Searching for dark matter
with CEvNS detectors at the SNS

Dan Pershey (Duke University)
for the COHERENT Collaboration

Snowmass CSS, U Washington, Jul 23, 2022

Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL)

❑ A premier neutron accelerator complex which produces an incredibly intense flux of low-energy neutrinos with exciting physics agenda complementary to its neutron studies

❑ In early stages of upgrade to double accelerator power and increase beam energy

❑ The Proton Power Upgrade (coming few years):
- Beam energy: 1.0 GeV → 1.3 GeV
- Beam power: 1.4 MW → 2.8 MW
- Pulse duration (FWHM): 350 ns

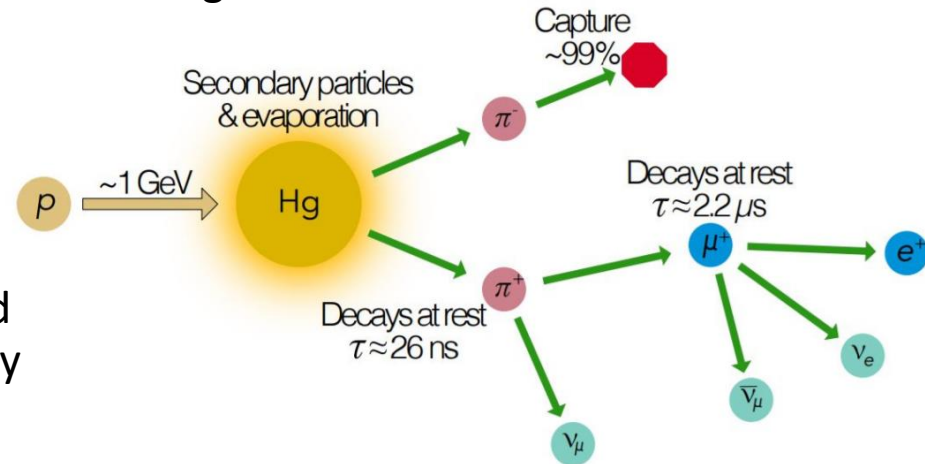# Construction of the Second Target Station (STS)
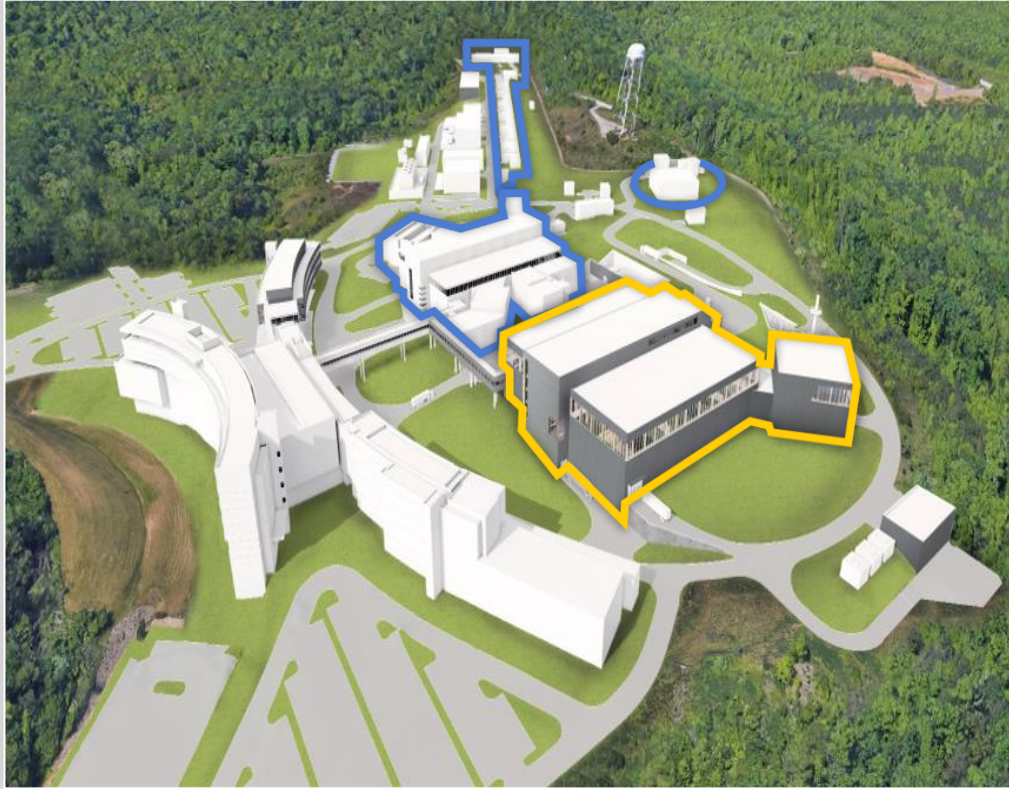
- Along with upgrade to accelerator power, the complex will construct the Second Target Station (STS) with expected completion $\approx$ 2030 which will run simultaneously with the First Target Station (FTS)

- After completion, both targets will operate with beam pulses delivered at 45 Hz (15 Hz) for the FTS (STS)

- Facilitates significant expansion of neutrino program at ORNL

- Collaborating with lab to design specialized detector hall large enough to fit 10t-scale detectors with sufficient shielding from bright neutron flux

Duke UNIVERSITY   ((COHERENT SNS

Neutrino flux at the SNS

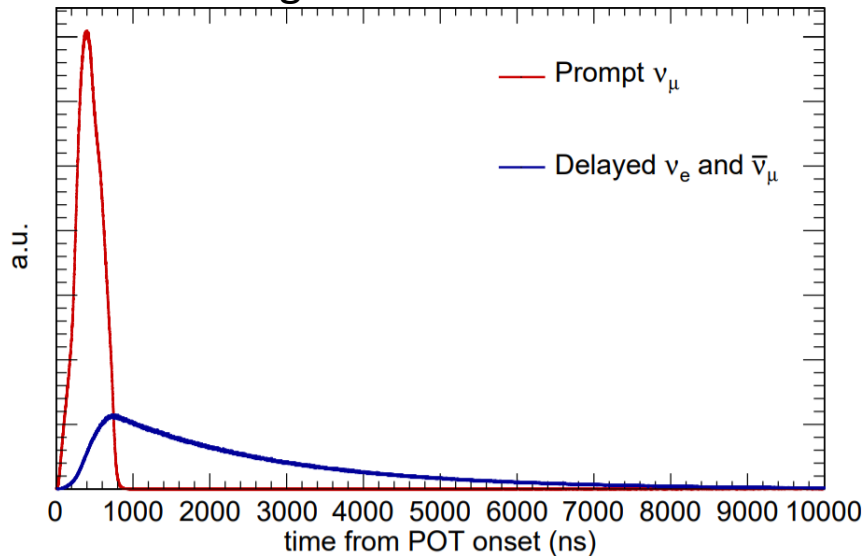☐ **Low energy pions are a natural by-product of SNS running**

- π^+ will stop and decay at rest

  $\pi^+ \to \mu^+ + \nu_\mu$: $\tau = 26$ ns
  $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$: $\tau = 2200$ ns

- Flux includes three flavors of neutrinos → can test flavor universality as a BSM signature

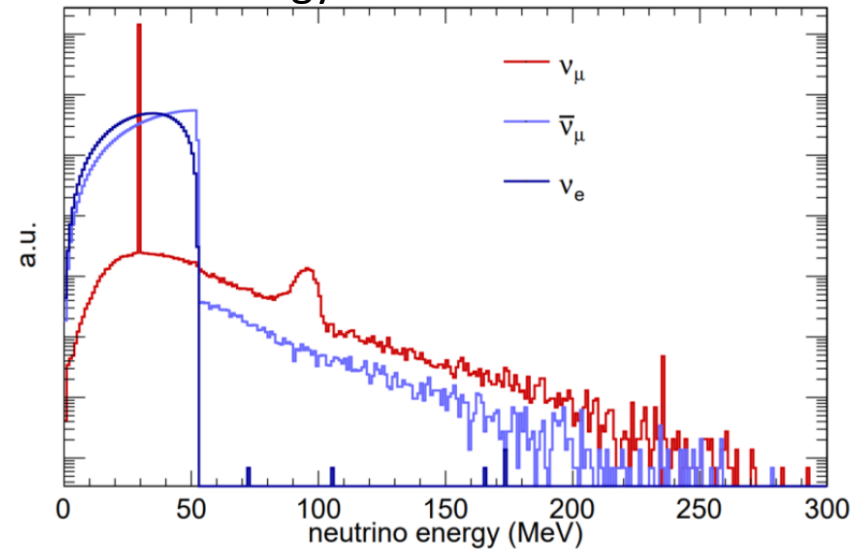☐ **Flux shape is very well known in both time and energy with very small contribution from decay in flight**

Secondary particles & evaporation

Capture ~99%

π^-

p ~1 GeV   Hg

π^+

Decays at rest $\tau \approx 26$ ns

Decays at rest $\tau \approx 2.2\,\mu s$

μ^+ → e^+

ν_e

$\bar{\nu}_\mu$

ν_μ

Timing distribution at SNS

— Prompt ν_μ
— Delayed ν_e and $\bar{\nu}_\mu$

a.u.

time from POT onset (ns)

Energy distribution at SNS

— ν_μ
— $\bar{\nu}_\mu$
— ν_e

a.u.

neutrino energy (MeV)

Duke UNIVERSITY   ((C❂HERENT))

Measuring CEvNS at the SNS with COHERENT

- ❑ COHERENT formed to search for coherent elastic neutrino-nucleus scattering (CEvNS)

- ❑ Only visible signature is low-energy nuclear recoil
  - Need low-threshold detectors similar to dark matter direct detection

- ❑ Made first measurements of CEvNS on CsI (2017/21) and Ar (2020) more data on Ge, NaI, Ar, CsI in the near future, all at the FTS

- ❑ Currently transitioning from first-light results to precision measurements and searches for BSM physics
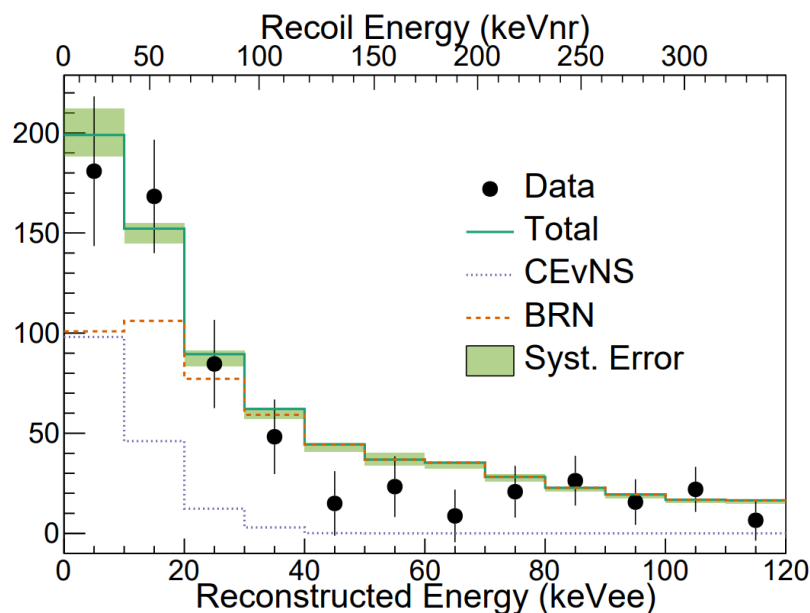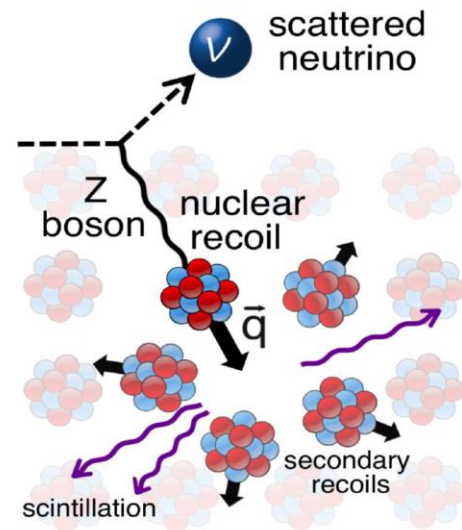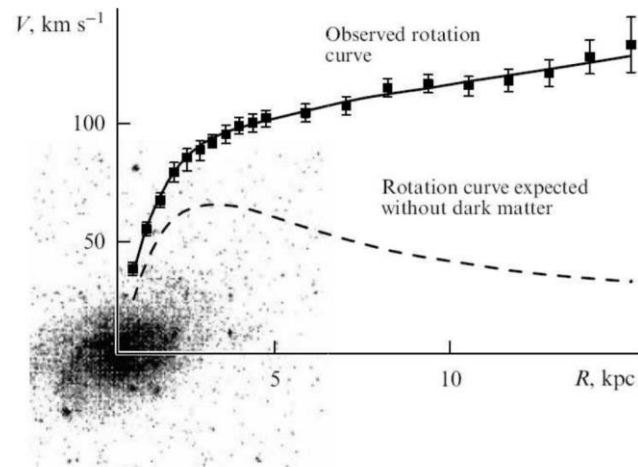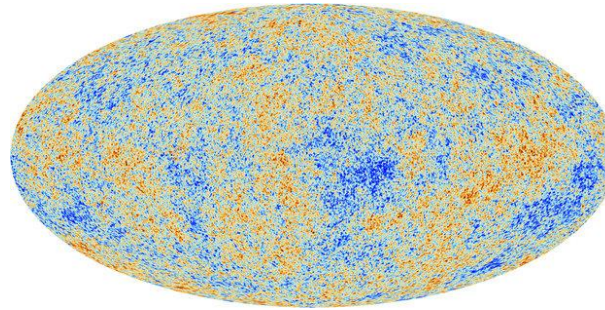

