Neutrino Astrophysics with Hyper-Kamiokande

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For Hyper-Kamiokande Proto Collaboration

Topics in Astroparticle and Underground Physics

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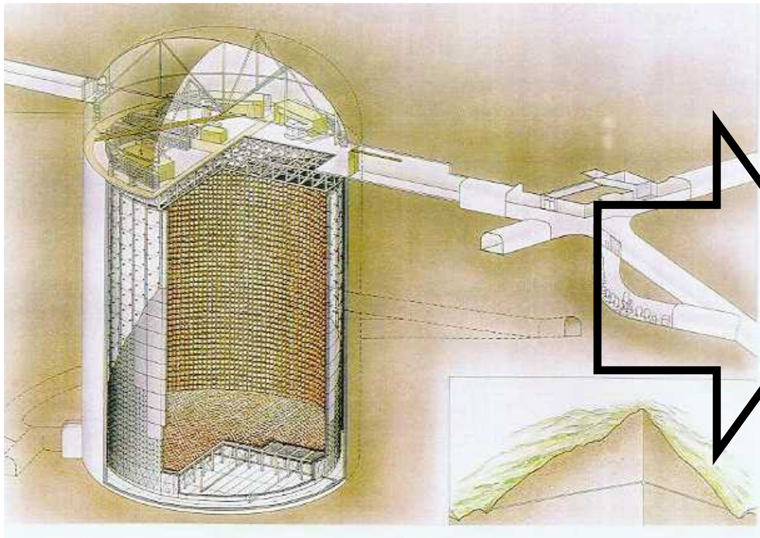
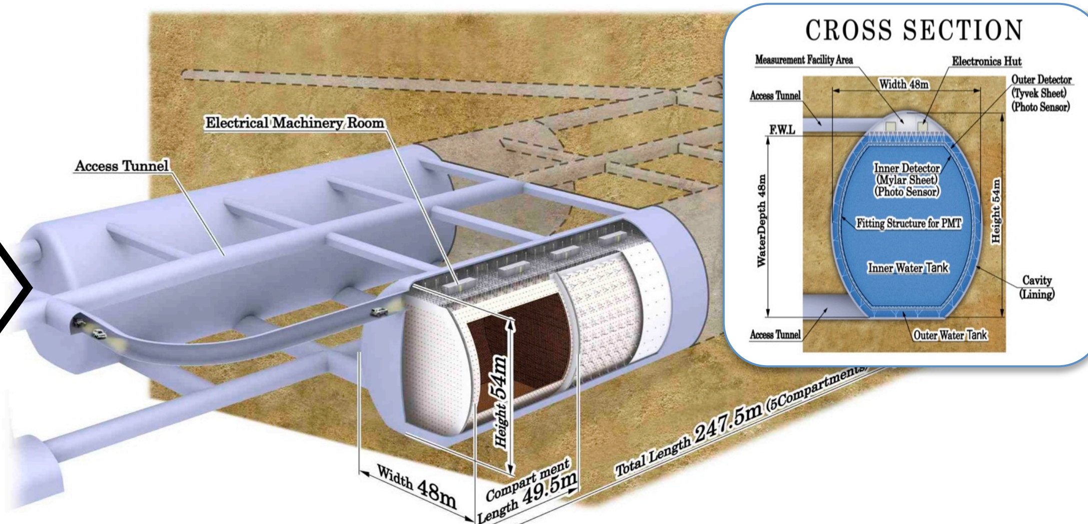
Hyper-Kamiokande Project



Super-Kamiokande (50kt)



Hyper-Kamiokande (1Mt)

Design baseline	Super-Kamiokande	Hyper-Kamiokande
Caverns	1 cylindrical cavern, No compartments	2egg shape caverns, 10 compartments
Num. of ID/OD PMTs	11,129 / 1,885	~99,000 / ~25,000
Photocoverage	40%	~20% (to be optimized)
Total / Fiducial Volume	50 kt / 22.5 kt	0.99 Mt / 0.56 Mt

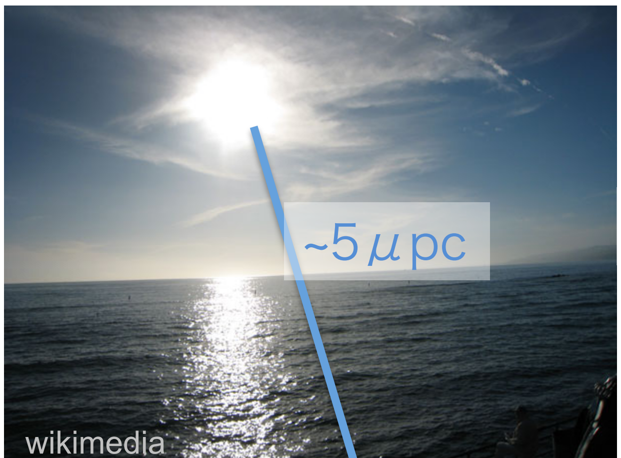
×25!

Hyper-Kamiokande is a next generation large water Cherenkov detector.

Astrophysical Neutrino at HK

Solar neutrino

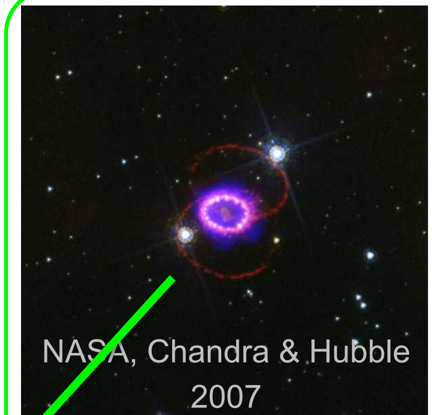
- Burning processes, modeling of the Sun
- Property of neutrino


