Hyper-Kamiokande

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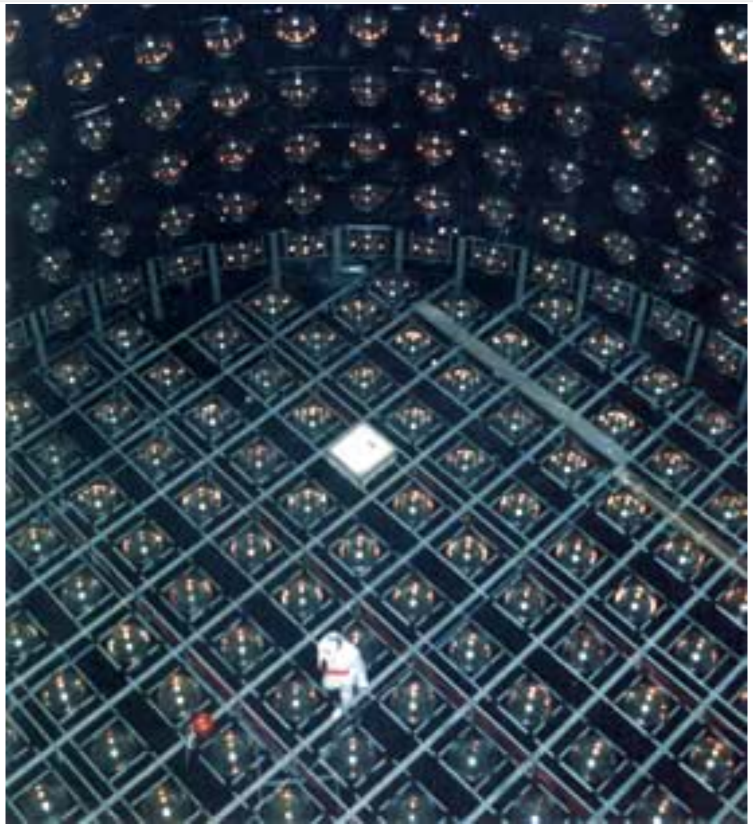
for Hyper-Kamiokande proto-collaboration

ICRR Young Researchers' Workshop, November 13, 2020

3rd generation underground water Č in Kamioka

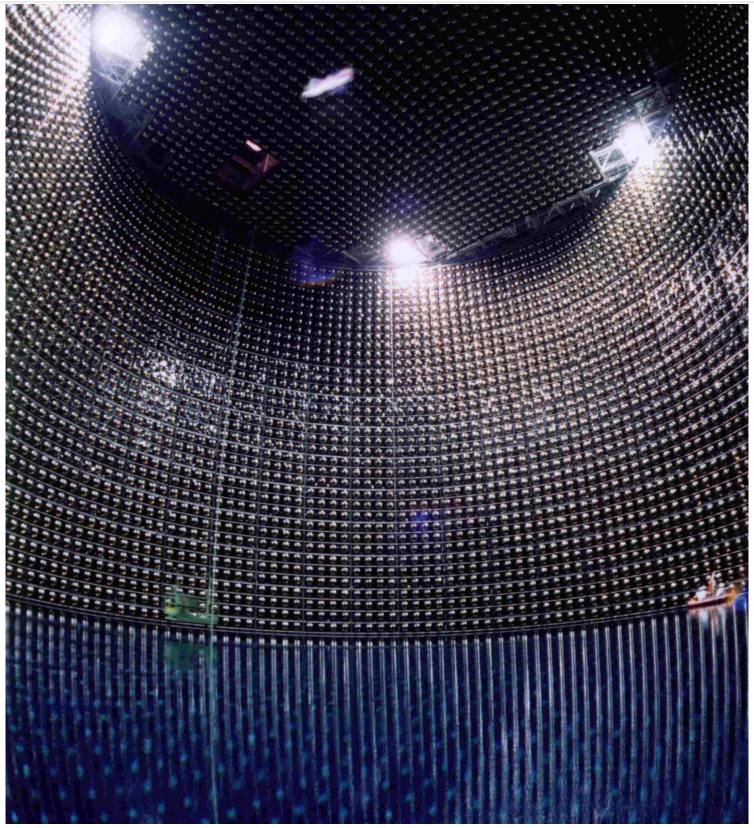


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino "anomaly"
- Supernova 1987A

Birth of neutrino astrophysics

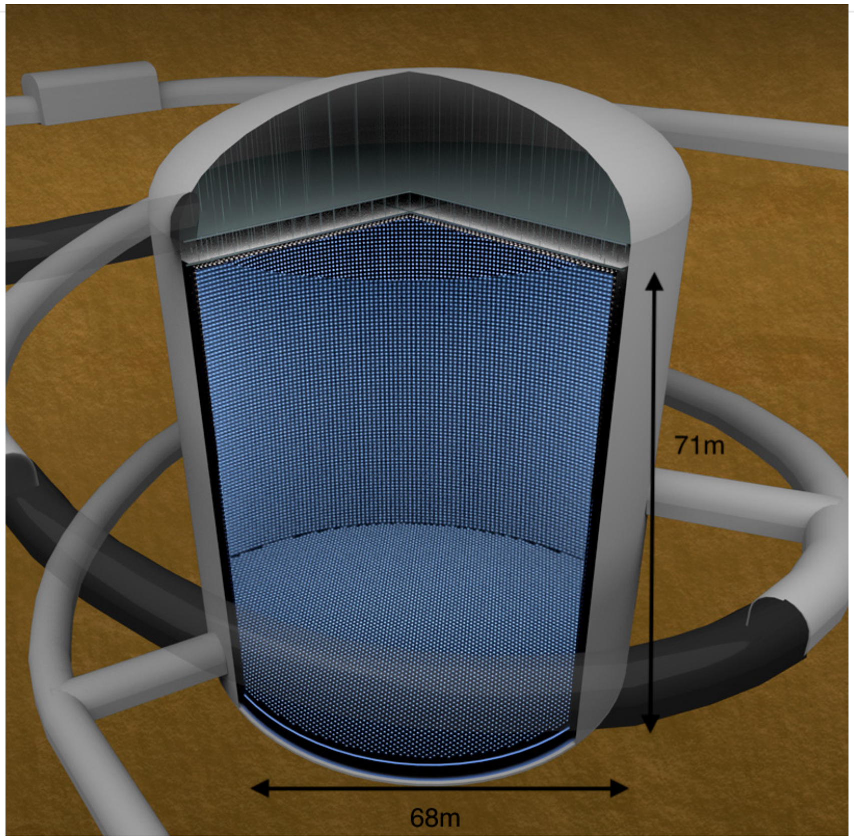


Super-Kamiokande

(1996 - ongoing)

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

Discovery of neutrino oscillations



Hyper-Kamiokande

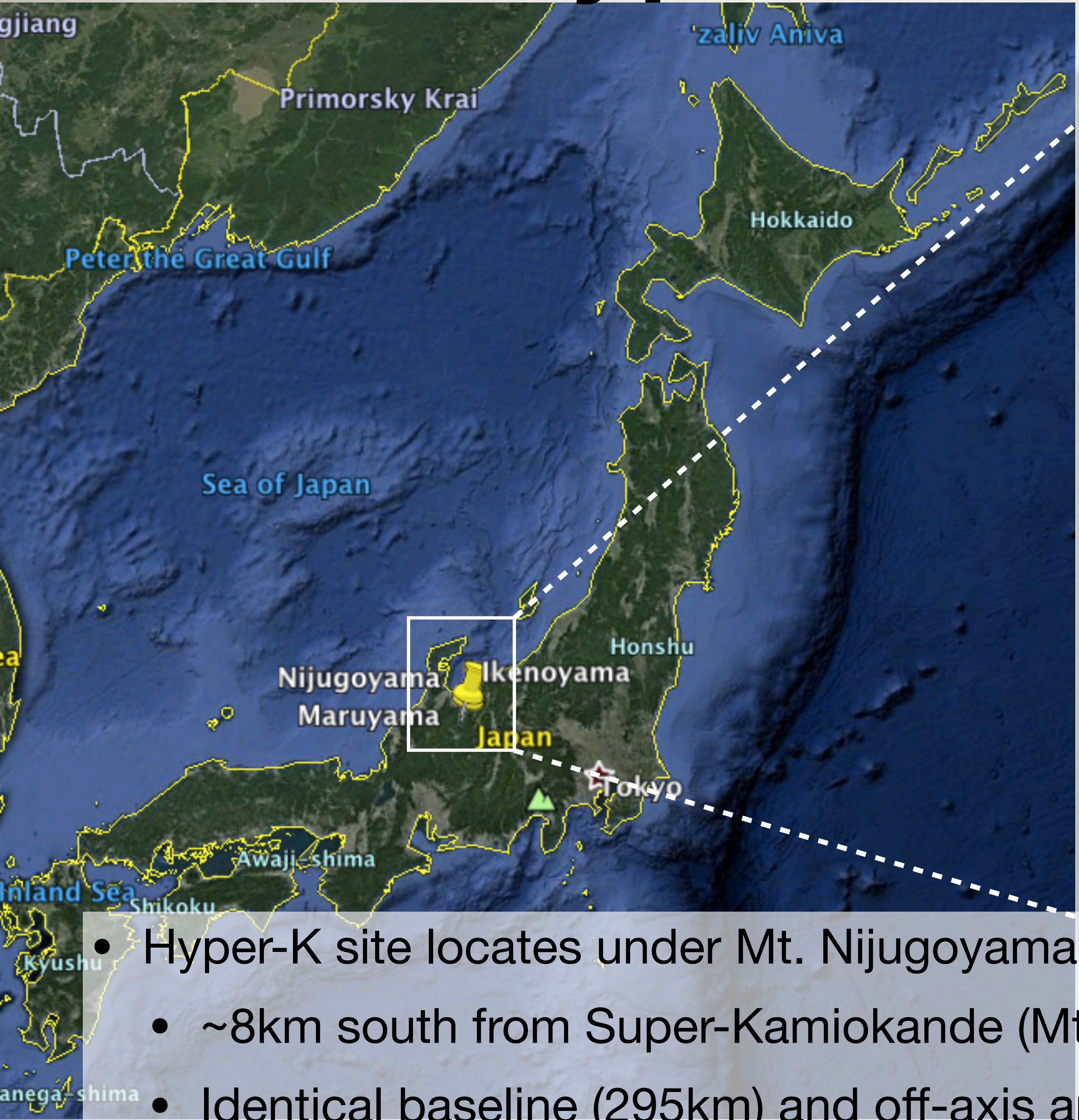
(start operation in 2027)

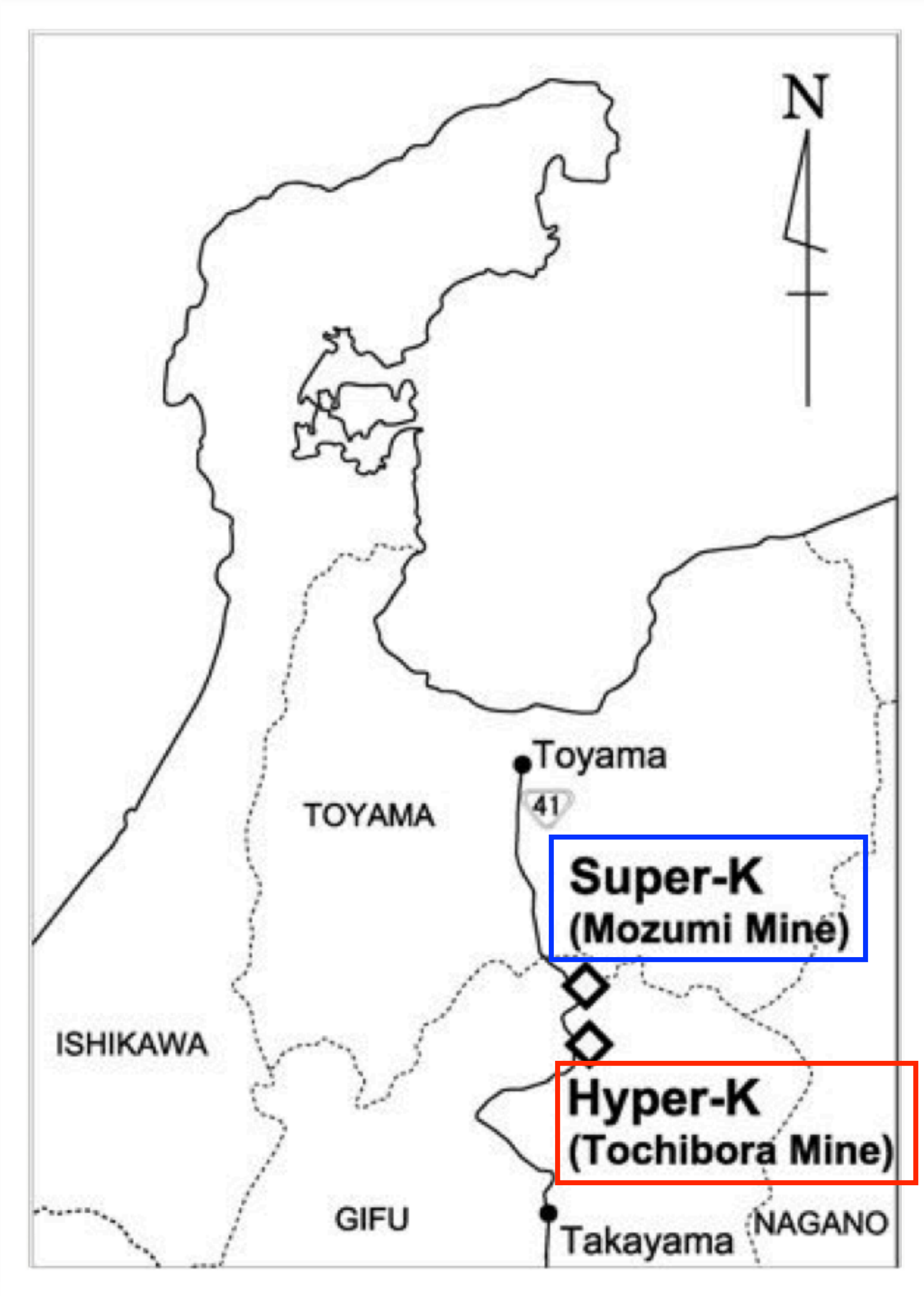
- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Explore new physics

