Neutrino Physics at the ORNL Second (and First) Target Station

Snowmass Neutrino Frontier White Paper Coordination Meeting

LOI submitted in August 2020

…now we need to turn this into a white paper…

Note several other connected LOIs/whitepapers (CEvNS, COHERENT, Neutrinos@ORNL, specific physics topics)

Neutrino Opportunities at the ORNL Second Target Station

August 2020

NF Topical Groups:
- ■ (NF1) Neutrino oscillations
- ■ (NF2) Sterile neutrinos
- ■ (NF3) Beyond the Standard Model
- ■ (NF4) Neutrinos from natural sources
- ■ (NF5) Neutrino properties
- ■ (NF6) Neutrino cross sections
- ■ (TF11) Theory of neutrino physics
- ■ (NF9) Artificial neutrino sources
- ■ (NF10) Neutrino detectors
- ■ (CF1) Dark matter: Particle-like
- ■ (IF1) Quantum Sensors
- ■ (IF2) Photon Detectors
- ■ (IF7) Electronics/ASICs
- ■ (IF8) Noble Elements

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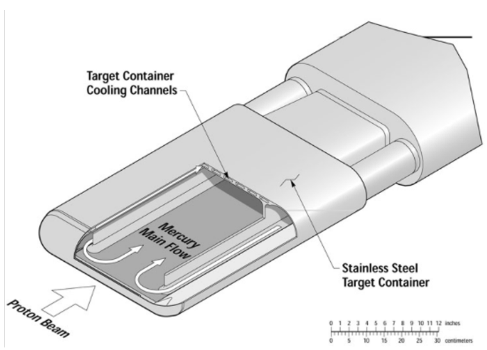
Authors:

Abstract: The Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS) First Target Station (FTS), used by the COHERENT experiment, provides an intense and extremely high-quality source of pulsed stopped-pion neutrinos, with energies up to 50 MeV. Upgrades to the SNS are planned, including a Second Target Station (STS), which will approximately double the expected neutrino flux while maintaining quality similar to the FTS source. We describe here several opportunities for neutrino physics, other particle physics, and detector development using the FTS and STS neutrino sources.

First Target Station

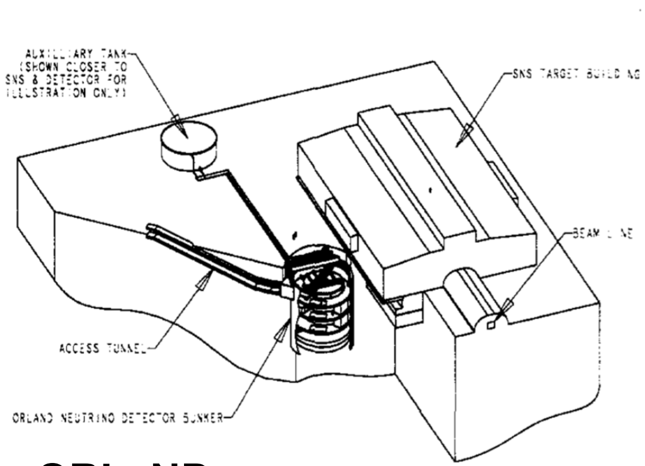


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

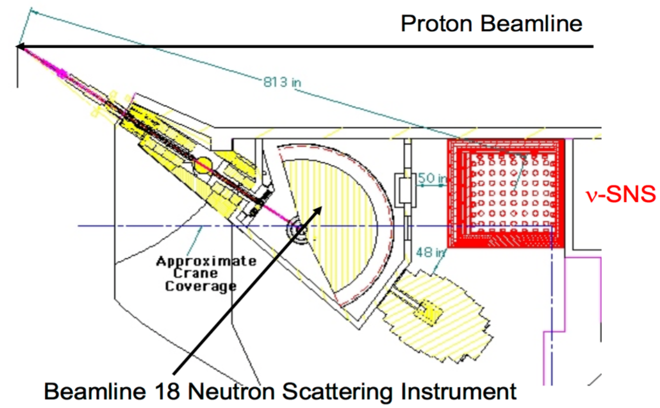
Past neutrino efforts at the SNS

Year 2000



ORLaND
2000-ton liquid scintillator

Year 2005

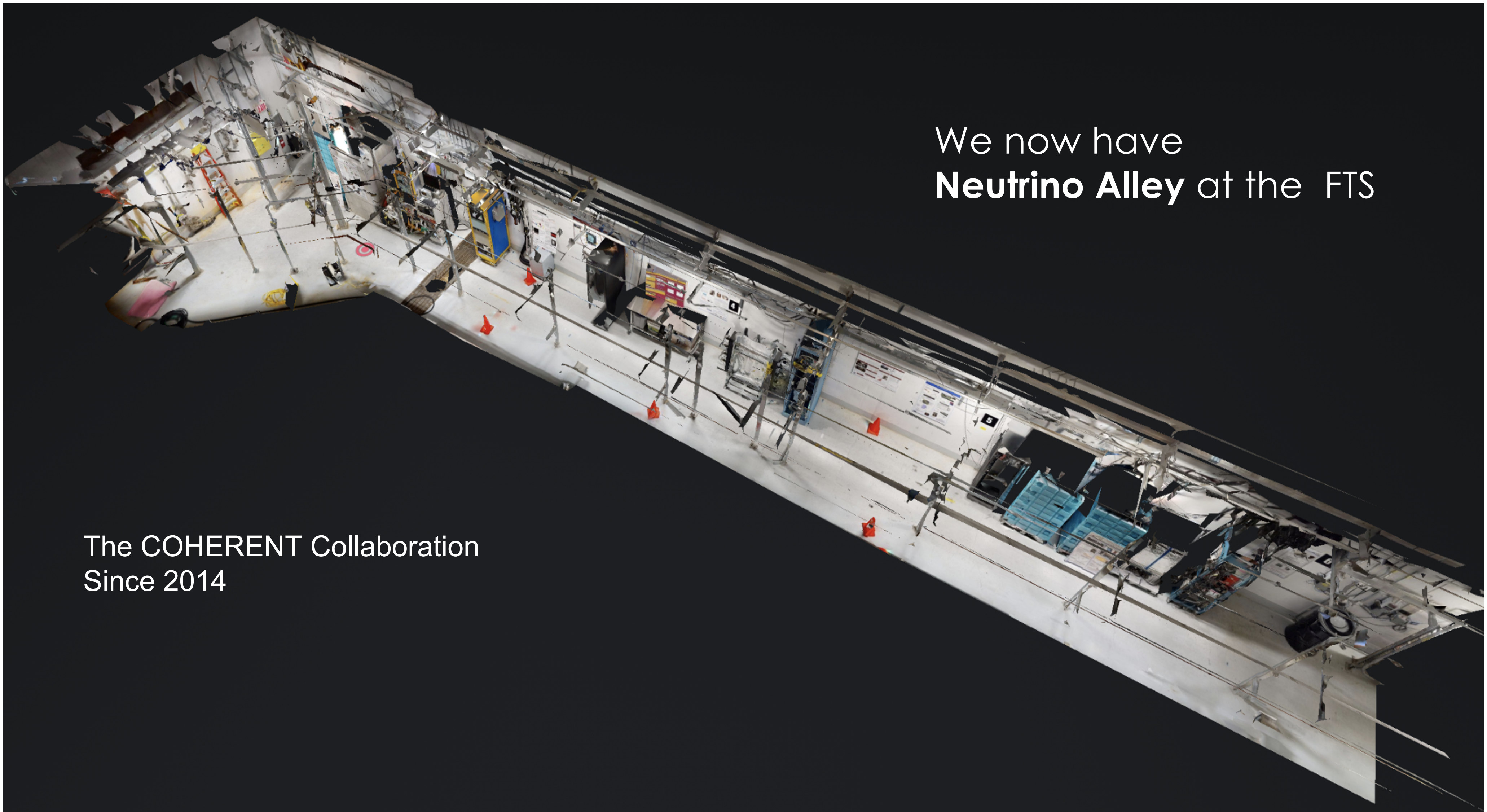


νSNS
20-ton Liquid Scintillator Detector
20-ton Solid-target Gas Detectors

- SNS construction completed in 2006 and began neutron scattering program in 2007.
- In 2009, CLEAR proposed to install 0.5-ton detector 46 m from source.
- As of 2013, there was still no neutrino experimental program at the SNS.

Workshop at ORNL considered what could be done with a ~10kg detector.

