Integration challenges for Neutrino Experiments

Filippo Resnati (CERN)

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Acknowledgement

Based on input session for the ECFA Detector R&D Roadmap
https://indico.cern.ch/event/994687/

And from input and discussion with:
M. de Jong, E. James, L. Labarga, T. LeCompte, T. Lux,
J. Maneira, C. Montanari, D. Montanari, M. Nessi,
F. Pietropaolo, L. Stanco, R. Tsenov, M. Weber

Disclaimer

The list of integration challenges for future neutrino experiments/facilities is obviously very long.

Here the focus is put on development that cannot be classified as solely engineering challenges and require developments or important infrastructures to allow R&D.

There is no sharp line between engineering challenges and R&D, especially in integration work.

Considered Projects

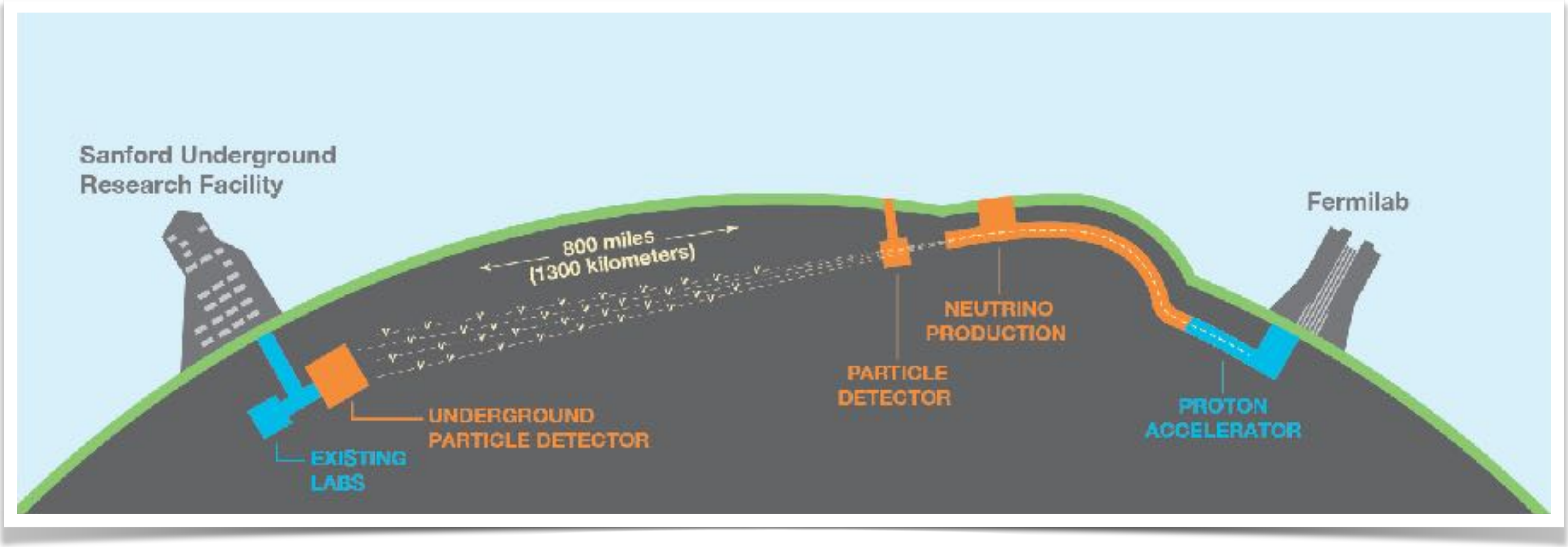
Long baseline neutrino oscillation experiments
DUNE, T2HK, T2K, ESSnuSB

