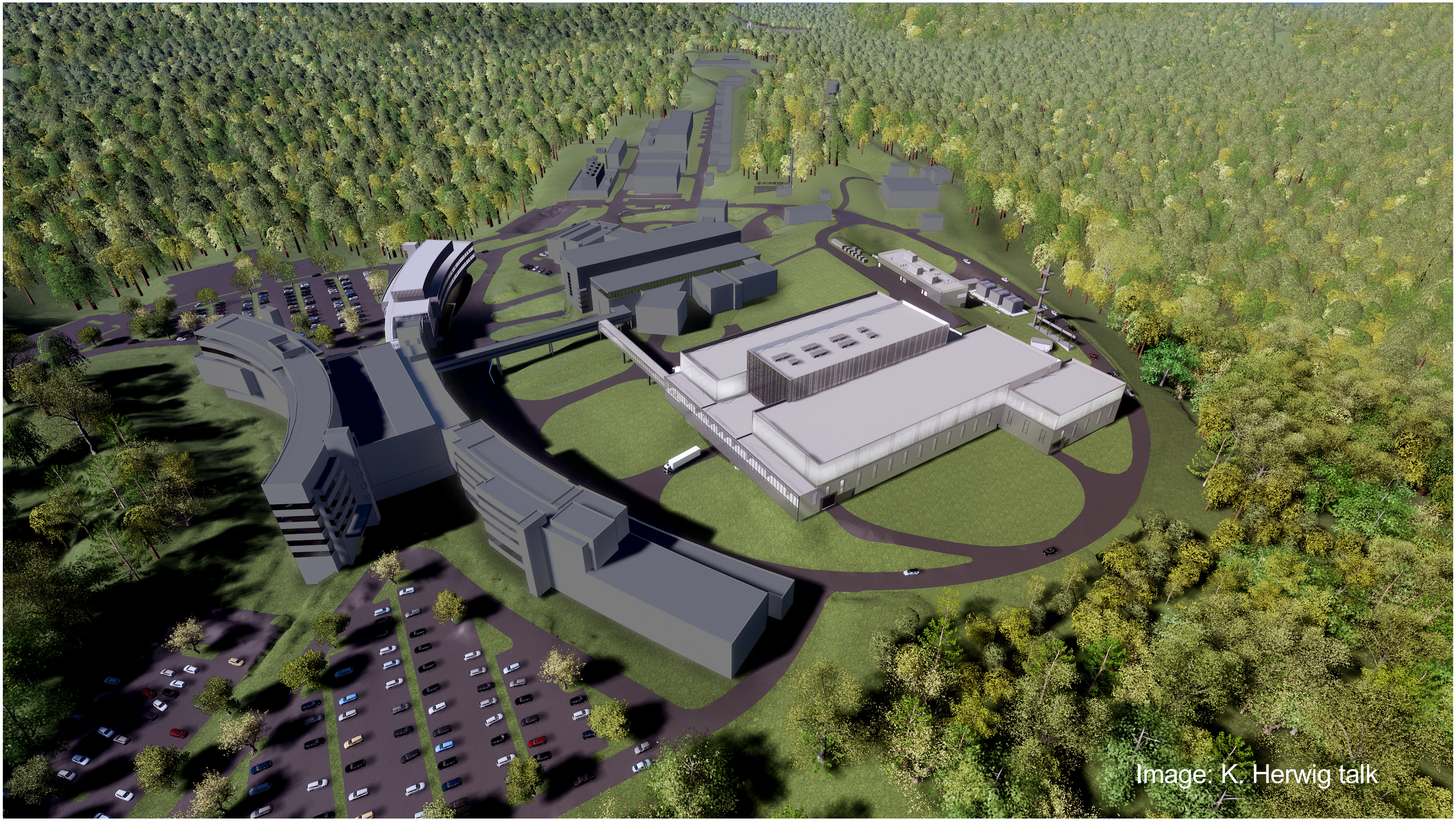
Opportunities at the ORNL Spallation Neutron Source Second Target Station

Kate Scholberg, Duke University

Interplay of Nuclear, Neutrino and BSM Physics at Low Energies

Institute for Nuclear Theory, Seattle.

April 20, 2023

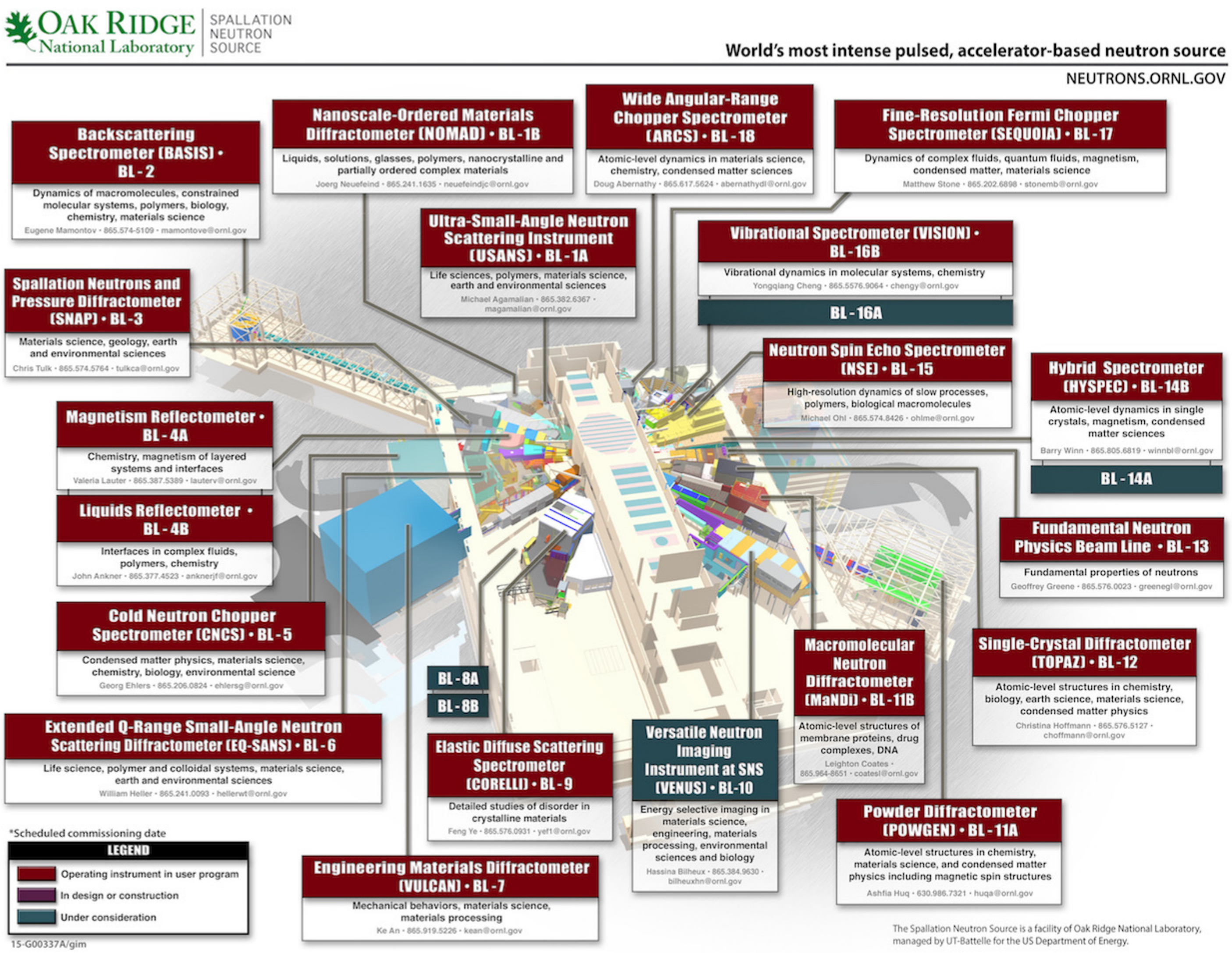


Outline

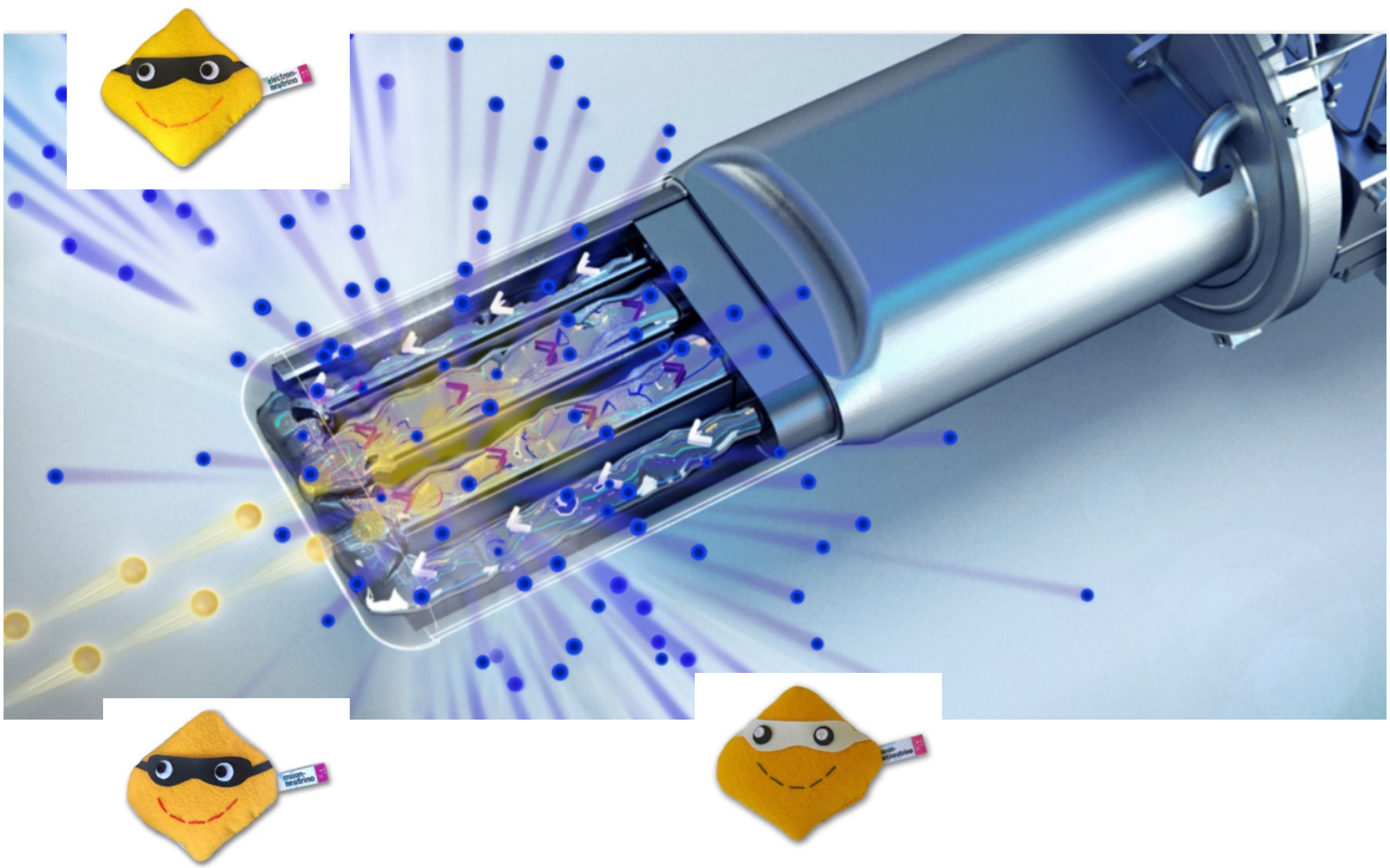
- Spallation Sources for Fundamental Physics
- Neutrino Production (and more)
- The SNS @ ORNL
- The COHERENT Experiment
- Physics with COHERENT at the FTS
  - Low-energy recoils
  - MeV to tens-of-MeV scale events
- The ORNL Second Target Station
- Future Opportunities

Spallation Neutron Sources

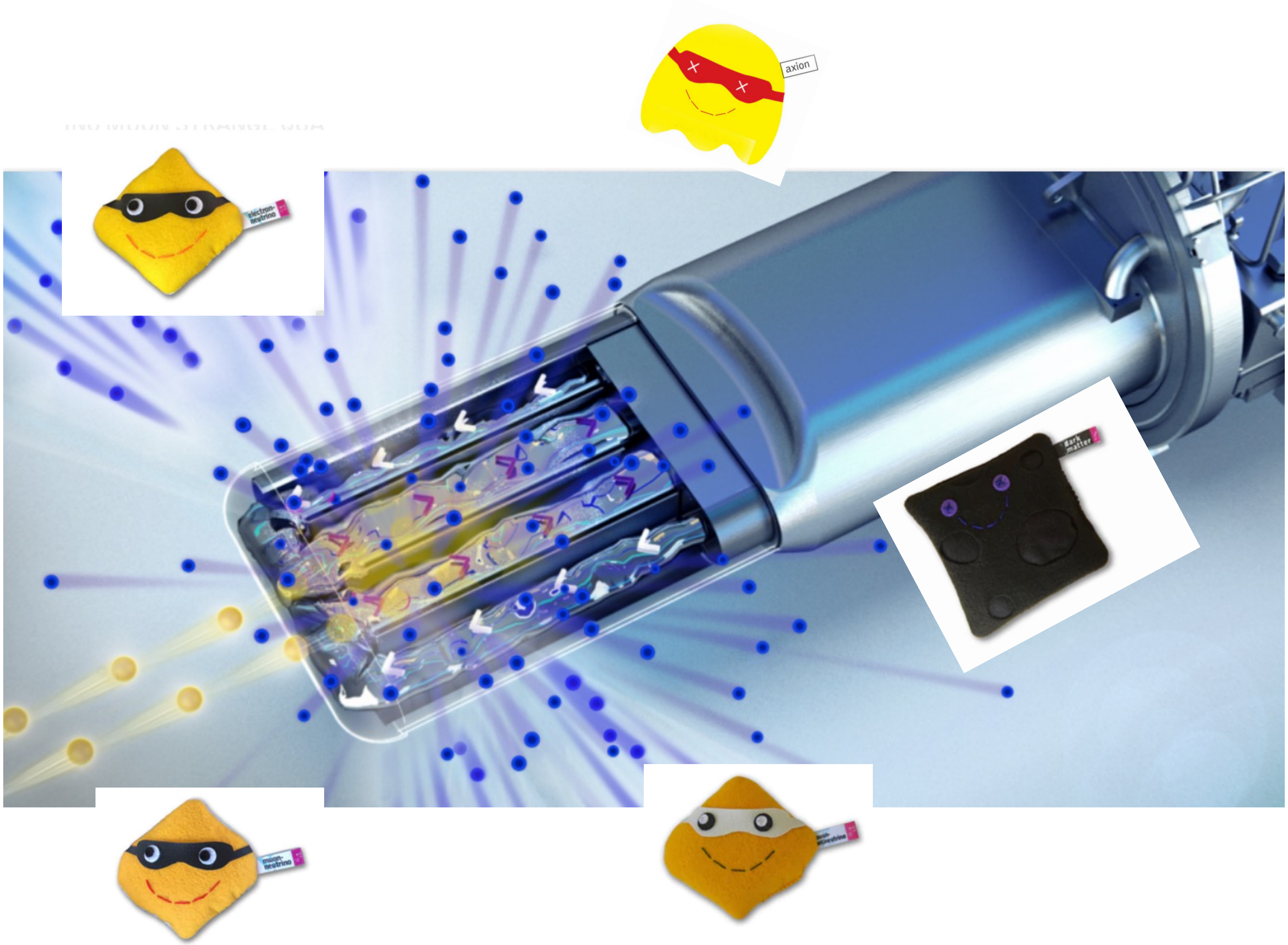
Neutrons
for many
science topics



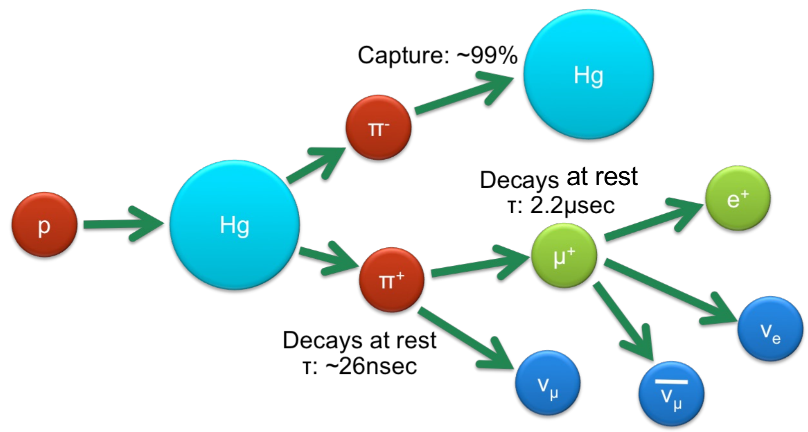
They also make weakly-interacting particles as a free by-product

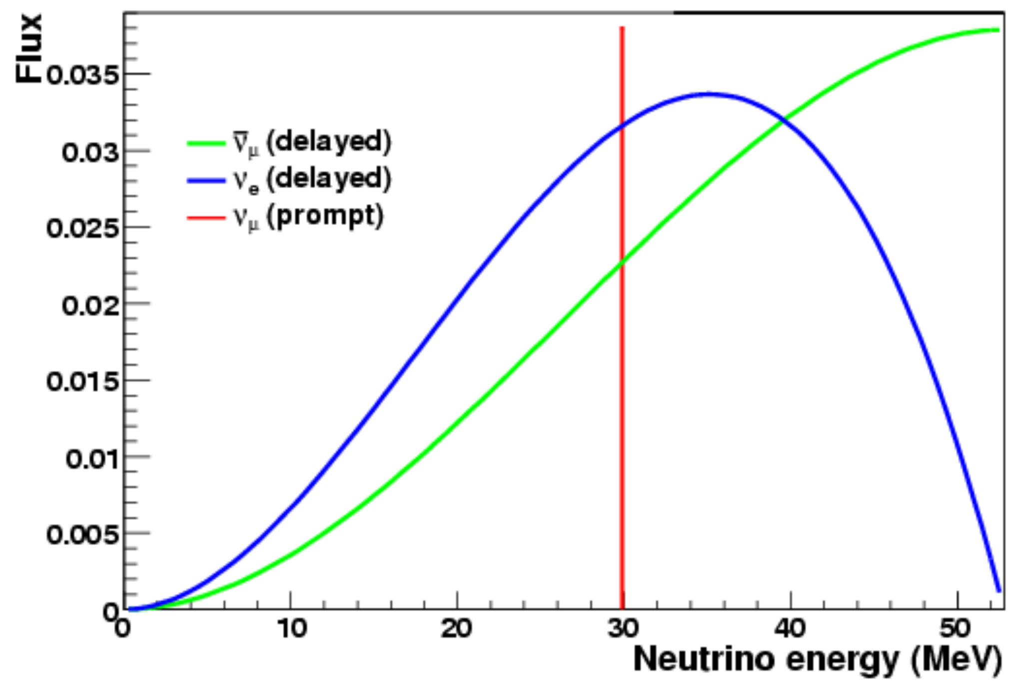


Maybe even exotic ones...



Stopped-Pion (πDAR) Neutrinos





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

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

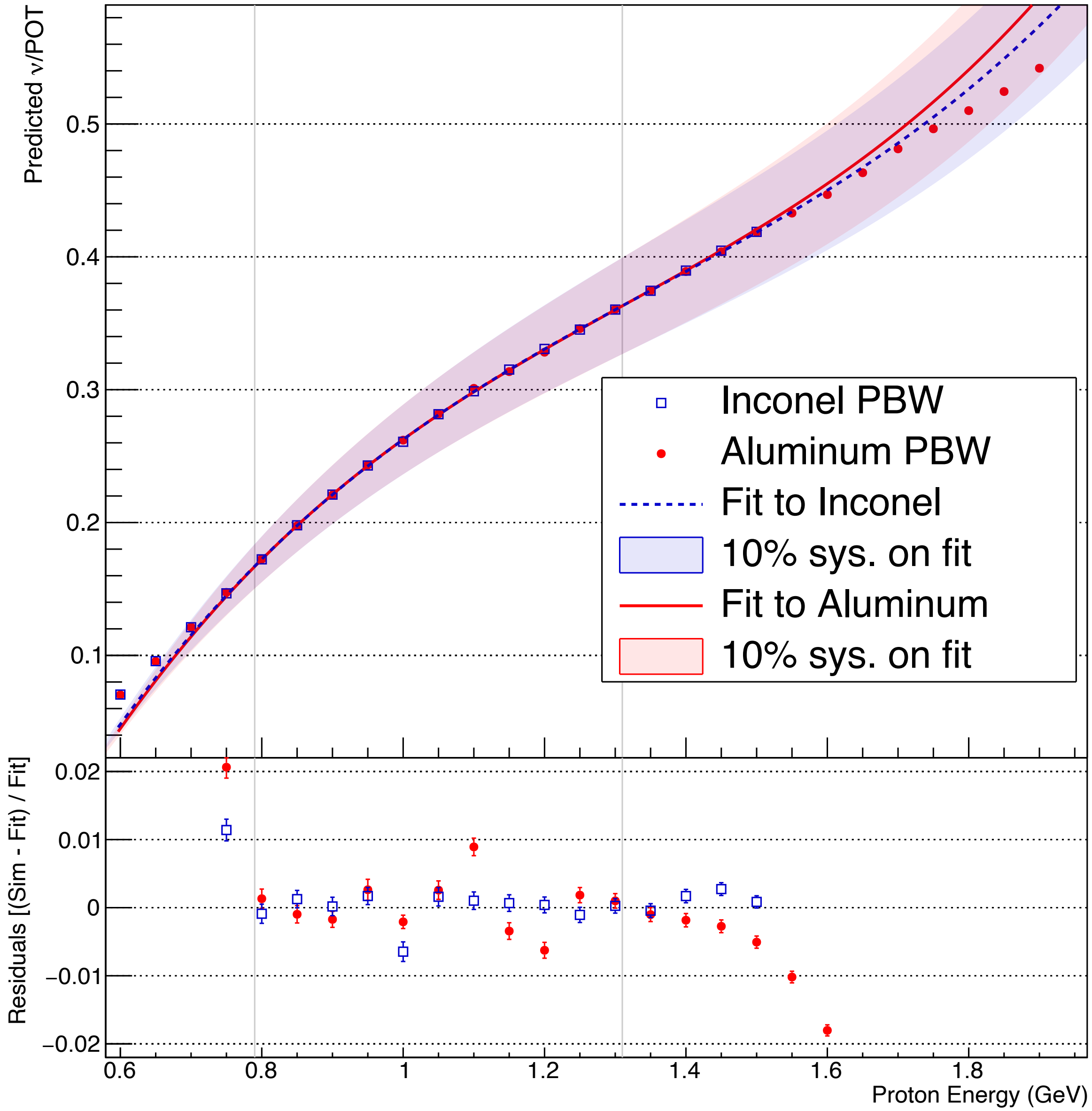
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