wikimedia

~5μpc

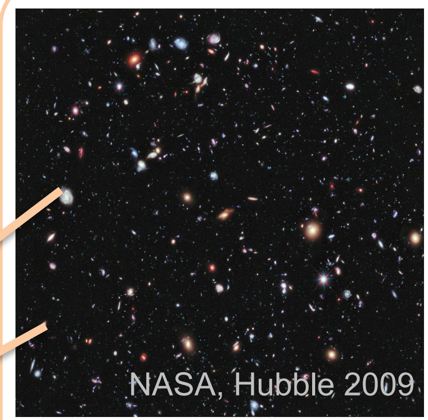
kpc ~ Mpc

Supernova ν


NASA, Chandra & Hubble 2007

- SN explosion mechanism
- SN monitor
- Nucleosynthesis

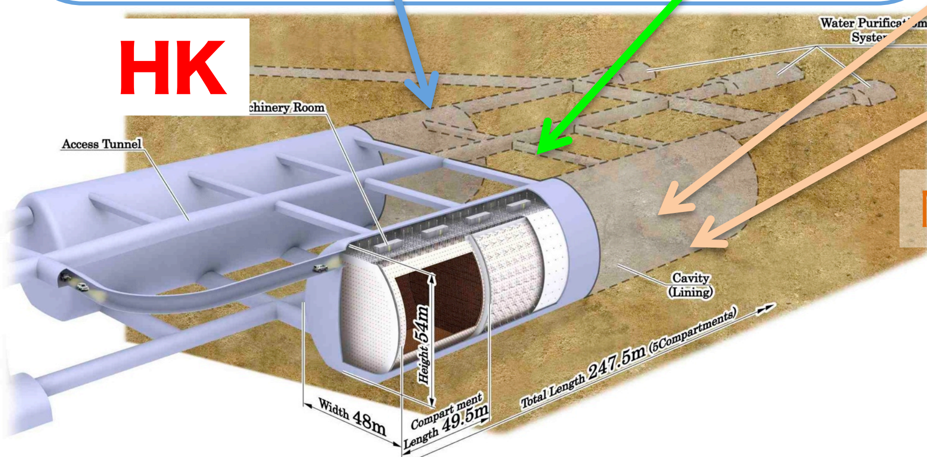
SN relic ν


NASA, Hubble 2009

- SN mechanism
- Star formation history
- Extraordinary SNe

Mpc ~

HK



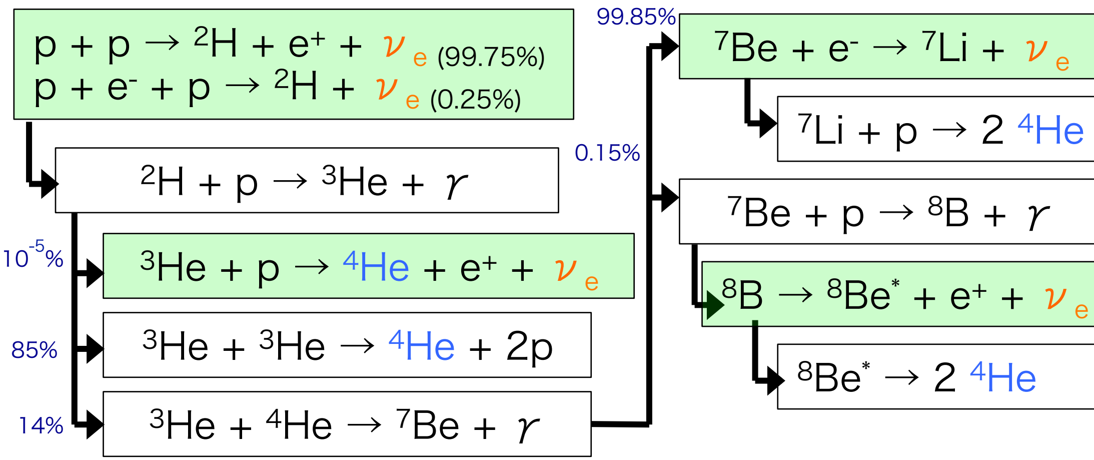
and DM annihilation, GRB ν…

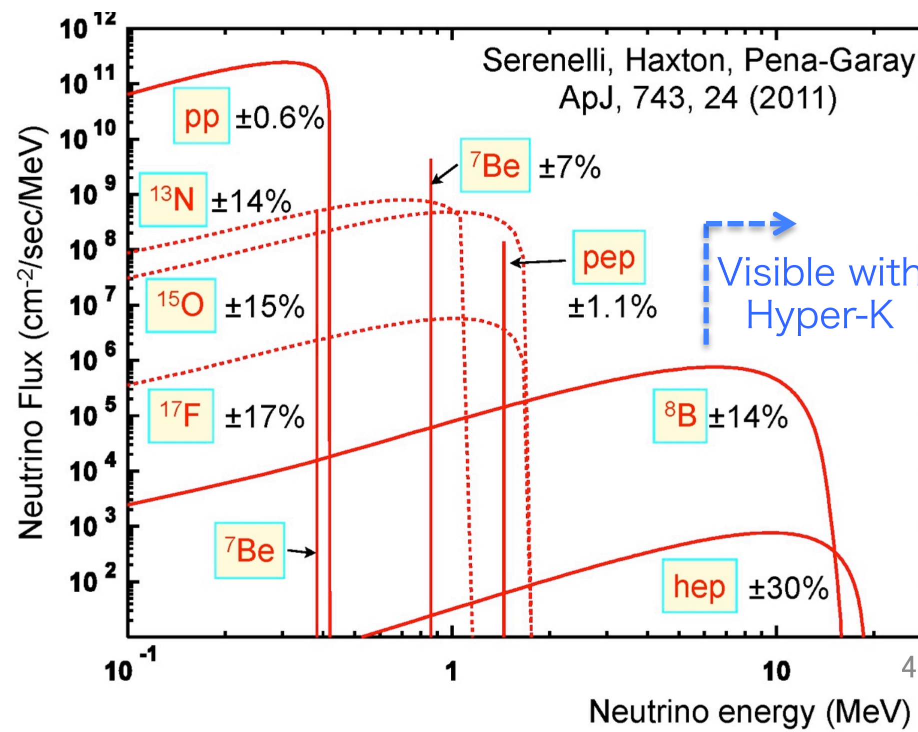
Solar neutrino

- The **Sun** is burning with nuclear fusion reactions, called pp-chain and CNO-cycle, emitting neutrinos.
- Only neutrinos can bing out the information of “today’s” status of solar center.

- With **Hyper-K**, a large statistics is expected :
- **200 ν ev./day**, E_ν>6.5MeV
- (15 ν ev./day in SK-I ~ SK-IV)

pp-chain & ν Energy specturm



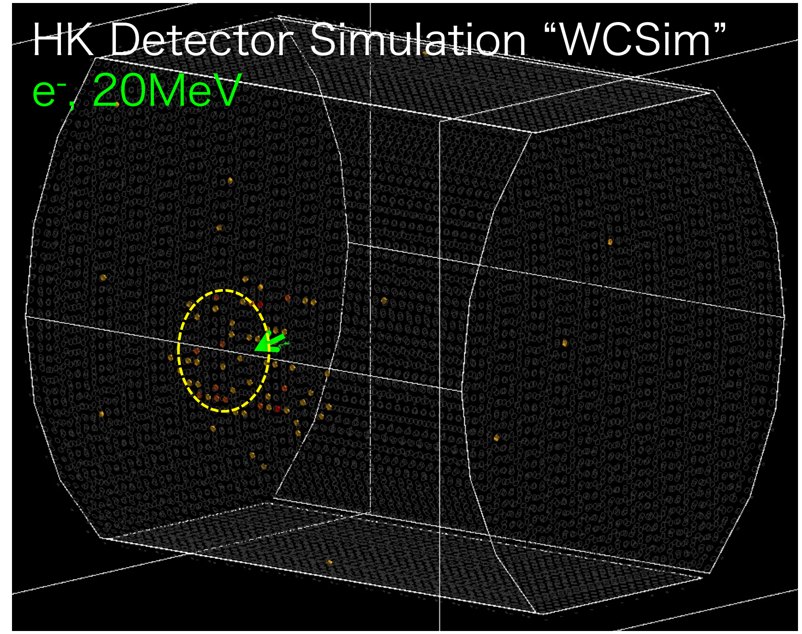


Solar neutrino observation

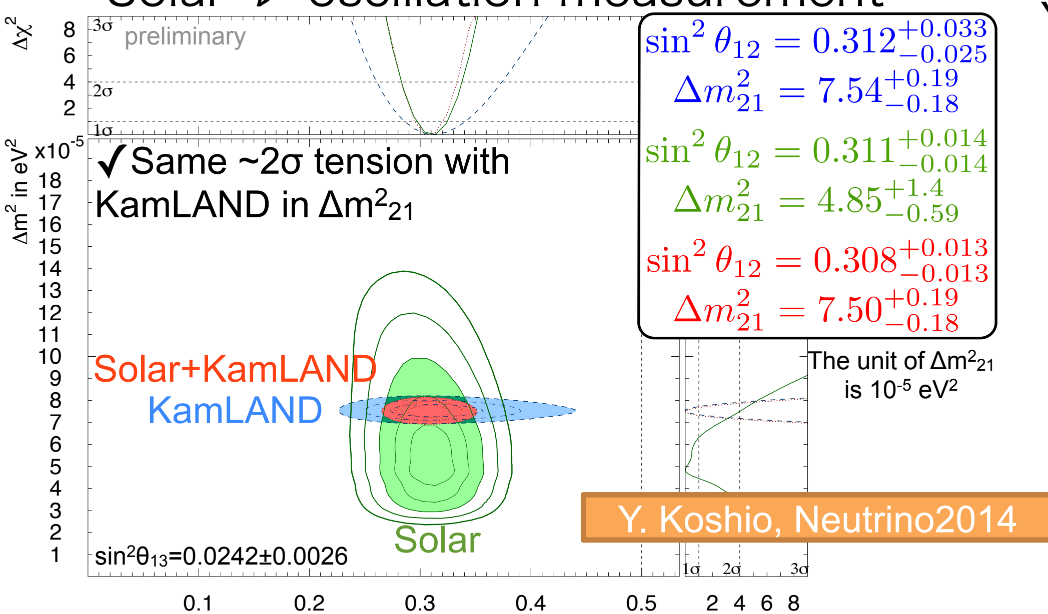
- In water detector, we observe the neutrinos with the **Cherenkov light** of the scattered electron.

