Liquid Argon Experiments

Nicola McConkey

YETI 2020

Context and Contents of this talk

- Liquid Argon is a commonly used active detector medium in particle physics
  - Especially in rare event physics

- Why?
  - Liquid Argon as a detector medium
  - Types of LAr detectors (and how they work)
    - Some Neutrino detectors
  - LAr Neutrino Physics
  - Some BSM physics searches

Liquid Argon

- Excellent charge transport and optical properties
- Density of 1400kg/m^3
- Least expensive, most abundant noble gas

- Cryogenic: liquid between 83K and 87K

Charge transport in noble liquids

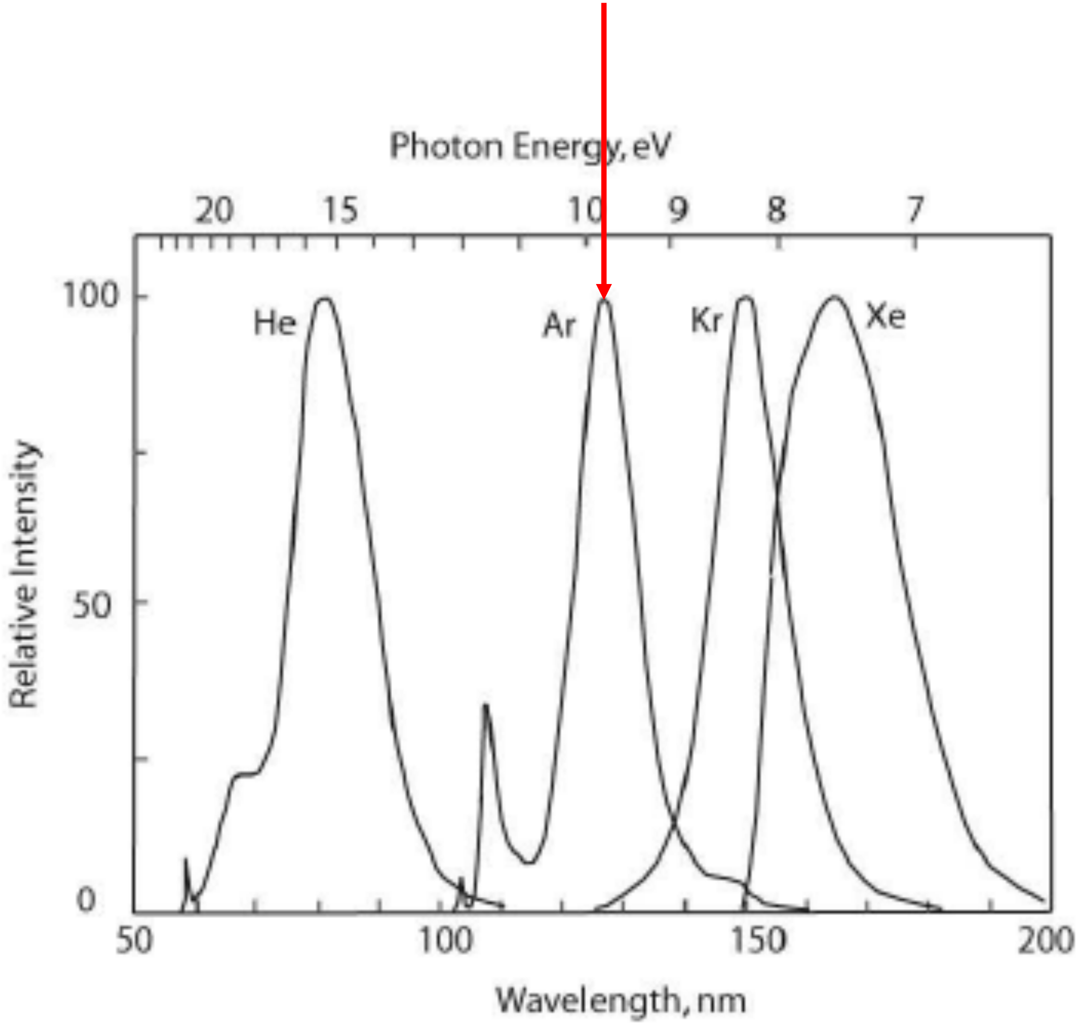
- Noble liquids have high mobility and charge yield

- Energy deposition in a noble liquid causes ionisation of argon atoms
  - Charge yield: around 55,000 electrons per cm from a minimum ionising particle track (muon)

- Liquid argon has a dielectric strength of around 30-40kV/cm
  - Can put a strong electric field across a volume of LAr and drift charge to a readout plane
  - Electron mobility of around 5mm/us at 1kV/mm E field

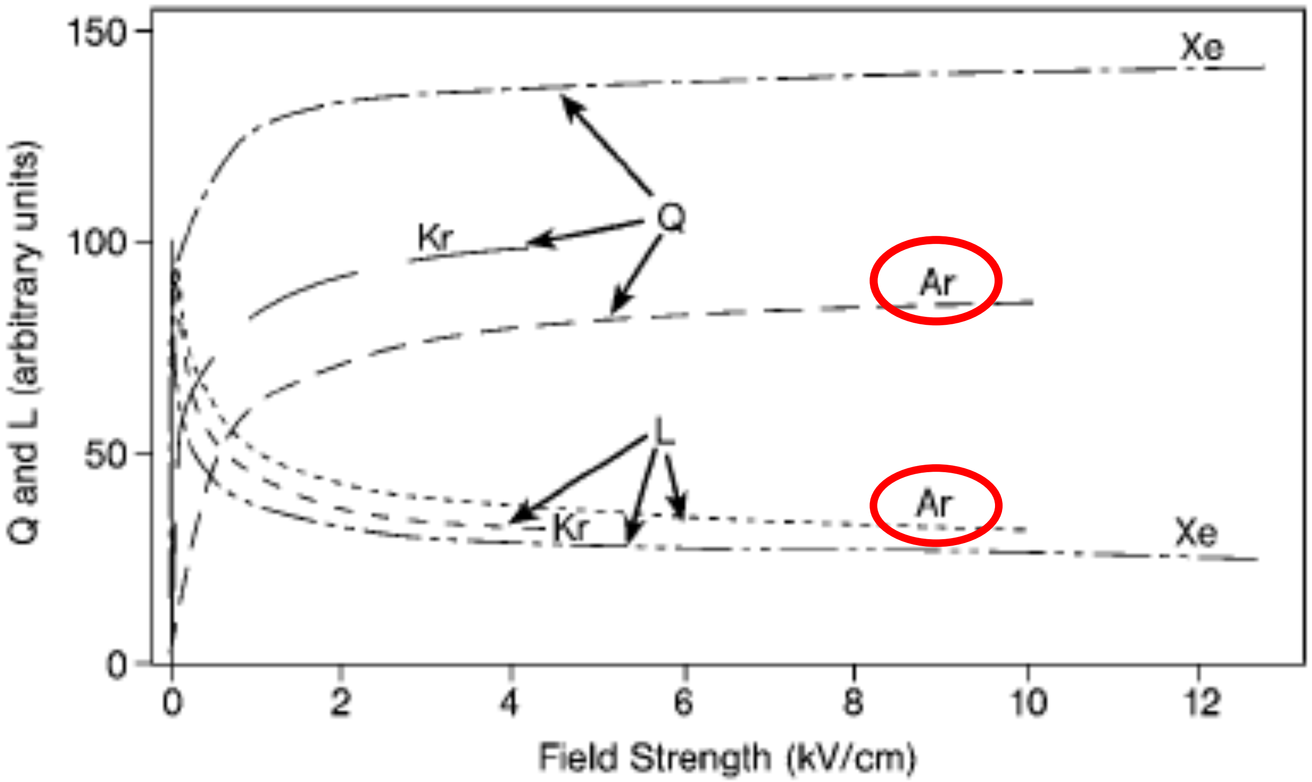
Scintillation in noble liquids

- Noble liquids are good scintillators
  - Energy deposition in a noble liquid causes excitation of an atom, and emission of a scintillation photon
- Argon scintillates at 128nm
  - Vacuum Ultraviolet
  - This is challenging for most photon detectors to measure
    - E.g. won't transmit through glass
  - Primary scintillation light is often Stokes shifted to a longer wavelength as part of the photon detection process



Scintillation and charge transport

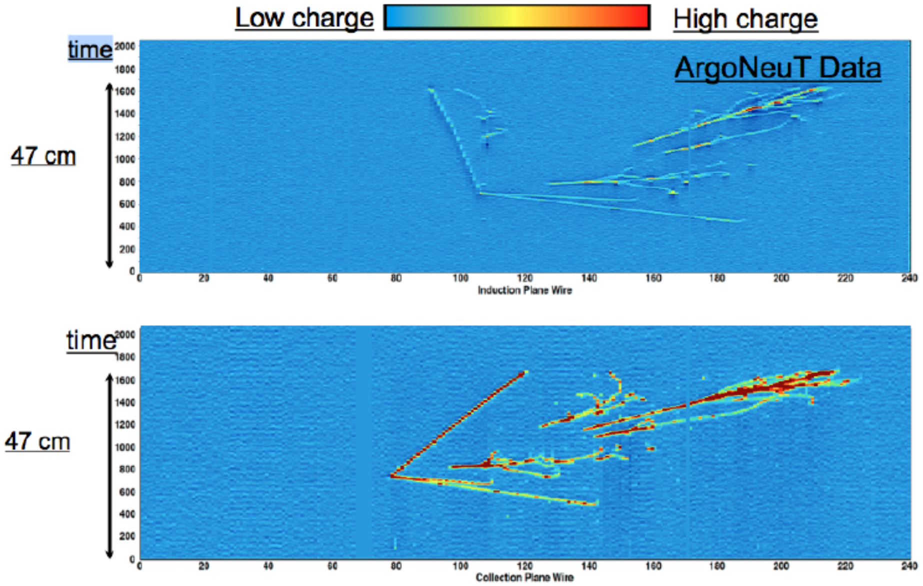
- The ratio of ionisation electrons and scintillation light which is observed varies as a function of electric field in the detector
- With no electric field present, ionisiation electrons recombine with argon ions to emit scintillation light

