Supernova detection study; GW and Neutrino

A03 bi-monthly meeting

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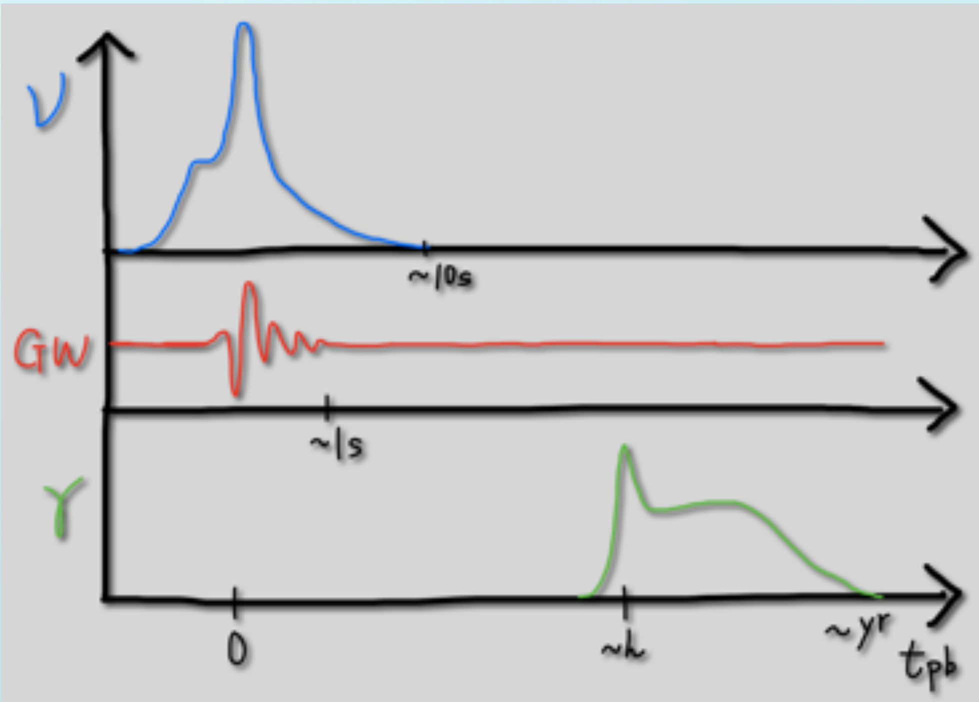
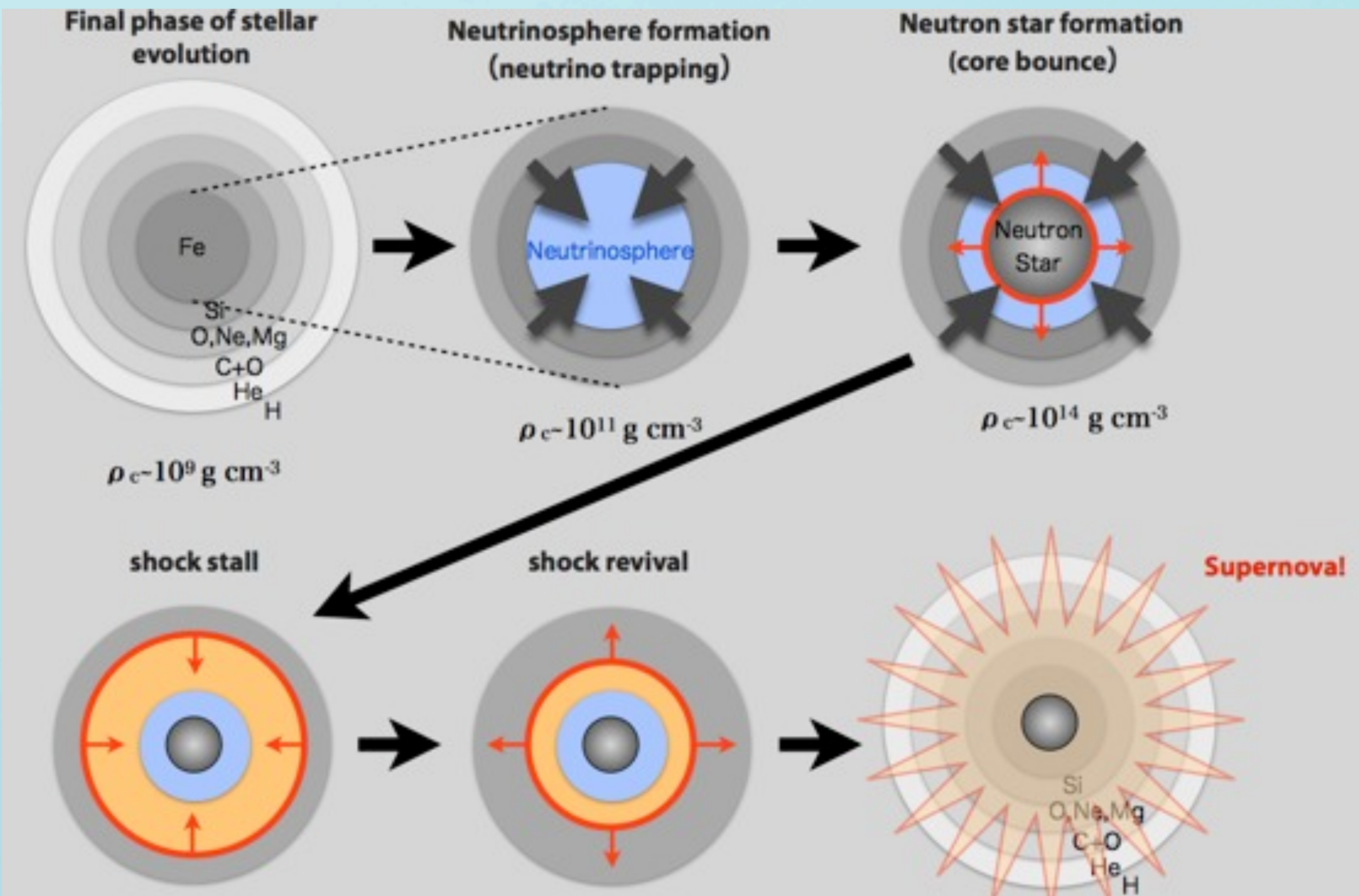
Contents

Supernova

- One of the most energetic phenomena
  - 10^{53} erg gravitational energy
  - 99% of total energy is emitted by Neutrino
  - One of the important GW source

- Unknown explosion mechanism
  - Current 2D simulation show success explosion
  - Observation show asymmetric mechanism
  - Dependence on progenitor core status





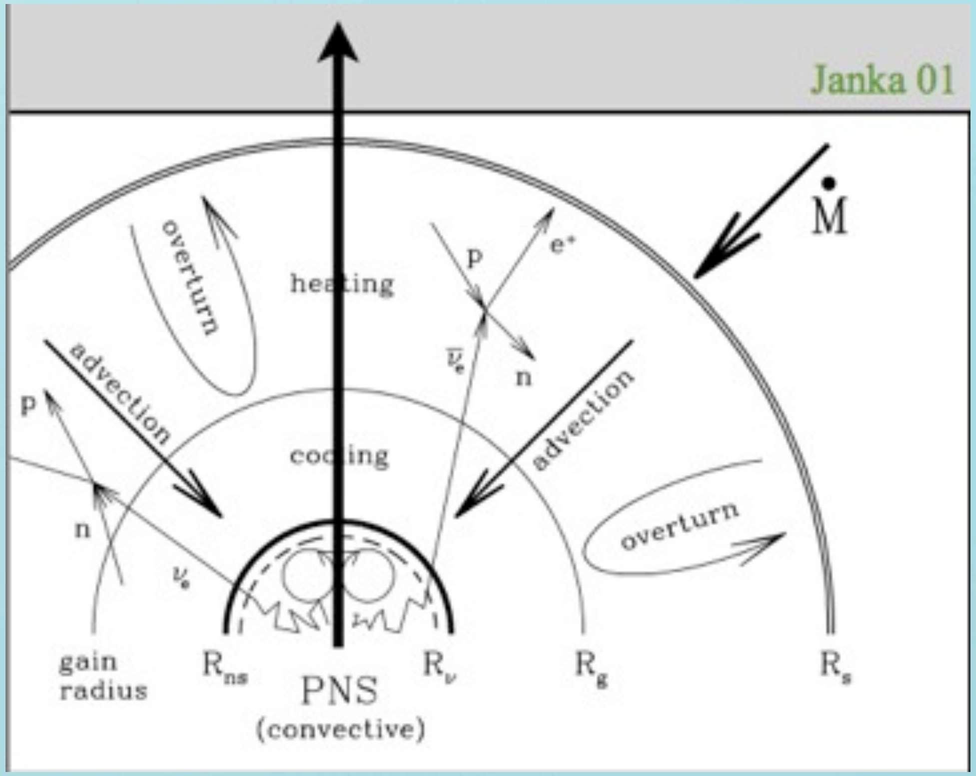
GW, Neutrino observation
- Both GW and Neutrino have inner core information
- Key of understanding explosion mechanism
- Time variation of emission

Keywords :
- Neutrino sphere
- Core bounce
- Neutronization burst

Fig: From Suwa-san

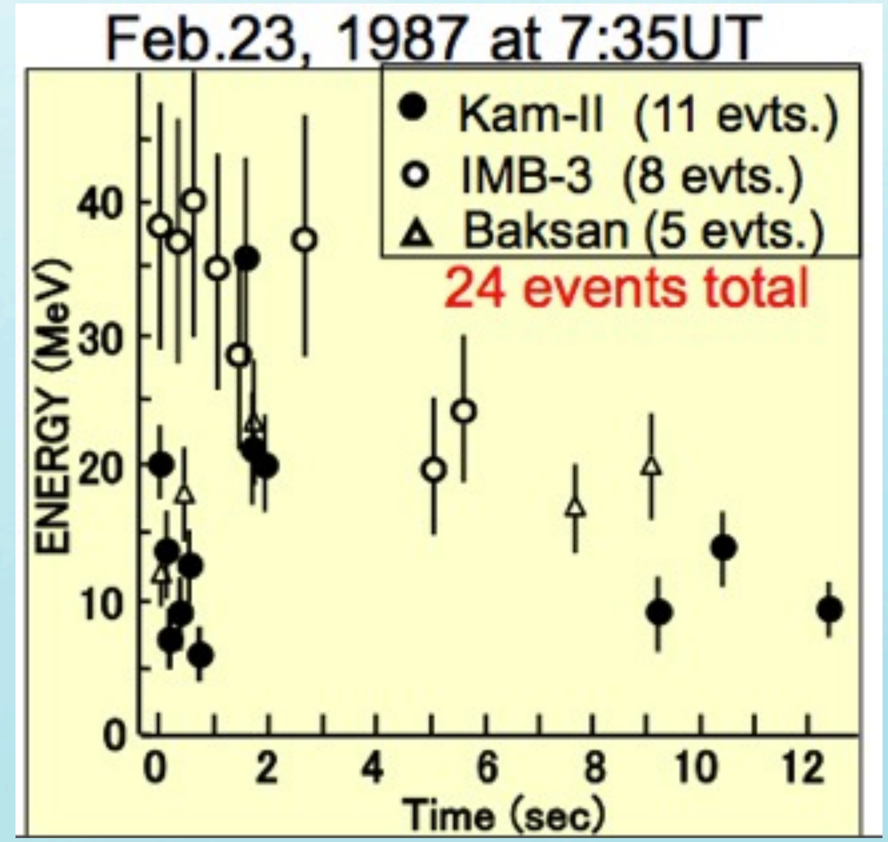
Supernova

- To understand the explosion mechanism
  - Consistent model for both emission
  - Co-operating with Theory and GW, Neutrino analysis group
- Supernova detection study for both GW and neutrino
  - Detection efficiency
  - Extract progenitor core information
    - progenitor mass
    - mass density distribution
    - progenitor core rotation
    - rotation distribution
  - Condition of SASI and convection ...etc



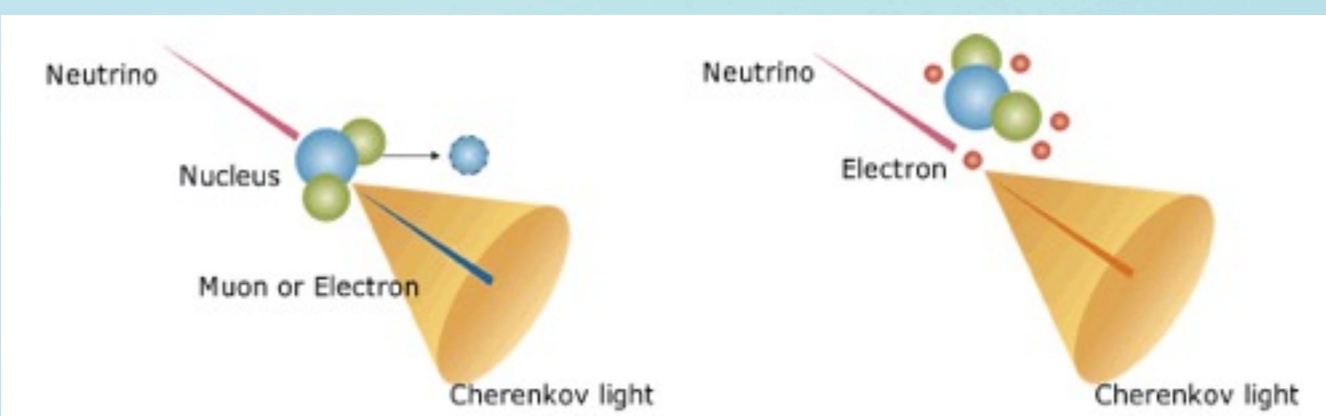
Supernova Neutrino

- Observed neutrinos from 1987A Supernova
    - Total 24 events
- Possible to obtain inner information
    - help to understand the explosion mechanism
- Various detectors are ready for observing



Observed neutrino information of 1987A

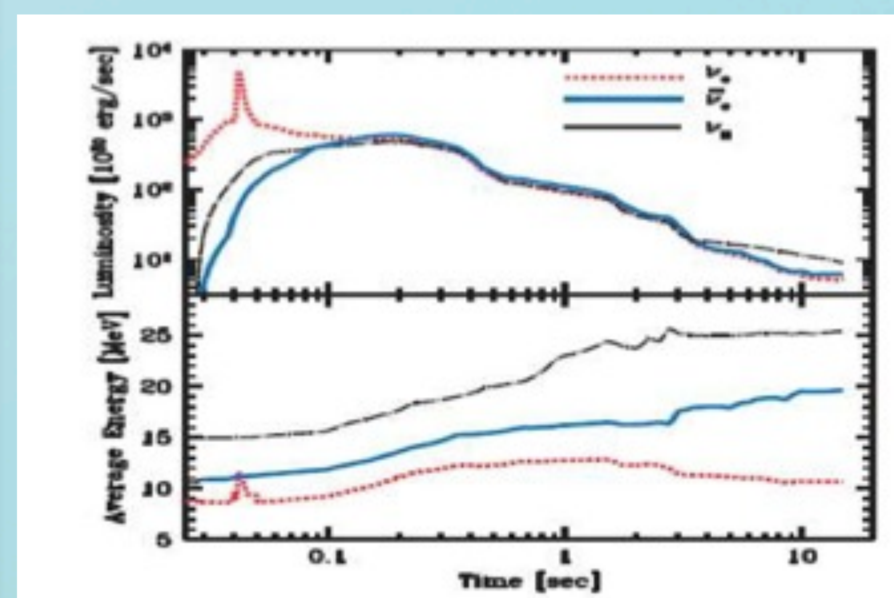
detection principle
(water Cherenkov detector)



main interaction mode :

$\nu + e \rightarrow \nu + e$ (Scattering)

$\bar{\nu_e} + p \rightarrow n + e^+$ (Inverse beta decay)

