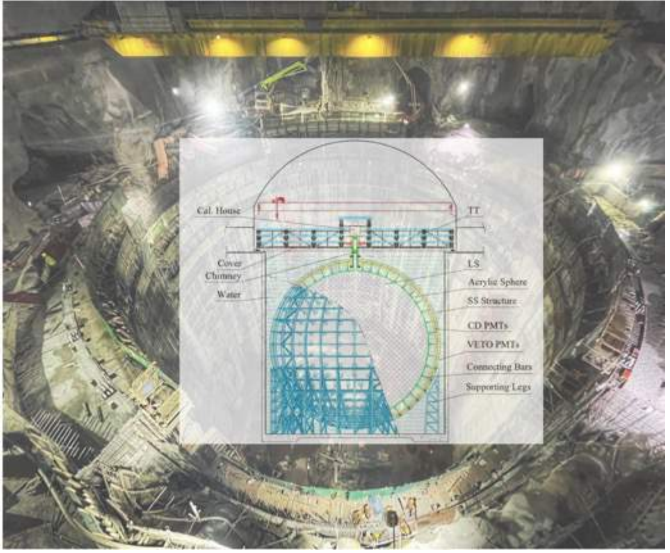


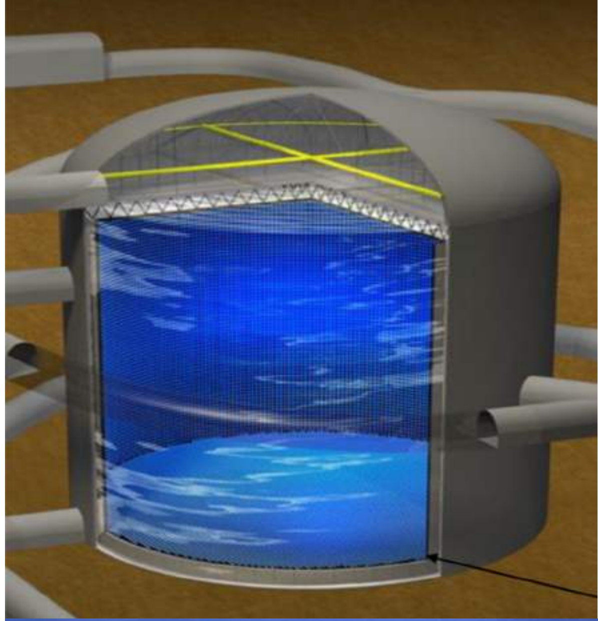
THE UNIVERSITY OF WINNIPEG

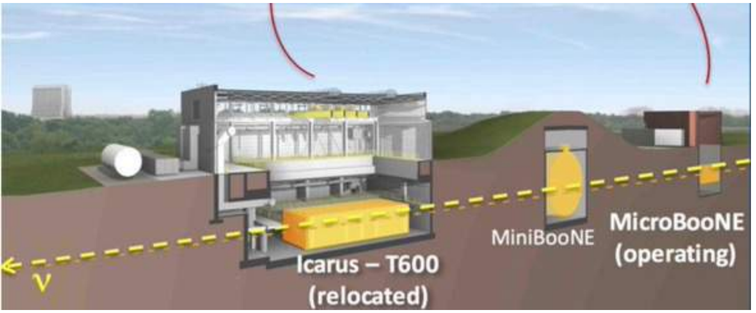
BACK TO THE FUTURE NEUTRINO EXPERIMENTS

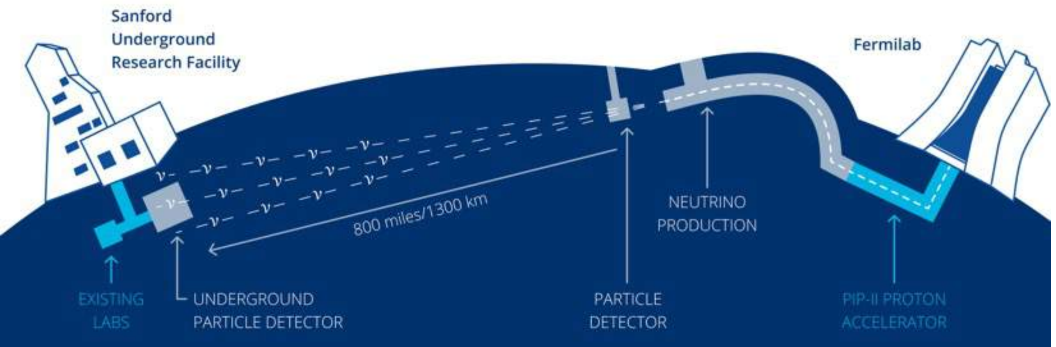
Blair Jamieson
Bl.jamieson@uwinnipeg.ca

On behalf of Hyper-Kamiokande

FCPC 2022
May 2022



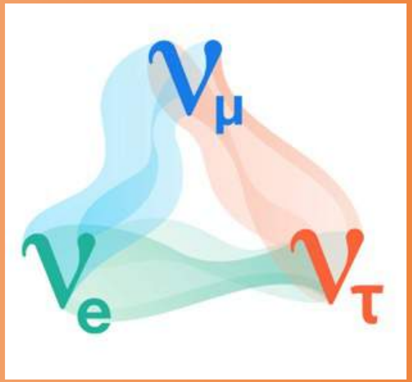




OVERVIEW WLL REVIEW IN ORDER OF (#)

Long baseline neutrino oscillation

- **DUNE (1)**
- **Hyper-Kamiokande (2)**



Medium baseline neutrino oscillation

- **JUNO (3)**

Short baseline neutrino oscillation

- **Fermilab SBL (4)**
- Prospect-II
- JUNO-TAO

- Project 8
- ECHo Ho exeriment

Neutrino mass measurement

- Legend-1000
- nEXO
- CUPID
- JUNO-$\beta\beta$

$0\nu\beta\beta$

- KM3Net/ORCA
- Ice Cube

Neutrino astrophysics

Nb. Sorry if I missed your experiment here!

Long baseline oscillation program

DUNE and Hyper-Kamiokande

Neutrino oscillations

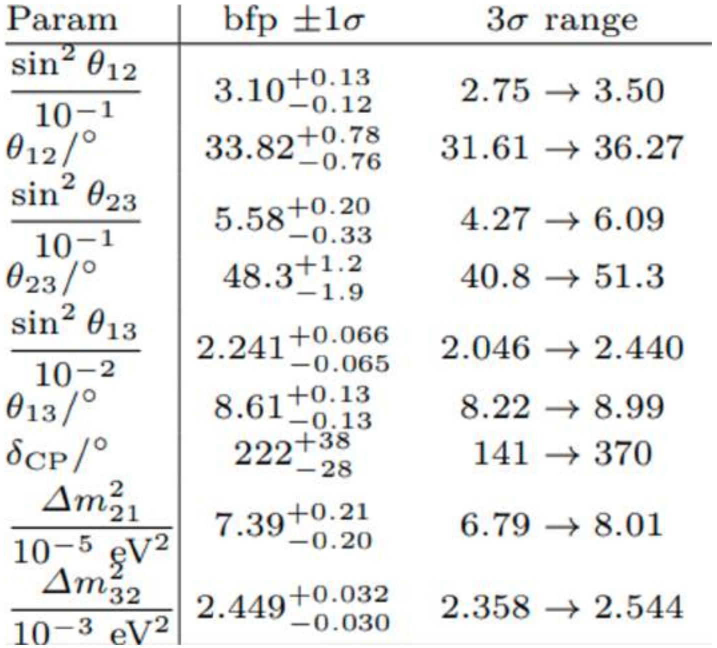
- For 3 neutrinos → Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{“Solar neutrinos”}} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{“Atmospheric neutrinos”}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- 3 non zero mixing angles → possible CP violation in the lepton sector

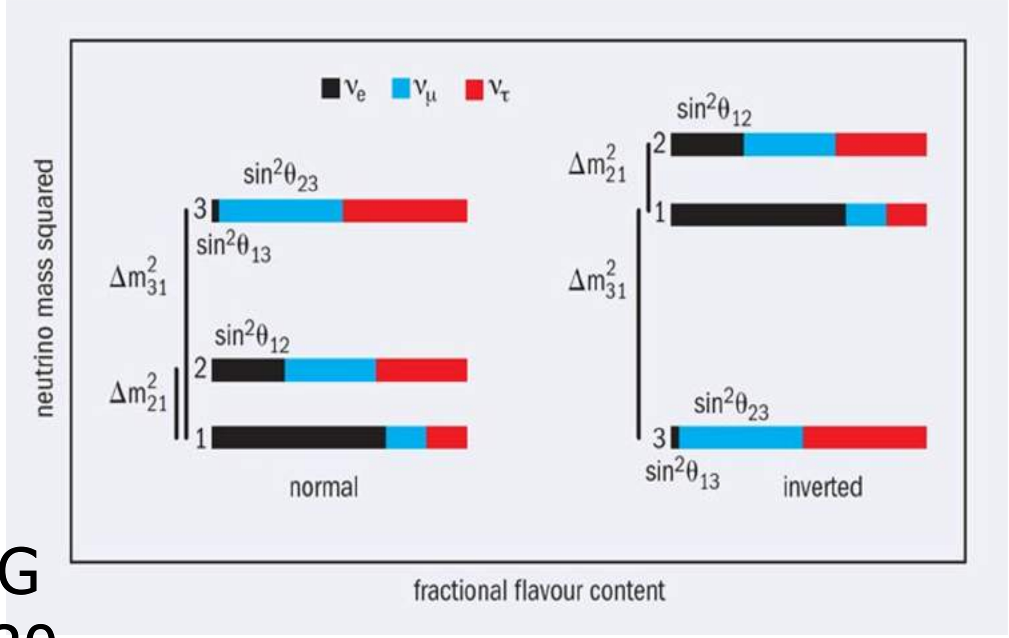
$$P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$$

Open questions:
- CP violation
- Mass hierarchy
- θ_{23} octant



Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$
$\theta_{12}/°$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	$4.27 \to 6.09$
$\theta_{23}/°$	$48.3^{+1.2}_{-1.9}$	$40.8 \to 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	$2.046 \to 2.440$
$\theta_{13}/°$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$
$\delta_{CP}/°$	222^{+38}_{-28}	$141 \to 370$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$	$2.449^{+0.032}_{-0.030}$	$2.358 \to 2.544$

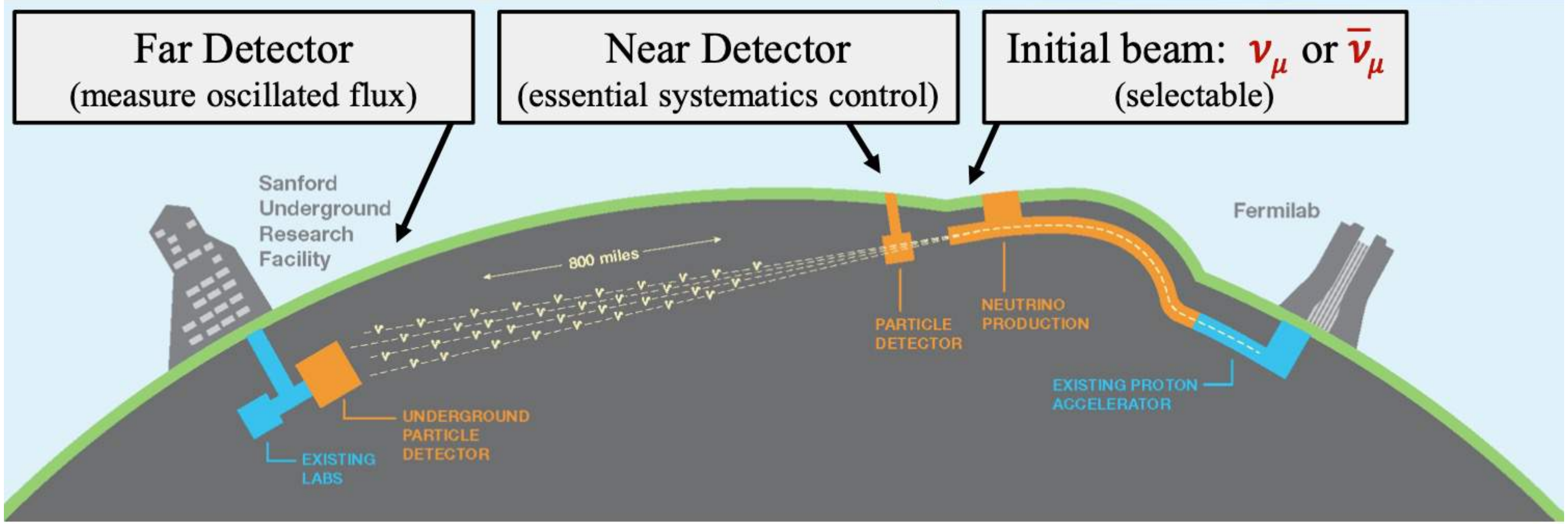
PDG 2020



DUNE Overview

A next generation experiment for **neutrino science**, **supernova physics,** and **physics beyond the Standard Model**

1300 km baseline



Far Detector
(measure oscillated flux)

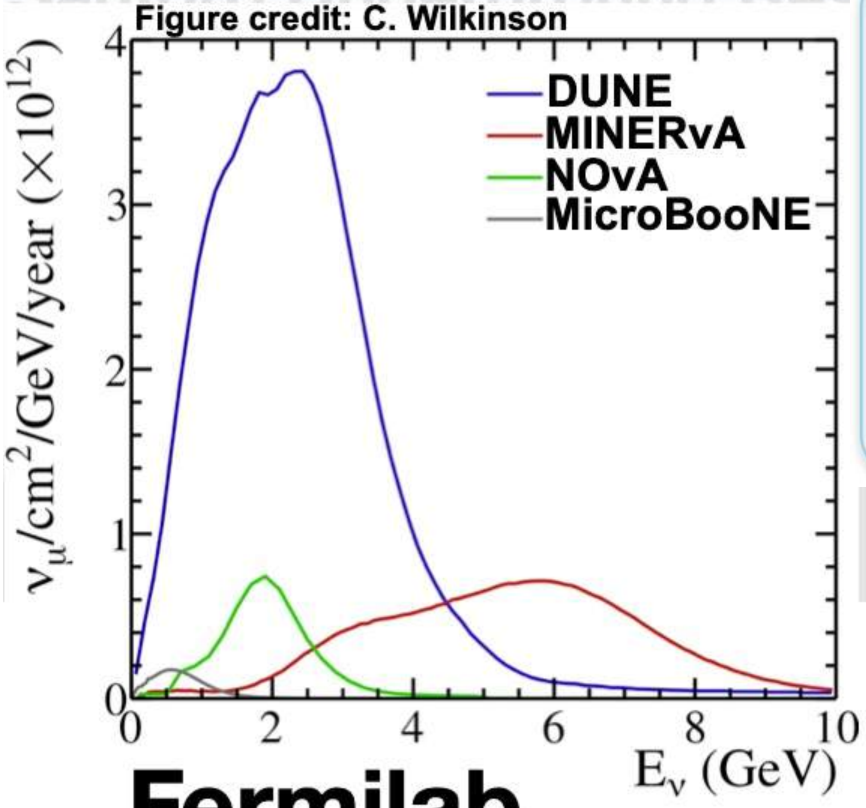
Near Detector
(essential systematics control)

Initial beam: ν_μ or $\bar{\nu}_\mu$
(selectable)

DUNE Beam

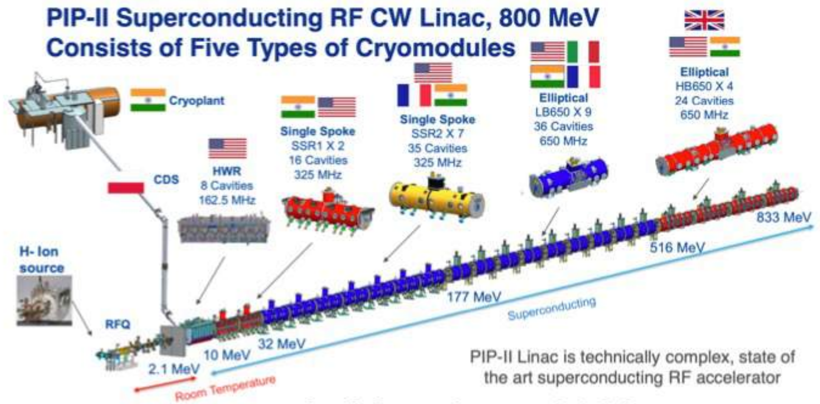
Sanford Underground Res

Figure credit: C. Wilkinson



Fermilab neutrino fluxes

PIP-II Superconducting RF CW Linac, 800 MeV
Consists of Five Types of Cryomodules



