Neutrino Physics at The Short Baseline Near Detector at Fermilab

Iker Loïc de Icaza Astiz, University of Sussex

i.de-icaza-astiz@sussex.ac.uk or icaza@fnal.gov

Seminario Altas Energías

ICN-UNAM

4th May 2022

UNIVERSITY OF SUSSEX

About:

- Postdoc at Sussex Uni, pending Viva to become a doctor
- Member of the EPP Neutrino group working on SBND and DUNE
- Bachelors at UNAM in Mexico, my thesis was on MiniBooNE
- Collaborated on MiniBooNE's Boosted Dark Matter search
- Also had a couple of jobs as software developer and data scientist

Other interests:

- Gigs and concerts
- Cycling
- Swimming
- Mountaineering
- Camping
- Being outside

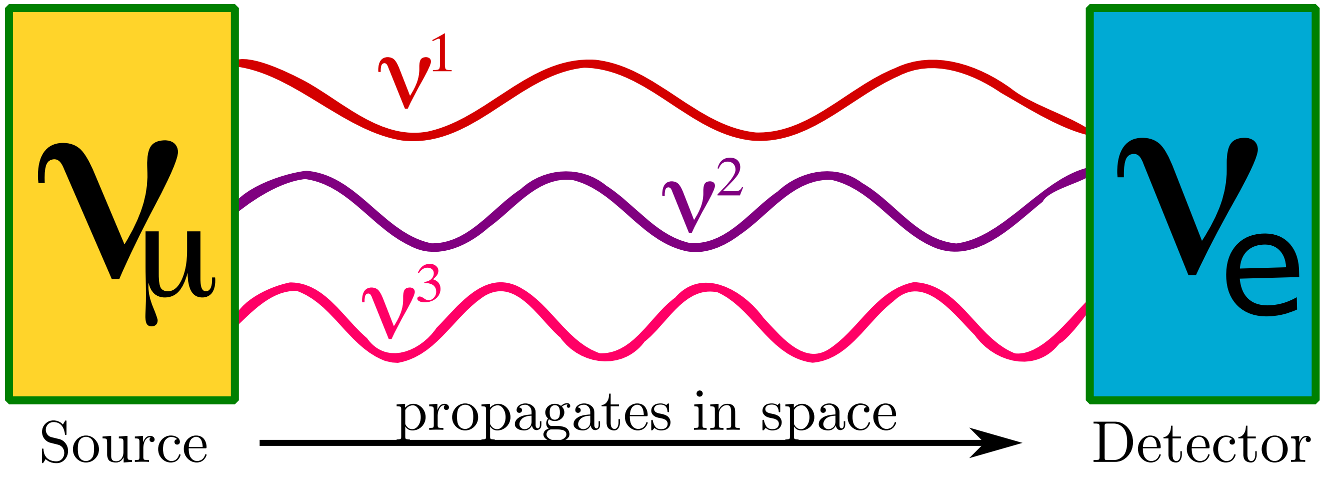
Overview

- Neutrino Oscillations
- Anomalies at ~1 eV^2
- The Short Baseline Neutrino program at Fermilab
- SBND
- Dark Neutrinos
- DUNE and the LArTPC programme

Neutrino Oscillations

Layman explanation:

- There are three distinct neutrino flavours: ν_e , ν_μ, ν_τ
- Each flavour is a particular mixture of three different masses: ν_1, ν_2, ν_3
- Due to this mass difference, each component propagates differently in space. This means that the composition of neutrinos travelling in space changes, hence there's a probability of finding it later with another flavour.
- We call **neutrino oscillations** to these flavour transitions.



2 Neutrino Oscillations

Neutrino Oscillations for the case of only two neutrinos:

$$[\Delta m^2] = \mathrm{eV}^2,\ [L] = \mathrm{m},\ [E_\nu] = \mathrm{MeV}$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta\ \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

In a neutrino oscillation experiment the relevant parameters:

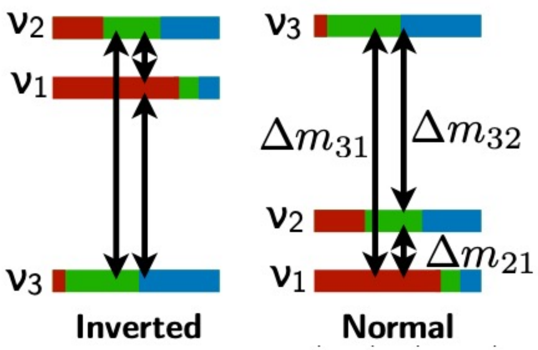
- Nature: θ determines the amplitude, Δm^2 the frequency → ***We want to measure these!***
- Experiment controls: E_ν and the baseline length L

Current Oscillations Landscape

Mixing Angles

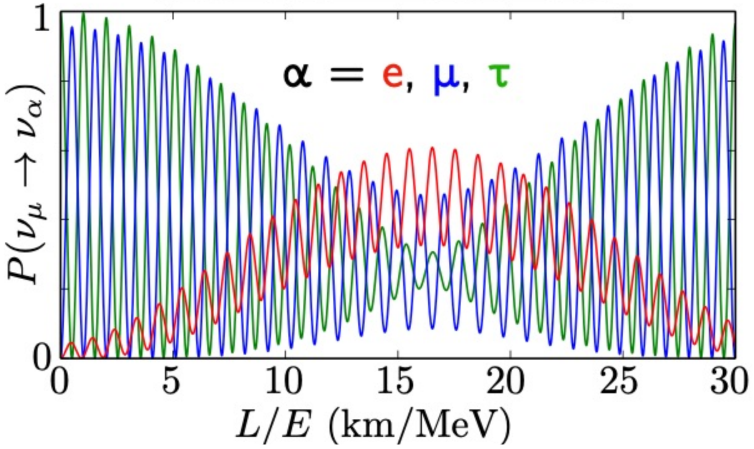
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \; +$$

Mass Splittings (e μ τ)



↔

Oscillation Probabilities

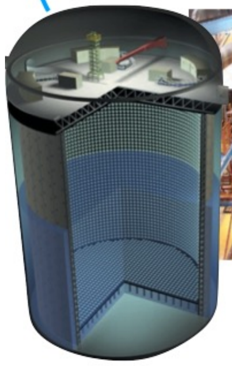


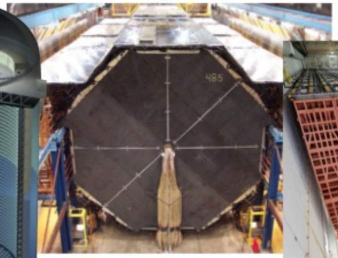
Atmospheric & Accelerator

Reactor

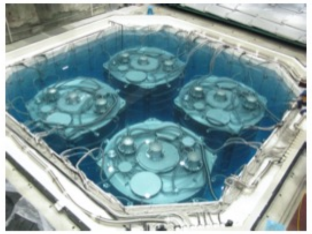
Solar & KamLAND

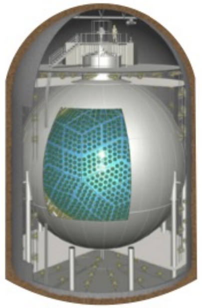
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$


Super-Kamiokande


MINOS


NOvA


Daya Bay


KamLAND


SNO

(and many more!)

4

LSND and MiniBooNE anomaly

UNIVERSITY OF SUSSEX

L

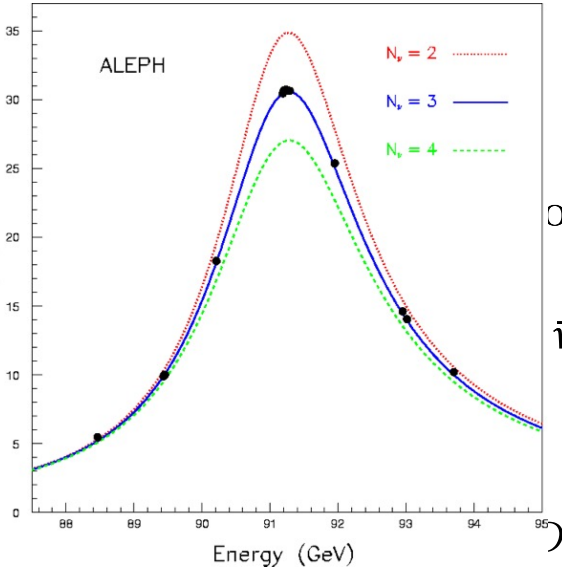
•R

•N ... on

•$\bar{\nu}$

•3 ... $\bar{\nu}_e$

ap



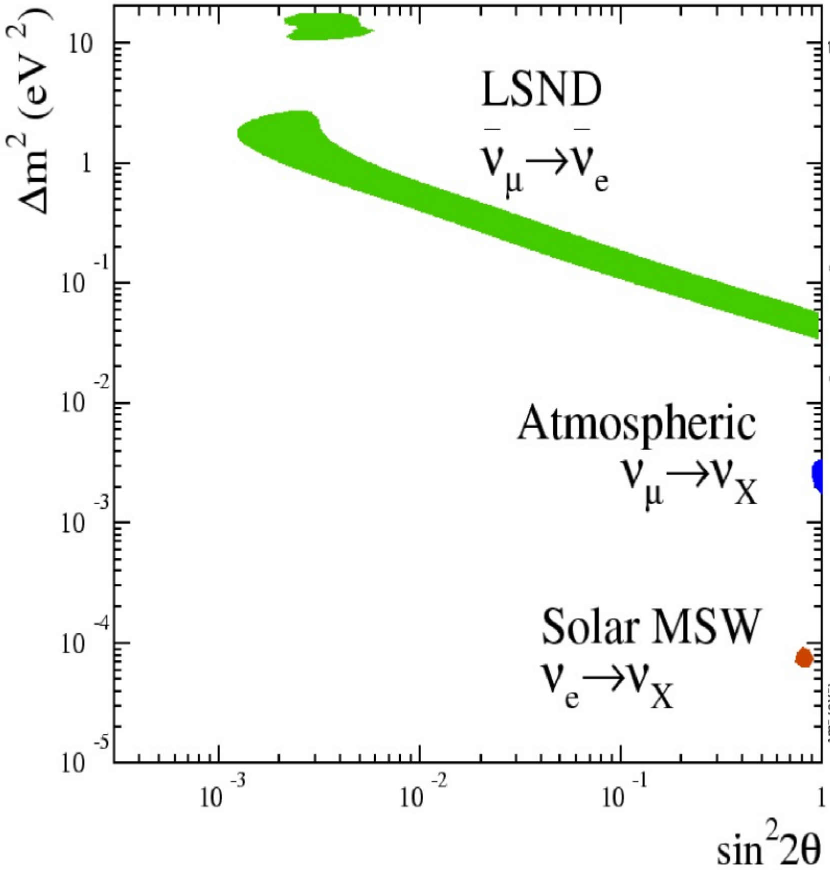
N

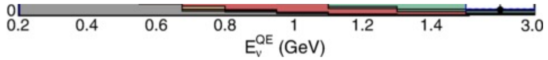
•R ... Of Tim

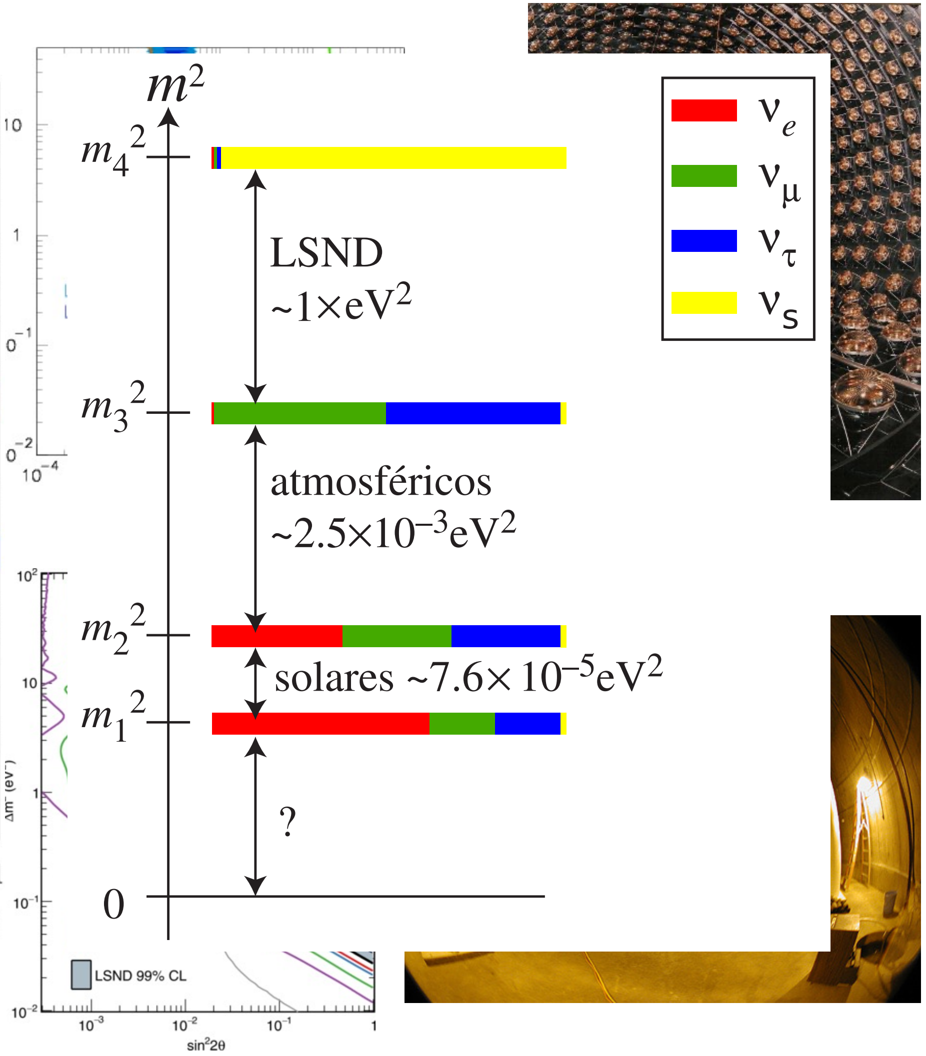
•Mineral Oil using Cherenkov and scintillation

•ν_μ and $\bar{\nu}_\mu$ from $\pi^\pm$ decay, L ~ 500

•4.8σ excess in neutrino and antineutrino at Δm^2 ~ 1 eV^2





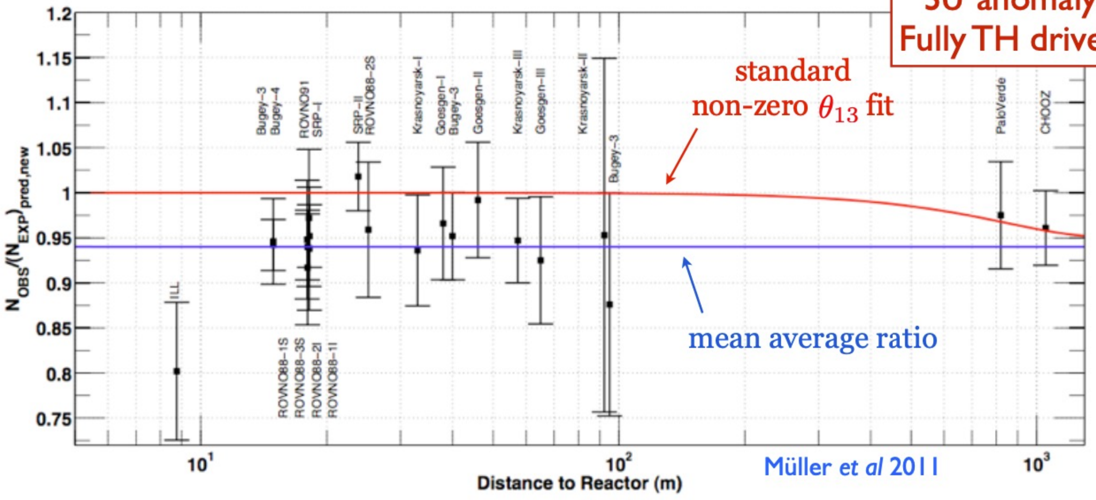


Reactor antineutrino anomaly

Nuclear reactors: electron spectra from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu are translated to $\bar{\nu}_e$ flux Schreckenbach 82, 85

A recalculation of fluxes lead to ~ 6% discrepancy with 2% error bars Müller *et al* 2011, Huber 2011

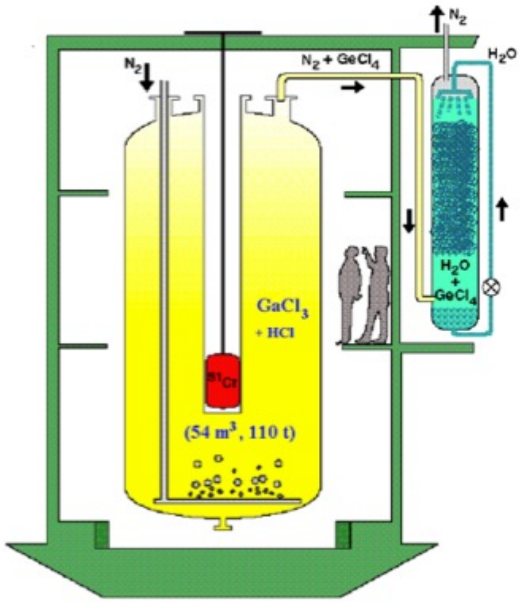
3σ anomaly
Fully TH driven

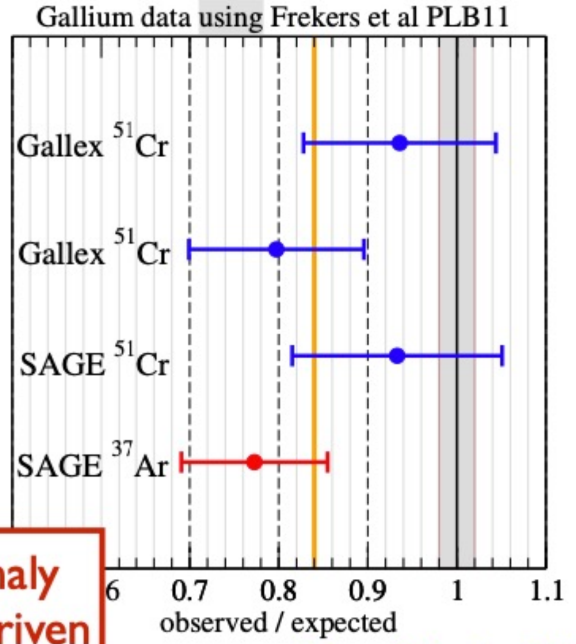


Müller *et al* 2011

But others say that the error bar should be more like 5% Hayes et al 2013

Gallium anomaly





Schwetz@Neutrino 2012

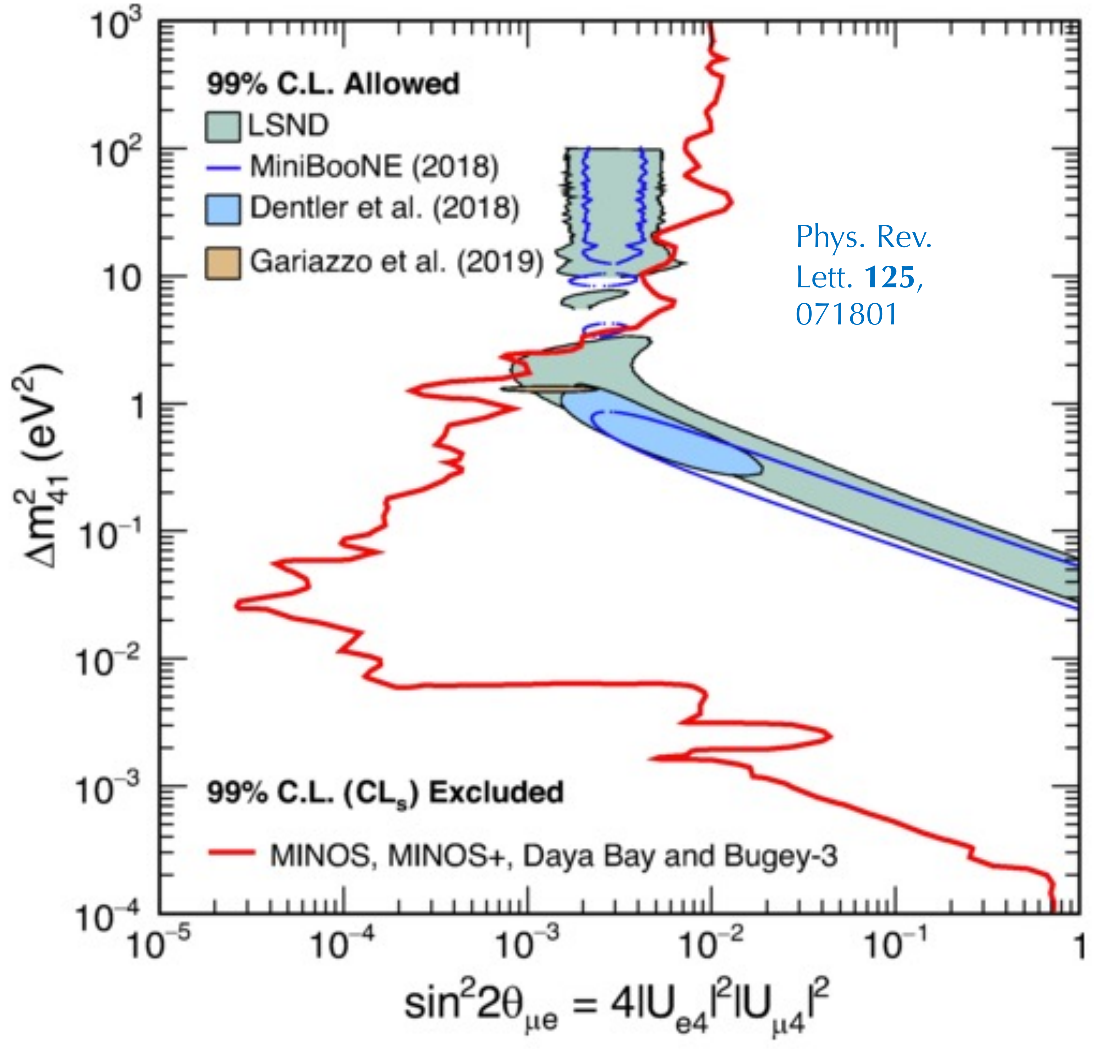
3σ anomaly
Fully TH driven

New estimates using new nuclear shell-model wave functions diminish significance to 2.3σ… Kostensalo et al 2019