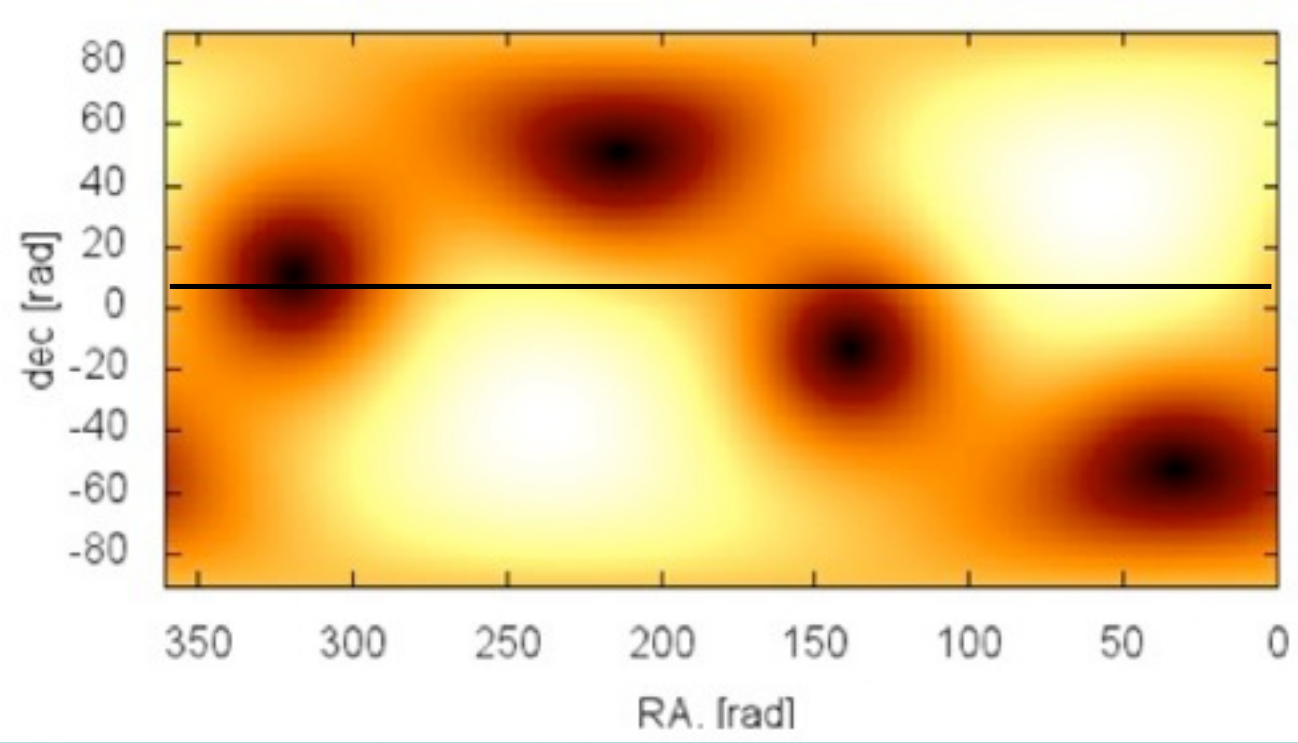


Luminosity and mean energy estimated by Livermore group (Astrophys. J 295(1985)14)

Betelgeuse

- Betelgeuse had withered by 15 percent during current 15 years
    - C.H.Townes et al., Astrophys. J. 697 (2009)127.
- Many Neutrinos and Large amplitude of GW will be observed in Many detectors
- Focus on Betelgeuse supernova neutrinos this talk

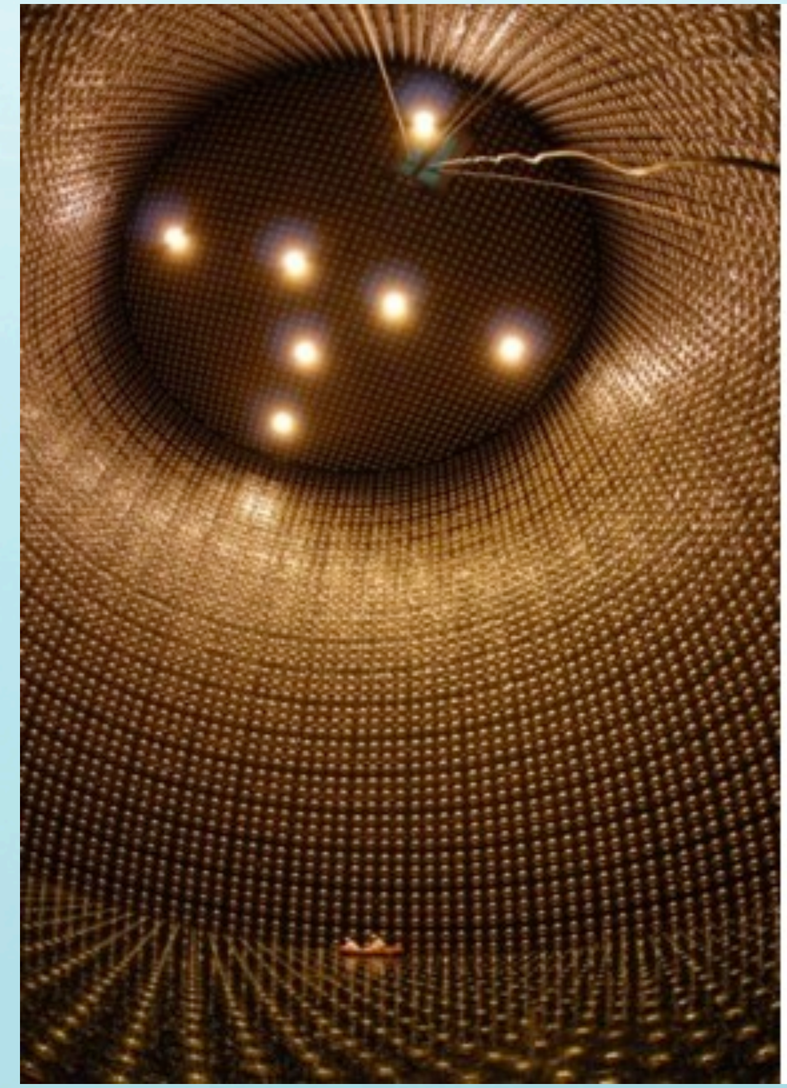
Betelgeuse information
- RA : $05^h\ 55^m\ 10.30536^s$ Dec : +07° 24′ 25.4304″
- Distance : 642±146ly(197pc)   Mass : $20M_\odot$

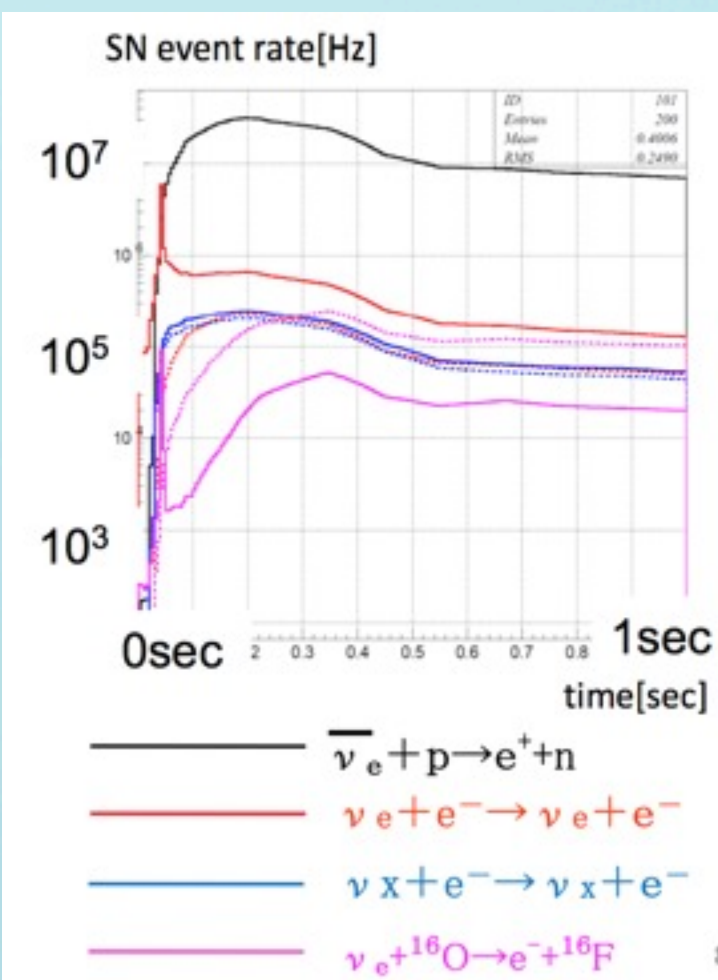


Orbit of Betelgeuse with KAGRA antenna pattern
(fig:Yuzurihara-san)

Super Kamiokande

- Located 1000m underground at Ikenoyama (Kamioka)
  - reduce cosmic ray muon background (1/100,000)
- Large ring imaging water Cherenkov detector
  - 50,000 tons of pure water, ~13,000 PMT
- Start observation in 1996
  - In 2008, new electronics was installed (SK-IV)
- Expect event rate 30Mevent/20sec
  - maximum rate ~30Mevent/Hz
  - Need another DAQ for nearby Supernova



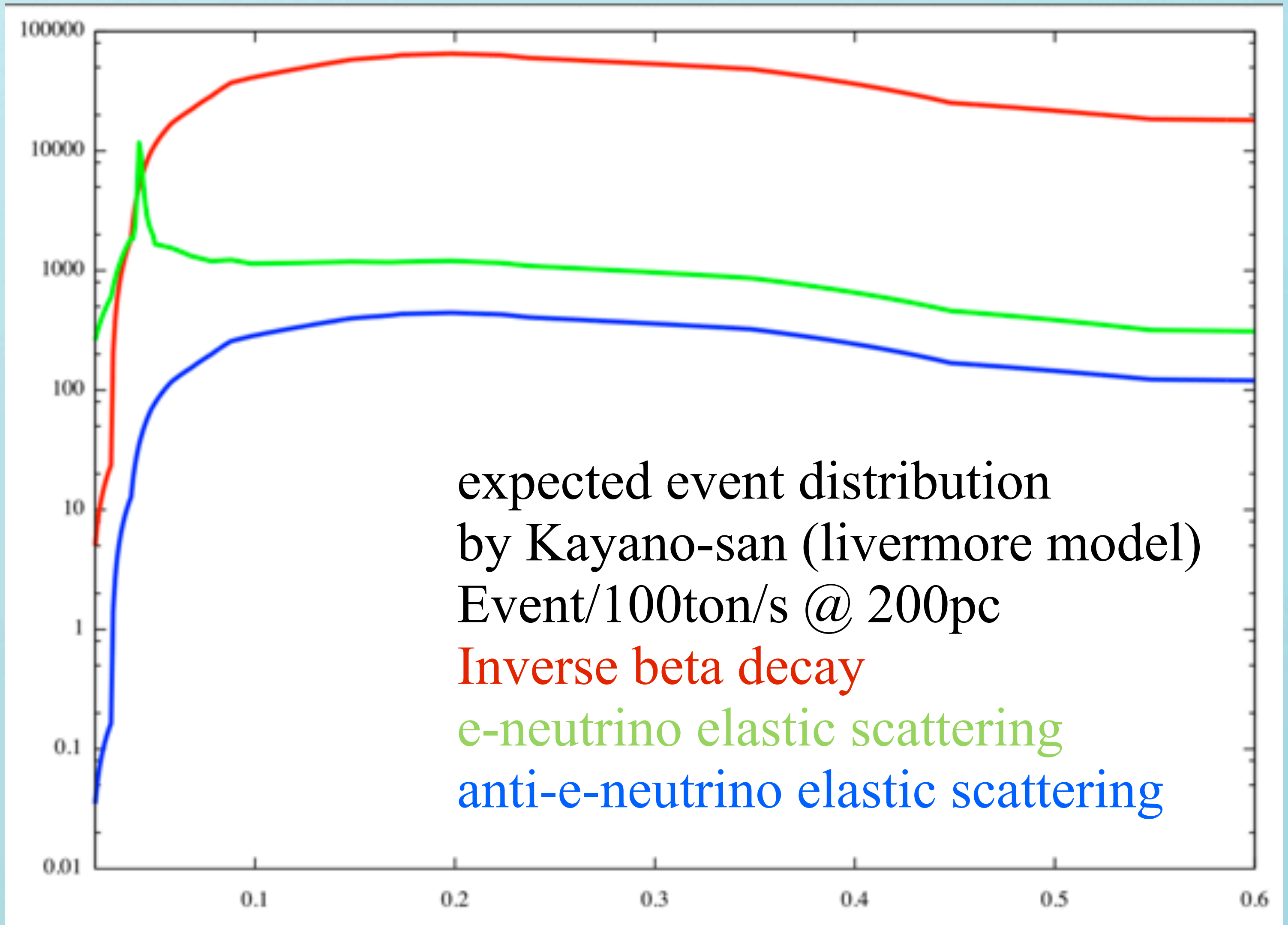


Expect event rate for Betelgeuse explosion (Yokozawa)
The detail is presented in first symposium

Electronics for Nearby supernova (Orii-san at 2014JPS meeting)

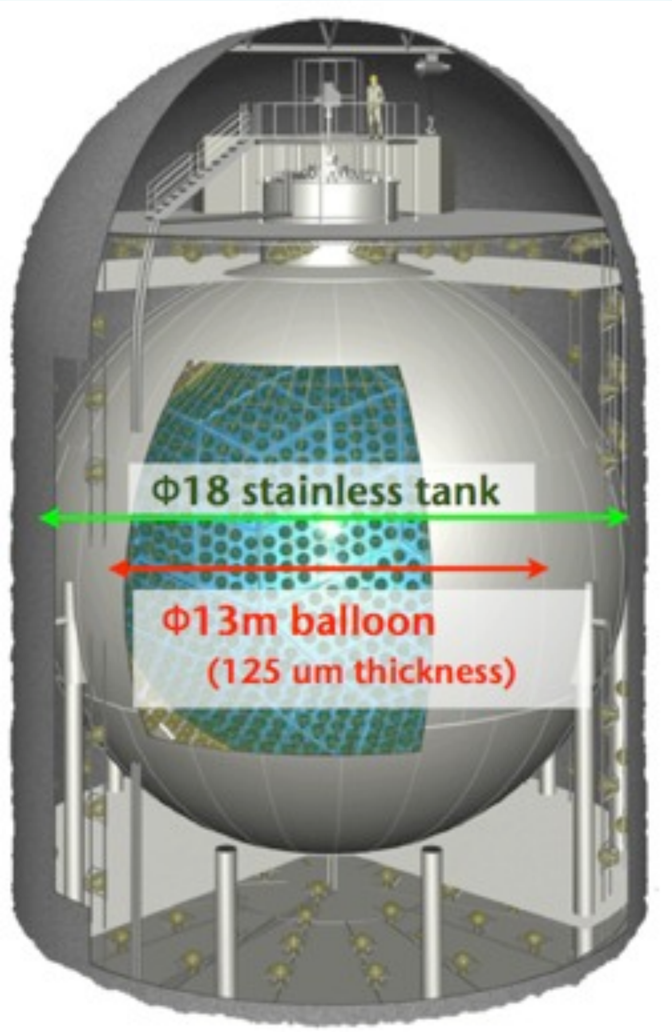
EGADS detector

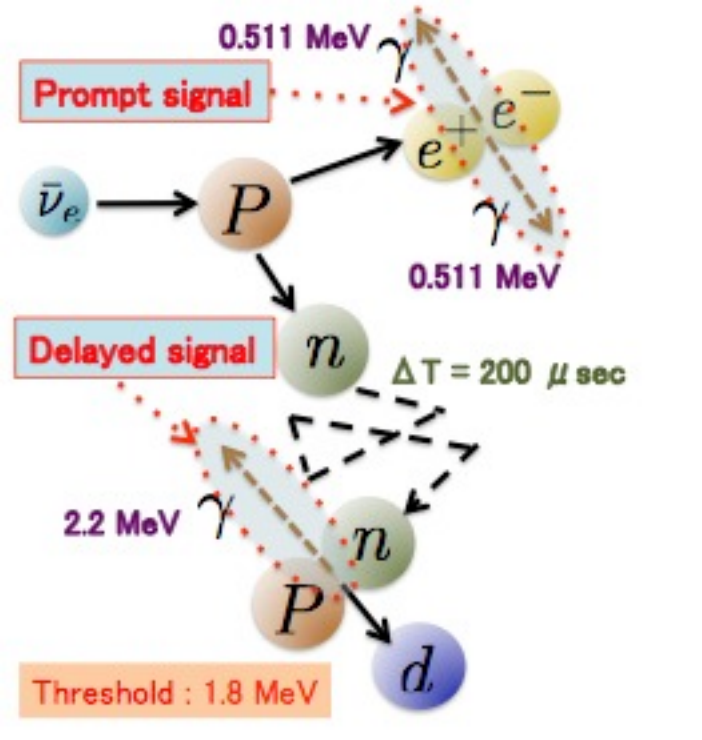
- 100ton water Cherenkov detector
    - 0.2% Gd loaded
        - 90% neutron tagging
- Expected event rate (livermore model) @0.6s
    - electron neutrino elastic scattering : ~500
    - inverse beta decay : ~22000
    - anti-electorn neutrino elastic scattering : ~150

