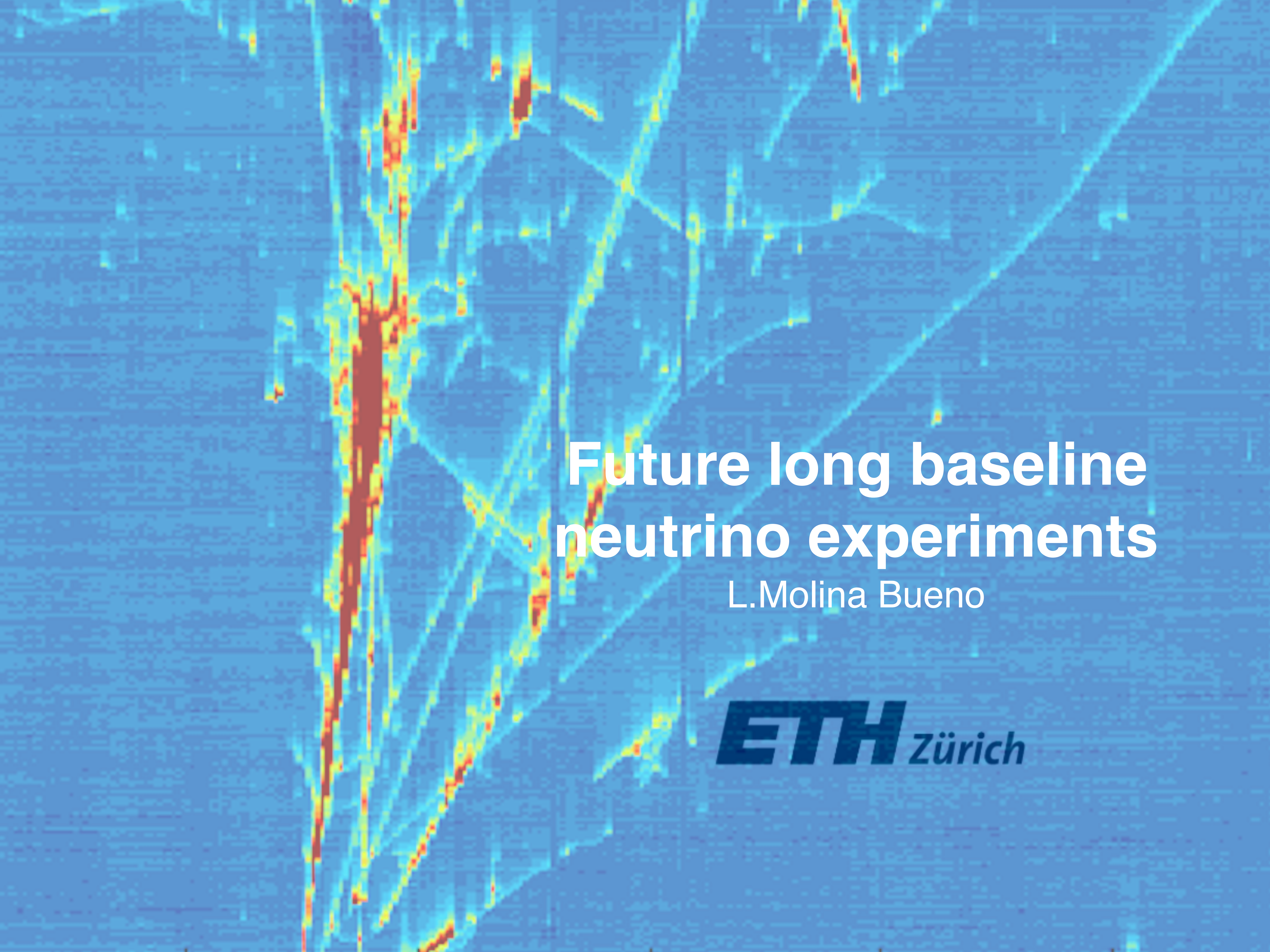


Future long baseline neutrino experiments

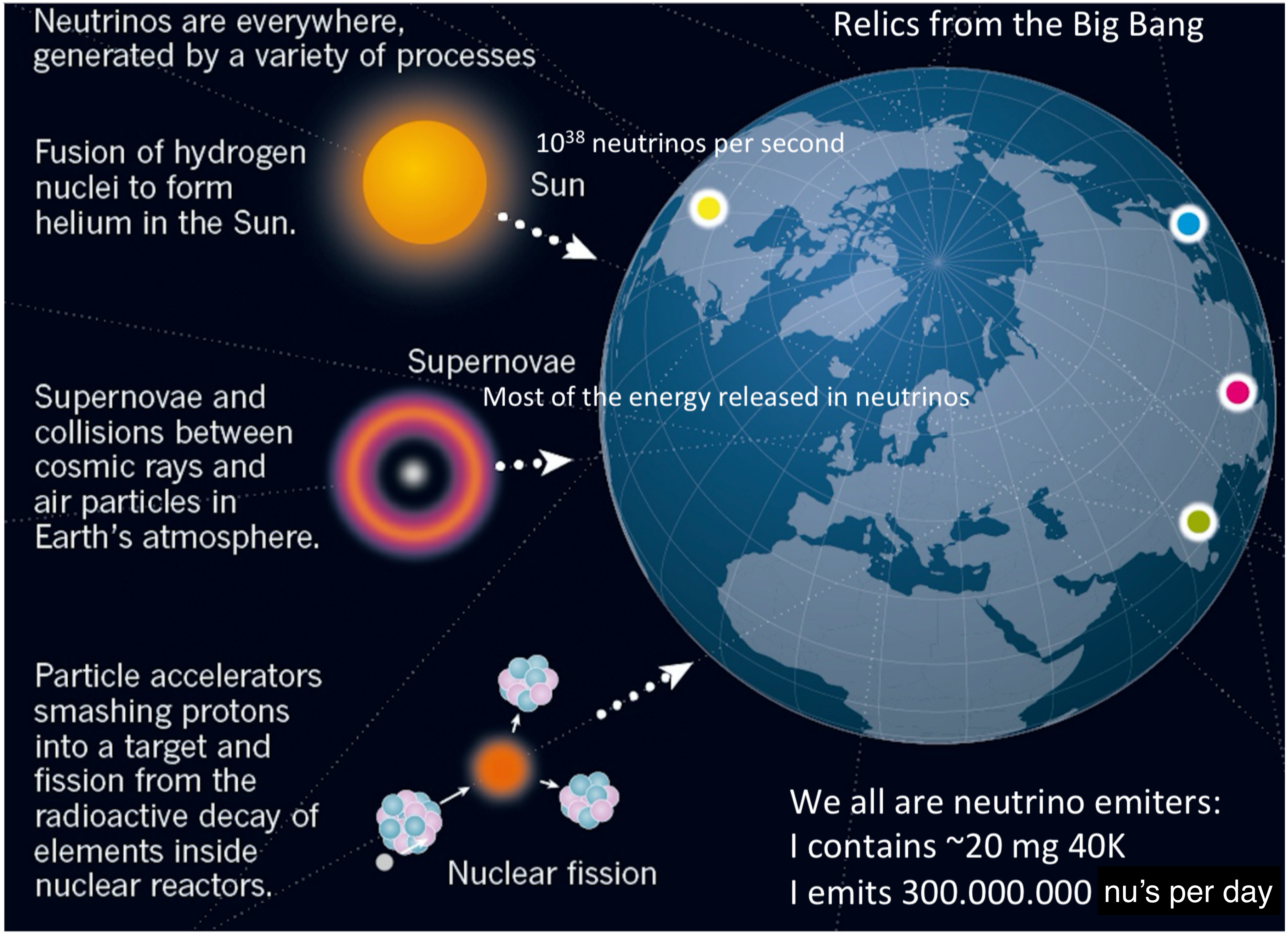
L.Molina Bueno

ETH Zürich

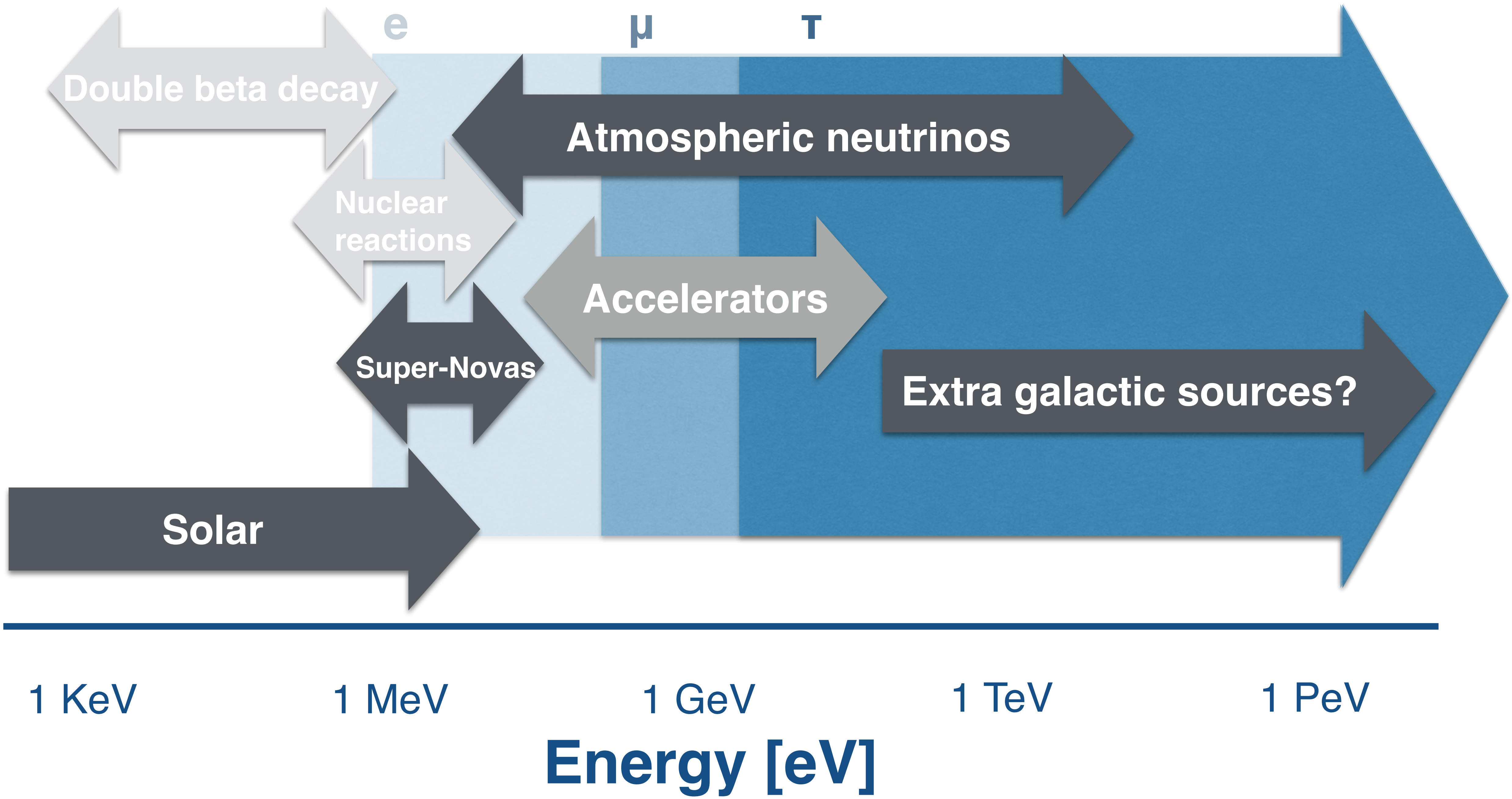
Outline

1 Introduction

Neutrinos are everywhere…



With a wide range of energies



Neutrino detection involves **different techniques, different detector masses** and **volumes**

What do we measure?

$$N_\nu(E) = \phi_\nu(E) \times \sigma_\nu(E) \times target$$

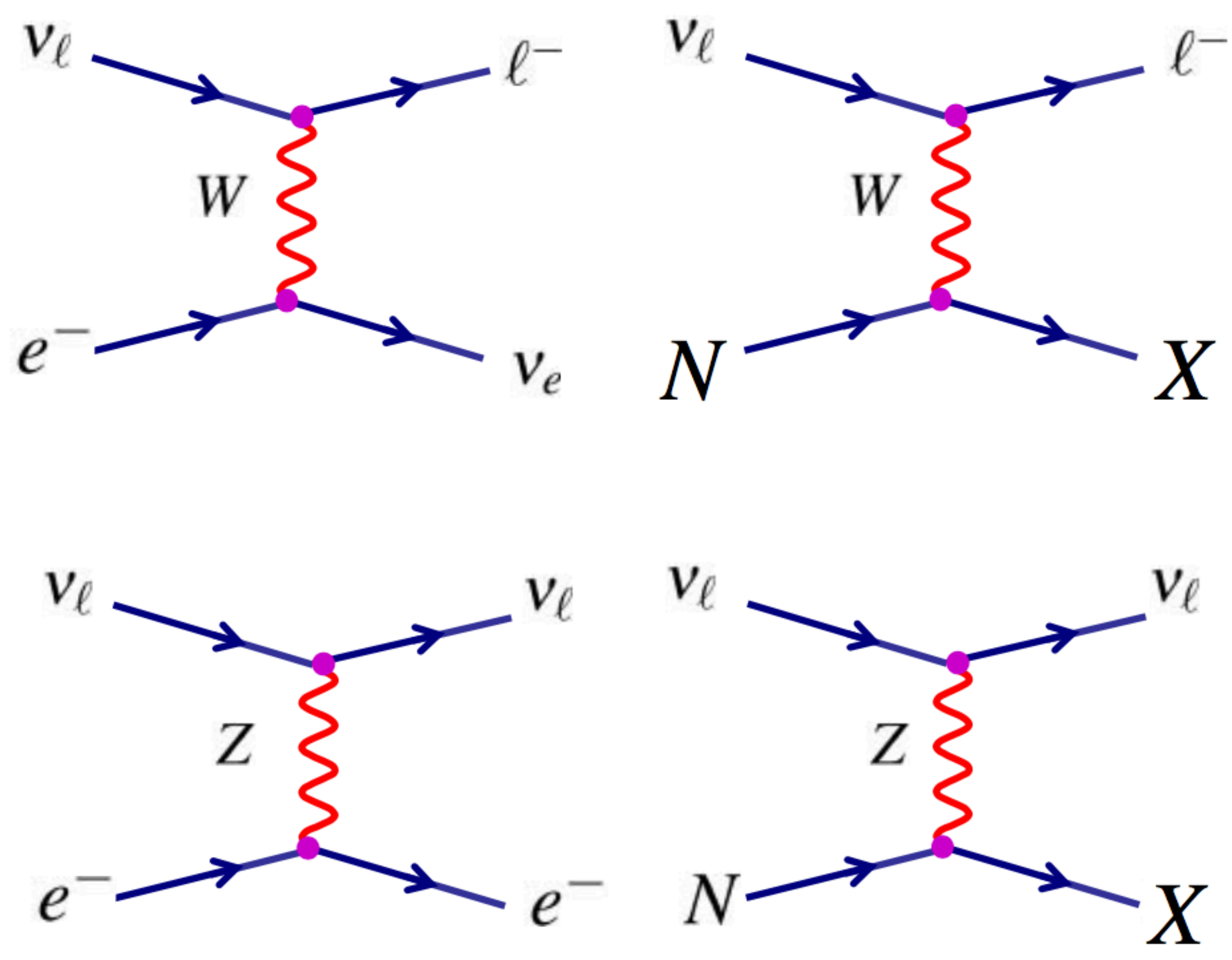
Number of events = Flux **X** Cross-section **X** target

Flux	Cross-section	target
Depends on your source	It is very small (~10^{-38} cm^2 for E in GeV) and depends on the energy	Detector
Very energetic sources	**Go to higher energies**	**Make it huge**

Neutrino interactions

Charged current

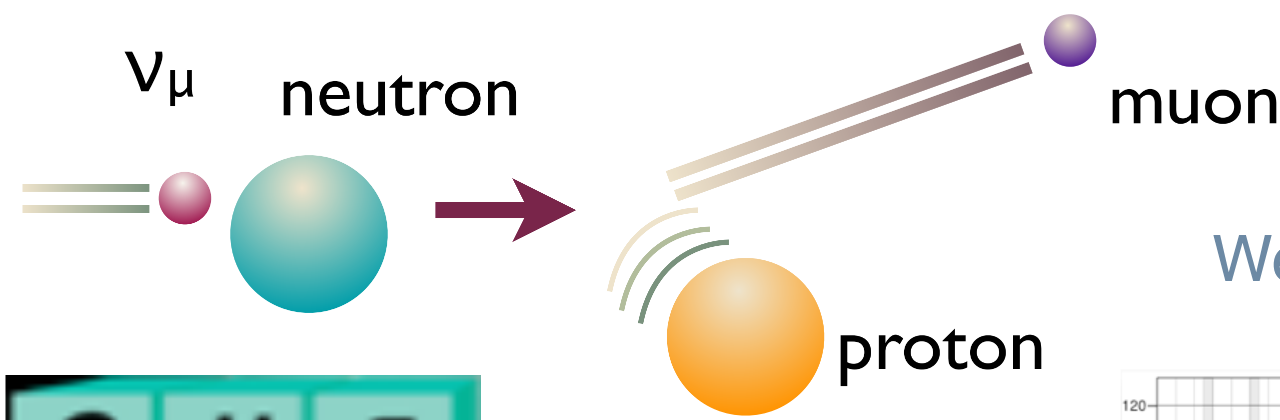
Neutral current

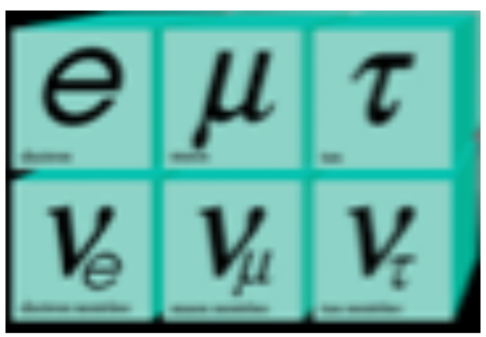


"Neutrino physics course" ETH Zürich A. Rubbia/C.Regenfus

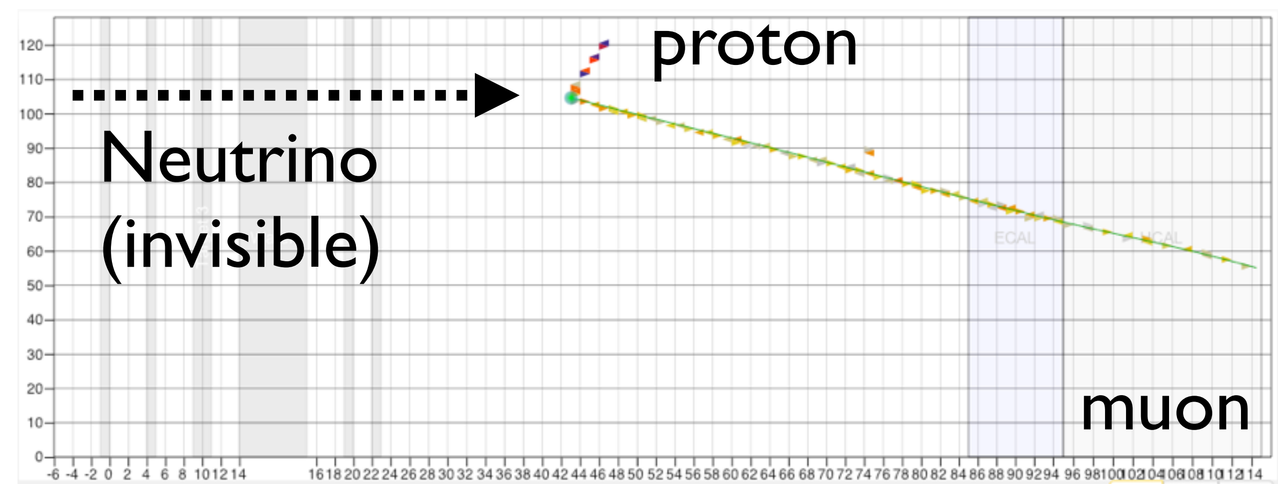
Neutrino interactions

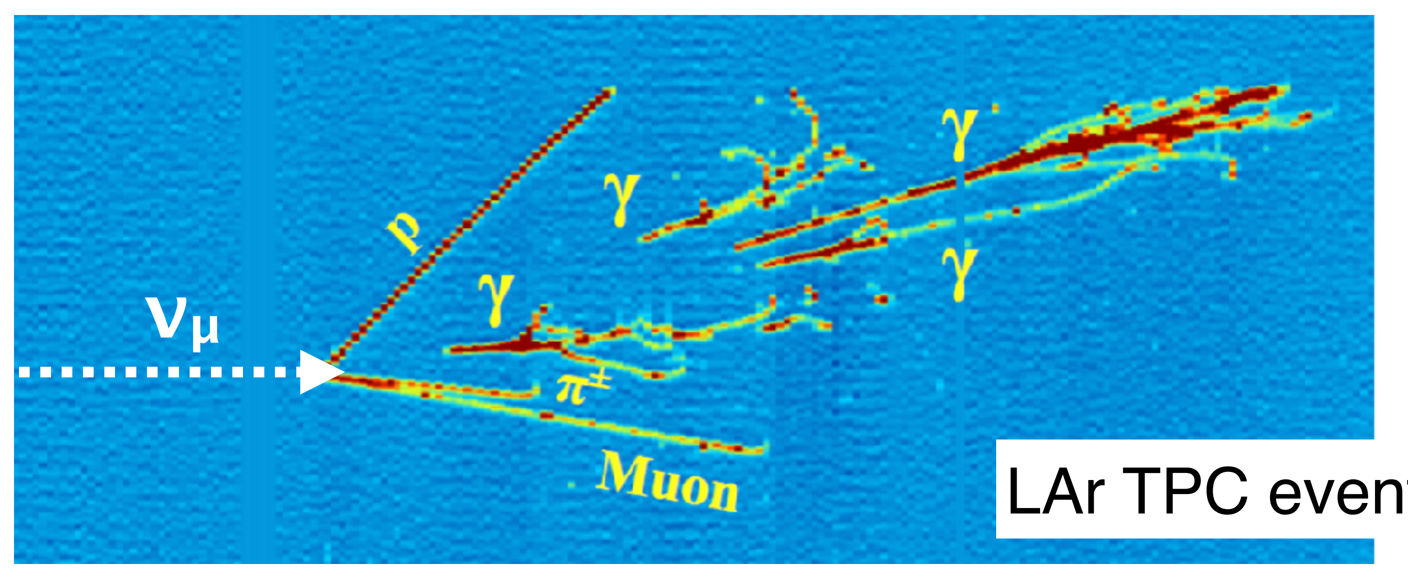
Neutrino charged current interaction





We can detect the secondary particles



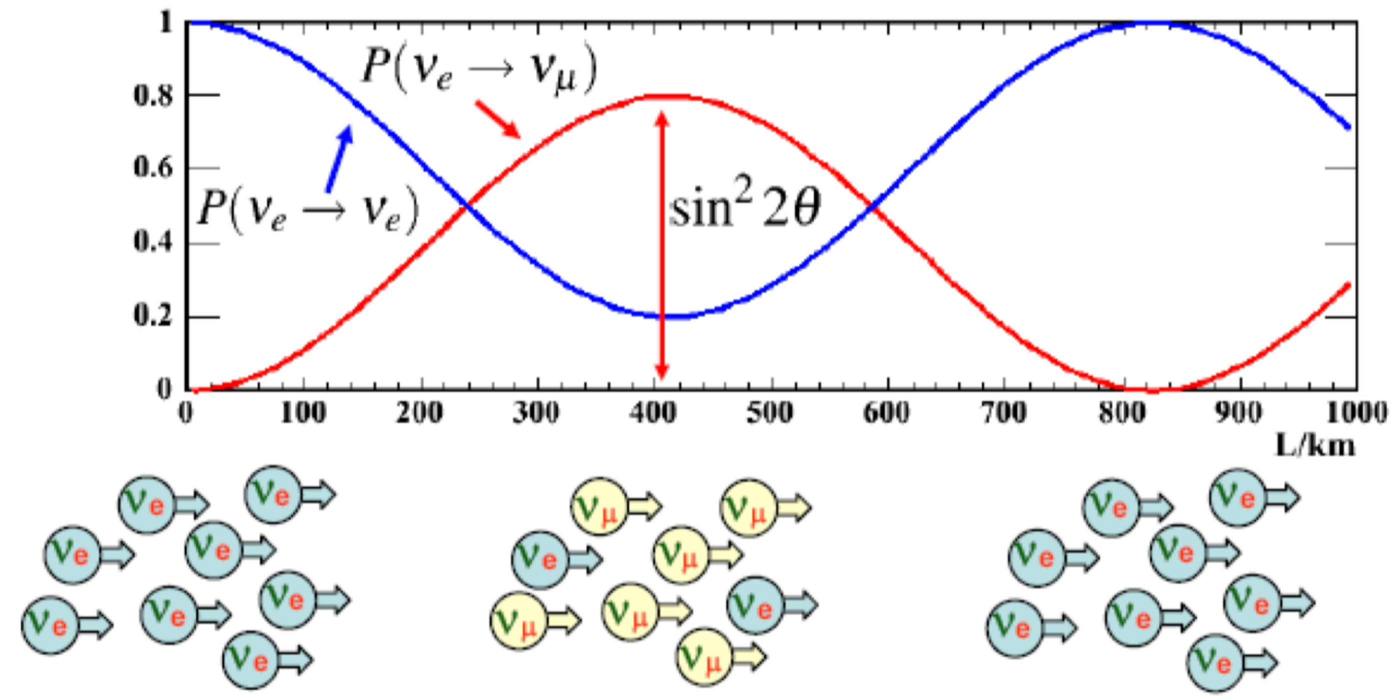


1 Introduction

2 Neutrino oscillations

Neutrino oscillations

Neutrino oscillations represent the first evidence of physics beyond the standard model:
Neutrinos are not massless!



