Neutrino Astrophysics at Hyper-Kamiokande

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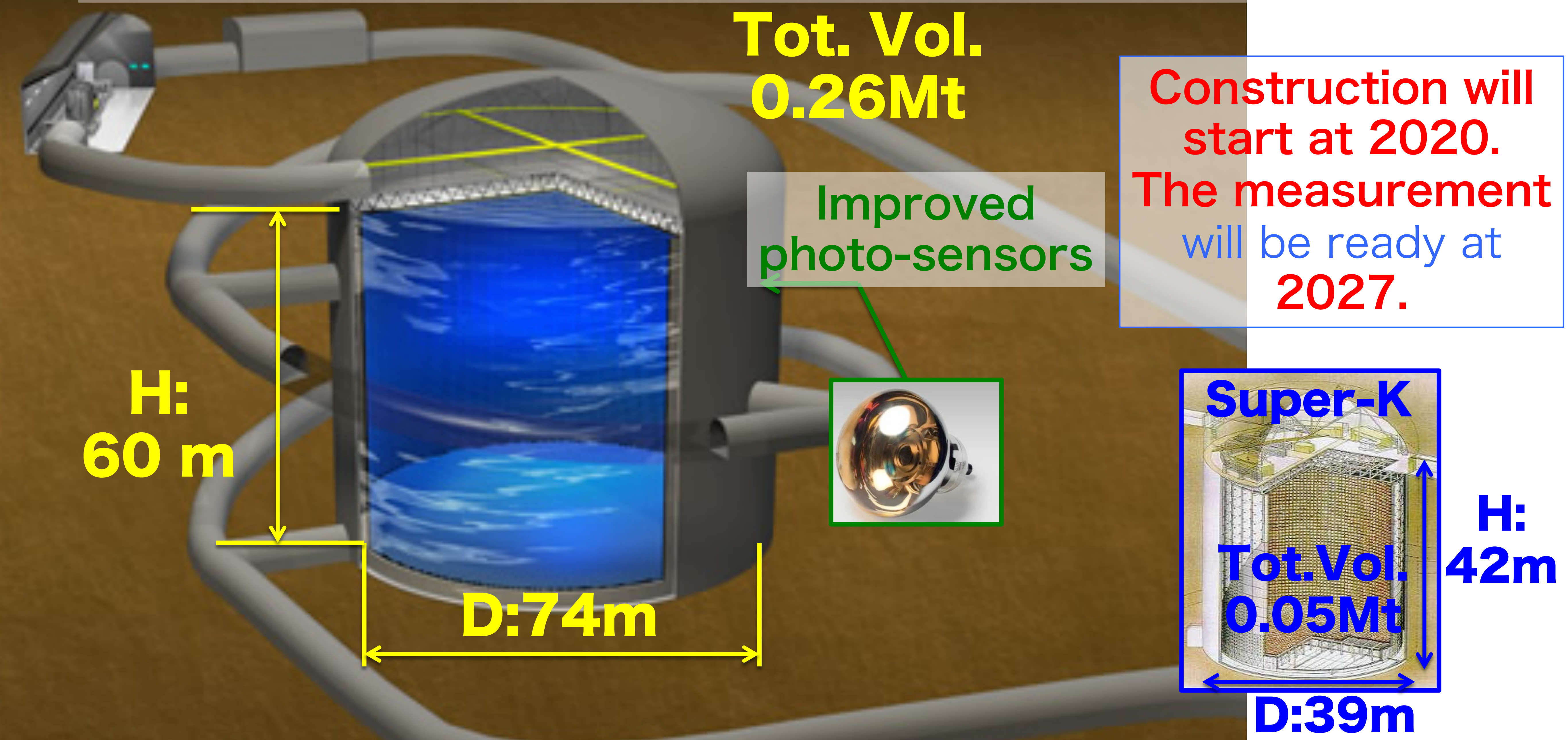
ICRR

Revealing the history of the universe with underground particle and nuclear research 2019

Tohoku Univ., 9th Mar. 2019

Hyper-Kamiokande Project



Construction will start at 2020.
The measurement will be ready at 2027.

Design	Hyper-Kamiokande	Super-Kamiokande
No. of PMTs (ID/OD)	40,000 / 6,700	11,129 / 1,885
Photocathode coverage	40% (×2 efficient p.e. detection)	40%
Total / Fiducial V.	0.26 Mt / 0.19Mt (per tank)	50 kt / 22.5 kt

Hyper-K Site

- Hyper-K will be located in deep underground, Kamioka mine.
  - Super-K : 1 km vertical depth
  - Hyper-K : 640 m

- Simulation study for muon spallation backgrounds is done.

