Title: Searching for accelerator-produced dark matter particles and other BSM signatures with the COHERENT CsI[Na] detector

Speakers: Daniel Pershey

Series: Particle Physics

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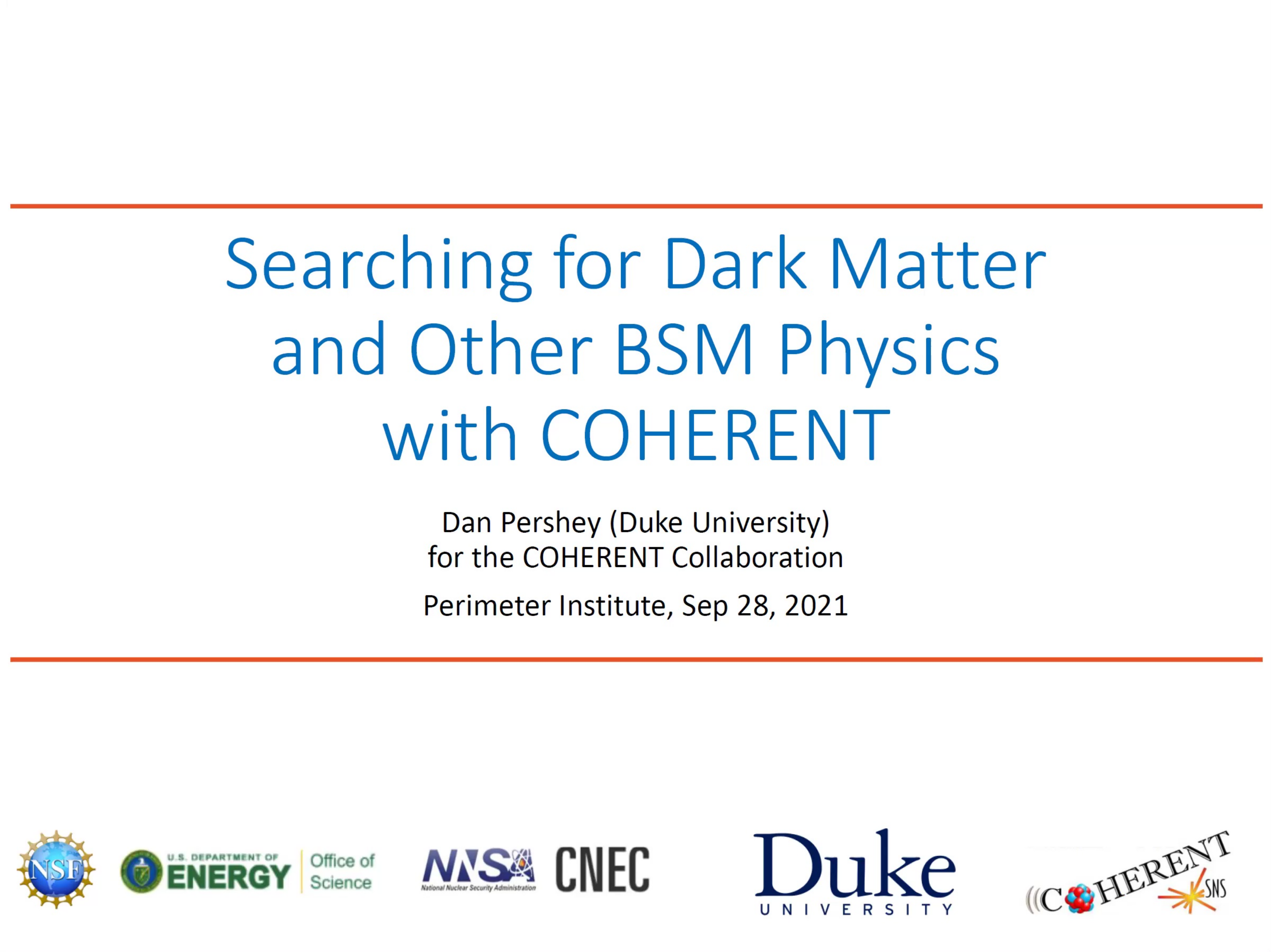
Abstract: The COHERENT collaboration made the first measurement of coherent elastic neutrino nucleus scattering(CEvNS) in 2017 using a low-background, 14.6-kg CsI[Na] detector at the SNS. Since initial detection, this detector has opened a new era of precision CEvNS measurements by doubling the detector exposure and improving understanding of the detector response. We these improvements, we now use CsI[Na] data to make competitive constraints of beyond-the-standard-model physics.

We will focus on our recent search for dark matter particles produced at the SNS. With our experience measuring CEvNS, we are sensitive to analogous coherent dark matter induced recoils in our detector. This is a novel approach for accelerator-based dark matter experiments. Searching in this channel is also very powerful, allowing relatively small detectors to explore new parameter space inaccessible to much larger detectors. We will briefly discus other BSM opportunities with COHERENT, showing current results from CsI[Na] along with future sensitivity.



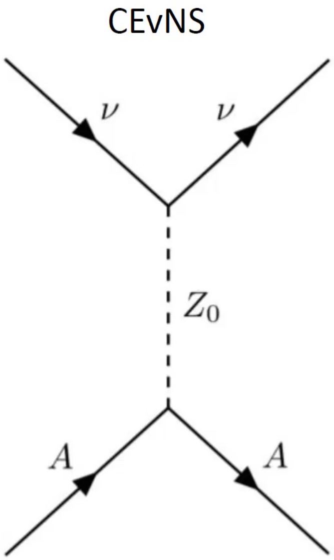
Searching for Dark Matter and Other BSM Physics with COHERENT

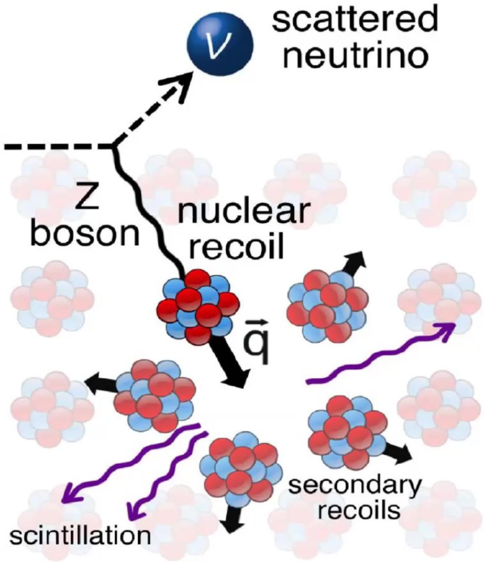
Dan Pershey (Duke University)
for the COHERENT Collaboration

Perimeter Institute, Sep 28, 2021

NSF U.S. DEPARTMENT OF ENERGY Office of Science NNSA National Nuclear Security Administration CNEC Duke UNIVERSITY COHERENT SNS

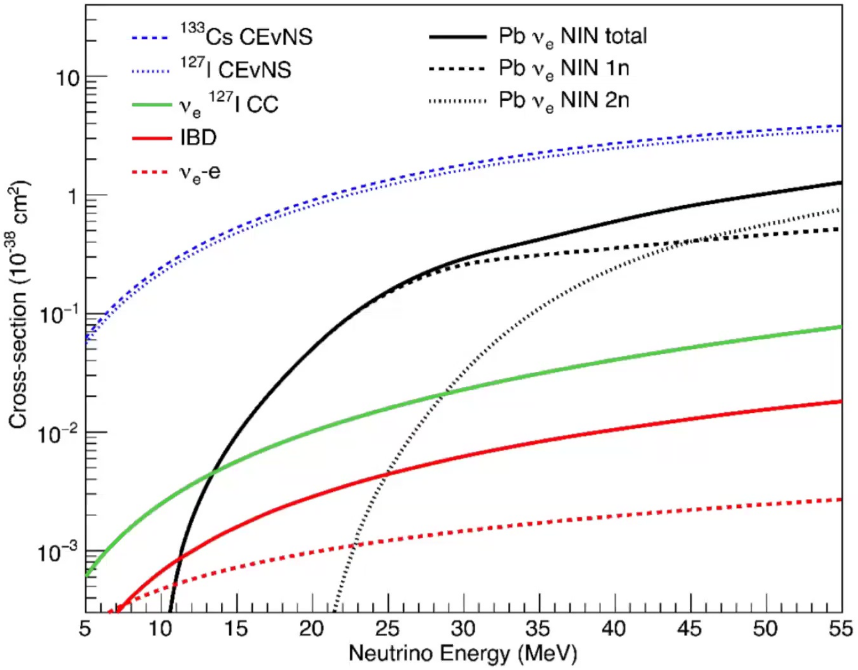
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)





- ❑ CEvNS is a neutral current scattering process off nuclei with a momentum transfer so low, the nuclear state is preserved
- ❑ Only experimental signature is small kinetic energy transferred to the struck nucleus
  - The max recoil energy is $2E_\nu^2/M$, 15 keV for CsI at 30 MeV
- ❑ Detector with low threshold and high flux critical to CEvNS measurements

CEvNS cross section



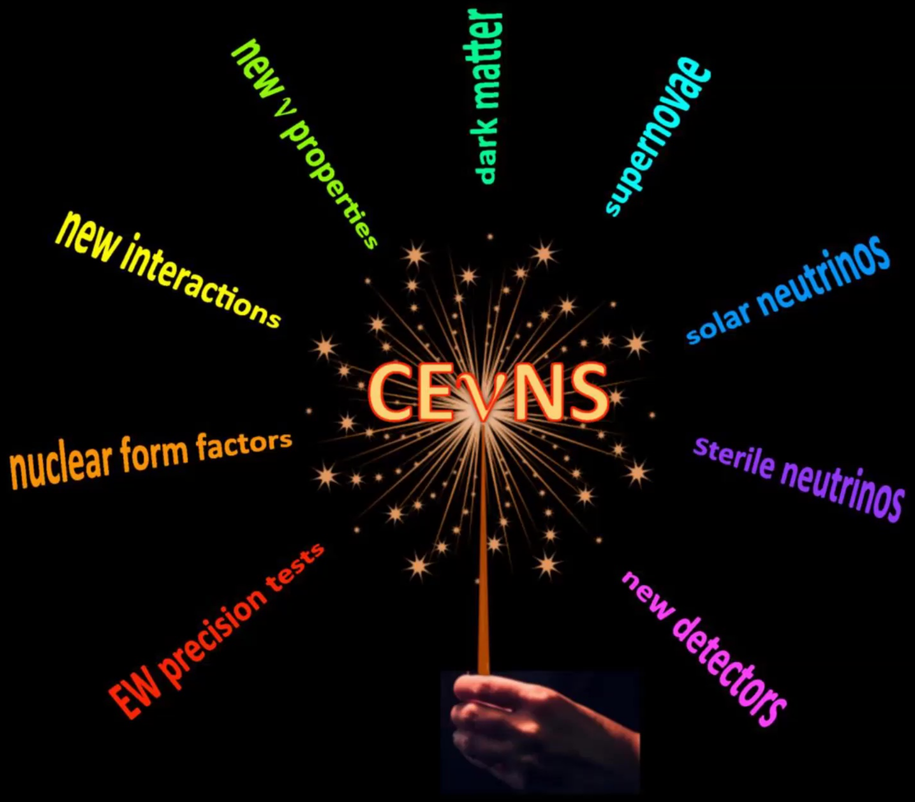
- The process is coherent which gives a large cross section, roughly scaling with the square of the number of neutrons

$$\sigma \approx \frac{G_F^2}{4\pi}(N - (1 - 4\sin^2\theta_W)Z)^2 E_\nu^2$$

- Very large cross section, compared to low-energy neutrino processes
  - Measurements within reach of kg-scale detectors

First measurements by COHERENT in 2017 with CsI[Na] – full exposure dataset today

Why measure CEvNS?



