Hyper-Kamiokande project

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INR, Moscow
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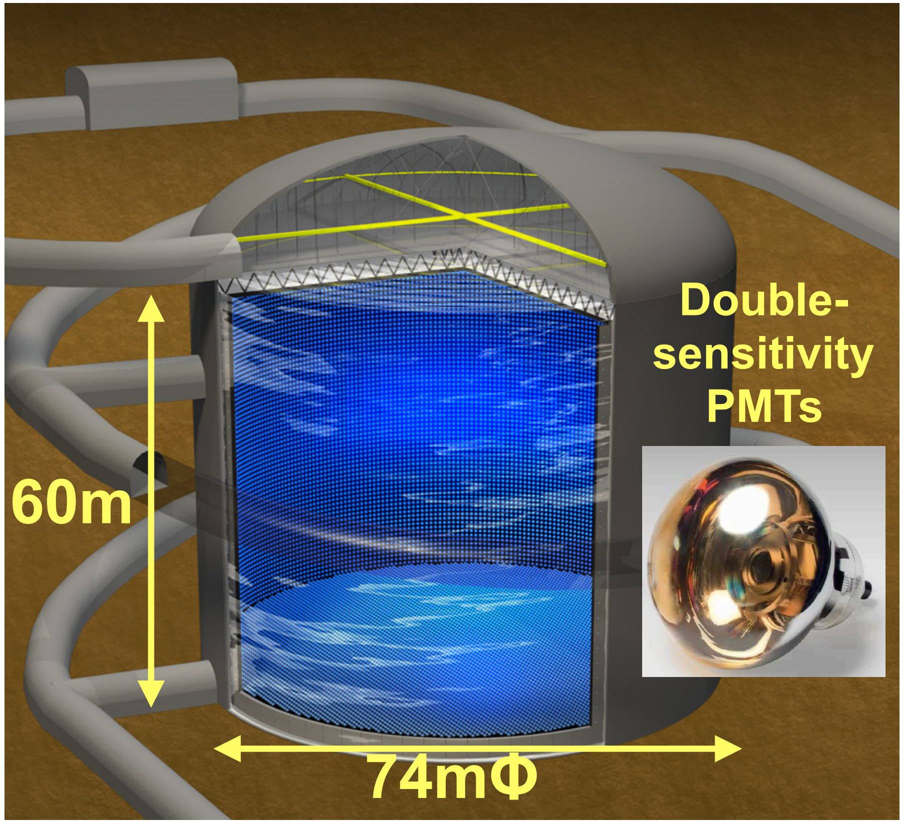
Hyper-Kamiokande detector

	Super-K	Hyper-K (1st tank)
Site (depth)	Mozumi (1000 m)	Tochibora (650 m)
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**

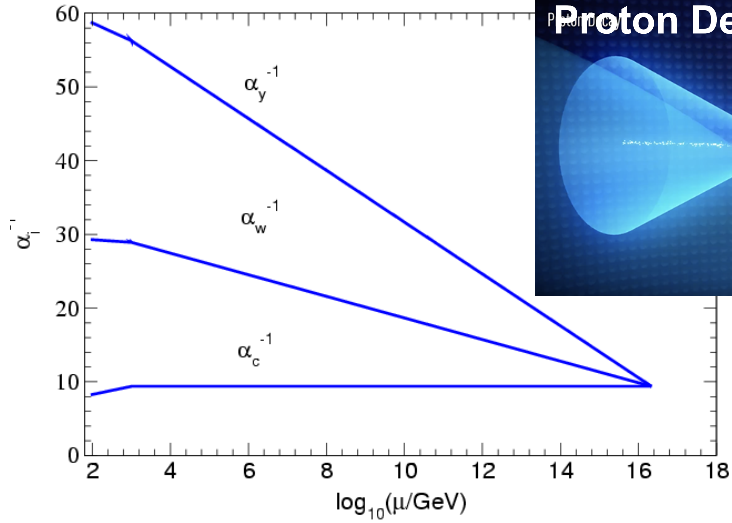
- High mass (**~10 × Super-K**) and high light-yield (**~2 × Super-K**) will significantly enhance the physics sensitivities
- Construction starts in 2020
- Data taking starts in 2027



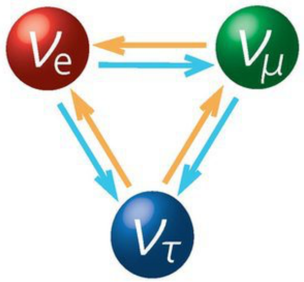
"Hyper-Kamiokande Design Report", arXiv:1805.04163

Goals of Hyper-K Physics

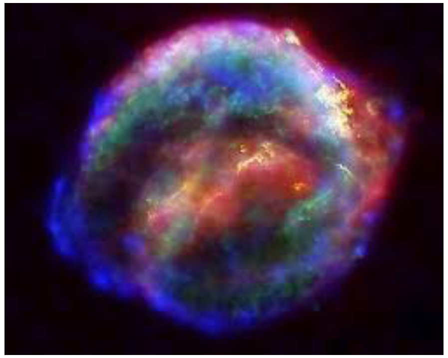
1. Nucleon Decay Searches

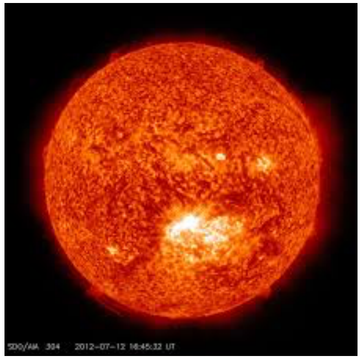


2. Explore full picture of neutrino oscillation including δ_{CP} and Mass hierarchy



3. Neutrino astronomy and astrophysics



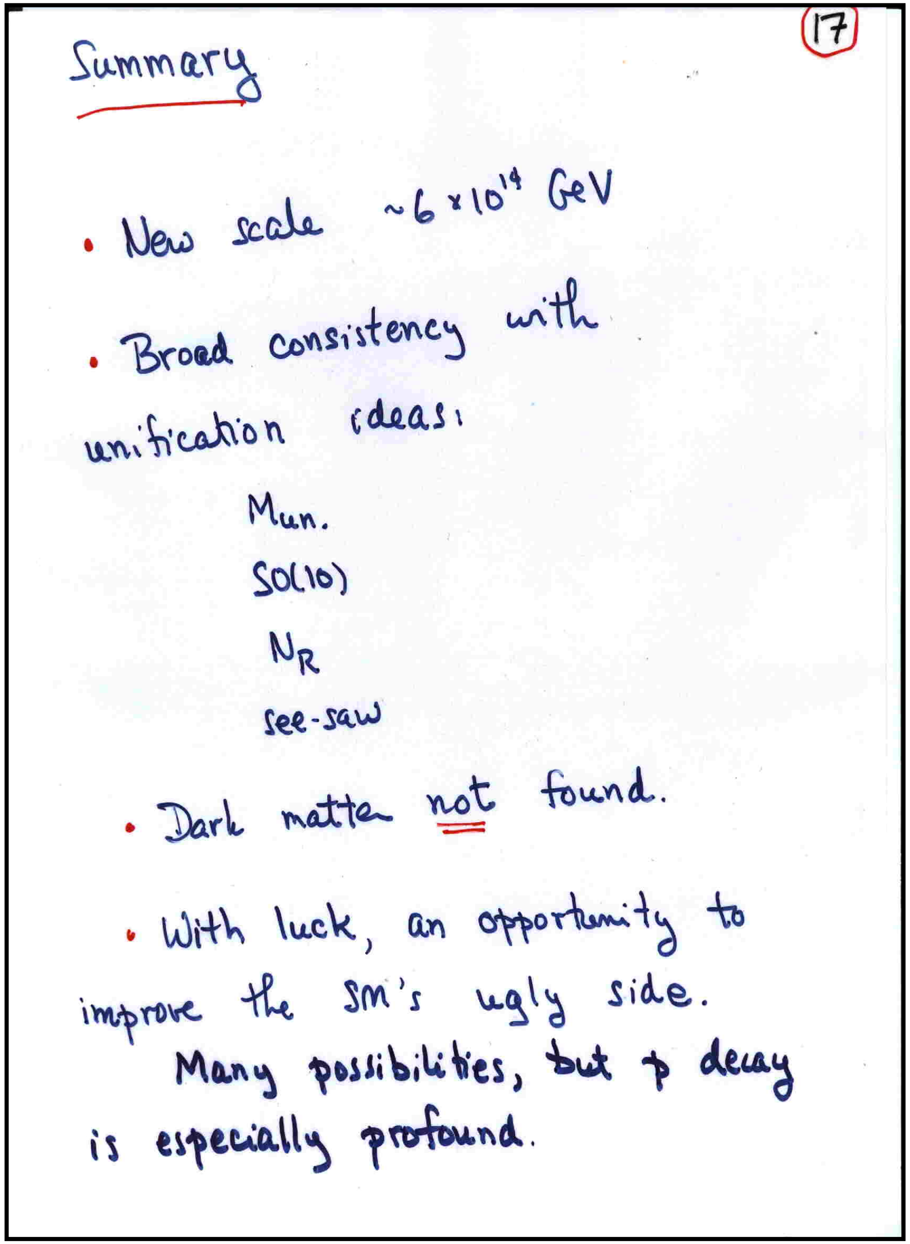


Proton decays

Summary Talk by F.Wilczek @ Neutrino1998, Takayama

- New scale **~6×10^{14} GeV**
- Broad consistency with **unification ideas**:
  - $M_{Unification}$
  - SO(10)
  - N_R
  - see-saw
-
- … Many possibilities, but **p decay is especially profound**.