Anomalies at ~1eV^2

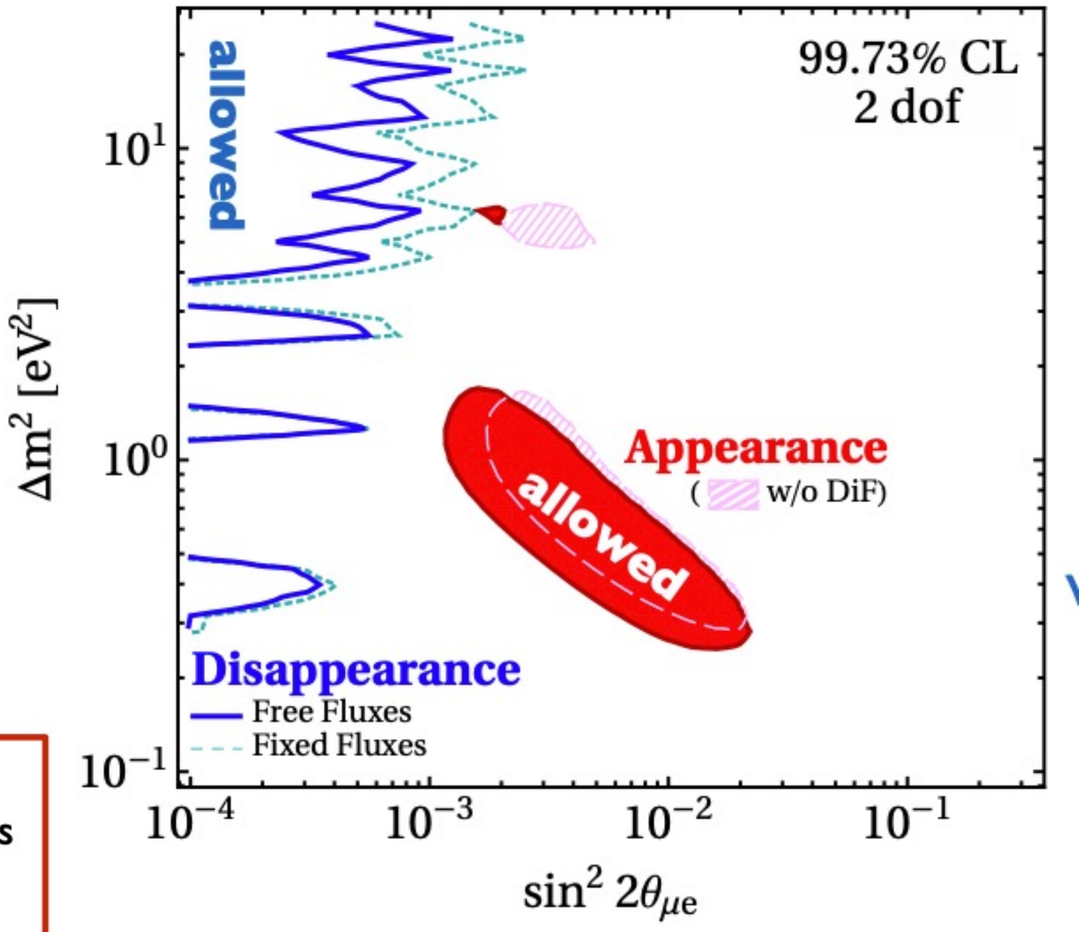
UNIVERSITY OF SUSSEX

• Osc



Phys. Rev. Lett. **125**, 071801

a sets
ion
ment
ves

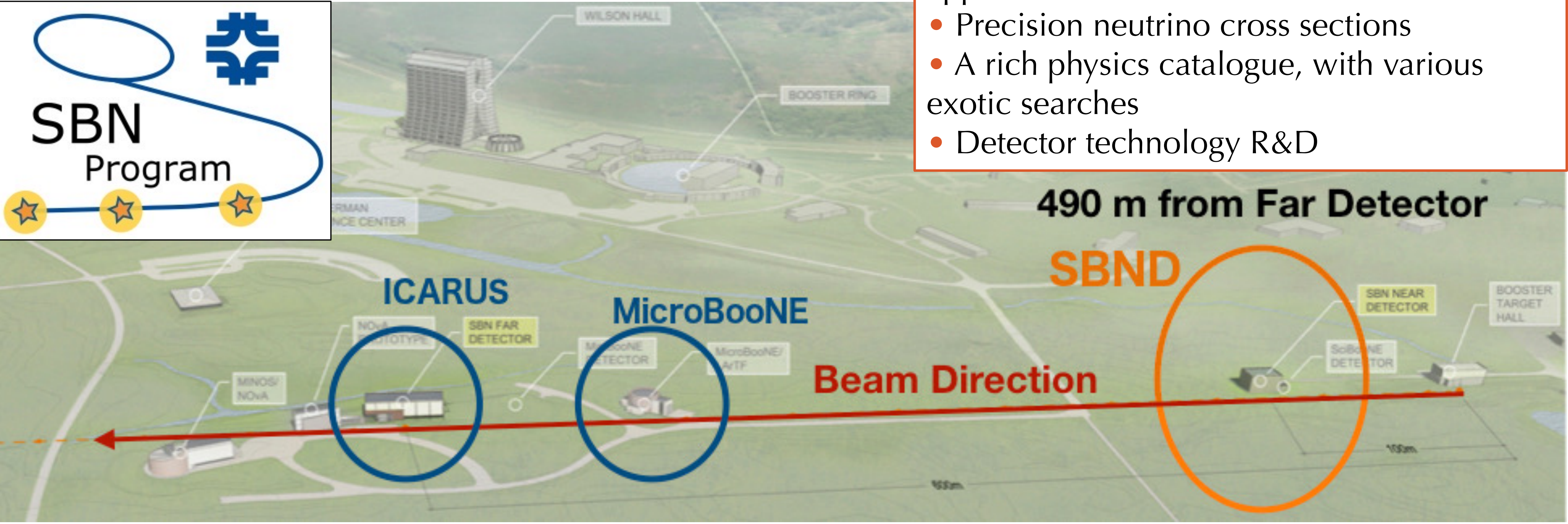


Maltoni Schwetz 2007

Short Baseline Neutrino program

Three LArTPCs in the Fermilab Booster Neutrino Beam:
Same argon target, functionally similar detectors

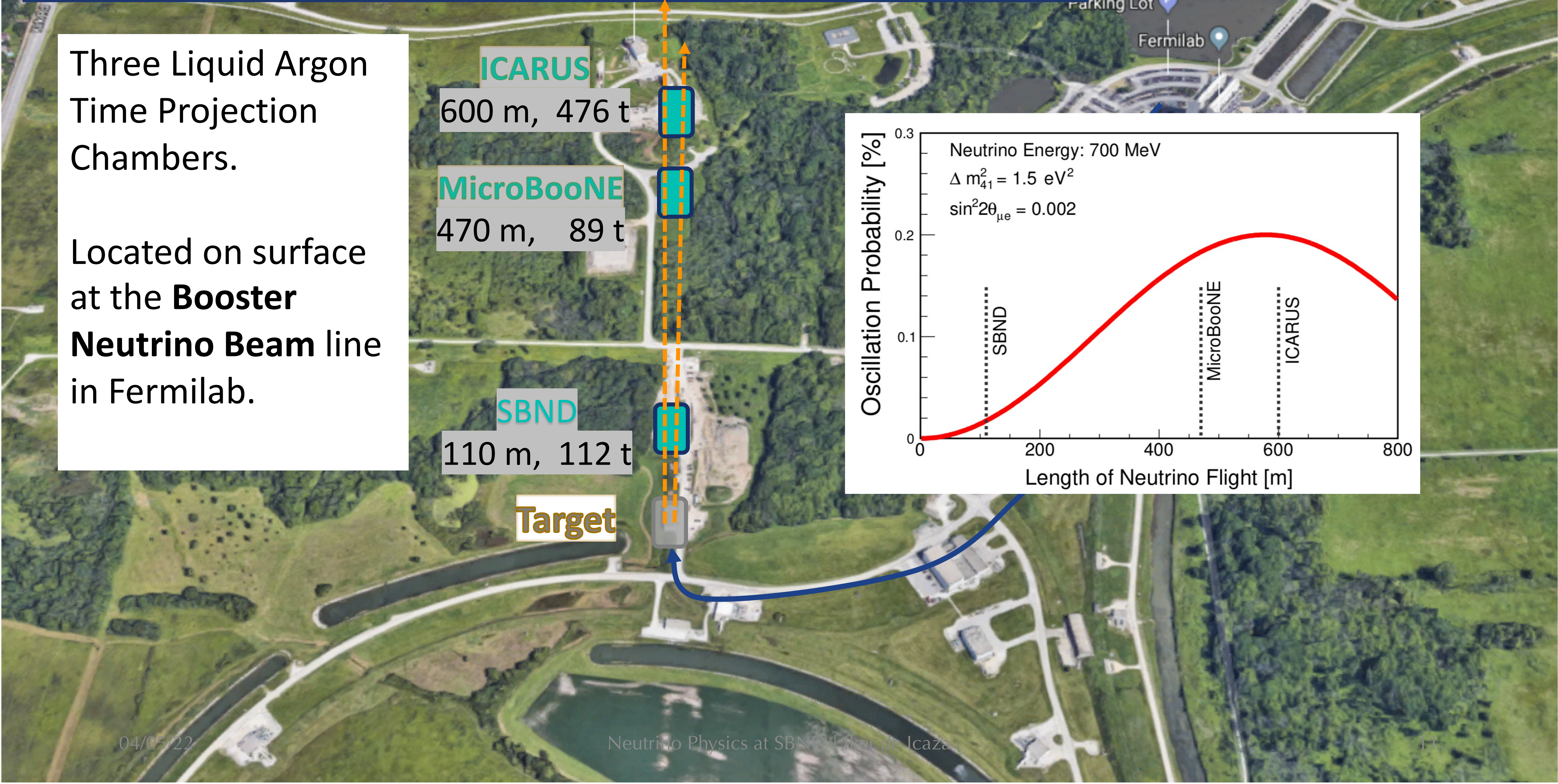
- Definitive 5σ test of LSND/MB oscillations using three baselines
- Simultaneous disappearance and appearance searches
- Precision neutrino cross sections
- A rich physics catalogue, with various exotic searches
- Detector technology R&D



The Short Baseline Neutrino program

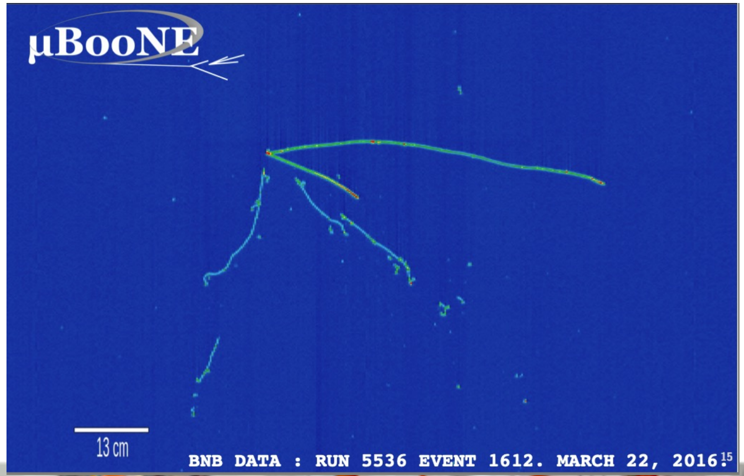
Three Liquid Argon Time Projection Chambers.

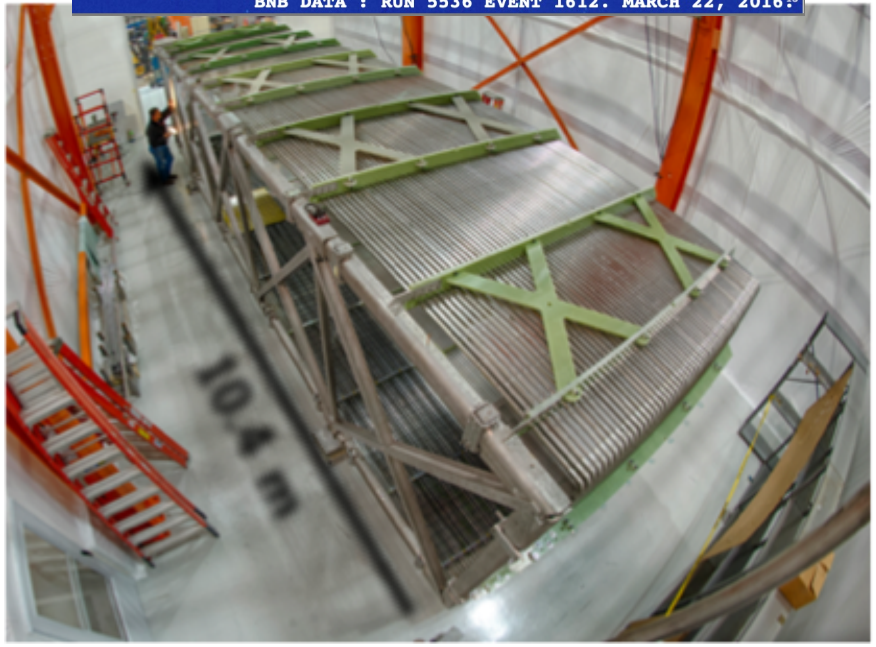
Located on surface at the **Booster Neutrino Beam** line in Fermilab.



MicroBooNE

- Stable operation since October 2015
- 1 TPC with 2.3 m drift. 89 ton active LAr. 470 m from the target. 32 PMTs.
- They have produced a wealth of knowledge about LArTPC:
  - Calibration
  - Simulation
  - Detector design
  - Detector effects: noise, diffusion, recombination, light yield, space charge
  - Analysis techniques
  - ν-Ar interactions
  - No LEE observed:
    - Not from single photons
    - Not from various electron neutrino channels

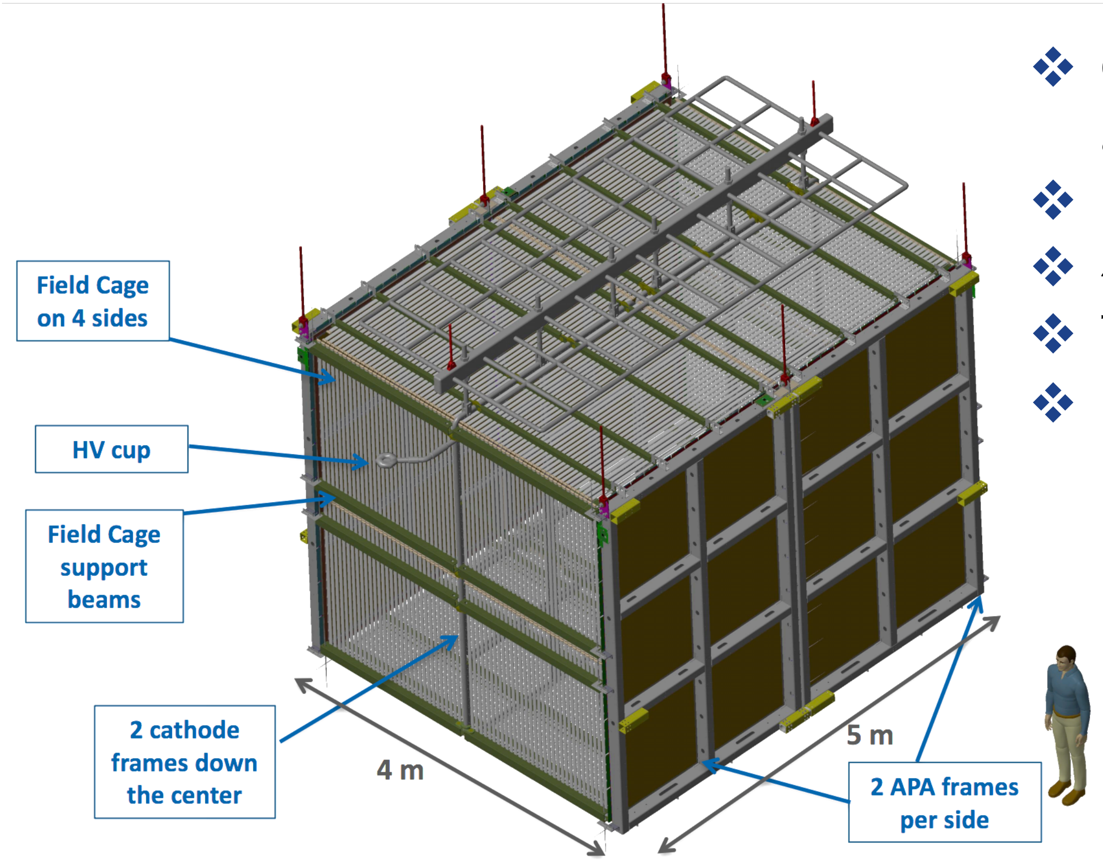




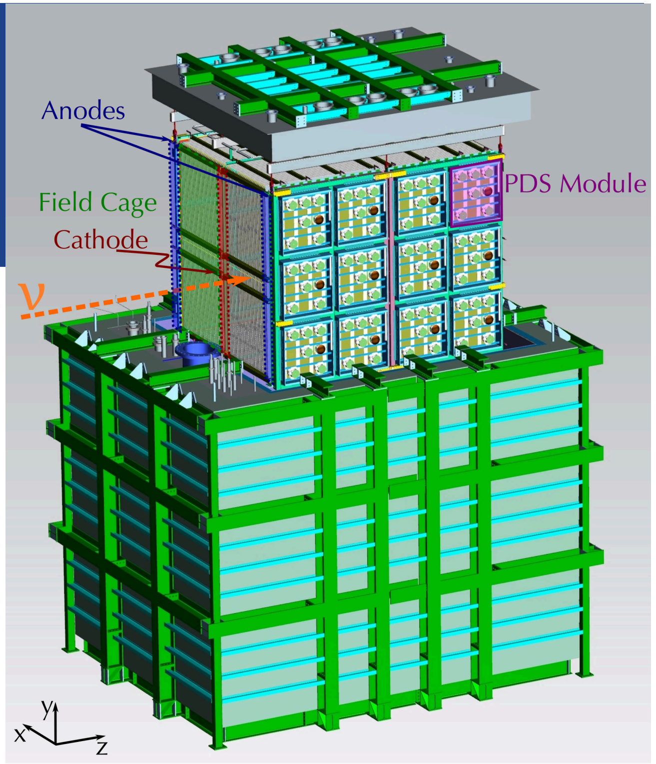
ICARUS

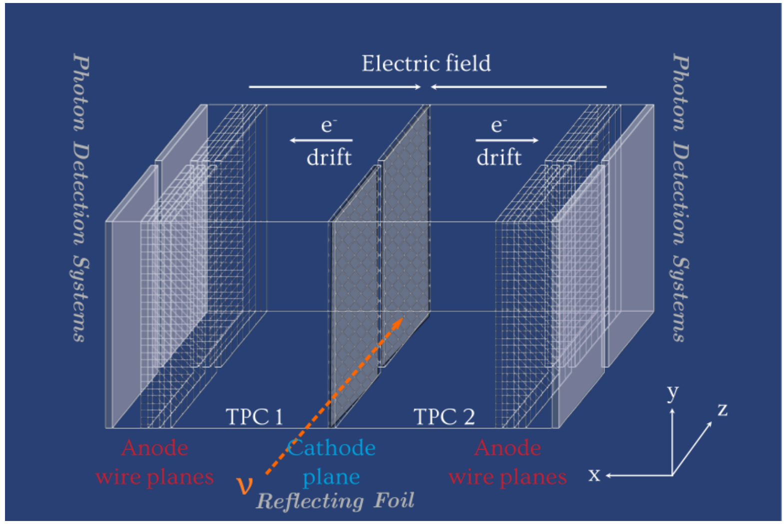
- It was operational at LNGS from 2010-2013. In 2015, sent to CERN for refurbishment. Shipped to Fermilab in June 2017.
- Far Detector: 600 m from the source
- Three readout wire planes (2 induction, 1 collection) per TPC, ~54000 wires at 0, ±60 degrees with 3 mm spacing
- Composed of two cryostats, each 19.6 x 3.6 x 3.9 m^3.
- Total 760 t Lar. Active volume 476 t LAr.
- Each with 2 TPCs of 1.5 m drift length.
- 360 8″ PMTs
- Full CRT coverage, and overburden
- Sensible to BNB and NuMI neutrinos
- Currently taking neutrino data

