重力波、ニュートリノの同時観測による超新星爆発メカニズム解明に向けた研究

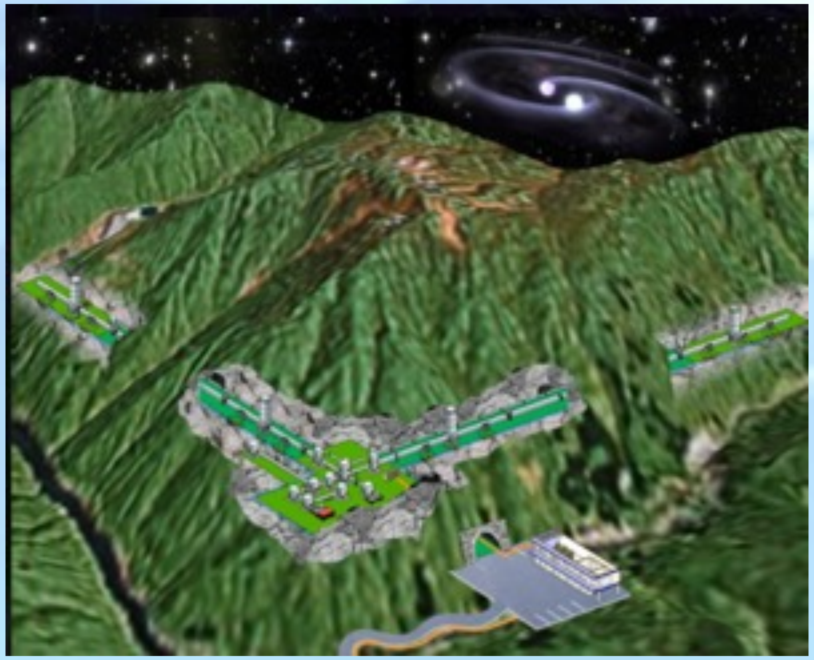
第一回超新星ニュートリノ研究会@東京理科大学

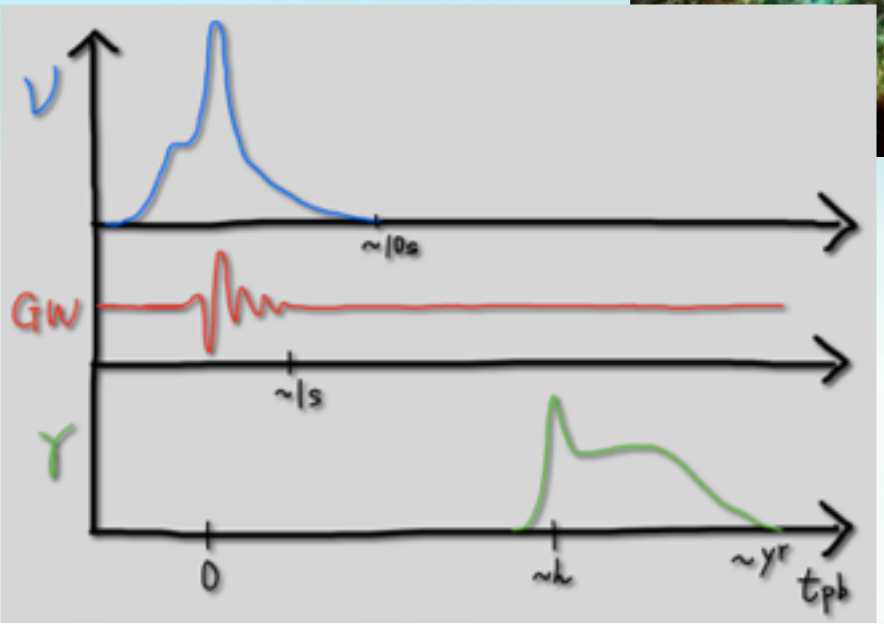
2015/03/17

大阪市立大学　横澤孝章

Contents

- Gravitational Wave(GW) detectors
    - KAGRA status
    - Candidate GW sources
- Analysis strategy from Supernova signal
    - TF clustering
    - Multi detector coherent network analysis
    - With External trigger
- Messages from Supernova
    - Multi-messenger astronomy
    - Our latest results





GW and Laser interferometer

- Einstein Equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- For a small perturbation "h", a wave equation is derived

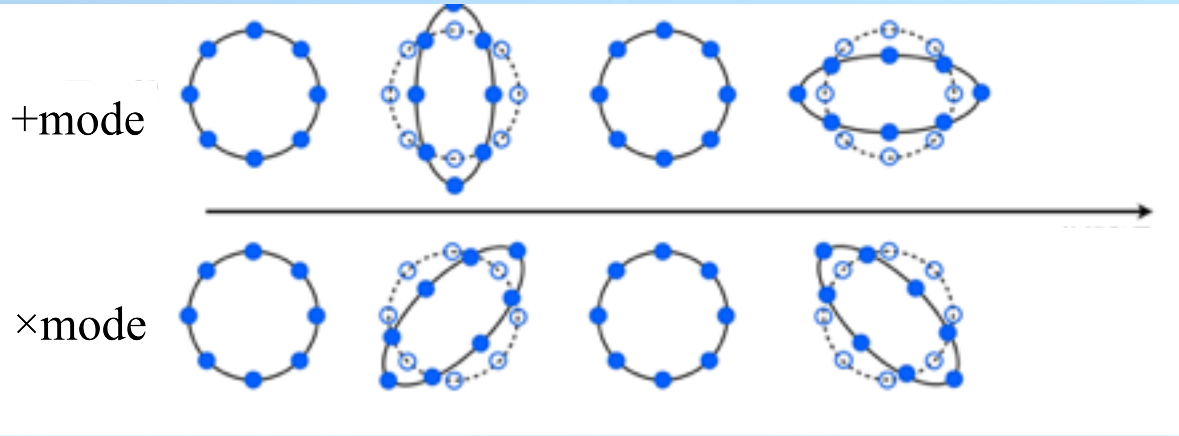
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

perturbation

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{\mu\nu} = 0$$

- Two polarization : + mode and × mode

$$h_+ = h\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad h_\times = h\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



- Energy of GW

$$I_{\mu\nu} = \int \rho(\vec{r})(x_\mu x_\nu - \frac{1}{3}\delta_{\mu\nu}r^2)d^3x$$

$$\mathcal{L}_{gw} = \int_{r\to\infty} T_i^{0gw} n^i r^2 d\Omega$$

$$= \frac{G}{5c^5} < \dddot{I}_{\mu\nu}\dddot{I}^{\mu\nu} >$$

$$h_{\mu\nu} \simeq \frac{2G}{rc^4}\ddot{I}_{\mu\nu}$$

Mass quadruple moment

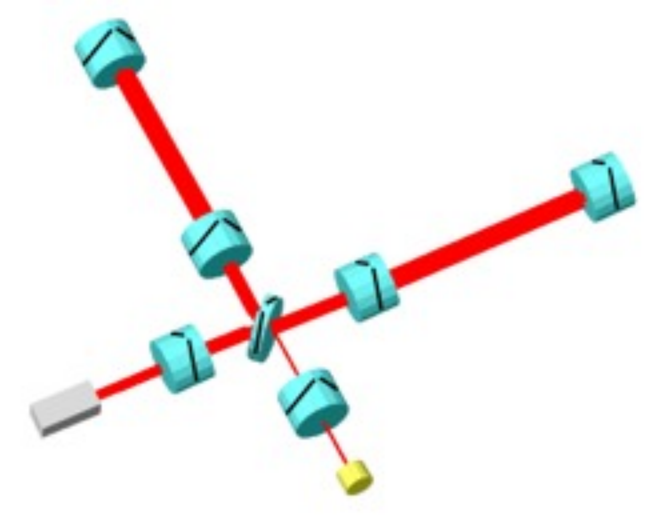
axis asymmetry

- Laser interferometer

Fabry-perot Michelson interferometer

Observe the optics of interface

Direction dependence

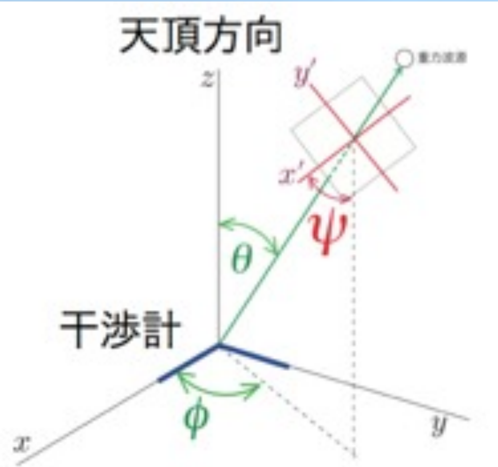


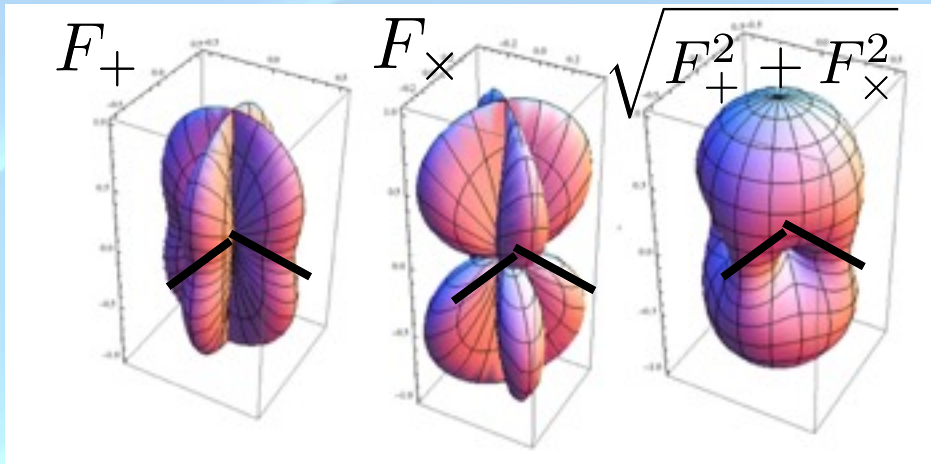
GW and Laser interferometer

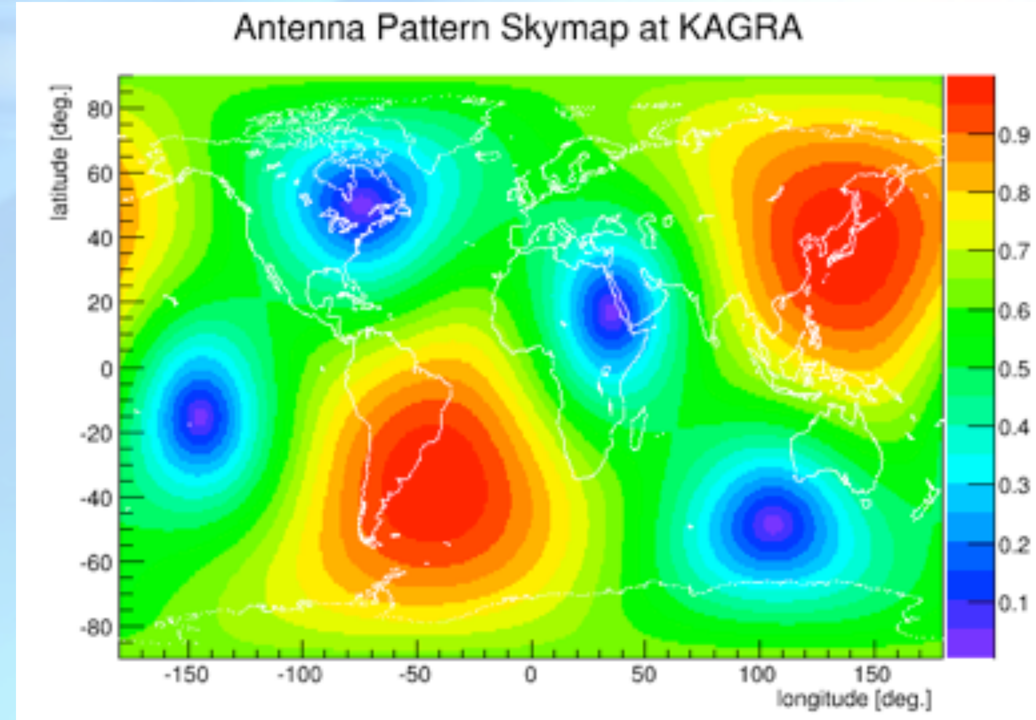
- Antenna pattern

$$F_+ = \frac{1}{2}(1+\cos^2\theta)\cos 2\phi\cos 2\psi - \cos\theta\sin 2\phi\sin 2\psi$$
$$F_\times = \frac{1}{2}(1+\cos^2\theta)\cos 2\phi\sin 2\psi + \cos\theta\sin 2\phi\cos 2\psi$$

