Hyper-Kamiokande

A Nucleon Decay Discovery Experiment

Volodymyr Takhistov

(on behalf of the Hyper-Kamiokande Collaboration)

QUP & Theory Center, KEK & SOKENDAI & Kavli IPMU, U. Tokyo

Mark Garlick

Do protons decay?

- Lightest baryon (proton) stable
- ***B*-number** proposed to explain matter stability [Weyl, 1929; Stueckelberg, 1939; Wigner, 1949]
- In Standard Model (SM) ***B*** not fundamental, accidental global symmetry

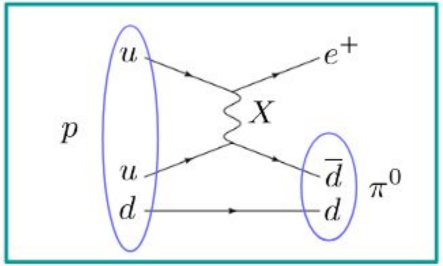
  But… long history of such symmetries later found violated (e.g. *C*, *P*)
- Already in SM ***B*** is violated by non-perturbative effects [t'Hooft, 1976]
- SM incomplete, ***B*** viol. in many theories (baryogenesis, GUTs, SUSY, extra-dim...)
- Global symmetries expected to be violated by quantum gravity
- Proton decay can be essential for fate of astrophysical objects [Adams, Laughlin, 1997]

Grand Unified Theories (GUTs)

- Unify SM gauge groups [Georgi, Glashow, 1974; Fritzch, Minkowski, 1975] ($SU(5)$, $SO(10)$)
  → explain charge quantization, coupling unification, anomaly cancellation…
- **Leptons** ↔ **quarks** interact → nucleon decay

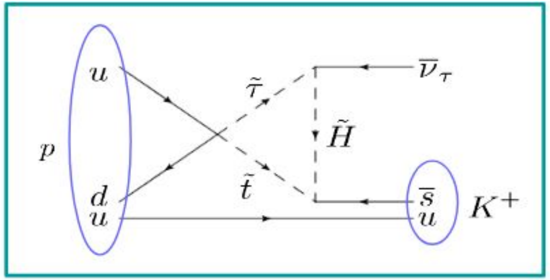
typically dominant: $p \to e^+\pi^0$ $SU(5)$

$\tau = \frac{1}{\Gamma} \propto \left[\frac{M_X^2}{\alpha^2}\right]^2$



SUSY $SU(5)$: $p \to \overline{\nu} K^+$

$\tau = \frac{1}{\Gamma} \propto \left[\frac{M_s M_T}{\alpha^2}\right]^2$



→ prediction $\tau \sim 10^{29-36}$ yrs
→ minimal model ruled out (IMB-3, Kamiokande, Super-K)

→ prediction $\tau \sim 10^{29-36}$ yrs
→ minimal (TeV-)SUSY model ruled out by Super-K [Kobayashi+ (SK), 2005]

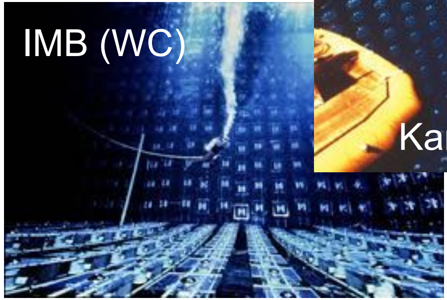
- Big uncertainties in predictions, very many models (e.g. [Nath, Perez, 2006] review)

How to search?

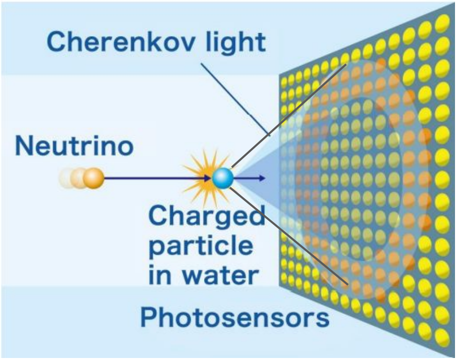
- Already in 1950s, Goldhaber argued on general grounds $\tau > 10^{18}$ yrs
  → Many searches with different methods since

- Proton lives $\tau > 10^{30}$ yrs, how to test?
  - Look at 1 proton VERY long time ❌
  - Look at many protons for few years ✓

- **Large-scale water Cherenkov detectors - excellent targets**
  - Cheap, easily scalable (e.g. iron calorimeters are not)
  - Proven technology
  - H_2O includes 2 hydrogen “free protons” (high selection efficiency, low uncertainty)



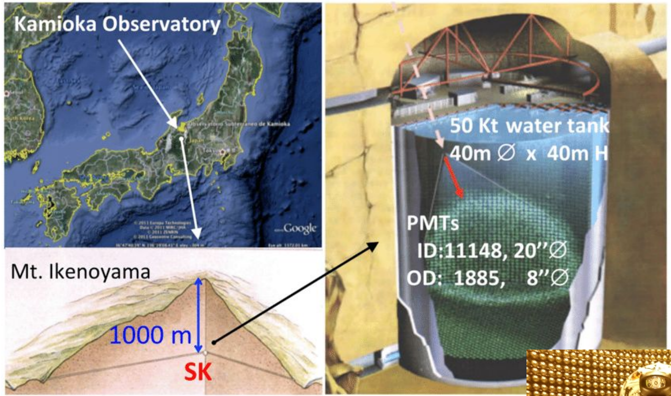
Water Cherenkov Detection and State-of-the-Art



