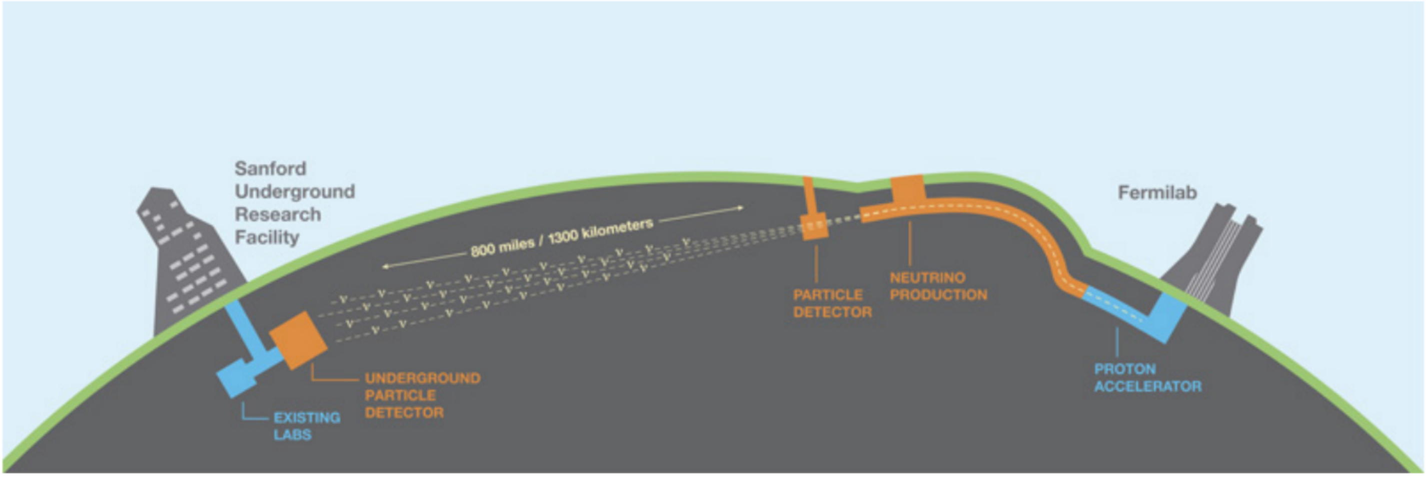
DUNE (for collider physicists)

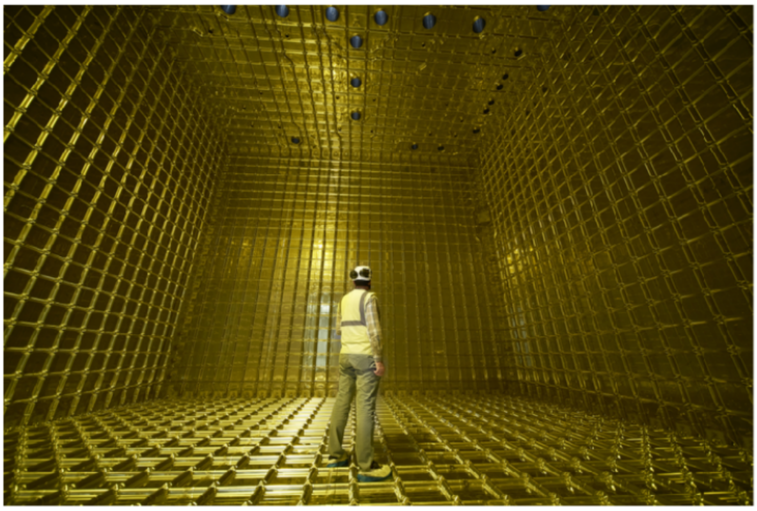
Dave Newbold
24-June-20



Science & Technology Facilities Council Rutherford Appleton Laboratory

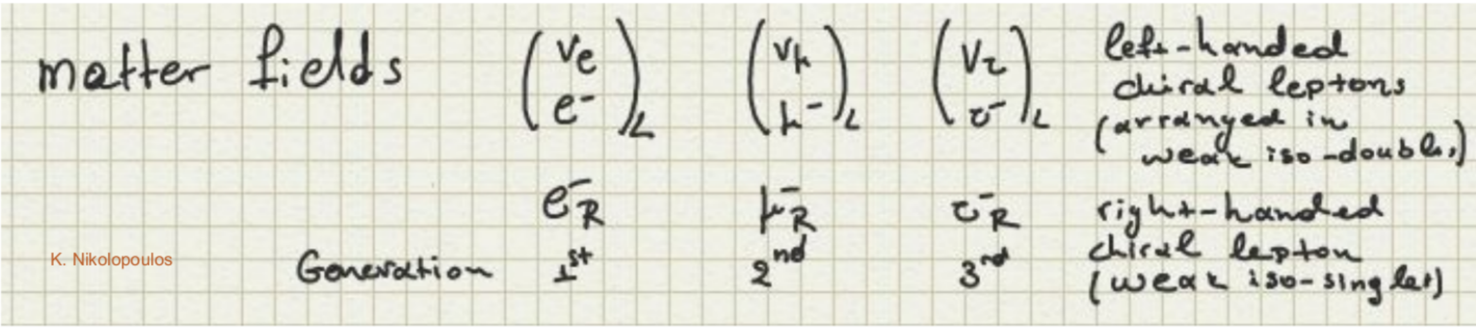
DUNE (for collider physicists)

- (Recap of) neutrino physics
- LBN programme
- Experimental choices
- Design and technology
- ProtoDUNE
- Outlook



- Executive summary
  - The basic three-neutrino paradigm is well-established through experiment
  - 'Precision' neutrino experiments well-placed to look beyond the SM
    - We finally know enough to build 'optimised' large-scale accelerator experiments
  - Extracting the physics is difficult, expensive and fun
    - Even by the standards of collider physics

Neutrinos in the Standard Model



- Only LH ν in the 'classic' Standard Model
  - By definition massless, since both helicities appear in Yukawa coupling
- Mathematically tidy, but a bit odd
  - Massless / degenerate states normally indicate a fundamental symmetry
  - Most plausible extensions of the SM require / allow for RH and massive ν
  - Rules out hope of a fundamental relation between quarks and leptons

Neutrino mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

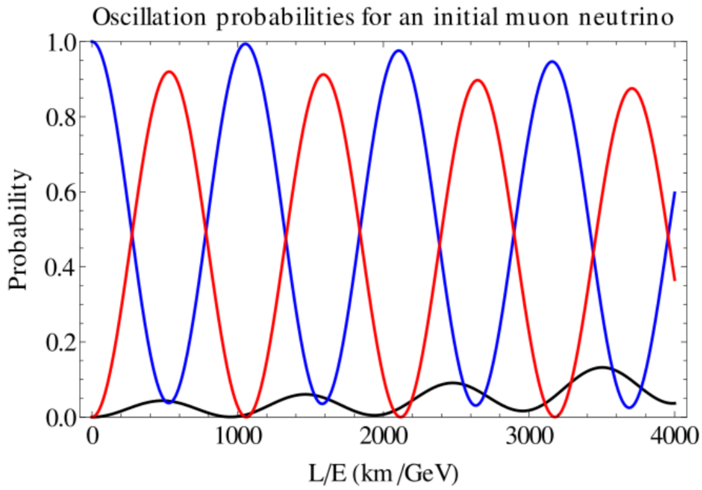
- Neutrino mass is an experimental fact
  - Measured through flavour mixing
- How can we accommodate this?
  - "Dirac ν" => ν_R exist, do not interact 'normally'
  - "Majorana ν" => ν and $\bar{\nu}$ are the same state
  - Something completely new
- All imply directly the existence of BSM physics
- We else should we care?
  - Existence of a weak mixing matrix invites comparison with quark sector
  - Rich interplay of neutrino phenomenology with cosmology
    - Light fermions 'wash out' structure formation in the early universe
  - Neutrino sector a source of CP-violation and lepton number violation
    - Possible driver for observed matter-antimatter asymmetry today

Neutrino mixing

- Weak eigenstates do not align with mass eigenstates
  - Neutrinos produced in state of definite flavour
  - Propagating wave packet is mixture of mass eigenstates
  - For different mass eigenvalues, interference occurs
  - Measured flavour $\neq$ produced flavour in general

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

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



- Note: L/E is time in neutrino frame

Neutrino experiments

1967 Homestake solar ν experiment

- Can look for 'appearance' or 'disappearance' in flight
  - Sensitivity depends on data sample and modelling of source
  - Material on the way (all matter, not antimatter) also matters.
- Intense neutrino sources available
  - Sun: ν_e, continuum and line spectrum; MeV - 10's MeV
  - Cosmics on atmosphere: ν_μ, $\bar{\nu}_\mu$, ν_e; GeV - 10's GeV
  - Reactors: $\bar{\nu}_e$; MeV
  - Accelerators via pion decay: ν_μ, $\bar{\nu}_\mu$, bgd ν_e, $\bar{\nu}_e$; GeV - 10's GeV
    - Advantages: Known source spectrum, choice of baseline, can produce both particle and antiparticle
  - Supernovae (prompt and diffuse background): all flavours; MeV - 10's MeV
    - Sample currently limited to 25 interactions from SN1987A
- Large detectors required, operated in low background conditions
- Where possible, seek to cancel (large) systematics in measurement
  - Power, baseline, particle / antiparticle, ratio between flavours

Three-neutrino paradigm

- Conventional parametrisation of the PMNS matrix:

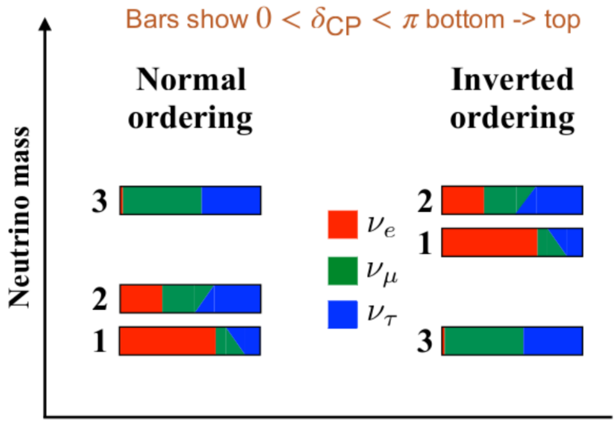
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

'Atmospheric' sector (~10GeV, ~10^3 km)	'Reactor' sector (~MeV, ~1 km)	'Solar' sector (~MeV, ~10^6 km)	$0\nu\beta\beta$ expts (not accessible via oscillation)

- 3 angles, 1 CP-violating phase, 2 mass splittings
  - Δm^2_{21} (> 0) ; Δm^2_{32} ($\approx \Delta m^2_{31}$) ; sgn(Δm^2_{32})
  - Note: only sensitive to $\Delta m^2_{ij} = m^2_i - m^2_j$
  - sgn(Δm^2_{32}): normal ($m_1 < m_2 < m_3$) or inverted ($m_3 < m_1 < m_2$) ordering
- (Almost) all expt. results accommodated in this parametrisation

Values of parameters

$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.558^{+0.020}_{-0.033}$	$0.427 \to 0.609$
$\theta_{23}/^\circ$	$48.3^{+1.1}_{-1.9}$	$40.8 \to 51.3$
$\sin^2\theta_{13}$	$0.02241^{+0.00066}_{-0.00065}$	$0.02046 \to 0.02440$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$
$\delta_{\rm CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.523^{+0.032}_{-0.030}$	$+2.432 \to +2.618$



$$U_{\rm PMNS} = \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.35 & 0.55 & 0.72 \\ 0.40 & 0.58 & 0.68 \end{pmatrix} \qquad U_{\rm CKM} = \begin{pmatrix} 0.97 & 0.23 & 0.0045 \\ 0.23 & 0.97 & 0.041 \\ 0.0087 & 0.040 & 1.0 \end{pmatrix}$$

