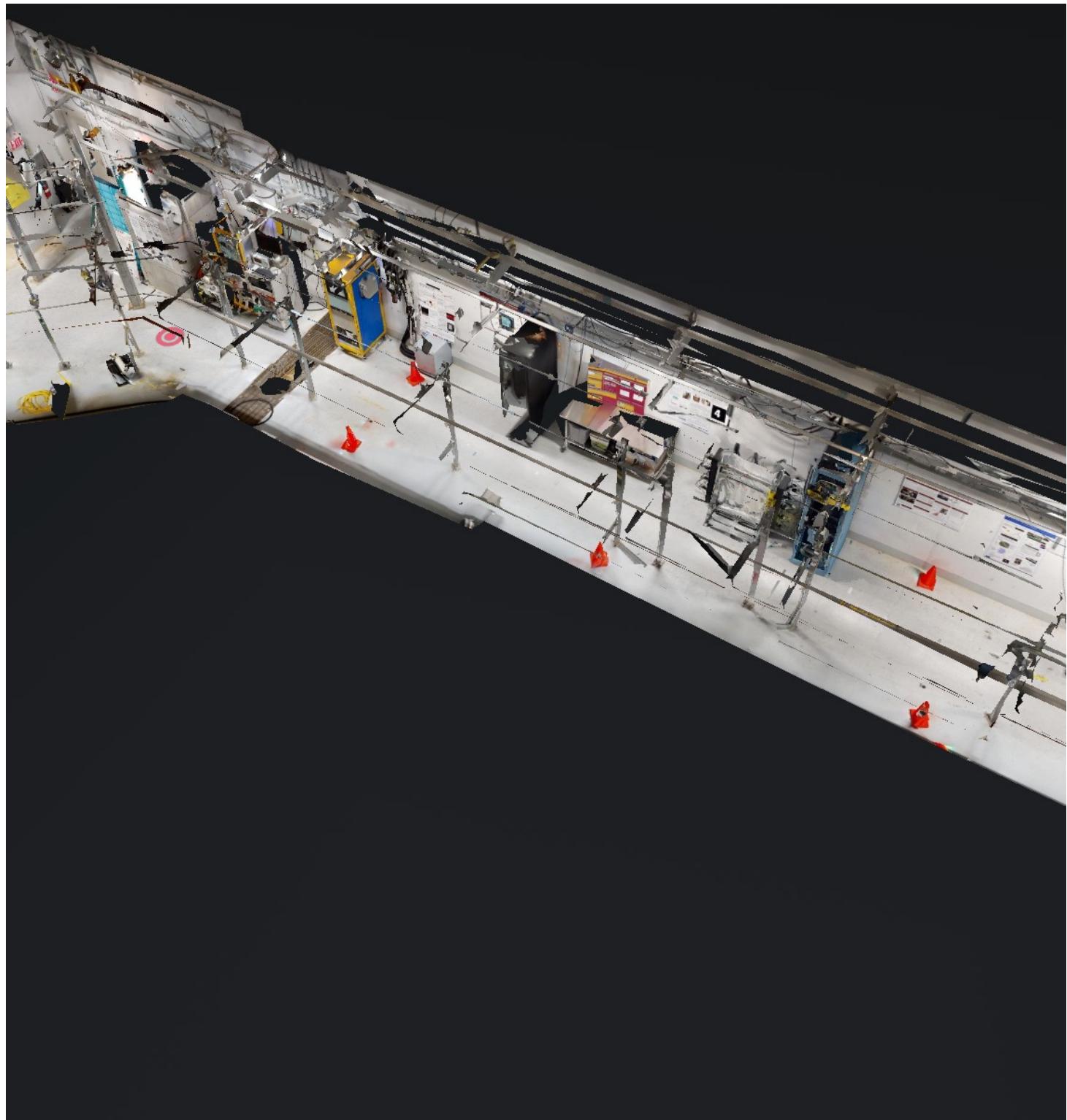


Physics from Coherent Elastic Neutrino- Nucleus Scattering

Kate Scholberg,
Duke University

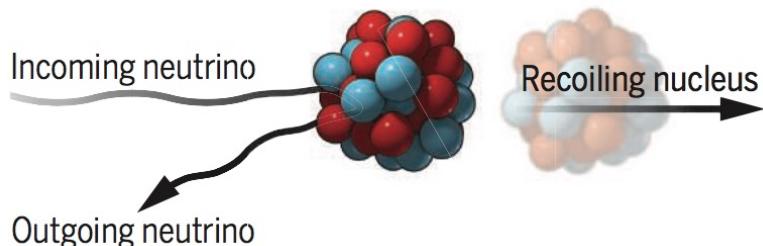
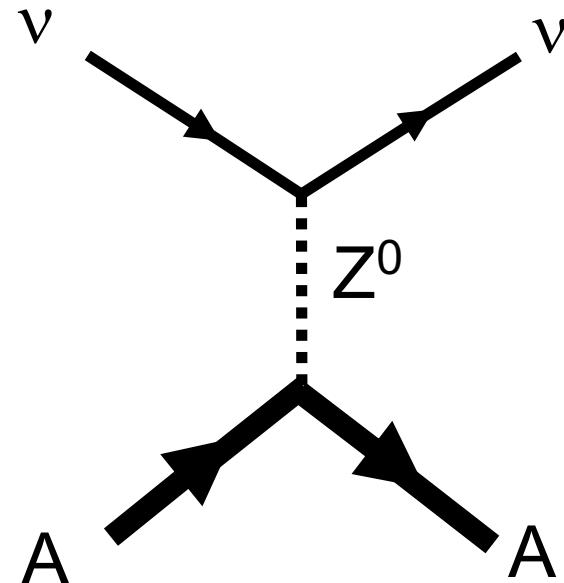
NuSym22
September 29, 2022



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 $E_\nu \sim 50$ MeV



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

For $QR \ll 1$, [total xscn] $\sim A^2 * [\text{single constituent xscn}]$

A: no. of constituents

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

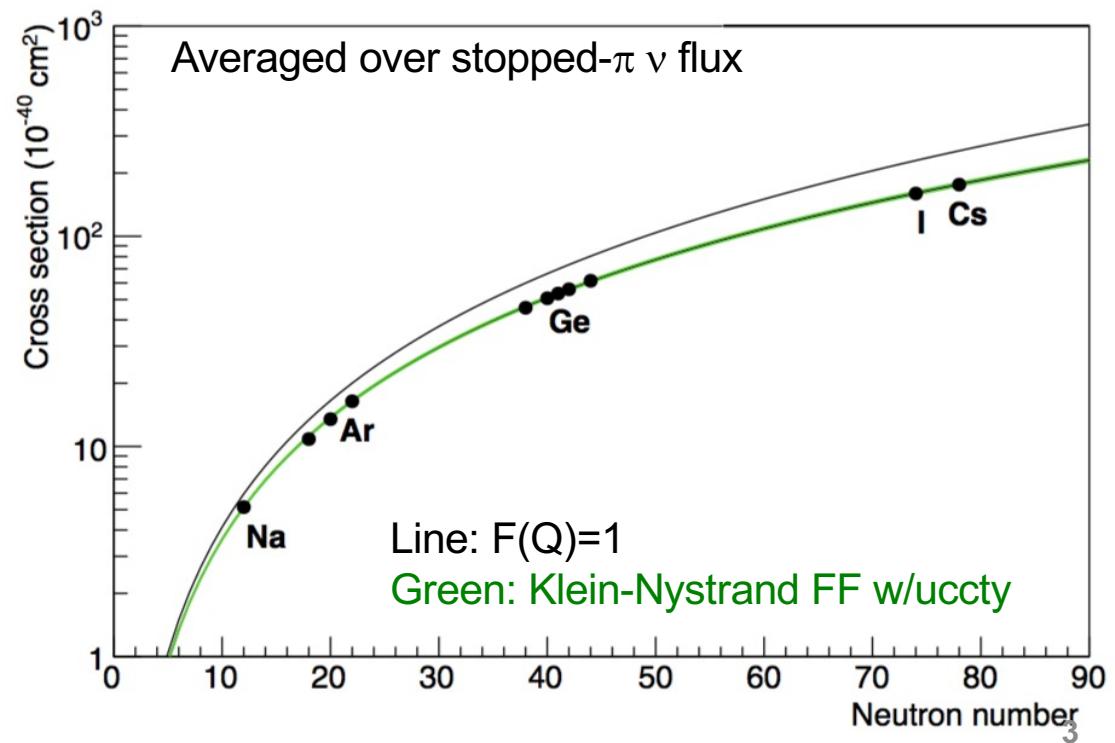
E_ν : neutrino energy
 T : nuclear recoil energy
 M : nuclear mass
 $Q = \sqrt{2MT}$: momentum transfer

weak nuclear charge

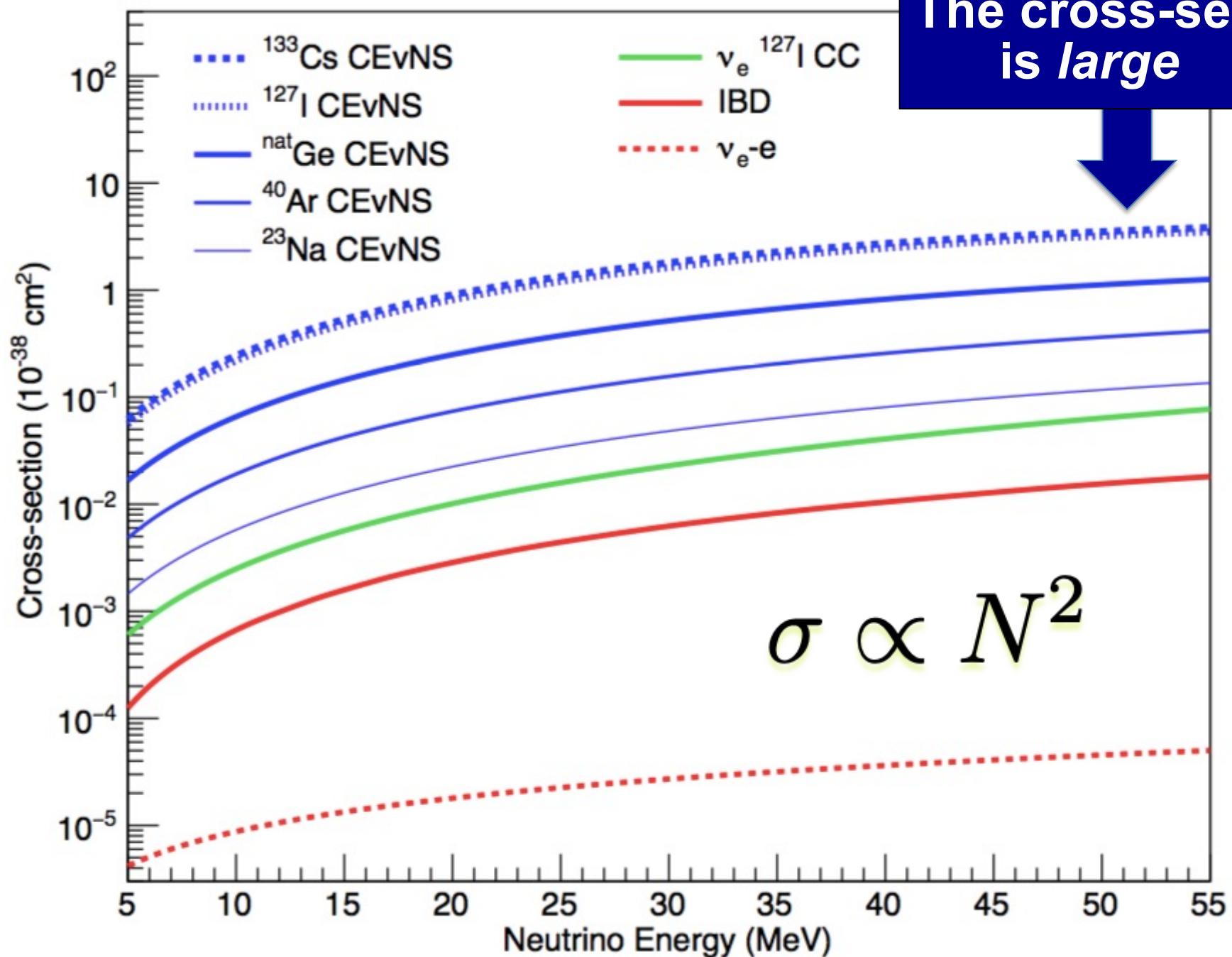
Form factor: $F=1 \rightarrow$ full coherence

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

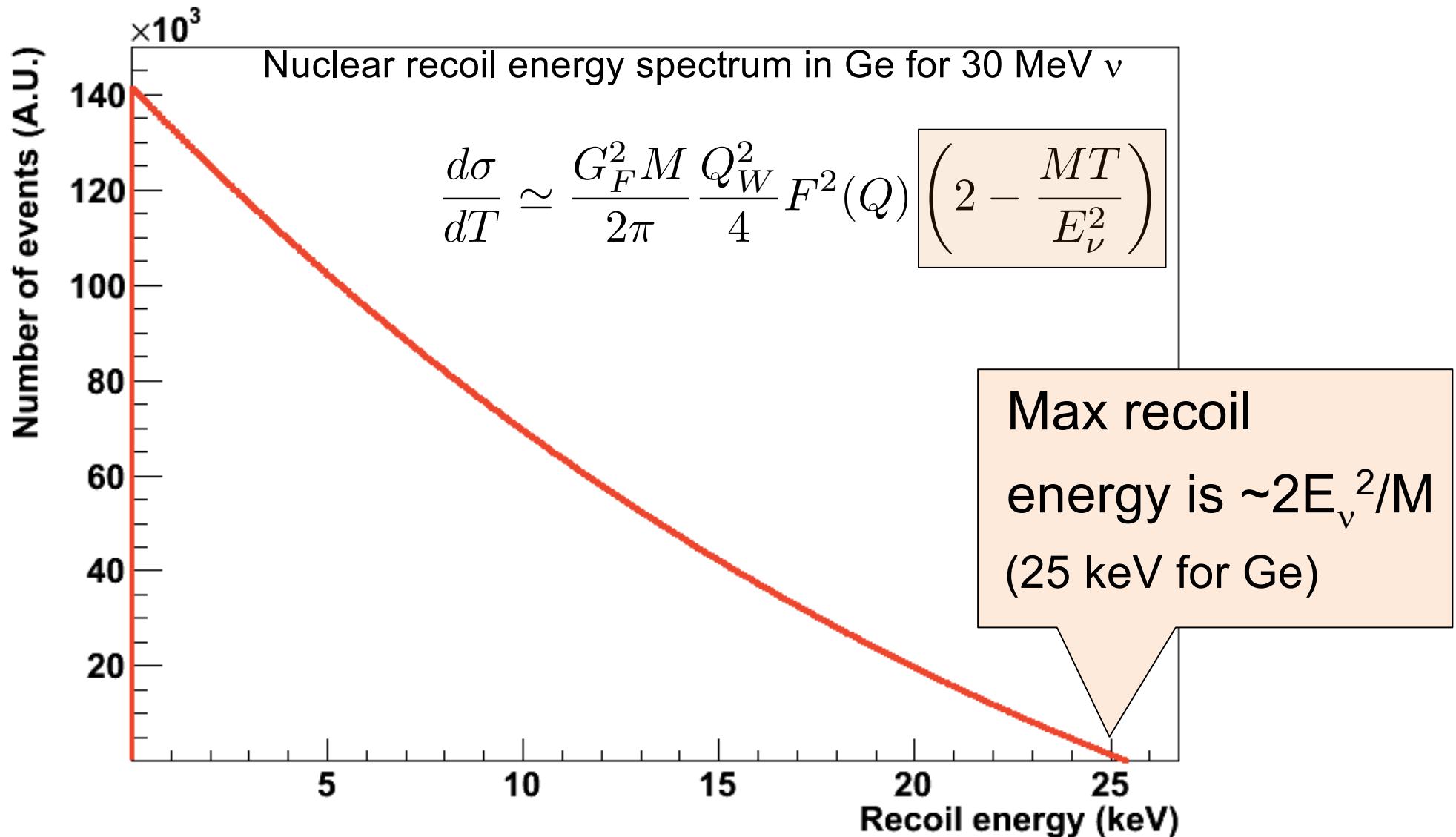
$$\Rightarrow \frac{d\sigma}{dT} \propto N^2$$



The cross-section
is *large*

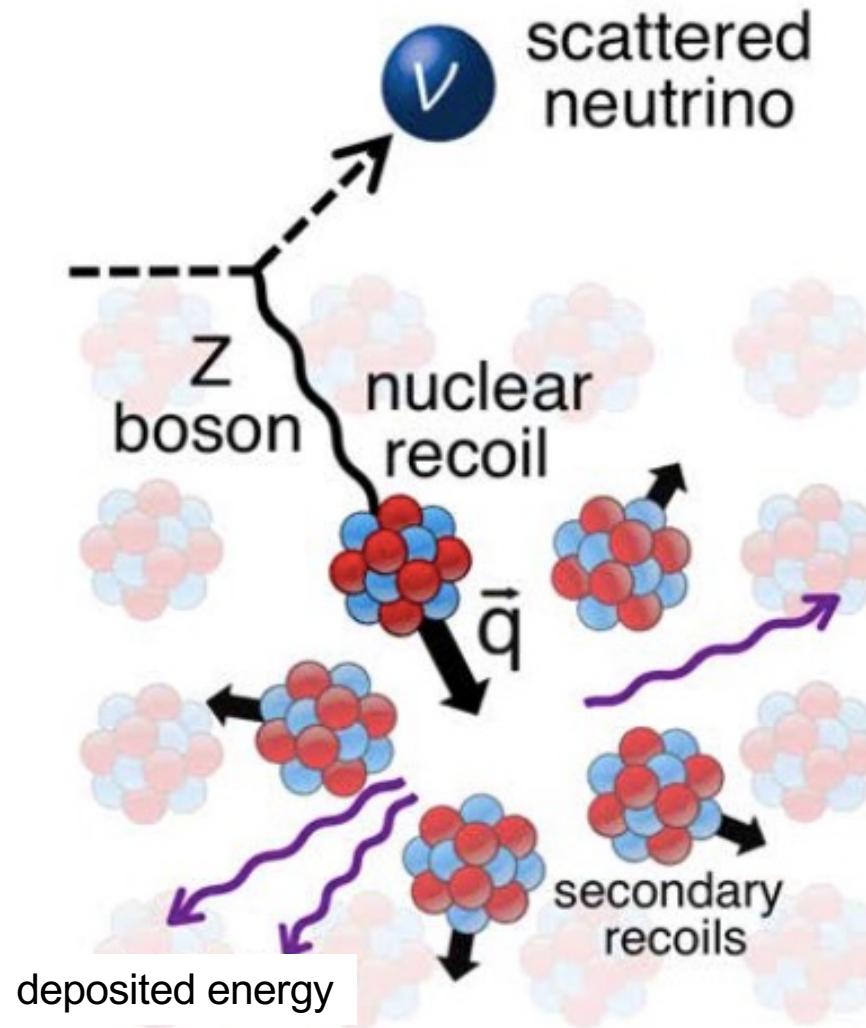


Large cross section (by neutrino standards) but hard to observe due to **tiny nuclear recoil energies**:



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

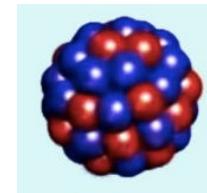
① So
② Many !
③ Things
(not a complete list!)

CEvNS: what's it good for?

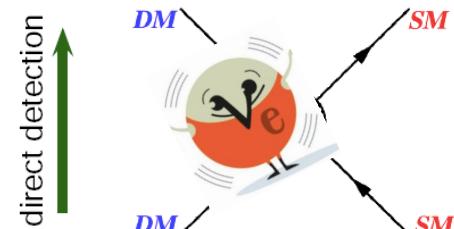
CEvNS as a **signal**
for signatures of *new physics*



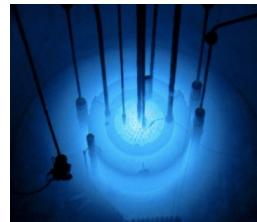
CEvNS as a **signal**
for understanding of “old” physics



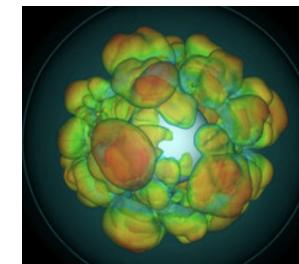
CEvNS as a **background**
for signatures of new physics



CEvNS as a **signal** for astrophysics



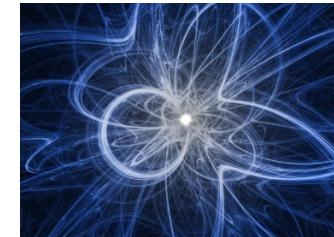
CEvNS as a **practical tool**



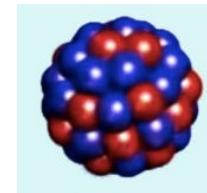
① So
② Many !
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CEvNS: what's it good for?

