neutrino oscillation physics and nucleon decay with Hyper-Kamiokande

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On behalf of

The Hyper-Kamiokande proto-Collaboration

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H2020-MSCA-RISE-2014-GA641540, SKPLUS

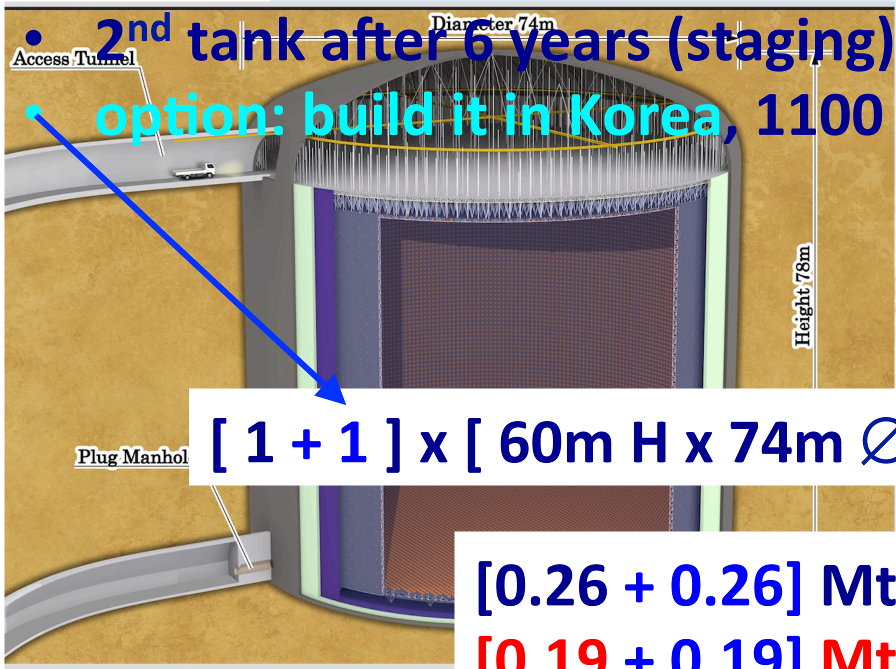
neutrino physics in Japan: **A most successful experimental program**

Kamiokande → Super-Kamiokande [K2K , T2K] ➔

- maximizes available resources → minimizes time, useless efforts …
- maximizes experience & know-how → minimizes risks, delays, failures

➔ Hyper-Kamiokande [T2HK]

- uses Water-Cherenkov:
  - unique technique to achieve **huge amount of instrument matter**
  - **2nd tank after 6 years (staging)**
  - **option: build it in Korea, 1100 - 1300 Km**

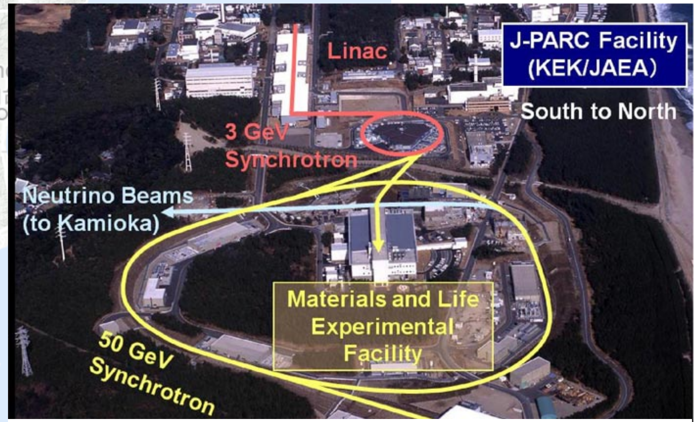


[1 + 1] x [60m H x 74m ∅]

[0.26 + 0.26] Mt

[0.19 + 0.19] Mt fiducial

295 Km



1.3 MW, 2.5° off-axis
narrow-band, ~600 MeV

  - precise rec. of particle’s energy, position, direction, type …

Kamiokande → Super-Kamiokande [K2K , T2K] →

the Hyper-Kamiokande [T2HK] experimental physics program

ν oscillation physics

- determination of **ν** **M**ass **H**ierarchy (atmospheric & beam)
- determination of θ_{23} octant (atm. & beam)
- measurement of **CP V**iolation in leptonic sector (atm. & beam)
- reveal exotic scenarios

→ *this talk*

#798-talk **B. richards**
"The Hyper-Kamiokande Experiment"

Solar ν physics

- precision measurement of Δm^2_{21}
- measurement of energy spectrum **up-turn**
- discovery & measurement of **hep** neutrino

#518-talk **J. Migenda**
"Astroparticle Physics in HK"

ν Astrophysics

- energy spectrum of **D**iffuse **S**upernova **N**eutrino **B**ackground
- galactic Supernova, high statistics, energy, time evolution …
- indirect **D**ark **M**atter search from GC, Sun, Earth

Grand Unification physics

- $p \to e^+\pi^0$, $p \to \nu K^+$ & all visible modes
- reach 10^{35} sensitivity

---> *this talk*

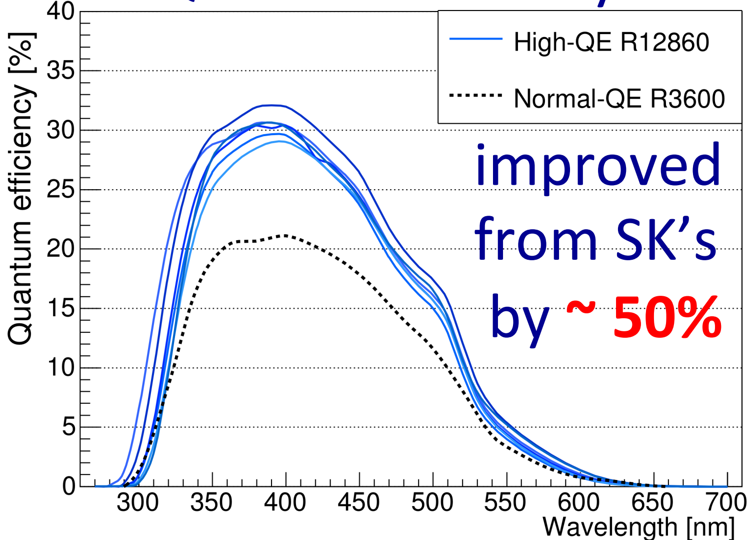
The key of Hyper-Kamiokande: very large mass and excellent photosensitivity

particularly relevant for the stuff of this talk:

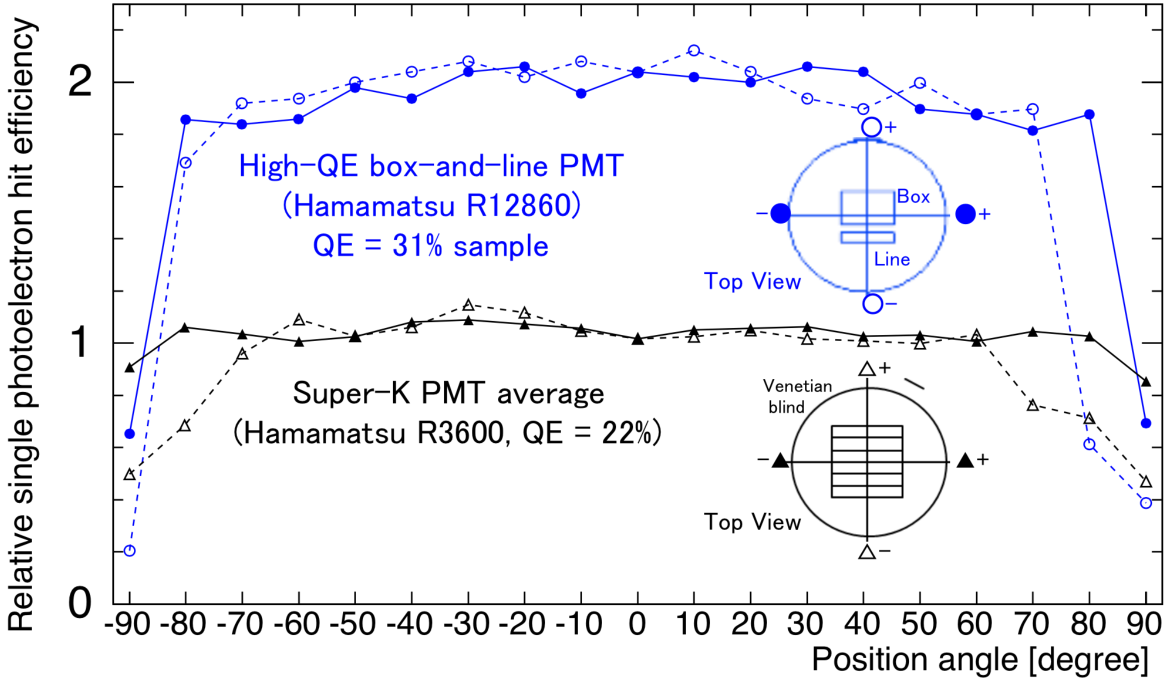
high-QE Box&Line PMT

Hamamatsu R12860

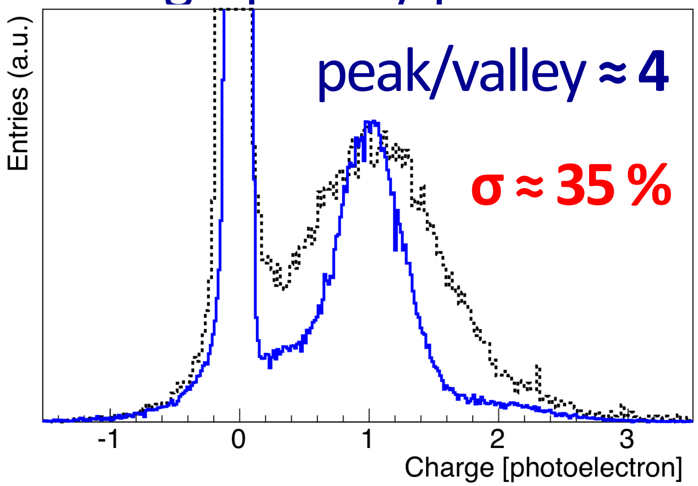
Quantum Efficiency



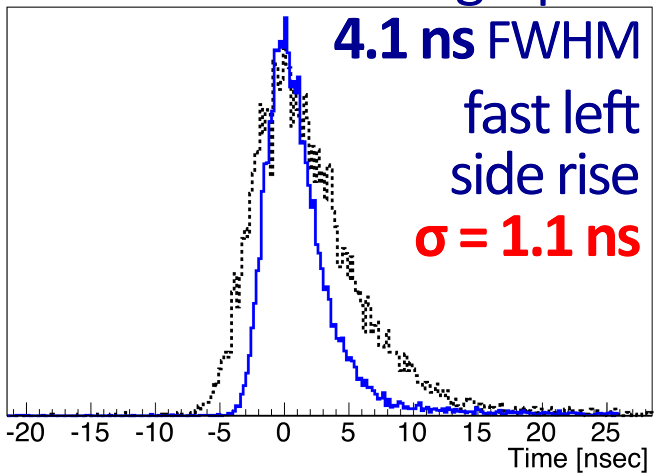
relative single photoelectron det. efficiency [Quantum, Collection, and Cut efficiencies]



single p.e. w/ pedestal



transit time for single p.e.



