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Search for proton decay in the Hyper-Kamiokande experiment

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Baryon Number Violation: From Nuclear Matrix Elements to BSM Physics

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Outline

- Introduction
- State of the art in Super-Kamiokande
- Hyper-Kamiokande overview
- Proton decay in Hyper-Kamiokande
- Conclusions

Introduction

- Matter is very stable (age of the Universe ~ 10^{10} years)
- Electrons must be stable due to the conservation of electric charge
- Neutrons decay if left outside of the nucleus

- What about protons?

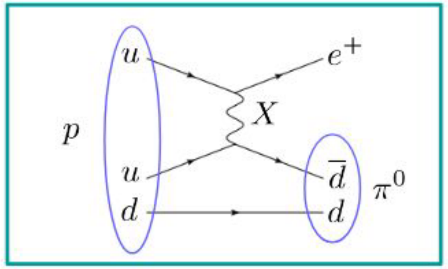
- Conservation of Baryon number introduced to explain matter stability [Weyl, 1929; Wigner, 1949]
  Accidental global symmetry in the Standard Model, might be violated.

Proton decay is a valuable tool to probe physics Beyond the Standard Model (BSM)

Grand Unified Theories (GUTs)

- Unify SM gauge groups [Georgi, Glashow, 1974; Fritzch, Minkowski, 1975]
- GUTs scale: $10^{14\text{-}16}$ GeV, well beyond collider energies.
- Lepton and baryon numbers are not conserved: protons can decay.

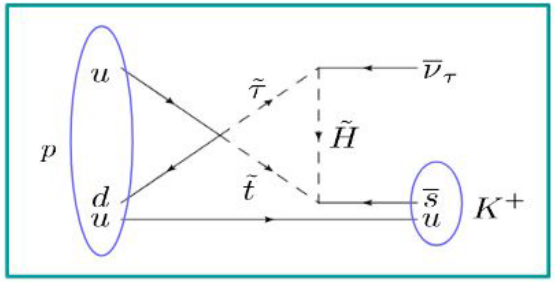
$p \to e^+ \pi^0$



SU(5)

$\tau \sim 10^{30\text{-}40}$ years

$p \to \nu K^+$



SUSY SU(5)

$\tau \sim 10^{30\text{-}40}$ years

Many models and predictions!

P S B Dev et al 2024 J. Phys. G: Nucl. Part. Phys. 51 033001

How to search for proton decay

- Predicted proton lifetimes > 10^{30} years
  - Age of the Universe: 10^{10} years

- Watch many (10^{30} or more!) protons for (relatively) short time
  need many observable protons!

  - Large scale water Cherenkov detectors are a good choice:

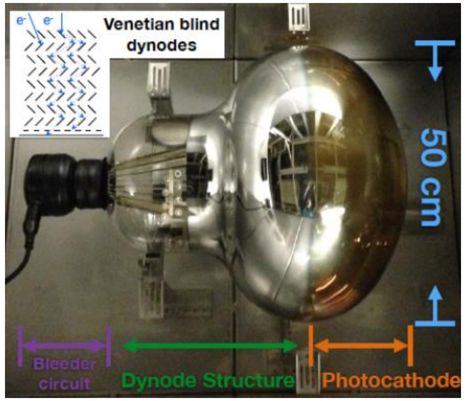
    - Water is cheap and abundant
    - Water contains 10 protons per molecule, of which 2 are free (no nuclear momentum)
    - Water Cherenkov detectors are scalable

Super-Kamiokande: state of the art

Location: Kamioka mine, Japan, ~1000 m underground below Mount Ikeno.

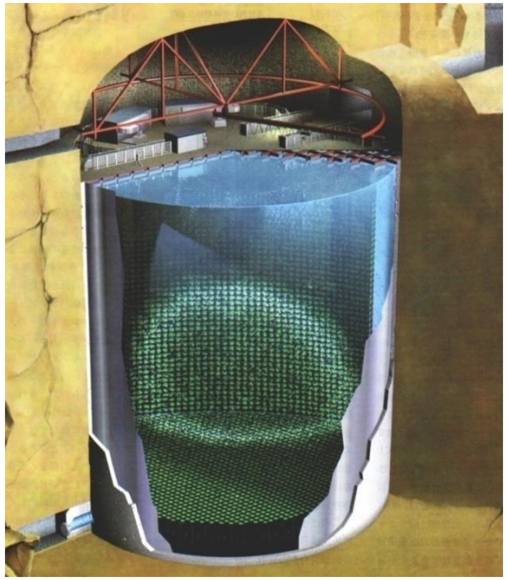
39 m x 42 m cylindric tank filled with 50 kton of ultrapure water:

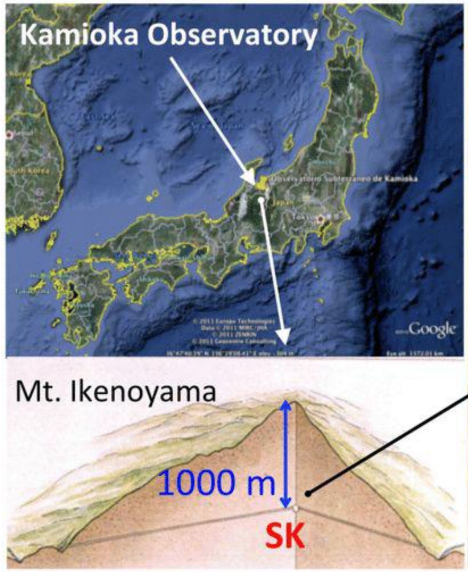
- **Inner Detector (ID):** 11k 50 cm Photomultiplier Tubes (PMTs) (40% coverage) facing inwards.
- **Outer Detector (OD):** 2k 20cm PMTs facing outwards



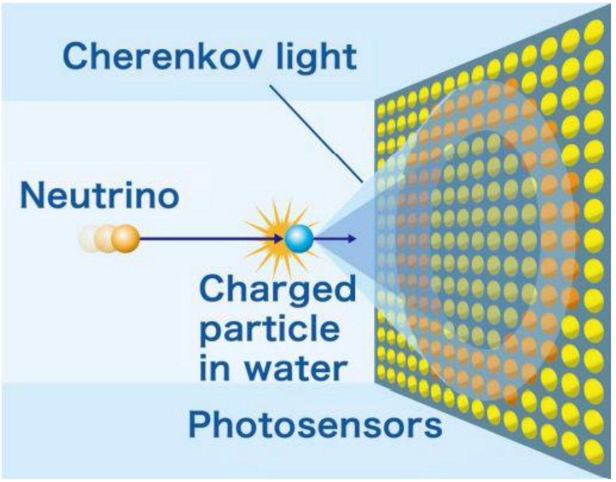
Some research topics in SK:

