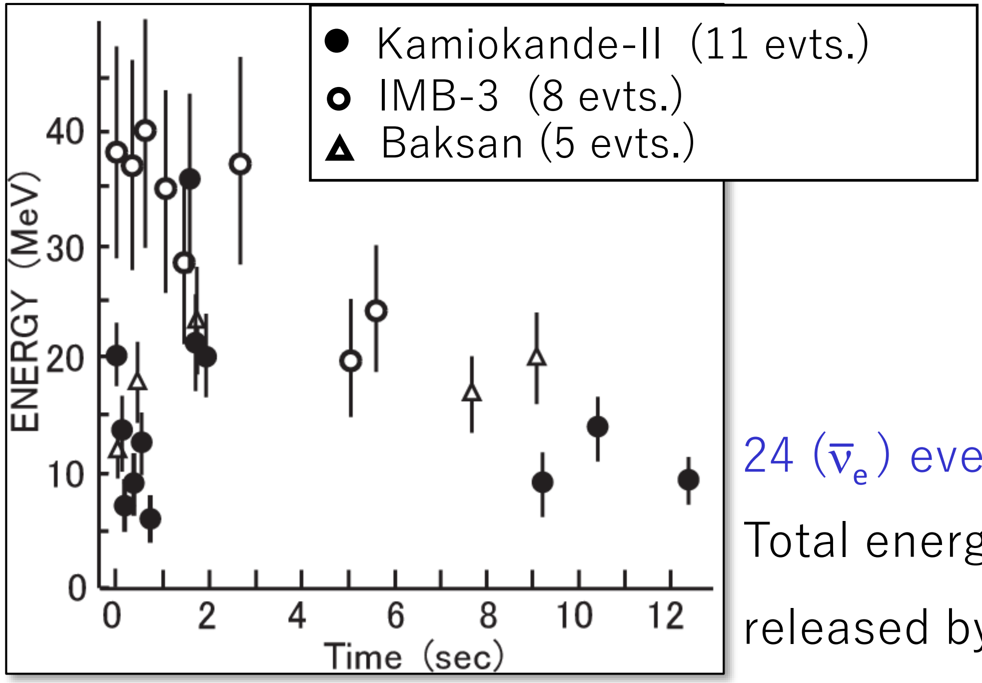
Status of Super-K(-Gd) and Hyper-K for supernova neutrinos

Hiroyuki Sekiya

ICRR, University of Tokyo

Supernova neutrinos from 1987A

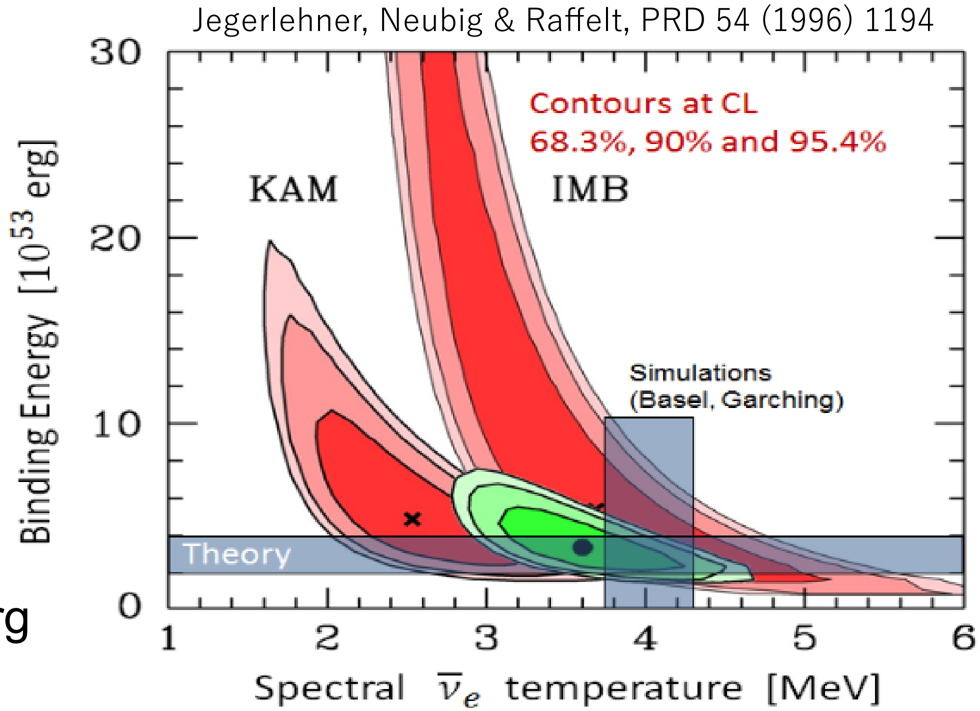
- The only detected SN neutrinos are from LMC(50kpc)



24 ($\overline{\nu}_e$) events in total.

Total energy

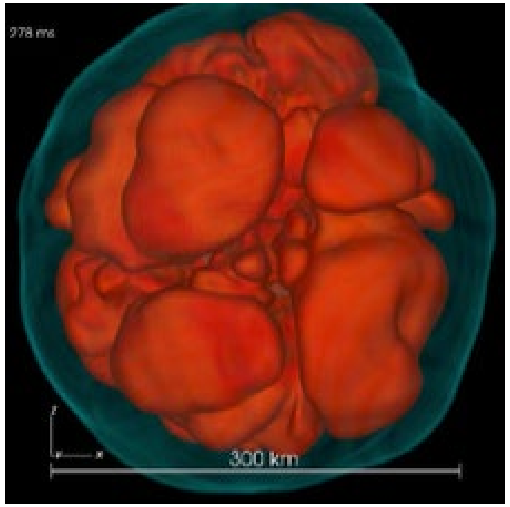
released by $\overline{\nu}_e$: ~5x10^{52} erg



- The obtained binding energy is almost as expected, but large error in neutrino mean energy. No detailed information of burst process.
- We need energy, flavor and time structure.

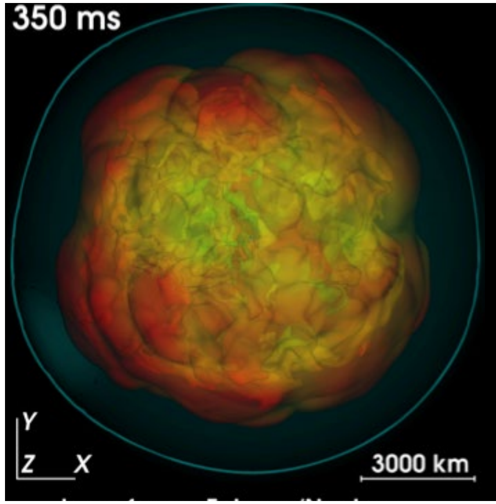
Recent 3D simulations burst

- Mechanism of CCSN needs to be determined by data　K.Nakamura



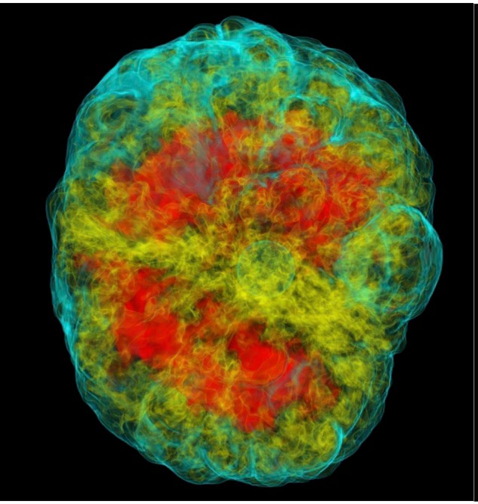
Hanke+'13

27 $M_{\odot}$ (WHW02)
t < ~400 ms
LS220 EoS
1D gravity
+ GR correction



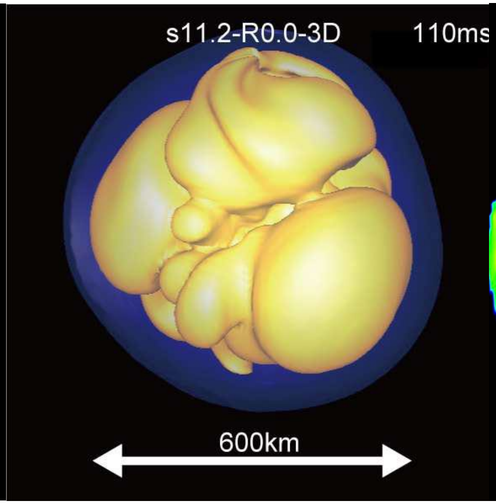
Melson+'15

9.6 $M_{\odot}$ (A. Heger)
t < ~400 ms
LS220 EoS
1D gravity
+ GR correction
Yin-Yang grid



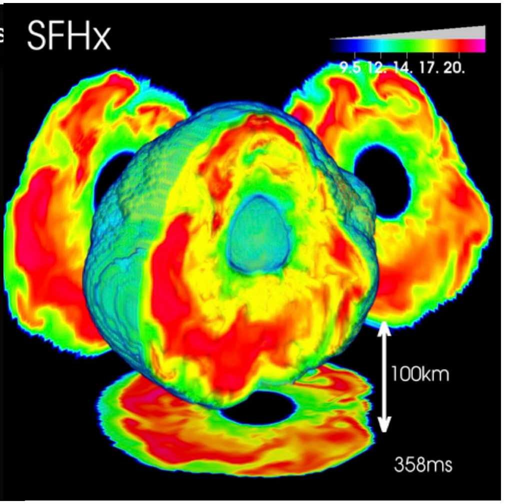
Roberts+'16

27 $M_{\odot}$ (WHW02)
t < 380 ms
LS220 EoS
GR
Cartesian AMR



Takiwaki+'16

11.2 (&27) $M_{\odot}$ (WHW02)
t < ~300 (400) ms
LS220 EoS
Newtonian



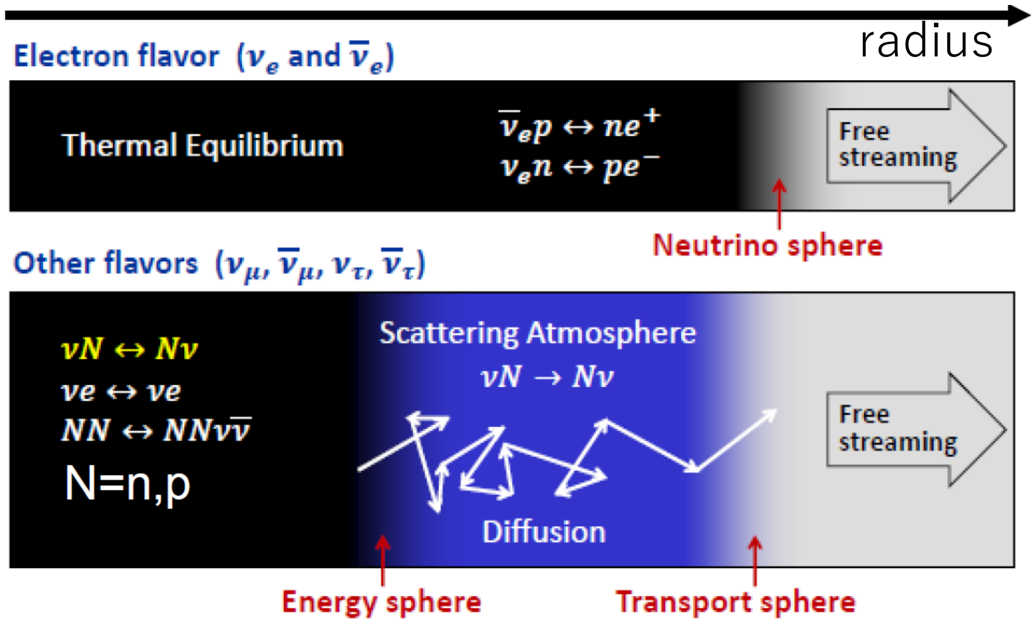
Kuroda+'16

15 $M_{\odot}$ (WW95)
t < ~400 ms
DD2/TM1/SFHx EoS
GR; Cartesian FMR

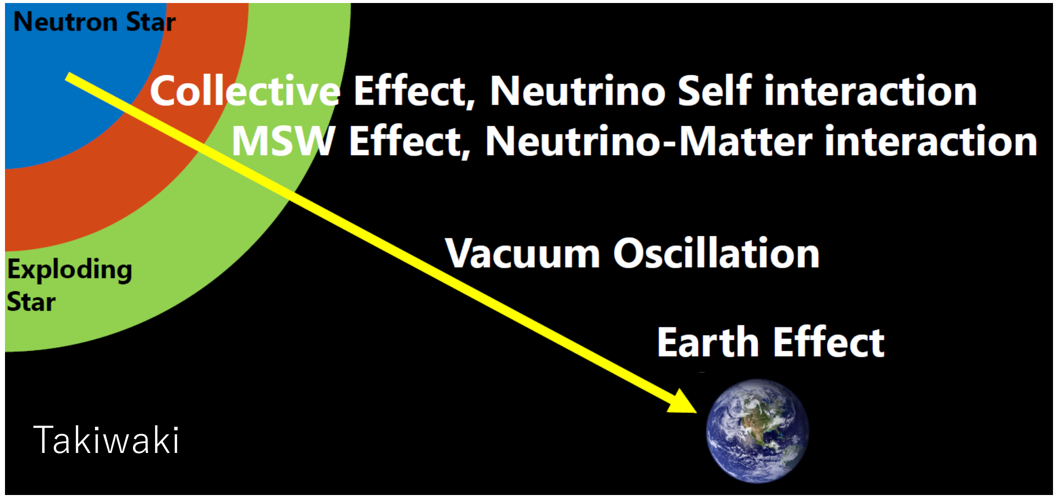
Difficulties

- Neutrino interaction and transportation in high density situation

$e^-p \longleftrightarrow \nu_e n$	$e^+n \longleftrightarrow \bar{\nu}_e p$	$e^-A \longrightarrow \nu_e A'$	$e^+A \longrightarrow \bar{\nu}_e A'$
$e^-e^+ \longleftrightarrow \nu\bar{\nu}$	$\text{plasmon} \longleftrightarrow \nu\bar{\nu}$	$NN \longrightarrow NN\nu\bar{\nu}$	$\nu_e\bar{\nu}_e \longleftrightarrow \nu_x\bar{\nu}_x$
$\nu N \longrightarrow \nu N$	$\nu A \longrightarrow \nu A$	$\nu e^{\pm} \longrightarrow \nu e^{\pm}$	$\nu\nu' \longrightarrow \nu\nu'$



Janka 2017



- Neutrino oscillation in high density
  - MSW effect in much much higher density than in SUN!
  - Collective oscillation; neutrino self-interaction near the core

$t > 1\text{sec}$ $r < 10^3\text{km}$, $n_\nu > n_e$

$$\omega \equiv \frac{\Delta m^2}{2E}$$

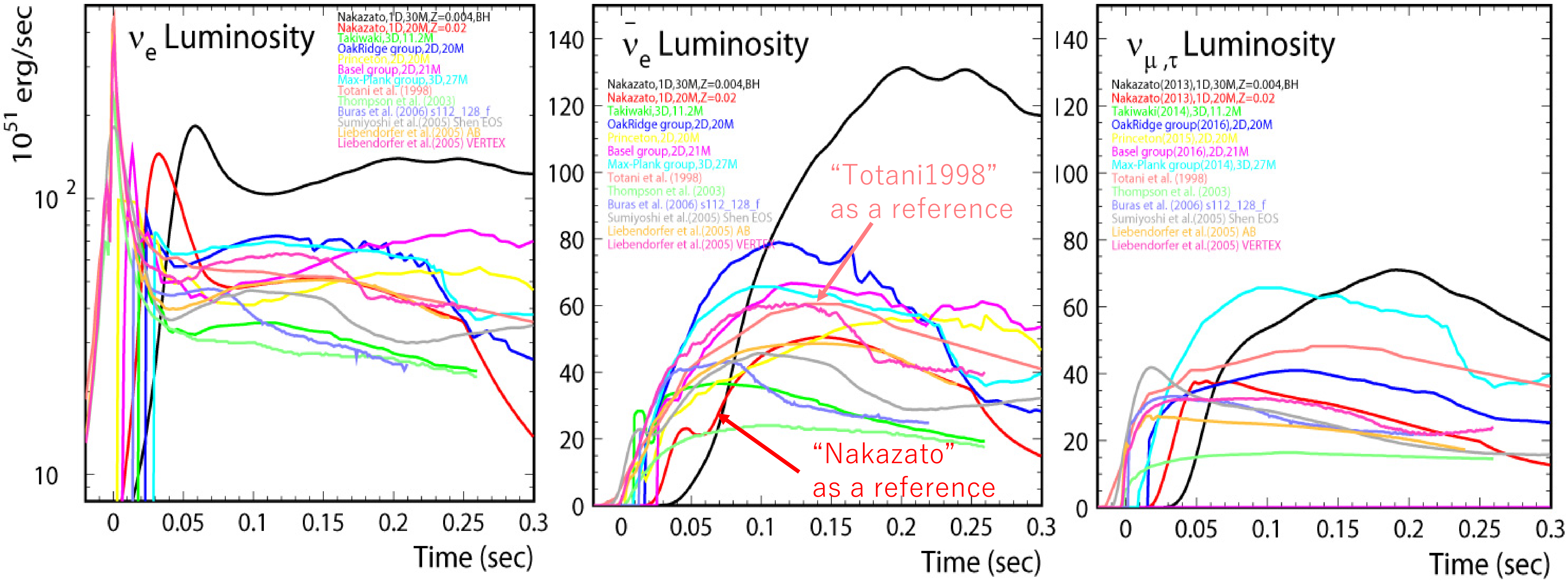
$$\lambda \equiv \sqrt{2}G_F(n_{e^-} - n_{e^+})$$

$$\mu \equiv \sqrt{2}G_F(n_{\bar{\nu}_e} - n_{\bar{\nu}_x}) = \frac{\sqrt{2}G_F}{4\pi r^2}\left(\frac{L_{\bar{\nu}_e}}{\langle E_{\bar{\nu}_e}\rangle} - \frac{L_{\bar{\nu}_x}}{\langle E_{\bar{\nu}_x}\rangle}\right)$$

H. Suzuki

Many models･･･　Need data!