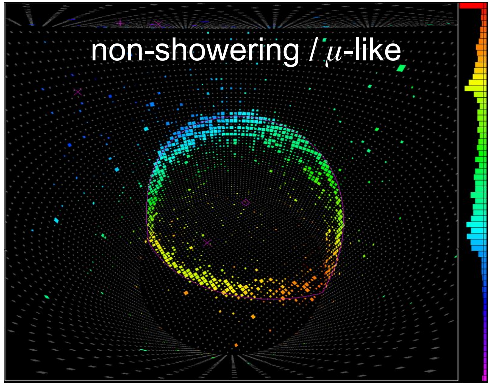
current state-of-the-art

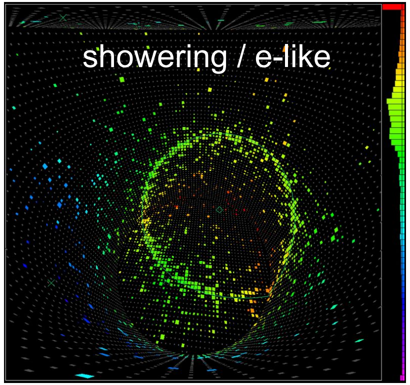
Super-Kamiokande (SK, Super-K)

~20+ years of data



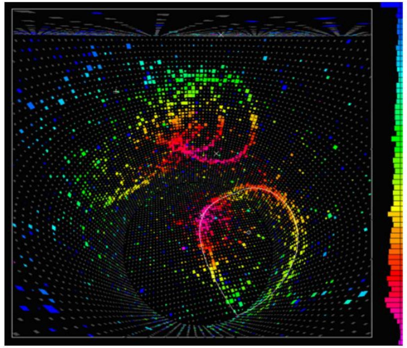
real SK data (1998)

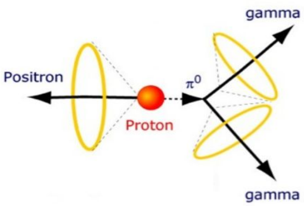


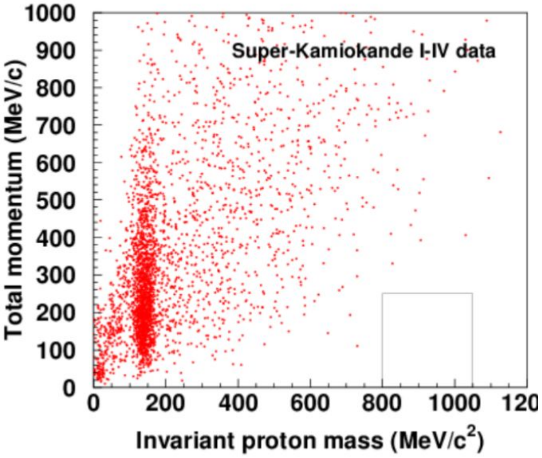


$p \to e^+\pi^0$ in Super-K

- Final state (positron + 2 gammas) is fully visible, easy to identify
  → can reconstruct proton mass/momentum, clean channel nearly background-free

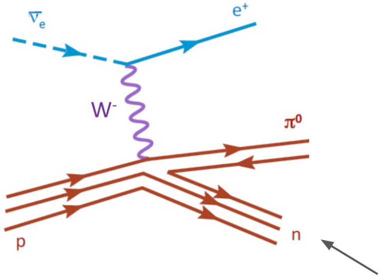






- *Exposure:* 450 kton*yr
- *Signal efficiency:* 38.6% (SK I-IV)
- *Expected background:*
0.05 ev. $P_{\rm tot} < 100$ MeV
0.58 ev. in region $100 \leq P_{\rm tot} < 250$ MeV

typical atm. ν background



neutron hard to see, benefits from improved n-tag efficiency (SK pure water ~ 20%)

[Abe+ (SK), 2020]

No candidates, set most stringent lower limit:

$> 2.4 \times 10^{34}$ yrs.

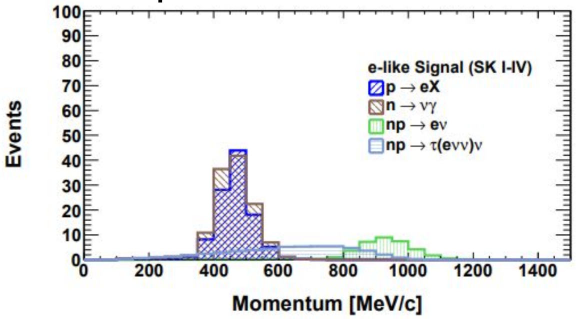
Previous Super-K Searches Set Many World Best Limits

- SK already probed 25+ channels (incl. dinucleon decays..)
- **Some candidates, no evidence of nucleon decays**
  → many world best limits

- Analysis strategy depends on channel specifics
  → visible Cherenkov rings, backgrounds…

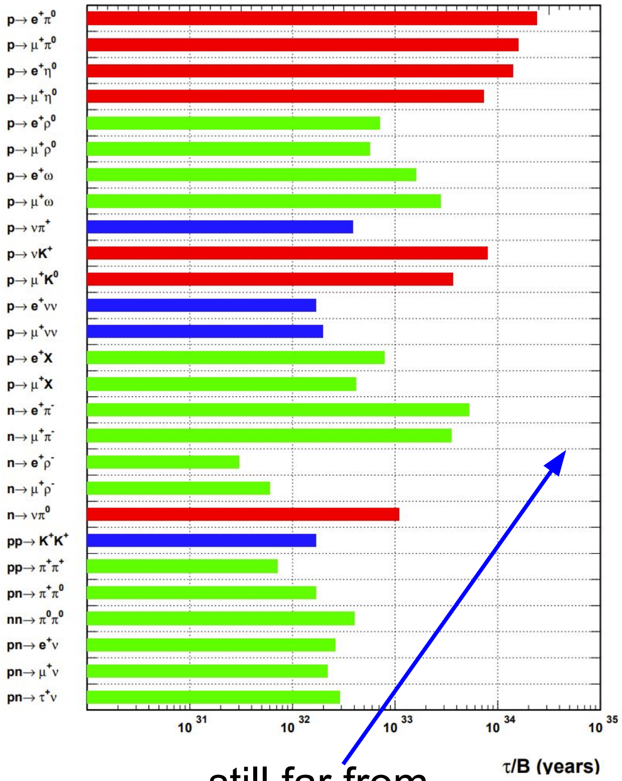
spectral fit searches

Example:



[**VT+** (SK), *PRL*, (2014)]
[**VT+** (SK), *PRL*, (2015)]

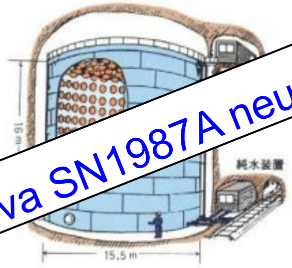
some missing energy, hard to reconstruct parent nucleons, lots of background



still far from
$\tau \sim 10^{35}\,\mathrm{yrs}$

Into the Future with Hyper-Kamiokande (Hyper-K, HK)

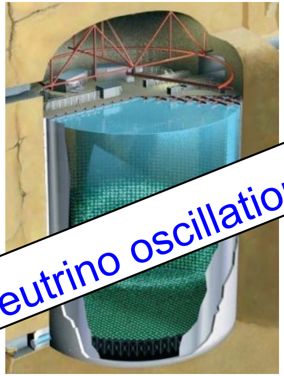
Kamiokande



Supernova SN1987A neutrinos

3 kton
(1983-1996)

Super-Kamiokande

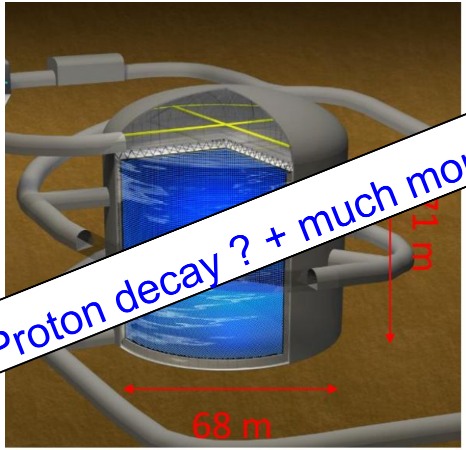


Neutrino oscillations

50 kton
(1996- Present)

[starts soon !]

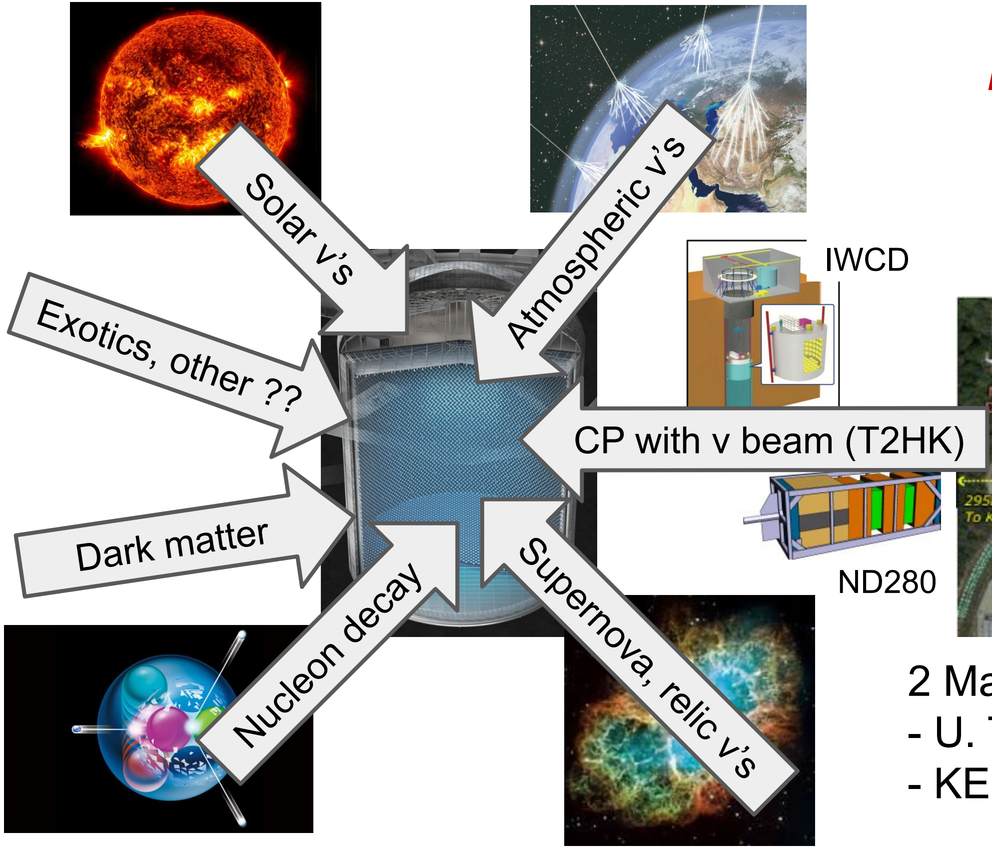
Hyper-Kamiokande



Proton decay ? + much more…

260 kton
(2027? -)

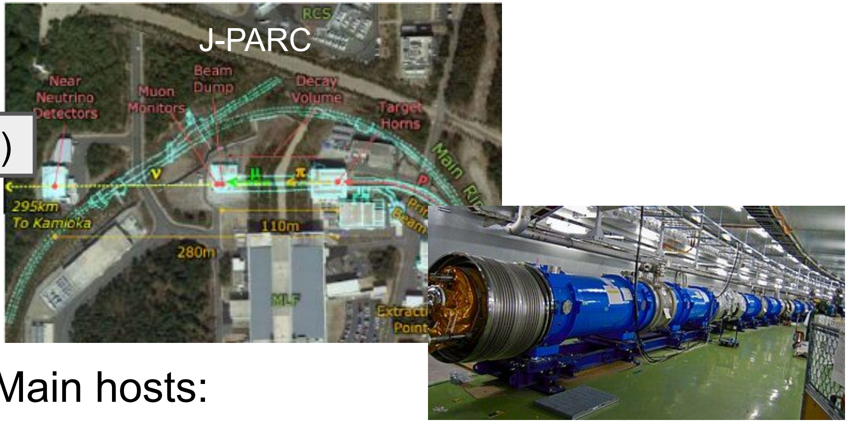
Hyper-K Truly Spectacular Multipurpose Experiment



