Neutrino Experiments at the Spallation Neutron Source

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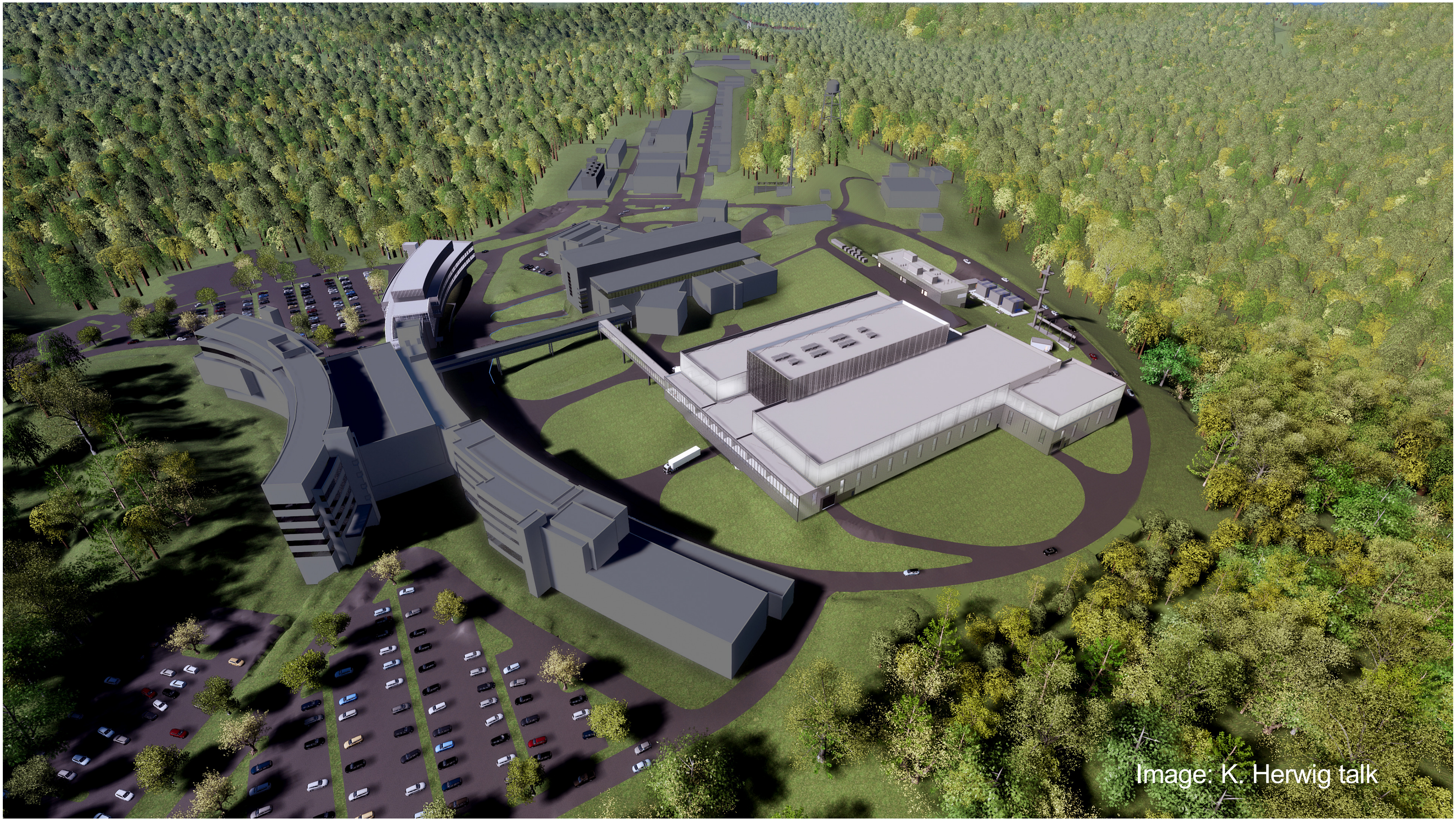
Neutrino Scattering at Low and Intermediate Energies

Mainz Institute for Theoretical Physics

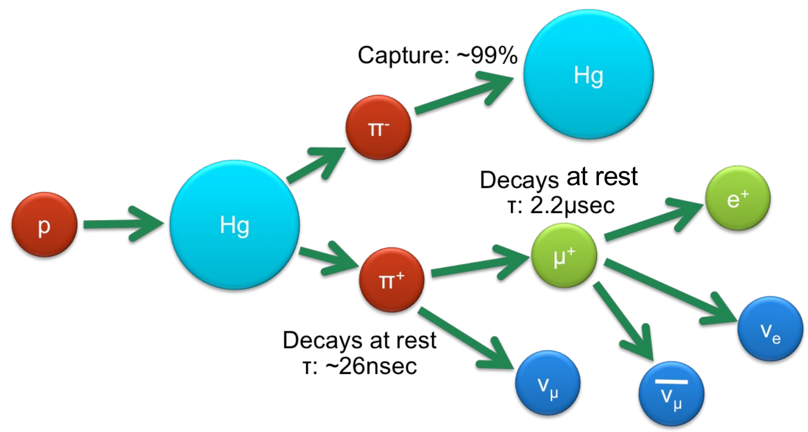
June 26, 2023

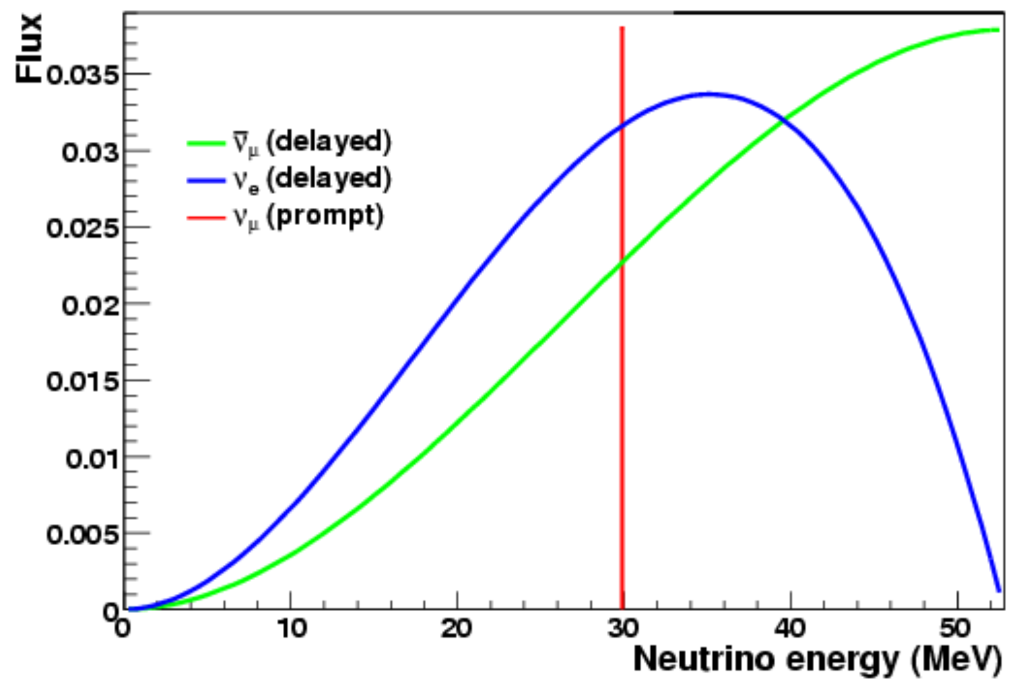


Outline

- 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

Stopped-Pion (πDAR) Neutrinos





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

2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

$$\downarrow$$

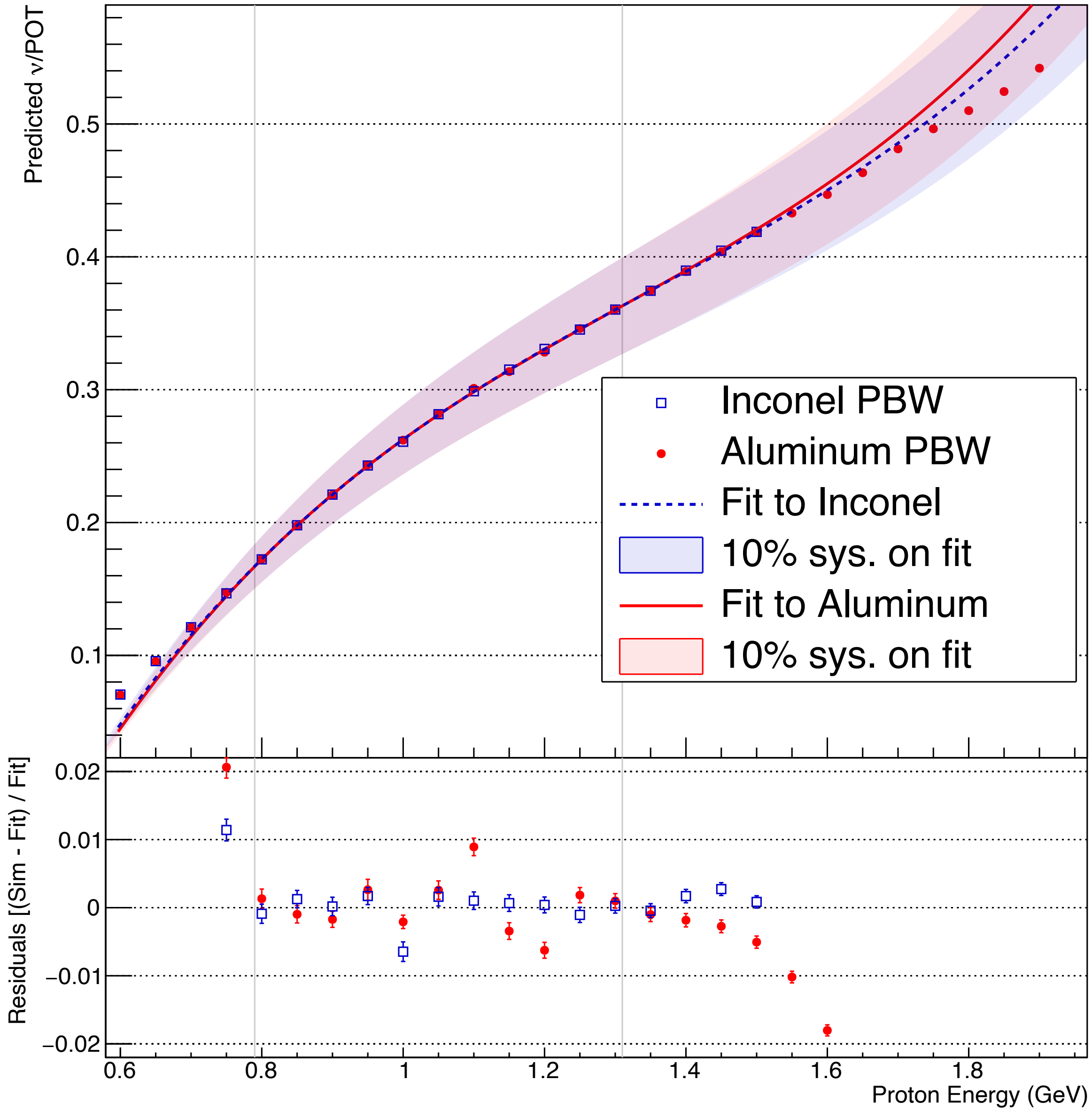
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

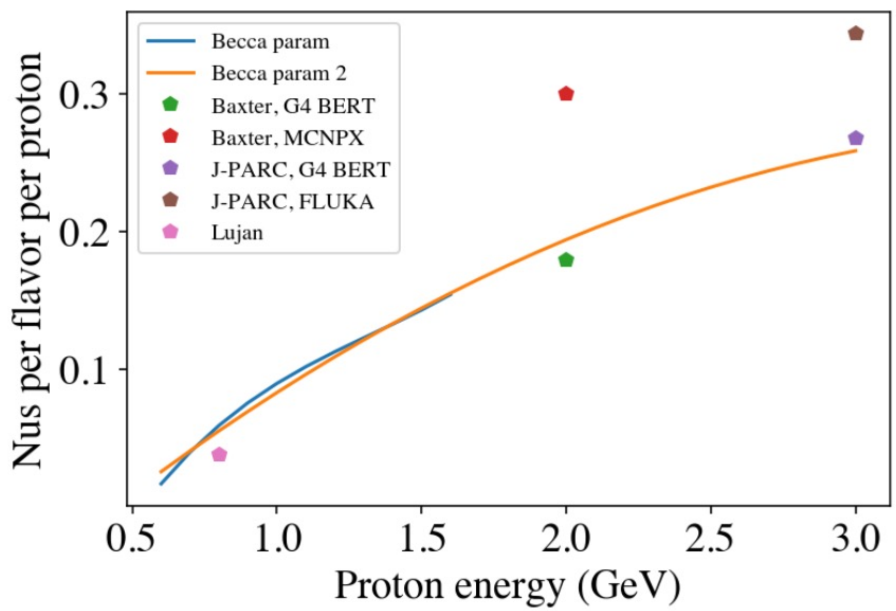
Total neutrinos per proton (all 3 flavors)



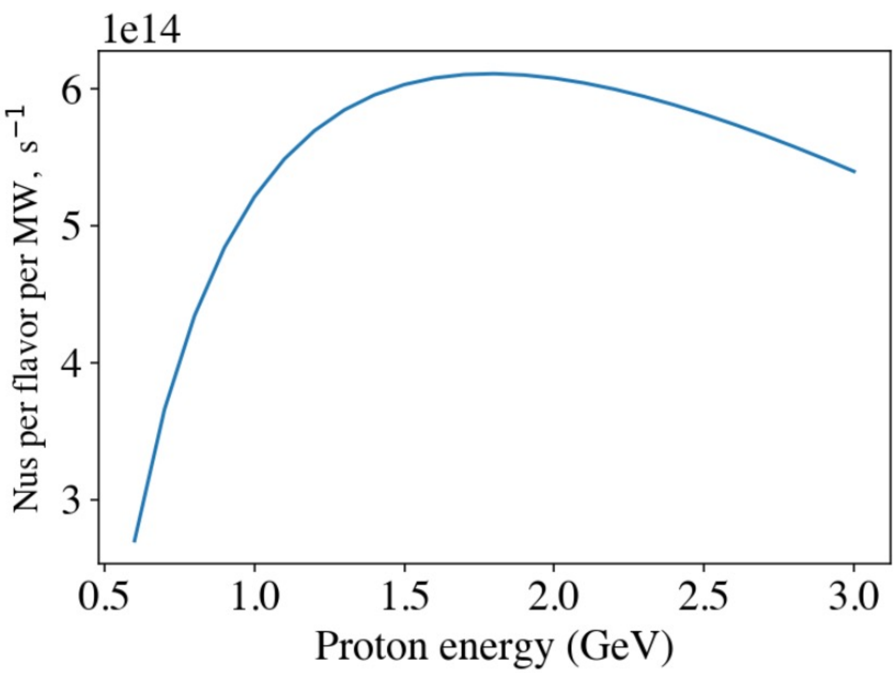
G4 QGSP_BERT, validated vs HARP/HARP-CDP

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

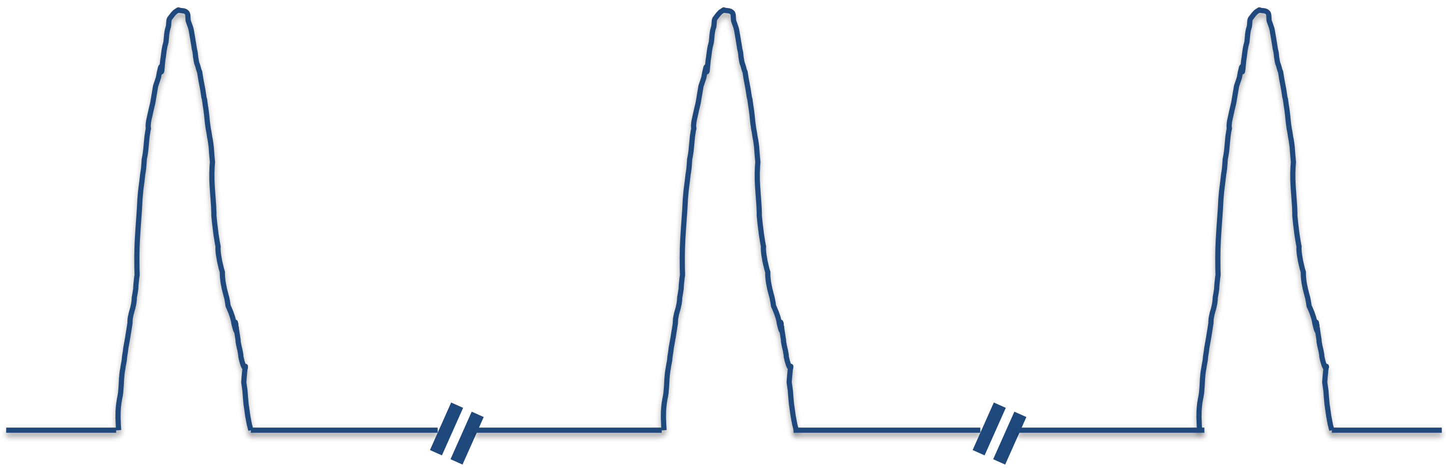


- Assuming QGSP_BERT
  parameterization to 3 GeV,

~1.5 GeV is optimal νs/power

Note:
higher proton energy,
fewer protons per MW

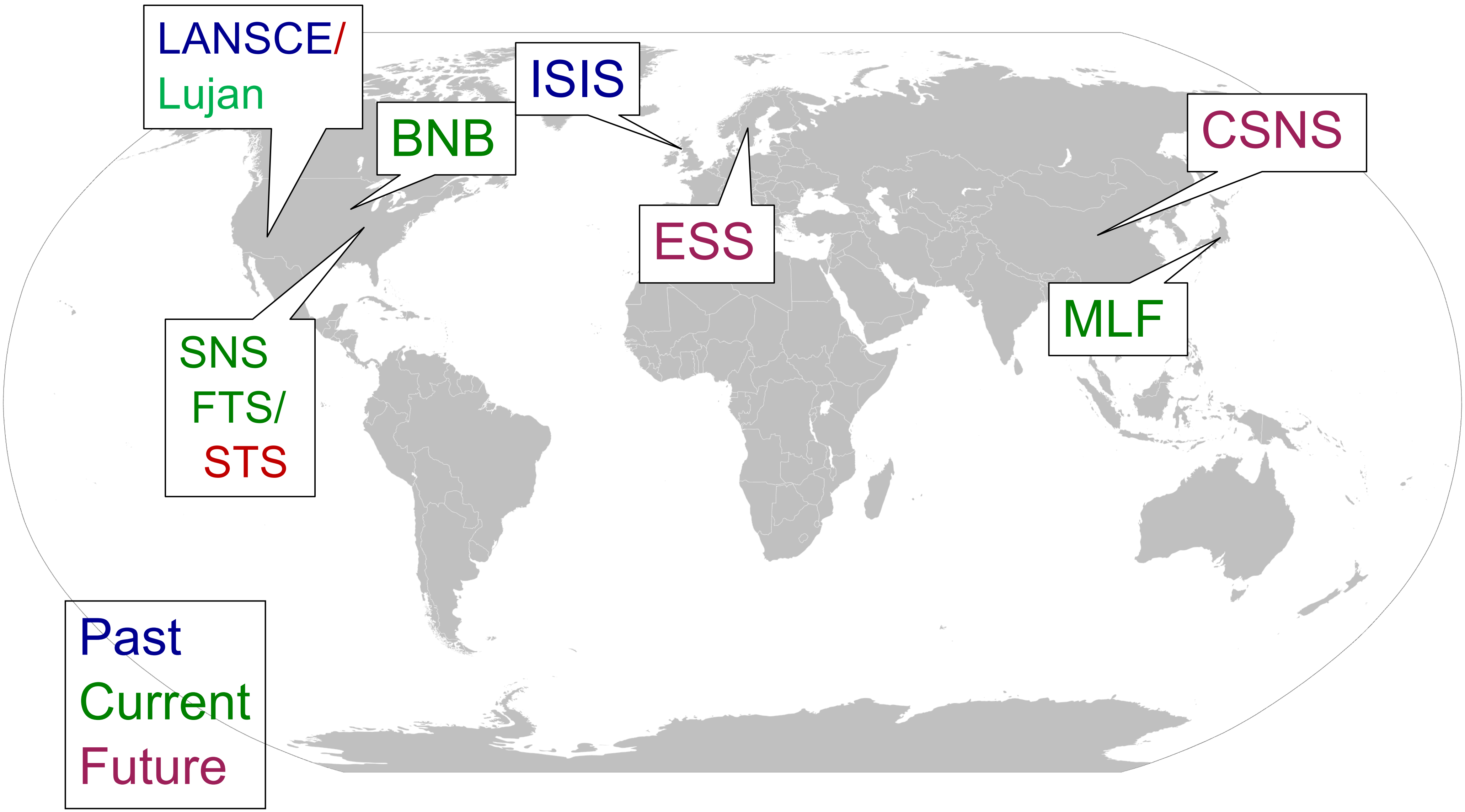
When the beam is **pulsed**, make use of the time structure to reject background



- 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... )

