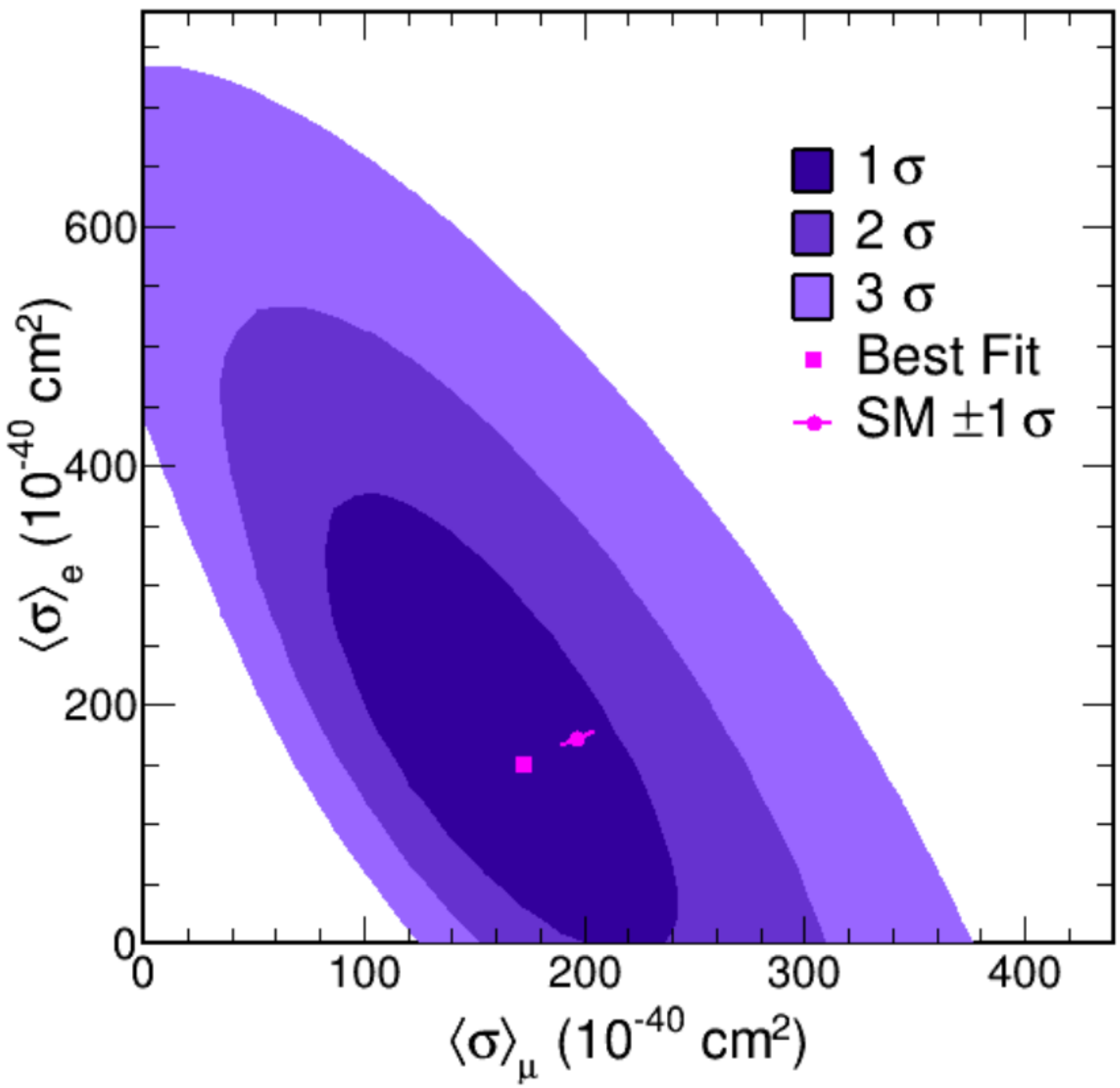
arXiv: 2110.07730



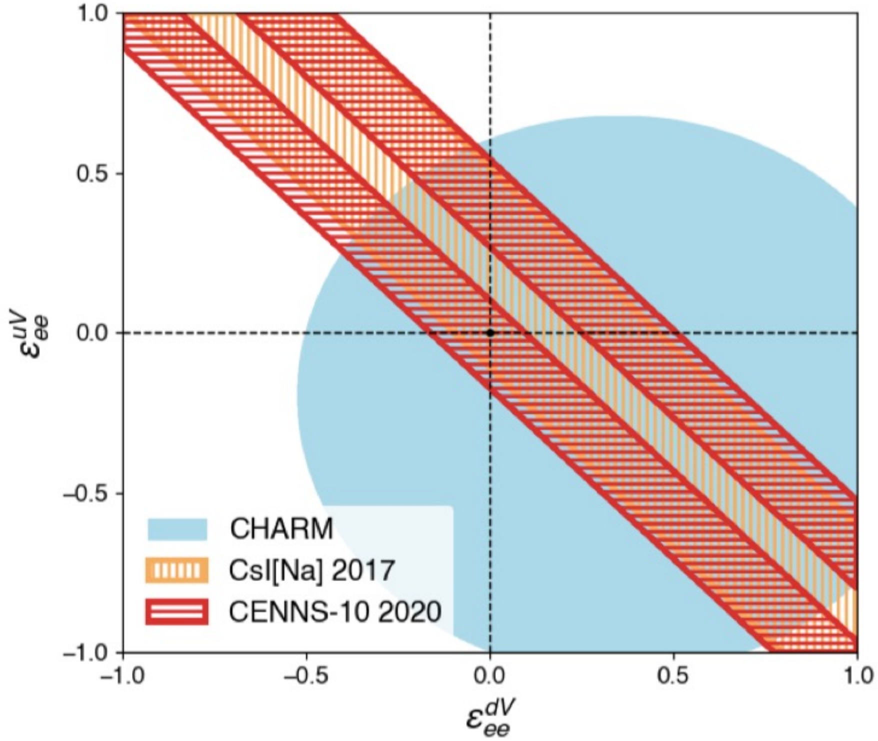
Still consistent with the SM... squishing down the error bars!
Cross section (10^{-40} cm^2)
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
90
Neutron number
Na
Ar
Ge
I
Cs
COHERENT measurements
SM prediction
FF = unity
Klein-Nystrand FF

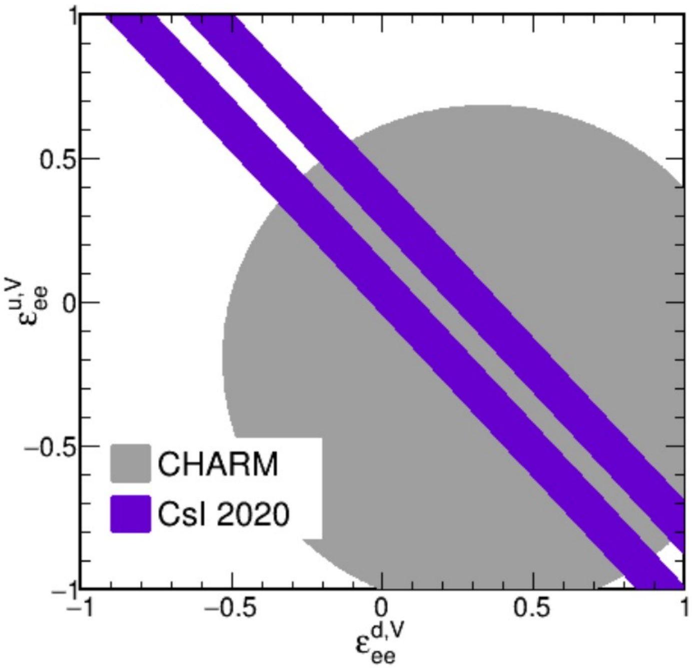
Flavored CEvNS cross sections

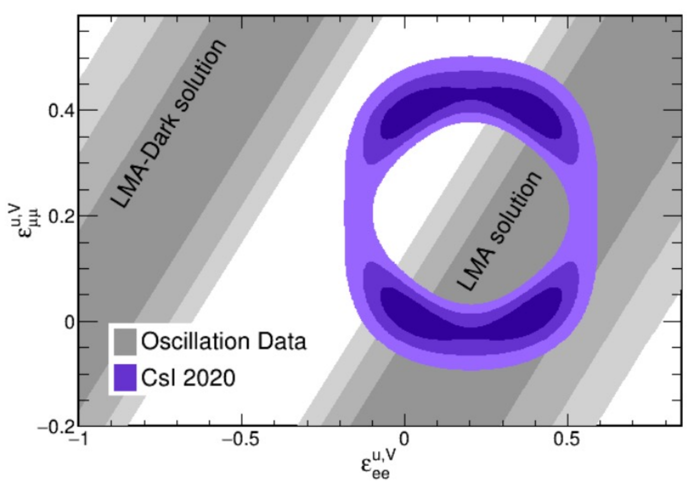
Separate electron and muon flavors by timing



And squeezing down the possibilities for new physics...