Fluxes depend on proton energy as well as power

From Becca Rapp: Geant4 simulations on Hg target

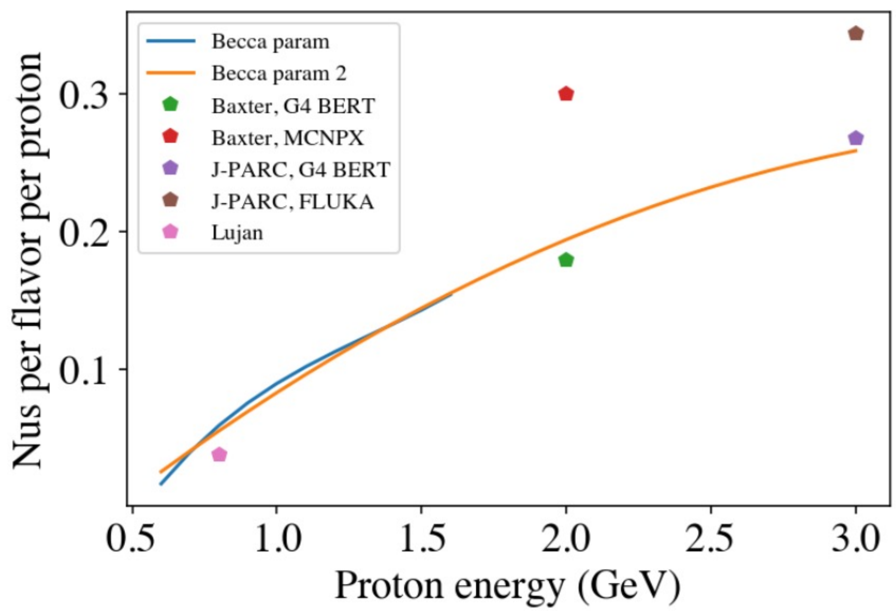
Total neutrinos per proton (all 3 flavors)



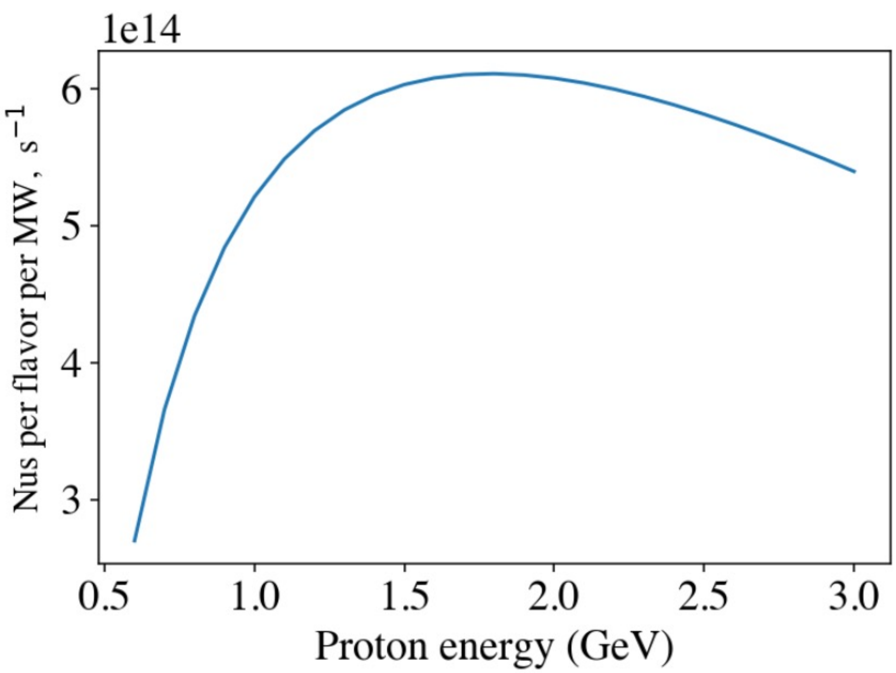
G4 QGSP_BERT, validated vs HARP/HARP-CDP

Based on: *Phys.Rev.D* 106 (2022) 3, 032003 arXiv:2109.11049

Neutrinos per proton, per MW



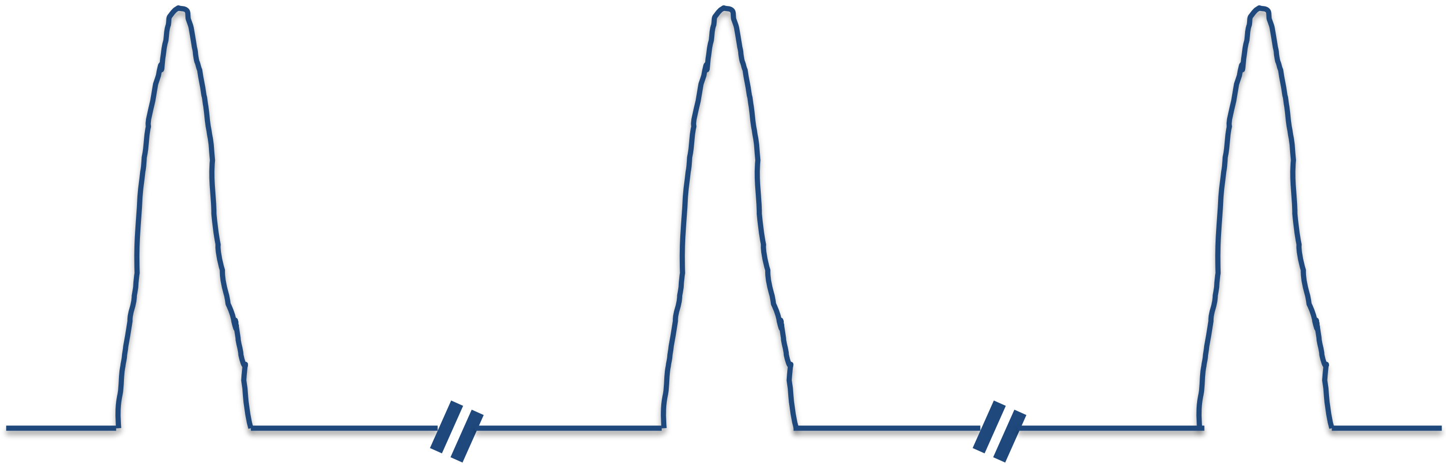
- Quite large uncertainties
  > 1.5 MeV
- QGSP_BERT is
  less optimistic



- Assuming QGSP_BERT parameterization to 3 GeV,
  ~1.5 GeV is optimal νs/power

Note:
higher proton energy,
fewer protons per MW

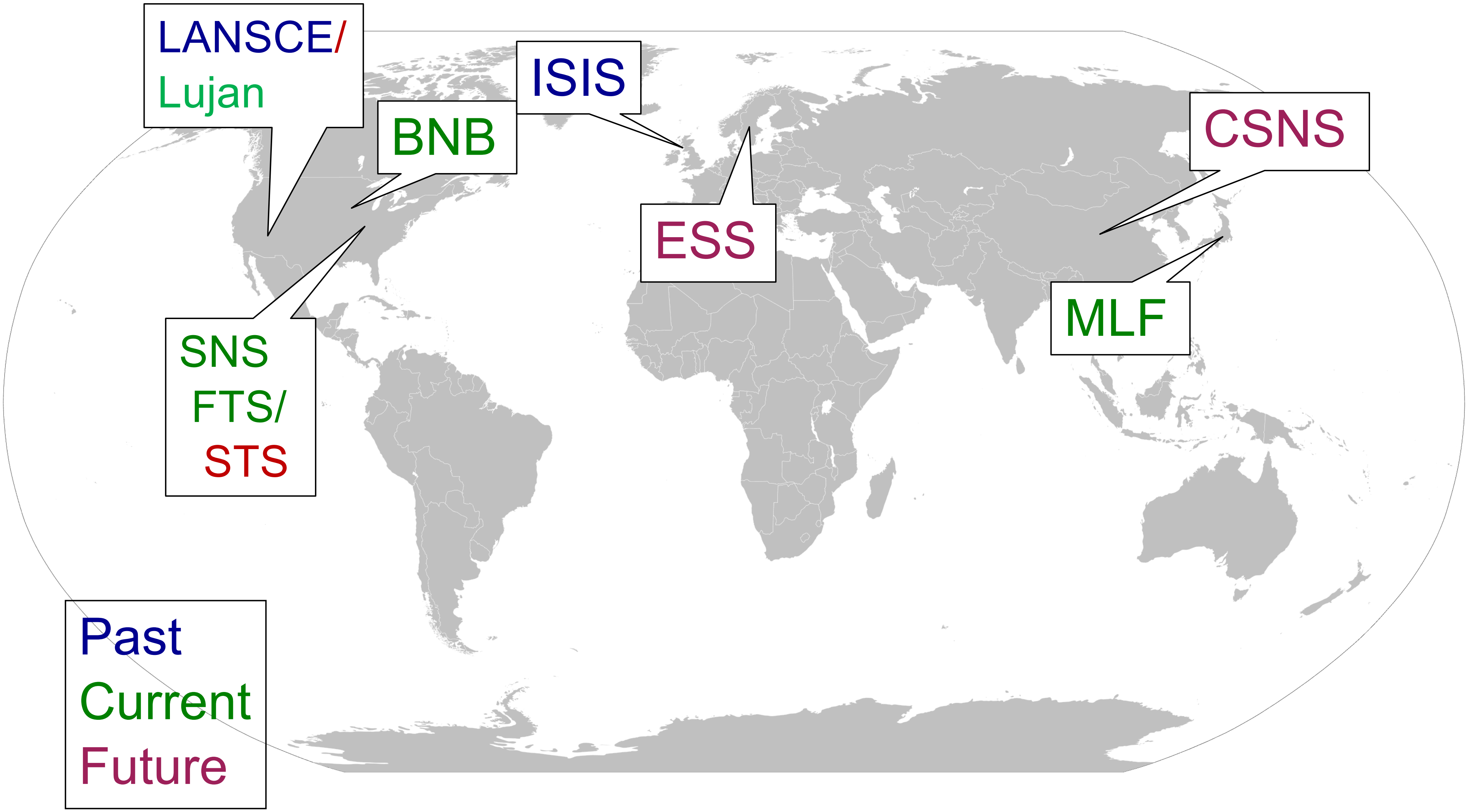
When the beam is **pulsed**, make use of the time structure to reject background



- Only look for stopped-π ν's within few μs of proton pulse
- ***Measure*** the steady-state background off-pulse
- You only care about sqrt of steady-state bg...
- (Beam-related bg is more pernicious... )

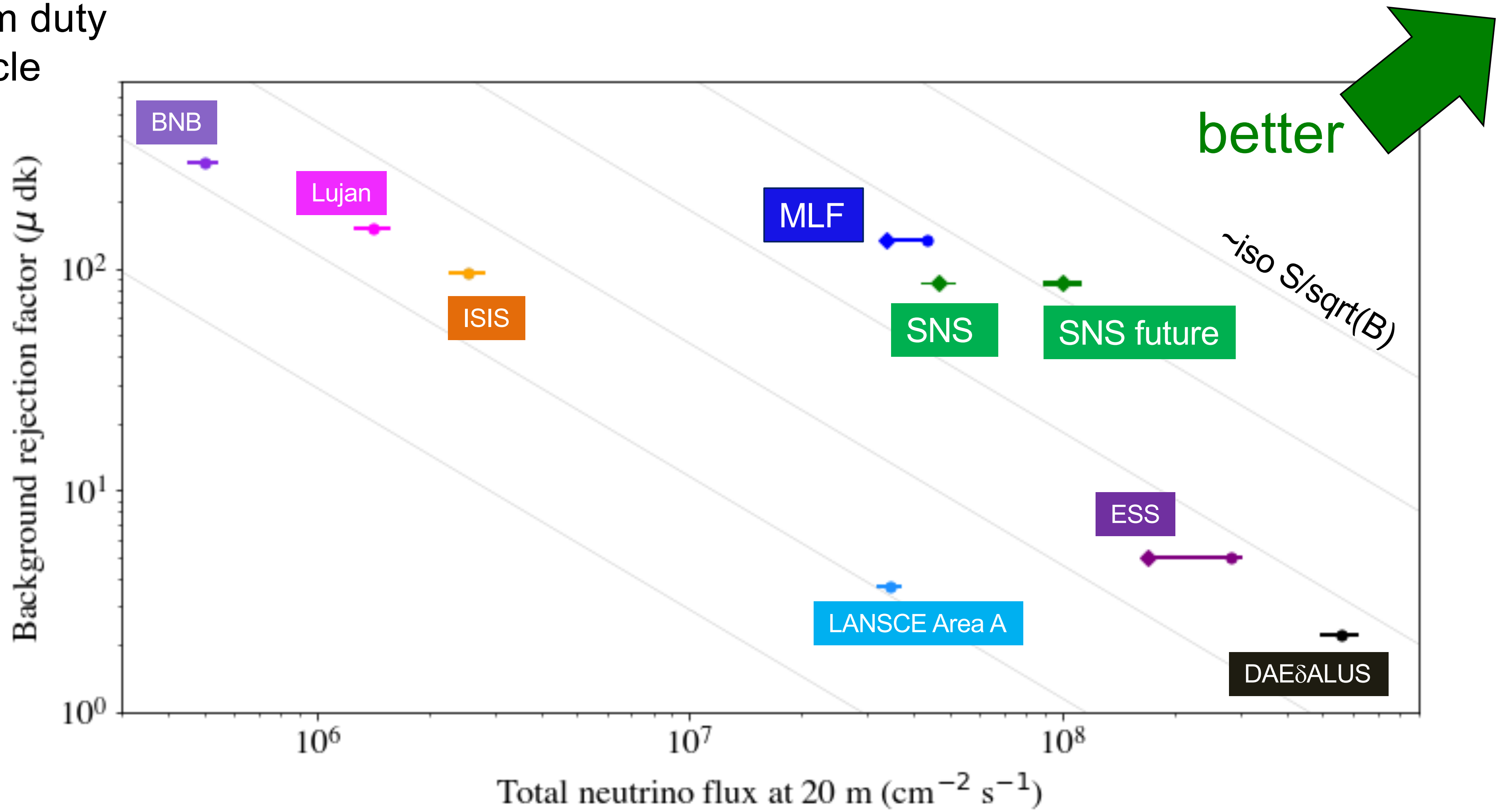
  - "Duty factor" or "duty cycle" = fraction of time beam is on
  - Inverse duty factor → "background rejection factor"

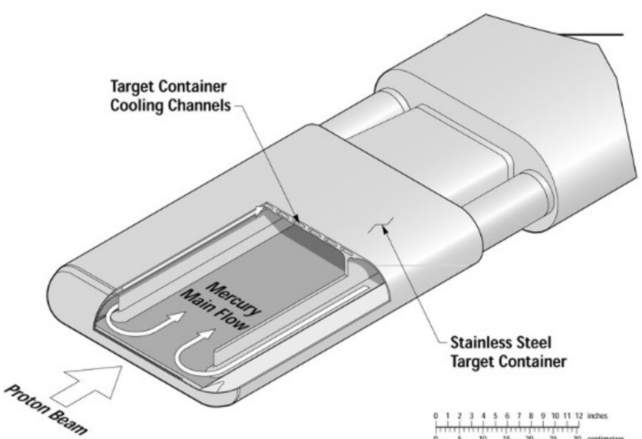
Stopped-Pion Neutrino Sources Worldwide



Comparison of stopped-pion ν sources

from duty cycle



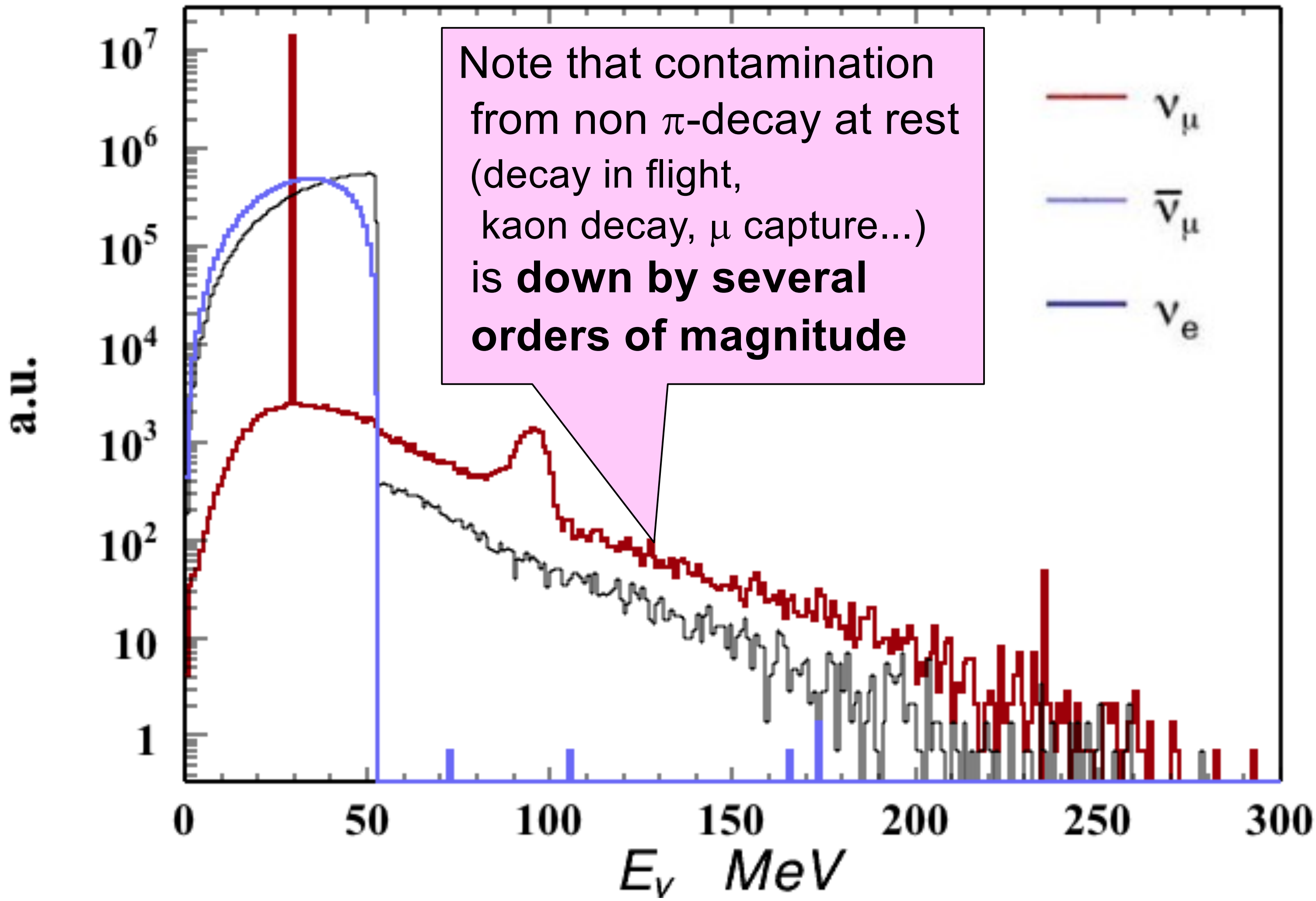


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW +...
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

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

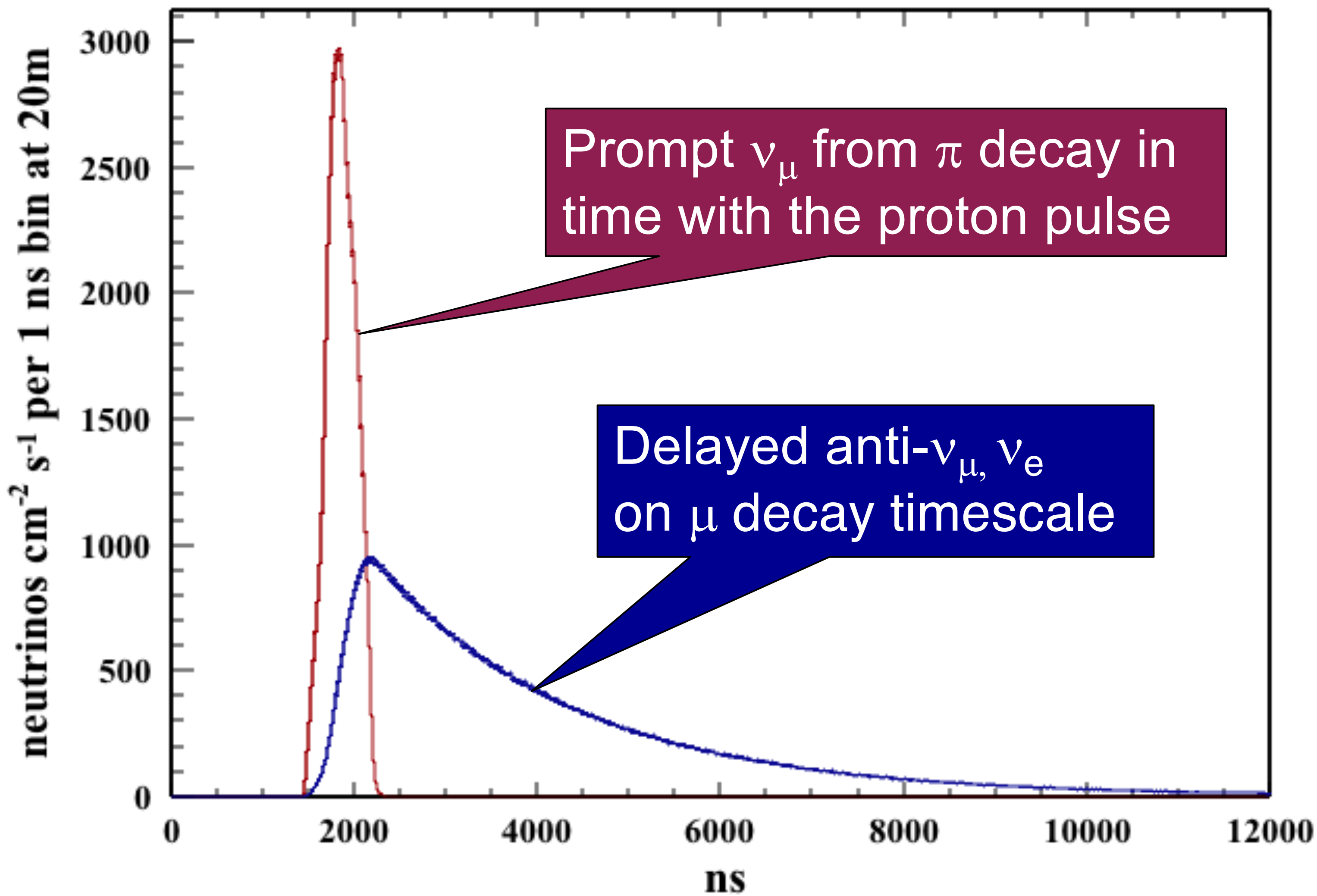
0.08 neutrinos per flavor per proton on target