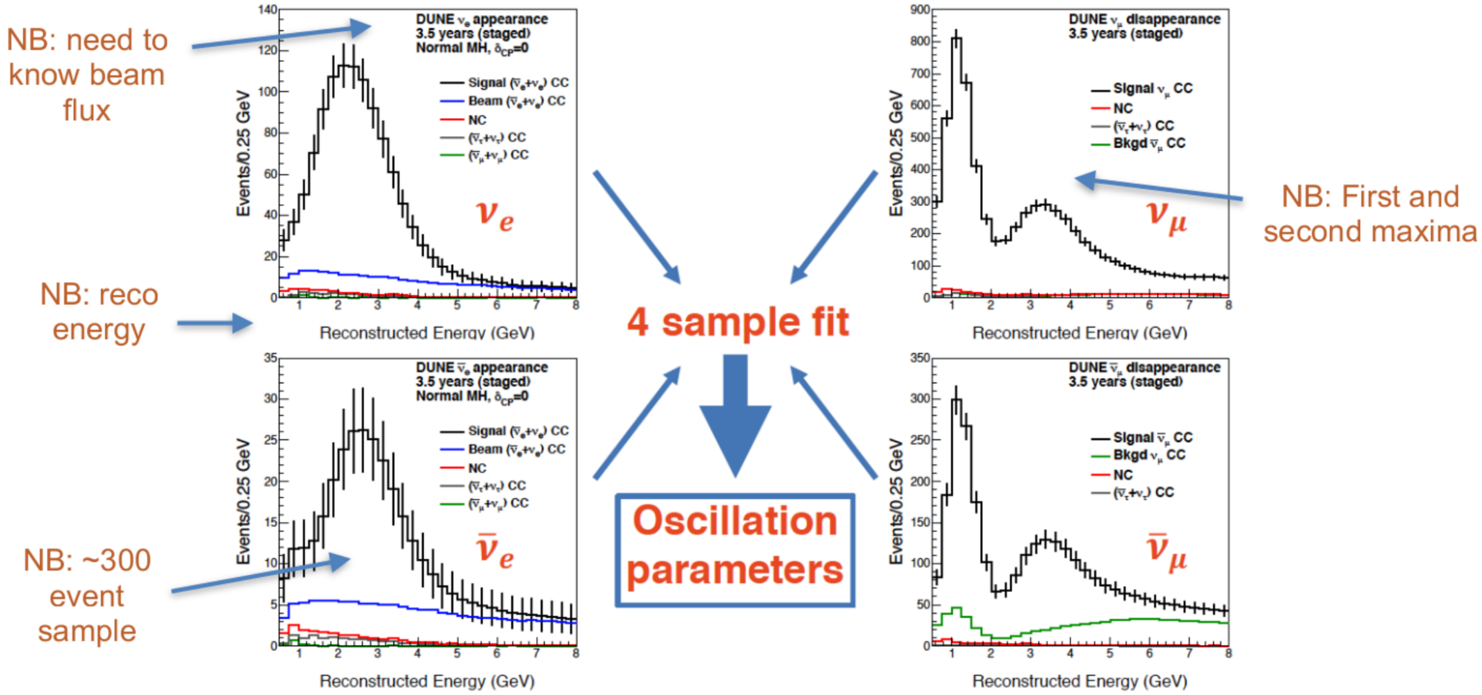
- Neutrinos are really, really mixed
- All measurements are from a complex fit to experimental data
  - Uncertainties are heavily correlated; http://nu-fit.org

What don't we know?

- Unknown knowns
  - δ_{CP} barely measured
- Known unknowns
  - MO; how close θ_{23} is to maximal mixing
  - The fundamental nature of the neutrino
  - Light sterile neutrinos (is PMNS matrix unitary?)
    - Various suggestive 'anomalies' in low-energy results still be investigated
- Unknown unknowns
- The mission for the next decade
  - Increase precision on parameters; determine δ_{CP} and mass ordering
  - Challenge three-neutrino model, determine unitarity, look for non-standard oscillation
  - Provide input (MO, θ_{13}) to Majorana-sensitive experiments
  - Use new experiments as 'observatories' for astrophysics, baryon decay, etc

DUNE experiment

- Accelerator ν_μ dis. / ν_e app. (wide-band ~GeV beam, L=1300km)
  - Measure as fn of E_ν: $P(\nu_\mu \to \nu_\mu)$, $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$



DUNE appearance equation

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \quad &\simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
&+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}}) \\
&+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2
\end{aligned}
$$

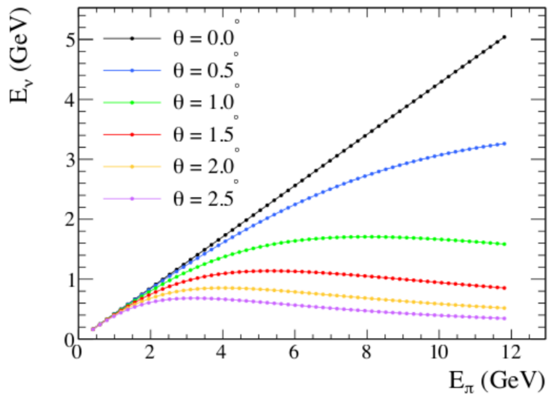
$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$, $a = G_F N_e/\sqrt{2}$

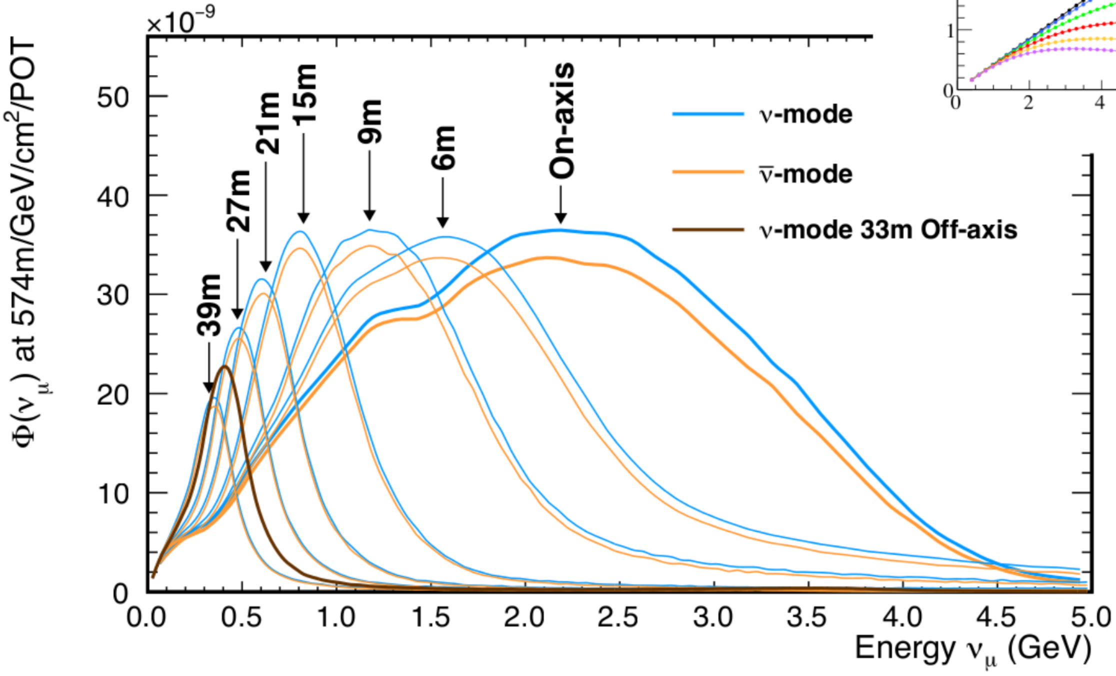
- Comments
  - a accounts for matter-enhanced oscillations
    - The mid-west is believed to be made of matter, not anti-matter
  - Both δ_{CP} and a change signs between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
    - But not for disappearance! (CPT theorem)
  - Long baseline, appreciable value of θ_{13} allow disentangling of two effects
    - Allows simultaneous measurement of δ_{CP}, Δm^2_{32}, θ_{23} and MO

Experiment parameters

- FD exposure needed for physics goals: 120 kt MW yr
  - Practical limit of ~ 1.5 MW for beam delivery system
  - Would like reach in five-year time span (with staged detectors)
  - Require around 40 kt fiducial mass
- Choice of baseline
  - On-axis (wideband) or off-axis (narrowband beam)?
    - On-axis allows higher flux, observation of second oscillation minimum
  - Optimisation of energy vs baseline for $\delta_{\rm CP}$ indicates $1 - 1.5$ Mm required
    - Geodesic distance from FNAL (Chicago IL) to SURF laboratory (Lead, SD) 1300 km
- Background requirements
  - Shielding from cosmic rays vital for low-energy physics programme
    - Also massively reduces non-useful data rate from experiment (still dominated by muons)
  - SURF 4850ft level is just about deep enough

On-axis vs Off-axis



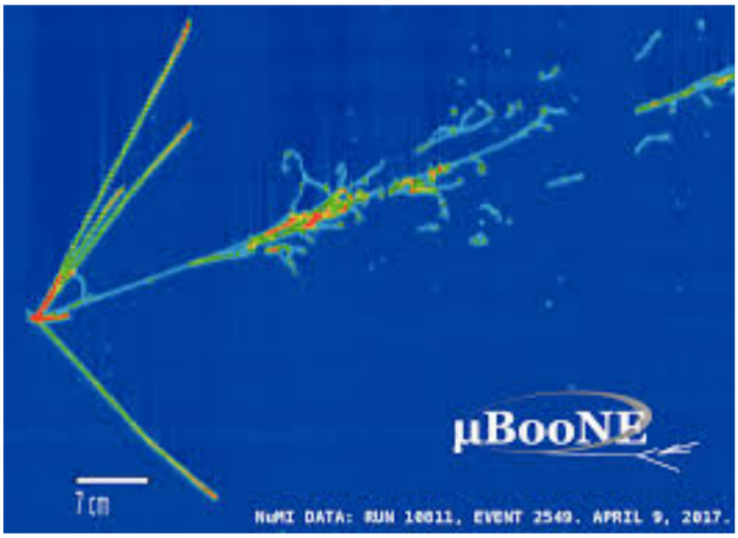


Interaction medium

- Emphasis on energy and position resolution over wide range
  - Homogeneous medium is required, no iron etc

Medium	LAr TPC	Water Cherenkov	Scintillator
Cost	✓	✓✓✓	✓✓
Density	✓✓✓	✓✓	✓
Logistics	✓	✓✓	✓✓
E. res.	✓✓	✓✓	✓✓
Threshold	✓✓	✓	✓✓✓
Posn. res.	✓✓✓	✓	✓
Example	DUNE	Hyper-K	JUNO
Principle	Charge + light	Light	Light

DUNE events



- Inelastic events on LAr have complex final states ($\lambda_{\nu} \approx 1$ fm)
- The 'killer feature': track by track reconstruction within events
  - Keeps energy resolution under control
  - Allows significant reduction in detector systematics / mis-ID
  - Enables low-energy (MeV) and zero-background medium-energy (GeV) physics
- At 1mm resolution, effectively $\sim 3 \times 10^{13}$ voxels (cf BEBC, $\sim 4 \times 10^{12}$)

So what *else* can it do?