Short Baseline neutrino oscillation experiments
SBN @ Fermilab

AstroParticle neutrino experiments
KM3NeT, IceCube

Long baseline
LAr TPC

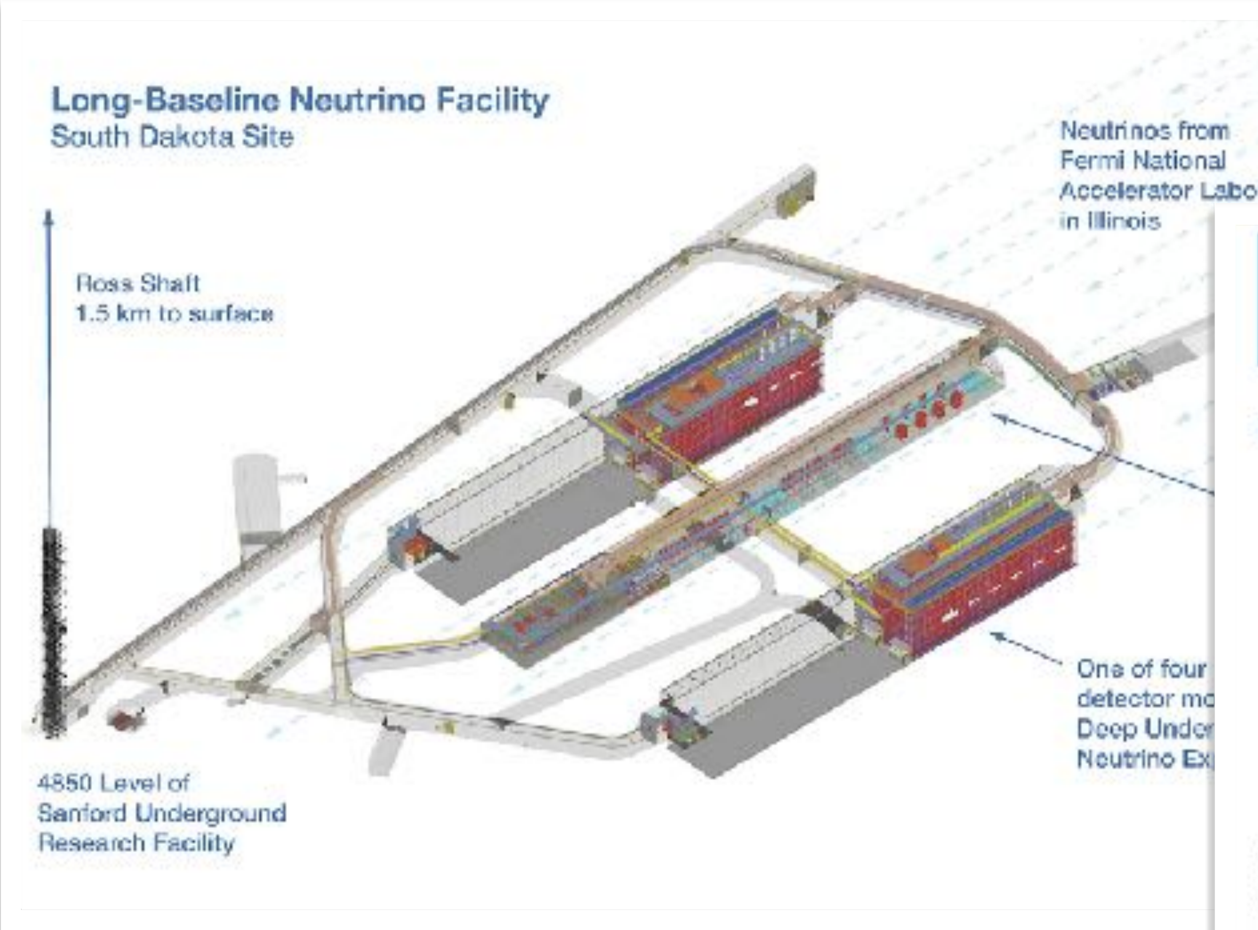
LBNF/DUNE

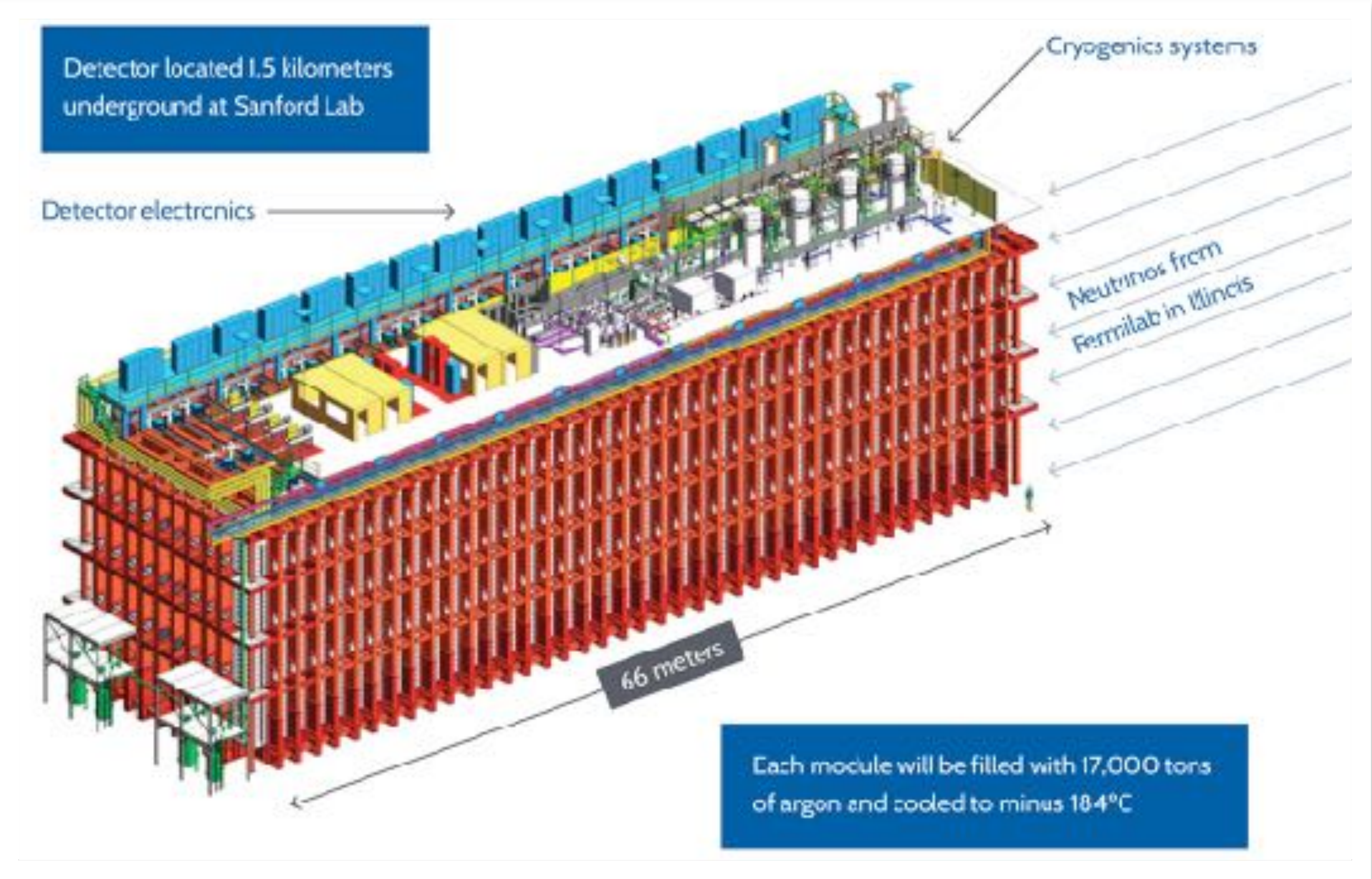


Long baseline (1300 km) neutrino oscillation experiment.
Neutrino beam from FNAL: 1.2 MW upgradeable to 2.4 MW, 0.5-4 GeV.
Physics reach:

- CP Violation
- Mass Ordering
- Precision Mass and Mixing
- Supernova Neutrino Bursts
- Baryon Number Violation
- BSM Searches

DUNE Far Detectors

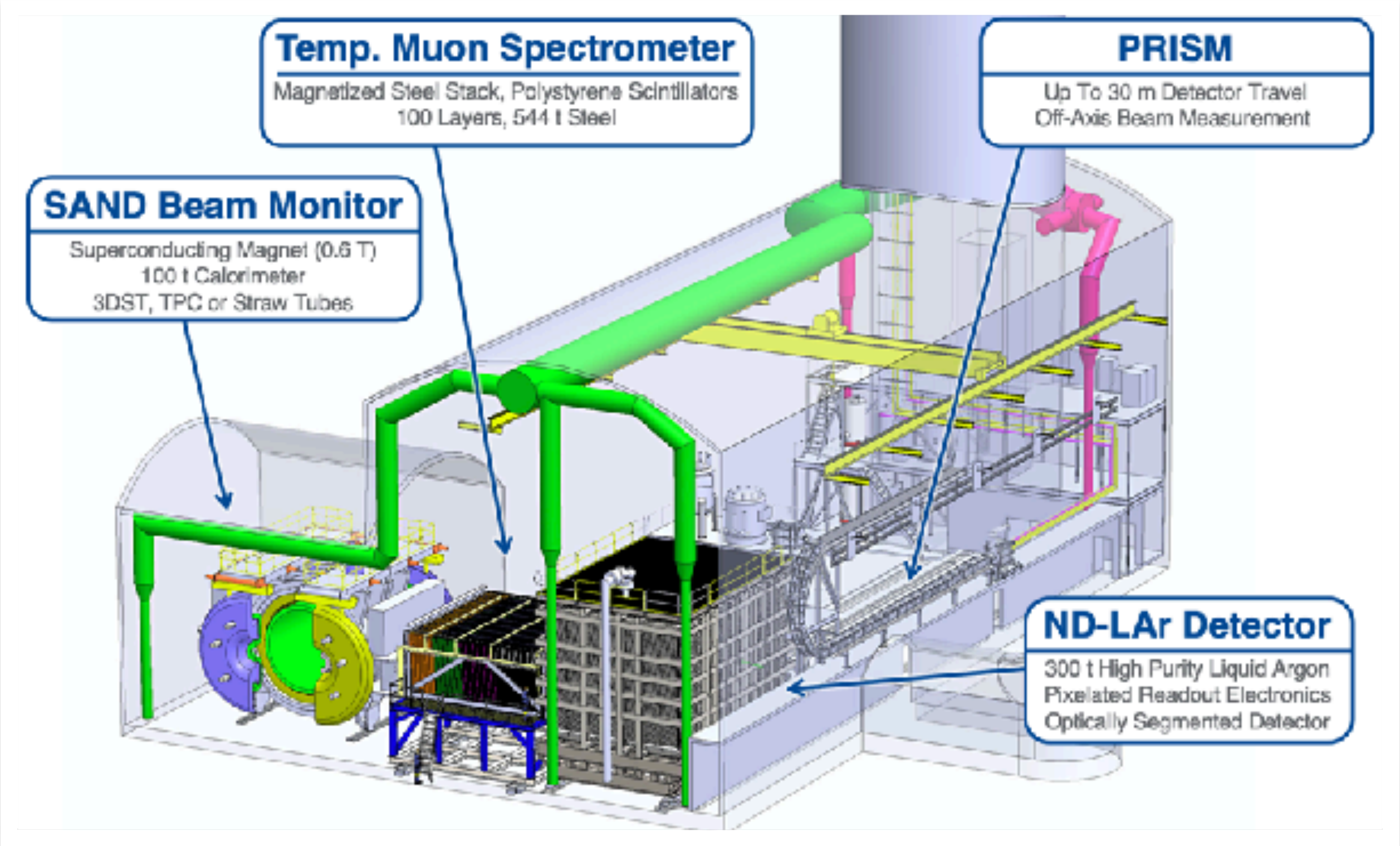




4 independent detector modules 1.5 km underground at Homestake Mine (South Dakota):
- 3x ~15 kTon active volume LAr TPCs + 1 “open technology” module (> 2030)
- Construction of the first cryostat foreseen in 2025, start operation in 2027, with beam in 2028.
- Different LAr TPC implementations with several common developments:

low noise very long lasting cold electronics, UV sensitive photon detectors, DAQ, low noise HV (200-300 kV), online calibration methods, monitor/diagnostic, access/replace components, cryostat, LAr cryogenics, LAr purity, LN2 distillation, …

DUNE Near Detector



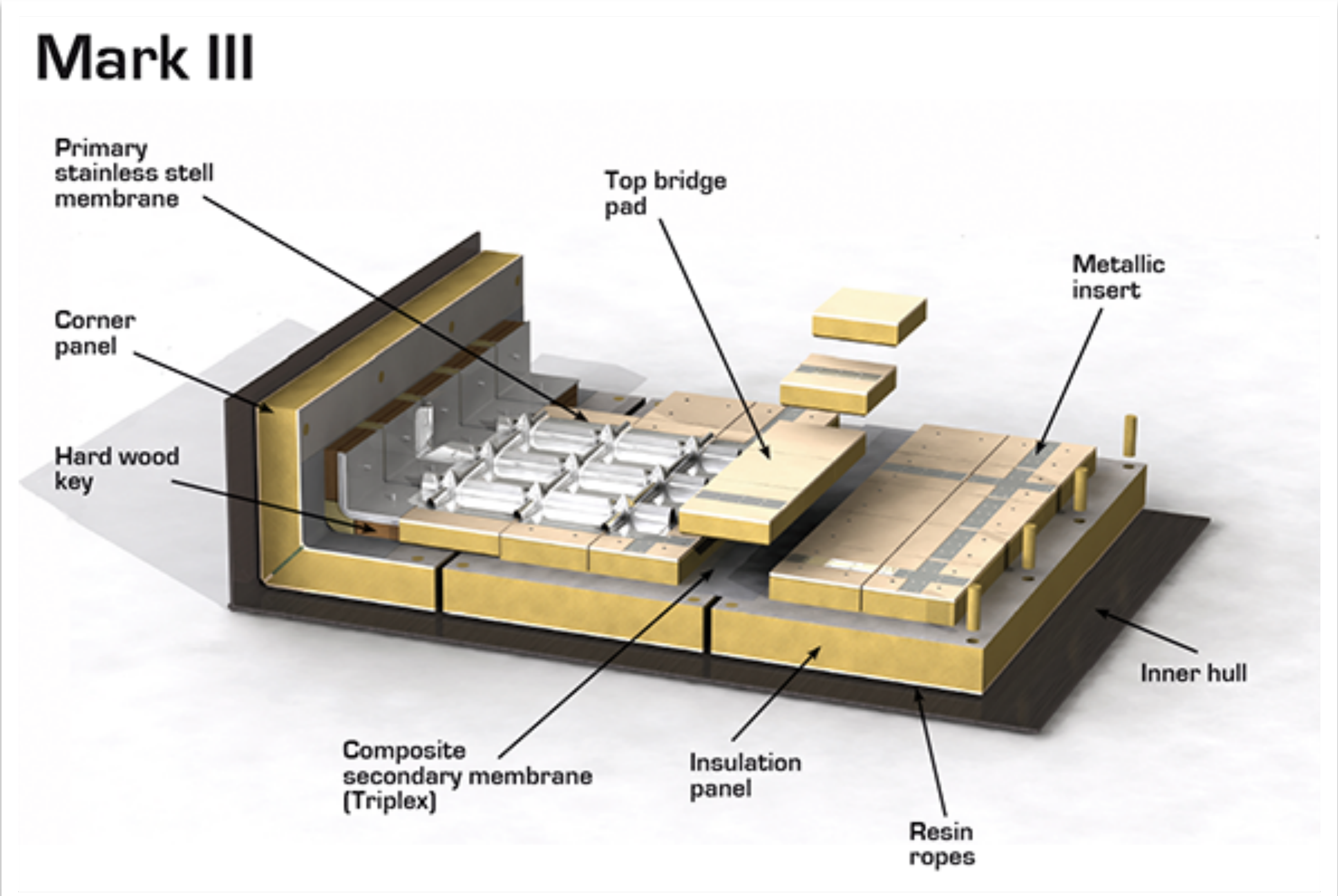
At Fermilab:
- ND-LAr: 300 ton modular LAr TPC with pixelated readout. Investigation on removal of modules while at cold. Movable for off axis beam measurement (PRISM system). Low material budget downstream cryostat wall.
- Temporary Muon Spectrometer (TMS): Magnetised steel stack O(100) with polystyrene scintillator (movable).
- Muon spectrometer will be upgraded with Multi-Purpose Detector (MPD): high-pressure (10 bar) gas TPC + ECAL (high granularity scintillator & SiPM) + muon tagger incorporated in the magnet (Superconducting 5-coil Helmholtz) return yoke
- SAND Beam Monitor: 0.6 T superconducting solenoid magnet (from KLOE) + LHe plant + ECAL Pb-scintillating fibre sampling calorimeter (from KLOE) + 3D scintillator tracker as active neutrino target (other tracker solutions under investigation) - need of moving system only during installation

