Supernova detection study; Investigation of progenitor core rotation with Gravitational Wave and Neutrino detector

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Neutrino2014@Boston
June 2-7, 2014

Abstract :

Core-collapse supernova is one of the most energetic phenomenon in the universe and when it happens in our galaxy, Various detectors would detect gravitational waves (GWs) and neutrinos. Current numerical simulations of supernova explosion are succeeded to introduce multi-dimensional effects, SASI and asymmetric convection. But the explosion mechanism is not understood well. One of the main key point to understand is the identification of the progenitor star core conditions(ex: mass, mass density profile, rotation rate).

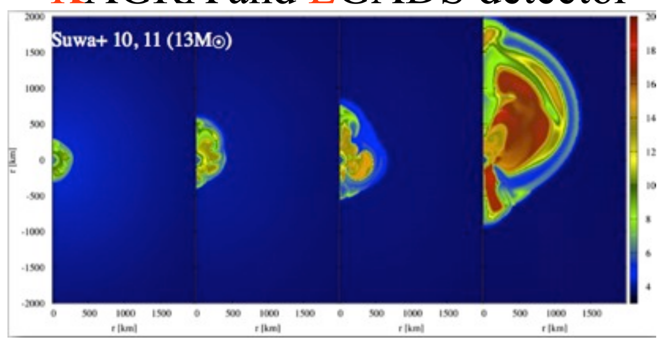
By using a consistent model for both GW and neutrino, we are discussing how supernova signals are observed, especially focusing on the time correlation variation between GW waveform and electron neutrinos/anti-electron neutrinos flux.

The GW detector is assumed to advanced detectors, mainly based on **KAGRA detector** which is the 3km laser interferometric detector located in Kamioka mine. The neutrino detector is assumed to **EGADS detector**, which is 200 ton water Cherenkov detector with 0.1% Gd loading. The characteristics of EGADS detector is the 90% neutron capture probability, which can identify observed event as from inverse beta decay or other interactions. We devised the method of extraction of the start time of GW emitting, t_start_gw and the neutronization burst time, t_nburst. And to compare them, we calculated the possibility of progenitor core is rotated or not from observation.

Our simulation results show that we can judge about 100% no core rotation for the no core rotation model, and about 90% core rotation for the strong core rotation model when the close supernova(<1kpc) is occurred.

Team SKE!

Supernova detection study team with KAGRA and EGADS detector



SNe Theory(A05)

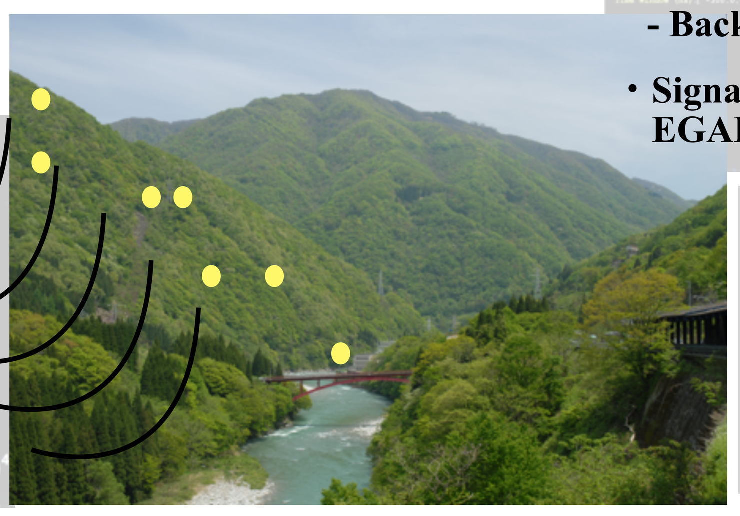
Y. Suwa

- **Provide time correlated data, GW and neutrino**
- **Suggest signature signals physical phenomenon**

GW analysis(A04)