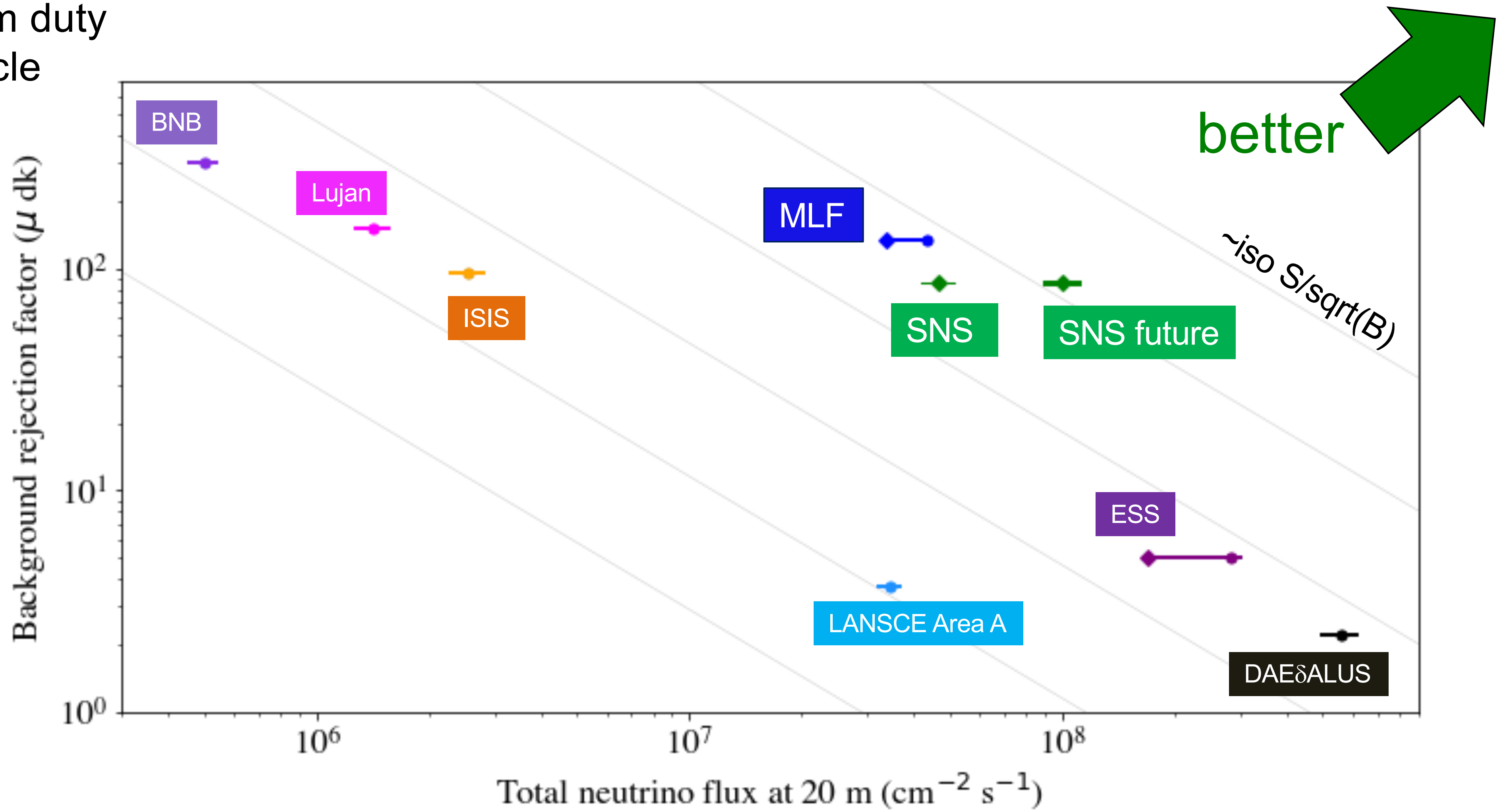
  - "Duty factor" or "duty cycle" = fraction of time beam is on
  - Inverse duty factor → "background rejection factor"

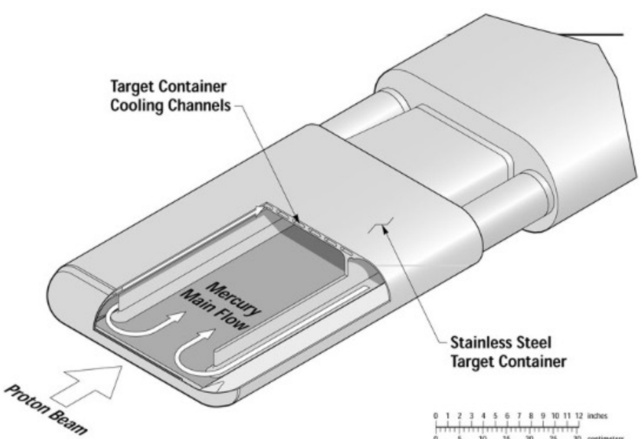
Stopped-Pion Neutrino Sources Worldwide



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

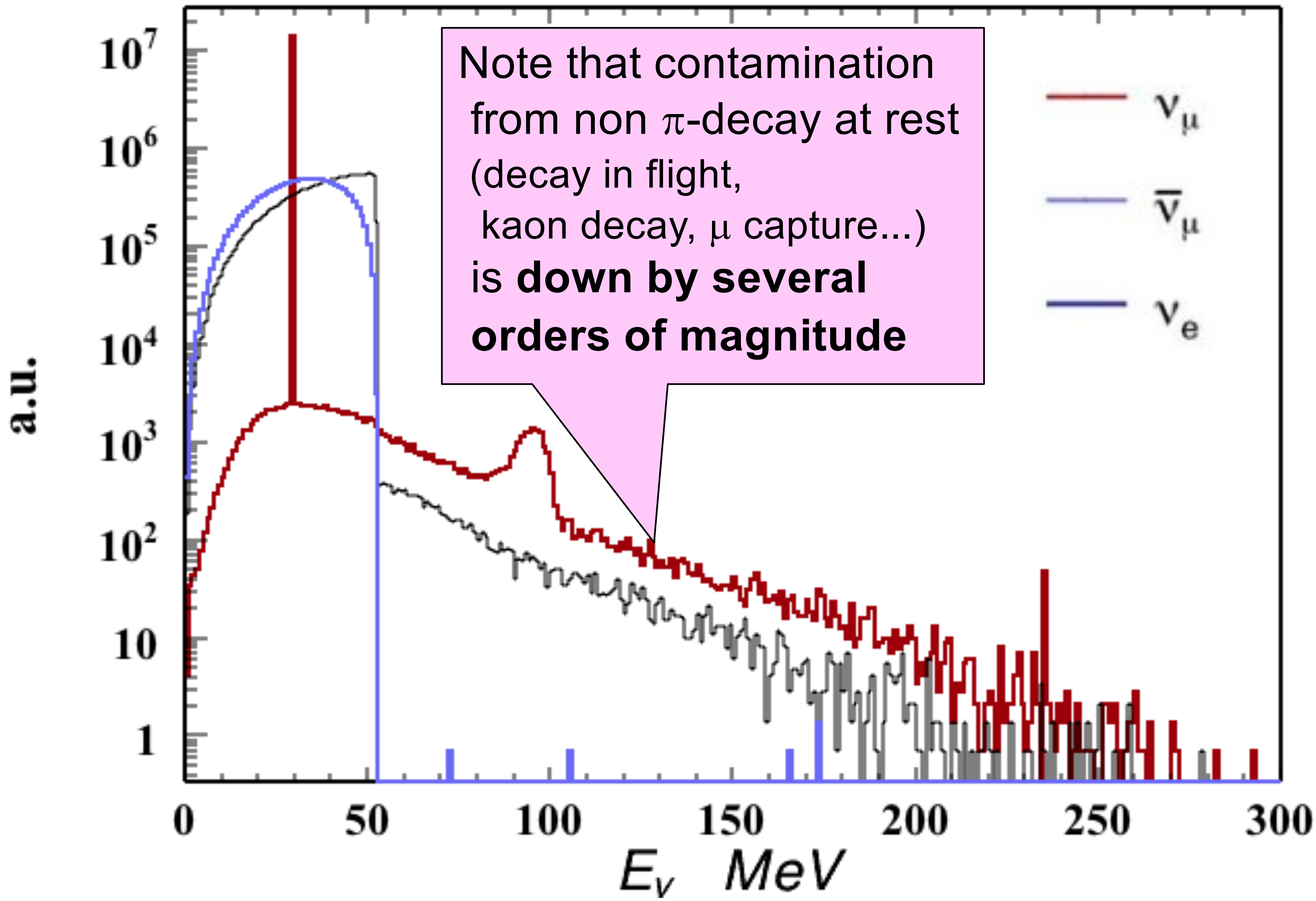
Repetition rate: 60 Hz

Liquid mercury target

The neutrinos are free!

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

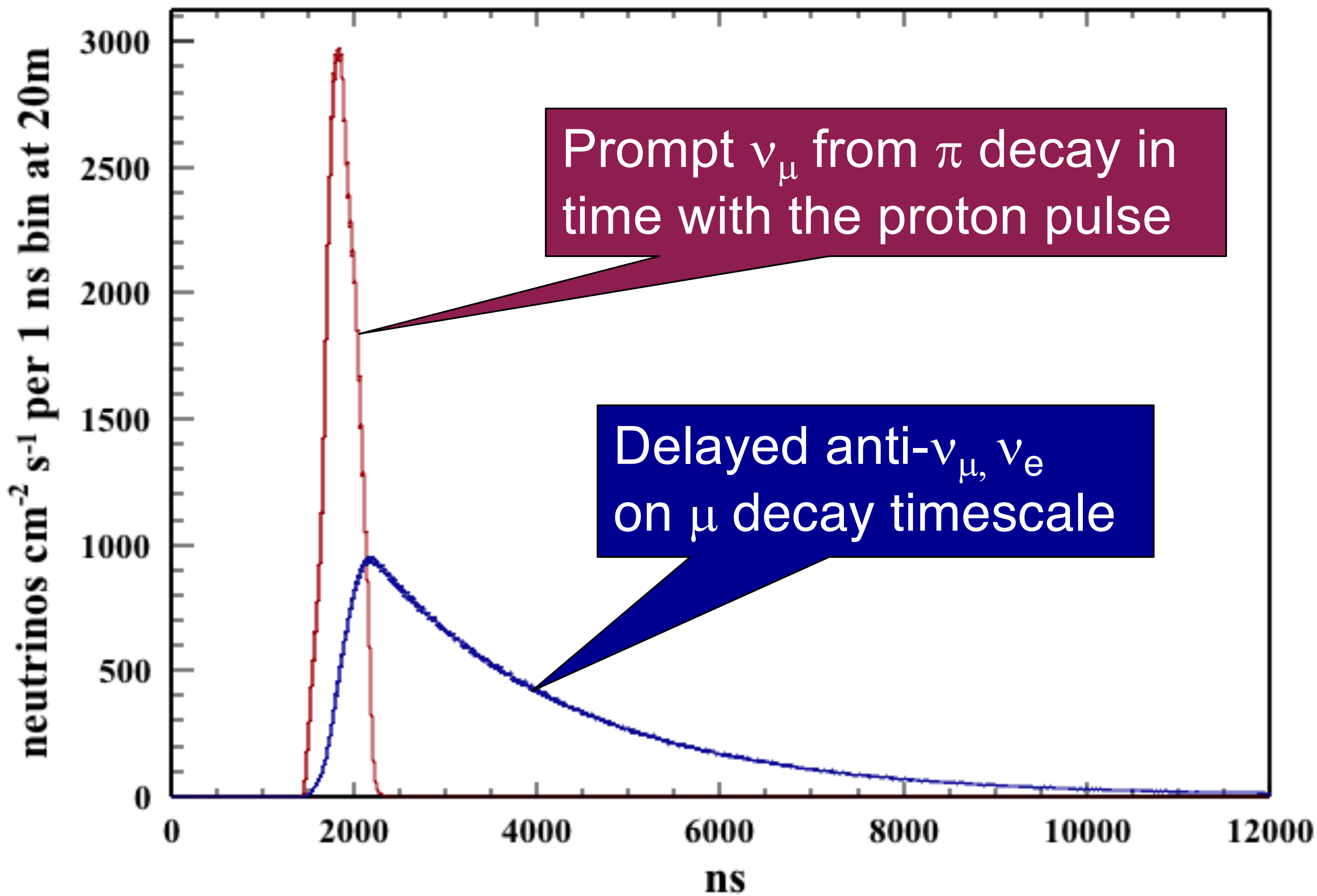
0.08 neutrinos per flavor per proton on target



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

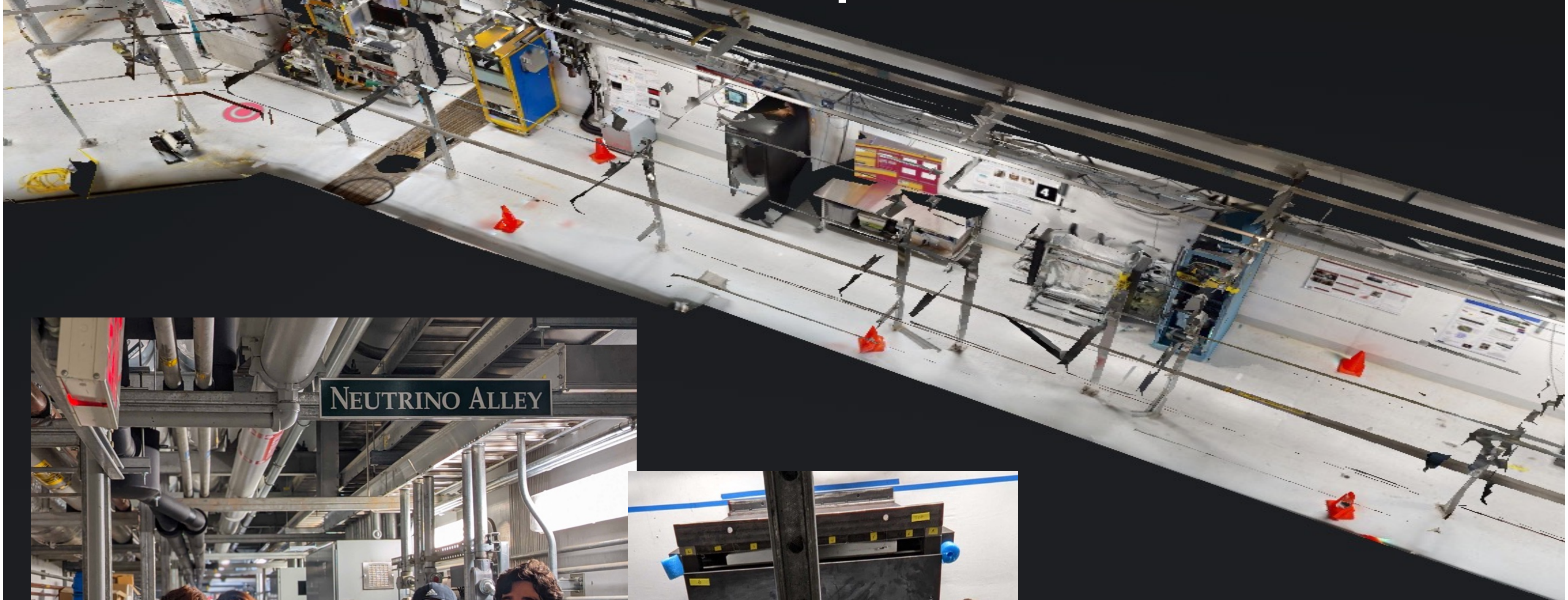
Time structure of the SNS source

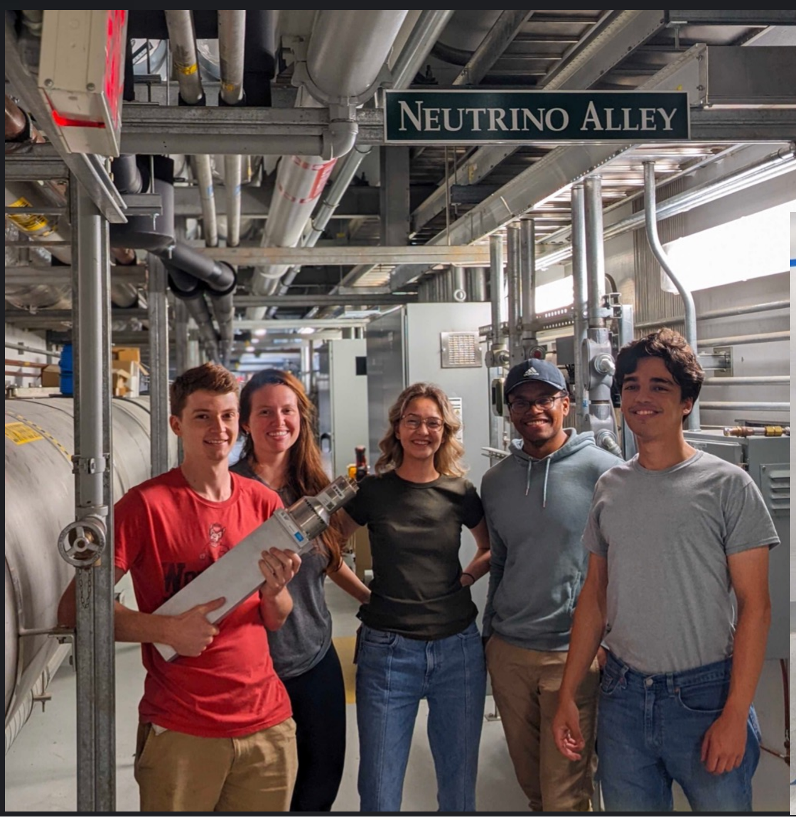
60 Hz *pulsed* source



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

COHERENT in Neutrino Alley at the ORNL Spallation Neutron Source





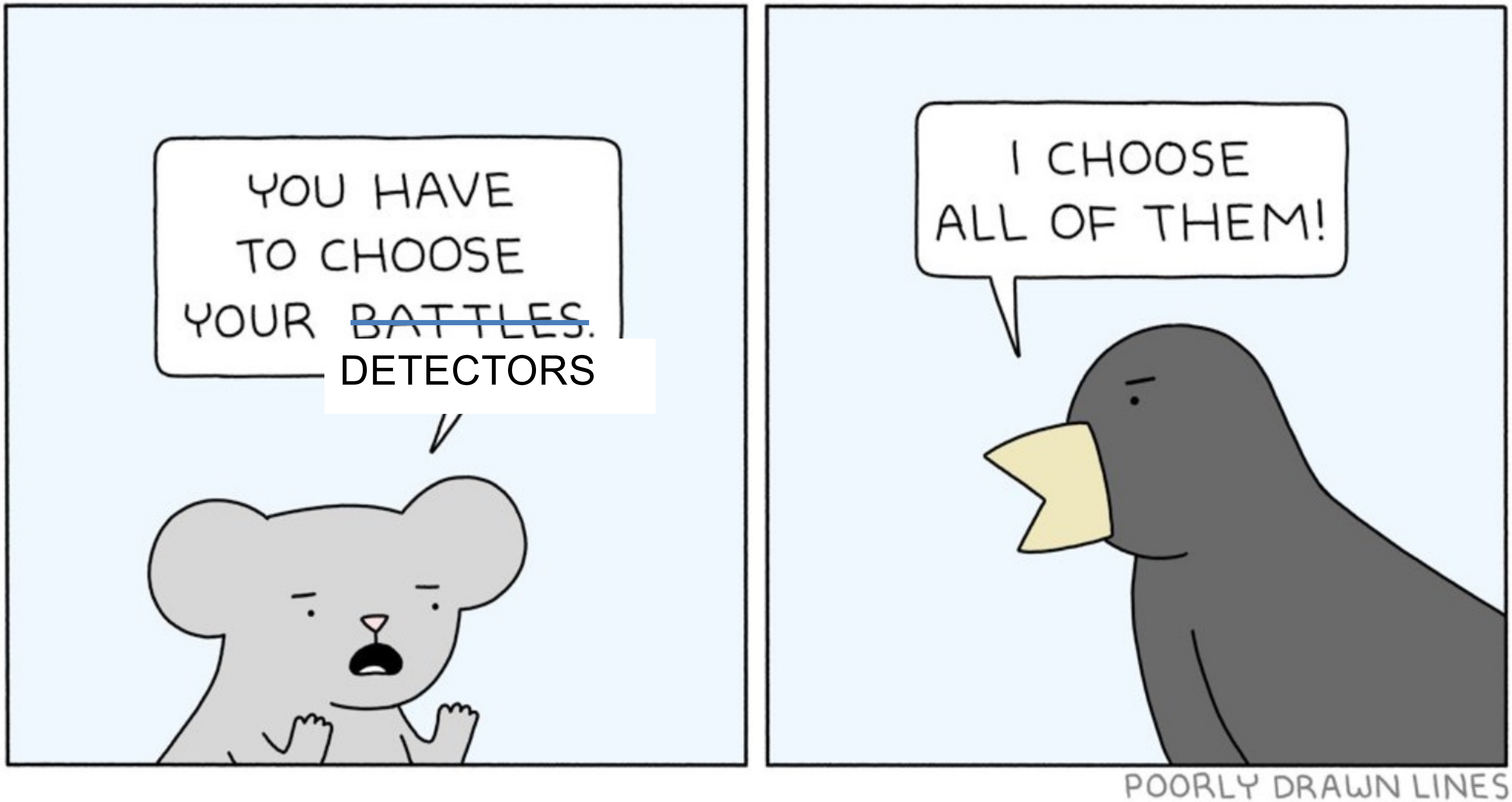
COHERENT
SNS
SPALLATION NEUTRON SOURCE

The COHERENT collaboration

http://sites.duke.edu/coherent

~90 members,
23 institutions
4 countries

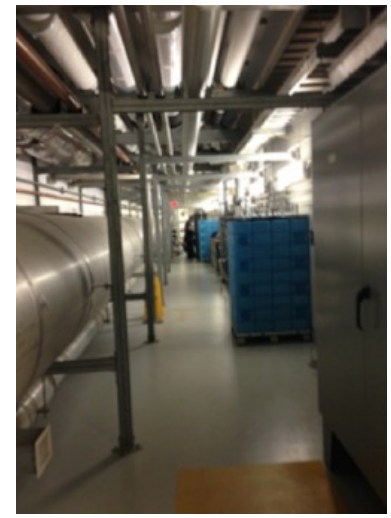
The COHERENT Spirit (so far)