- Hyper-K will be the world largest underground water Cherenkov detector

Hyper-K site

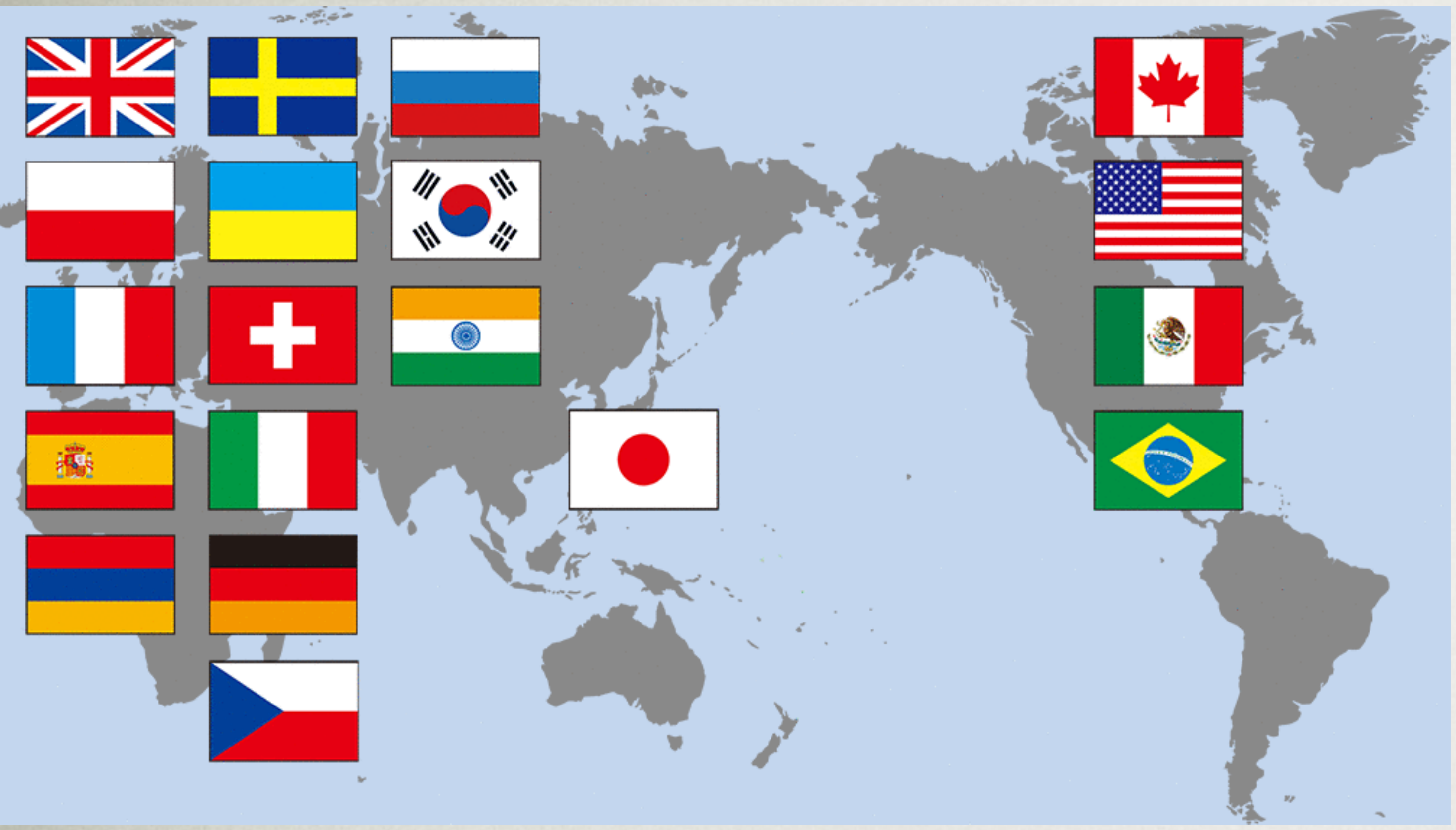




- Hyper-K site locates under Mt. Nijugoyama
  - ~8km south from Super-Kamiokande (Mt. Ikenoyama)
  - Identical baseline (295km) and off-axis angle (2.5deg) to T2K

Ikenoyama
(Super-Kamiokande location)

Hyper-K proto-collaboration

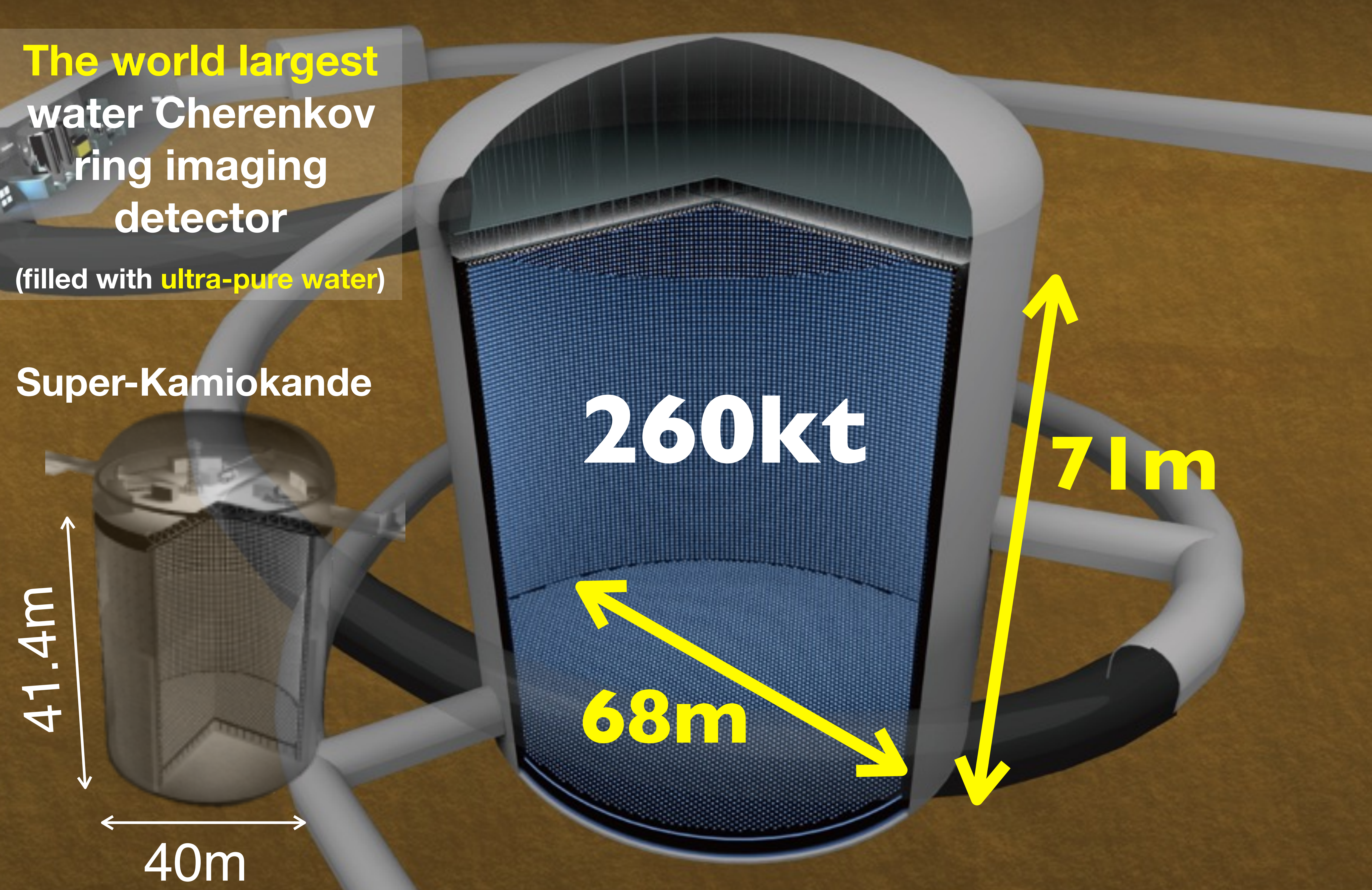


19 countries, 90 institutes,
~430 members
(as of July 2020)

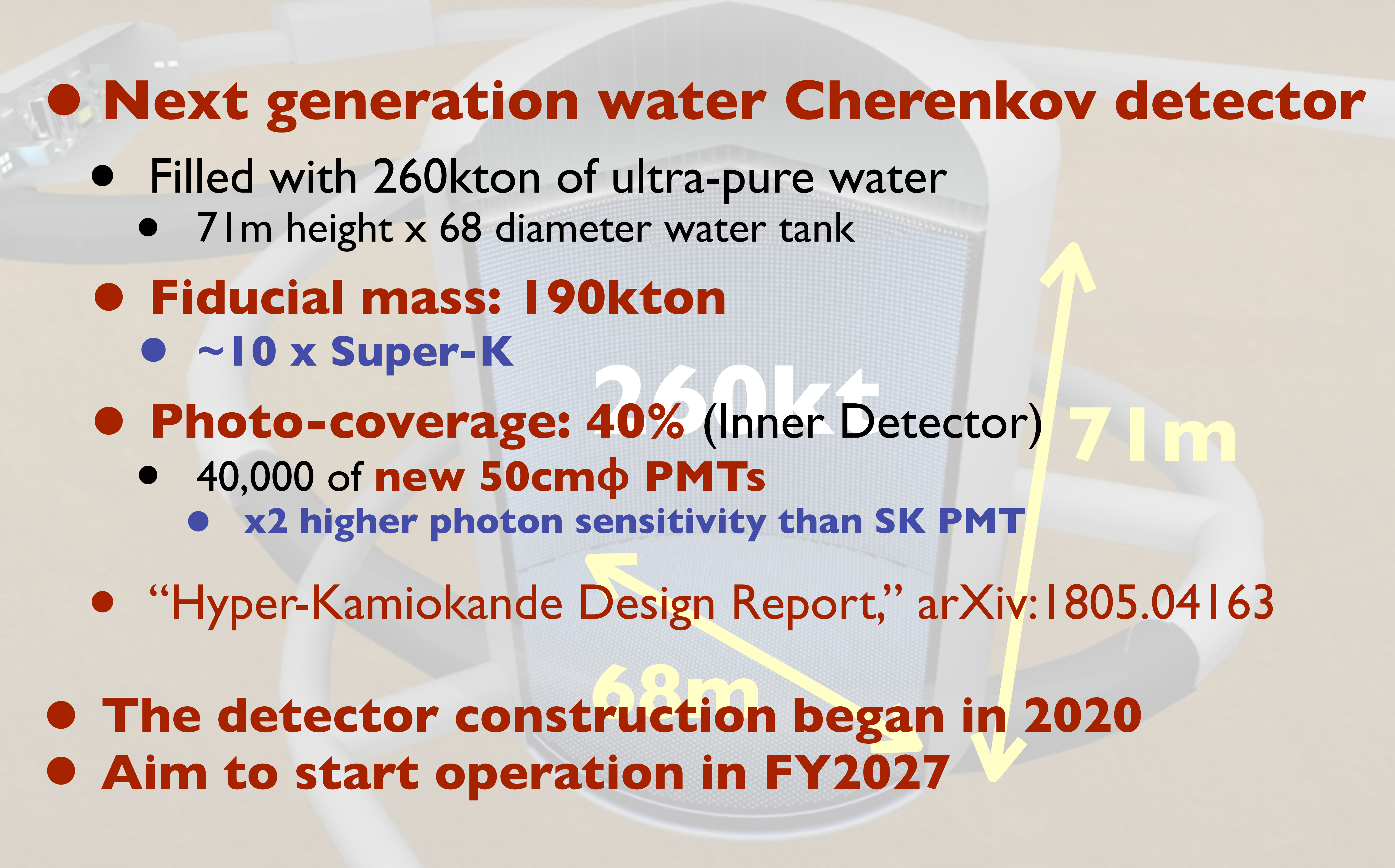
Hyper-Kamiokande

The world largest water Cherenkov ring imaging detector

(filled with **ultra-pure water**)