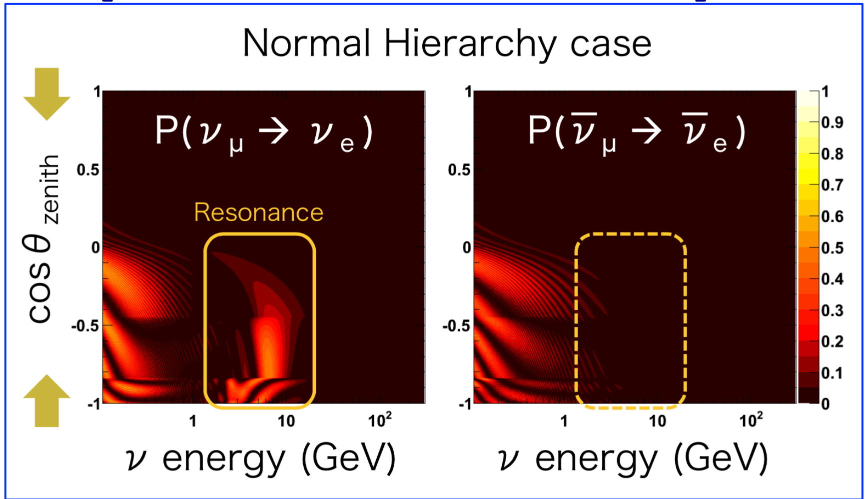
2 x better efficiency, timing resolution, charge resolutions →

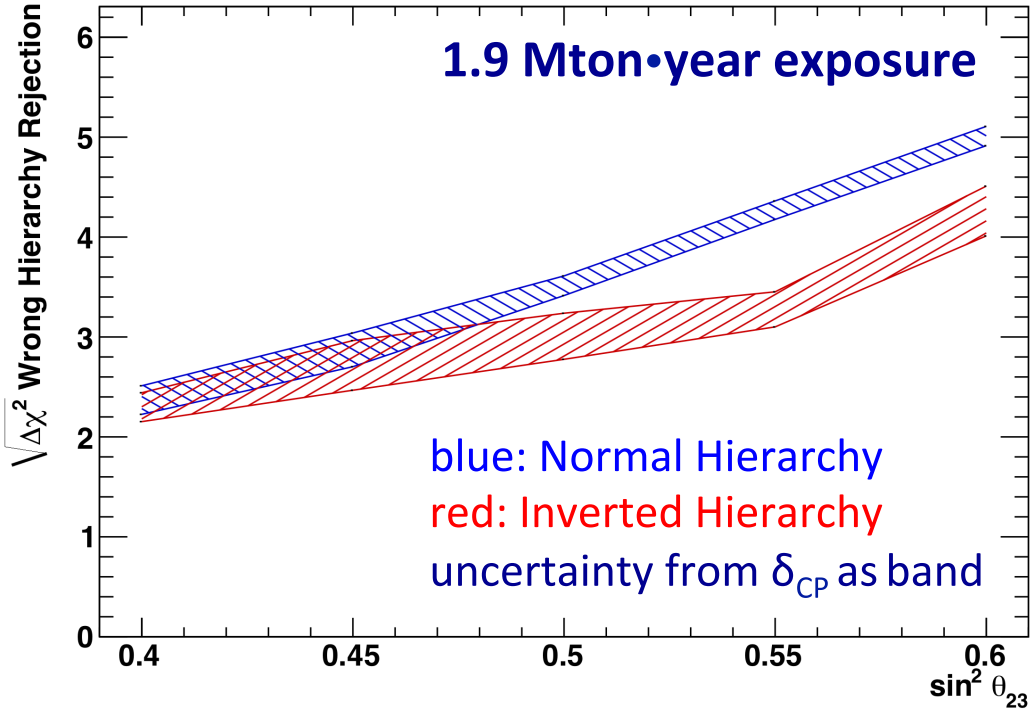
- enhance solar ν_s ,
- signature n(p,d) γ
- p → ν K^+
- ....

neutrino mass hierarchy

from atmospheric ***ν*** →

[matter effects enhanced]

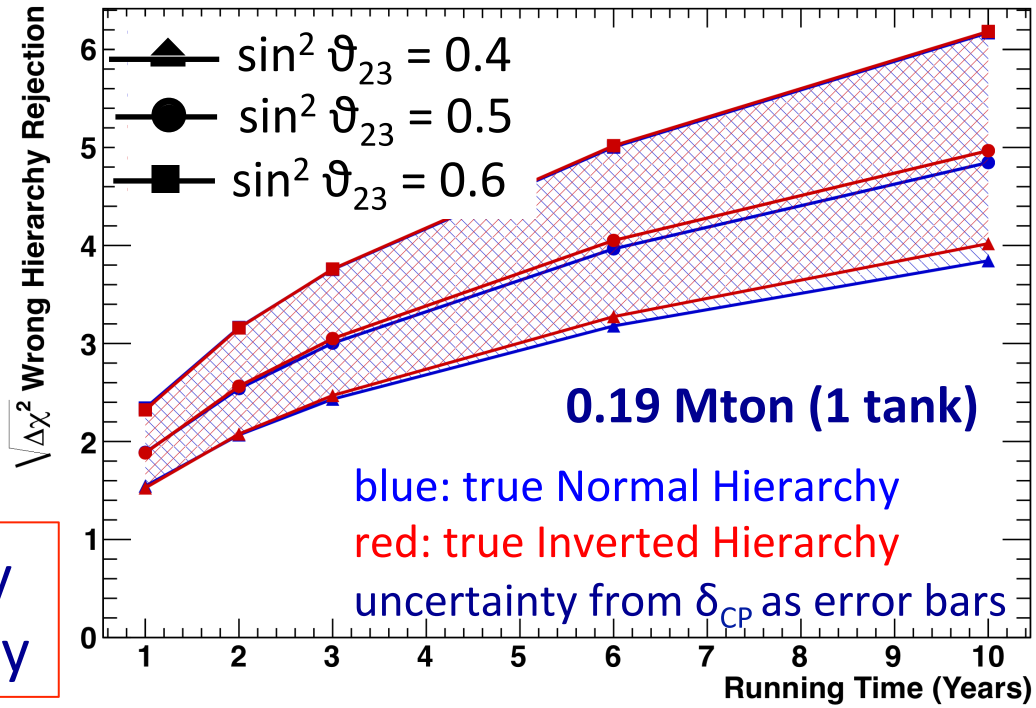




atmospheric

\+ beam ***ν*** →

[precise prediction of the expected amount of $\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_e}$ appearance expected in the resonance region]

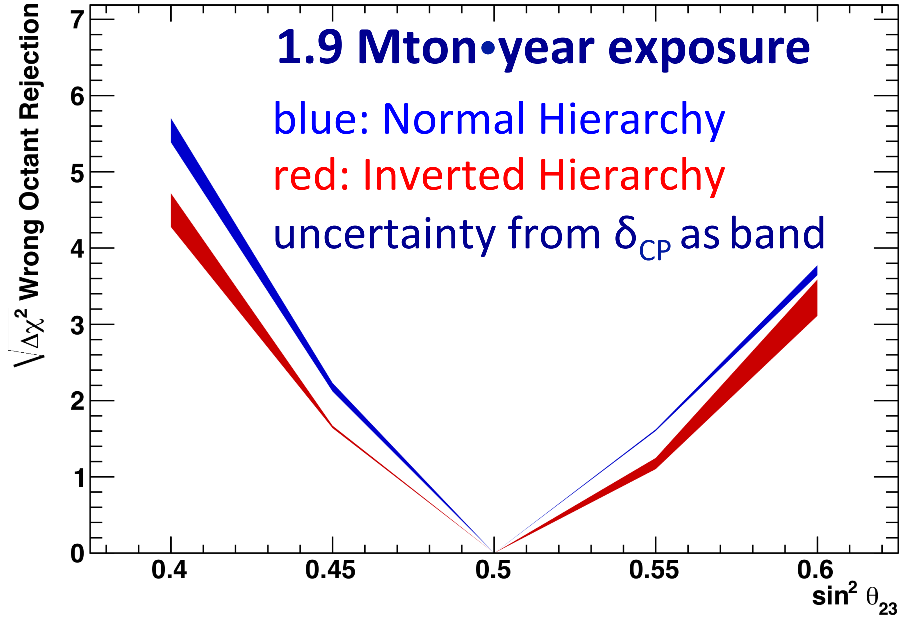


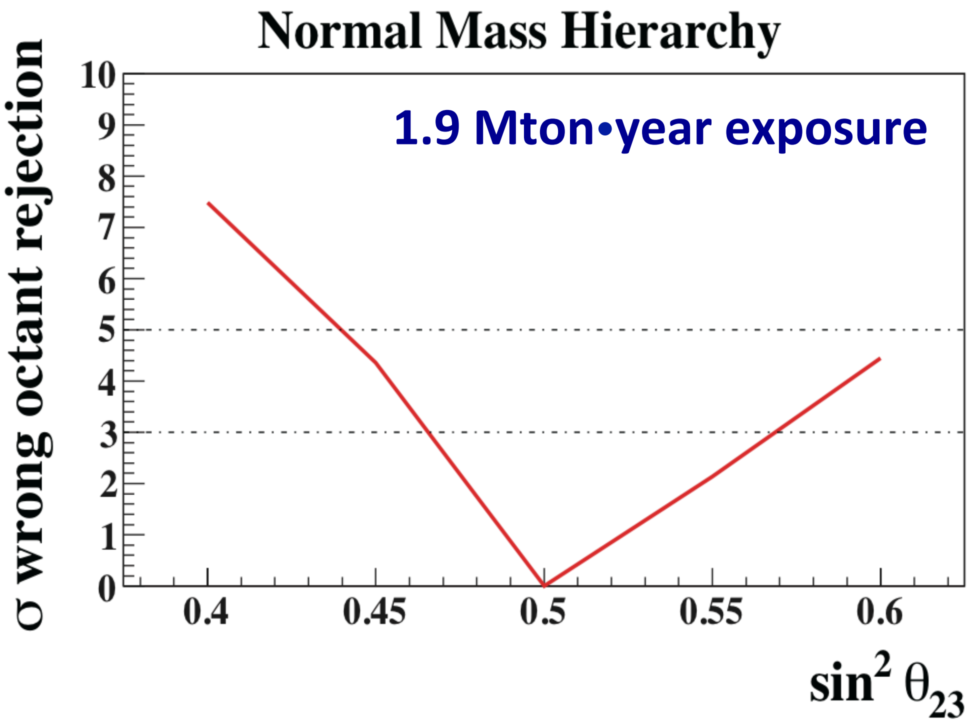
1 tank, 5 years: better than 3σ ability to reject the incorrect mass hierarchy

