Future LBL projects and neutrino observatories

SWICH April 2018

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Neutrino physics in Switzerland

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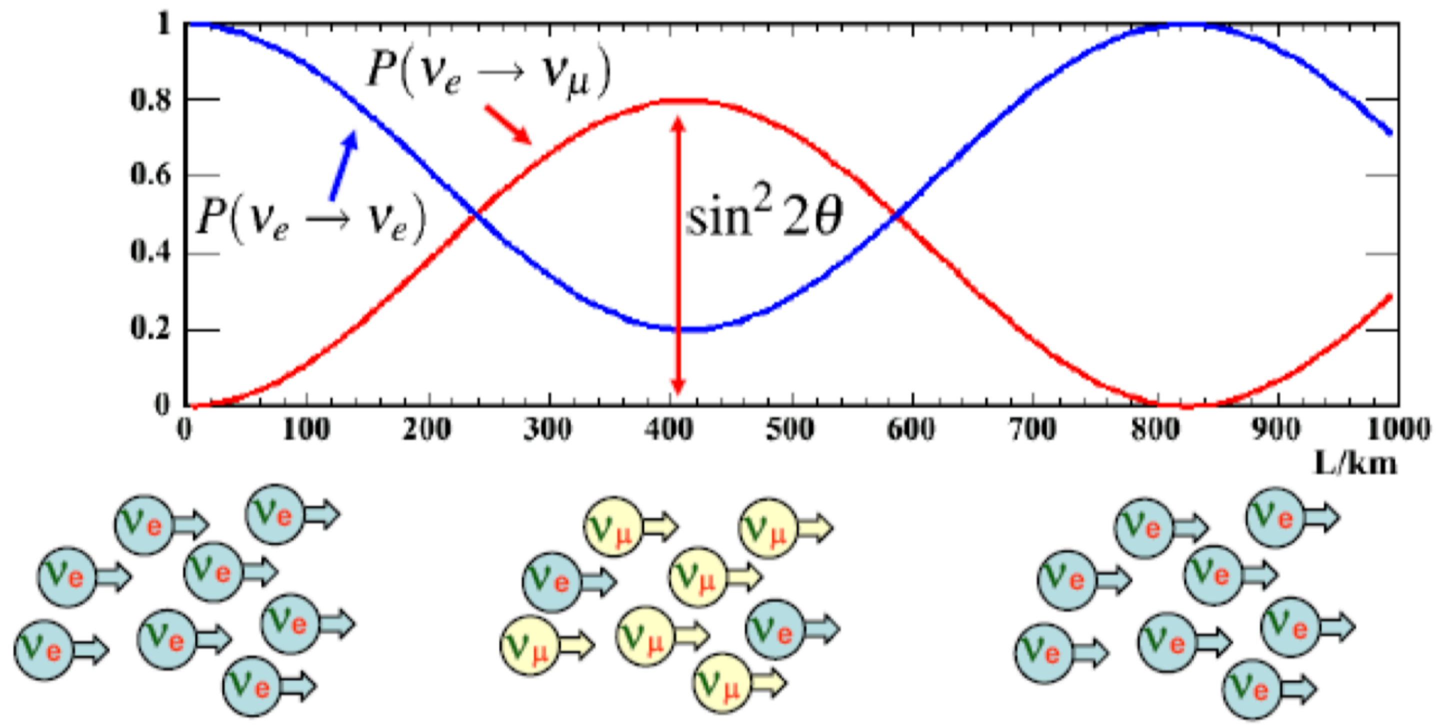
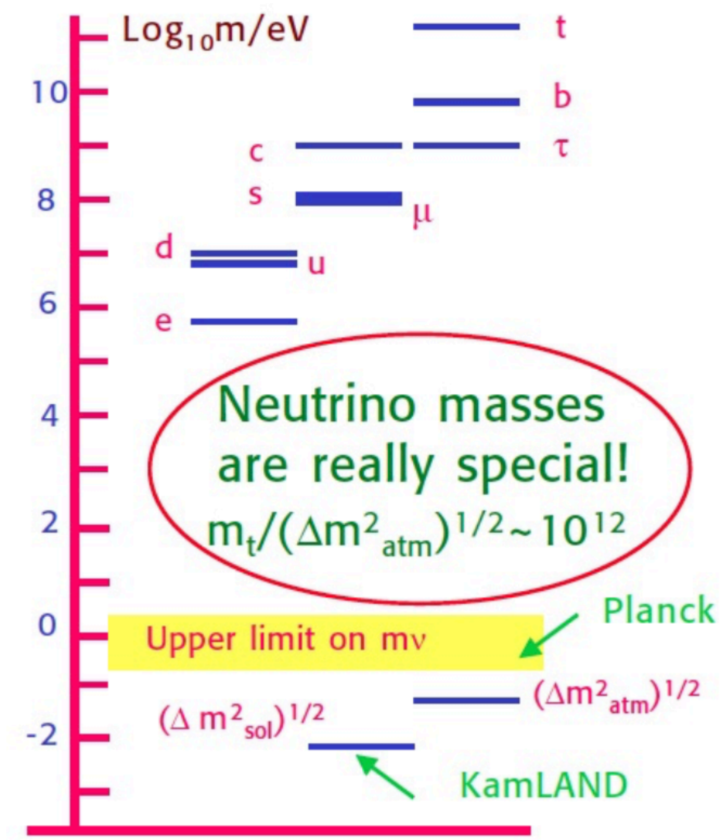
Why neutrinos?

Neutrino oscillations represent the first evidence of physics beyond the standard model.

Mass eigenstates ≠ Flavour eigenstates





Neutrino masses with respect to the other Standard Model particles (fermions). (Image: Planck/KamLAND)

However, still many unsolved questions

- Which is the origin of neutrino masses and mixing?
- Can be the matter-antimatter asymmetry in the universe explained through leptogenesis?
- Are there more than three neutrino families?

Worldwide effort

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT, ICECUBE SOUTH POLE NEUTRINO OBSERVATORY, μBooNE, JUNO, ANTARES, SBN Program, T2K, NOvA, INO India-based Neutrino Observatory, KATRIN, MAJORANA A search for neutrinoless double-beta decay of germanium-76, supernemo collaboration, Hyper-Kamiokande, Double Chooz, Daya Bay θ13

Motivation for long baseline experiments

Mixing angles, matter effects and CP phase addressed in the same experiment

What we measure → $P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Matter effects

$$\frac{16a}{\Delta m^2_{31}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \underbrace{c^2_{13} s^2_{13} s^2_{23} (1-2s^2_{13})}_{\text{constant}} \quad \text{(i)}$$

Matter effects

$$-\frac{2aL}{E} \sin\left(\frac{\Delta m^2_{31} L}{4E}\right) \underbrace{c^2_{13} s^2_{13} s^2_{23} (1-2s^2_{13})}_{\text{constant}} \quad \text{(ii)}$$

CPV

$$-8\frac{\Delta m^2_{21} L}{2E} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\delta \cdot \underbrace{s_{13} c^2_{13} c_{23} s_{23} c_{12} s_{12}}_{\text{constant}} \quad \text{(iii)}$$

What we want

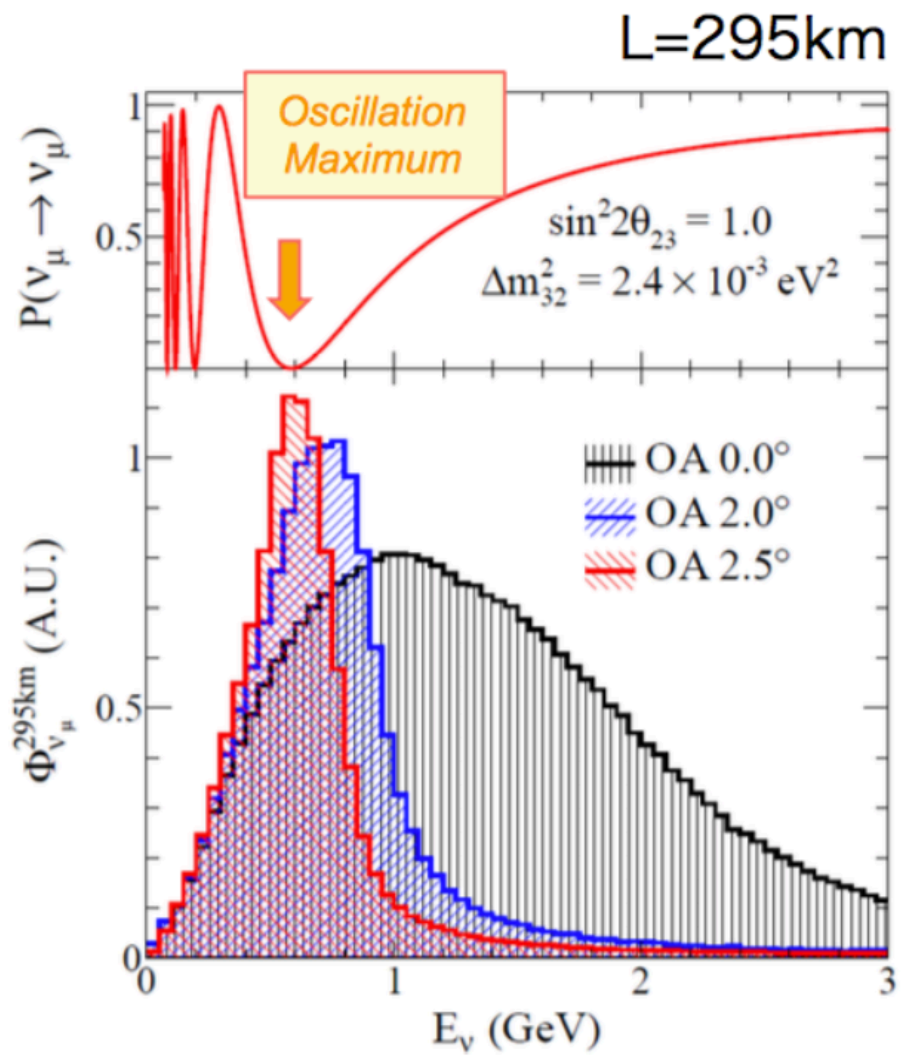
$$a = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$$

δ_{CP} and a switch signs when going from the **neutrino** to the **antineutrino** channel

Two current strategies: DUNE vs T2HyperK

T2HK

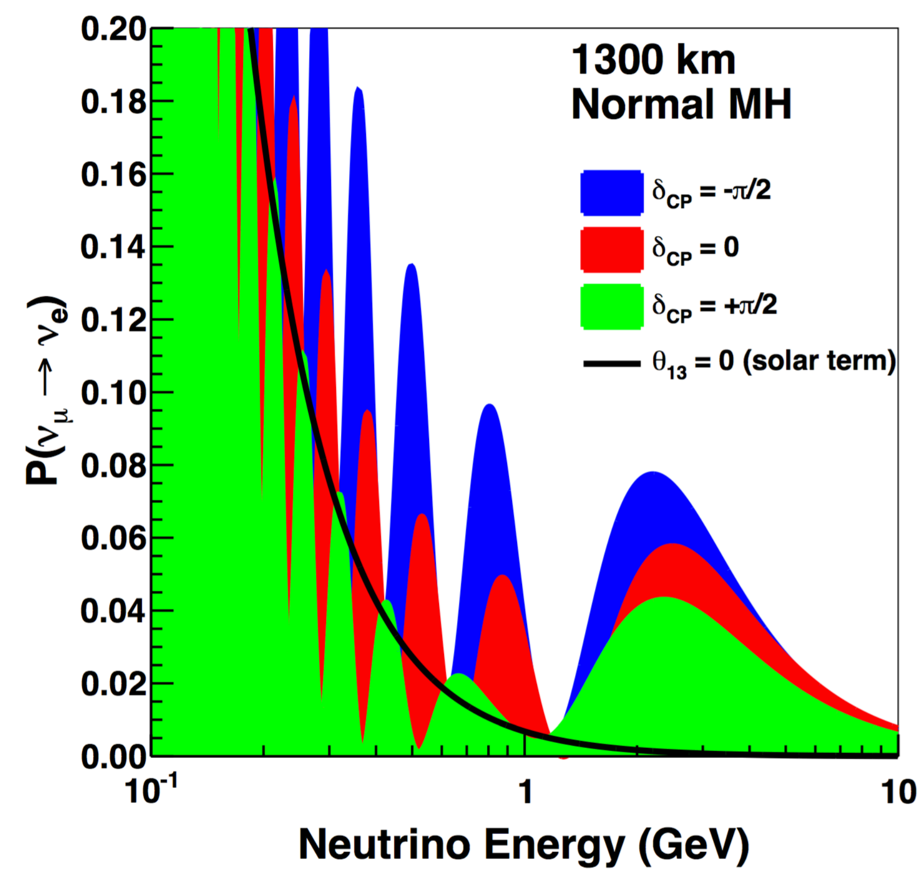
- Keep matter effects small using a short baseline.
- **High flux at first oscillation maximum**
- Off-axis technique: **narrow range of neutrino energies**



"Status of the Hyper-Kamiokande Experiment", Erin O'Sullivan NuFact 2017

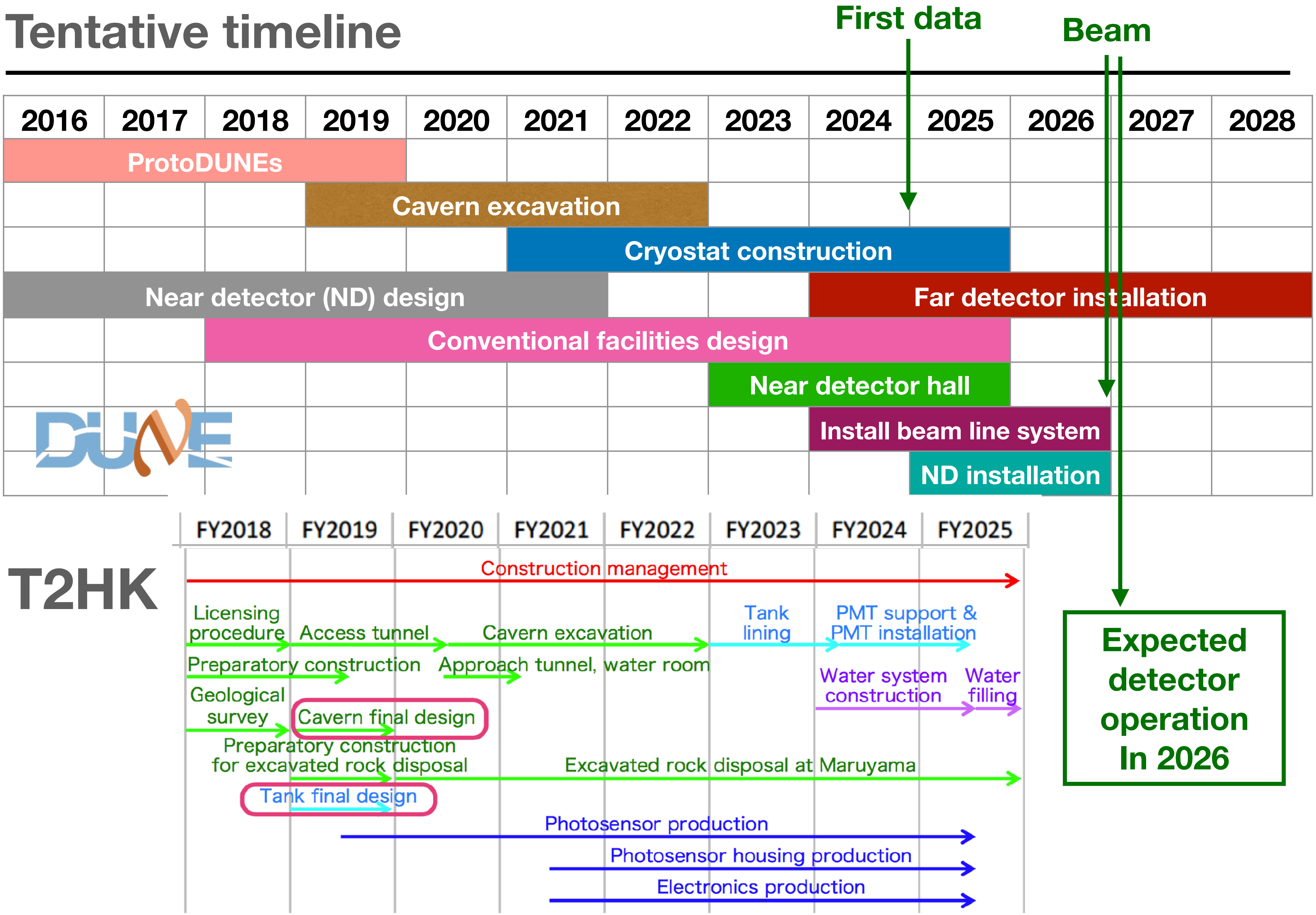
DUNE

- Enhanced matter effects.
- First and second maximum.
- **Unfold CPV from matter effects through neutrino energy dependency.**
- On-axis technique: **wide range of energies.**



