Status of the Hyper-K Experiment

17th International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

Oct. 27, 2017

I. Shimizu (Tohoku Univ.)

Hyper-K Proto-Collaboration

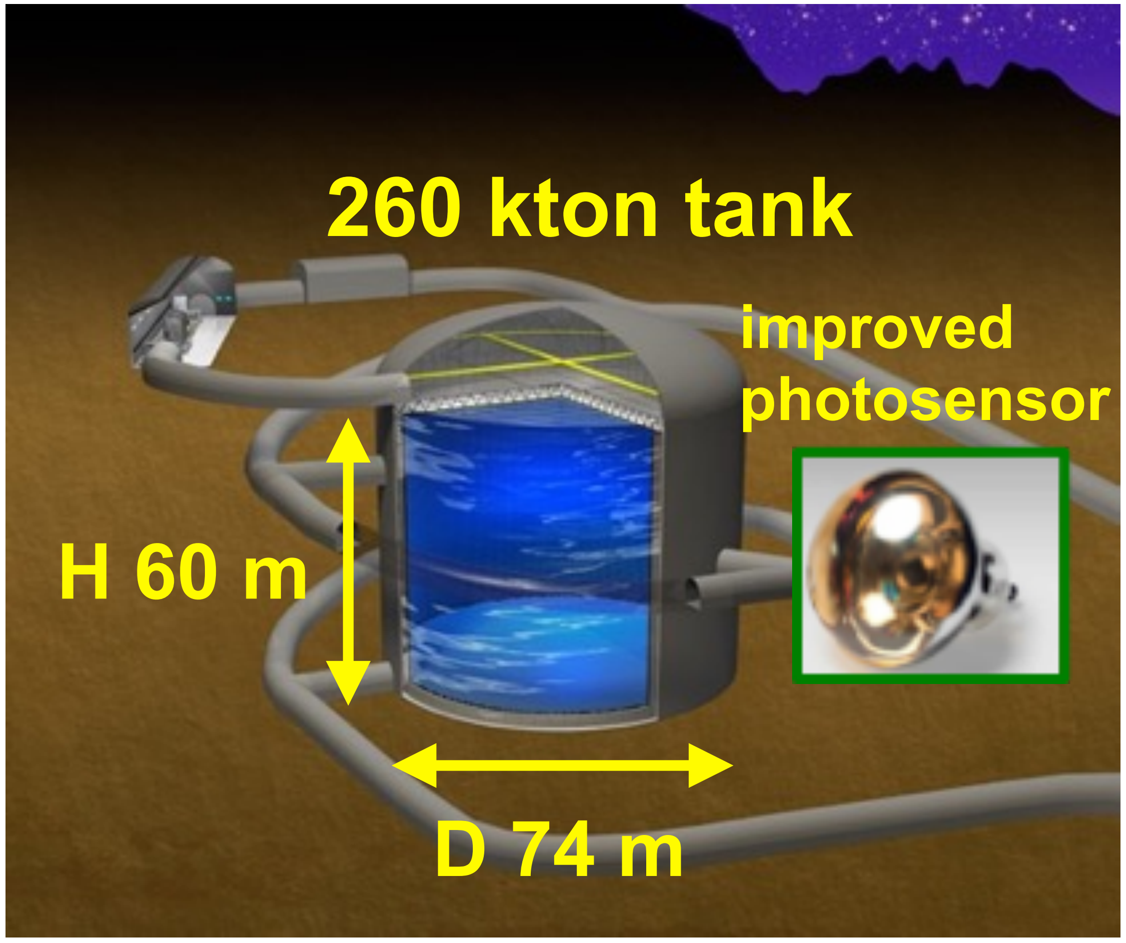
Proto-collaboration formed in 2015

International team: ~300 members from 15 countries (~70% overseas)

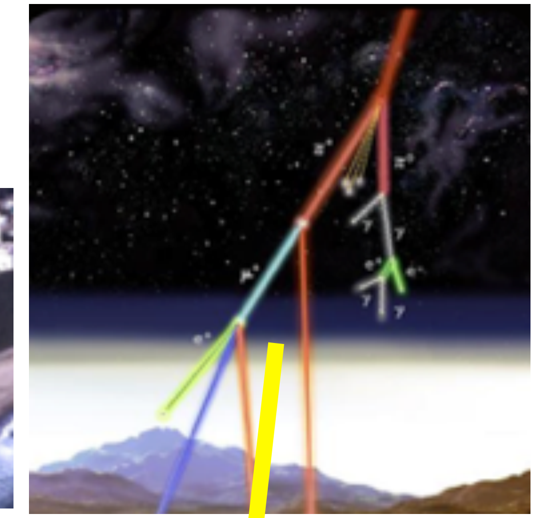
Hyper-K Detector

	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	**11,129**	**40,000**
Photo-coverage	40%	40% (**×2 sensitivity**)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**

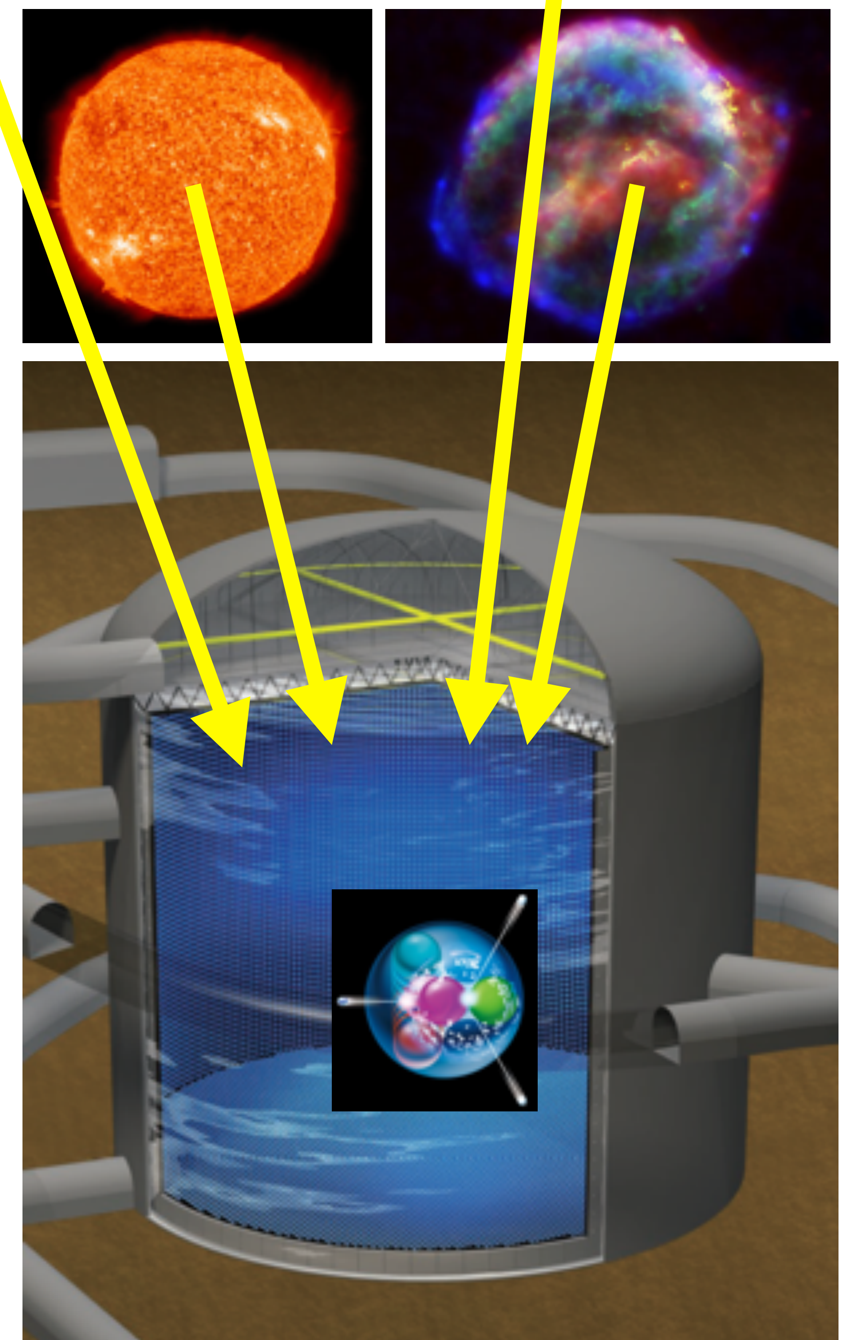
- High statistics (**~10 × Super-K**) keeping low energy threshold and low background will significantly enhance the physics sensitivities
- Aim for quick start with 1 tank
- Optional 2nd tank after 1st tank is under consideration



Target Physics

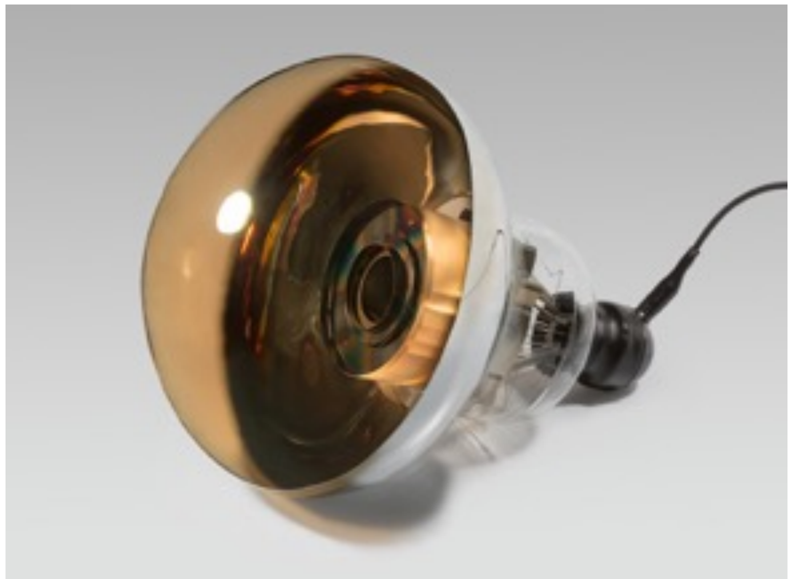


- Neutrino oscillation
  - δ_{CP} measurement
  - neutrino mass ordering and mixing parameters
- Nucleon decay
  - Great potential for discovery
- Neutrino astrophysics
  - Solar neutrino
  - Supernova (relic) neutrino
  - Dark matter annihilation neutrino

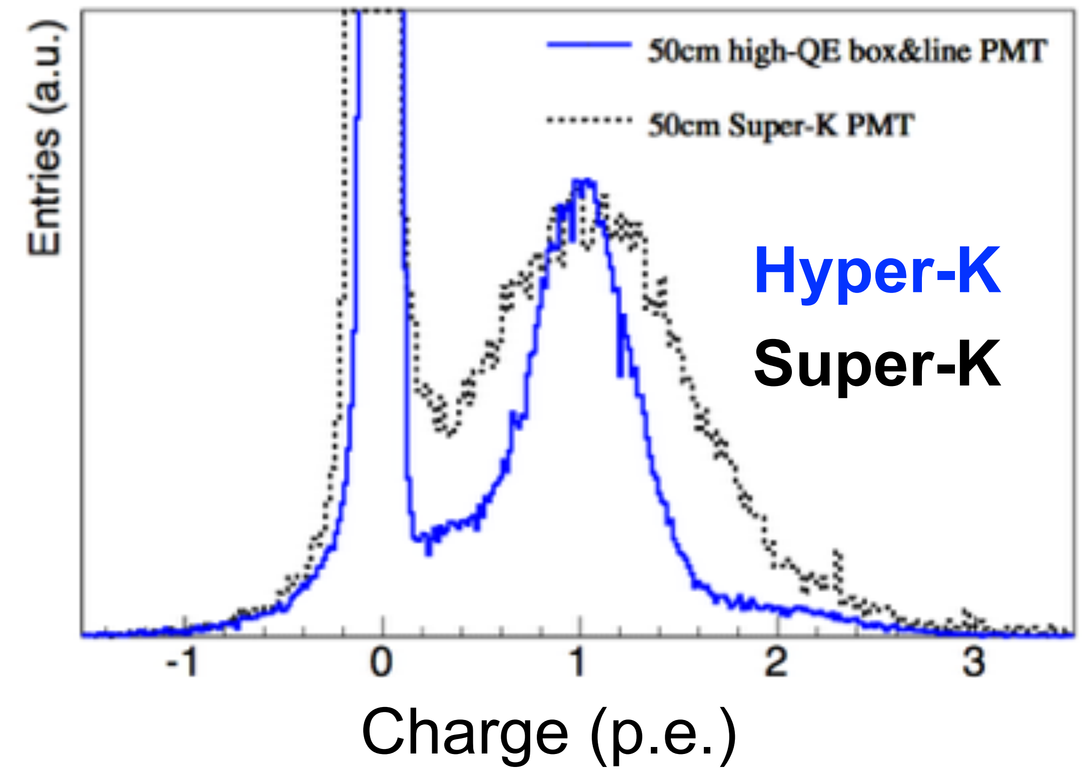


Rich program to explore the fundamental physics questions

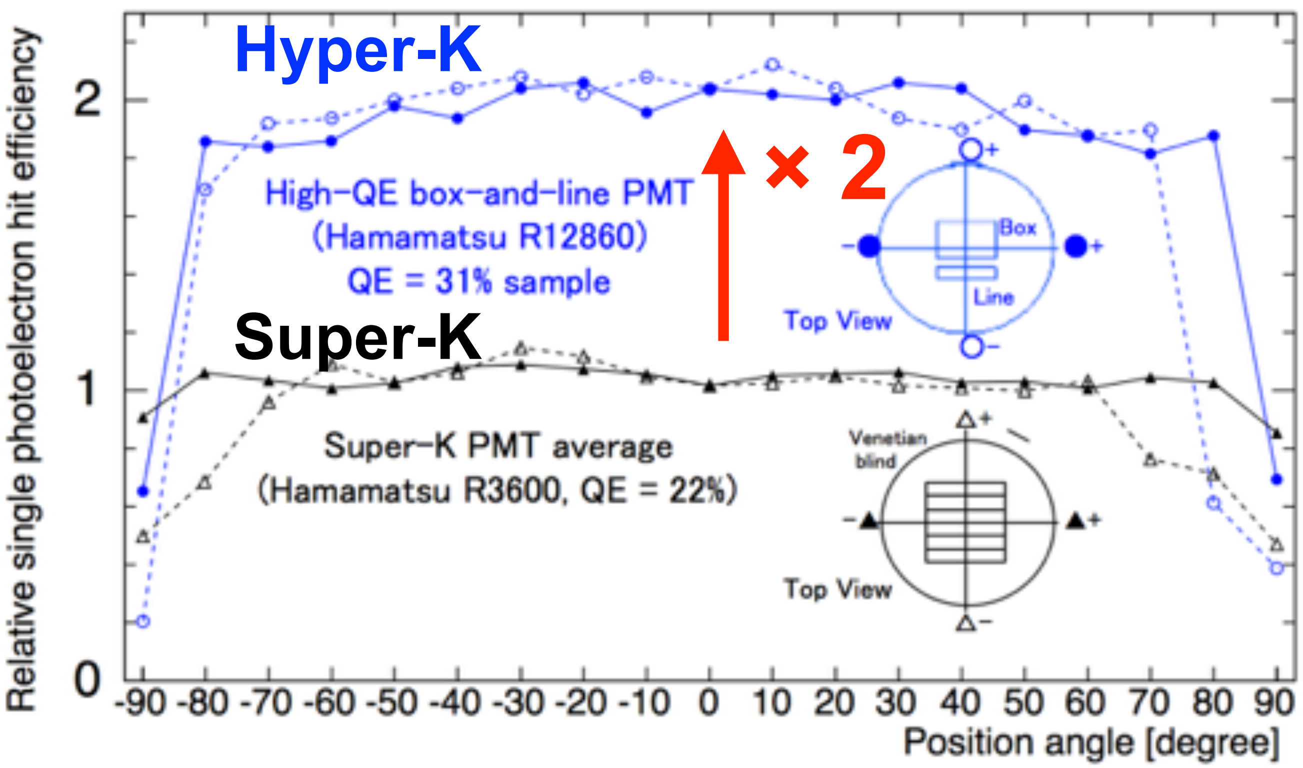
Photo-Sensor R&D

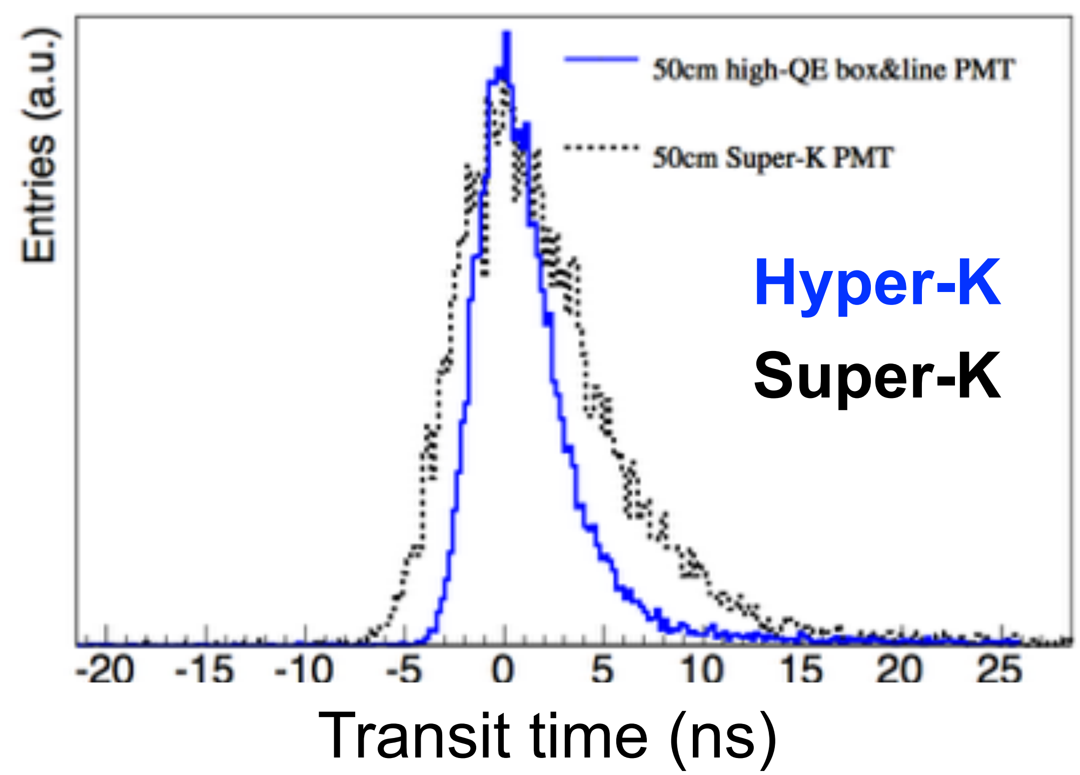


High Q.E. 50 cm box-and-line PMT (Hamamatsu)



relative photo detection efficiency (p.e.)