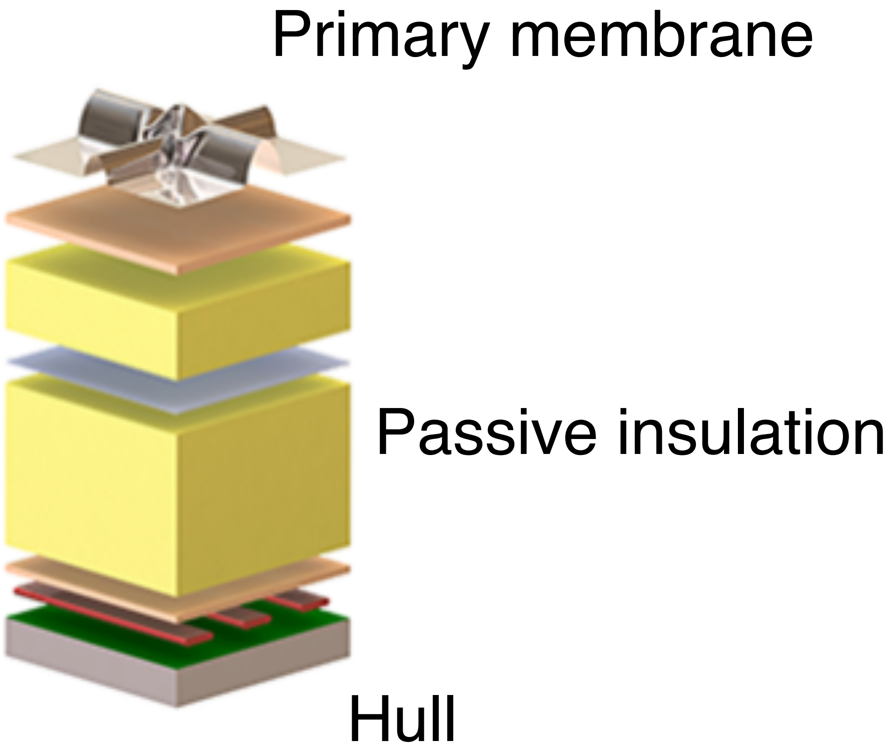
DUNE cryostats

Industrial technology (GTT Mark III technology) adopted on LNG carriers adapted to the LAr TPC needs. Proven technology with the ProtoDUNE detectors at CERN.

Approach used also for SBND and DS-20k.

- Passive insulation to minimise operational risks.
- Modular assembly for underground compatibility.