ϑ_{23} octant

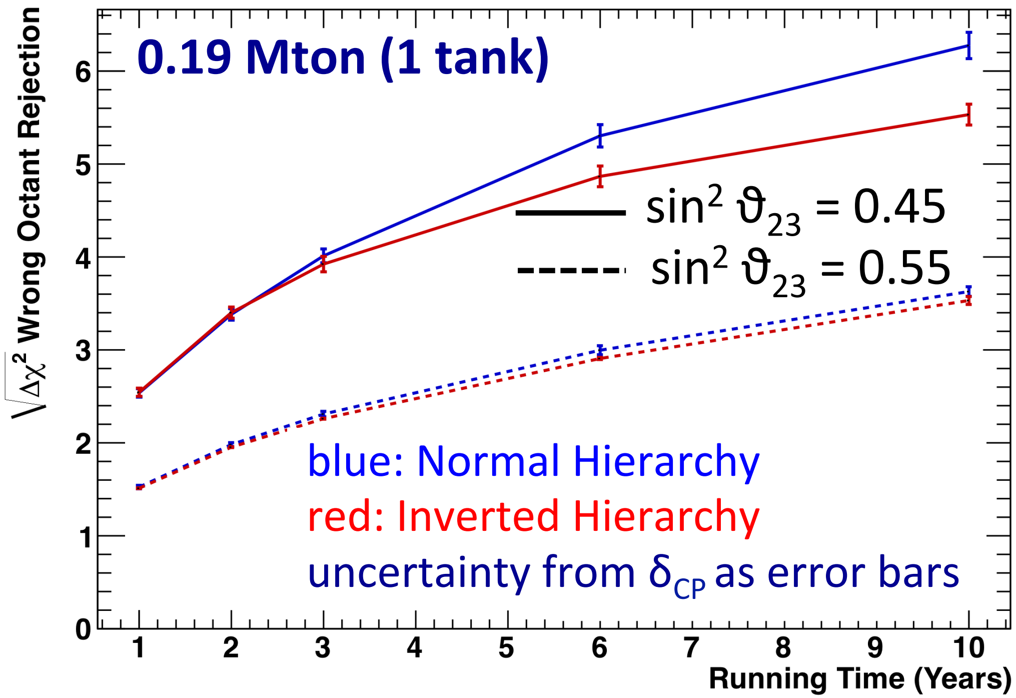
from beam ν →

from atmospheric ν ↓





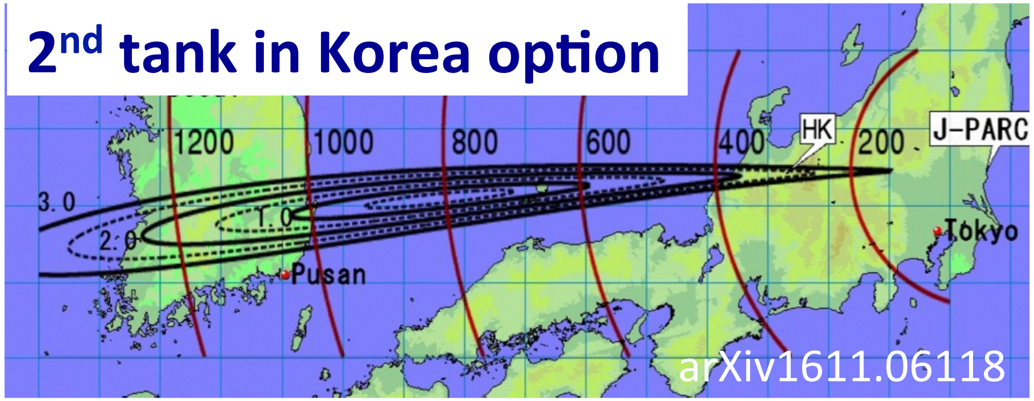
atmospheric + beam ν →

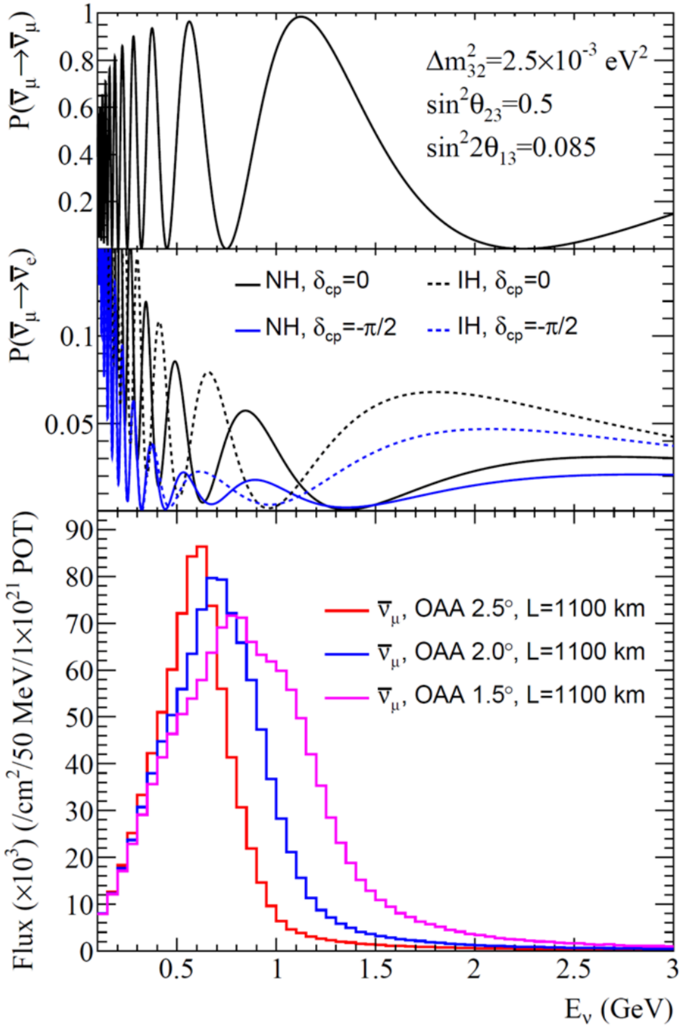


1 tank, 10 years:

- atmospheric neutrinos resolve octant at 3 σ if $|\theta_{23} - 45| > 4^o$
- atmospheric + beam resolves it already for $|\theta_{23} - 45| > 2.3^o$

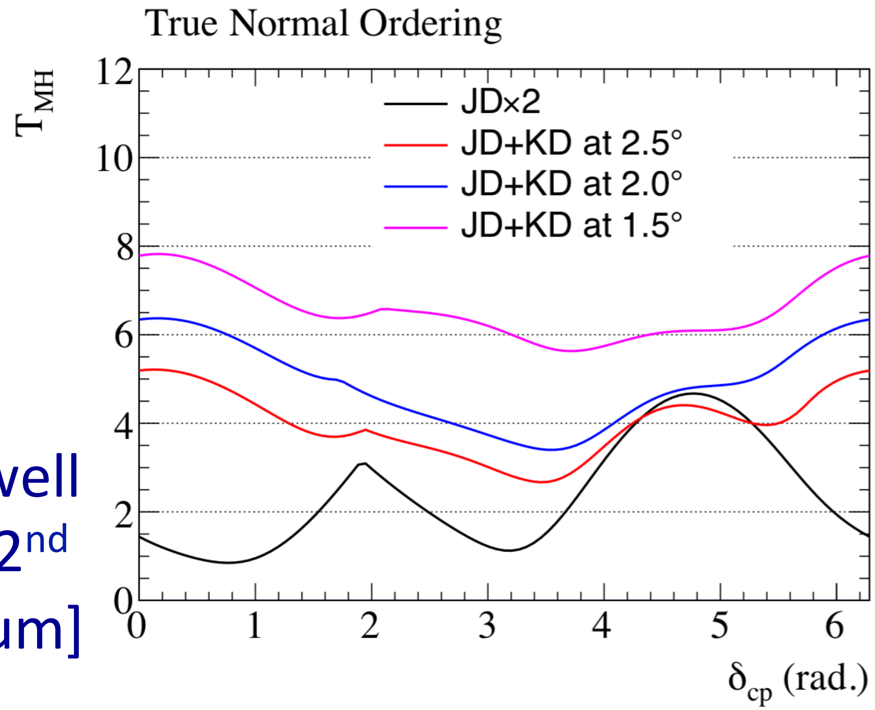
2^{nd} tank in Korea option

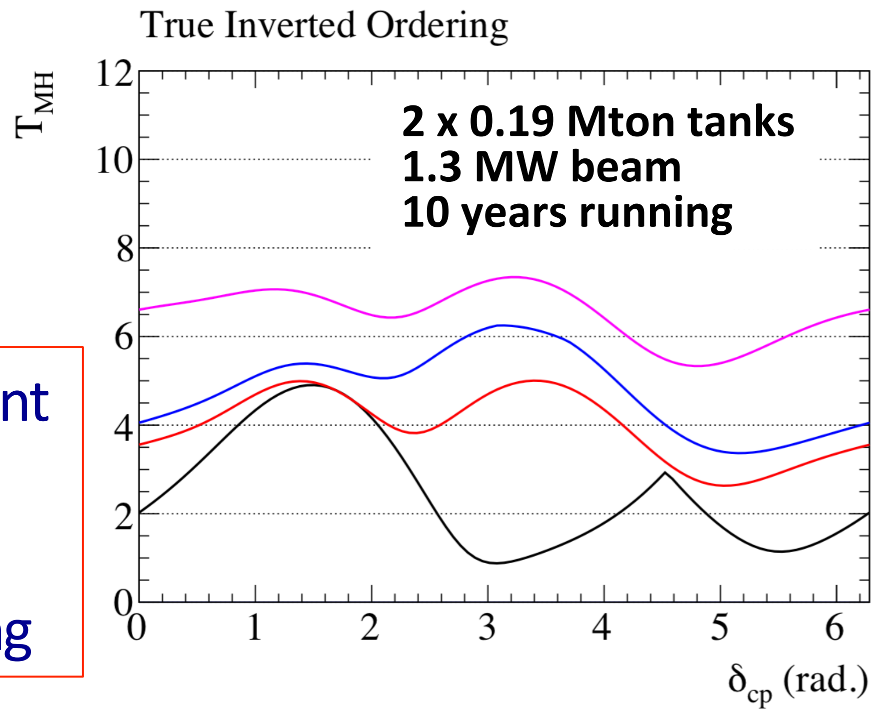




[explore as well around the 2^{nd} osc. maximum]