Figures: H.Suzuki, M. Nakahata



The Fainting of Betelgeuse, the red supergiant

https://apod.nasa.gov/apod/ap200102.html

Astronomy Picture of the Day

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

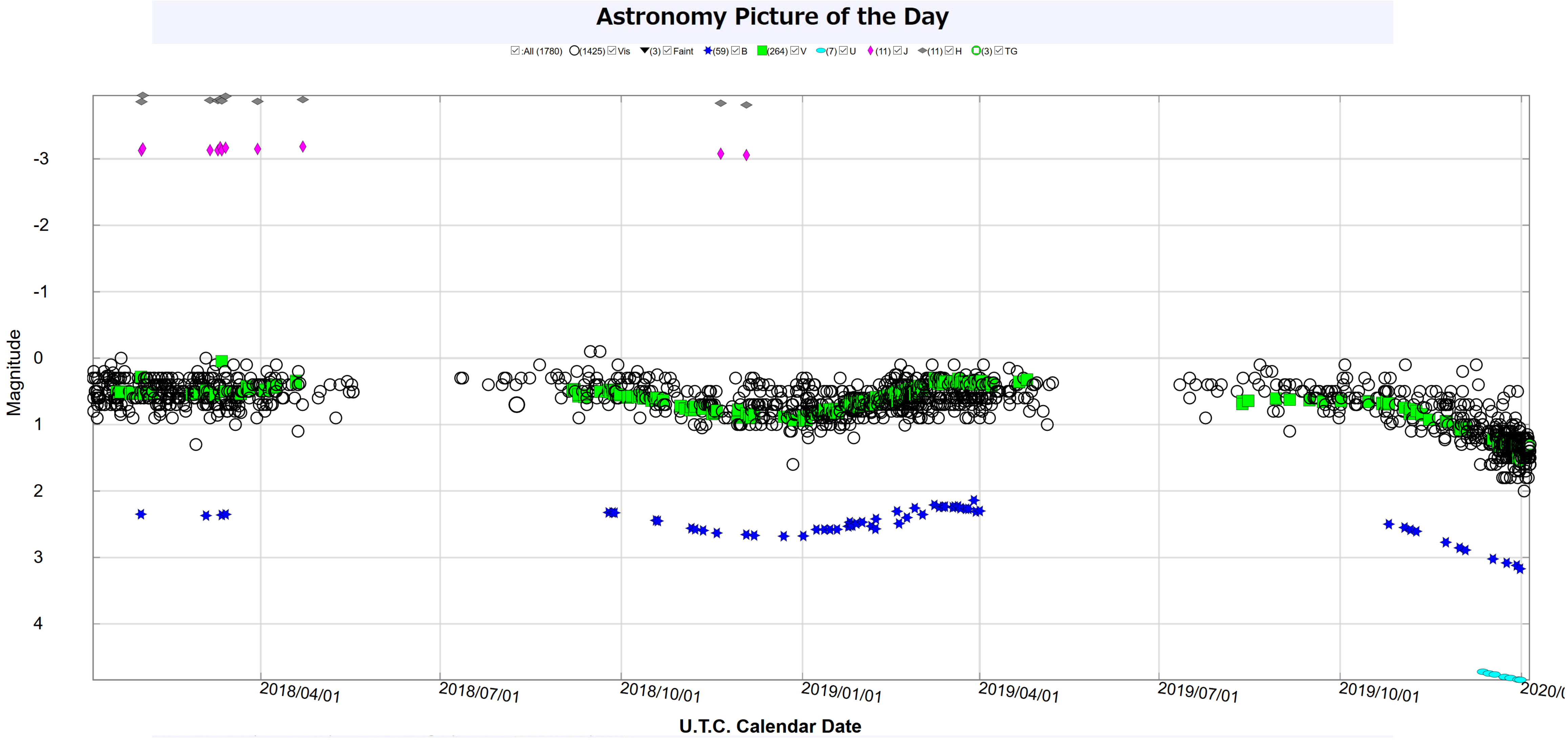
2020 January 2

The Fainting of Betelgeuse
Image Credit & Copyright: Jimmy Westlake (Colorado Mountain College)

Explanation: Begirt with many a blazing star, Orion the Hunter is one of the most recognizable constellations. In this night skyscape the Hunter's stars rise in the northern hemisphere's winter sky on December 30, 2019, tangled in bare trees near Newnan, Georgia, USA. Red supergiant star Betelgeuse stands out in yellowish hues at Orion's shoulder left of center, but it no longer so strongly rivals the blue supergiant star Rigel at the Hunter's foot. In fact, skygazers around planet Earth can see a strikingly fainter Betelgeuse now, its brightness fading by more than half in the final months of 2019. Betelgeuse has long been known to be a variable star, changing its brightness in multiple cycles with approximate short and long term periods of hundreds of days to many years. The star is now close to its faintest since photometric measurements in 1926/27, likely due in part to a near coincidence in the minimum of short and long term cycles. Betelgeuse is also recognized as a nearby red supergiant star that will end its life in a core collapse supernova explosion sometime in the next 1,000 years, though that cosmic cataclysm will take place a safe 700 light-years or so from our fair planet.

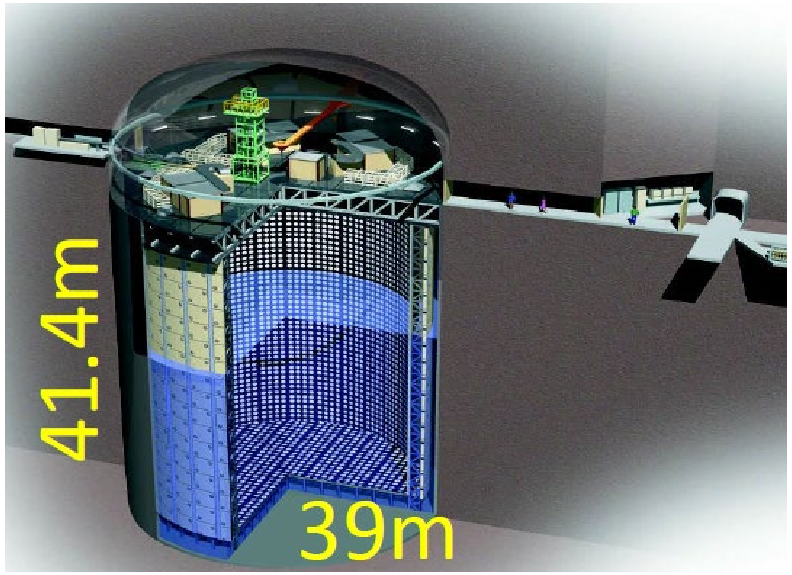
Realtime light curve of Betelgeuse by AAVSO

https://www.aavso.org/LCGv2/



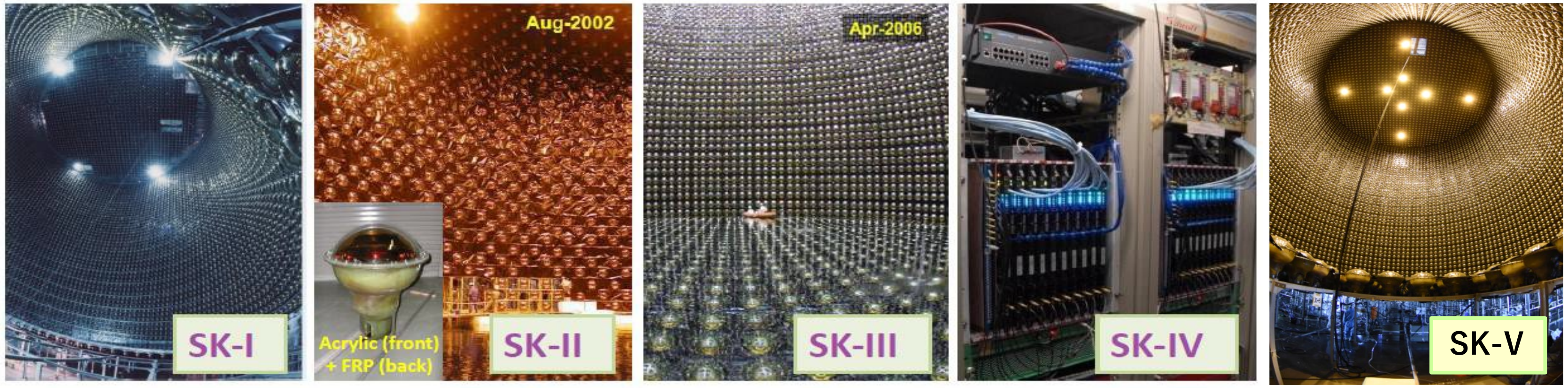
Super-Kamiokande V

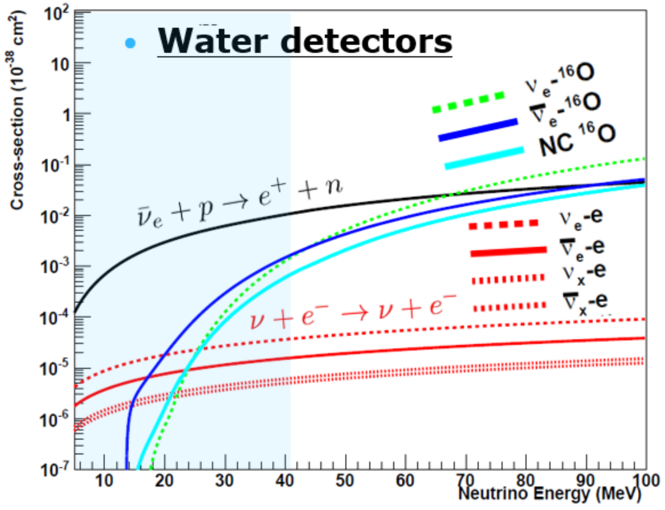
- 32kton ring imaging pure water Cherenkov detector for SNe
  - 11129 50cm PMTs for Inner detector
- 1km (2700 mwe) underground in Kamioka
- Most sensitive to SN $\bar{\nu}_e$ through inverse beta decay
- Since Jan 29, 2019, SK-V has been operated
  - After the tank refurbishment work for coming Gd-loading



1996 2002 2006 2008 2018 **2019**

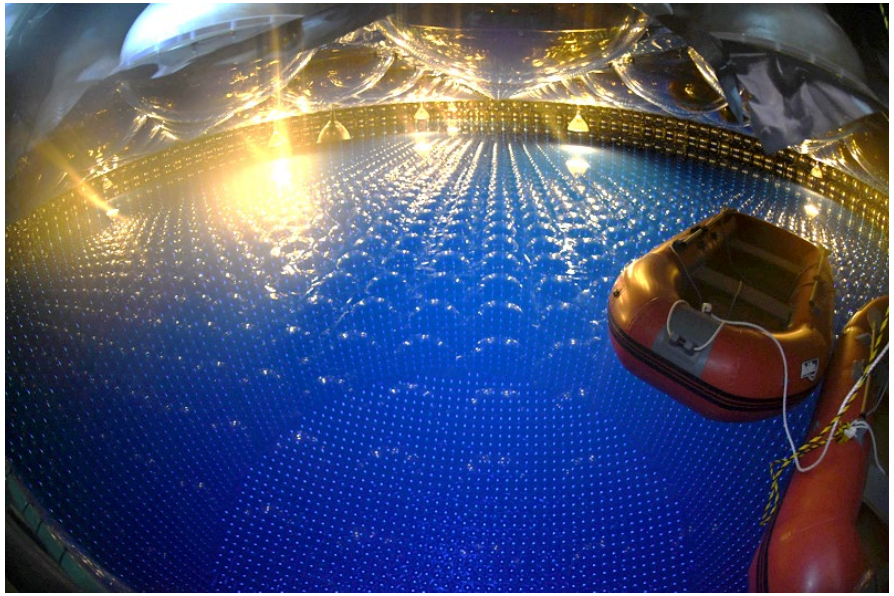
SK-I | SK-II | SK-III | SK-IV | SK-V





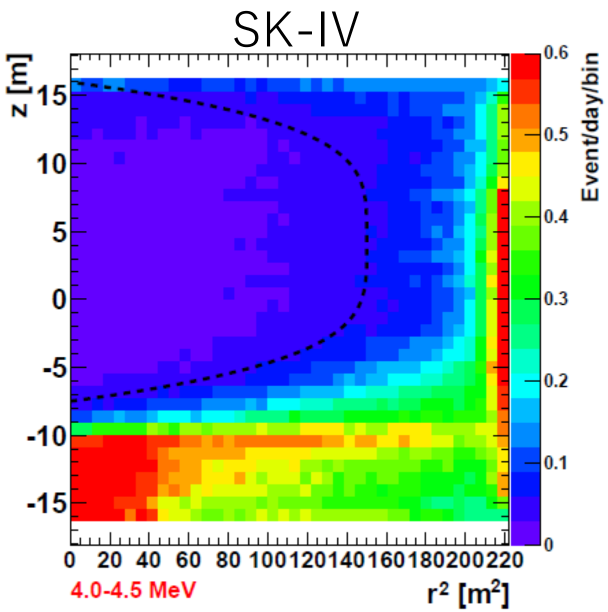
SK-V: The lowest BG phase

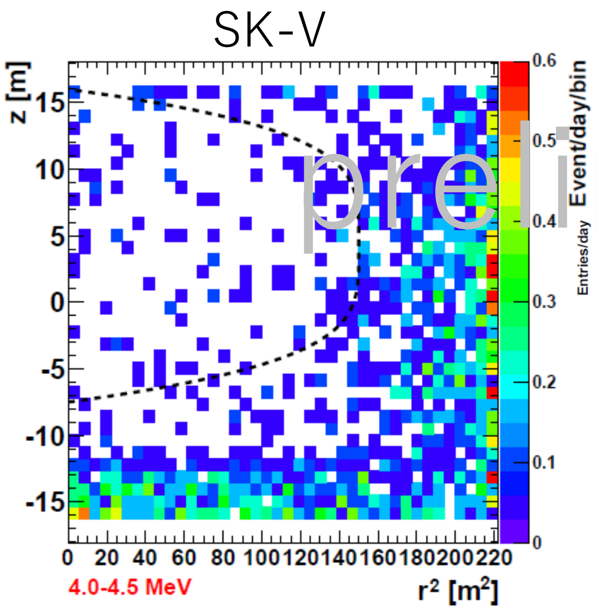
- Cleaning in 2018



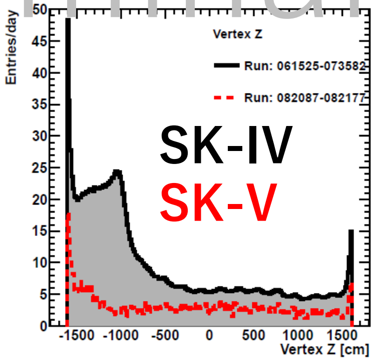
- Tuning the water flow in 2019
  - Water convection is successfully suppressed