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

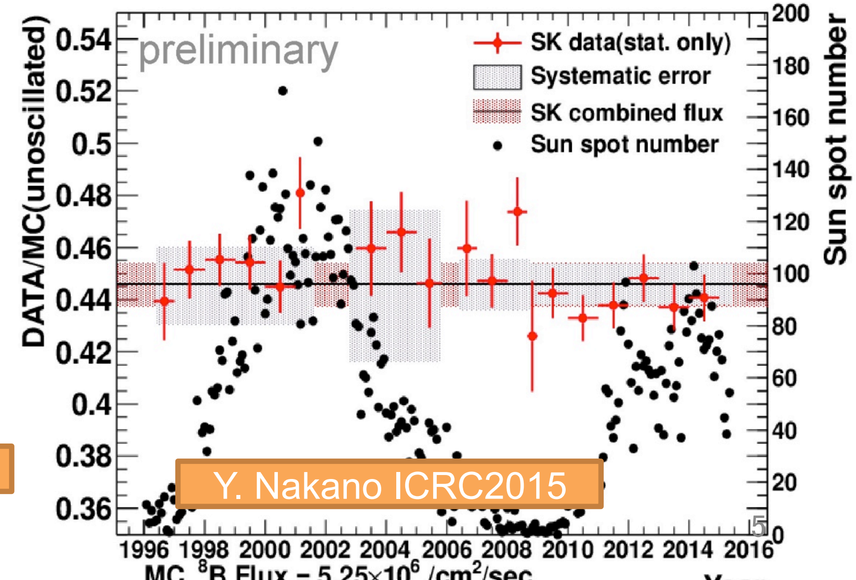
- Sensitivity of **direction** and **energy**.
- Real-time measurement
  - **Day-night flux asymmetry**
  - **Neutrino flux variation**



Solar ν oscillation measurement



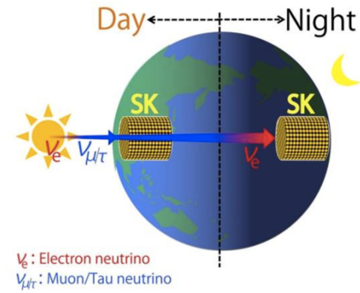
Yearly ν variation & Sun spots (SK)

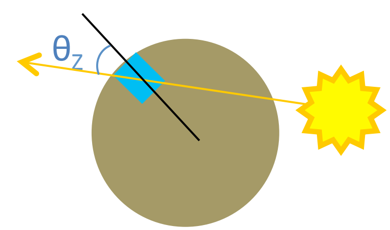


Solar Day/Night asymmetry

- **Non-0 D/N asymmetry** of solar ν caused by terrestrial matter effect is indicated by SK.
  [PRL 1212, 091805(2014)]
- The D/N asymmetry leads smaller Δm^2_{21} value in solar neutrino analysis, comparing to reactor neutrino analysis.

→ **How about with Hyper-K?**

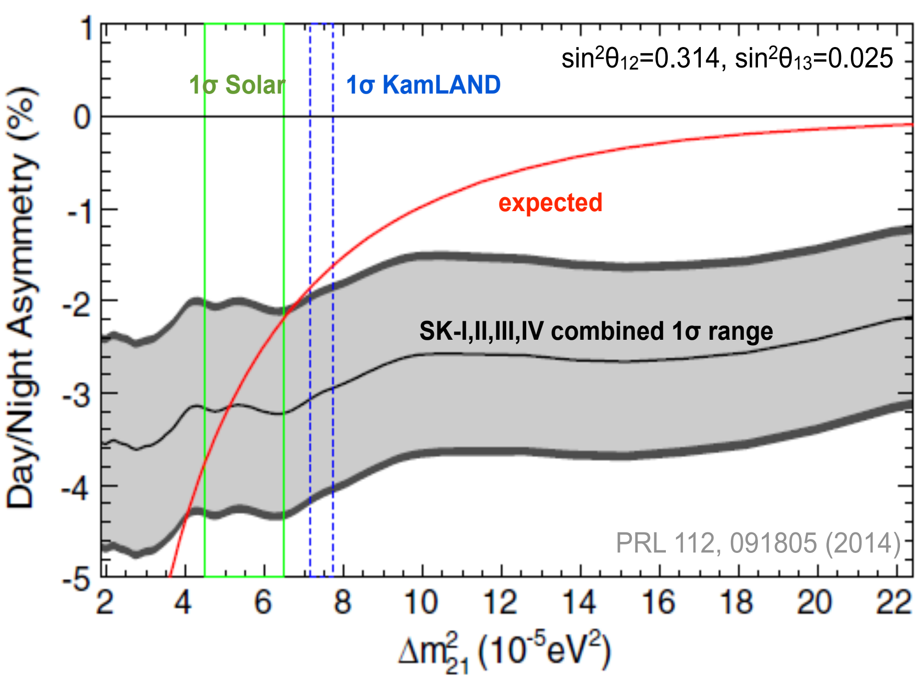


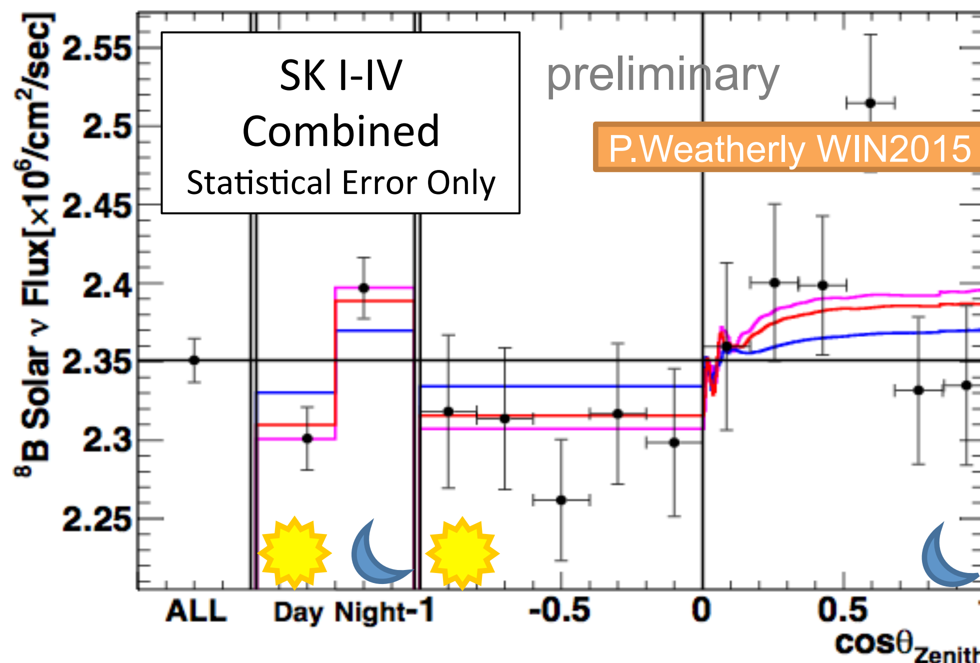


All solar
$\sin^2(\theta_{12}) = 0.311$
$\Delta m_{21}^2 = 4.85\times10^{-5}\ \mathrm{eV}^2$