LBNF and DUNE CDR, arXiv: 1512.06148

Tentative timeline

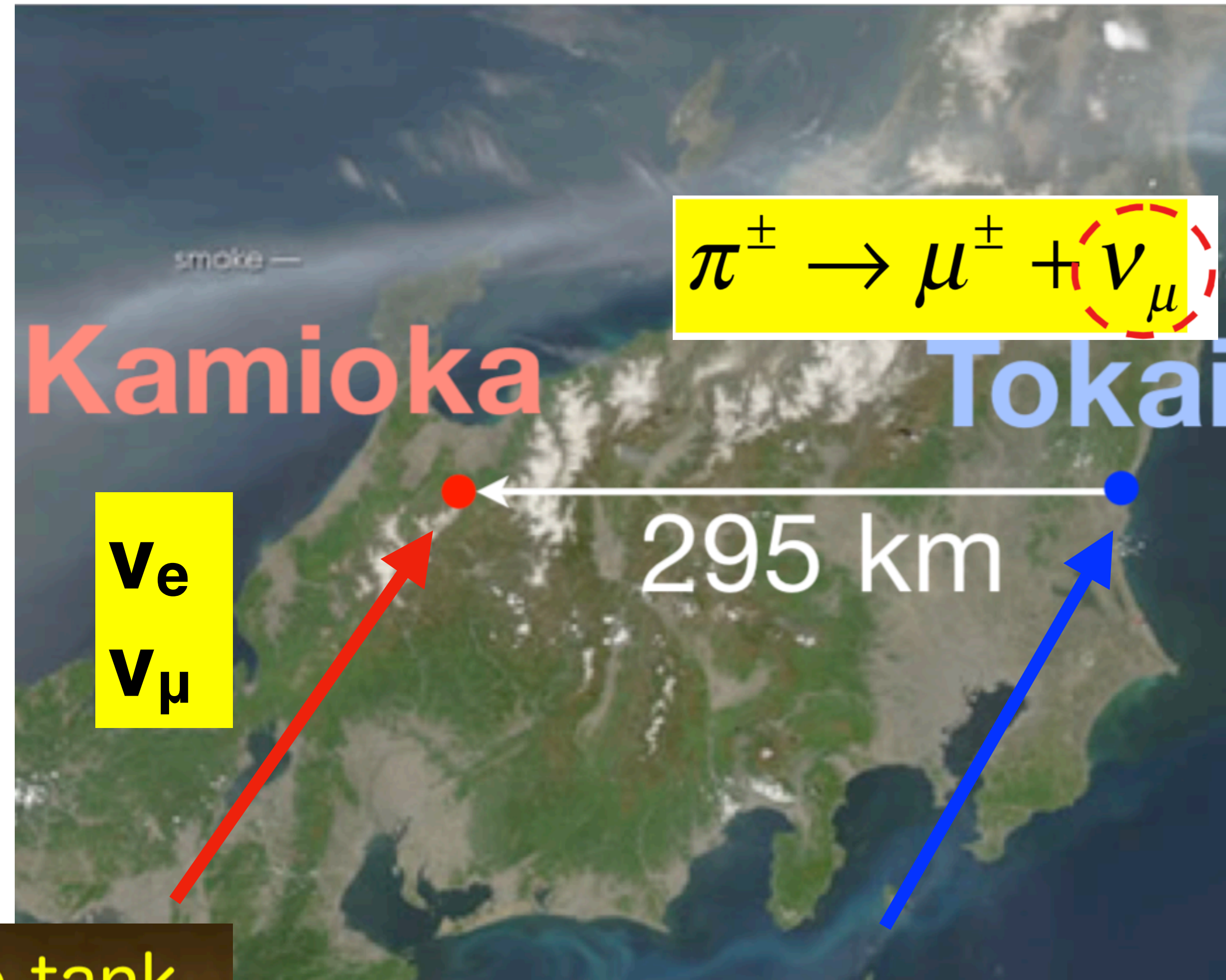


"Status of the Hyper-Kamiokande Experiment", Erin O'Sullivan NuFact 2017

T2HK experiment

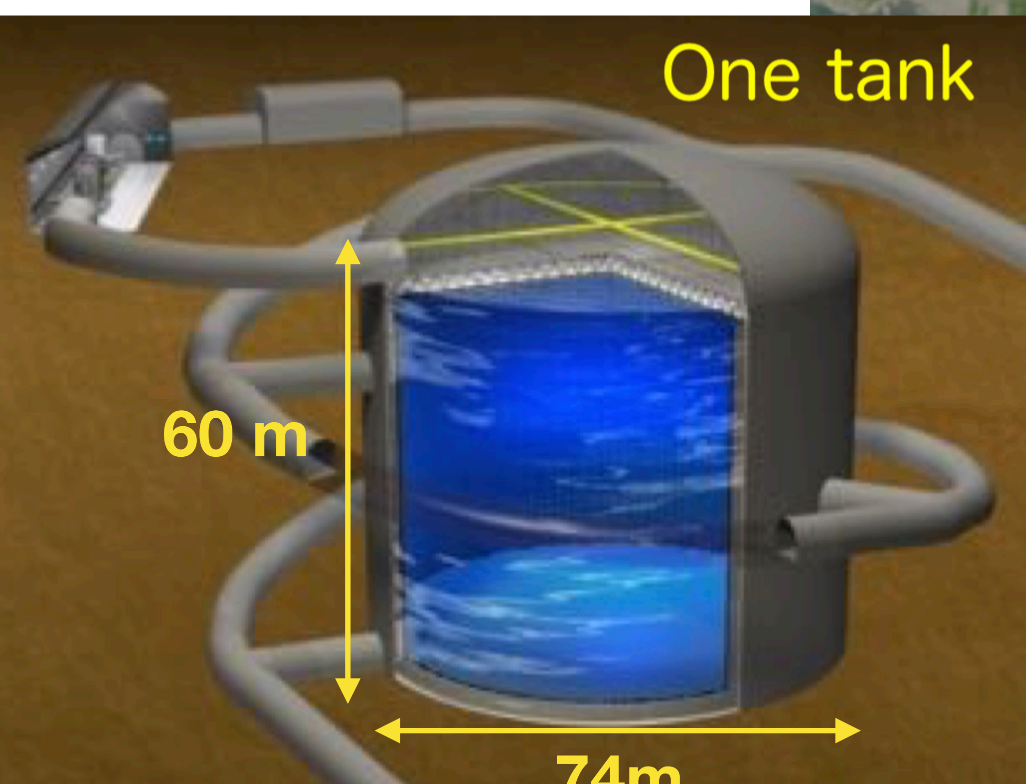
Far detector
HyperK

- 260 kton
- Fiducial volume: 190 kton (10xSuper-K)
- 40%PMT coverage
- PMTs with x2 Super-K Photon sensitivity

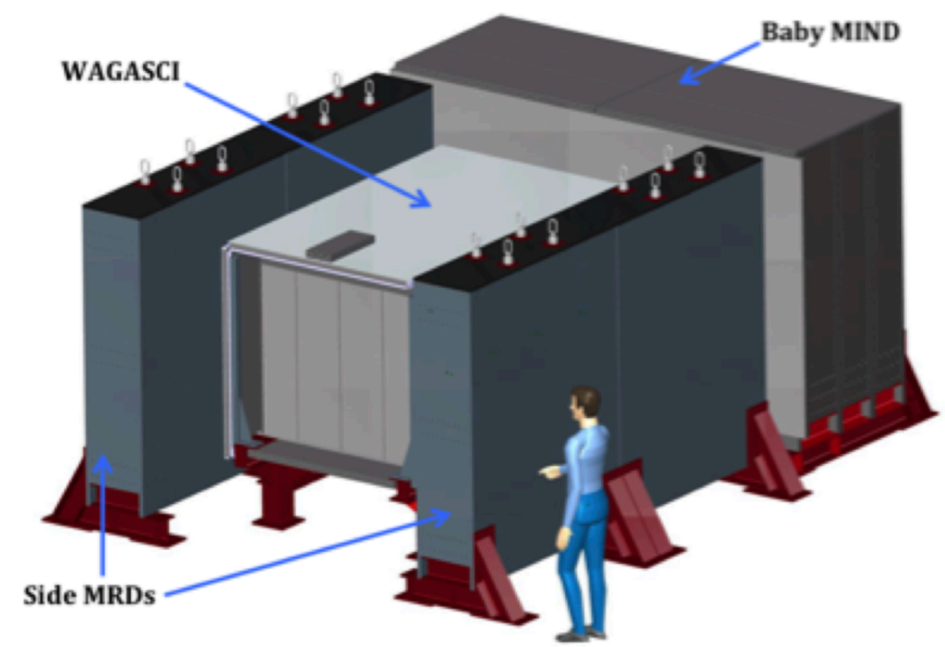


Neutrino beam
J-PARC facility
- 1MW (2020)
- 1.3 MW (2025)

Detectors underground to shield against cosmic rays



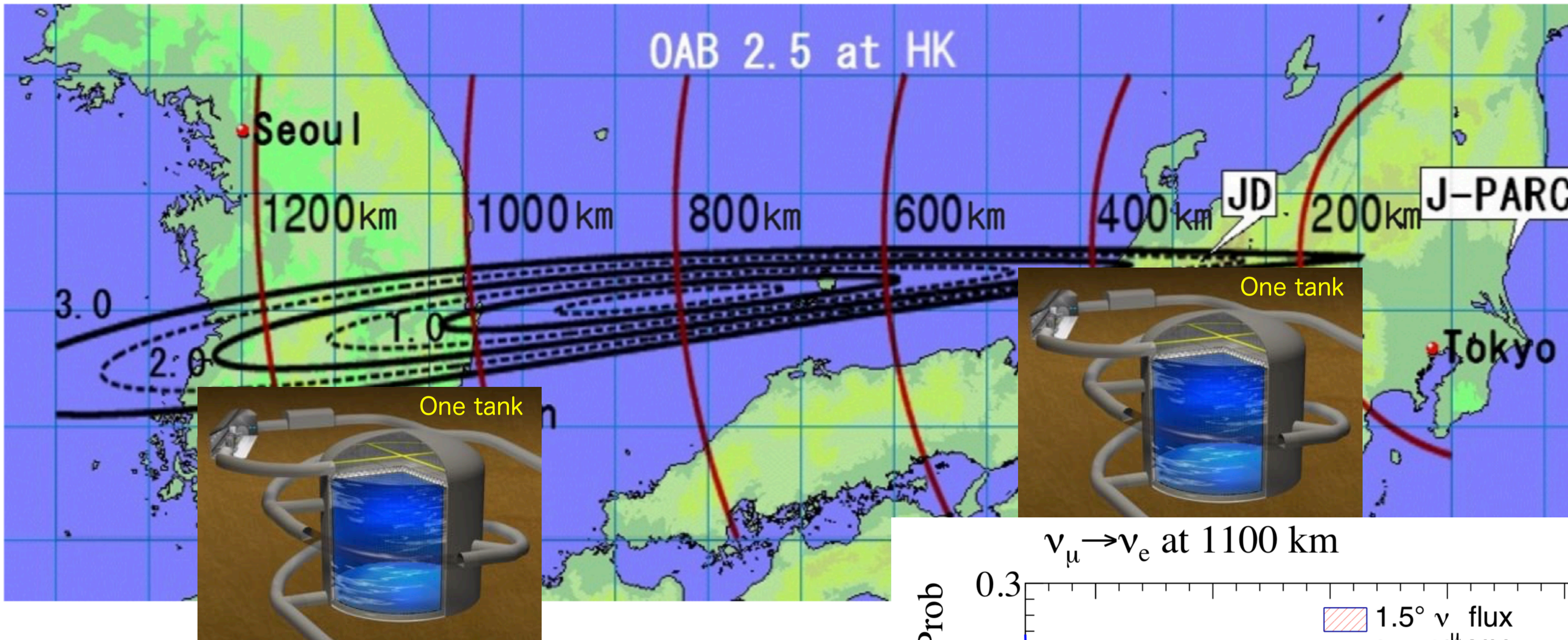
Near detector
similar concept than T2K experiment: on-axis+off-axis detectors

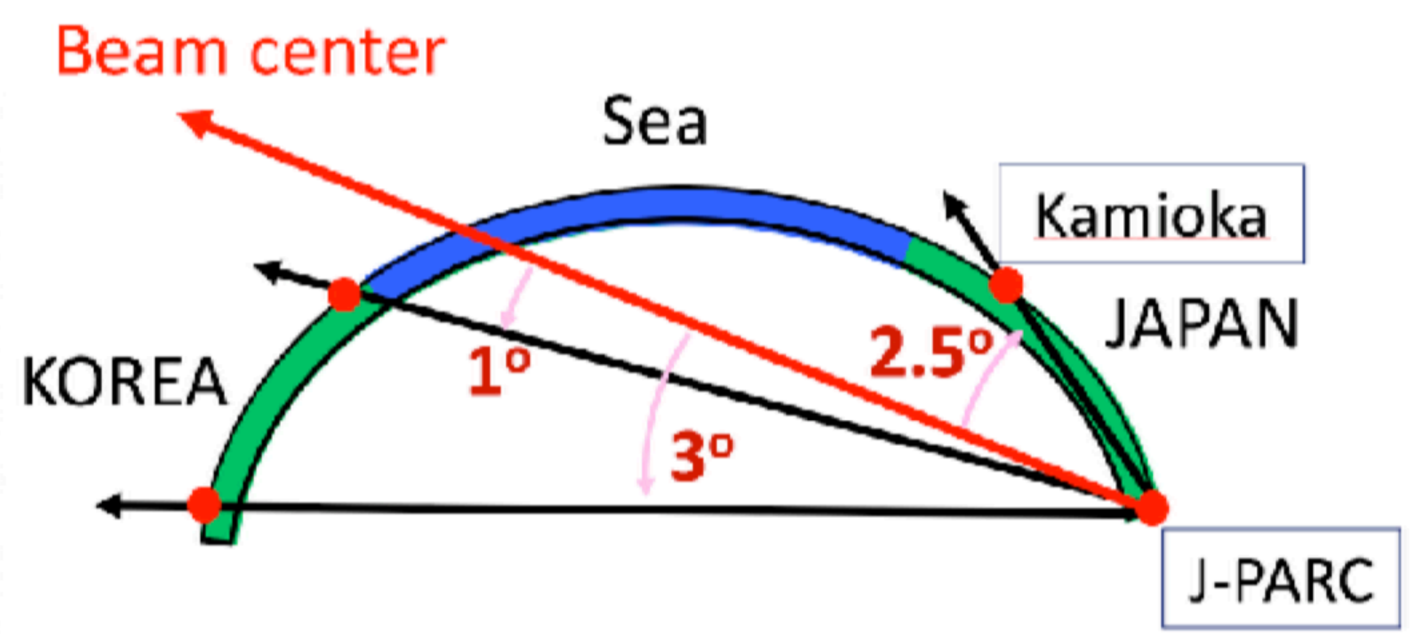


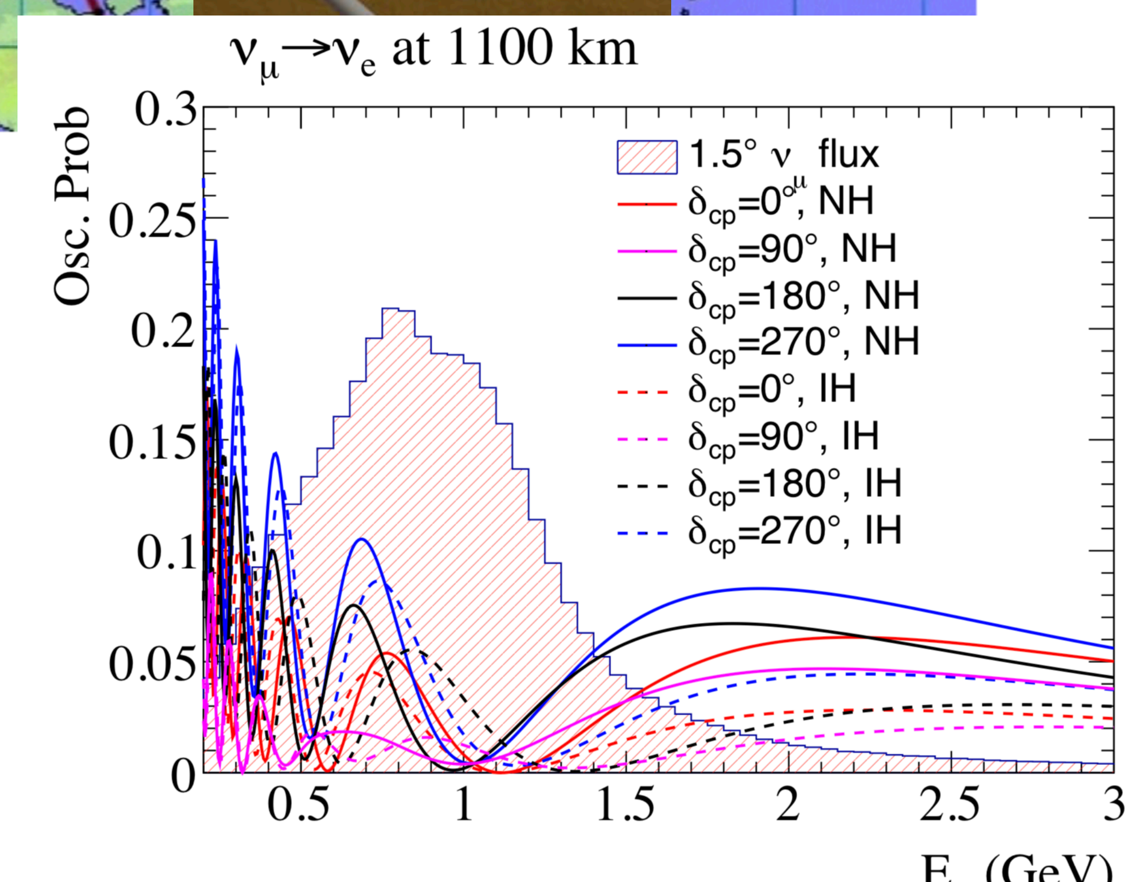
T2HKK: HyperK in Korea

Installing a second detector in Korea

"Summary of the 3rd International Workshop on a Far Detector in Korea for the J-PARC Beam" T. Kajita, S.B. Kim and A. Rubbia



