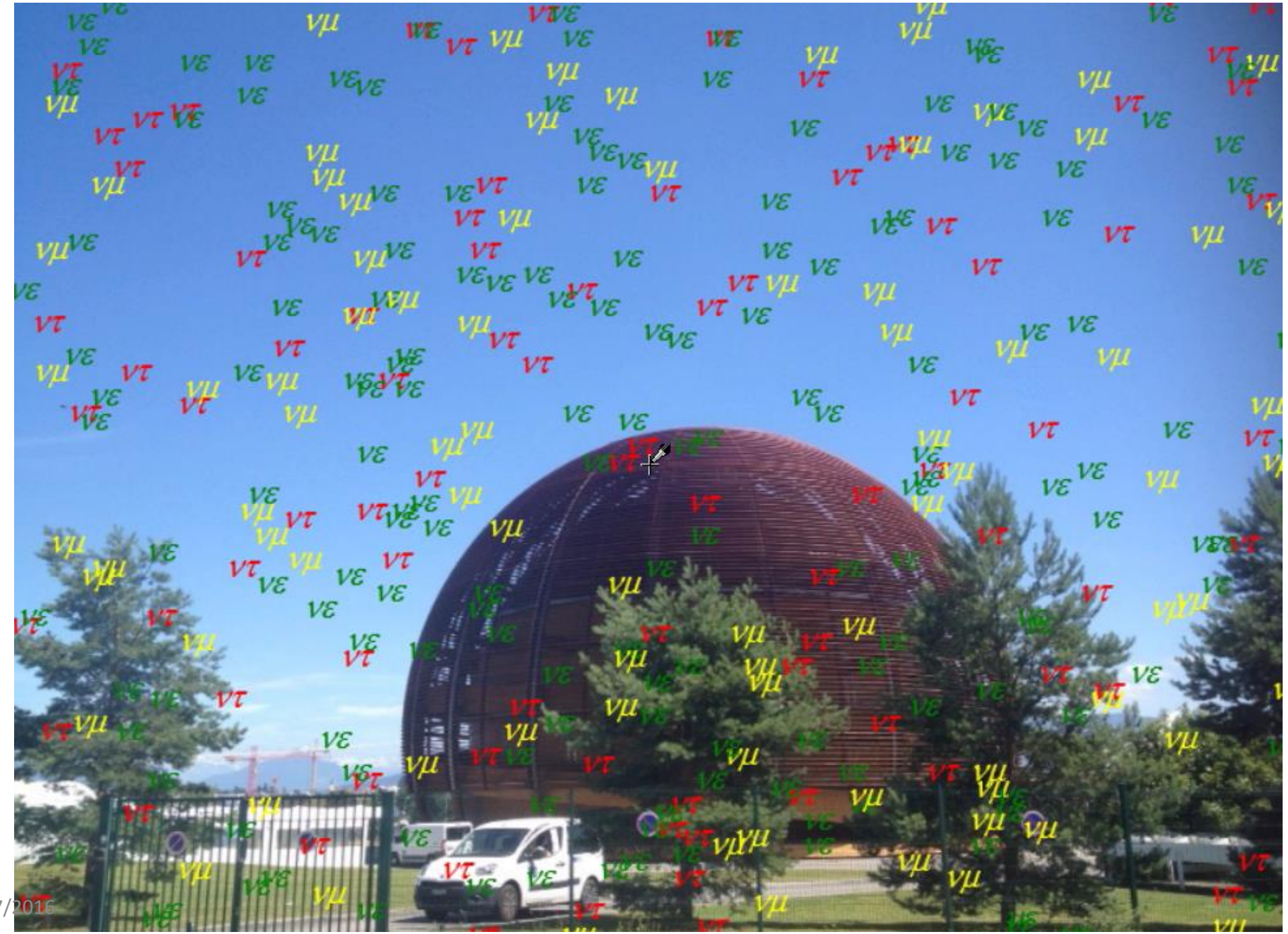
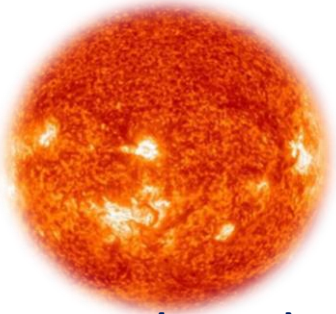
CURIOUS NEUTRINOS MORNING

Diamanto Smargianaki, Umut Kose
05.07.2016, IdeaSquare

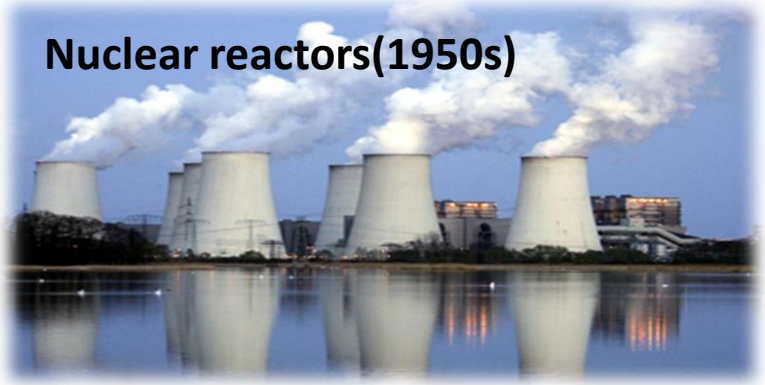
Neutrinos are everywhere...

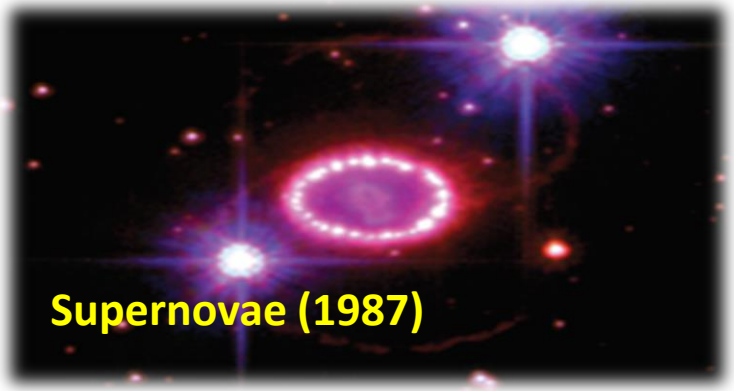


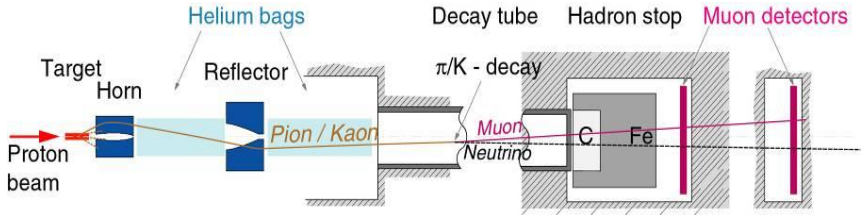
… coming from:



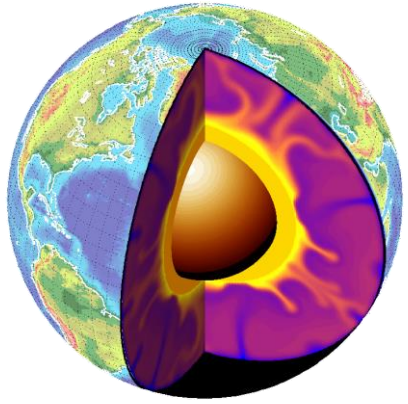
Sun (1960s)



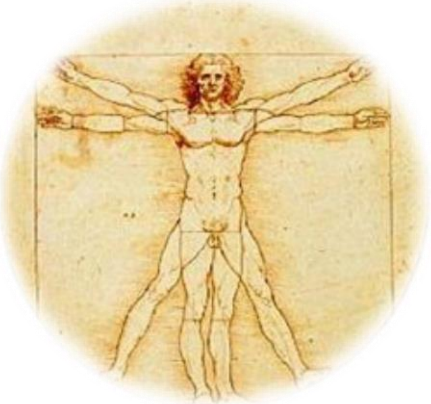




Accelerator (1962)



Earth (2005)

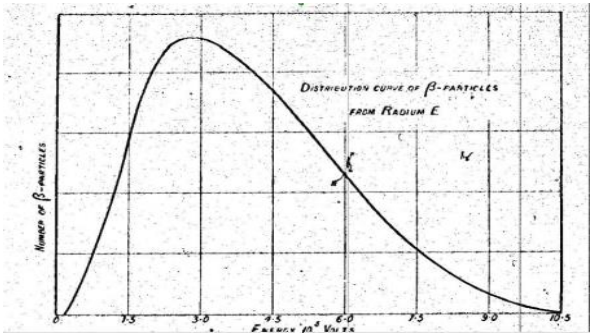


Human being (K^{40})

Bananas (K^{40})

A bit of history:

Energy spectrum of beta decay → Discrete or continuous!



Ellis & Wooster, 1927

Niels Bohr, 1929, "At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations" *"β-ray spectra and Energy Conservation, 1929 unpublished manuscript": N. Bohr collected works, Vol. 9, Nuclear Physics (1929-1952).*

Wolfgang Pauli, 1930, "Dear Radioactive Ladies and Gentlemen" in which he proposed **a "desperate remedy"** to save the law of energy conservation introducing a new neutral particle with intrinsic angular momentum or "spin" of 1/2. The new particle would be emitted together with the electron in beta decay so that the total energy would be conserved.

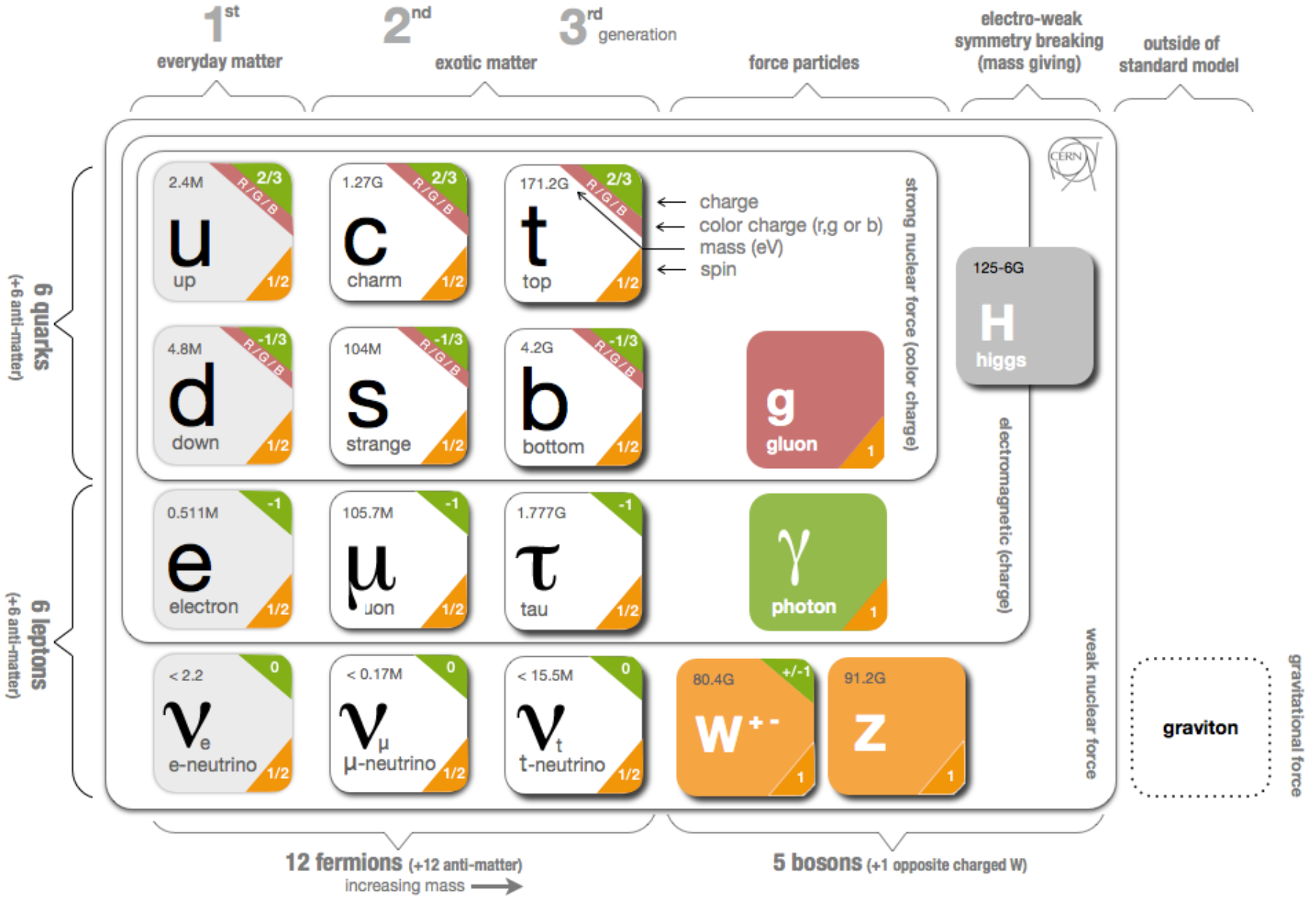
Enrico Fermi, 1934, formulation of the first theory of nuclear beta decay. He also discussed the mass of the neutrinos.