SNS flux (1.4 MW):
430 x 10^5 ν/cm^2/s
@ 20 m

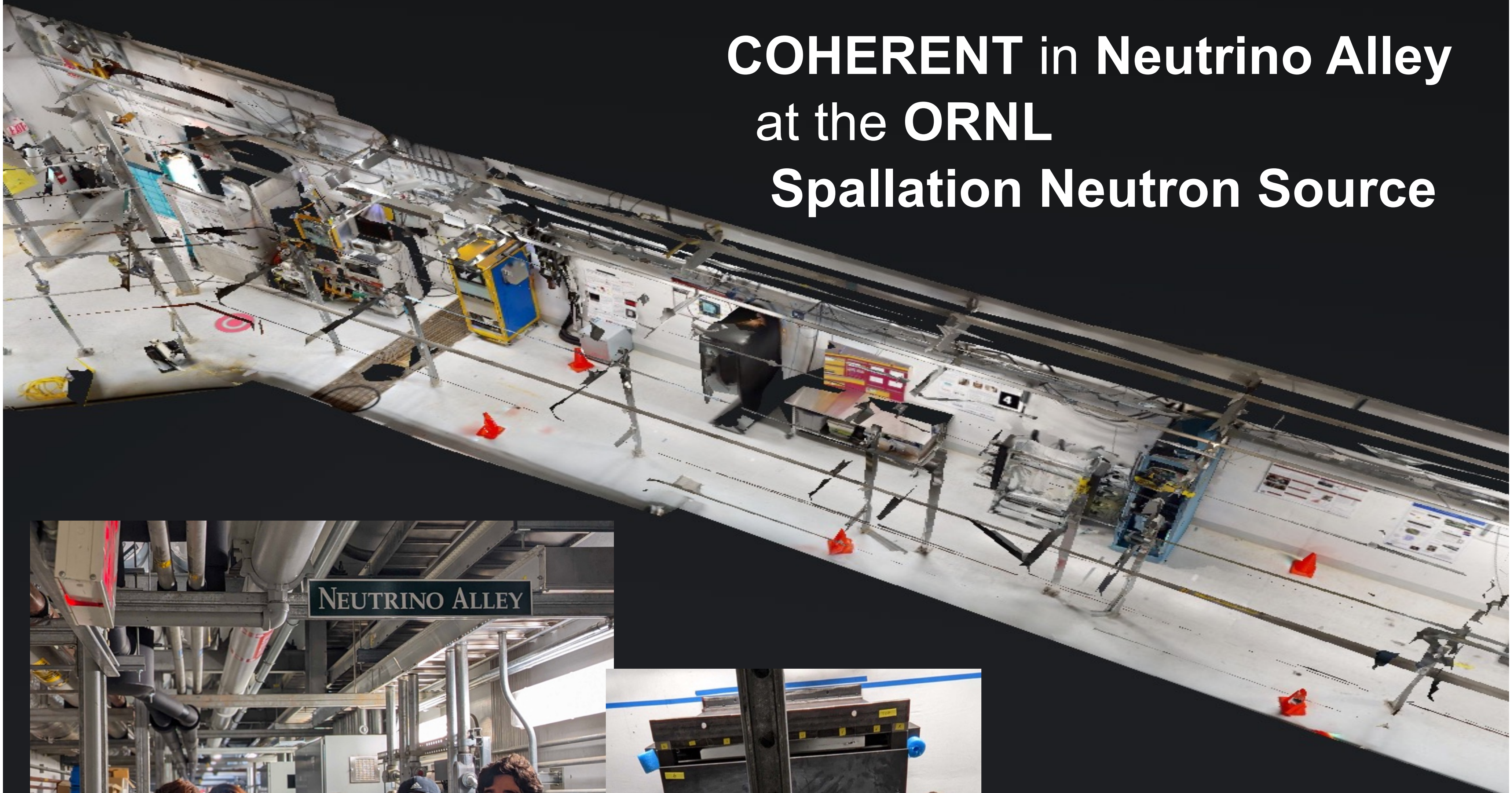
Time structure of the SNS source

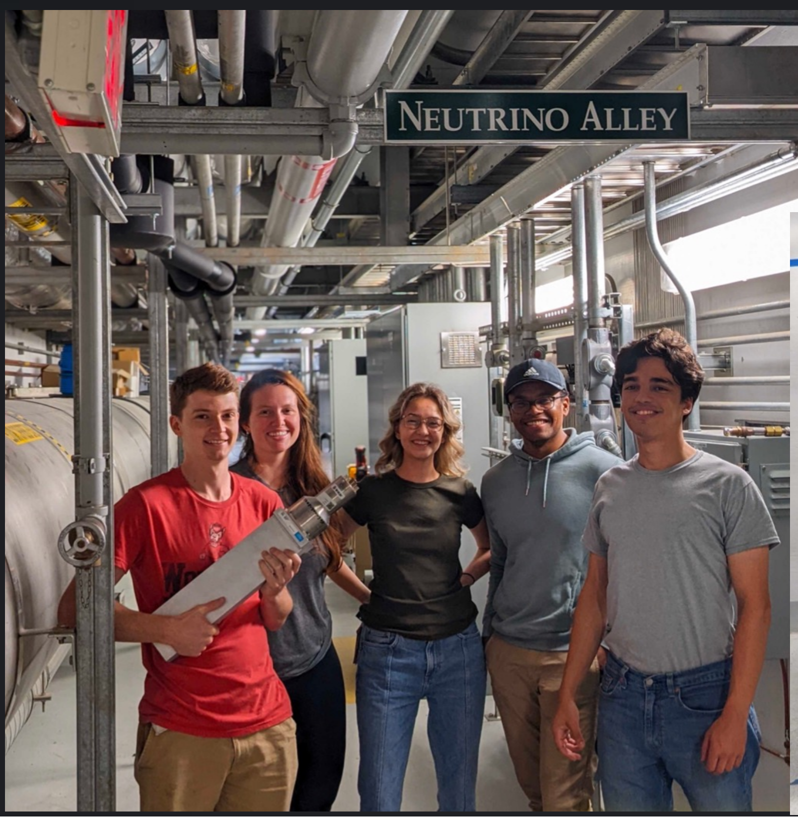
60 Hz *pulsed* source



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

COHERENT in Neutrino Alley at the ORNL Spallation Neutron Source





COHERENT
SNS
SPALLATION NEUTRON SOURCE

The COHERENT collaboration

http://sites.duke.edu/coherent

COHERENT

SNS SPALLATION NEUTRON SOURCE

Carnegie Mellon University	Duke University	UF University of Florida	
	Laurentian University Université Laurentienne	Los Alamos National Laboratory Est. 1943	MEPhI
NC Central University	NC State University	Oak Ridge National Laboratory	Sandia National Laboratories
서울대학교 Seoul National University	SLAC National Accelerator Laboratory	University of South Dakota	The University of Tennessee UT Knoxville
Tufts University	TUNL Triangle Universities Nuclear Laboratory	VT Virginia Tech	W University of Washington
Washington & Jefferson College 1781			

~90 members,
20 institutions
4 countries

U.S. Department of Energy | Office of Science

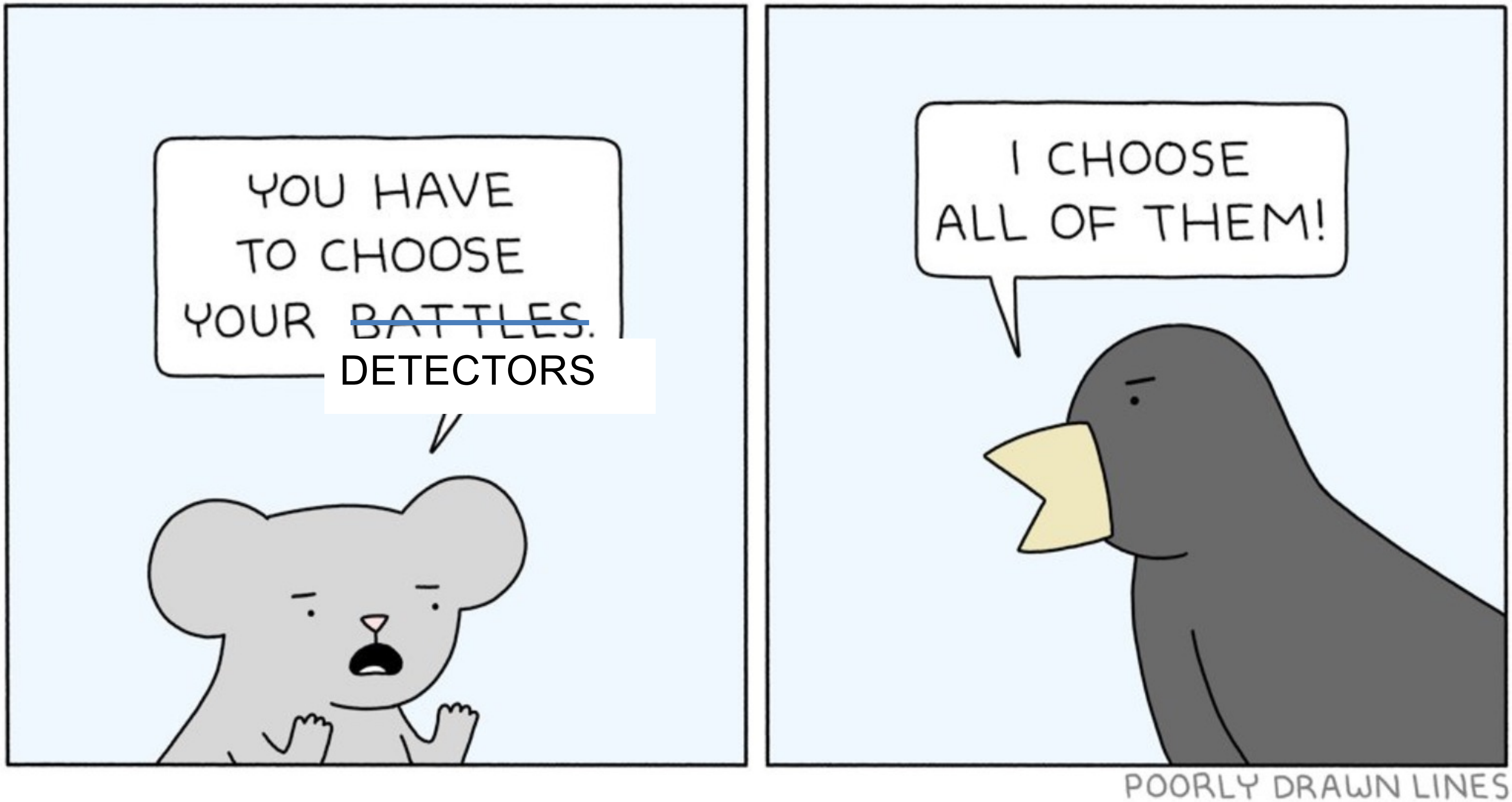
NSF

NNSA National Nuclear Security Administration

Consortium for Monitoring, Technology, and Verification

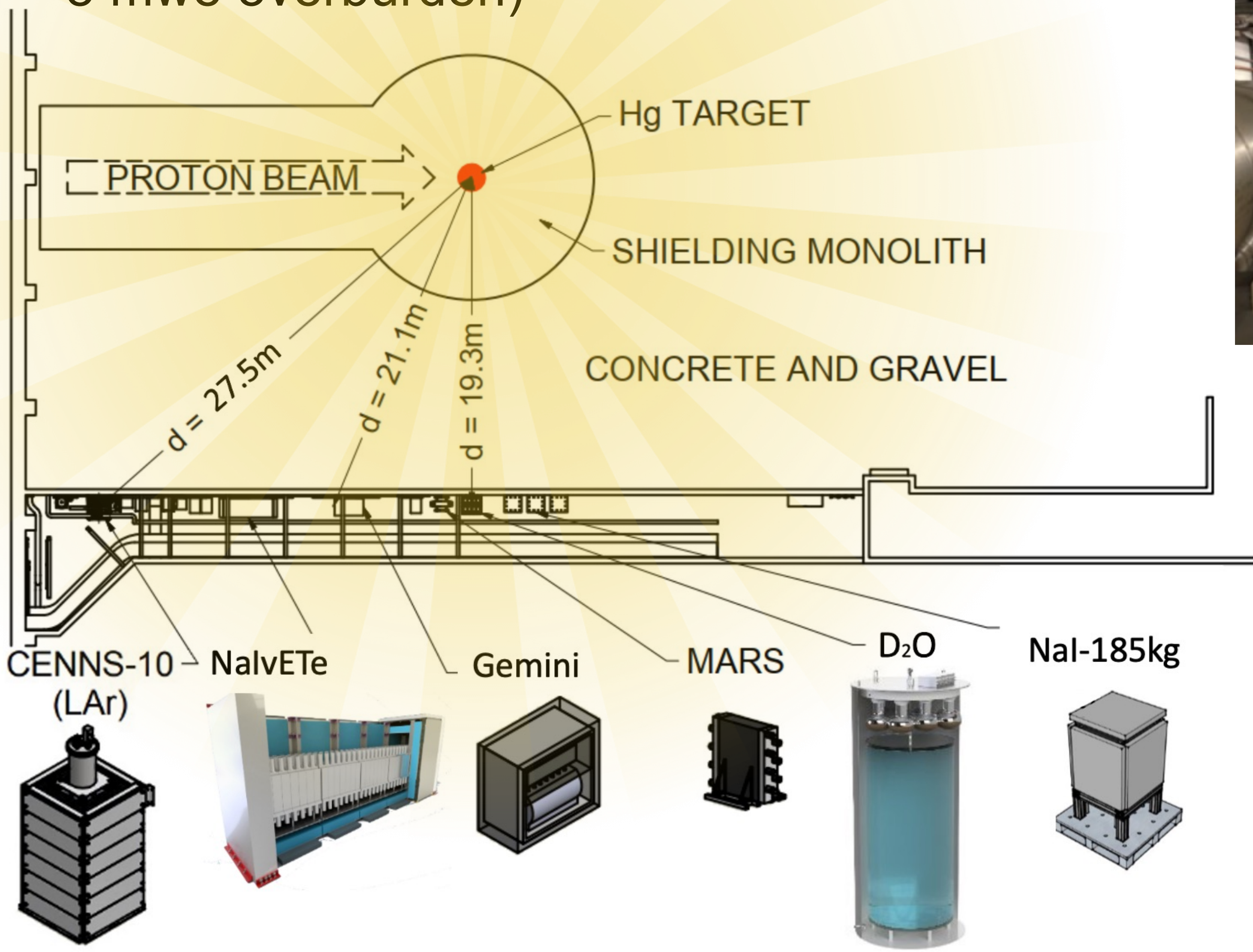
NRF 한국연구재단

The COHERENT Spirit (so far)

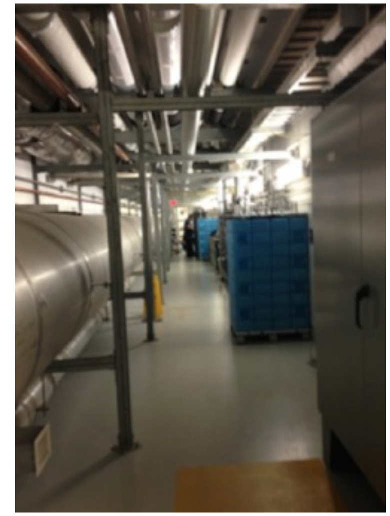


Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)



View looking down "Neutrino Alley"

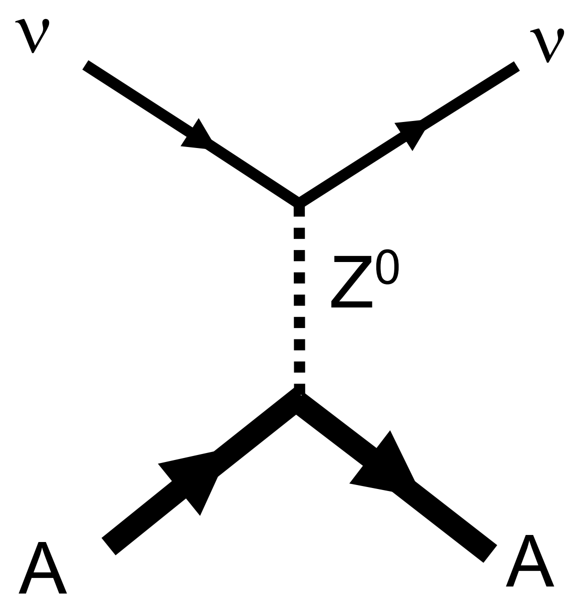


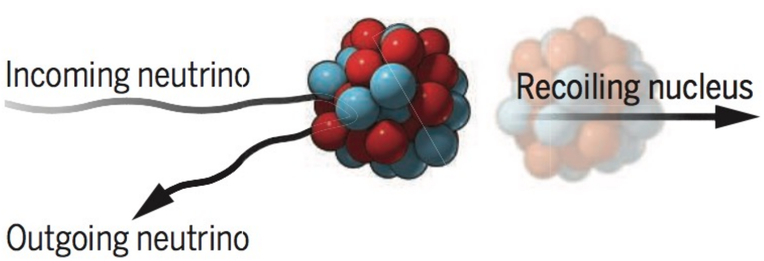
Isotropic ν glow from Hg SNS target

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

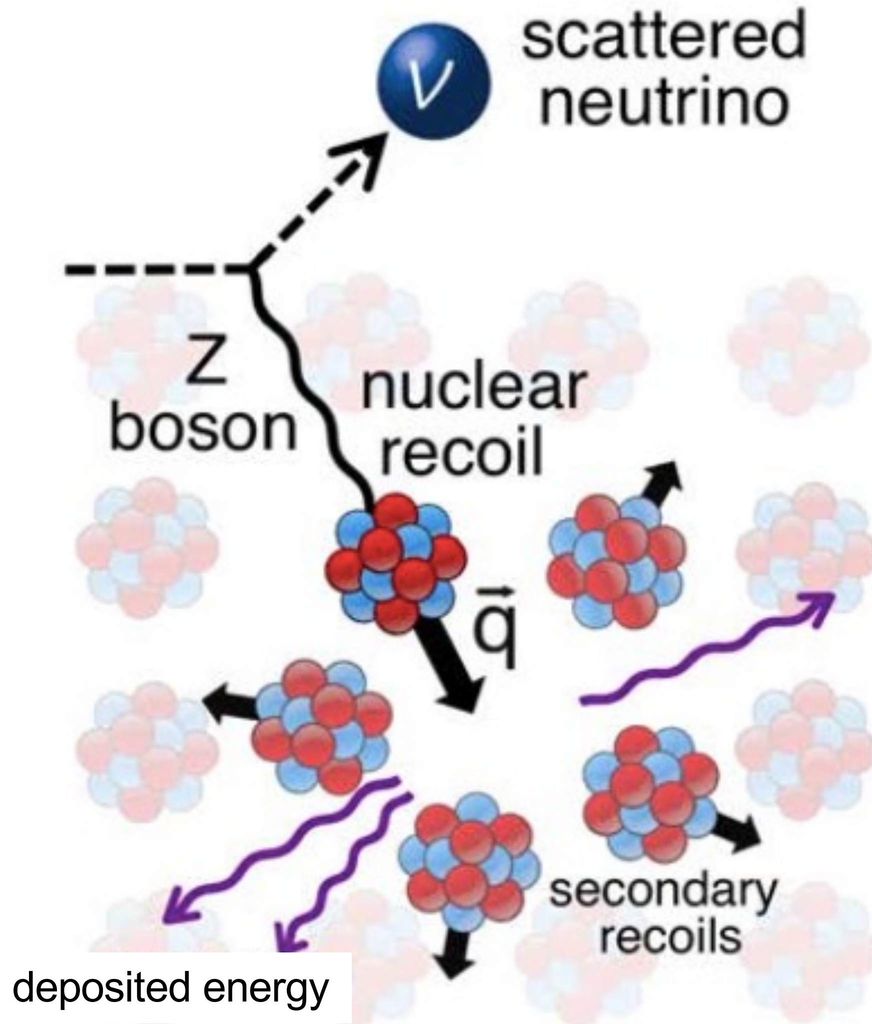
For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

Image: J. Link *Science* Perspectives

A: no. of constituents

The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



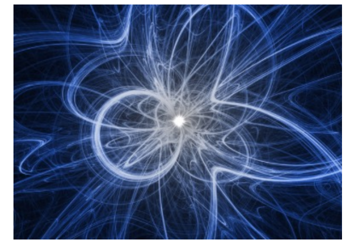
➔ **Low-threshold detectors** (e.g. for WIMPs) developed over the last ~decade are sensitive to ~ keV to 10’s of keV recoils

[...understanding of detector response matters!]

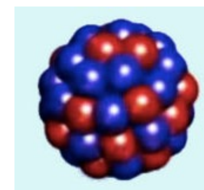
CEvNS: what's it good for?

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

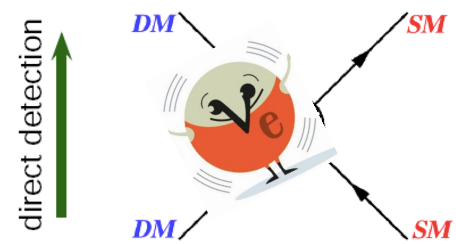
CEvNS as a **signal**
for signatures of *new physics*



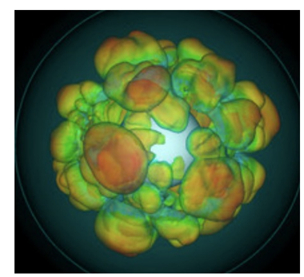
CEvNS as a **signal**
for understanding of "old" physics



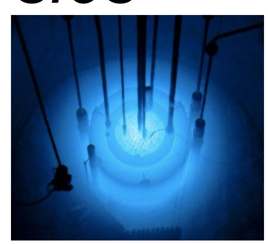
CEvNS as a **background**
for signatures of new physics



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



CEvNS as a **practical tool**



What we can get at experimentally (in principle)

<u>Observables:</u>

Event rate
Recoil spectrum
Time distribution wrt beam pulse
Scattering angle

Shape systematics can be hard!