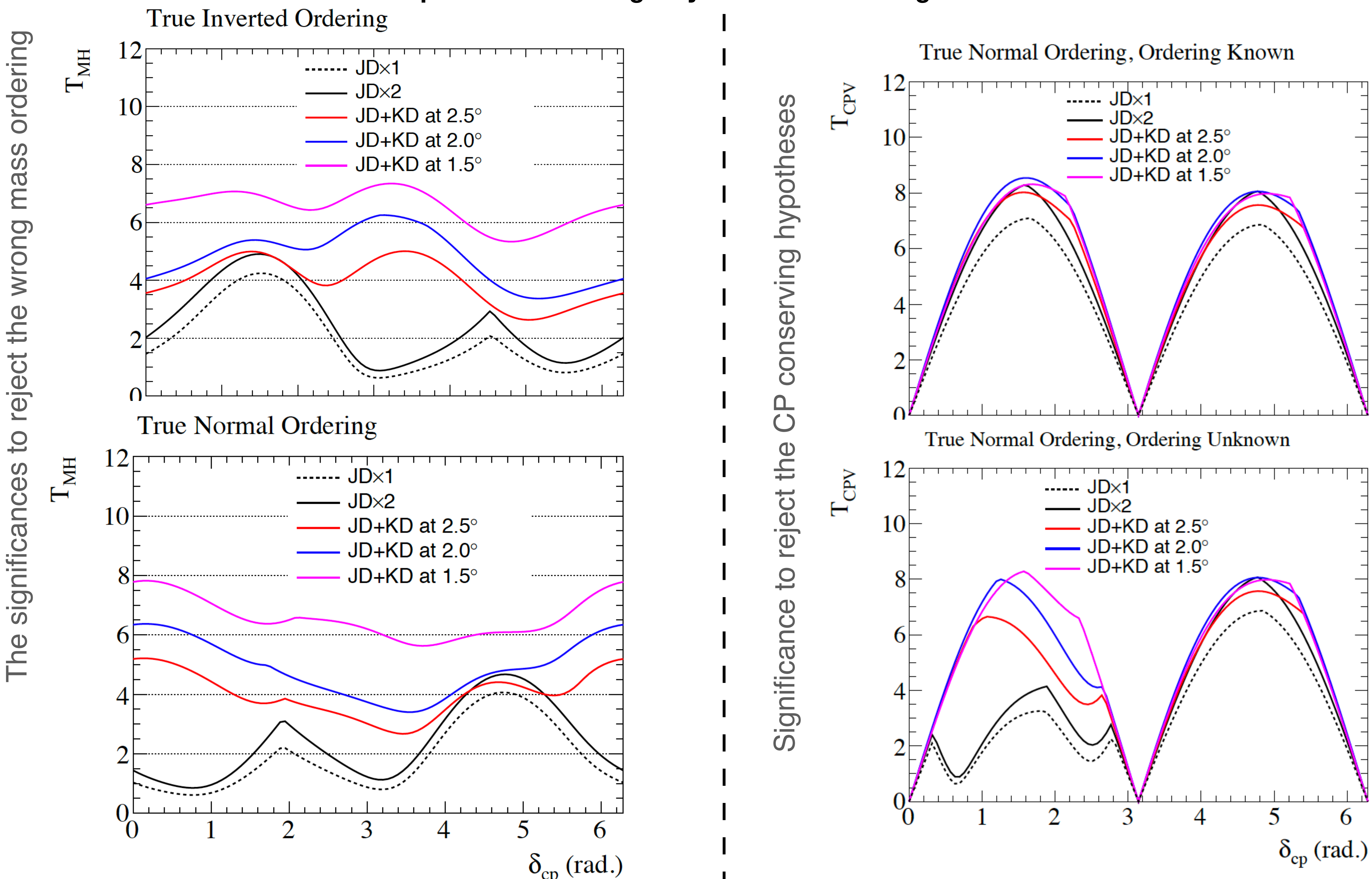




MH and CP sensitivities

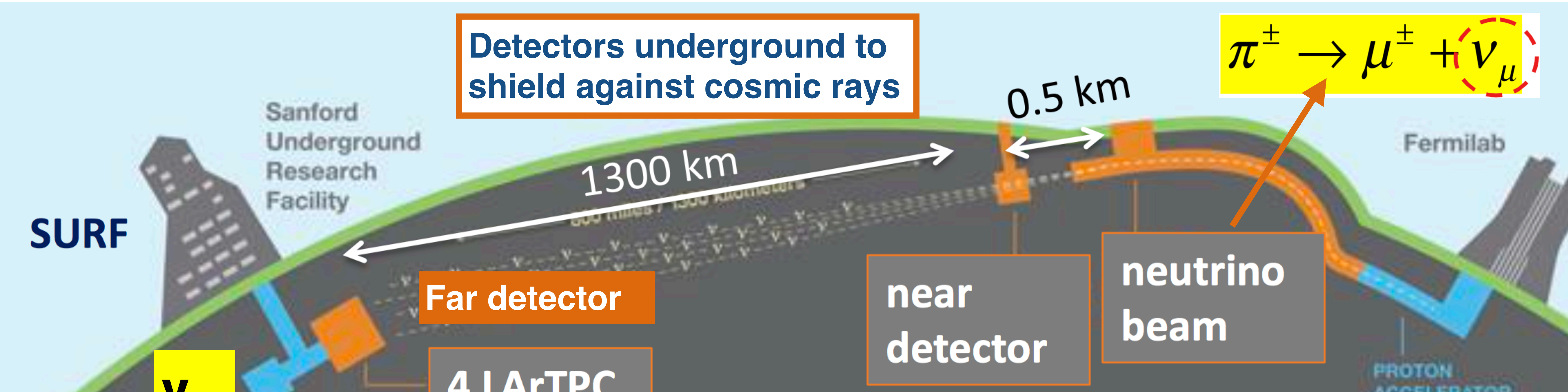
"Physics Potentials with the Second Hyper-Kamiokande Detector in Korea" arXiv:1611.06118

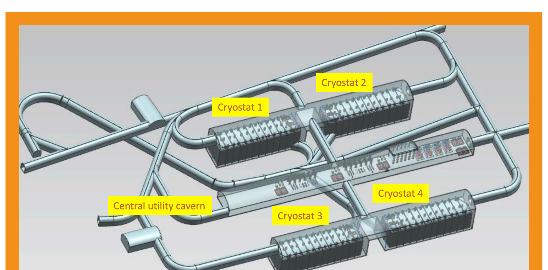
Exposures assuming 10 years of data taking with a beam of 1.3 MW

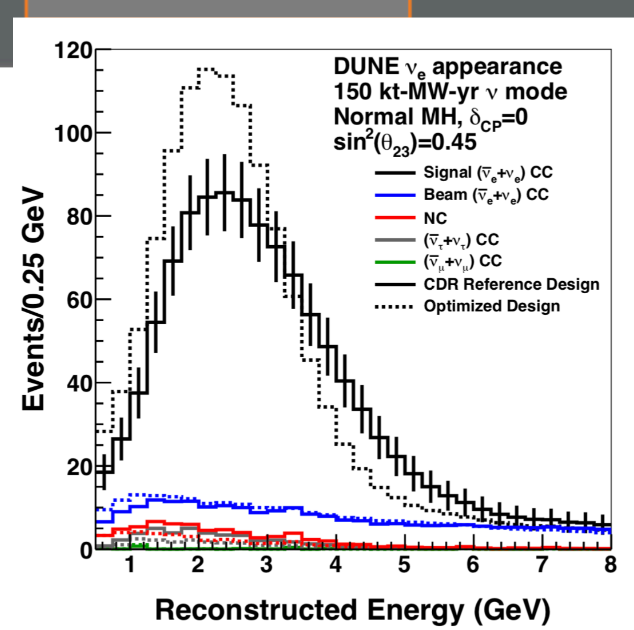


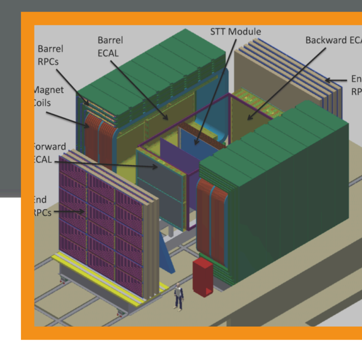
DUNE experiment

- **DUNE is the merger of LBNE and LBNO.**
- **The foreseen proton beam power is 1.2 MW [upgradable to 2.4 MW].**







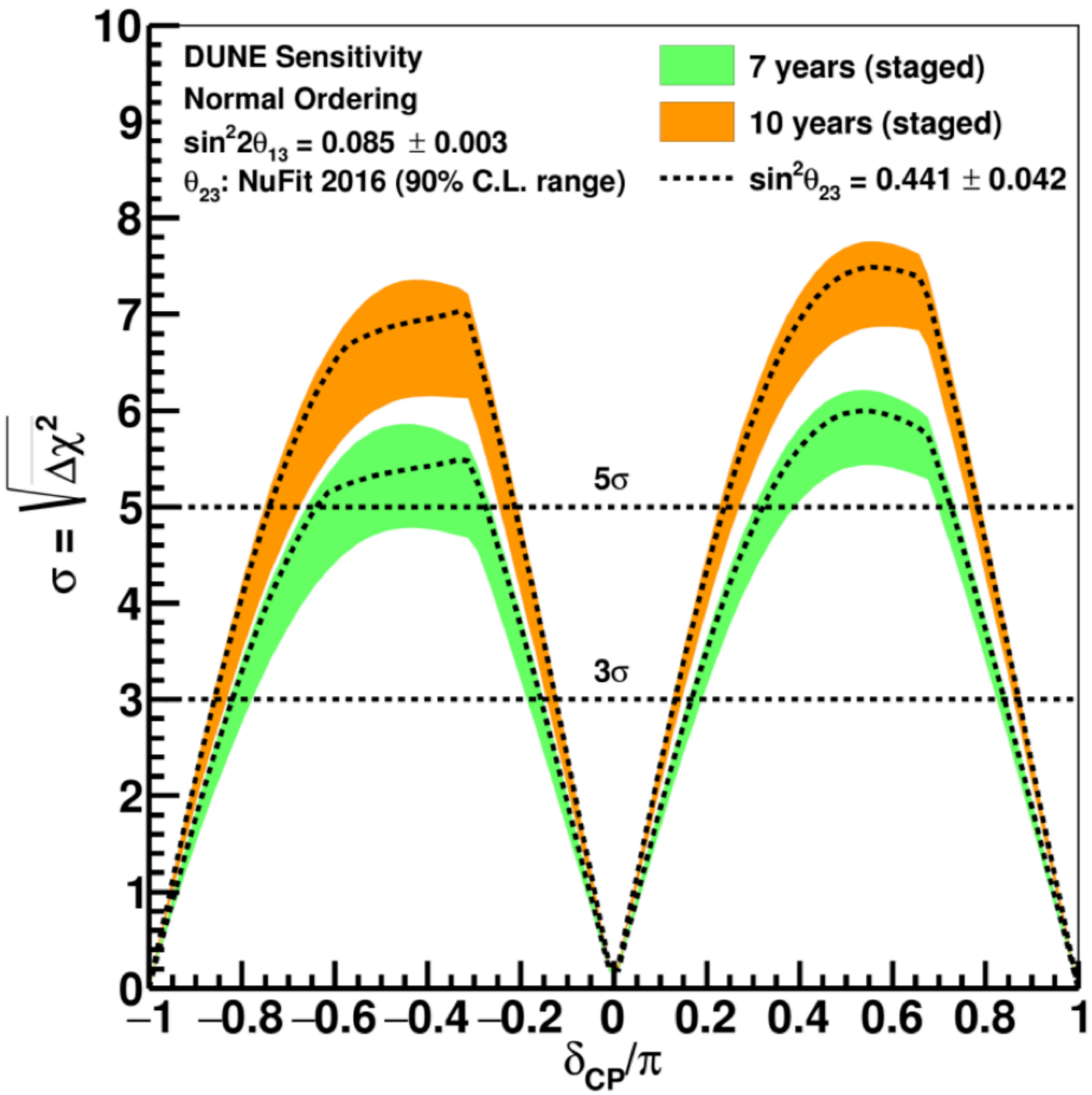


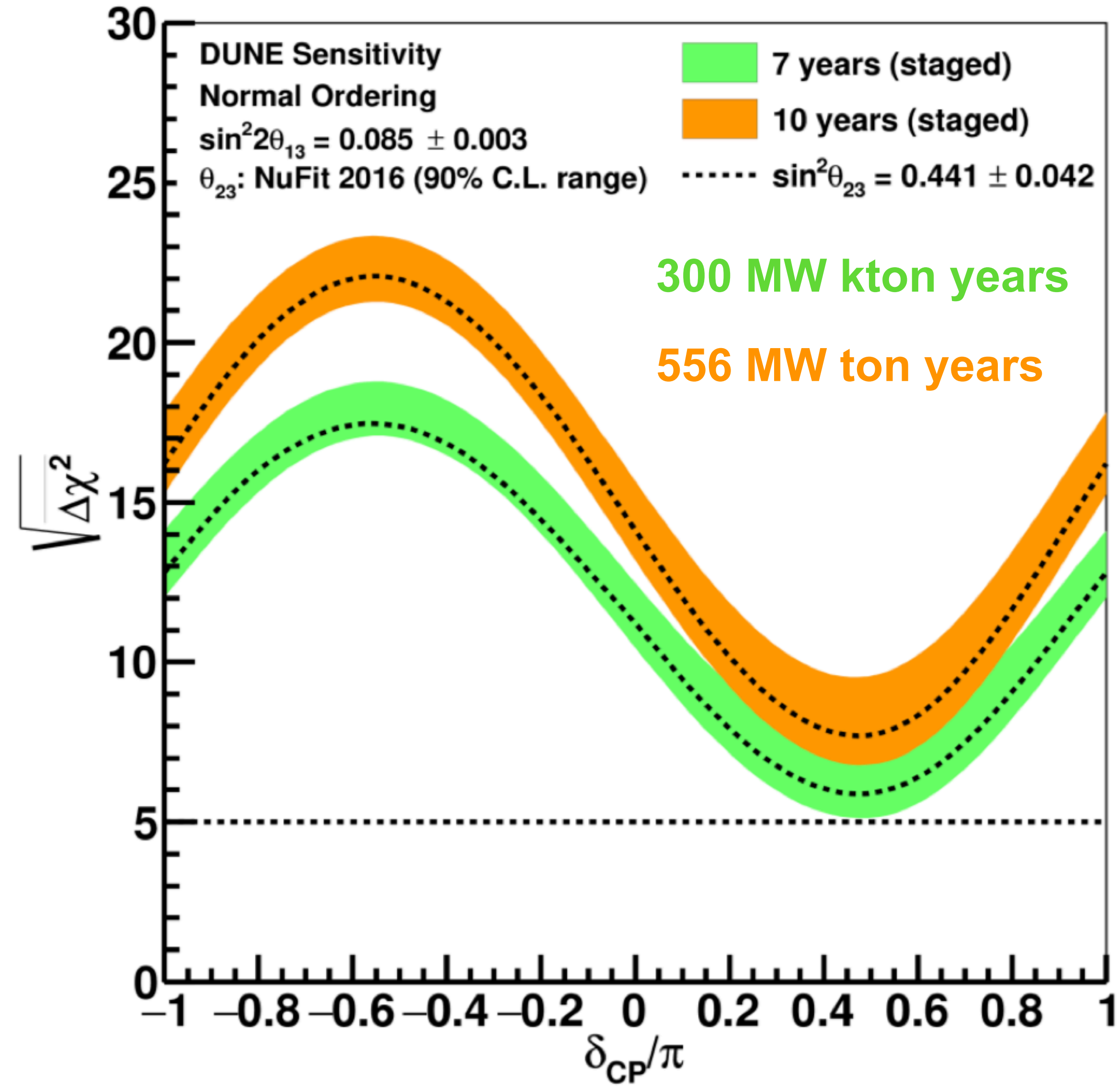
- **40 kton fiducial volume detector**

- **Constrain the systematics in the neutrino oscillation measurements**
- **Measurements of different neutrino interaction cross-section**