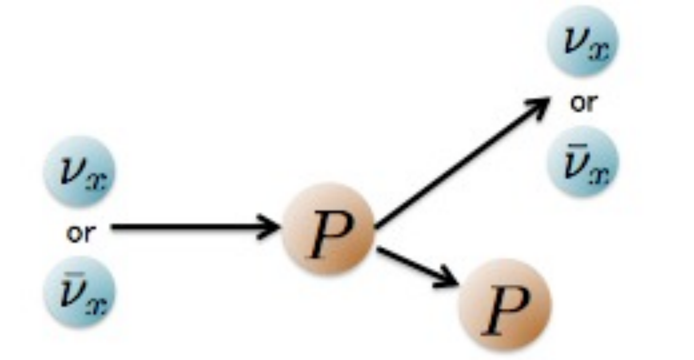


KamLAND

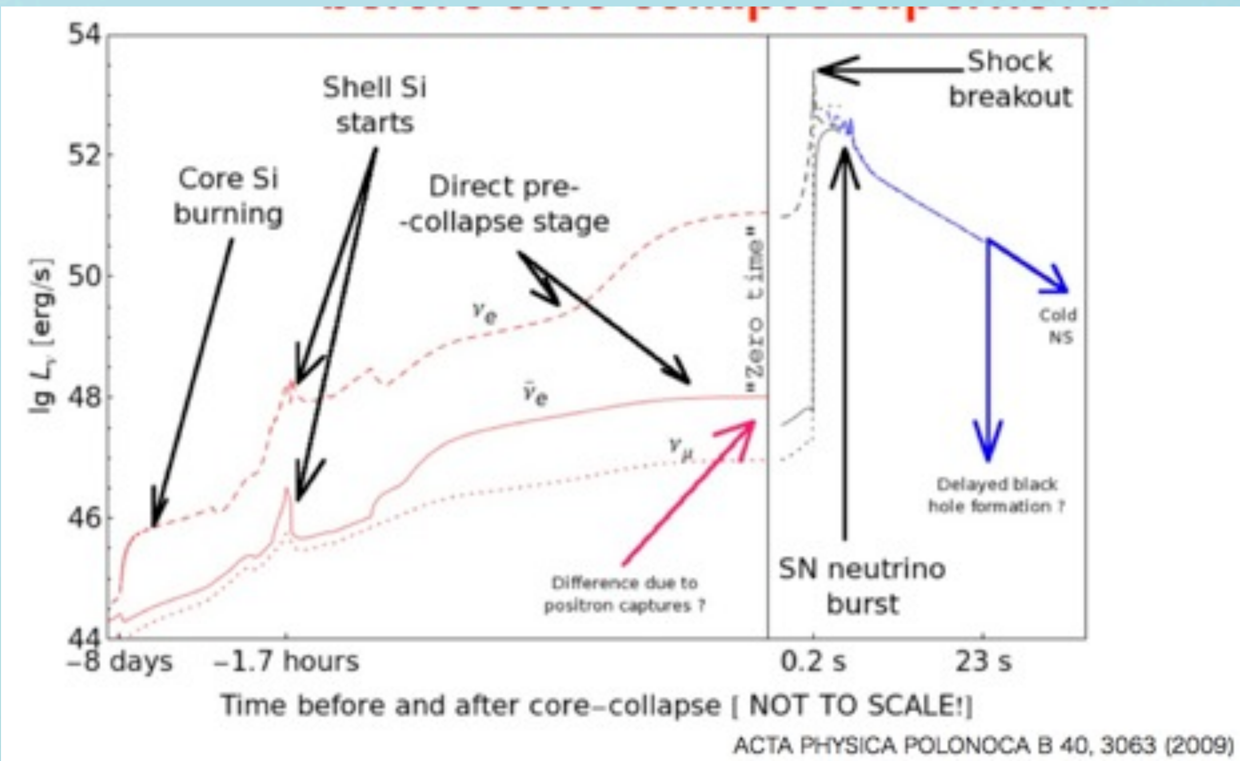
- Kamioka Liquid Scintillator Anti-Neutrino Detector
- 1,000m depth, Kamioka mine, 1,000t liquid scintillator
- Low energy threshold, low background
- Expect 0.5-2.4M event/20sec
    - inverse bata decay, proton scattering
    - Nakazato-model
- PreSN neutrino
    - emitted neutrinos in Si burning phase





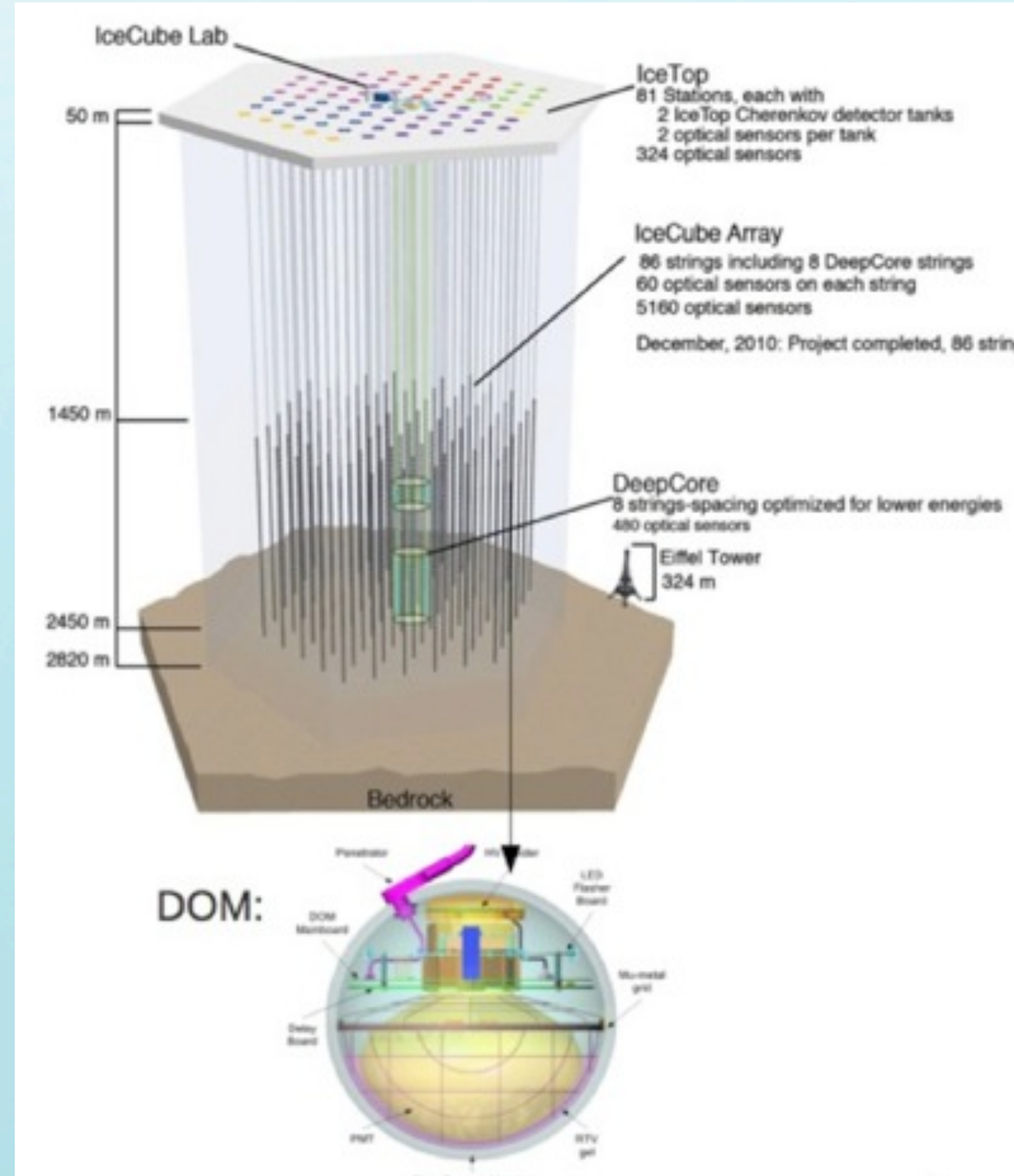


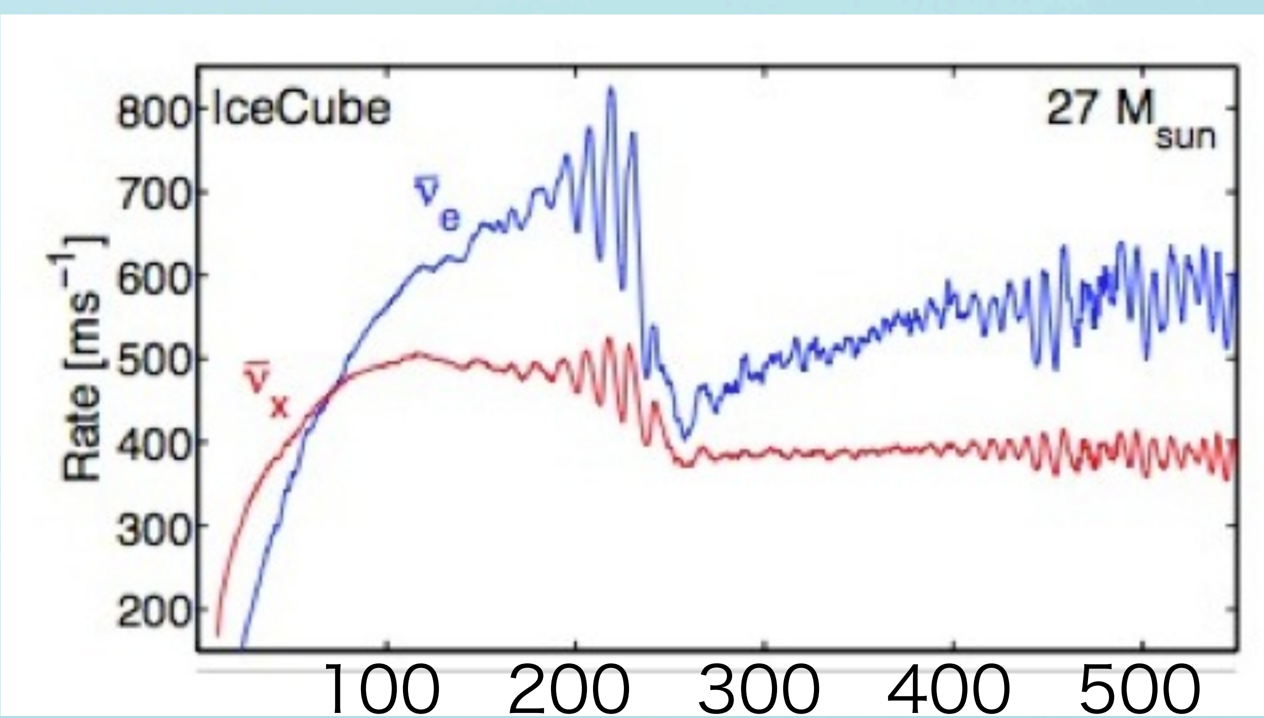
From Hayashida-san JPS slide(2013)
inverse beta ... 0.2-1.0Mevent/20sec
proton scat. ... 0.1-0.4Mevent/20s
From Ishidosiro-san 2nd annual sympo.
neutrinos from Si-burning



IceCube

- Large ice Cherenkov detector @South Pole
  - 1450-2450m depth
  - 5160 DOM(Digital Optical Modules)
  - 1km³ volume
  - lower dark rate ~290Hz/DOM
- Expect to observe ~100,000event
  - 1 event/p.e.
  - expect to observe fine time structure
  - possibility to observe SASI activity
    - arXiv1307.7936
- SNDAQ system
  - number of hits every 2ms
  - arXiv1108.0171





Signal modulation in the 27 M⊙ model.

Clear SASI activity at 120–260 ms.

~220 ms a SASI spiral mode sets in and remains largely confined to an almost stable plane.

Summary of Supernova neutrino

Detector	Volume	# of total event @Betelgeuse	Characteristic
Super Kamiokande	32kton	~30M	# of hit PMT + trigger veto
EGADS	100ton	~90,000	Neutron capture Full data taking
KamLAND	1kton	~1M	# of event rate + trigger veto
Icecube	$1km^3$	~250M	Fine time structure 1 event/1p.e.

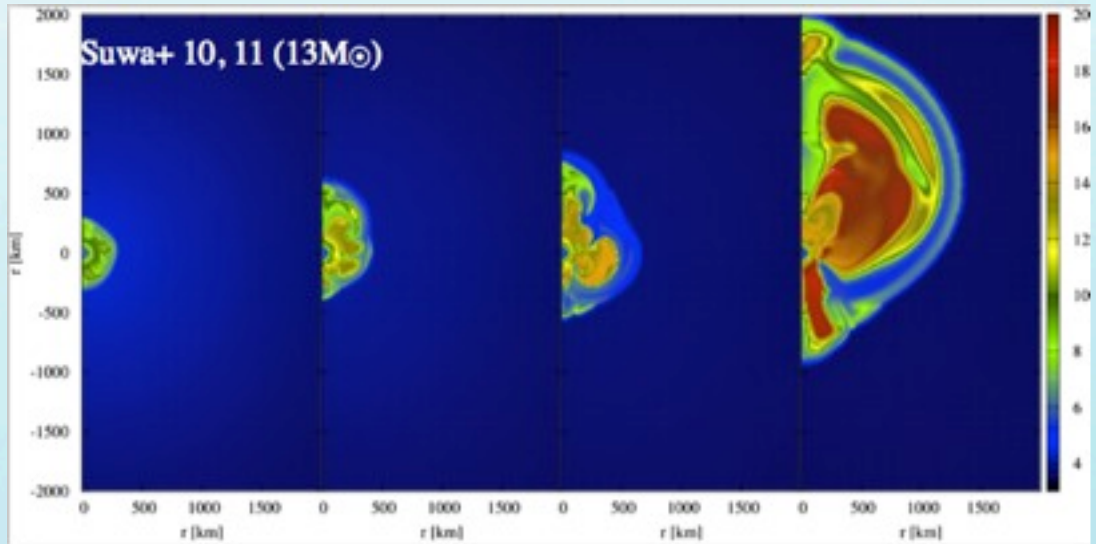
- Can't introduce, there are many detector which can observe supernova neutrinos
- Also, next generation detectors are planned
- Many neutrino observation achieve the inner core infomation
    - Next page

Team SKE

SNe Theory(A05)

Y. Suwa

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



Neutrino analysis(A03)

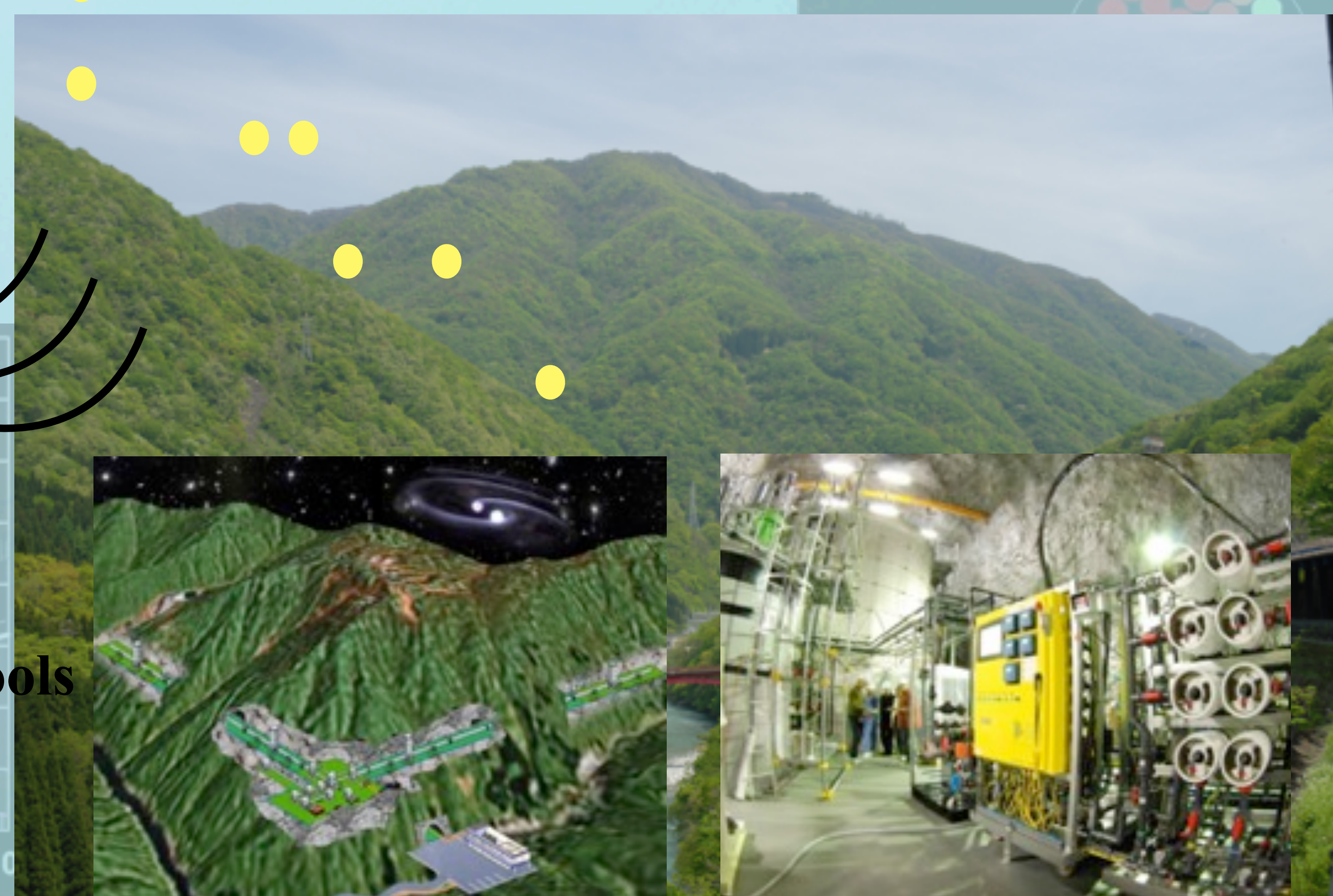
T. Kayano, Y. Koshio
M. Vagins

- **R&D of EGADS detector**
- **Signal simulations with EGADS and SK**

GW analysis(A04)