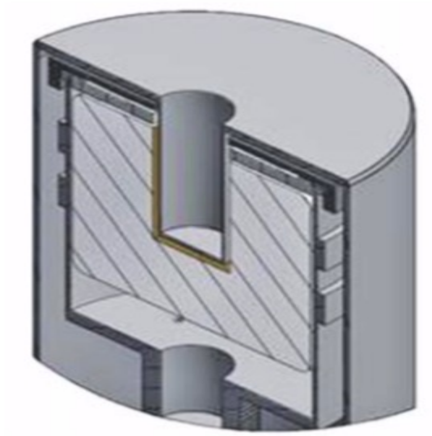


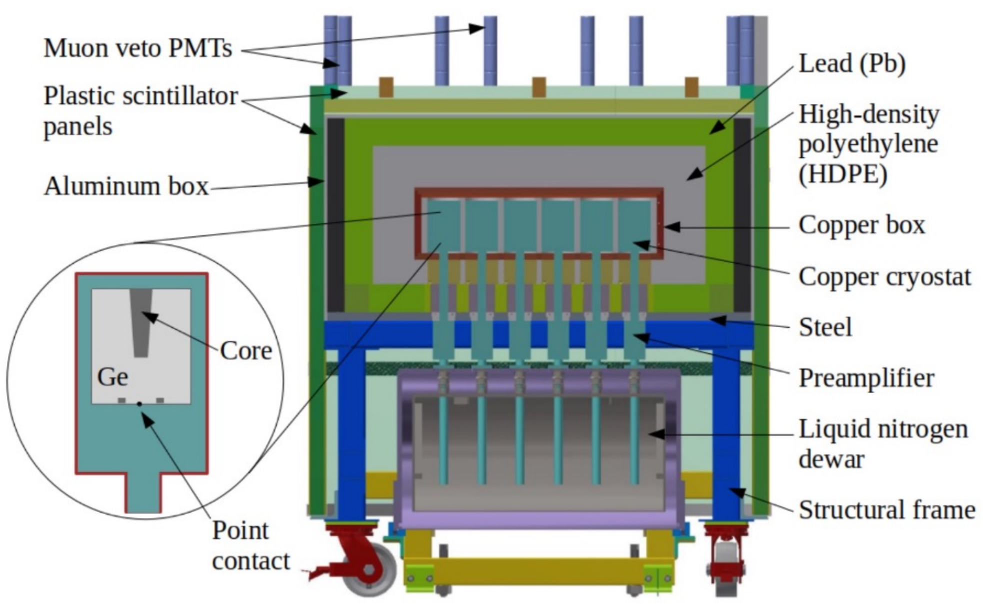


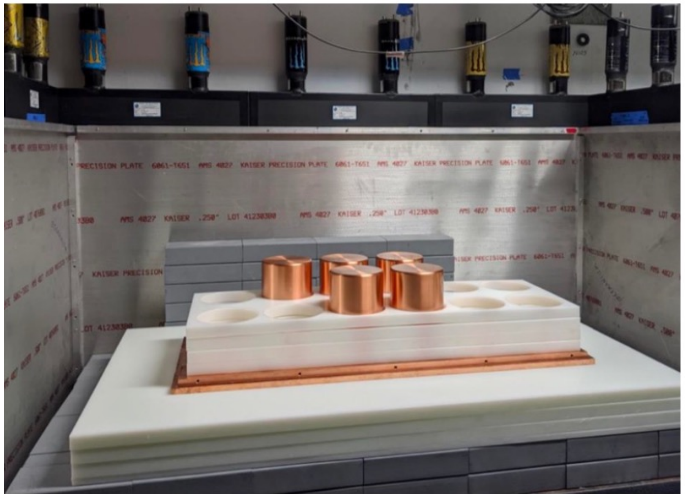


COHERENT Germanium Detectors

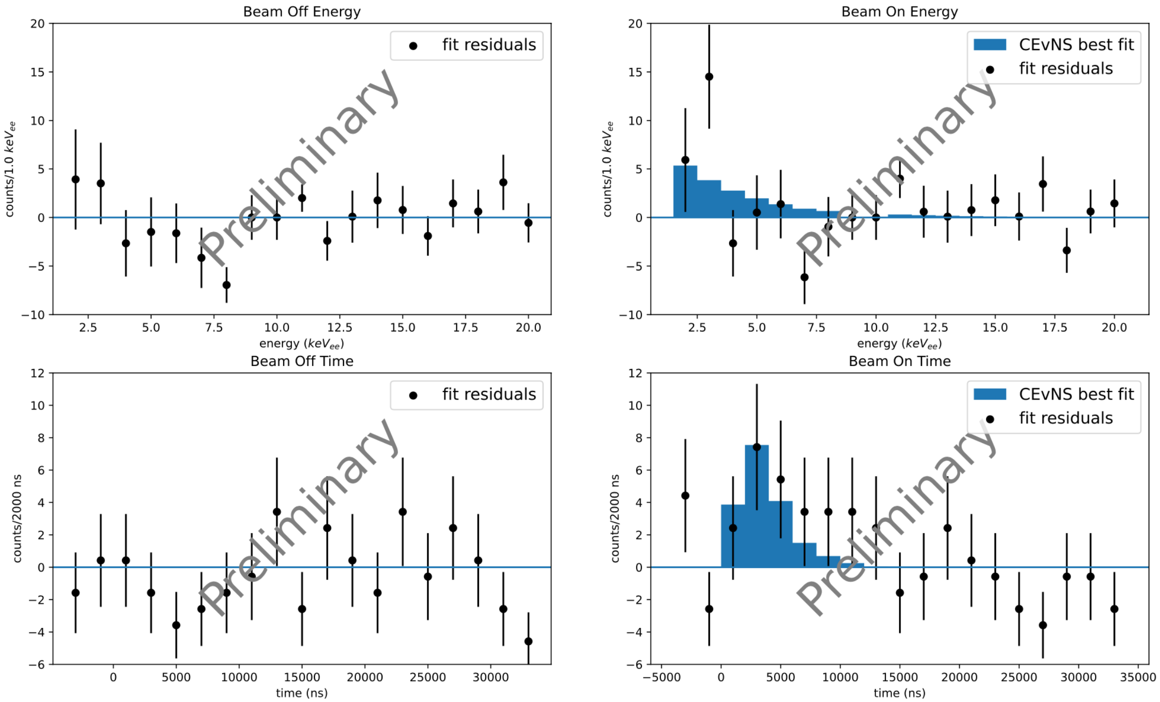
- 8 2.2-kg Ge PPC detectors from Mirion
- First deployment 2022
- Physics run 2023
- 110-150 eV FWHM pulser resolution/noise