Solar+KamLAND
$\sin^2(\theta_{12}) = 0.308$
$\Delta m_{21}^2 = 7.50\times10^{-5}\ \mathrm{eV}^2$

D/N best
$\sin^2(\theta_{12}) = 0.311$
$\Delta m_{21}^2 = 4.17\times10^{-5}\ \mathrm{eV}^2$



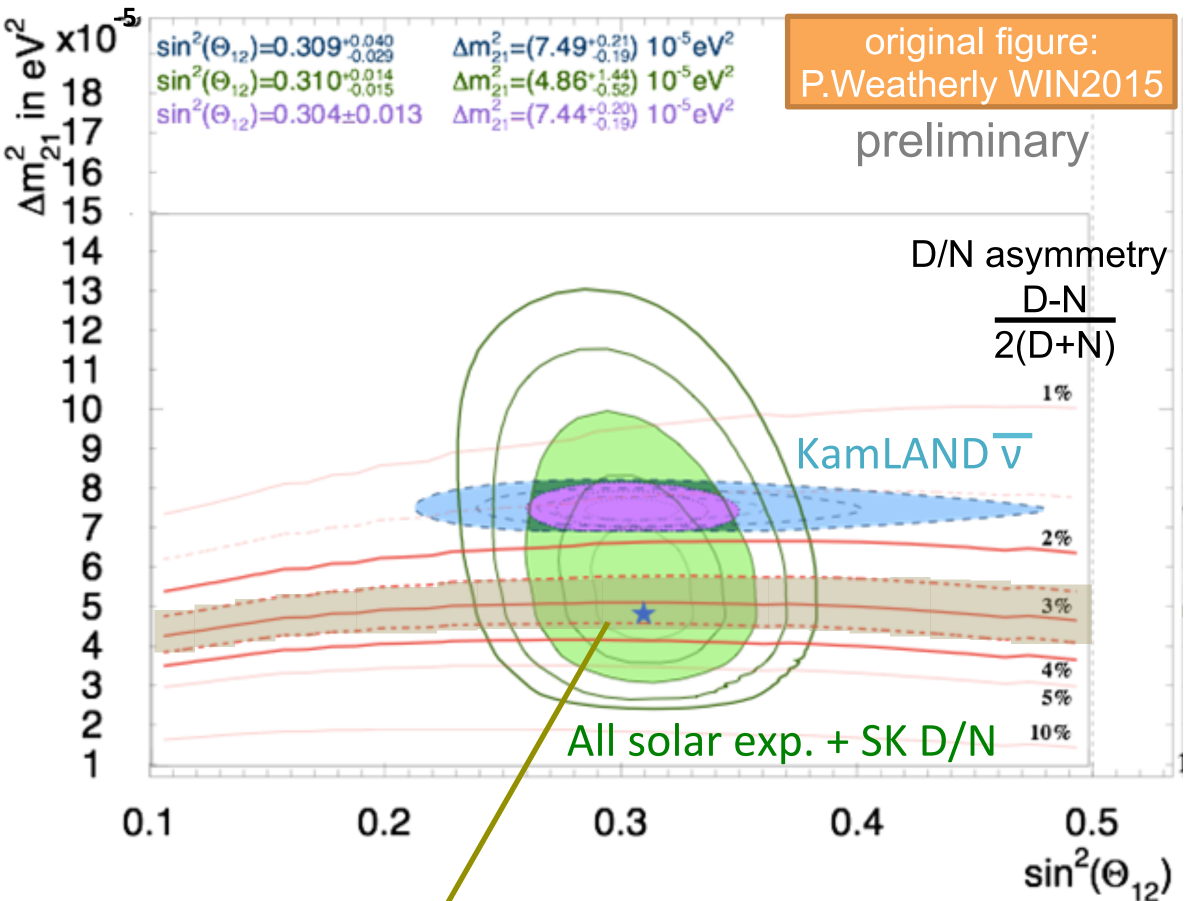


Solar D/N asymmetry at HK

- With Hyper-K statistics, we can measure the D/N asymmetry with ±~0.5% precision. (stat. only.)
  - ~0.5% of sys. error is applied on SK analysis.
- To separate solar best Δm^2_{21} and KamLAND best above 2.5σ.
  - 1σ = ~1×10^{-5}eV^2

→ CPT violation test, difference between $P_{\nu e \to \nu e}$ and $P_{\overline{\nu e} \to \overline{\nu e}}$.

→ Better measurement of Δm^2_{21} for CPV test in HK long-baseline part.



±1σ region with Hyper-K 10years
*assumuing solar best Δm², statistic (signal and background) error only

Other solar ν topics

Hep process neutrino

- Undiscovered solar neutrino, with small branching ratio.
- With Hyper-K 10 years, there is chance to discover.
  → To test the solar models.

Energy spectrum up-turn

- To confirm the solar neutrino oscillation, or to see new physics beyond the SM.
  → Non-standard interaction, sterile neutrinos ···

- **Optimizing detector, reducing systematic, statistic error and careful calibration will be needed.**

Takeuchi

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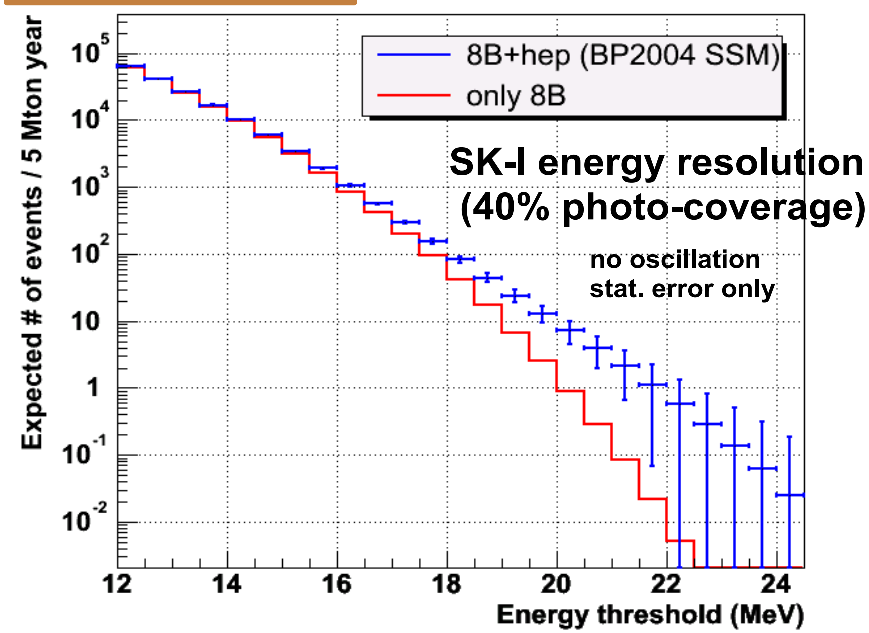
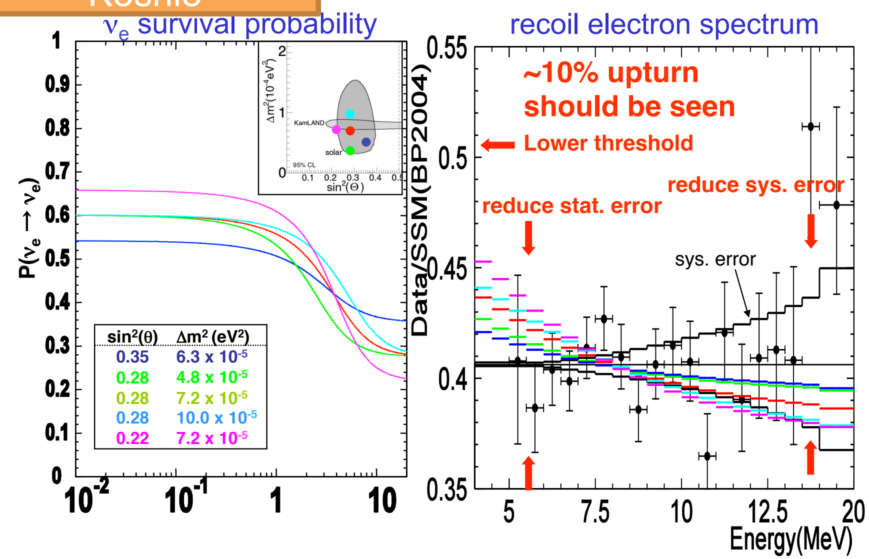
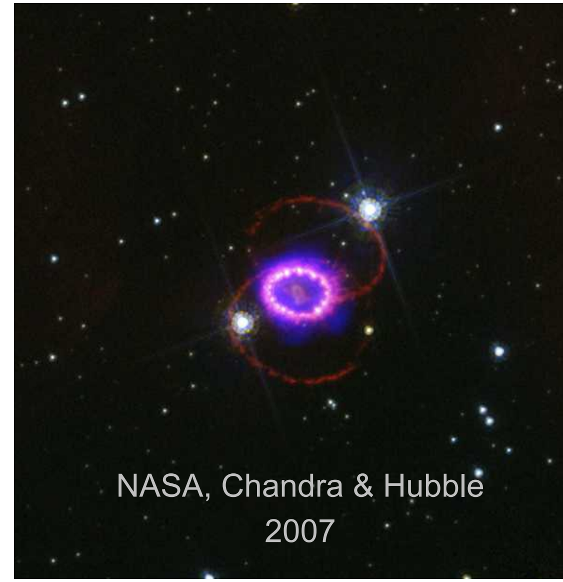