- **Proton decay**
- Neutrino oscillations (2015 Nobel Prize)
- Neutrino astrophysics



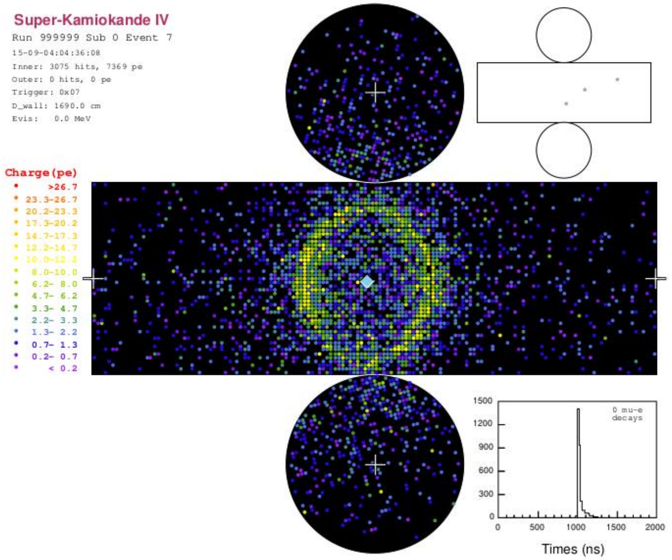


Events in Super-Kamiokande

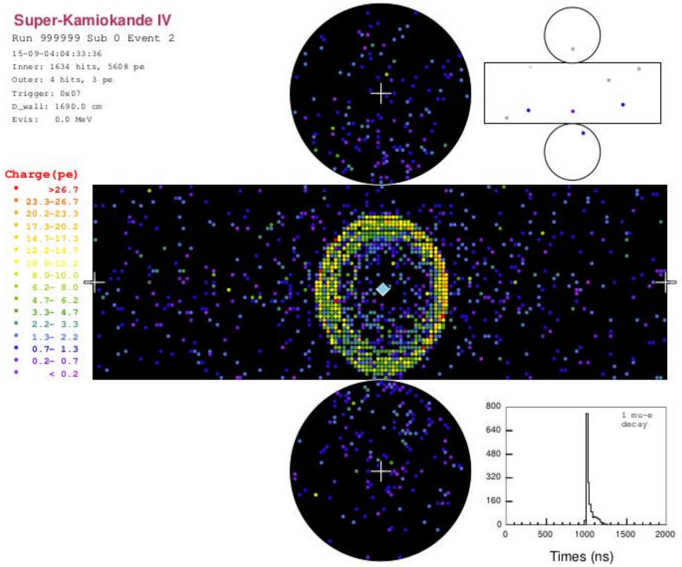


Monte Carlo simulated events

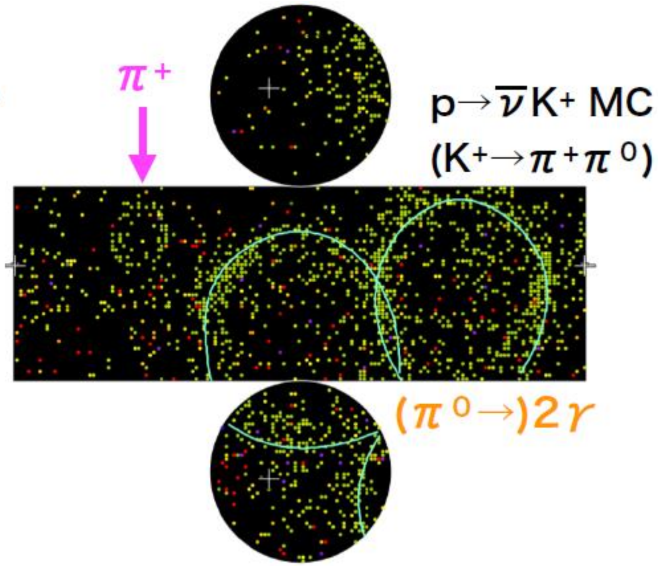
Showering (e-like)



Non showering (muon-like)



Multi-ring

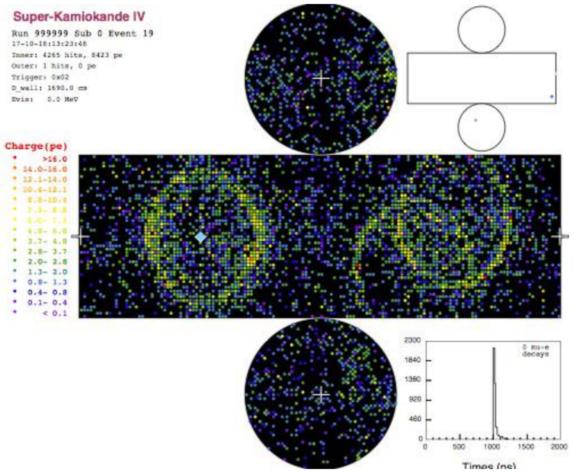


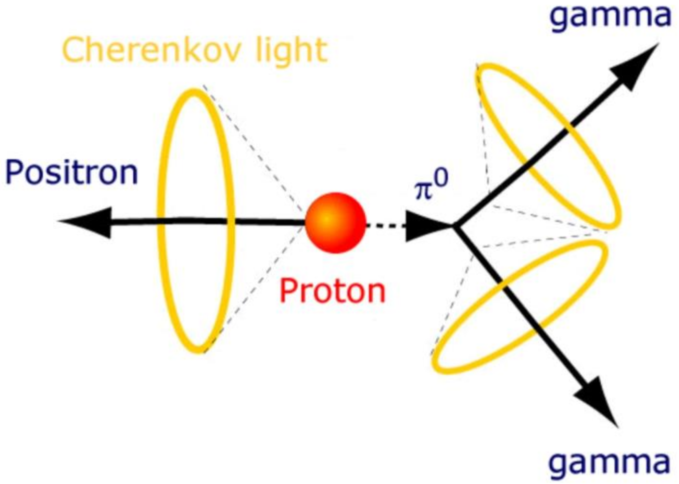
Event reconstruction

	APfit	fiTQun
Type of fit	Sequential fits	Single log-likelihood function minimization $L(\mathbf{x}) = \prod_j^{\text{unhit}} P_j(\text{unhit}\|\mathbf{x}) \prod_i^{\text{hit}} [1 - P_i(\text{unhit}\|\mathbf{x})]\, f_q(q_i\|\mathbf{x}) f_t(t_i\|\mathbf{x})$
Used by	Super-Kamiokande	T2K, MiniBooNE, Super-Kamiokande, Hyper-Kamiokande
Max # rings	5	6
PID	$e^{\pm}$, $\mu^{\pm}$	$e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$

