# Low-Energy Neutrino-Nucleus Interactions


Kate Scholberg,

Duke University

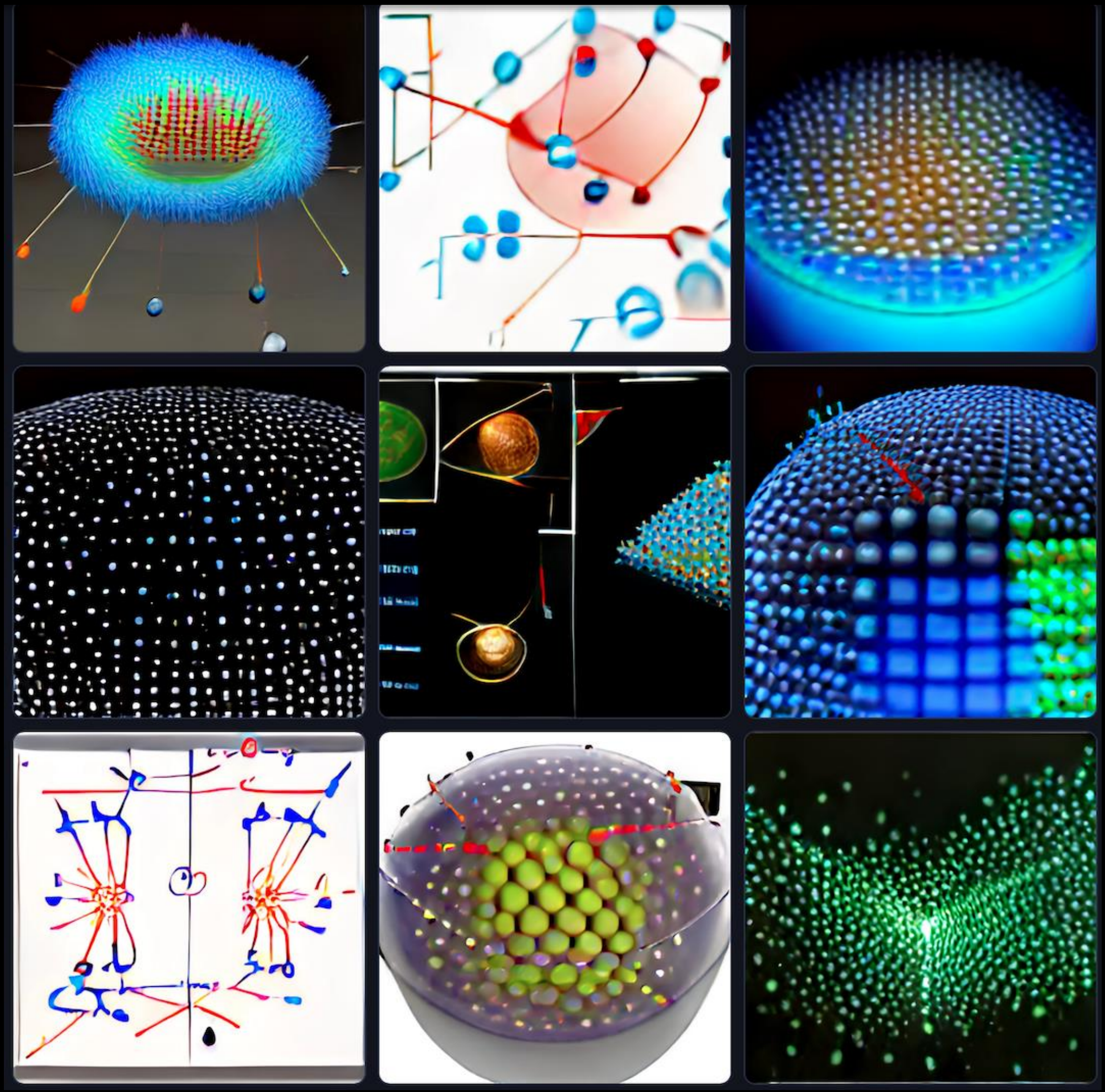

Low Energy Electron

Positron Physics at

Jefferson Lab

LEEPP 2026

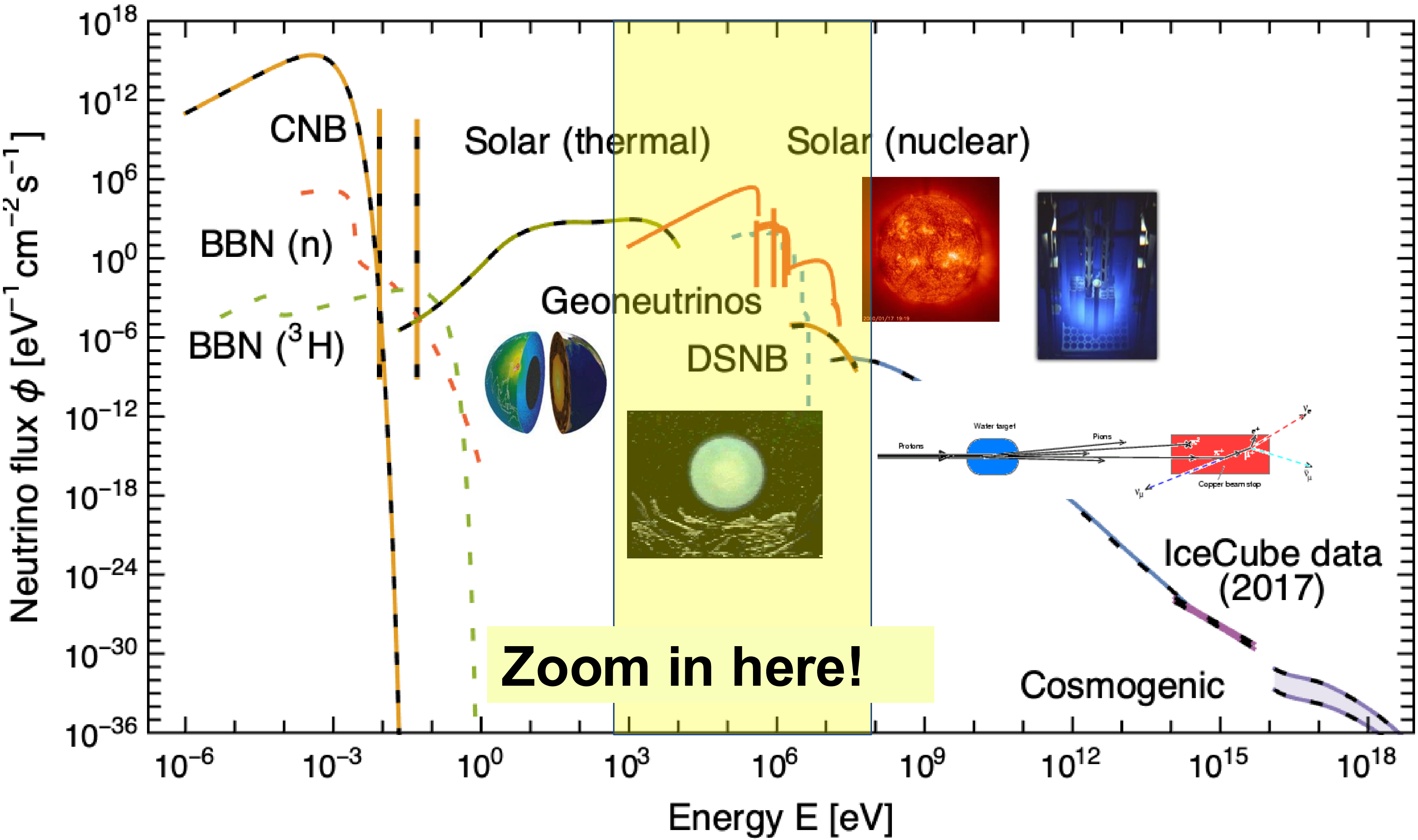
March 26, 2026



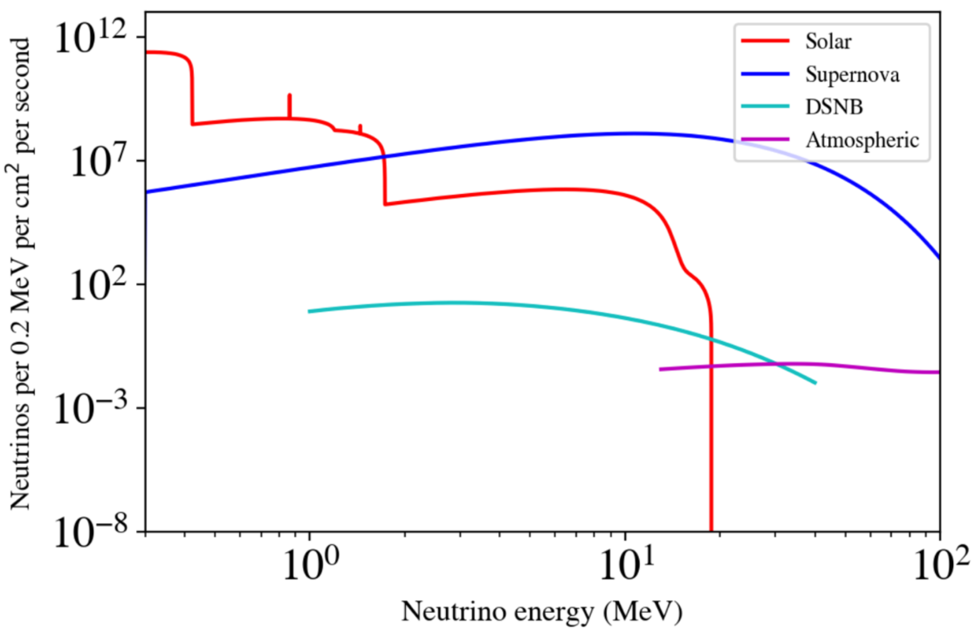
craiyon.ai's concept of this talk title

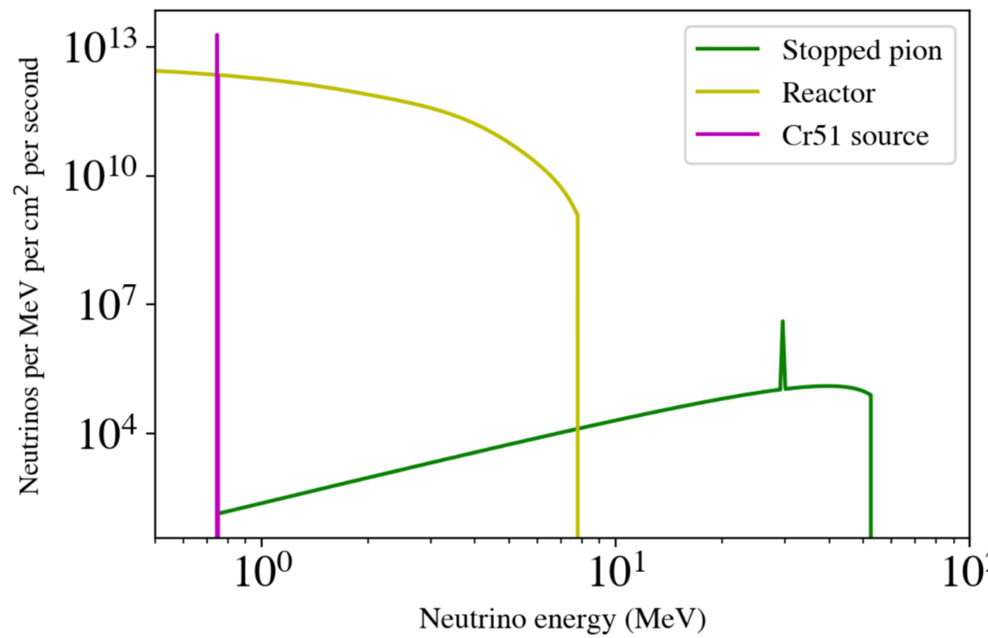
# What does "low energy" mean?

Here, few to few tens of MeV



# Zooming in on source fluxes in this regime



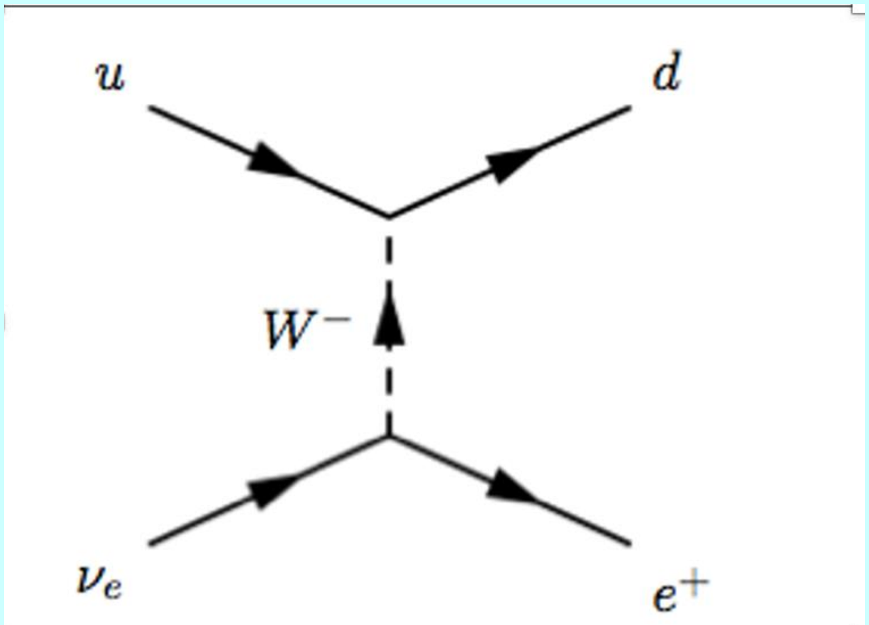




Physics motivations for both wild & tame ν's:

- 3-flavor parameters
- BSM
- astrophysics & cosmology
- nuclear physics

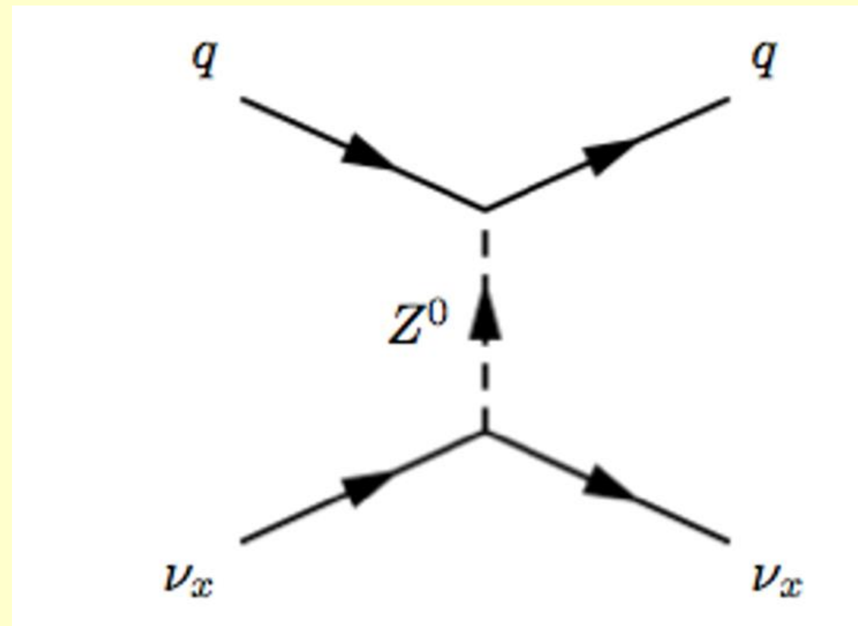
# Neutrino Interactions with matter in the SM

## Charged Current (CC)



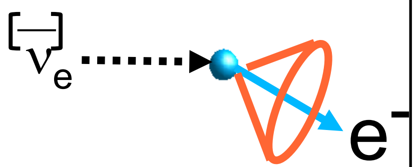
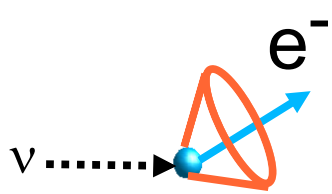

Cares about ν flavor
→ lepton in final state
has same flavor as ν
(must be kinematically allowed)

## Neutral Current (NC)

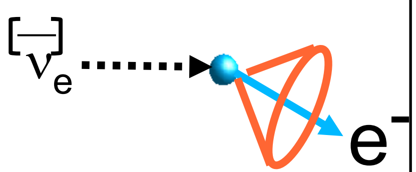
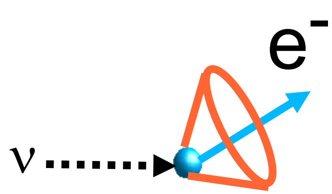
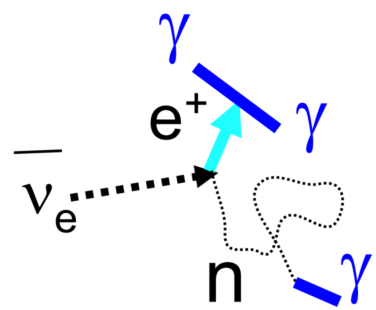
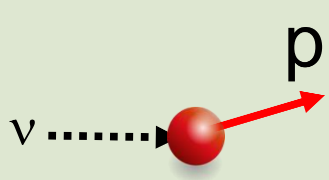



flavor-blind

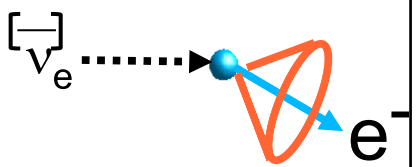
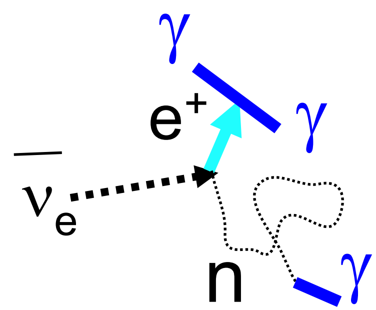
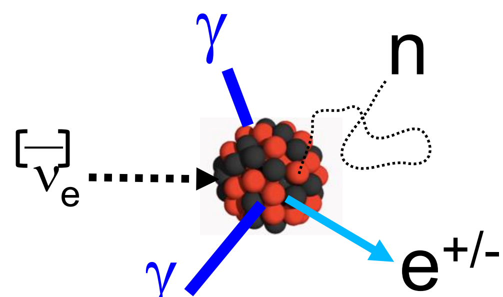
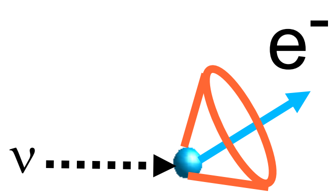
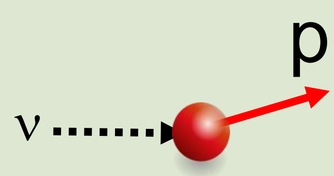
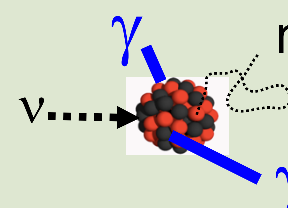
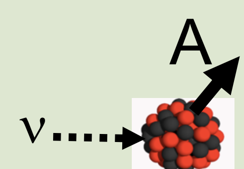
# Low-energy neutrino interactions

| | Electrons | | |
|---|---|---|---|
| **Charged current** | Elastic scattering<br>$\nu + e^- \to \nu + e^-$<br><br> | | |
| **Neutral current** | <br><br>Useful for pointing | | |

# Low-energy neutrino interactions

<table>
<tr><th></th><th>Electrons</th><th>Protons</th><th></th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering<br>$\nu + e^- \rightarrow \nu + e^-$<br>
<br>
<br>Useful for pointing</td><td>Inverse beta decay<br>$\bar{\nu}_e + p \rightarrow e^+ + n$<br>
</td><td></td></tr>
<tr><td>Neutral current</td><td>Elastic scattering<br>
<br>very low energy recoils</td><td></td></tr>
</table>

# Low-energy neutrino interactions

| | Electrons | Protons | Nuclei |
|---|---|---|---|
| **Charged current** | Elastic scattering<br>$\nu + e^- \rightarrow \nu + e^-$<br> | Inverse beta decay<br>$\bar{\nu}_e + p \rightarrow e^+ + n$<br> | $\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$<br>$\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$<br><br>Various possible ejecta and deexcitation products |
| **Neutral current** | <br>Useful for pointing | Elastic scattering<br><br>very low energy recoils | $\nu + A \rightarrow \nu + A^*$<br><br><br>$\nu + A \rightarrow \nu + A$<br>Coherent elastic (CEvNS) |