MH and CPV sensitivities

CPV *LBNF and DUNE CDR, arXiv: 1512.06148* MH



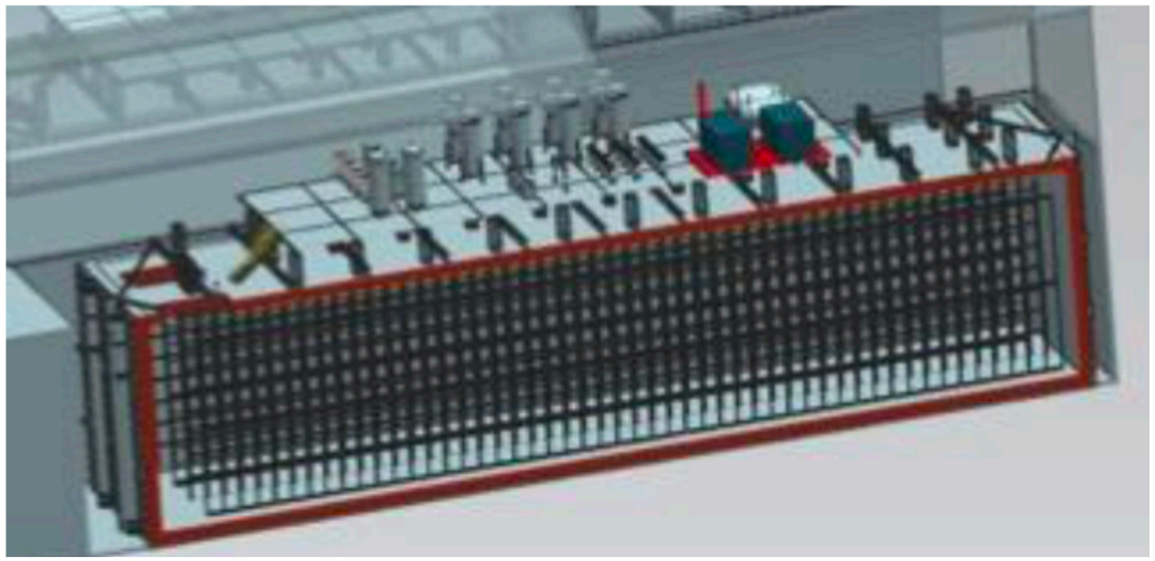


- The dashed line is the sensitivity for the NuFit central value of θ_{23}.
- Width of band corresponds to 90% CL variations in value of θ_{23} based on NuFit 2016 fit values.

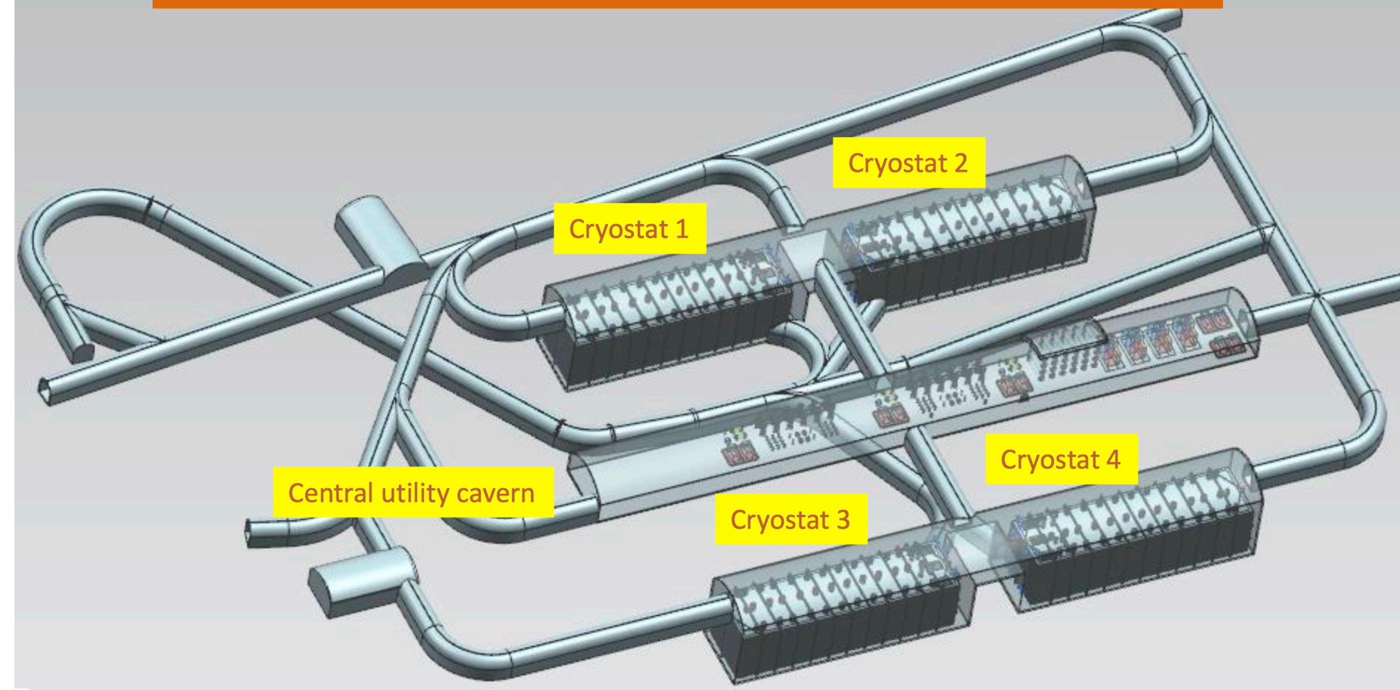
In year 7 (2032) beam upgraded foreseen to 2.4 MW

Towards the DUNE Far detector

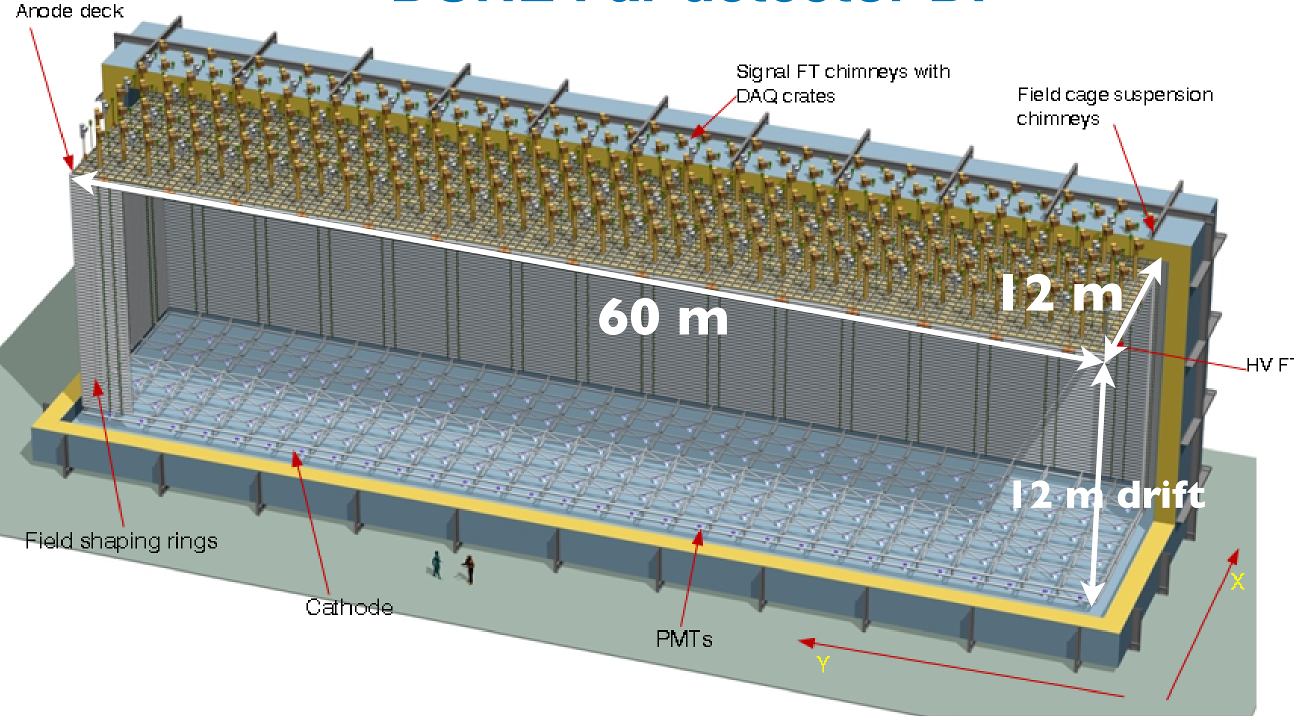
DUNE Far detector SP



DUNE Far detector: 4modules of 10kton detectors



DUNE Far detector DP



ProtoDUNEs project

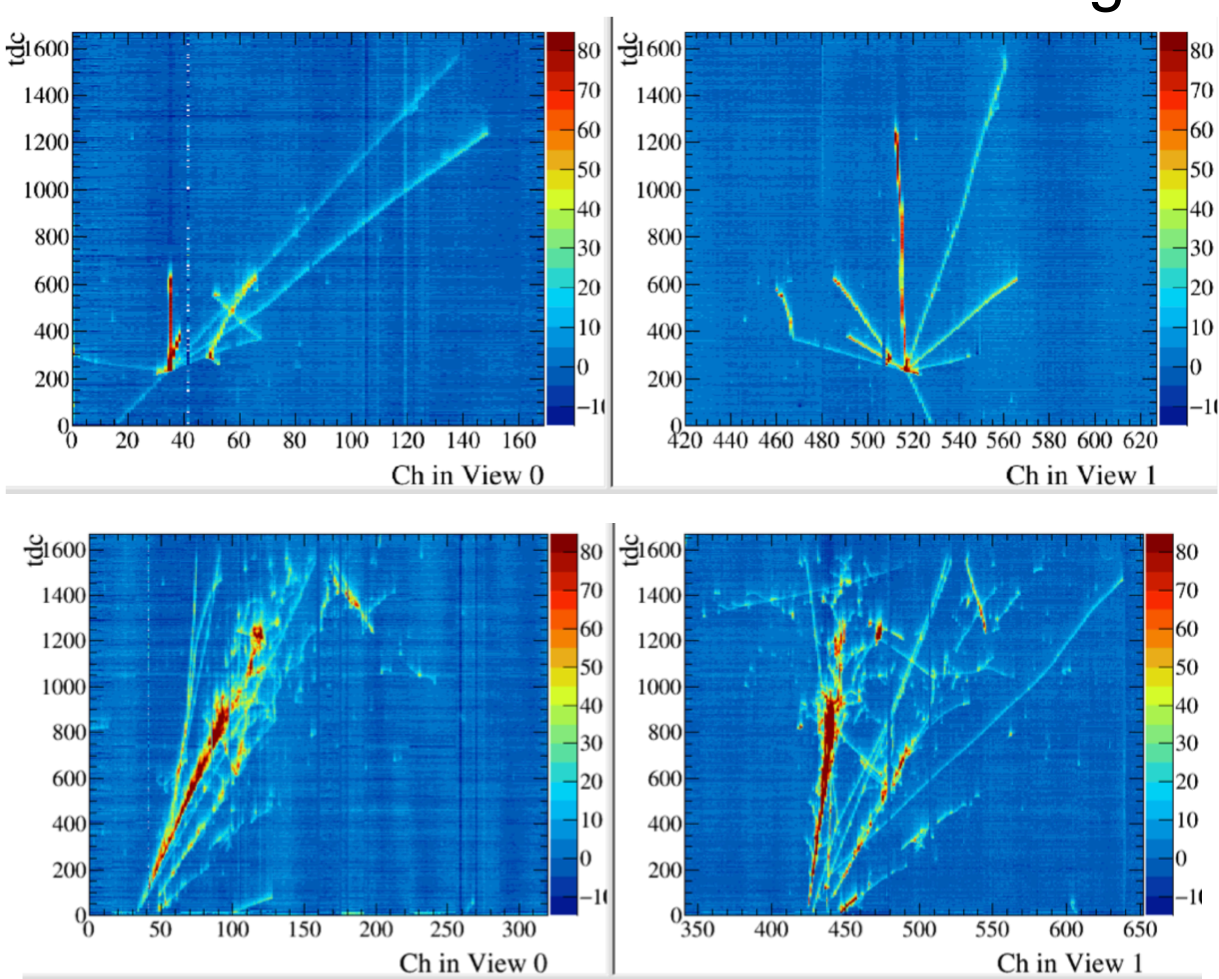
- **Engineering the technology through the 10 kton detector.**
- **Test two different technologies: *single phase* and *dual phase***
- **Develop the construction and QA processes**

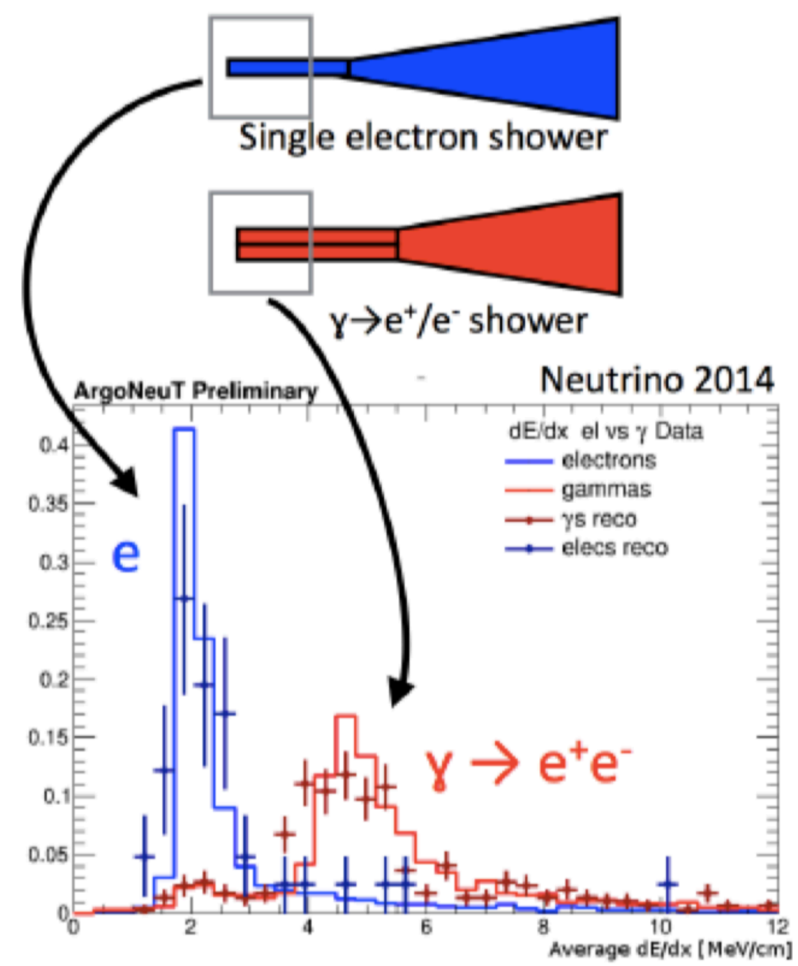
LAr TPC concept

Why LAr TPCs?