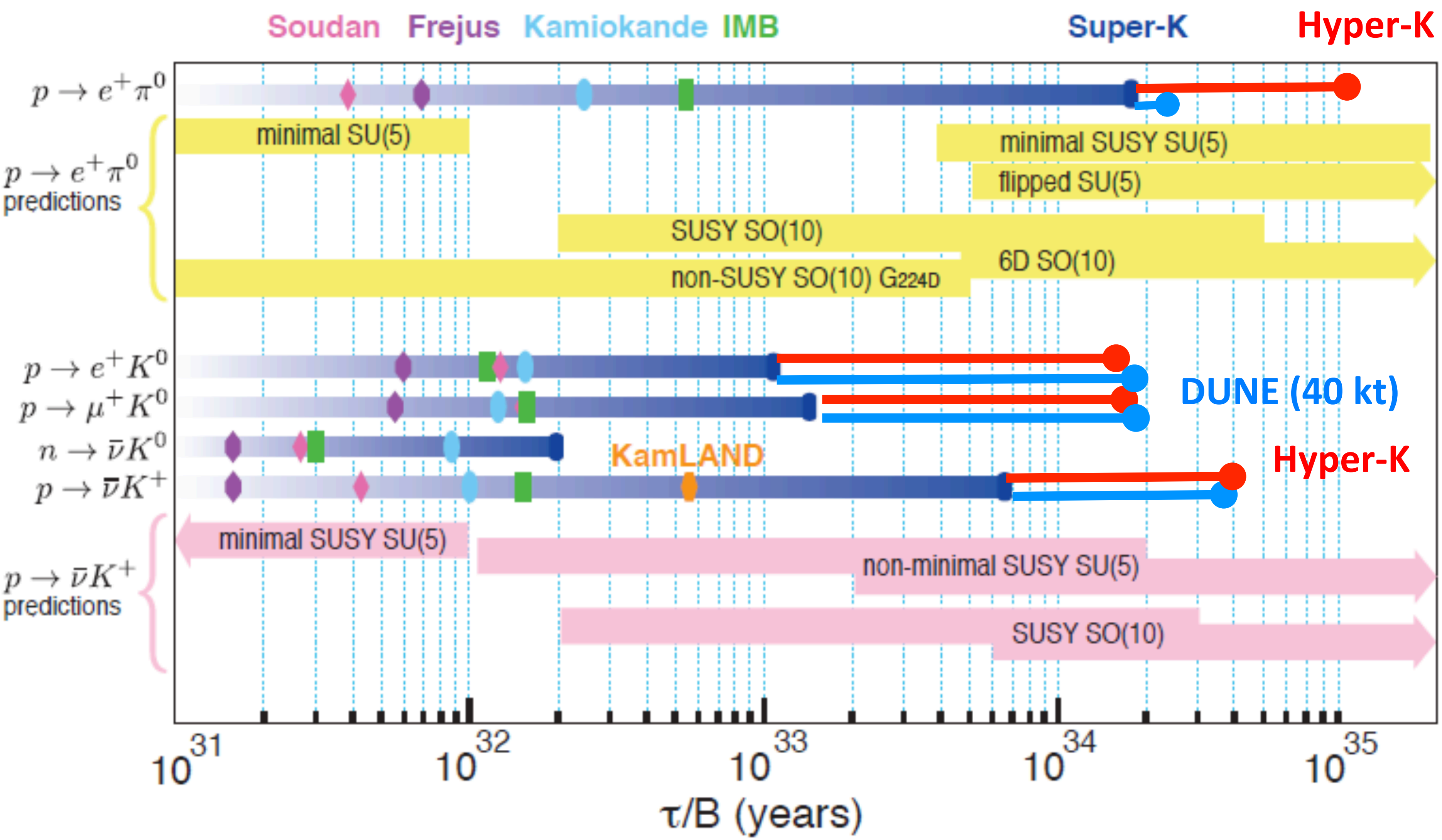
very significant increase of sensitivity to mass ordering





an Hyper-Kamiokande primary goal: nucleon decay

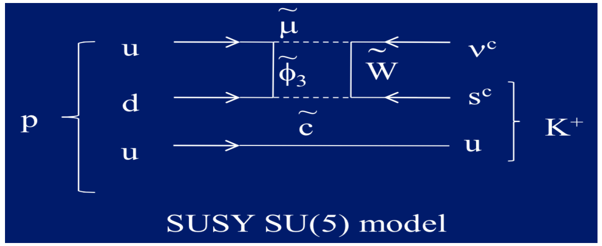
status & next generation expectations (10 y exposure), most important modes:



design emphasizes **p → e$^+\pi^0$**, **p → ν K$^+$** while keeping sensitivity to many other

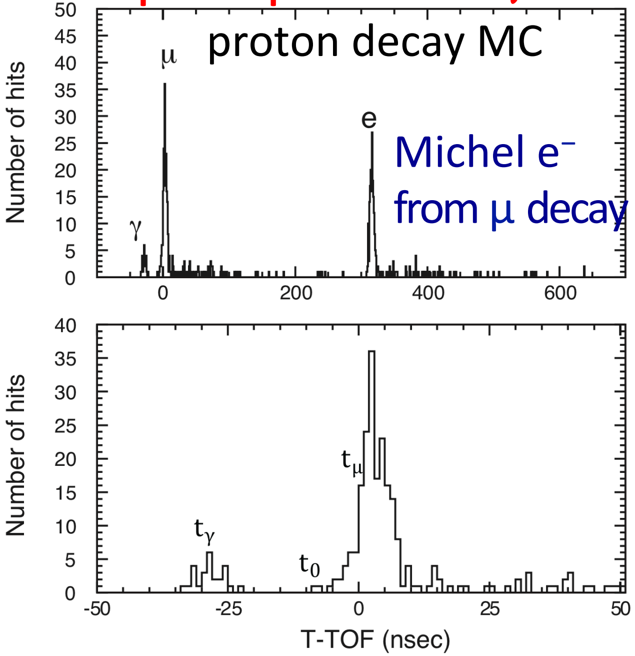
$p \rightarrow \bar{\nu} K^+$

- feature of super-symmetric GUTs

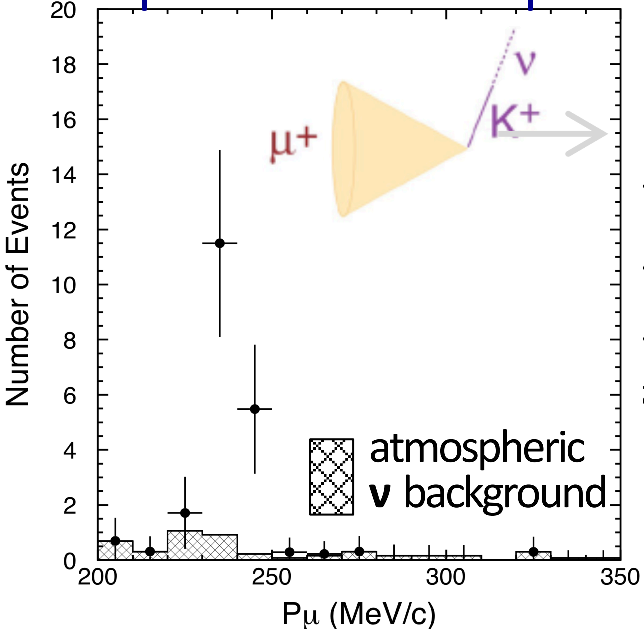


- rather interesting but difficult to reconstruct
- at decay $p(K^+)$= 340 MeV, K^+ ch-light threshold: 749 MeV → reconstruct K^+ from its decay products $K^+ \rightarrow \nu \mu^+$ *(64%)*, $K^+ \rightarrow \pi^+\pi^0$ *(21%)*
- 2-body decays → monochromatic particles: $p(\mu^+)$= 236 MeV,
  $p(\pi^+)= p(\pi^0)$= 205 MeV
- $\tau(K^+) \approx$ 12ns → possible to observe prompt 6 MeV γ from ^{16}O de-excitation

