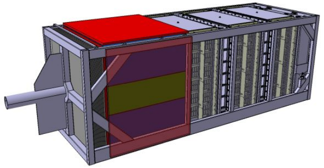
Fine-grained detectors for neutrino oscillations in the T2K and HK projects

GDR DI2I - IP2I Lyon

18/June/25

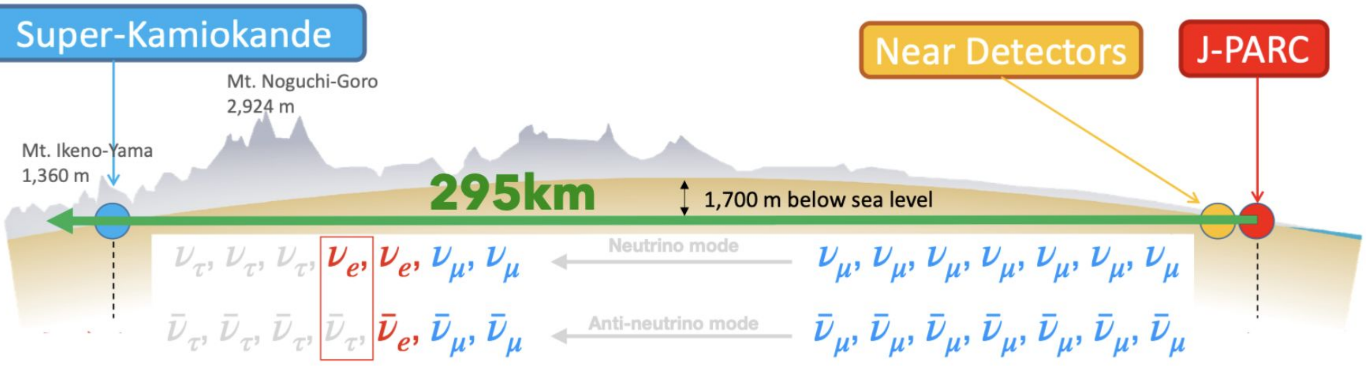
William Saenz



Outline

- **Neutrino oscillation** in long baseline experiments - **T2K & HK**
- **Fine grained detectors** (FGD) of J-Parc near detector
- **FGD prototypes** for HK's near detector upgrade

Neutrino oscillation - T2K project



- T2K → Tokai to Kamiola
- A long baseline experiment
- Measurement of **PMNS mixing parameters** (including δ_{CP}) and mass differences
- Results could reveal first evidence of CP-violation in lepton sector

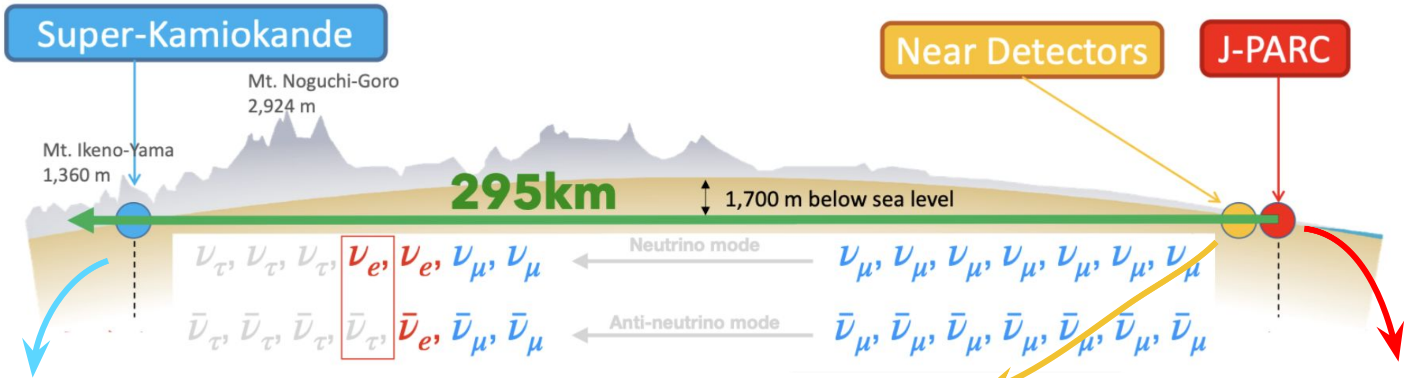
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{\mathrm{CP}}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{\mathrm{CP}}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