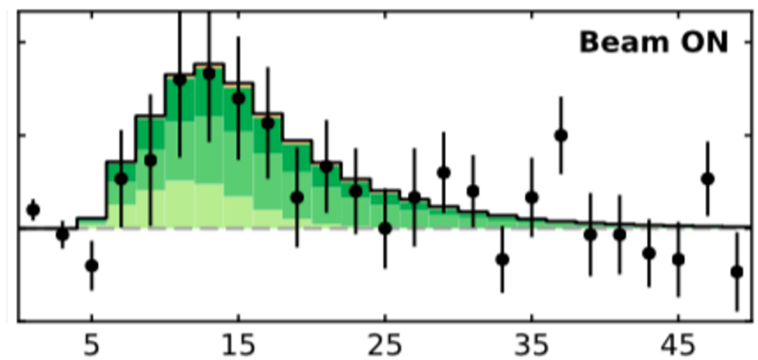
We now have
Neutrino Alley at the FTS

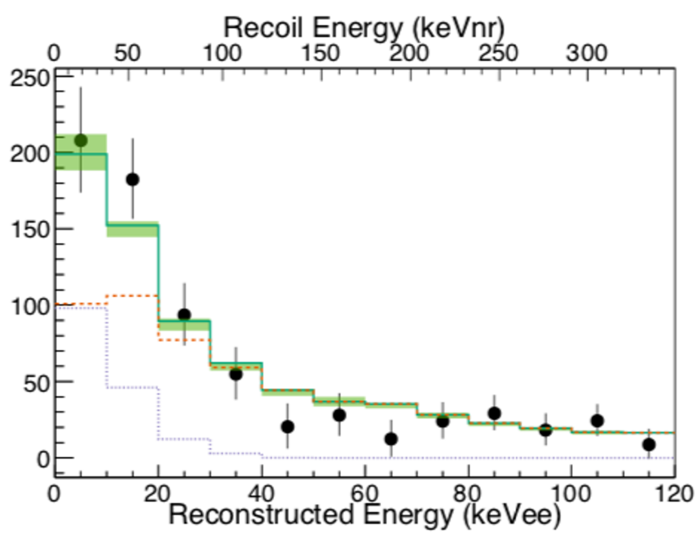


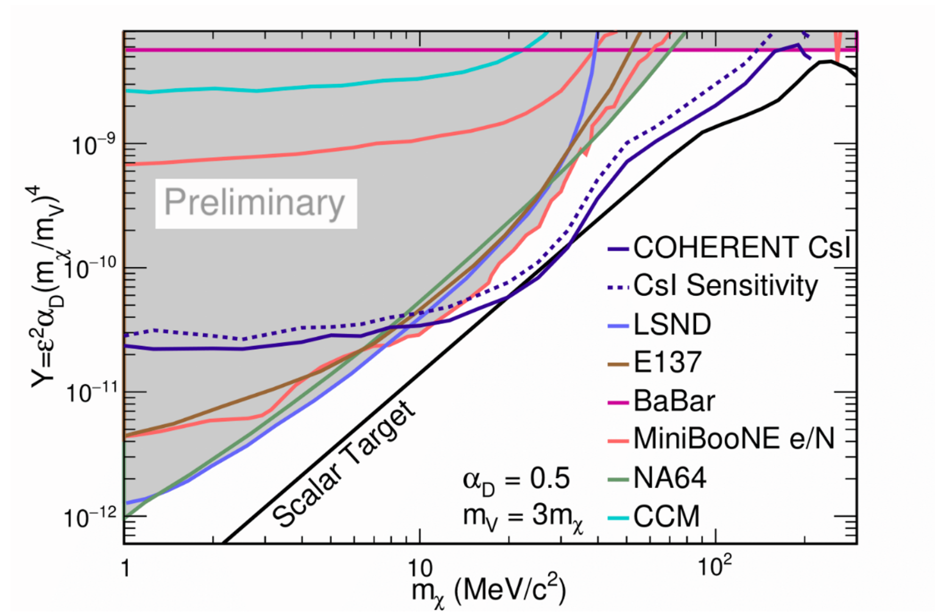
The COHERENT Collaboration
Since 2014

COHERENT Physics Results

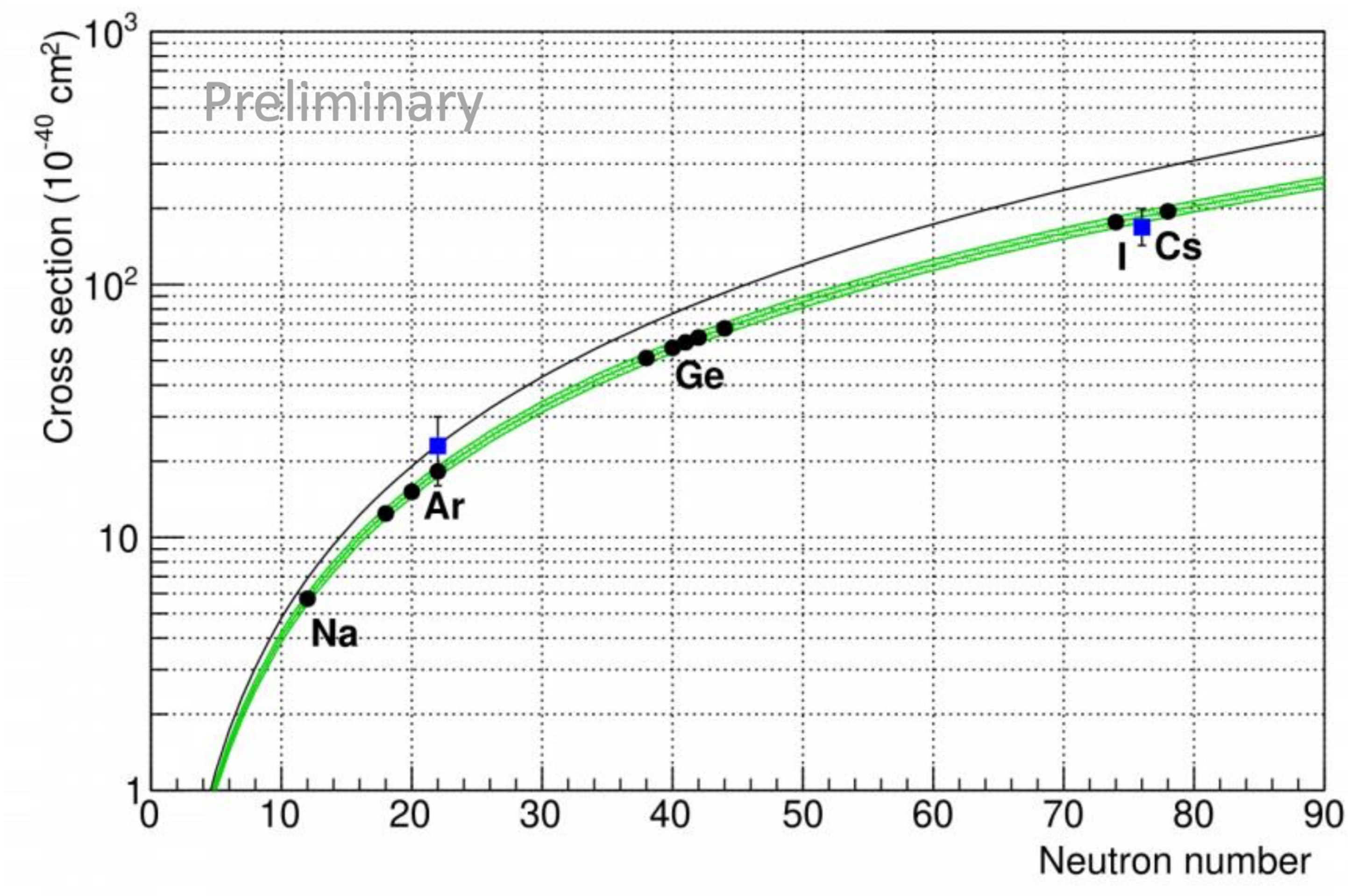
- First light CEvNS on CsI (Cover of *Science*, 2017)
- Second CEvNS measurement on argon (2020)
- **NEW:** First dark matter limits to probe beyond the scalar target (2021)
  https://indico.phy.ornl.gov/event/126/





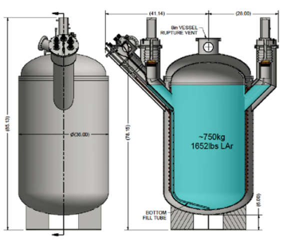


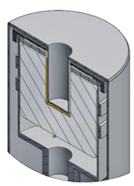
Aim for precision CEvNS SM test over a range of N

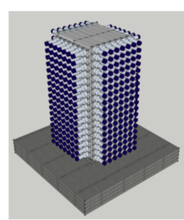


COHERENT **CEvNS** Detector Status and **Farther Future**

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	19.3	6.5	9/2015	Decommissioned
Ge	HPGe PPC	18	22	<few	2021	Funded by NSF MRI, in progress
LAr	Single-phase	24	27.5	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	25	13	*high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes





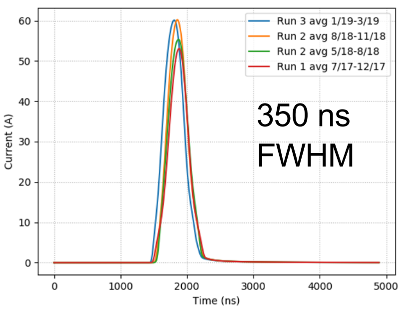


+D_2O for flux Normalization
+ CryoCsI
+ concepts for other targets...