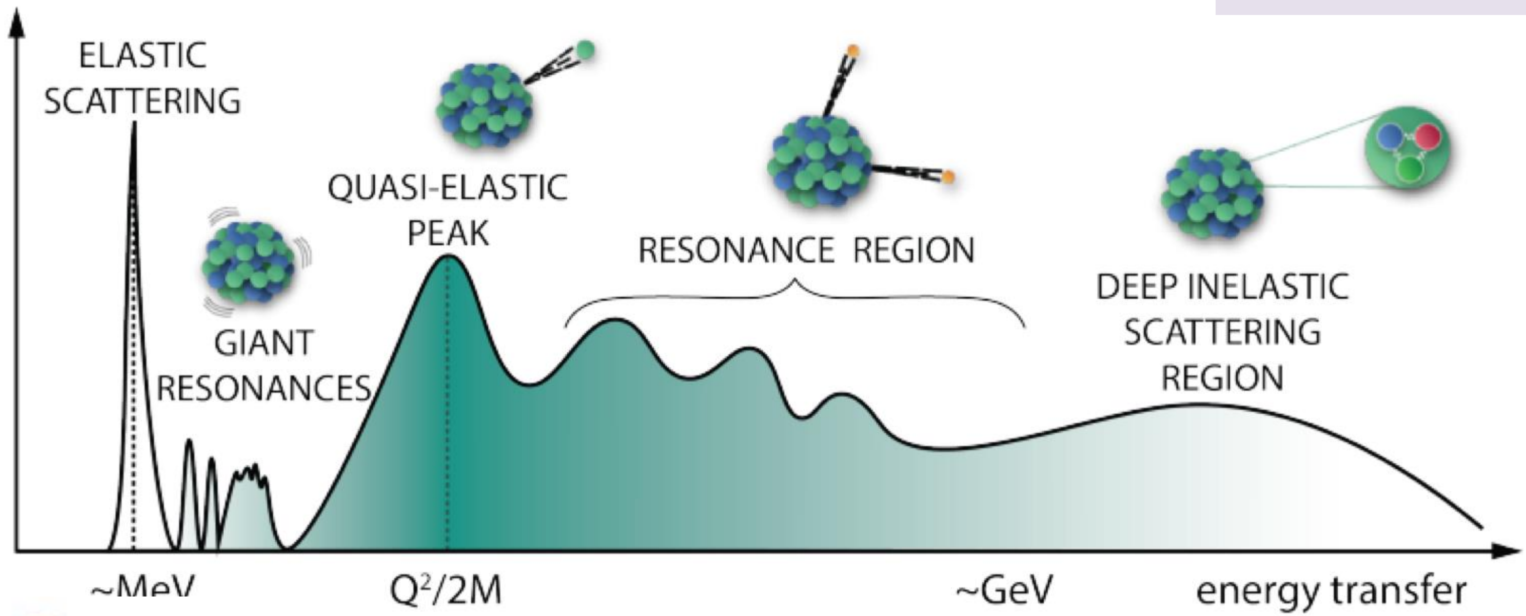
# Neutrino Interactions with Nuclei

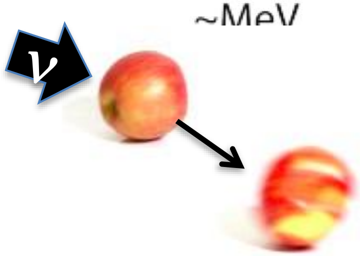
Coherent elastic neutrino-nucleus scattering

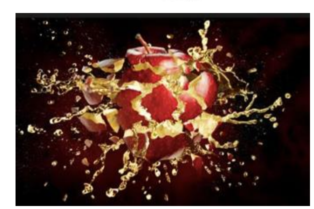
Interactions with nuclei, minimally disruptive of the nucleus

Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Deep Inelastic Scattering



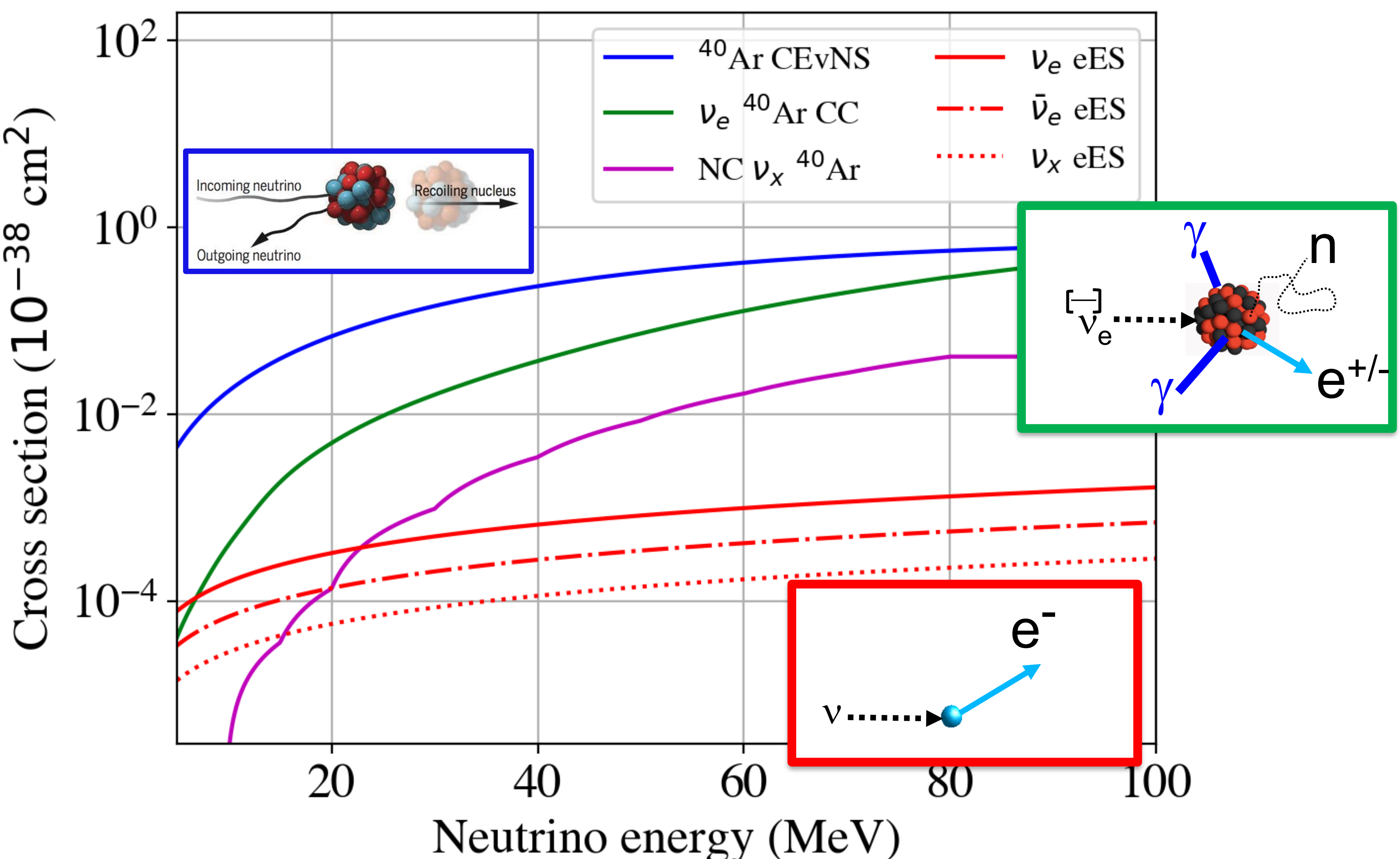



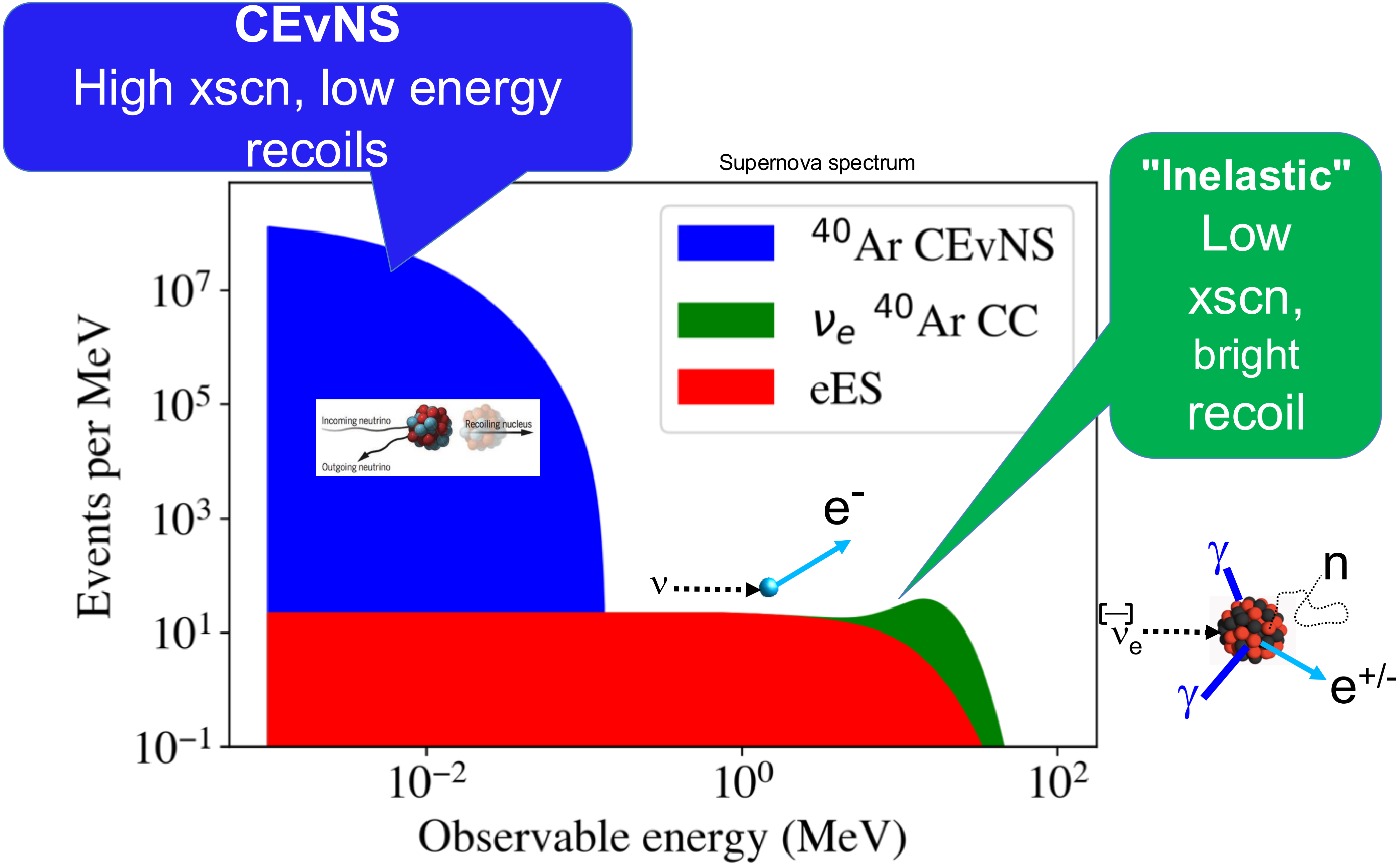
L.Munteanu energy transfer plot

# Cross sections in this energy regime

Argon

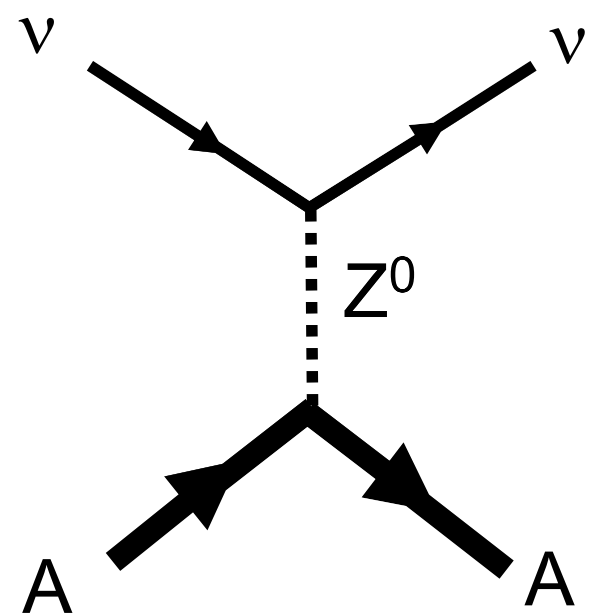


# Neutrino interaction signals in the few to few-tens of MeV range

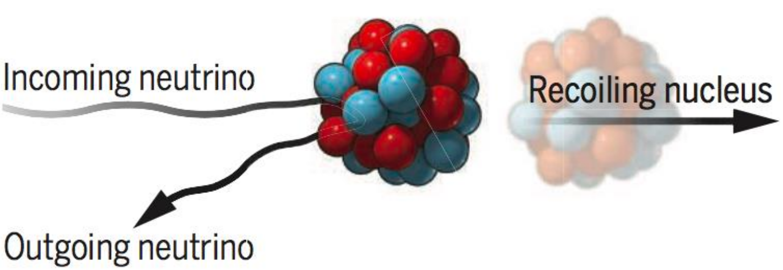


# Coherent elastic neutrino-nucleus scattering (CEvNS)

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




A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu$~ 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

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

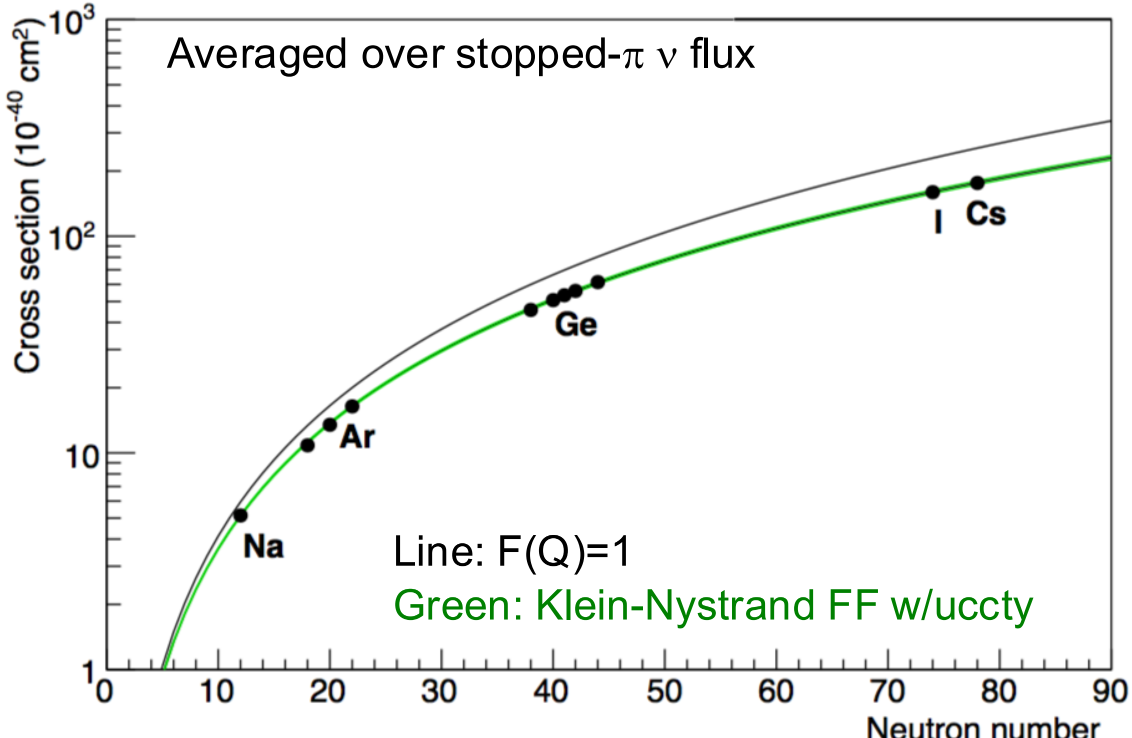
$E_\nu$: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