T. Yokozawa, M. Asano
T. Arima, N. Kanda

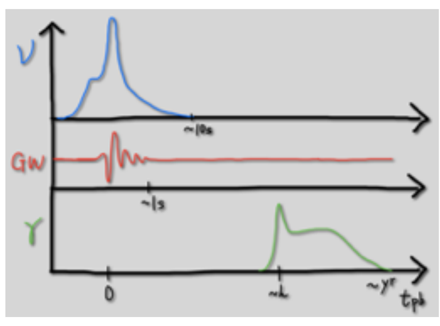
- **KAGRA detector simulations**
- **Develop/Optimize GW analysis tools**
- **Prepare for realtime observation**



Neutrino analysis(A03)

T. Kayano, Y. Koshio
M. Vagins

- **R&D of EGADS detector**
- **Estimate various parameters**
  - **Event reconstruction**
  - **Neutron tagging efficiency**
  - **Background**
- **Signal simulations with EGADS and SK detector**



Time-correlated GW and Neutrino signals

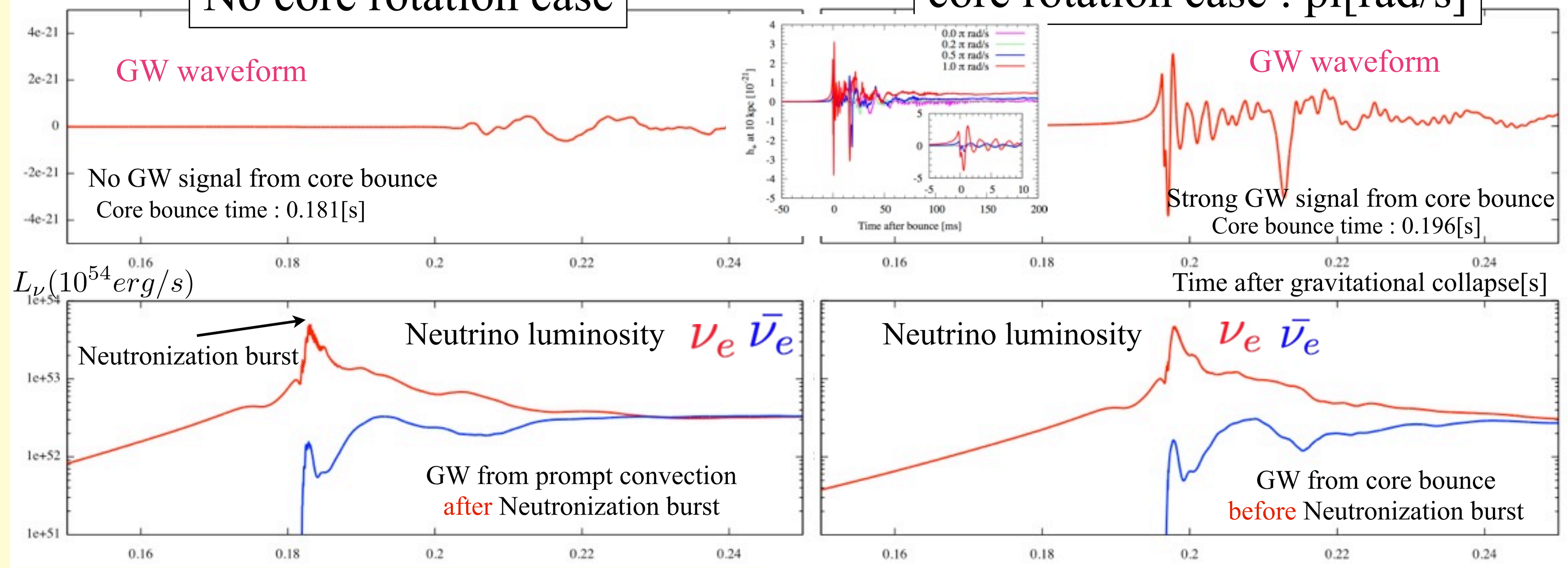
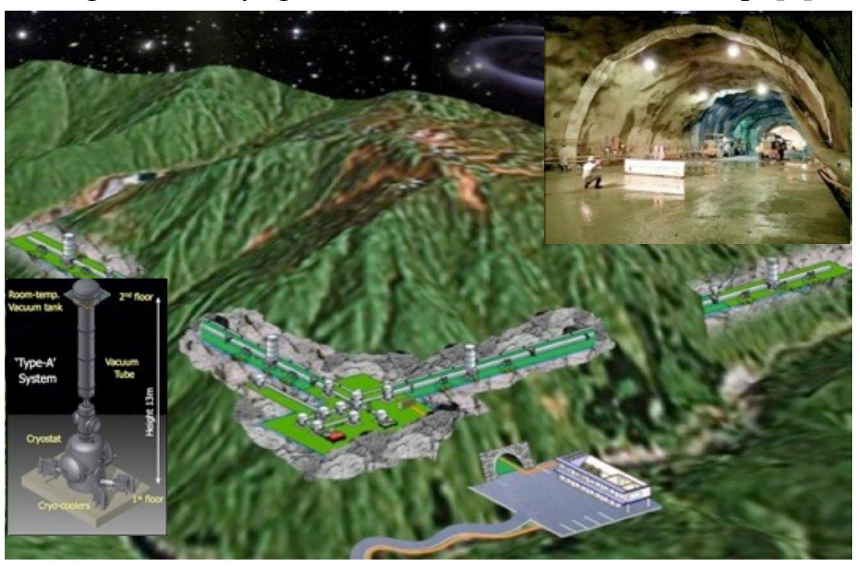