Flavour eigenstates **Mass eigenstates**

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

Atmospheric **Accelerator/reactor** **Solar**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix where $c_{ij}=\cos\theta_{ij}$ $s_{ij}=\sin\theta_{ij}$

Neutrino oscillations: what do we know?

Latest results for oscillations parameters, NuFit 4.0 2018

$\theta_{12} = 33.82^{+0.78}_{-0.76}$ $\theta_{23} = 49.7^{+0.9}_{-1.1}$ $\theta_{13} = 8.61^{+0.12}_{-0.13}$

Of the three mixing angles θ_{23} holds the largest uncertainty.
Is it maximal?

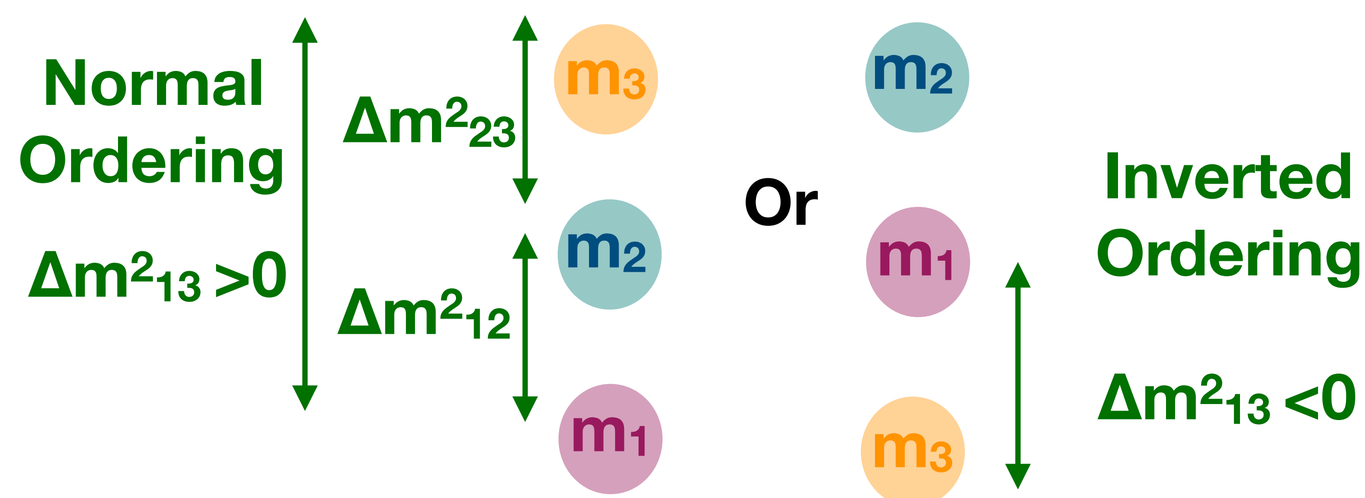
$\delta_{CP}\left(^{0}\right) = 217^{+40}_{-28}$ **CP violation in the leptonic sector?**

The absolute neutrino mass scale and its ordering is unknown.

$$\Delta m^2_{21} = m^2_2 - m^2_1 = \left(7.4^{+0.21}_{-0.20}\right) 10^{-5} eV^2$$

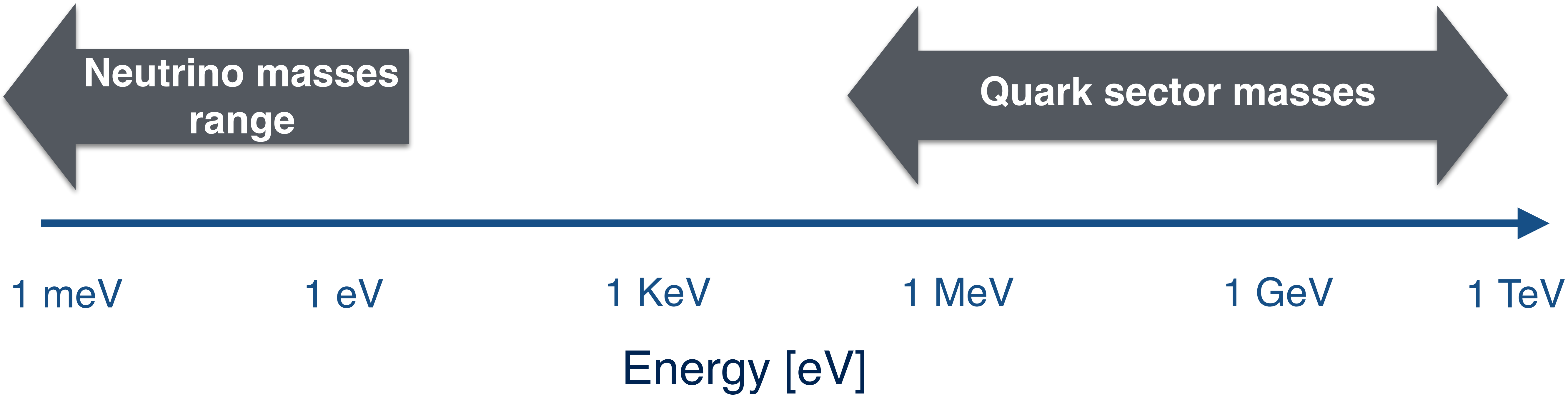
$$\Delta m^2_{3l} = m^2_3 - m^2_l = \left(2.525^{+0.033}_{-0.031}\right) 10^{-3} eV^2$$

where l = 1,2



But… still many unknowns

- **What is the origin of neutrino masses and mixing?**



- **Can the matter-antimatter asymmetry in the universe be explained through leptogenesis?**

  At the beginning of the universe ➡ same amount of particles and antiparticles

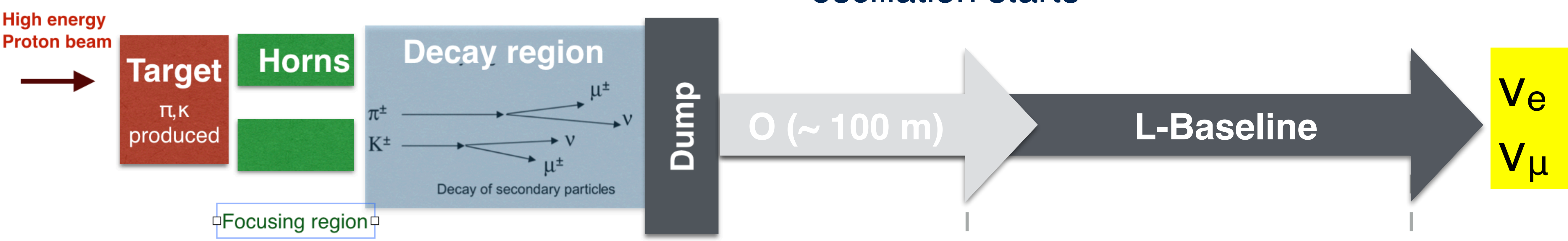
- **Are there sterile/heavy neutrinos?If yes, how many?**

But… still many unknowns

Worldwide effort

Long baseline neutrino experiments in a nutshell

Production of High energy neutrino/antineutrino beam	Near detector	Far detector
Particle accelerators used to produce high energy beams at the desired energy, E.	Located at few hundred meters from the beam to measure the events before the oscillation starts	Measures the events after the oscillation taking into account oscillation predictions



$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

Distance L chosen to maximise the oscillation probability at L/E (O ~100-1000km)

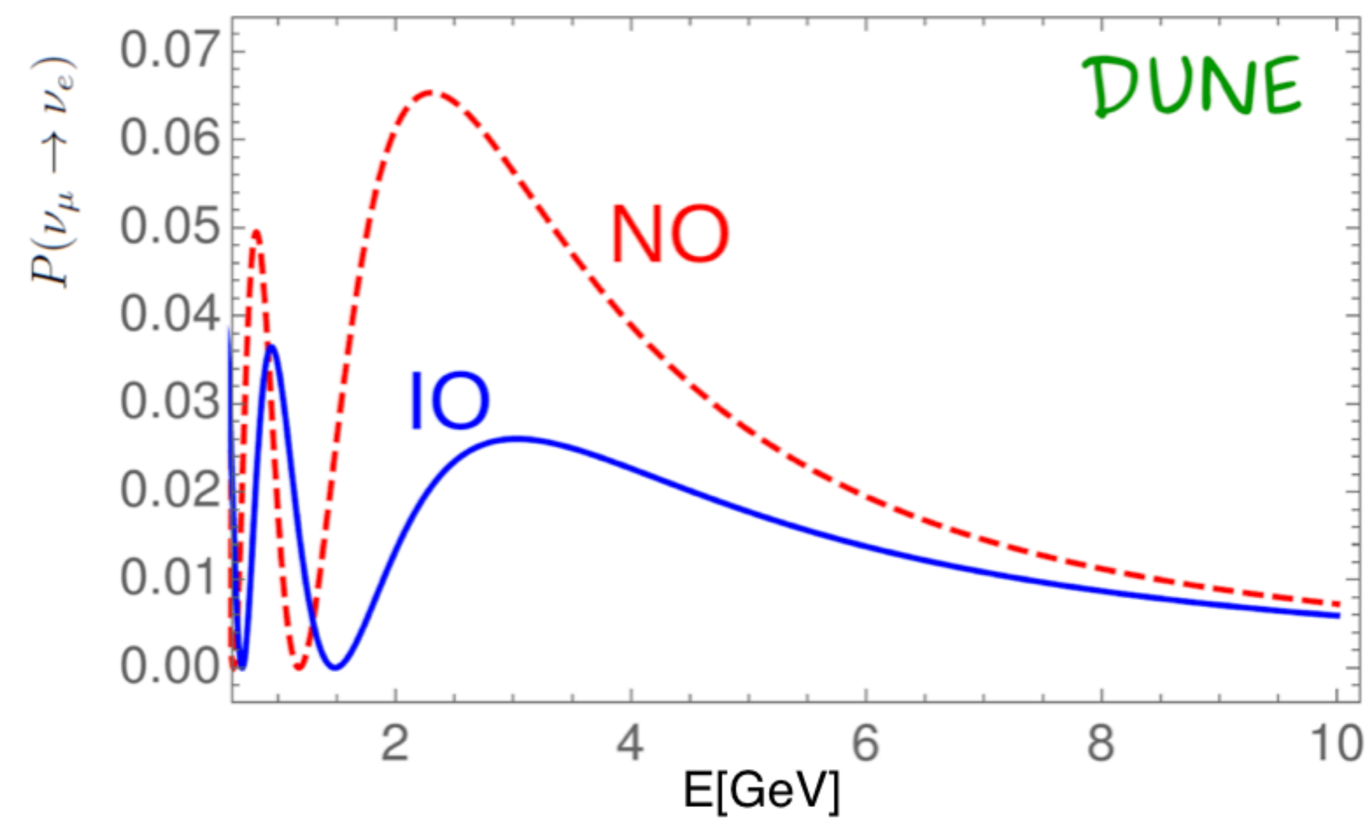
Matter effects in neutrino oscillation experiments

Near detector → **L-Baseline (O ~100-1000 km)** → **Far detector**

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$a = G_F N_e/\sqrt{2}$$
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

Neutrinos travel through material which is dominated by matter



Asymmetry between **neutrinos** and **antineutrinos** introduced by matter effects

The experiment strategy

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

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

constant

Matter effects

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

constant

CPV

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

constant

What we want (δ)

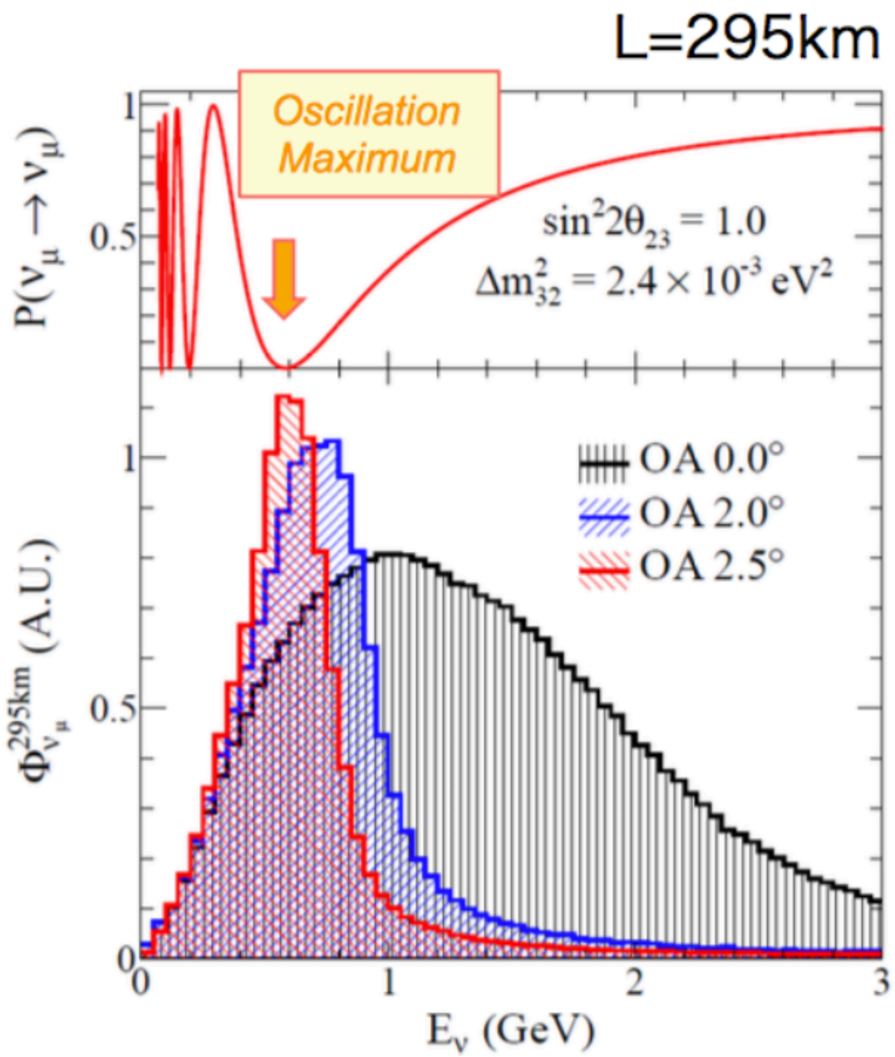
$$a = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$$

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

Two current strategies: T2HyperK Vs DUNE

T2HyperK

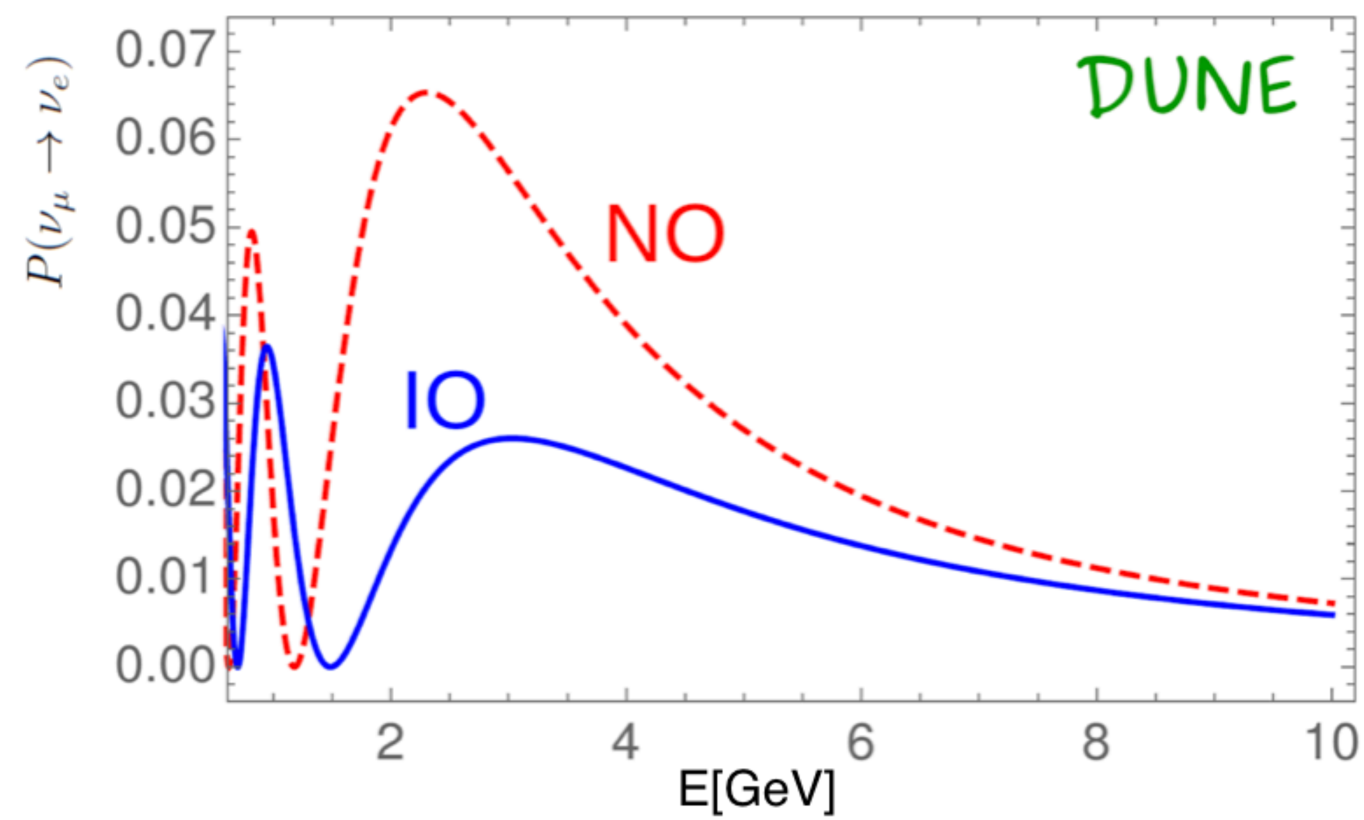
- Keep matter effects small using a short baseline.
- High flux at first oscillation maximum
- Off-axis technique: narrow range of neutrino energies



“Status of the Hyper-Kamiokande Experiment”, Erin O’Sullivan NuFact 2017

DUNE

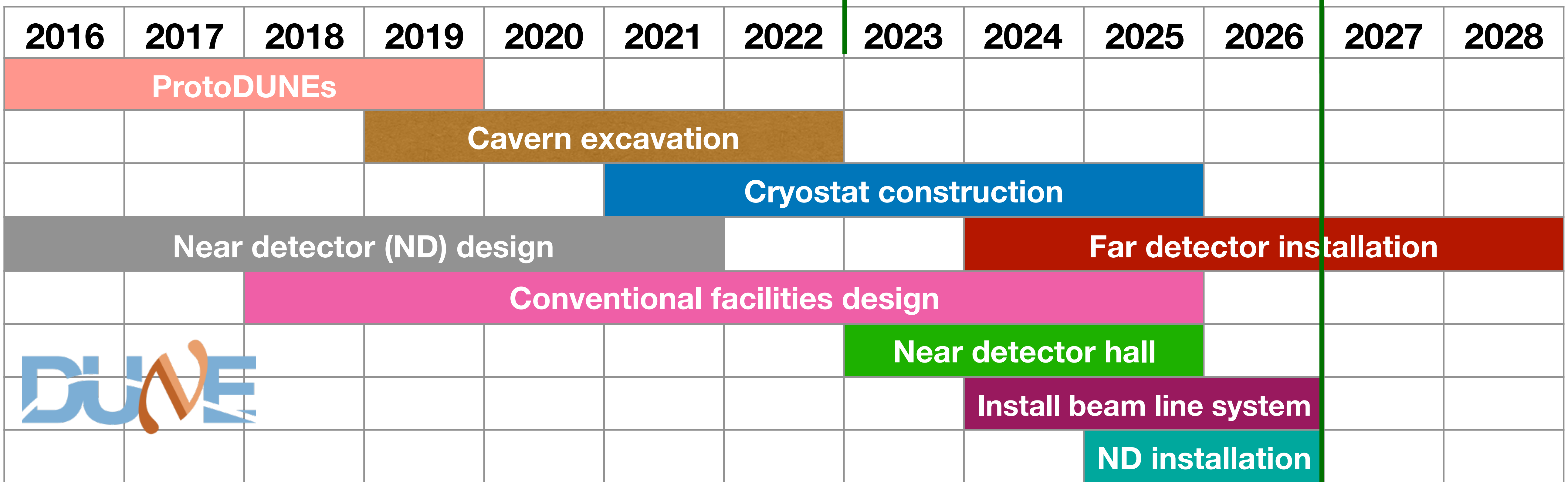
- Enhanced matter effects.
- First and second maximum.
- Unfold CPV from matter effects through neutrino energy dependency.
- On-axis technique: wide range of energies.