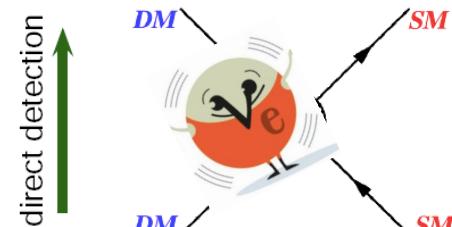
CEvNS as a **signal**
for signatures of *new physics*



CEvNS as a **signal**
for understanding of “old” physics



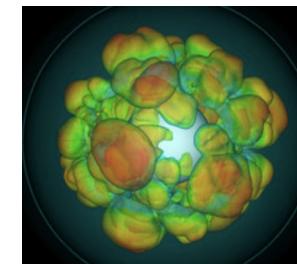
CEvNS as a **background**
for signatures of new physics



CEvNS as a **signal for astrophysics**



CEvNS as a **practical tool**



The cross section is cleanly predicted in the Standard Model

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

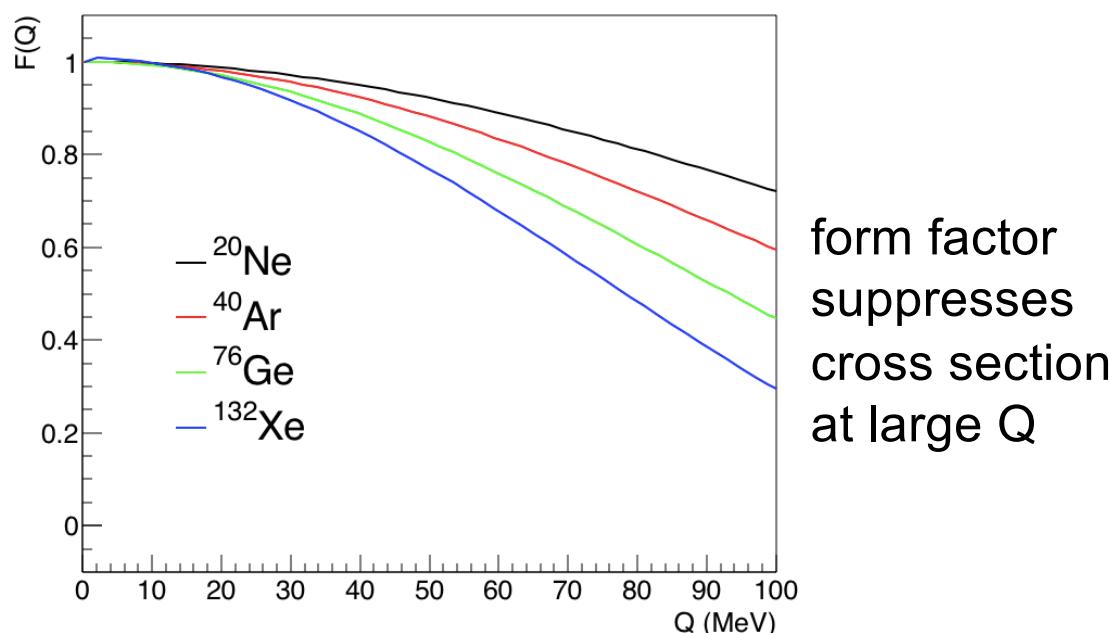
E_ν : neutrino energy

T: nuclear recoil energy

M: nuclear mass

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

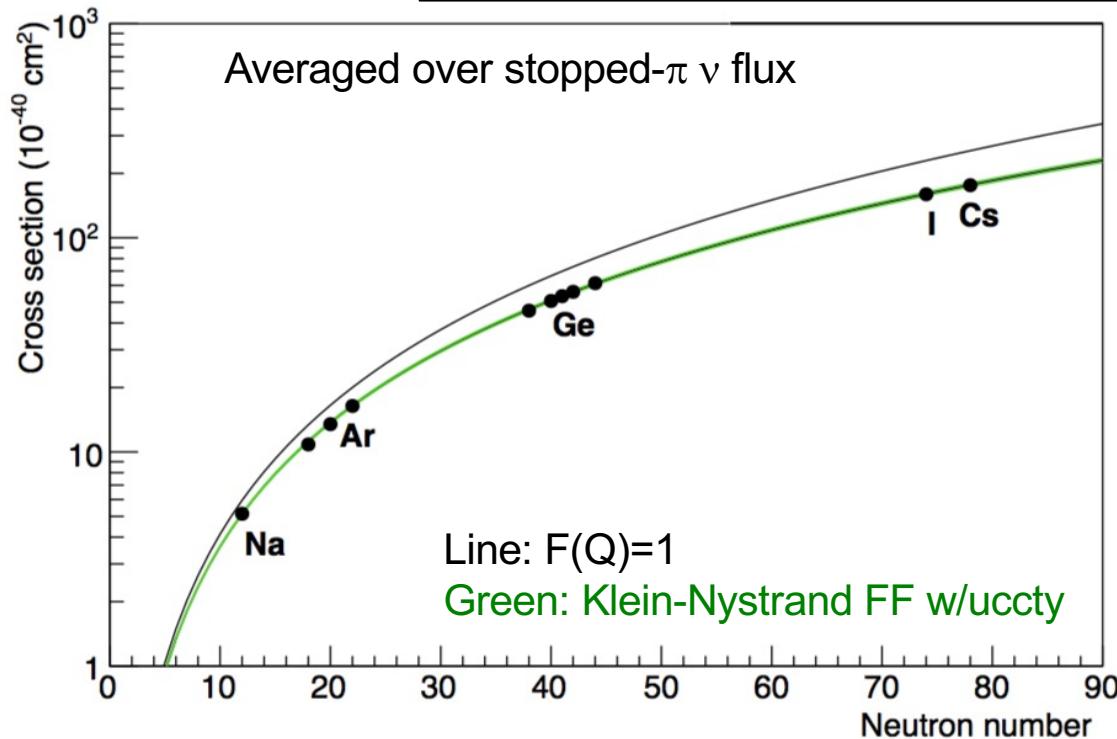
$F(Q)$: nuclear **form factor**, $\sim 5\%$ uncertainty on event rate



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

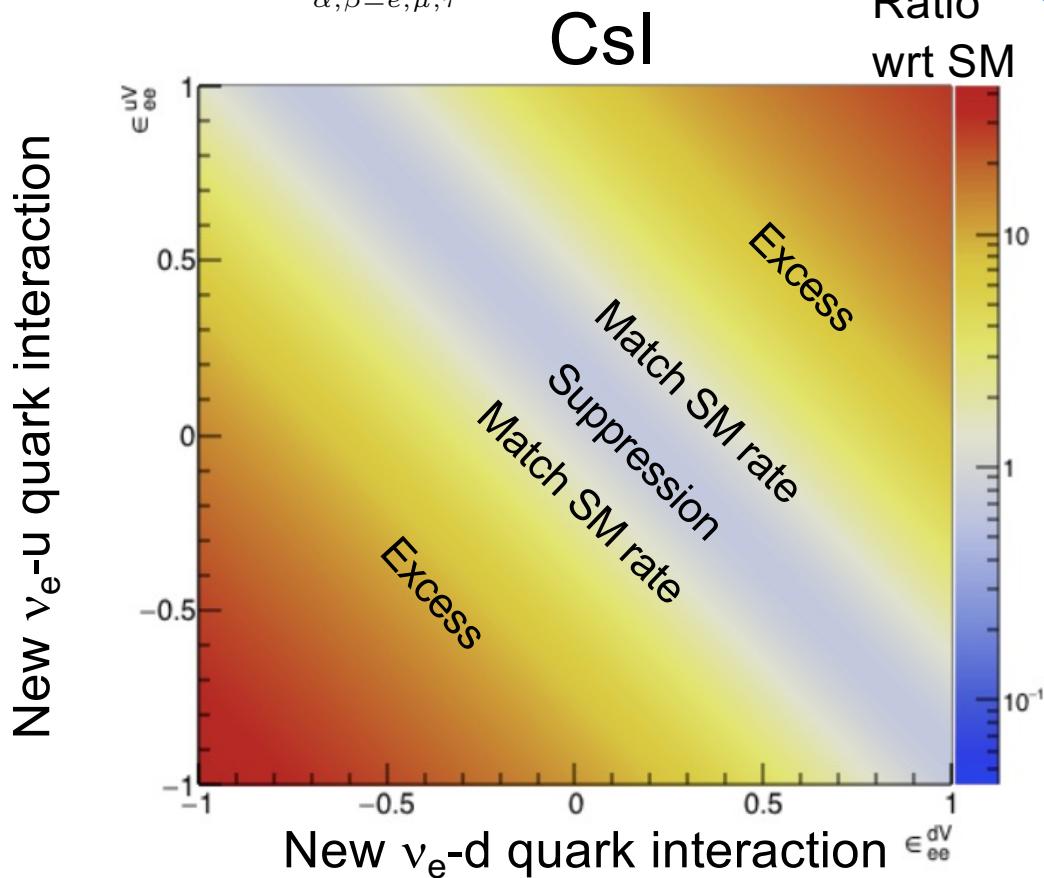


A deviation from $\propto N^2$ prediction can be a signature of beyond-the-SM physics

Non-Standard Interactions of Neutrinos:

new interaction **specific to ν 's**

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



Ratio
wrt SM

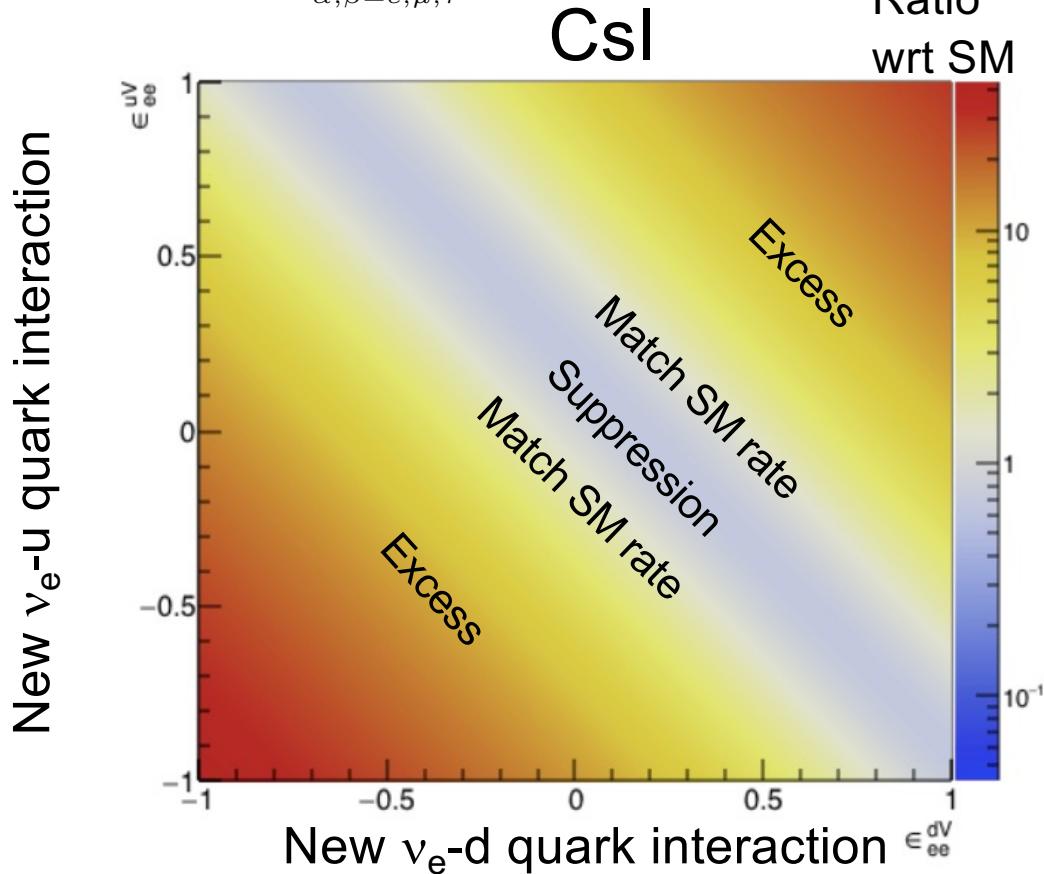
If these ε 's are
~unity, there is
a new interaction
of ~Standard-model
size... many not
currently
well constrained

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

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

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

Effective weak charge in presence
of light vector mediator Z'

$$Q_{\alpha, \text{SM}}^2 = (Z g_p^V + N g_n^V)^2$$



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

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 $\sim 1/T$ upturn
at low recoil energy

Sterile Neutrino Oscillations

$$P_{\nu_\alpha \rightarrow \nu_\alpha}^{\text{SBL}}(E_\nu) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right)$$

“True” disappearance with baseline-dependent Q distortion

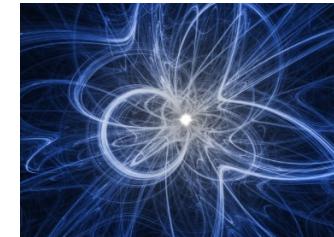
e.g. arXiv: 1511.02834,
1711.09773, 1901.08094

- ① So
- ② Many !
- ③ Things

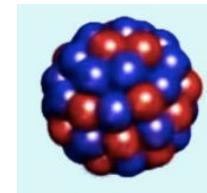
(not a complete list!)

CEvNS: what's it good for?

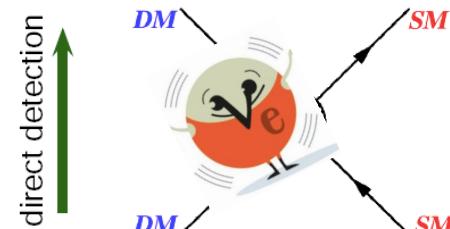
CEvNS as a **signal**
for signatures of *new physics*



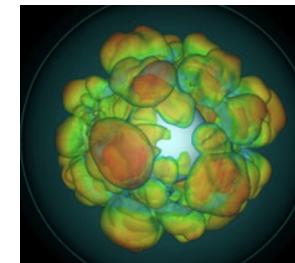
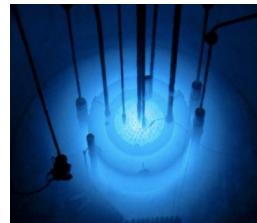
CEvNS as a **signal**
for understanding of “old” physics



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

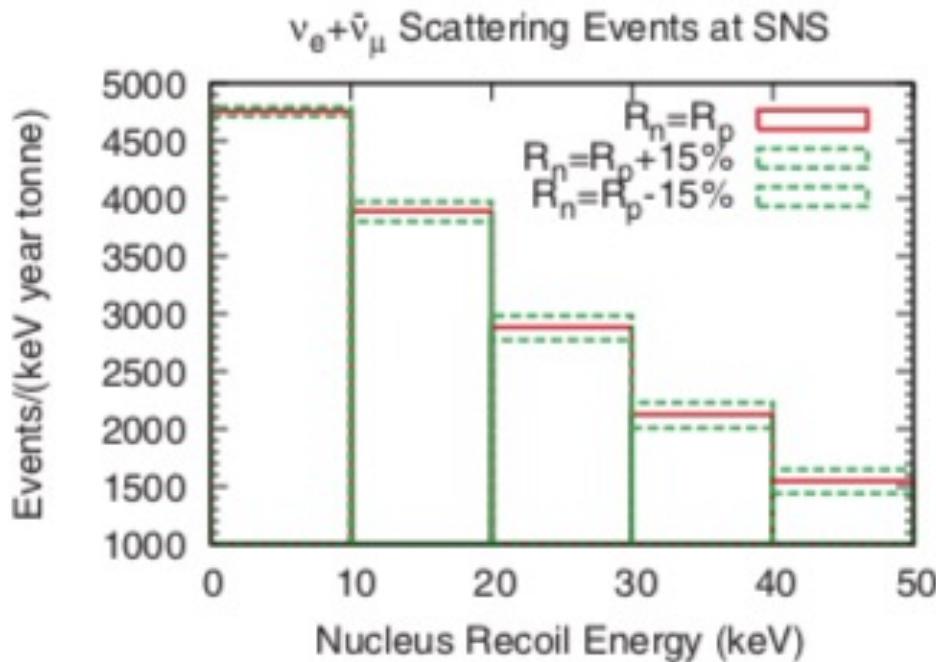


CEvNS as a **signal for astrophysics**



CEvNS as a **practical tool**

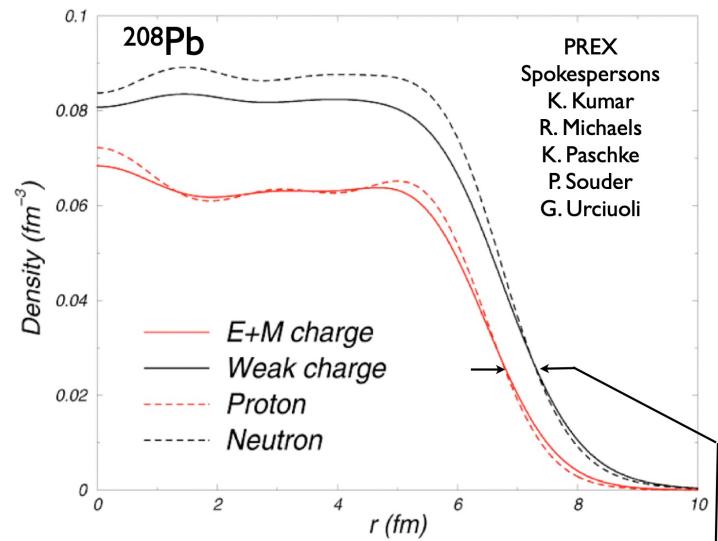
What can we learn about nuclear physics with CEvNS?



