Nucleon Decay Searches in Super-Kamiokande and Hyper-Kamiokande

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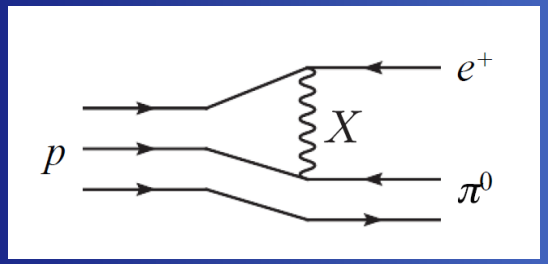
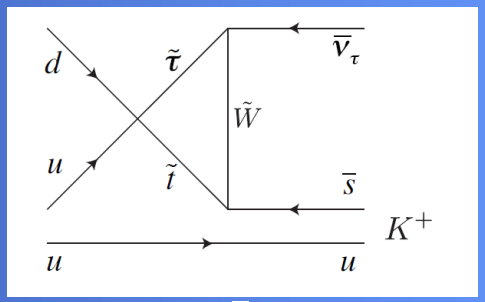
1. Introduction

- Proton decays are Baryon number violating phenomena which predicted by many GUT models.



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



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

Proton lifetime predictions

Model	Mode	Prediction (years)
Minimal SU(5)	$p \rightarrow e^+\pi^0$	$10^{28.5} \sim 10^{31.5}$ [1]
Minimal SO(10)	$p \rightarrow e^+\pi^0$	$10^{30} \sim 10^{40}$ [2]
Minimal SUSY SU(5)	$p \rightarrow \nu K^+$	$\leq 10^{30}$ [3]
SUGRA SU(5)	$p \rightarrow \nu K^+$	$10^{32} \sim 10^{34}$ [4]
SUSY SO(10)	$p \rightarrow \nu K^+$	$10^{32} \sim 10^{34}$ [5]

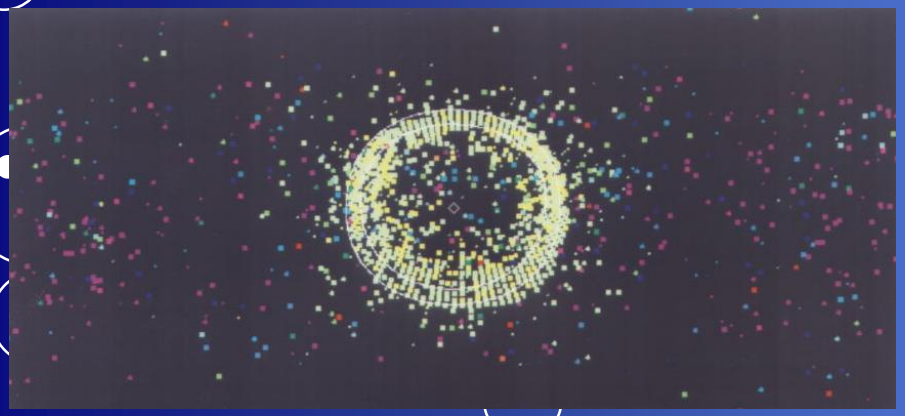
[1] P. Langacker, Phys. Reports 72, 185 (1981)
[2] D.G. Lee, M.K. Parida, and M. Rani, Phys. Rev. D51, 229 (1995)
[3] H.Murayama and A. Pierce, Phys. Rev. D65, 55009 (2002)
[4] T. Goto and T. Nihei, Phys. Rev. D59, 115009 (1999)
[5] V. Lucas and S. Ruby, Phys. Rev. D55, 6986 (1997)

$> 10^{30}$ years !
Need huge detector .

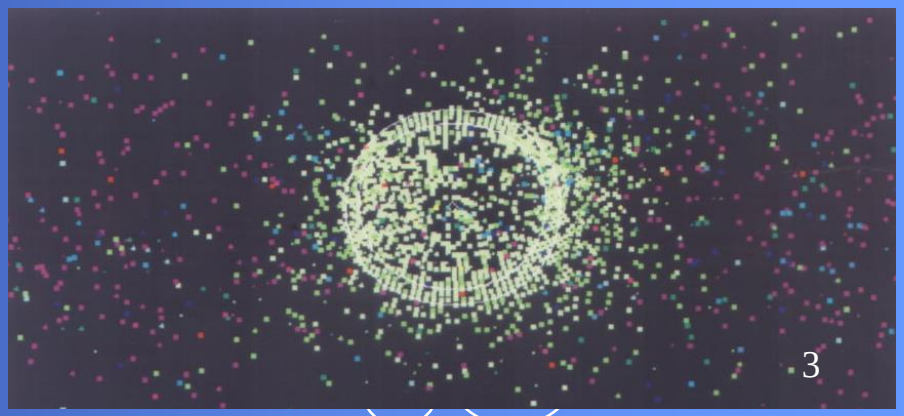
2. Super-Kamiokande

Location: Kamioka mine, Japan. ~1000 m under ground.
Size: 39 m (diameter) x 42 m (height), 50kton water.
Optically separated into inner detector (ID) and outer detector (OD, ~2.5 m layer from tank wall.)
Photo device: 20 inch PMT (ID), 8 inch PMT (OD, veto cosmic rays, ~1/3 comes from IMB).
Mom. resolution: 3.0 % for e 1 GeV/c (4.1%: SK-2).
Particle ID: Separate into EM shower type (e-like) and muon type (μ-like) by Cherenkov ring angle and ring pattern.

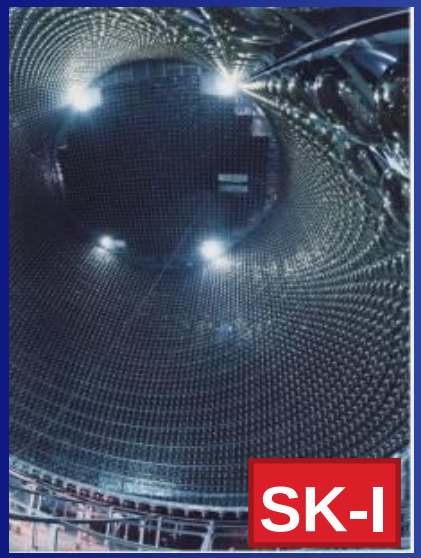
μ-like ($\mu^{\pm}$)



e-like ($e^{\pm}$, γ)