θ : Zenith angle
ϕ : Azimuth angle
ψ : Polarization



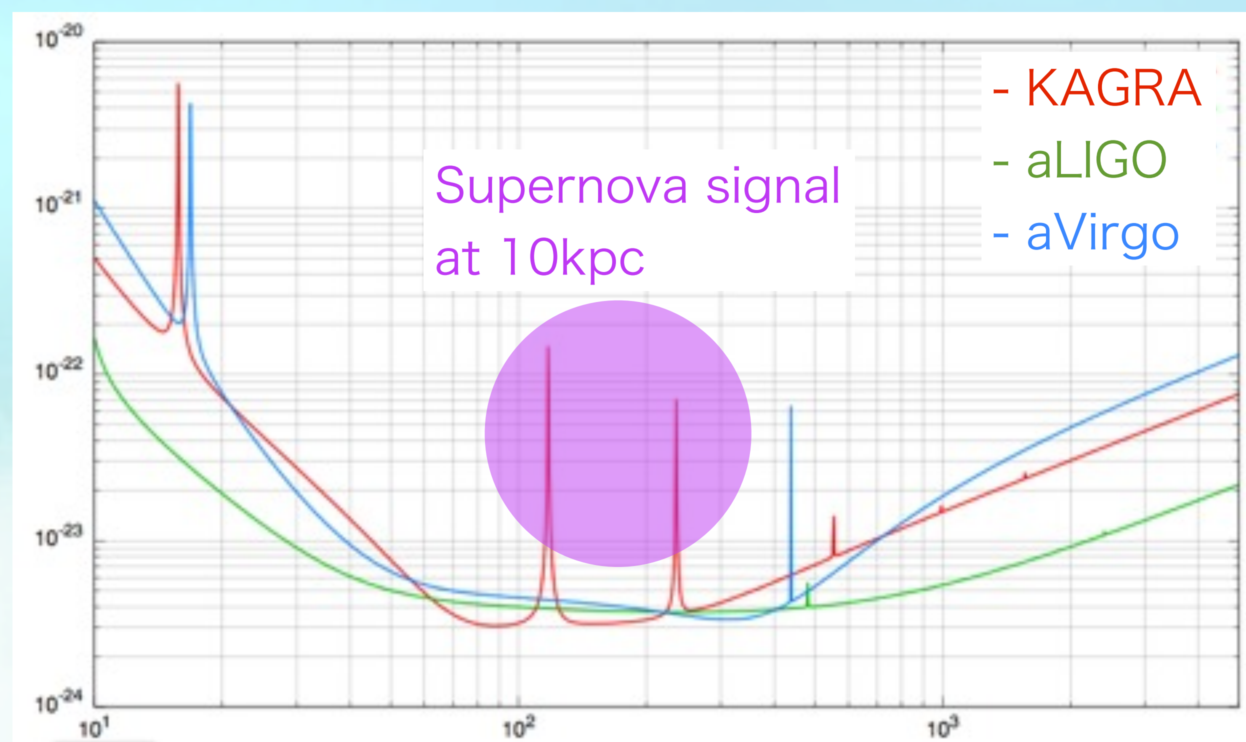




- Detector sensitivity curve

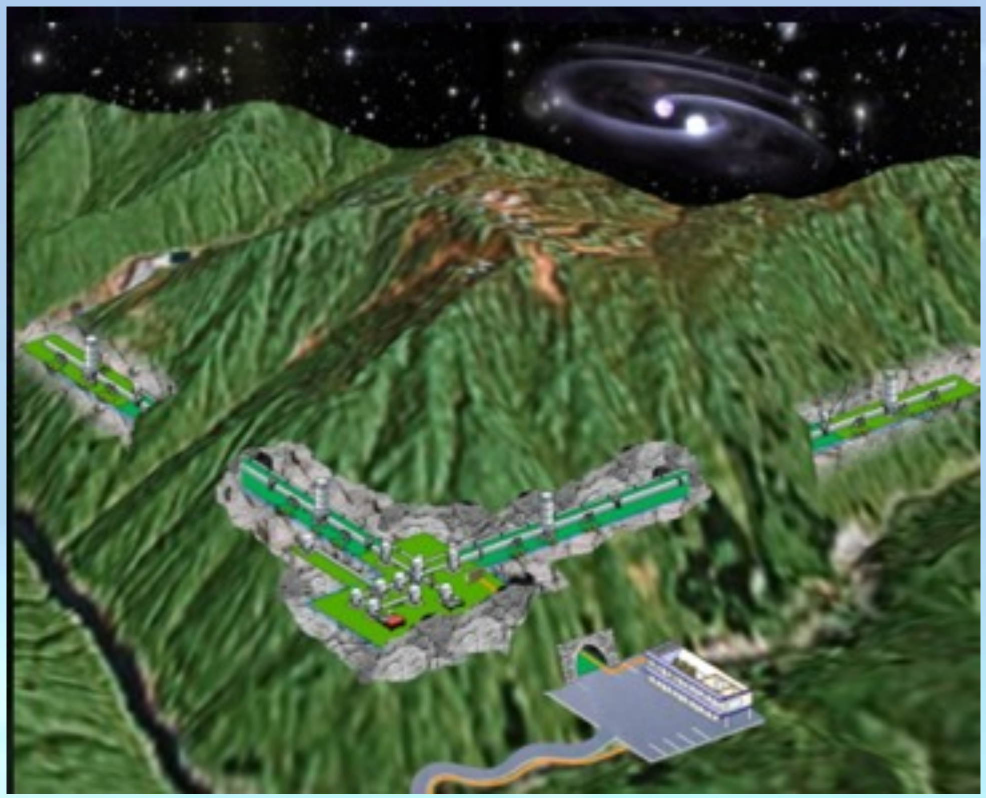
Horizontal axis : Frequency[Hz]
Vertical axis : [1/rHz]
strain equivalent noise spectrum

Best sensitivity : a few10^{-24}@~100Hz



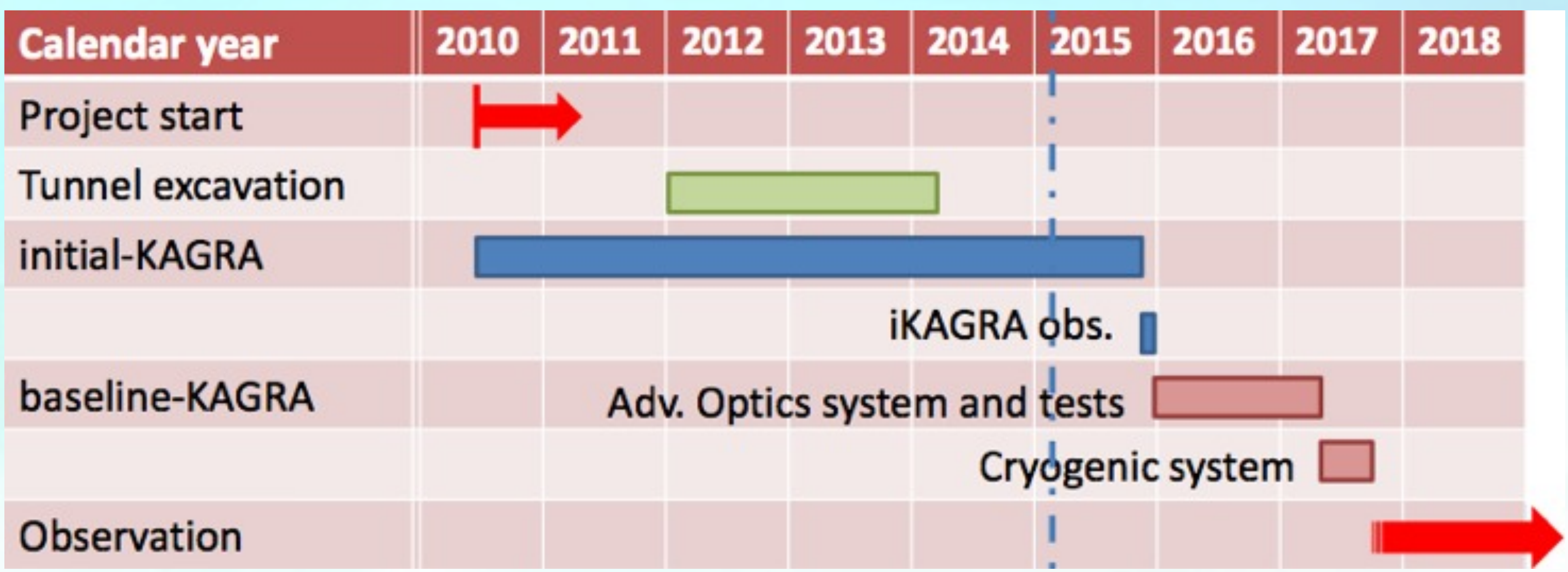
Frequency[Hz]

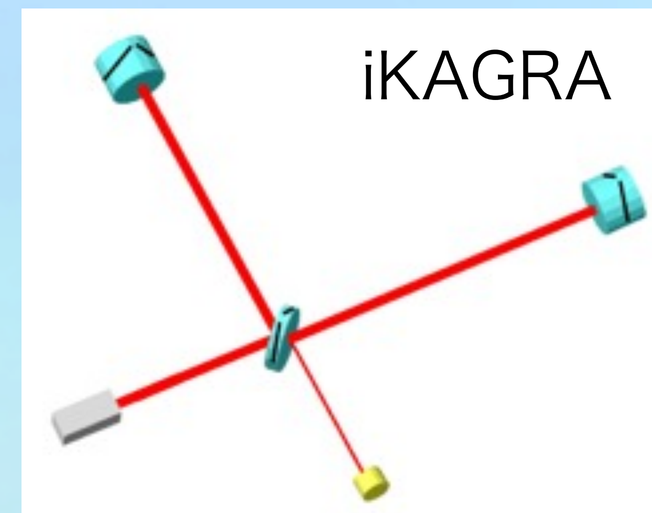
KAGRA : detector overview

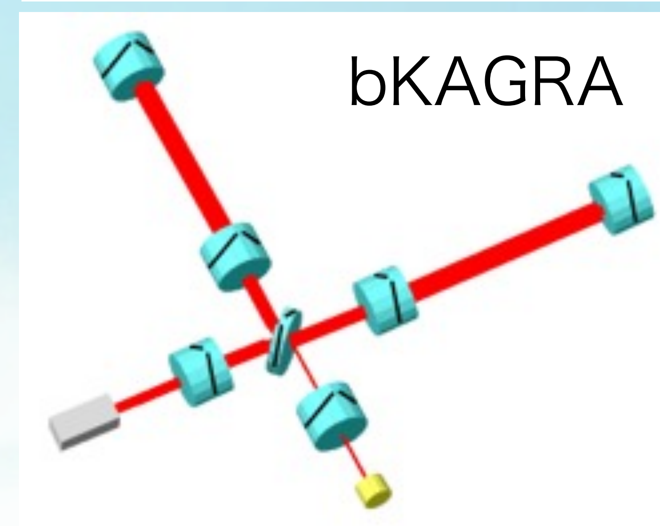


2nd generation GW detector in Japan

- Large-scale Detector
  arm length : 3km each
- Cryogenic interferometer
  Mirror temperature : 20K
- Underground site
  Kamioka Mine







KAGRA : installation

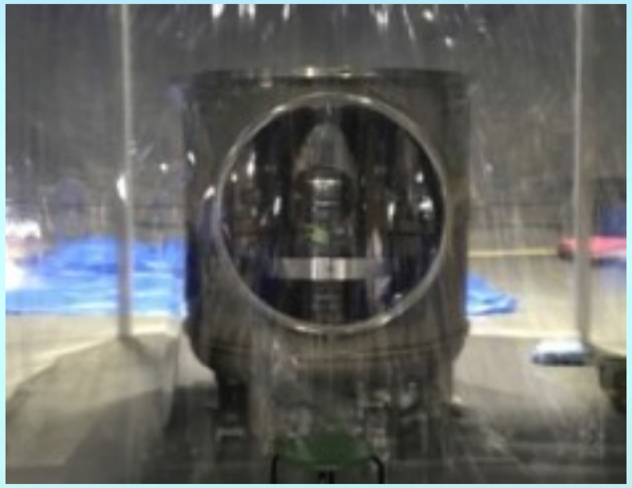
Beam duct :

Cryostat :

Laser booth :

Digital control room :

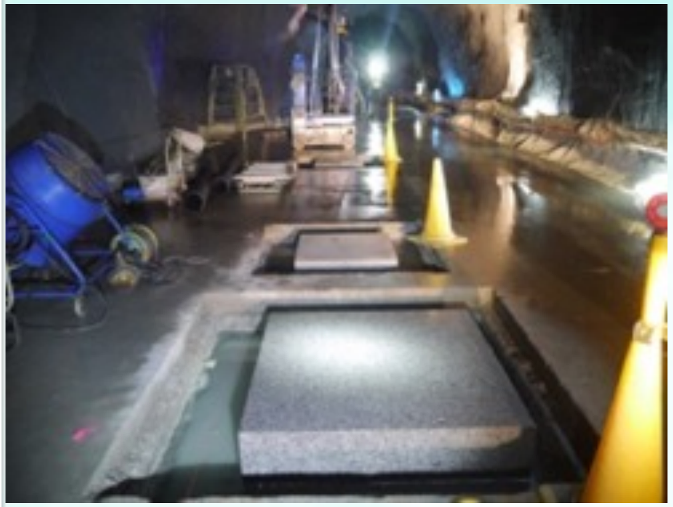
Stack Vibration :

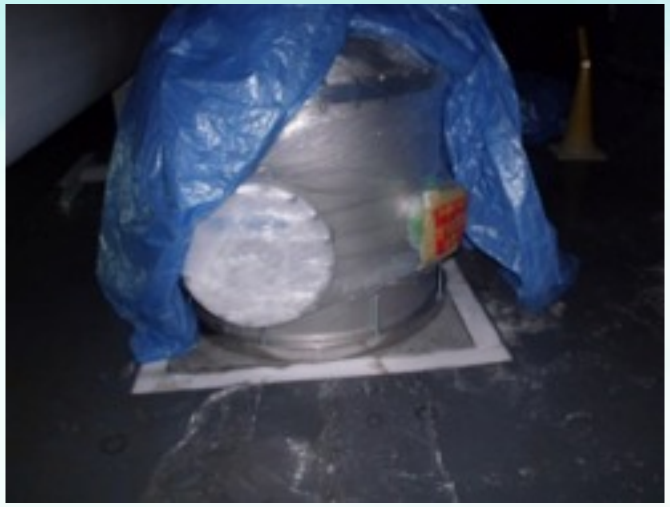


I went to inside mine at February :

Computer installation

Geophysical interferometer :





Pictures by T.Uchiyama

KAGRA : data analysis group

Chief: H.Tagoshi
Sub-chiefs: Y.Itoh, H.Takahashi
Core members: N.Kanda, K.Oohara, K.Hayama

Osaka Univ : H. Tagoshi, K.Ueno, T.Narikawa
Osaka City Univ : N.Kanda, K.Hayama, T.Yokozawa, H.Yuzurihara, T.Yamamoto, K.Tanaka, M. Asano, M. Toritani, T. Arima, A. Miyamoto
Univ Tokyo : Y.Itoh, K. Eda, J. Yokoyama,
Nagaoka Tech : H.Takahashi,
Niigaka Univ : K.Oohara, Y.Hiranuma, M. Kaneyama, T. Wakamatsu
Toyama Univ : S. Hirobayashi, M. Nakano

Total: 26 (Graduate students are included. Undergrad. are not included)
+ associated people (S. Mano, N.Ohishi,...)
About 30 people in the mailing list.