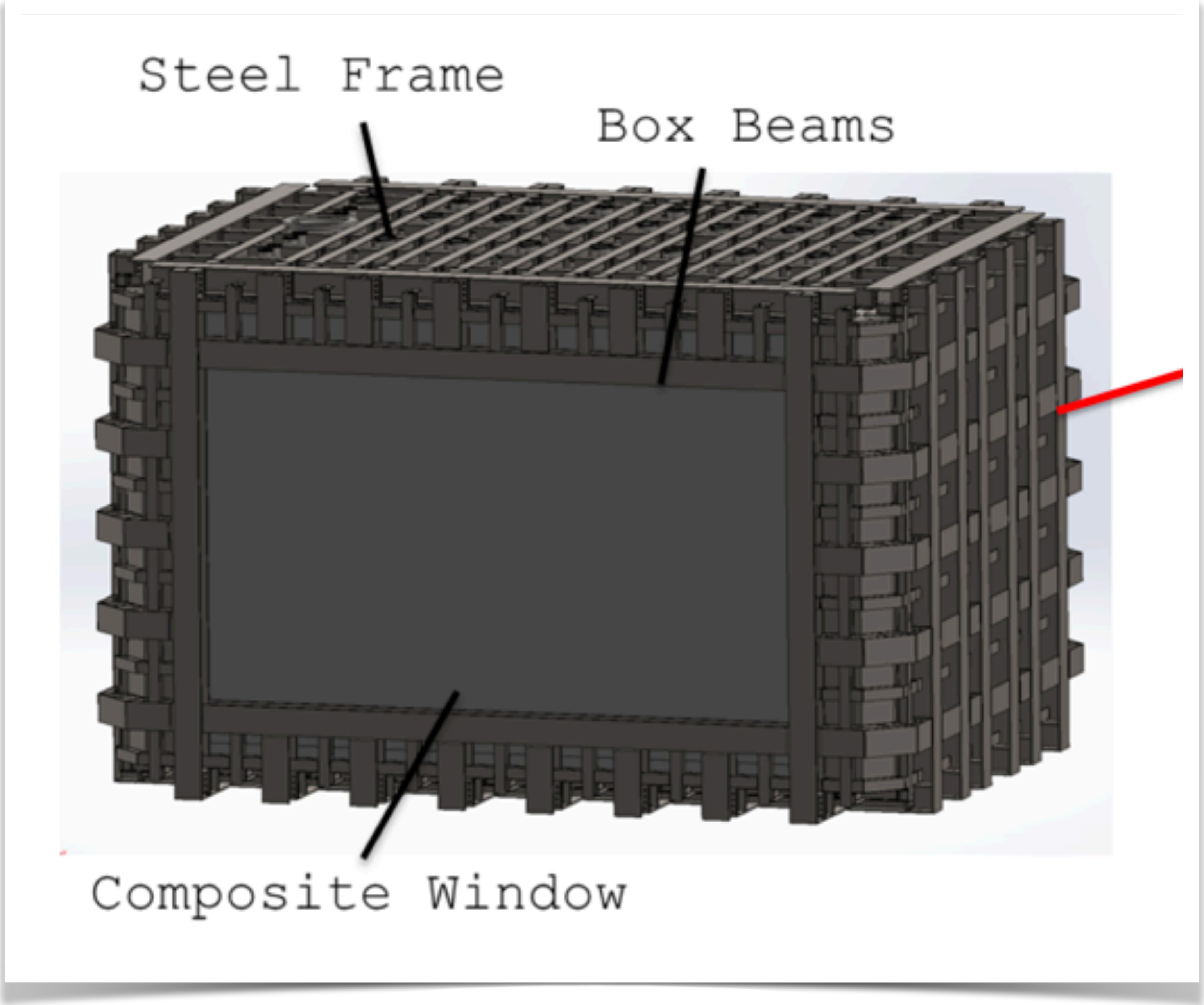




DUNE ND cryostat R&D

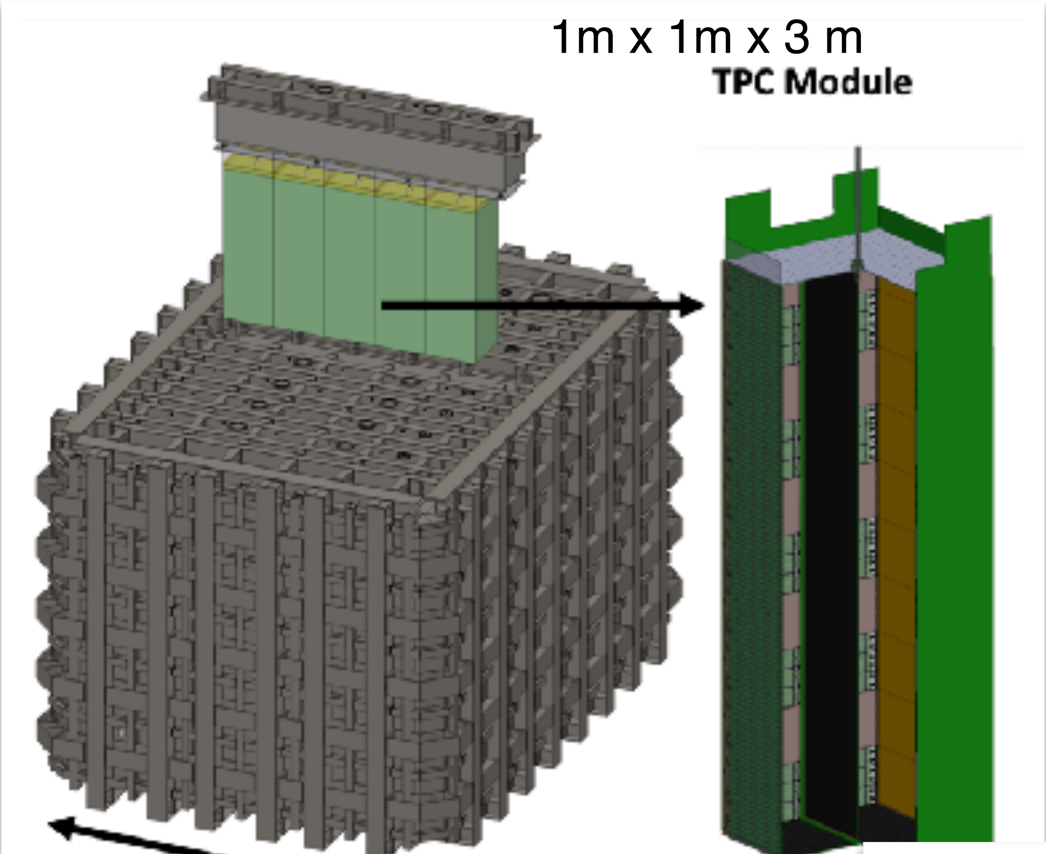
Low material budget cryostat wall to minimise the energy loss in inactive material for muons exiting the cryostat and being detected by the downstream muon spectrometer:

- low density insulation and composite structural materials
- R&D also in collaboration with GTT proprietary of the Mark III technology



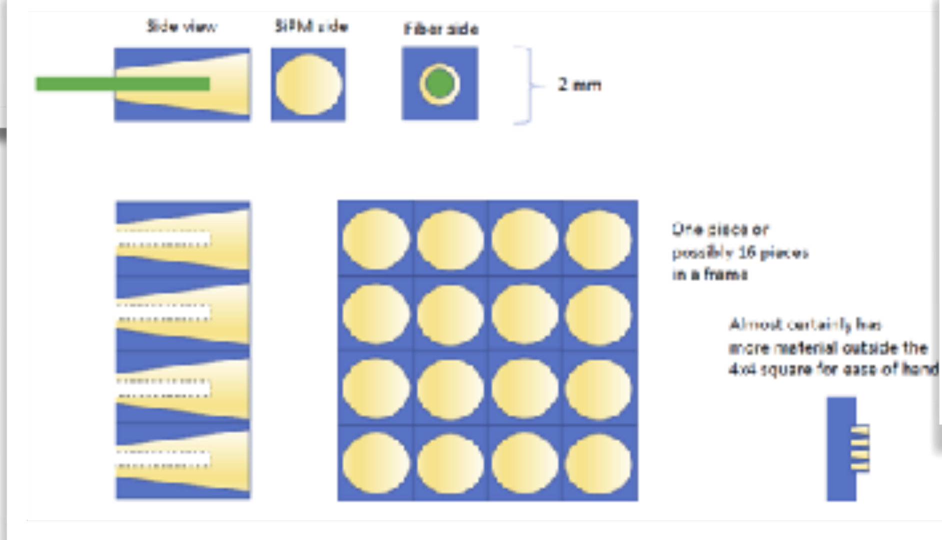
DUNE ND R&D

Under study the possibility to extract a single detector row (or module) in cold to fix/upgrade detectors. The modular technology is being considered also for the 4th Far Detector module. R&D required to ensure cryostat sealing and a handling methods to avert LAr pollution.



Interests in 3D printing the TPC module buckets:
- Main challenges are leak tightness at junctions and reliable field cage printing.

More on 3D printing for TMS:
- extensively used for SiPM positioning and light tight mechanics in prototyping.
- R&D on optical couplers for 4x4 SiPM arrays, with 3-D printed Winston cones (3D-printing clear plastic is relatively uncommon).



Tom LeCompte

Cryogenic system

Reliability: well established industrial solutions

The challenge is the underground installation. Development with industries equipment suitable for underground installation and employment.

Stability: Proven multiple times $\Delta P < 1$ mbar and $\Delta T < 100$ mK

Purity: from O(ppm) O_2^{eq} to better than 30 ppt

fast and reliable circulation and purification system scale up (25x), R&D on efficient and long lasting filtering materials, with attention to radio-purity (Rn emanation) to enable low energy physics studies. R&D on filters to removal of N_2, important in case the cryostat needs to be opened while full to upgrade detector components/modules.

Uniformity:

Need of reliable and proven advanced CFD calculations of LAr movements in the cryostats to estimate the concentrations of ions, impurities and dopants, e.g Xe.

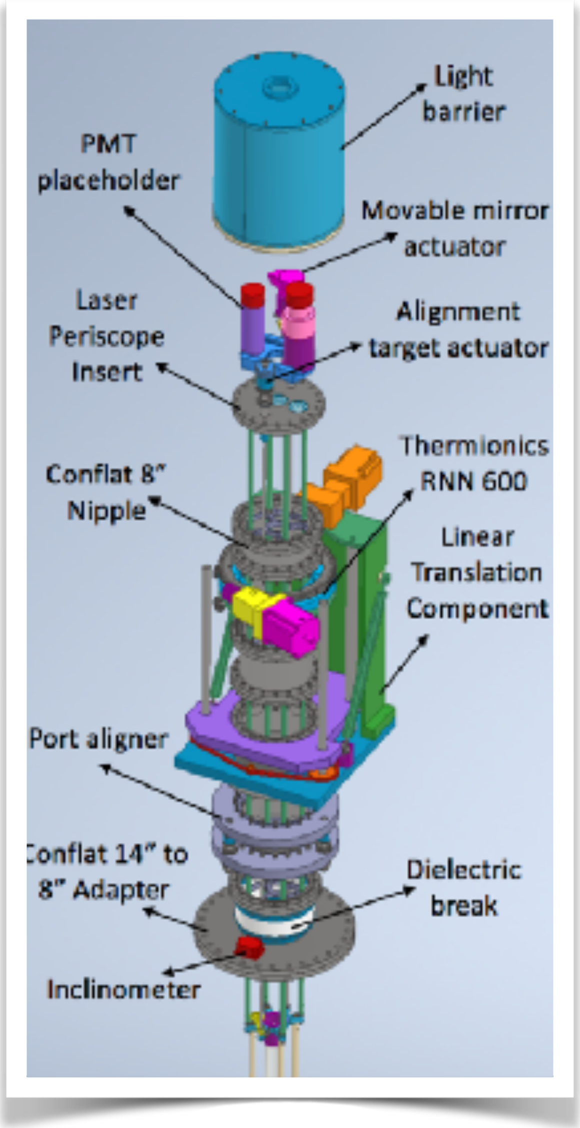
HV system

Longer drifts implies larger potential at the cathode beyond -300 kV:
- HV feedthroughs and filters (scale up or innovative feedthrough through the cryostat wall)
- With industries ground shielded cables from extruded materials with resistive conductors
- Low noise power supply (industrial scale up, but also R&D on new insulating materials)

Photodetector on HV (cathode and field cage) -> development of floating power supplies for SiPM operated in LAr and referred to HV with Power over Fibre technology.

Calibration/monitor systems

Ionisation laser:
Developed since the ’90, employed at MicroBooNE. At DUNE unprecedented requirements on energy calibration and electric field measurement.
- wide coverage (uniform characterisation of the detector response),
- position precision for electric field distortion measurements,
- stable and predictable light source (ionised charge) for absolute ionisation measurements.



Purity monitors:
Developments to improve LAr Purity monitor long term stability and avoid photocathode degradation (new photocathodes materials/treatment, radiation sources, …).