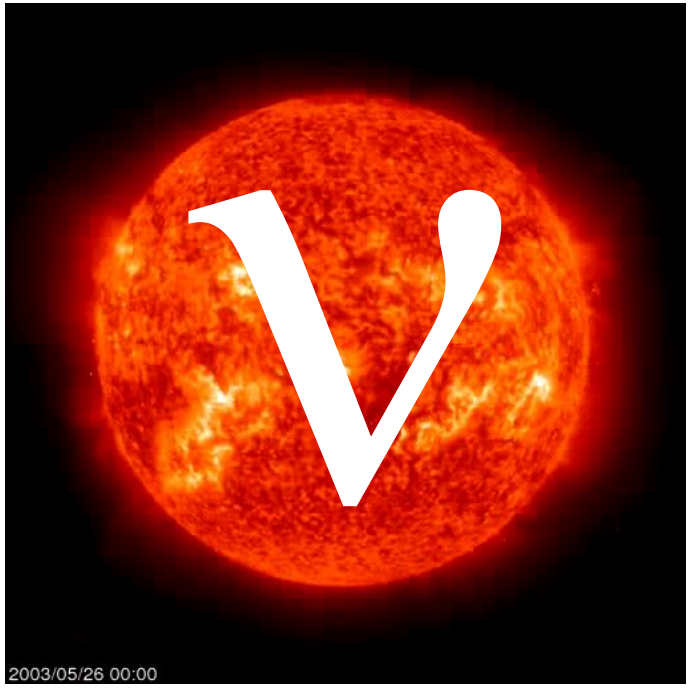
Fred Reines & Clyde Cowan, 1956, the first observation of antineutrinos.

L. Lederman, M. Schwartz, Jack Steinberger, 1962, at least two neutrinos, $\nu_e \neq \nu_\mu$.

DONUT experiment, 2000, observation of ν_τ

Standard Model





Ray Davis, John Bachal, 1968, The Homestake experiment, search for solar neutrinos

$$\frac{\phi_{\nu_e}(Experiment)}{\phi_{\nu_e}(Theory)} = 0.34 \pm 0.06$$

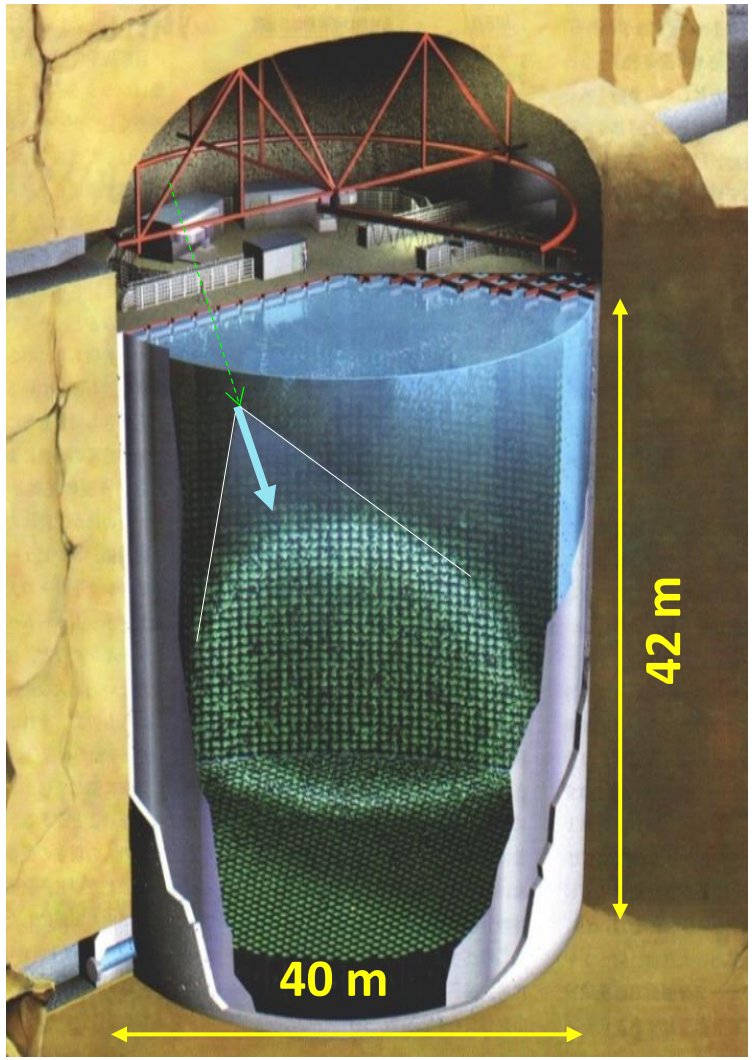
The experiment was wrong!

The theory was wrong!

Both were wrong!

SOLAR NEUTRINO PROBLEM

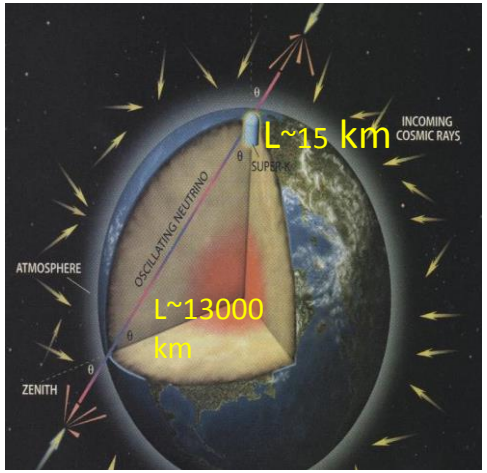
The Neutrino Revolution



$$\nu_l + N \rightarrow l^- + X\,, \quad l = e, \mu$$

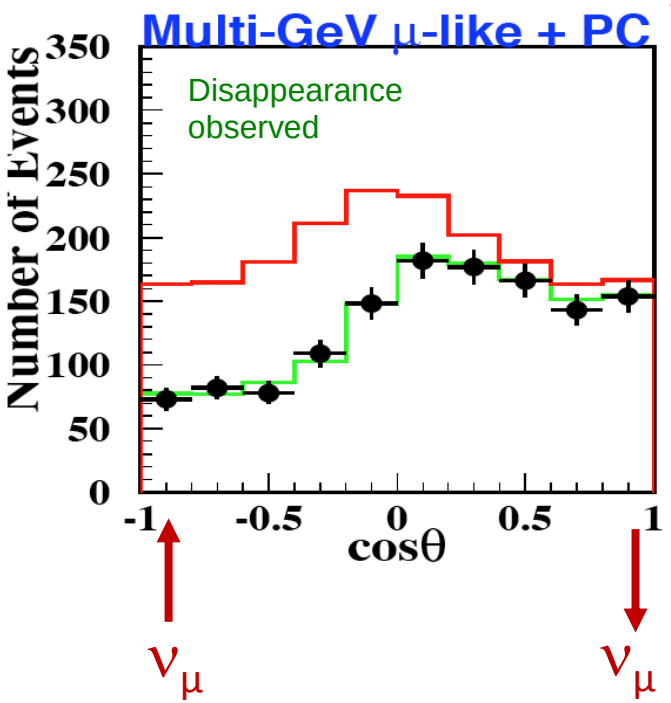
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

Super Kamiokande, 1989, same anomaly seen in atmospheric neutrinos



Cosmic rays are isotropic on the sky, neutrino flux is expected:

$$\frac{\phi_{\nu_\mu}(Up)}{\phi_{\nu_\mu}(Down)} = 1$$

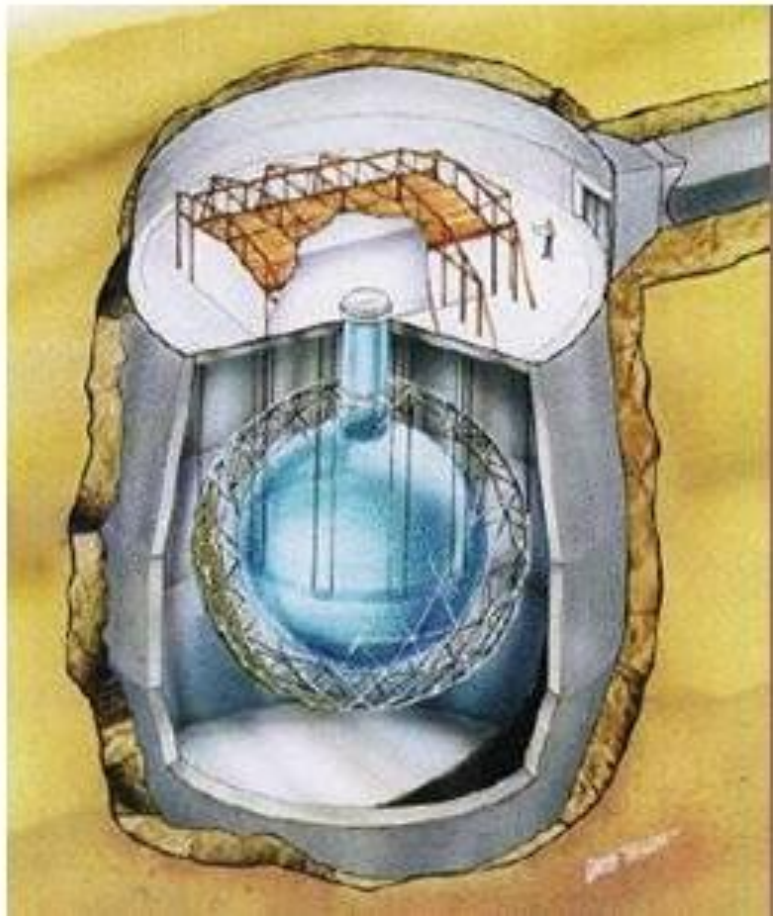


Observation:

$$\frac{\phi_{\nu_\mu}(Up)}{\phi_{\nu_\mu}(Down)} \cong \frac{1}{2}$$

→ "Neutrinos have nonzero masses!"

Solving the mystery in solar neutrinos



The Sudbury Neutrino Observatory (SNO), 200x

$$\nu_e + d \rightarrow p + p + e^- \quad \Rightarrow \Phi_{\nu_e}$$

$$\nu_{e,\mu,\tau} + d \rightarrow p + n + \nu_{e,\mu,\tau} \quad \Rightarrow \Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau}$$

$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau}} = 0.301 \pm 0.033$$

$\Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau}$ = (5.54±0.32±0.35)x10^6 /cm^{2}sec

In a good agreement with theoretical calculation (J. Bachal et al.):

Φ_{total} = (5.69±0.91)x10^6 /cm^{2}sec

Neutrinos change flavour!

Basic Oscillation formalism:

Neutrino flavours are defined as superposition of the definite mass eigenstates.

$$\underbrace{|\nu_\alpha\rangle}_{\text{Neutrino of flavour}} = \sum_i \underbrace{U^*_{\alpha i}|\nu_i\rangle}_{\text{Neutrino of definite mass } m_i}$$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}$$

Solar and nuclear reactors

CP phase
Nuclear reactor and atmospheric

Atmospheric and accelerator neutrinos

Majorana phases
Neutrinoless double beta decay

Two neutrino flavour oscillations: $P(\nu_\alpha \rightarrow \nu_\beta) = \overbrace{\sin^2 2\theta}^{\text{Mixing angle}} \sin^2(1.27 \frac{\Delta m^2[eV^2]L[km]}{E[GeV]})$ $\Delta m^2 \neq 0$

L: distance source-detector
E: Neutrino energy
$\Delta m^2 \equiv m_2^2 - m_1^2$

Three neutrino flavours oscillations:

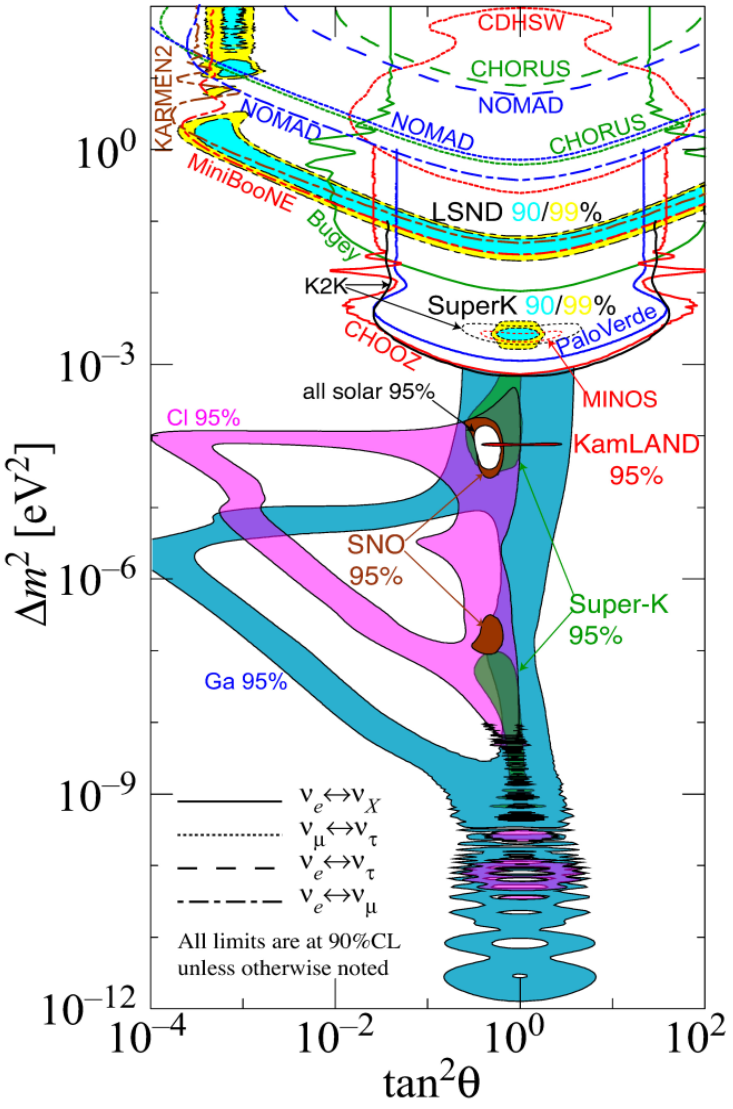
$$P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

$$= sin^2(\theta_{23})sin^2(2\theta_{13})sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) + cos^2(\theta_{23})sin^2(2\theta_{13})sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$- Jsin(\delta)\sin\left(\frac{\Delta m_{32}^2 L}{4E}\right) + Jcos(\delta)\cos\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

where $J = \cos(\theta_{13})\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\sin\left(\frac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$