L. Merminga, 2020

PIP-II

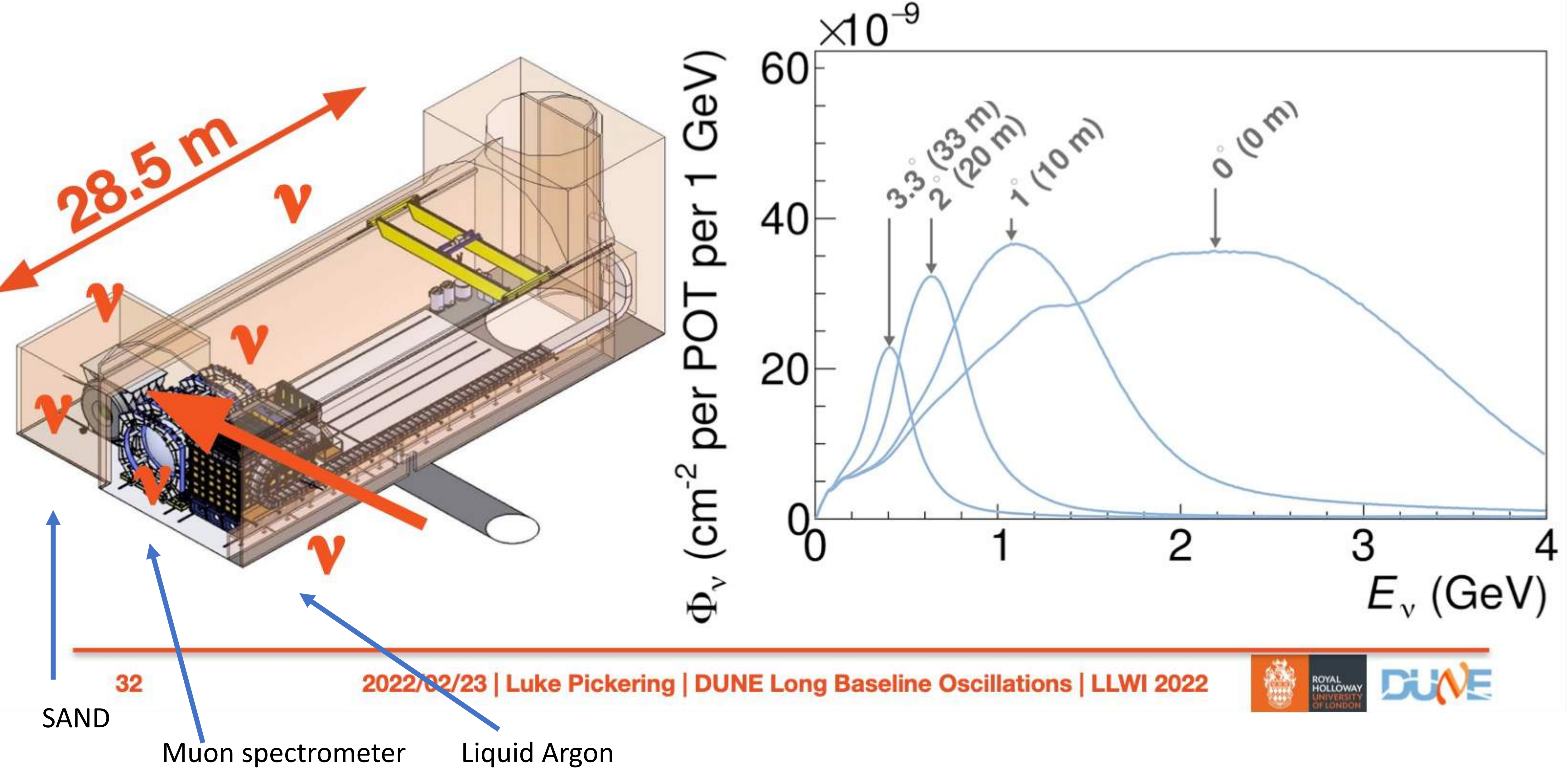
- Upgrade to Fermilab's accelerator complex
- PIP-II will make the accelerator complex capable of 1.2 MW
  - A future Booster replacement can enable 2+ MW

Accelerator

The DUNE Neutrino Beam

- 1.2 MW neutrino beam
- Optimized for CPV sensitivity

DUNE Near Detectors (DUNE PRISM)

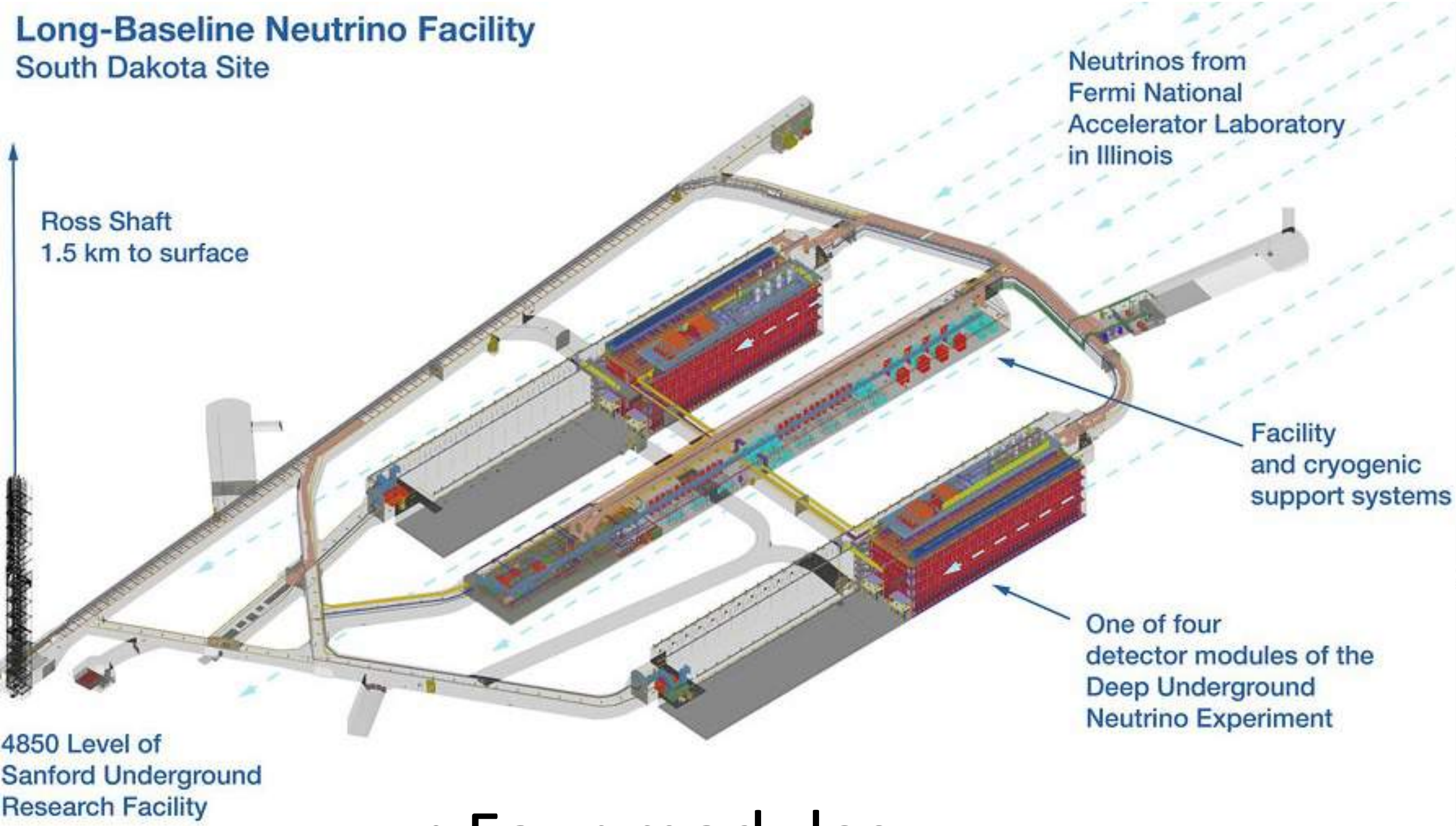


32 2022/02/23 | Luke Pickering | DUNE Long Baseline Oscillations | LLWI 2022

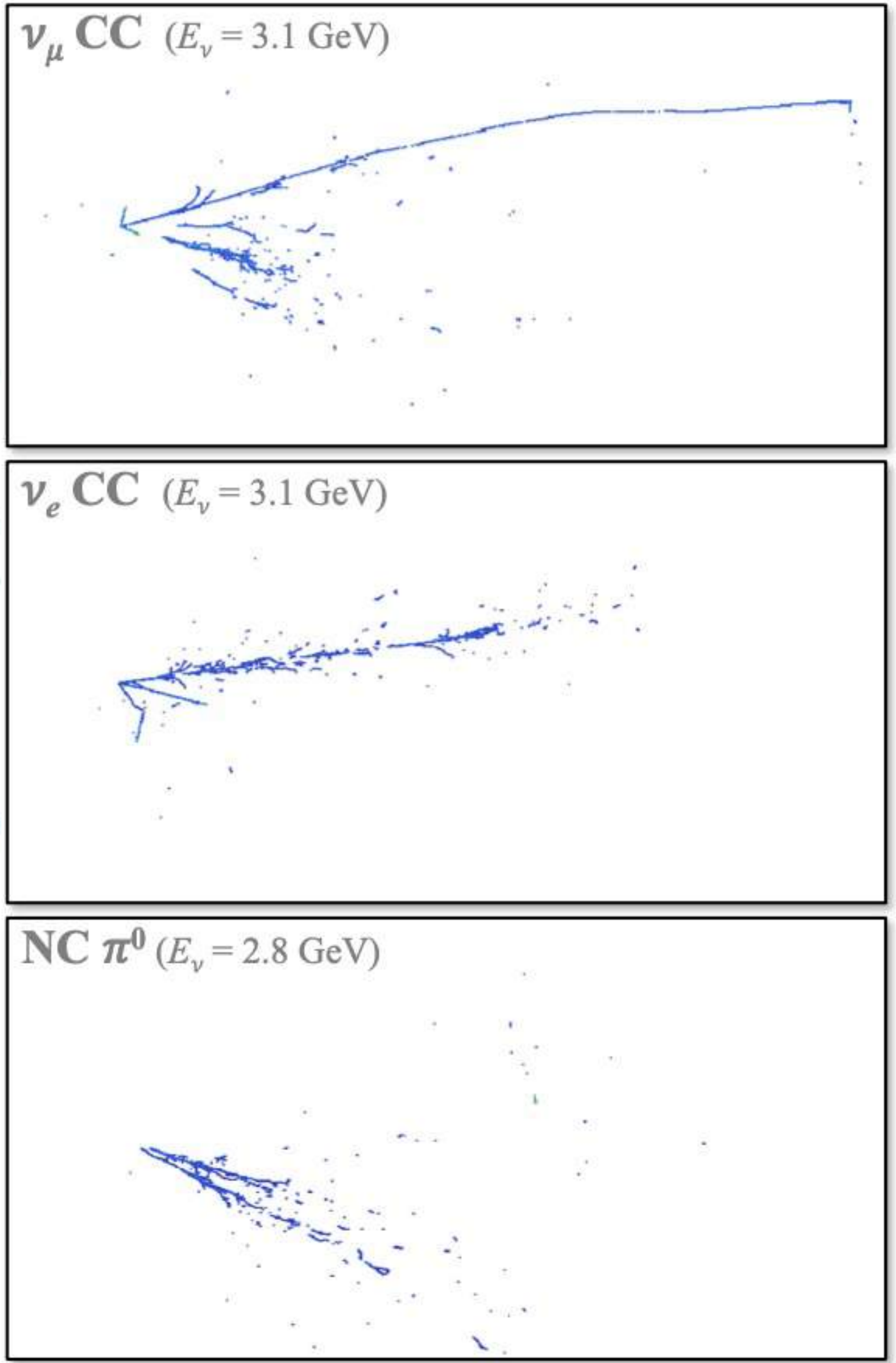
ROYAL HOLLOWAY UNIVERSITY OF LONDON

DUNE

DUNE far detector



- Four modules
- Each 17 kT Ar TPC

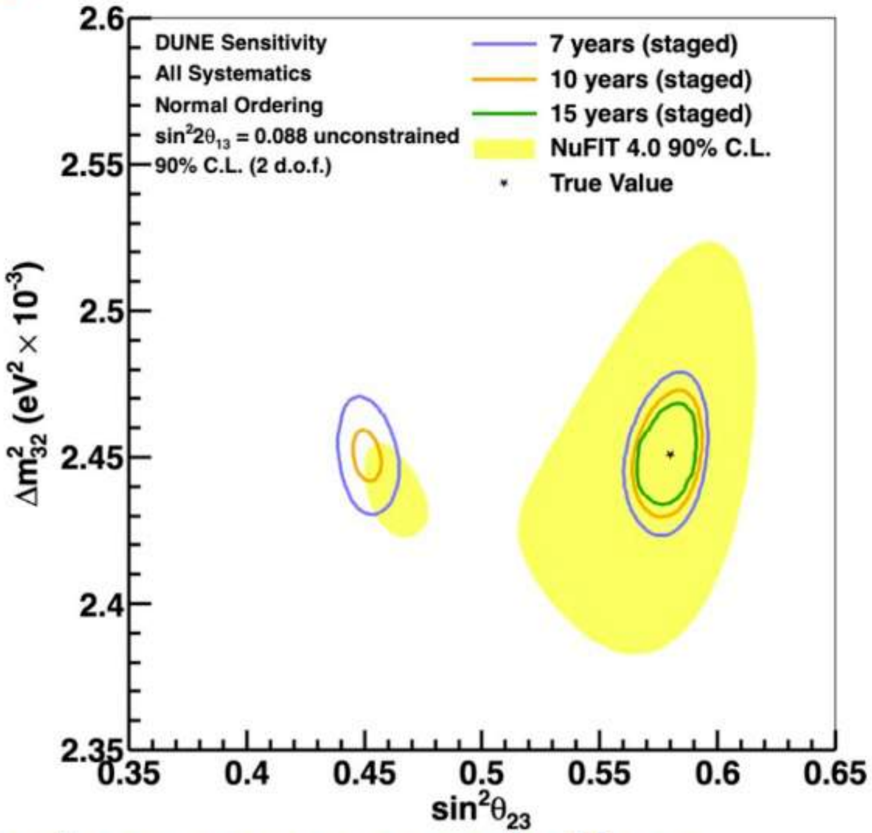


ν_μ CC ($E_\nu = 3.1$ GeV)

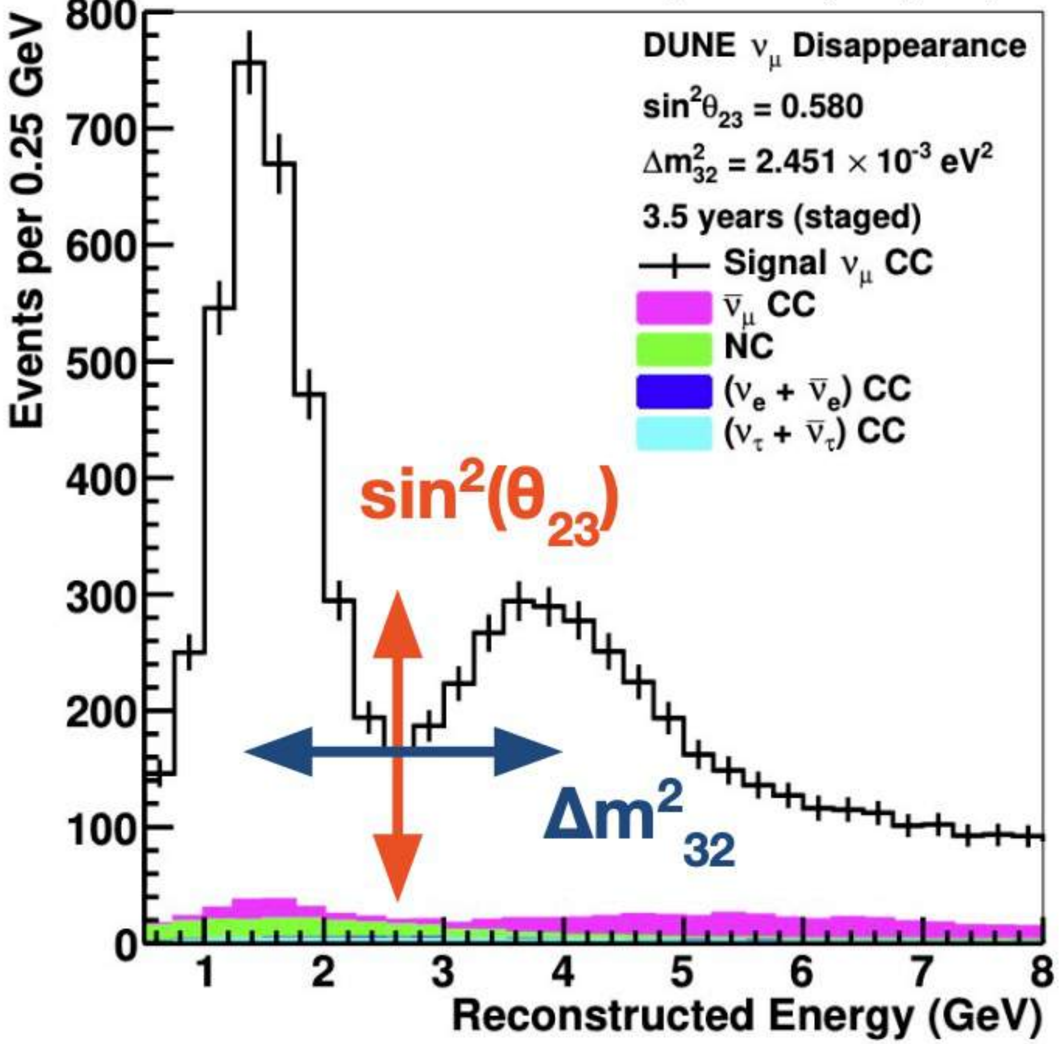
ν_e CC ($E_\nu = 3.1$ GeV)

NC π^0 ($E_\nu = 2.8$ GeV)

Disappearance Sensitivity

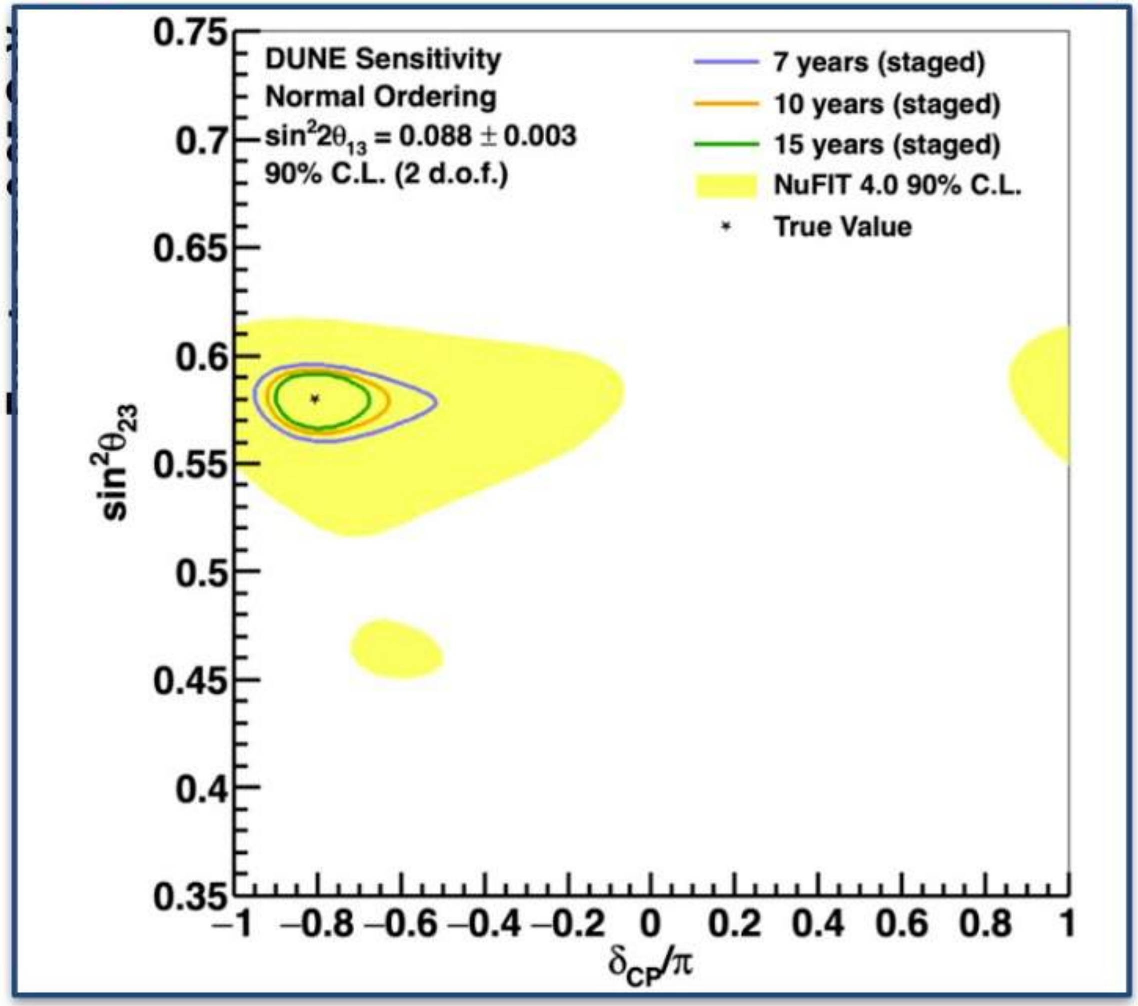


Eur. Phys. J. C 80, 978 (2020)