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

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

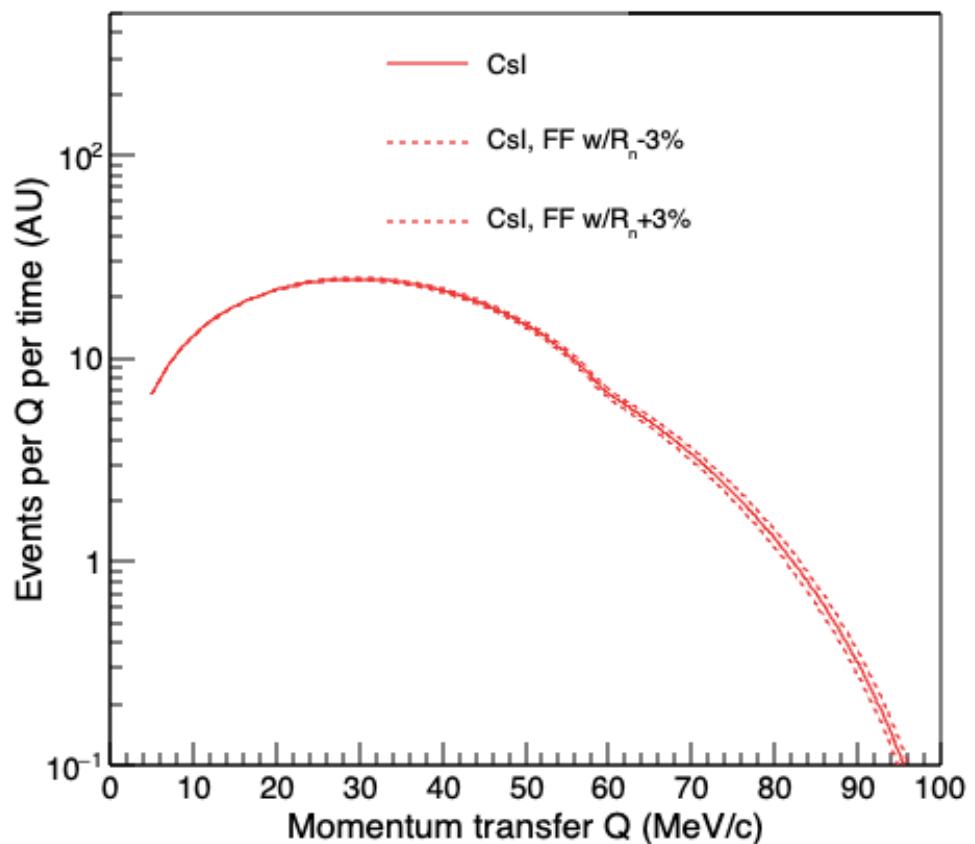
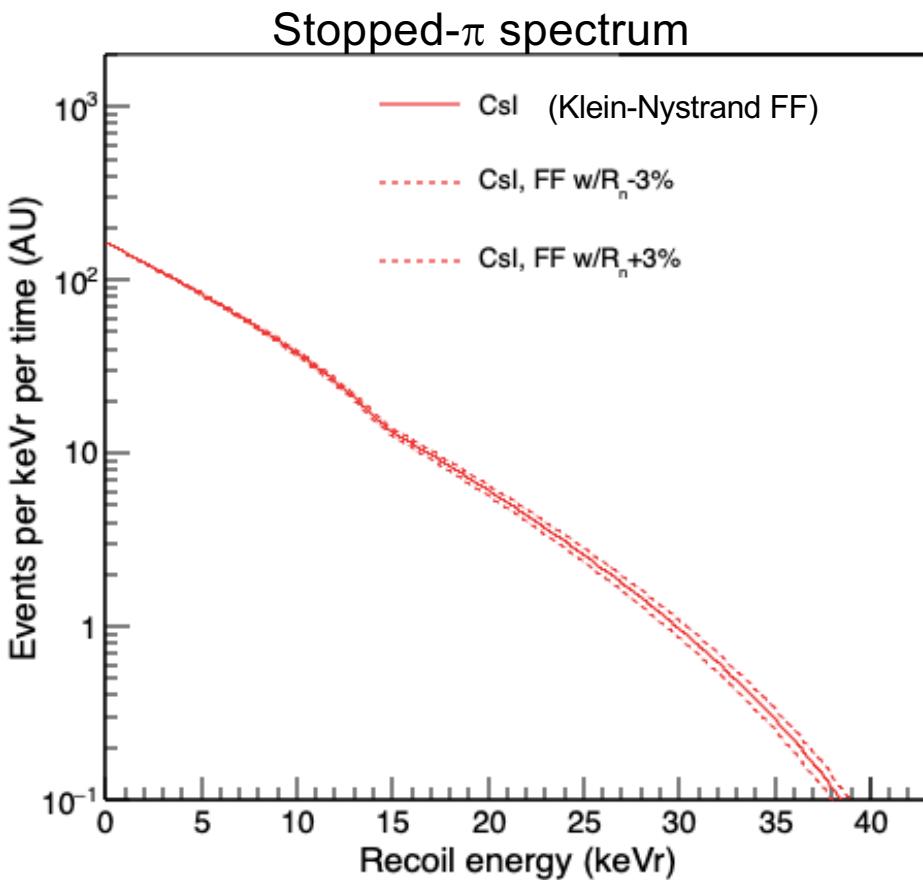
Observable is
recoil
spectrum
shape



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

Effect of form-factor *theoretical uncertainty* on the recoil spectrum: estimate as $R_n \pm 3\%$

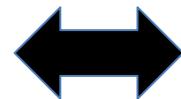
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu} \right)^2 - (G_V^2 - G_A^2) \frac{MT}{E_\nu^2} \right]$$



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

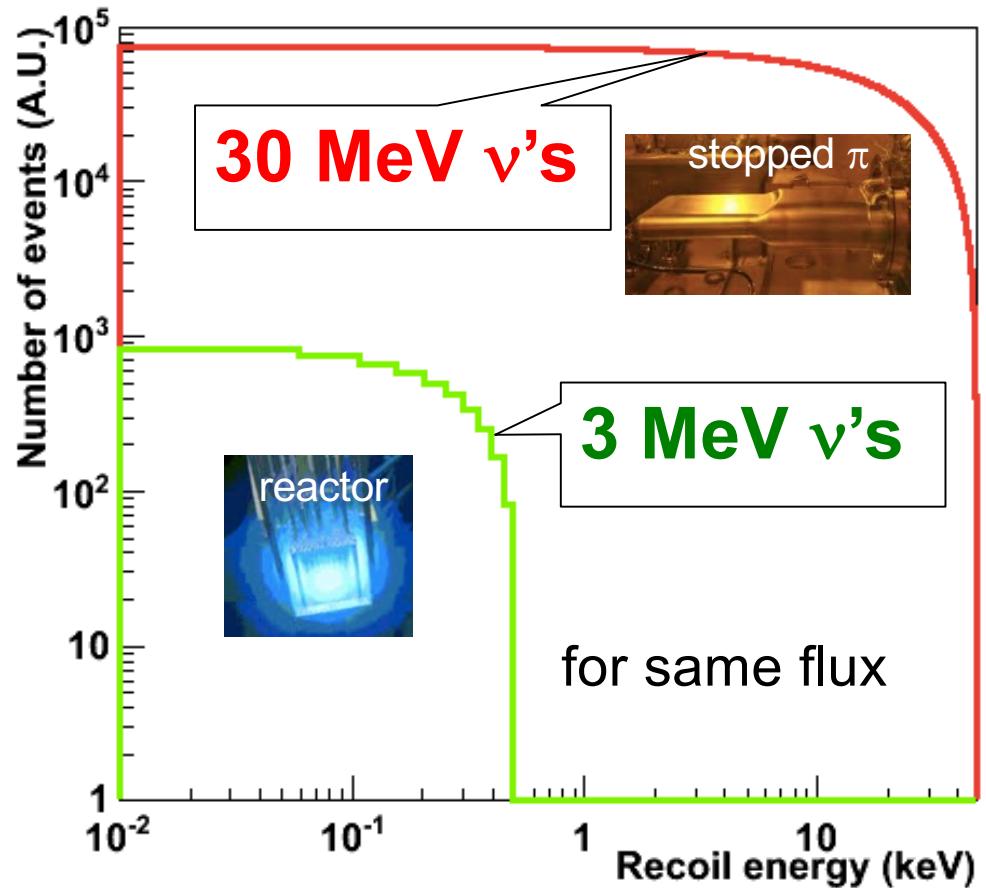
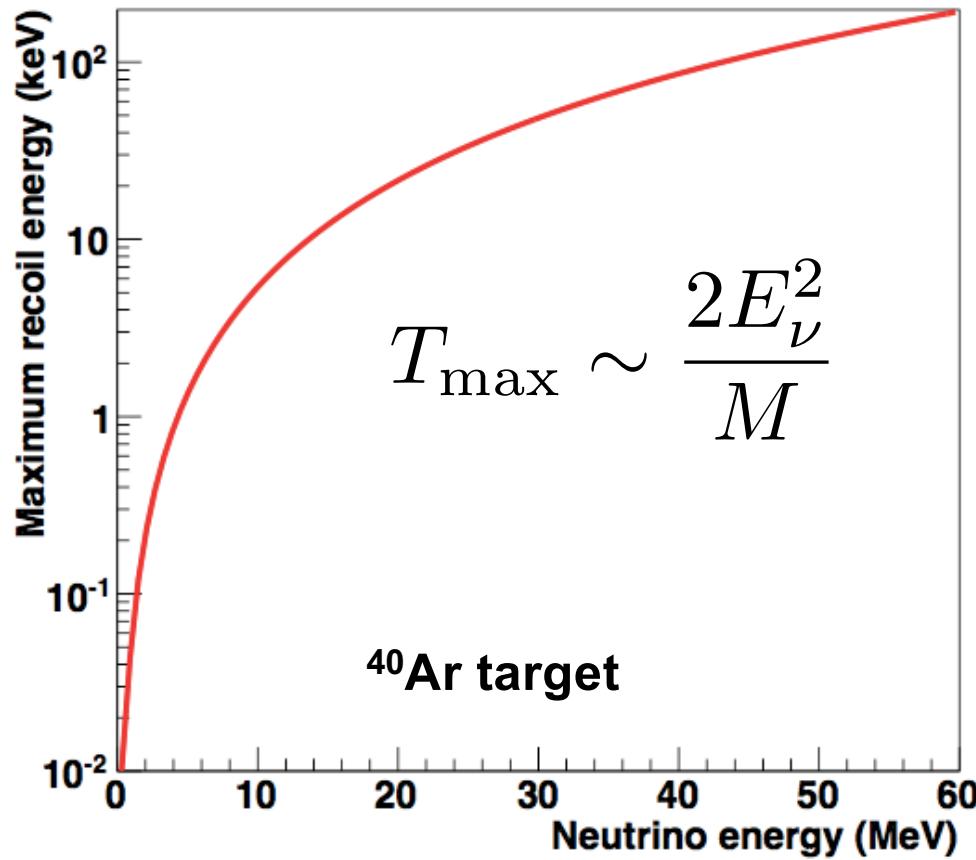


and “new” physics

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

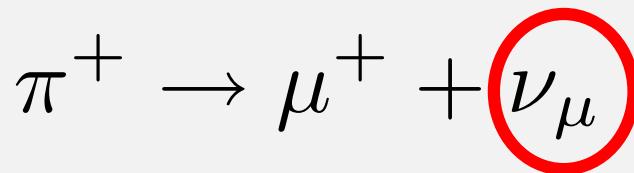
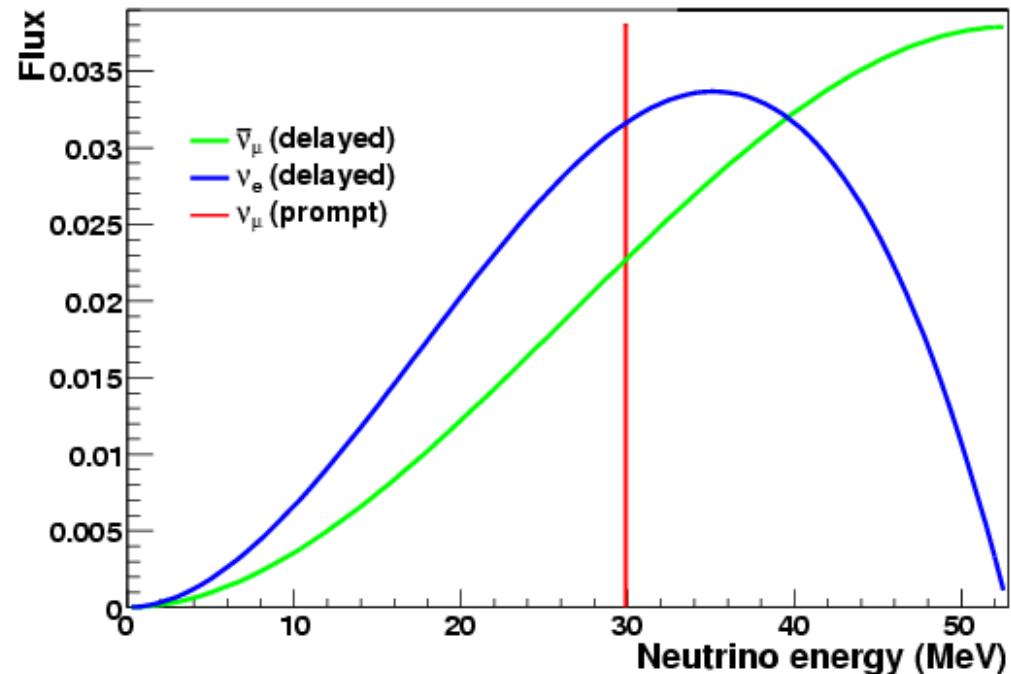
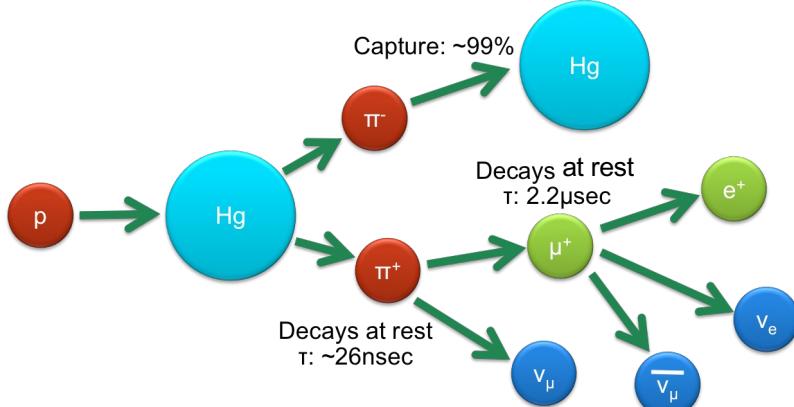
[See e.g.: D. Aristizabal Sierra et al. arXiv:1902.07398]

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

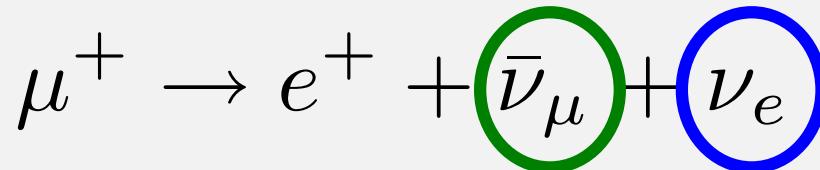
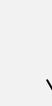


Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (~ 50 MeV for medium A)

Stopped-Pion (π DAR) Neutrinos



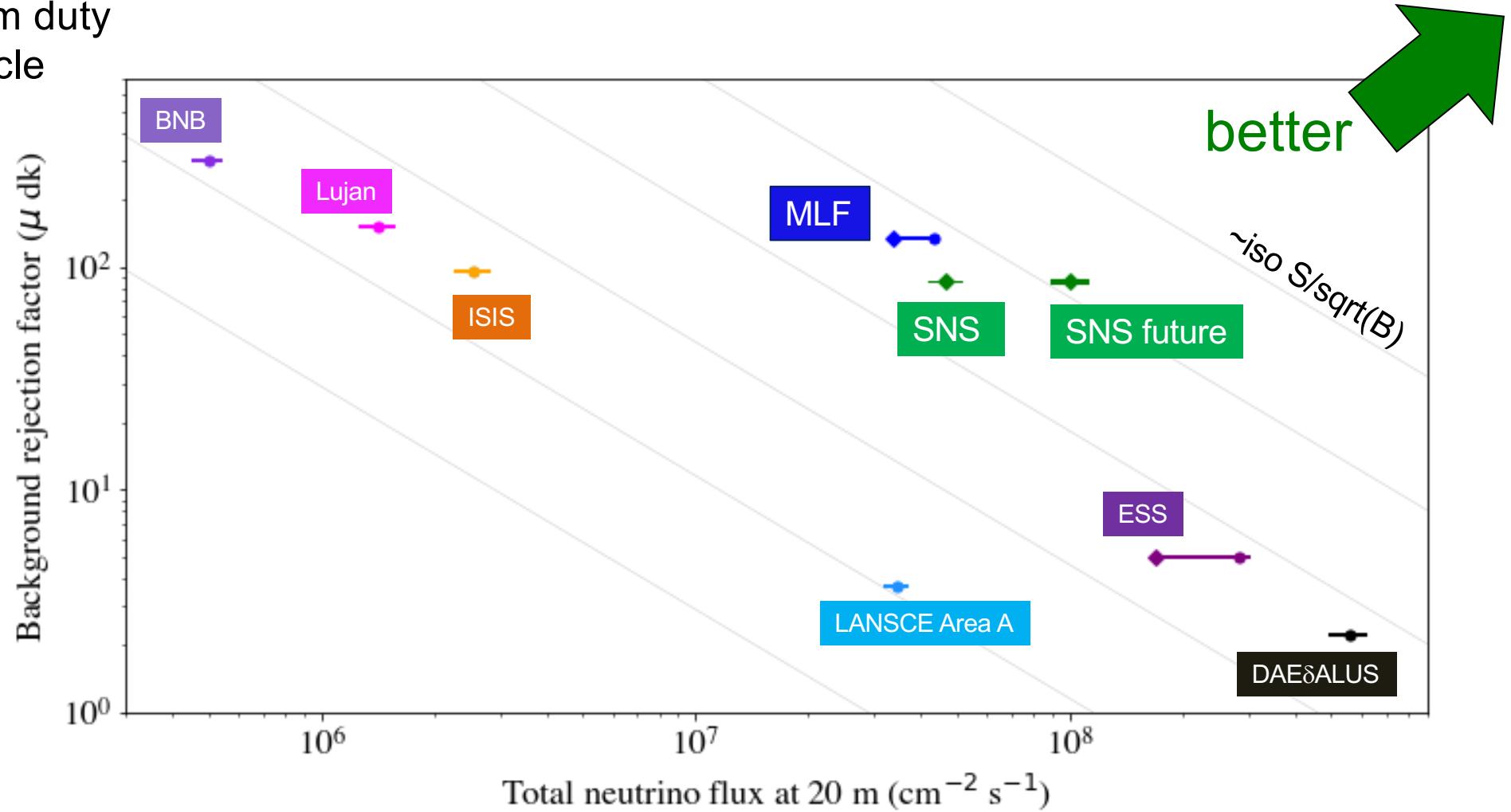
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT



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

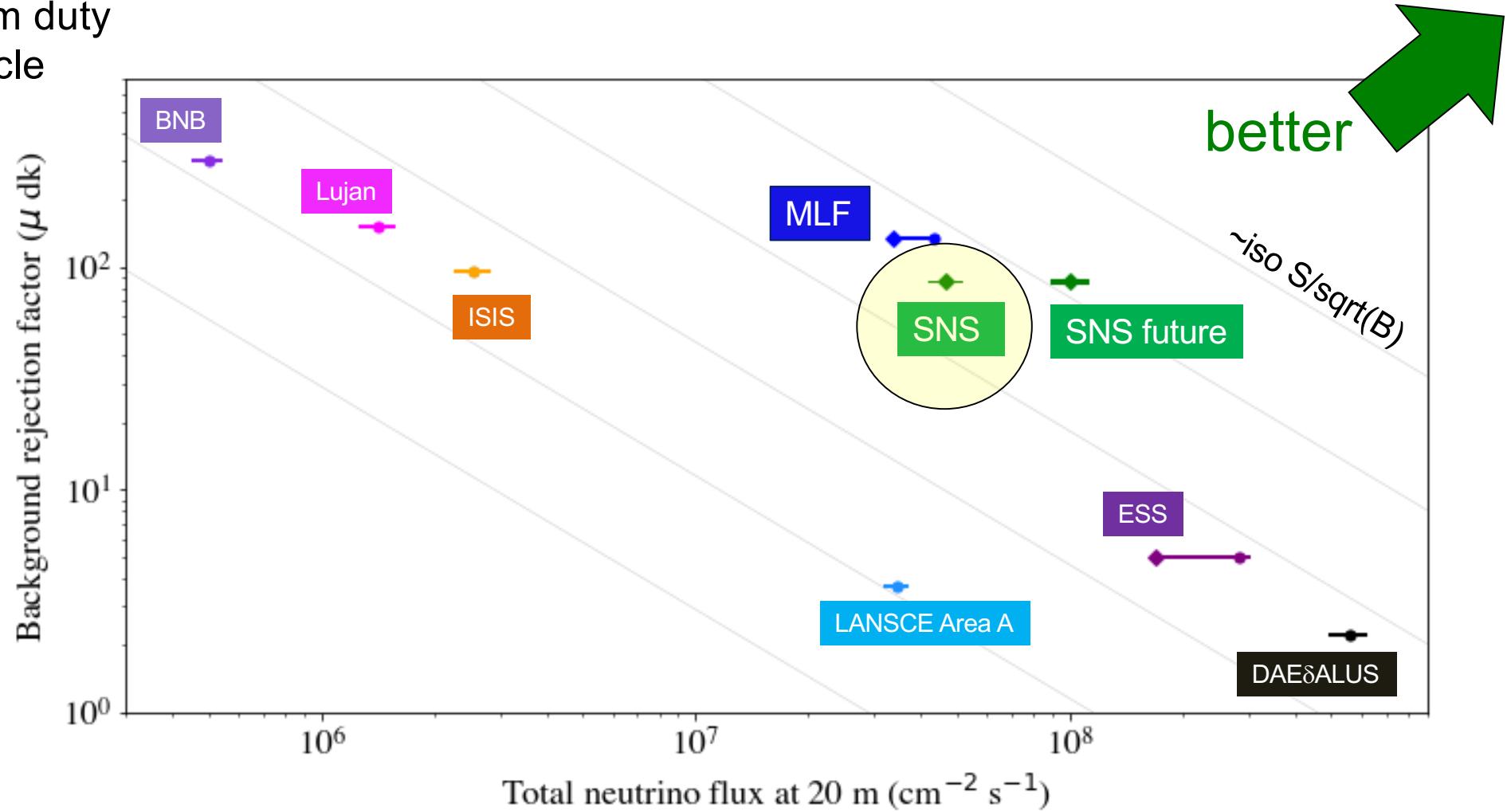
Comparison of pion decay-at-rest ν sources