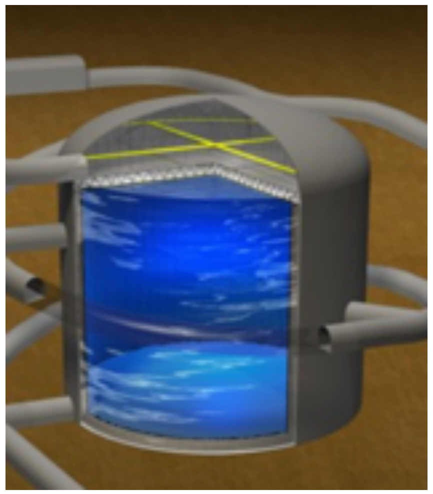




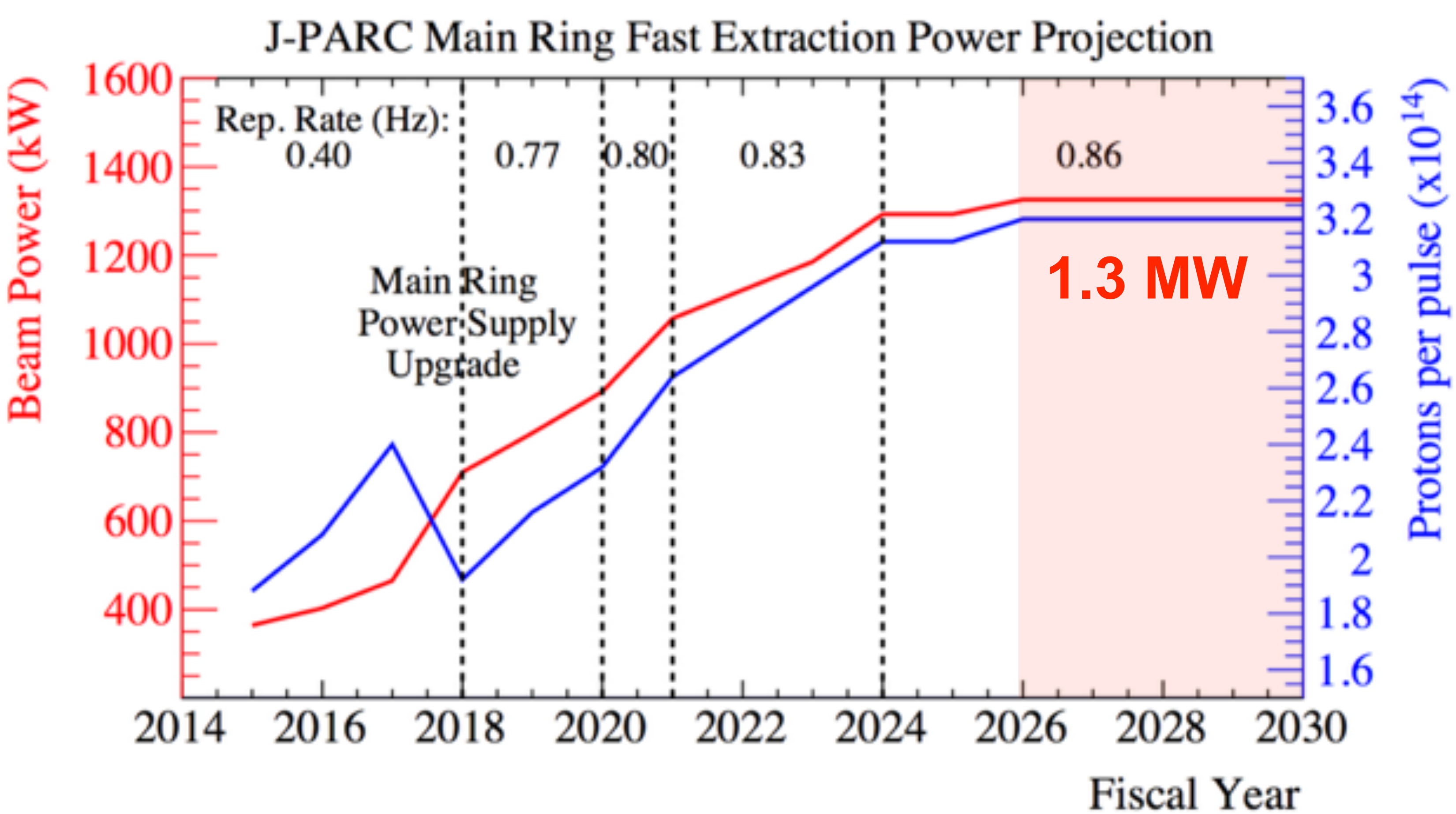
Twice better photo-detection efficiency than Super-K PMTs

Good charge / time resolution

Accelerator Neutrino



Hyper-Kamiokande



2.5° Off-axis ν beam from the direction to Hyper-K and Super-K

→ narrow band ν beam

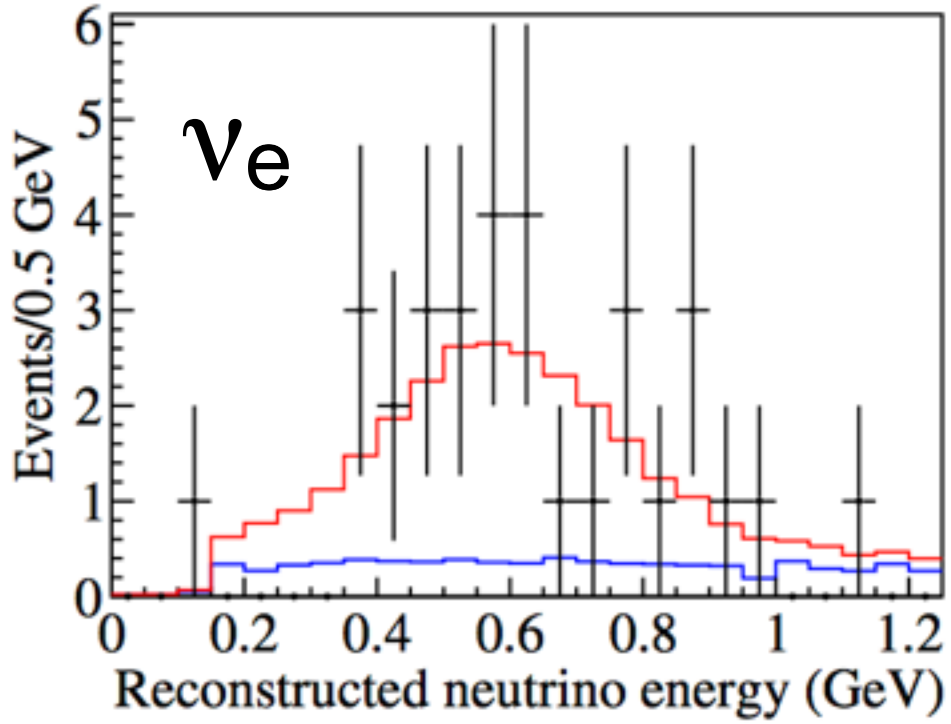
J-PARC plan to an upgrade of the proton drivers

Beam power → 1.3 MW before Hyper-K start

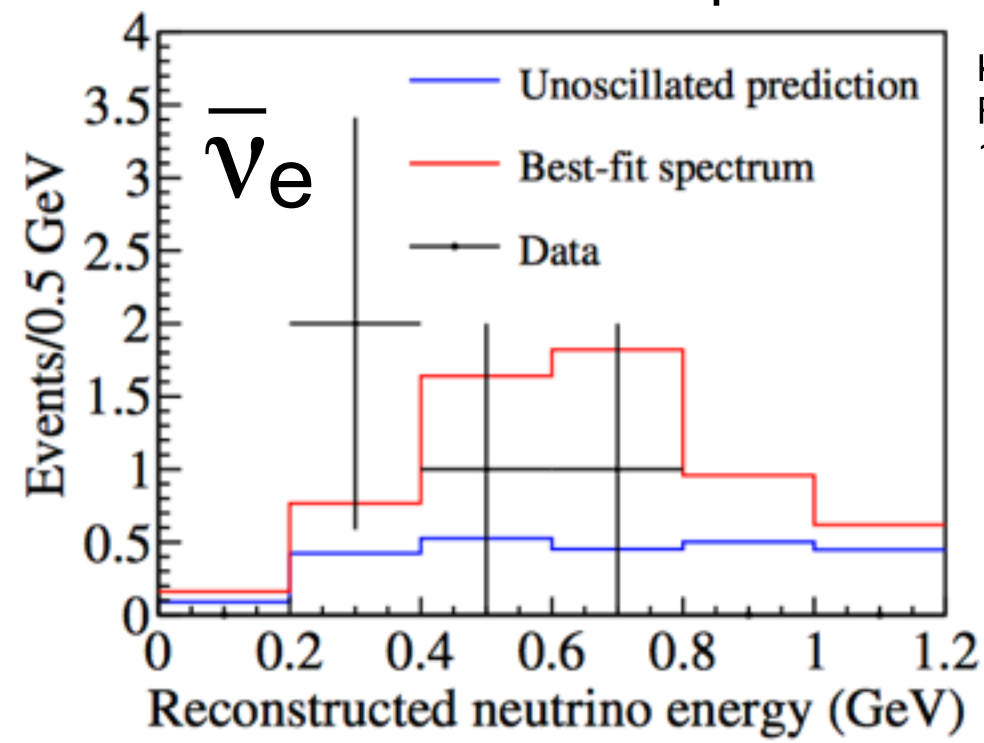
T2K → Hyper-K →

T2K results on CP phase (δ_{CP})

reconstructed E_ν spectra

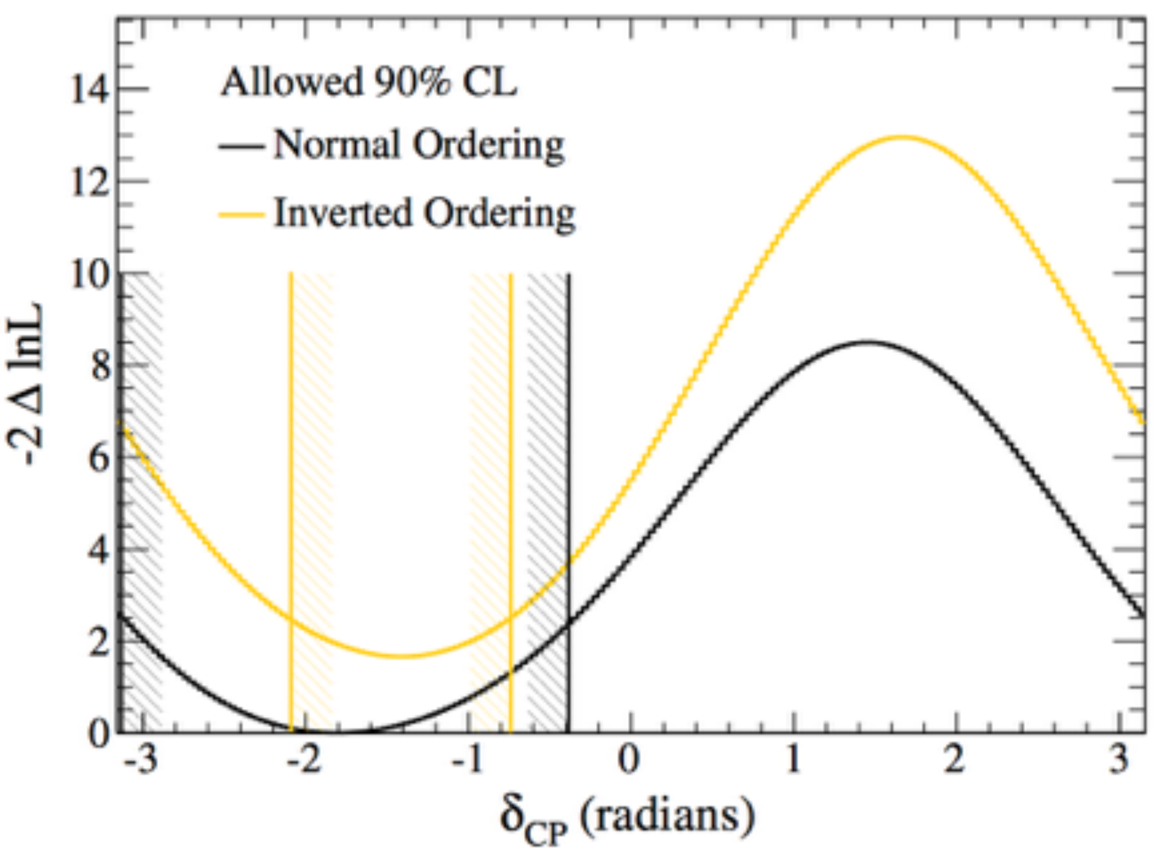


reconstructed E_ν spectra



K. Abe et al., Phys. Rev. Lett. 118, 151801 (2017)

constraint on δ_{CP}



number of event in T2K (Run 1-7)

Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4
Inverted	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\bar{\nu}_e$	6.5	7.4	8.4	7.4	4

$-3.13 < \delta_{CP} < -0.39$ (normal MH, 90% C.L.)

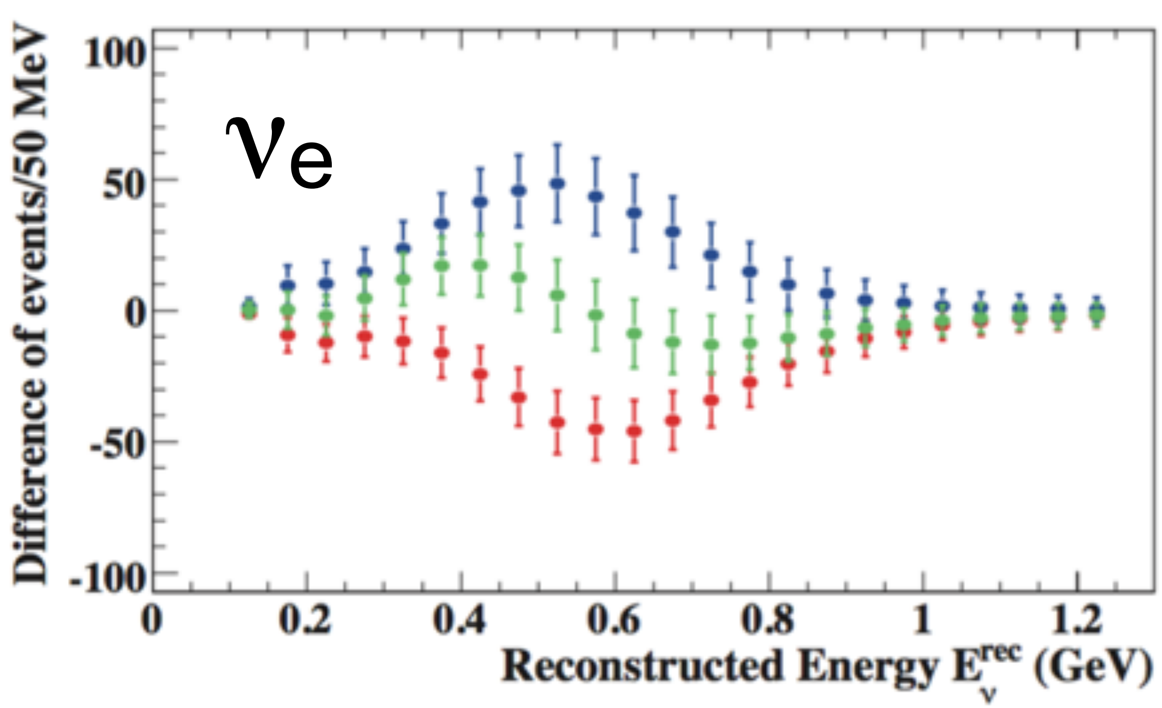
CP conservation hypothesis ($\delta_{CP} = 0, \pi$) is excluded at 90% C.L.