- Excellent energy resolution
- Massive far detector event rate
- Unprecedented oscillation parameter sensitivity

Appearance Sensitivity



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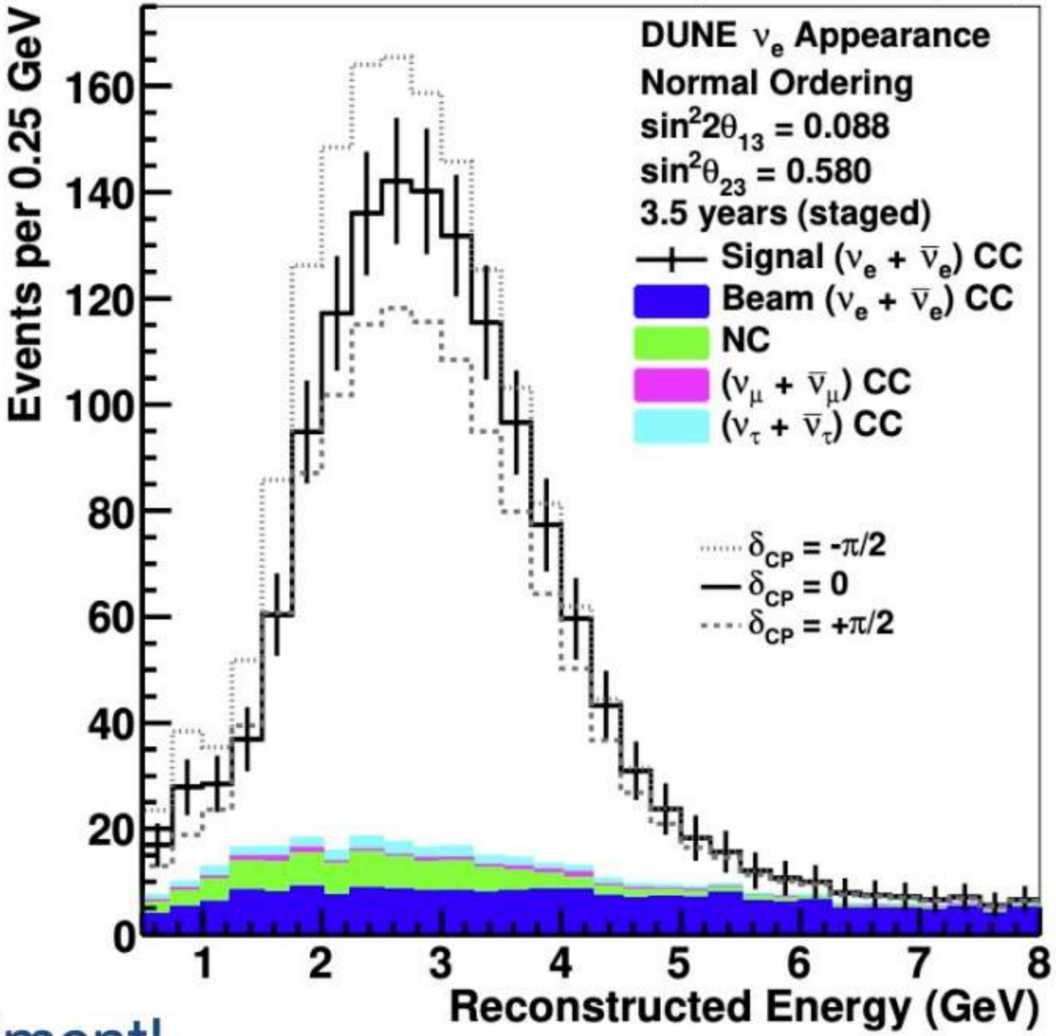


- Unique access to MO + CPV in one experiment!

The Hyper-Kamiokande Experiment

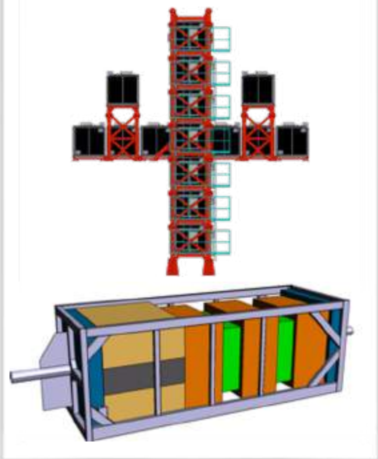
Hyper-Kamiokande (Hyper-K) is a world-leading neutrino experiment, building on success of Super-Kamiokande & T2K.

Broad & ambitious physics programmes covering many neutrino sources as well as proton decay measurements.

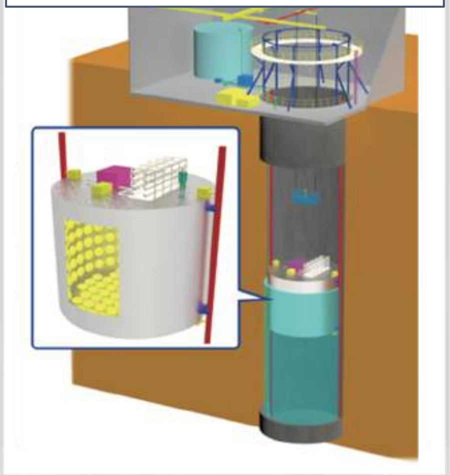
Water Cherenkov detector technology provides huge target mass with excellent particle ID and reconstruction capabilities.

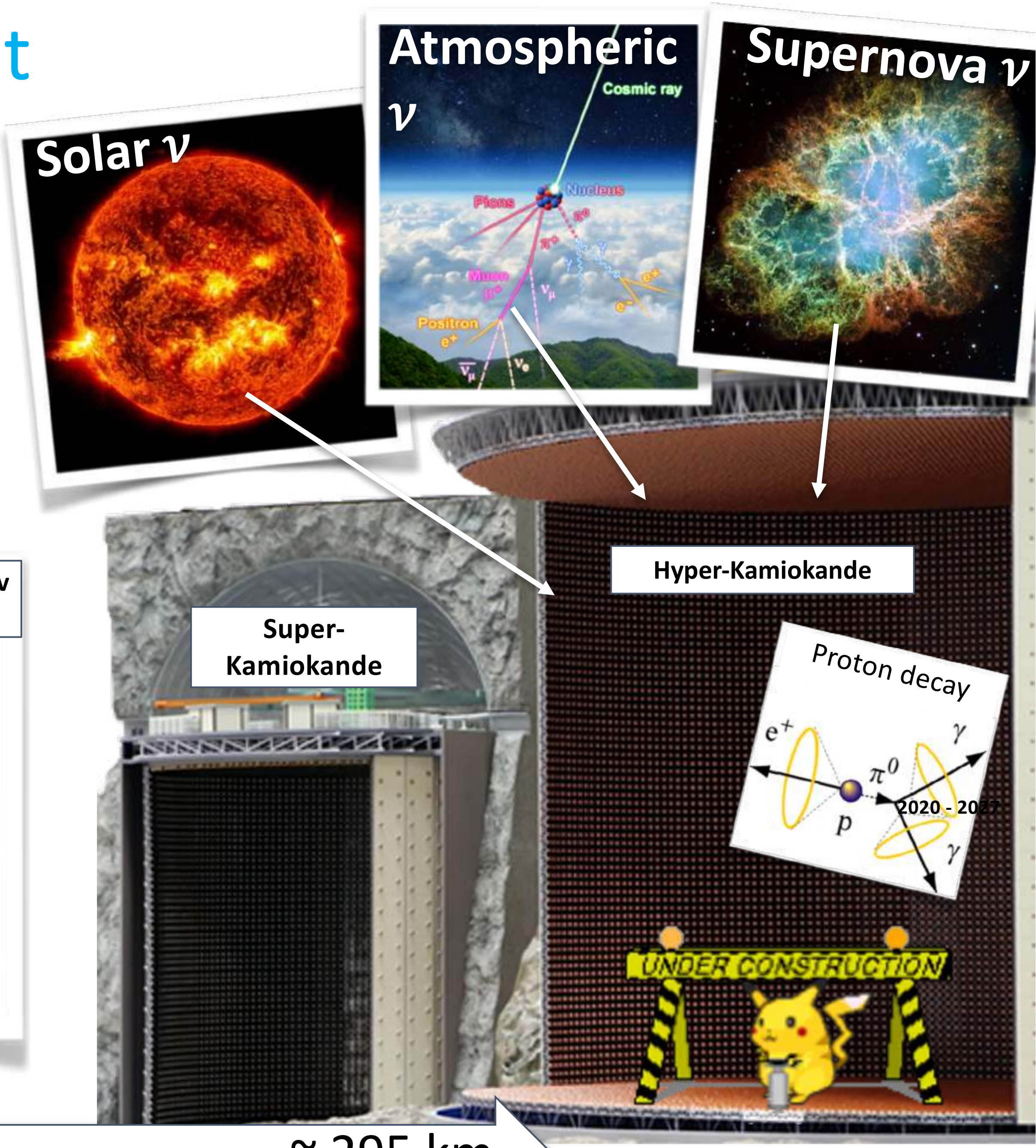

Water Cherenkov Test-beam Experiment (WCTE) at CERN

Near detectors



Intermediate Water Cherenkov Detector (IWCD)





280 m → ~ 1 km → ~ 295 km

Hyper-K Detector

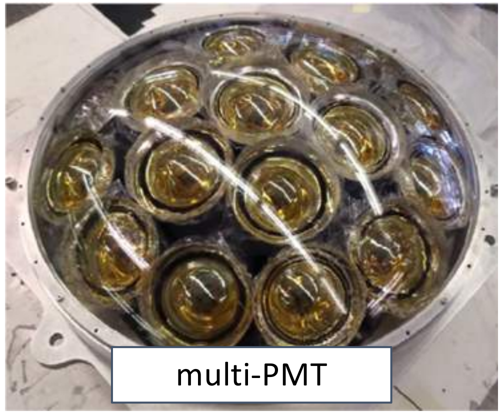
8 x increase in fiducial mass over Super-K

- 71 m tall x 68 m diameter = 258 kt total mass
  188 kt fiducial mass
- Outer detector region for active veto of incoming particles
  - 1 m wide around barrel, 2 m at top & bottom

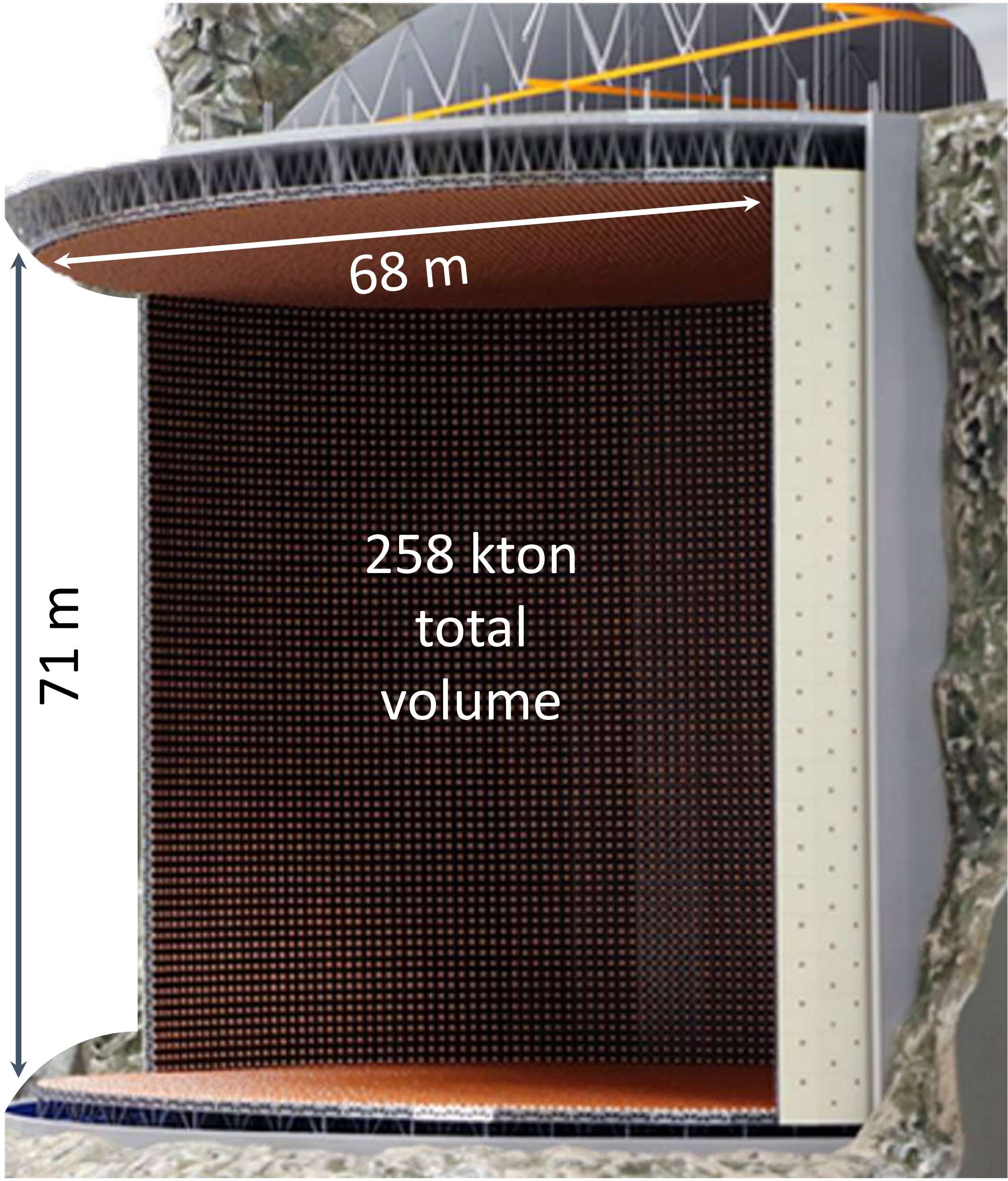
New photo-detector technology for increased sensitivity

- 20,000 B&L 50 cm PMTs = 20% photo-coverage
  - 1.5 ns timing resolution (half that of SK PMTs)
  - Double quantum efficiency of SK PMTs
- Additional photo-coverage from multi-PMT modules
  - 8 cm PMTs grouped in modules of 19 PMTs
  - Improved position, timing, direction resolution
  - Also used for in-situ calibration of 50cm PMTs

50cm B&L PMT



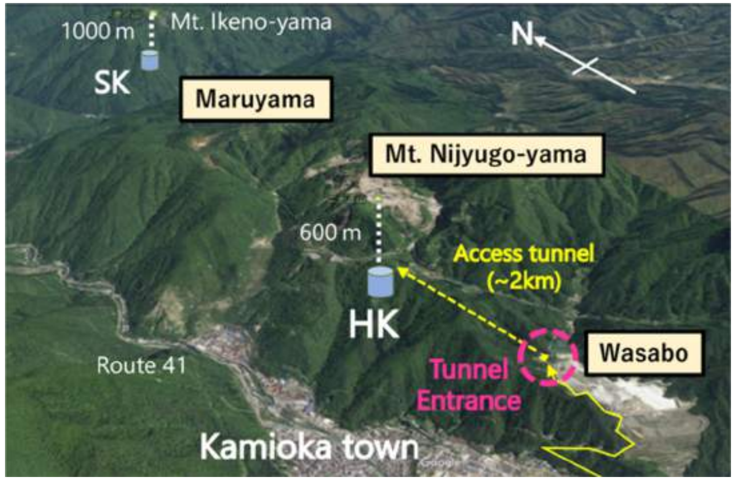
multi-PMT



Detector Construction

Access tunnel excavation is going well!

Cavern excavation starting soon!



PMT production on schedule

Inspection and testing is ongoing

R&D for 50cm PMT covers is in progress

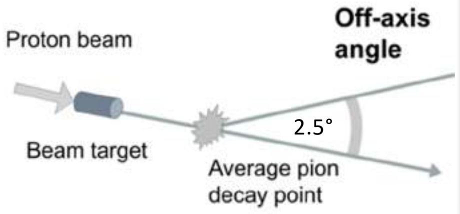
Long-Baseline Neutrinos

Neutrino beam produced at J-PARC, 295 km baseline from Hyper-K.

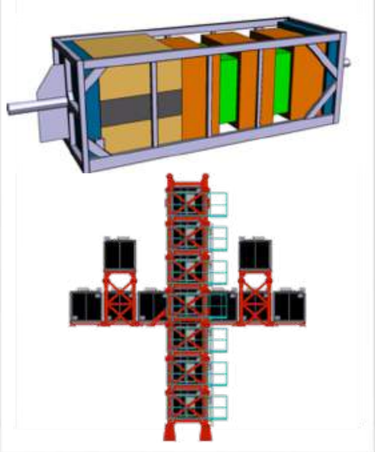
Near and intermediate detectors measure unoscillated flux and cross sections.

Oscillations observed through ν_μ disappearance and ν_e appearance, for both neutrinos and antineutrinos.