Fig1 : h(t) and Luminosity@10kpc for each model ; Time[s] : 0 is start time of gravitational collapse

KAGRA Detector

Large-scale Cryogenic Gravitational-wave Telescope[1]



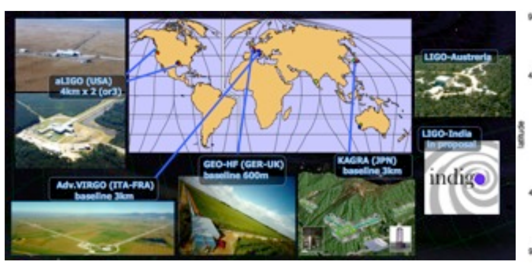


Fig3: World GW detectors

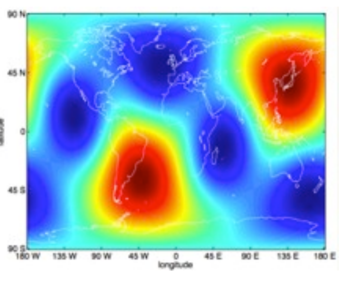


Fig4: KAGRA antenna pattern

- Advanced generation laser interferometric detector in Japan
  - 3km baseline length
    - Cryogenic interferometer (20K)
    - High-power laser
    - Stable and silent environment with 1000m underground site
  - KAGRA status
    - Finish tunnel excavation
    - Start installation/commissioning
    - Generate KAGRA analysis pipeline
  - Schedule
    - iKAGRA observation : End of 2015
    - Adv. Optics system and test
    - bKAGRA physics observation : End of 2017

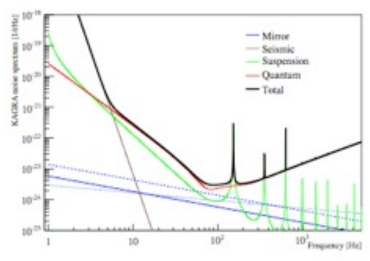
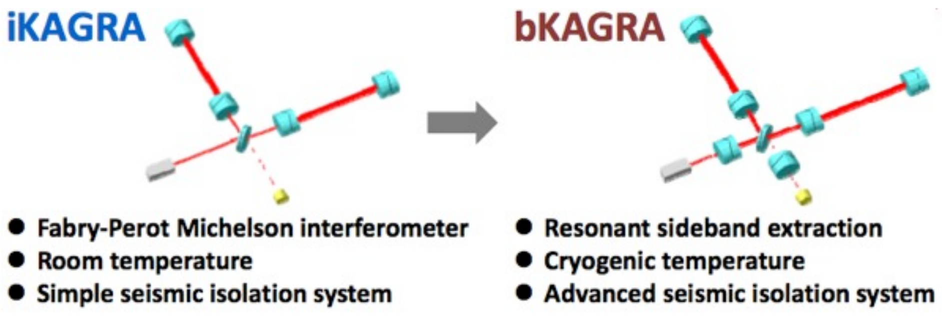