- **Excellent dielectric which allow high voltages inside the detector.**
- **It is cheap and easy to obtain, so it is scalable to large detectors.**
- **High energy resolution.**
- **Excellent calorimeters which allow for precise 3D reconstruction of the track of ionising particles traversing the liquid.**

Raw data no noise filtering



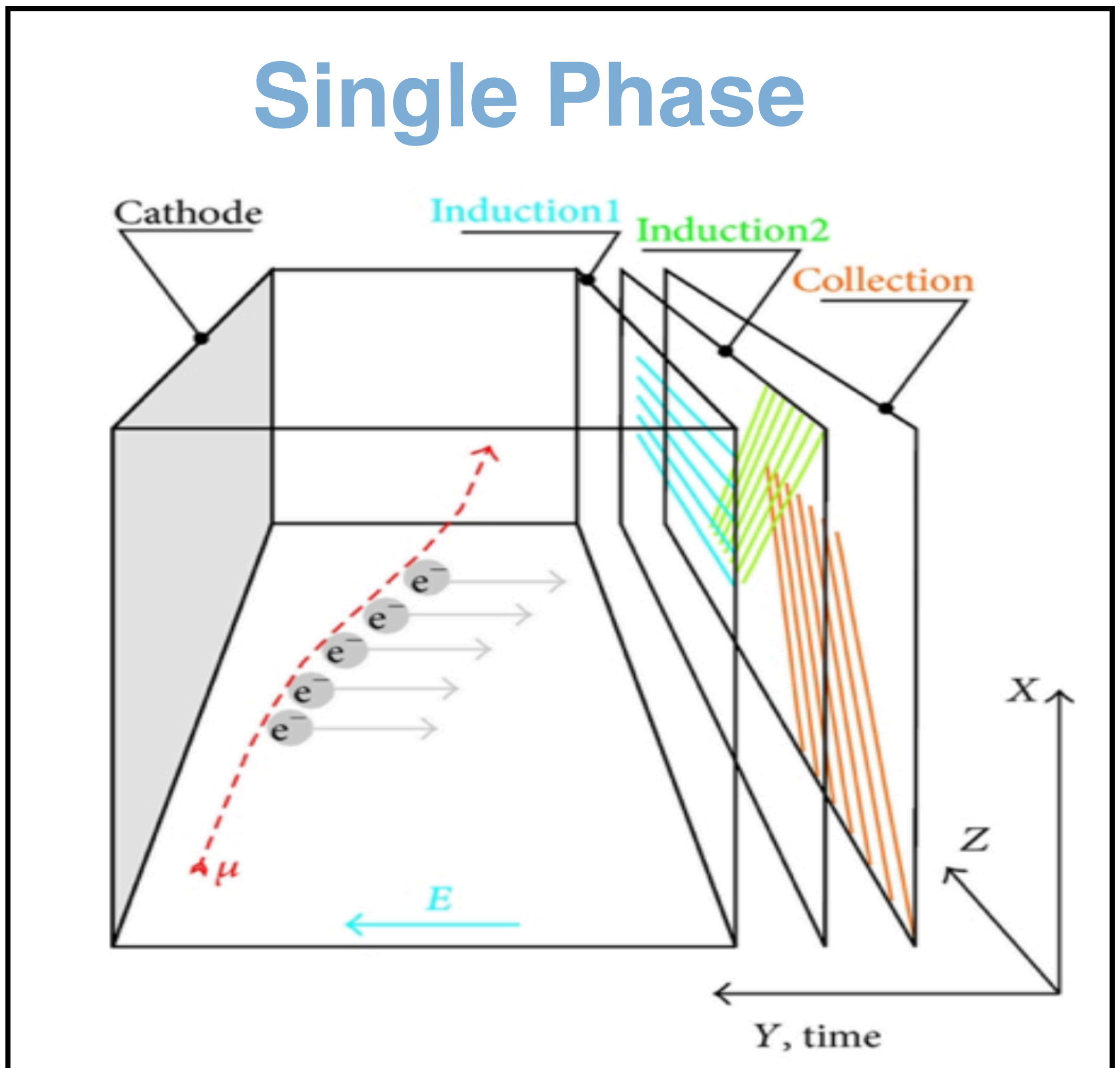


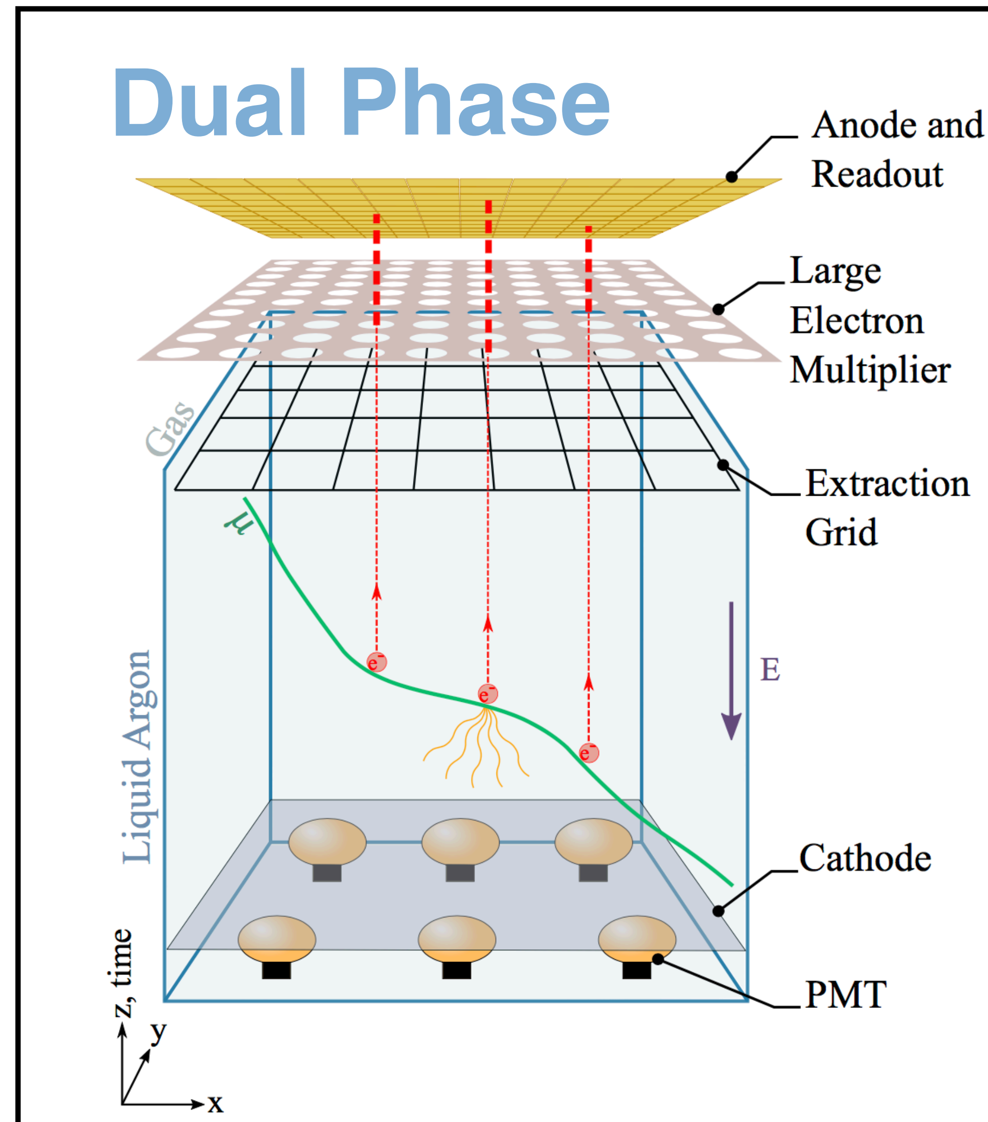
Data from the 3x1x1 prototype (WA105)

Two complementary technologies: **Single phase** Vs **Dual phase**

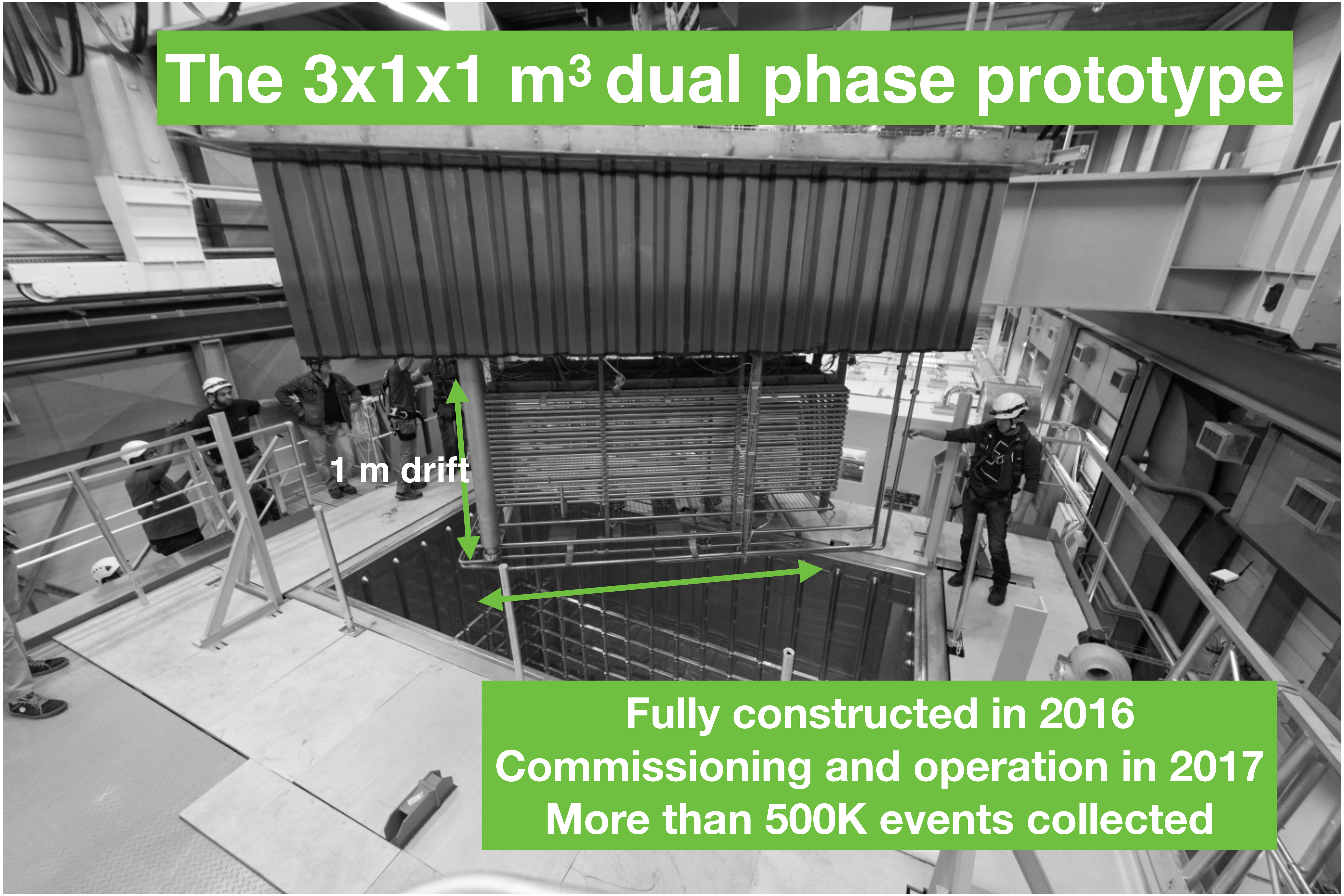
- **Only liquid argon**
- **Ionisation charges are drifted horizontally and readout by wires.**
- **No amplification of the signal**

- **Liquid and Gas Argon**
- **charges are drifted vertically**
- **Signal amplification in Large electron multipliers (LEMs)**
- **Readout by 2 views PCB anode**



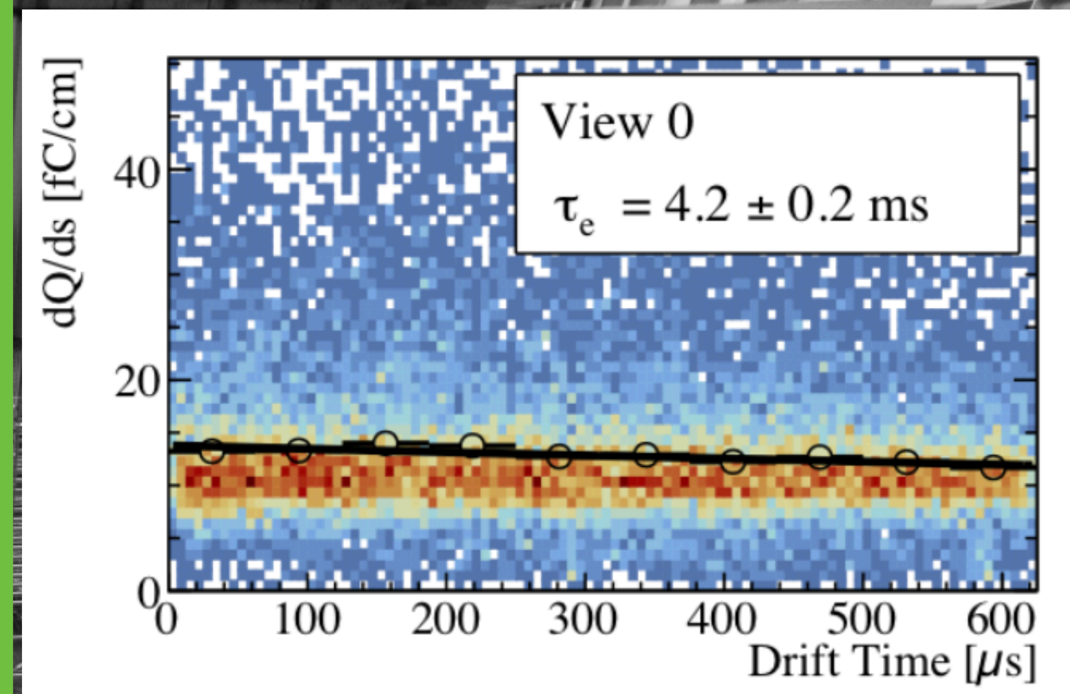


Towards large scale dual phase detectors

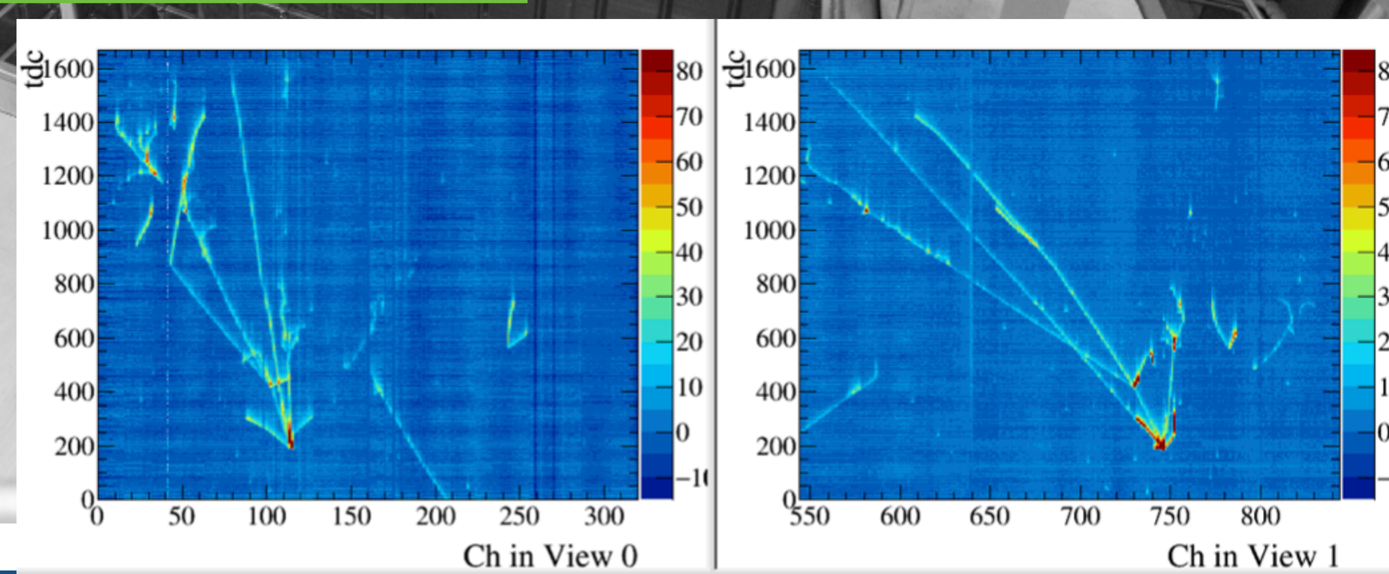


The 3x1x1 m³ dual phase prototype

- **First GTT constructed cryostat for LAr.**
- **Fully engineered versions of many detector components** with pre-production and direct implementation.
- **First overview of the complete system integration**: set up full chains for QA, construction, installation and commissioning.
- **First results of extraction and amplification in 3 square meter area and LEM 50x50 cm² amplification.**
- **Stable drift field of 500V/cm over 1m.**
- **Purity compatible with 1ms electron lifetime.**

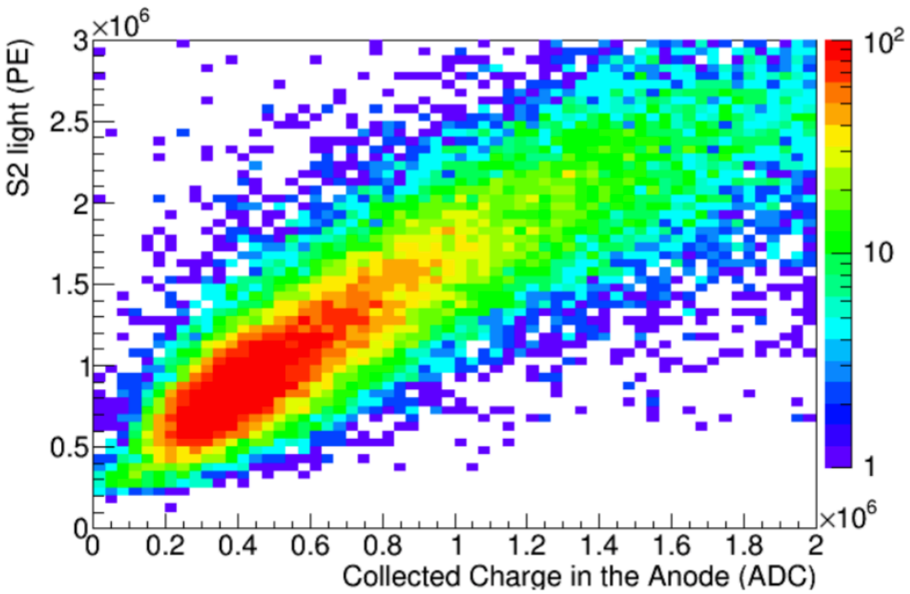


Crossing muons + showering events
Many topological interesting events to test neutrino reconstruction algorithms.