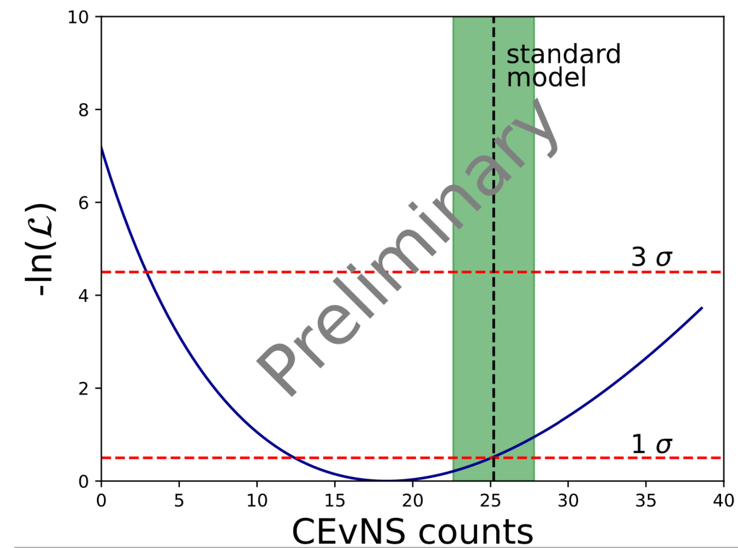


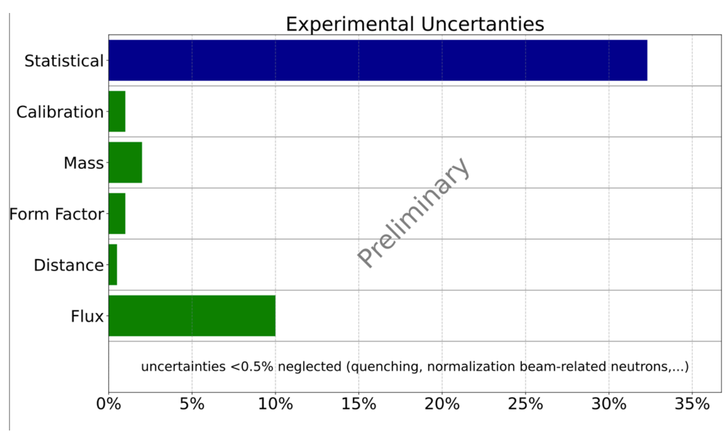


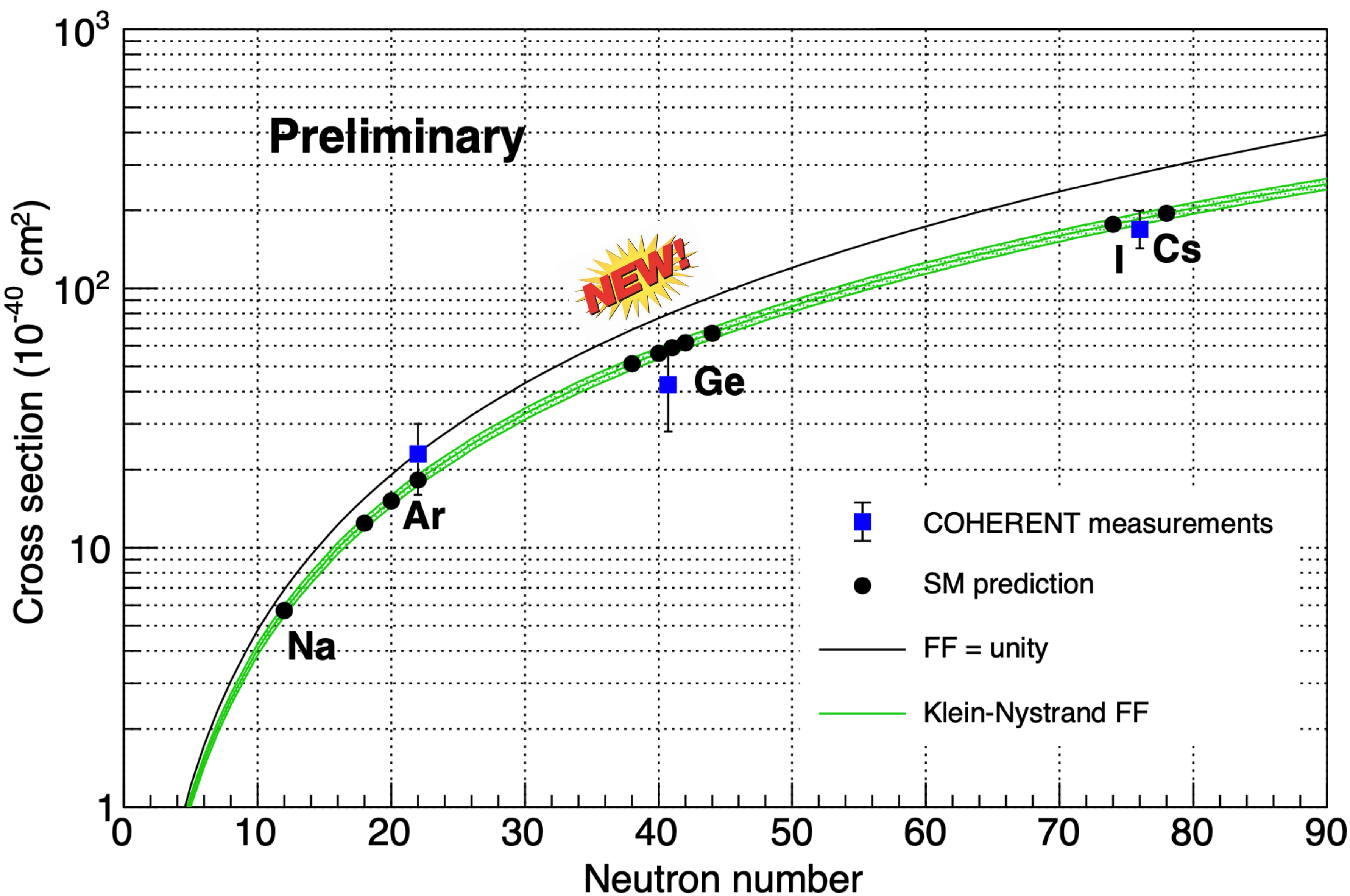


First Ge Results (preprint very soon!)



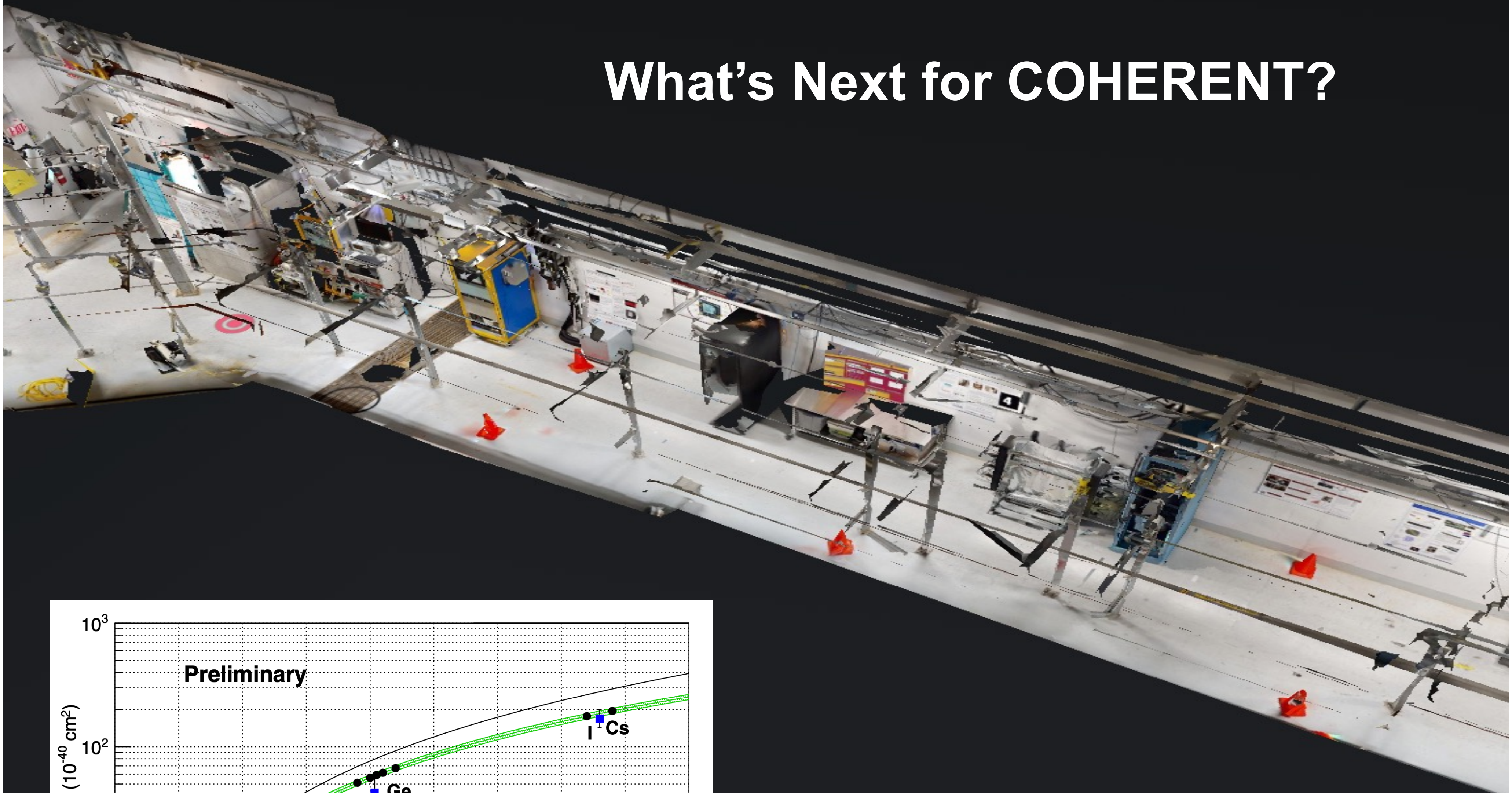


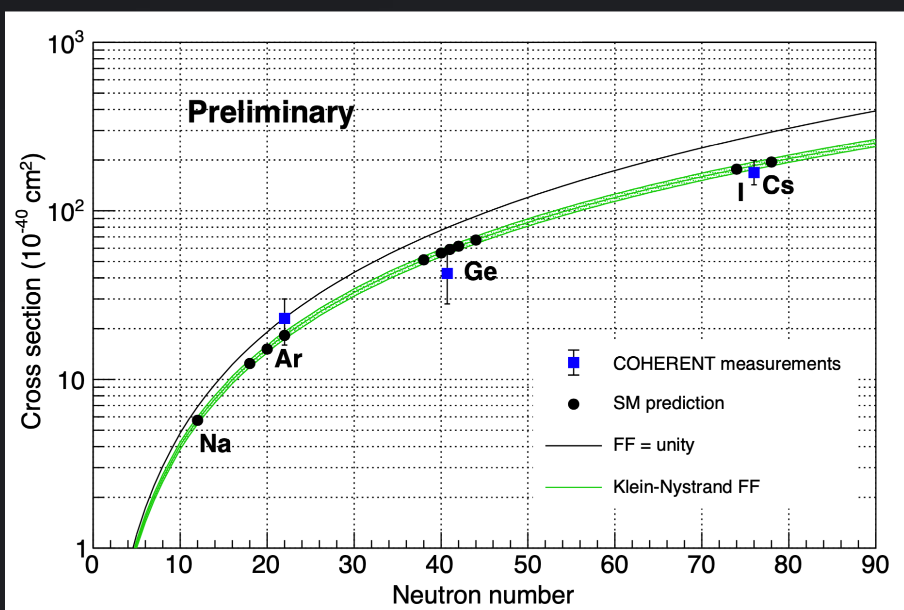




Preliminary
NEW!
Cross section (10^{-40} cm^2)
Neutron number
Na
Ar
Ge
I
Cs
COHERENT measurements
SM prediction
FF = unity
Klein-Nystrand FF
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
90