What makes Neutrino Alley so good for neutrinos?

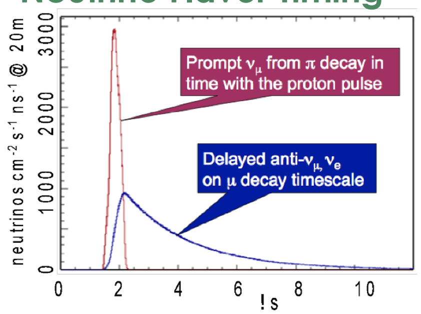
Pulsed Timing Structure of Neutrinos

Measured Proton Pulse

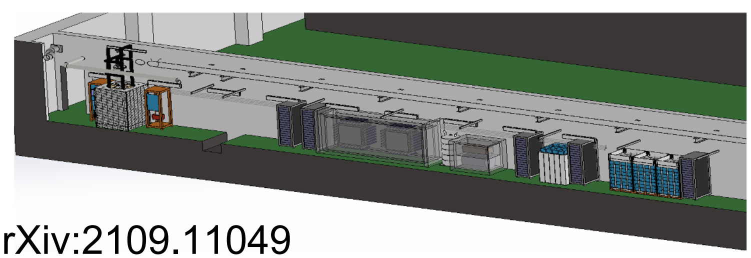


Lara Blokland, UTK

Neutrino Flavor Timing

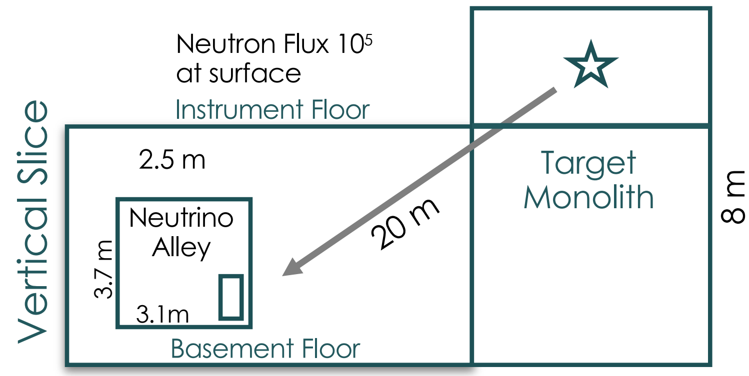


- Constrains systematics on beam-related backgrounds.
- Enables flavor dependent analyses
- Enables prompt searches for exotic particles

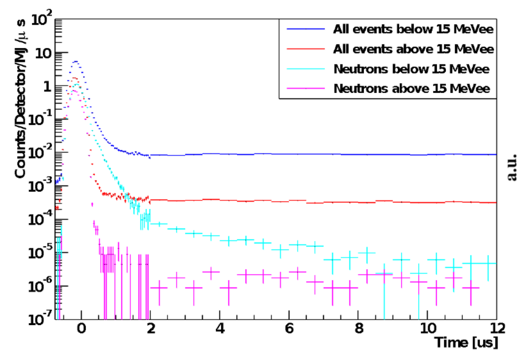


arXiv:2109.11049
4.7×10^7 ν_x/cm^2/s @ 20 m

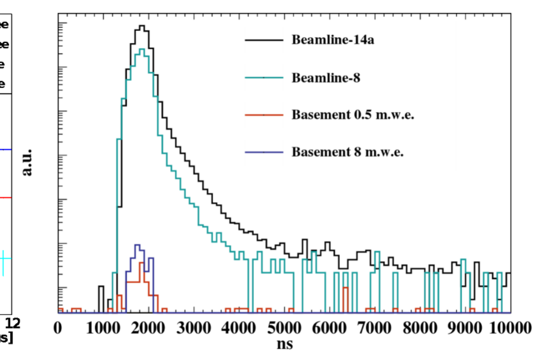
Neutrino Alley is well-shielded from beam related backgrounds



SNS Instrument Floor



Basement Shielding



An ORNL Perspective on the Future of Neutrinos at the SNS

PPU project: Double the power of the existing accelerator structure

- First Target Station (FTS) is optimized for thermal neutrons
- Increases the brightness of beams of pulsed neutrons
- Provides new science capabilities for atomic resolution and fast dynamics
- Provides a platform for STS

STS project: Build the second target station with initial suite of beam lines

- Optimized for cold neutrons
- World-leading peak brightness
- Provides new science capabilities for measurements across broader ranges of temporal and length scales, real-time, and smaller samples

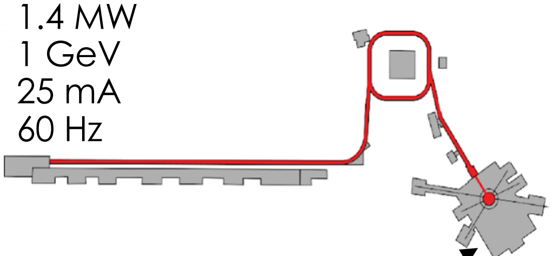
Slide from Ken Herwig, Workshop on Fundamental Physics at the Second Target Station (FPSTS18)