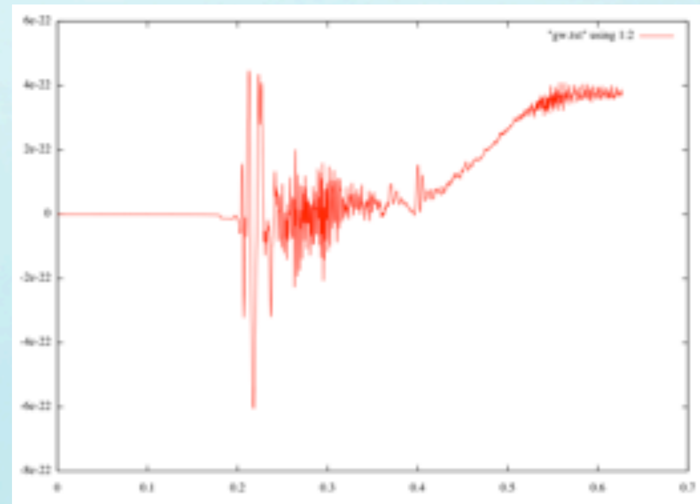
T. Yokozawa, M. Asano
N. Kanda

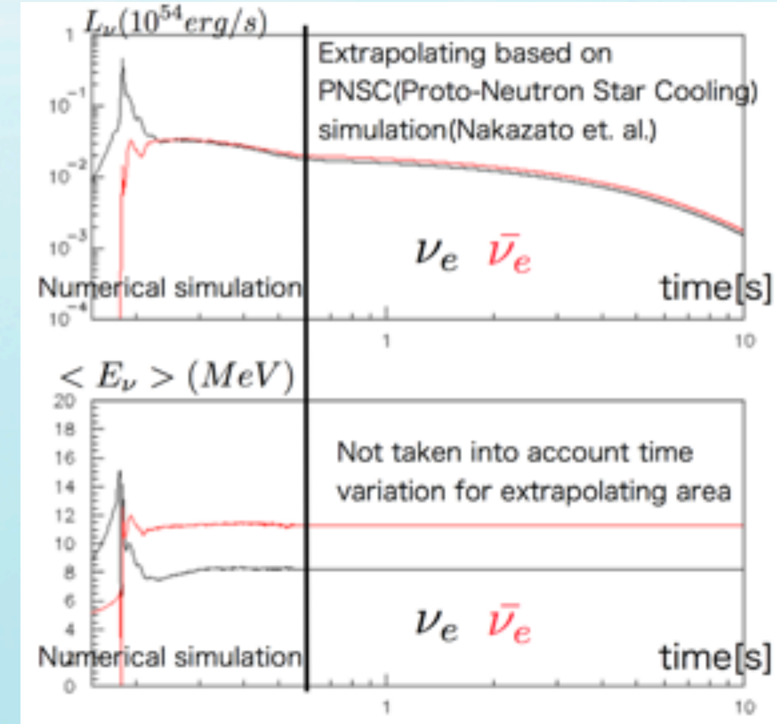
- **KAGRA detector simulations**
- **Develop/Optimize GW analysis tools**
- **Prepare for realtime observation**



Supernova model

- 2D Numerical simulation
- Progenitor star mass : 11.2M⊙
- Progenitor core rotation rate
    - 0.0-1.0[Pi/rad]





Numerical Simulations

Hydrodynamic equations

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \Phi$$

$$\frac{\partial e^*}{\partial t} + \nabla \cdot [(e^* + P)\mathbf{v}] = -\rho \mathbf{v} \cdot \nabla \Phi + Q_\nu,$$

$$\triangle \Phi = 4\pi G \rho$$

Solve simultaneously

Neutrino Boltzmann equation

$$\frac{df}{cdt} + \mu \frac{\partial f}{\partial r} + \left[\mu \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr}\right) + \frac{1}{r}\right](1-\mu^2)\frac{\partial f}{\partial \mu} + \left[\mu^2 \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right] E \frac{\partial f}{\partial E}$$
$$= j(1-f) - \chi f + \frac{E^2}{c(hc)^3} \times \left[(1-f)\int R f' d\mu' - f \int R (1-f') d\mu'\right].$$

Gravitational Wave

Neutrino transform

Motivation

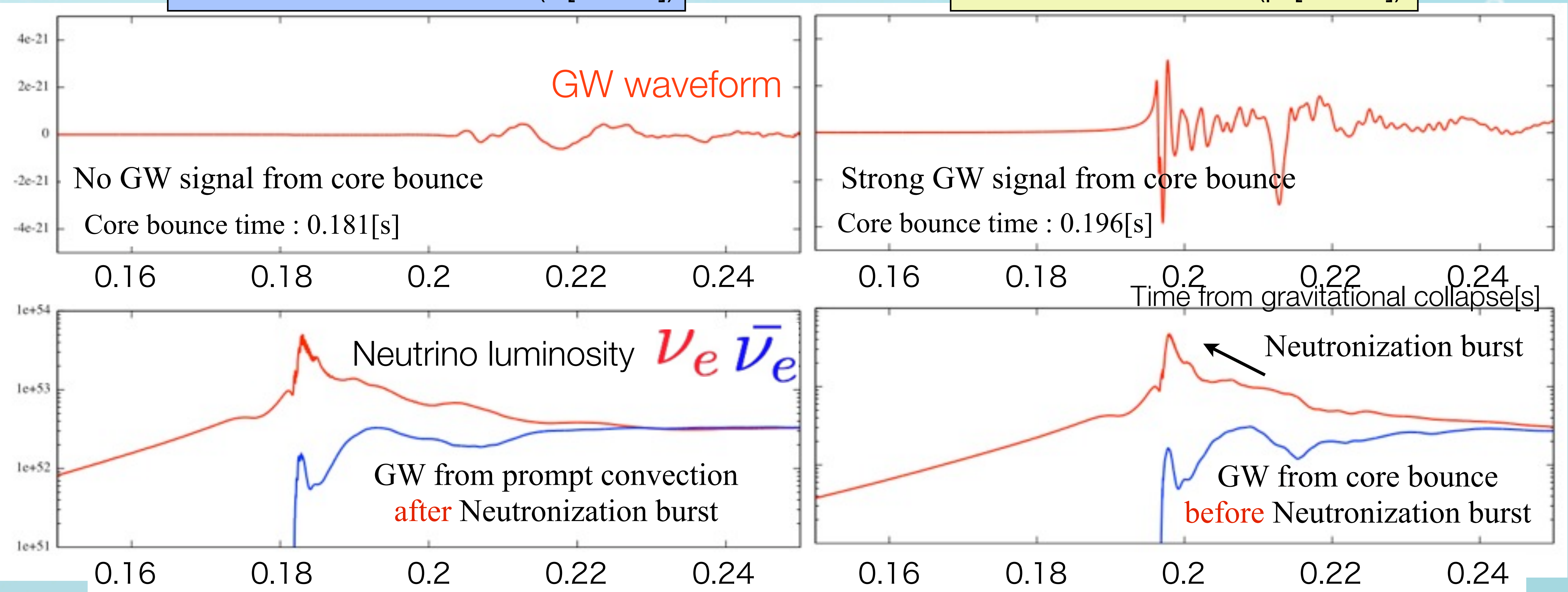
- Focus on **GW observed time(t_obs_gw)** and **Neutronization burst time(t_obs_nburst)**
- Supernova detection simulation with KAGRA and EGADS detector

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

No core rotation case (0[rad/s])

core rotation case(pi[rad/s])



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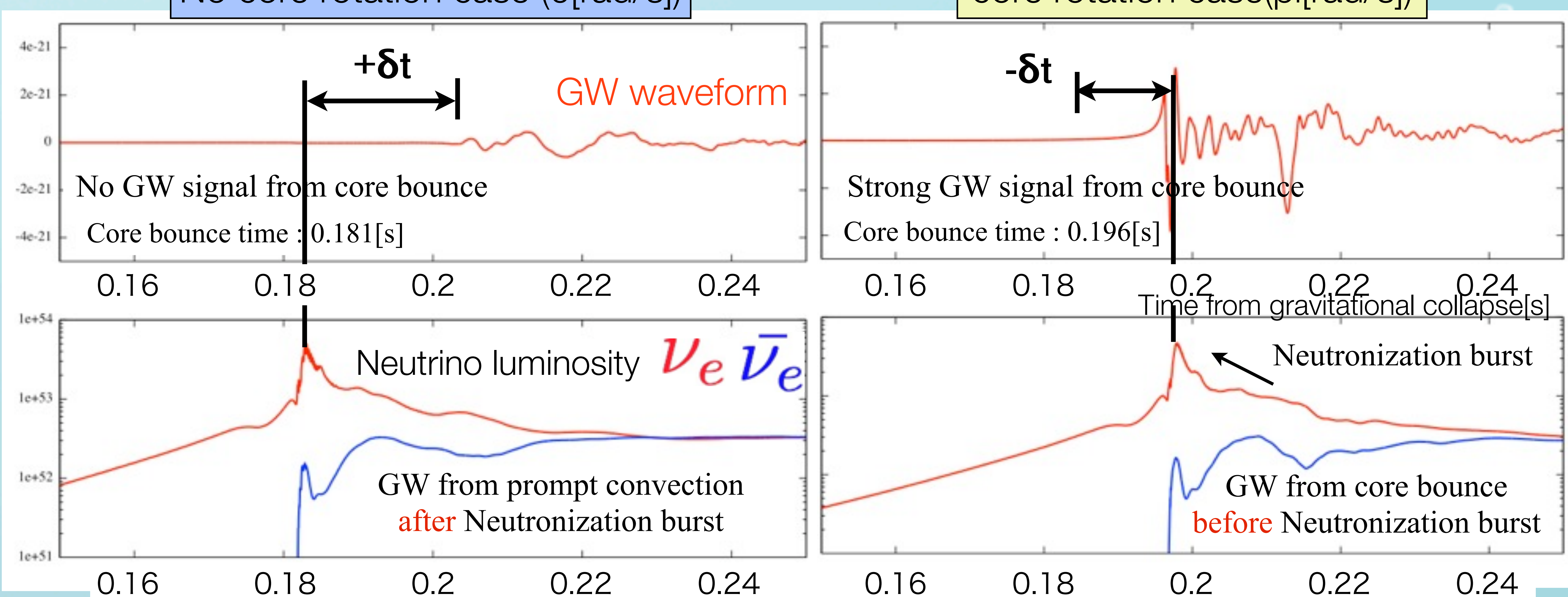
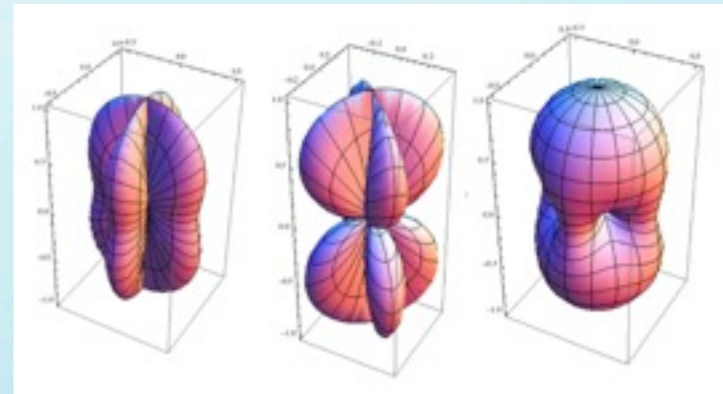
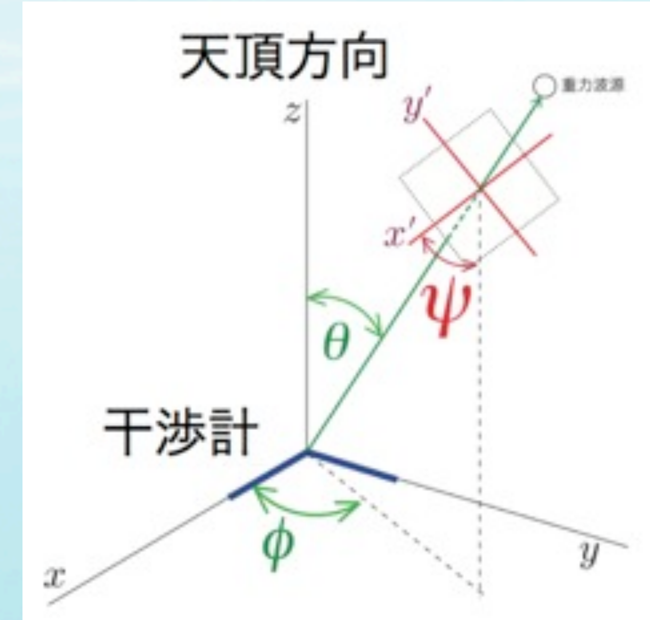


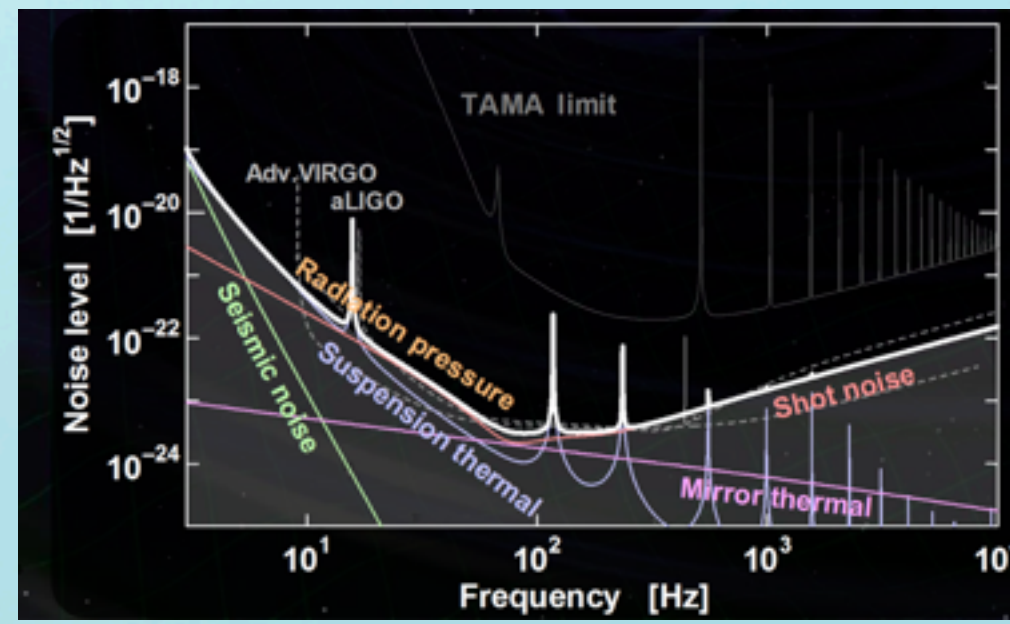
GW analysis



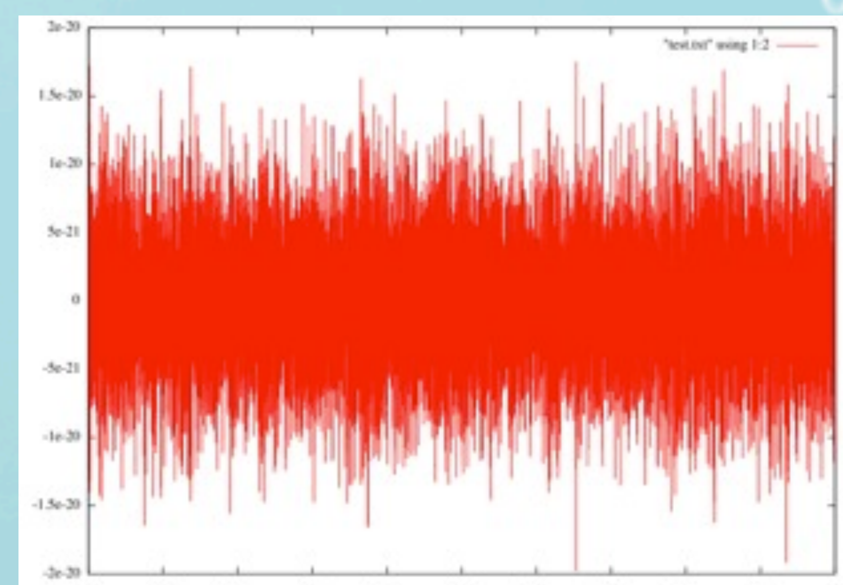


- KAGRA detector information
  - bKAGRA sensitivity curve
  - Sampling frequency = 16,384[Hz]

- Analysis tools
  - Excess power filter + Short Time Fourier Transform



- Generation signal
  - s(t) = h(t) + n(t)
  - Time series of noise generation
    - Assume stationary Gaussian noise + suspension thermal noise
    - Make whiting filter for this analysis
    - 40 - 5000[Hz]
  - Time domain supernova signal
    - Taken into account Distance, antenna pattern, polarization.