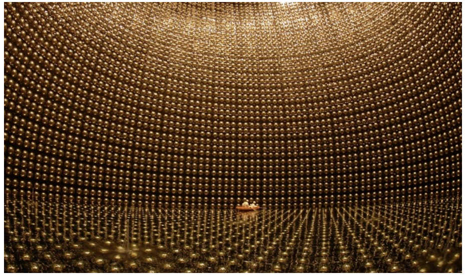
flavour eigenstates

U_{PMNS} matrix

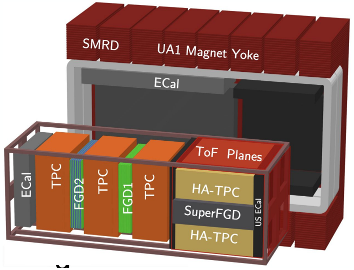
mass eigenstates

Neutrino oscillation - T2K project





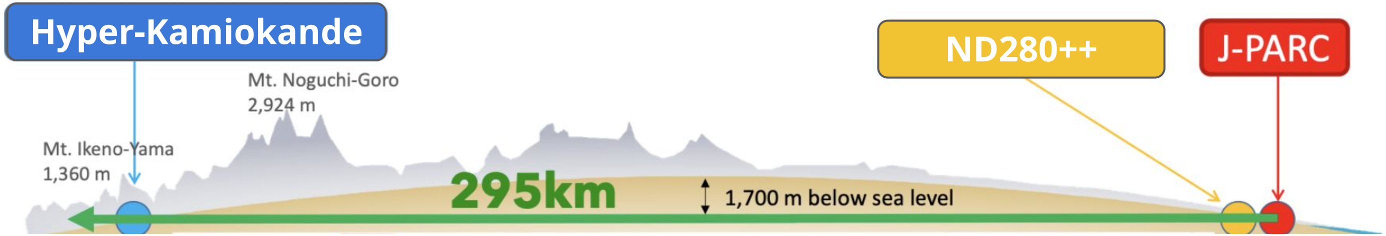
- 50 ktons water Cherenkov tank
- Readout by 12k PMTs
- Sensible to beam and atmospheric ν

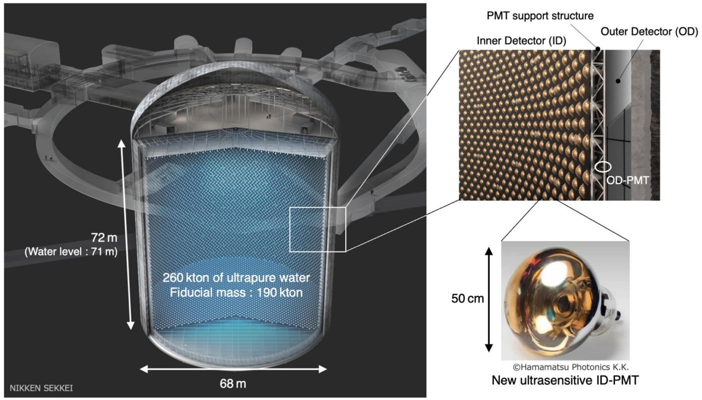


- Multi-detector (gas, scintillators)
- 0.2 T magnet for PID
- Characterises ν_μ flux and cross-section

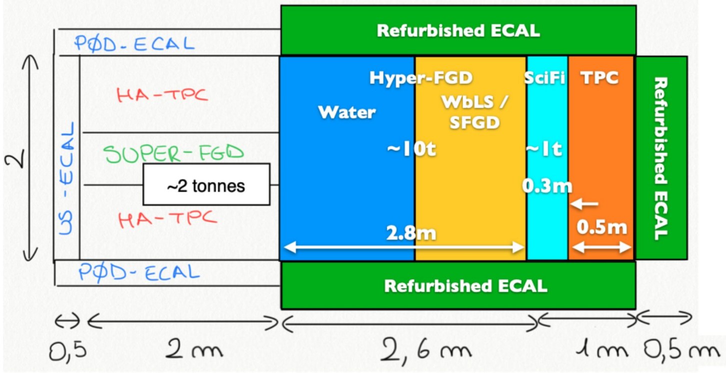
- 30 GeV protons on graphite target → Kaons + pions
- ν_μ and $\bar{\nu}_\mu$ beam

New generation and upgrade detectors - HK project





- 5 times bigger than SK
- Readout by 20k PMTS
- Under construction (expected to run in 2027)



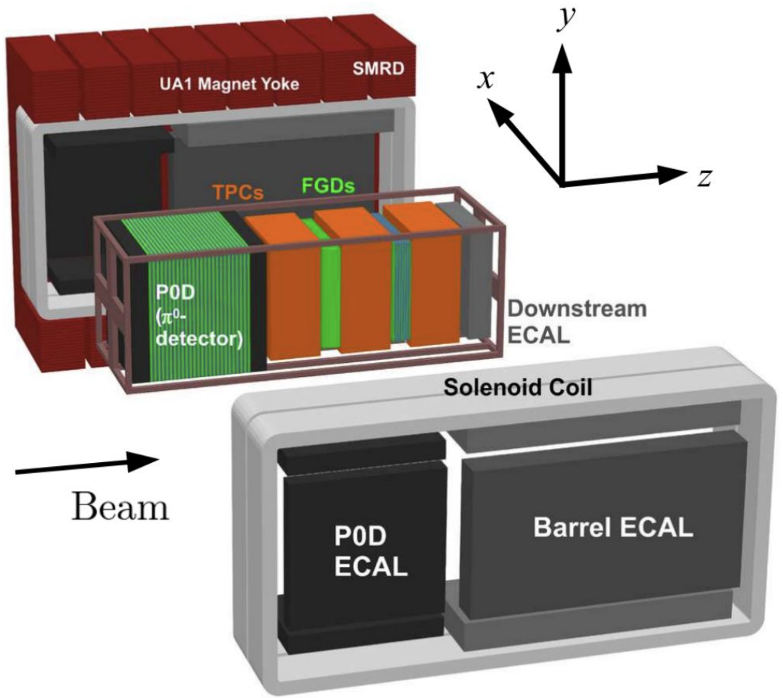
- 1st upgrade: haTPC + **superFGD** + TOF (operational since nov 2024)
- **hyperFGD** : study of water-base liquid scintillator (WbLS) prototypes