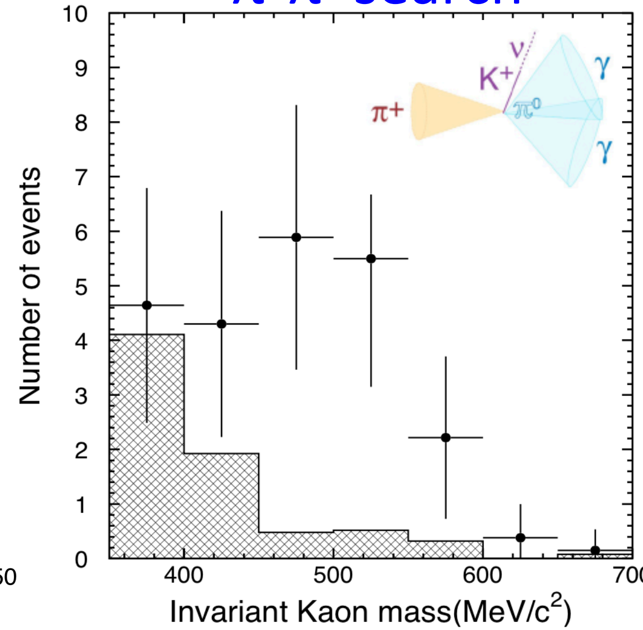
prompt 6 MeV γ



μ^+ from $K^+ \rightarrow \nu \mu^+$



$\pi^+\pi^0$ search

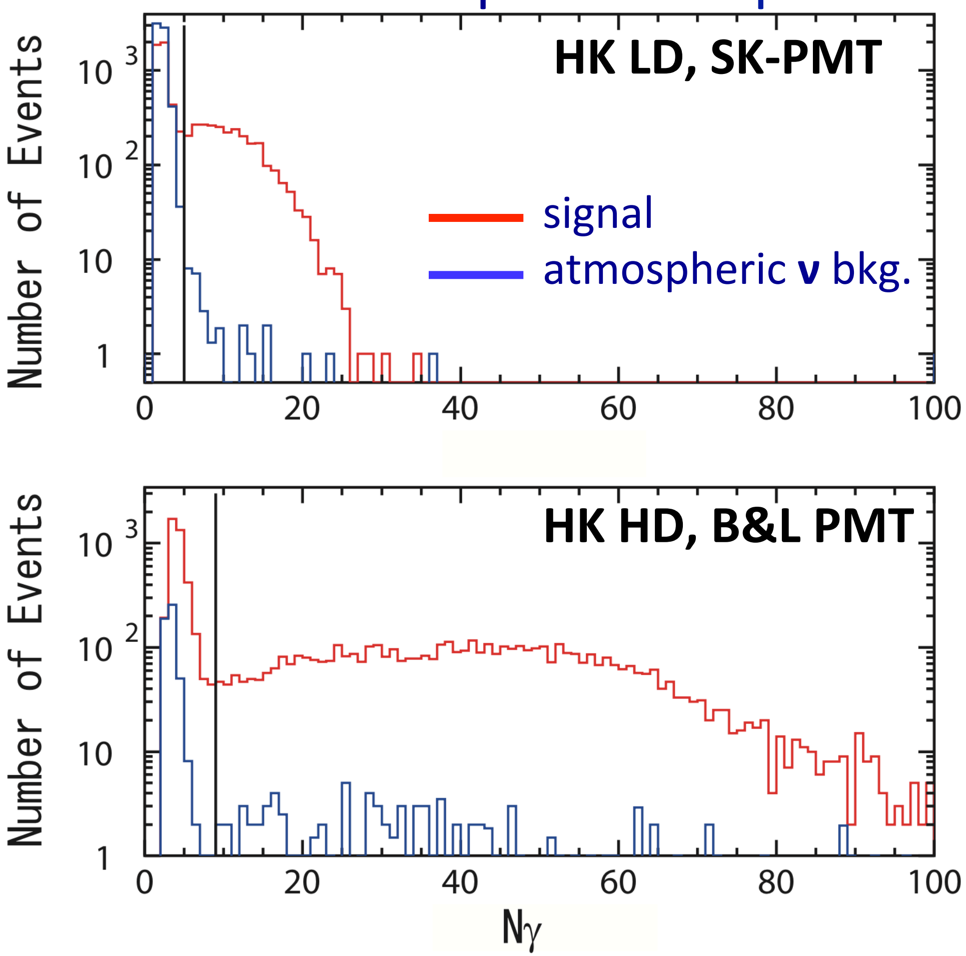


used τ_p= 6.6 • 10^{33} (SK limit), 10 years exposure

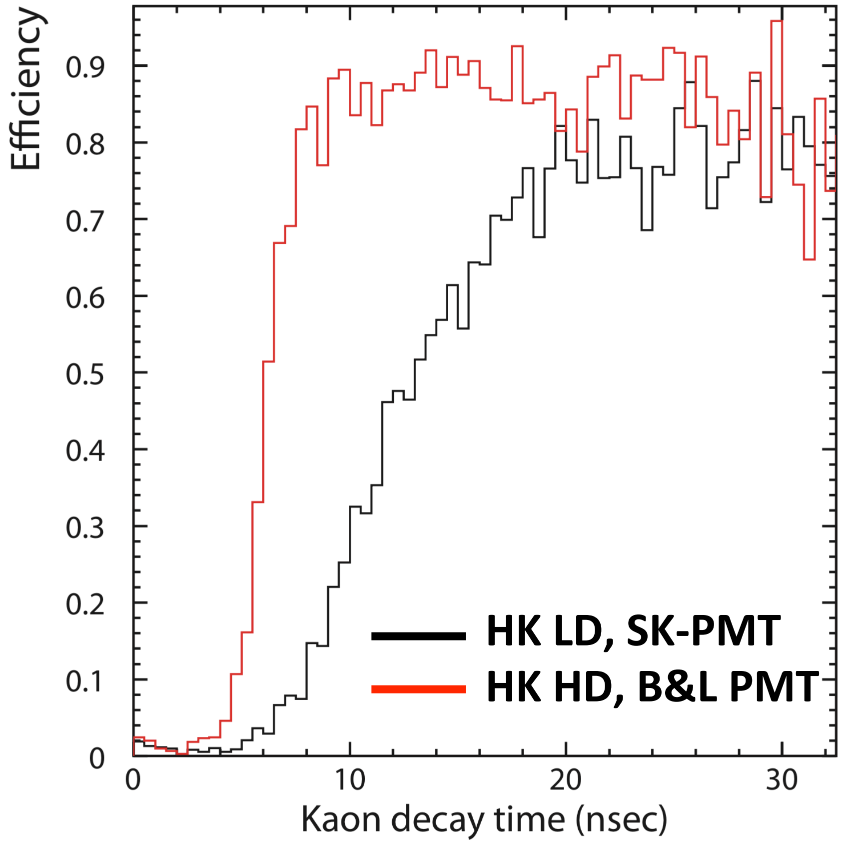
p → $\bar{\nu}$ K^+ benefits from increased photon yield and timing resolution

- search for the prompt 6 MeV γ from ^{16}O de-excitation:

number of hits within 12 ns wide time window prior to the μ^+



prompt-γ tagging efficiency as a function of the K^+ decay time

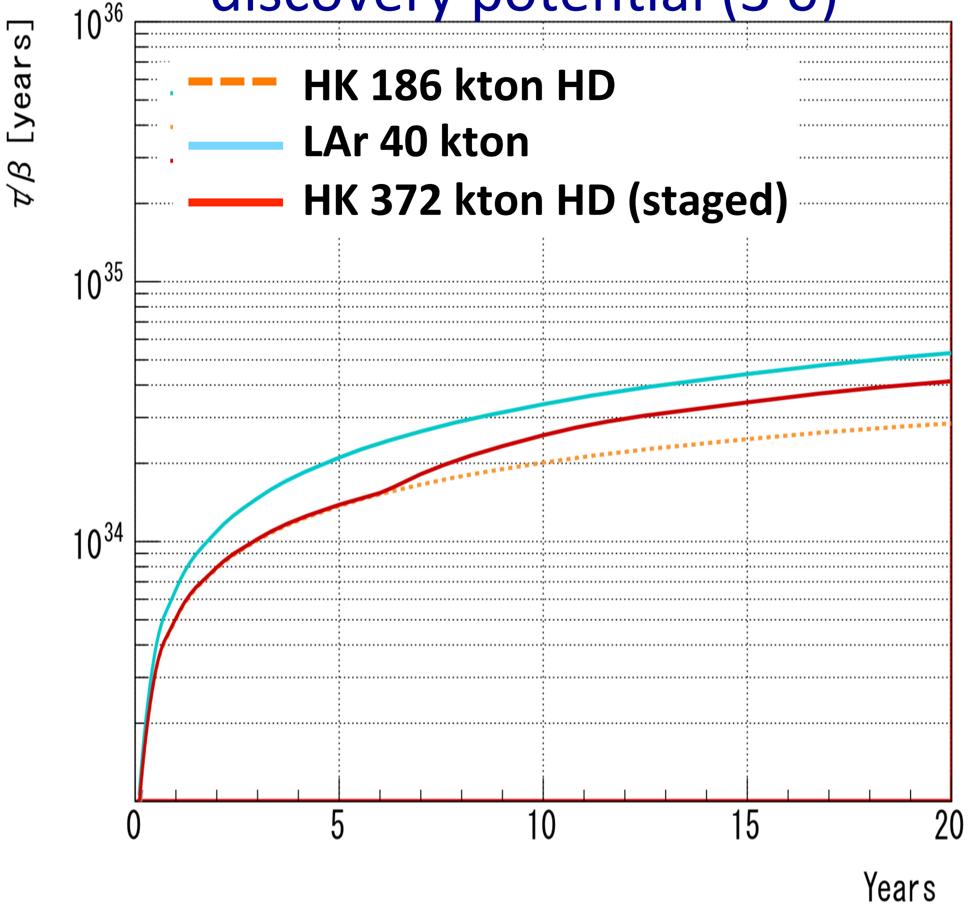


K^+ that decay earlier can be used in the analysis

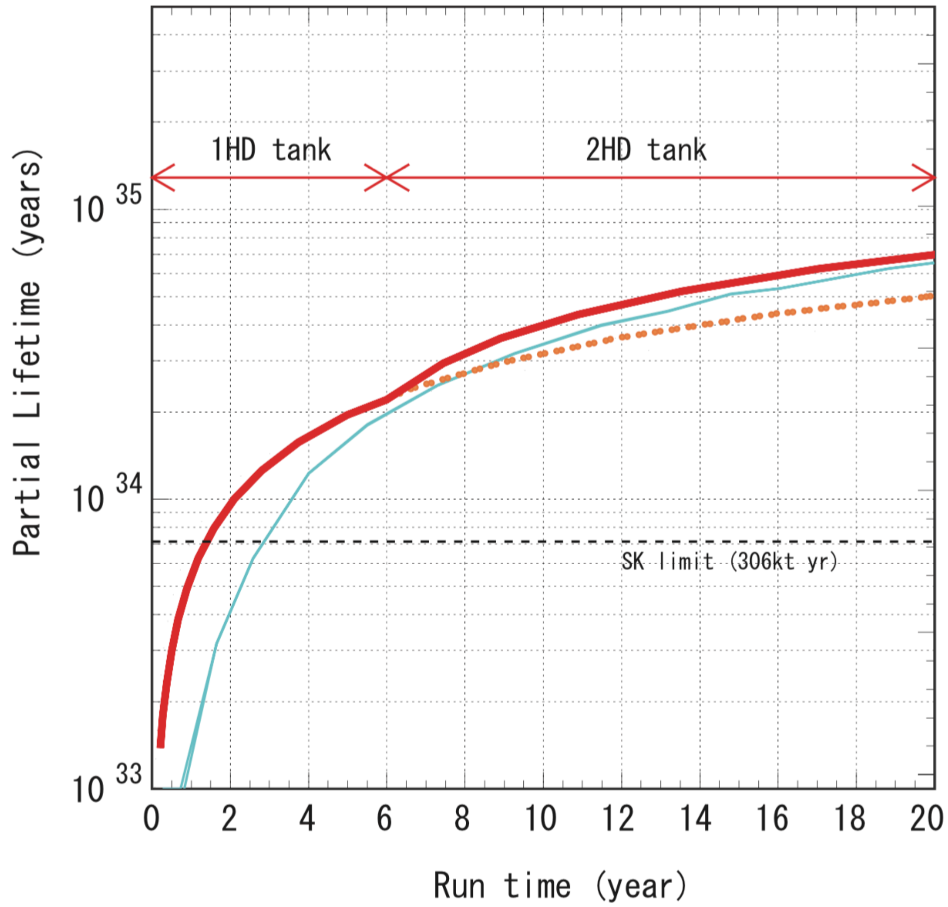
LD / HD : 20% / 40 % photo-coverage

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

discovery potential (3 σ)