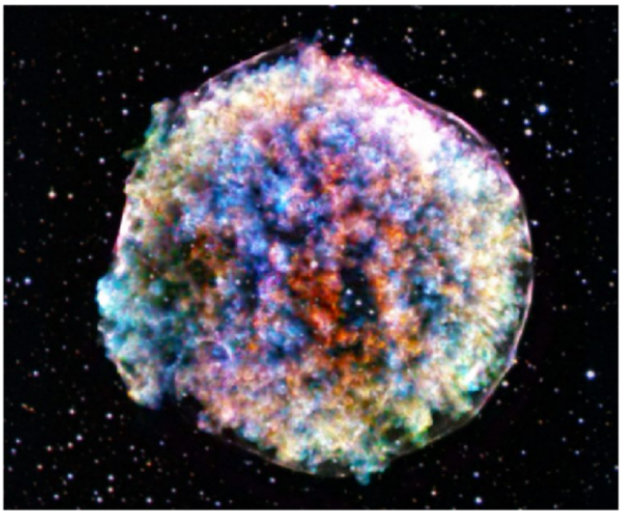
- Precision measurements allow comparison with theory
  - In the long term, aim for ~few percent measurement of mixing angles
  - Allows (e.g.) testing against generic sum rules based on group structure of BSM theories:

$$\sin\theta_{12} - \sin\theta_{13}\tan\theta_{23}\cos\delta_{\mathrm{CP}} = A$$

- Astrophysical measurements
  - Principally: prompt detector of ν from core-collapse supernovae
  - Solar neutrinos (stretch goal)
- BSM physics
  - Baryon decay (mainly SUSY-motivated p $\rightarrow K^{+}\bar{\nu}$)
  - 'Beam-dump' style neutral particle searches using near detector (see later)
  - Covering specific gaps in DM parameter space
- Non-beam physics places significant constraints on DAQ, computing
  - Designing an 'always-open telescope' turns out to be challenging

Supernova bursts

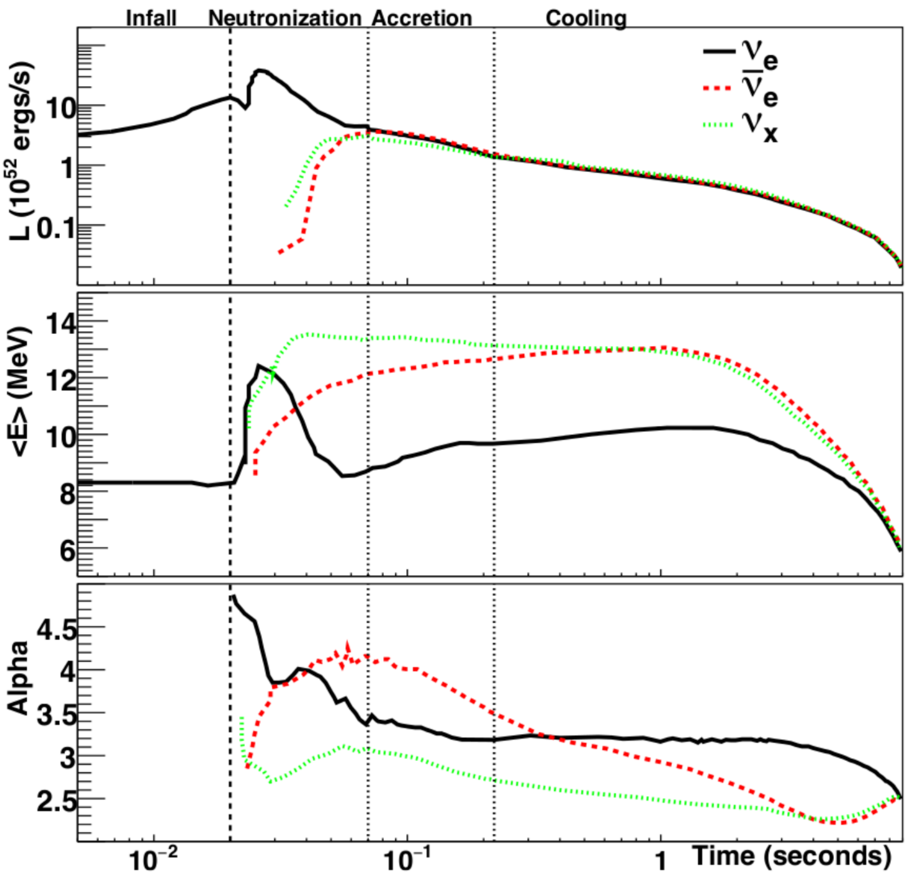
- Core-collapse supernova
  - Essentially a neutrino-driven explosion
- Stages of collapse
  - Infall: increased ν_e emission, but most leptons are trapped
  - Neutronisation: huge rapid release of ν_e as shock wave stalls on nuclear matter
  - Accretion: all-flavour emission from hot neutron star envelope
  - Cooling over a few seconds



Here's one we prepared 8000 years ago

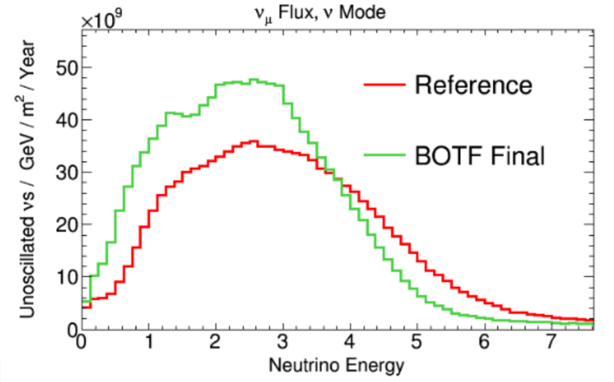
- {Flux, energy spectrum, flavour distribution} can be measured
  - Specific information on process, progenitor, final object is carried
- Rate of 'nearby' core-collapse supernovae is ~per few decades
  - DUNE sensitivity is sufficient to trigger for SNB across the galaxy

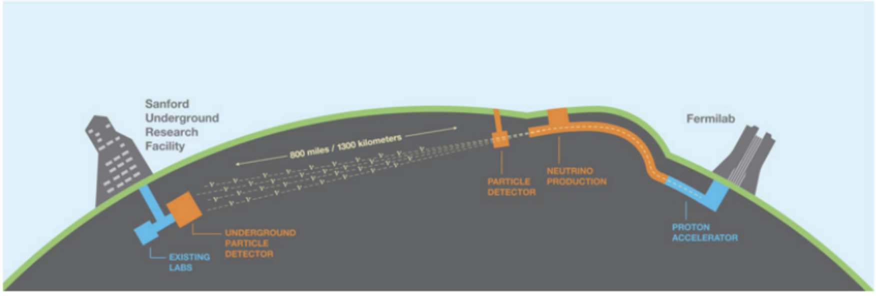
Supernova bursts

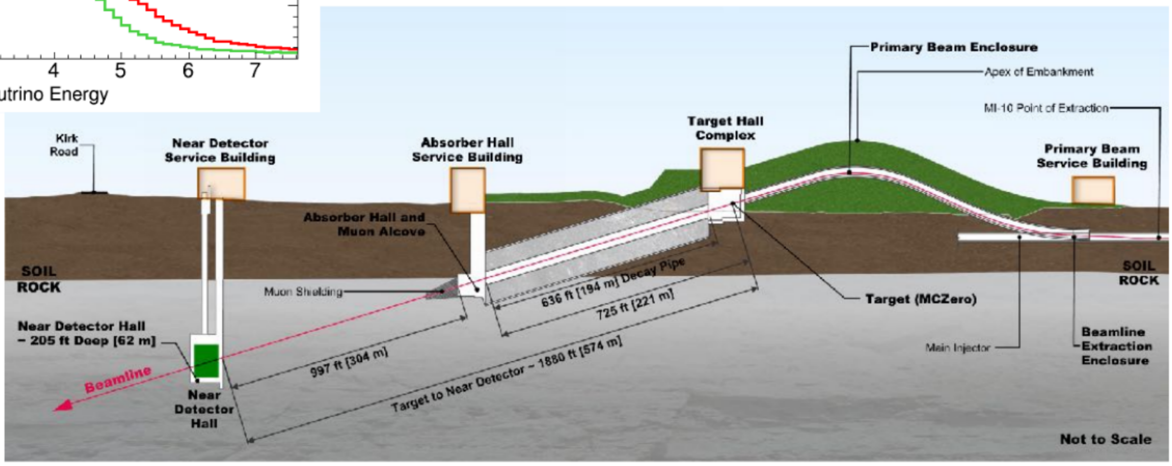


- DUNE sensitive to ν_e via nuclear reaction:
  - $\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$
- Water detectors sensitive primarily to $\bar{\nu}_e$ via hydrogen IBD
- Complementarity is vital to obtain full picture
- Fast trigger capability (~minutes / hours before photons arrive)
- Need to be 'always on'