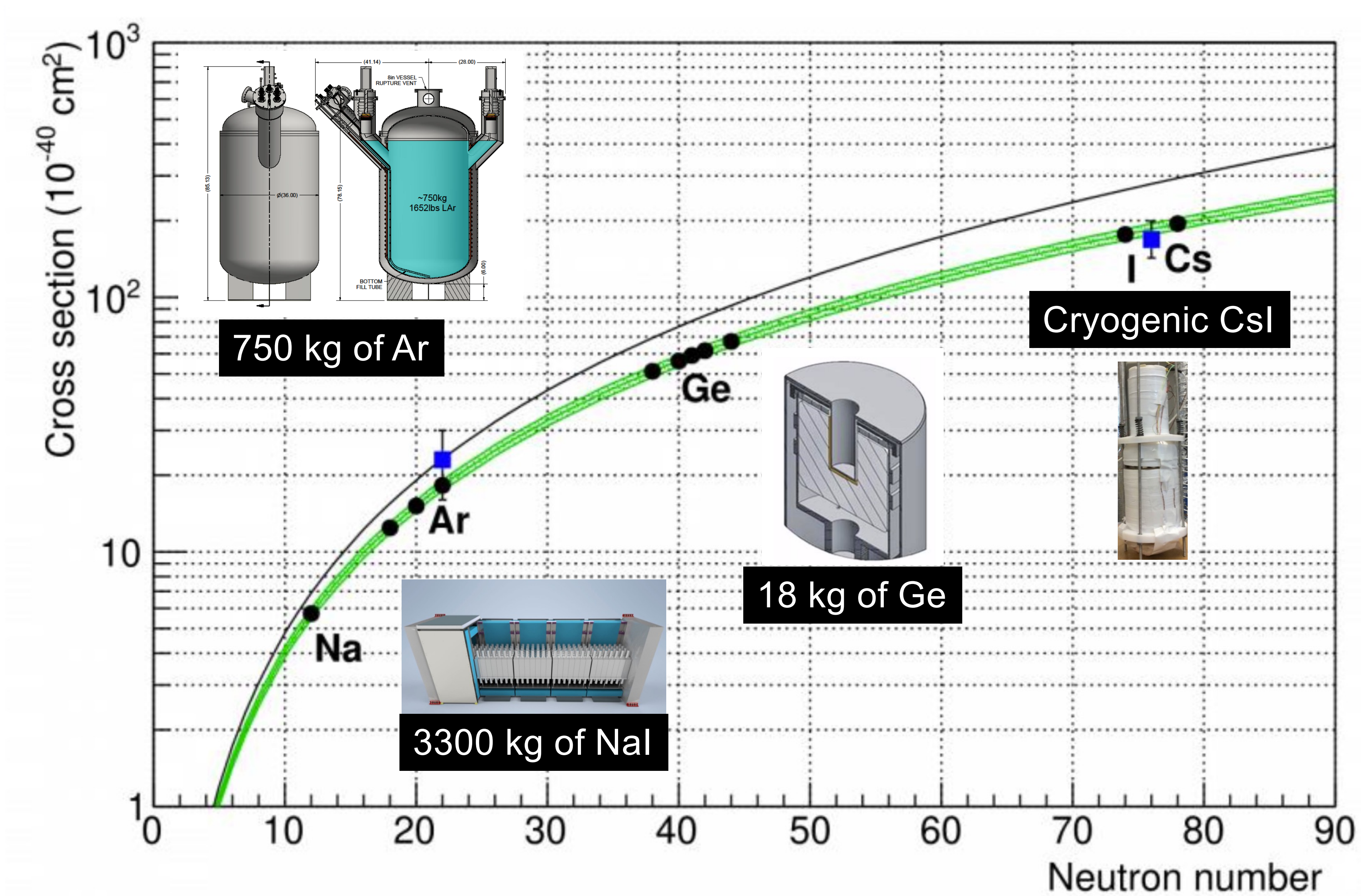
What's Next for COHERENT?





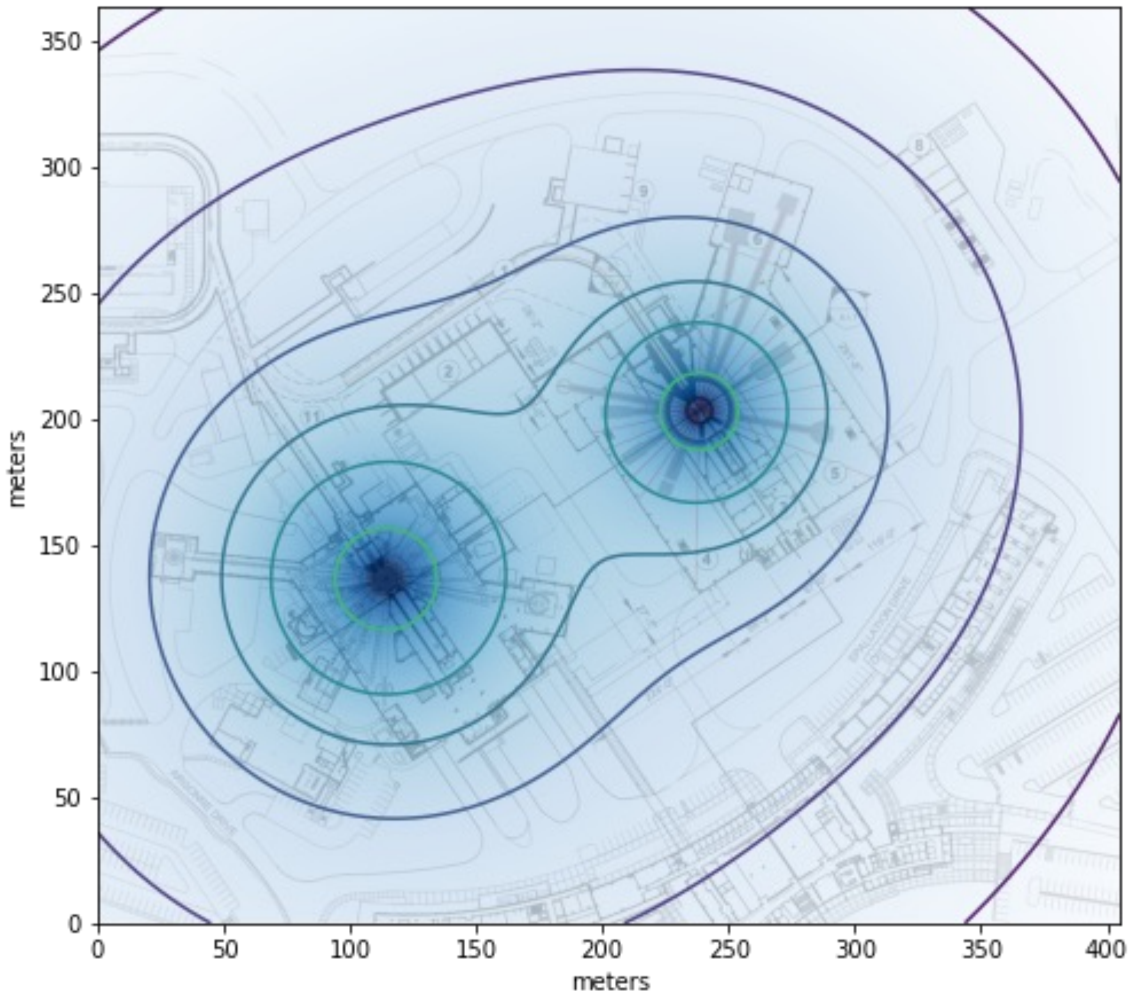
Three down!
But still more
to go!