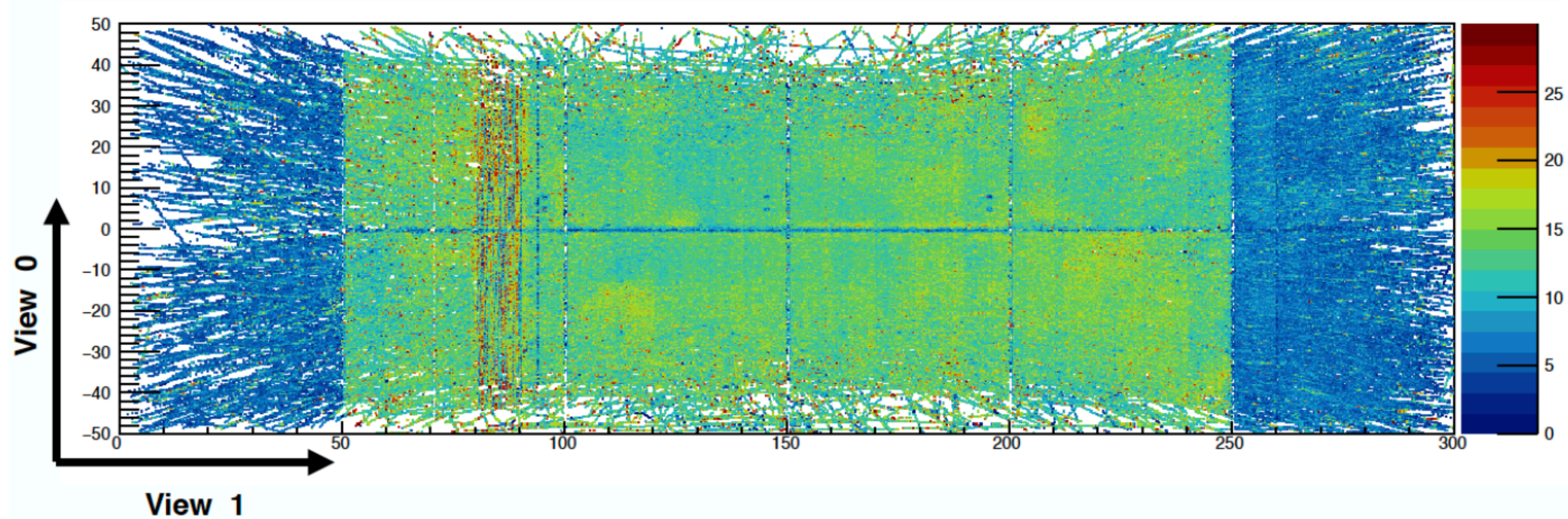


Towards large scale dual phase detectors

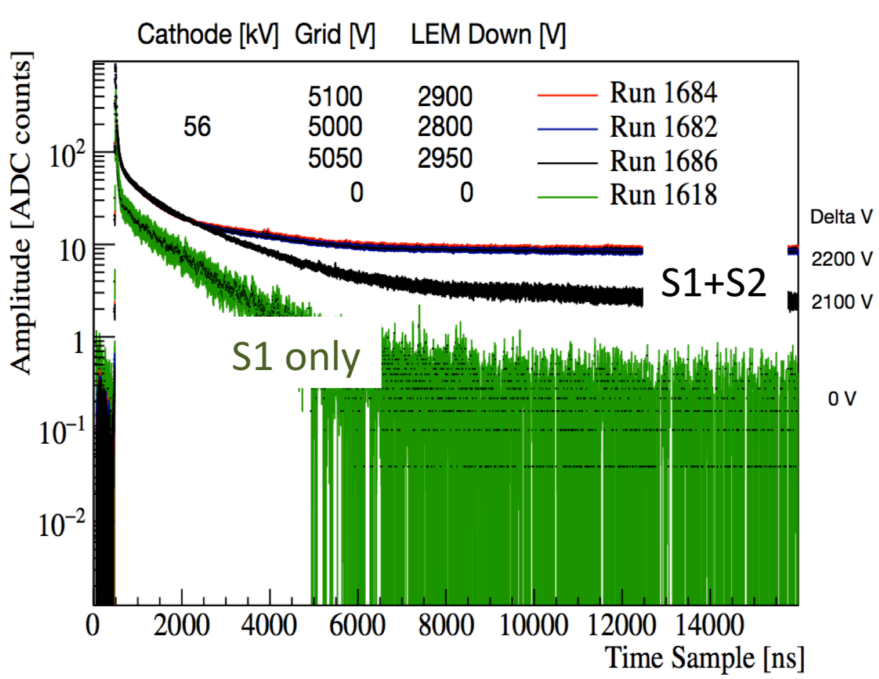
Charge and light correlation



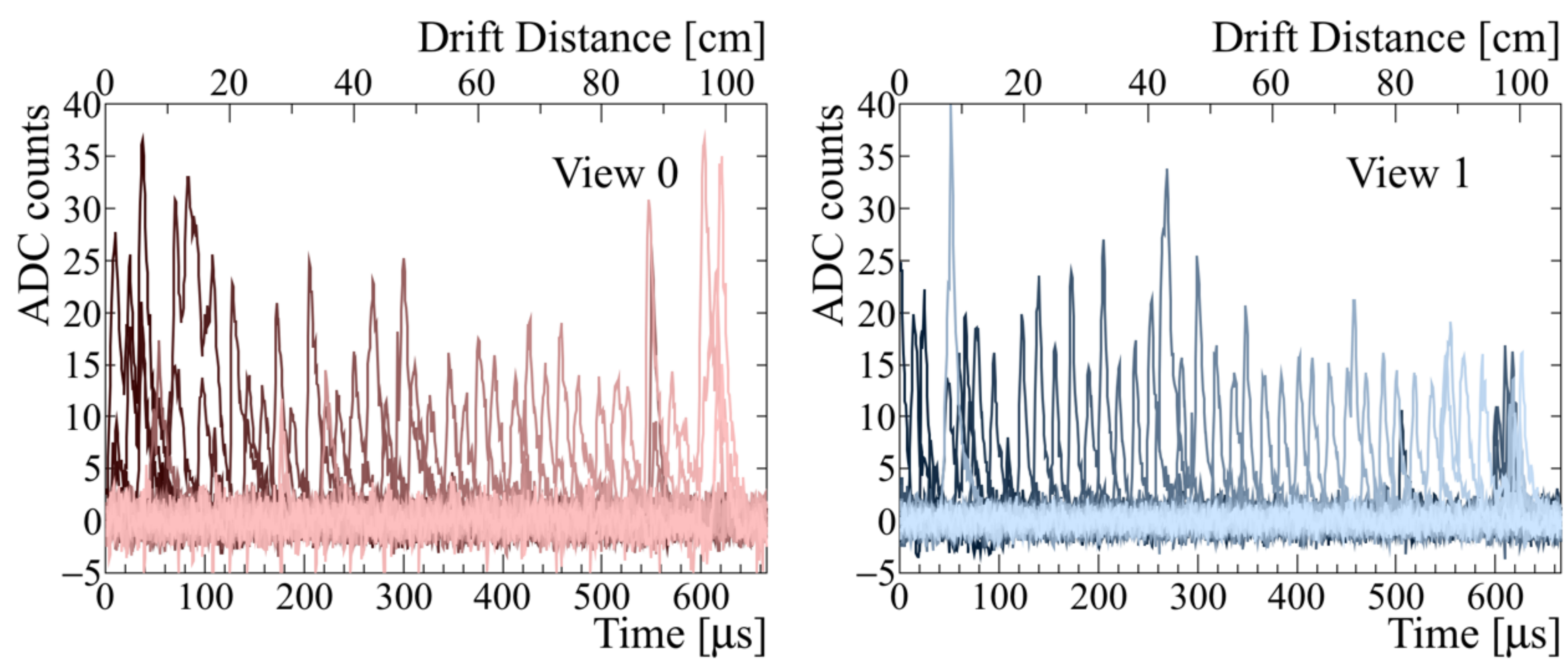
<dQ/ds> uniformity across the CRP



Primary and secondary scintillation light



Successful 50% charge sharing between both views



Towards large scale dual phase detectors

First paper ready under internal reviewing

A 4 tonne demonstrator for large-scale dual-phase liquid argon time projection chambers

Abstract

A 10 kilo-tonne dual-phase liquid argon TPC is one of the detector options considered for the Deep Underground Neutrino Experiment (DUNE). The detector technology relies on amplification of the ionisation charge in ultra-pure argon vapour and offers several advantages compared to the traditional single-phase liquid argon TPCs. A large 4.2 tonne dual-phase TPC prototype with an active volume of 3×1×1 m^3 has been constructed and operated at CERN. In this paper we describe in detail the experimental setup and detector components as well as report on the operation experience. We also present the first results on the achieved charge amplification and purity of the liquid argon from analyses of a collected sample of cosmic ray muons.

Keywords: Neutrinos, liquid argon TPC, tracking.

Next steps: **protoDUNEs**

Impressive progress in a short time.
The goal is to have the protoDUNE DP inform the DUNE technical design report by October 2019.

ProtoDUNE DP

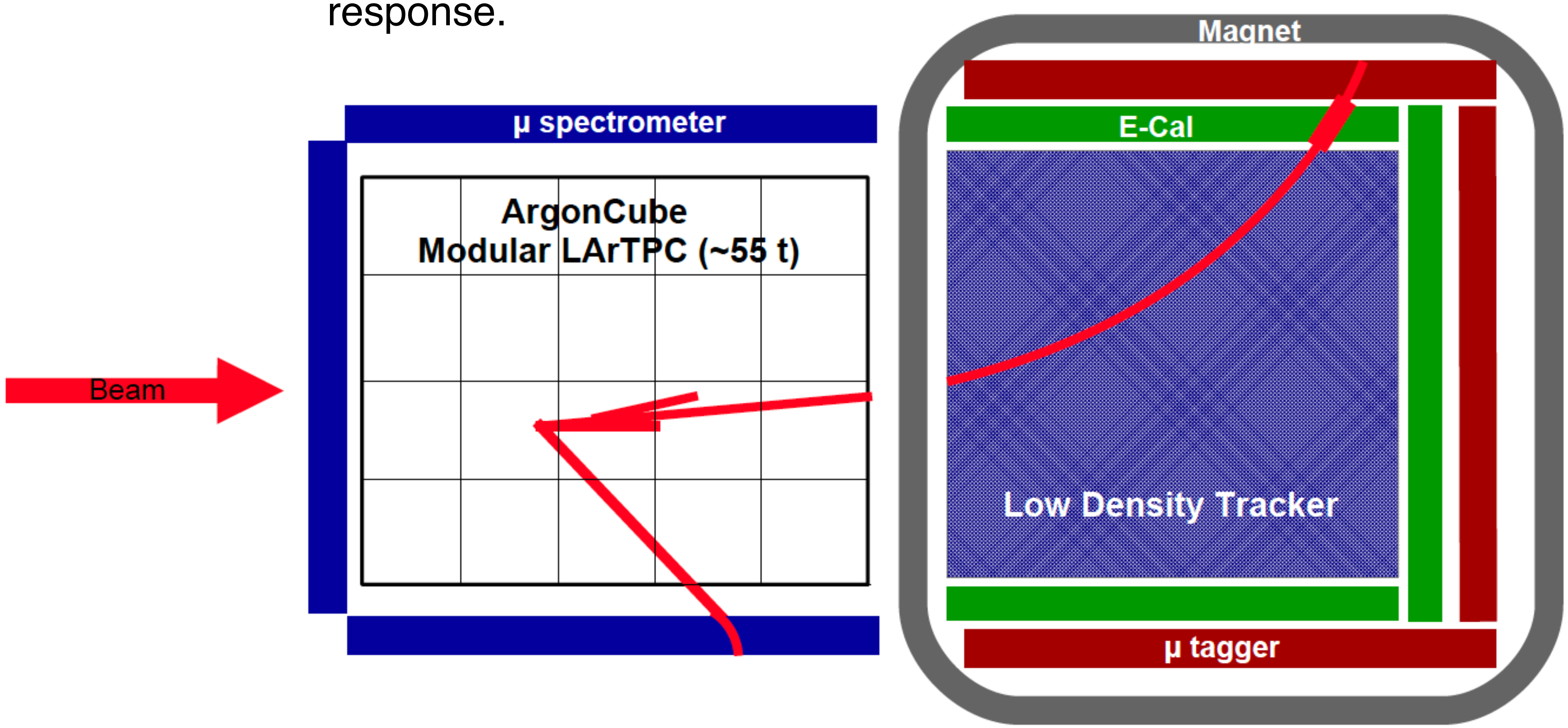
It will represent the final test of the components for the FD

DUNE ND concept

The current DUNE concept design is: **‘hybrid’ LArTPC + low density tracker.**

Modular LAr-TPC:
- high statistics ν-Ar interactions
- assessment of LArTPC response.

Low Density Tracker:
- precision characterization of ν-nucleus interactions complementary signal vs. BG discrimination



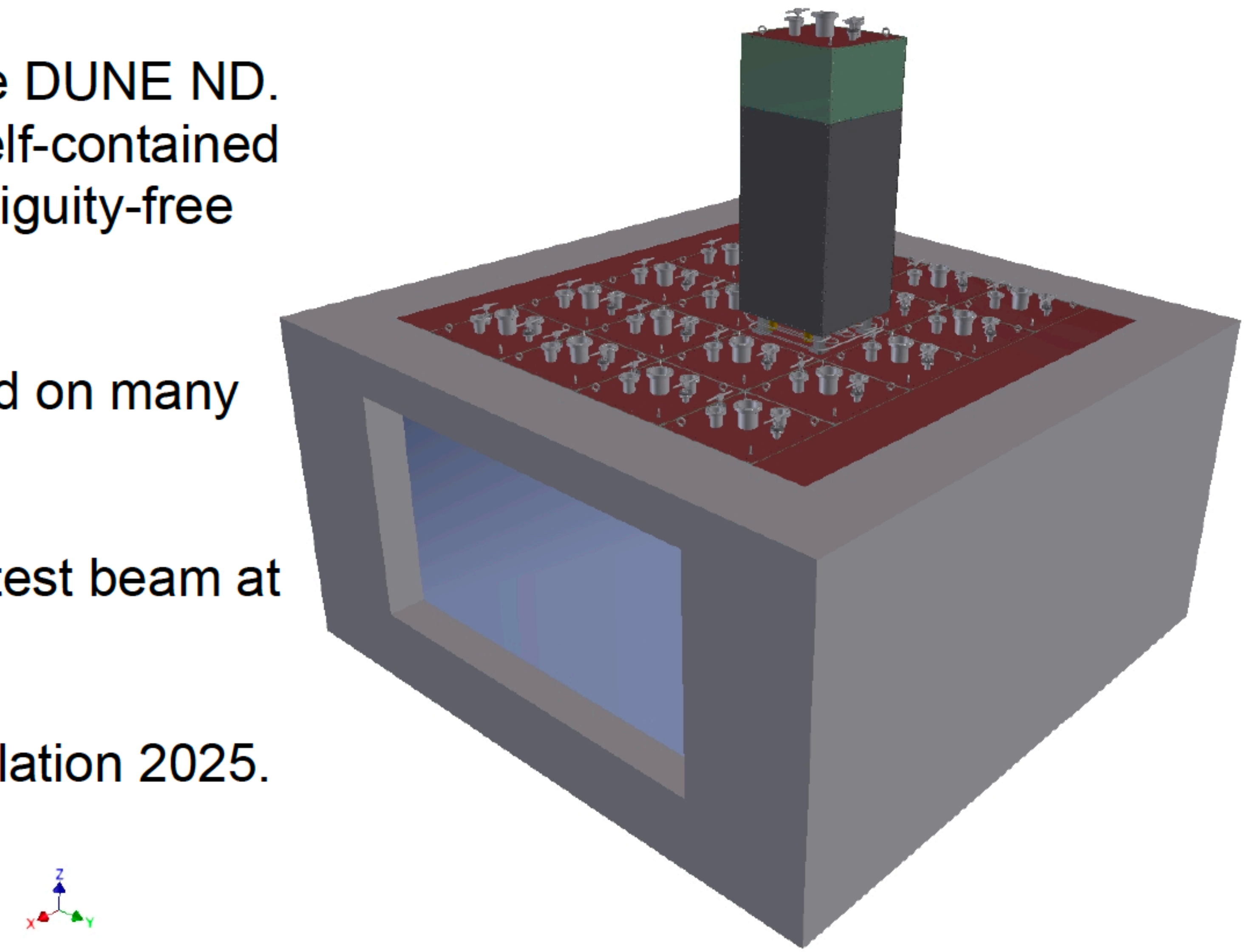
ArgonCube

ArgonCube is the LAr component of the DUNE ND. Novel modular LArTPC; a number of self-contained TPCs sharing a common cryostat. Ambiguity-free pixelated charge readout.