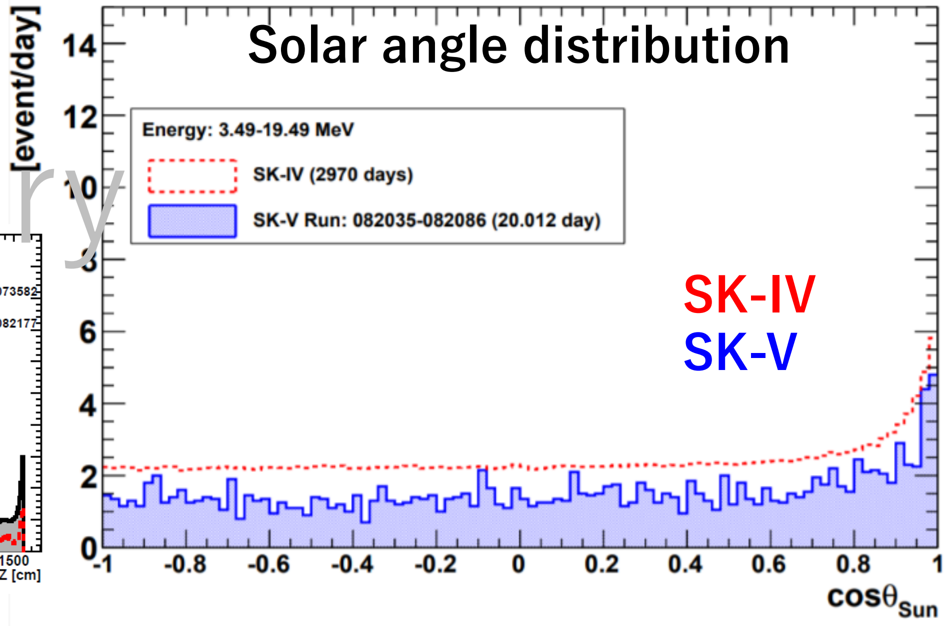
Vertex distributions





preliminary

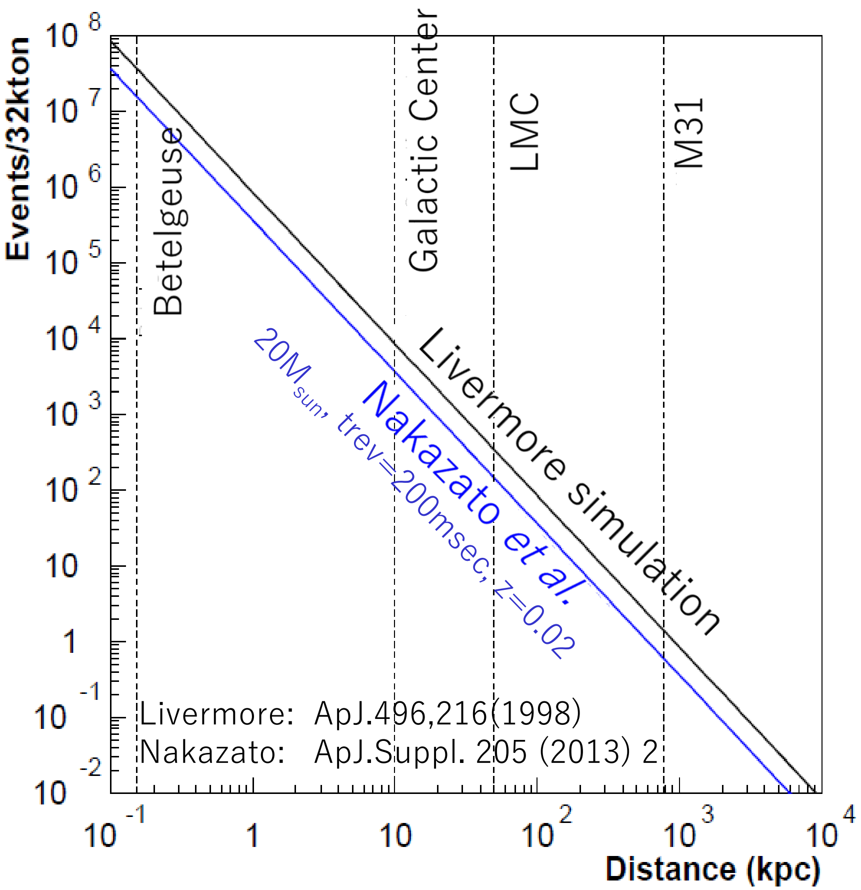




Expected events in SK-V

	Totani1998	Nakazato
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

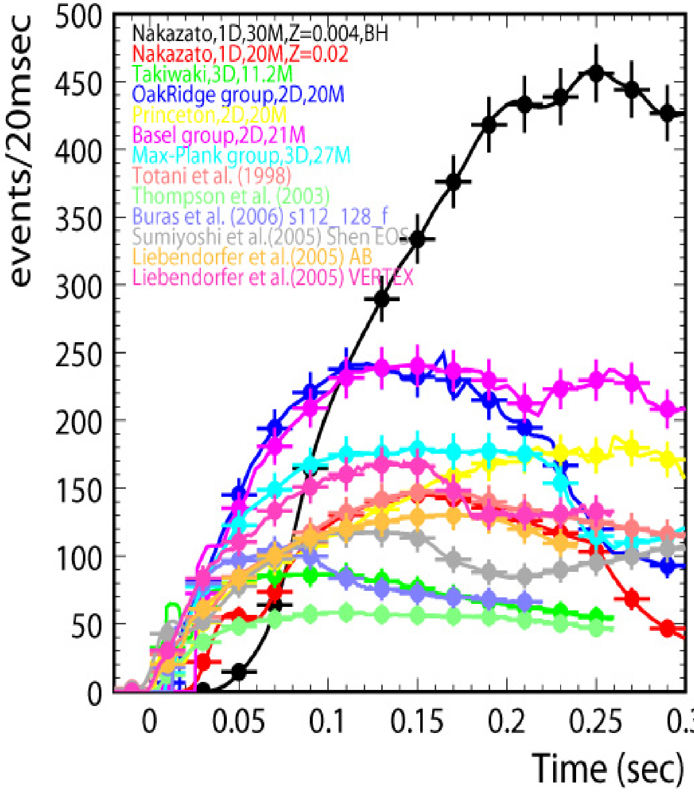
SN at 200pc
~10^8 events



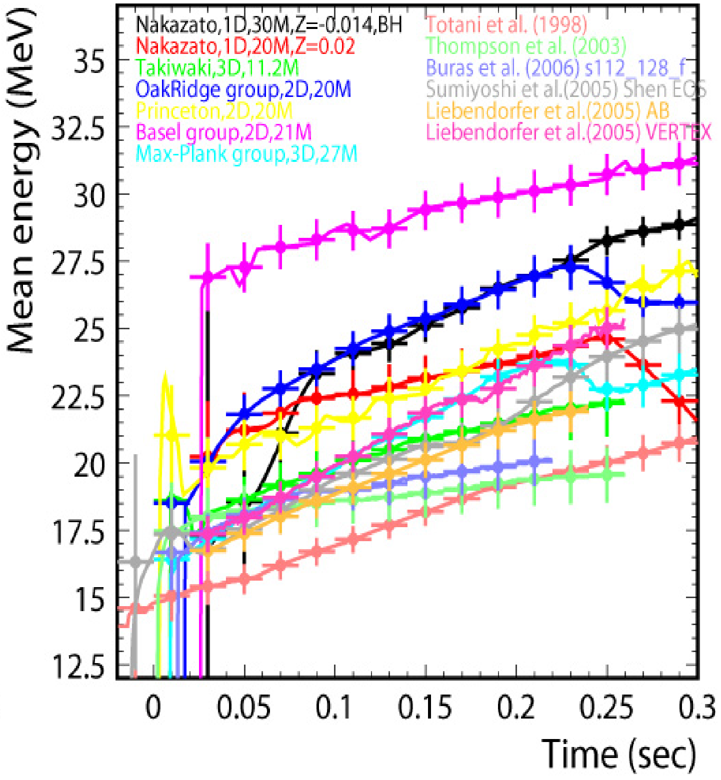
SN at 10 kpc

Enough statistics to discriminate models!

Time variation of event rate

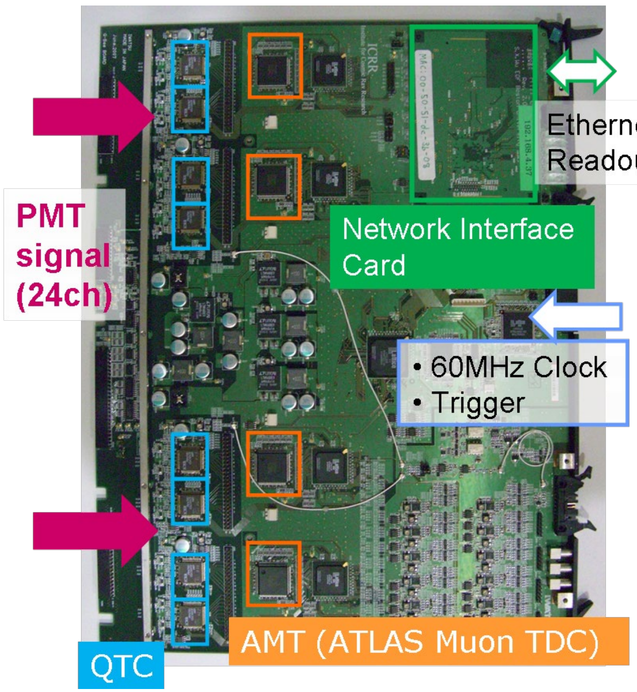


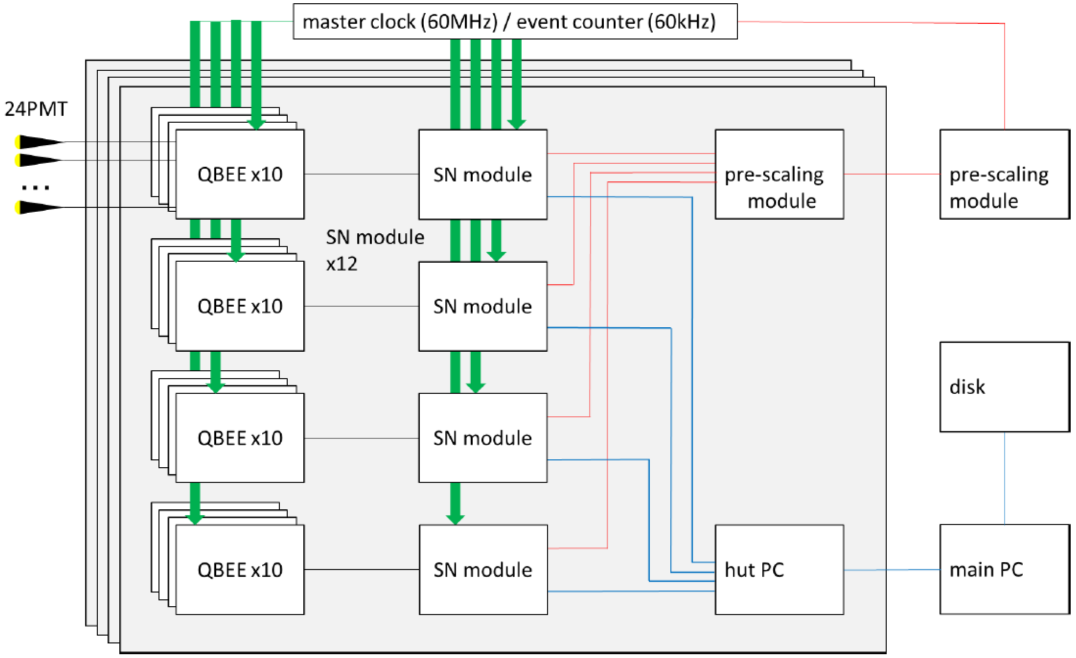
Time variation of mean energy

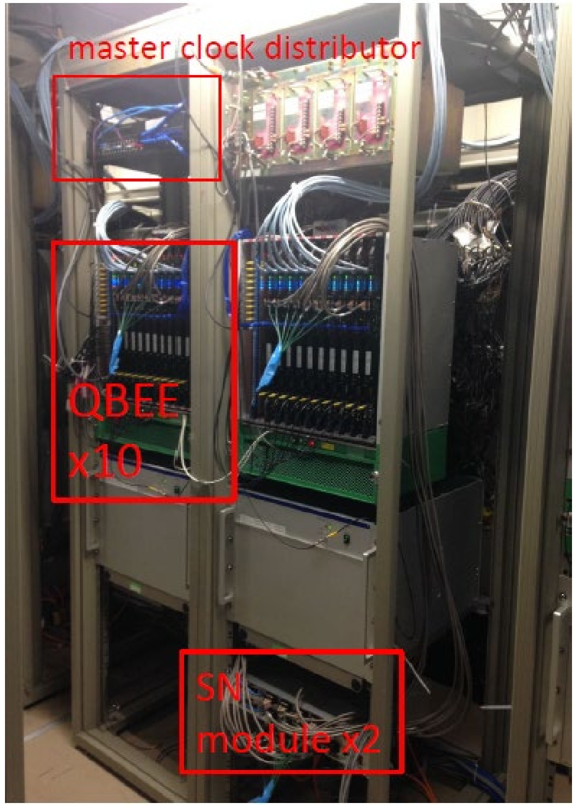


Preparations for Betelgeuse burst

- Betelgeuse is too near: 300M events/10sec
- SK DAQ (QBEE) can deal with up to 6MHz (buffer full)
- With new SN module, number of PMT Hits are retained even for 30MHz burst events

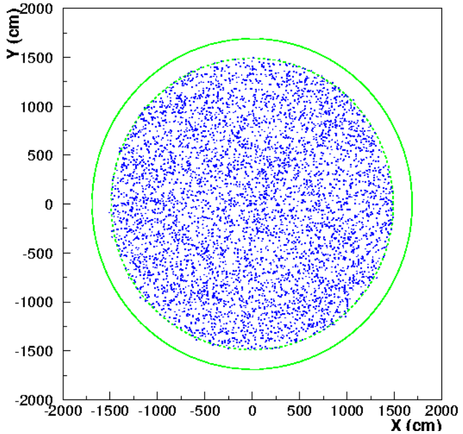


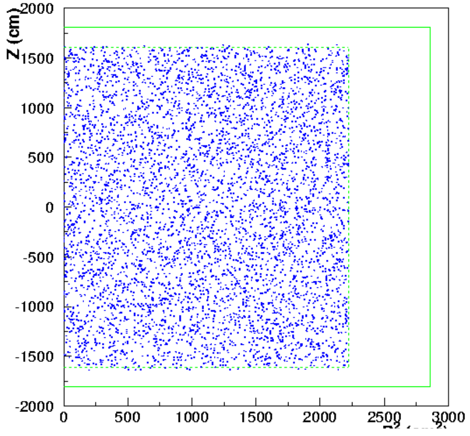


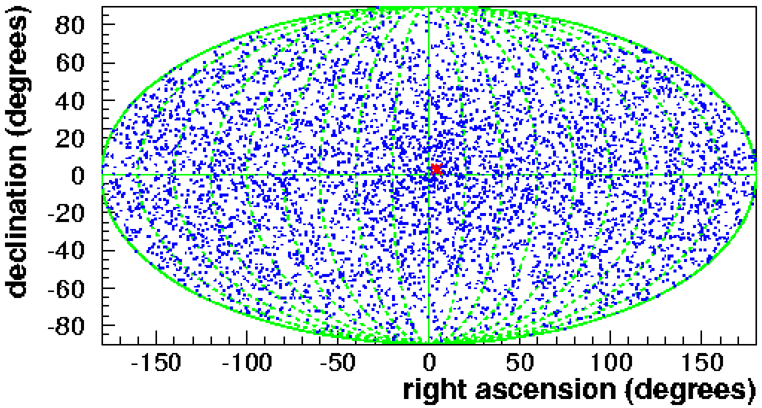


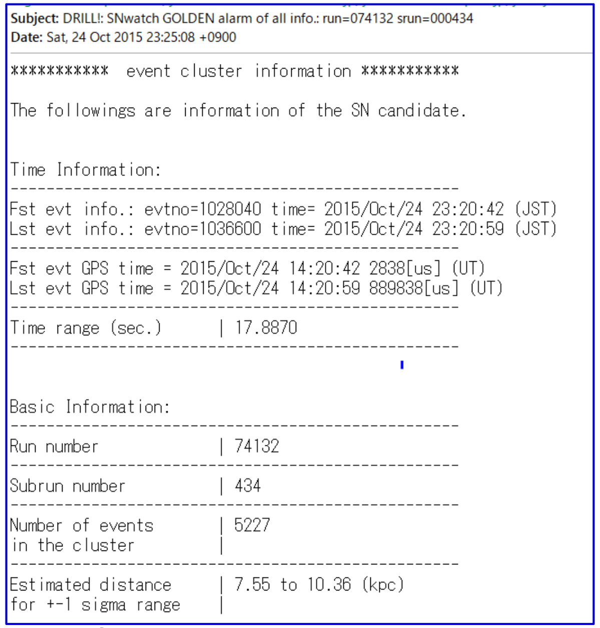
What if SN happens now? @Super-K

- SN simulation @10kpc (RA=0, decl=0), generated by Wilson model
- SNwatch: Real-time supernova neutrino burst monitor   Astropart. Phys. 81(2016)39
  - In several minutes plots are generated automatically and auto-emails+ auto-phone calls follow








Subject: DRILL!: SNwatch GOLDEN alarm of all info.: run=074132 srun=000434
Date: Sat, 24 Oct 2015 23:25:08 +0900

*********** event cluster information ***********

The followings are information of the SN candidate.

Time Information:

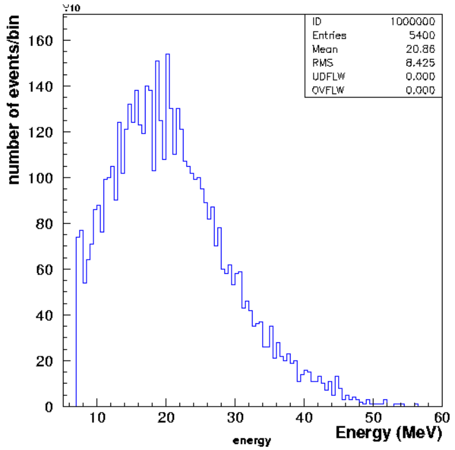
Fst evt info.: evtno=1028040 time= 2015/Oct/24 23:20:42 (JST)
Lst evt info.: evtno=1036600 time= 2015/Oct/24 23:20:59 (JST)

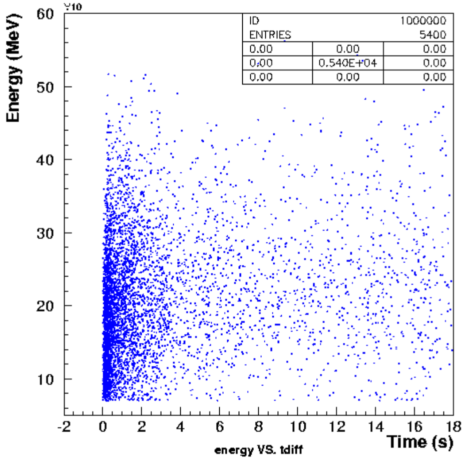
Fst evt GPS time = 2015/Oct/24 14:20:42 2838[us] (UT)
Lst evt GPS time = 2015/Oct/24 14:20:59 889838[us] (UT)

Time range (sec.)	17.8870

Basic Information:

Run number	74132
Subrun number	434
Number of events in the cluster	5227
Estimated distance for +-1 sigma range	7.55 to 10.36 (kpc)

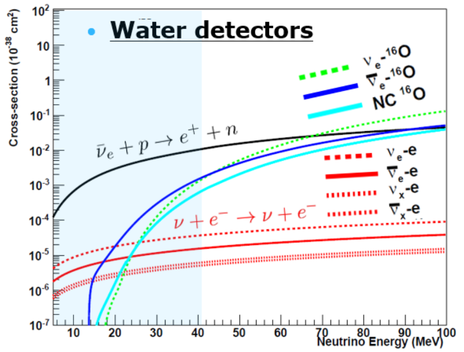


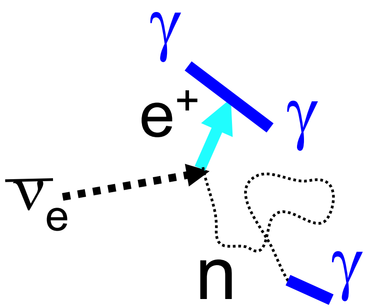


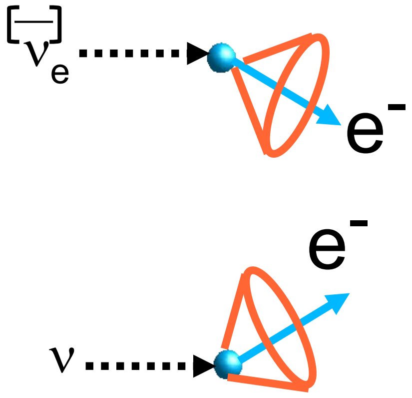
- Golden Alarm:
  - 60 events in 20sec
- The process time depends on the events
  - It takes about 10minutes for the process of 10k events
  - After processing first 1000 events, 1st alarm issued
  - 2nd alarm after finishing all the process

Pointing accuracy

- Advantage of WC detectors
  - Inverse beta events are useless
  - Excess of elastic scattering events