CEνNS

new ν properties

dark matter

supernovae

solar neutrinos

sterile neutrinos

new detectors

EW precision tests

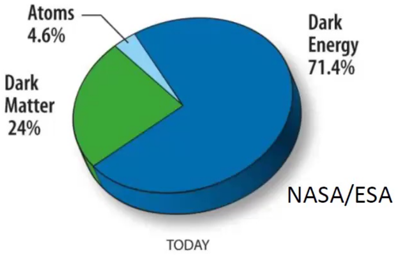
nuclear form factors

new interactions

E Lisi, Neutrino
2018

Dark matter in our universe

❑ Dark matter (DM) accounts for 85% of matter in our universe
  - Its existence is apparent from several methods: galactic rotation curves, the cosmic microwave background, and gravitational lensing
  - DM is new physics we know about – just need to know where to look
  - COHERENT data gives powerful constraints for DM with masses 1 to 220 MeV – parameters space not covered by astroparticle methods



NASA/ESA

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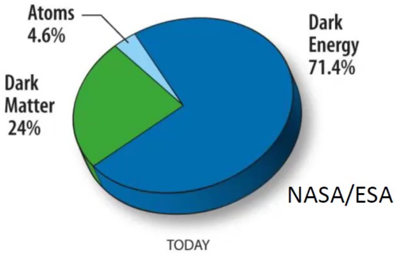

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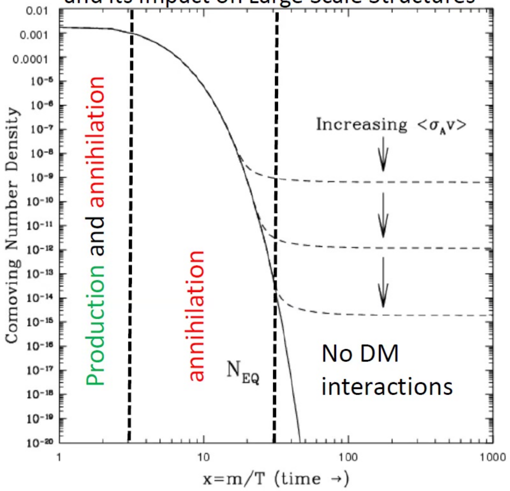
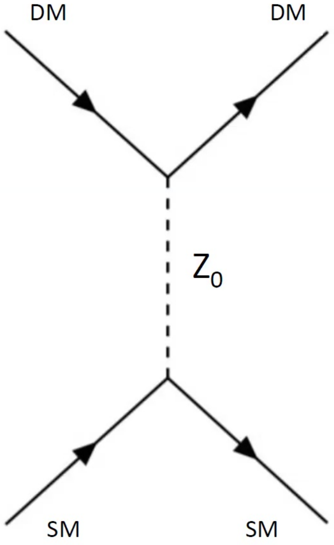
Chatterjee: Dark Matter Self Interaction and its impact on Large Scale Structures



- We search for standard DM with popular "freeze-out" cosmology
  - In the early universe, DM in equilibrium with SM particles with production and annihilation
  - DM production by SM particles quenches as universe cools
  - Inflation will then stop DM annihilation to SM particles as concentration dwindles
- Inverse relationship – larger DM cross section gives smaller relic abundance in modern universe
- For given DM mass, we can predict DM cross section from observed relic abundance

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 close the universe, preventing modern the universe



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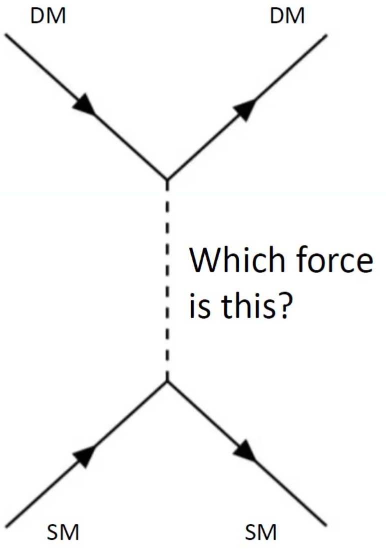
  - If $m_\chi < 2$ GeV/c^2, predicted relic abundance would be so large it would close the universe, preventing modern the universe
- No longer assume DM interacts with SM particles via the weak force, but some yet unknown hidden sector particle, V
- In this scenario, $\sigma \sim m_\chi^2/m_V^4$ which is consistent with modern cosmology even at low mass scales
- Simplest scenario postulates 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 $Y = \varepsilon^2\alpha_D\left(m_\chi/m_V\right)^4$



Which force is this?

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)

Searching for BSM interactions with CEvNS

- CEvNS is sensitive to non-standard interactions (NSI) between neutrinos and quarks mediated by some heavy (> 50 MeV/c^2), undiscovered particle
- Generally parameterized by coupling constants: $\varepsilon^{N}_{\alpha\beta}$ $(\alpha, \beta \in e, \mu, \tau)$

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

Barranco et al., JHEP 12 021 (2005)

- NSI scenarios would scale the observed CEvNS rate and several ε parameters are only constrained at ~ unity
    - ε_{ee} / $\varepsilon_{\mu\mu}$ / $\varepsilon_{\tau\tau}$ break flavor universality predicted by the standard model (at tree level)
    - $\varepsilon_{e\mu}$ / $\varepsilon_{e\tau}$ / $\varepsilon_{\mu\tau}$ change neutrino flavors
- NSI would affect our interpretation of neutrino oscillation data from long-baseline neutrino oscillation results from experiments like NOvA and DUNE which CEvNS data can resolve
    - CEvNS can resolve these measurements of the CP violating angle and neutrino mass ordering

Δm^2_{32}: Coloma et al., PRD 94 055005 (2017)
δ_{CP}: Denton et al., arXiv:2008.01110 (2020)
θ_{12}: Coloma et al., PRD 96 115007 (2017)

The Spallation Neutron Source at ORNL
+ Neutrinos + Dark Matter

- 1.4 MW proton beam on mercury target at T_p = 1.01 GeV
- Pulse width is 340 ns FWHM at 60 Hz, reducing backgrounds by a factor of ~3×10^4 from beam pulsing

- Opportunistic neutrino program expands fundamental physics reach of the SNS
- Possible production of dark matter / hidden sector particles widens list of BSM opportunities

Future beam improvements at the SNS

❑ Two staged improvement to the beam

1: Proton Power Upgrade

- Increases the power of neutron beam 1.4 → 2.8 MW
- Feasibility of a second target station

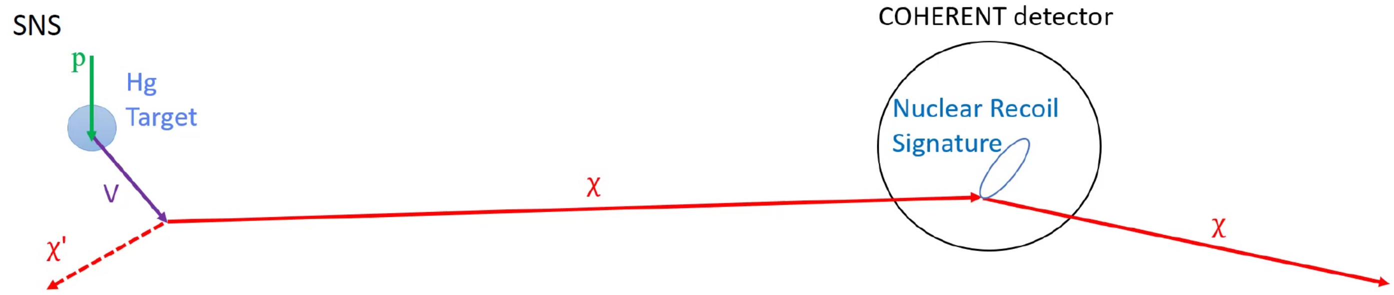
2: Second Target Station

- Implements a second beamline at the accelerator

❑ Expected completion ≈2030s

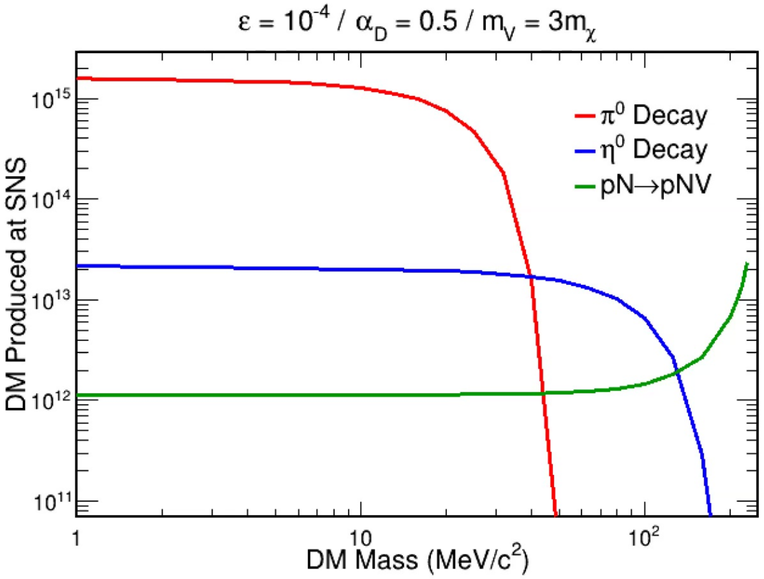
❑ Interest from the lab to design STS to accommodate a specialized detector hall for neutrino measurements capable of fitting a 10-t detector

