Next generation (long-baseline) neutrino experiments

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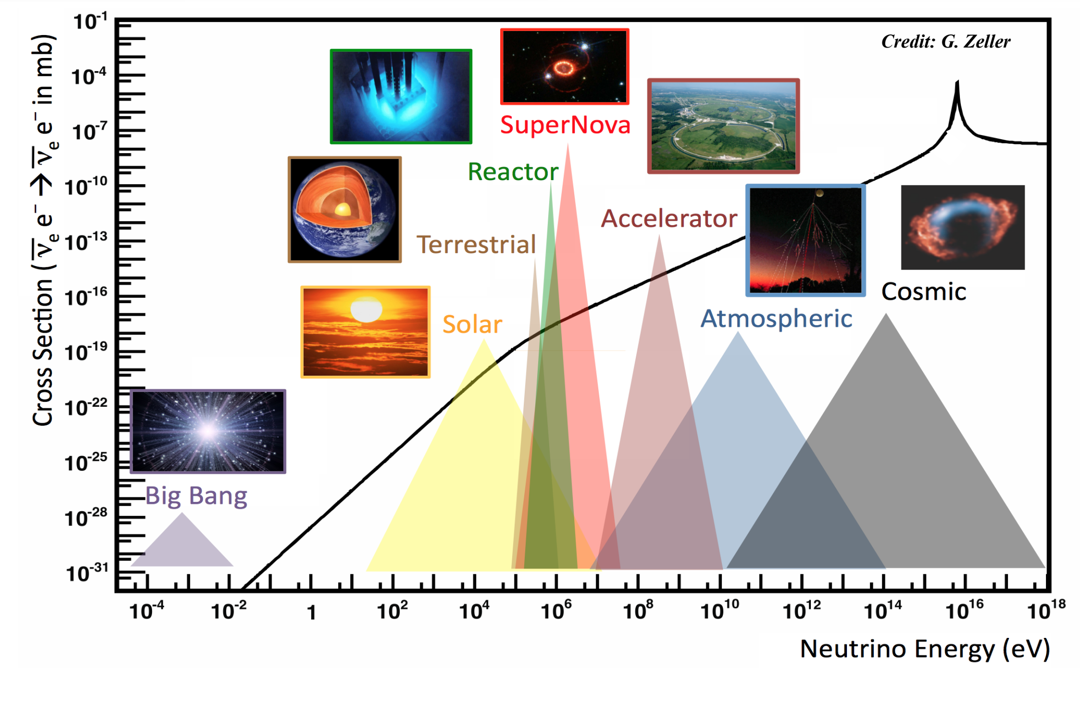
Neutrinos Span Multiple Fields!



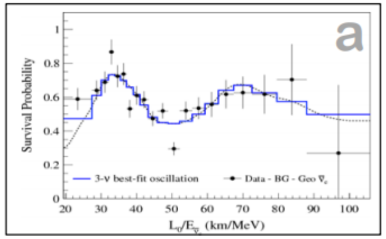
- Overwhelming number of sources, wide range of energies
- Need wide spectrum of experiments and technologies!

- **Particle Physics**
- **Astrophysics**
- **Cosmology**
- **High energy Astro- particle physics**
- **Nuclear physics**

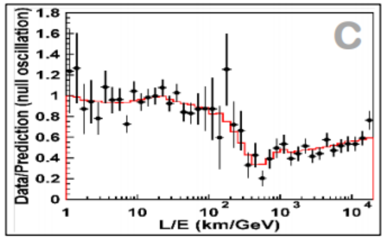
This talk will be focused on the expected contributions from the next generation of long baseline experiment (Dune & HyperK)

Neutrino oscillations

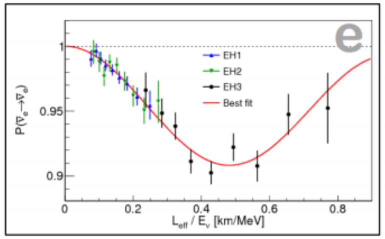
e→e (δm^2 , θ_{12})



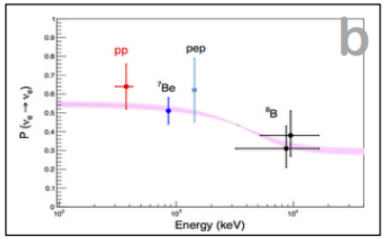
μ→μ (Δm^2 , θ_{23})



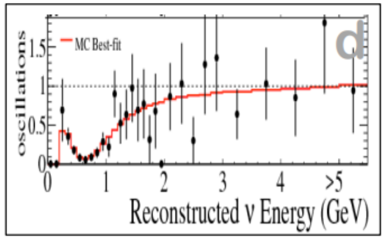
e→e (Δm^2 , θ_{13})



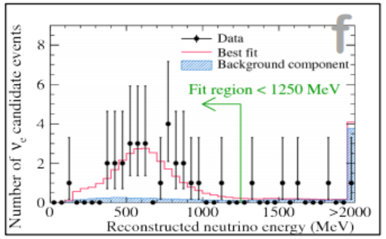
e→e (δm^2 , θ_{12})



μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



led to the discovery of a nonzero neutrino mass

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric and accelerator

$\theta_{23} \approx 50^\circ$

$|\Delta m^2_{32}| \sim 2.5 \times 10^{-3} \mathrm{eV}^2$

Reactor and accelerator

$\theta_{13} \approx 8^\circ$

Accelerator only: $\delta_{CP} = ?$

Solar and reactor

$\theta_{12} \approx 34^\circ$

$\Delta m^2_{12} \sim 7.5 \times 10^{-5} \mathrm{eV}^2$

$0\nu\beta\beta$ experiments

Normal hierarchy **Inverted hierarchy**

Breakthrough Prize 2016

T2K & K2K	KamLAND	Daya Bay	SNO	Super-Kamiokande
Δm^2_{32}	Δm^2_{21}	Δm^2_{31}	Δm^2_{21}	Δm^2_{32}
θ_{23} θ_{13}	θ_{12}	θ_{13}	θ_{12}	θ_{23}

…. "For the fundamental contributions to the discovery of neutrino Oscillation"

Everything solved ???

No !!

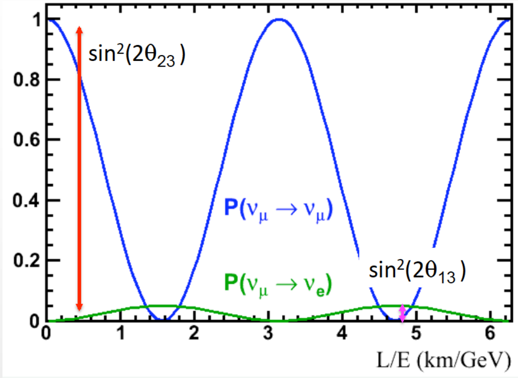
- Precision Measurement of mixing parameters
- Neutrino mass ordering
- Is θ_{23} maximal?
- CP violation in the neutrino sector $P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e]$?

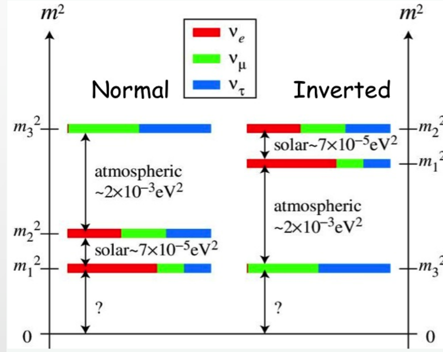
PDG2021

	Parameter	best-fit	3σ
~4%	Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
~3%	$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
~11%	$\sin^2\theta_{12}$	0.297	0.250 – 0.354
	$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
~15%	$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
~7%	$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
	$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
~31%	δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Most of the parameters measured with <10% precision

θ_{23} is known with 15% precision



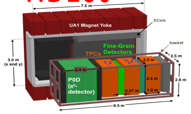


- ν_e appearance (θ_{13}, MH, CPV)
- ν_μ disappearance (θ_{23})
- Distortion to the neutrino spectrum ($\Delta m_{23}{}^2$)

Current long-baseline experiments (T2K & Nova)

J-PARC Main Ring (30 GeV) ~500 kW
<E> ~ 0.6 GeV (2009)

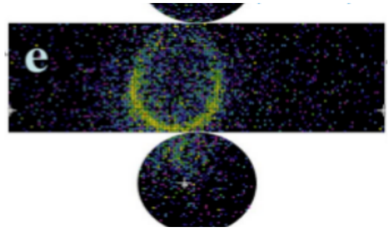
ND280

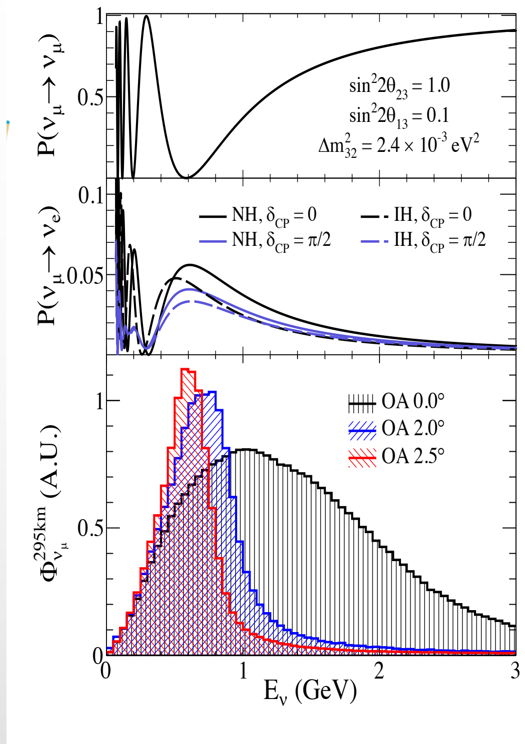


295 km
2.5° off-axis

underground
Super-K 22.5 kt

Water Cherenkov

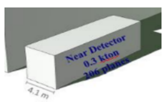




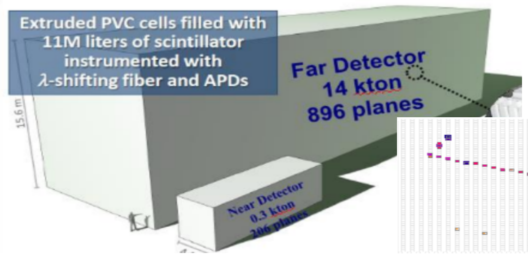
Off-axis Beam

FNAL Main Injector (120 GeV) 670 kW
<E> ~ 2 GeV (2013)

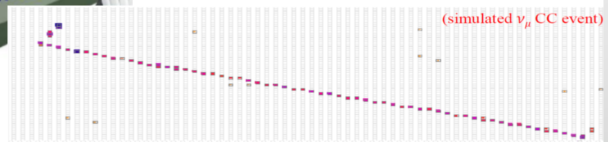
810 km
0.84° off-axis



~ at surface
NOνA 14 kt



Liquid scintillator



$\Delta m_{23} \sim 10^{-3}$ => L/E ~1000

See A. Mislivec Talk

Reach of Current Experiments (T2K & NOvA)

- **What do we know?**
  - **Atmospheric Sector**

    Picture is looking consistent across experiments

    Preference for Normal Ordering and non-maximal mixing
  - **CPV**: joint fits underway (T2K+NOvA and T2K+SK)

    to understand interesting differences in **δCP**

    T2K+NOvA can reach around 2-3 σ for CPV and MH

    (depends on parameter choices and systematics reach)