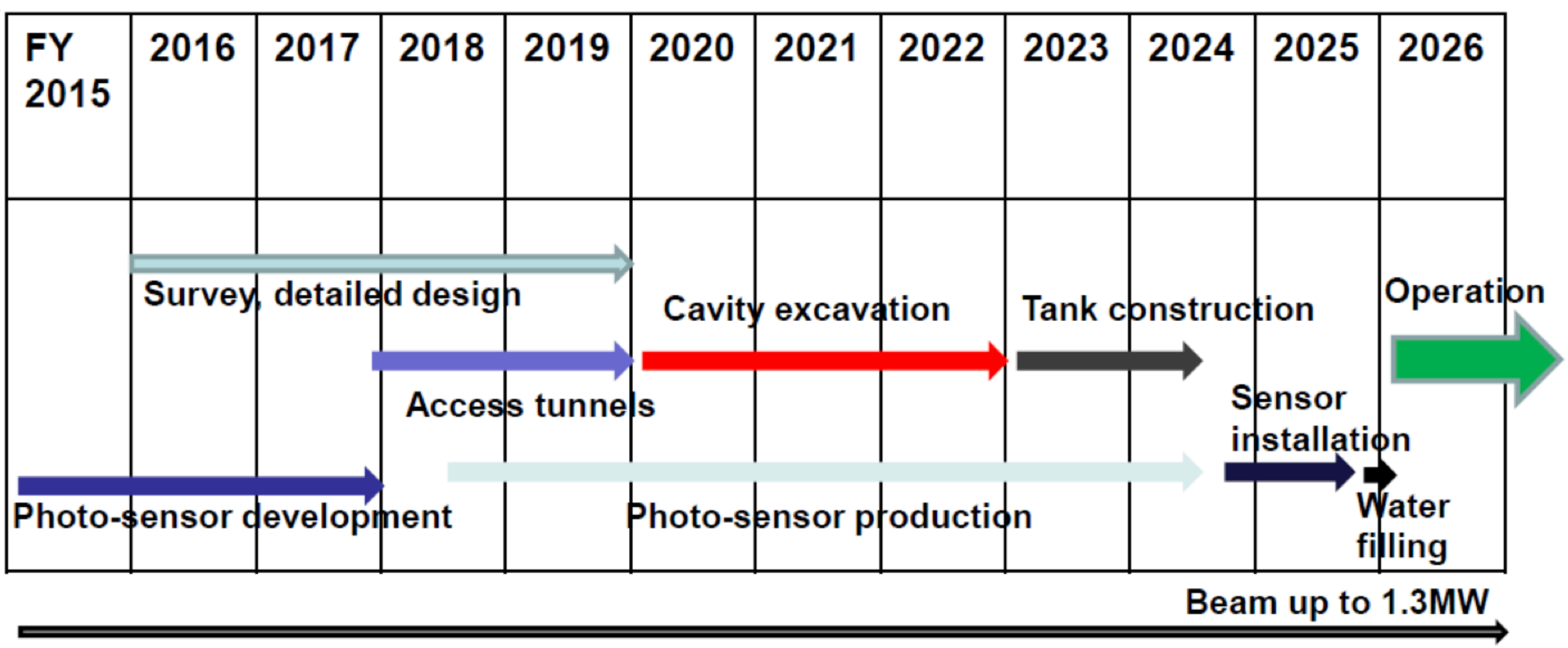


Tentative timeline

First module installation begins

Beam





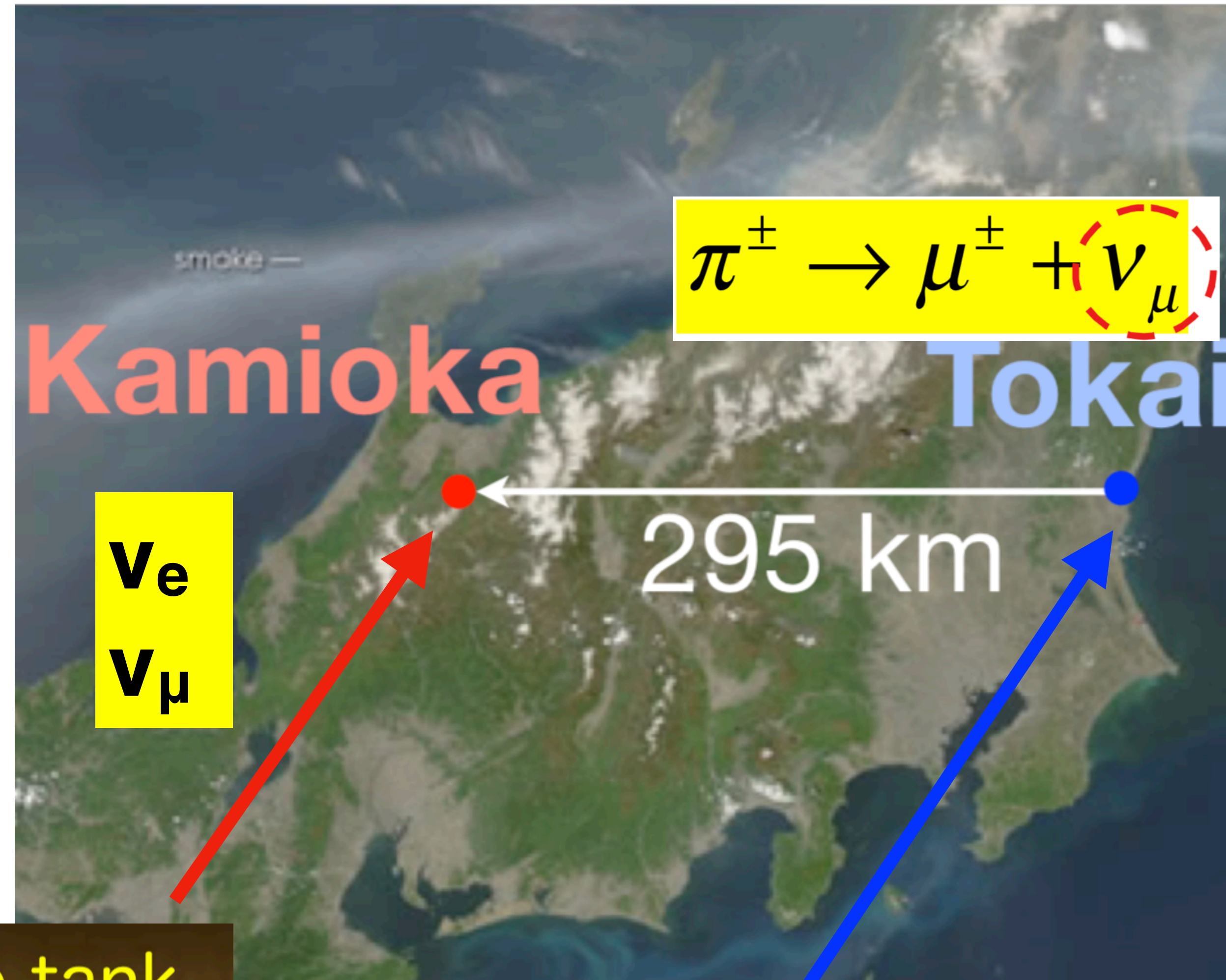
Expected detector operation In 2026

"Status of Hyper-Kamiokande", A. Blondel NuFact 2018

The T2HyperK experiment

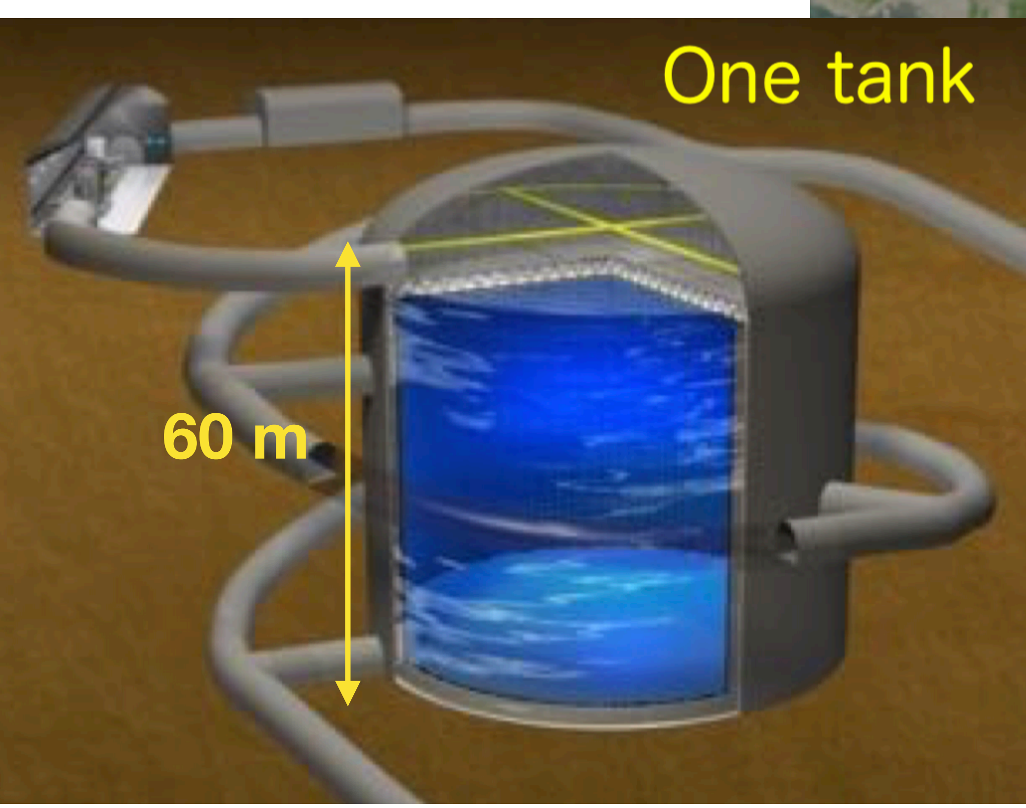
Far detector
HyperK

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

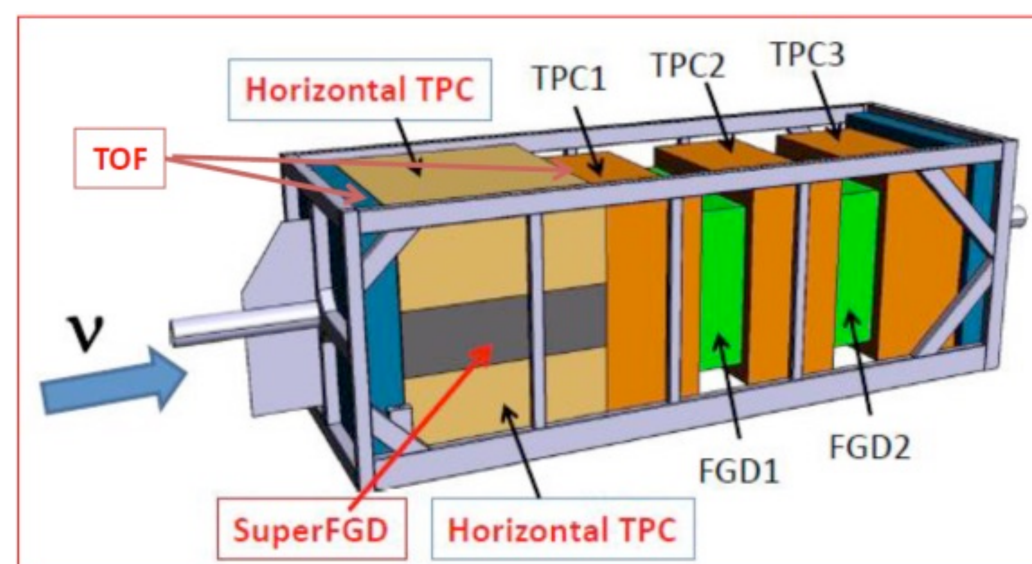


Neutrino beam J-PARC facility
- 1MW (2020)
- 1.3 MW (2025)

Detectors underground to shield against cosmic rays



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



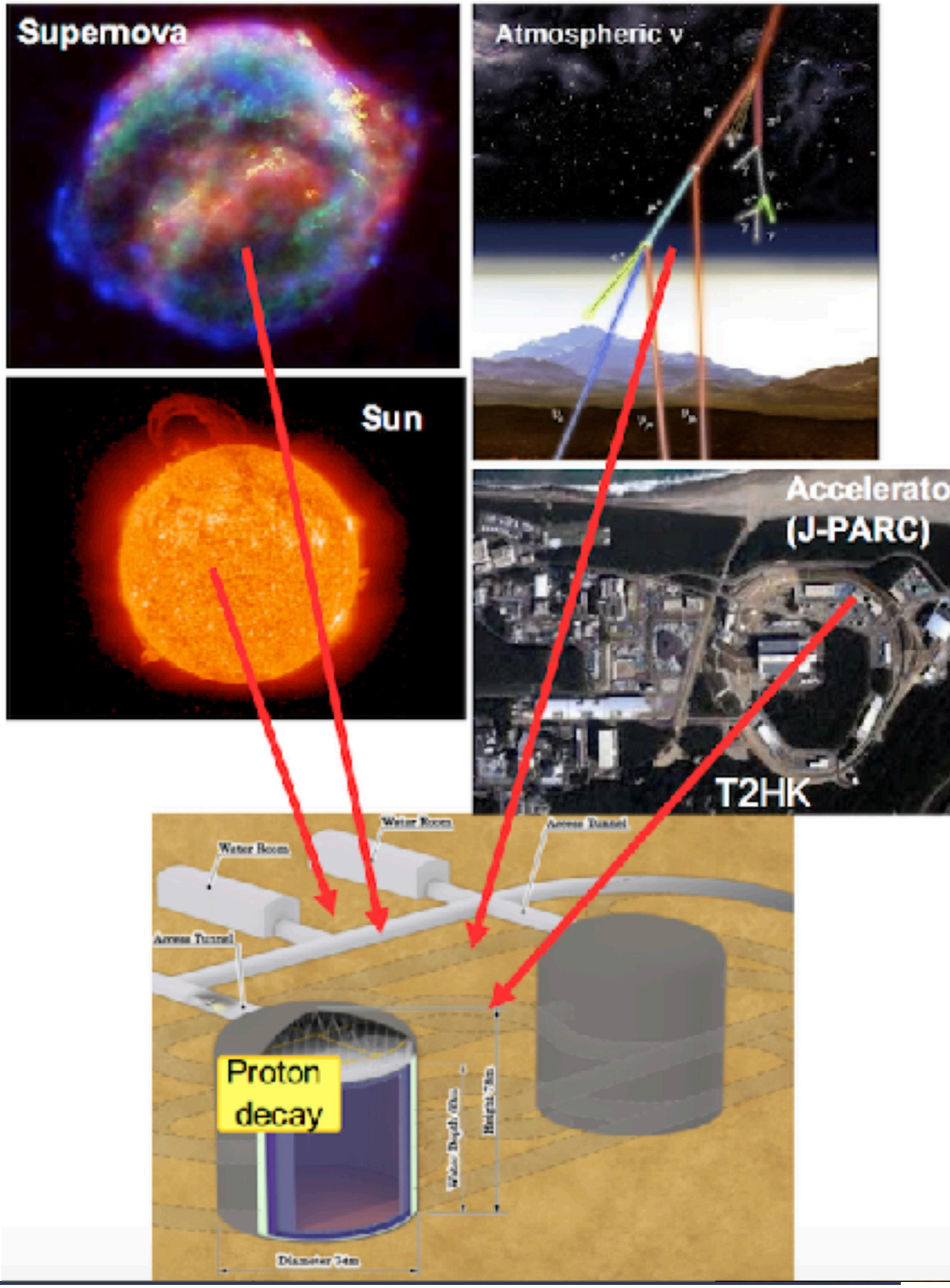
T2HyperK physics goals

- **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

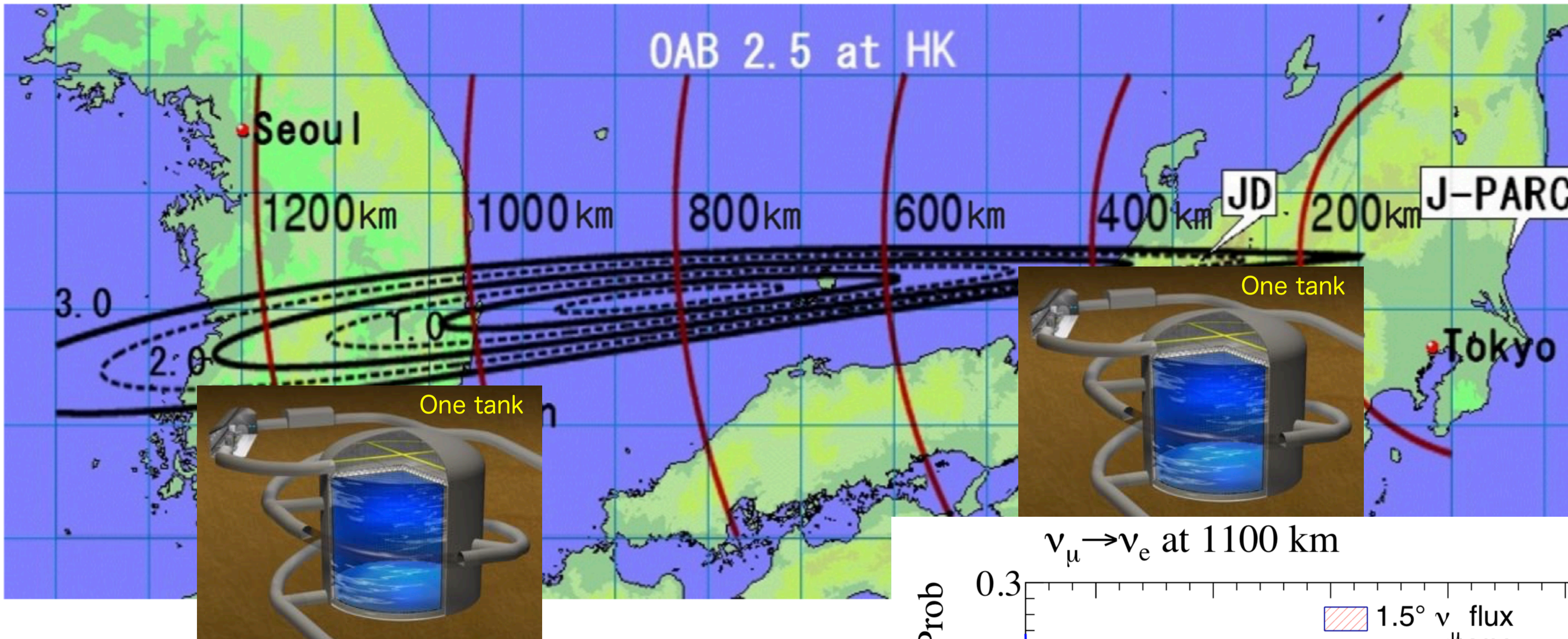
- **Geophysics**
  Neutrinography of the interior of the Earth

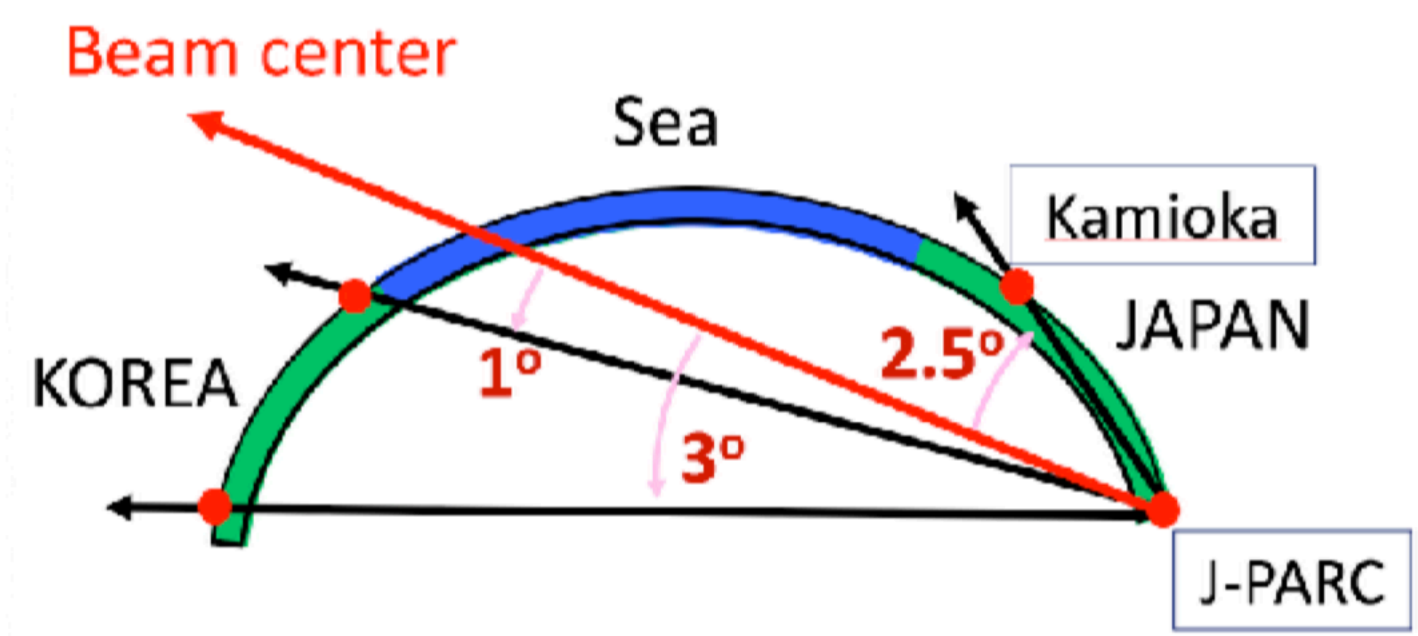


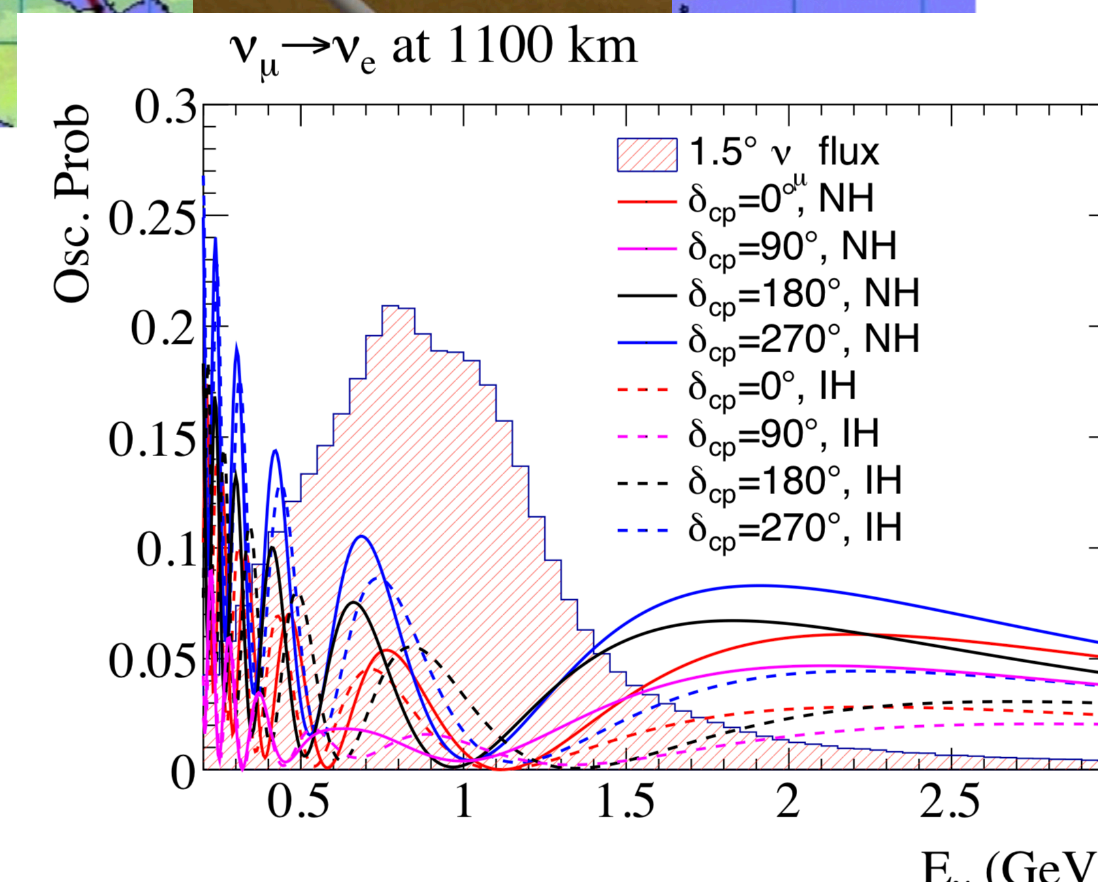
T2HyperKK: A possible second detector in Korea