Making DM at the SNS



- ☐ Any hidden sector particles with masses below ≈ 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
- ☐ 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

DM production channels



❑ Our expected dark matter flux is produced through three channels

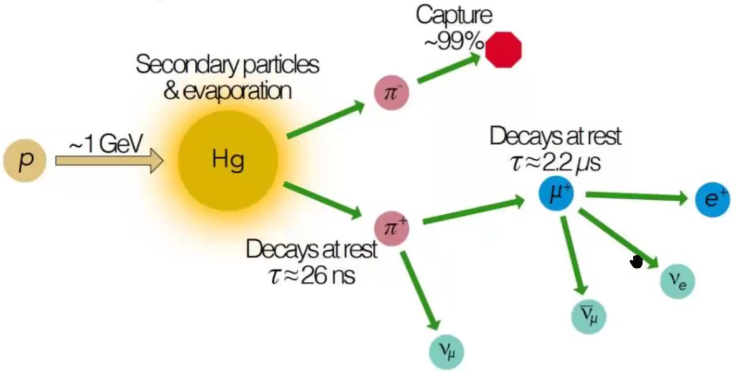
- $\pi^0 \to V\gamma$ decay: dominant channel where kinematically allowed, $2m_\chi < m_\pi$,
- $\eta^0 \to V\gamma$ decay: similarly only contributes for $2m_\chi < m_\eta$
- $pN \to pNV$ bremsstrahlung: only dominant at high energies and rate increases significantly at the ρ resonance, $m_V \approx m_\rho$

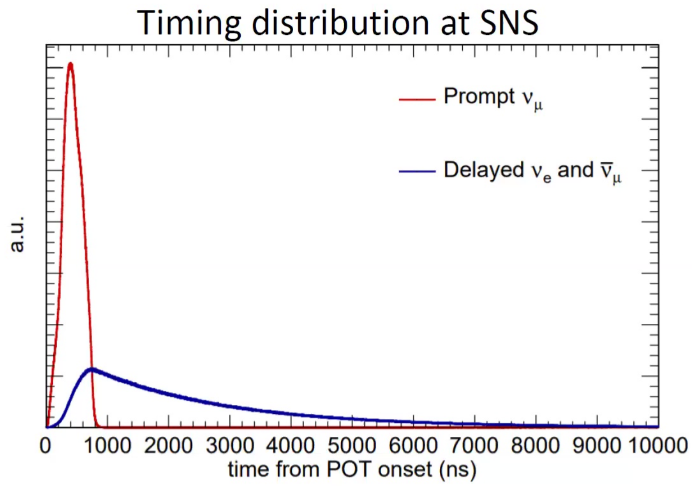
Neutrino flux at the SNS

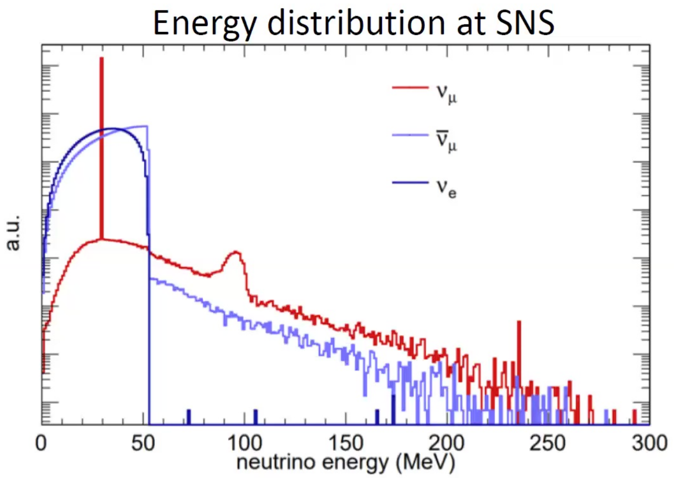
- ❑ Low energy pions are a natural by-product of SNS running
  - π^+ will stop and decay at rest

    $\pi^+ \rightarrow \mu^+ + \nu_\mu$: $\tau = 26$ ns

    $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$: $\tau = 2200$ ns
  - Flux includes three flavors of neutrinos → can test flavor universality as a BSM signature
- ❑ Flux shape is very well known and very small contribution from decay in flight at the SNS




Timing distribution at SNS


Energy distribution at SNS

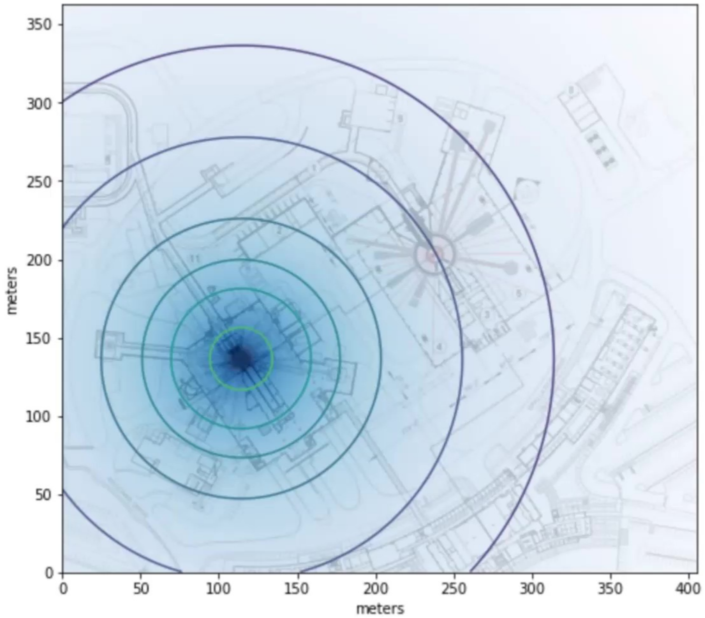
Directionality of flux at the SNS

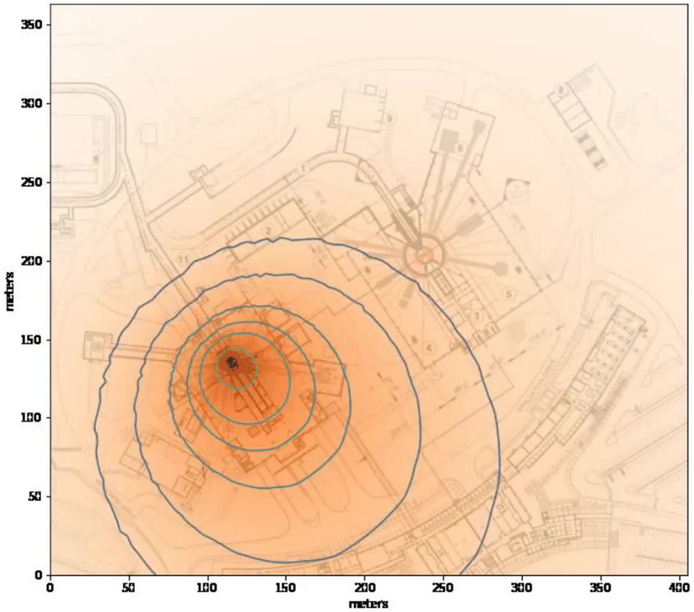
Neutrino flux produced at rest – isotropic

Largest beam-related background for DM searches at the SNS

DM produced in-flight – is boosted

A forward-directed detector would optimize DM / background



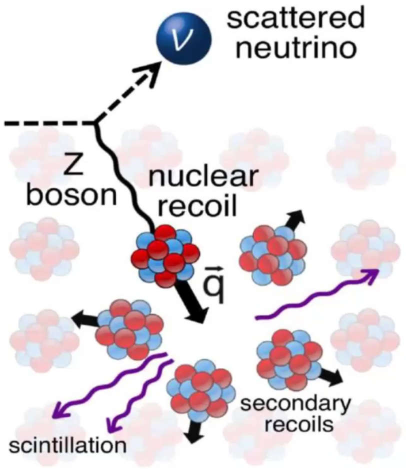


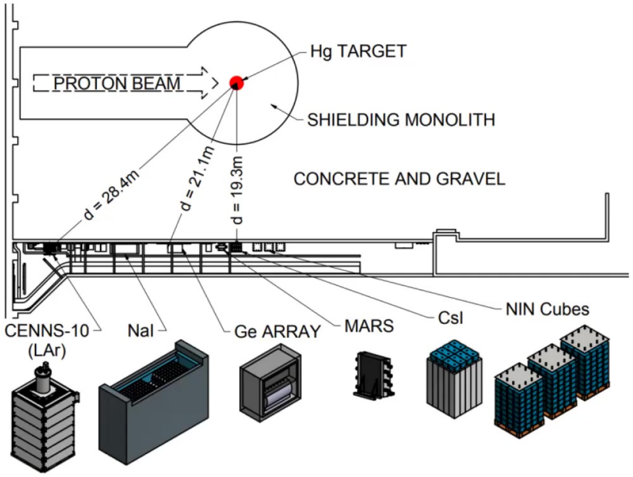
- ☐ After STS is built, both targets will operate with 3(1)/4 bunches sent to FTS (STS)
- ☐ If DM is in this mass regime, SNS very advantageous – a single detector monitors DM flux from two beams allowing confirmation of the expected angular dependence of the flux

The COHERENT collaboration at the SNS

The COHERENT experiment

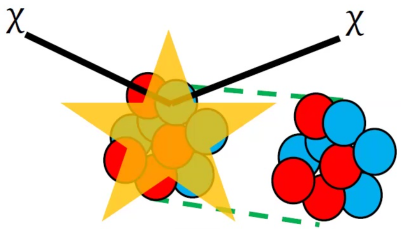
- ❑ COHERENT formed to search for Coherent Elastic Neutrino-Nucleus scattering (CEvNS)
- ❑ Only visible signature is low-energy nuclear recoil
  - Need low-threshold detectors now possible due to innovation in instrumentation achieved for astroparticle DM experiments
- ❑ Made first detection of CEvNS in 2017
  - New results on CsI and Ar, with detectors studying Ge and Na commissioning this year





- ❑ Many detectors installed in “Neutrino Alley” – a basement hallway with sufficiently low neutron flux for neutrino measurements
- ❑ Multiple scattering targets to test wide range of BSM physics
- ❑ Specialized detectors to study neutron backgrounds