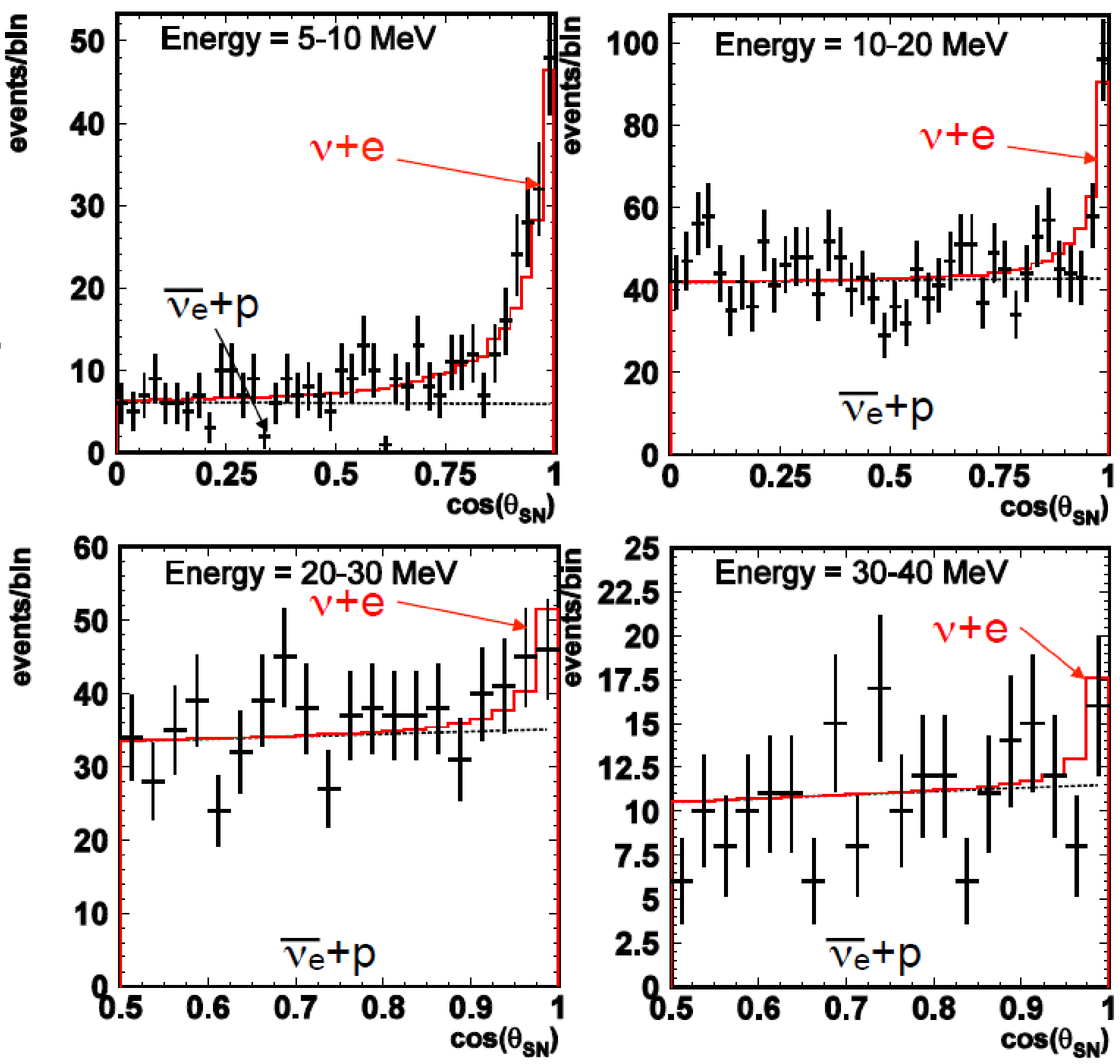






$\bar{\nu}_e p \rightarrow e^+ n$	7300
$\nu + e^- \rightarrow \nu + e^-$	320
^{16}O CC	110

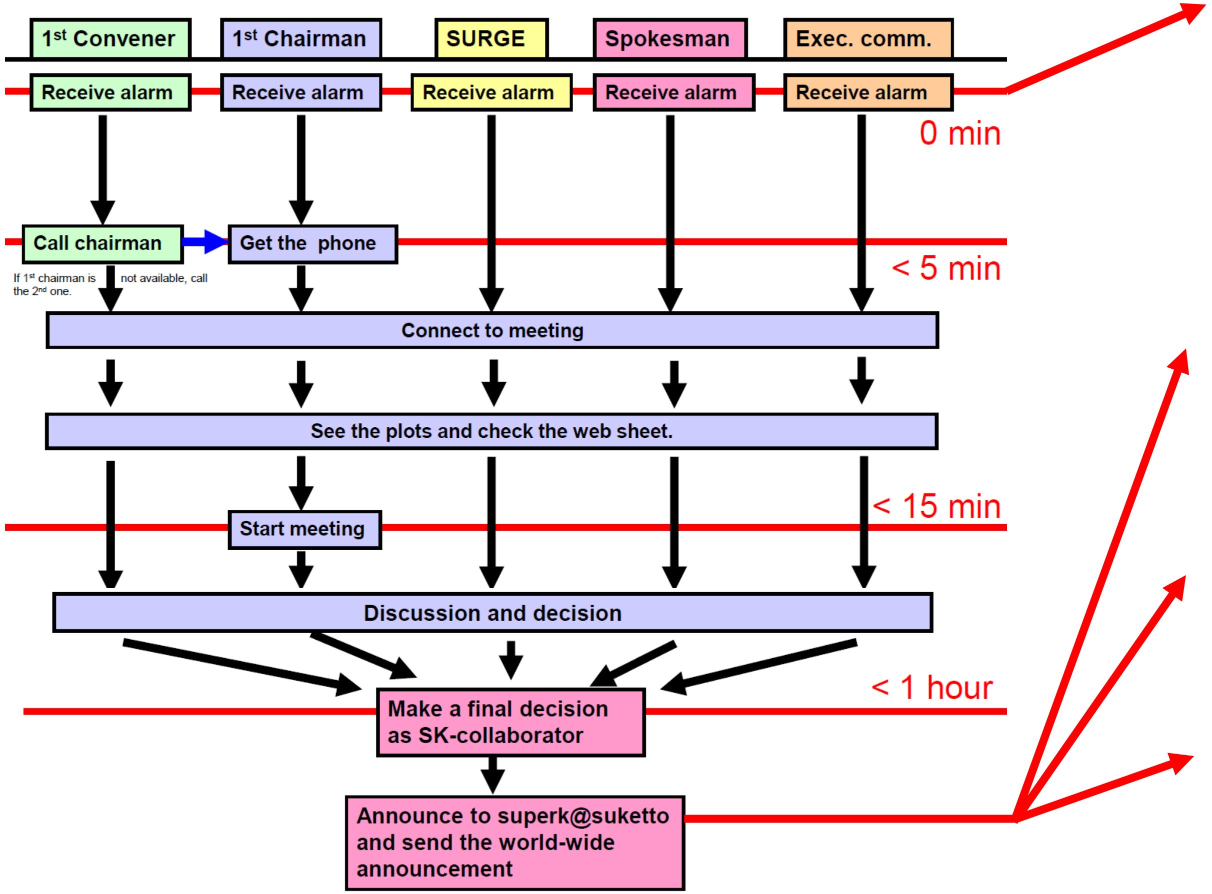
Pointing accuracy ~5° @10kpc SN



- BG reduction by neutron tagging
  - → SK-Gd

Announcements

SURGE:
Supernova Urgent Response Group of Experts



SNEWS level "0"

SNEWS:
SuperNova Early Warning System

http://snews.bnl.gov/

Super-K (Japan), LVD (Italy), Ice Cube (South Pole), KamLAND (Japan), Borexino (Italy) Daya Bay (China), and HALO (Canada).

- IAU CBAT: International Astronomical Union Central Bureau for Astronomical Telegrams
  http://www.cbat.eps.harvard.edu/
- ATEL: The Astronomer's telegram
  http://www.astronomerstelegram.org/
- GCN: The Gamma-ray Coordinates Network
  https://gcn.gsfc.nasa.gov/

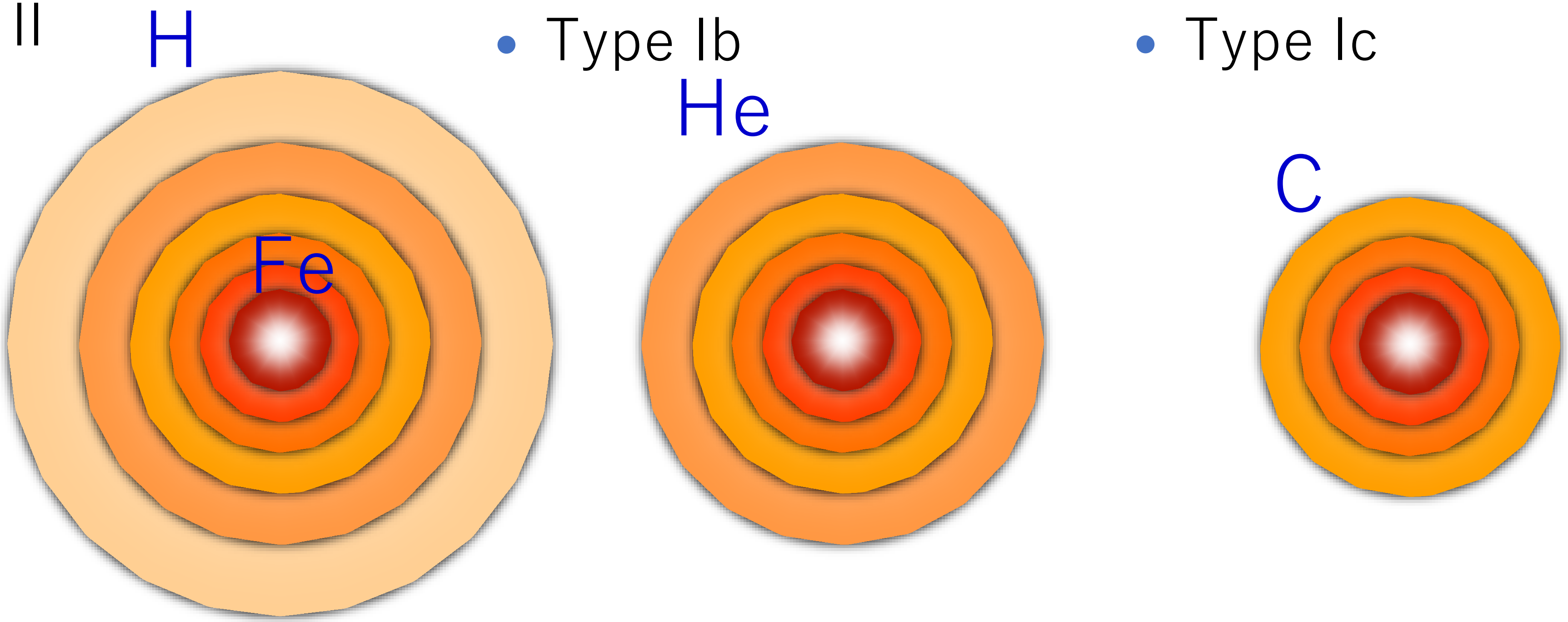
SK's directional information is important for optical telescopes in the multi-messenger astronomy era

Is 1-hour delay OK?

Progenitors of CCSNe

M. Tanaka
@30 years from SN1987A

- Type II
- Type Ib
- Type Ic



N.B. scale is arbitrary

Red supergiants

$R \sim 1000 R_\odot$

Wolf-Rayet stars

$R \sim 1\text{-}10 R_\odot$

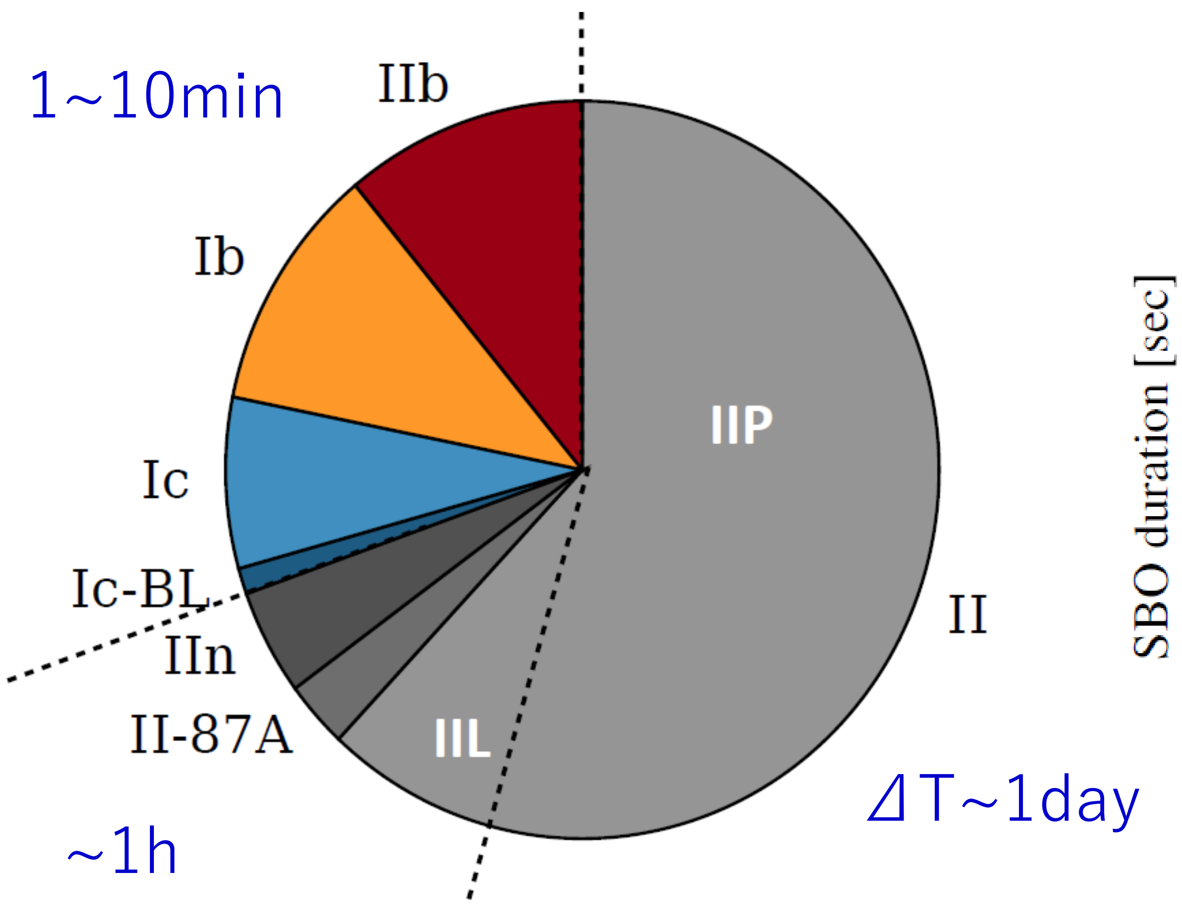
Average shock speed inside of the star
$v \sim 10{,}000 \text{ km s}^{-1} = 10^9 \text{ cm s}^{-1}$

$R_\odot \sim 7 \times 10^{10}$cm

$\Delta T \sim R/v \sim 1\text{day}$

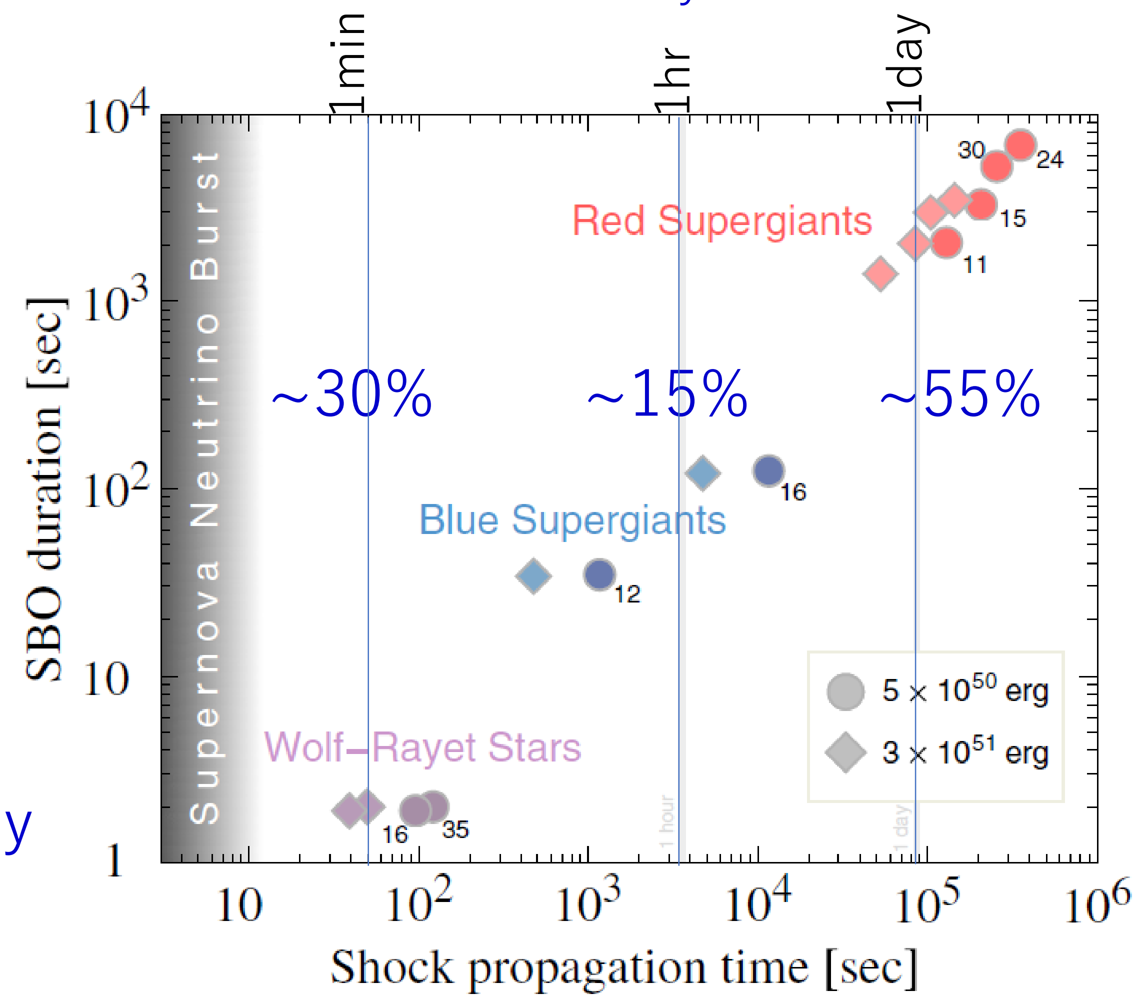
$\Delta T \sim R/v \sim 1\text{-}10\text{min}$

The ratio of each category



I. Shivvers et al., 2017 PASP

M. Tanaka
@30 years from SN1987A



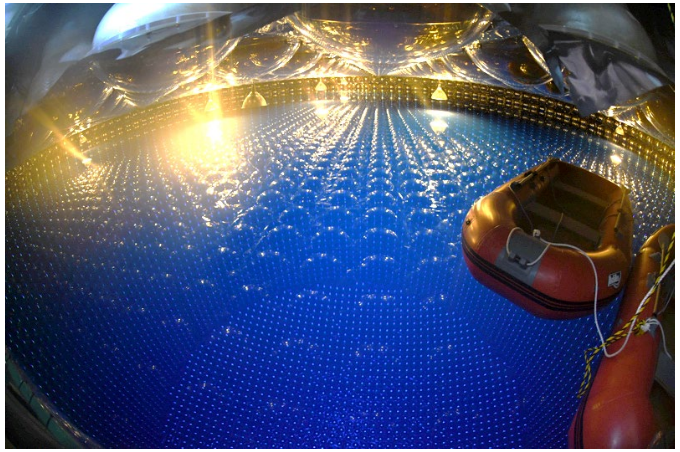
M Kistler et al.,ApJ 778 (2013) 81

- 1 hour may be late.. quicker warning system needed.