90% C.L. limits achievable if no event is observed

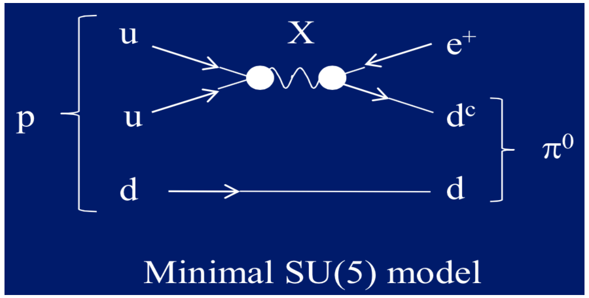


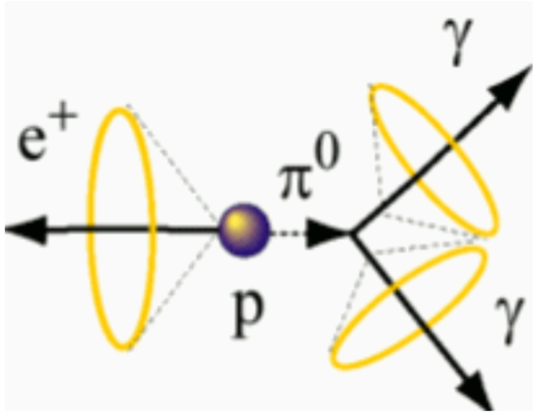
[Staging: 2nd tank comes into operation after 6 years]

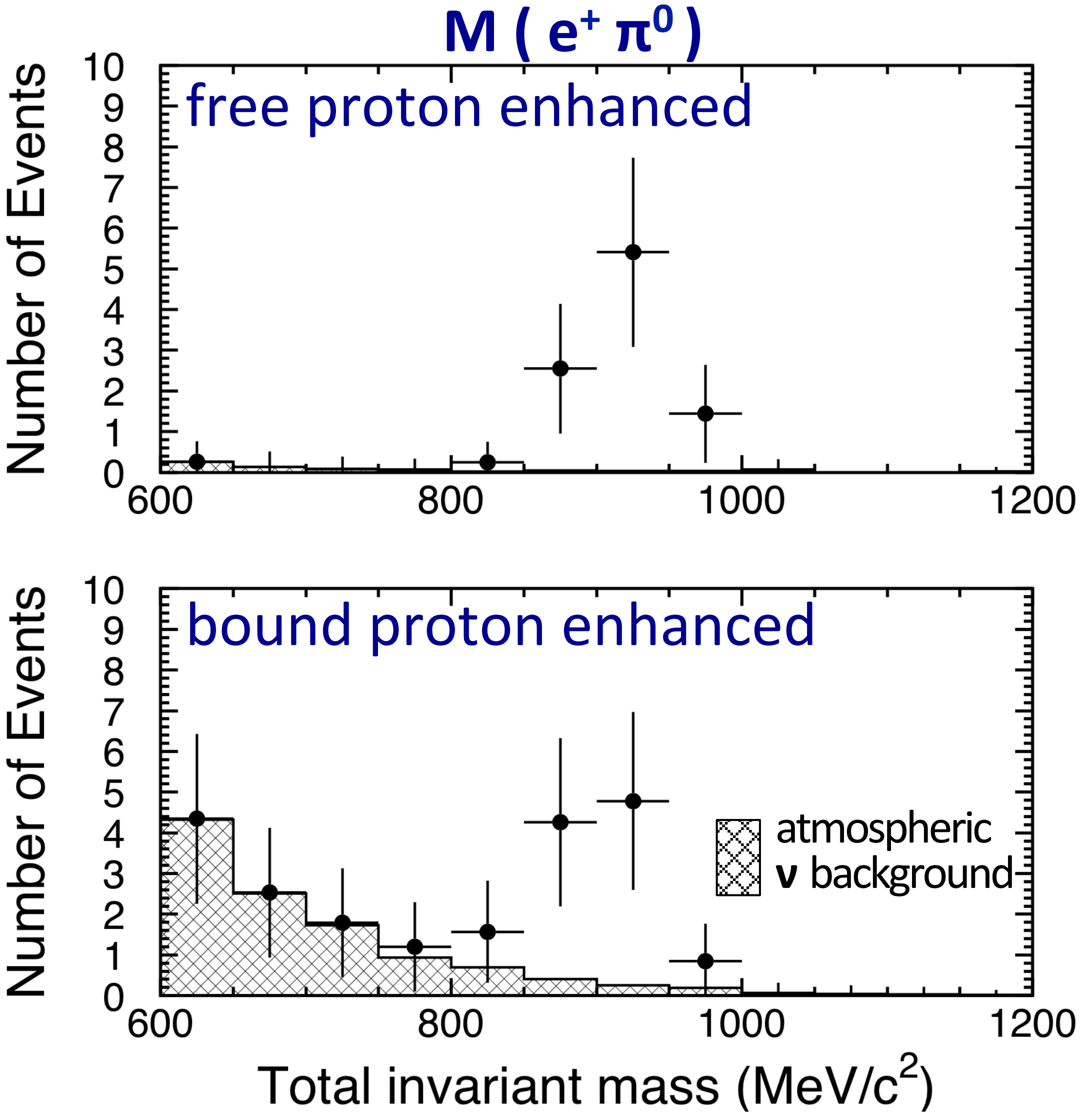
LAr discovery potential computed using numbers from DUNE CDR 2015:
97% signal efficiency, background 1 event Mton/year, no systematic errors

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

- favored by non supersymmetric GUTs
- nearly model independent reaction





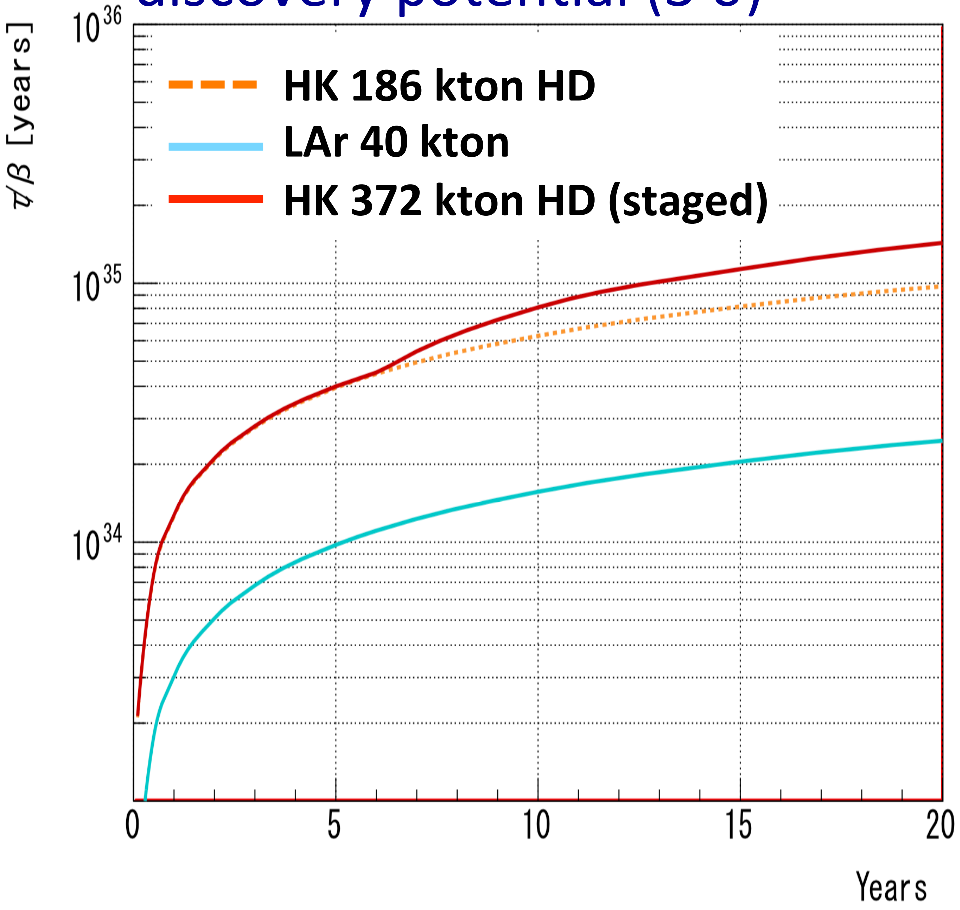


- back-to-back e^+, π^0 (459 MeV)
- e^+, π^0 ($\to \gamma\ \gamma$) are detected
- final state fully reconstructed in Water Cherenkov detectors