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

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.4 MW
1 GeV
25 mA
60 Hz

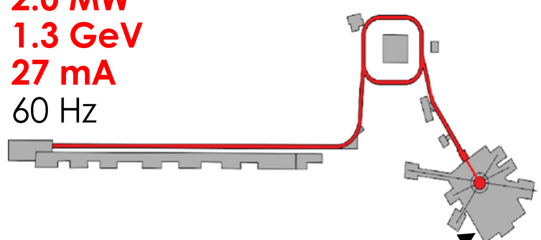


FTS
1.4 MW
60 Hz

2024 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



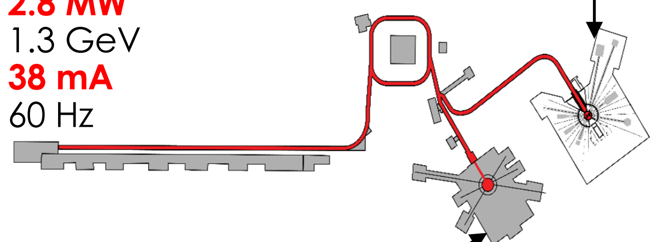
FTS
2 MW
60 Hz

2028 after STS

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

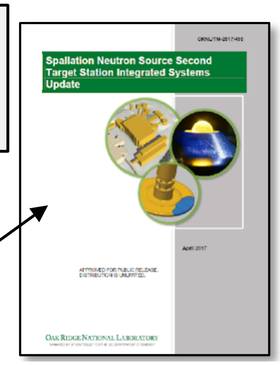
STS
0.7 MW
15 Hz

2.8 MW
1.3 GeV
38 mA
60 Hz

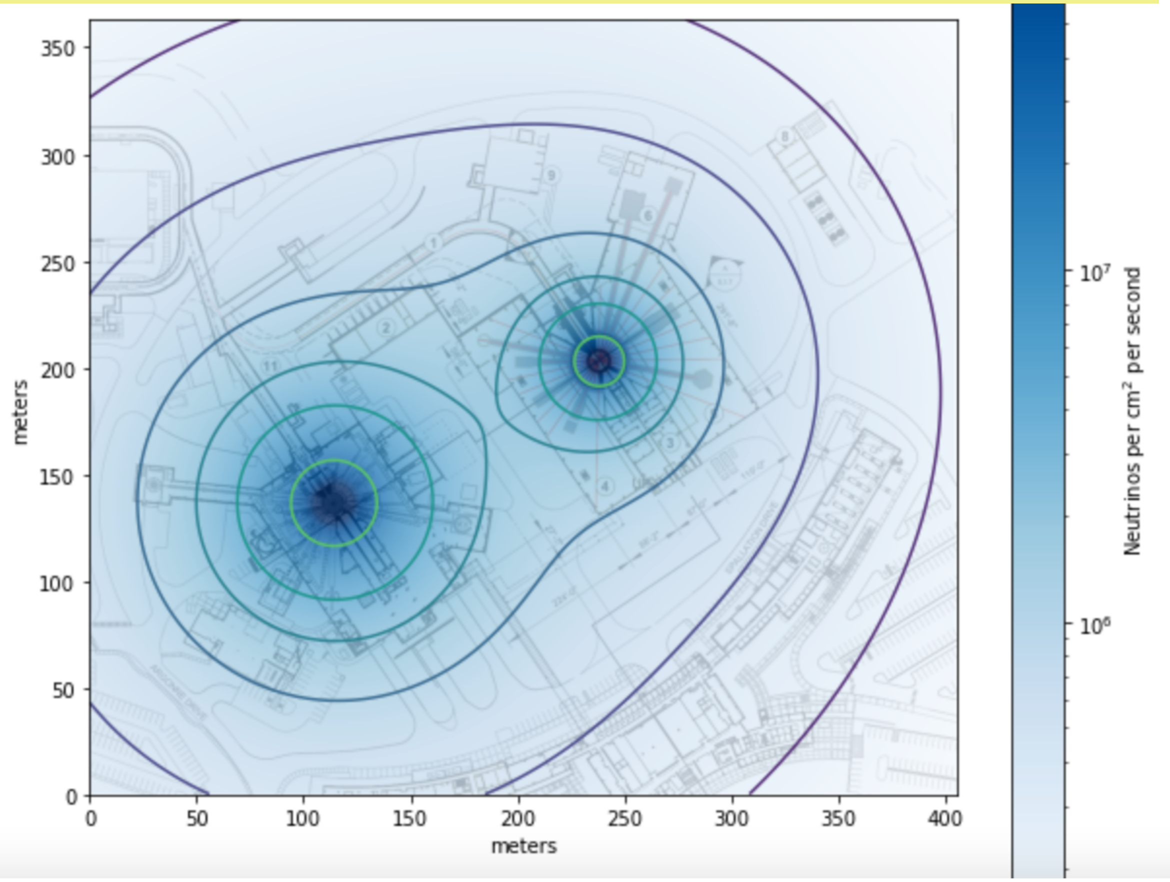


FTS
2 MW
45 pulses/sec

The choice of 15 Hz and 0.7 MW resulted from a detailed analysis of STS design (reviewed by a panel of experts in 2017) and optimizes performance of STS without impacting performance of FTS



SNS power upgrade to 2 MW in 2023,
Second Target Station upgrade to 2.8 MW ~2030



Many exciting possibilities for ν's + DM!

Physics reach for next generation @ SNS

Precision CEvNS: NSI, electromagnetic properties, nuclear structure; **flavor separation**

Sterile neutrino searches: **cancel systematics with multiple baselines**

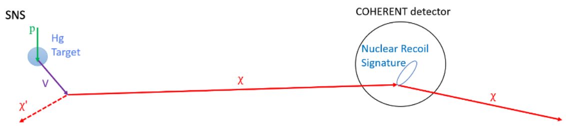
Accelerator-produced dark matter: reach for multiple models: **timing**

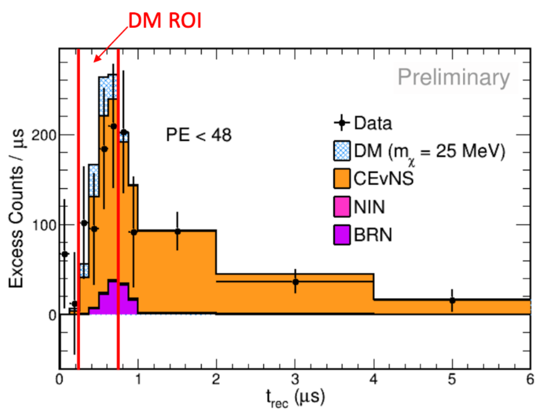
Axions, other BSM?

Inelastic neutrino interactions: CC and NC relevant for supernova, nuclear physics

Detector R&D

Example 1: Accelerator-Produced Dark matter





Late time distributions constrain CEvNS systematics for DM search

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

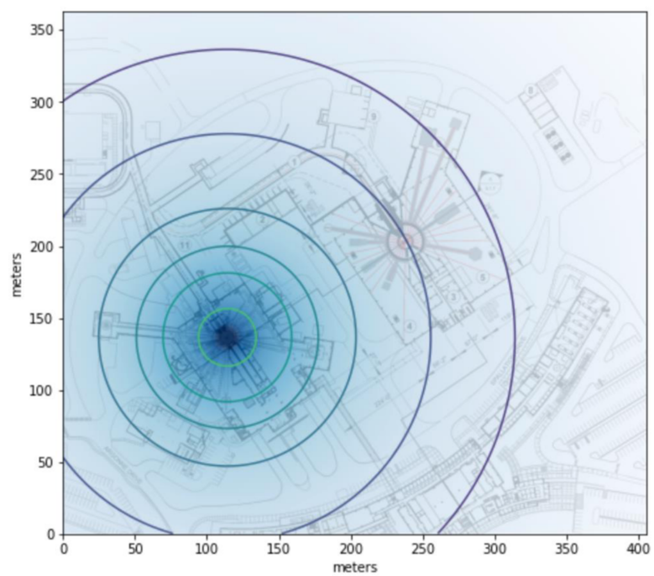
Directionality of flux at the SNS

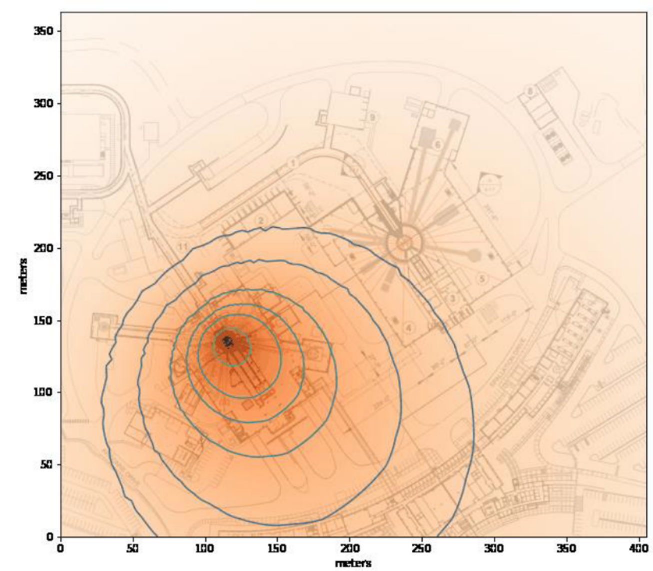
Neutrino flux produced at rest – isotropic

Largest beam-related background for DM searches at the SNS

DM produced in-flight – is boosted

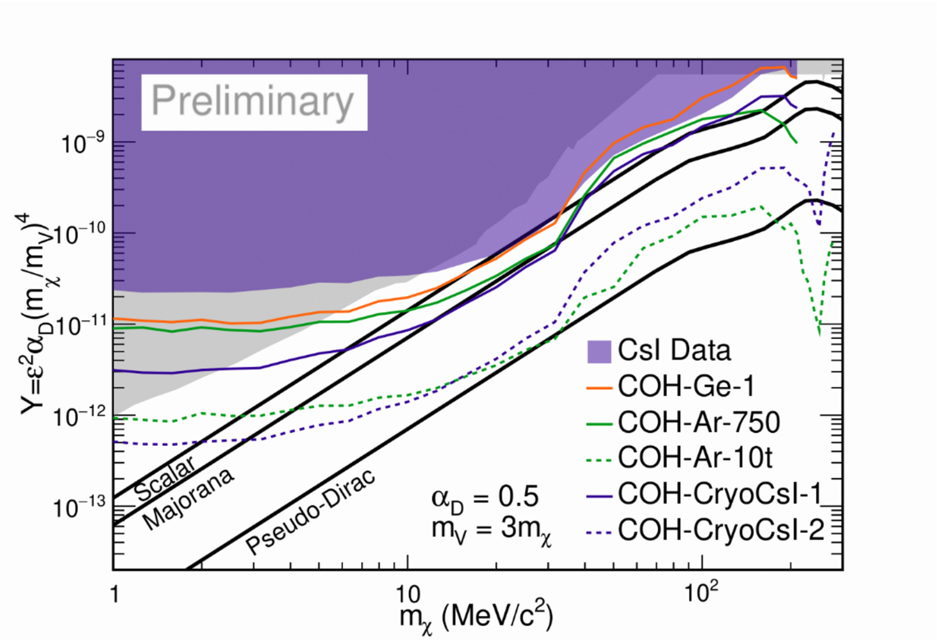
A forward-directed detector would optimize DM / background