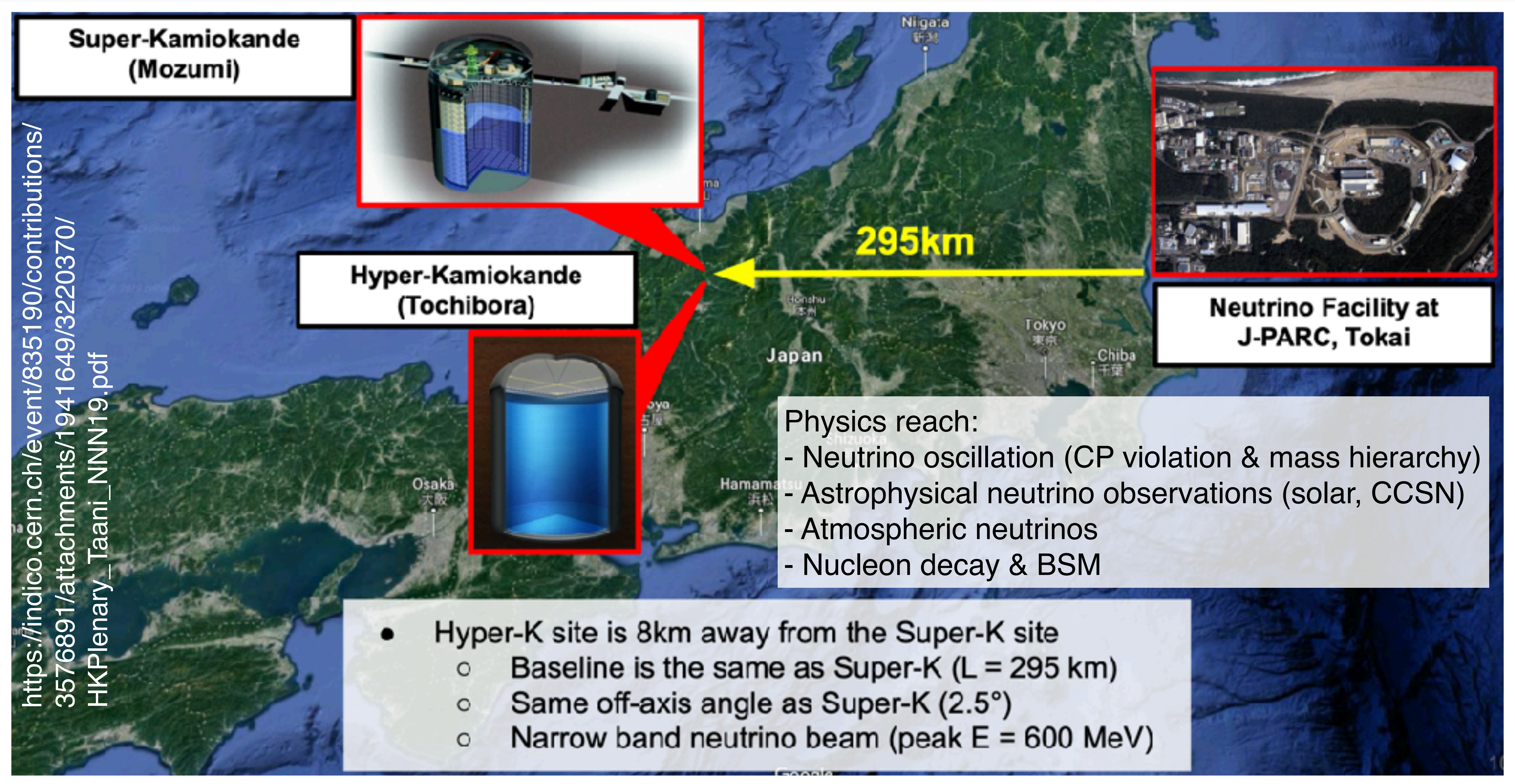
Cryo cameras:
Improved cryogenic cameras (enable motion, zoom, focus adjustment in cryogenic conditions)

Fibre-bragg grating for temperature (10 mK precision) and flow measurements deployed in liquid argon and on HV

Cryo compatible robotics:
See talk by Lorenzo and Mario.

Long baseline water Cherenkov

T2HK



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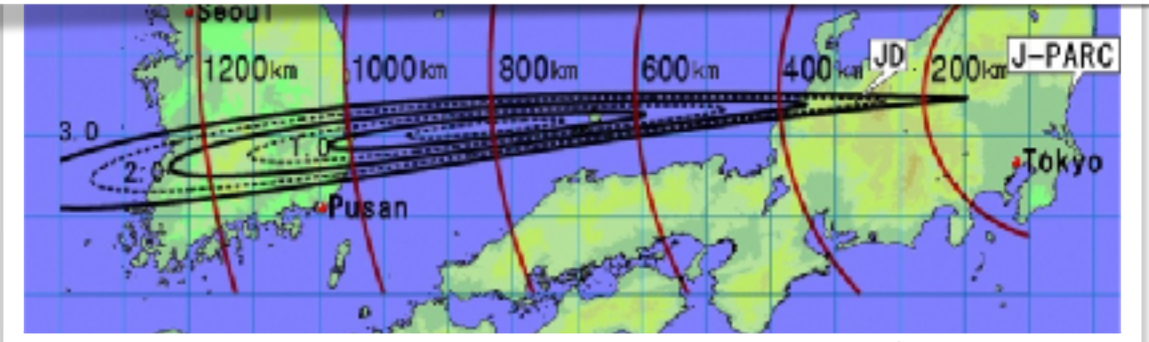
Physics reach:
- Neutrino oscillation (CP violation & mass hierarchy)
- Astrophysical neutrino observations (solar, CCSN)
- Atmospheric neutrinos
- Nucleon decay & BSM

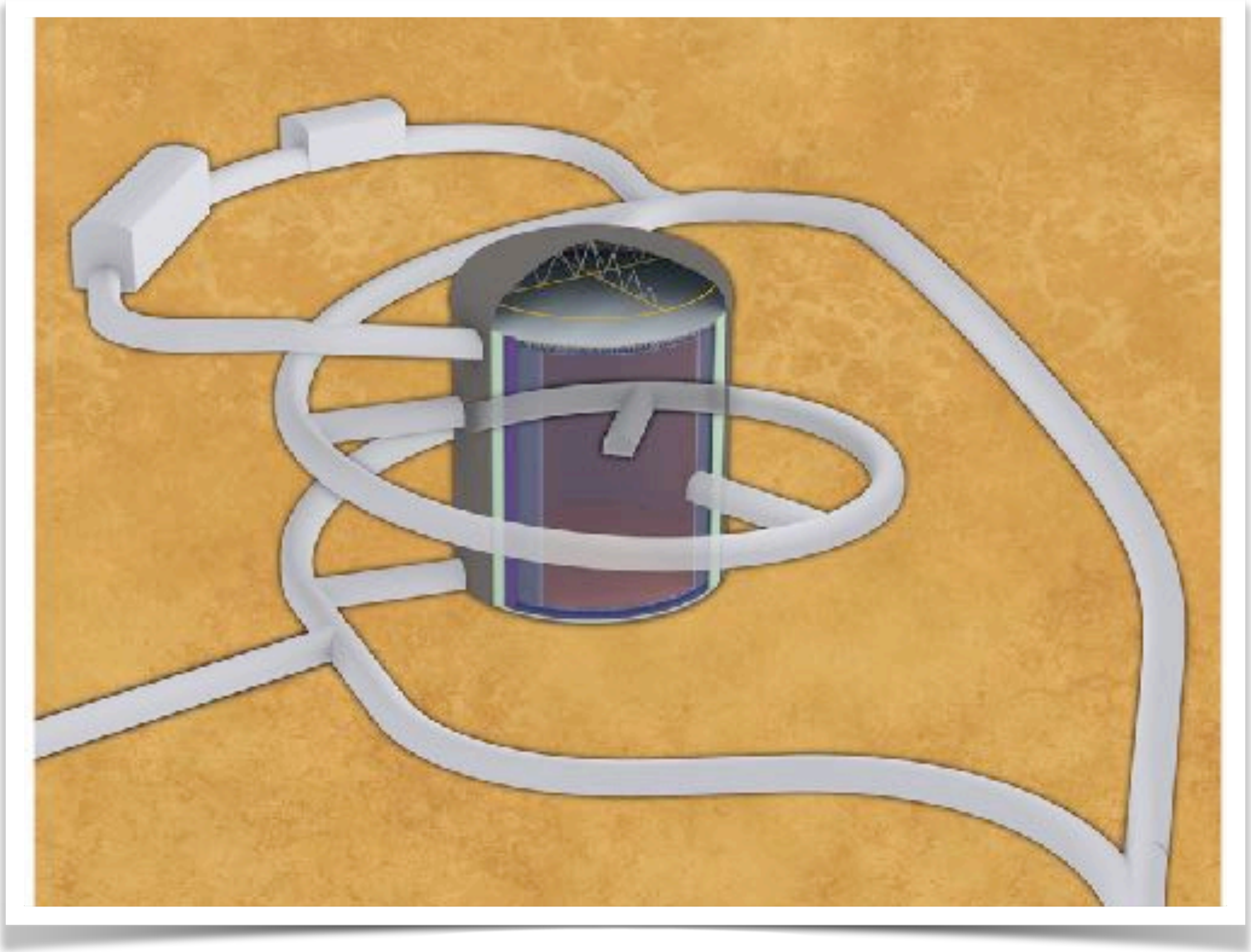
- Hyper-K site is 8km away from the Super-K site
  - Baseline is the same as Super-K (L = 295 km)
  - Same off-axis angle as Super-K (2.5°)
  - Narrow band neutrino beam (peak E = 600 MeV)



Staged approach: 2nd identical detector in South Corea
- baseline $O(1000\text{ km})$
- 1°-2.5° off-axis

HK Far Detector

https://arxiv.org/pdf/1805.04163.pdf



Hyper-Kamiokande: 258 kTon (187 kTon fiducial) water Cherenkov. Start operation in 2027.
- 40’000 20” high QE PMTs (40% photo-coverage) inner detector
- 6’700 8” PMT outer detector