Stronger the case of new physics at high scale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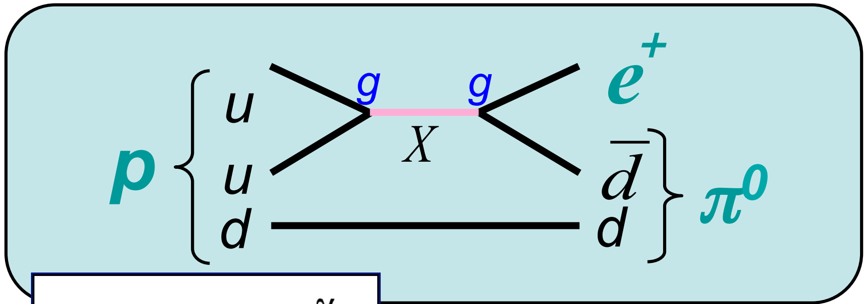
Summary

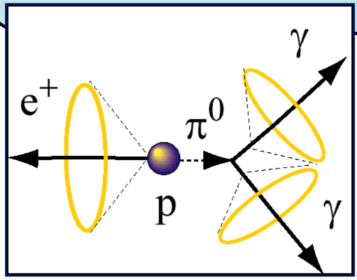
- New scale ~6×10^{14} GeV
- Broad consistency with unification ideas:
  - M un.
  - SO(10)
  - N_R
  - see-saw
- Dark matter not found.
- With luck, an opportunity to improve the SM's ugly side. Many possibilities, but p decay is especially profound.

Various proton decay modes

- Two prominent decay modes

Mediated by gauge bosons



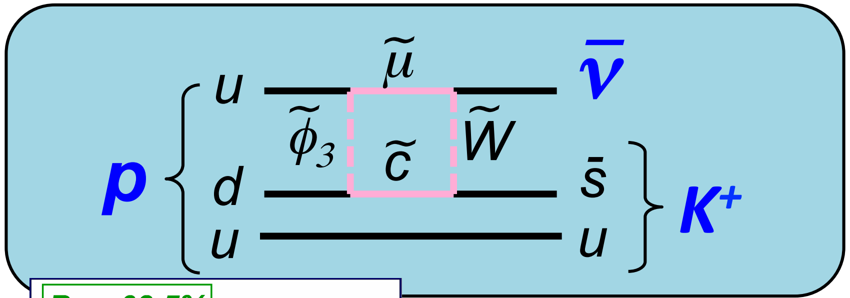


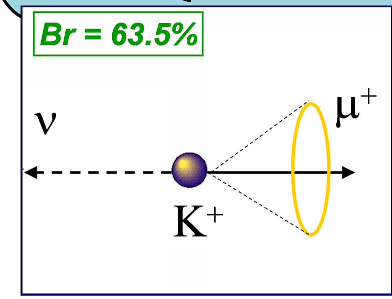
$p \rightarrow e^+\pi^0$

$$\Gamma(p \rightarrow e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

→ Aim at GUT scale (*Mx*) determination

SUSY mediated





$p \rightarrow \nu K^+$

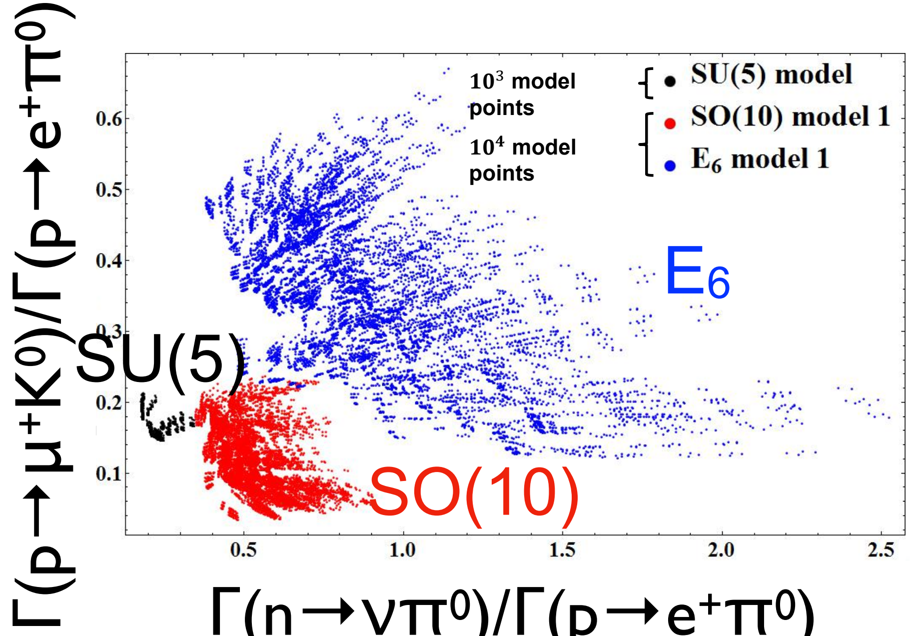
$$\Gamma(p \rightarrow \bar{\nu} K^+) \sim \frac{\tan^2\beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

→ highly model-dependent but unique test of SUSY and GUT

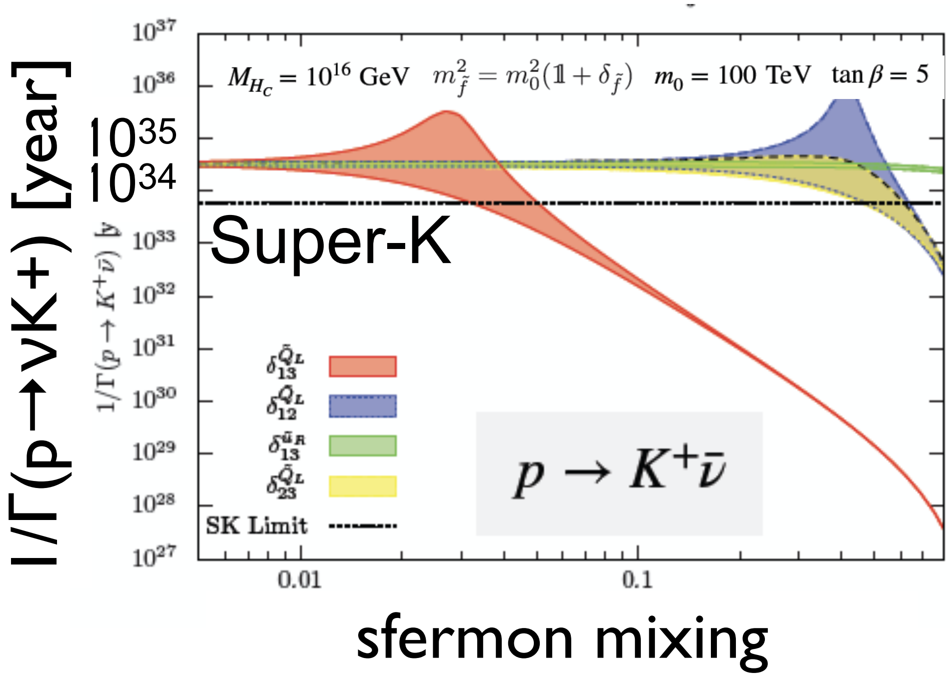
→ We need to experimentally pursue both and other decay modes

GUT gauge group and more

- We could identify details of unification picture, e.g. gauge group and other symmetries
  - $\Gamma(n\to\nu\pi^0)/\Gamma(p\to e^+\pi^0)$ depends on SU(5), SO(10), E_6 (Y. Muramatsu)



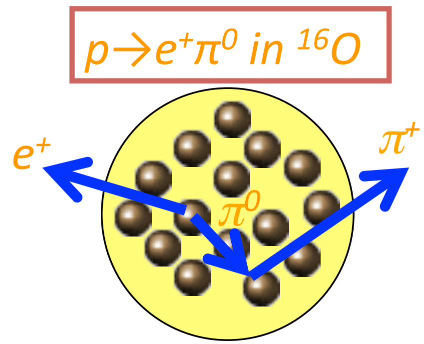
- P-decay Br. ratio could tell us flavor structure of SUSY particles.
  - Decay branches depends on the size of sfermion mixing. (N.Nagata and S.Shirai, JHEP 1403, 049 (2014))

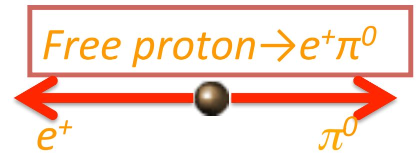


World-leading p-decay detector

- **High mass (190kton fiducial mass)**
  - much beyond Super-K, world-highest mass
- **Free-p (^{1}H) available**
  - No Fermi motion, nuclear effect
  - High efficiency & good S/N separation
- **Excellent detector performance**
  - Good ring-imaging capability, particle ID (e or μ) capability, and Energy resolution.

	material	Fiducial Mass (kton)
Super-K	Water	22
Hyper-K	Water	**190**
Dune	Argon	40
JUNO	Liq. Scinti	20





- No Fermi motion
- No π's re-scattering

Hyper-K is only experiment which can perform searches beyond 10^{35} years for $p \to e^+\pi^0$ and aim to determine GUT scale, and more.

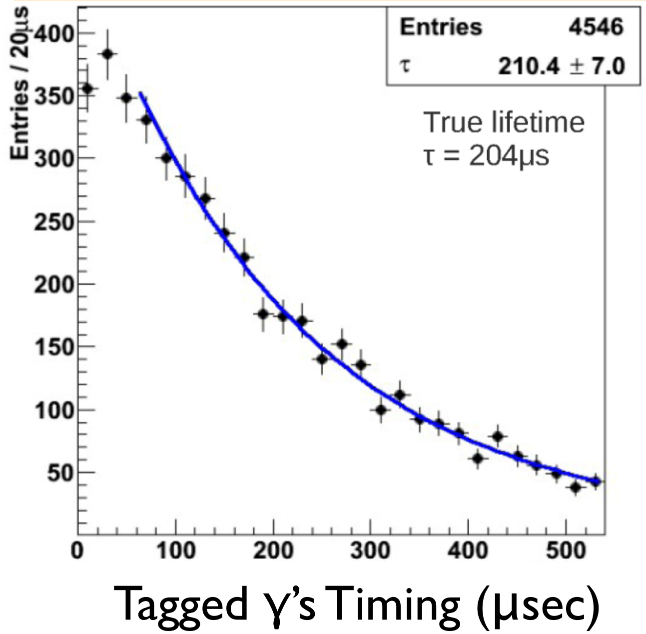
Neutron tagging to eliminate BG

- Shiozawa@NNN00 workshop
- Beacom and Vagins PRL93:171101(2004)