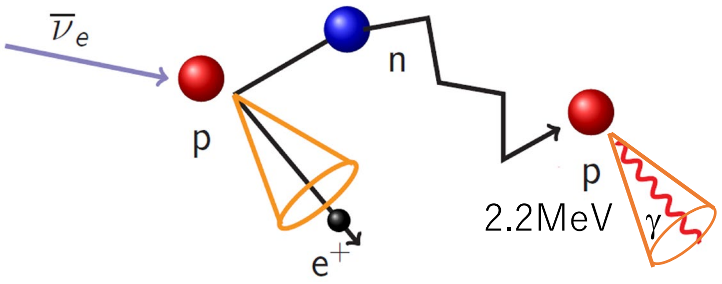
SK-Gd Project

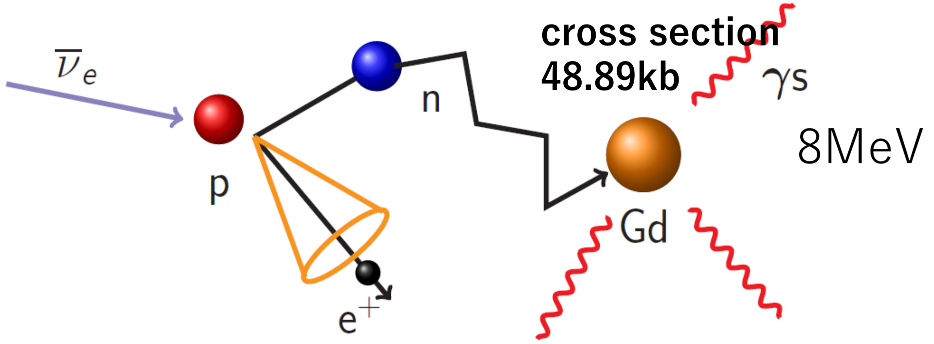
Physic targets

- Precursor of nearby supernova by Si-burning neutrinos
- Improve pointing accuracy for galactic supernova
- **First observation of Supernova Relic Neutrinos**
- Others
  - Reduce proton decay background
  - Neutrino/anti-neutrino discrimination
    (For T2K and atmospheric nu's analyses)
  - Reactor neutrinos

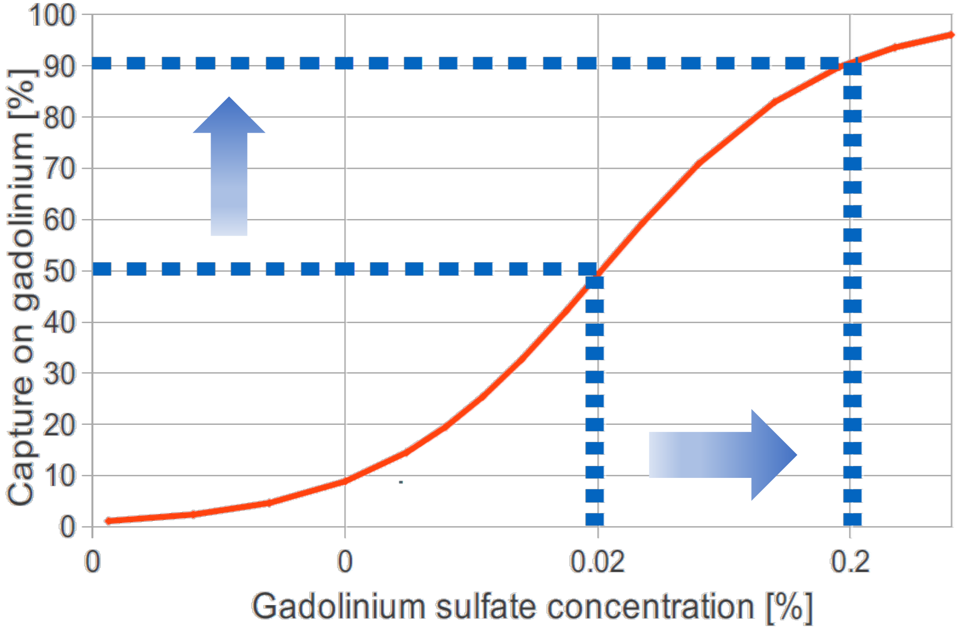


SK-Gd project





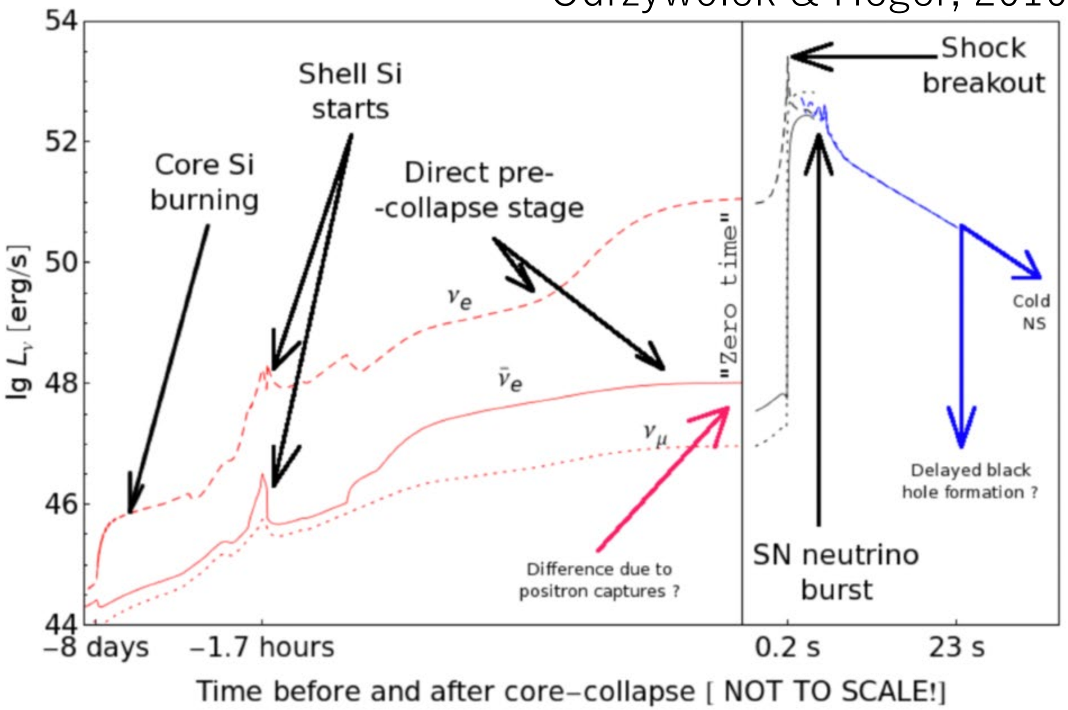
- Loading Gd to SK
  - To significantly enhance detection capability of neutrons from $\bar{\upsilon}$ interactions
  - 0.02% $Gd_2(SO_4)_3$ concentration in Apr. 2020.
    - About 50% of neutron would be captured by Gd, enhancing neutron tagging efficiency by 2-3 times.
- Planned gradual increasement of Gd
  - Final target: 90% of neutron tagging



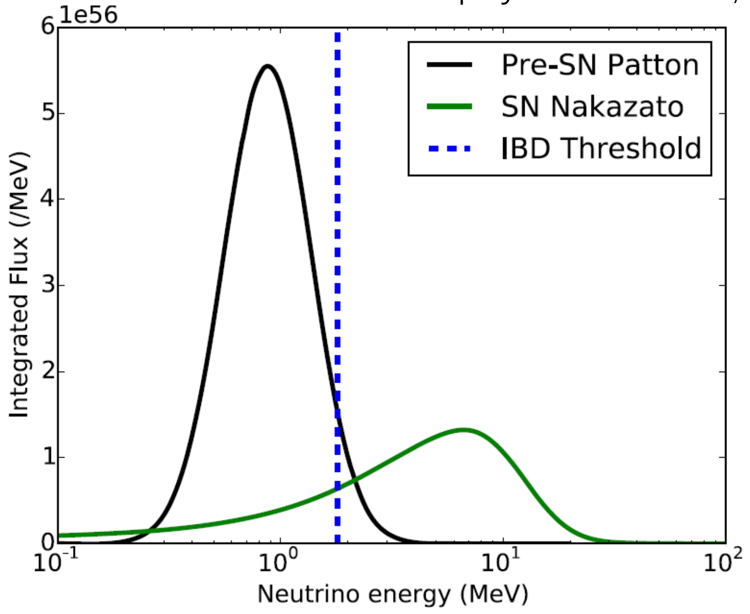
Pre-supernova signals

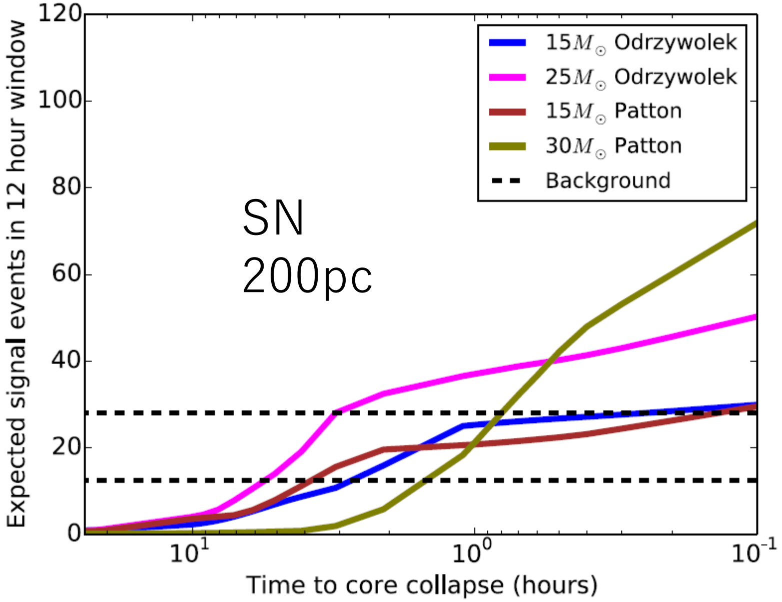
- Precursor signal from Si-burning is detectable for SK-Gd
  - Pre-SN's ν energy is lower than SN's
  - Gd loading is a requirement for SK

Odrzywolek & Heger, 2010



The Astrophysical Journal, 885:133, 2019

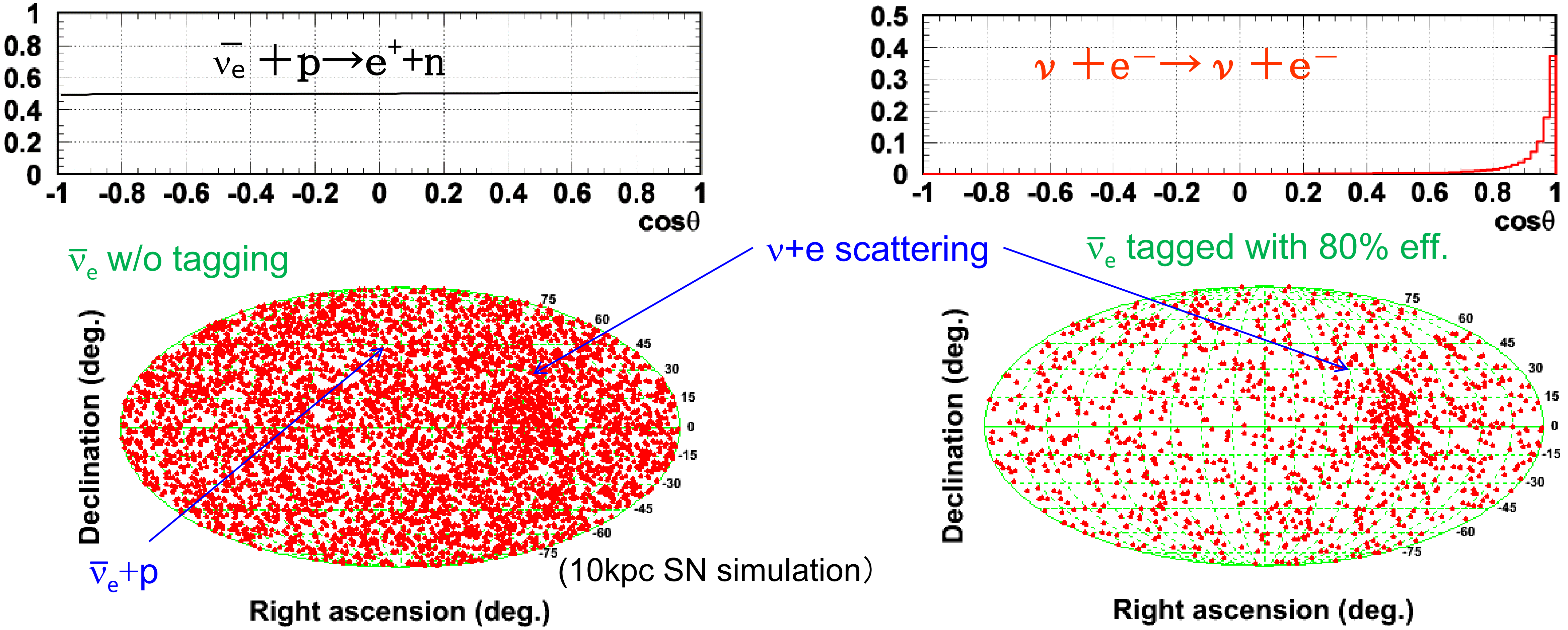




Early warning system will be prepared

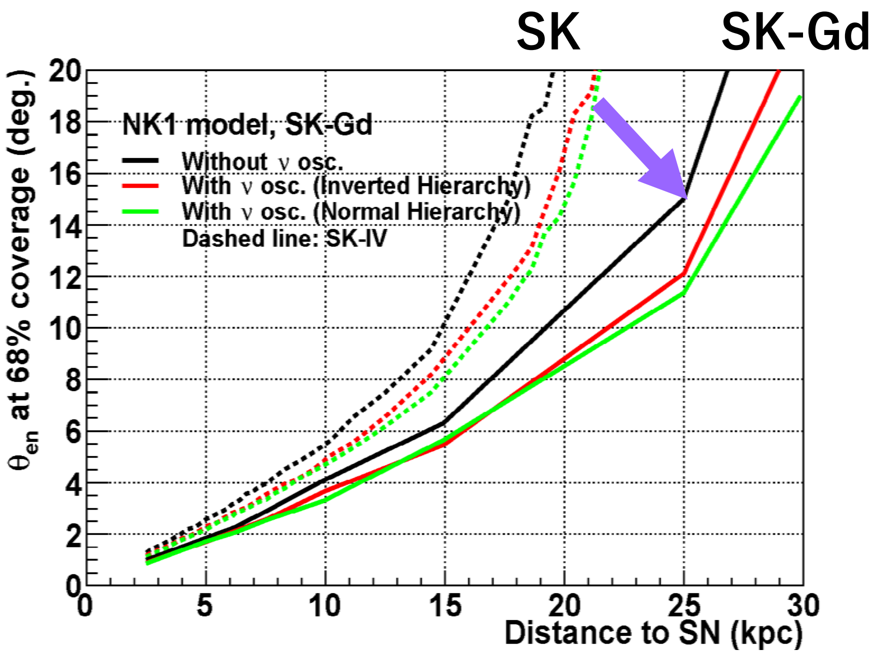
SK-Gd pointing accuracy

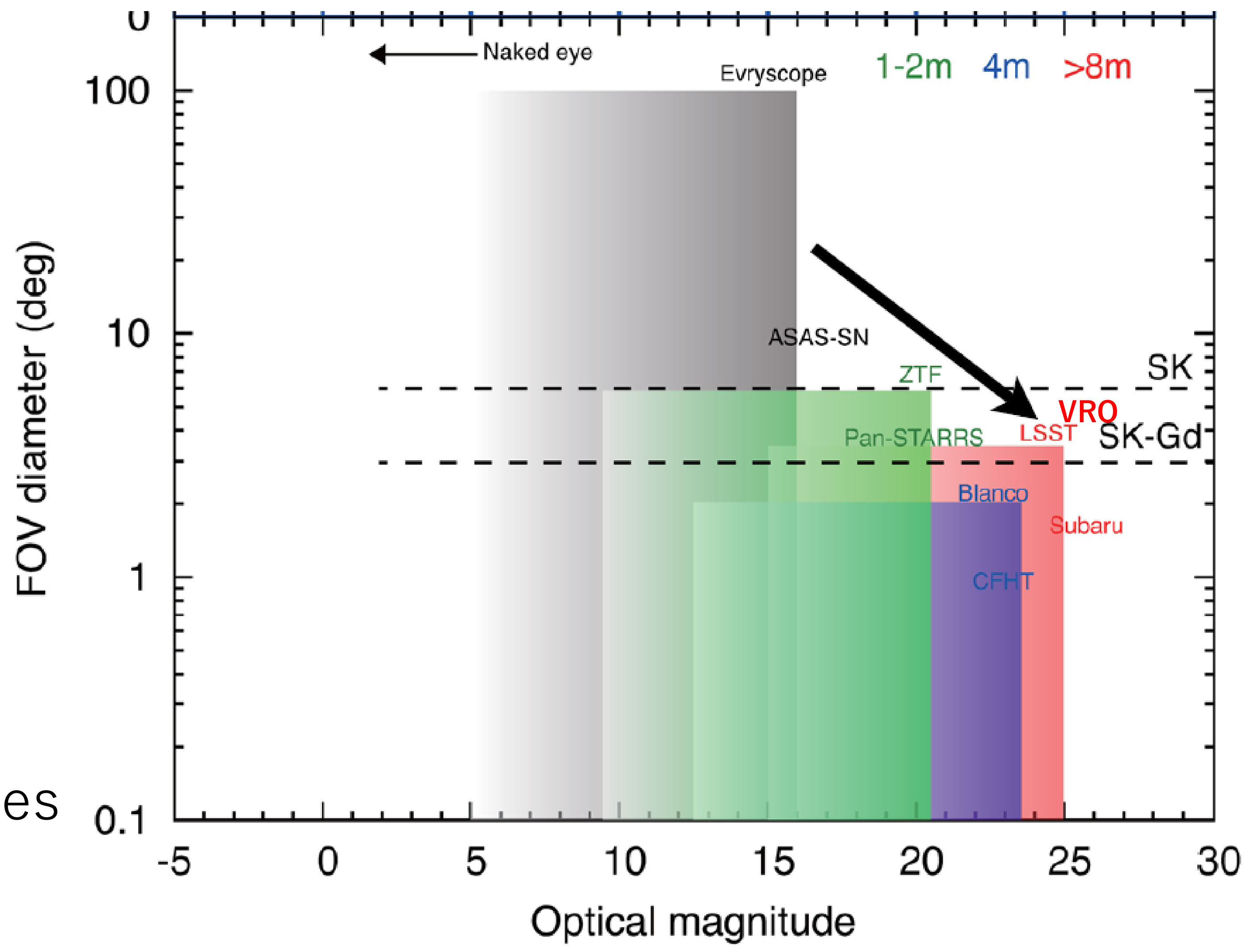
- $\bar{\nu}_e$ events can be tagged and rejected, and directional events (ν_e+e scattering events) are enhanced.