Ar: COHERENT, Phys. Rev. Lett. 126 012022 (2021)
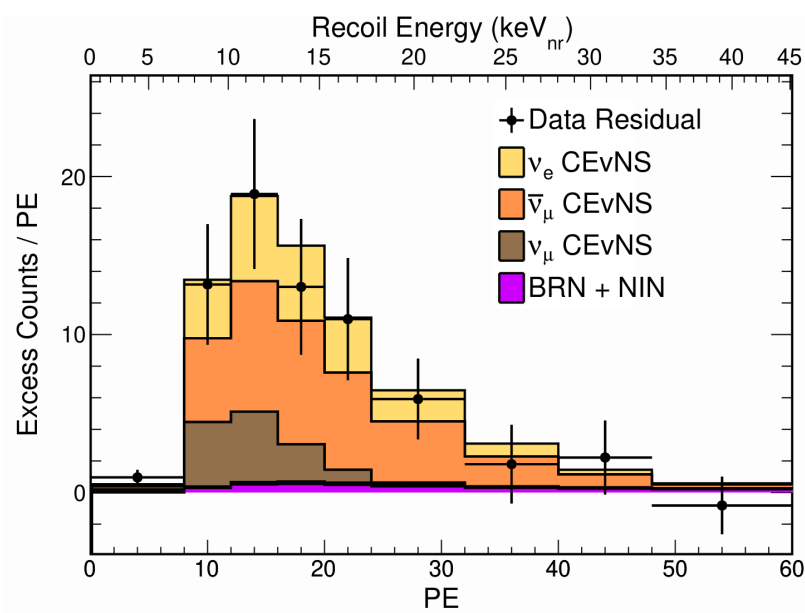
CsI: COHERENT, arXiv:2110.07730 (2021)

Dark matter in our universe
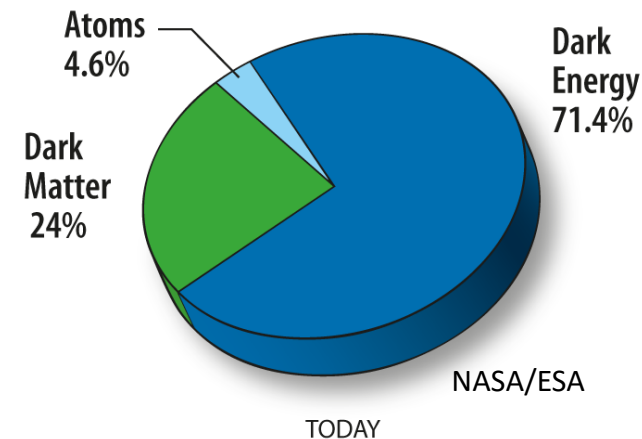
A. Zasov et al., arXiv 1710:10630 (2017)
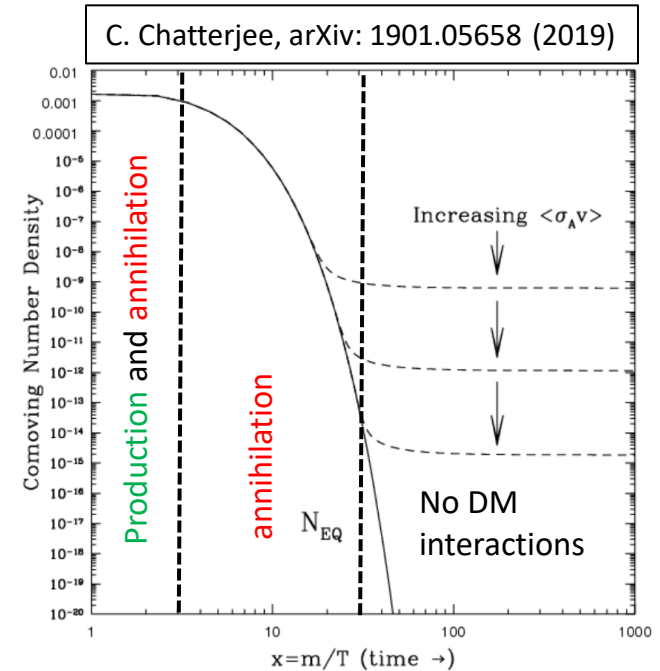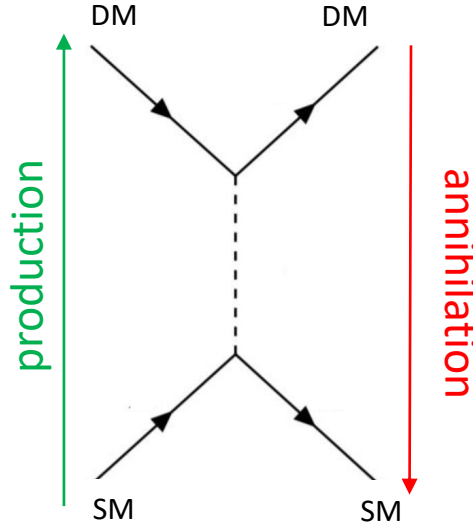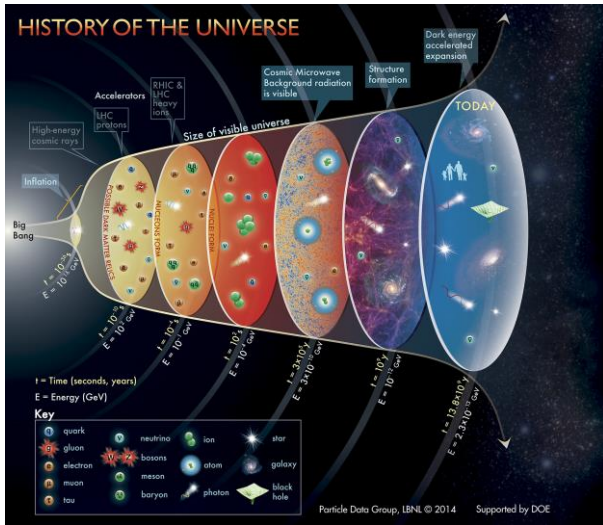
Plank, Astron Astrophys **641** A1 (2020)

X. Huang et. Al, ApJ 909 27 (2021)

- First evidence for dark matter (DM) comes from rotation curves of galaxies in early 20th century (e.g. Zwicky 1933)

- In 2003, precision CMB data confirmed the existence of dark matter and estimated that roughly 80% of matter in the universe is dark matter

- Continuing understanding distribution of dark matter from weak gravitational lensing data

- 100 years since postulation, and we still haven't found the particle nature of DM despite many attempts – new physics we know exists, we just need to find a new place to look


Atoms 4.6%
Dark Matter 24%
Dark Energy 71.4%
NASA/ESA
TODAY

Origin of weakly-interacting dark matter

HISTORY OF THE UNIVERSE — Particle Data Group, LBNL © 2014, Supported by DOE

C. Chatterjee, arXiv: 1901.05658 (2019)

DM — DM

production

annihilation

SM — SM

Comoving Number Density vs $x = m/T$ (time →)

Production and annihilation

annihilation

N_{EQ}

No DM interactions

Increasing $\langle \sigma_A v \rangle$

- ❑ Assuming that DM is a particle that interacts weakly with standard-model (SM) matter, in the very early universe, DM was in thermal equilibrium with SM fermions
  - As the universe cools, DM production is no longer kinematically allowed, and the DM concentration falls exponentially
  - Later, as the universe continued expanding, the DM concentration became so low that DM annihilation stopped since DM particles could no longer find partners to annihilate with
- ❑ At this point, the universe "freeze-out" of DM occurred, with the DM concentration fixed to the modern observed value
- ❑ Freeze-out concentration depends on DM cross section – higher cross section implies DM can annihilate even when less dense so that concentration is lower
 - Modern relic abundance tells us what the cross section is (as a function of DM mass)

Low-mass DM phenomenology

❑ For decades, experiments have focused on classic WIMP searches assumed to interact with the weak force

❑ The DM scattering cross section is $\sigma \sim m_\chi^2 / m_z^4$

- Lower DM mass → lower cross section → higher DM abundance
- If $m_\chi < 2$ GeV/c^2, predicted relic abundance would be so large it would overclose the universe, preventing modern the universe

DM   DM

Z_0

SM   SM
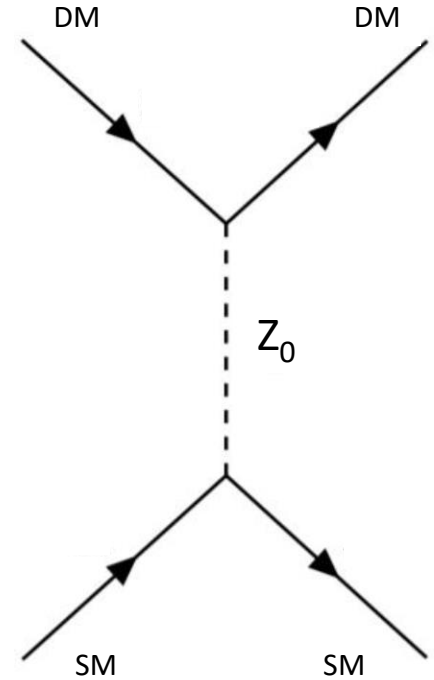
# Low-mass DM phenomenology

□ For decades, experiments have focused on classic WIMP searches assumed to interact with the weak force

□ The DM scattering cross section is $\sigma \sim m_\chi^2/m_Z^4$

- Lower DM mass → lower cross section → higher DM abundance
- If $m_\chi < 2$ GeV/c², predicted relic abundance would be so large it would overclose the universe, preventing modern the universe

□ No longer assume DM interacts with SM particles via the weak force, but some yet unknown hidden sector particle, V

□ In this scenario, $\sigma \sim m_\chi^2/m_V^4$ which is consistent with modern cosmology even at low mass scales

□ Simple, general model assumes a vector mediator that kinematically mixes with SM photon: $\mathcal{L} \sim \frac{1}{2}\varepsilon^2 F_{\mu\upsilon}V^{\mu\upsilon}$

□ Model parameters

- DM and mediator masses: m_χ and m_V
- SM-mediator and DM-mediator couplings: ε and α_D

□ Relic abundance given in terms of $Y = \varepsilon^2\alpha_D\left(m_\chi/m_V\right)^4$

DM   DM

Which force is this?

SM   SM
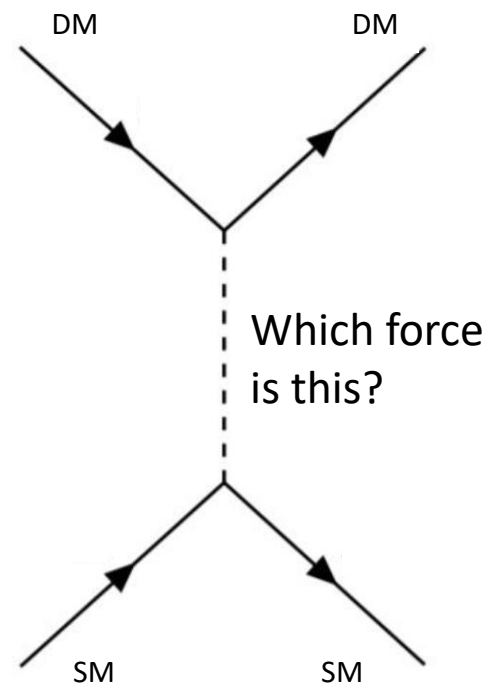
Classical WIMP mass regime:
  Lee and Weinberg, Phys. Rev. Lett. **39** 165 (1977)
Early sub-GeV DM phenomenology:
  Fayet, Phys. Rev. **D70**, 023514 (2004)
  Boehm and Fayet, Nuc. Phys. **B683**, 219 (2004)
  Pospelov et al., Phys. Lett. **B662**, 53 (2008)
Coherent DM scattering / DM at the SNS:
  deNiverville et al., Phys. Rev. **D84**, 075020 (2015)
  Dutta et al., Phys. Rev. Lett. **123**, 061801 (2019)

Making DM at the SNS

SNS

COHERENT detector

p

Hg
Target

V

χ

Nuclear Recoil
Signature

χ'

χ
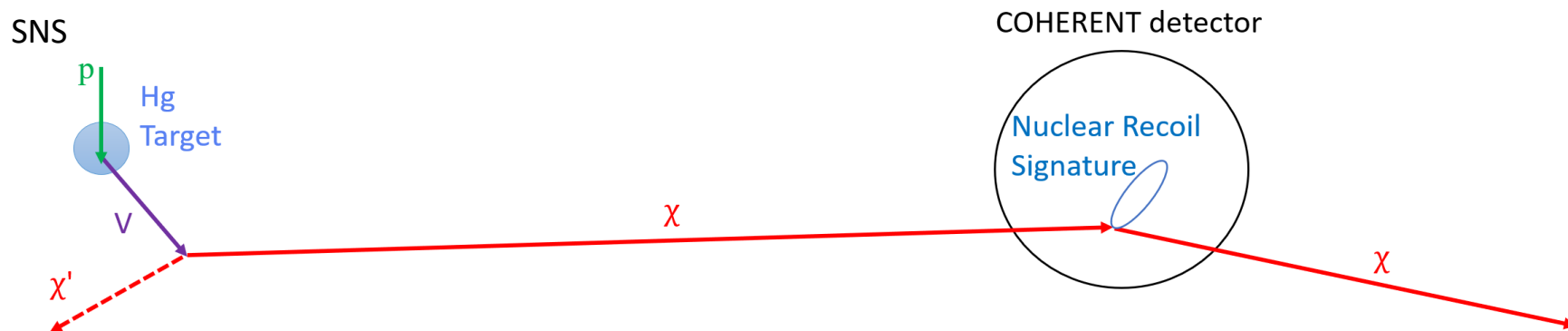
❑ Any hidden sector particles with masses below $\approx$ 220 MeV/c^2 could be produced in the many proton-Hg interactions within the SNS target