COHERENT future deployments



SNS power upgrade to 2 MW over next few years

Second Target Station upgrade to 2.8 MW ~2030's

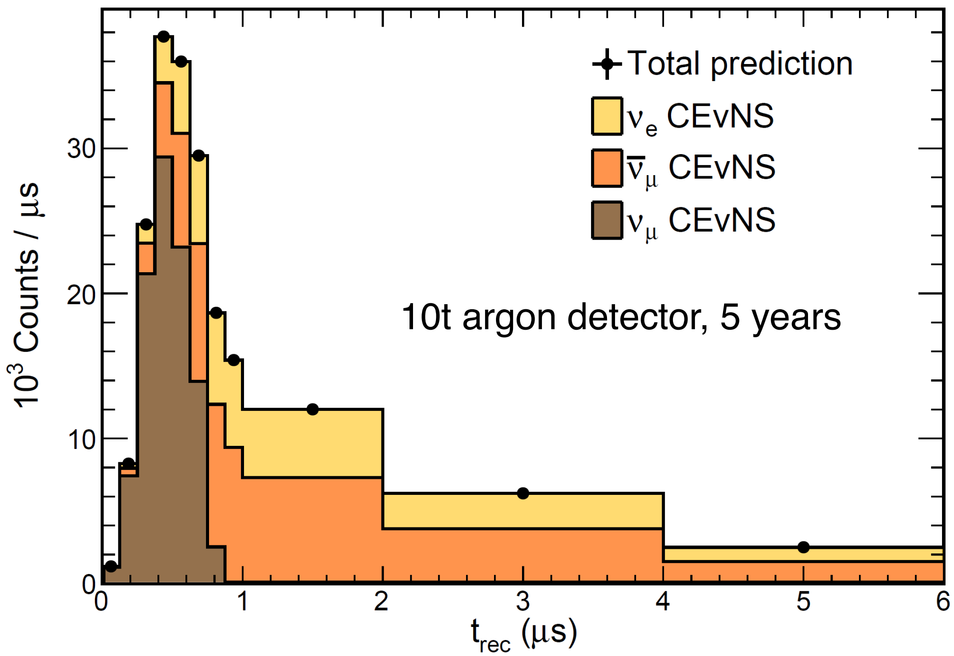


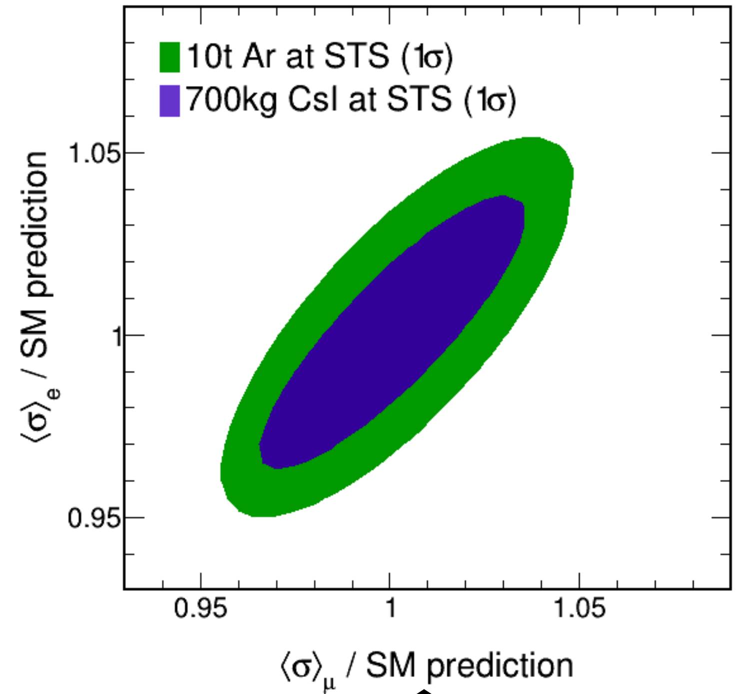
¾ bunches to FTS
¼ bunches to STS

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

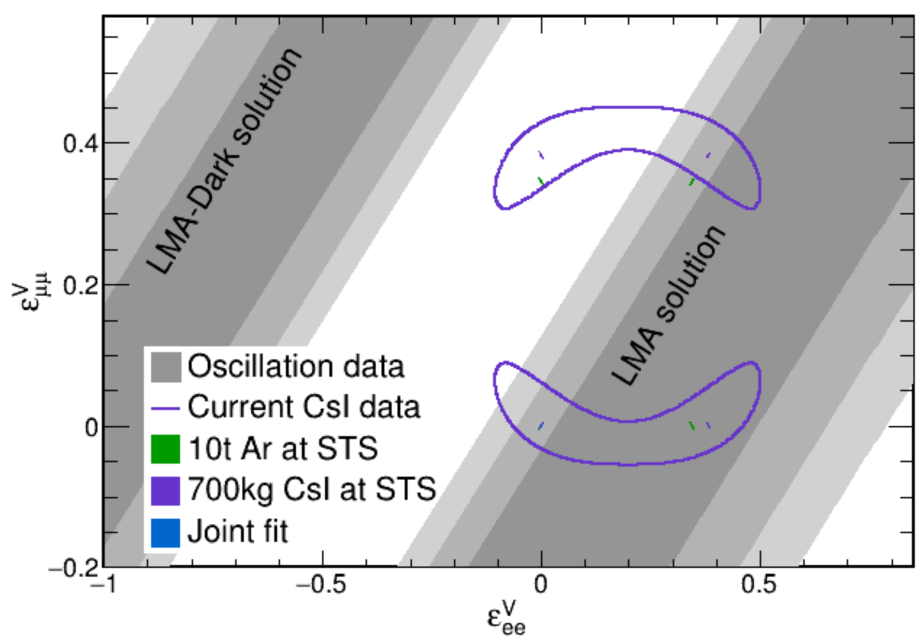
Many exciting possibilities for ν's + DM!

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)

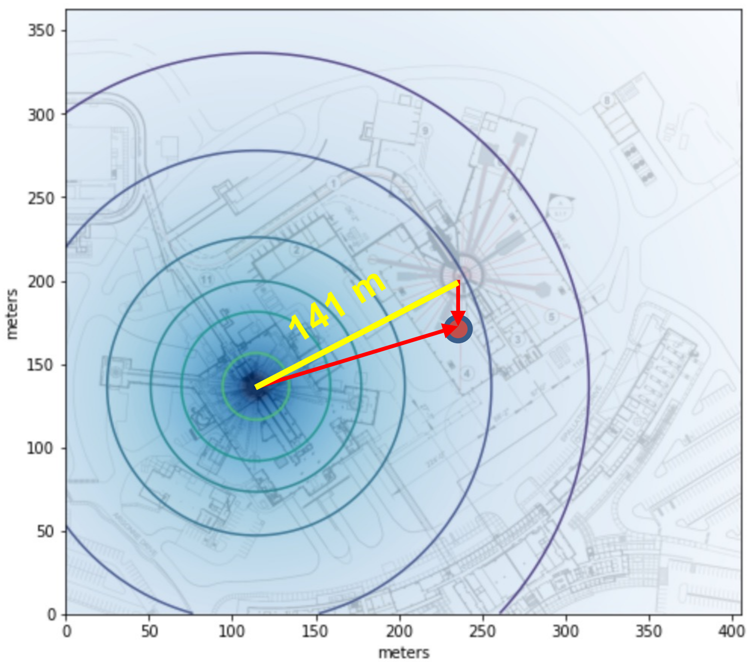


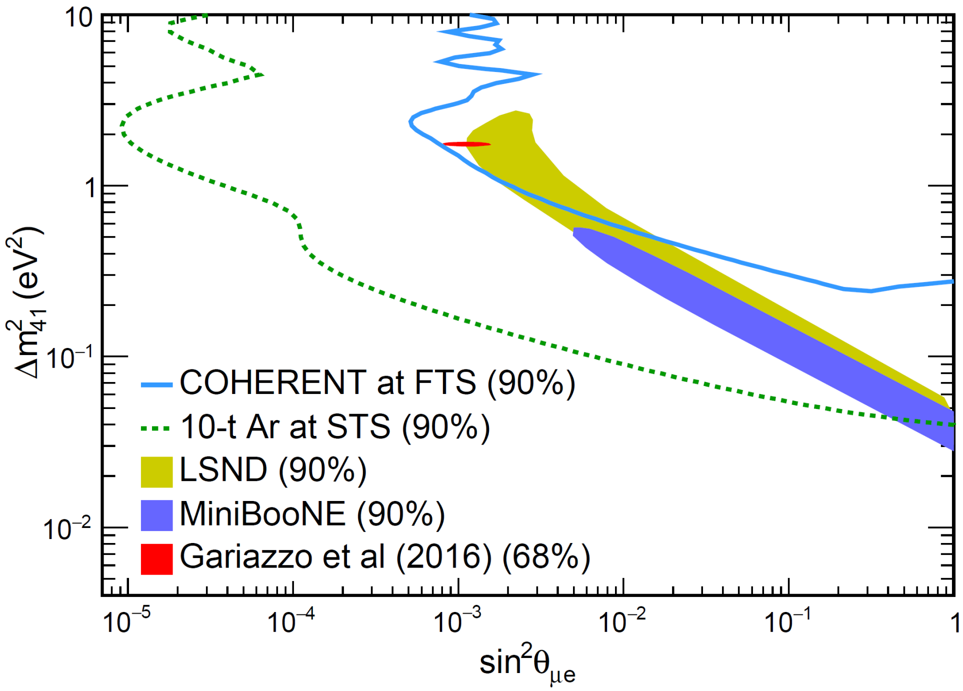
Stringent NSI parameters constraints, resolving oscillation ambiguities