Impact of SK-Gd

Nakamura, Horiuchi et al., MNRAS, 461, 3296 (2016)

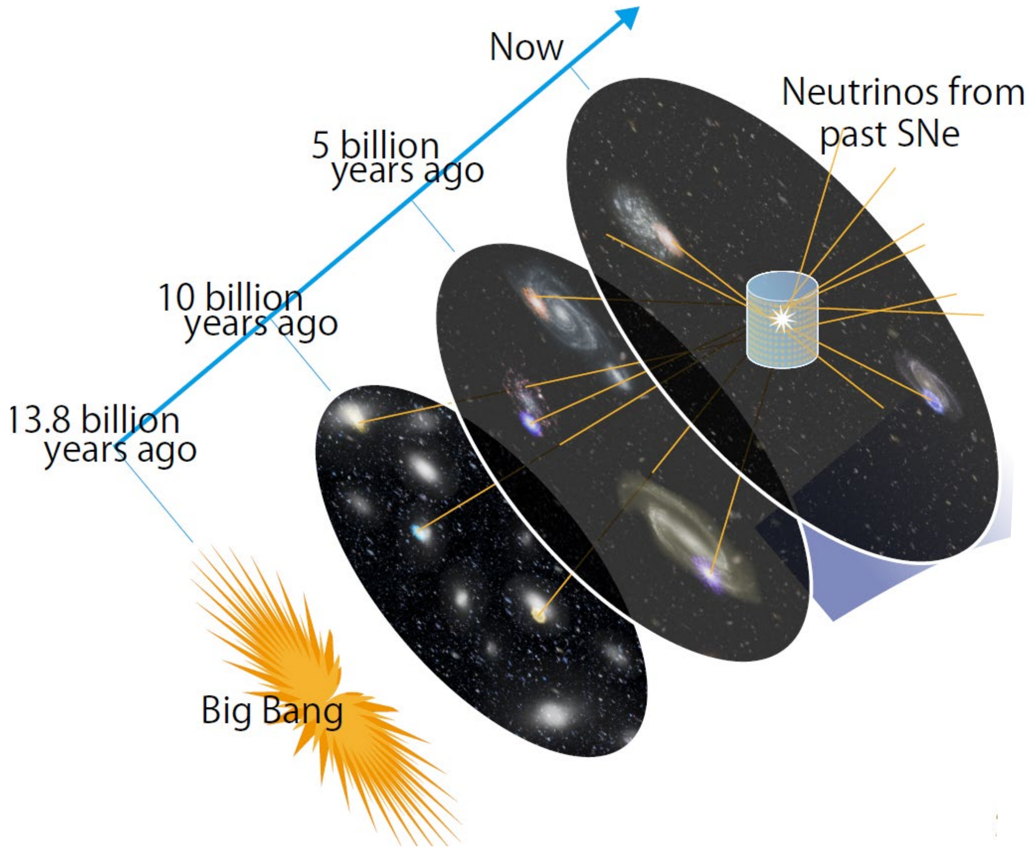




For 10kpc SN ~5° → ~3°

- Pointing in 3° accuracy will allow the follow-up with large telescopes

Diffused Supernova Neutrino Backgrounds
Supernova Relic Neutrino

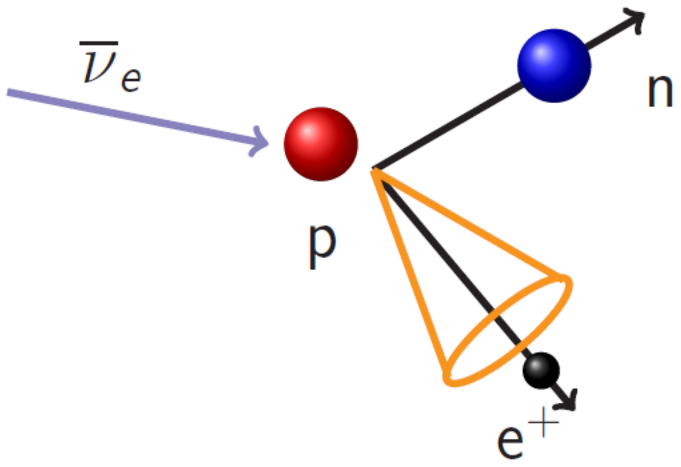


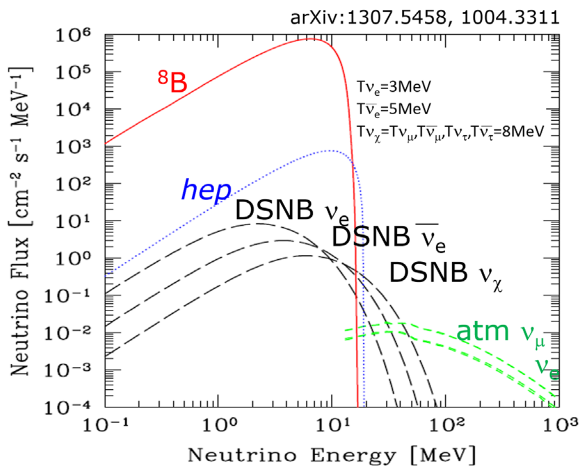
- Neutrinos produced from the past SN bursts and diffused in the current universe.
  - ~ a few SN explosions every second → $O(10^{18})$ SNe so far in this universe
  - Can study history of SN bursts with neutrinos

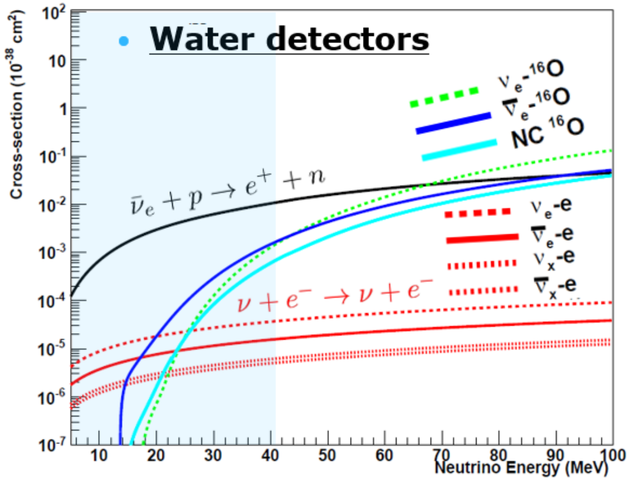
$$\boxed{\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\mathrm{SN}}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz}$$

DSNB signal in SK

- Inverse beta decay channel





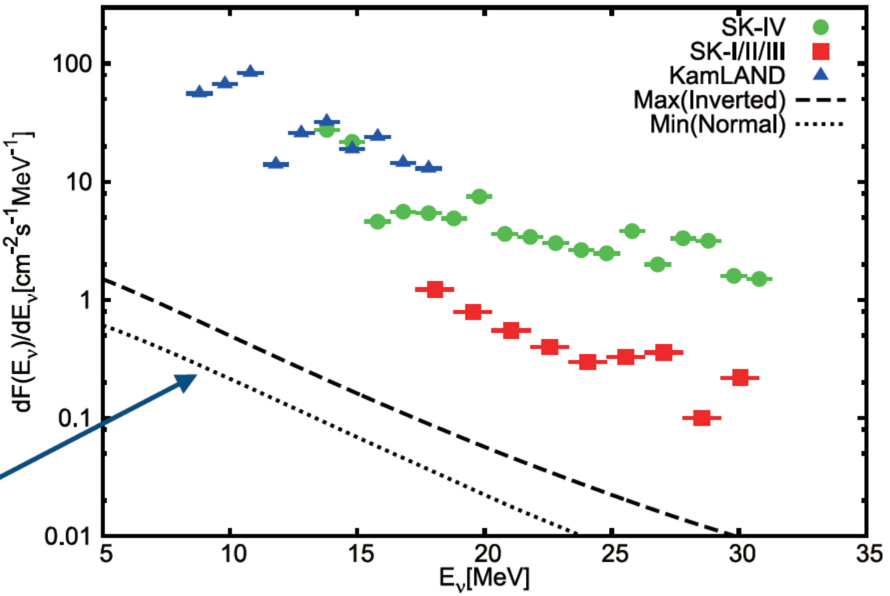


- Super-K holds the current best limits for the DSNB flux
- Sensitivity limited by backgrounds

  However, only one order magnitude above theoretical predictions.
- Should be within Super-K's reach, once we were able to reduce background!

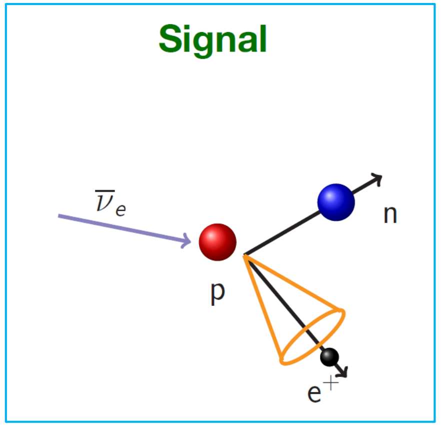
  ➡ Neutron tagging!

Astrophys. J. **804**, 75 (2015)

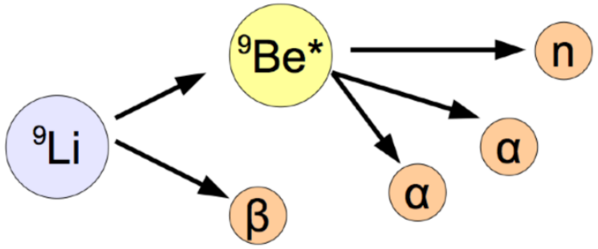


Theoretical predictions

Major backgrounds
after n-tagged

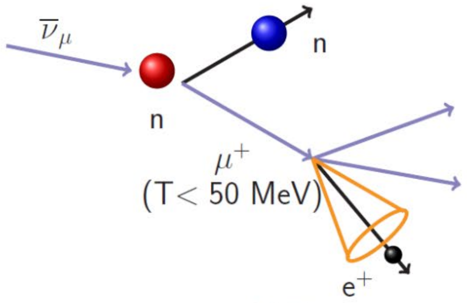


^{9}Li (from cosmic muon spallation)

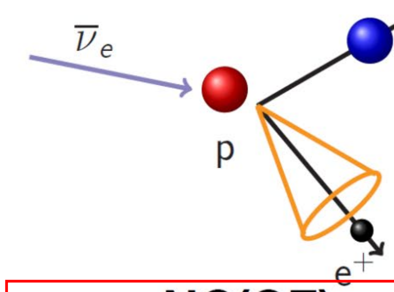


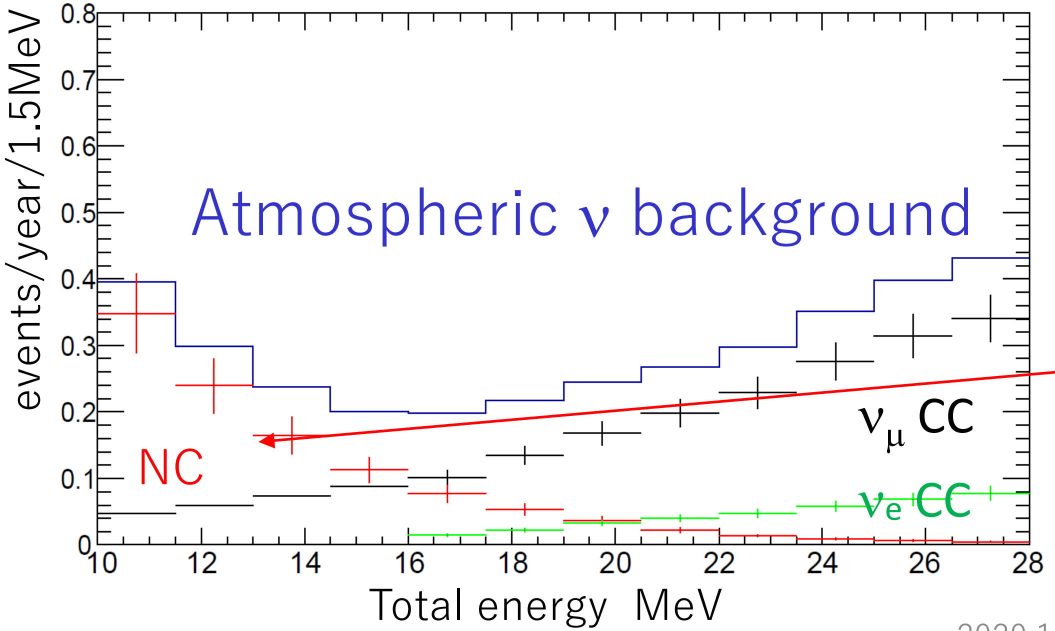
Atmospheric neutrinos

ν_μ CC

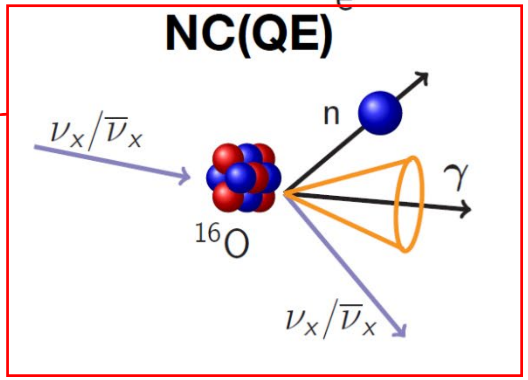


ν_e CC





Among these, atmospheric ν's NC events are the most problematic BG



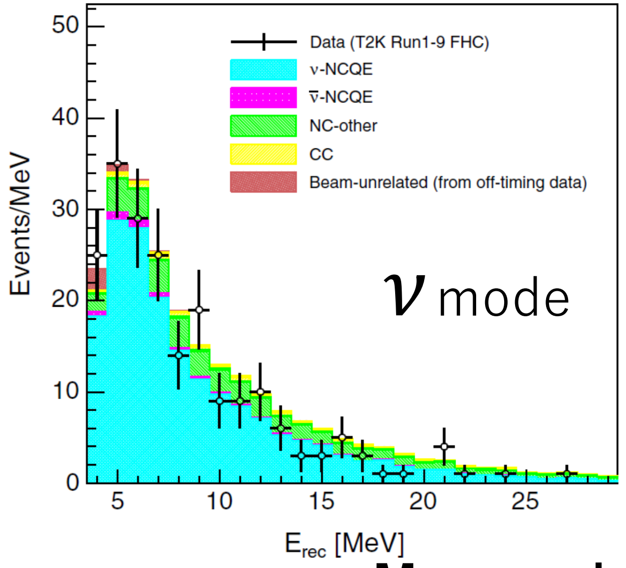
Neutrino calibration source: T2K

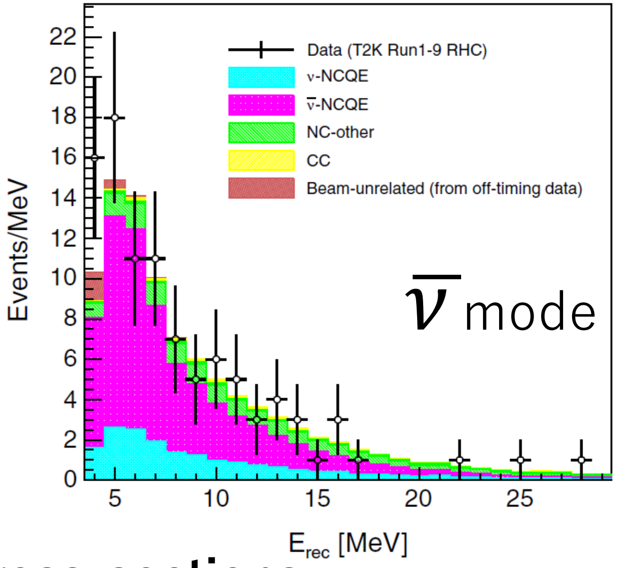
T2K Run 1-9 Phys. Rev. D 100, 112009 (2019)