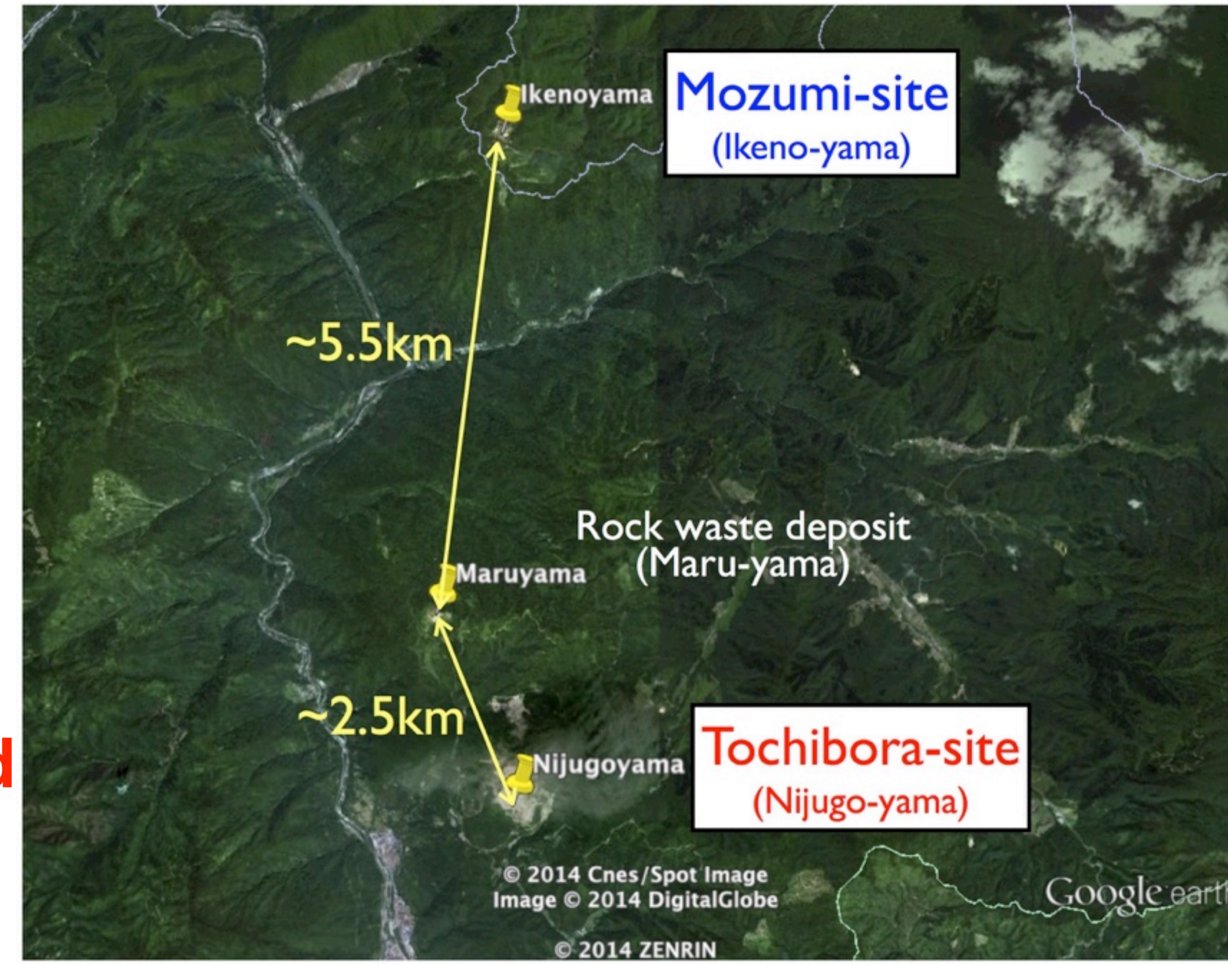
Muon flux : Hyper-K = **~5** × Super-K

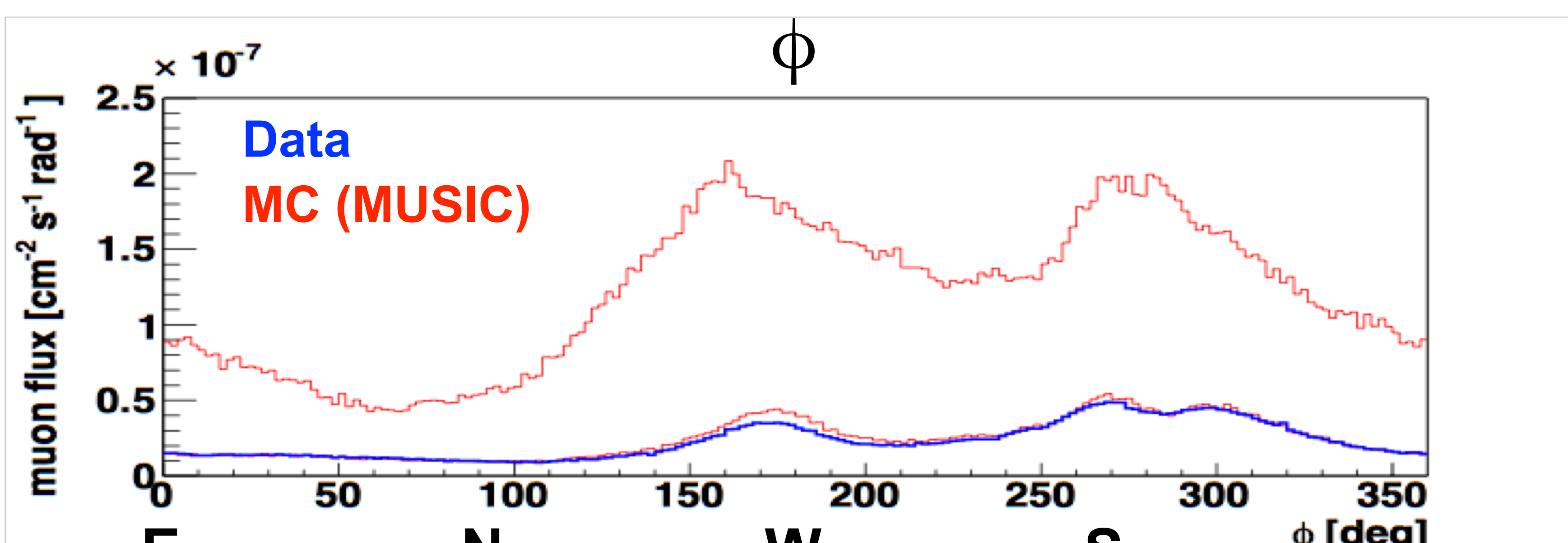
larger muon spallation background

Spallation product : Hyper-K = **~4** × SK

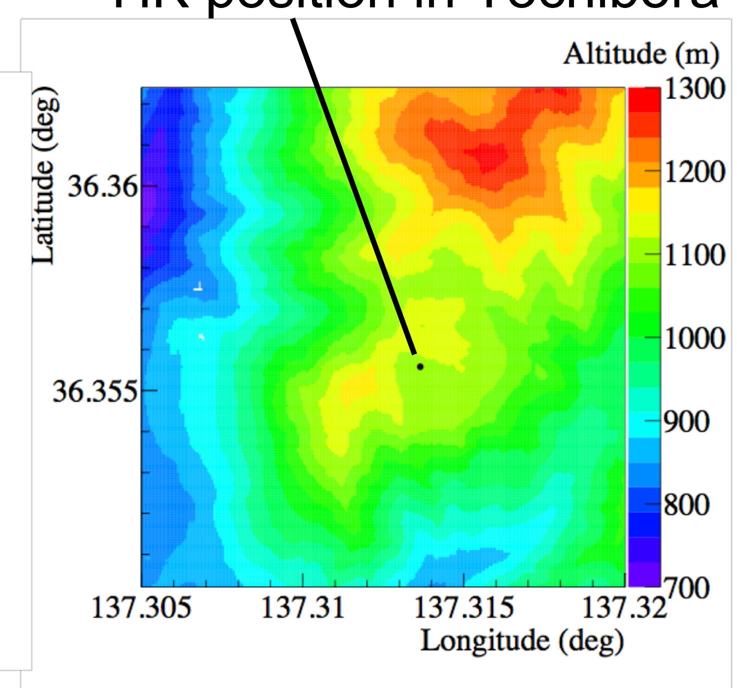
new likelihood cut ↓

~2.7 × SK





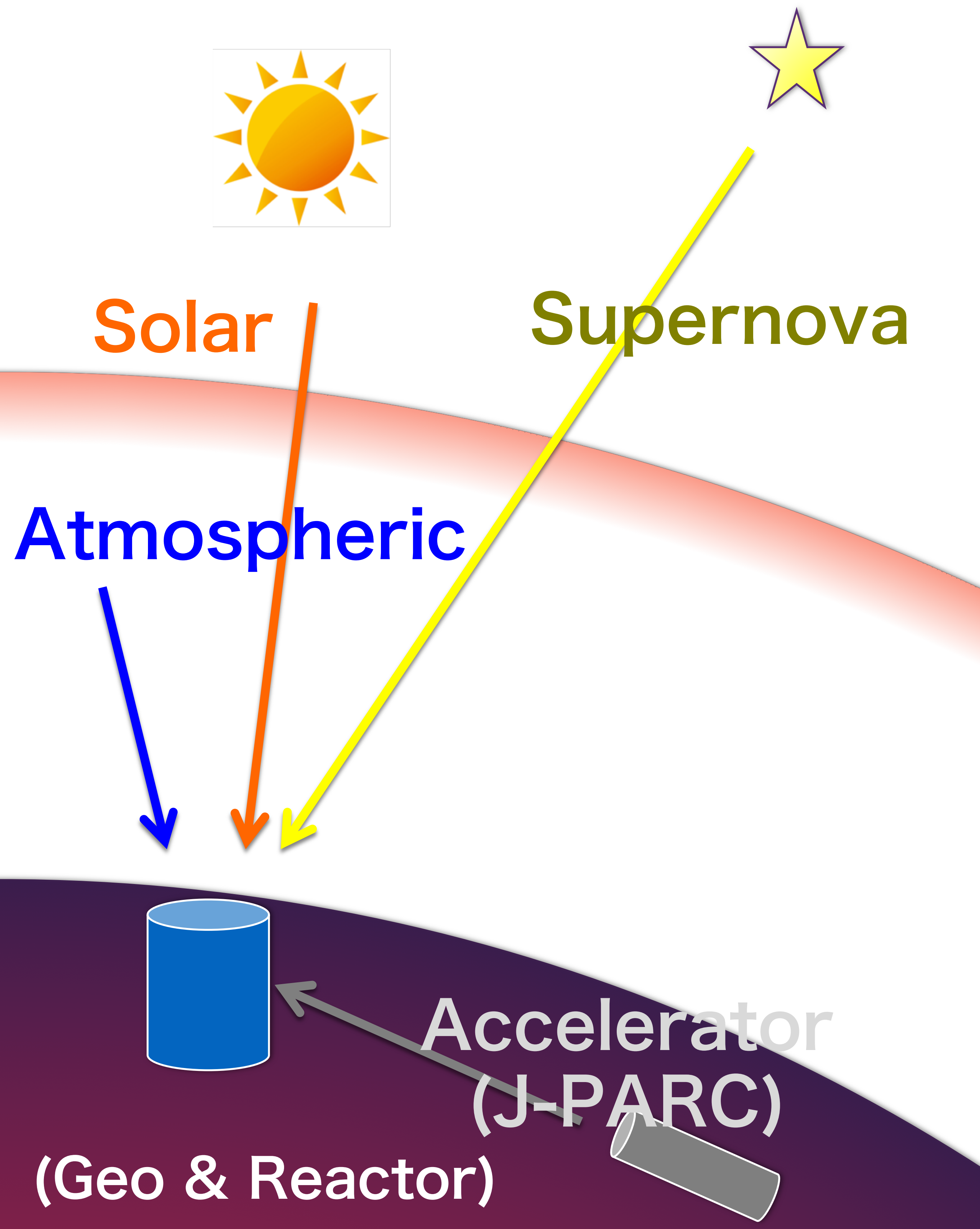
HK position in Tochibora



vertical depth ~ 600 m

Neutrino, Messenger from Nature

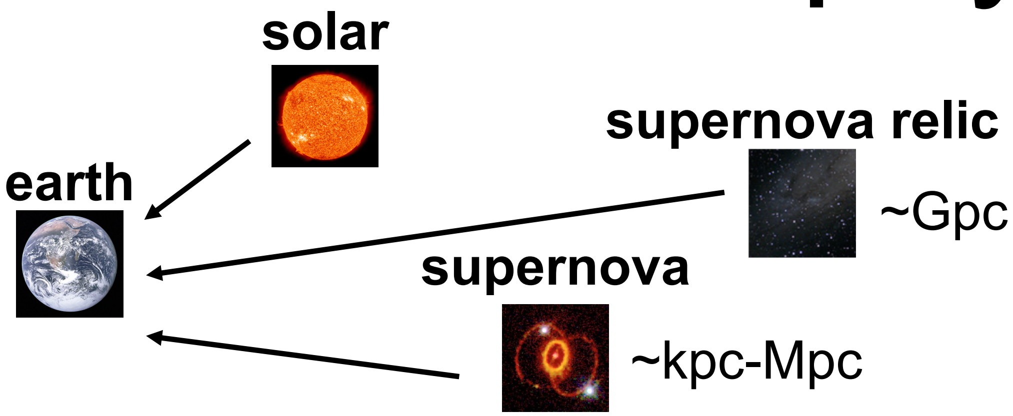
Source of Neutrinos

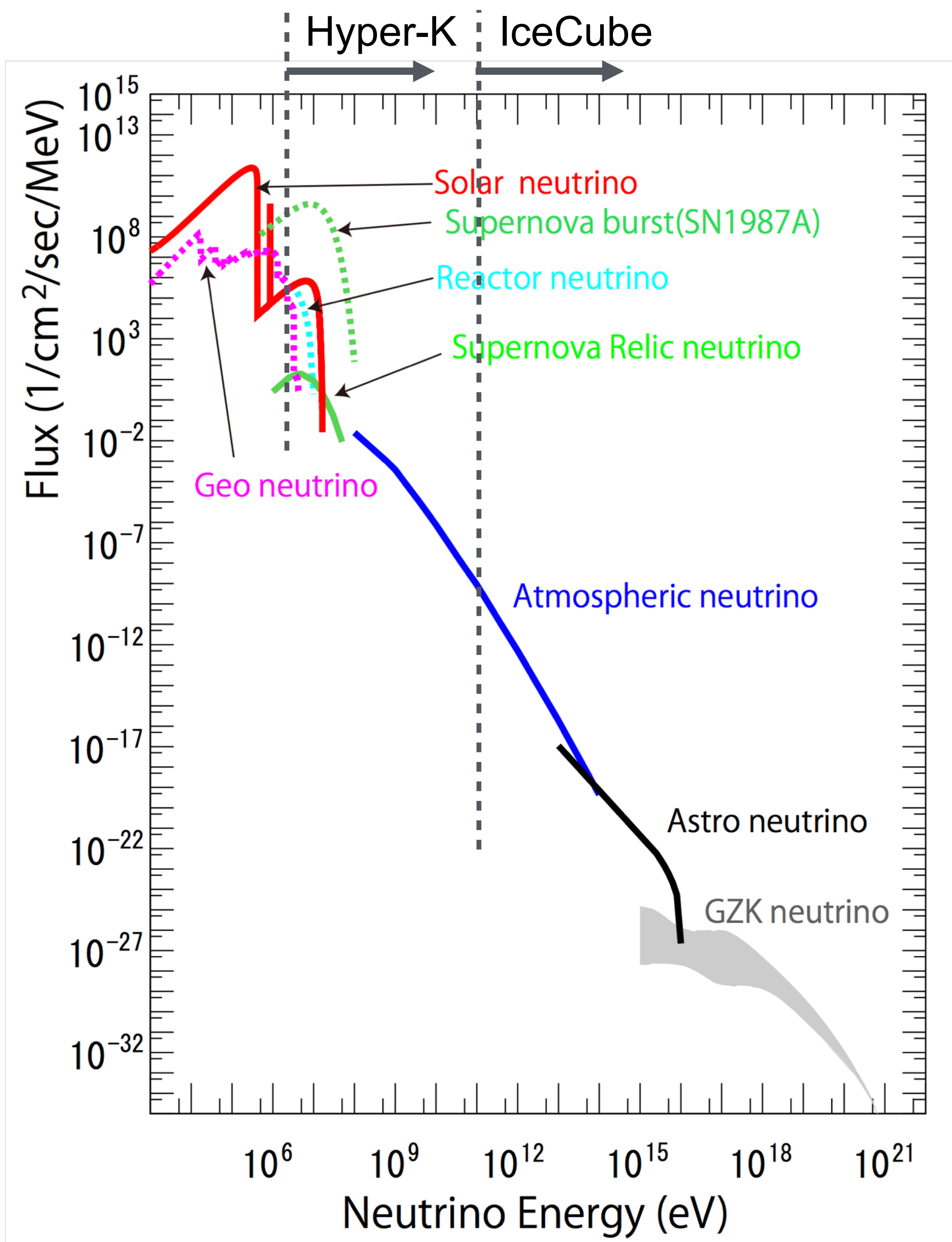


Physics of Neutrinos

- Neutrino Mixing
  - Mixing angles, Mass differences
- Difference between ν & $\bar{\nu}$
  - CPV, CPTV (Leptogenesis)
- Tiny neutrino masses
  - Mass hierarchy
- **Astrophysics**
  - **Prove of supernova, Sun, Earth and our universe.**
- **ν's role in nature**
  - **ν heating in supernova**

Astrophysical Neutrinos





Hyper-K (187 kton H_2O)

^{8}B solar neutrino	130 events / day
Supernova neutrino	~50,000 events / burst
Supernova relic neutrino	~18 events / year

highest statistics / directional information

DUNE (40 kton Ar)

Supernova neutrino	~3,000 events / burst

sensitive to only electron neutrinos

no directional information

JUNO (17 kton LS)

Supernova neutrino	~5,000 events / burst
Supernova relic neutrino	~3 events / year

no directional information

IceCube (2,400 kton H_2O)

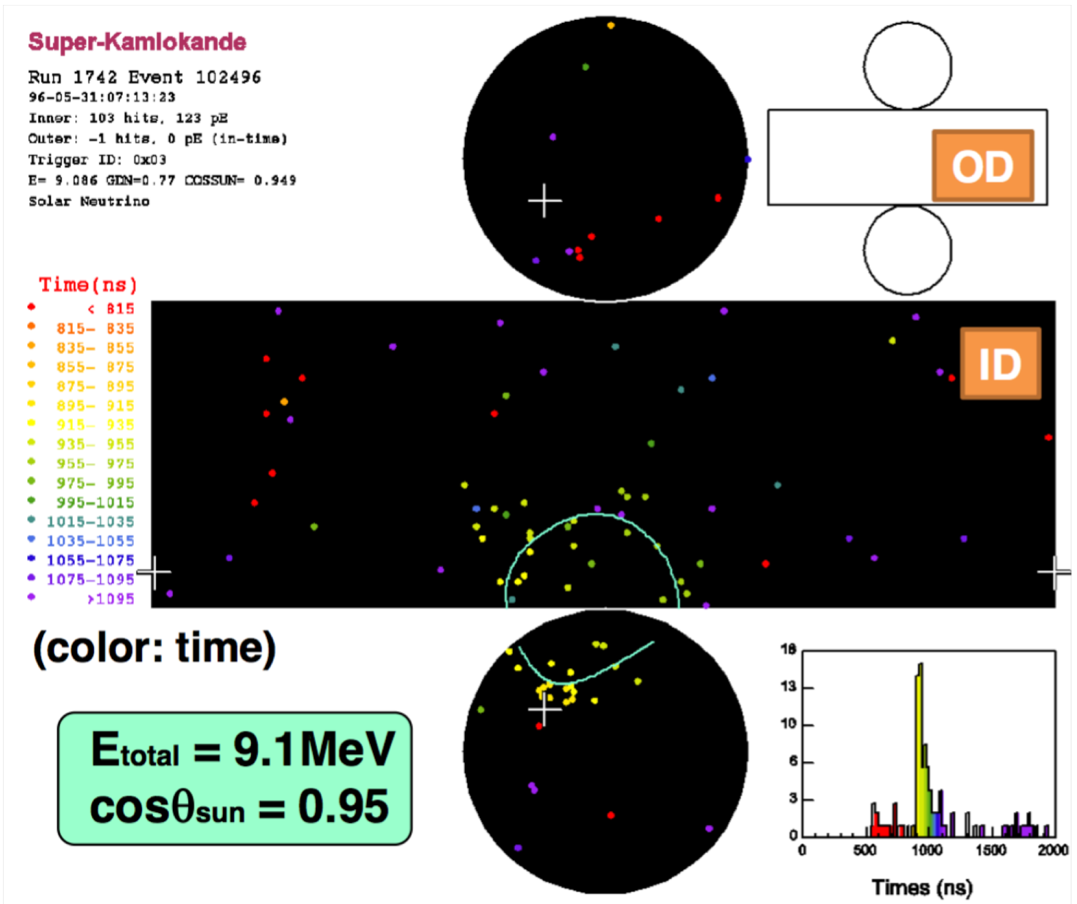
Supernova neutrino	~300,000 events / burst

no energy / directional information

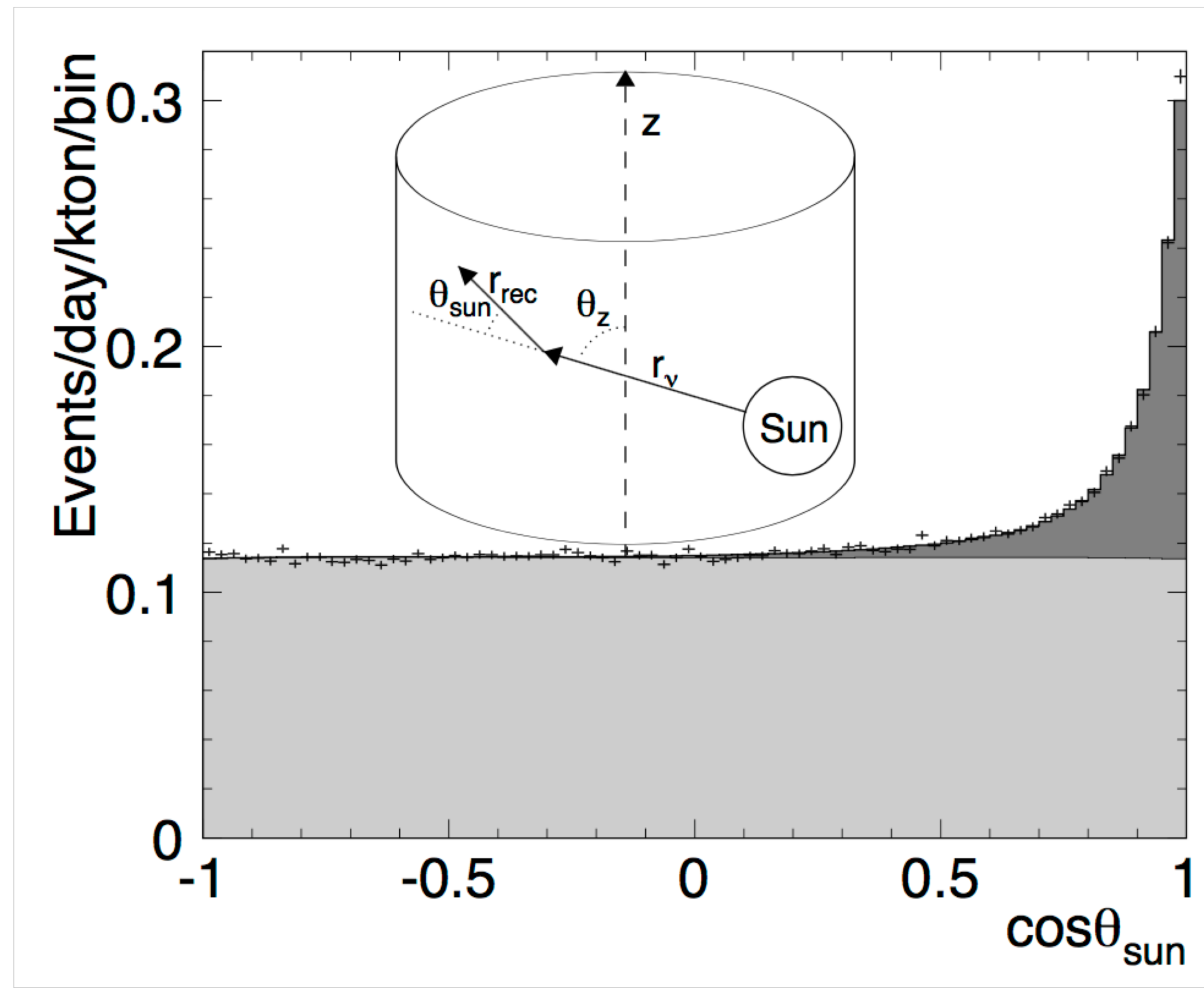
Solar Neutrino

Real time measurement allowing solar neutrino spectroscopy

Cherenkov ring image in Super-K



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



Prospect in future solar neutrino

MSW matter effect of the neutrino oscillations in the Sun

Neutrino regeneration in the Earth (Day-Night effect)

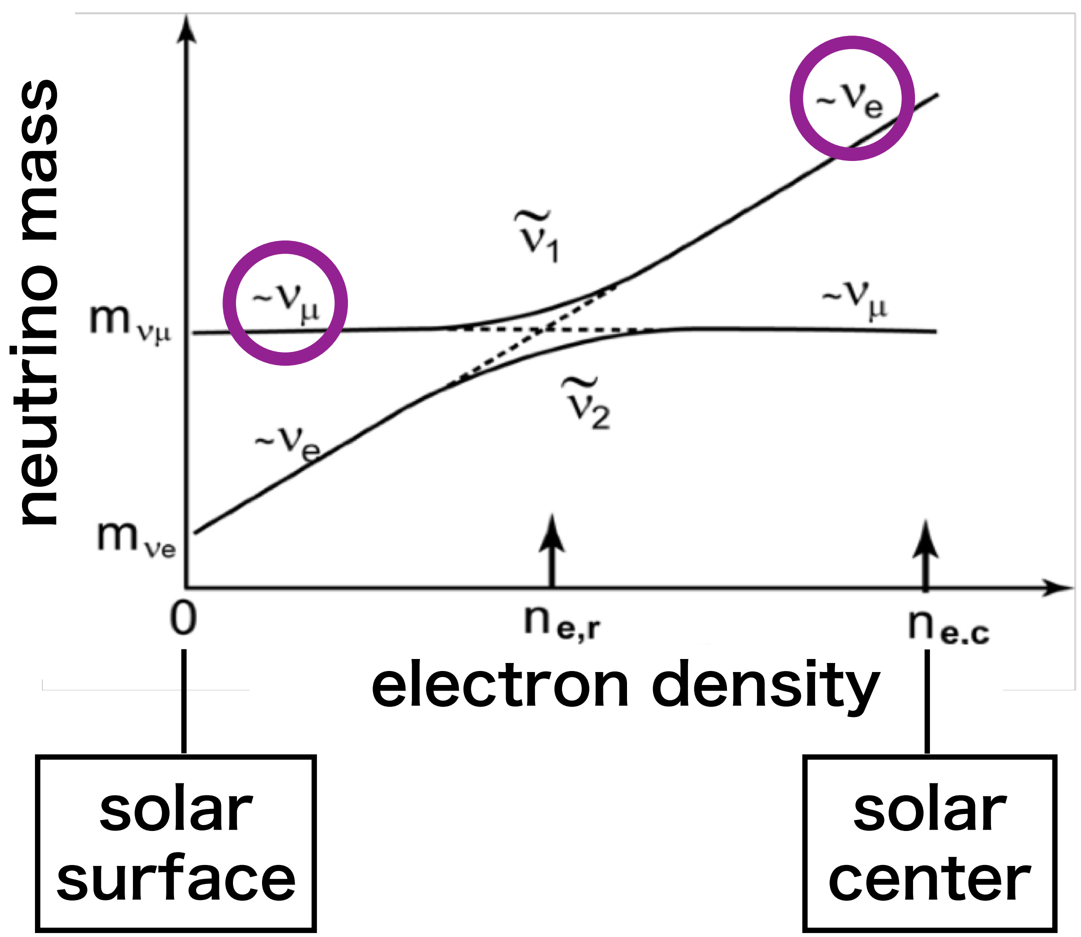
Temporal flux variation / relation with solar activities

Branching ratio of nuclear fusion reactions

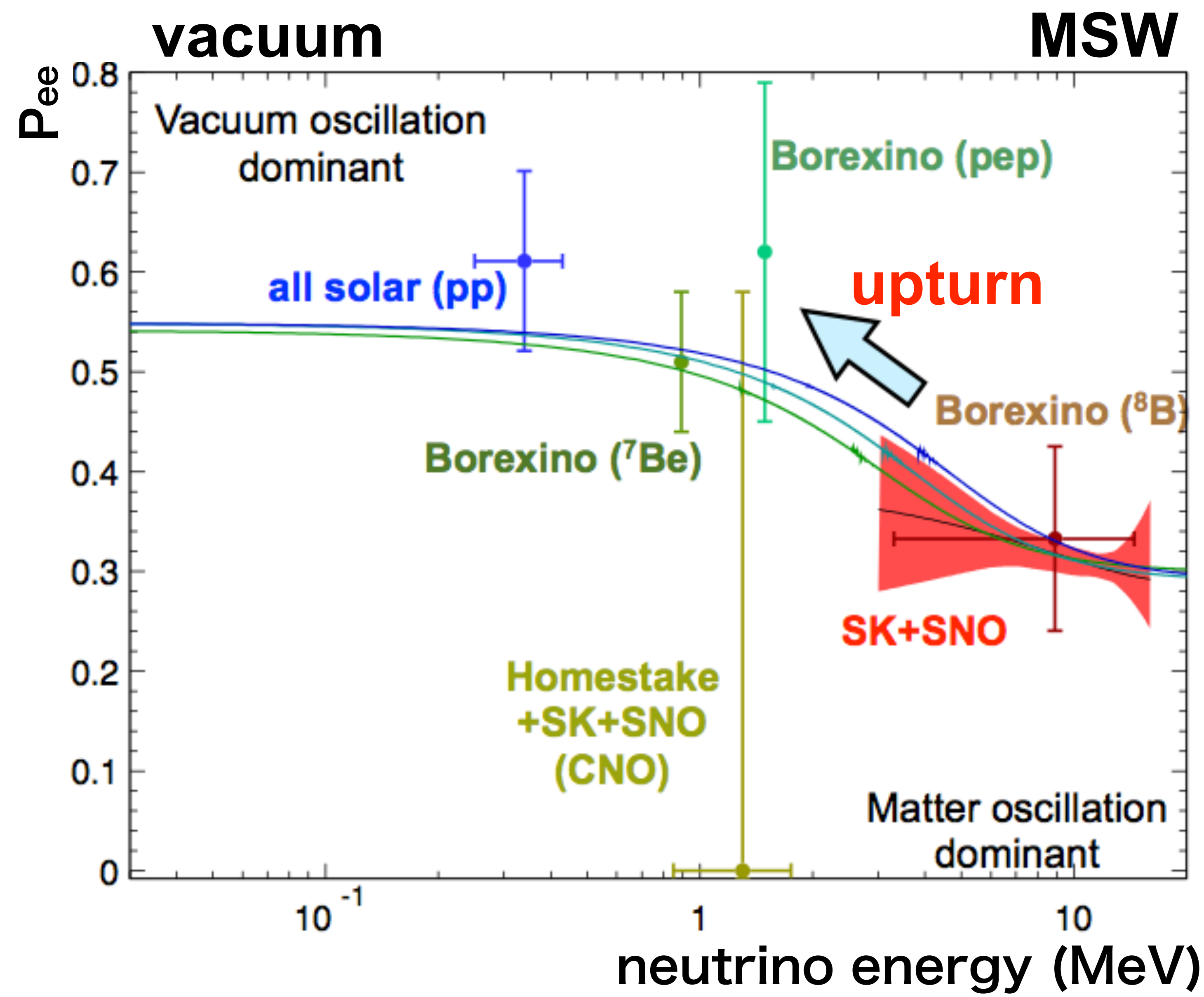
Hyper-K can address the issues

MSW Matter Effect

Required by observed energy dependence of survival probability (P_{ee})