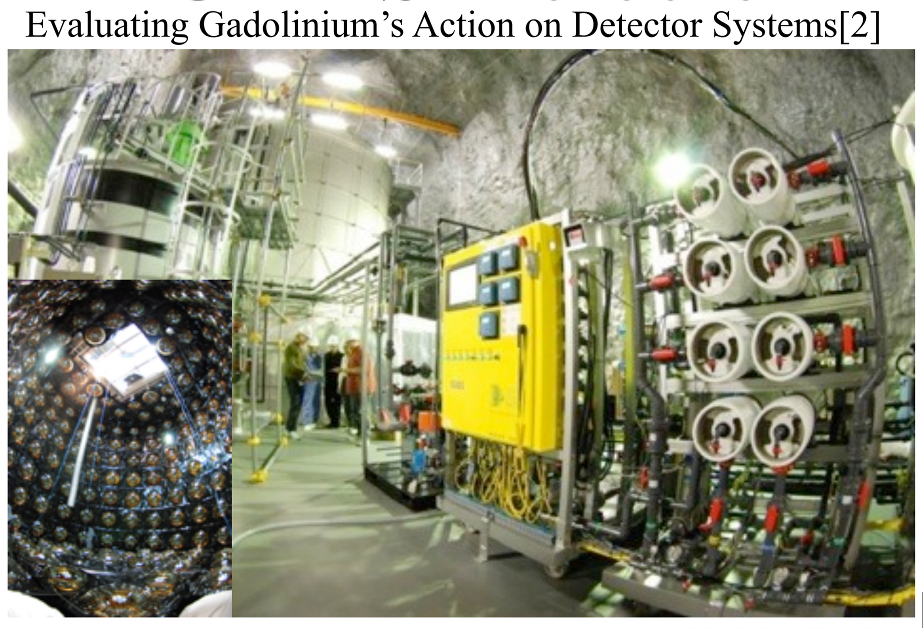
Fig:2 KAGRA sensitivity curve

[1] Y.Aso et. al. Phys Rev. D 88, 043007 (2013)



EGADS Detector

Evaluating Gadolinium's Action on Detector Systems[2]



- Gd loaded Water Cherenkov detector in Kamioka mine
  - Placed close to Super-Kamiokande, KAGRA
  - 100ton FV, 0.1% Gd loaded water
    - 90% neutron capture by Gd, emit total ~8MeV gamma
      - Identify inverse beta decay
    - 240 20inch PMT, 40% coverage(Same as SK)
    - EGADS status
      - Water purification work well
      - 400kg Gd loading test
      - Full Automated instant supernova alert capability
    - Schedule
      - Summer, Electronics upgrade ATM->QBEE
      - Ready for supernova detection

[2] J.F. Beacom and M.Vagins Phys. Rev. Lett. 93, 171101 (2004)

Evaluating Gadolinium's Action on Detector System → Employing Gadolinium to Autonomously Detect Supernovas