from duty
cycle



Comparison of pion decay-at-rest ν sources

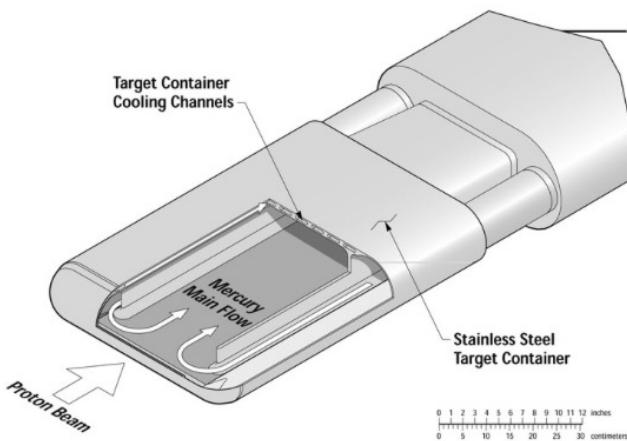
from duty
cycle





Spallation Neutron Source

Oak Ridge National Laboratory, TN

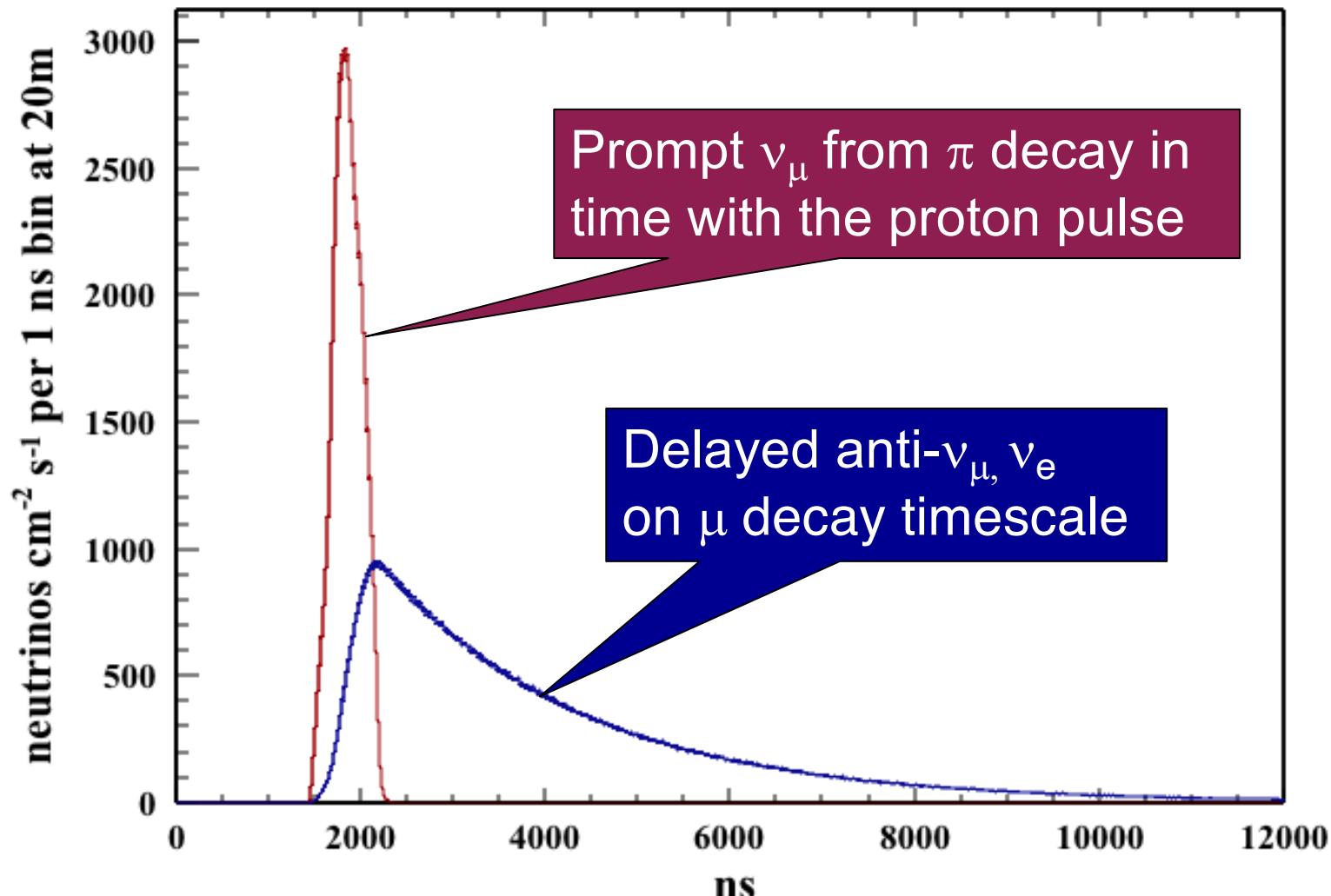


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

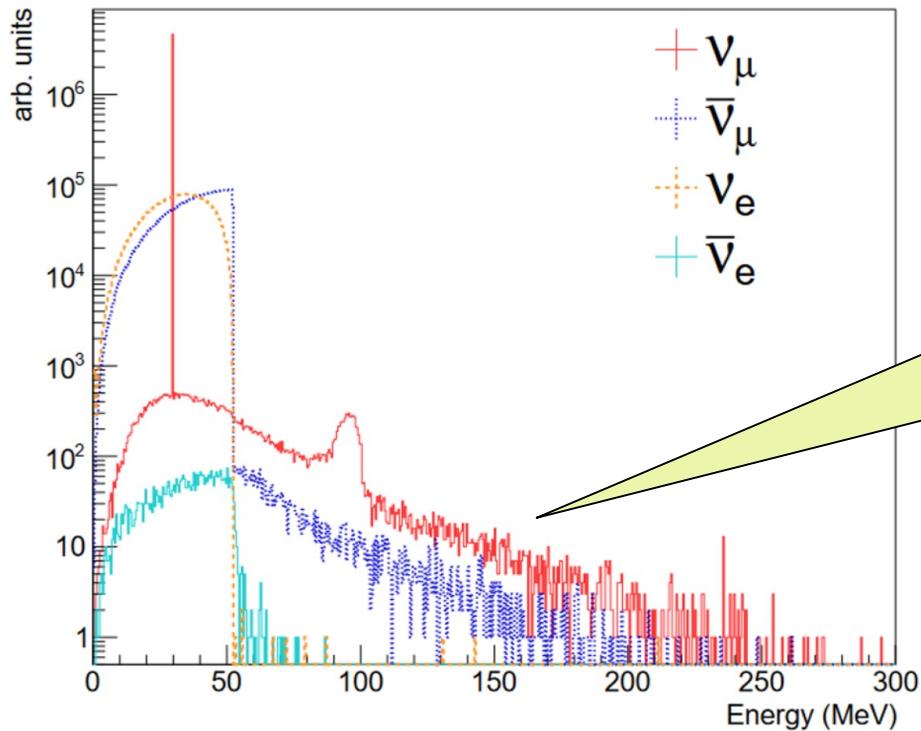
Time structure of the SNS source

60 Hz pulsed source

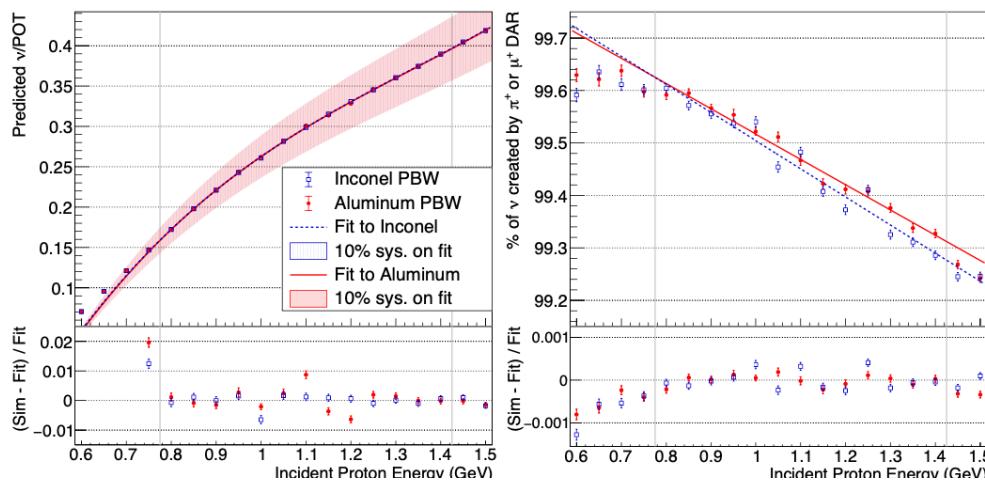


Background rejection factor \sim few $\times 10^{-4}$

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



SNS flux (1.4 MW):
 $470 \times 10^5 \nu/\text{cm}^2/\text{s}$ @ 20 m
>99% pure decay at rest

The COHERENT collaboration

<http://sites.duke.edu/coherent>

~90 members,
20 institutions
4 countries



Carnegie
Mellon
University



UF UNIVERSITY of
FLORIDA



Laurentian University
Université Laurentienne

Los Alamos
NATIONAL LABORATORY
EST. 1943



NC Central
UNIVERSITY

NC STATE
UNIVERSITY

OAK RIDGE
National Laboratory

Sandia
National
Laboratories

서울 대 학 교
SEOUL NATIONAL UNIVERSITY

SLAC
NATIONAL
ACCELERATOR
LABORATORY

UNIVERSITY OF
SOUTH DAKOTA

UNIVERSITY of
TENNESSEE
KNOXVILLE



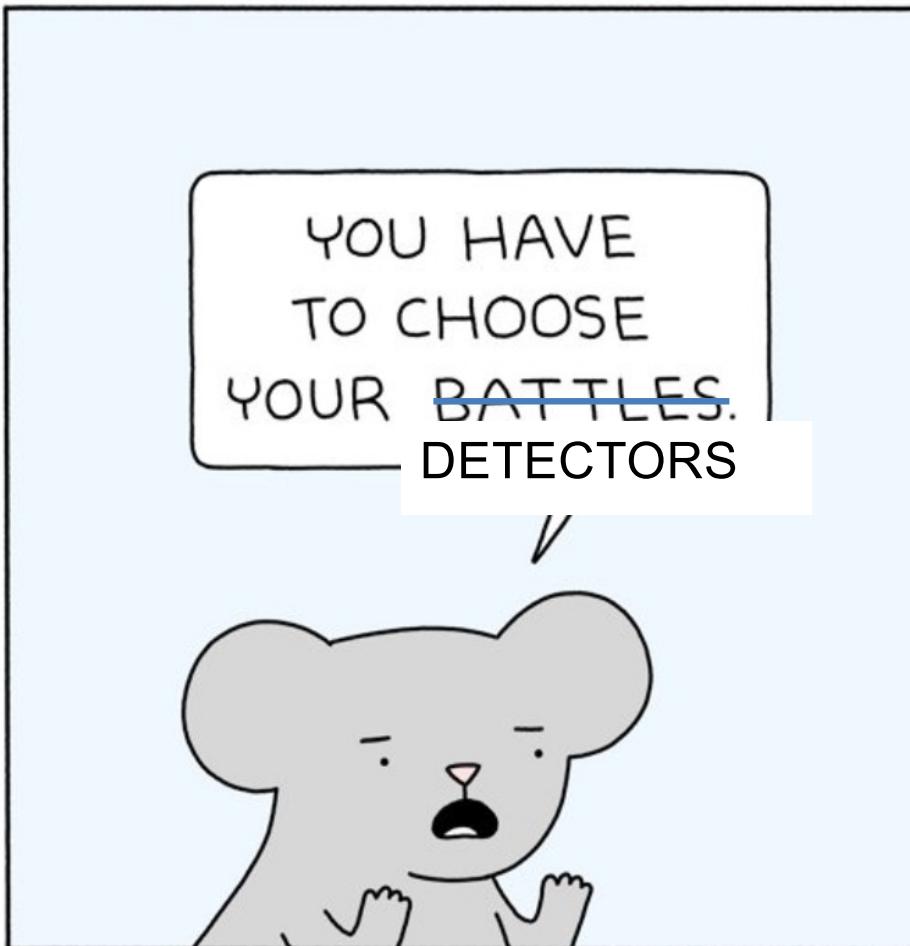
Tufts
UNIVERSITY

TUNL
TRIANGLE UNIVERSITIES
NUCLEAR LABORATORY

VIRGINIA TECH.

W
UNIVERSITY of
WASHINGTON

The COHERENT Spirit (so far)

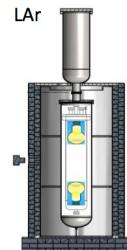


POORLY DRAWN LINES

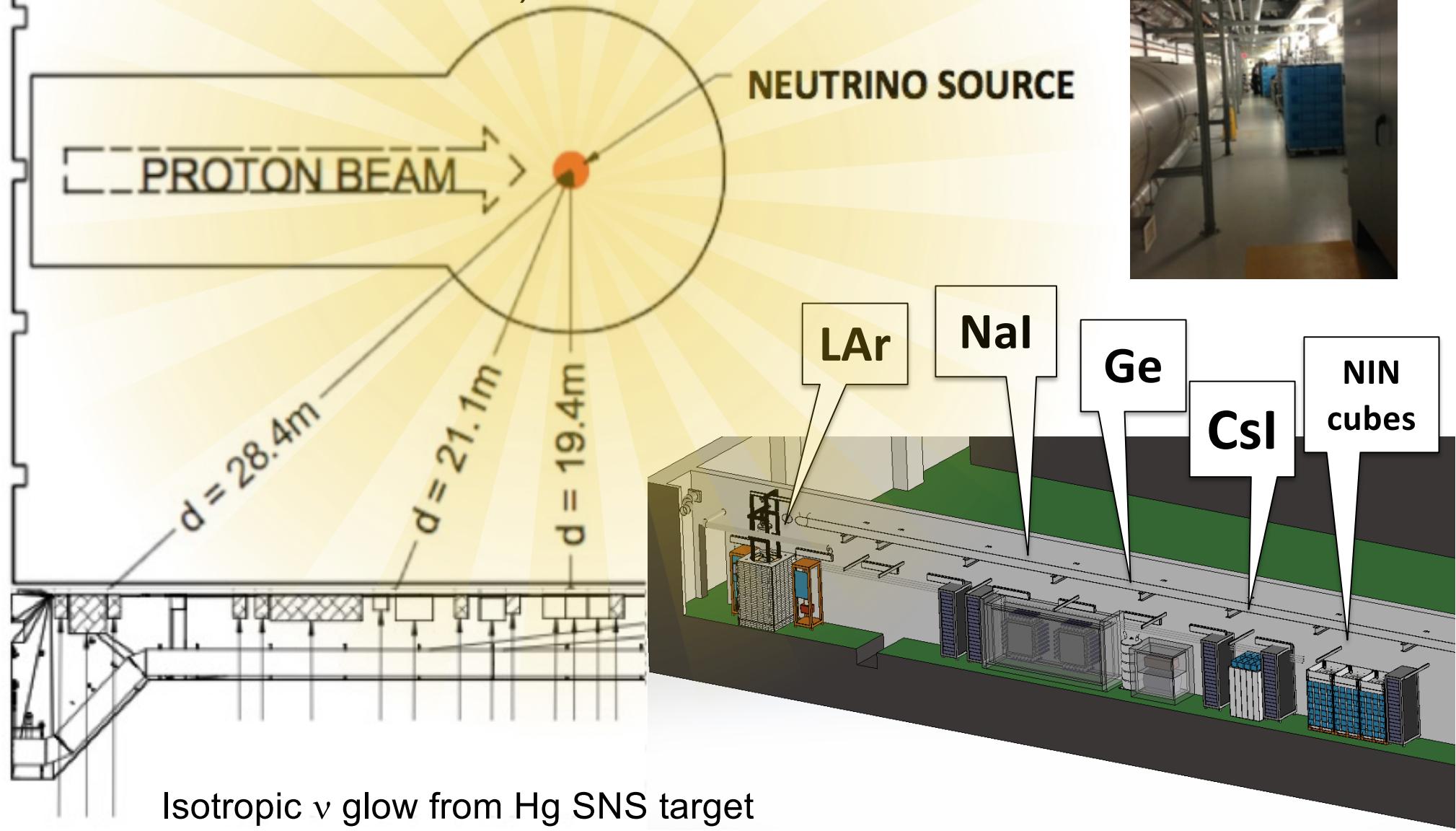
COHERENT CEvNS Detectors

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
Ge	HPGe PPC	18	22	<few
LAr	Single-phase	24	27.5	20
NaI(Tl)	Scintillating crystal	185*/3338	25	13

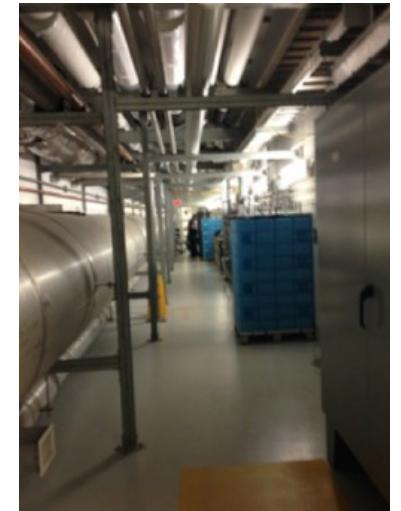
Multiple detectors for N^2 dependence of the cross section



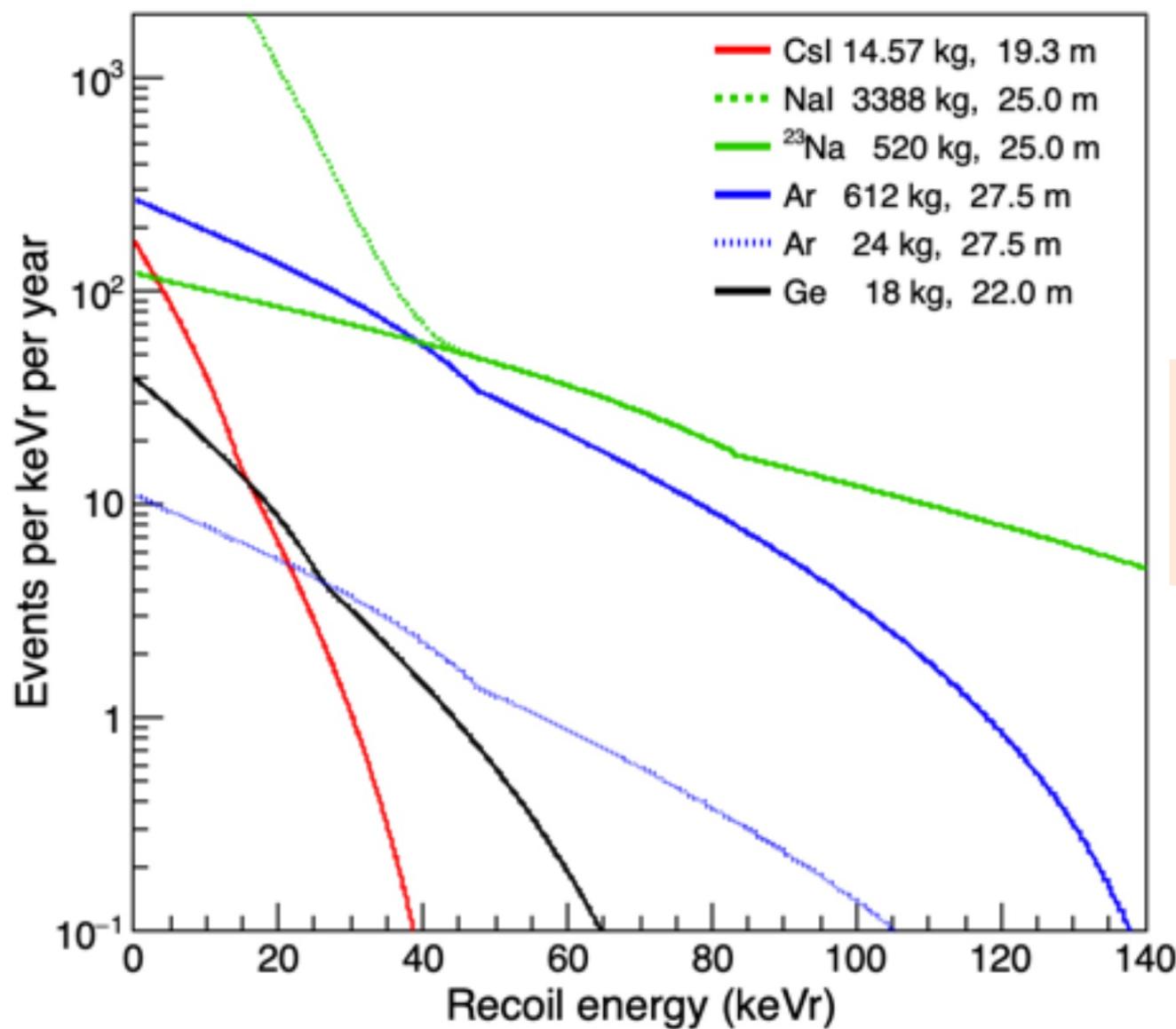
Siting for deployment in SNS basement
(measured neutron backgrounds low,
~ 8 mwe overburden)