SBND



- Currently being assembled
- 112 t LArTPC
- 4x4x5 m^3 active volume
- Two drift volumes
- Four Anode Planes
  - 3 wire directions: 0, ±60°
  - 3 mm wire pitch
  - 11,264 total wires



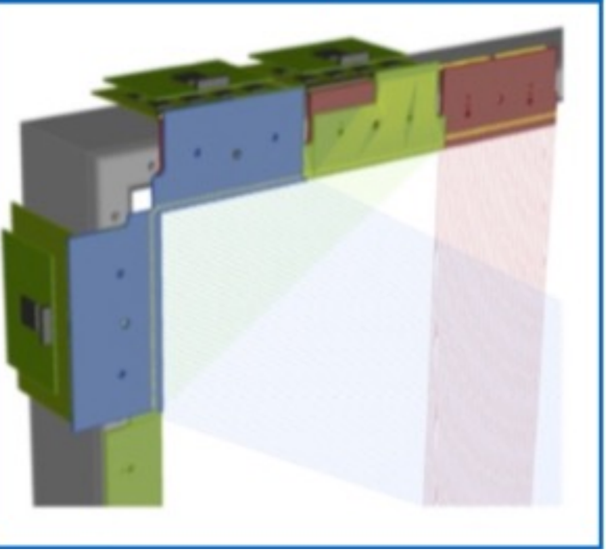


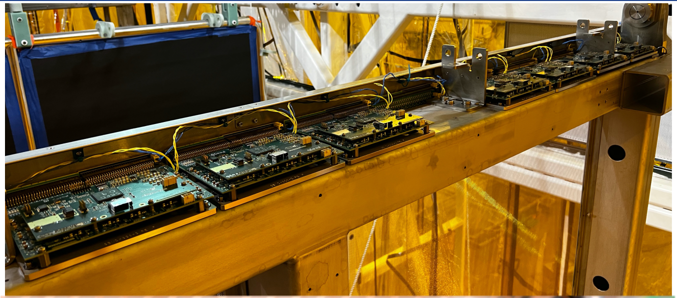
- 2 Cathode Planes biased at -100kV
- High Voltage feed-through located at the top of TPC
- Field cage set on the perpendicular side to maintain 500 V/cm field

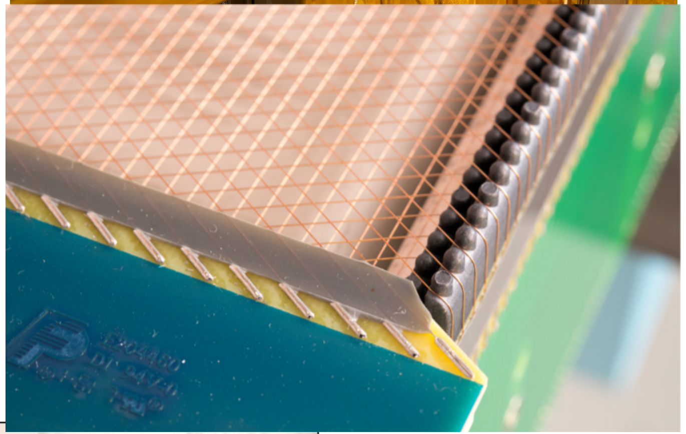
Anode Plane Assembly (APA)

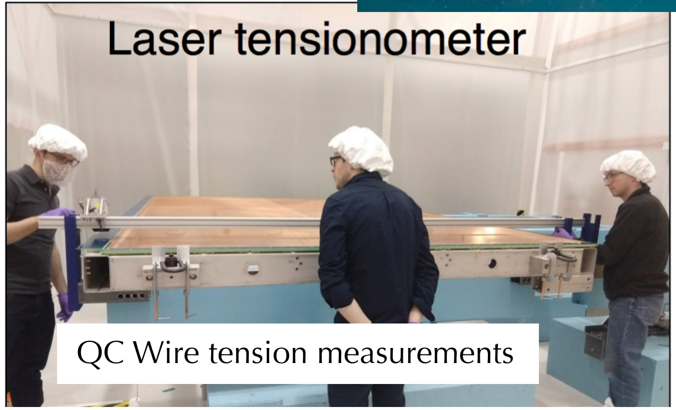
- Two wiring sites: Darusbury, UK; and Yale, USA
- All four APAs at Fermilab aligned, QC tested, and assembled
- Warm and Cold electronics connected

APA: steel frame supporting
150 μm CuBe wires, 3mm pitch
Vertical (Y collection plane)
± 60° to vertical (U plane, V plane)



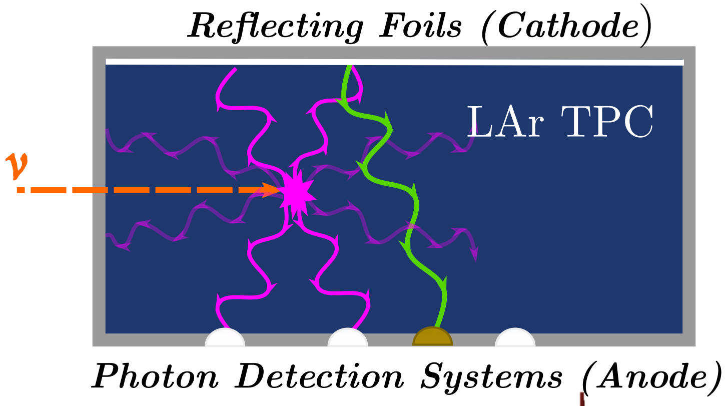


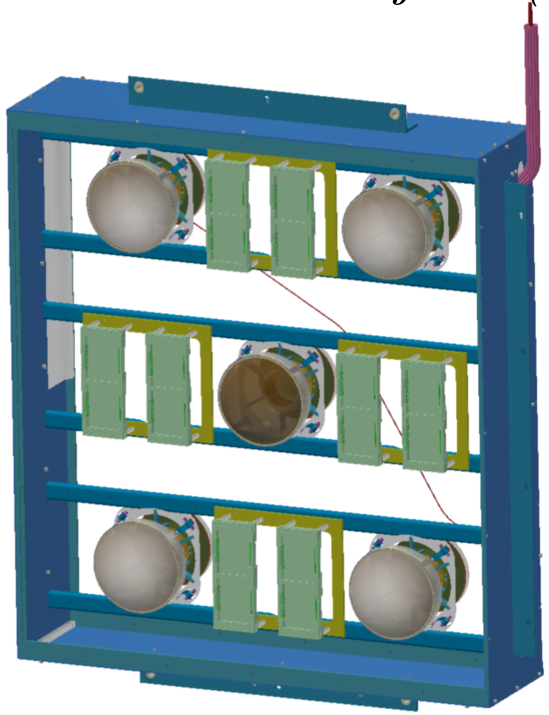




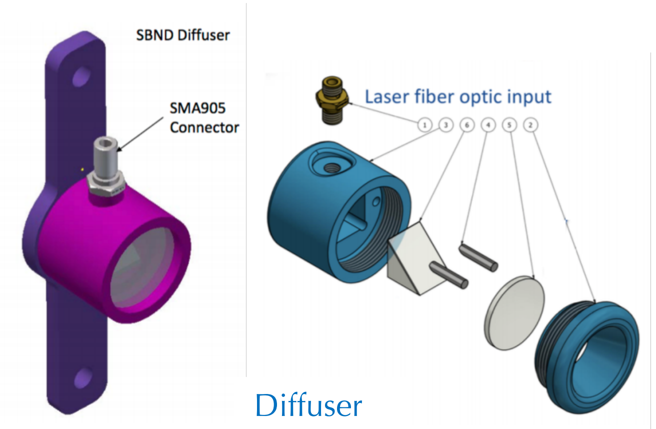
Photon Detection Systems

- Composite light detection system that both enhances the amount of light collected and provides an R&D opportunity
- Light detection for: Primary scintillation light (VUV) and Reflected light (visible)
- 24 PDS boxes mounted behind APAs
- 120 8″ Hamamatsu Photo multipliers:
  - 96 coated with wavelength-shifting TetraPhenyl Butadeine (TPB)
  - 24 uncoated for observing visible light
  - Ready and tested at CCM in Los Alamos
- 192 XARAPUCA; equal VUV/VIS sensitive split
- 5 diffusers for calibration
- Currently all detectors are ready.
- Assembly of PDS boxes, and cabling is ongoing.



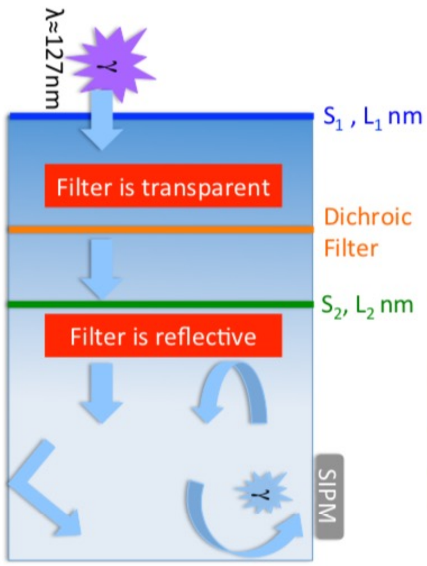


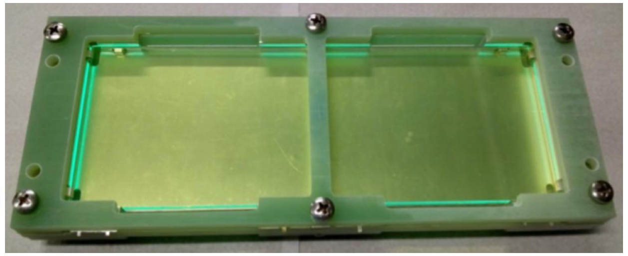

PMTs in CCM @LANL

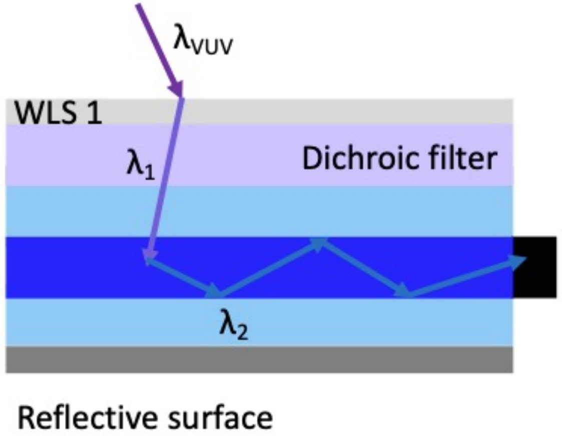


Diffuser

Photon Detection System Innovations





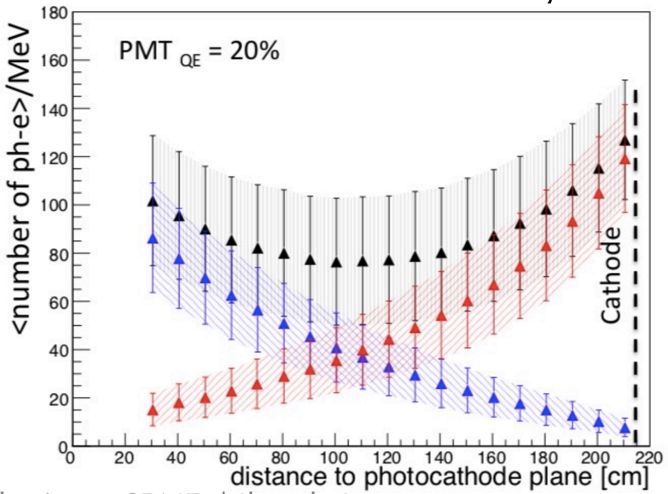


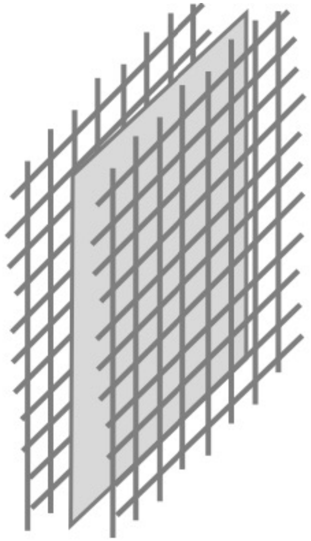
X-ARAPUCA:
Using a dichroic filter and a wavelength shifter light gets *trapped* in a box where it gets collected by a SiPM

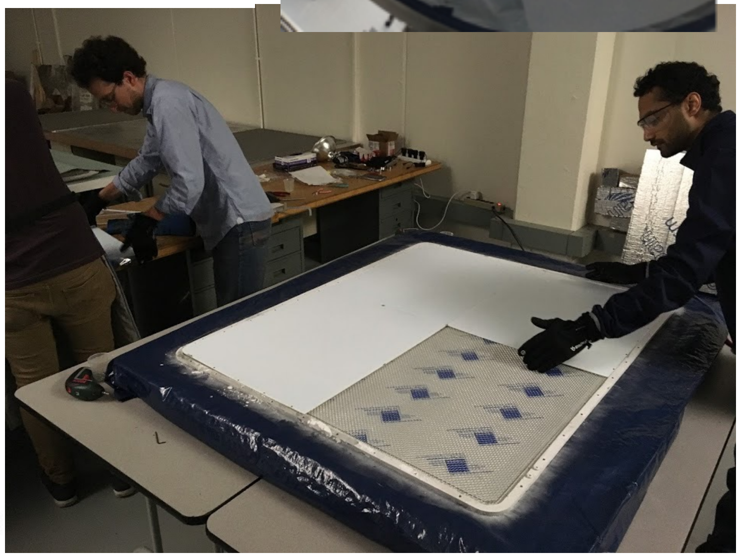
JINST **11** C02004,
JINST **13** C04026

Wavelength Shifting Reflective Foils:

- Highly reflecting dielectric foils with an evaporated fil of TPB.
- It greatly increases the ligh yield, specially from light originating closer to the cathode.
- Improved timing, position reconstruction, calorimetry

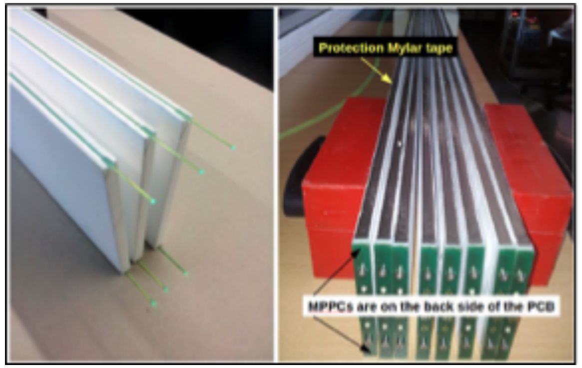


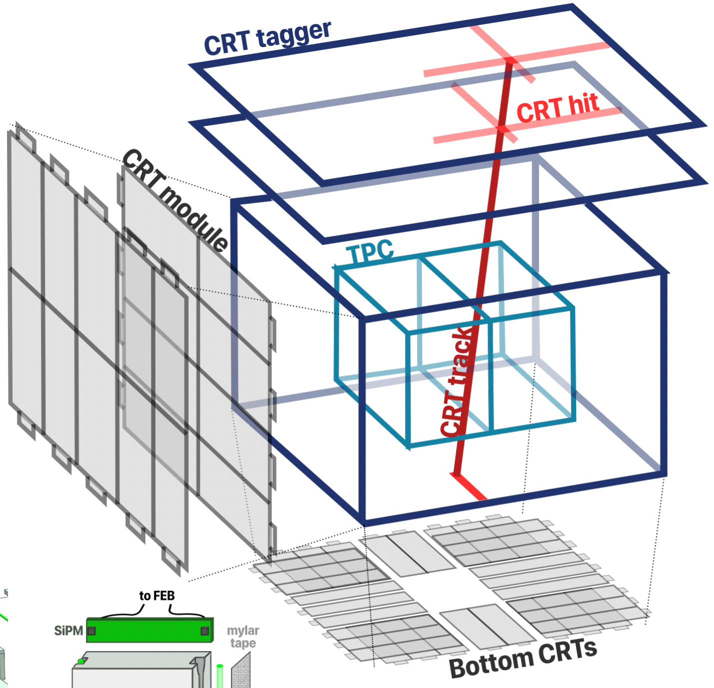


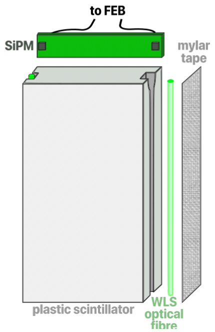


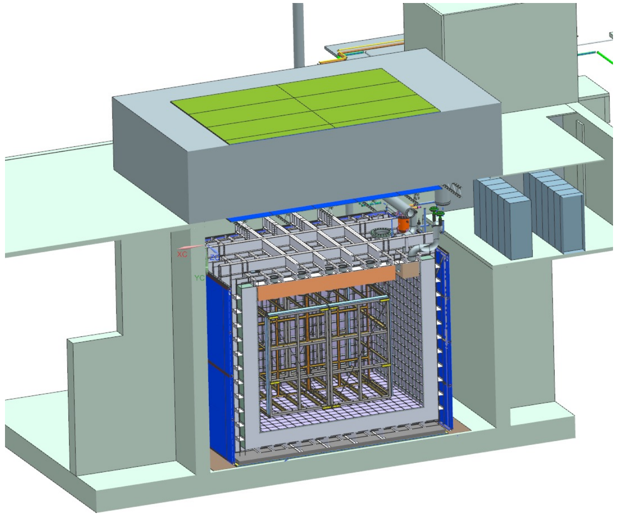
Cosmic Ray Tagger and Overburden

- SBND is on surface. In order to mitigate the cosmic ray background, it is equipped with a CRT system
- All sides of the cryostat are surrounded by planes of extruded scintillator strips read out by SiPMs
- The strips have two optical fibres at the edges, by looking at the ratio of light we improve spatial resolution
- Extra plane on the top for telescopic tagging
- Close to 4π coverage
  - 135 single modules (from 1.80m x 1.80m to 4.5m x 1.8m)
  - Bottom and Side CRT panels fabricated and shipped to FNAL. Production of the Top CRT is almost finish.
- No overburden as it increases dirt background (neutrino interactions outside the active volume)