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

Direct-detection experiments searching for light dark matter

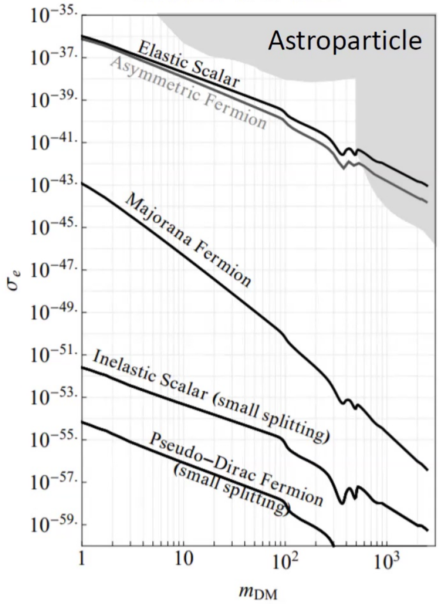
	Mass (t)
LSND	167
MiniBooNE	450
COHERENT CsI	0.0146

- ❑ This coherency gives a Z^2 enhancement in the cross section → big effect for CsI (Z of 53/55)
- ❑ Game-changing – investing in a small 14-kg detector can compete with multi-ton detectors

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 $v/c < 0.001$
- Predictions span 20 orders of magnitude

arXiv 1707.04591



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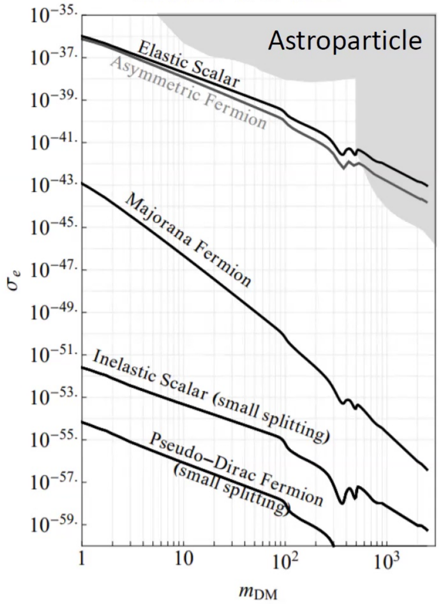

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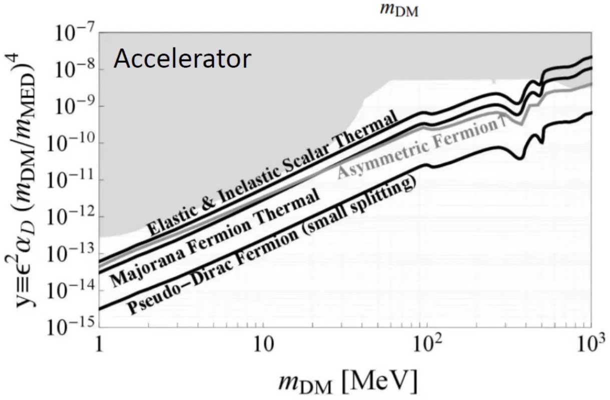
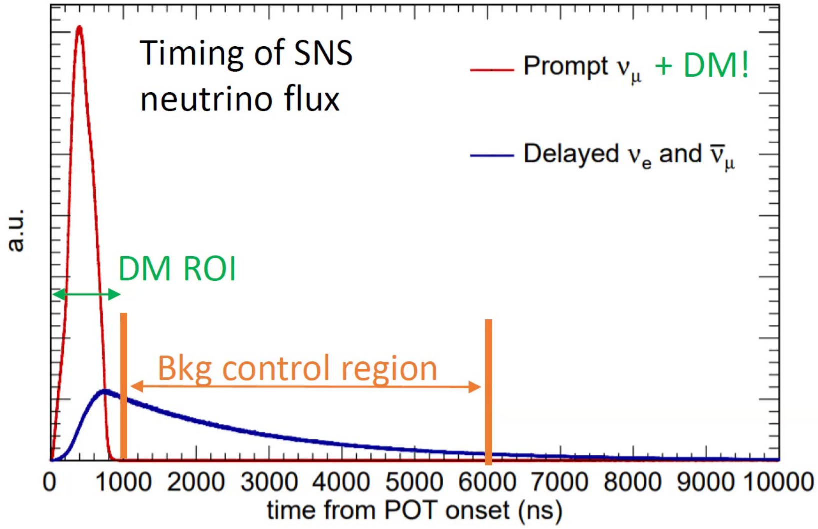


- ❑ At accelerators, DM is relativistic with only a factor of 20 between different expectations
  - Accelerator searches only viable options to test fermionic DM
- ❑ COHERENT gets the best of both worlds
  - Independent of DM particle nature like accelerator methods
  - Large coherent cross section like astroparticle methods

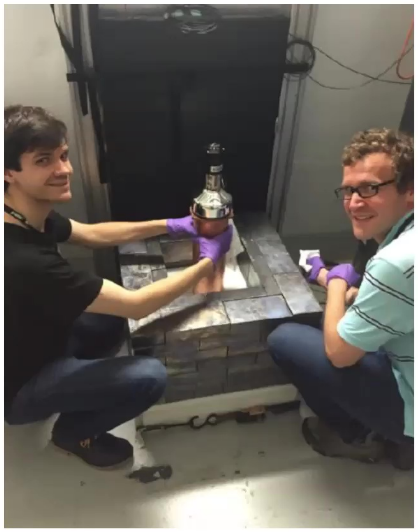
Advantages of spallation sources: constraining uncertainties

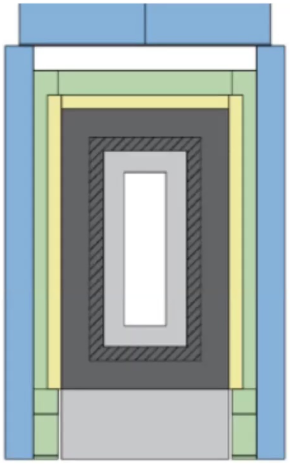


- CEvNS is the principal beam-related background for DM search
  - SM cross section precisely calculated, but uncertainties in detector response unique to each detector
- Since DM is relativistic, it is expected coincident with protons on target
  - No DM coincident with delayed CEvNS from $\upsilon_e/\bar{\upsilon}_\mu$ 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

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



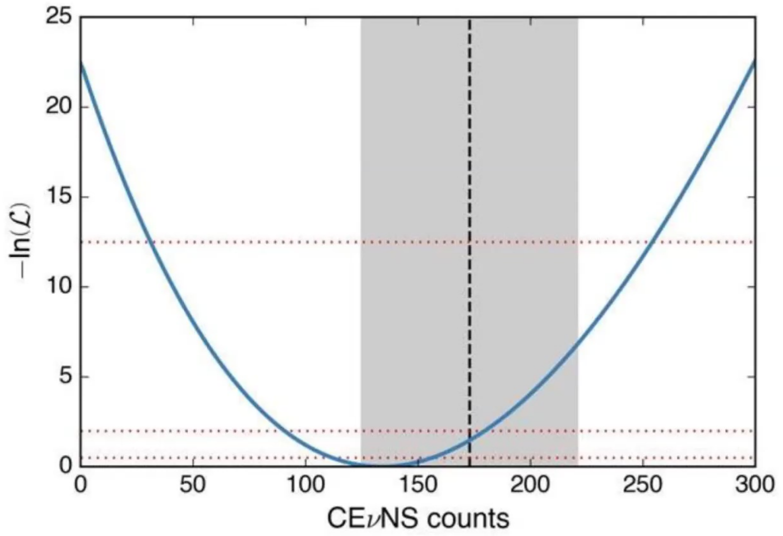


Shielding design

- 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	⬜	▨	⬛	🟨	🟦

First observation of CEvNS with CsI[Na]



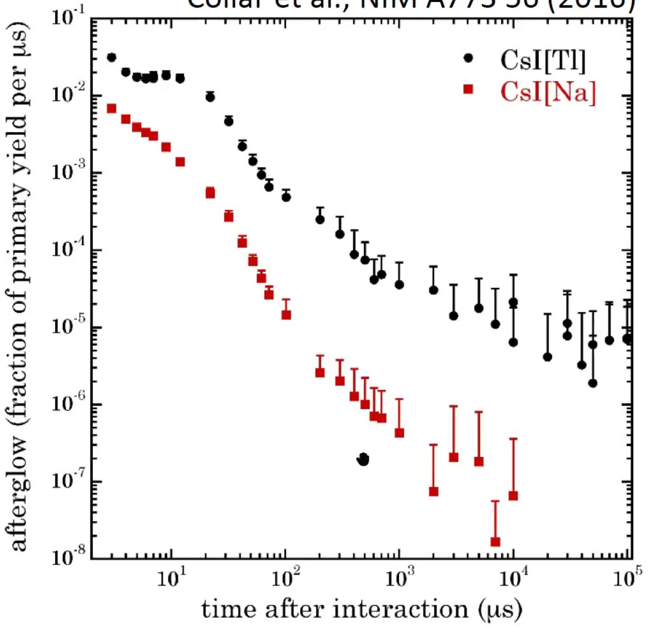
Made first observation of CEvNS
- Established the existence of CEvNS to 6.7σ
- 134 ± 22 CEvNS events
- 173 ± 48 CEvNS predicted

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

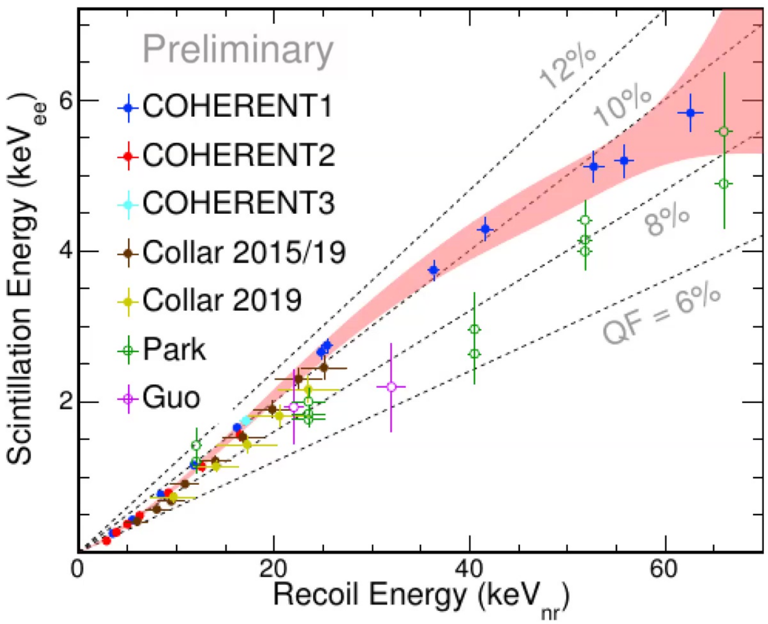
Timing of scintillation in CsI[Na]