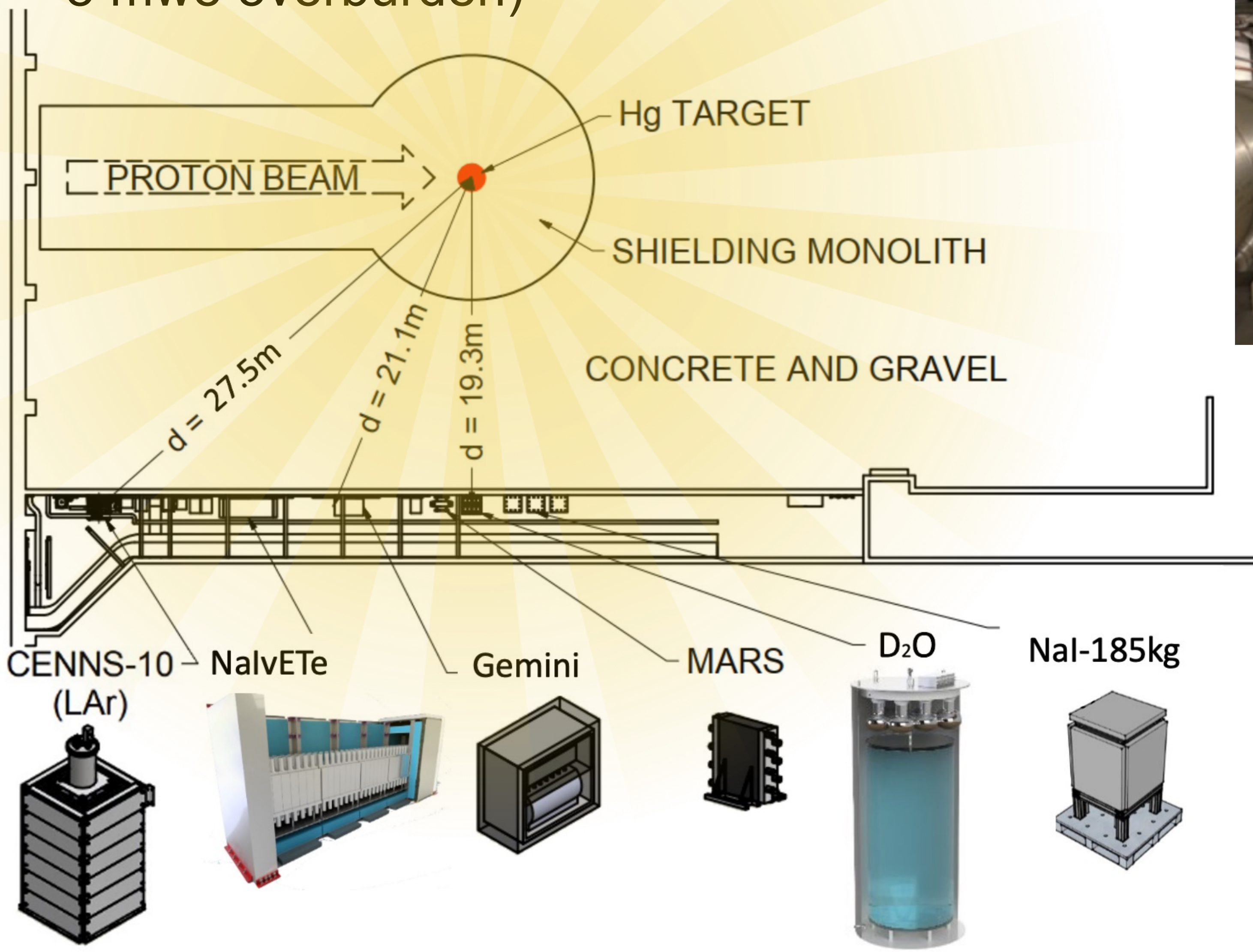


Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

View looking down "Neutrino Alley"

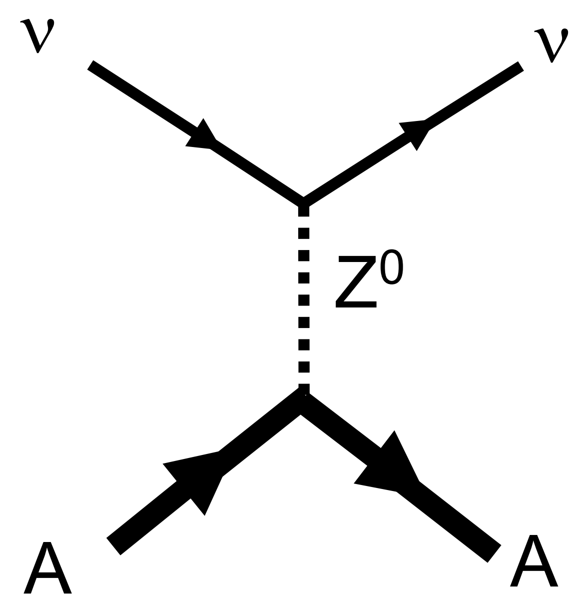




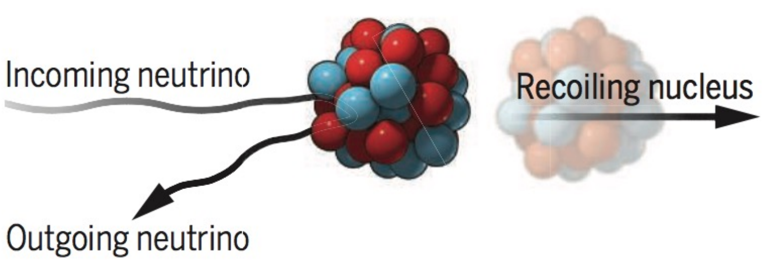
Isotropic ν glow from Hg SNS target

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

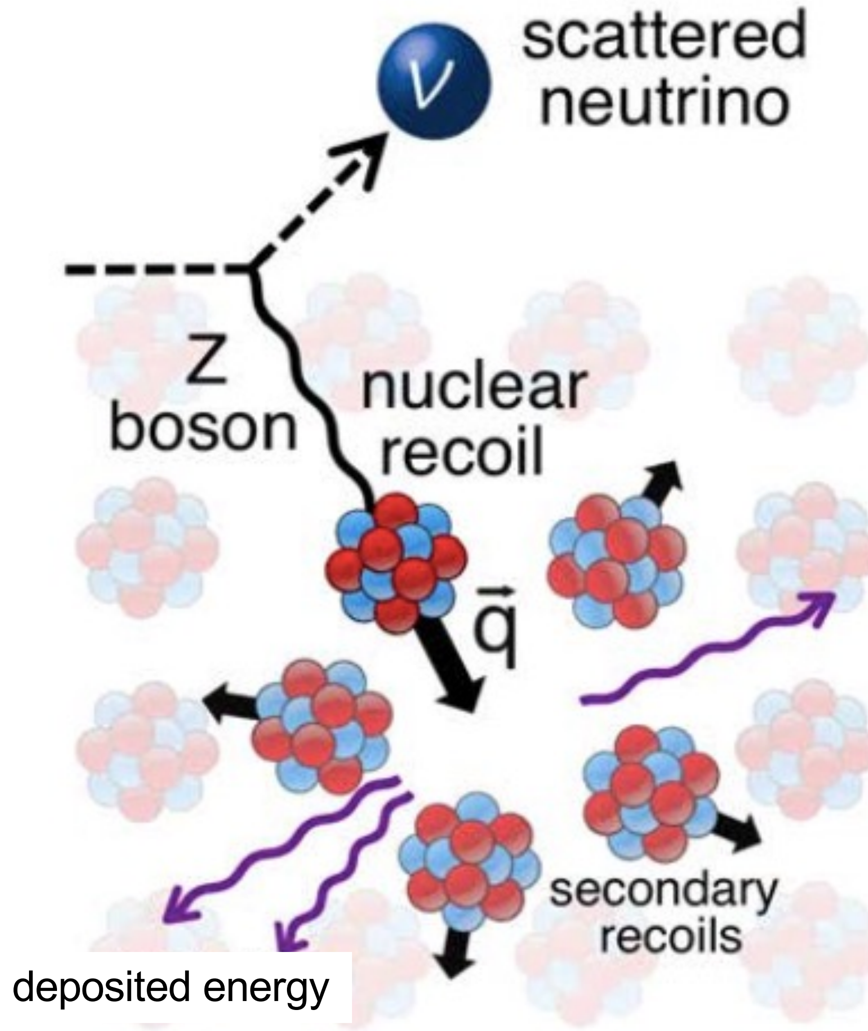
For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

A: no. of constituents

Image: J. Link *Science* Perspectives

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

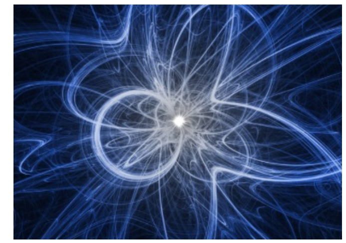
[...understanding of detector response matters!]

CEvNS: what's it good for?

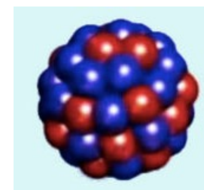
!

(not a complete list!)

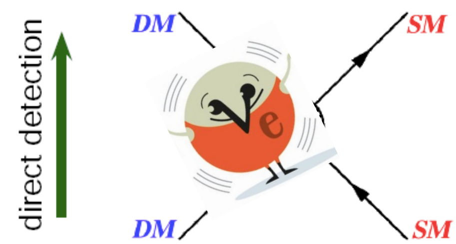
CEvNS as a **signal**
for signatures of *new physics*



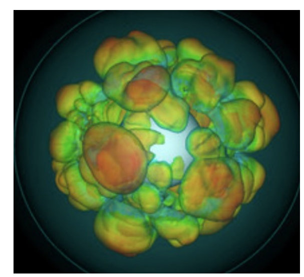
CEvNS as a **signal**
for understanding of "old" physics



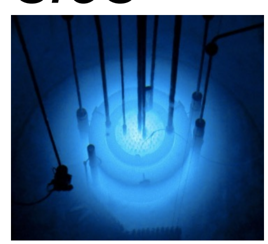
CEvNS as a **background**
for signatures of new physics



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



CEvNS as a **practical tool**



What we can get at experimentally (in principle)

<u>Observables:</u>

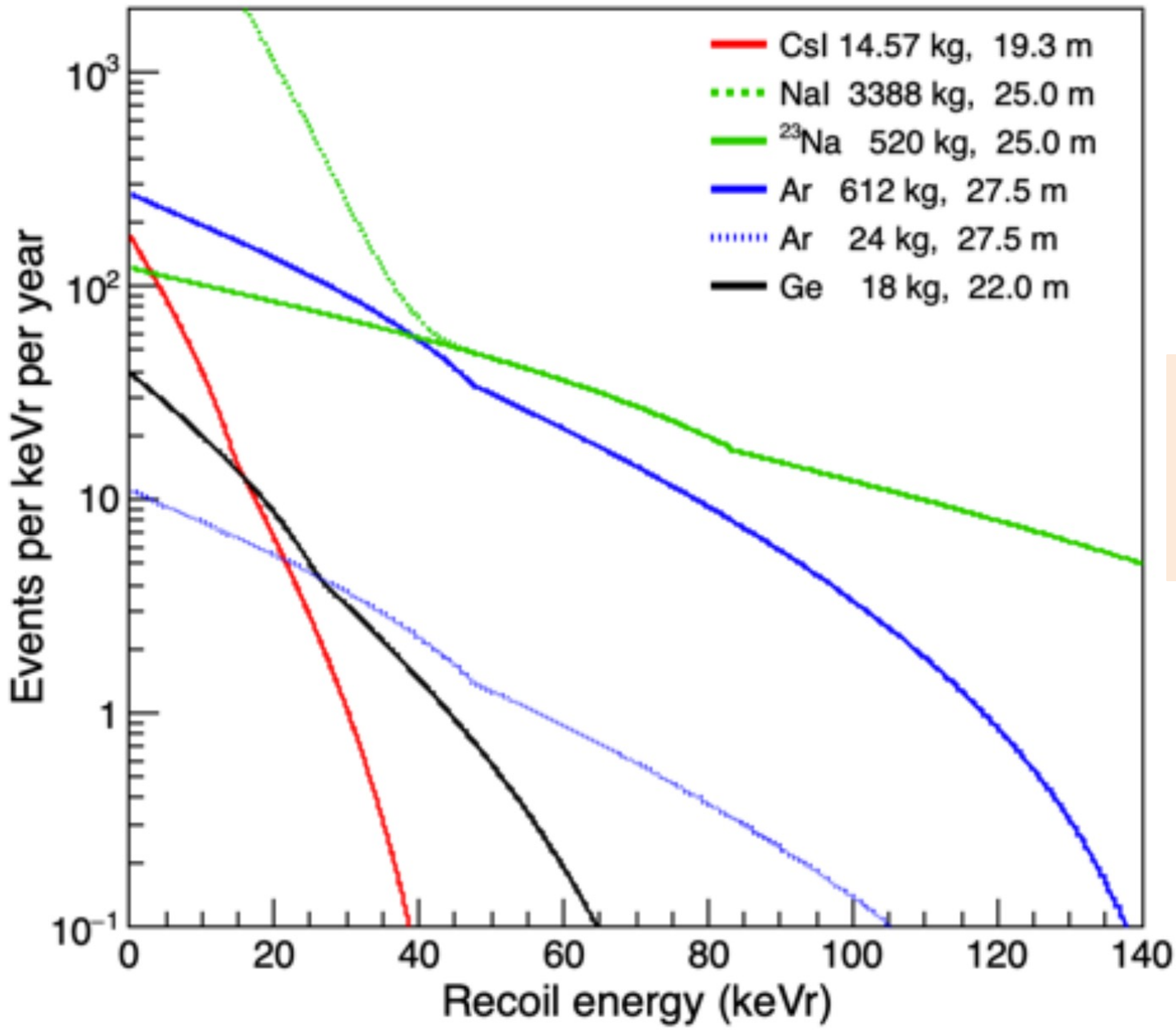
Event rate
Recoil spectrum
Time distribution wrt beam pulse
Scattering angle

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

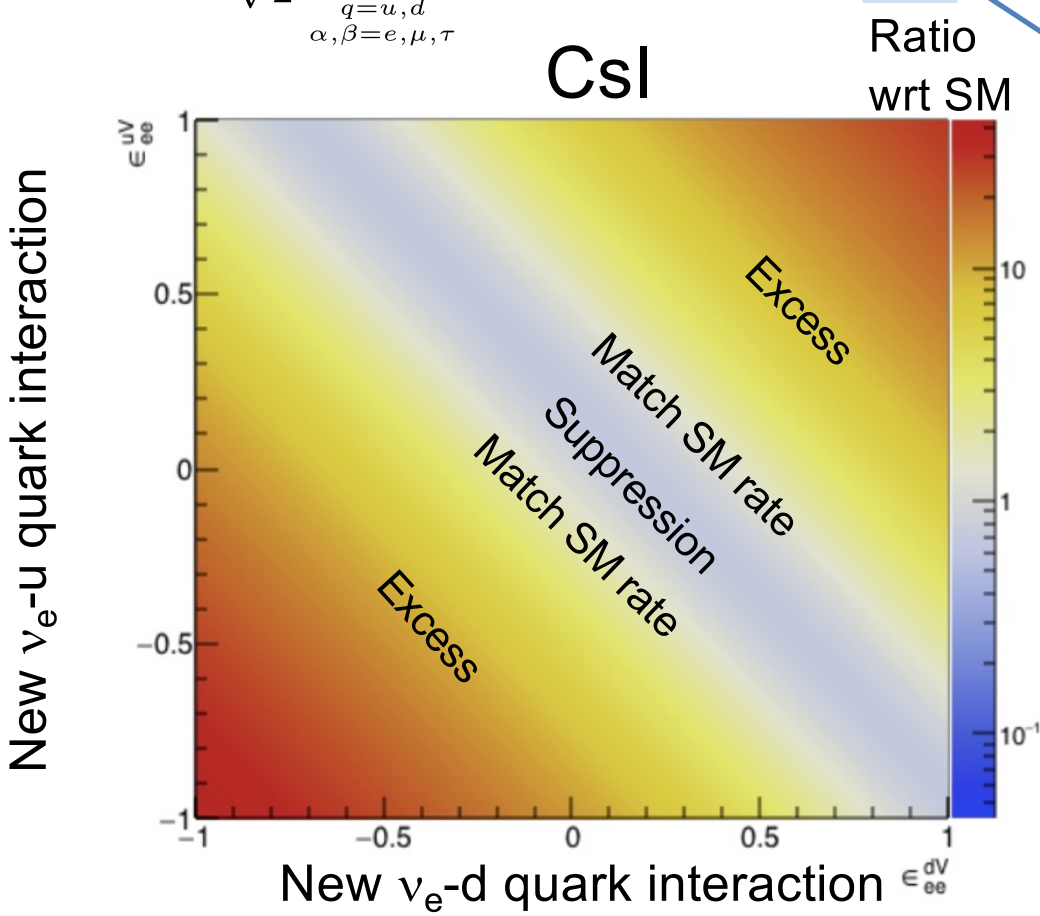


Lighter targets:
less rate per mass,
but kicked to
higher energy

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

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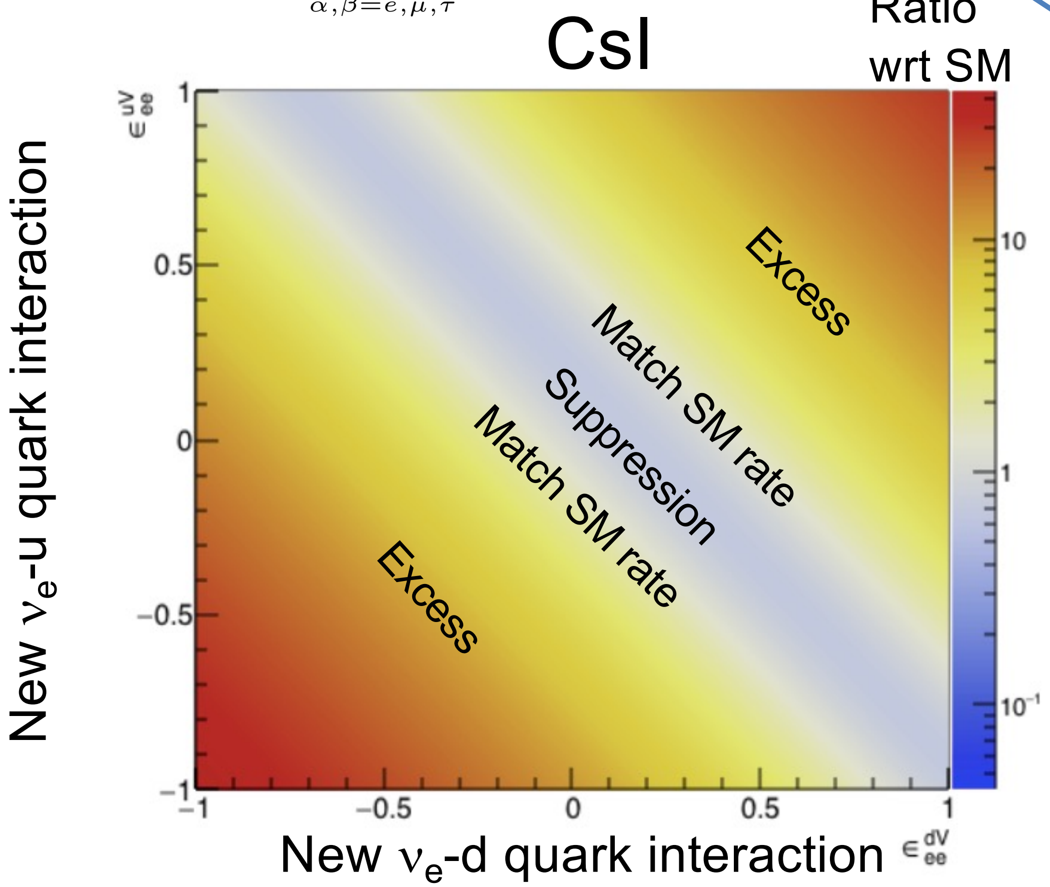

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For heavy mediators, expect ***overall scaling*** of CEvNS event rate, depending on N, Z

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

$$Q^2_{\alpha,\mathrm{SM}} = \left(Zg_p^V + Ng_n^V\right)^2$$

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

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

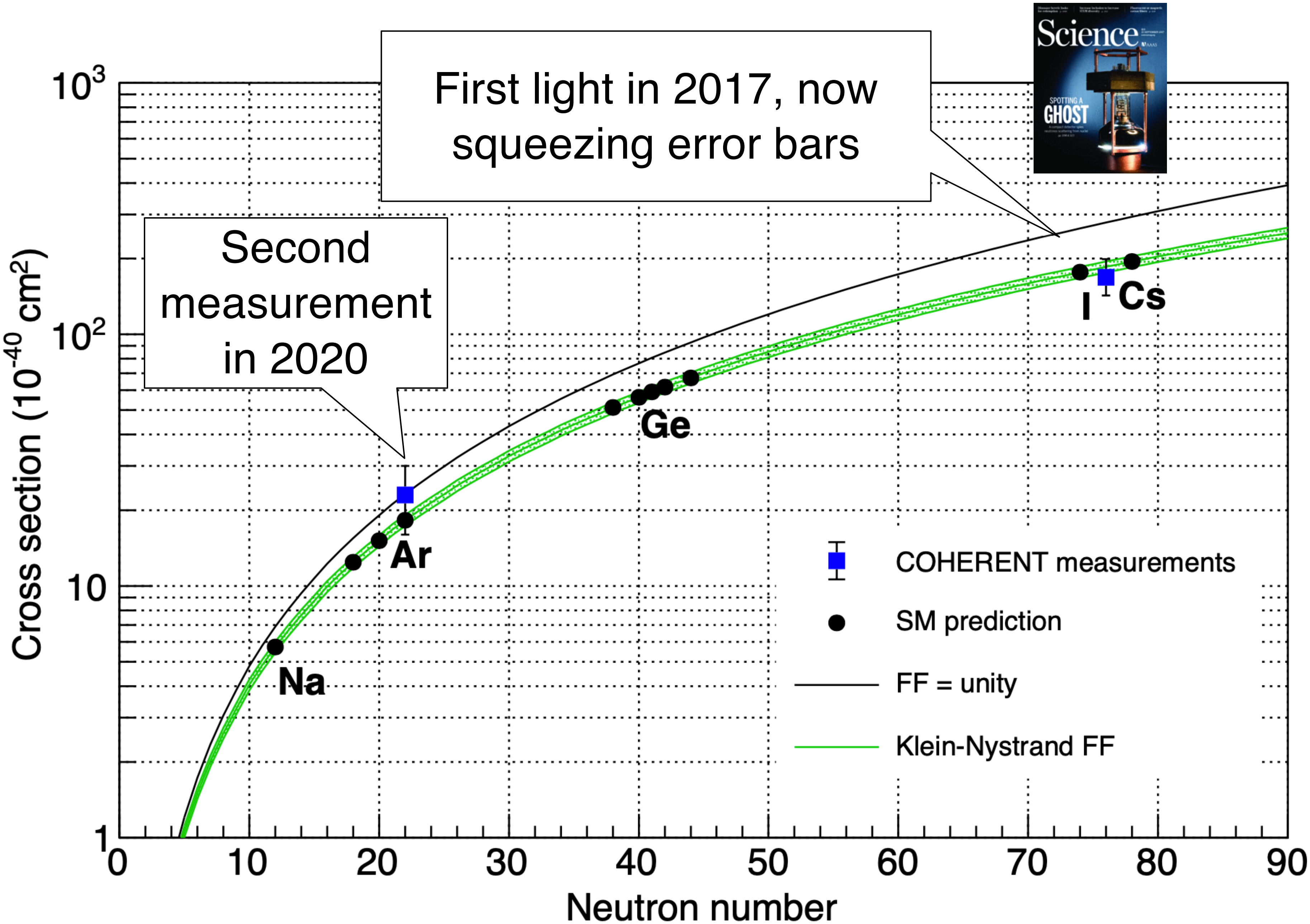
Specific ~1/T upturn at low recoil energy