Expected Number of Event in Hyper-K

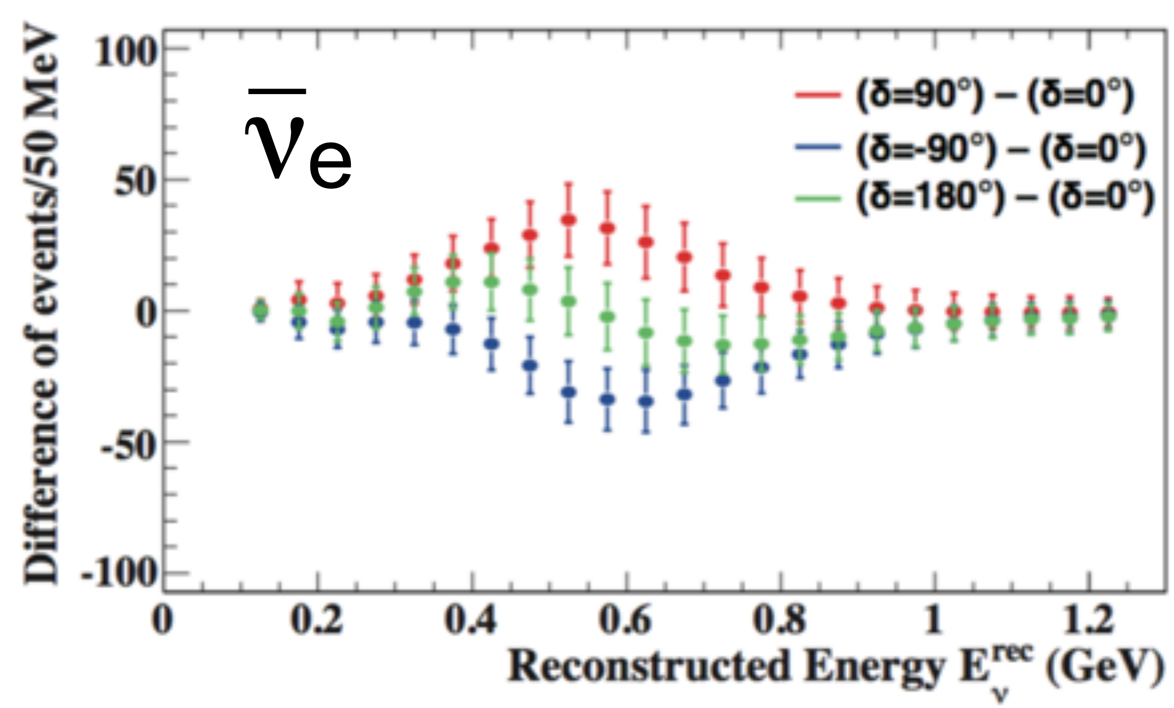
expected number of event in ν_e / $\overline{\nu}_e$ appearance (10 years)

		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG Total	
ν mode	Events	1643	15	7	0	248	11	134	400	2058
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\bar{\nu}$ mode	Events	206	1183	2	2	101	216	196	517	1906
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

difference of reconstructed E_ν spectra

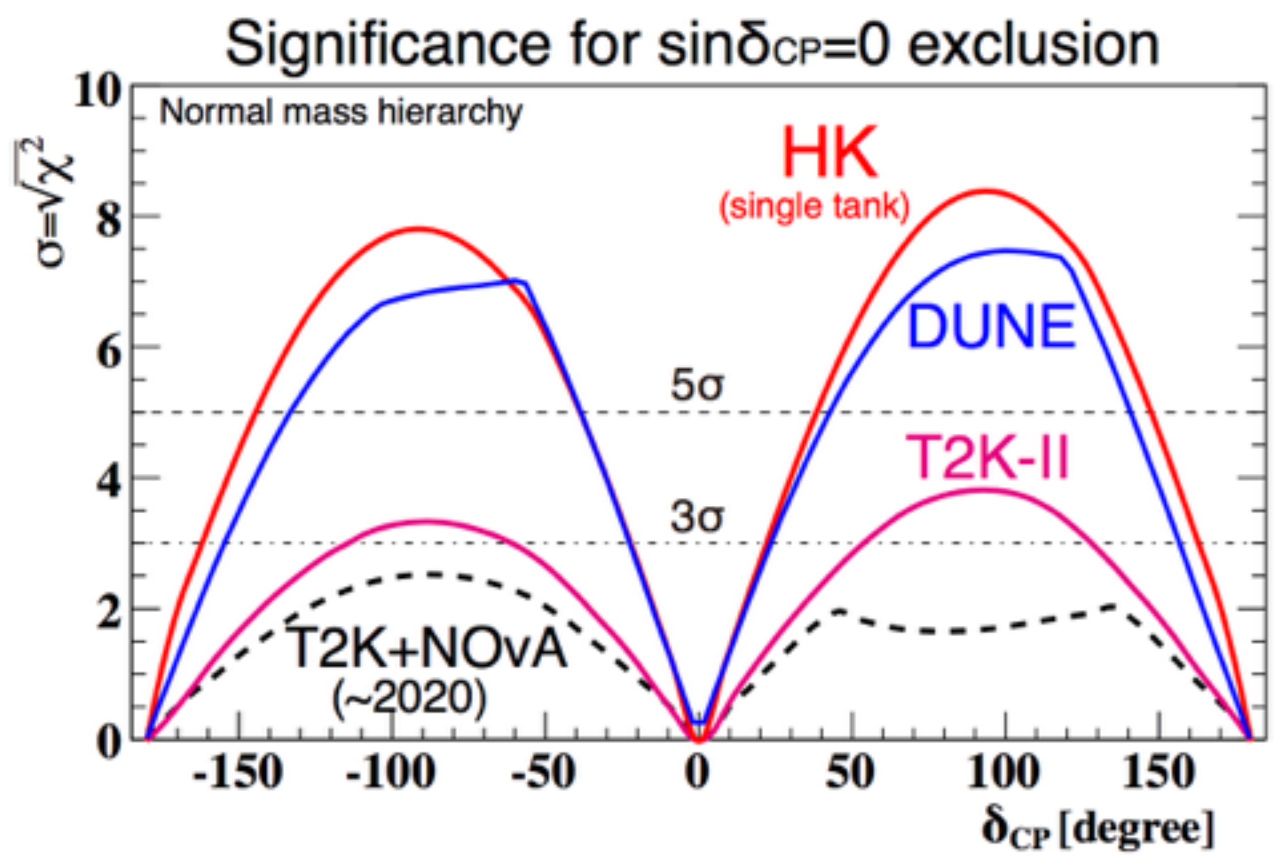


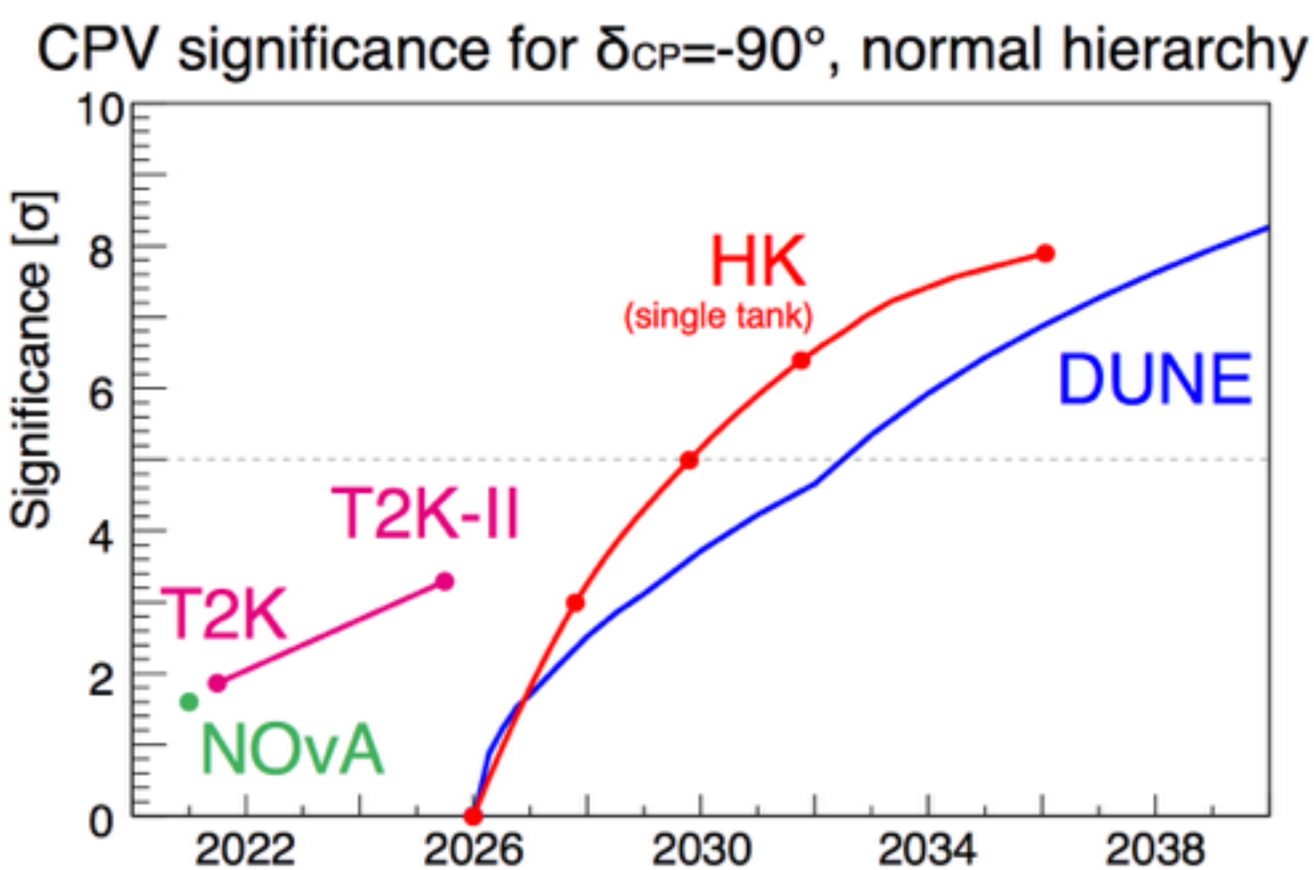
difference of reconstructed E_ν spectra



Effect of δ_{CP} will be clearly confirmed with energy spectra

CP Violation Significance





Expected sensitivity in Hyper-K
(1.3 MW × 10 years, $\nu : \overline{\nu} = 1 : 3$)

<u>significance for $\sin\delta_{CP} = 0$ exclusion</u>

~8σ significance if $\delta_{CP} = \pm 90°$

~6σ significance if $\delta_{CP} = \pm 45°$

Observe CP violation for 58% of δ_{CP} space with 5σ

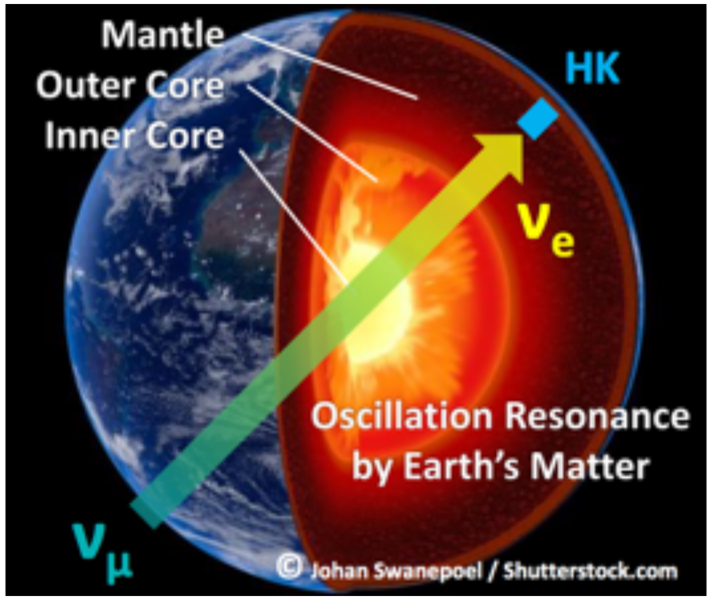
<u>uncertainty on δ_{CP}</u>

22° for $\delta_{CP} = \pm 90°$

7° for $\delta_{CP} = 0°/180°$

assuming 3-4% systematic uncertainty smaller than 5-6% in T2K (2017)

Atmospheric Neutrino

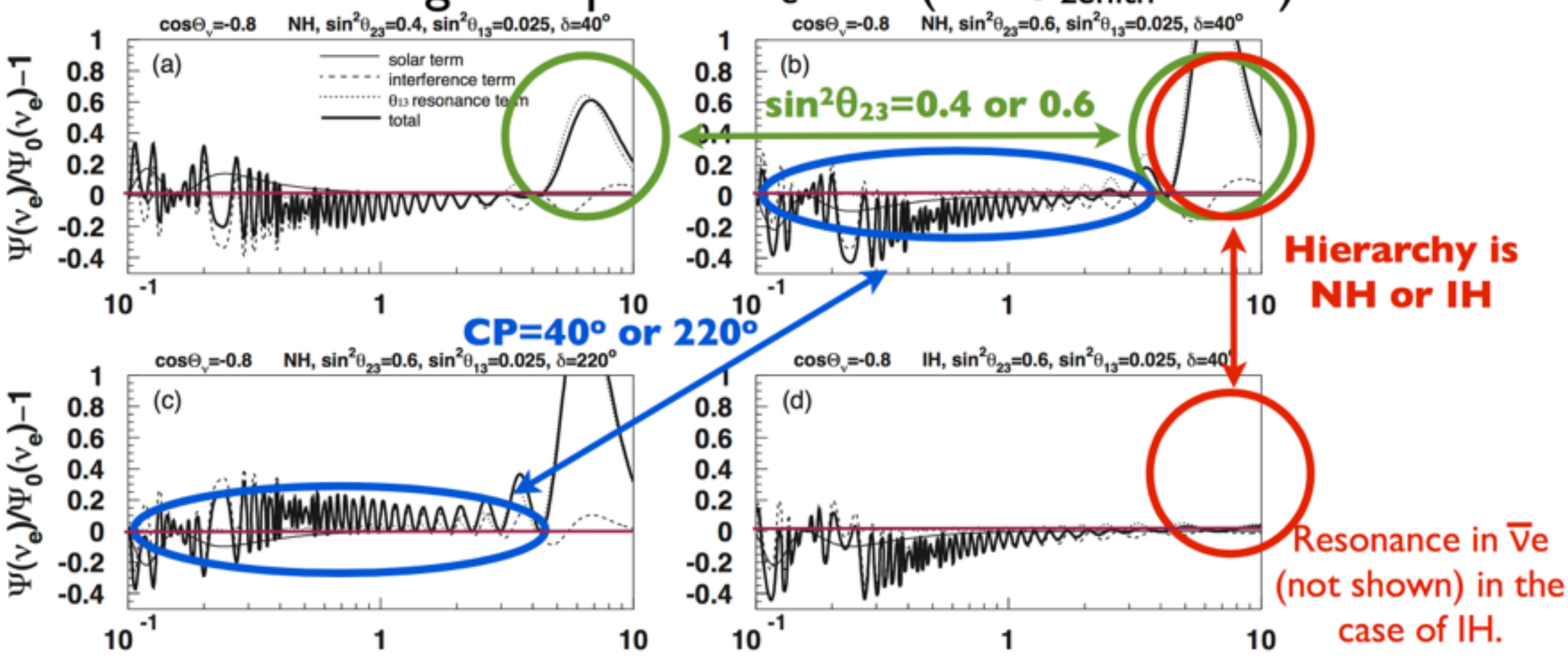


For upward-going multi-GeV atmospheric ν, oscillation resonance in the Earth's core causes

- ν_e appearance for normal hierarchy (NH)
- $\overline{\nu}_e$ appearance for inverted hierarchy (IH)

Effect reverses for NH and IH

"Fractional change of upward ν_e flux ($\cos\Theta_{zenith}$=-0.8)"