Koshio



Supernova Neutrino

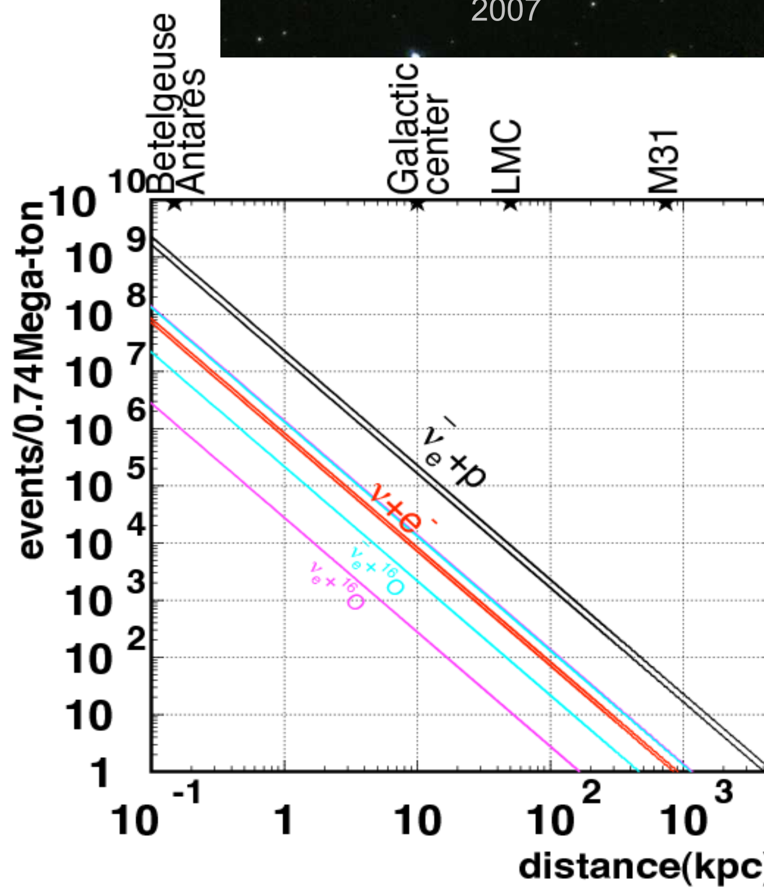


Core collapse supernova emits all kinds of neutrinos.

- **11** neutrino events by Kamiokande from SN1987A at **50kpc** (LMC).
- **170 ~ 260k** events are expected in HK from SN at **10kpc** (galactic center).

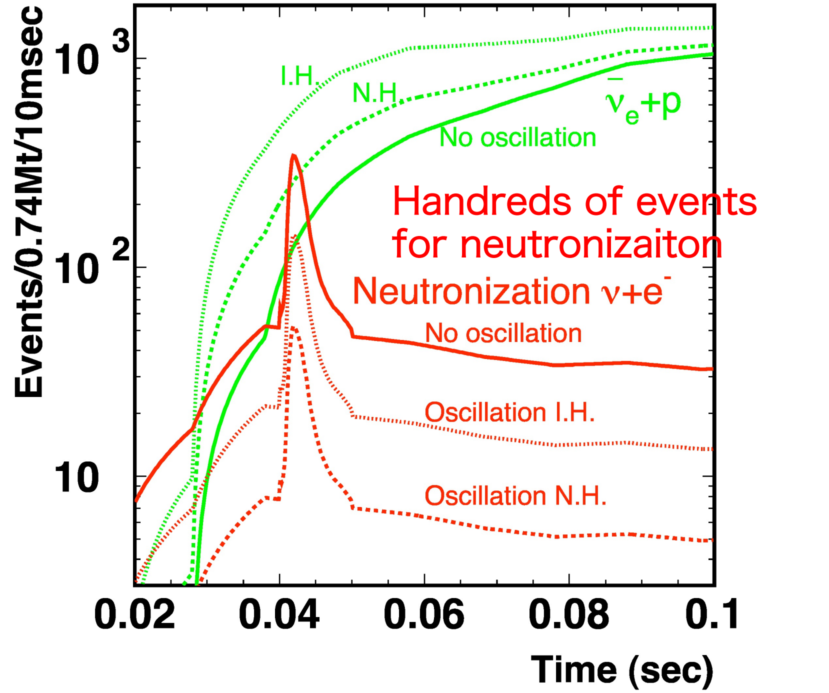
Physics Motivation

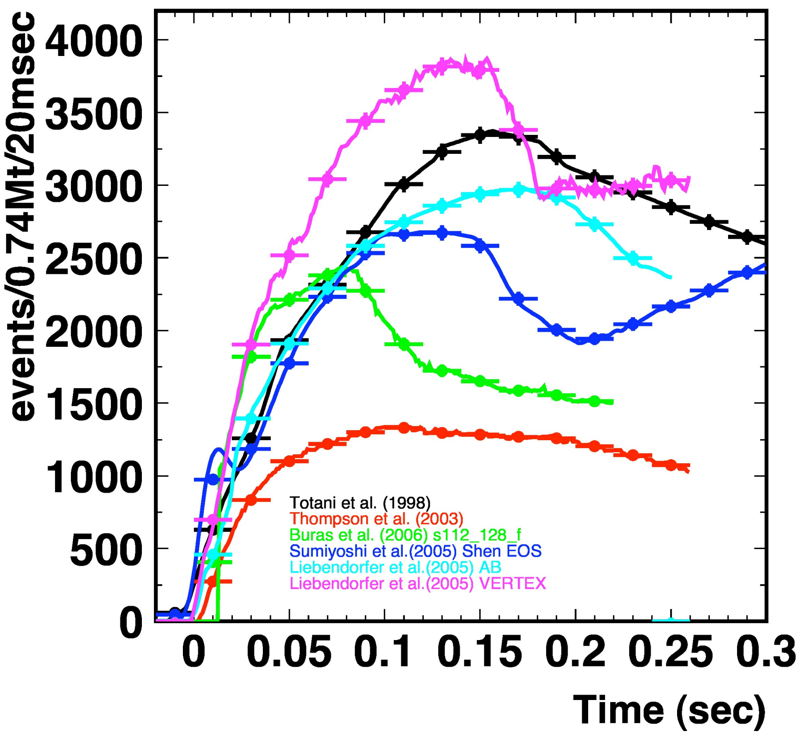
- Core collapse SN physics
  - Explosion mechanism
  - Proto-neutron star formation
  - Black hole formation
- Neutrino Physics
- Multi-messenger analysis
  - With gravitational wave, gamma-ray, X-ray, telescope…