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

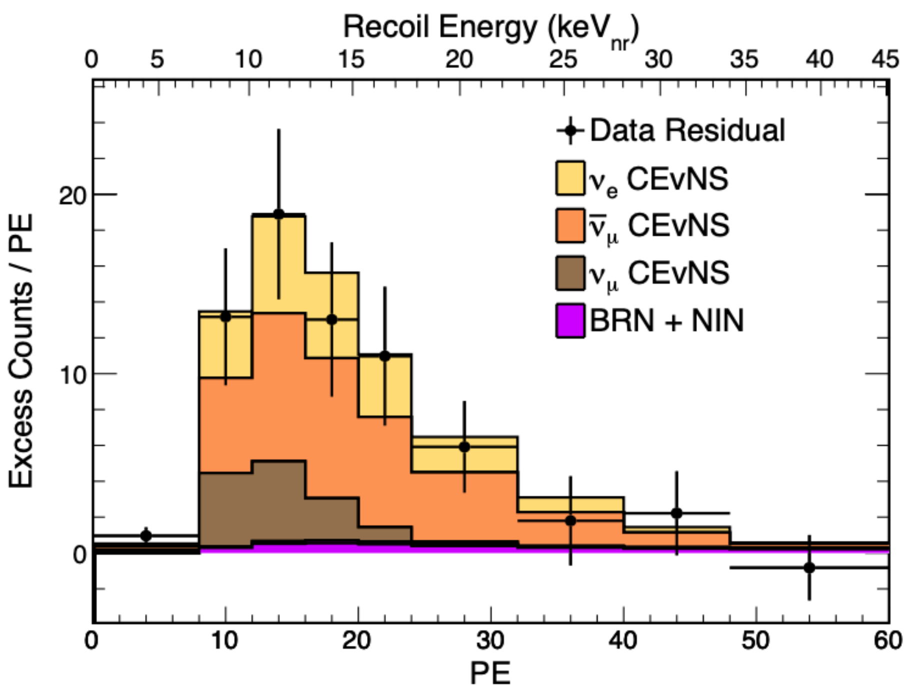

First light in 2017, now squeezing error bars
Second measurement in 2020
Science
SPOTTING A GHOST
Cross section (10^{-40} cm^2)
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
90
Neutron number
Na
Ar
Ge
I
Cs
COHERENT measurements
SM prediction
FF = unity
Klein-Nystrand FF

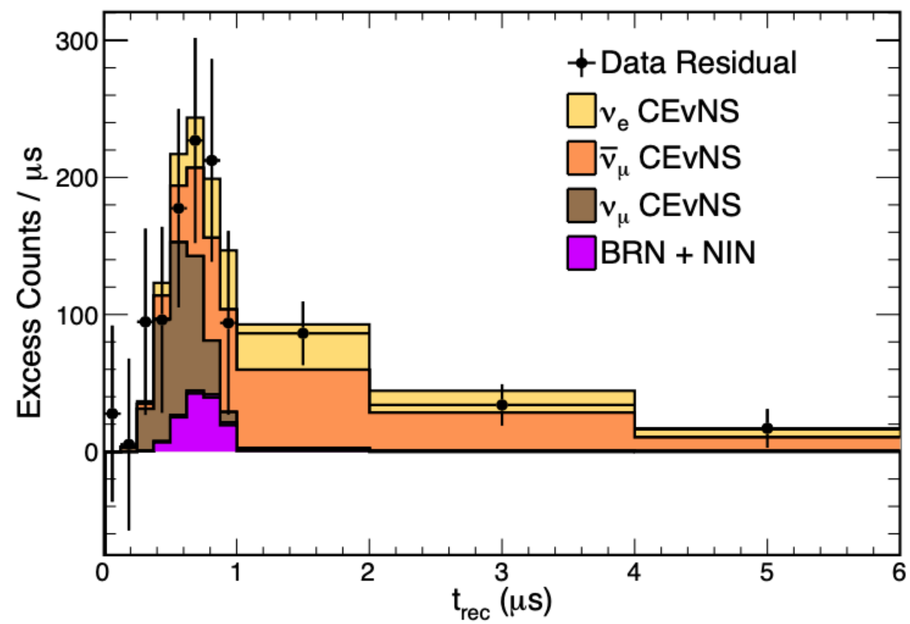
Full CsI[Na] dataset

with >2 x statistics

+ improved detector response understanding

+ improved analysis

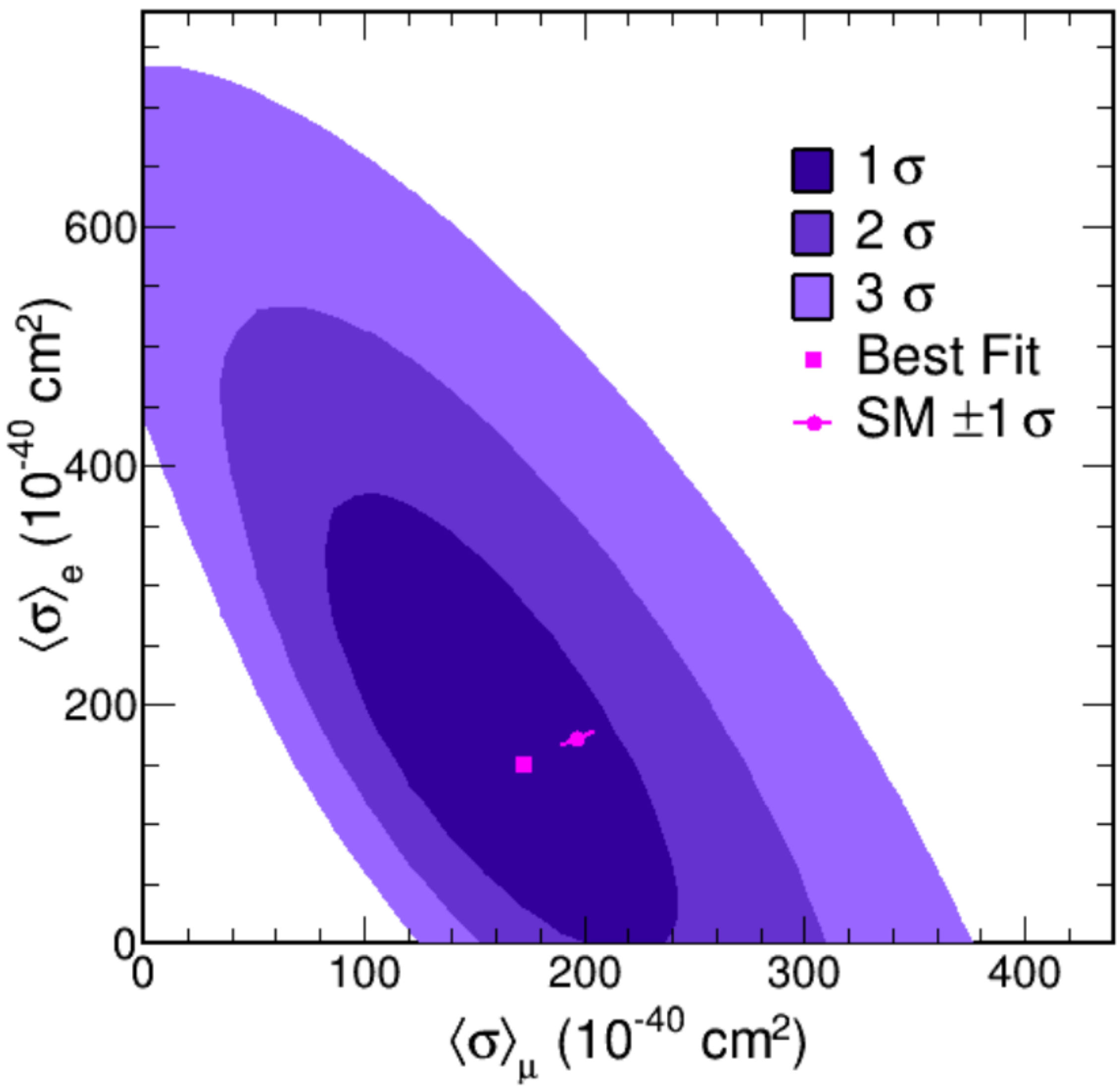




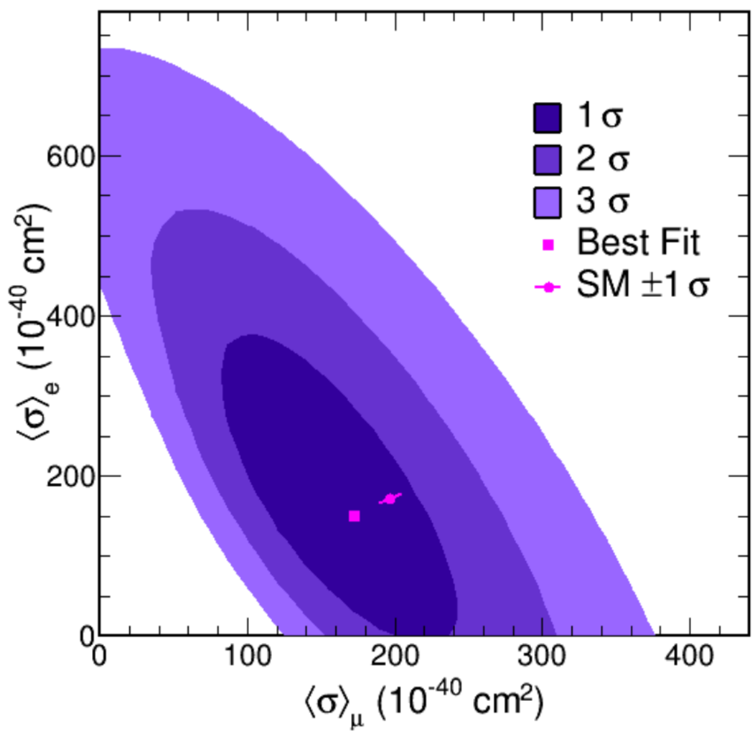
arXiv: 2110.07730

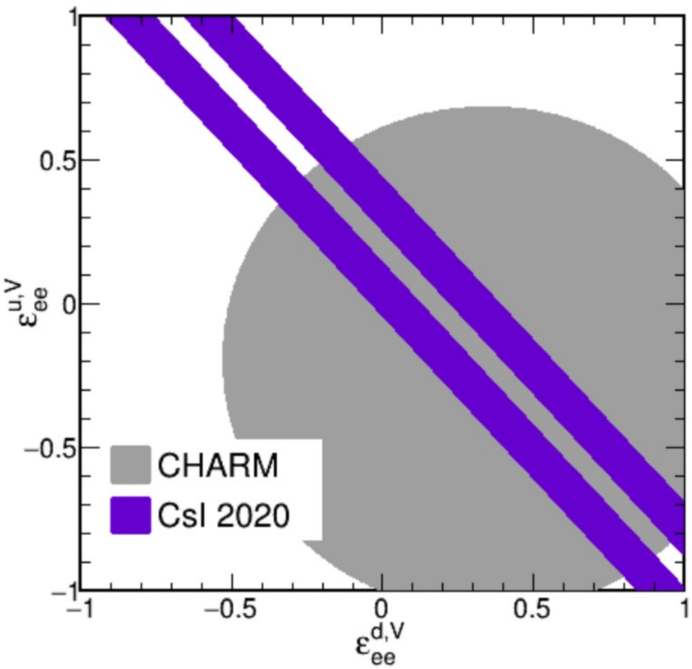
Flavored CEvNS cross sections

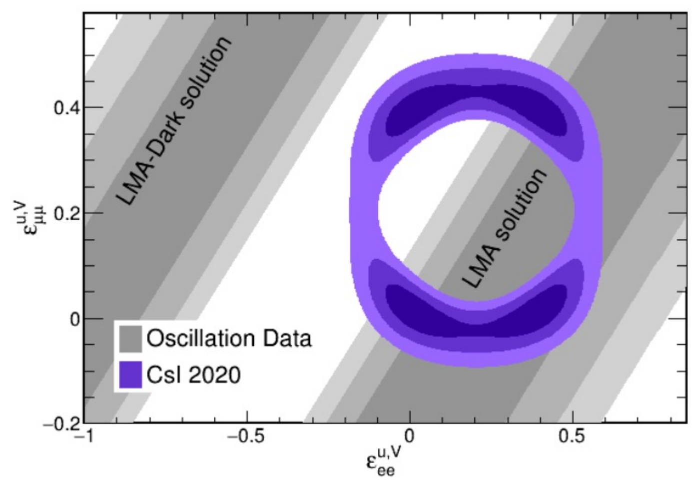
Separate electron and muon flavors by timing



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*)

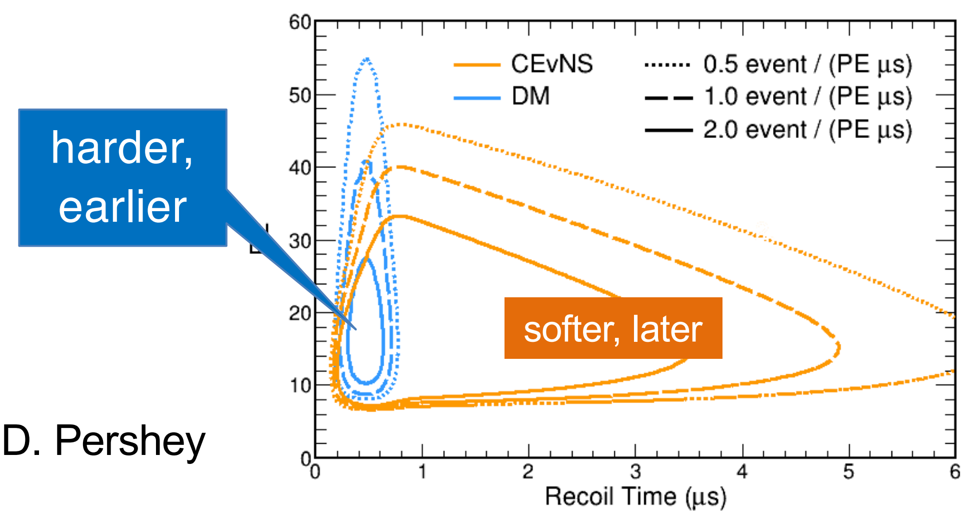
- "Vector portal": mixing of vector mediator with photons in π^0/η^0 decays
- "Leptophobic portal": new mediator coupling to baryons

} 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

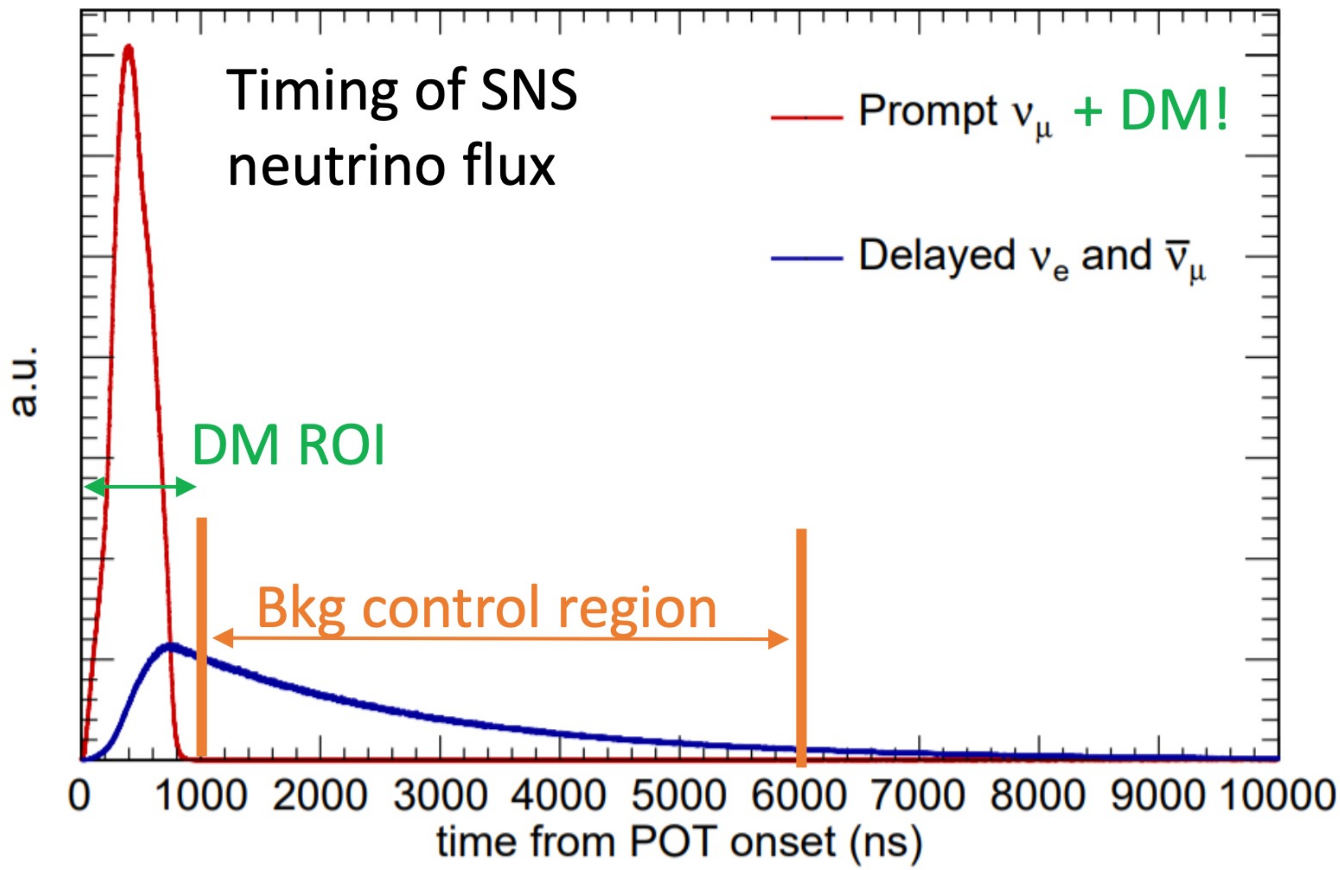


D. Pershey

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

Important advantage of a clean stopped-pion source:

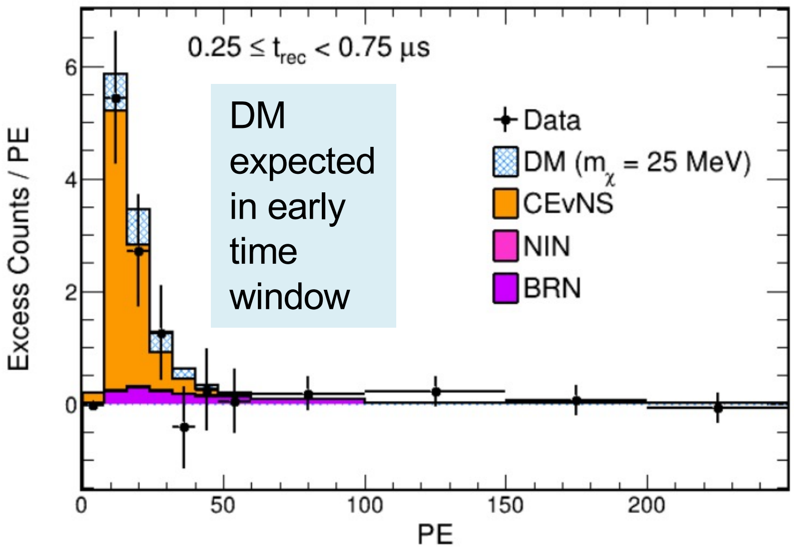
Measure the delayed CEvNS to **constrain** uncertainties in the prompt DM ROI