GW analysis

- Short Time Fourier Transform
  - open searching timing window : 1/32 = 31.25ms
    - corresponds to 512 point
  - Window function ; Hamming
  - Apply STFT and obtain signal power
  - shift 1ms(16point) and STFT again

- SNR definition
  - Integrate signal power
    - Remove around suspension noise peak

signal power;

$$\rho = \sqrt{\frac{\int s_w^*(f) \cdot s_w(f) df}{\int < n_w^*(f) \cdot n_w(f) > df}}$$

noise power;

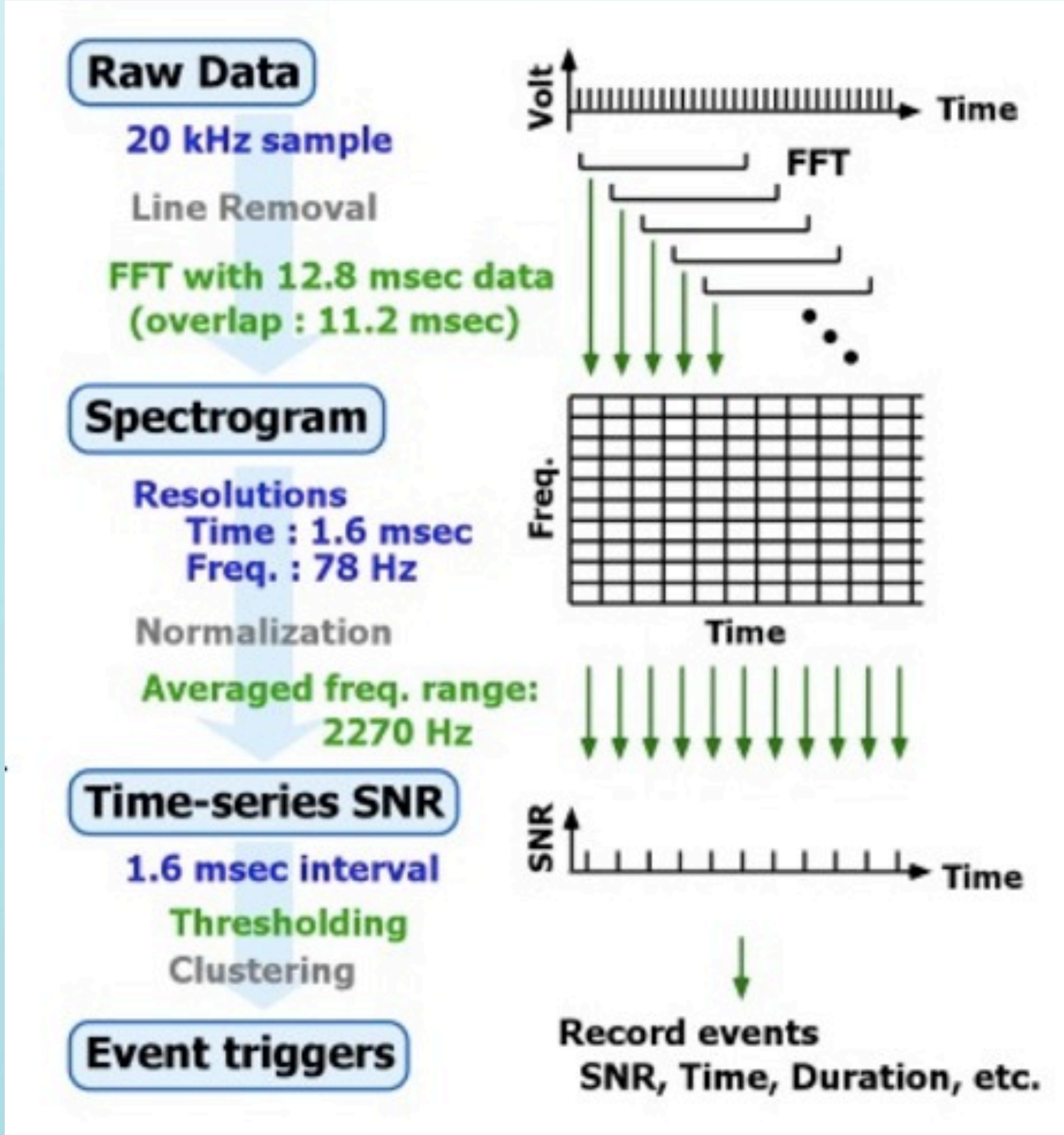
$$\rho_0 = \sqrt{\frac{\int n_w^*(f) \cdot n_w(f) df}{\int < n_w^*(f) \cdot n_w(f) > df}}$$

- Estimation of Signal to Noise Ratio

$$\frac{S}{N} = \frac{\mu - m}{\sigma}$$

m : mean of ρ0 dist. (~1.0)
σ: deviation of ρ0 dist. (~0.06)
μ : ρ value (signal power)

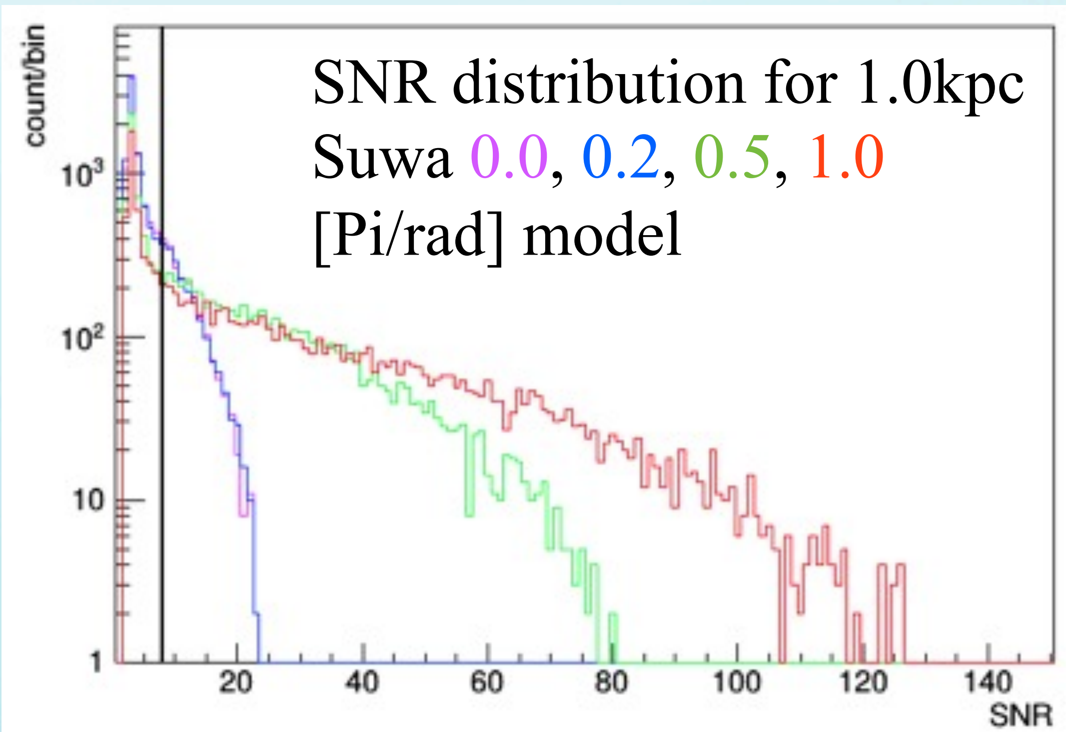
- Obtained GW emit time
  - Left edge of timing window which gives max SNR
  - Assume strong signal come when core bounce and continue weak signal by SASI, convection



From TAMA burst paper

PHYSICAL REVIEW D 71, 082002 (2005)

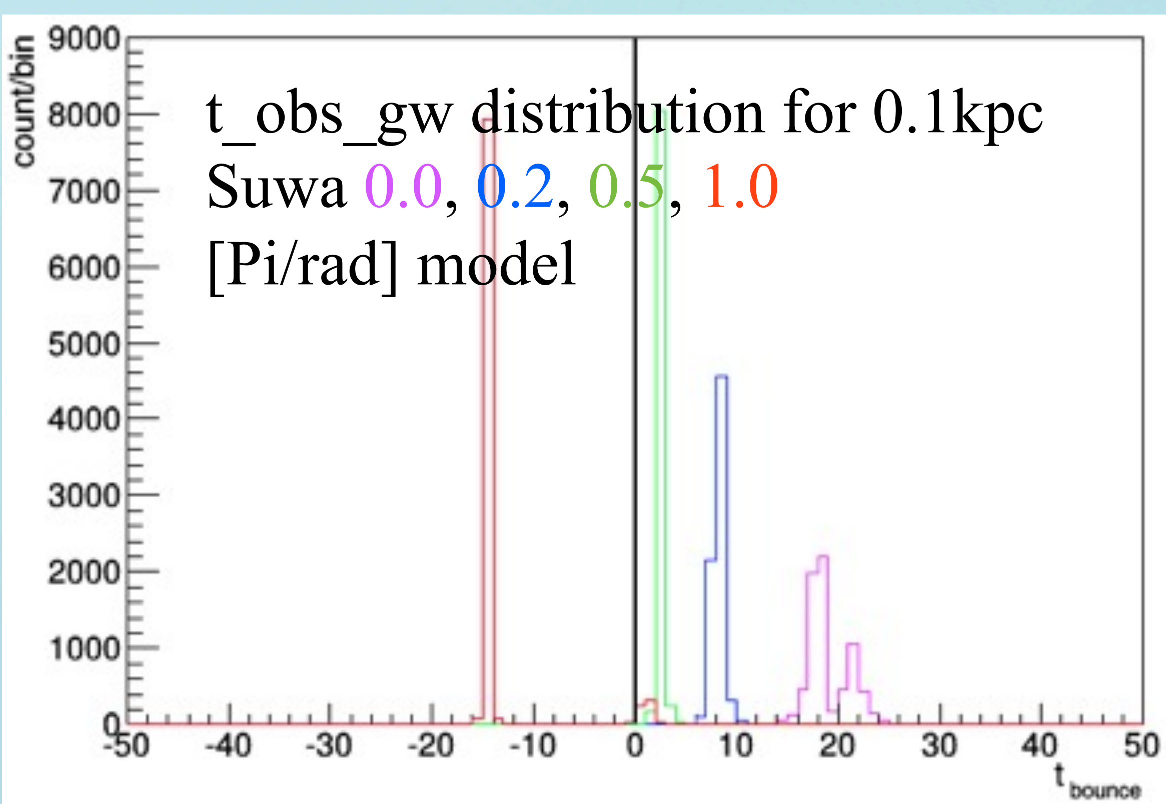
GW analysis result

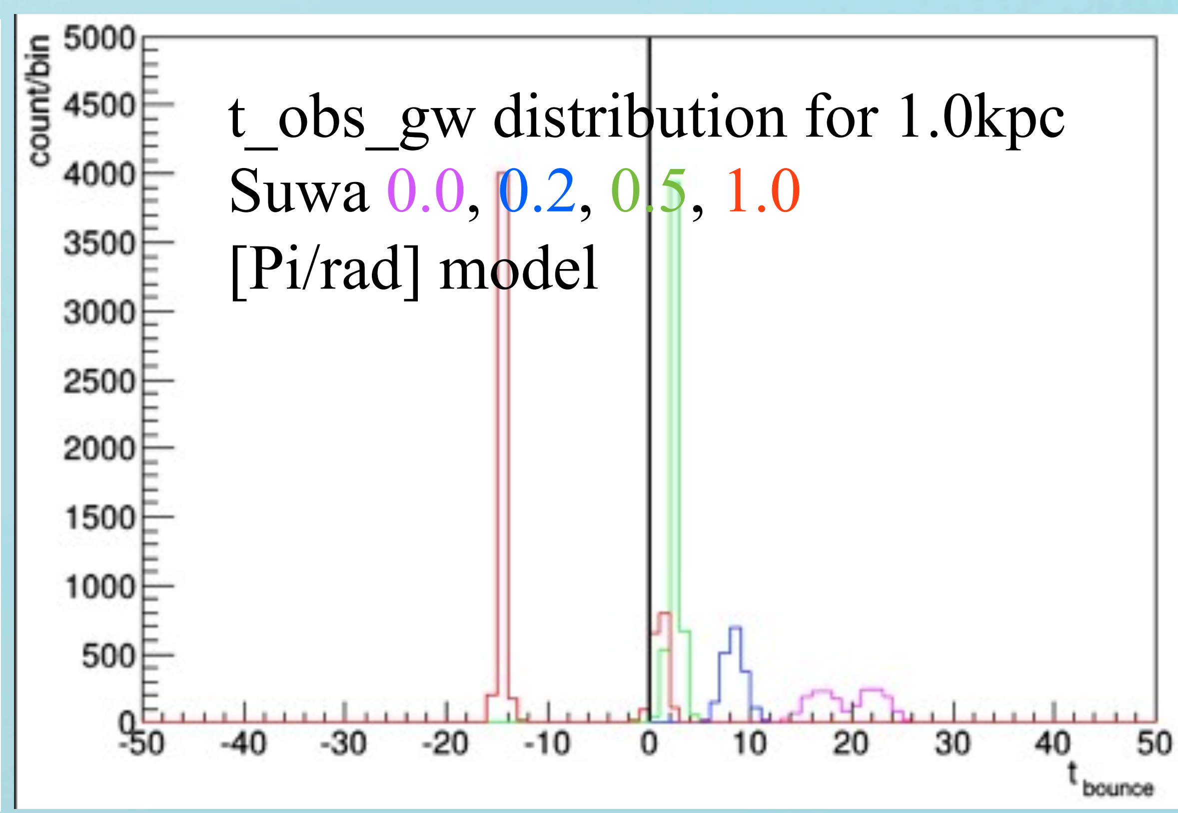


- Core rotation model(1.0[Pi/rad]) : high SNR
    - SNR threshold : SNR > 8

- t_obs_gw distribution with core bounce time
    - Core rotation model : earlier
    - good timing resolution (RMS~1ms)