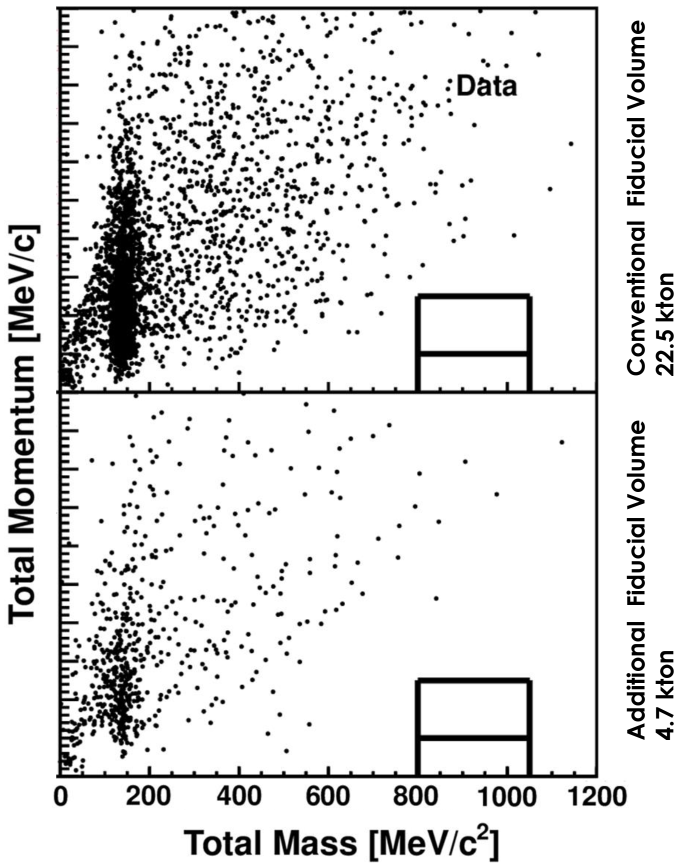
- fiTQun is part of the official reconstruction software suite for Hyper-Kamiokande.
- Machine Learning algorithms for Hyper-Kamiokande are under development and study.

p -> $e^+\pi^0$ in Super-Kamiokande

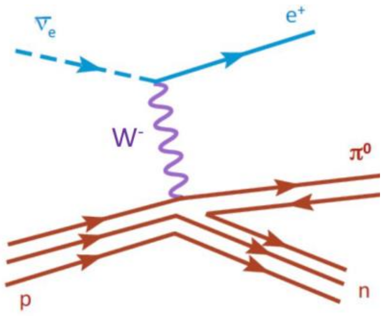




PHYSICAL REVIEW D 102, 112011 (2020)



Final state: three rings visible, all three showering.
Signal from both free (hydrogen) and bound (oxygen) protons.
Nuclear effects are an unavoidable source of inefficiency.



Typical background from atmospheric ν interaction

Neutron tagging algorithm (~20% efficiency) applied to reduce background

Exposure: 450 kton*year

	Conventional FV	Additional FV
Signal efficiency	39.8%	25.8%
Expected background	0.49 events	0.10 events

Total Exp. Bkg
1.3 ev / Mton * yr

No candidates: lower limit on proton partial lifetime set at

$\tau > 2.4 \times 10^{34}$ years

p -> ν K⁺ in Super-Kamiokande

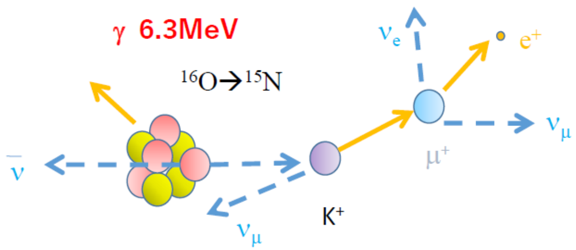
K^+ Cherenkov threshold in water is 560 MeV/c
most of K^+ can't emit a ring

Most of K^+ produced stop in water (~89%)

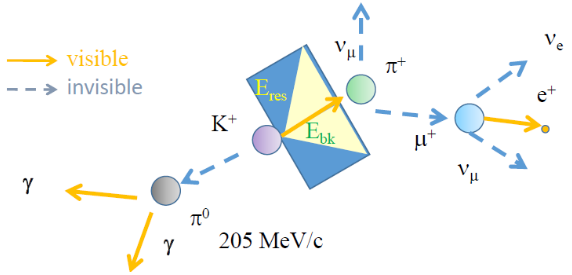
Look for K^+ decays:

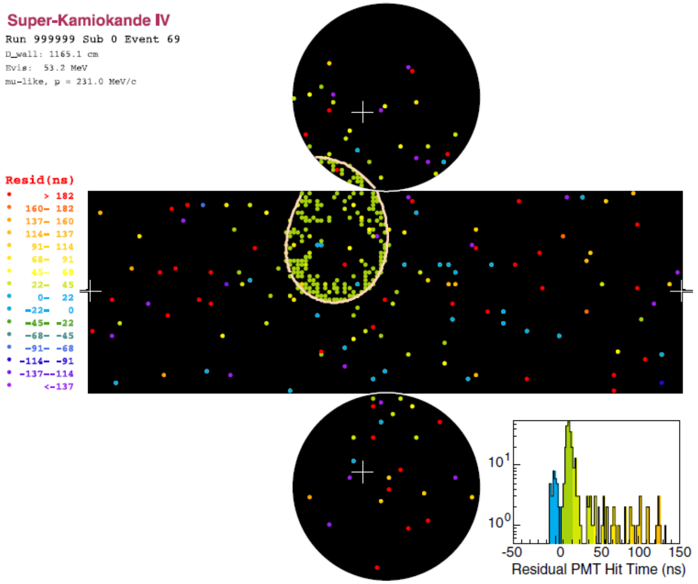
- $K^+ \to \nu\mu^+$: 64%
  (P = 236 MeV/c if decay at rest)