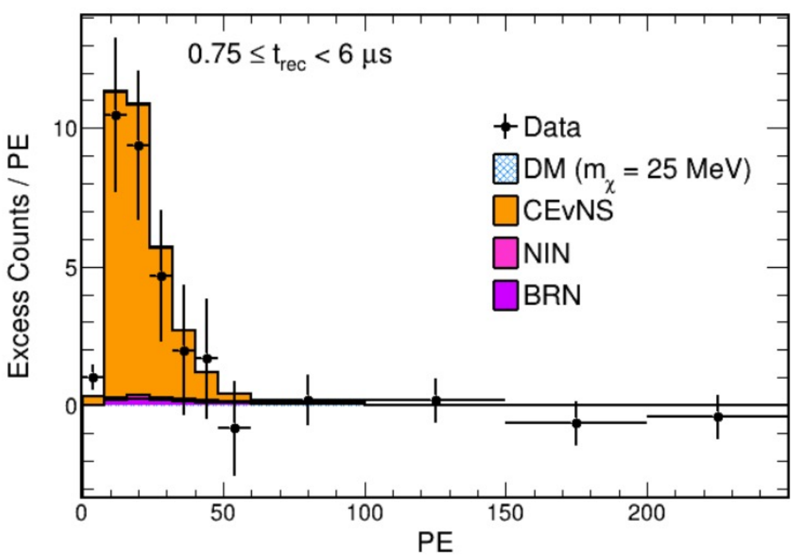


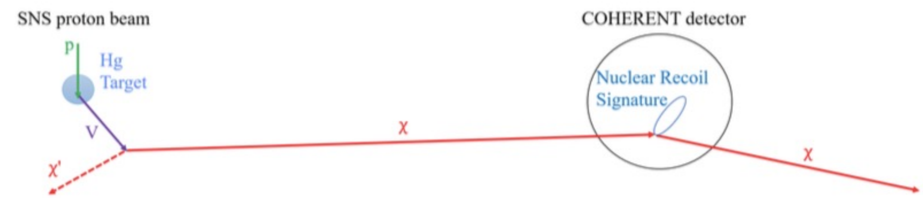
D. Pershey

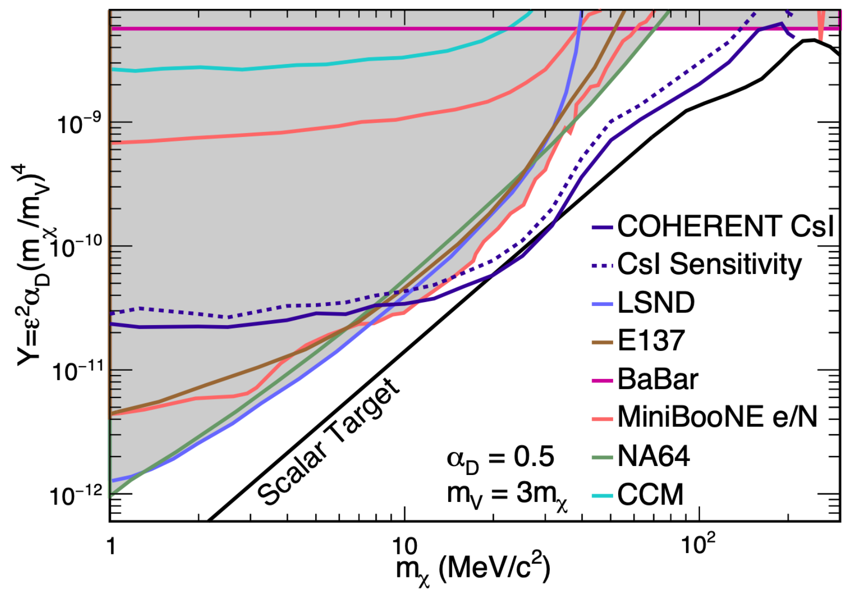
Accelerator-produced DM search

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







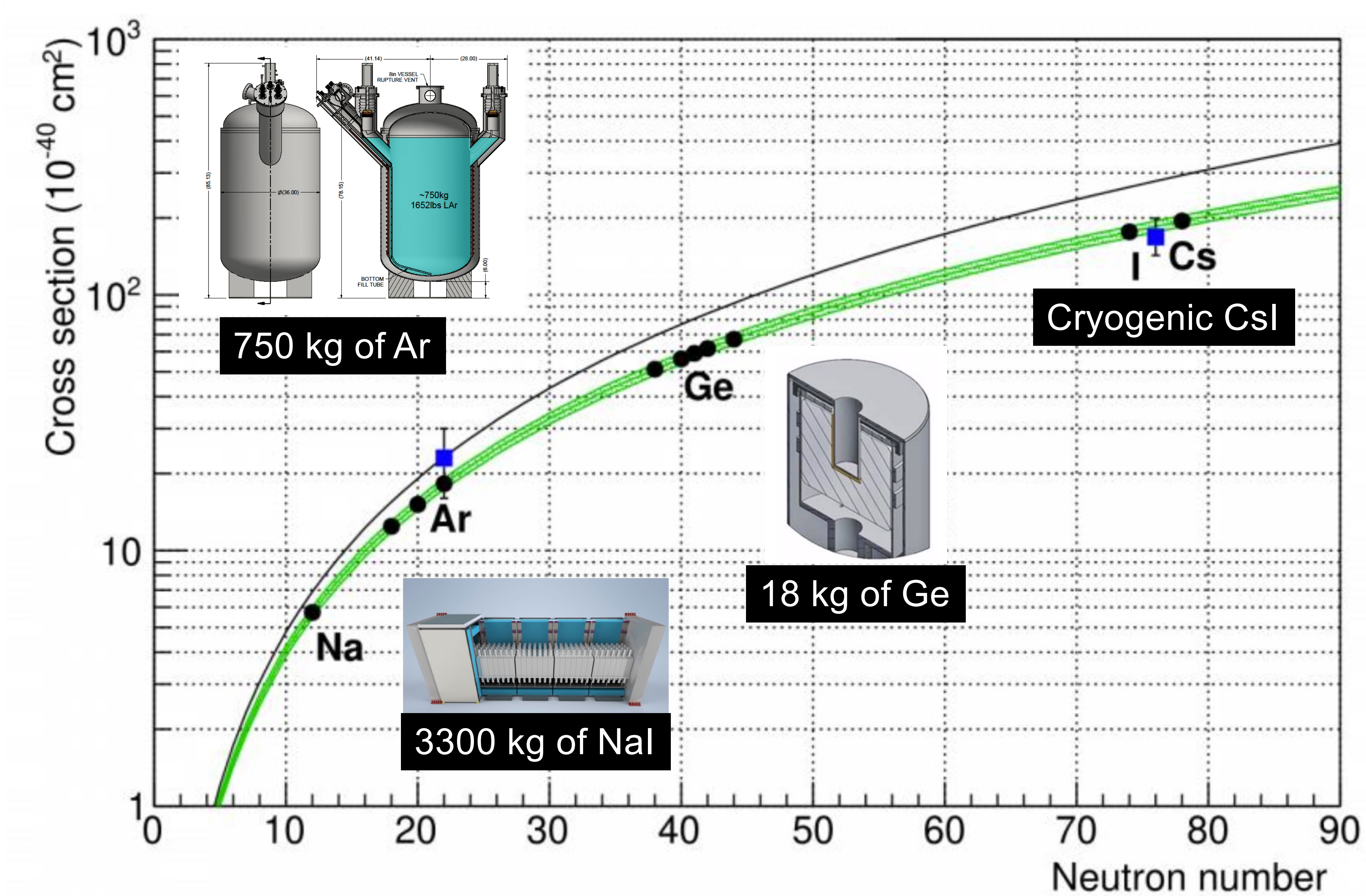


Limits down to cosmological expectation for scalar DM particle

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

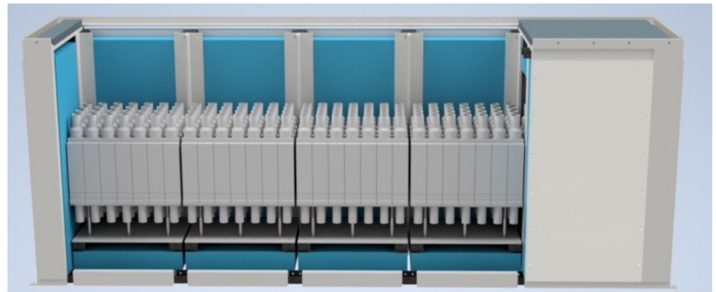
Phys.Rev.D 106 (2022) 5, 052004 arXiv:2205.12414 leptophobic DM

COHERENT future CEvNS deployments in Neutrino Alley



Sodium Iodide (NaI[Tl]) Detectors

- 3.3 tons, 5 modules
- QF measured
- PMT base refurbishment (dual gain) to enable low threshold for CEvNS on Na measurement



more from Sam Hedges tomorrow

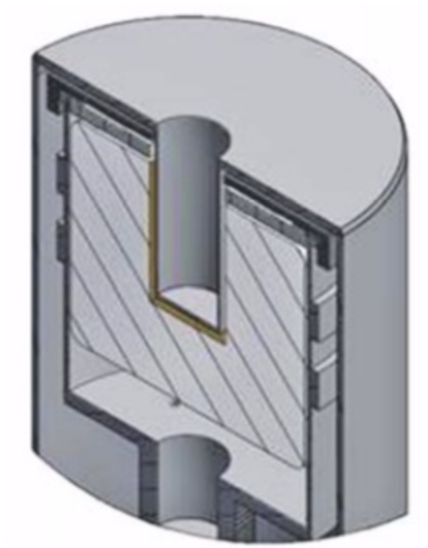
NaIvE: 185 kg [illegible] at SNS to go after ν_eCC on ^{127}I

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

- first commissioning data from first module 22/23
- **second module now deployed**

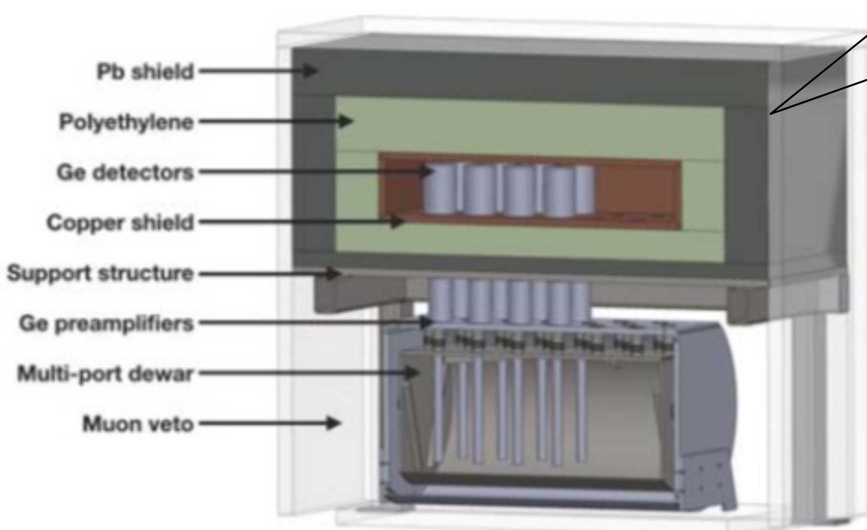
High-Purity Germanium Detectors

P-type Point Contact



- Excellent low-energy resolution
- Well-measured quenching factor
- Reasonable timing

- 8 Canberra/Mirion 2 kg detectors in multi-port dewar
- Compact poly+Cu+Pb shield
- Muon veto
- Designed to enable additional detectors

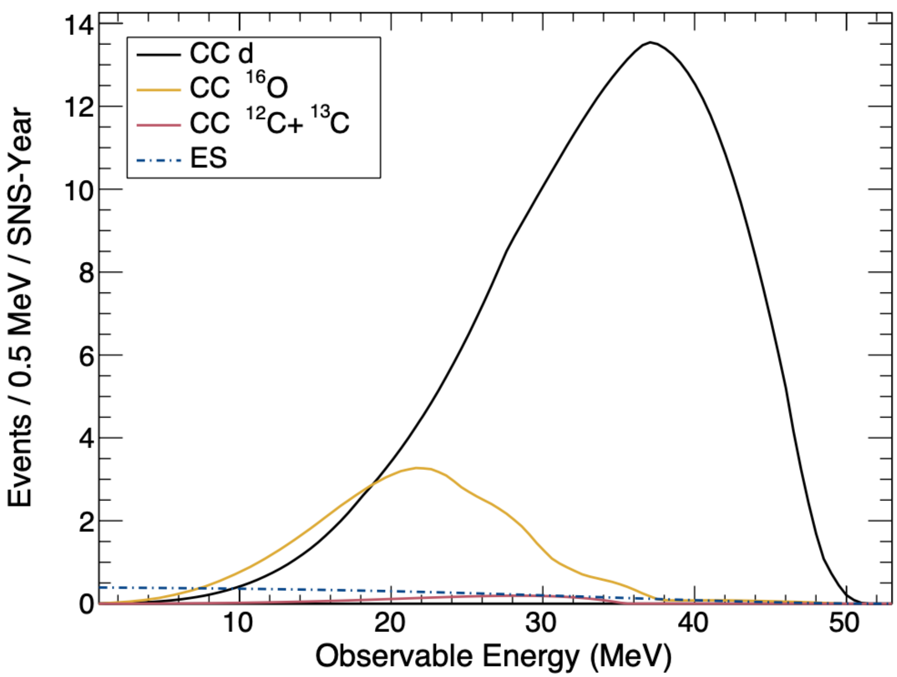


- first commissioning data 22/23
- **campaign-2 now with 6/8 detectors**

Heavy water detector in Neutrino Alley

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

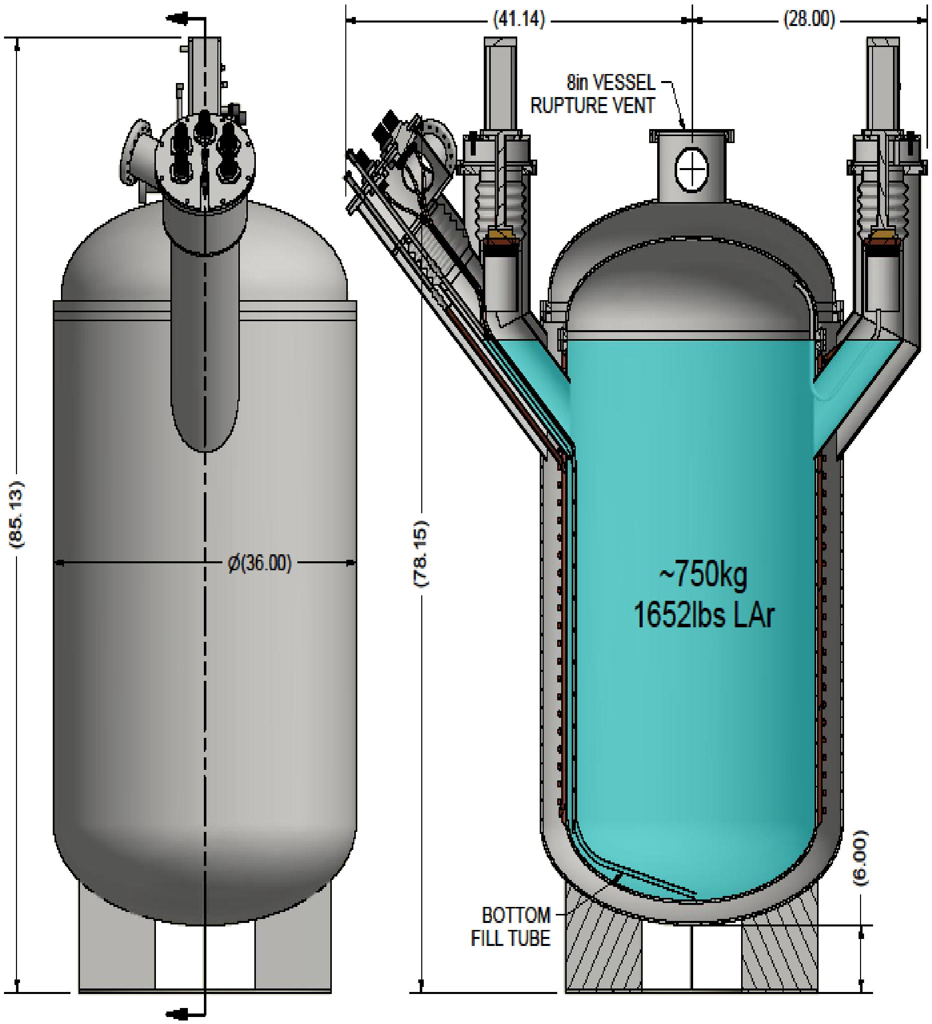
$\nu_e + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$ cross section known to ~1-2%

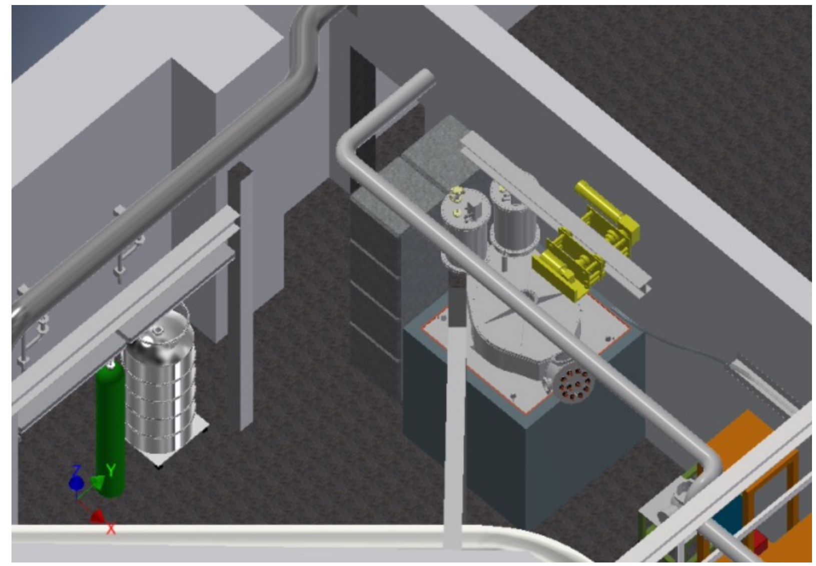


- Measure electrons to determine flux normalization
- Inelastics on ^{16}O [studying dedicated light water detector]

- fcommissioning w/light water 22/23
- **nearly ready for D_2O fill**

Tonne-scale LAr Detector



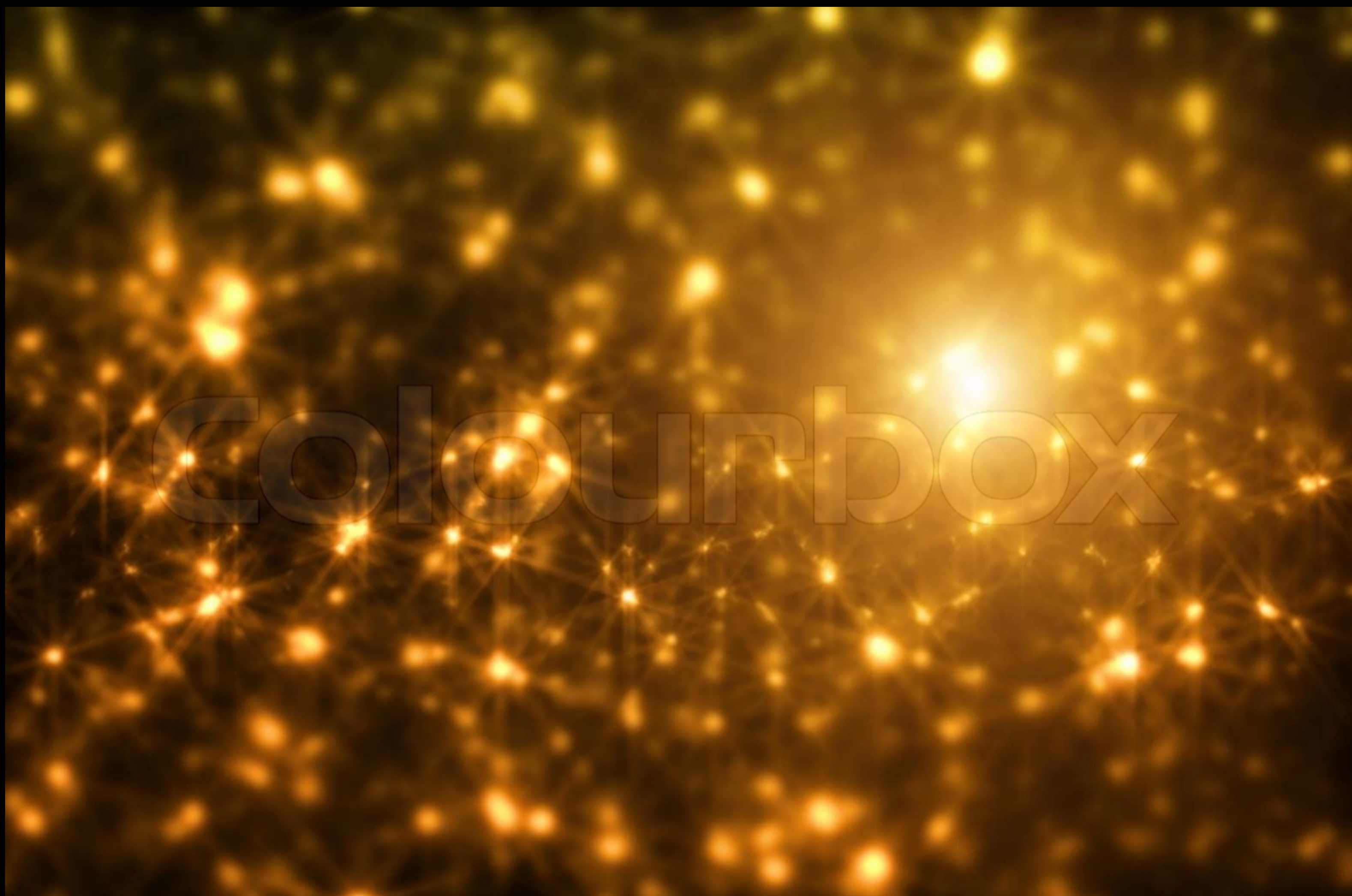


- 750-kg LAr will fit in the same place, will reuse part of existing infrastructure
- Could potentially use depleted argon
- **Deployment in 2024**

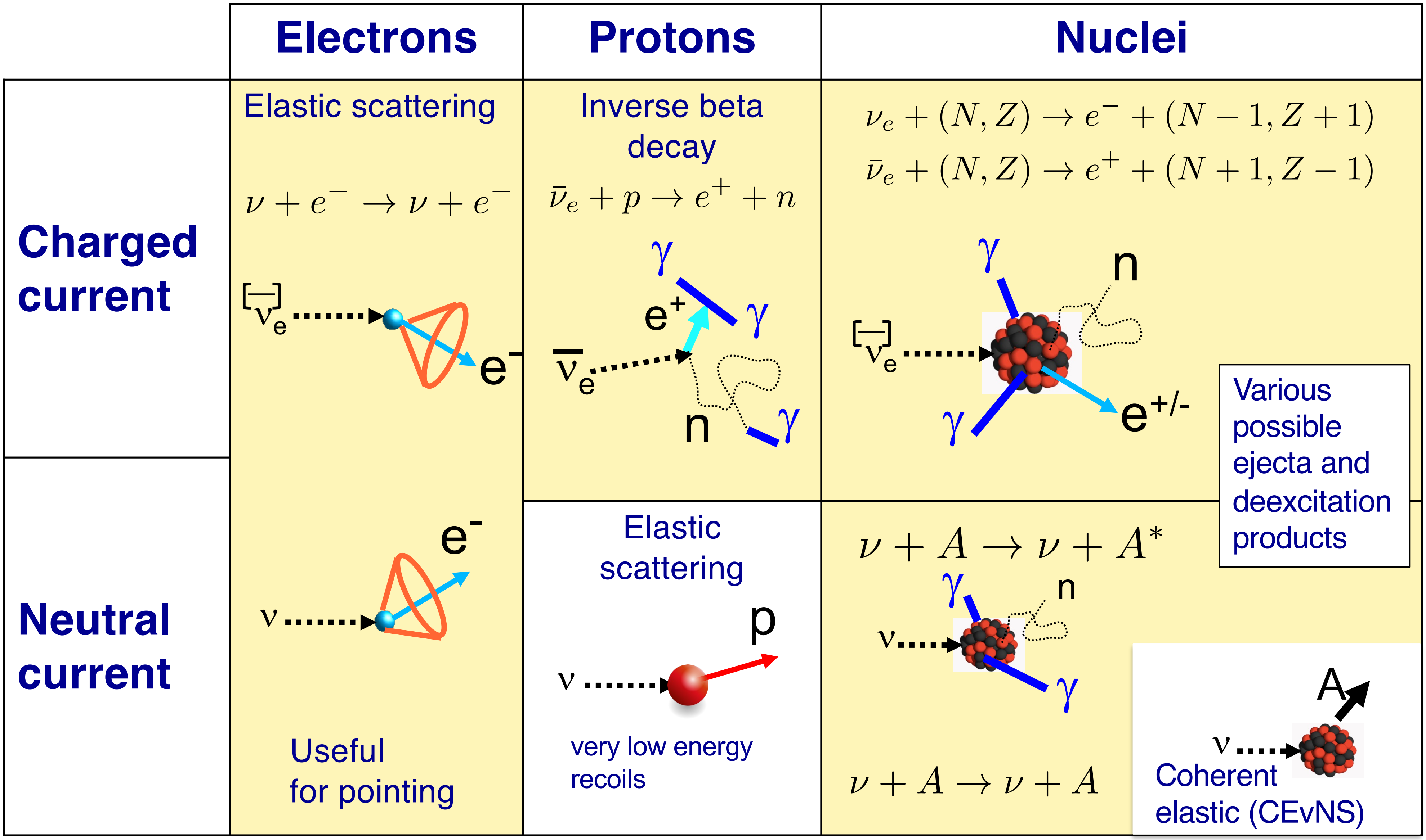
So far considered signal from faint recoils...

bright signals are possible too...