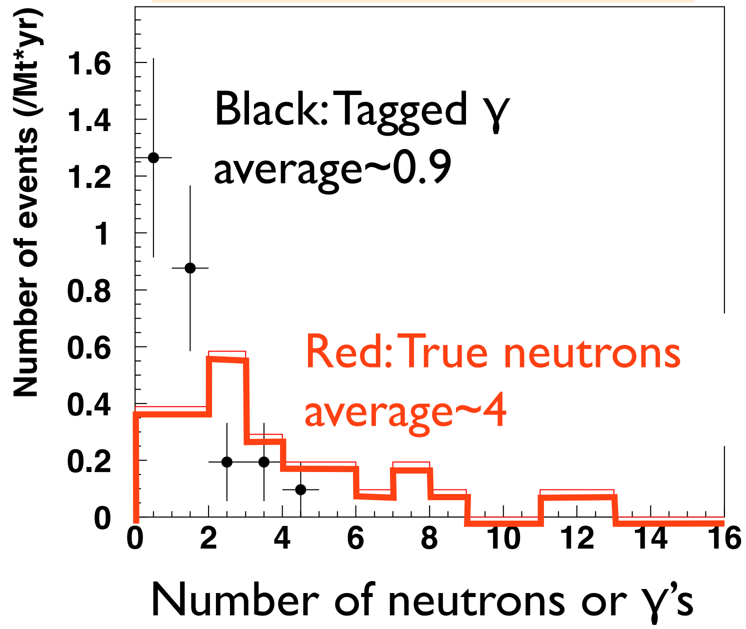
- **Neutrino interactions** are often accompanied with **neutrons** but proton decays are not.
- Record faint signature of neutrons; n+p→d+**γ(2.2MeV, τ~200μsec)**

- Full coverage of High-efficiency PMTs essential to keep discovery potential w/ 0.25/20 yrs BG level (ptot<100MeV/c for e+π0)
- Another technical challenge is developing neutron tagging algorithm.

SK-IV 1297days atmν Data

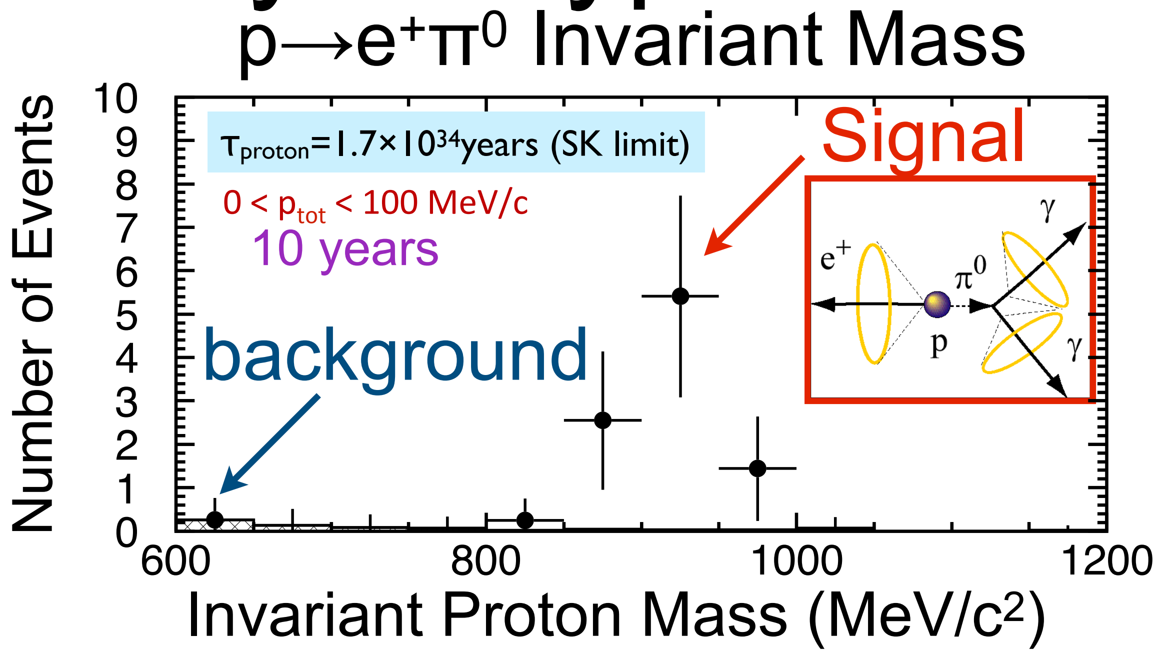


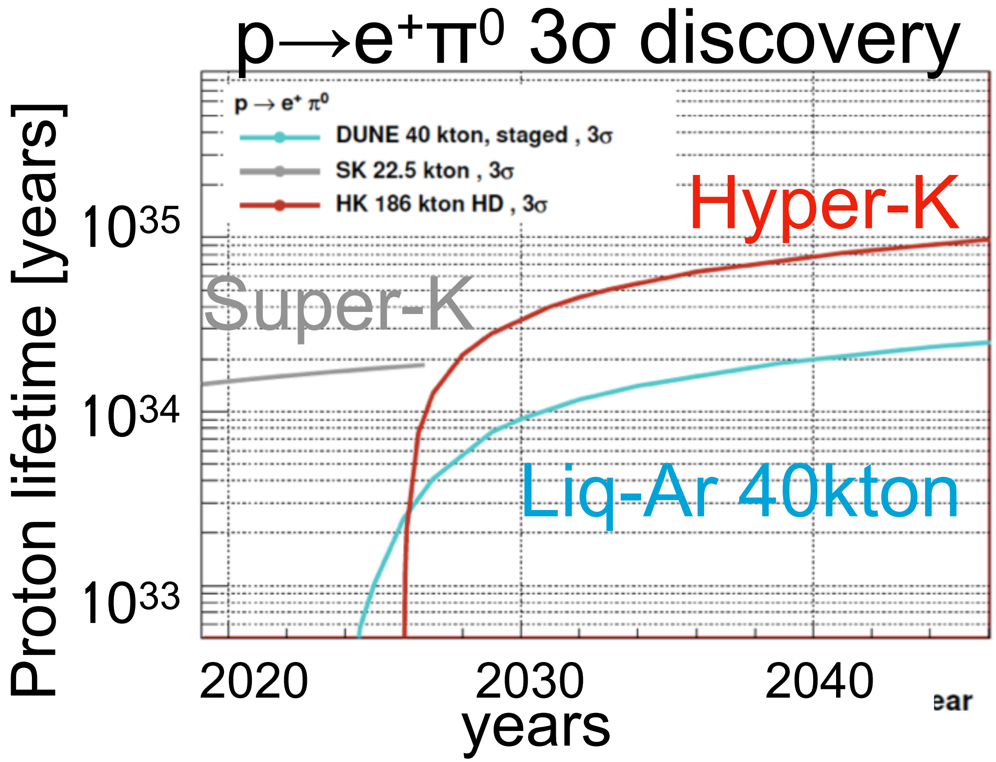
p→e⁺π⁰ BG Monte Carlo



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

- Invariant proton mass would be a compelling evidence
- Reach to 10^{35} yrs
- BG free search possible: 0.06 BG/Mton・year

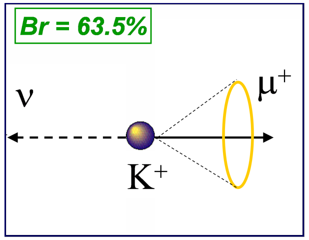


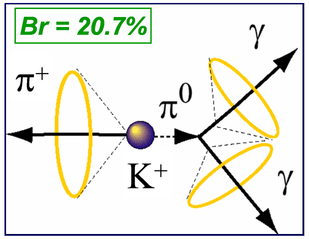


	p_{tot}<100MeV/c		100<p_{tot}<250MeV/c	
	Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
HK	18.7	0.06	19.4	0.62

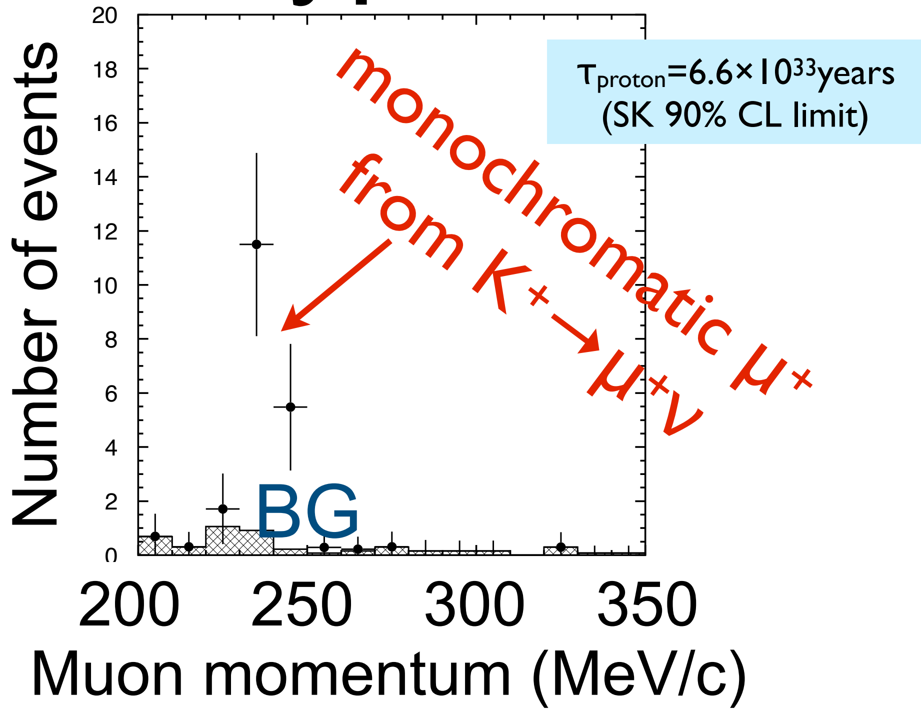
$p \rightarrow \nu K^+$ discovery in Hyper-K