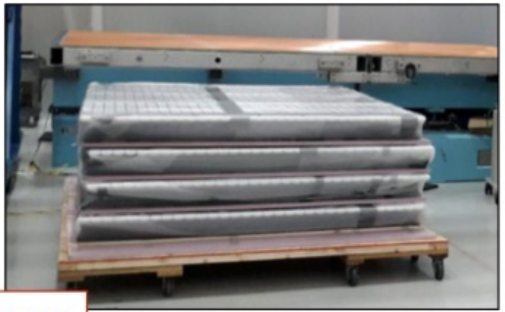


CPA, Field Cage, HV Feedthrough

UNIVERSITY OF SUSSEX

HV FT test

Coaxial FT: a stainless steel core and grounding sheath with polyethylene insulator, contacting the cathode donut with a spring-loaded tip

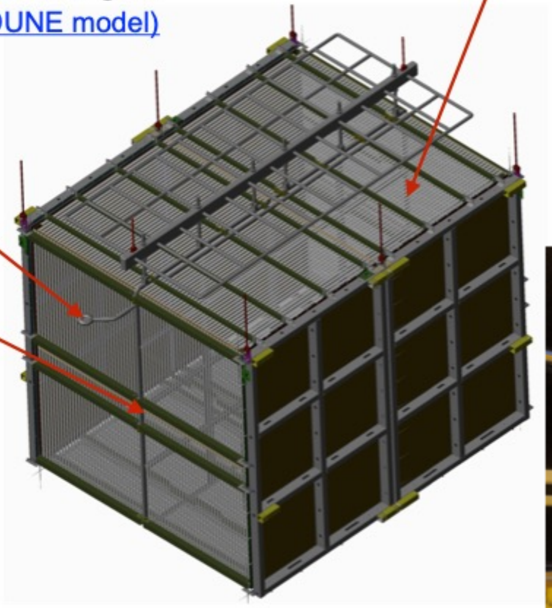


Roll formed aluminium profiles, with polyethylene end caps.
Same design as in ProtoDUNE

HV system designed
(ProtoDUNE model)

High Voltage Feedthrough

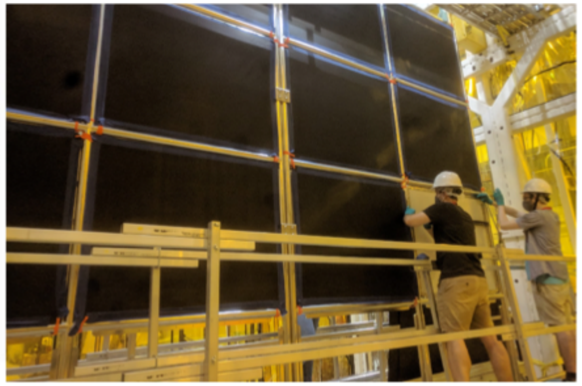
Field cage

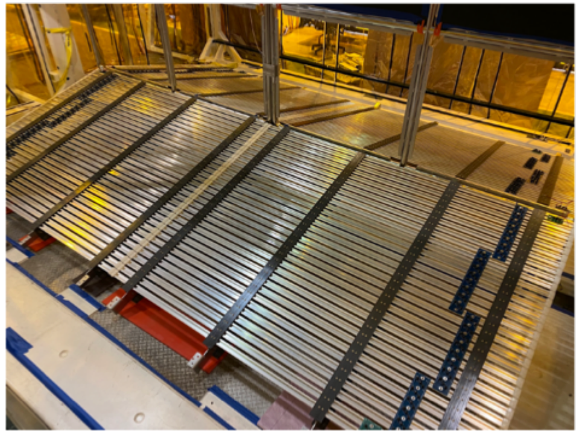


Welded, electropolished assembly composed of a stainless steel tube frame supporting stainless mesh panels (see slide 17)

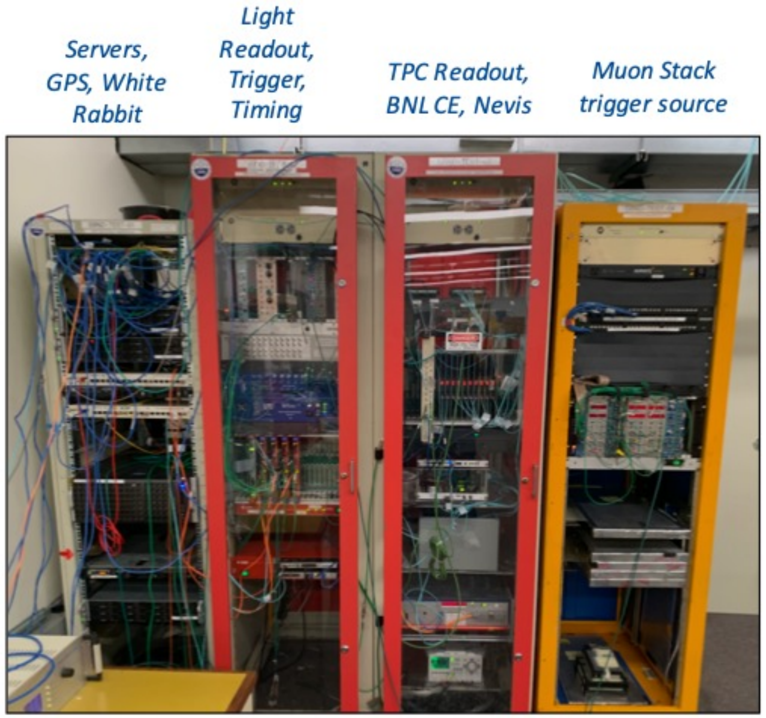
Cathode Plane Assembly

CPA assembled upright in clean tent at DAQ





DAQ



DAQ readout Test Stand at DAB

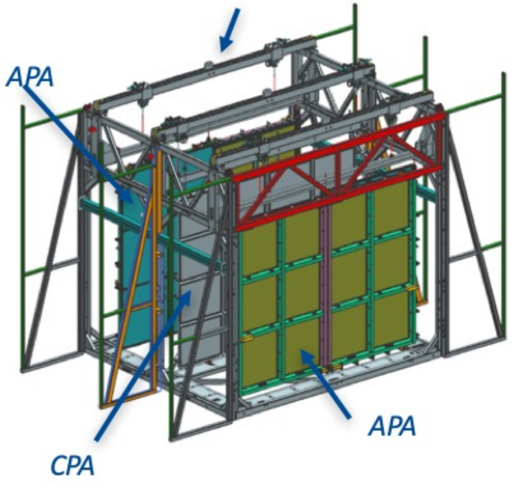
- All DAQ fronts are mature, robust and ready: readout electronics, software, servers, connectivity, trigger hardware…
- Our DAQ software is SBNDAQ: an implementation of artDAQ.

- Common to ICARUS and SBND; developed, tuned and implemented by collaborators from both experiments at our dedicated test stand

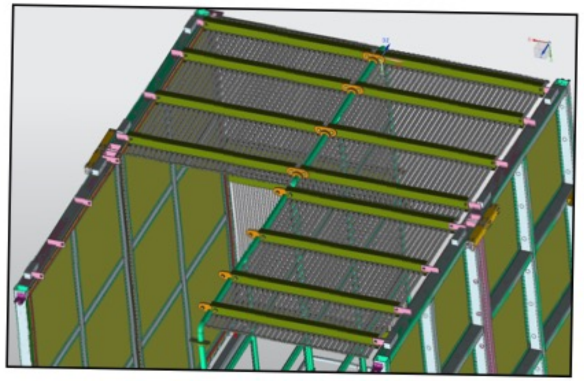
- We'll use CERN's White Rabbit to synchronize clocks

TPC Assembly

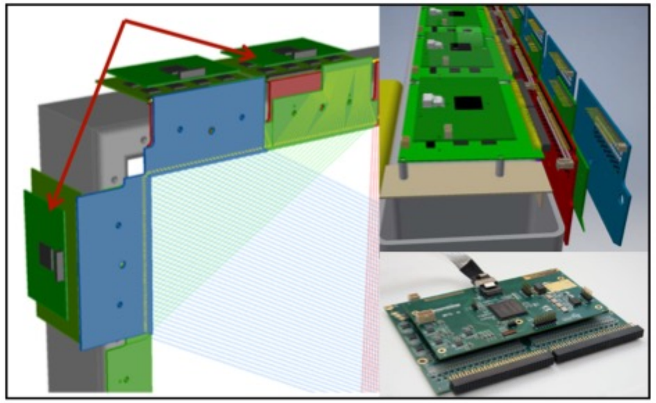
1) Install APAs and CPA



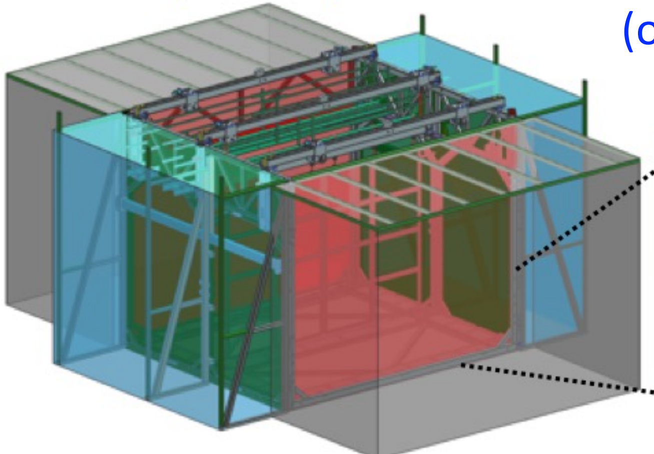
2) Install field cage

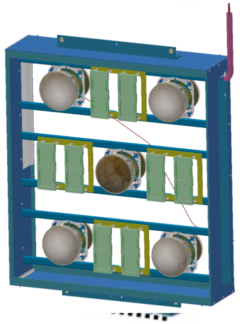


3) Install cold electronics



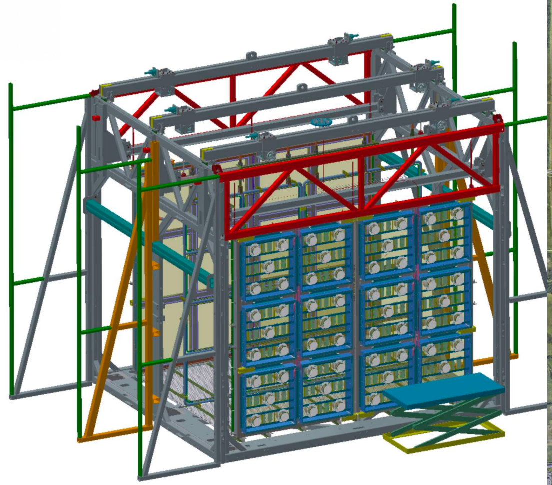
4) Install photon detection system (ongoing)

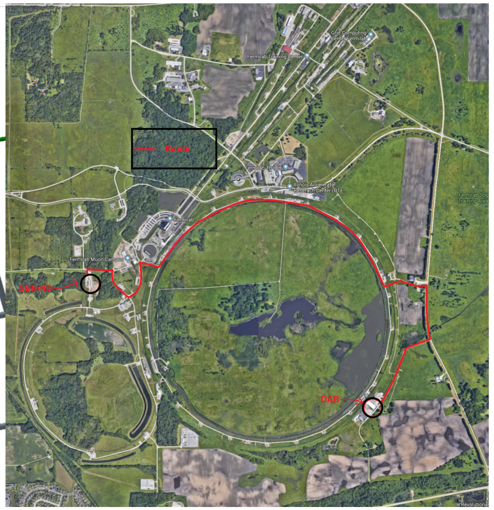


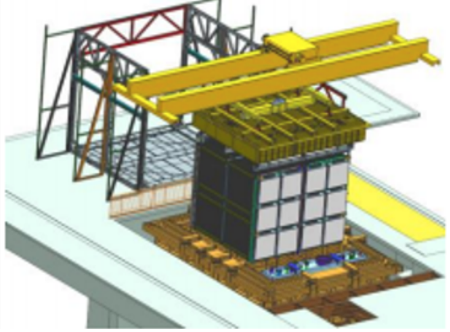


atf with outer removable clean tents (UV blocking)

5) Ready to be moved to ND mid 2022



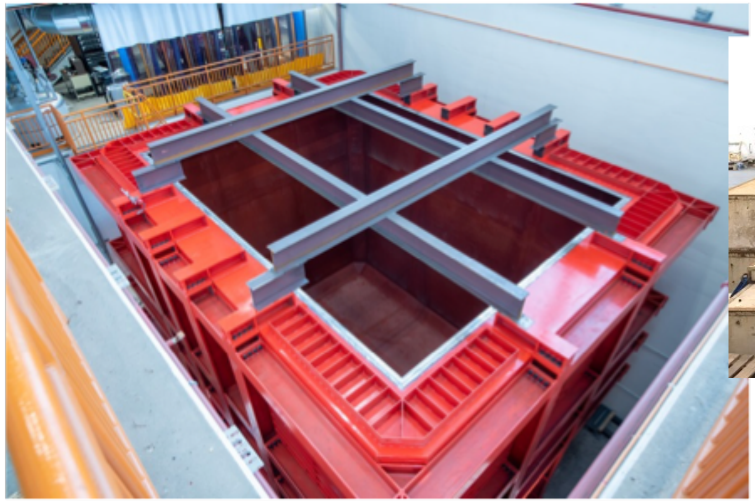


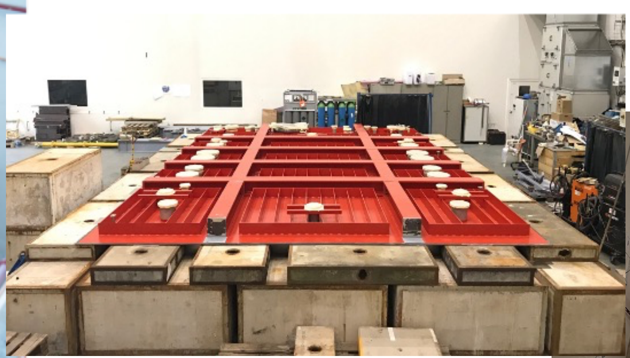


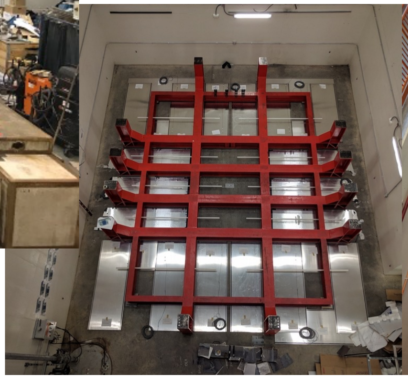
Cryostat and Cryogenics

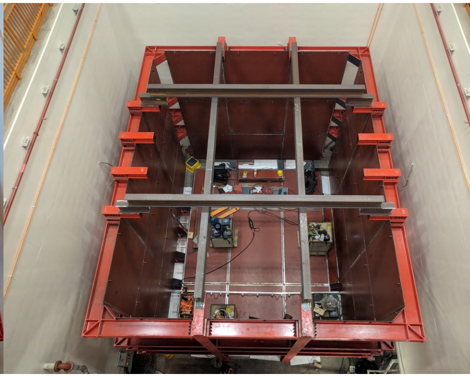
- Outer steel structure + GTT designed membrane cryostat
- SBND cryostat is the 3rd generation prototype
- Warm cryostat fabricated, pre-assembled at CERN and shipped to FNAL
- Several cryogenics systems have been severely affected by lockdowns and the pandemic
- Warm outer vessel is already installed