❑ This may include mediator particles between SM and DM particles
- Dominant production from $\pi^0/\eta^0 \to V\gamma$

❑ Mediator decays to a pair of DM particles, sending a flux out of the SNS
- Suitable detector placed in this flux can directly detect DM particles scattering within the detector

Duke
UNIVERSITY

((C❋HERENT
SNS

Advantages of low-recoil detectors: cross section

$$\lambda = h/\sqrt{Q^2} \gg R_p$$
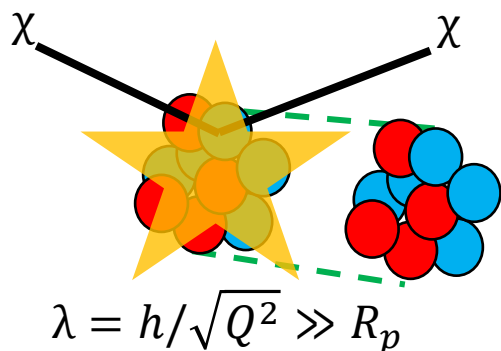
❑ We're dealing with low enough Q^2 that the deBroglie wavelength is large compared to nuclear radius

❑ All nucleons within nucleus recoil coherently from neutrino or DM scattering

❑ Astroparticle direct-detection experiments have exploited this for years – now accelerator experiments can too with CEvNS detectors

❑ This coherency gives a Z^2 enhancement in the cross section

❑ Game-changing – small investment in a 14-kg CEvNS detector competes with multi-ton detectors

❑ Potential for 10^3 x exposure increase at STS compared to first light CEvNS detectors

Direct-detection experiments searching for light dark matter

	Mass (t)
LSND	167
MiniBooNE	450
COHERENT CsI	0.0146
Argon at STS	10

Current CEvNS
Future CEvNS

Advantages of accelerator searches: higher recoil energies

Example: CsI[Na] detector at FTS

□ Galactic DM is slow, thermal with β around 0.001 → struck nuclei get very soft kick

- Maximum recoil energy $2p_\chi^2/m_{Nuc} \approx 0.01$ eV
- Much less than scintillation / ionization thresholds
- About 1 kT for liquid Xe or liquid Ar detectors
- Coherent DM-nucleus scattering unobservable

Scalar relic abundance
$m_\chi = 25$ MeV/c^2 and $\alpha_D = 0.5$
— Galactic DM ($\times 10^{-10}$)
···· Galactic DM in beam window ($\times 10^{-10}$)
— SNS-produced DM
■ Selected SNS-produced DM
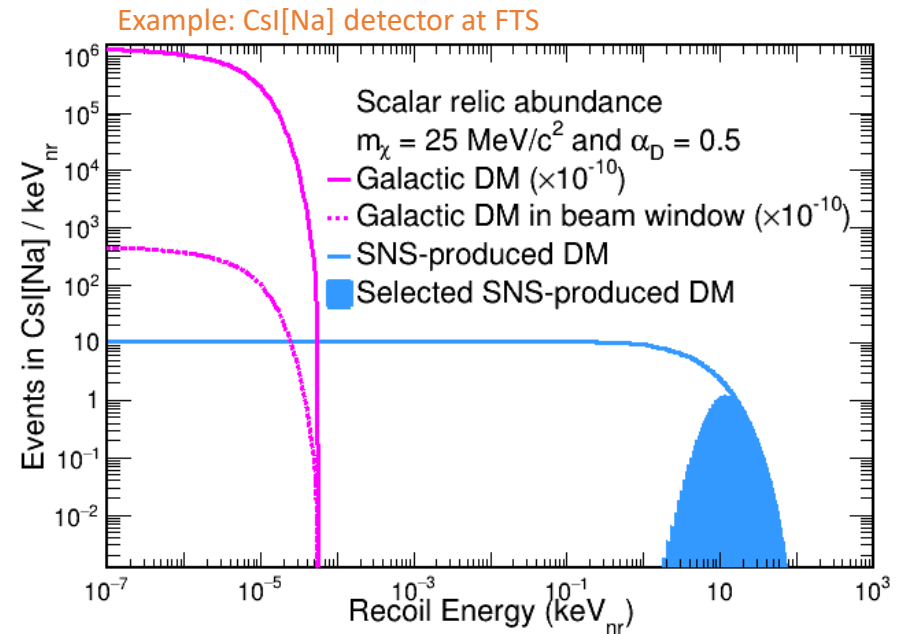
□ DM produced at accelerators would be relativistic

- Maximum recoil energy $2p_\chi^2/m_{Nuc} \approx 100$ keV → $10^7 \times$ higher recoil energies compared to galactic DM

Detecting coherent DM-nucleus scattering easily within reach of CEvNS detectors with modest thresholds between 1 and 20 keV$_{nr}$
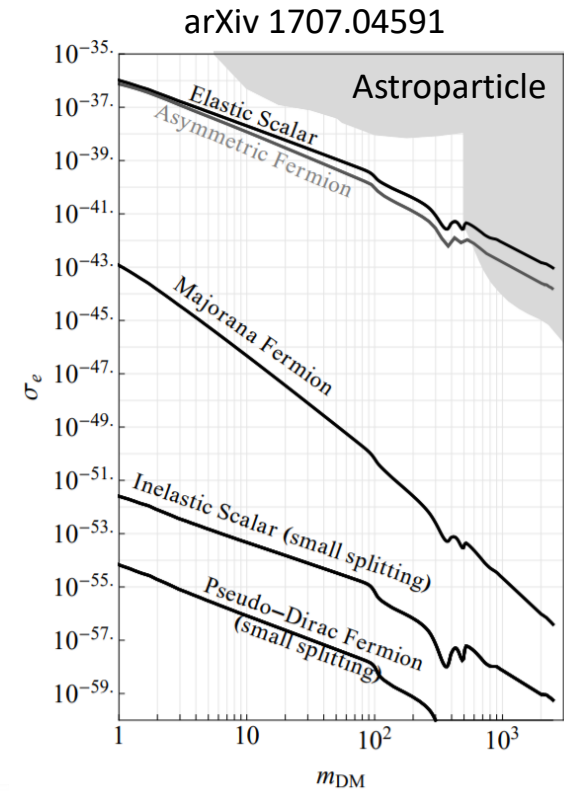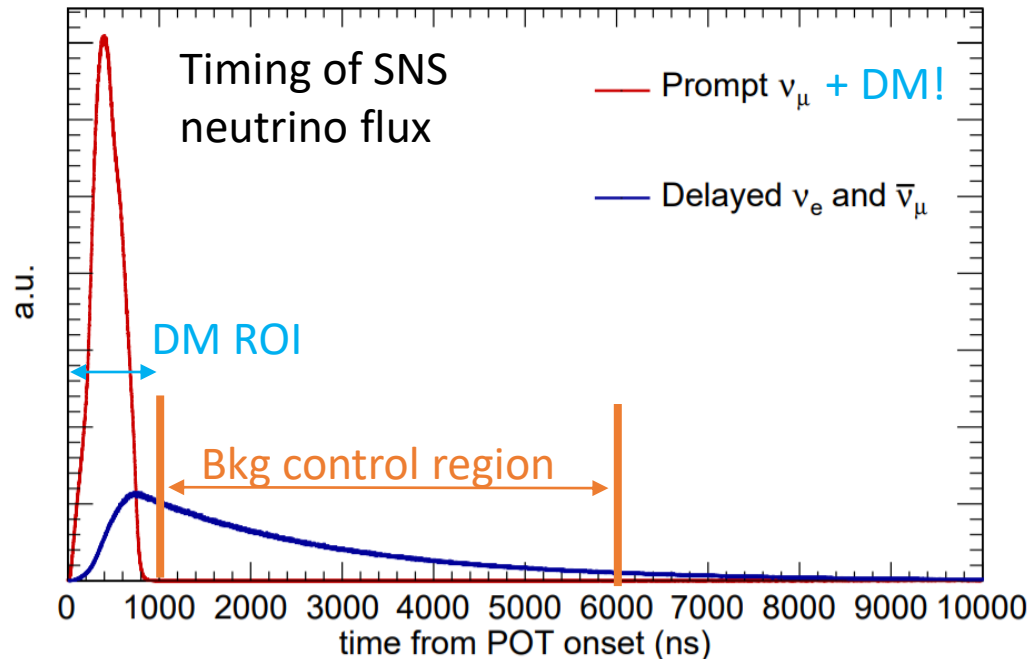
Advantages of accelerator searches: less model dependent

Astroparticle experiments are within grasp of the expected dark matter concentration for scalar DM

But if DM is a fermion, the scattering cross section is heavily suppressed by DM speed, $\beta \approx 0.001$

Predictions span 20 orders of magnitude

arXiv 1707.04591
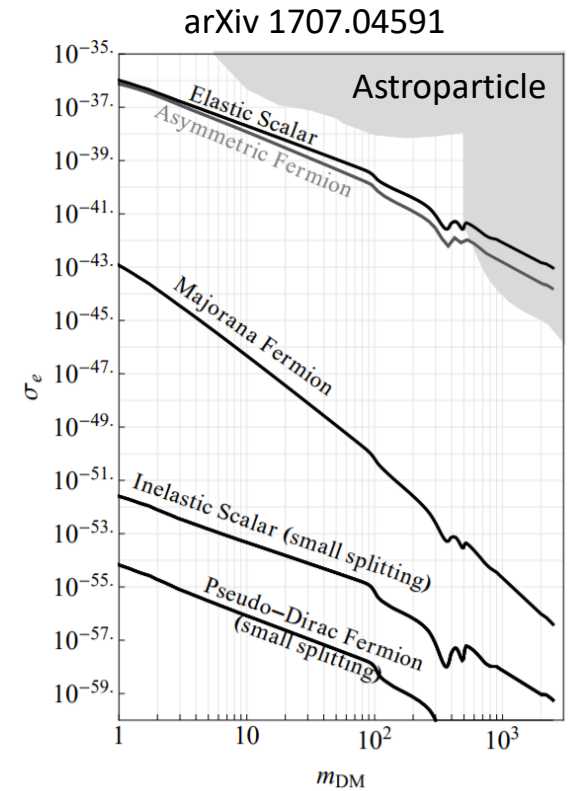
Advantages of accelerator searches: less model dependent

❑ Astroparticle experiments are within grasp of the expected dark matter concentration for scalar DM

❑ But if DM is a fermion, the scattering cross section is heavily suppressed by DM speed, $\beta \approx 0.001$

❑ Predictions span 20 orders of magnitude

❑ At accelerators, DM is relativistic with only a factor of 20 between different expectations

- Accelerator searches only viable options to test fermionic DM

❑ COHERENT gets the best of both worlds

- Independent of DM particle nature like accelerator methods
- Large coherent cross section like astroparticle methods
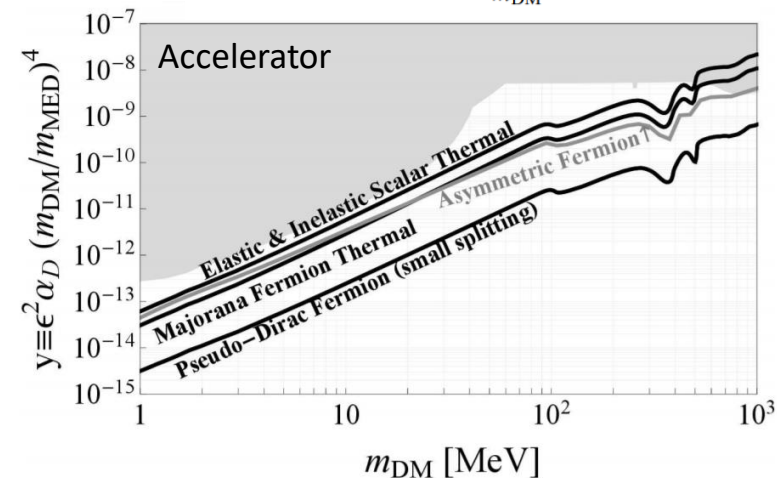
Advantages of spallation sources: constraining uncertainties

Timing of SNS neutrino flux

— Prompt ν_μ + DM!