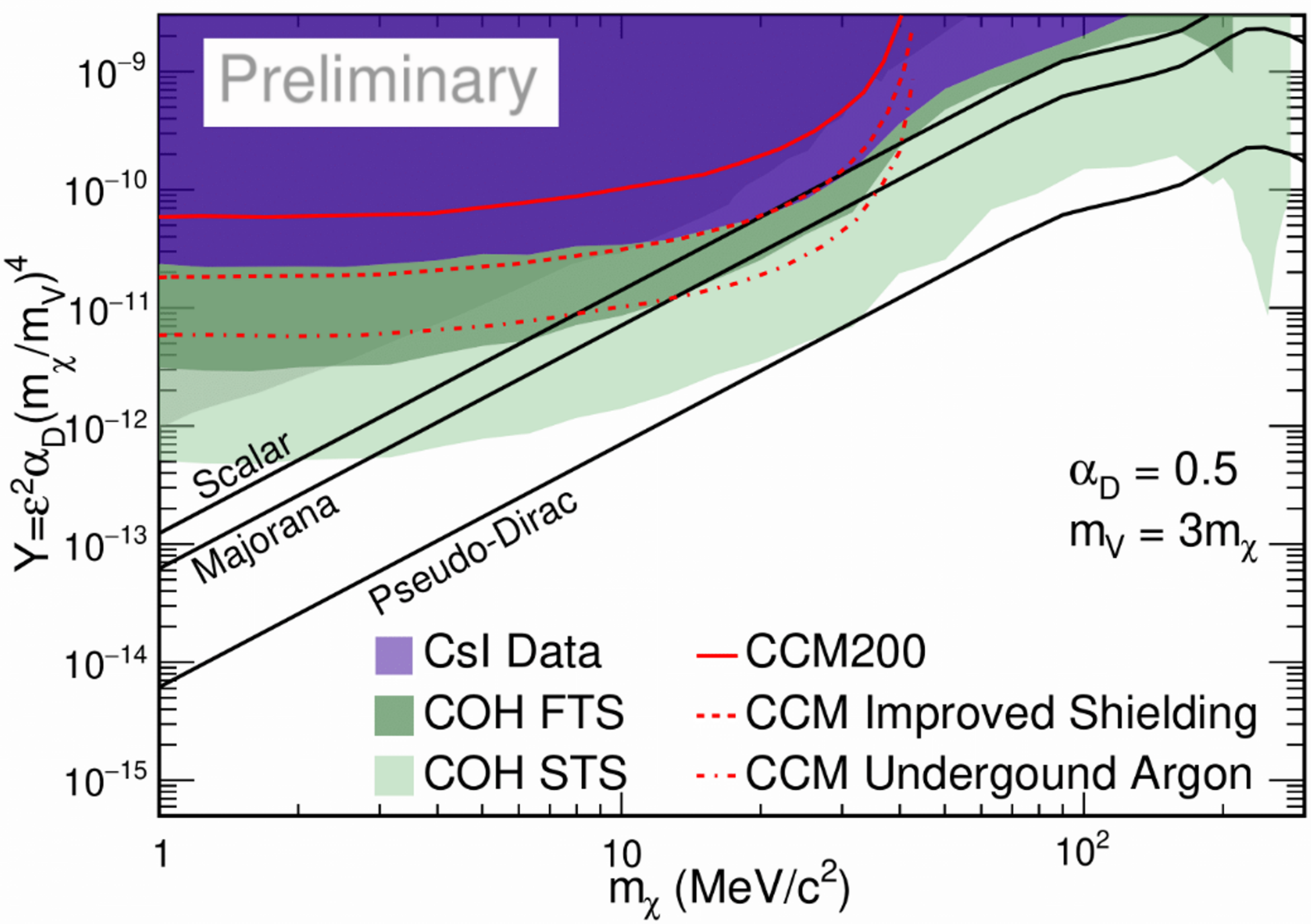
- After STS is built, both targets will operate with 3(1)/4 bunches sent to FTS (STS)
- If DM is in this mass regime, SNS very advantageous – a single detector monitors DM flux from two beams allowing confirmation of the expected angular dependence of the flux

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

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



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

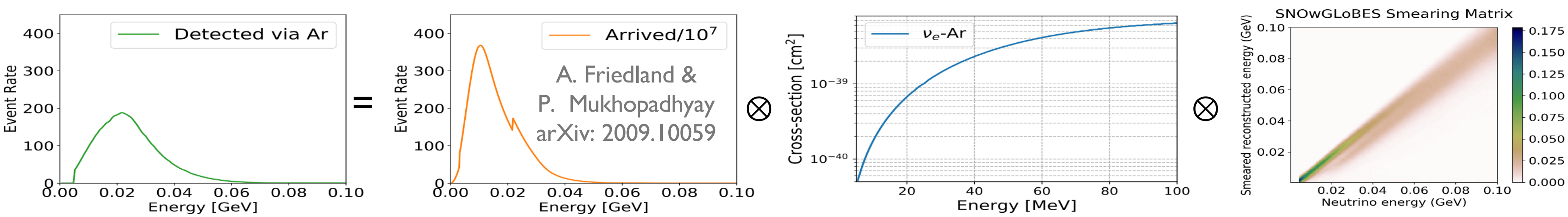
COH STS =
50 t-yr Ar +
3.5 t-yr Cryo CsI

CCM sensitivity:
arXiv: 2105.14020

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

Yun-Tse Tsai

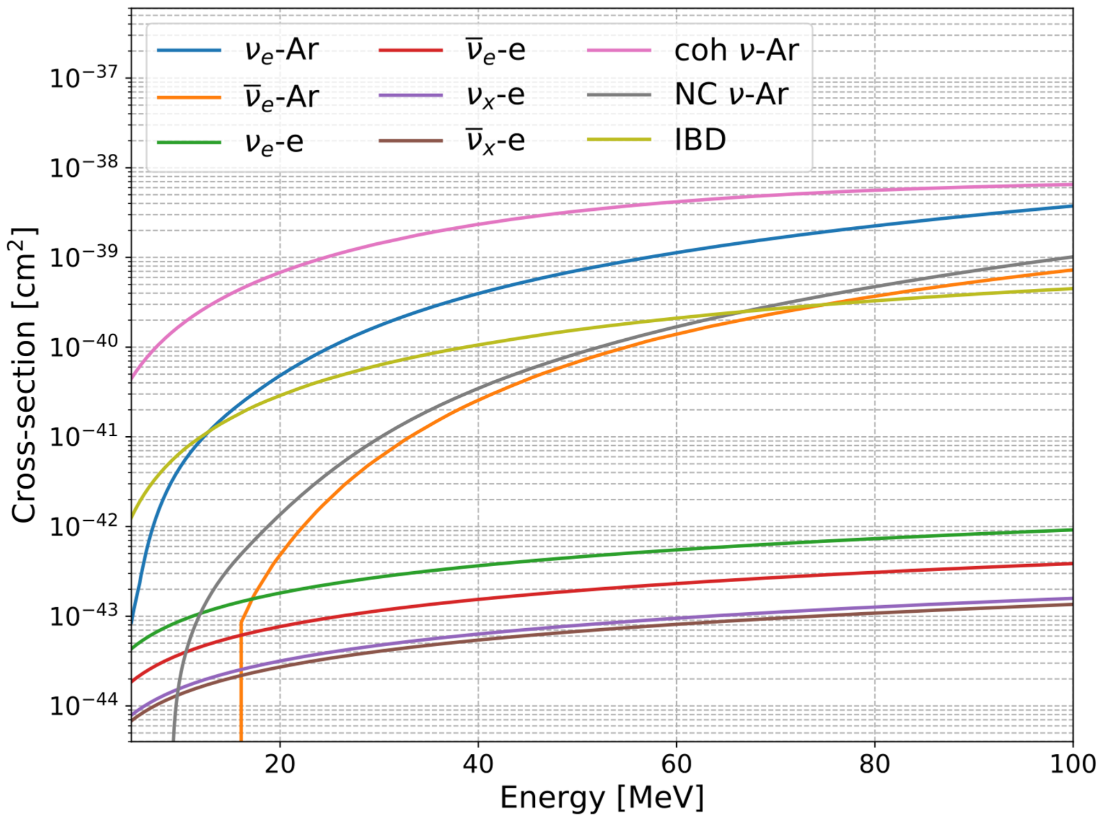
Example 2: Supernova neutrino cross sections for DUNE



- Large impact on supernova neutrino measurements in DUNE comes from systematic uncertainties of ν_e-Ar cross section
  - ν-Ar cross section at O(1-10 MeV) have never been measured
  - Double differential ν_e-Ar cross section measurements with Spallation Neutron Source (SNS) at Oak Ridge (ORNL) to address this issue