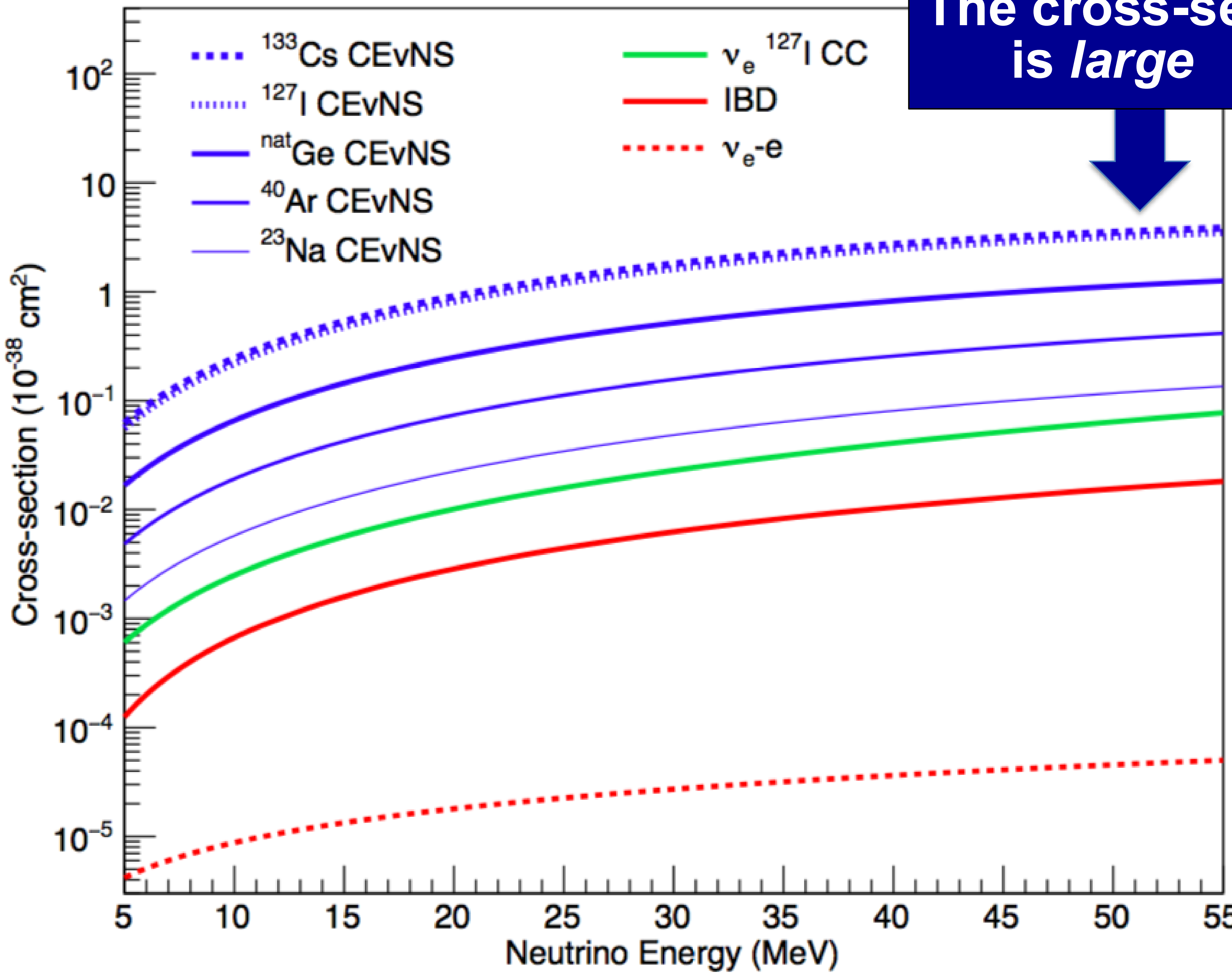
weak nuclear charge

Form factor: F=1 ➔ full coherence

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

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



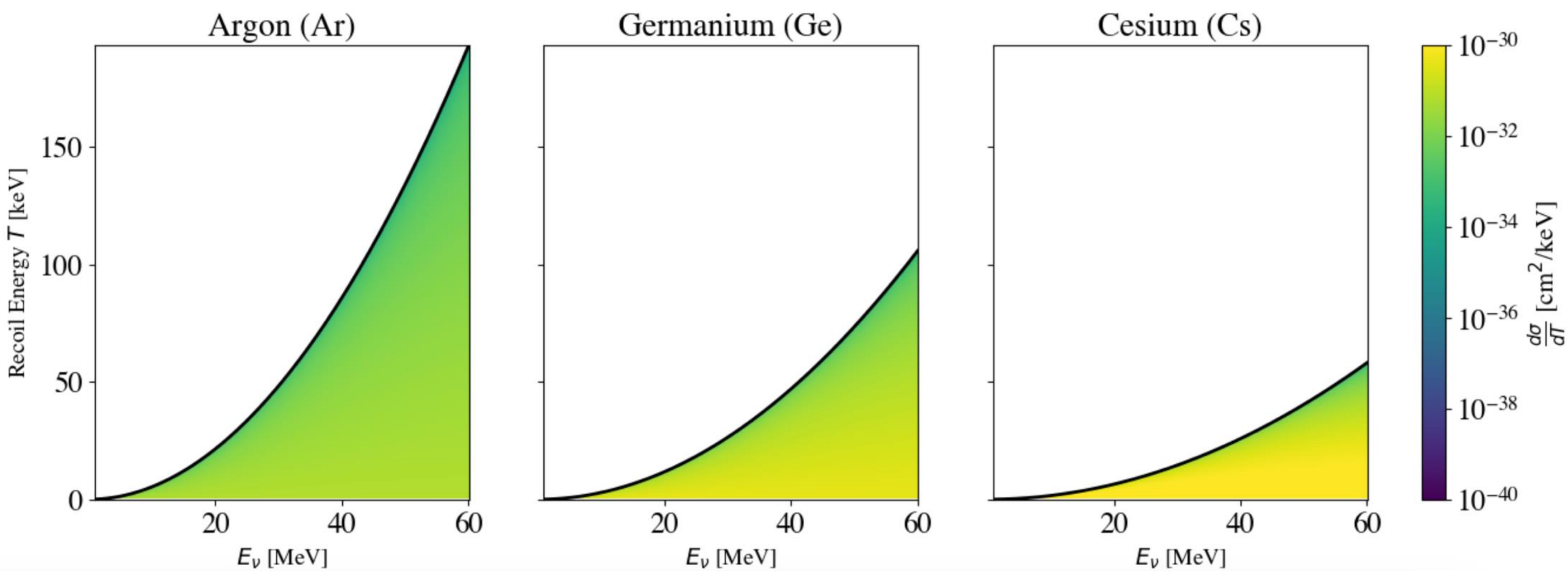



**The cross-section is *large***

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

Nuclear recoil energy spectra

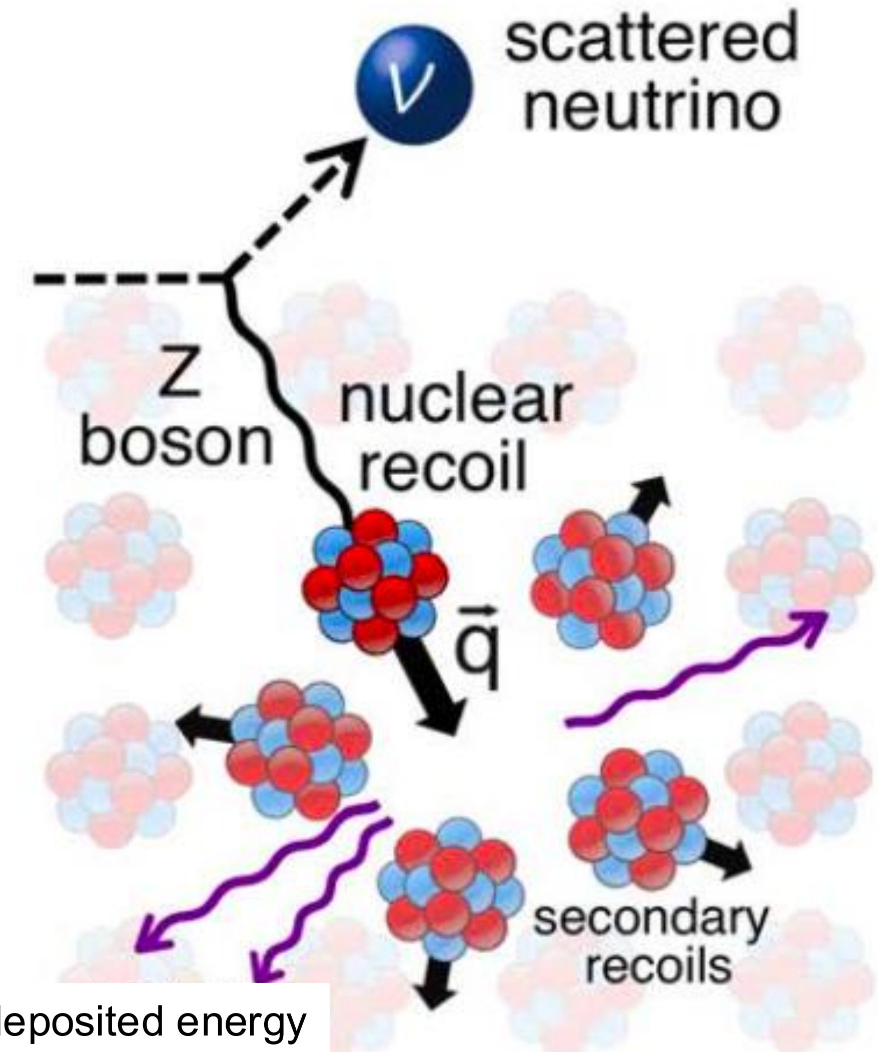
$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$




**Few to ~tens of keV recoils** in the regime where CEvNS dominates. $E_\nu$ <~ 50 MeV

The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



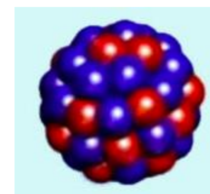

➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

# CEvNS: what's it good for?

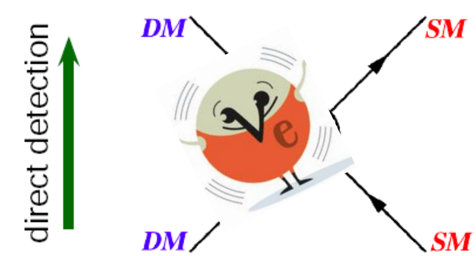
① So ② Many ③ Things **!** (not a complete list!)

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

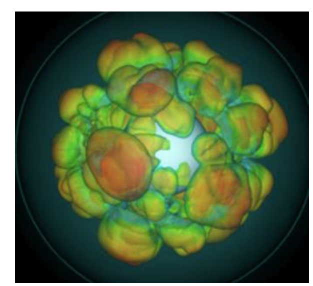
CEvNS as a **signal**
for understanding of "old" physics



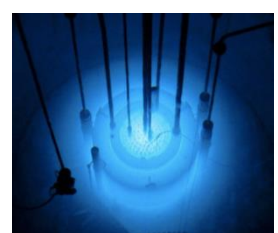
CEvNS as a **background**
for signatures of new physics




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



CEvNS as a **practical tool**



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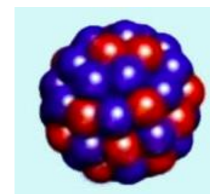

CEvNS as a **background**
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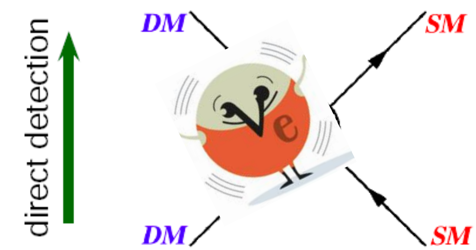


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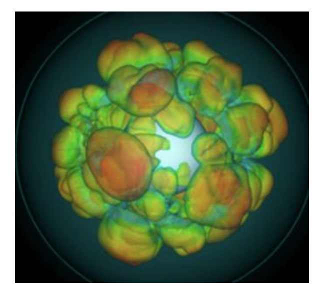

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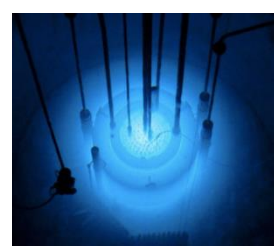


# CEvNS cross section in the Standard Model

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

$E_\nu$: 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

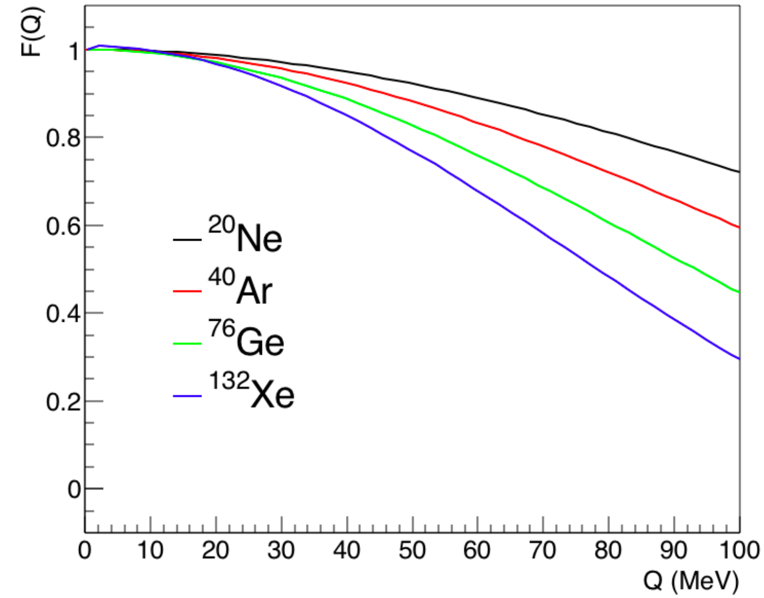
axial $G_A = g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)$ ← small for most nuclei, zero for spin-zero

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

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

SM electroweak in here

nuclear physics in here, with ~percent uncertainties




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

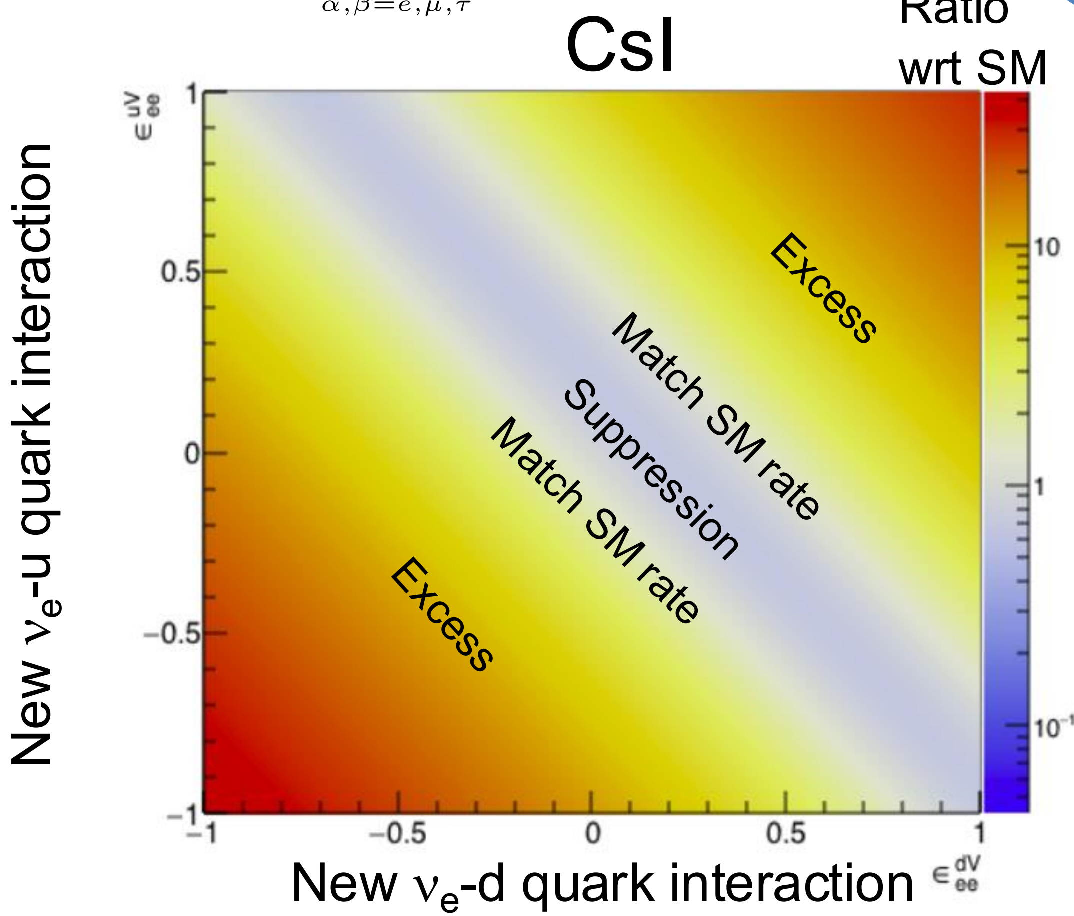
- In the context of the SM, measure $\sin^2\theta_W$ at low Q
- Look for anomalies in rate, N or Q distribution to search for BSM

- Bigger suppression for for larger Q and larger nucleus

# 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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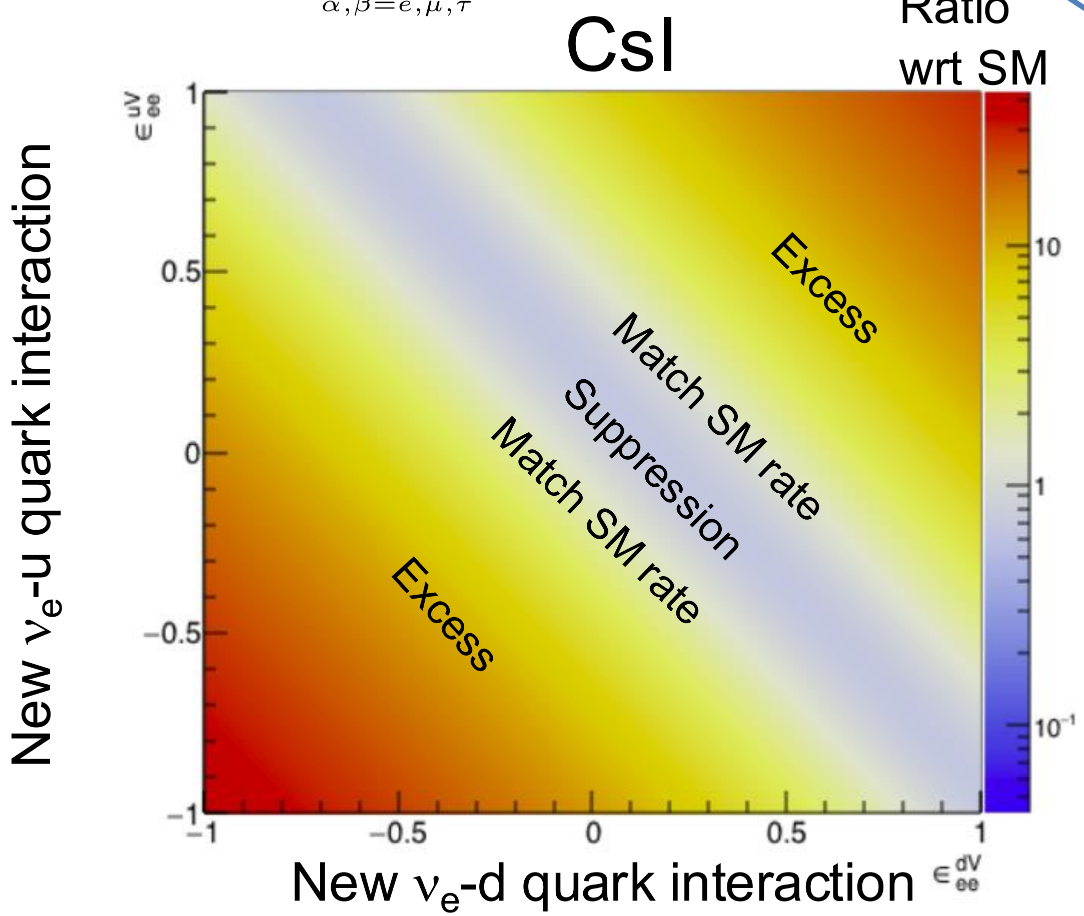


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For heavy mediators, expect ***overall scaling*** of CEvNS event rate, depending on N, Z

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

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

Effective weak charge in presence of light vector mediator Z'

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

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 ~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

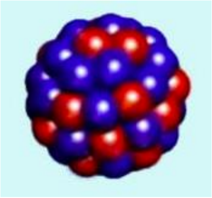
# CEvNS: what's it good for?


!

(not a complete list!)

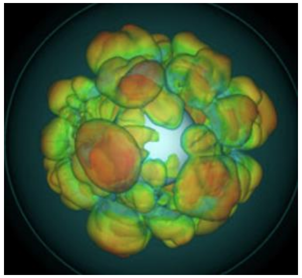
CEvNS as a **signal** for signatures of *new physics*

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

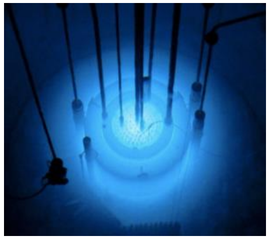


CEvNS as a **background** for signatures of new physics


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

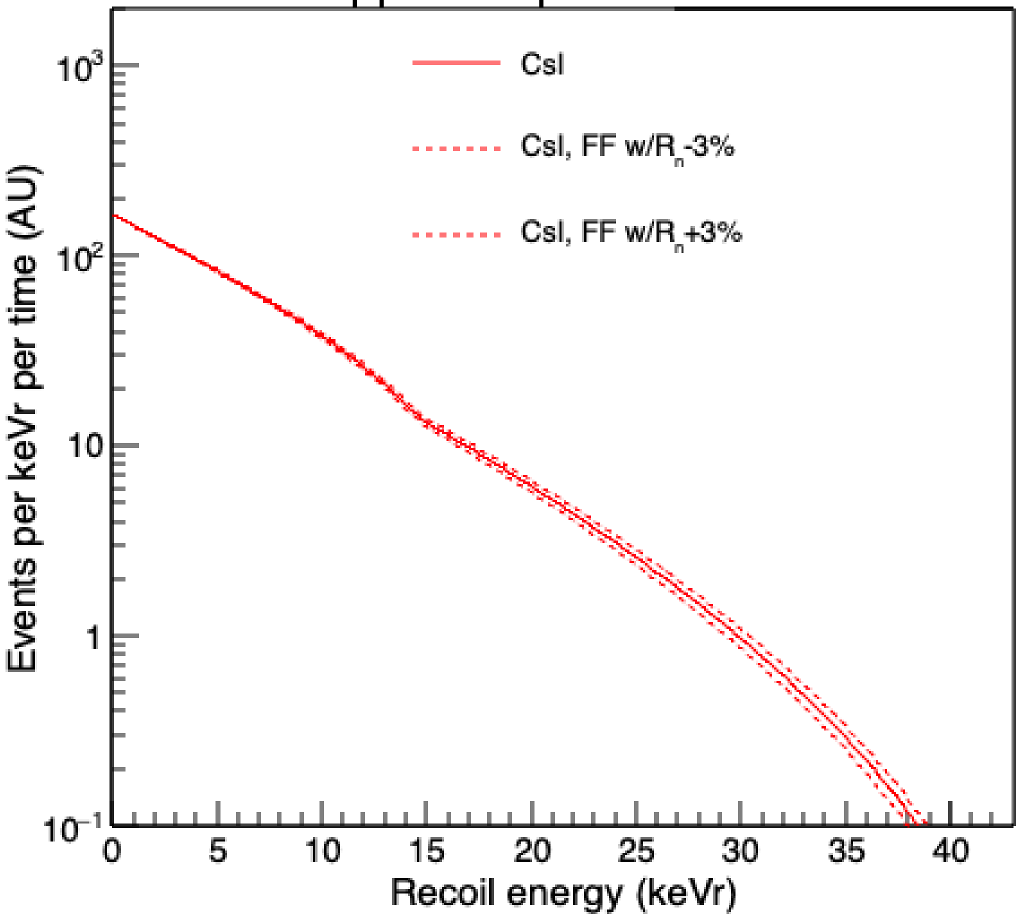


CEvNS as a **practical tool**



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

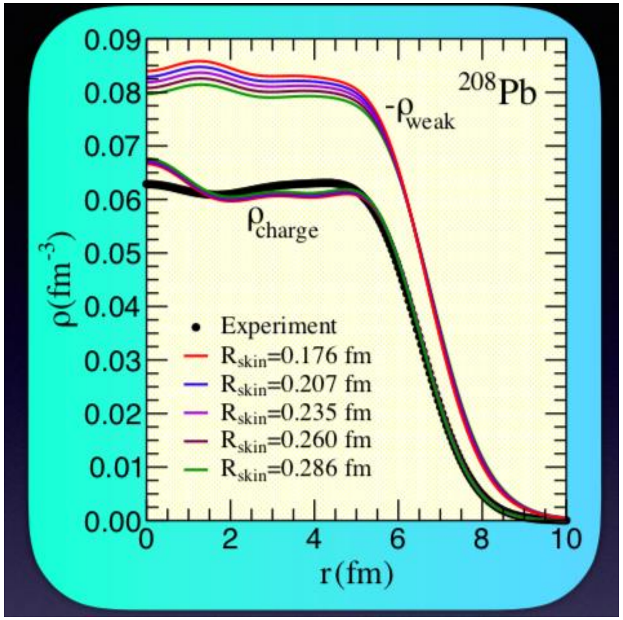
Stopped-$\pi$ spectrum




P S Amanik and G C McLaughlin 2009
*J. Phys. G: Nucl. Part. Phys.* 36 015105

K. Patton et al., Phys.Rev. C86 (2012) 024612

Observable is
**recoil spectrum shape**
(Q-dependent suppression)




Neutron radius and "skin" ($R_n$-$R_p$) relevant for understanding of neutron star EOS

J. Piekarewicz

So: if you are hunting for BSM physics
as a distortion of the recoil spectrum

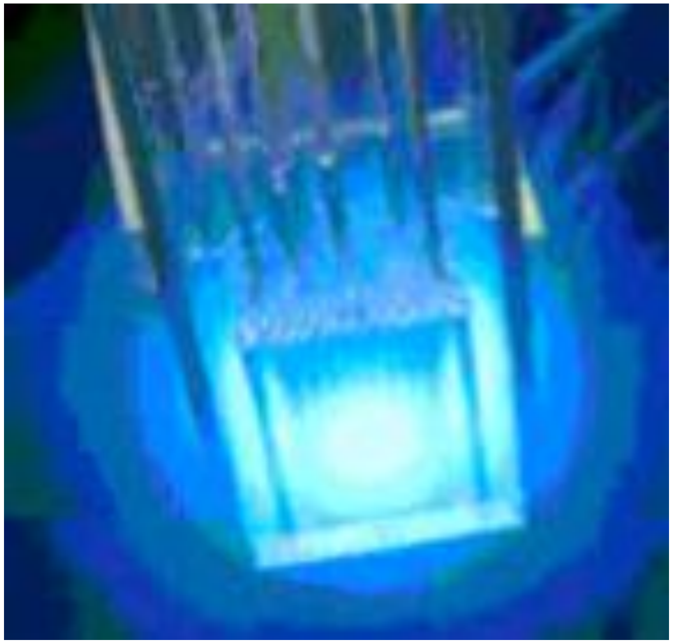
… **uncertainties in the form factor are a nuisance**!