ArgonCube is a Swiss lead effort, based on many years of Swiss R&D.

Prototyping underway in Bern. Further test beam at Fermilab in 2019.

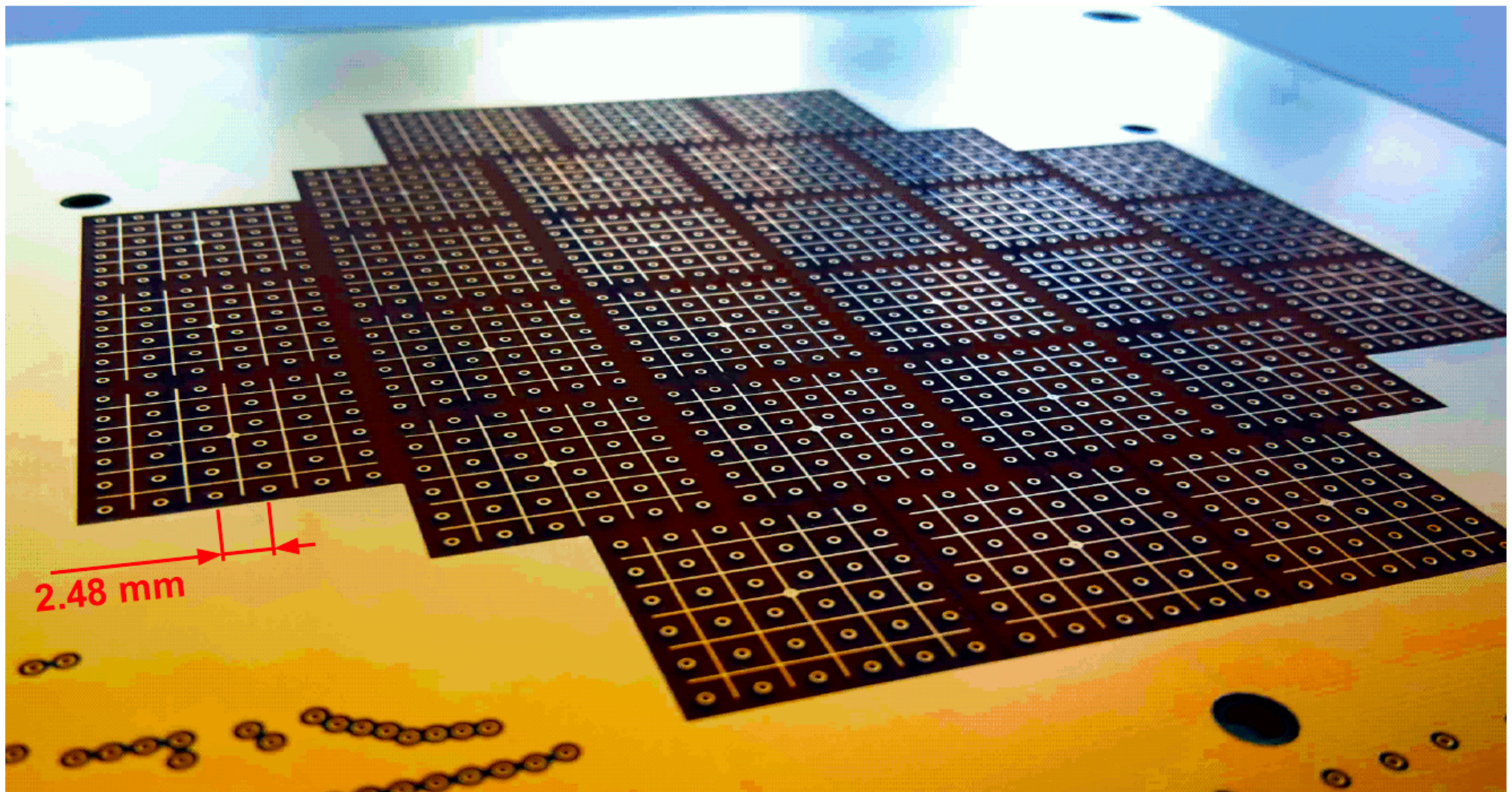
DUNE ND CDR 2019, TDR 2020, Instalation 2025.



Argon Cube DUNE Near Detector, 3 x 4 x 5 m^3 active volume

R&D efforts on DUNE Near Detector

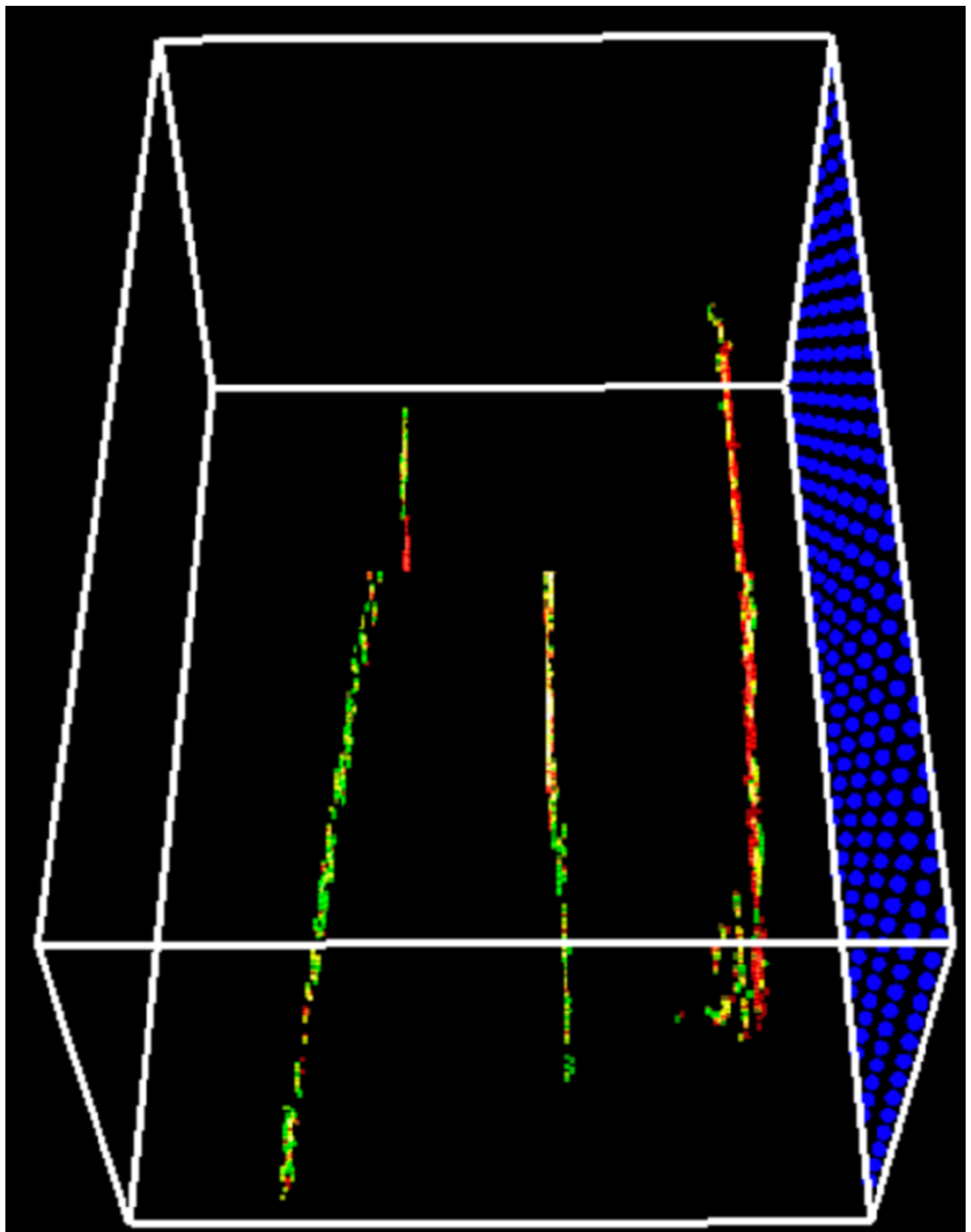
2016/17



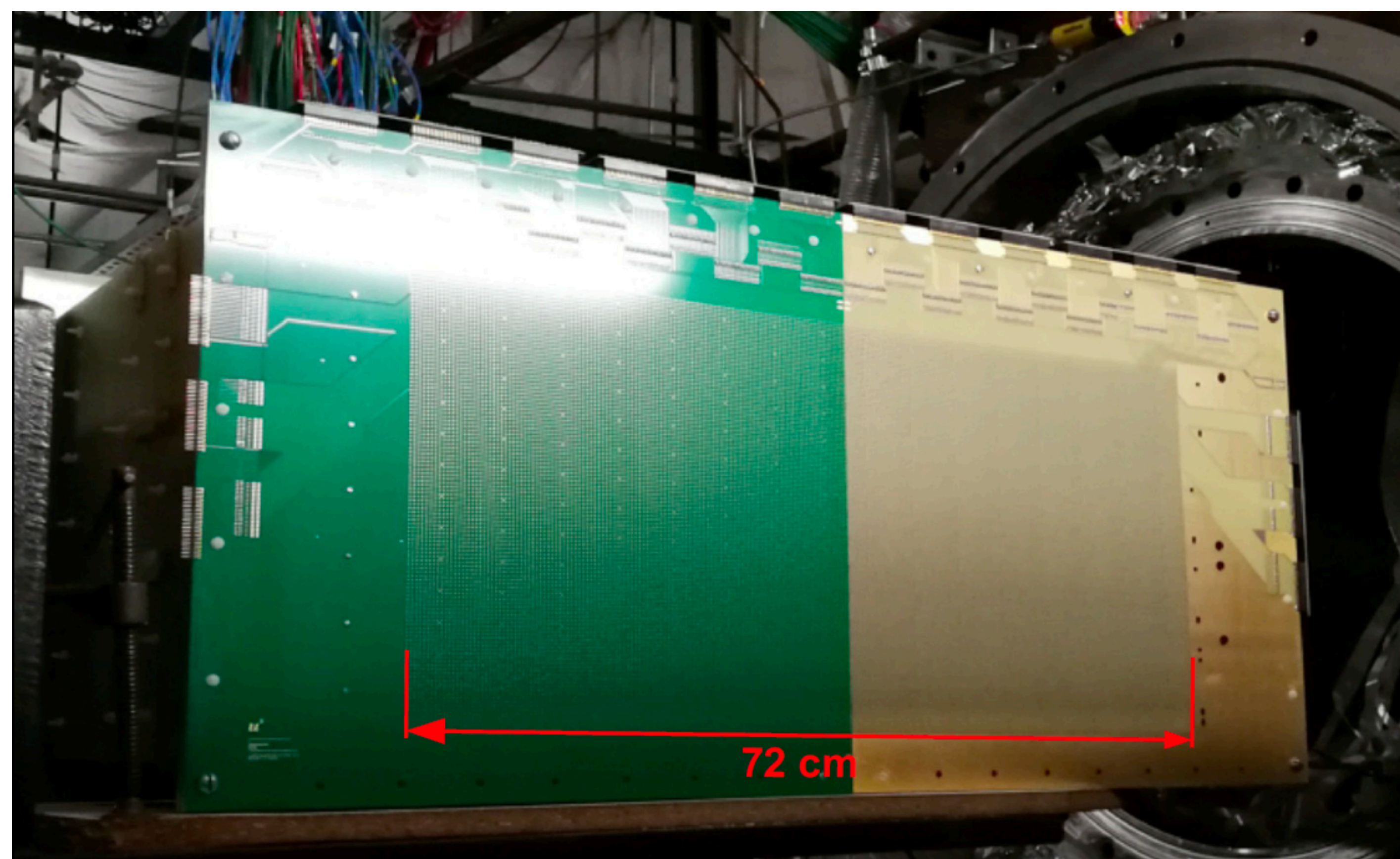
First pixel demonstrator in Bern successfully reconstructed cosmic muons in a 60 cm drift LArTPC.

R&D efforts on DUNE Near Detector

2017/18



Bern pixel readout was deployed in a 0.2 to 2.0 GeV π+/e+ test beam at FNAL.



Conclusions

- The **main discovery goal of future LBL experiments** is **CP violation.**
- Since 2004, **Swiss groups have been pioneering and leading the development of DP LAr TPCs,** an adopted option for the DUNE Far detector.
- The 3x1x1 has successfully opened the path towards large DP LAr TPCs:
  - **Extraction efficiency over 3m^2 area and LEM amplification with gain has been demonstrated on the 50x50 cm^2 for the first time.**
  - **First LAr TPC operation in a membrane tank** and excellent performance of the cryogenic system.
  - **The necessary experience has been gained to now move to protoDUNE-DP installation and commissioning**.
- DUNE priority is the construction of the Far Detector. In parallel, there has been progress towards the **Conceptual Design of the Near Detector** where Swiss groups also visibly participate.
- Once funded, an alternative and complementary scenario will be provided by HyperK, in particular if complemented by a second detector in Korea.

Back-up

Motivation for long baseline experiments

Mixing angles, matter effects and CP phase addressed in the same experiment

How do we do it?

Appearance probability

$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2\theta_{23}}\boxed{\sin^2 2\theta_{13}}\frac{\sin^2(\Delta_{31}-\boxed{aL})}{(\Delta_{31}-\boxed{aL})^2}\Delta_{31}^2$$

$$+\boxed{\sin 2\theta_{23}}\boxed{\sin 2\theta_{13}}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-\boxed{aL})}{(\Delta_{31}-\boxed{aL})}\Delta_{31}\frac{\sin(\boxed{aL})}{(\boxed{aL})}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$

$$+\boxed{\cos^2\theta_{23}}\sin^2 2\theta_{12}\frac{\sin^2(\boxed{aL})}{(\boxed{aL})^2}\Delta_{21}^2$$

δ_{CP} and a switch signs in going from the $\nu_\mu \to \nu_e$ to the $\bar{\nu}_\mu \to \bar{\nu}_e$ channel; i.e. $\nu/\bar{\nu}$ asymmetry is introduced both by CP violation and the matter effect.