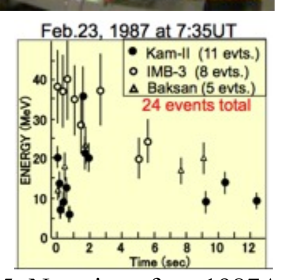


Fig5: Neutrinos form1987A

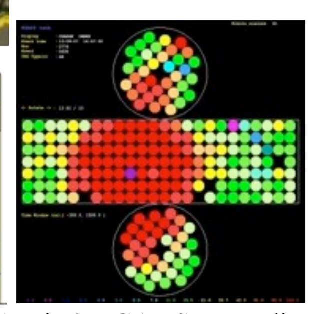
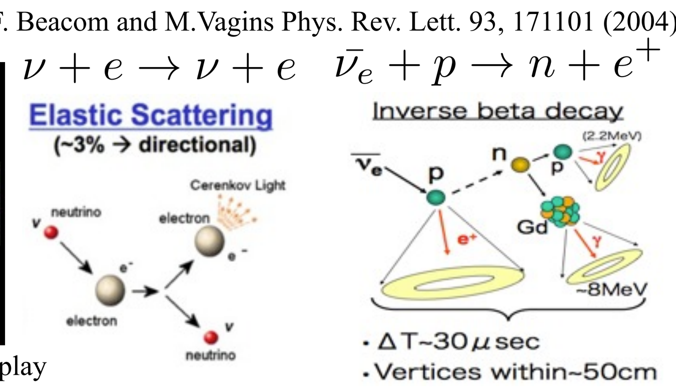


Fig6: EGADS event display

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



GW analysis

- Short Time Fourier Transform + Excess power filter
  - simulate time series of signal s(ti)=h(ti)+n(ti)
  - bKAGRA sensitivity curve
  - timing window 31.25[ms], Hamming window function
  - Evaluate signal power for (t~$t+\Delta t$) and (f~$f+\Delta f$)
  - Shift 1ms and STFT again
- Estimate Signal to Noise Ratio(SNR)
- Left edge of Max SNR window is t_obs_gw

$$P_s = \sqrt{\frac{\int \tilde{s}^*_w(f)\tilde{s}_w(f)df}{\int < \tilde{n}^*_w(f)\tilde{n}_w(f) > df}} \quad P_n = \sqrt{\frac{\int \tilde{n}^*_w(f)\tilde{n}_w(f)df}{\int < \tilde{n}^*_w(f)\tilde{n}_w(f) > df}} \quad \frac{S}{N} = \frac{P_s - m}{\sigma}$$

Signal power for given timing window. Noise power for given timing window. m : mean of Pn dist. σ : deviation of Pn dist.

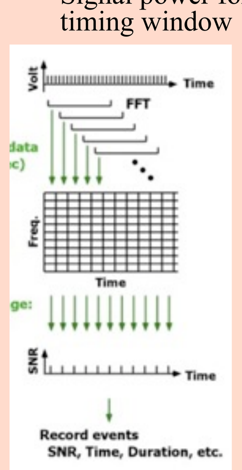


Fig:8 Excess power filter, Phys. Rev. D 71, 082002 (2005)

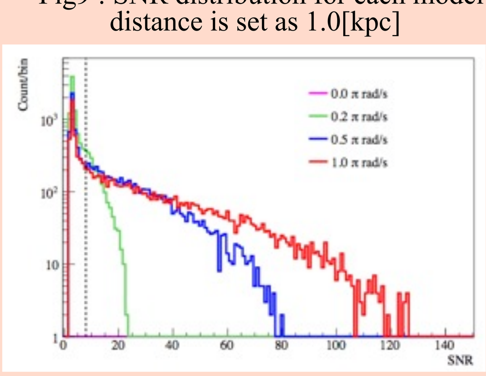


Fig9 : SNR distribution for each model distance is set as 1.0[kpc]

