Searching for dark matter with COHERENT at the SNS

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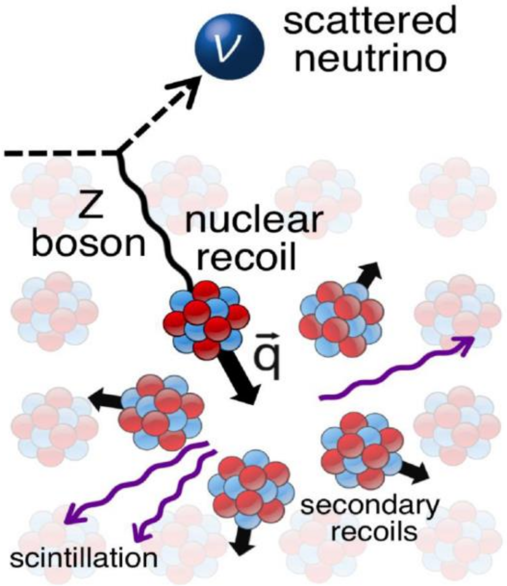
for the COHERENT Collaboration

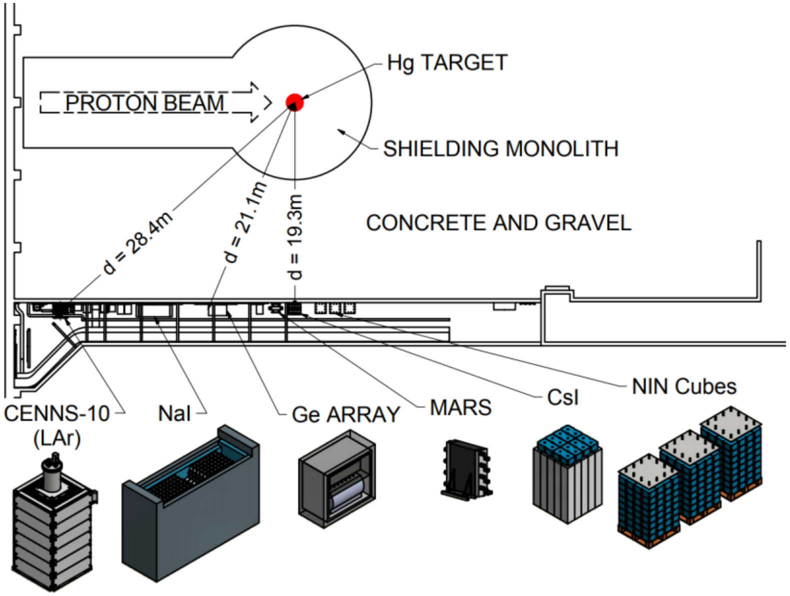
Mitchell Conference, Texas A&M, May 25, 2022

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 similar to dark matter direct detection
- ❑ Made first detection of CEvNS in 2017
  - New results on CsI and Ar, with detectors studying Ge and Na commissioning this year

Today focus on COHERENT CsI[Na] data



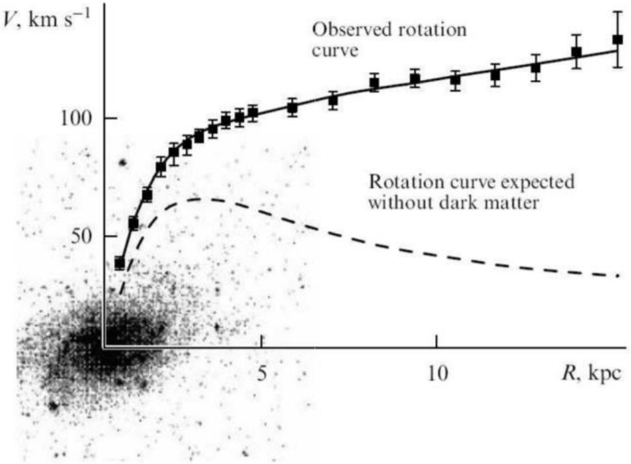


- ❑ Many detectors installed in “Neutrino Alley” – a basement hallway with sufficiently low neutron flux for neutrino measurements
- ❑ Multiple scattering targets to test wide range of BSM physics
- ❑ Specialized detectors to study neutron backgrounds

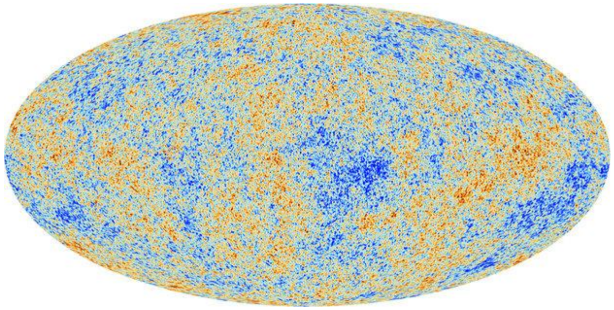
See Phil Barbeau’s talk yesterday for more

Dark matter in our universe

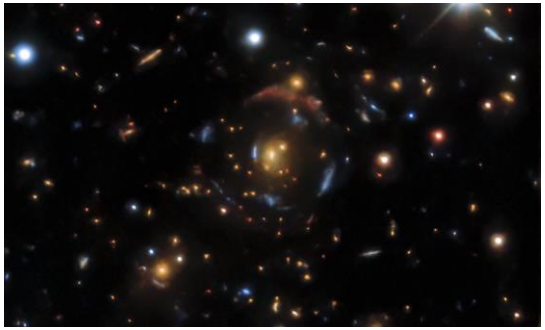
A. Zasov et al., arXiv 1710:10630 (2017)



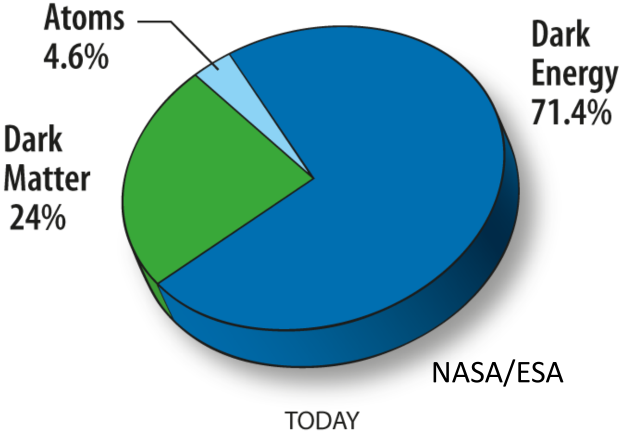
Plank, Astron Astrophys **641** A1 (2020)



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

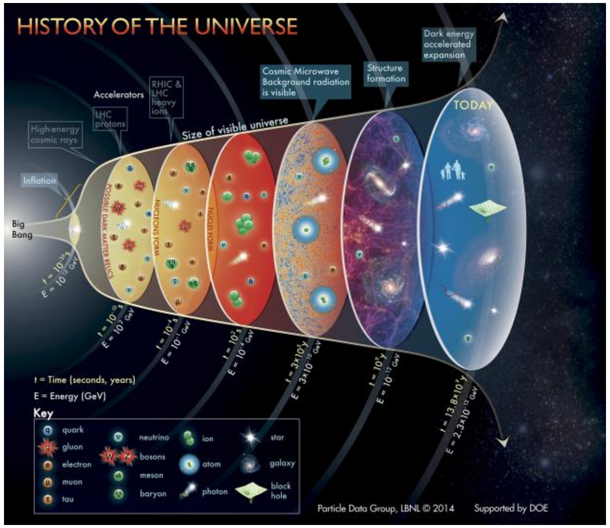


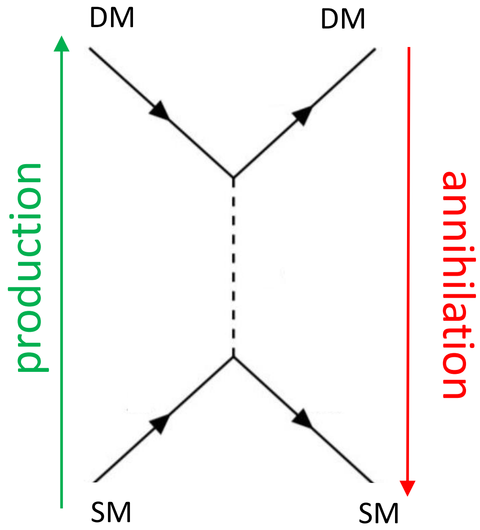
- First evidence for dark matter (DM) comes from rotation curves of galaxies in early 20th century (e.g. Zwicky 1933)
- In 2003, precision CMB data confirmed the existence of dark matter and estimated that roughly 80% of matter in the universe is dark matter
- Continuing understanding distribution of 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



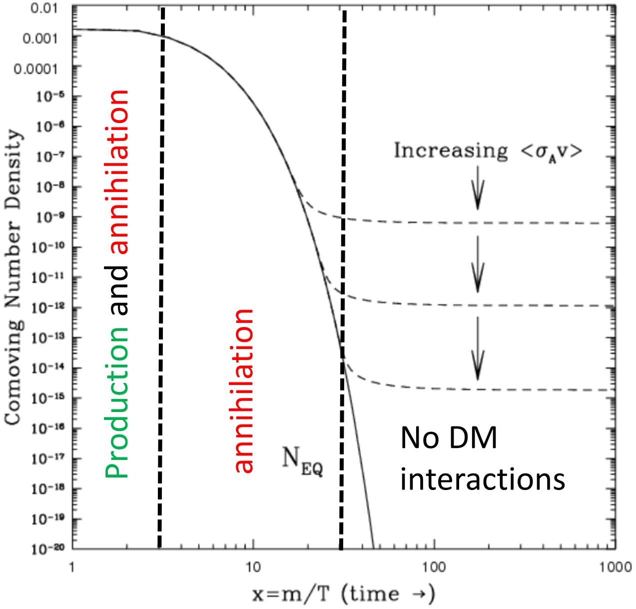
NASA/ESA

Origin of weakly-interacting dark matter





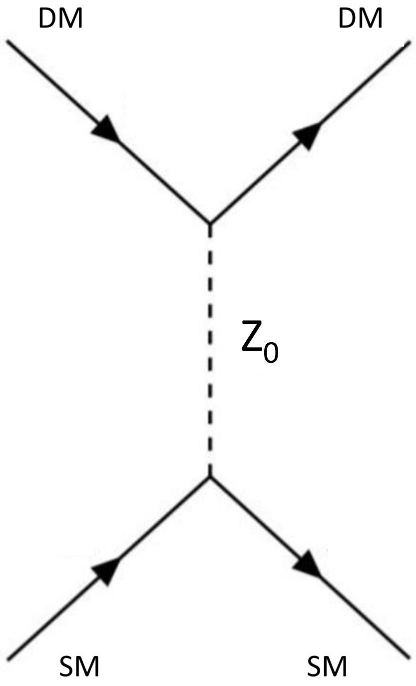
C. Chatterjee, arXiv: 1901.05658 (2019)



- ❑ 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 close the universe, preventing modern the universe



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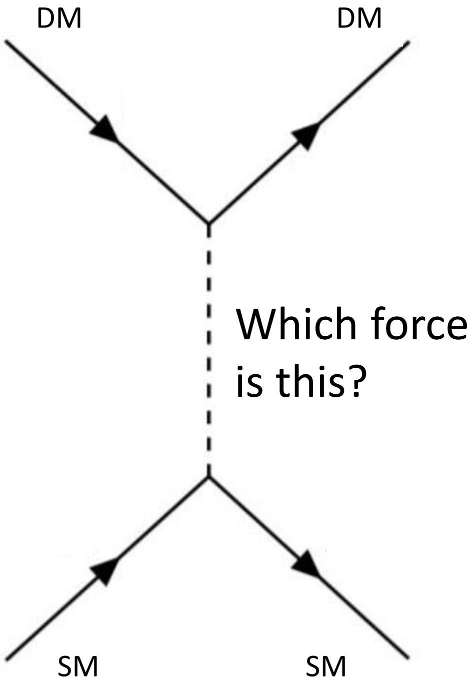


Which force is this?

- 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 $Y = \varepsilon^2\alpha_D\left(m_\chi/m_V\right)^4$

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)

The Spallation Neutron Source at ORNL

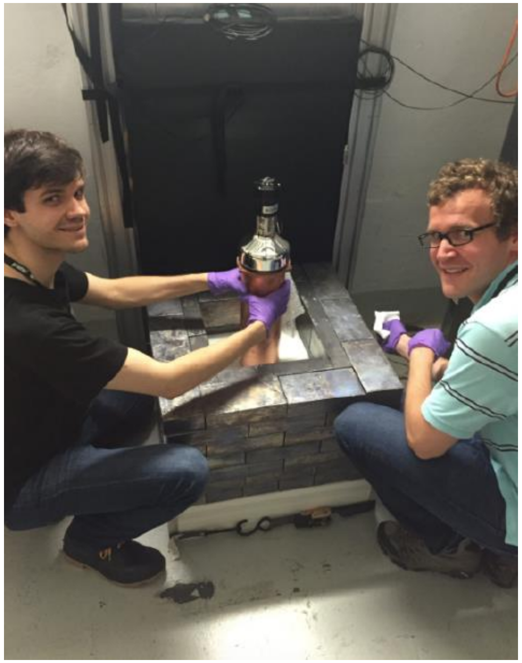
+ Dark Matter + Neutrinos

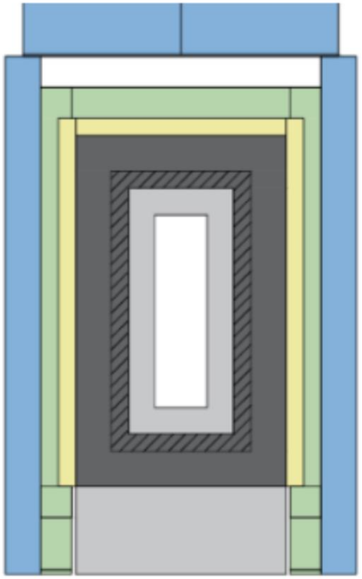
- 1.4 MW proton beam on mercury target at $T_p = 1.01$ GeV
- Pulse width is 340 ns FWHM at 60 Hz, reducing backgrounds by a factor of $\sim 3\times10^4$ from beam pulsing

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

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





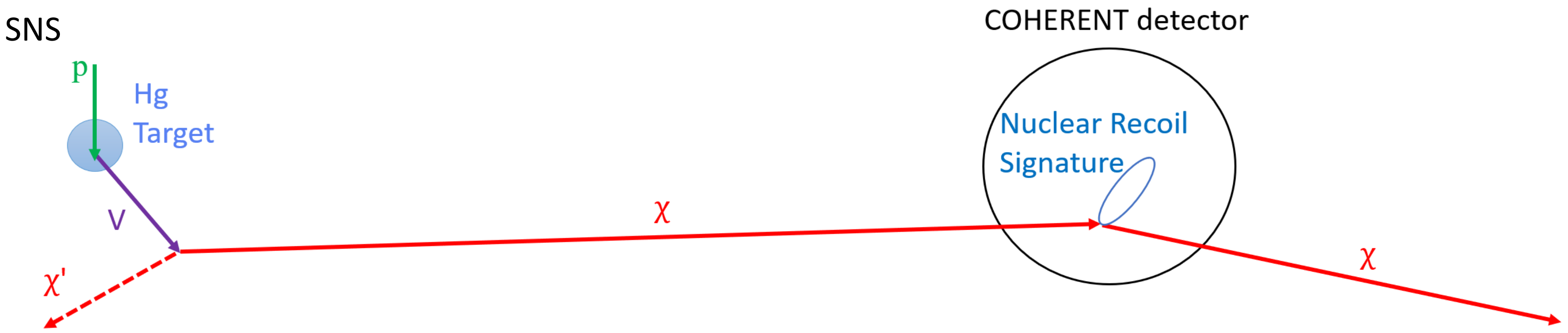
Shielding design

– 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)

Making DM at the SNS



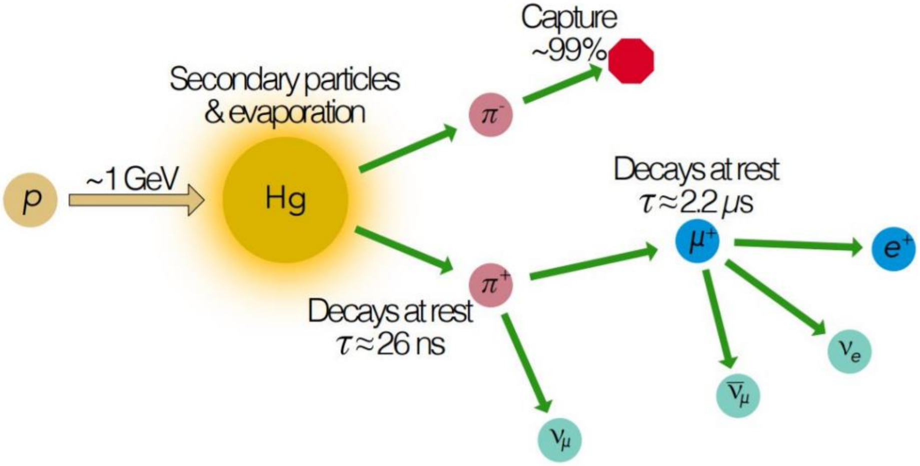
- Any hidden sector particles with masses below ≈ 220 MeV/c^2 could be produced in the many proton-Hg interactions within the SNS target
- This may include mediator particles between SM and DM particles
  - Dominant production from $\pi^0/\eta^0 \to V\gamma$
- Mediator decays to a pair of DM particles, sending a flux out of the SNS
  - Suitable detector placed in this flux can directly detect DM particles scattering within the detector