MSW resonance oscillation



<u>Energy dependence of survival probability</u>

$$P_{\mathrm{ee}} = \sin^2\theta_{12} \quad (\beta > 1,\ \mathrm{MSW})$$

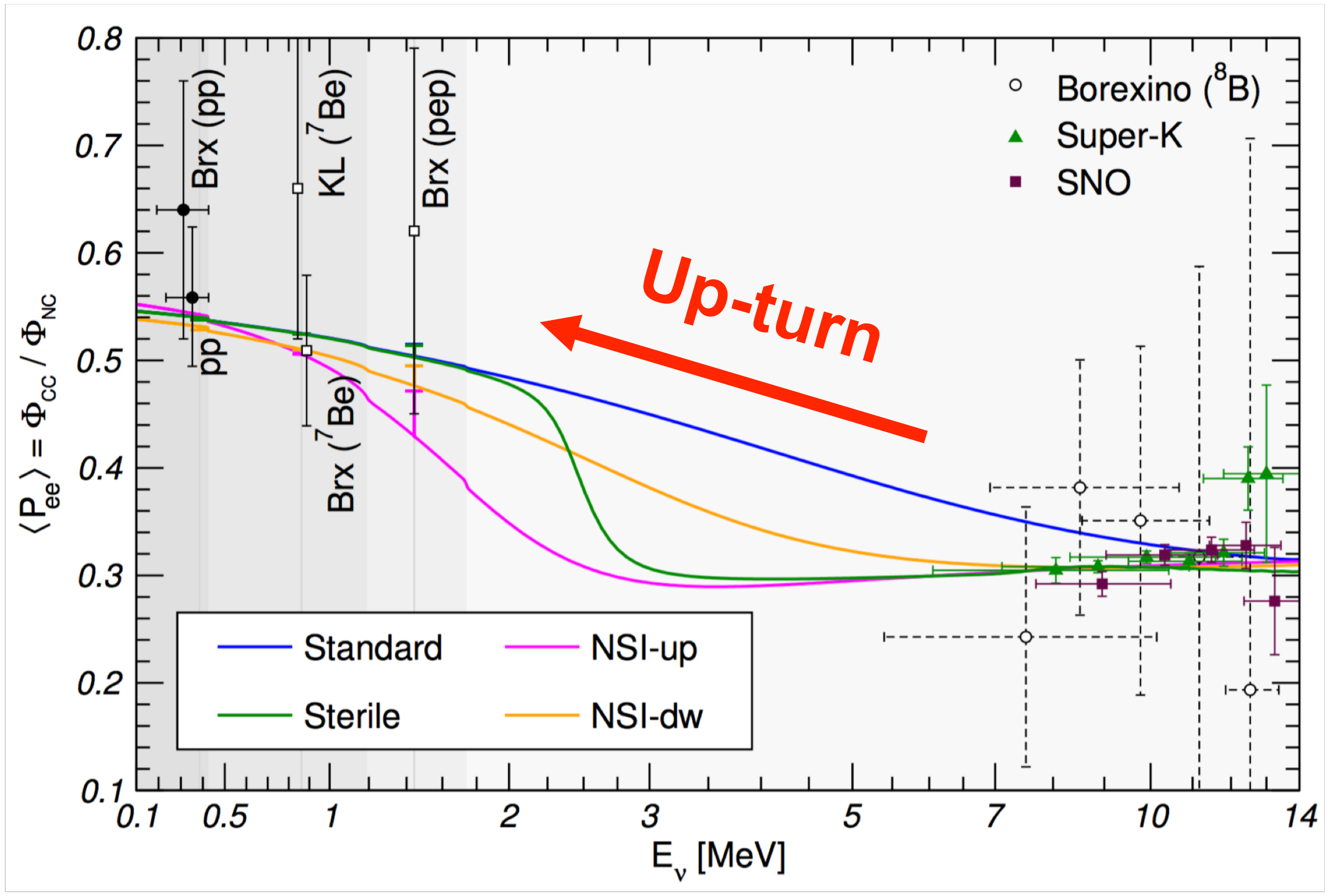
$$\beta = \frac{2\sqrt{2}G_F n_e E_\nu}{\Delta m^2}$$

$$P_{\mathrm{ee}} = 1 - \frac{1}{2}\sin^2 2\theta_{12} \quad (\beta < \cos 2\theta_{12},\ \mathrm{vacuum})$$

Spectrum Up-turn

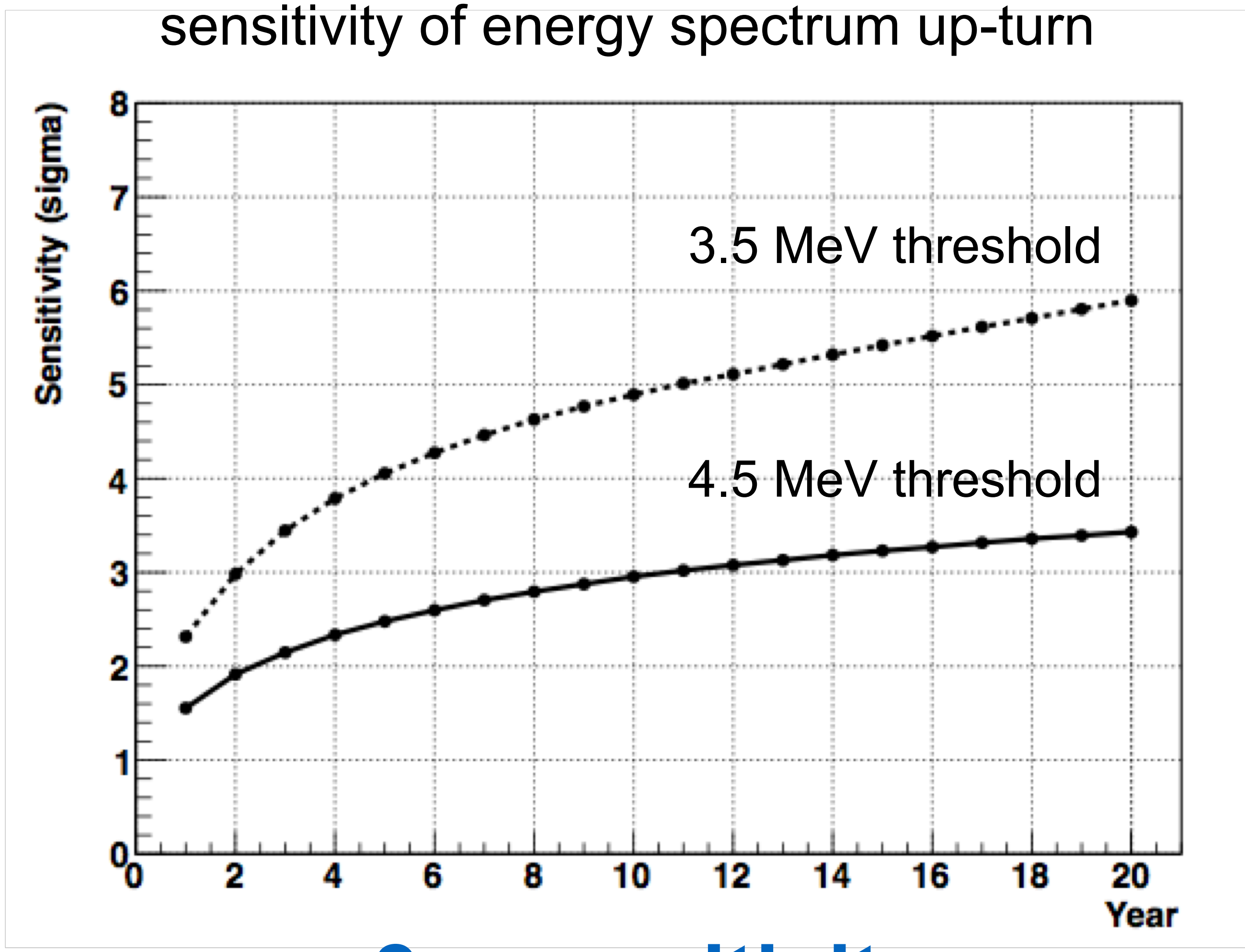
Intermediate energy region between vacuum and MSW oscillation (up-turn) can be measured more precisely in Hyper-K

survival probability of electron solar neutrinos



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

sensitivity of energy spectrum up-turn



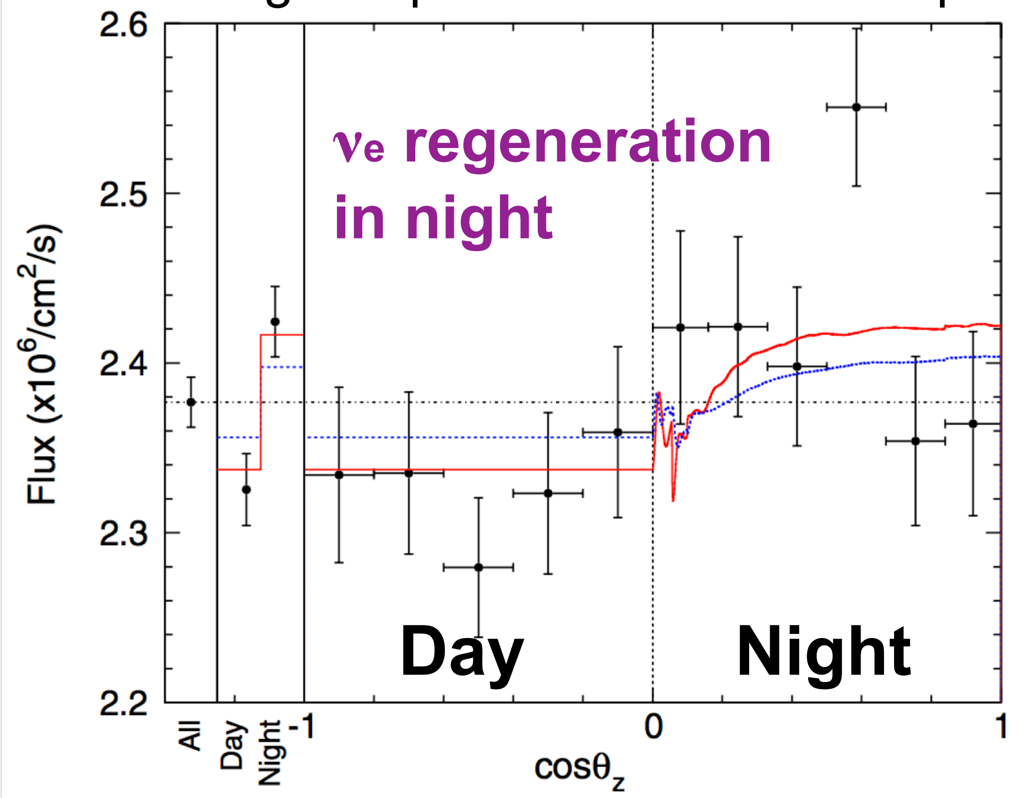
>3σ sensitivity

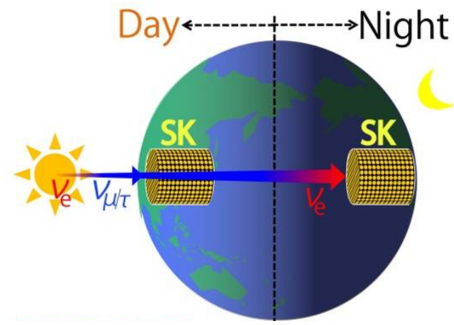
Observation of MSW oscillation with single neutrino source (^{8}B)