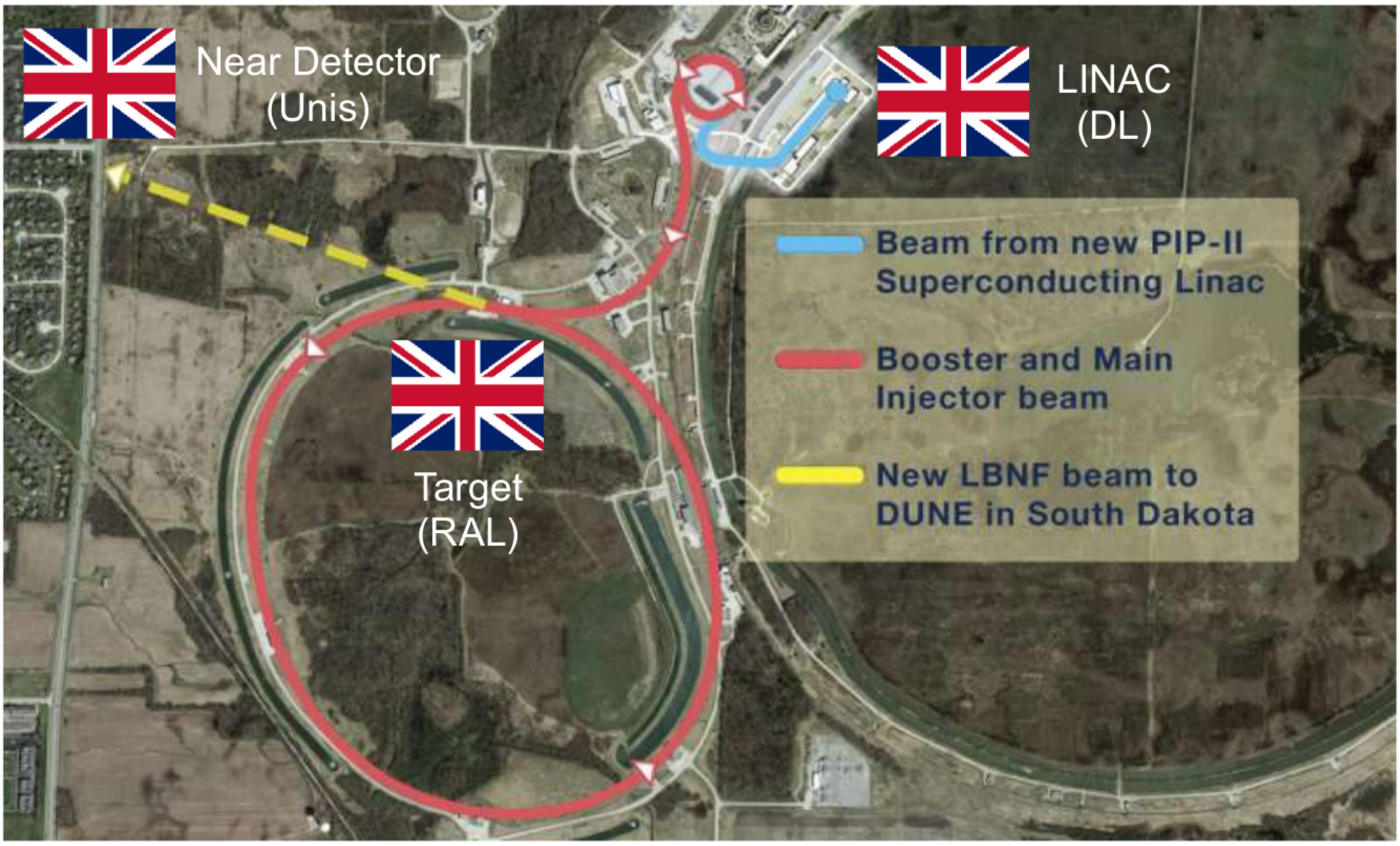
LBNF / DUNE layout



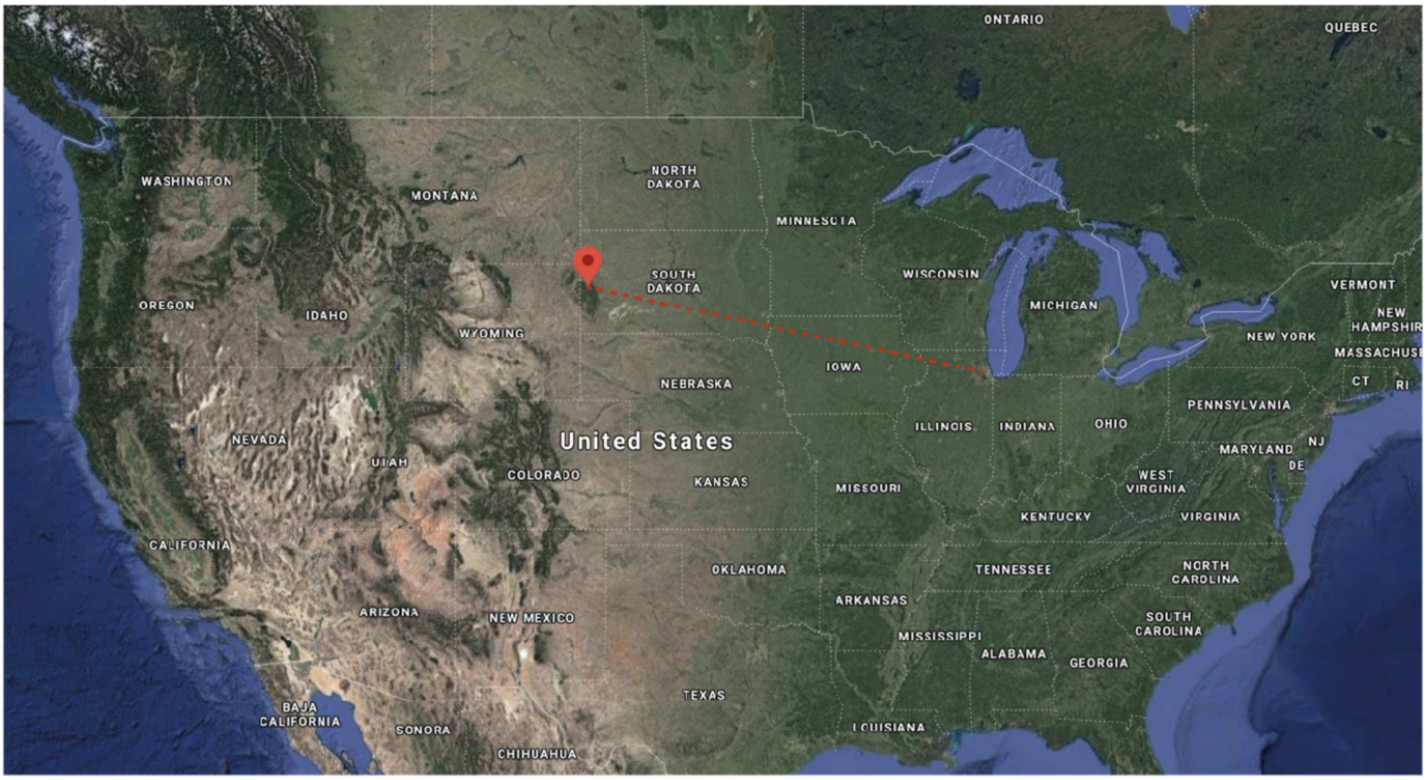




PIP-II layout

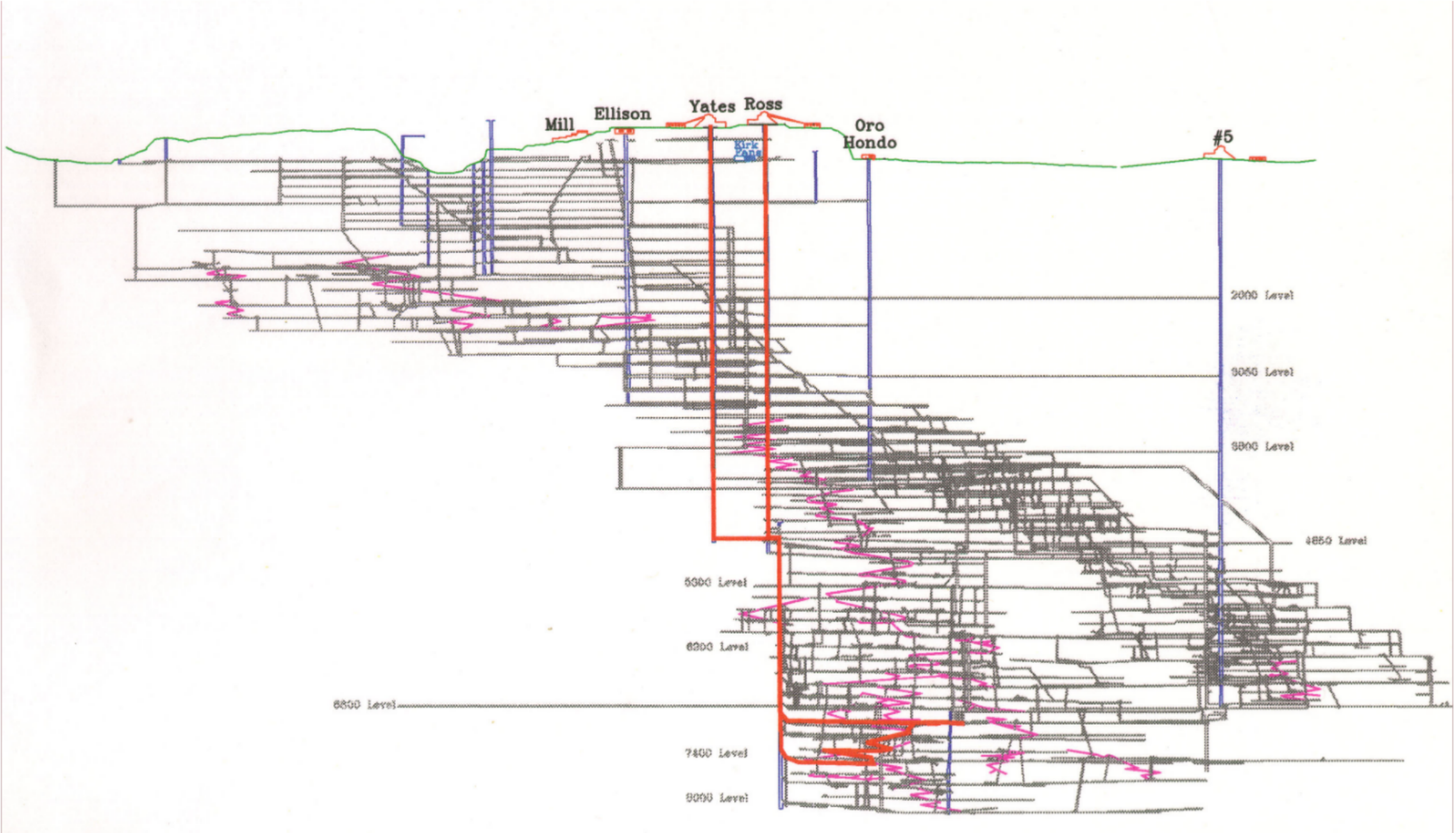


In transit

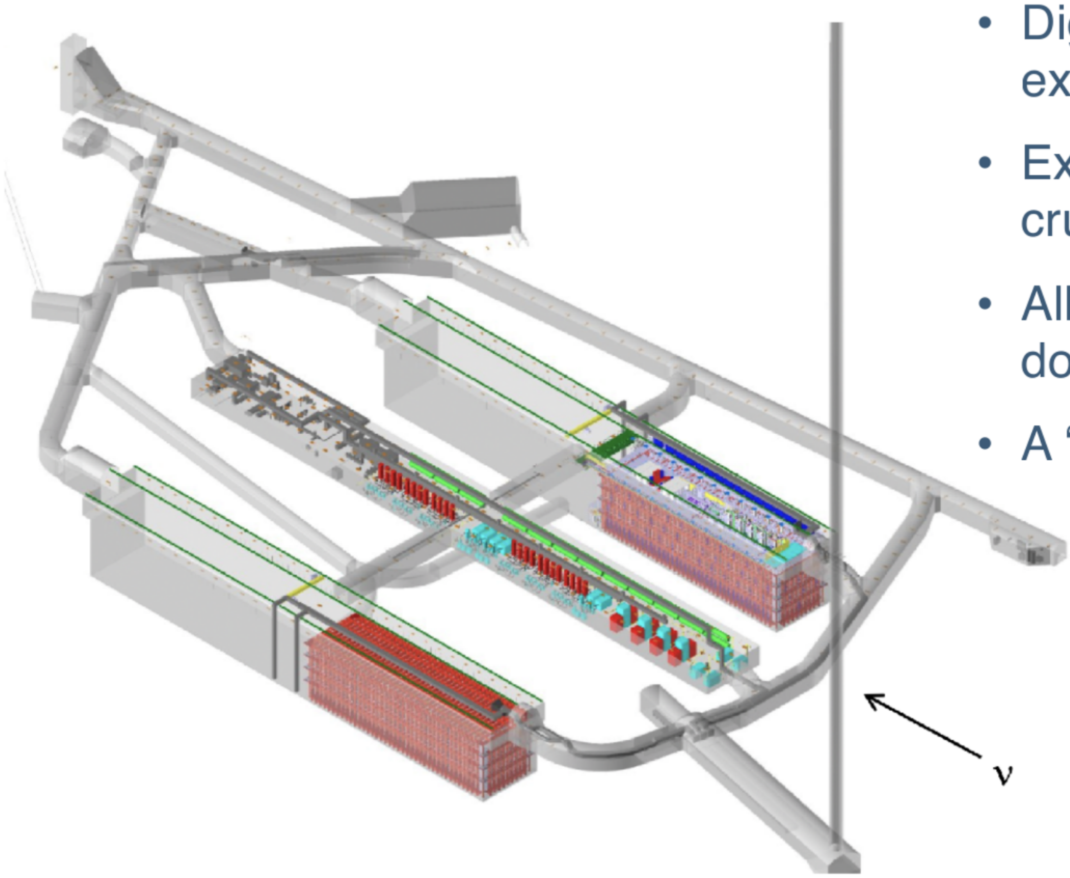


ONTARIO
QUEBEC
WASHINGTON
MONTANA
NORTH DAKOTA
MINNESOTA
SOUTH DAKOTA
WISCONSIN
MICHIGAN
VERMONT
NEW HAMPSHIR
OREGON
IDAHO
WYOMING
NEW YORK
MASSACHUSE
IOWA
CT
RI
NEBRASKA
PENNSYLVANIA
ILLINOIS
INDIANA
OHIO
NEVADA
United States
UTAH
NJ
MARYLAND
DE
COLORADO
KANSAS
MISSOURI
WEST VIRGINIA
KENTUCKY
VIRGINIA
CALIFORNIA
OKLAHOMA
TENNESSEE
NORTH CAROLINA
ARKANSAS
ARIZONA
NEW MEXICO
SOUTH CAROLINA
MISSISSIPPI
ALABAMA
GEORGIA
TEXAS
BAJA CALIFORNIA
SONORA
LOUISIANA
CHIHUAHUA