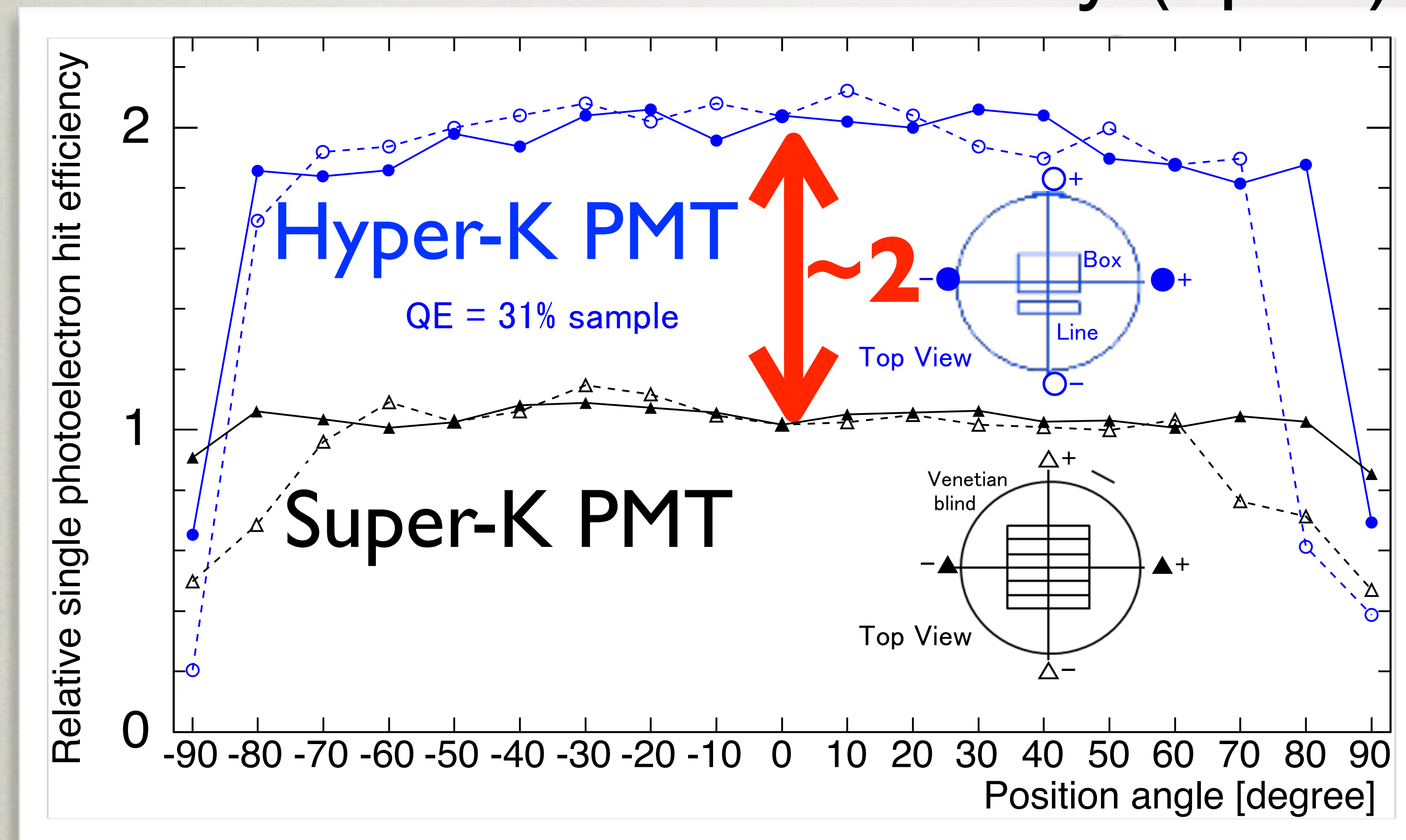
Hyper-Kamiokande



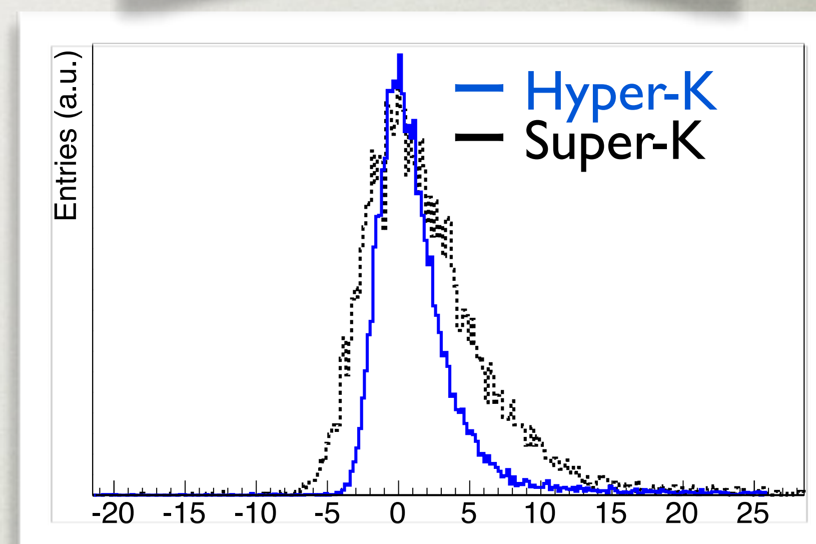
- **Next generation water Cherenkov detector**
  - Filled with 260kton of ultra-pure water
    - 71m height x 68 diameter water tank
  - **Fiducial mass: 190kton**
    - **~10 x Super-K**
  - **Photo-coverage: 40%** (Inner Detector)
    - 40,000 of **new 50cmϕ PMTs**
      - **x2 higher photon sensitivity than SK PMT**
  - "Hyper-Kamiokande Design Report," arXiv:1805.04163
- **The detector construction began in 2020**
- **Aim to start operation in FY2027**

New 50cmϕ PMT for Hyper-K

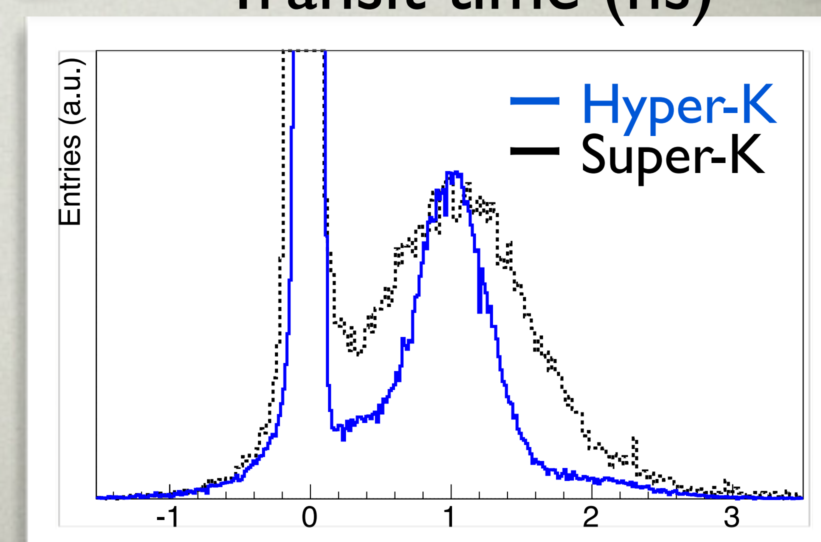
Photo-detection efficiency (1p.e.)



Box & line dynode PMT



Transit time (ns)

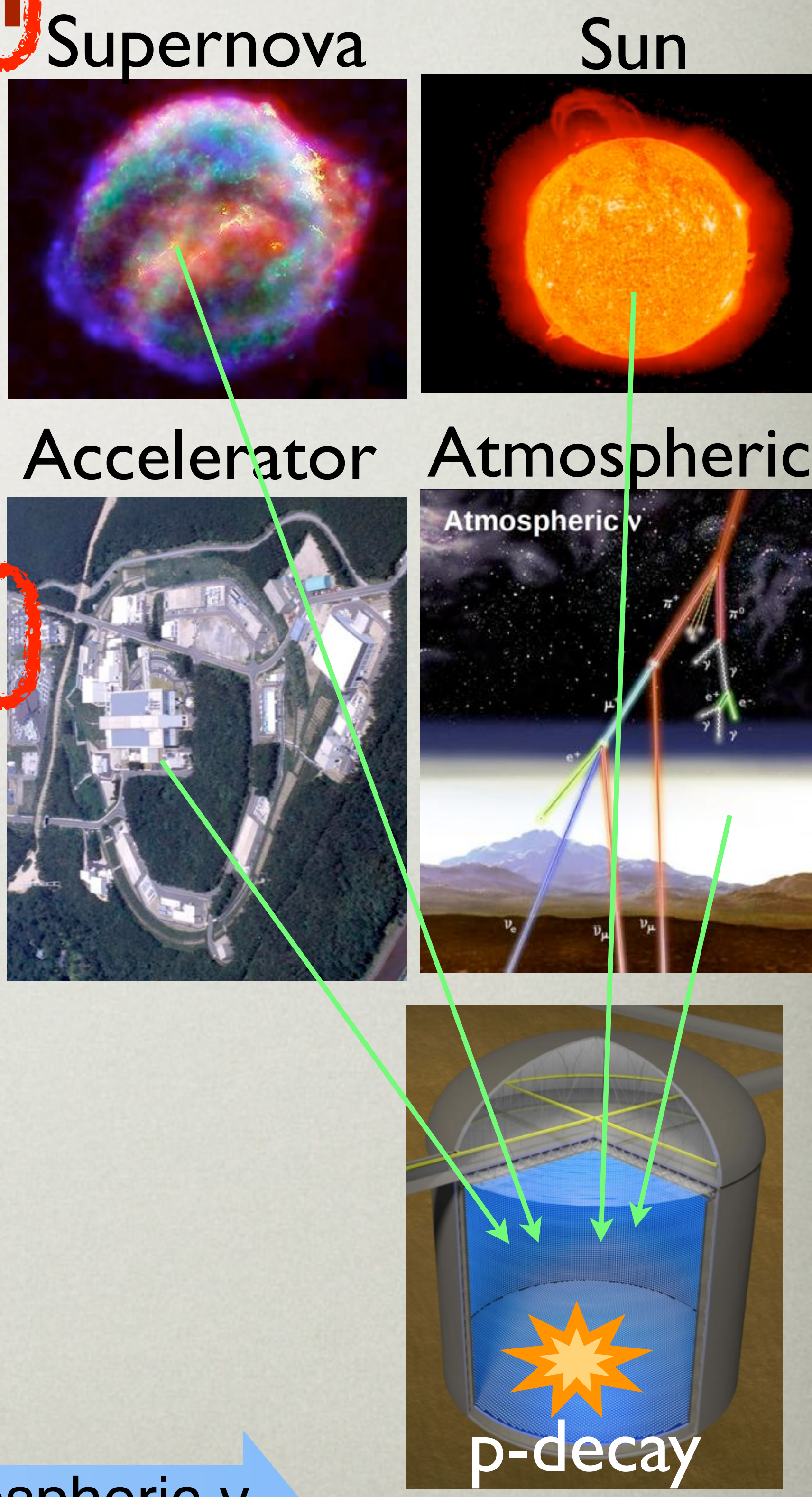


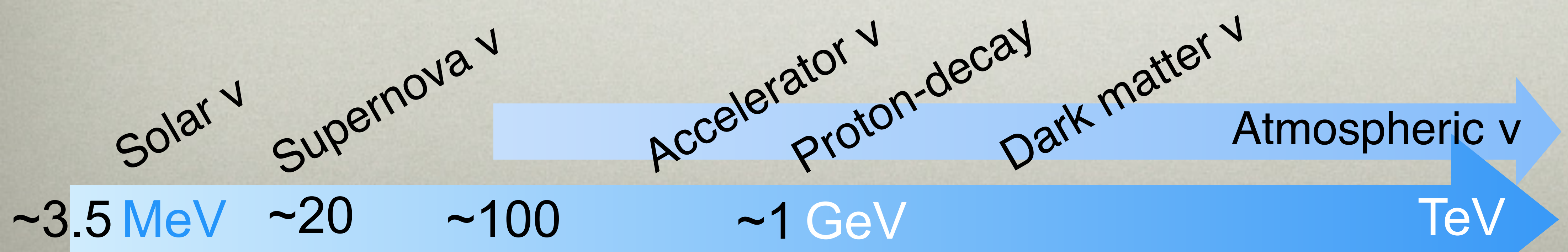
Charge (p.e.)