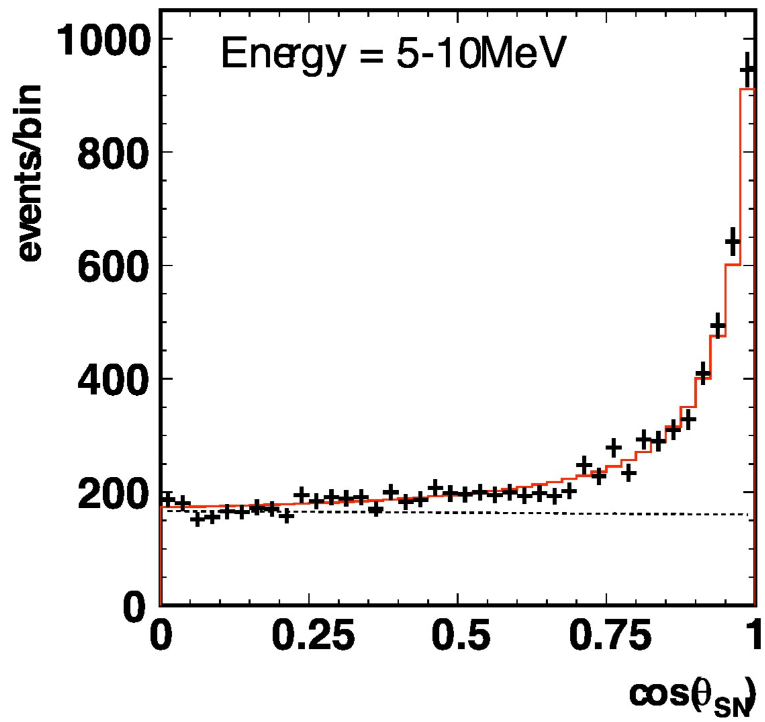


Features

- Detection of neutronization ν
- Measurement of supernova burst time
- Better directional measurement for SN monitor
- Energy spectrum measurement
- Extraordinary SN (BH, dim SN)







Short time variation of SN ν

- Two kind of short time variance is proposed from 3D MC simulation.
  - Convection (SASI) : ± 100 events/ms @ 10kpc
  - Rotation : ± 40 events/ms @ 10kpc

  Convection leads an explosion to 3D simulation model.
  -> Detection/frequency analysis of these variance is important input to supernova theories.

S A S I
(Standing Accretion Shock Instability)

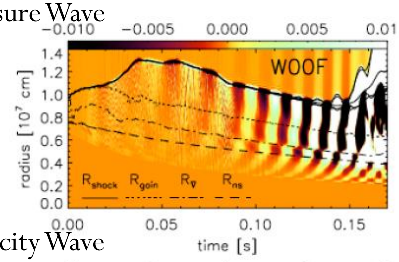
Takiwaki

Scheck+ 2008

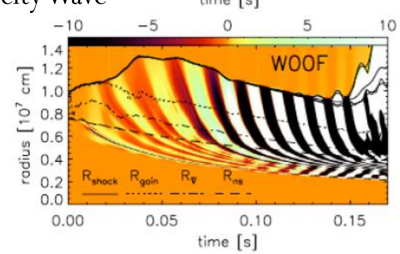
Advective-acoustic cycle
From Foglizzo's slides

Standing Accretion Shock Instability(SASI)