View looking
down “Neutrino Alley”



Expected recoil energy distribution



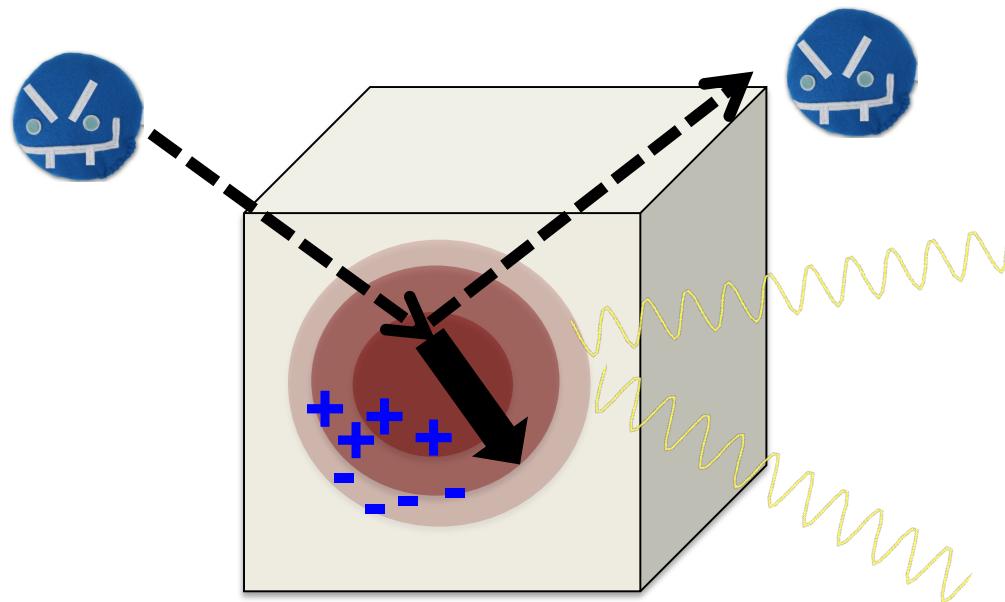
Lighter targets:
less rate per mass,
but kicked to
higher energy

Backgrounds

Usual suspects:

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

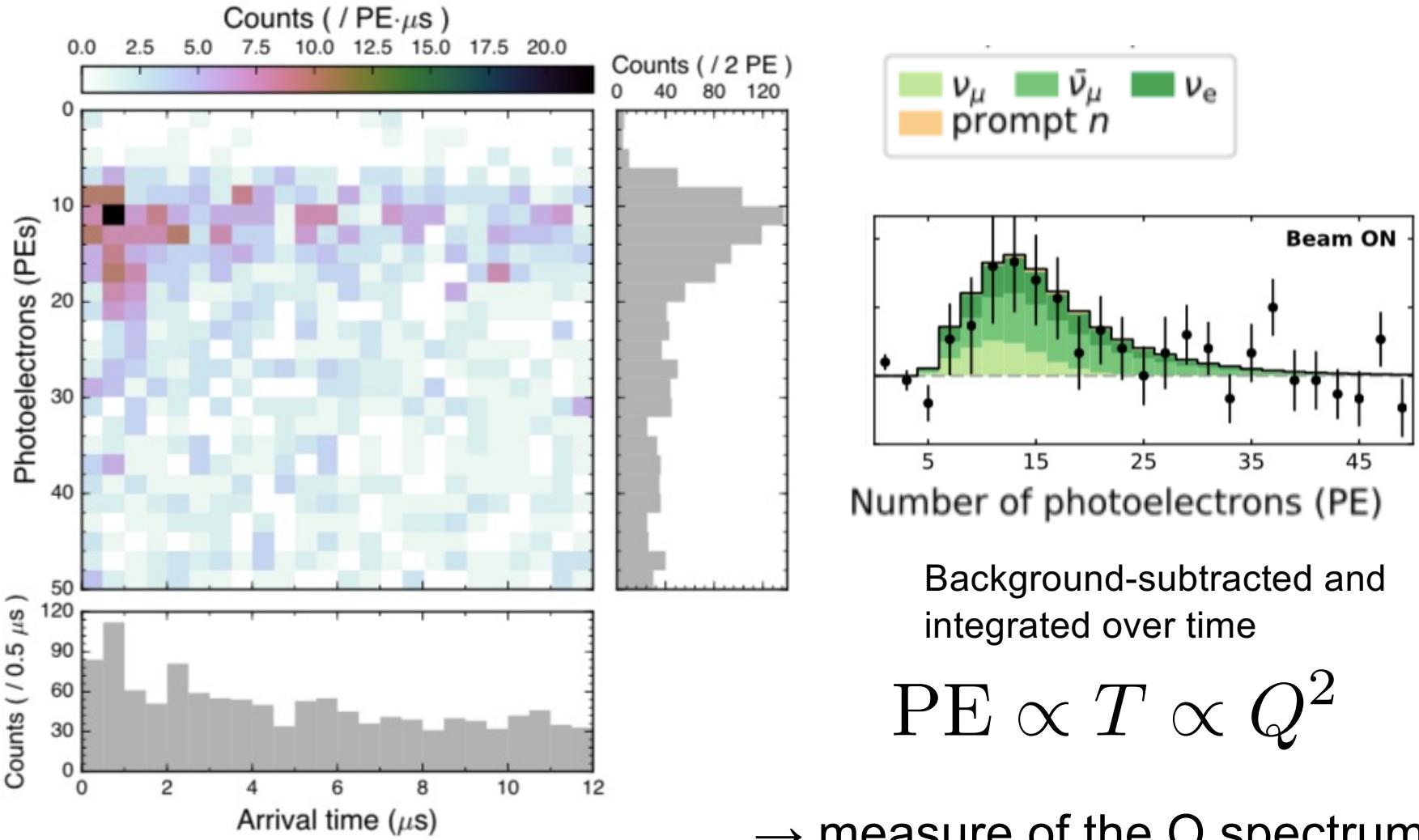
Neutrons are especially not your friends*



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

*Thanks to Robert Cooper for the “mean neutron”

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

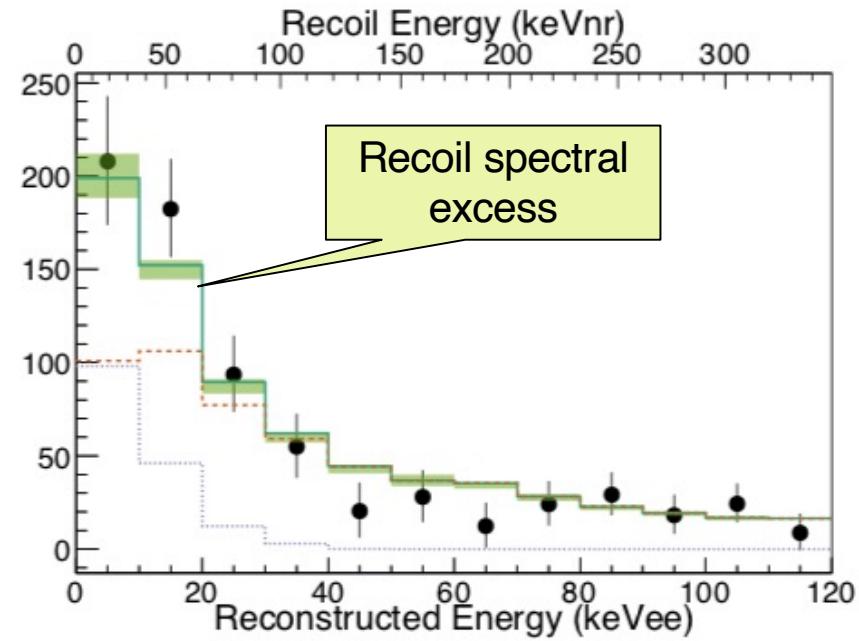
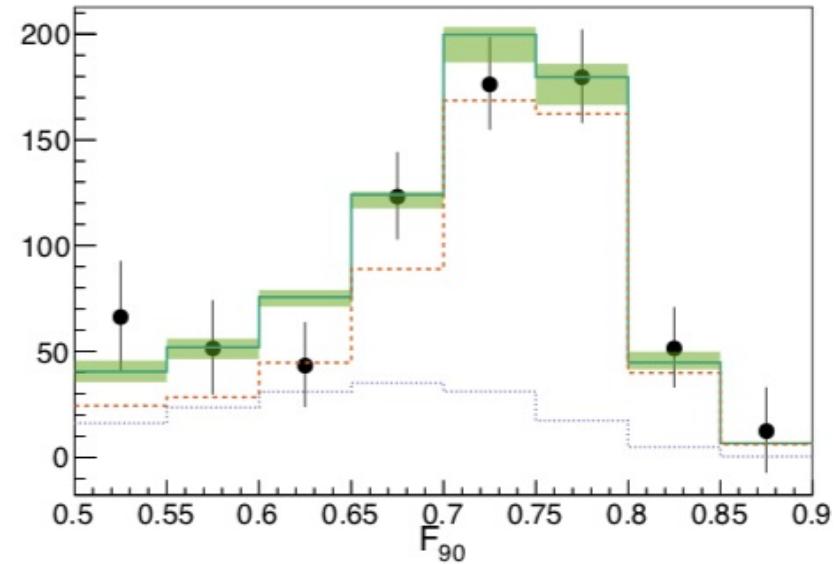
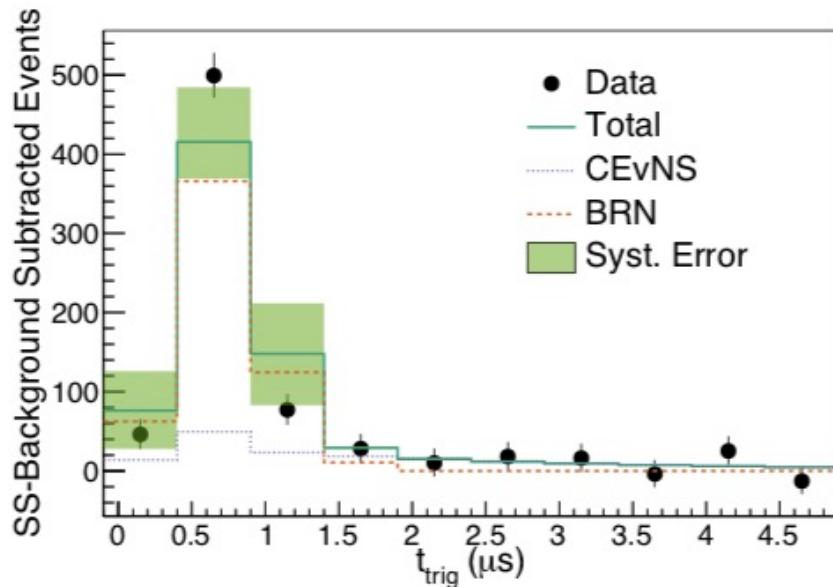


DOI: 10.5281/zenodo.1228631

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

Likelihood fit in time, recoil energy, PSD parameter

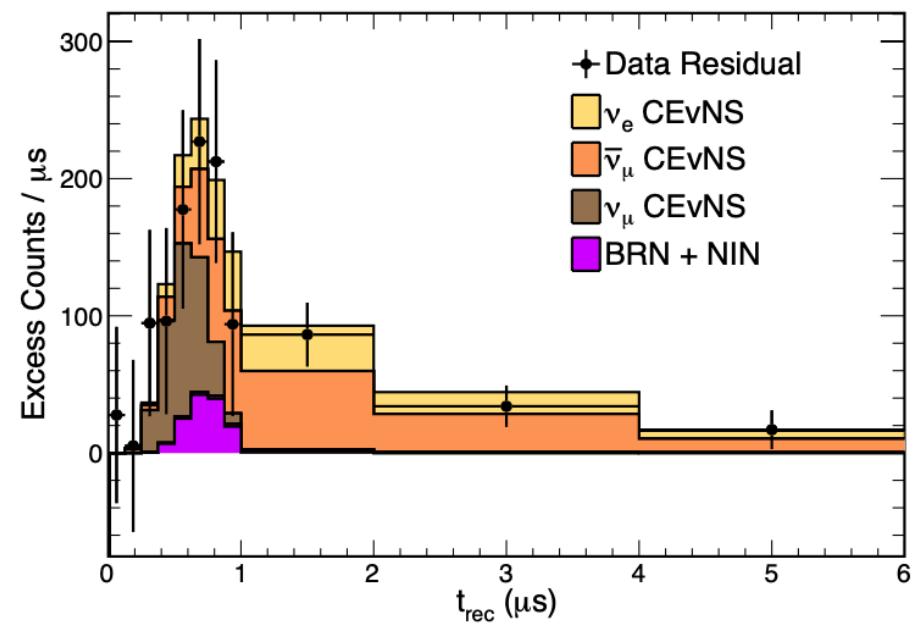
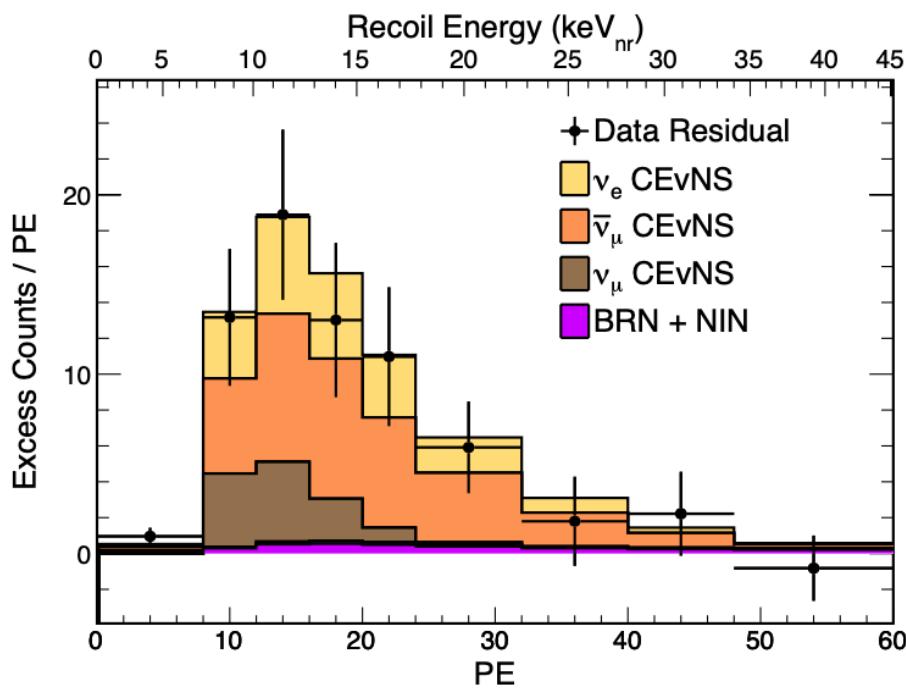
Beam-unrelated-background-subtracted projections of 3D likelihood fit

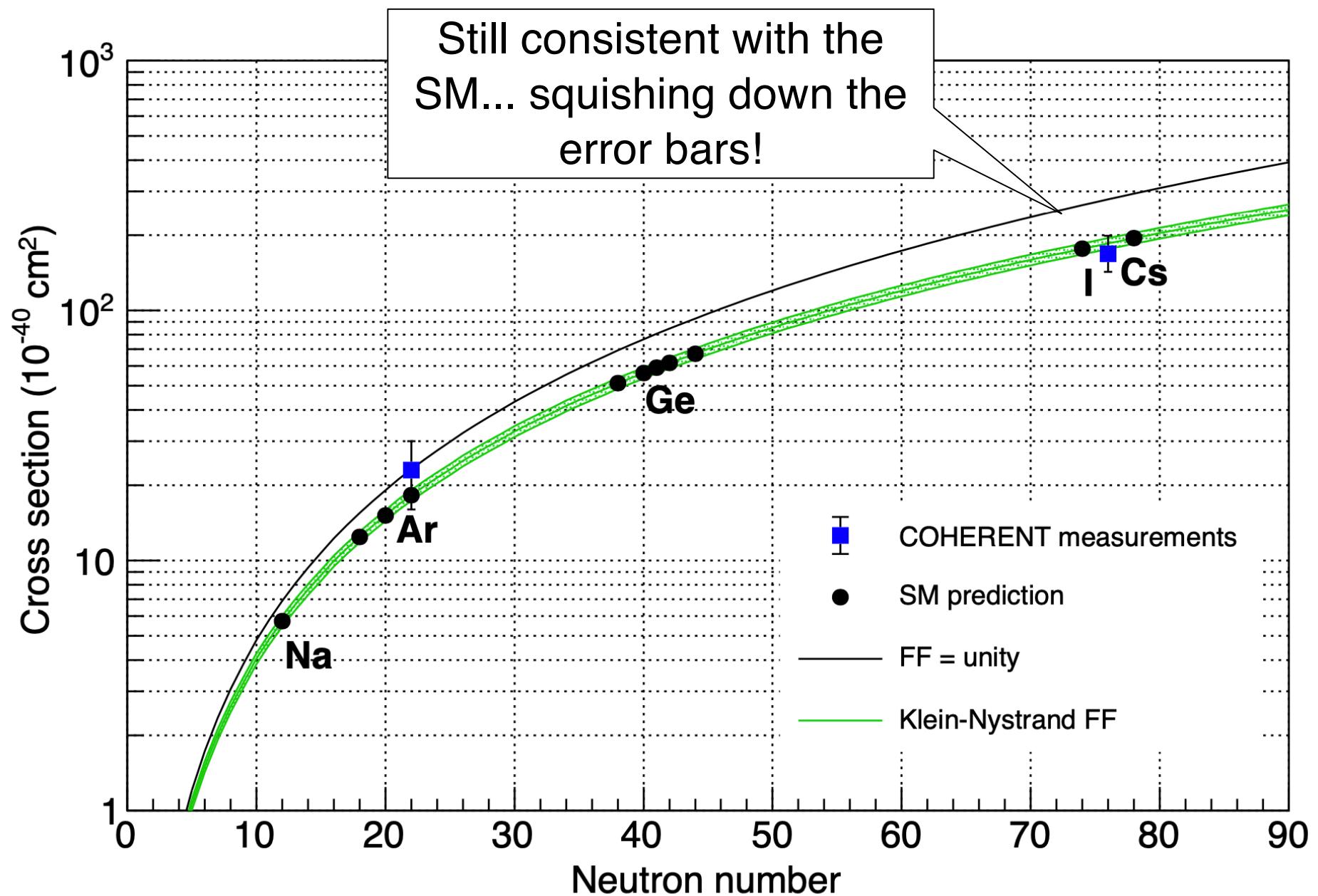


- Bands are systematic errors from 1D excursions
- 2 independent analyses w/separate cuts, similar results
(this is the “A” analysis)