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

Day-Night Effect

zenith angle dependence of flux in Super-K



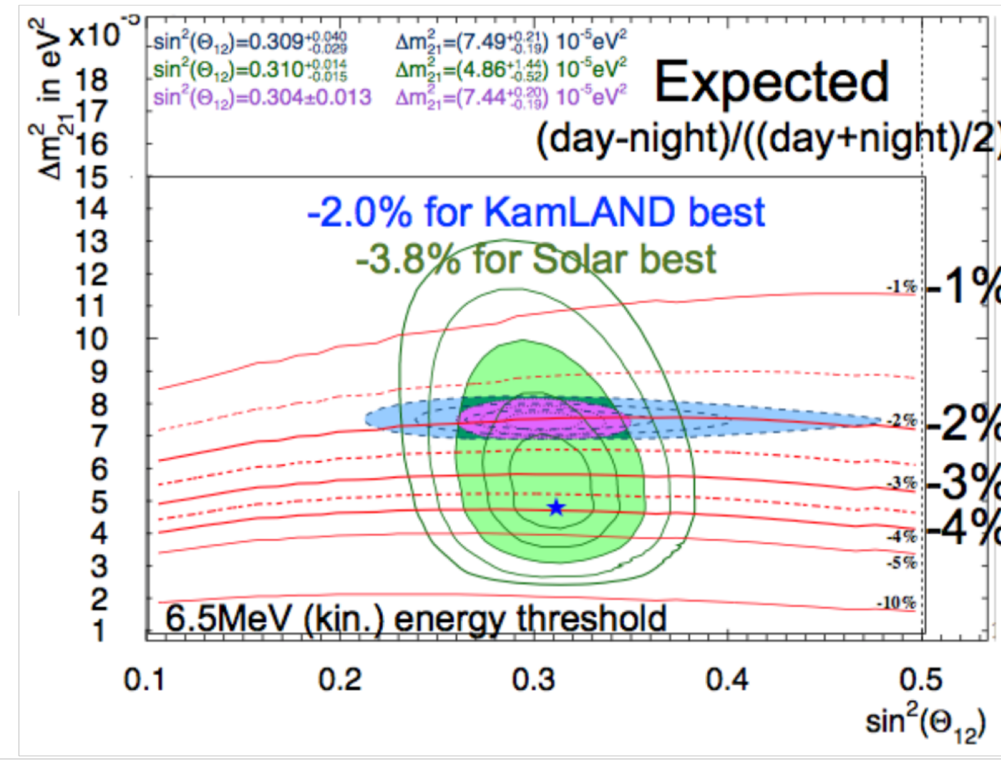


Super-K best

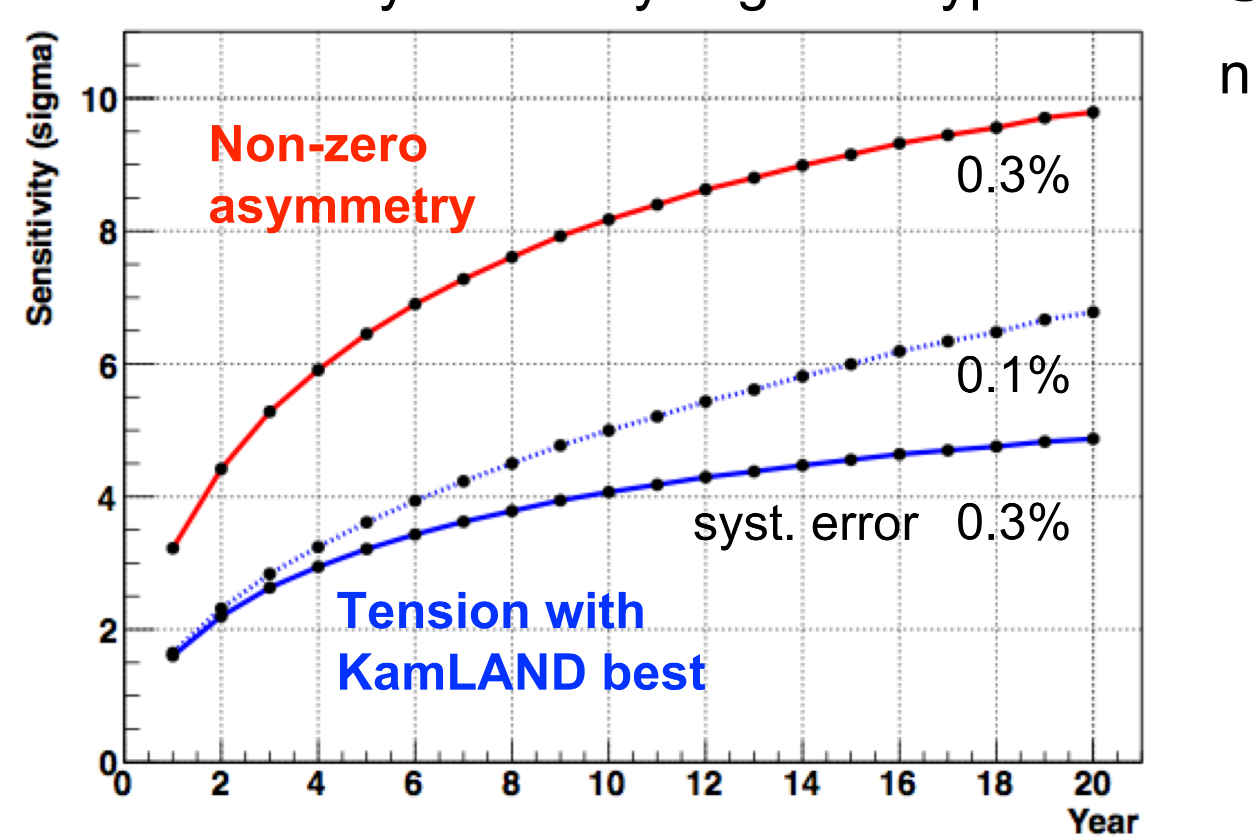
Solar + KamLAND

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

oscillation parameters : Solar and KamLAND



sensitivity from Day-Night in Hyper-K



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

dominant error

mainly from BG shape

non-zero significance : 2.7σ

Hyper-K

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

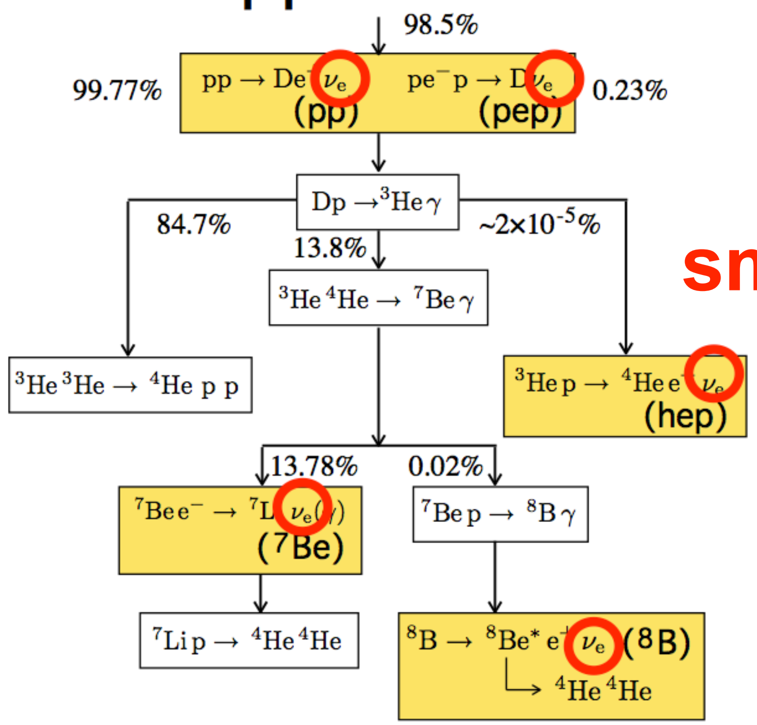
>4σ for non-zero asymmetry

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

Hep Solar Neutrino

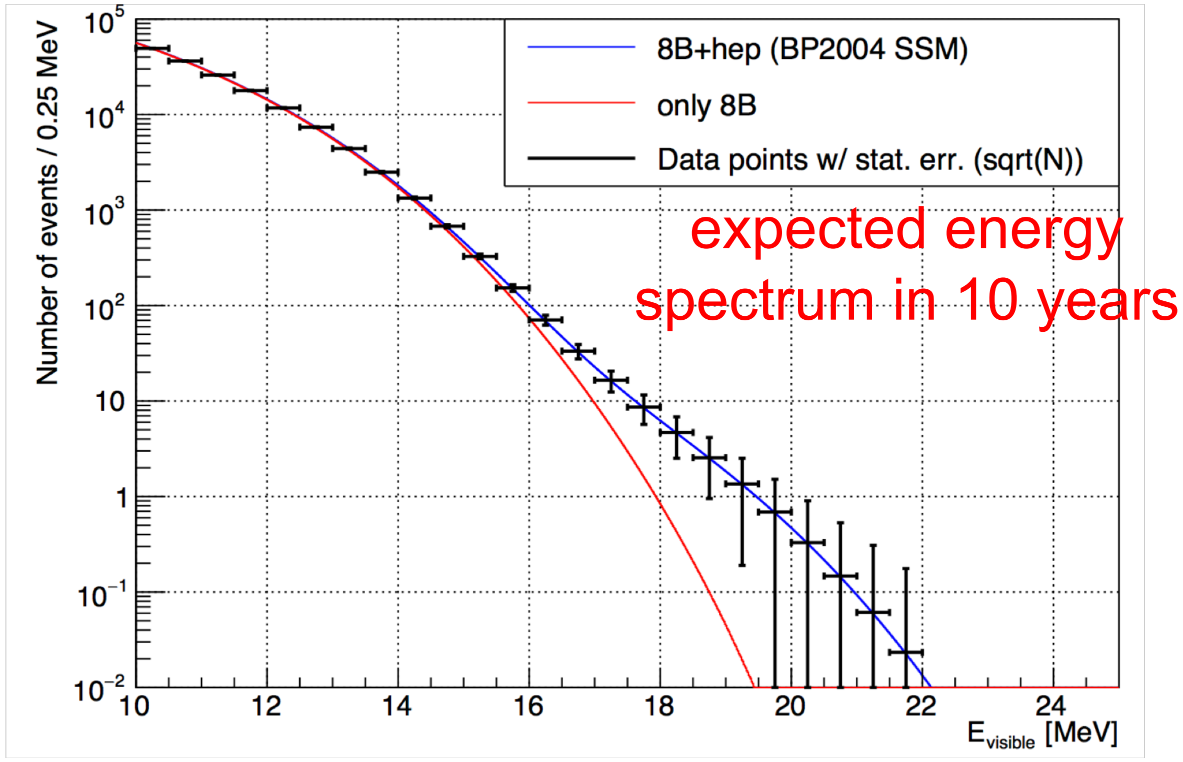
Three orders of magnitudes smaller than ^{8}B solar neutrino flux

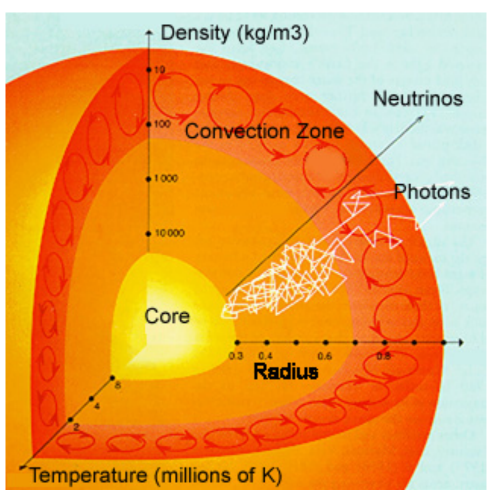
pp chain



small branch

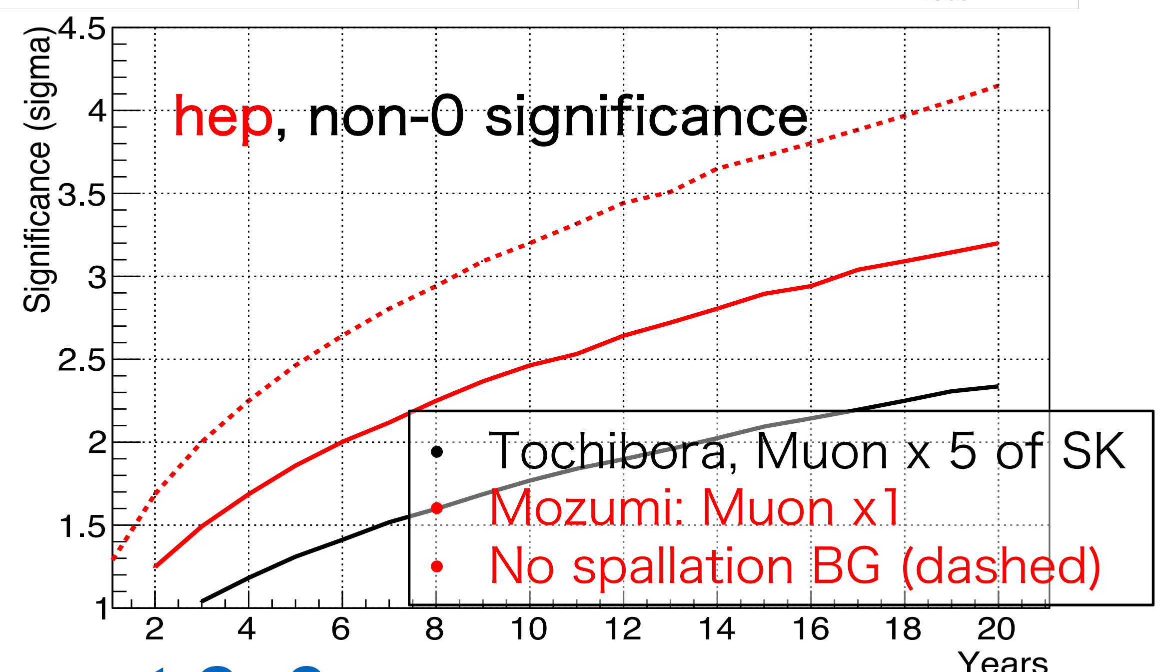
not detected yet





convection may enhance hep ν production at the high temperature core

$$^{3}\mathrm{He}\ p \rightarrow {}^{4}\mathrm{He}\ e^{+}\ \nu_e$$

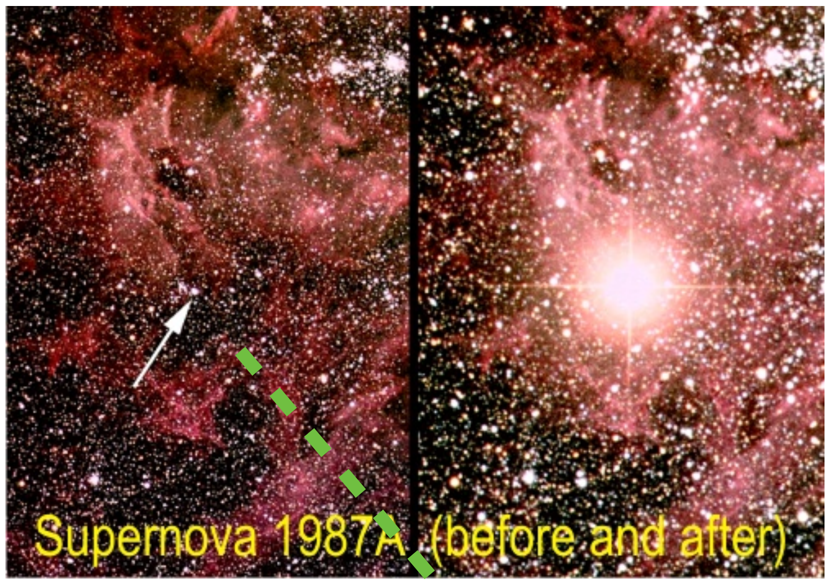


First measurement of hep solar neutrinos at 2~3 σ

Test cross-section of He + p fusion, convection (non-standard SSM)

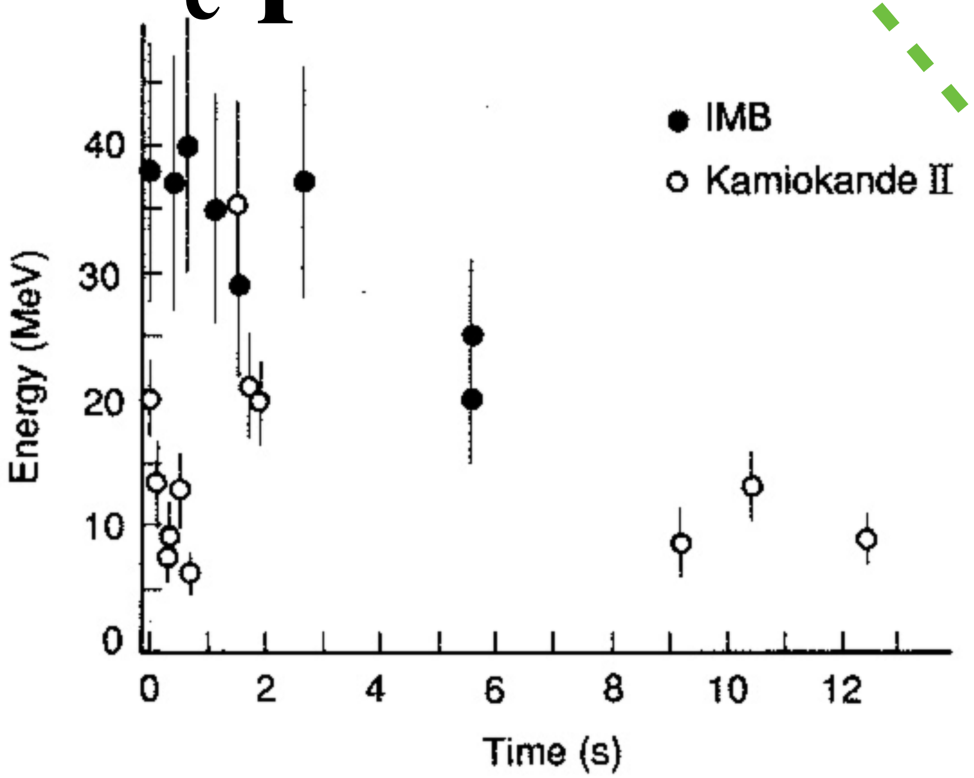
Supernova Neutrino

SN1987A at 50 kpc : first detection of supernova burst neutrino

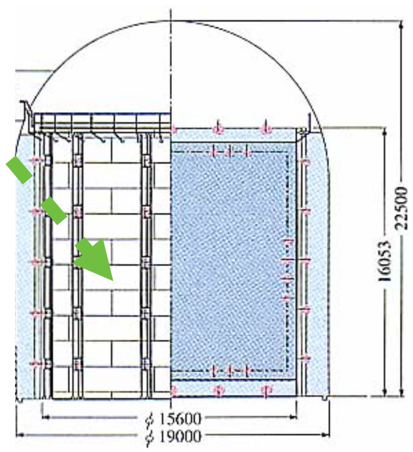


main reaction

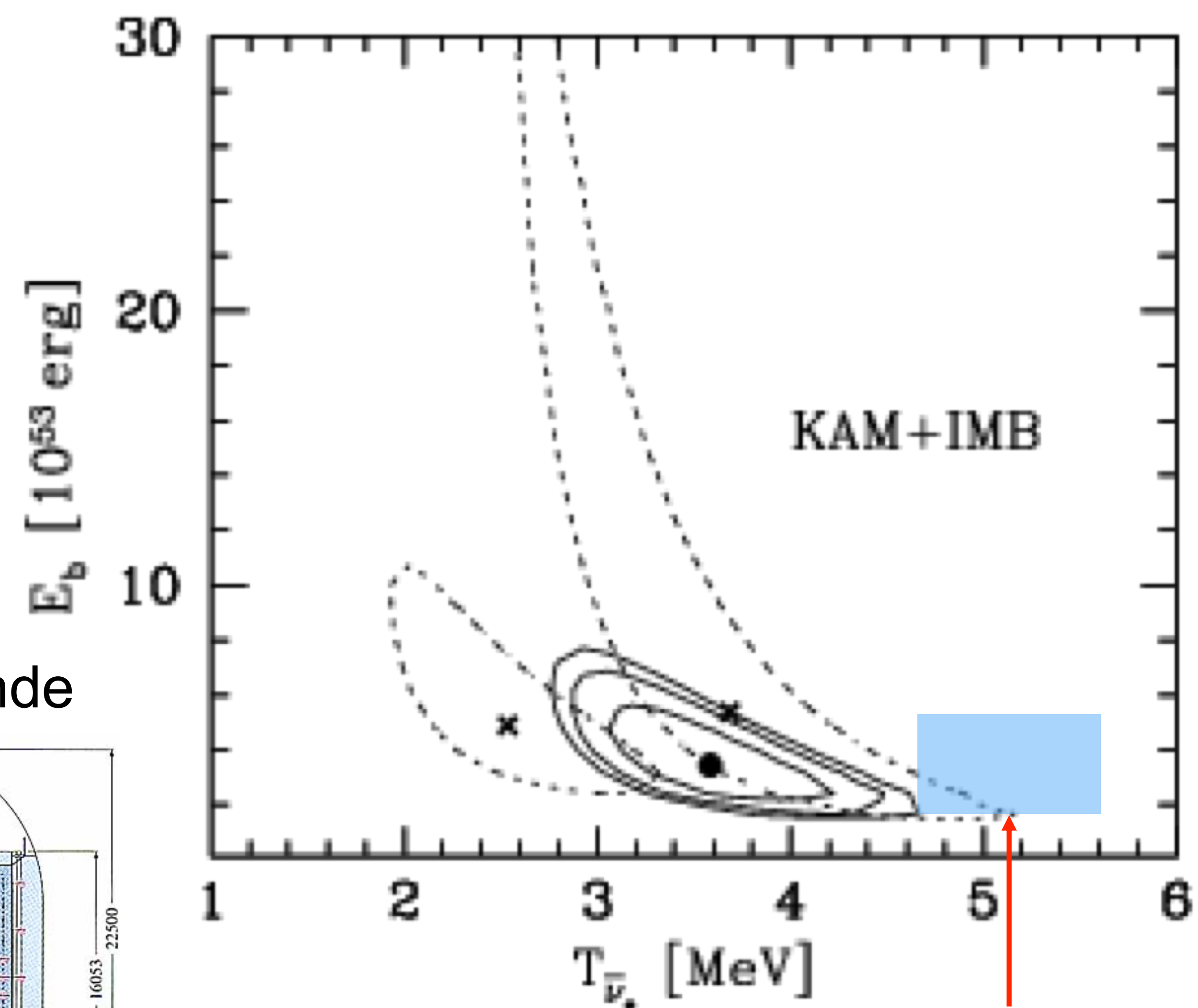
$$\bar{\nu}_e \, p \longrightarrow n \, e^+$$