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

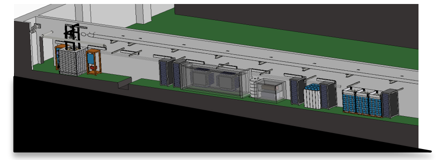
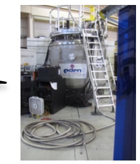
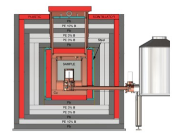
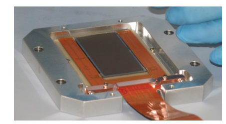
Can also exploit flavor separation by timing

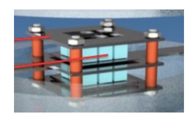
Assume L_{STS} = 20 m and L_{FTS} = 121 m, 10-t argon CEvNS detector

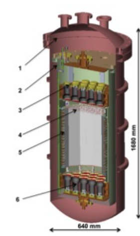
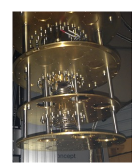
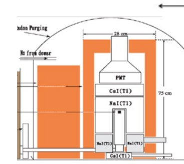
In 5 years, test ~entire parameter space allowed by LSND/MiniBooNE

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

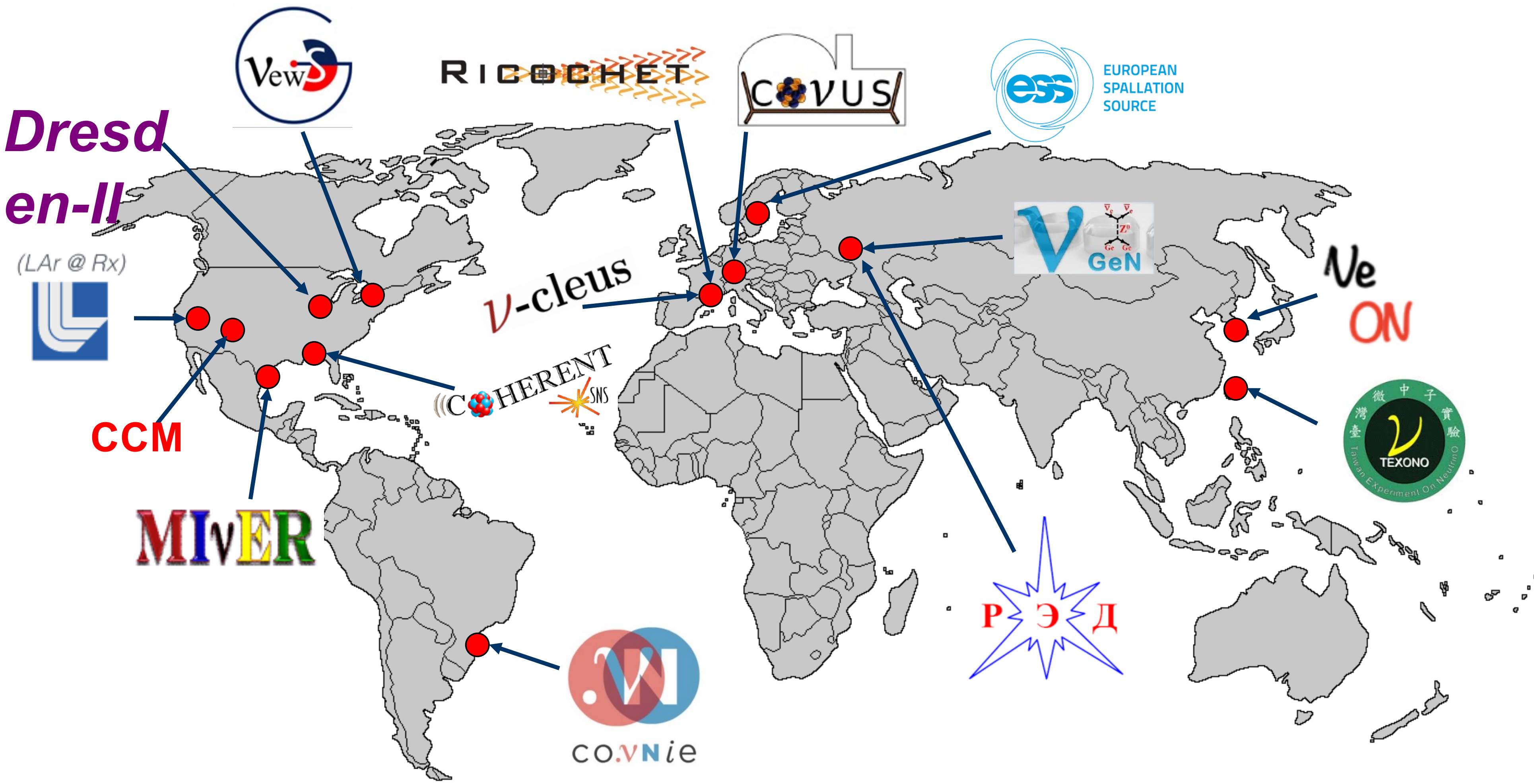







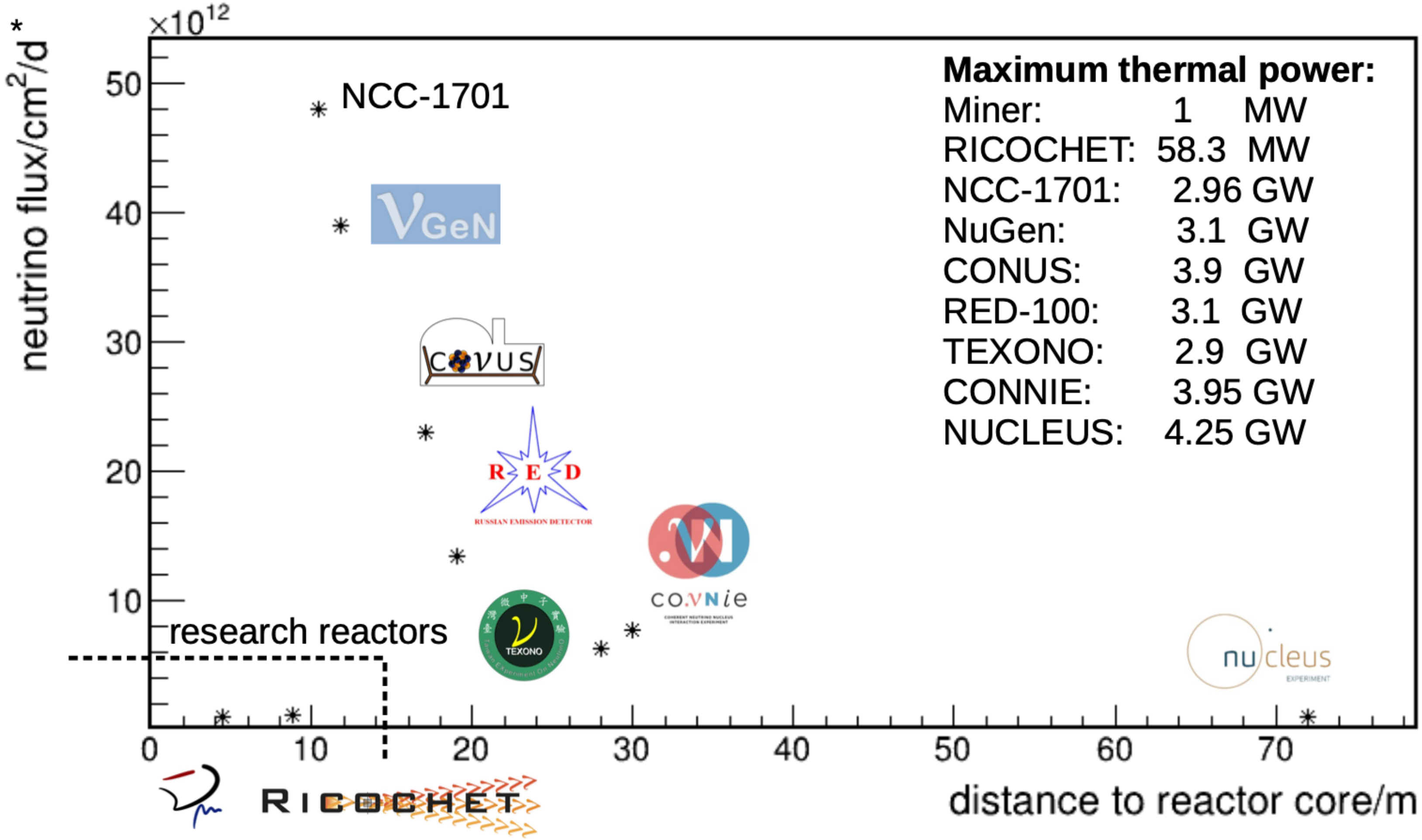
+ DM detectors, +directional detectors +more...(NEON, SBC...)