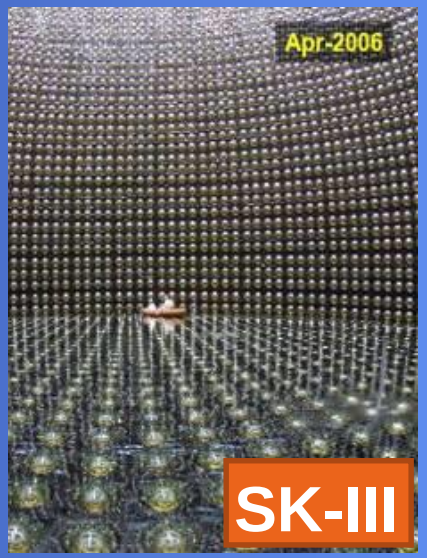


History of Super-Kamiokande



11146 ID PMTs
(40% coverage)

5182 ID PMTs
(19% coverage)



11129 ID PMTs
(40% coverage)

Electronics
Upgrade

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18

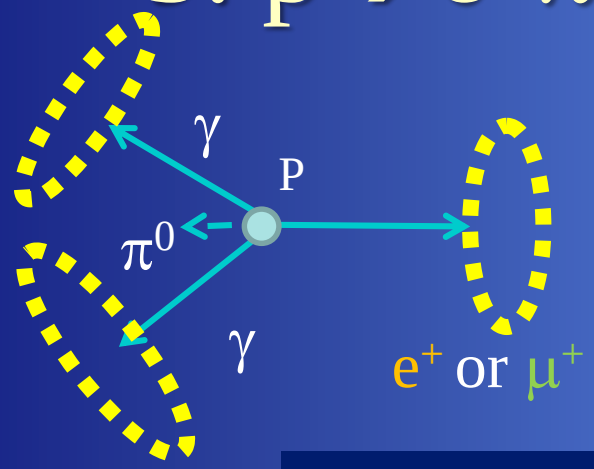
SK-I SK-II SK-III SK-IV

- SK has been running more than 20 years (amazingly!)
- Collected 372 kton·year exposure until 2018

➔ Many of the current limits come from SK.

PRD **95**, 12004 (2017)→ updated

3. $p \rightarrow e^+\pi^0$, $\mu^+\pi^0$ mode



Event features;

- e^+ ,$\mu^+$and π^0 are back-to-back (459 MeV/c)
- $\pi^0 \rightarrow 2\gamma$s : all particles are detectable.

➔ Reconstruct proton mass and momentum.

Selection;

- Fully contained, VTX in fiducial volume.
- 2 or 3 ring

$e^+\pi^0$ case;

- all e-like, w/o decay-e.

Selected by simple cuts!

$\mu^+\pi^0$ case;

- one μ-like with decay-e.

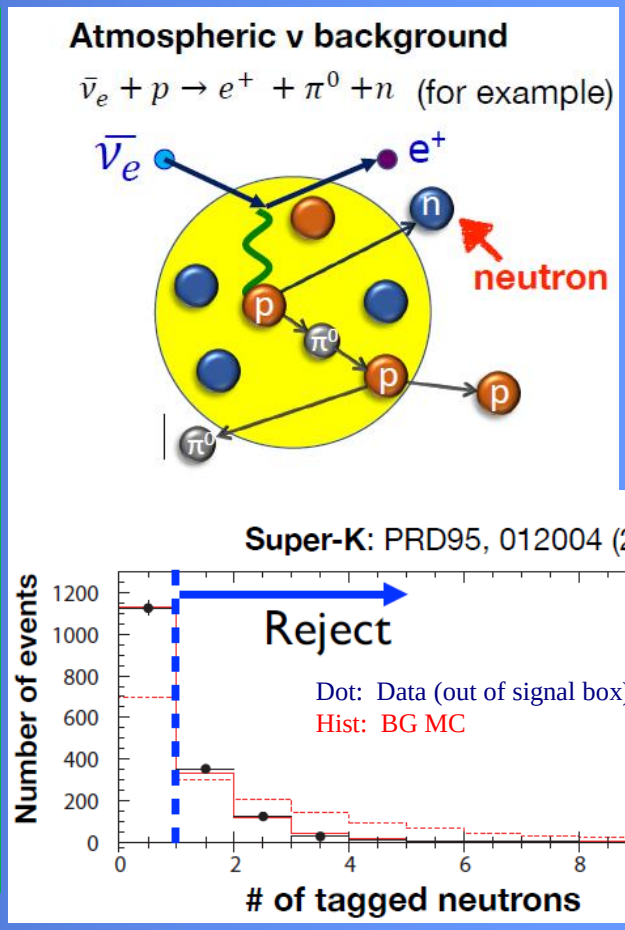
- $85 < M\pi^0 < 185$ MeV (for 3-ring event) .
- $800 < M_P < 1050$ MeV & $P_{tot} < 250$ MeV/c

New technique : Neutron tag

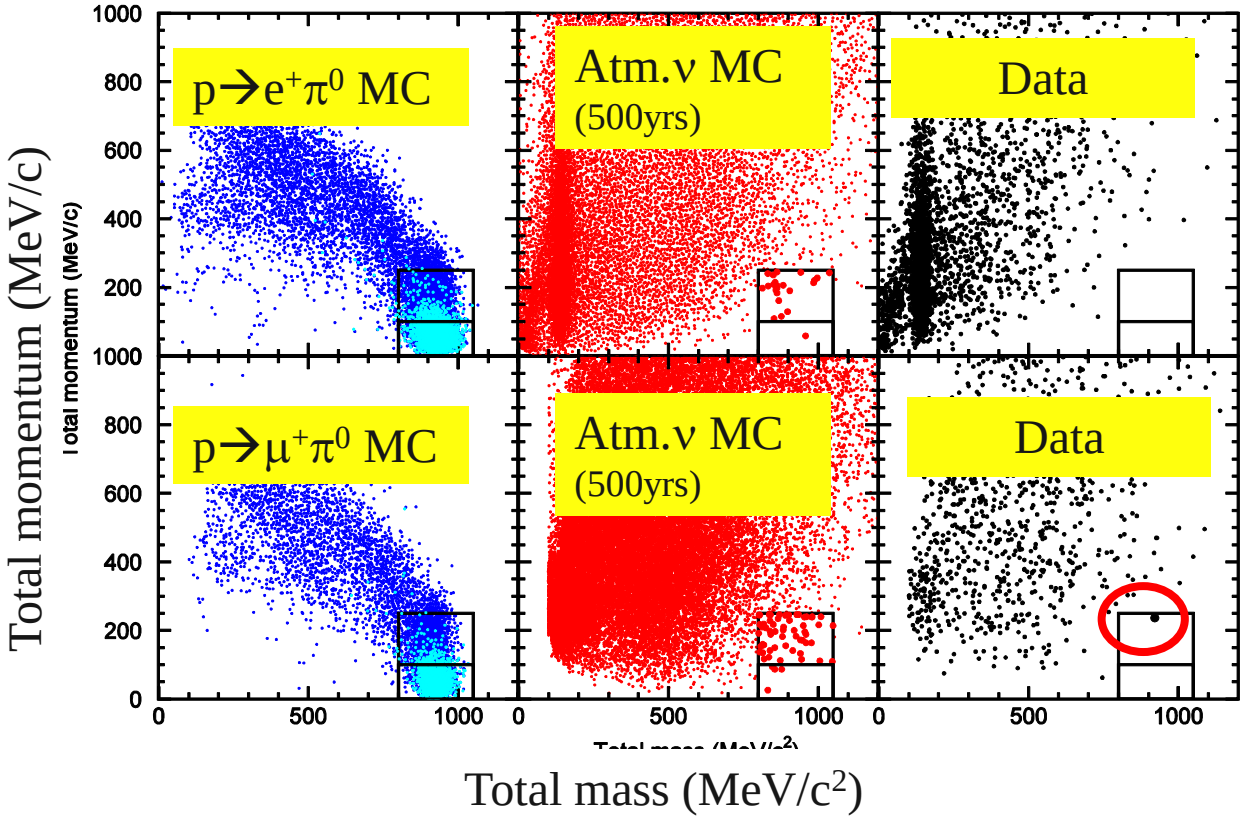
- Most of atmospheric ν BG are accompanied by neutrons.
- A neutron is captured by a hydrogen (~200μsec) and emits γ ray;