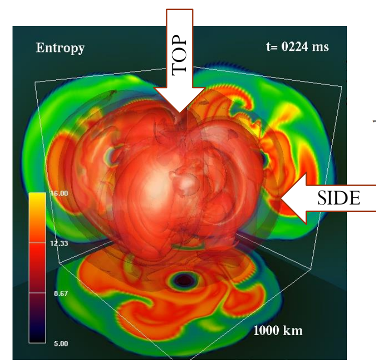
Pressure Wave

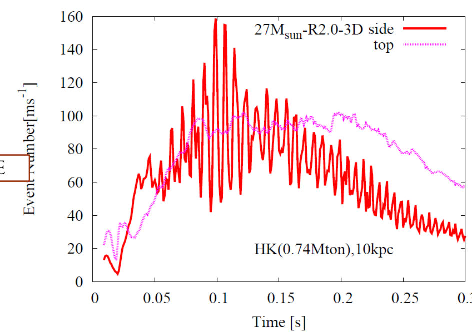


Vorticity Wave



Neutrino signals from rotating model

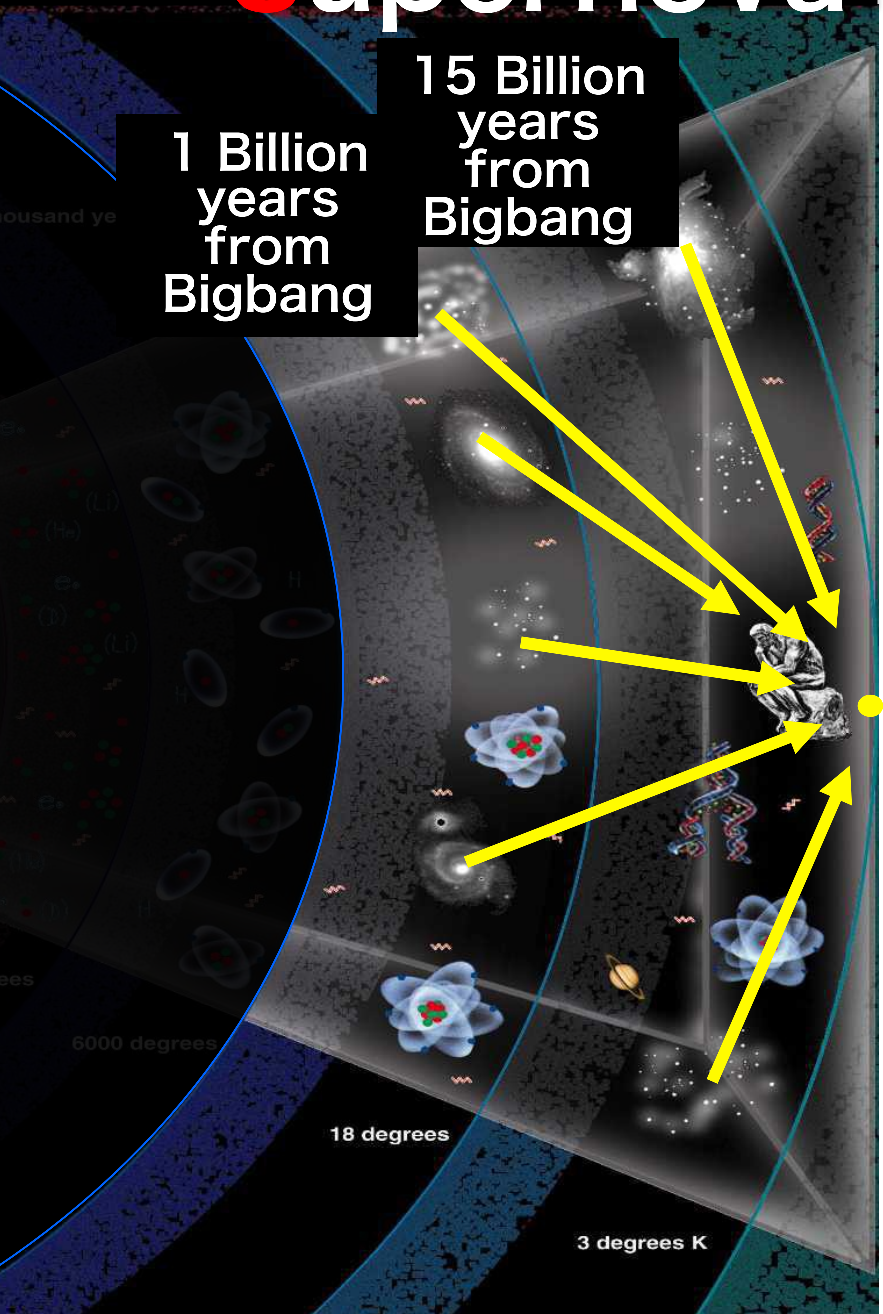




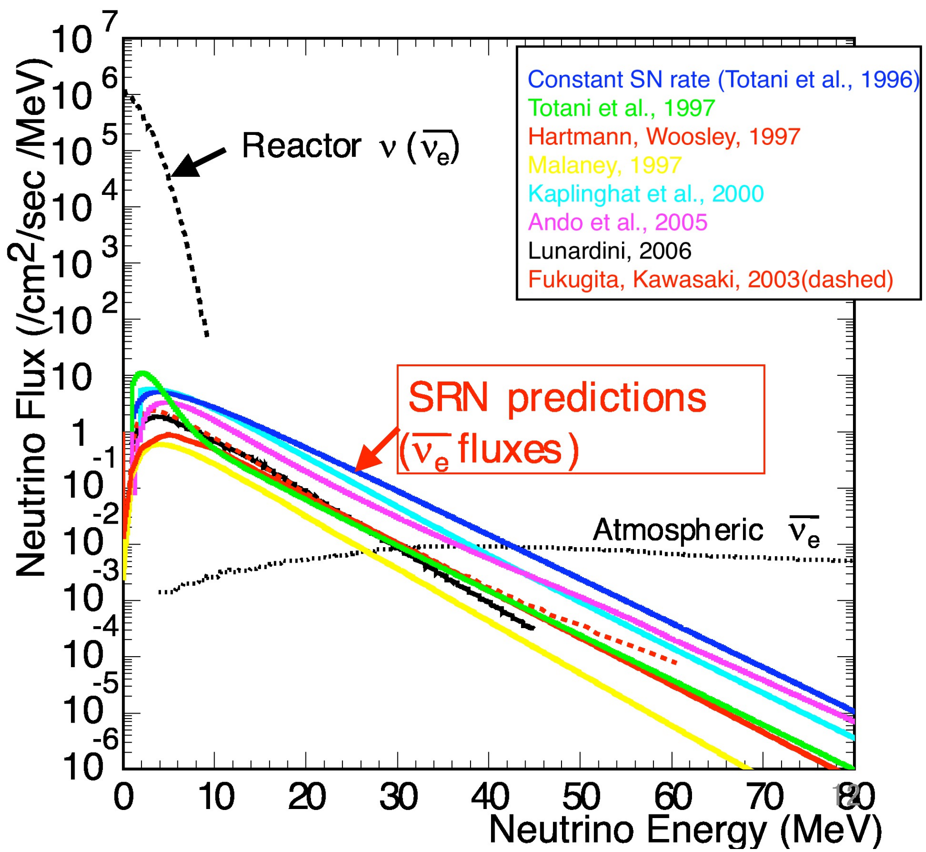
Takiwaki+ in prep

Period of spiral mode is extracted by ν −signal

Supernova Relic Neutrino

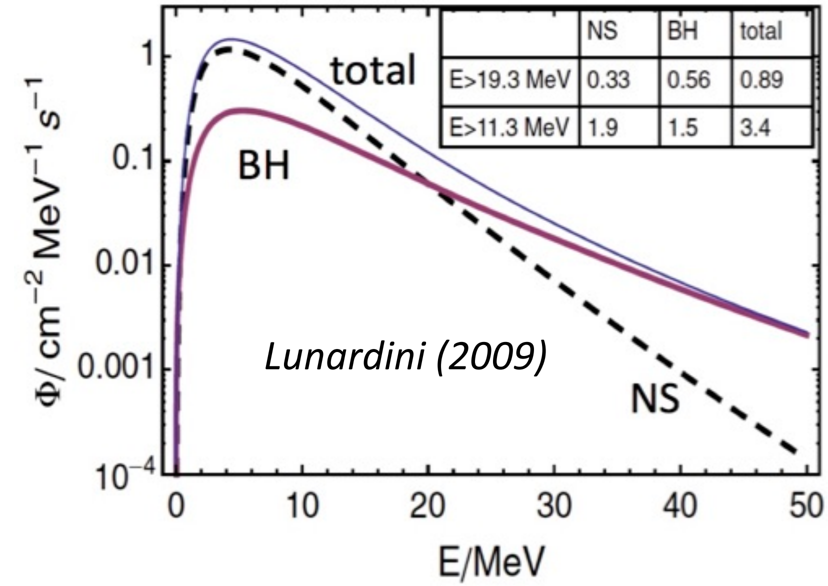


- **Supernova Relic Neutrino (SRN)** is diffused neutrinos coming from all past supernovae.
- Not discovered but **promising** source of extra-galactic neutrino.

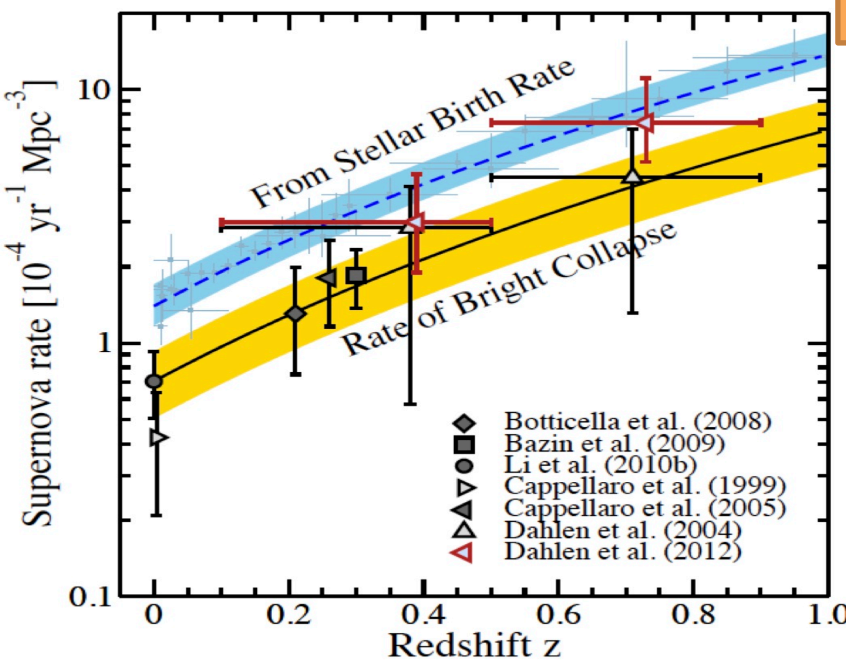


Physics of SRN

- Star formation rate
- Energy spectrum of supernova burst neutrinos
- Extraordinary SN (black hole, neutron star formation, dim supernova)