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

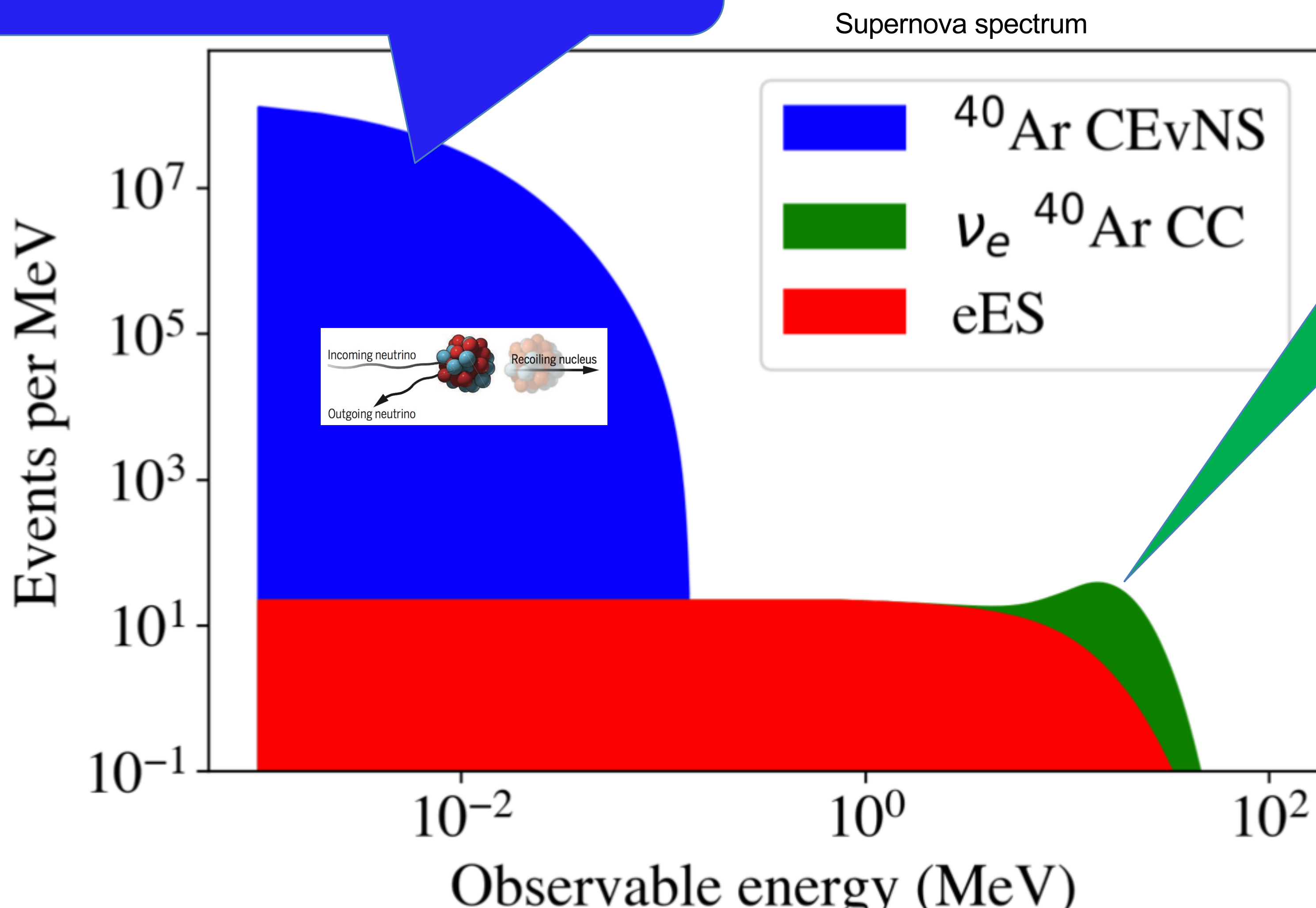


Low-energy neutrino interactions

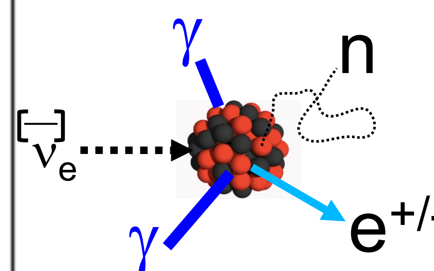


Neutrino interaction signals in the few to few-tens of MeV range

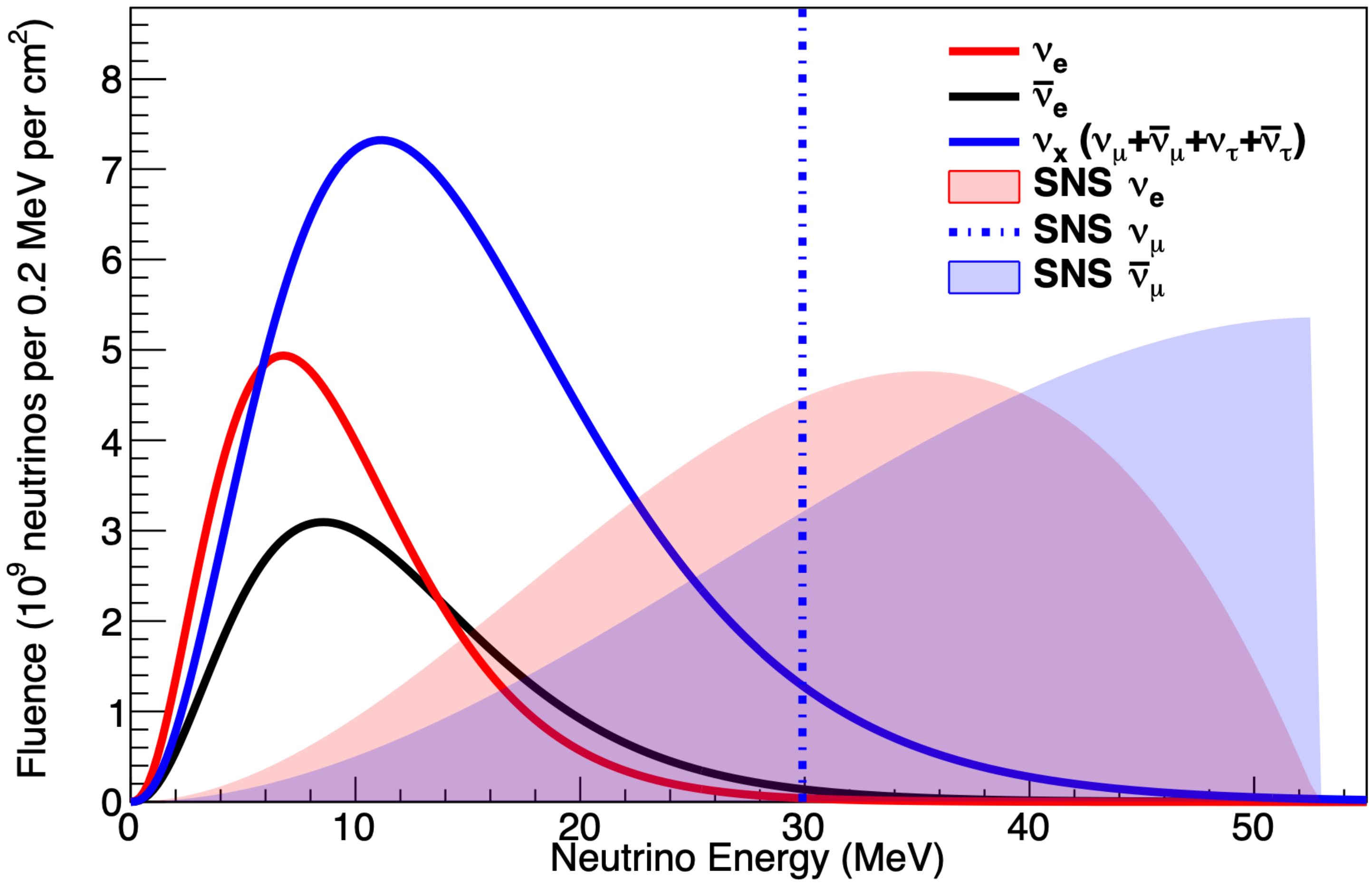
CEvNS
High xscn, low energy recoils



Inelastic
Low xscn,
bright
recoil



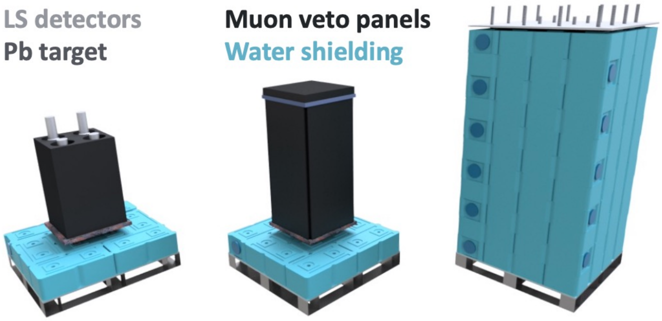
Stopped-pion neutrinos relevant for supernova burst regime

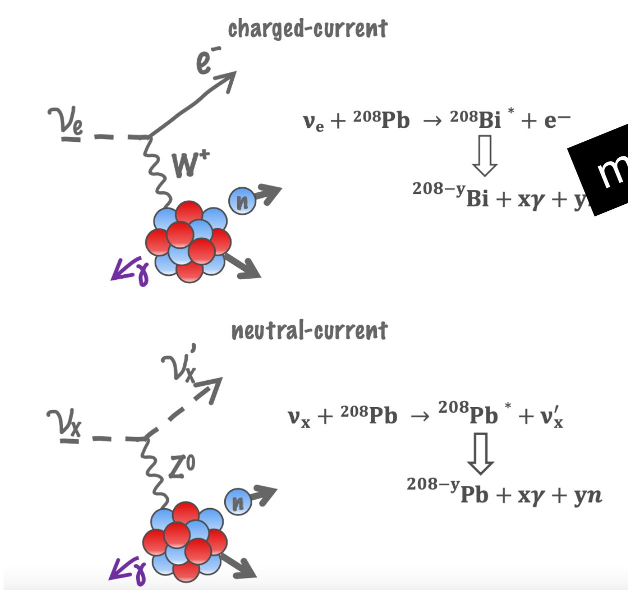


- understanding of SN processes & detection
- understanding of weak couplings (g_A quenching) & nuclear transitions

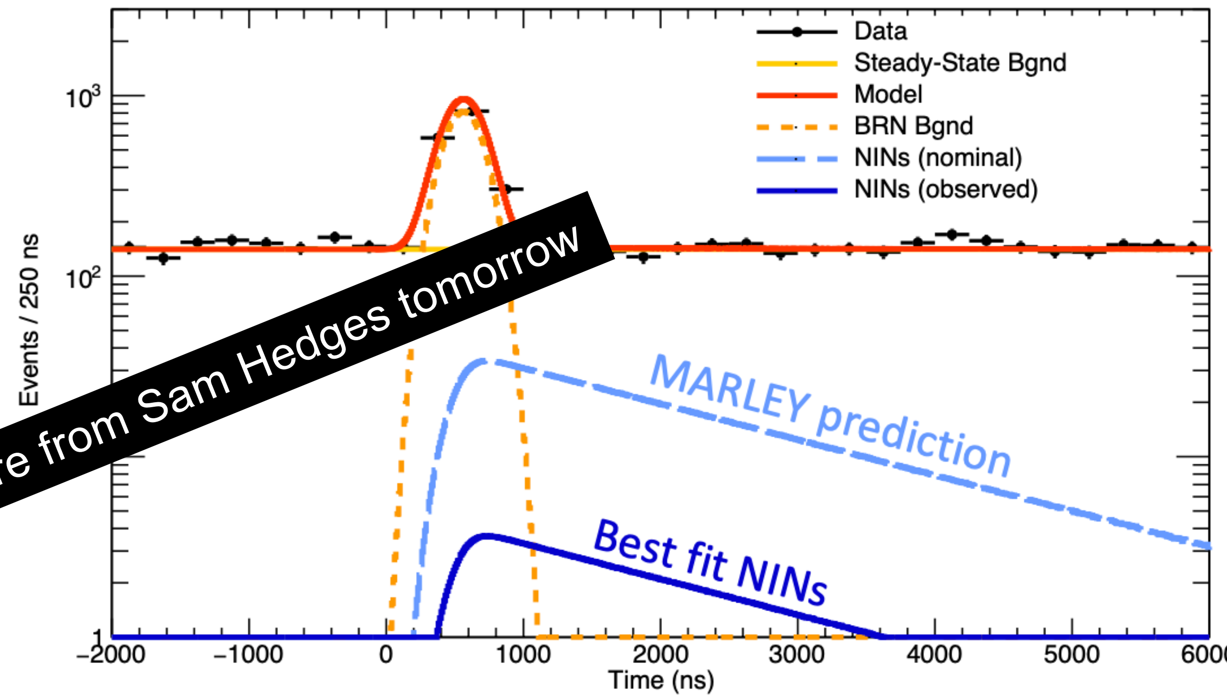
See:Workshop on Neutrino Interaction Measurements for Supernova Neutrino Detection
https://indico.phy.ornl.gov/event/217/

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





Sam Hedges talk



more from Sam Hedges tomorrow

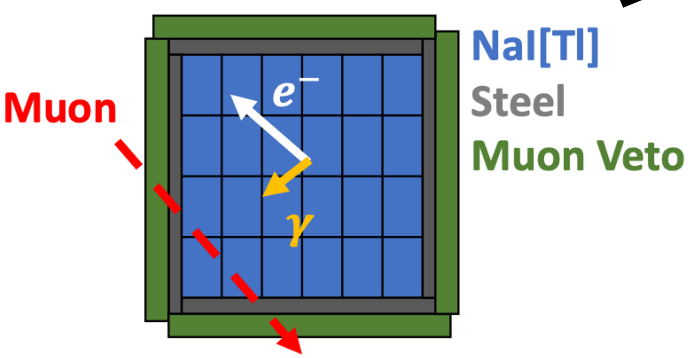
Combined fit yields MARLEY cross section suppressed by a factor of $0.29^{+0.17}_{-0.17}$

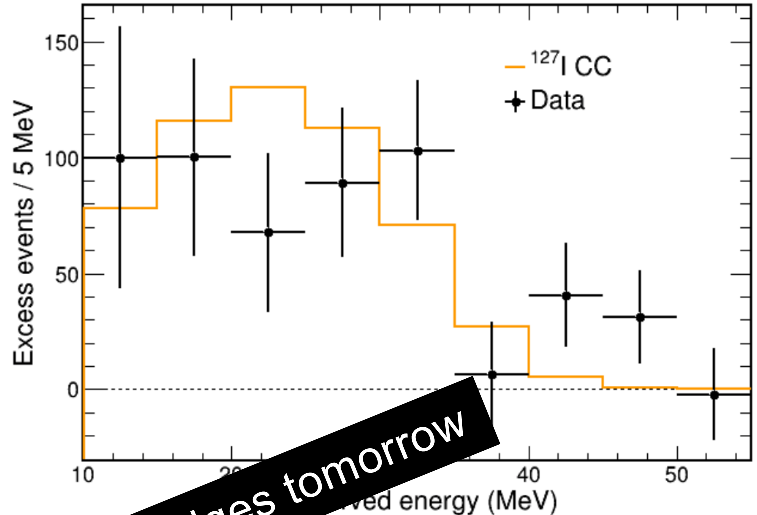
- 1.8σ significance, >4σ disagreement with MARLEY model

Lower than expectation

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

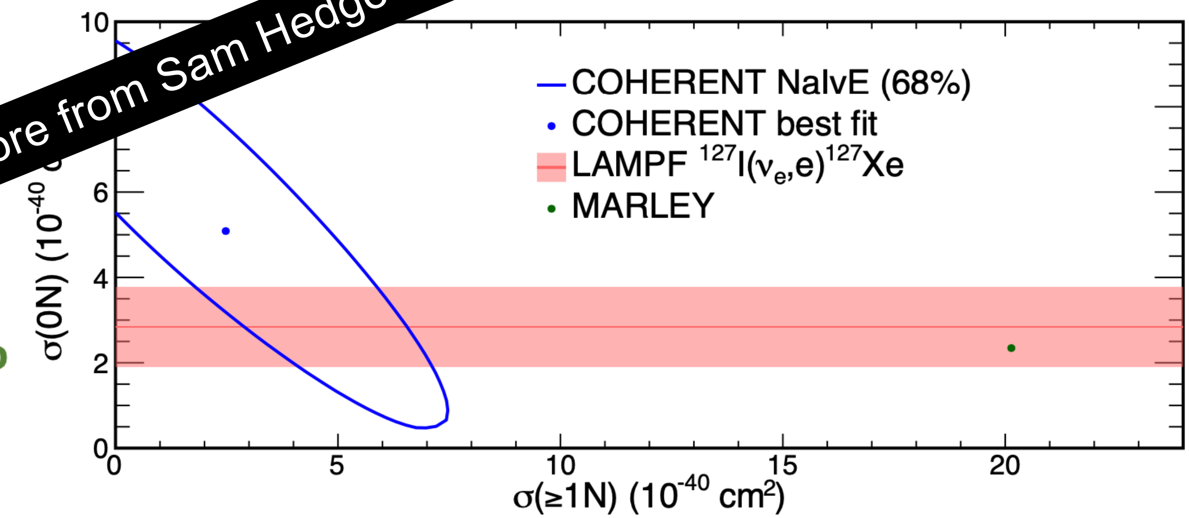
NEW! COHERENT results for CC ν_e on ^{127}I





Preliminary

more from Sam Hedges tomorrow



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

Also low!

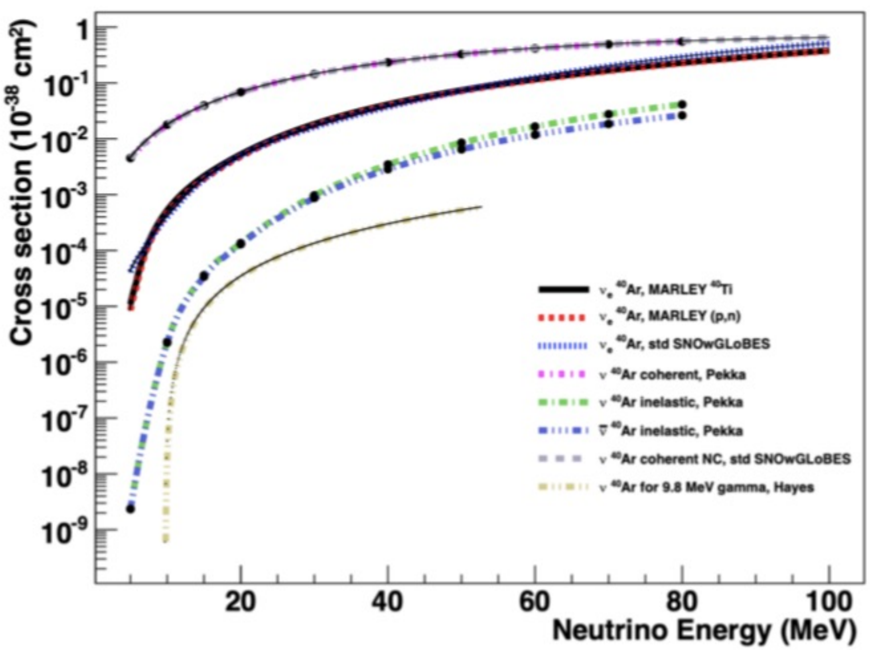
S. Hedges thesis, FNAL Wine & Cheese

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

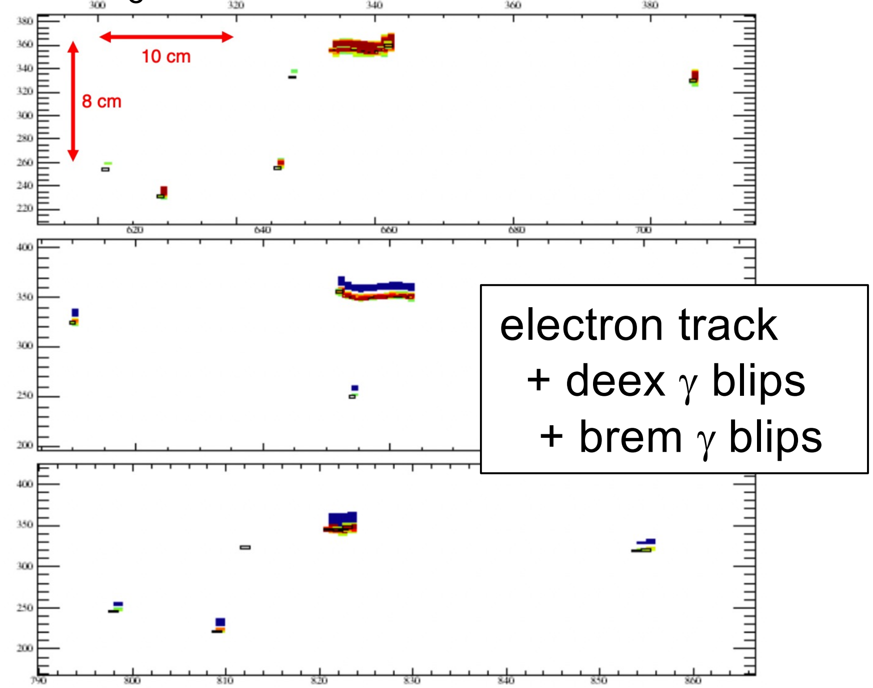
$$\text{CC} \quad \nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

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

- 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

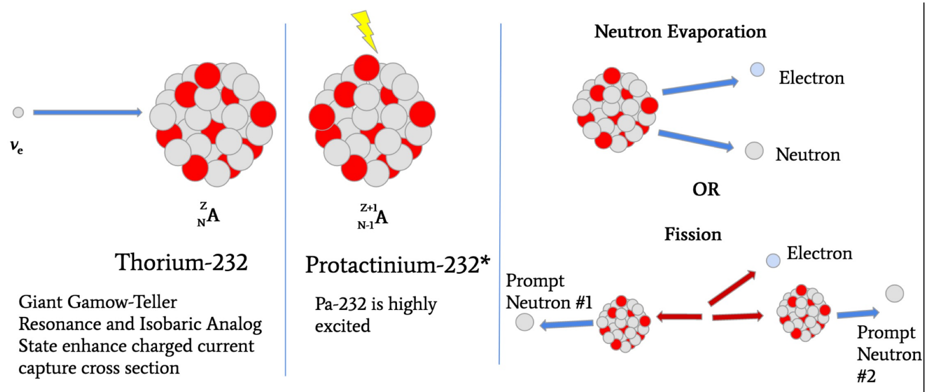


Impact on SNB in DUNE arXiv:[2303.17007](https://arxiv.org/abs/2303.17007)

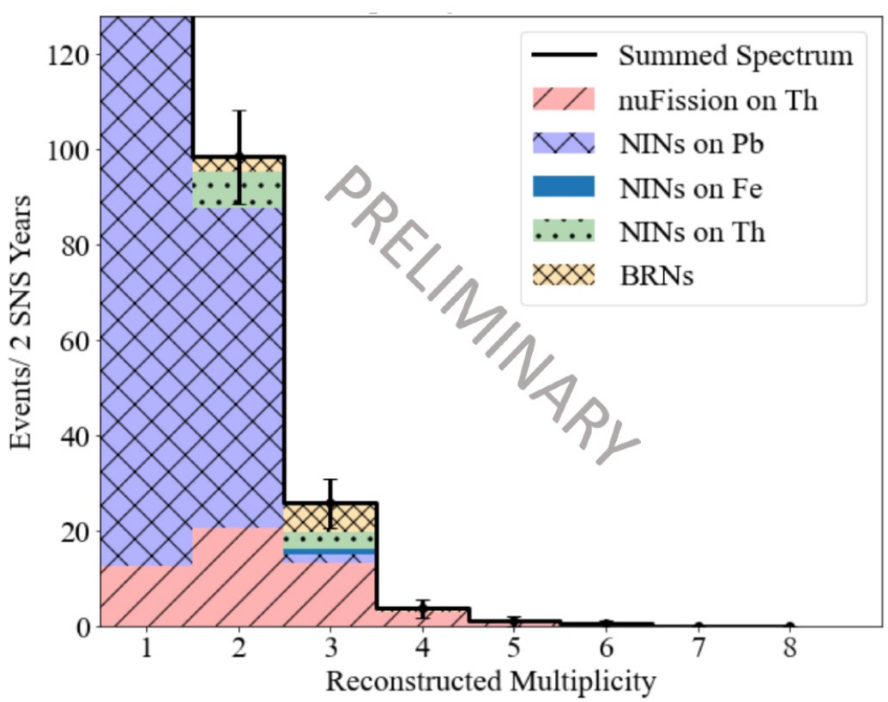
More soon from COHERENT!