n+p → d+γ (2.2 MeV)

- New electronics installed in SK4 enables us to record all hits including this γ ray.
- Search for hit cluster N≥7 in 10 ns window after prompt signal, and neutrons are selected by neural network.
- Eff. 20.5 %, BG 1.8 %.
- About half of the background events can be rejected by requiring no neutron.



Results



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

	Eff. (%)	BKG	OBS
Low P_{tot}	18.7	0.05	0
High P_{tot}	19.9	0.58	0
Total	38.6	0.63	0

$p \rightarrow \mu^+\pi^0$

	Eff.(%)	BKG	OBS
Low P_{tot}	18.0	0.07	0
High P_{tot}	16.7	0.65	1
Total	34.7	0.72	1

Lifetime limt (90% CL,365kton·yrs data)

$p \rightarrow e^+\pi^0$: $> 2.0 \times 10^{34}$ years

$p \rightarrow \mu^+\pi^0$: $> 1.2 \times 10^{34}$ years

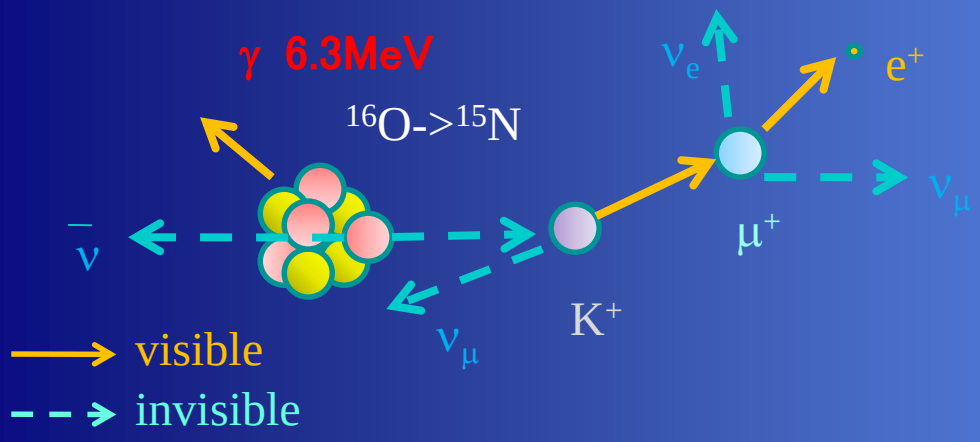
PRD **90**, 072005 (2014) → Updated

4. $p \rightarrow \bar{\nu} K^+$ mode

General features

- $\bar{\nu}$ cannot be detected = we cannot reconstruct proton mass and momentum.
- Momentum of K^+ ~ 339MeV/c: below Cherenkov threshold and not visible by SK.
- K^+ stops in water and decay with τ = 12ns:
  - $K^+ \rightarrow \nu\mu^+$: Br. 64 % (Method A)
  - $K^+ \rightarrow \pi^+\pi^0$: Br. 21 % (Method B)
- In these two body decay case, decayed particles have monochromatic momentum.

Method (A) $K^+ \rightarrow \mu^+\nu_\mu$



Event features;

- K^+ is invisible, stops and 2 body decay (P_μ = 236 MeV/c).

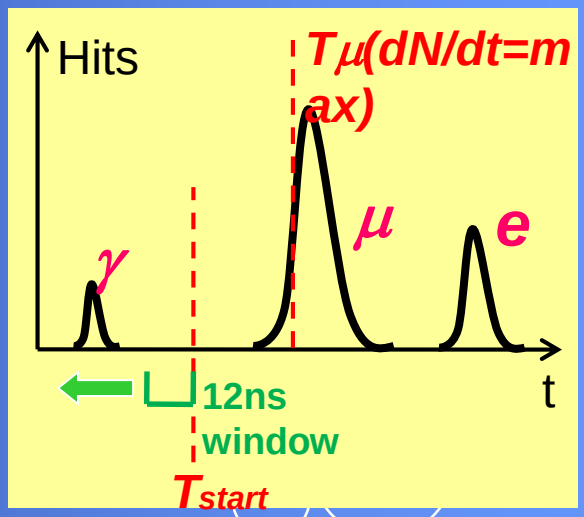
➔ Excess in P_μ.

- Proton in ^{16}O decays and excited nucleus emits 6 MeV γ (Prob. 41%, not clear ring).

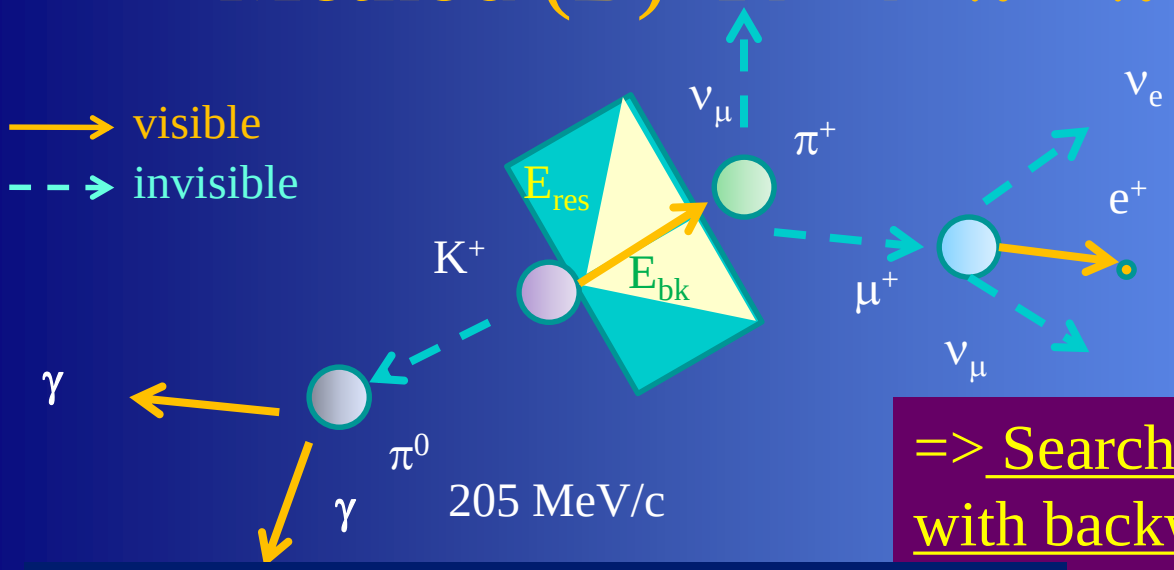
=> Tag γ to eliminate BKG.