Very broad physics program, many opportunities for discoveries

2020 - Construction started

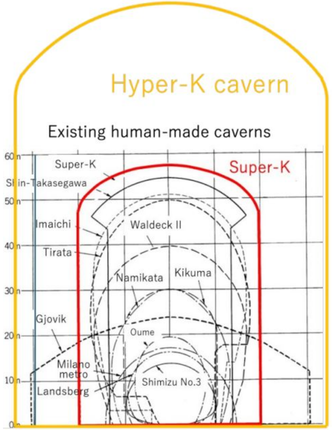
2027 - Operation start



2 Main hosts:
- U. Tokyo for HK detector
- KEK J-PARC for beam/near detectors

→ *welcome your help! e.g. IWCD…*

Hyper-K Overview



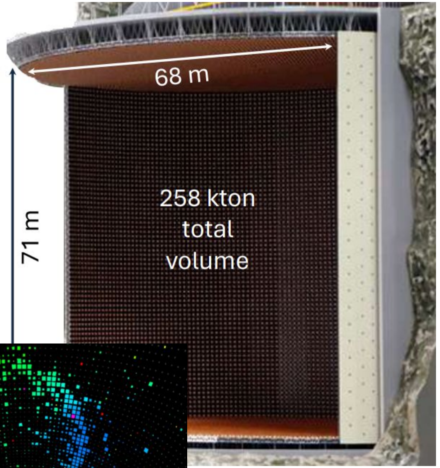
- **Next generation flagship neutrino observatory in Japan**

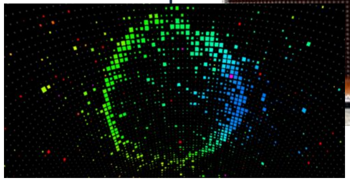
- **Big construction progress:**
  - access tunnel → *done* ✓
  - dome cavern → *done* ✓
  - cavern excavation → *underway*


HK dome - Oct. 3, 2023

- **Engineering marvel** - largest man-made cavern in world !

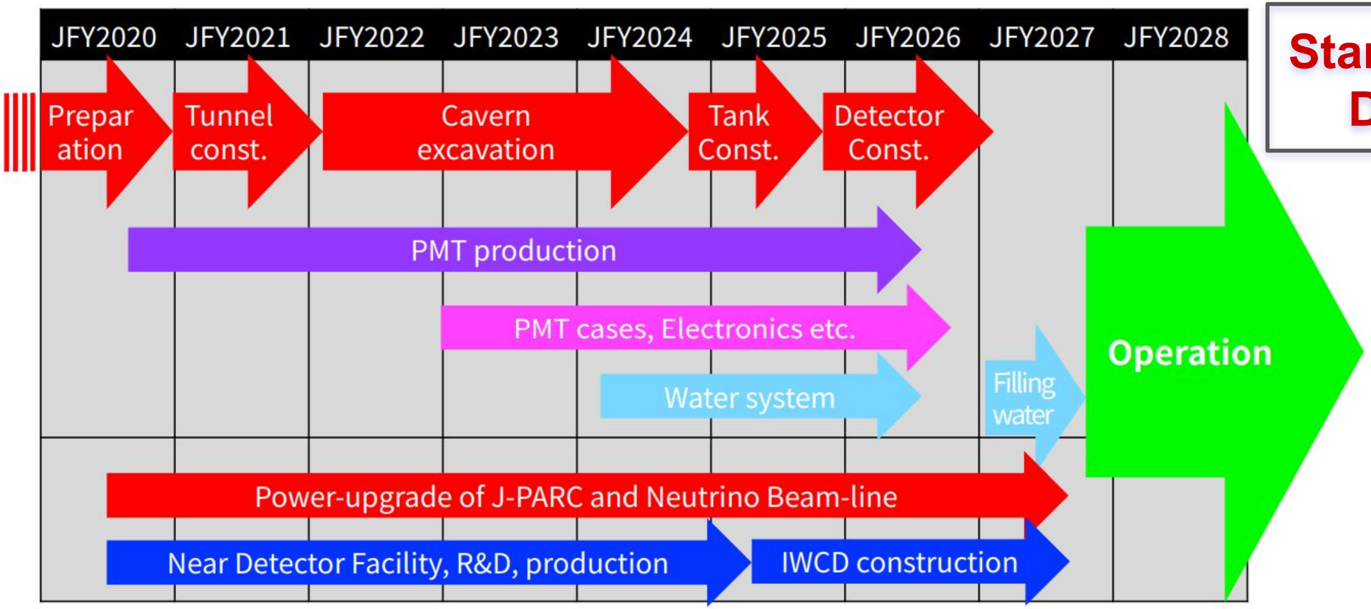
	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% (×2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton





Hyper-K Status Schedule

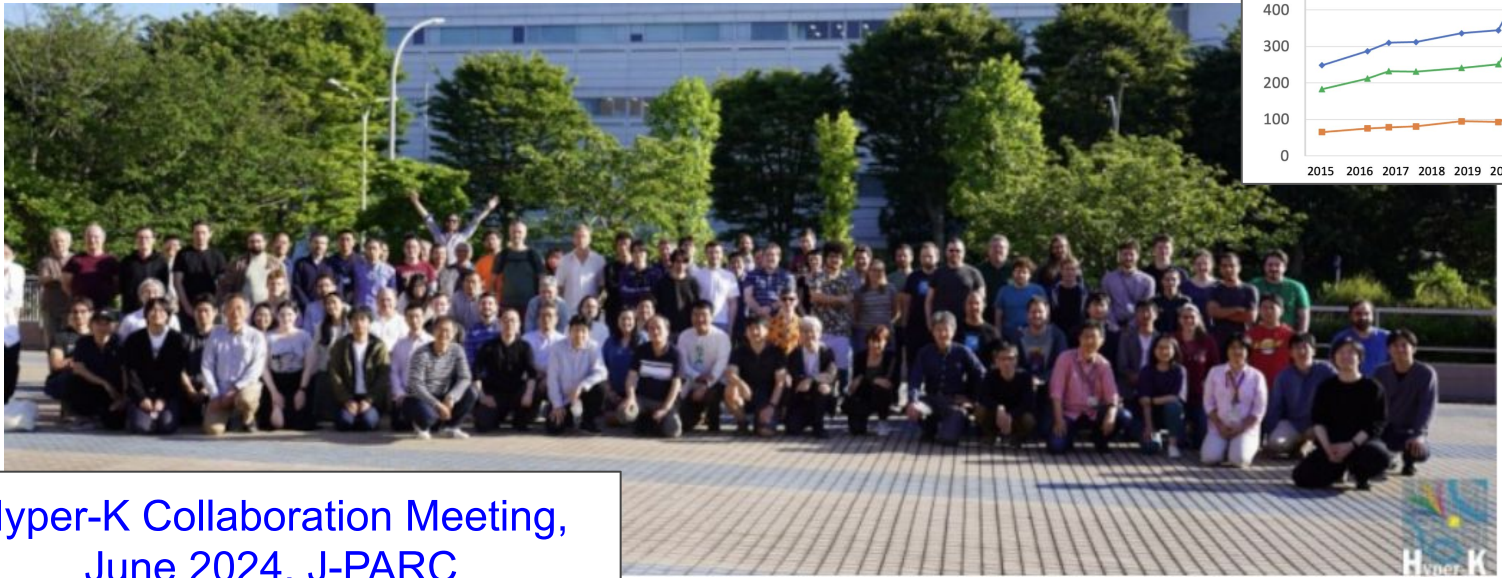
- Construction extended by 6 months, primarily due to top structure changes

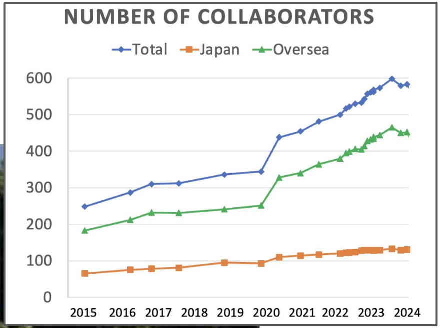


Start operation Dec. 2027

Hyper-K Collaboration

22 countries, 104 institutes, ~590 people (Aug. 2024)



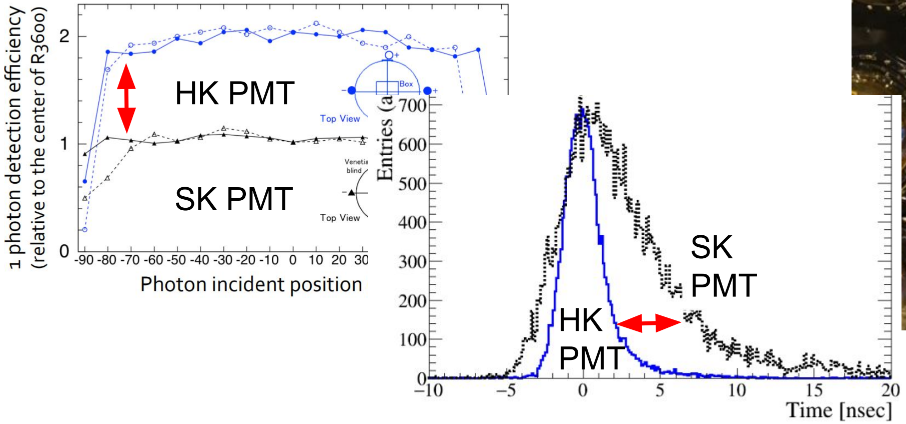


Hyper-K Collaboration Meeting, June 2024, J-PARC

Hyper-K as Nucleon Decay Discovery Experiment

- **Fiducial Mass ~ 8 x SK:** 190 kton (HK) vs. 22.5 kton (SK)
- **Upgraded photo sensors** (Box & Line PMT)
  - Photon detection efficiency 2x better vs. SK
  - Timing resolution 2x better vs. SK
  - Pressure tolerance 2x better vs. SK

Proton decay @ Hyper-K
→ expect ~order sensitivity gain
→ start probing $\tau \sim 10^{35}\,\mathrm{yrs}$