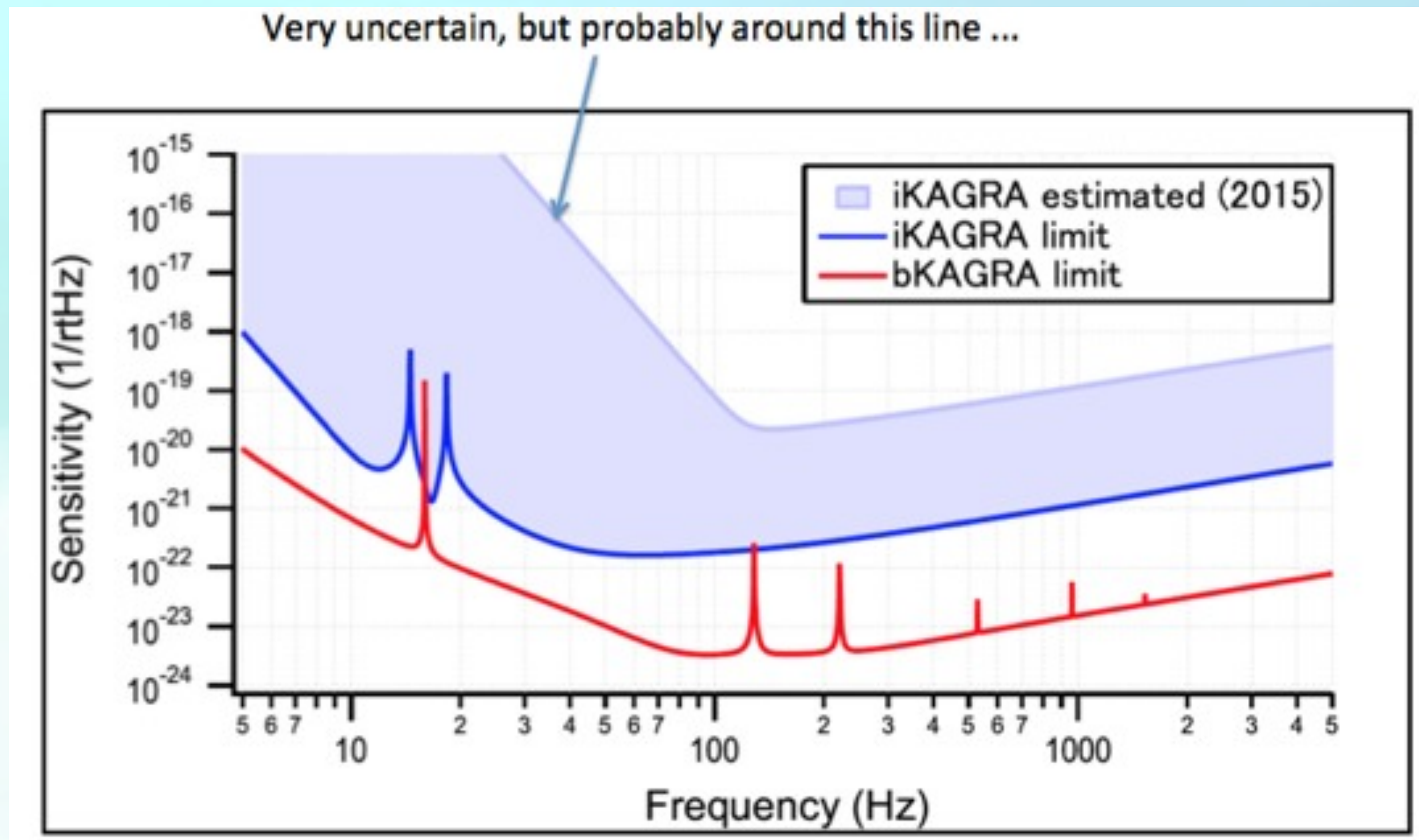
Korean subgroup
Leader: Hyung Won Lee

Inje Univ. : Hyung Won Lee
Jeongcho Kim
Kyung Hee Univ. /KISTI:
Chunglee Kim

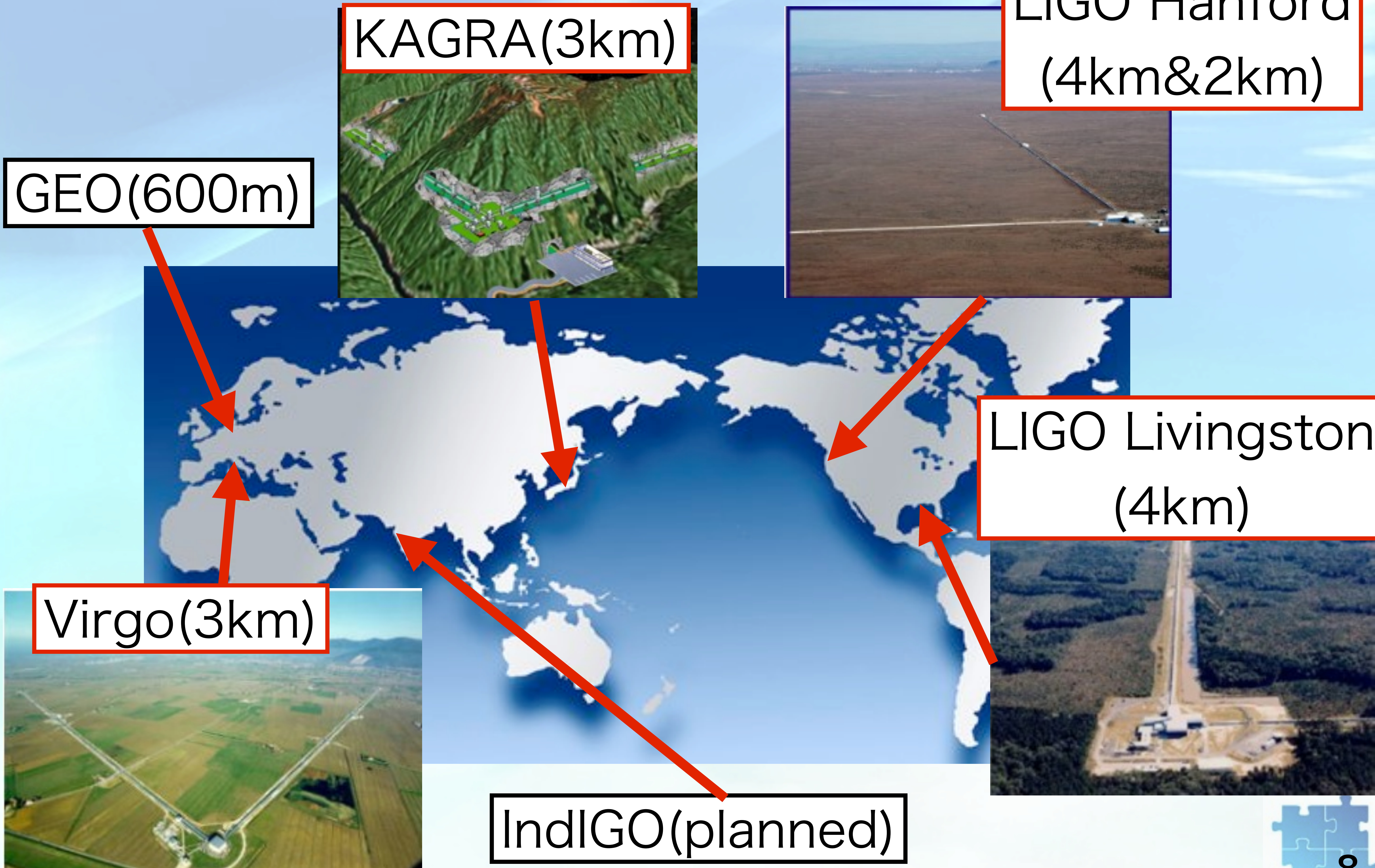
Data analysis tasks
- CBC search
- Burst GW search
- CW search
- Stochastic background
- New TF methods
- Calibration
- etc..

Targets on iKAGRA observation
- Stable operation of the data transfer system, data analysis pipeline

- To gain experience to analyze real data toward bKAGRA observation

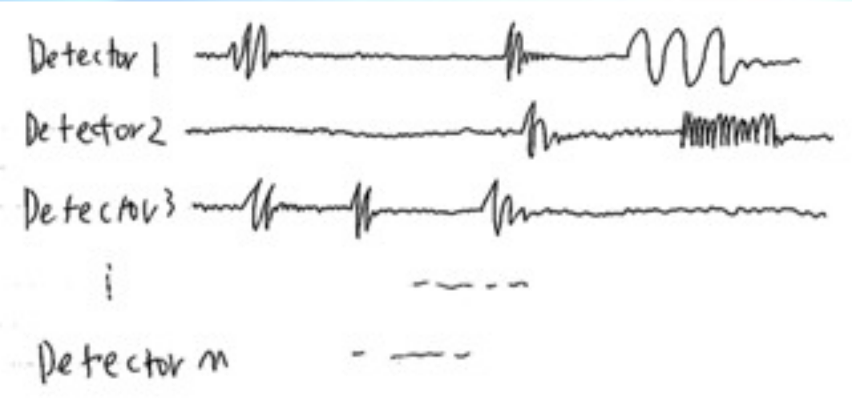


World GW detectors

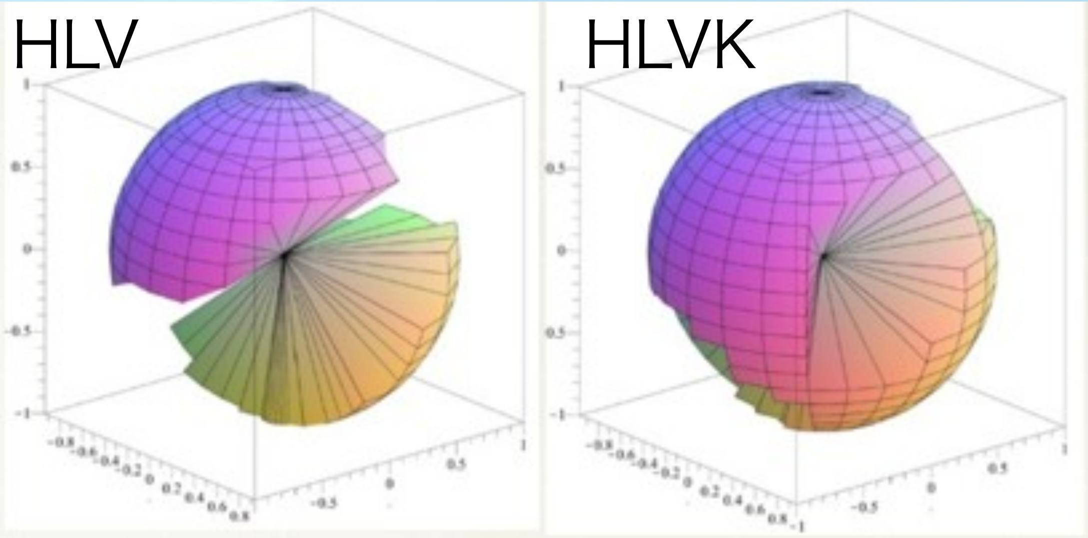


Why World detector

- Reduce the False Alarm Ratio (chance coincidence)
  - Detector noise => non detector correlation
  - Supernova signal => correlation
  - Applying Coherent Network Analysis(explain later)