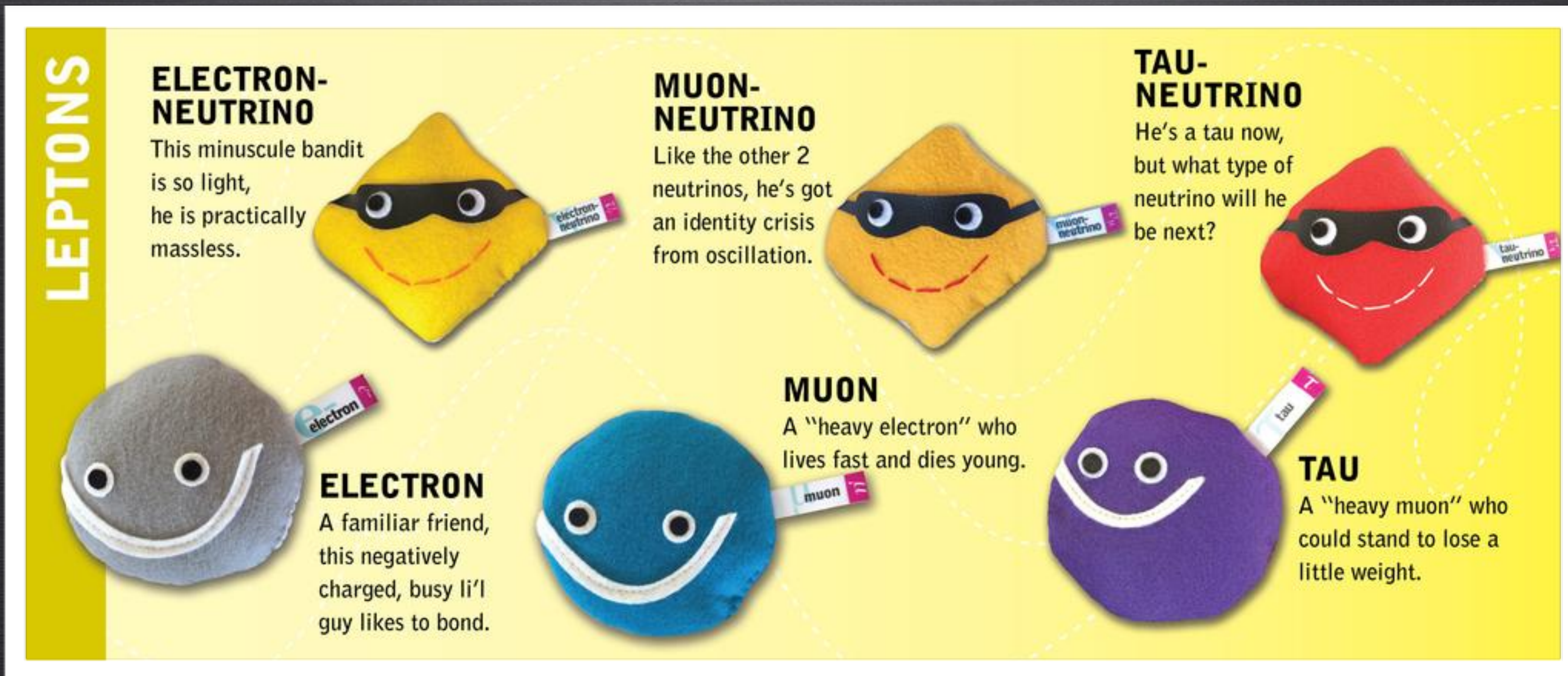
- Twice better photo-detection efficiency than SK PMTs
- Timing resolution (TTS): 1.1ns
  - cf. SK PMT: 2.1ns
- Hyper-K: established detector technique + new technology (photo-sensor)

Hyper-K: multi-purpose detector

- **Comprehensive study of ν oscillation**
  - CPV: 76% of δ space w/ 3σ, <22° precision
  - MH determination for all δ with J-PARC/Atm ν
  - θ_{23} octant determination at $|\theta_{23}-45°|>2°$
  - <1% precision of Δm^2_{32}
  - Test standard ν oscillation scenario w/ acc/atm ν
- **Proton decay 3σ discovery potential**
  - 1×10^{35} years for $p \to e^+\pi^0$
  - 3×10^{34} years for $p \to \nu K^+$
- **Astrophysical neutrino**
  - Solar ν: test standard matter effect (MSW) model
  - Supernova ν, supernova relic-ν
  - Dark matter neutrinos from Sun, Galaxy, Earth







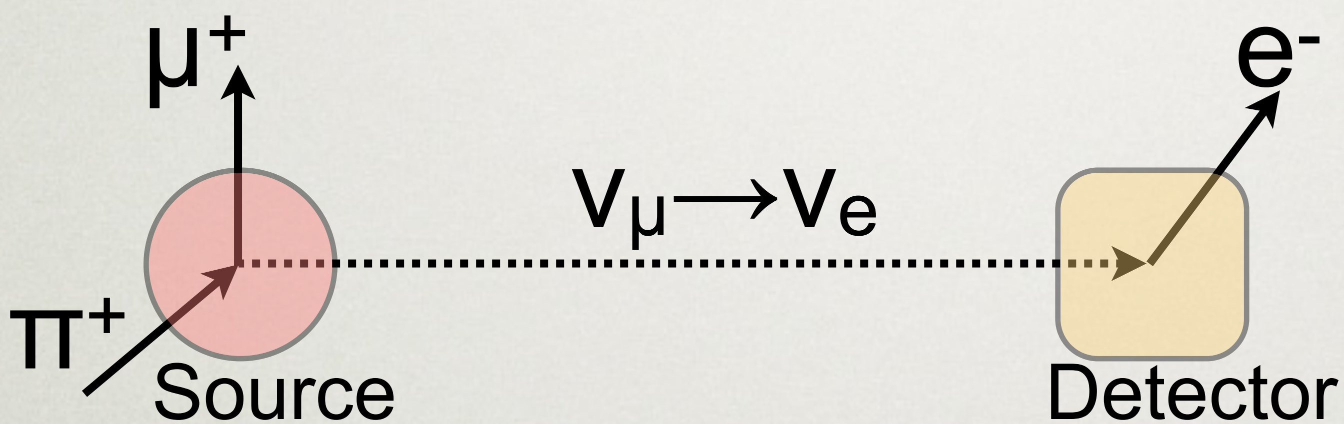
Neutrino Oscillation

Neutrino Oscillation

If neutrinos have masses, flavor state can be a mixture of the mass states.

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Flavor eigenstate — Mass eigenstate

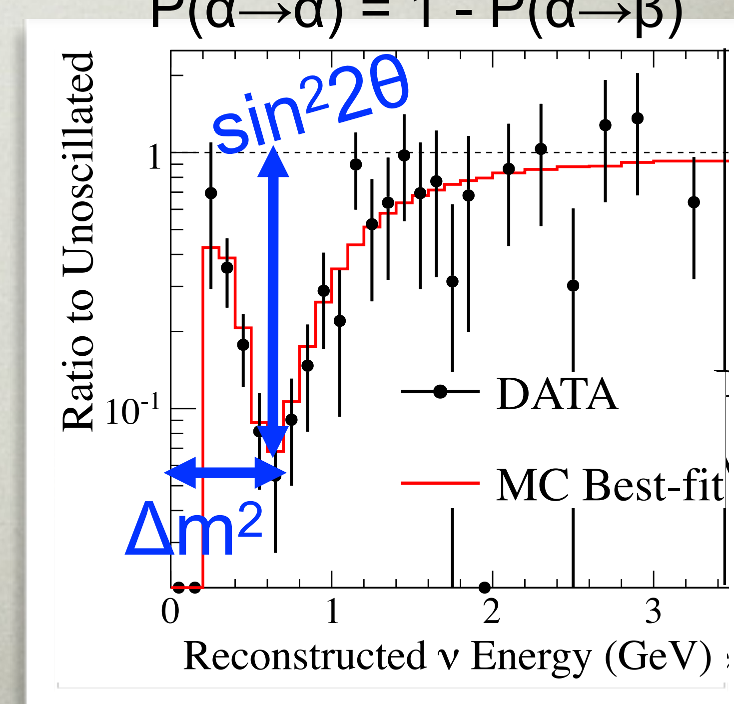


The probability to observe ν_β at distance L(km) from a ν_α source is:

$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left[1.27\frac{\Delta m^2 L}{E}\right]$$

where E (GeV) is the energy of the neutrino and $\Delta m^2 \equiv m_1^2 - m_2^2$ (eV^2).

Survival probability
$P(\alpha\to\alpha) = 1 - P(\alpha\to\beta)$



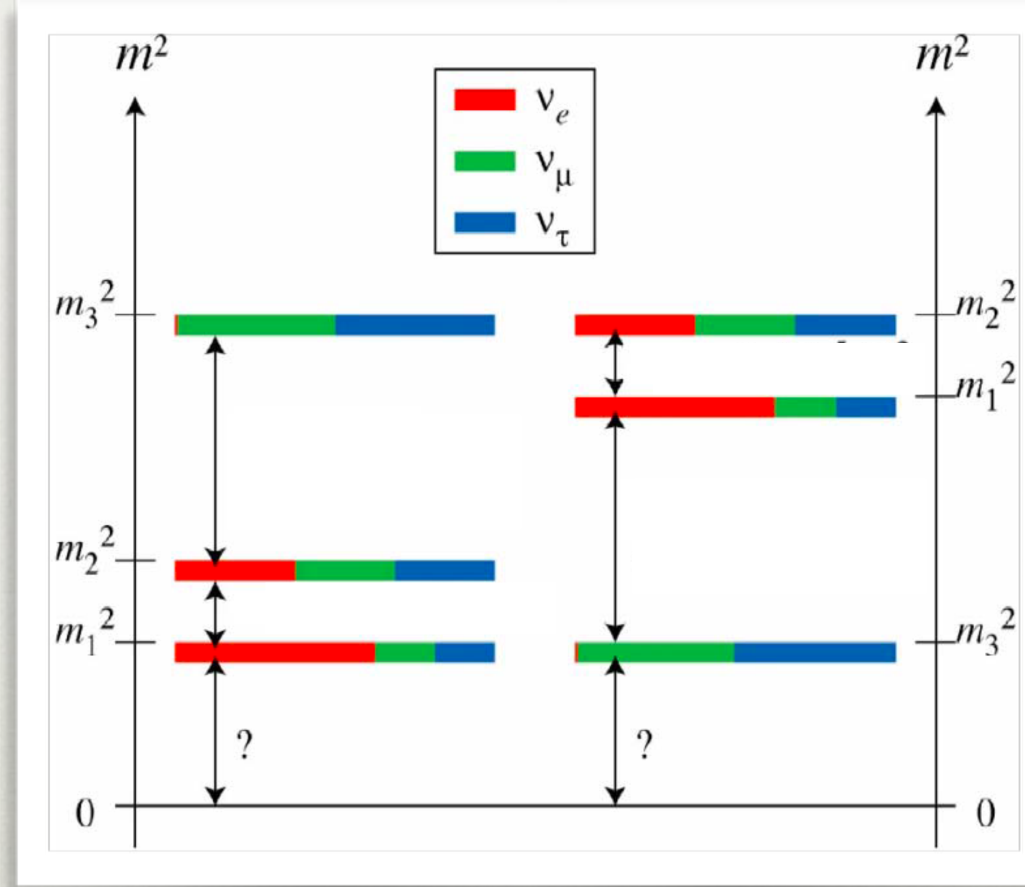
PRL 112, 181801 (2014)