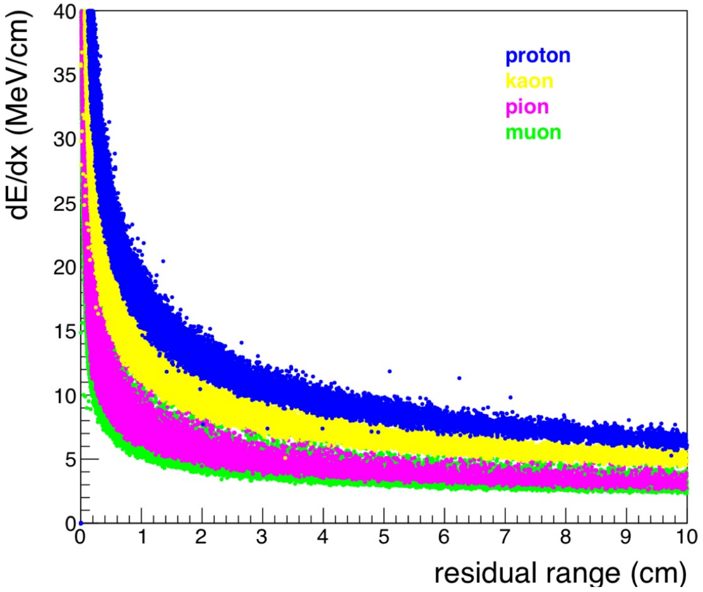


Liquid argon density

- LAr density of 1400kg/m^3
  - Less dense than Lxe
  - More dense than water
  - WAY more dense than gaseous argon

- High enough for a large target mass
- Low enough to give good event topology
  - Low energy tracks and showers are distinguishable
  - Powerful ability to measure the charge deposition per unit length (dE/dx) of particles, which enables particle identification

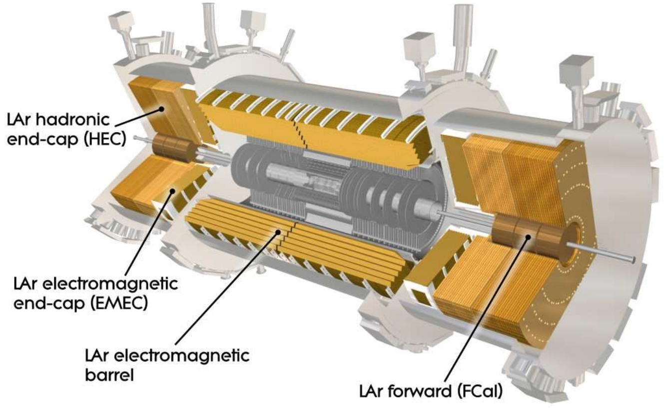


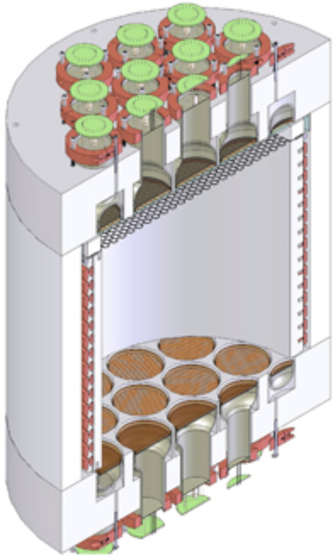


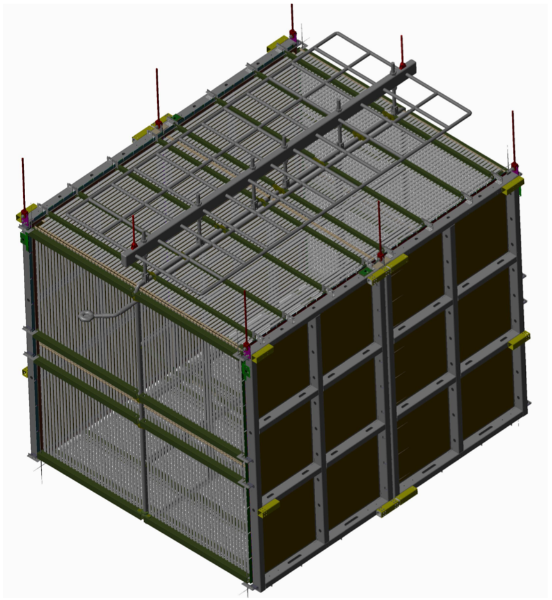
LAr detectors for particle physics experiments

- Properties of liquid argon mean it lends itself well to stopping particles and measuring them at a fine level of granularity
  - Density, charge and scintillation yield, dielectric strength

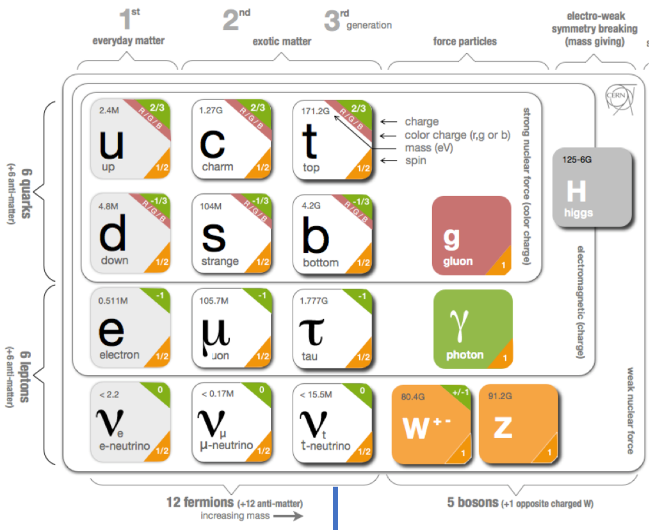
- Neutrino experiments
  - Eg. DUNE, MicroBooNE
- Dark matter
  - Eg. DarkSide, DEAP
- Calorimetry
  - Eg. ATLAS ECAL







Neutrino physics measurements



- Neutrino propagation states not identical to their interaction states
  - Neutrinos oscillate
- Linear combinations:
  - Related by the PMNS matrix

Neutrino flavour states

Neutrino mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mass states m_i

Neutrino oscillation physics

- PMNS mixing matrix parametrised:
    - Three mixing angles and one complex phase

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Neutrino Oscillations vary as a function of neutrino path length (L) and energy (E):
    - Two Neutrino mixing example

$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \sin^2 2\theta_{ij} * \sin^2\left(1.27 \Delta m_{ij}^2 \frac{L}{E}\right)$$

- Neutrino oscillation experiments typically fix L and E and measure ν_e, ν_μ and ν_τ

Neutrino oscillation physics

- PMNS mixing matrix parametrised:
  - Three mixing angles and one complex phase

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-\boxed{i\delta}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-\boxed{i\delta}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

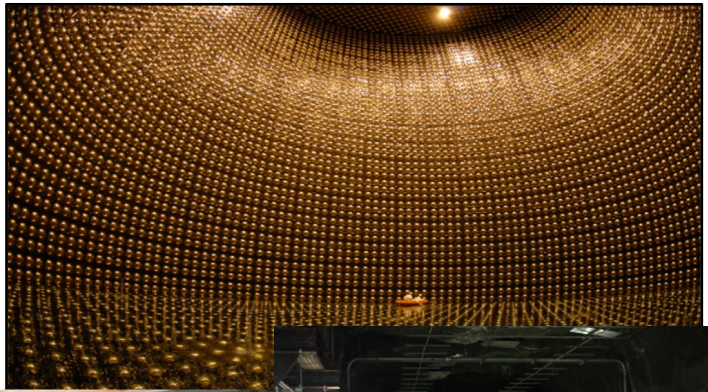
- Neutrino Oscillations vary as a function of neutrino path length (L) and energy (E):
  - Two Neutrino mixing example

$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m^2_{ij}\boxed{\frac{L}{E}}\right)$$

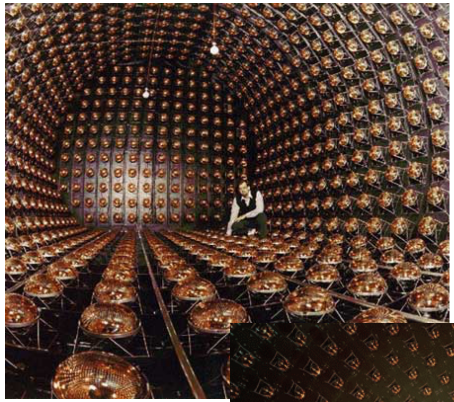
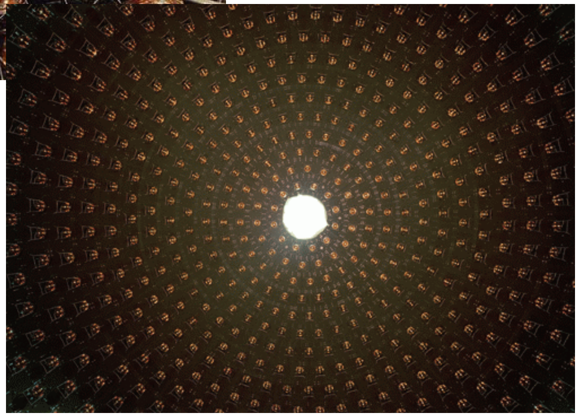
- Neutrino oscillation experiments typically fix L and E and measure ν_e, ν_μ and ν_τ

Neutrino beamline experiments

- Long baseline experiments



- Short baseline experiments
  - Typically L<1km

Neutrino beamline experiments

- Detector needs
  - Uniformity
    - Neutrino interaction could happen anywhere in the detector
    - Wish to measure interactions at high precision throughout
  - Large volume and target mass
    - Neutrino interaction cross section very low – need sufficient statistics to make significant measurement
    - Beam spread over long baseline distances
    - Cost of material

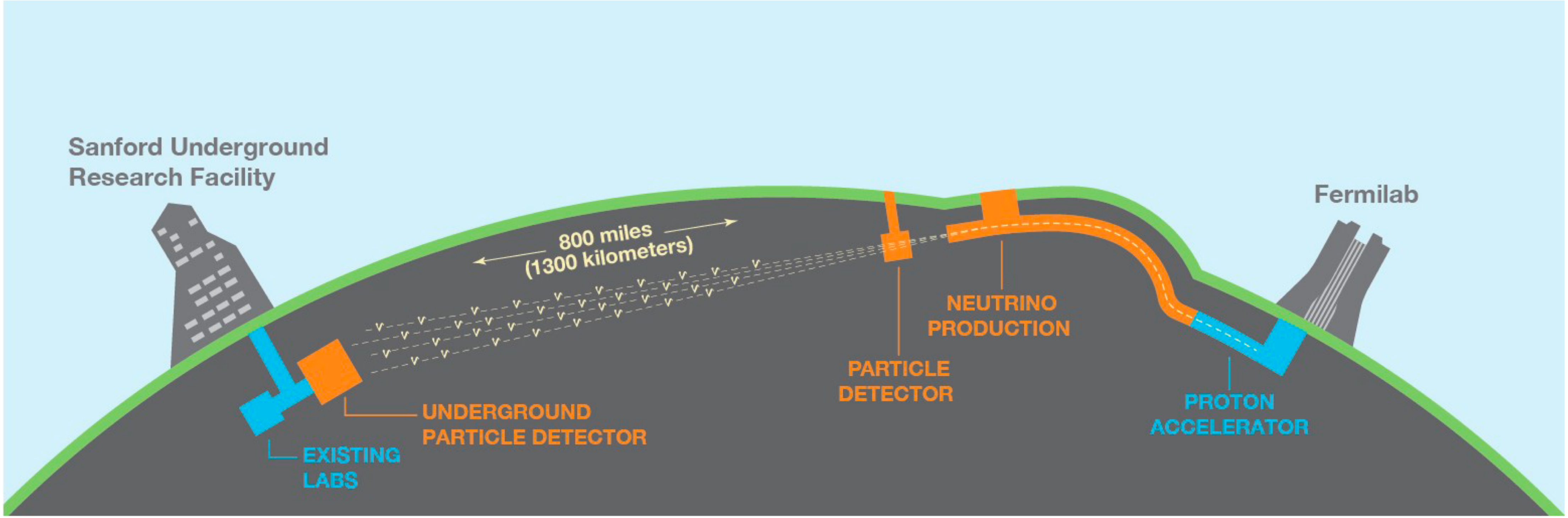
Neutrino beamline experiments

- Detector needs
  - Uniformity
    - Neutrino interaction could happen anywhere in the detector
    - Wish to measure interactions at high precision throughout
  - Large volume and target mass
    - Neutrino interaction cross section very low – need sufficient statistics to make significant measurement
    - Beam spread over long baseline distances
    - Cost of material

"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."