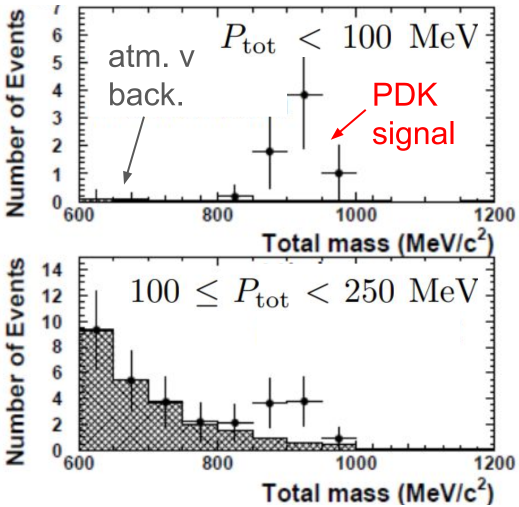


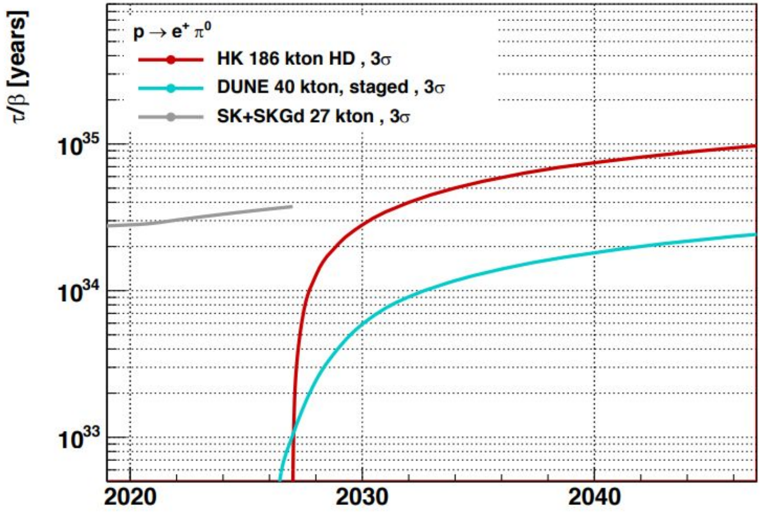
PMTs validated in SK

p →$e^+\pi^0$ in Hyper-K

Assuming life. around SK limit $\sim \text{few} \times 10^{34}\text{yrs}$

HK
(10 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 at 3σ lifetime $\tau \sim 10^{35}\text{yrs}$

HK background ½ of SK
(improved n-tag with upgraded PMTs…)

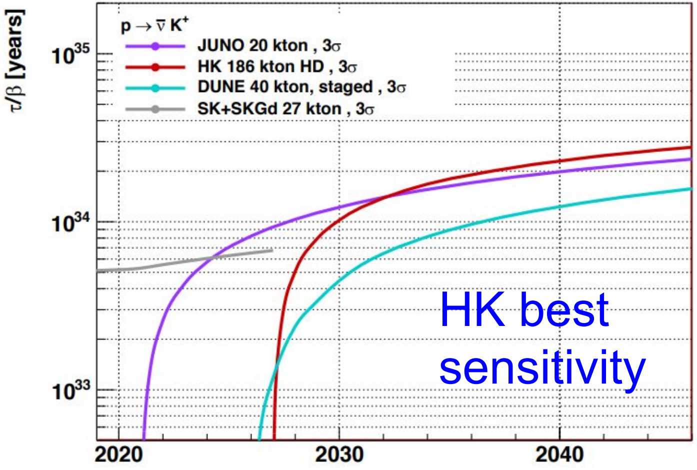
p →νK⁺ in Hyper-K

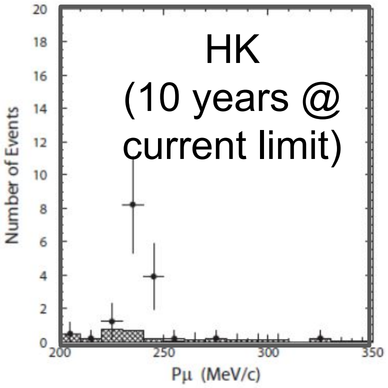
- Invisible ν, can't reconstruct proton
- Most K^+ are below Cherenkov threshold (560 MeV)
- 3 different analyses based on K^+ decays

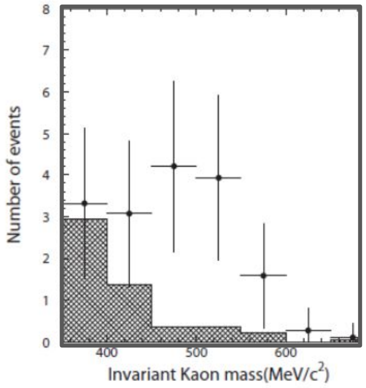
  $K^+ \rightarrow \nu\mu^+$: 64 %

  $K^+ \rightarrow \pi^+\pi^0$: 21 %

- SK results at 365 kton*yr exposure show no evidence, limit $> 0.8 \times 10^{34}$yrs







p_μ Spectrum		
ϵ_{sig} [%]	Bkg [/Mton·yr]	σ_{fit} [%]
31.0	1916.0	8.0

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

Many New Search Opportunities, Hyper-K to Lead the Game

Many channels still never searched…

Channel	$\|\Delta(B-L)\|$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$p \to e^- + e^+ + e^+$	0	793 [65]
$p \to e^- + e^+ + \mu^+$	0	529 [65]
$p \to e^+ + e^+ + \mu^-$	0	529* [65]
$p \to e^- + \mu^+ + \mu^+$	0	6 [64] (359* [65])
$p \to e^+ + \mu^- + \mu^+$	0	359 [65]
$p \to \mu^- + \mu^+ + \mu^+$	0	675 [65]
$p \to e^+ + 2\nu$	0,2	170 [81]
$p \to \mu^+ + 2\nu$	0,2	220 [81]
$p \to e^- + 2\pi^+$	2	30 [62] (82* [65])
$p \to e^- + \pi^+ + \rho^+$	2	
$p \to e^- + K^+ + \pi^+$	2	75 [65]
$p \to e^+ + 2\gamma$	0	100 [82] (793* [65])
$p \to e^+ + \pi^- + \pi^+$	0	82 [65]
$p \to e^+ + \rho^- + \pi^+$	0	
$p \to e^+ + K^- + \pi^+$	0	75* [65]
$p \to e^+ + \pi^- + \rho^+$	0	
$p \to e^+ + \pi^- + K^+$	0	75* [65]
$p \to e^+ + 2\pi^0$	0	147 [65]
$p \to e^+ + \pi^0 + \eta$	0	
$p \to e^+ + \pi^0 + \rho^0$	0	
$p \to e^+ + \pi^0 + \omega$	0	
$p \to e^+ + \pi^0 + K^0$	0	
$p \to \mu^- + 2\pi^+$	2	17 [62] (133* [65])
$p \to \mu^- + K^+ + \pi^+$	2	245 [65]
$p \to \mu^+ + 2\gamma$	0	529* [65]
$p \to \mu^+ + \pi^- + \pi^+$	0	133 [65]
$p \to \mu^+ + K^- + \pi^+$	0	245* [65]
$p \to \mu^+ + \pi^- + K^+$	0	245* [65]
$p \to \mu^+ + 2\pi^0$	0	101 [65]
$p \to \mu^+ + \pi^0 + \eta$	0	
$p \to \mu^+ + \pi^0 + K^0$	0	
$p \to \nu + \pi^+ + \pi^0$	0,2	
$p \to \nu + \pi^+ + \eta$	0,2	
$p \to \nu + \pi^+ + \rho^0$	0,2	
$p \to \nu + \pi^+ + \omega$	0,2	
$p \to \nu + \pi^+ + K^0$	0,2	
$p \to \nu + \rho^+ + \pi^0$	0,2	
$p \to \nu + K^+ + \pi^0$	0,2	