SURF

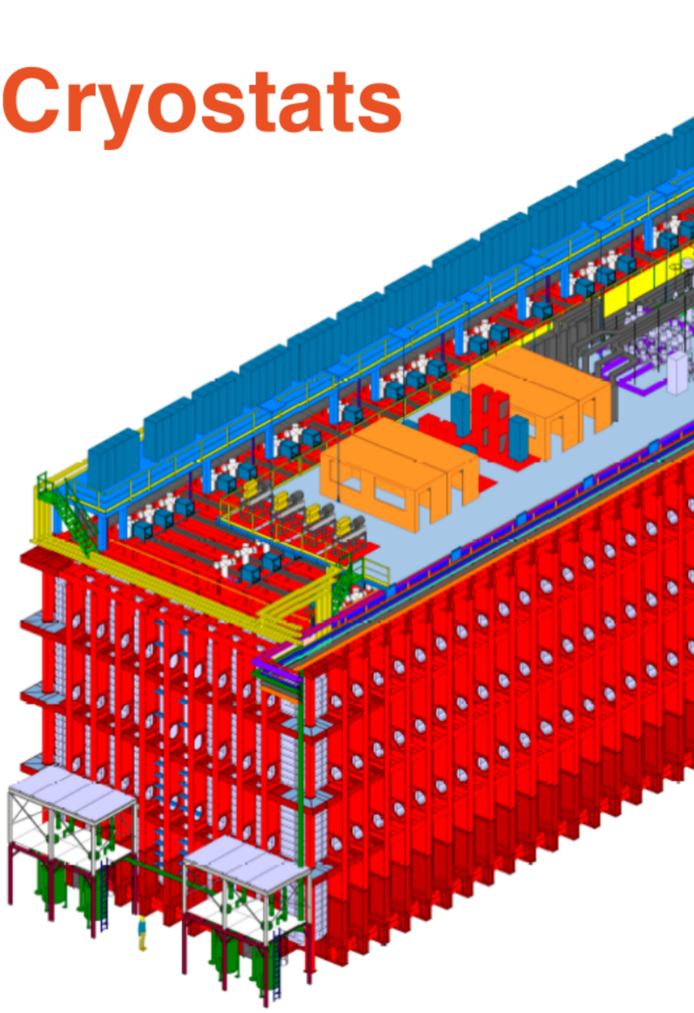

Mill
Ellison
Yates
Ross
Kirk
Oro Hondo
#5
2000 Level
3050 Level
3800 Level
4850 Level
5300 Level
6200 Level
6800 Level
7400 Level
8000 Level

Underground layout

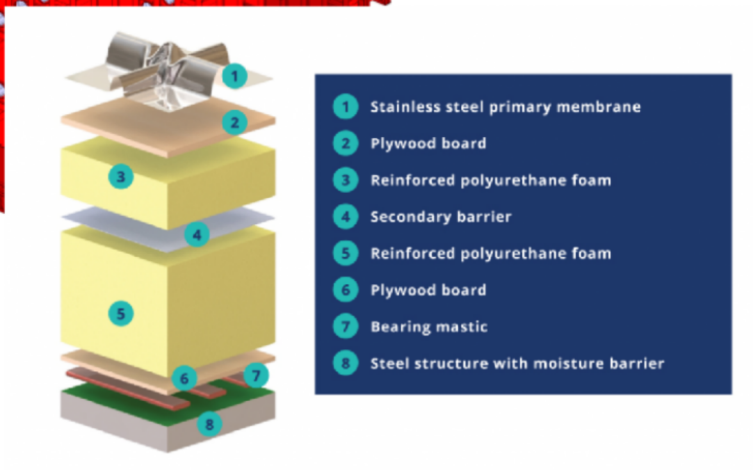


- Dig using explosives
- Excavate 800kt of crushed rock
- All components down a 14’ shaft
- A ‘ship in a bottle’

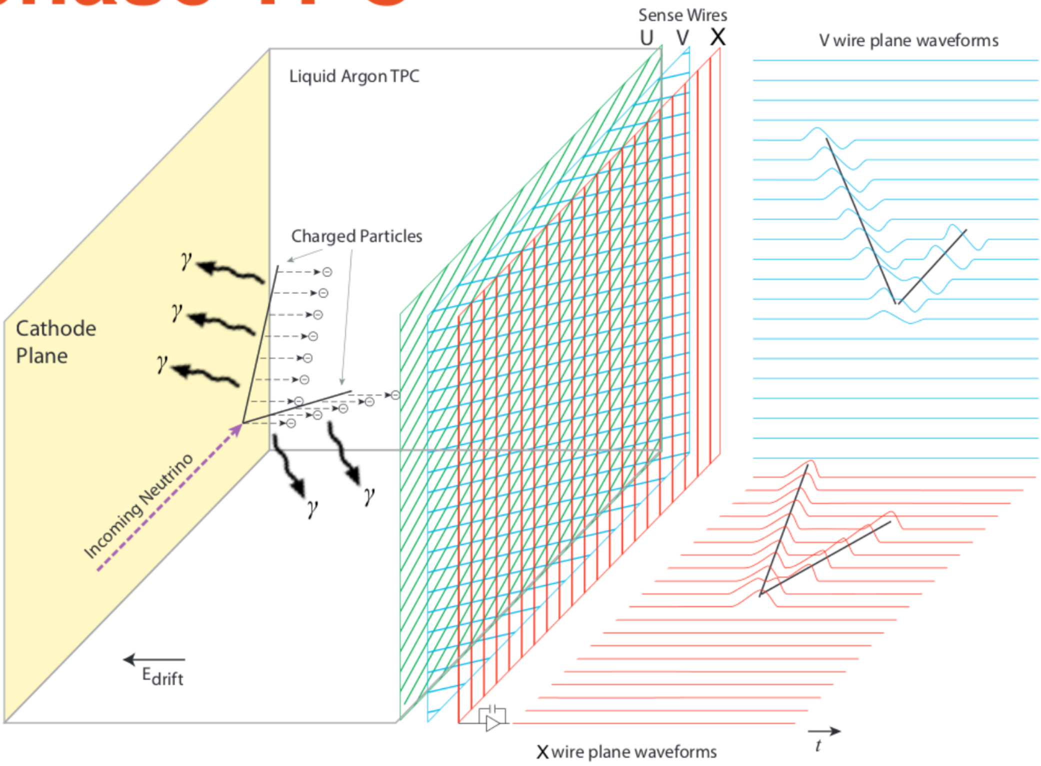
Cryostats



58m long by 14m wide x 12m high
(Stack of four olympic swimming pools)

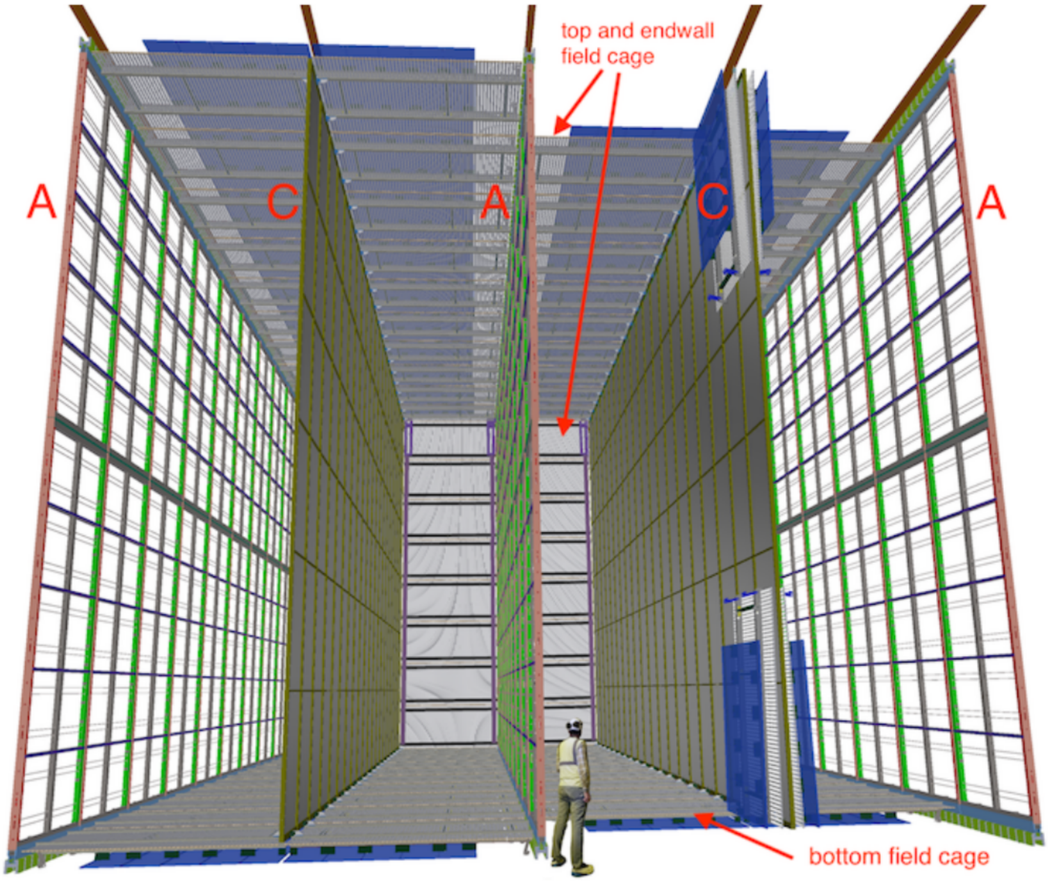


Single-phase TPC



- Readout
  - 2MHz sampling on collection + induction wires (few k electrons)
  - Low noise, large dynamic range needed; ASICs immersed in LAr

Construction

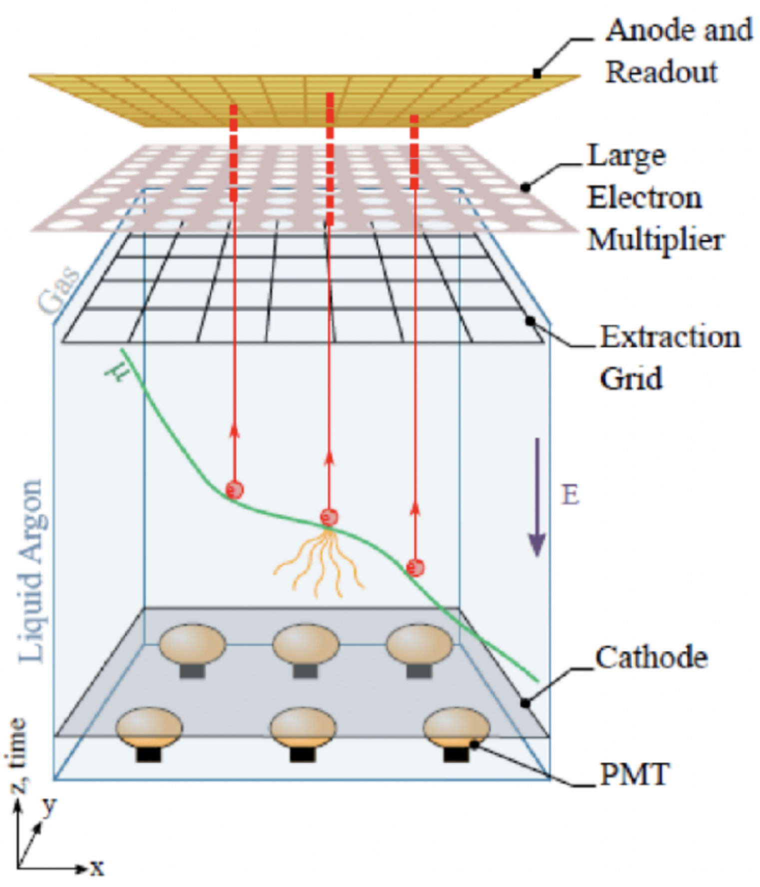


Anode Plane Assemblies

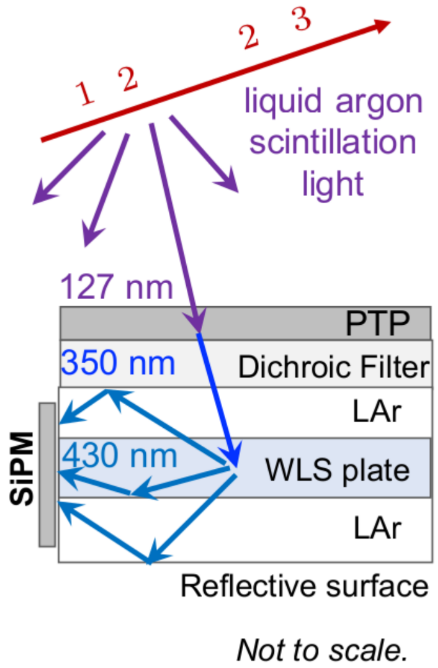
- 2560 wires in three planes
- Control of dimensions and wire tension critical
- Shrinks by several mm at LAr temperature!
- Size dictated by shaft (but also by UK trucks…)