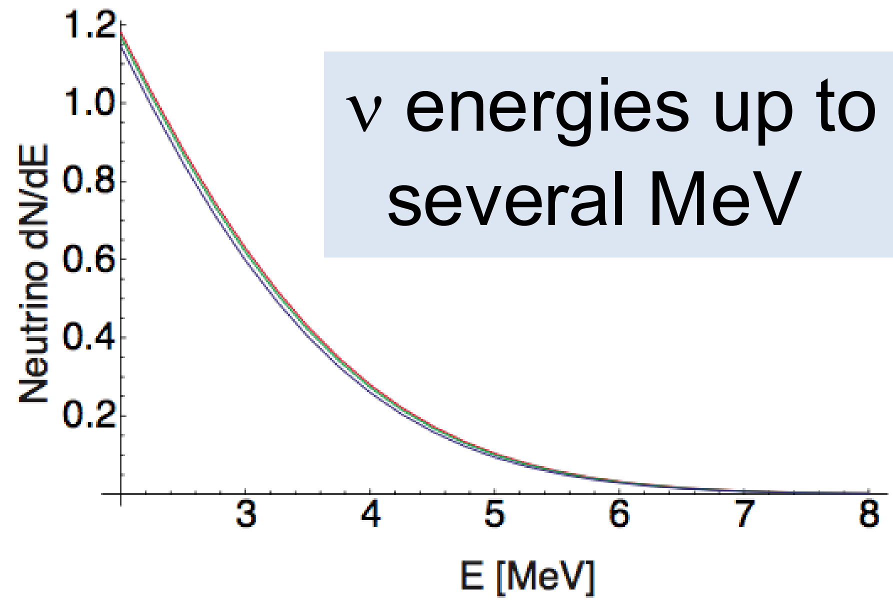
There are degeneracies in the observables between
"old" (but still mysterious) physics

and "new" physics

At current level of precision,
form factor shape is **not a dominant effect**
... but we will need to think carefully about
how to disentangle these effects for the longer term

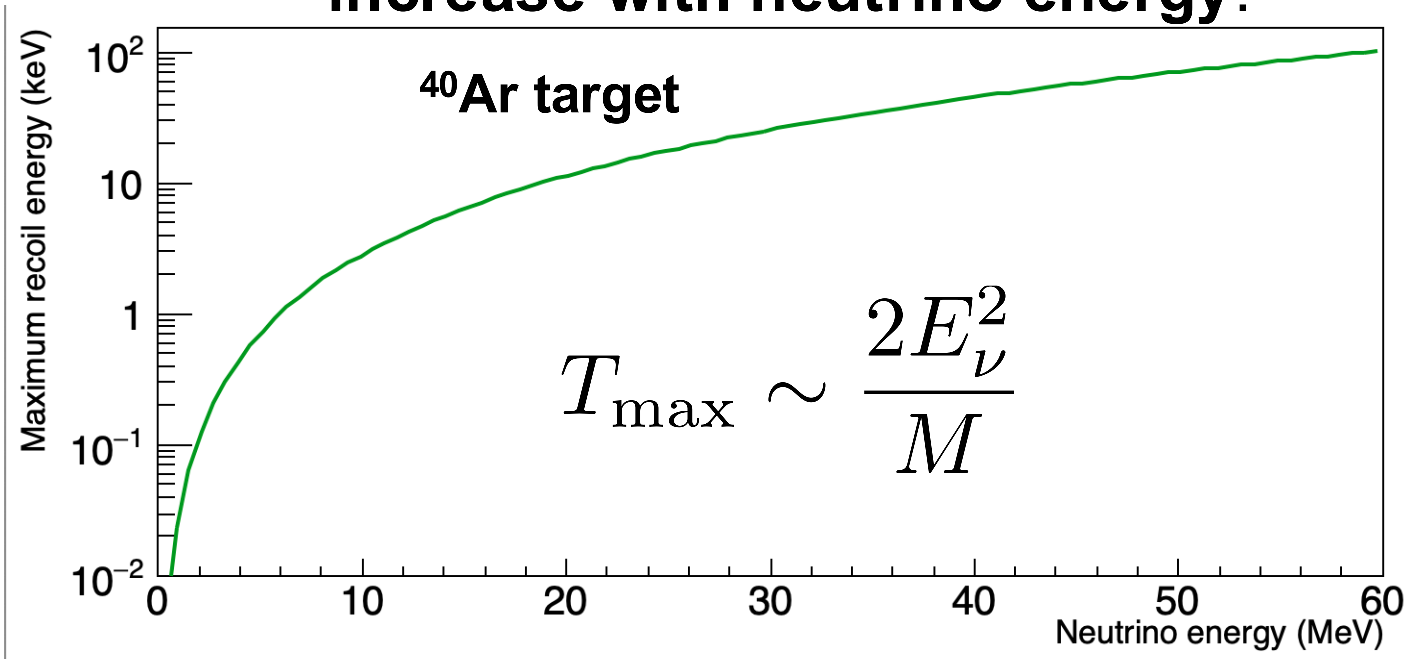
# Neutrinos from nuclear reactors






- $\nu_e$-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2x$10^{20}$ $s^{-1}$ 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**:

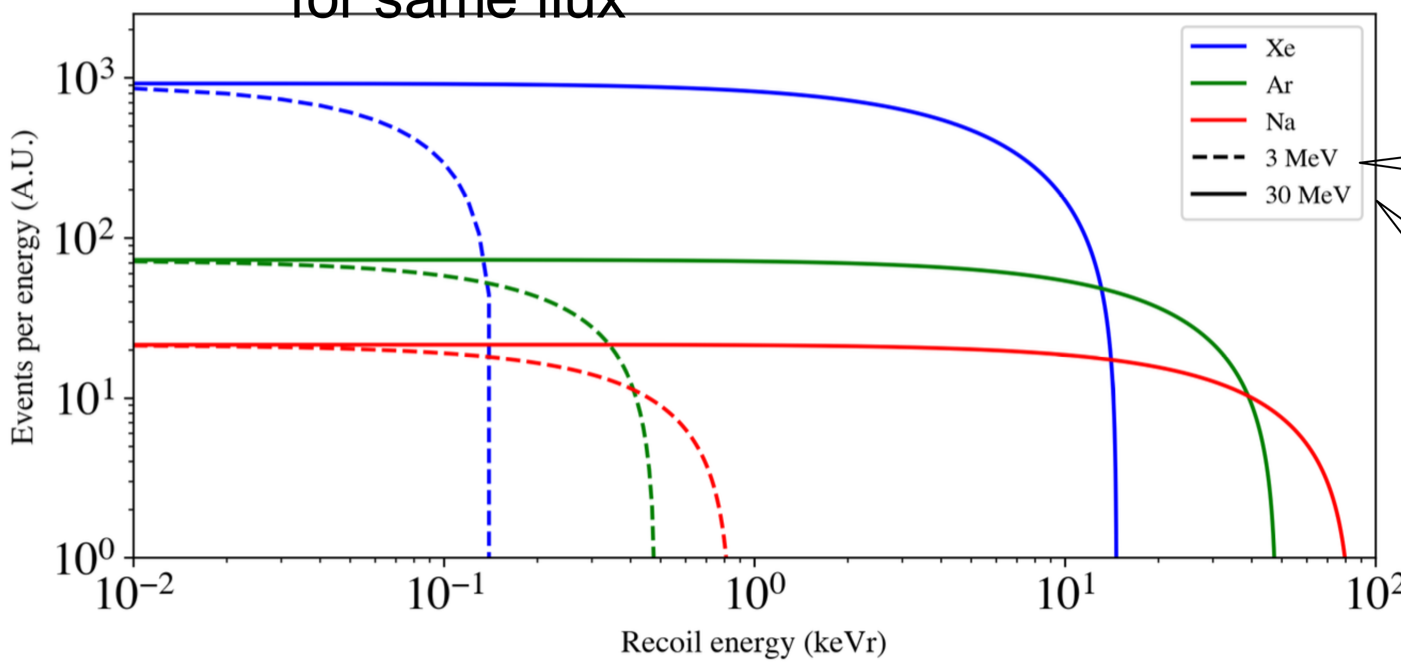


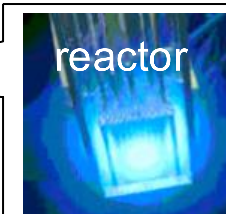

Want energy as large as possible while satisfying coherence condition

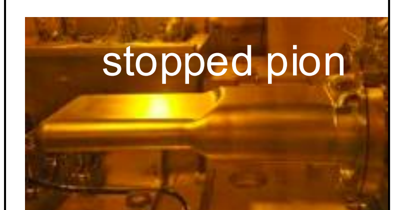
$$Q \lesssim \frac{1}{R}$$

(<~ 50 MeV for medium A)

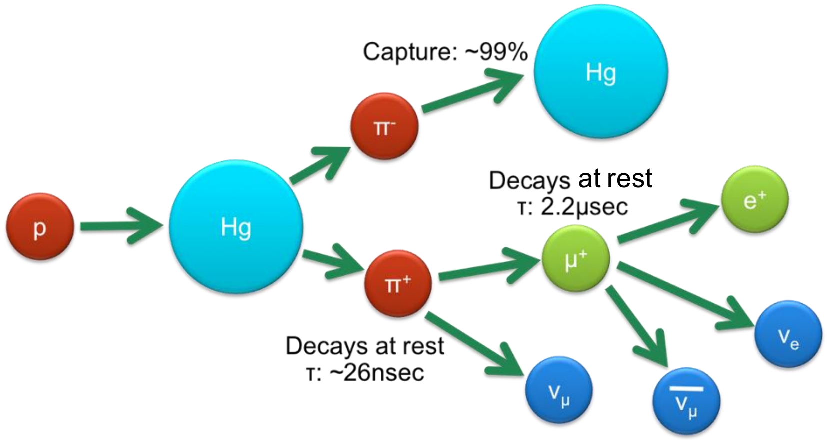
for same flux

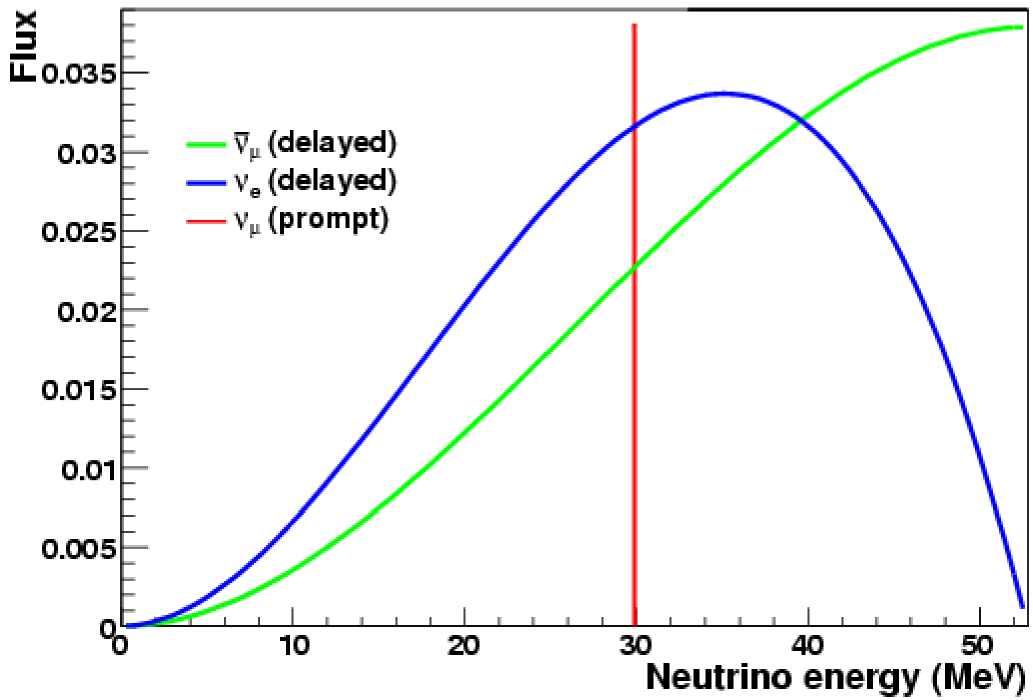


# Stopped-Pion (πDAR) Neutrinos




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

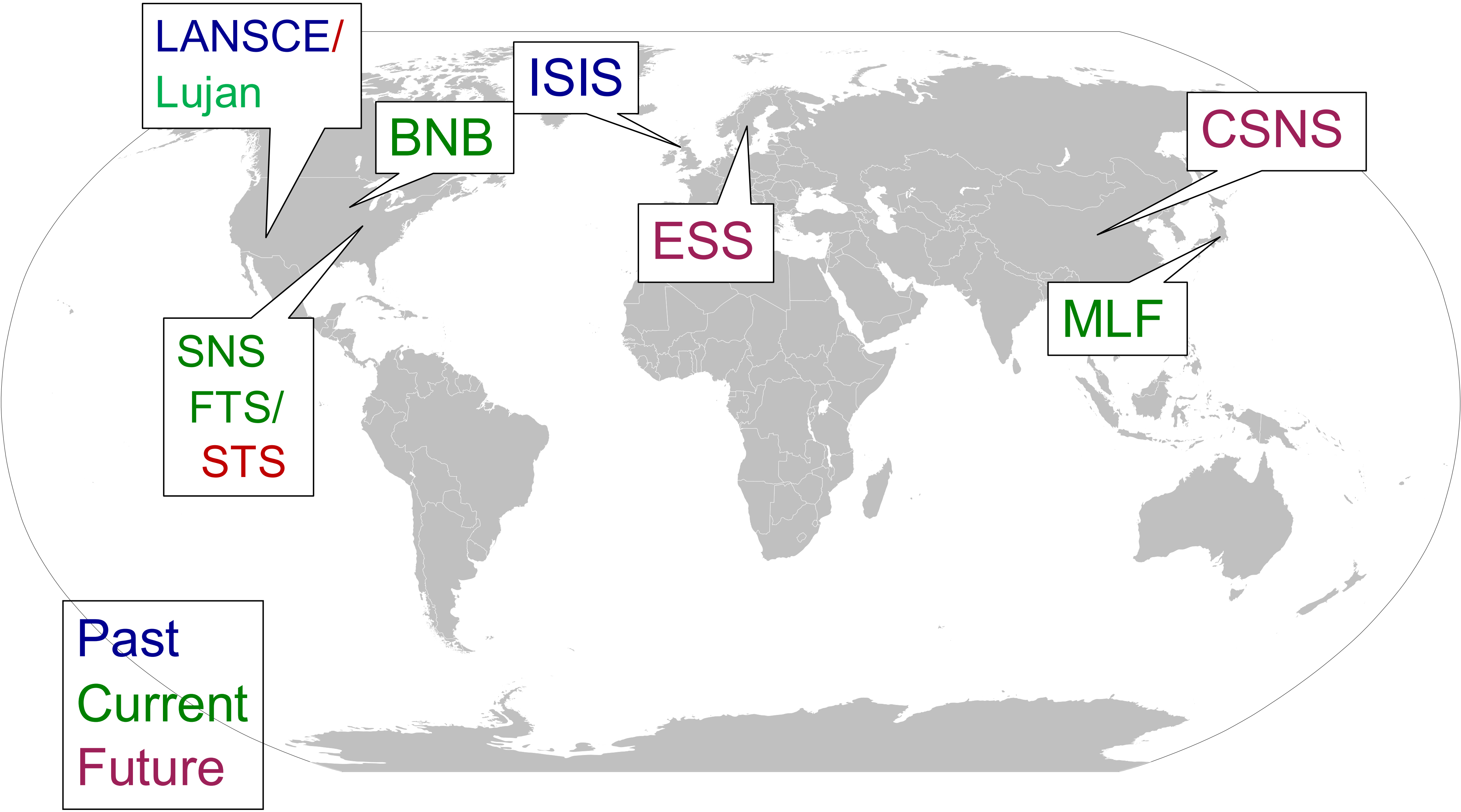
2-body decay: monochromatic 29.9 MeV $\nu_\mu$
PROMPT

$$\downarrow$$

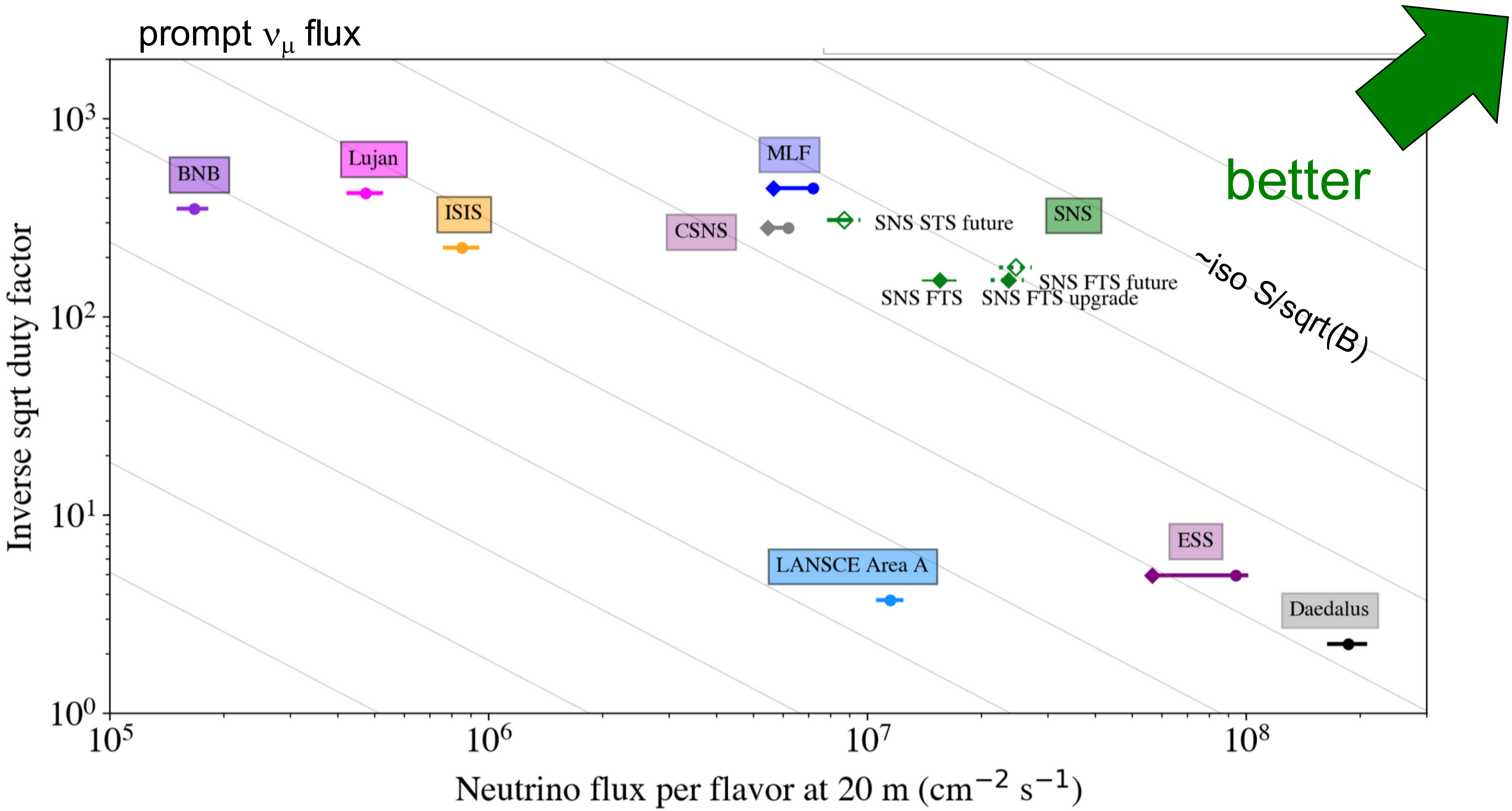
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