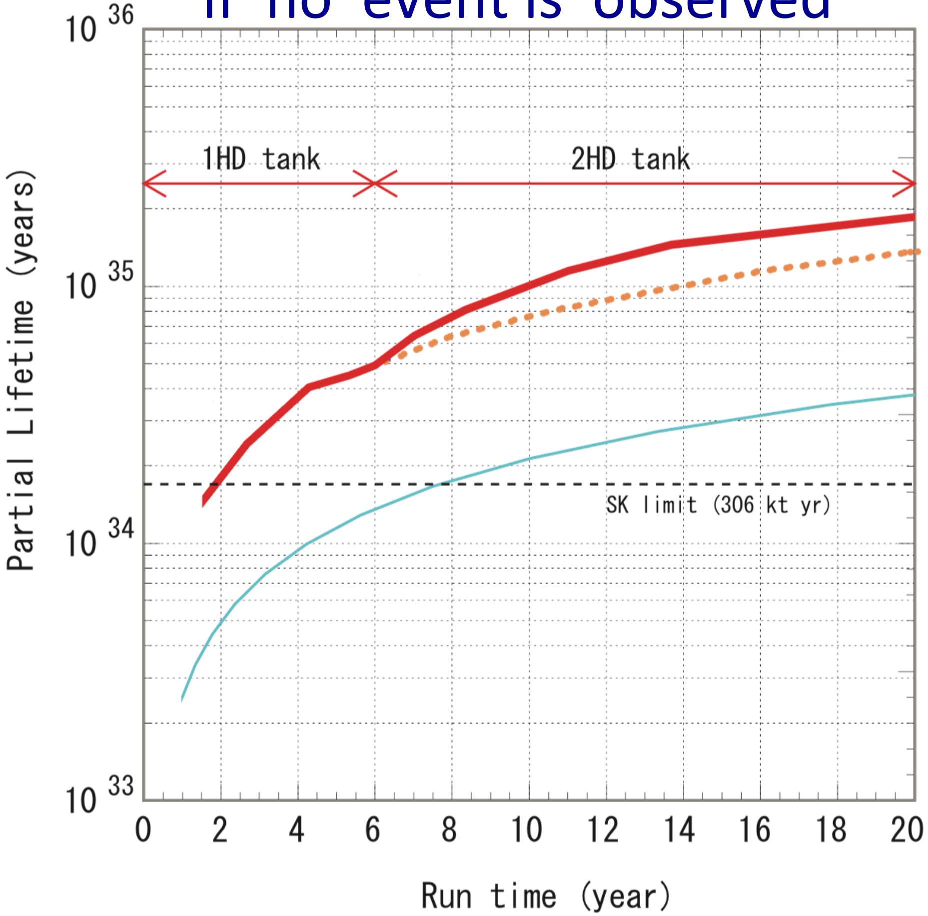
used $\tau_p = 1.7 \cdot 10^{34}$ (SK limit), 10 years exposure

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

discovery potential (3 σ)



90% C.L. limits achievable
if no event is observed



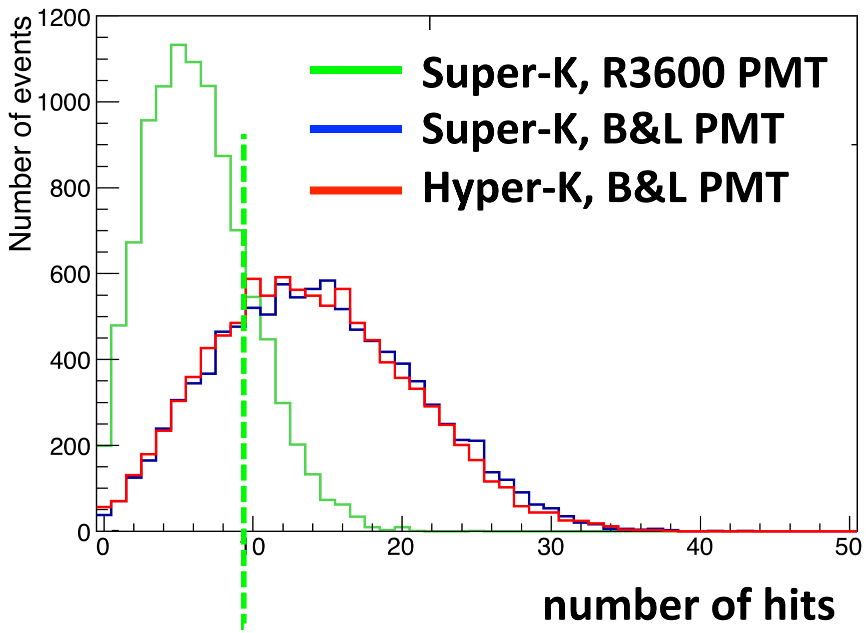
[Staging: 2nd tank comes into operation after 6 years]

LAr discovery potential computed using numbers from DUNE CDR 2015:
97% signal efficiency, background 1 event Mton/year, no systematic errors

p → $e^+\pi^0$ some of the benefits from increased photon yield

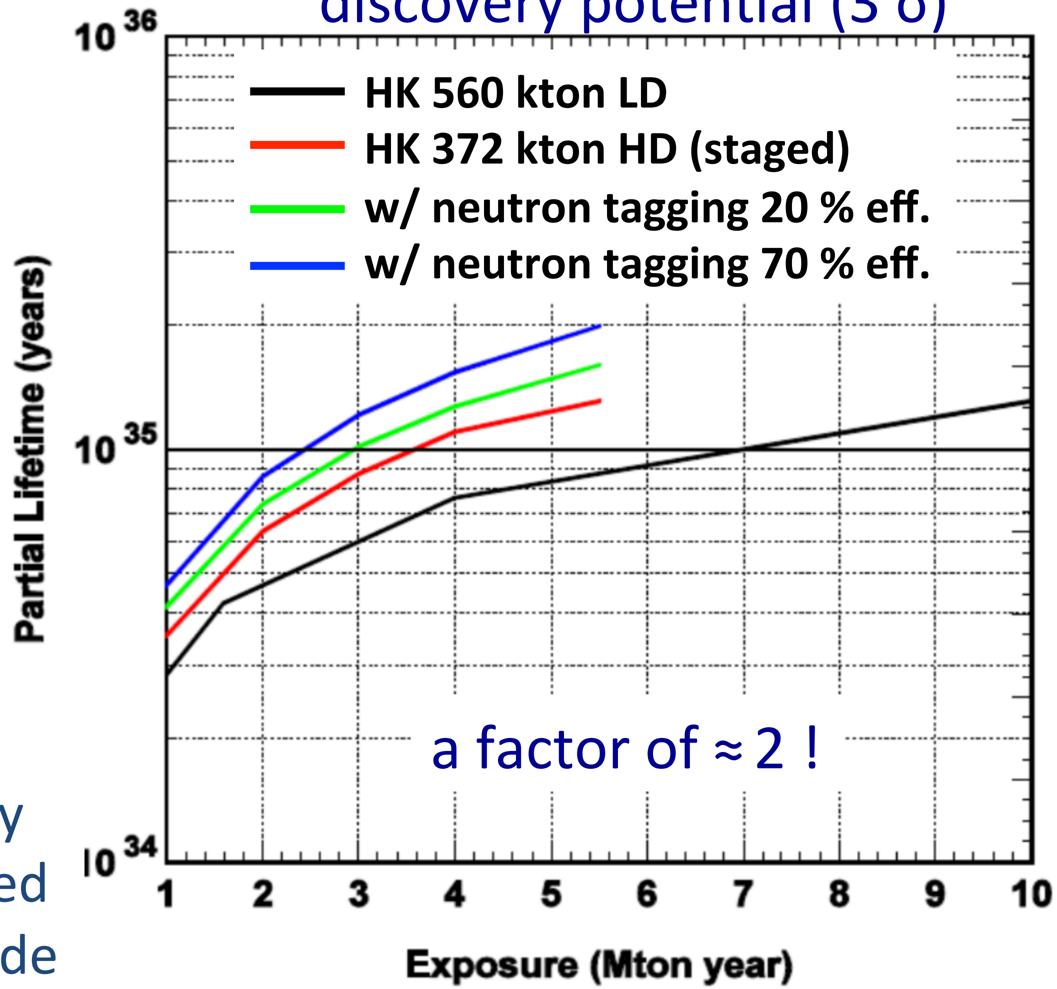
- neutron tagging (veto):
  - p decay: **no** neutrons // atmospheric ν background: **yes** neutrons
  - neutrons at (pure) water: 2.2 MeV γ from n (p, d) γ

8 MeV γ cascade if Gd capture



→ SK criterion:
≈ 18% tagging efficiency
→ much better expected for Hyper-Kamiokande

discovery potential (3 σ)



other modes
| B - L | conserving

90% C.L. limits achievable if no event is observed
[exposure: 2.6 Mton•year,
detector: HK 372 kton HD staged]

Mode	τ_{disc} 3σ [years]	current limit (90% CL)
$p \to e^+\pi^0$	8.0×10^{34}	17. x 10^{33}
$p \to \bar{\nu}K^+$	2.5×10^{34}	7.0 x 10^{33}
$p \to \mu^+\pi^0$	8.7×10^{34}	7.7 x 10^{33}
$p \to e^+\eta^0$	3.9×10^{34}	10 x 10^{33}
$p \to \mu^+\eta^0$	4.7×10^{34}	4.7 x 10^{33}
$p \to e^+\rho^0$	5.0×10^{33}	0.7 x 10^{33}
$p \to \mu^+\rho^0$	1.6×10^{33}	0.6 x 10^{33}
$p \to e^+\omega$	6.9×10^{33}	1.6 x 10^{33}
$p \to \mu^+\omega$	1.0×10^{34}	2.8 x 10^{33}

SK, arXiv1705.07221, PRD

Mode	τ_{disc} 3σ [years]	current limit (90% CL)
$n \to e^+\pi^-$	1.6×10^{34}	5.3 x 10^{33}
$n \to \mu^+\pi^-$	1.5×10^{34}	3.5 x 10^{33}
$n \to e^+\rho^-$	1.5×10^{33}	0.03 x 10^{33}
$n \to \mu^+\rho^-$	8.1×10^{32}	0.06 x 10^{33}

SK, arXiv1705.07221, PRD

~ 1 order of magnitude for most of the modes

Summary / Conclusions / Outlook

- Hyper-Kamiokande: the very-high mass, high precision, high beam power, highly reliable next generation M-ton neutrino and nucleon decay experiment
- The photo-sensor is now ready for mass production. It features a 2x better efficiency, time and charge resolutions.