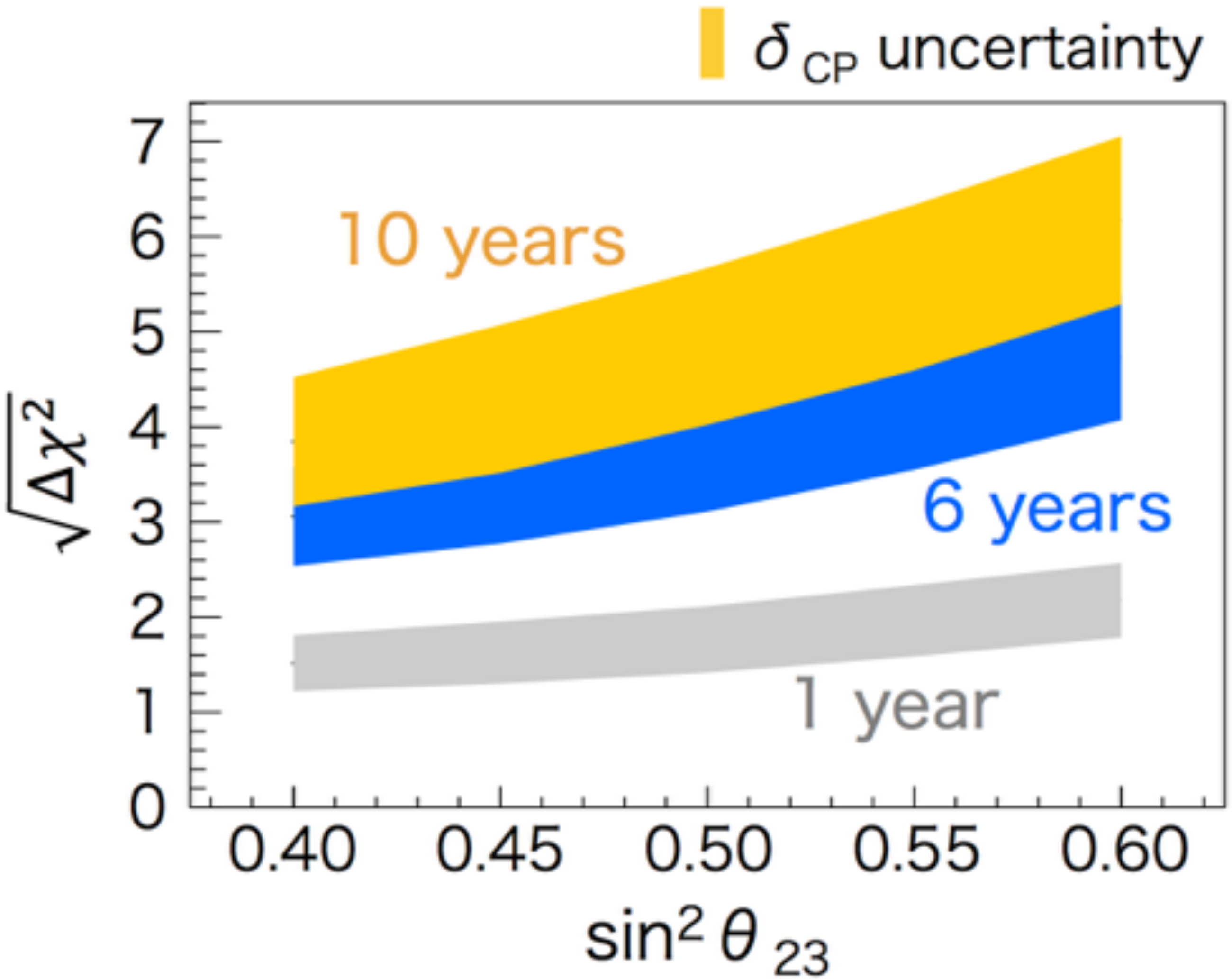
M. Shiozawa, NuTel 2017

Sensitivity on Mass Hierarchy

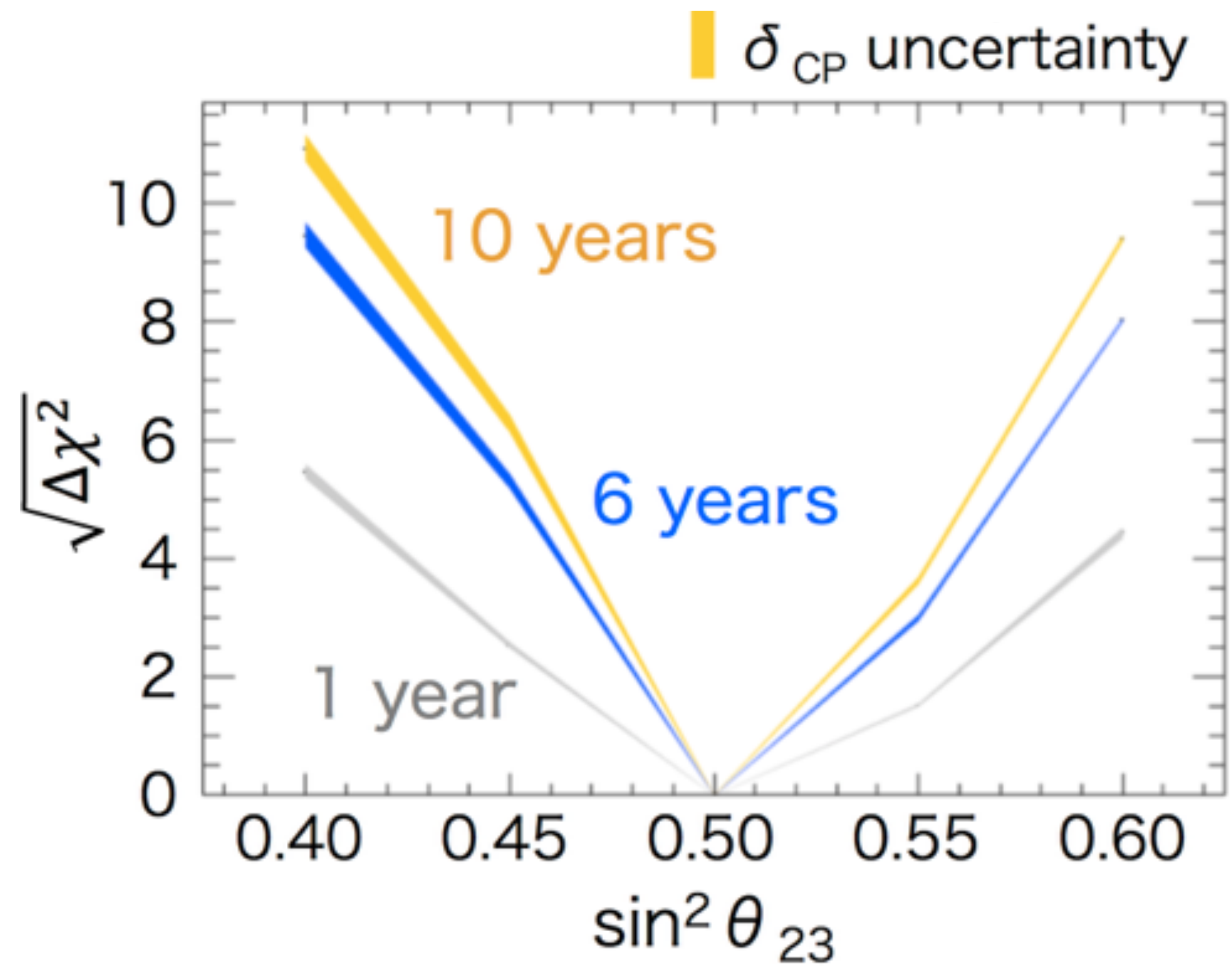
Combining atmospheric + beam neutrino data

→ complementary for oscillation parameters, mass hierarchy, θ_{23} octant

wrong mass hierarchy rejection



wrong θ_{23} octant rejection

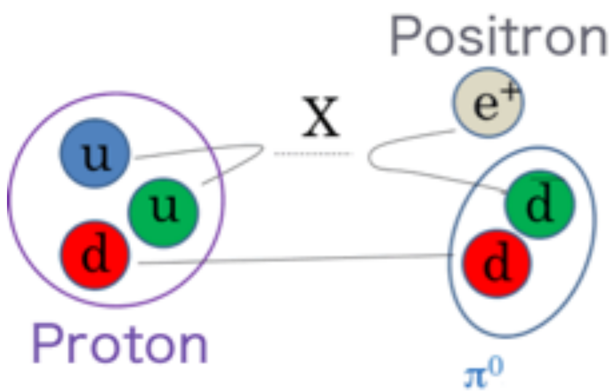


Mass hierarchy determination with 3σ for any θ_{23}

θ_{23} octant determination with 3σ for $|\theta_{23} - 45°| > 2°$

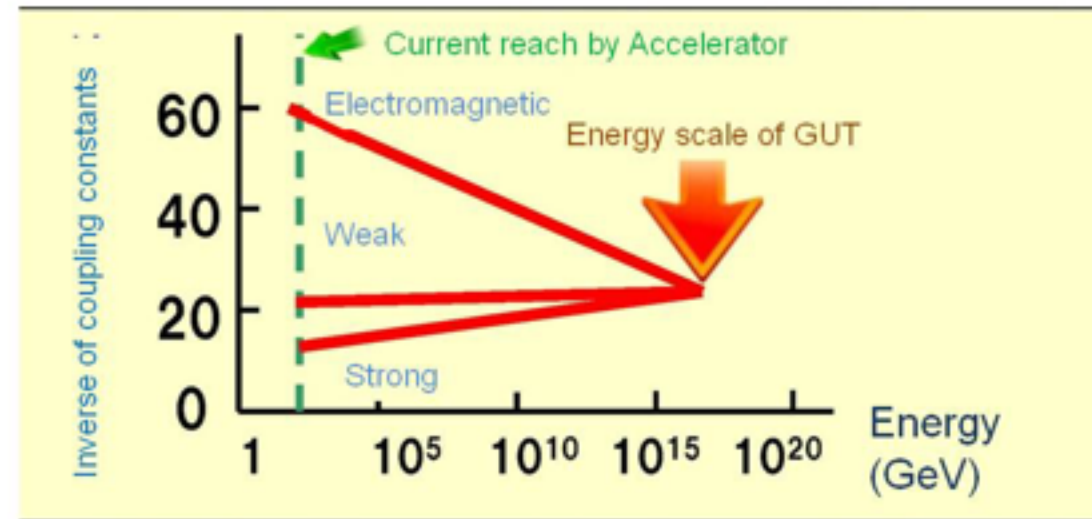
Nucleon Decay

GUT (Grand Unified Theory) predicts the existence of interactions that change the number of quarks by X boson exchange

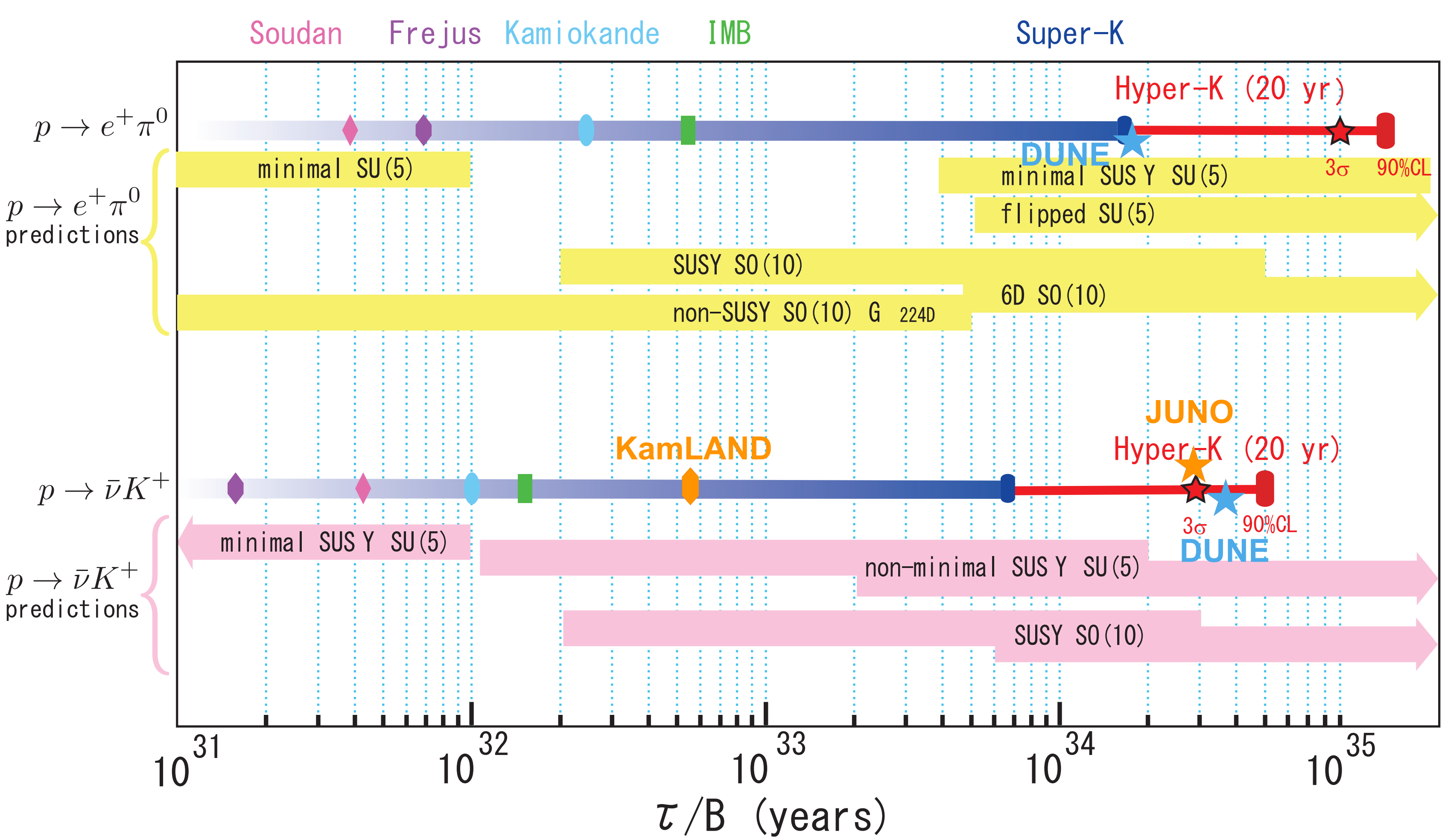


extremely weak
$\sim 1/M_X^4$

unification of forces



proton decay search : current and future prospect



Current detectors

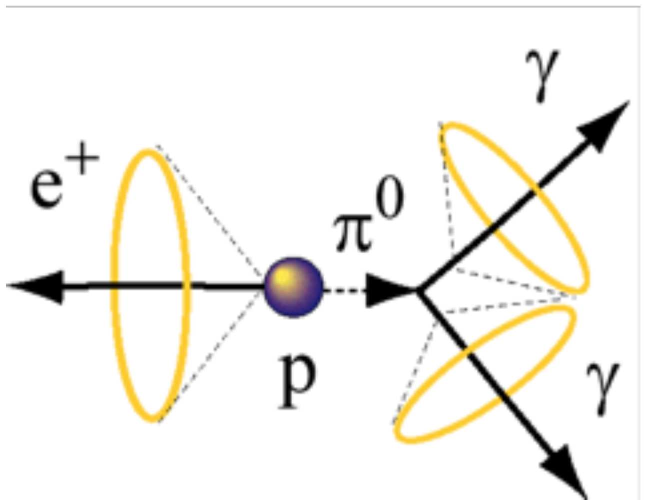
Super-K	**50 kton H_2O**
KamLAND	**1 kton LS**