— Delayed ν_e and $\bar{\nu}_\mu$

DM ROI

Bkg control region

a.u.

time from POT onset (ns)

- ❑ CEvNS is the principal beam-related background for DM search
  - SM cross section precisely calculated, but uncertainties in detector response unique to each detector
- ❑ Since DM is relativistic, it is expected coincident with protons on target
  - No DM coincident with delayed CEvNS from $\upsilon_e/\bar{\upsilon}_\mu$ flux
- ❑ The delayed time window gives us a control sample – can constrain systematic uncertainties in situ and use to refine background estimates in the DM timing ROI
- ❑ Ensures DM search never systematics limited – syst uncertainty shrinks as fast as stat

Current data – constraing dark matter with COHERENT CsI[Na]
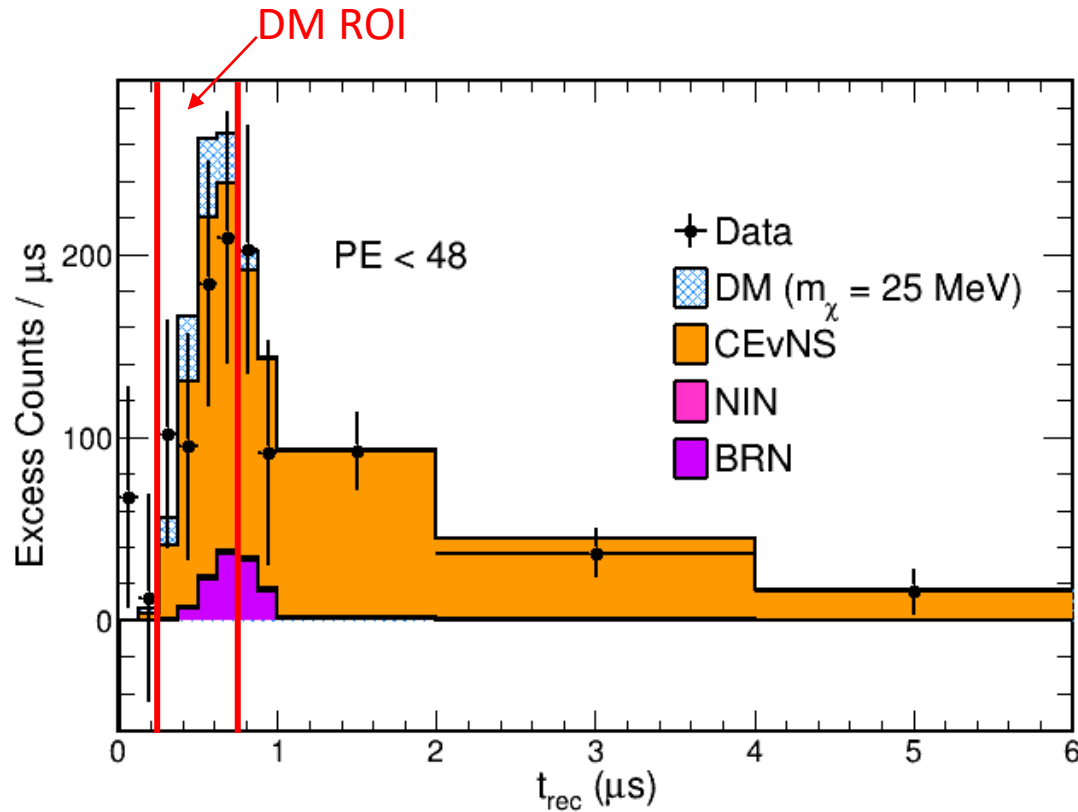
	Prediction	Data
CEvNS	341 ± 41	320 ± 33
BRN	27.6 ± 6.9	25.8 ± 6.6
NIN	7.6 ± 2.7	7.4 ± 2.7

❑ Current data from COHERENT CsI[Na] is consistent with predictions for the standard-model backgrounds within expected errors – no DM signal yet observed, must extend sensitivity with future searches

Recoil energy distribution of COHERENT CsI[Na] data
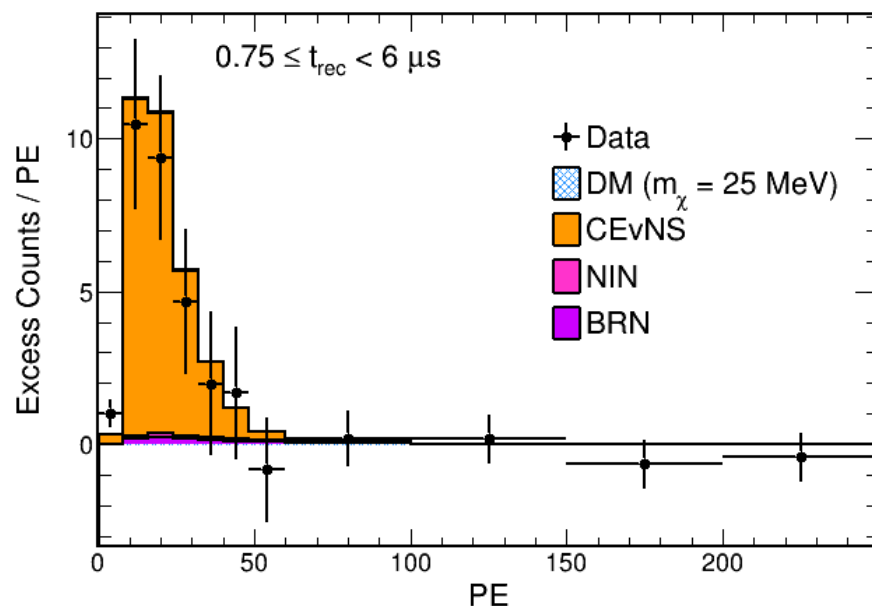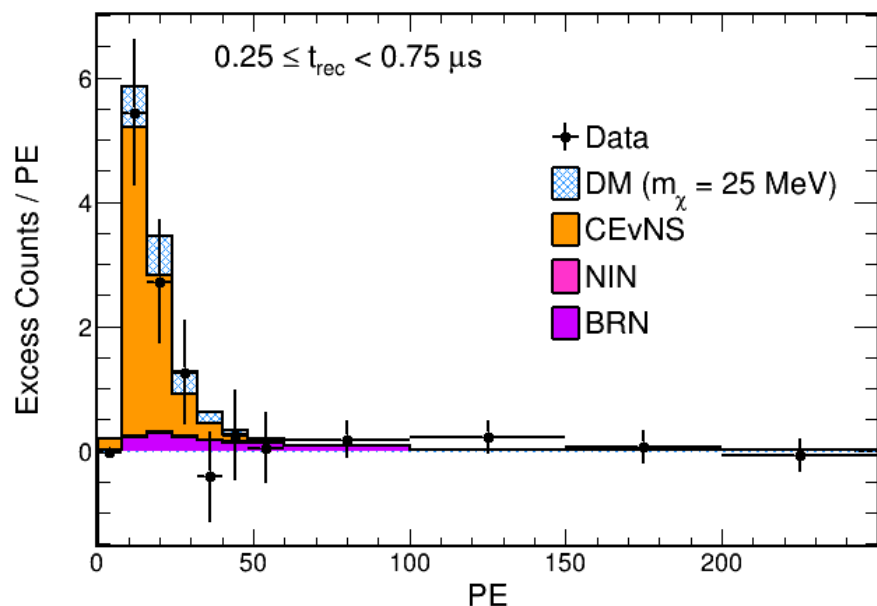
- Data also agrees well with the background-only prediction for the recoil energy distribution
  - $\chi^2 = 103/120$ for background-only 2D fit
- Look for an excess in the DM ROI while controlling backgrounds with delayed events

COHERENT constraint on sub-GeV dark matter

❑ At 90% confidence, current CsI[Na] data significantly improves on constraints

  • Constraint slightly stronger than our sensitivity due to deficit of events in DM timing ROI

❑ First to probe beyond the scalar target that matches the DM relic abundance

❑ Achieved with small 14.6 kg detector – how much further can STS extend these bounds
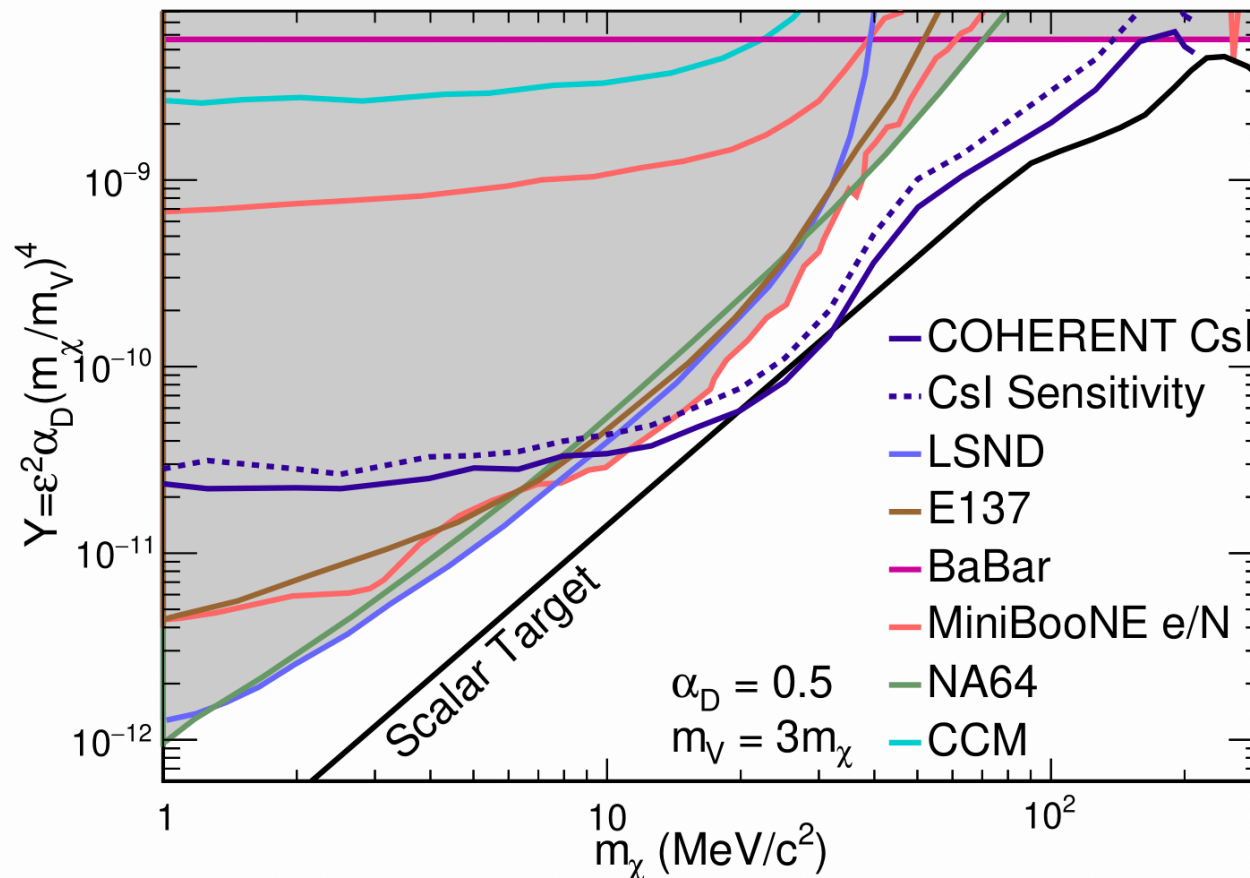
Potential for new CEvNS detectors at the STS

□COHERENT already successful with CEvNS detection with argon using a 24kg single-phase, scintillating calorimeter

□At the STS, we are working with ORNL to accommodate a 10t upgrade to this concept at a baseline of 20m

□Threshold and dynamic range designed to allow simultaneous measurement of 10 keV to 50 MeV to measure both CEvNS

FIDUCIAL VOL = pi/4(2.08m)^3 = 7.07m^3 = 9895kg = 10.9tons

Ø2.08 m

2.08 m

10 ton LAr
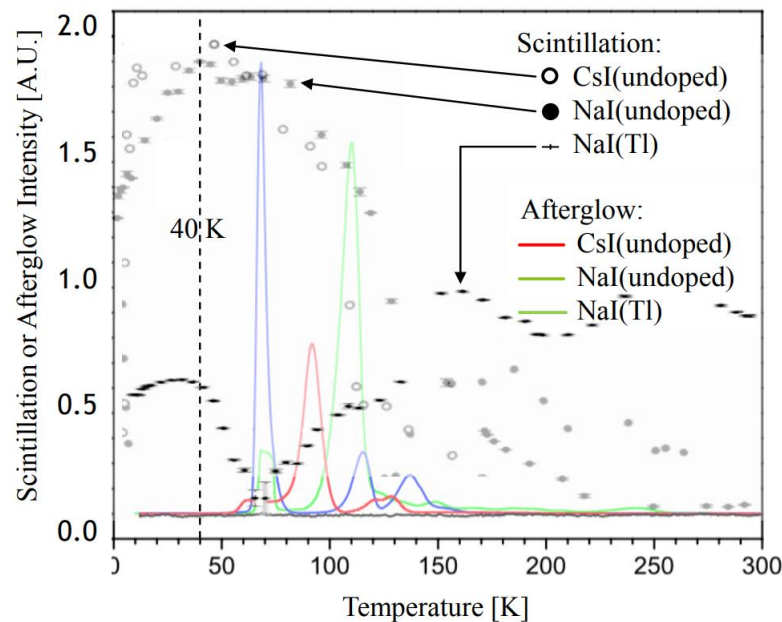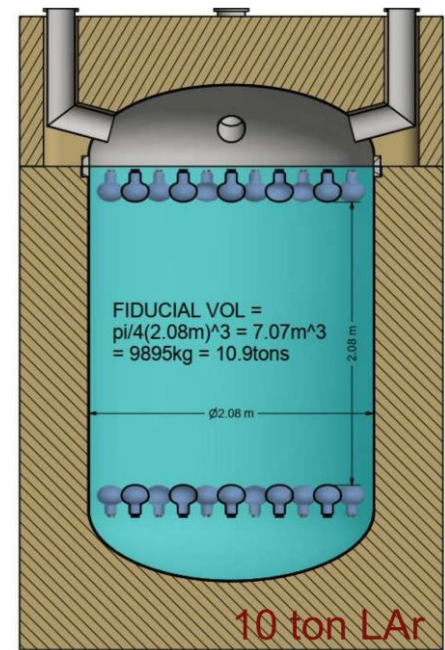
□We also plan for an array of cryogenic, undoped CsI scintillating detectors