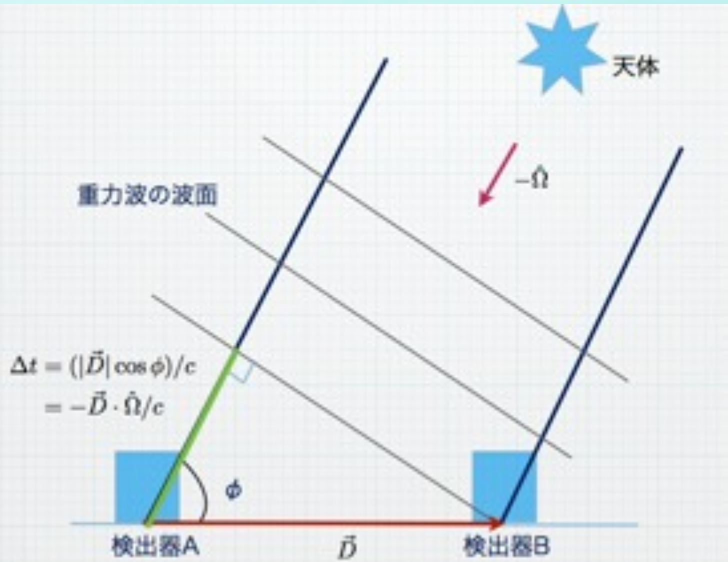
- Expand sky coverage

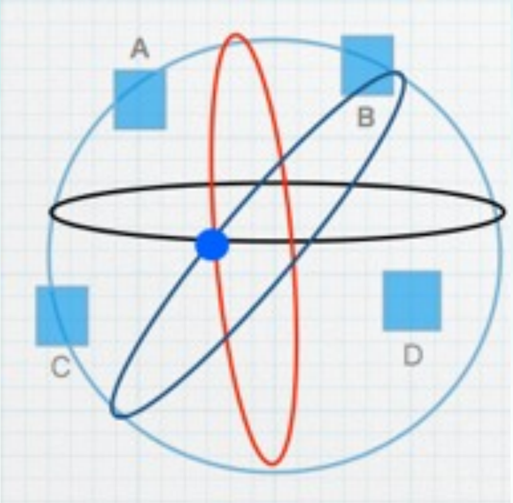


- Cover all sky is very important
  - multi detector help it

B.Schutz(2011)

- Estimation of source direction





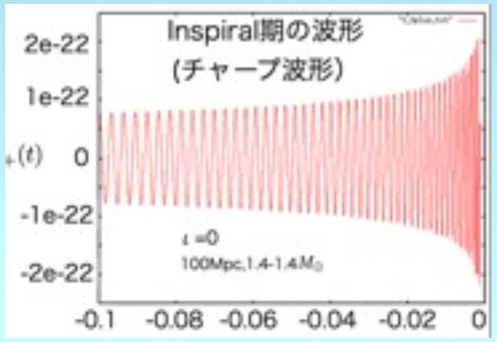
- Need (more than) Four detector
- Coincidence, Coherence

T.Arima

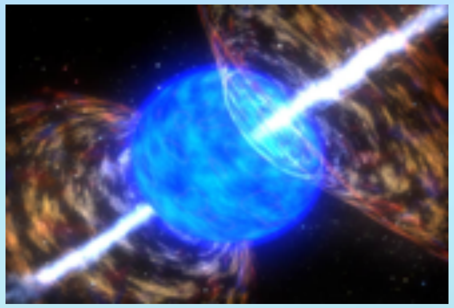
Candidate GW sources

	Known waveform	Unknown waveform
Short duration	Compact Binary Coarseness NS-NS, NS-BH, BH-BH,... Matched filtering	Supernova, GRB, pulsar glitch Soft Gamma Repeater,... Excess power, TF clustering,...
Long duration	mili-second pulsar, radiometry LMXB search F-statistics, performance GPGPU	Stochastic GW, Cosmic string GW, ...

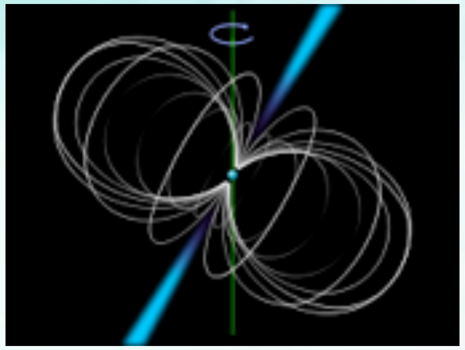
http://www.nasa.gov



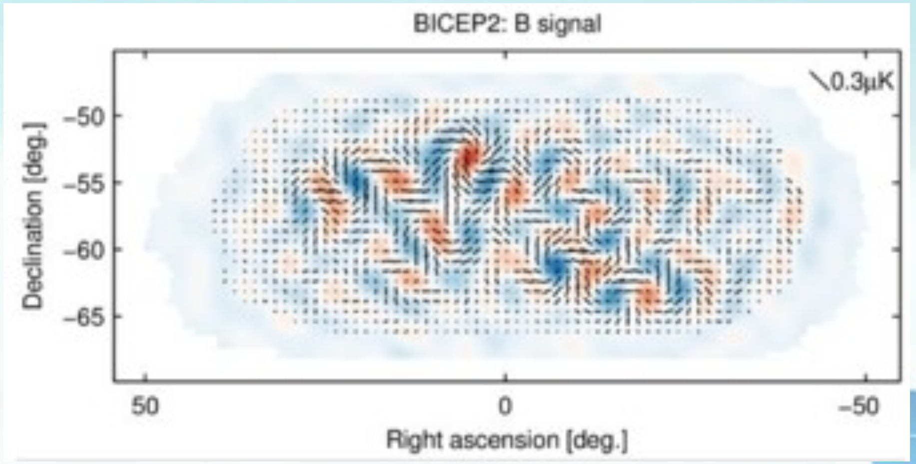
http://www.eso.org



http://www.nasa.gov



Wikipedia



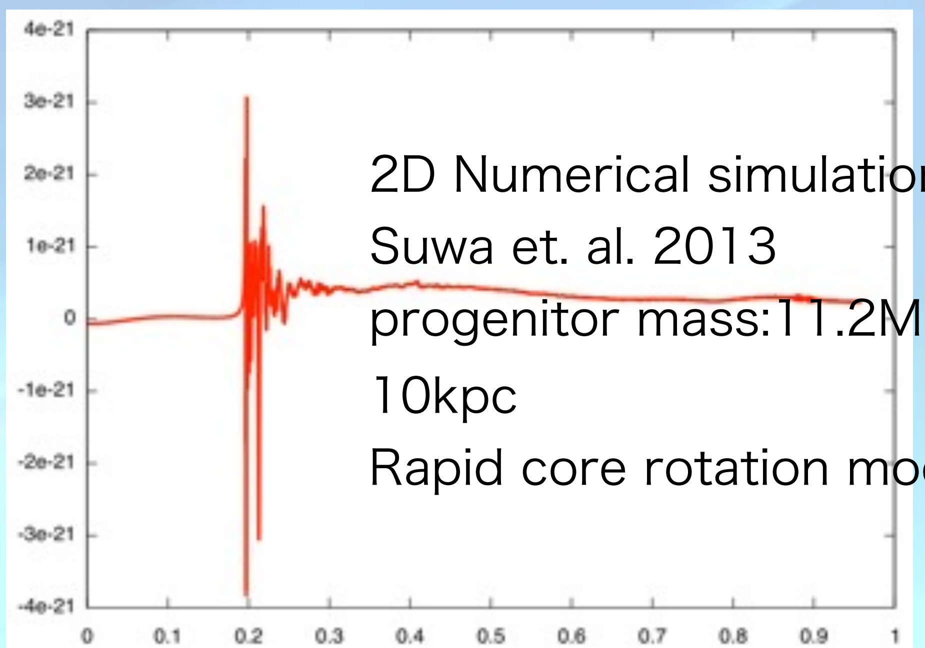
http://bicepkeck.org

Analysis strategy - Observed signal-

$$S_{obs}(t) = \underbrace{(F_{+}h_{+}(t) + F_{\times}h_{\times}(t))}_{\text{GW signal}} + \underbrace{n(t)}_{\text{Detector noise}}$$

GW signal

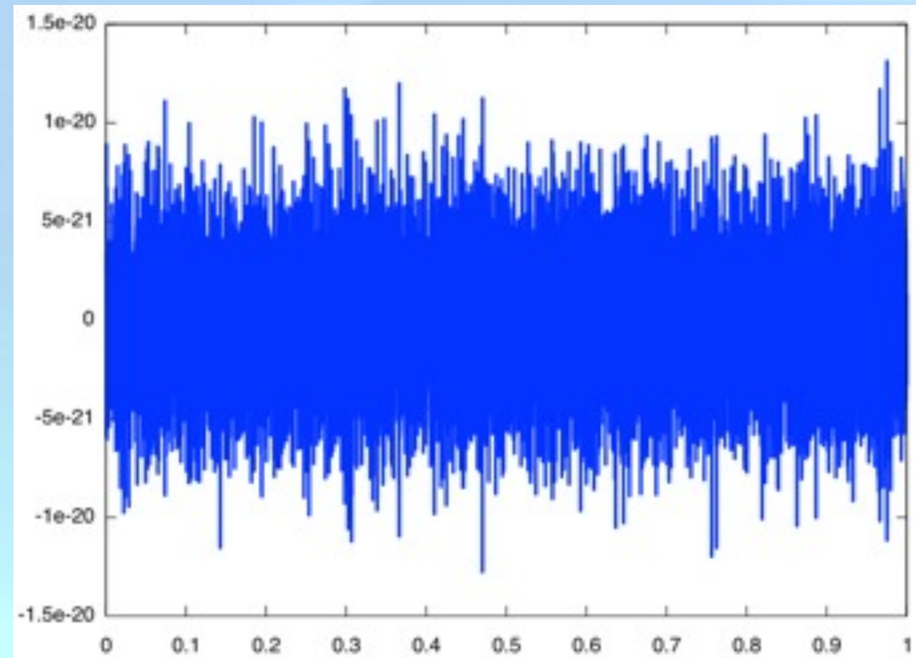
Detector noise



2D Numerical simulation
Suwa et. al. 2013
progenitor mass:11.2M⊙
10kpc
Rapid core rotation model

Time form gravitational collapse[s]

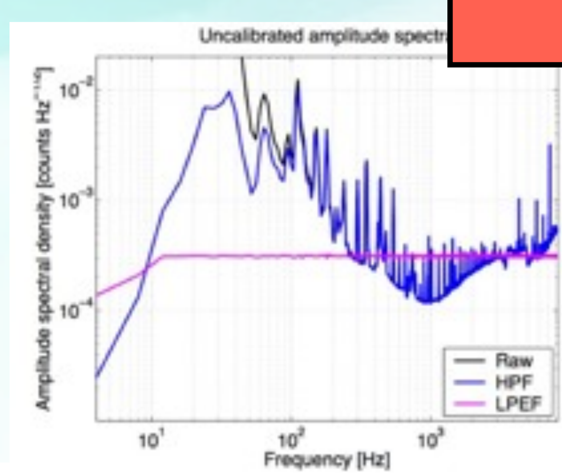
+



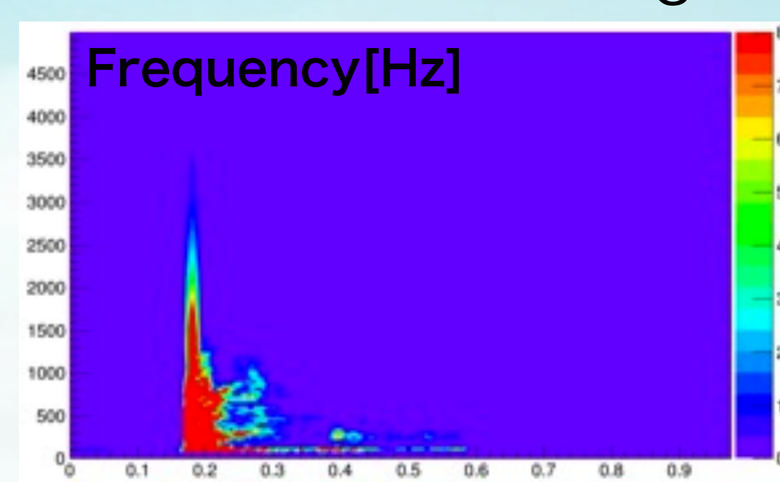
Simulation :
KAGRA noise
Stationary,
Gaussian noise