Future detectors

JUNO	**17 kton LS**
DUNE	**40 kton Ar**
Hyper-K	**187 kton H_2O**

search sensitivity
$\sim 10^{35}$ years

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

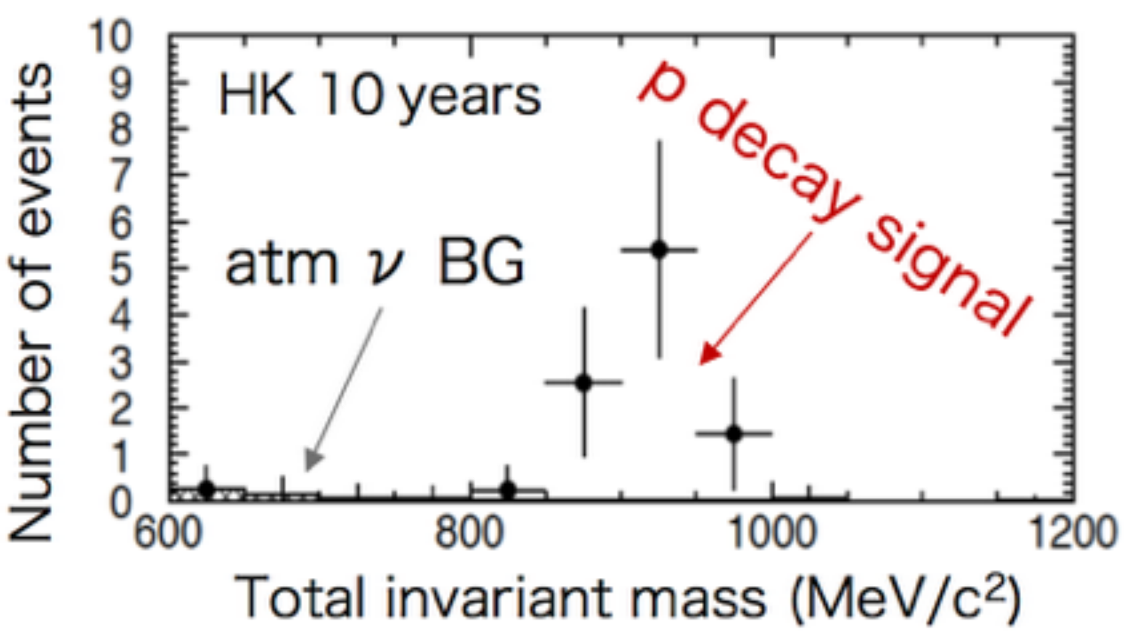


"background free" search ~0.06 events/Mton-year

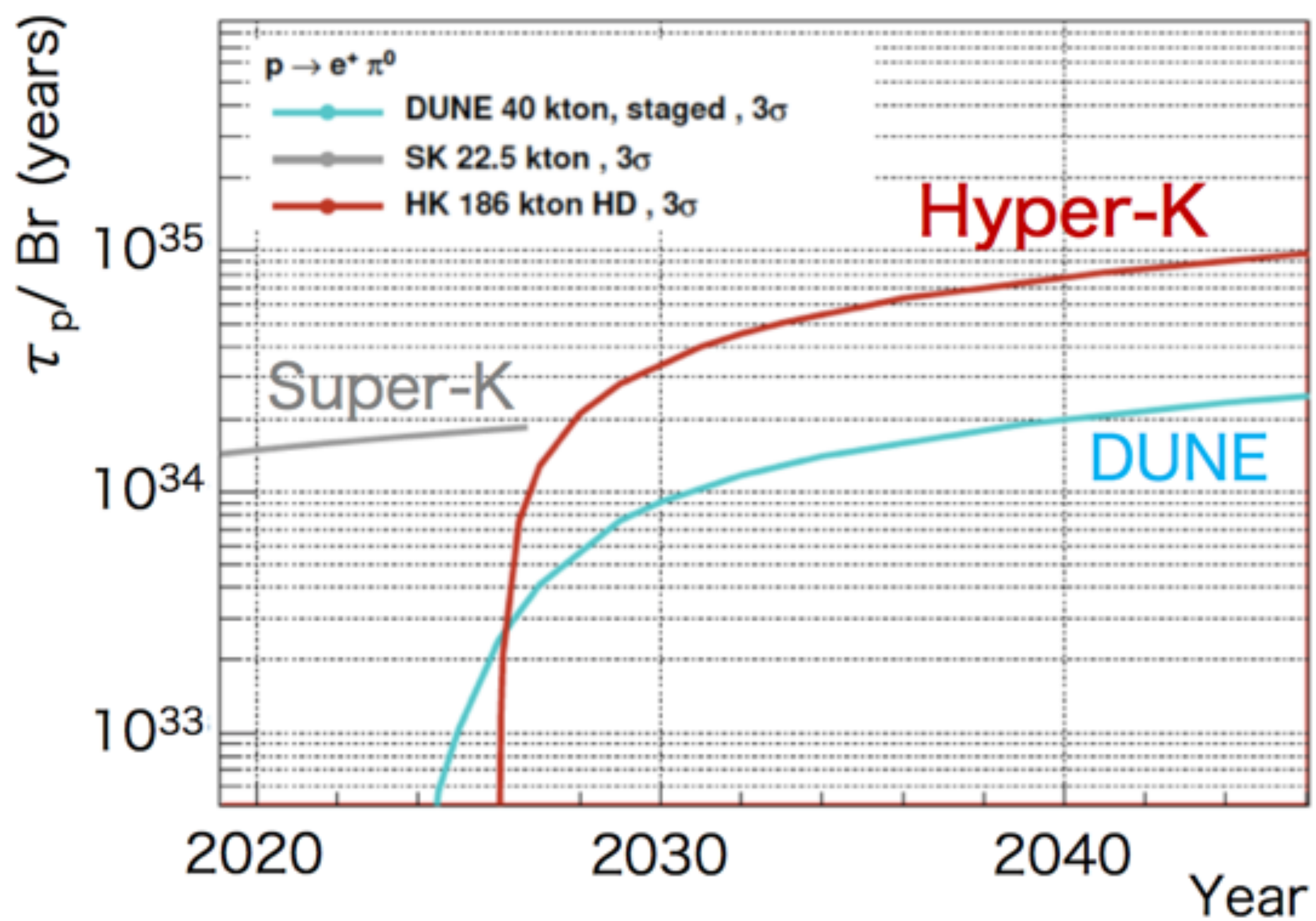
atmospheric neutrino backgrounds can be reduced by improved neutron-tagging

$n + p \to d + \gamma$ (2.2 MeV)

Invariant mass assuming τ/Br = 1.7 × 10^{34} years (SK 90% C.L. limit)



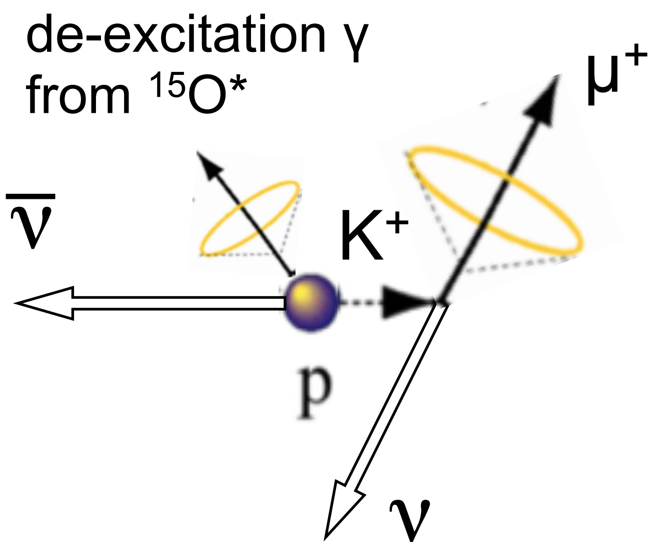
3σ sensitivity for $p \to e^+ \pi^0$



Great potential for discovery

3σ sensitivity : τ/Br = 10^{35} years

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

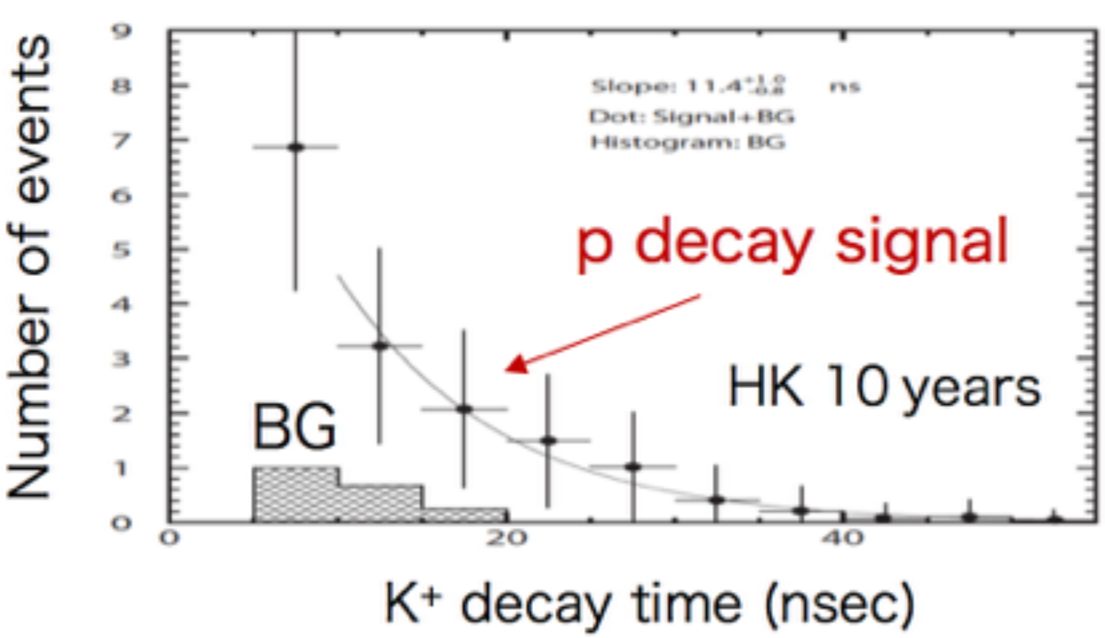


K^+ identification by decay products

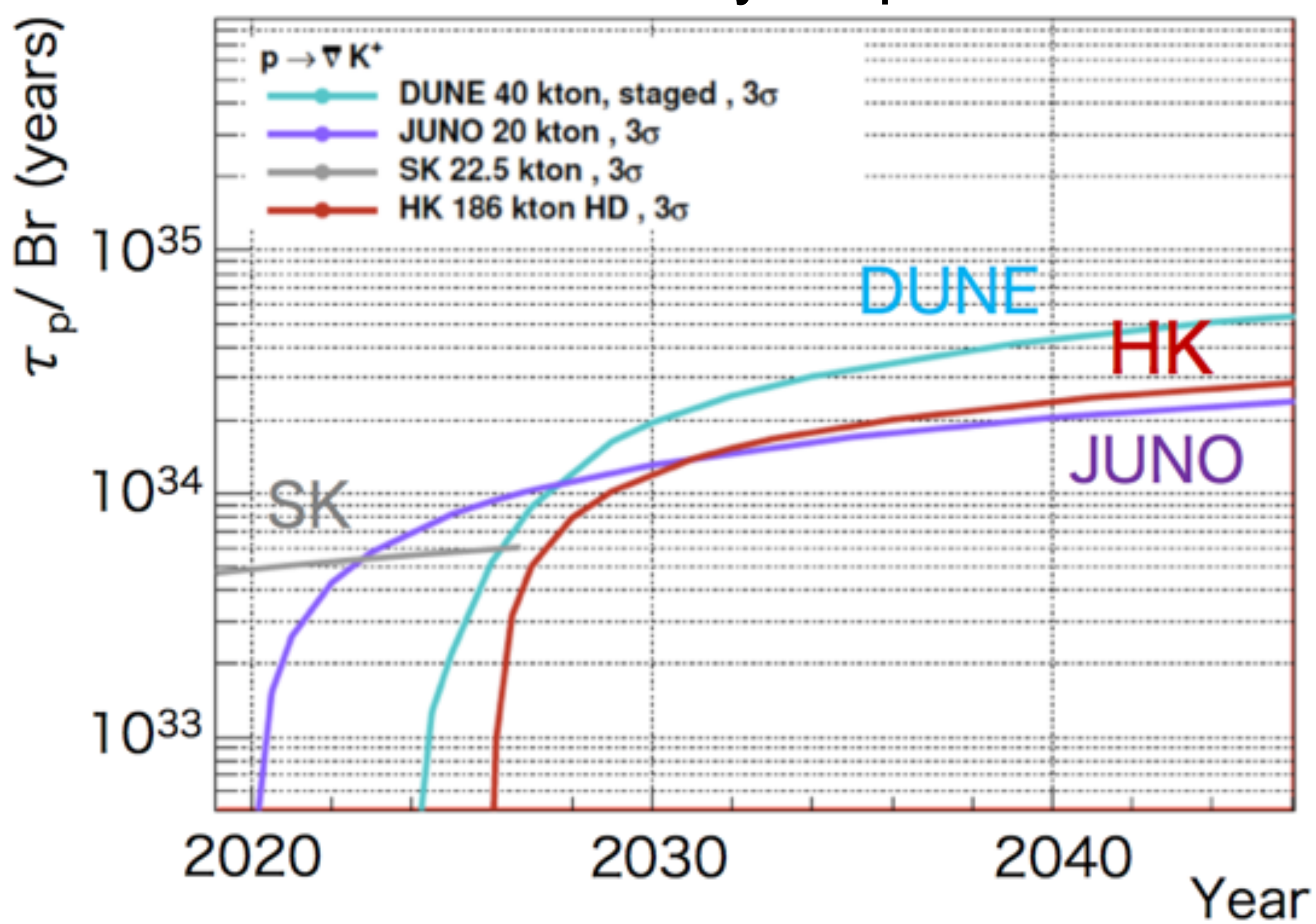
$K^+ \to \mu^+ \nu$ (64%)   236 MeV/c μ^+ + decay e^+
de-excitation γ from $^{16}O^*$ (6 MeV)

$K^+ \to \pi^+ \pi^0$ (21%)   205 MeV/c π^+ + π^0 back-to-back

K^+ decay time assuming τ/Br = 6.6×10^{33} years (SK 90% C.L. limit)