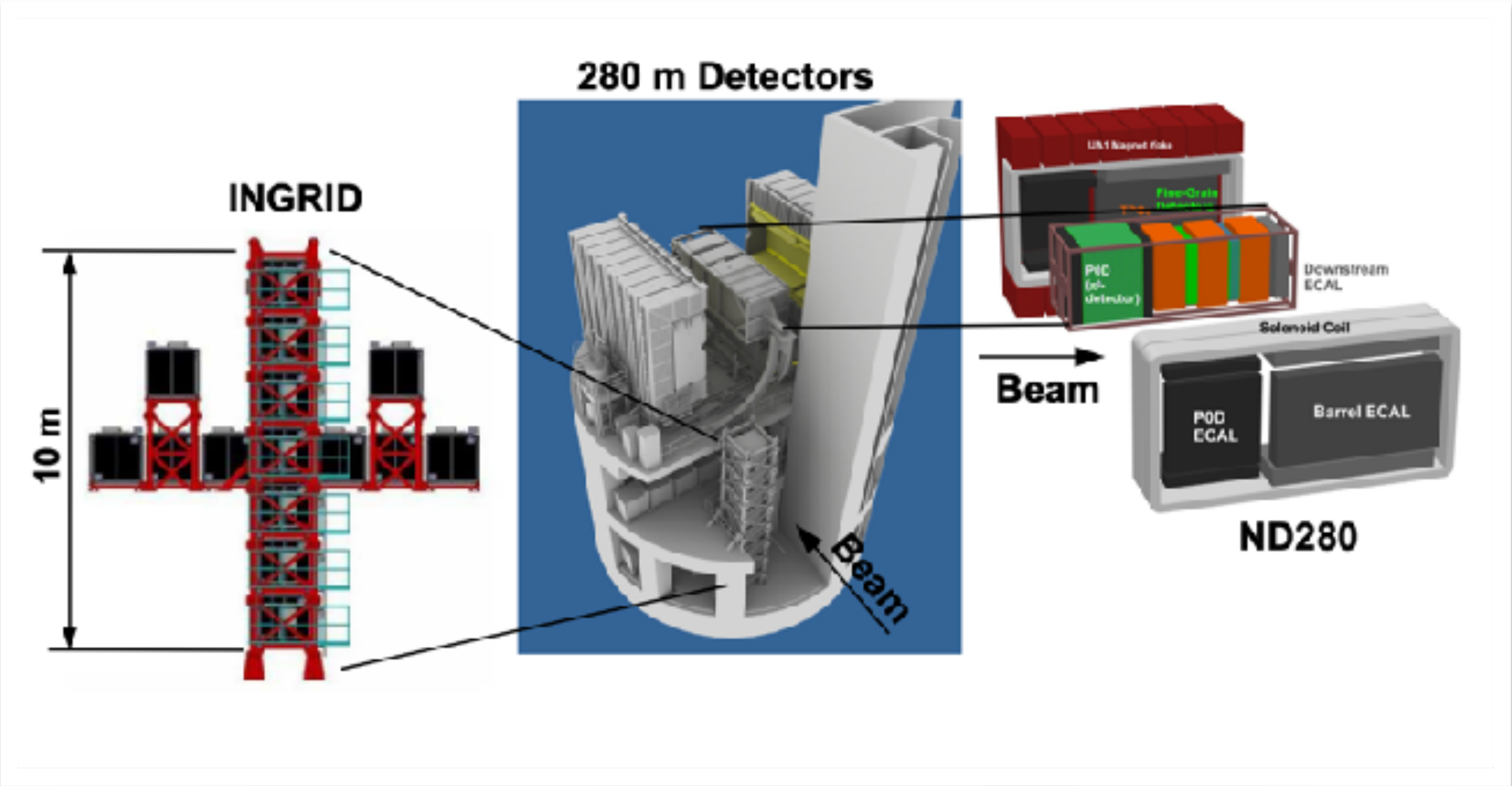
650 m underground (8 km south of SK), 74 m in diameter 60 m tall tank.
Possibly Gd loaded for a fraction of the exposure to effectively tag neutrons.

T2K Near Detector

https://arxiv.org/pdf/1805.04163.pdf

- ND280 (upgraded next year):
  - Super FGD: horizontal segmented (1 cm^3) scintillator cubes (2 x 10^6) (precise drilling / precise support / 3D printing considered) with optical fibres in three directions + SiPMs
  - High angle TPCs: ambient pressure gas TPCs + resistive MM + gas system
  - Time of flight: 6 scintillator panels around the TPC
  - Magnets and downstream detectors stays the same

- Interactive Neutrino GRID: beam monitor already existing

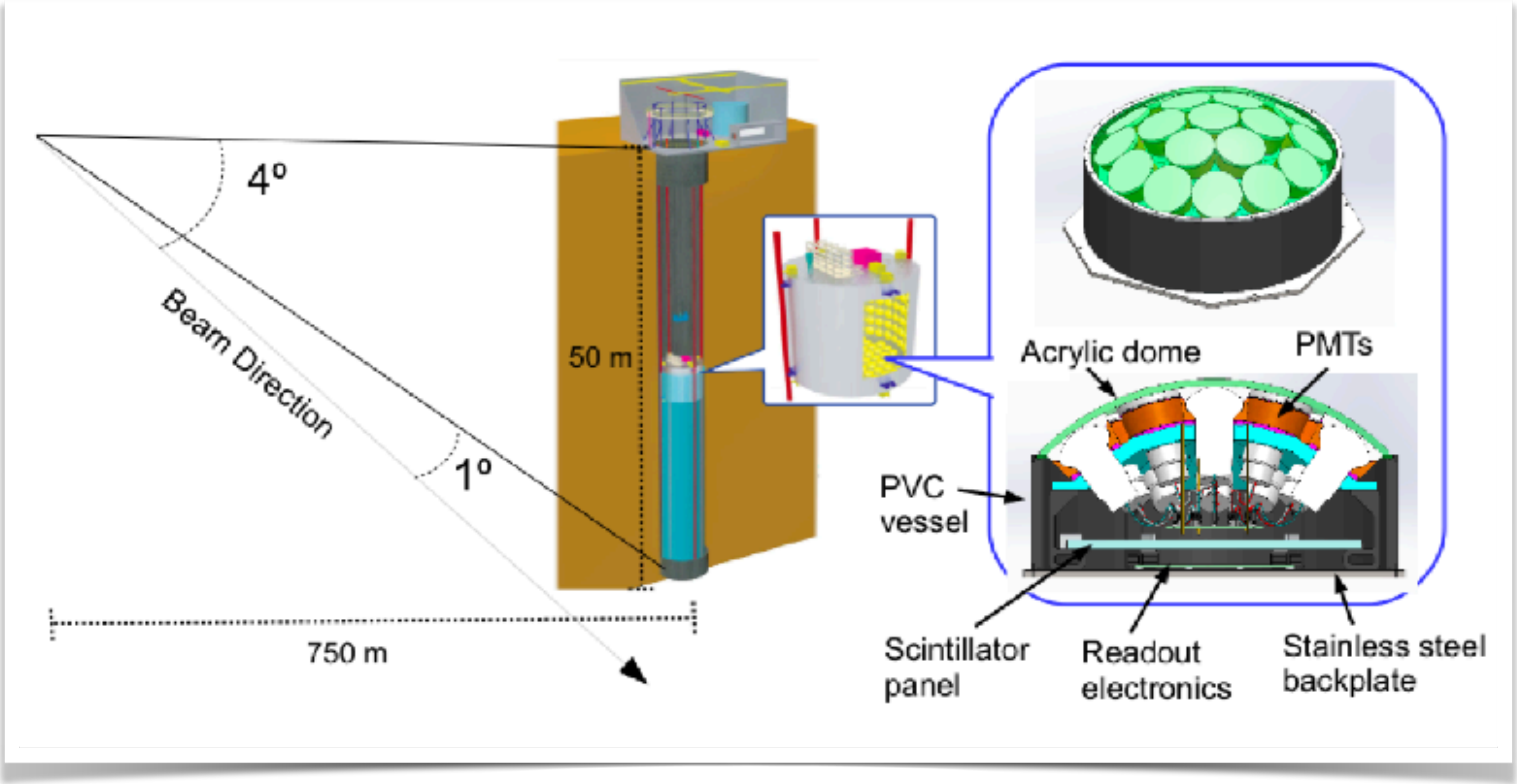


IWCD

https://arxiv.org/pdf/1805.04163.pdf

Intermediate Water Cherenkov Detector (IWCD) in addition to the T2K Near Detector suite: Proposed 1 kTon water Cherenkov detector @ 0.7-2 km from target (including inner and outer -veto- detectors) with 40% photocathode coverage movable up and down 50 m (1°-4°) by means of a crane system and adjusting the water level in the shaft.