Neutrino flux at the SNS

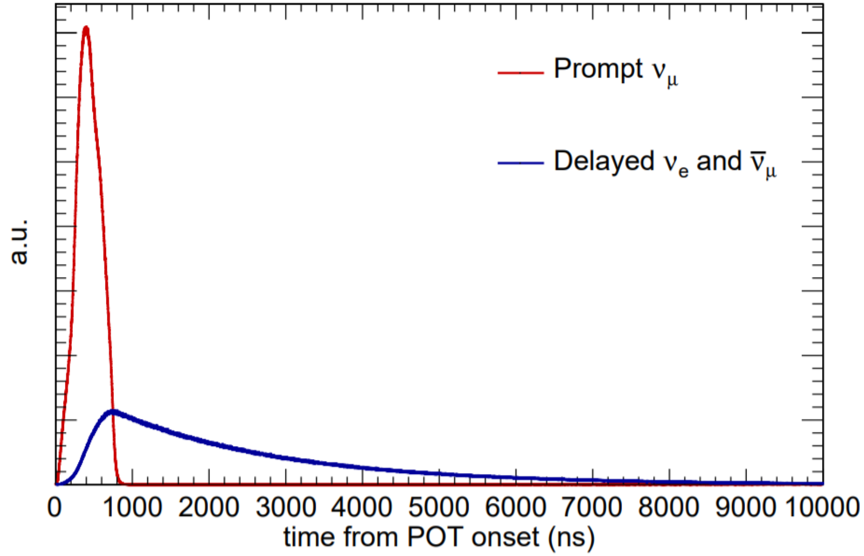
- ❑ Low energy pions are a natural by-product of SNS running
  - π^+ will stop and decay at rest

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

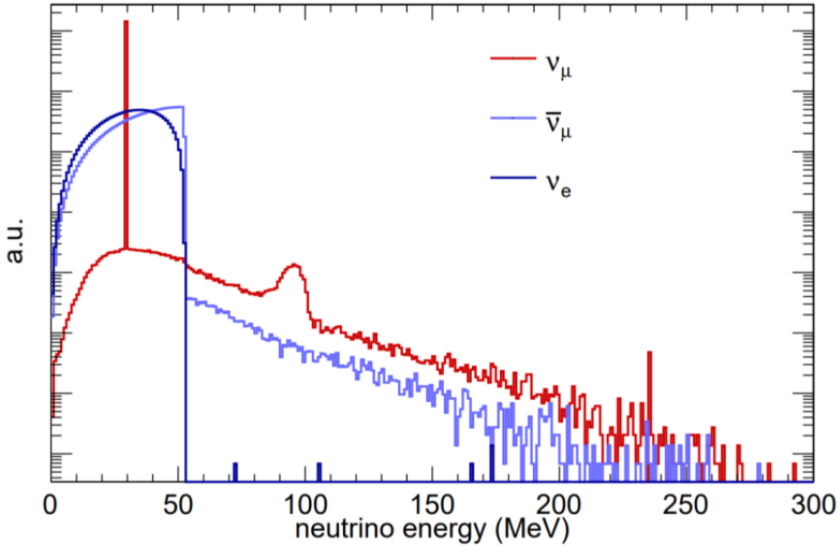
  - Flux includes three flavors of neutrinos → can test flavor universality as a BSM signature
- ❑ Flux shape is very well known and very small contribution from decay in flight at the SNS



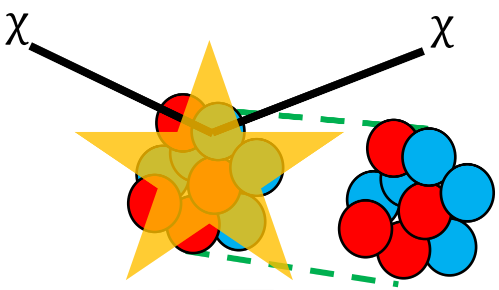
Timing distribution at SNS



Energy distribution at SNS



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

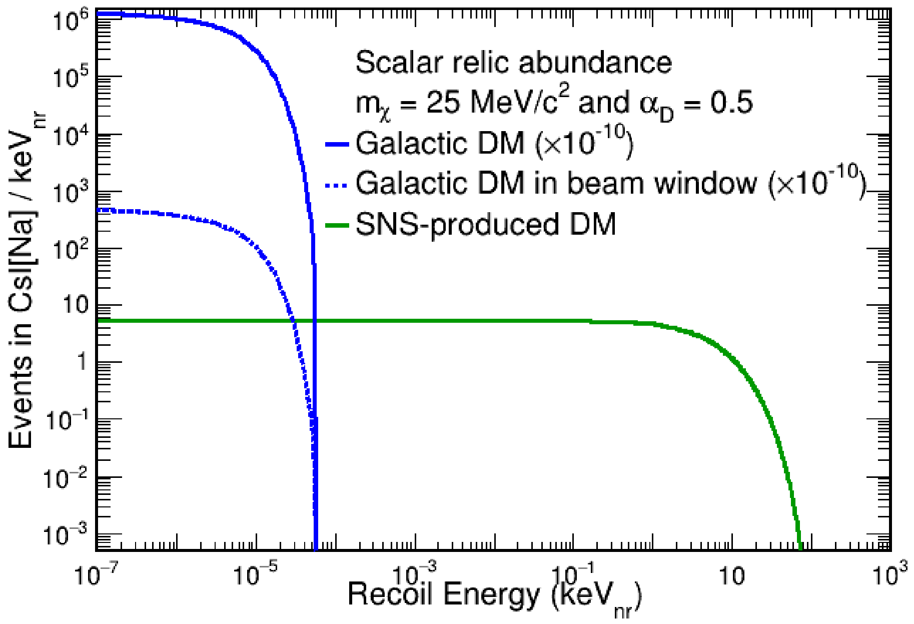
- This coherency gives a Z^2 enhancement in the cross section → big effect for CsI (Z of 53/55)
- Game-changing – investing in a small 14-kg detector can compete with multi-ton detectors

Direct-detection experiments searching for light dark matter

	Mass (t)
LSND	167
MiniBooNE	450
COHERENT CsI	0.0146

Advantages of accelerator searches: higher recoil energies

- Galactic DM is slow, thermal with β around 0.001 → struck nuclei get very soft kick
  - Maximum recoil energy $2p_\chi^2/m_{\mathrm{Nuc}} \approx$ 0.01 eV
  - Much less than scintillation / ionization thresholds
  - About 1 kT for liquid Xe or liquid Ar detectors
  - Coherent DM-nucleus scattering unobservable



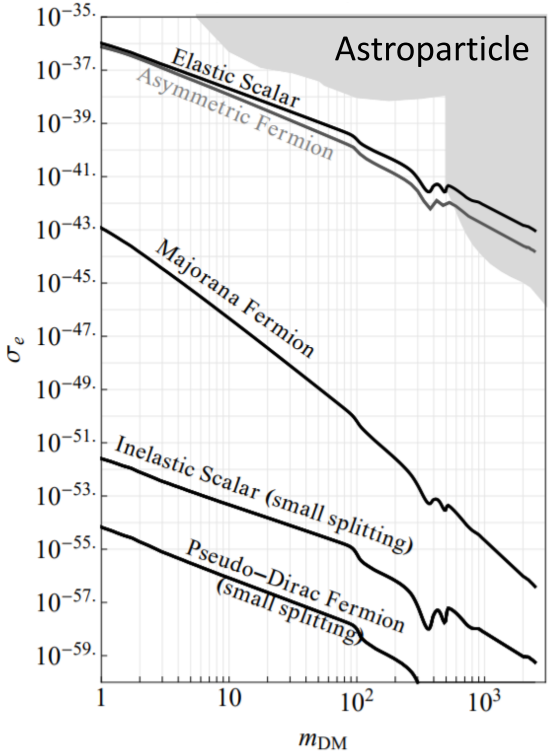
- DM produced at accelerators would be relativistic
  - Maximum recoil energy $2p_\chi^2/m_{\mathrm{Nuc}} \approx$ 100 keV → $10^7\times$ higher recoil energies compared to galactic DM

Detecting coherent DM-nucleus scattering easily within reach of COHERENT detectors that have thresholds between 1 and 20 $\mathrm{keV_{nr}}$

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



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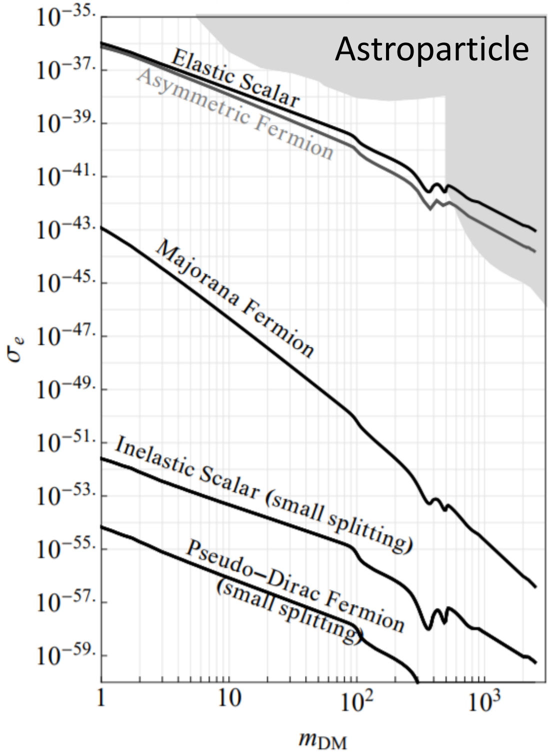

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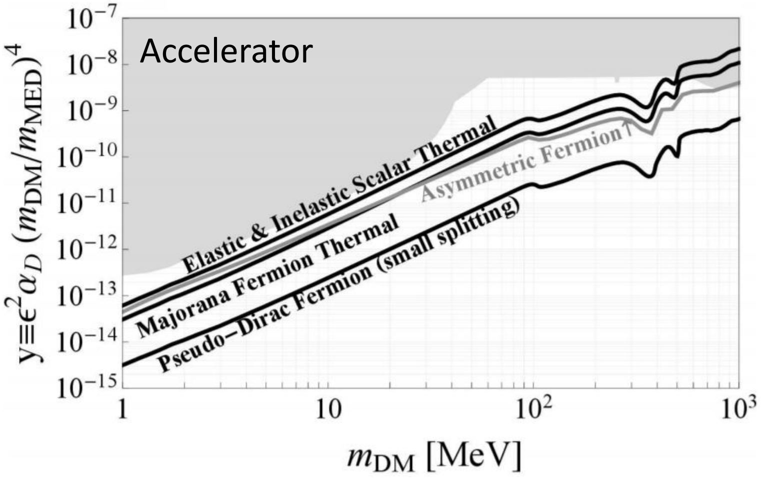
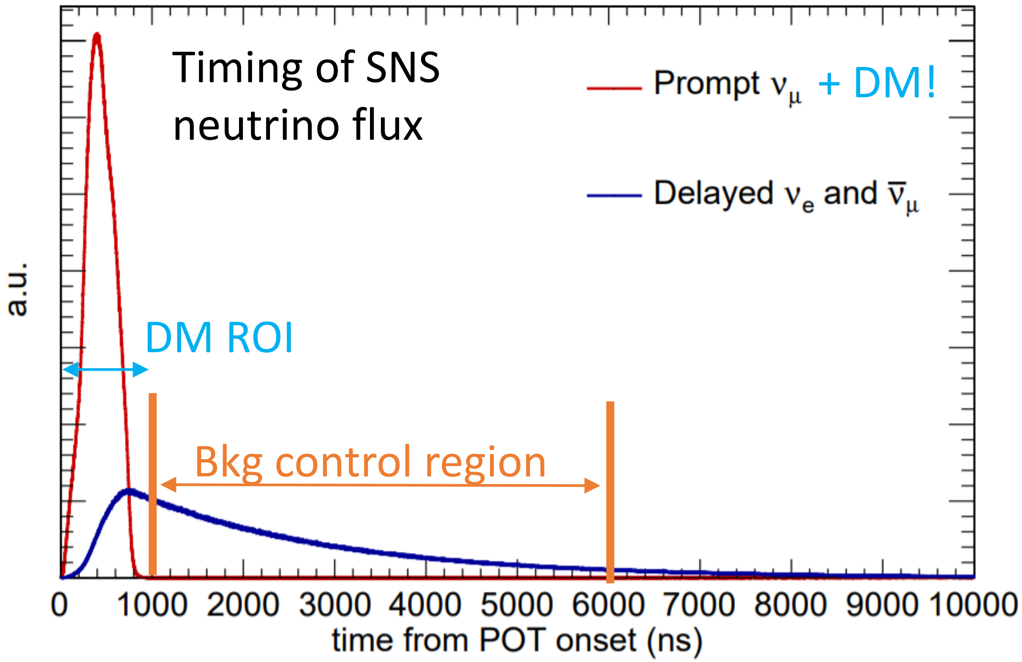
- At accelerators, DM is relativistic with only a factor of 20 between different expectations
  - Accelerator searches only viable options to test fermionic DM
- COHERENT gets the best of both worlds
  - Independent of DM particle nature like accelerator methods
  - Large coherent cross section like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

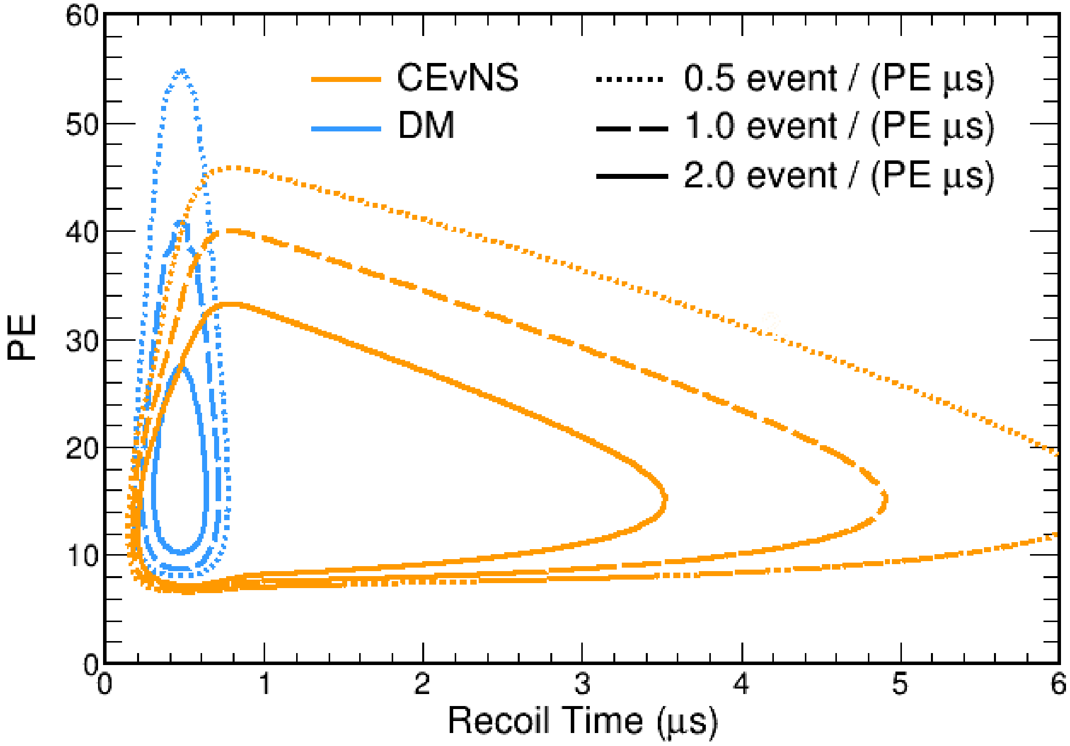


Advantages of spallation sources: constraining uncertainties



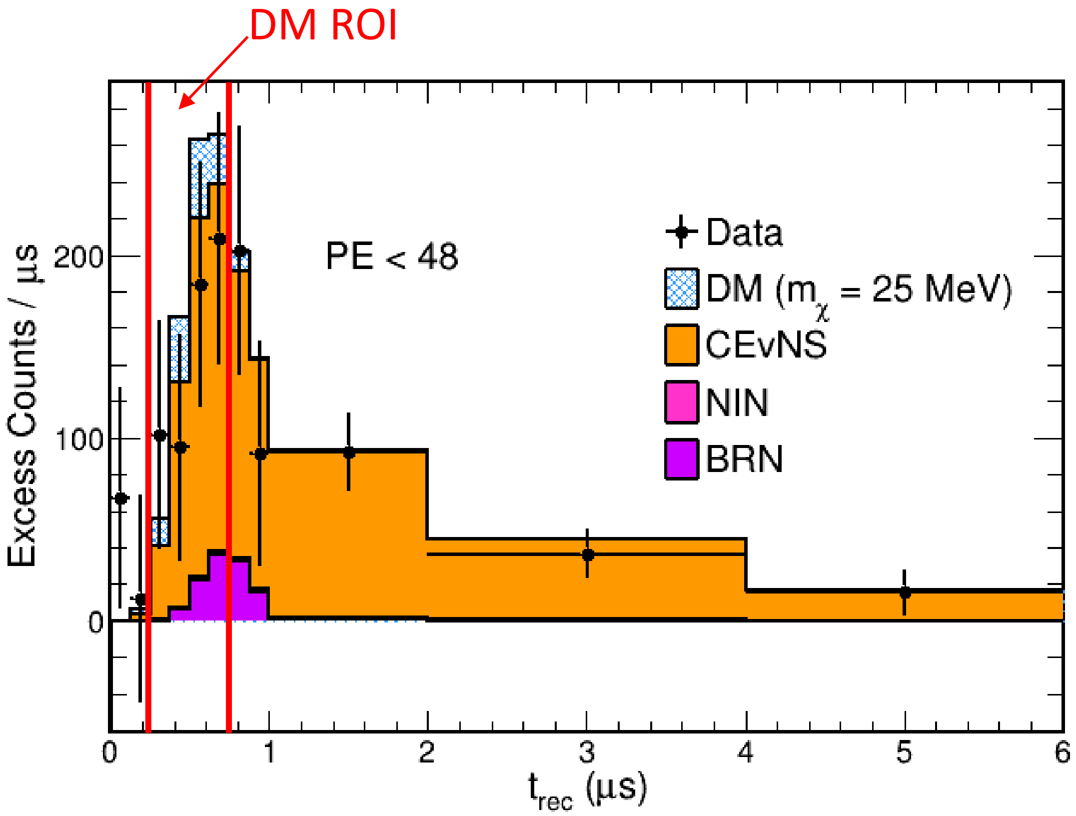
- CEvNS is the principal beam-related background for DM search
  - SM cross section precisely calculated, but uncertainties in detector response unique to each detector
- Since DM is relativistic, it is expected coincident with protons on target
  - No DM coincident with delayed CEvNS from $\upsilon_e/\bar{\upsilon}_\mu$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