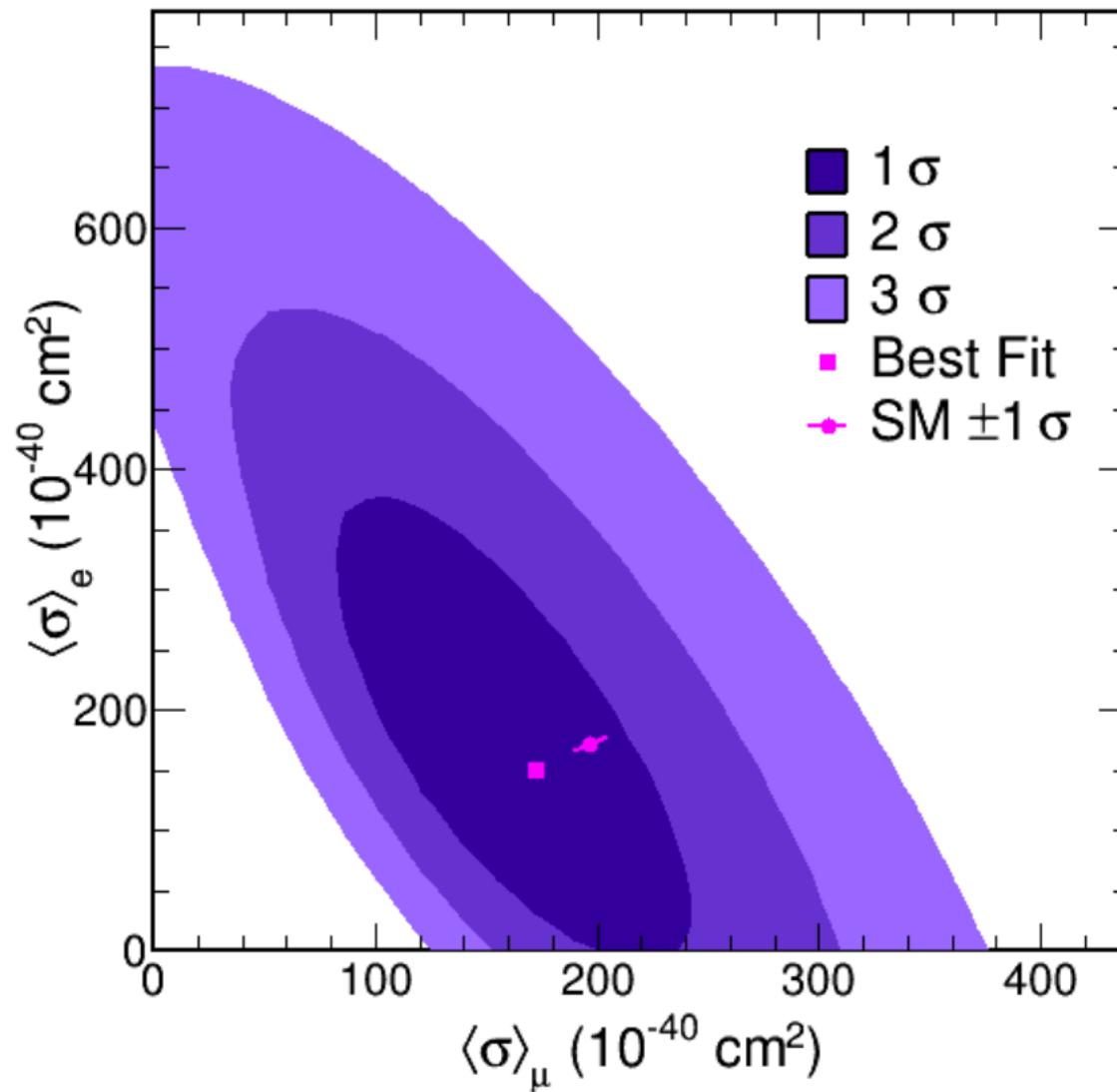
Remaining CsI[Na] dataset,
with $>2 \times$ statistics
+ improved detector response understanding
+ improved analysis



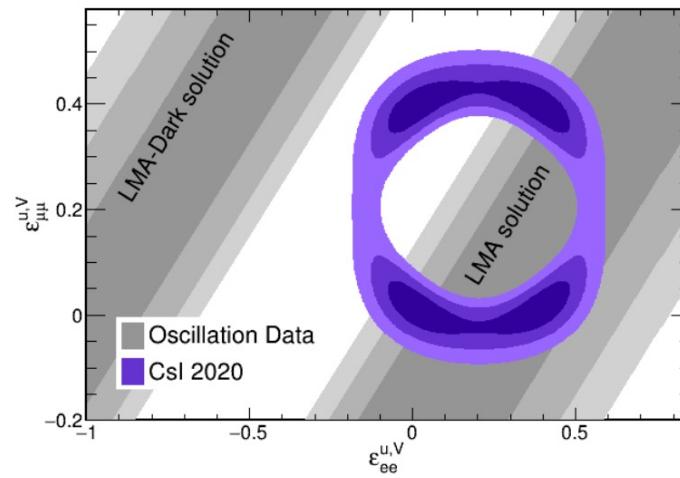
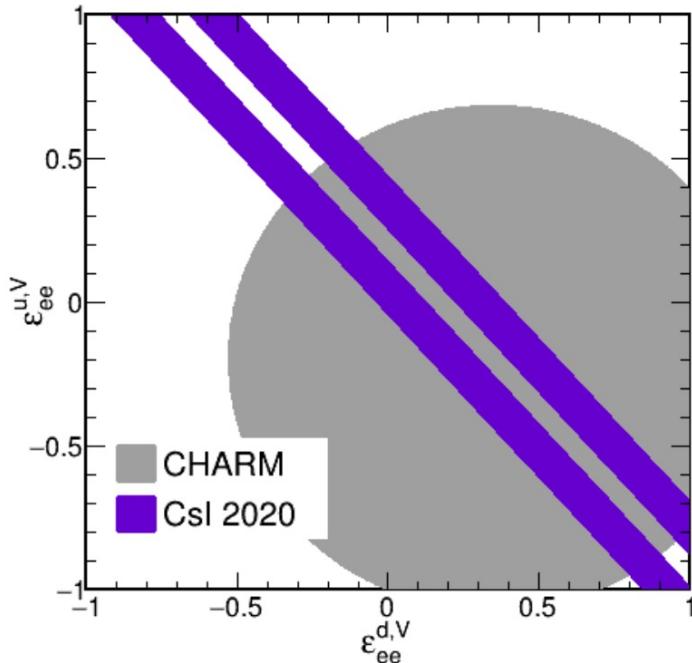
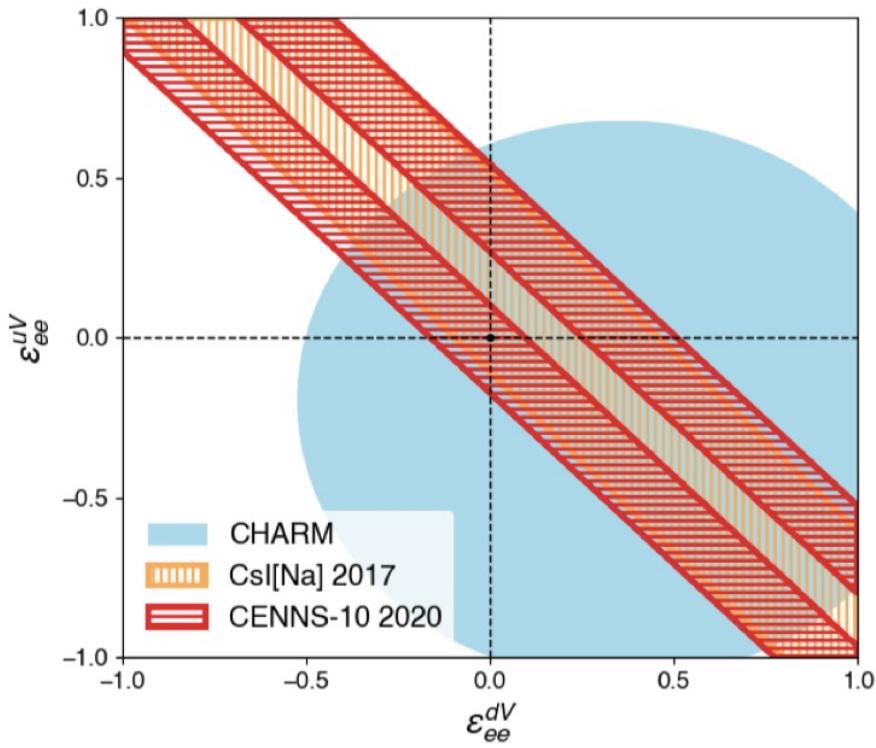


Flavored CEvNS cross sections

Separate electron and muon flavors by timing

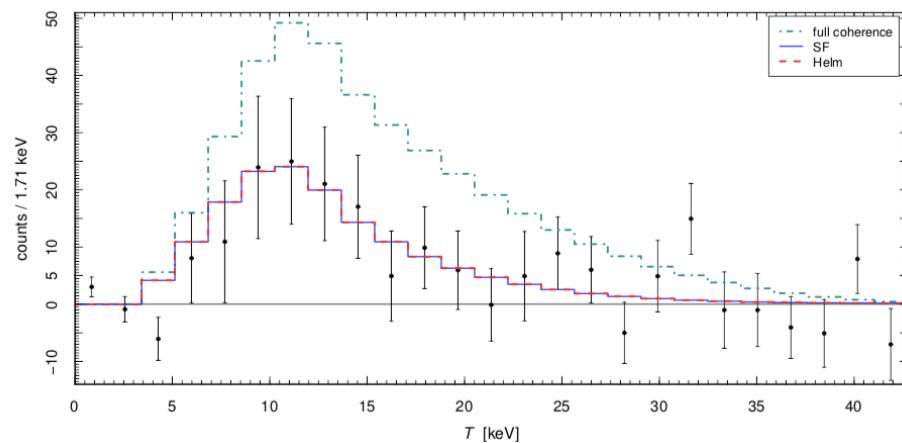


And squeezing down the possibilities for new physics...



What can we learn about form factors?

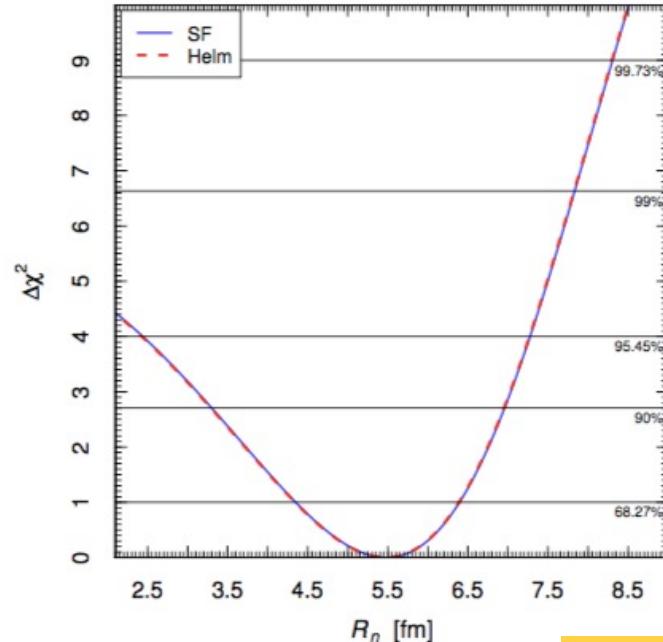
M. Cadeddu, C. Giunti, Y. F. Li, and Y. Y. Zhang. "Average CsI neutron density distribution from COHERENT data." (2017). 1710.02730.



Helm functional form

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

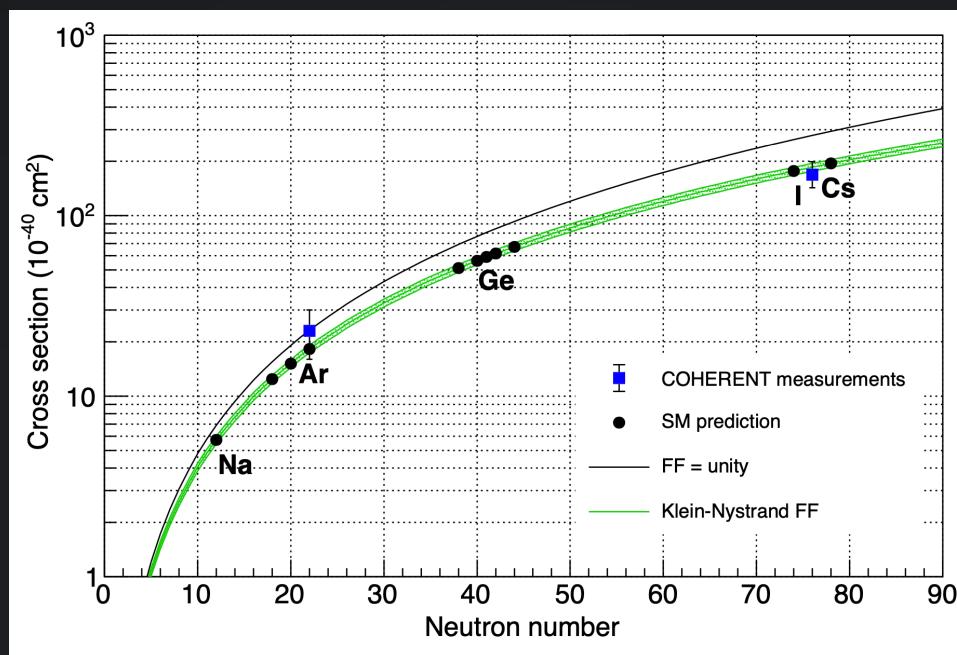
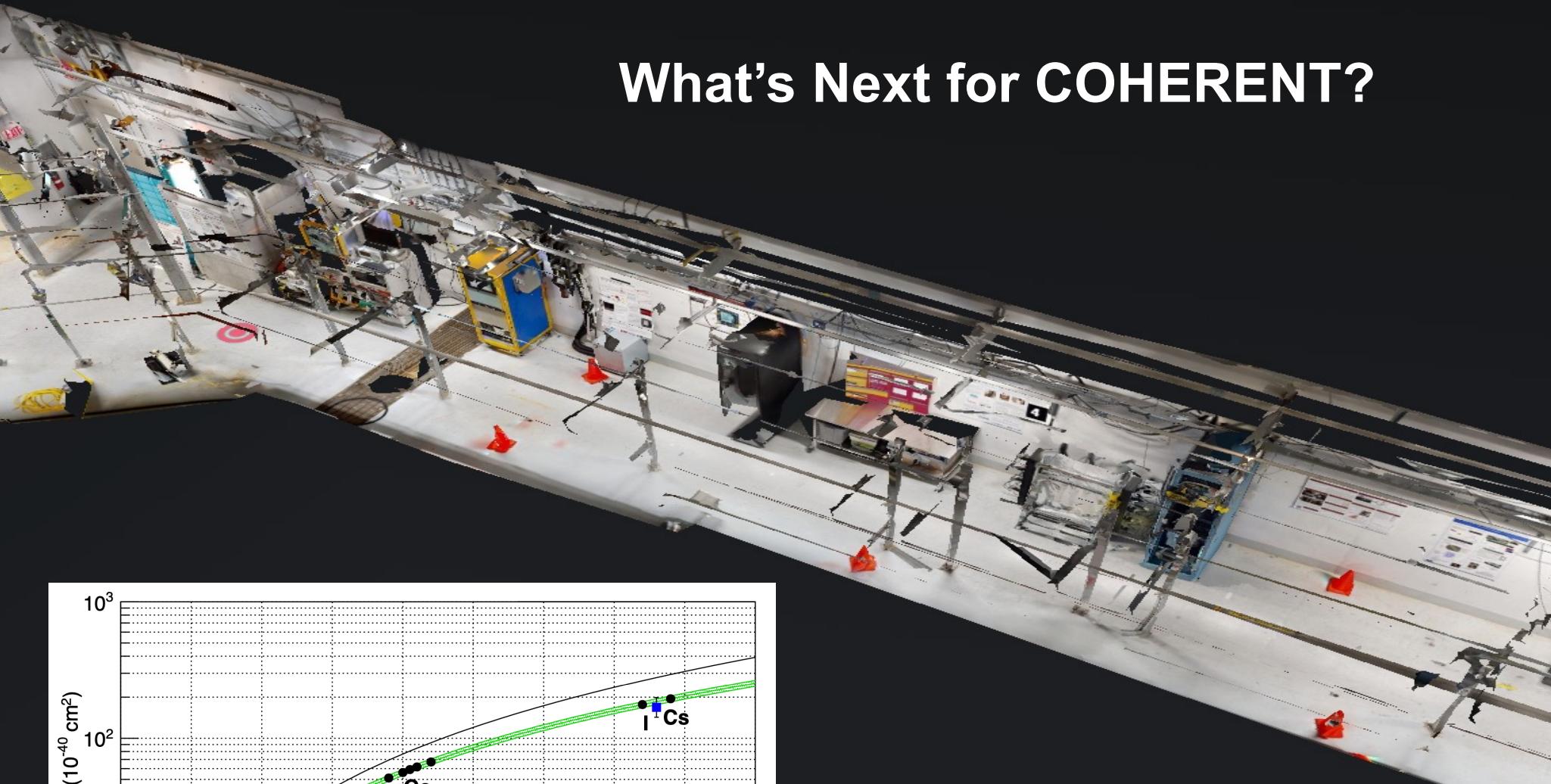
$$R_n = 5.5^{+0.9}_{-1.1} \text{ fm.} \quad \Delta R_{np} \simeq 0.7^{+0.9}_{-1.1} \text{ fm.}$$



Spectral shape systematics are hard!

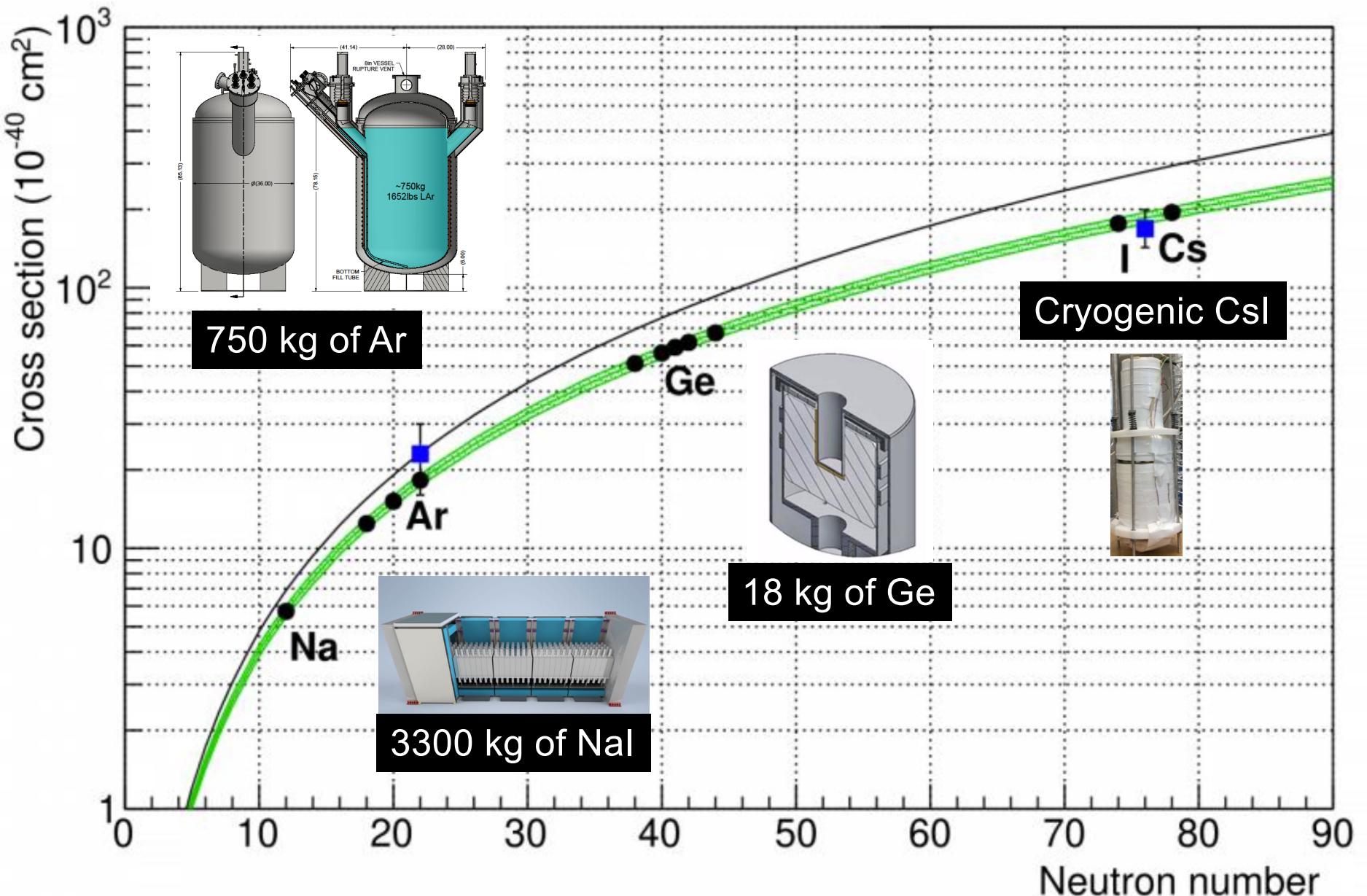
- Fit to neutron radius resulting in ~18% uncertainty, as well as neutron skin measurement
- We now have good quenching factor information w/uncertainties (arXiv:2111.02477)

What's Next for COHERENT?