- Cooling undoped CsI to 40 K increases the crystal light yield while also eliminating background scintillation within the crystal (afterglow light)

□Can deploy 700 kg of crystal with a threshold of ≈ 0.1 keV$_{ee}$ due to the favorable light yield

Future COHERENT sensitivity to dark matter
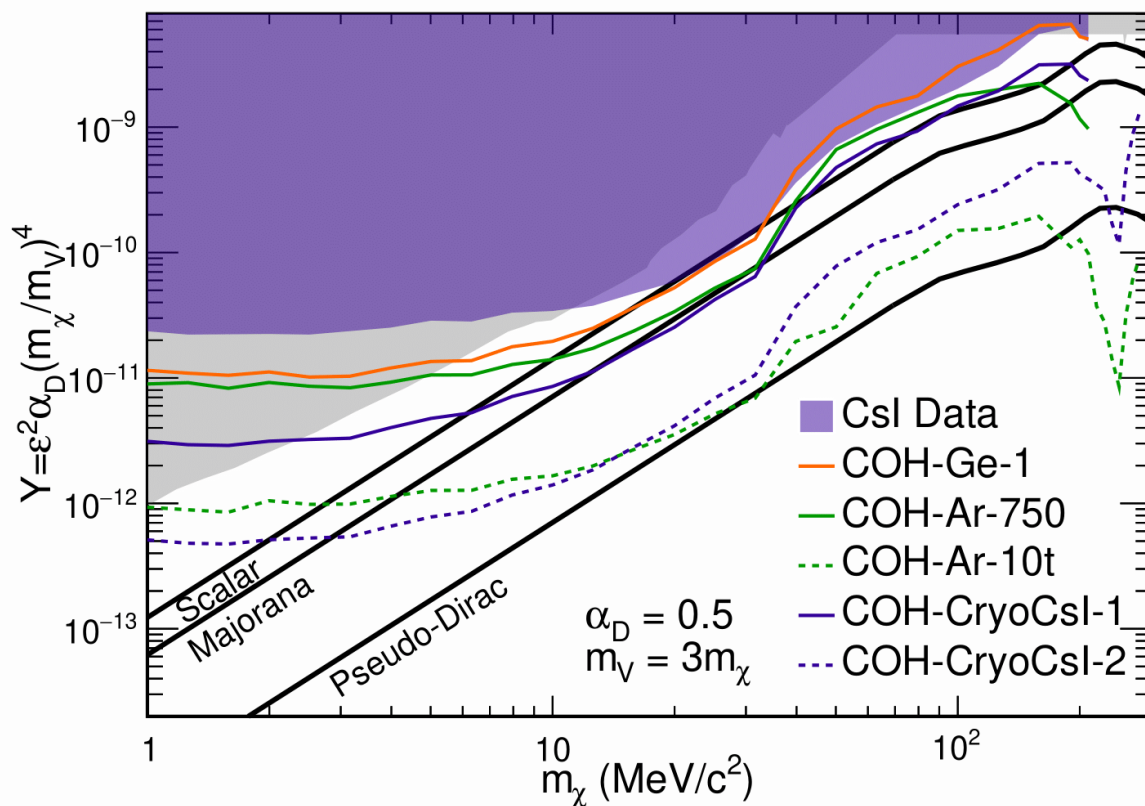
❑**Immediate future:** germanium detector currently being commissioned – will fully explore scalar target at lower masses

❑**In coming years:** future (funded by Korea) argon and cryogenic CsI detector at the FTS – will be sensitive to a lower DM flux and probe the Majorana fermion target (solid lines)

❑**In next decade:** large detectors placed forward at the STS will begin to ambitiously test even the most pessimistic spin scenarios (dashed lines)

Summary

- COHERENT opened a new pathway to direct detection of accelerator-produced dark matter by making the first detection of CEvNS at the SNS at ORNL

- CEvNS experiments show impressive potential for constraining dark matter at beam dump experiments with several unique advantages

- First constraint already probes scalar dark matter consistent with the relic abundance with just 14.6 kg of target mass

- Promising future for CEvNS experiments promising strong probes of dark matter parameter space exploring relic lines for all viable spin scenarios
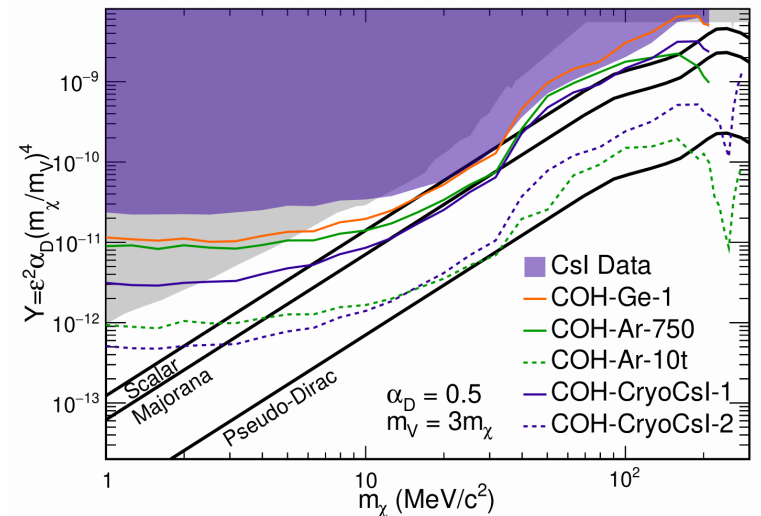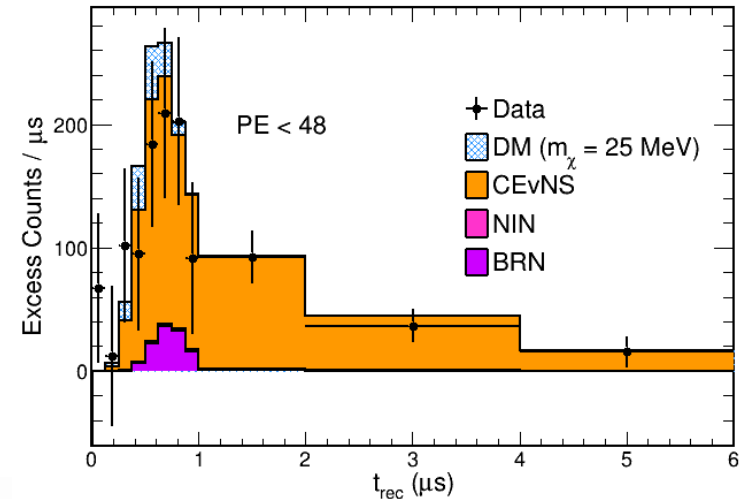
Future beam improvements at the SNS

❑ Two staged improvement to the beam

1: Proton Power Upgrade

- Increases the power of neutron beam $1.4 \to 2.8$ MW
- Feasibility of a second target station

2: Second Target Station

- Implements a second beamline at the accelerator

❑ Expected completion $\approx$2030s

❑ Interest from the lab to design STS to accommodate a specialized detector hall for neutrino measurements capable of fitting a 10-t detector

The COHERENT CsI[Na] detector

A hand-held neutrino detector
– Built at U Chicago
– 14.6-kg CsI[Na] crystal
– Manufactured by Amcrys-H
– Single R877-100 PMT

Shielding design

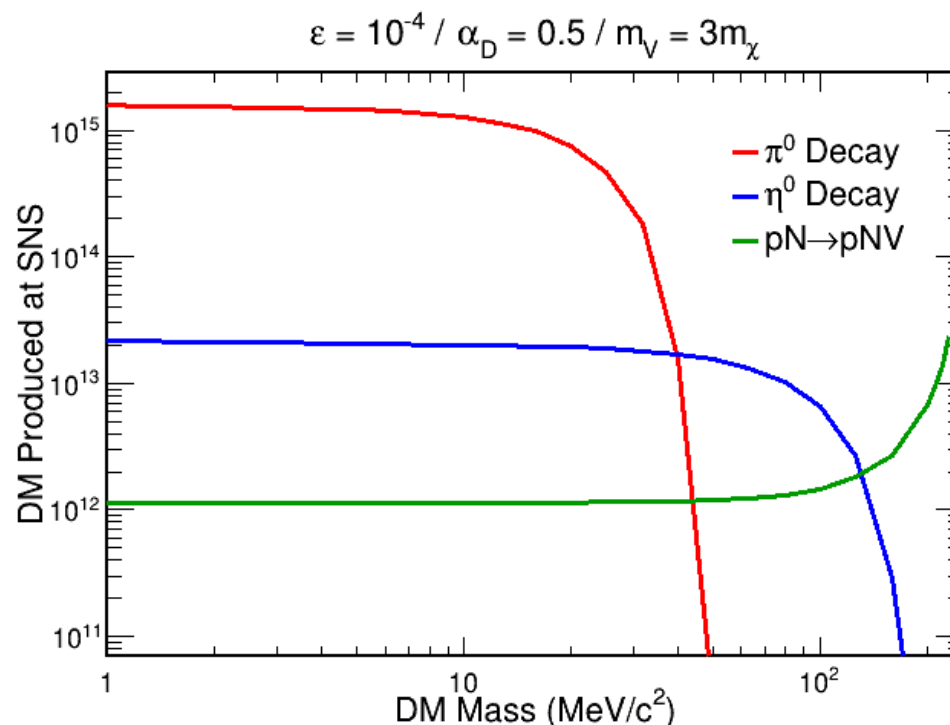– Veto to tag cosmic events
– Lead to shield from gammas
– Water and plastic to
  moderate neutrons

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

Detector made first detection of CEvNS (2017)

DM production channels

$$\varepsilon = 10^{-4} \ / \ \alpha_D = 0.5 \ / \ m_V = 3m_\chi$$

- Legend: π^0 Decay, η^0 Decay, $pN \to pNV$
- Y-axis: DM Produced at SNS
- X-axis: DM Mass (MeV/c^2)

☐ **Our expected dark matter flux is produced through three channels**

- $\pi^0 \to V\gamma$ decay: dominant channel where kinematically allowed, $2m_\chi < m_\pi$,

- $\eta^0 \to V\gamma$ decay: similarly only contributes for $2m_\chi < m_\eta$

- $pN \to pNV$ bremsstrahlung: only dominant at high energies and rate increases significantly at the ρ resonance, $m_V \approx m_\rho$
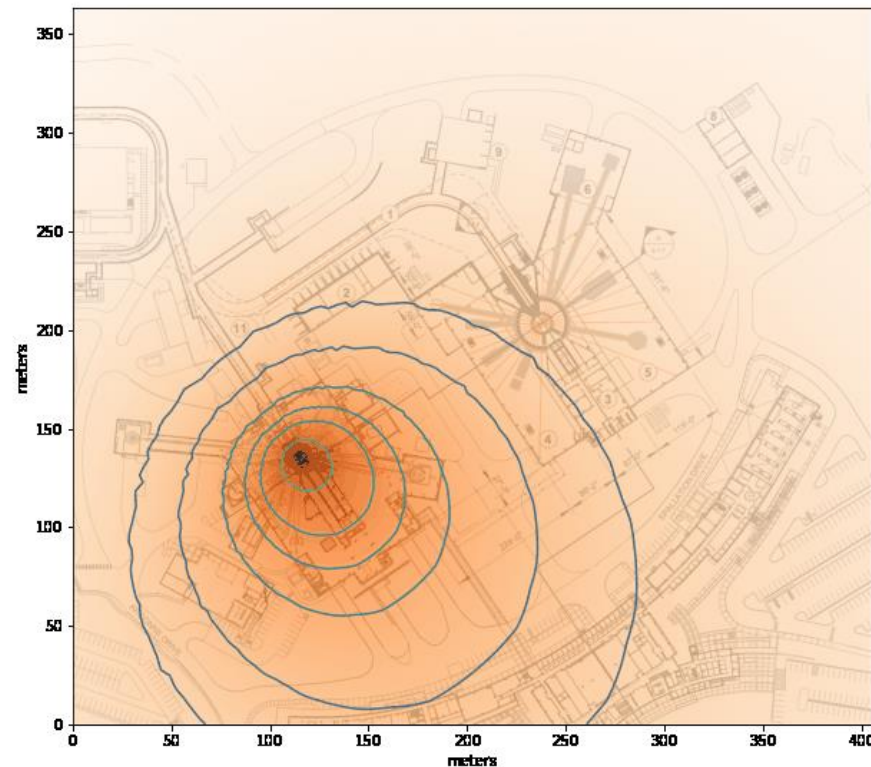
Directionality of flux at the SNS