- **Looking Ahead (T2K)**

  Extended run of T2K (20xE21 POT) can result in 3σ for CPV

  ND280 upgrades, WAGASCI/BabyMIND to reduce neutrino interaction uncertainties

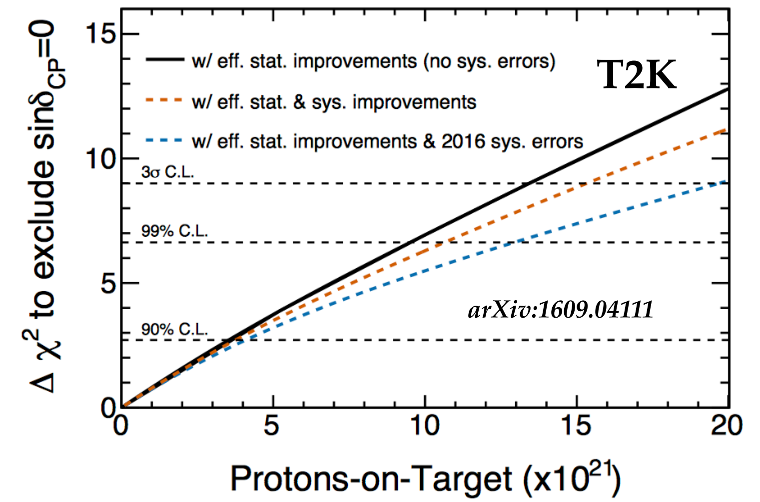
  SK-Gd loading: neutron tagging for enhanced ν/anti-ν separation

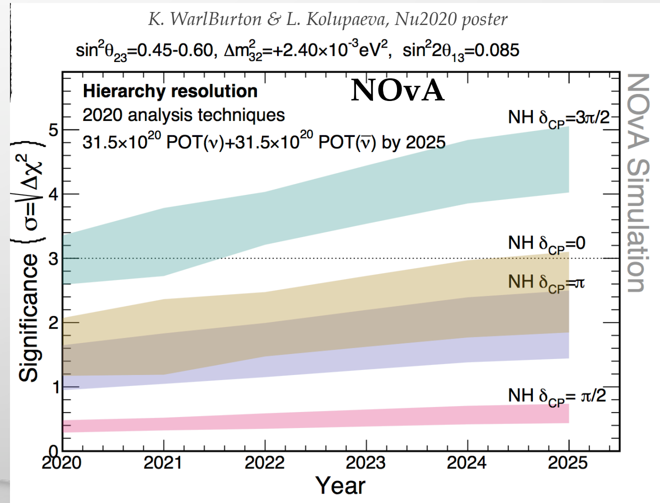
- **Looking Ahead (NOvA)**

  Can reach 3σ MH sensitivity for 30-50% of δ values, with the

  full dataset and an **upgraded beam , improved systematic**

  Can reach 2σ for CPV





Long-Baseline Facilities Across the Globe

- Dune & Hyper-K approved and under construction
- Beautiful results expected by the end of this decade

Future:
DUNE (US)
Hyper-K (Japan)

- New Technology, high intensity beams, large volume detectors are needed for precision
- **Next Generation Experiments: DUNE & Hyper-K**

Dune & Hyper-K in a nutshell

- DUNE
- Mass ~ 70 KTons
- L = 1300 Km
- E (peak) = 2-3 GeV/c (on-axis)
- Beam (Intensity) = 1,2 MW > 2,4 MW
- New Near Detector Suite
- Technology (FD) = Liquid Argon
- New Technology at this mass scale
- Beam physics (Oscillation): >> MH sensitivity
- No-beam physics: possibility to measure ν_e from supernovae (different technology)

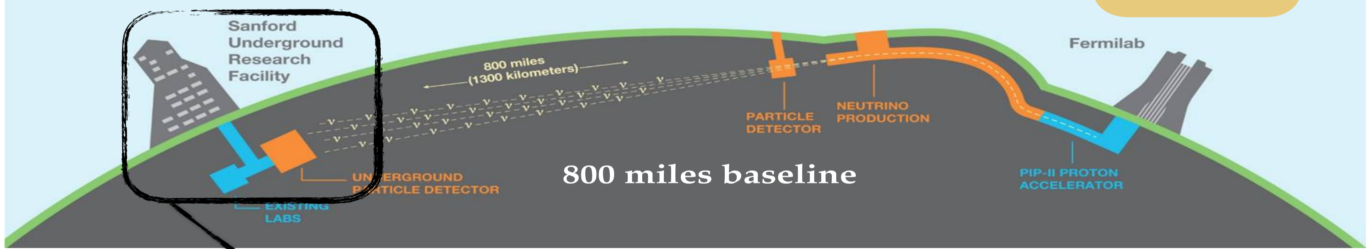
- Hyper-K
- Mass ~ 190 Ktons
- L = 300 Km
- E (peak) = 0,6 GeV/c (off-axis)
- Beam (Intensity) = 1,3 MW
- Upgraded T2K Near Detector Suite (+IWCD)
- Technology (FD) = Water-Cherenkov
- Technology already used in large detectors (SK)
- Beam physics (Oscillation): >> CP sensitivity
- No-beam physics: >> proton decay and solar/atm. sensitivity (larger mass)

The Deep Underground Neutrino Experiment (DUNE)

Sanford Underground Research Facility (South Dakota)

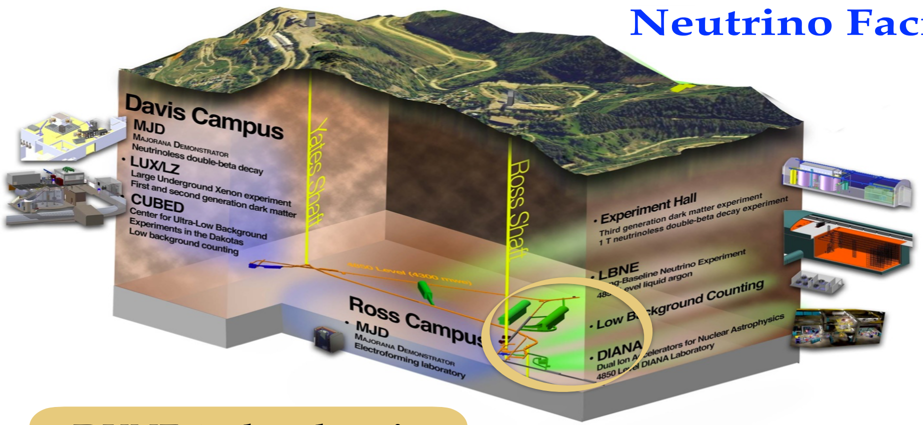
1100+ collaborators
30+ countries
190+ institutes

Fermilab



- Deep underground location
- 70 kton Far Detector (FD)
- Multiple technologies for the Near Detector (ND)
- MW-scale wide band neutrino beam
- FD Physics date in late 2020s
- Details of timeline will be finalized after project baselining (expected this year)

Dual site facilities provided by the Long Baseline Neutrino Facility (LBNF)



DUNE 1.5 km deep in Home Stake Mine

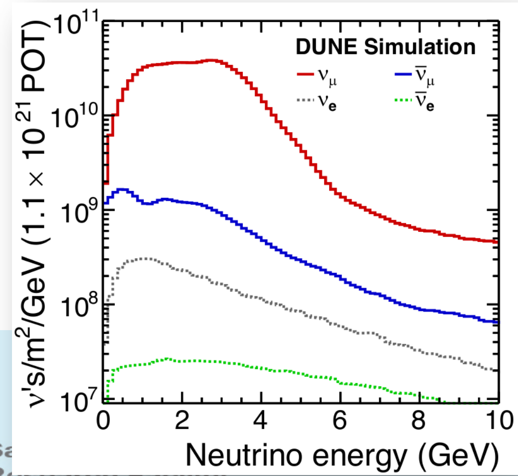
Very Rich Physics Program

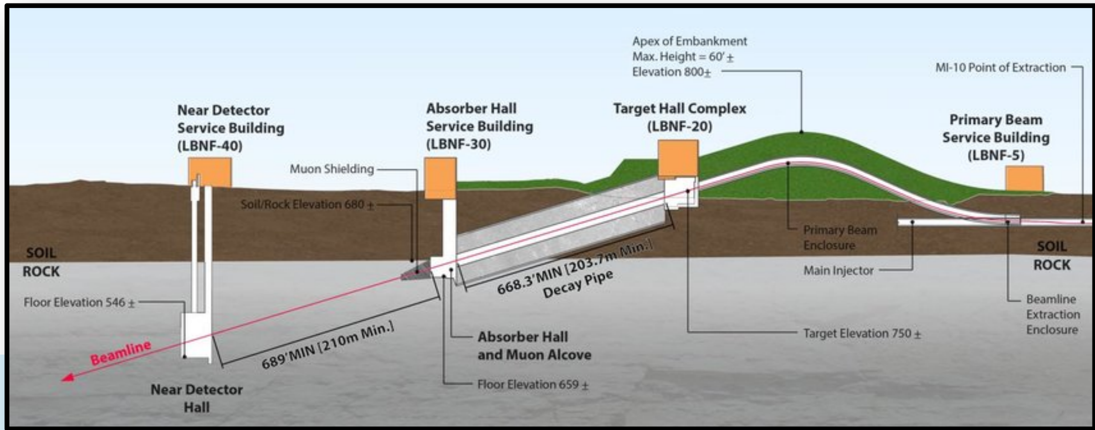
- CP Violation
- Neutrino Mass Hierarchy
- Precision measurements of neutrino oscillation parameters
- Supernova & Astrophysics
- Nucleon Decay (e.g. $p \rightarrow K^{+}\nu$)
- Many BSM searches

DUNE: Neutrino Beam

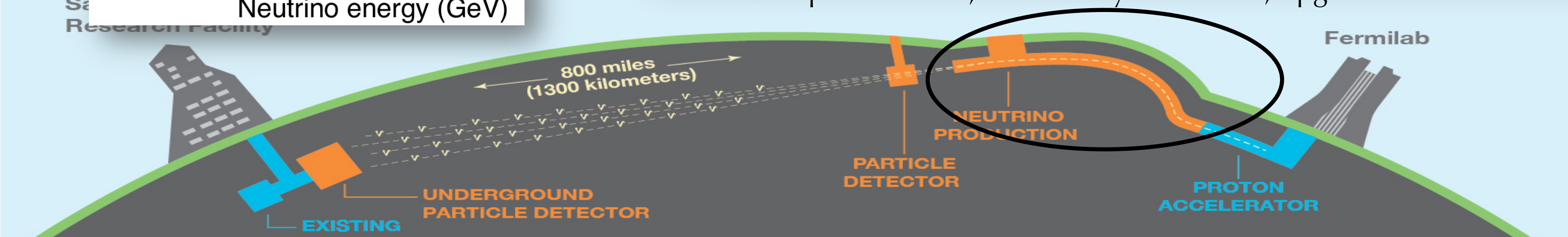
(1.1-1.9) x 10^{21} POT*/y @ 1.2 MW
10 μs pulse duration
*Protons On Target

- **DUNE's neutrino source: LBNF beam, from US Fermi National Lab (FNAL)**





60-120 GeV proton beam, 1.2 MW by late 2020s, upgradable to 2.4 MW

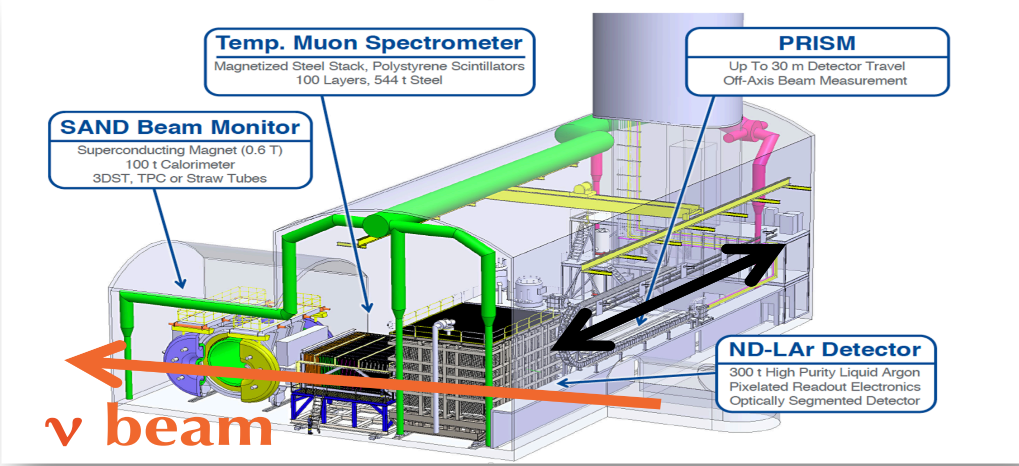


DUNE: Near Detector (ND)

- **DUNE ND complex**

  Multiple complementary systems:

  - **ND-LAr**: modular, pixelated LArTPC
    Primary target, similar to FD
  - **TMS → ND-GAr**: measures muons not captured by LArTPC → high-pressure GArTPC, surrounded by ECAL and magnet
    Muon spectrometer; nuclear interaction model constraints
  - **SAND**: tracker surrounded by ECAL and magnet
    On-axis beam spectrum/time-stability monitor

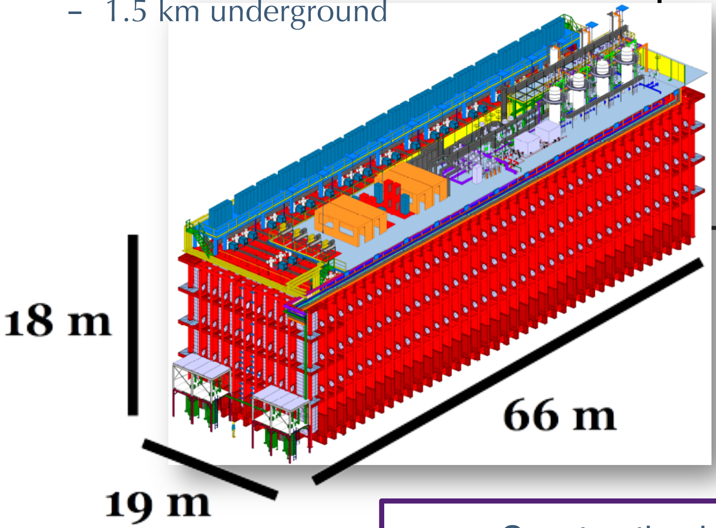


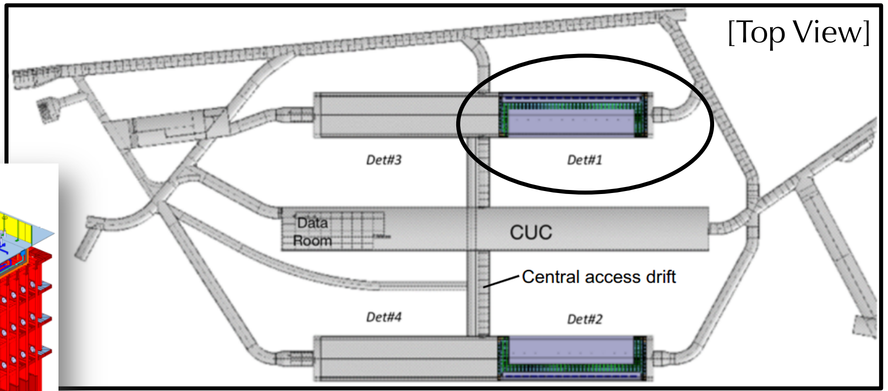
ND-LAr/TMS are **movable on/off-axis (PRISM)**
Probes different neutrino energies

- Located 574 m from neutrino beam target
- Primary purpose: **characterization of neutrino beam** and **constraining of cross-section uncertainties** for long-baseline neutrino oscillation measurements

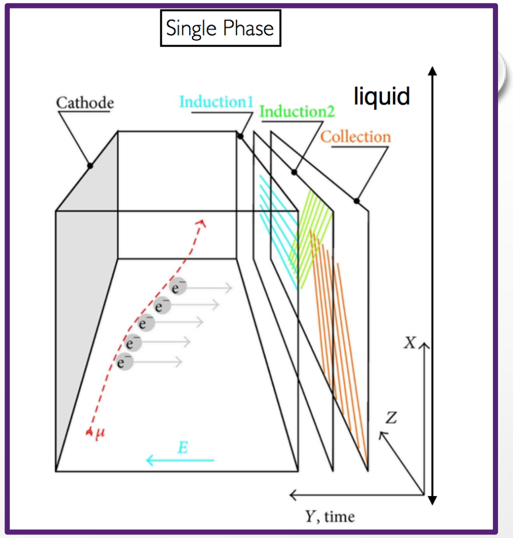
Far Detector Site – SURF

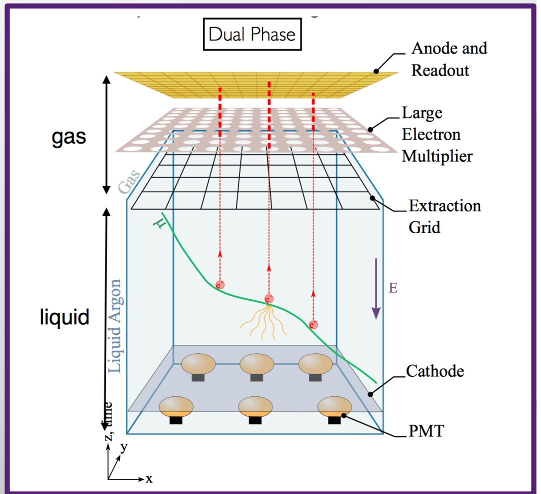
- **Four (4) LArTPC FD Modules, deployed in stages**
  - 17 kton each
  - 1.5 km underground





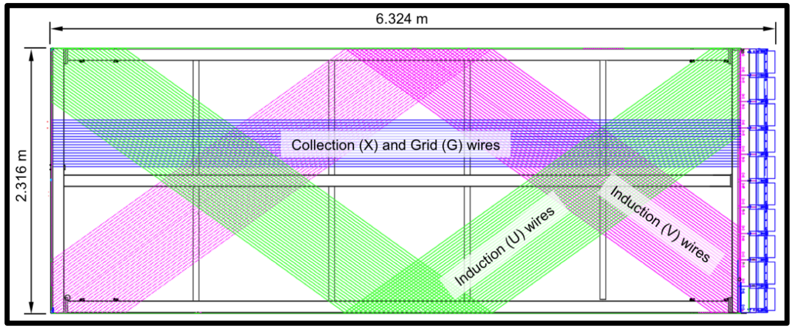
- Two far detector designs: **Horizontal Drift** and **Vertical Drift** (both employ liquid argon phase only)
- First detector module will be Horizontal Drift (HD)
  - Construction in stages
- **FD #1, #2** will be **single-phase (SP) LAr-TPCs,** with Horizontal Drift (HD) and Vertical Drift (VD), respectively
- FD #1 construction starts in mid 2020's



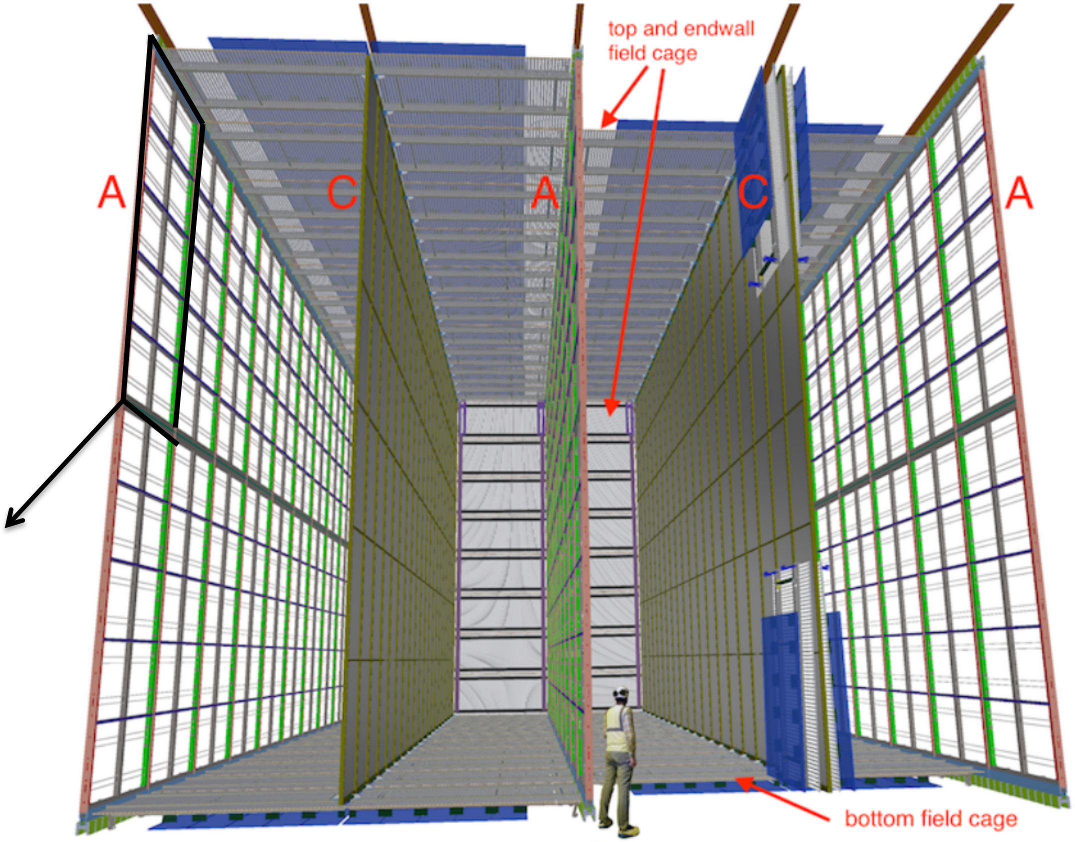


DUNE FD HD LArTPC Module

- HD FD uses **modular drift cells** (scalability)
- Electric field: 500 V/cm, 3.6 m drift
- Suspended **Anode** and **Cathode Plane Assemblies** (APAs and CPAs)
- APA:
  - Wrapped induction wires, reducing number of readout channels, cabling complexity
  - Single plane of collection wires

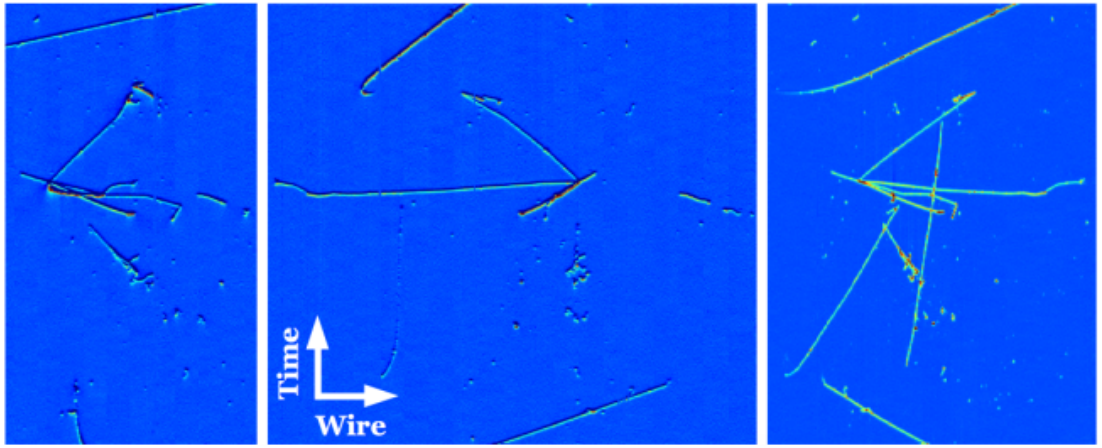


- **Photodetectors** also employed, providing timing and possibility of off-beam triggering



ProtoDUNEs @ CERN

Low-noise on all readout planes
S/N > 10 in all cases (>40 for collection plane)
Stable running (first operations in 2018)