3σ sensitivity for $p \to \bar{\nu} K^+$

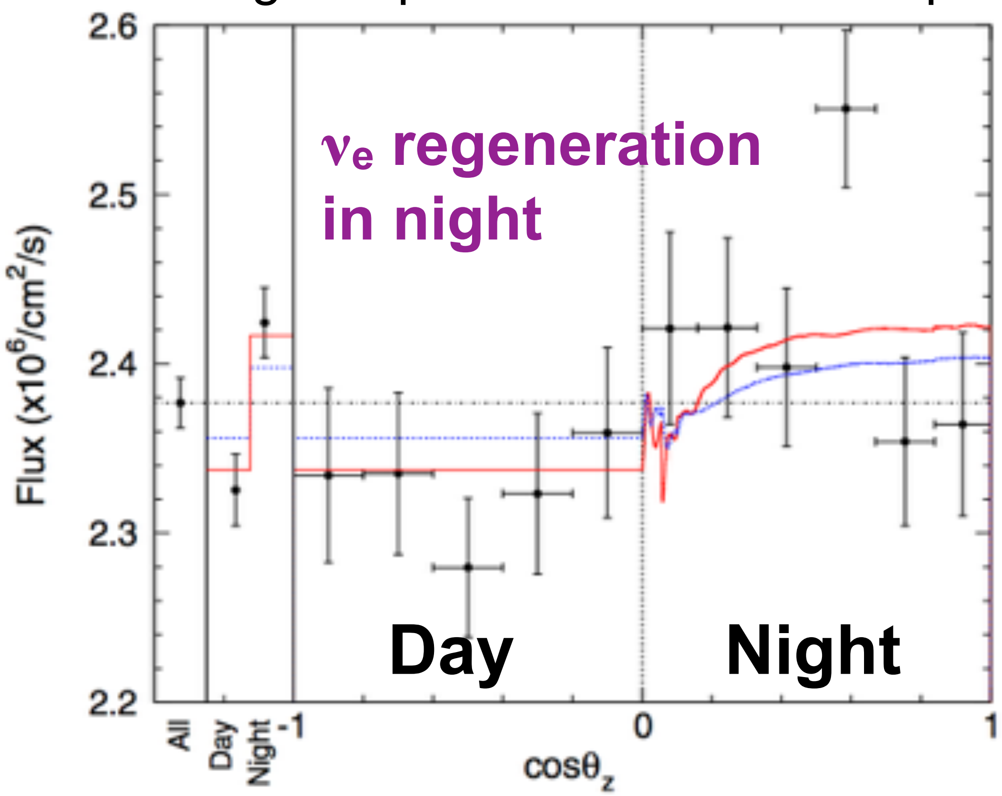


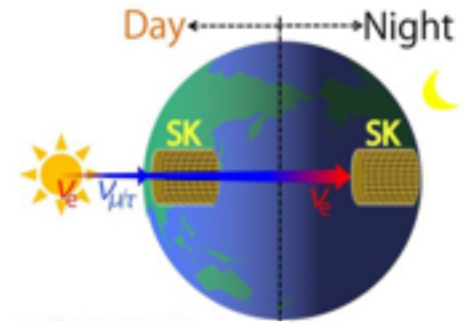
Great potential for discovery

3σ sensitivity : $\tau/Br = 3 \times 10^{34}$ years

Solar Neutrino : Day-Night Asymmetry

zenith angle dependence of flux in Super-K



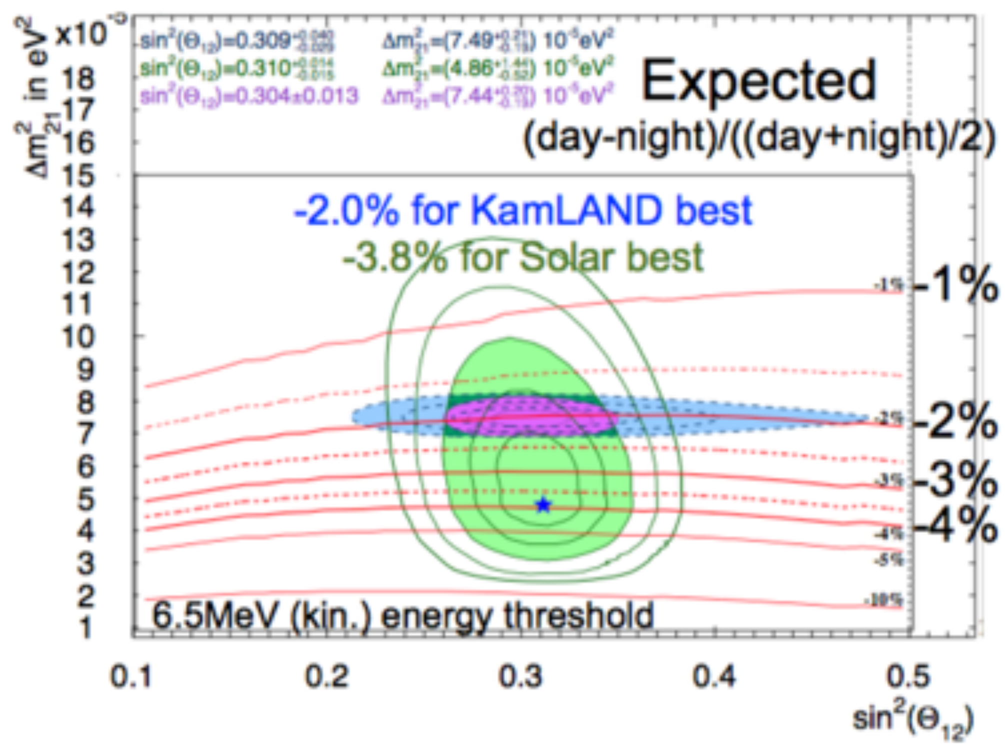


Super-K best

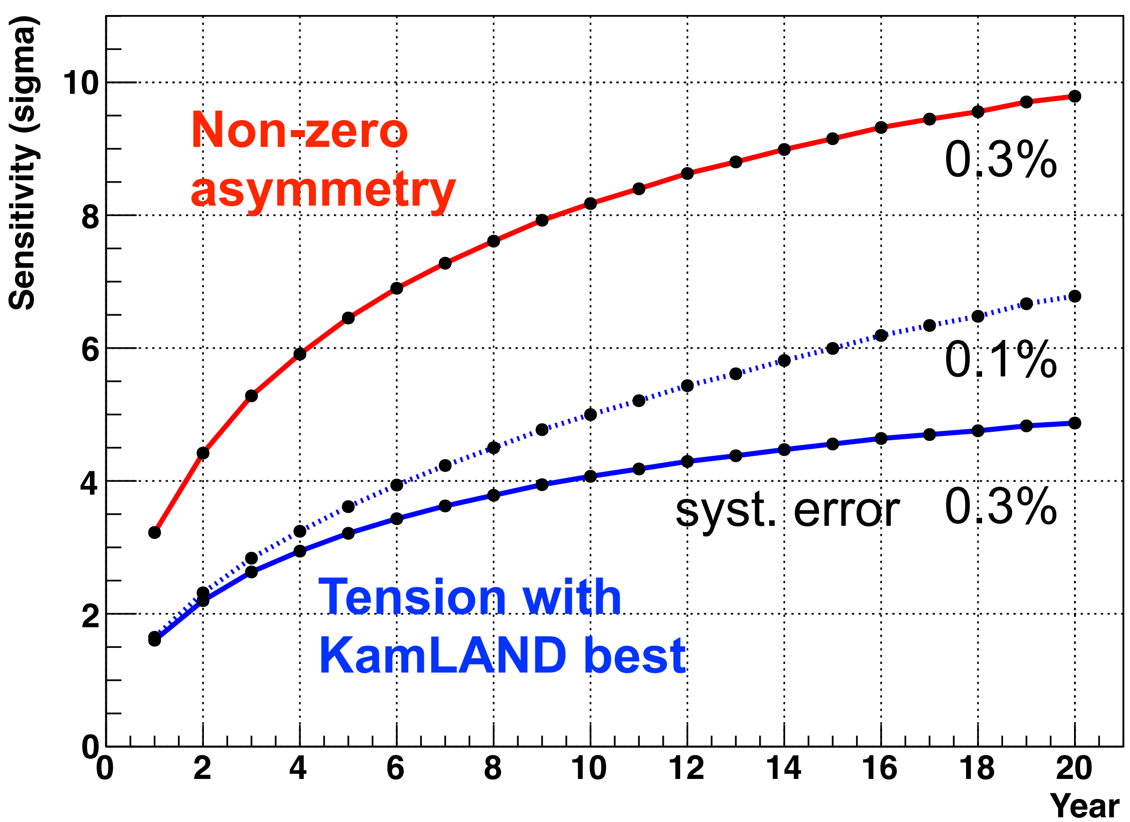
Solar + KamLAND

A. Renshaw et al., Phys. Rev. Lett. 112, 091805 (2014)

oscillation parameters : Solar and KamLAND



sensitivity from Day-Night in Hyper-K



Super-K $A_{\mathrm{DN}}^{\mathrm{fit}} = [-3.2 \pm 1.1(\mathrm{stat}) \pm 0.5(\mathrm{syst})]\%$

non-zero significance : 2.7σ

dominant error

mainly from BG shape

Hyper-K

<u>Goal of systematic error : 0.3%</u>

- higher energy threshold (6.5 MeV)
- precise energy calibration / BG shape

>4σ for non-zero asymmetry

& CPT invariance ($P_\nu = P_{\bar{\nu}}$) test

Solar Neutrino : Spectrum Up-turn

Low energy neutrinos

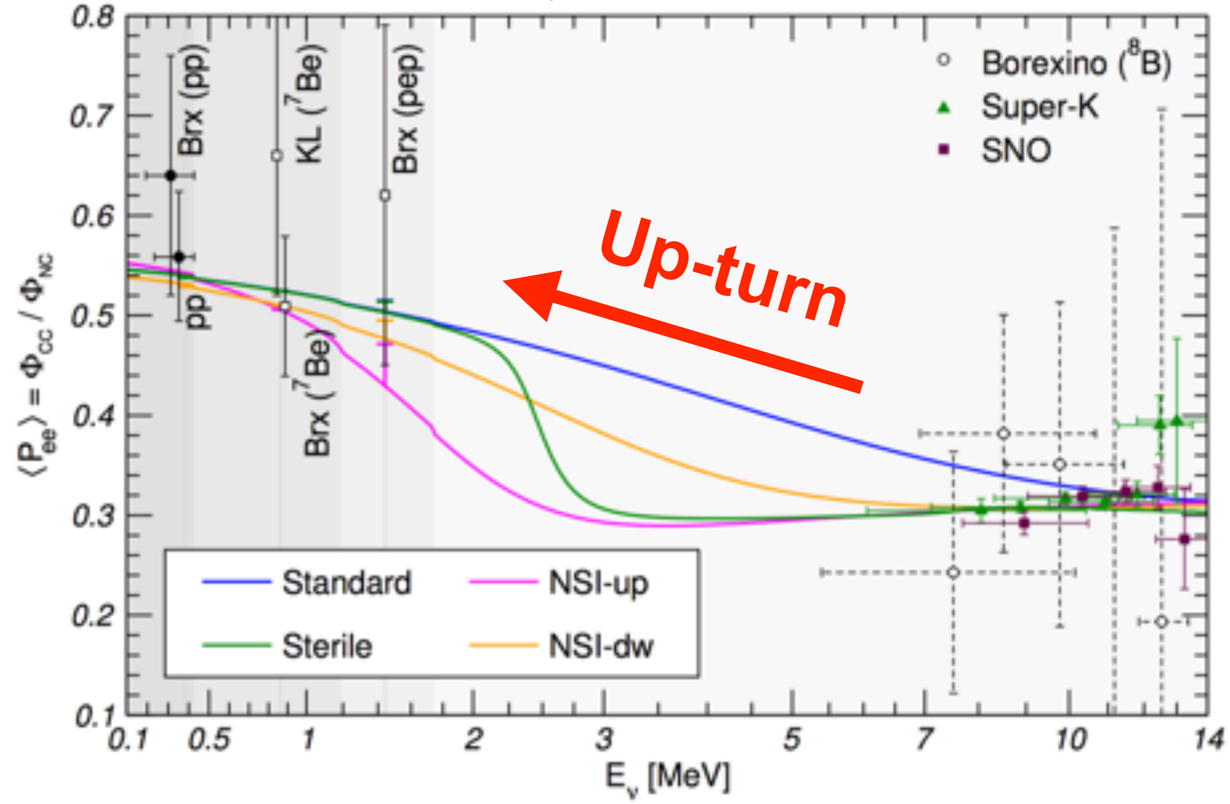
Borexino, KamLAND

High energy neutrinos (^8B / hep ν)

Kamiokande, Super-K, SNO

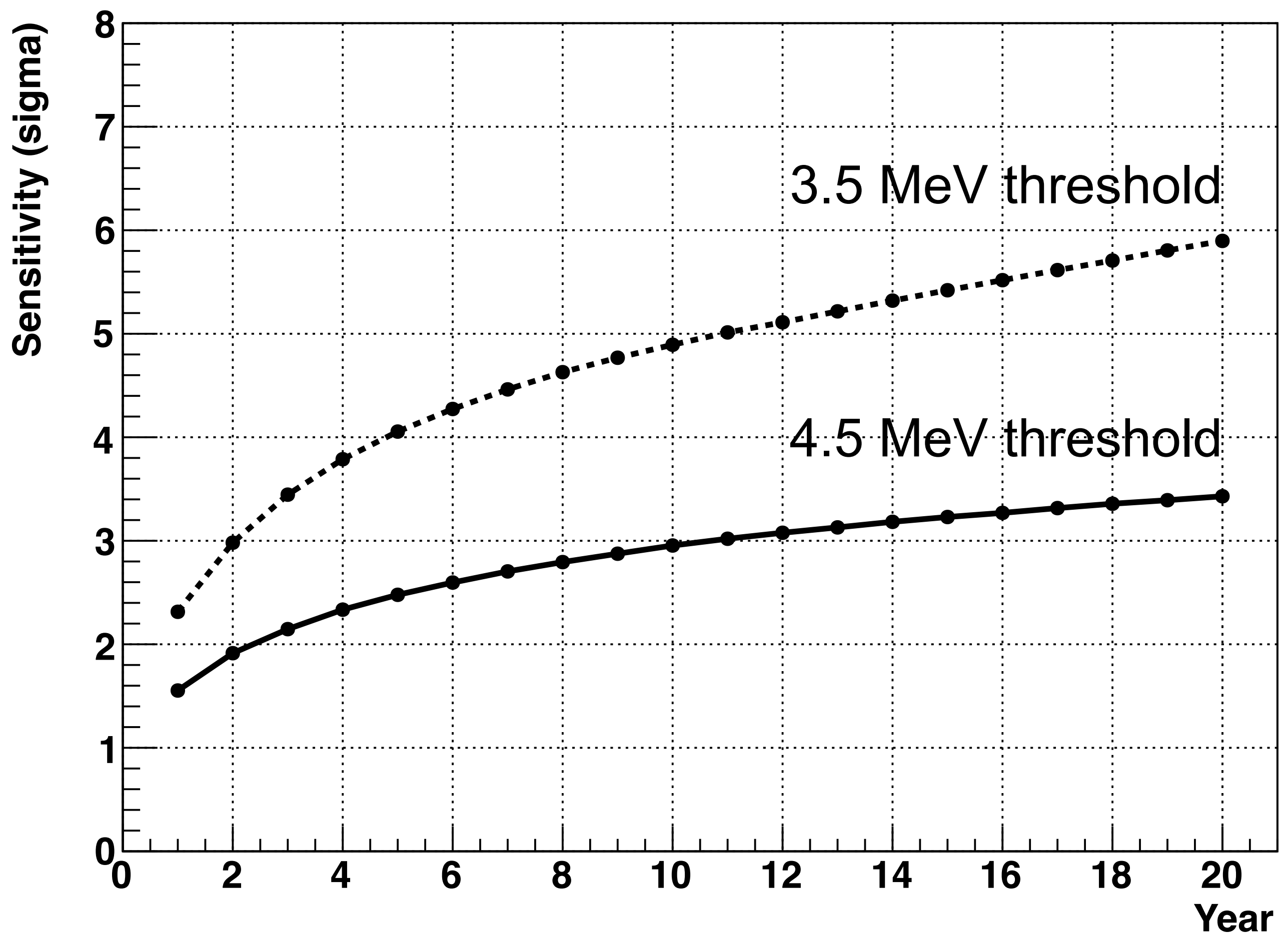
Observed energy dependence of survival probability requires non-vacuum oscillation (MSW neutrino oscillation)

survival probability of electron solar neutrinos



M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)

energy spectrum up-turn



<u>Assumptions</u>

- Hyper-K low energy BG level is similar to Super-K
- Similar calibrations to Super-K

>3σ for spectrum up-turn

MSW oscillation test with single neutrino source (^8B)

Supernova Neutrino

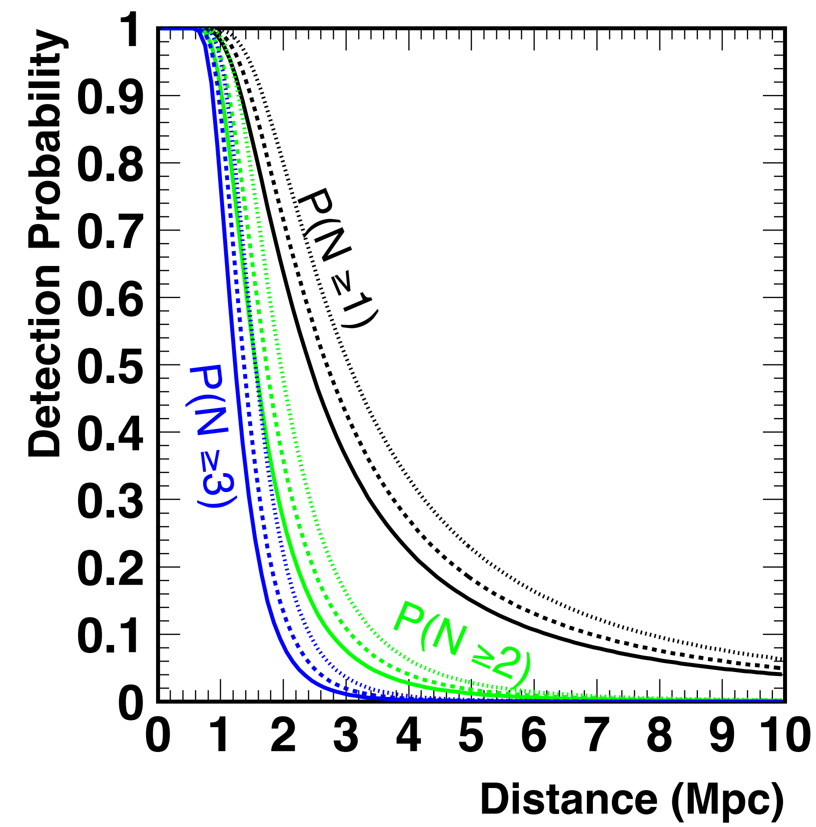
SN1987A at 50 kpc : first detection (11 + 8 events)

No other supernova neutrino observation yet

Future observation

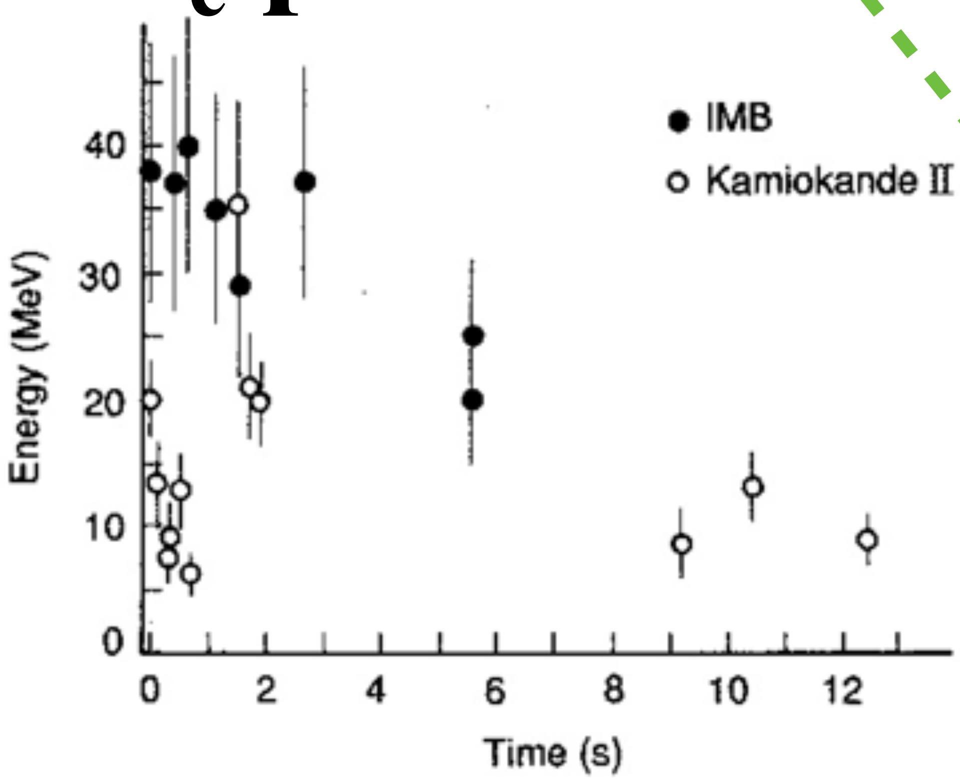
- Detailed study of the supernova explosion mechanism with high statistics
- Understand a large variety of supernovae

detection probability in Hyper-K

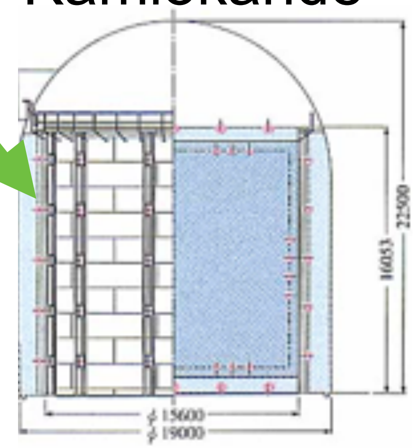


main reaction

$$\overline{\nu}_e\ p \longrightarrow n\ e^+$$



Kamiokande



Hyper-K can extend the supernova search distance to extra-galaxy

Shock Revival by Neutrino Heating

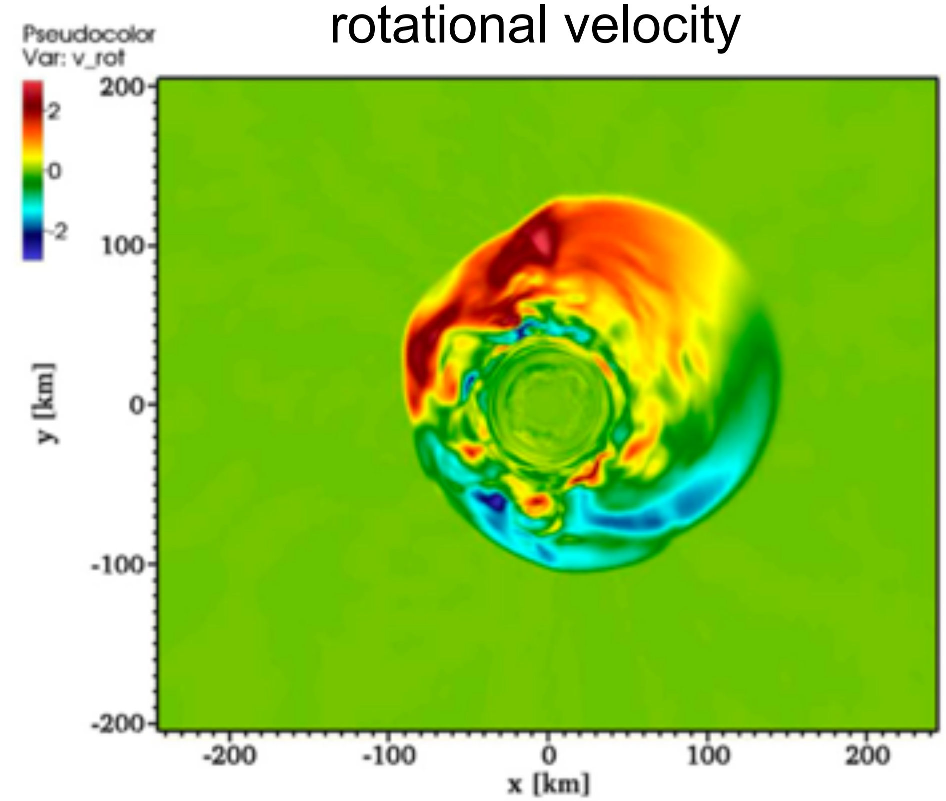
Neutrino heating is a key phenomenon
in the supernova explosion mechanism