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







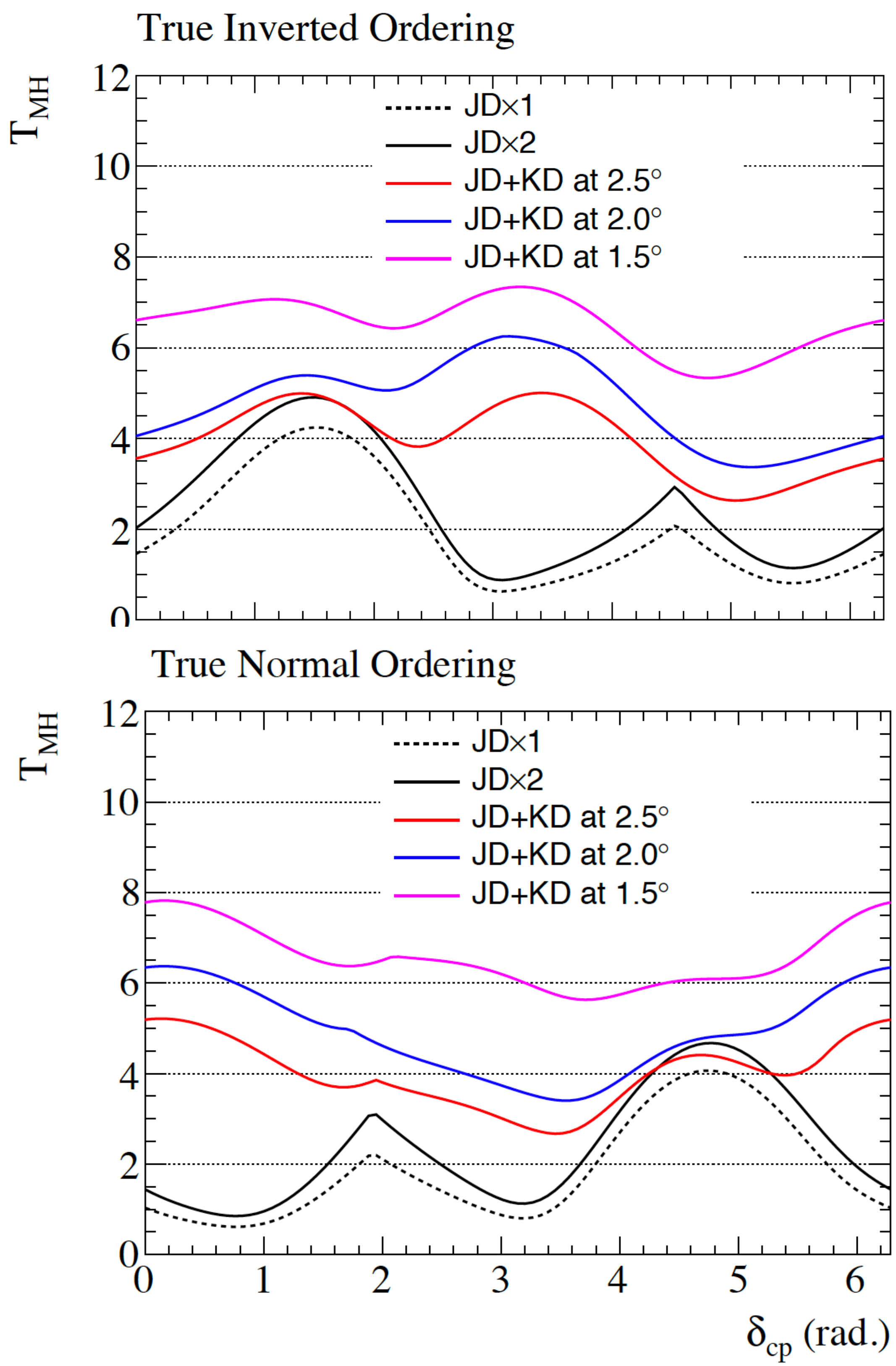
MH and CP sensitivities

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

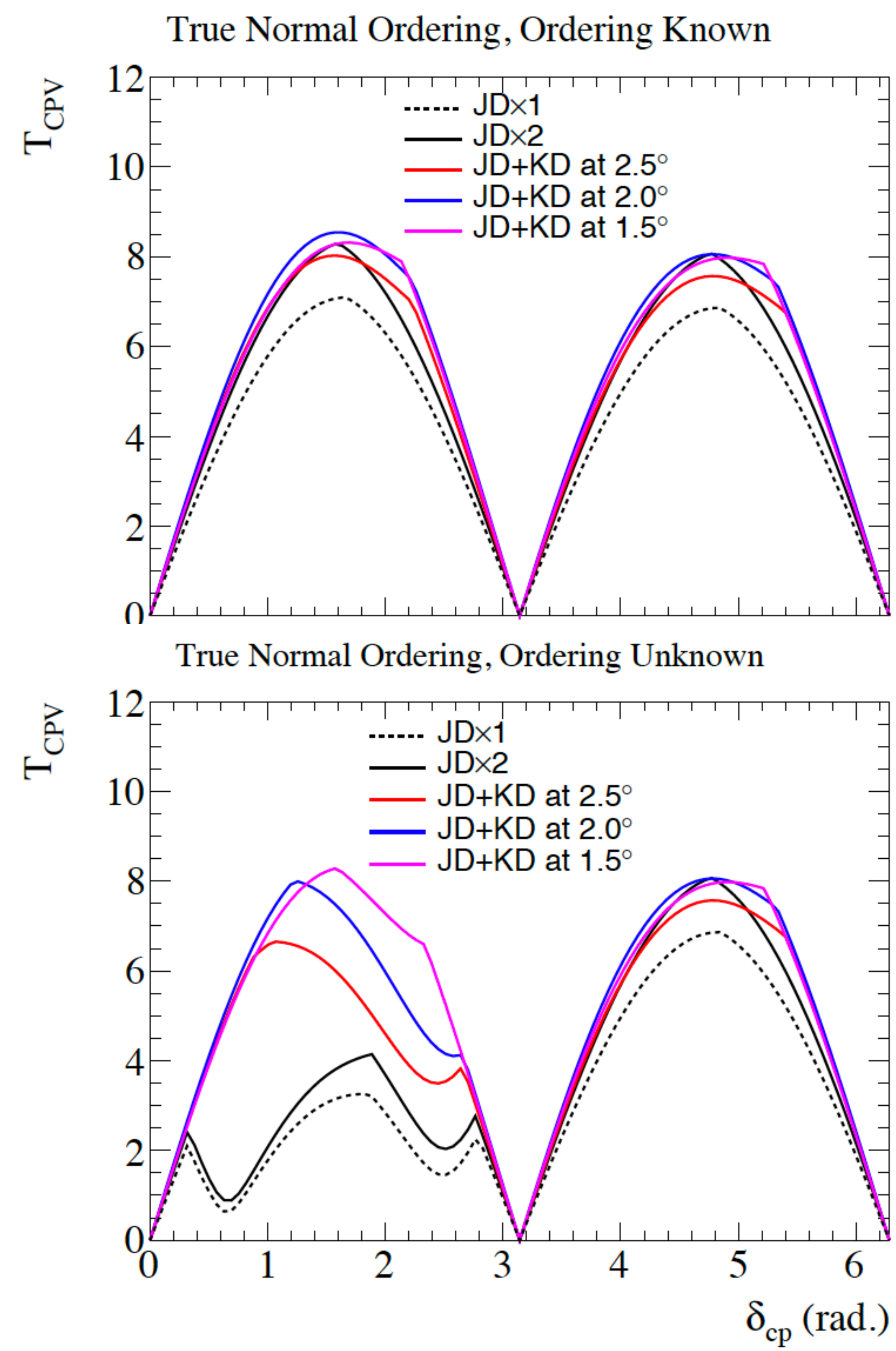
Exposures assuming 10 years of data taking with a beam of 1.3 MW

JD (Japan detector)
KD (Korea detector)

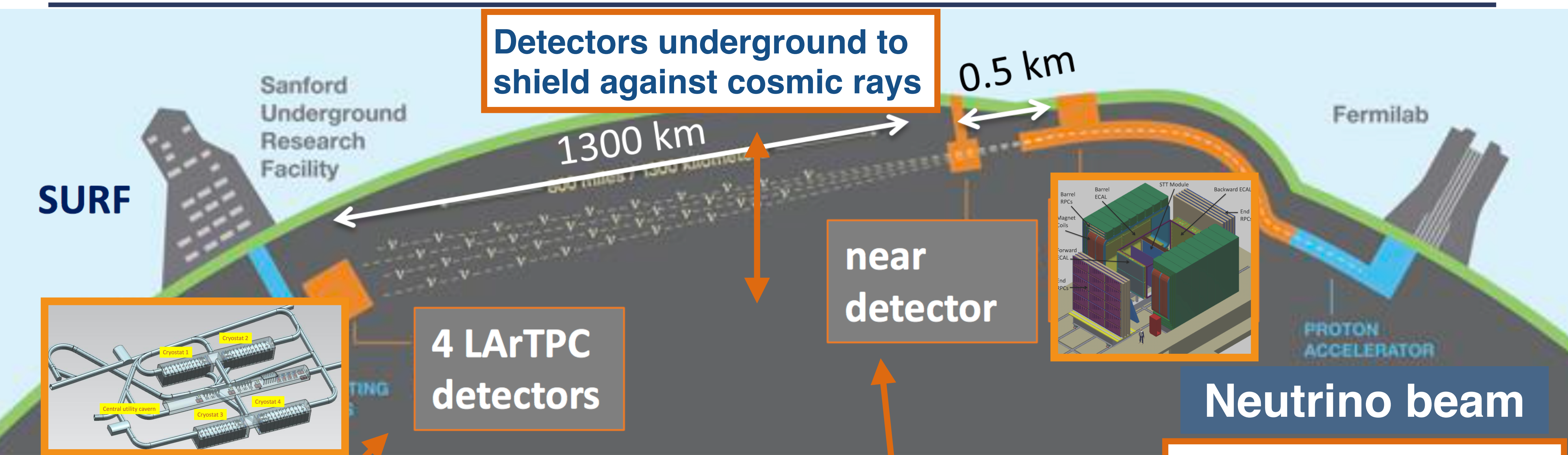
The significances to reject the wrong mass ordering



Significance to reject the CP conserving hypotheses



The DUNE experiment

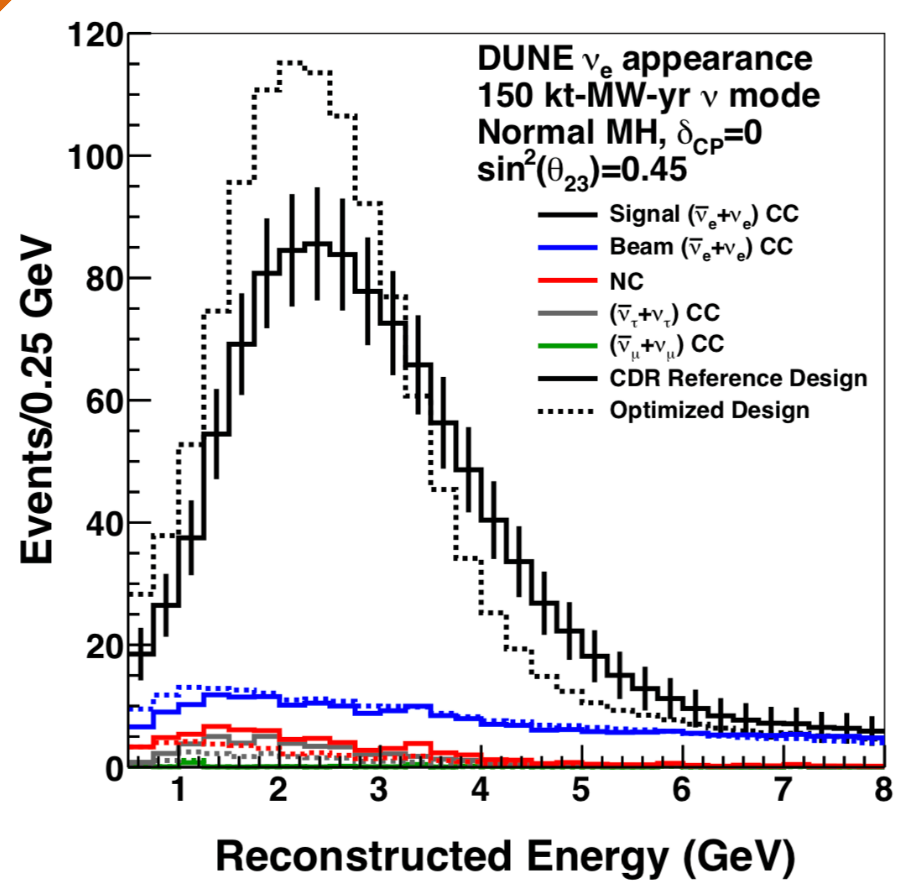


Neutrino beam

The foreseen proton beam power is 1.2 MW[upgradable to 2.4 MW].

Far detector

- 40 kton fiducial volume



Near detector

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

DUNE physics goals

Measure neutrino spectra at 1300 km in a wide-band energy beam:
Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment

Nucleon decay

- Proton decay searches in several important decay channels

Astrophysics

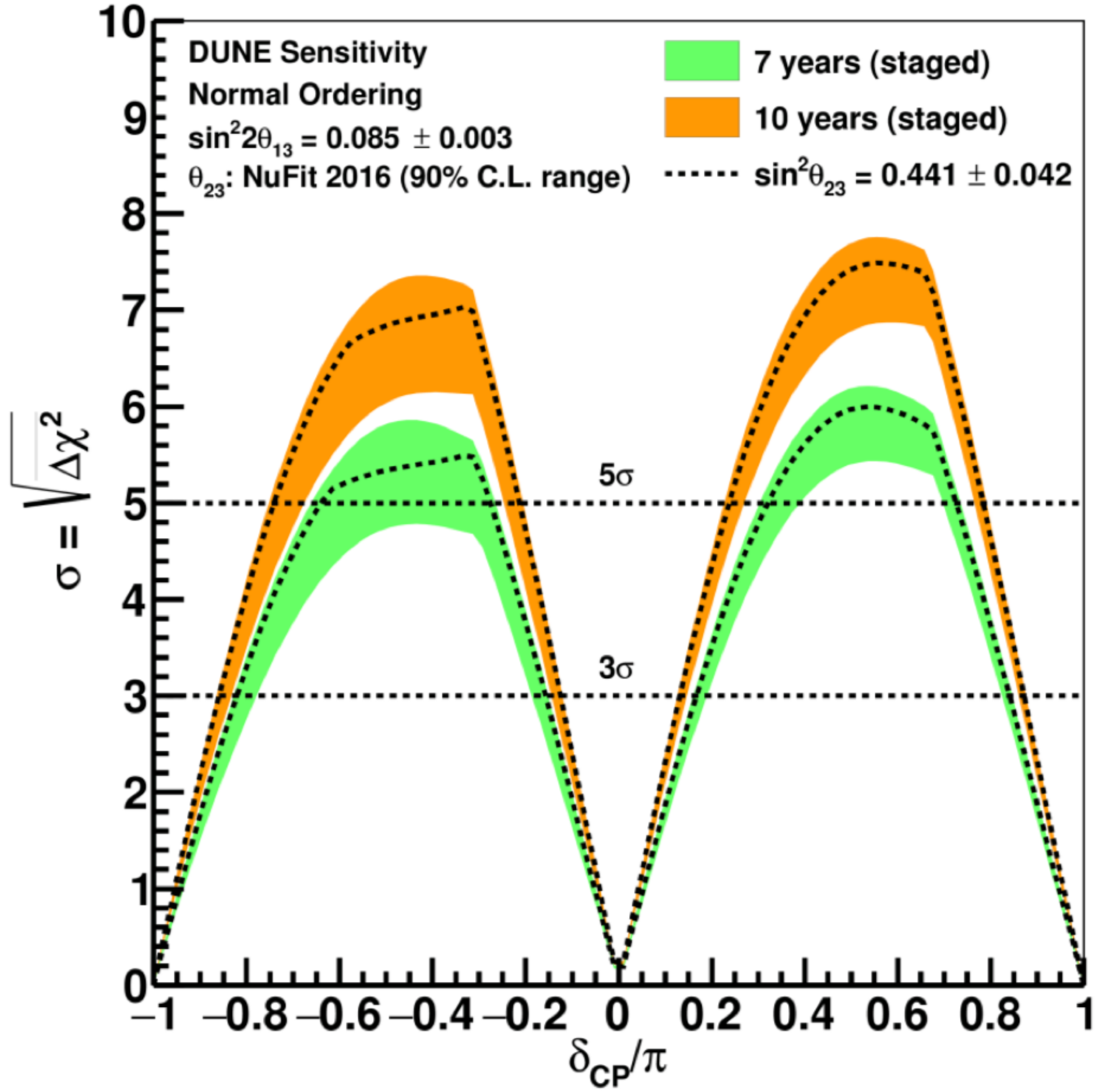
- Detection and measurement of the ν_e flux from a core-collapse supernova within our galaxy.

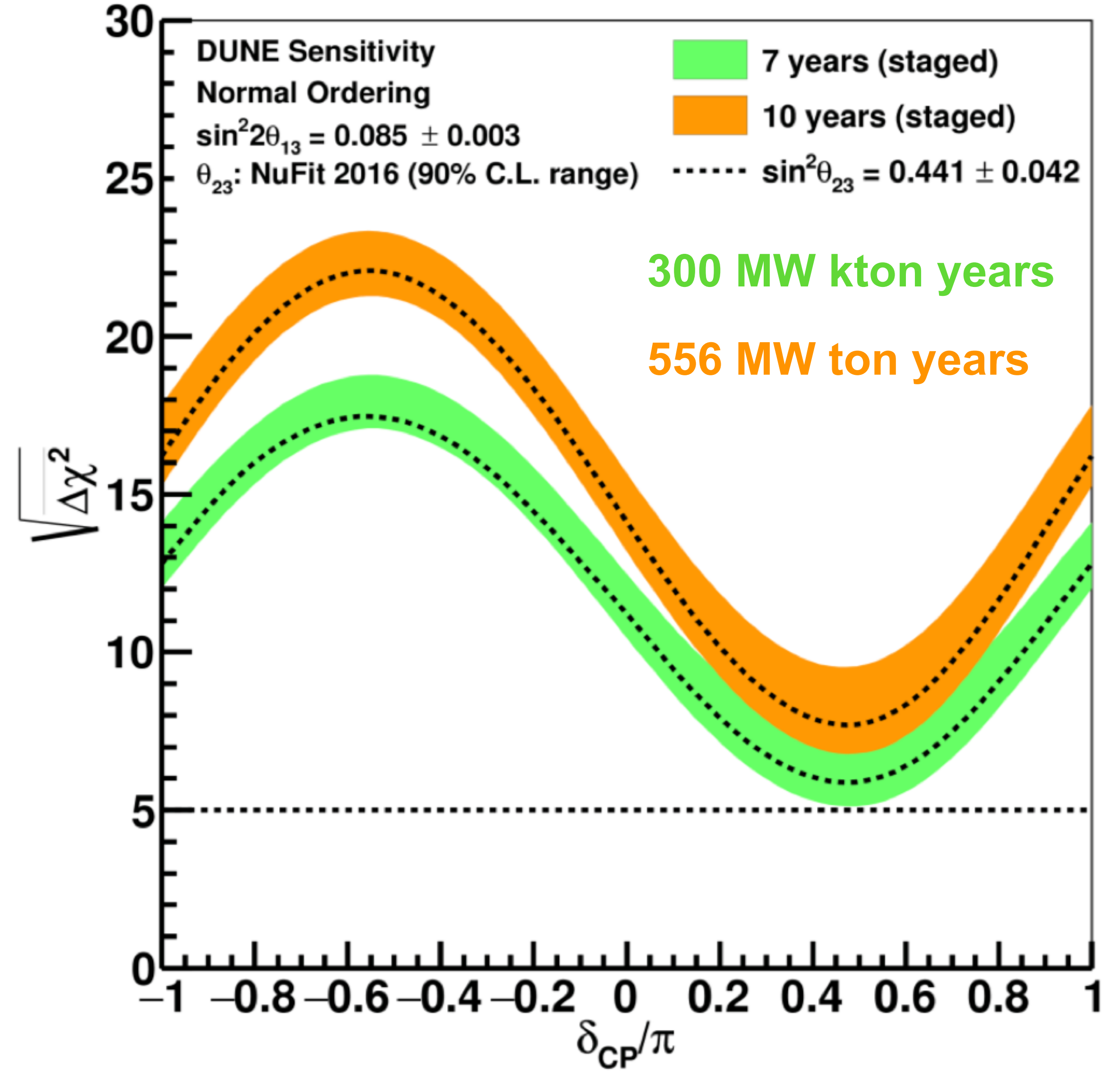
And…

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

Mass hierarchy and CP violation uncertainties

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



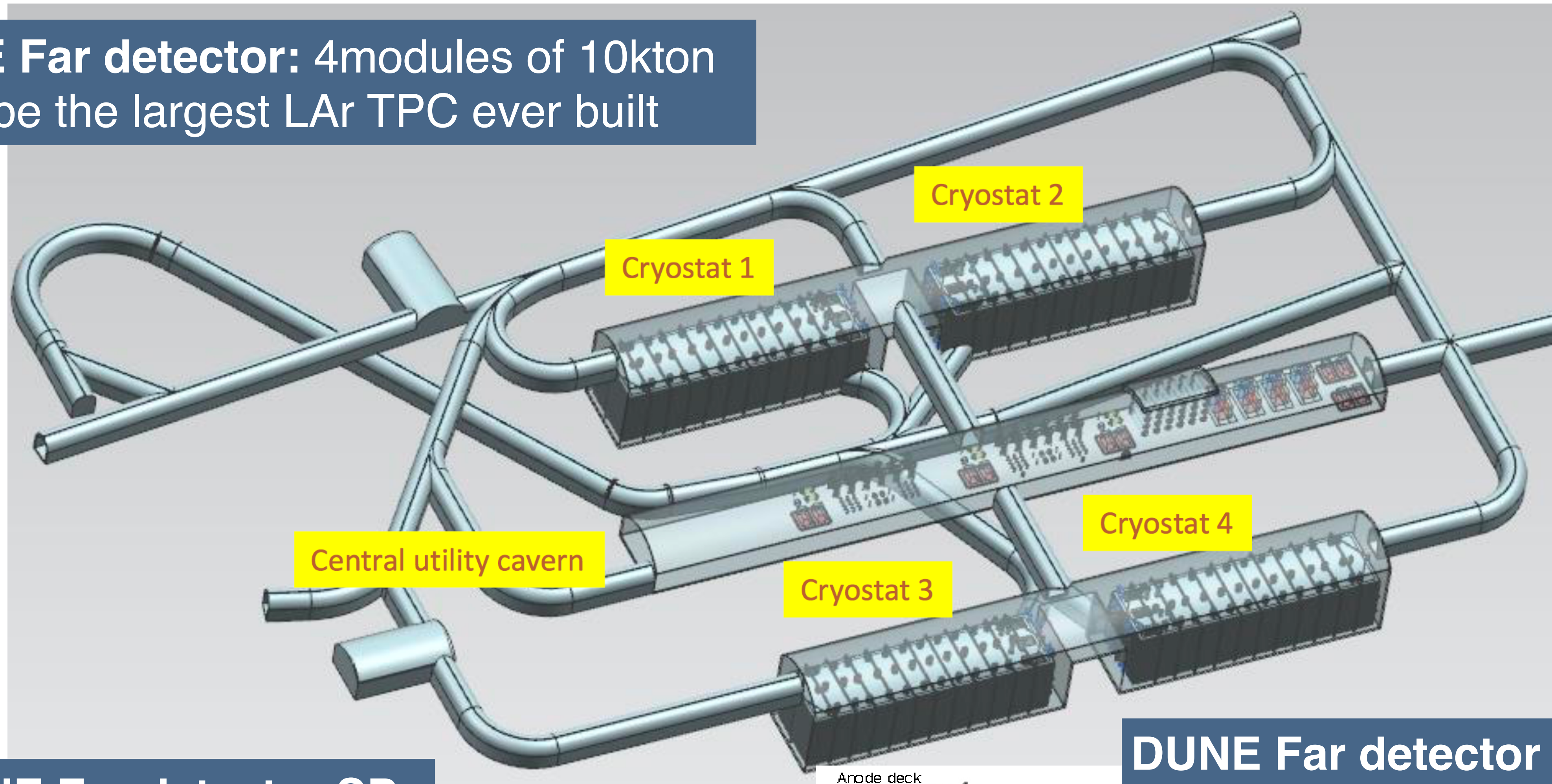


- The dashed line is the sensitivity for the NuFit central value of θ_{23}.
- Width of band corresponds to 90% CL variations in value of θ_{23} based on NuFit 2016 fit values.