-Douglas Adams

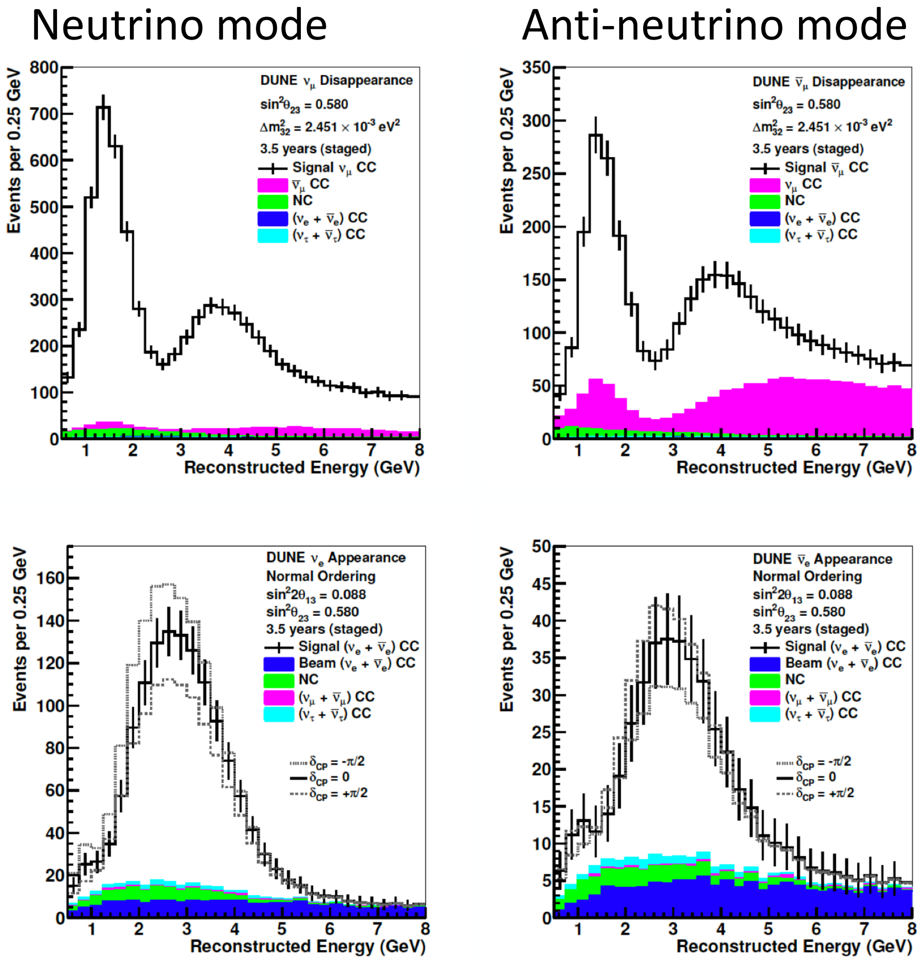
Deep Underground Neutrino Experiment (DUNE)



- Long baseline neutrino experiment in beamline from Fermilab (Illinois, USA) to SURF (South Dakota, USA)
- Liquid argon far detector (1300km downstream)

DUNE Neutrino Oscillation Physics

- Wide band beam, on-axis far detector
  - Sensitivity to first and second oscillation maxima
- Neutrino and antineutrino running modes
- Measurement of ν_μ disappearance and ν_e appearance gives sensitivity to multiple PMNS parameters

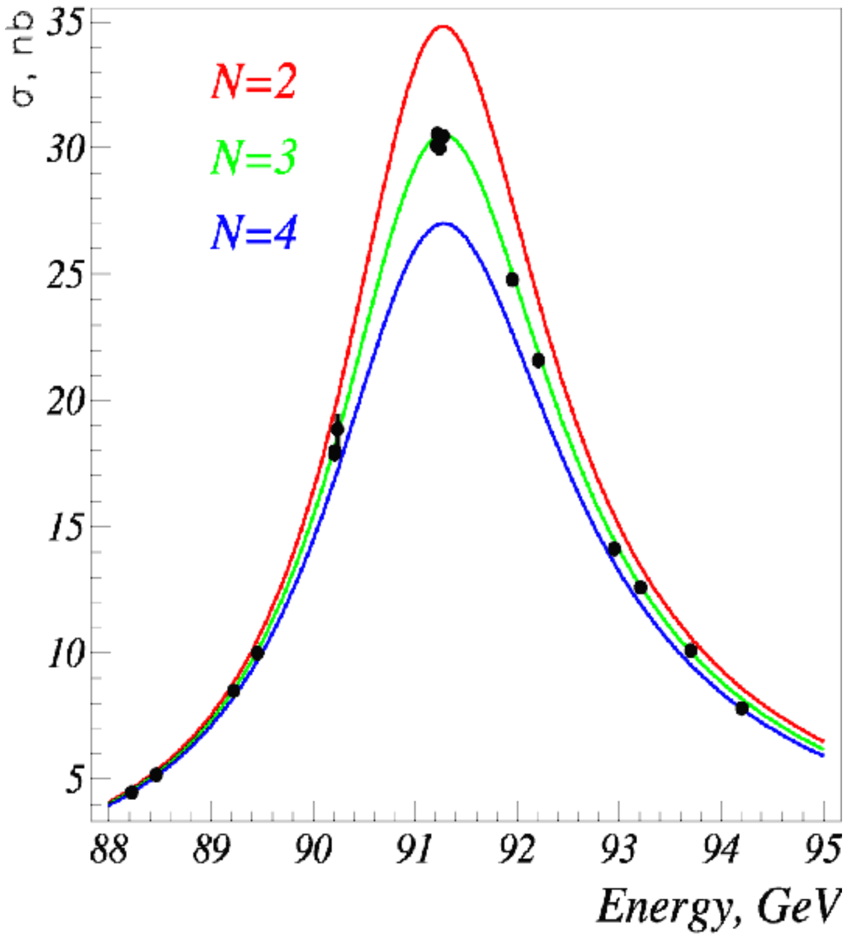


DUNE Neutrino Oscillation Physics goals

- ”Ultimate” goal is to measure $\boldsymbol{\delta}_{CP}$
  - Is there any charge-parity violation in the lepton sector?
  - Can this explain the matter/antimatter asymmetry in the universe
- In order to measure this we need to know other PMNS parameters to a high precision
- Neutrino mass hierarchy
- Unitarity of PMNS matrix?
- How many flavours of neutrinos are there?

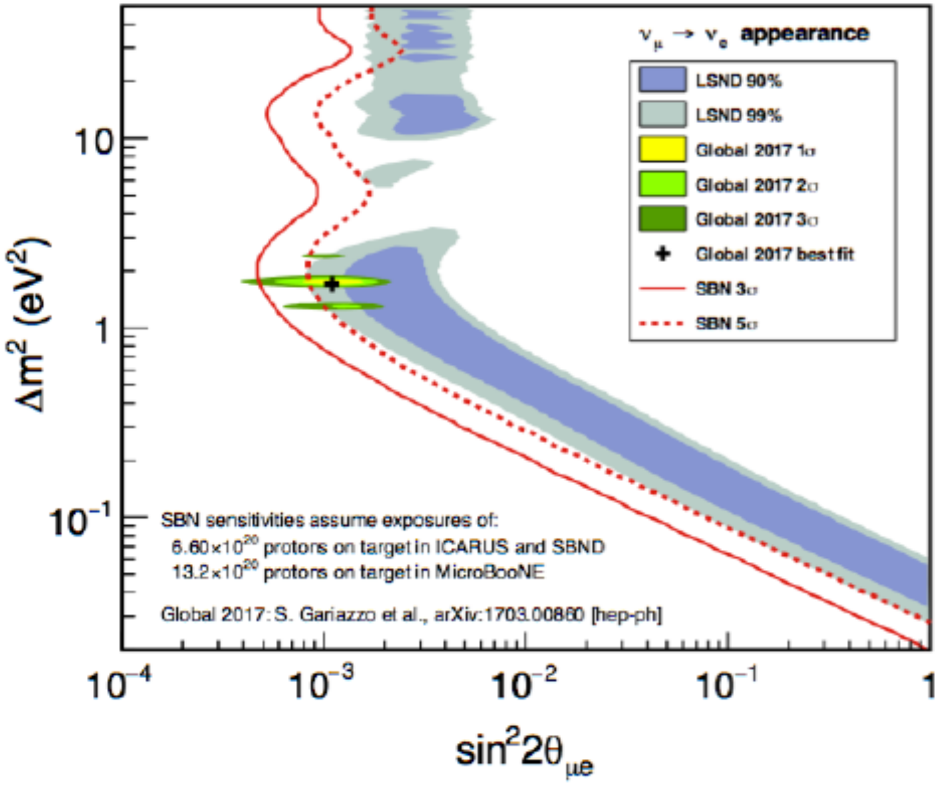
How many flavours of Neutrino are there!?