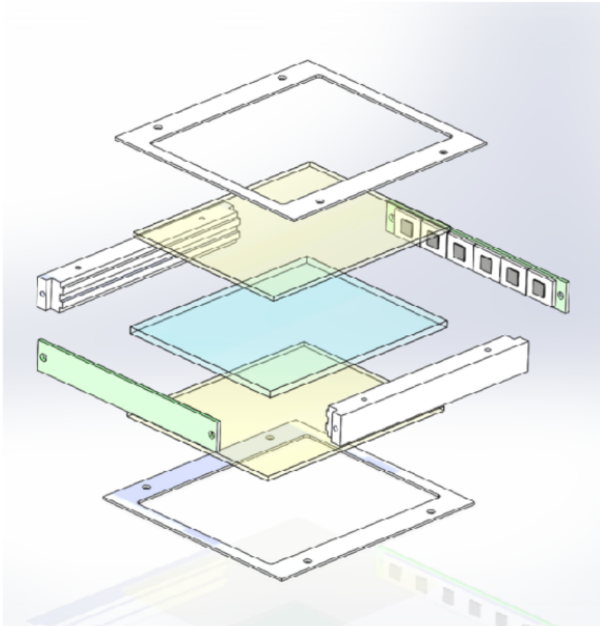
Dual-phase TPC

- Dual-phase readout
  - Extract charge into surface gas via micro channel plate
  - Intrinsic gain improves S/N
  - Pixelated readout
  - Efficient use of LAr volume
- Challenges
  - Longer collection length (6m)
  - Mechanical precision
  - 600kV potential
- Technology still developing
  - First module will be SP



Photon detection (SP)

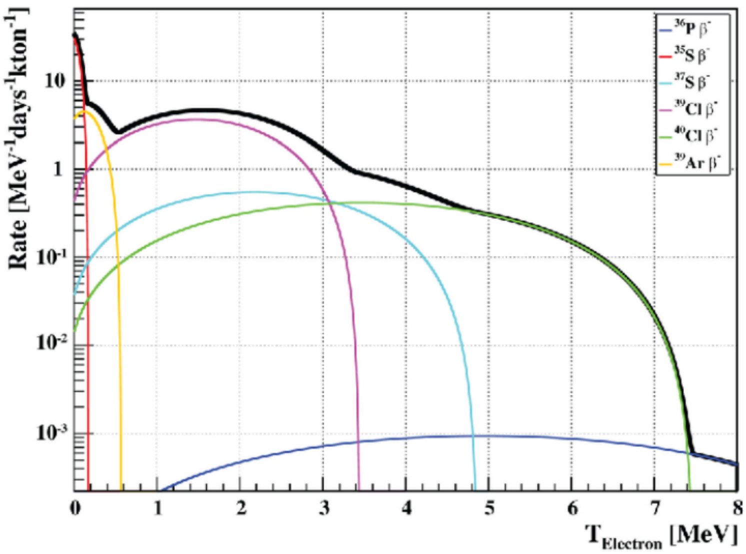




- X-arapuca concept maximises collection area per SiPM
  - Sampling of LAr fast scintillation component (6ns) allows t_0 determination

Key experimental challenges

- Drift volume conditions
  - E field uniformity (1%)
  - LAr purity – up to 6m (4us) drift required, <ppt contamination
- Mechanical stability
- Readout
  - No access to cryogenic electronics
  - Longevity concerns

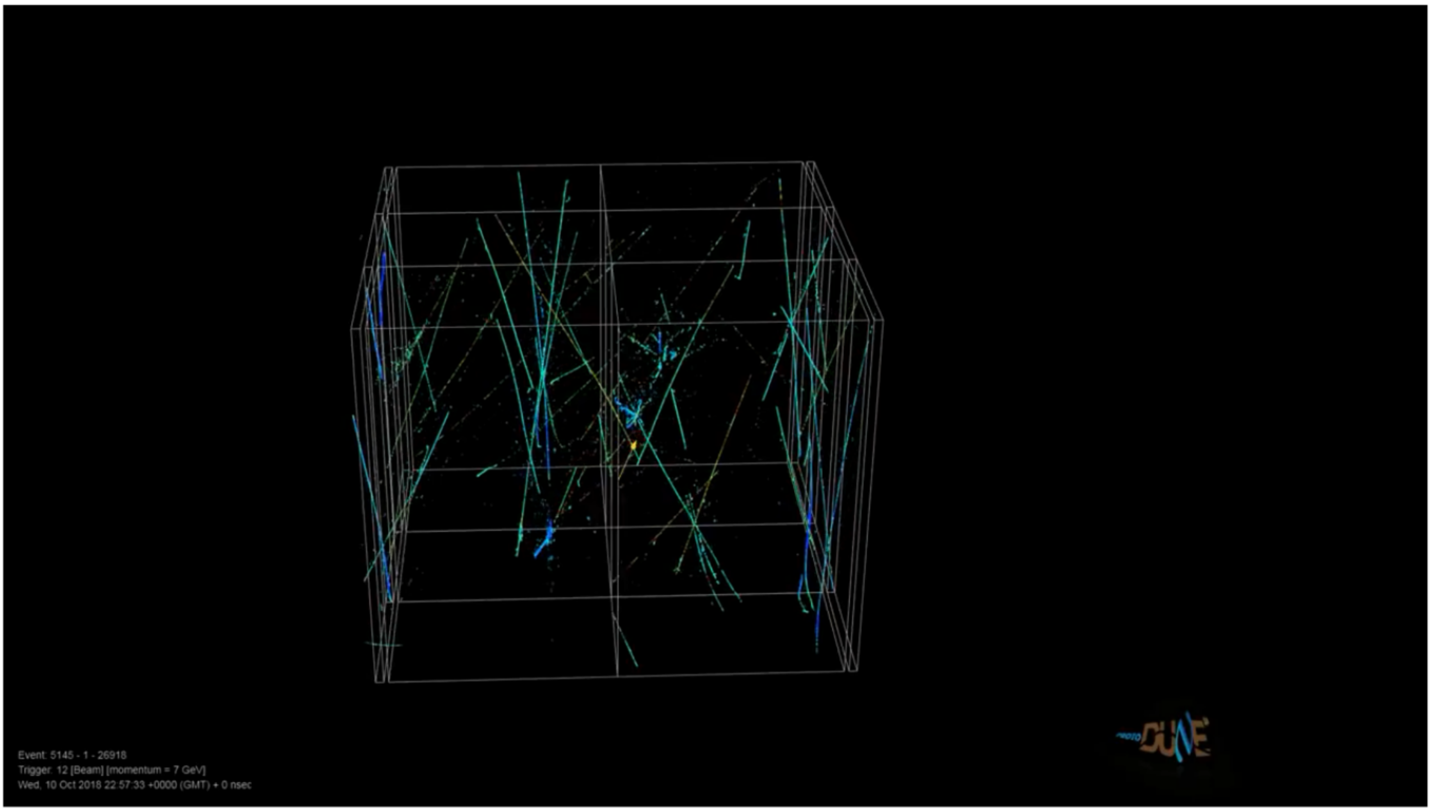


- Monitoring and calibration
  - Calibration from both dedicated systems and detector backgrounds
- Logistics
  - Building a 40kt anything is hard, doing it a mile underground is very hard
- DAQ

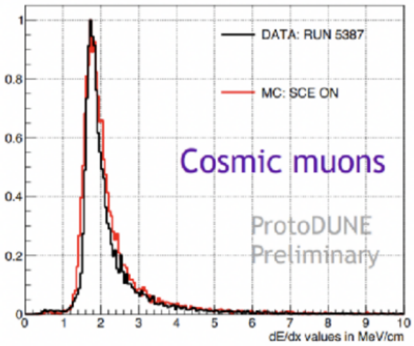
ProtoDUNE

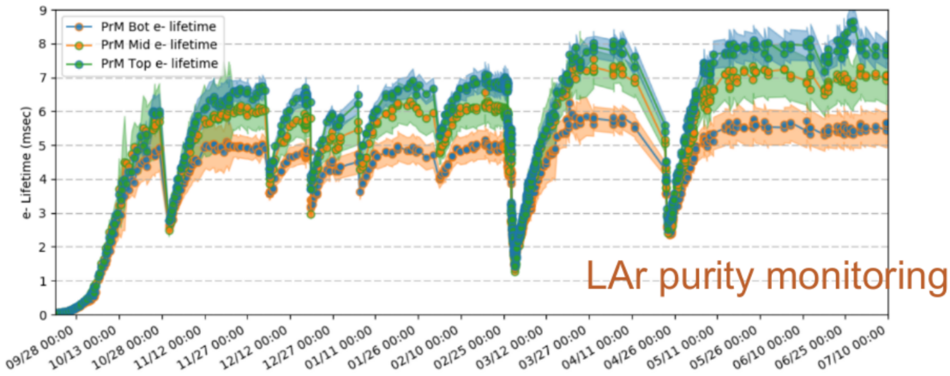
December 2015: EHN1 extension (CERN North Area)