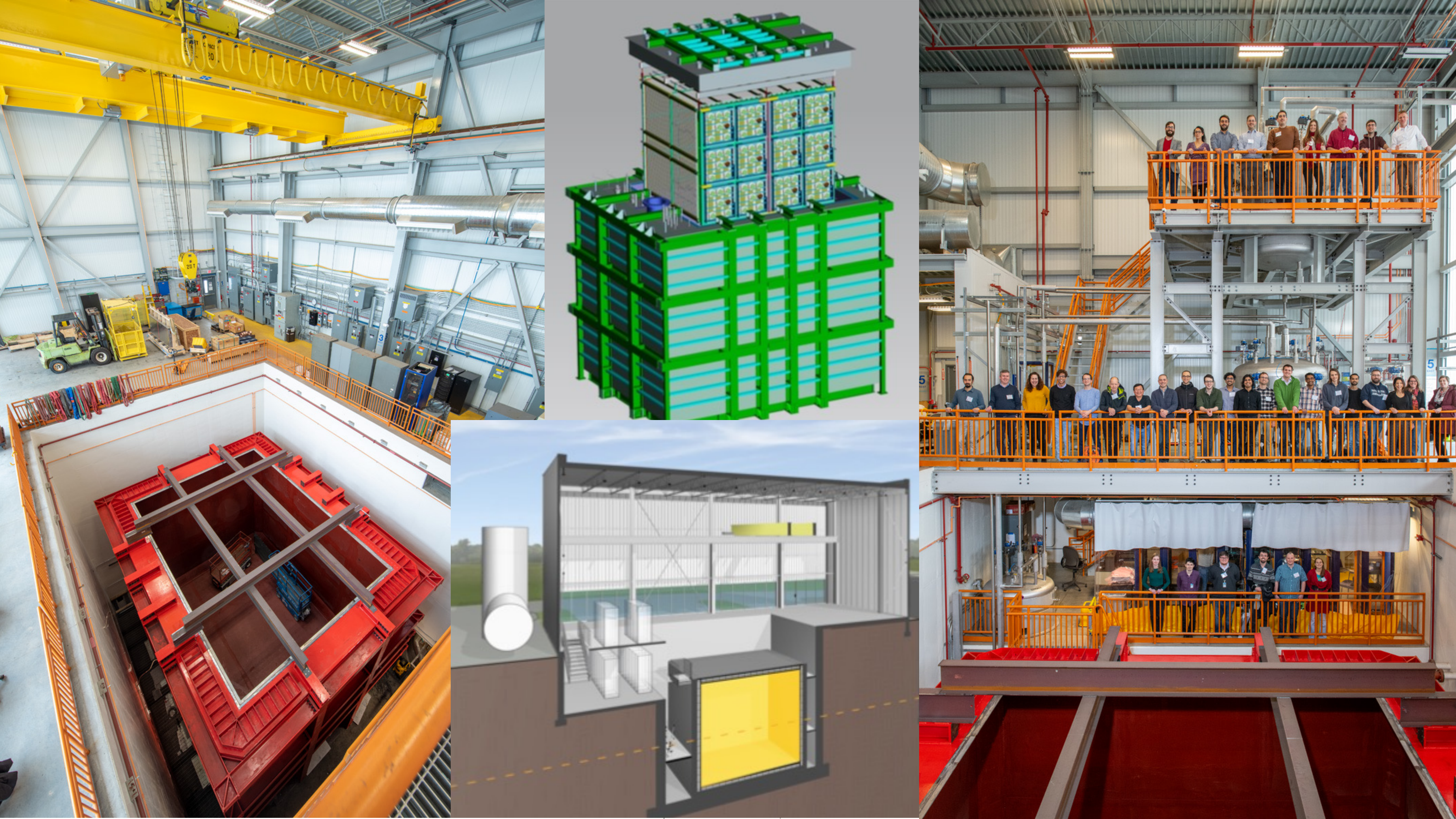
Top cap ready to be fit



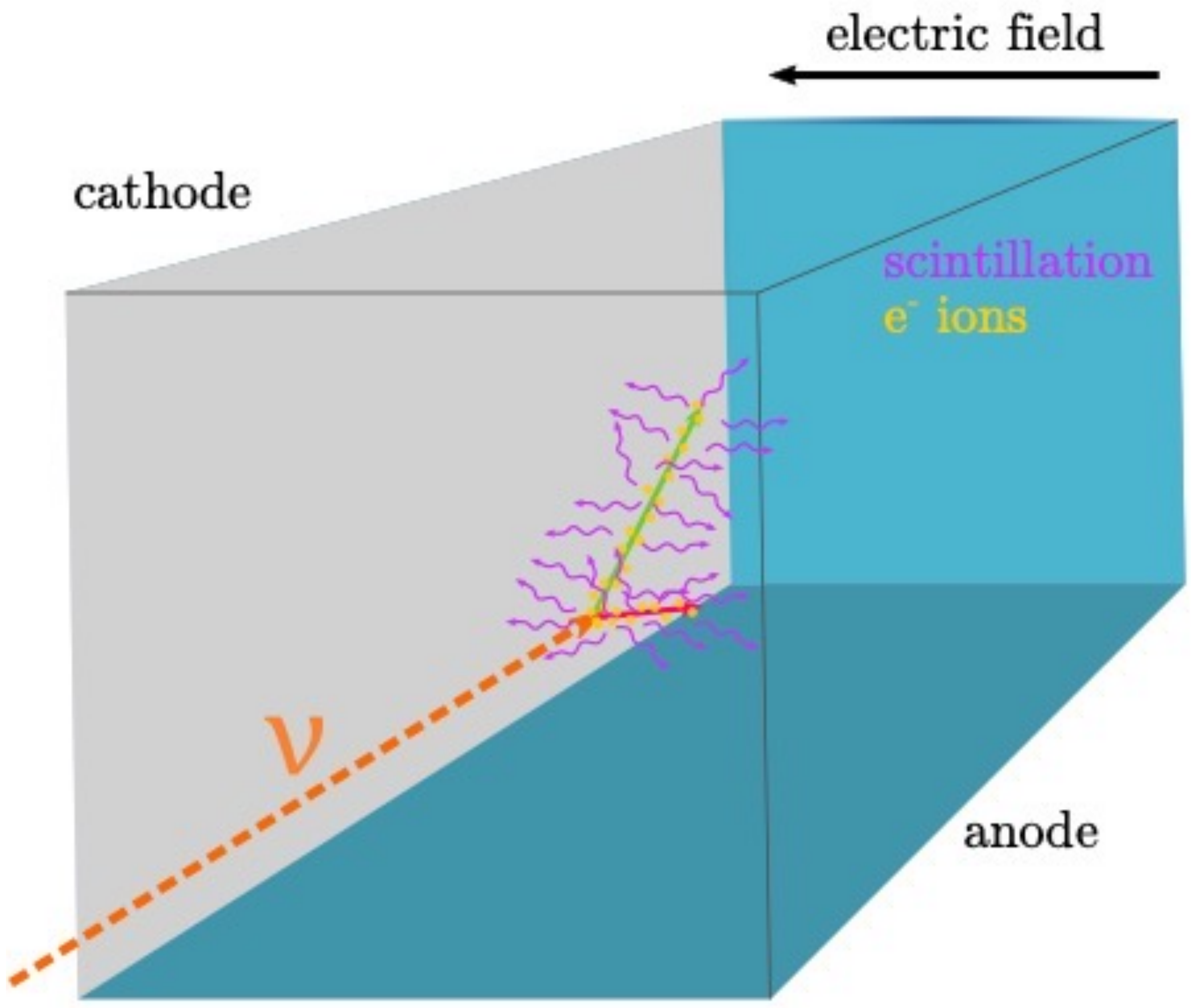






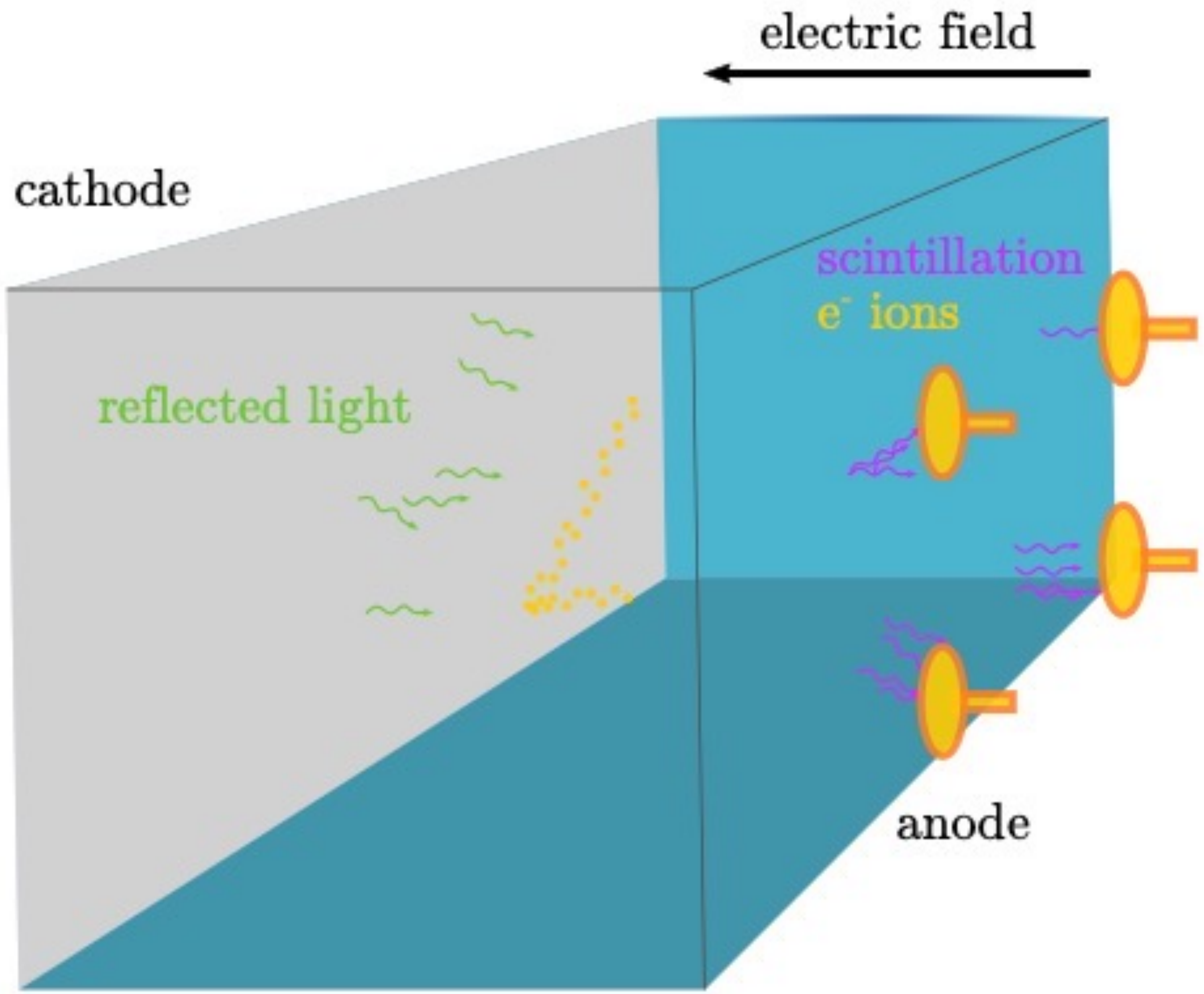


LAr Time Projection Chamber



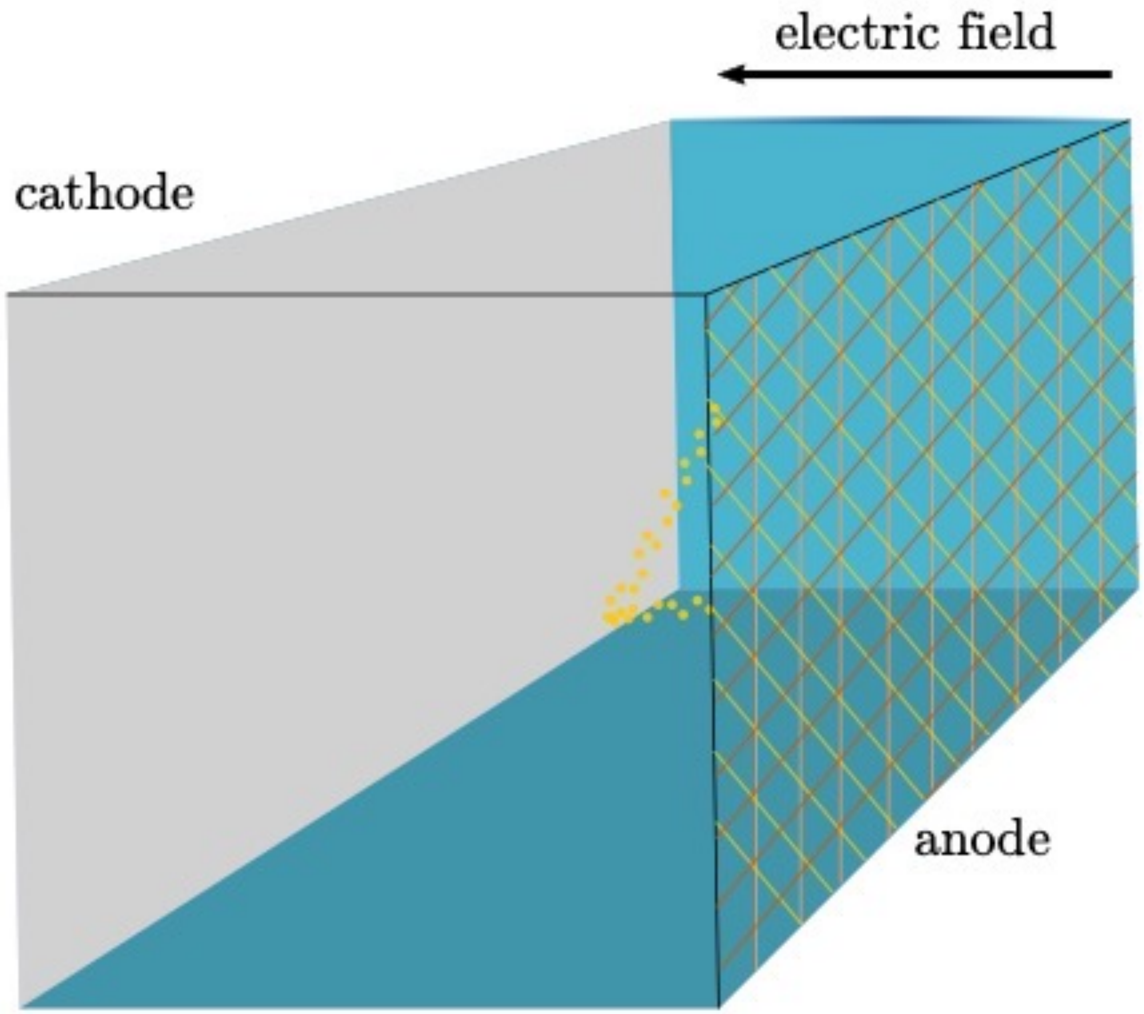
- Neutrino interacts with LAr.
- Charged particles come out of this interaction and ionise the medium
- Scintillations VUV photons are also produced

LAr Time Projection Chamber



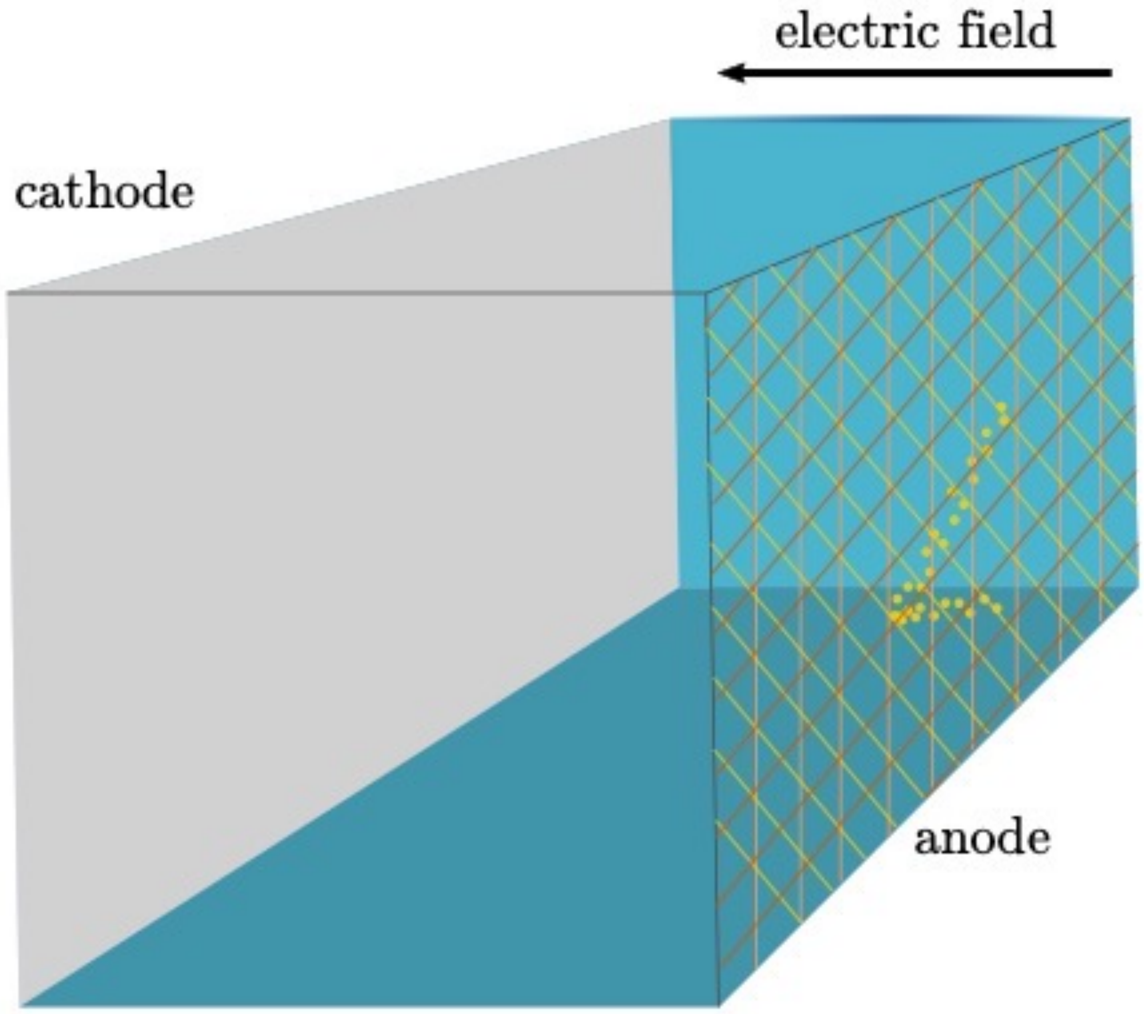
- VUV light is created isotropically, part of it will get lost but some will be collected by photon detectors
- Some of it will become wavelength shifted to visible light and reflected at the cathode (SBND specific)
- This occurs in ~10 ns, but with a long tail of ~1μs

LAr Time Projection Chamber



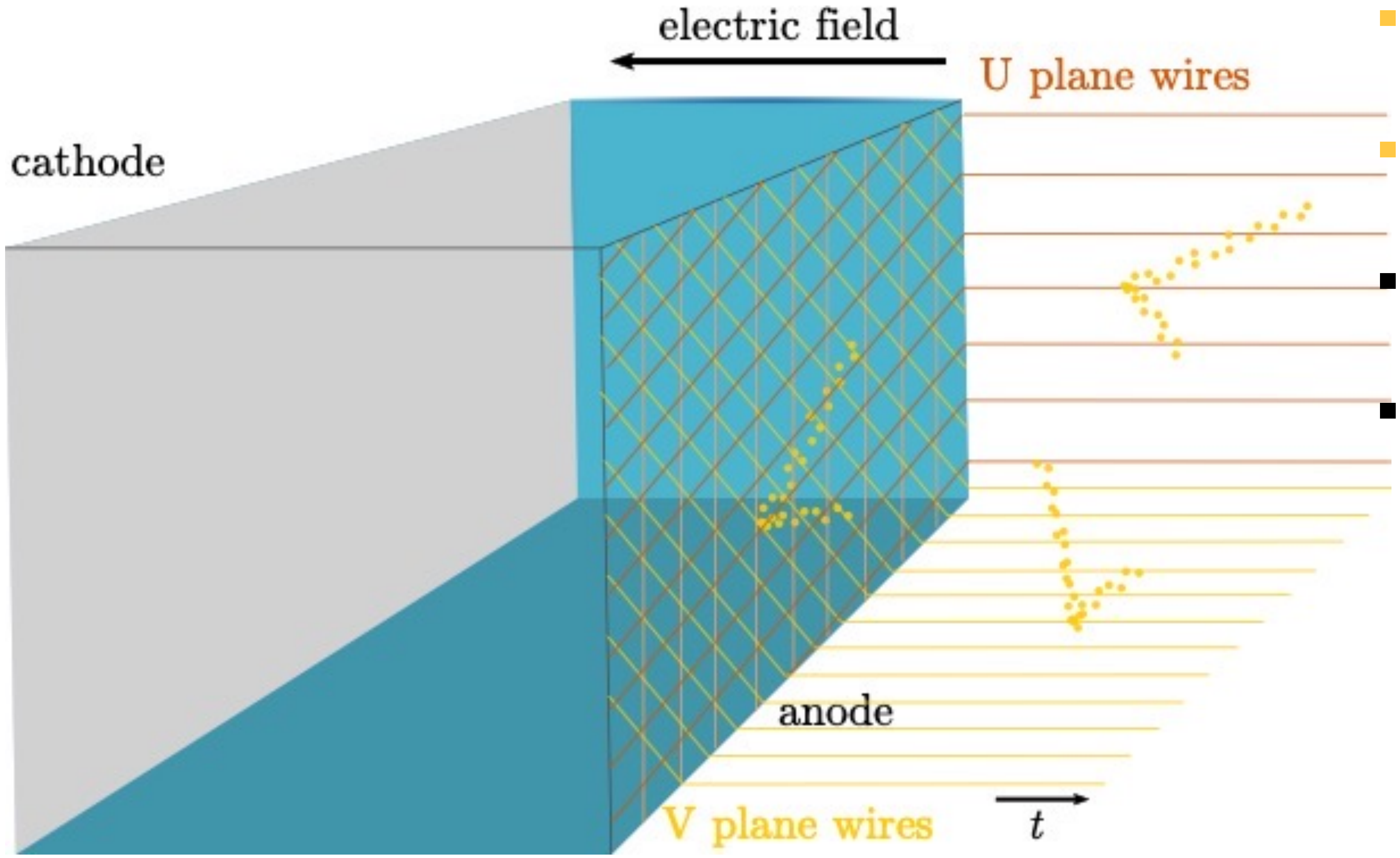
- The ionised electrons will slowly drift towards the anode due to the effect of the field
- Conversely heavy ions will drift towards the cathode, not shown

LAr Time Projection Chamber



- … slowly
- Drift time is around ~1 ms
- The drift position of the tracks is deduced from the time: later times mean interactions happened further away from the anode

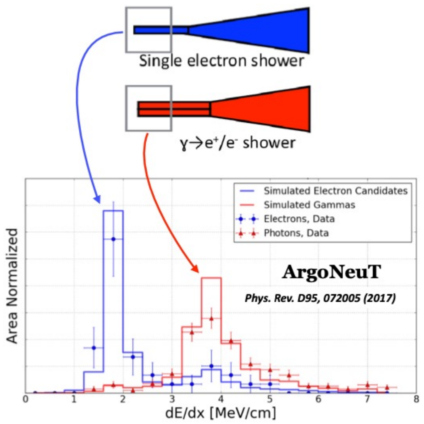
LAr Time Projection Chamber

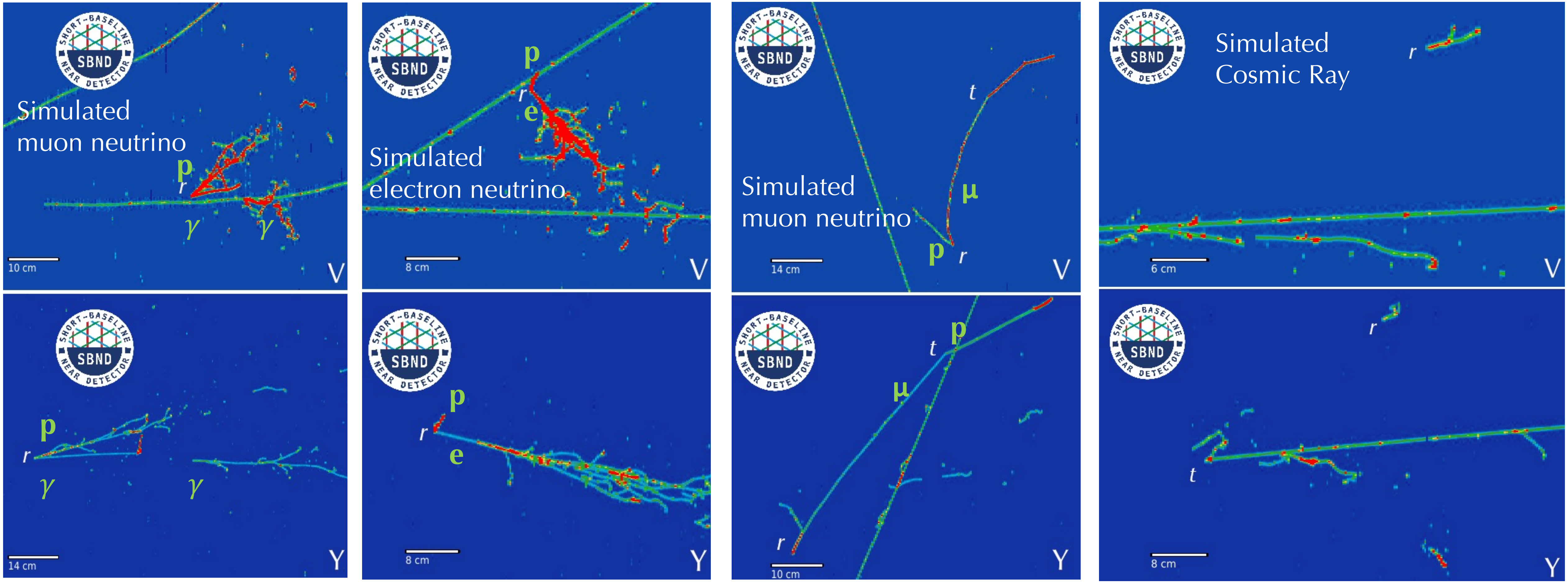


- Charge is read out in the three wire planes
- Three different views are created U,V,Y.
- 3D images are created
- In order to have good spatial resolution the electric field needs to be constant and uniform