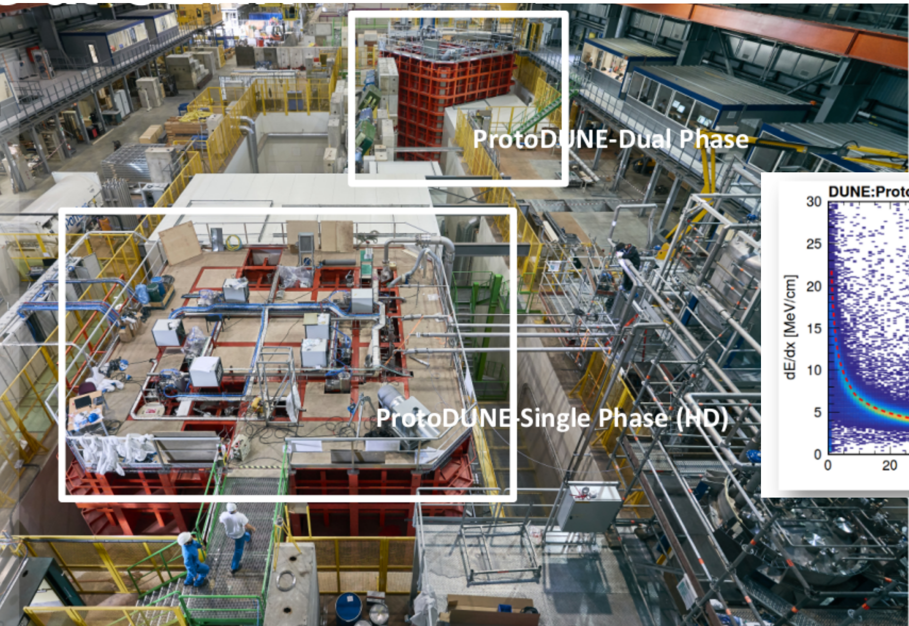
Two 1-kton prototypes in a charged particle test beam at CERN

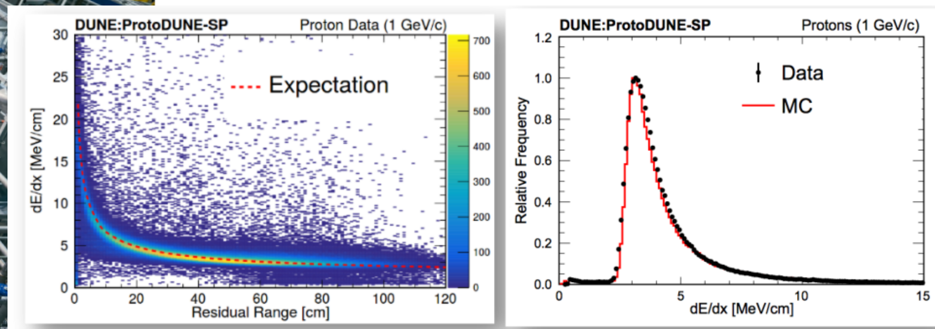
Testing component installation, commissioning, and performance

ProtoDUNE-Single Phase (HD) operated 2018-2020

ProtoDUNE-Dual Phase (LAr+GAr) operated 2019-2020

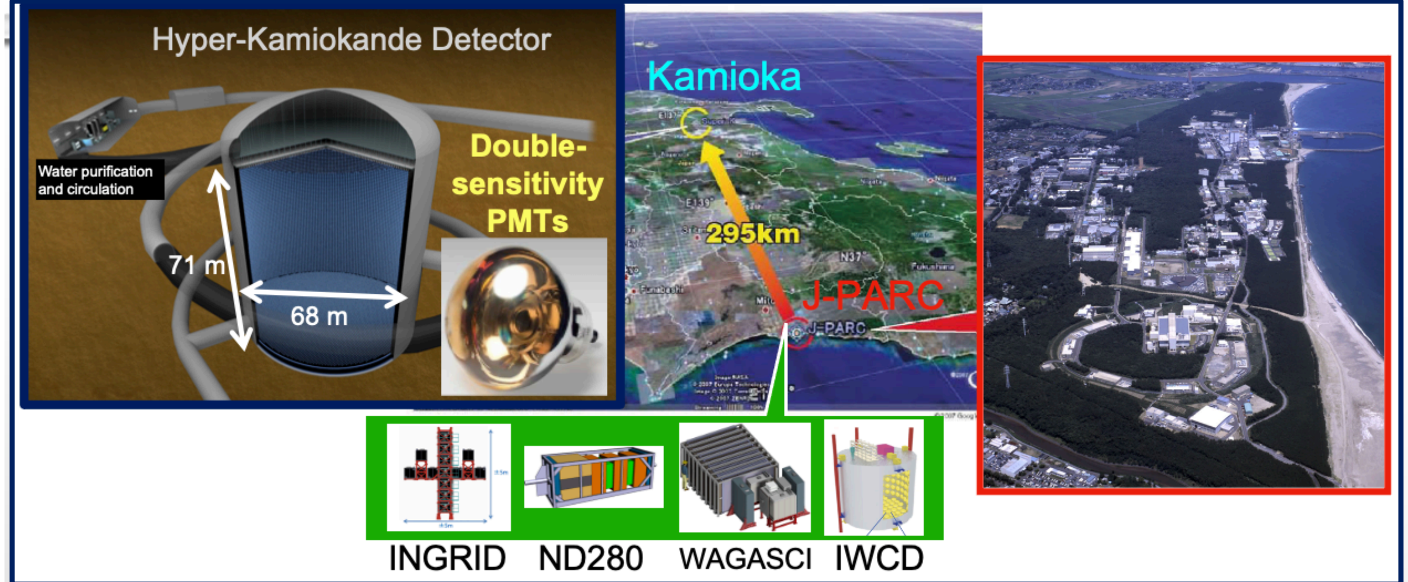
Preparing for phase II operations

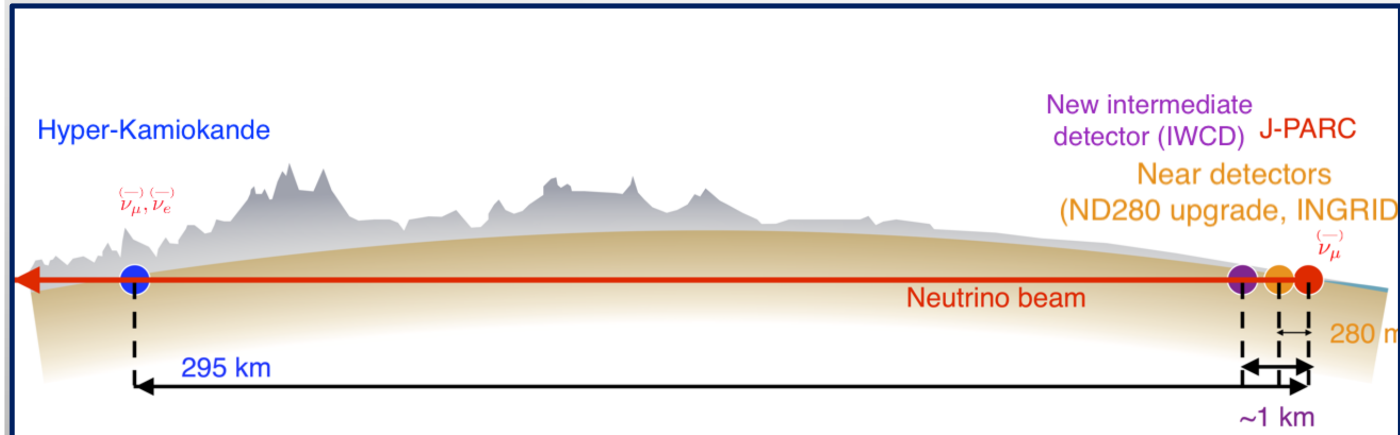




JINST 15 (2020) 12, P12004

Hyper-Kamiokande Experiment

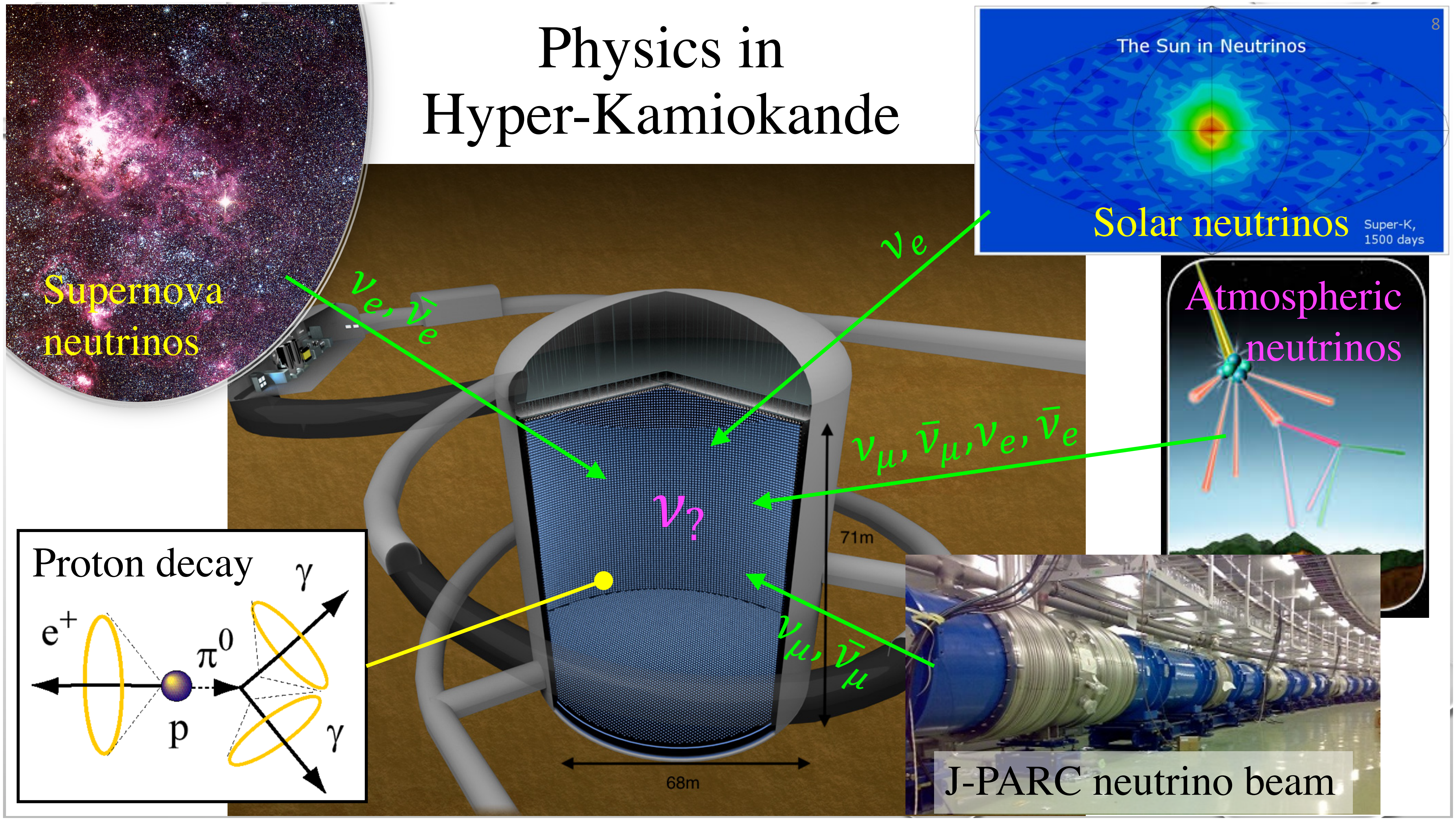




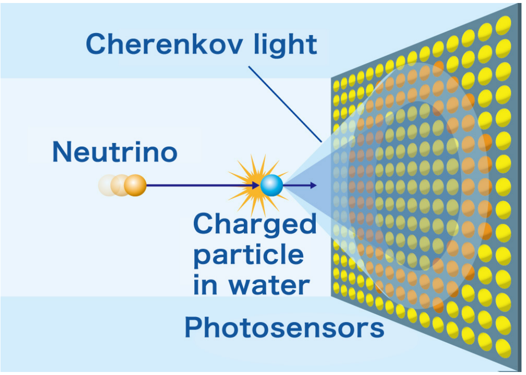
- Hyper-K detector with **8.4 times larger fiducial mass** (190 kiloton) than Super-K with **double-sensitivity PMTs**
- J-PARC neutrino beam will be upgraded from 0.5 to 1.3MW (**x2.5** higher than current T2K beam power)
- New (IWCD) and upgraded ND280) near detectors to control systematic error.