# Stopped-Pion Neutrino Sources Worldwide



# Comparison of stopped-pion ν sources



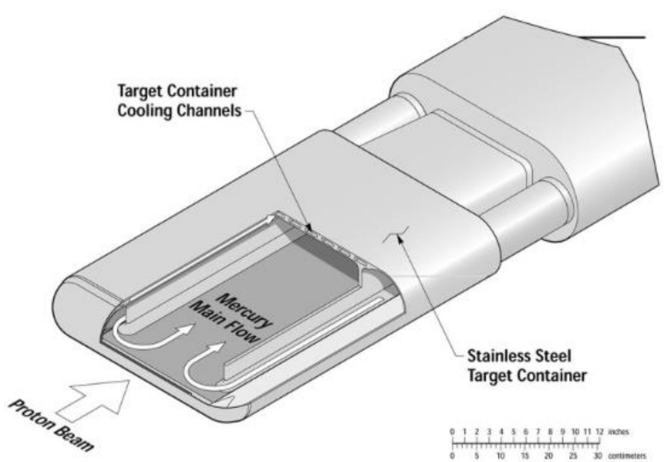

rough figure of merit: ~flux/sqrt(duty cycle) (~S/sqrt(B))

[does not capture all relevant characteristics]

[JLab beam dump? CW, ~SNS/100]

# Spallation Neutron Source

Oak Ridge National Laboratory, TN




Proton beam energy: 0.9-1.3 GeV

Total power: 0.9-1.9 MW (increasing)

Pulse duration: 380 ns FWHM

Repetition rate: 60 Hz

Liquid mercury target

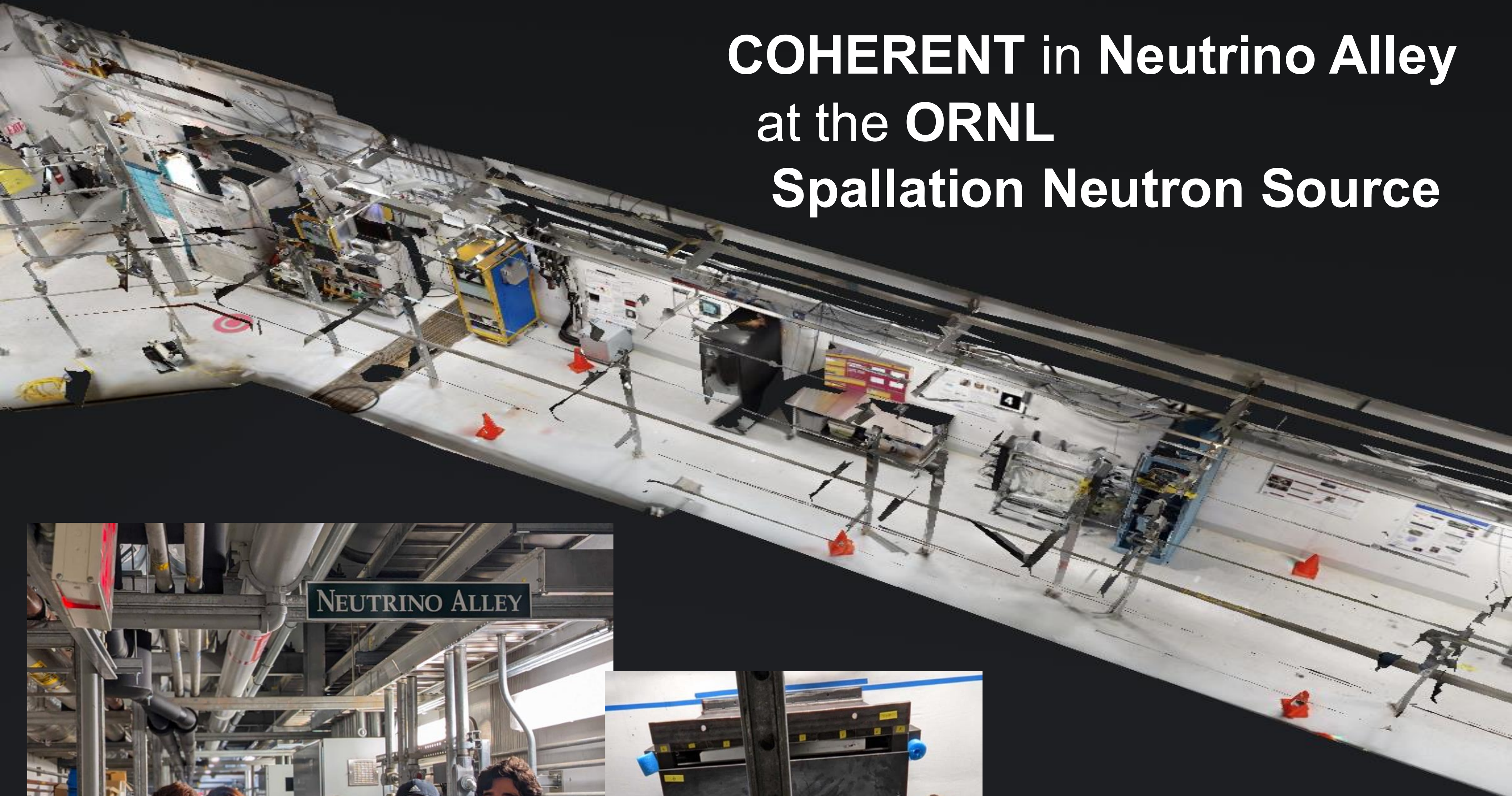
**The neutrinos are free!**

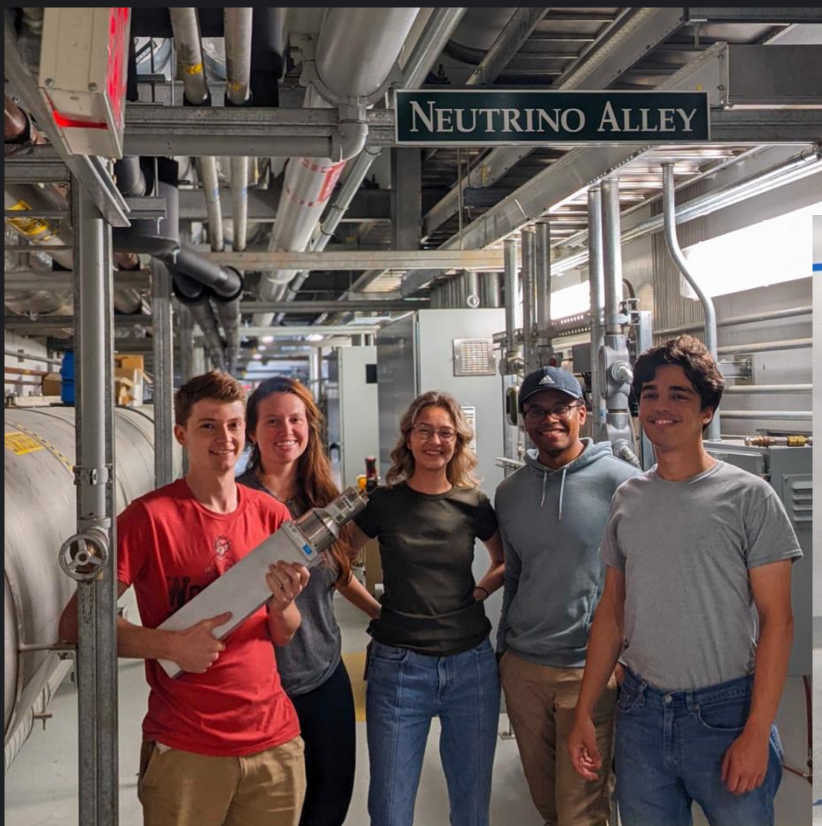
# The COHERENT collaboration

http://sites.duke.edu/coherent

~100 members,
25 institutions
5 countries

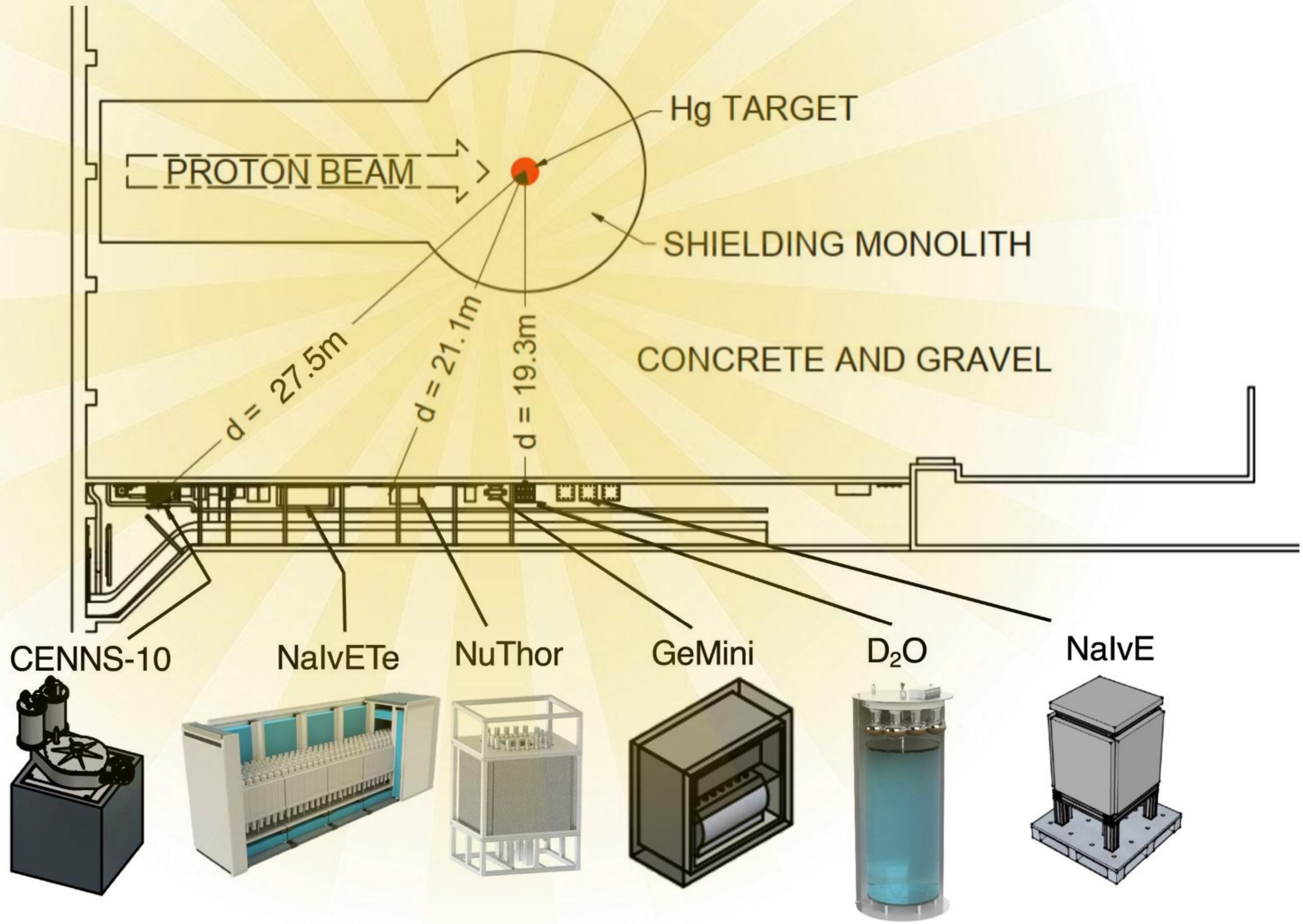
# COHERENT in Neutrino Alley at the ORNL Spallation Neutron Source



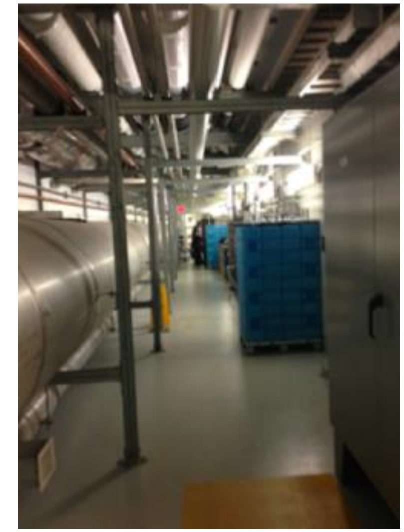



# Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

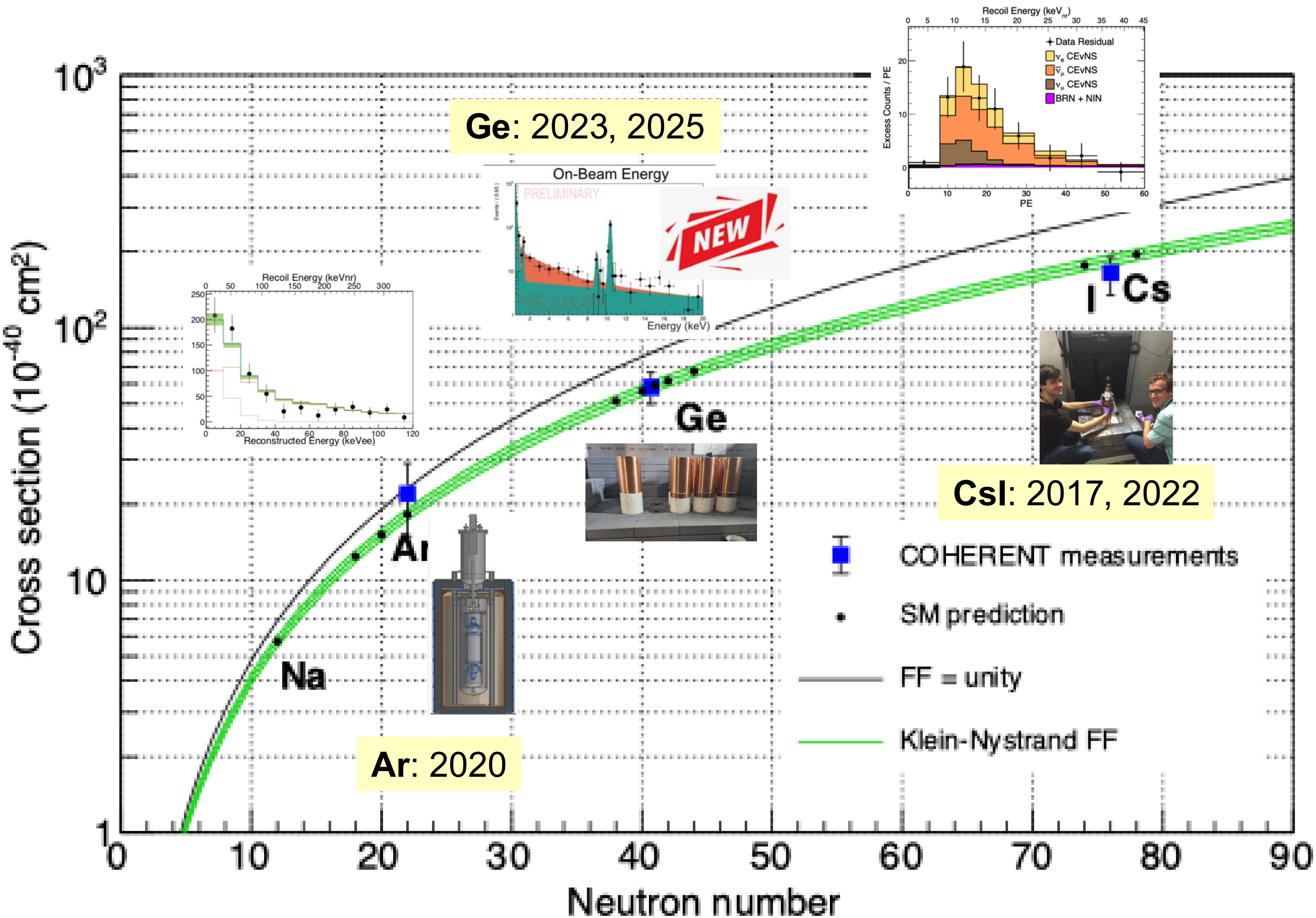



View looking
down “Neutrino Alley”



Isotropic ν glow from Hg SNS target

# Measurements in 3 targets from COHERENT

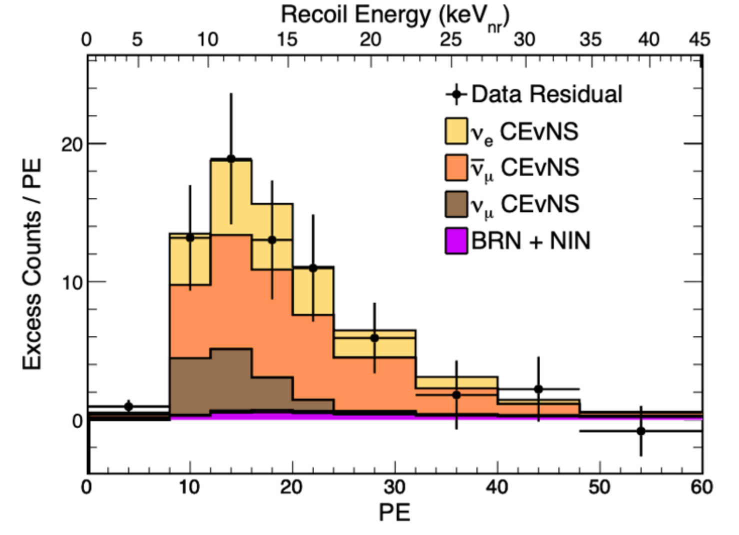


# Example physics interpretations from COHERENT CsI CEvNS

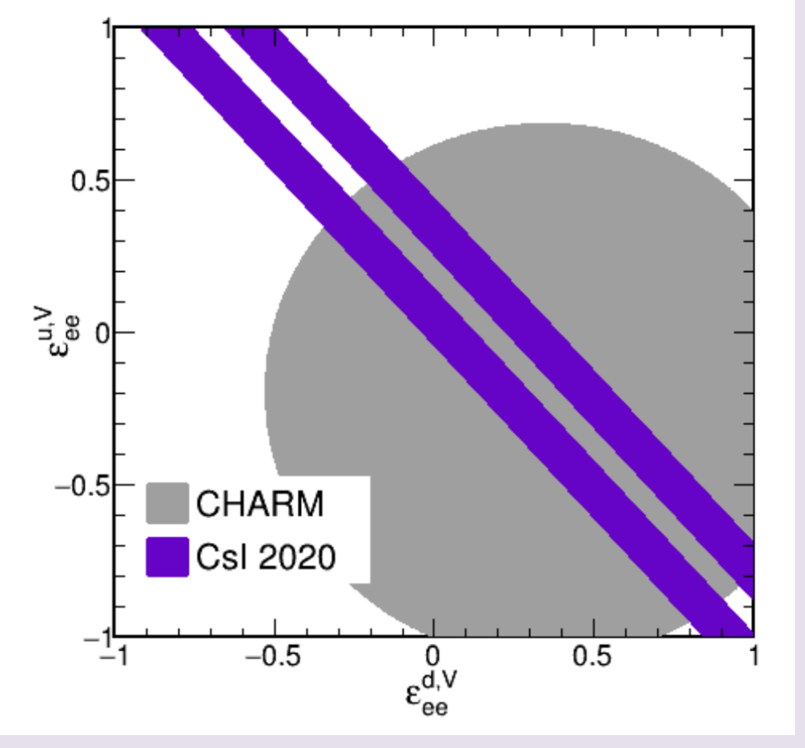
*Phys.Rev.Lett.* 129 (2022) 8, 081801 • e-Print: 2110.07730 [hep-ex]