NuThor

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

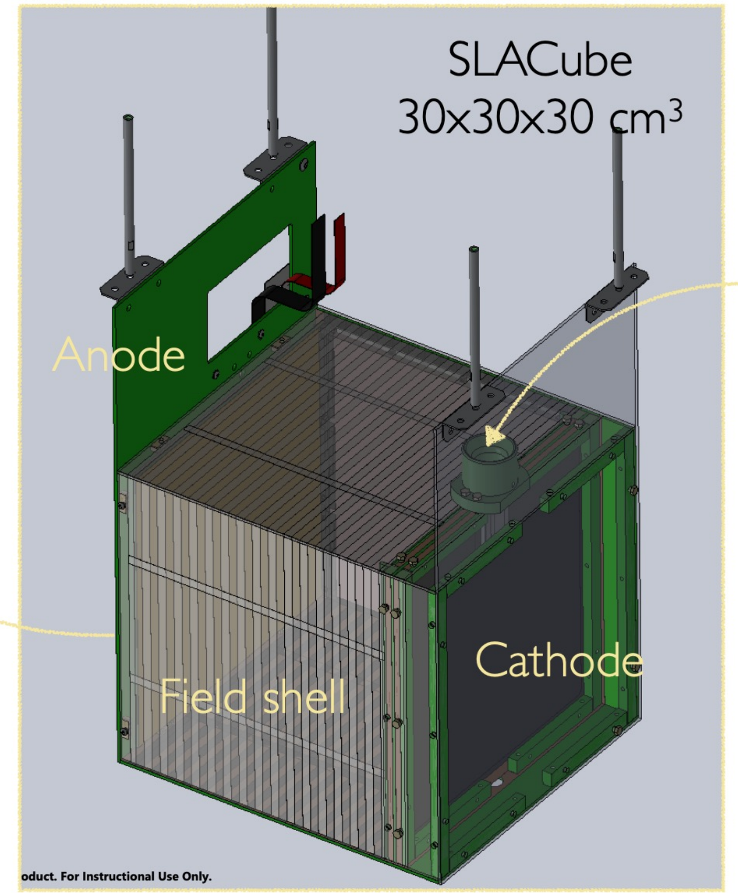


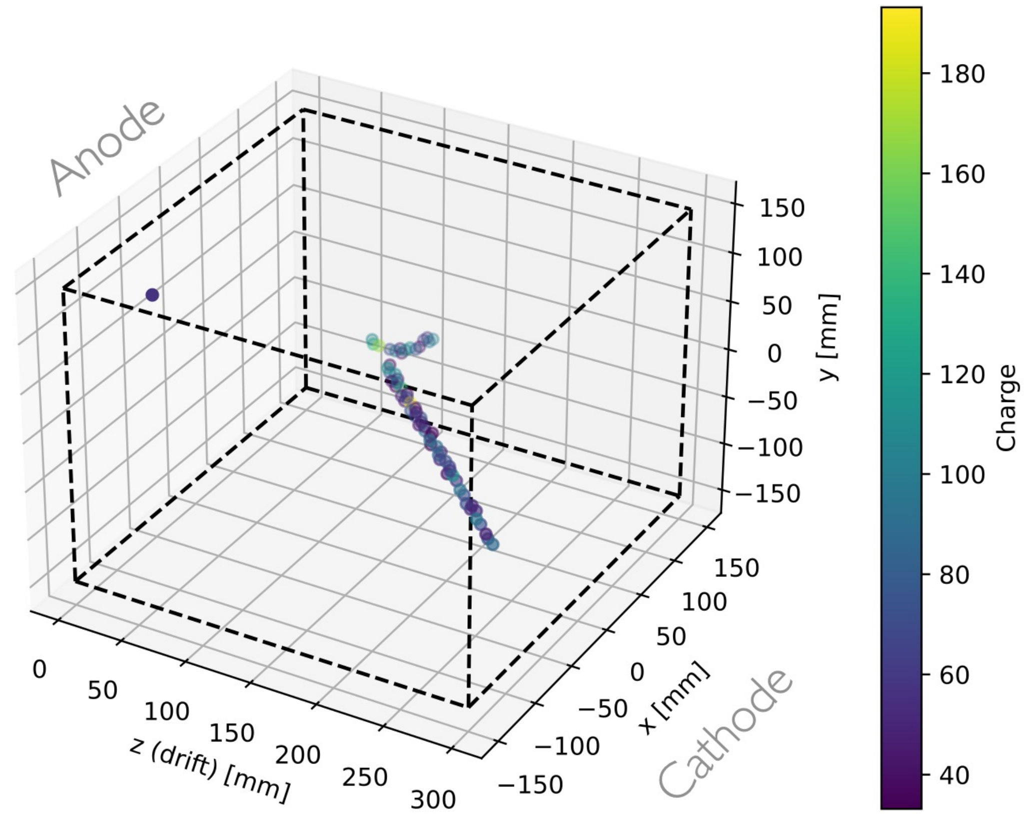
Tyler Johnson



Phil Barbeau, APS 2023

Future LArTPC



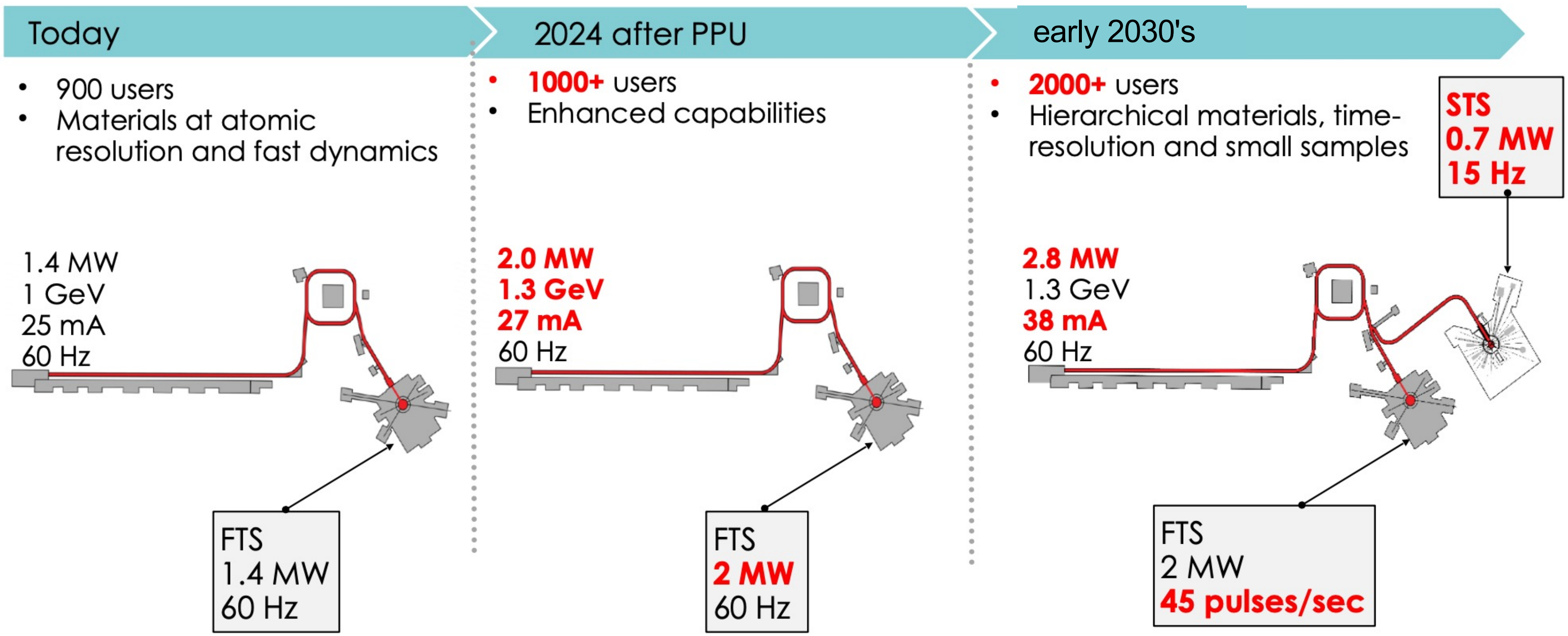


Yun-tse Tsai, SLAC

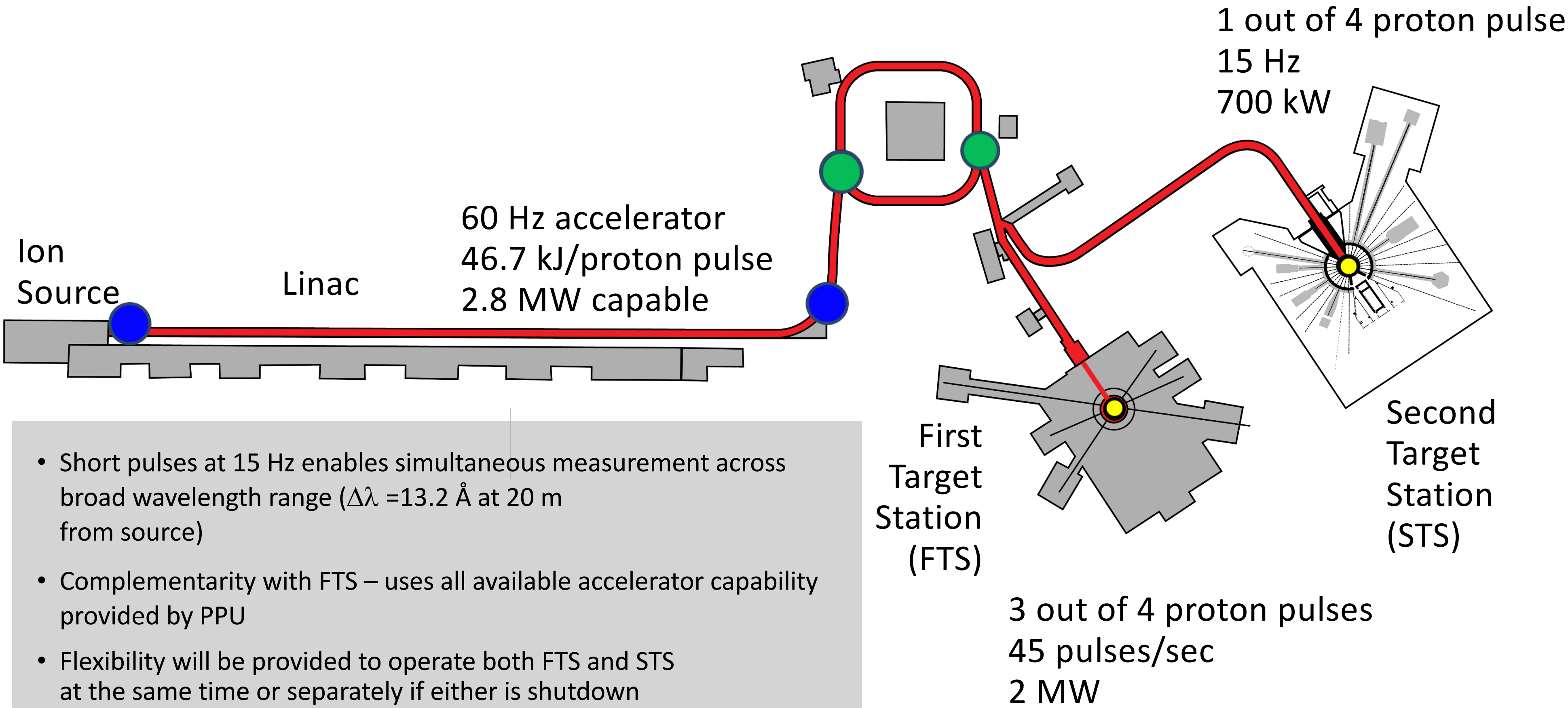
- Proposed: 250 kg Ar (50x60x60 cm^3) [larger for STS]
- DUNE-like, relevant for SN burst & solar detection
- R&D test bed (e.g. pixelated readout, photon detectors, ...)

SNS upgrades: Beam Power and Second Target Station

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



STS will make optimal use of the SNS accelerator capability

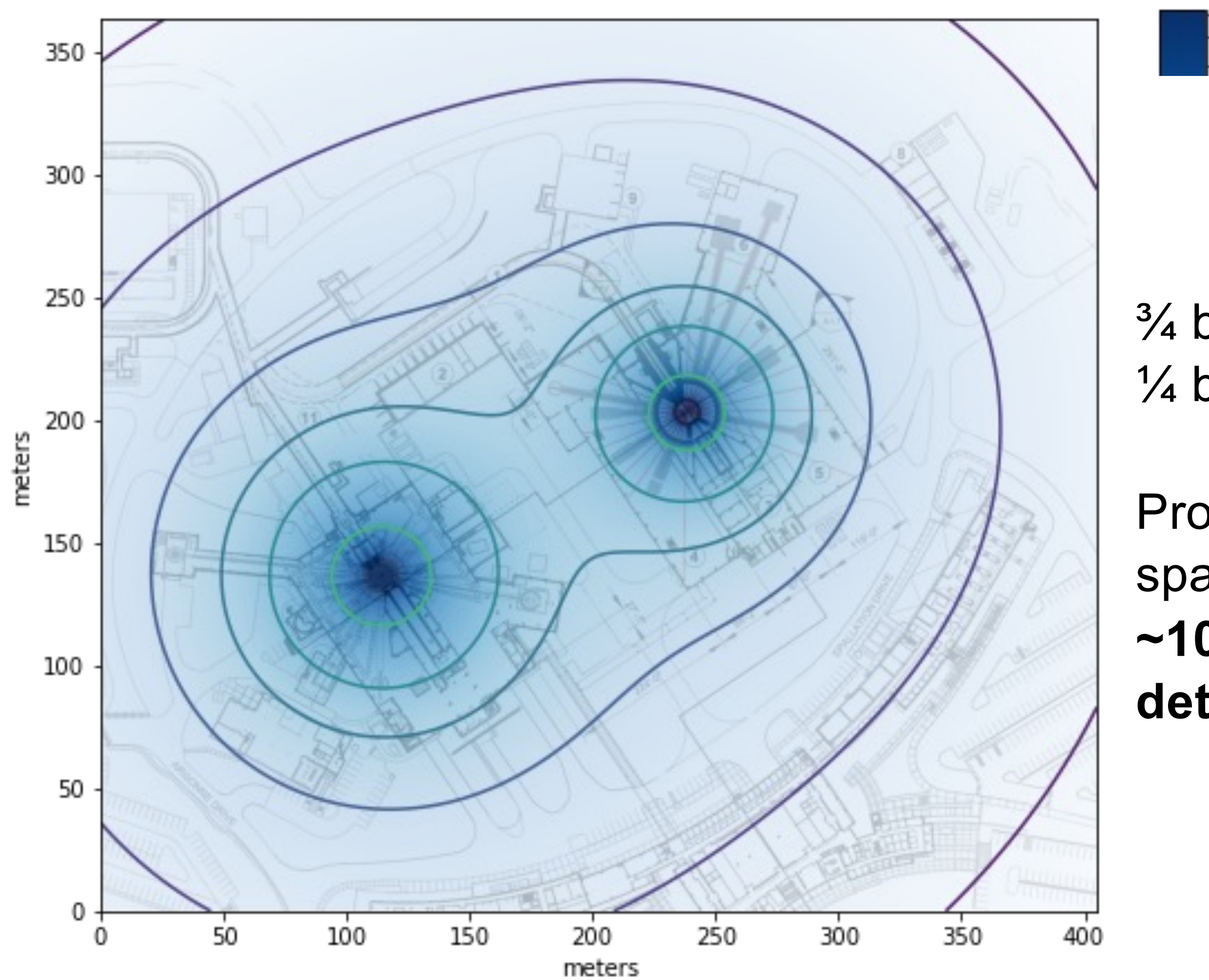


- Short pulses at 15 Hz enables simultaneous measurement across broad wavelength range ($\Delta\lambda$ =13.2 Å at 20 m from source)
- Complementarity with FTS – uses all available accelerator capability provided by PPU
- Flexibility will be provided to operate both FTS and STS at the same time or separately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

*animation courtesy of Matt Stone

From Ken Herwig

Second Target Station Neutrino Opportunities

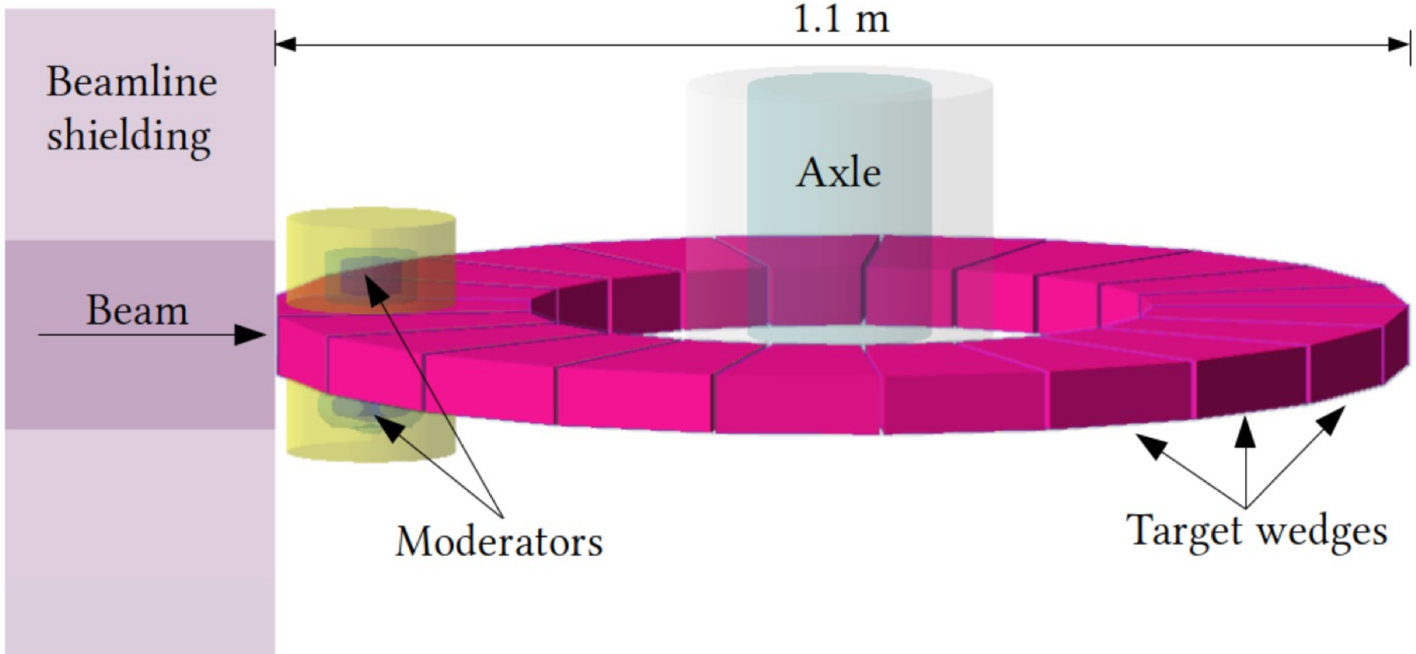


¾ bunches to FTS
¼ bunches to STS

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

Many exciting possibilities for ν's + DM!