Selection:

- 1 μ-like ring with decay-e.
- 215 < Pμ < 260 MeV/c
- Search Max hit cluster by sliding time window (12ns width);
  - 8 < Nγ < 60 hits for SK-1,3,4
    4 < Nγ < 30 hits for SK-2
  - T_μ-T_γ < 75 nsec
- No neutrons (only for SK-4)



Method (B) $K^+ \rightarrow \pi^+ + \pi^0$



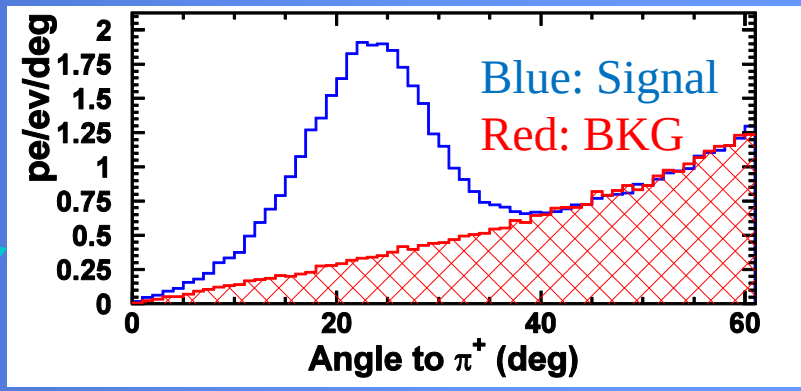
Event features;

- Br. 21 %.
- π^0 and π^+ are back-to-back and have 205 MeV/c.
- $P\pi^+$ is just above Č thres. (not clear ring).

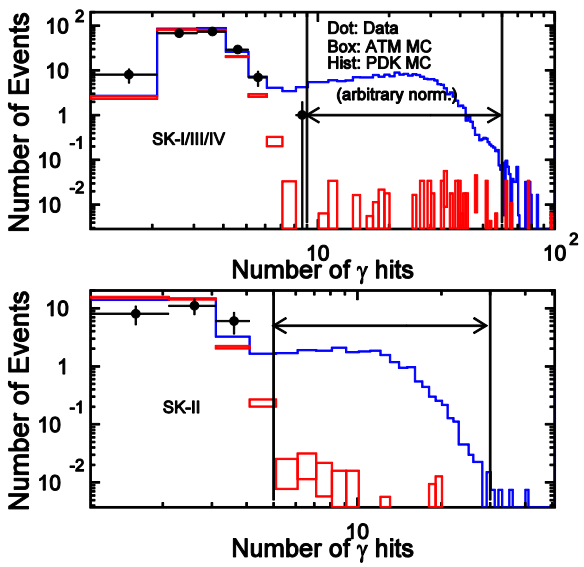
=> Search for monochromatic π^0 with backward activities.

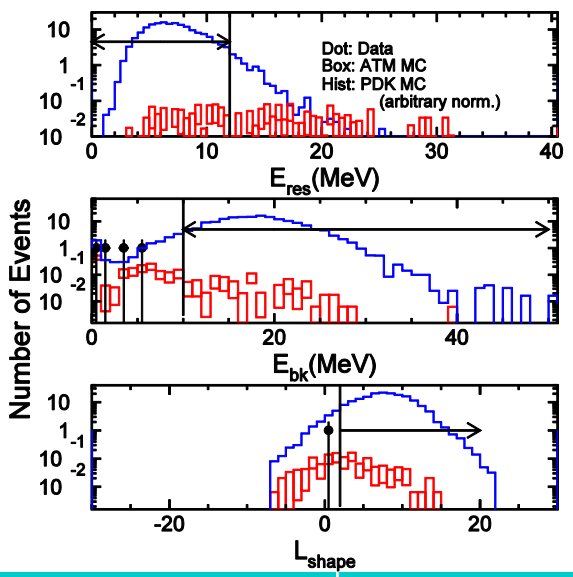
Selection:

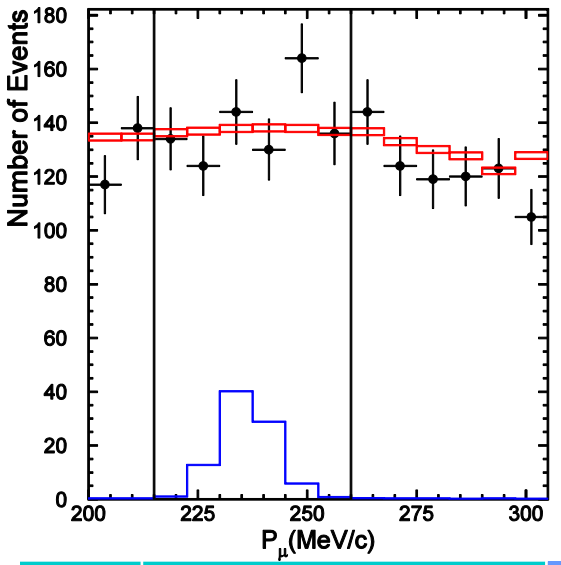
- 1 or 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$ MeV.
- $175 < P\pi^0 < 250$ MeV/c.
- E_{bk}: visible energy sum in 140-180 deg. of π^0 dir,
  E_{res}: in 90-140 deg,
  L_{shape}: Likelihood based on charge profile
  $10 < E_{bk} < 50$ MeV
  $E_{res} < 12$ MeV (20 MeV for 1ring)
  $L_{shape} > 2.0$ (3.0 for 1ring)
- No neutrons



No Candidate observed.