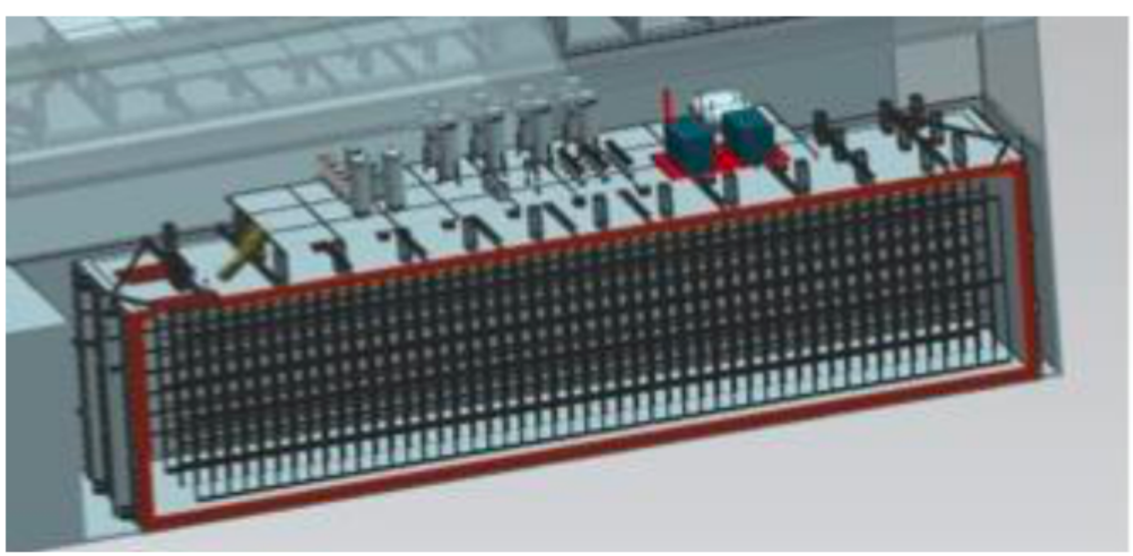
In year 7 (2032) beam upgraded foreseen to 2.4 MW

DUNE far detector

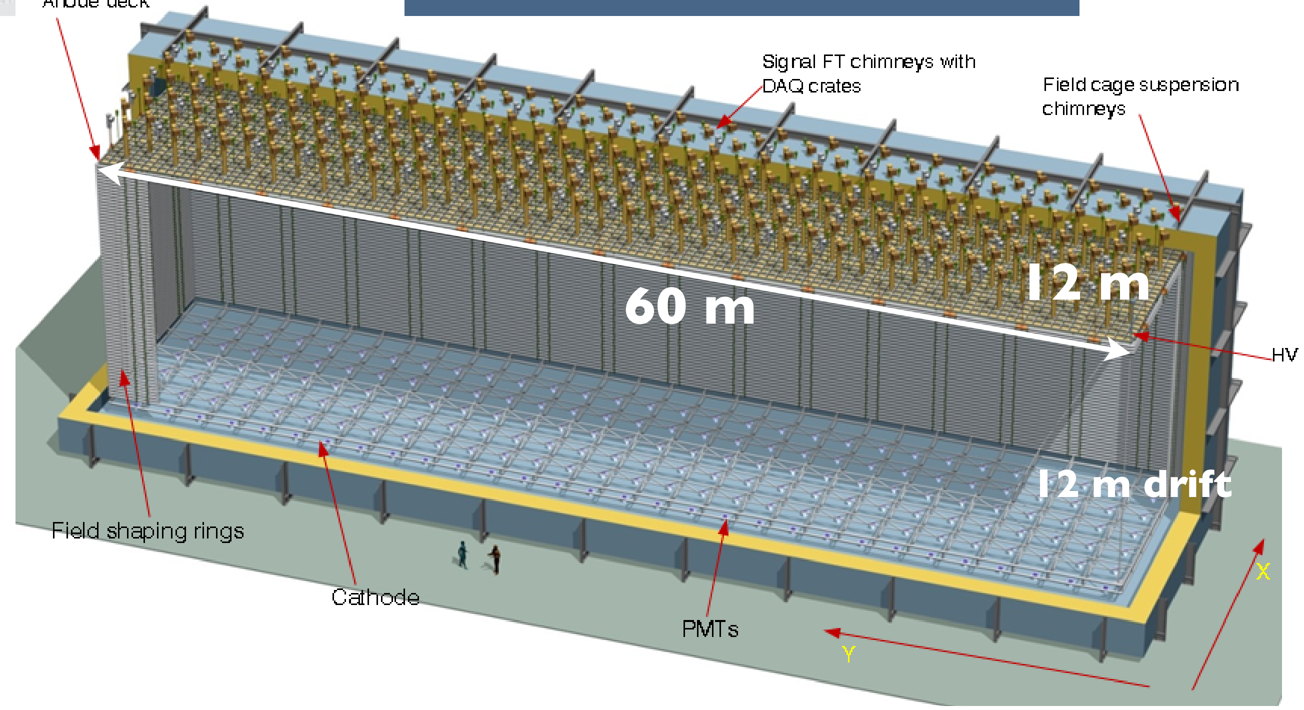
DUNE Far detector: 4modules of 10kton
It will be the largest LAr TPC ever built



DUNE Far detector SP



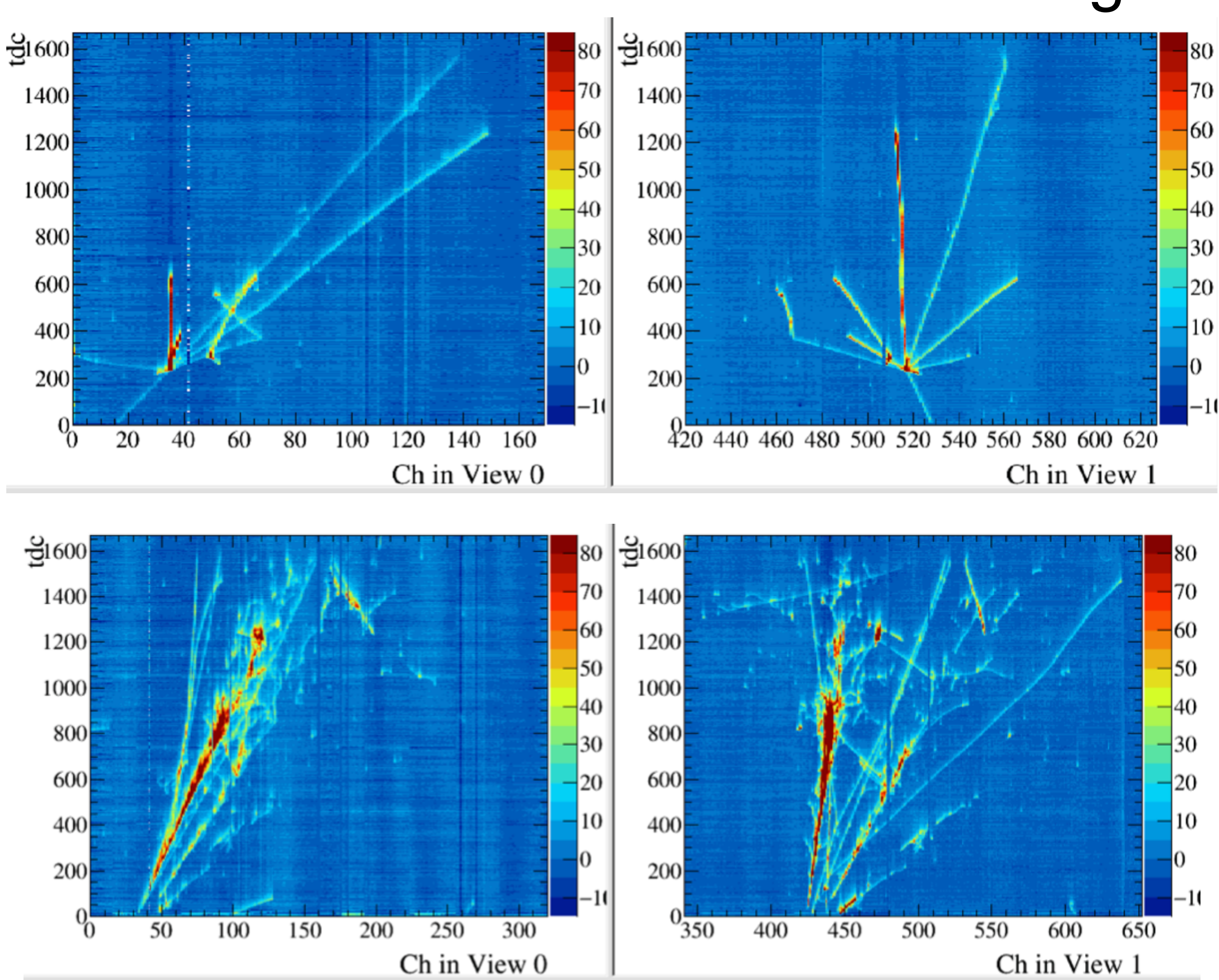
DUNE Far detector DP



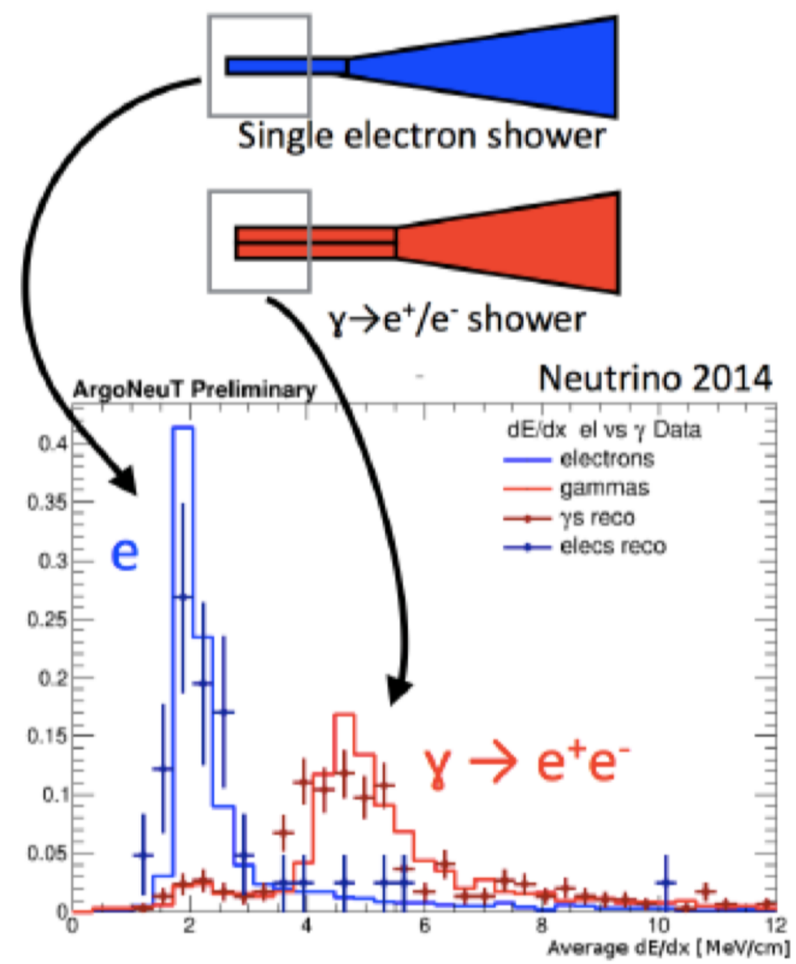
Why LAr TPCs?

- **High density medium.**
- **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.**

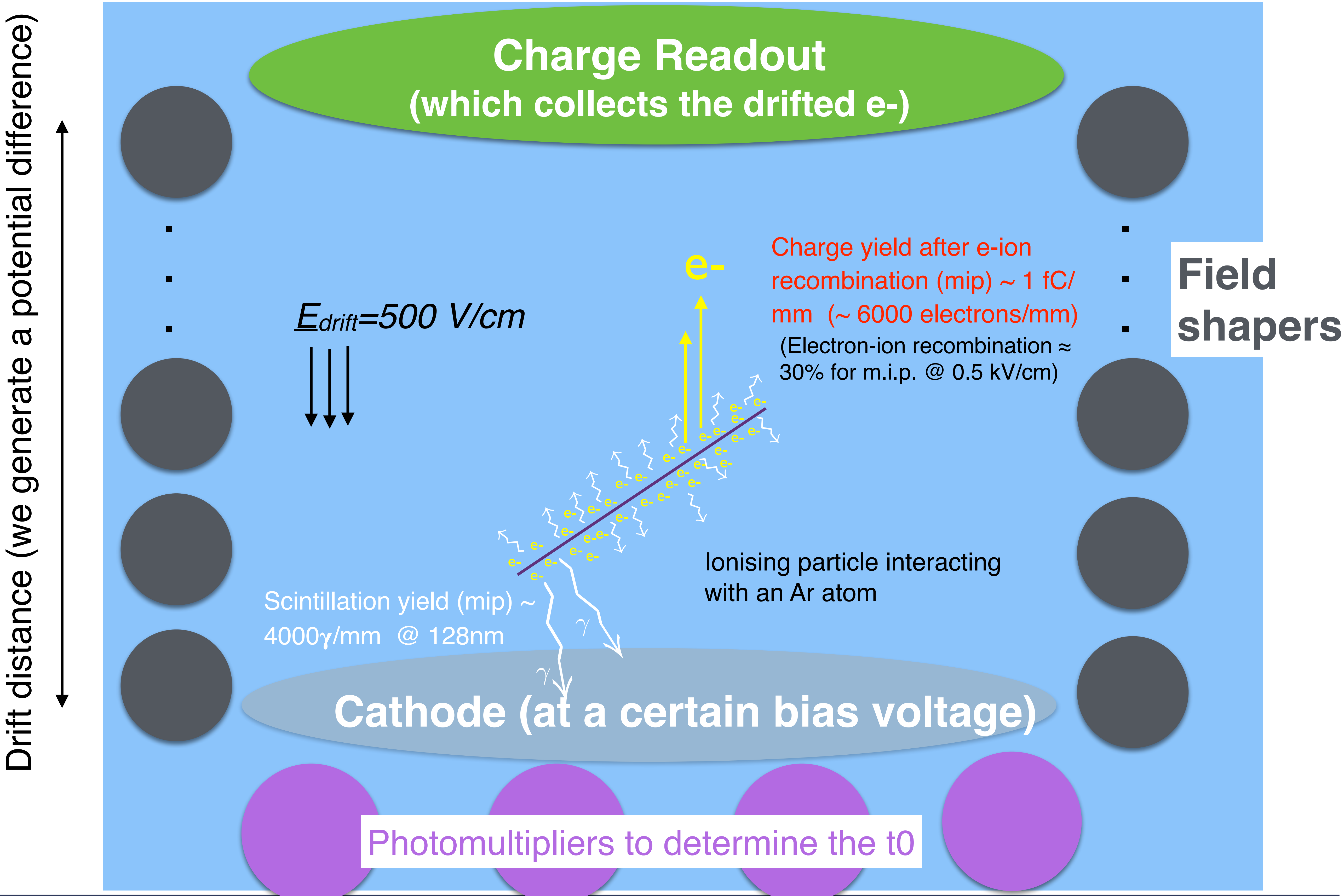
Raw data no noise filtering



Data from the 3x1x1 prototype (WA105)