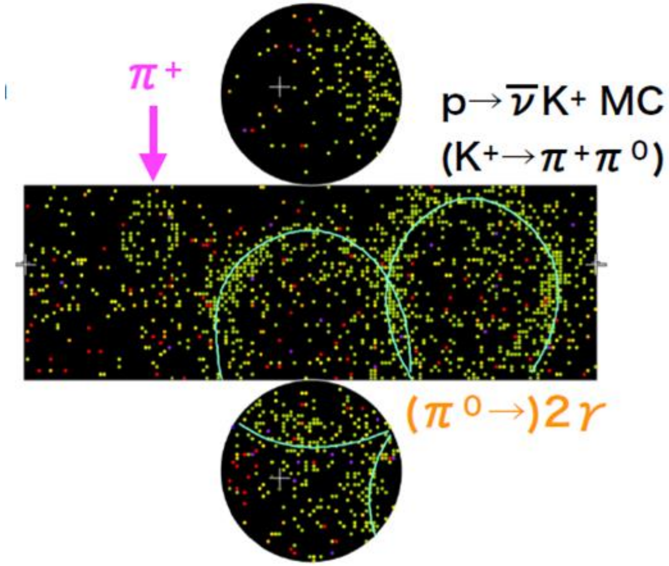
γ emission prob. 40%



- $K^+ \to \pi^+\pi^0$: 21%
  (P = 205 MeV/c if decay at rest)







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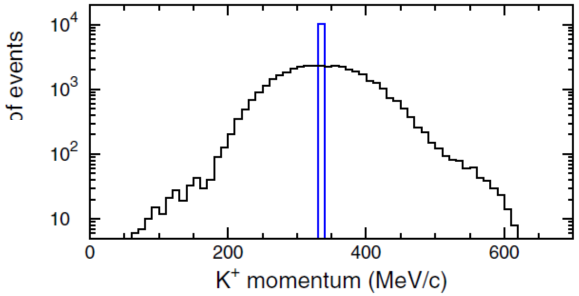


2 possible methods for $K^+ \to \nu\mu^+$ search:

1. Prompt γ
2. Spectrum fit

Dominant background:
$\nu p \to \nu\Lambda K^+$, $\Lambda \to p\pi^-$

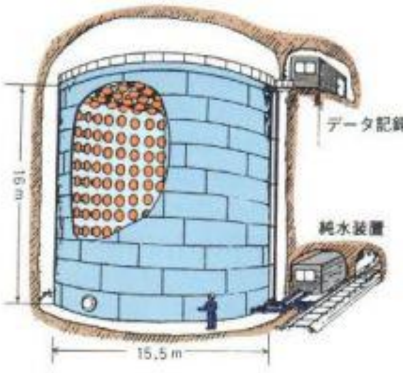
Dominant background:
ν_μCC1π

Three methods combined over 260 kton*year exposure:

τ > 5.9 x 10^{33} years

The future: Hyper-Kamiokande (Hyper-K, HK)