	SK1			SK2			SK3			SK4		
	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)	Eff (%)	BG (ev)	Obs (ev)
Pr.γ	7.9 ±0.1	0.078	0	6.5± 0.1	0.082	0	7.5 ±0.1	0.018	0	9.4 ±0.1	0.12	0
$\pi^+\pi^0$	7.8 ±0.1	0.21	0	6.5± 0.1	0.19	0	8.3± 0.1	0.07	0	9.6 ±0.1	0.14	0

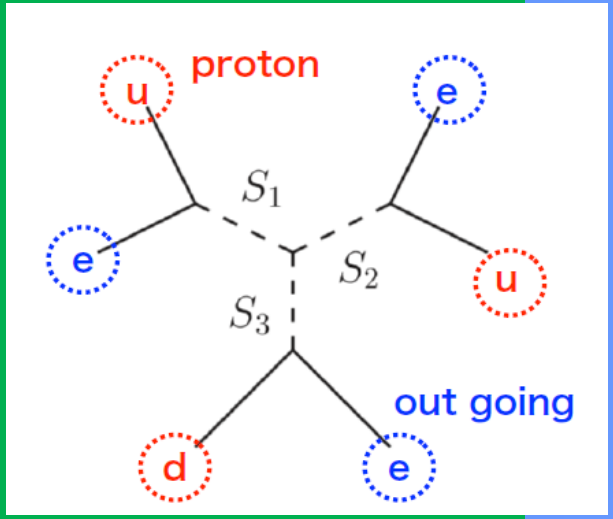
$p \rightarrow \nu K^+$ Lifetime limit (90% CL) :

$> 8.2 \times 10^{33}$ yrs (365 kton·yr exposure)

NEW!

4. p→ three charged leptons

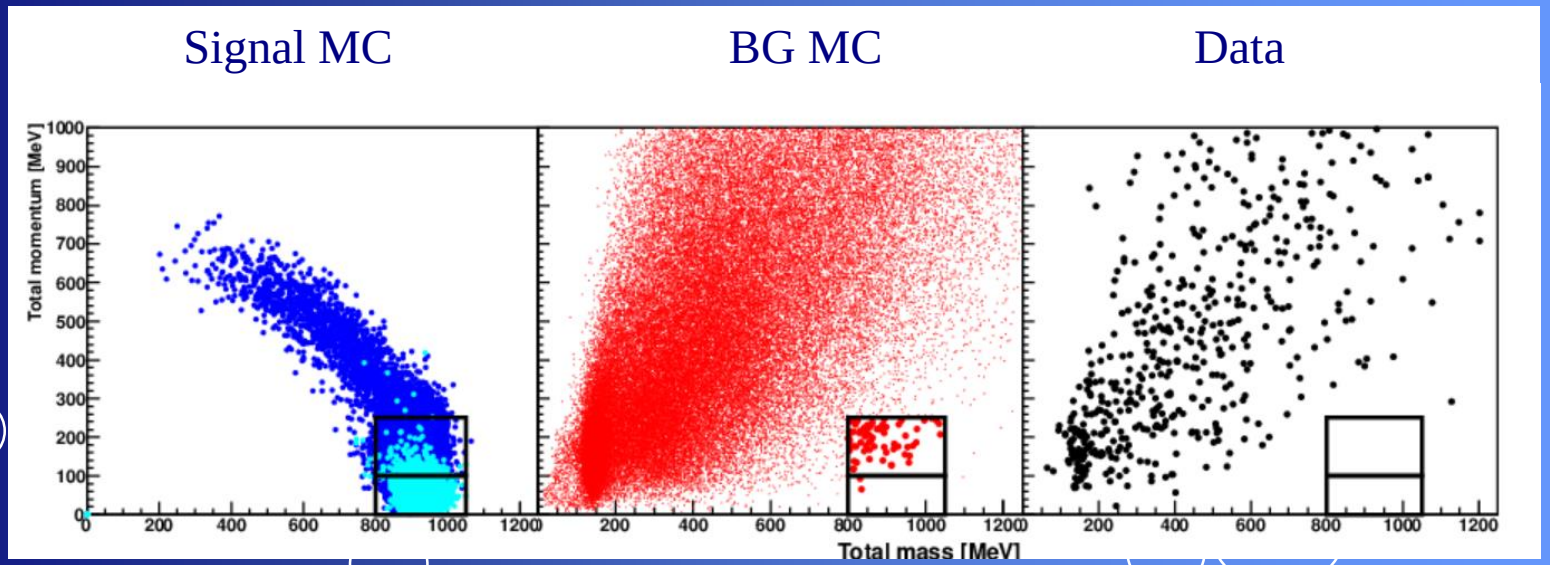
- Suggested by T.Hambye, J.Heeck (PRL120,171801(2018)).
  - Expected lifetime ~ 10^{33} years.
- All combination of electron and muon are examined ($p \rightarrow e^+e^+e^-$, $e^+e^-\mu^+$, $e^+e^+\mu^-$, $e^+\mu^+\mu^-$, $e^-\mu^+\mu^+$, $\mu^+\mu^+\mu^-$).
  - All particles can be detected by SK. → High efficiency.
  - No π in final state → Lower uncertainty.
- The latest results came from IMB 20 years ago.
- This is the first trial to search for those modes in SK.
  - ~ 50 times larger exposure than IMB.
  - may discover proton decays, or update lifetime limits.



Event selection: similar to $p \rightarrow e^+\pi^0$

- 3 rings with proper number of e-/μ-like rings(ex. $p \rightarrow e^+e^-\mu^+$: 2 e-like 1 μ-like)
- Require same number of Michel electrons as number of μ.
- No tagged neutron (SK4)
- 800 < Total Mass < 1,050 MeV、Total Momentum < 250 MeV
- Total momentum cut is divided to P < 100 MeV & 100 < P < 250 MeV