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

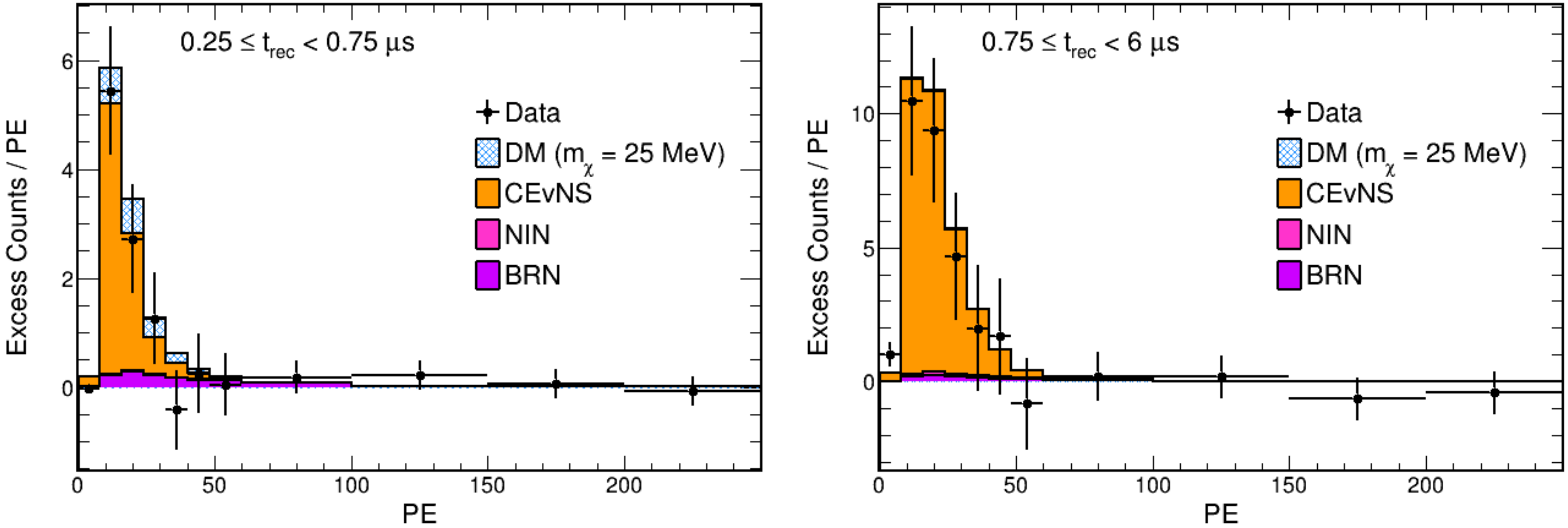
Current dark matter data at SNS: CsI[Na]



	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

- 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

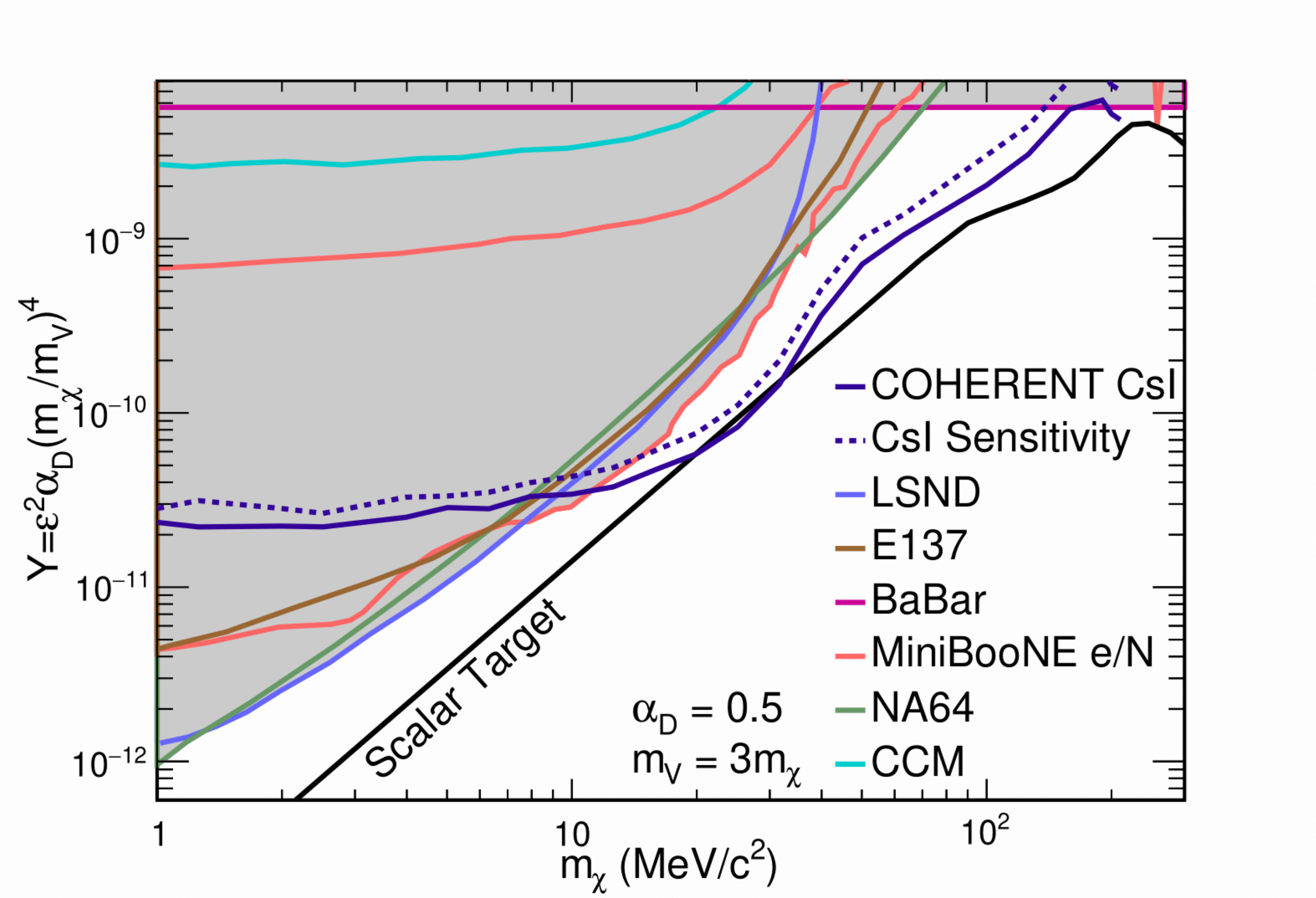
Recoil distribution of data



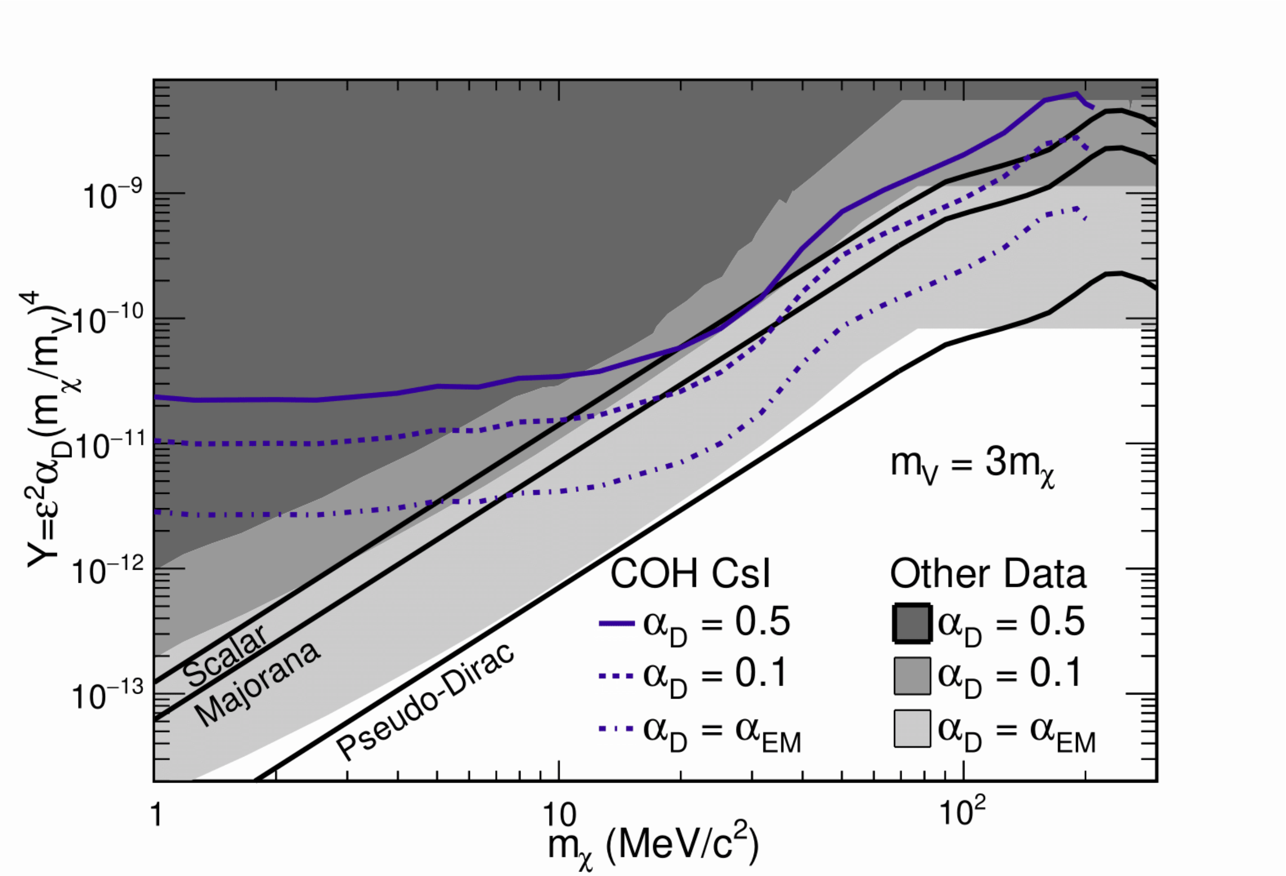
- Data also agrees well with the background-only prediction for the recoil energy distribution
  - $\chi^2 = 103/120$ for background-only 2D fit
- Look for an excess in the DM ROI while controlling backgrounds with delayed events

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



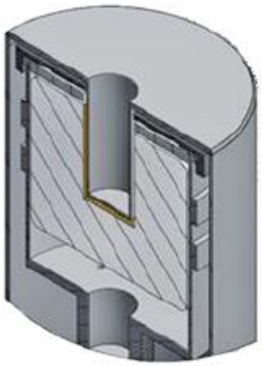
Less conservative scenarios: lowering α_D

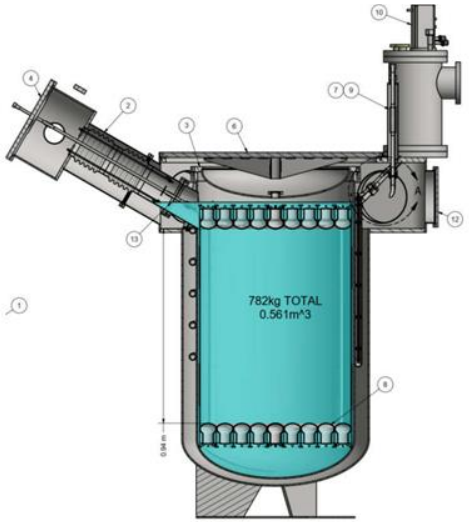


- ❑ Our dark matter model has two couplings: ε and α_D
  - Complicates parameter space since our relic abundance depends on $Y \propto \varepsilon^2 \alpha_D$
- ❑ Our contour depends on our assumption of α_D – smaller values give tighter constraints
- ❑ $\alpha_D = 0.5$ is the largest, most conservative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

Future COHERENT dark matter detectors

- 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 summer 2022

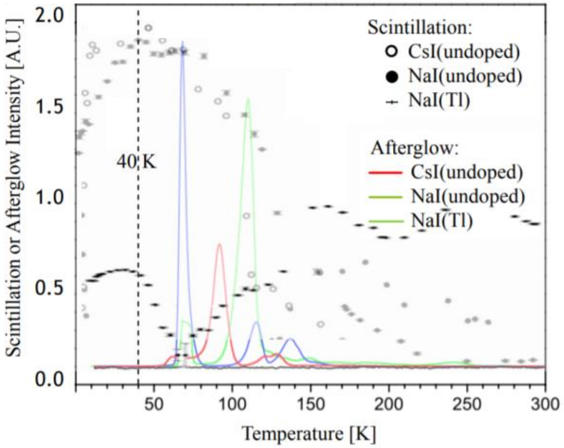




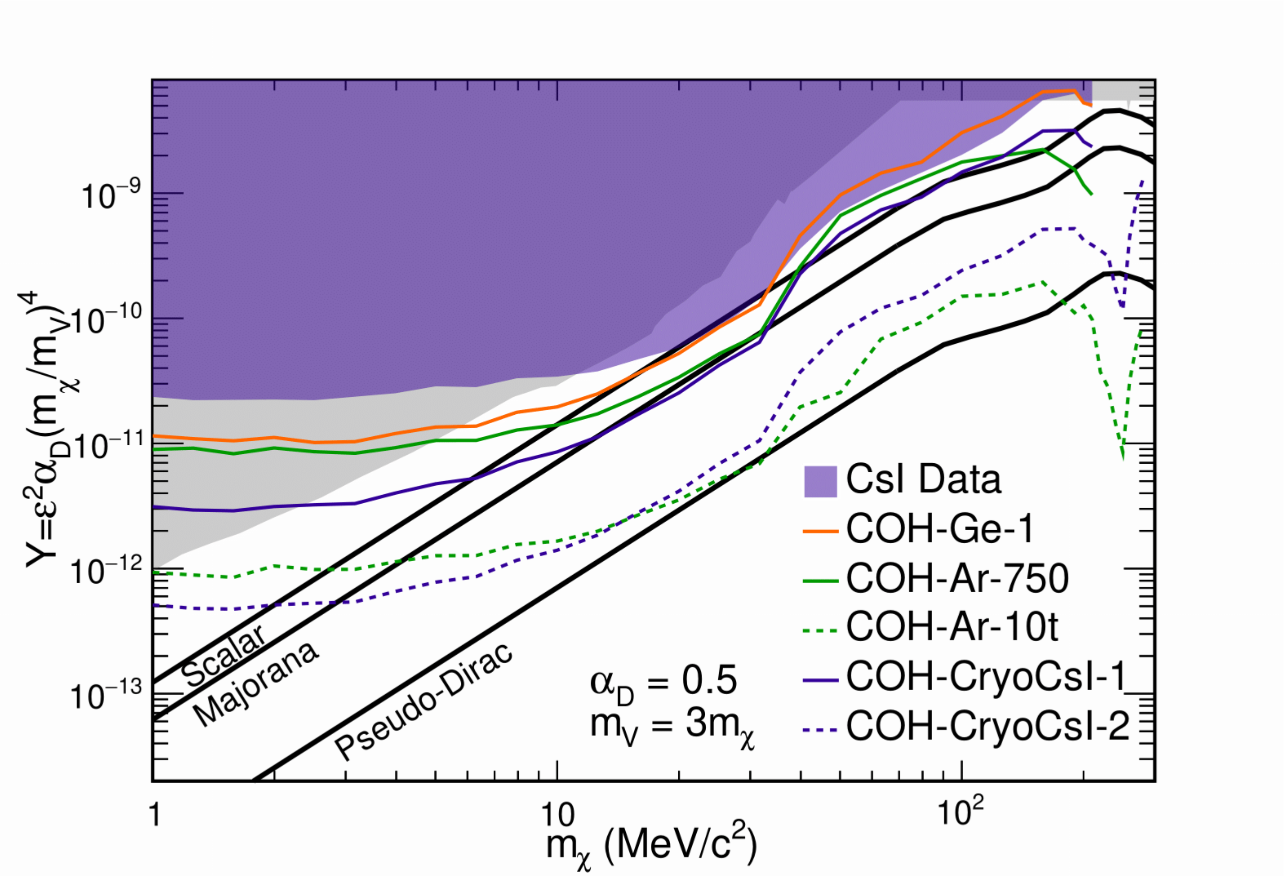
- COH-Ar-750: next-generation argon scintillator
- Large 610-kg fiducial volume
- Preliminary plans for 10-t argon detector at the STS placed forward from beam exploiting DM flux directionality

- 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)