Status of ν oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

- Mixing between all three neutrino flavors has been observed
  - $\theta_{12} \sim 34° \pm 0.1°$
  - $\theta_{13} \sim 9° \pm 0.8°$
  - $\theta_{23} \sim 45° \pm 1°$ (maximal?)
- Two mass differences
  - $\Delta m^2_{21} \sim 7.4 \times 10^{-5}$ eV^2
  - $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2 (hierarchy?)
- CP phase δ_{CP} remains unknown
- Also need to test “standard” 3-flavor neutrino oscillation paradigm



Normal hierarchy ($\Delta m^2_{32}>0$)

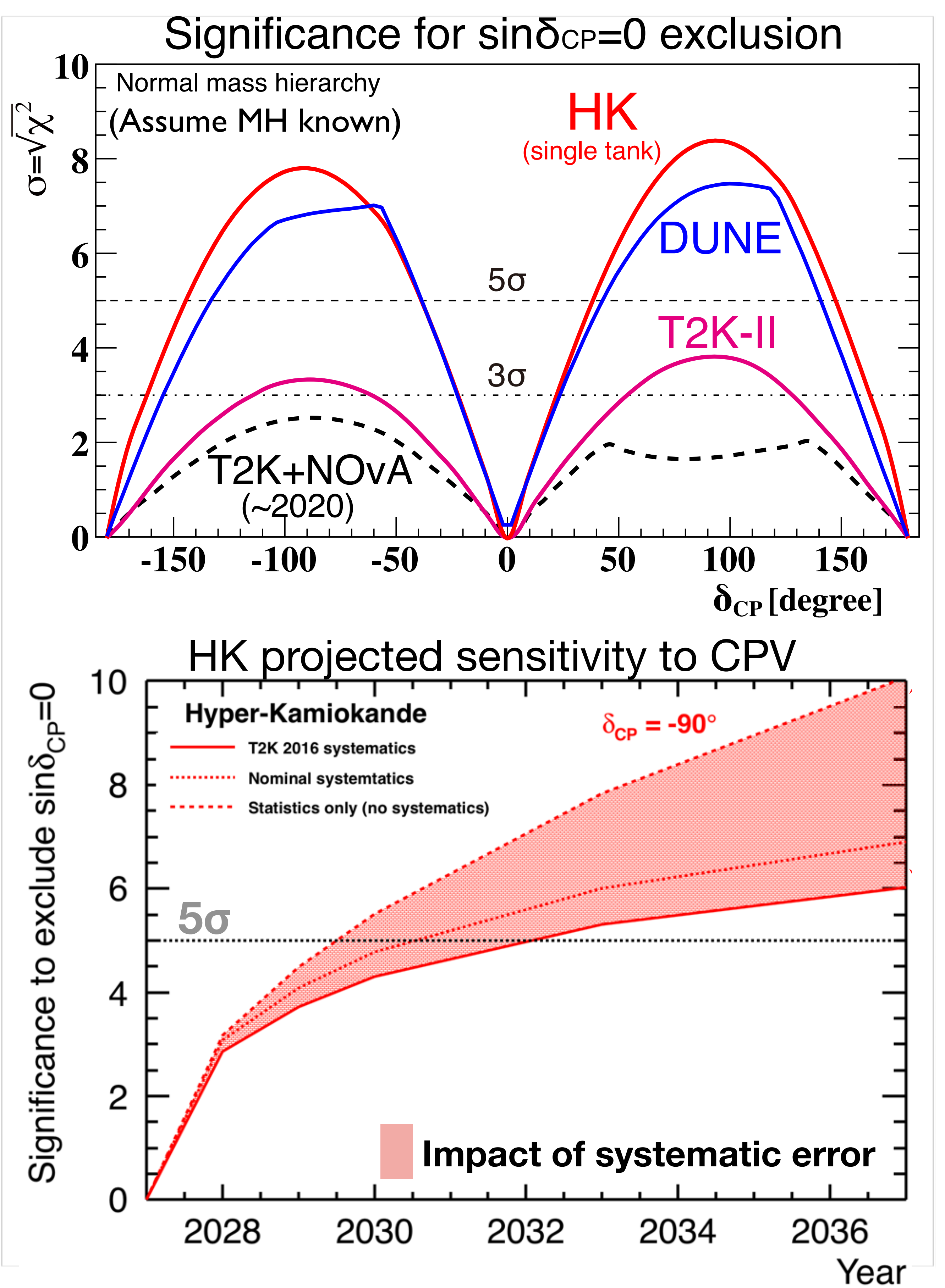
Inverted hierarchy ($\Delta m^2_{32}<0$)

ν Beam for **Hyper-K**

- 2.5 deg. off-axis narrow band neutrino beam (same as T2K)
- **Beam power: 1+MW** (before Hyper-K begins)
  - KEK Project Implementation Plan: top priority on 'J-PARC upgrade for Hyper-K'

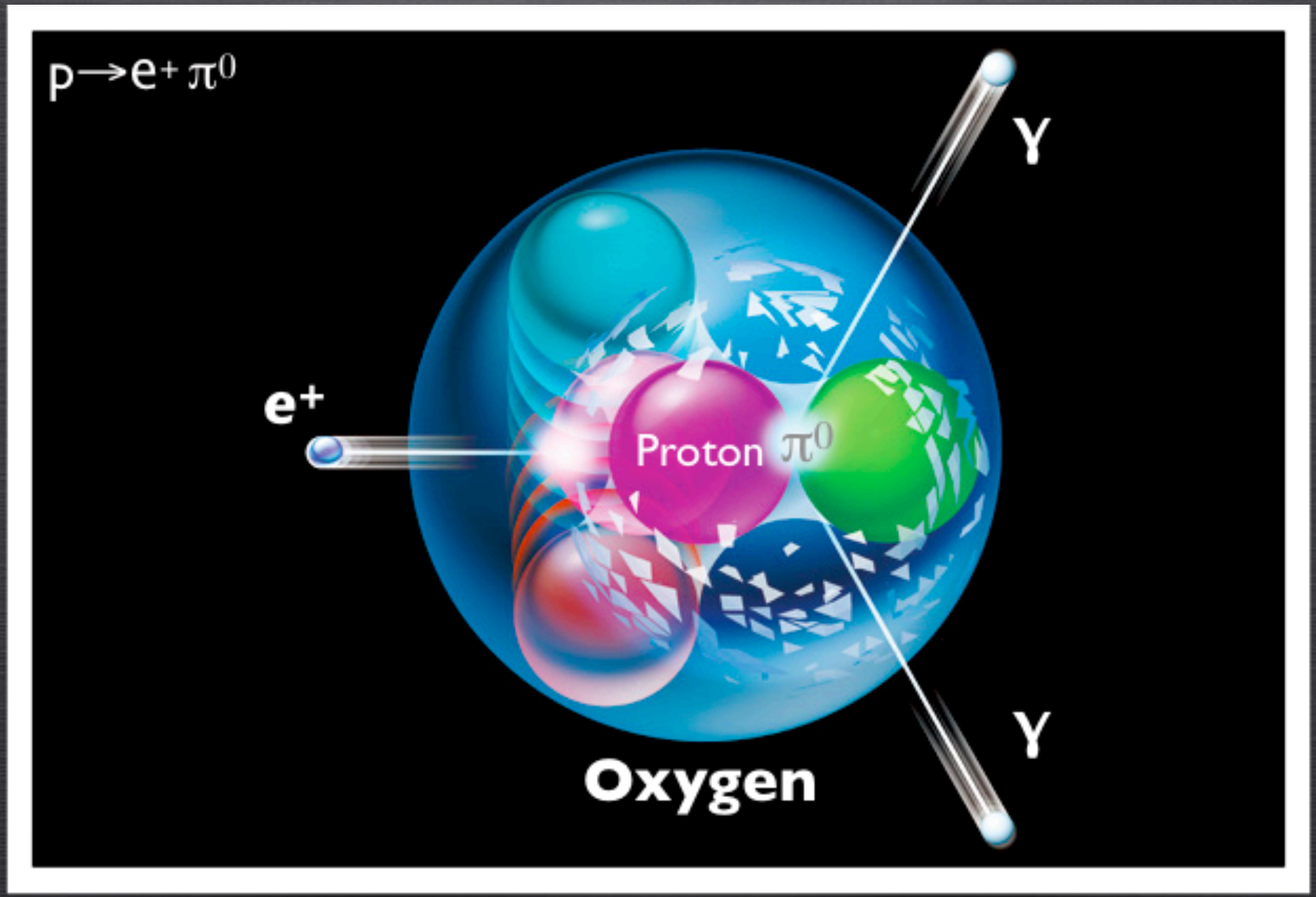
- cf. **T2K** → **T2HK**
  - × 8.4 fiducial mass (SK→HK)
  - × 2.6 beam power (J-PARC upgrade)
  - **➜ 20+ times more stat.**

Hyper-K CPV sensitivity



- Significance for sinδ=0 exclusion
  - Assume MH known
- Hyper-K >5σ sensitivity near δ=-90° after 10ys operation
  - Sensitivity studies adopt analysis techniques and systematic uncertainties used in T2K
    - Realistic syst. error plus expected reduction of error
    - 3~4% syst. err (cf. 6~7% in T2K)