Neutrino flux produced at rest – isotropic

Largest beam-related background for DM searches at the SNS
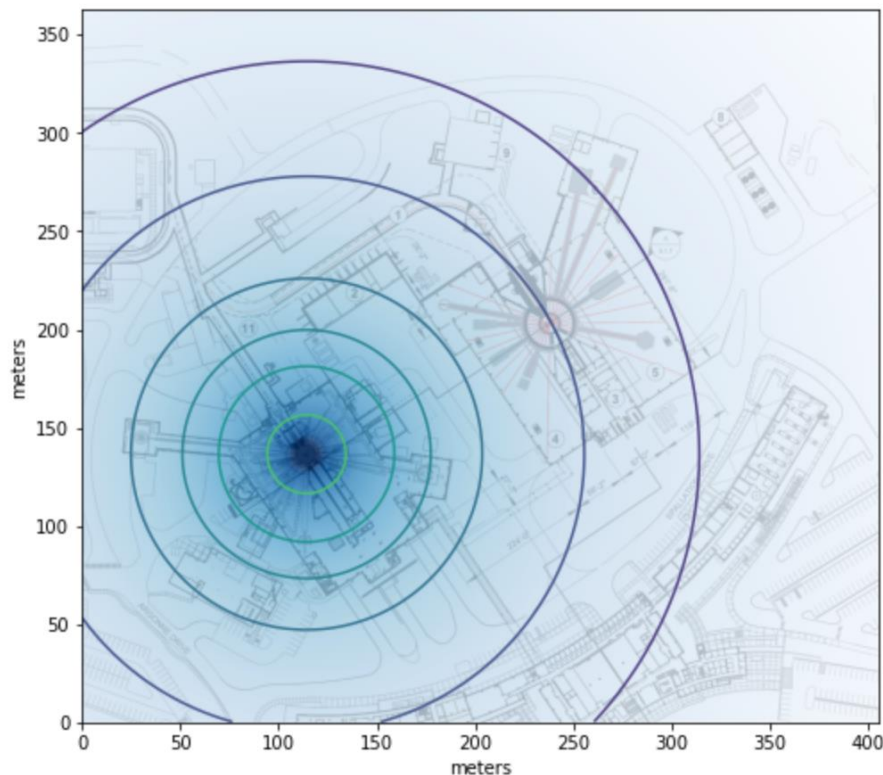
DM produced in-flight – is boosted

A forward-directed detector would optimize DM / background

❑ After STS is built, both targets will operate with 3(1)/4 bunches sent to FTS (STS)

❑ If DM is in this mass regime, SNS very advantageous – a single detector monitors DM flux from two beams allowing confirmation of the expected angular dependence of the flux

Recent updates to cross section generator (BdNMC)

❑ DM particles scatter with coherent cross section

- $\frac{d\sigma}{dE_r} = 4\pi Z^2 \varepsilon^2 \alpha_{EM} \alpha_D \frac{2m_N E_\chi^2}{p_\chi^2 (m_V^2 + 2m_N E_r)^2} |F(Q^2)|^2$

❑ This model has changed significantly since our previous sensitivity estimates

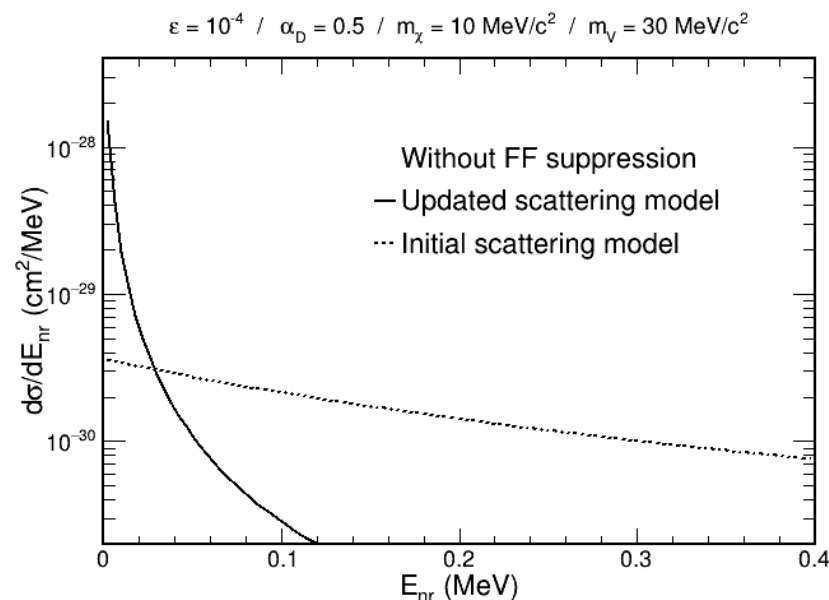❑ 1: A substitution of $m_p \rightarrow m_N$ for a proper treatment of coherent scattering

- Overall increases cross section, but spectrum is much softer – detector thresholds much more impactful for DM analyses
- Degrades (Improves) sensitivity for DM masses below (above) 10 MeV/c^2

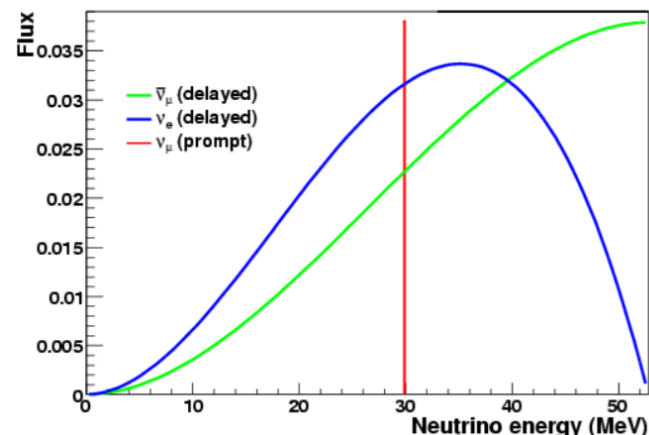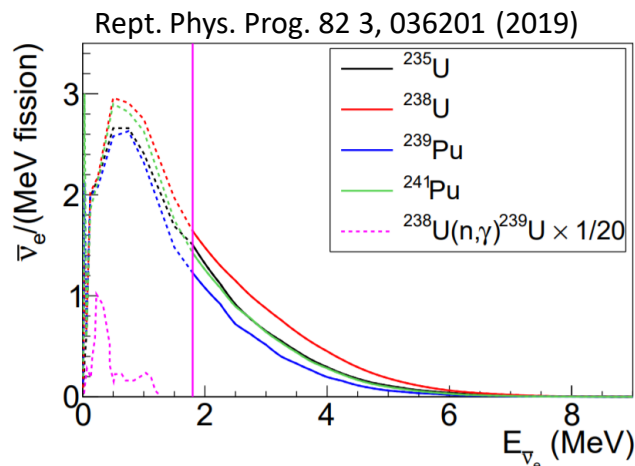❑ 2: A more accurate form factor treatment

- BdNMC now uses the nuclear form factor accounting for spread of protons within nucleus rather than the proton form factor accounting for spatial spread of charge within each proton
- Significantly reduces sensitivity at higher masses

❑ 3: Improved configured resolution of DM scattering cross section from 100 MeV to 1 MeV

- Gives slight reduction in event rate, but is more accurate

$\varepsilon = 10^{-4}$ / $\alpha_D = 0.5$ / $m_\chi = 10$ MeV/c^2 / $m_V = 30$ MeV/c^2

Without FF suppression
— Updated scattering model
··· Initial scattering model

High-flux Sources for Low-energy Neutrinos

Rept. Phys. Prog. 82 3, 036201 (2019)

❑ **Nuclear reactors**
- Very high flux: ~2×10^{20} $\overline{\nu}_e$ / s — reactors win
- Maximum recoil energy for CsI: 1 keV
- Reactor-off data → in-situ background constraint

❑ **Pion decay-at-rest (πDAR) at accelerators**
- High flux: ~3×10^{14} $\nu_\mu / \nu_e / \overline{\nu}_\mu$ / s — πDAR wins
- Maximum recoil energy for CsI: 15 keV
- Pulsed beam → in-situ background constraint

Fermilab collaboration

Coherent Captain Mills @

Neutrino production at spallation sources

The plot shows Background rejection factor (μ dk) versus Total neutrino flux at 20 m (cm^{-2} s^{-1}), with a legend:

- LANSCE Area A: 0.77 GeV, 0.8 MW
- ISIS: 0.75 GeV, 0.16 MW
- BNB: 8 GeV, 0.032 MW
- MLF: 3 GeV, 1 MW
- Lujan: 0.8 GeV, 0.08 MW
- ESS: 2 GeV, 5 MW
- Daedalus: 800 MeV, 7 MW
- SNS FTS: 1.01 GeV, 1.4 MW
- SNS FTS upgrade: 1.3 GeV, 2 MW
- SNS STS: 1.3 GeV, 0.7 MW
- SNS STS+FTS: 1.3 GeV, 2.8 MW
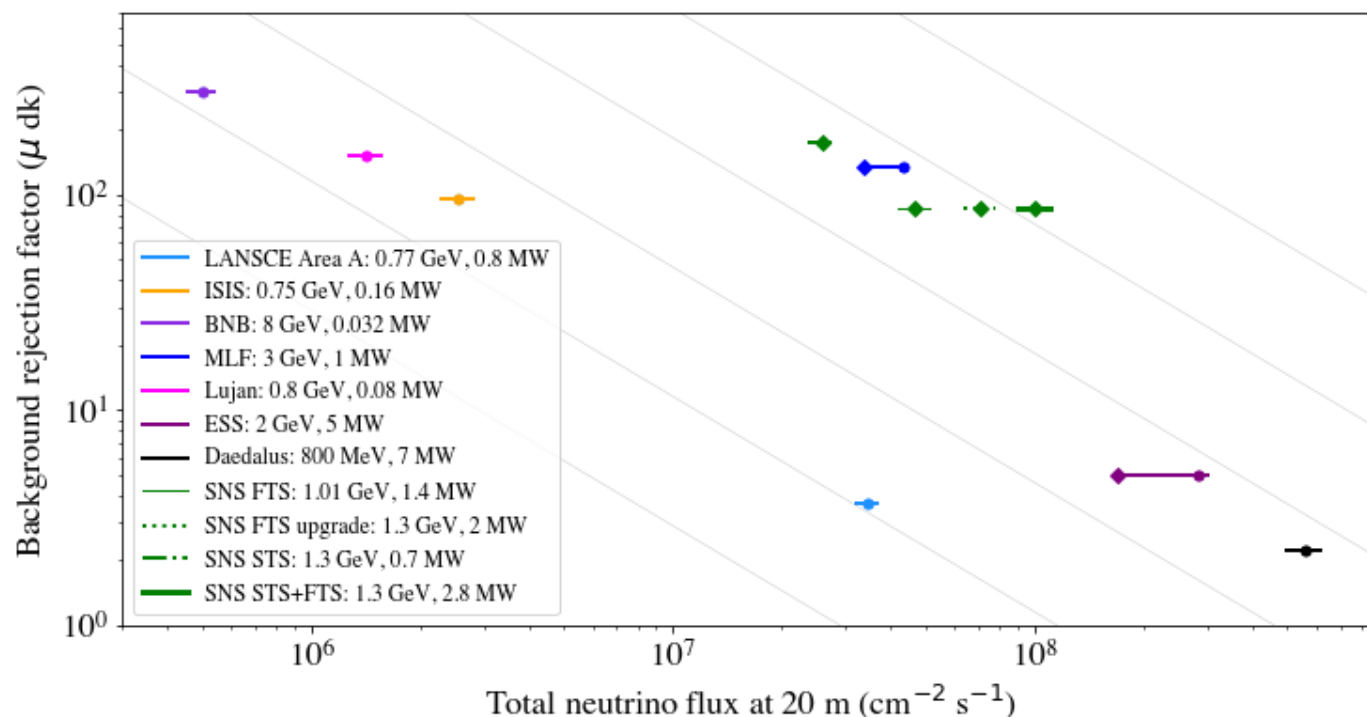
❑ For selecting a source, we want

- High beam power → faster accumulation of signal
- Low duty factor → improved background rejection through beam pulsing

❑ With power upgrades and construction of the STS, the SNS will be the most effective machine for studying CEvNS

- Further SNS timing (350 ns FWHM) is ≪ the muon lifetime allowing separation of neutrino flavors

The COHERENT CsI[Na] detector

A hand-held neutrino detector
– Built at U Chicago
– 14.6-kg CsI[Na] crystal
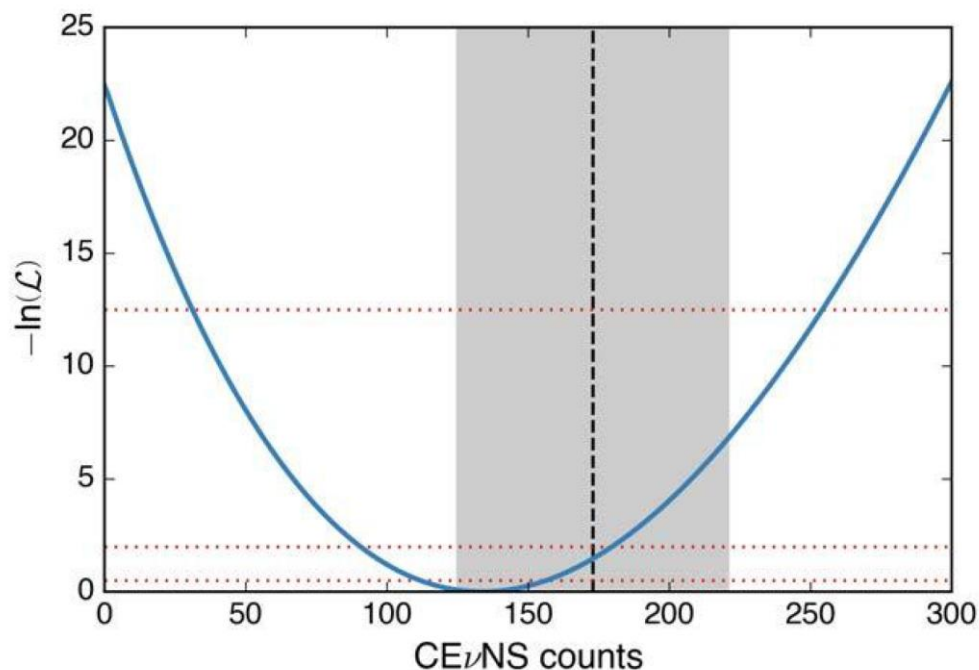– Manufactured by Amcrys-H
– Single R877-100 PMT