ν_e-Ar Cross Sections

Yun-Tse Tsai

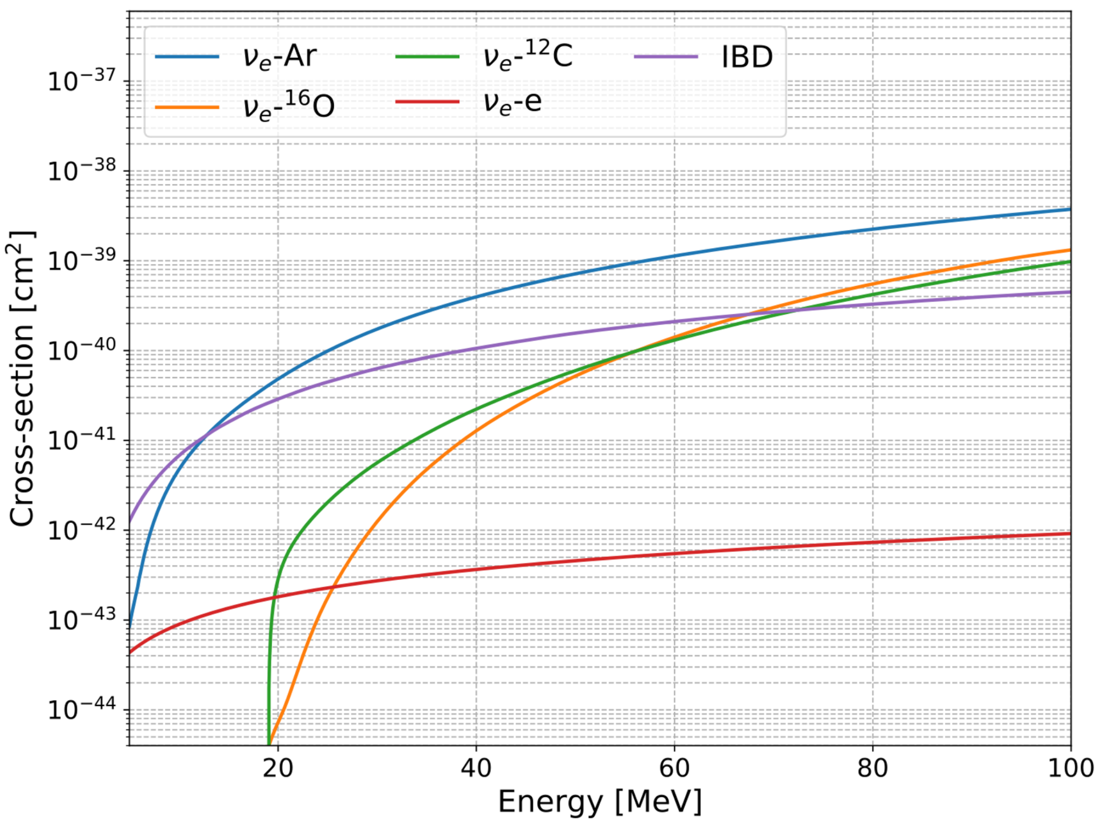


IBD: Inverse Beta Decay

ν_e-Ar from MARLEY, others from JCAP, 0408:001, 2004 and J. Phys., G29:2569–2596, 2003

ν_e Cross Sections

Yun-Tse Tsai



IBD: Inverse Beta Decay

ν_e-Ar from MARLEY, ν_e-O from Phys. Rev., D66:013007, 2002, ν_e-C from Nucl. Phys., A652:91–100, 1999

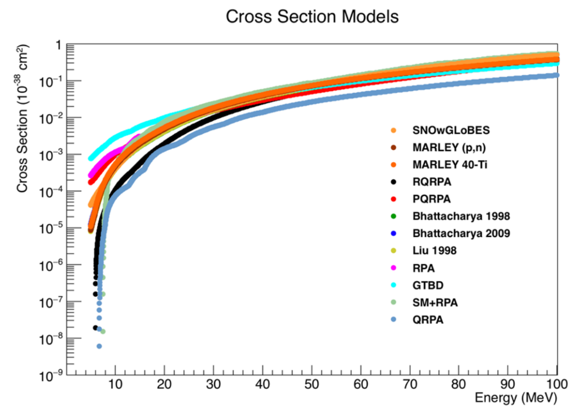
Impact from ν_e-Ar σ

Yun-Tse Tsai

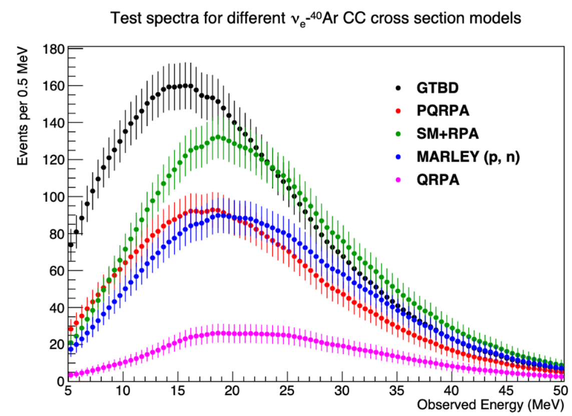
- Pinched-thermal form of supernova neutrino flux

$$\phi(E_\nu) = \mathcal{N}(\frac{E_\nu}{< E_\nu >})^\alpha \exp[-(\alpha+1)\frac{E_\nu}{< E_\nu >}]$$

- E_ν: neutrino energy
  $<E_\nu>$: average E_ν
  $N \propto \nu$ luminosity, ε
  α: pinching parameter
- ν_e-Ar cross section models vary > O(10%)
- Impacts from ν cross section models particularly on ε, varying from -94% to 1400%



E. Conley, DUNE note 14068, paper in preparation



Improve SN ν Detection

Yun-Tse Tsai

- Measure double-differential ν_e-Ar CC cross sections with E_ν = O(1-10)MeV

  Neutrino produced from π^+ decay at rest (DAR)

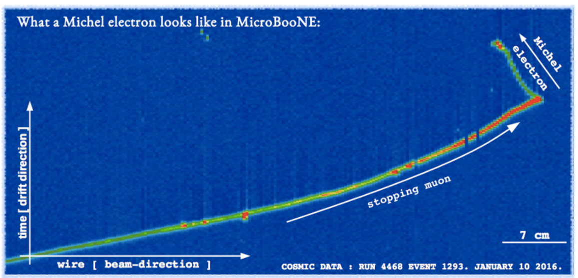
  $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow (e^+ \nu_e \overline{\nu}_\mu) \nu_\mu$

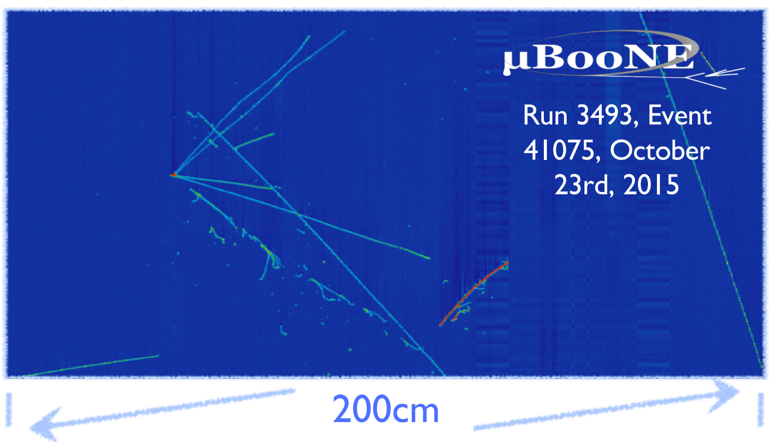
- Characterize LArTPC detector response in the MeV regime

  Smaller-scale, advanced LAr detector

Why LArTPC?

Yun-Tse Tsai





- Argon target
- Millimeter resolution
  - Tracking capability
- Calorimetric measurement
- ν flavor identification
- Technology for DUNE far detector
  - Study detector response in the MeV regime

MeV-Scale Physics Goal

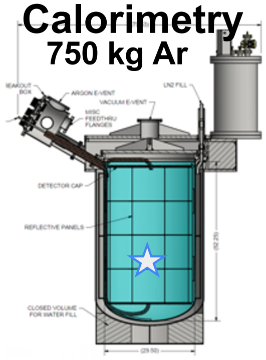
Yun-Tse Tsai

- Physics measurement limited by CEvNS detectors
  - Short-baseline ν oscillation; sterile ν
  - Neutral-current ν-Ar inelastic cross section measurements
  - Search for exotics, e.g. axion-like particles (ALPs)
- Potential 10-ton scale LArTPC at the future Second Target Station for double differential measurements

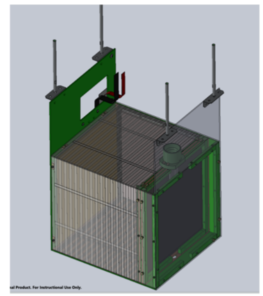
Power Upgrade and STS Facilities create new opportunities …

Calorimetry
750 kg Ar

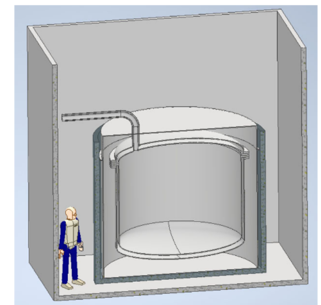
Walt Fox
IU



Directionality



Discovery Scale



FTS 2021 2022 2023 2024 2025 **STS**

Ton-Scale Argon Calorimetry
- CEvNS studies
- Dark Matter searches
- Limits on quark-lepton couplings for DUNE mass ordering degeneracy
- Supernovae neutrino cross sections for DUNE

COHERENT "First Light" Program
- Heavy Water Flux Normalization of FTS
- CEvNS with HPGe, NaI
- Low Threshold Detector R&D: Quantum Enhanced Light Collection, Xenon Doping, SiPM

Ton-Scale Directionality with Low Threshold Detector R&D

Heavy Water Ring Imaging Design
- Improved Flux Normalization
- Neutrino oxygen Interactions for Super-K, Hyper-K