Fine grained detectors (FGD) of J-Parc near detector

Fine grained detectors (FGD) of J-Parc near detector

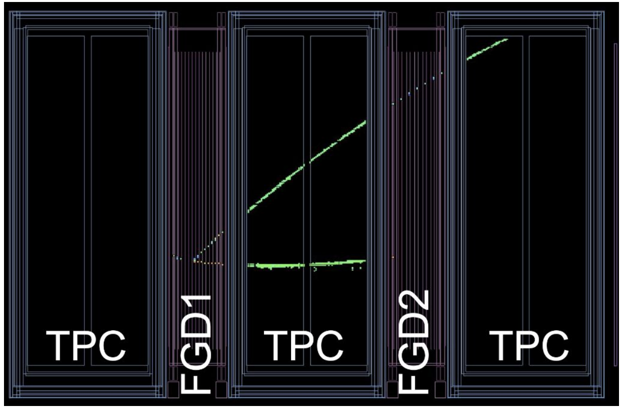
Main purposes:

- ν target mass
- Charged particle tracking

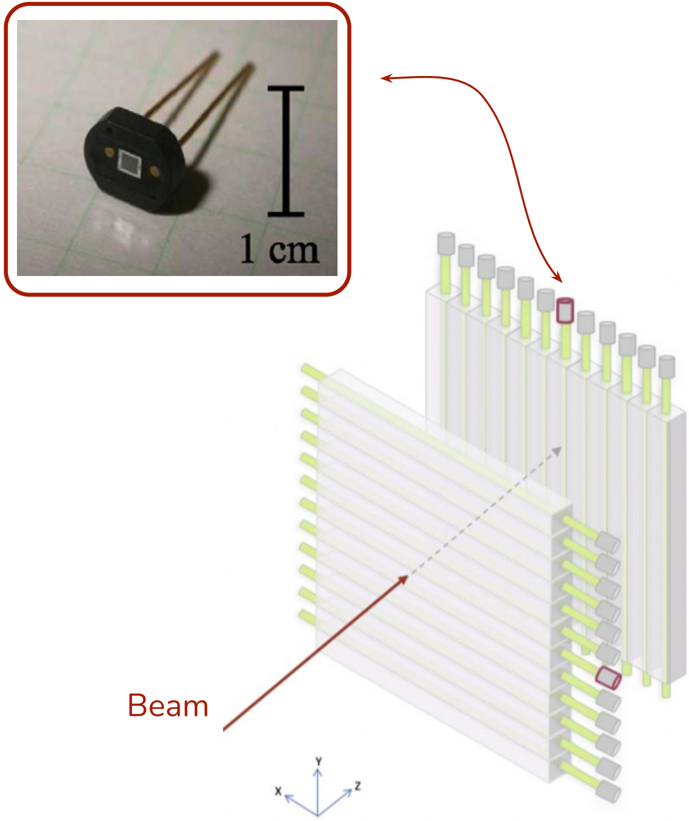


1st generation: FGD1 & FGD2

- Polystyrene scintillator bars: 9 x 9 x 1864 mm^3
- 1.1 ton per FGD
- Composition:
  - FGD1: 5760 bars (30 layers)
  - FGD2: 2688 bars (7 layers) + 6 layers of H_2O