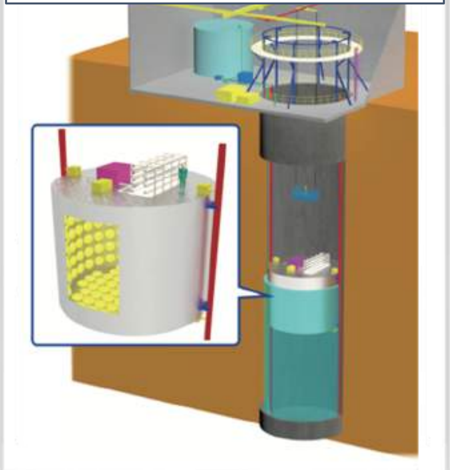
Difference between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ provides sensitivity to CP violation and δ_{CP} measurement.



Near detectors



Intermediate Water Cherenkov Detector (IWCD)

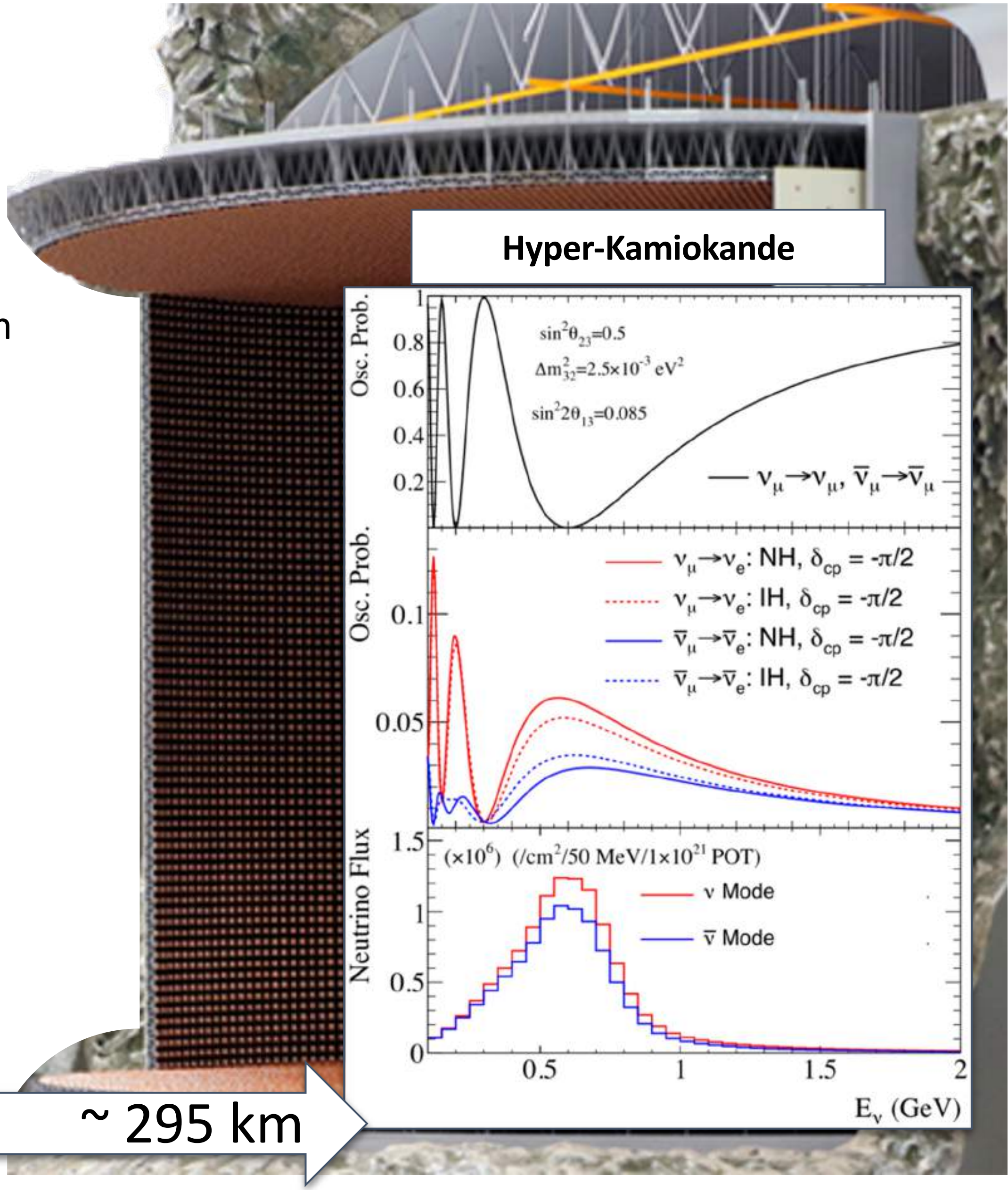


280 m

~ 1 km

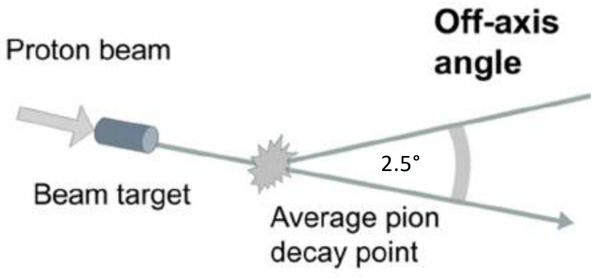
~ 295 km

Hyper-Kamiokande



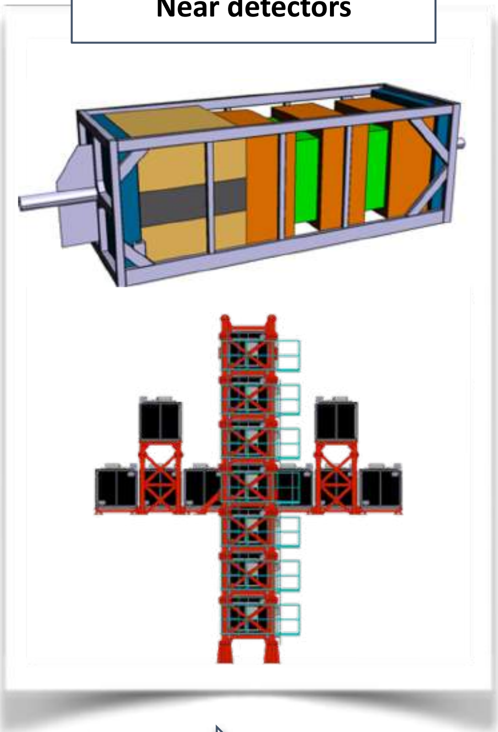
J-PARC Beam & Detectors

J-PARC beam upgrade 0.75 → 1.3 MW for increased event rate



Upgraded T2K near detectors to continue to Hyper-K era

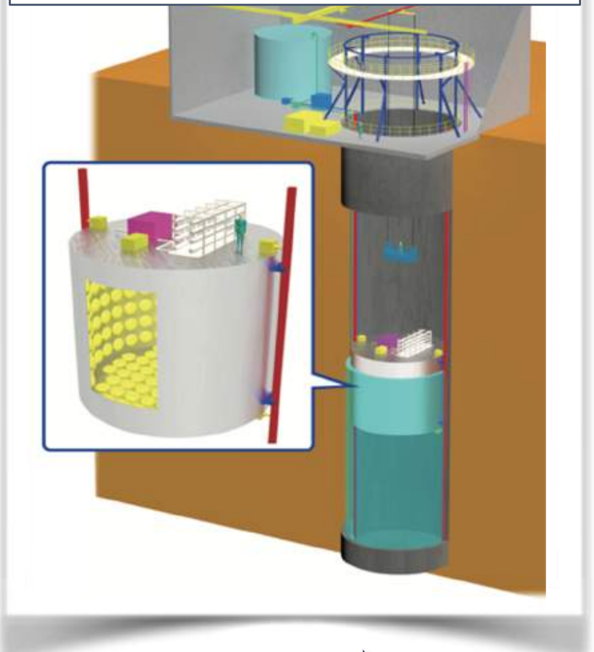
Near detectors



New Intermediate Water Cherenkov Detector

- Measure flux and cross sections of mostly unoscillated beam
    - Reduce systematics at far detector
- Moves vertically in ~50 m tall pit
    - Spans off-axis angles for different ν energy spectra
- 6 m tall x 8 m diameter surrounded with ~ 500 multi-PMT modules
- Gadolinium doped water provides enhanced neutron detection

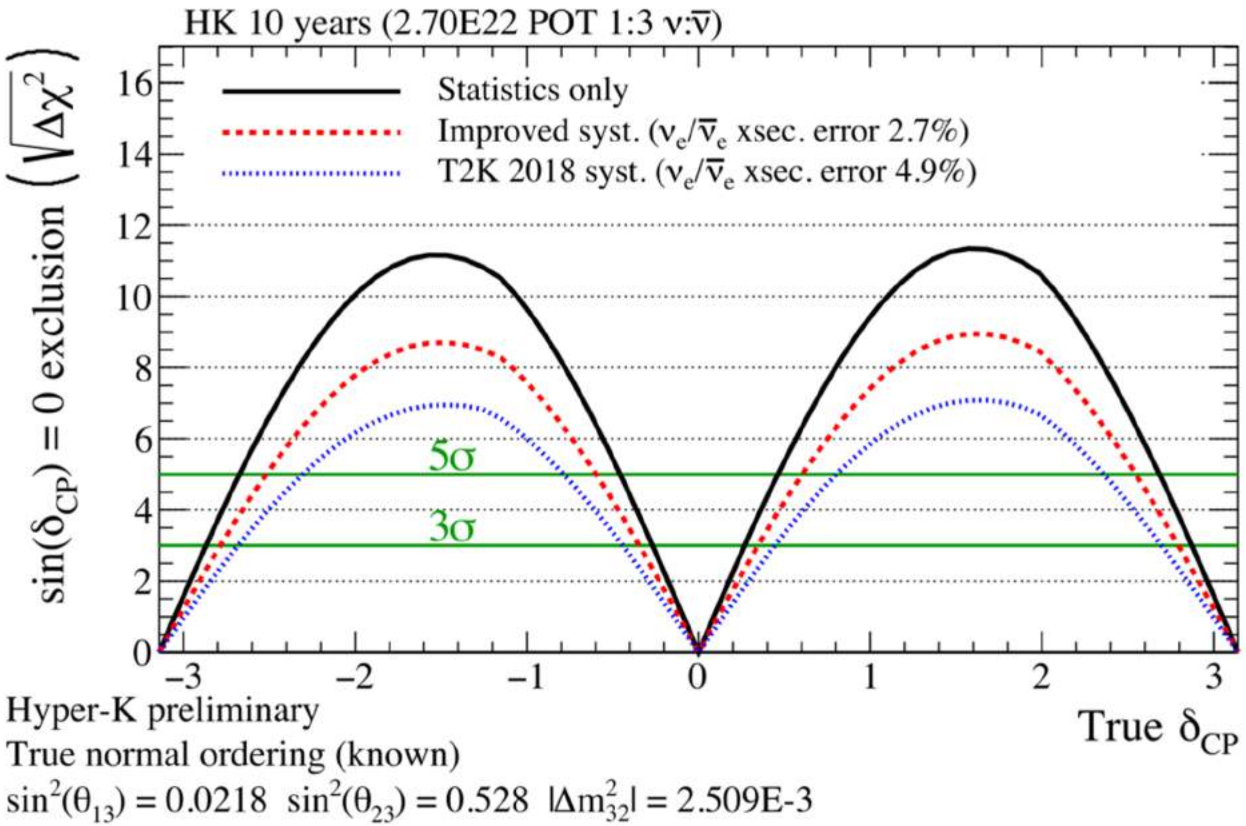
Intermediate Water Cherenkov Detector (IWCD)

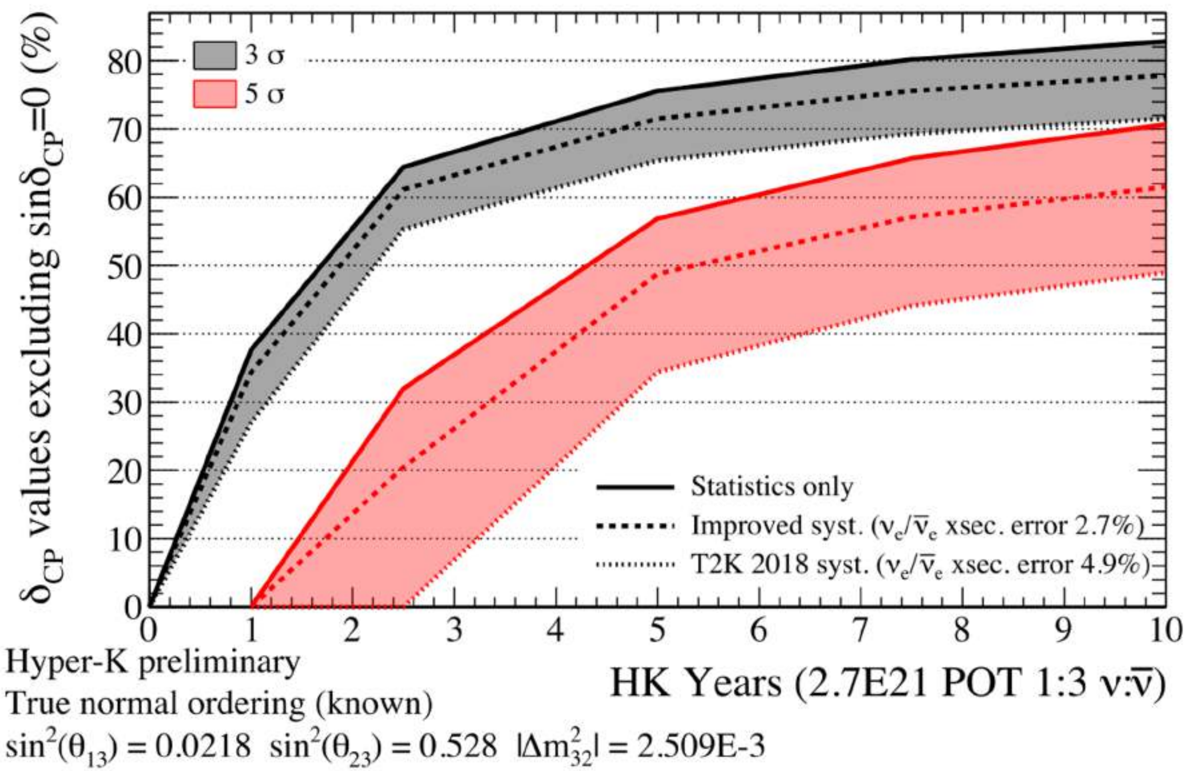


280 m

~ 1 km

Oscillation Measurements - Search for CP Violation





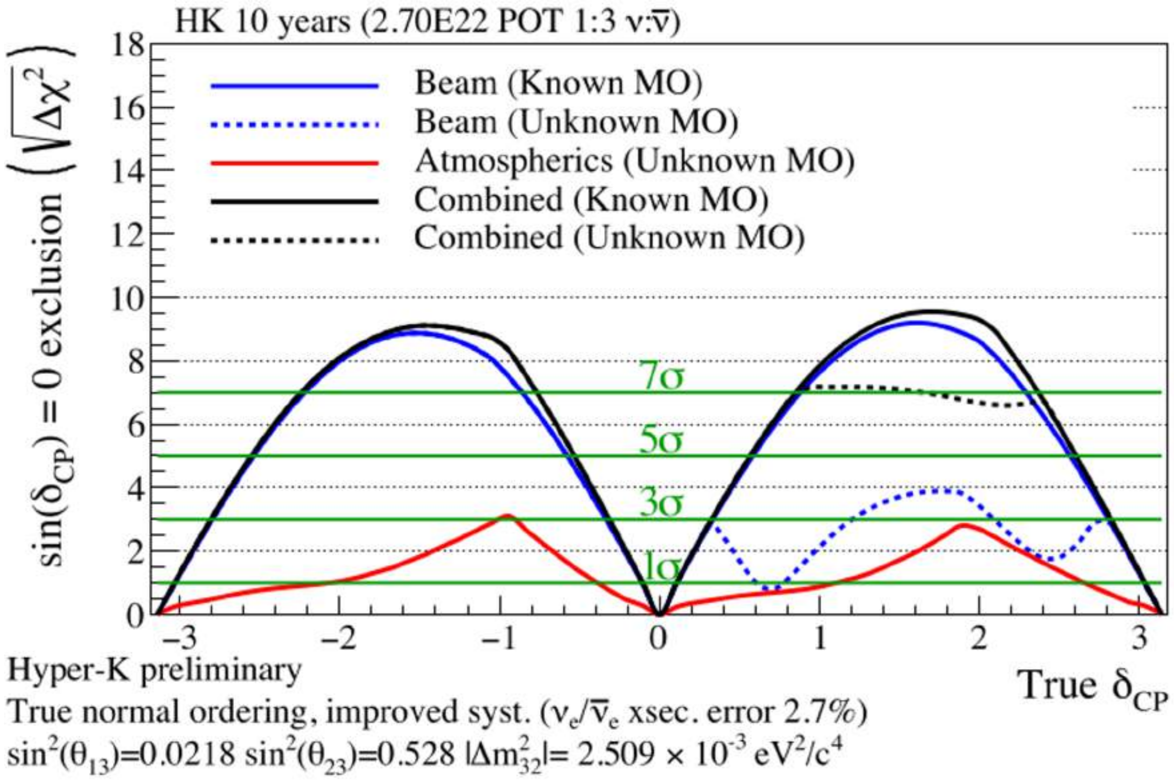
- Reduction of systematic errors has large impact on potential to discover CP violation
- $>5\sigma$ discovery after 10 years for 60% of δ_{CP} values
- $\sim 8\sigma$ around $\delta_{CP} = -\pi/2$ (favoured by T2K measurements)

Oscillation Measurements - Atmospheric ν + Beam

	$\sin^2\theta_{23}$	Atmospheric ν	Atmospheric + beam ν
Mass ordering	0.40	$2.2\,\sigma$	$3.8\,\sigma$
	0.60	$4.9\,\sigma$	$6.2\,\sigma$
θ_{23} octant	0.45	$2.2\,\sigma$	$6.2\,\sigma$
	0.55	$1.6\,\sigma$	$3.6\,\sigma$

10 years with 1.3 MW, normal mass ordering is assumed

- Atmospheric neutrinos sensitive to mass ordering through Earth's matter effect
- Beam measurements enhance sensitivity to mass ordering and atmospheric mixing angle



HK 10 years (2.70E22 POT 1:3 $\nu:\bar{\nu}$)

Hyper-K preliminary

True normal ordering, improved syst. ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)