Neutrino oscillation results:



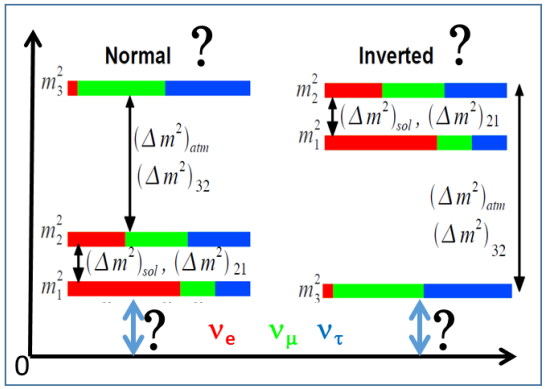
Particle Data Group

- **global data fits nicely with the 3 neutrinos from the SM**
- **a few "anomalies" at 2-3 σ: LSND, MiniBoone, reactor and Gallium anomaly → STERILE NEUTRINO ?**

3-ν mixing parameters (pdg)	Normal ordering	
Δm^2_{21} (eV²)	(7.53±0.18) x 10^{-5}	
Δm^2_{32} (eV²)	0.00242±0.00006	
Δm^2_{31} (eV²) = $\Delta m^2_{32} - \Delta m^2_{21}$		**Hierarchy?**
$sin^2\theta_{12}$	0.304±0.014	
$sin^2\theta_{23}$	0.514-0.056+0.055	**Maximal?**
$sin^2\theta_{13}$	0.0219±0.0012	
δ/π	unknown	**CP phase?**

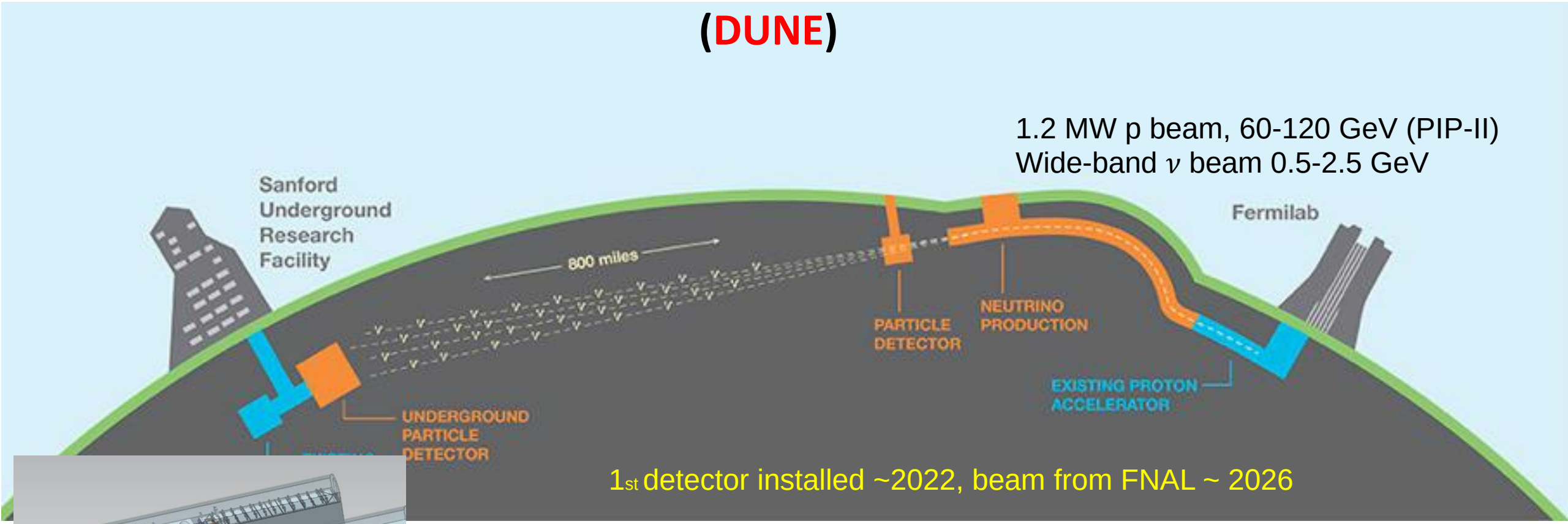
Current precision:

$\delta(\theta_{12})\approx 4\%$, $\delta(\theta_{23})\approx 10\%$, $\delta(\theta_{13})\approx 5\%$,
$\delta(\Delta m^2_{21})\approx 3\%$, $\delta(\Delta m^2_{31})\approx 2\%$

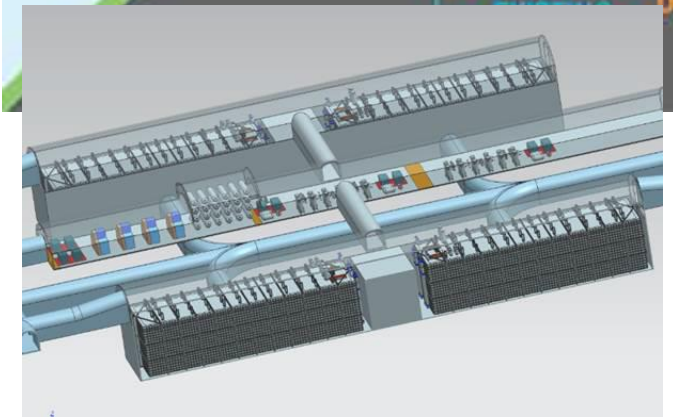


Long Baseline programme: The Deep Underground Neutrino Experiment (DUNE)

1.2 MW p beam, 60-120 GeV (PIP-II)
Wide-band ν beam 0.5-2.5 GeV



1st detector installed ~2022, beam from FNAL ~ 2026



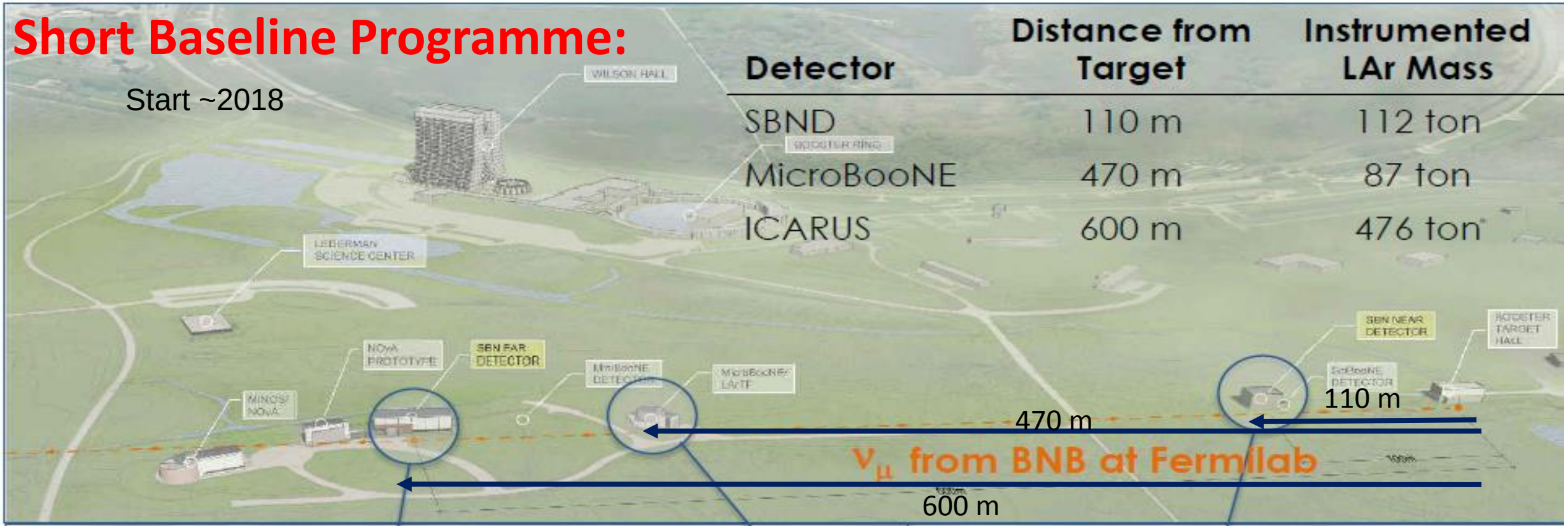
4x10 kt LAr detectors
~1.5 km underground

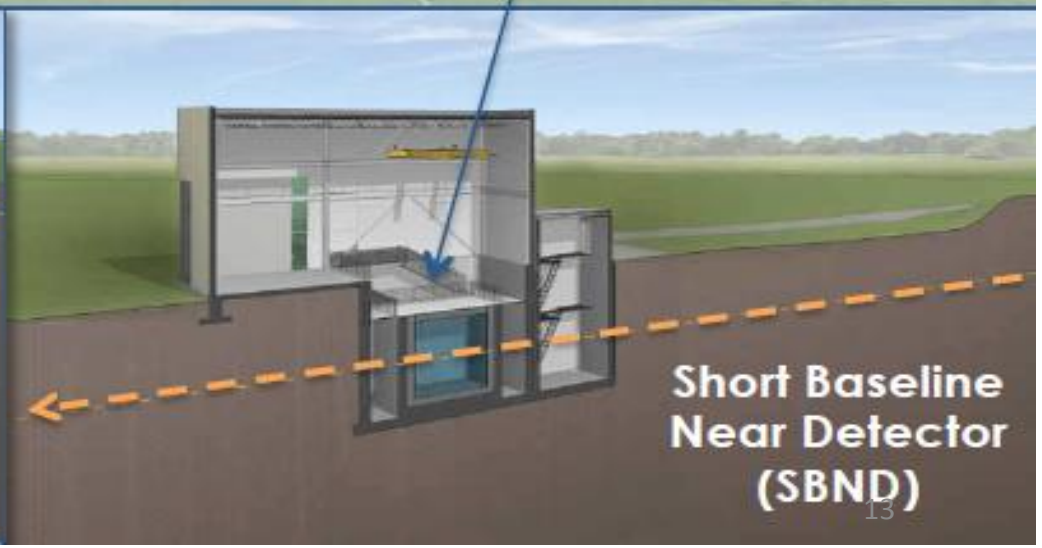
DUNE is designed to provide a broad program of:
- ν oscillation physics
- ν interaction physics
- Proton decay
- Supernova physics
- BSM physics

Short Baseline Programme:

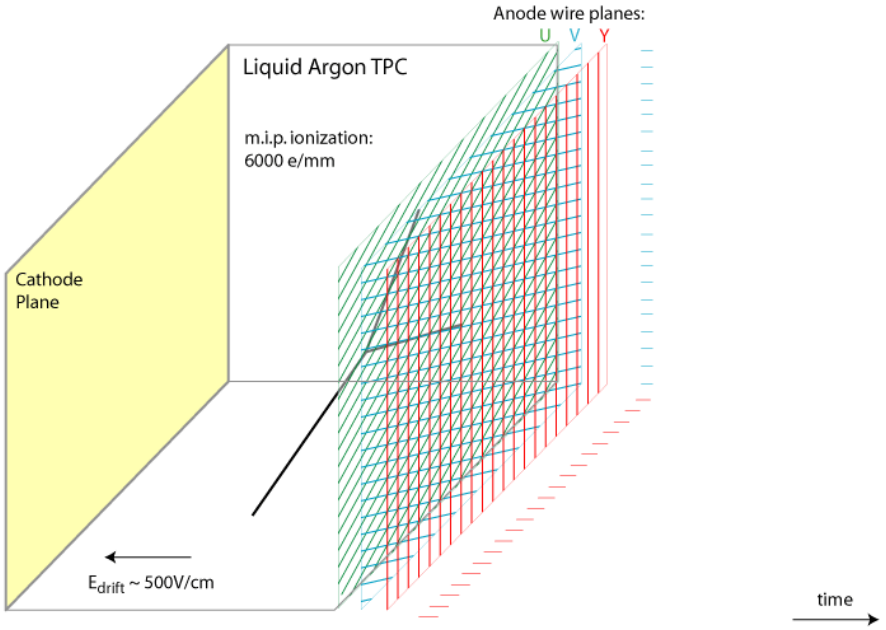
Start ~2018

Detector	Distance from Target	Instrumented LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

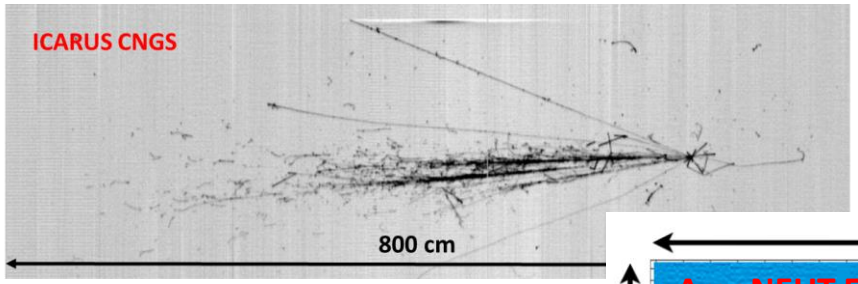


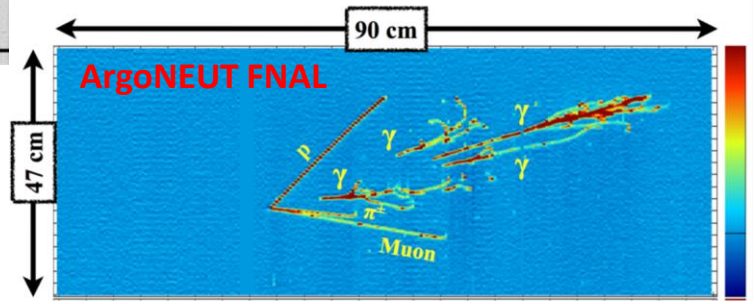


Liquid Argon technology has been chosen for the next generation of neutrino experiments in the short and long baseline neutrino programmes.