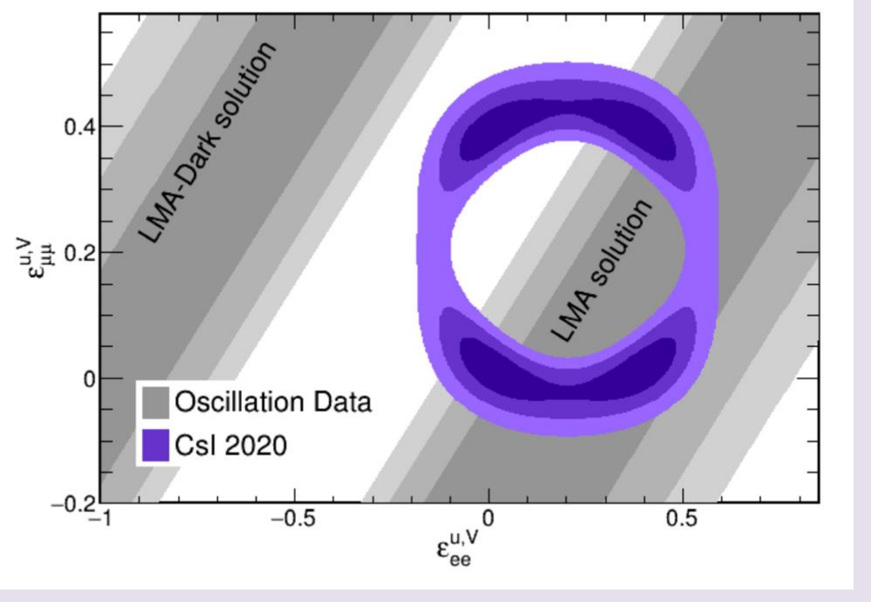
## Weak Mixing Angle

$$\sin^2 \theta_W = 0.220^{+0.028}_{-0.026}$$




## NSI constraints



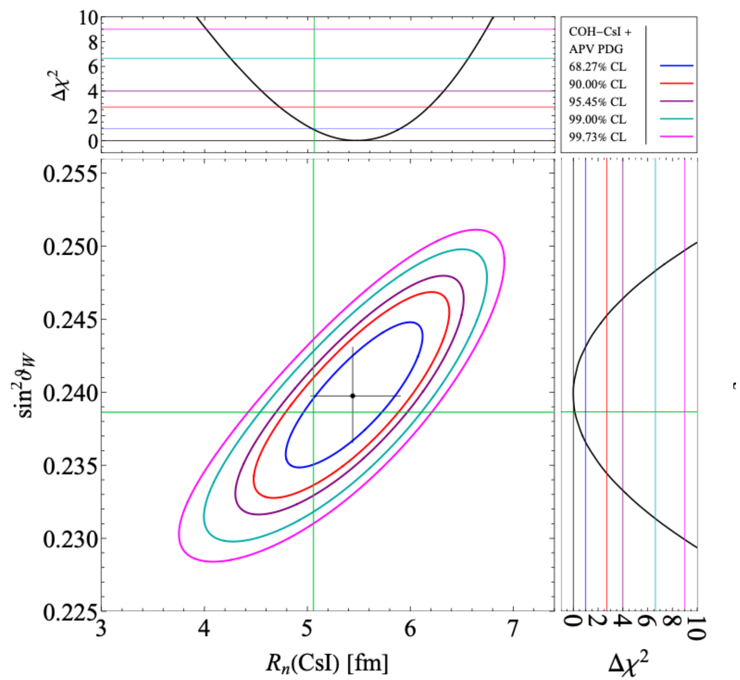



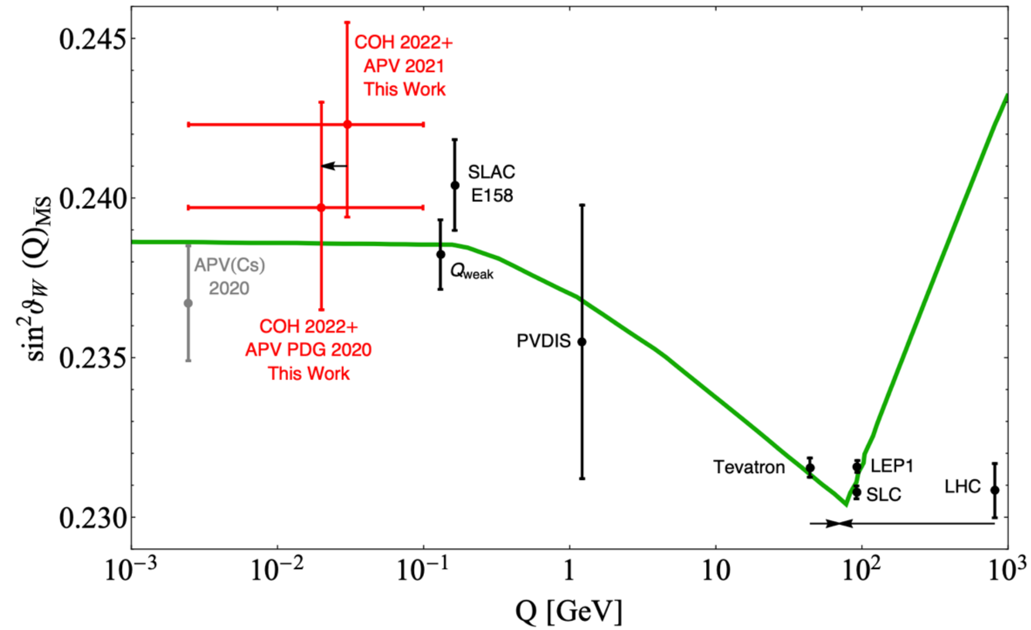
# WMA and Neutron Radius from COHERENT CsI data

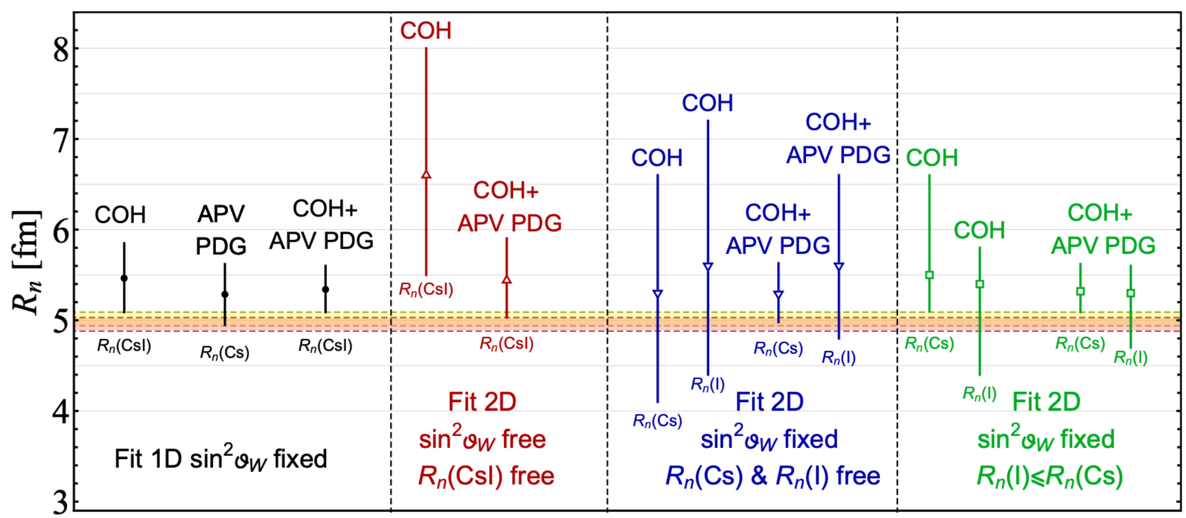
: *Eur.Phys.J.C* 83 (2023) 7, 683 • e-Print: 2303.09360 [nucl-ex]

**COHERENT combined w/APV result**

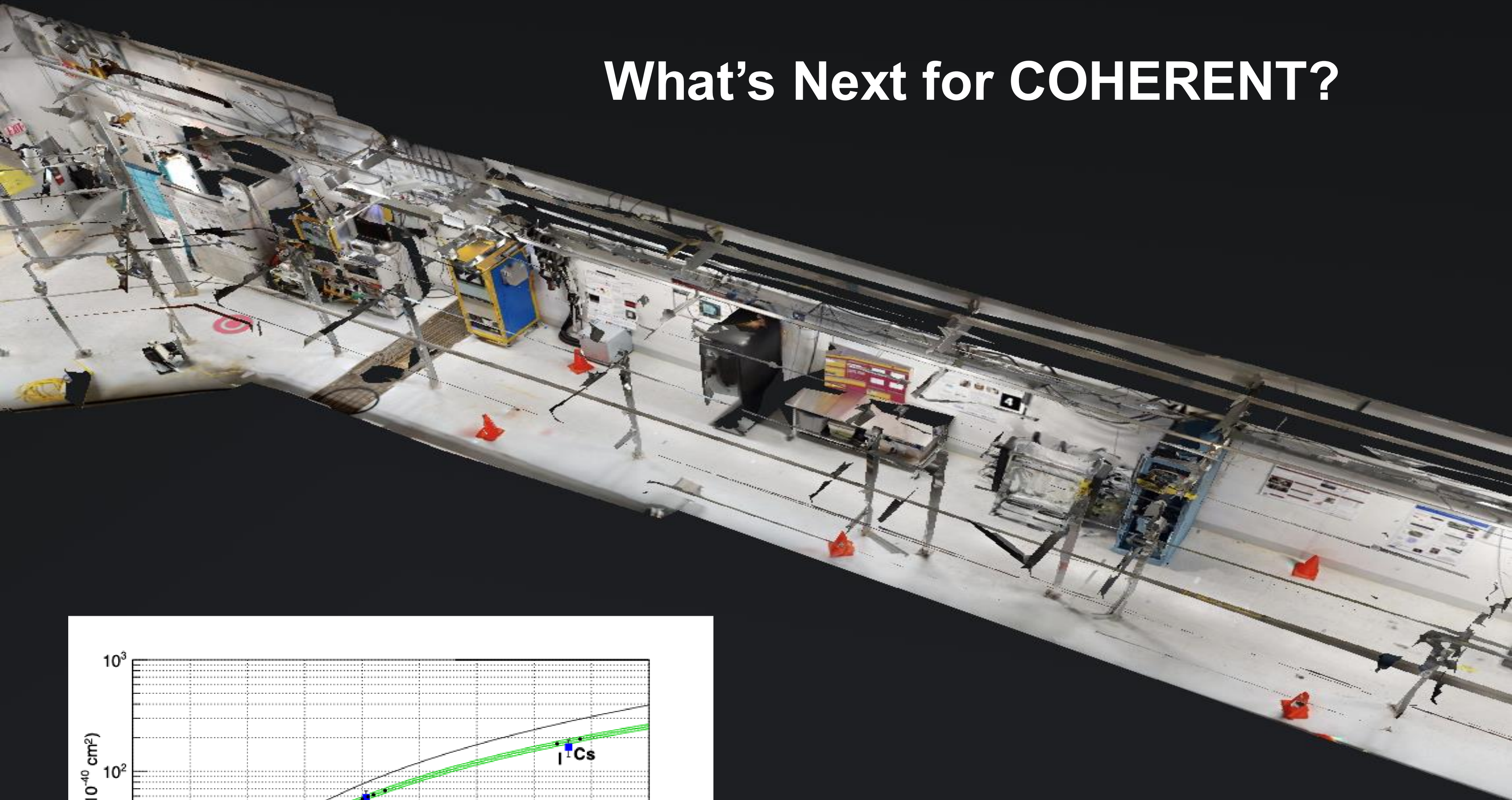
$R_n$ (CsI)=$5.4^{+0.5}_{-0.4}$ fm $\sin^2\vartheta_W$=$0.2397^{+0.0033}_{-0.0032}$ $\chi^2_{\min}$= 85.2

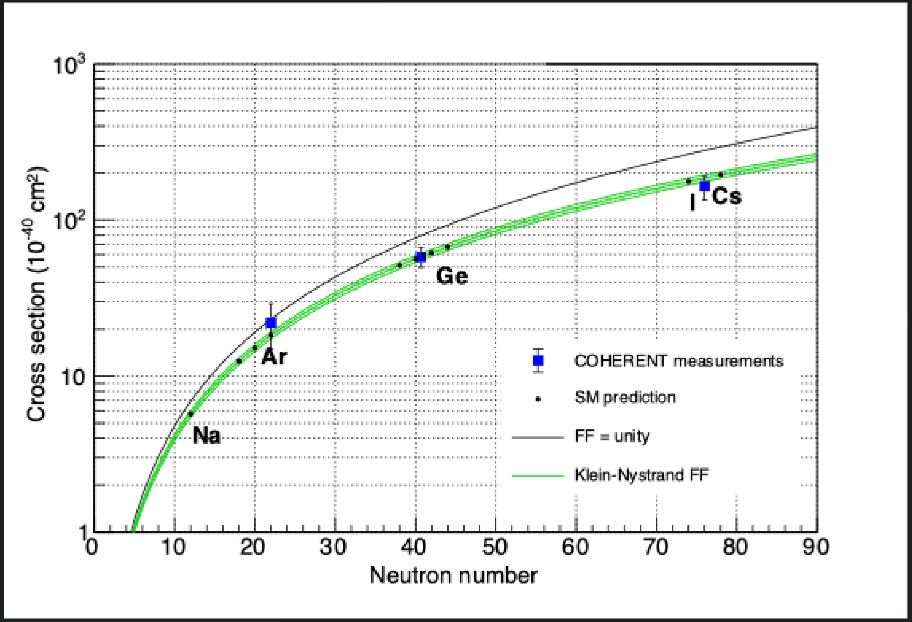


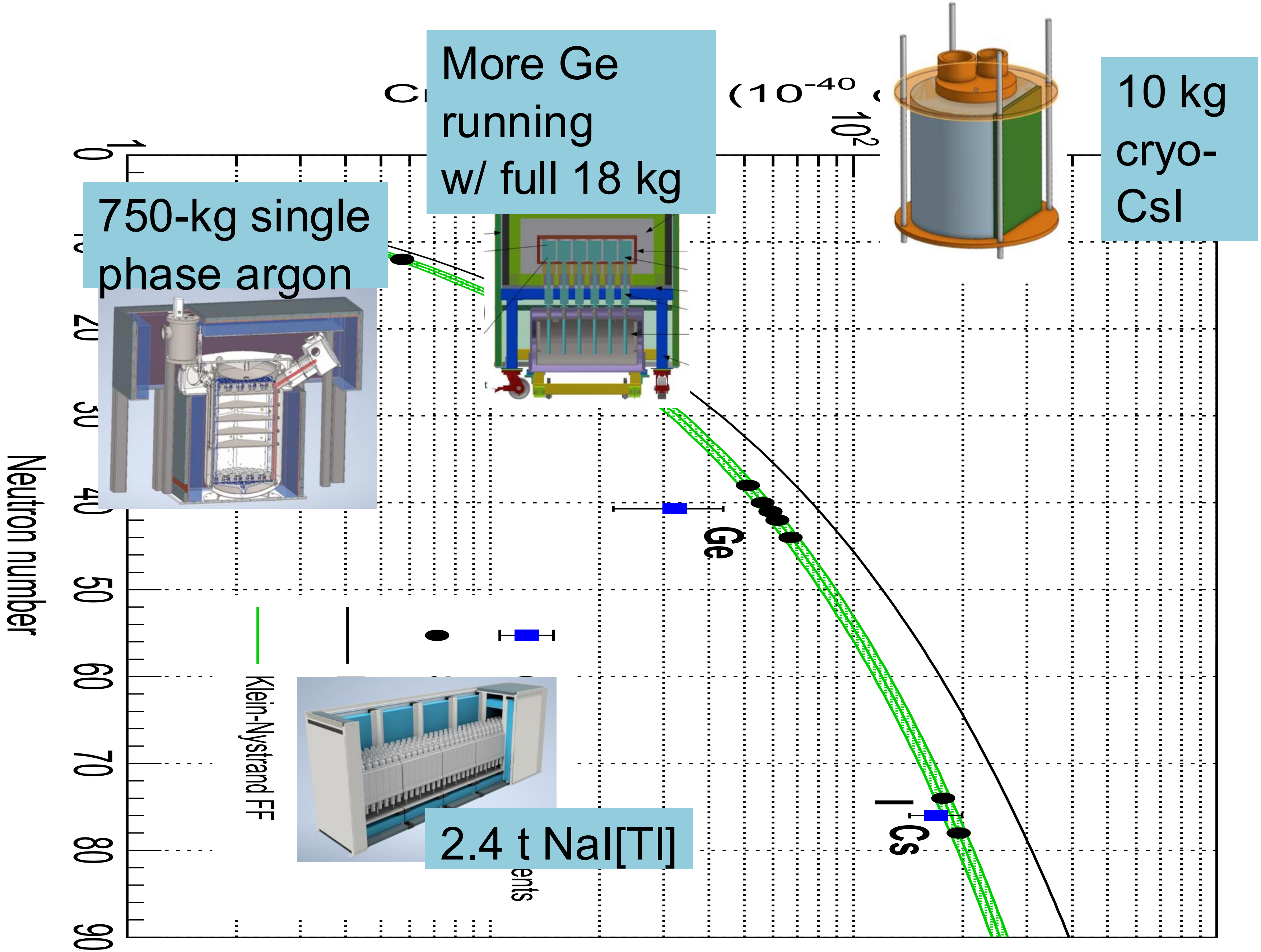
# What's Next for COHERENT?






Three down!
But still more
to go!