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



Dresden-II
(LAr @ Rx)
CCM
MIνER
RICOCHET
CONUS
EUROPEAN SPALLATION SOURCE
ν-cleus
COHERENT
SNS
νGeN
РЭД
νeON
TEXONO
Taiwan EXperiment On NeutrinO
CONνNie

CEνNS detection at reactor

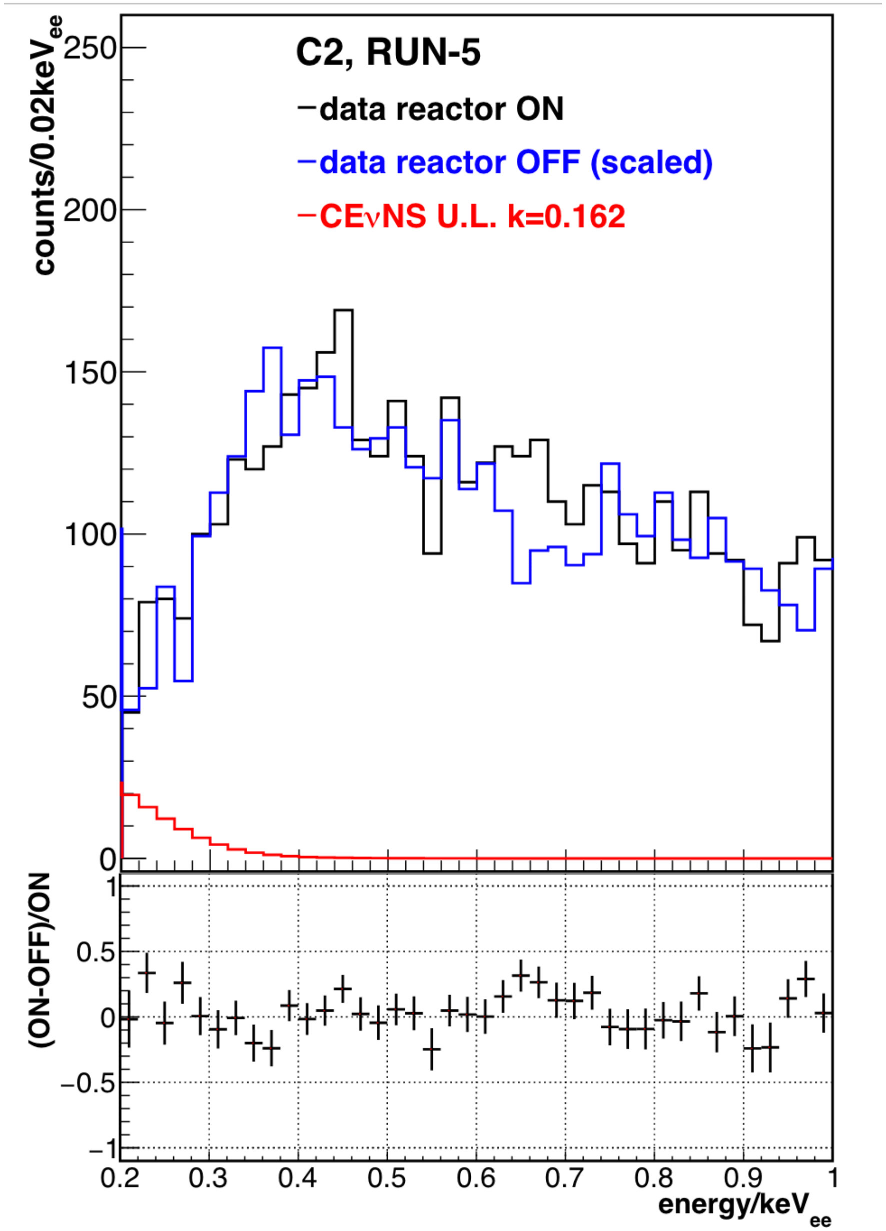


*values reported by experiments

J. Hakenmuller, NDM 2022

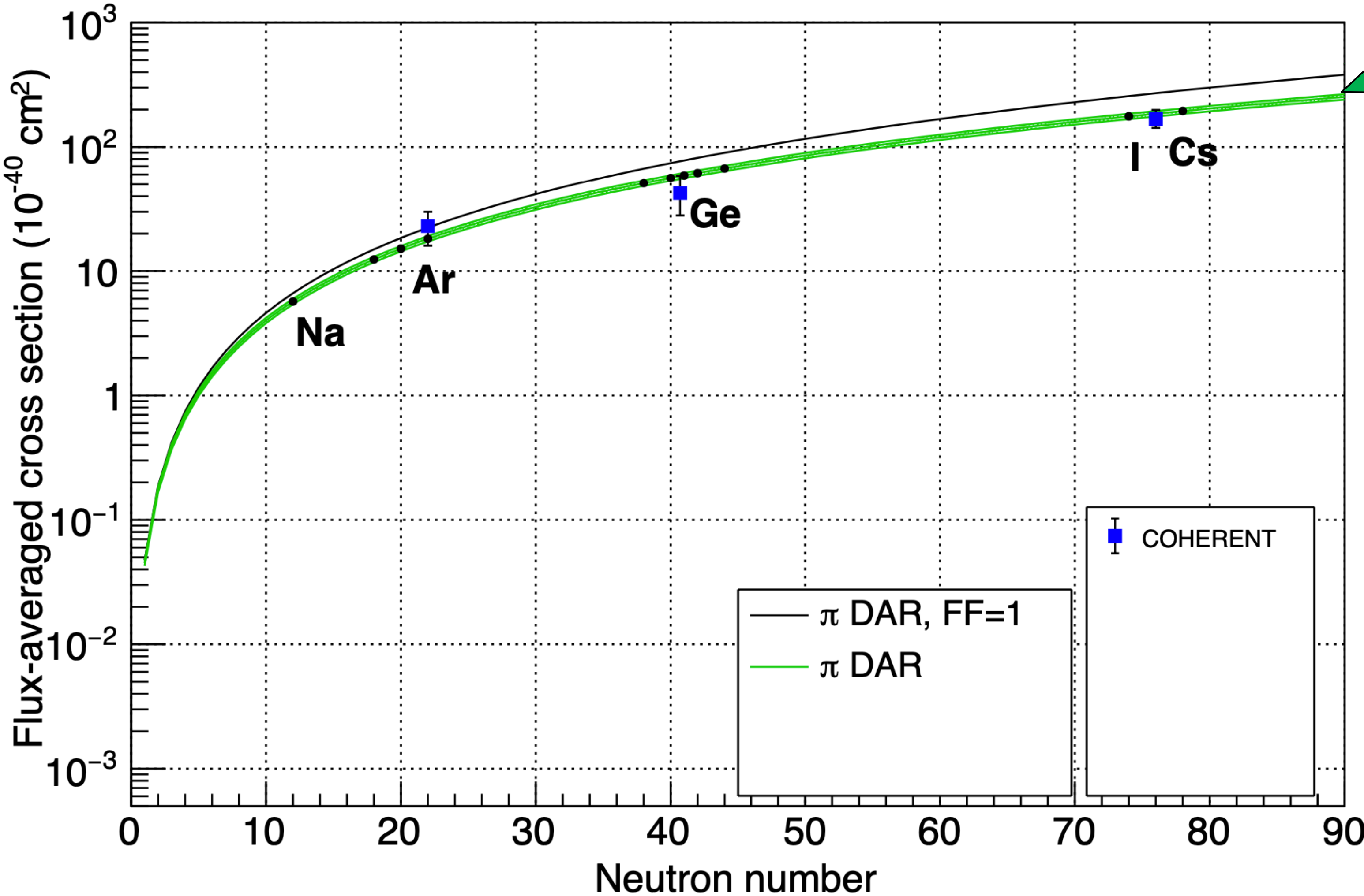
Final results from CONUS Ge @ Brokdorf

quenching description	prediction	Run-5 limit (90% C.L.)
Lindhard (k=0.162 [22])	91^{+11}_{-9}	143
linear low E excess [24]	645^{+59}_{-90}	99
cubic low E excess [24]	115^{+13}_{-11}	122