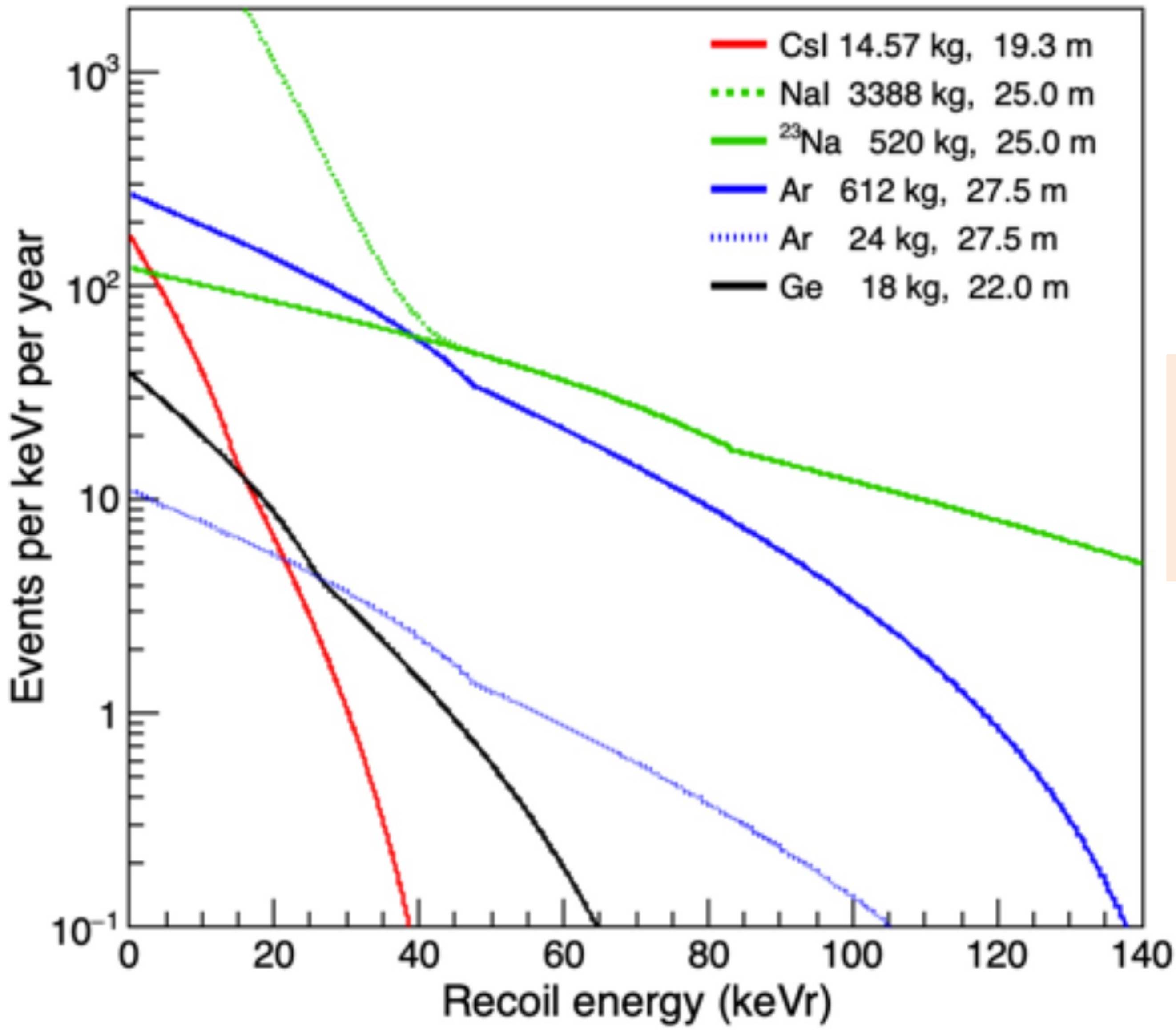
<u>Knowable/controllable parameters:</u>

Neutrino flavor, via source, and timing

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

N, Z via nuclear target type
Baseline
Direction with respect to source

Expected recoil energy distribution

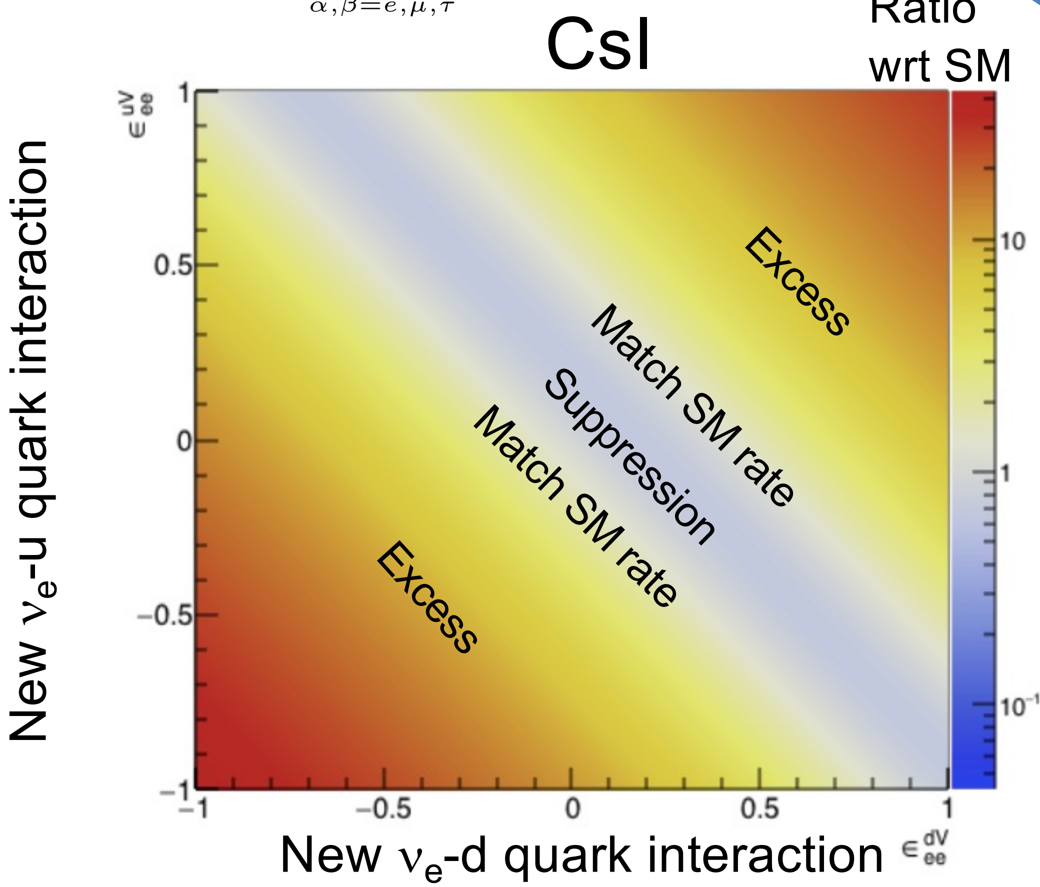


Lighter targets:
less rate per mass,
but kicked to
higher energy

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

Non-Standard Interactions of Neutrinos:

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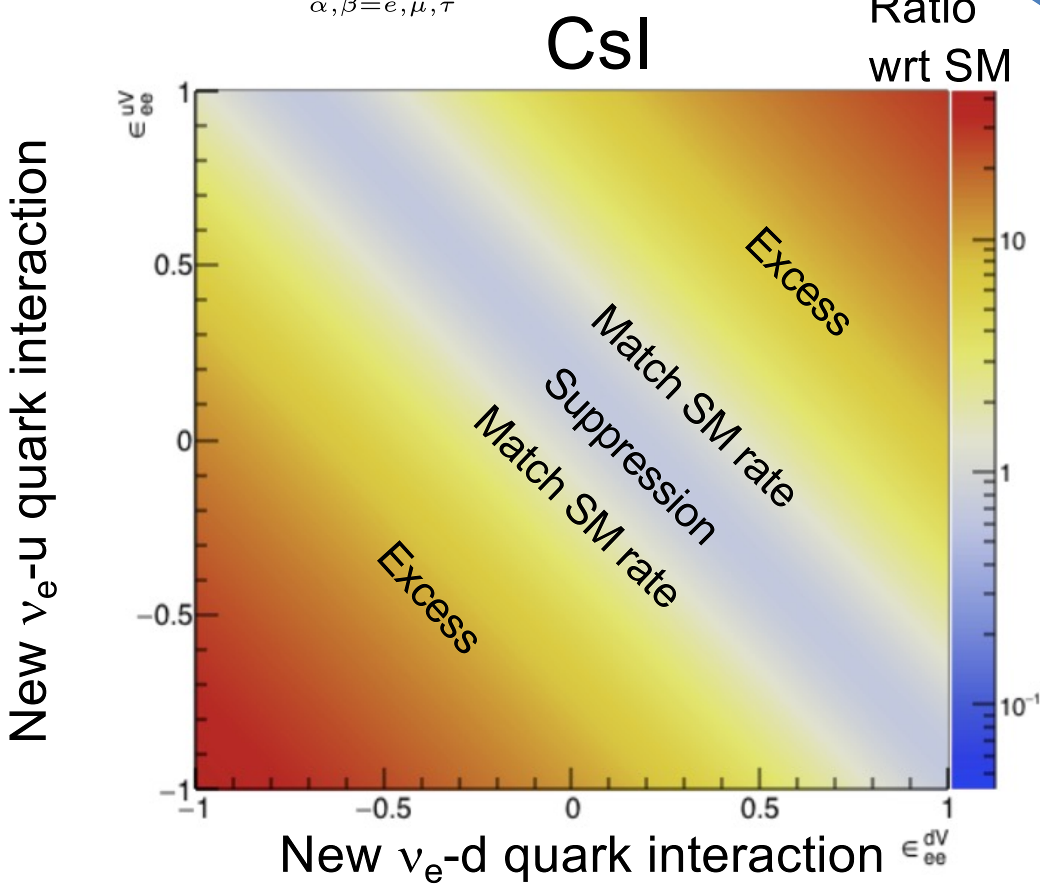

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For heavy mediators, expect ***overall scaling*** of CEvNS event rate, depending on N, Z

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

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

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

$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1 - T/E_\nu}{T} + \frac{T}{4E_\nu^2}\right)$$

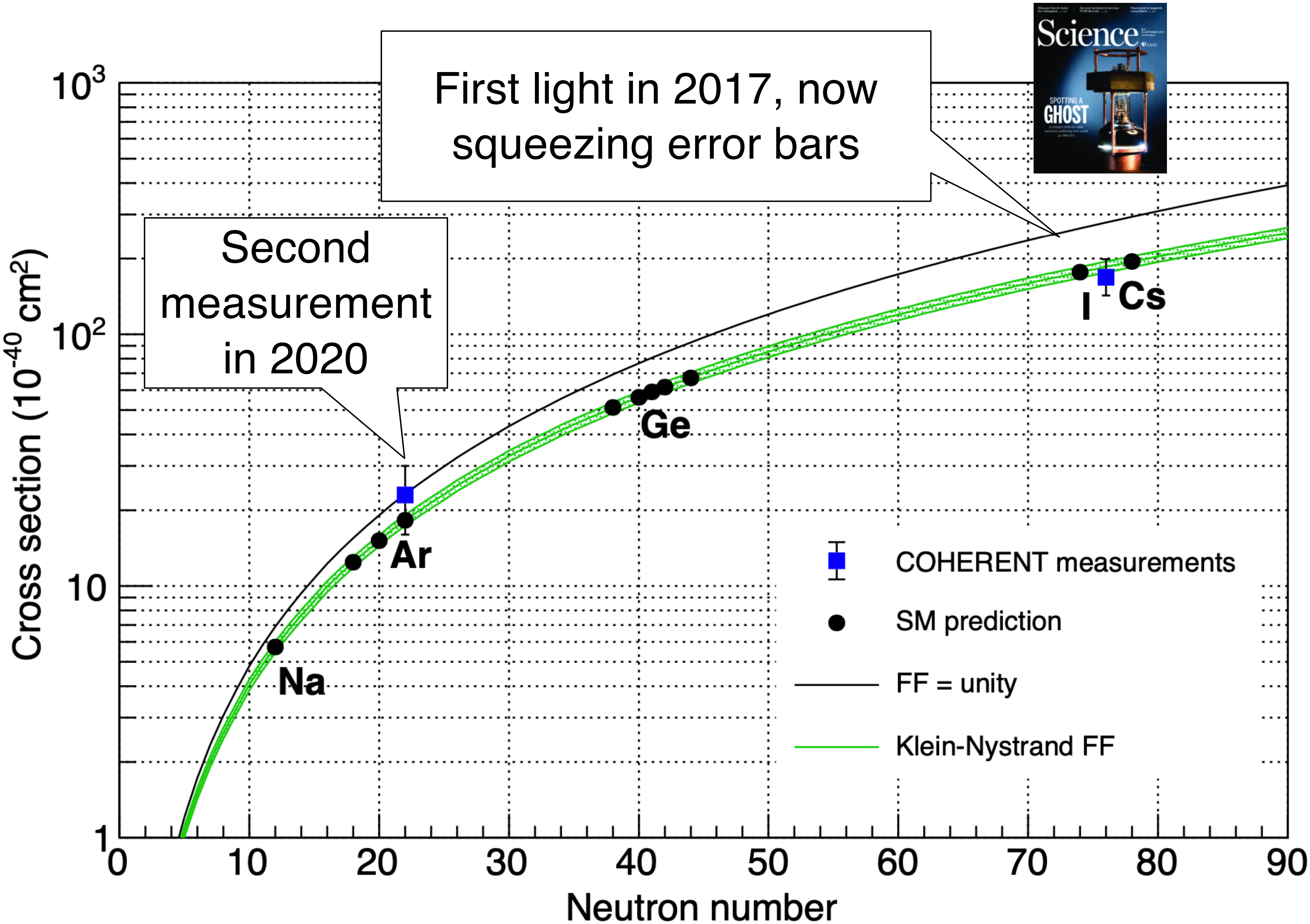
Specific ~1/T upturn at low recoil energy

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

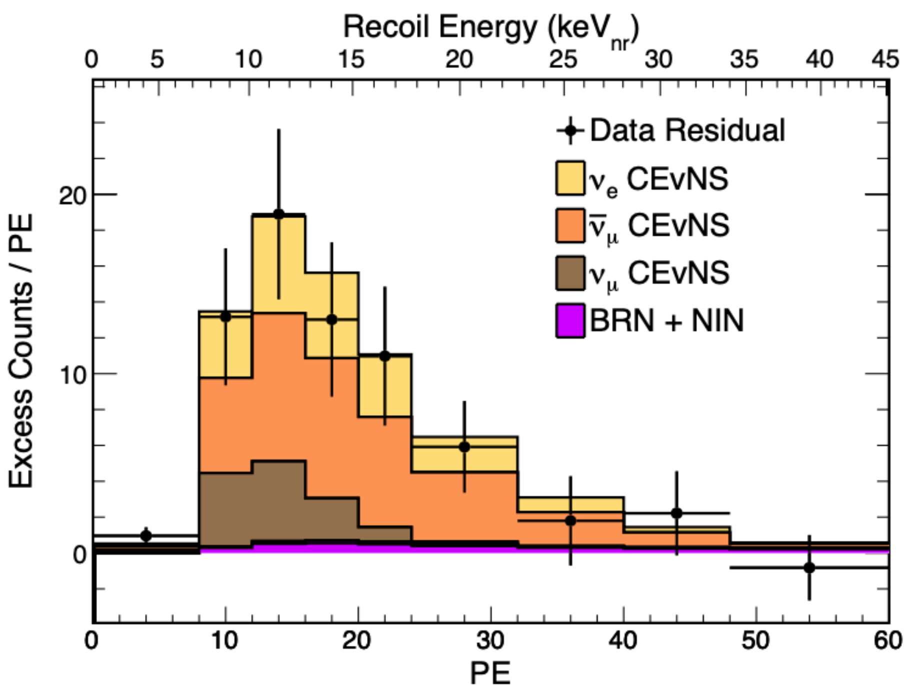

First light in 2017, now squeezing error bars
Second measurement in 2020
Science
SPOTTING A GHOST
Cross section (10^{-40} cm^2)
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
90
Neutron number
Na
Ar
Ge
I
Cs
COHERENT measurements
SM prediction
FF = unity
Klein-Nystrand FF

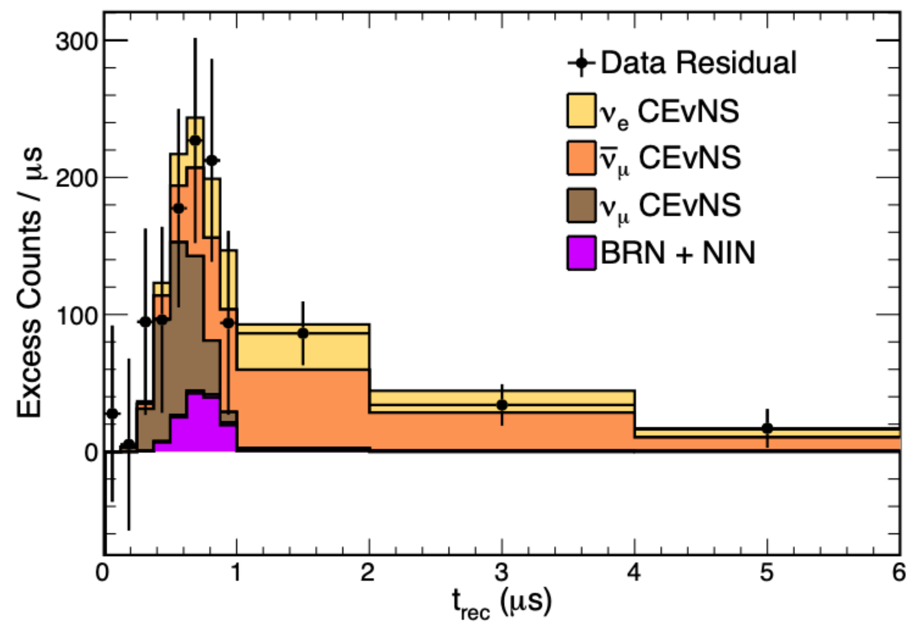
Full CsI[Na] dataset

with >2 x statistics

+ improved detector response understanding

+ improved analysis

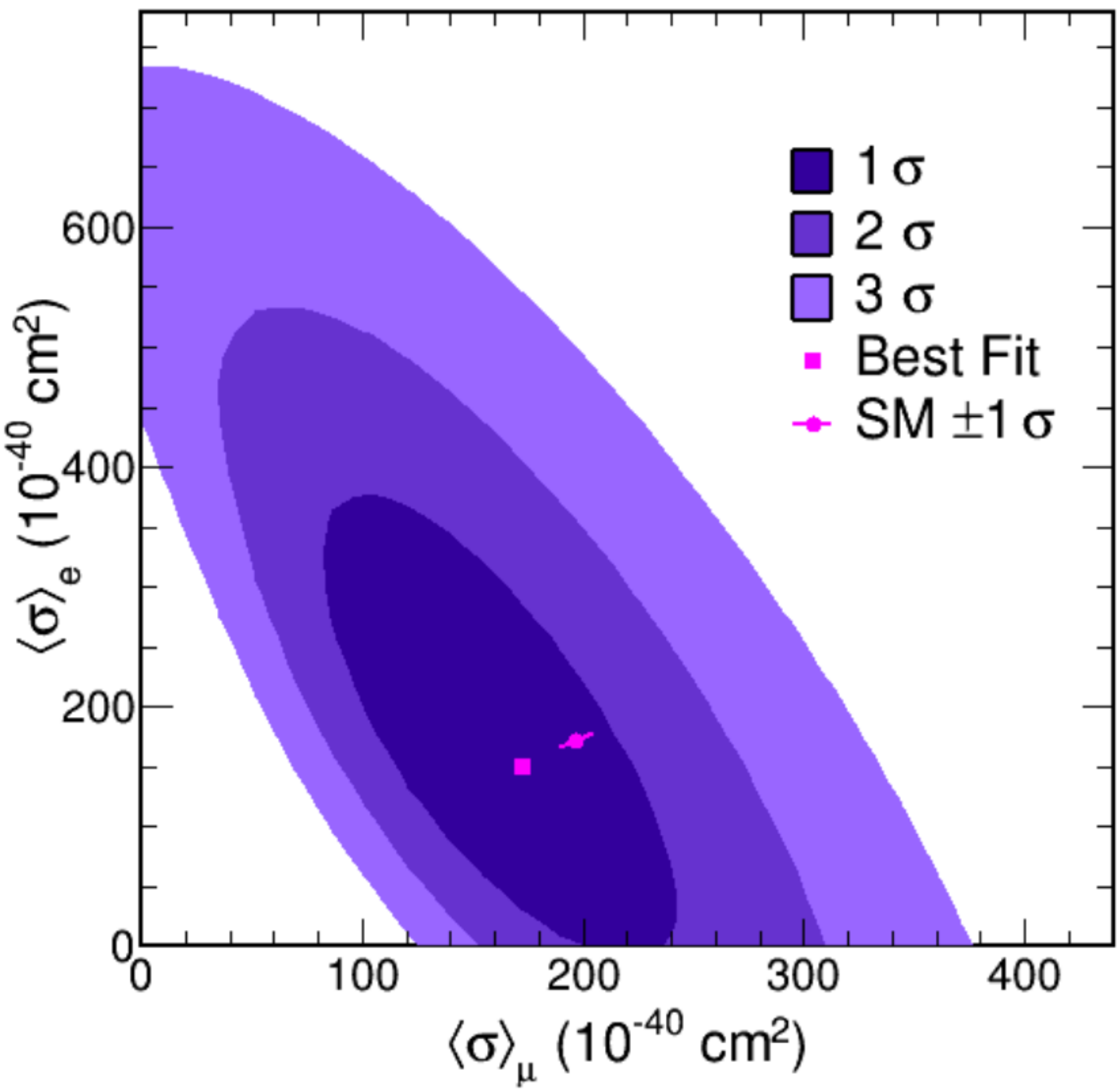




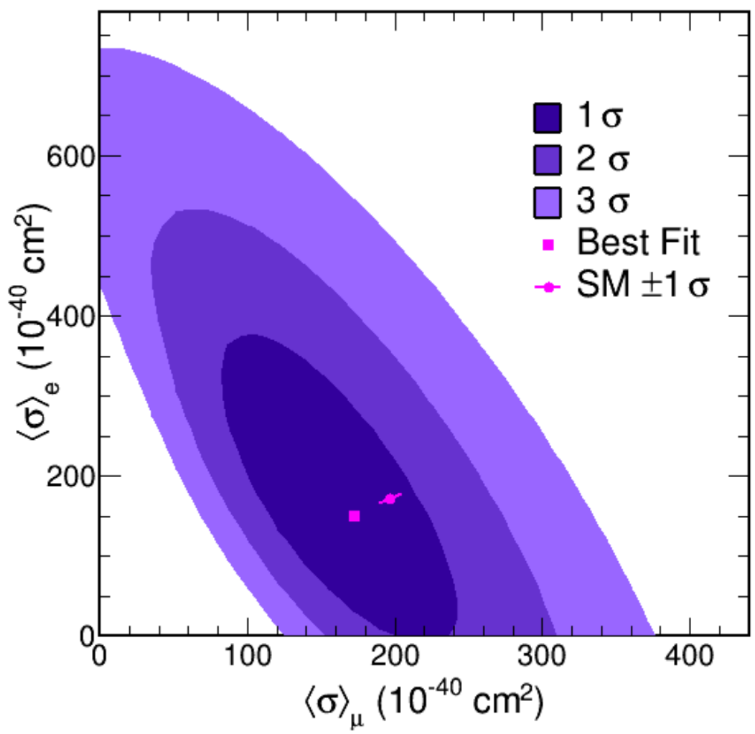
arXiv: 2110.07730

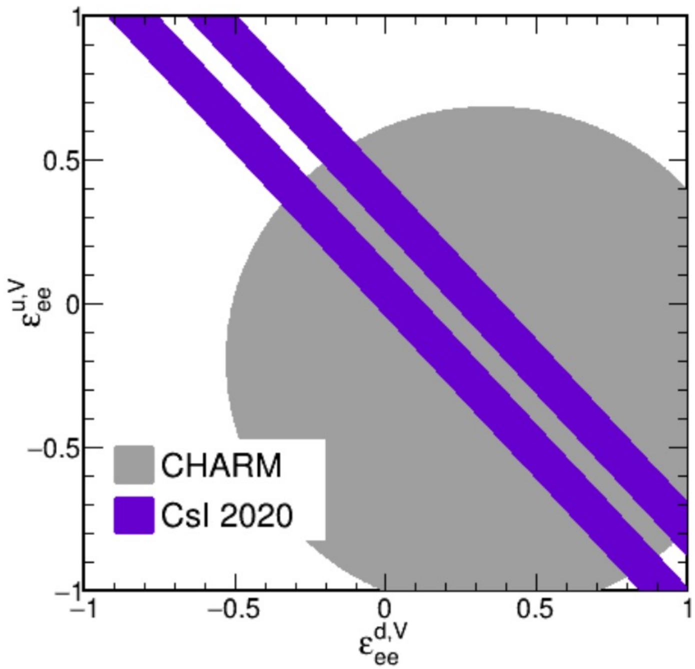
Flavored CEvNS cross sections

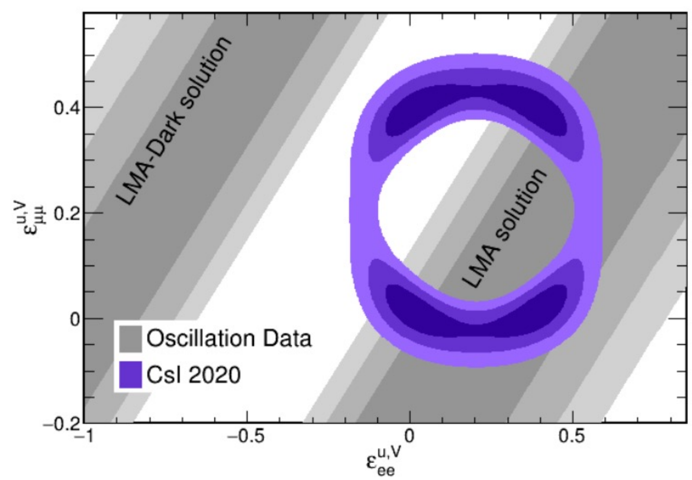
Separate electron and muon flavors by timing