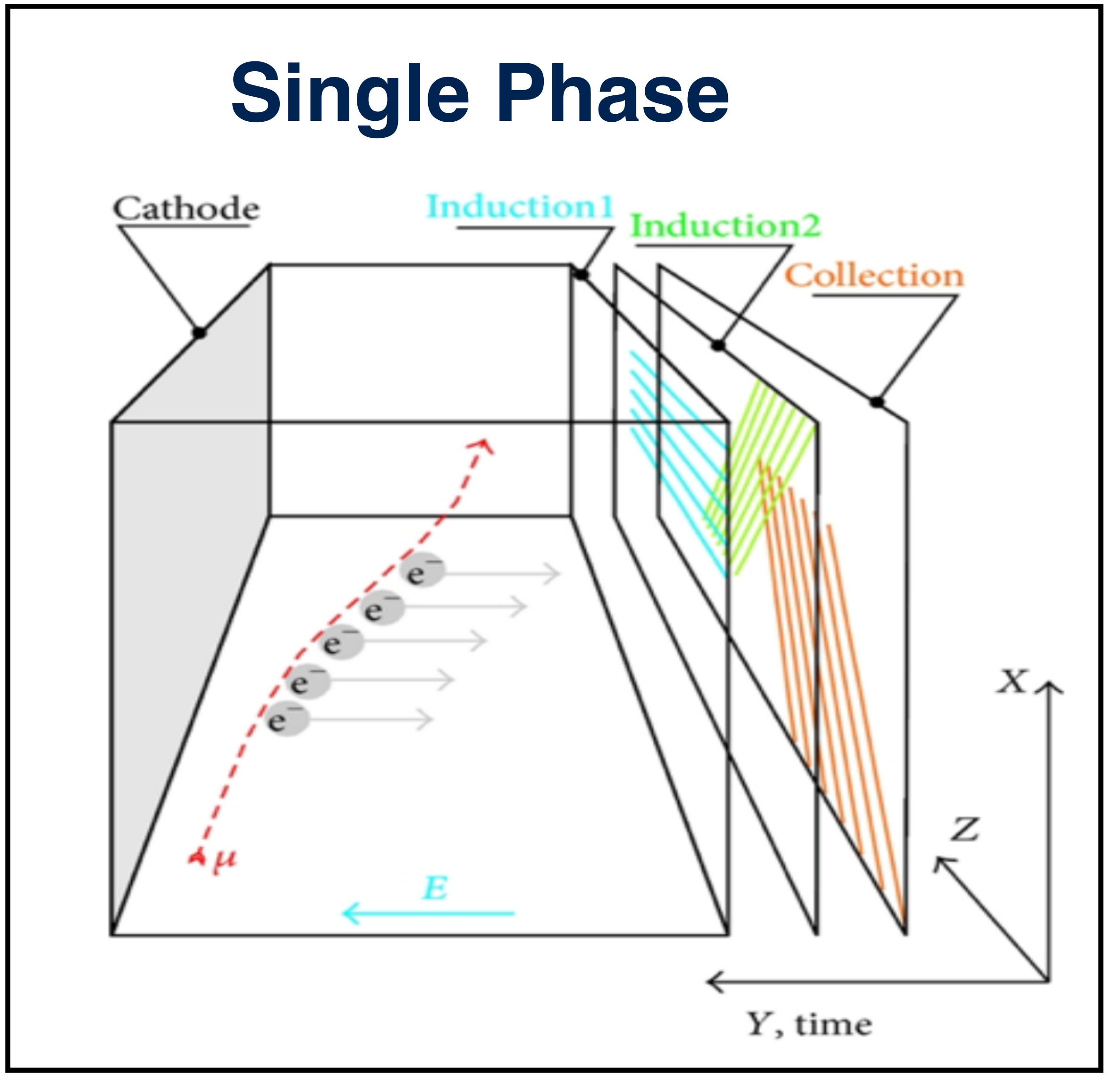
LAr TPC principle

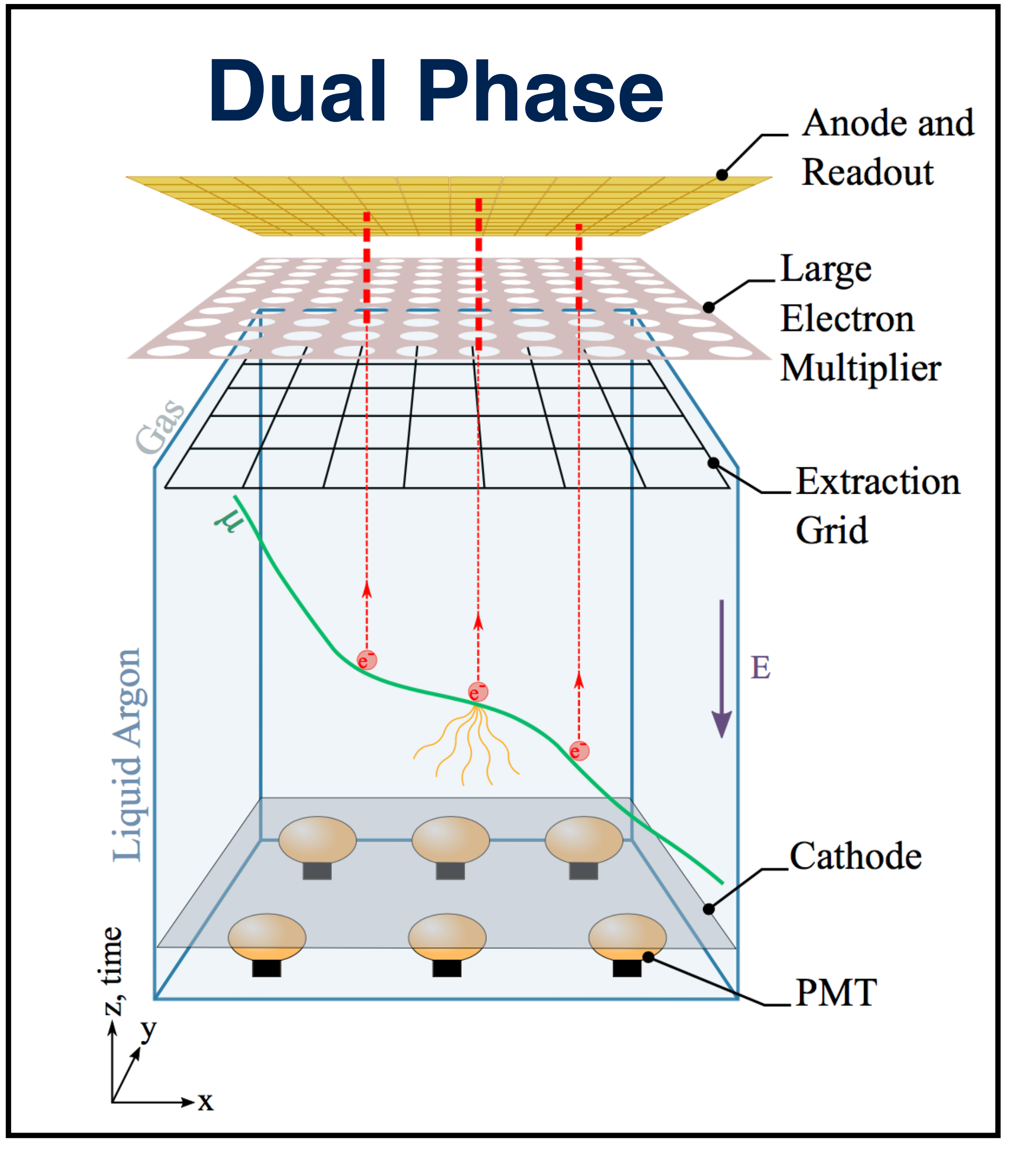


Two complementary technologies

- 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





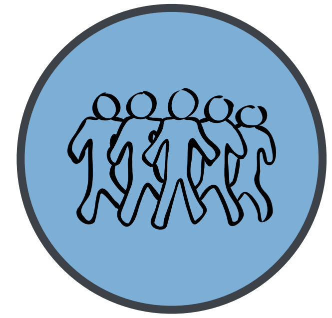
Towards the 10 kton detector

Single-Phase LAr TPC

Dual-Phase LAr TPC

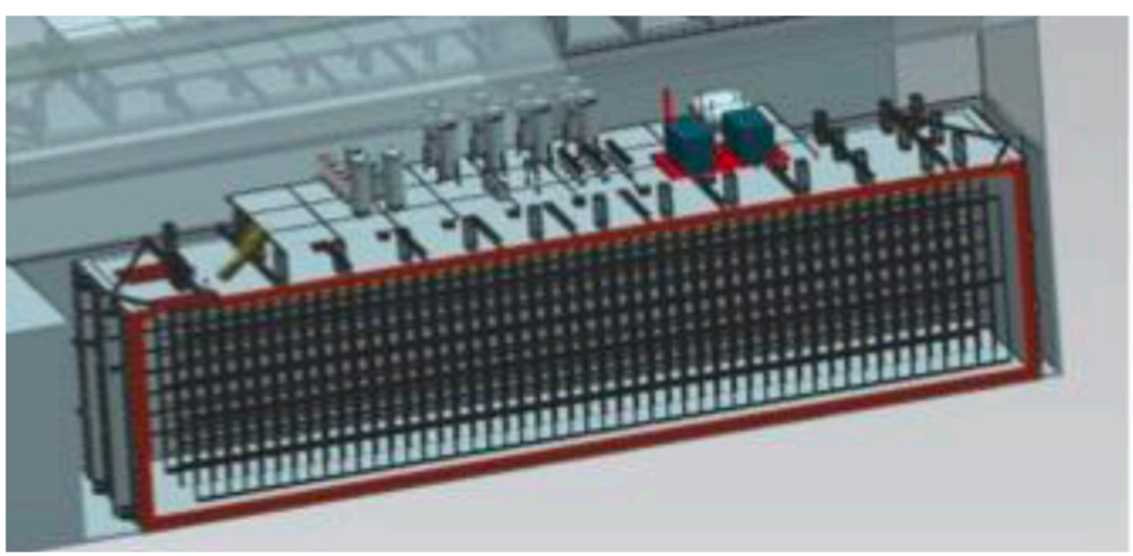
R&D

FUNDING

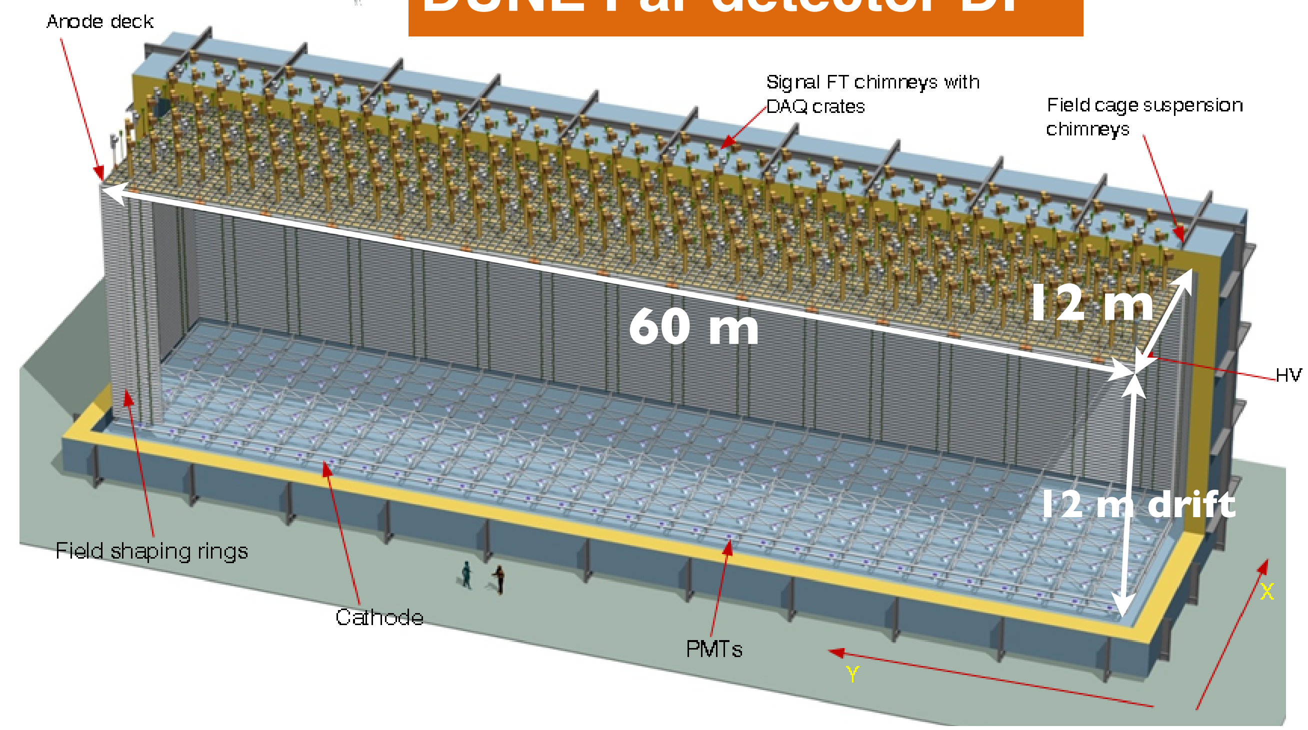


PEOPLE

DUNE Far detector SP

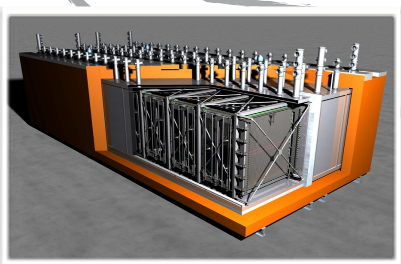


DUNE Far detector DP



Towards the 10 kton detector

ICARUS
LNGS→FNAL
2010-13→2018

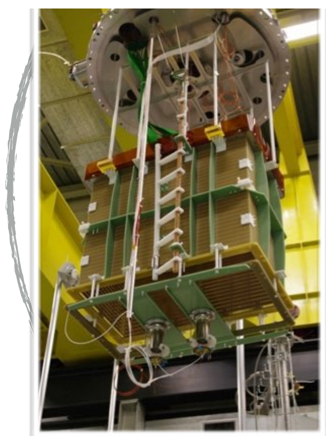


ArgoNeuT
FNAL 2009-10

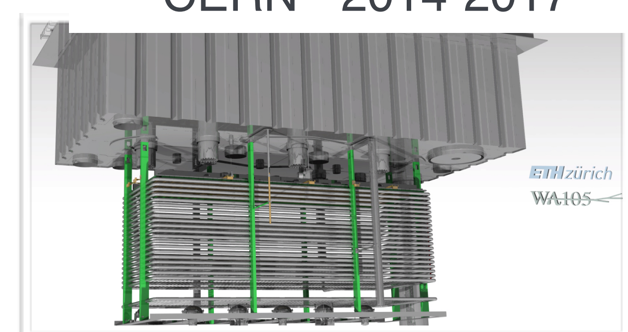
LAPD
FNAL 2010-11

3L 10x10 cm³ TPC
ETHZ R&D (at CERN)

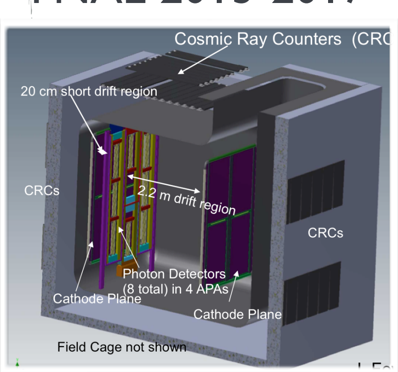
250L 40x80 cm³ TPC
ETHZ R&D (at CERN)



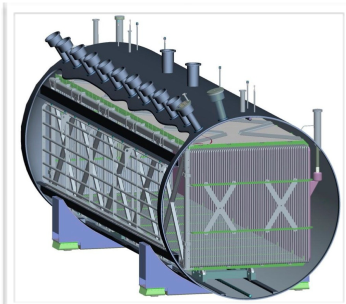
WA105 3x1x1 m³
DP LAr TPC demonstrator
CERN - 2014-2017



35 t
FNAL 2013-2017

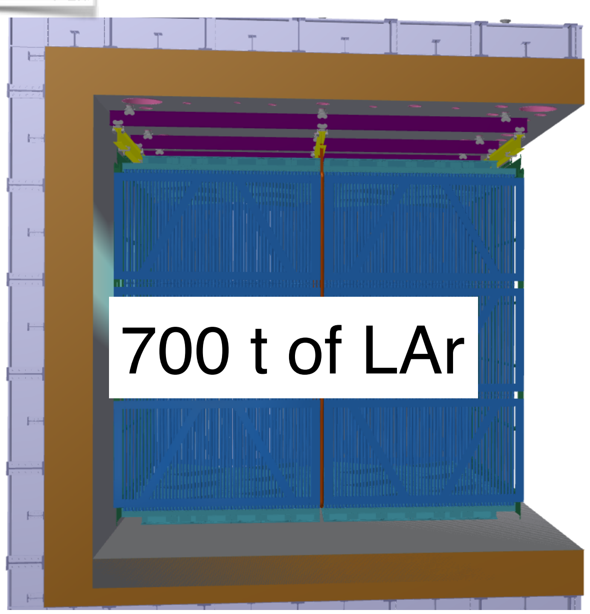


μBooNE
FNAL 2015-in run

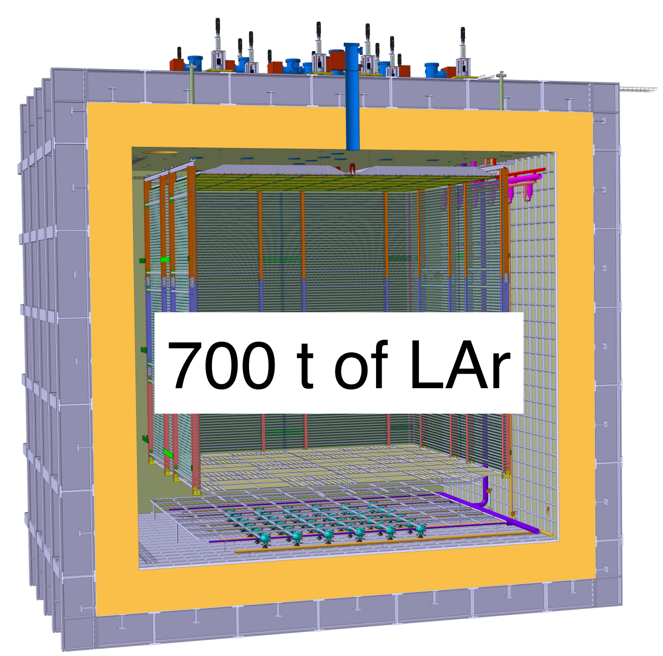


LArIAT
FNAL 2014-2018

ProtoDUNE Single-Phase



After many decades of R&D, the technology has matured into a fundamental and necessary technique to address the current neutrino physics challenges.

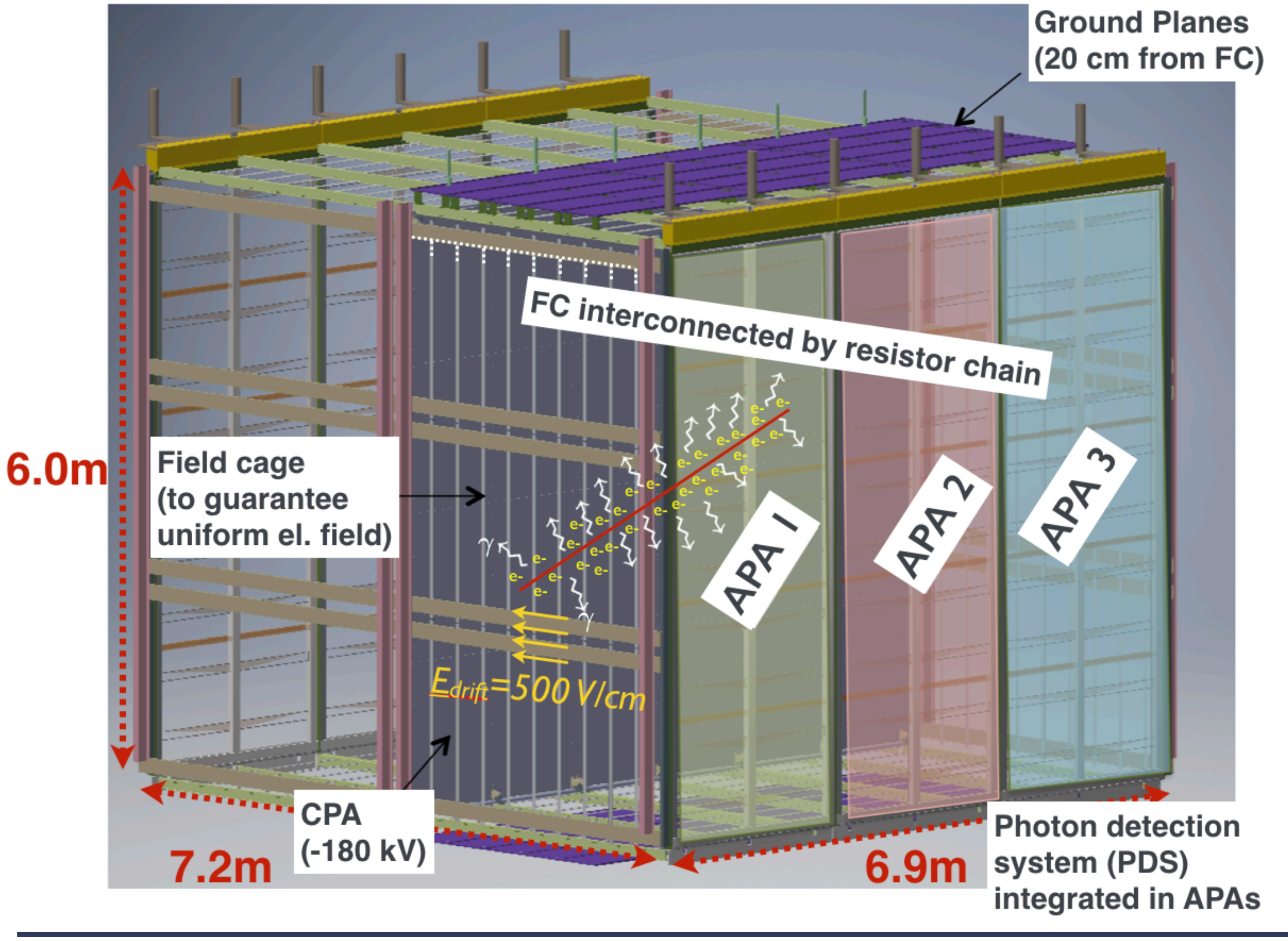


ProtoDUNE Dual-Phase

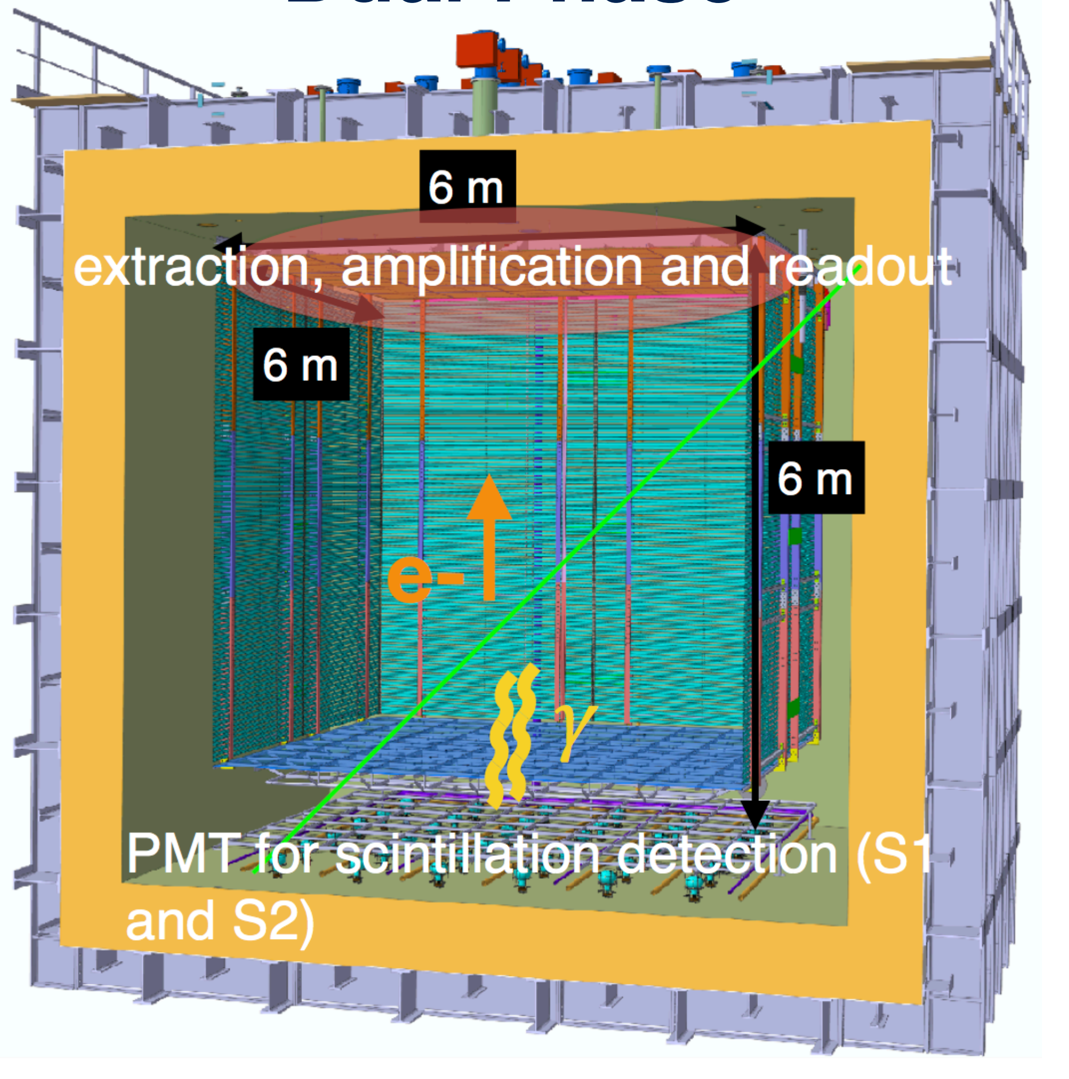
Towards the 10 kton detector: The ProtoDUNEs project

- Engineering the technology through the 10 kton detector
- Test two different technologies: ***single phase*** and ***dual phase***
- Develop the construction and QA processes
- Test the detectors with cosmics and beam data

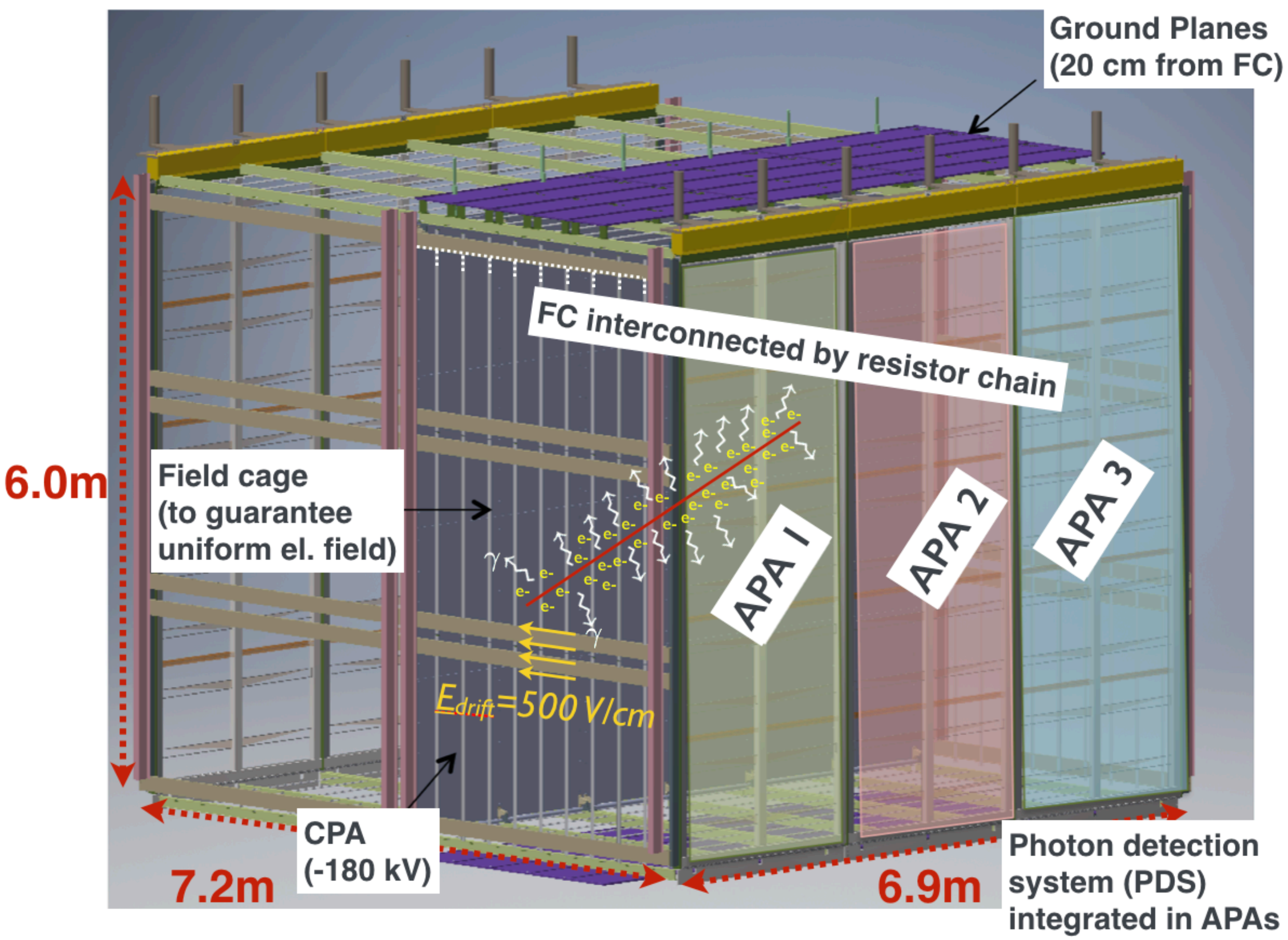
Single Phase



Dual Phase



Single Phase

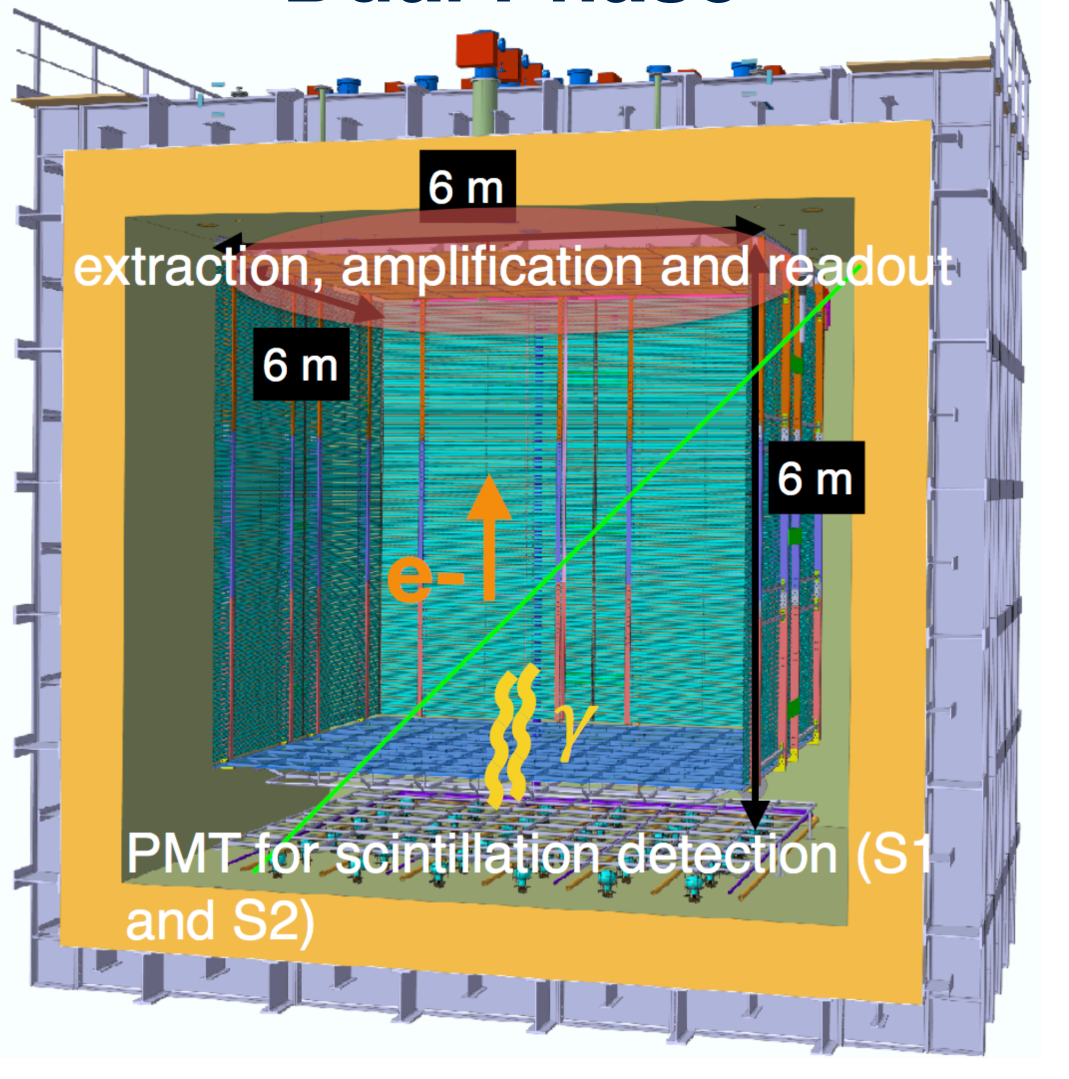


- Total mass **770 t**
- Two drift regions 3.6 m long (same as DUNE-SP drift length)
- Central Cathode plane Assembly (CPA) 180 kV for 500 kV/cm
- Anode plane assembly (APA)
- 2 planes with 3 APAs each
- 5 mm wire pitch
- 1 APA 6 m x 2.3 m
- Photosensor (SiPMs) integrated in APA
- Cold electronics

Towards the 10 kton detector: The ProtoDUNEs project

- Total mass **700 t**
- **One drift region 6 m long**
- **Level meters** to monitor the liquid level
- Cathode at **-300 kV** (for a 500 V/cm drift field)
- Four 3x3 m² Charge Readout Planes (CRP),
- 36 Photomultipliers tubes for light collection
- 2 CRPs with 36 LEMs each to be installed
- 2 not instrumented CRPs