LAr TPC idea: Ionization present in the aftermath of a neutrino interaction in liquid argon is drifted towards fine-grained readout wire planes that are connected to low-noise electronics.





Despite the tremendous advantages of the LArTPCs, some technical challenges remain. Worldwide efforts are being dedicated to R&D efforts to demonstrate the advantages of LAr detectors.

European High Energy Physics strategy mandate

"Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. CERN should develop a neutrino program to ***pave the way*** *for a substantial European role in future long baseline experiments. Europe should explore the possibility of major participation in leading long baseline neutrino projects in the US and Japan."*

CERN Neutrino Platform

- offering a platform for Neutrino detectors R&D to demonstrate large-scale LAr technology (cryostats, cryogenics, detectors)
- constructing a large neutrino test area (EHN1 extension) with charged beams capabilities.
- supporting European participation in accelerator neutrino experiments in US and Japan.
- assisting the EU neutrino community in their long term common plans.

Neutrino Platform Projects list

6 projects presented to the SPSC and approved as a real experiments at CERN:

NP01: WA104, ICARUS as a far detector for FNAL Short baseline

NP02: WA105, demonstrator and engineering prototype for a double phase LAr TPC for DUNE

NP03: PLAFOND, a generic R&D Framework

NP04: ProtoDUNE, engineering prototype for a single phase LAr TPC for DUNE

NP05: Baby MIND, a muon spectrometer for the WAGASCI experiment at T2K.

ArgonCube: as a modular LAr TPC R&D

RECONSTRUCTIONS

CRYOGENIC

DAQ

CRYOSTAT

COLD ELECTRONIC TEST

CHARGED BEAM TEST

SiPM TEST

SIMULATION

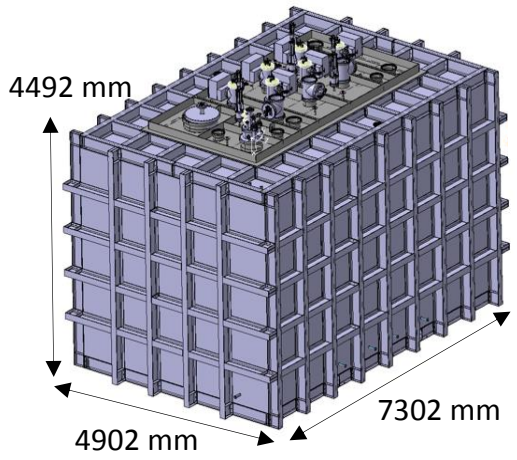
PHYSICS

PMT TEST

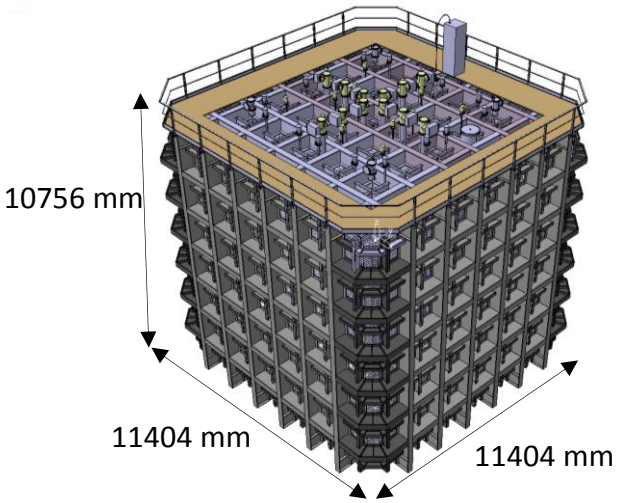
ENGINEERING

LAr Detectors

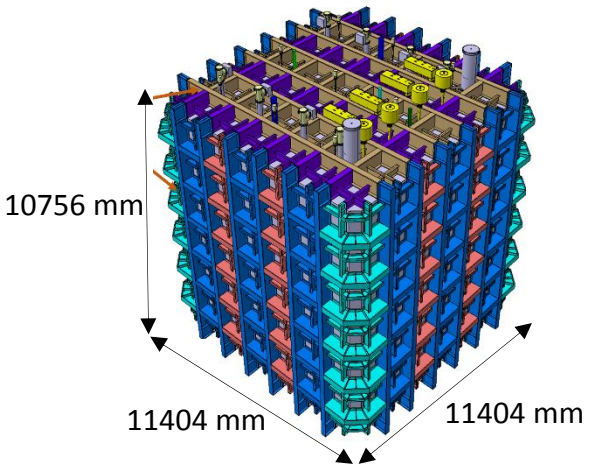
NPO2-double phase (17 m^3)



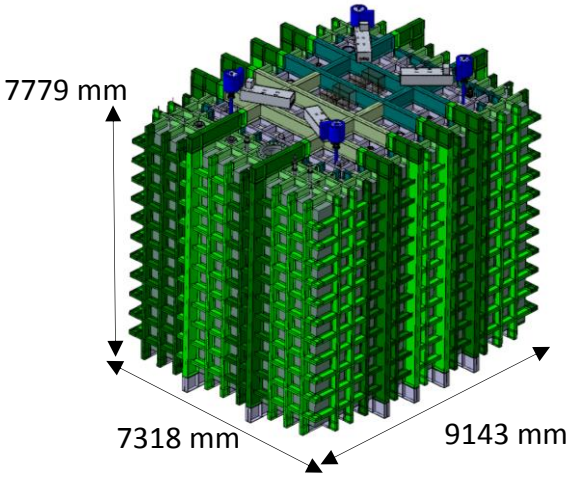
NPO2-ProtoDune double phase (EHN1 extension)



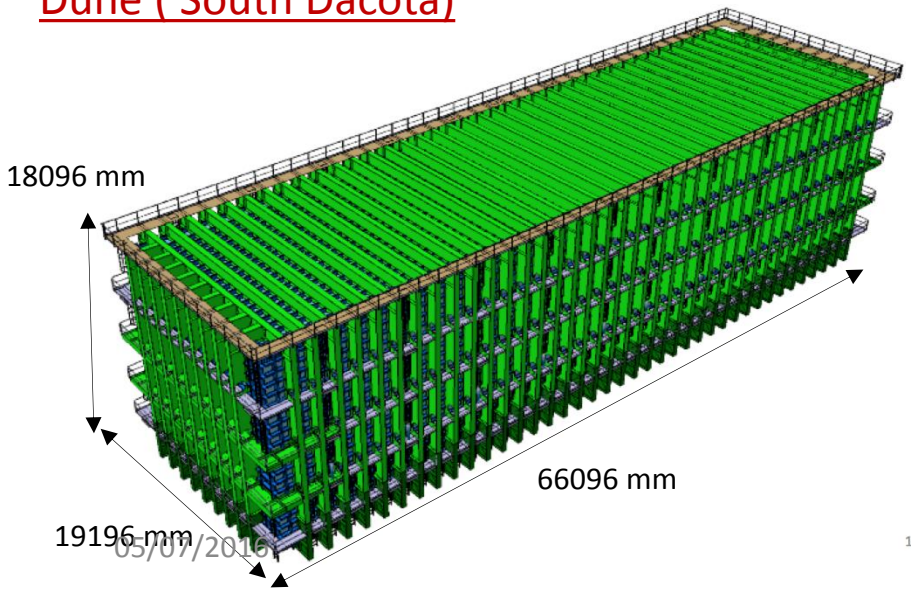
NPO4-ProtoDune single phase (EHN1 extension)



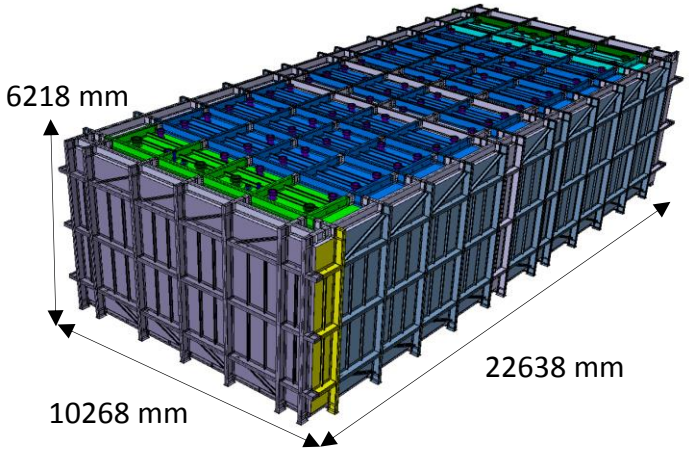
SBND (Chicago)



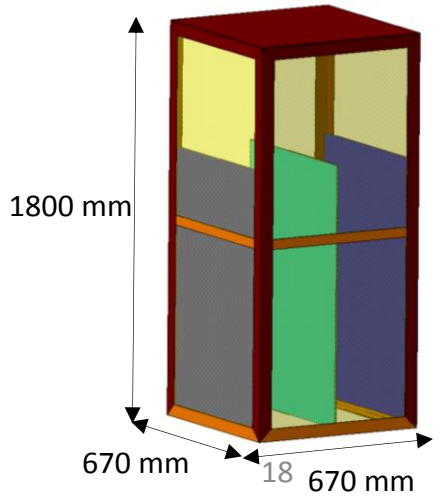
Dune (South Dacota)



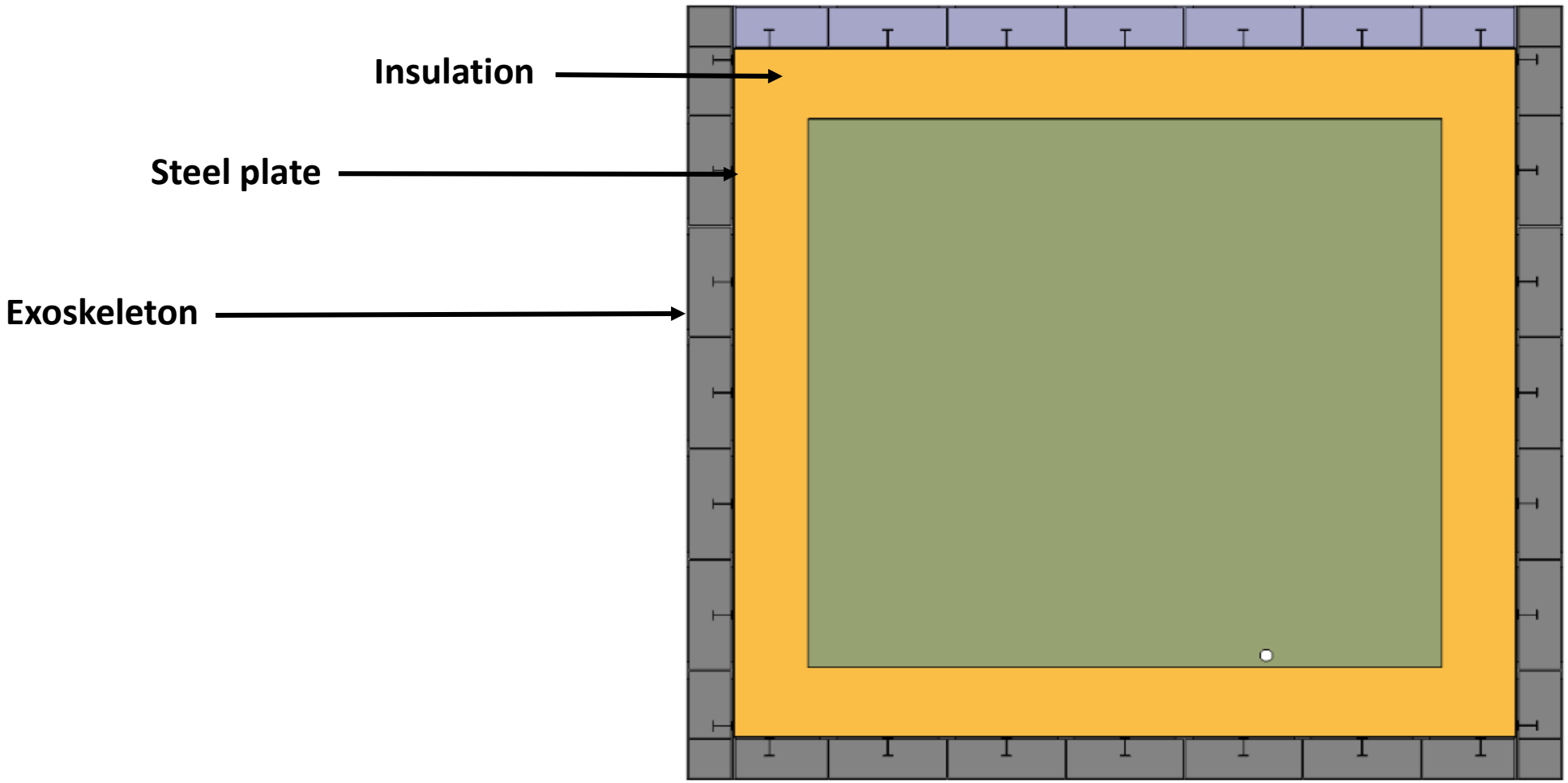
NPO1-Icarus



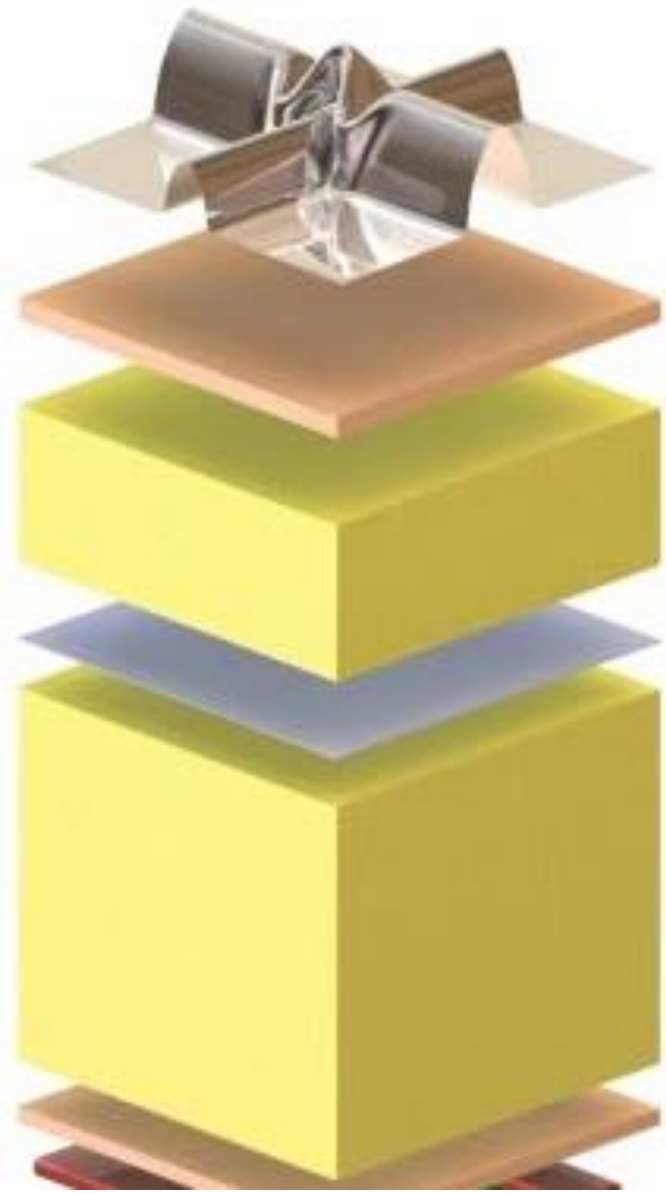
ArgonCube (BERN)