- Hyper-K DR: arXiv1805.04163
- DUNE CDR: arXiv:1512.06148

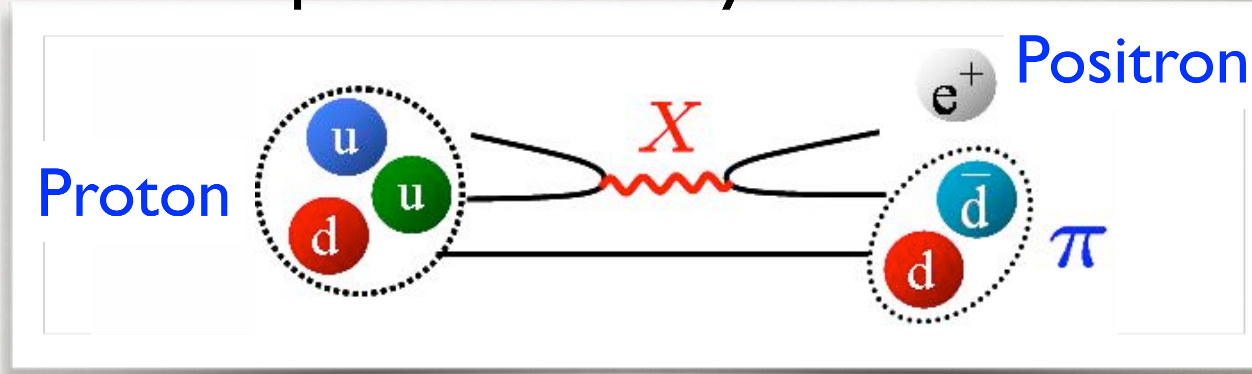


Search for Nucleon Decay

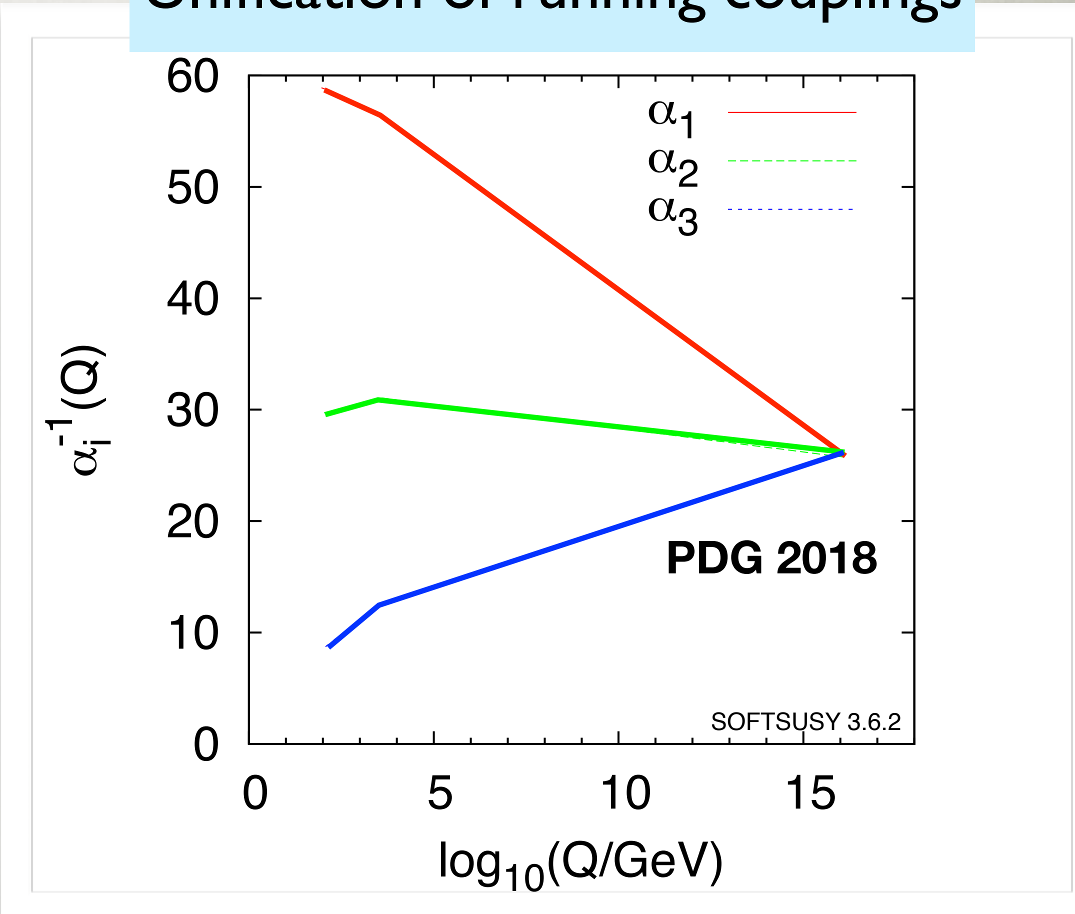
Nucleon Decay

- Nucleon decay can occur via a (direct) transition from quark into lepton
  - Baryon numbers (*B*) not conserved
  - Standard Model violates *B* at an extremely small level
  - **➜ Observation of nucleon decay clear evidence of beyond the standard model**
- Grand Unified Theory (GUT)
  - Attempt to unify forces and particles (at $10^{15\text{-}16}$ GeV)
  - → Imply nucleon decay
  - Many GUT models and variety of predictions on nucleon lifetime, decay modes and branching ratio
- **Nucleon decay search an unique probe for GUT and physics in very high energy**

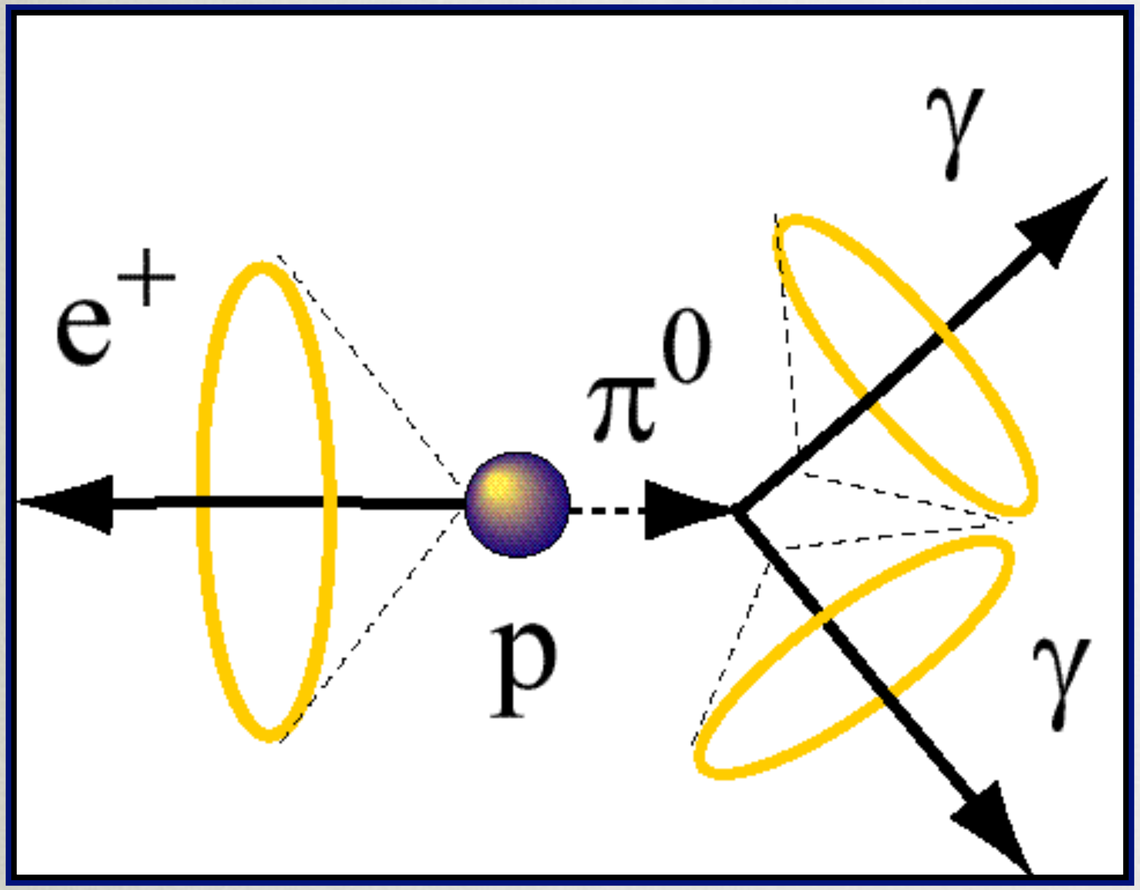
$p \rightarrow e^+\pi^0$ decay mode

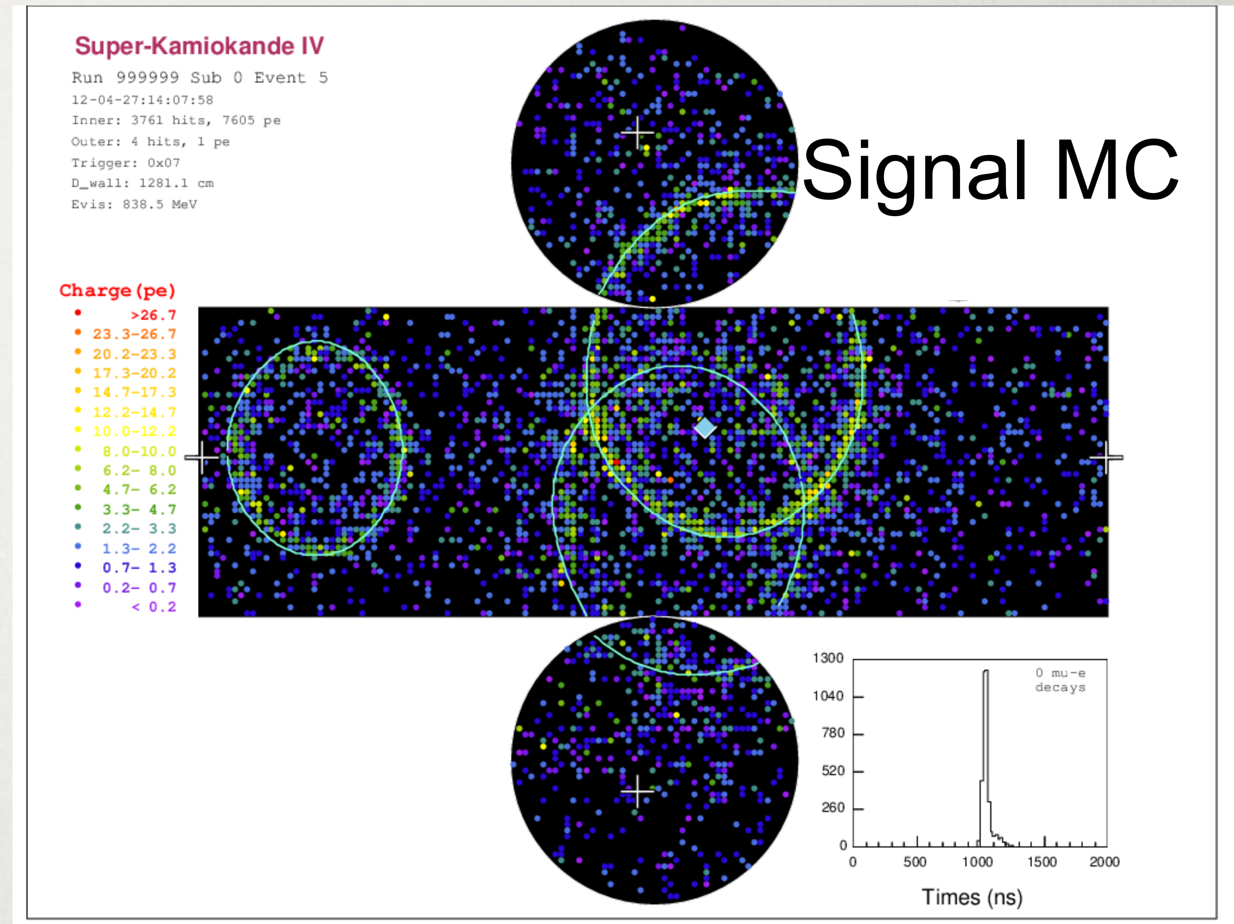


Unification of running couplings



Search for $p \rightarrow e^{+}\pi^{0}$

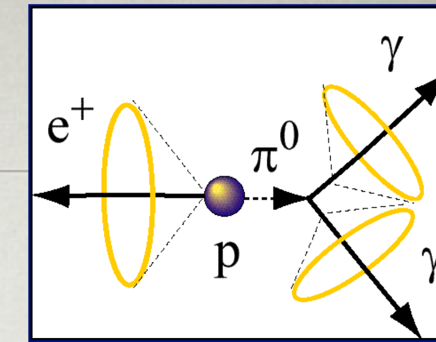




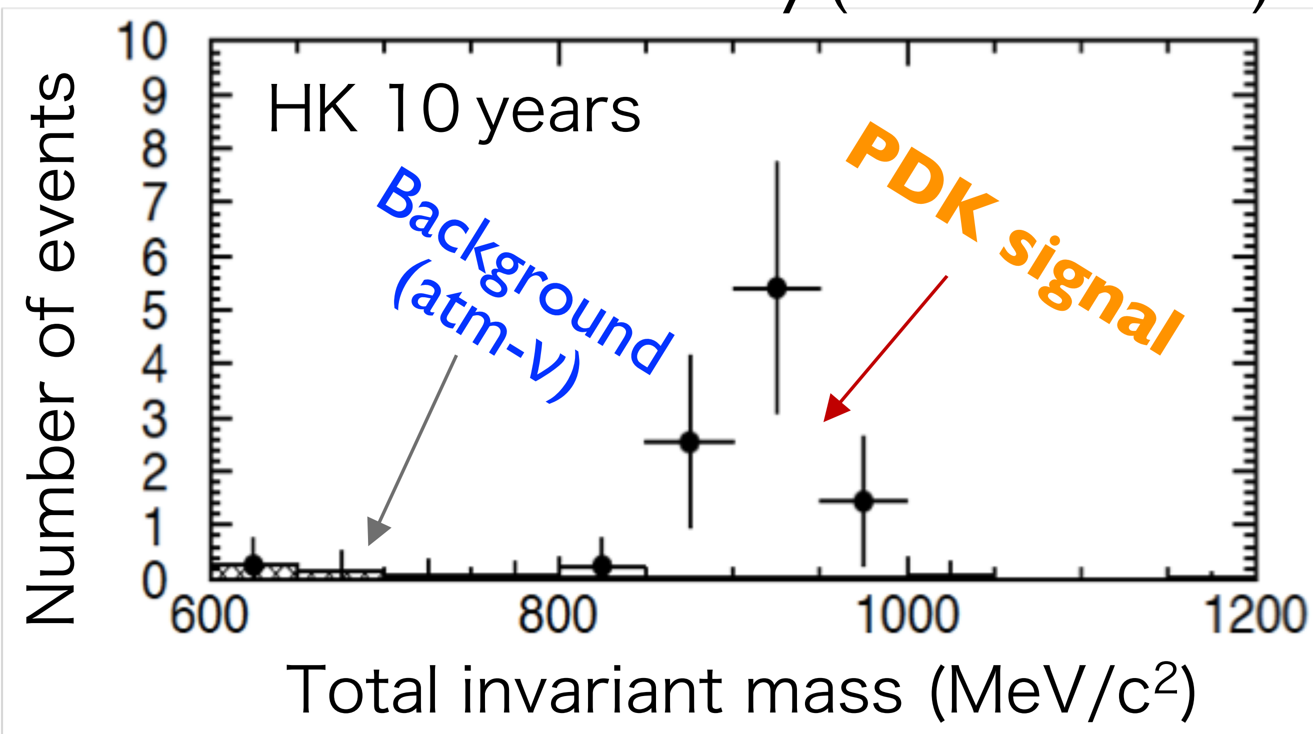
- **Positron and π^0 run back-to-back**
  - Momentum 459 MeV/c
- **All particles in the final stable are visible with water Č detector**
  - **Able to reconstruct p mass and momentum**