- Large part of beam energy spectrum overlaps with atmospheric neutrinos

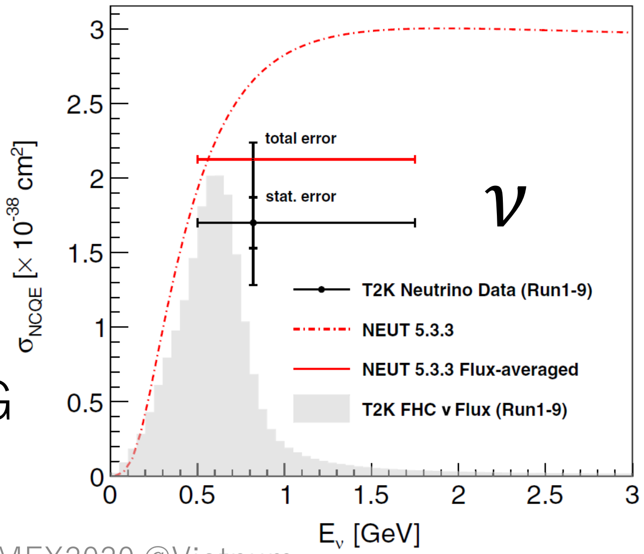
➡ Control sample of NCQE interaction

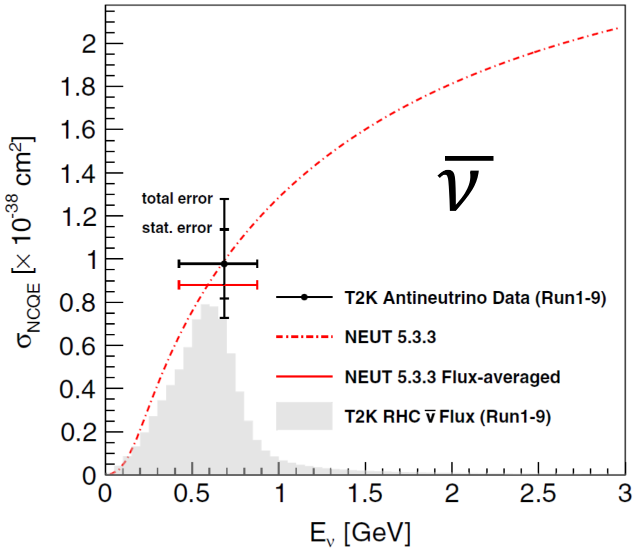
- NCQE cross sections has been measured by T2K for the first time.
    - Still large uncertainty:
        - due to small statistics
        - ~30% systematic error for NCQE BG
    - More data will come





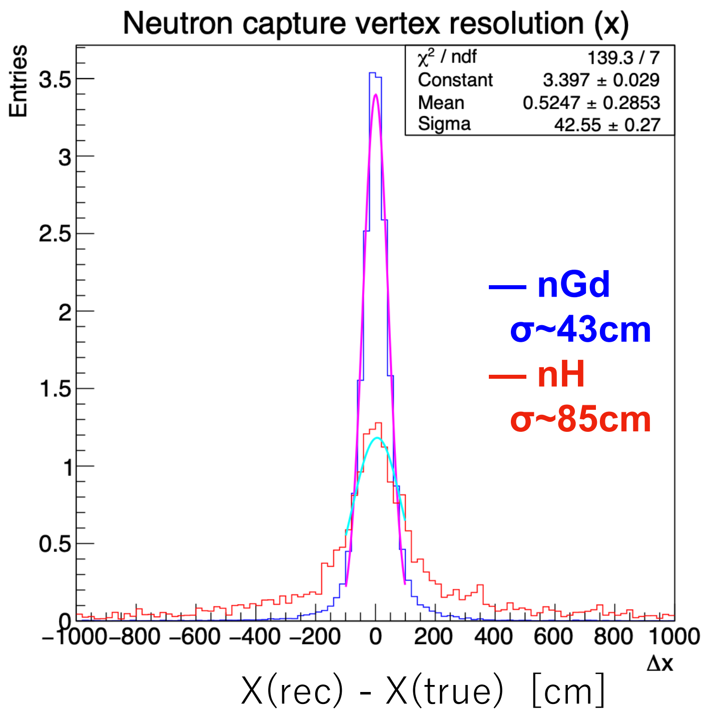
Measured cross-sections

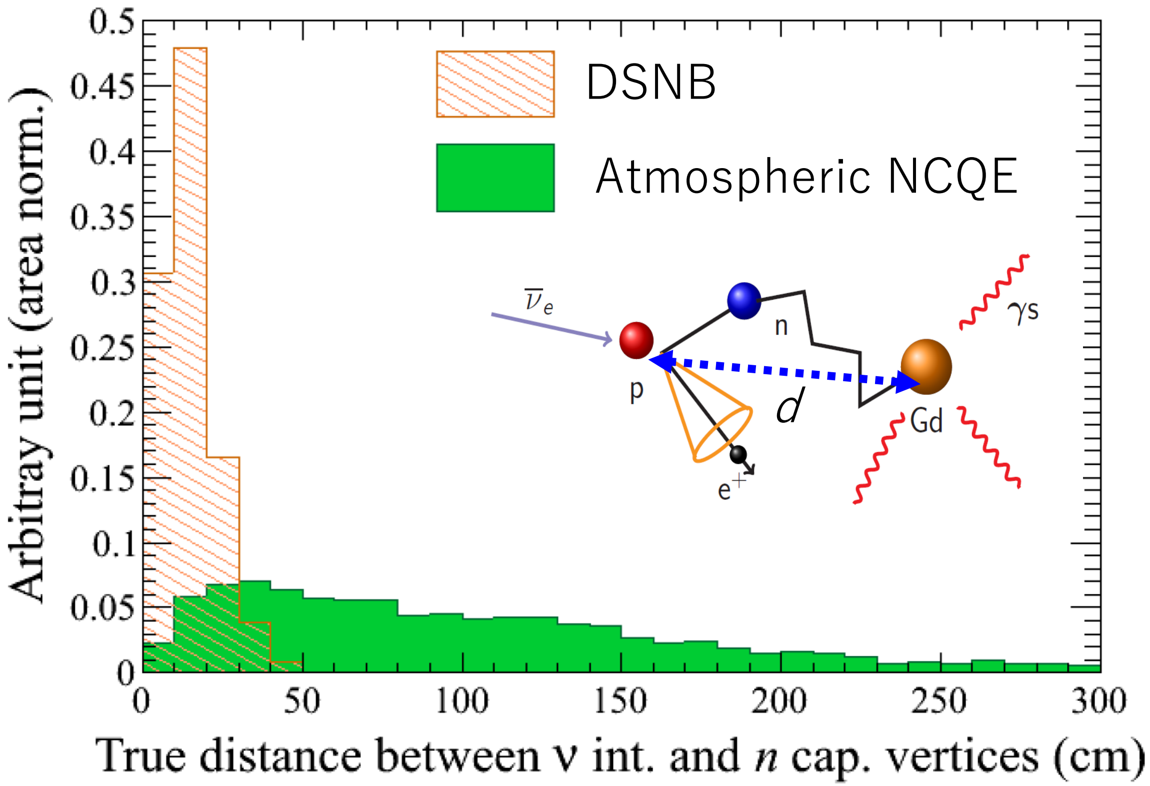




Development of NCQE cut w/ T2K data

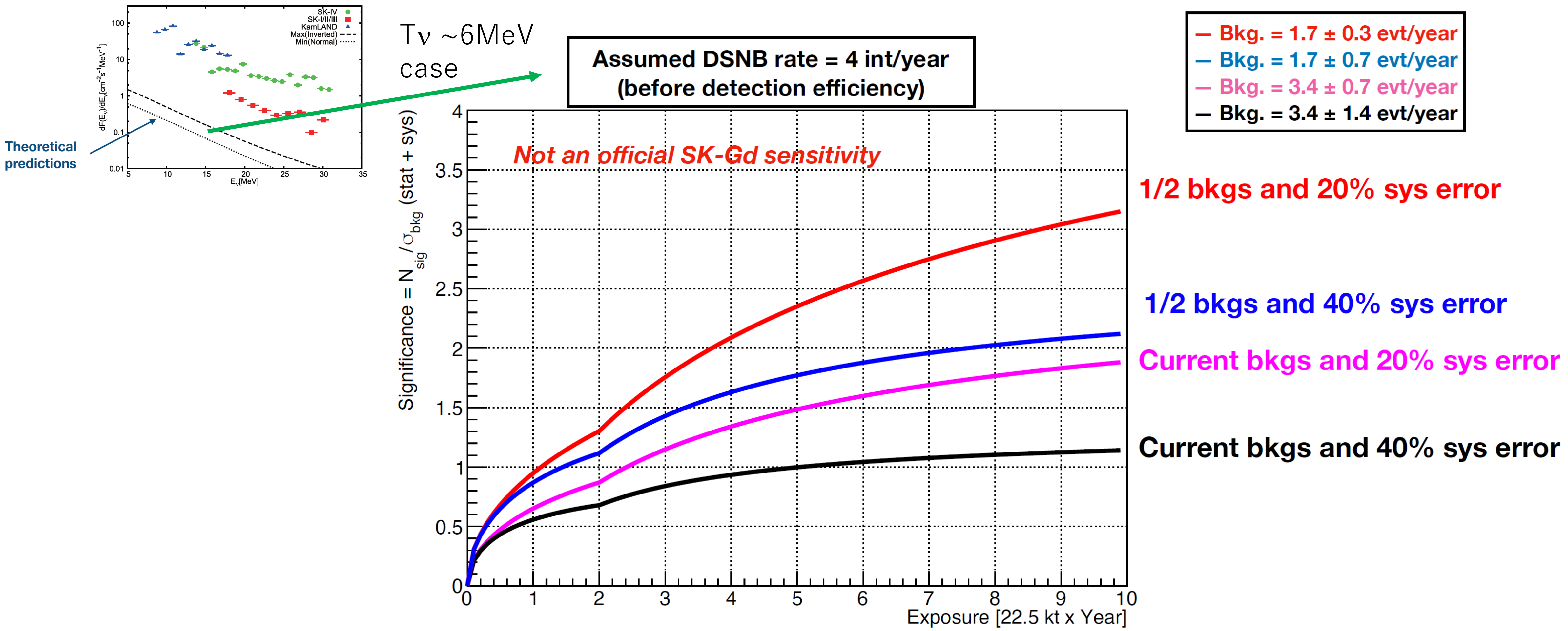
- Improved vertex resolution w/Gd will enable topology cuts.
- Further background reduction w/ event topology
  - Neutron from NQCE interaction should be more energetic





DSNB sensitivity

- Assuming neutron tagging efficiency increased to >70% in 2022

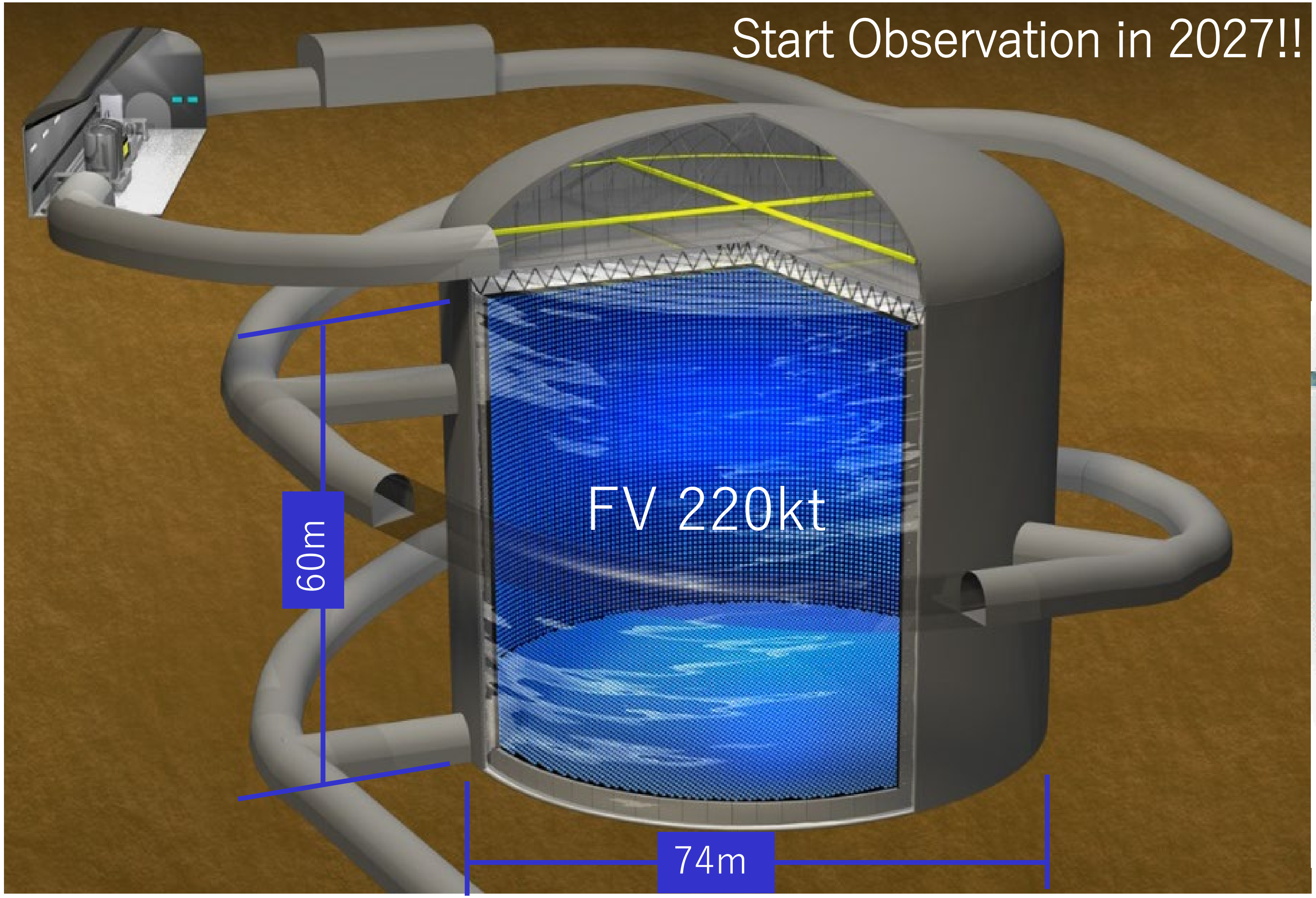


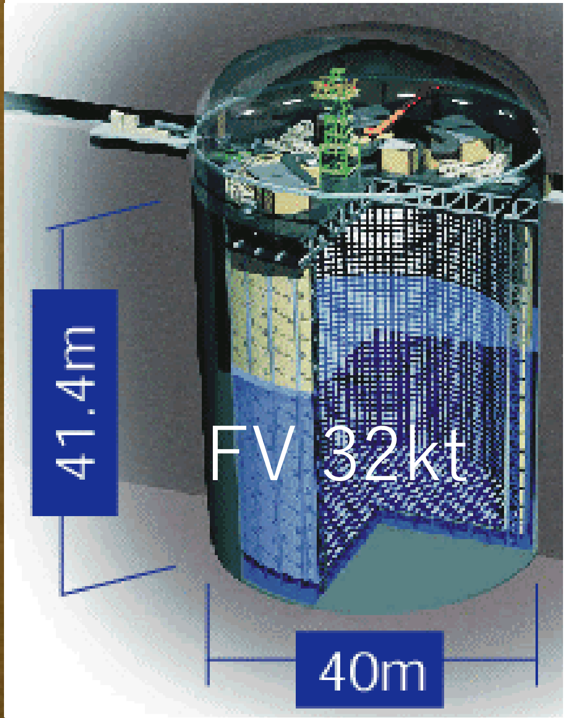
Water system & Gd are ready to go

- 14 tons of ultrapure $Gd_2(SO_4)_3\ 8H_2O$ are prepared.

- These Gd will be dissolved in this April!