Fine grained detectors (FGD) of J-Parc near detector



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- Composition:
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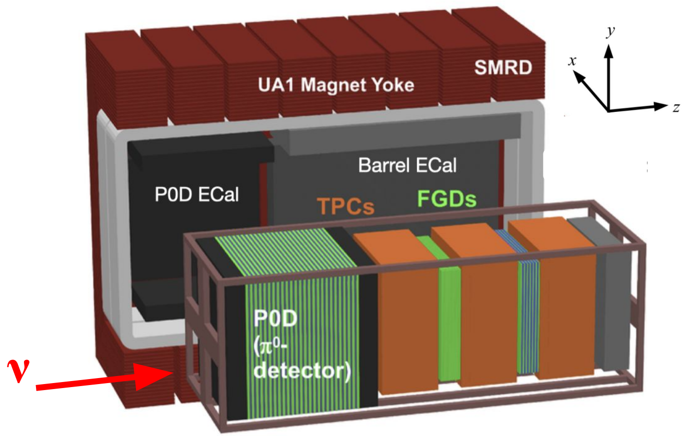
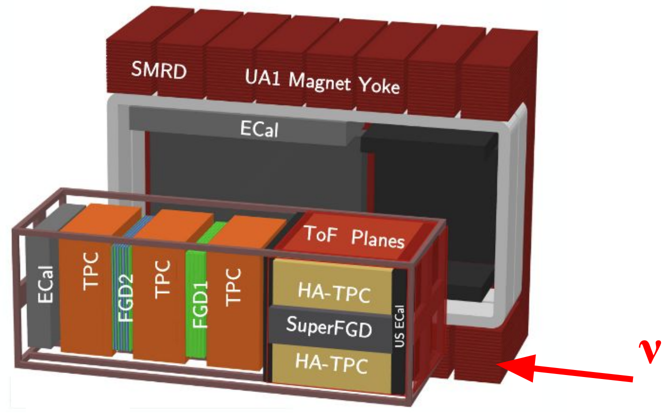
- Alternating direction layers for X-Y readout
- Wavelength shifting (WLS) fibers: 1 mm ∅ Y11 Kurarey
- Multi-pixel photon counters (MPPC)
  - 667 pixels
  - 1.3 x 1.3 mm^2
  - Gain ~ 10^6
  - PDE (525 nm) ~ 30%

Fine grained detectors (FGD) of J-Parc near detector

1st generation: FGD1 & FGD2



2nd generation: SuperFGD



Original near detector limitations:

- Angular acceptance (X-Y plane readout)
- High proton reconstruction energy threshold

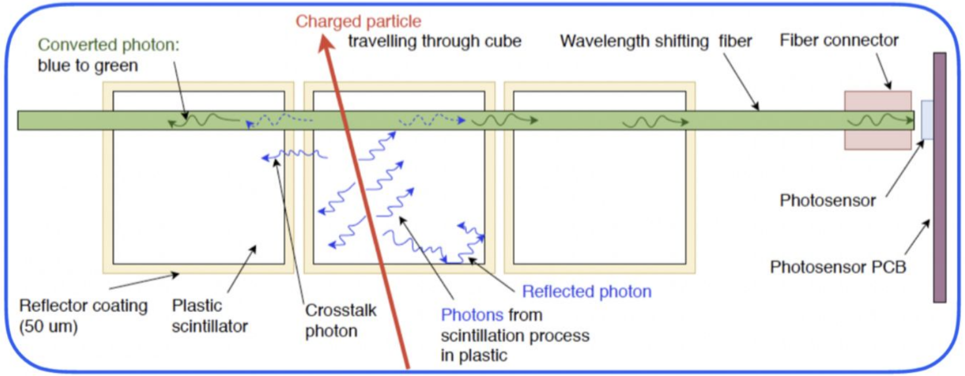
Near detector upgrade (2024)

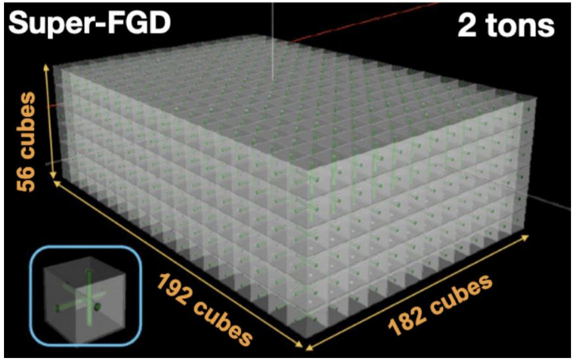
- PØD replaced by **SuperFGD** + haTPC + TOF

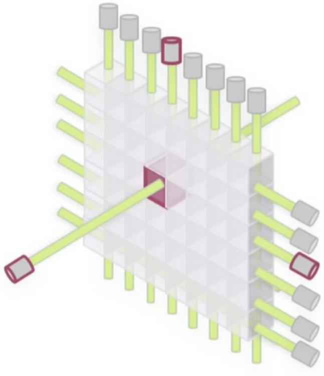
Fine grained detectors (FGD) of J-Parc near detector

2nd generation: SuperFGD

- 2 million 1 cm^3 plastic scintillating cubes
- Highly segmented readout in X-Y-Z
  - Three orthogonal Y11 Kurarey WLS fibers per cube
  - Each fiber coupled to a MPPC