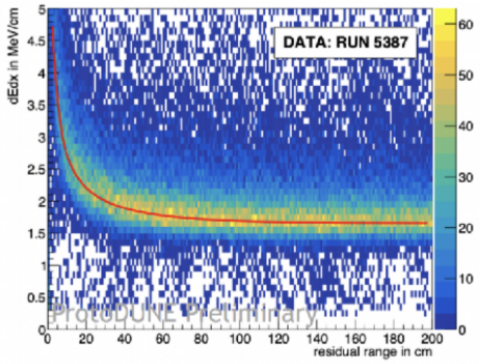
ProtoDUNE beam event



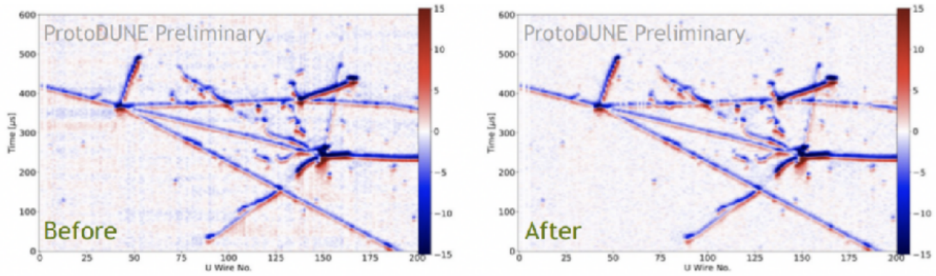
ProtoDUNE-SP outcome







Coherent noise removal

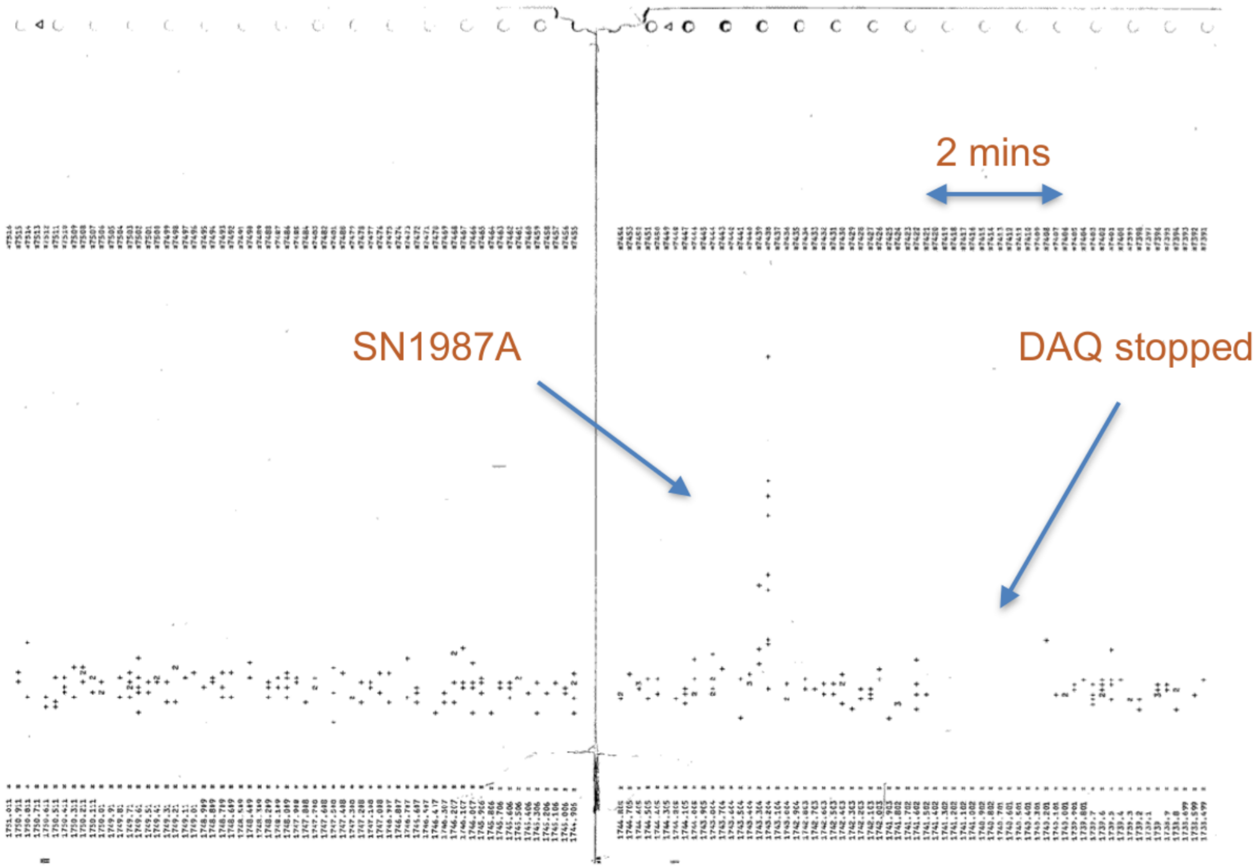


- Success! Basic concept of SP detector validated
  - ProtoDUNE-SP runs ends ~now, LAr removed for upgrade – back in 2022

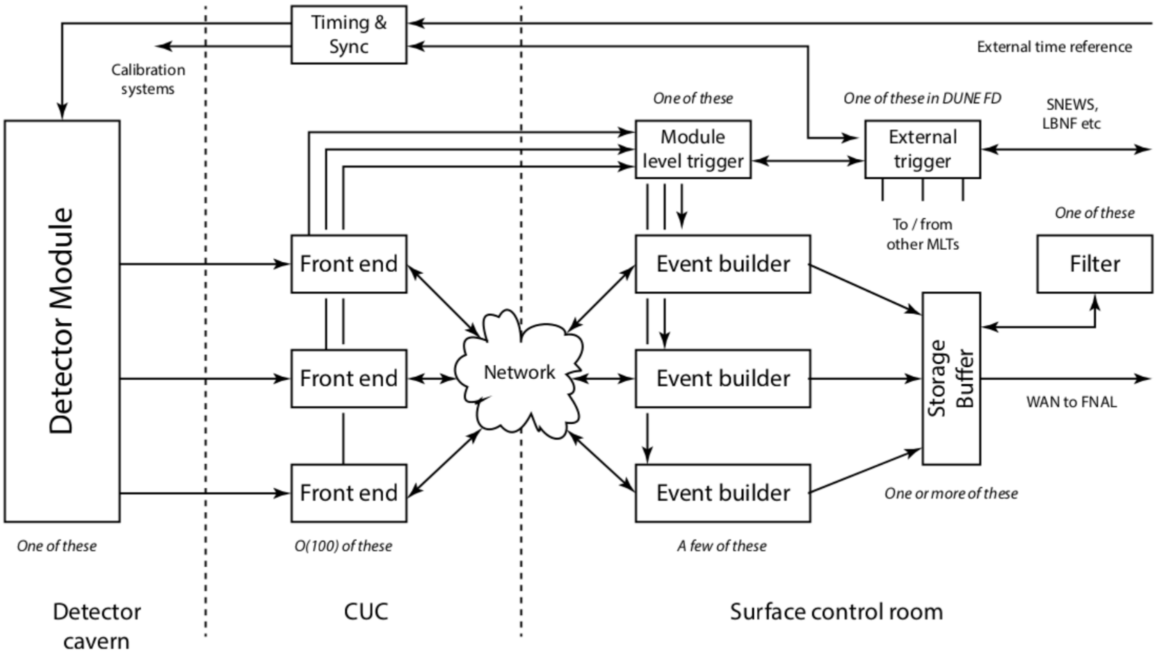
TDAQ challenges

- Data rates ('LHC-sized' system)
  - Data in: ~10Tb/s, out: 100Gb/s
  - Self-triggering on noisy data
- Power and space constraints
  - 100kW per module; confined space over cryostat
  - Detector is huge and distributed
- Access and location: 'no humans allowed'
- Reliability
  - '3 nines' uptime: unprecedented from HEP DAQ systems
  - Redundant everything, to the extent possible (but not the network)
- SNB data handling
  - On SNB trigger, need to store ~100s data continuously (Nobel Prizes, etc)
- Technology choices
  - This is an 'interesting time' to be designing an online system of this type

Lesson from history



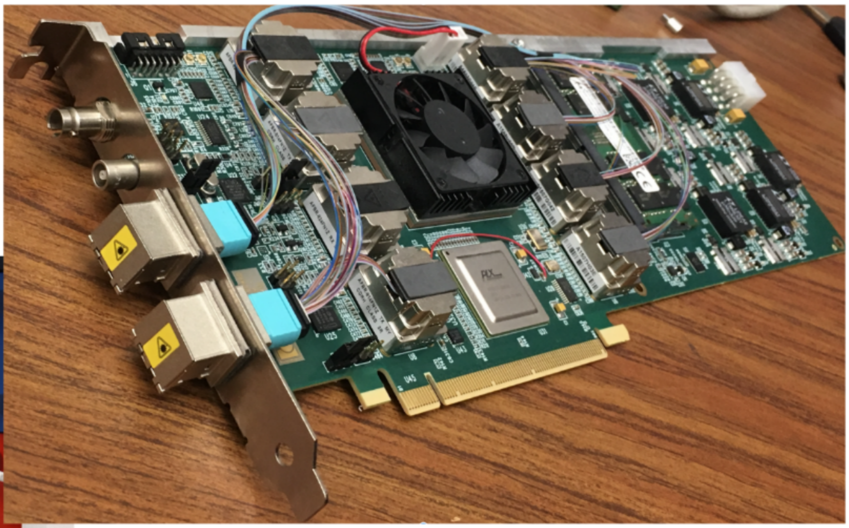
TDAQ design



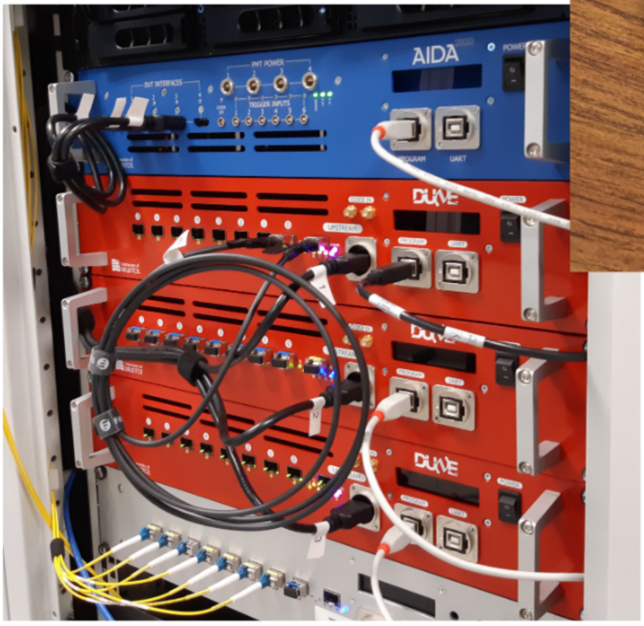
- Highly 'network-centric' design – allows redundancy
- Technology choices for some components to be determined for PD-II
  - e.g. use of 'pure CPU' vs 'FPGA + CPU' vs 'coprocessing' in front end of system

TDAQ custom hardware

FELIX card (BNL / NIKHEF)



DUNE Timing System (Bristol)

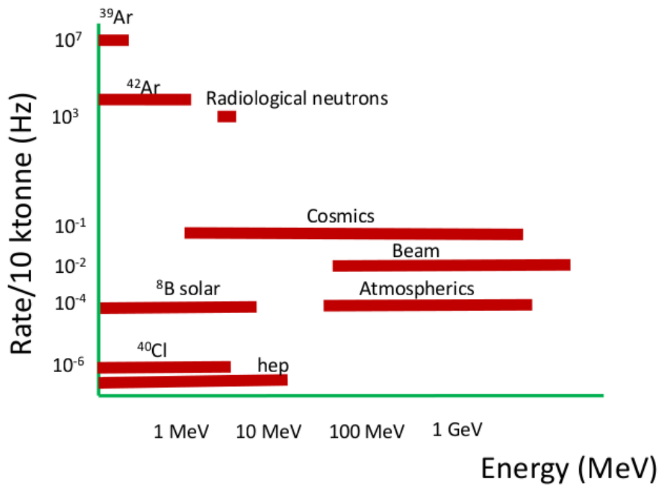


+ a few hundred

Data volumes

Headline number:
30PB raw data per year

Scale set by WAN link SURF -> FNAL



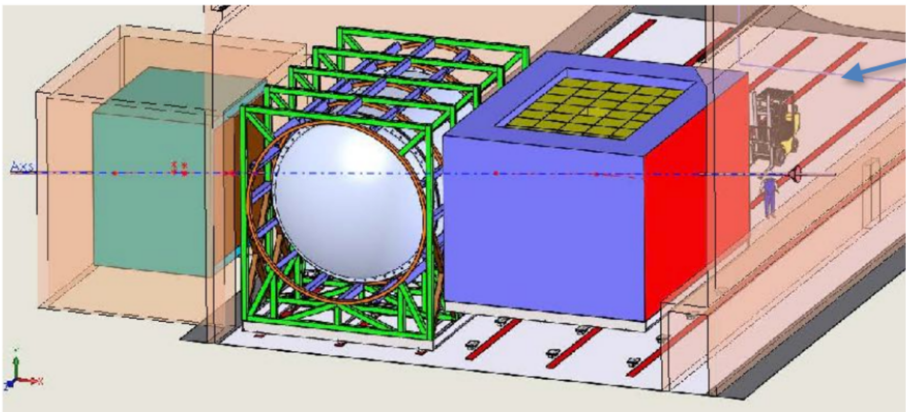
Source	Annual Data Volume	Assumptions
Beam interactions	27 TB	10 MeV threshold in coincidence with beam time, including cosmic coincidence; 5.4 ms readout
Cosmics and atmospheric neutrinos	10 PB	5.4 ms readout
Radiological backgrounds	$<$ 2 PB	$<$ 1 per month fake rate for SNB trigger; 100 s readout
Cold electronics calibration	4 TB	scaled from ProtoDUNE-SP experience
Radioactive source calibration	100 TB	$<$ 10 Hz source rate; single APA readout; 5.4 ms readout
Laser calibration	200 TB	10^6 total laser pulses; half the TPC channels illuminated per pulse; lossy compression (zero-suppression) on all channels
Random triggers	60 TB	45 per day; 5.4 ms readout
Trigger primitives and detector performance studies	$<$ 15 PB	^{39}Ar dominated