- LEP produced strong evidence for three flavours of light neutrino (ν_e , ν_μ, ν_τ)
- "Light" means less than half of the mass of Z^0



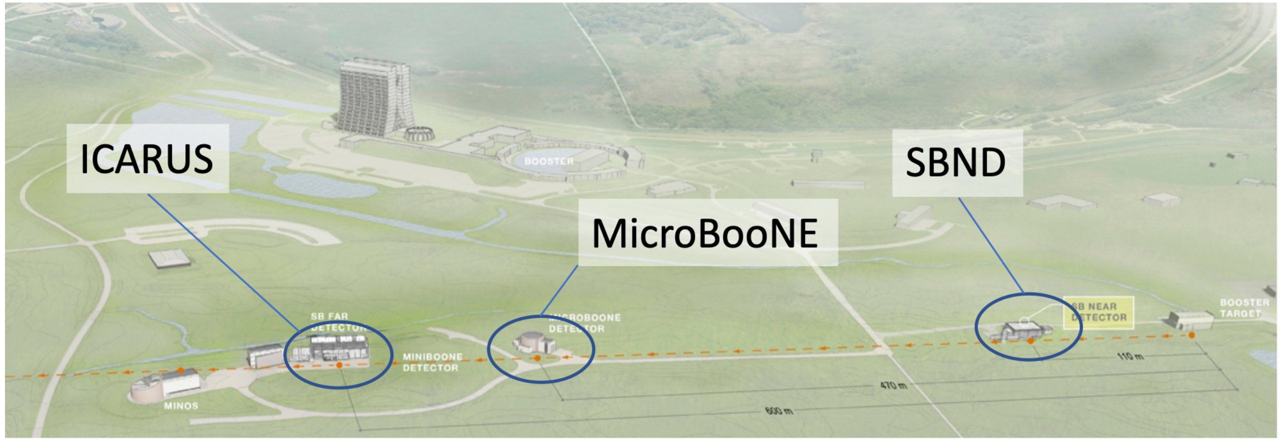
How many flavours of Neutrino are there!?

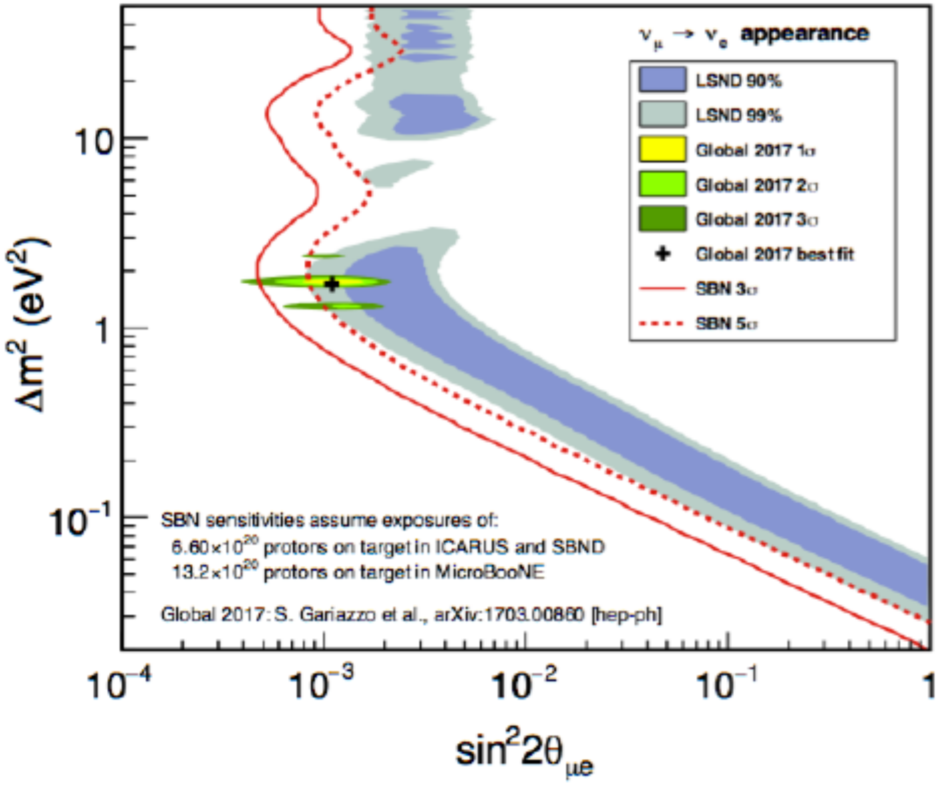
- Experimental anomalies have been observed in short baseline (< 1 km) neutrino experiments:
  - LSND: measured an 3.8σ excess in $\bar{\nu}_\mu$-> $\bar{\nu}_e$ appearance channel
  - MiniBooNE: measured a 3.4σ excess in ν_μ-> ν_e and a 2.4σ excess in $\bar{\nu}_\mu$-> $\bar{\nu}_e$ appearance channels
- Can be interpreted as a large Δm^2 oscillation
  - Requires the addition of a fourth "sterile" neutrino
  - $\Delta m^2_{41} \approx 1\ eV^2$



Short Baseline Neutrino Program (SBN)

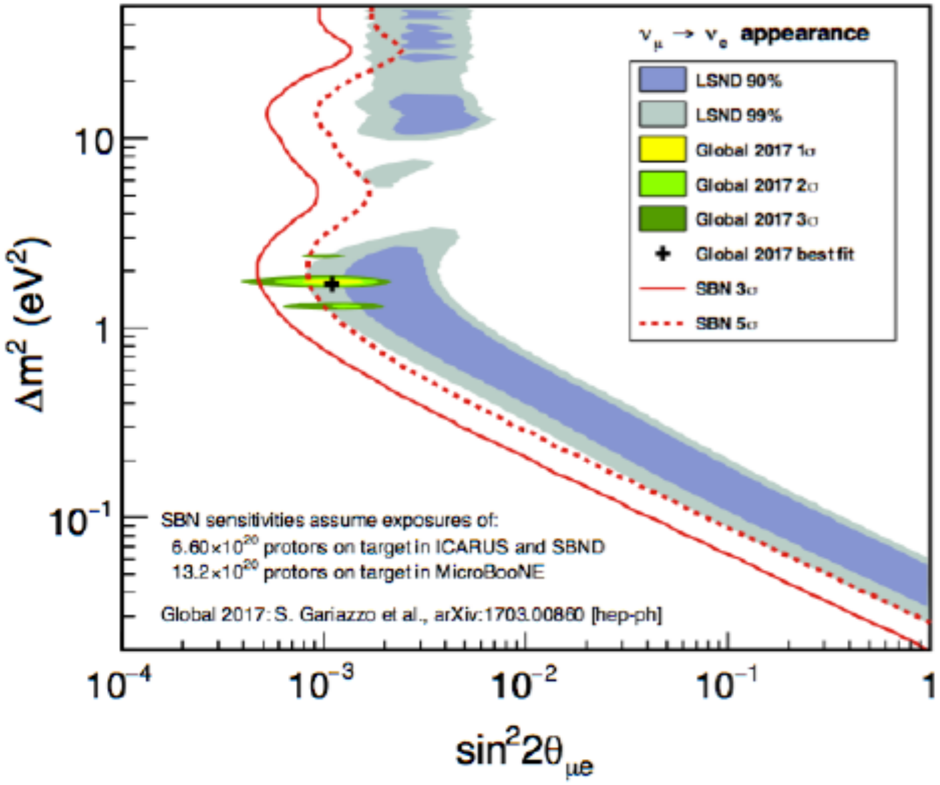
- Short Baseline Neutrino program at Fermilab is a collection of 3 LAr detectors in a neutrino beam at Fermilab





Short Baseline Neutrino Program (SBN)

- Short Baseline Neutrino program at Fermilab is a collection of 3 LAr detectors in a neutrino beam
- SBN has 5σ sensitivity to
  - entire LSND phase space for $\nu_\mu \rightarrow \nu_e$ appearance
  - ν_μ disappearance
- SBN will confirm or definitively refute the LSND and MiniBooNE results, with major implications for neutrino physics



Back to Liquid Argon Detectors

- What type of detectors can we build that allow us to do these experiments and have sensitivity to this physics?

Neutrino beamline experiments

- Detector needs
  - Uniformity
    - Neutrino interaction could happen anywhere in the detector
    - Wish to measure interactions at high precision throughout
  - Large volume and target mass
    - Neutrino interaction cross section very low – need sufficient statistics to make significant measurement
    - Beam spread over long baseline distances
    - Cost of material

Neutrino beamline experiments

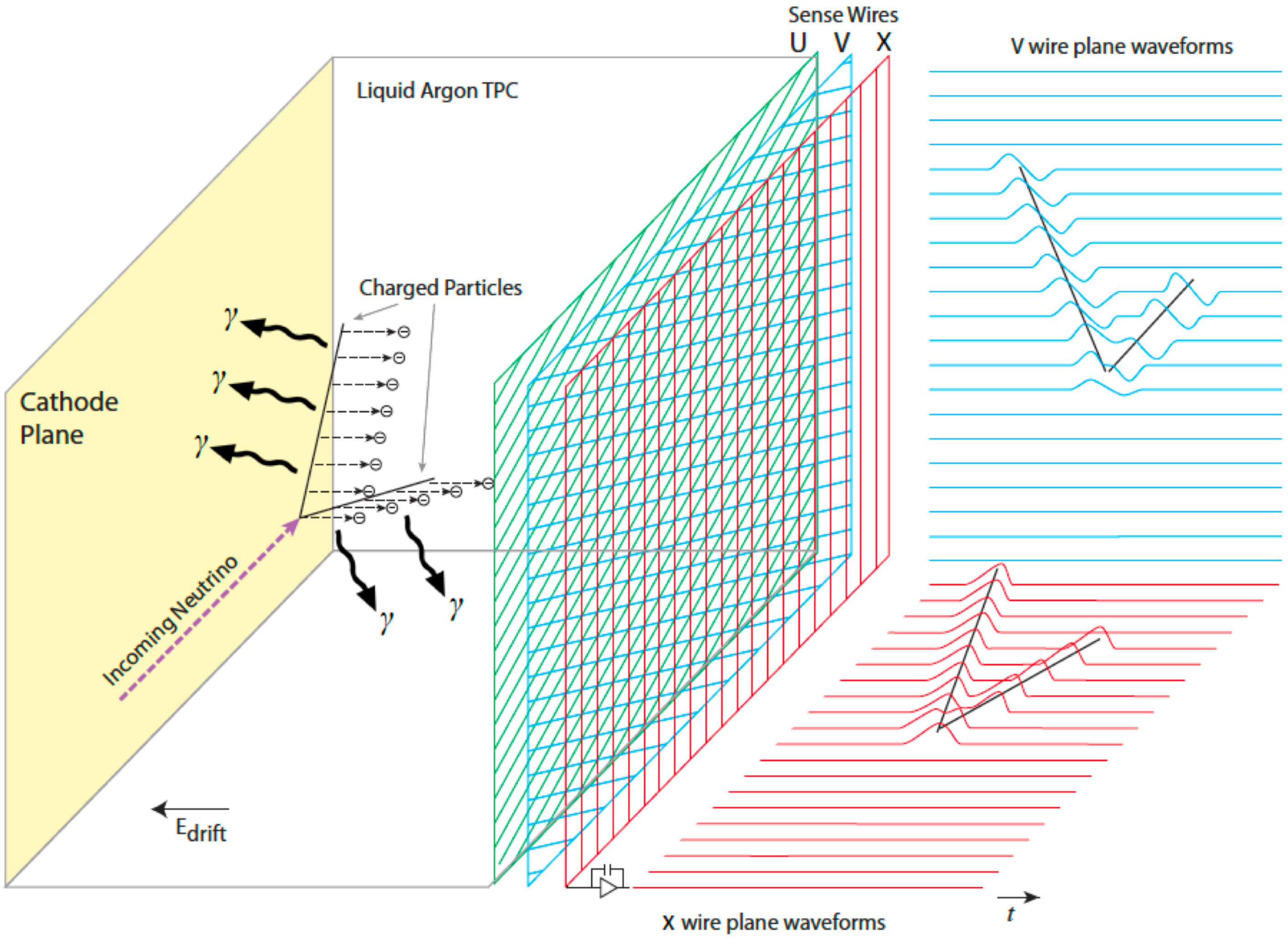
- Detector needs
  - Uniformity
    - Neutrino interaction could happen anywhere in the detector
    - Wish to measure interactions at high precision throughout
  - Large volume and target mass
    - Neutrino interaction cross section very low – need sufficient statistics to make significant measurement
    - Beam spread over long baseline distances
    - Cost of material

LAr ticks all of these boxes!