19 countries, 93 institutes, ~440 people as of November 2020, growing

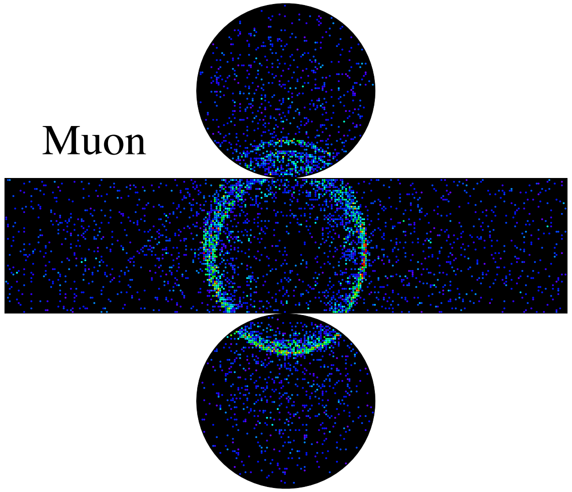
Physics in Hyper-Kamiokande



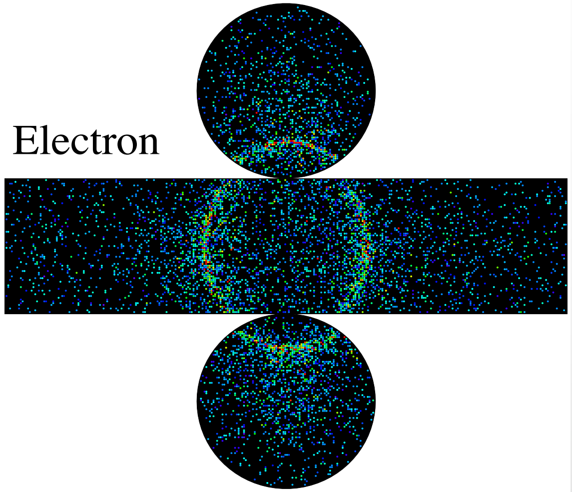
Water Cherenkov detector



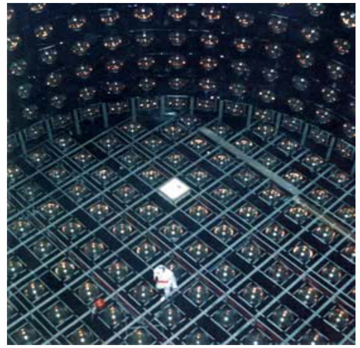
Muon



Electron



- Cherenkov ring
  - ➢ Particle identification (>99% efficiency for μ/e separation)
  - ➢ Momentum reconstruction (energy and direction)
- Scalable to larger mass ⇒ rare process (proton decay search and neutrino observation)

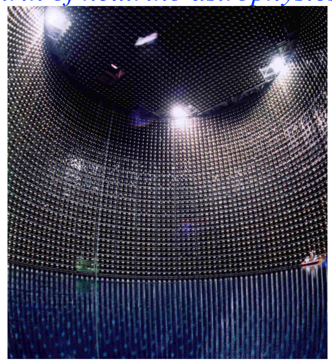


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino “anomaly”
- Supernova 1987A

Birth of neutrino astrophysics



Super-Kamiokande

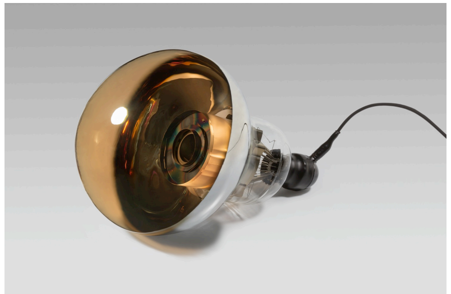
(1996 - ongoing)

- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - ➢ All mixing angles and $\Delta m^2 s$

Discovery of neutrino oscillations

The Hyper-Kamiokande FD

High QE Box&Line PMT



×2 pressure tolerance

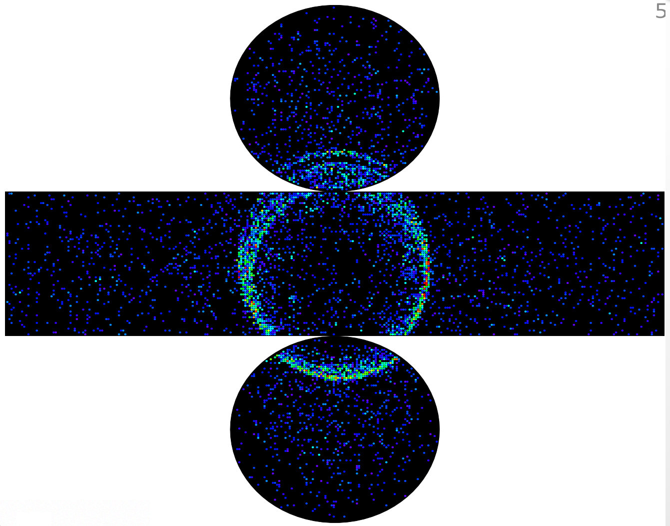
×2 photon detection

×2 timing resolution

Precision measurement

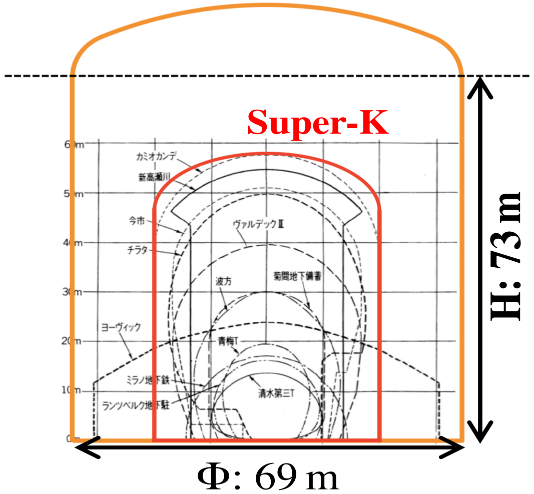
Recent update:

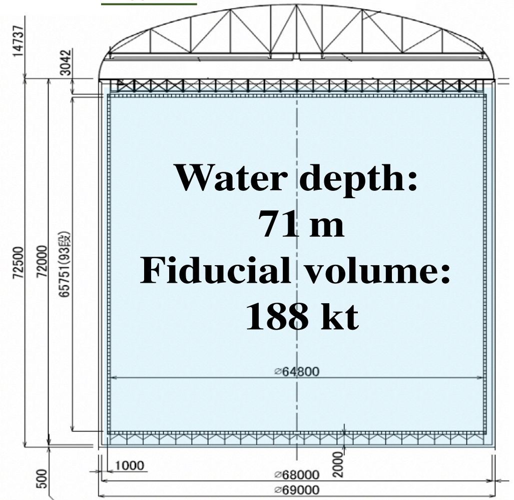
- Lower dark rate (similar level to SK)
- Lower radioactive contamination



New detector design (cost reduction)

R&D for large cavern



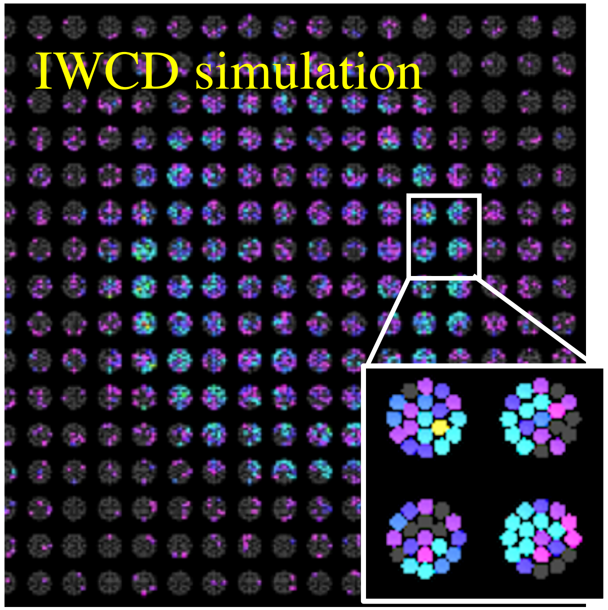


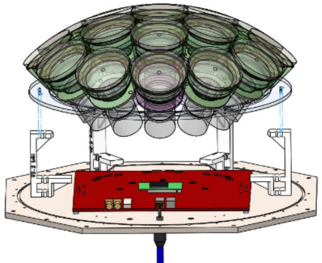
High statistics neutrino data

New detector design by synergy of different technologies

Detector R&D for Hyper-Kamiokande

Multi-PMT module:
(ref. KM3NeT)
High resolution Cherenkov ring imaging essential for IWCD
Consider to use for part of HK