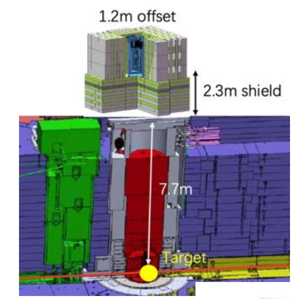
# Ongoing CEvNS in Neutrino Alley

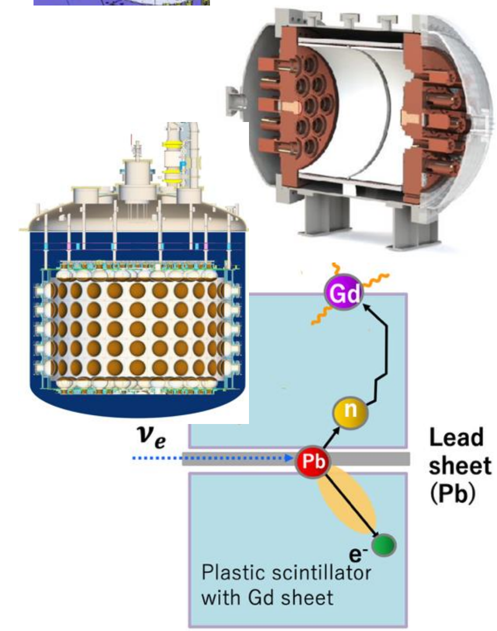



(... and more inelastics)

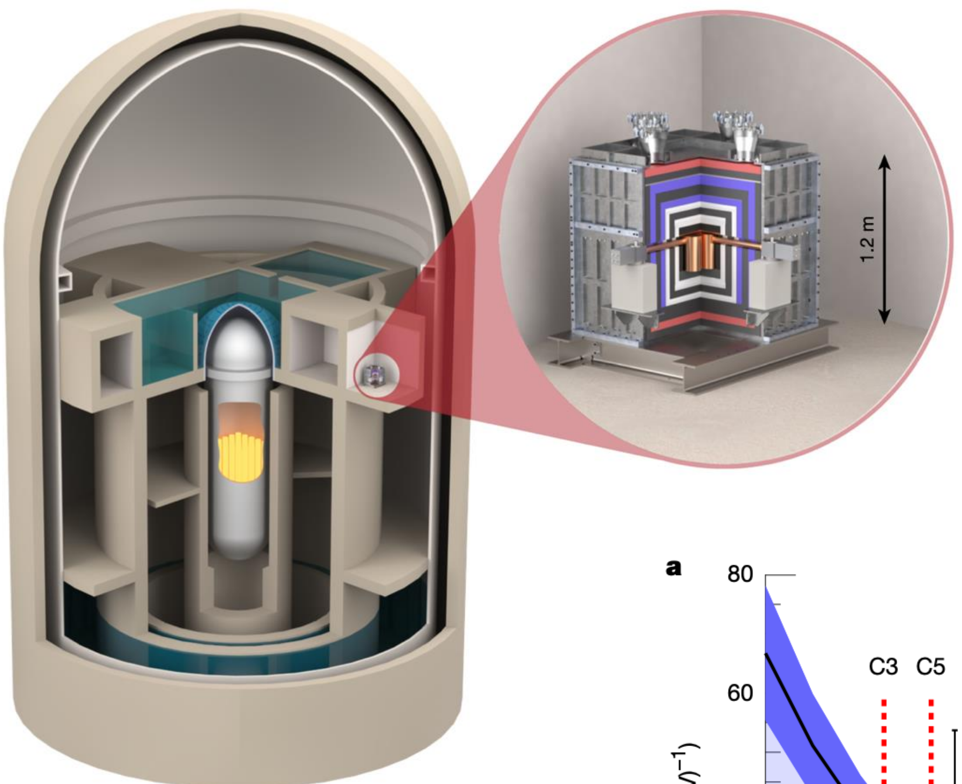
# Other Experiments at Stopped-Pion Sources

| Facility | Country | Experiment(s) |
|---|---|---|
| China Spallation Neutron Source | China | CLOVERS |
| European Spallation Source | Sweden | NuESS (several) |
| Lujan, LANL | USA | Coherent Captain Mills |
| Materials and Life Science Facility, J-PARC | Japan | JSNS$^2$, DArVeX [not CEvNS] |
| Spallation Neutron Source, ORNL | USA | COHERENT, (EOS) |



# And reactor CEvNS has finally been seen!

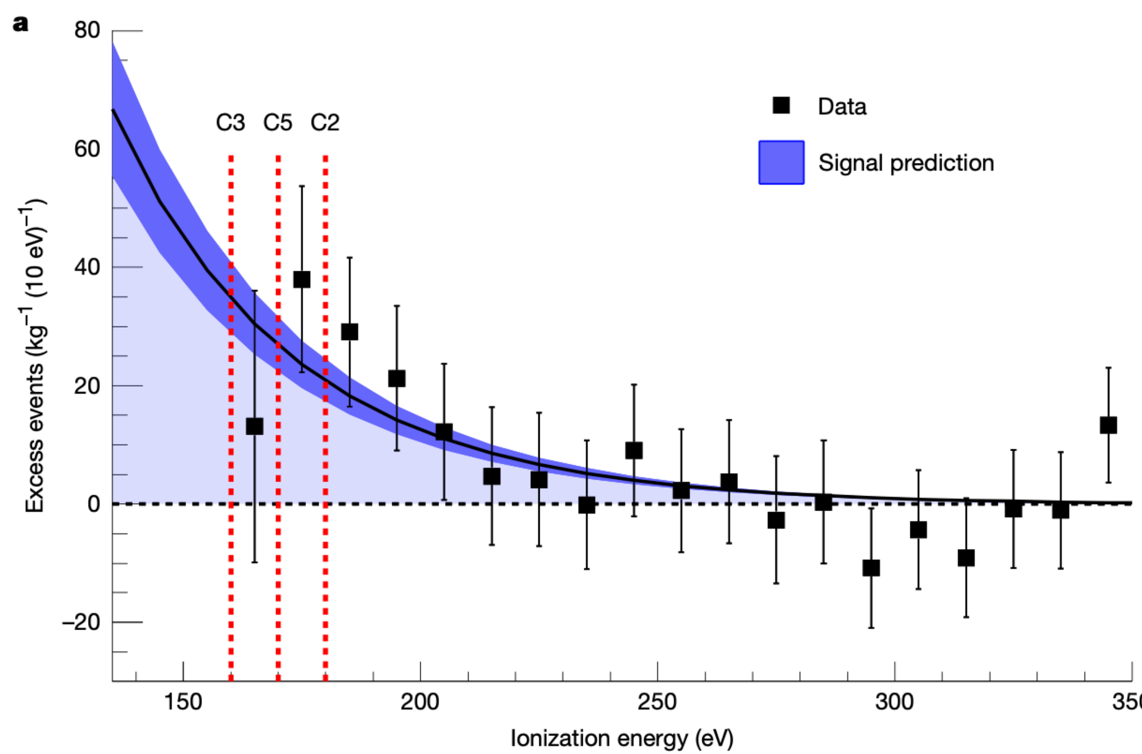



## CONUS+

4 ~1kg HPGe detectors

3.7σ measurement

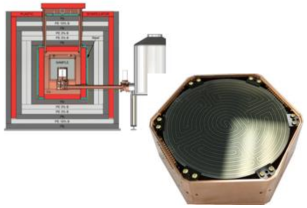
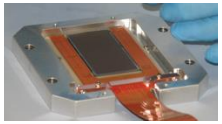
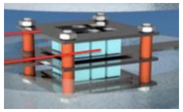
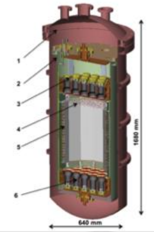
Nature 643, 1229–1233 (2025)

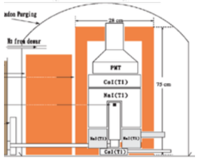
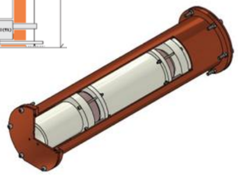



Ratio to SM:
1.14+-0.36

# Many technologies in play, going for low threshold

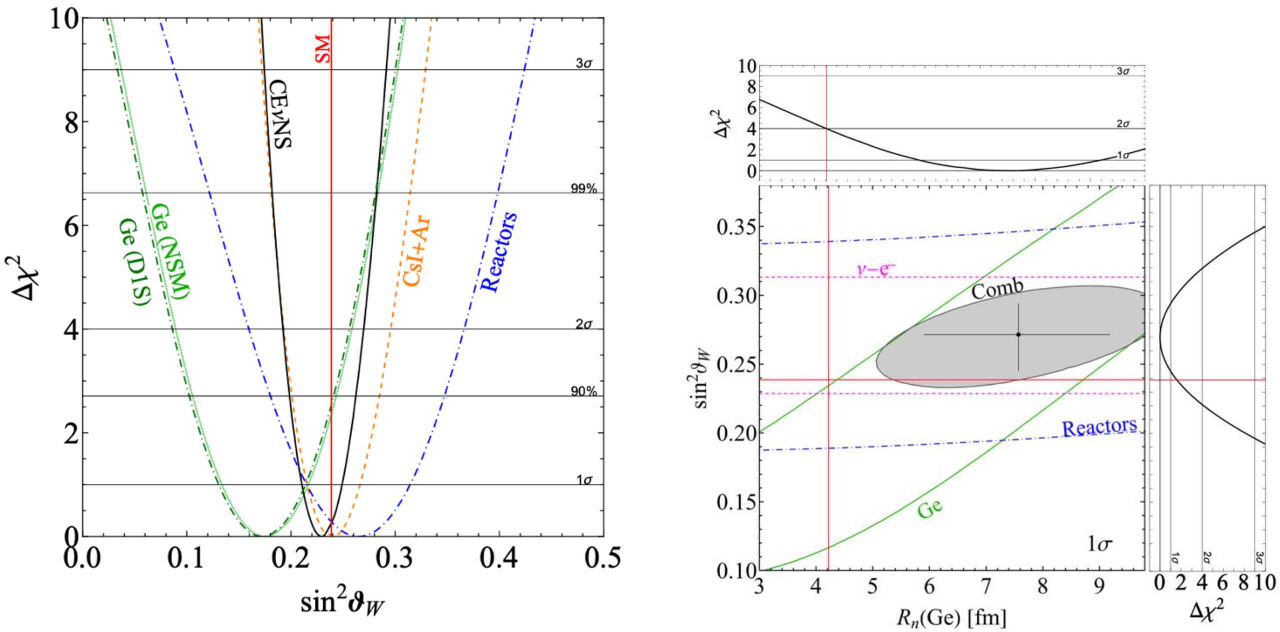
| Experiment | Distance to core ( m) | max. $\nu$ flux ($cm^{-2}s^{-1}$) | Target nuclei | $E_{nr}$ recoil best (eff.) (keVr) | Status |
|---|---|---|---|---|---|
| **Semiconductor** | | | | | |
| CONUS+ [80] | 20.7 | $1.5 \cdot 10^{13}$ | Ge | 0.9 (>95%) | running |
| NuGeN [122] | $11.1^{(***)}$ | $4.4 \cdot 10^{13}$ | Ge | 1.6 (90%) | running |
| CONNIE [83] | 30 | $7.8 \cdot 10^{12}$ | Si | 0.24 (15%) | running |
| CONUS [121] | 17.1 | $2.3 \cdot 10^{13}$ | Ge | 1.2 (20%) | finished |
| TEXONO [123] | 28 | $6.4 \cdot 10^{12}$ | Ge | 1.1 (30%) | finished |
| NCC-1701 [125] | 10.4 | $4.8 \cdot 10^{13}$ | Ge | 1.1 (0%) | finished |
| RECODE [129] | ~25 | $\sim 1.0 \cdot 10^{13}$ | Ge | $0.9^{(**)}$ | comm. |
| Atucha II [130] | 12 | $2.3 \cdot 10^{13}$ | Si | 0.44 (45%) | comm. |
| **Cryogenic bolometers** | | | | | |
| NUCLEUS [92] | 72, 102 | $3.0 \cdot 10^{12}$ | W, Ca Al, O | $0.02^{(**)}$ | comm. |
| RICOCHET [136]$^{(*)}$ | 8.8 | $1.1 \cdot 10^{12}$ | Ge, Zn | $0.01^{(**)}$ | comm. |
| **Noble gas/liquid** | | | | | |
| RED-100 [89] | 19 | $1.4 \cdot 10^{13}$ | Xe, Ar | 2 (15%) | running |
| RELICS [132] | ~25 | $\sim 1.0 \cdot 10^{13}$ | Xe | $0.6\text{-}1.4^{(**)}$ | comm. |
| **Scintillating crystals** | | | | | |
| NEON [78] | 23.7 | $8.1 \cdot 10^{12}$ | Na, I | $2, 6^{(**)}$ | running |

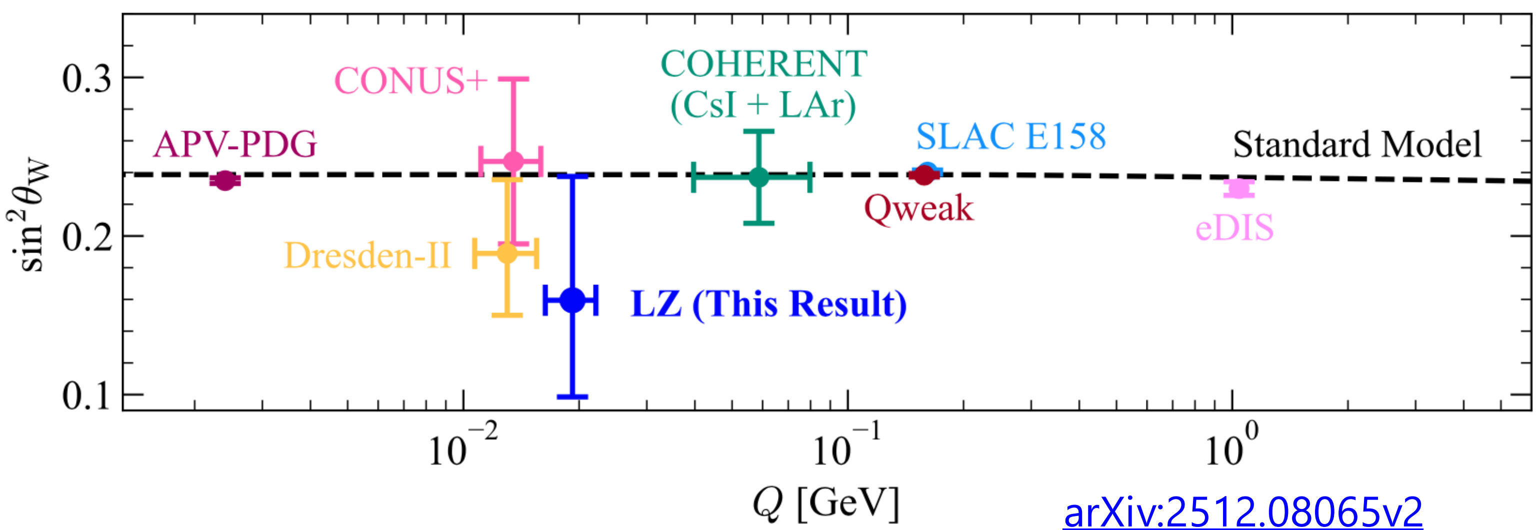
+ directional recoils (CYGNUS), mineral detection (PALEOCCENE), supernova (RES-NOVA) and more...

# More interpretation with new data rolling in




*Phys.Lett.B* 869 (2025) 139856 • e-Print: 2506.13555 [hep-ph]

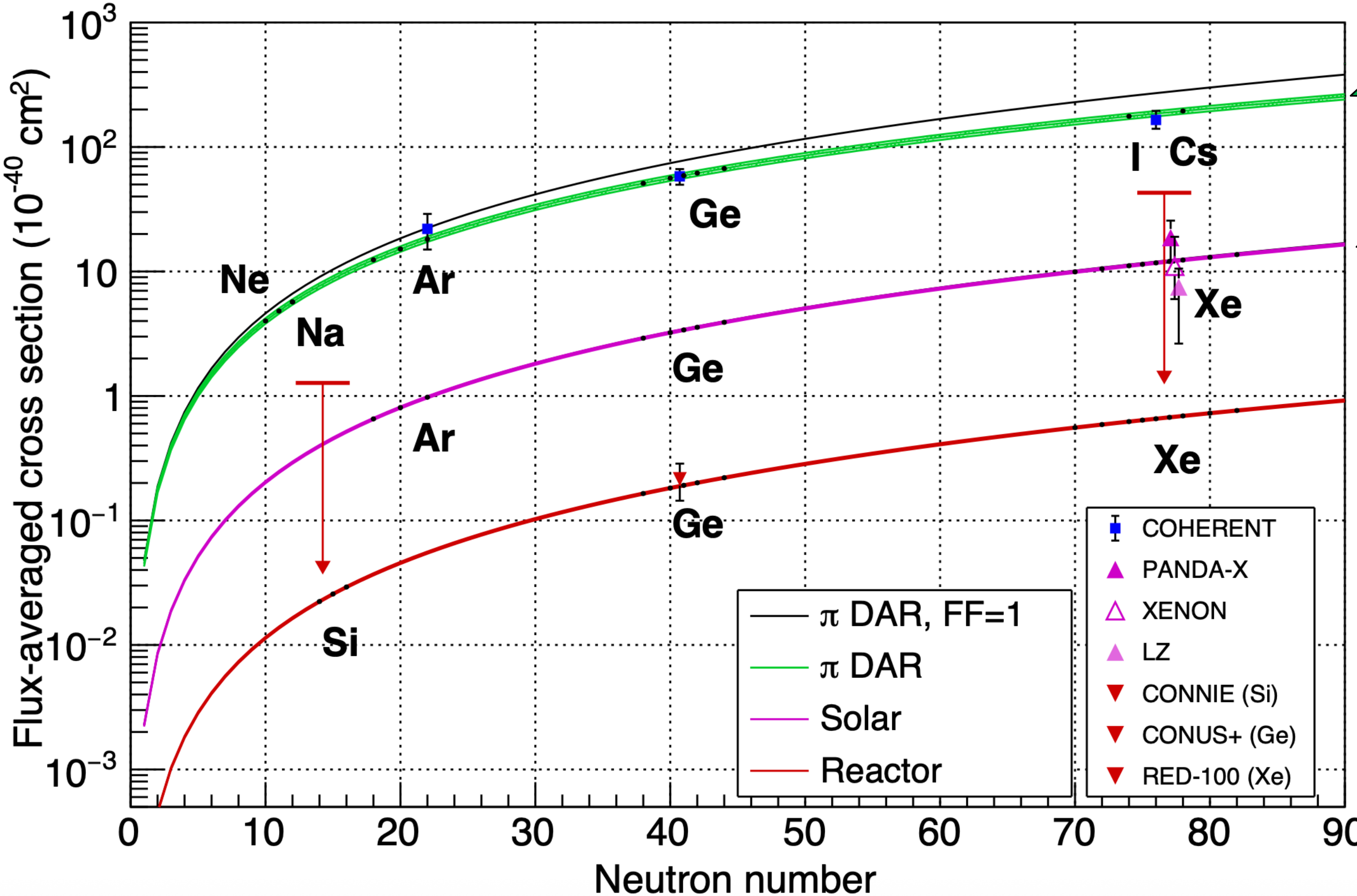
COHERENT (first Ge) and CONUS+ Ge data

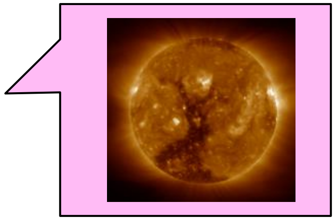


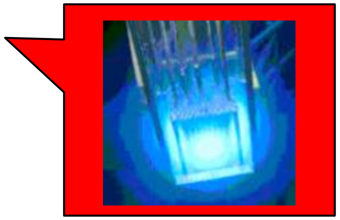

[arXiv:2512.08065v2](https://arxiv.org/abs/2512.08065v2)