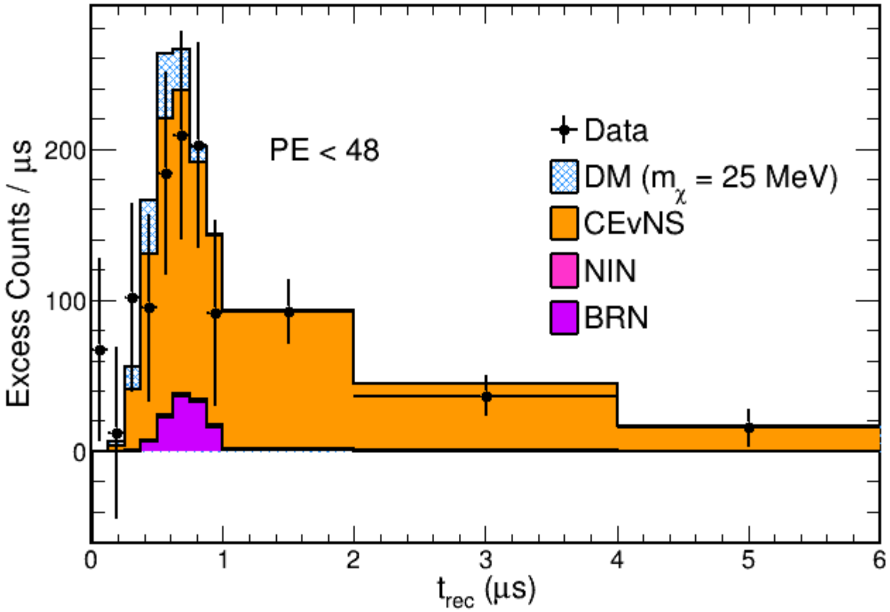


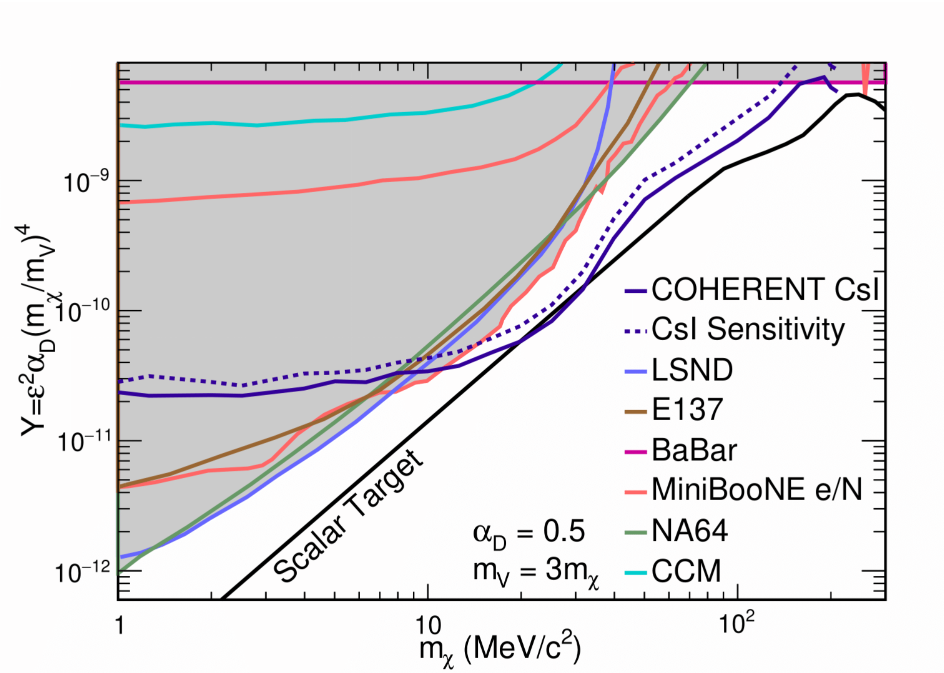
Future COHERENT sensitivity to dark matter



- 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

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

- ❑ 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


COHERENT
SNS

Future beam improvements at the SNS

- ☐ Two staged improvement to the beam

1: Proton Power Upgrade

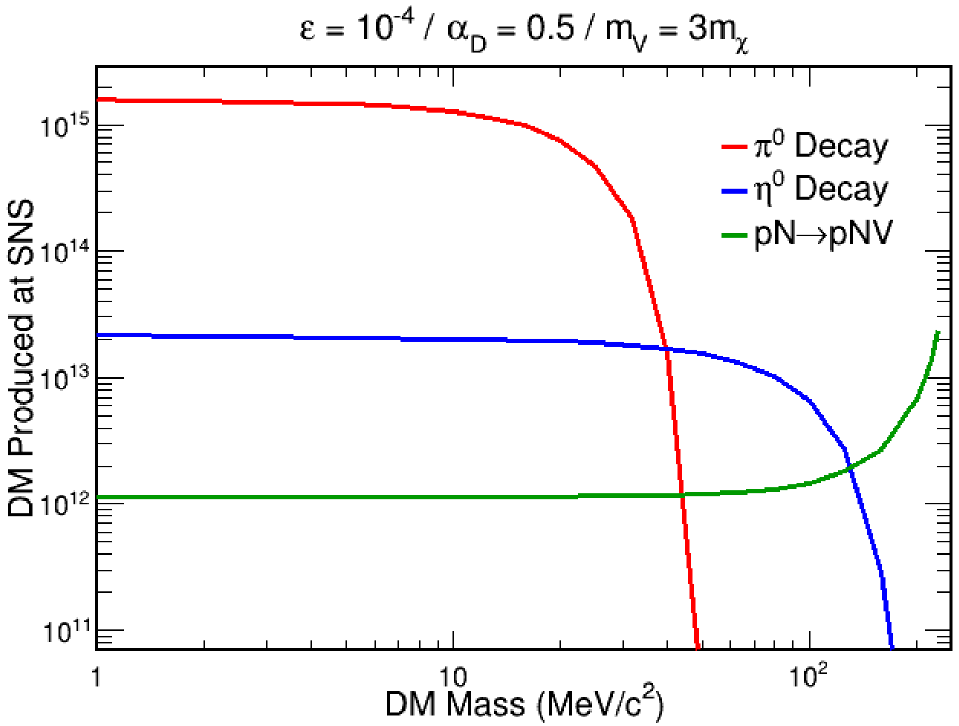
- Increases the power of neutron beam 1.4 → 2.8 MW
- Feasibility of a second target station

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

DM production channels



- Our expected dark matter flux is produced through three channels
    - $\pi^0 \rightarrow V\gamma$ decay: dominant channel where kinematically allowed, $2m_\chi < m_\pi$,
    - $\eta^0 \rightarrow V\gamma$ decay: similarly only contributes for $2m_\chi < m_\eta$
    - $pN \rightarrow pNV$ bremsstrahlung: only dominant at high energies and rate increases significantly at the ρ resonance, $m_V \approx m_\rho$

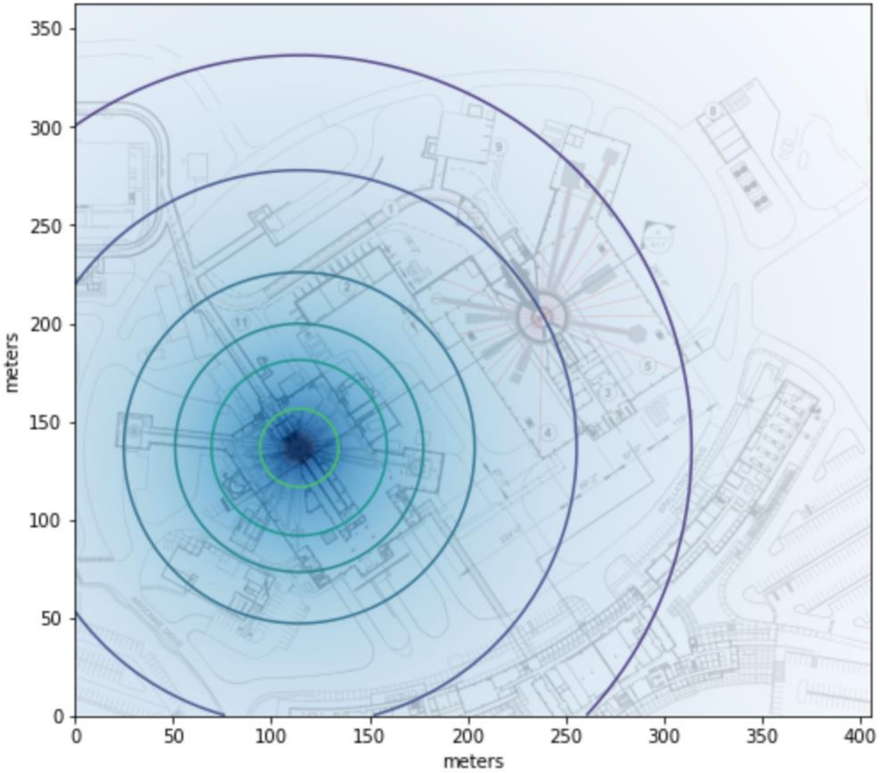
Directionality of flux at the SNS

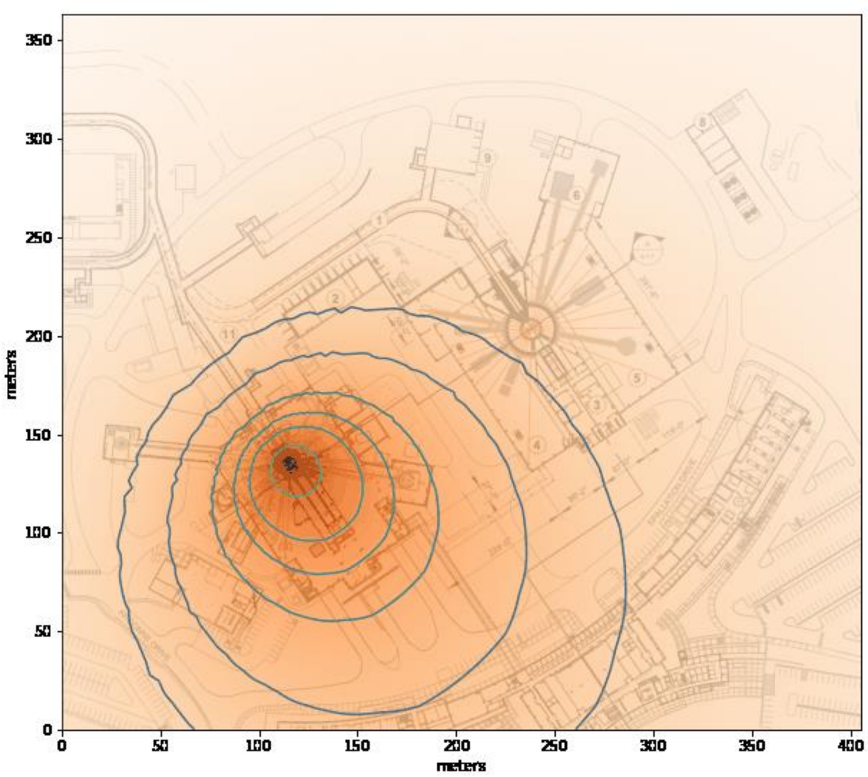
Neutrino flux produced at rest – isotropic

Largest beam-related background for DM searches at the SNS

DM produced in-flight – is boosted

A forward-directed detector would optimize DM / background

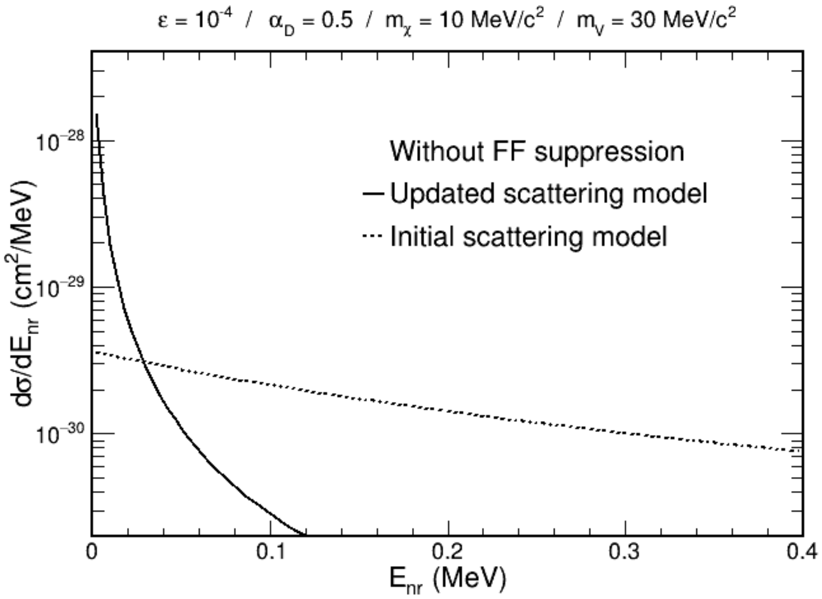




- ❑ After STS is built, both targets will operate with 3(1)/4 bunches sent to FTS (STS)
- ❑ If DM is in this mass regime, SNS very advantageous – a single detector monitors DM flux from two beams allowing confirmation of the expected angular dependence of the flux

Recent updates to cross section generator (BdNMC)

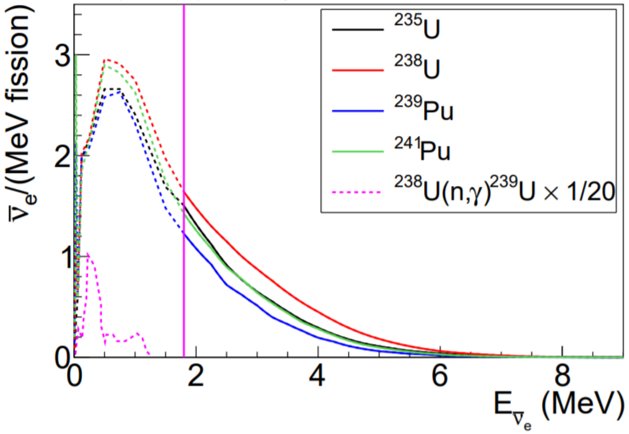
- DM particles scatter with coherent cross section
  - $\frac{d\sigma}{dE_r} = 4\pi Z^2 \varepsilon^2 \alpha_{EM} \alpha_D \frac{2 m_N E_\chi^2}{p_\chi^2 (m_V^2 + 2 m_N E_r)^2} |F(Q^2)|^2$
- This model has changed significantly since our previous sensitivity estimates
- 1: A substitution of $m_p \rightarrow m_N$ 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

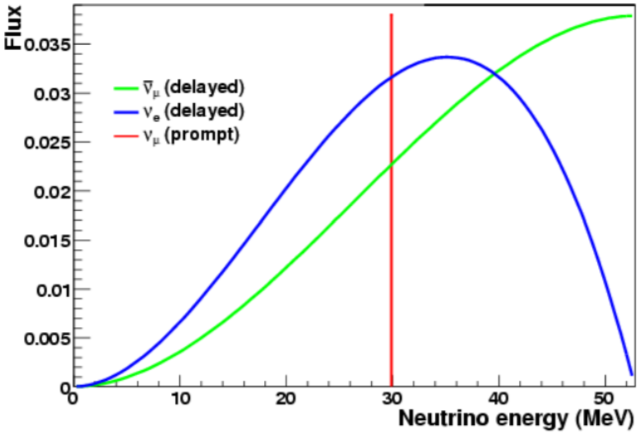


- 2: A more accurate form factor treatment
  - BdNMC now uses the nuclear form factor accounting for spread of protons within nucleus rather than the proton form factor accounting for spatial spread of charge within each proton
  - Significantly reduces sensitivity at higher masses
- 3: Improved configured resolution of DM scattering cross section from 100 MeV to 1 MeV
  - Gives slight reduction in event rate, but is more accurate

High-flux Sources for Low-energy Neutrinos

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





- Nuclear reactors
  - Very high flux: $\sim 2\times10^{20}\ \bar{\nu}_e$ / s
  - Maximum recoil energy for CsI: 1 keV
  - Reactor-off data → in-situ background constraint

reactors win

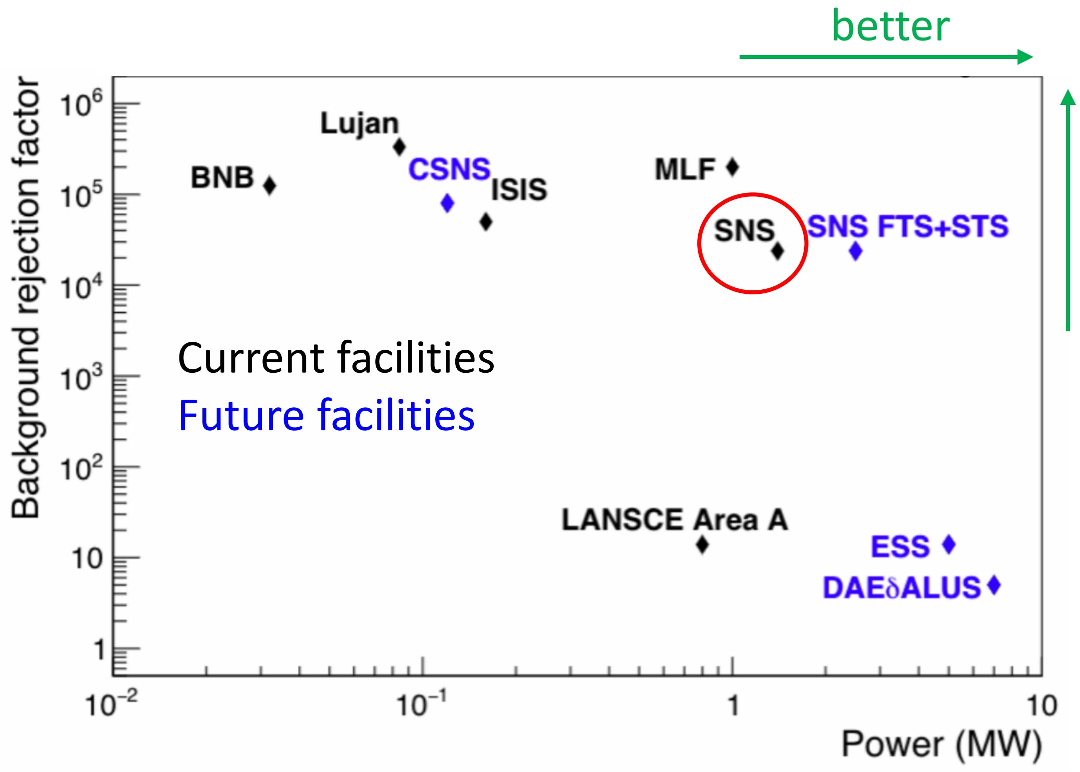
- Pion decay-at-rest (πDAR) at accelerators
  - High flux: $\sim 3\times10^{14}\ \nu_\mu/\nu_e/\bar{\nu}_\mu$ / s
  - Maximum recoil energy for CsI: 15 keV
  - Pulsed beam → in-situ background constraint