Flatten a frequency characteristic
Whitening
Linear prediction error filter

$$\tilde{x}[n] = \sum_{m=1}^{M} c[m]x[n-m]$$



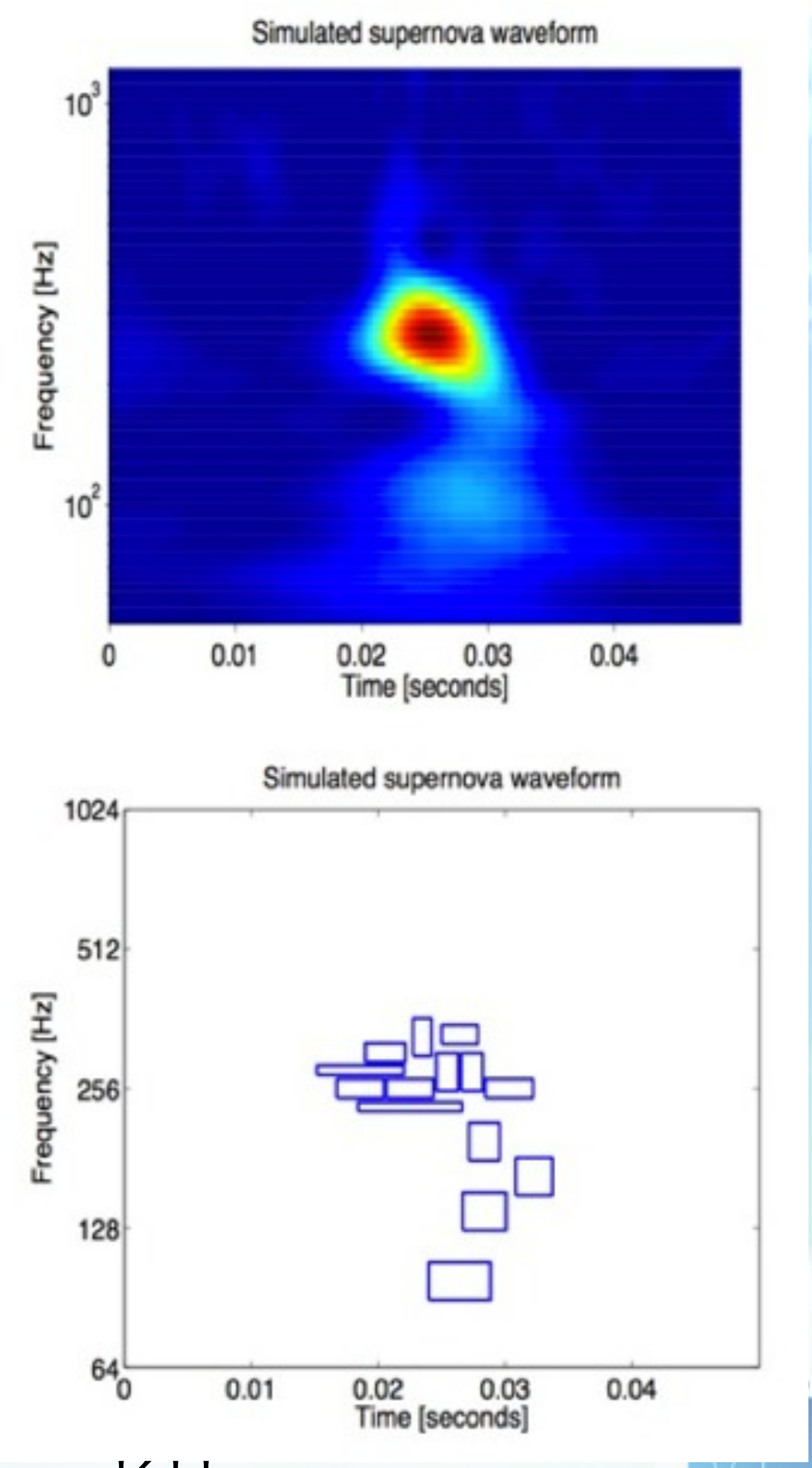
Expand to TF plane
Search transient signal



Time[sec]

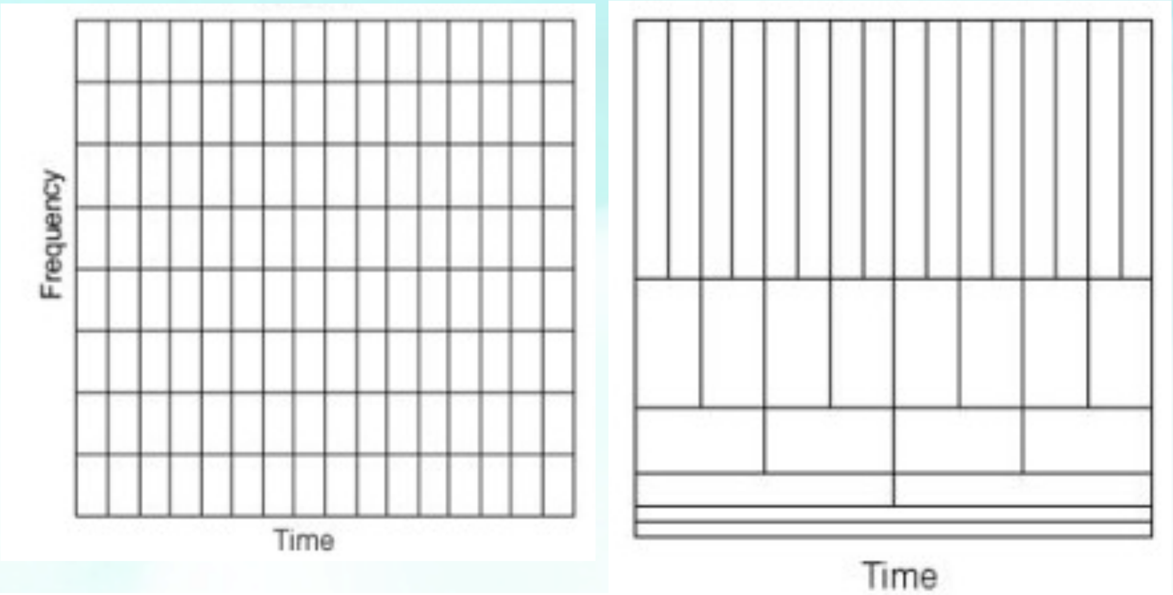
Single detector -TF clustering-

- Analysis flow :
  - Data quality check, commissioning
  - Transform to TF plane
  - Search the local high power pixel
  - Clustering
  - Event reconstruction
- Obtain Signal to Noise ratio effectively
- Extract characteristics Time and Frequency
- Check with noise catalogue



Short Time Fourier Transform

Wavelet

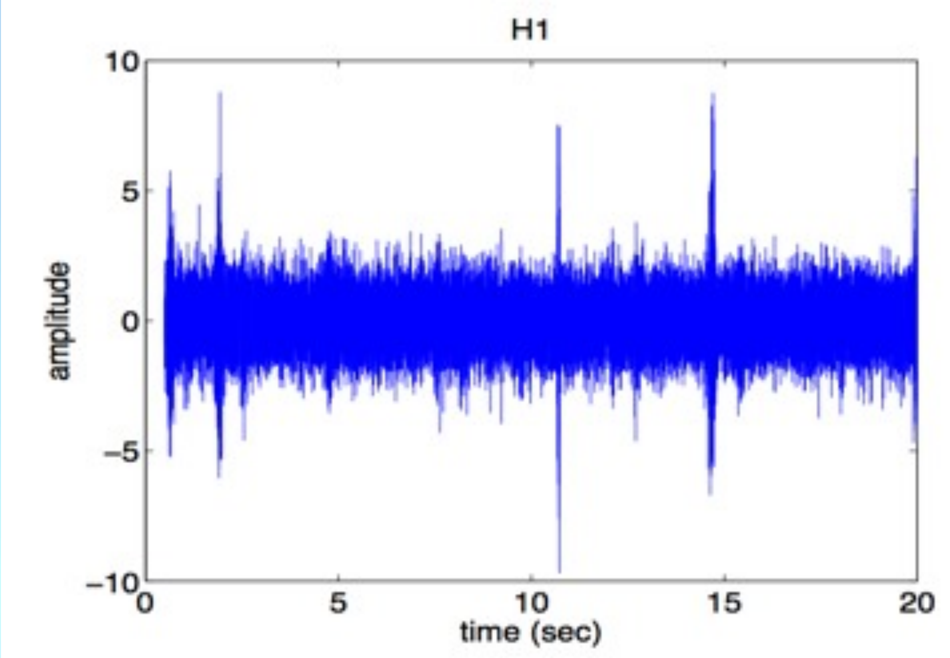


K.Hayama

Analysis strategy -Detector noise-

But real detector has
- Non-stationary noise
    - Change noise floor level
    - Many glitch noise with short time
- Non-gaussian noise
    - Glitch noise
        - seismic motion
            - earthquake, oscine wave, etc...
        - electro-magnetic noise
        - etc...

Example of LIGO S5 data



-reduce/identify them (important task)
- Correlation analysis with Environmental channels
    - linear correlation(Pearson correlation factor)
    - non-linear correlation(Maximum Information Coefficients)
- Noise classification
    - Bayesian non-parametric clustering
- Non-stationarity, non-gaussian noise monitor etc...

Multi detector -Coherent network analysis-

- Coherent network analysis

$$\begin{bmatrix} x_1(t) \\ \vdots \\ x_d \end{bmatrix} = \begin{bmatrix} F_{1+}(\theta,\phi) & F_{1\times}(\theta,\phi) \\ \vdots & \vdots \\ F_{d+}(\theta,\phi) & F_{d\times}(\theta,\phi) \end{bmatrix} \begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ \vdots \\ n_d(t) \end{bmatrix}$$

Data / Detector response / GW / Detector noise

$$\mathbf{x} = \mathbf{A}\mathbf{h} + \mathbf{N}$$

- Solve the inverse problem h with maximum likelihood method
- Changing source direction(θ, ϕ)
- Find the likely GW waveform h

$$\mathbf{L} = \max(-||\mathbf{x} - \mathbf{A}\mathbf{h}||^2)$$

where $||x||^2 = \sum_{i=1}^{d} \int_0^T x_i(t)^T x_i(t) dt$

$$||\mathrm{data}(x) - \mathrm{estimated\ signal}(\xi)||^2$$

$$h = (A^T A)^{-1} A^T x$$

- Various pipelines are proposed
  - coherent WaveBurst
  - Xpipeline
  - RIDGE etc...

Latest simulation result

arXiv.org > astro-ph > arXiv:1501.00966

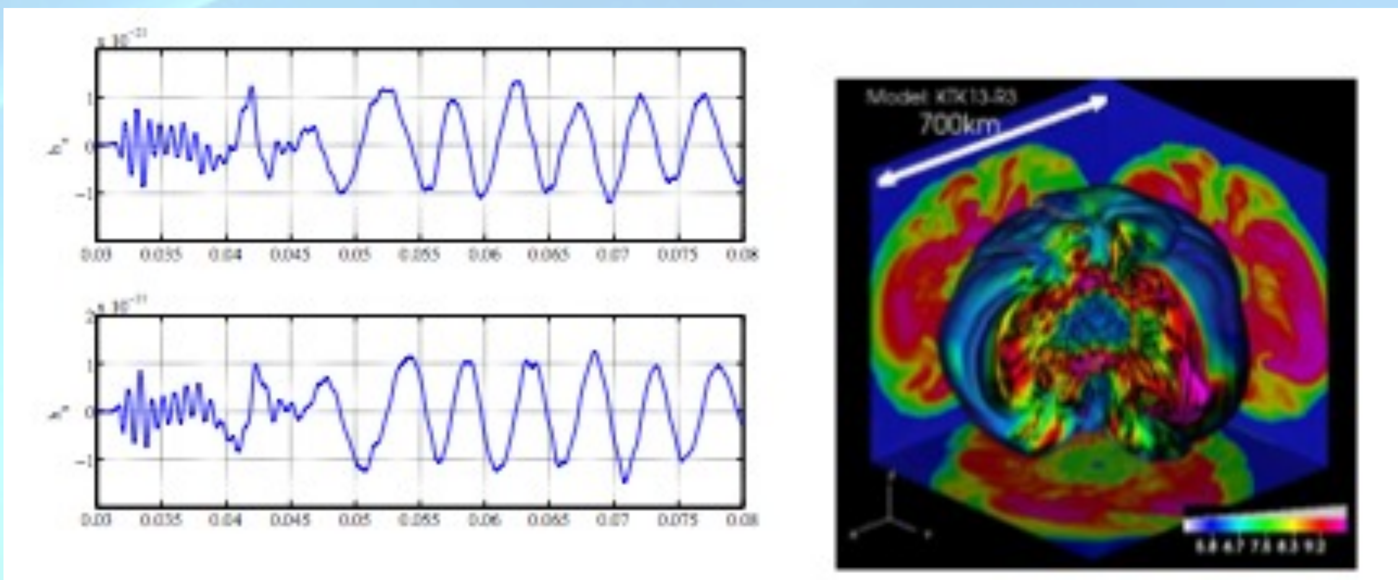
Astrophysics > High Energy Astrophysical Phenomena

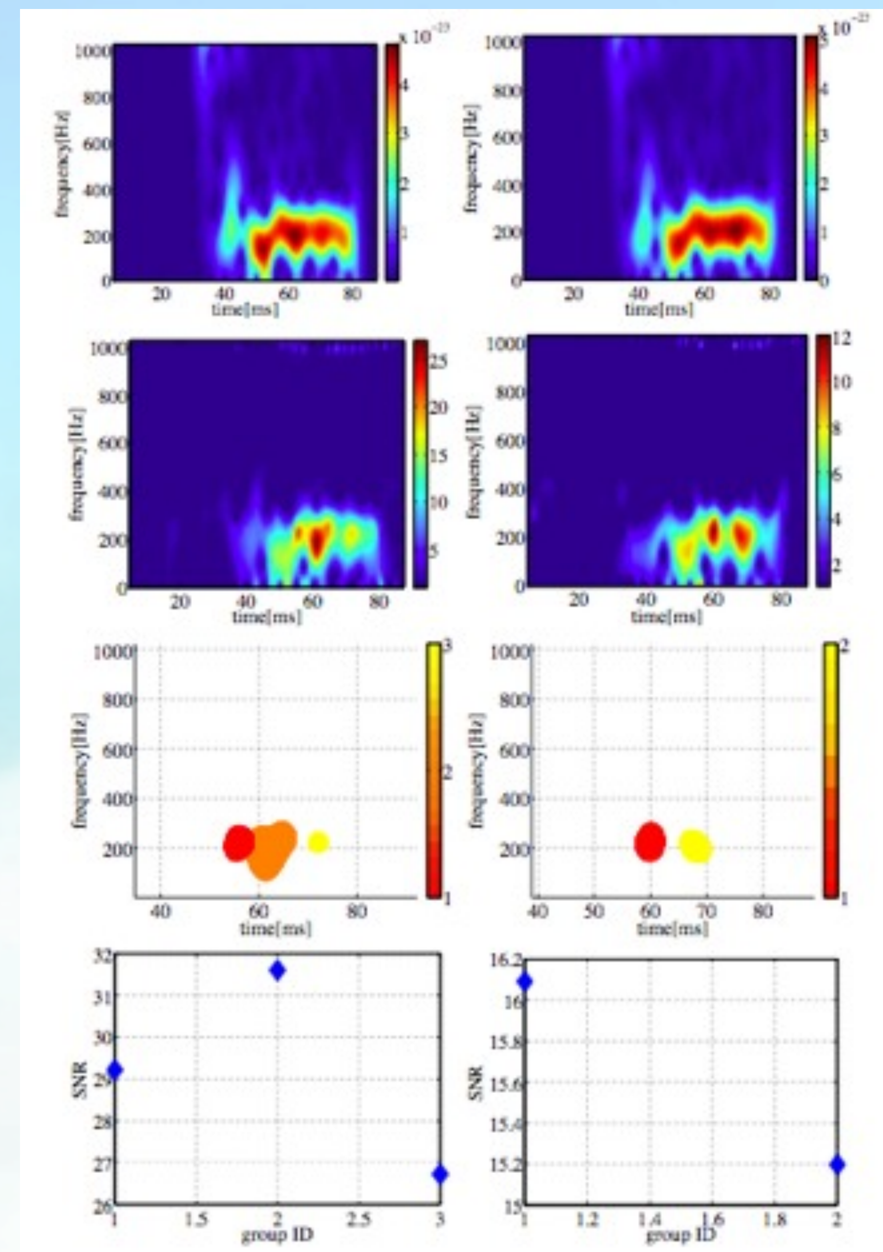
Coherent Network Analysis of Gravitational Waves from Three-Dimensional Core-Collapse Supernova Models