What detectors types are best to use to measure neutrinos (and other particles)?

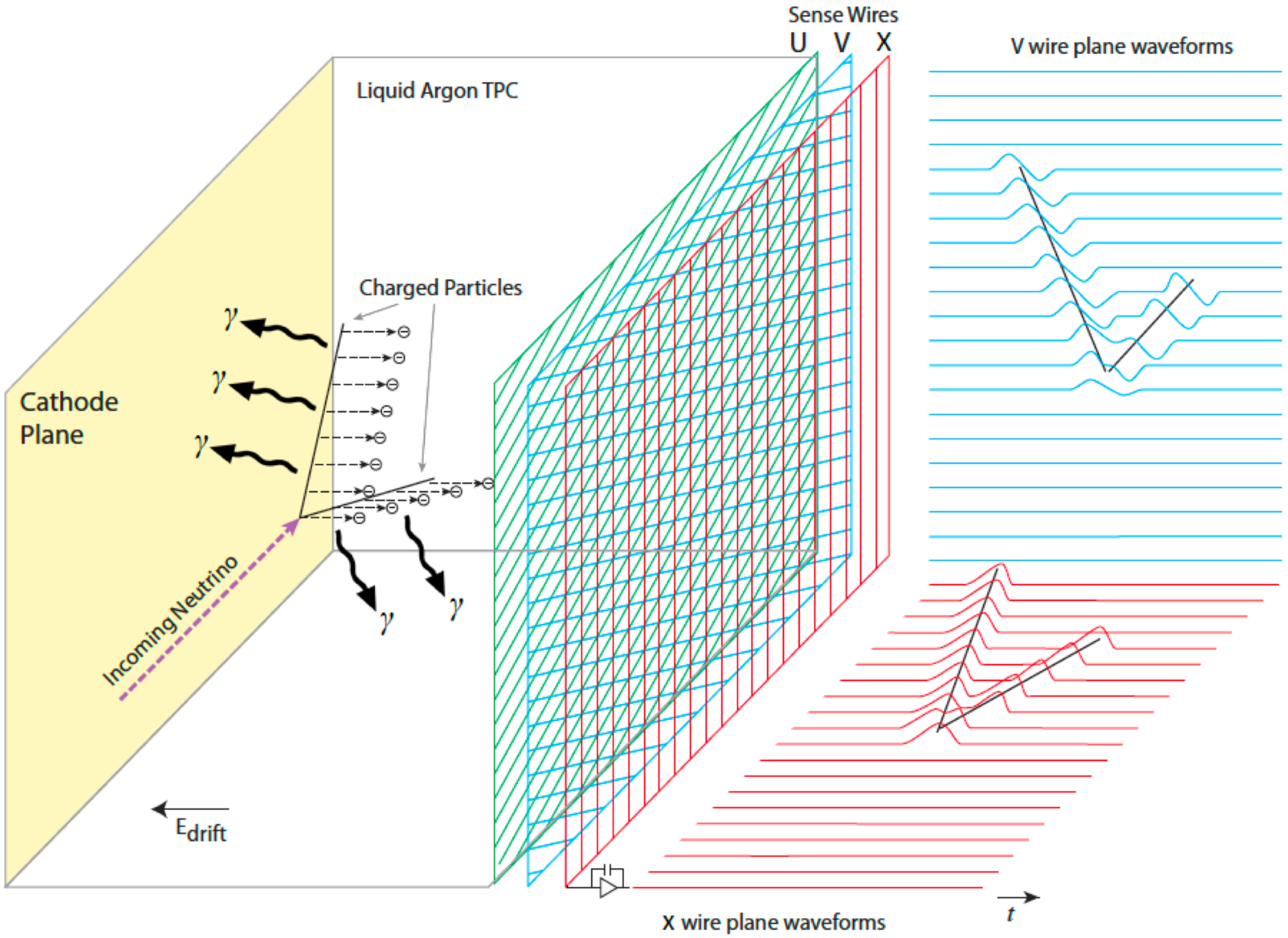
Liquid Argon Time Projection Chambers

- An electric field is applied across the LAr, creating a drift volume
- Charged particles deposit energy in the drift volume, creating ionisation electrons, and scintillation light
  - Ionisation electrons are drifted towards anode readout plane
  - Scintillation light is isotropically emitted
- In this case – anode readout is a series of wire planes

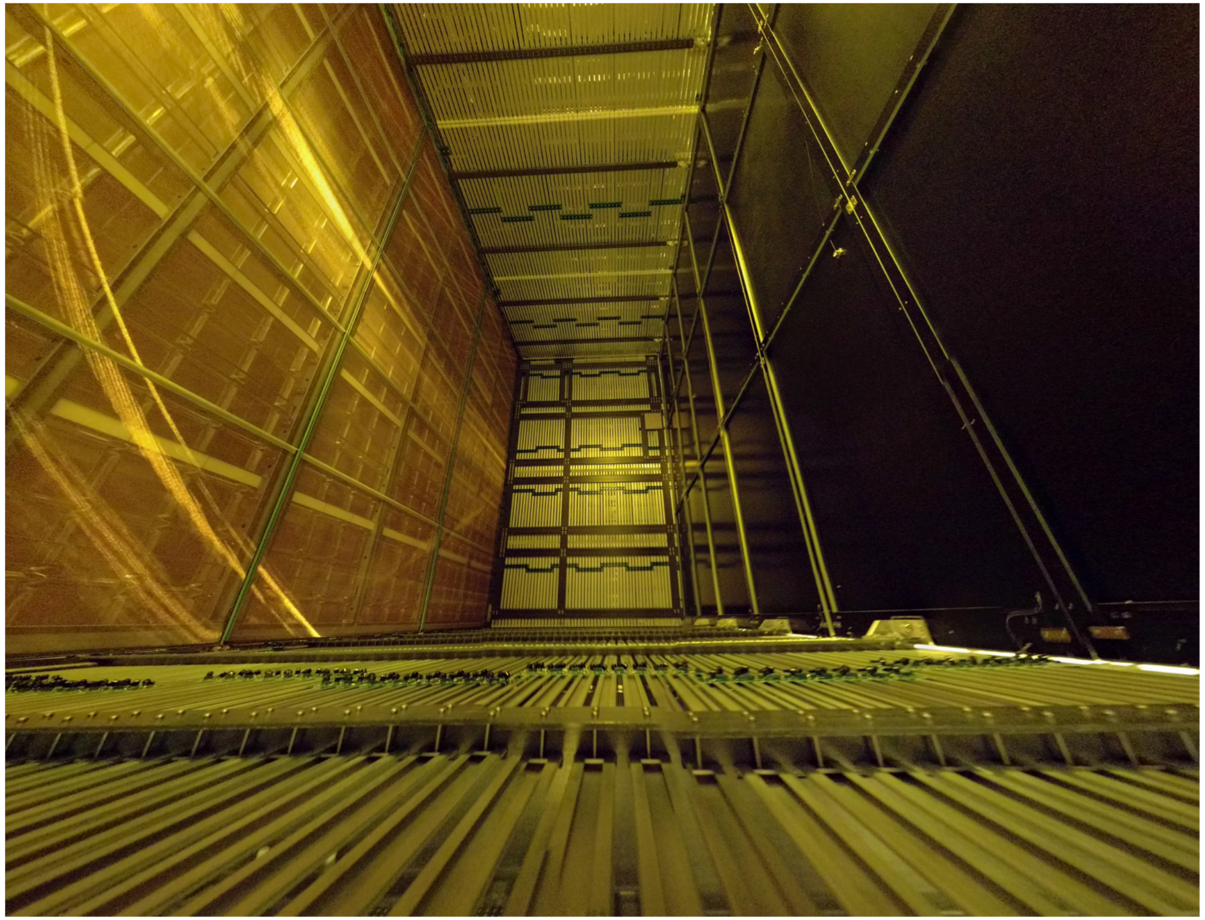


Liquid Argon Time Projection Chambers

- Anode plane creates a 2D image of particle track
- 3rd dimension comes from the arrival time of the charge at the anode
- “Prompt” scintillation signal allows absolute position determination, due to knowing precisely when the interaction happened (t0)