- Event selection:
  - All particles are fully contained in FV
  - 2 or 3 rings (two of them from π0)
  - All particles are e-like, w/o Michel-e
  - $85 < M_{\pi 0} < 185$ MeV/c^2
  - $800 < M_p < 1050$ MeV/c^2
  - $100 < P_{tot} < 250$ or $P_{tot} < 100$MeV/c
  - Neutron-tagging
    - Further reduce bkg by ~50%

$p \rightarrow e^{+}\pi^{0}$



Assume τ/Br=1.7x10^{34}y (SK 90%CL limit)

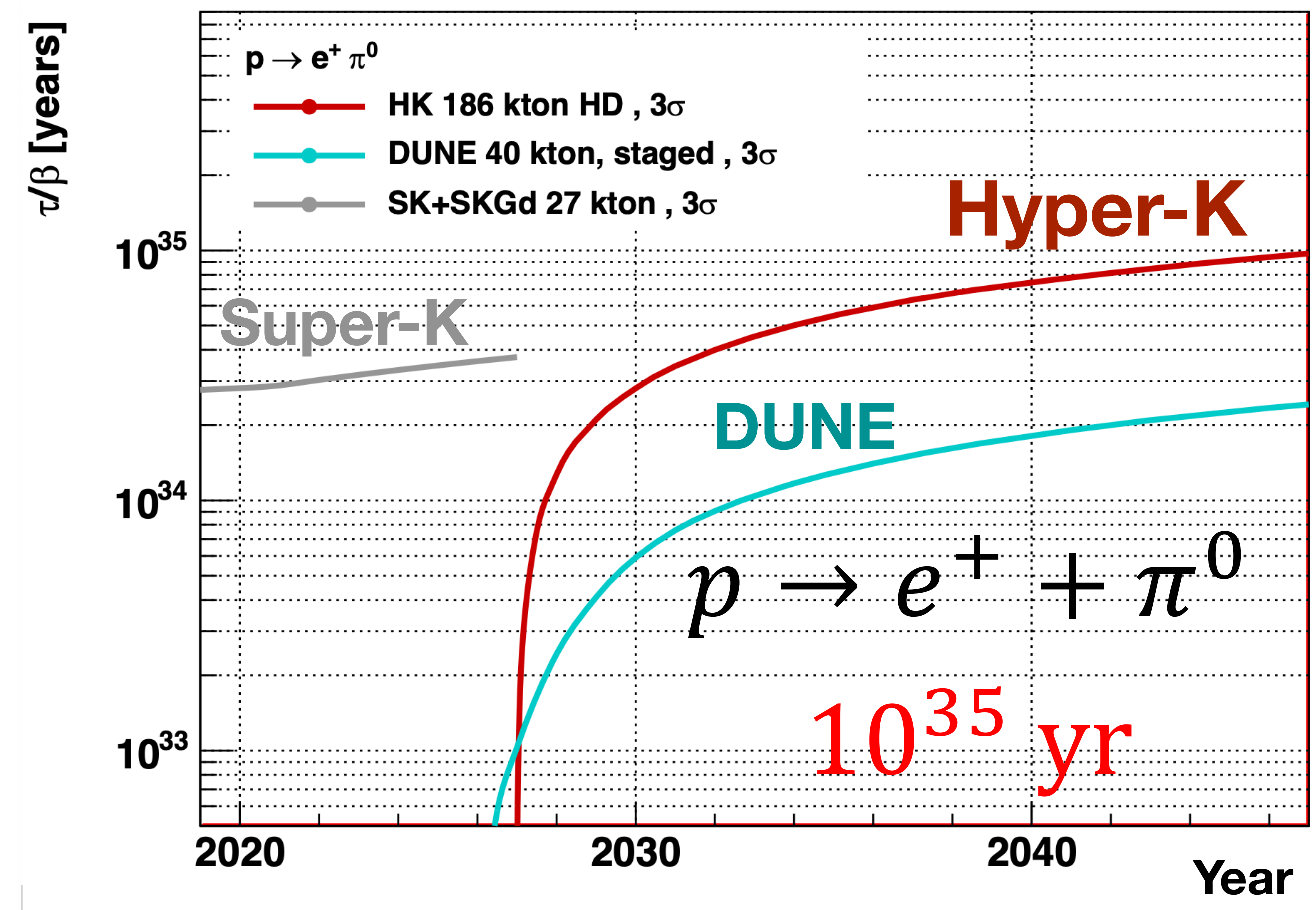


"Background free" NDK search
thanks to the new photo-sensors
(ex. n-tag eff: ~20% at SK → ~70% at HK)

(0.06 bkg events / Mt·year)

~9σ discovery potential if nucleon lifetime at the current SK limit (τ_p/Br=1.7x10^{34}yrs)

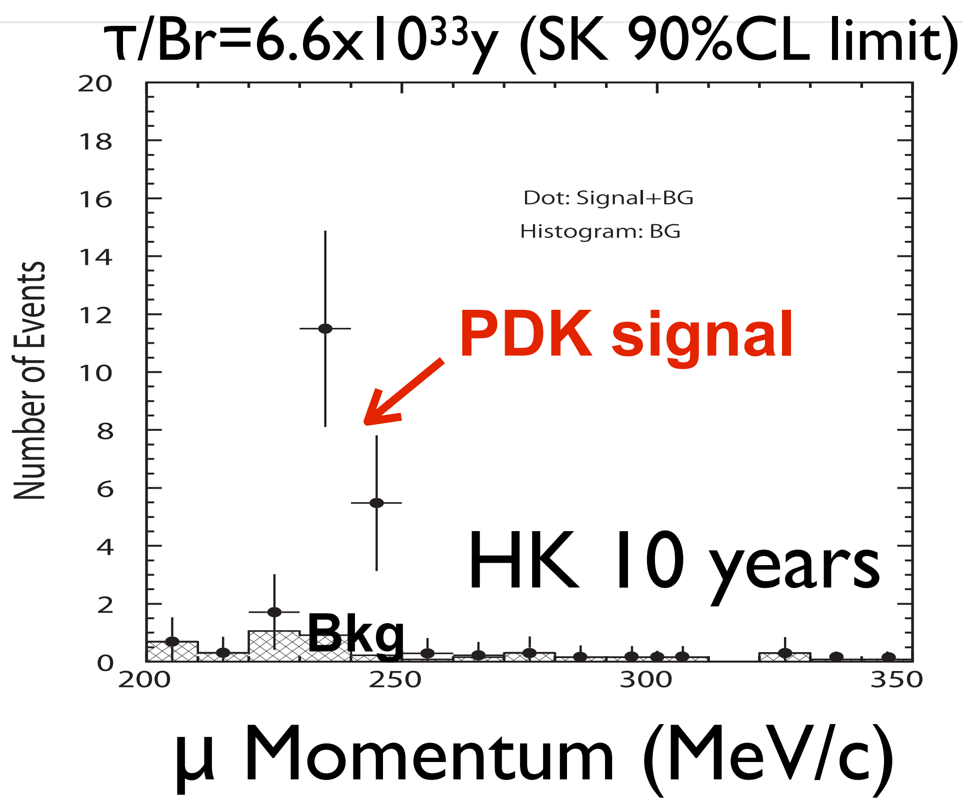
3σ discovery sensitivity

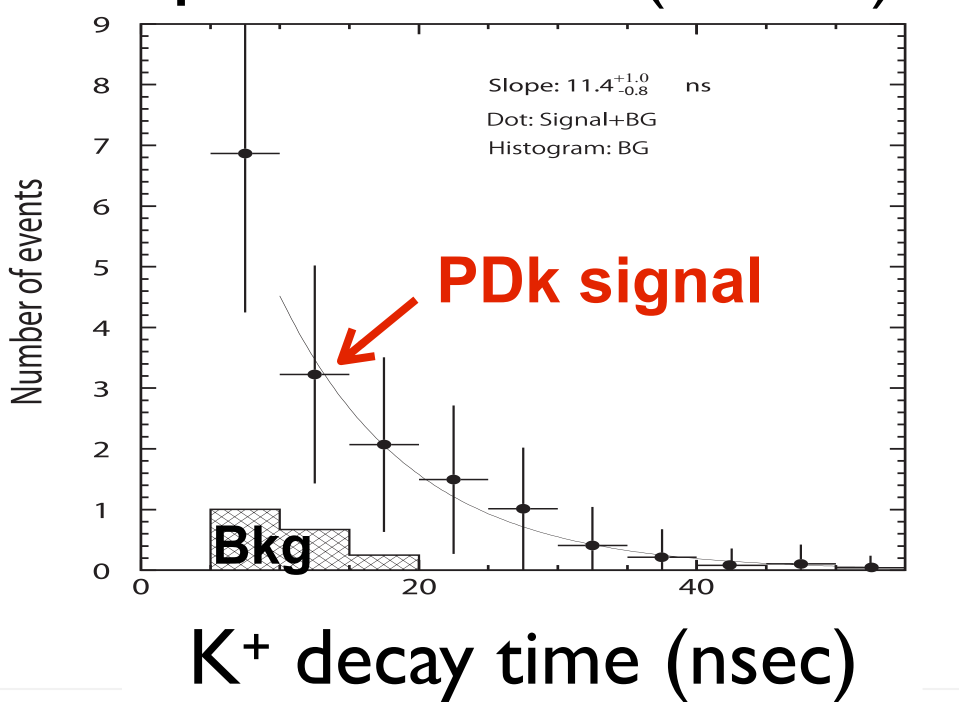


DUNE: FERMILAB-PUB-20-025-ND (arXiv:2002.03005)

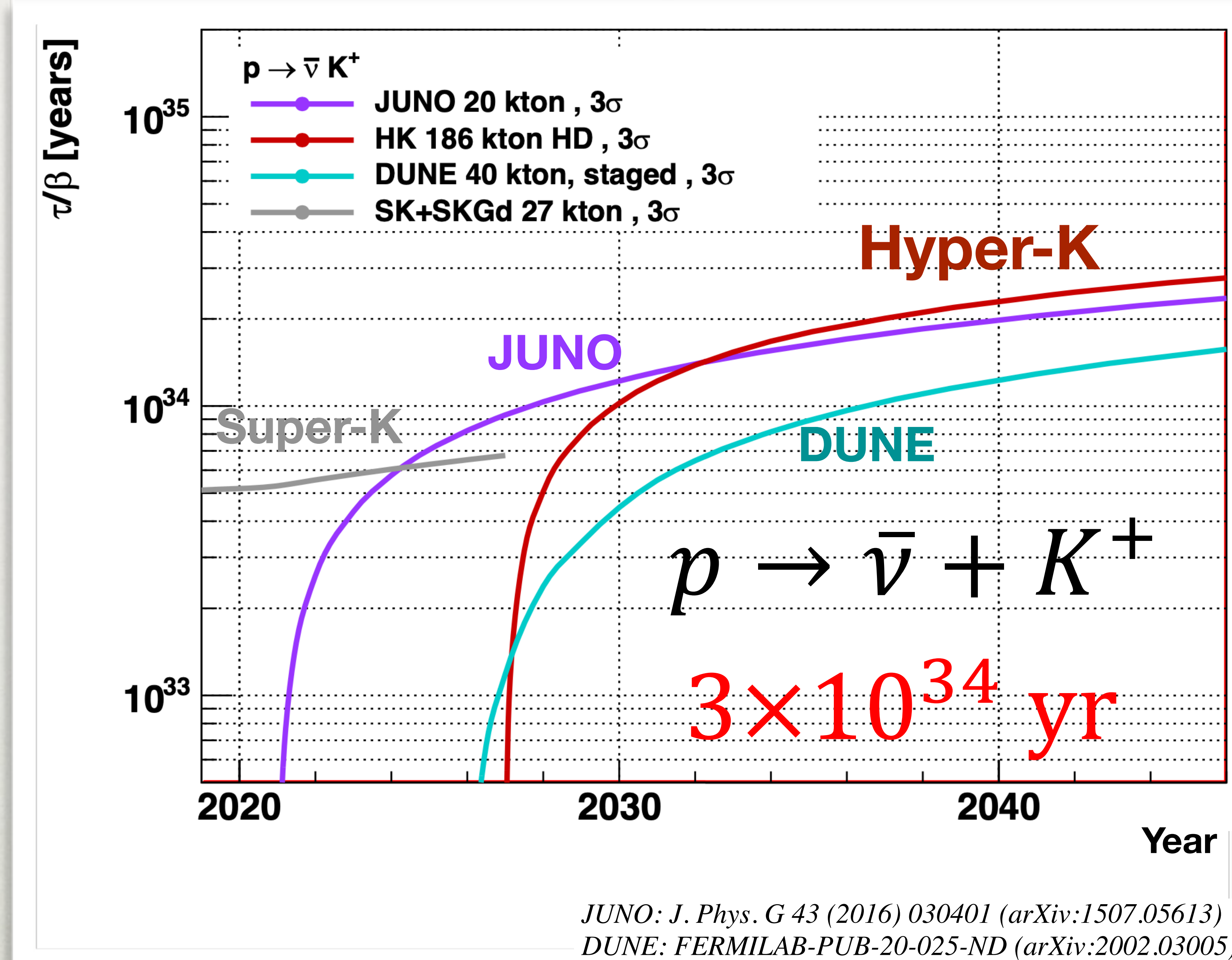
- **Hyper-K reaches to 10^{35} yrs with 3σ discovery sensitivity**