Second Target Station Neutrino Production



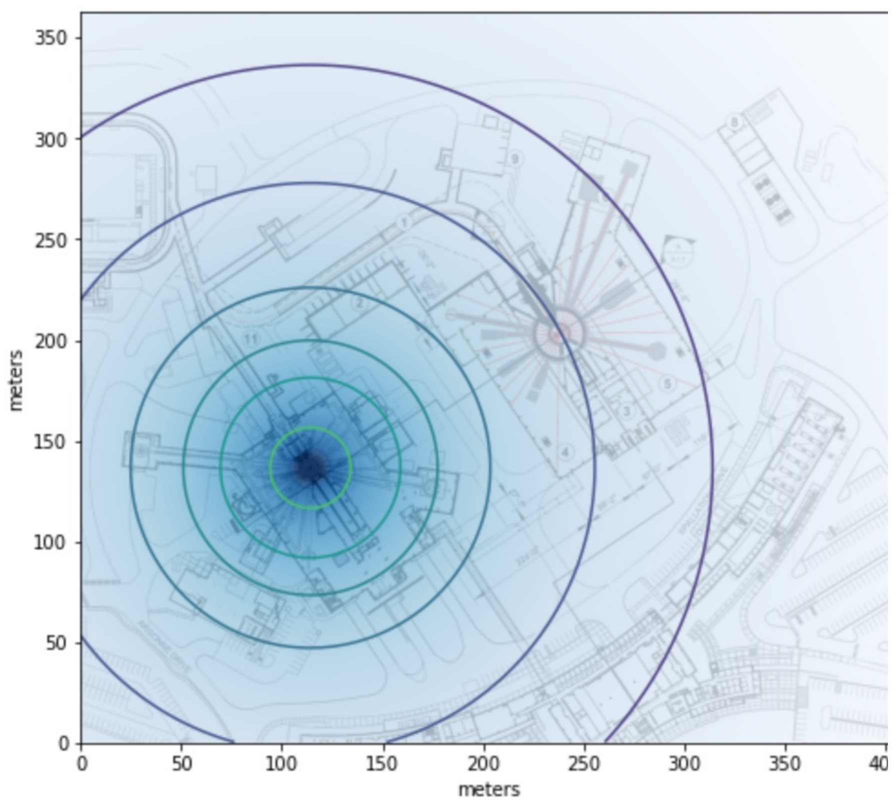
- tungsten wedges
- 0.39 ν/proton (slightly larger than FTS @1.3 GeV)
- still very clean DAR

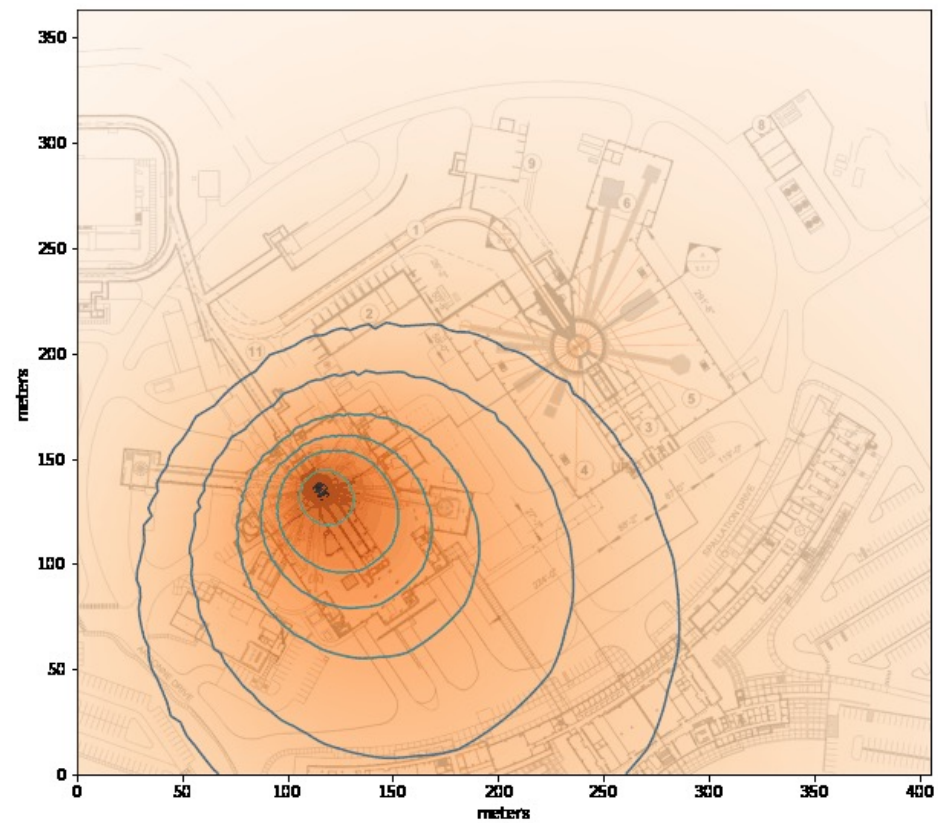
Phys.Rev.D 106 (2022) 3, 032003 arXiv:2109.11049

Directionality of flux at the SNS

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

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





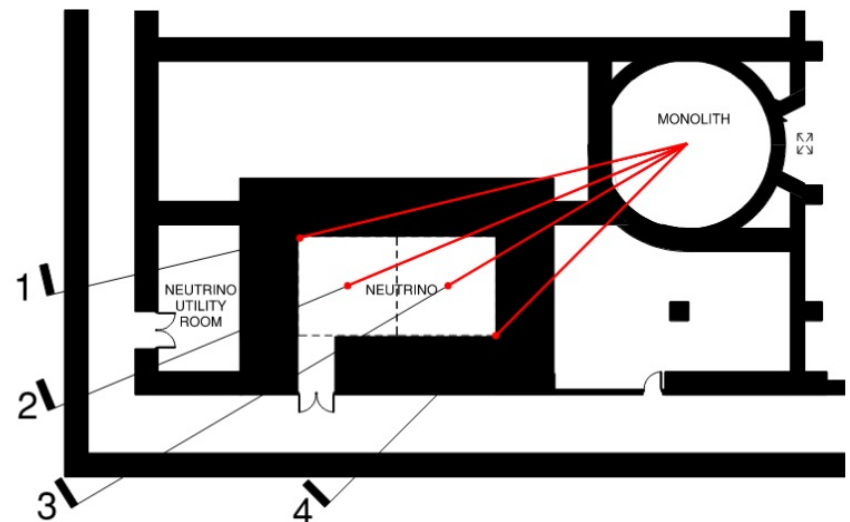
Can in principle test angular dependence
of boosted DM flux

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

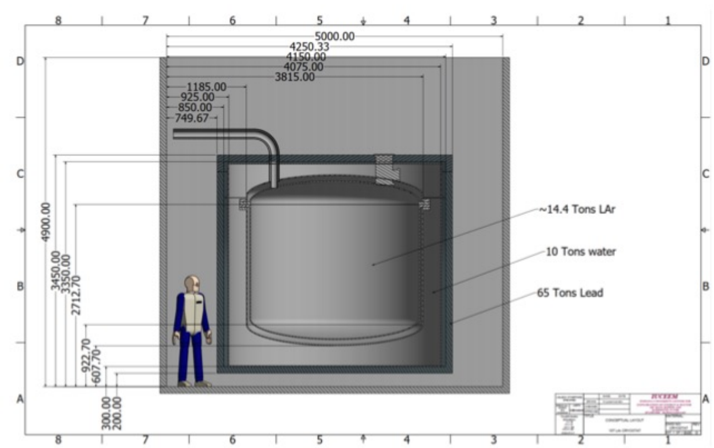
STS Basement Concept for Neutrinos



Jason Newby

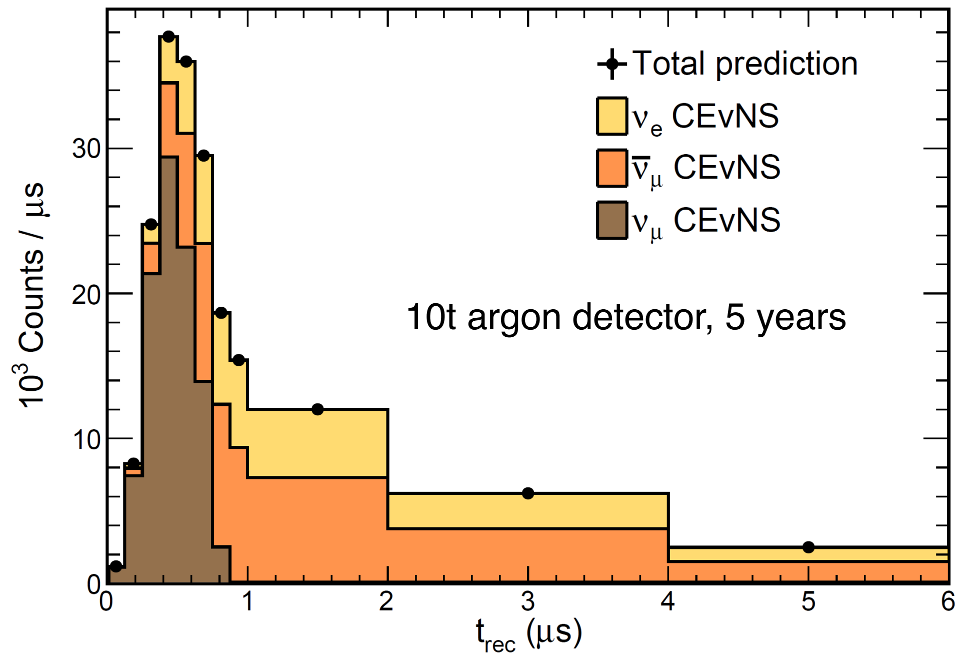
Many possible detector concepts

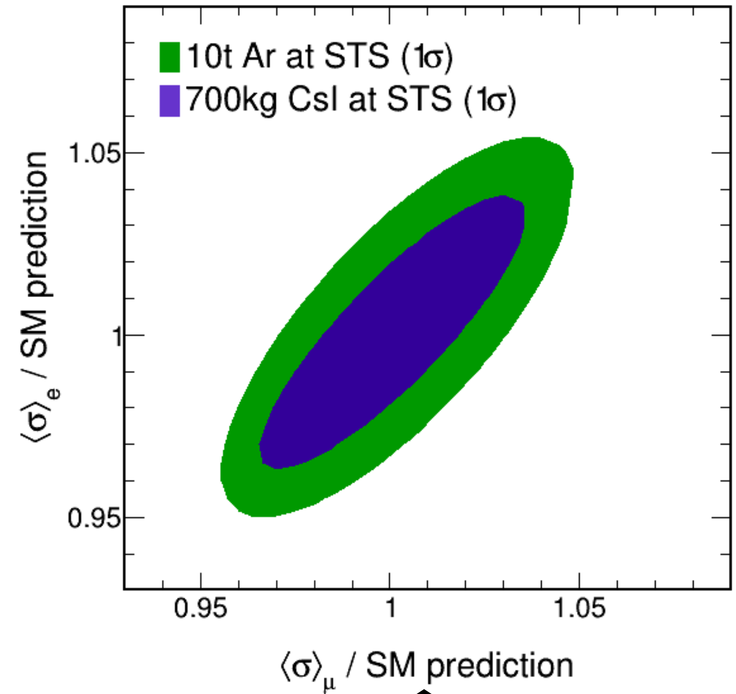
- "Strawperson":
  10-ton argon, single phase or TPC
- Others: germanium, cryoCsI, water,
  scintillator, directional, solids, ...

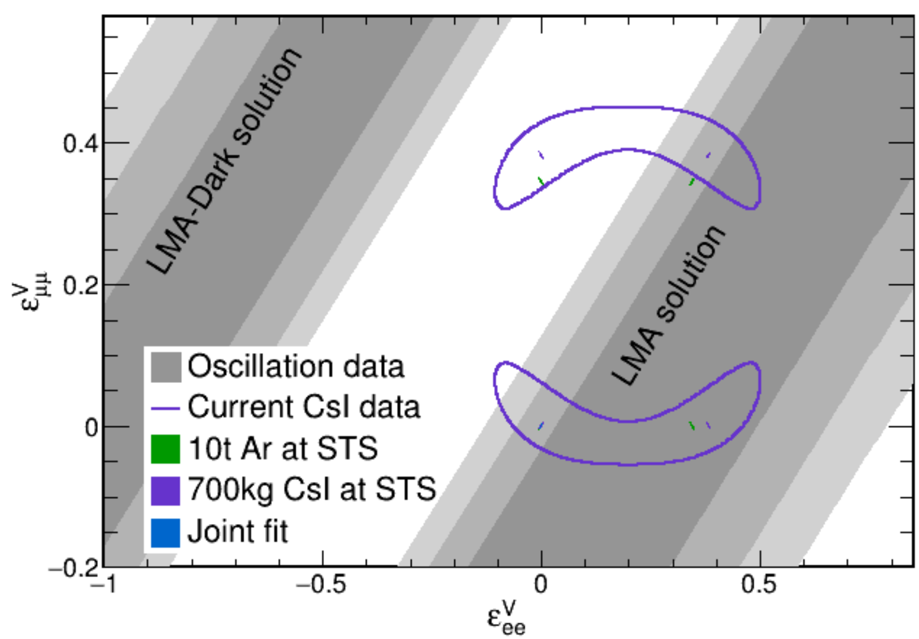


10-ton Argon Cryostat Concept, IU

Future flavored CEvNS cross section measurements







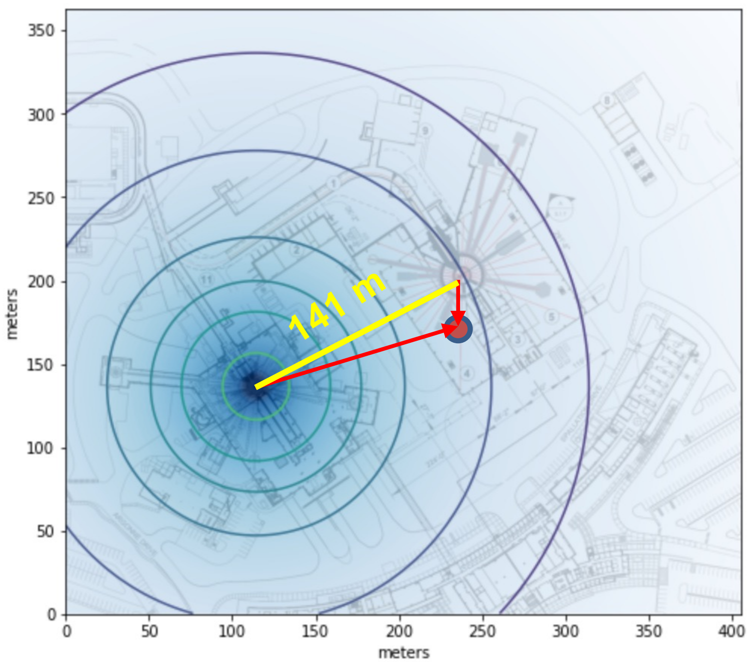
Sensitive to ~few % SM differences in μ- and *e*-flavor cross sections, testing lepton universality of CEvNS (at tree level)

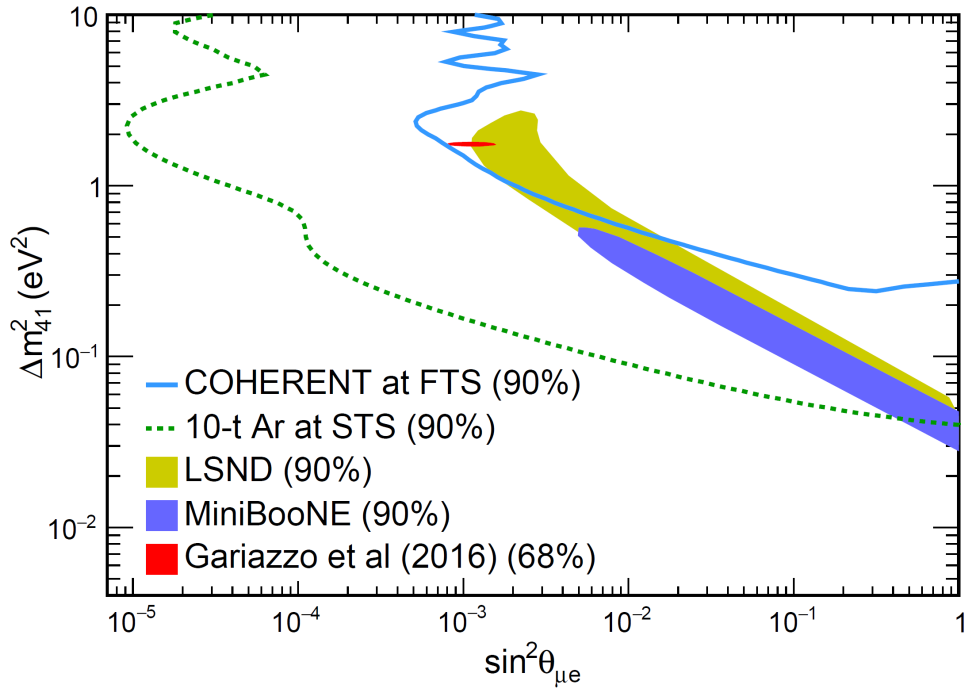
Stringent NSI parameters constraints, resolving oscillation ambiguities

Sterile neutrino sensitivity

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

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





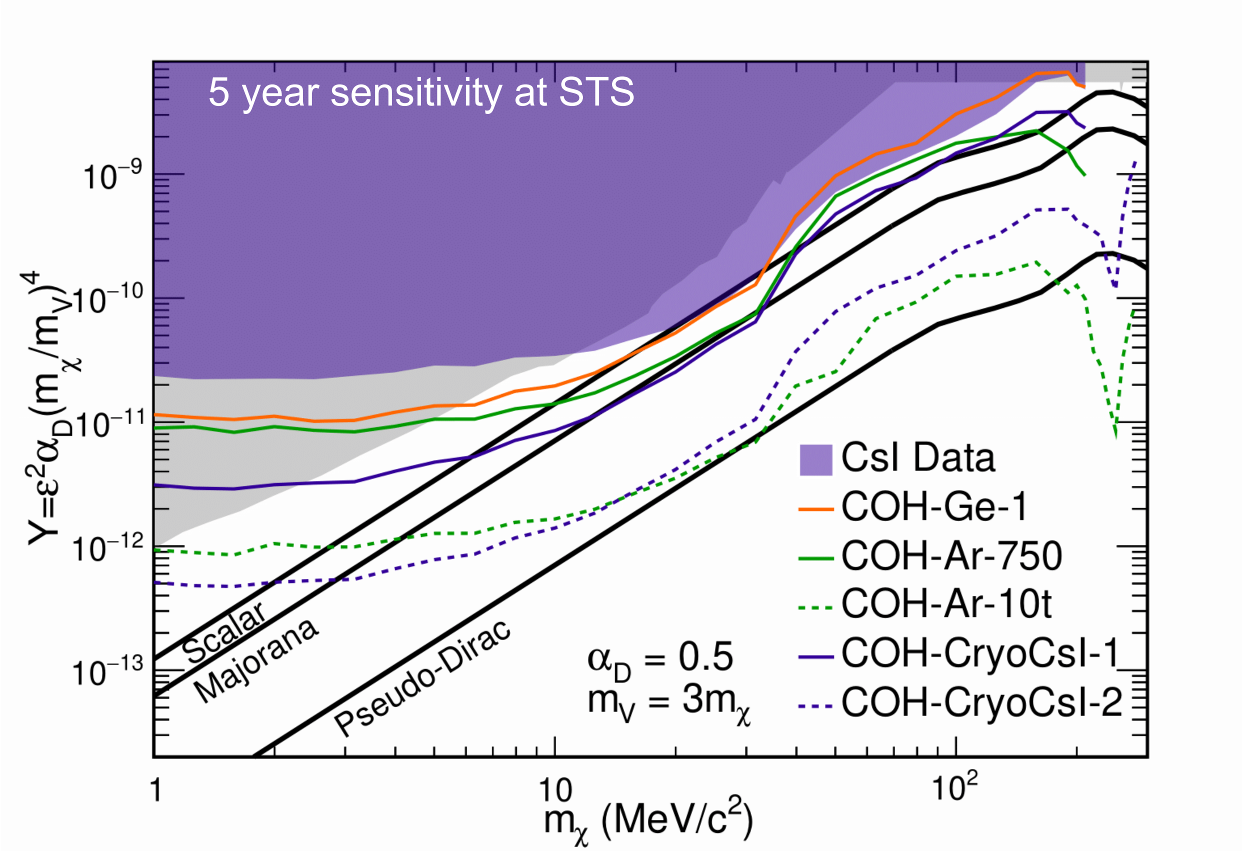
Cancel detector-related systematic uncertainties
w/ different baselines in one CEvNS detector seeing 2 sources

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

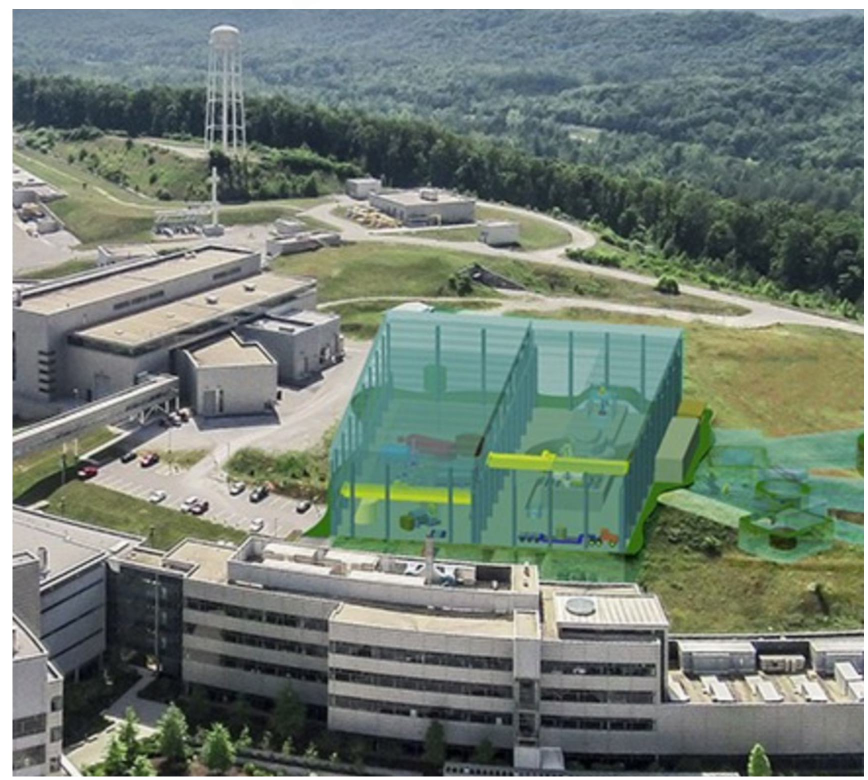
- **Spallation sources are prodigious producers of πDAR neutrinos, and maybe BSM signatures...**

- **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