Including LZ data

# Worldwide CEvNS status

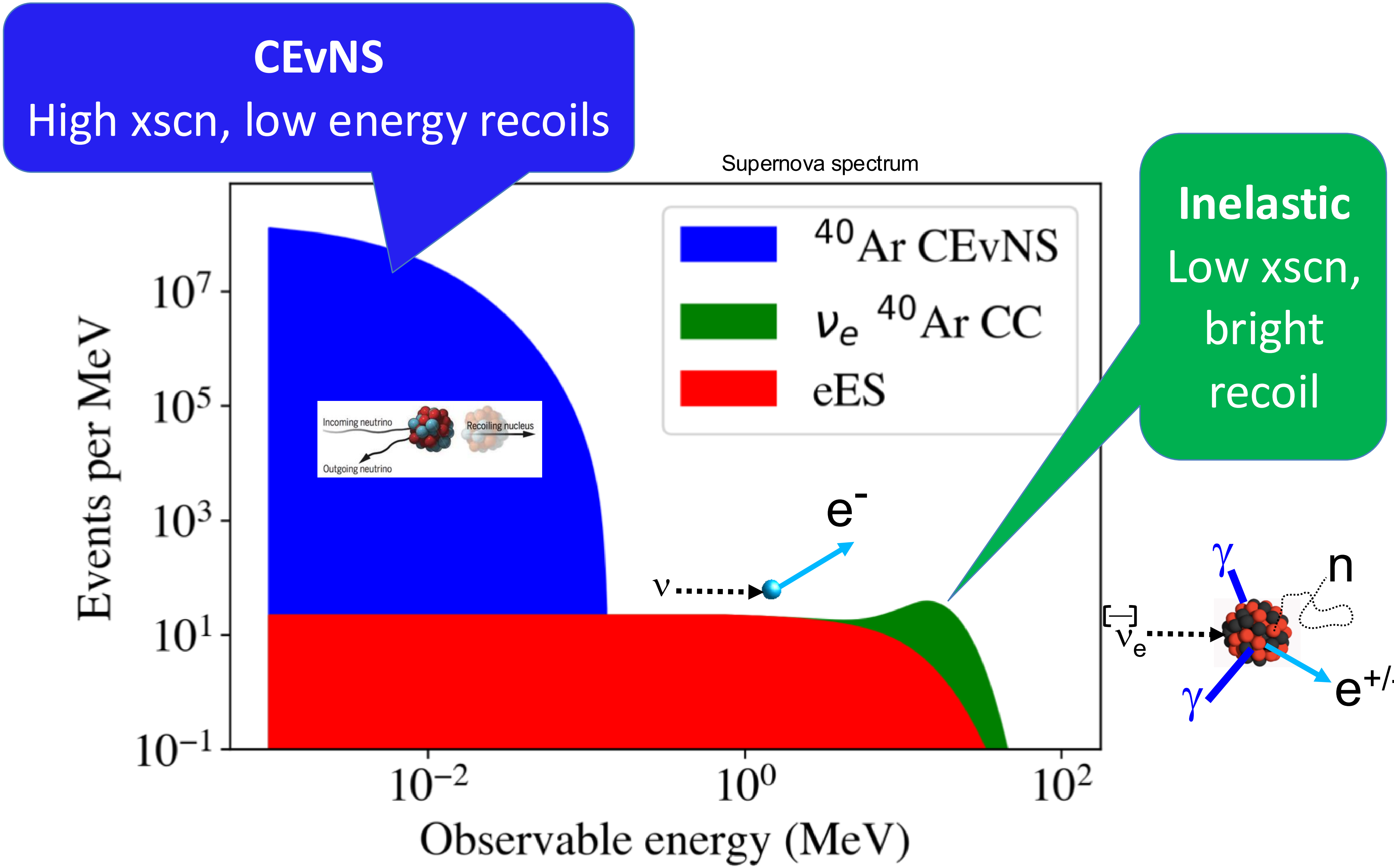


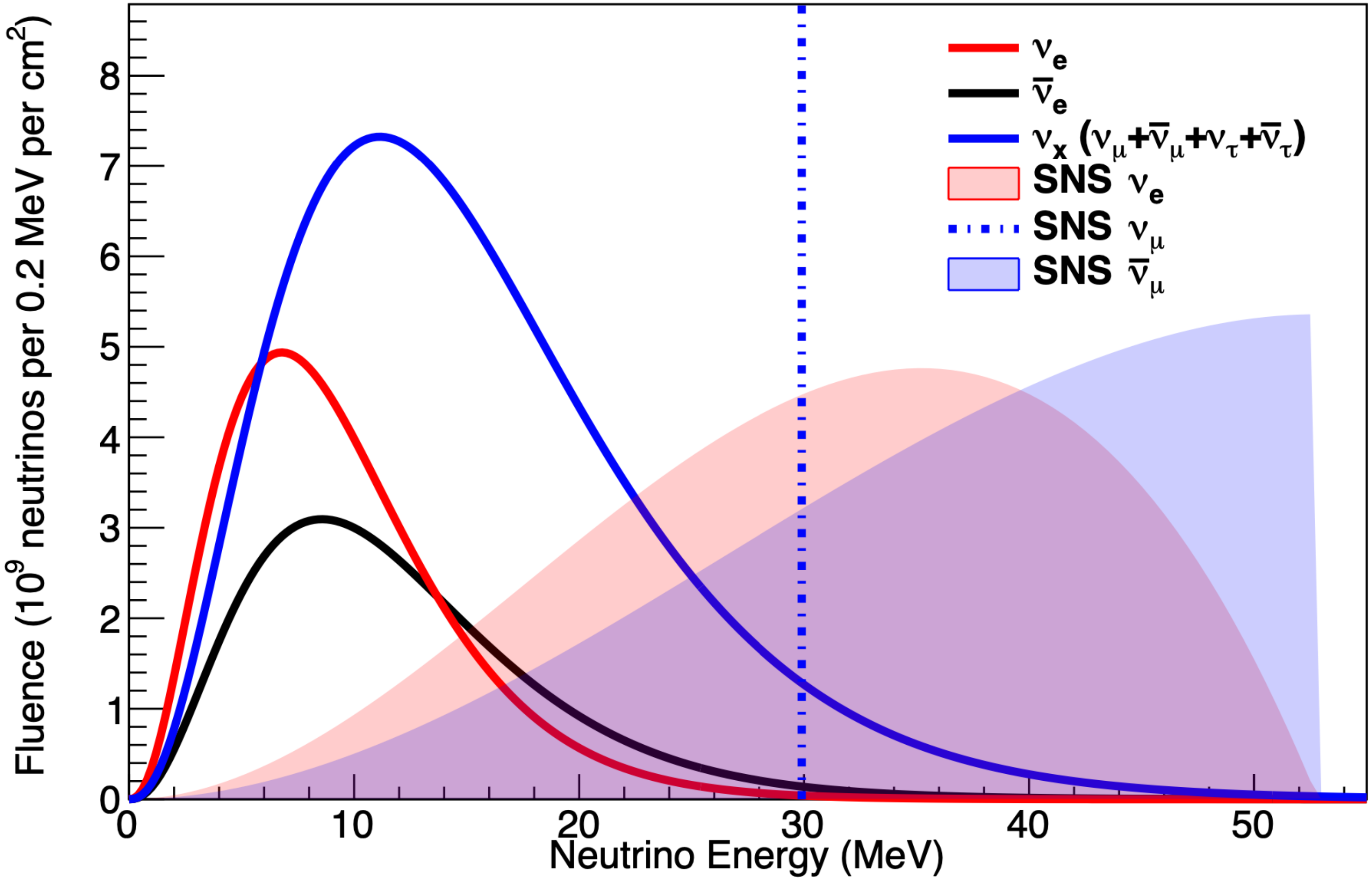


"Best" measurement for each target/source combination

# Now look at the rare, bright ones...



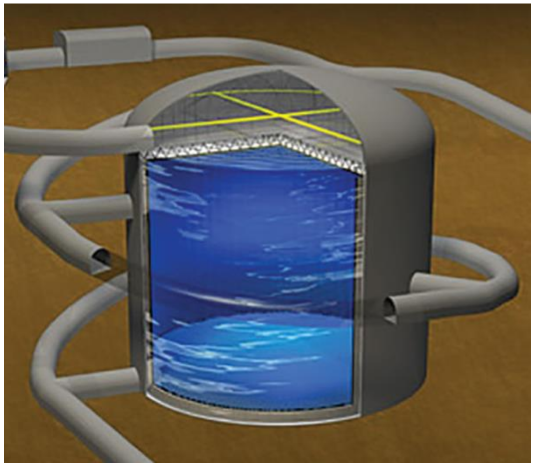
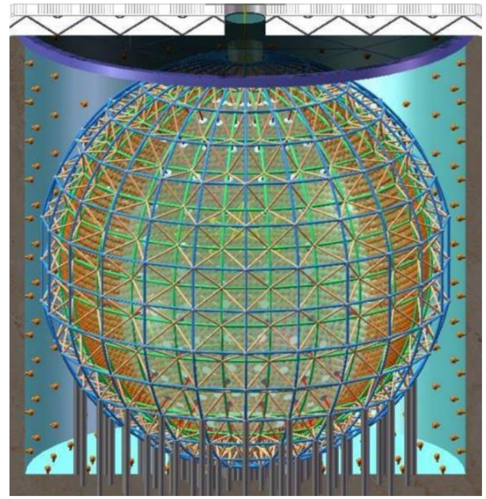
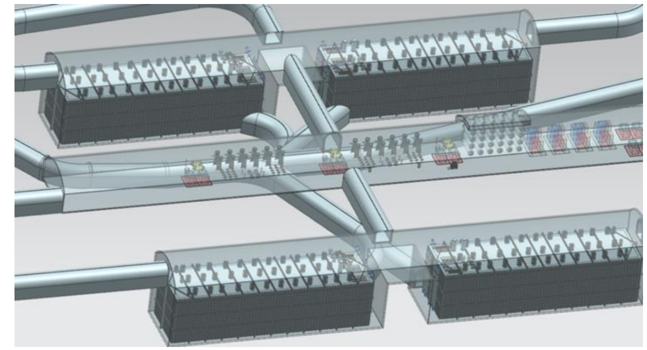
# Stopped-pion neutrinos relevant for **supernova burst** regime




- understanding of SN processes & detection
- understanding of weak couplings ($g_A$ quenching) & nuclear transitions

See:Workshop on Neutrino Interaction Measurements for Supernova Neutrino Detection
https://indico.phy.ornl.gov/event/217/

# Future Large Supernova-Burst-Sensitive Neutrino Detectors

**Hyper-Kamiokande**
260 kton water
Japan

**JUNO**
20 kton scintillator (hydrocarbon)
China

**DUNE**
40 kton argon
USA

- Hyper-K /JUNO are primarily sensitive to **nuebar**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- DUNE is primarily sensitive to **nue**

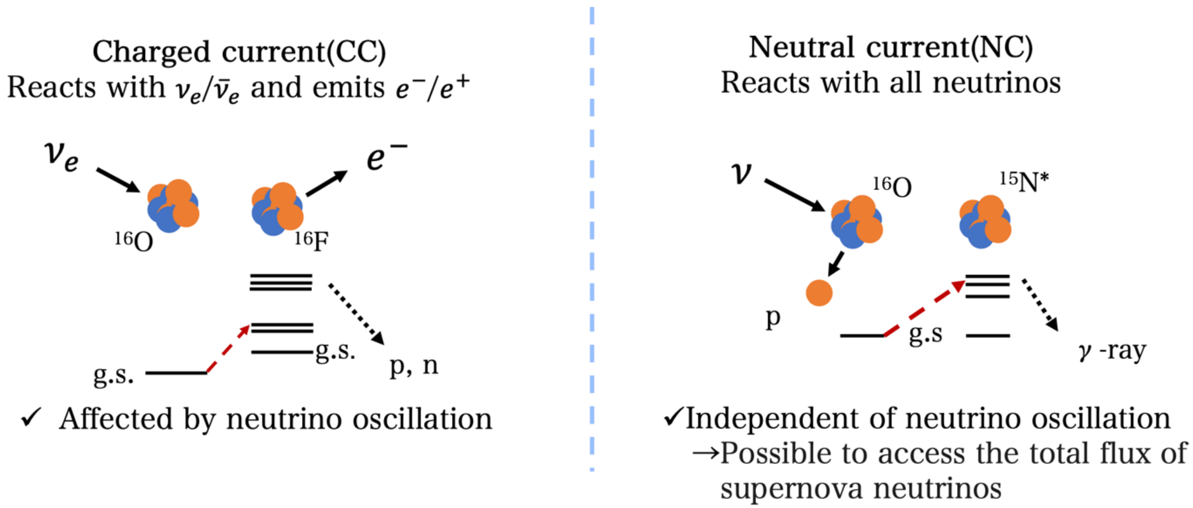
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

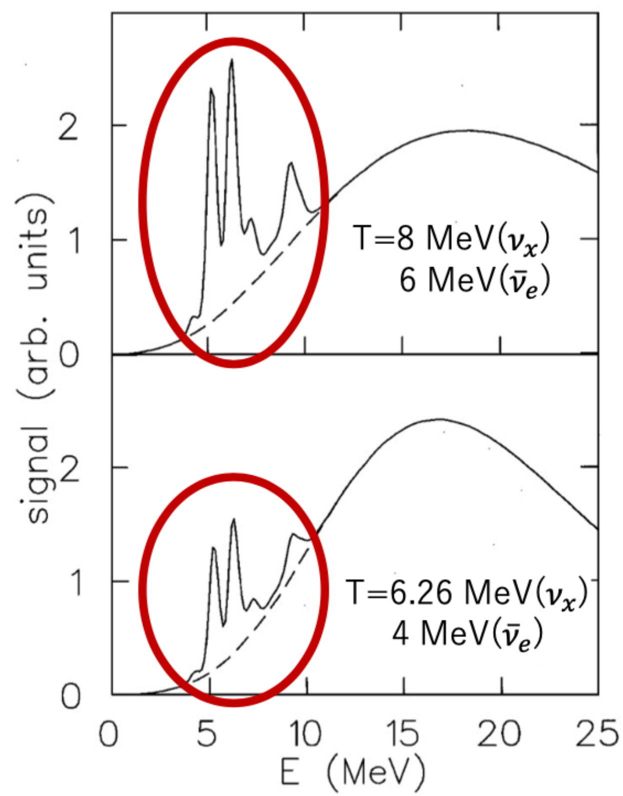
***extreme*** complementarity

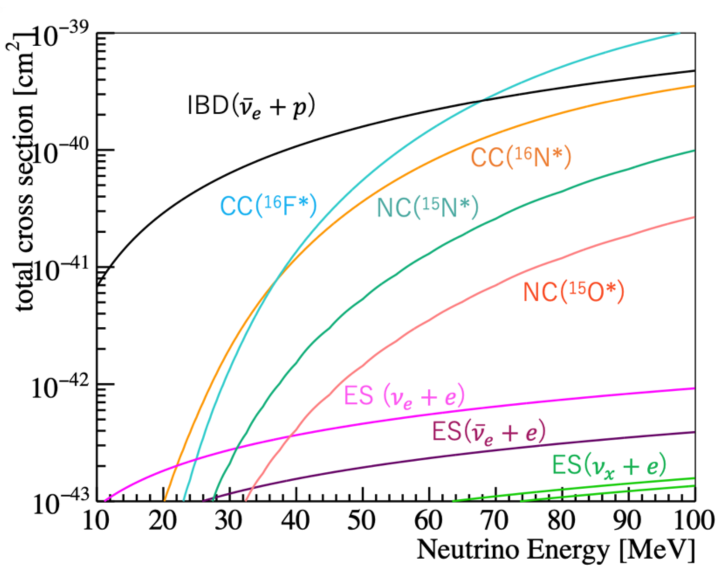

[....but each also has subdominant channels. at few to ~10% level, e.g. $\nu_e$+$^{16}$O ]

# Example 1: **CC and NC interactions on oxygen**

F. Nakanishi, ORNL workshop 2023




Observables depend on nuclear structure

Expected energy spectrum in SK from K. Langanke et al.

Newer calcs by Nakazato et al.

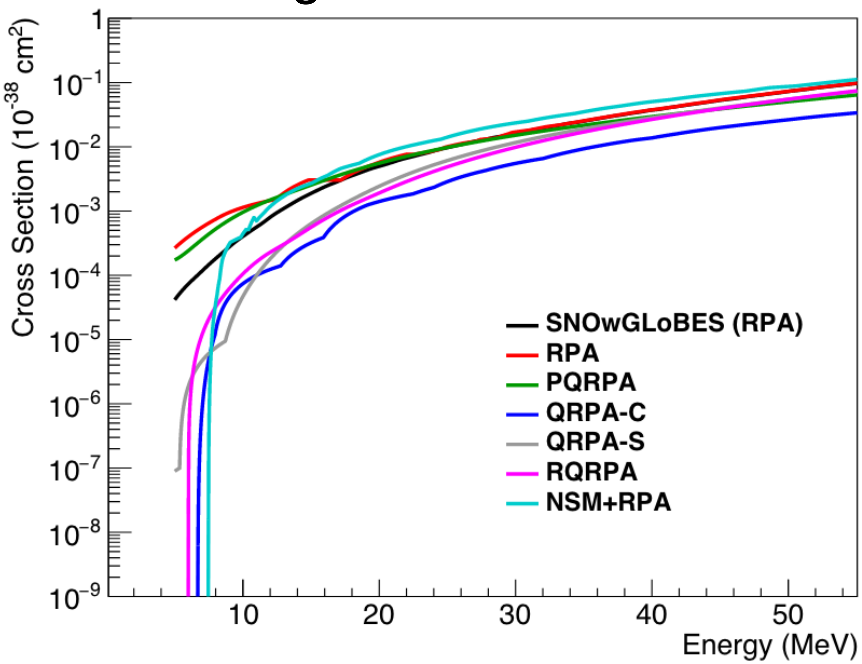
**Best to *measure* it!**

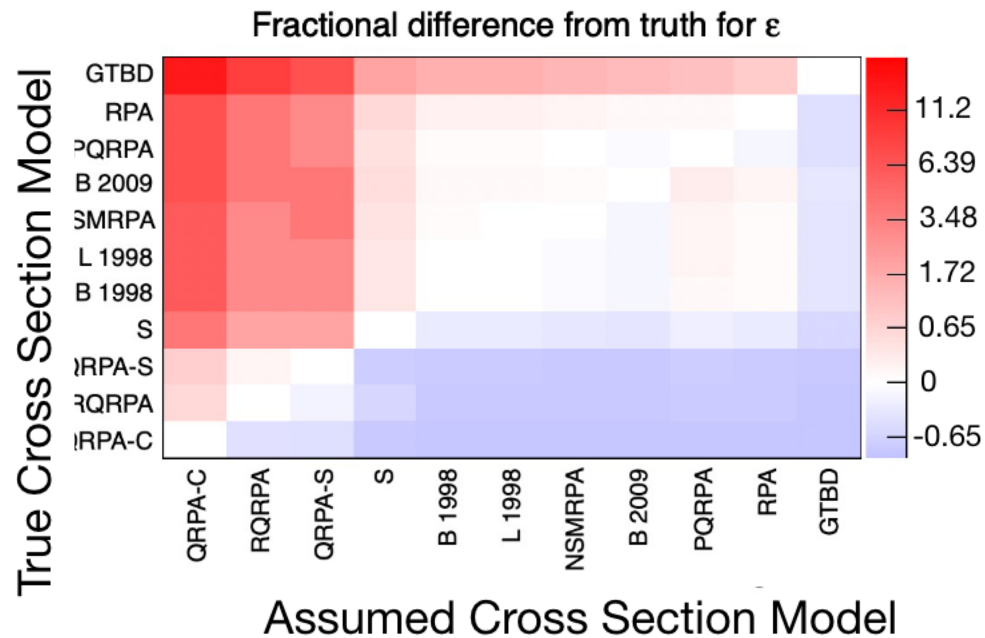
# Example 2: **CC and NC interactions on on argon**

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

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

- critical to understand (differential) cross sections for supernova physics in DUNE
- large theoretical uncertainties on cross sections
- **no** existing measurements




**Impact of cross-section uncertainties on supernova neutrino spectral parameter fitting in the Deep Underground Neutrino Experiment**

DUNE Collaboration • A. Abed Abud (CERN) et al. (Mar 29, 2023)

Published in: *Phys.Rev.D* 107 (2023) 11, 112012 • e-Print: 2303.17007 [hep-ex]

Best to ***measure*** it!

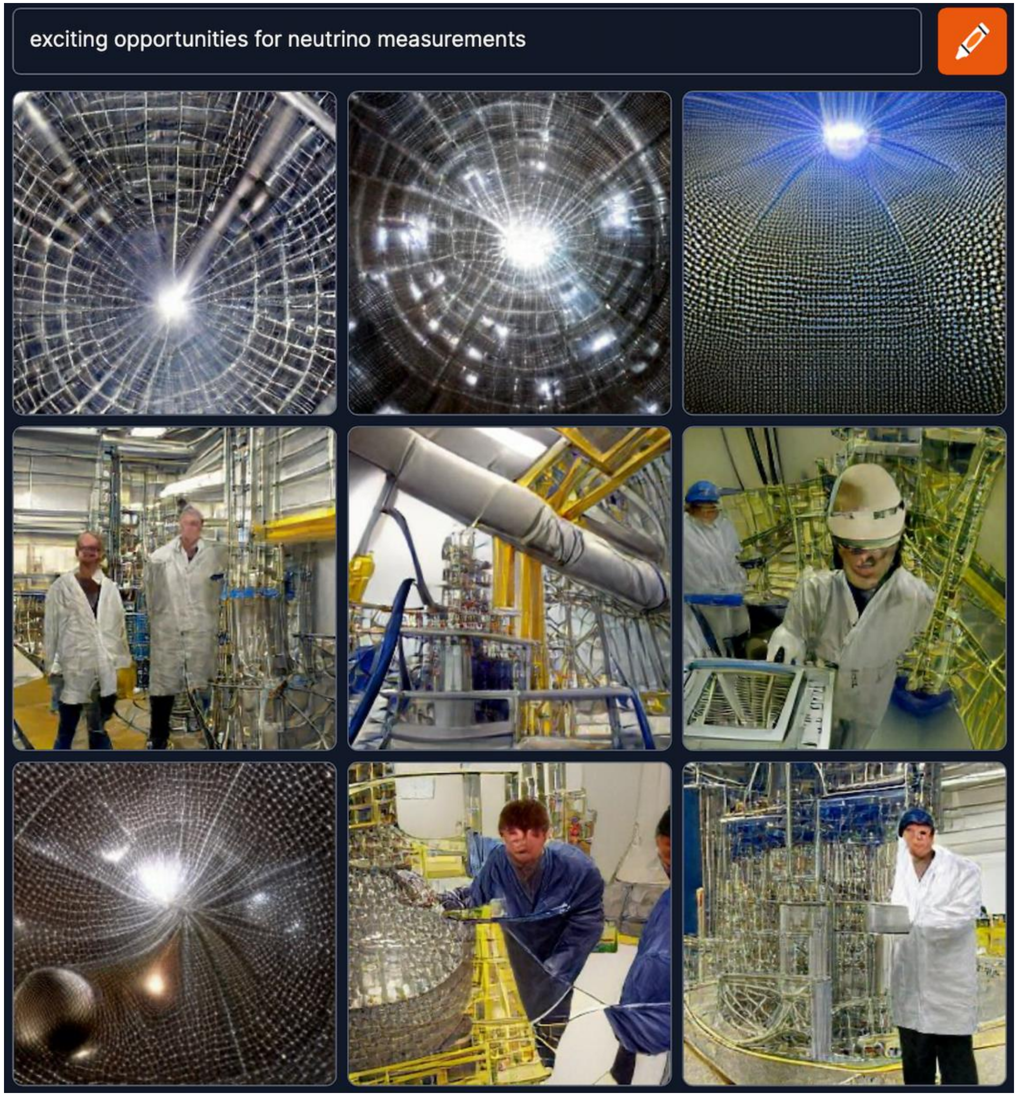
# Take-Away Messages

- **Understanding of neutrino interactions** is critical for neutrino physics over a huge range of energies

- **CEvNS is a new low-energy frontier**
  - BSM searches
  - Nuclear form factors

- **Few-tens-of-MeV inelastics regime is largely unexplored**

- **Many exciting opportunities for measurements in the years ahead** (and theory needed!)



# Extras/Backups