Results for $p \rightarrow e^+e^+e^-$



Summary of search for decay to 3 leptons

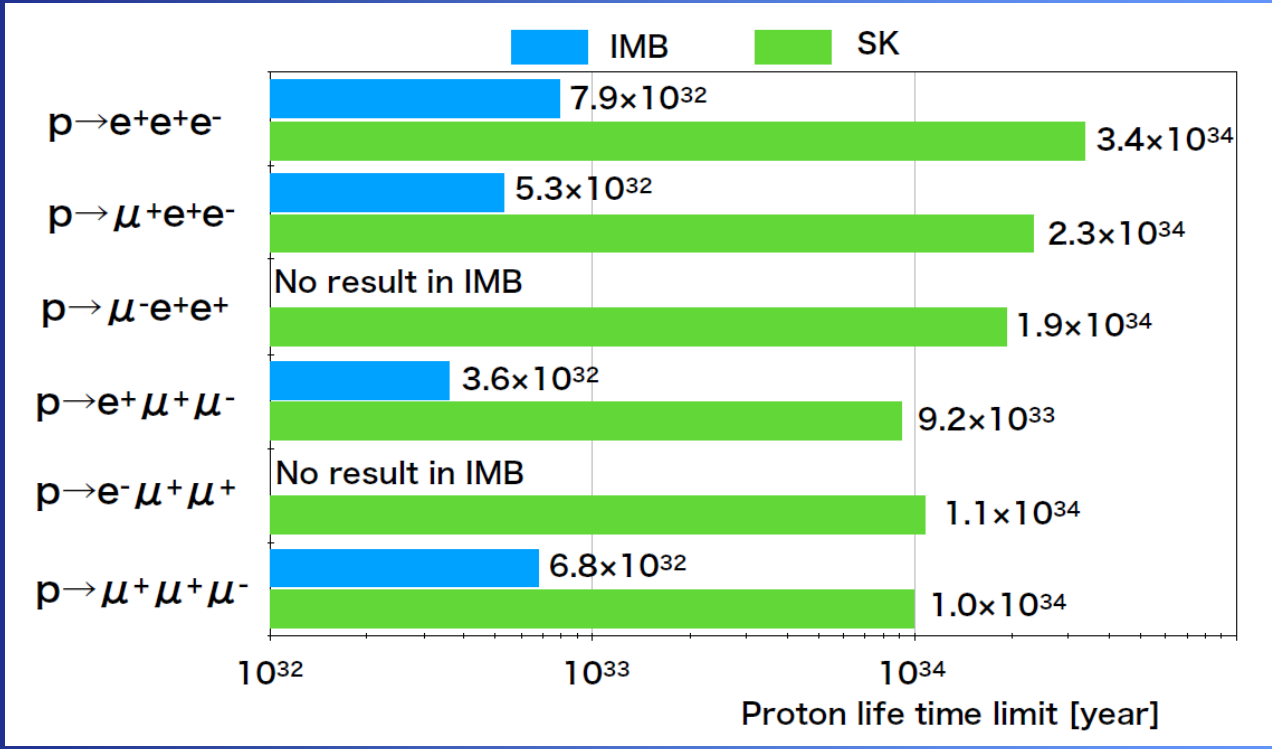
Modes	Efficiency [%] (Livetime normalized)	Background [events] (SK I-IV total)	Candidate [events] (SK I-IV total)
$p \to e^+e^+e^-$			
(Low)	22.2	0.01±0.01	0
(High)	42.0	0.56±0.08	0
$p \to \mu^+e^+e^-$			
(Low)	16.3	0.04±0.01	0
(High)	28.7	0.47±0.06	0
$p \to \mu^-e^+e^+$			
(Low)	13.5	0.04±0.01	0
(High)	23.5	0.47±0.06	0
$p \to e^+\mu^+\mu^-$			
(Low)	10.4	<0.01	0
(High)	18.3	0.26± 0.04	1
$p \to e^-\mu^+\mu^+$			
(Low)	12.9	<0.01	0
(High)	22.0	0.26± 0.04	1
$p \to \mu^-\mu^+\mu^+$			
(Low)	11.6	0.01±0.01	0
(High)	19.9	0.38±0.07	1

Same samples because SK cannot identify charge.

Efficiencies are different because of μ^- capture in water.

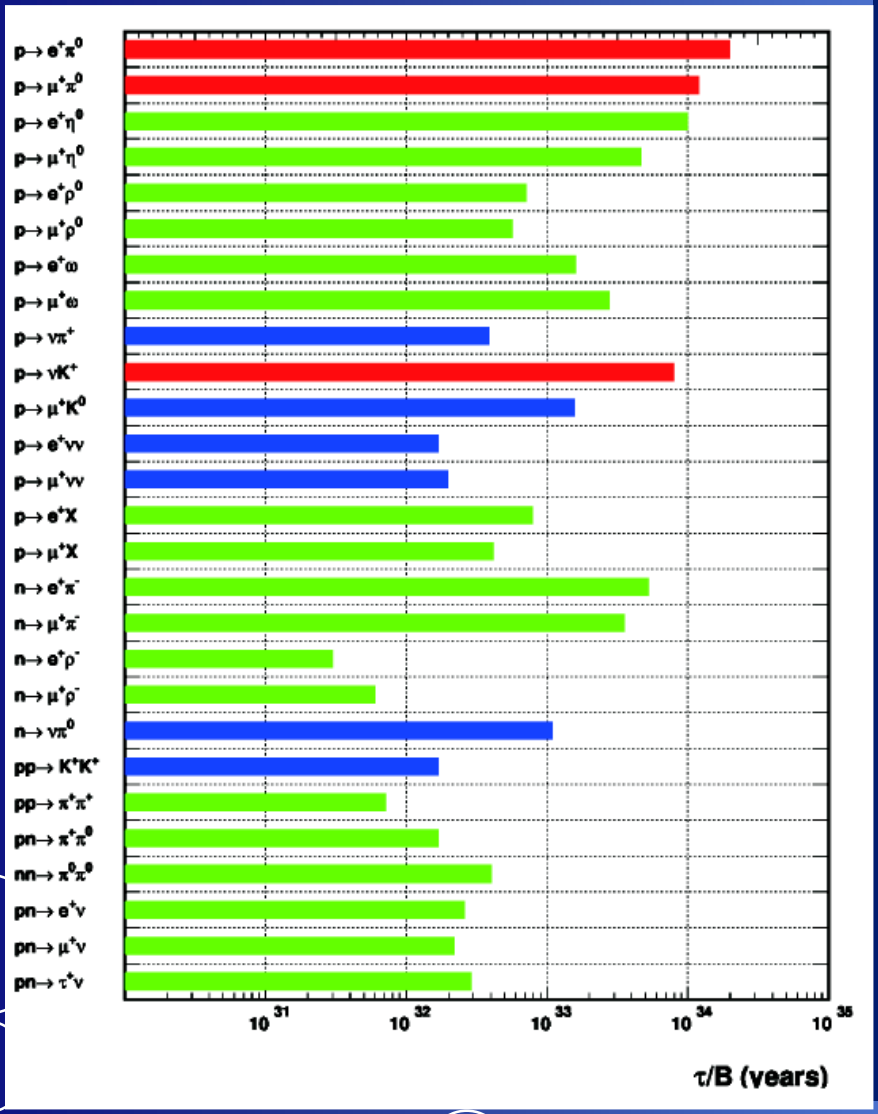
Two candidates, but consistent with BG.

Lifetime limits for p→3 leptons



- Lifetime limits: ~ 10^{34} years.
- We appreciate suggestion from T.Hambye and J.Heeck .
- The result will be published soon.