Argon Detector R&D for STS
- Simultaneous Low threshold Light and Time Projection Readout of Charge

Exact time evolution of program to be determined by the collaboration

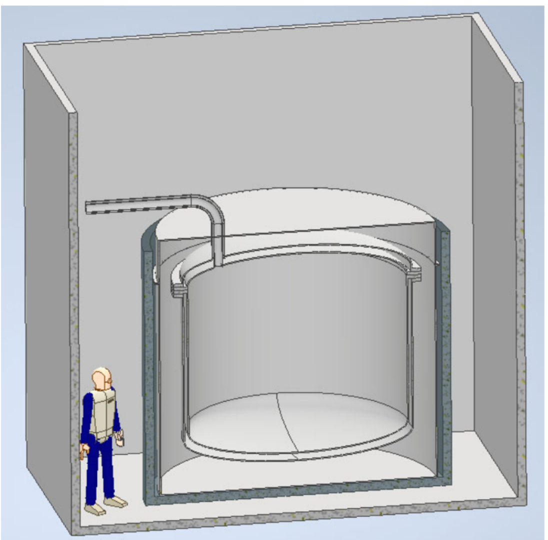
HEP Program at STS

Argon TPC
- Dark Matter searches
- Precision CEvNS studies
- Precision Ar cross sections for DUNE
- Weak Mixing Angle
- Neutrino EM properties

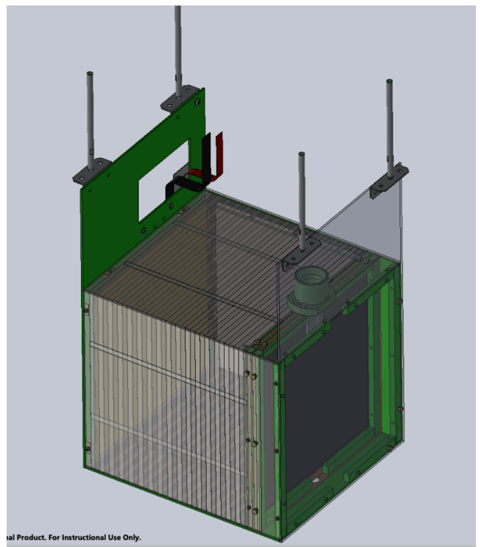
Heavy Water Ring Imaging
- Flux Normalization of STS
- Precision oxygen cross sections for Super-K, Hyper-K

Two “Straw Person” Detector Technologies

Liquid Argon
Single Phase Scintillation



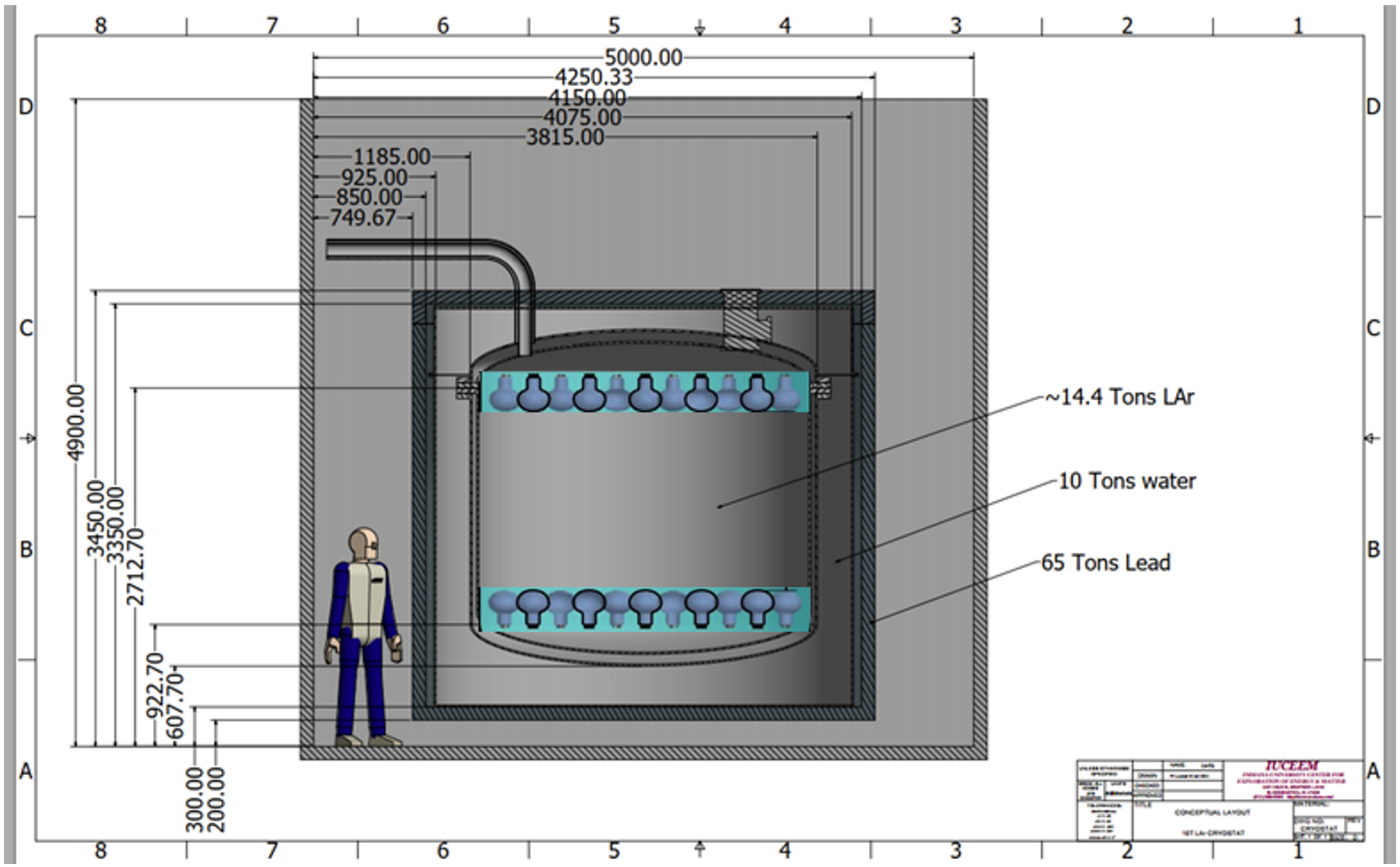
Liquid Argon
Time Projection Chamber



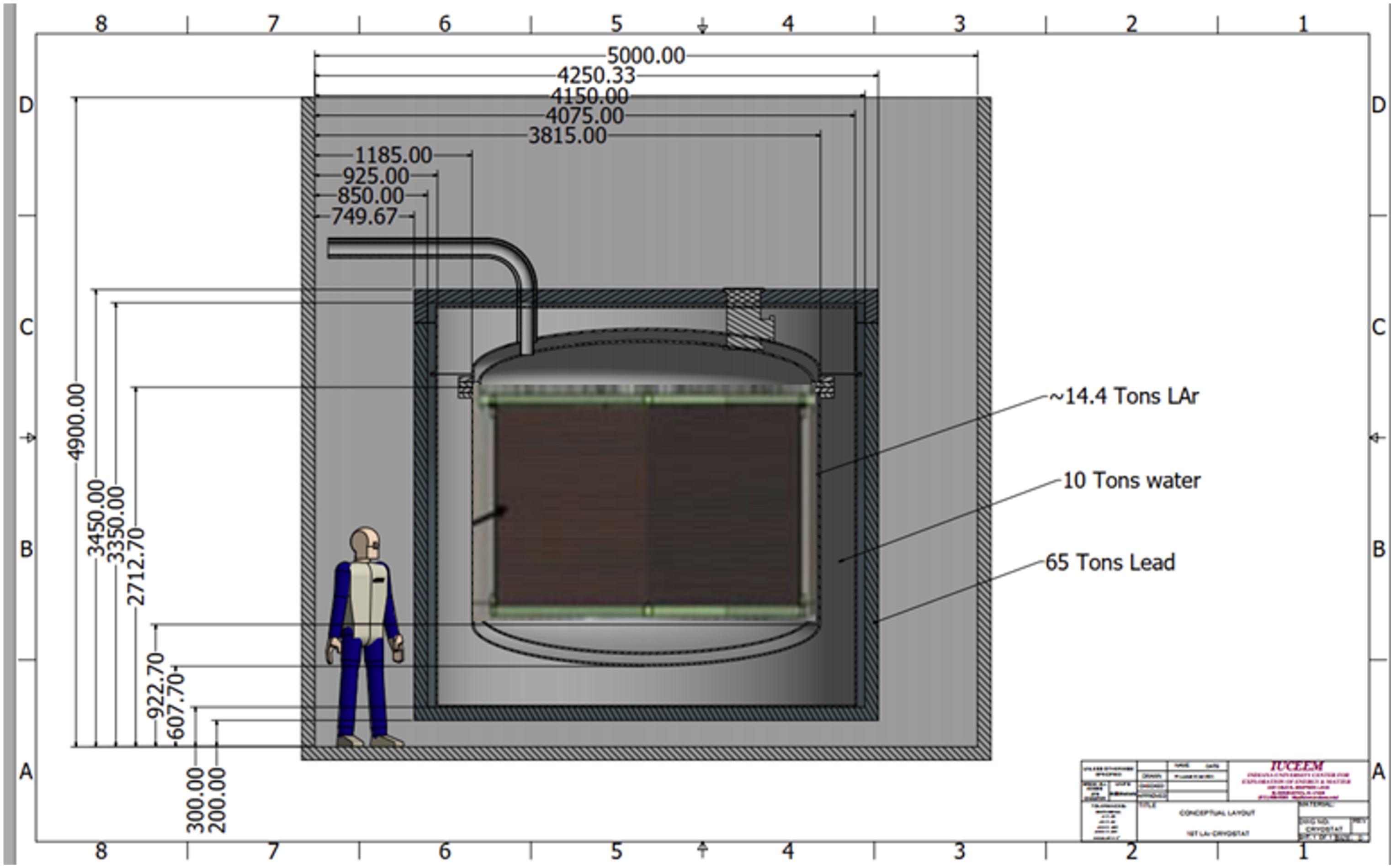
And many more …
- Cryogenic Scintillator Crystals
- Ton-scale semiconductor (Ge)
- Dual phase Xenon
- Single Phase LNe
- Heavy Water Detector
- Low Threshold Bolometers
- Gas phase directional recoil