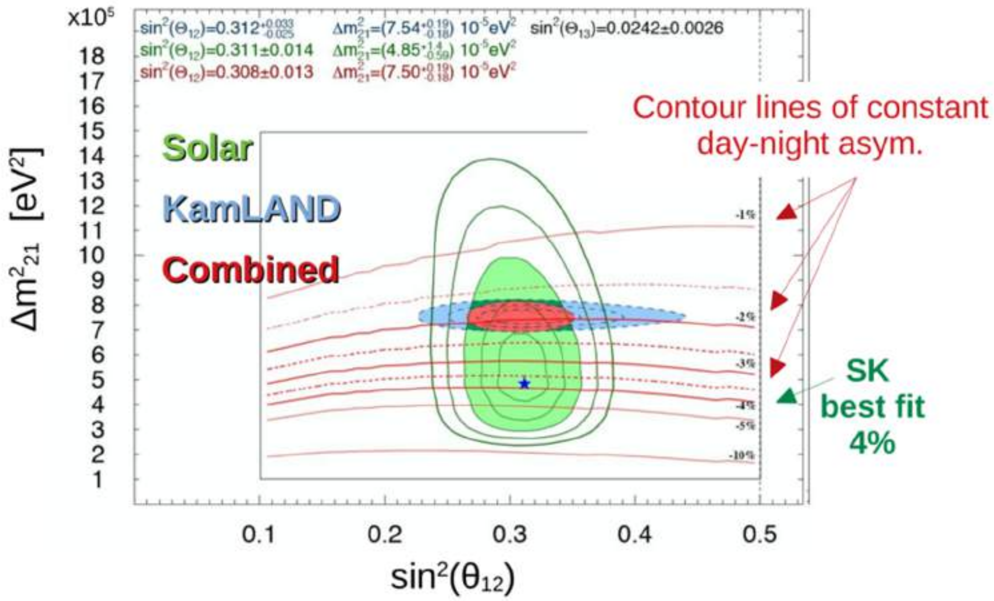
$\sin^2(\theta_{13})=0.0218$ $\sin^2(\theta_{23})=0.528$ $|\Delta m^2_{32}|= 2.509 \times 10^{-3}\ \mathrm{eV}^2/c^4$

- CP violation and matter effect both create difference between ν and $\bar{\nu}$ oscillations
- Breaking degeneracies also enhances CP violation search

Solar & Supernova Neutrinos

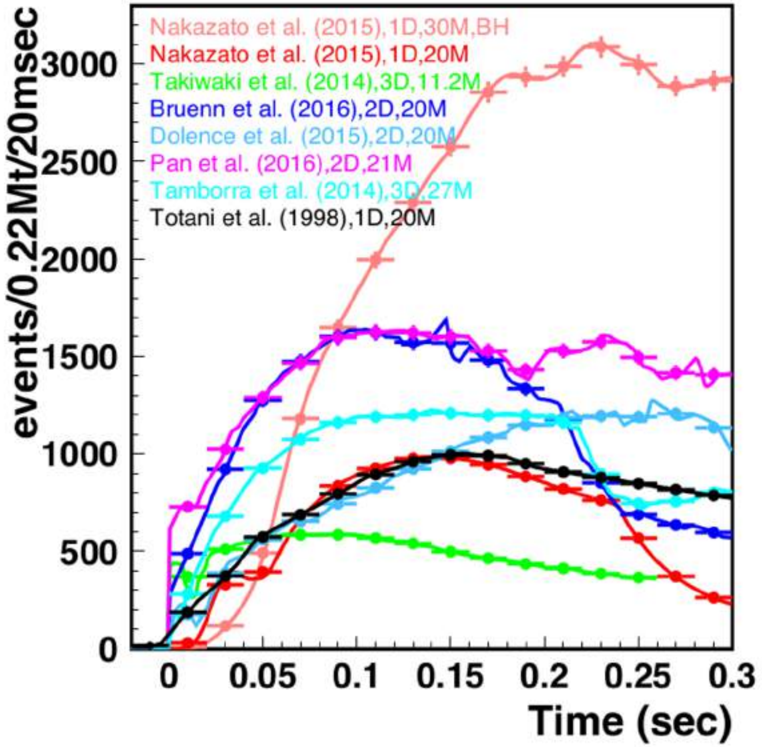
Solar neutrinos

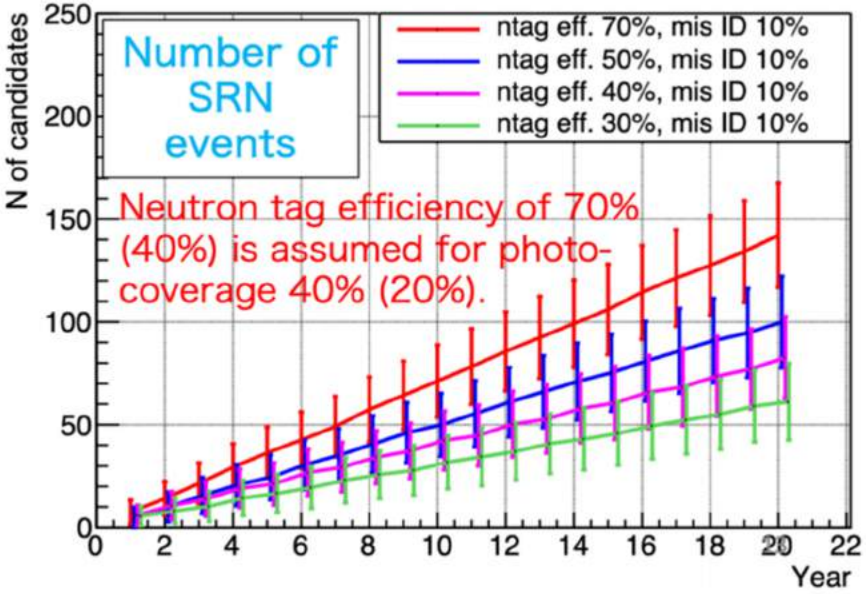
- Measure solar upturn predicted by MSW effect
- Day-night asymmetry (from matter effect through Earth)
    - Study ~2σ tension in Δm^2_{21} between solar & KamLAND



Contour lines of constant day-night asym.

SK best fit 4%




Number of SRN events

Neutron tag efficiency of 70% (40%) is assumed for photo-coverage 40% (20%).

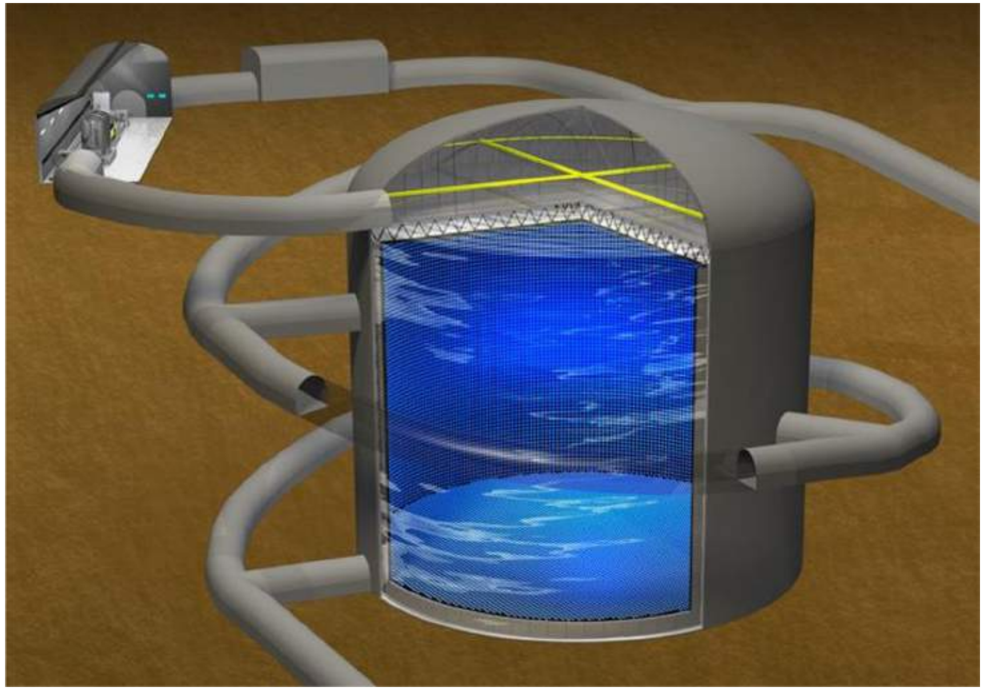
Supernova neutrinos

- O(100,000) ν events from a supernova in galactic centre
    - Ability to distinguish supernova models
- O(10) events from supernova in Andromeda galaxy
- Observation of supernova relic neutrinos within 10 years

Hyper-K Summary

Hyper-Kamiokande construction has begun, with first data taking planned for 2027!

- Building on the success of Super-K & T2K with a next generation neutrino experiment
  - New far detector with 8 x fiducial mass of Super-K
  - Improved photosensors with 2 x detection efficiency & timing resolution reduced by half
  - Upgraded near detectors and new intermediate detector
  - Beam upgrade from 750 kW to 1.3 MW
- Wide range of physics measurements
  - Search for CP violation with precision oscillation measurements
  - Neutrino astrophysics through solar and supernova neutrinos
  - Searches for proton decay and other new physics



Medium baseline

JUNO experiment

JUNO Experiment: Layout

- A multi-purpose liquid scintillator experiment in China:
  - **Reactor $\overline{\nu}_e \sim 60/\text{day}$**
  - **Atmospheric ν's: several/day**
  - **Solar $\nu_e \sim$ 10-1000/day**
  - Supernova ν's ~ 10^4 in 10 s for 10 kpc
  - DSNB 2-4 IBD/year
  - Geo-ν's 1-2/day

This talk

See also Giulio Settanta's talk: "JUNO Non-oscillation Physics"

- Optimized baseline for neutrino mass ordering determination with reactor $\bar{\nu}_e$

Jiangmen Underground Neutrino Observatory

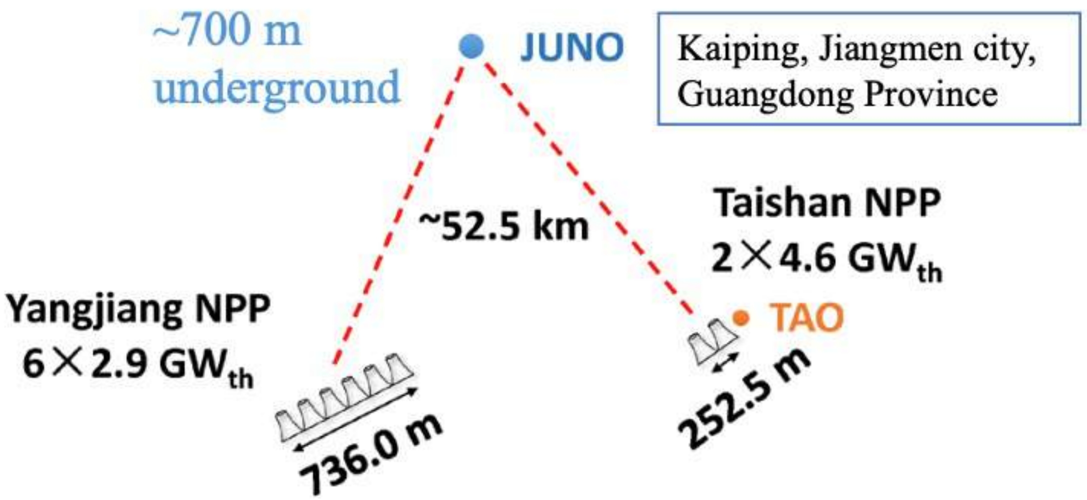
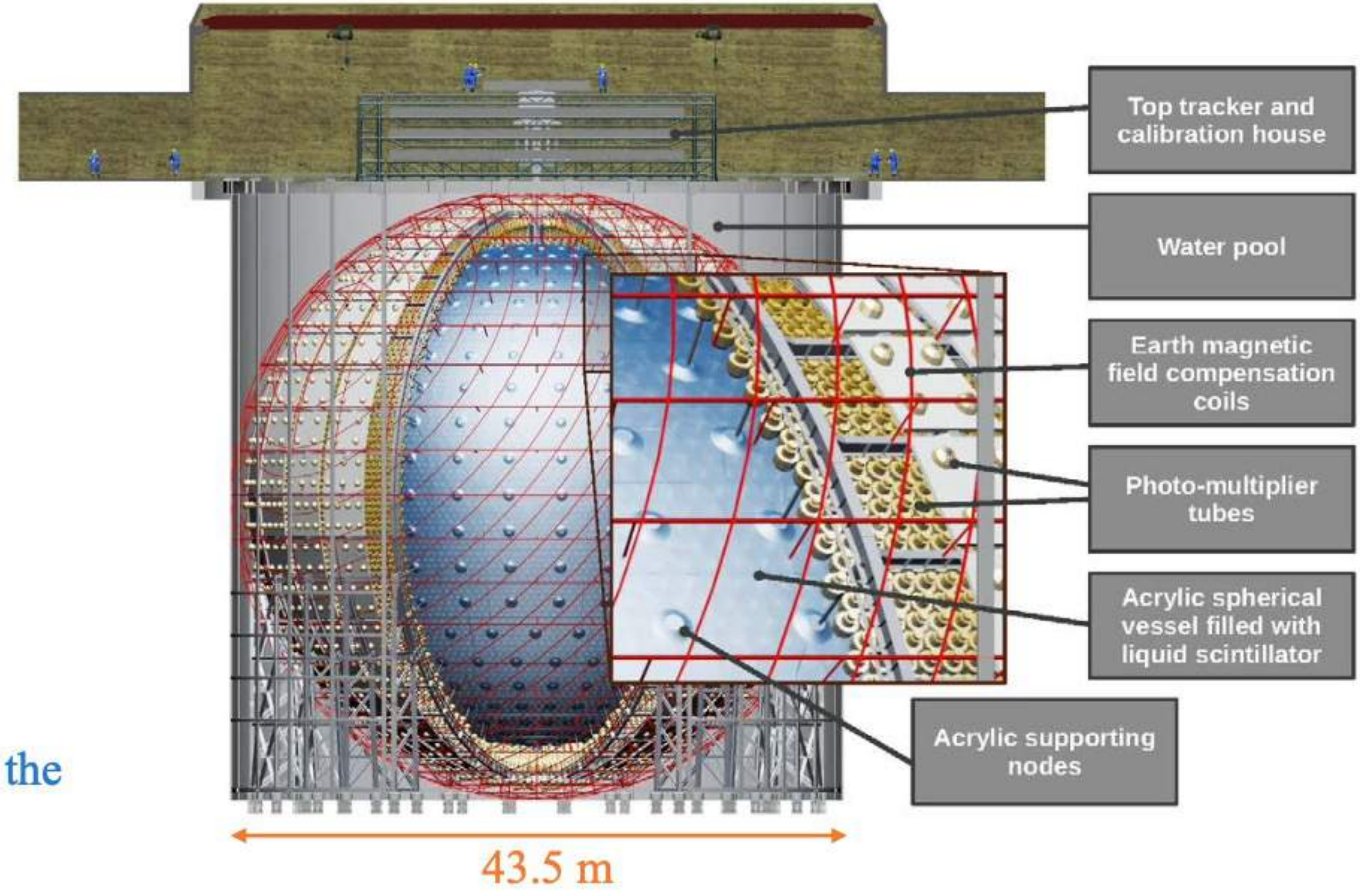


Figure: Setup of JUNO experiment, with the main 20-kton JUNO detector and satellite 2.8-ton TAO detector.

JUNO Experiment: Detector

- A multi-purpose liquid scintillator experiment.
- **Energy resolution $< 3\%/\sqrt{E(\mathrm{MeV})}$:**
  - ~78% PMT coverage, ~1350 PE/MeV:
    - 5000 Hamamatsu 20″ dynode-PMTs
    - 12612 NNVT 20″ MCP-PMTs
    - 25600 HZC 3″ PMT
- **Large target volume:**
  - 20-kton LAB-based liquid scintillator
- **Energy scale uncertainty <1%**
  - JHEP03(2021)004: "Calibration strategy of the JUNO experiment"
- **Background control**
  - arXiv:2107.03669: "Radioactivity control strategy for the JUNO detector"



See also Zhimin Wang's talk: "JUNO Detector Design & Status"

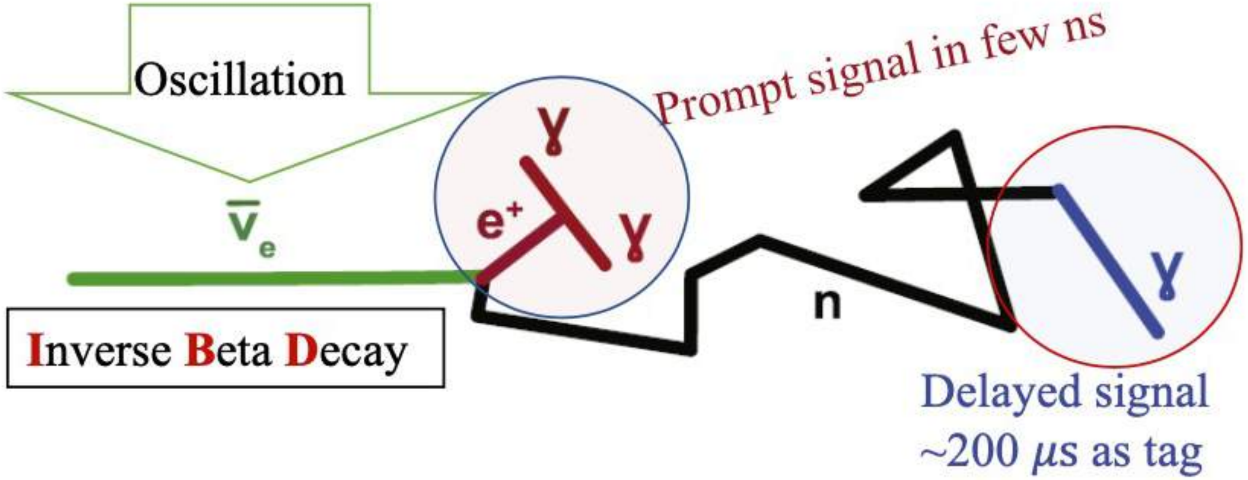
Reactor $\bar{\nu}_e$: Source and Oscillation

- **Source**: reactor antineutrino from fission of four isotopes:
  - ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu
  - Major: 6 YJ cores, ~~4~~ → 2 TS cores

J. Phys. G43:030401 (2016) → arXiv:2104.02565

Table: Thermal power and baseline to the JUNO detector for the Yangjiang (YJ), Taishan (TS), Daya Bay (DYB), and Huizhou (HZ) reactor cores.

Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265



Oscillation

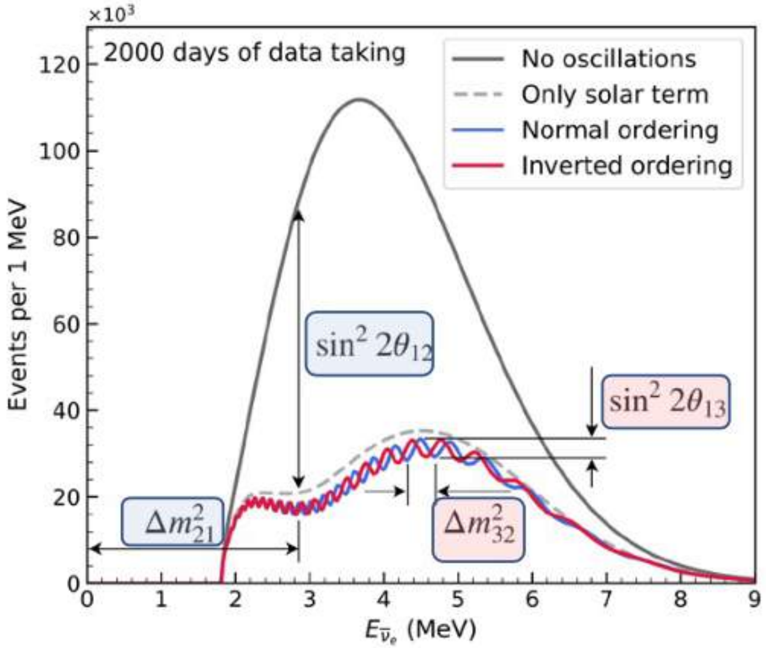
Prompt signal in few ns

Inverse **B**eta **D**ecay

Delayed signal ~200 μs as tag

- **Oscillation**: $\bar{\nu}_e$ survival probability in vacuum[1]:

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \cos^4\theta_{13}\boxed{\sin^2 2\theta_{12}}\sin^2\frac{\boxed{\Delta m^2_{12}}L}{4E} - \boxed{\sin^2 2\theta_{13}}\left(\cos^2\theta_{12}\sin^2\frac{\boxed{\Delta m^2_{31}}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\boxed{\Delta m^2_{32}}L}{4E}\right).$$



The energy resolution is one of the key factors for determining neutrino mass ordering (NMO).

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[1]. Oscillation in matter with effective oscillation parameters (j.physletb.2020.135354).

Reactor $\bar{\nu}_e$: Precision Measurement of Oscillation Parameters

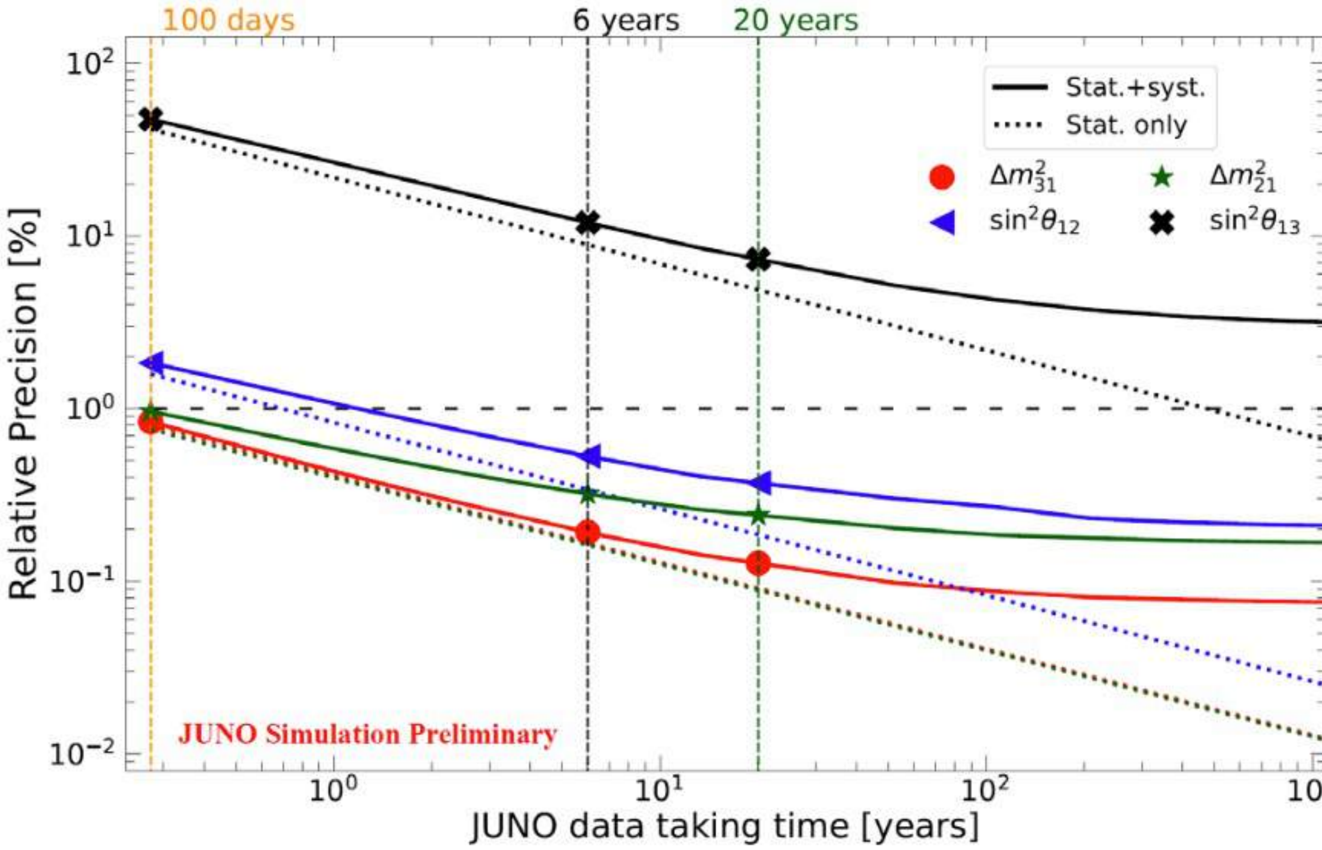
- Precision measurement of oscillation parameters:

Relative Precision (%)	$\sin^2\theta_{12}$	Δm^2_{21}	$\sin^2\theta_{13}$	$\Delta m^2_{31}/\Delta m^2_{32}$
Current global fit (Nufit 5.0) [1]	**4.0**	**2.8**	**2.8**	**1.1**
PDG2020 [2]	**4.2**	**2.4**	**3.2**	**1.4**
JUNO 6 years	**0.5**	**0.3**	**12**	**0.2**

JUNO Simulation Preliminary

- JUNO will dominant the precision of $\Delta m^2_{31}/\Delta m^2_{32}$, Δm^2_{21}, and $\sin^2\theta_{12}$ in 1 year
- To sub-percent level in 1-2 years

[1]. JHEP09(2020)178 [2]. PTEP 2020 (2020) 8, 083C01



A publication on the precision measurement of the oscillation parameters is coming soon.

JUNO Physics Summary

- **Multipurpose experiment JUNO**:
- Neutrino mass ordering determination:
  - $> 3\sigma$ in 6 years with only reactor $\bar{\nu}_e$
  - $> 1\sigma$ with JUNO atmospheric neutrinos
- Precision measurement of oscillation parameters
  - Sub-percent for $\Delta m^2_{31}/\Delta m^2_{32}, \Delta m^2_{21}$, and $\sin^2\theta_{12}$ with reactor $\bar{\nu}_e$
  - θ_{23} octant with atmospheric neutrinos
  - Independent Δm^2_{21} and $\sin^2\theta_{12}$ measurement with solar ^{8}B neutrino
- TAO detector
  - High precision reactor neutrino spectrum
  - Sterile neutrino exploration
- JUNO will start operation in 2023

Short baseline

FERMILAB Short baseline program

Hints on anomalies from the past decades

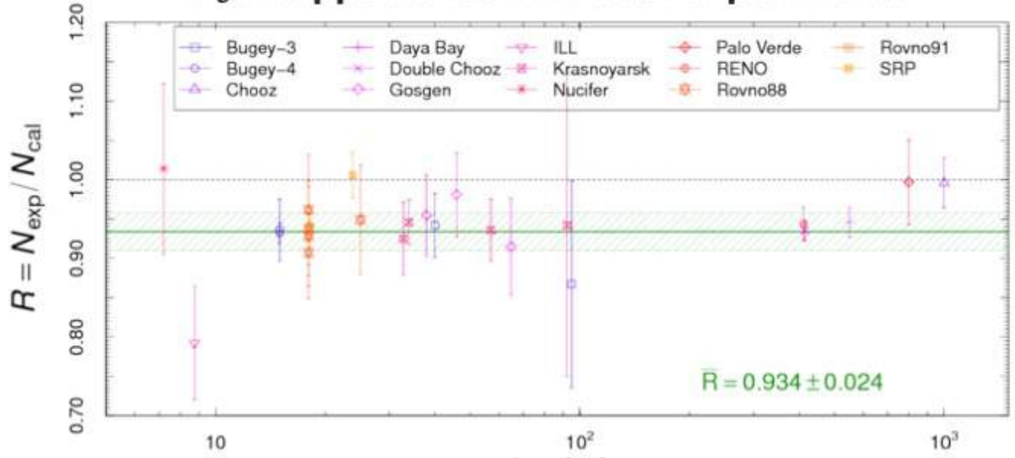
- Several neutrino experiments showing unexpected results at an L/E ~ 1 km/GeV
  - $\overline{\nu}_e$ disappearance in reactor experiments
  - ν_e disappearance in source calibrations of solar ν experiments
  - Appearance of ν_e and $\overline{\nu}_e$ in neutrino beam experiments
  - But no hints in ν_μ disappearance experiments so far

credit: A. Fava

Experiment	Type	Channel	Significance
LSND	DAR accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8 σ
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8 σ
GALLEX/SAGE	Source – e capture	ν_e disappearance	2.8 σ
Reactors	β decay	$\bar{\nu}_e$ disappearance	3.0 σ

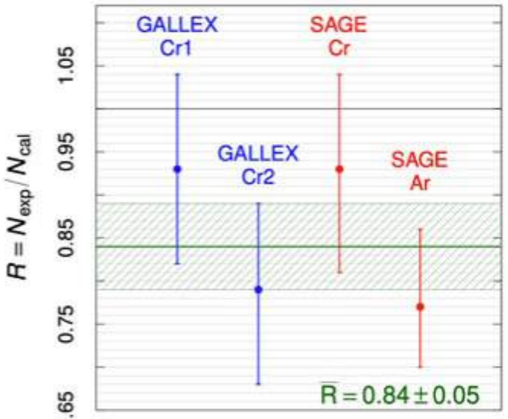
- Observations can possibly be explained by sterile neutrinos (1 or more) with a Δm^2 of ~ 1 eV².
- However, no model describes all observations and other interpretations are definitely possibly and exciting!

$\overline{\nu}_e$ disappearance in reactor experiments



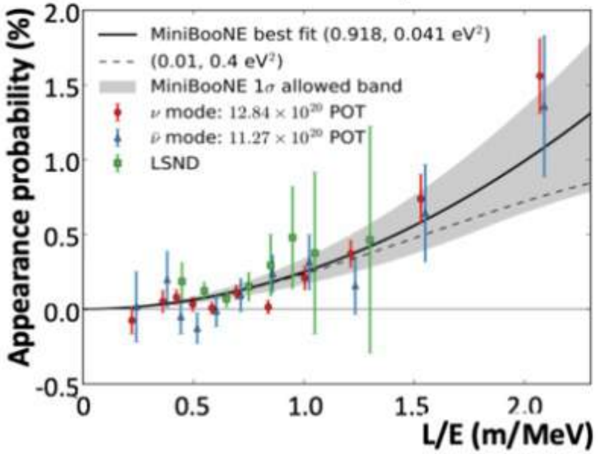
K. N. Abazajian et al., 2012

ν_e disappearance in solar ν experiments



arXiv:1906.01739

ν_e and $\overline{\nu}_e$ appearance in neutrino beam experiments

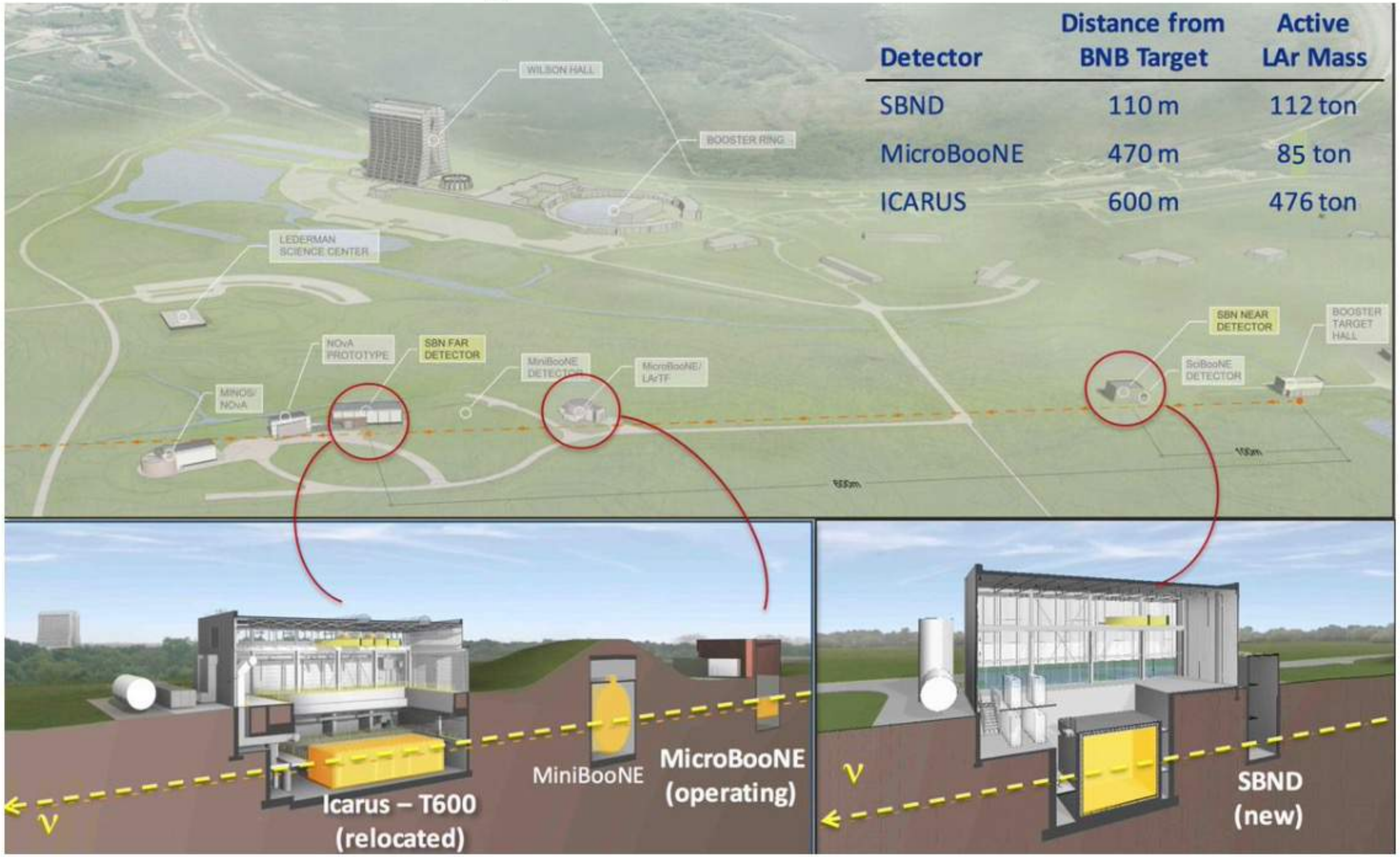


Phys. Rev. Lett., vol. 121, no. 22, p. 221801, 2018

Fermilab Short Baseline Neutrino Program

- **Goal:**
  Resolving the electromagnetic event excess observed by MiniBooNE and LSND
- Excellent shower reconstruction and e / γ separation capabilities in LArTPCs
- Study of ν_e appearance, ν_μ disappearance in the same experiment!
- **MicroBooNE** is up and running since October 2015
- Far detector (**ICARUS T600**) is now commissioning
- Near detector (**SBND**) under construction.