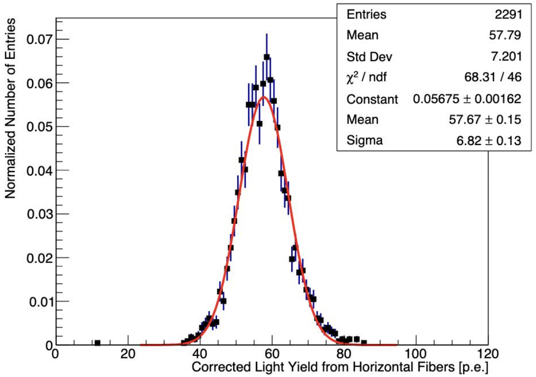




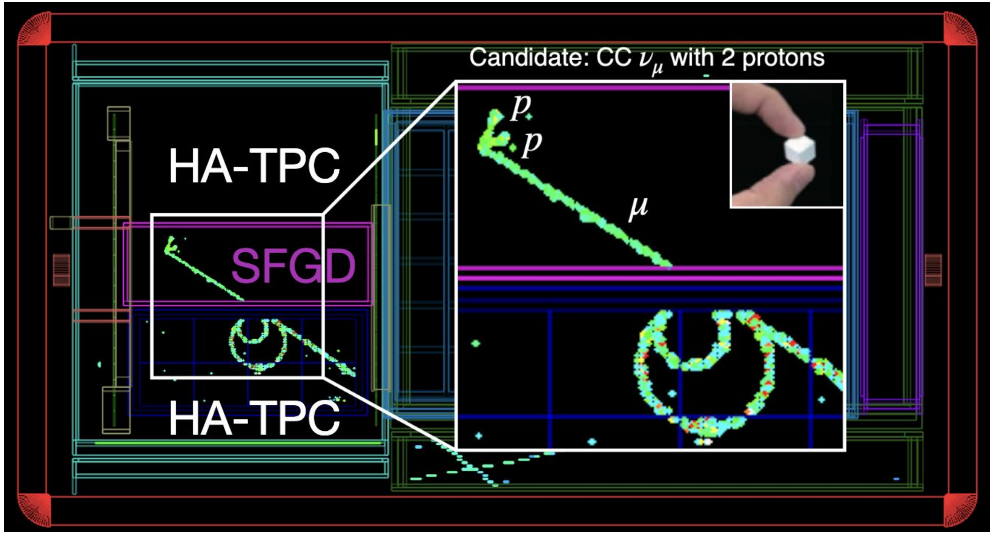
Fine grained detectors (FGD) of J-Parc near detector

2nd generation: SuperFGD

- Sub ns time resolution
- Limited crosstalk (~3 %). Reflecting surface from etching process.
- Light yield ~ 58 PE per MIP per cube per fiber
- Good PID due to high granularity



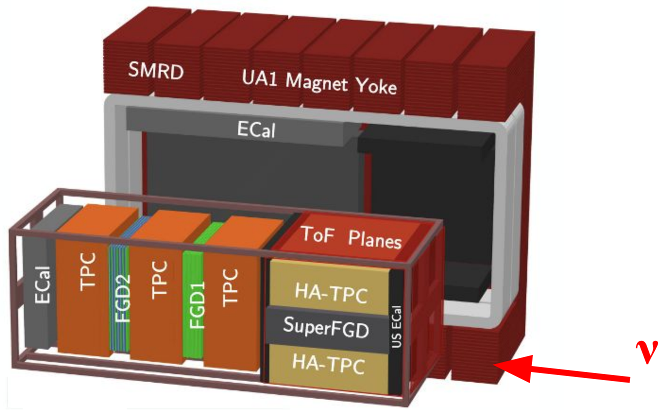
Sample event display

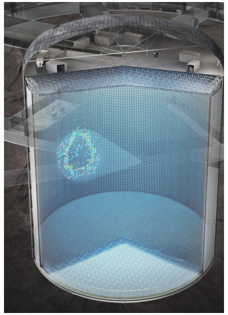


FGD prototypes for HK’s near detector

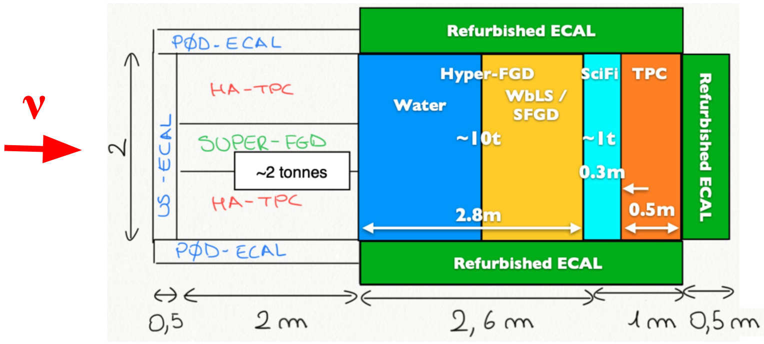
FGD prototypes for HK's near detector

2nd generation: SuperFGD





Next generation: HyperFGD



Upgraded near detector limitations:

- Large uncertainty of $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ reduces δ_{CP} exclusion power by HK
- Opposite to near detector, far detector is water base:
  - Cherenkov light yield < scintillation light
  - Water is inactive and cannot track protons

Near detector ultimate upgrade (2031)