LAr Detectors - Structural Components



Insulation



- Cold cryostats technology based on LNG transport techniques

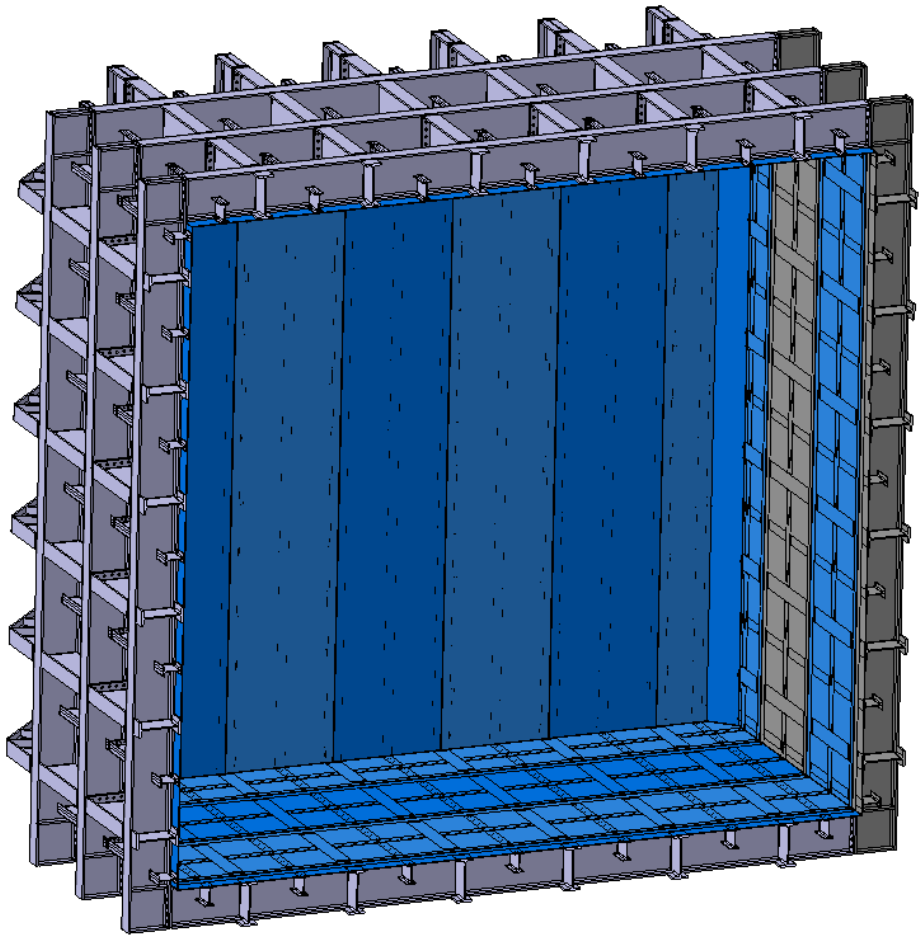
SS 1.2 mm primary membrane in contact with the liquid (primary containment)

Insulation : reinforced polyurethane foam

secondary membrane : composite laminated material (secondary containment)

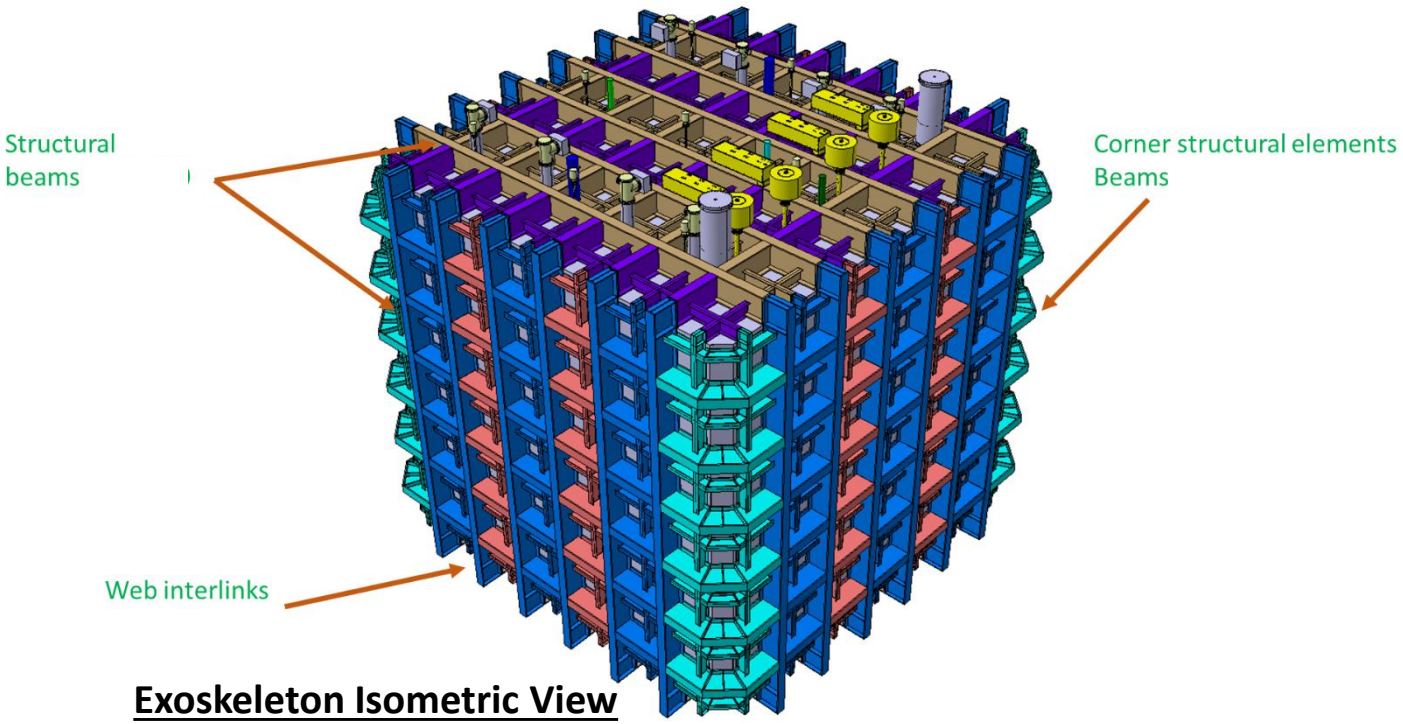
Insulation : reinforced polyurethane foam

Steel Plate



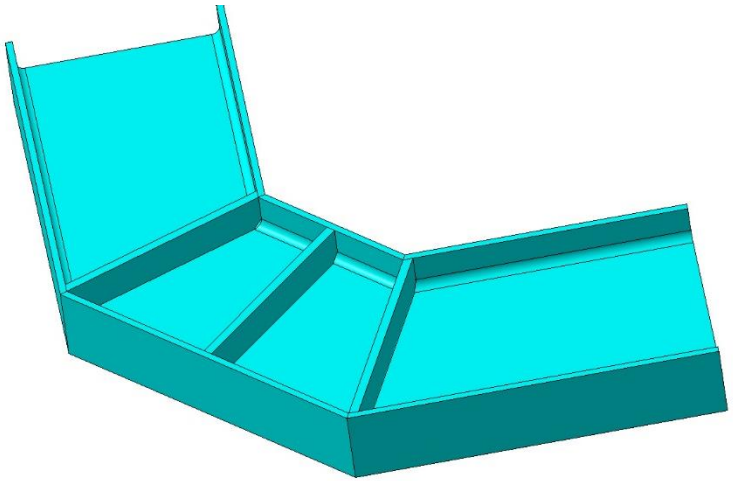
- Creates gas containment barrier to the inside
- Ensures better support for the insulation

Exoskeleton Structural Parts

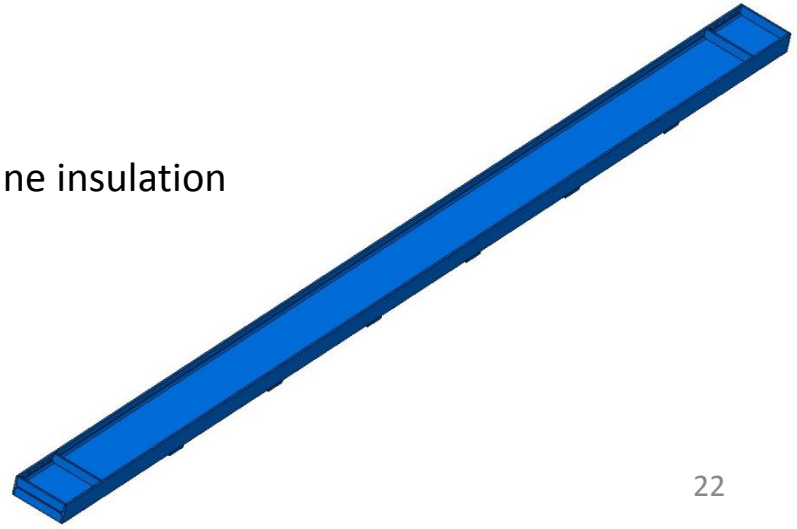


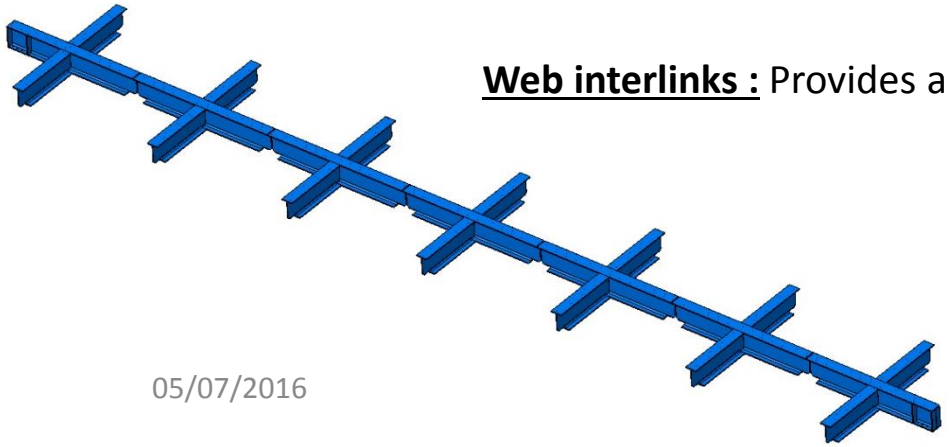
Exoskeleton Isometric View

Corner structural element : Principal load bearing elements



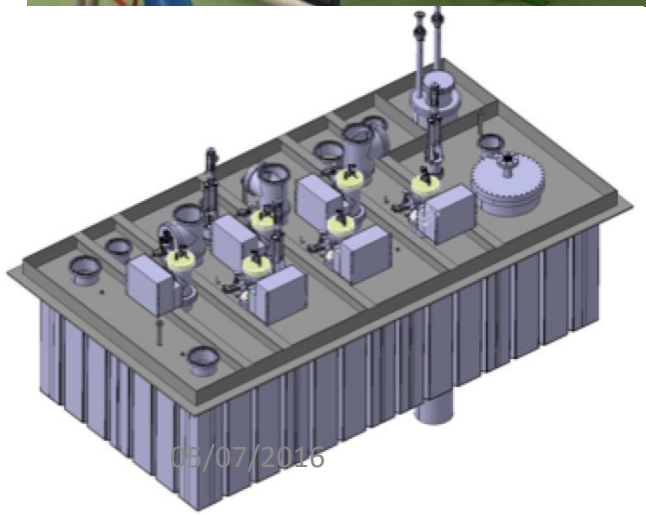
Structural beam : Principal load bearing elements