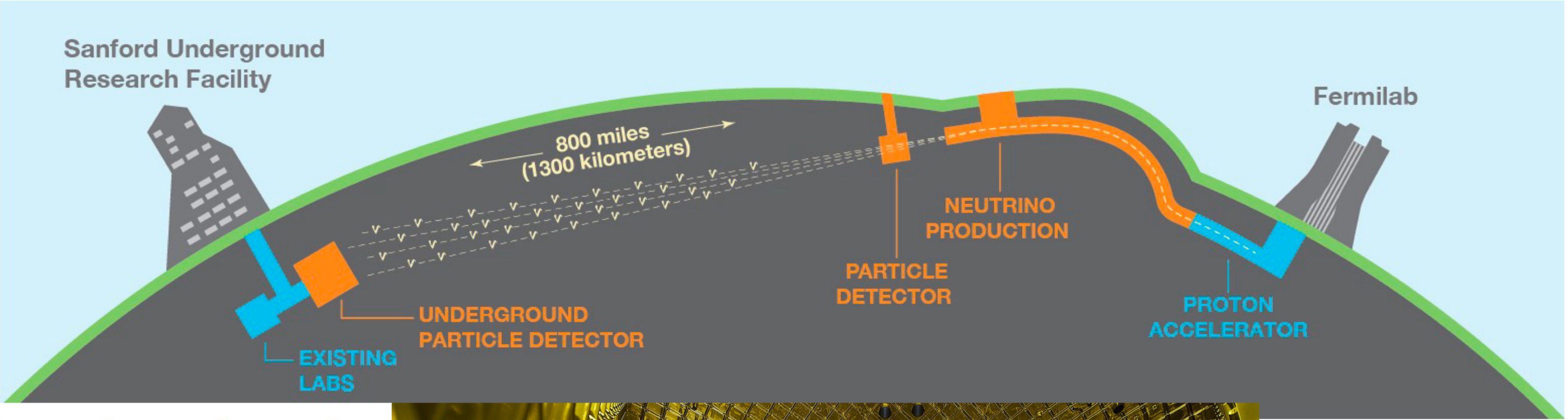


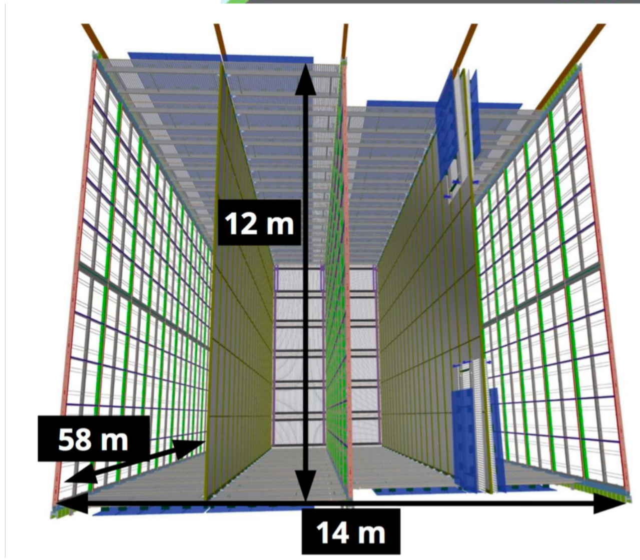
Example: ProtoDUNE single phase TPC

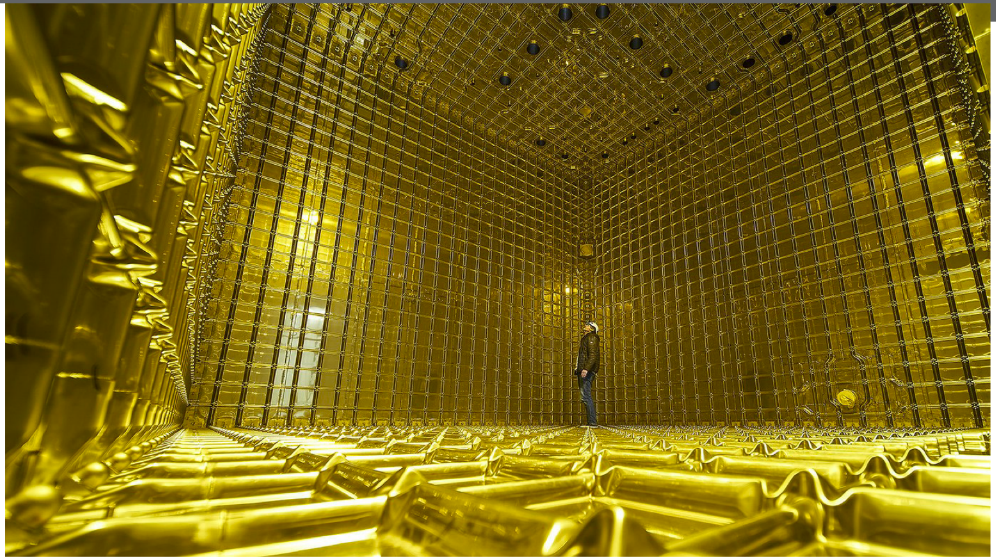


- Wire readout anode planes
  - Composed of many thousands of wires at spacing of 5mm
  - Millimeter position resolution
- 3.5m drift distance to cathode
- 2 drift volumes
- Can be scaled up to very large scale – for DUNE this will be roughly 60 x larger

The DUNE detector



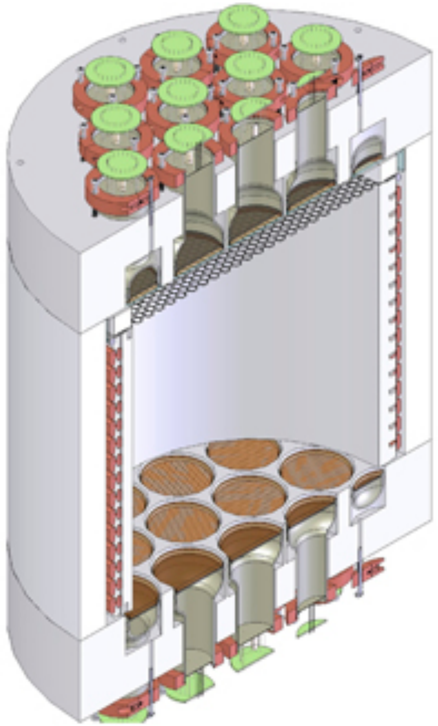


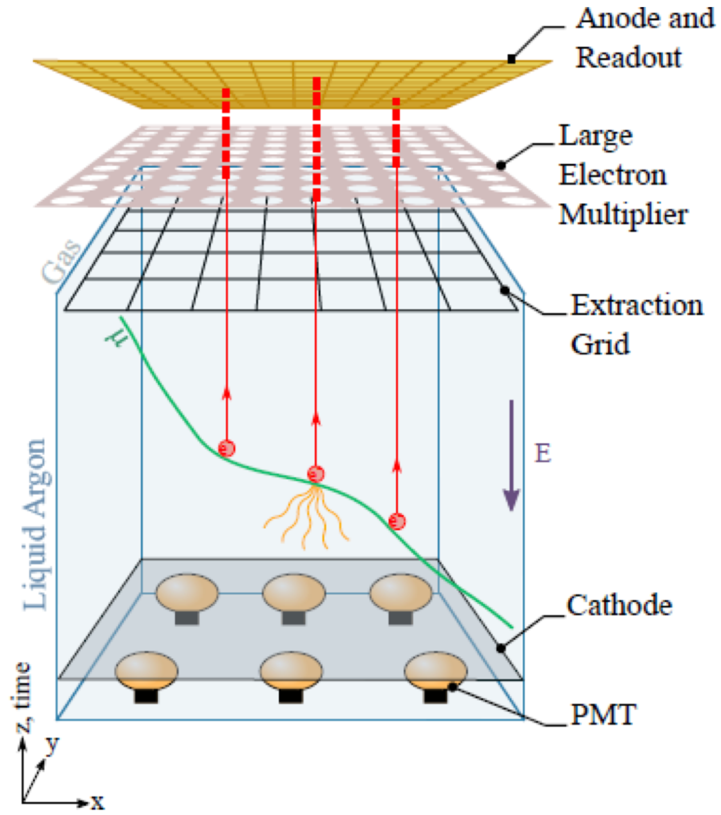


- 4x 10kton modules in mine at SURF

Dual Phase TPCs

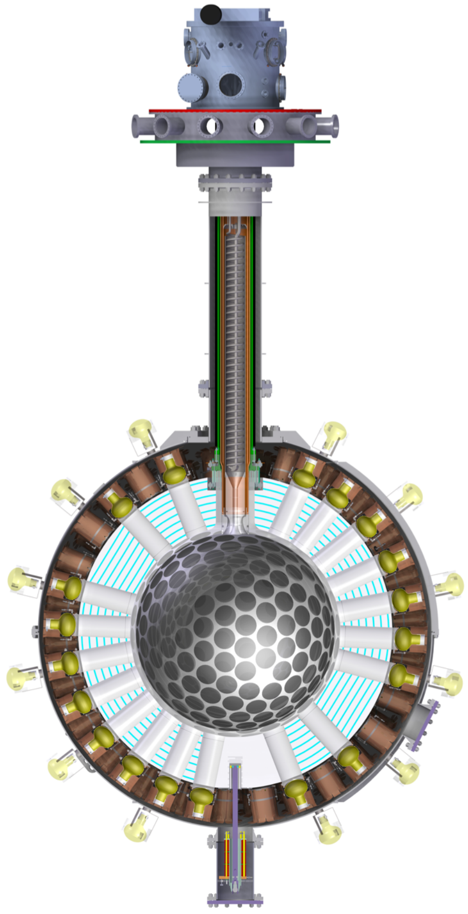
- Commonly used for Dark Matter searches and Neutrino physics
  - ProtoDUNE dual phase
  - DarkSide
- LAr is the target
- Readout in gas above LAr
  - Either optical or charge





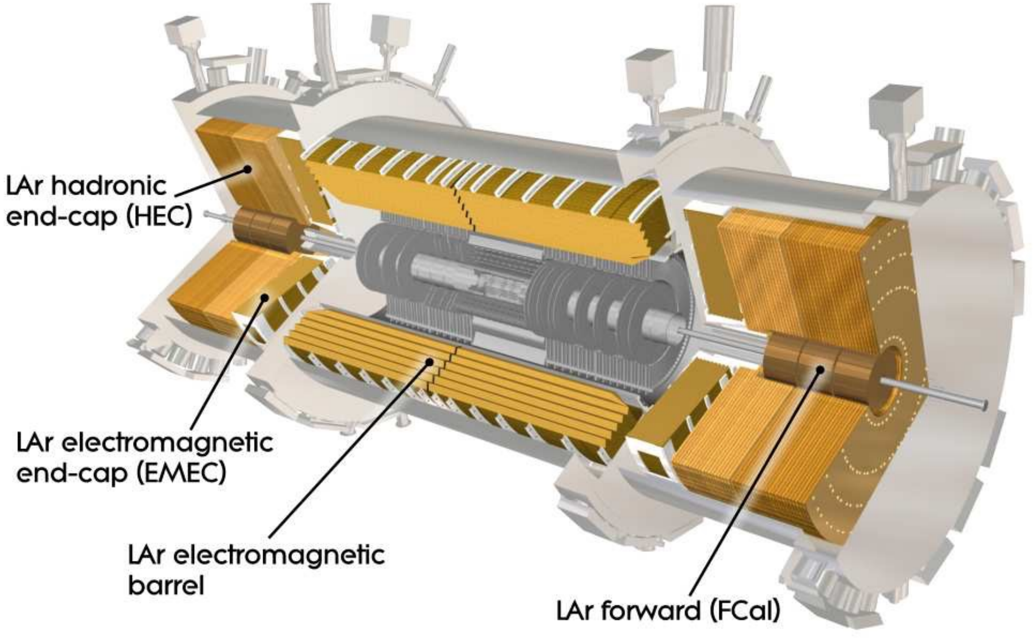
Non-TPC Liquid Argon detectors

- Argon's scintillation properties can be measured in a scintillation counting experiment
- DEAP 3600 Experiment
  - Dark matter experiment searching for weakly interacting massive particles (WIMPs) operating in SnoLab since 2016
  - Volume of liquid argon surrounded by photon detectors
  - Scintillation light is collected and timing is used to discriminate between signal and background events