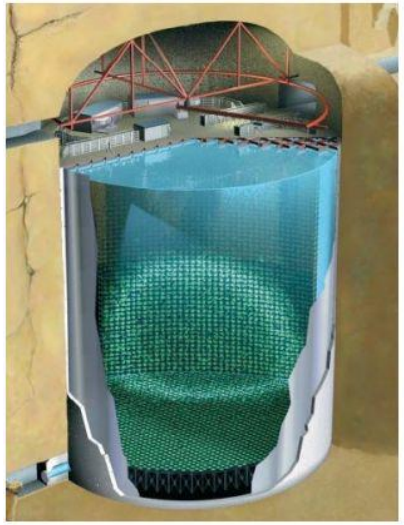
Kamiokande



3 kton
1983 - 1996

Supernova SN1987A neutrinos

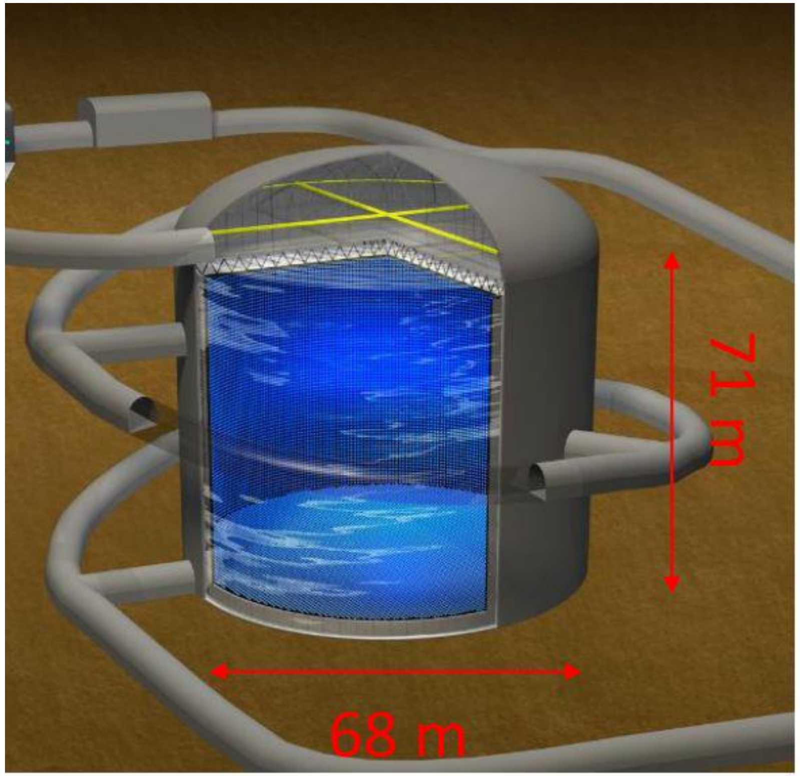
Super-Kamiokande



50 kton
1996 – Present

Neutrino oscillations

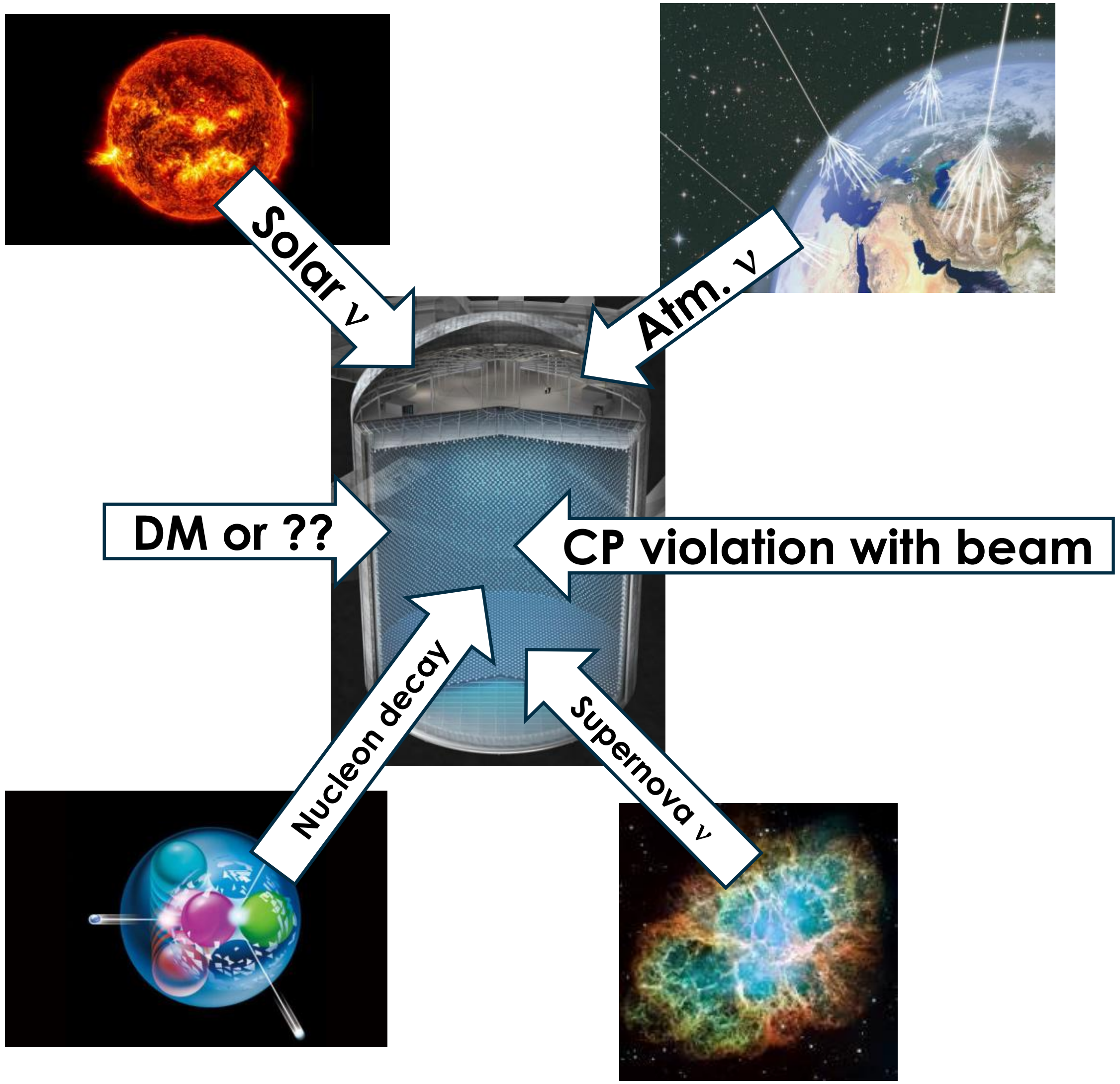
Hyper-Kamiokande



260 kton
2027 - …

Proton decay? + much more…

Hyper-K is a multipurpose experiment



Very broad physics program,
many opportunities for discovery!

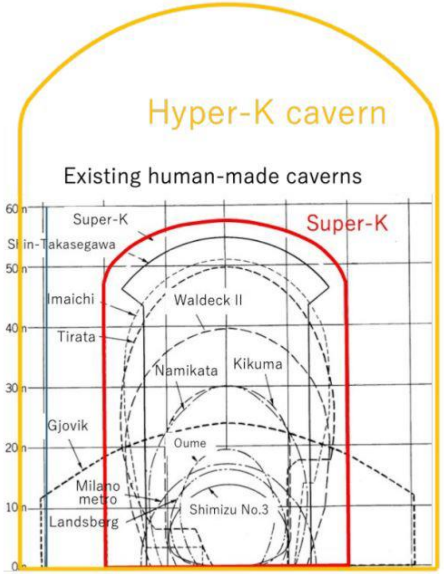
2020 – Construction started
2027 – Operation start

2 Main hosts:

- U-Tokyo for HK detector
- KEK J-PARC for beam/near detectors

Hyper-K Overview

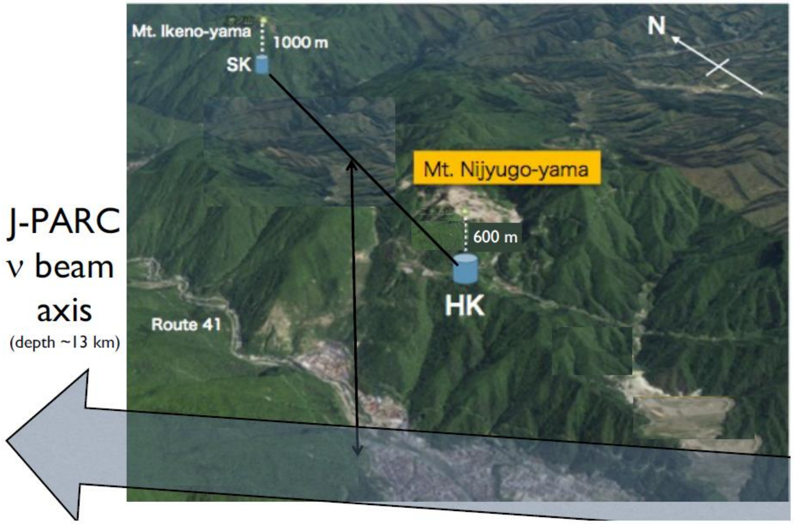
Hosted in the world's largest human-made cavern

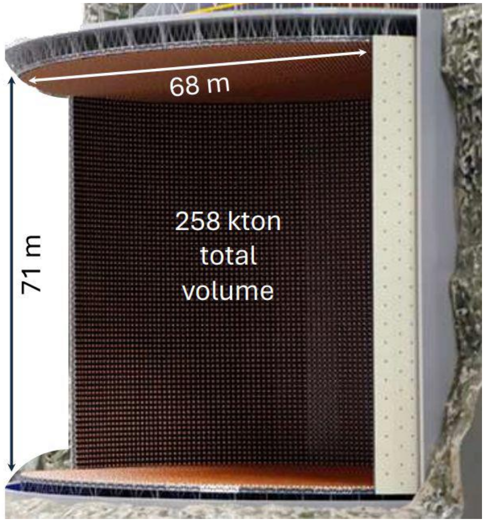


Excavation is in progress:

- **Access tunnel: done**
- **Dome: done**
- **Cavern: in progress**

	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% (×2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton



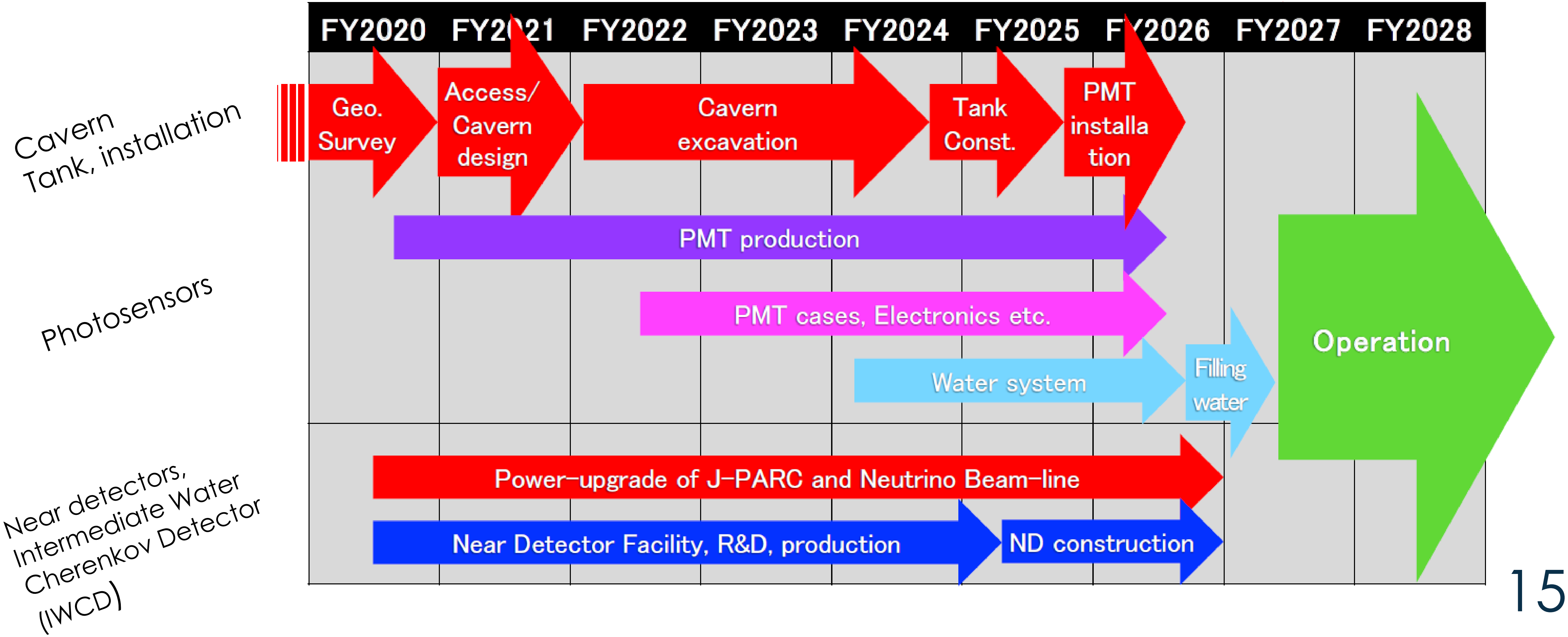


Hyper-K Overview

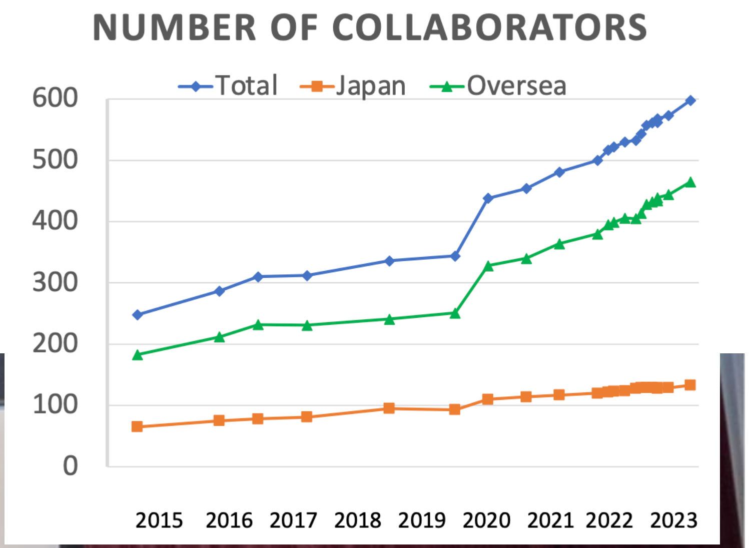
HK dome completed – Oct. 3, 2023

Hyper-K Status Schedule

Aiming at operation start in 2027



Hyper-K Collaboration



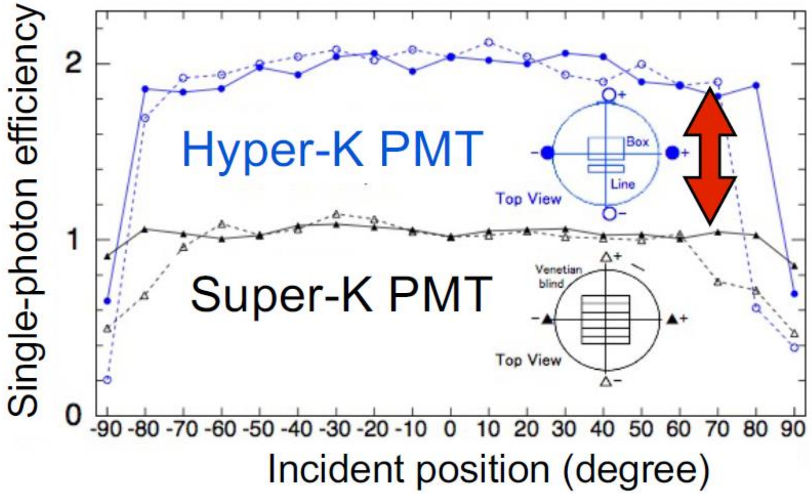
22 countries, 104 institutes, 583 members as of April 1, 2024

Hyper-K Collaboration Meeting,
October 2024, Toyama.