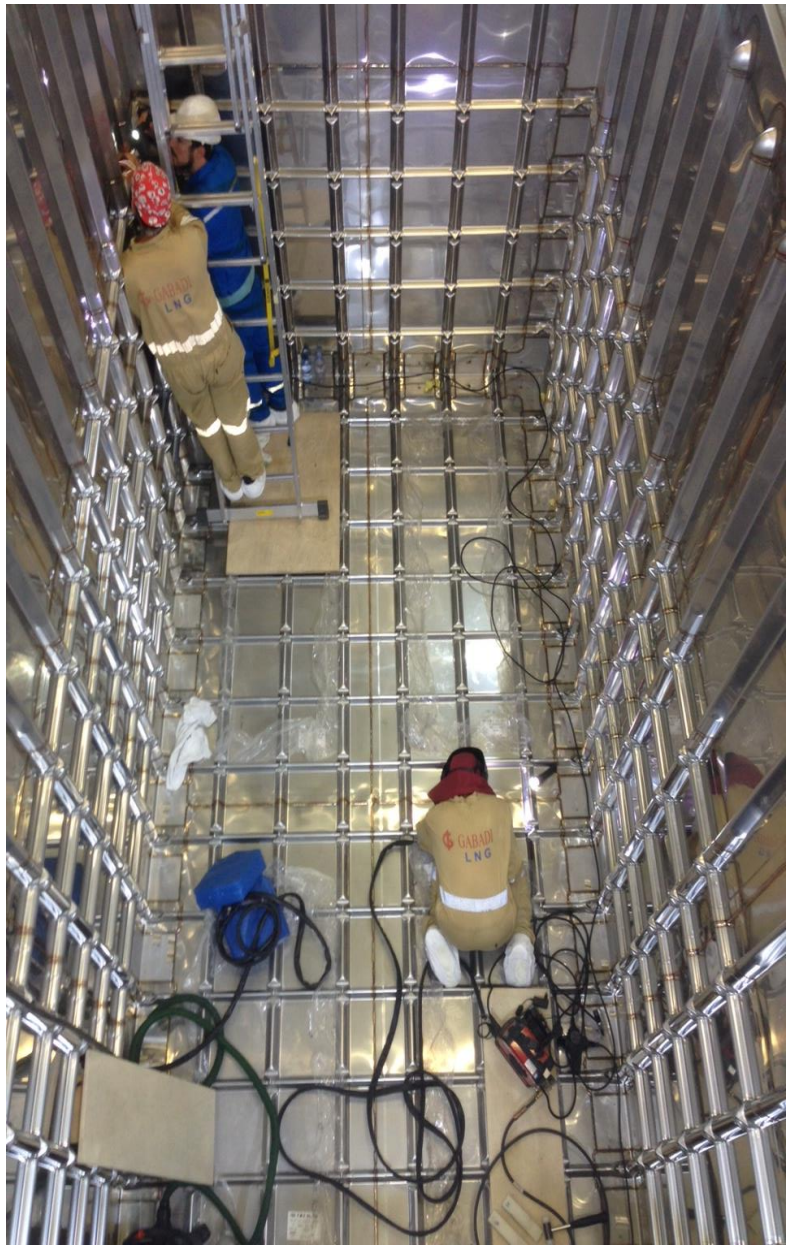




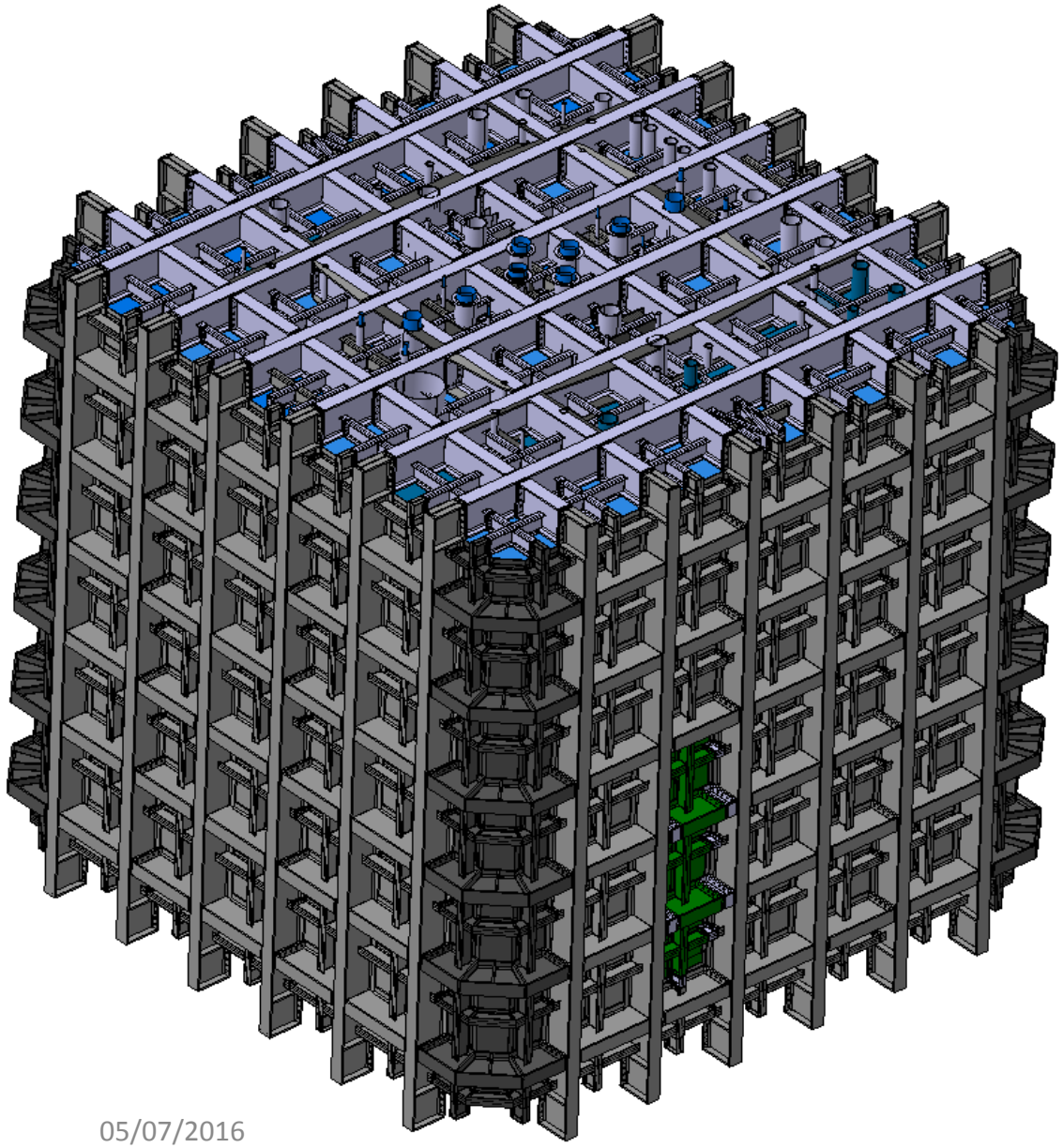
Web interlinks : Provides an adequate support of the polyurethane insulation

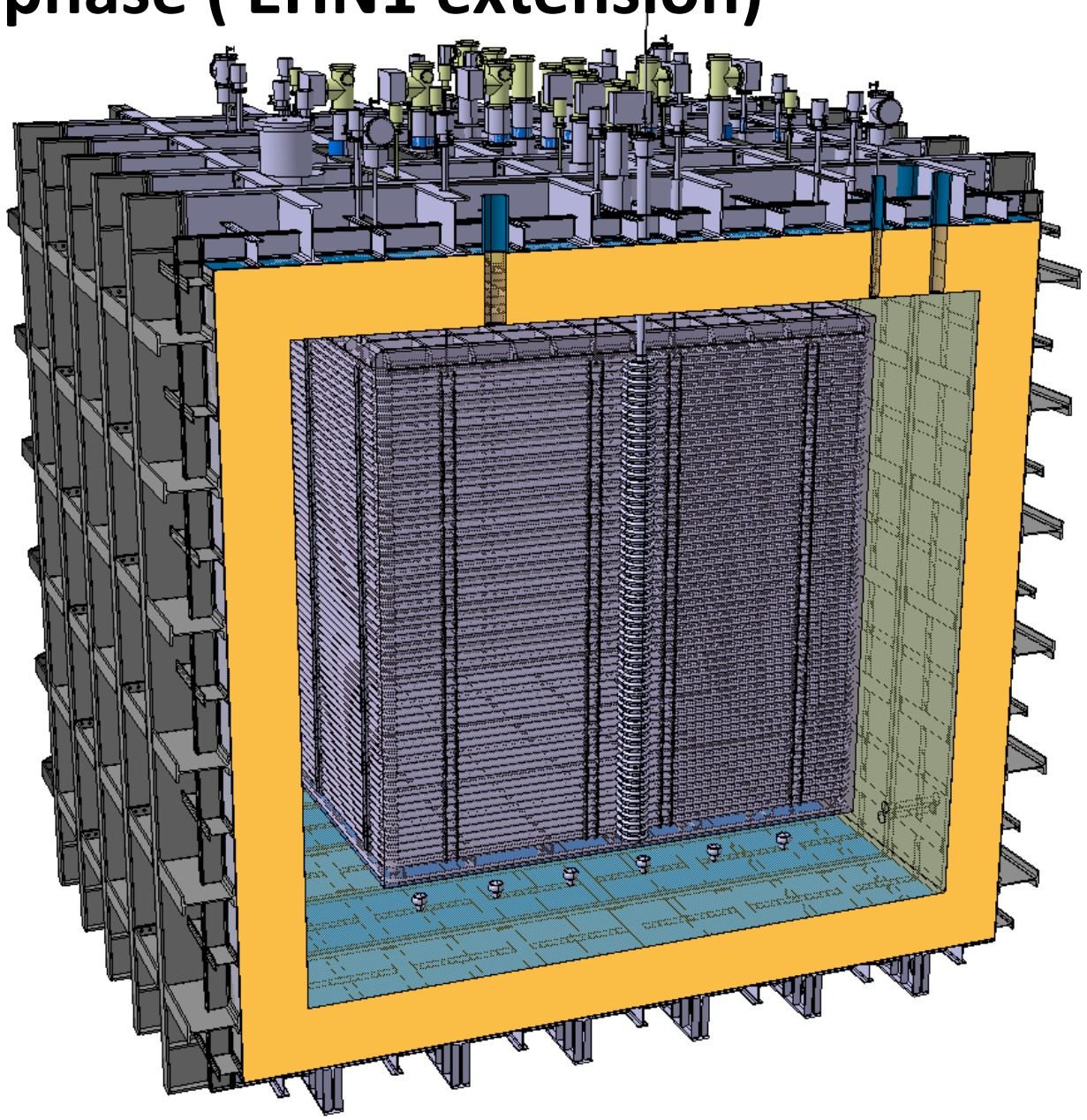
NPO2-double phase (17 m^3)