Example constraints on BSM physics with ***flavored*** CEvNS cross sections







Separate electron and muon flavors by timing

Phys.Rev.Lett. 129 (2022) 8, 081801 e-Print: 2110.07730

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

(CEvNS is *background*)

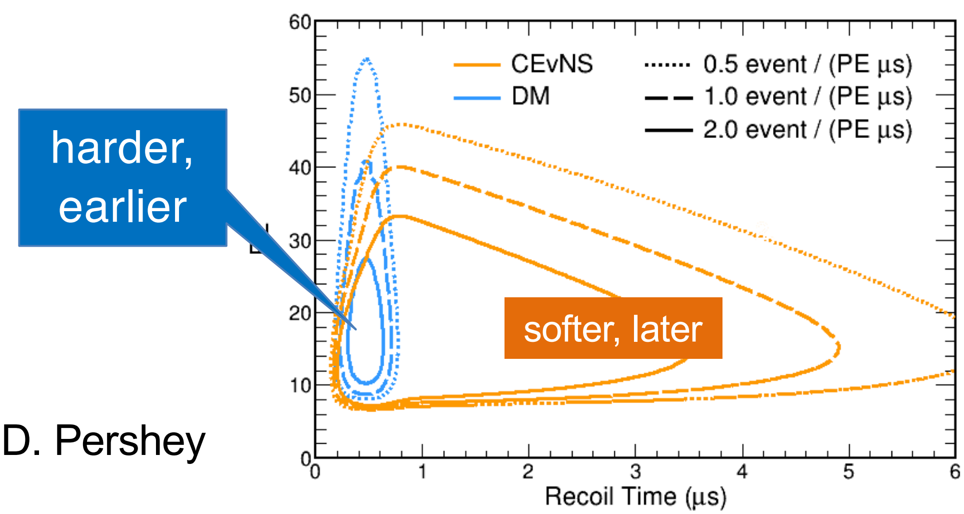
- "Vector portal": mixing of vector mediator with photons in π^0/η^0 decays
- "Leptophobic portal": new mediator coupling to baryons

} decay product χ then makes nuclear recoil

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

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

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

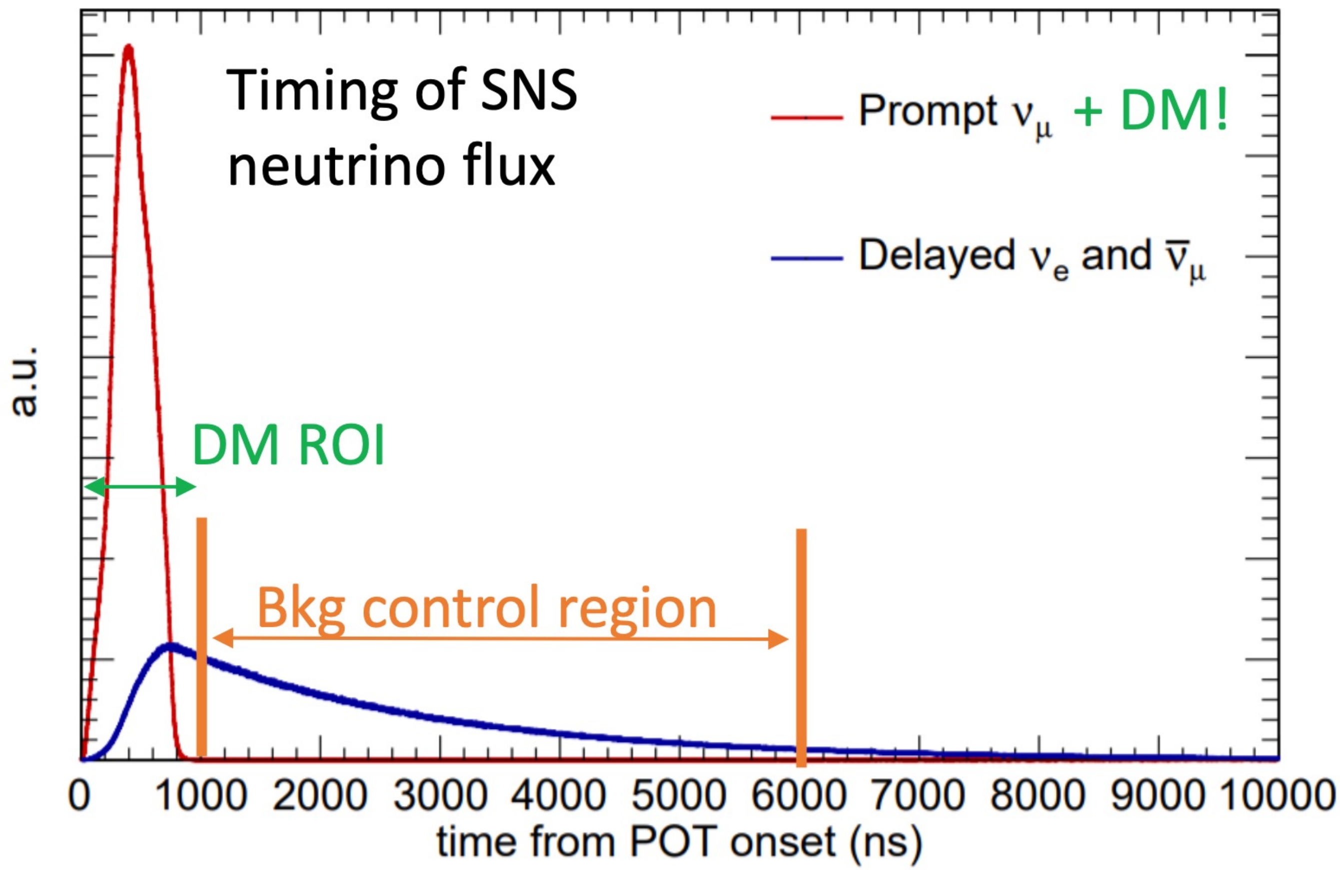


D. Pershey

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

Important advantage of a clean stopped-pion source:

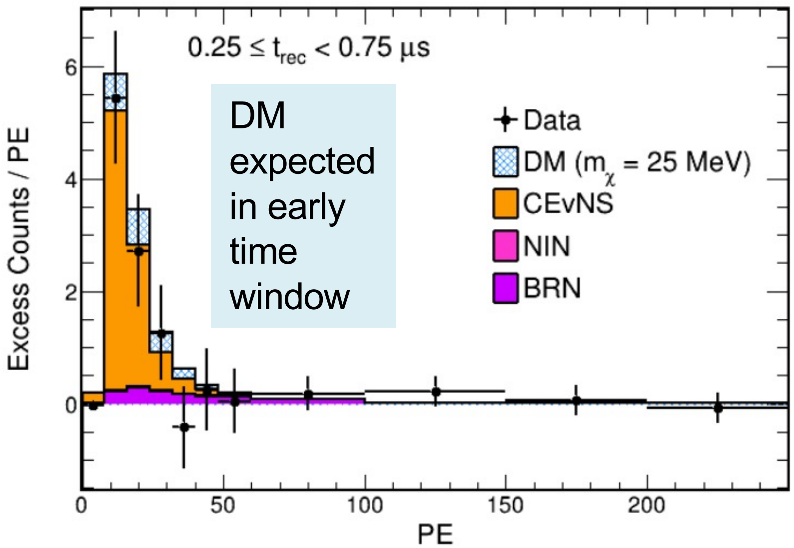
Measure the delayed CEvNS to **constrain** uncertainties in the prompt DM ROI

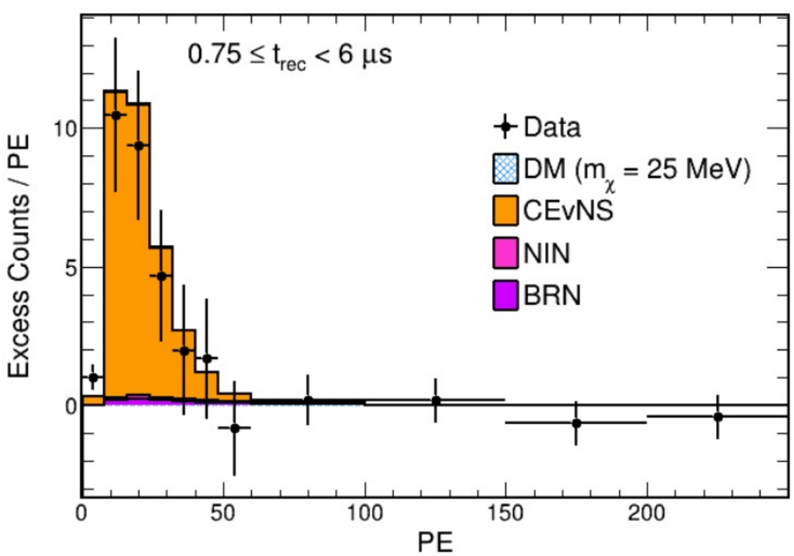


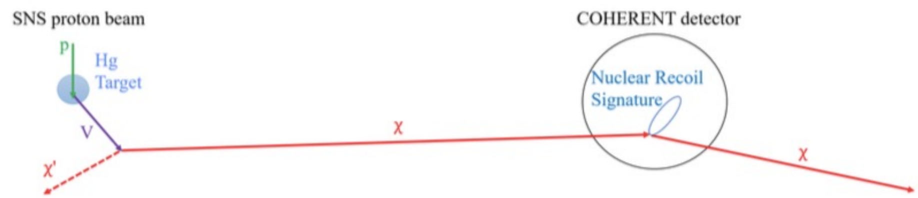
D. Pershey

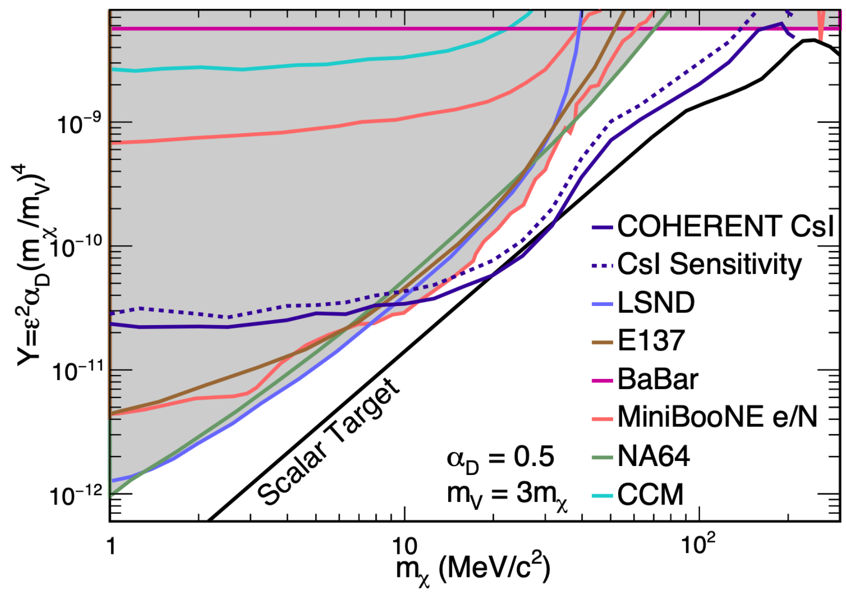
Accelerator-produced DM search

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







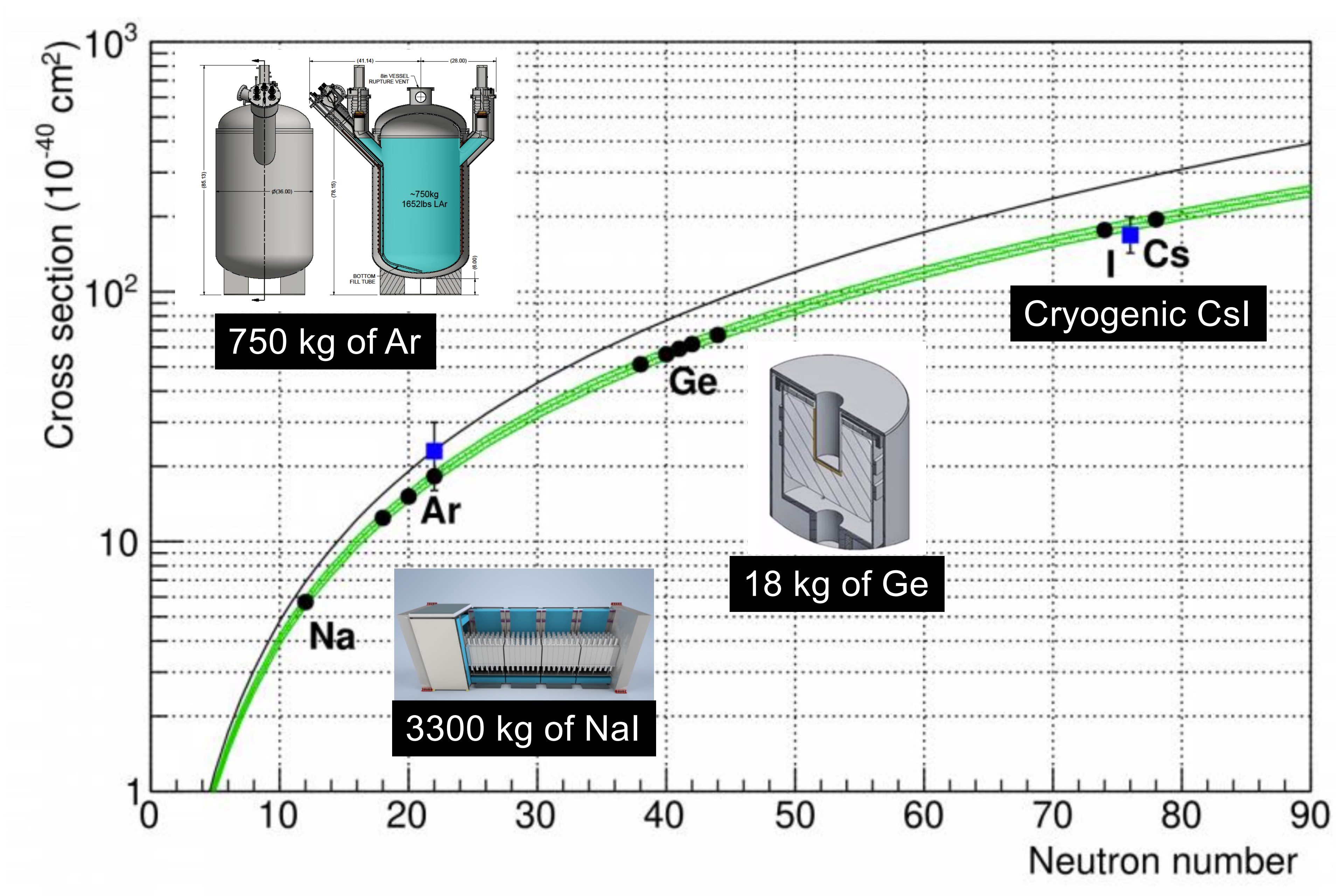


Limits down to cosmological expectation for scalar DM particle

Phys.Rev.Lett. 130 (2023) 051803 arXiv:2110.11453

Phys.Rev.D 106 (2022) 5, 052004 arXiv:2205.12414 leptophobic DM

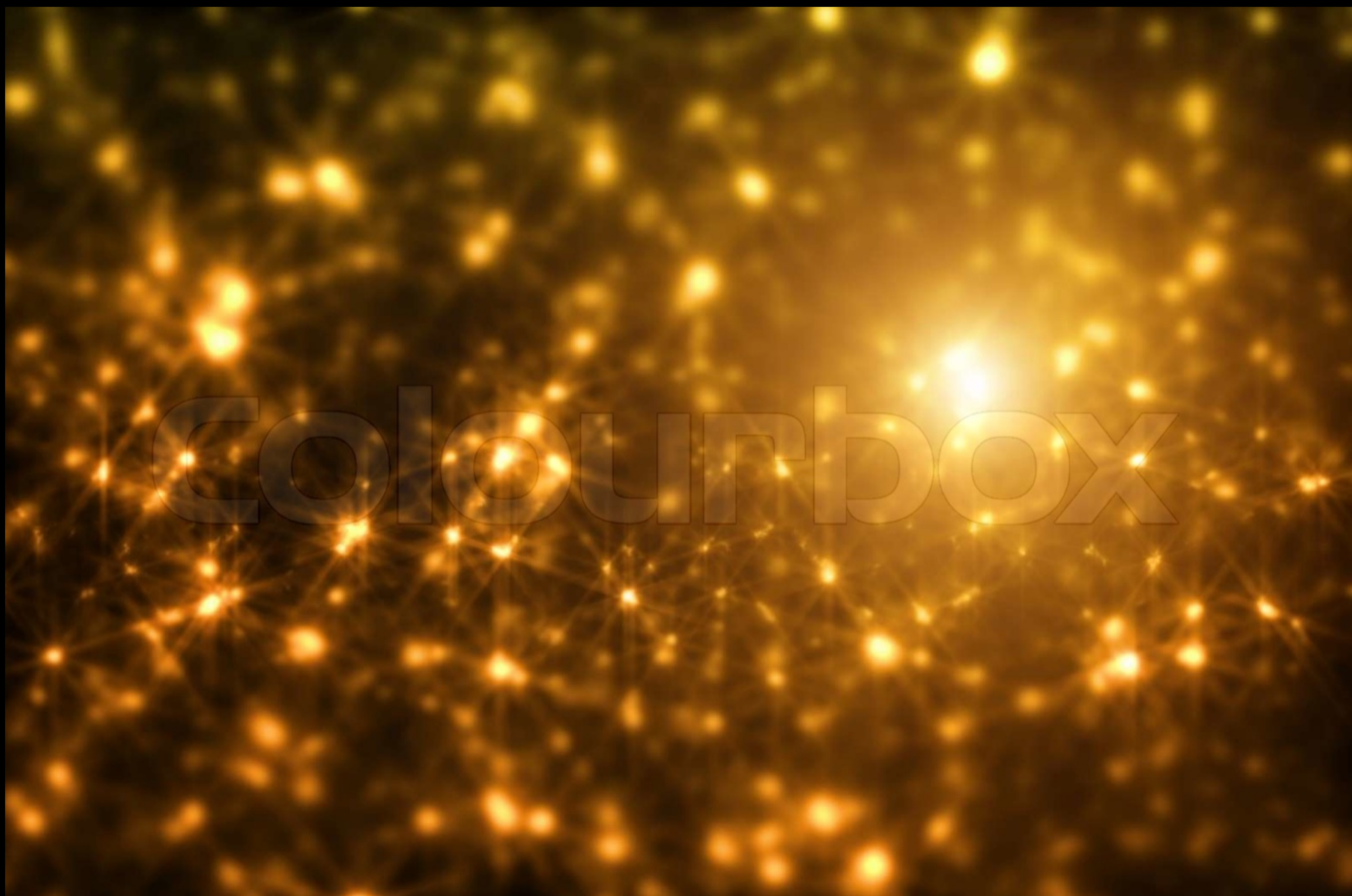
COHERENT future deployments in Neutrino Alley



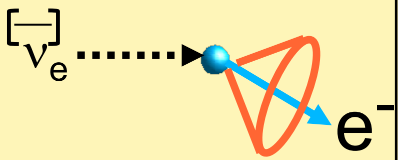
So far considered signal from faint recoils...

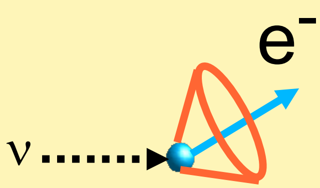
bright signals are possible too...

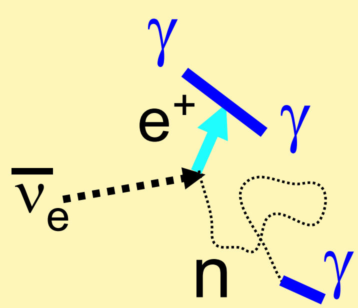
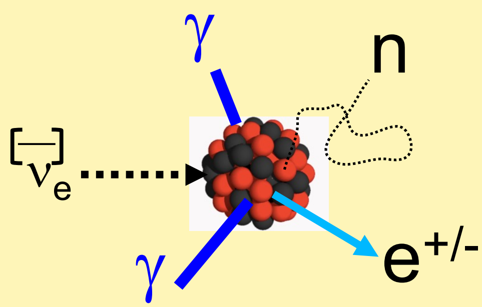
Neutrinos: eES, inelastic neutrino-nucleus interactions, [inelastic DM interactions, axions...]