Probably not to storage

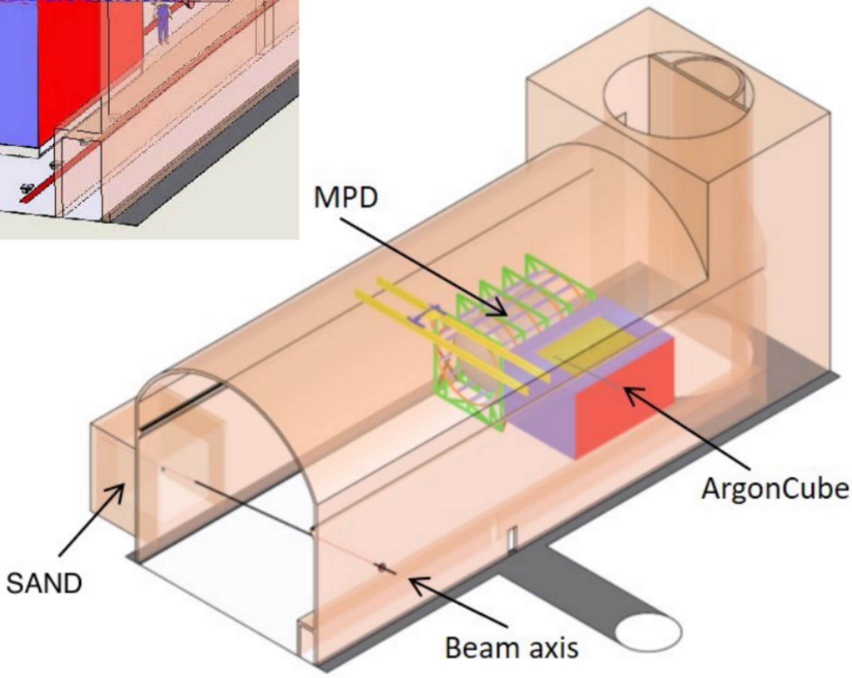
Near Detector

- The observed spectra are a convolution of
  - Actual neutrino flux $\phi_\nu^{\mathrm{FD}}(E_\nu)$ – not precisely known
  - Interaction cross-sections $\sigma_\nu^{\mathrm{FD}}(E_\nu)$ – need to measure for Ar, but hard
  - Efficiency / smearing $T_\nu^{\mathrm{FD}}(E_\nu, E_{\mathrm{det}})$ – simulation only an approximation
- At first order, these cancel in the ratio of near and far observation
  - Position a near detector in the un-oscillated beam
  - Can be ‘small’ since flux is much higher
- However
  - Large detectors and small detectors response differs
  - Flux and backgrounds will differ
  - Cross-sections differ unless identical composition (and ν_e cross-section not constrained)
- Lessons learnt for the ‘precision’ era
  - ND must deconvolute and correct for {flux, spectrum, cross-sections, efficiencies}

Near Detectors



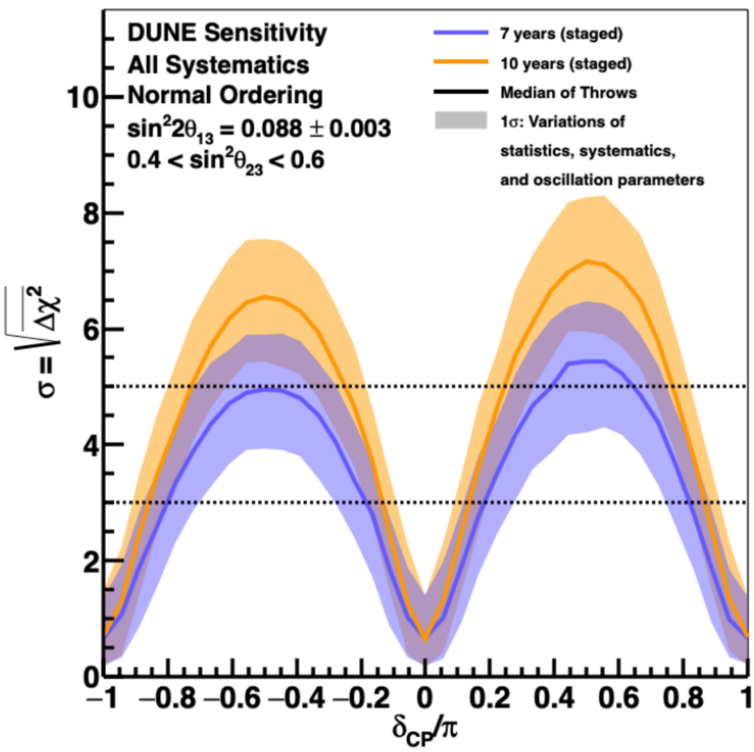
Eppur si muove: can measure beam profile!



- 574m downstream
- ArgonCube: LAr TPC
- MPD: GAr TPC
  - With ECAL and 0.5T field
  - Also muon spectrometer for A.C.
- SAND: 3D scintillator array beam monitor

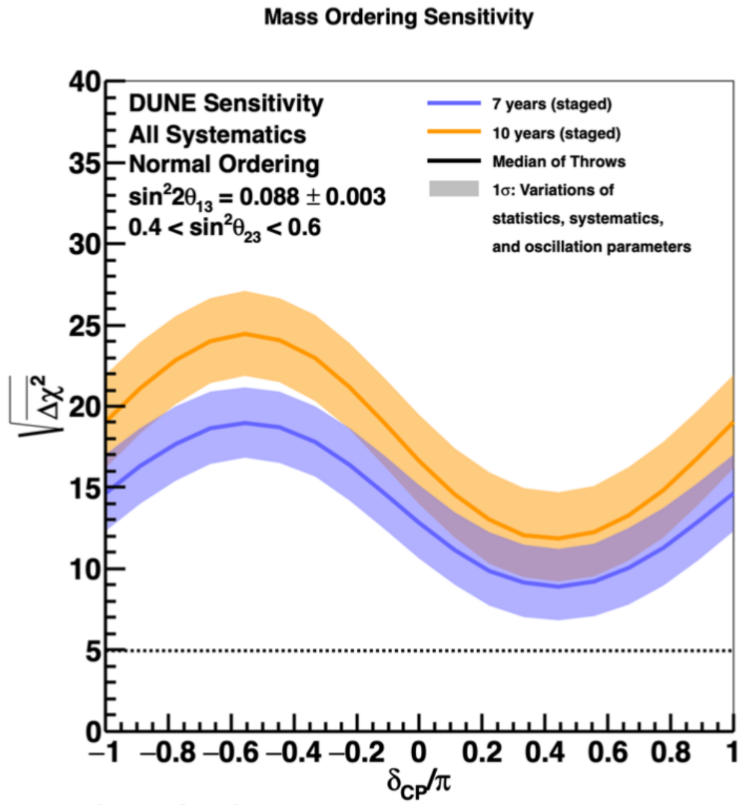
Sensitivities

CP Violation Sensitivity



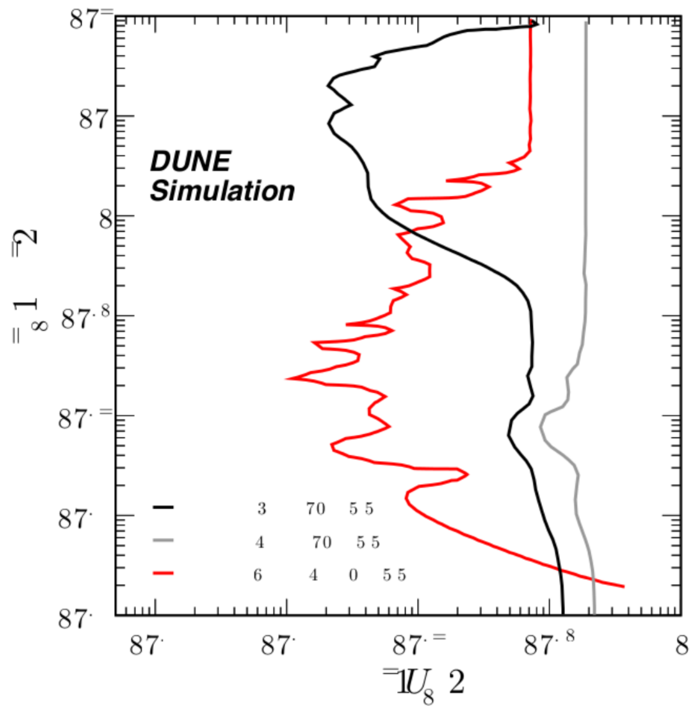
- Zero sensitivity to zero CPV

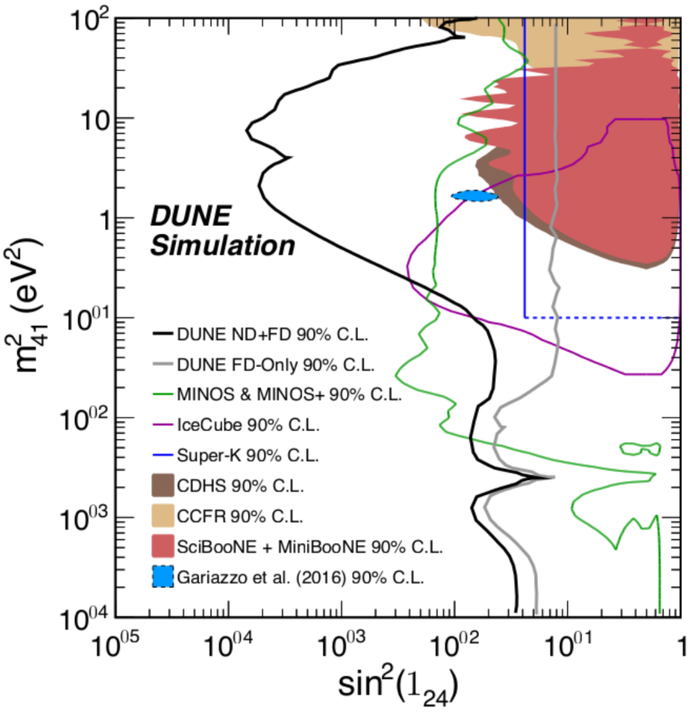
Sensitivities



- Assuming normal ordering

Sensitivities





- 7 years (staged) sensitivities

Conclusions and Outlook

- 'Precision era' of neutrino physics is (almost) here
- Many ways to probe BSM physics
  - No time to cover the 'novel' analyses
- Detectors are large, complex and challenging
  - Even by the standards of collider physics
  - Much knowledge to exchange across the two fields
- Watch this space!
  - New collaborators always welcome

- DUNE tentative timeline:
  - 2022: ProtoDUNE-II starts
  - 2024: Surface facilities available at SURF
  - 2026: Module #1 installation
  - 2027: Module #1 filling, module #2 installation
  - 2028: Module #1 commissioning with beam
  - 2029: Running with 20kt
  - 2031: Running with 30kt, ND operating
  - 2033: Running with 40kt
  - 2035: Upgrade to 2.4MW beam