Kamiokande



binding energy v.s. neutrino temperature



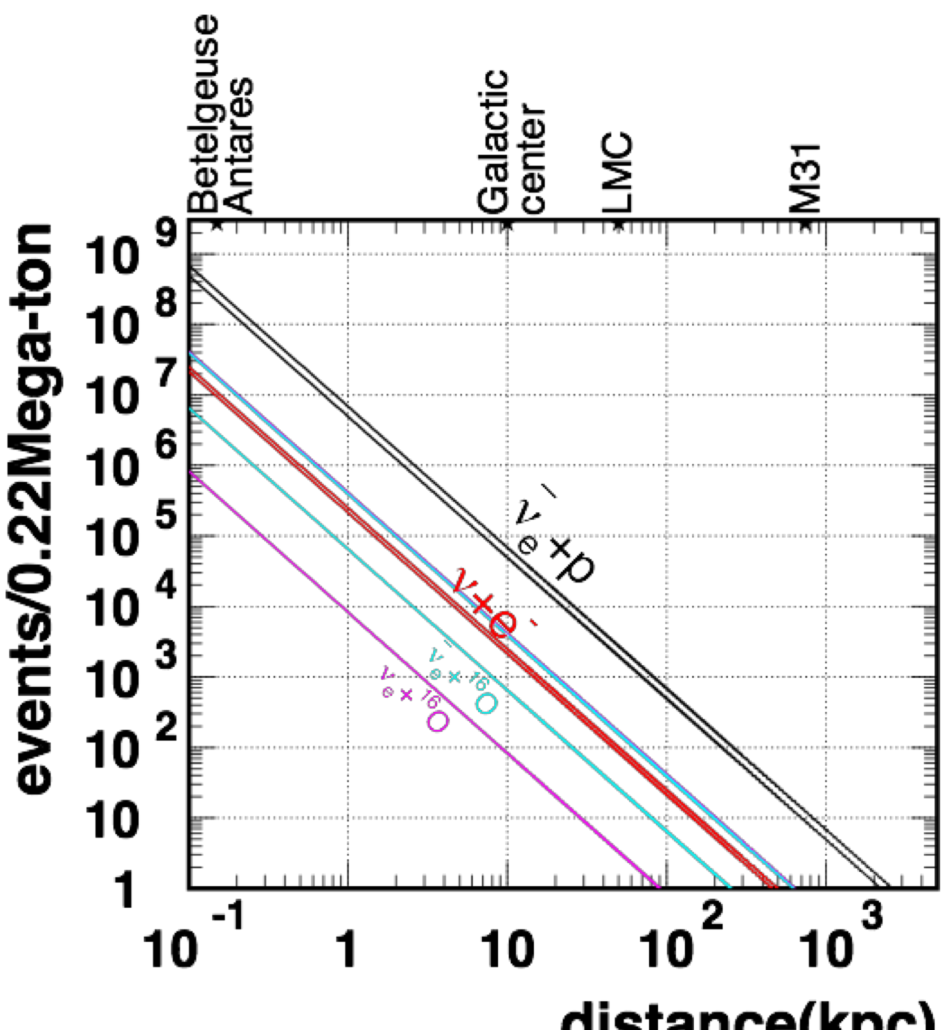
theoretical prediction

Confirmed that neutrinos bring most of the burst energy only in 10 sec

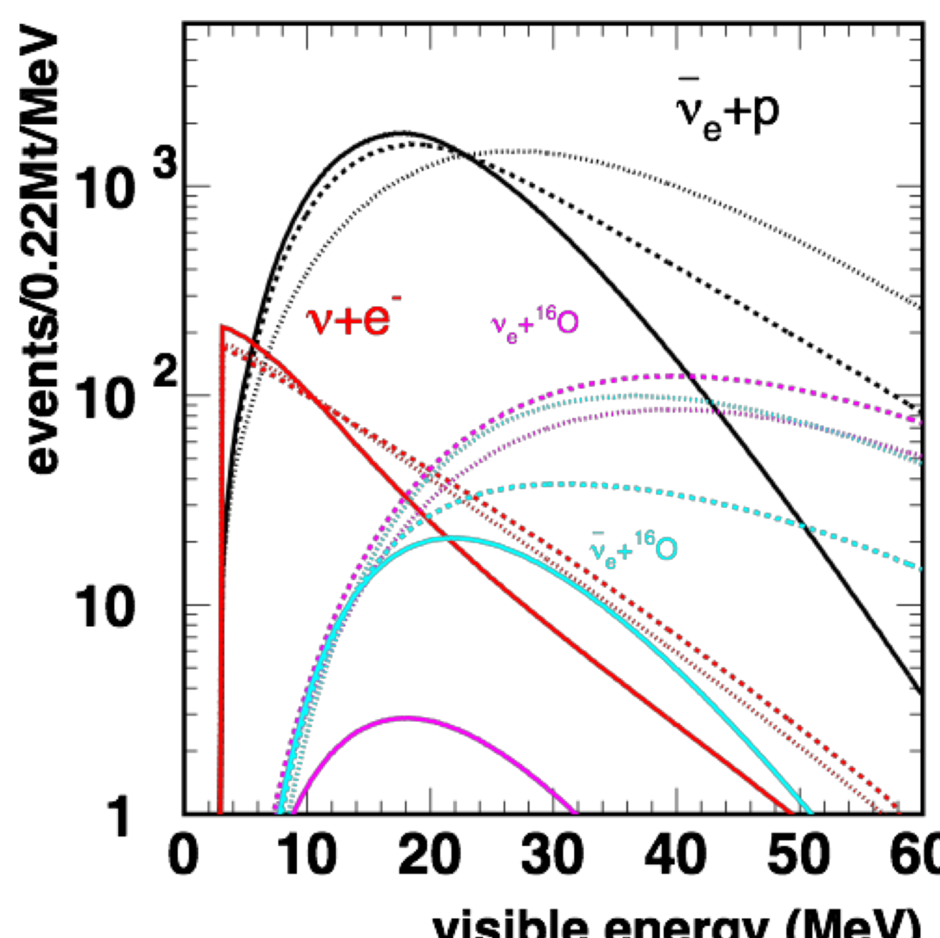
Supernova Neutrino in Hyper-K

Main detection channels

Inverse beta decay	$\bar{\nu}_e + p \rightarrow e^+ + n$	E > 1.8 MeV
ν-e scattering	$\nu + e^- \rightarrow \nu + e^-$	
ν_e ^{16}O CC	$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$	E > 15 MeV
$\bar{\nu}_e$ ^{16}O CC	$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$	E > 11 MeV



Total energy spectrum



galactic supernova at 10 kpc

54,000-90,000 events in total

high statistics

Time Modulation w/ Neutrino Oscillation

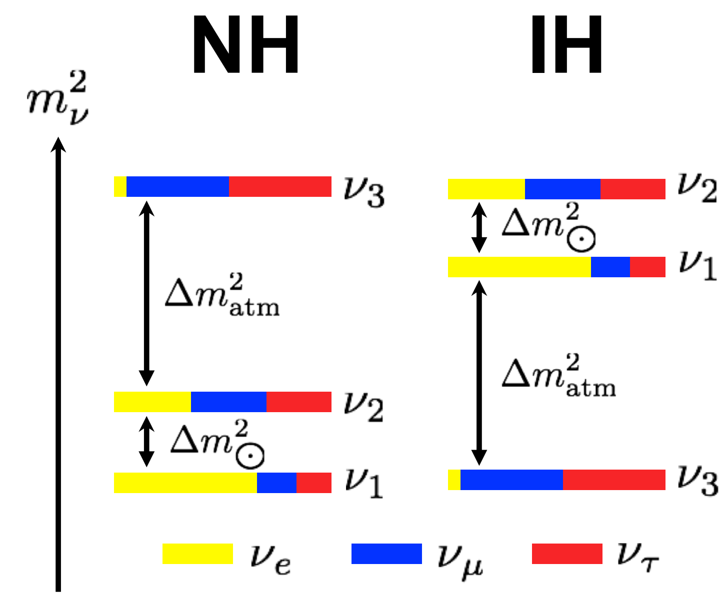
Normal Hierarchy (NH)

$$\frac{\mathrm{d}N_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} = |U_{\mathrm{e}1}|^2 \frac{\mathrm{d}N_{\bar{\nu}_1}}{\mathrm{d}E_{\bar{\nu}_1}} + |U_{\mathrm{e}2}|^2 \frac{\mathrm{d}N_{\bar{\nu}_2}}{\mathrm{d}E_{\bar{\nu}_2}} + |U_{\mathrm{e}3}|^2 \frac{\mathrm{d}N_{\bar{\nu}_3}}{\mathrm{d}E_{\bar{\nu}_3}}$$

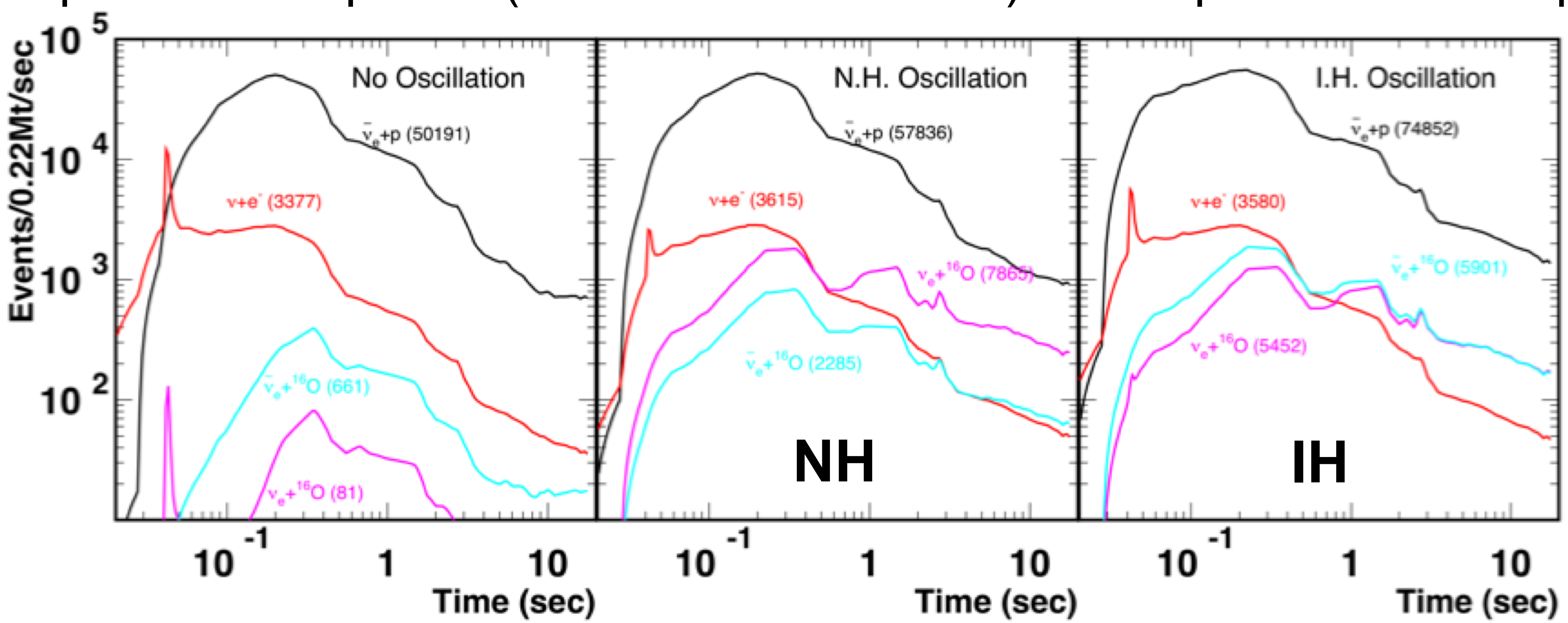
$$= |U_{\mathrm{e}1}|^2 \frac{\mathrm{d}N^0_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} + \left(1 - |U_{\mathrm{e}1}|^2\right) \frac{dN^0_{\nu_\mathrm{x}}}{dE_{\nu_\mathrm{x}}},$$

Inverted Hierarchy (IH)

$$\frac{\mathrm{d}N_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} = |U_{\mathrm{e}3}|^2 \frac{\mathrm{d}N^0_{\bar{\nu}_\mathrm{e}}}{\mathrm{d}E_{\bar{\nu}_\mathrm{e}}} + \left(1 - |U_{\mathrm{e}3}|^2\right) \frac{\mathrm{d}N^0_{\nu_\mathrm{x}}}{\mathrm{d}E_{\nu_\mathrm{x}}} \simeq \frac{\mathrm{d}N^0_{\nu_\mathrm{x}}}{\mathrm{d}E_{\nu_\mathrm{x}}}$$



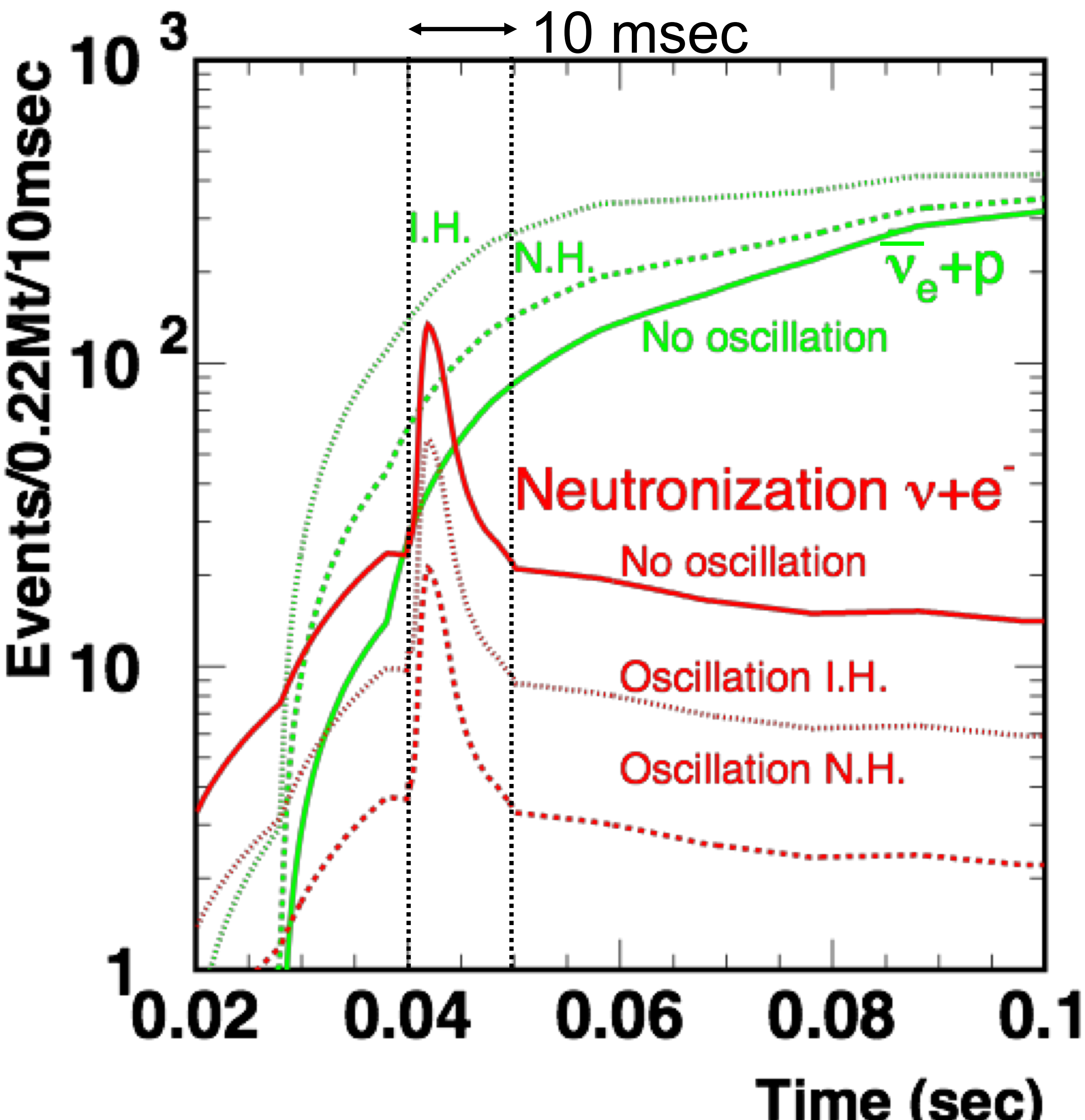
Expected time profile (Livermore simulation) of a supernova at 10 kpc



Neutralization Burst

Unique feature in ν-e scattering from neutralization burst

supernova at 10 kpc (Livermore simulation)



neutralization burst

ν_e emission for ~10 msec

shock wave propagation outward

↓

dissociation of nuclei in free nucleon which triggers $e^- p \rightarrow \nu_e n$

↓

shock wave pass through neutrinosphere

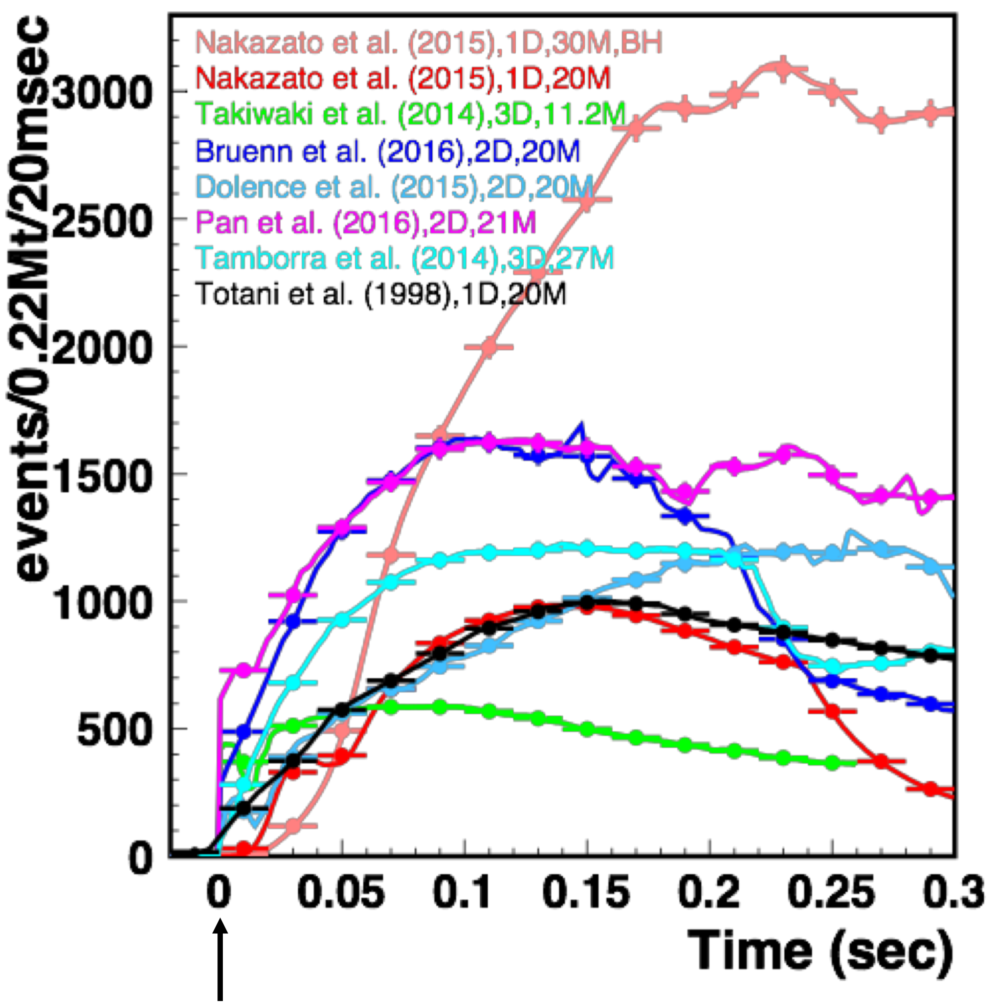
Hyper-K will observe the neutralization burst