- ❑ 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)

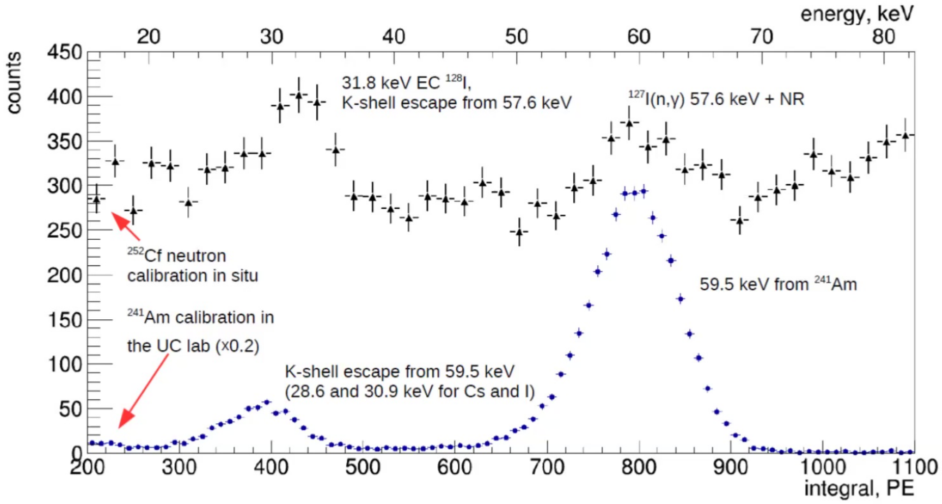


Scintillation response of the crystal to nuclear recoils



- 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

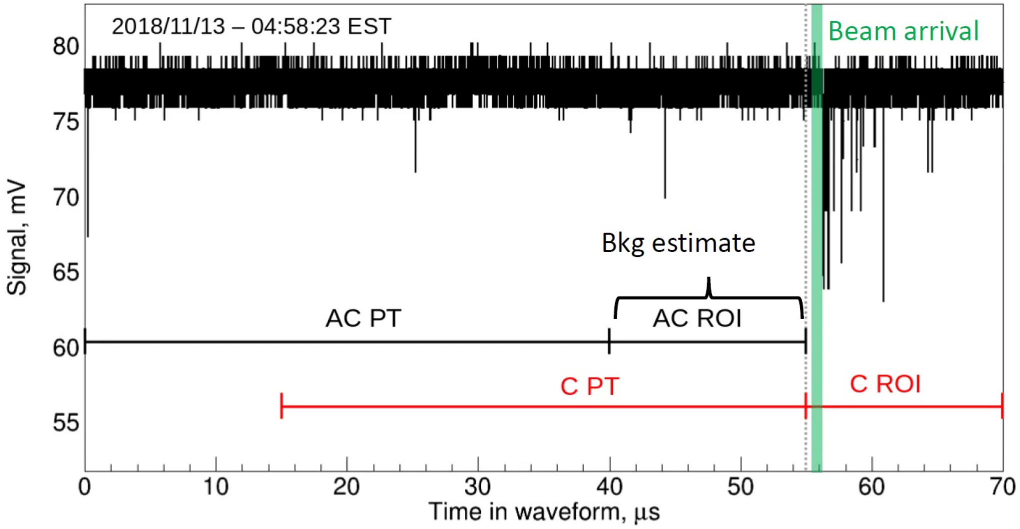


- ❑ Detector calibrated
  - 59.5 keV gamma using ^{241}Am decay calibration source
  - 57.6 keV ^{127}I(n,γ) peak using a ^{252}Cf neutron source

- ❑ 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

Waveform reconstruction

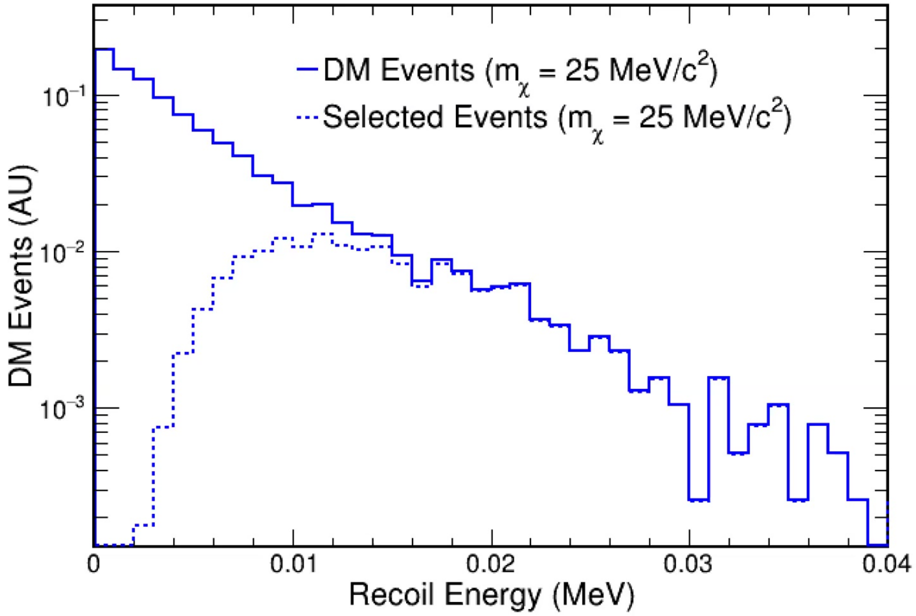


- ❑ Each waveform has a two regions-of-interest: coincident (C) with the beam and anticoincident (AC), immediately preceding the arrival of the beam
  - ROI is 15 µs
  - Each ROI has a 40 µs pretrace region to monitor scintillation activity in the crystal in real-time
  - Event begins with first reconstructed pulse in ROI and has a 3 µs integration window

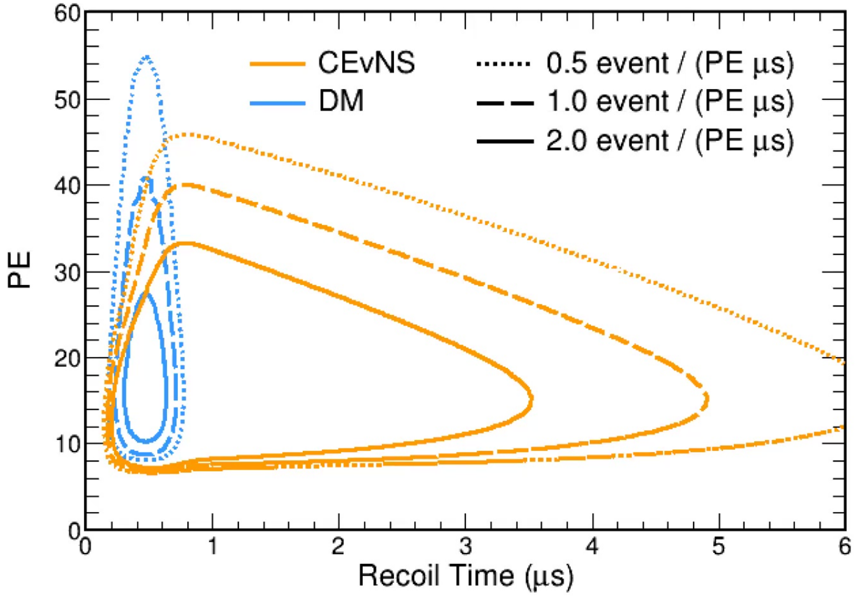
- ❑ AC events give an unbiased in-situ estimate of steady state backgrounds in neutrino alley

Efficiency for expected signal

- ❑ We have a 50% detection efficiency around a threshold of 9 keV_{nr}
- ❑ We expect 21% efficiency at our most sensitive DM mass, 25 MeV/c^2
- ❑ Efficiency curve is well understood from ^{133}Ba calibration data