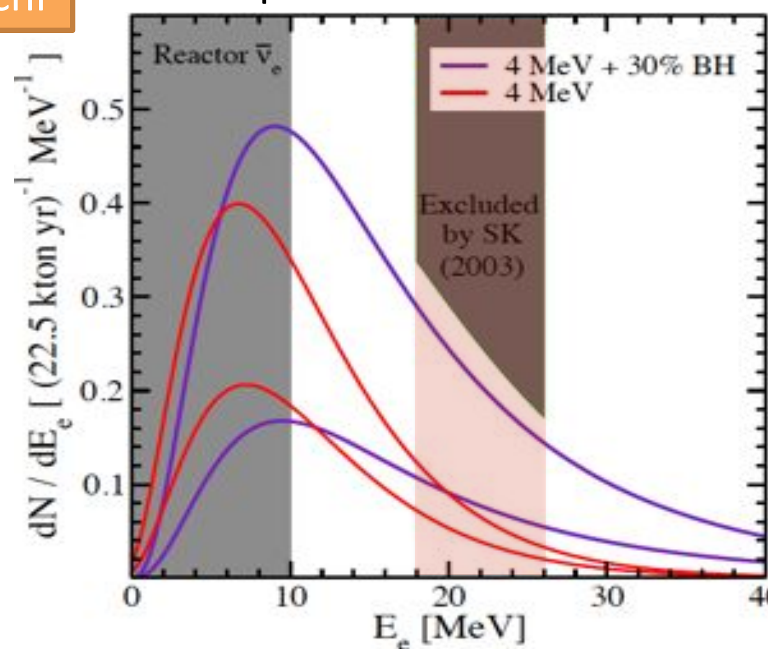
Stellar birth rate(=collapse rate) and Bright collapse rate



Horiuchi et.al (2011) with data from Dahlen et.al (2012)

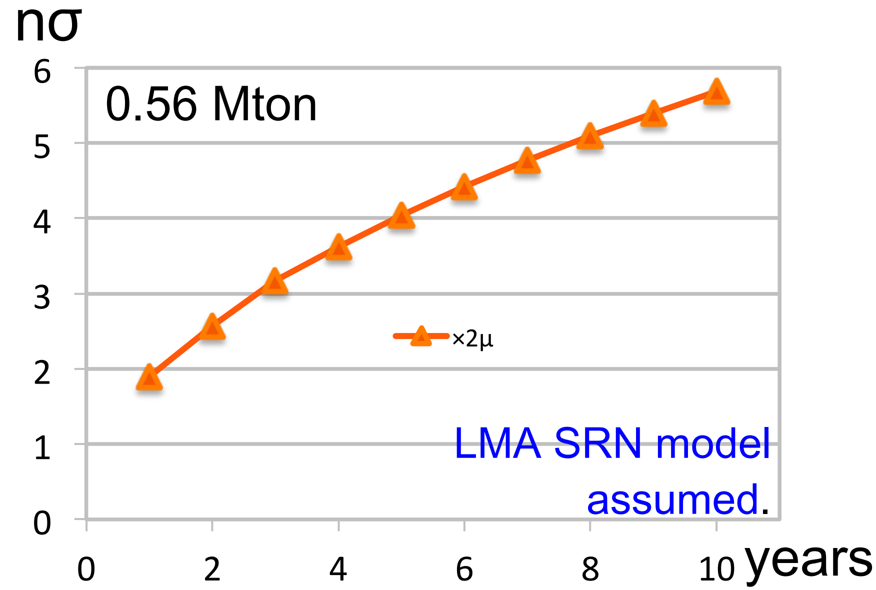
Horiuchi

Event spectra with uncertainties



Adopted from Horiuchi et al. (2009)

SRN measurement with HK



SRN with Hyper-K

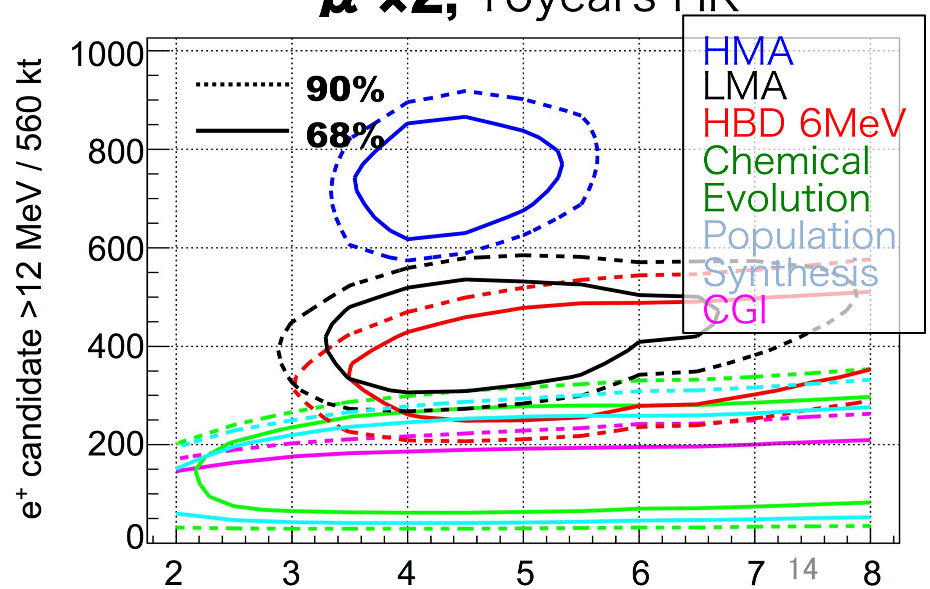
- ~200 SRN events are expected between 20 MeV and 30 MeV, with Hyper-Kamiokande 10 years.
- 4.5~6 sigma detection of SRN is expected.

SRN with Hyper-K+Gd

- By adding Gadolinium and applying neutrino tagging, we can lower the analysis threshold down to 12-14 MeV.
  - $\overline{\nu}_e + p \to e^+ + n$
  - Gd + n -> Gd + γ s (~8 MeV)
- With Gd, the measurement of T_ν and model separation will be possible.

SRN Model Recognition

μ **×2,** 10years HK



Summary

- **Hyper-K project is a next generation large water Cherenkov detector.**
  - Several studies are being performed. e.g. photosensor R&D, detector simulation, design and physics optimization…
- **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, extraordinaly SN

Solar neutrino fluxes of models.

J.N. Bahcall and A.M. Serenelli, Astro. Phys. J. 621, 85 (2005)

Table 2: Predicted solar neutrino fluxes from seven solar models. The table presents the predicted fluxes, in units of $10^{10}(pp)$, $10^{9}(\,^{7}\mathrm{Be})$, $10^{8}(pep, {}^{13}\mathrm{N}, {}^{15}\mathrm{O})$, $10^{6}(\,^{8}\mathrm{B}, {}^{17}\mathrm{F})$, and $10^{3}(\mathrm{hep})$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for the same solar models whose characteristics are summarized in Table 1.

Model	pp	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
BP04(Yale)	5.94	1.40	7.88	4.86	5.79	5.71	5.03	5.91
BP04(Garching)	5.94	1.41	7.88	4.84	5.74	5.70	4.98	5.87
BS04	5.94	1.40	7.86	4.88	5.87	5.62	4.90	6.01
BS05(^{14}N)	5.99	1.42	7.91	4.89	5.83	3.11	2.38	5.97
BS05(OP)	5.99	1.42	7.93	4.84	5.69	3.07	2.33	5.84
BS05(AGS,OP)	6.06	1.45	8.25	4.34	4.51	2.01	1.45	3.25
BS05(AGS,OPAL)	6.05	1.45	8.23	4.38	4.59	2.03	1.47	3.31

Solar neutrino upturn

Maltoni et al. http://arxiv.org/pdf/1507.05287.pdf