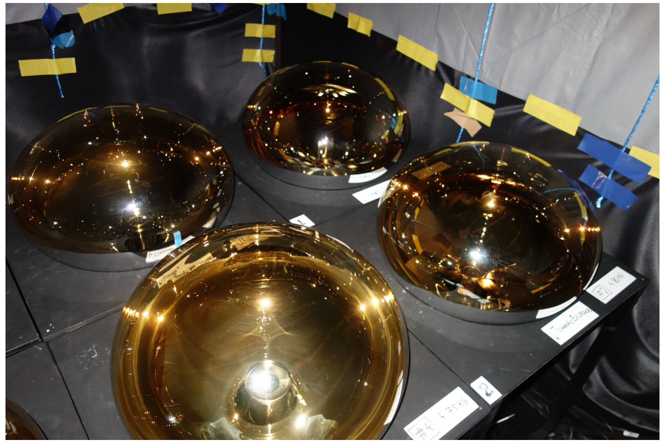


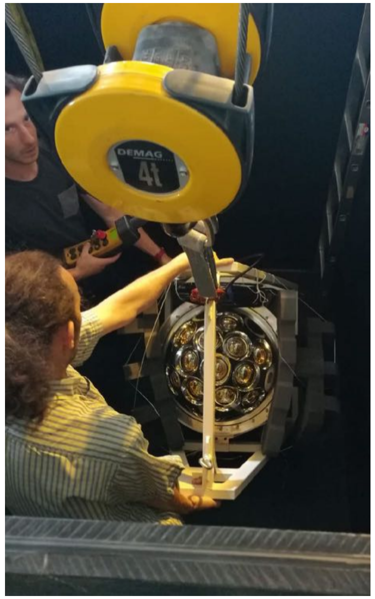


Prototype at TRIUMF

Electronics at INFN

20-inch MCP PMT:
Test in dark room

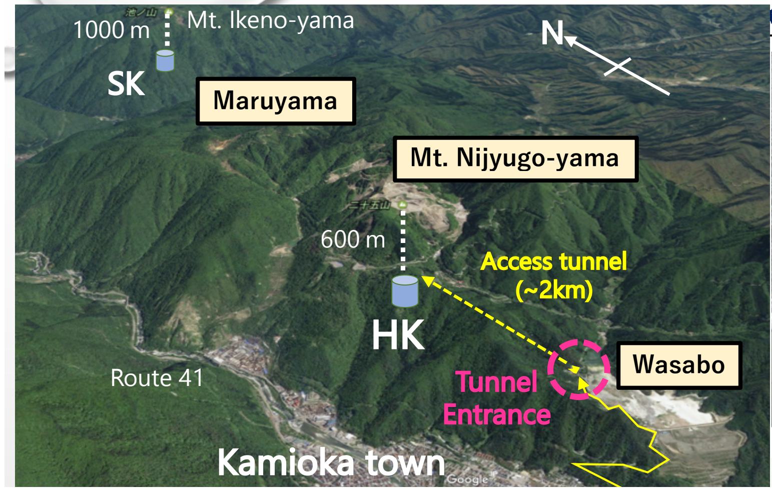


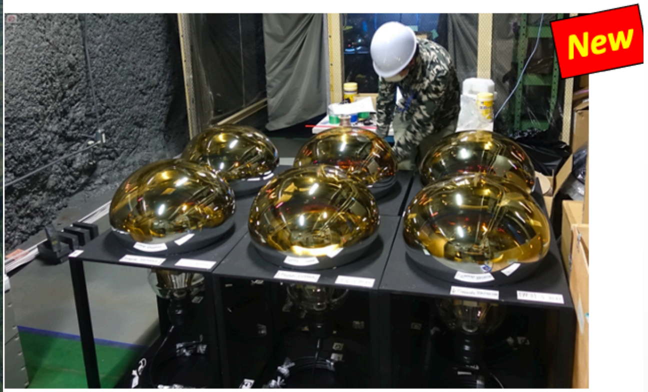


mPMT in Memphyno water tank in France

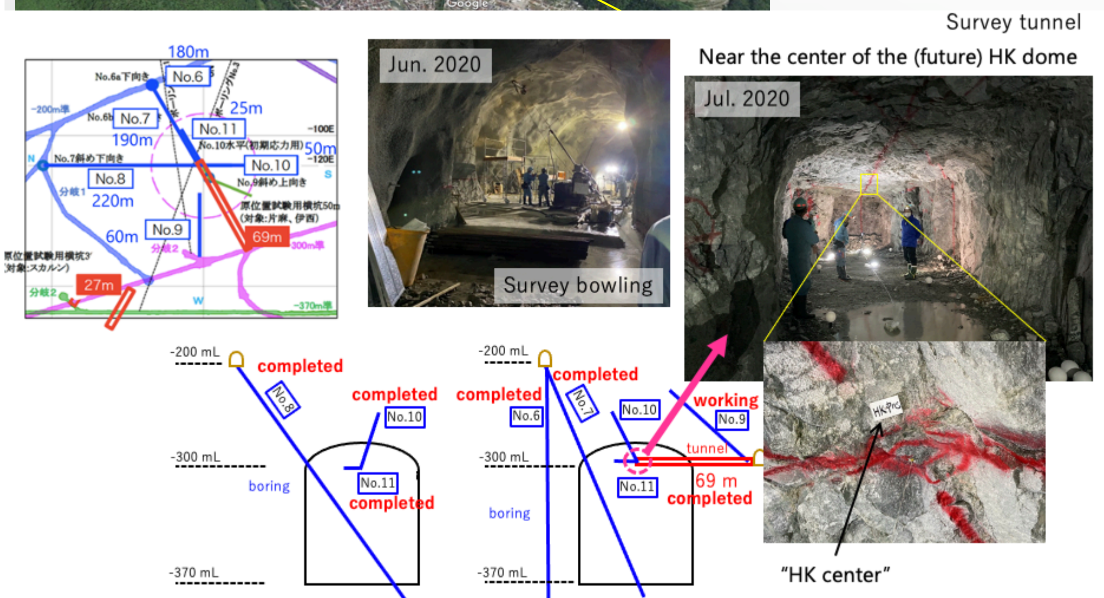
Box&Line PMT in Super-K

The Hyper-K Construction



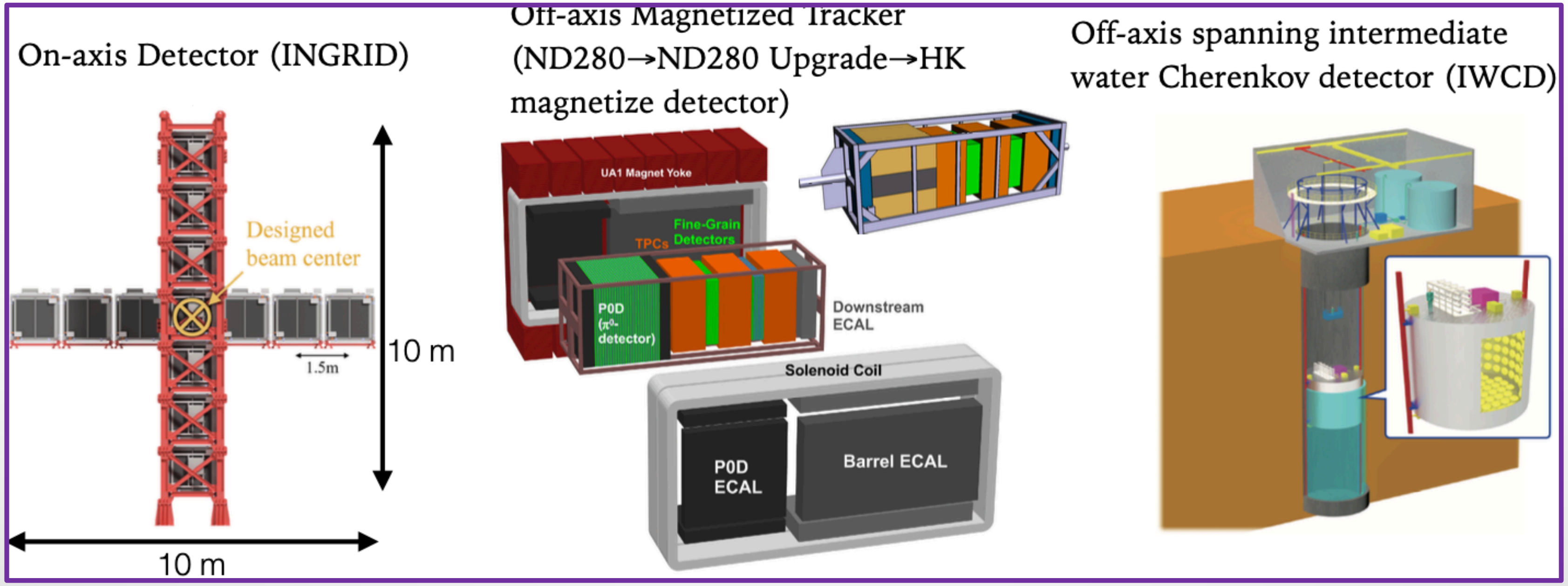


2020/12 First six PMTs delivered to Kamioka



- Feb. 2020: First year construction budget approved
- April 2020: Construction started
- May 2020: U. of Tokyo and KEK signed MOU
- December 2020: First PMTs delivered in Kamioka
- May 2021 Start of the Tunnel excavation
- Operation to start in 2027

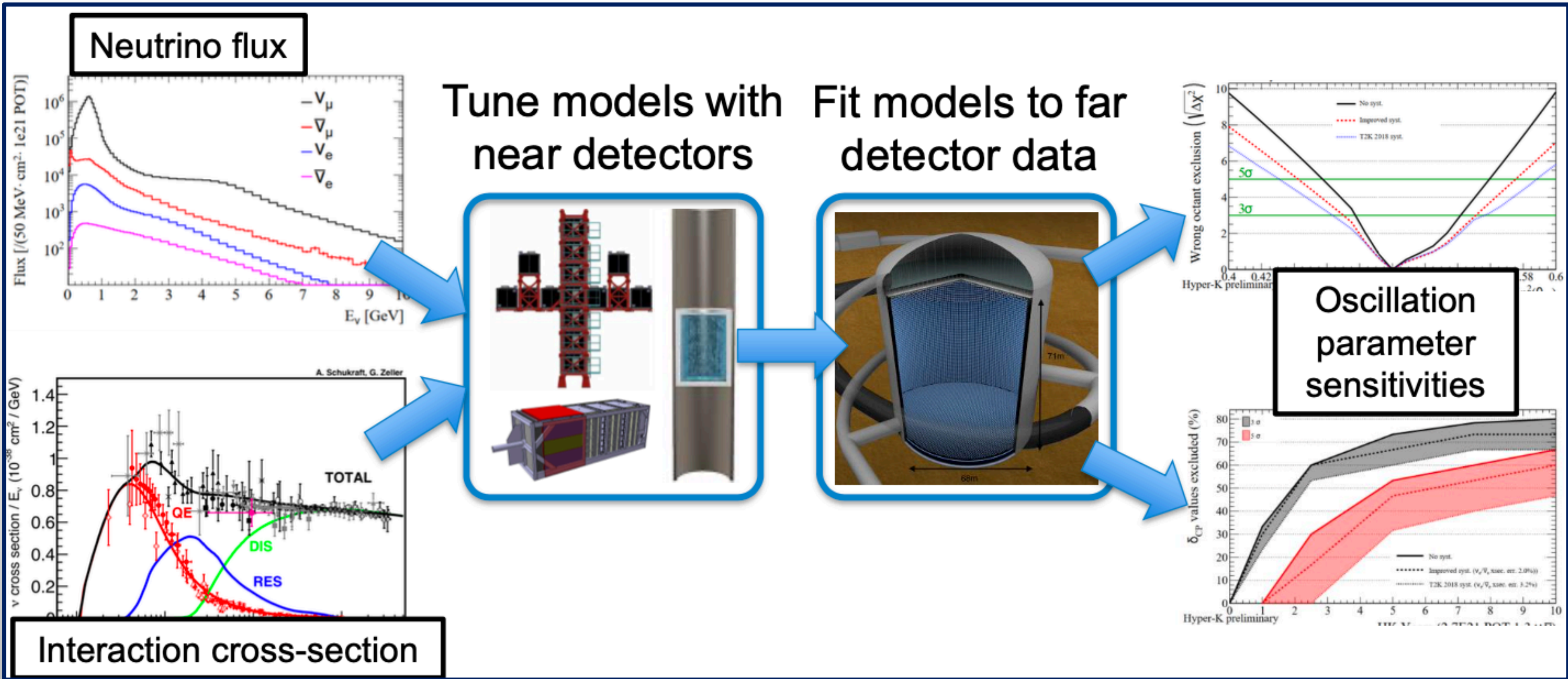
Near Detectors Suite



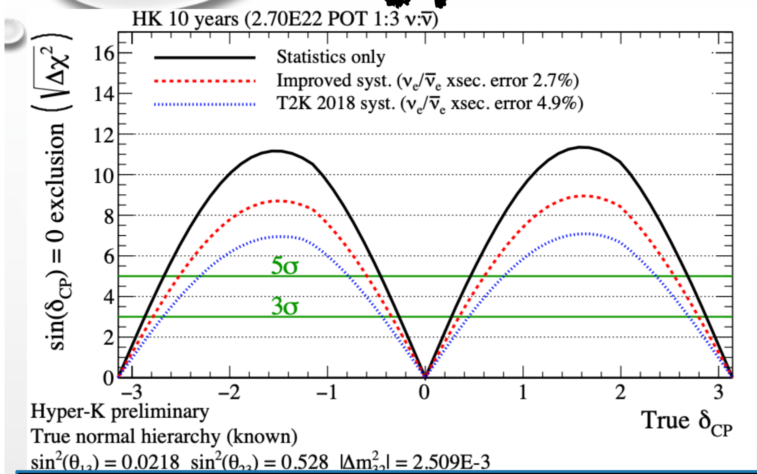
- ✓ On-axis detector: measure beam direction, monitor event rate.
- ✓ Off-axis magnetized tracker: charge separation (wrong-sign background), recoil system
- ✓ Off-axis spanning water Cherenkov detector: intrinsic backgrounds, electron.
- ✓ (anti)neutrino cross-sections, neutrino energy vs. observables, H_2O target.

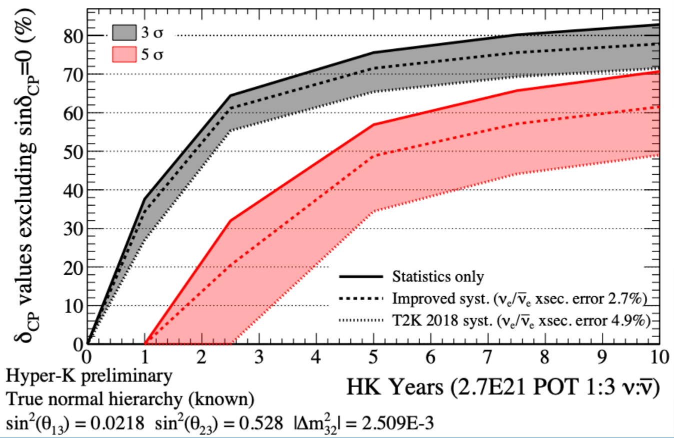
Hyper-K Beam Oscillation Analysis

Based on T2K oscillation method.