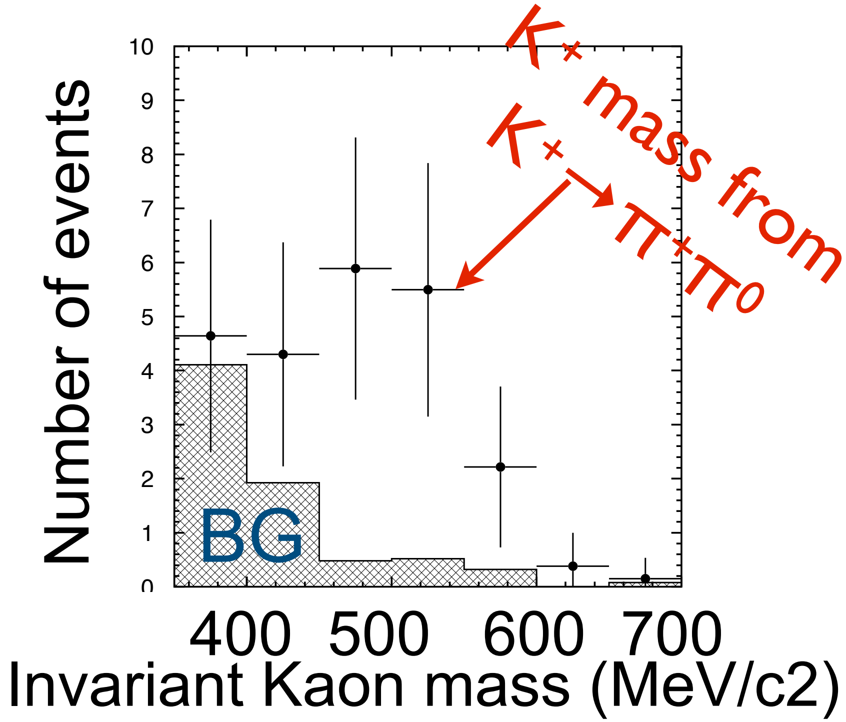
- K+ is invisible so signal signature are:
    - 236 MeV/c muon
    - $\pi^+\pi^0$
- Discovery reach beyond 10^{34} years





	prompt-γ & $K^+ \rightarrow \mu^+\nu$		$K^+ \rightarrow \pi^+\pi^0$	
	Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
HK	12.7	0.9	10.8	0.7





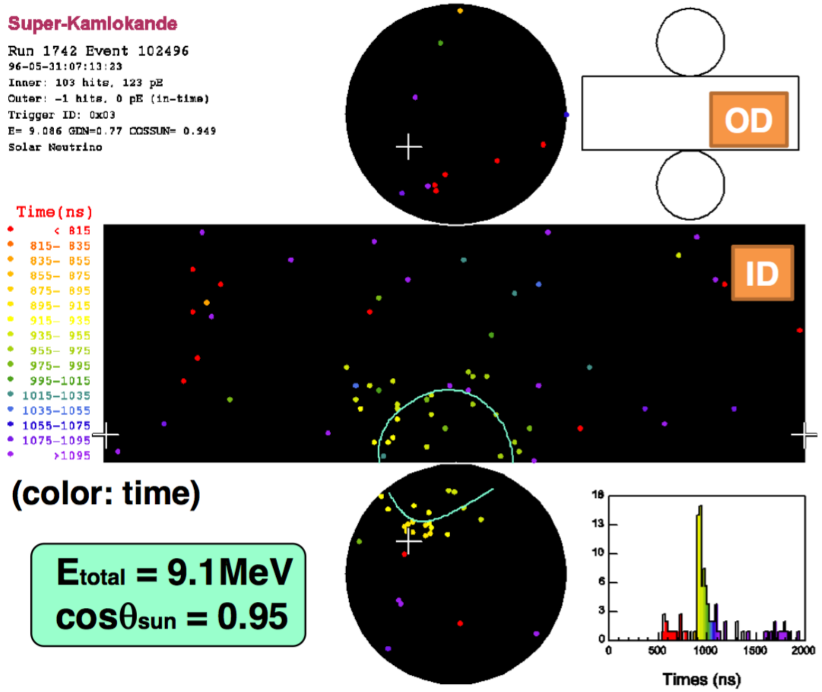
Neutrino astrophysics

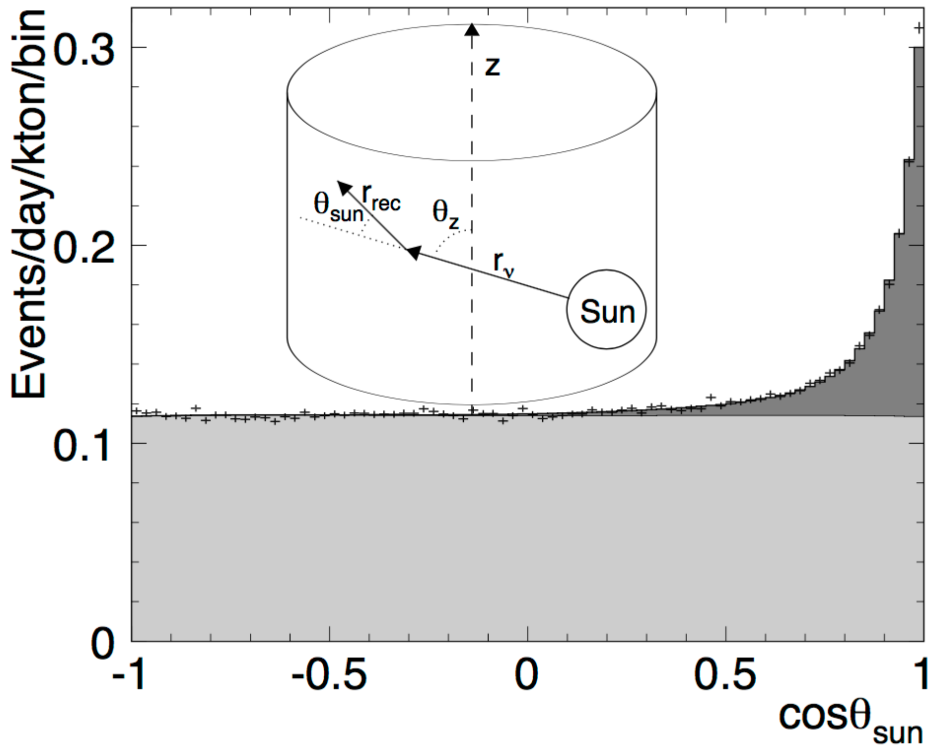
> a few MeV neutrino astronomy

Real time, source pointing, neutrino spectroscopy

Cherenkov ring image in Super-K

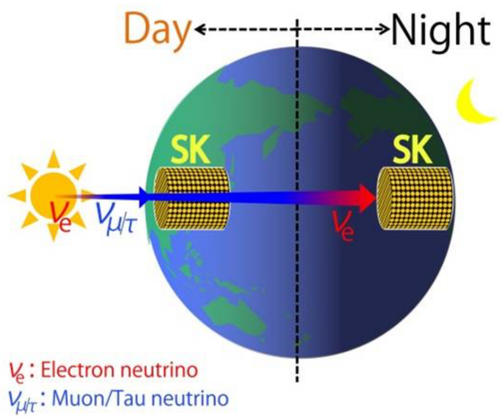
$$\nu + e^- \rightarrow \nu + e^-$$





- Neutrinos from Sun, Supernova, and new sources?
- 6 hits/MeV (Super-K) → 12 hits/MeV (Hyper-K) to improve detector resolution and BG control
- High statistical observation (10 x Super-K)

Day-Night Effect



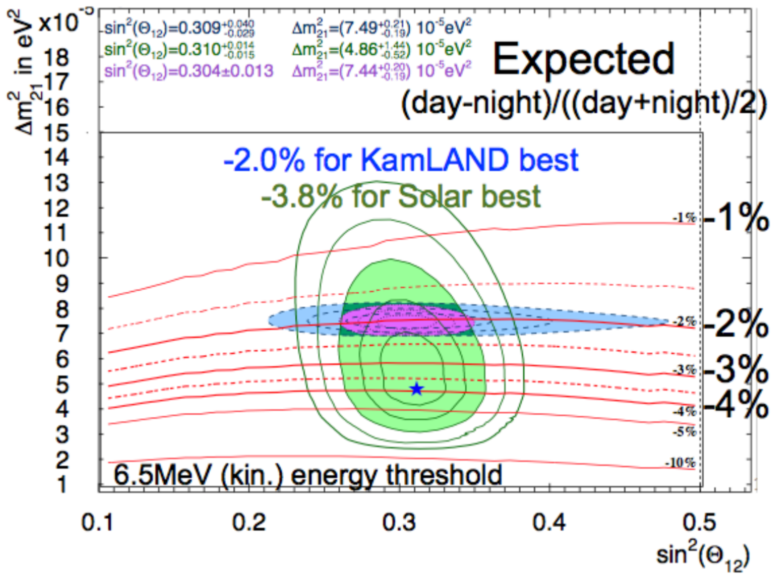
Super-K $A_{\rm DN}^{\rm fit} = [-3.2 \pm 1.1({\rm stat}) \pm 0.5({\rm syst})]\%$

non-zero significance : 2.7σ

dominant error

mainly from BG shape

oscillation parameters : Solar and KamLAND



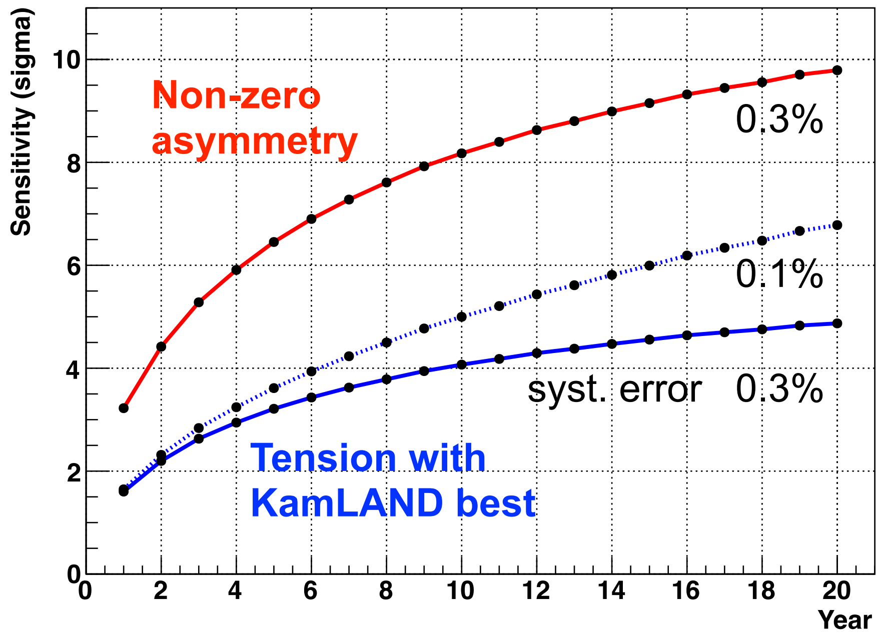
Hyper-K

Goal of systematic error : 0.3%

- High photon-yield, precision energy calibration, BG control

- **Establish Sun's matter density and theory of matter oscillations**
- **CPT invariance ($P_\nu = P_{\bar{\nu}}$) test**