Hyper-K as a Nucleon Decay Discovery Experiment

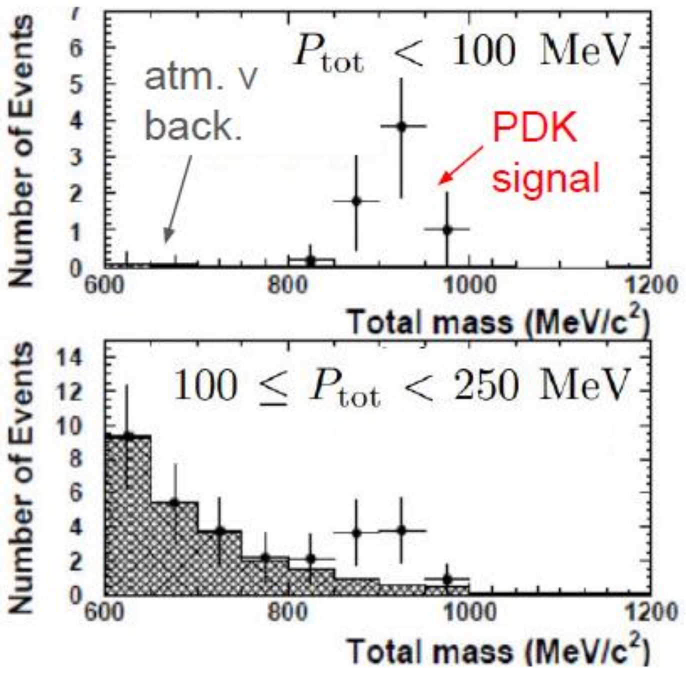
- **Fiducial Mass ~ 8 times SK: 186 kton (HK) vs. 22.5 kton (SK)**
- **Upgraded photosensors (50 cm Box & Line PMTs)**
  - **2x detection efficiency**
  - **2x timing resolution**
  - **2x pressure tolerance**

Expected ~1 order of magnitude sensitivity gain for proton decay search.
Start probing lifetimes ~ 10^{35} years



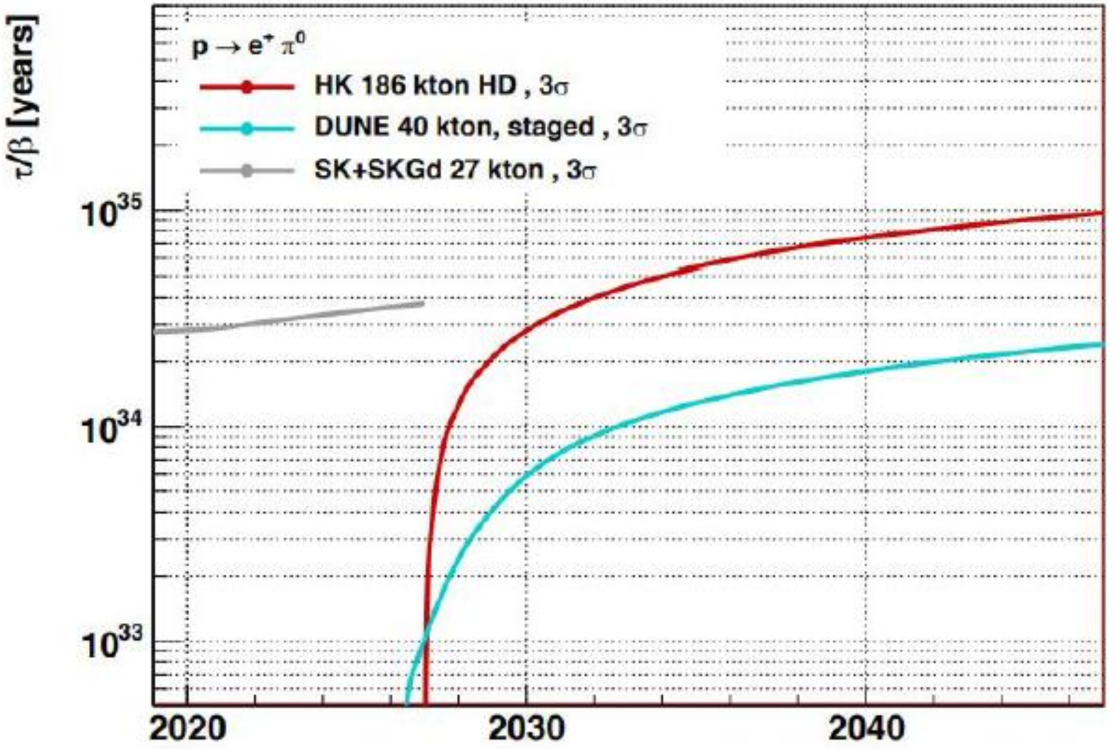
p -> $e^+\pi^0$ in Hyper-K

Assuming 10 years of HK exposure and lifetime limit ~ SK (1.7 x 10^{34} years)