Shielding design

– Veto to tag cosmic events
– Lead to shield from gammas
– Water and plastic to
  moderate neutrons

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

Detector made first detection of CEvNS (2017)

# First observation of CEvNS with CsI[Na]

Made first observation of CEvNS
– Established the existence of CEvNS to 6.7σ
– 134 ± 22 CEvNS events
– 173 ± 48 CEvNS predicted

Data released publicly, used to study
– neutrino NSI
– new forces
– neutrino magnetic moment
– $\sin^2 \theta_W$ at low-Q^2
– neutrino charge radius
– nuclear weak charge distribution
– + more

Timing of scintillation in CsI[Na]

CsI has a high light yield and low background, but afterglow photons can be troublesome

- CsI can scintillate for up to 1 s following a large energy deposit within the crystal

The afterglow rate in Na-doped CsI is low enough to allow a search for small, few keV nuclear recoils associated with DM and CEvNS scatters

Collar et al., NIM A773 56 (2016)
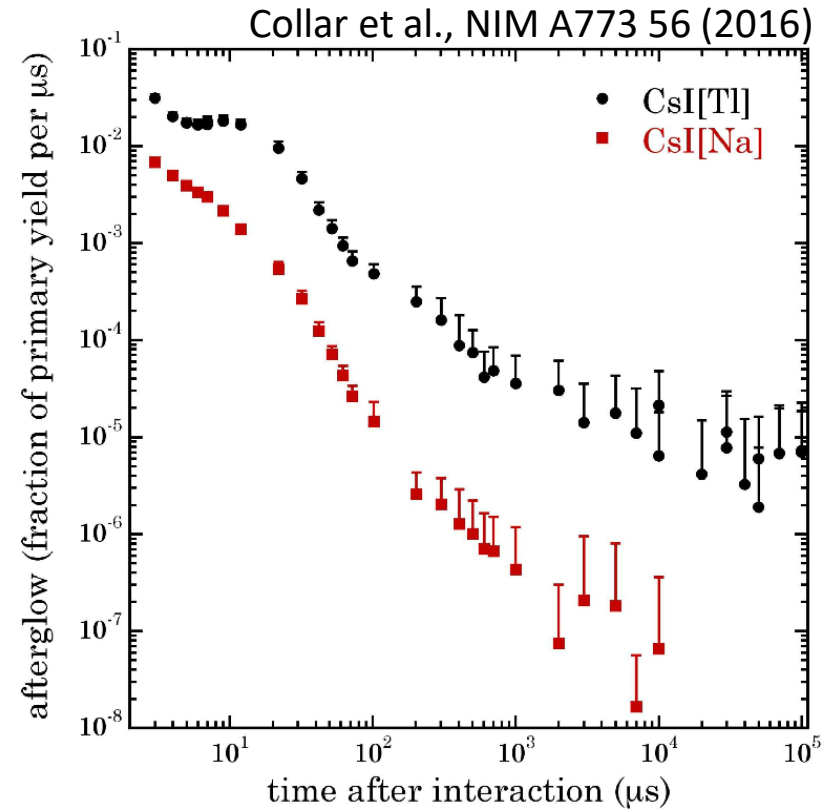
Scintillation response of the crystal to nuclear recoils
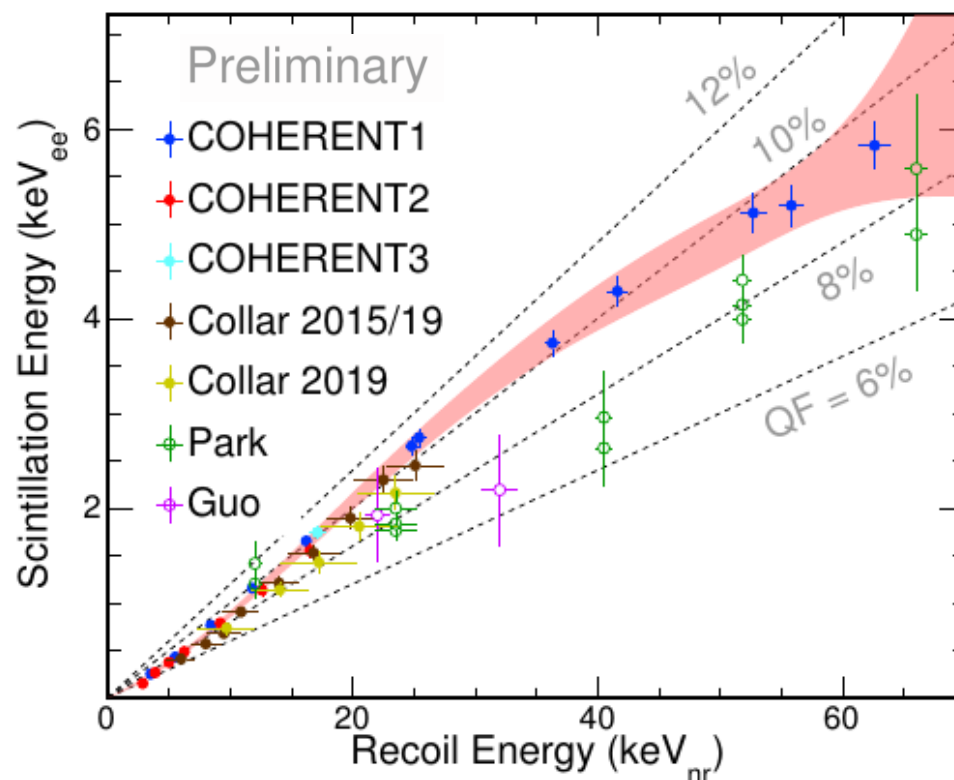
☐ Only a fraction of the struck nucleus's kinetic energy, E_{nr}, goes into scintillation energy, E_{ee}

☐ There are five separate measurements of the scintillation response using CsI[Na] grown by the same manufacturer used for our detector

- Empirically model $E_{ee}(E_{nr})$ as a fourth order polynomial with $E_{ee}(0) = 0$ and fit to the global data

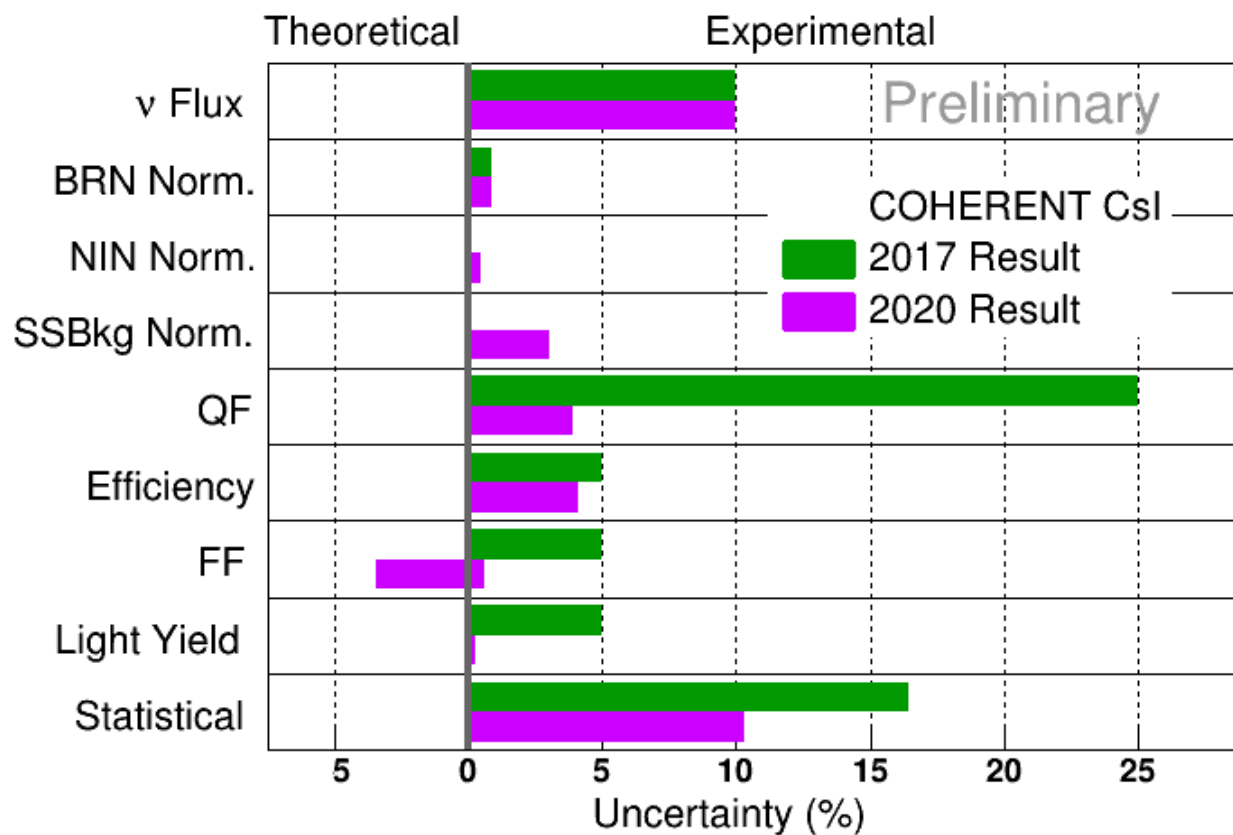# Calibrating the CsI[Na] detector
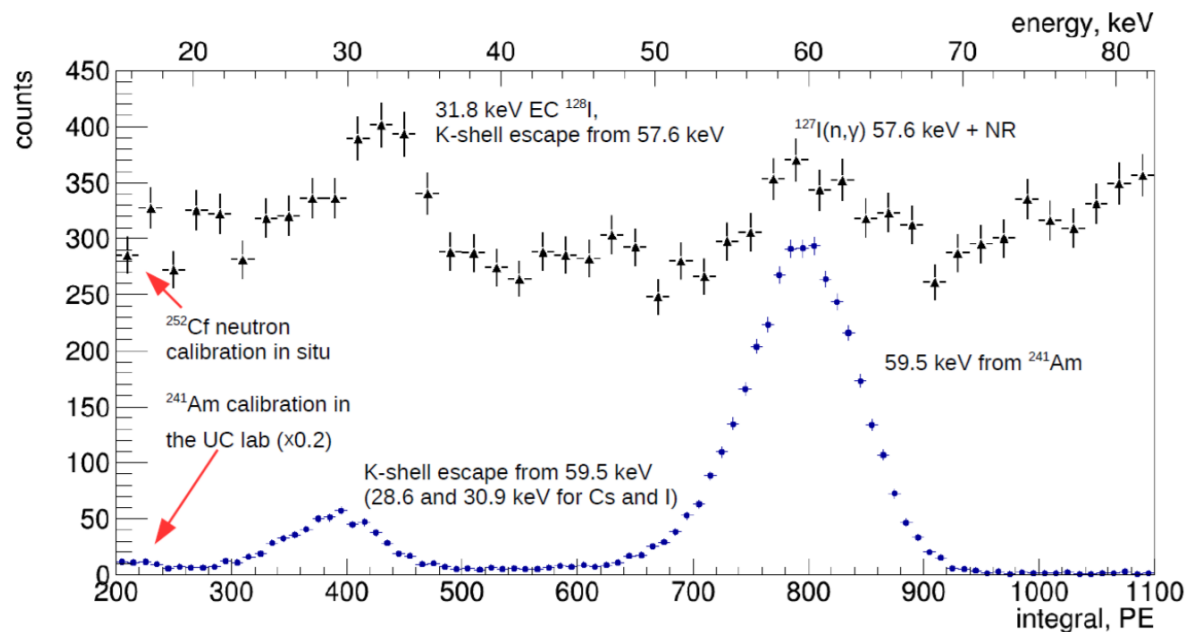
□ **Detector calibrated**
  - 59.5 keV gamma using ^{241}Am decay calibration source
  - 57.6 keV ^{127}I(n,γ) peak using a ^{252}Cf neutron source

□ **A 13.35 photon / keV light yield is achieved**
 - LY uniformity across crystal shown to be everywhere within 3%

□ **Single PE charge monitored during data collection using accidental peaks**

Measurement Uncertainties

- Re-assessed all systematic uncertainties

- Huge improvement to QF error from newly available data, better model and fit strategy