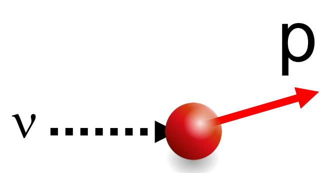


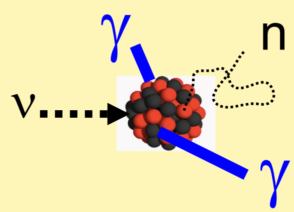
Low-energy neutrino interactions

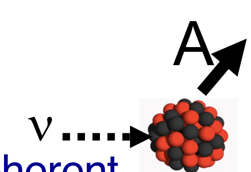
<table>
<tr><th></th><th>Electrons</th><th>Protons</th><th>Nuclei</th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering
$$\nu + e^- \rightarrow \nu + e^-$$




Useful for pointing</td><td>Inverse beta decay
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

</td><td>$$\nu_e + (N,Z) \rightarrow e^- + (N-1, Z+1)$$
$$\bar{\nu}_e + (N,Z) \rightarrow e^+ + (N+1, Z-1)$$


Various possible ejecta and deexcitation products</td></tr>
<tr><td>Neutral current</td><td>Elastic scattering


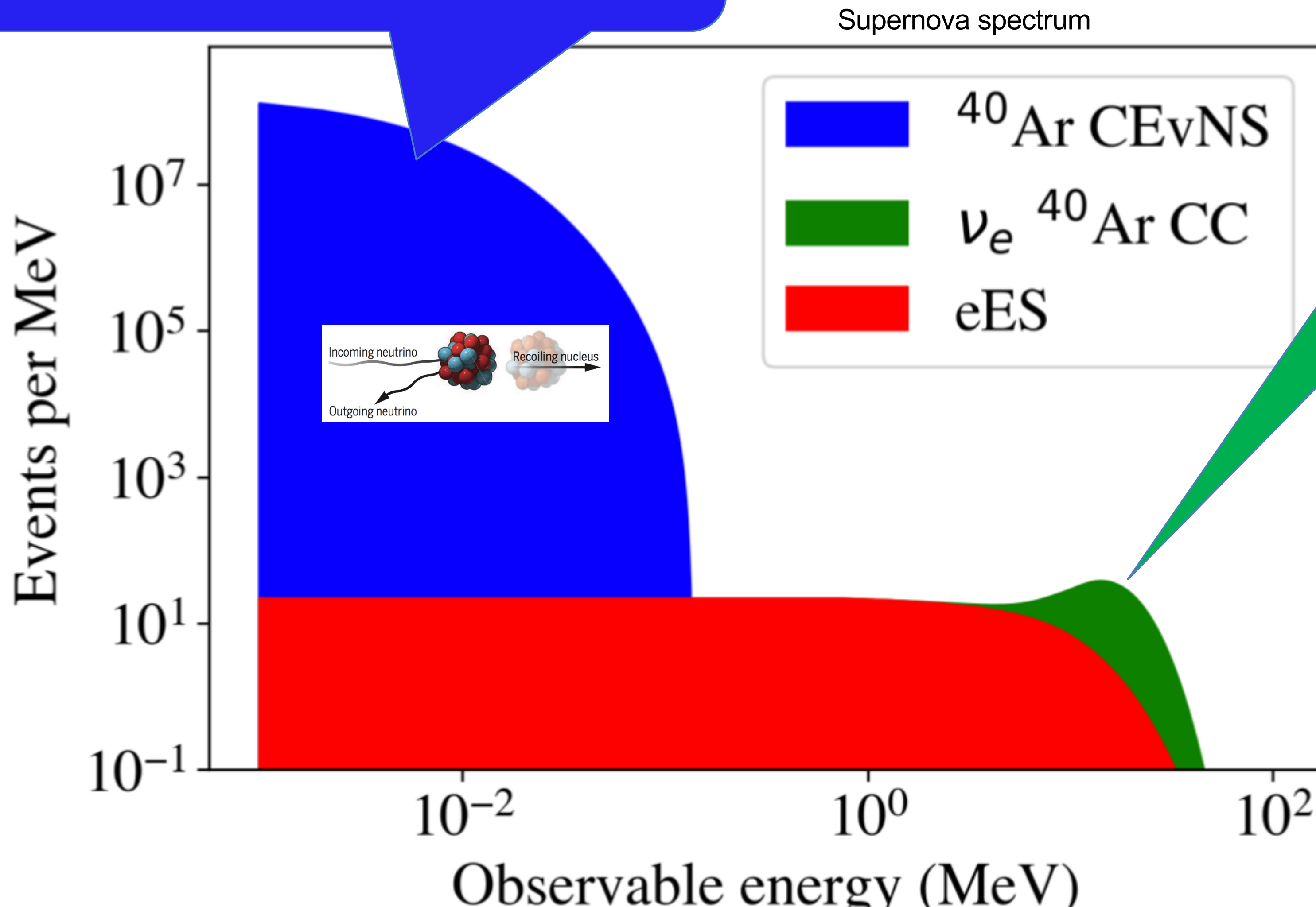
very low energy recoils</td><td>$$\nu + A \rightarrow \nu + A^*$$


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


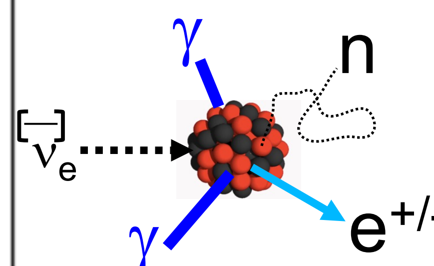
Coherent elastic (CEvNS)</td></tr>
</table>

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

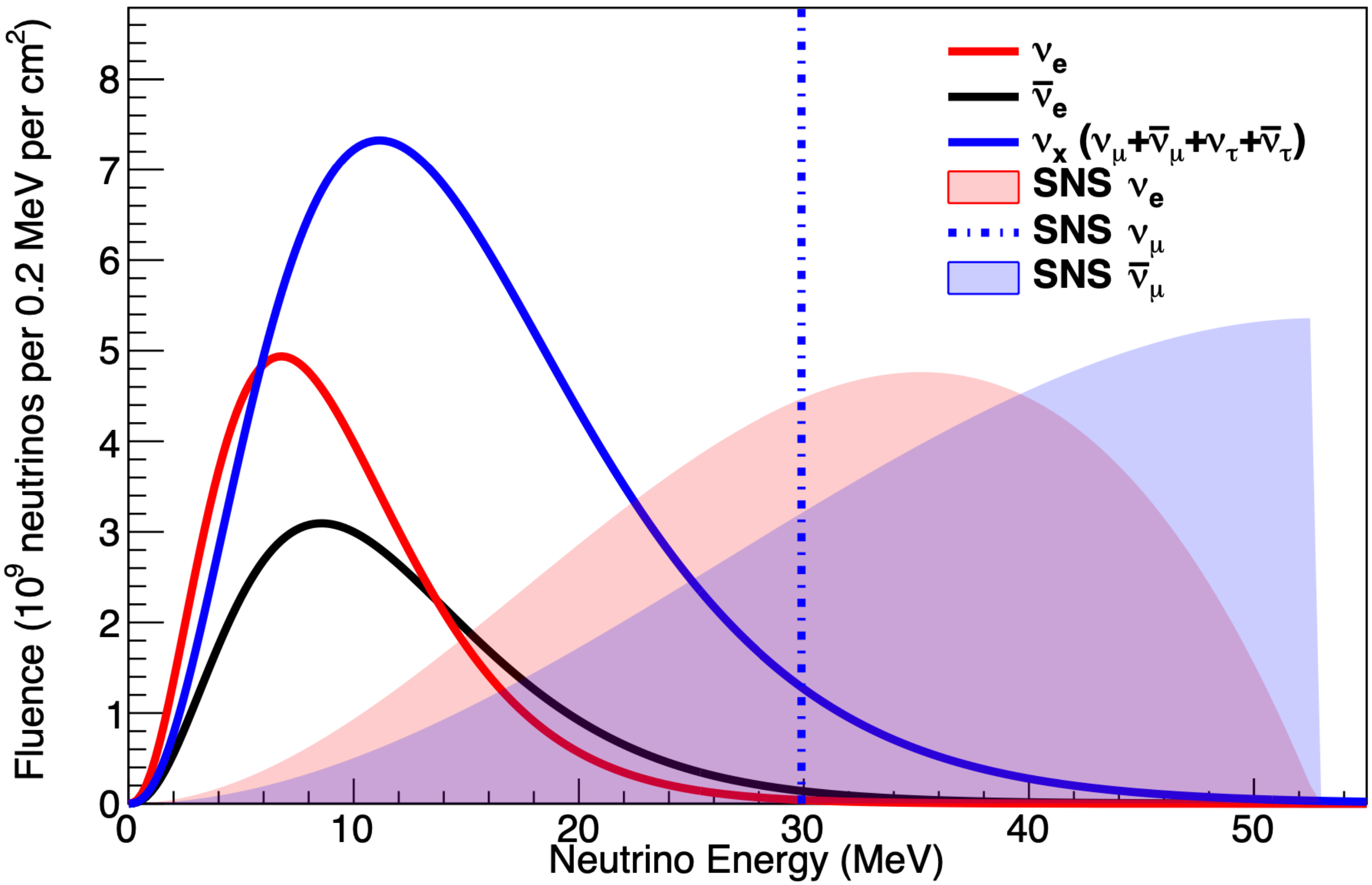
CEvNS
High xscn, low energy recoils



Inelastic
Low xscn,
bright
recoil



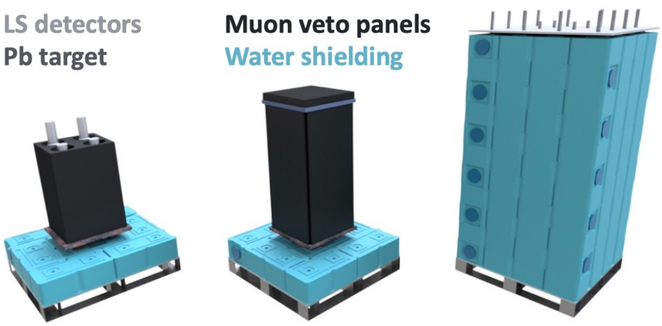
Stopped-pion neutrinos relevant for supernova burst regime

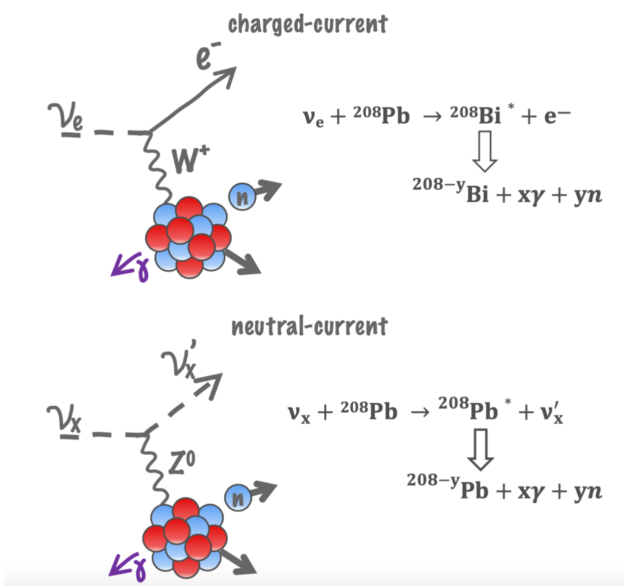


- understanding of SN processes & detection
- understanding of weak couplings (g_A quenching) & nuclear transitions

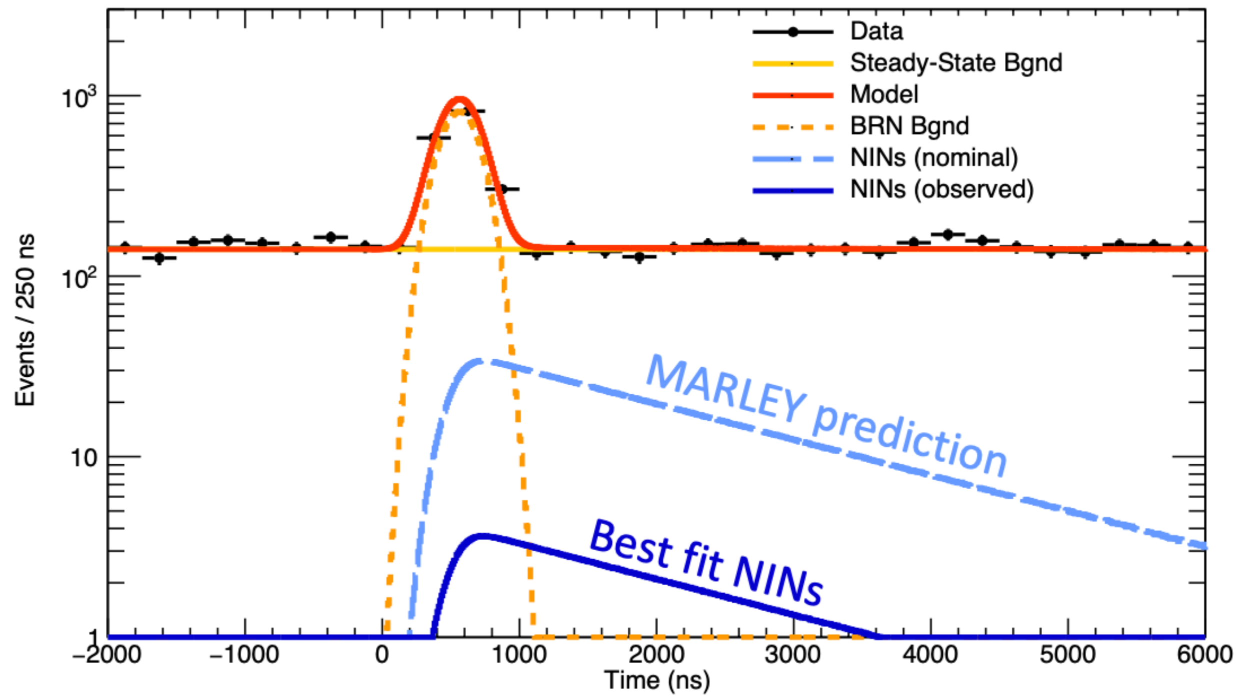
See:Workshop on Neutrino Interaction Measurements for Supernova Neutrino Detection
https://indico.phy.ornl.gov/event/217/

COHERENT results for **neutrino-induced neutrons (NINs)** on Pb





Sam Hedges talk



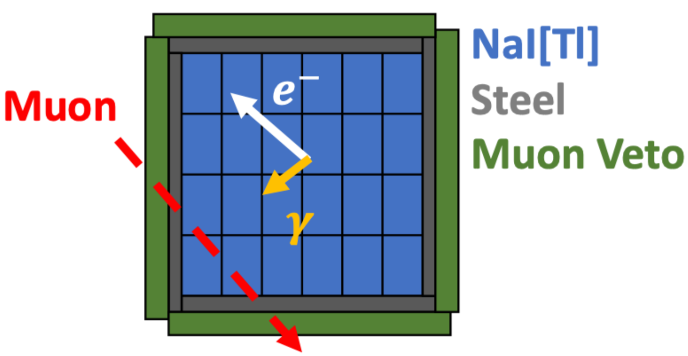
Combined fit yields MARLEY cross section suppressed by a factor of $0.29^{+0.17}_{-0.17}$

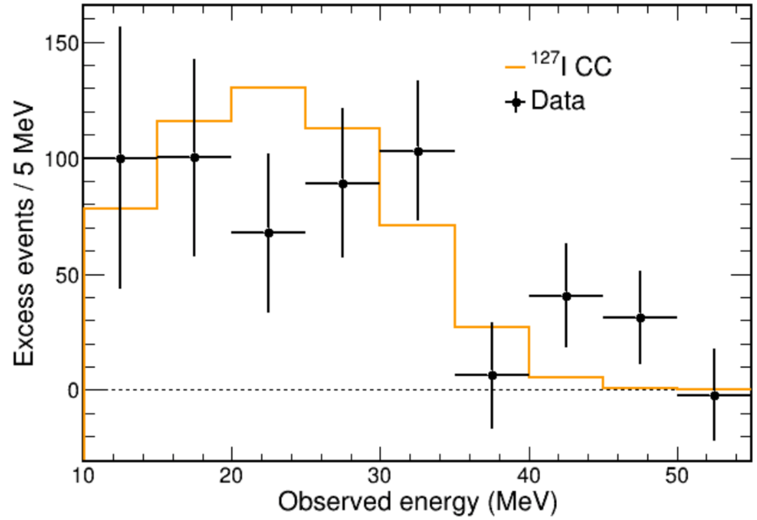
- 1.8σ significance, >4σ disagreement with MARLEY model

Lower than expectation

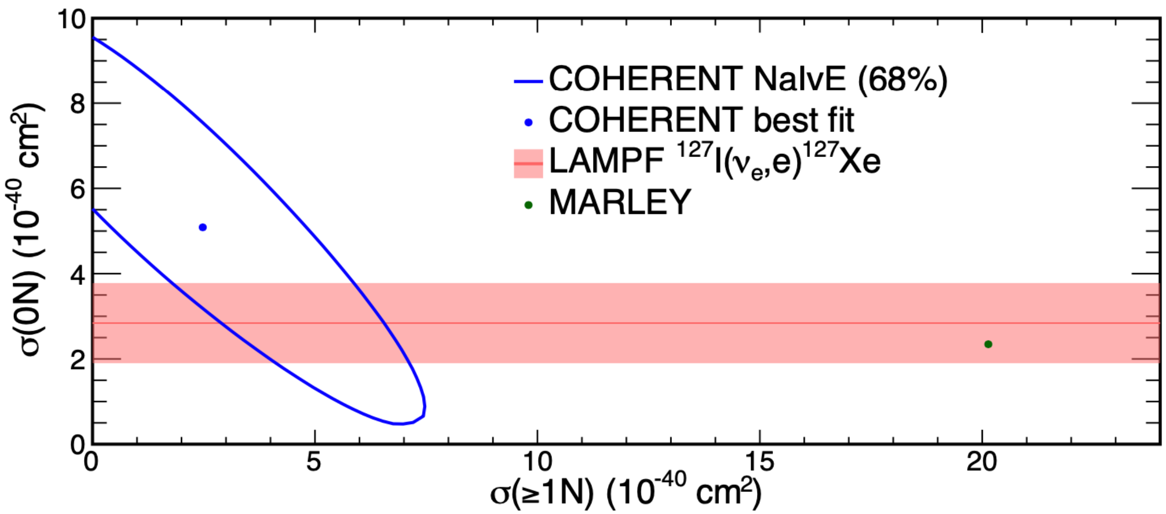
D. Pershey, Nu2022
S. Hedges thesis, FNAL Wine & Cheese

COHERENT results for CC ν_e on ^{127}I





Preliminary



- 0n cross section: $5.2^{+3.4}_{-3.1} \times 10^{-40}$cm²
  - Compare to LAMPF measured value: $2.84 \pm 0.91(stat) \pm 0.25(sys)$×10⁻⁴⁰ cm²
- 1n cross section: $2.4^{+3.3}_{-2.4} \times 10^{-40}$cm²

Sam Hedges talk

S. Hedges thesis, FNAL Wine & Cheese

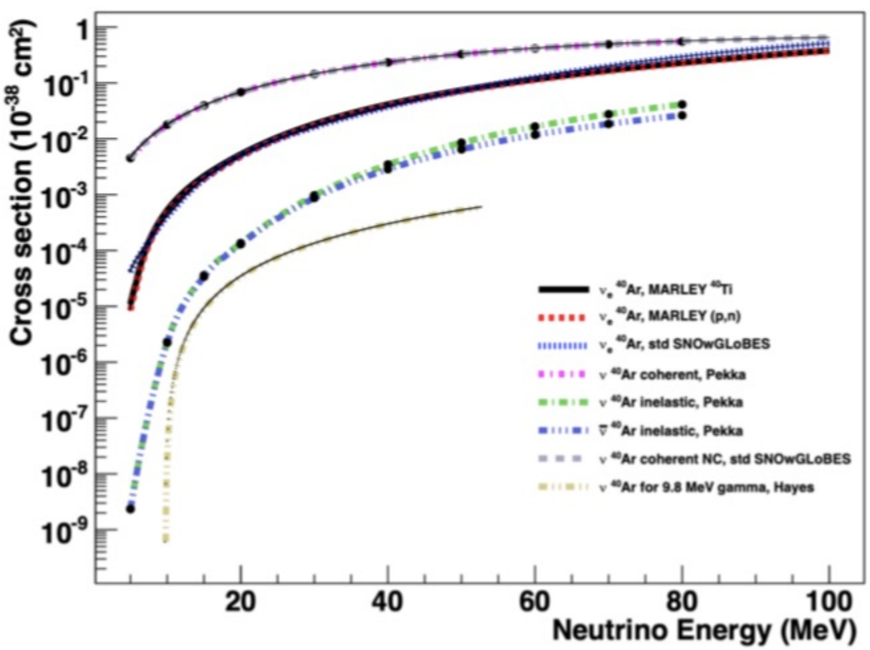
Also low!

Especially interesting to measure **electron neutrino interactions on on argon in the few tens of MeV range**

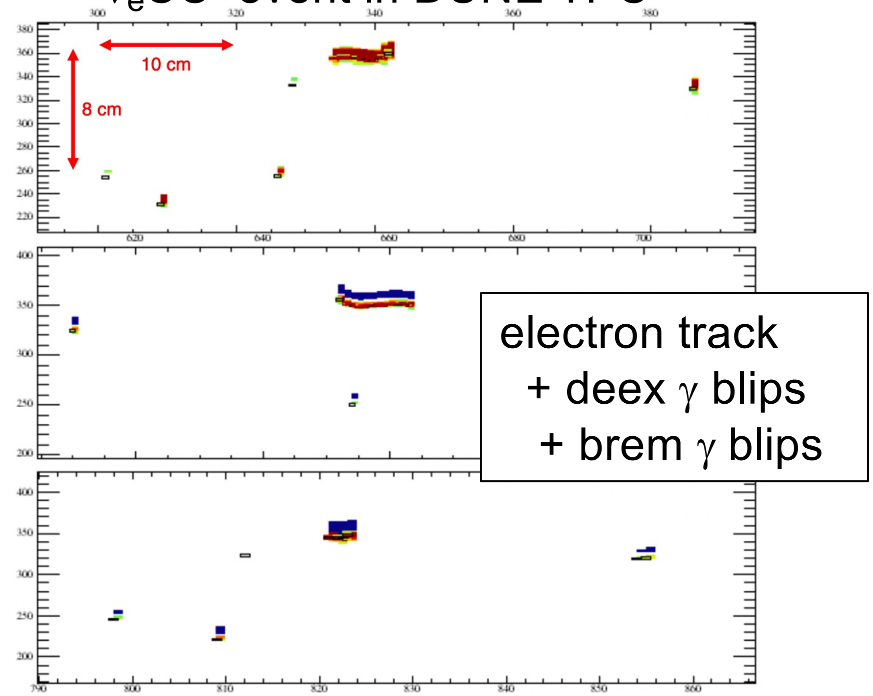
$$\text{CC} \quad \nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

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

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



ν_eCC event in DUNE TPC



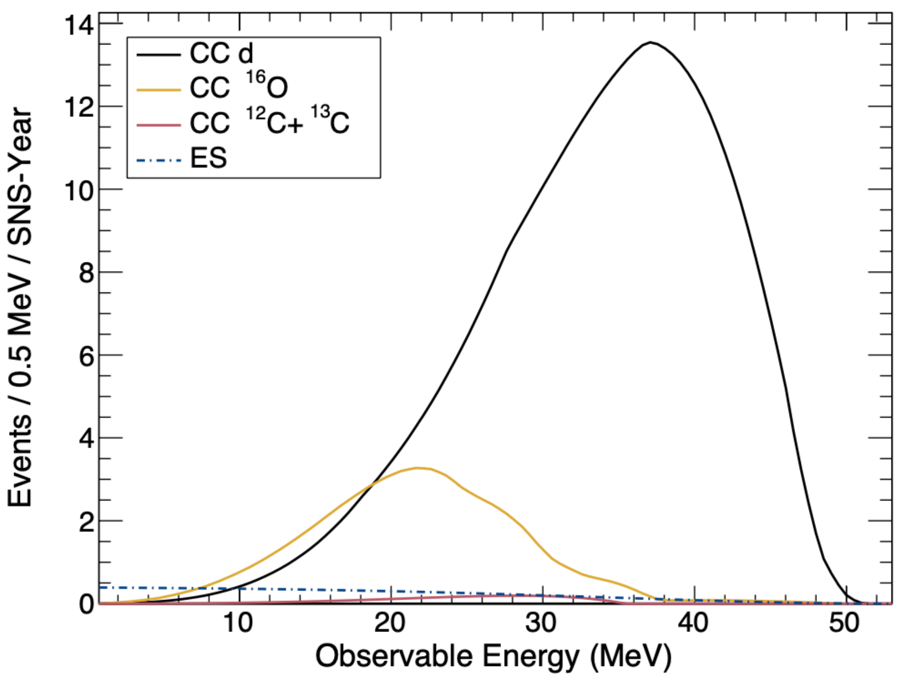
Impact on SNB in DUNE arXiv:[2303.17007](https://arxiv.org/abs/2303.17007)

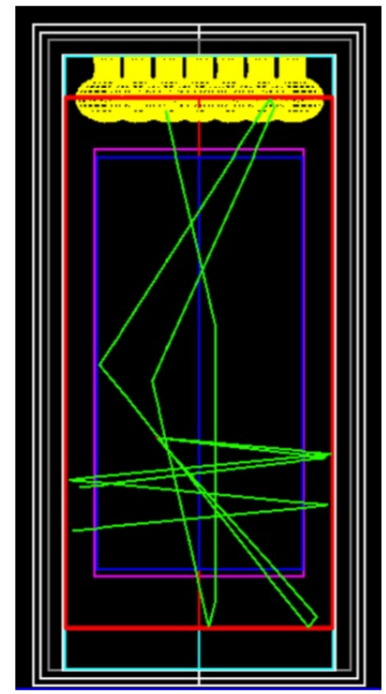
More soon from COHERENT!