- Shock wave from core bounce stalls in 100-200 km
- Neutrino heating revives the shock wave after ~10-100 ms

Some 2D and 3D simulations indicate
SASI (Standing Accretion Shock Instability) is
important process for the supernova explosion

SASI or neutrino-driven convection is controversial

rotational velocity



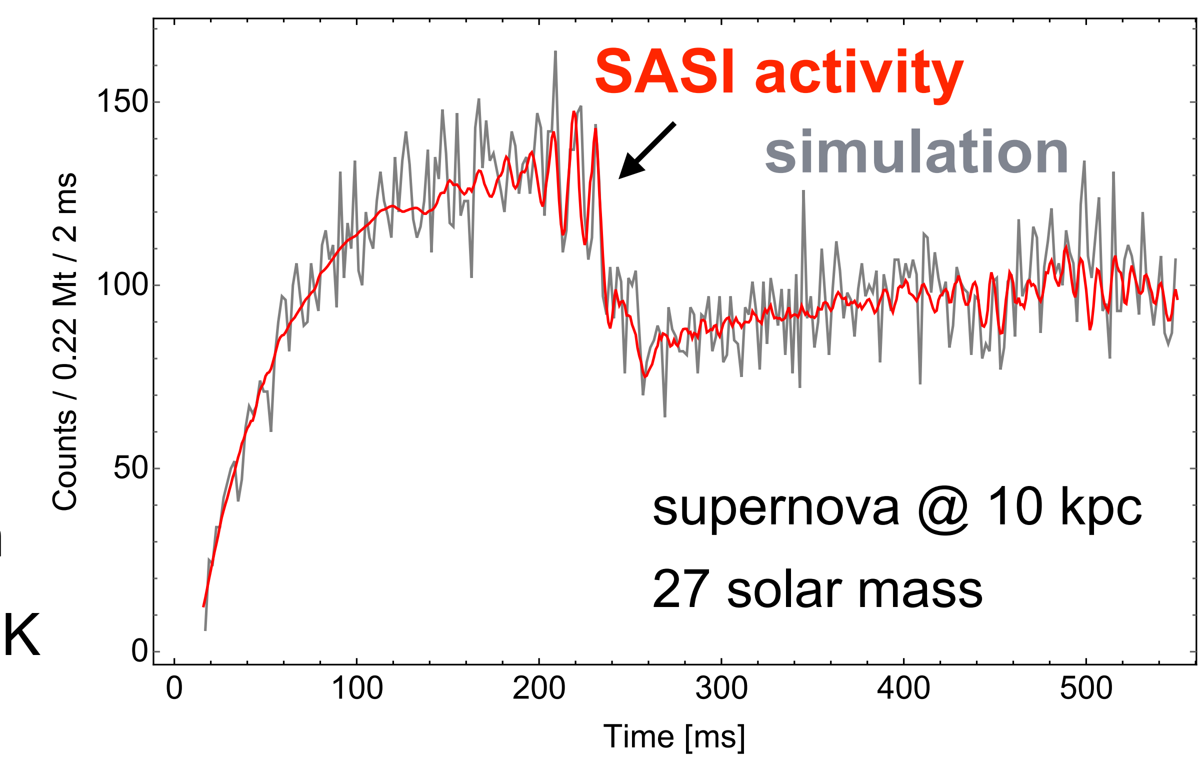
F. Hanke et al., Astrophy. J 770, 66 (2013)

SASI activity will cause the modulation
in the accretion flow to the neutron star
and the neutrino emission

Hyper-K will test the supernova neutrino flux modulation

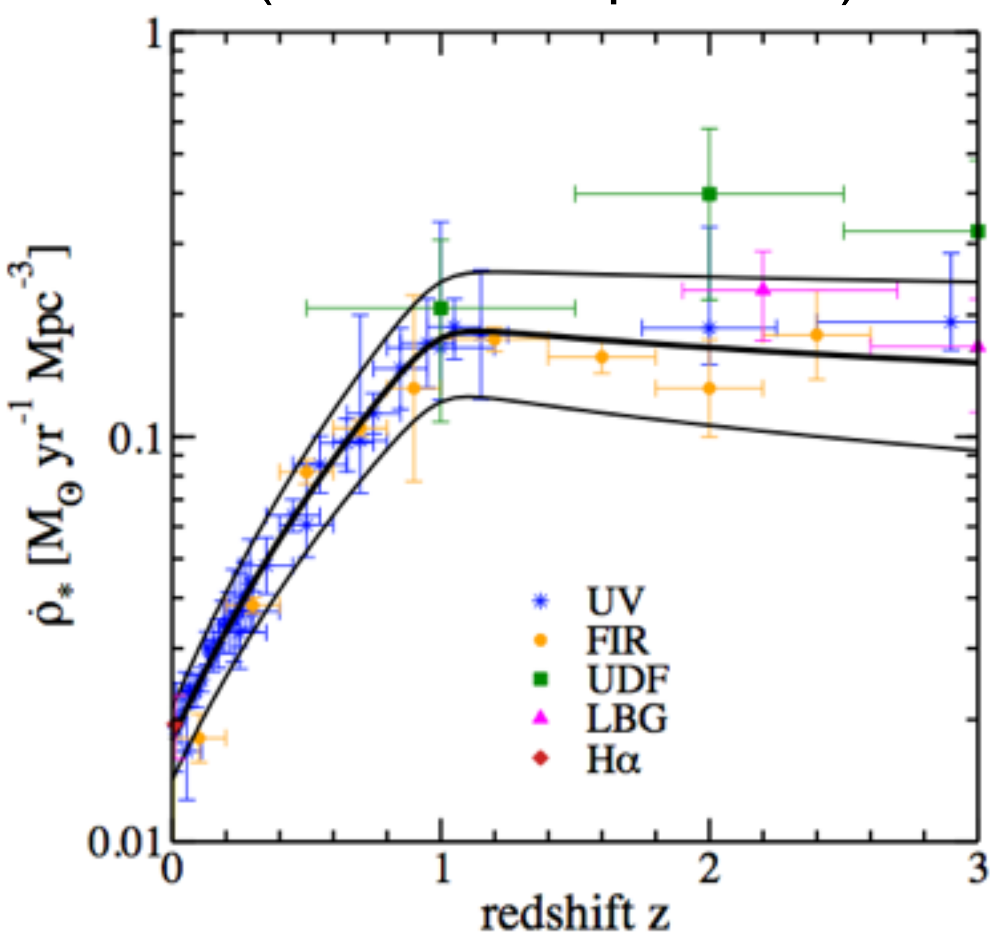
- Amplitude of modulation depends on spiral direction
- For the case of 3% amplitude of modulation, Hyper-K covers 90% of galactic supernova

event rate modulation in Hyper-K



Supernova Relic Neutrino

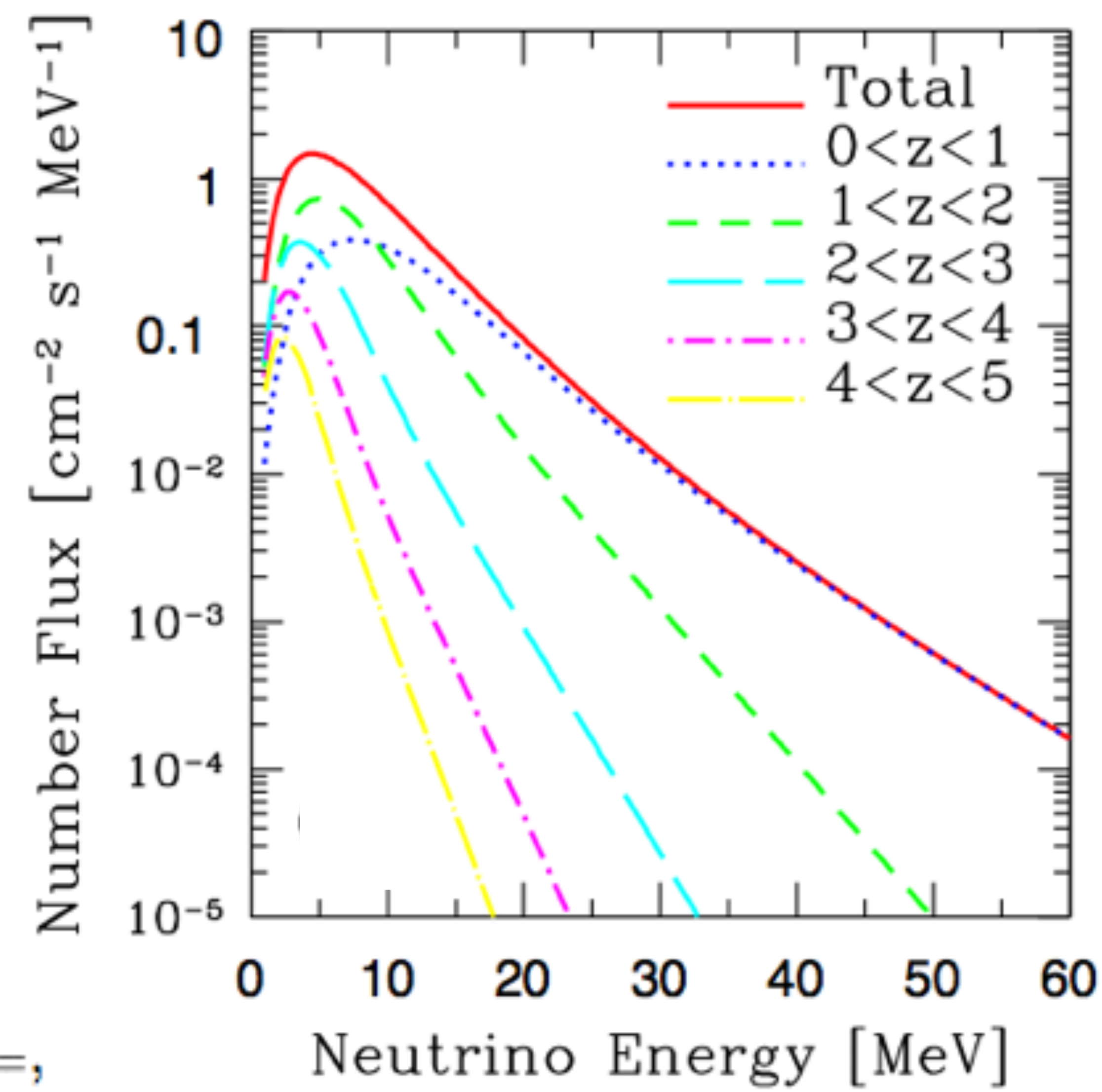
star formation rate
(= core-collapse rate)



supernova model

integrate over past supernova neutrinos

SRN energy spectrum
(including red shift)



S. Ando and K. Sato, New J. Phys. 6, 170 (2004)

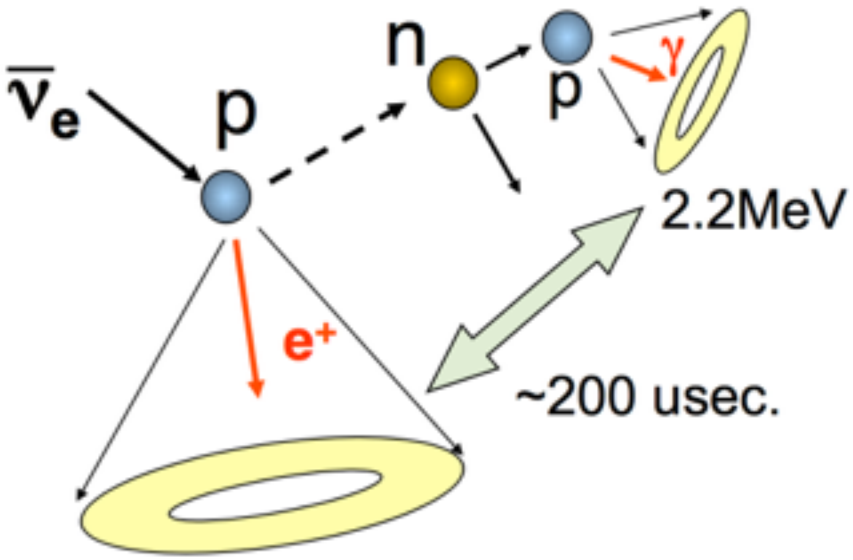
$$\frac{dF_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}\frac{dz}{\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}},$$

Neutrinos from supernova explosions in the early universe to the present day

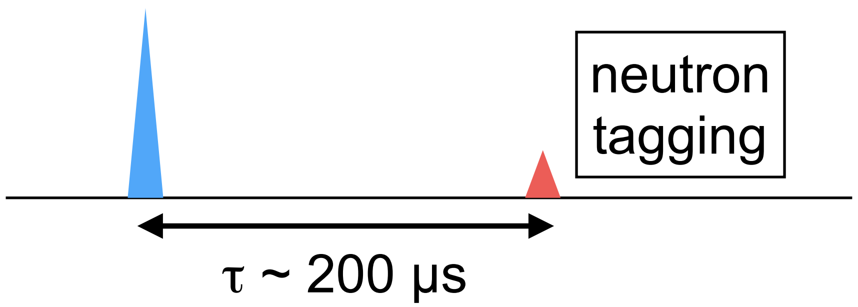
integrated flux ~10 cm^{-2}sec^{-1} **enough flux detectable in Hyper-K**