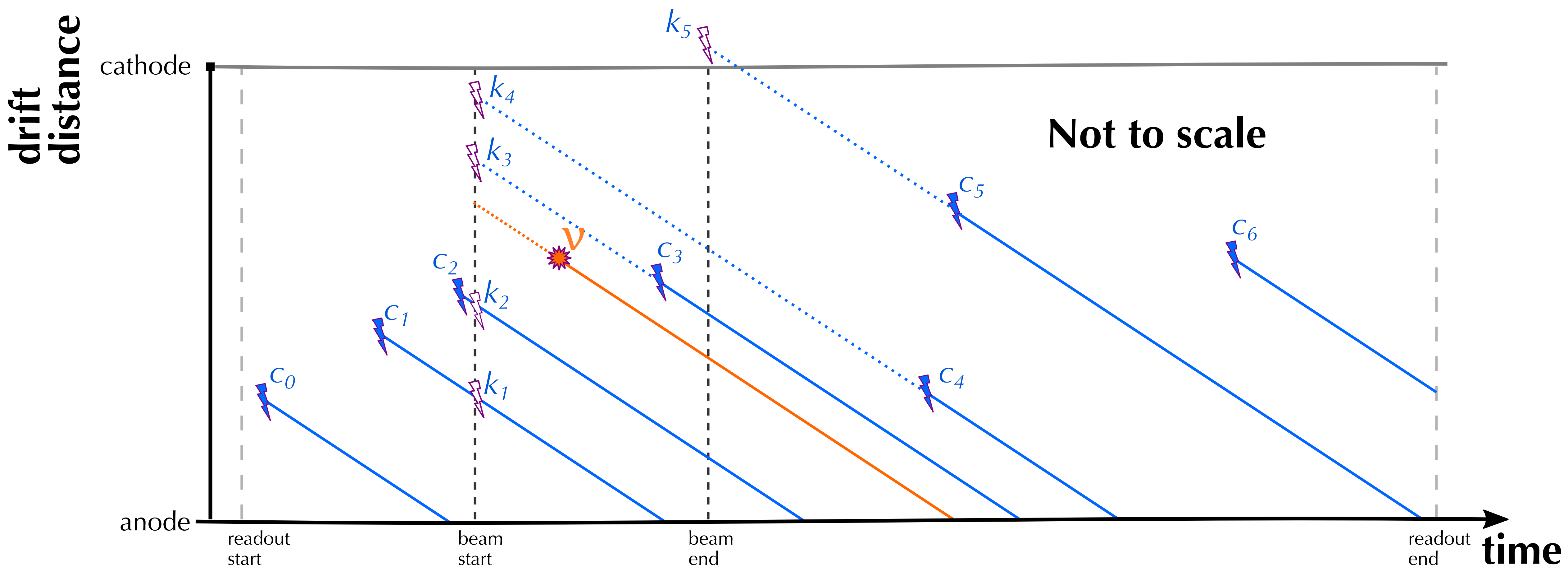
LArTPC technology

- 3D images with ~mm spatial resolution
- Detailed calorimetry that assists with particle identification
  - Discrimination of electrons and photons using: vertex displacement and initial dE/dx measurement





Cosmic Rays at SBND



TPC Readout Window ~1 ms

Charge Flash Matching

The boxes we need to check:

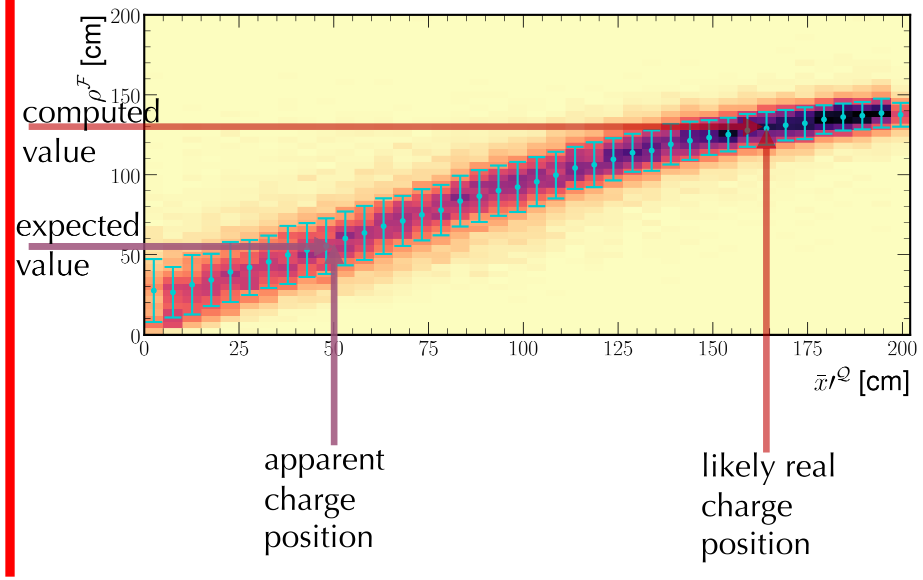
- Associate the ions (slow to read-out) with scintillation (fast to read-out)
- Provide T_0 for each activity
- Identify neutrino interactions from cosmic backgrounds
- Provide a *match score* to the association, as well as complementary information about reconstruction

To achieve that the steps we take:

- Define a set of metrics that quantify geometric qualities of neutrino interactions
- Get the expectation values and variance of those quantities for a large simulation of neutrino events at various drift distances
- Now for every interaction, compute their light and charge metrics
- Compare the metrics against the expected values of an interaction in that apparent drift position
- Assign a low score if if there's a good match, high score for poor matches

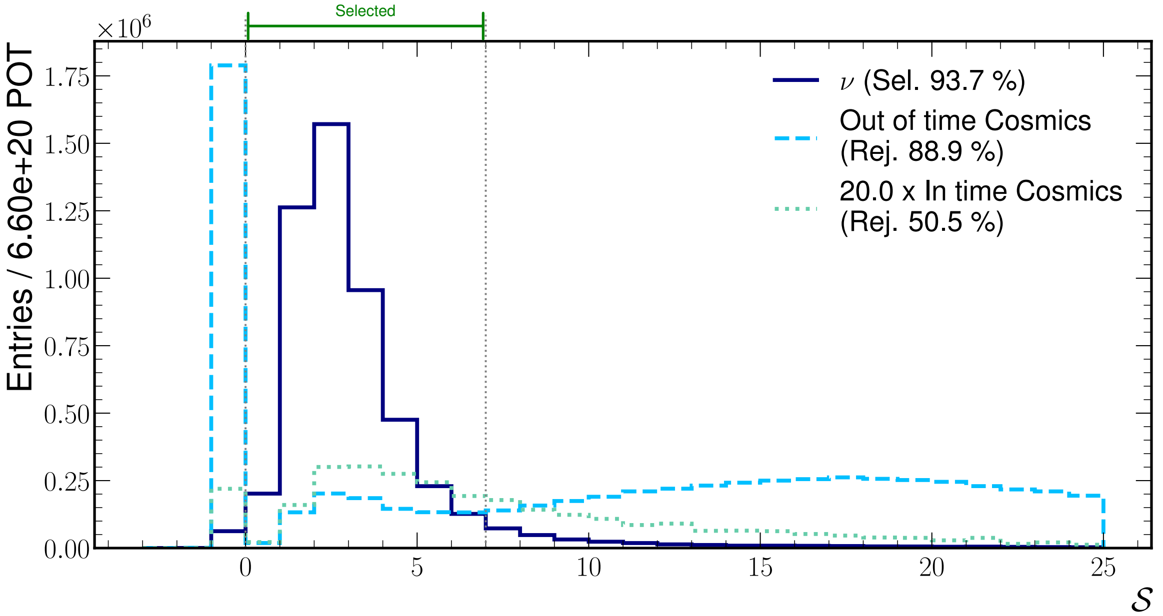
Example

1. Got a track (collection of charge deposits)
2. Apparently is 50 cm from the anode
3. Computing the spread of light from an in time flash comes at 130 cm
4. It should only be 55 cm!
5. Poor match: high scored
6. The flash was likely created by a track that's 165 cm from the anode

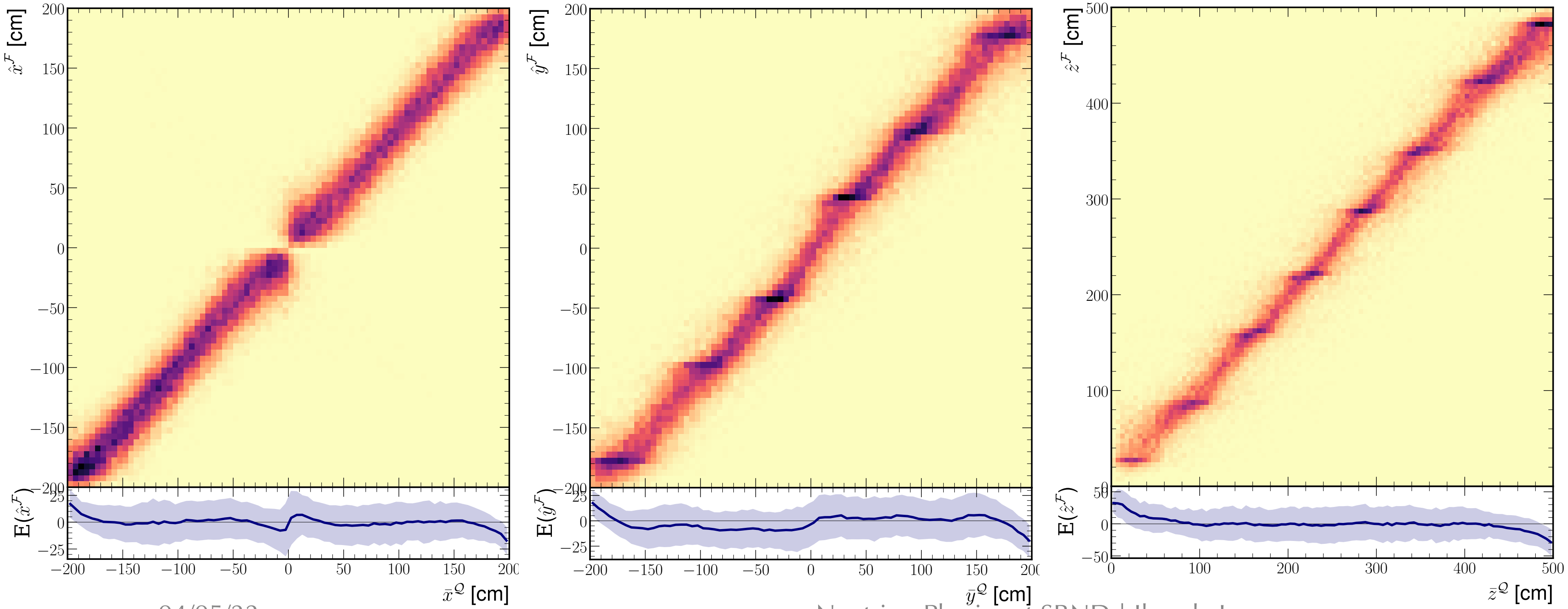


Flash Matching Performance

- Accept ~95% of neutrino interactions
- Reject >99.5% of cosmogenic interactions
- It helps in assessing if independent collections of charge should belong together



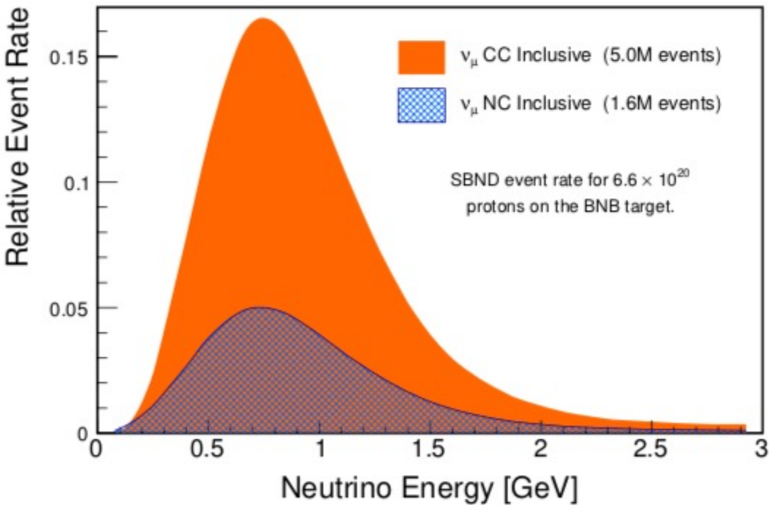
Flash vs Charge Centres

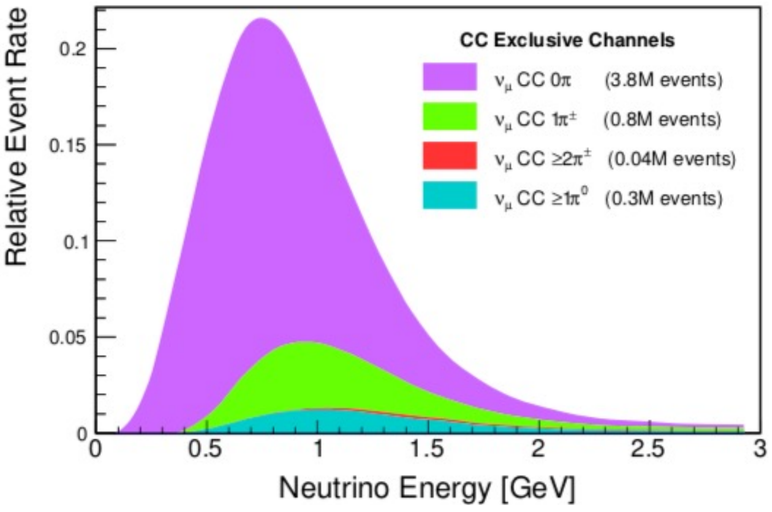


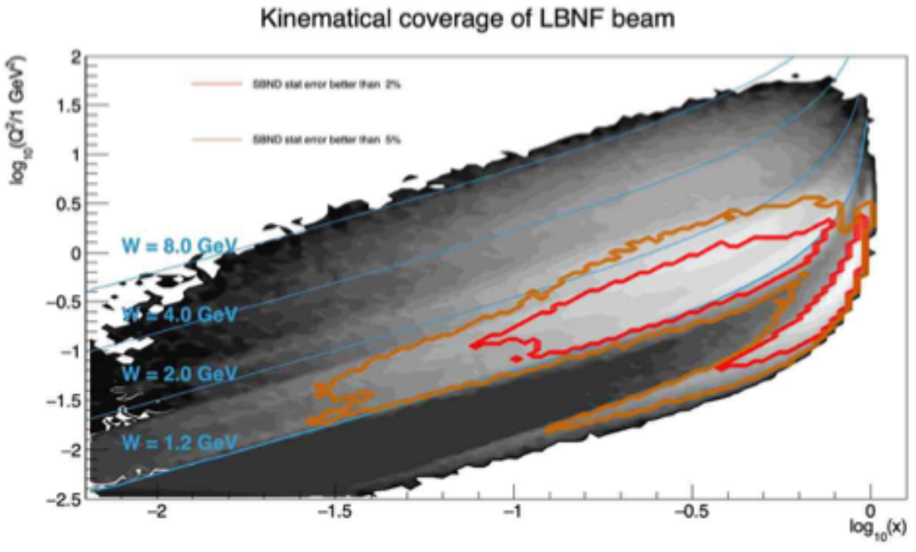
Physics: ν-Ar interactions

- Due to its close distance to the target, SBND observes the largest flux.
- Few month's worth of data will yield record high statistics.
- Over 7 million ν interactions in the span of 3 years: ~4 interactions per minute.
- Rich catalogue of ν-nucleus interactions.
- Will cover a large space of DUNE's program

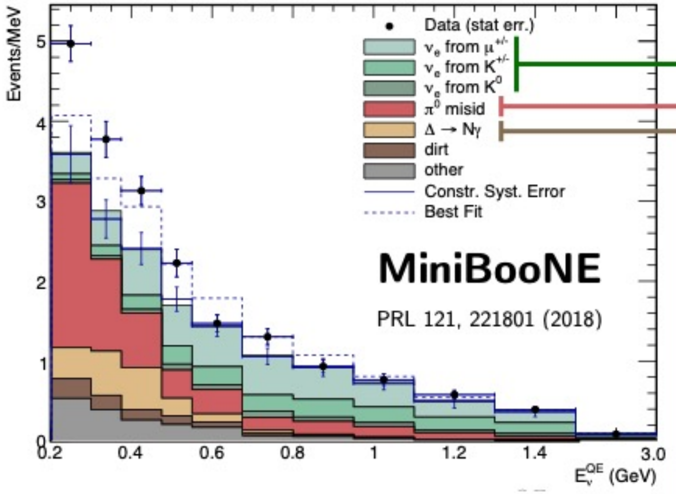
Annu. Rev. Nucl. Part. Sci. 2019 DOI 10.1146