Channel	$\|\Delta(B-L)\|$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$nn \to \pi^0 + \phi$	2	
$nn \to 2\eta$	2	
$nn \to \eta + \rho^0$	2	
$nn \to \eta + \omega$	2	
$nn \to \eta + \eta'$	2	
$nn \to \eta + K^0$	2	
$nn \to \eta + K^{*,0}$	2	
$nn \to \eta + \phi$	2	
$nn \to 2\rho^0$	2	
$nn \to \rho^0 + \omega$	2	
$nn \to \eta' + \rho^0$	2	
$nn \to K^0 + \rho^0$	2	
$nn \to K^{*,0} + \rho^0$	2	
$nn \to \rho^0 + \phi$	2	
$nn \to \rho^- + \rho^+$	2	
$nn \to K^+ + \rho^-$	2	
$nn \to K^{*,+} + \rho^-$	2	
$nn \to K^- + \rho^+$	2	
$nn \to K^{*,-} + \rho^+$	2	
$nn \to 2\omega$	2	
$nn \to \eta' + \omega$	2	
$nn \to K^0 + \omega$	2	
$nn \to K^{*,0} + \omega$	2	
$nn \to \omega + \phi$	2	
$nn \to \eta' + K^0$	2	
$nn \to \eta' + K^{*,0}$	2	
$nn \to K^- + K^+$	2	170* [116]
$nn \to K^+ + K^{*,-}$	2	
$nn \to K^- + K^{*,+}$	2	
$nn \to 2K^0$	2	
$nn \to K^{*,0} + K^0$	2	
$nn \to K^0 + \phi$	2	
$nn \to 2K^{*,0}$	2	
$nn \to K^{*,-} + K^{*,+}$	2	

Channel	$\|\Delta(B-L)\|$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$n \to \nu + e^- + e^+$	0,2	257 [65]
$n \to \nu + e^- + \mu^+$	0,2	83 [65]
$n \to \nu + e^+ + \mu^-$	0,2	83* [65]
$n \to \nu + \mu^- + \mu^+$	0,2	79 [65]
$n \to 3\nu$	0,2,4	0.58 [83]
$n \to e^- + \pi^+ + \pi^0$	2	29 [62] (52* [65])
$n \to e^- + \pi^+ + \eta$	2	
$n \to e^- + \pi^+ + \rho^0$	2	
$n \to e^- + \pi^+ + \omega$	2	
$n \to e^- + \pi^+ + K^0$	2	
$n \to e^- + \rho^+ + \pi^0$	2	
$n \to e^- + K^+ + \pi^0$	2	
$n \to e^+ + \pi^- + \pi^0$	0	52 [65]
$n \to e^+ + \pi^- + \eta$	0	
$n \to e^+ + \pi^- + \rho^0$	0	
$n \to e^+ + \pi^- + \omega$	0	
$n \to e^+ + \pi^- + K^0$	0	18 [62]
$n \to e^+ + \rho^- + \pi^0$	0	
$n \to e^+ + K^- + \pi^0$	0	
$n \to \mu^- + \pi^+ + \pi^0$	2	[illegible] [62] (74 [illegible])
$n \to \mu^- + \pi^+ + \eta$	2	
$n \to \mu^- + \pi^+ + K^0$	2	
$n \to \mu^- + K^+ + \pi^0$	2	
$n \to \mu^+ + \pi^- + \pi^0$	0	74 [65]
$n \to \mu^+ + \pi^- + \eta$	0	
$n \to \mu^+ + \pi^- + K^0$	0	
$n \to \mu^+ + K^- + \pi^0$	0	
$n \to \nu + 2\gamma$	0,2	219 [65]
$n \to \nu + \pi^- + \pi^+$	0,2	
$n \to \nu + \rho^- + \pi^+$	0,2	
$n \to \nu + K^- + \pi^+$	0,2	
$n \to \nu + \pi^- + \rho^+$	0,2	
$n \to \nu + \pi^- + K^+$	0,2	
$n \to \nu + 2\pi^0$	0,2	
$n \to \nu + \pi^0 + \eta$	0,2	
$n \to \nu + \pi^0 + \rho^0$	0,2	
$n \to \nu + \pi^0 + \omega$	0,2	
$n \to \nu + \pi^0 + K^0$	0,2	

[Heeck, **VT**, (2019)]

Non-canonical channels with new particles in final states barely explored, very many …

Examples

$(\Delta B, \Delta L)$	Dim	Decay modes	New Field(s)
$(1,1)$	6	$p(n) \to \pi^{+(0)} N$	sterile neutrinos
$(1,-1)$	7	$n \to N\gamma$ $p(n) \to \pi^{+(0)} N\gamma$	sterile neutrinos
$(1,1)$	7	$p \to e^+\phi$ $p(n) \to e^+\pi^{0(-)}\phi$	dark scalars, majorons
$(1,1)$	7	$n \to \nu X$ $p(n) \to \nu\pi^{+(0)} X$ $n \to e^+\pi^- X$	dark photons
$(1,1)$	8	$n \to \nu\phi$ $n \to e^+\pi^-\phi$	dark scalars, majorons
$(1,1)$	8	$n \to \nu a$ $p(n) \to e^+\pi^{0(-)} a$ $p(n) \to e^+\pi^{0(-)} a$	axion-like particles
$(1,-1)$	8	$n \to Na$ $p(n) \to \pi^{+(0)} Na$	axion-like particles with sterile neutrinos
$(1,1)$	9	$p \to e^+\nu N$ $n \to e^+e^- N$	sterile neutrinos
$(1,3)$	9	$p \to e^+ NN$	sterile neutrino