Kazuhiro Hayama, Takami Kuroda, Kei Kotake, Tomoya Takiwaki

One example of their results : used numerical simulation result

T. Kuroda, T. Takiwaki, and K. Kotake, Phys. Rev. D 89, 044011 (2014), arXiv:1304.4372

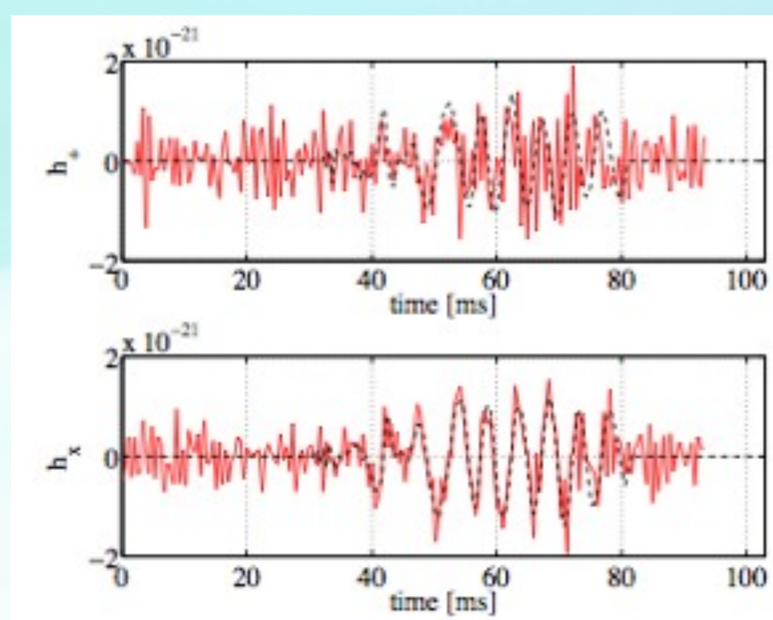




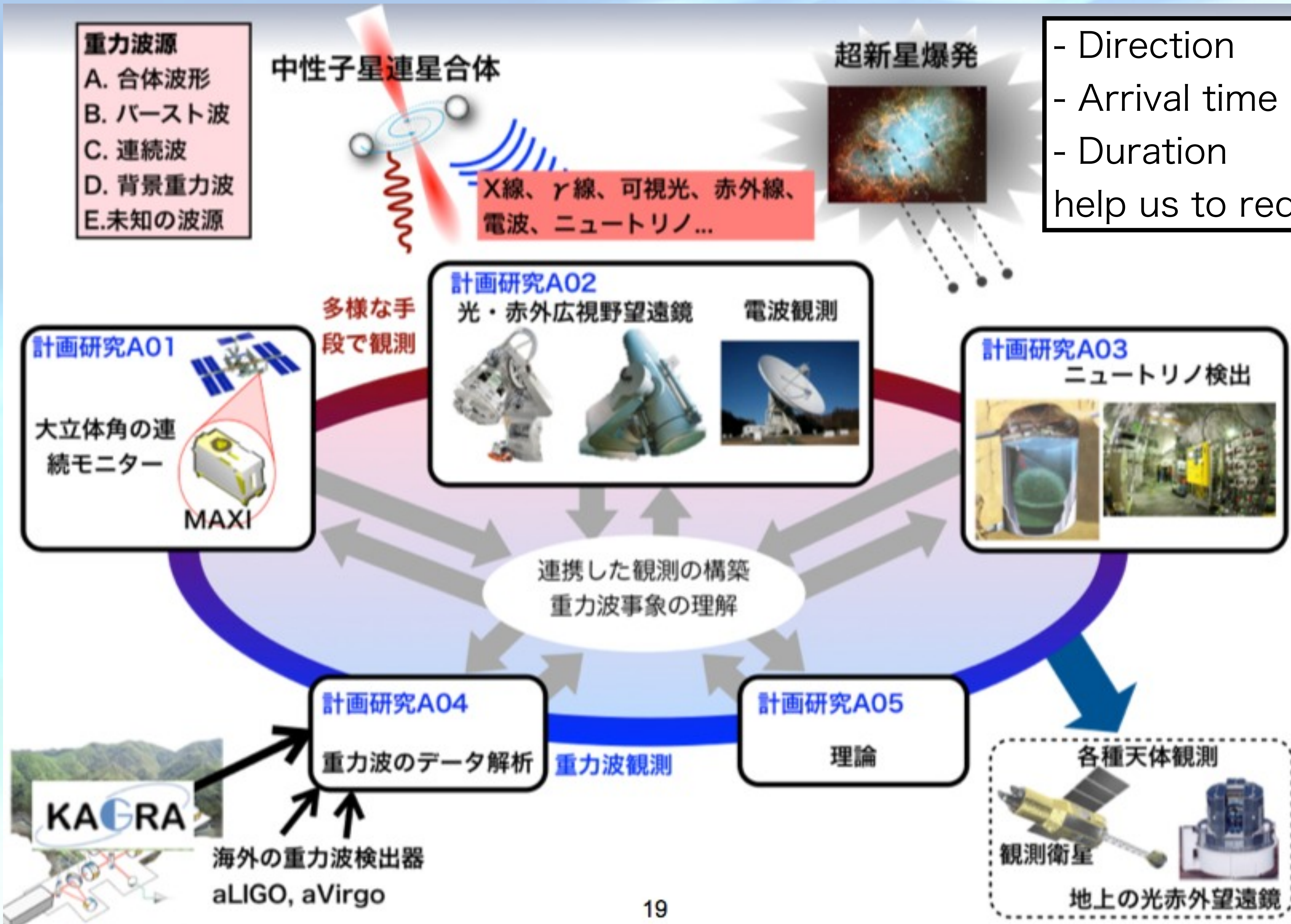
15M⊙ π rad/s angular momentum

Detectors:
aLIGO, aVirgo, KAGRA

detection range
39.4kpc(+), 20.1kpc(×)



With external trigger



- Direction
- Arrival time
- Duration

help us to reduce FAP

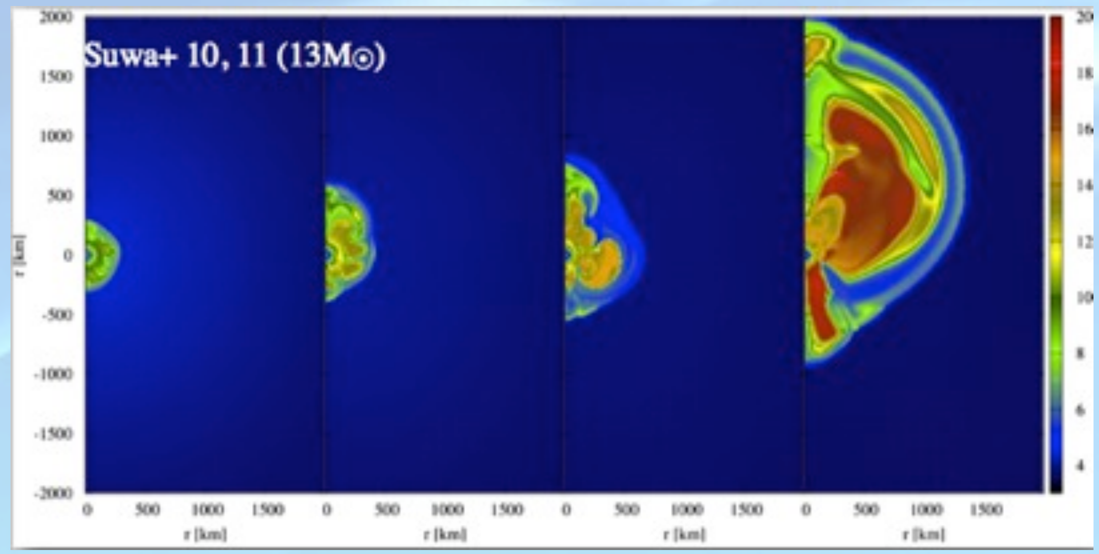
Message from Supernova

Analysis team

SNe Theory

Y. Suwa

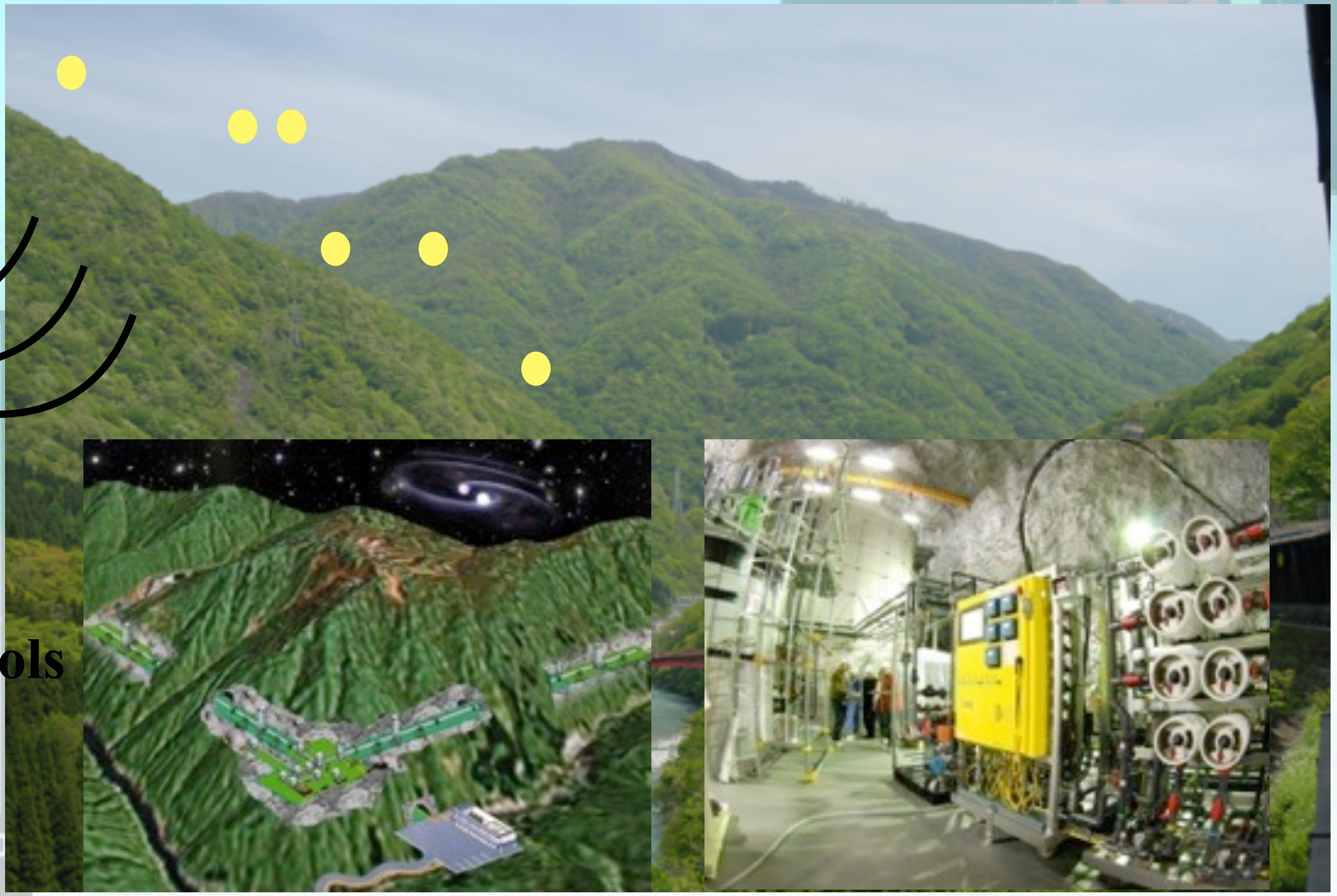
- **Provide time correlated data, GW and neutrino**
- **Suggest signature signals physical phenomenon**