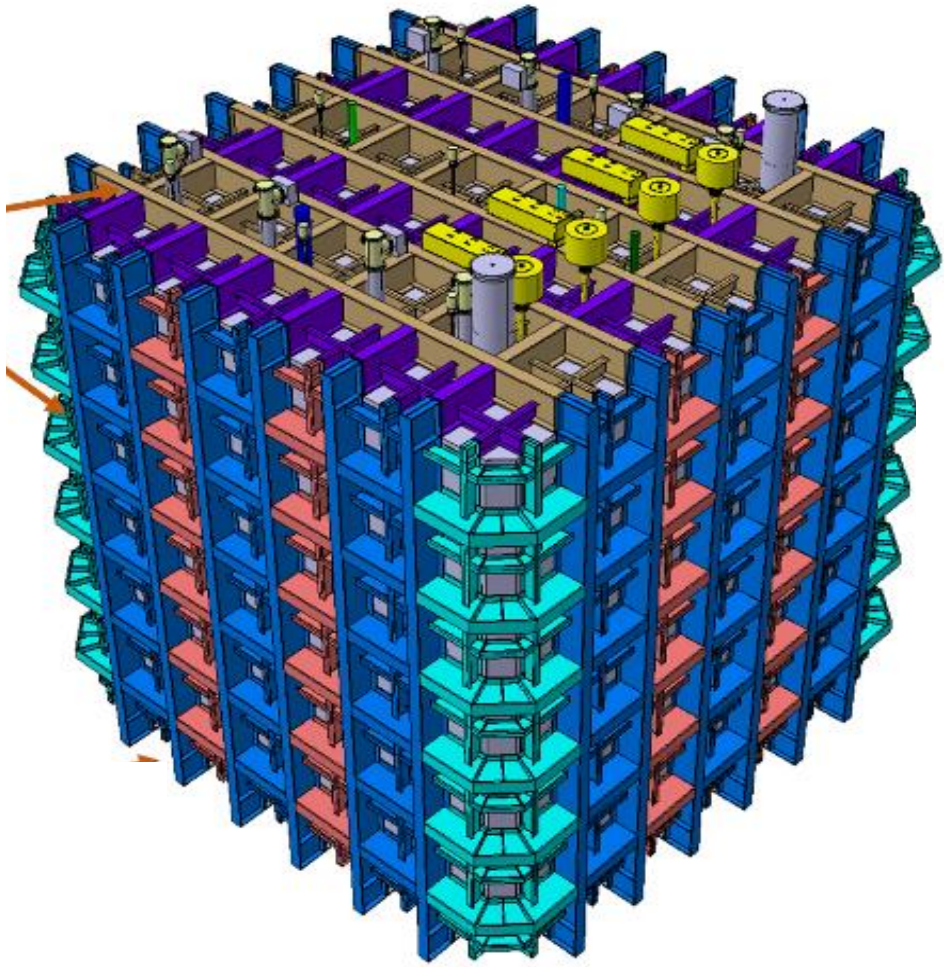


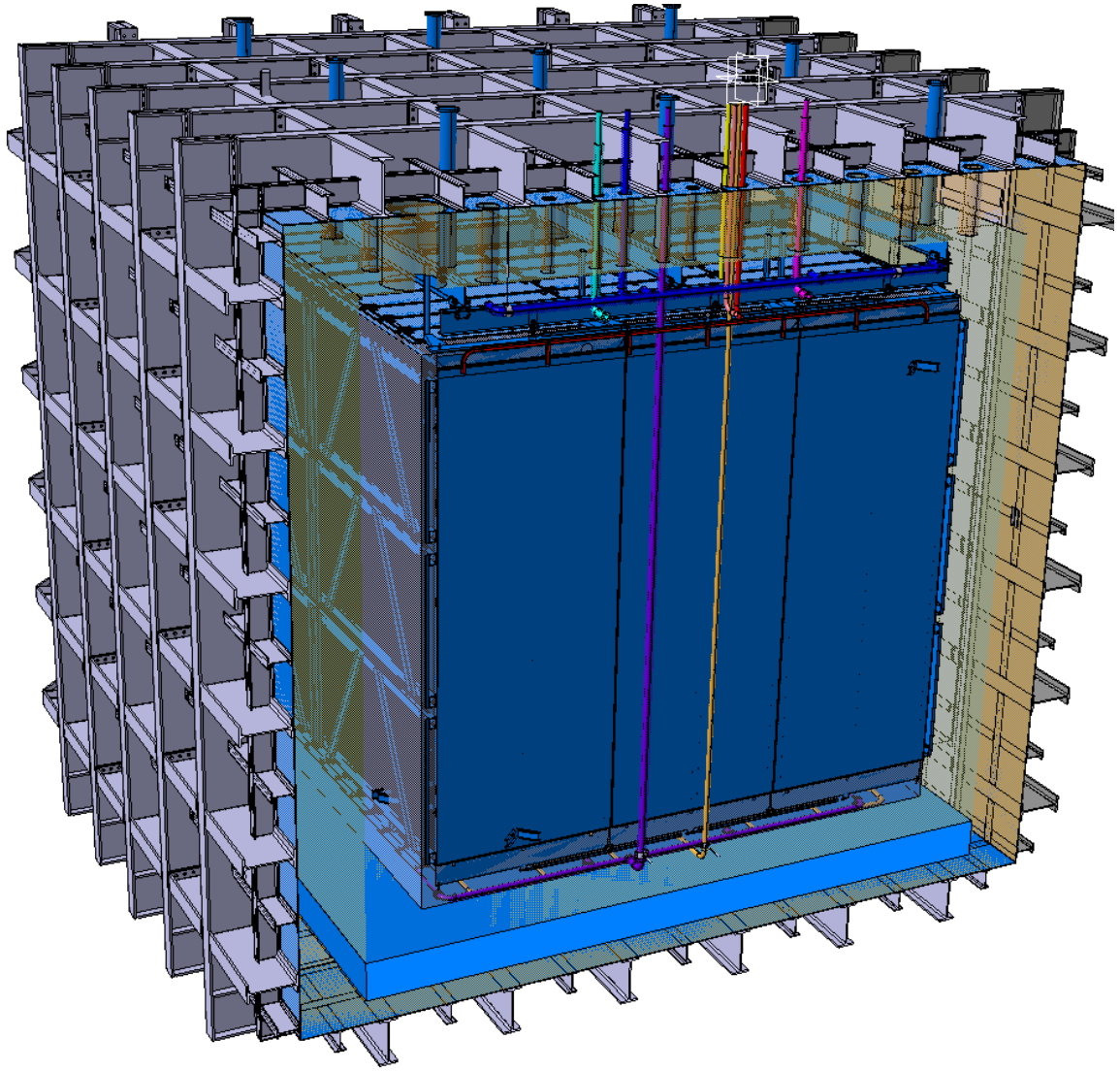
NPO2-ProtoDune double phase (EHN1 extension)



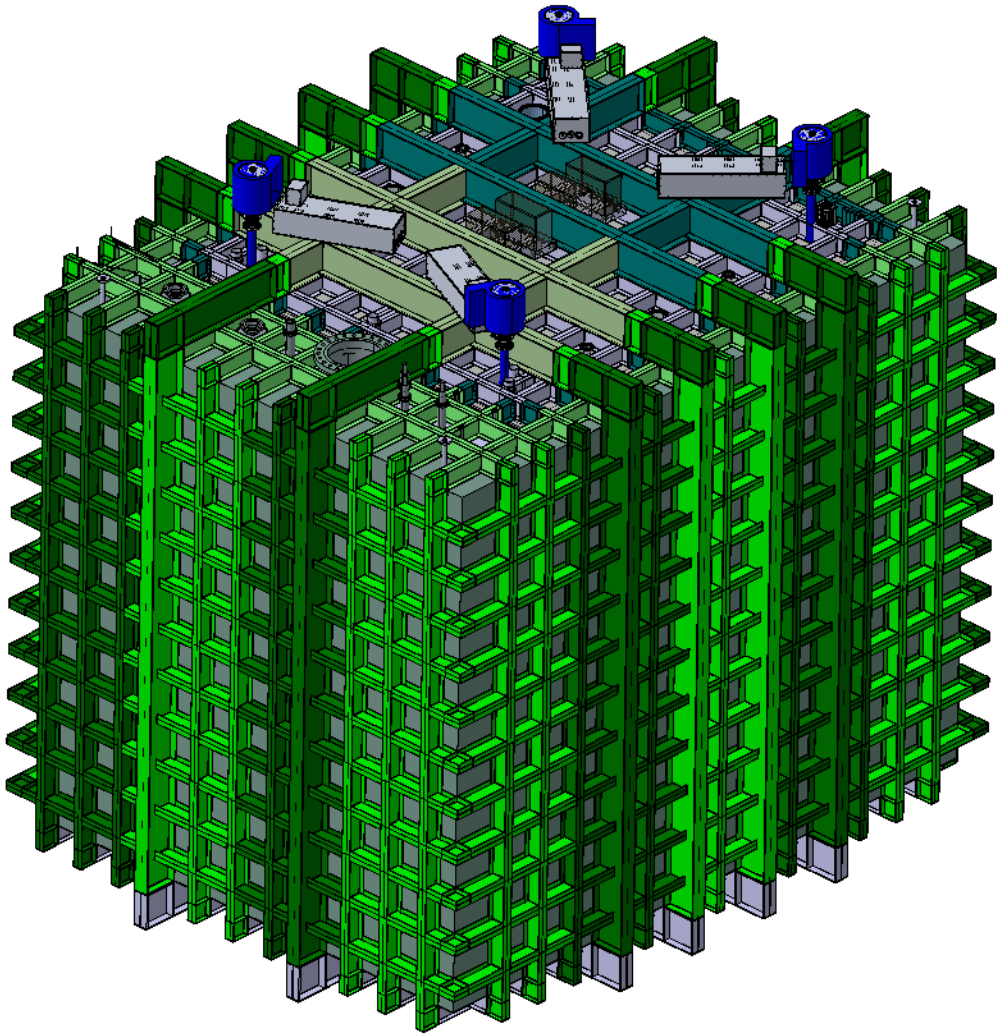


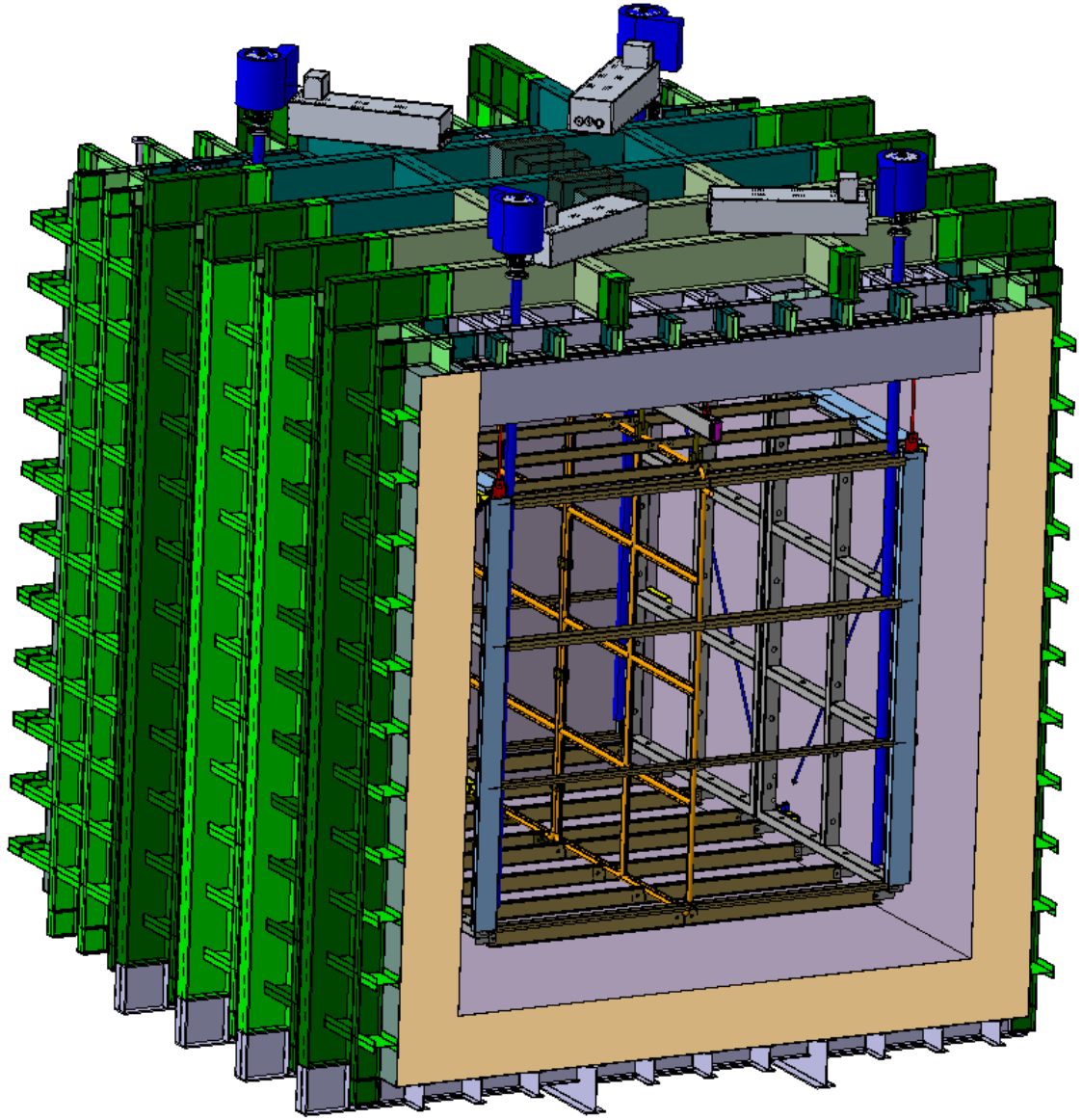
NPO4-ProtoDune single phase (EHN1 extension)