- Need to optimize the method to determine t_obs_gw



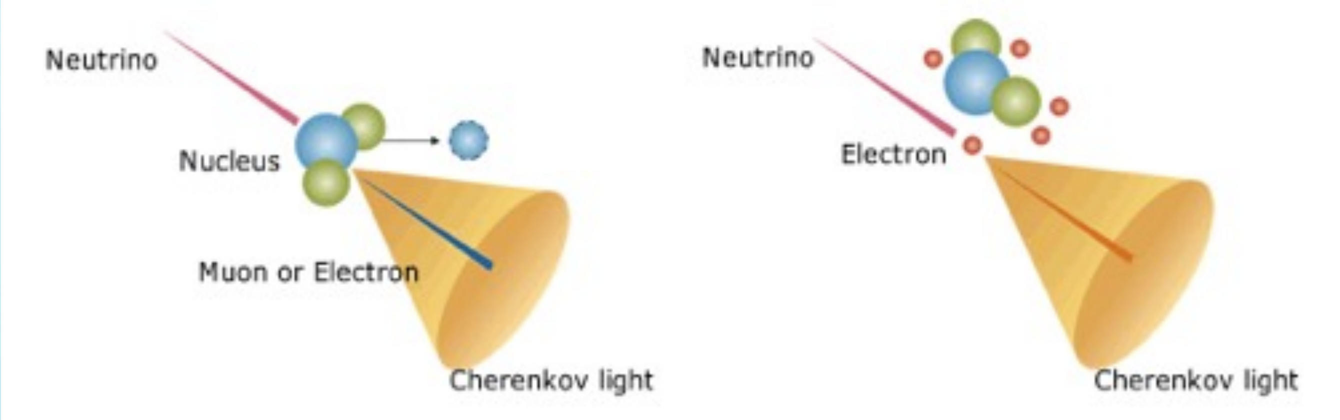


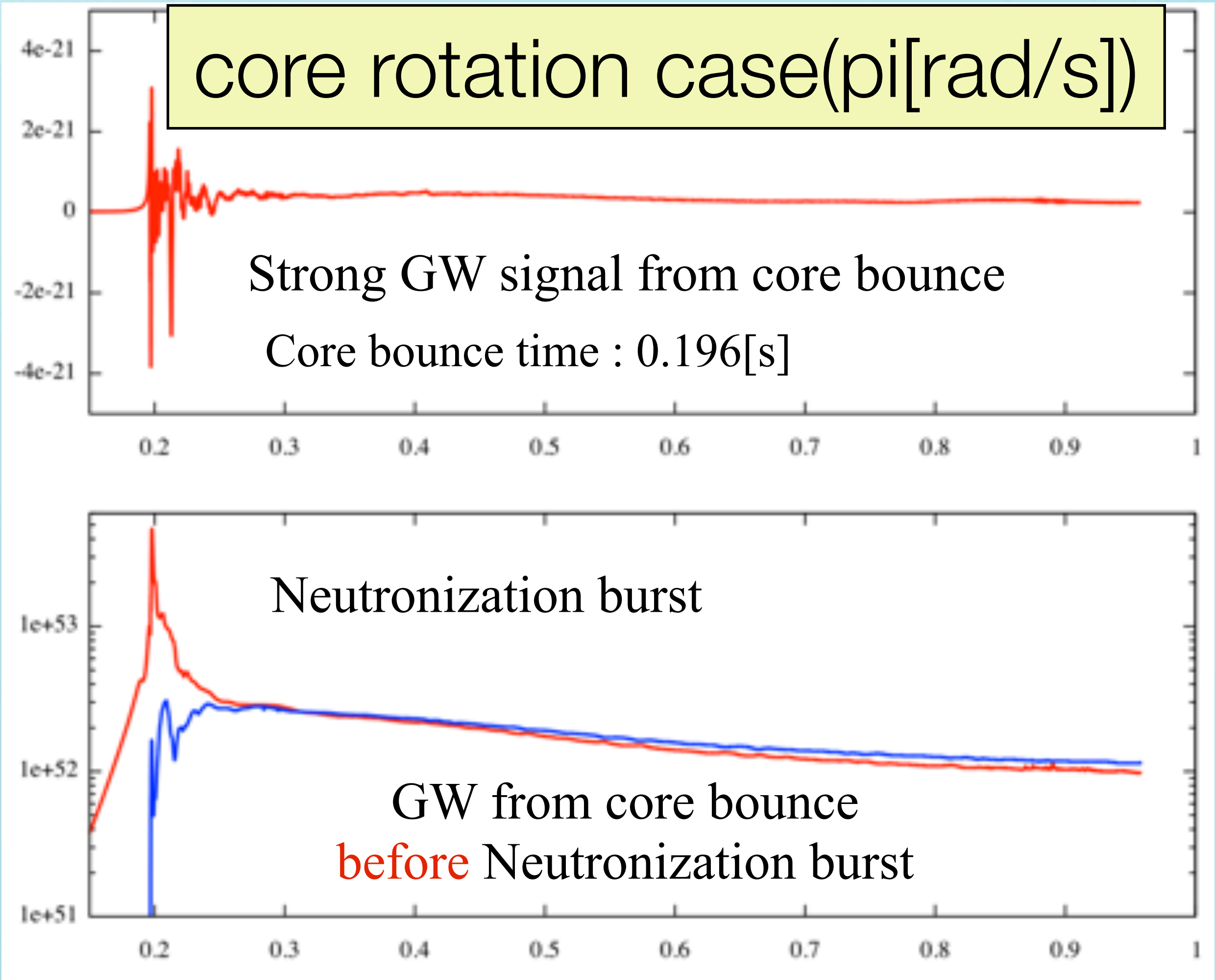
Neutrino analysis

- EGADS detector information
  - Fiducial volume 100ton
  - Neutron tagging efficiency 90%
  - Energy threshold 5.0MeV

- Neutrino fluxes in Earth
  - Estimate from L_nu[erg/s] and <E_nu>[MeV]
  - Assume Fermi-Dirac distribution
  - Not taken into account Neutrino oscillation
  - Taken into account only electron flavor

- Interaction rate in EGADS tank
  - Inverse beta decay
  - electron neutrino - electron scattering
  - anti-electron neutrino - electron scattering
  - not consider
    - neutrino - Oxygen interactions
    - detector background (<1event/s)
    - Nu_x - electron scattering





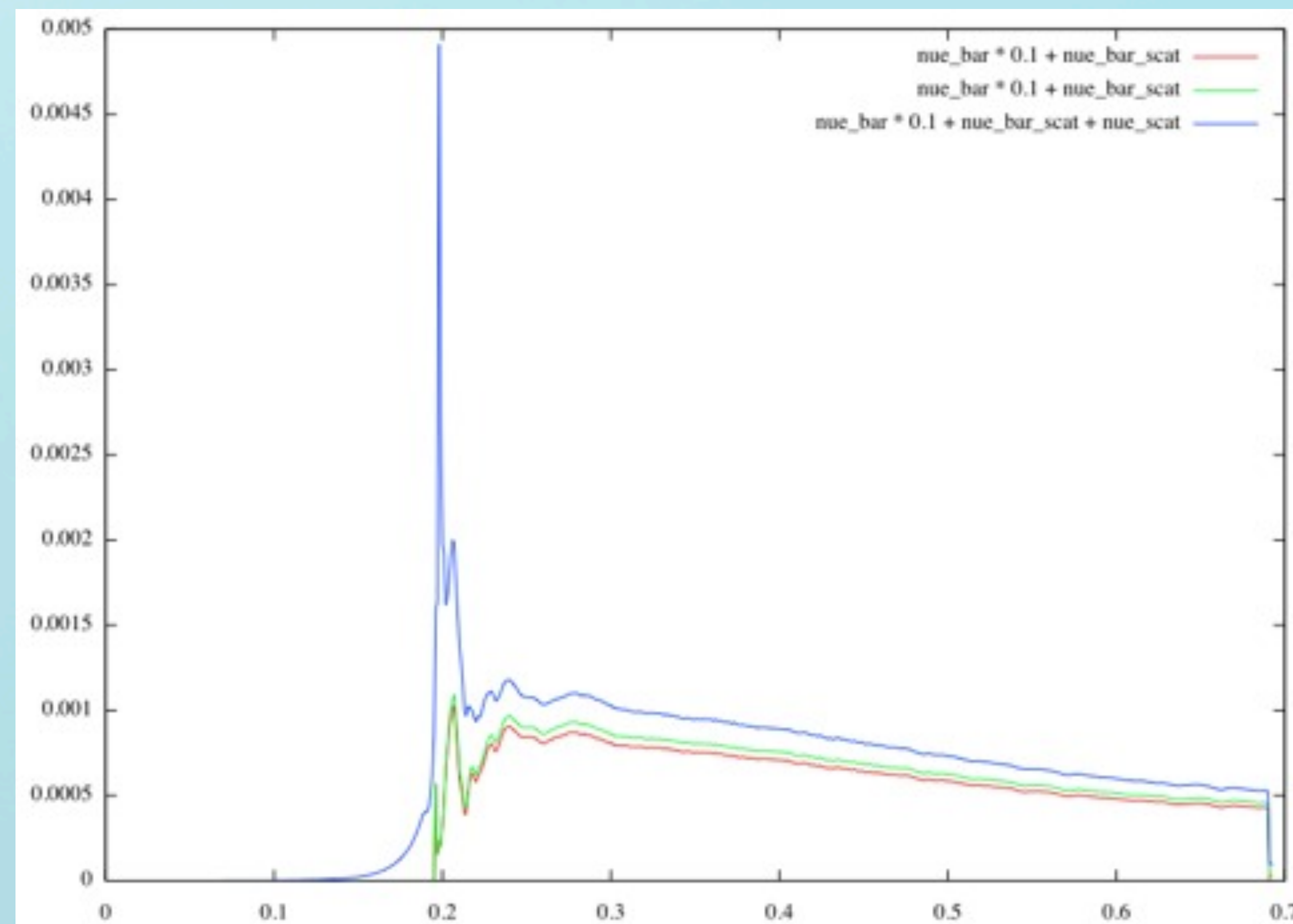
Neutrino analysis

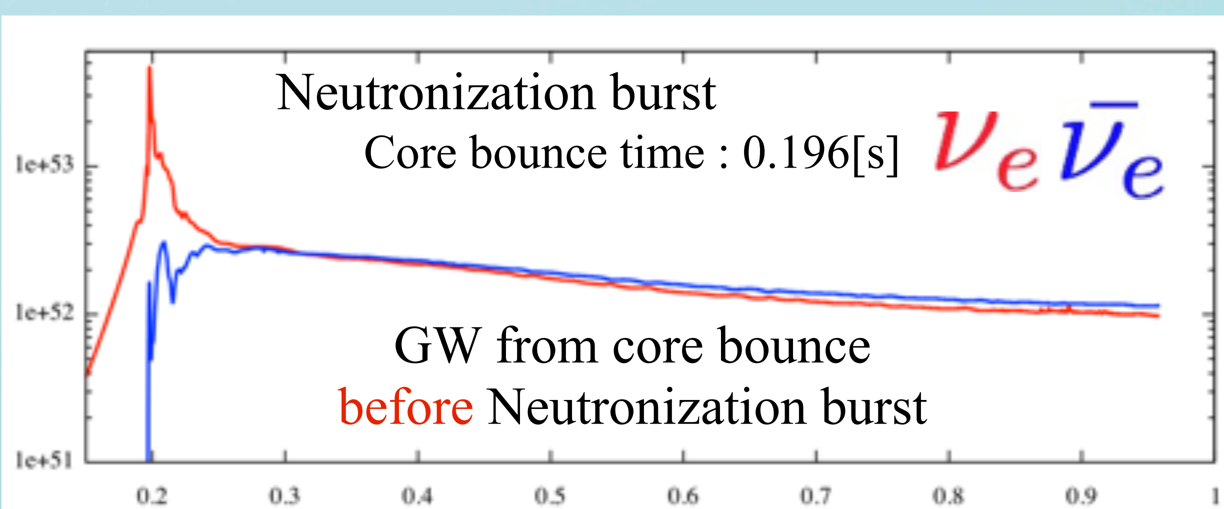
- Neutronization burst is event which emit ‘electron neutrino’ with very short time
- If distinguish electron and anti-electron, we’re possible to identify the time of Neutronization burst correctly.
- Egads detector can distinguish scattering event and Inverse beta decay event!

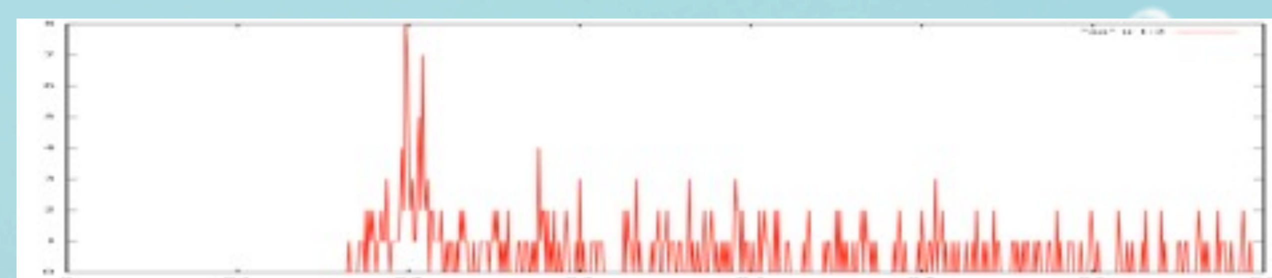
- Signal
    - Electron Nu - electron scattering
- Background
    - mis-neutron tagged inverse beta decay(10%)
    - anti-electron Nu - electron scattering

- Using Poisson distribution, simulate number of interact neutrino with each time(1ms resolution)