Hyper-Kamiokande



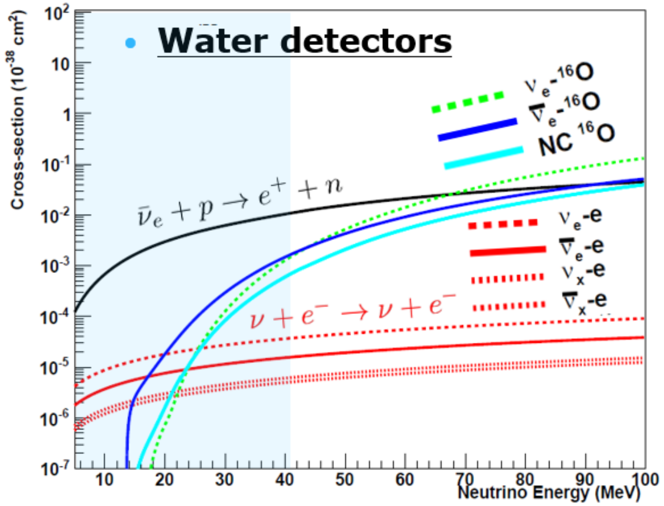


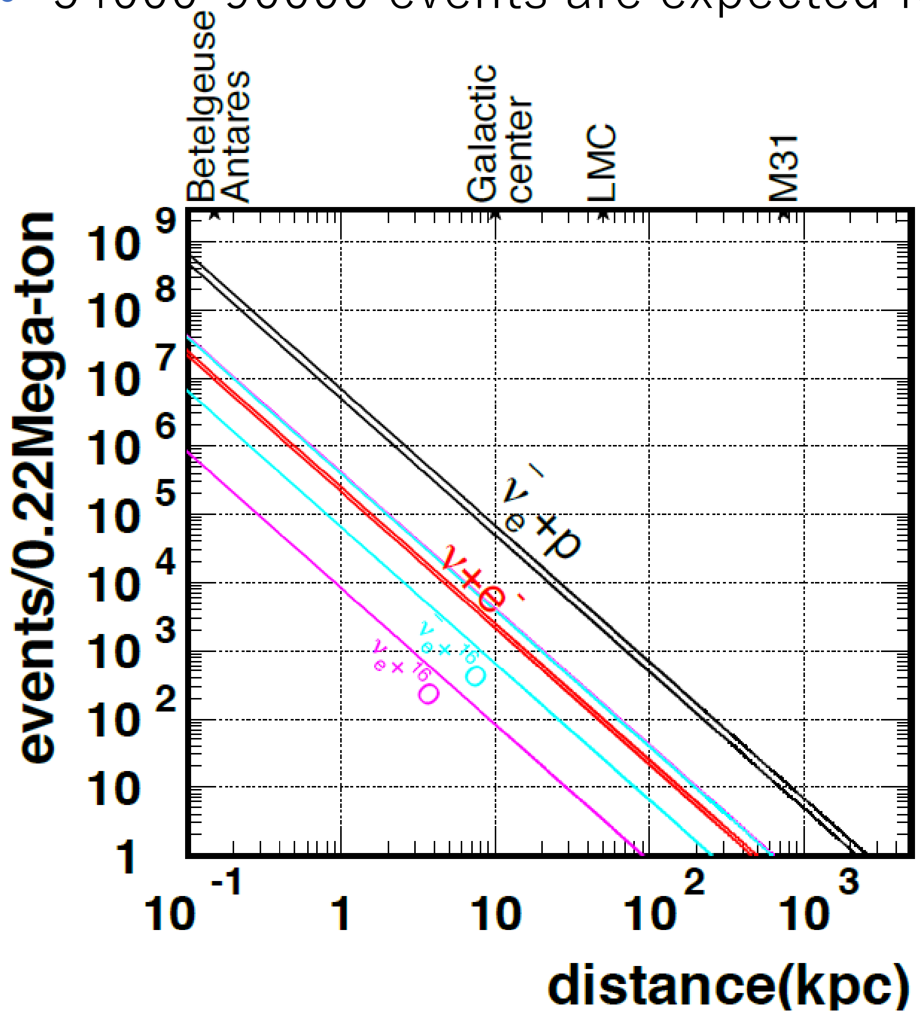
Hyper-Kamiokande

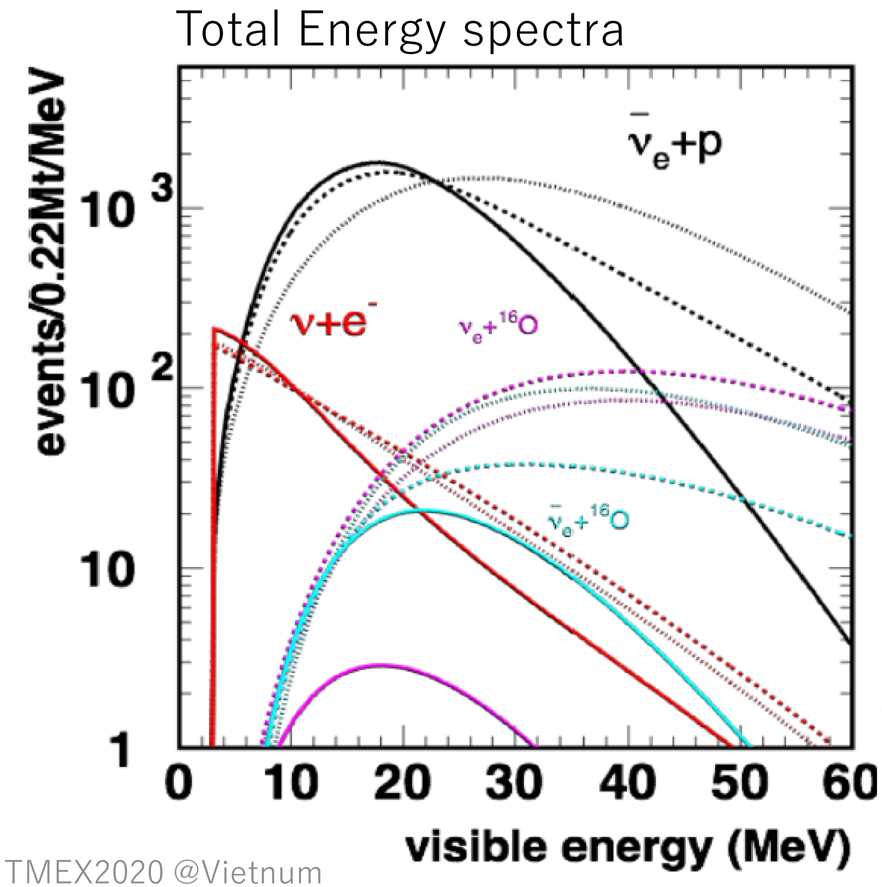
- On December 13, the Japanese cabinet decided new supplemental budget proposal of JFY2019 which includes 3.5 billion JPY for the Hyper-K
- On December 20, the Japanese cabinet decided budget proposal of JFY2020 which includes 0.3 billion JPY for the Hyper-K.
- The construction has been started already.

Expected events in HK

- SK 32kt → HK 220kt
  - Not only inverse beta decay, but also other interactions
- 54000-90000 events are expected for the galactic SN





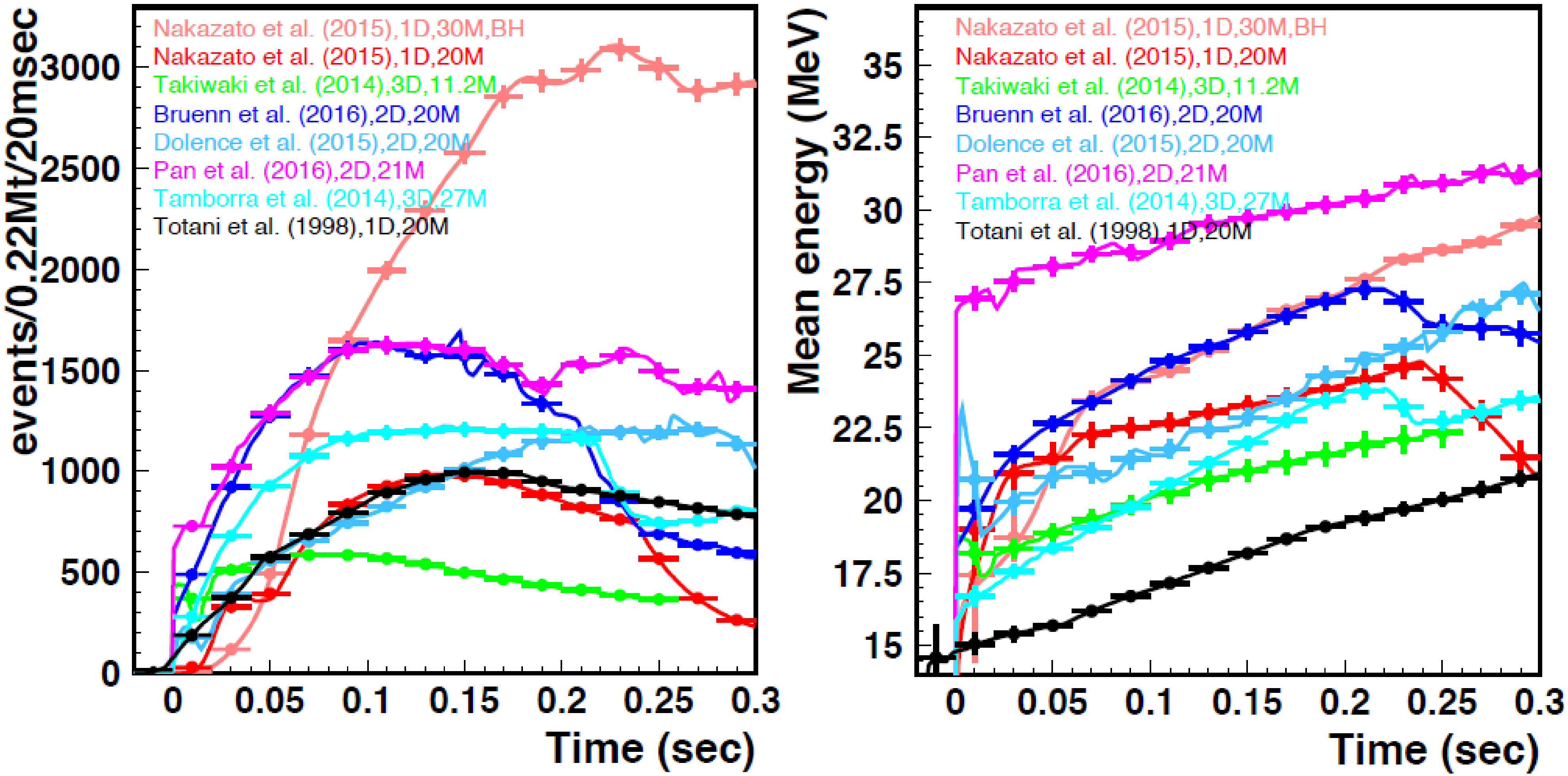


Totani1998

Expected events in HK

- SK 32kt → HK 220kt
  - Inverse beta decay events

Easier to discriminate models!



SN at 10 kpc

Power of the statistics

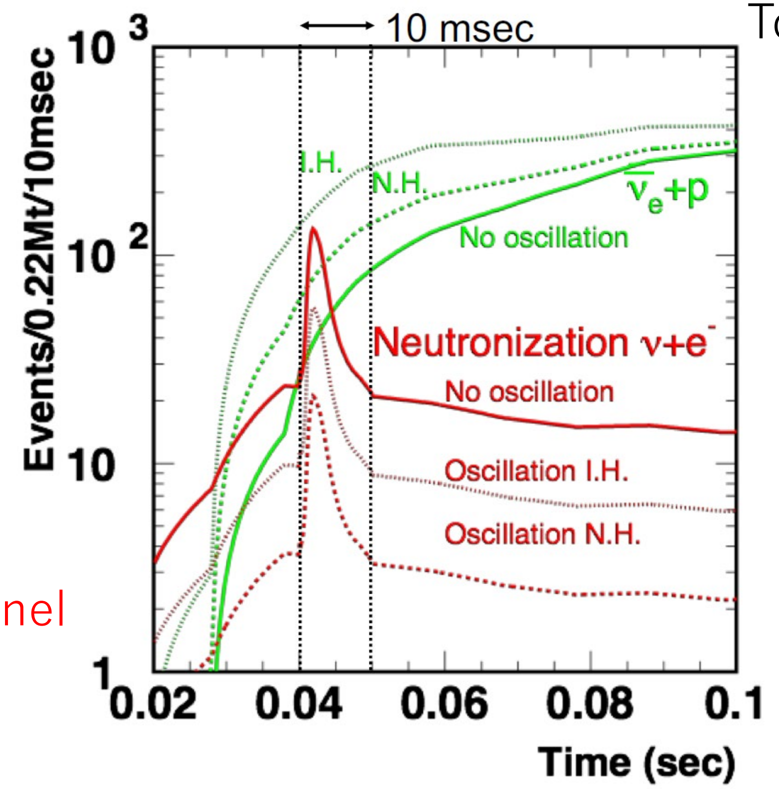
- Direct observation of key features of SN mechanism

Neutronization burst

When shockwave pass through the neutrino sphere

SN at 10 kpc

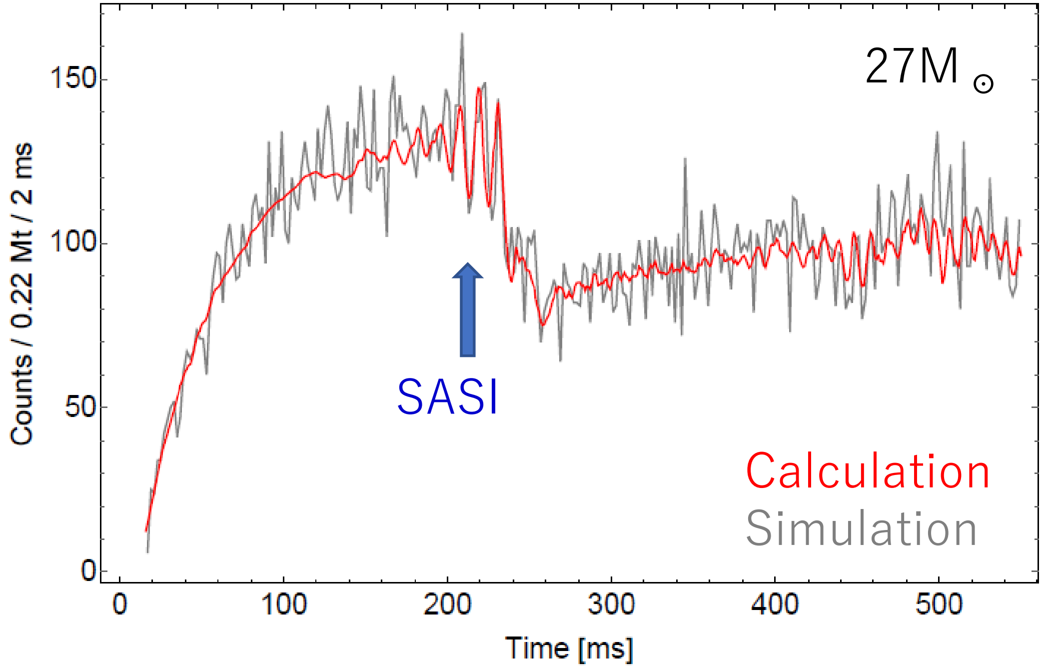
Totani2018



ES channel

SASI? Convection?

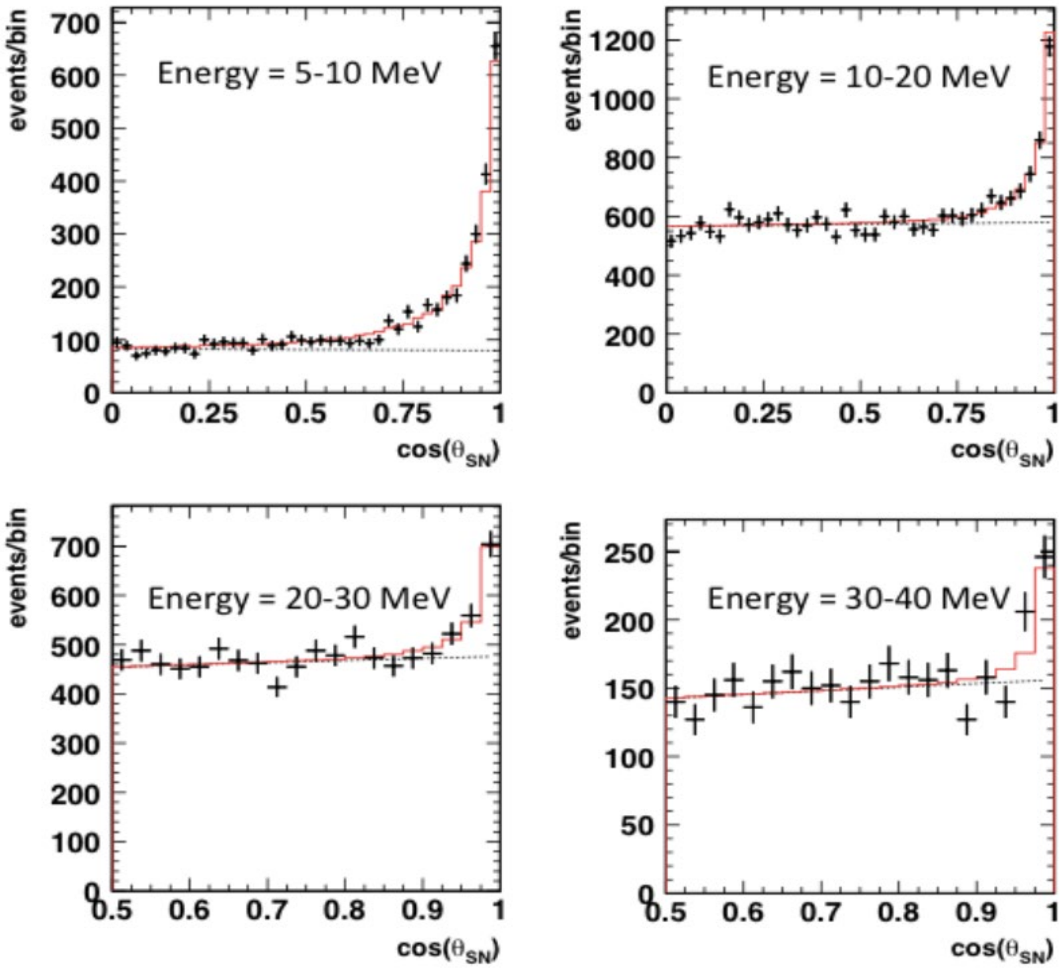
Shock revival by neutrino heating?
Key phenomenon of the burst!

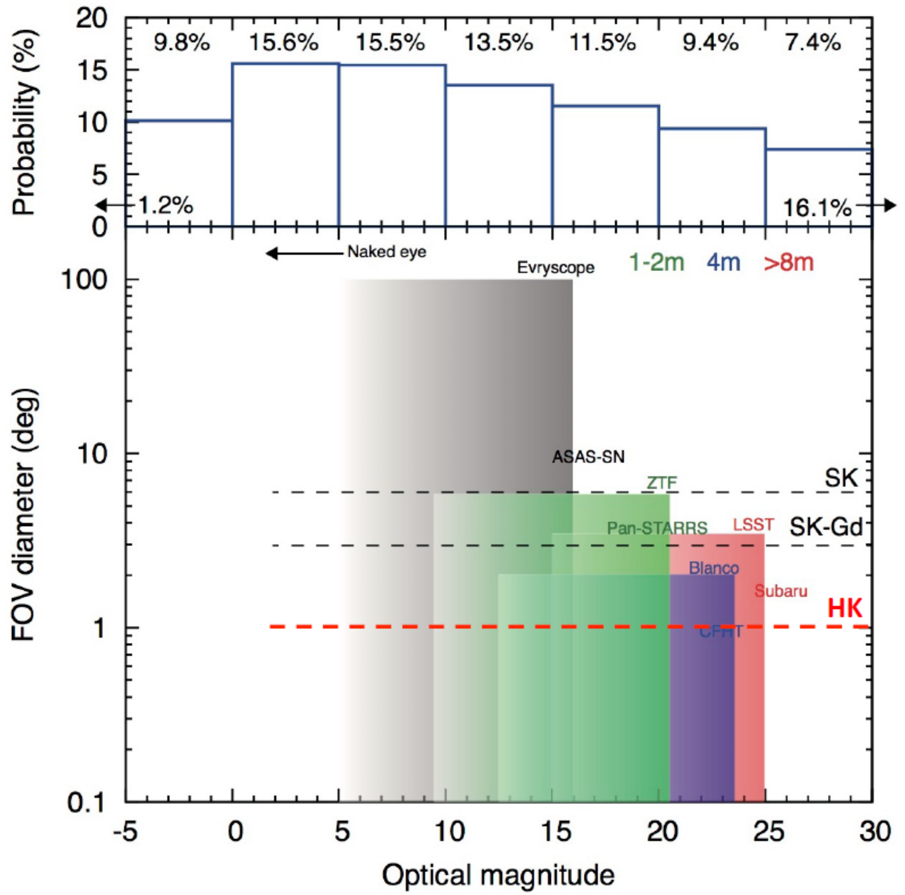


Pointing accuracy of HK

- Further help for Multi-messenger observation

Totani1998 10kpc





1～2° @10kpc SN

Summary

SUPER K is ready for the next galactic supernova.

SUPER K Gd will start soon, providing more SN pointing accuracy and a new early warning system.

- Aiming for the first observation of Diffuse Supernova Neutrino Background in 10 years.

HYPER K has been funded and started to construct. A giant SNe ν telescope will be available in 2027.