Dual Phase



The ProtoDUNEs project

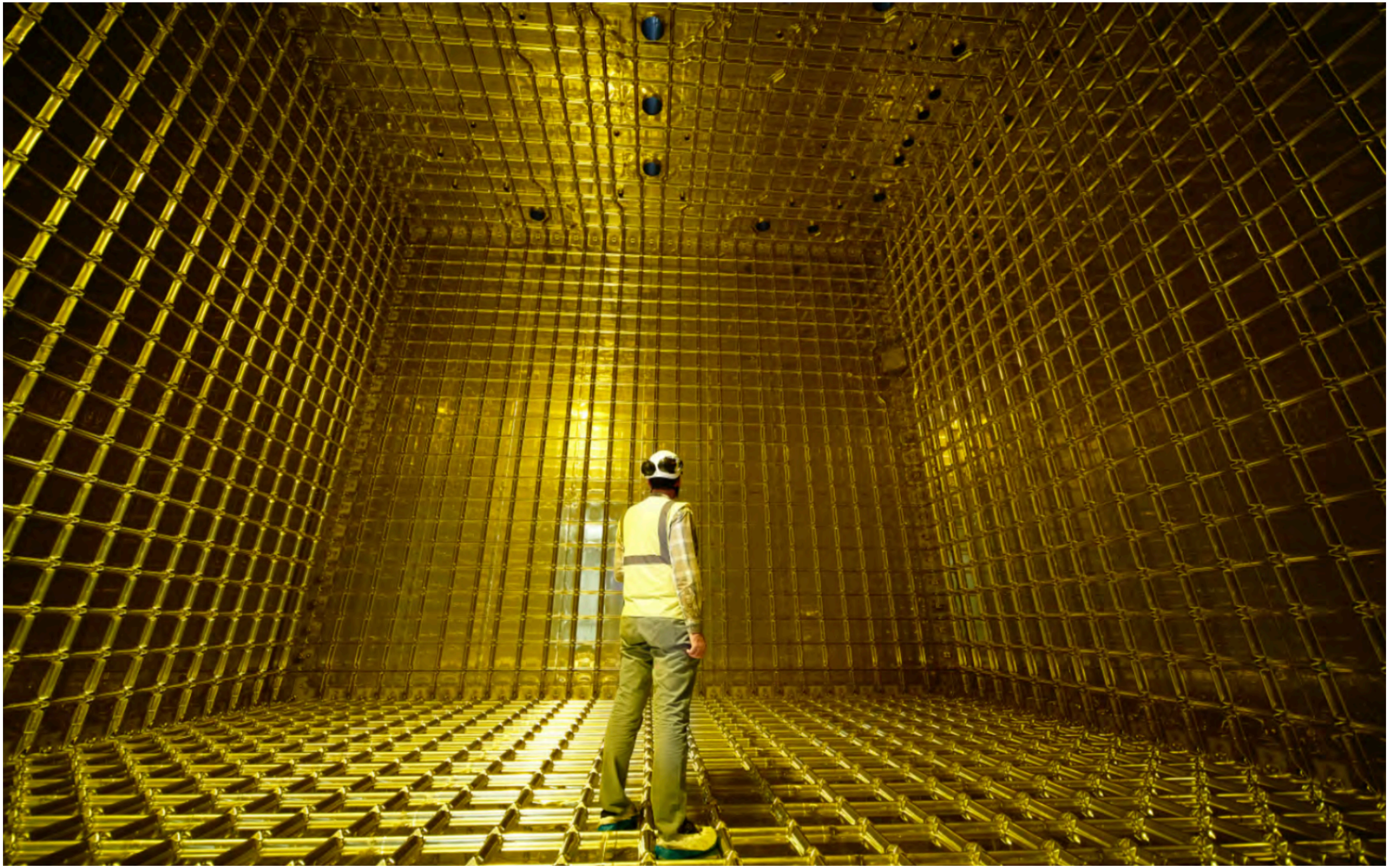
The ProtoDUNEs project

The ProtoDUNEs project: Synergies

Both detectors are LAr TPC embedded in the same non-evacuable membrane cryostat

- Cryostat
- Cryogenic system
- Drift cage
- Very high voltage system
- Time projection chamber instrumentation
- Slow control
- Safety aspects
- Beam requirements

The cryostat

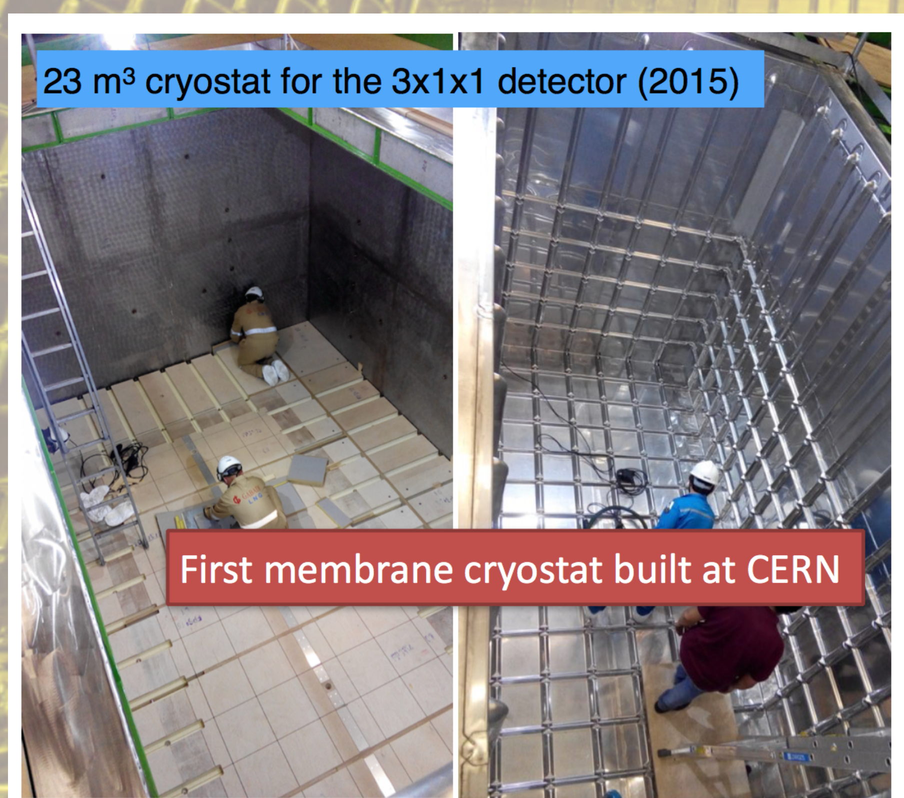


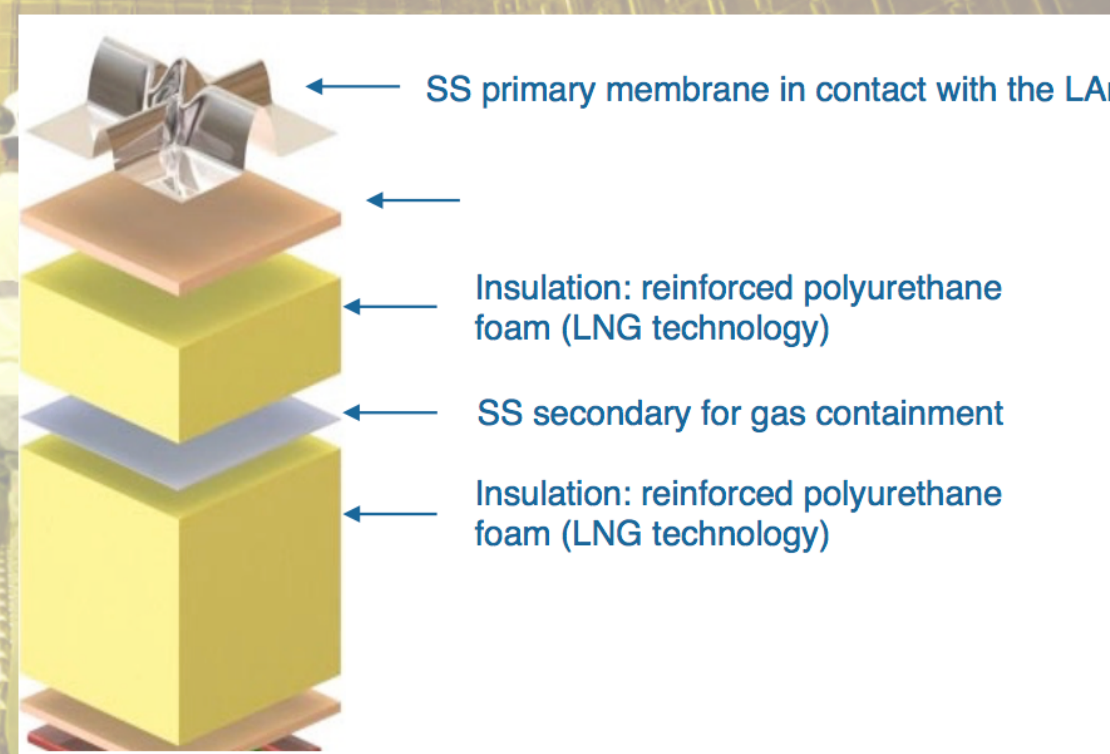
The cryostat

Non-evacuable membrane cryostat

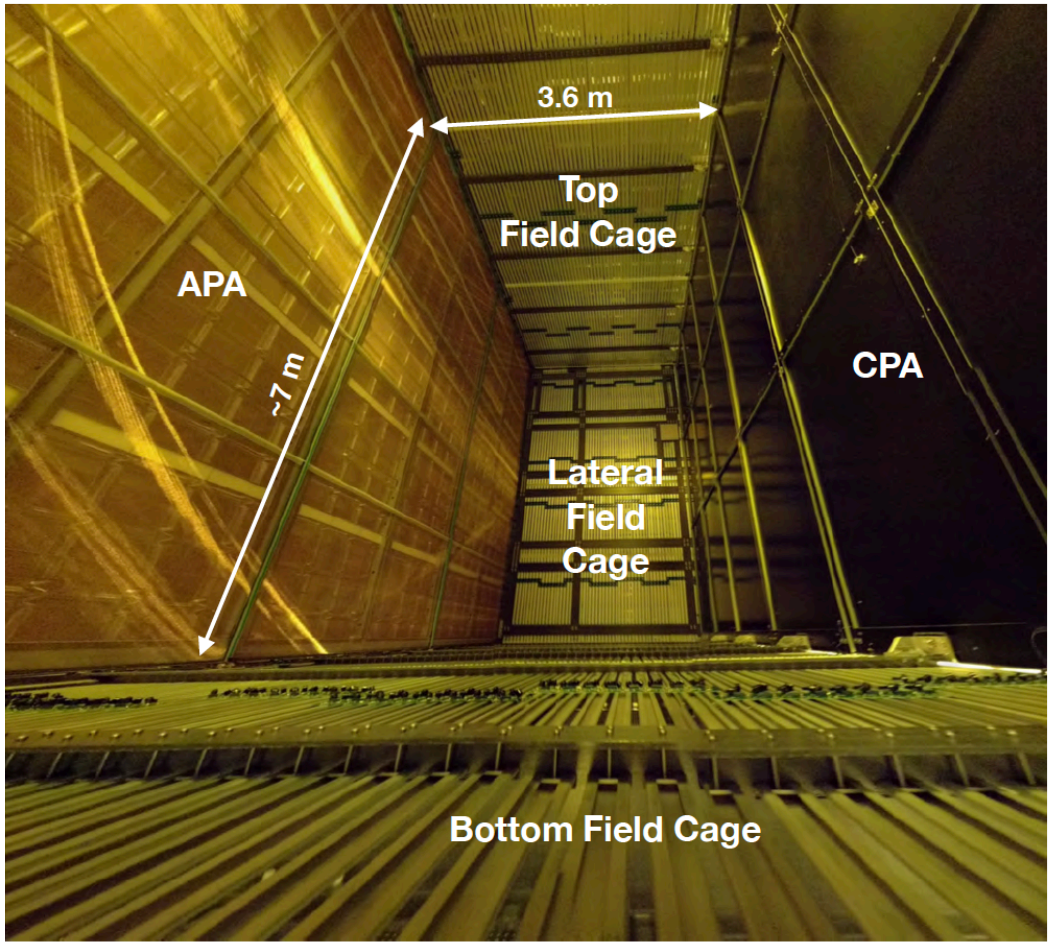
Same design for both protoDUNEs (and future DUNE far detector) constructed by Gaz Transport and Technigaz (GTT) company.

First GTT constructed cryostat for LAr at CERN for the 3x1x1 dual-phase prototype.
Three levels of passive insulation with less than 1 m thickness made with polyurethane foam and plywood.

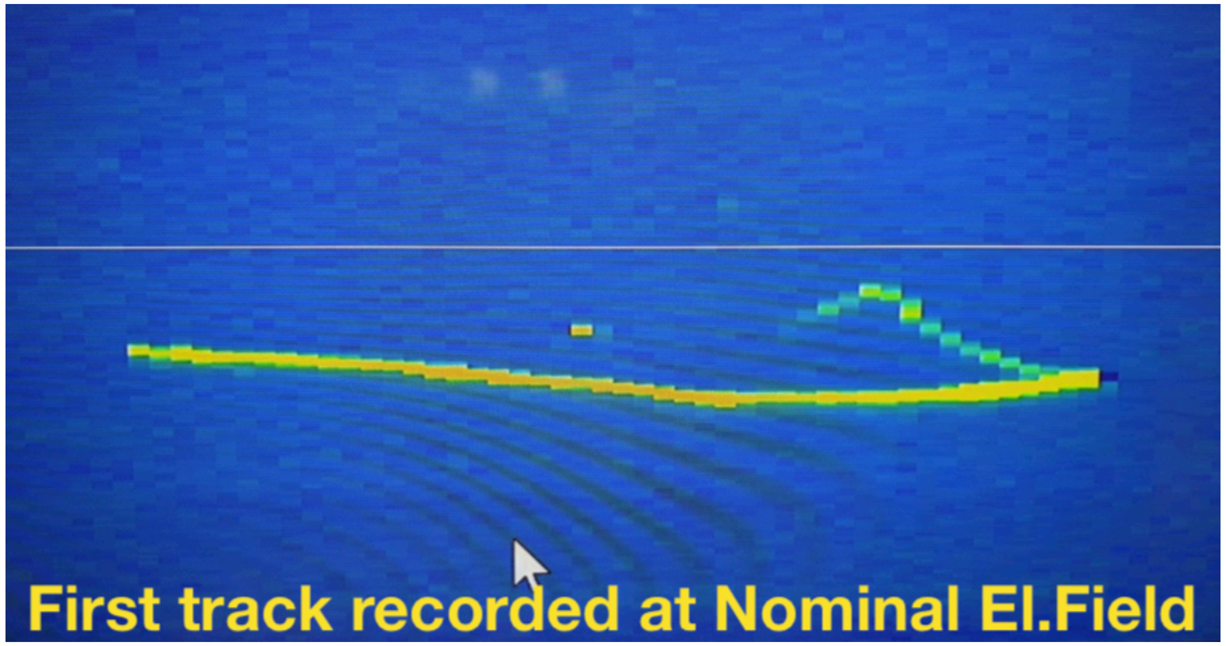


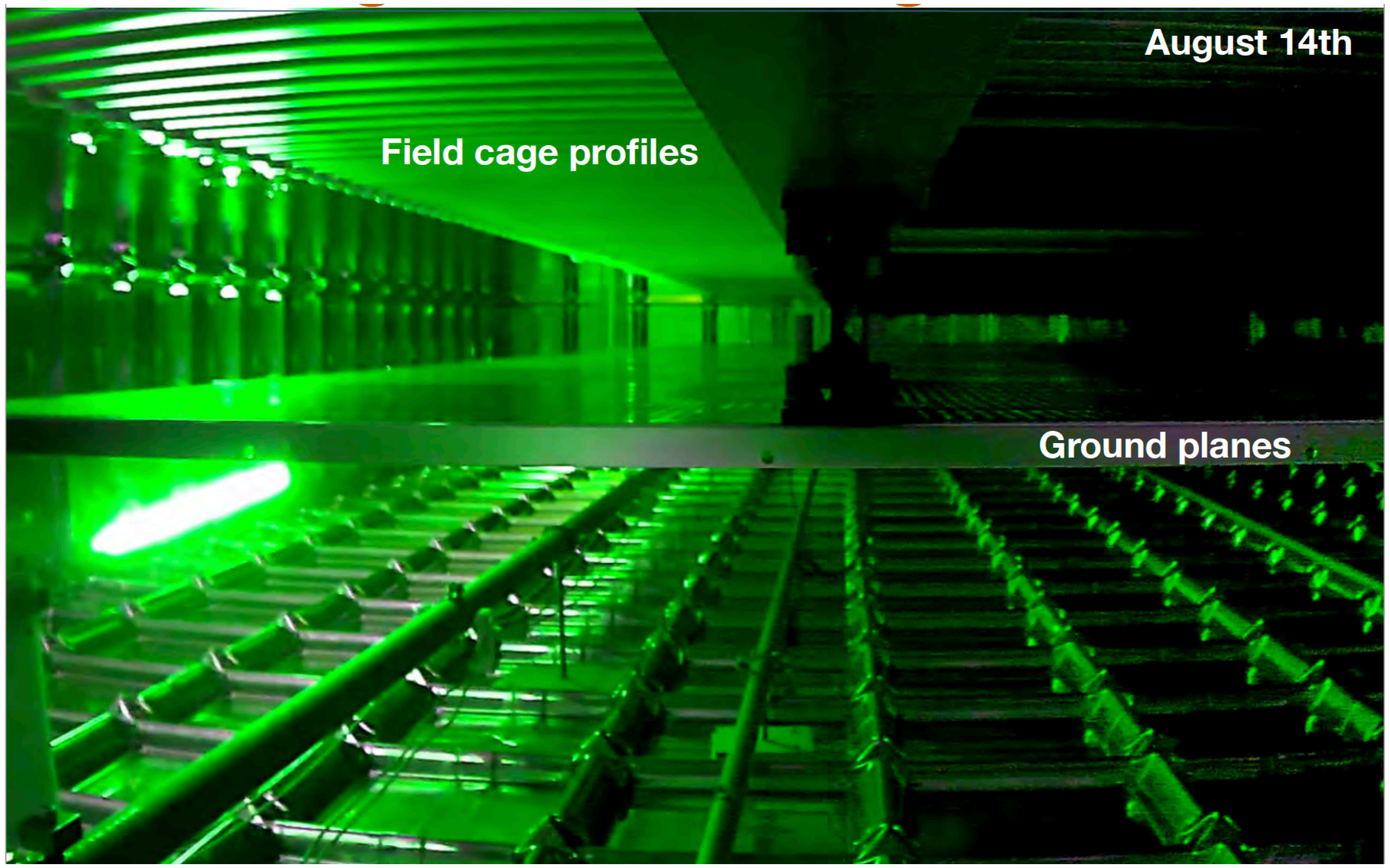


The ProtoDUNEs project: Single phase



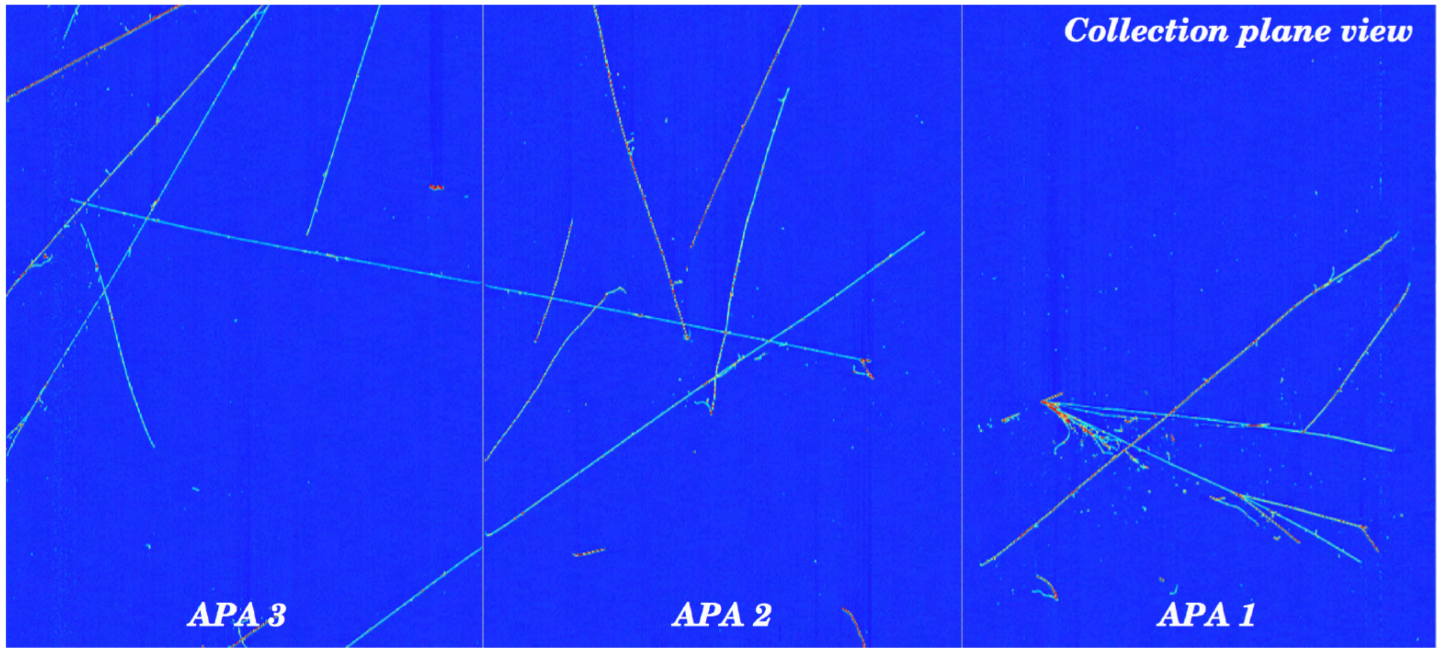
- Construction and installation completed in July 2018
- Filling between August and September 2018
- First track recorded at nominal field 21st of September 2018
- Beam data between September and November 2018