πDAR wins

Fermilab collaboration

Coherent Captain Mills @

Selecting a πDAR Source

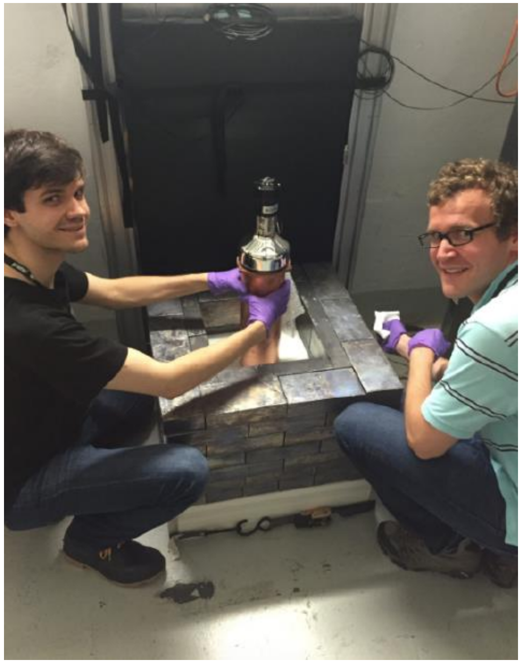


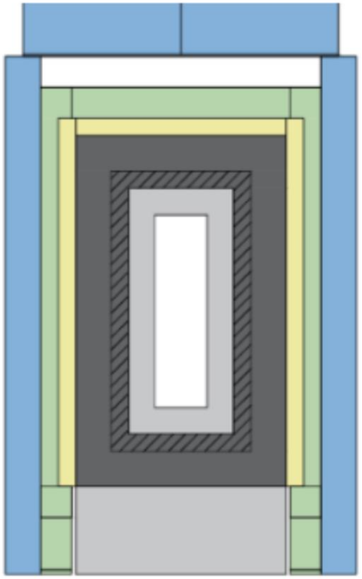
- For selecting a source, we want
  - High beam power → faster accumulation of signal
  - Low duty factor → improved background rejection through beam pulsing

- Move to the Spallation Neutron Source at ORNL
  - Upgrade will double beam power and construct second target station by 2028

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



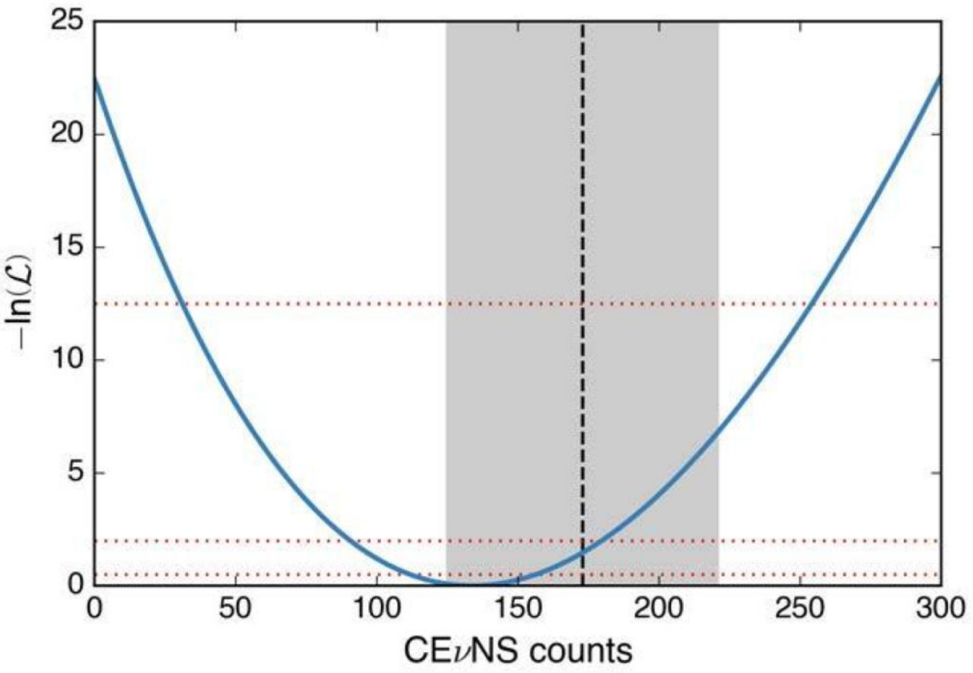


Shielding design

- 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]



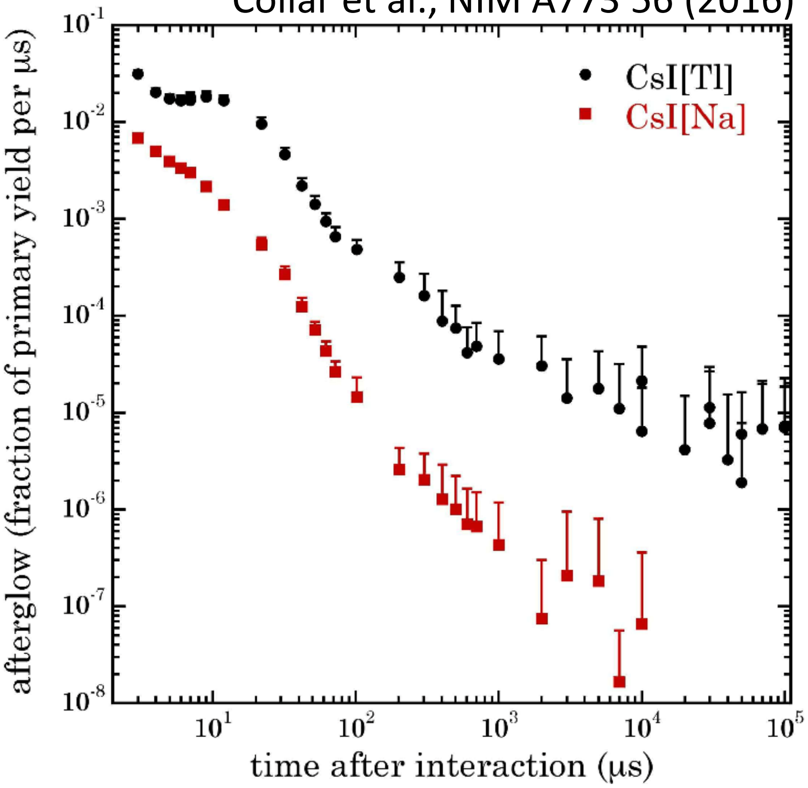
Made first observation of CEvNS
– Established the existence of CEvNS to 6.7σ
– 134 ± 22 CEvNS events
– 173 ± 48 CEvNS predicted

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

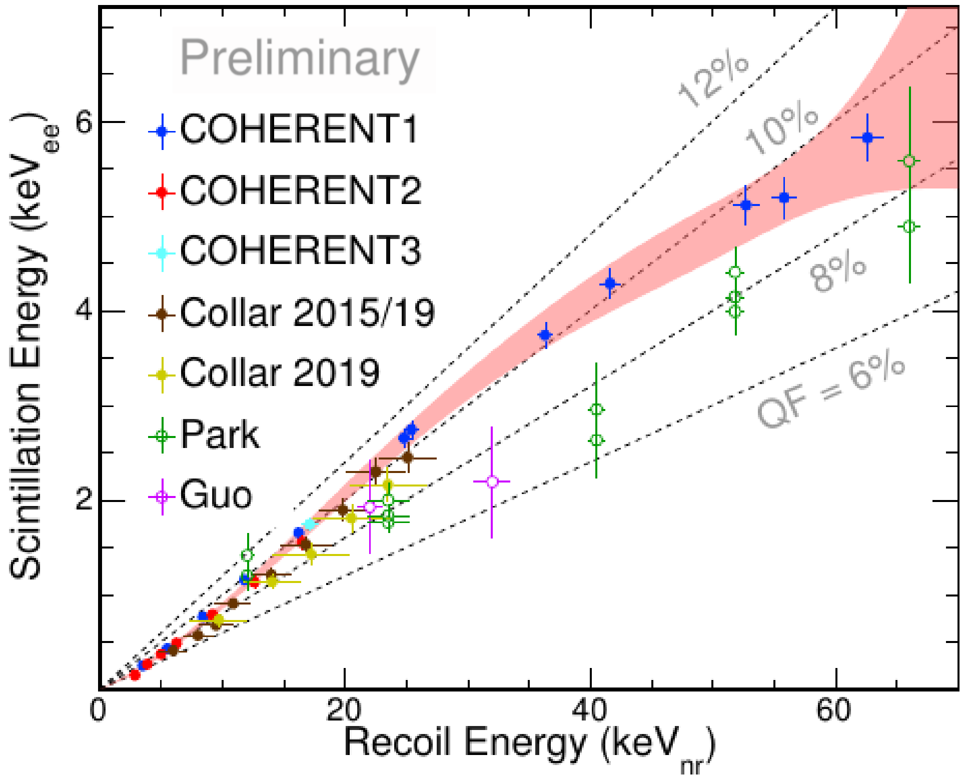
Timing of scintillation in CsI[Na]

- ❑ 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)

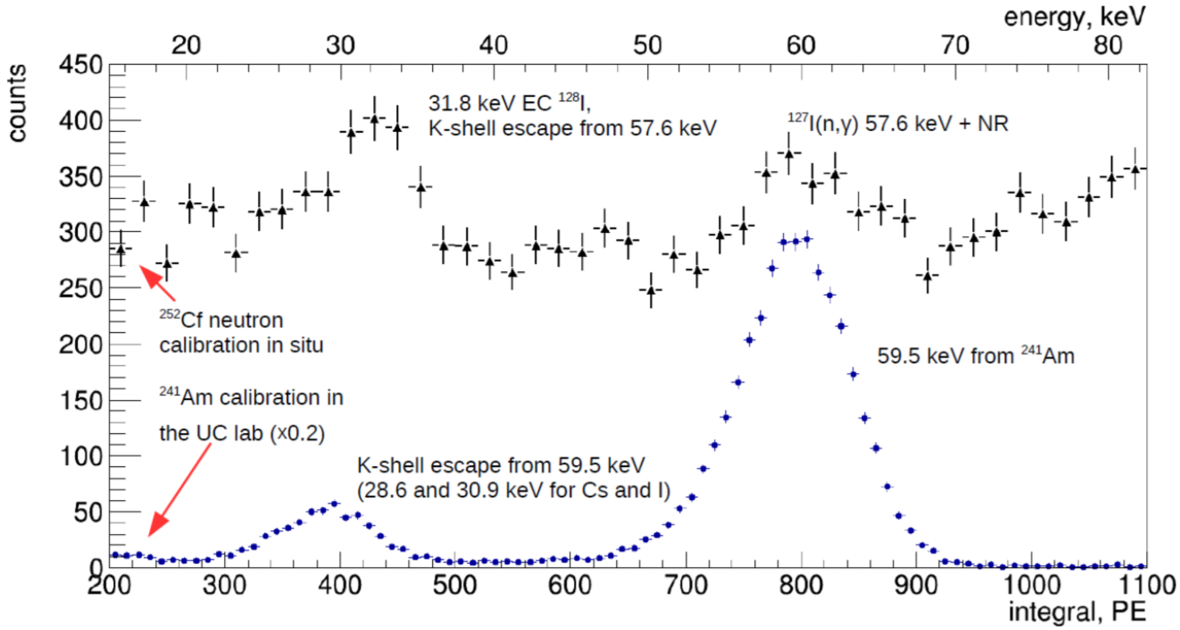


Scintillation response of the crystal to nuclear recoils



- ❑ 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

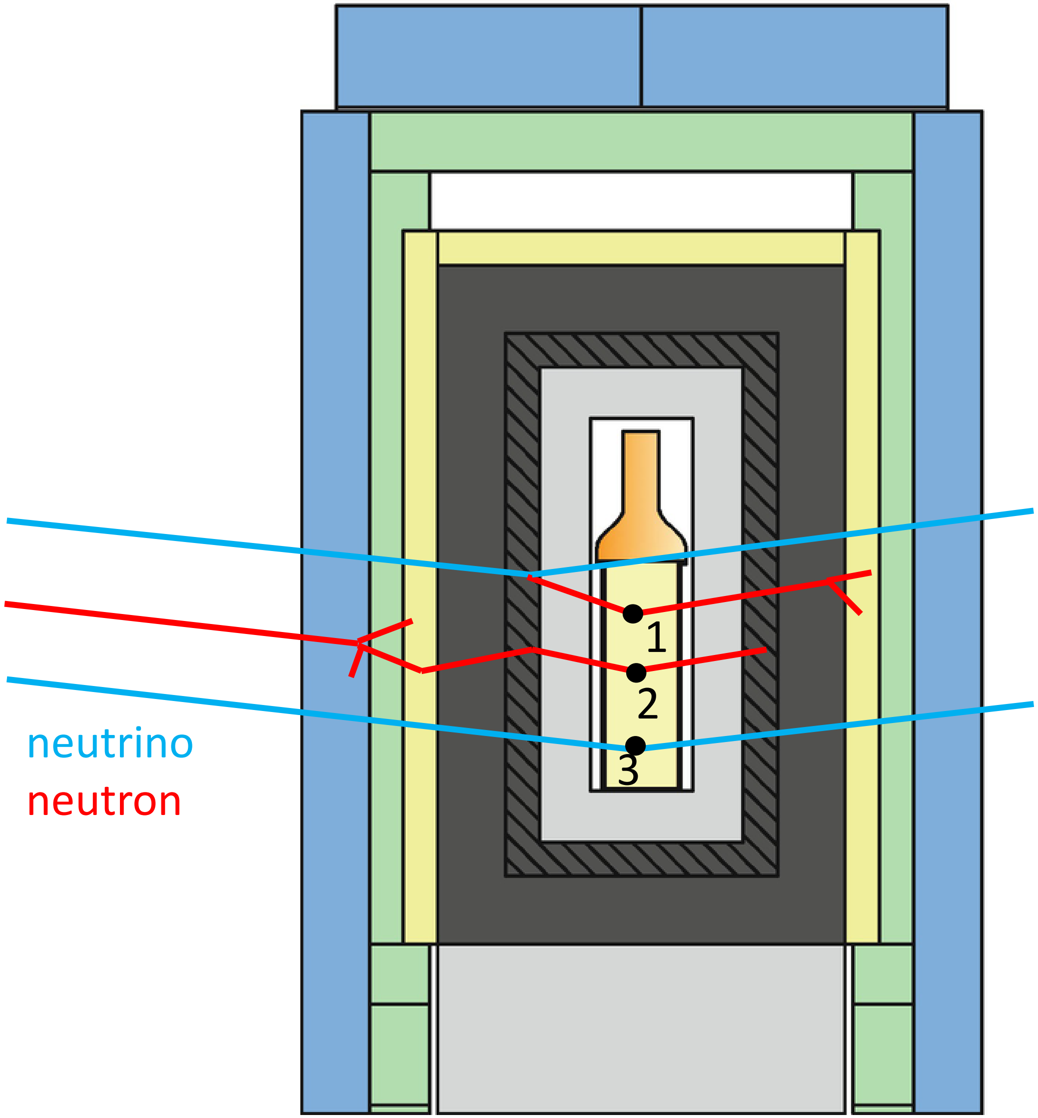


- ❑ Detector calibrated
  - 59.5 keV gamma using ^{241}Am decay calibration source
  - 57.6 keV ^{127}I(n,γ) peak using a ^{252}Cf neutron source

- ❑ 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

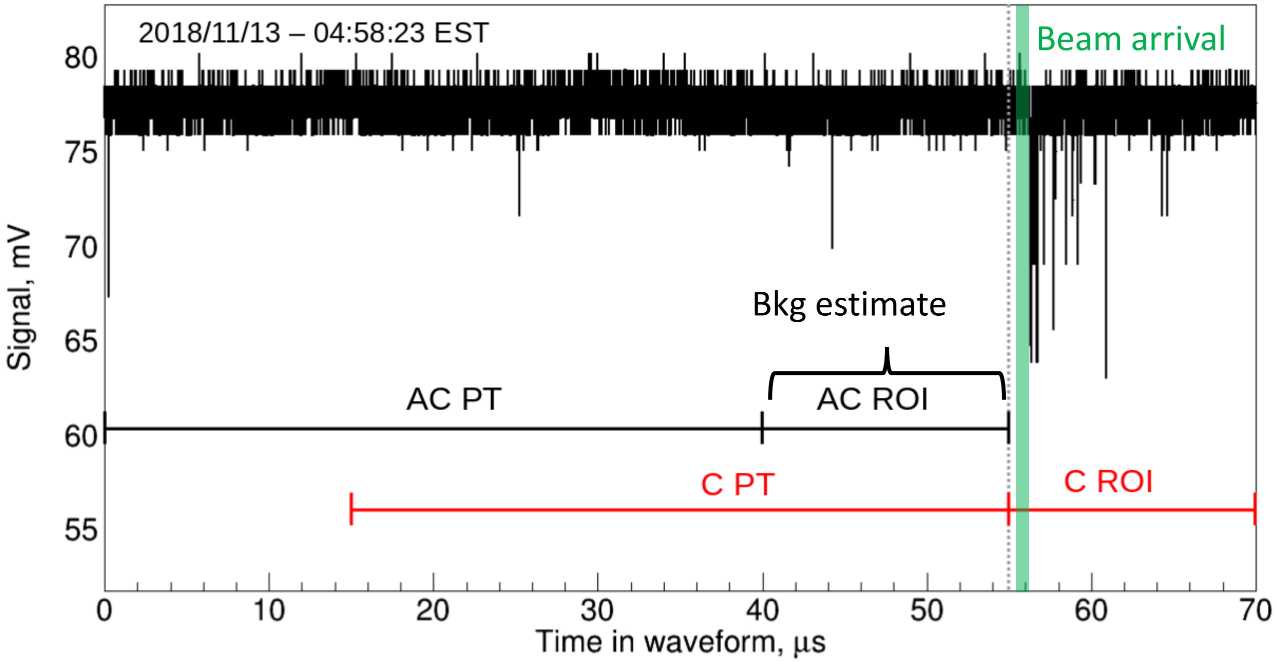
Beam-related backgrounds for DM search



- ☐ 1: Neutrino-induced neutron (NIN)
  - A neutrino from the SNS hits a lead nucleus in detector shielding, ejecting a neutron which can interact in detector
- ☐ 2: Beam-related neutron (BRN)
  - Primary neutron from accelerator sneaks through SNS and detector shielding to leave a recoil in detector
- ☐ 3: CEvNS
  - Most understood background and accounts for 91% of total

- ☐ Data from neutron detector in CsI location used to estimate neutron background and uncertainty

Waveform reconstruction

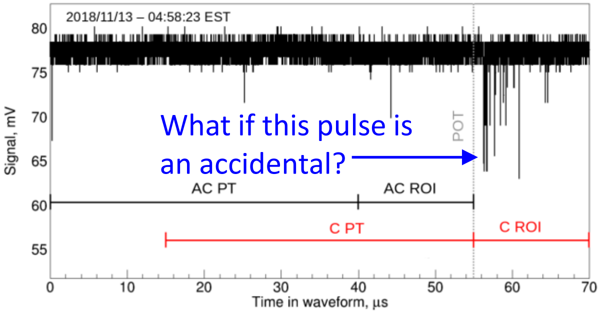


- ❑ Each waveform has a two regions-of-interest: coincident (C) with the beam and anticoincident (AC), immediately preceding the arrival of the beam
  - ROI is 15 µs
  - Each ROI has a 40 µs pretrace region to monitor scintillation activity in the crystal in real-time
  - Event begins with first reconstructed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

Mitigating common reco pathologies and background events

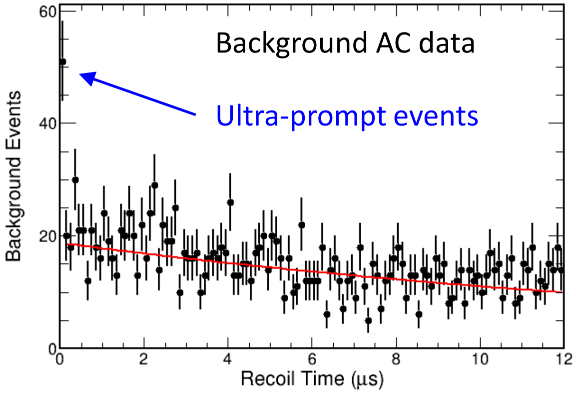
Misidentified onset



What if this pulse is an accidental?