- Neutrino flux normalization now dominates our cross section uncertainty

- Overall precision improves 33% → 16%

Neutron Backgrounds in CsI[Na]
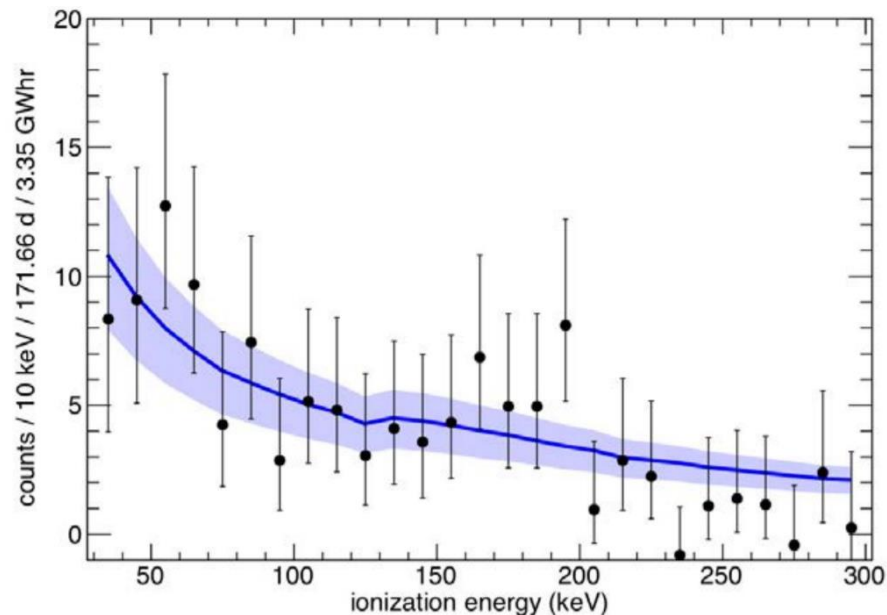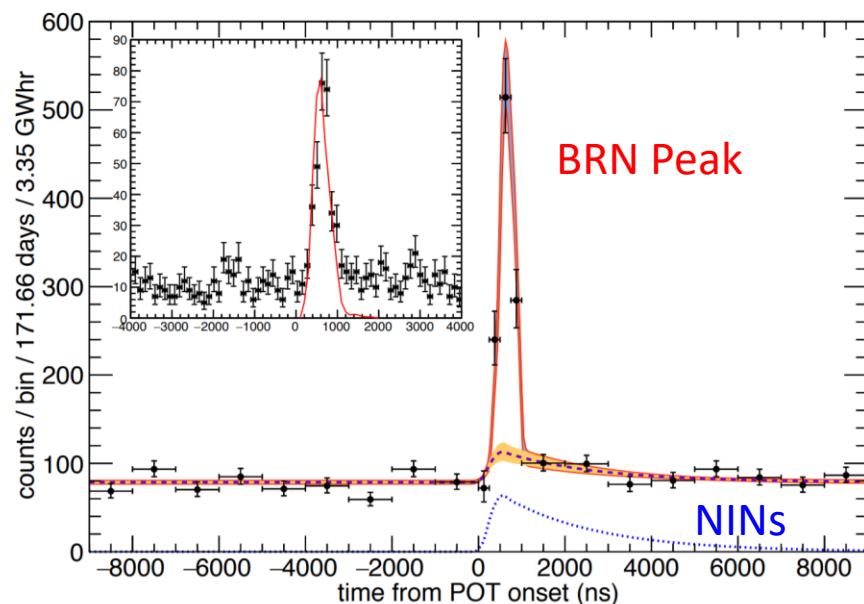
- ❑ Ran Eljen cell scintillator in CsI shielding to study neutron backgrounds in detector location
- ❑ Fit to timing data gives the relative ratio of BRN and NIN events with uncertainties
- ❑ MCNP simulation predicts the observed recoil distribution very well in the Eljen cells
- ❑ Ran observed neutrino flux through CsI simulation to determine analysis backgrounds
  - • Together, only 7% of signal

Predicted excess in our sample
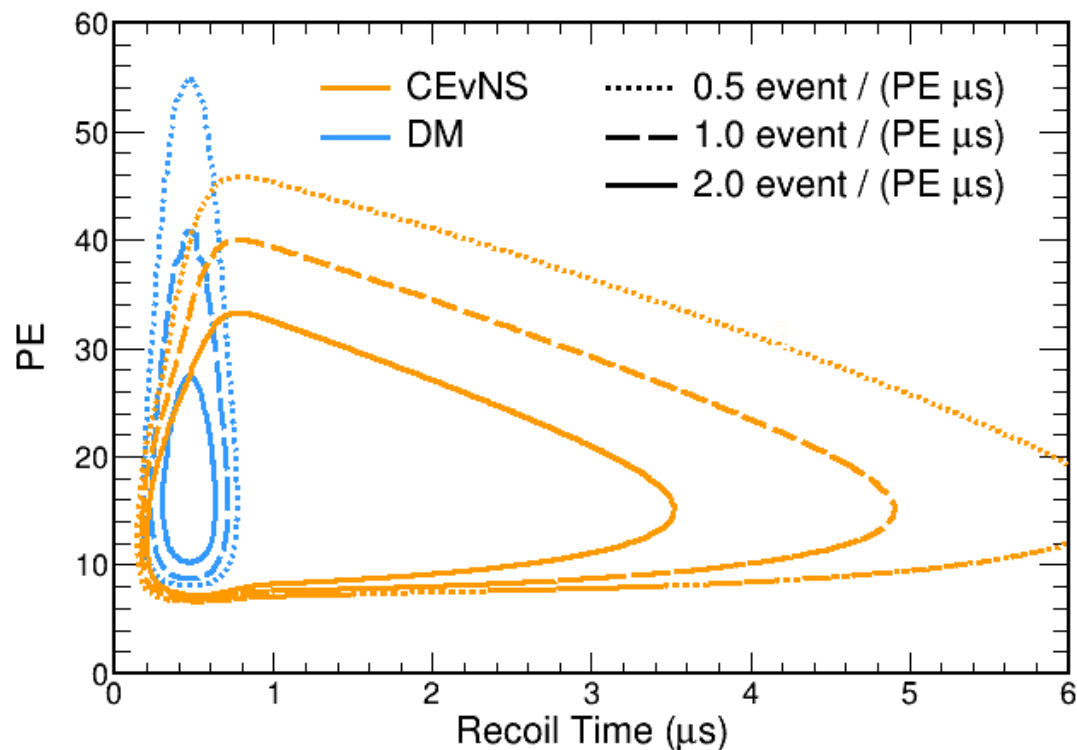
❑ If there is DM in the SNS beam, it would give an additional population of nuclear recoils at times coincident with the arrival of the beam

❑ The recoil distributions are also different – though most of our sensitivity comes from CEvNS/DM overlap region

❑ 2D fit to data for these two signals will give an estimate of DM produced at the SNS

Less conservative scenarios: lowering α_D
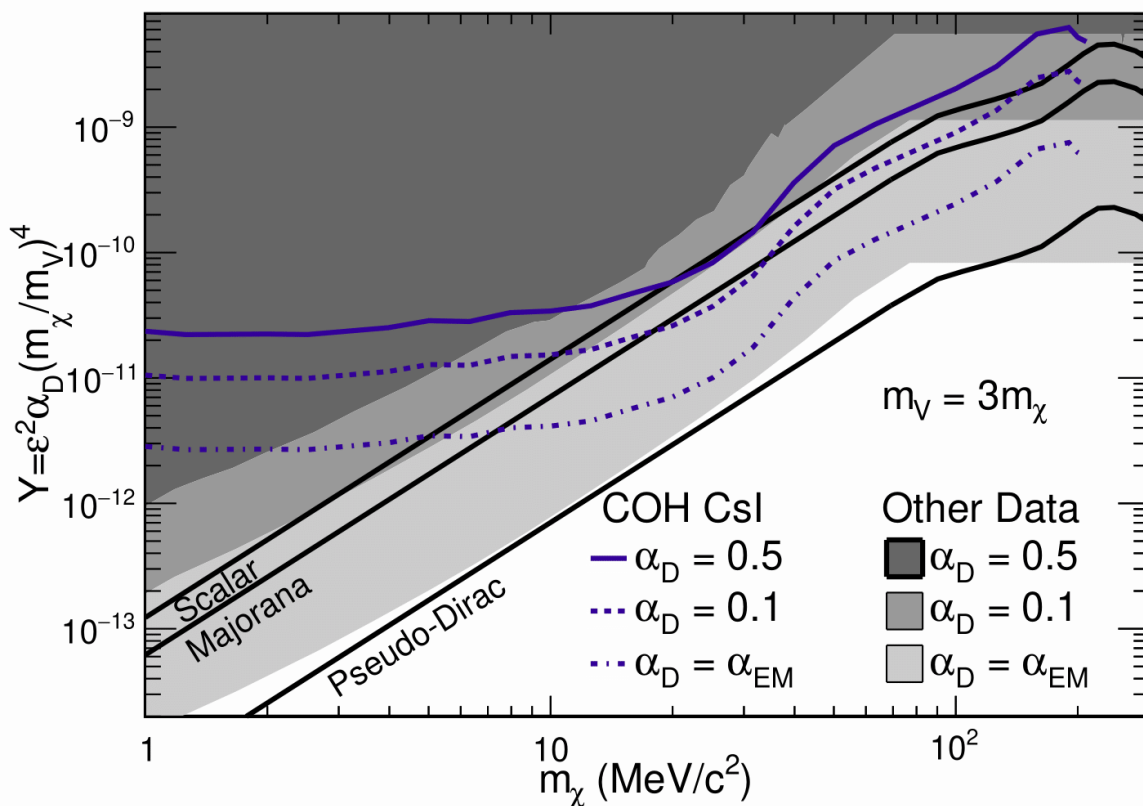
- ❑ Our dark matter model has two couplings: ε and α_D
  - Complicates parameter space since our relic abundance depends on $Y \propto \varepsilon^2 \alpha_D$

- ❑ Our contour depends on our assumption of α_D – smaller values give tighter constraints

- ❑ $\alpha_D = 0.5$ is the largest, most conservative assumption before perturbative effects important

Future COHERENT dark matter detectors at FTS

□ COH-Ge-1: 18 kg of Ge PPC detectors

□ Low threshold, ∼ 0.2 keV$_{ee}$, improves sensitivity at low masses

□ Funded with NSF MRI, detector commissioning late 2022

782kg TOTAL
0.561m^3
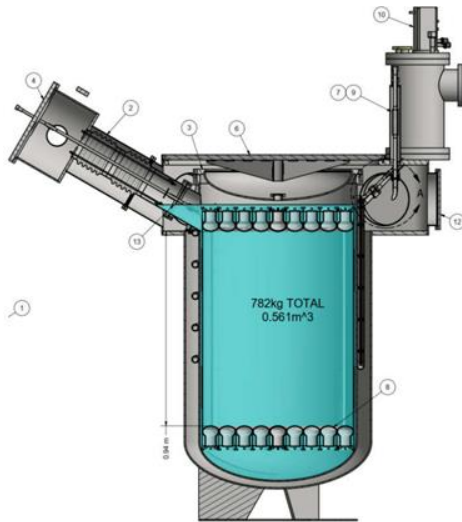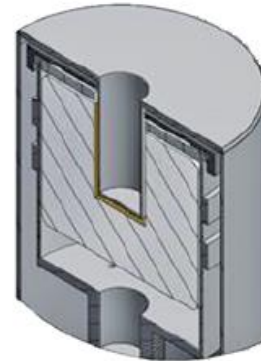
□ COH-Ar-750: next-generation argon scintillator

□ Large 610-kg fiducial volume

□ Preliminary plans for 10-t argon detector at the STS placed forward from beam exploiting DM flux directionality

□ COH-CryoCsI-1: future 10-kg, undoped CsI scintillator

□ Crystals cooled to 40 K, significantly reducing afterglow scintillation while improving overall light yield

□ With low threshold and high Z, small detector has very favorable sensitivity

Chernyak et al., Eur. Phys. **C80** 547 (2020)
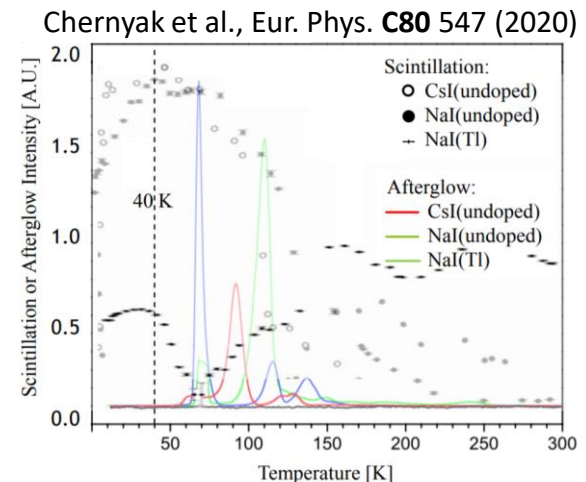
Searching for leptophobic dark matter

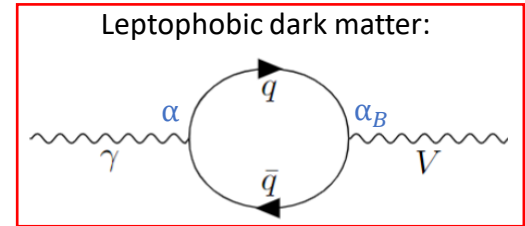□ Above model assumes a general BSM kinetic mixing between photon and portal particle

General kinetic mixing:
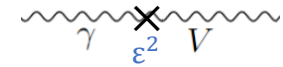
□ Leptophobic dark matter: it is also possible that light dark matter preferentially interacts with quarks – leptophobic DM: a specific case of general model

- Interaction Lagrangian: $\mathcal{L} \sim \sqrt{4\pi\alpha_B} V^\mu \sum_q \bar{q}\gamma_\mu q$

Leptophobic dark matter:

□ Differences in terminology, $\alpha\alpha_B$ analogous to kinetic mixing parameter, ε^2

□ Experiments sensitive to coherent nuclear scattering well suited for searching for this DM

□ Lepton scattering experiments unable to probe Vqq coupling, COHERENT data more unique

- E.g.: LDMX, BDX, NA64, electron-recoils in direct detection