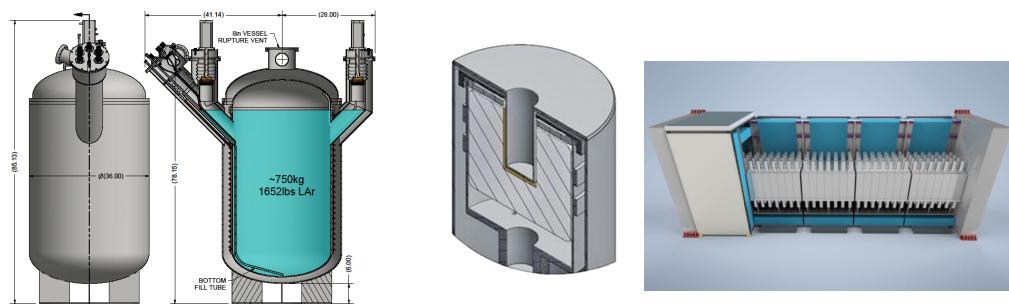
Two down!
But still more
to go!

COHERENT future deployments



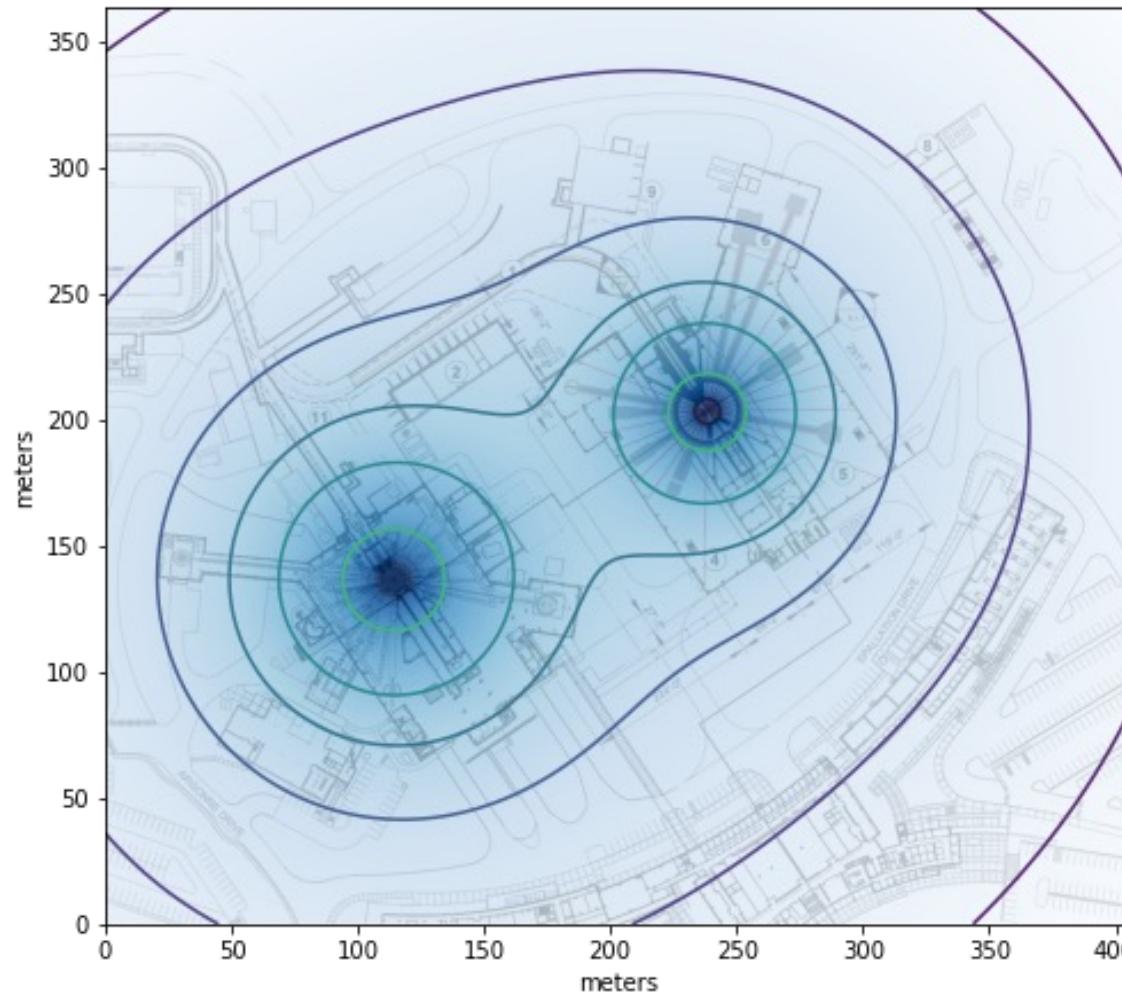
COHERENT CEvNS Detector Status and Farther Future

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



- +D₂O for flux normalization
- + CryoCsI
- + Th for nu-fission
- + LArTPC concepts
- + concepts for more...

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



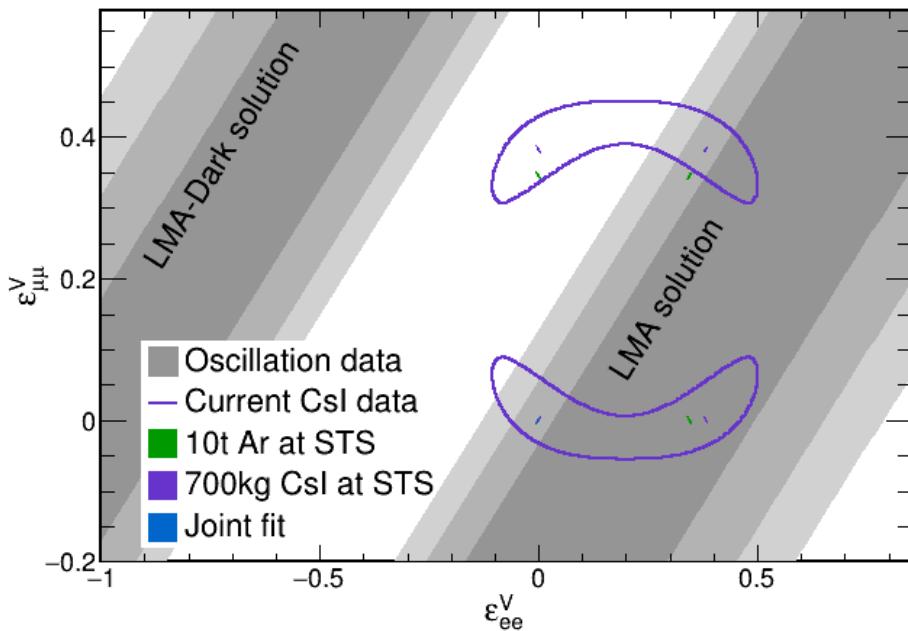
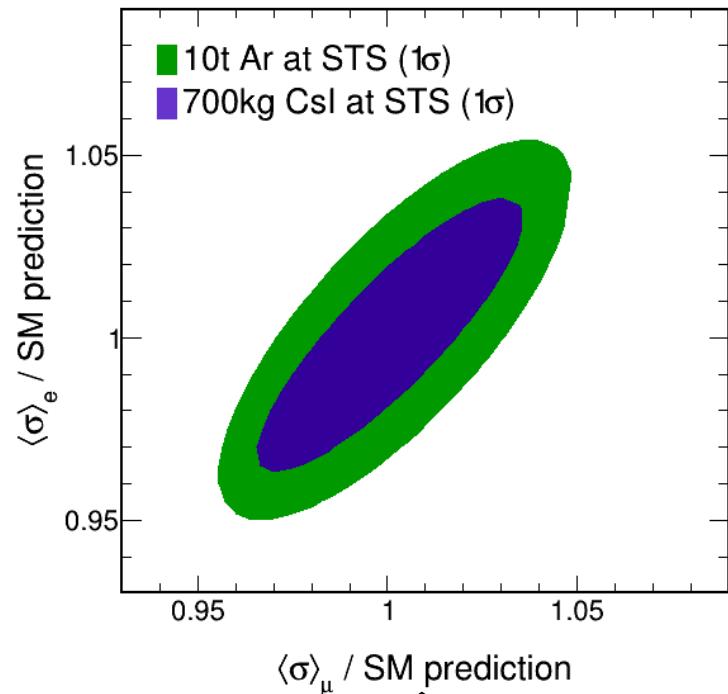
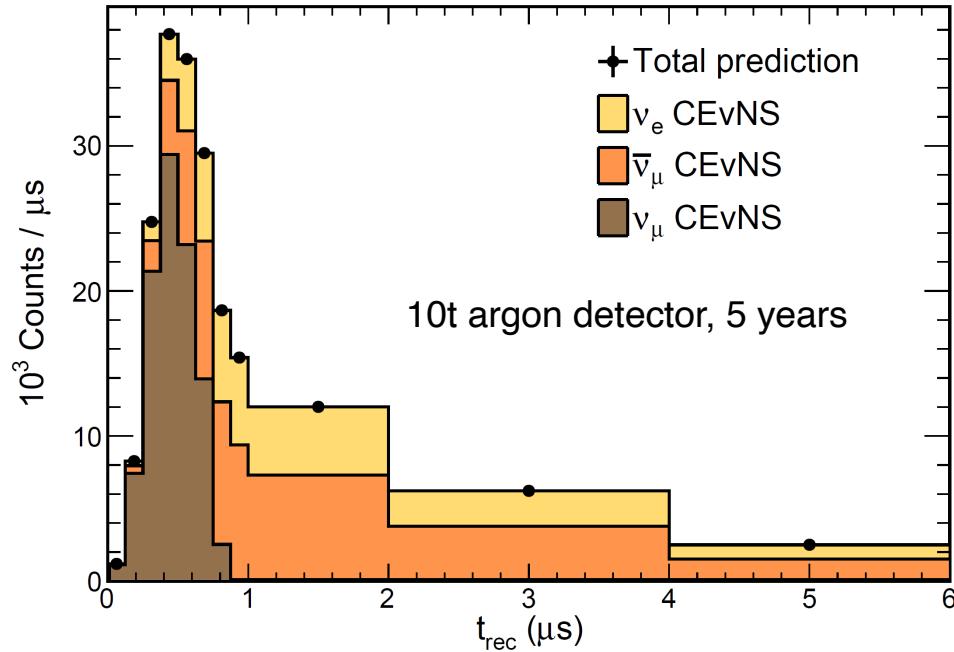
$\frac{3}{4}$ bunches to FTS
 $\frac{1}{4}$ bunches to STS

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



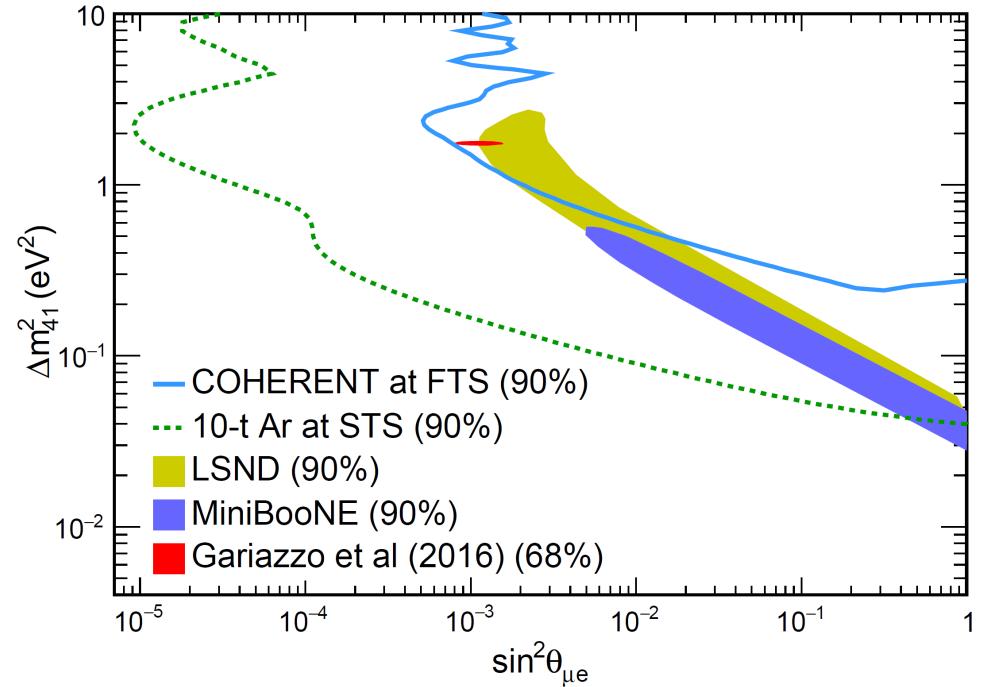
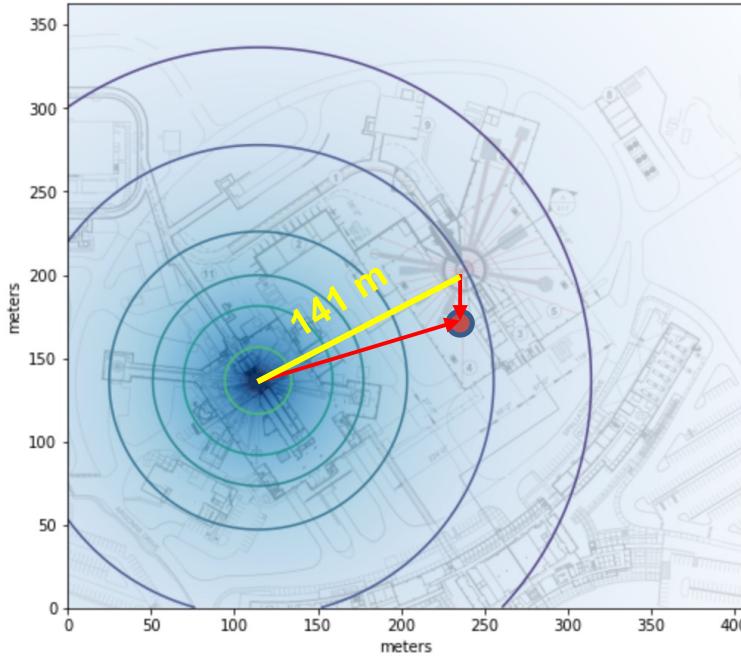
Sensitive to ~few % SM differences
in μ - and e -flavor cross sections,
testing lepton universality of
CEvNS (at tree level)

Stringent NSI parameters
constraints, resolving
oscillation ambiguities

Sterile neutrino sensitivity

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

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



Cancel detector-related systematic uncertainties

w/ different baselines in one CEvNS detector seeing 2 sources

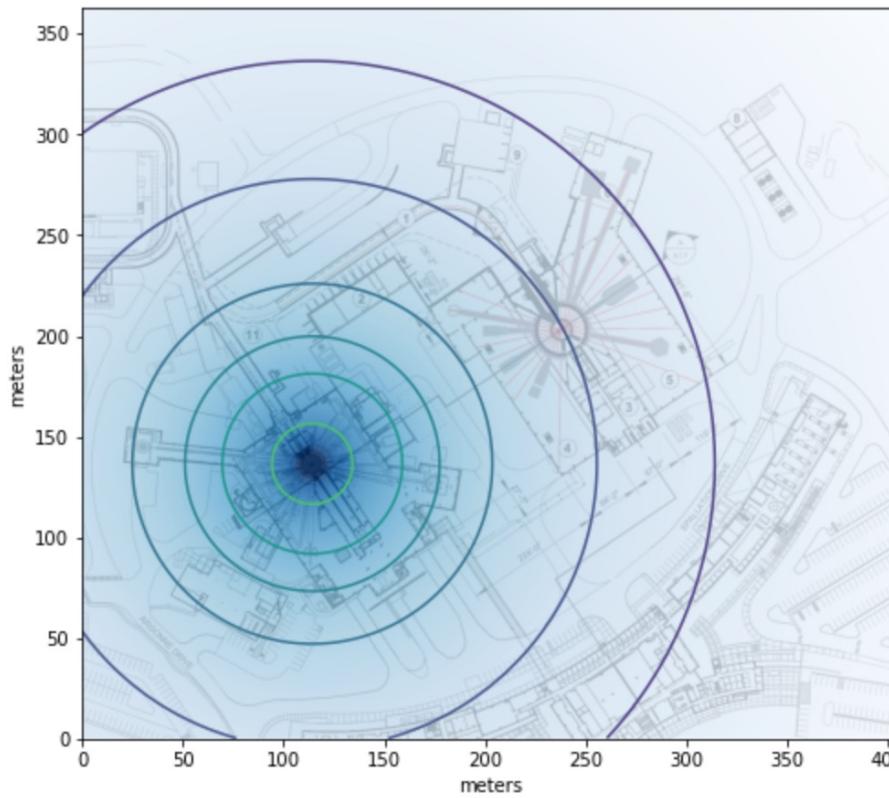
Can also exploit flavor separation by timing

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

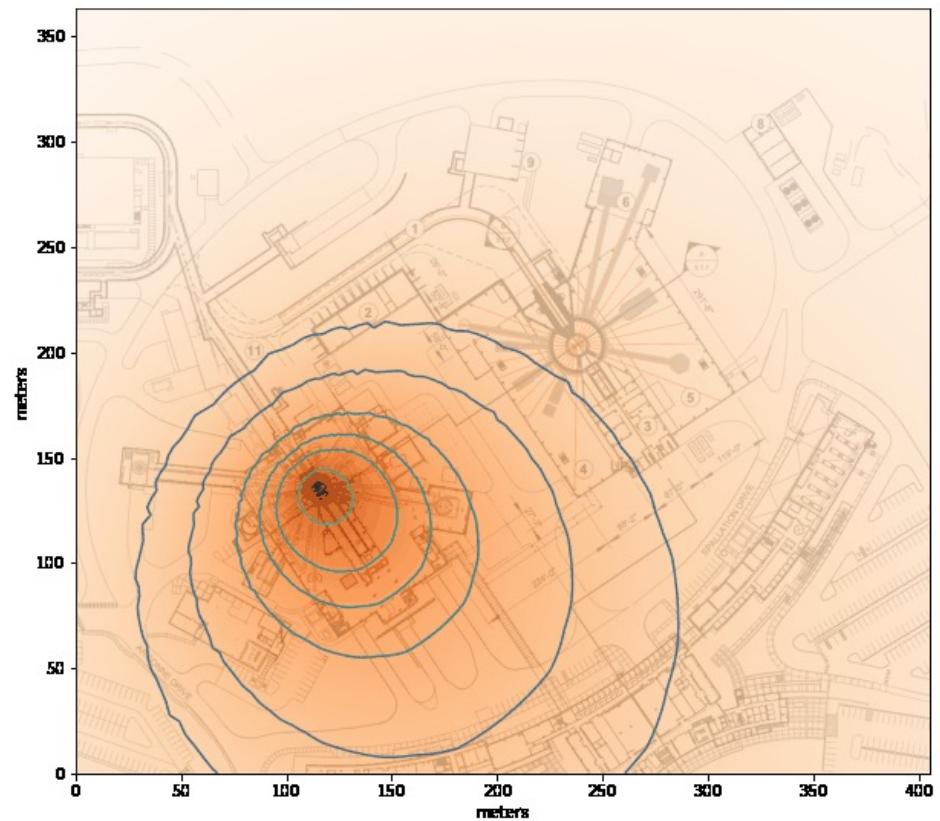
In 5 years, test ~entire parameter space allowed by LSND/MiniBooNE