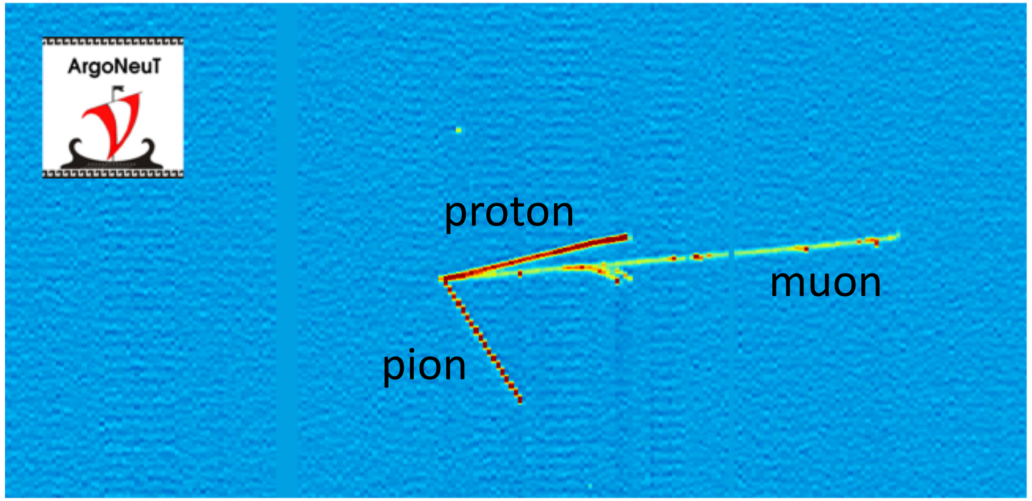
Non-TPC Liquid Argon detectors

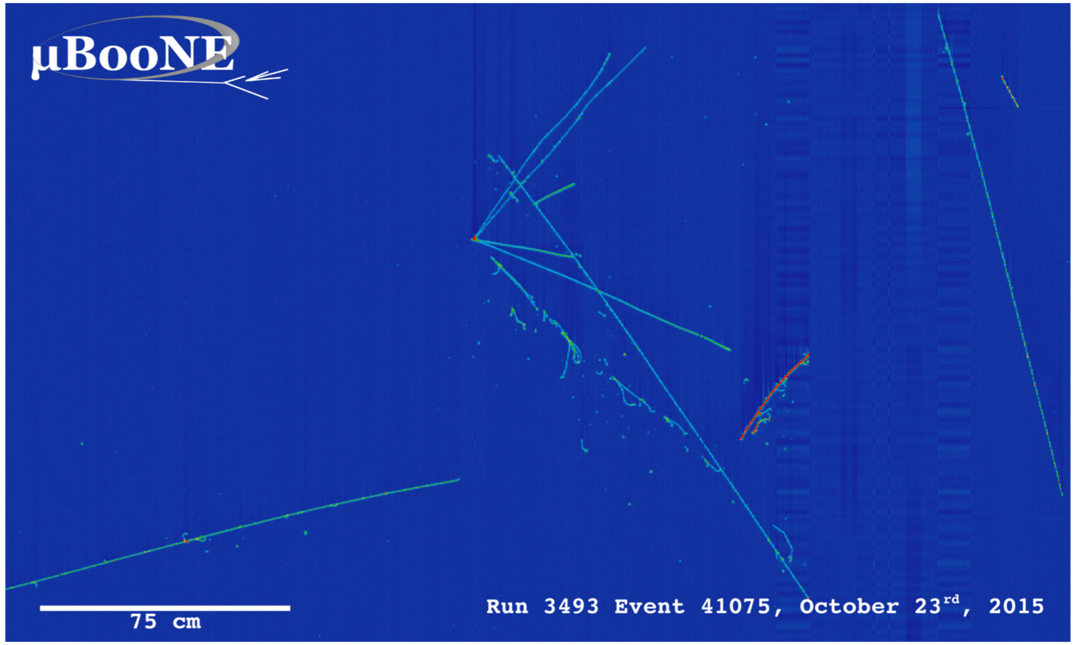
- The ATLAS electronic calorimeter is a sampling calorimeter
  - Layers of lead / stainless steel and argon interspersed
  - EM Showers develop over a short radiation length in the lead, and ionisation electrons are quickly drifted to readout pads in the argon
- The detector is optimised for particle identification:
  - electrons vs jets
  - Photons vs pi0
- Fine granularity of the detector gives position and angular resolution
- This allows the fast timing necessary in such a high flux environment

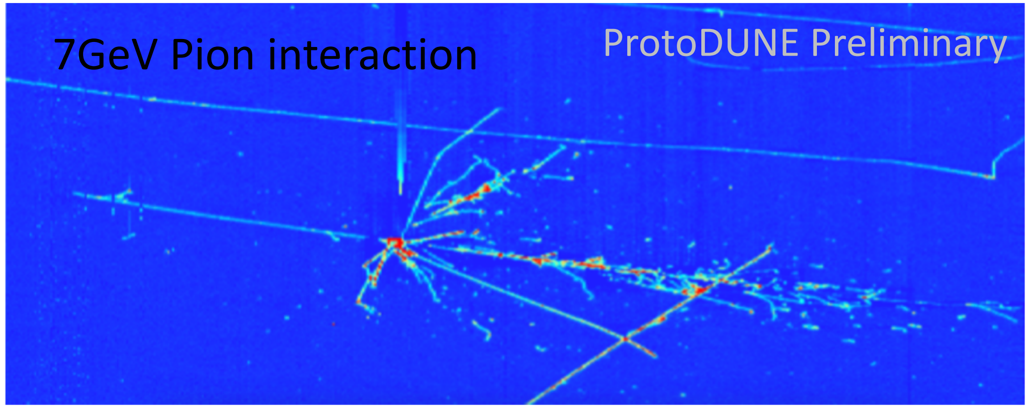


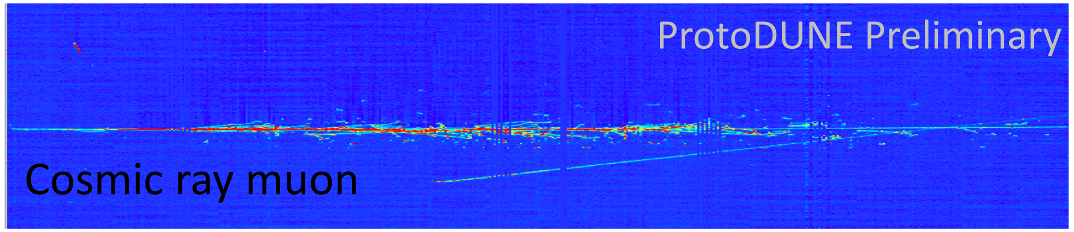
Neutrino physics sensitivities

- What are the advantages of a LAr TPC for neutrino physics?









Neutrino physics sensitivities

- What are the advantages of a LAr TPC for neutrino physics?

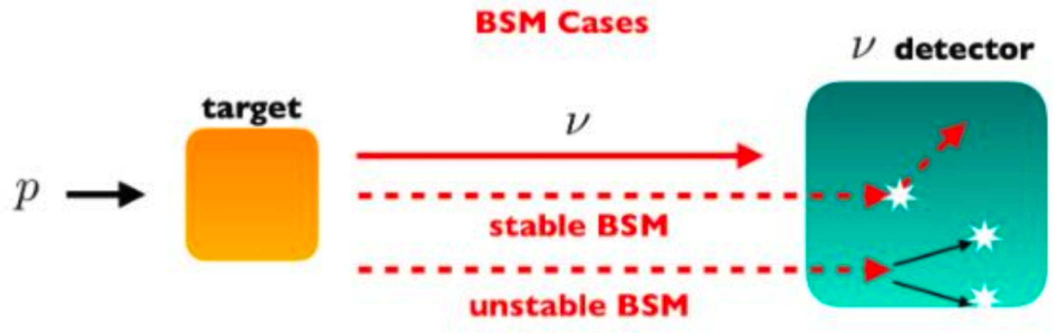
- Particle identification and dE/dx information
  - leveraging techniques such as deep learning for pattern recognition
- Excellent granularity across entire detector
  - And uniformity*

- Disambiguating complex event topologies is essential to make precision measurements of neutrinos

- **Caveat: LAr detectors also have many challenges such as maintaining uniformity*

Beyond Standard Model measurements for LAr experiments

- Detectors close to a beam source
  - Can probe new particles via their interactions in LAr



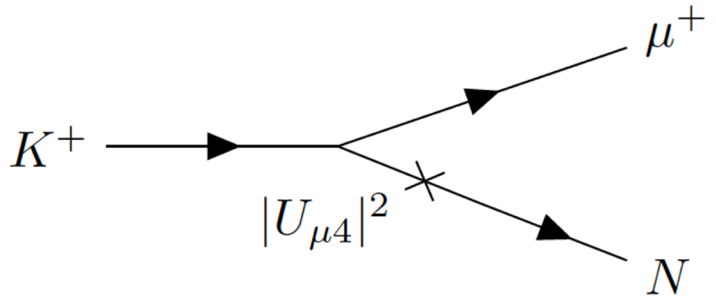
- Large detectors with low background
  - Can probe interactions that we currently know exist to high precision

NB. I will discuss the symptoms not the cause!

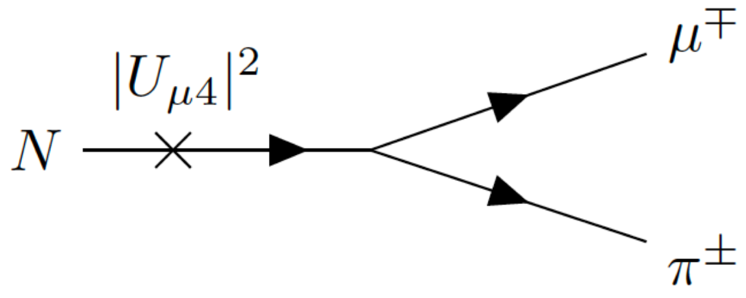
By which I mean the particle signatures in the detector that we would expect for certain types of physics, not the full details of the new physics that produced them

Heavy Neutral Leptons

- A neutral lepton with mass of order 100 MeV
  - Could be a right handed neutrino?
- Ongoing searches in MicroBooNE for such types of particle
- Particles produced in target eg. from Kaon decay