- Open 6ms timing window and search maximum



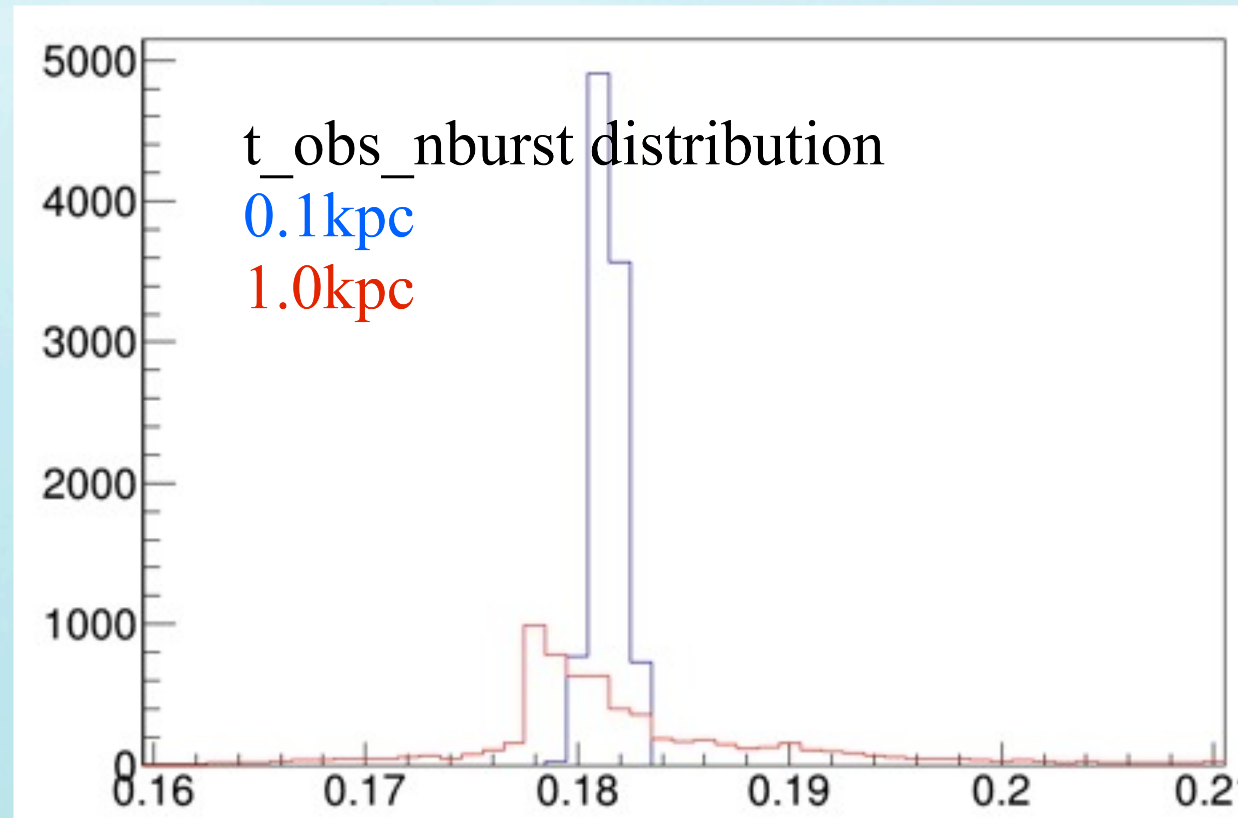


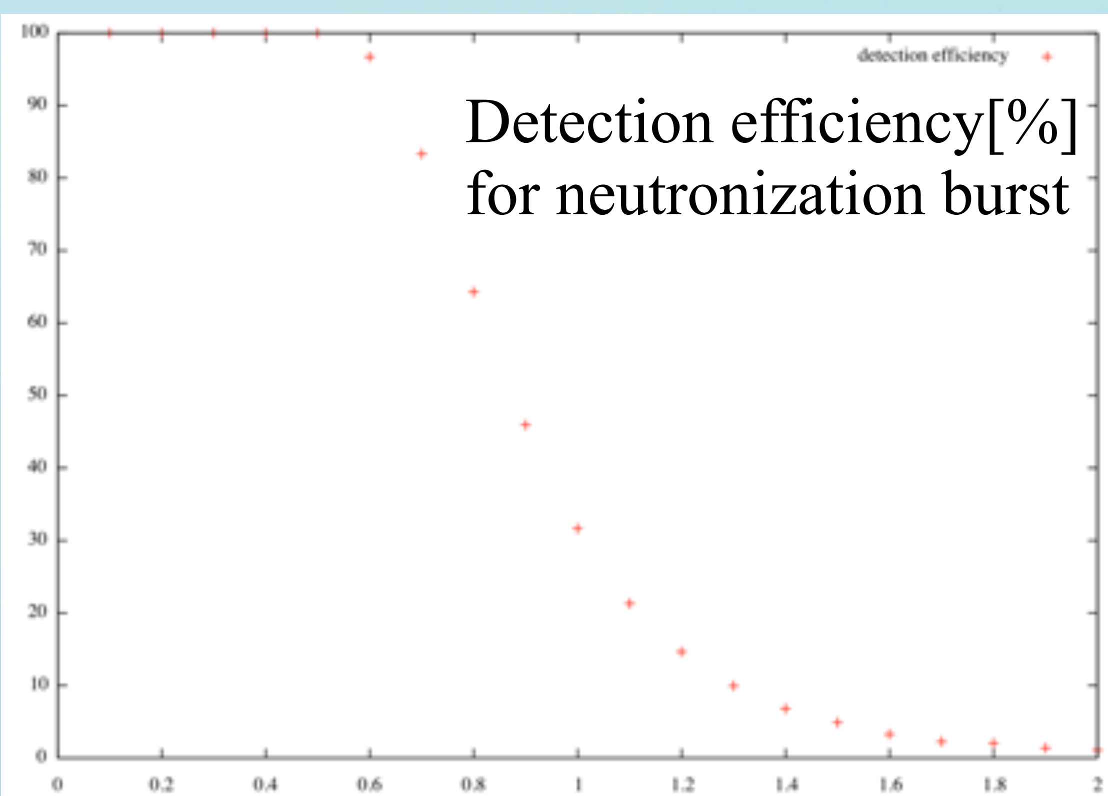


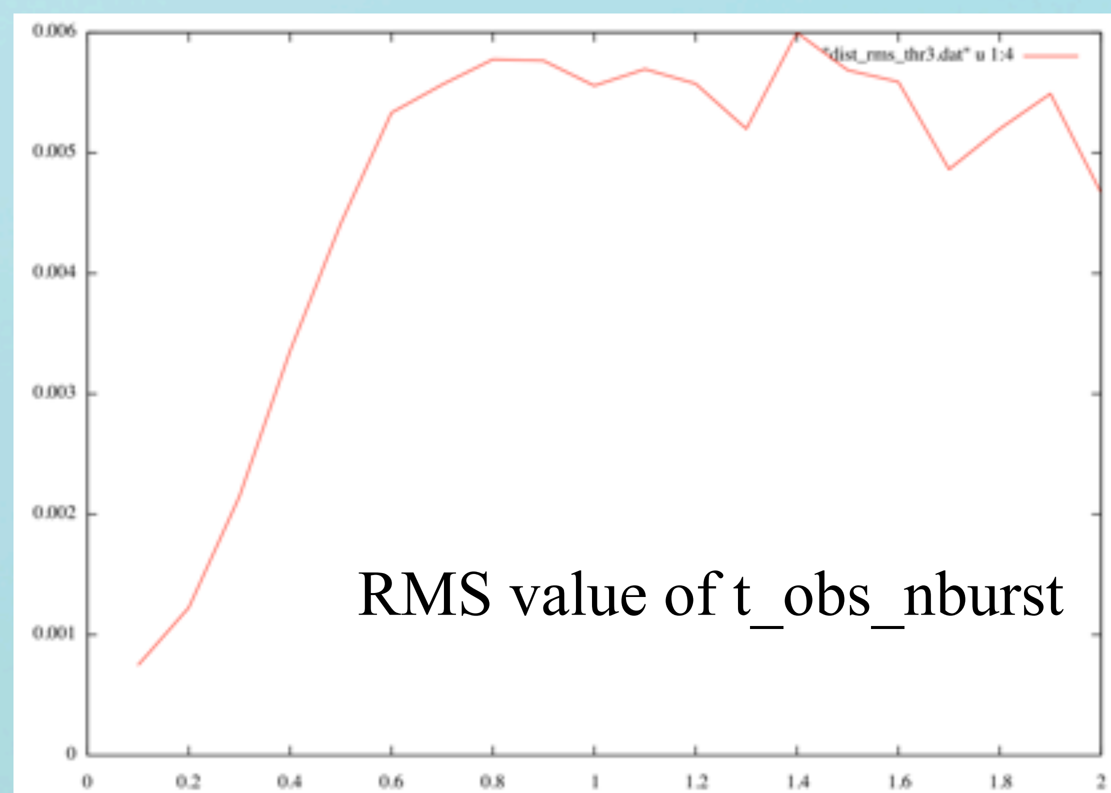
Neutrino analysis result

- Threshold : 3 [event/6ms]

- t_obs_nburst distribution(0.1kpc)
  - 100% detection efficiency
  - good timing resolution(~1ms)
- But, resolution becomes worse for >1kpc
  - # of small observed event
  - GADZOOKS!



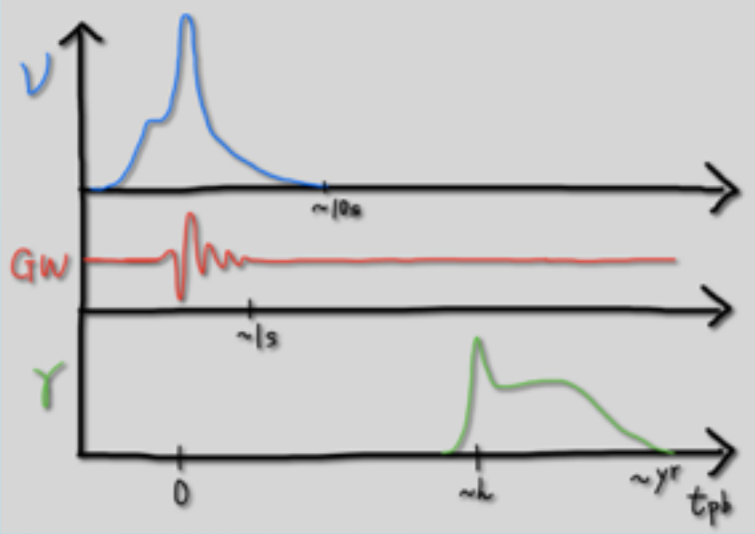




Combined analysis

- Analysis strategy summary
    - estimate time of
        - GW emit time by KAGRA
        - Neutronization burst time by EGADS
    - SN uniformly distributed for each distance 0.1 - 2.0kpc
    - loop 10,000 SN simulation

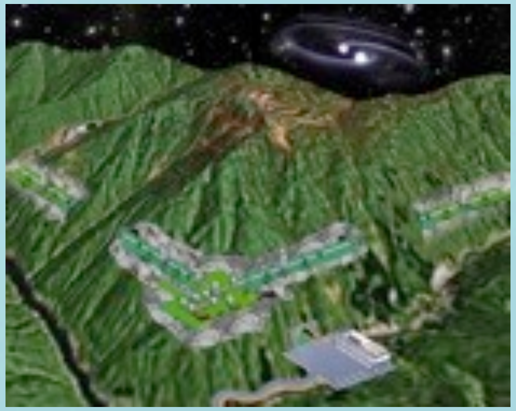
- Analysis results
    - Estimate detection efficiency of GW and Neutronization burst
        - GW : t_obs_gw : SNR >8
        - Neutrino : t_obs_nburst : 3[event/6ms]
    - compare t_ obs_gw and t_obs_nburst
    - Judge core rotation by two parametes



Are we rotating??

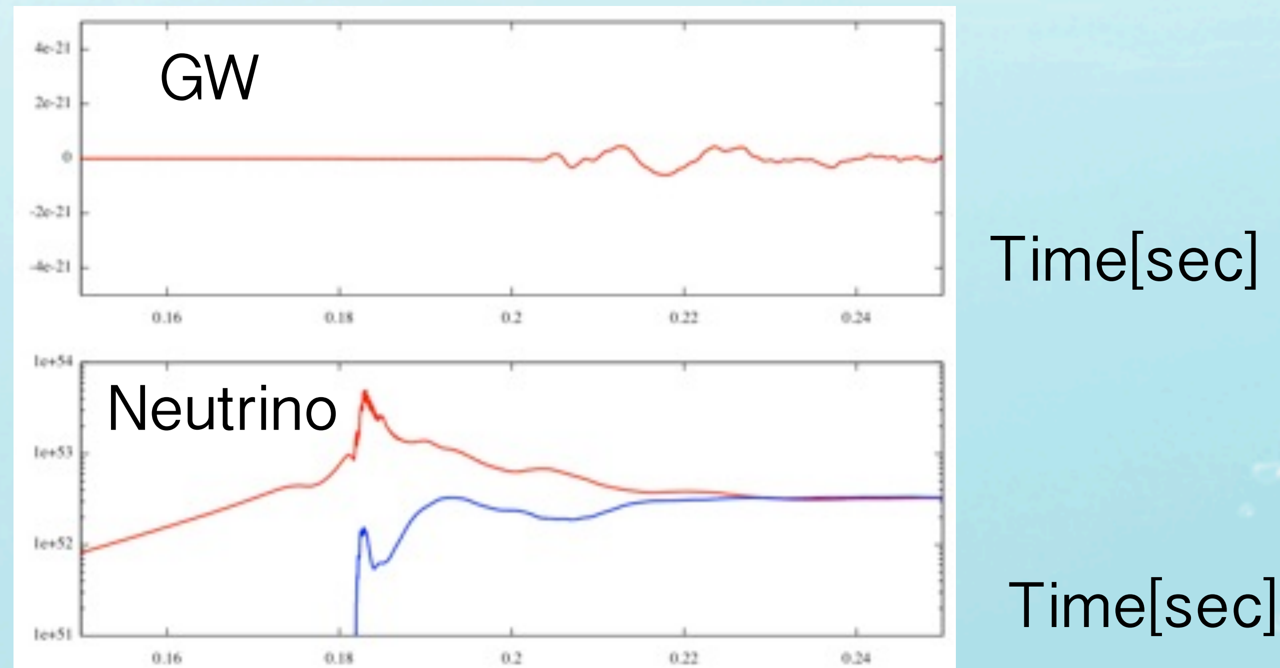
We can judge!!