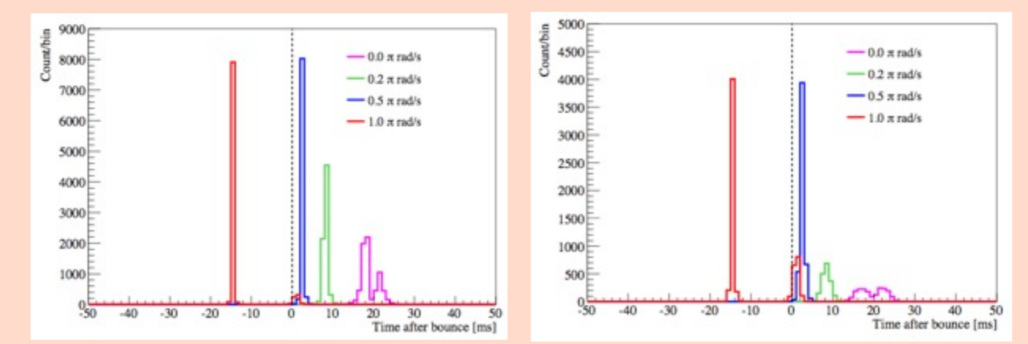


Fig9 : t_obs_gw distribution for each model, Left : 0.1kpc, Right : 1.0kpc

Analysis motivation

- Focus on **GW observed time(t_obs_gw)** and **Neutronization burst time(t_obs_nburst)**
- Judge core rotation probability to compare these times, detector simulation with KAGRA and EGADS
  - Dependencies of Core rotation rate, Distance from Earth, Direction ...

No core rotation: No GW signal from core bounce, GW from prompt convection after Neutronization burst ⟷ Strong core rotation: Strong GW signal from core bounce, GW from core bounce before Neutronization burst

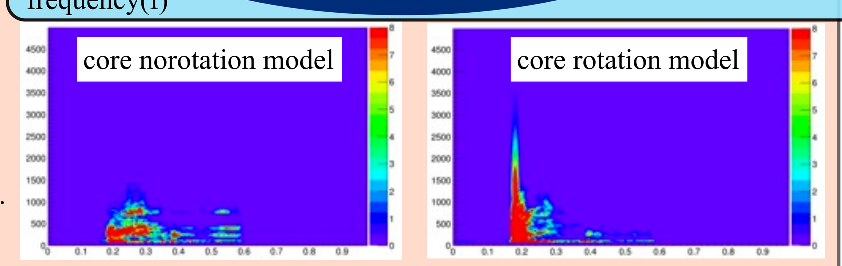
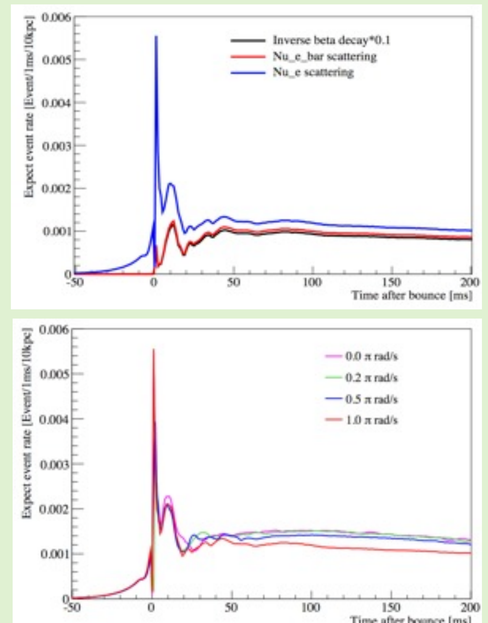
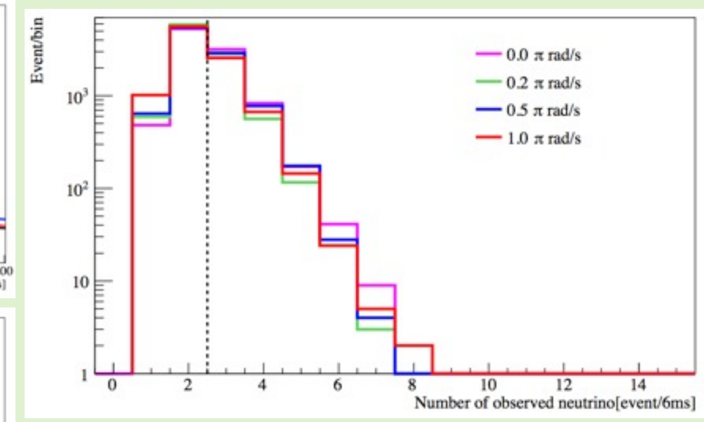