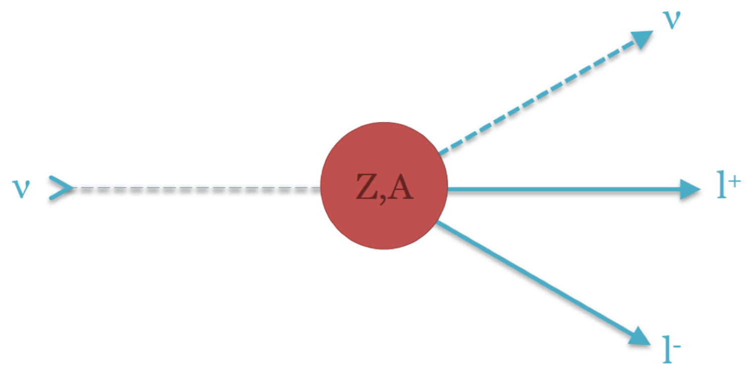


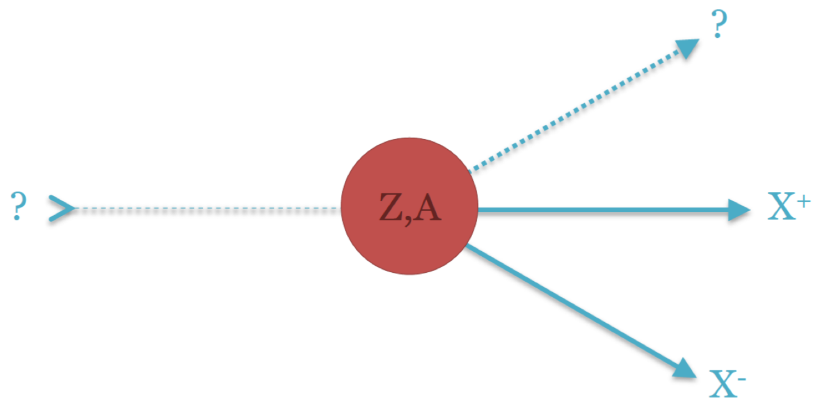
- HNLs will be produced in time with the beam, but will propagate slower than neutrinos
  - Look in a trigger window after the neutrino beam spill for these signatures



Neutrino Tridents

- Neutrinos scatter off of a nucleus, coherently producing a di-lepton pair
  - Produces a “trident”
  - This is a standard model process with small cross section
- This interaction can also happen with another new neutral particle (HNL, gauge boson)
  - An enhancement in the trident cross section can be measured
  - Limits on the mass of new particles come from production mechanism
- Also decay of long lived neutral particles without scattering
- LAr TPCs have fine granularity and good particle identification capabilities
  - Possible to distinguish these processes from backgrounds



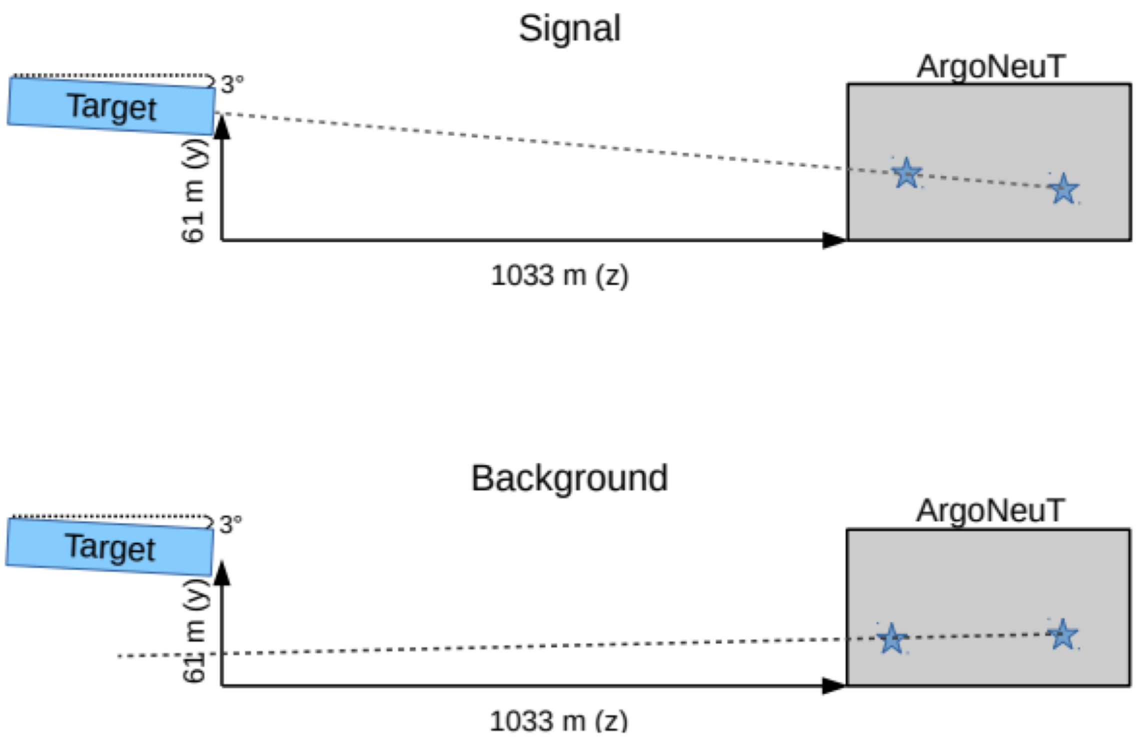


Millicharged particles

- Particles with fractional charge (10^{-3})
  - Could come from dark photons mixing with photons at very small angle resulting in daughter particles with fractional charge
- As these particles propagate through a particle detector they deposit charge
  - ~100 MeV deposits along track
- These particles could be produced in target at a neutrino beamline experiment, eg. from Kaon decay
  - Granularity and energy resolution of a LAr TPC gives sensitivity to such a signal!

Millicharged particles

- As these particles propagate through a particle detector they deposit charge
  - ~100 MeV deposits along track
- These particles could be produced in target at a neutrino beamline experiment, eg. from Kaon decay
  - Granularity and energy resolution of a LAr TPC gives sensitivity to such a signal!

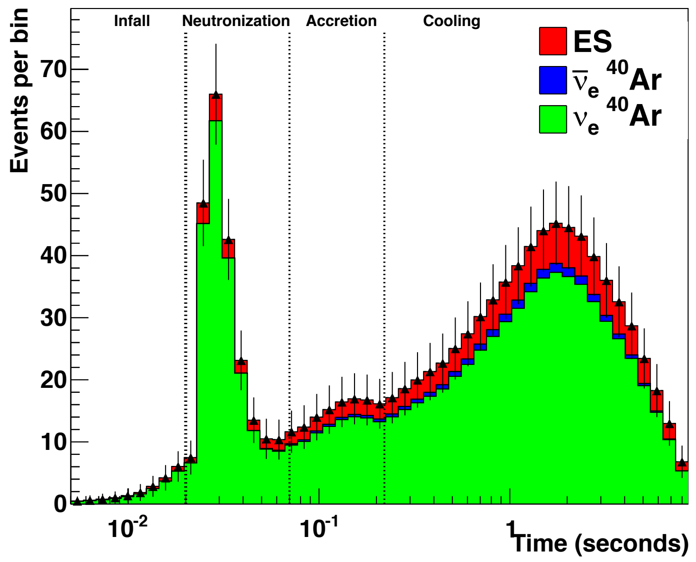


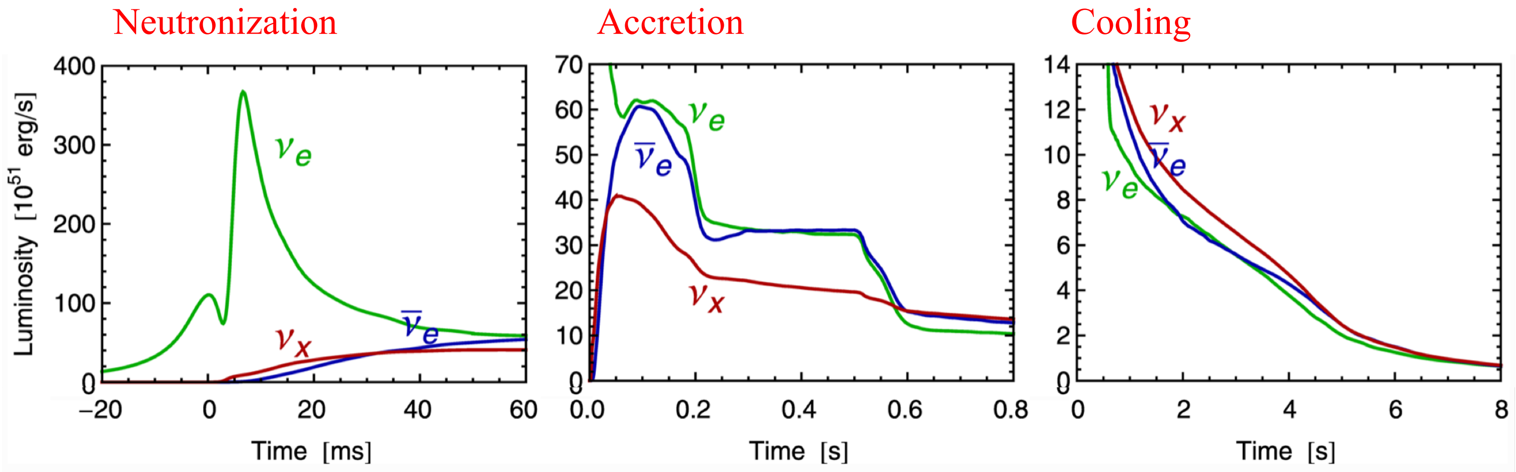
Astroparticle physics with DUNE Far Detector

- DUNE FD will be a 40kT LAr TPC detector in a mine in South Dakota
  - Large volume
  - Very low background from cosmic rays
- Sensitivity to Supernova Neutrinos
  - 99% of energy released in a core-collapse supernova is carried away by neutrinos!
- Supernova physics:
  - core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling…
- Particle physics:
  - flavour transformations in core, collective effects, mass ordering, nuclear equation of state…

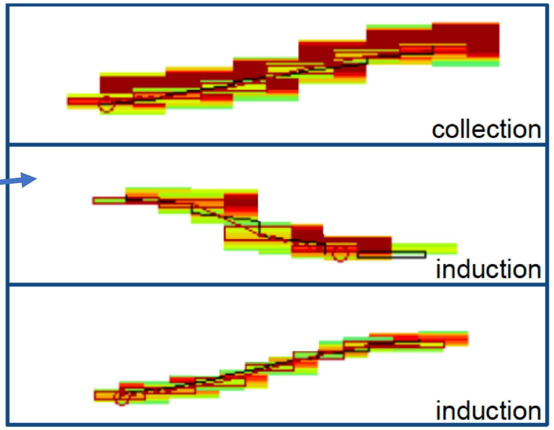
Astroparticle physics with DUNE Far Detector

- Large mass of far detector gives sensitivity to supernova spectrum
  - 3000 ν_e over 10 seconds
- LAr has unique sensitivity to ν_e flux





Low energy 10.25 MeV electron (simulated + reconstructed)



Summary

- Liquid argon is an extremely versatile and powerful particle detection medium
- LAr detectors currently play a significant role in a plethora of particle physics experiments
  - Especially rare event physics
- The future of neutrino physics will be shaped by results from LAr detectors
- There are many Beyond Standard Model signatures and hence theories which can be probed using existing (or forthcoming LAr detectors)

Thanks!

- I hope to have provided inspiration and information about what is possible to measure with LAr detectors, which could help you to choose models / theories to investigate

- …and here’s a picture of me playing violin inside of the ProtoDUNE detector, because it’s also good to take inspiration from the world around you!