Heavy water detector in Neutrino Alley (R2D2O)

Dominant current uncertainty is ~10%, on neutrino flux from SNS

$\nu_e + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$ cross section known to ~1-2%

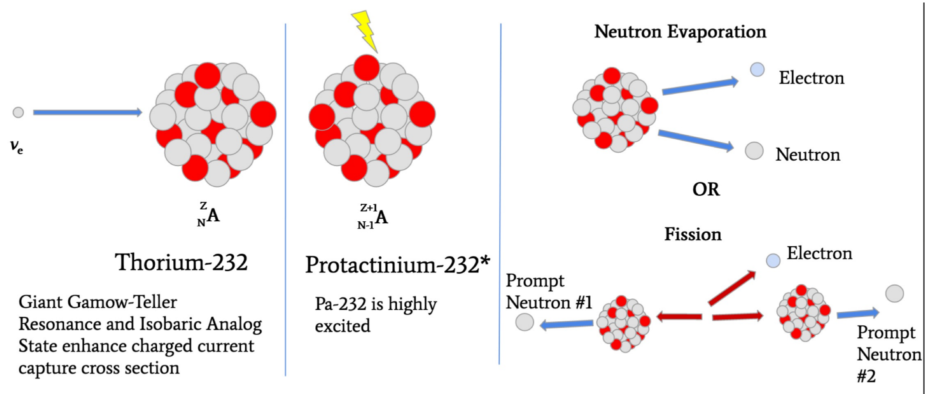




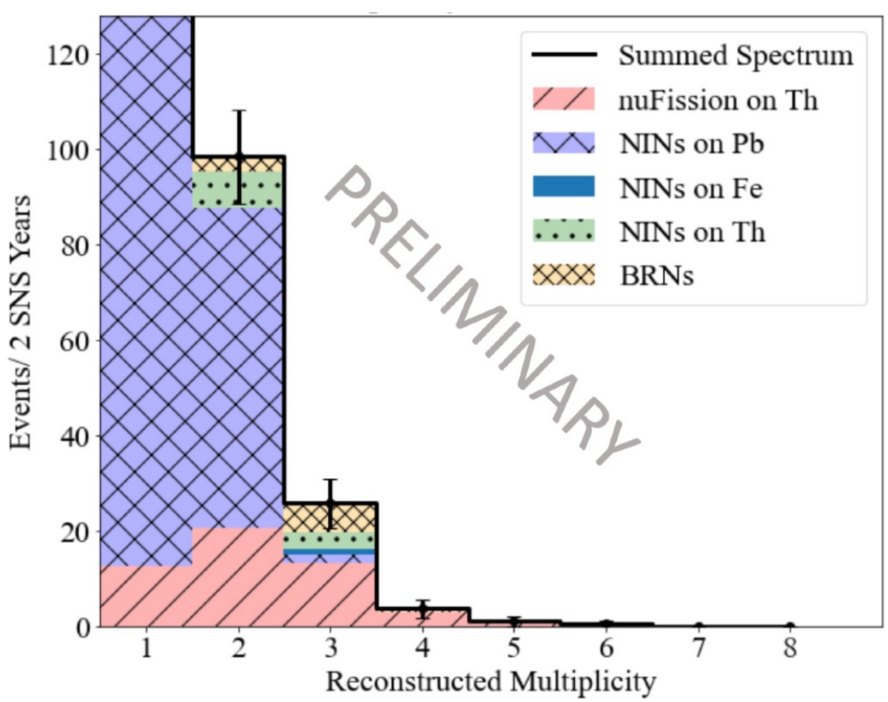
- Measure electrons to determine flux normalization
- Currently deployed with light water
- Opportunity to measure inelastics on ^{16}O

NuThor

Neutrino-induced fission in 52 kg of ^{232}Th

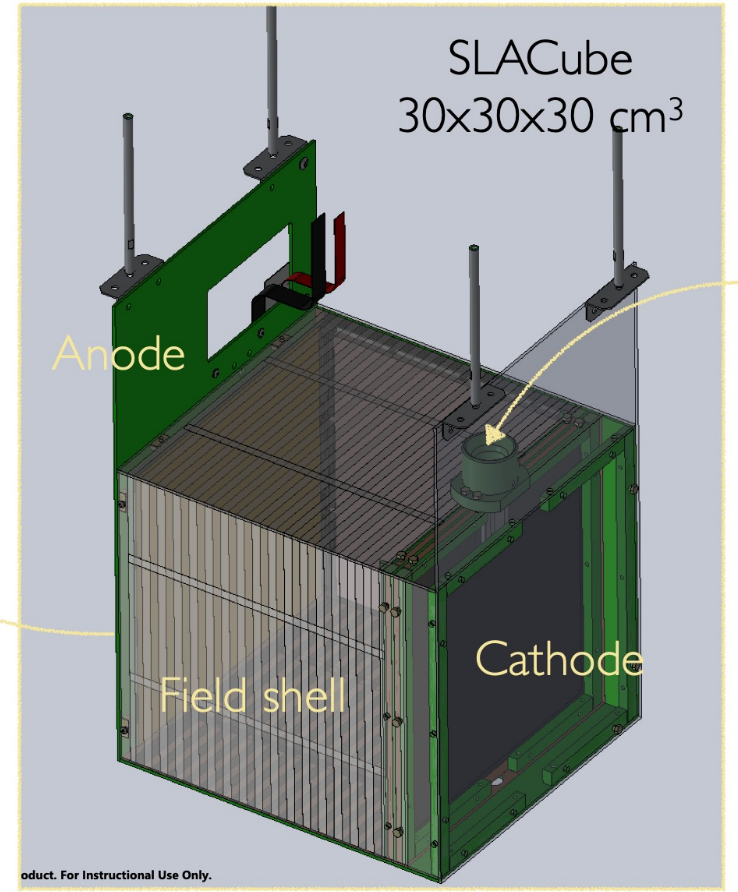


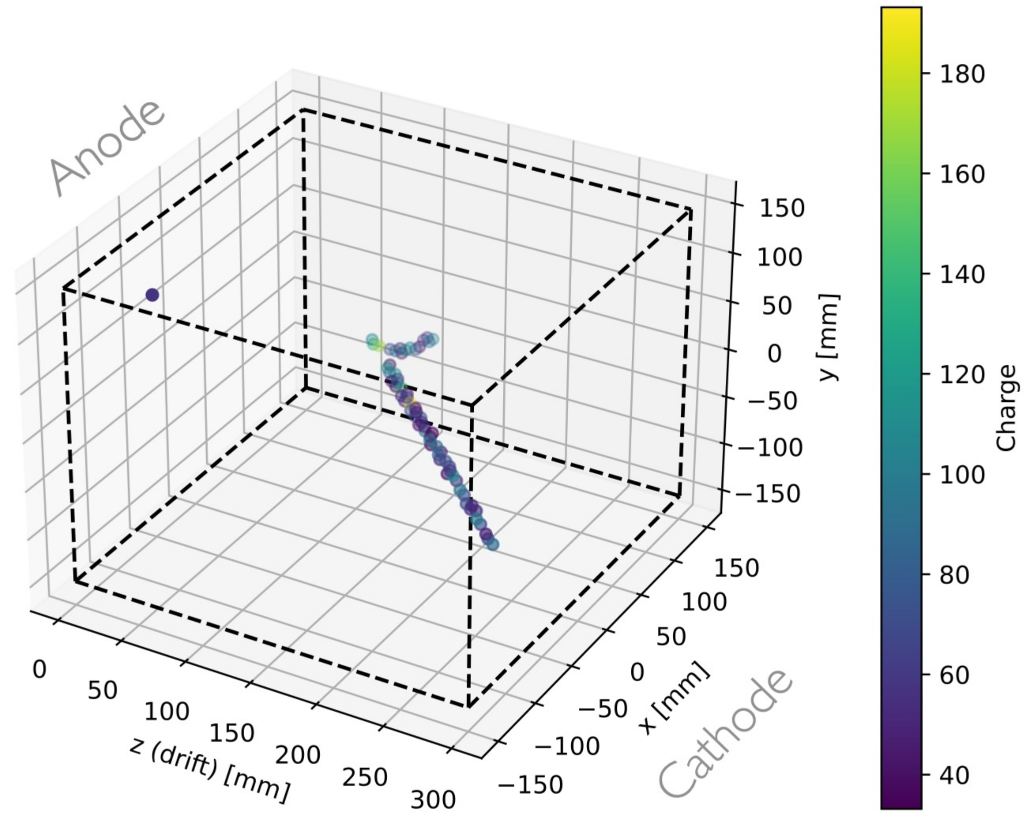
Tyler Johnson



Phil Barbeau, APS 2023

Future LArTPC





Yun-tse Tsai, SLAC

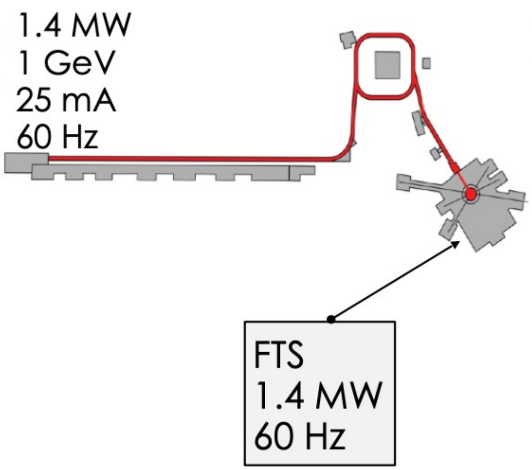
- Proposed: 250 kg Ar (50x60x60 cm^3) [larger for STS]
- DUNE-like, relevant for SN burst & solar detection
- R&D test bed (e.g. pixelated readout, photon detectors, ...)

SNS upgrades: Beam Power and Second Target Station

PPU and STS upgrades will ensure SNS remains the world's brightest accelerator-based neutron source

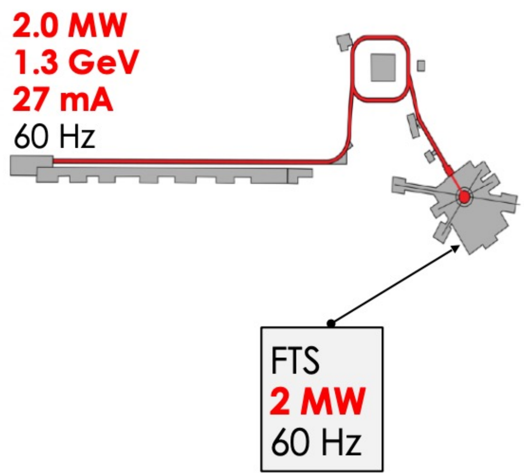
Today

- 900 users
- Materials at atomic resolution and fast dynamics



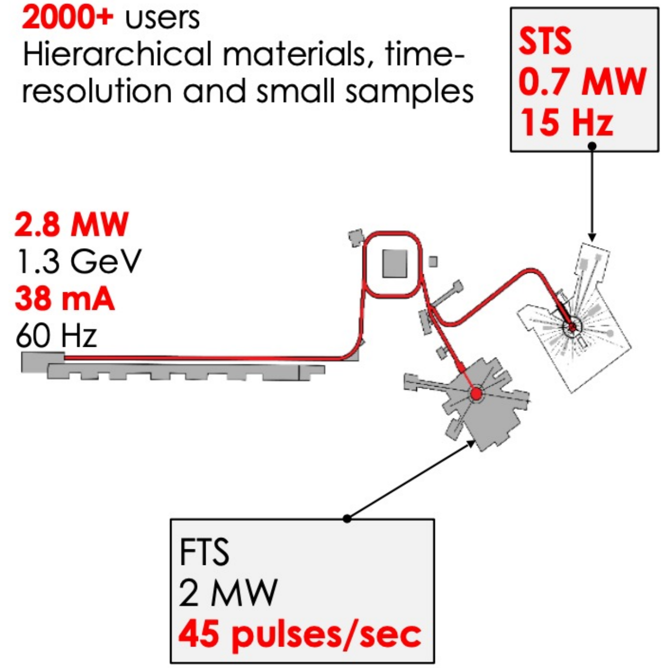
2024 after PPU

- **1000+** users
- Enhanced capabilities

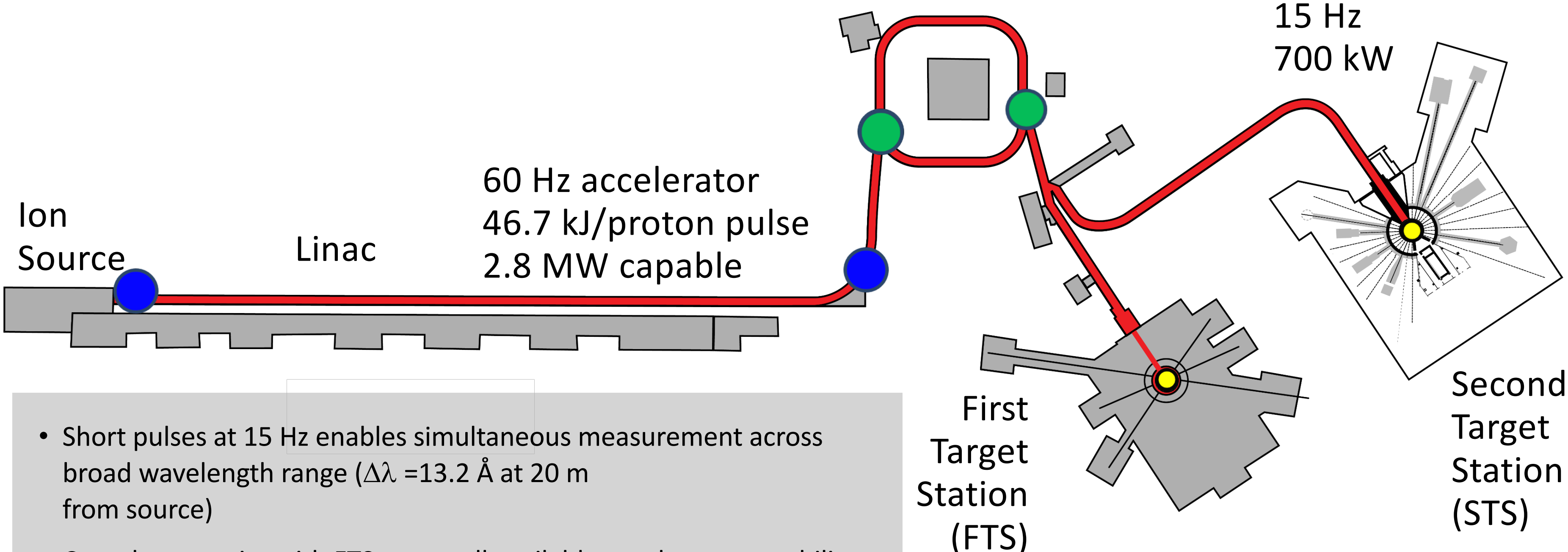


early 2030's

- **2000+** users
- Hierarchical materials, time-resolution and small samples



STS will make optimal use of the SNS accelerator capability



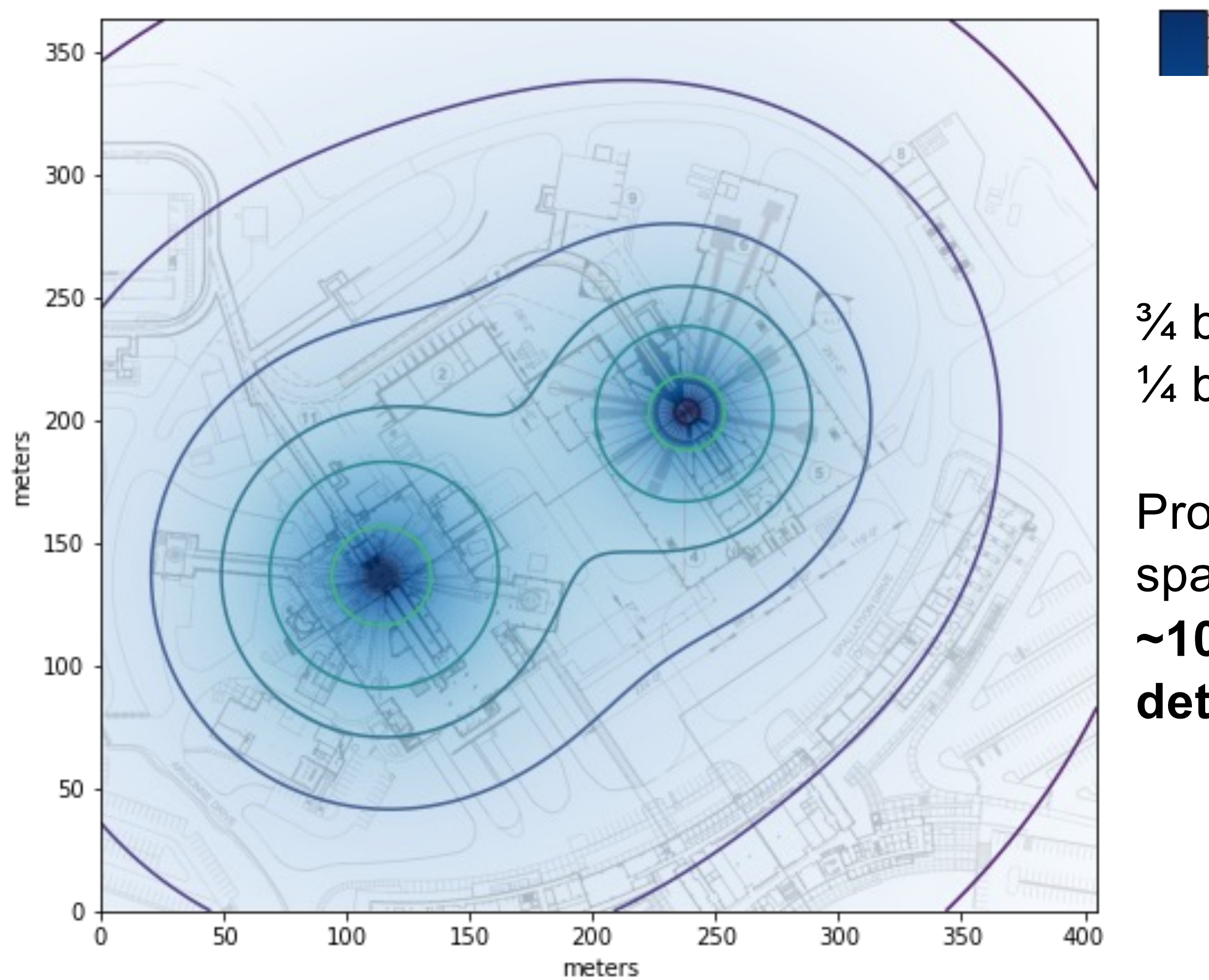
3 out of 4 proton pulses
45 pulses/sec
2 MW

- Short pulses at 15 Hz enables simultaneous measurement across broad wavelength range ($\Delta\lambda$ =13.2 Å at 20 m from source)
- Complementarity with FTS – uses all available accelerator capability provided by PPU
- Flexibility will be provided to operate both FTS and STS at the same time or separately if either is shutdown

*animation courtesy of Matt Stone

From Ken Herwig

Second Target Station Neutrino Opportunities

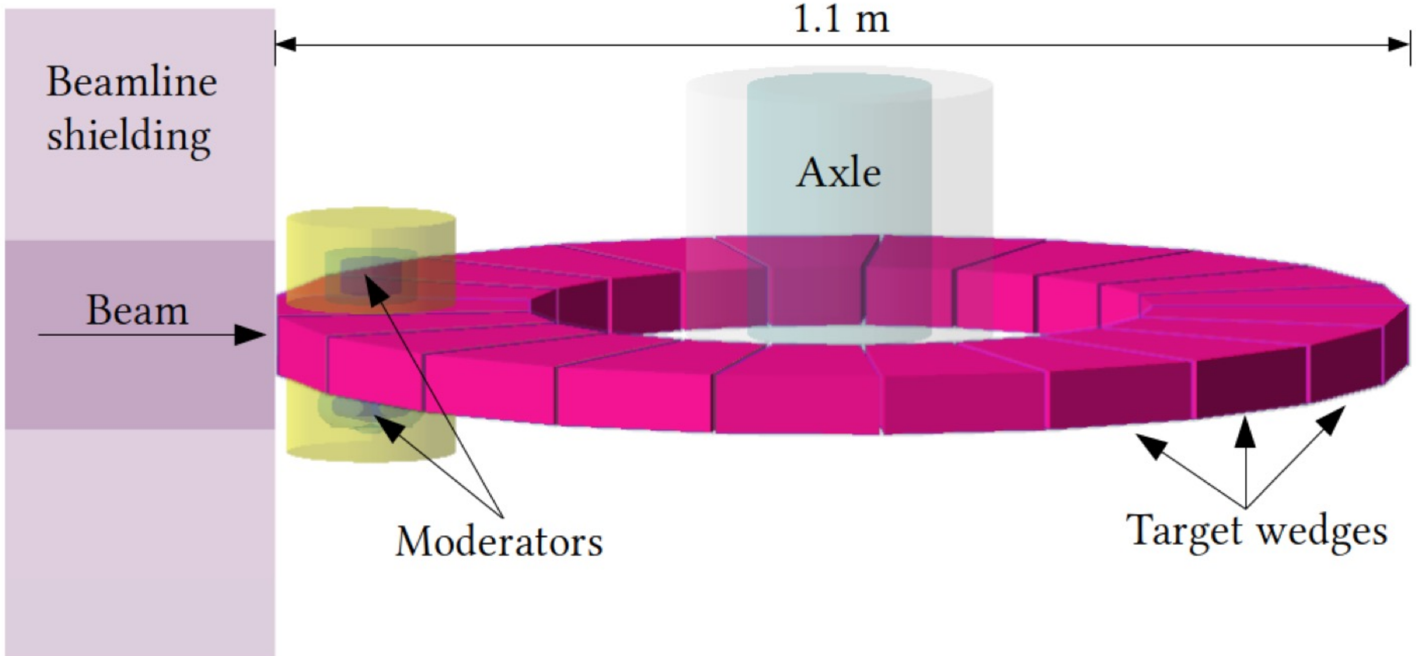


¾ bunches to FTS
¼ bunches to STS

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

Many exciting possibilities for ν's + DM!