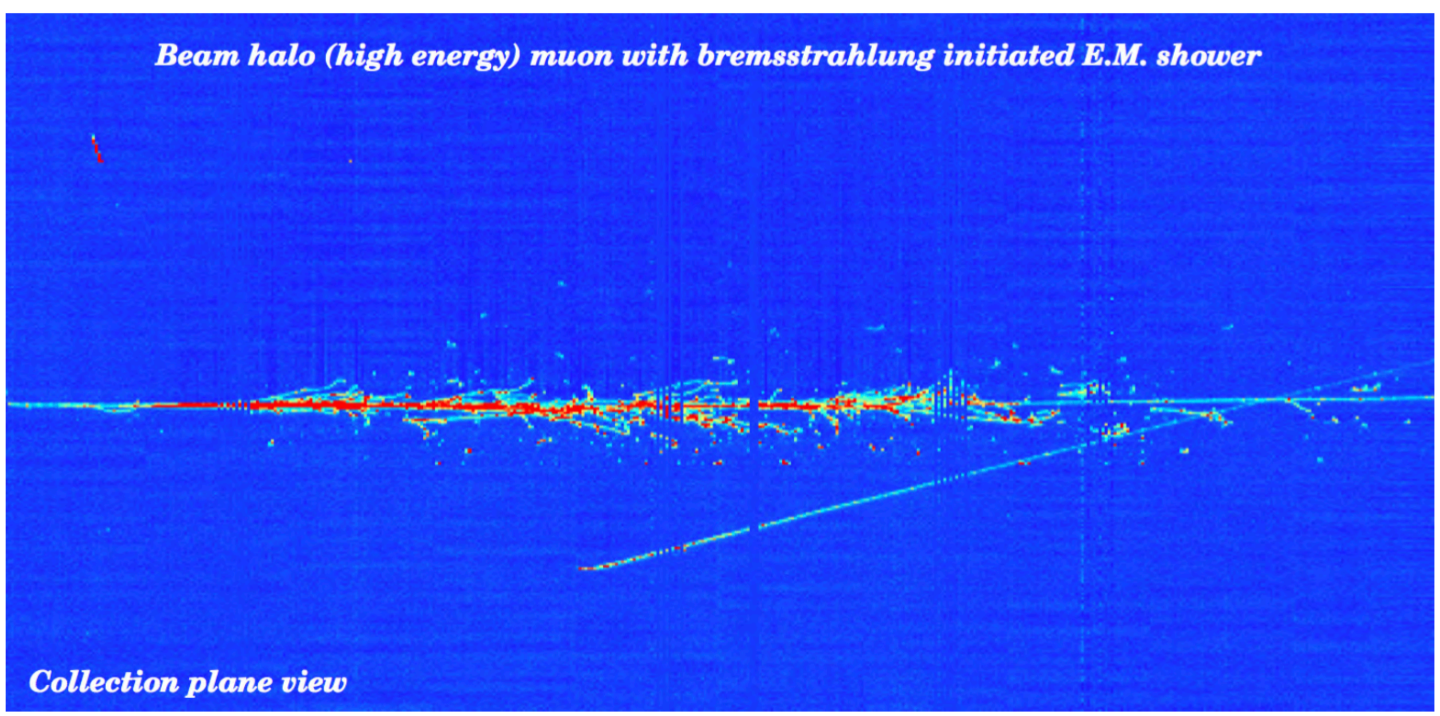
The ProtoDUNEs project: Single phase

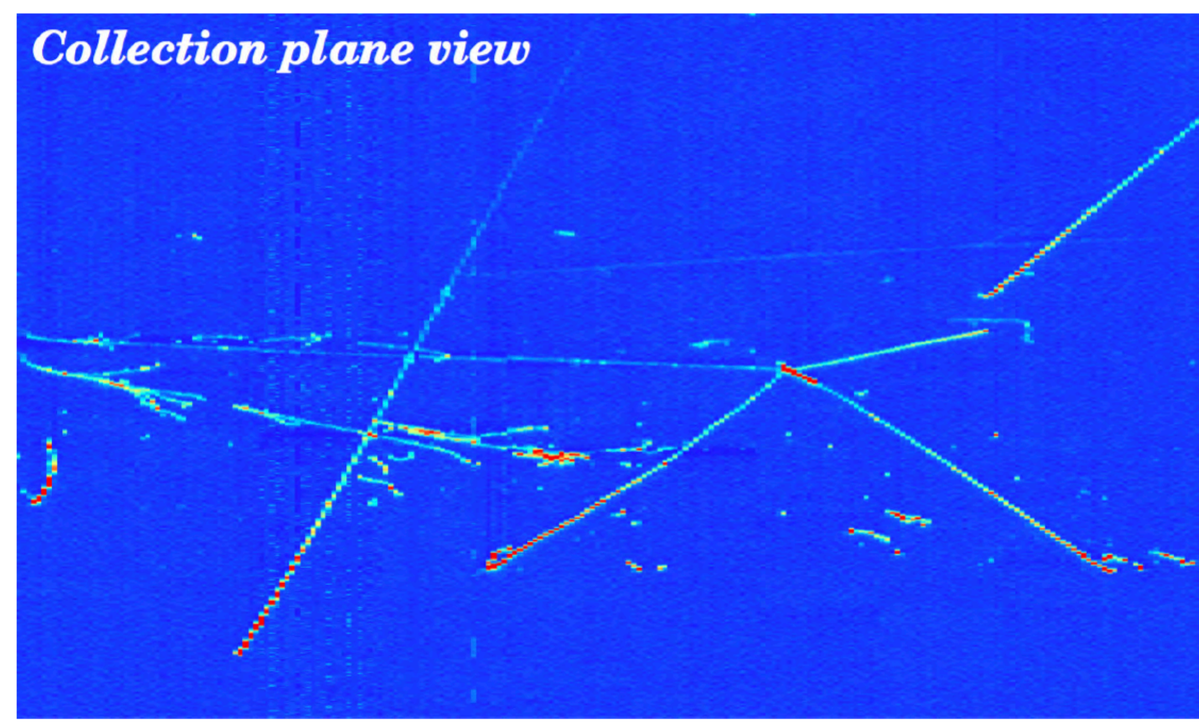
7 GeV beam proton



7 m

- More than 4 million of events collected.
- Excellent purity achieved compatible with electron lifetime better than 6 ms.
- Stable high voltage operation at nominal field.

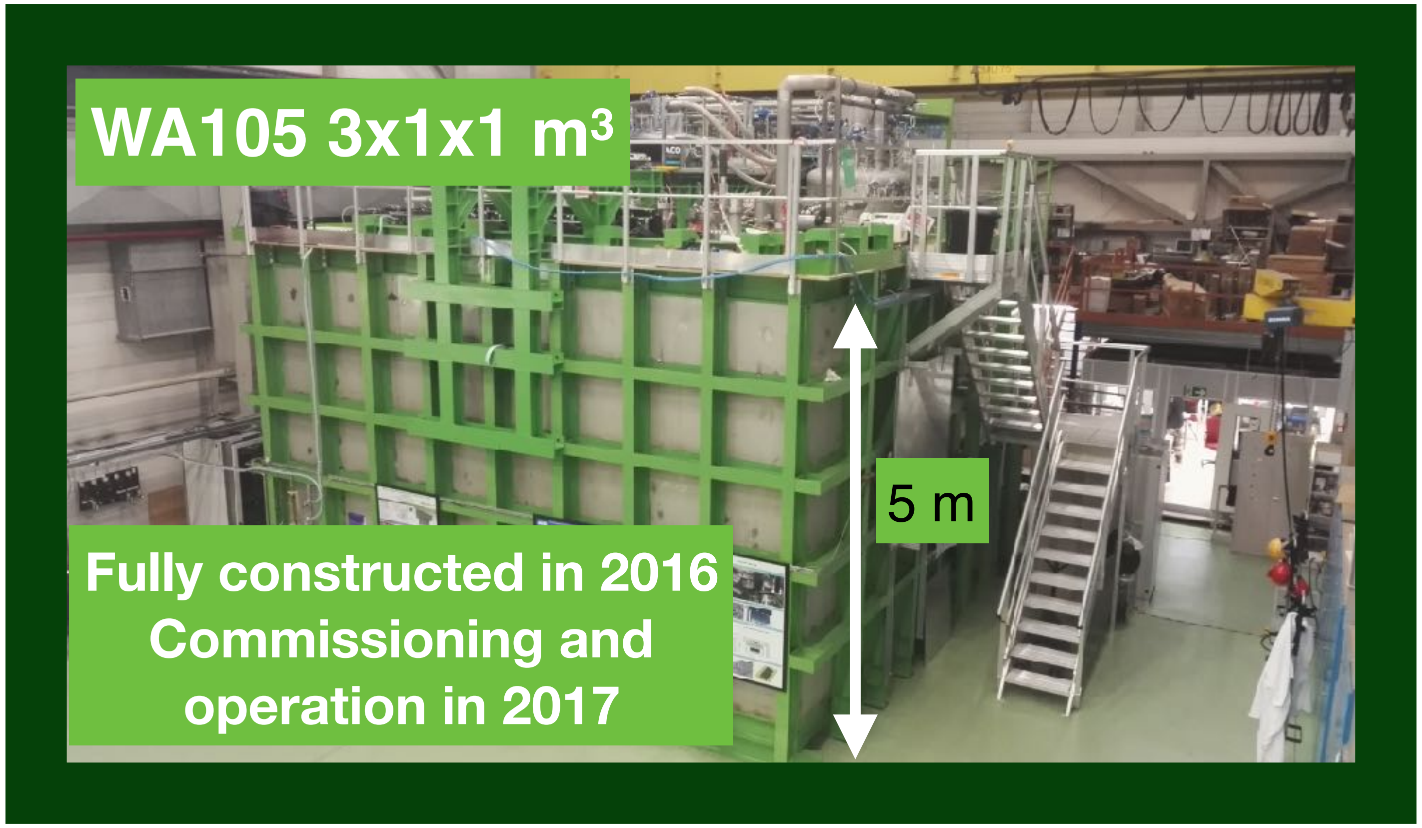




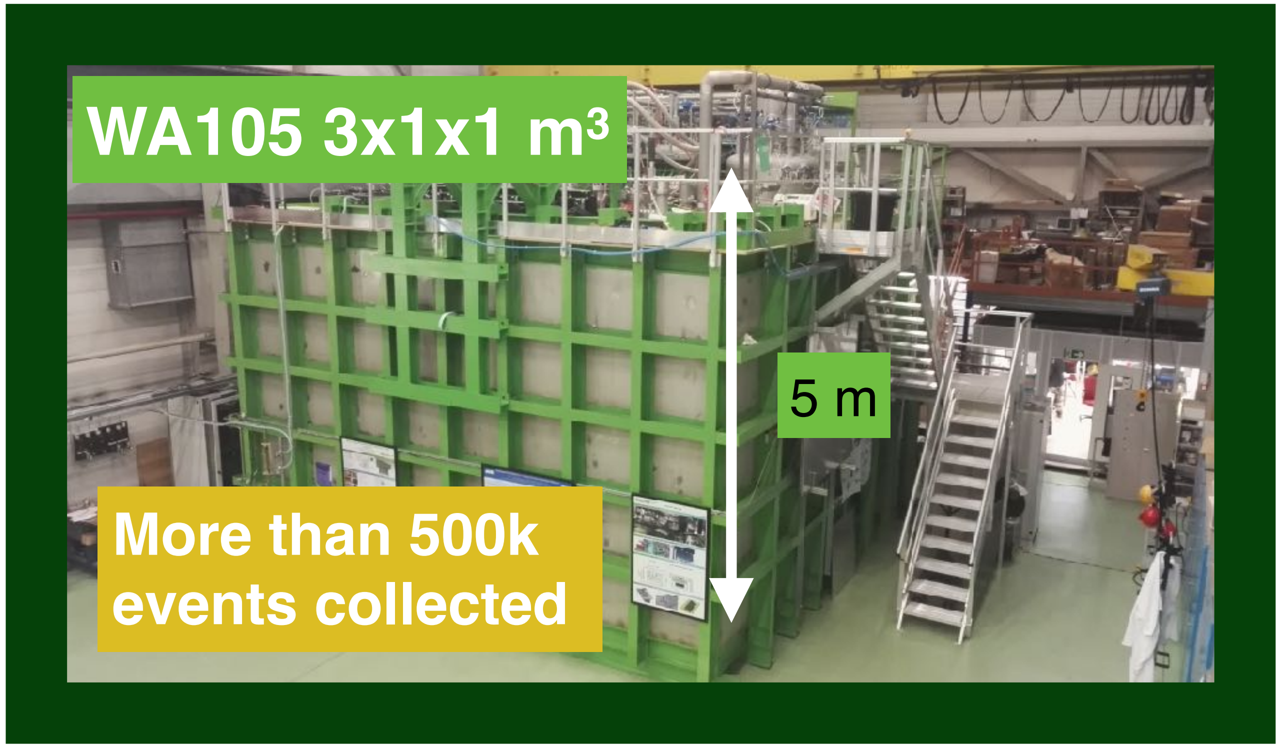
The ProtoDUNEs project: Dual phase

Common aspects

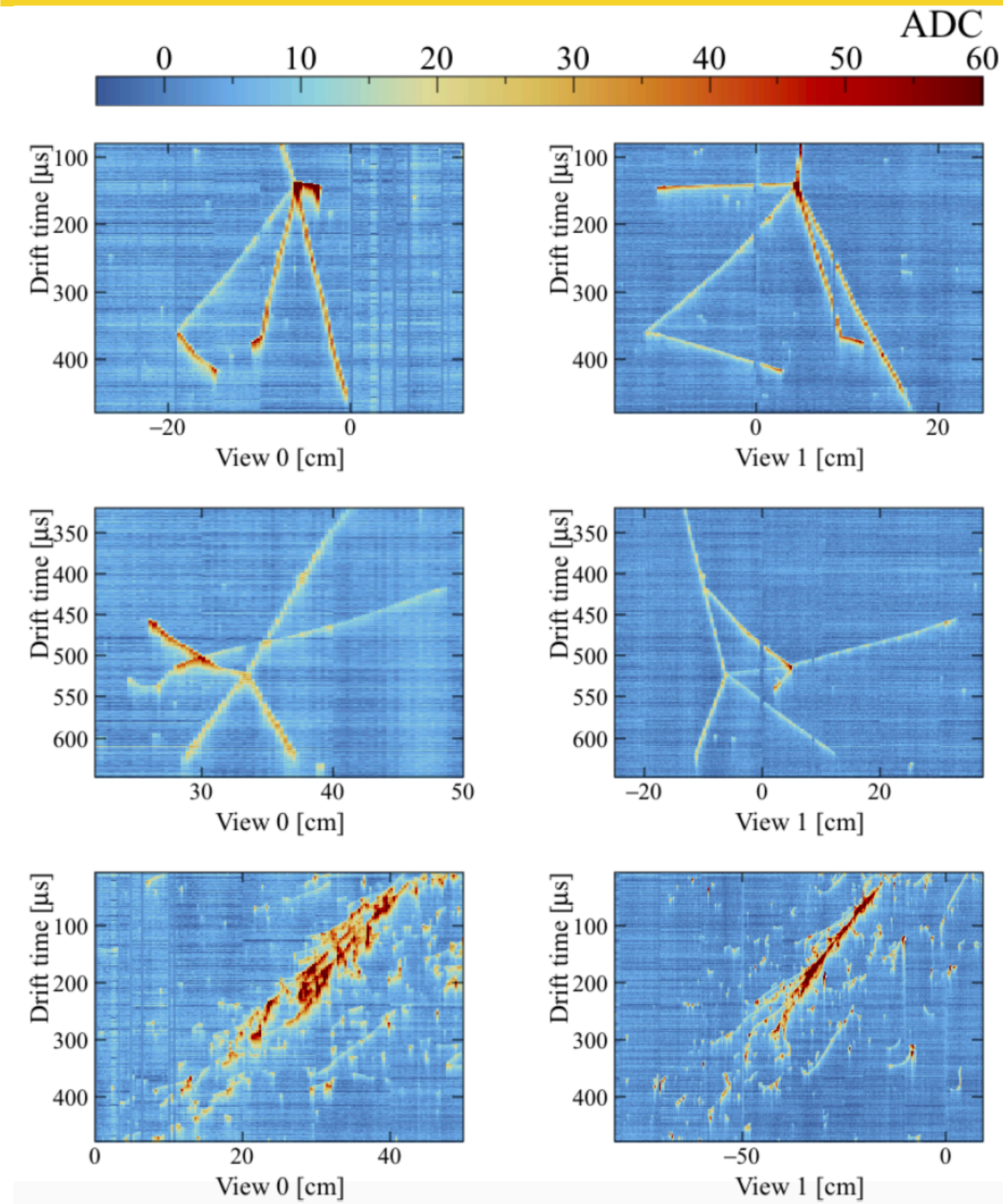
- ✓ LEMs and anode: design, purchase, cleaning and QA
- ✓ chimneys, FT and slow control sensors
- ✓ membrane tank technology
- ✓ Accessible cold front-end electronics and DAQ system
- ✓ amplification in pure Ar vapour on large areas



The ProtoDUNEs project: Dual phase



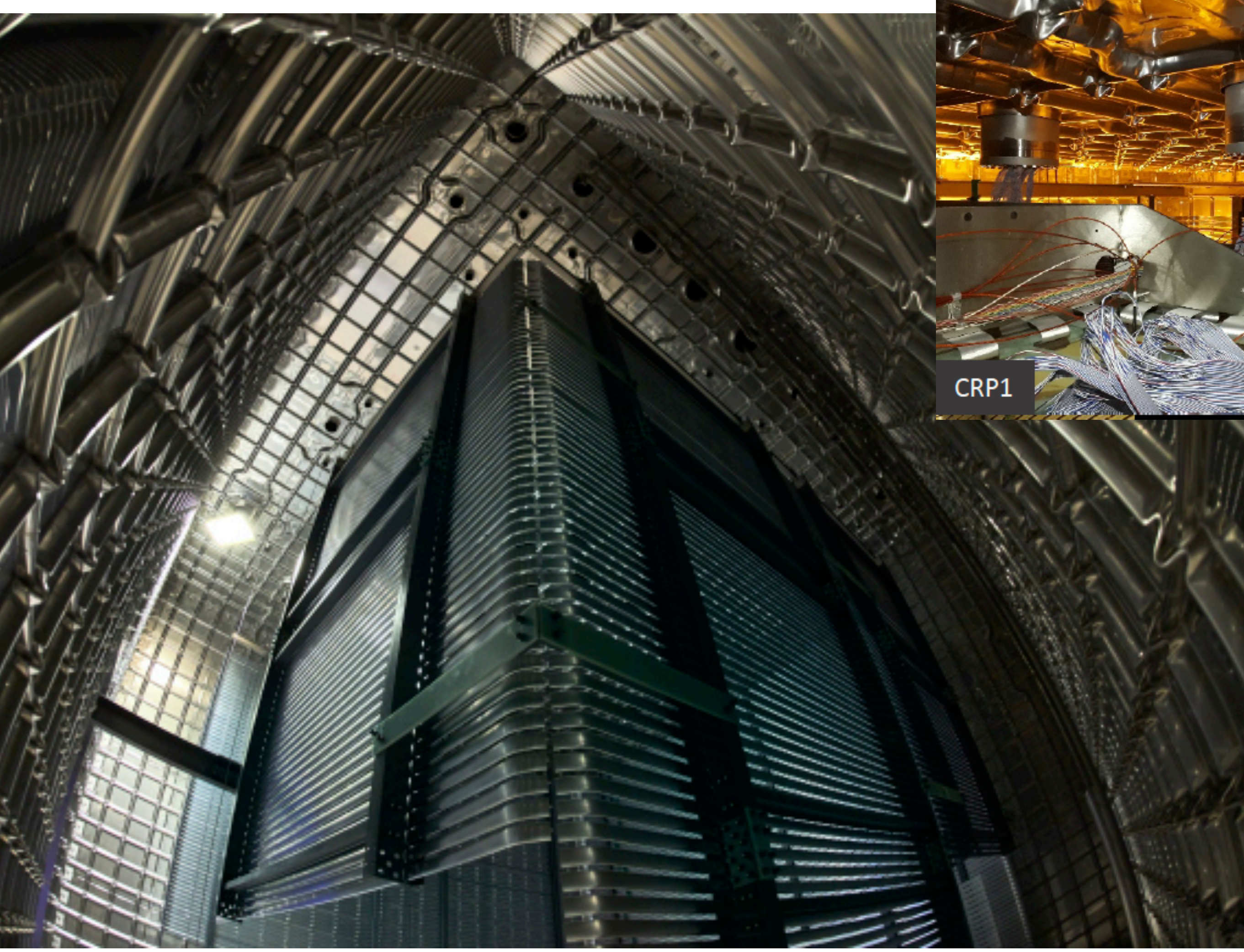
Summary of the performance in:
“A 4-tonne demonstrator for large-scale dual-phase liquid argon time projection chamber”
arXiv: ins-det/1806.03317, submitted to JINST

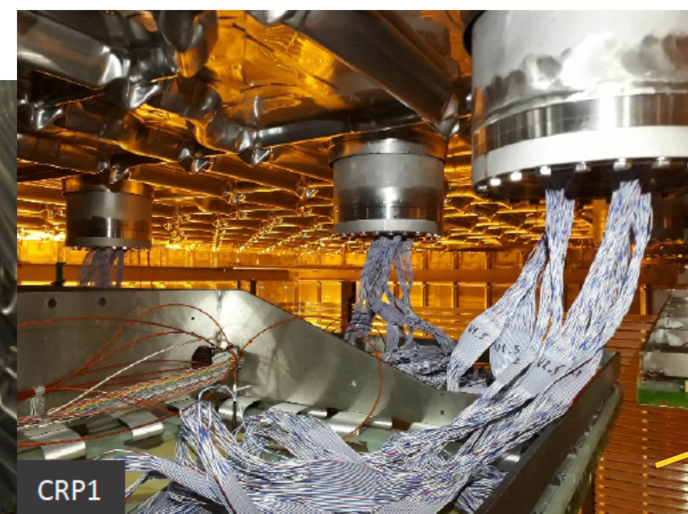


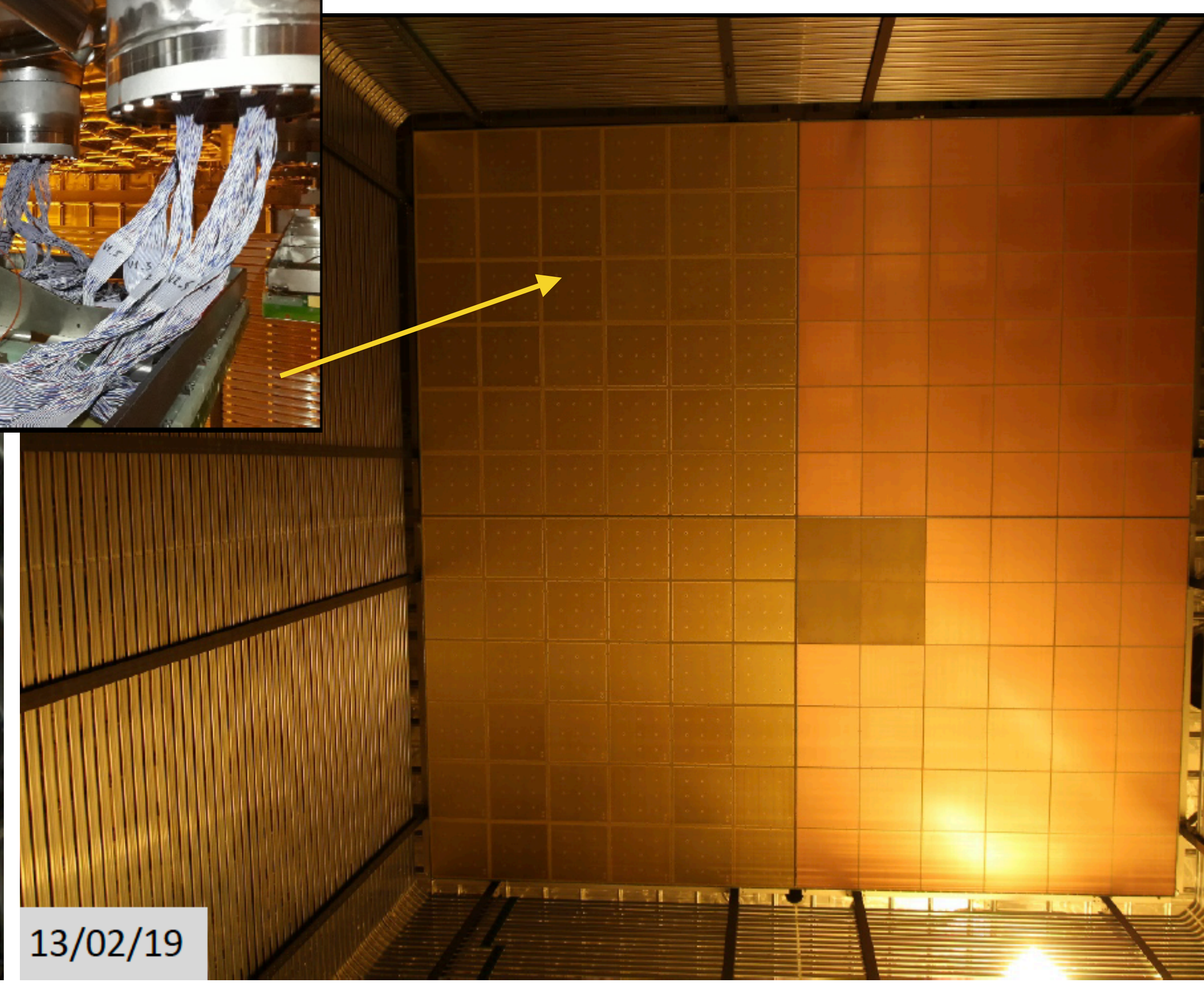
- **First time charge extraction over a 3 m² squared area and amplification inside 50x50 cm² LEMs.** However, the target effective gain of 20 was not reached. Performance limited due to discharges of the extraction grid at -5kV (nominal -6.5 kV).
- **Stable liquid surface** as required for detector operation, **good performance of the cryogenic system and excellent liquid argon purity (compatible with ms electron lifetime)**.
- Stable drift field of 500V/cm.
- Observation of first (in liquid) and second (in gas) scintillation light.

The ProtoDUNEs project: Dual phase

- Final installation with 4 CRPs (two fully instrumented).
- PMTs, cathode and ground grid installation has started.
- Start filling in May.
- Data taking with cosmics expected in July 2019.







Summary

- The **main discovery goal of future LBL experiments** is **CP violation.**
- Two alternative and complementary scenarios will be provided by **HyperK,** in particular if complemented by a second detector in Korea, and **DUNE.**
- After many years of R&D LAr TPCs have proven to provide excellent imaging of neutrino interactions.
- ProtoDUNEs project have been a great progress towards the future far detector construction: understanding of the technology, construction and installation.
- **Detector operations foreseen by 2026: Stay tuned!!**