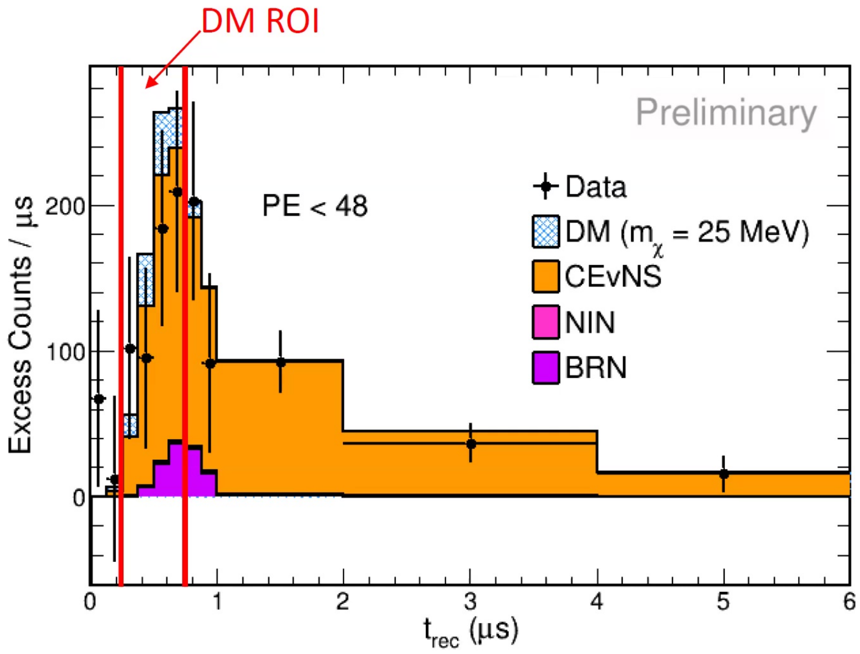


Predicted excess in our sample



- ❑ 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

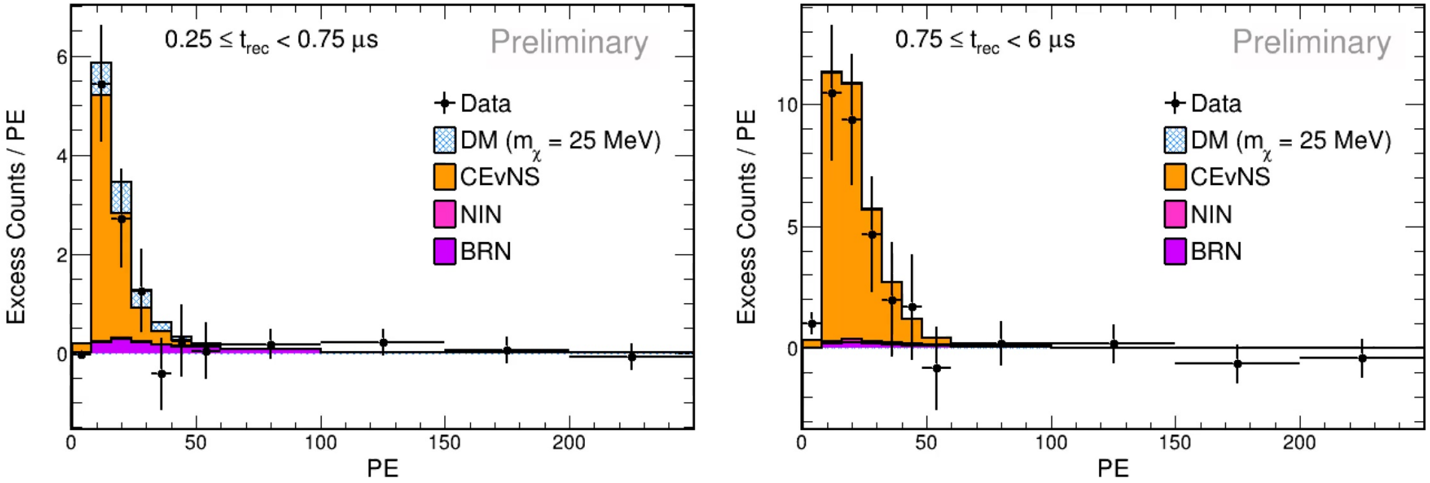
Observed CsI data



	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

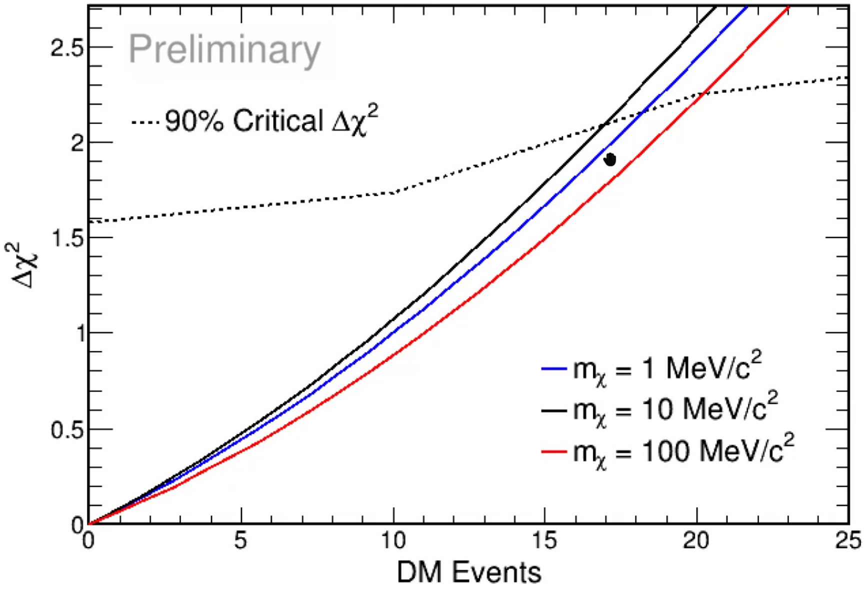
- ❑ Our data is consistent with predictions for the standard-model backgrounds within expected errors
- ❑ In DM signal region, we see a slight deficit relative to the standard-model prediction
  - Doesn’t look like a dark matter signal – best we can do is set a limit
  - DM normalization in plot set to 90% limit from our data

Recoil distribution of 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

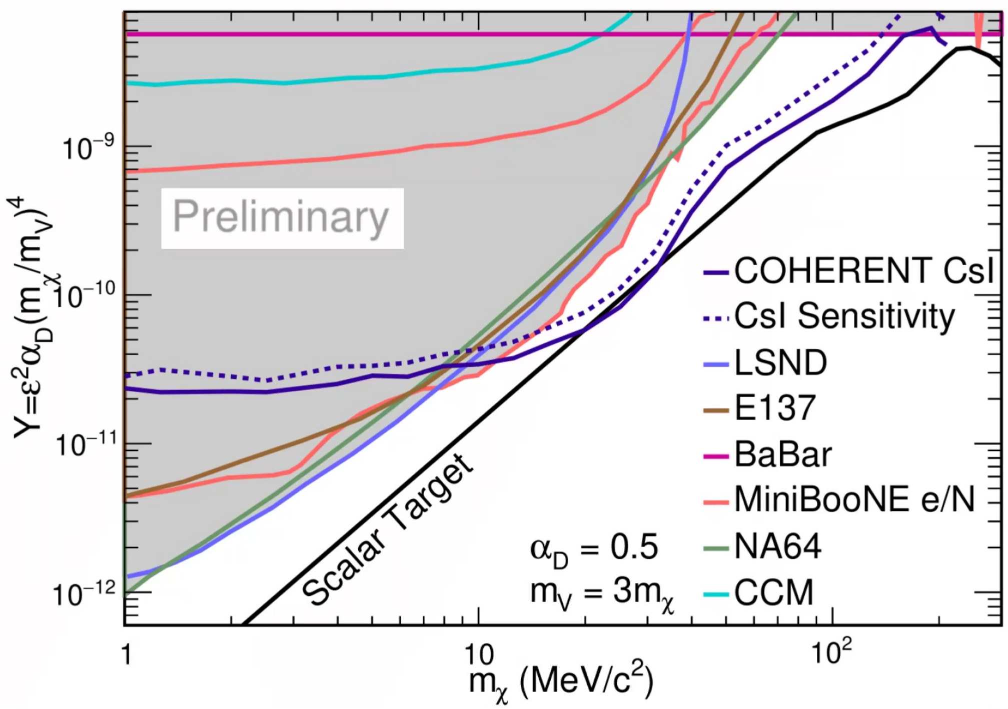
Looking for dark matter in our data



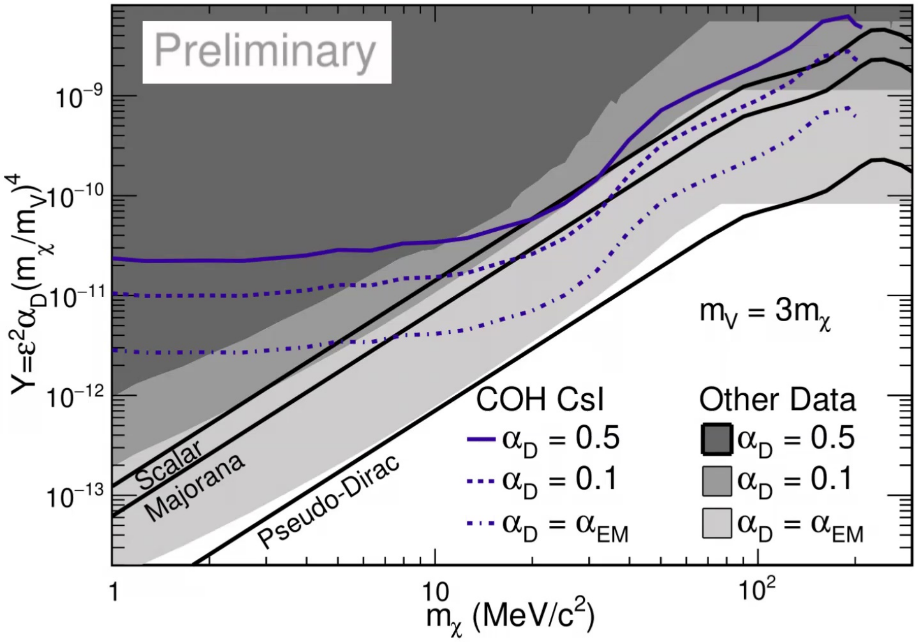
- ❑ No evidence for DM – best fit is $N_{\mathrm{DM}} = 0$ and best we can do is constrain parameter space
- ❑ Since we're near a boundary, $N_{\mathrm{DM}} \geq 0$, we expect non-Gaussian statistics and thus simulate the expected $\Delta\chi^2$ explicitly with the Feldman-Cousins method

COHERENT constraint on sub-GeV dark matter

- ❑ At 90% confidence, CsI data significantly improves on constraints for masses 11 - 165 MeV/c^2
  - 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 – but we can build bigger promising a bright future

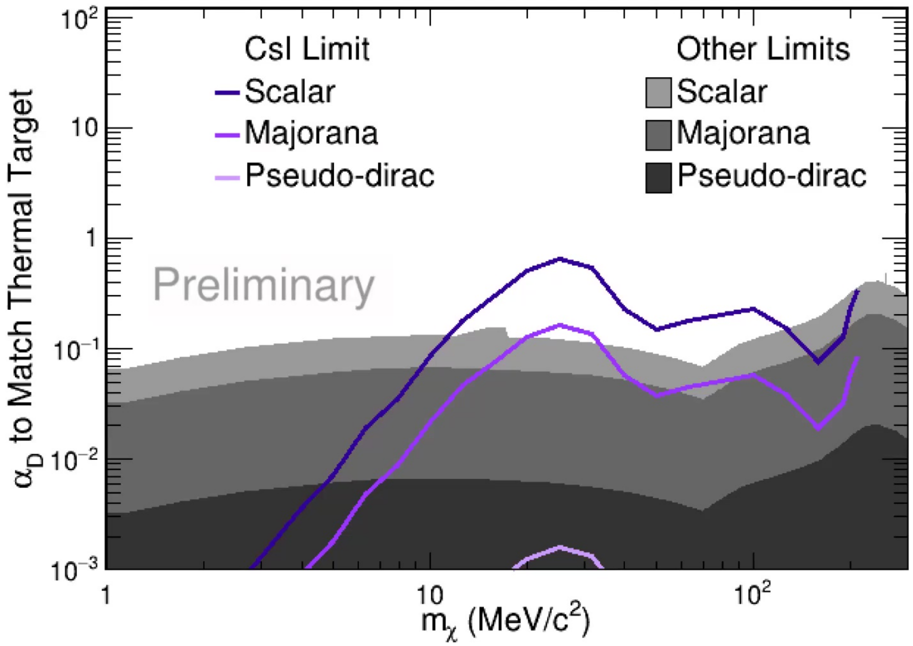


Less conservative scenarios: lowering α_D



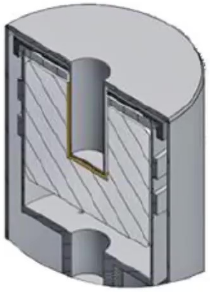
- Our dark matter model has two couplings: ε and α_D
  - Complicates parameter space since our relic abundance depends on $Y \propto \varepsilon^2\alpha_D$
- Our contour depends on our assumption of α_D – smaller values give tighter constraints
- $\alpha_D = 0.5$ is the largest, most conservative assumption before perturbative effects important