Fig7: t-f cluster distribution for each model(red shows S/N>8)

Neutrino analysis

- Calculate expect number of event with 1ms bin
  - Only electron flavor, no neutrino oscillation
  - Electron neutrino elastic scattering (Blue in Fig.10)
  - Mis-neutron-tagged Inverse Beta Decay (Red in Fig.10)
  - Anti-electron neutrino elastic scattering (Black in Fig.10)
- Simulate number of interaction and recode interaction time
- Open 6ms timing window and search maximum
  - left edge of maximum observation window is t-obs-nburst





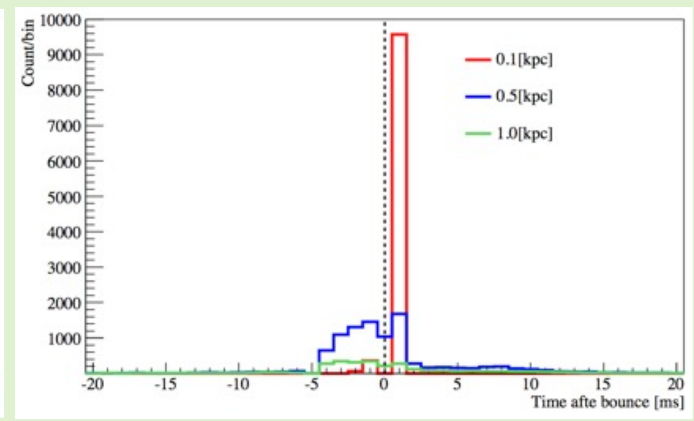
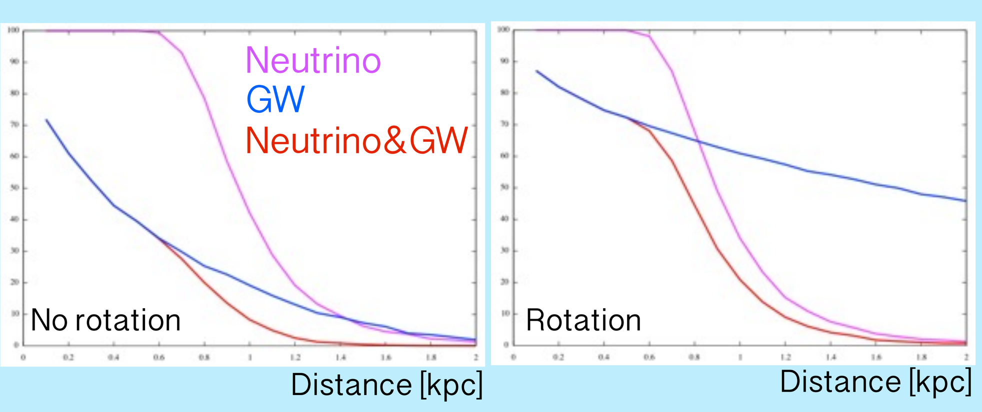


Fig10(Left) : Number of expected interaction rate of EGADS detector [Event/1ms/10kpc]
(upper figure) : interaction mode dependence for 0.0 [pi rad/s] model of expected number event
(lower figure) : Supernova mode dependence of expected number event
Fig11(Center) : The number of maximum observed neutrino with 6ms window for 1.0[kpc] case.
Fig 12(Right) : t-obs-nburst distribution for each model

Results

- Why choose KAGRA and EGADS detector?
  - Placed in same mountain, same arrival time
  - Distinguish electron/anti-electron neutrino
- Detection threshold
  - GW : SNR > 8 (Fig.8)
  - Neutrino : 3[event/6ms] (Fig.11)
- Judge core rotation or not, calculation of Pr[%]
  - compare t-obs-gw(Fig.9) and t-obs-nburst(Fig.12)
  - Pr : the probability to judge core rotation
- Results:

Fig13 : Detection efficiency [%] of Neutrnization burst, GW, and those combination for no core rotation model(left) and strong core rotation model(right)