Explosion Mechanism

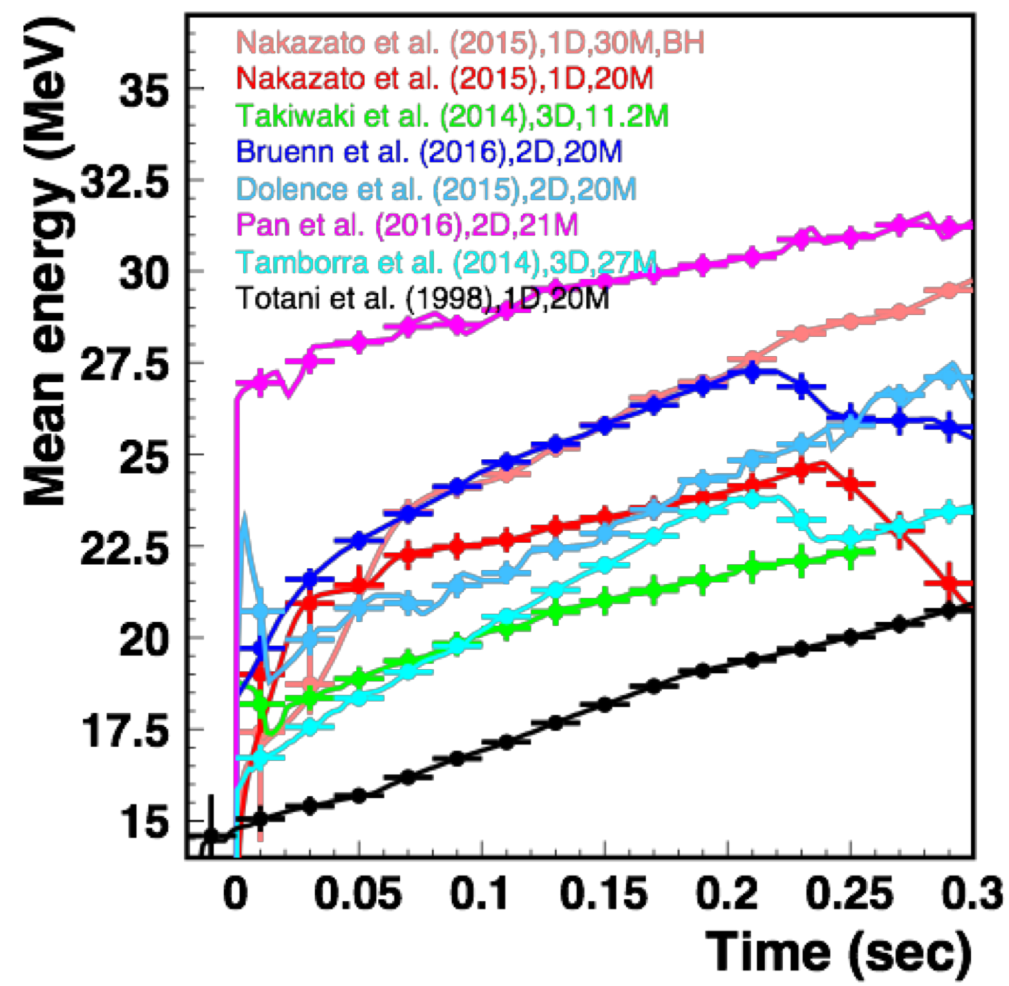
First 0.3 sec after the onset of supernova burst

inverse beta decay for supernova at 10 kpc

Time modulation of event rate



Time modulation of mean energy



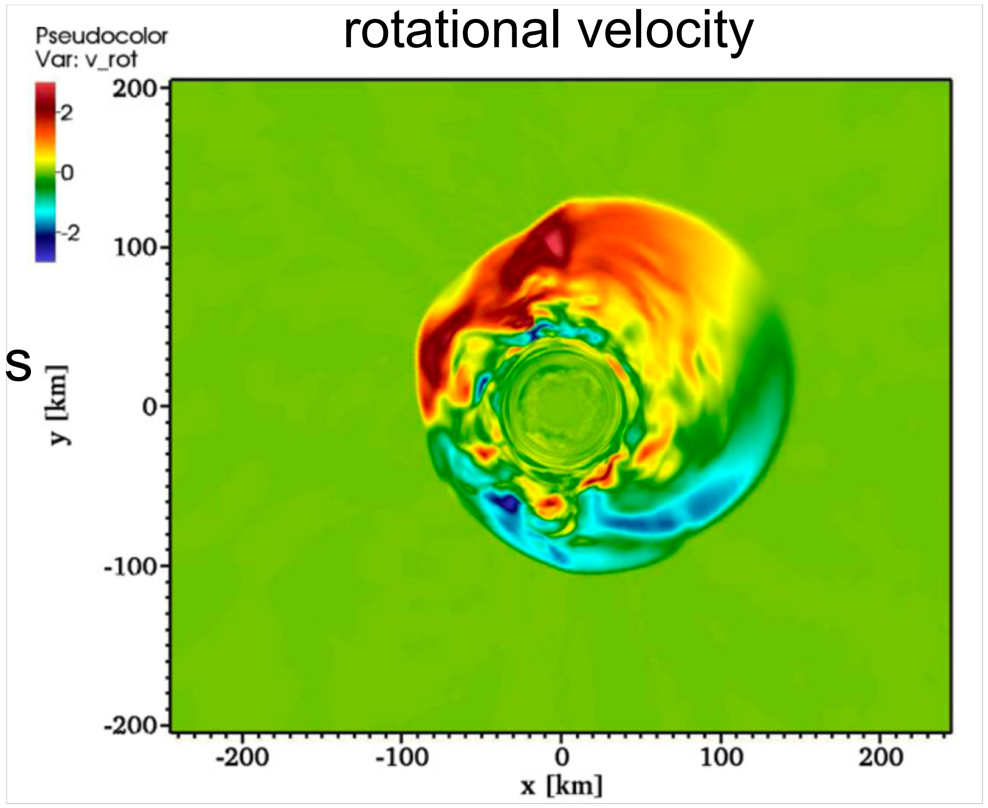
onset time ~ 1 msec accuracy

Hyper-K will test the explosion mechanism, and investigate the core infall in conjunction with gravitational wave data

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 O(10)-O(100) ms



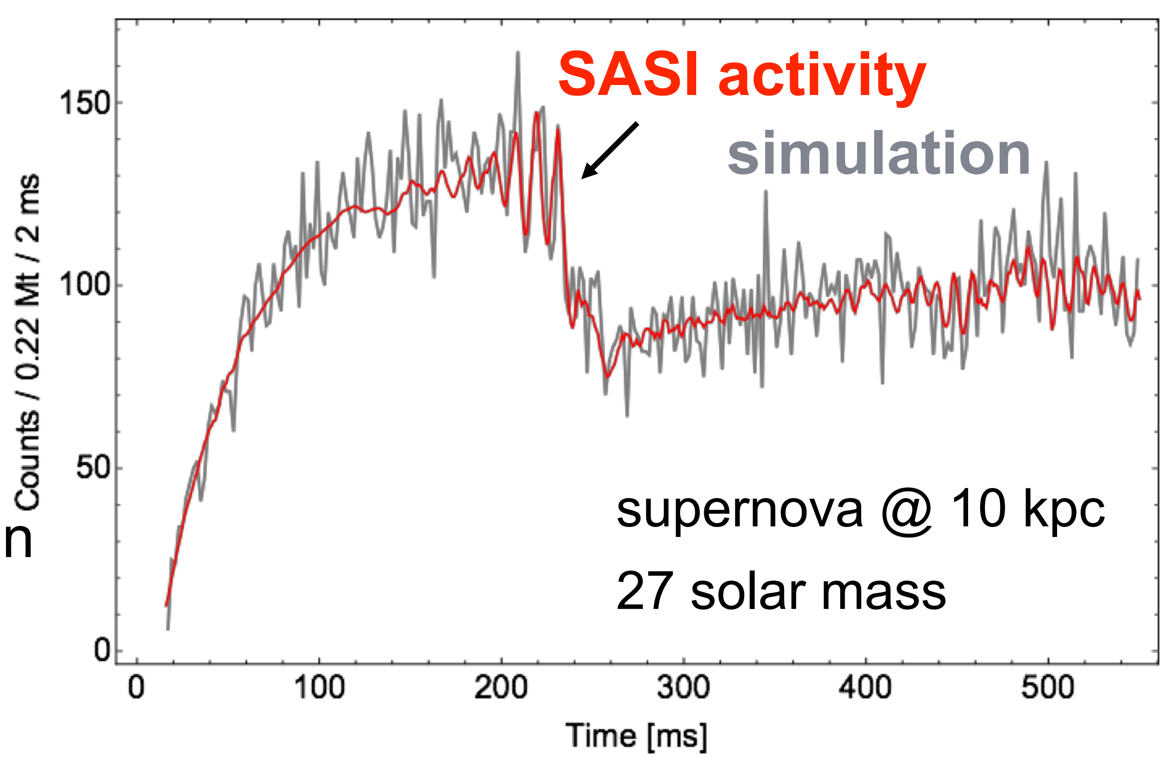
F. Hanke et al., Astrophy. J 770, 66 (2013)

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

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

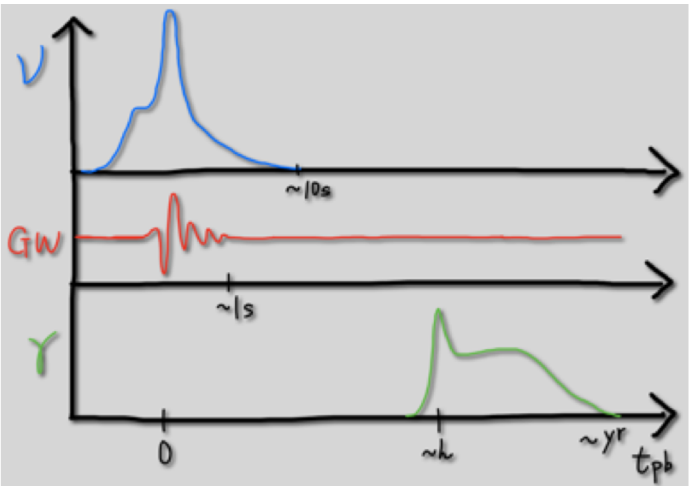
Hyper-K will test the supernova neutrino flux modulation



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

Multi-Messenger Signals

complementary observation with 3 signals!



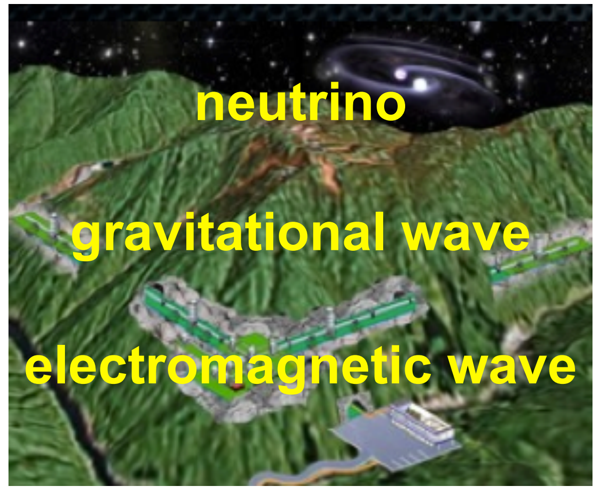


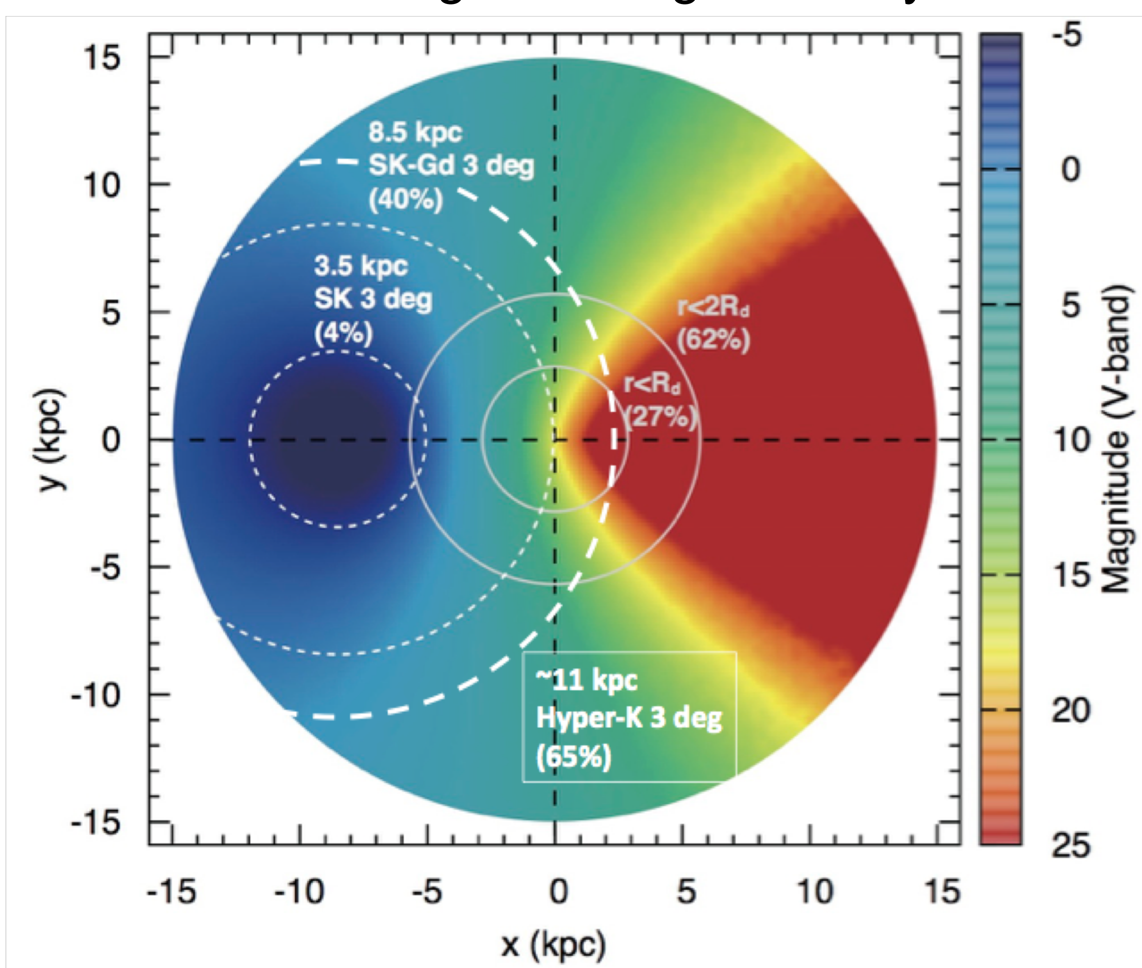
Fig. by Y. Suwa

For the SN explosion, electromagnetic signal will delay in minutes to hours.