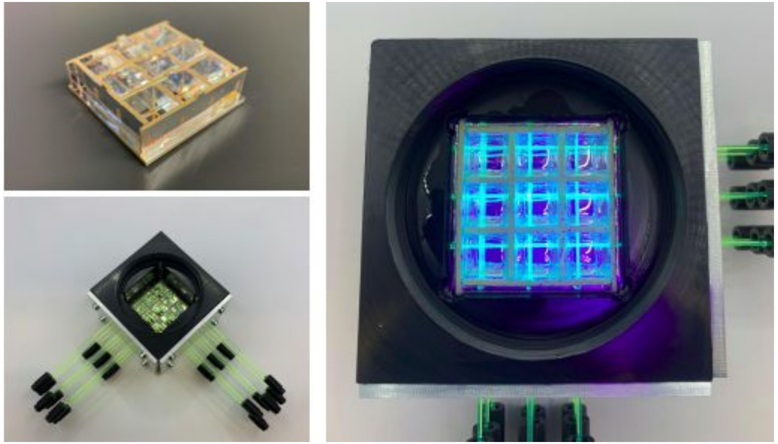
- Former **FGD + TPC** replaced by active water-base tracker detectors
- Proposal: 5 ton of water-base liquid scintillator (WbLS) → HyperFGD

FGD prototypes for HK's near detector

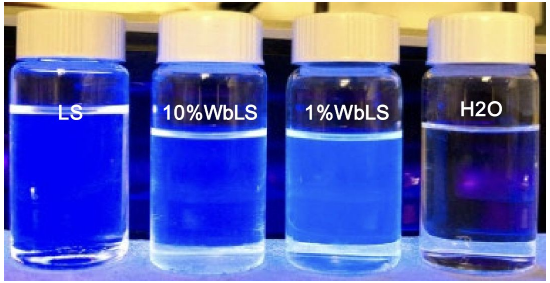
Next generation: HyperFGD

- ANR project. LPNHE - ETH collaboration
- Water-base Liquid Scintillator (WbLS) prototype
    - Organic liquid scintillator (developed at BNL)

  90% water + 10% LAB + PPO/bis-MSB
- Voxels of 1 cm^3 (same granularity as SFGD)
- Inner walls: Divinycell foam + 3M reflector
- X-Y-Z readout with Kuraray Y11 WLS fibers
- Hamamatsu MPPC: pitch 50 μm, PDE ~40%



Setup @ETH Zurich

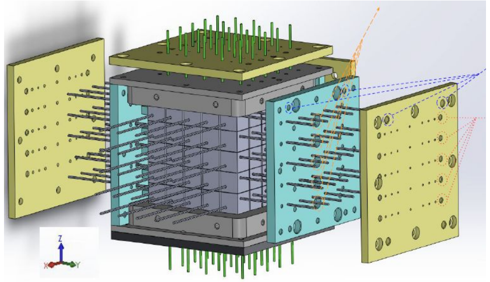


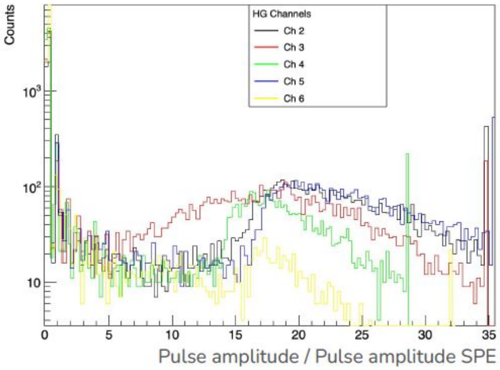
FGD prototypes for HK’s near detector

Next generation: HyperFGD

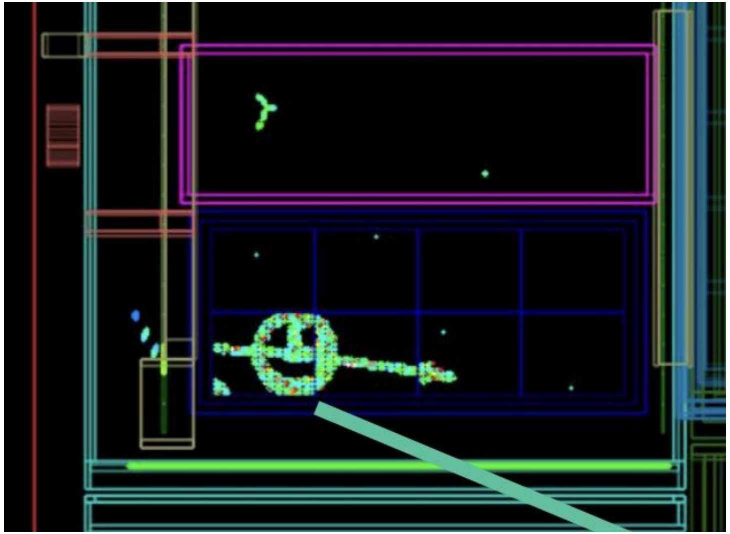
- Dedicated new experimental room at LPNHE
- Goals:
  - Optimise water - WbLS mix → Light Yield maximization
  - Study different geometrical configurations for cells (cubes holes, fiber groves, fiber - MPPC coupling)

Work in progress!