Hyper-K & DUNE Sensitivites : δ_{CP}

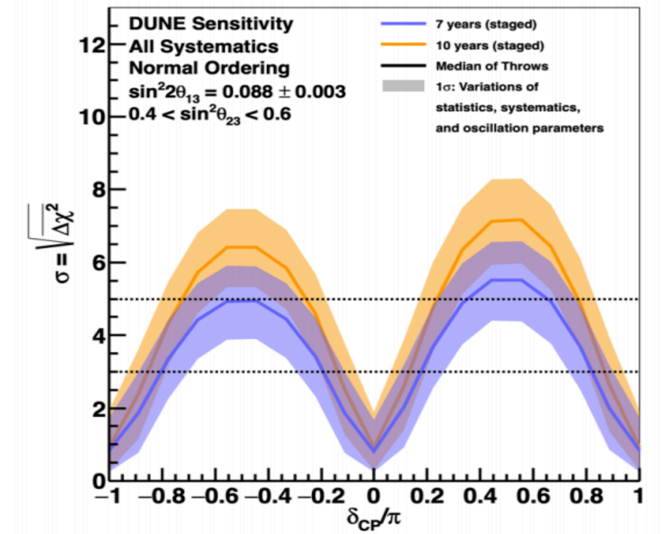


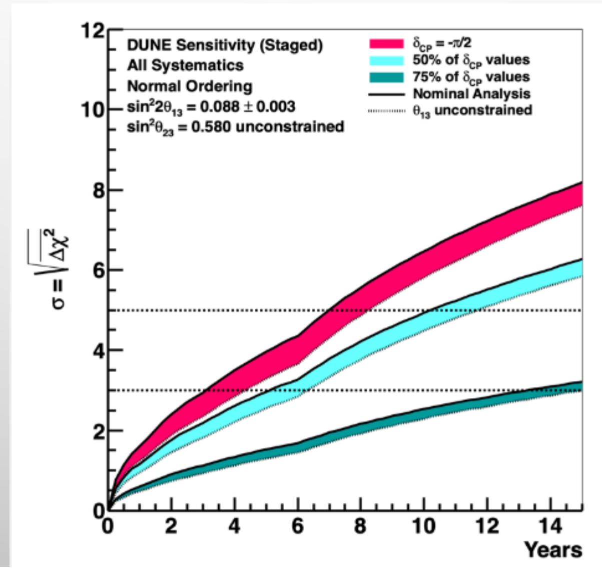


Hyper-K

Exclusion of $\sin\delta_{cp} = 0$
- ➢ ~8 σ for $\delta_{cp} = -90°$
- ➢ More than 50% of δ range >5 σ

- Measurement of δ_{cp}
- ➢23°for δ_{cp} =90°/ 7° for δ_{cp} =0°





DUNE

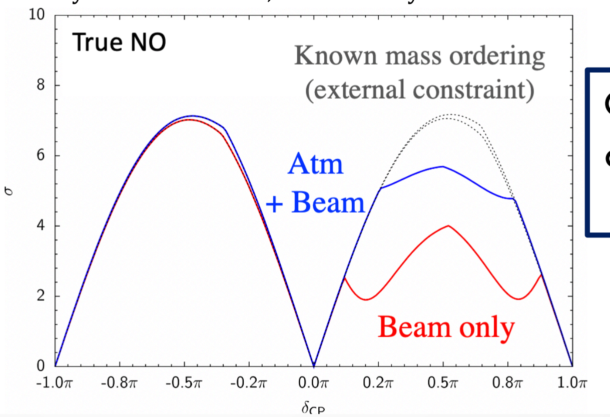
Staged scenario
- ➢ Assumes equal running in neutrino and antineutrino mode
- ➢ CPV: 65% of δ range at 3σ in 7 years

Hyper-K & DUNE Sensitivites : MH

	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ
θ_{23} octant	0.45	2.2 σ	→ 6.2 σ
	0.55	1.6 σ	→ 3.6 σ

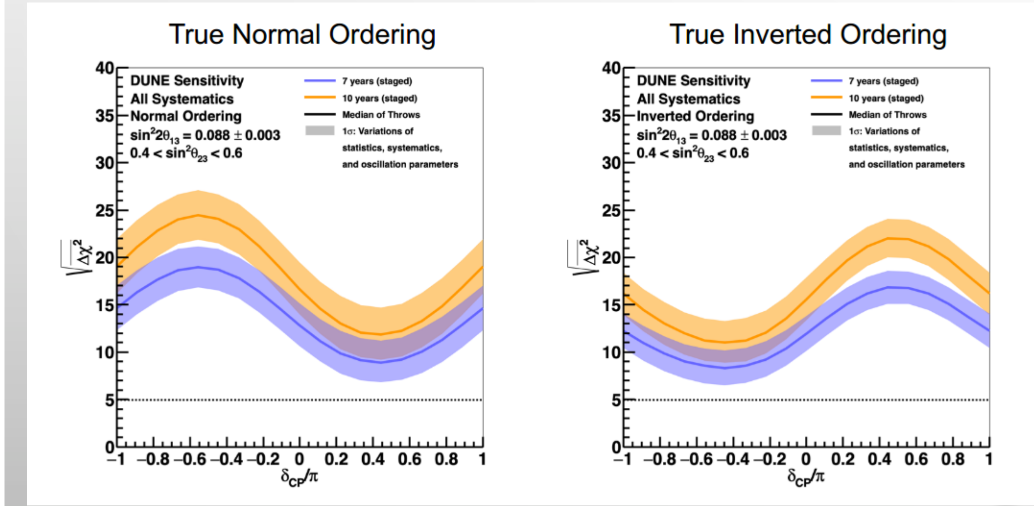
10 years with 1.3MW, normal mass ordering is assumed

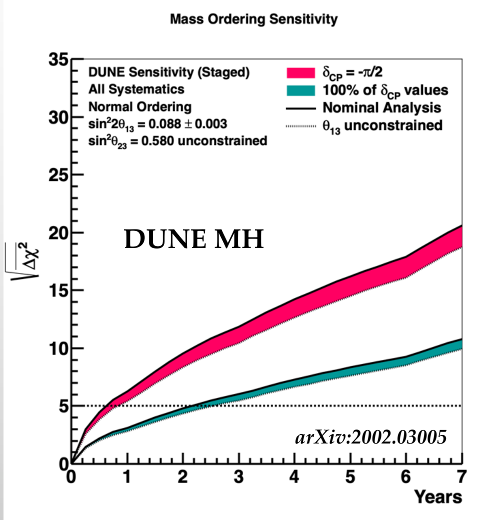
10 years with 1.3MW, T2K 2018 systematic error



Hyper-K

Combination of long-baseline and atmospheric neutrino observations



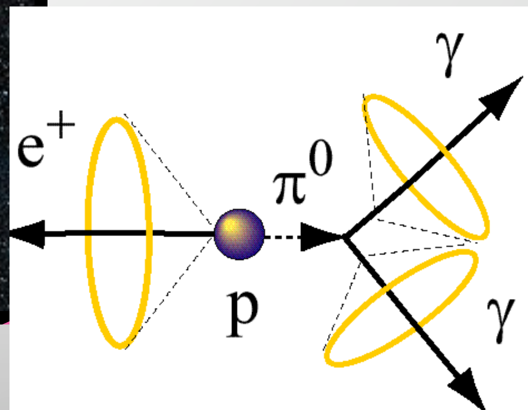


DUNE

2-3 years to unambiguously determine mass hierarchy (NO or IO)

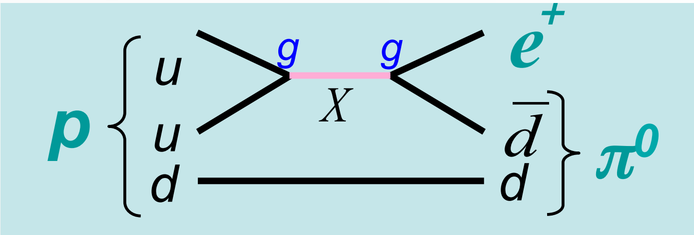
Hyper-K & DUNE are Observatories !

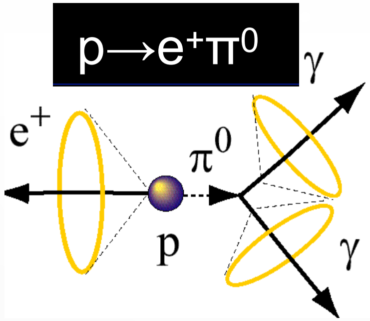
- Nucleon decay searches
- Supernovae physics
  - SN explosion mechanism
  - SN monitor
  - Nucleosynthesis
- Supernova Relic Neutrino
  - SN mechanism
  - Star formation history
- Solar neutrinos
  - Burning processes, modelling of the Sun
  - Property of neutrino
- BSM physics (sterile searches, non-standard interactions)

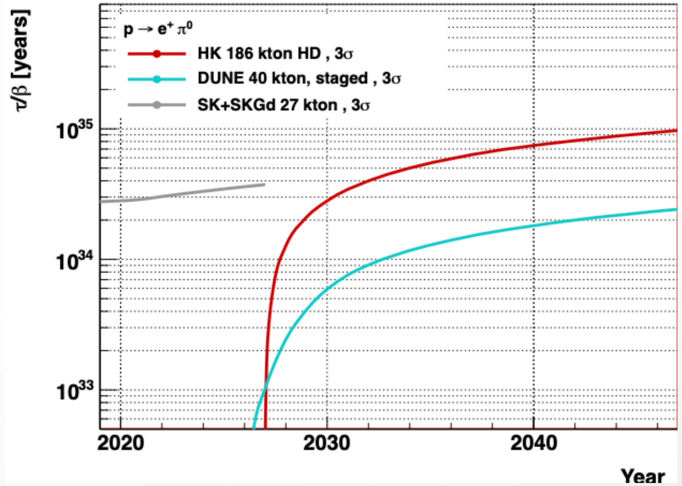


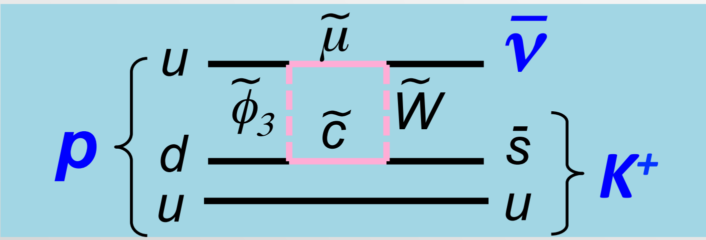
Proton Decay Searches

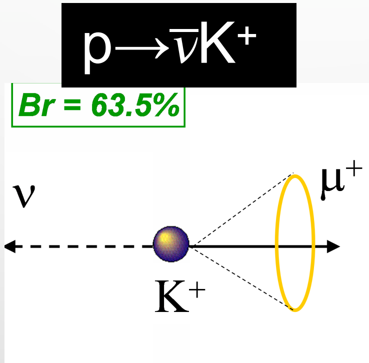
Two major modes predicted by many models