Neutrino analysis

T. Kayano, Y. Koshio
M. Vagins

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



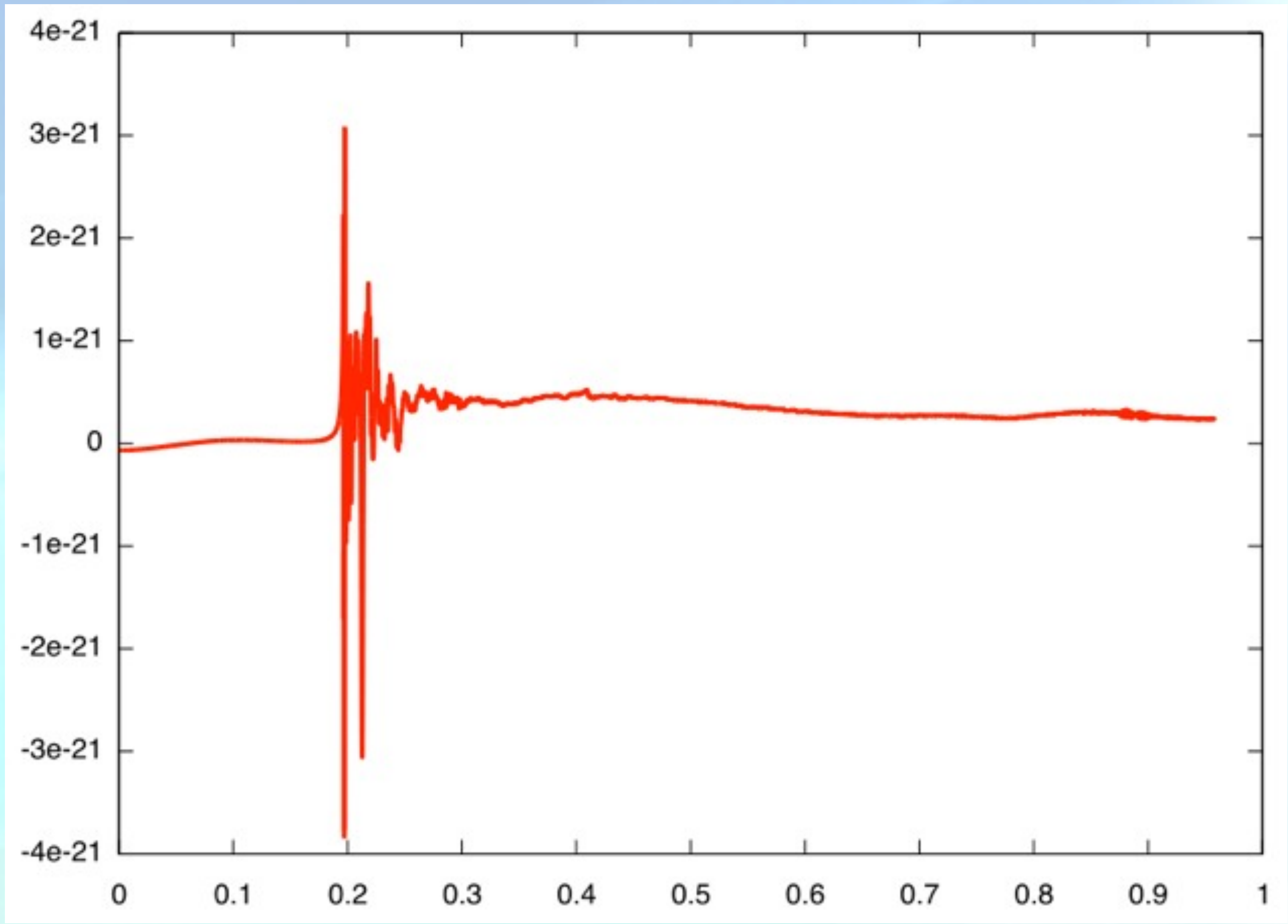
GW analysis

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

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

GW waveform

$h_+(t)$



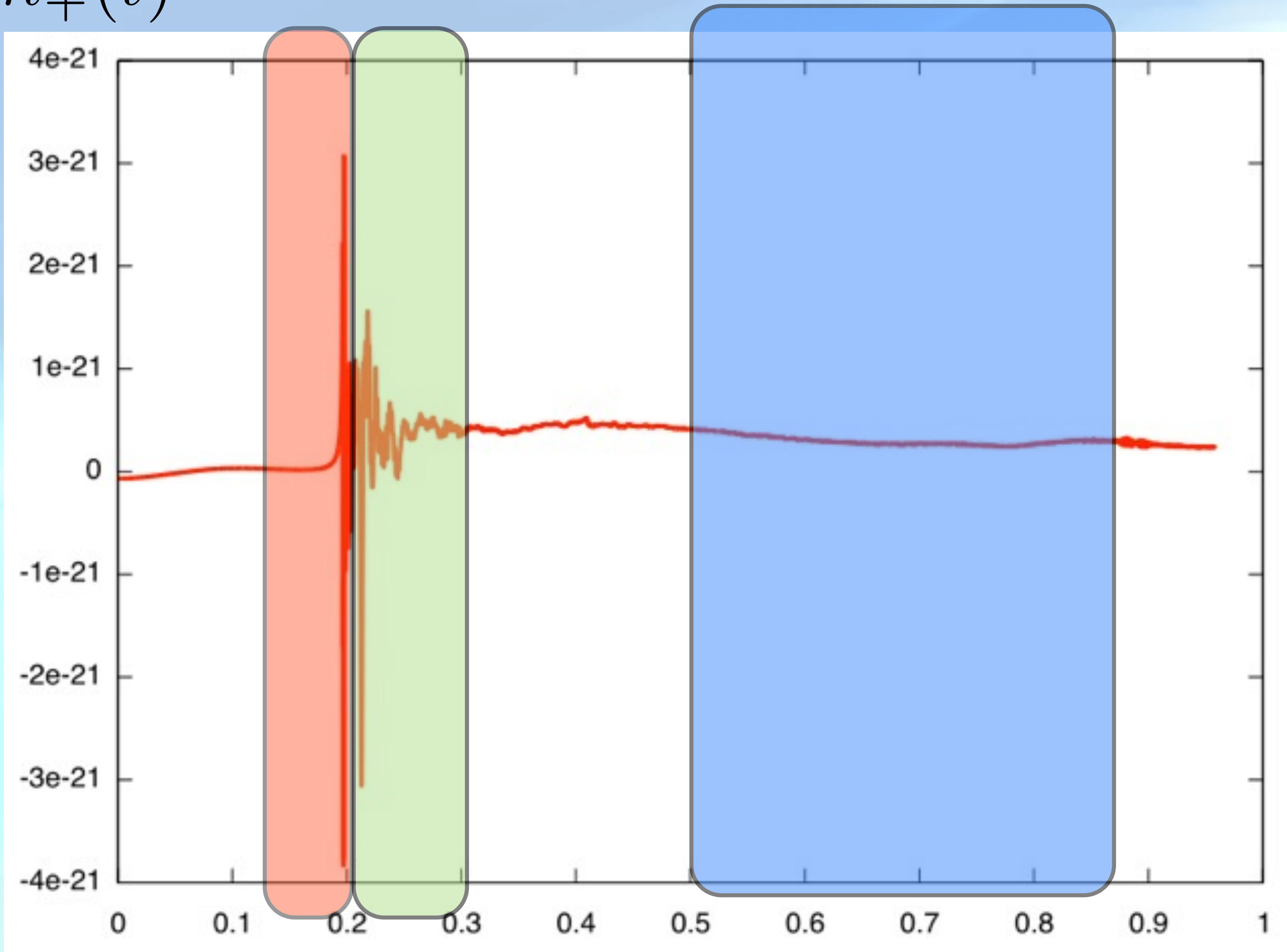
2D Numerical simulation
Suwa et. al. 2013
progenitor mass:11.2M⊙
Rapid core rotation model

Bring us the inner core information.
Identify the characteristics waveform for each phase

Time form gravitational collapse[s]

GW waveform

$h_+(t)$



2D Numerical simulation
Suwa et. al. 2013
progenitor mass:11.2M⊙
Rapid core rotation model

Bring us the inner core information.
Identify the characteristics waveform for each phase

Time form gravitational collapse[s]

Strong GW from core bounce?

Characteristics of prompt convection phase?

Characteristics of SASI phase?

Probing core rotation -motivation-

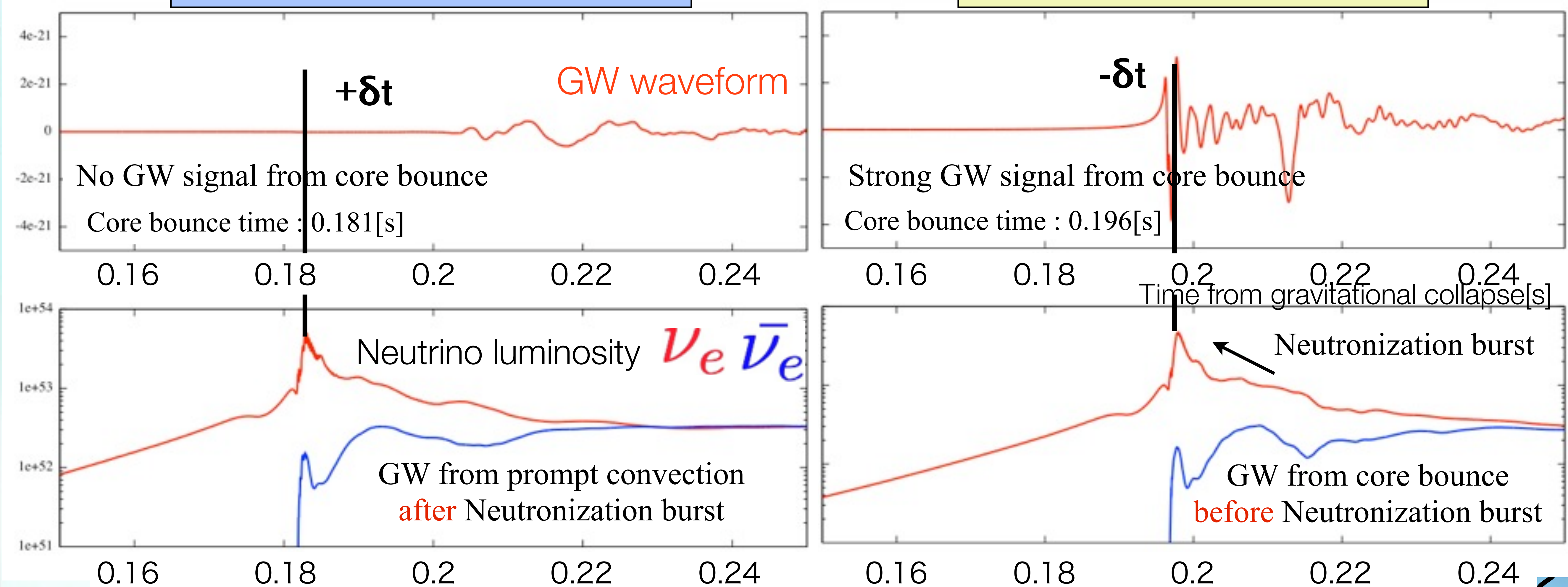
- Submitted to ApJ (arXiv : 1410.2050)
- Focus on **GW observed time**(**t_obs_gw**) and **Neutronization burst time**(**t_obs_nburst**)
- Supernova detection simulation with KAGRA and EGADS/SK+Gd detector

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])



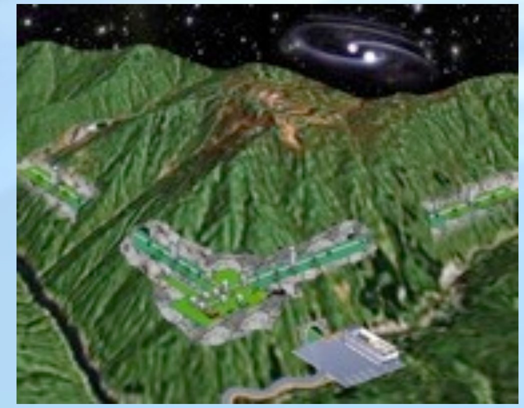
Probing core rotation -detector-

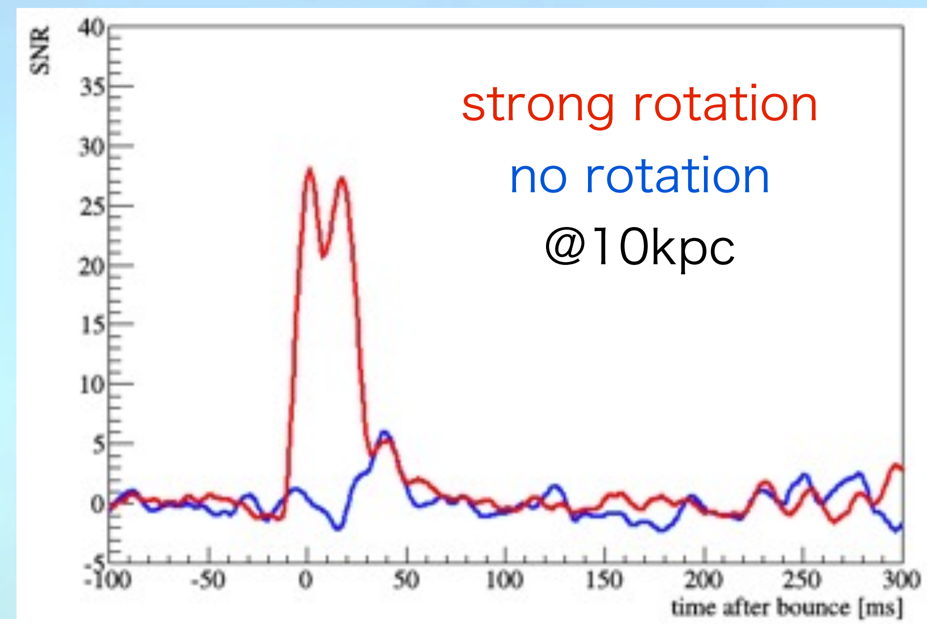
Robust analysis
- Simple search, single detector