Thank you



Want to join us?

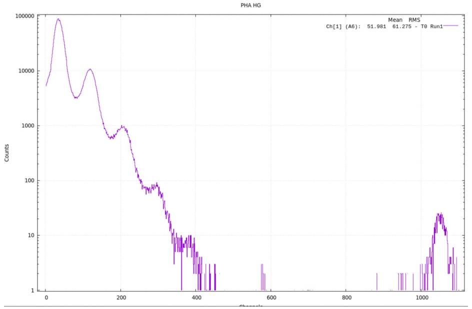
Upcoming research engineer position at LPNHE (CDD)

- Mechanical design of the 10 tons upgrade
- Design and production of the water-tight prototype
- Optimisation of the optical coupling
- Study alternatives for internal hyperFGD walls

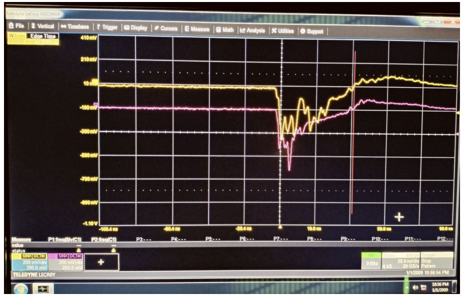
Hello world setup at LPNHE

- 1 SFGD cube + 2 WLS fibers to test electronics and printed structures

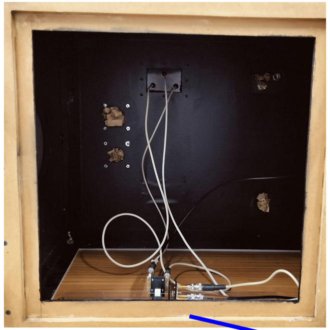
First SiPM dark current spectrum



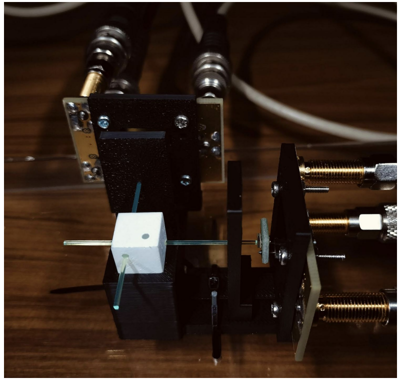
First muon candidate



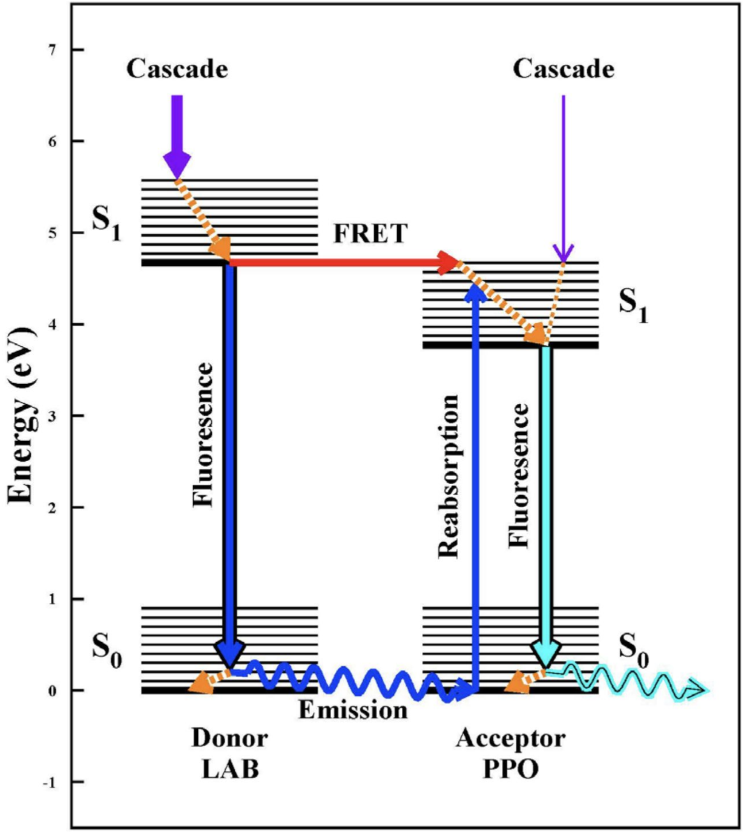
Almost a Dark box



First 3D printed support



Light emission in LAB + PPO



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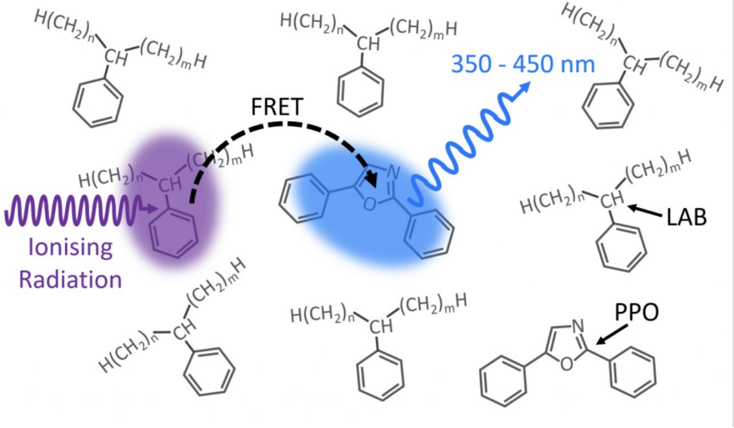
Förster resonance energy transfer (FRET)