To obtain the electromagnetic signal follow-up, neutrino experiments need to predict the supernova direction as soon as possible

global collaboration by SNEWS network

cover-range in 3 deg accuracy

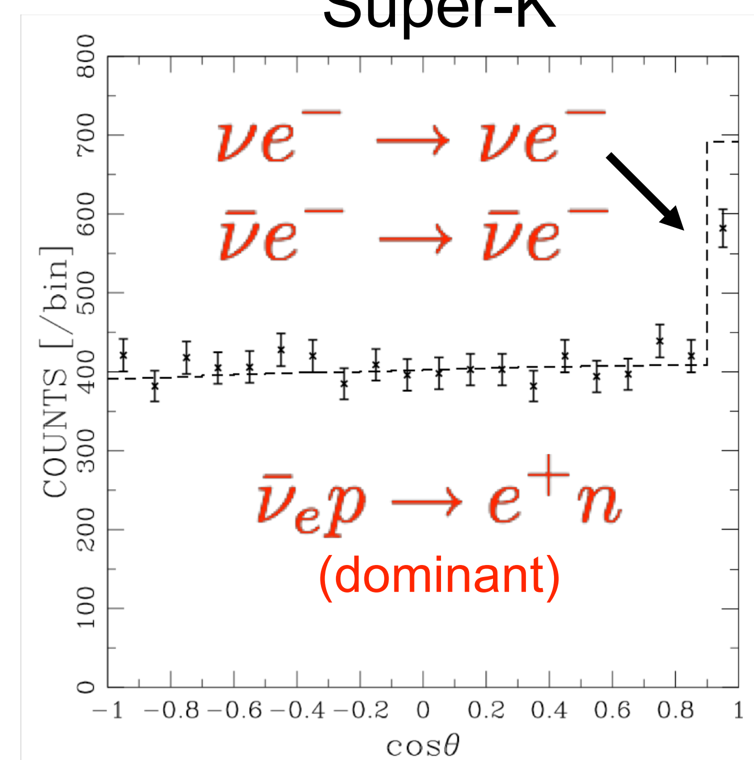


Only large water Cherenkov detector can measure the supernova direction

supernova @ 10 kpc

SK	$\Delta\theta_{SN} \sim 6°$
SK-Gd	$\Delta\theta_{SN} \sim 3°$
Hyper-K	$\Delta\theta_{SN} \sim 2°$

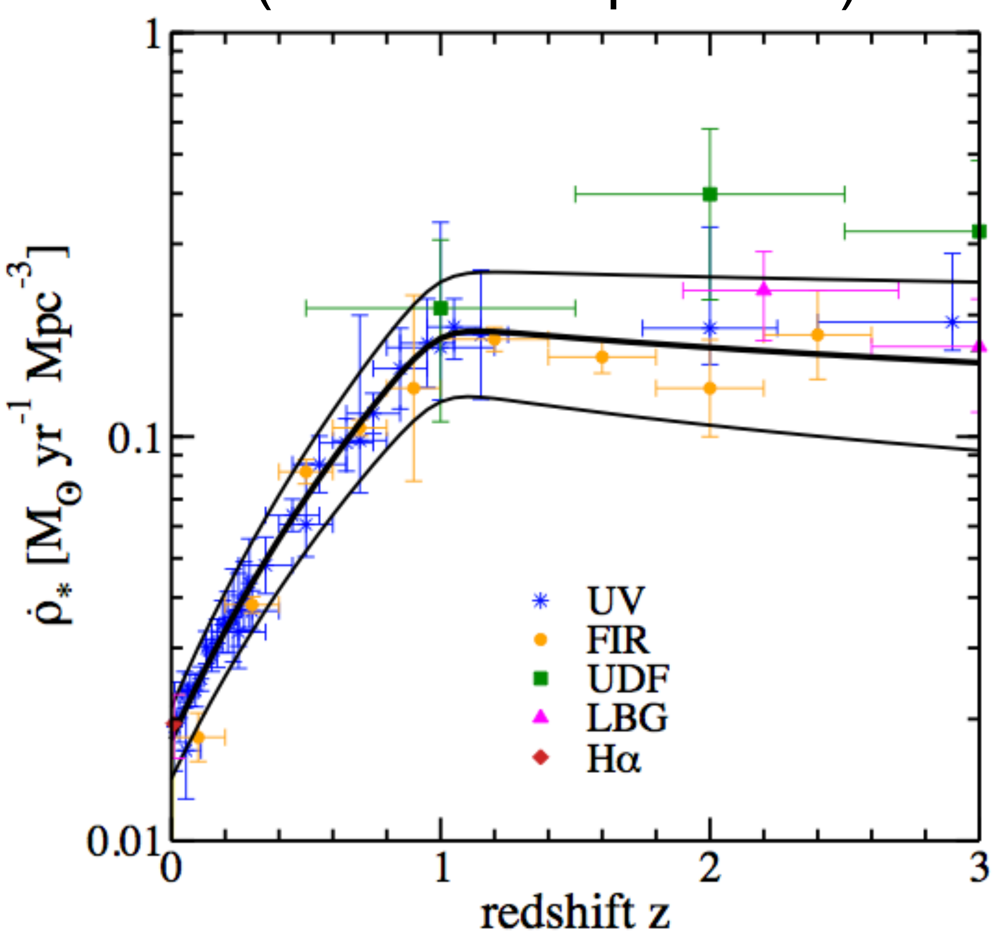
Super-K

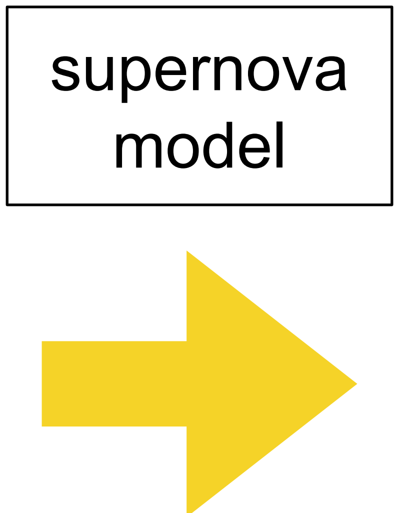


Pointing in 1.5 deg accuracy will allow the follow-up with large telescopes (> 1m)

Supernova Relic Neutrino

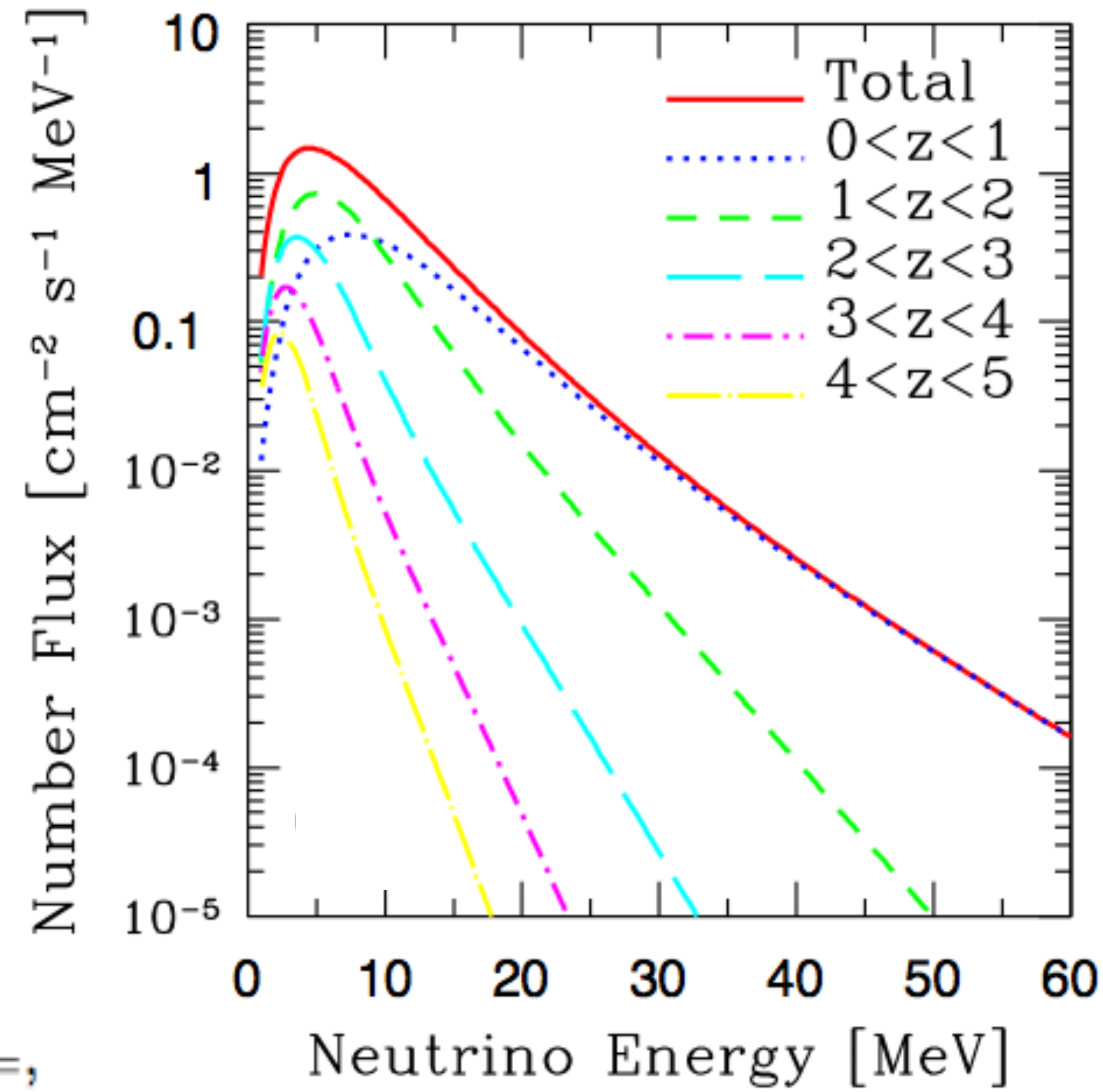
star formation rate
(= core-collapse rate)





integrate over past supernova neutrinos

SRN energy spectrum
(including red shift)



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

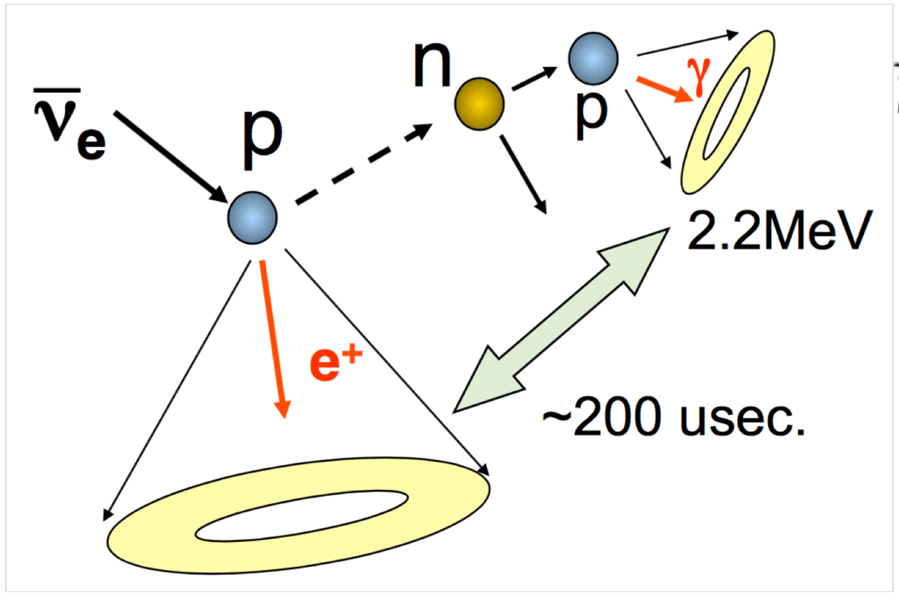
$$\frac{dF_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}\frac{dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}},$$

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**

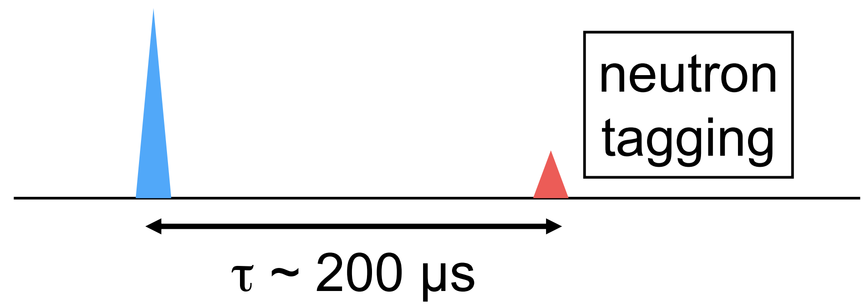
Hyper-K will measure the average flux and energy in supernovae

Signal Detection

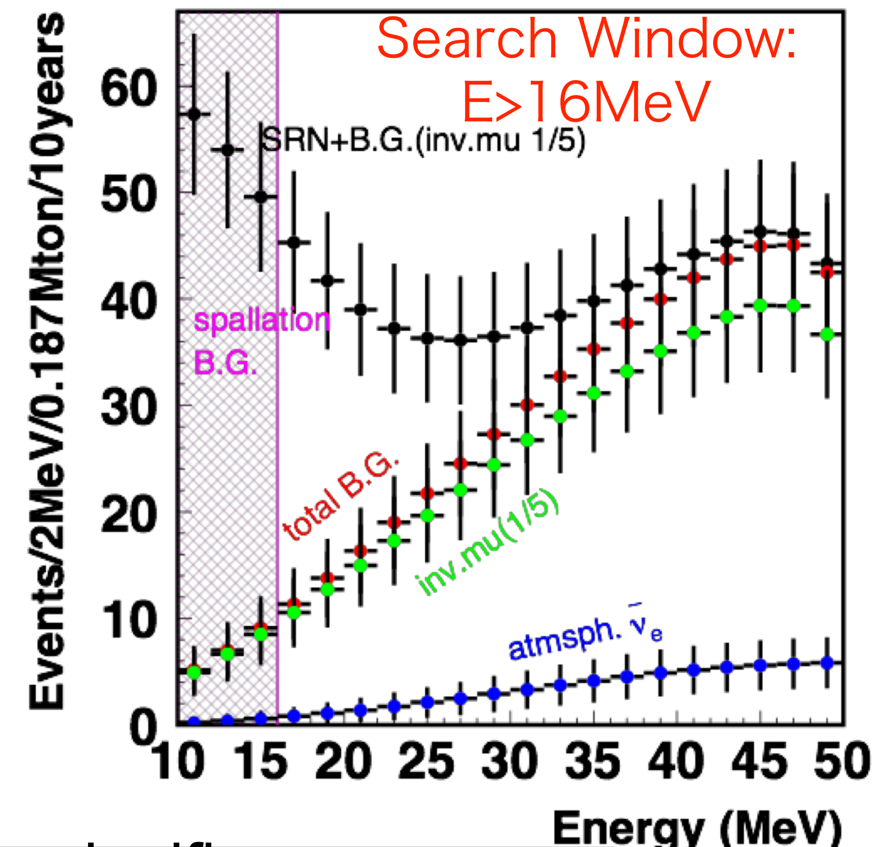


$$\overline{\nu}_e + p \rightarrow e^+ + n$$

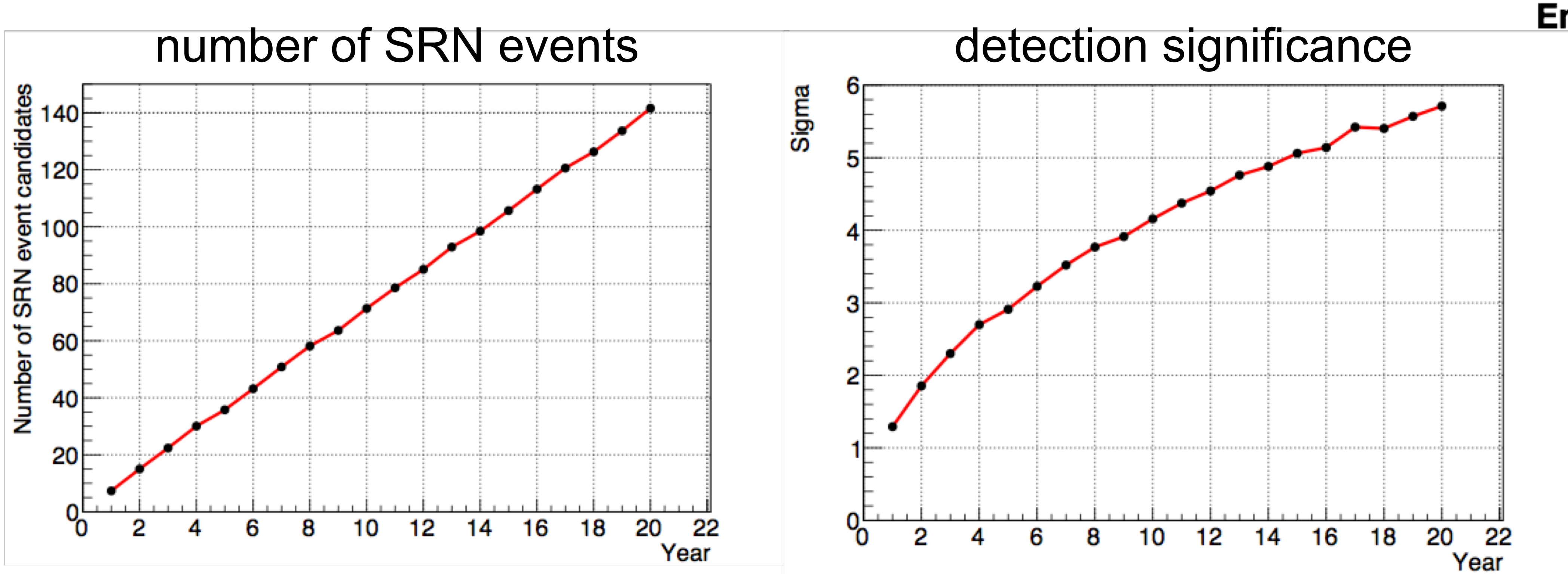
$$n + p \rightarrow d + \gamma$$



expected energy spectrum in Hyper-K (10 year)