10-ton cryostat is a representative place holder
- Ø 2 meters x 4 m height
- +Pb/H2O shielding
- Cryogenic systems
- Electonics racks
- Ventillation
- Safety: ~800:1 Gas Expansion
- …

10ton-scale LAr detector for **scintillation** or TPC detector



10ton-scale LAr detector for scintillation or **TPC (time projection chamber)** detector



More possible detector ideas...

Low-threshold recoil detectors:

- Large cryogenic scintillator
- Dual-phase xenon
- Ton-scale Ge
- Single-phase LNe
- Silicon
- Scintillating bolometer
- Scintillating bubble
- Directional recoil detectors

Inelastic focus

- Large organic liquid scintillator
- NuSNS style?
- Different style LArTPCs
- Heavy water, or light water

Many others...

Desired Locations for Neutrino / Dark Matter Experiments

- Location 1: **Off axis 90 degrees of beam – 1 or 2 10-ton instruments**
    - 10 meters below beam axis at 20m distance (17m in plane)
    - Dark Matter, CEvNS, CC, NC
    - Minimal conflict with other operations
    - Preference for locating same side as FTS
- Location 2: **On axis – 1 10-ton instrument**
  - Option 1: Ideally Less than 10 degrees
    - 3.4 meters below beam axis at 20m, 5.2m @ 30m, 6.9m @ 40m
    - Dark Matter, CEvNS
    - Likely requires instrument floor footprint at 20m distance to target.
  - Option 2: If constrained to basement level, then distance/angle optimal at 30 degrees
    - 10 meters below beam axis at 20m distance (17m in plane)
    - Dark Matter, CEvNS
    - No instrument floor footprint, but underneath target service area

General Shielding Requirements

- 20 meters of line of sight shielding between target and neutrino instrument (45-50 interaction lengths, HD concrete reduces distance)
- 3.5 meters of overburden for cosmic ray shielding (could include neutron instrument shielding above)
- 3 meters hermetic shielding around instrument in directions open to beam (learning from FTS BL1 instrument trenches)

This shielding can be comprised of a combination of structural materials, target monolith, etc. and dedicated shielding for neutrinos instruments.

STS Target Building Vertical Slice

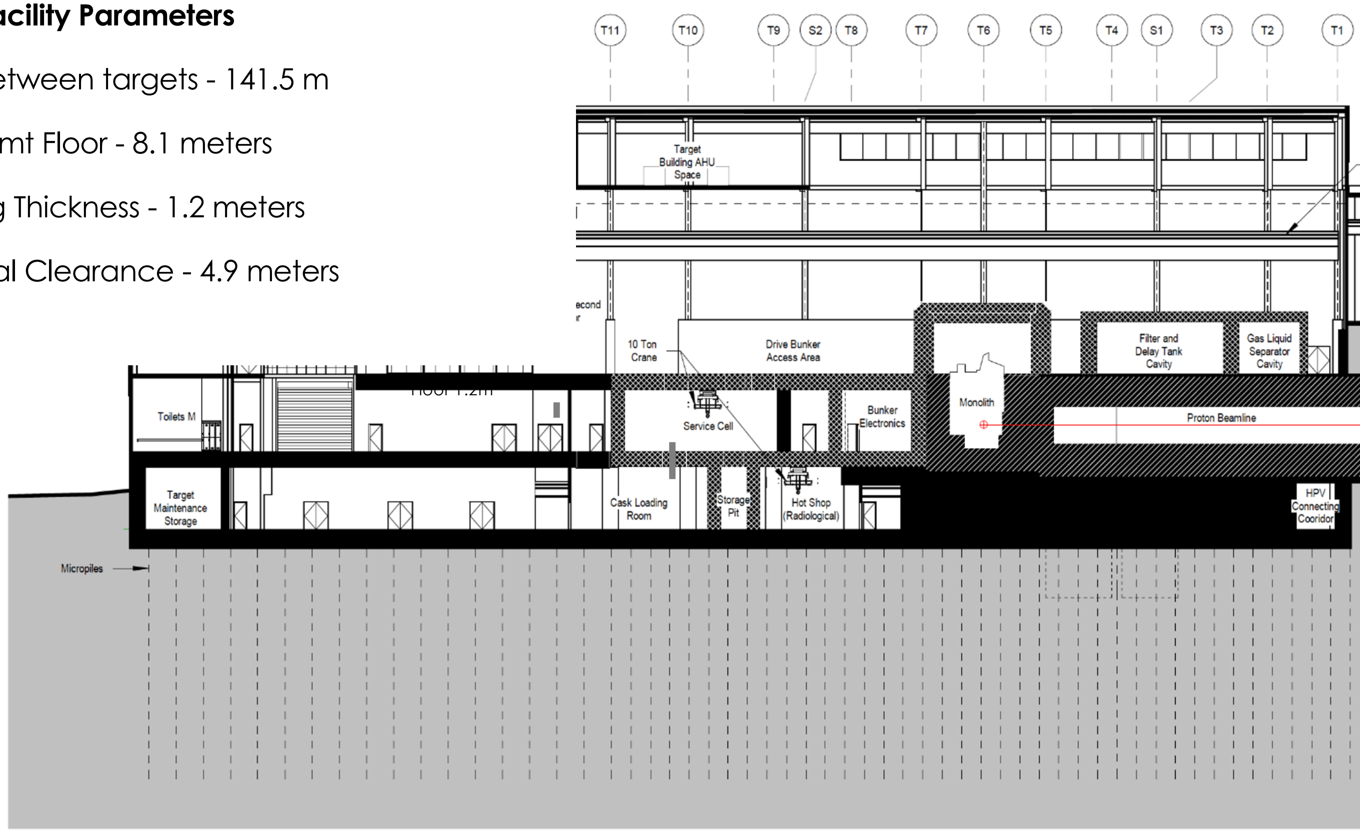
Some STS Facility Parameters

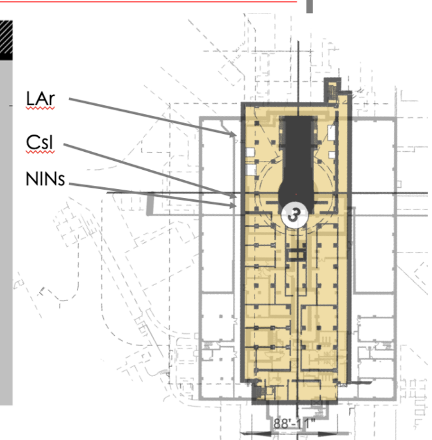
Distance between targets - 141.5 m

Target to Bsmt Floor - 8.1 meters

Bsmt Ceiling Thickness - 1.2 meters

Bsmt Vertical Clearance - 4.9 meters





STSNu Working group fully engaged with STS Project team on conventional facilities design - A/E charrette July 2021

FTS/STS Basement Overlay

Take-Away Messages

The SNS is the best neutrino source in the world, and will be even better with the upgrades…peak brightness approach is the best for neutrinos

The neutrinos are free! We just have to stop as many of them as possible in sensitive detectors.

High visibility, cost-effective physics track record so far at the SNS

Many exciting physics possibilities, complementary and supportive of other endeavors

STS construction offers opportunities for optimization

Please join us! Regular meetings 3 pm Eastern on Tuesdays

White paper outline

Please ask for Overleaf link!

- Overview of SNS
- Physics Opportunities
  - Recoils
  - Inelastics
- Detector possibilities
  - Example detectors

Need to flesh these out