sensitivity from Day-Night in Hyper-K



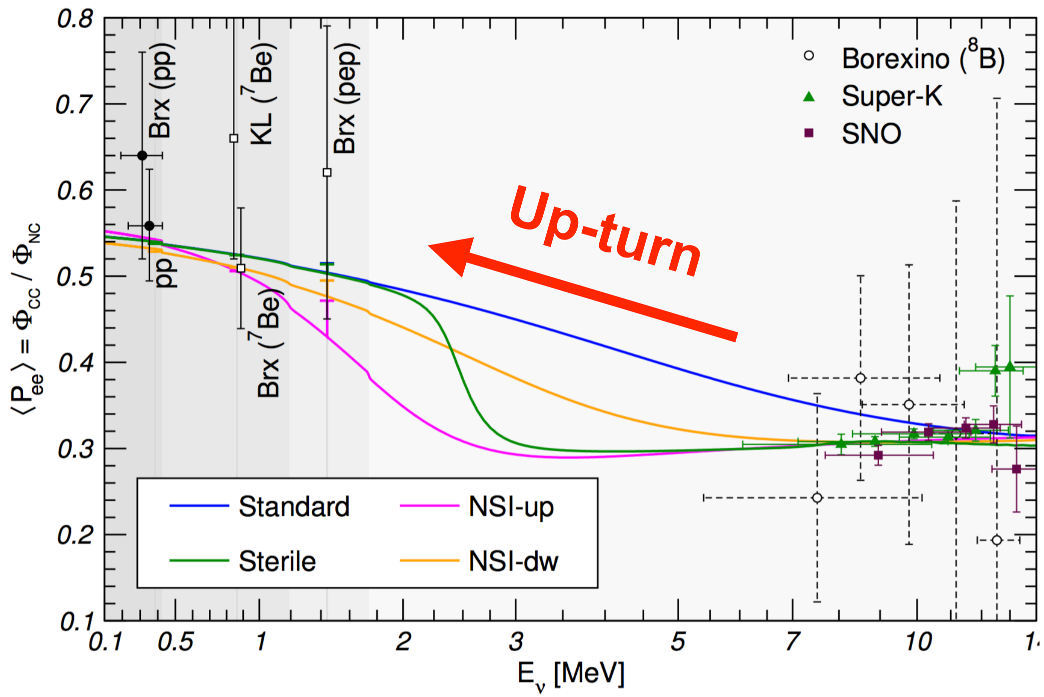
Spectrum Up-turn

Intermediate energy region between vacuum and MSW oscillation (up-turn) can be measured more precisely in Hyper-K

Observation of MSW oscillation with single neutrino source (^8B)

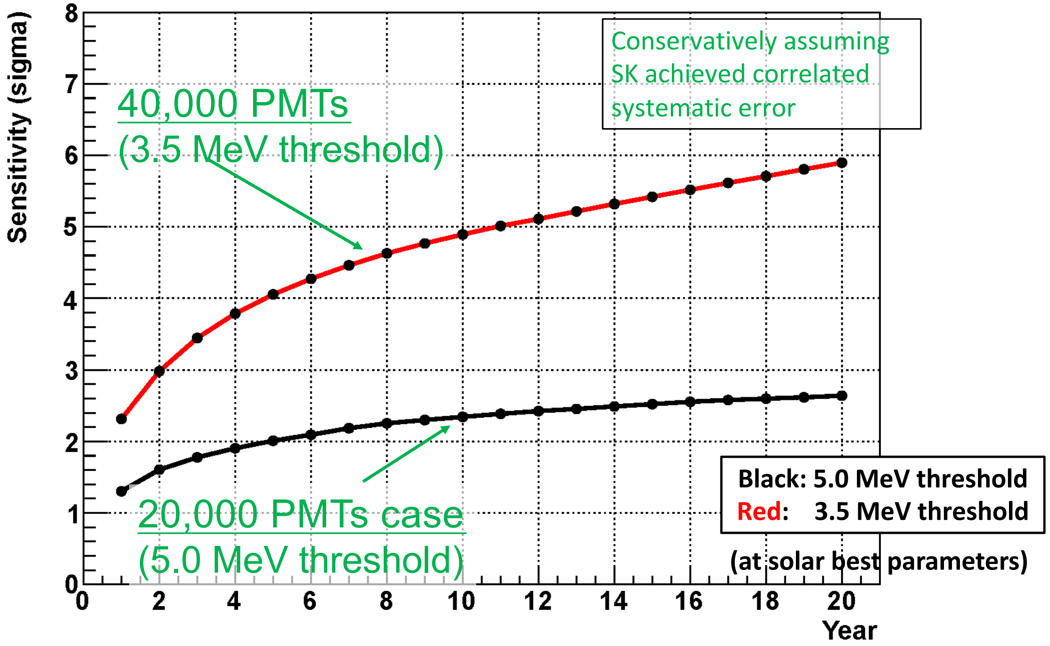
Test exotic scenario (non-standard interaction, sterile neutrino)

survival probability of electron solar neutrinos



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

sensitivity of energy spectrum up-turn

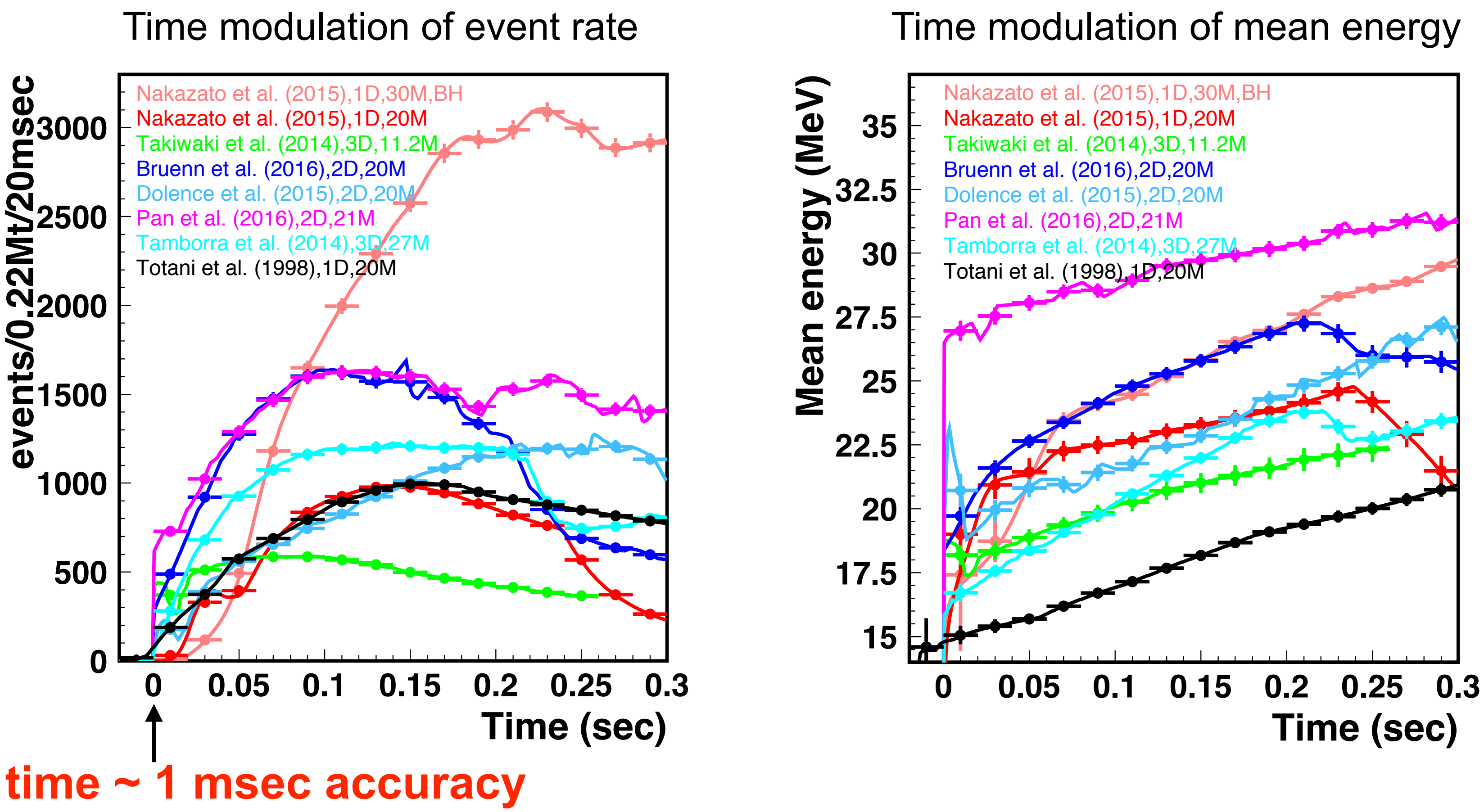


>5σ sensitivity

lowering energy threshold by full PMT is critical

Supernova Neutrino in Hyper-K

High statistics: 54,000-90,000 events in total for GC (10kpc)