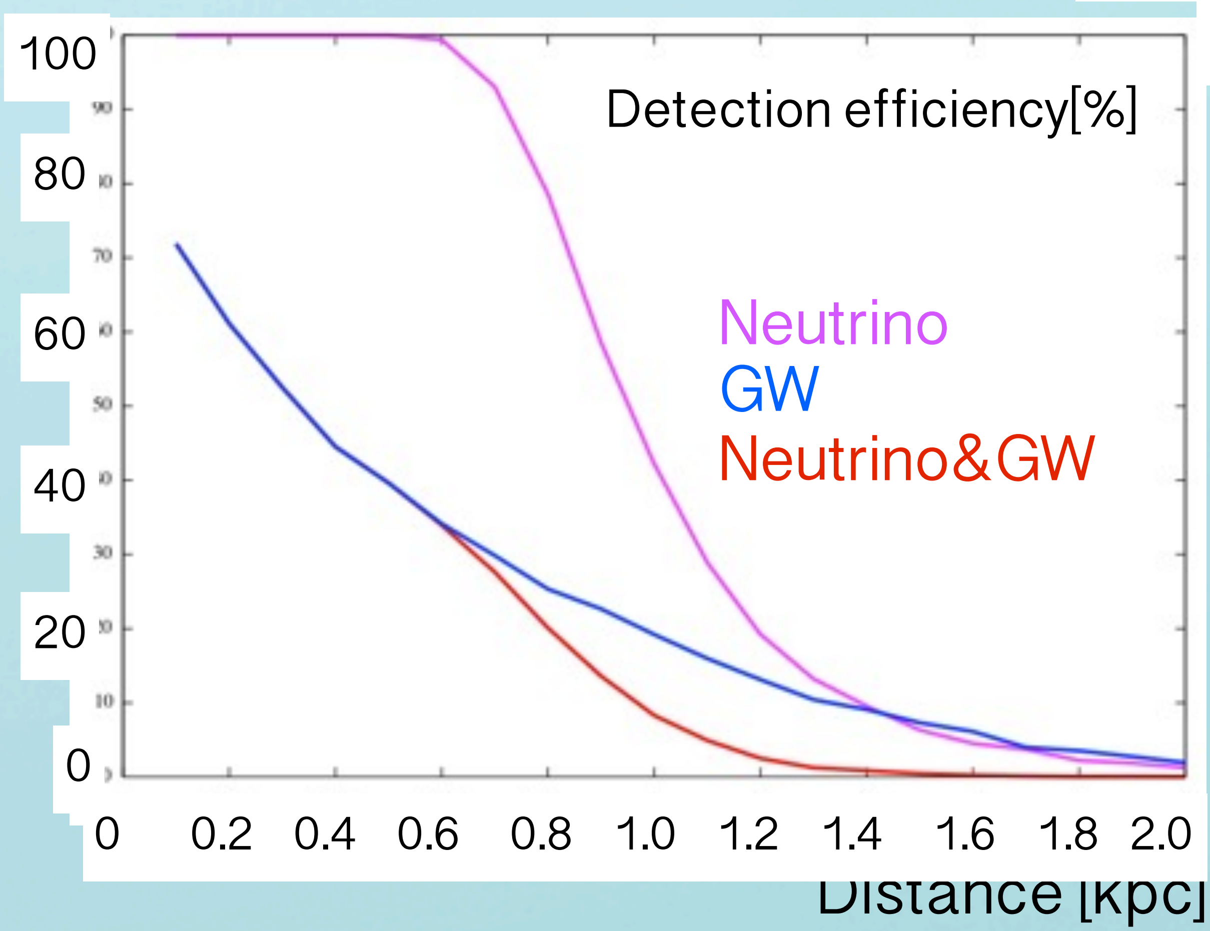
超新星 SN1987A

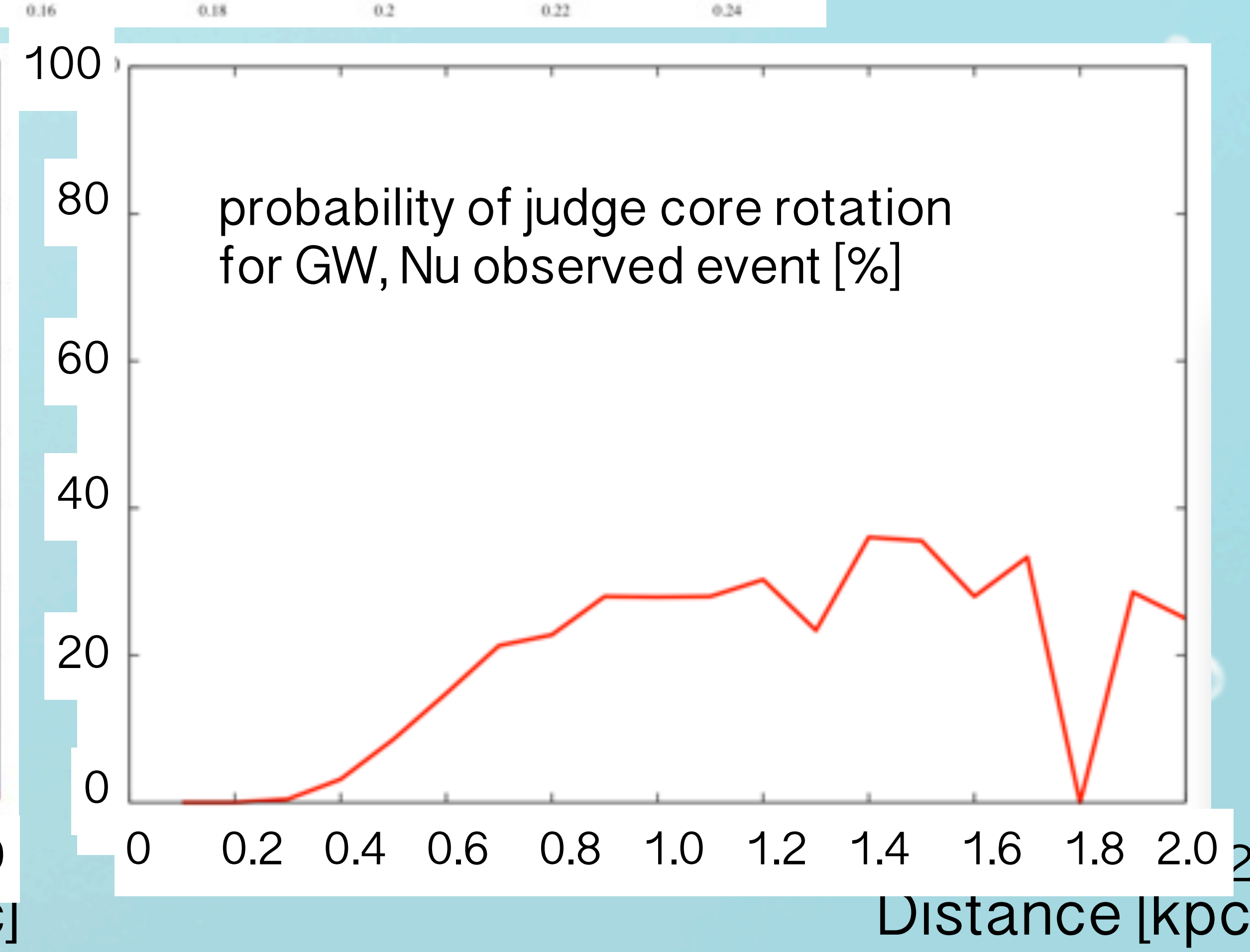


Combine analysis 0.0[pi/rad] result

- 0.1[kpc]
  - 71.9% detection efficiency
  - 100% judge NO core rotation
- 0.5[kpc]
  - 39.6% detection efficiency
  - 91.4% judge NO core rotation
- 1.0[kpc]
  - 8.3% detection efficiency
  - 72.1% judge NO core rotation

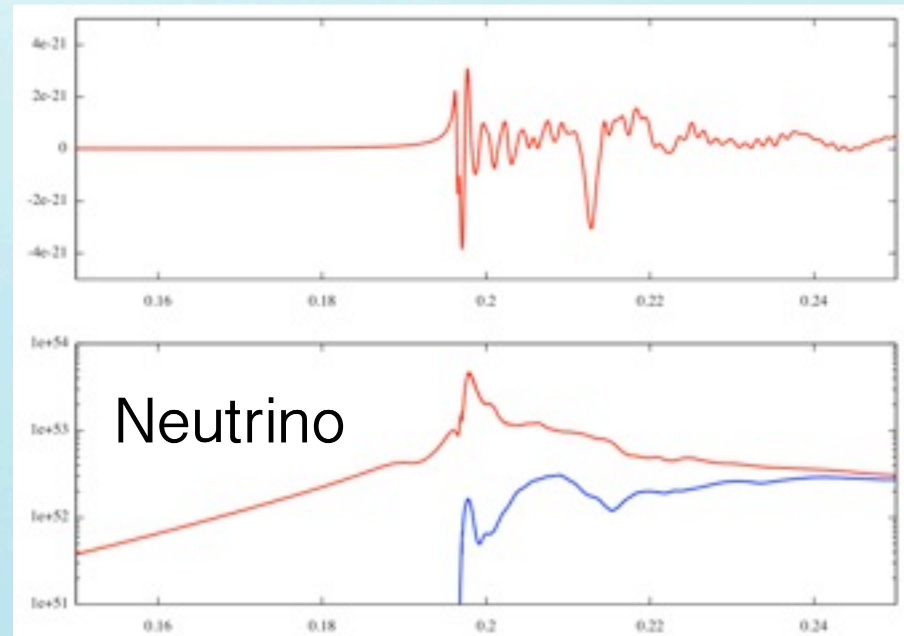


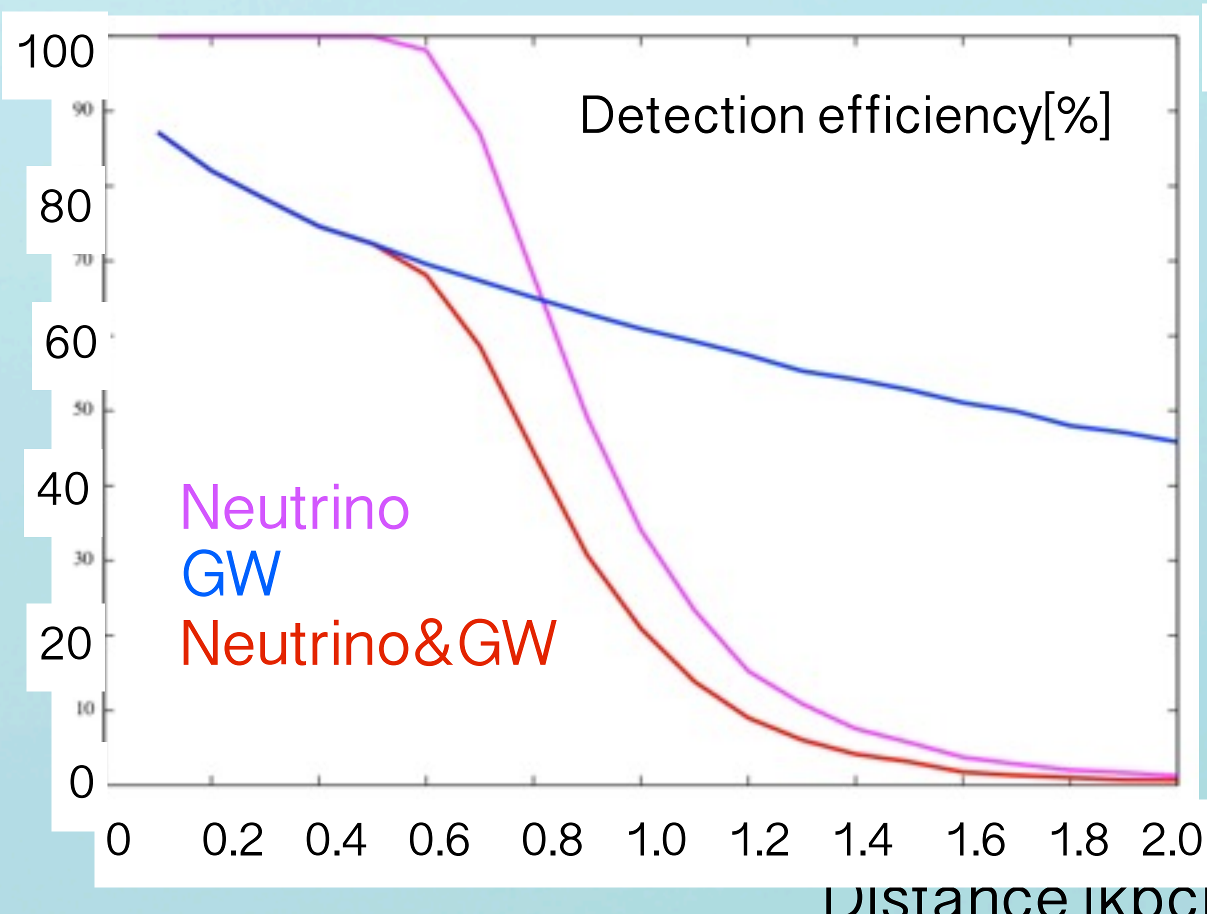


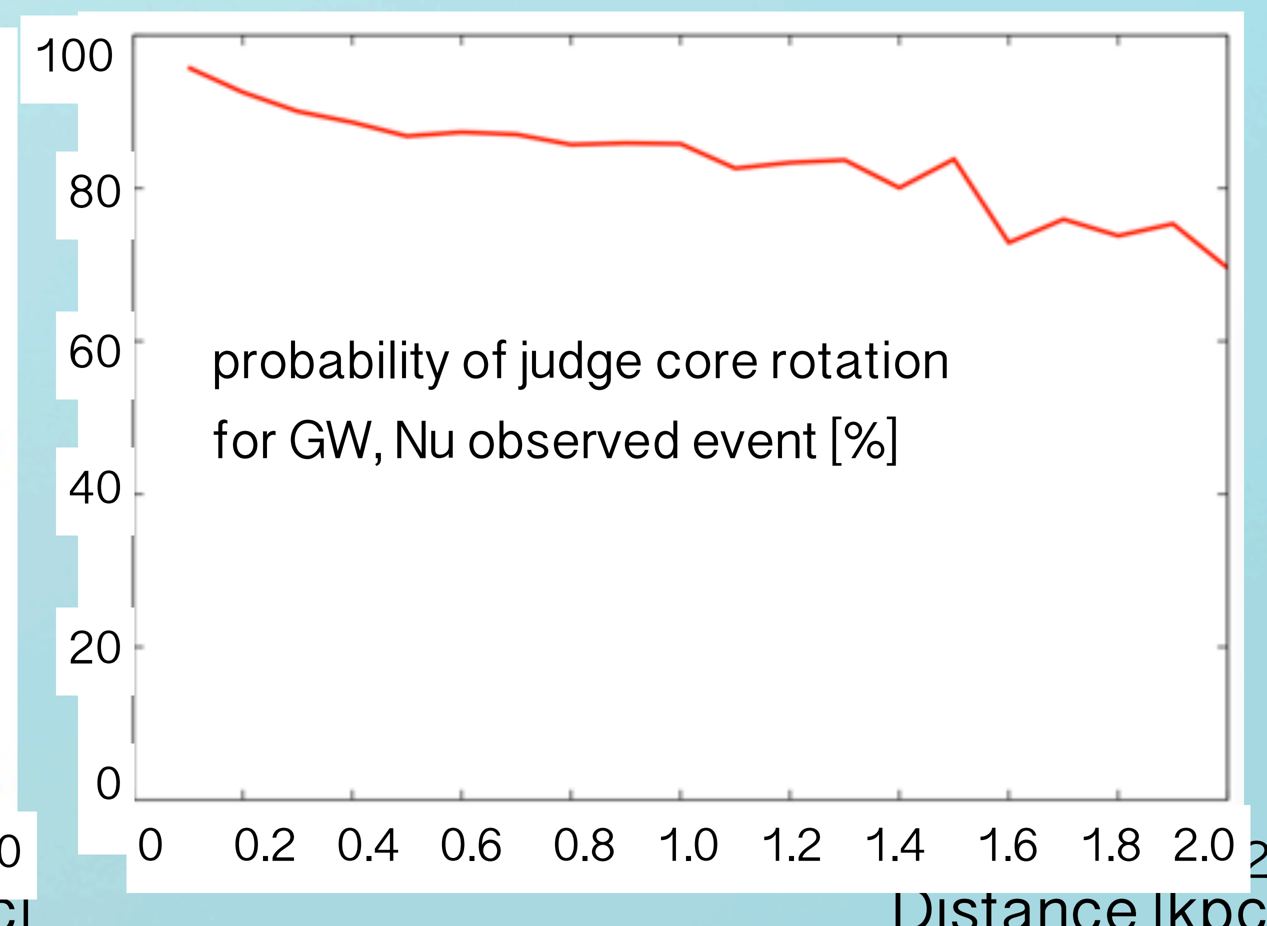


Combined analysis 1.0[pi/rad] result

- 0.1[kpc]
  - 87.2% detection efficiency
  - 95.8% judge core rotation
- 0.5[kpc]
  - 72.3% detection efficiency
  - 86.8% judge core rotation
- 1.0[kpc]
  - 20.9% detection efficiency
  - 85.8% judge core rotation





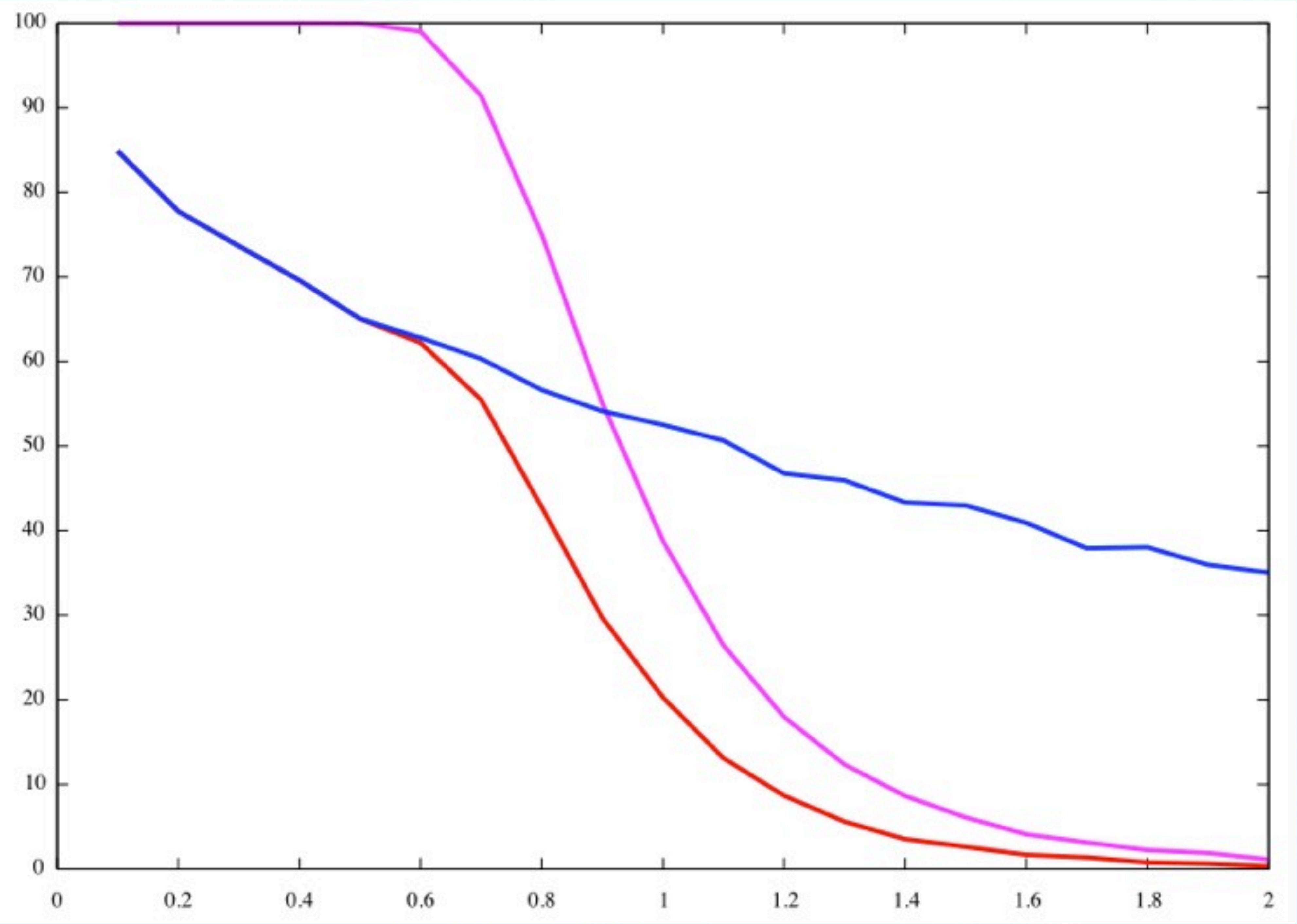


Summary

- Introduce Supernova neutrinos for Betelgeuse explosion
    - Many detector will help to understand explosion mechanism
- Evaluation of progenitor core rotation
    - Co-operating with Theory, GW and Neutrino Analysis gorup
    - Compare GW emit time and Neuitronization burst
        - Detector simulation
    - When SN occurred in 0.1kpc distance,
        - For no-rotation model
            - about 70% detection efficiency
            - Judge almost 100% NO core rotation
        - For strong-rotation model
            - about 90% detection efficiency
            - Judge 96% core rotation

Backups

0.5[pi/rad]



0.2[Pi/rad]