Three liquid argon TPC detectors in the same beamline



Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	85 ton
ICARUS	600 m	476 ton

arXiv: 1503.01520

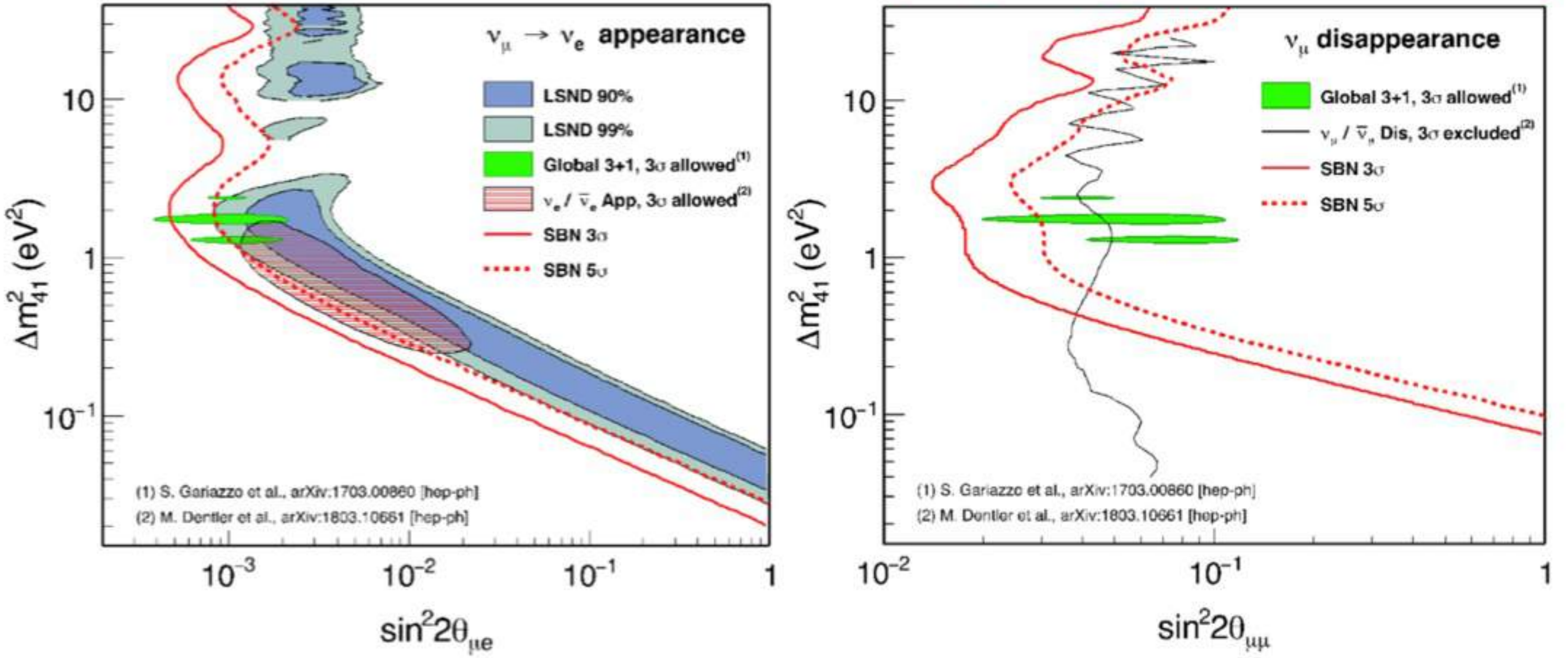
SBN Sensitivity

SBN joint analysis with
SBND (ND) and **ICARUS (FD)**

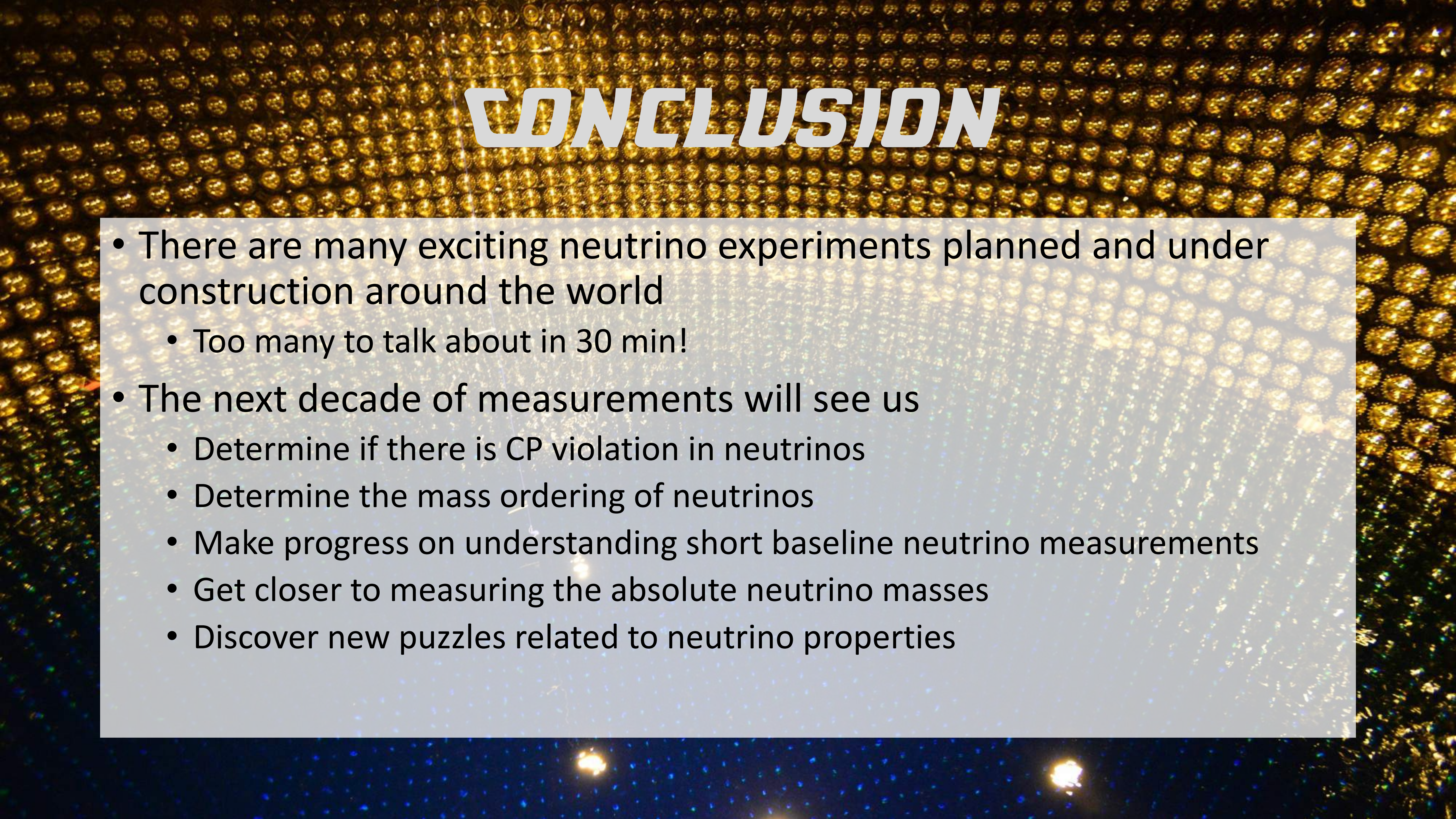
- Unique capability to study ν_e appearance and ν_μ disappearance in the same beam and experiment
- The sterile neutrino 3+1 parameter space preferred by LSND/MiniBooNE appearance anomaly is covered with 3-5σ by SBN (6.6 x 10^{20} POT, equivalent to ~ 3 years of data taking)
- Improved sensitivity to the disappearance channel over current limits
- ICARUS and SBND collaborations are working jointly on developing reconstruction & analysis tools

$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity

$\nu_\mu \rightarrow \nu_x$ Disappearance sensitivity



Source: Ann. Rev. Nucl. Part. Sci. 2019.69:363-387



CONCLUSION

- There are many exciting neutrino experiments planned and under construction around the world
  - Too many to talk about in 30 min!
- The next decade of measurements will see us
  - Determine if there is CP violation in neutrinos
  - Determine the mass ordering of neutrinos
  - Make progress on understanding short baseline neutrino measurements
  - Get closer to measuring the absolute neutrino masses
  - Discover new puzzles related to neutrino properties

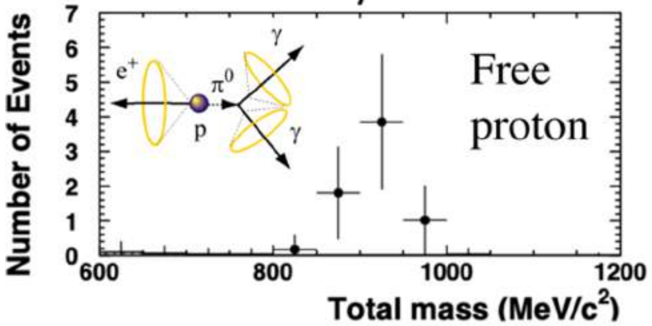
Thanks for your attention!

Proton Decay

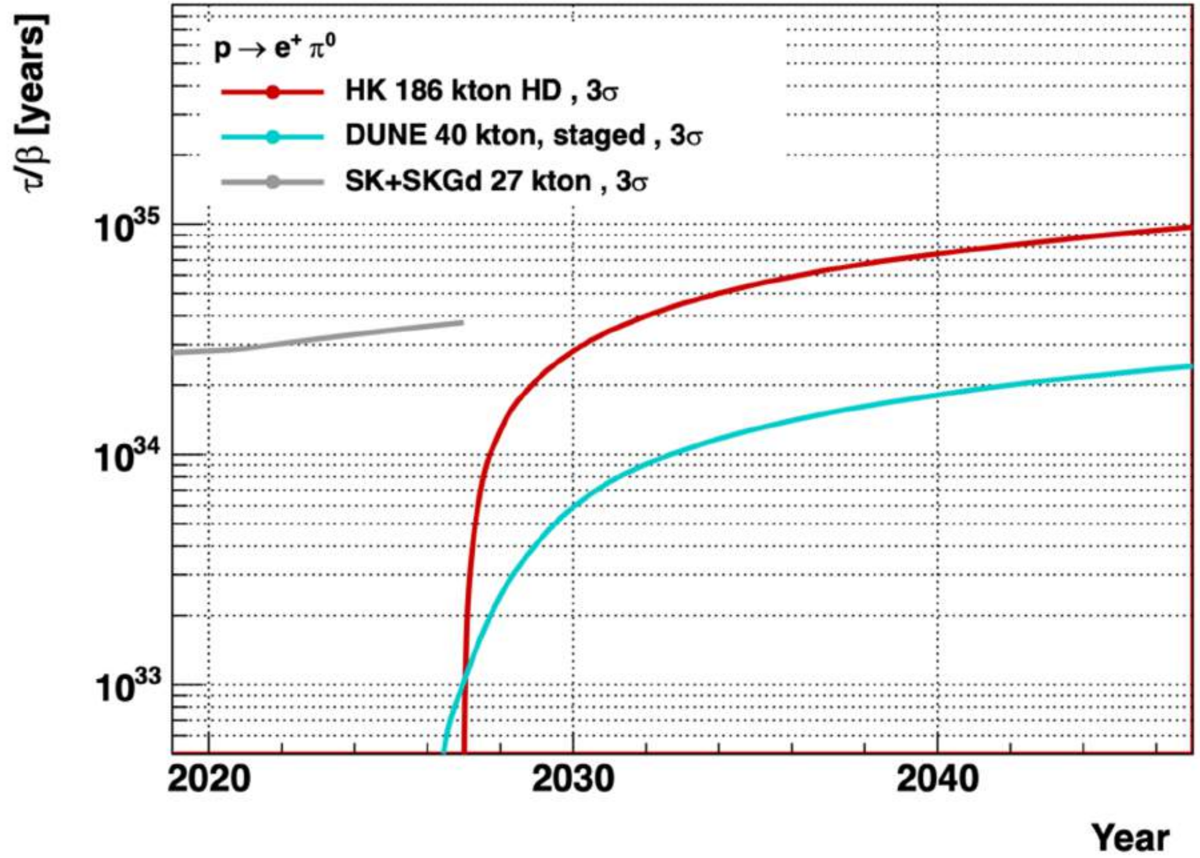
- Huge detector volume for searching for proton decay
- Push limits an order of magnitude beyond current limits