Exploring α_D allowed consistent with relic abundance

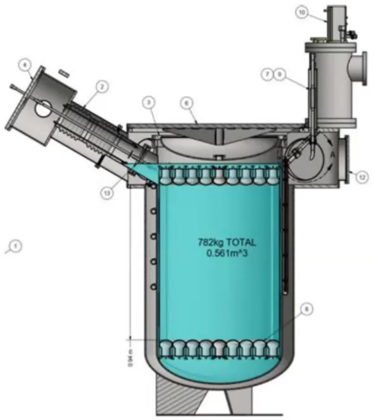


- Since our constraint depends on an assumption of α_D, we can connect our data directly to cosmology by asking for which α_D is our data inconsistent with the expected concentration
- In the scalar scenario, we can reject al $\alpha_D < 0.64$ at our most sensitive mass
- We currently can make a statement for fermion DM scenarios, but constraints are looser and to be explored with future data

Future COHERENT dark matter detectors



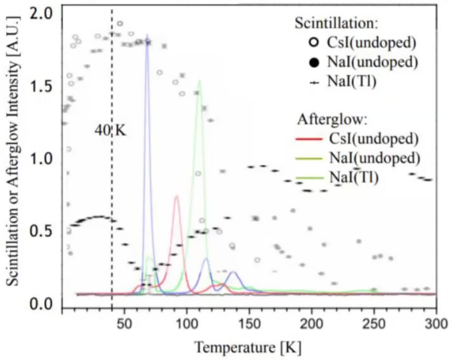
- ❑ COH-Ge-1: 16 kg of Ge PPC detectors
- ❑ Low threshold, ~ 0.2 keV_{ee}, improves sensitivity at low masses
- ❑ Funded with NSF MRI, detector commissioning now starting



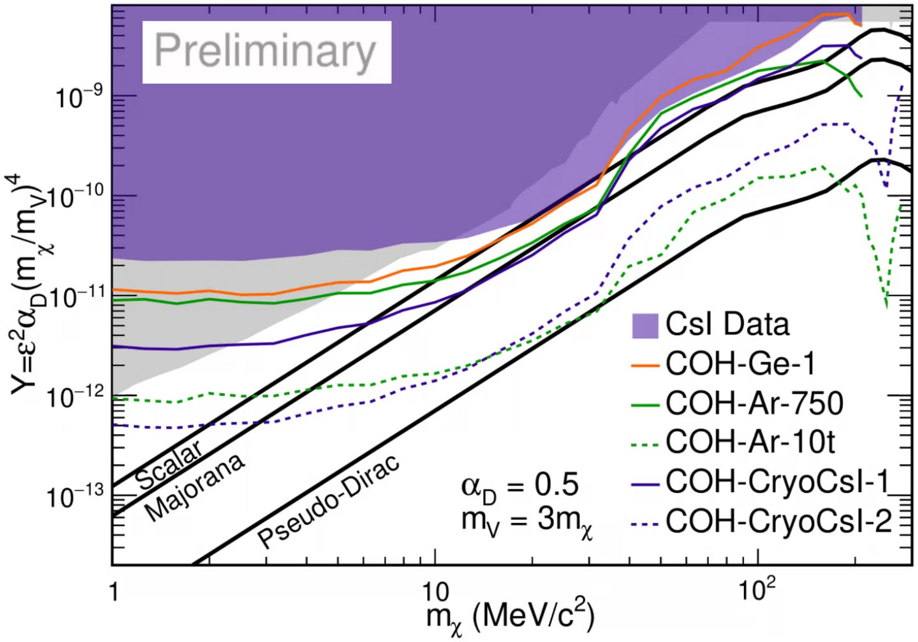
- ❑ COH-Ar-750: next-generation argon scintillator
- ❑ Large 610-kg fiducial volume
- ❑ Preliminary plans for 10-t argon detector at the STS placed forward from beam exploiting DM flux directionality

- ❑ 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)

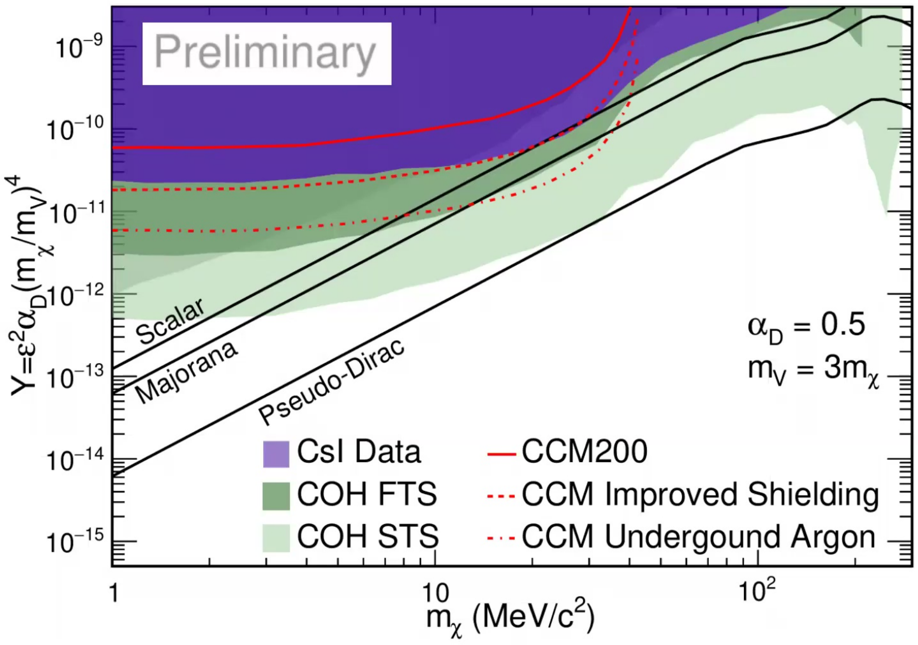


Future COHERENT sensitivity to dark matter



- ❑ Immediate future: germanium detector currently being commissioned – will fully explore scalar target at lower masses
- ❑ In coming years: future argon and cryogenic CsI detector – will be sensitive to a lower DM flux and probe the Majorana fermion target
- ❑ In next decade: large detectors placed forward at the STS will begin to ambitiously test even the most pessimistic spin scenarios

Other prospects for direct detection of sub-GeV DM



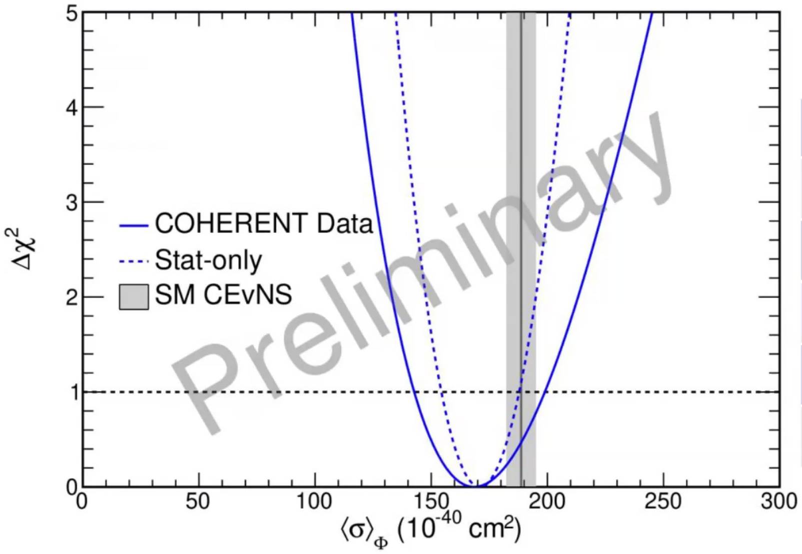
COH FTS =
52 kg-yr Ge +
1.83 t-yr Ar +
30 kg-yr Cryo CsI

COH STS =
50 t-yr Ar +
3.5 t-yr Cryo CsI

CCM sensitivity:
arXiv: 2105.14020

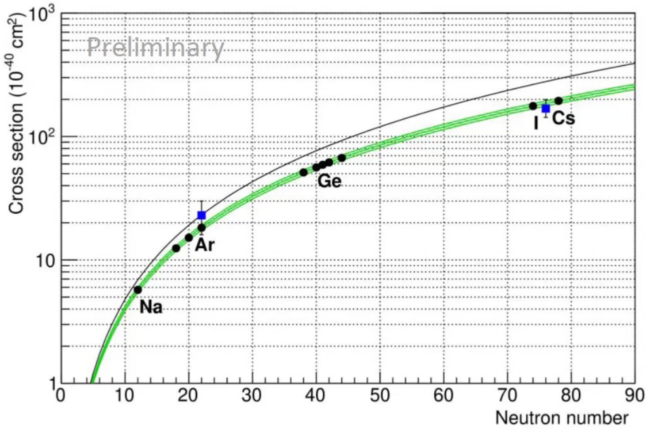
- ☐ Many other neutrino experiments also studying direct-detection of DM at accelerators
  - Most sensitive is Coherent Captain Mills (CCM)
- ☐ CCM sensitivity still preliminary, focusing on pinning down background levels and argon contaminates
  - Most optimistic CCM scenario has comparable sensitivity to our reach at the FTS