- ❑ Afterglow rate is high enough the first pulse found in the ROI may not be from a nuclear recoil
  - "Misidentified-onset events"
  - 6% of signal events
- ❑ Stray afterglow pulses also cause us to lose signal whose first pulse is ≥ 3 µs after the afterglow pulse
  - 2% of signal events
- ❑ Also implies the timing for signal and backgrounds should be exponential

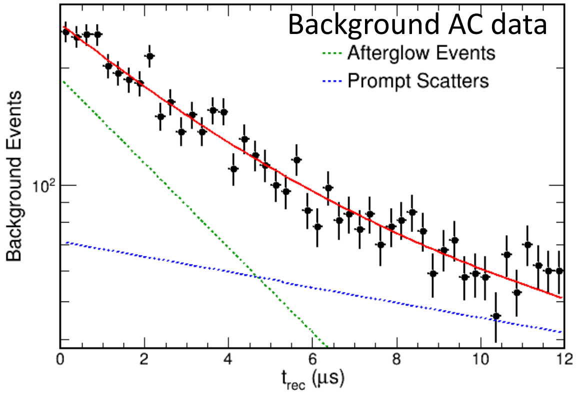
Ultra-prompt background



Ultra-prompt events

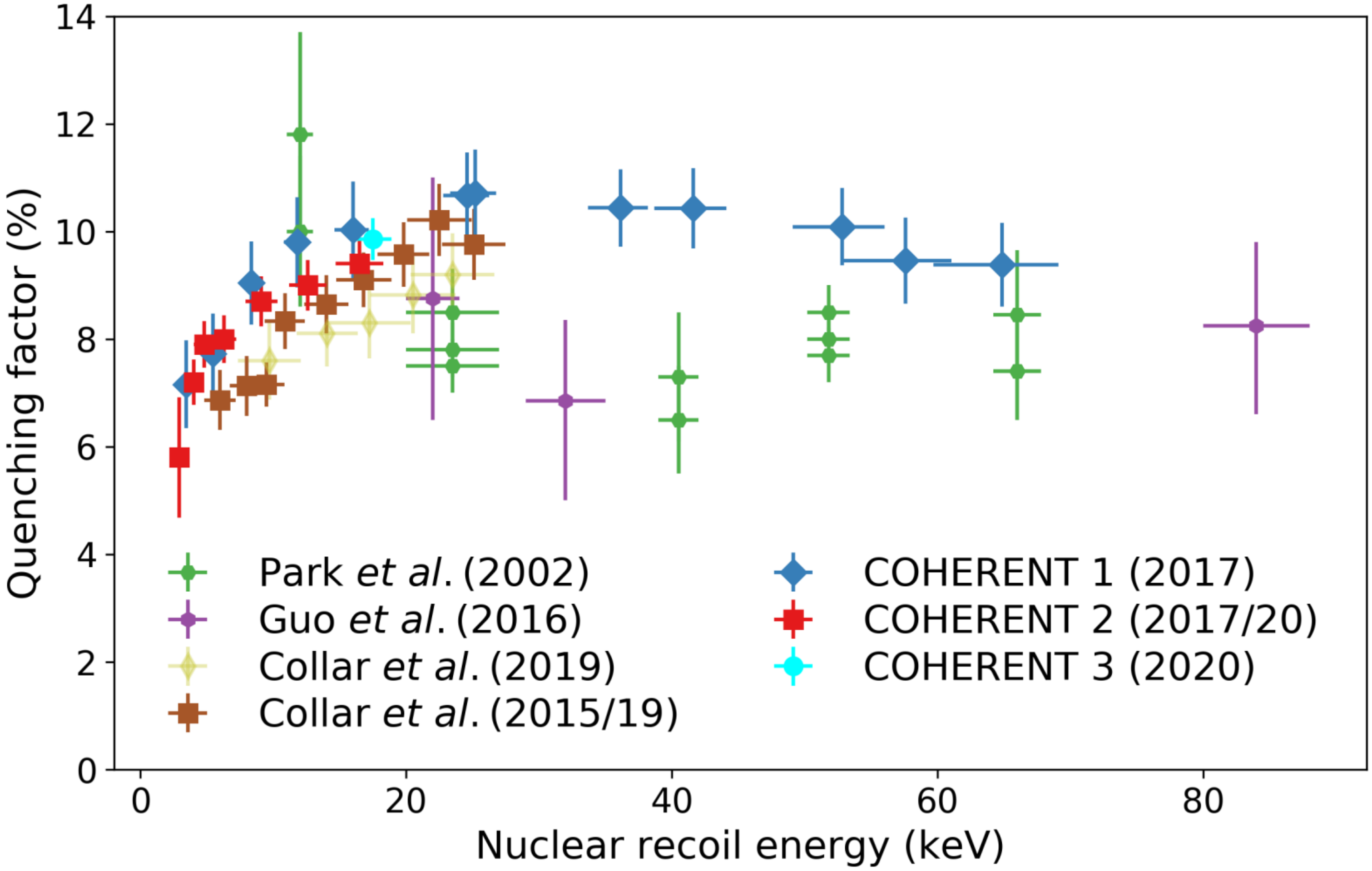
- ❑ A background event starting in the tail-end of the pretrace can sneak into the waveform ROI
  - "Ultra-prompt events"
- ❑ Requiring no PE pulse in the final 0.2 µs of the pretrace reduces the background from ≈40 events to ≈1

Afterglow background

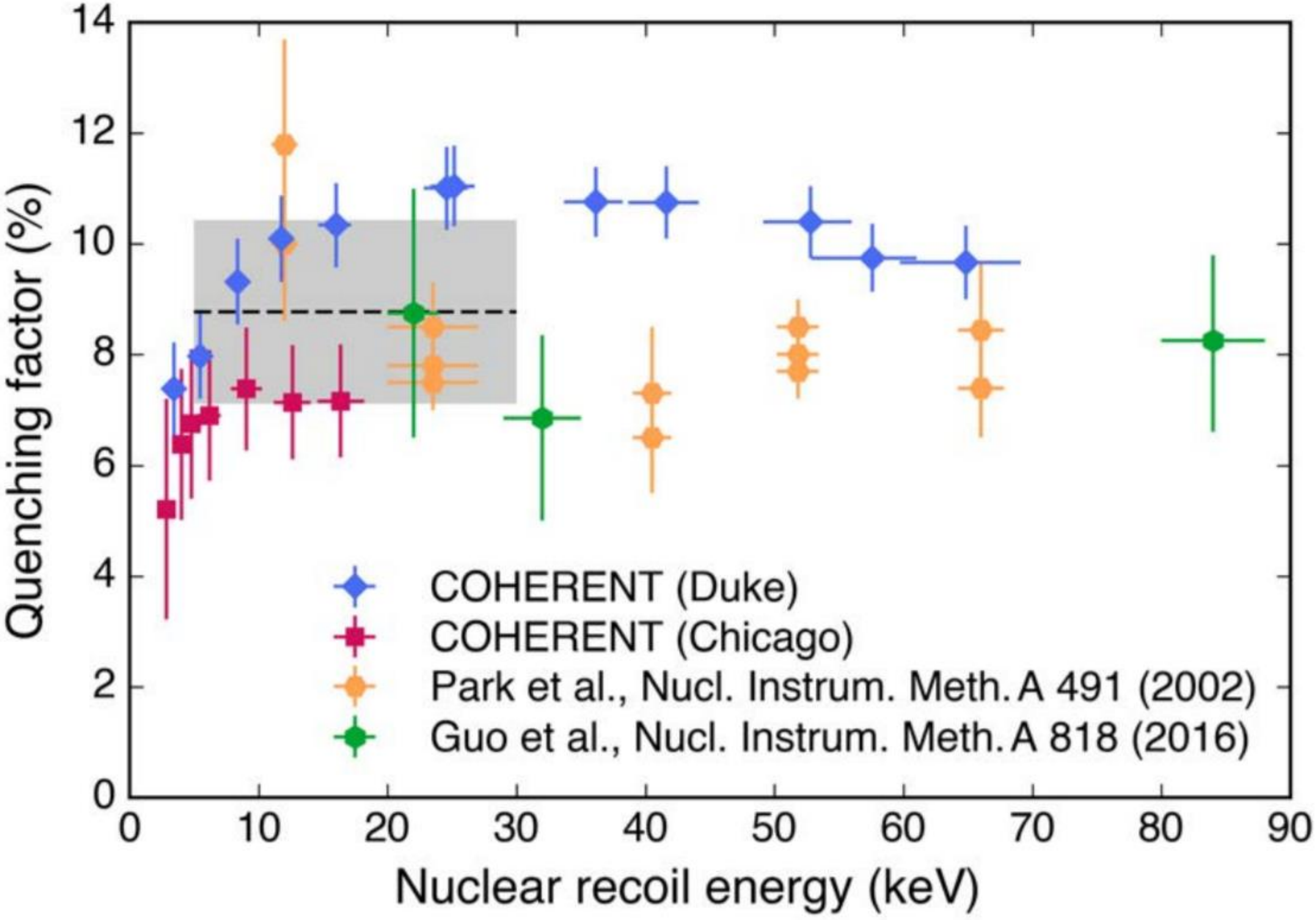


- ❑ Coincidence of afterglow pulses can fake an event
- ❑ Waveform simulation predicts these events to fall sharply in time and we see this behavior in data
- ❑ Simulation and beam-off data show afterglow events can be eliminated with a cut on the number of pulses reconstructed

Global Quenching Factor Data for CsI[Na]

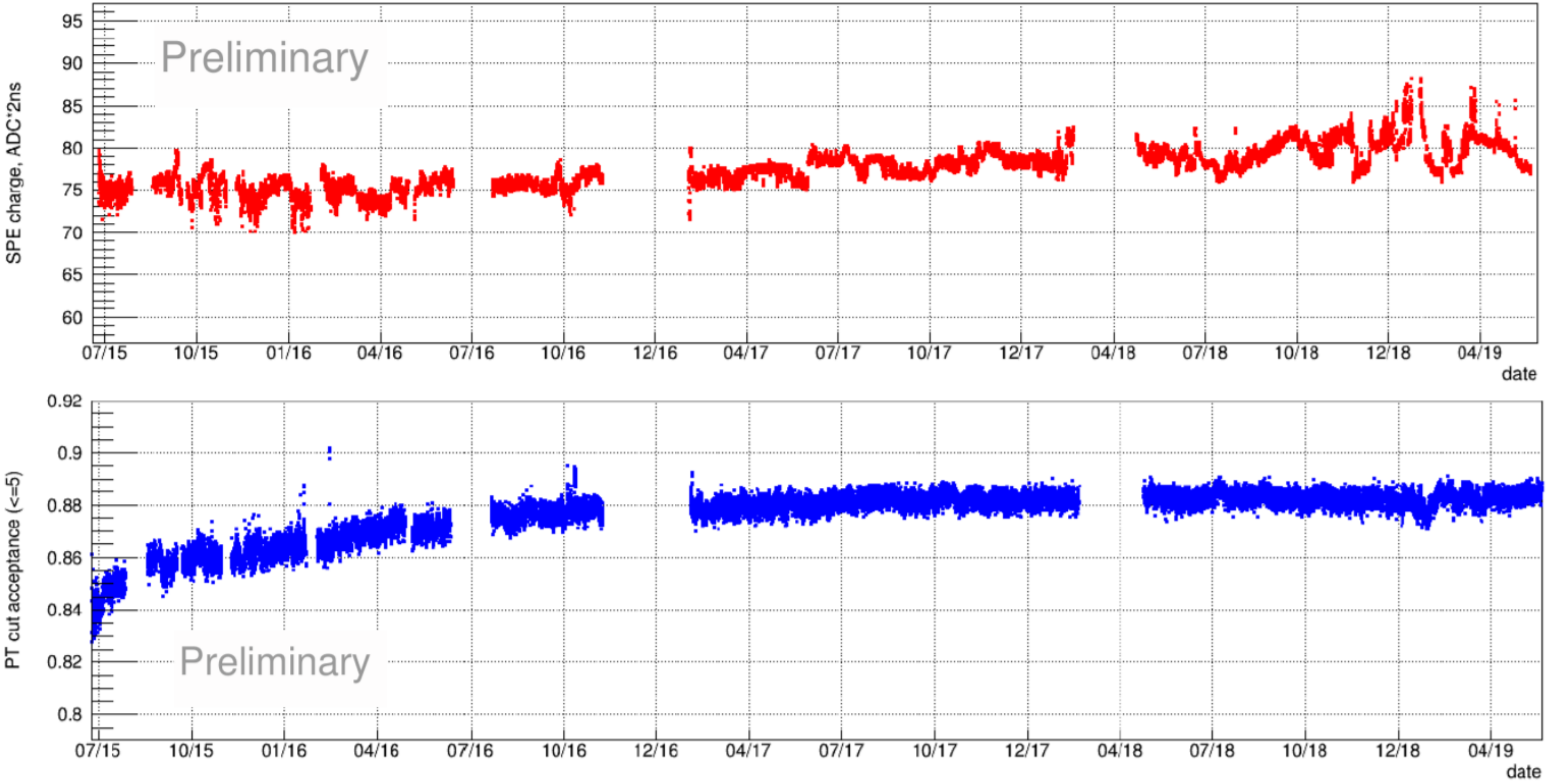


Quenching Factor Model Used in 2017 Result



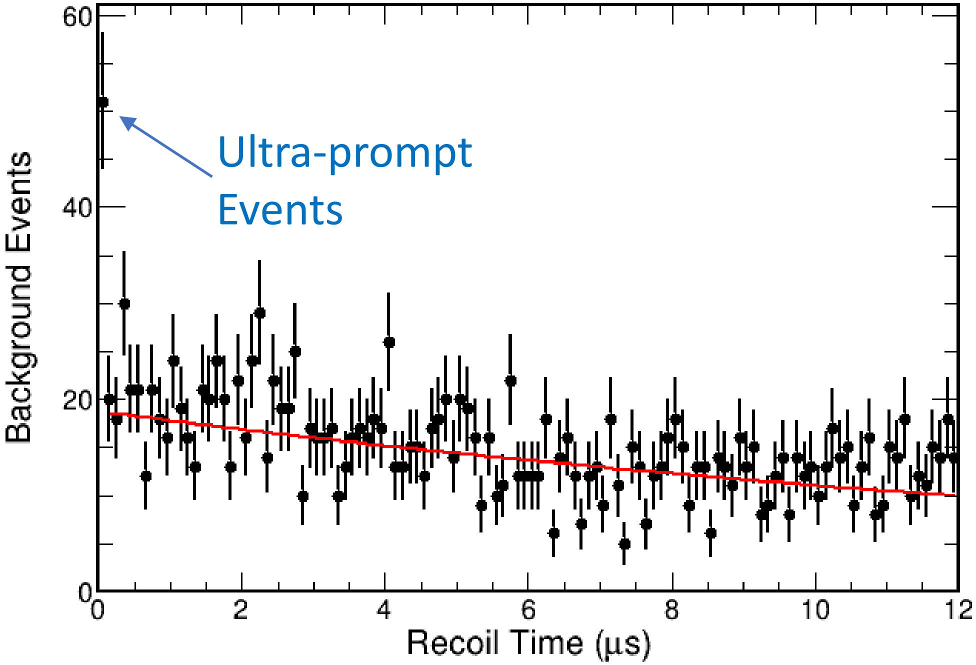
- Constant QF model with large error to encompass energy dependence for all measurements

CsI Detector Stability



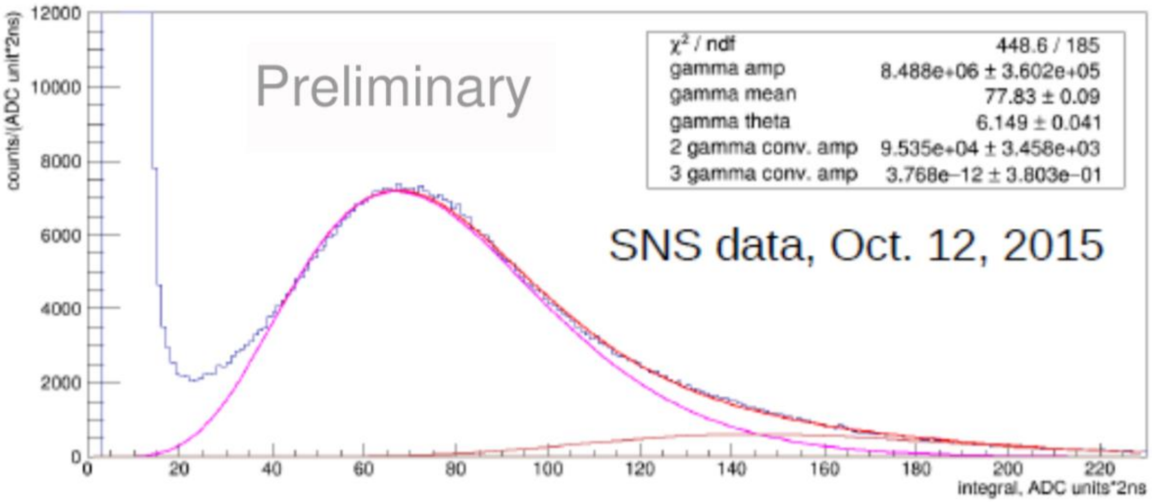
- ❑SPE charge drifts by ± 7% over detector operations which is accounted for within analysis
- ❑Acceptance is flat after one year, after initial increased afterglow rate has decayed