Hyper-K will measure the average flux and energy in supernovae

Signal Detection

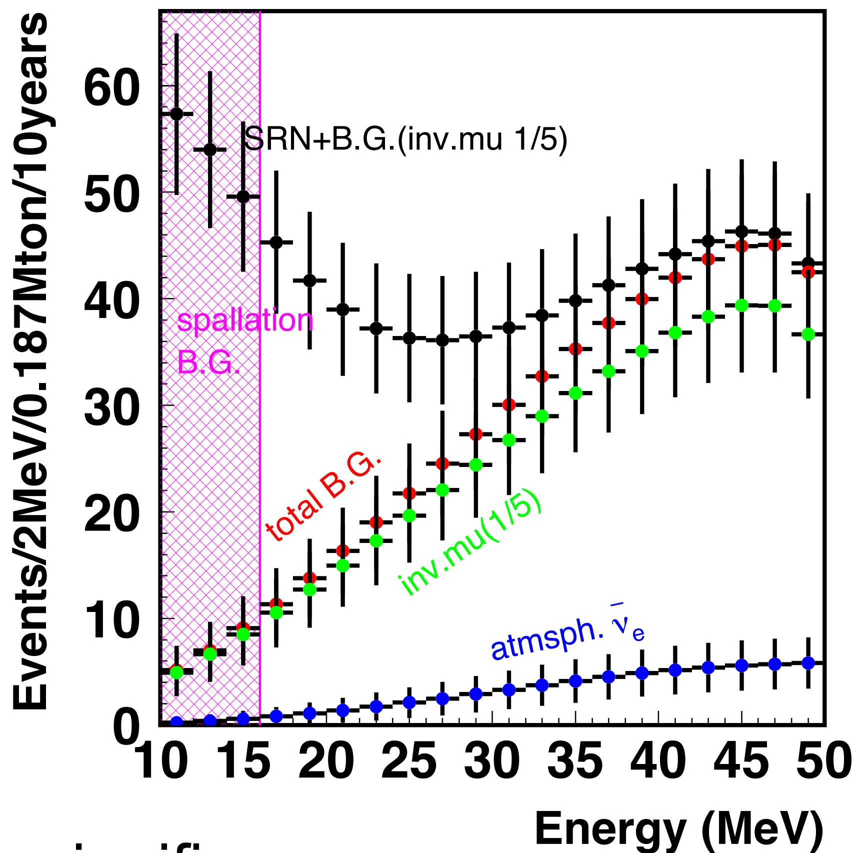


$$\overline{\nu}_e + p \rightarrow e^+ + n$$
$$n + p \rightarrow d + \gamma$$

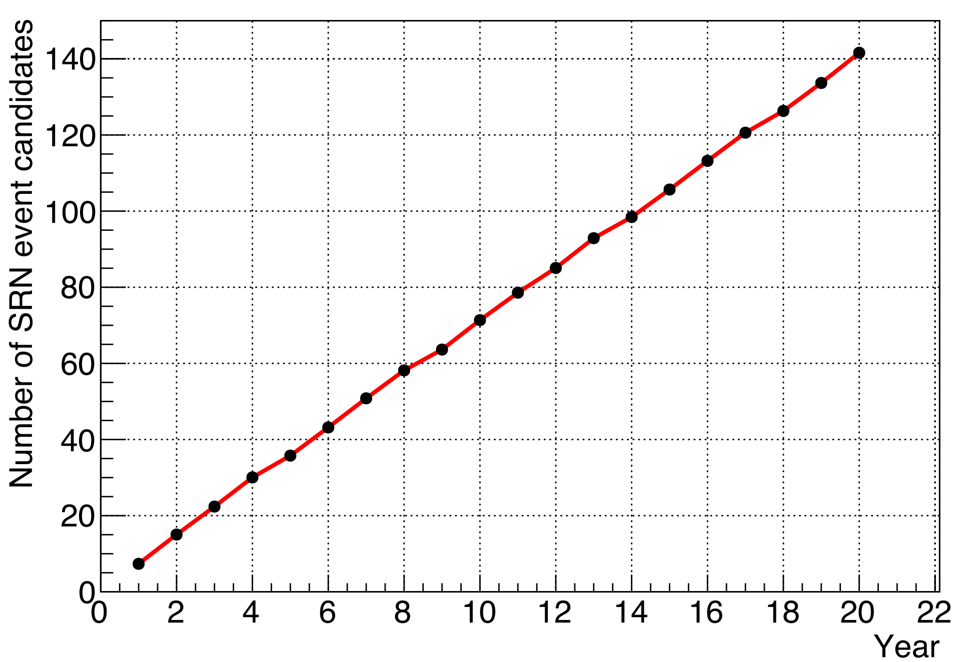


Neutron tagging effectively reduces the "invisible muon" background from atmospheric neutrinos → ×1/5

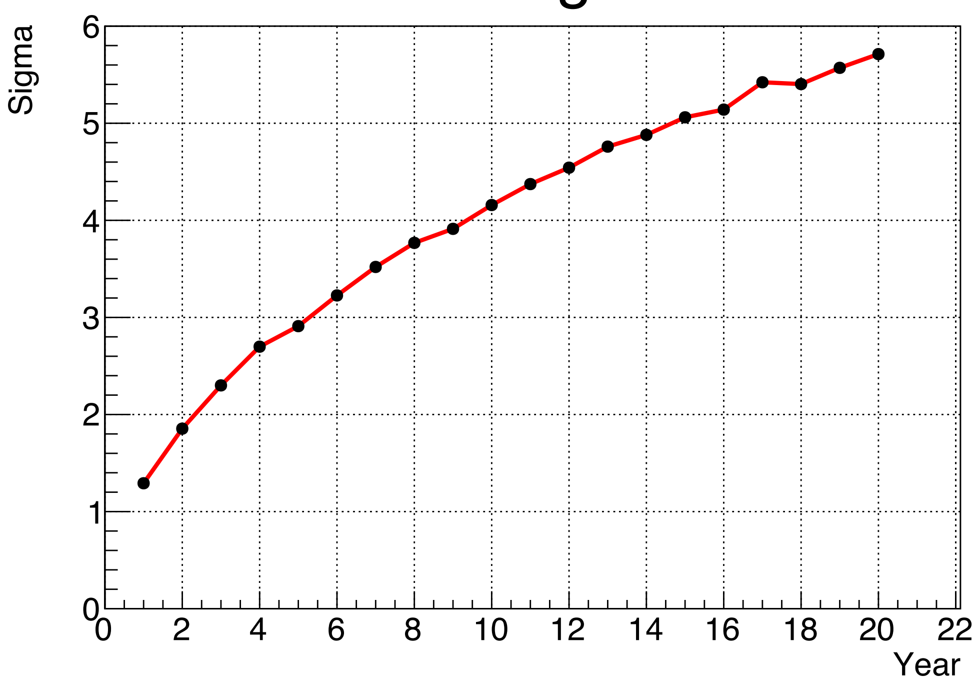
expected energy spectrum in Hyper-K (10 year)



number of SRN events



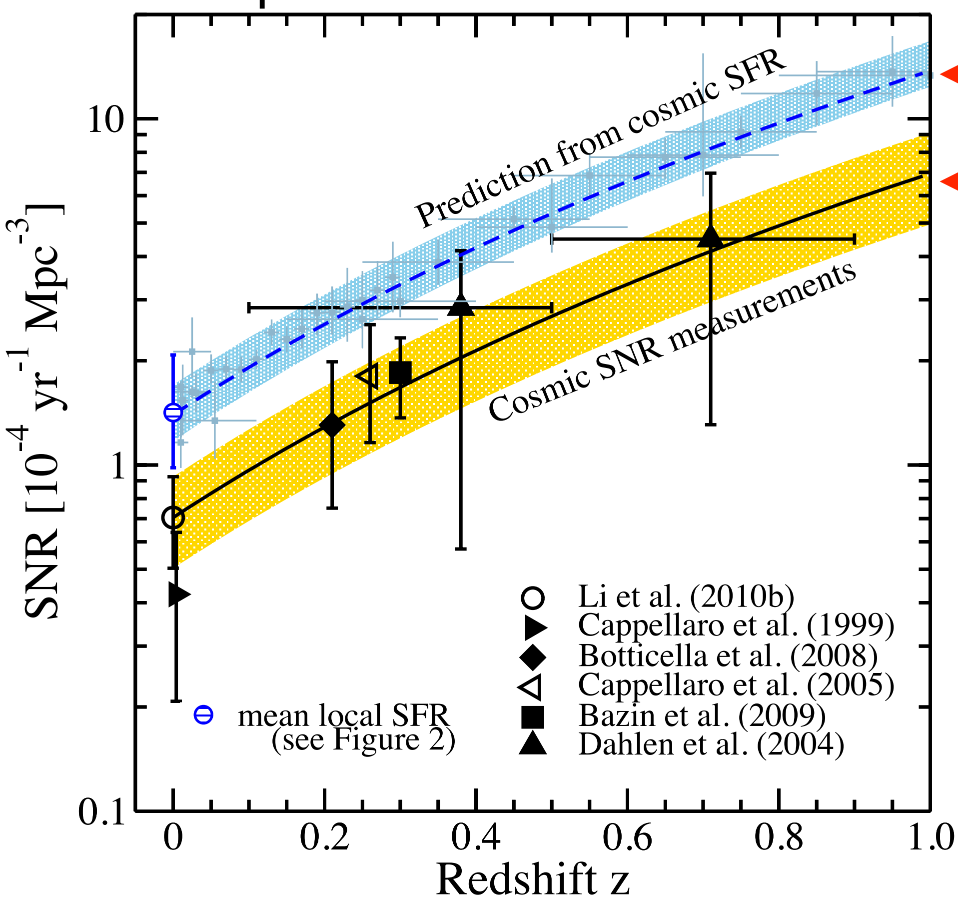
Detection significance



~70 events / 4σ detection significance in 10 years

Star Formation History

supernova rate v.s. redshift



core-collapse rate predicted from star formation rate

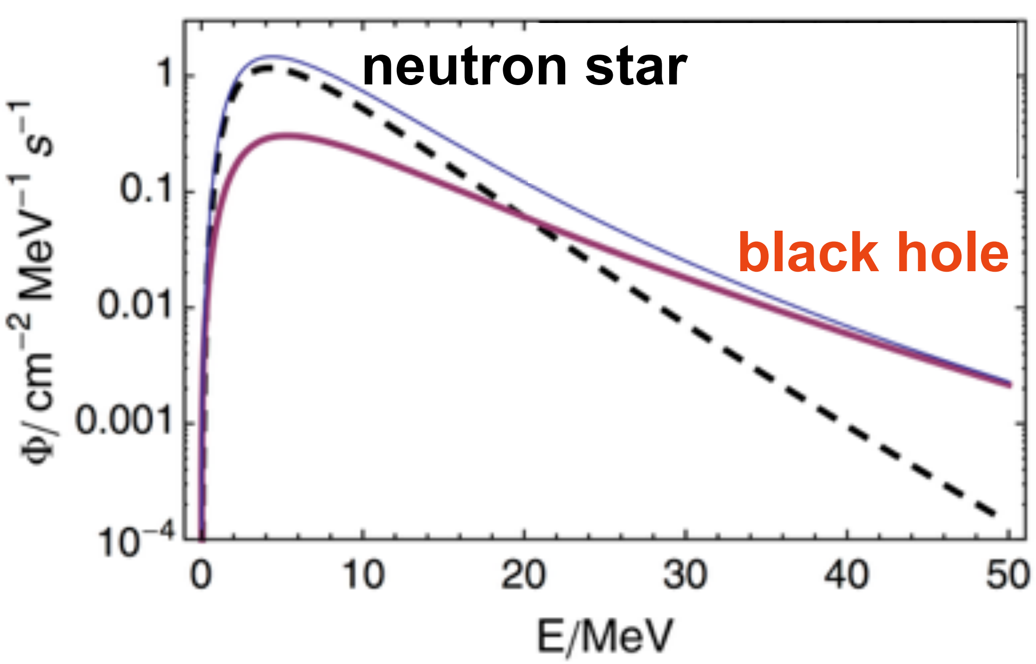
observed supernova rate visible supernovae

factor ~2 smaller than the expectation
from star formation rate

→ **invisible dim supernova or black hole formation?**

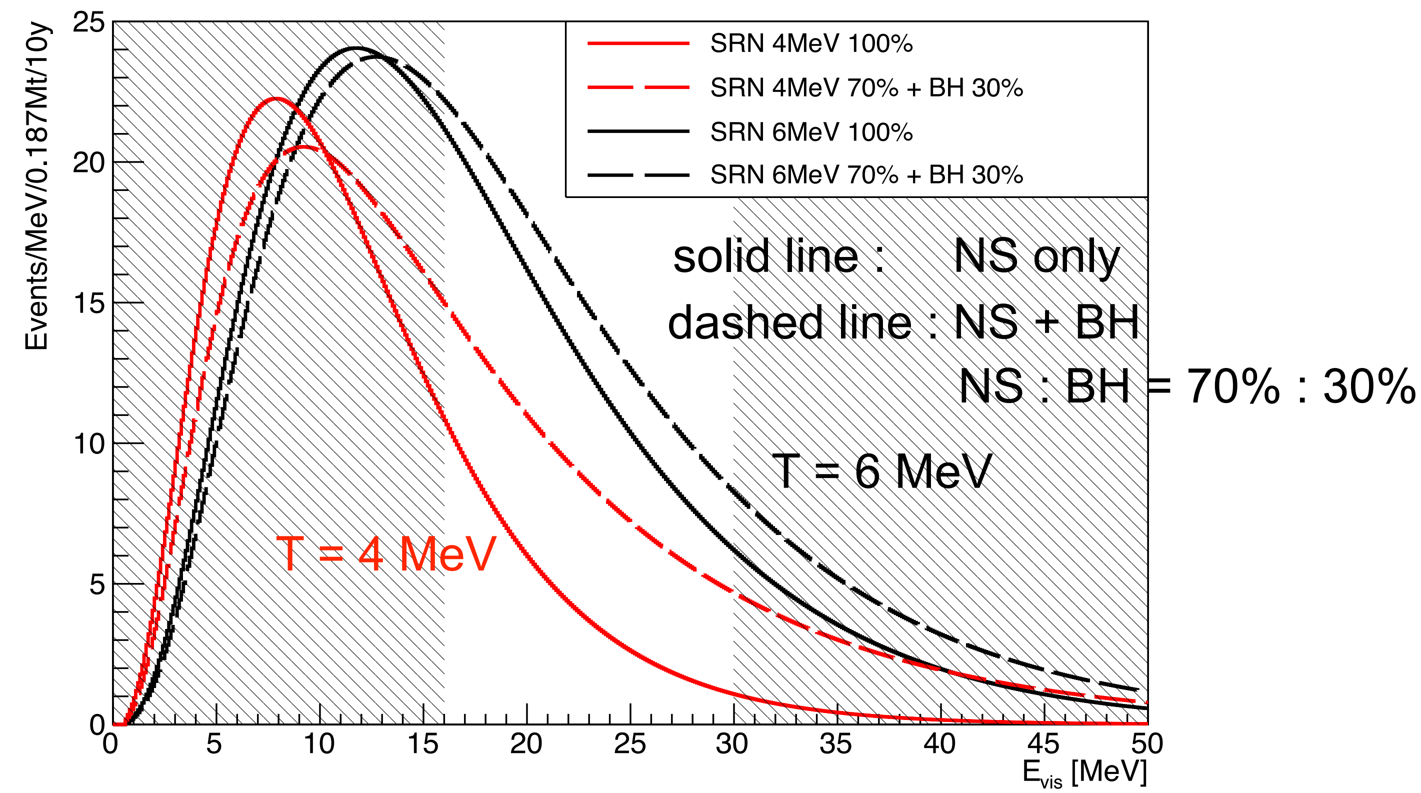
supernova explosions in massive stars (~30 solar mass)
result in **black hole formation, high E neutrino production**

neutrino flux



harder in black hole formation

expected energy spectrum in Hyper-K (10 year)



History of black hole formation can be investigated

Reports on Physics Sensitivity

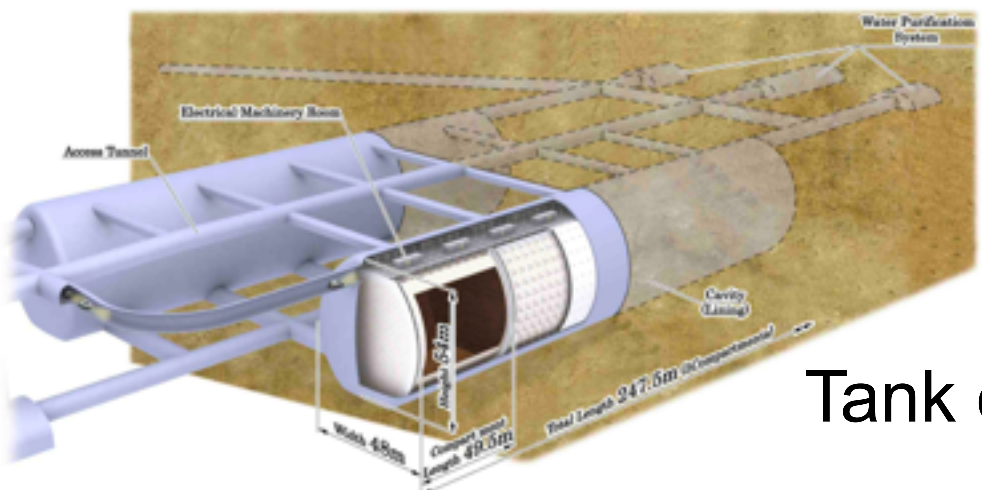
arXiv:1109.3262 Letter of Intent

Letter of Intent:

The Hyper-Kamiokande Experiment

— Detector Design and Physics Potential —

(Hyper-Kamiokande working group)



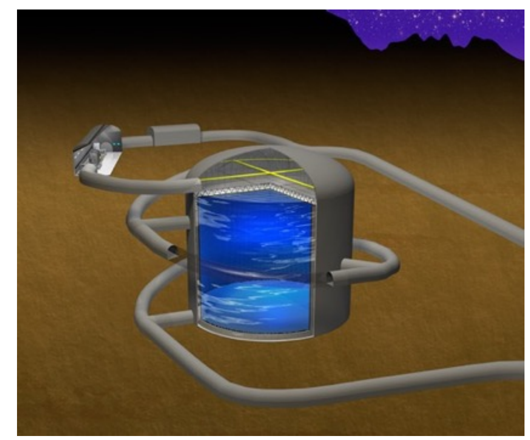
Tank optimization →

Prog. Theor. Exp. Phys. 053C02 (2015)

PTEP

Prog. Theor. Exp. Phys. **2015**, 053C02 (35 pages)
DOI: 10.1093/ptep/ptv061

Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande



Physics sensitivity with optimized tank will be reported in "Design Report"

arXiv:1611.06118 optional 2nd tank in Korea (under investigation)

Physics Potentials with the Second Hyper-Kamiokande Detector in Korea

(Hyper-Kamiokande Proto-Collaboration)

Having two detectors at different baselines improves sensitivity to CP violation, neutrino mass ordering

Summary

- Hyper-K will be a leading experiment in the neutrino oscillation, nucleon decay, and astroparticle physics research
- Project is boosted toward an early realization
  - Selected in ‘Master Plan’ of Science Council in Japan
  - Selected in ‘Roadmap 2017’ of MEXT
  - Budget request being submitted to start the construction in JFY 2018 and the operation in JFY 2026