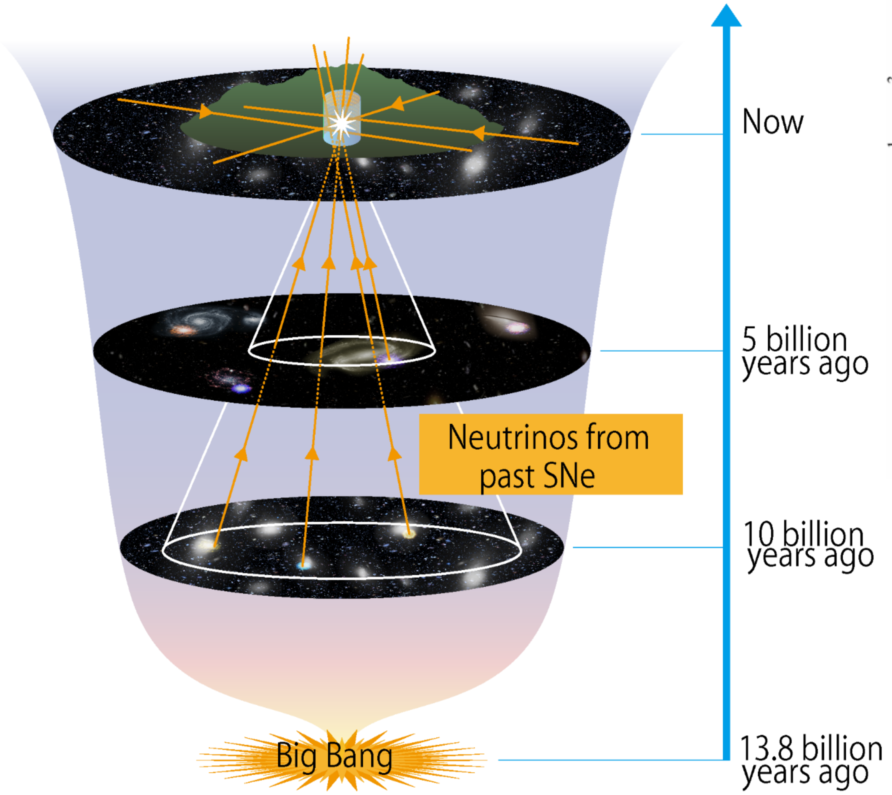


Quite high statistics to observe fine time structure to test explosion models.

Compare onset time with gravitational wave with Δt ~ 1msec.

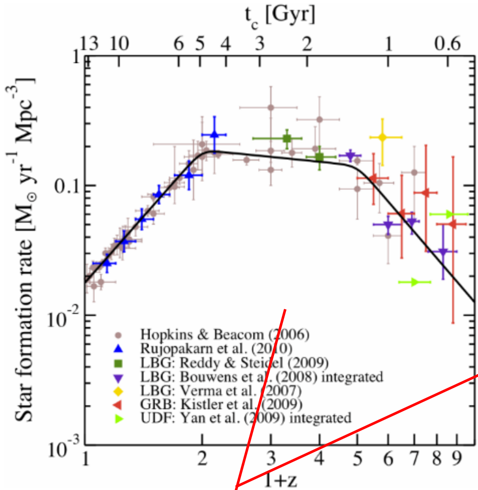
What is Supernova Relic Neutrinos（SRN）?

$10^{22\text{-}23}$ stars in the universe（～10^{11} galaxies, ~$10^{11\text{-}12}$ stars/galaxy）
At present, we are getting neutrinos from 10^{17} supernovae

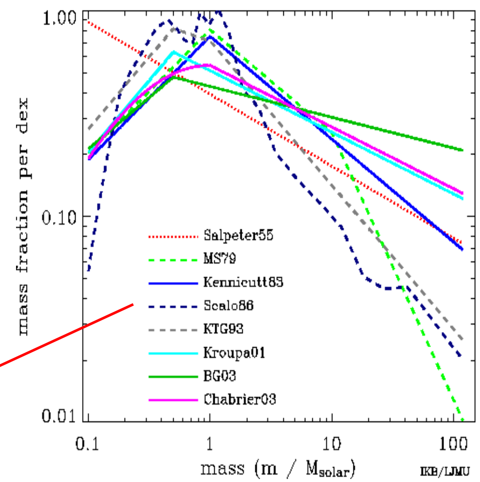


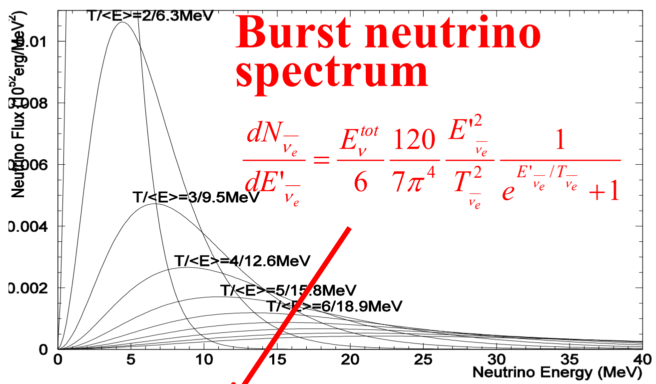
Horiuchi,Beacom(2010)

Star Formation Rate



Initial Mass Function





$$\frac{dN_{\bar{\nu}_e}}{dE'_{\bar{\nu}_e}} = \frac{E_{\nu}^{tot}}{6}\frac{120}{7\pi^4}\frac{E'^2_{\bar{\nu}_e}}{T^2_{\bar{\nu}_e}}\frac{1}{e^{E'_{\bar{\nu}_e}/T_{\bar{\nu}_e}}+1}$$

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z\mathrm{max}} R_{\mathrm{SN}}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

We can study
star formation history and
averaged neutrino spectrum.

SRN in JUNO, SK-Gd and HK(-Gd)

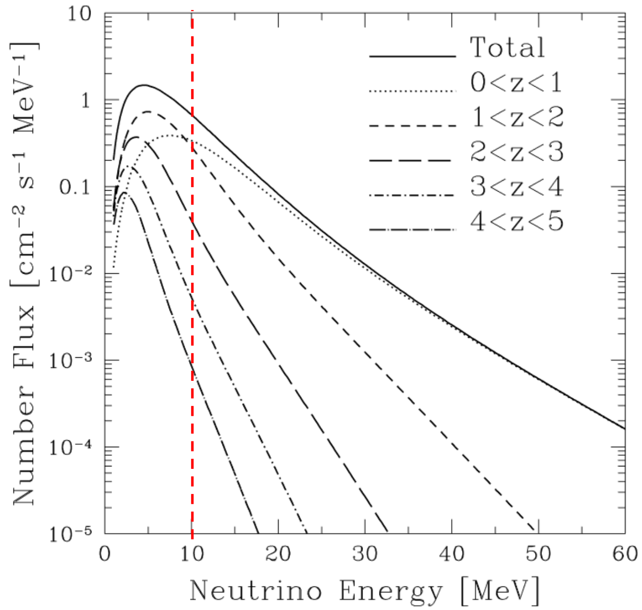
Number of SRN events

Detector	Number of signals	Number of B.G.	Significance
JUNO 10 years (11-30 MeV)	12 (<E_ν>=15MeV, after PSD)*	7.1	4.5σ
SK 10 years (10-28 MeV)	17 (JUNO model*, <E_ν>=15MeV)	34	2.9σ
HK 10 years (10-28 MeV)	141 (JUNO model*, <E_ν>=15MeV)	294	8.2σ

JUNO and SK would discover SRN events. HK will measure energy spectrum.

*J. Phys. G 43 (2016) 030401, arXiv:1507.05613

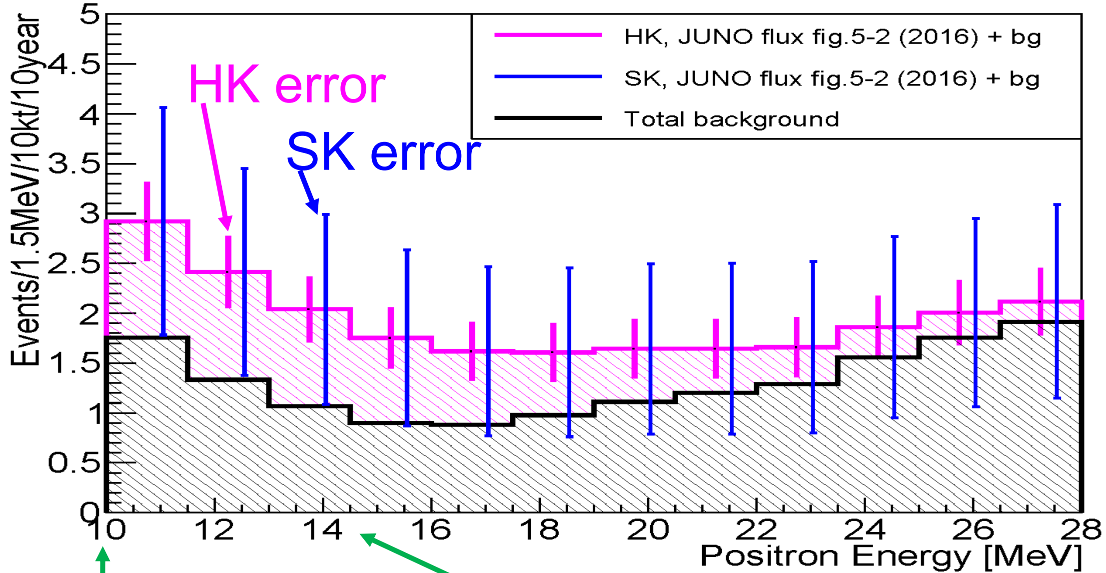
Spectrum measurement of SRN



S.Ando, Astrophys.J. 607, 20(2004)

If we can measure energy spectrum down to 10MeV, we can reach red shift (z) of about 1, i.e. 7 billion years ago.