10years of HK

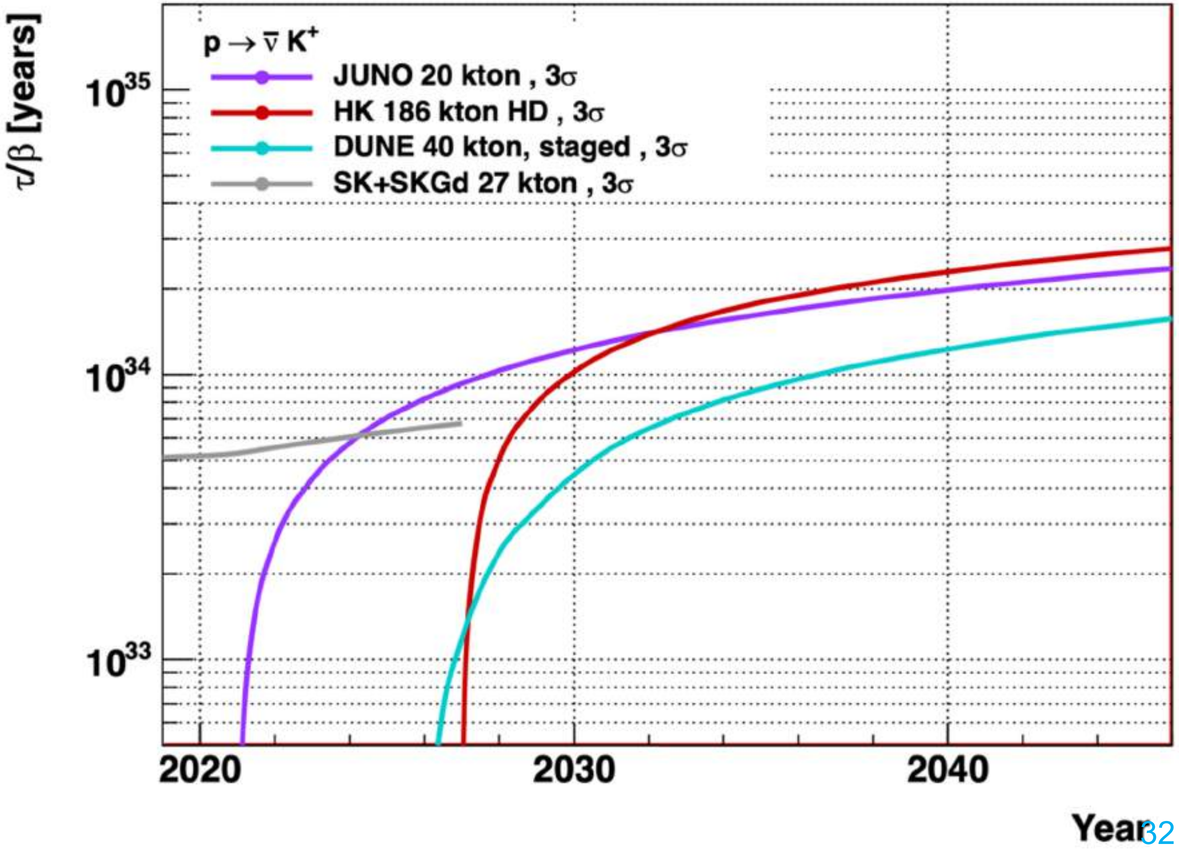
τ = 1.7 x 10^{34} years case



$p \longrightarrow e^+ + \pi^0$ 10^{35} years



$p \longrightarrow \overline{\nu} + K^+$ 3×10^{34} years

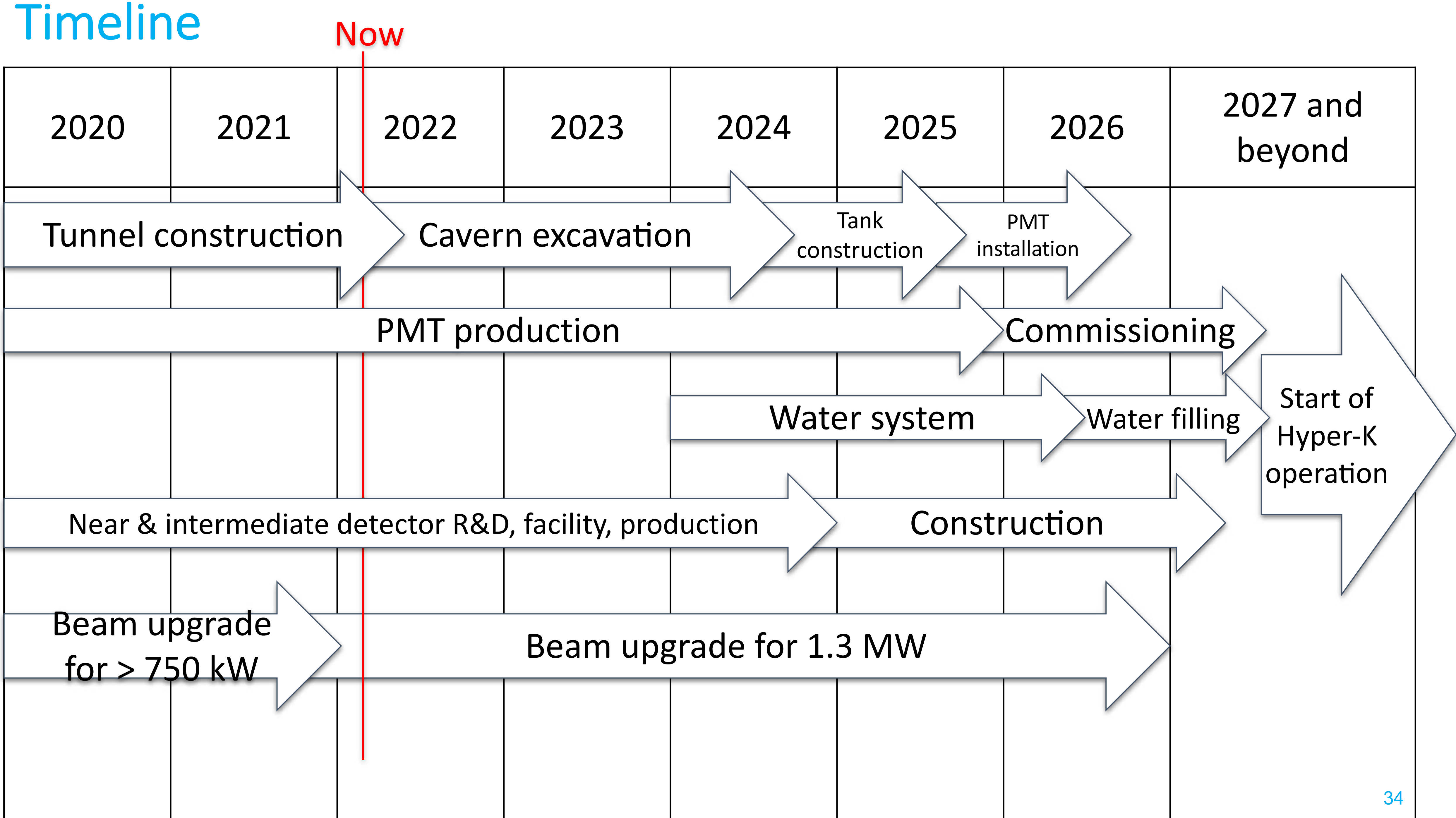


Detector Construction

Groundbreaking Ceremony May 2021

©Institute for Cosmic Ray Research, The University of Tokyo

Timeline



Now

2020

2021

2022

2023

2024

2025

2026

2027 and beyond

Tunnel construction

Cavern excavation

Tank construction

PMT installation

PMT production

Commissioning

Water system

Water filling

Start of Hyper-K operation

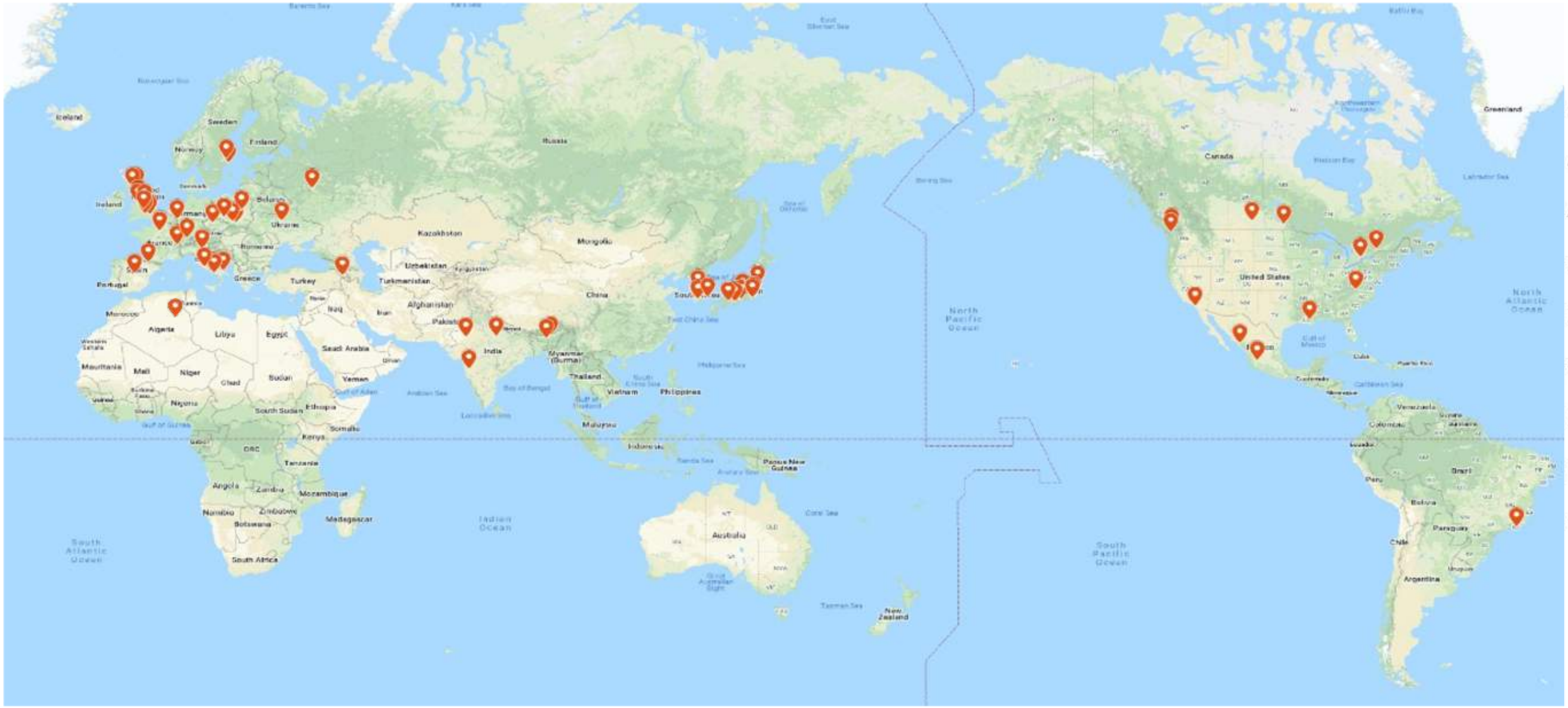
Near & intermediate detector R&D, facility, production

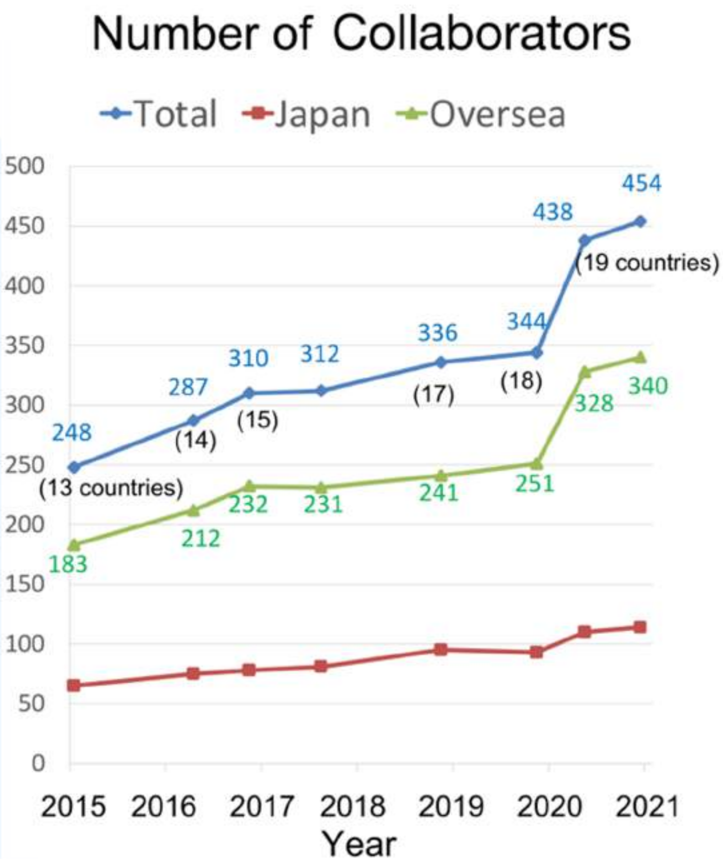
Construction

Beam upgrade for > 750 kW

Beam upgrade for 1.3 MW

Hyper-Kamiokande Collaboration



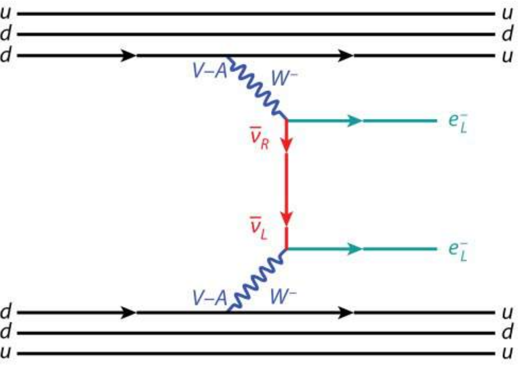


Over 450 collaborators from 99 institutions in 20 countries and growing!

Neutrino mass measurement

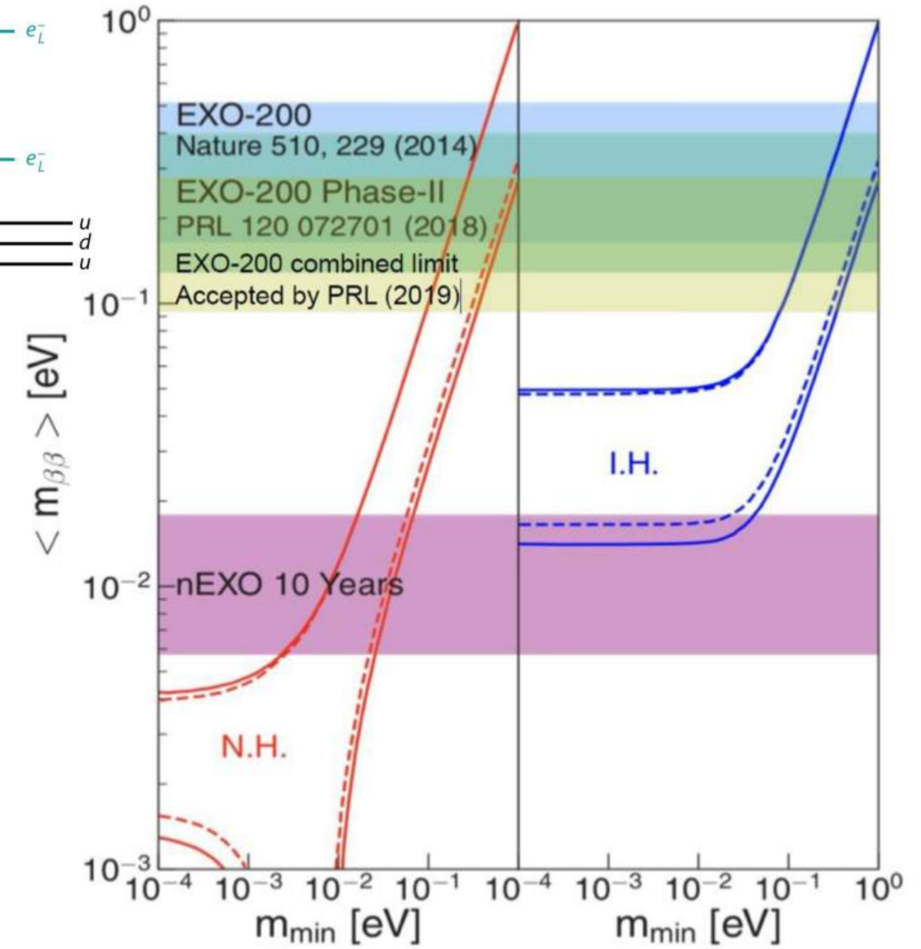
Katrin->Project8, Zero neutrino double beta decay experiments

$0\nu\beta\beta$



Present best Limits on $T_{1/2}$

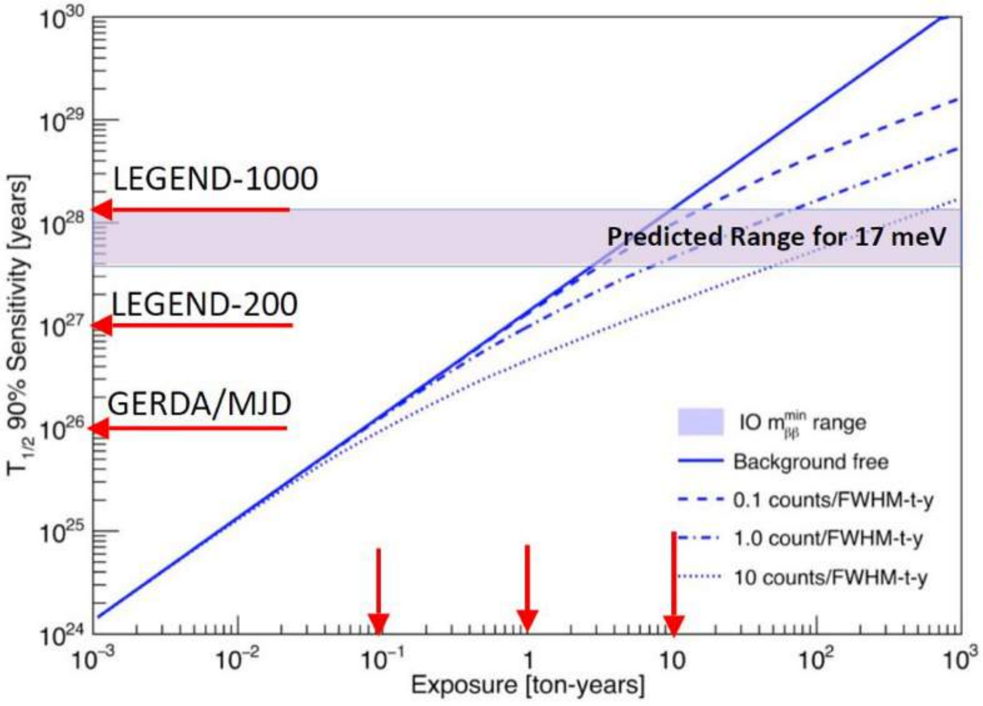
- ^{136}Xe *(KamLAND-Zen)*: > 10^{26} yrs
- ^{76}Ge *(GERDA)* : > 1.8 x 10^{26} yrs
- ^{130}Te *(CUORE)* : > 3.2 x 10^{25} yrs



Future goal

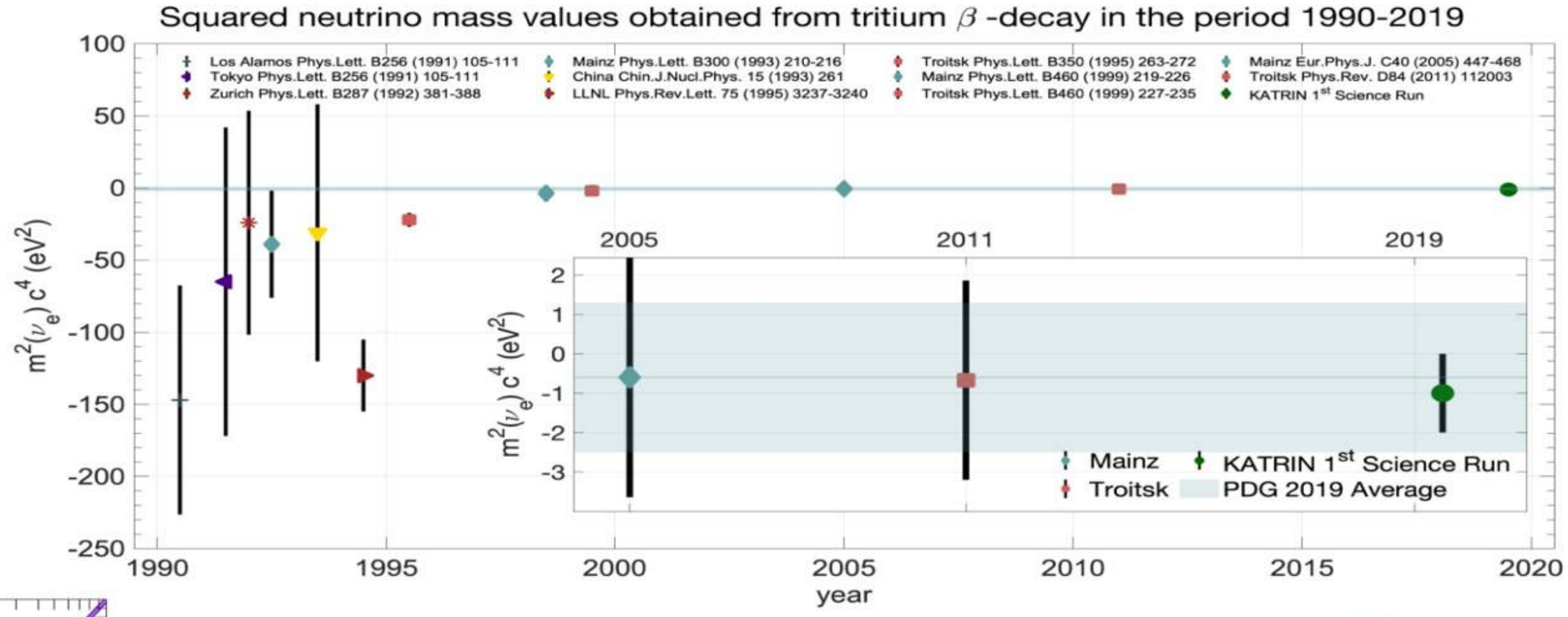
- ~100x improvement in $T_{1/2}$
- Covers Inverted ν-mass ordering region

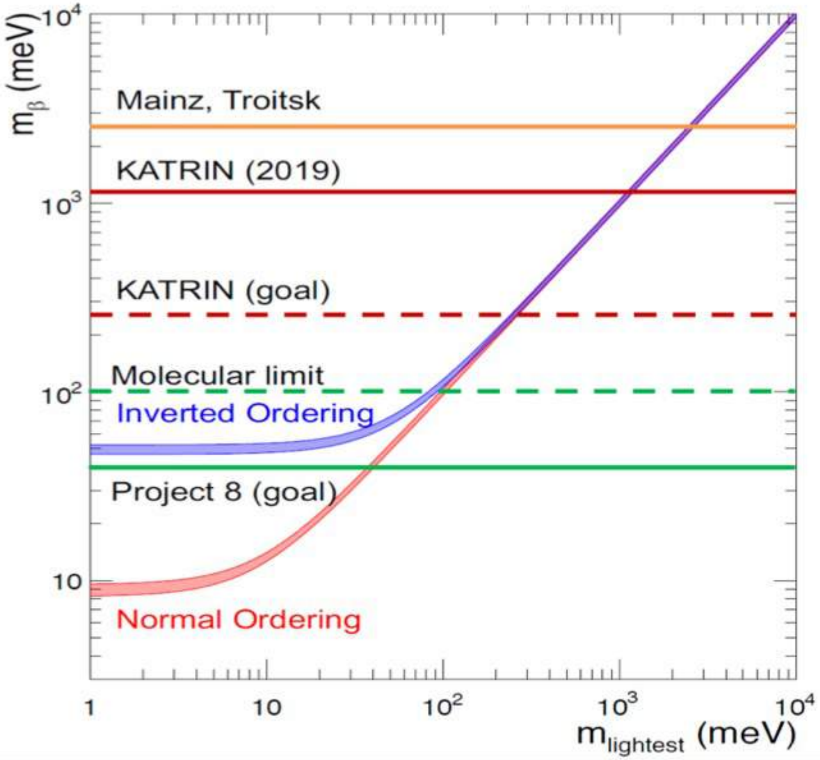
- ^{136}Xe *(nEXO)* : $T_{1/2} > 10^{28}$ yrs
- ^{76}Ge *(LEGEND-1000)* : $T_{1/2} > 10^{28}$ yrs
- ^{130}Te *(CUPID)* : $T_{1/2} > 10^{27}$ yrs

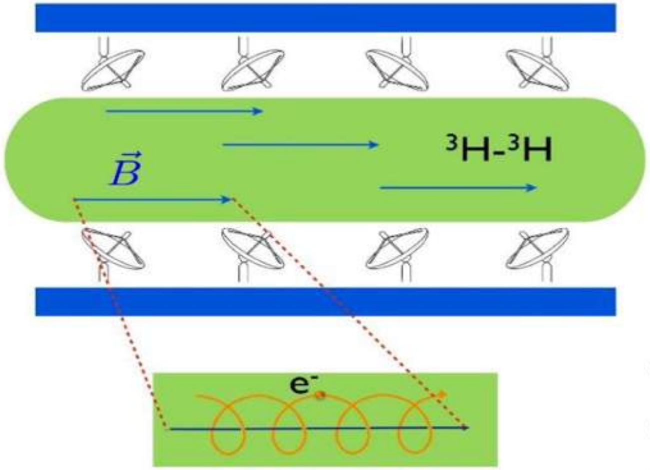


30 yrs history of β-decay measurement

KATRIN will continue delivering world-leading sensitivity


Squared neutrino mass values obtained from tritium β -decay in the period 1990-2019





Cyclotron Radiation Emission Spectroscopy (CRES)

PROJECT 8

Next generation β-decay

Targeted sensitivity: 40 meV

- Multi m^3·yr effective exposure
- High flux atomic tritium source
- ~0.1 eV resolution
- 10^{-7} field uniformity