Removing Ultra-prompt Events



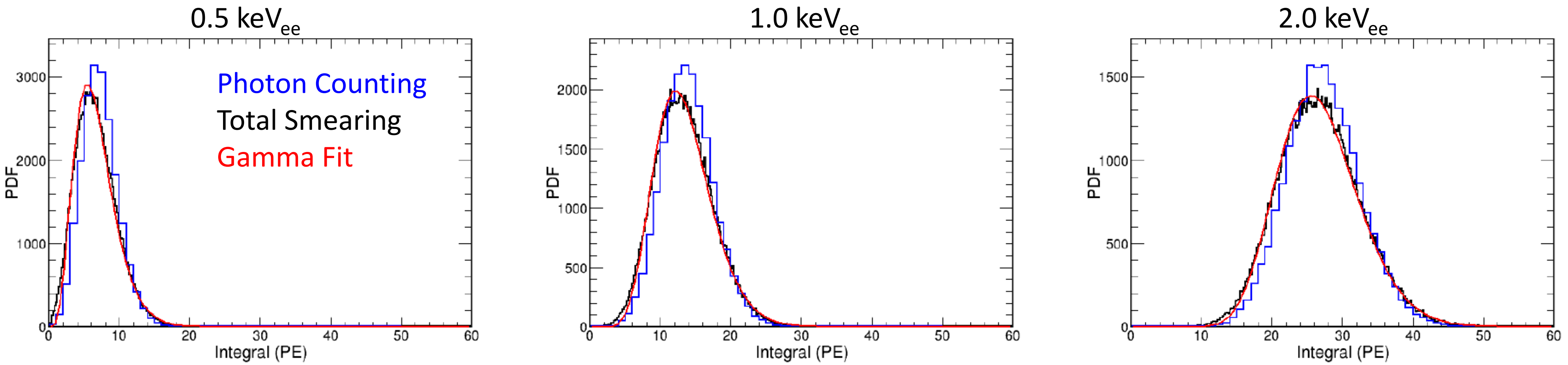
- ☐ Background events that begin in the tail-end of the AC region can sneak into the analysis C region and reconstruct within the first 0.1 μs of the ROI
- ☐ This background can be reduced from ≈40 events to ≈1 event by requiring no PE observed in the last 0.2 μs of the pretrace
  - Cut trained using waveform simulation and validated with effect on beam-off data

Single PE Shape



- We measure the single PE charge distribution during SNS conditions by integrating afterglow pulses
- High rate gives lets us monitor drifts in SPE charge on short timescales
- Width of the distribution is large, so we include smearing of single PE pulses in our energy smearing

Detector Smearing in CsI[Na]



$0.5\ \mathrm{keV_{ee}}$ $1.0\ \mathrm{keV_{ee}}$ $2.0\ \mathrm{keV_{ee}}$

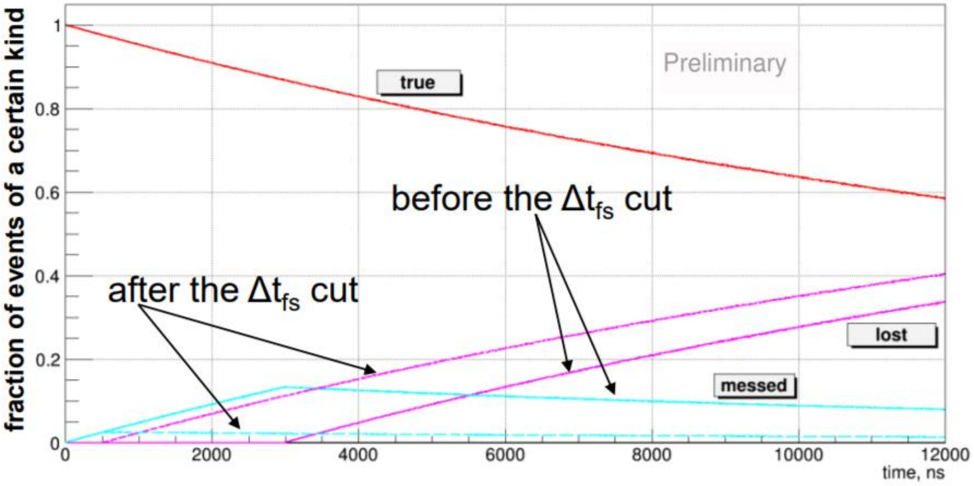
- ❑ We account for photon counting and the shape of the single PE charge distribution when determining energy smearing
- ❑ Our simulated smearing is non-Gaussian, fits well to a Gamma distribution

$$P(x) = \frac{(a(1+b))^{1+b}}{\Gamma(1+b)} x^b e^{-a(1+b)x} \qquad a = \frac{1}{x} \qquad b = 0.7157 \times x$$

x is LY × E_{ee}

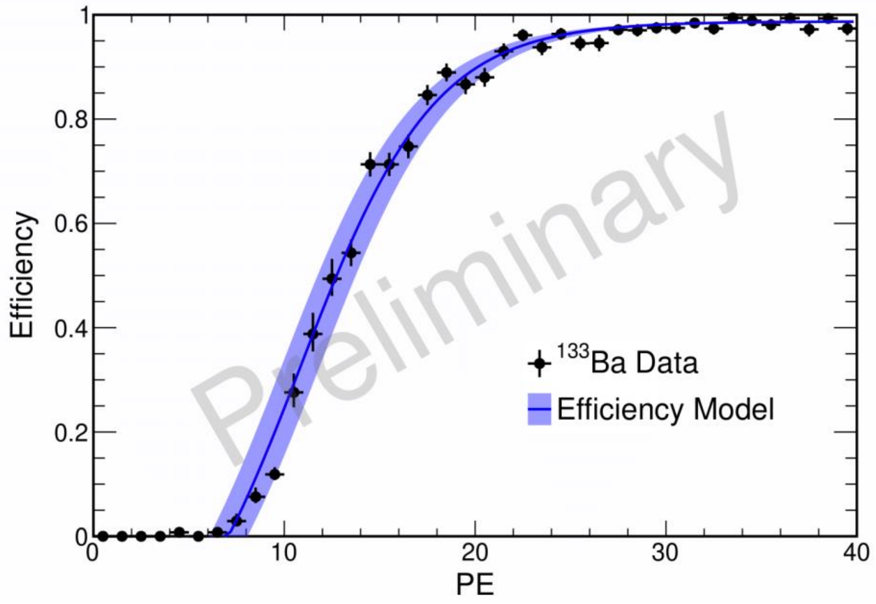
- ❑ Model shows degree of event smearing from absolute calibration of the SP charge has negligible effect on our result

Calculating Time Dependence of CEvNS Efficiency



- ☐ We estimate the t-dependence of our efficiency using a data-driven simulation
  - Overlay a simulated CEvNS recoil on a beam out-of-time data waveform
  - Library of data waveforms give unbiased sampling of afterglow pulse distribution
- ☐ Properly reconstructed events fit very well to an exponential distribution
- ☐ We can reduce the fraction of misidentified onset events by a factor of 5 by the Δt_{fs} cut

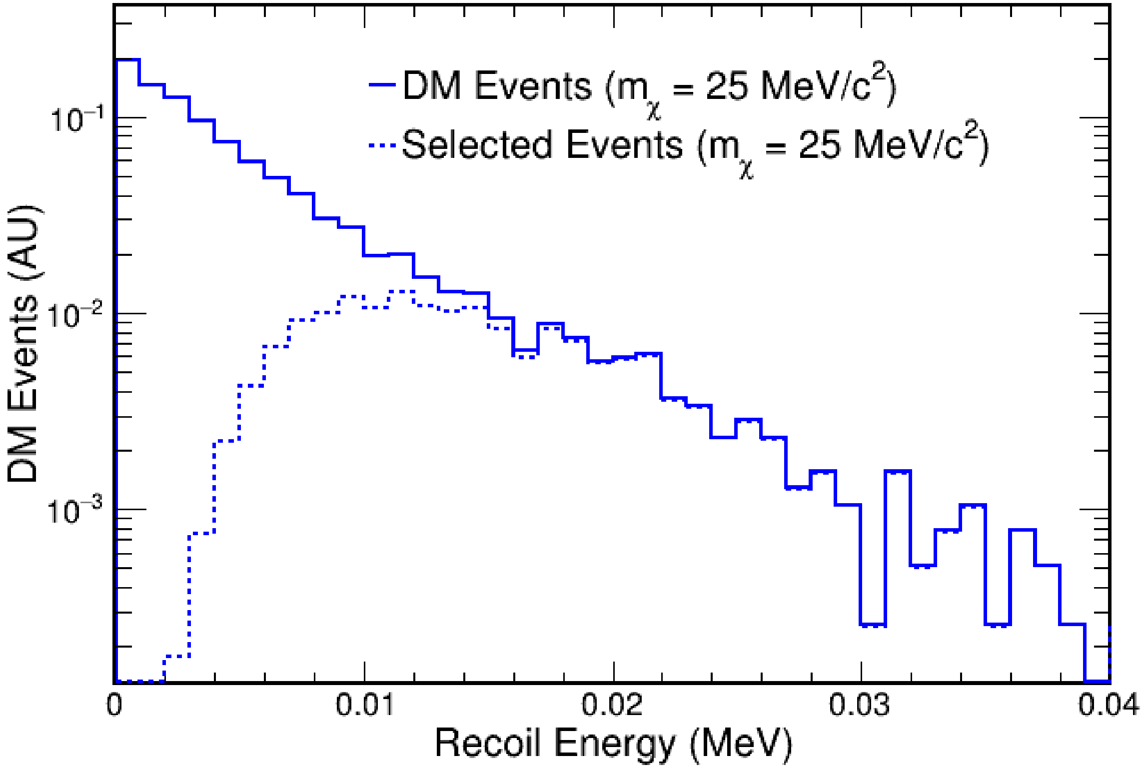
Efficiency Uncertainty



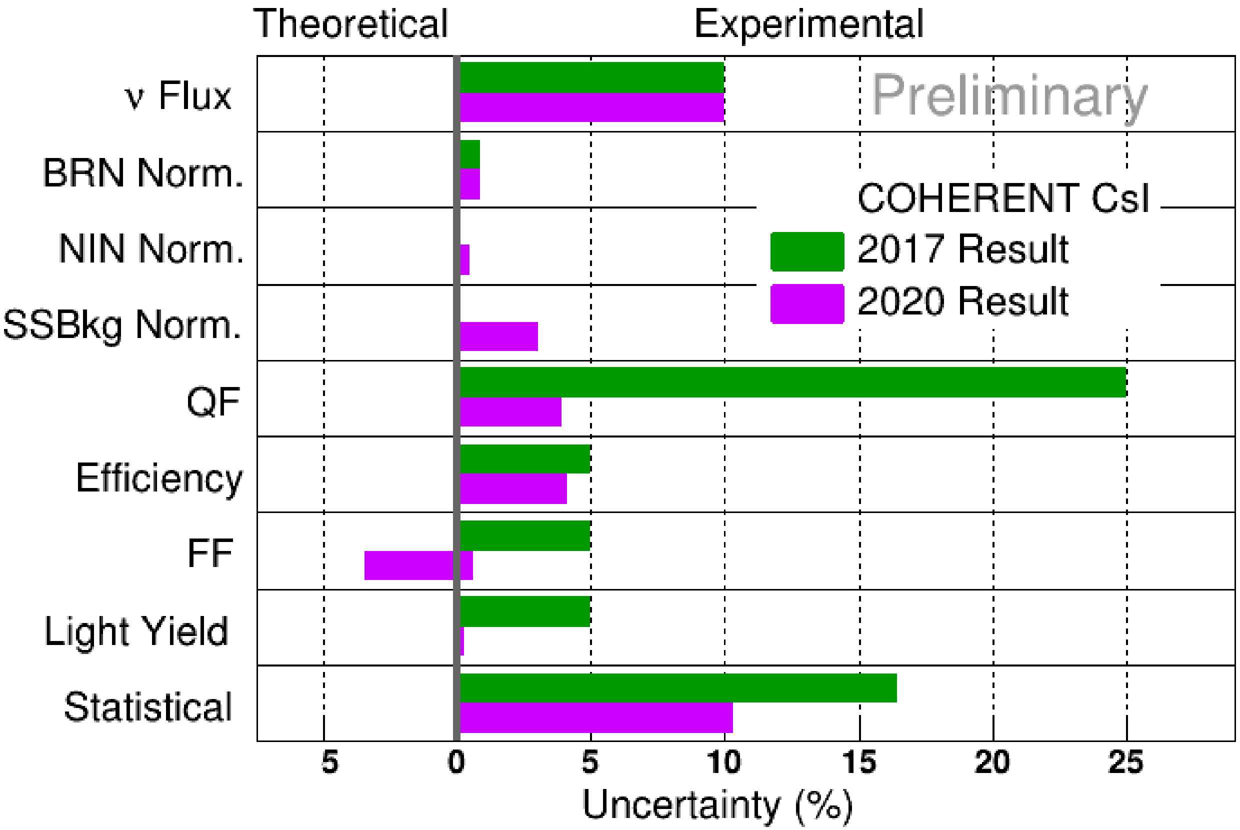
- ☐ Use same PCA strategy to determine an error band for our efficiency
- ☐ PE part of efficiency calibrated with ^{133}Ba data
- ☐ Almost all variance in the covariance matrix is explained by just the first eigenvector
  - Physically, this vector roughly equates to a change in the threshold by ≈1 PE

Efficiency for dark matter

- ❑ We have a 50% detection efficiency around a threshold of 9 keV_{nr}
- ❑ The t-dependence of our efficiency not a large effect since DM recoils are prompt
- ❑ We expect 21% efficiency at our most sensitive DM mass, 25 MeV/c^2