Expected spectrum at Hyper-K



Energy threshold with

40,000 PMTs

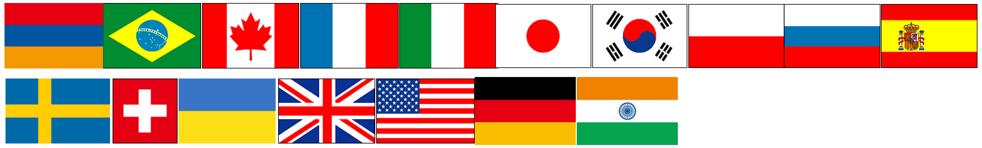
20,000 PMTs

40,000 PMTs are necessary to measure spectrum to reach Z=1

Organization etc

International Organization

- **International Hyper-K proto-collaboration**

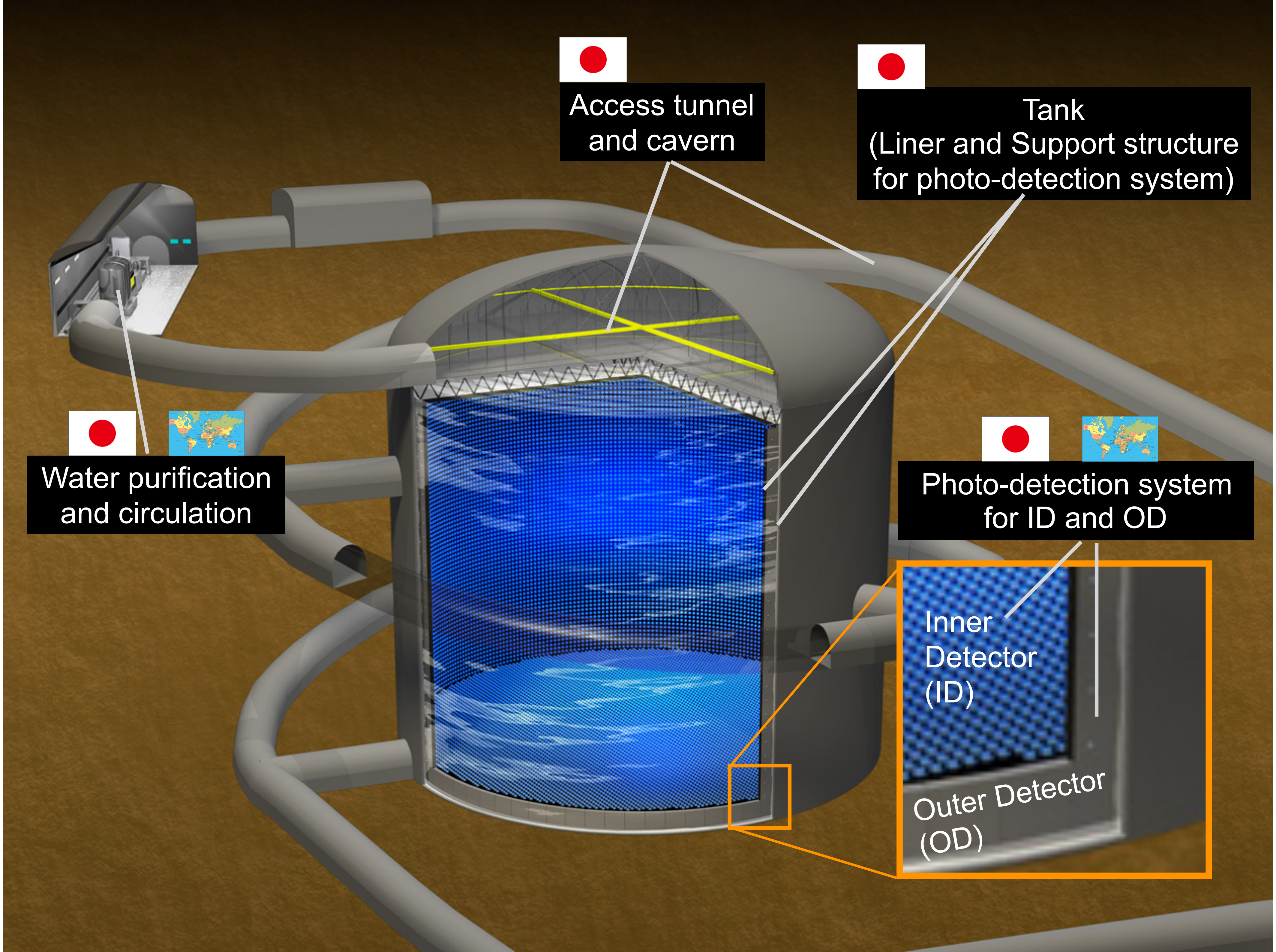


  - 17 countries, 82 institutes, ~300 members, ~75% from abroad
- 2 host institutes:
  - UTokyo/ICRR launched a institute for HK detector construction: Next-generation Neutrino Science Organization (NNSO)
  - KEK/IPNS for J-PARC and near detectors
- External review by Advisory Committee
  - international high-energy physicists and Japanese engineering specialists
- HK exp. Financial Forum
  - Representatives of funding agency and laboratories get together

Hyper-K meeting@Madrid, March 2018

Inaugural Symposium@Kashiwanoha, January 2015

NNSO Inaugural Ceremony@Kamioka, October 2017


Access tunnel and cavern
Tank (Liner and Support structure for photo-detection system)
Water purification and circulation
Photo-detection system for ID and OD
Inner Detector (ID)
Outer Detector (OD)

International Contributions to the Construction and Operation

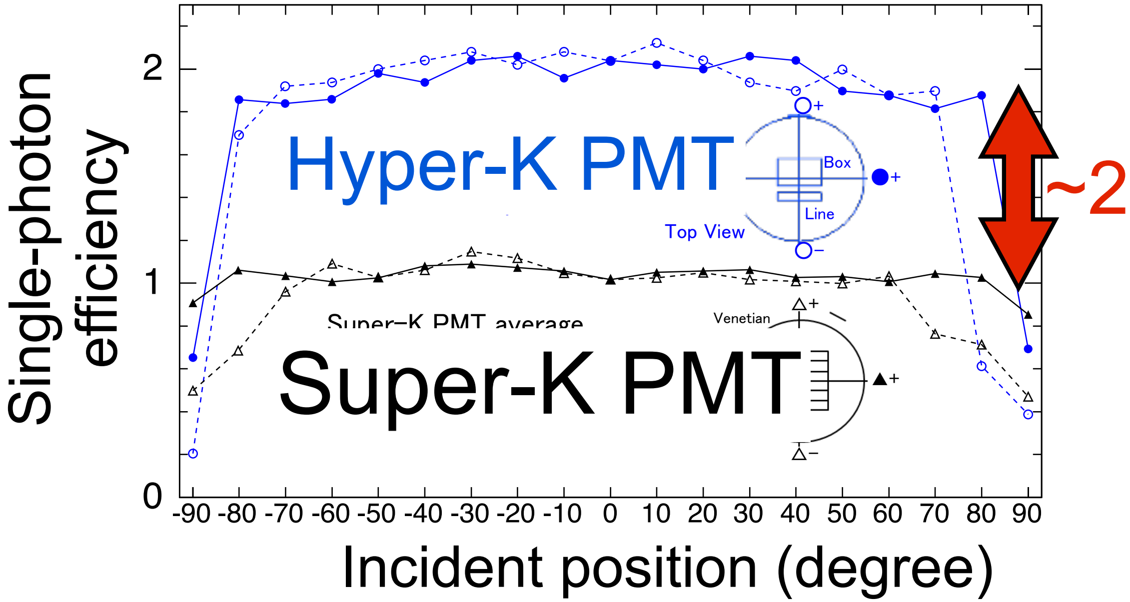
- Japan and foreign partners will make their best efforts to realize “Photo-detection system.”
  - Potential foreign contributions include **PMTs, their covers, readout electronics, HV power supply, data acquisition system, geomagnetic field compensation coils, and calibration system**.
- We also need international contributions to
  - **Computing and storage resources** for Hyper-K observation and simulation data
  - **Water purification system upgrade** for astrophysical neutrinos
  - **Neutrino beam-line power-upgrade** (J-PARC)
  - New and upgraded **near detector system**
  - **Calibration**, and others

We want to work with international partners to make innovative ideas and in-kind contributions to realize the exciting Hyper-K physics !

Key element: Photo-detection system

φ50cm

- sensitivity:
  2 x SK
- Time resolution:
  1/2 x SK
- Pressure:
  2 x SK



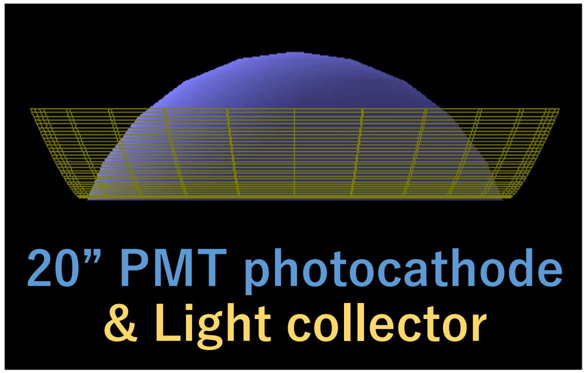
~140 new PMTs have been installed in Super-K this summer

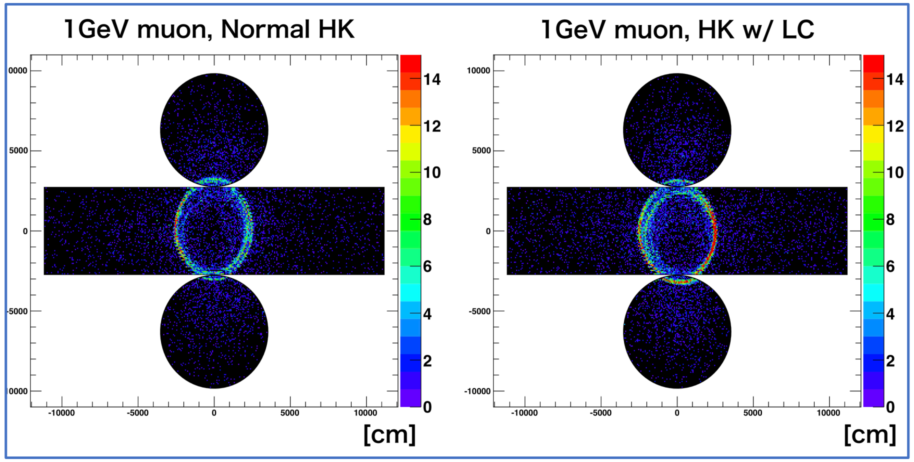
- Ongoing R&D of B&L-dynode PMT includes
  - dark rate reduction, cover & light-concentrator development
  - long-term performance evaluation in Super-K
- Budget request for 20,000 PMTs in Japan
  - corresponds to a half of Hyper-K full-coverage (40%). HK physics sensitivities are estimated by 40% coverage.