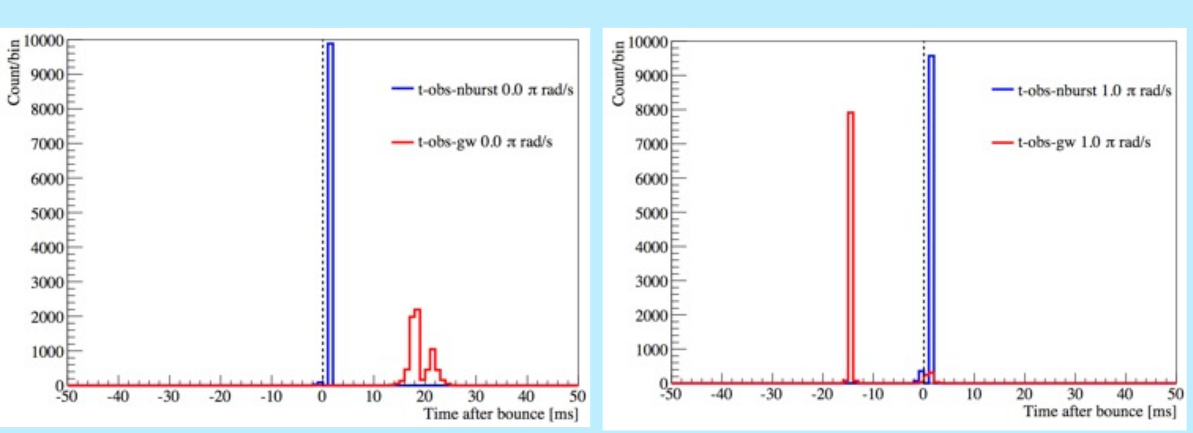


Fig:14 Comparison between t-obs-gw and t-obs-nburst for no rotation model(left) and strong core rotation model(right)

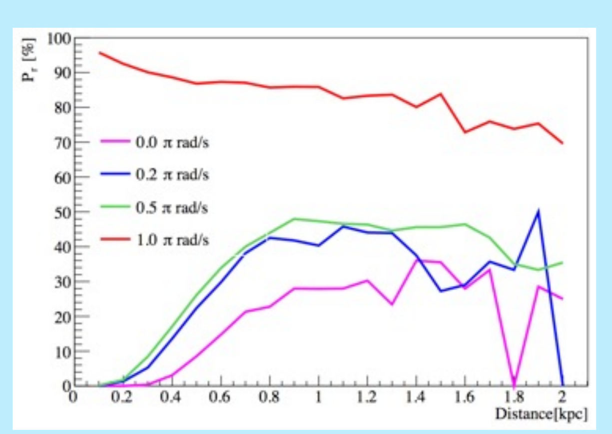


Fig:15 Distance dependence of Pr for each models

Summary and future prospect

- Co-operating with Theory group, GW analysis group and Neutrino experiment group, the supernova detection study team start working
- From the progenitor core rotation and no-rotation model, the observation time of GW, t-obs-gw, and Neutronization burst, t-obs-nburst, were estimated.
- Neutrino-GW combined analysis shows for the nearby collapse case,
  - When SN core is rotated (0.1kpc);
    - Detection efficiency of GW and Neutronization burst is ~90%
    - The probability to judge core rotation is 96.0%
  - When SN core is not rotated(0.1kpc);
    - Detection efficiency of GW and Neutrinoization burst is ~70%
    - The probability to judge NO core rotation is almost 100%
- Future plan
  - Optimize the estimation of GW/neutronization burst observed time
  - Multi classification analysis (add parameters from t-obs-gw and t-obs-nburst)
  - Multi detector with coherent/coincidence analysis
  - Focus on SASI and/or convection phase
    - Time-frequency analysis for both GW and neutrino luminosity

- Reference:
[1] Y.Aso et. al. Phys Rev. D 88, 043007 (2013)
[2] J.F. Beacom and M.Vagins Phys. Rev. Lett. 93, 171101 (2004)