$p \to \bar{\nu} K^+$





3σ discovery sensitivity

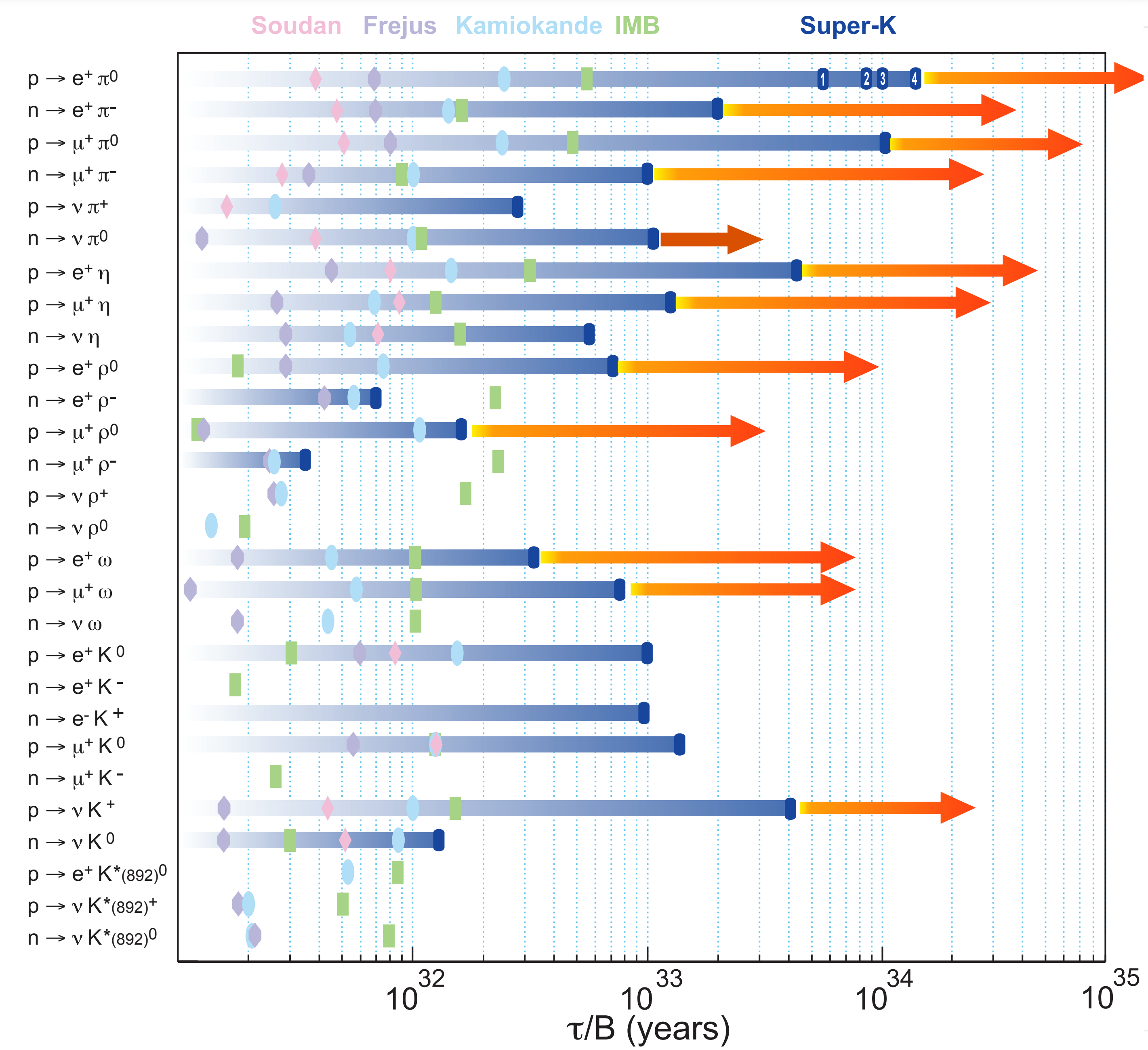


- $K^+ \to \mu + \nu$ (Br: 64%): 236MeV/c μ^+
  - de-excitation γ from $^{15}O^*$ (6MeV γ)
- $K^+ \to \pi^+ \pi^0$ (Br: 21%): 205MeV/c π^0 & π^+

- **HK 3σ discovery potential reaches 3×10^{34} years**

Hyper-K sensitivities

- **Improvements in many decay modes by a factor ~10**
  - Open for many decay modes
- **Hyper-K has a large potential for discovery**

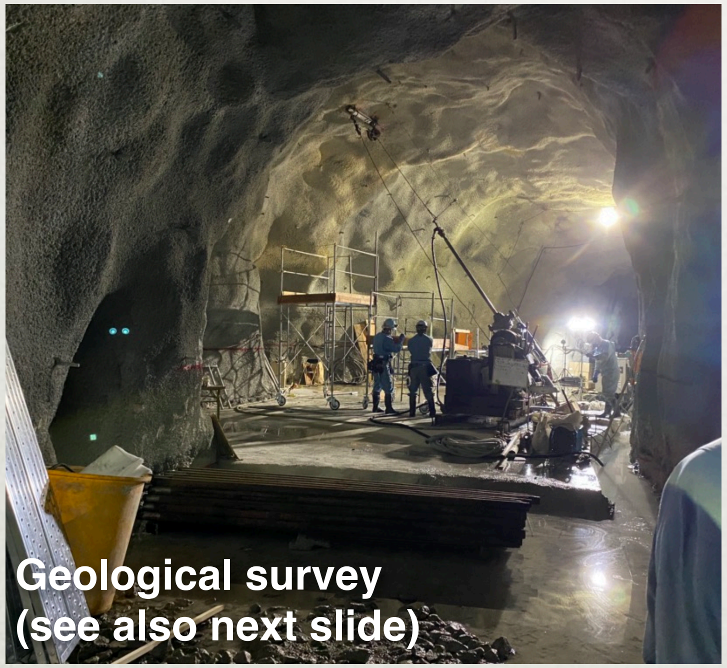


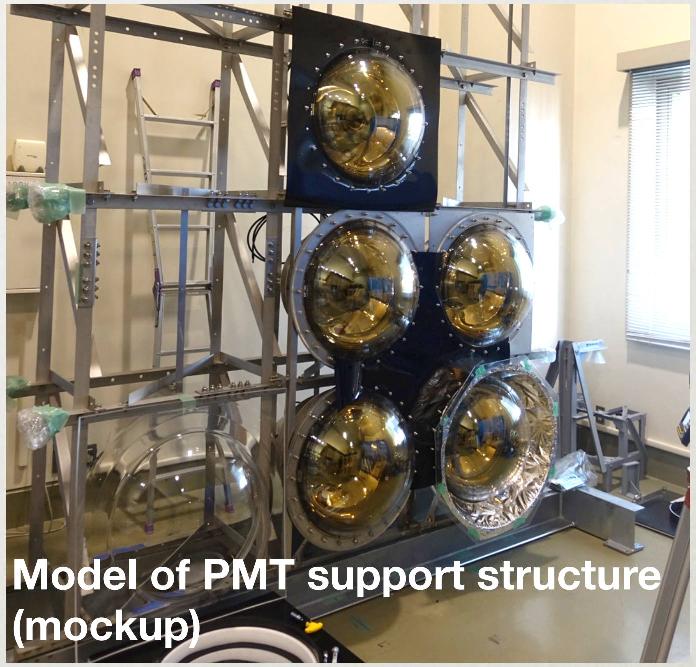
- *$p \to e^+ + \pi^0$*
  - $\tau_{proton}/Br > 1\times10^{35}$ years @90%CL
  - 5Mton×years (9 Hyper-K years)
- *$p,n \to (e^+, \mu^+) + (\pi, \rho, \omega, \eta)$*
  - $O(10^{34\sim35})$years
- *SUSY favored $p \to \nu + K^+$*
  - 3×10^{34} years
- K^0 modes, $\nu\pi^0$, $\nu\pi^+$ possible
- Others
  - (B-L) violated modes
  - radiative decays $p \to e^+\gamma$, $\mu^+\gamma$
  - neutron-antineutron oscillations ($|\Delta B|=2$)
  - di-nucleon decays ($|\Delta B|=2$)
    - pp→XX..., nn→XX...

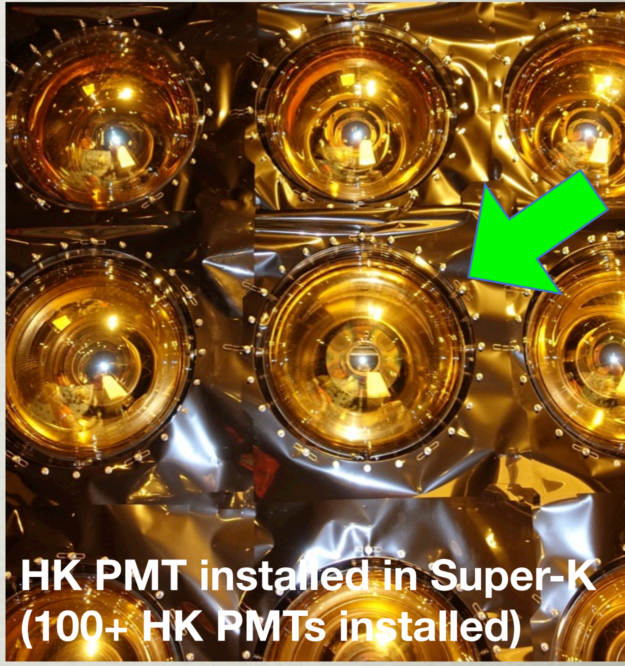
Hyper-K construction status

- **Hyper-K constructions have been started**
  - Geol. survey, prep. for electricity, constructions above ground
- PMT testing, PMT installation testing, … are on-going


New electric power line for HK


Geological survey
(see also next slide)


Model of PMT support structure
(mockup)


HK PMT installed in Super-K
(100+ HK PMTs installed)

A tunnel (for geological survey) reached to Hyper-K

Summary

- **Hyper-Kamiokande: multi-purpose detector and great discovery potential in various physics**
  - Neutrino oscillation, nucleon decay search, astrophysical neutrino, …
  - **Neutrino oscillation:**
    - **>5σ significance CP violation** (if δ_{CP}~-π/2)
    - **>4σ mass hierarchy determination** (if θ_{23}>45°)
  - **Nucleon decay search:**
    - **3σ discovery potential reaches to 10^{35} years for $p \rightarrow e^+\pi^0$ (10^{34} yrs for $p \rightarrow \bar{\nu}K^+$)**
    - Improvements for many decay modes by a factor ~10
- **<u>Detector construction began in FY2020</u>**
- **<u>Aim to begin the operation in FY2027</u>**


BACKUP