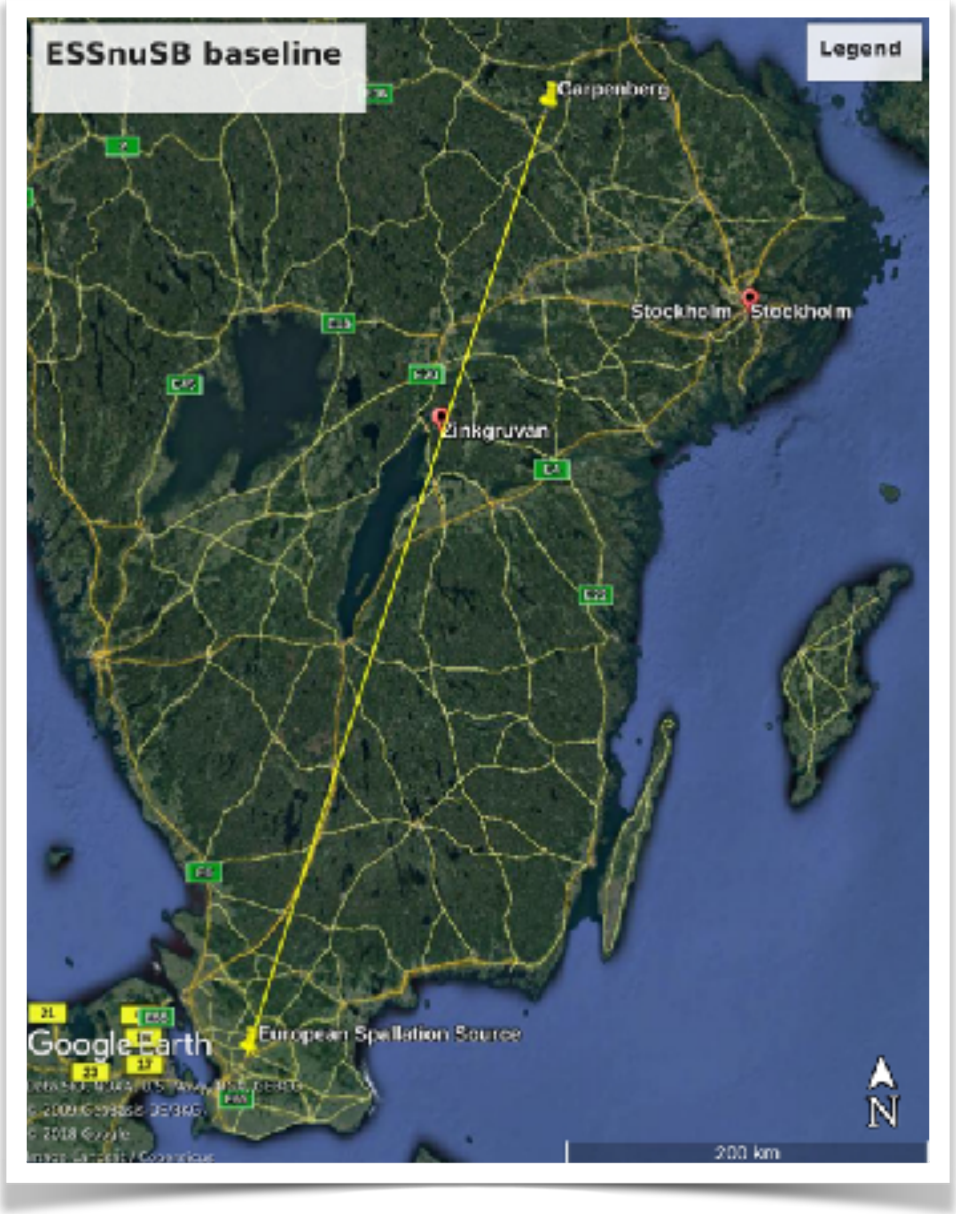
Major integration developments for detector tank, crane, guide rails, shaft water system.



ESSnuSB

Feasibility study funded under the EC Horizon 2020 Programme.
- Long baseline neutrino oscillation experiment (two baseline options: 360 km and 540 km).
- Neutrino beam in symbiosis to the ESS 5 MW proton linac in construction in LUND Sweden.

Measurements at the second oscillation maximum for enhanced sensitivity to δ_{CP}.

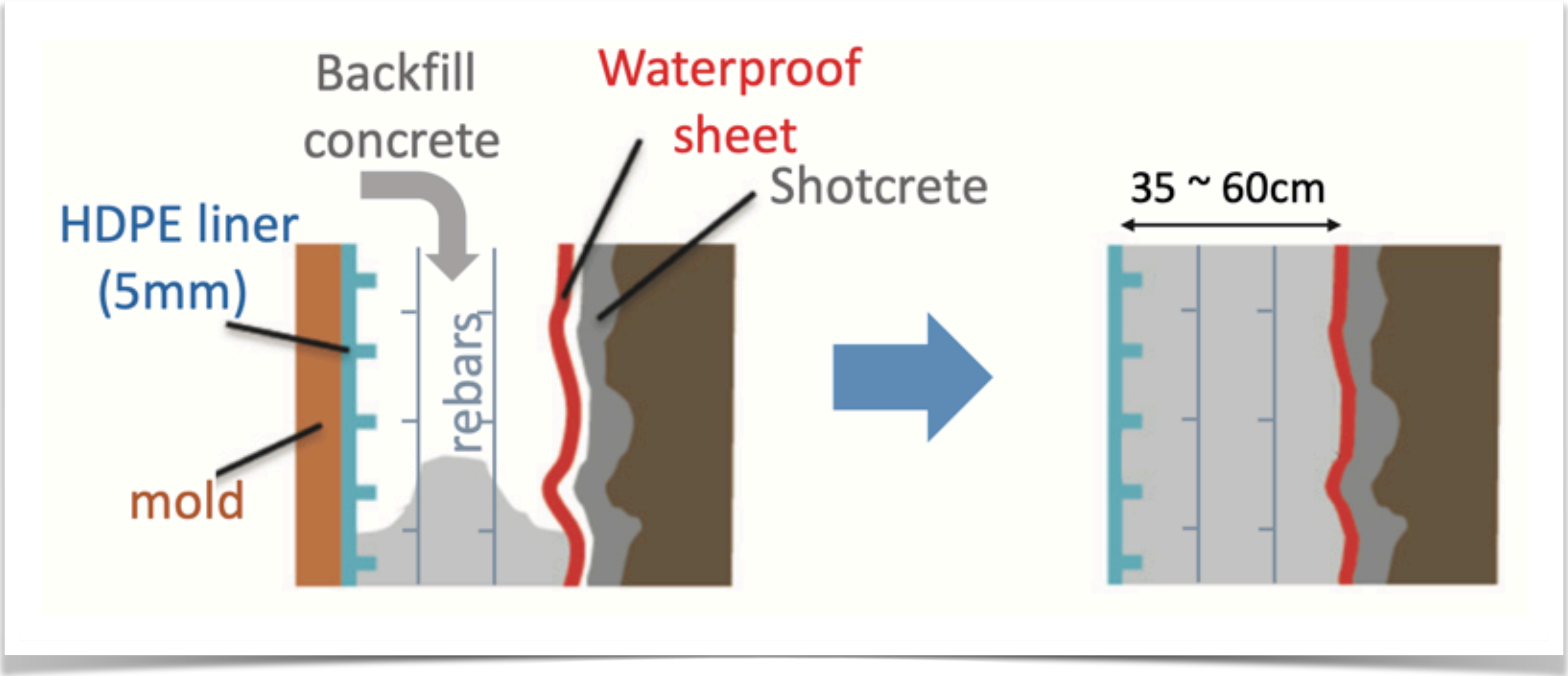


Far detector:
two water Cherenkov detectors in tanks 78 m diameter and 78 m tall filled with 2x 372 kTon of ultra-pure water.
2x ~40’000 20" PMTs (30% photocathode coverage).
Underground (~1.2 km), possibly in Garpenberg mine.
Study of the ideal location is ongoing. Fundamental studies of the rock properties with ~1 km coring require major funding.

Near detector complex:
- Water Cherenkov detector (10 m diameter and 10 m length),
- Fine grained scintillator tracker,
- Neutrino emulsion detector.

Integration challenges very much in common with HK

Water tank



Tank liner
Contain ultra purified water (UPW) or gadolinium sulfate (Gd2(SO4)3) water solution inside of the tank ideally without any leakage and without any dissolution of impurities into the medium.
Durable, impact/wear resistant, chemical resistant, highly impermeable, flexible, …
A lot of experience developed in SK. Main differences for HK rock characteristics and mass.

Development and tests of liner and lining materials ongoing to select the best option.
Concrete Protective Liner (CPL), made of High Density PolyEthylene (HDPE), has been chosen as the baseline candidate lining material.

Water purity

Ultra purity (Milli-Q type-1 like) for highly transparent water
- transparency > 100 m @ λ ~400 nm
- resistivity > 18.2 MOhm.cm @ 25°C

A lot of experience from SK. Almost a factor 10 in volume, different rock, lining, …
Tradeoff between water circulation speed/purity and system cost/complexity

Baseline:
- 78 ton/h filtered water during filling (180 days to fill including maintenance)
- 310 m^3/h for water circulation
- If Gd loaded foreseen, EGADS band-pass filtering system from SK scaled up a factor of 6

- Laminar flow is fundamental for effective replacement of water
- Vertical Laminar flow allows the Rn emanated from the PMT to decay in the vicinity of the source and have the least impact on background
- Materials in the filtration circuit must comply with constraints on Rn emanation (<2 mBq/m^3)
- Fundamental water flow simulations (forced circulation, inlet, detector geometry, water temperature, rock temperature, electronics heat load, …).