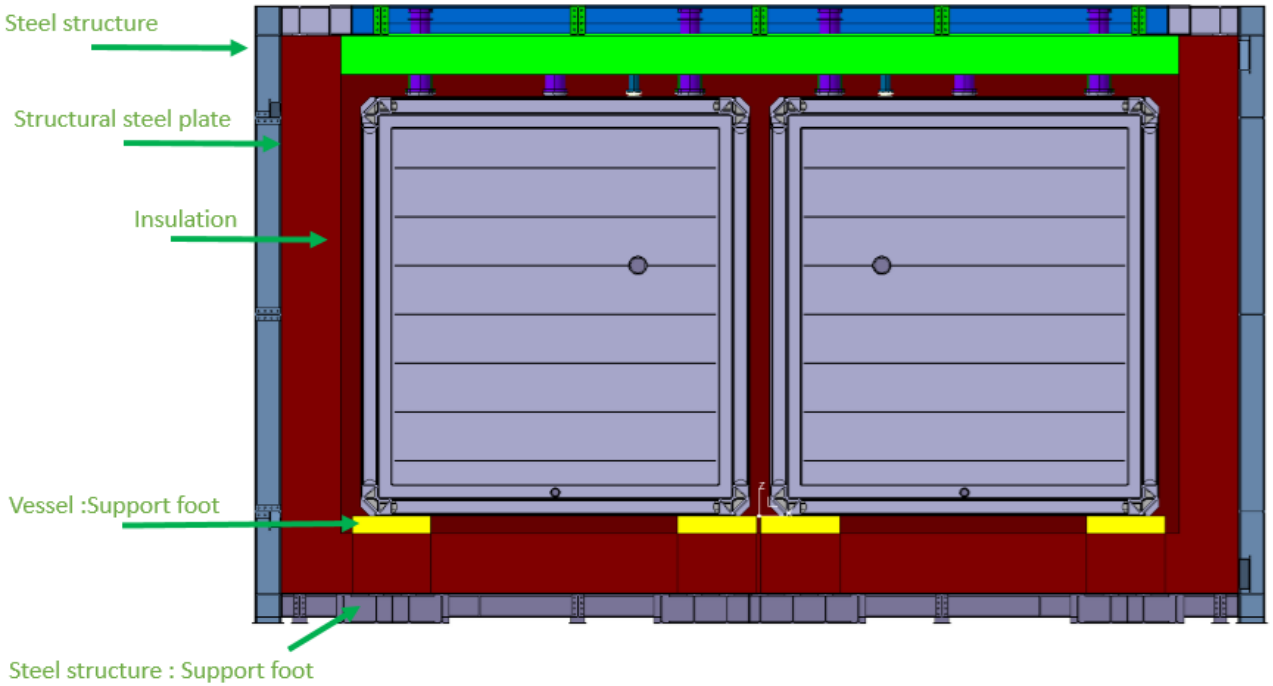


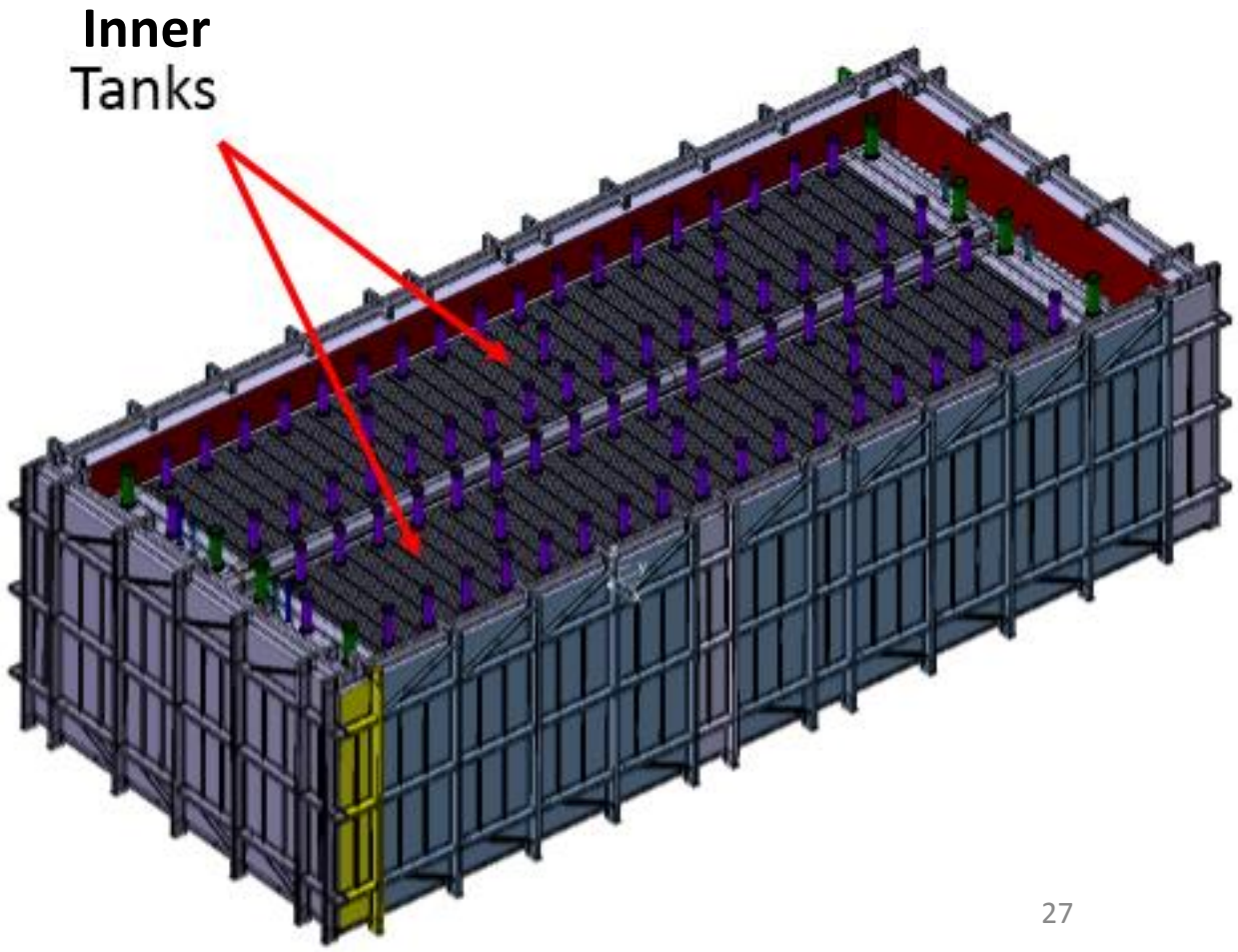
SBND(Chicago)



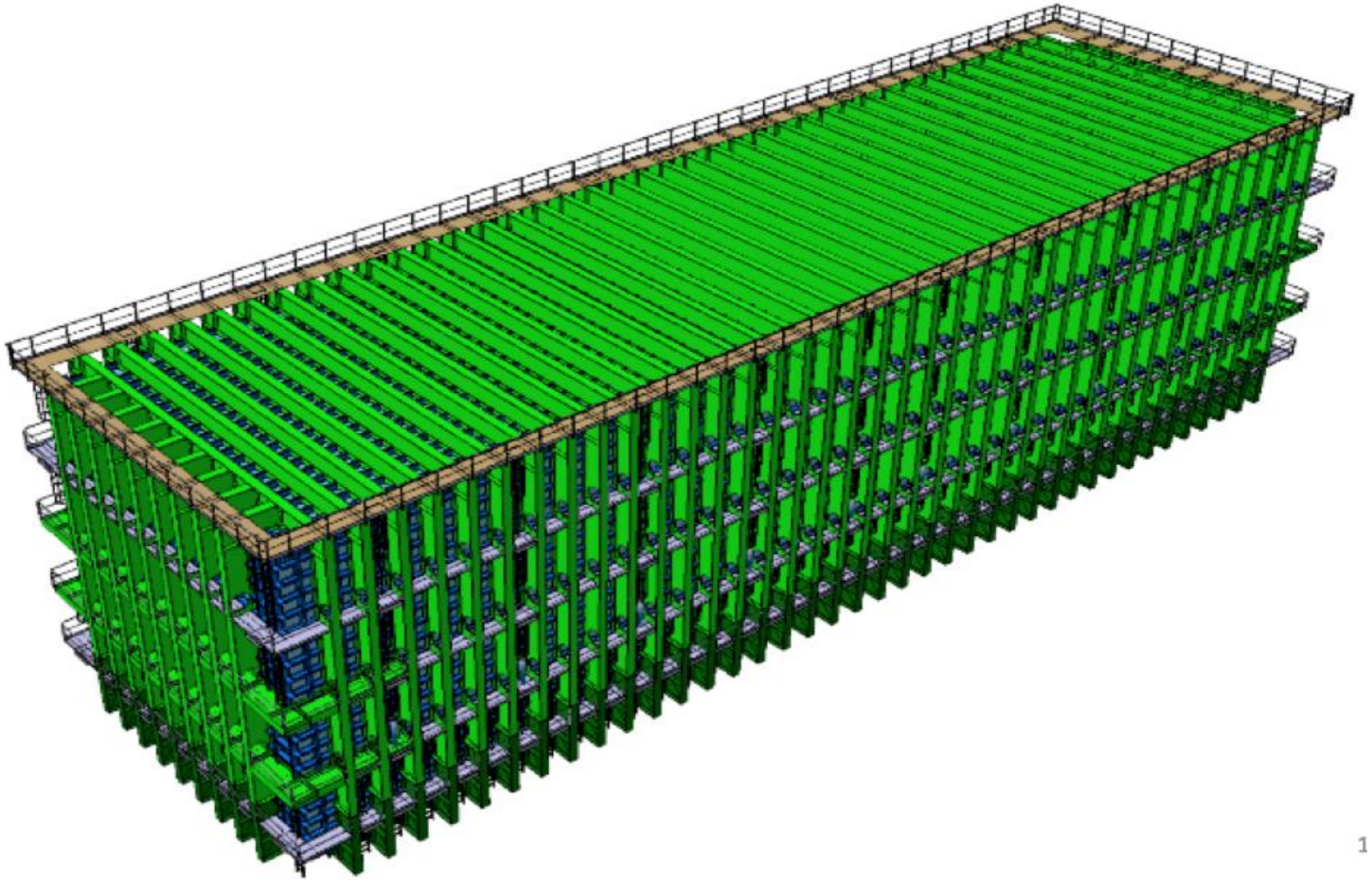


NPO1-Icarus


Steel structure
Structural steel plate
Insulation
Vessel :Support foot
Steel structure : Support foot

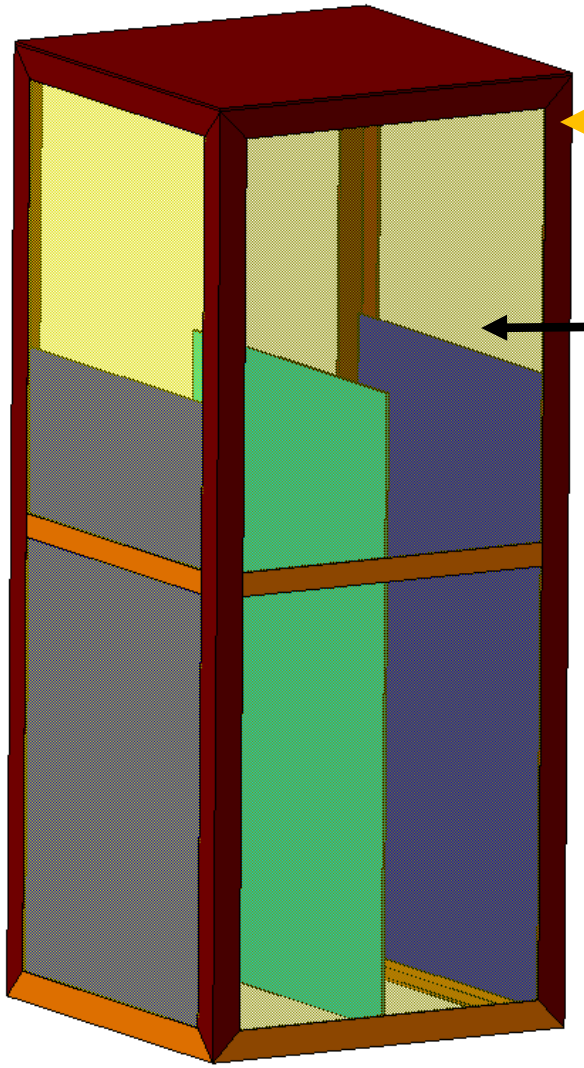

Inner
Tanks

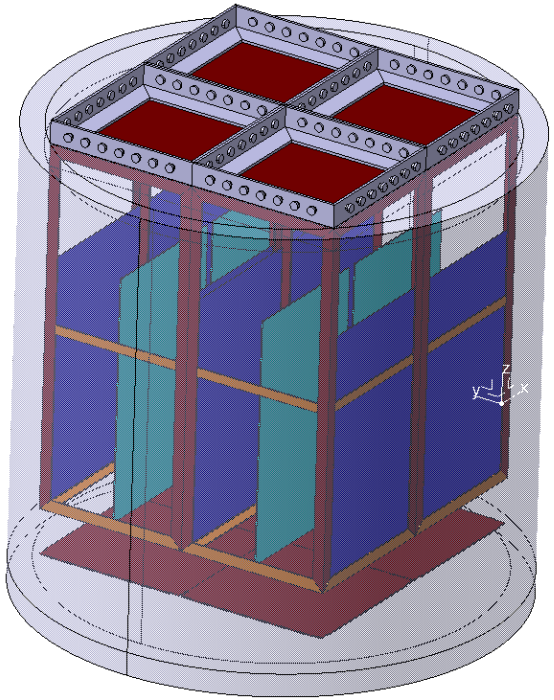
Dune (South Dacota)



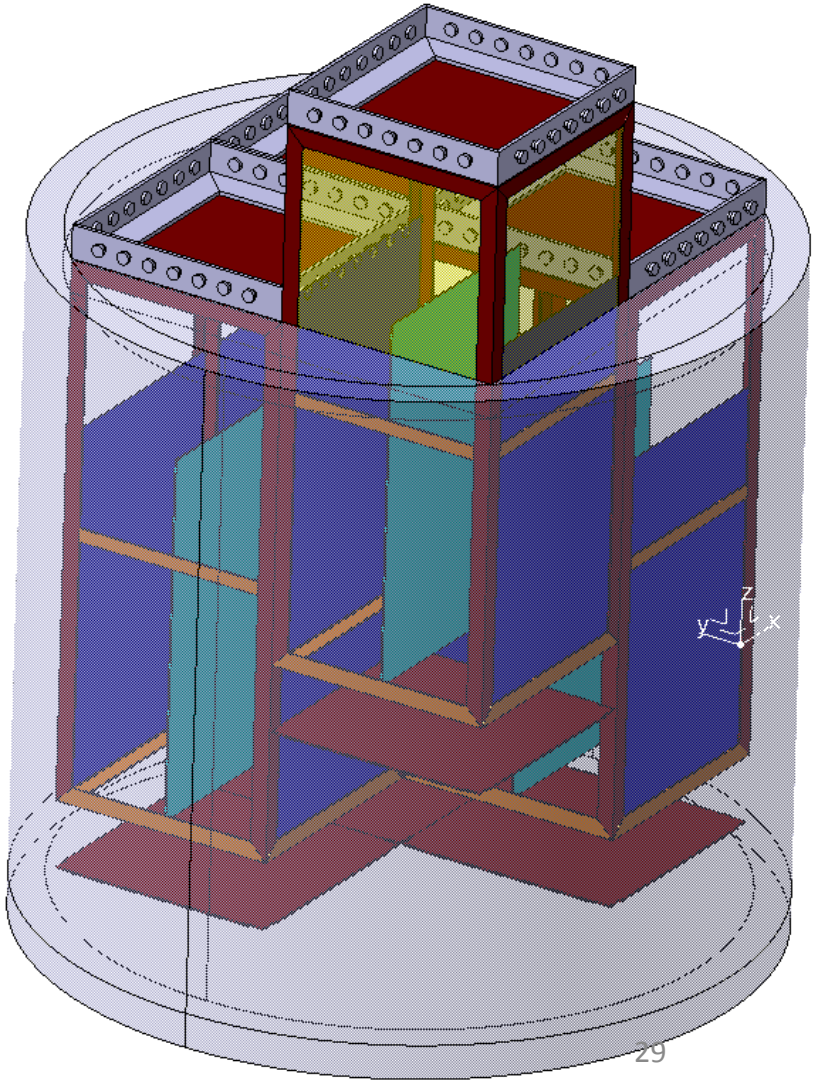
1

ArgonCube (BERN)





Modularity



Thank you!