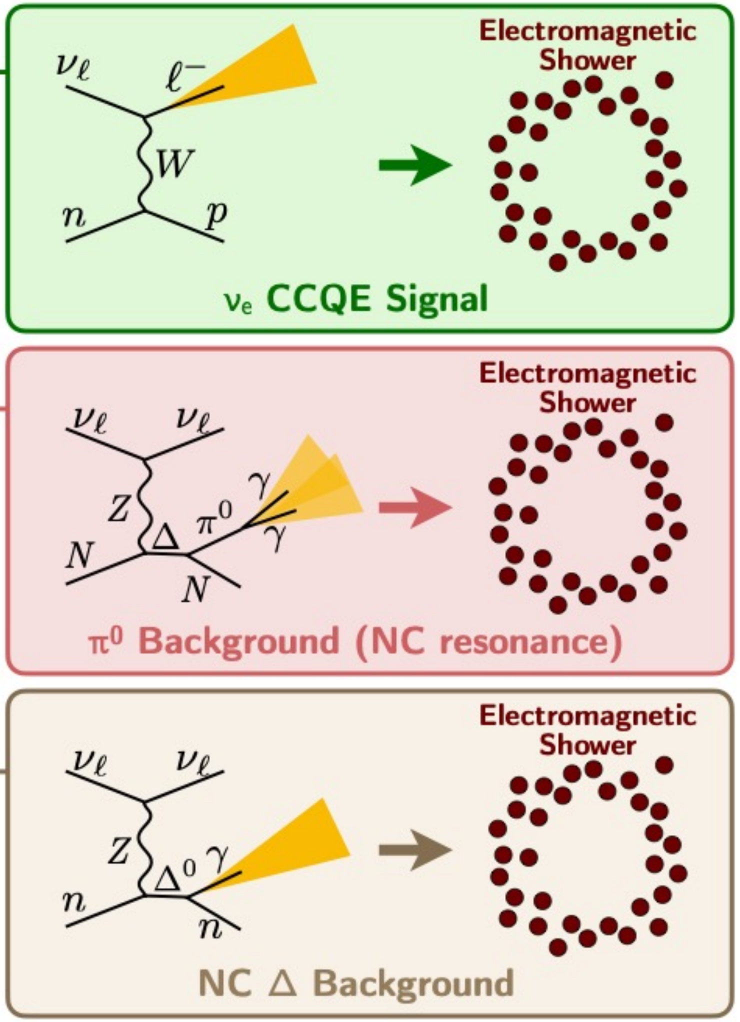


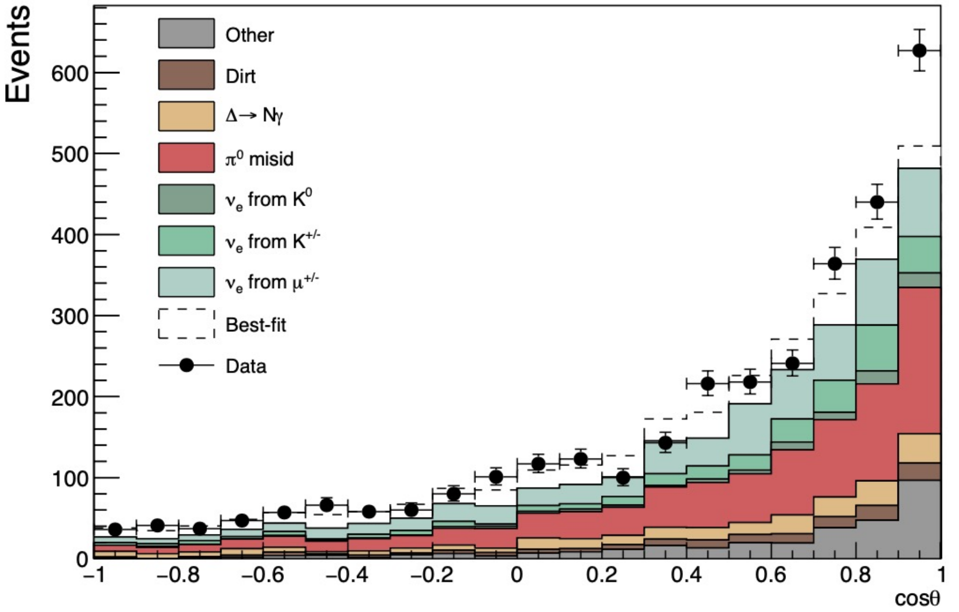




MiniBooNE's LEE in more detail



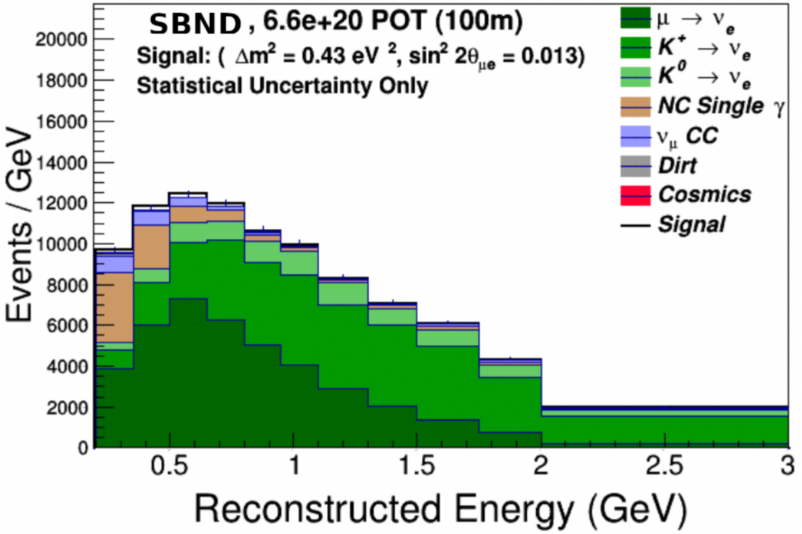


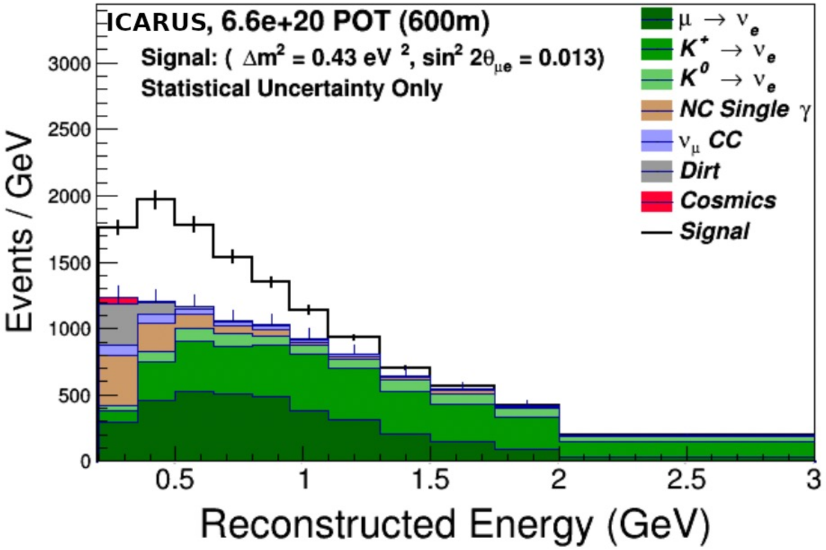


Electron excess	Sterile neutrinos? Something else?
Photon excess	$\Delta \rightarrow N\gamma$? π^0 mis-ID? Something else?

We need improved *event topology information*

Physics: Oscillations

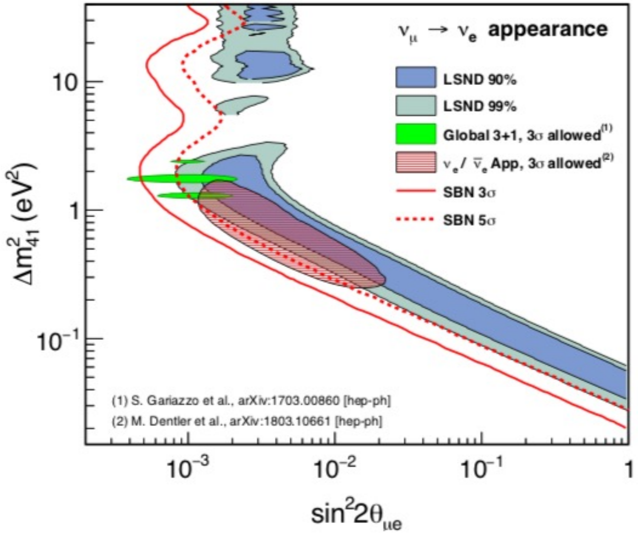




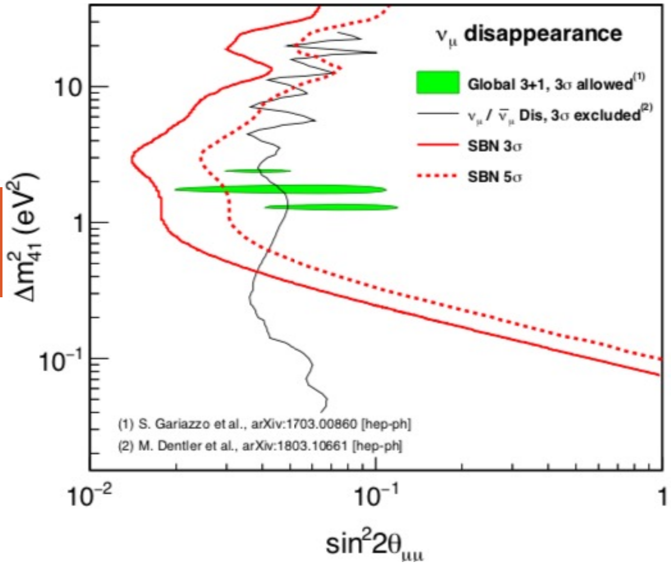
Near Detector will see the un-oscillated content of the beam

Far Detector will be able to see a distinctive oscillated signal, at the expected parameters

Appearance sensitivity



Disappearance sensitivity



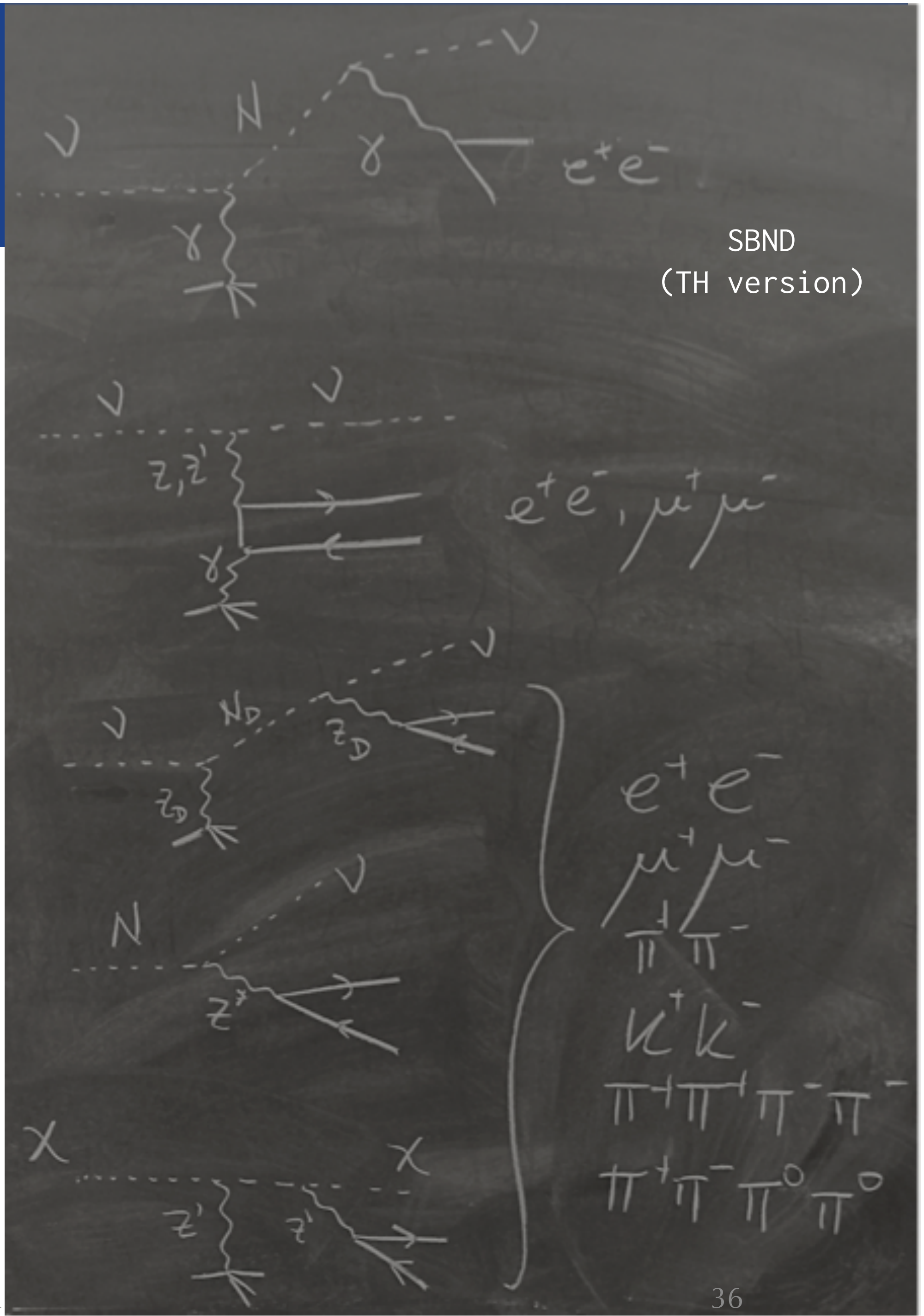
BSM and Rare Physics

SBND (SBN at large) qualities for a rich program of new exotic searches:

- ~1mm special resolution
- Excellent particle identification
- Fine calorimetry sampling
- High yield photon detection system
- High flux beam and large statistics
- Capacity to sample multiple off-axis fluxes due to its size and closeness to the source

arXiv: 1903.04608

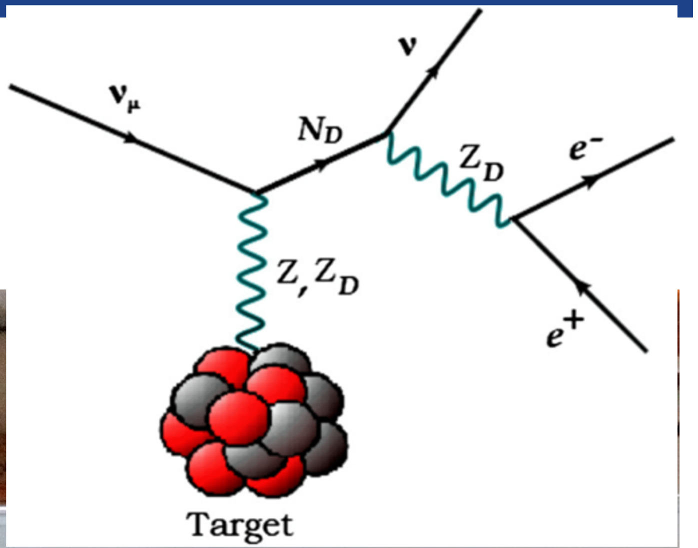
- **Electronvolt scale sterile neutrino decaying to active neutrinos**
- Large extra dimensions
- Resonant $\nu_\mu \rightarrow \nu_e$ oscillations
- Violation of Lorentz and CPT symmetry
- Sterile neutrinos and altered dispersion relations
- **Heavy neutral leptons**
- Charged current non-standard interactions
- **Dark neutrino sectors**
- Heavy neutrinos and transition magnetic moment
- **Neutrino tridents**
- **Millicharged particles**
- **Light Dark Matter**
- Neutrinophilic, lepton-number charged scalars
- Hyperon production and detection
- Your Theory Here

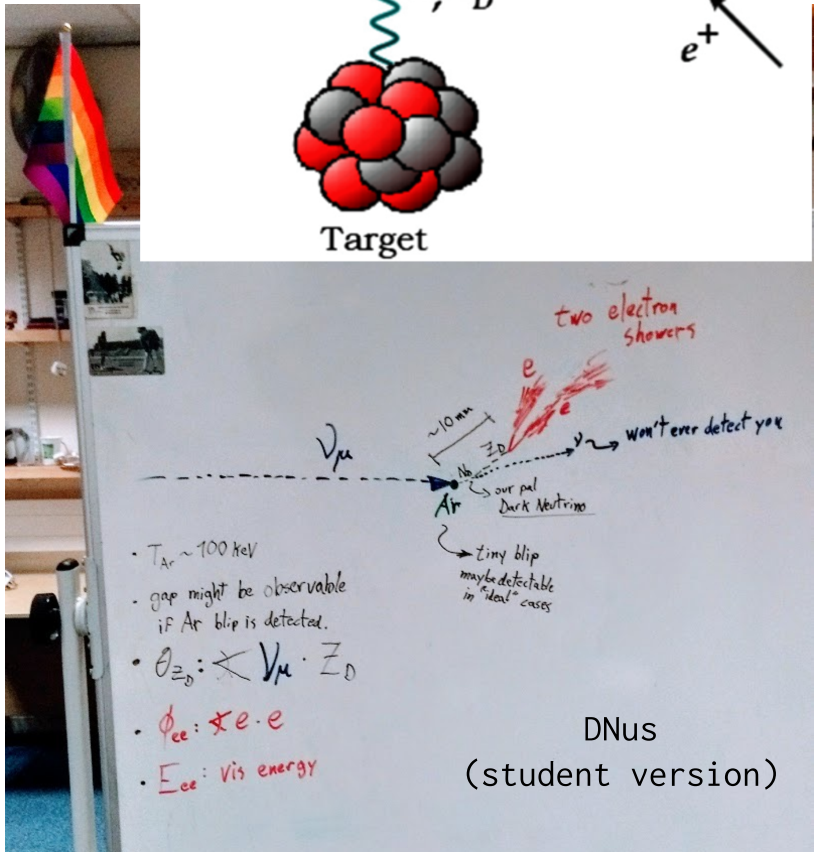


Dark Neutrino Portal to Explain MB

- New Dark Sector with a **dark neutrino** and **dark gauge boson**
- Both with masses in the range of ~10 to ~100 MeV
- The process goes:
  - beam neutrino **ν** interacts coherently with **Ar** nucleus
  - upscatters to **dark neutrino $N_{\mathcal{D}}$**, which in turn decays to
  - neutrino ν and **dark boson $Z_{\mathcal{D}}$**, this last one decays to
  - **e^+ e^-**, alias *the signal*
- Explain MiniBooNE Low Energy Excess:
  - ee is highly boosted such that MB can't distinguish them
  - ee is asymmetric, so one can't be seen

  and are construe as ν_e CCQE-like
- Main reference paper
  https://doi.org/10.1103/PhysRevLett.121.241801

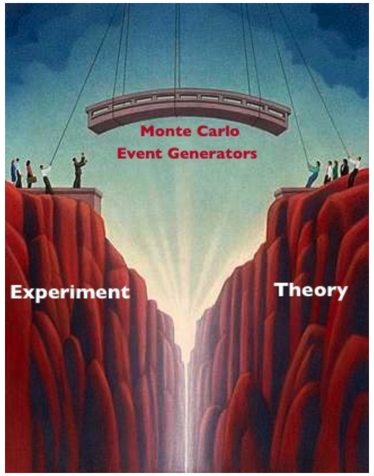




DNus in GENIE

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Nucl.Instrum.Meth.A614 (2010) 87-104



- **GENIE** is a *Universal Neutrino Event Generator:* It handles all neutrinos and targets, and all processes relevant from MeV to PeV energy scales.
- Takes care of the interactions of neutrinos with matter: the inputs are a neutrino flux and a geometry; the output are events of various neutrino interactions.
- Is the de-facto event generator for experimentalists these days, and it's the one used by SBND and all of the LArTPC experiments.
- Suited to simulate complex experimental setups in full detail, and takes the *no perfect theory approach: measurements are necessary, dealing with errors is unavoidable*

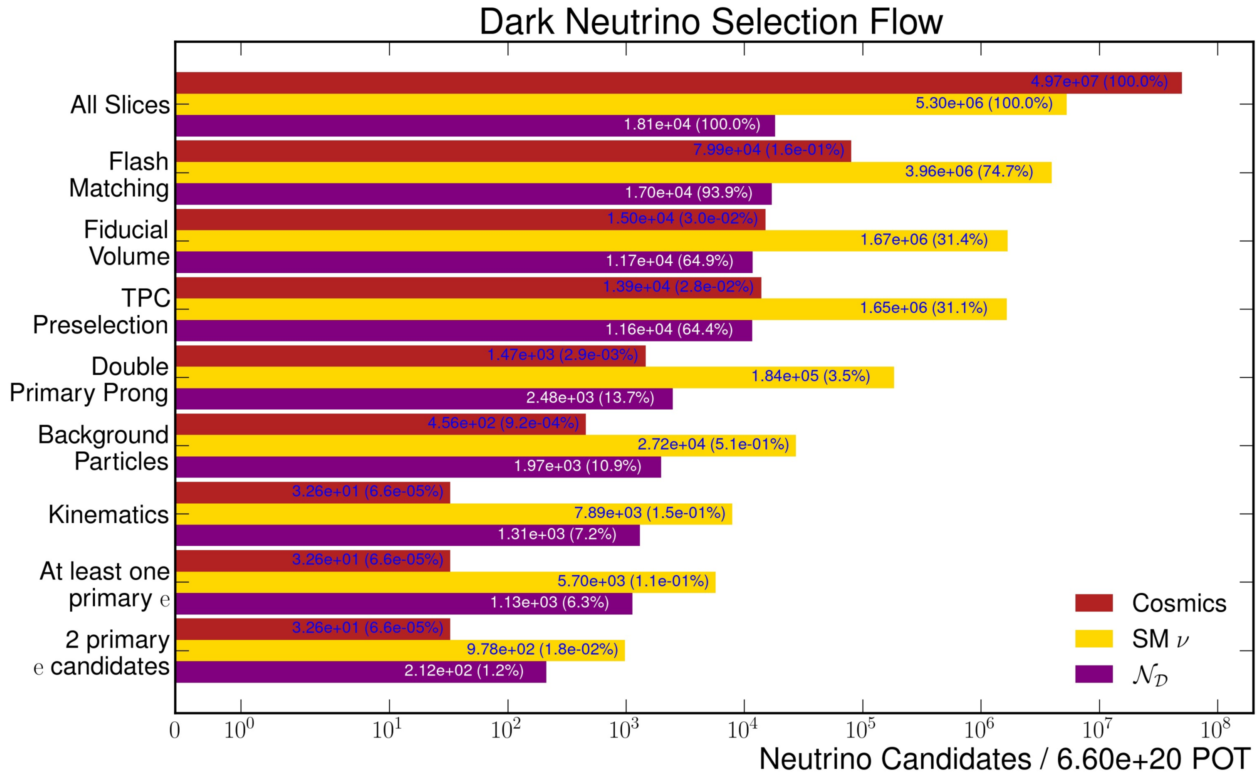
❖ With the guidance of one of the developers, I have created a fully functional module which generates Dark Neutrinos.