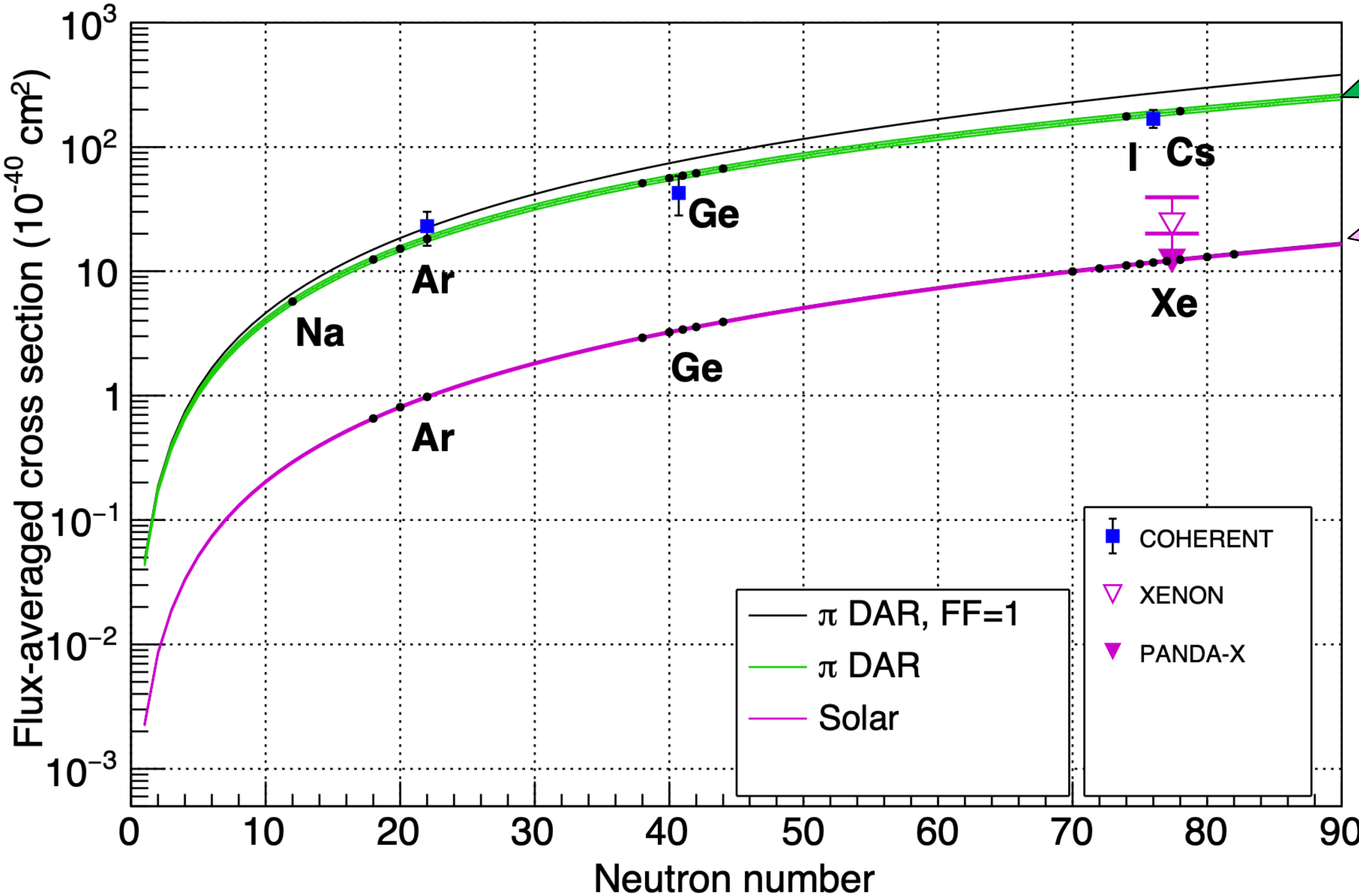
arXiv:2401.07684v1

Summary of CEvNS Results



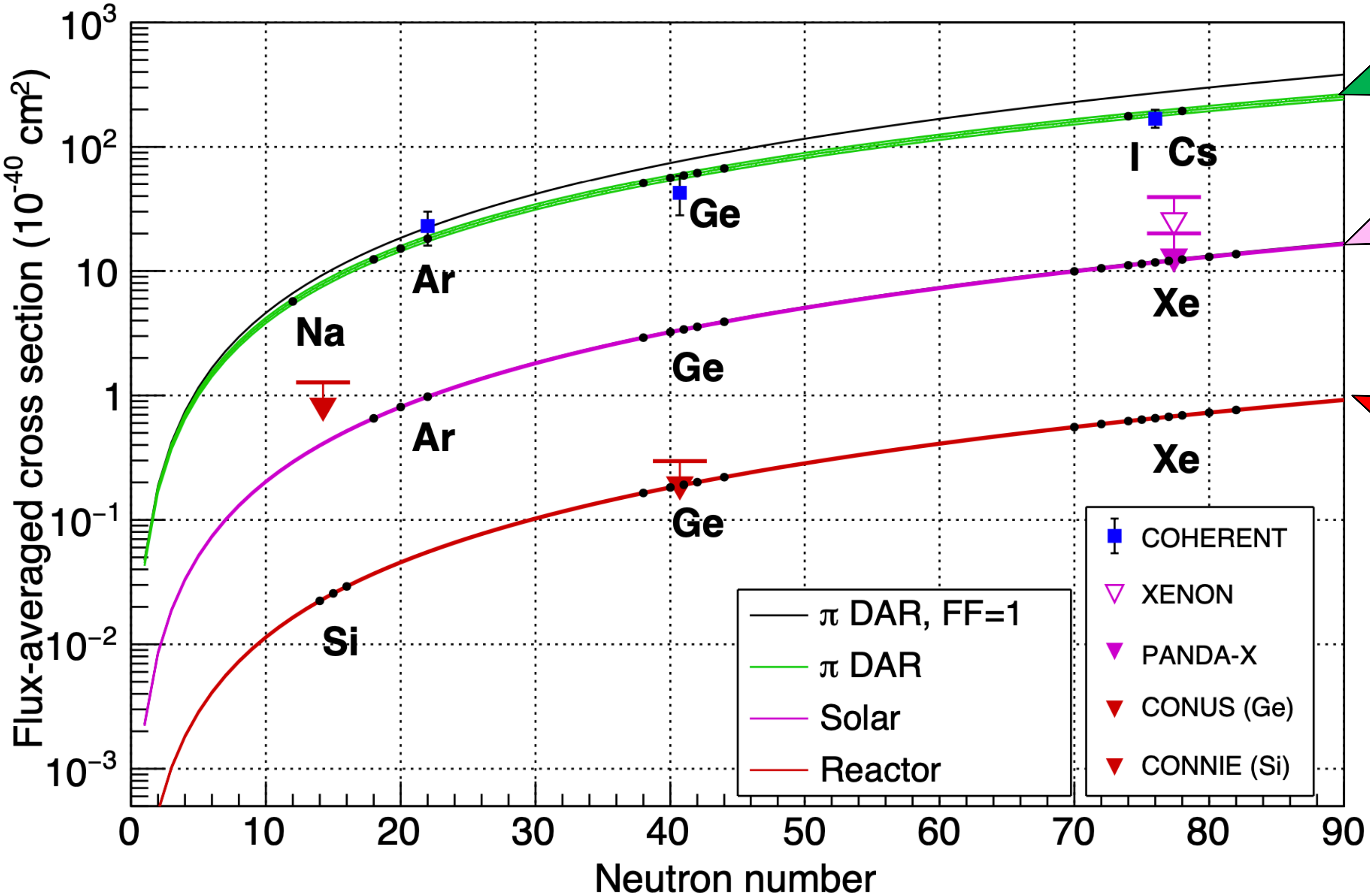
So far: measurements in CsI, Ar, Ge from COHERENT

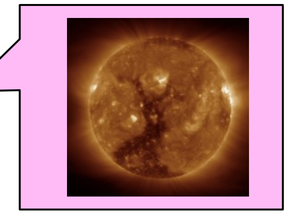
Summary of CEvNS Results

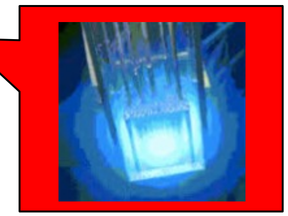


Limits from XENON on solar CEvNS

Summary of CEvNS Results



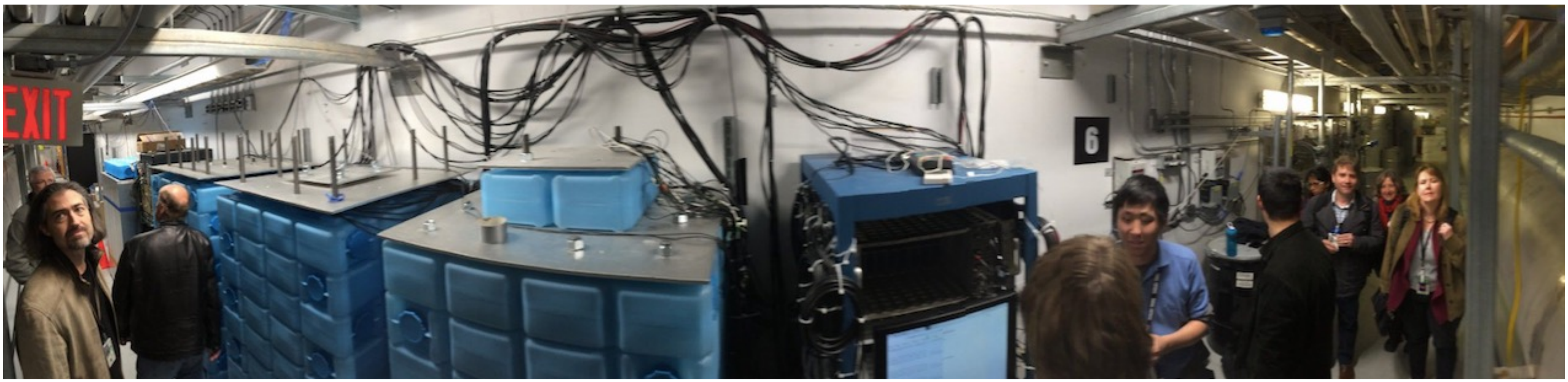




Limits on reactor CEvNS in Ge, Si... looking forward to more soon!

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 measurements** by COHERENT: CsI[Na], Ar, **now Ge**!
- **Meaningful bounds on beyond-the-SM physics**



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