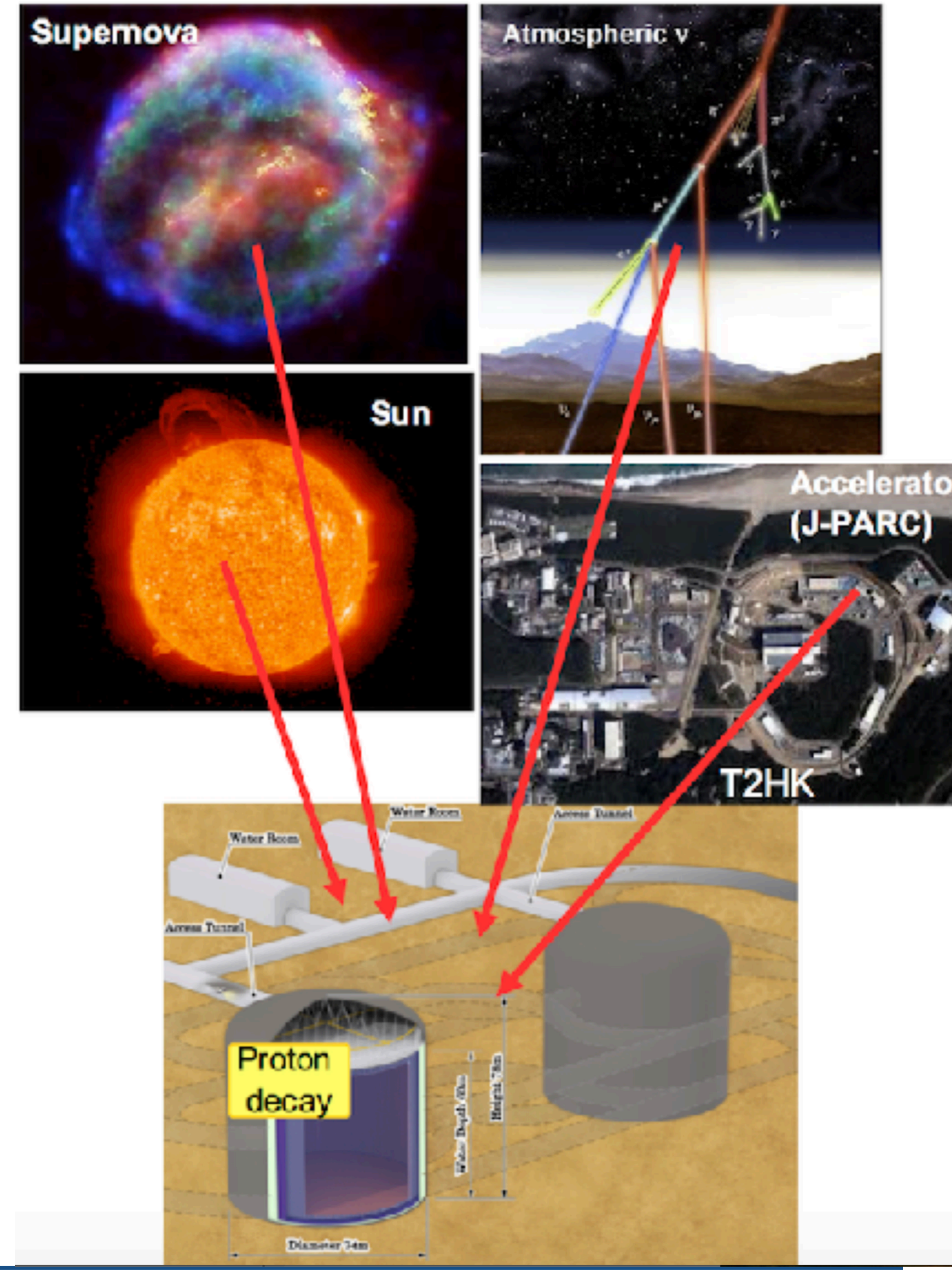
$$a = G_F N_e/\sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

- A measurement of the parameter δ_{CP} could be performed based on a spectrum shape fit with only neutrino beam data.
- Explicitly demonstration of CP violation by observing the asymmetry between neutrinos and antineutrinos.
- A comparison of the measured value of δ_{CP} based on neutrino data alone to that based on the combined fit of neutrino and antineutrino data will be a useful cross-check

T2HK physics goals

- **Neutrino oscillations physics**
  - Study with beam and atmospheric neutrinos
- **Search for nucleon decays**
- **Neutrino astrophysics**
  - Precision measurement of solar neutrino
  - High statistics measurements of SN burst neutrinos
  - Detection and study of relic SN neutrinos
- **Geophysics**
  - Neutrinography of the interior of the Earth



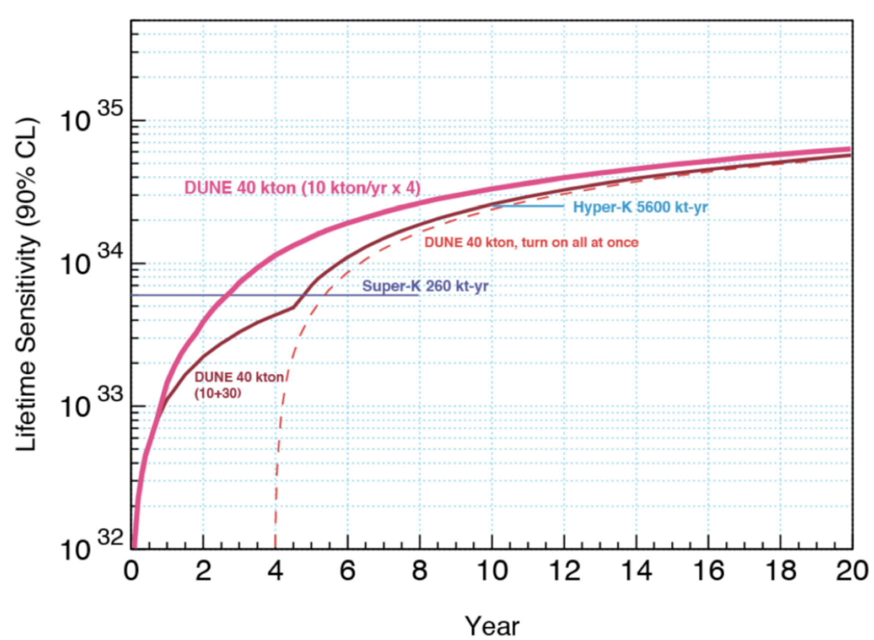
DUNE physics goals

Precise measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillations :
Measurement of leptonic CP violation + Neutrino mass ordering

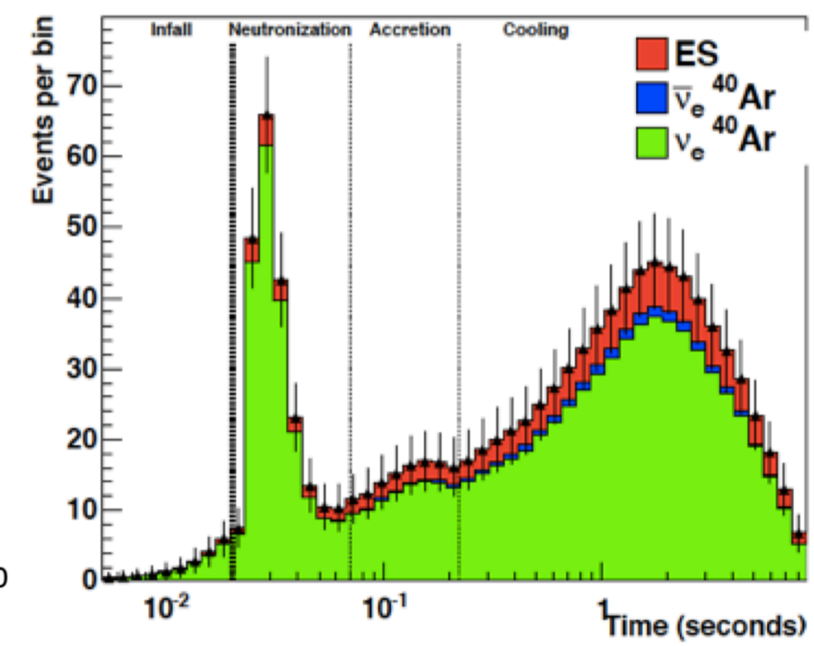
- **Proton decay searches in several important decay channels**

- **Detection and measurement of the ν_e flux from a core-collapse supernova within our galaxy.**

Nucleon decay



Astrophysics



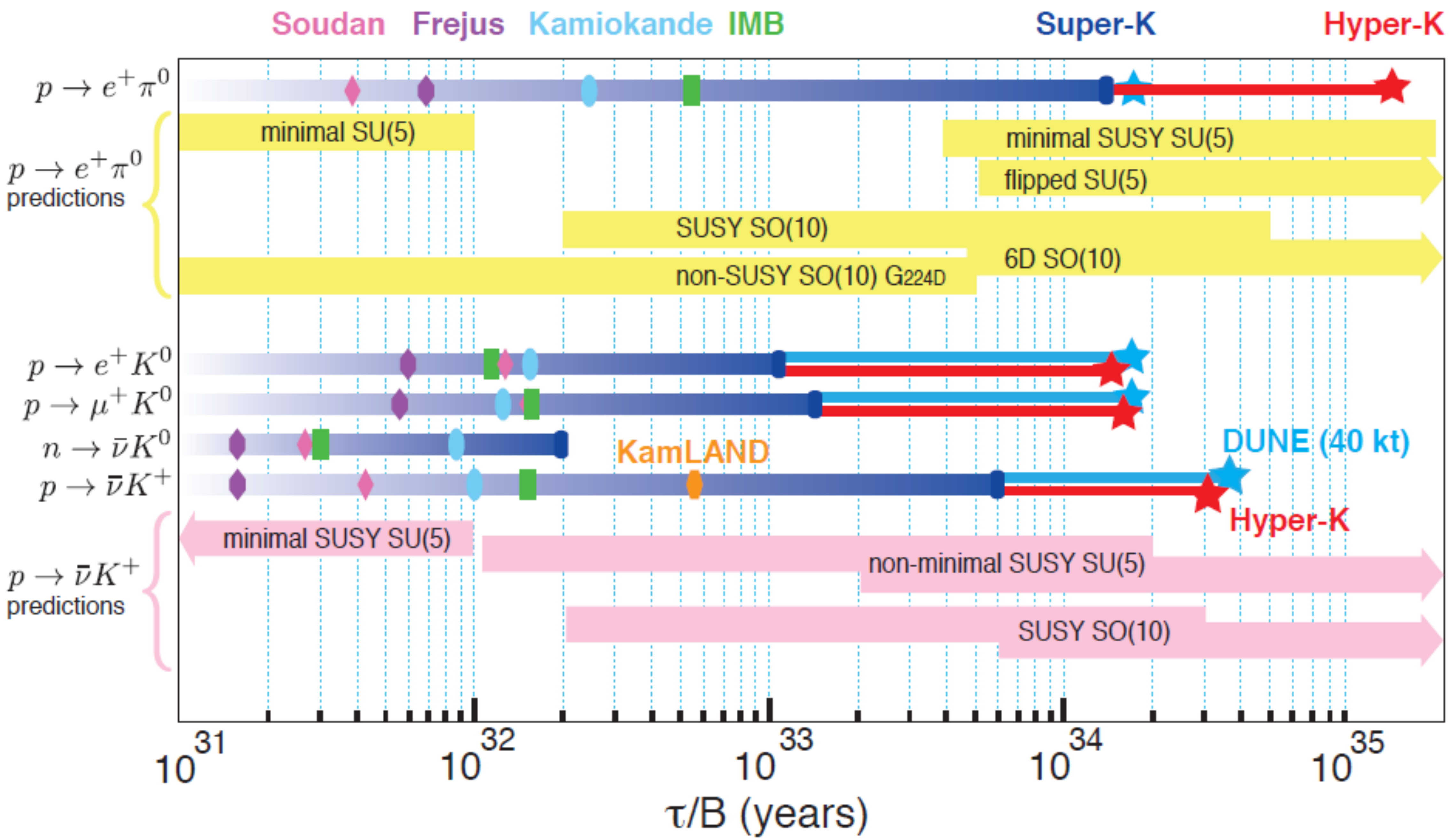
And…

- **Sterile neutrinos**
- **Possible observation of unpredicted rare events**
- **Precise measurements of neutrino interaction with the near detector**
- **Atmospheric neutrino oscillation measurements**
- **Dark matter**

DUNE physics milestones

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)	
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45	1 year
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60	
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100	2 years
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210	
MH at 5σ (worst point)	definite MH determination	230	5 years
10° resolution ($\delta_{\rm CP} = 0$)	450	290	
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	525	320	7 years
CPV at 5σ 50% of $\delta_{\rm CP}$	810	550	
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	reactor θ_{13} resolution	850	
CPV at 3σ 75% of $\delta_{\rm CP}$	1320	850	

Search for proton decay



NB JUNO starts in 2021

Planning for funding DUNE

- **Assumed timeline for DUNE (and LBNF) reviews**
  - May-2018: Technical Proposal for DUNE (+costs, responsibilities)
  - Jan/Feb 2019: **RRB** for to provide funding status
  - April 2019: LBNF and DUNE internal/external TDR reviews
  - July 2019: **LBNC review of TDRs**
    Review of international DUNE construction project
  - Sept 2019: **RRB** to confirm **funding** status for construction
    validation of **international** funding model
  - October 2019: DOE **CD-2** Review of LBNF/DUNE & "**CD-3**" review
    for far site and two far detector modules
  - August 2020: DOE "**CD-3**" for near facilities and near detector

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Milestones

Target Date	Milestone	Type	Tie	Original date	Complete
Jan-17	Launch of expressions of interest in ND Concept Study	ND	2	Jan-17	Feb-17
Mar-17	ND Concept Study workshop	ND	2	Mar-17	Mar-17
May-17	Define two/three ND concept options for further study	ND	2	May-17	May-17
Jun-17	ND Concept Study workshop	ND	2	Jun-17	Jun-17
Nov-17	ND Concept Study workshop (CERN)	ND	4	Nov-17	Nov-17
Nov-17	Document criteria/physics processes for ND tracker choice	ND	3	Nov-17	Nov-17
Nov-17	Document programme of studies to demonstrate physics benefits of 3D-Sc	ND	4	Nov-17	Nov-17
Nov-17	Document layout for PRISM concept and studies to demonstrate case	ND	4	Nov-17	Nov-17
Nov-17	Document criteria for comparison of magnet options	ND	3	Nov-17	Nov-17
Feb-18	**Report on cost implications/technical risks of Solenoid option**	**ND**	**3**	**Dec-17**	
Jan-18	**Status report on ND tracker studies - define next steps**	ND	**3**	**Jan-18**	
Jan-18	**Recommendation on whether to purse PRISM concept**	ND	**2**	**Jan-18**	
Jan-18	**Report on scientific arguments for magnet to EC**	ND	**3**	**Jan-18**	
Feb-18	**Decision on ND Magnet**	**ND**	**2**	**Feb-18**	
Mar-18	Report on comparison of tracker options and recommendation	ND	3	Mar-18	
Mar-18	Report on benefits of PRISM concept and recommendation	ND	3	Mar-18	
Mar-18	Report on benefits of 3-D scintillater as part of MPT and recommendation	ND	3	Mar-18	
Mar-18	ND Concept Study workshop	ND	4	Mar-18	
Apr-18	Decision on PRISM concept	ND	2	Apr-18	
Apr-18	Decision on 3-D scintillator	ND	2	Apr-18	
Apr-18	Decision on ND Tracker technology	ND	2	Apr-18	
May-18	**Decision on the conceptual design of the near detector systems**	**ND**	**1**	**Dec-17**	
Jun-18	**Start of ND EoI process**	**ND**	**2**	**Jan-18**	
May-19	CDR for Near Detector	ND	1	Sep-18	
Aug-19	Review of Near Detector CDR	ND	1	Aug-19	
Apr-20	TDR for Near Detector	ND	1	Apr-20	
Jun-20	LBNC Review of Near Detector TDR	ND	1	Jun-20	
Aug-20	CD-3 and LBNC Reviews for near site and Near Detector	ND	1	Aug-20	

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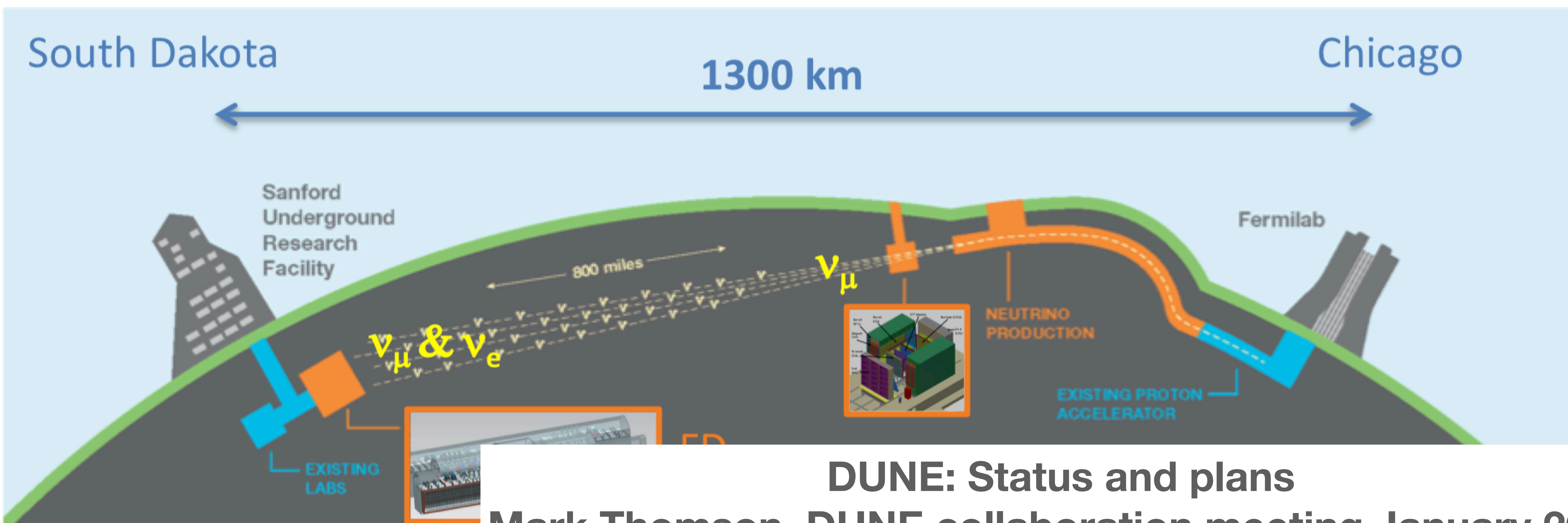
DUNE TDRs

- **Top-level milestones**
  - **Four 10-kt LAr-TPC Far Detector (FD) modules**
    - [At least] Modules #1 and #2: TDR review in **2019**
    - Modules #3 and #4: TDR before ~2022
  - **DUNE Near Detector & Computing**
    - ND and Computing CDR in 2019
    - ND TDR in 2020



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Near Detector Conceptual design group recommendation

"The ND CD group recommends that DUNE should have a LArTPC that is optically segmented, with a short drift and 2D pixelized readout, like the concept under study by the ArgonCube collaboration"

24 March 2018