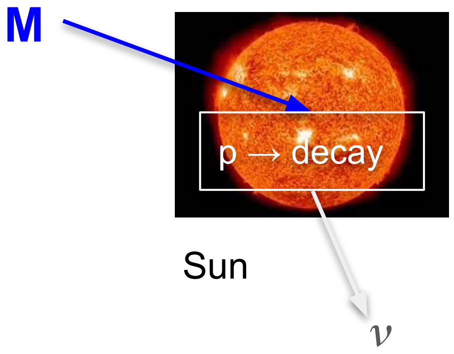
[Fridell, Hati, **VT**, PRD Lett. (2024)]

Many ideas in literature, e.g. also induced nucleon decays …

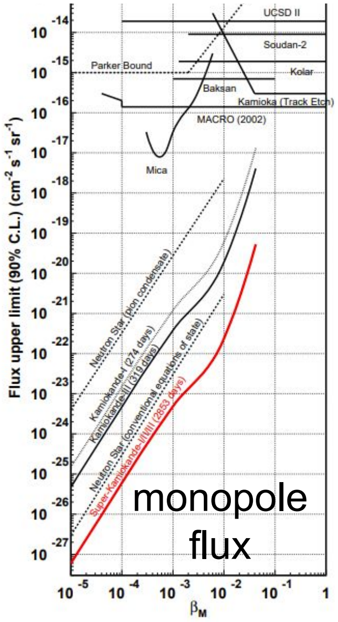
Even More Nucleon Decay Targets: Monopoles & Q-Balls

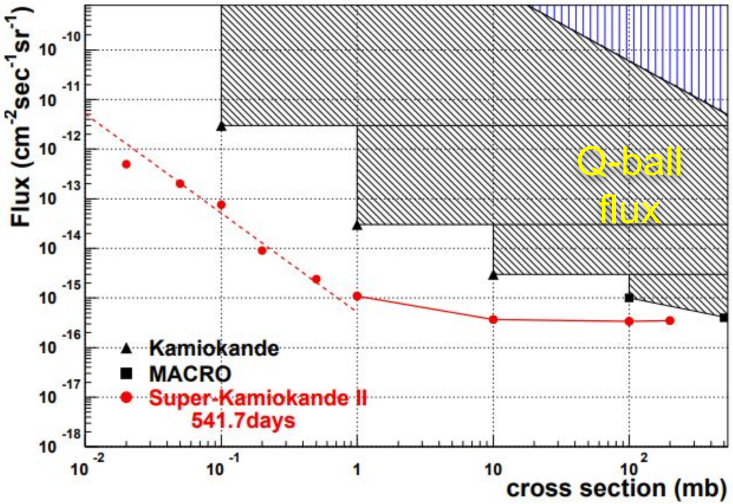
- Heavy monopoles from unified theories can be captured by Sun and catalyze proton decay via Callan-Rubakov process producing neutrinos → can detect in HK
- Q-balls naturally appear from field instabilities in e.g. supersymmetric theories, can induce nucleon decay in HK when they carry baryon number

$$p \to (\rho^0, \omega, \eta, K^+, \cdots) + e^+(\text{or} \;\; \mu^+)$$



[Ueno+ (SK), 2012]
+ Feng (SK), M.S. thesis, 2021

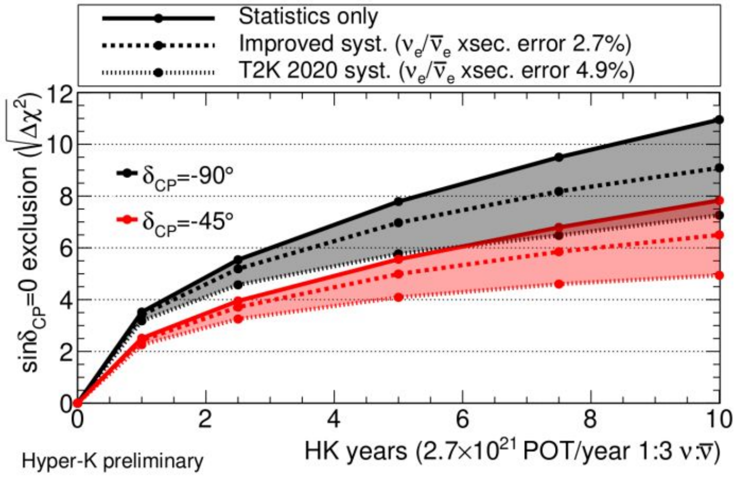




[Takenaga+ (SK), 2007]

Hyper-K Excels in Many Areas, Including Oscillation Program

- For ~60% of $\delta_{\rm CP}$ values, can discover $\delta_{\rm CP}$ with 5σ in 10 years (assuming mass ordering)
- For $\delta_{\rm CP} = \pm 90^\circ$, can discover within 5 years
- Combination of beam + atmospheric neutrinos allows resolving degeneracies and offers good sensitivity to mass ordering



	$\sin^2\theta_{23}$	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

HK can also give more constraints on atmospheric flux and cross sections
→ help our understanding of the nucleon decay background

Summary

- Nucleon decays offer unique opportunities to probe fundamental physics, often challenging to test otherwise
- Great success of Super-K WC experiment running for over 20 years enabled probing many nucleon decay process, with no evidence found and leading limits
- Hyper-K, as successor of Super-K, will spearhead nucleon decay searches. Plethora of processes, including completely new ones, are ripe to explore. Thanks to its versatility, Hyper-K will probe many of them with unprecedented sensitivity
- An excellent multipurpose experiment Hyper-K will play central role in many areas, including determination of remaining ν-oscillation parameters

Let’s enjoy exciting discoveries together