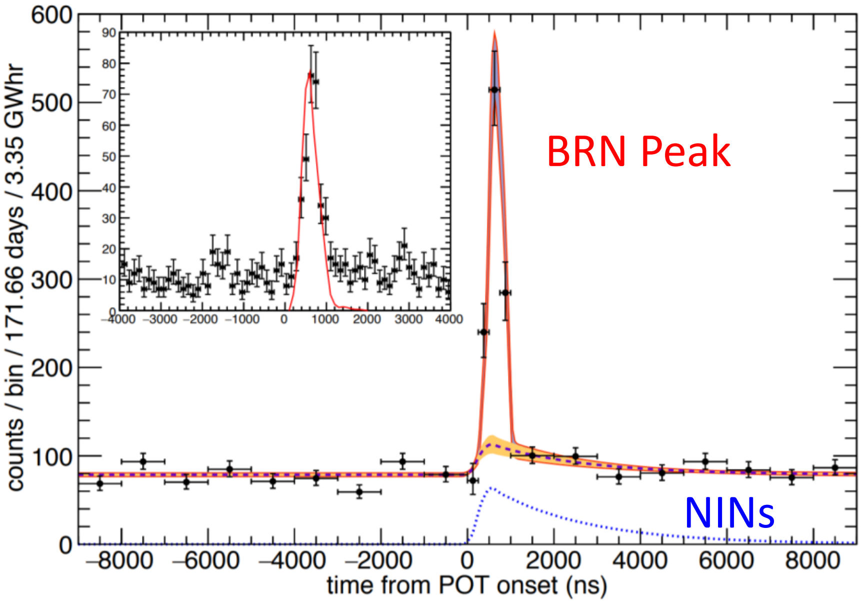


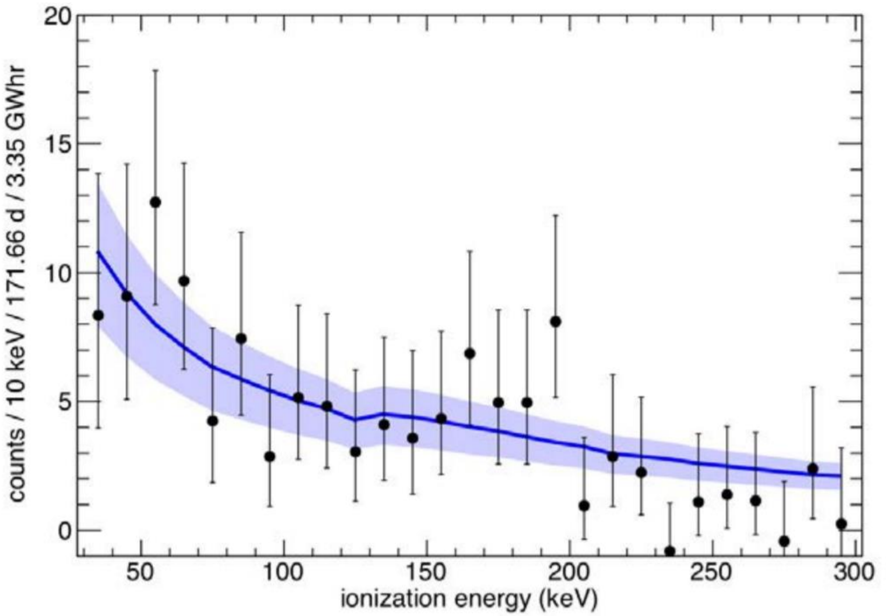
Measurement Uncertainties



- ❑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%

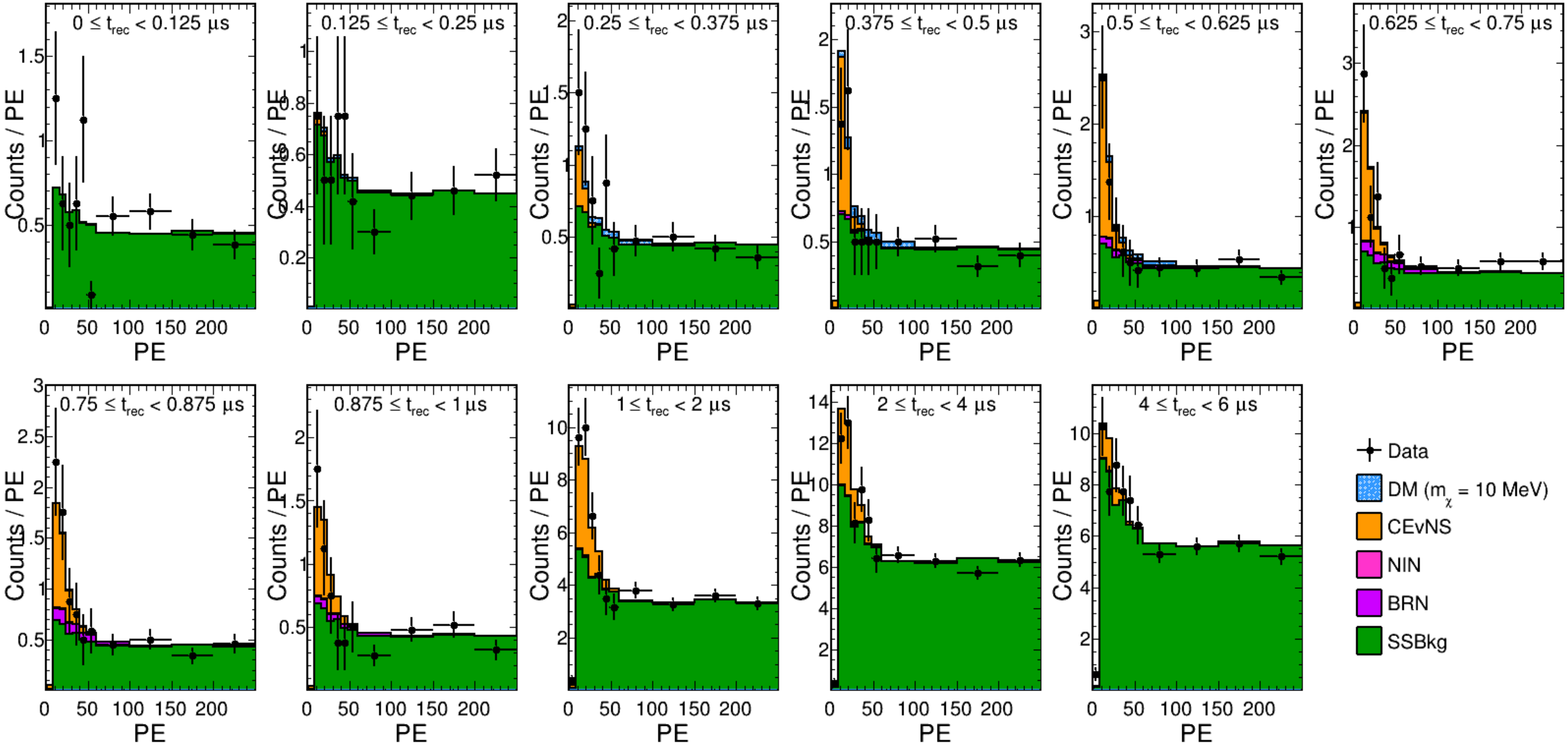
Neutron Backgrounds in CsI[Na]



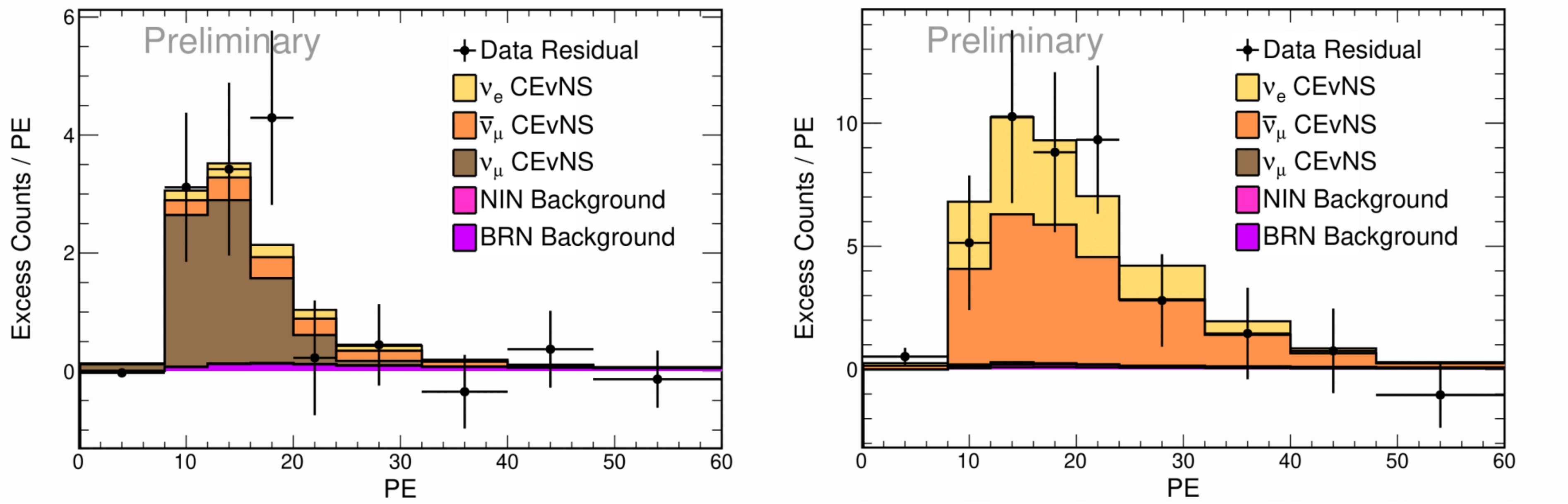


- ❑ Ran Eljen cell scintillator in CsI shielding to study neutron backgrounds in detector location
- ❑ Fit to timing data gives the relative ratio of BRN and NIN events with uncertainties
- ❑ MCNP simulation predicts the observed recoil distribution very well in the Eljen cells
- ❑ Ran observed neutrino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

2D Spectra for Dark Matter Search

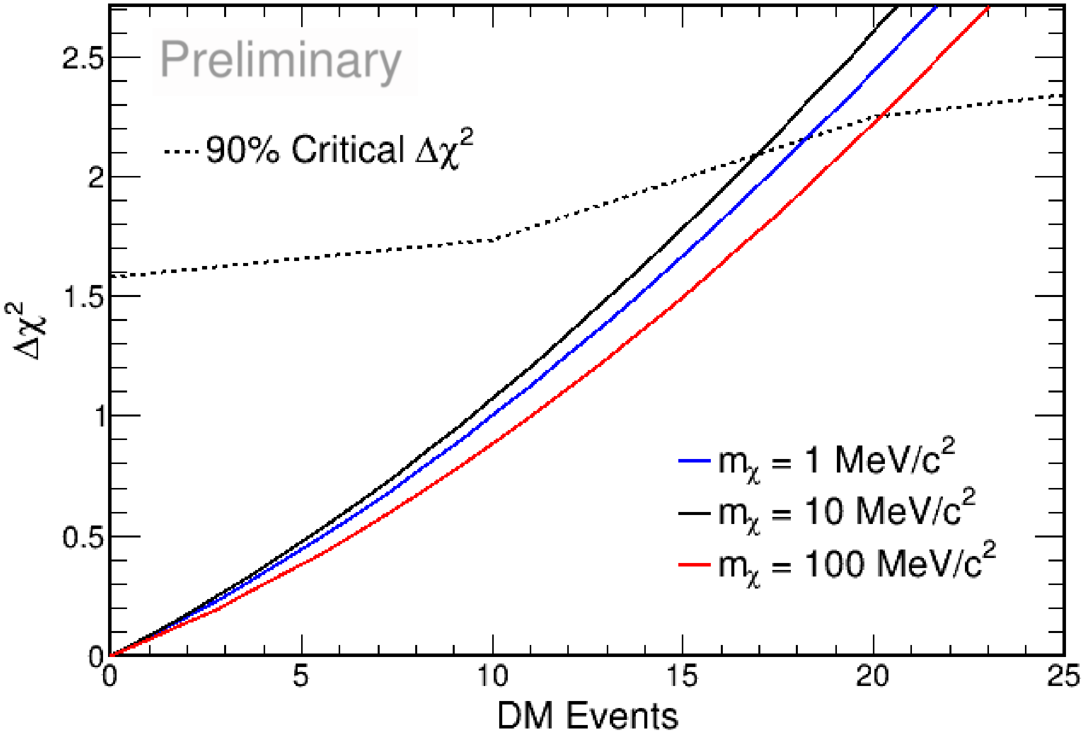


Counting Experiment-style Samples



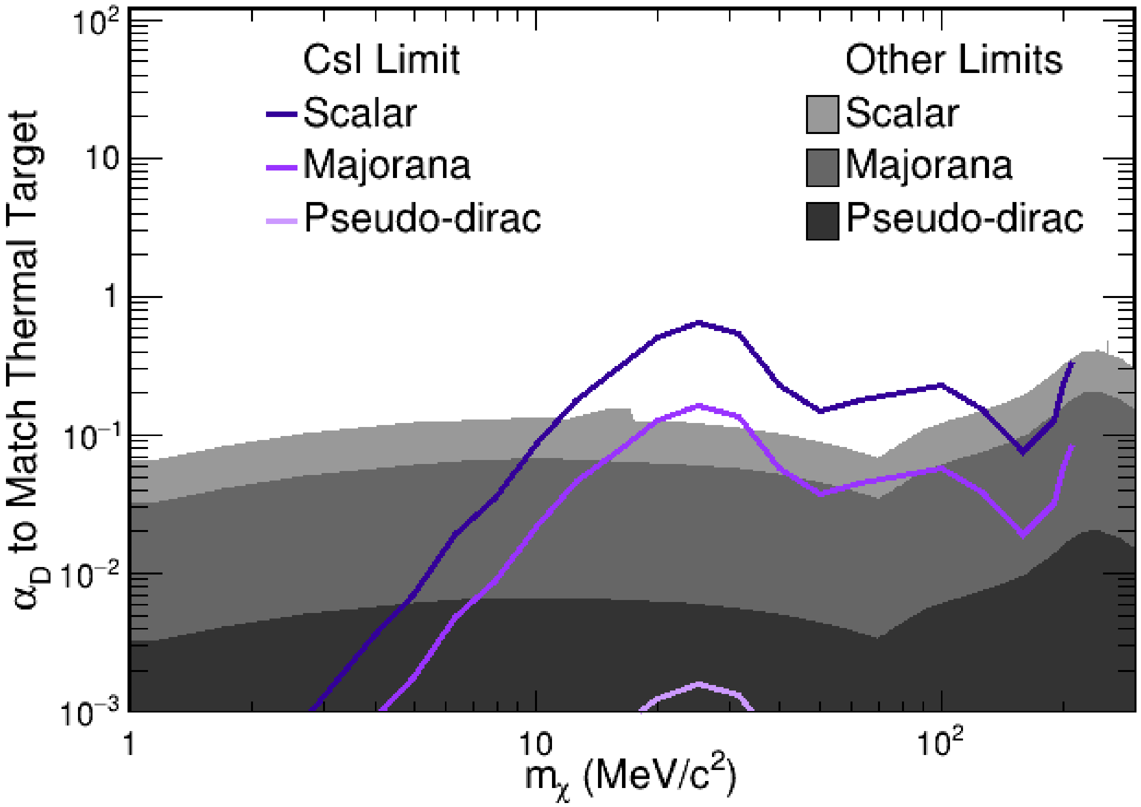
- ☐ We can isolate CEvNS from different neutrino flavors by selecting different time regions
  - ν_μ: $0.125 < t_{rec} < 0.5$ μs
  - $\nu_e/\bar{\nu}_\mu$ $0.875 < t_{rec} < 4$ μs
- ☐ Apply global best fit to prediction for each sample
- ☐ Agreement of observed shape good test of our understanding of shape effects in our flux, quenching, and efficiency

Looking for dark matter in our data



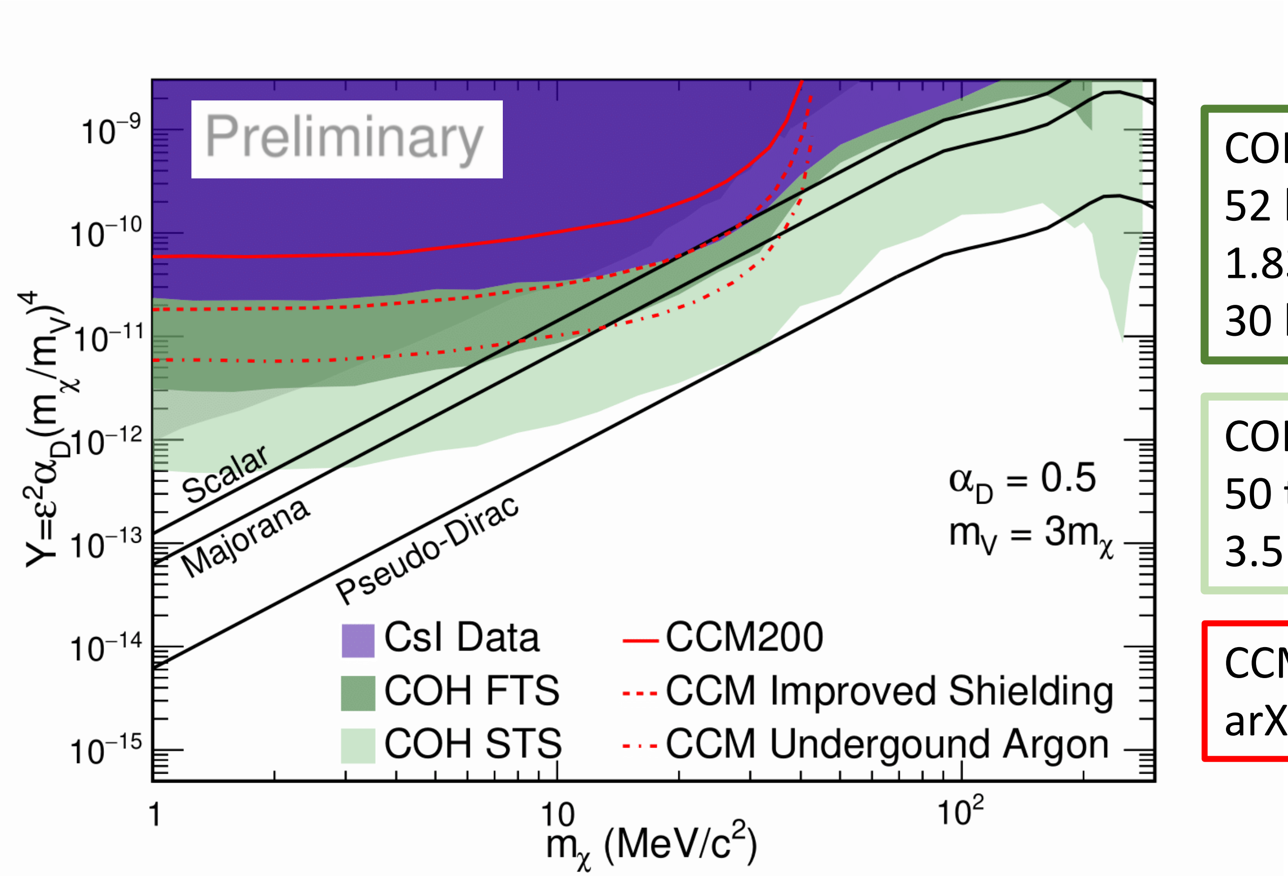
- ❑ No evidence for DM – best fit is $N_{\rm DM} = 0$ and best we can do is constrain parameter space
- ❑ Since we're near a boundary, $N_{\rm DM} \geq 0$, we expect non-Gaussian statistics and thus simulate the expected $\Delta\chi^2$ explicitly with the Feldman-Cousins method

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

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

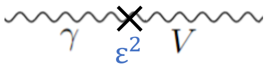
CCM sensitivity:
arXiv: 2105.14020

- 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

Searching for leptophobic dark matter

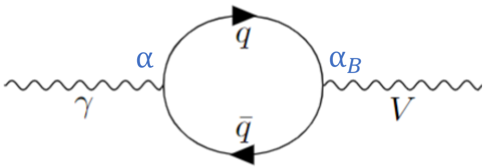
- ❑ Above model assumes a general BSM kinetic mixing between photon and portal particle

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

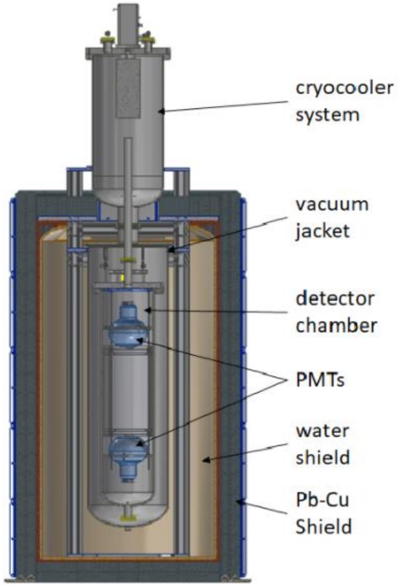
Leptophobic dark matter:



- ❑ 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

Ongoing COHERENT Activity

- ☐ NUBEs studying NIN cross sections
- ☐ Supernovae neutrinos + CEvNS background
- ☐ Scintillator encased in Pb/Fe/Cu with water brick shielding



- ☐ CENNS-10
- ☐ CEvNS on LAr
- ☐ Dataset doubled since first result
- ☐ Continued physics data + R&D for future Ar program

- ☐ NaIvE: 185 kg NaI scintillator
- ☐ Measuring inelastics on ^{127}I for 0νββ searches
- ☐ Prototype future ton-scale CEvNS detector

- ☐ Neutron flux studies with portable MARS
- ☐ Scintillator covered with Gd paint to study captures