Determining the CEvNS cross section

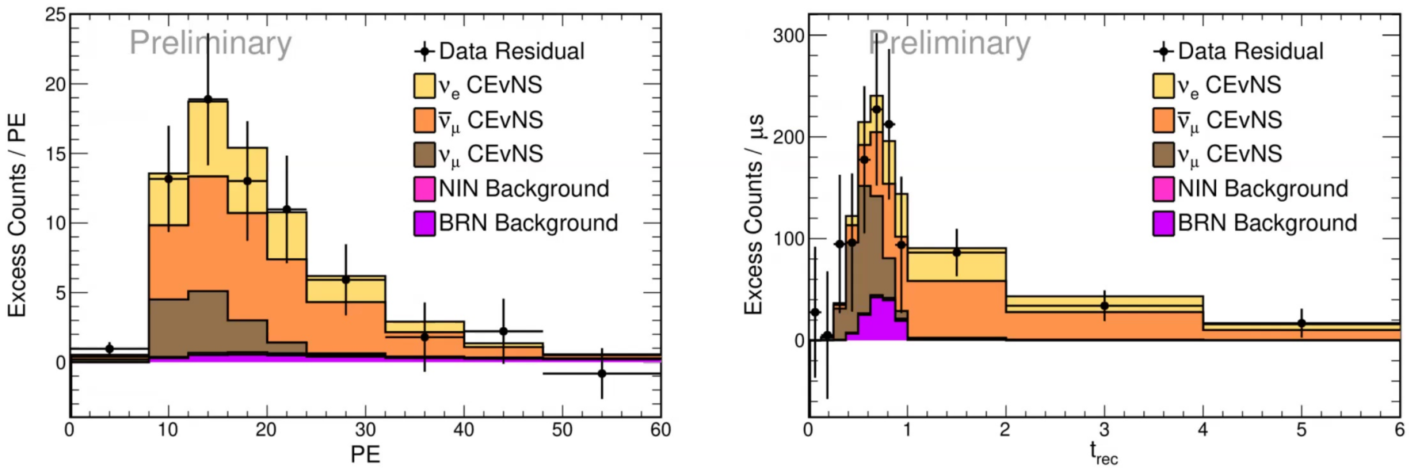


No-CEvNS rejection	11.6 σ
SM CEvNS prediction	$333 \pm 11(\text{th}) \pm 42(\text{ex})$
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

- ❑ From the observed CEvNS rate, we calculate the flux-averaged cross section
  - Result is consistent with the standard model prediction to 1 σ
- ❑ Observed cross section consistent with N^2 dependence



CEvNS spectra by flux component

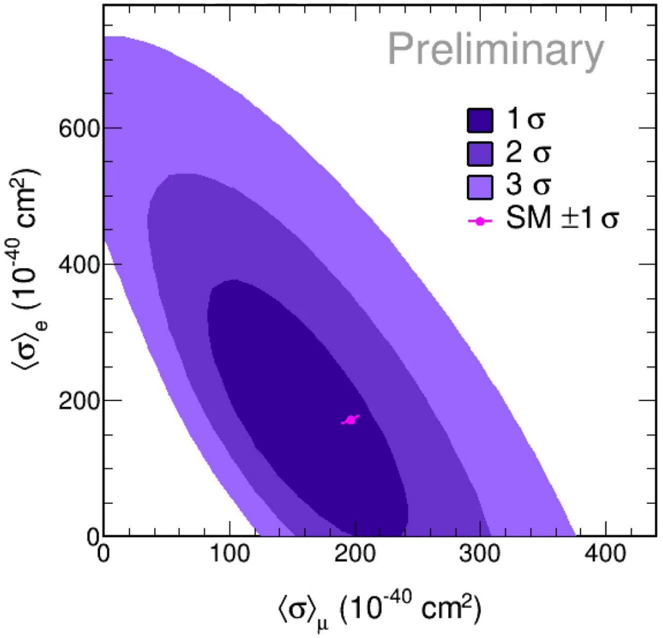


- ❑ At the SNS, CEvNS from ν_μ occur earlier than CEvNS from $\nu_e/\bar{\nu}_\mu$
- ❑ This is a lever arm for constraining CEvNS cross sections for different flavors separately
  - Advantage of spallation sources with beam width < muon lifetime
  - Now have collected enough exposure and understand our sample well enough to exploit this information, allowing precision measurements that exploit the SNS flux shape

- ❑ We measure the flavored CEvNS cross sections, $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$, to study CEvNS constraints of NSI
  - SM predicts flavor universality of the cross section at tree level
  - (There are small SM differences in $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$ cross sections which we account for)

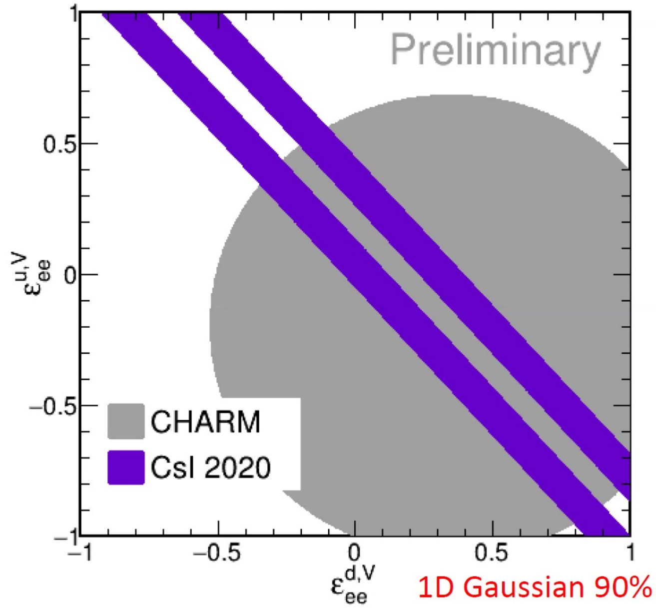
Flavored CEvNS cross section

- ❑ Allow for completely different $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$ as would be allowed in NSI scenarios
- ❑ ν_μ timing sheds light on the fraction of observed CEvNS that are from each flavor
- ❑ As in 1D CEvNS fit, the SM prediction is included within the 1 σ contour



COHERENT NSI constraints

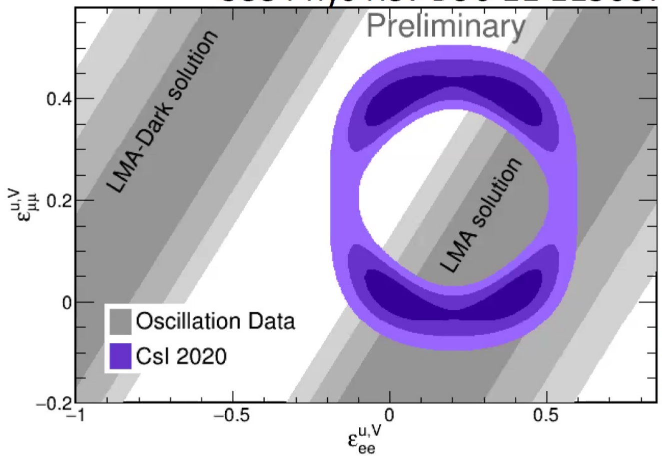
- Updated CsI data improves upon previous constraints
- Updated from 2017 result to include full spectral fit
- $\langle\sigma\rangle_\mu$ held fixed at SM prediction while $\langle\sigma\rangle_e$ floats freely



1D Gaussian 90% critical up-values

Interpreting solar neutrino oscillation data

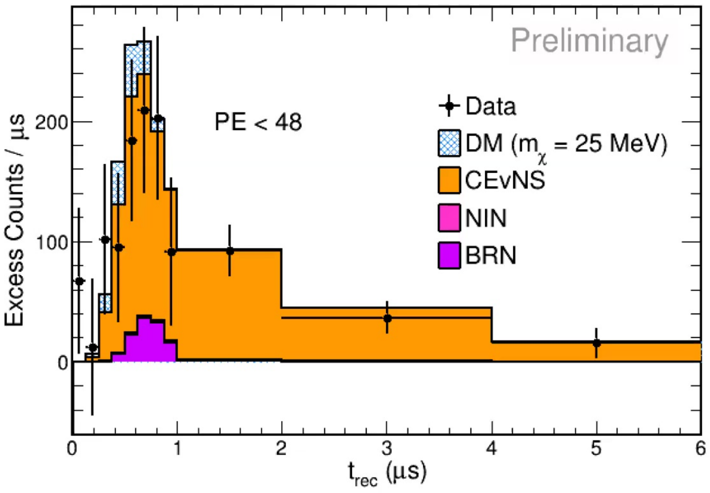
See Phys Rev D96 11 115007

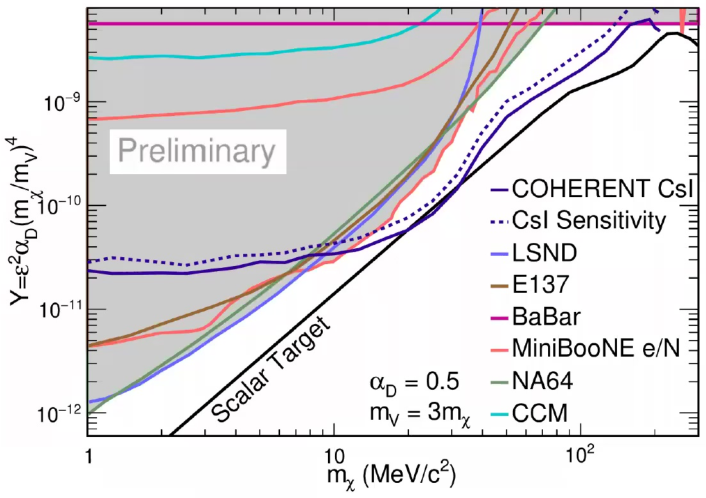


2D Gaussian 1/2/3σ critical up-values

- ❑ Measurement of PMNS parameters with neutrino oscillation experiments can be confused in NSI scenarios
- ❑ In particular, there is ambiguity between the large mixing angle (LMA) solution to solar oscillations and the LMA-Dark dark model
  - Would flip the θ_{12} octant: $\theta_{12} \rightarrow \pi/2 - \theta_{12}$
- ❑ LMA-Dark would require non-zero $\varepsilon_{ee}^{u,V}$ and $\varepsilon_{\mu\mu}^{u,V}$, which we can test given with our flavored cross section result

Summary





❑ COHERENT has made its first search for dark matter particles produced at the SNS

- Detection of nuclear recoils a novel and attractive technique
- First constraint probes scalar dark matter consistent with the relic abundance even in most pessimistic scenarios
- CEvNS new probe of neutrino-quark NSI which is already helping to understand neutrino oscillation data

❑ Promising future for CEvNS experiments

- Natural background control sample from SNS timing constrains systematic uncertainties
- Exploiting ORNL investment in SNS upgrades, we can cover parameter space consistent with cosmology over a wider range of masses with a relatively modest detectors