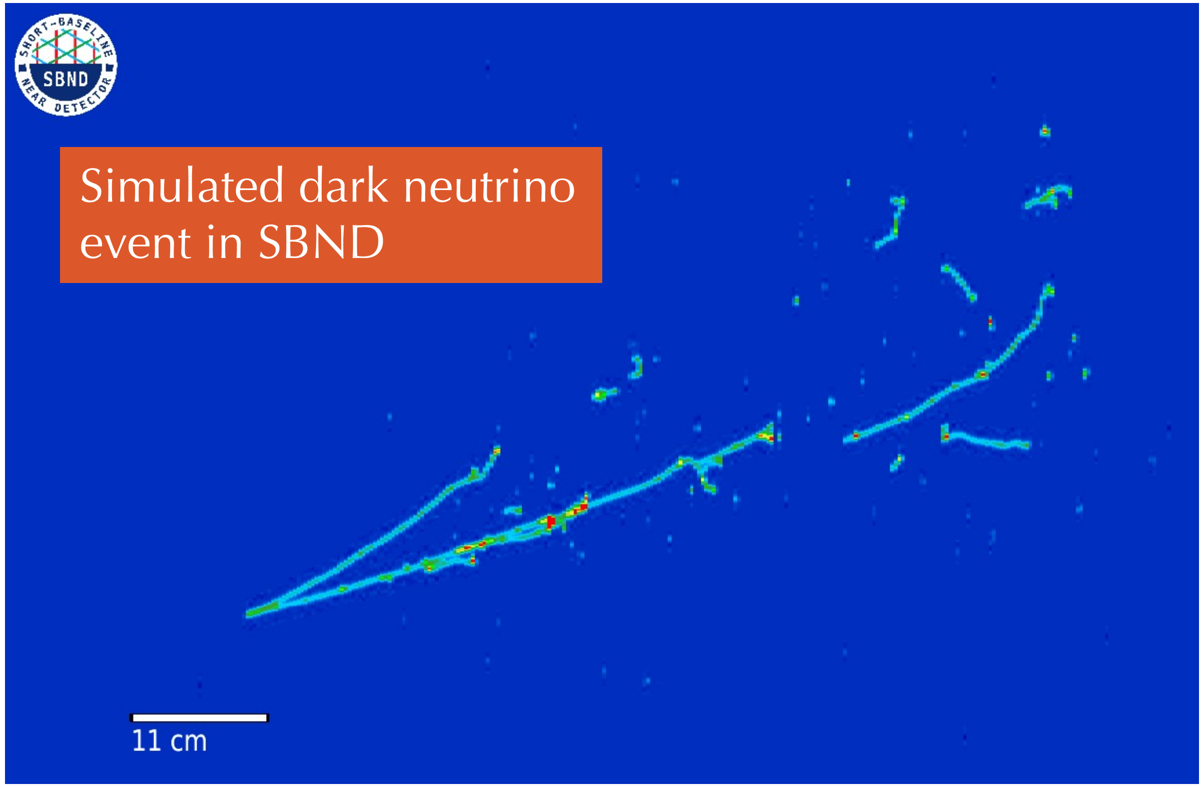
  - ➢ Form Factor suitable for this interaction
  - ➢ Integration of the 7 model parameters
  - ➢ 3+10 decay channels relevant to the energy range
  - ➢ Extensively stress tested: 100+ isotopes, 6 neutrinos and energies up to 1PeV

```
|-------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                             |
|-------------------------------------------------------------------------------------------------------|
| Idx |        Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m |
|-------------------------------------------------------------------------------------------------------|
|   0 |       nu_mu |   0 |         14 |  -1 |  -1 |   2 |   2 |   0.000 |   0.000 |   1.000 |   1.000 |   0.000 |
|   1 |        Ar40 |   0 | 1000180400 |  -1 |  -1 |   3 |   3 |   0.000 |   0.000 |   0.000 |  37.216 |  37.216 |
|   2 |        nu_D |   3 | 2000030000 |   0 |  -1 |   4 |   5 |   0.061 |   0.018 |   0.905 |   1.000 |   0.420 |
|   3 |        Ar40 |   1 | 1000180400 |   1 |  -1 |  -1 |  -1 |  -0.061 |  -0.018 |   0.095 |  37.216 |  37.216 |
|   4 |       nu_mu |   1 |         14 |   2 |  -1 |  -1 |  -1 |   0.128 |  -0.071 |   0.079 |   0.166 |   0.000 |
|   5 |         Z_D |   3 | 2000030001 |   2 |  -1 |   6 |   7 |  -0.067 |   0.089 |   0.826 |   0.834 |   0.030 |
|   6 |          e- |   1 |         11 |   5 |  -1 |  -1 |  -1 |  -0.045 |   0.069 |   0.682 |   0.687 |   0.001 |
|   7 |          e+ |   1 |        -11 |   5 |  -1 |  -1 |  -1 |  -0.022 |   0.019 |   0.144 |   0.147 |   0.001 |
|-------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                            |  -0.000 |   0.000 |   0.000 |  -0.000 |         |
|-------------------------------------------------------------------------------------------------------|
|       Vertex:         nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =   0.000000e+00 s) |
|-------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                        none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:    YES          |
|-------------------------------------------------------------------------------------------------------|
| sig(Ev) =       5.24919e-42 cm^2  | dsig(Ev;{K_s})/dK   =     3.00880e-38 cm^2/{K}   | Weight =       1.00000 |
|-------------------------------------------------------------------------------------------------------|
```

Dark Neutrino in SBND

- A preliminary event selection study using reconstructed quantities shows a promising potential for SBND to observe dark neutrinos.
- The initial signal to full background ratio is 3.3×10^{-4}, after all the cuts it becomes 2.1×10^{-1}, a **×640 improvement**.
- Considering only the SMν background, the STB ratio is $3.4{\times}10^{-3}$, after all cuts it becomes $2.2{\times}10^{-1}$, a **×63 improvement.**





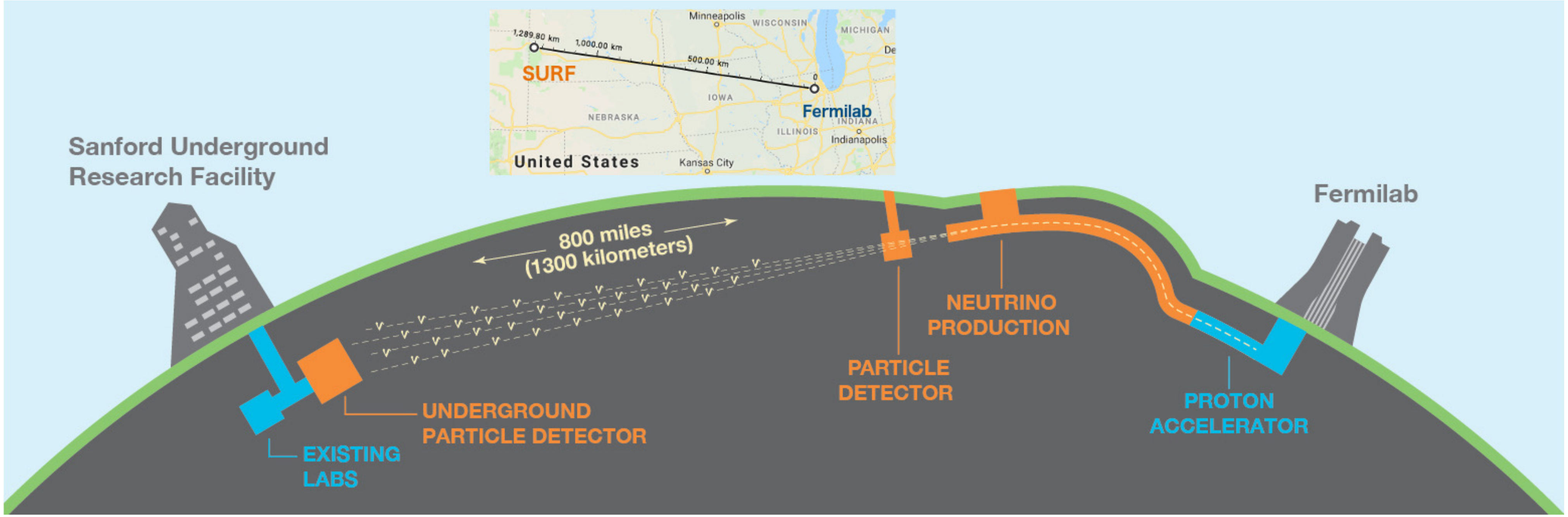
Towards DUNE

The Deep Underground Neutrino Experiment:

- CP violation
- Mass ordering
- Solar Neutrinos
- Super Nova neutrinos
- Nucleon Decay

Development towards making DUNE directly address by SBND:

- ✓ Analysis and reco software
- ✓ Particle ID software
- ✓ Particle generator software
- ✓ DAQ software
- ✓ Photon Detectors
- ✓ Cold Electronics
- ✓ Wavelength Shifting Foils
- ✓ Cross sections and ν-Ar interactions
- ✓ Digitiser hardware



Summary

- There's an unexpected and unexplained process at short baseline oscillations.
- Light Sterile Neutrinos are not a favored explanation: new avenues need to be explored.
- SBND is the Near Detector of SBN program, jointly tasked with searching short baseline neutrino oscillations. The SBN programme will make a definitive statement about 1eV^2 oscillations.
- SBND will record the highest number of ν-Ar interactions and will have the highest statistic on cross-section measurements to date.
- Despite the pandemic we're making progress, commissioning to start in mid 2023.
- SBND will test and perfect new technology relevant for DUNE.
- SBND is well suited to probe numerous BSM models.
- I've shown here what the Dark Neutrino avenue looks like, with promising simulations for detection in SBND and a potential explanation to MB LEE.

SHORT-BASELINE NEAR DETECTOR

Thanks for your attention!

The SBND Collaboration

266 Total Collaborators

221 Scientific Collaborators (faculty/scientists, postdocs, PhD students)

40 Institutions

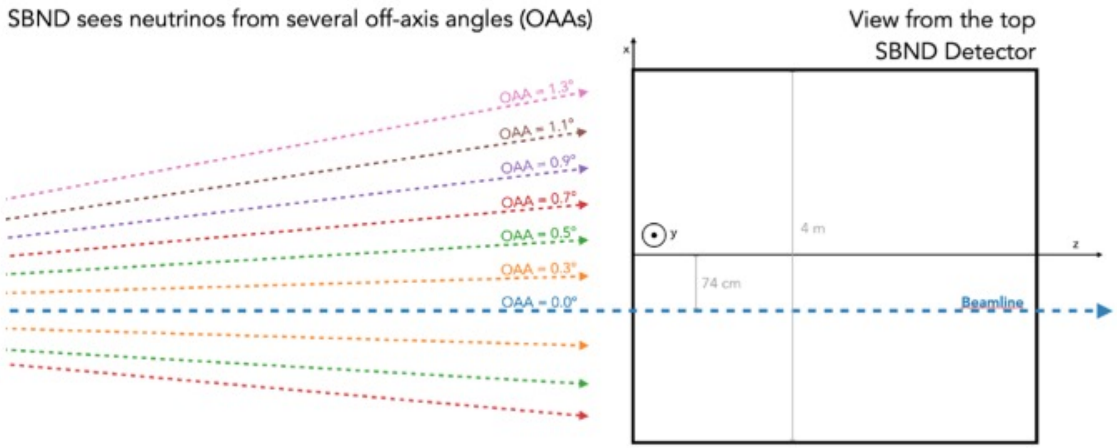
22 US Institutions
- 4 DOE National Laboratories
- 20 US Universities

18 International Institutions
- 5 Brazilian Universities
- 1 Paraguayan University
- 1 Spanish University, 1 National Laboratory
- 1 Swiss University
- 7 UK Universities, 1 National Laboratory
- CERN

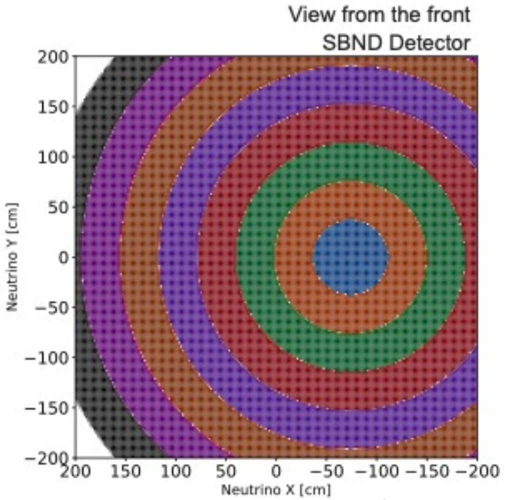
Backup

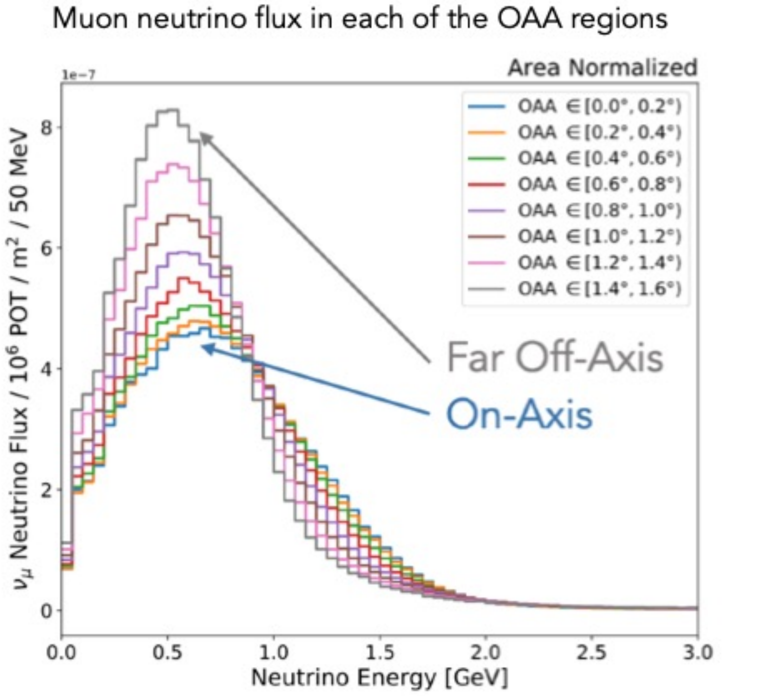
SBND-PRISM*

- Leverages the near location, detector geometry, and large neutrino rate of SBND to enhance the sensitivity in multiple areas of the SBN physics program.



The detector can be divided into annular rings to sample multiple off-axis fluxes in the same detector.





*Precision Reaction Independent Spectrum Measurement

[nuPRISM https://arxiv.org/abs/1412.3086]

Dark Sector Neutrinos

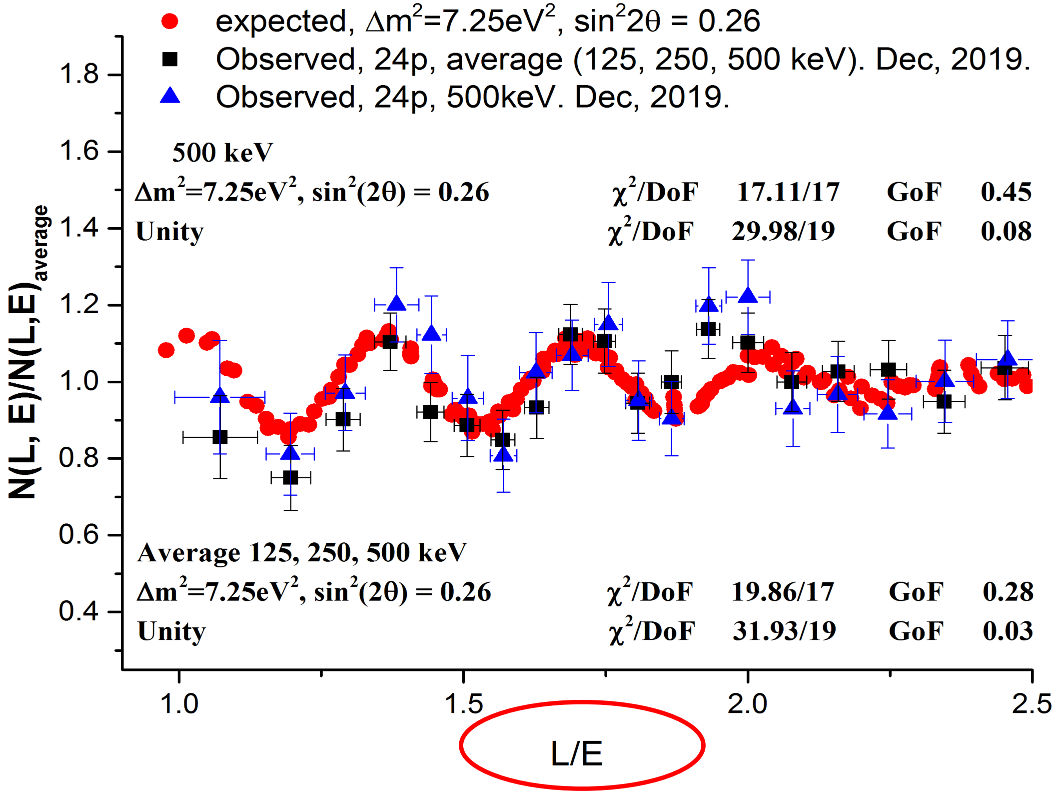
Dark neutrino sectors. A low-scale, dynamical mechanism of neutrino masses presents a deep connection between neutrinos and the dark sector (109). In this class of models, right-handed neutrinos are charged under a new gauge symmetry, leading to neutrino upscattering into a heavy state which then decays to a light neutrino and a gauge boson, followed by the gauge boson decay to visible particles, that is, $\nu A \rightarrow N A \rightarrow \nu Z' A \rightarrow \nu\, l^+ l^- A$, where A denotes a nucleus, see middle panel of Fig. 9. Given an appropriate mass spectrum (with particles between the MeV and GeV scales), this model may yield the MiniBooNE low energy excess, presenting excellent agreement with angular and energy spectra (110, 111). At SBN, typical signatures of this framework would be pair production of e^+e^-, $\mu^+\mu^-$ or $\pi^+\pi^-$, induced by neutrino interactions, with little to no hadronic activity. The signal would be present at all three detectors, since there is no L/E dependence.

~ arXiv:1903.04608

- Another one by the same authors: arXiv: 1808.02500
- In this one Z_D is heavier, but N_D is lighter arXiv: 1808.02915
- Other types of Dark Neutrinos

The first observation of effect of oscillation on search for sterile neutrino

$$P(\tilde{\nu}_e \rightarrow \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14} \ \sin^2\left(1.27 \frac{\Delta m_{14}^2[\mathrm{eV}^2] L[\mathrm{m}]}{E_{\tilde{\nu}}[\mathrm{MeV}]}\right)$$



The period of oscillation is 1.4 m for neutrino energy 4 MeV

A.P.Serebrov, et al.
JETP Letters,
Volume 109, 2019
Issue 4, pp 213–221.

arxiv:1809.10561
arxiv:2003.03199
arxiv:2005.05301