Integration of the electronics

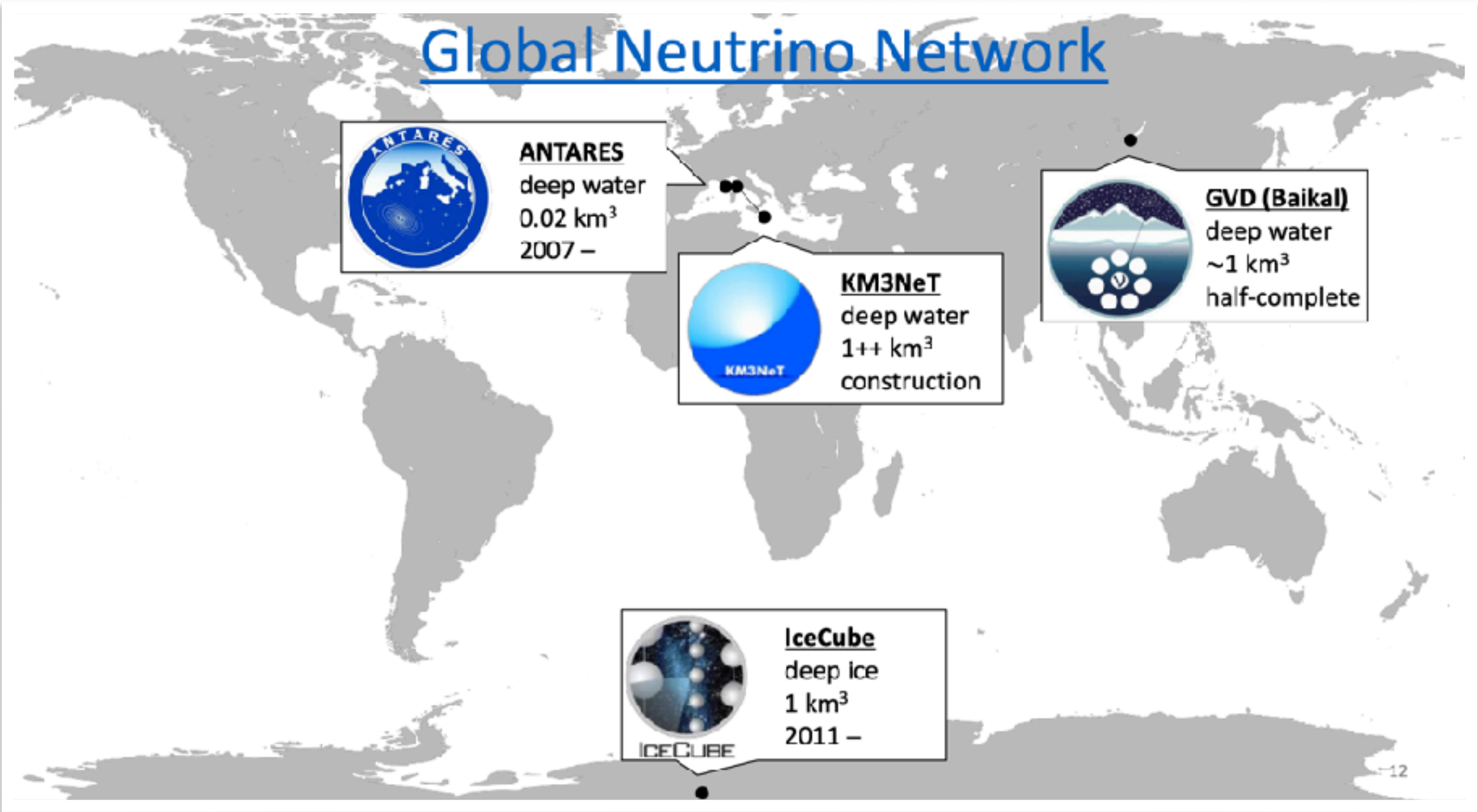
Still an open point whether electronics should be installed inside or outside the water.

Inside
- pros:
  much less cabling,
- contras:
  need very high reliability (basically no option of any change)
  heat dissipation impact the water flow (laminar flow disturbed)

Outside
- pros:
  basically the "inside/contras"
- contras:
  several tens of thousand ~100 m long cables must be routed out.
  Additional mass near the active volume that must comply with the stringent requirement of the Rn emanation and the Radioactive Isotopes content.

Astroparticle neutrino experiments

Astroparticle experiments



https://indico.cern.ch/event/994687/contributions/4181754/attachments/2193895/3709264/ECFA%20-%20Maarten%20de%20Jong.pdf

Cherenkov detector in water or ice with sparse photodetectors over *O*(km^3) volume

R&D on ps-tracking detectors would enable tagged neutrino beam experiments

Integration challenges

Deep-sea deep-ice cabling with electrical conductors and optical fibres.
The market is dominated by oil industry and products are generally very expensive.
Progress has been made within KM3NeT with the development of a custom, pressure-balanced oil-filled cable which now is produced in a (specialised) company.

Choice of materials limited by the need to resist against pressure (250 Atm) and corrosion (deep water) for tens of years.
Developments of aluminium alloys ongoing. Durability still needs to be demonstrated.
Any material that is good against corrosion (Ti, polyurethane, glass) is a bad heat conductor.
As power in deep sea or ice is expensive, the solution is to use (very) low power electronics.

Final remarks

General considerations

Challenges intrinsic to experiment location:

- Major civil engineering in *harsh* conditions
- Access limitation for equipment
- Access limitation for personnel
- Development with industries equipments, otherwise standard, suitable for underground deployment
- More strict safety requirements (material selection, fire retardant, emanations, …)

Facilities

In general, from the input of the experts emerged the need of facilities for R&D, prototyping and integration tests.

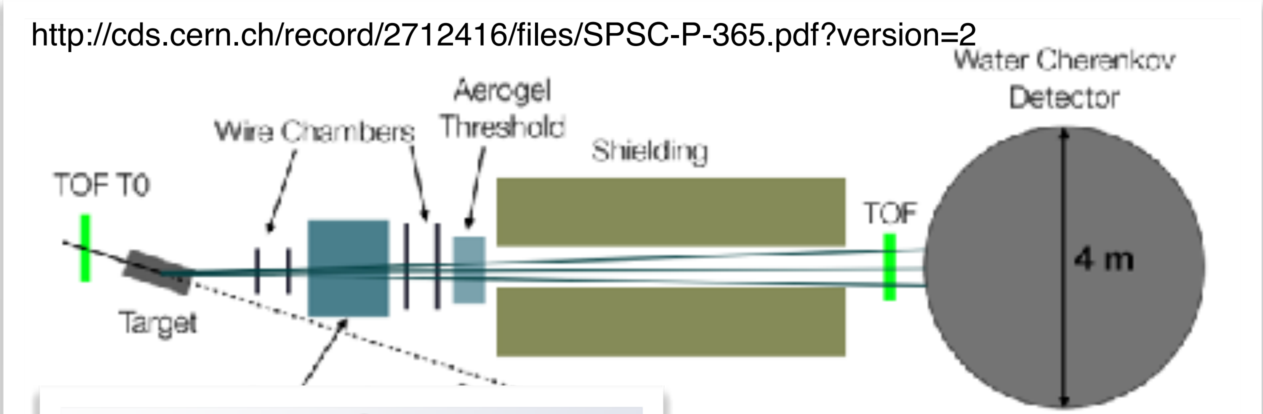
- ProtoDUNEs is the prototype facility for the DUNE far detectors
- CERN Neutrino Platform provides the infrastructure for several developments of neutrino detectors
- DUNE ND LArTPC would benefit from a facility at FNAL to demonstrate the transport, testing and installation of raws of modules
- HK, ESSnuSB and THEIA expressed interest in a test facility on a beam line for development of next generation Cherenkov detectors (proposal for T9 beamline at CERN East Area)
- KM3NeT needs facilities to enable the development and test of components for deep deployment in realistic conditions (refrigerated, 300 Atm, …)

Test facilities at CERN

Water Cherenkov Test Experiment

Tertiary low energy beam
e,mu,pi,p 140-1200 MeV/c
CERN east area T9

50 ton water Cherenkov (operational in 2023):
- benchmark new detector technologies
- develop calibration systems
- measure high-angle Cherenkov light, pion scattering and absorption, secondary neutron production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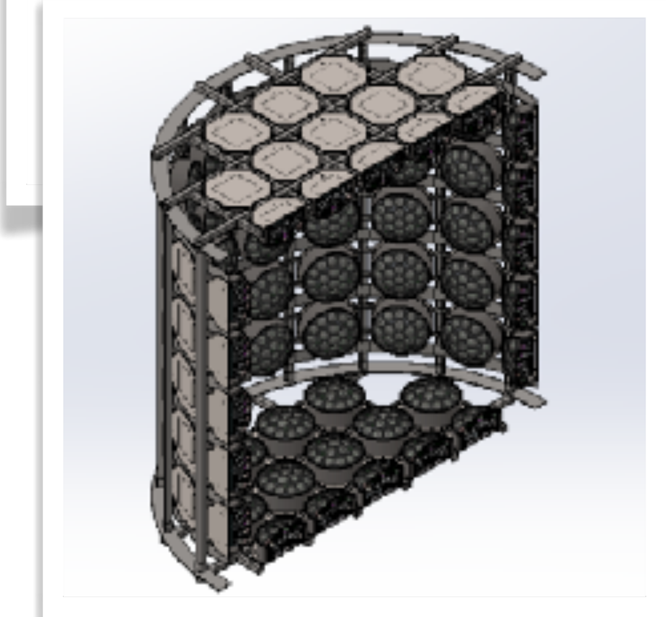

ProtoDUNE @ Neutrino Platform

2x 750 ton LAr TPCs
Phase 1: Prototyping and (beam) test of SP&DP LAr TPCs for DUNE completed
Next: Construction of module 0 SP-HD detector and R&D on VD layout

Conclusions

- Listed very diversified integration challenges for very different detector technologies

- Found development needs that are synergistic between different experiments

- Especially in integration, R&D activities and engineering go hand in hand

- Developments in strong collaboration with industry is paramount

- Need of facilities for R&D, prototypes, and integration tests

Additional comments/input/feedback are welcome:
ECFA-DetectorRDRoadmap-TF8Integration-Input@cern.ch