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



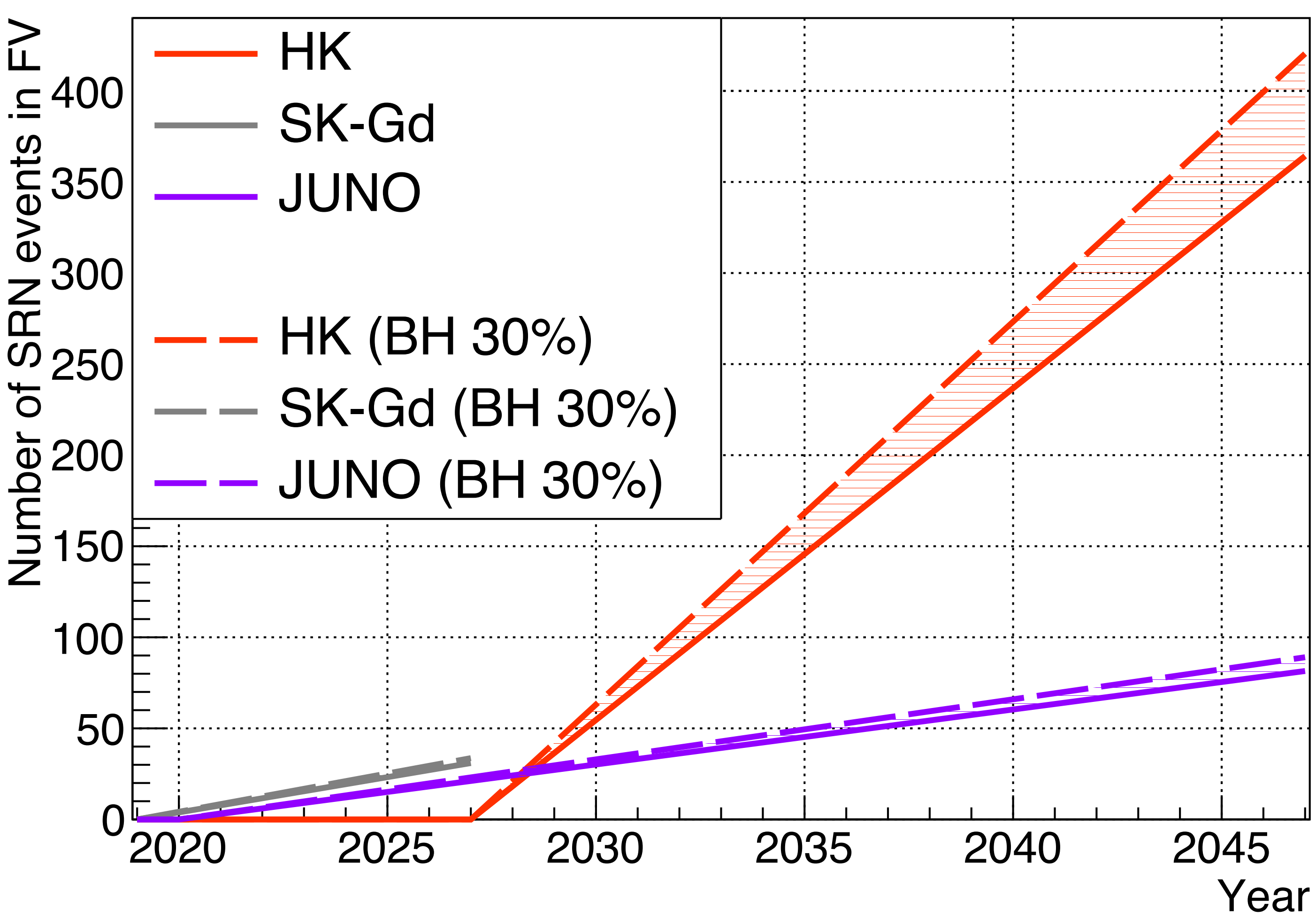
~70 events / 4σ detection significance in 10 years

Prospect

Relation with competing experiments to search for supernova relic neutrinos in the world

future projects : SK-Gd, JUNO, Hyper-K

number of SRN events in future projects



<u>Conditions</u>

SK-Gd (22.5 kton H_2O)

Low energy threshold : 10 MeV
neutron tagging by Gd-loading

Start data-taking in 2018

Aim for the first discovery

JUNO (17 kton LS)

Low energy threshold : 11 MeV

Start data-taking in 2020

Hyper-K (187 kton H_2O)

Energy threshold : 16 MeV

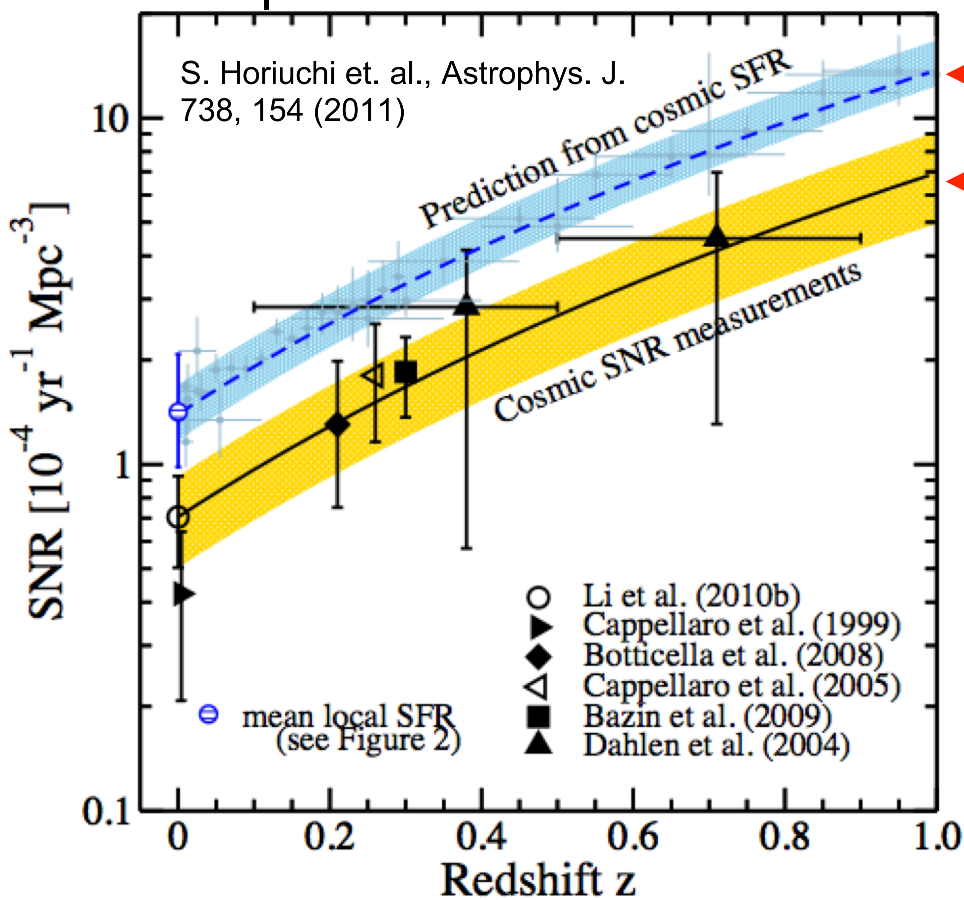
Start data-taking in 2027

Aim for the precise flux and energy spectrum measurement

Hyper-K will be a leading experiment for supernova relic neutrinos

Star Formation History

supernova rate v.s. redshift



core-collapse rate predicted from star formation rate

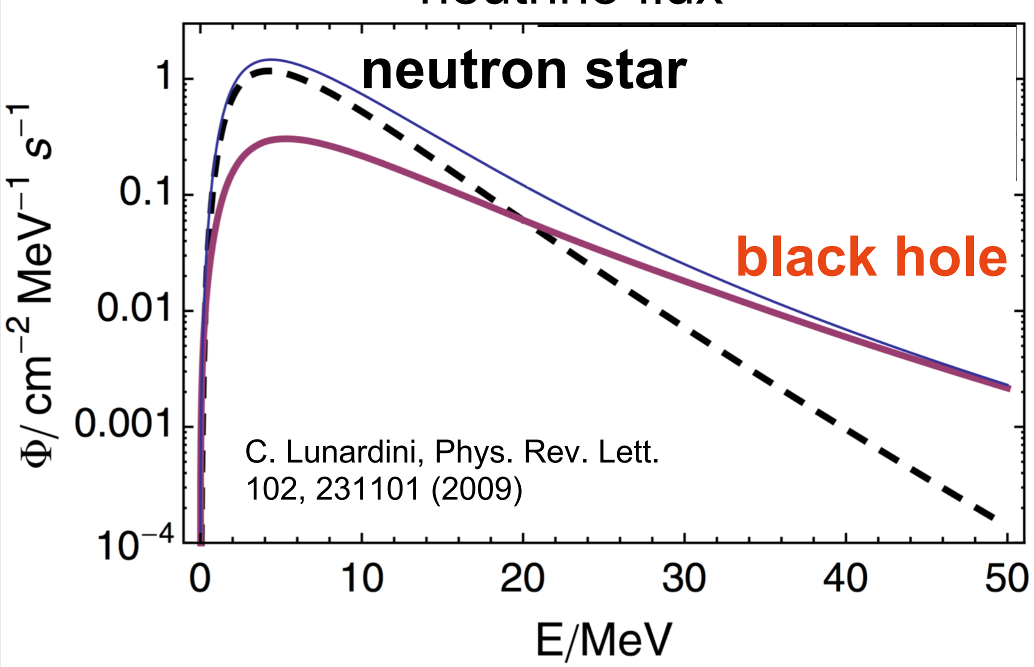
observed supernova rate visible supernovae

factor ~2 smaller than the expectation from star formation rate

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

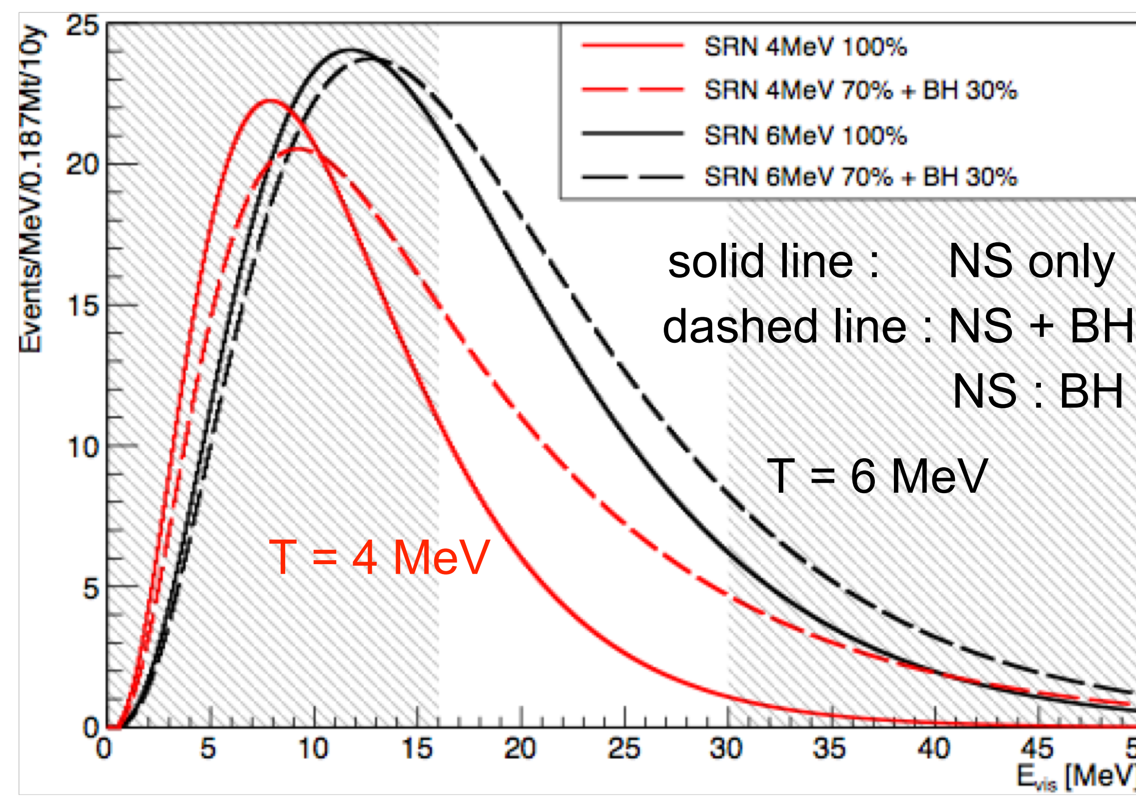
supernova explosions in massive stars (~30 solar mass) result in **black hole formation, high E neutrino production**

neutrino flux



harder in black hole formation

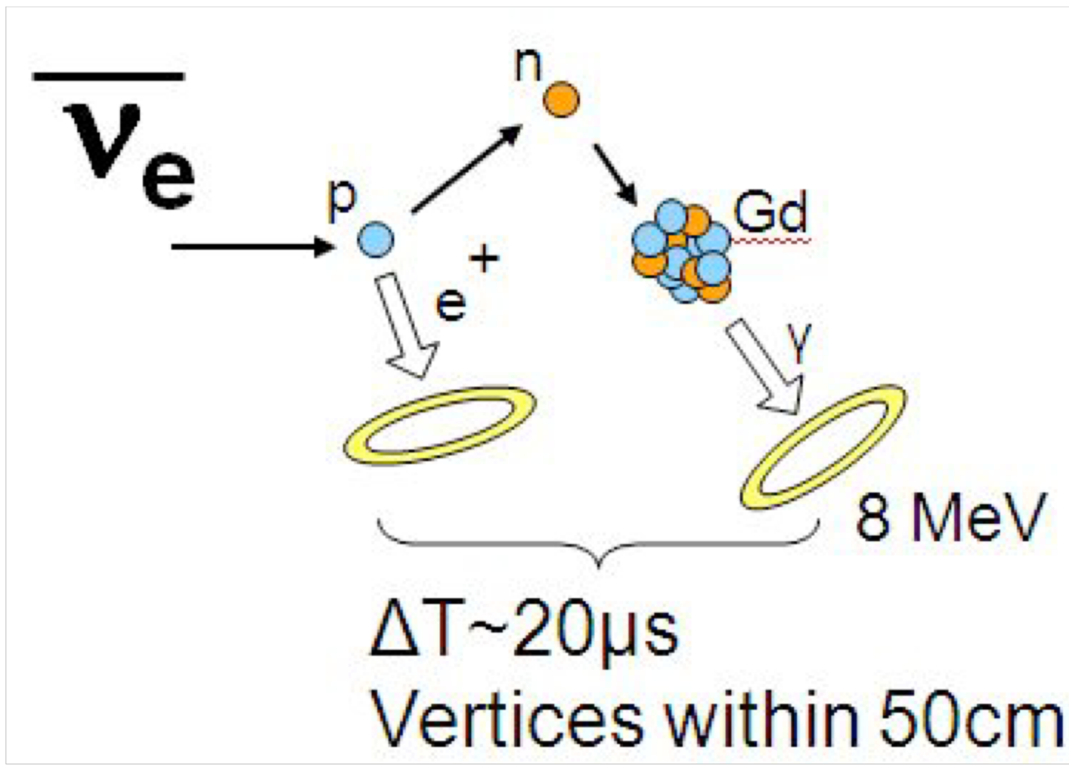
expected energy spectrum in Hyper-K (10 year)

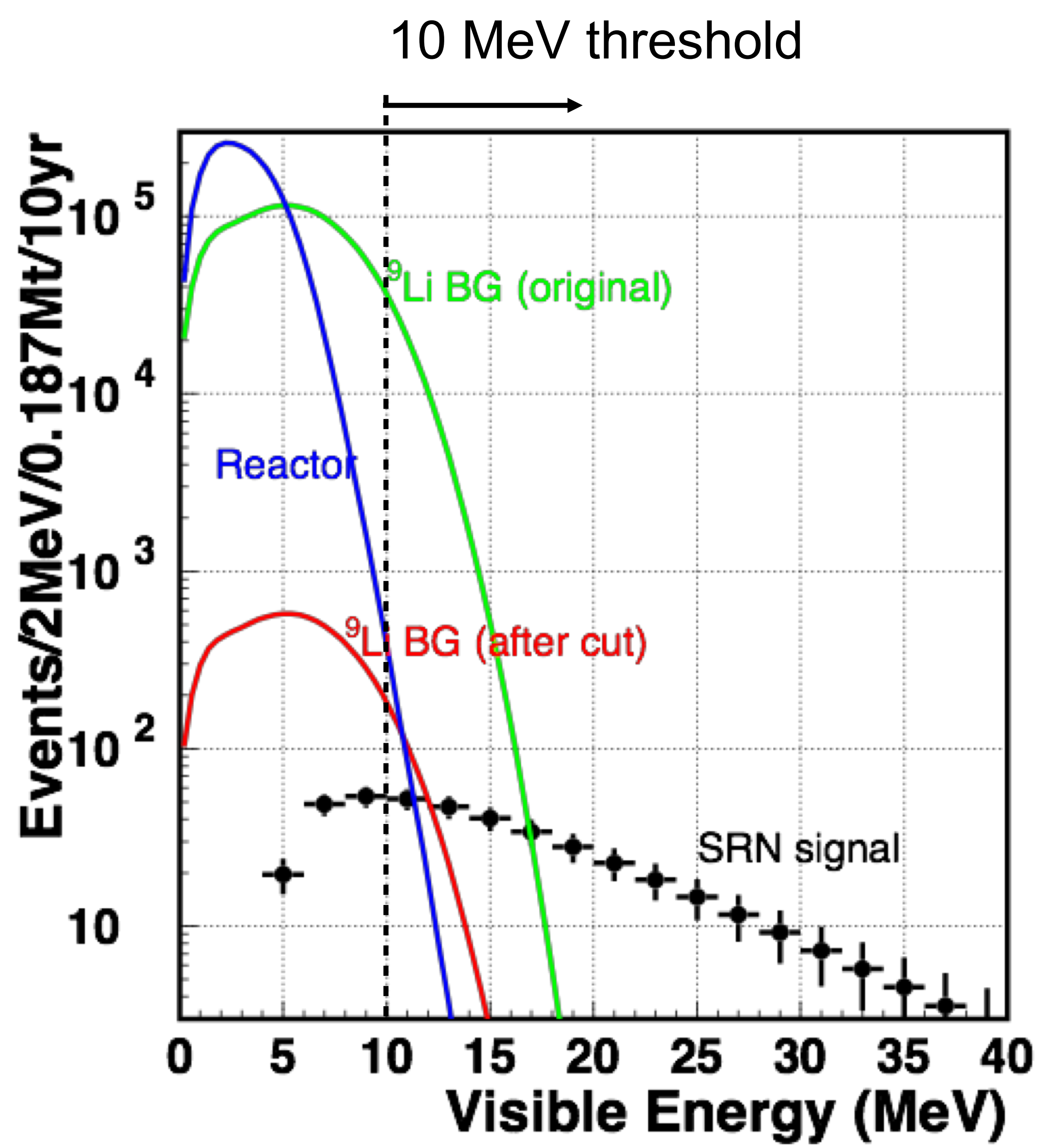


History of black hole formation can be investigated

Hyper-K with Gd

Option to add Gd compound in Hyper-K for neutron tagging





effective tagging to
reduce backgrounds

Energy threshold can be lowered from 16 MeV to 10 MeV

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

7.5×10^9 years

Summary

- Hyper-K will be a leading experiment in astroparticle physics research with the highest statistics and directional information
  - Our observation will start at 2027.
  - The detector design is being finalized.
- Astrophysical neutrino measurements is one of the features of Hyper-Kamiokande.
  - Solar neutrino
    - Hep neutrino, seasonal variation, up-turn etc…
  - Supernova neutrino
    - Energy and time spectrum measurement, SN alarming etc..
  - Supernova Relic Neutrino
    - Supernova and SFR models, extraordinary SN

Backup