$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

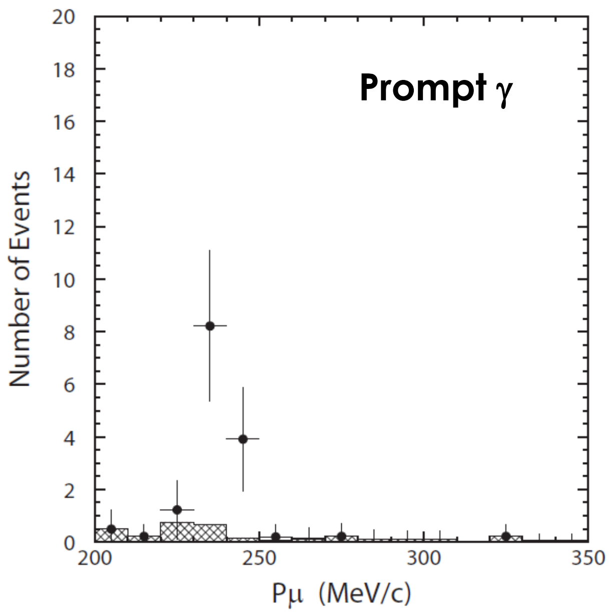
Probe τ ~ 10^{35} years

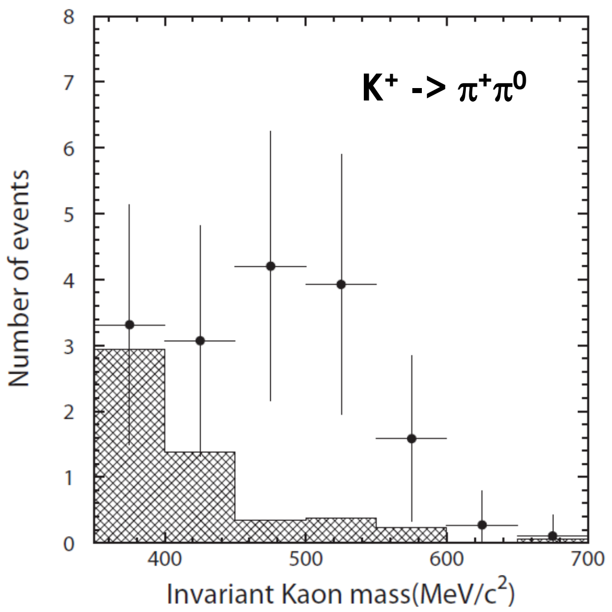


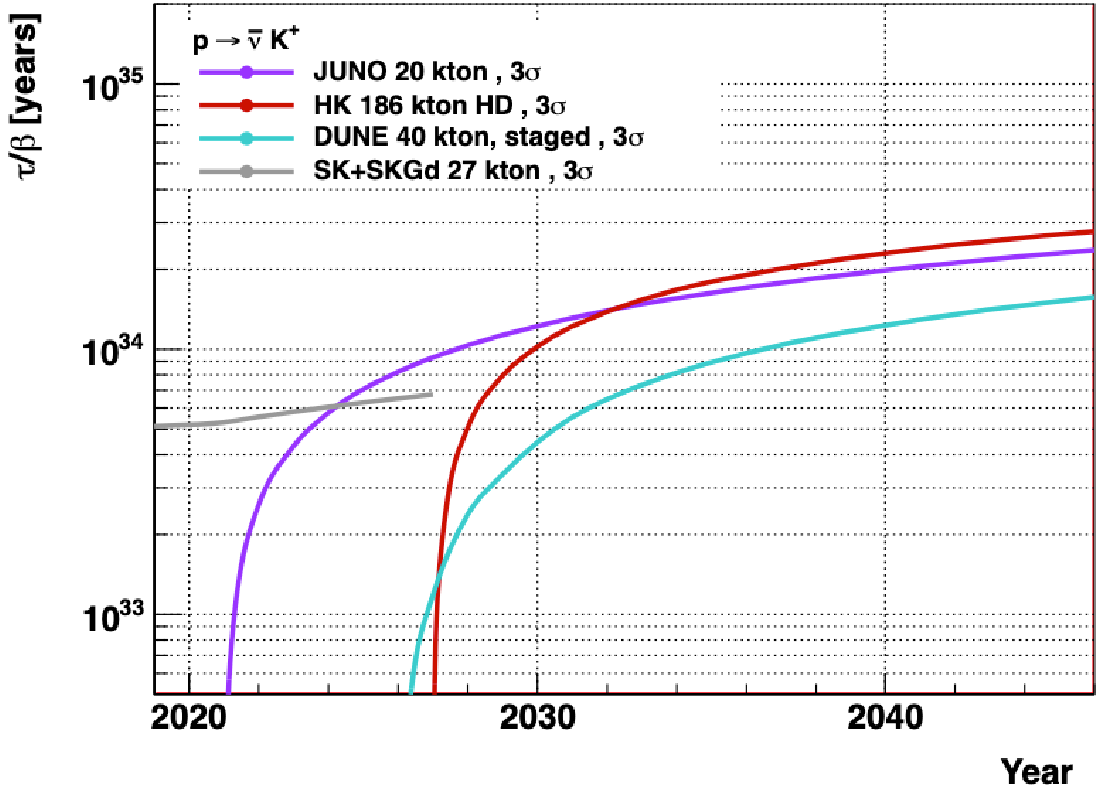
HK background is ~50% of SK

p -> ν K⁺ in Hyper-K

10 years HK exposure assuming $\tau = 6.6 \times 10^{33}$ years







Prompt γ		$\pi^+\pi^0$		p_μ Spectrum		
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	σ_{fit} [%]
12.7 ± 2.4	0.9 ± 0.2	10.8 ± 1.1	0.7 ± 0.2	31.0	1916.0	8.0

Other channels

Hyper-K TDR, Nov 2018, arXiv:1805.04163

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\pi^0$	$7.8\ \times 10^{34}$	1.6×10^{34}
$p \to \overline{\nu} K^+$	$3.2\ \times 10^{34}$	0.7×10^{34}
$p \to \mu^+\pi^0$	7.7×10^{34}	0.77×10^{34}
$p \to e^+\eta^0$	4.3×10^{34}	1.0×10^{34}
$p \to \mu^+\eta^0$	4.9×10^{34}	0.47×10^{34}
$p \to e^+\rho^0$	0.63×10^{34}	0.07×10^{34}
$p \to \mu^+\rho^0$	0.22×10^{34}	0.06×10^{34}
$p \to e^+\omega^0$	0.86×10^{34}	0.16×10^{34}
$p \to \mu^+\omega^0$	1.3×10^{34}	0.28×10^{34}
$n \to e^+\pi^-$	2.0×10^{34}	0.53×10^{34}
$n \to \mu^+\pi^-$	1.8×10^{34}	0.35×10^{34}

10 years of HK exposure

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\nu\nu$	$10.2\ \times 10^{32}$	$1.7\ \times 10^{32}$
$p \to \mu^+\nu\nu$	$10.7\ \times 10^{32}$	$2.2\ \times 10^{32}$
$p \to e{+}X$	$31.1\ \times 10^{32}$	$7.9\ \times 10^{32}$
$p \to \mu^+X$	$33.8\ \times 10^{32}$	$4.1\ \times 10^{32}$
$n \to \nu\gamma$	$23.4\ \times 10^{32}$	$5.5\ \times 10^{32}$
$np \to e^+\nu$	$6.2\ \times 10^{32}$	$2.6\ \times 10^{32}$
$np \to \mu^+\nu$	$4.2\ \times 10^{32}$	$2.0\ \times 10^{32}$
$np \to \tau^+\nu$	$6.0\ \times 10^{32}$	$3.0\ \times 10^{32}$

30 years of HK exposure

Also neutron – antineutron oscillation analysis possible:
Searched in SK with 90 kton*year exposure. τ > 2.7 x 10^8 s
[PHYSICAL REVIEW D 91, 072006 (2015)]

Summary

- Proton decay is a valuable probe to test Physics Beyond the Standard Model
- Hyper-K will play a central role in exploring the future of particle physics
- Hyper-K will bring proton decay searches to proton lifetimes ~ 10^{35} years
- Many exciting challenges and discoveries ahead: data taking is expected to start in 2027!

THANK YOU FOR YOUR ATTENTION!