Light Collector

More photoelectron, better physics.

- Light collector (light concentration mirror) is a chance to enhance HK detector.
  - Specific design for Super-K style detector
- ~1.3 times of photoelectron detection.
  - Better vertex resolution, energy resolution at O(1) - O(10) MeV.
- +10% neutron tagging efficiency with pure water, for proton decay search.





Contribution	Mirror Material	Performance	Design & Production
R&D issue	High reflective, stable material	Improving mirror shape w/ software simulation	Structure design
Test	Long-term stability of reflectivity in pure water	Actual measurement of light concentration	Production test, mechanical strength test
Production	Production and installation into Hyper-K detector		

Still open to innovative ideas and in-kind contributions to additional and/or alternative photo-detection system

Inner-Det.

MCP-PMT

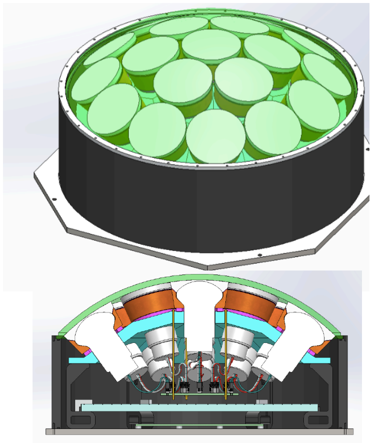
Ongoing R&D to improve timing, reduce dark rate, water-proofing, cover etc

φ50cm

Inner-Det.

Multi-PMT module

Many R&D are needed on module/ assembly, acrylic vessel, electronics, simulation&reconstruction etc



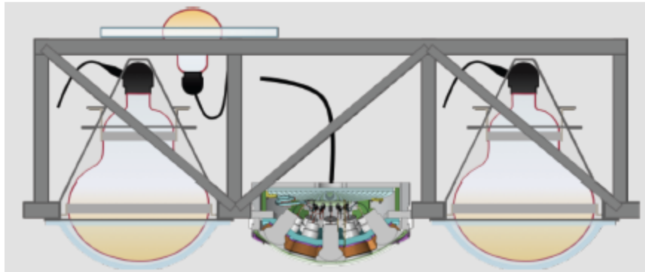
φ50cm

Outer-Det.

Outer-detector system

Open for photo-sensor type, density, light-concentrator, deployment method

Potential design of OD PMT w/ wavelength shifter plate



Potential combination of 50cm PMTs and multi-PMT modules

- MCP-PMT R&D aiming for better detector performance
- Studying potential combination w/ multi-PMT modules to improve light yield, granularity, timing resolution, and charge dynamic range
- Also need outer-detector system, still open for photo-sensor design

Challenges on HK electronics

Never miss Super Nova Burst!

- large data buffering/high speed transmission .. JP, PL

High pressure environment under water!

- water-proof case/connector ~ 10atm
- design of heat exchange .. JP, less covered!

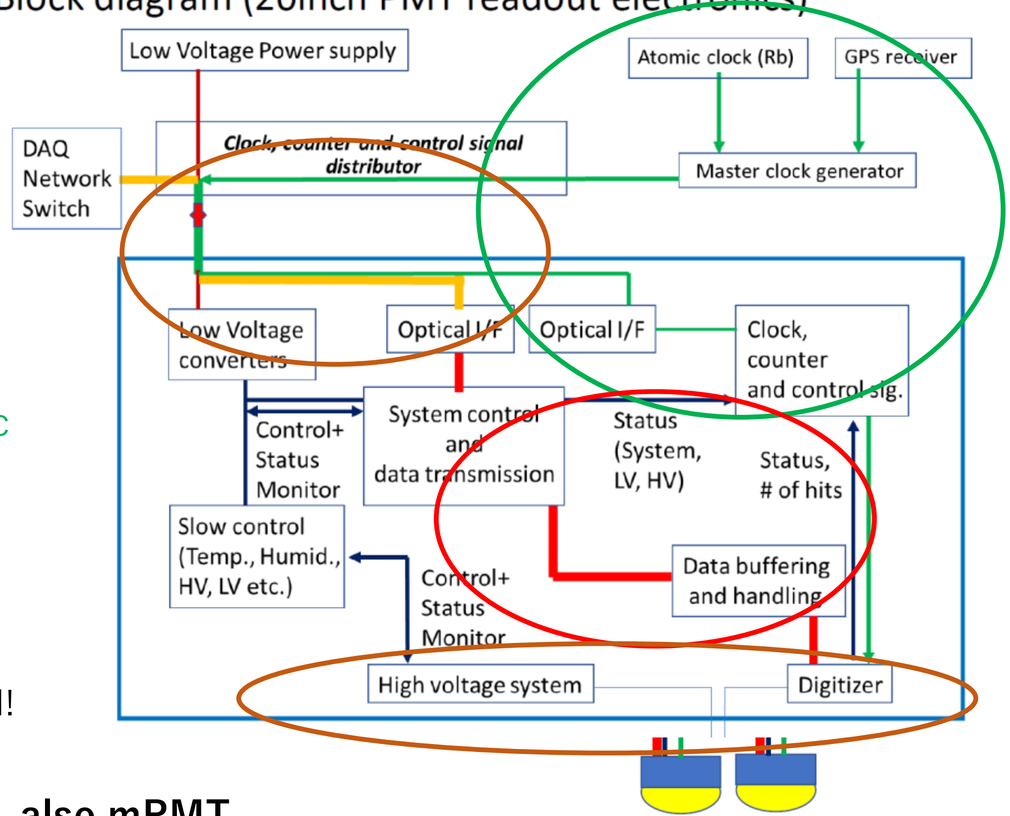
High scalability ever!

- synchronization system for ~ 2000 FEs and JParc .. JP, FR
- Trigger/DAQ on surface .. UK

High durability ~ 20years!

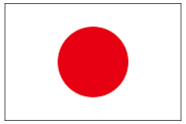
- protection circuit for analog ASIC .. JP, SW
- long stability HV module .. JP, less covered!
- backup strategy for communication .. JP

Block diagram (20inch PMT readout electronics)



also mPMT .. CA, IT, PL

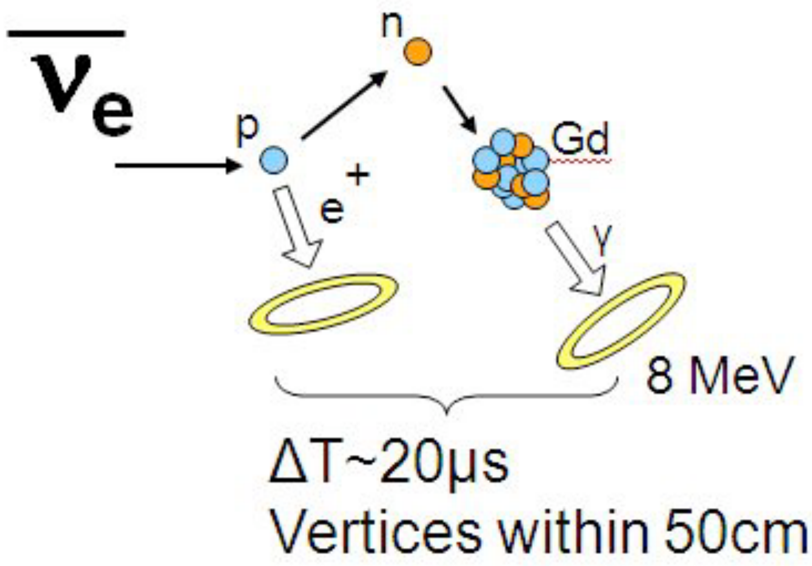
Water system



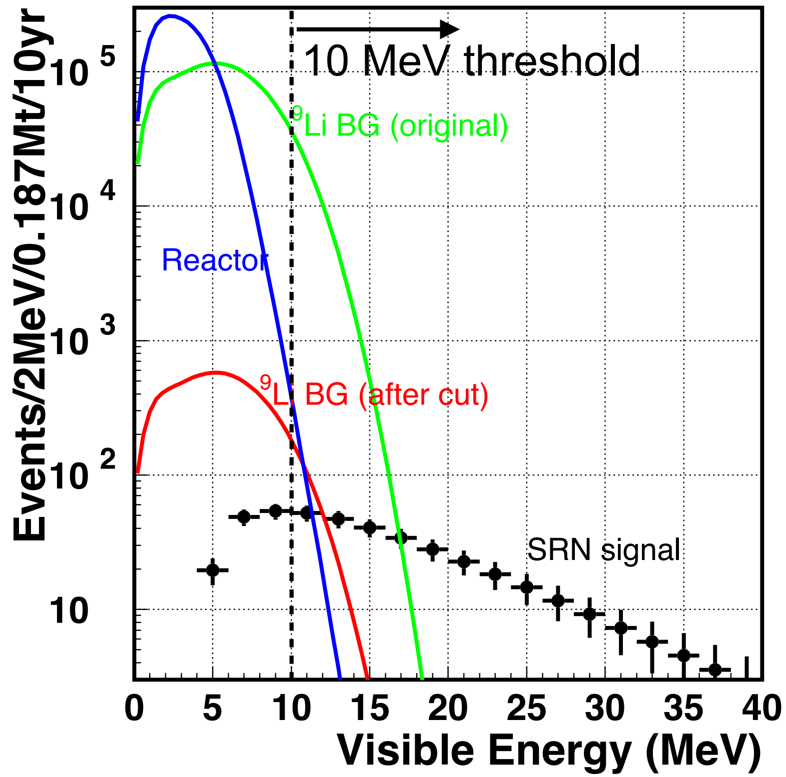
- Japan submitted budget request for pure water system.

- Additional capability could be realized by international partners, e.g. loading Gadolinium to enhance observation of Supernova relic neutrinos (SRN).

Explore the history of supernova burst back to red shift (z) ~ 1



effective tagging to reduce backgrounds



Summary

- Hyper-K will play central roles in exploring the future particle physics and contributes to the future astronomy.
- A lot of technical challenges ~ opportunities to go beyond Super-K.
  - Photo-detection system, Neutron tagging, New algorithm, Improve systematic uncertainties etc
- You are very welcome to join the project. Now is critical time as a starting point of new organization for HK construction.