- Neutrino oscillation: determination of Mass Hierarchy and ϑ_{23} octant within several years for the nearly entire parameter space
- The option of the second tank in Korea enhances largely the sensitivity to MH

- Nucleon decay: partial lifetimes limits (90% C.L., 10 y exposure) of $0.8 \cdot 10^{35}$ years for $p \rightarrow e^+\pi^0$, $3 \cdot 10^{34}$ years for $p \rightarrow \nu K^+$ and basically one order of magnitude improvement for many other modes

Particularly to this:
if you want to explore GUTs experimentally in the next decades you'd better work (within your field) for Hyper-Kamiokande

Additional

The key of HK: very large mass and excellent photosensitivity

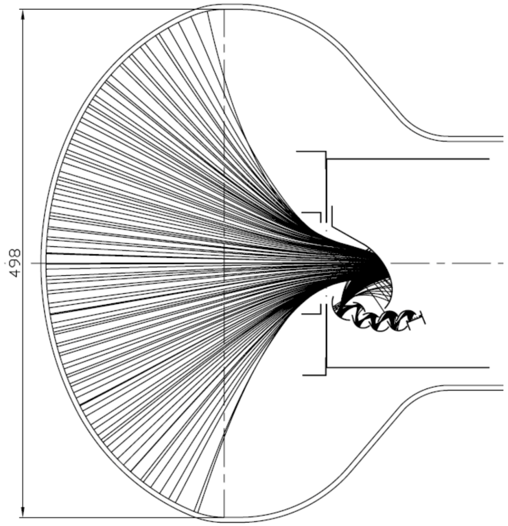
***#638-talk* Y. Nishimura** *"New 50 cm Photo-Detectors for HK"*

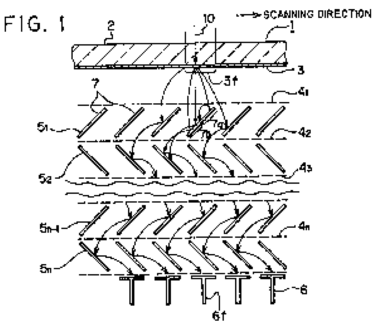
- current baseline: **high-QE Box&Line PMT** Hamamatsu R12860
    - R&D since 2011

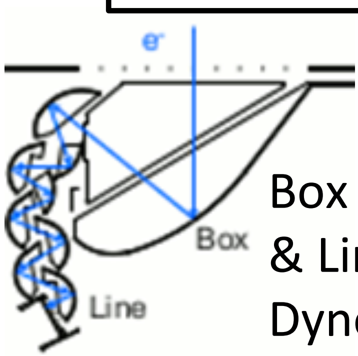
Super-K PMT

Venetian Blind

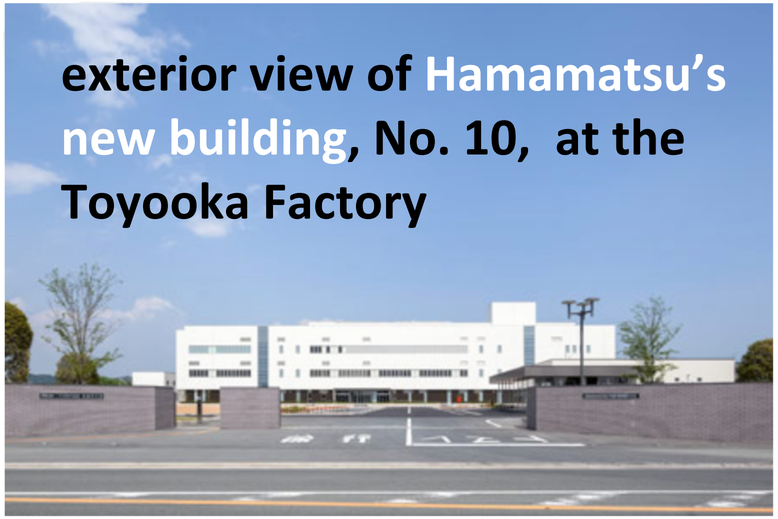
50 cm HQE Box&Line PMT







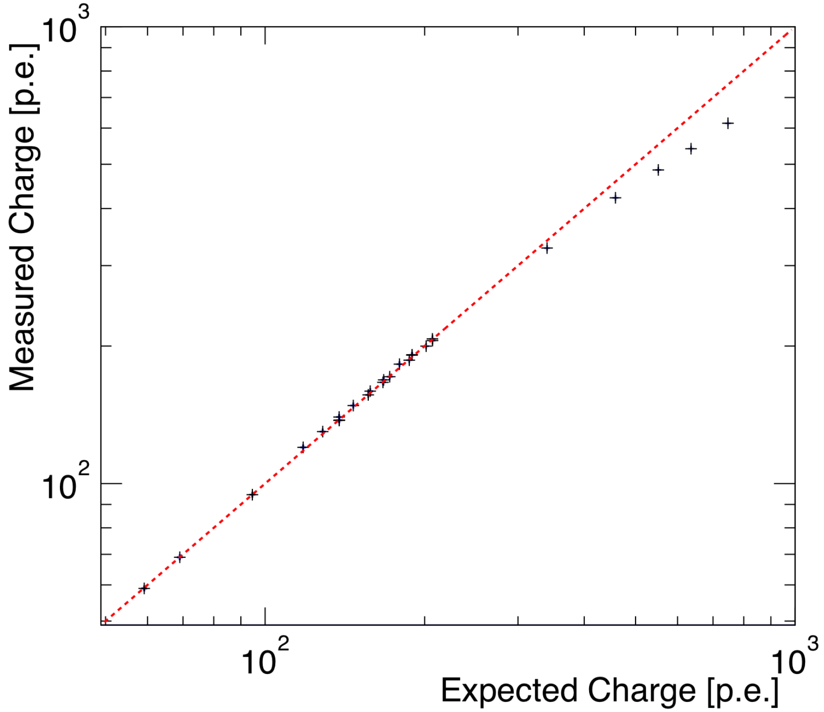
Box & Line Dynode

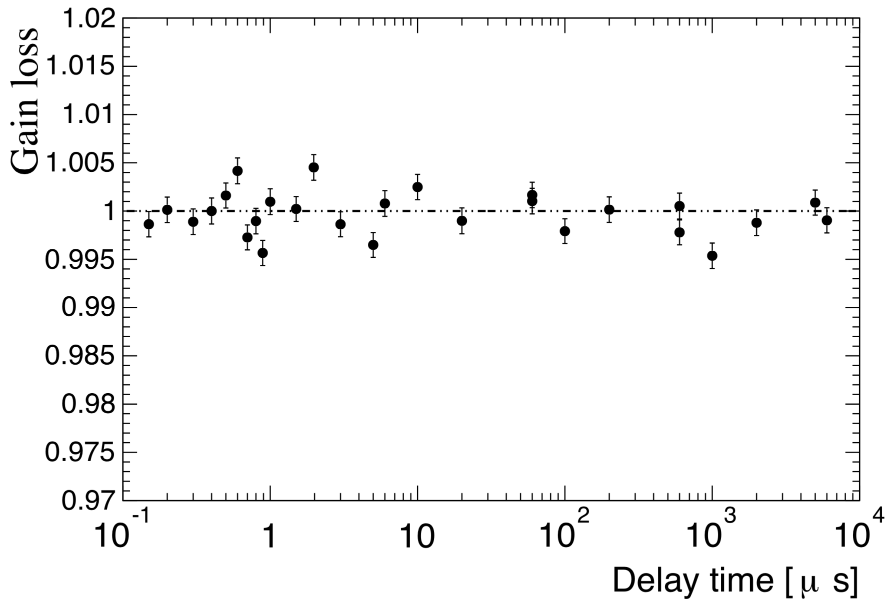


Exterior view of the new Building No. 10 at the Toyooka Factory

- also new bulb shape with higher pressure tolerance (> 100 m)
- now **ready** for mass production
- ≈ 80k 50 cm PMTs at inner detector

Box&Line PMT Hamamatsu R12860HQE





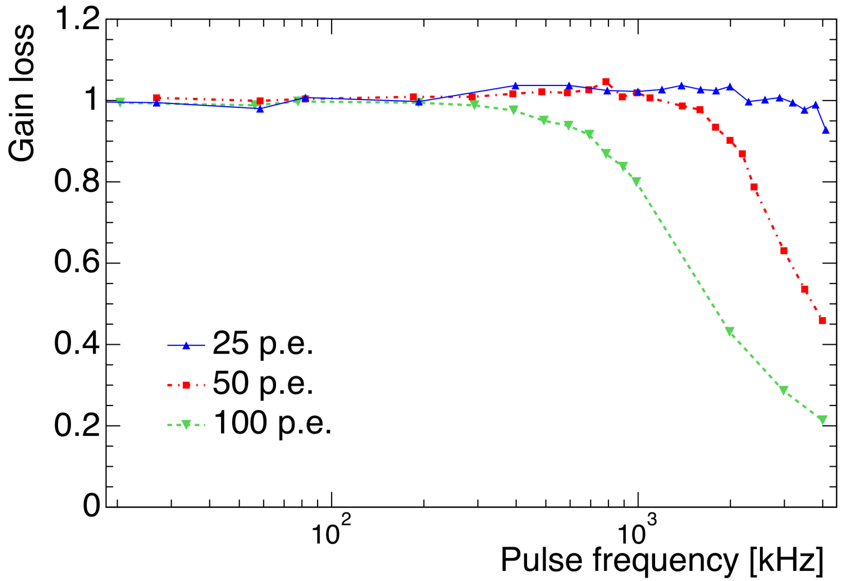


FIG. 62. Output linearity of the HQE B&L PMT in charge, where a dotted line shows an ideal linear response. It is derived by measurements of a coincident emission by two light sources compared with an expectation by sum of individual detections.

FIG. 63. Gain stability of a delayed pulse after a primary pulse, compared with no primary pulse. The charge set is about 150 PEs at 10^7 gain for both primary and delayed pulses in various delayed time.

FIG. 64. A measured gain stability as a function of the pulse rate in three light intensities of 25, 50 and 100 photoelectrons, relative to outputs at 100 Hz. Each charge is calculated using the baseline just before the pulse.

TABLE XXXIX. Expected 1σ uncertainty of Δm^2_{32} and $\sin^2\theta_{23}$ for true $\sin^2\theta_{23} = 0.45, 0.50, 0.55$. Reactor constraint on $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ is imposed.

True $\sin^2\theta_{23}$	0.45		0.50		0.55	
Parameter	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$
NH	1.4×10^{-5}	0.006	1.4×10^{-5}	0.017	1.5×10^{-5}	0.009
IH	1.5×10^{-5}	0.006	1.4×10^{-5}	0.017	1.5×10^{-5}	0.009

$0 < p_{tot} < 100$MeV/c				$100 < p_{tot} < 250$MeV/c			
ϵ_{sig} [%]	σ_ϵ [%]	Bkg [/Mton·yr]	σ_{Bkg} [%]	ϵ_{sig} [%]	σ_ϵ [%]	Bkg [/Mton·yr]	σ_{Bkg} [%]
18.7	6.5	0.06	32.8	19.4	14.9	0.62	31.9

TABLE XLIV. Signal efficiency and background rates as well as estimated systematic uncertainties for the analysis $p \to e^+\pi^0$ at Hyper-K.

Prompt γ				$\pi^+\pi^0$				p_μ Spectrum		
ϵ_{sig} [%]	σ_ϵ [%]	Bkg	σ_{Bkg} [%]	ϵ_{sig} [%]	σ_ϵ [%]	Bkg	σ_{Bkg} [%]	ϵ_{sig} [%]	Bkg	σ_{fit} [%]
12.7	19.0	0.9	27.0	10.8	10.0	0.7	31.0	31.0	1916.0	8.0

TABLE XLV. Signal efficiency and background rates as well as estimated systematic uncertainties for the analysis $p \to \bar{\nu}K^+$ at Hyper-K. Background rates are listed as events per Mton·yr.