5. Summary of the current results

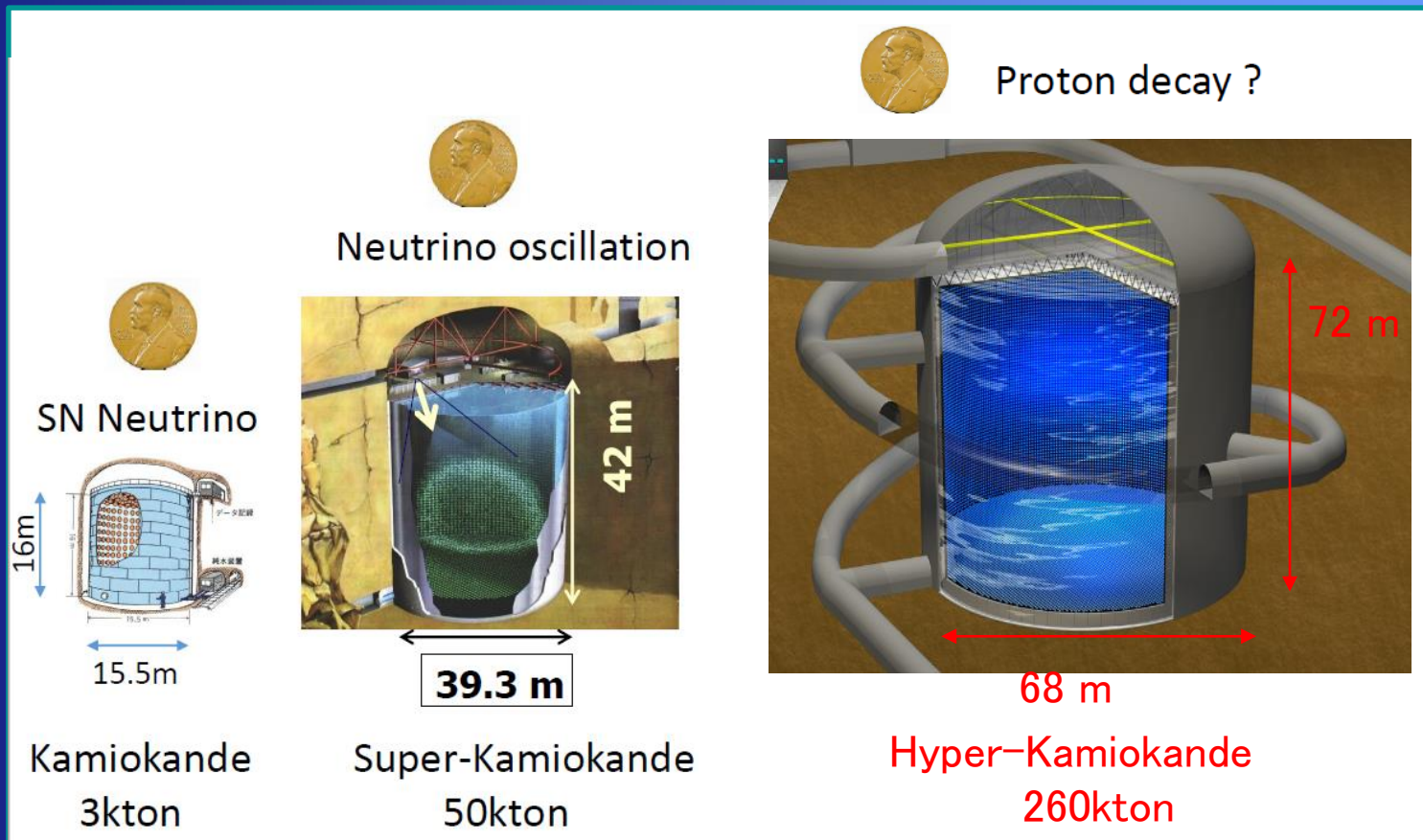


- Most of modes have been investigated with > 0.3 Mton·year exposure (red and green in the left figure).
- Super-Kamiokande can cover large number of decay modes.
- Many of them are the most stringent limits on nucleon lifetime.
- We observed some candidates, but still consistent with expected backgrounds and no evidence of nucleon decay has been observed.

6. Future Prospect and Hyper-Kamiokande

- Still no evidence has been found. Major decay modes are explored up to around 10^{34} years.
- Proton lives longer, ~10^{35} years ?
  - Run SK 10 times more (~200 years)? → Impossible.
  - Need "the 3rd generation" detectors.
- Several projects are moving forward.
  - Water Cherenkov: Hyper-Kamiokande (HK)
    - ✓ Well established and stable.
    - ✓ Larger volume.
    - ✓ Can cover several decay modes.
  - Other type: DUNE (LAr), JUNO (L-Scintillator)
    - ✓ Excellent event reconstruction.
    - ✓ High efficiency, low background.

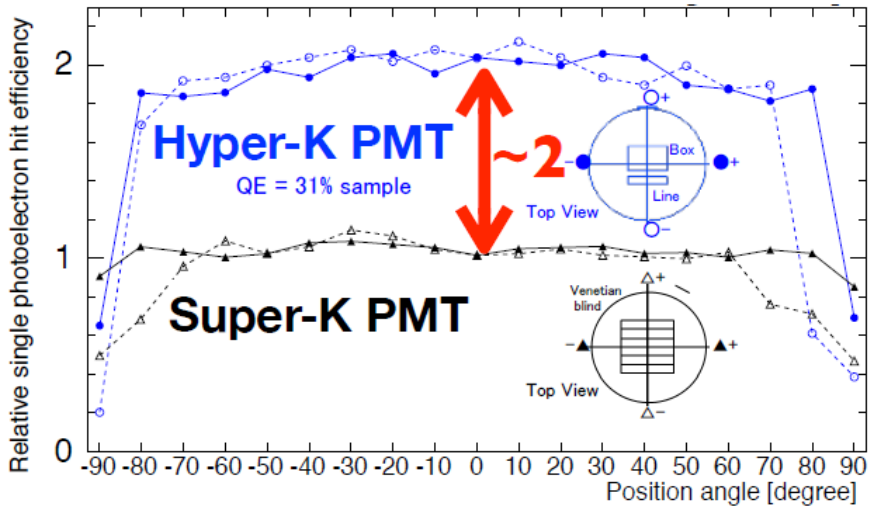
Hyper-Kamiokande Project



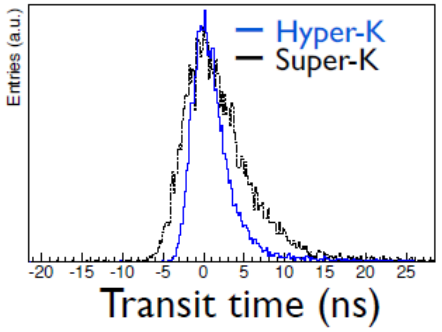
Fiducial Volume: 22.5kton (SK) → 188 kton (HK)
Hyper-K will use 40,000 new 20 inch PMTs .

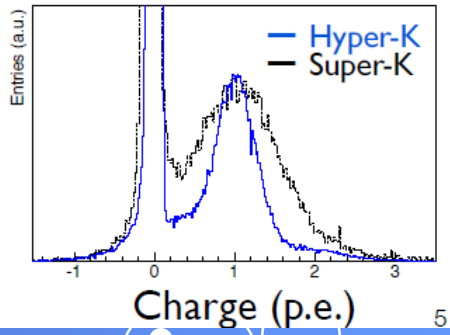
New 50cmΦ PMT for Hyper-K

Photo-detection efficiency (1 p.e.)