Directionality of flux at the SNS

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

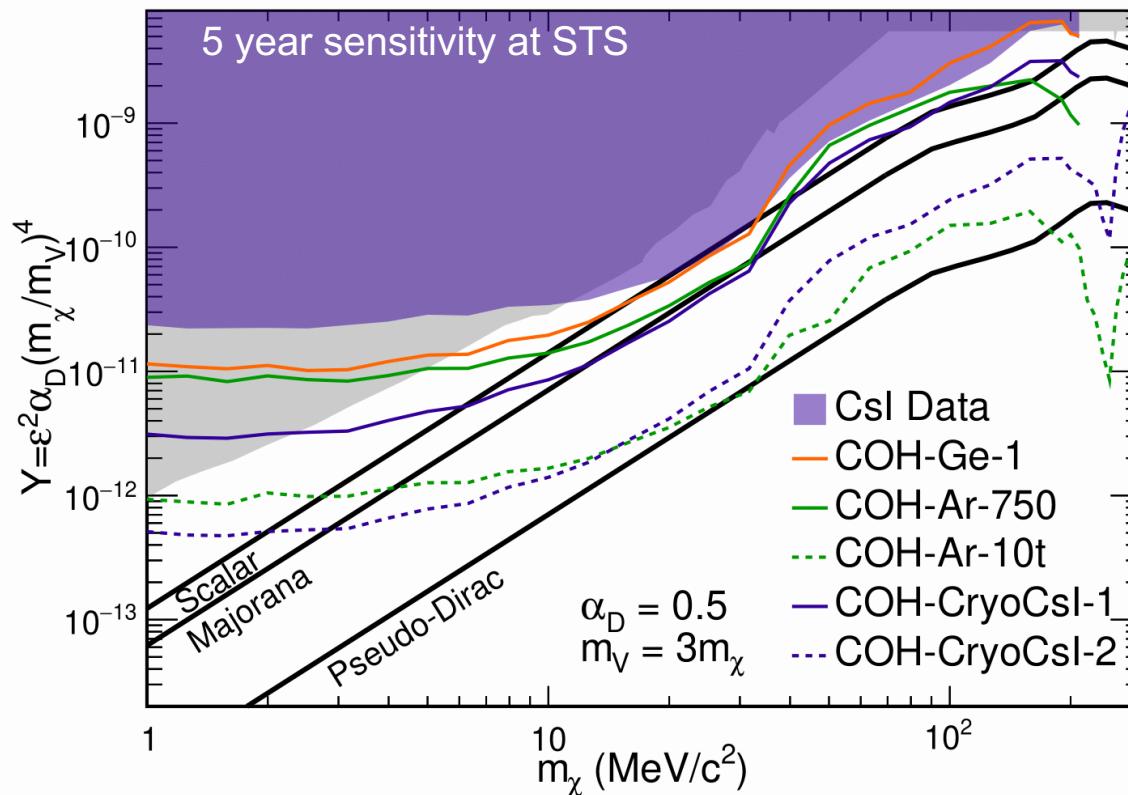


DM flux produced in-flight
is boosted forward



Can test angular dependence of boosted DM flux

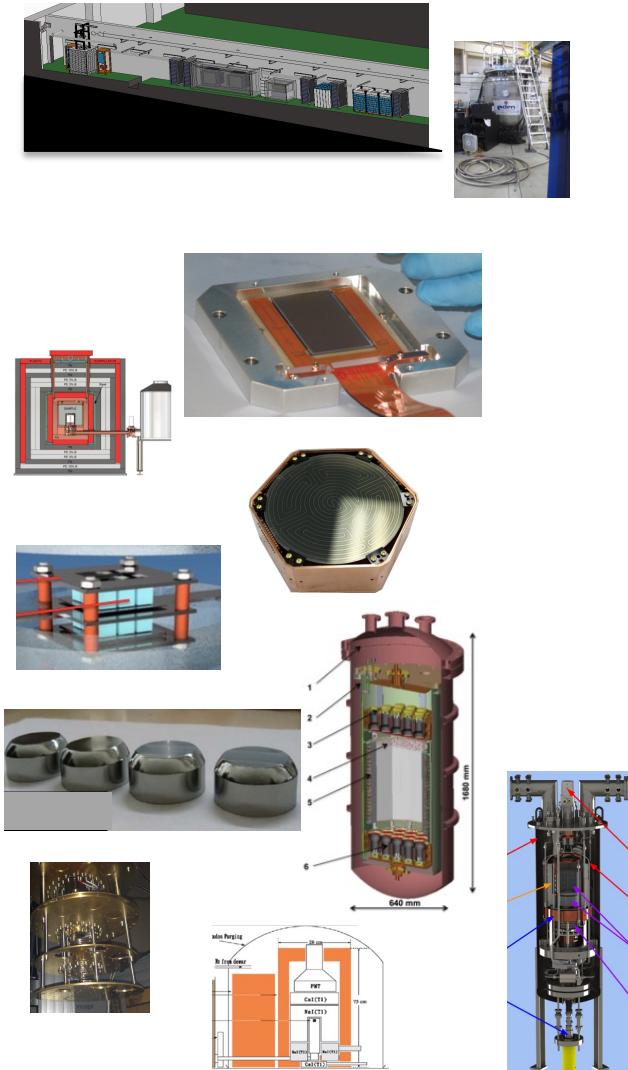
Future COHERENT sensitivity to dark matter



- **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]

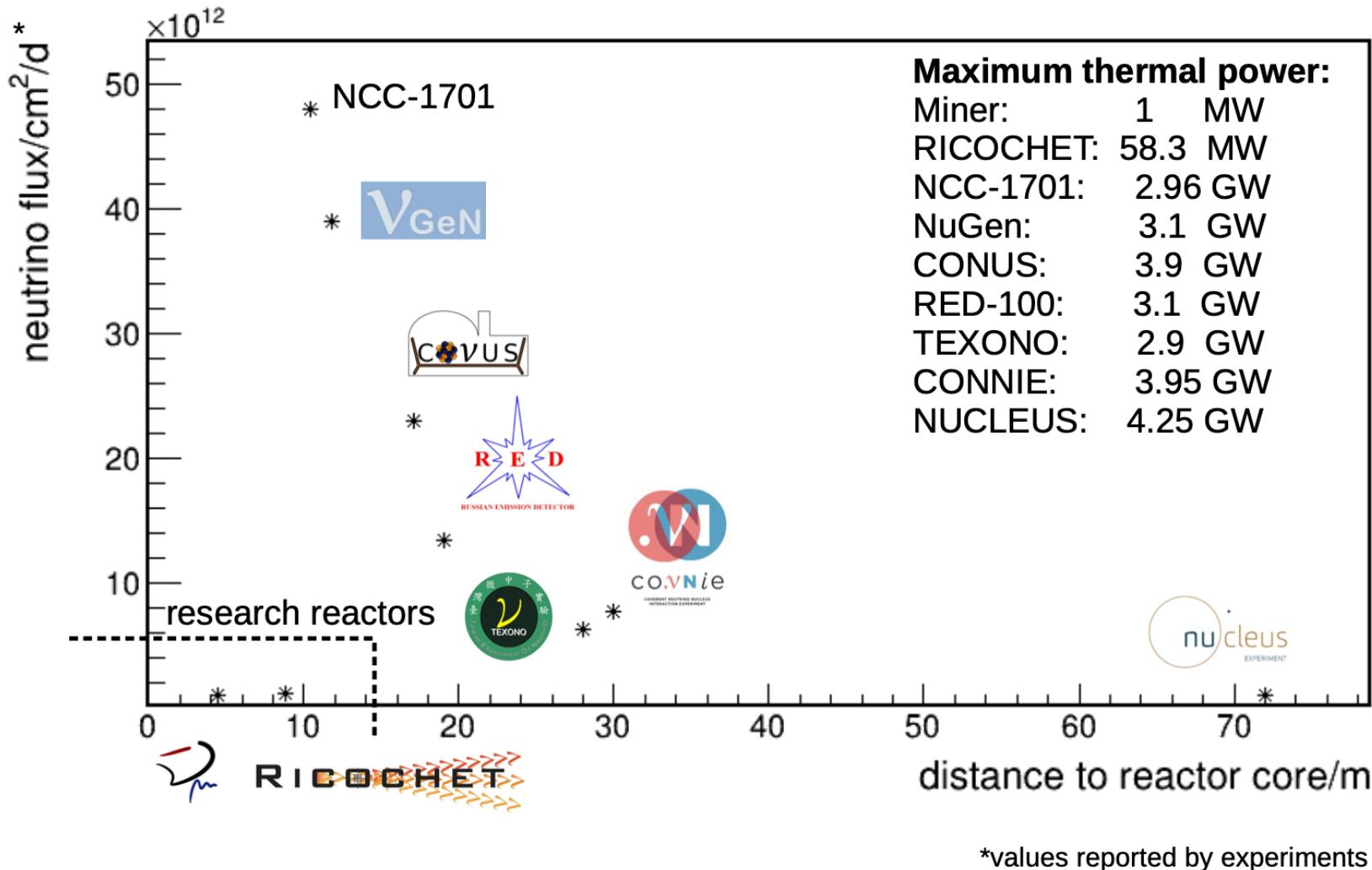
Experiment	Technology	Location	Source
COHERENT	Csl, Ar, Ge, NaI	USA	π DAR
CCM	Ar	USA	π DAR
ESS	Csl, Si, Ge, Xe	Sweden	π DAR
CONNIE	Si CCDs	Brazil	Reactor
CONUS	HPGe	Germany	Reactor
MINER	Ge/Si cryogenic	USA	Reactor
NUCLEUS	Cryogenic CaWO ₄ , Al ₂ O ₃ calorimeter array	Europe	Reactor
vGEN	Ge PPC	Russia	Reactor
RED-100	LXe dual phase	Russia	Reactor
Ricochet	Ge, Zn bolometers	France	Reactor
SBC	Xe, Ar	USA?	Reactor
TEXONO	p-PCGe	Taiwan	Reactor



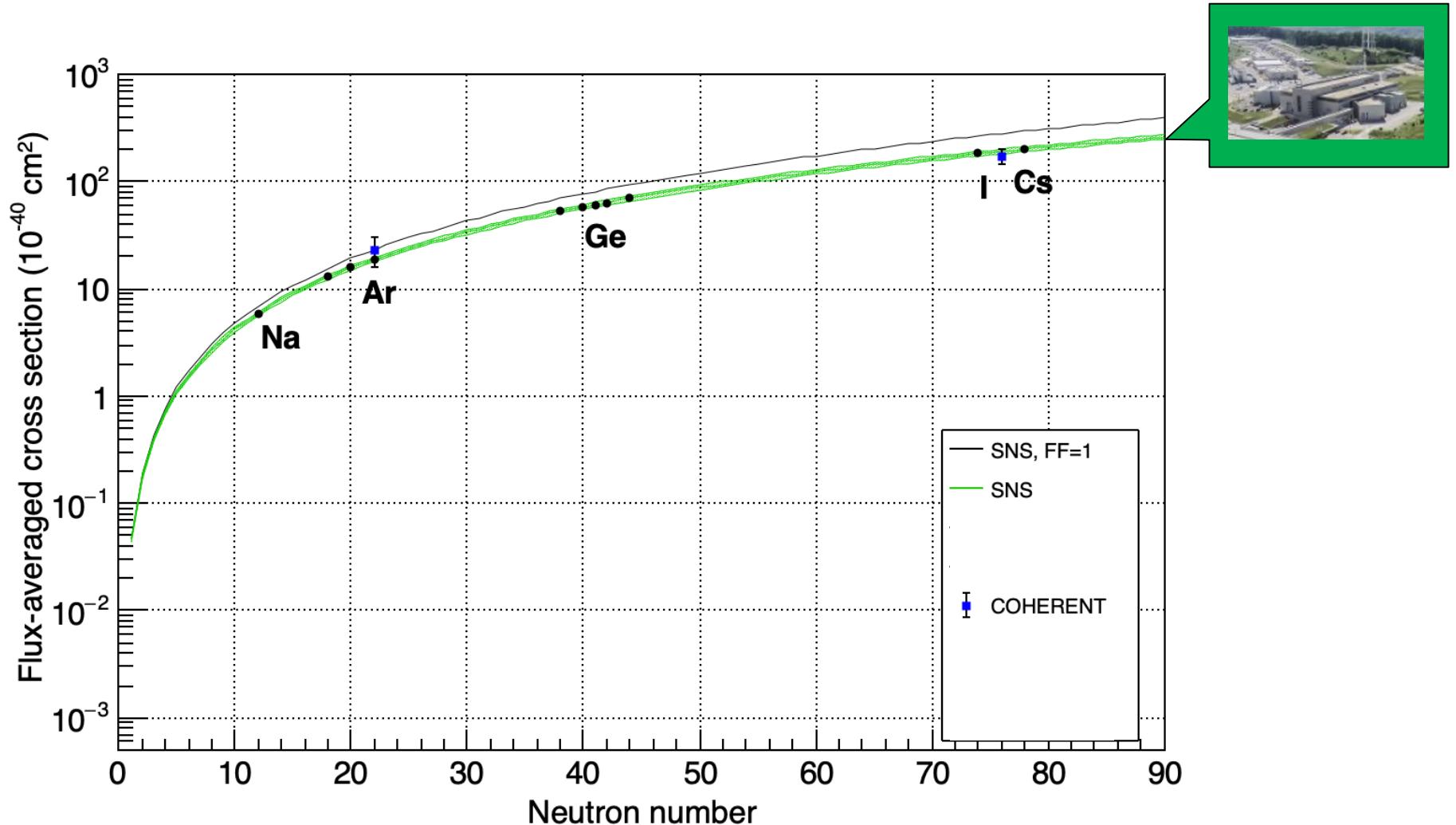
+ DM detectors, +directional detectors +more...

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

CEvNS detection at reactor

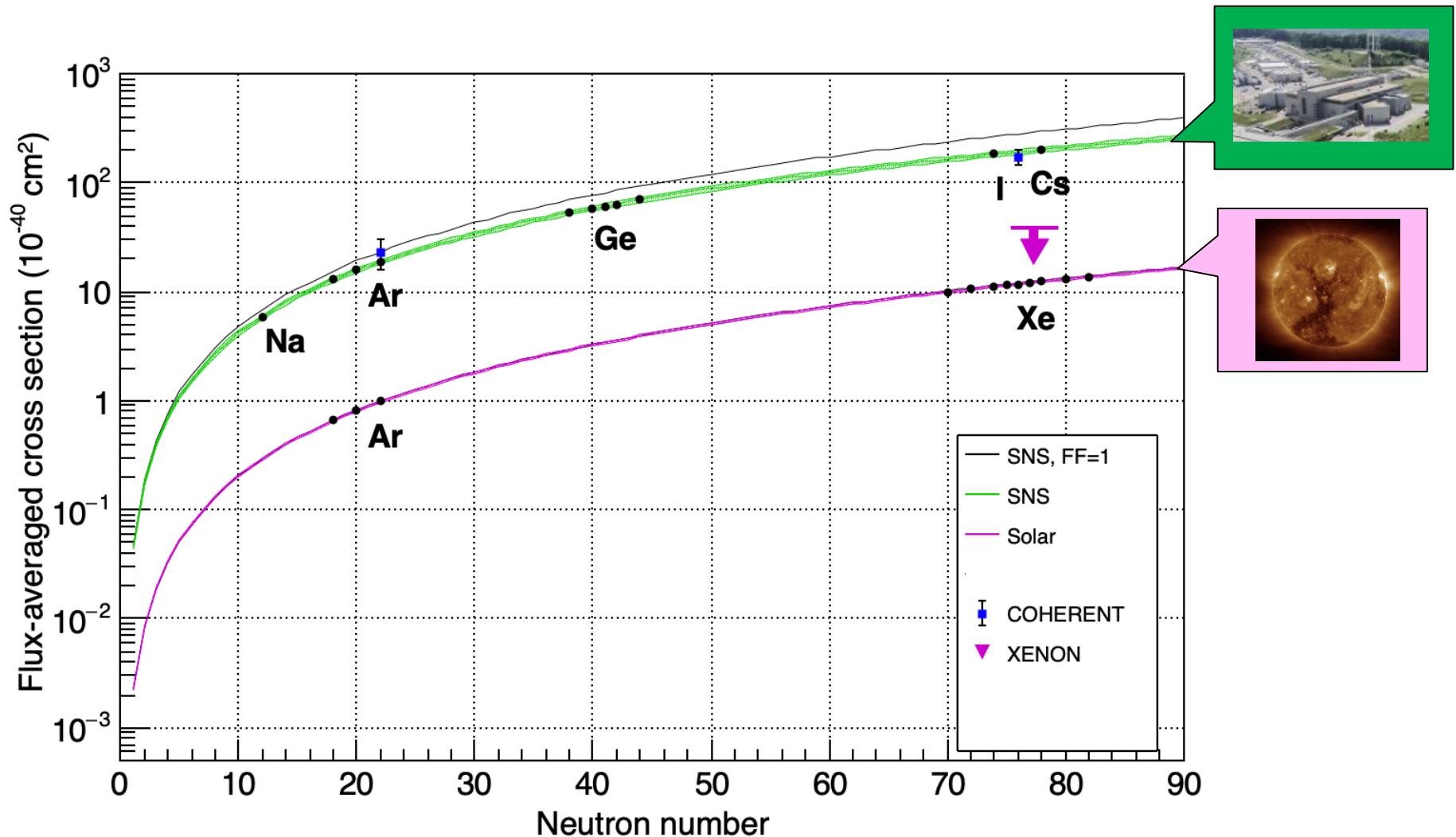


Summary of CEvNS Results



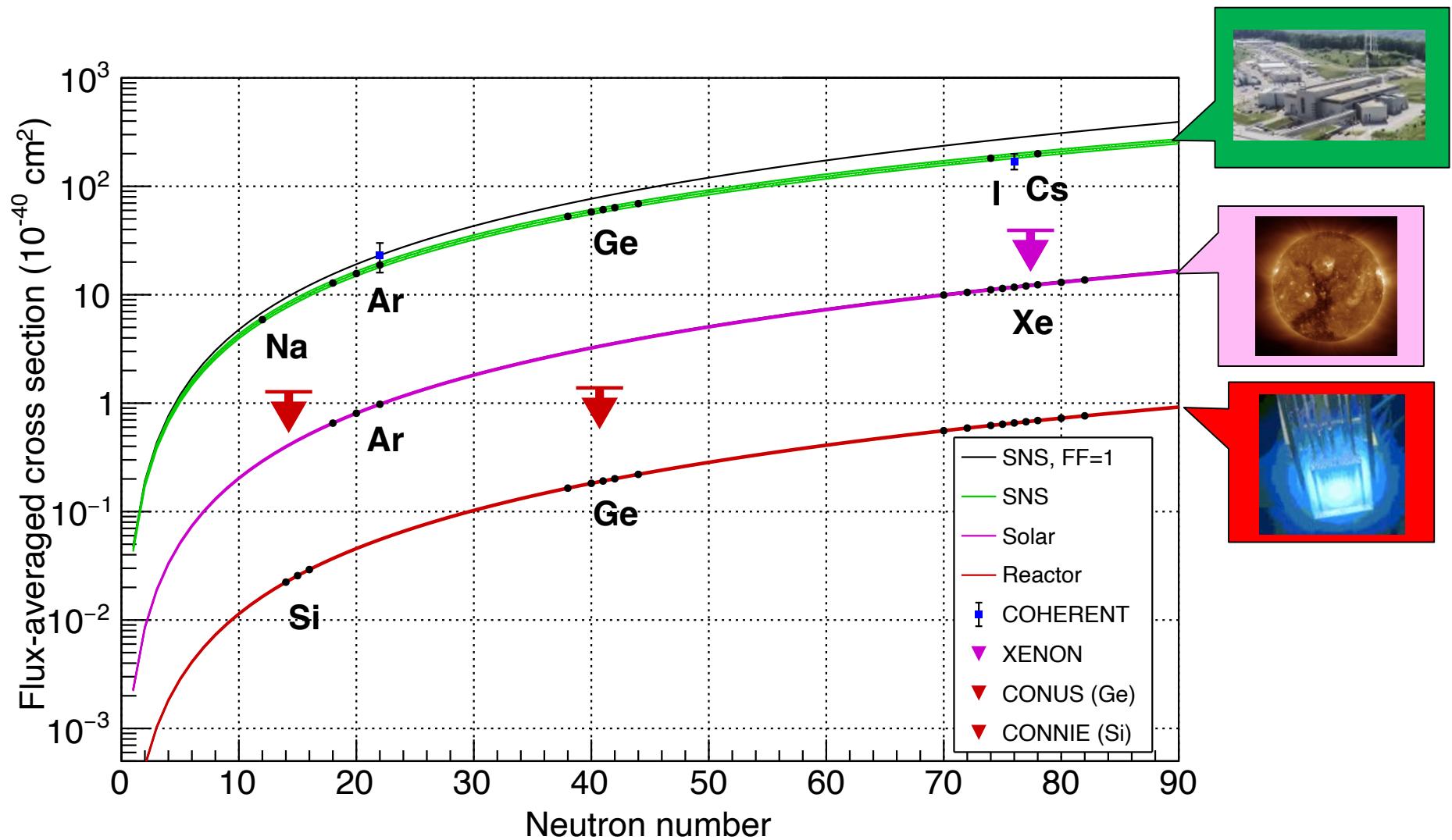
So far: measurements in CsI, Ar from COHERENT

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!
 - $F \sim 1$, 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

Summary

- **CEvNS:**
 - large cross section, but tiny recoils, $\propto N^2$
 - 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...)