Second Target Station Neutrino Production



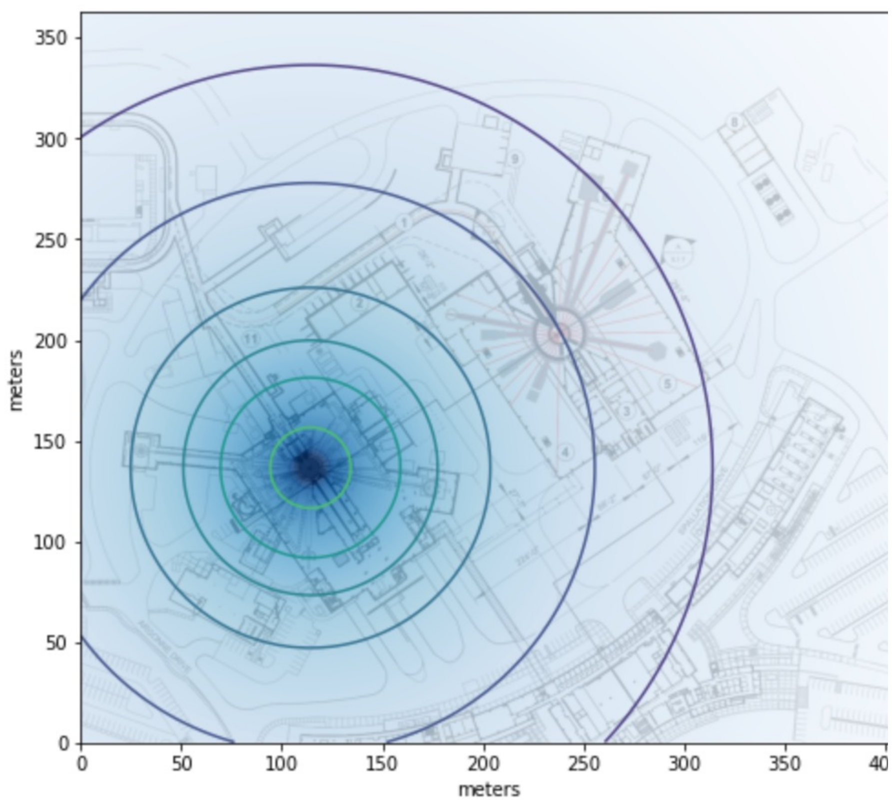
- tungsten wedges
- 0.39 ν/proton (slightly larger than FTS @1.3 GeV)
- still very clean DAR

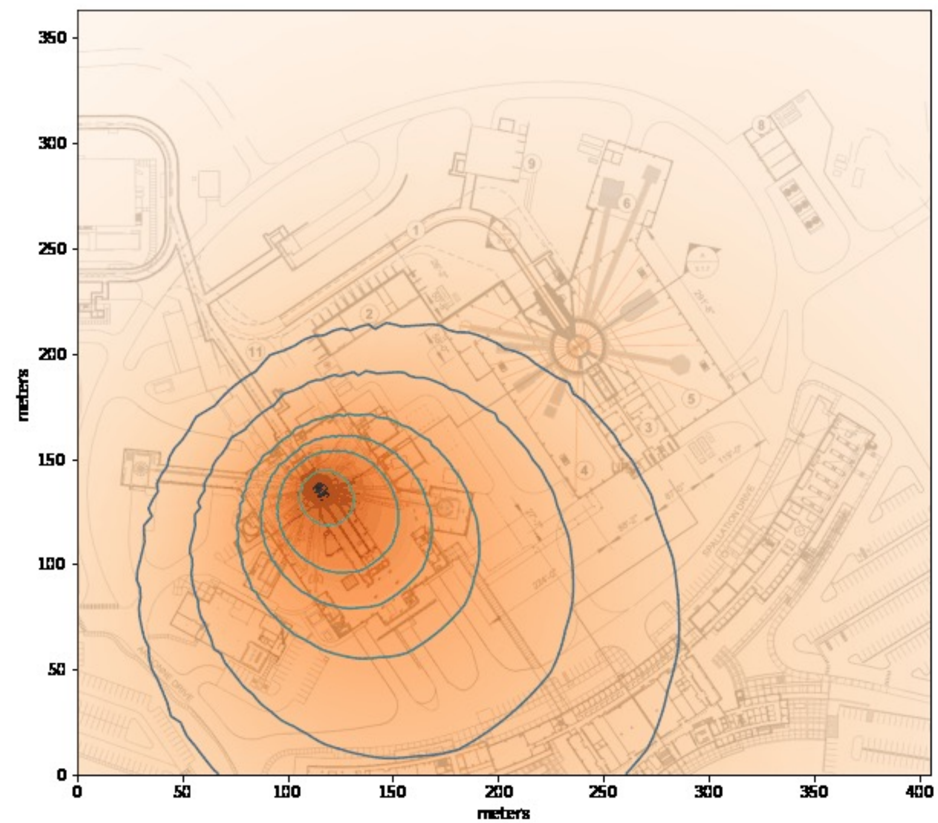
Phys.Rev.D 106 (2022) 3, 032003 arXiv:2109.11049

Directionality of flux at the SNS

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

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





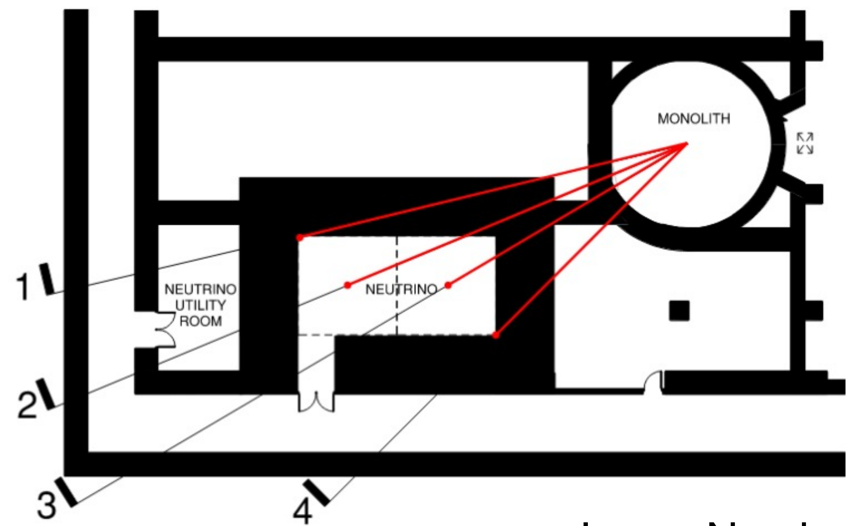
Can in principle test angular dependence
of boosted DM flux

STS Neutrino Facility Concept

Good options within basement footprint that do not affect the SNS mission

- accommodate
  2x10-ton-scale instruments
- dedicated neutron shielding
- overburden for cosmic suppression
- neutrino Instrument bunker 500 sqft
  + supporting utilities room 500 sqft
  + supporting corridor ~1500 sqft

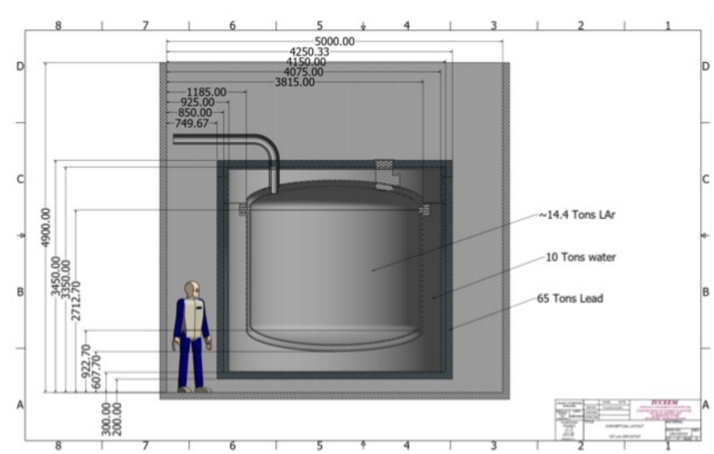
STS Basement Concept for Neutrinos



Jason Newby

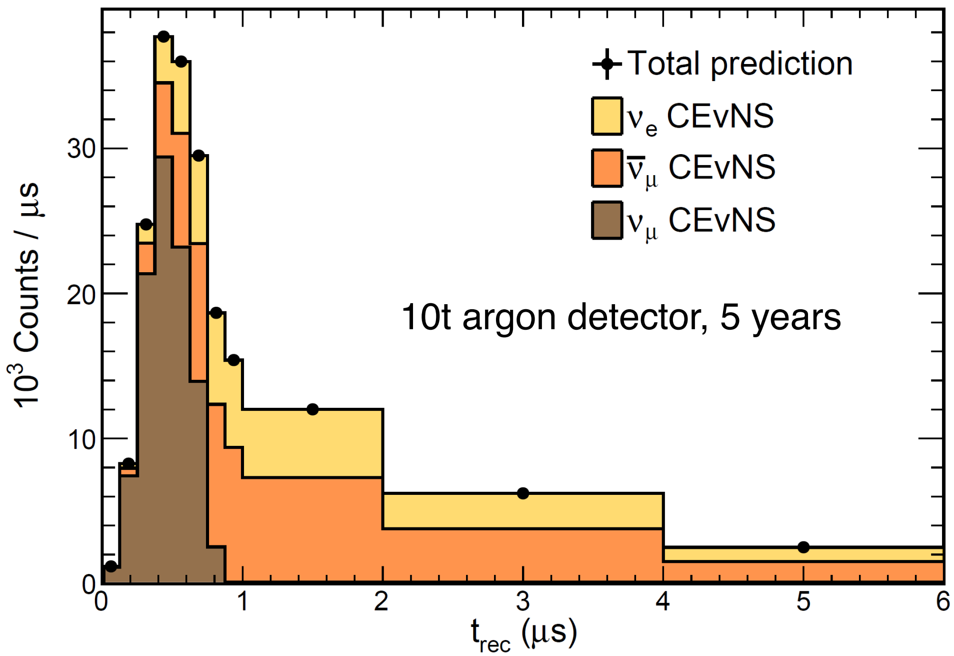
Many possible detector concepts

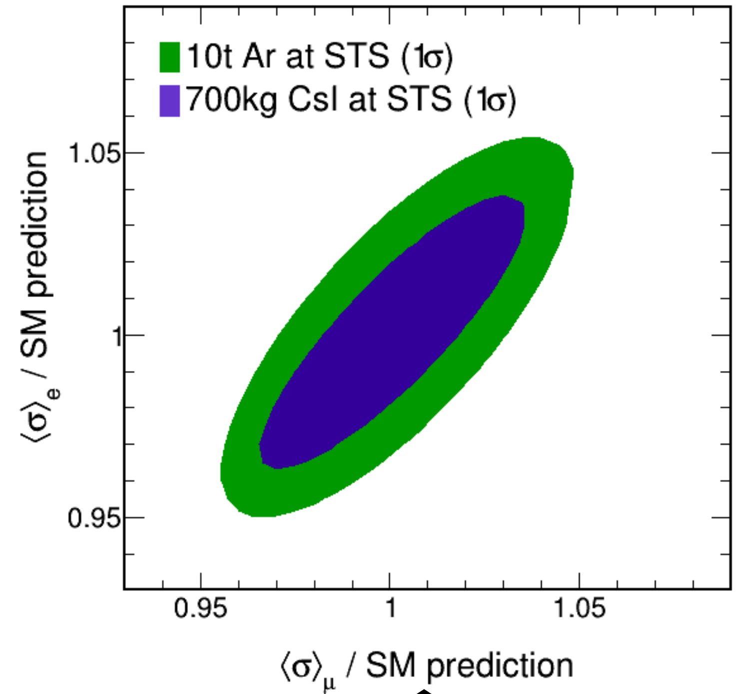
- "Strawperson":
  10-ton argon, single phase or TPC
- Others: germanium, cryoCsI, water,
  scintillator, directional, solids, ...



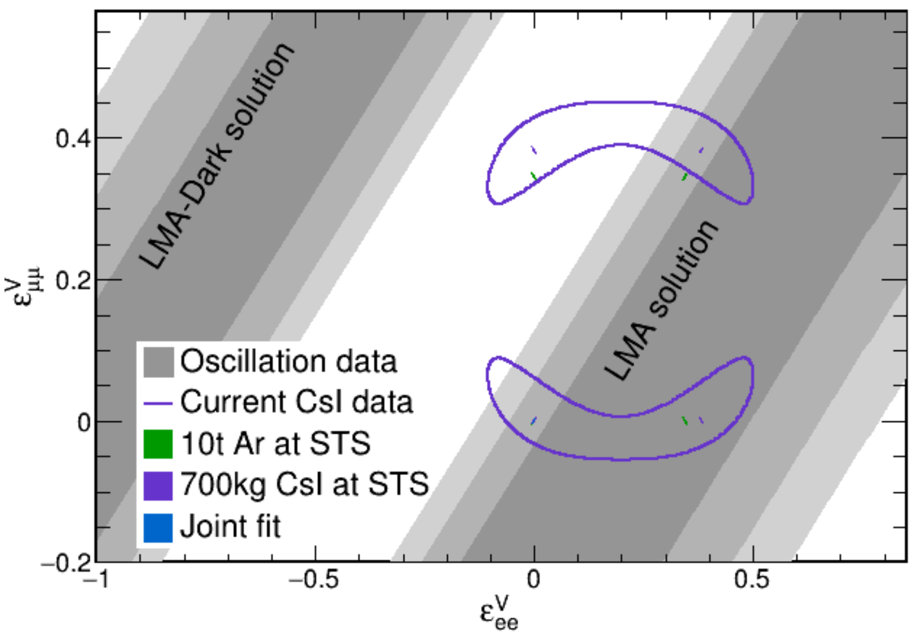
10-ton Argon Cryostat Concept, IU

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)

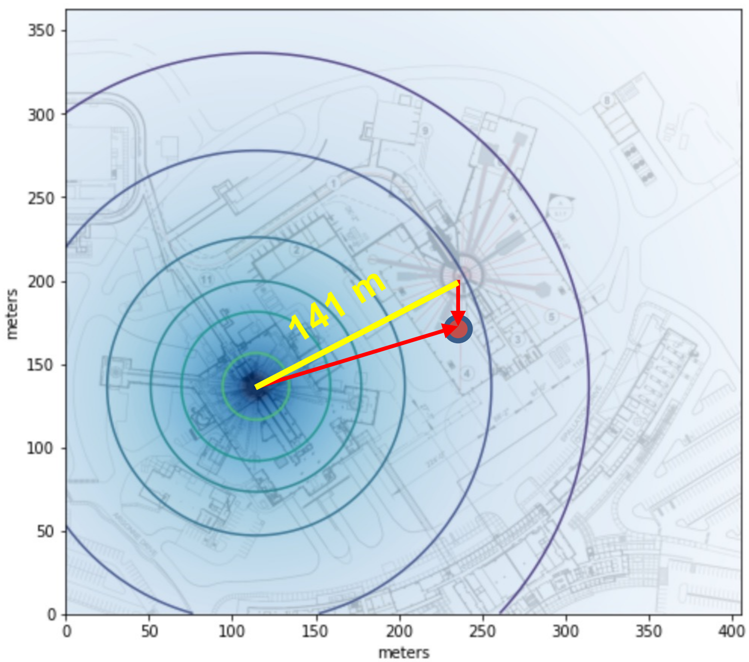


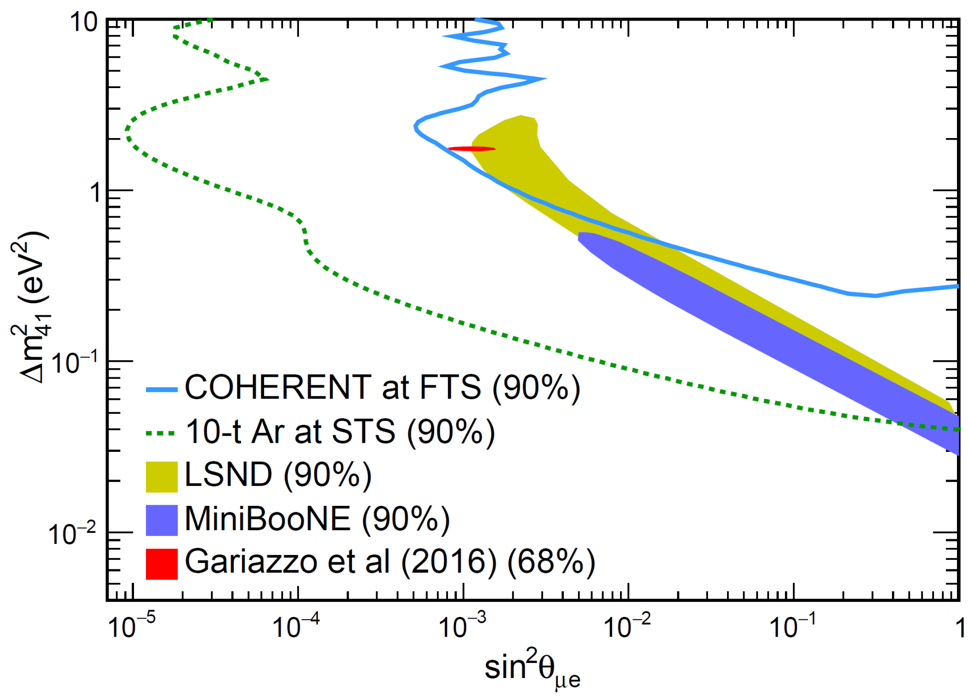
Stringent NSI parameters constraints, resolving oscillation ambiguities

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

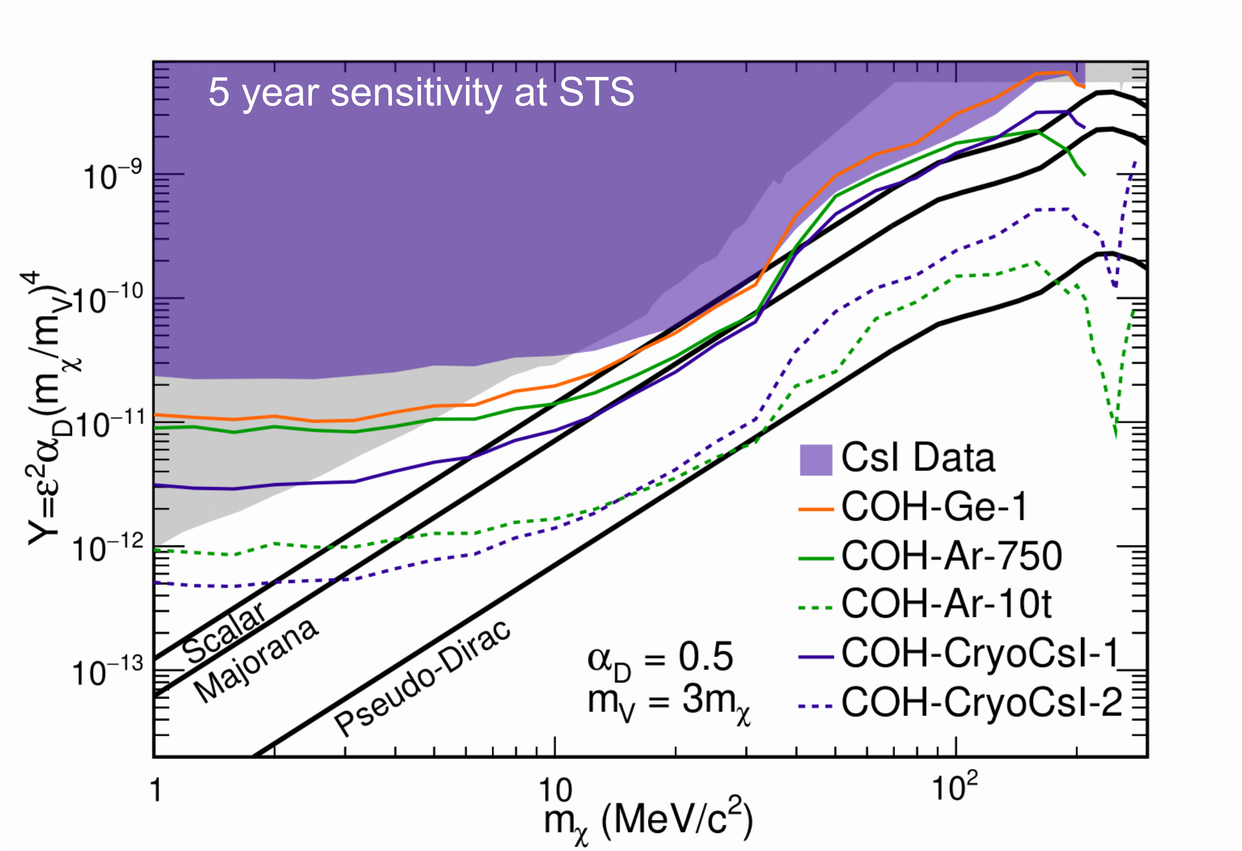
w/ different baselines in one CEvNS detector seeing 2 sources

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

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

Take-Away Messages

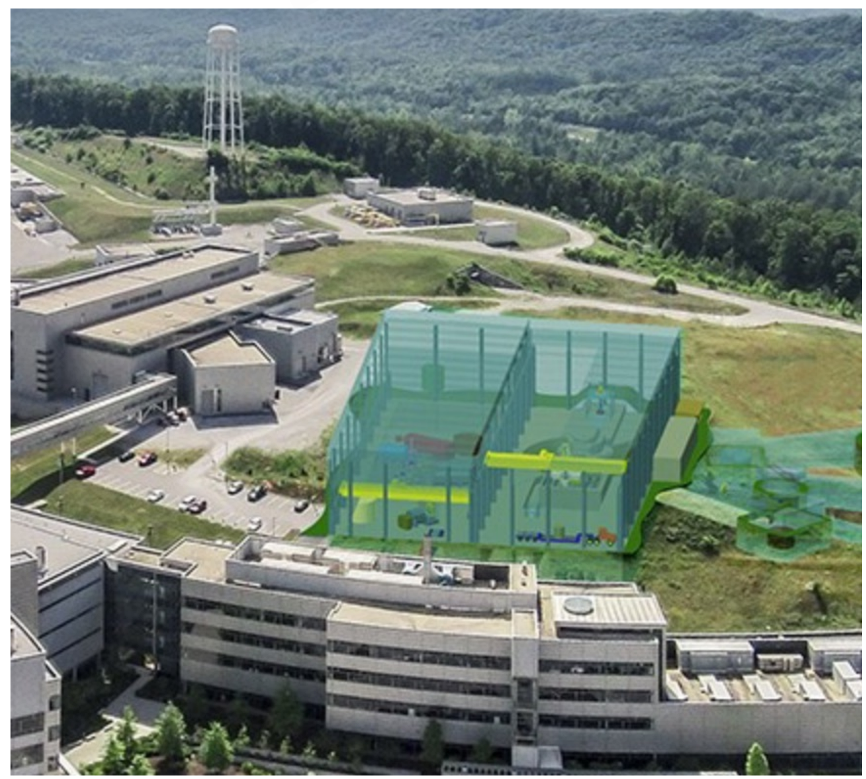
- **Spallation sources are prodigious producers of πDAR neutrinos, and maybe BSM signatures...**

- **Low energy nuclear recoil signals**
  - CEvNS (BSM & nuclear physics)
  - DM recoils
  - Sterile neutrinos

- **Few-tens-of-MeV signals**
  - Neutrino eES + inelastics, especially interesting for SN/solar
  - Other BSM opportunities

- **Many exciting opportunities at the SNS FTS+STS**
  - Power upgrade happening now
  - STS in early 2030's w/expanded space for neutrinos

arXiv: 2209.02883



Extras/Backups