Hyper-K PMT
(R12860 "Box & line PMT")





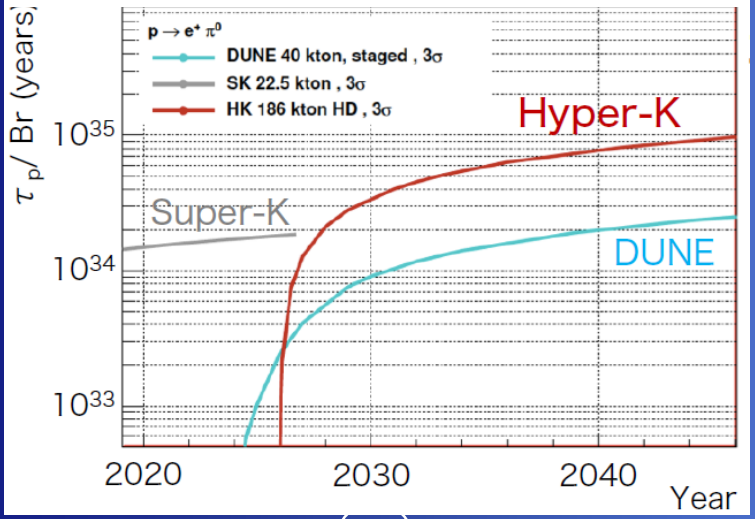
- **Twice better photo-detection efficiency than Super-K PMT (R3600)**
- **Timing resolution (T.T.S.): 1.1ns**
  - cf. Super-K PMT: 2.1ns
- New PMTs enhances Hyper-K physics sensitivity (ex. nucleon decay search)

5

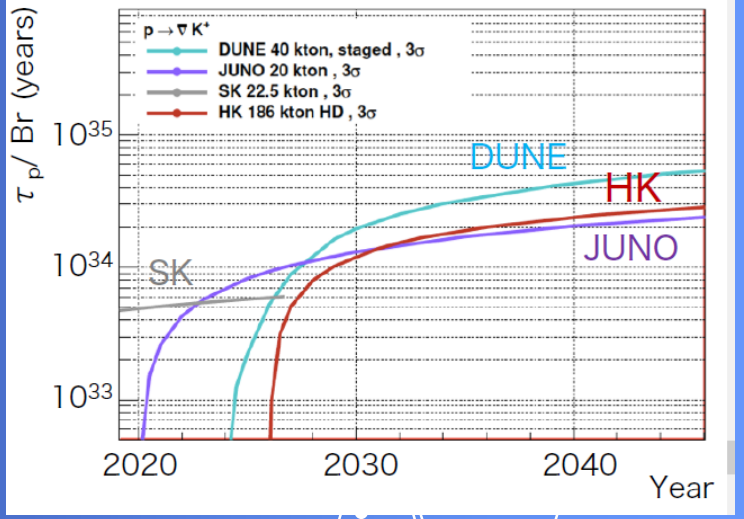
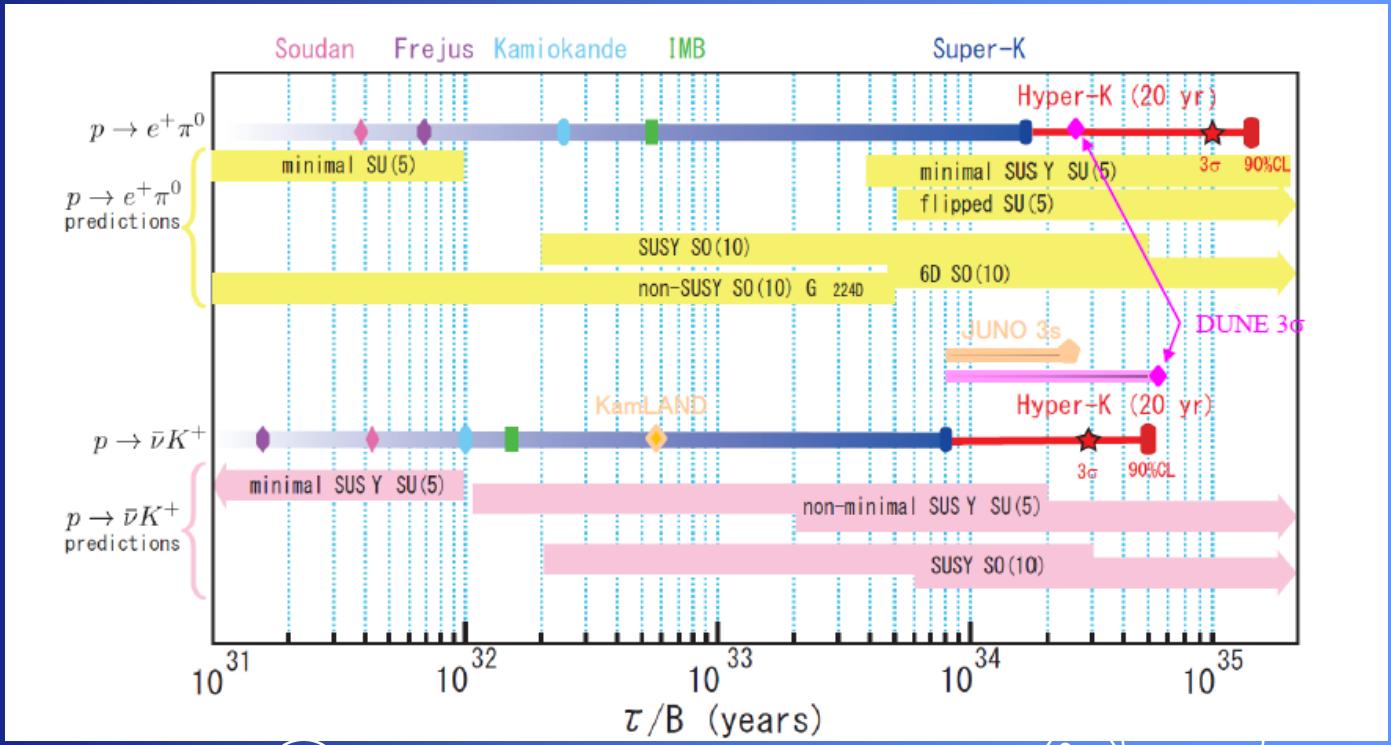
Not only volume, but performance of nucleon decay search will be improved thanks to new PMT.

- Better photon counting performance.
  - Improve neutron tagging effiicieny.
    - More BG rejection in $p \rightarrow e^+\pi^0$
- Better time resolution.
  - Better nuclear γ tagging.
    - More efficiency in $p \rightarrow \nu K^+$.

$p \rightarrow e^+\pi^0$ 3σ discovery sensitivity



$p \rightarrow \nu K^+ 3\sigma$ discovery sensitivity



- Hyper-K will be the only detector which can explore ~10^{35} years.
- Budget request has been submitted !
- Hyper-K construction will be started in 2020 and aim to start operation in 2027.