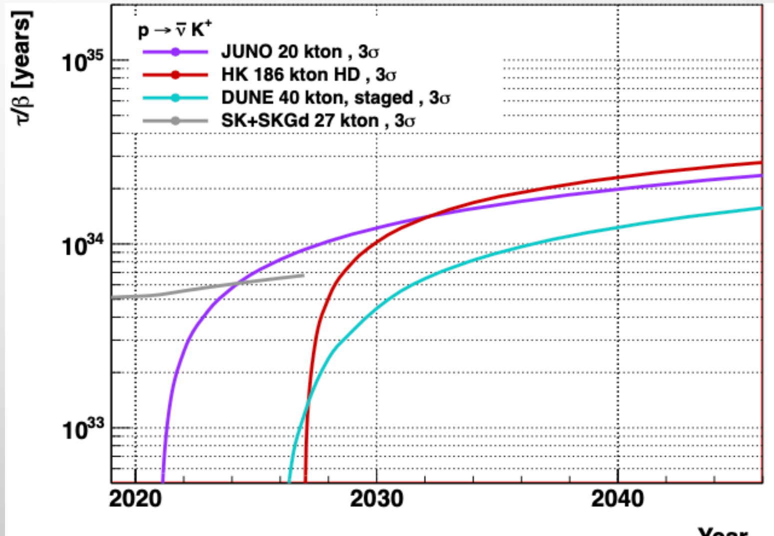








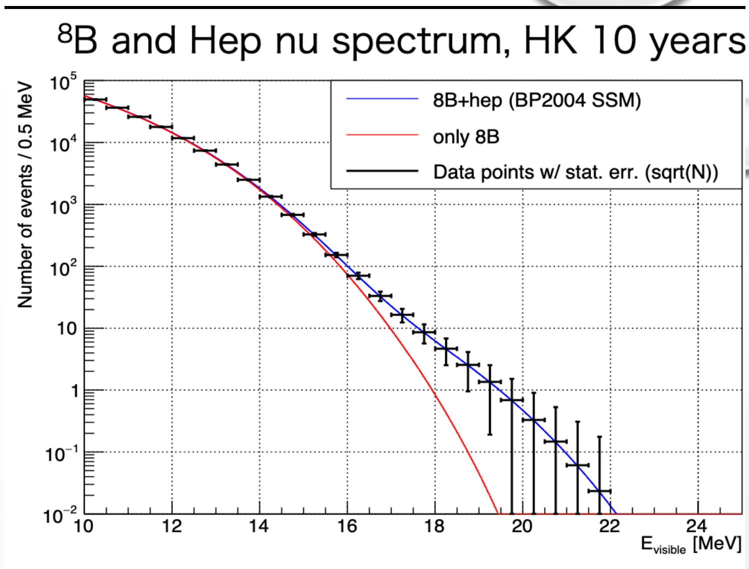


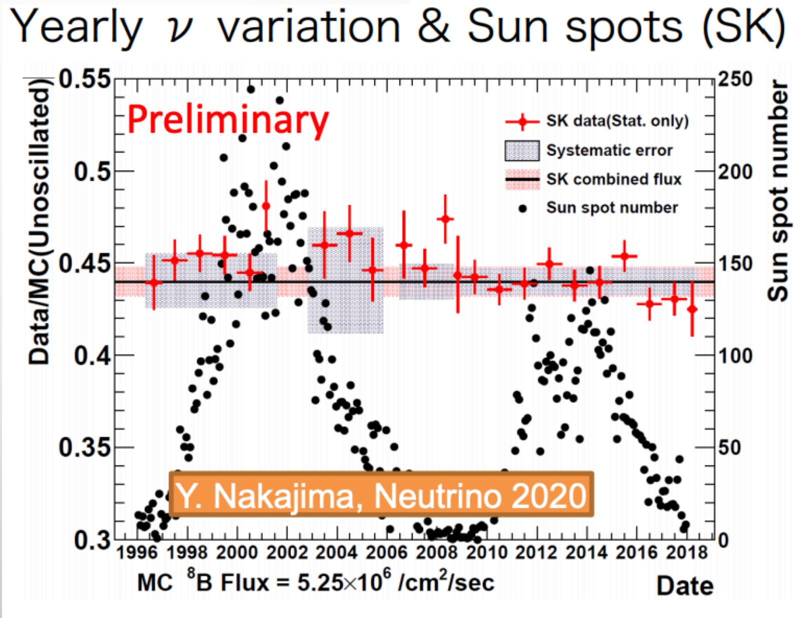


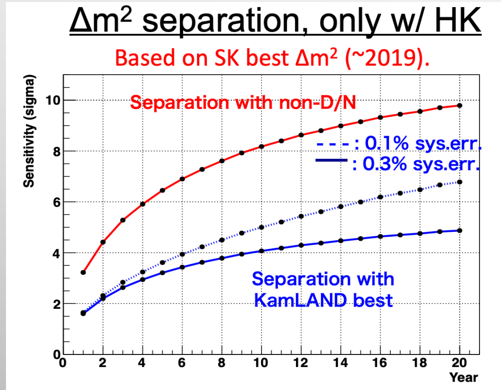
Hyper-K is able to pursue these and other final states with the highest precision.

Hyper-K: Solar Neutrinos

- Large statistics: 130 ν ev./day, *Evis*>4.5MeV
- Highlights of solar ν measurements in particle physics and astrophysics:
  - Day/Night asymmetry
  - Solar ν spectrum up-turn
  - Discovery of Hep neutrino
  - Variation of solar ν flux
  - Precision measurement Δm^2



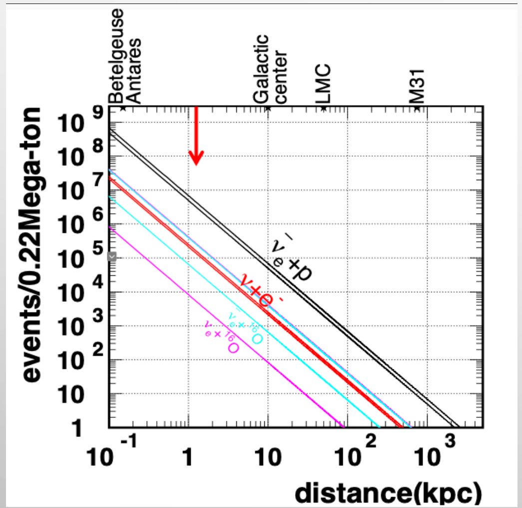


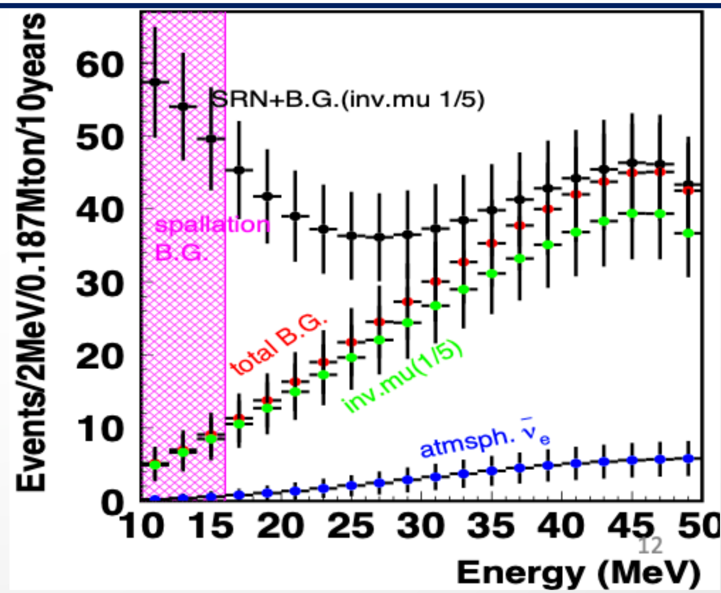


Hyper-K: Supernova and Relic Neutrinos

Supernova neutrino observation:

- 54-90k events for SN at 10 kpc (most sensitive to anti-ν_e)
- Precise Neutrino Time profile
- Precise spectrum measurement
- Investigation of the SN mechanism (SASI/ Rotation/Convection)





Supernova Relic Neutrino (SRN)

- Diffused neutrinos coming from all past supernovae.
- Not discovered but promising extra-galactic ν.
- SRN can be observed by HK in 10y with ~70±17 events. It is > 4σ for SRN signal.

Dune: Supernova Neutrinos

- Dominant interaction on argon:

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

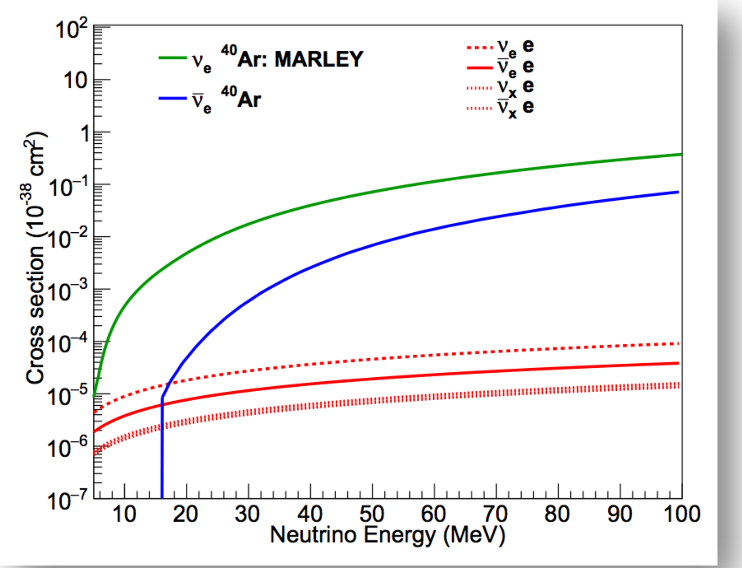
short electron track

nearby de-excitation gammas, Compton scattering

- Unique sensitivity to electron neutrinos from a supernova!

- In case of a **galactic supernova**, DUNE expects to observe up to thousands of neutrino interactions over the duration of the burst

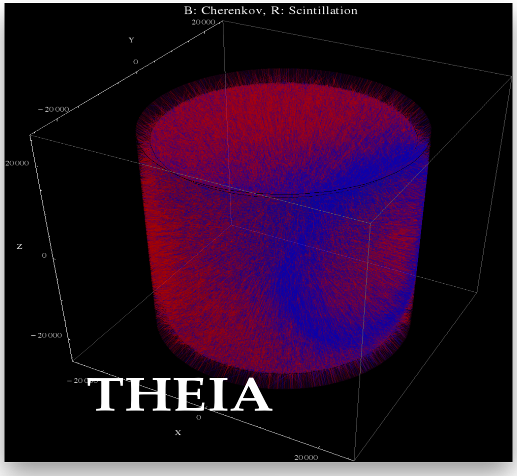
- arXiv:2008.06647

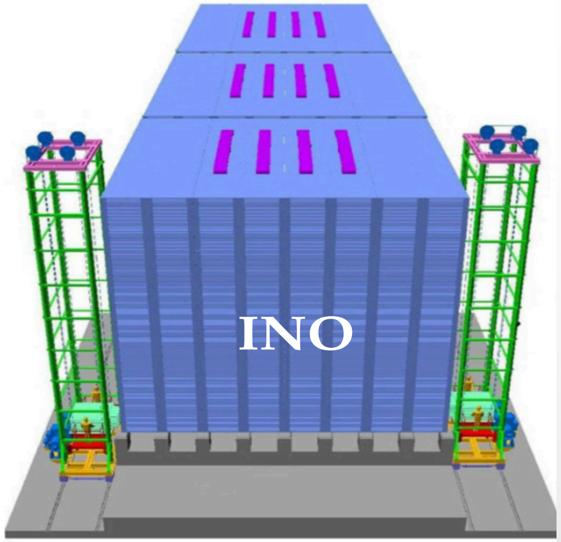


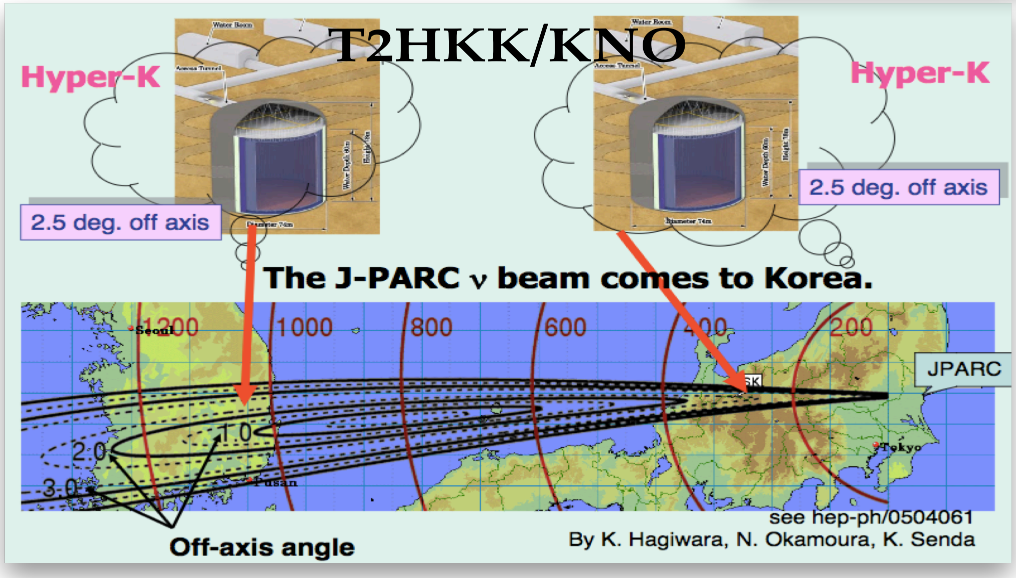
Channel	Livermore	GKVM	Garching
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	2744	3412	918
$\overline{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$	224	155	23
$\nu_X + e^- \rightarrow \nu_X + e^-$	341	206	142
Total	3309	3773	1083

Beyond next generation

- More like **observatories**, very broad physics programs
- Precision tests of 3-flavor mixing, new physics, and much more than just oscillation experiments
- Exact goals will depend on where we will be with next generation!







Thank You !