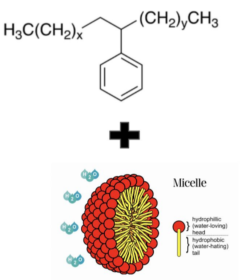


LAB:

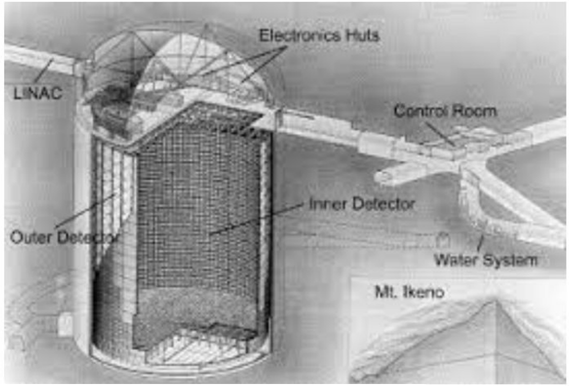
- low cost
- high flash point
- low toxicity

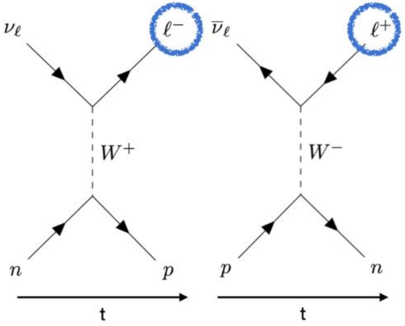
Addition of micelle for WbLS:

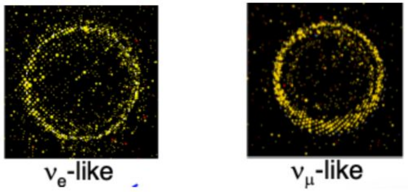
- Hydrophobic → scintillator
- Hydrophilic → water

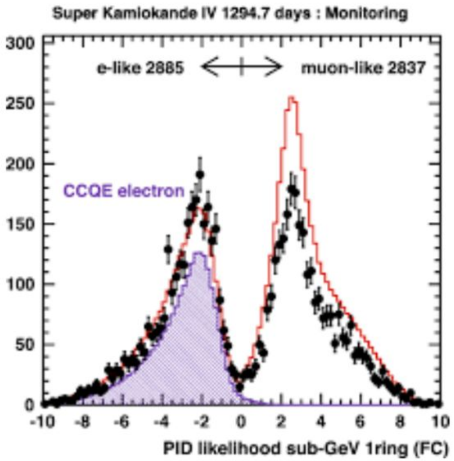


Nu detection in SK

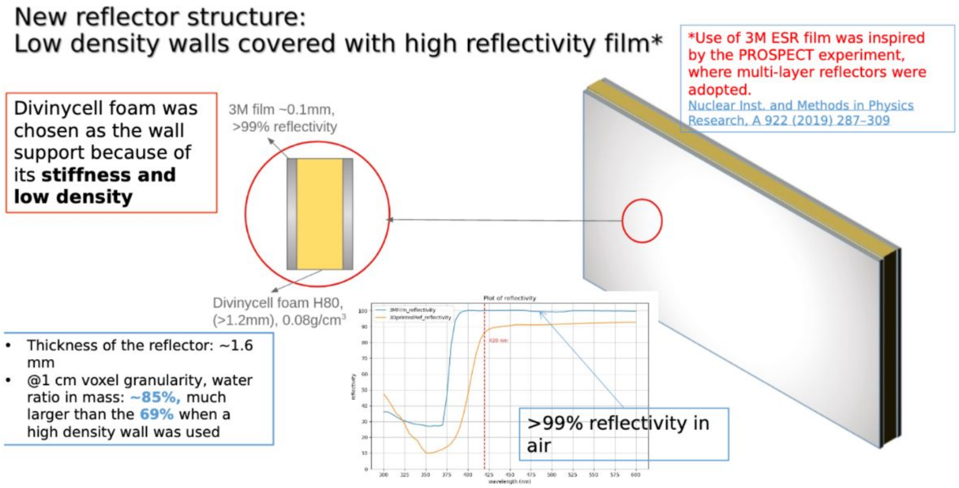








Reflector



- Need to assemble a grid of light materials
  - 1.2 mm width of foam (Divinycell) + 3M film to increase reflectivity