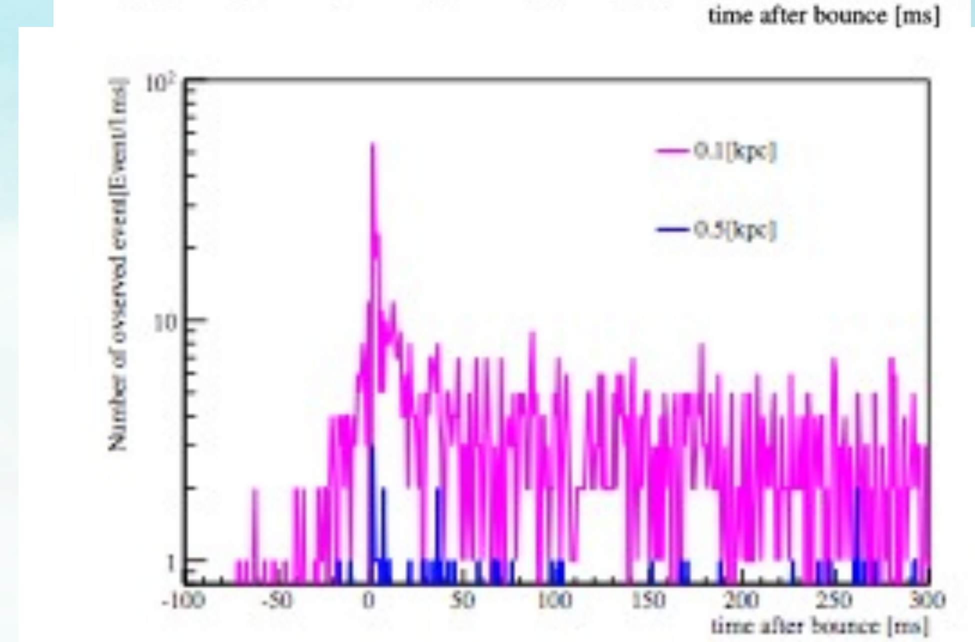
Study with KAGRA and EGADS/SK+Gd
- neutron tagging with Gd(90%)
- test tank for GADZOOKS! project

GW analysis
- Excess power filter
- + Short Time Fourier Transform
- Generate signal s(t)=h(t)+n(t)
- Search window which give SNR>8

Neutrino analysis
- generate signal with Poisson statistics
- search window which give max number of observation electron neutrino

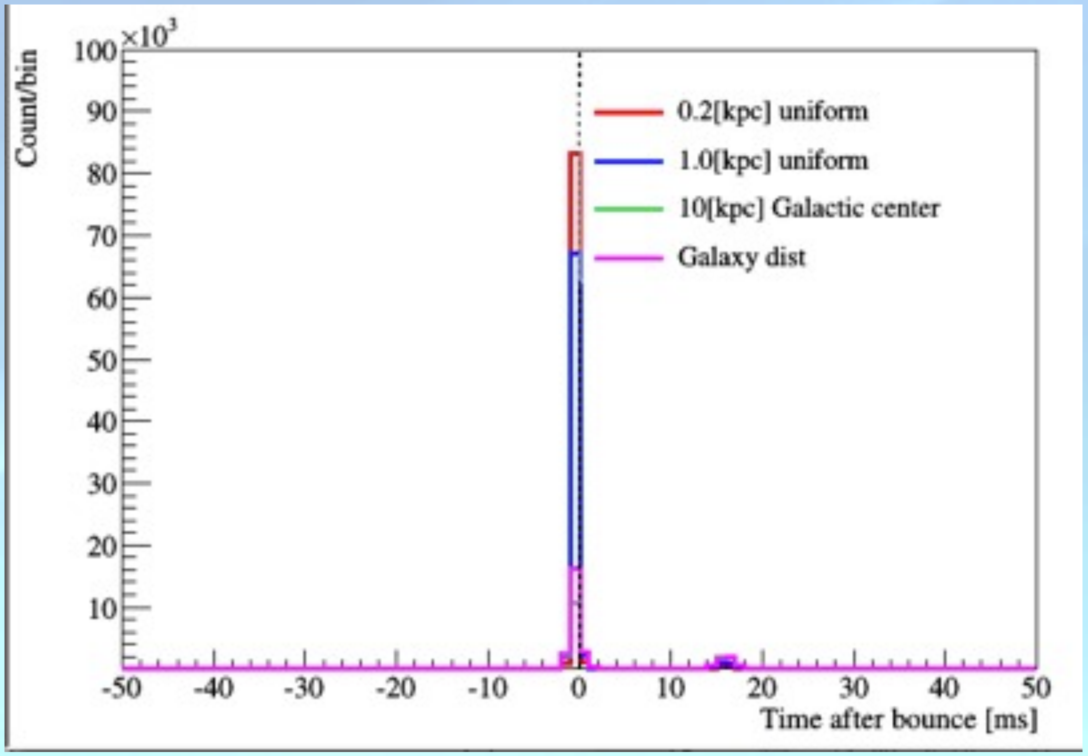


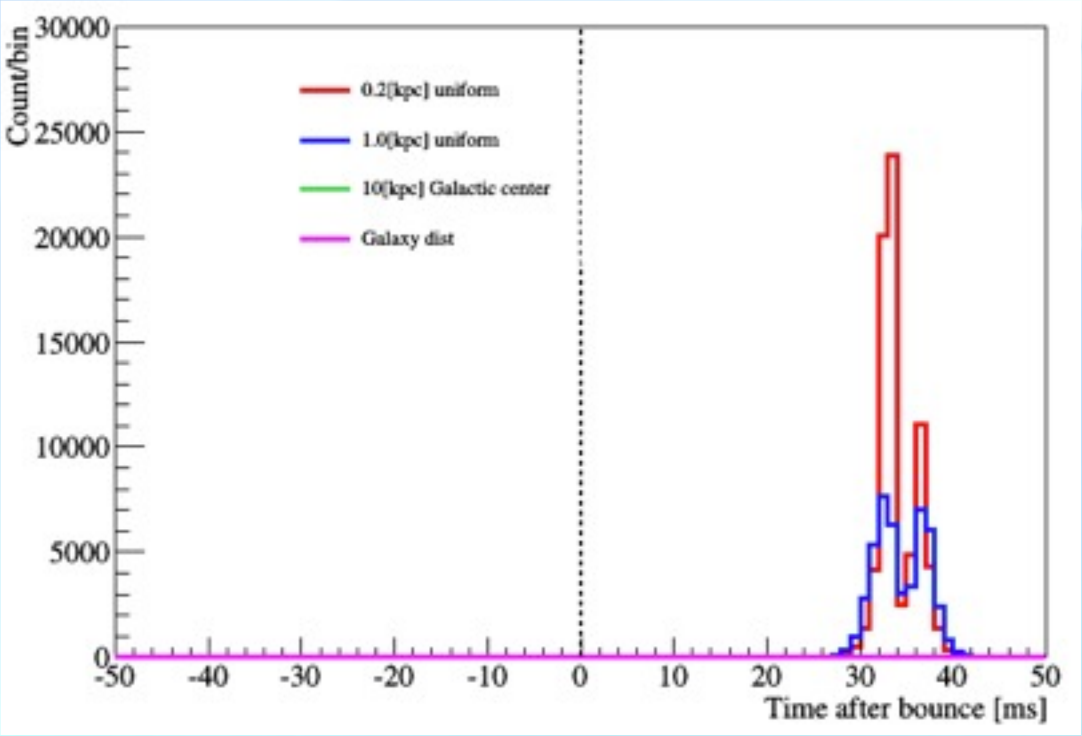




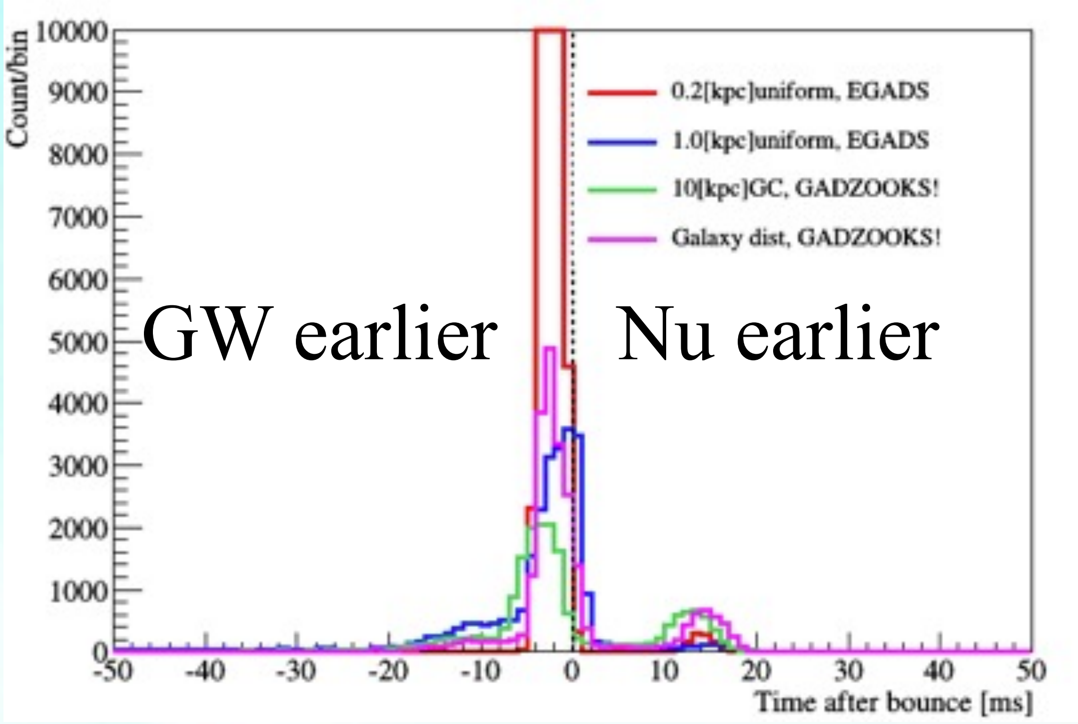
Probing core rotation -time epoch-

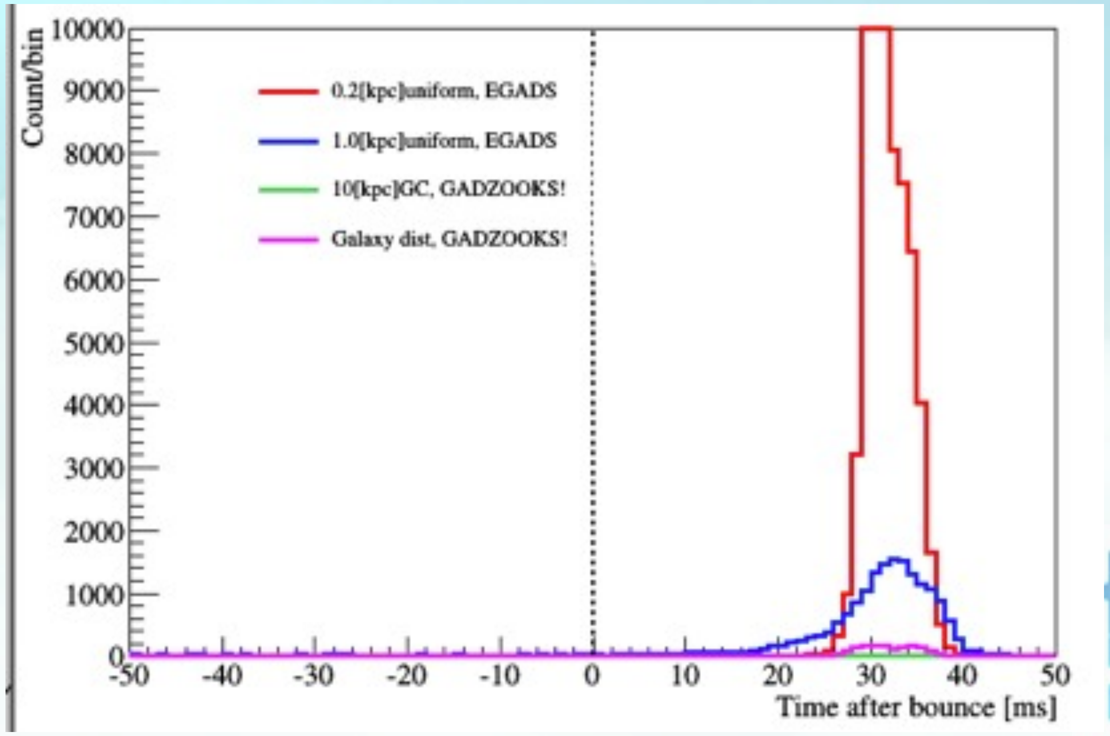
GW epoch : 1.0 pi rad/s 0.0 pi rad/s





GW - Nu epoch : 1.0 pi rad/s 0.0 pi rad/s

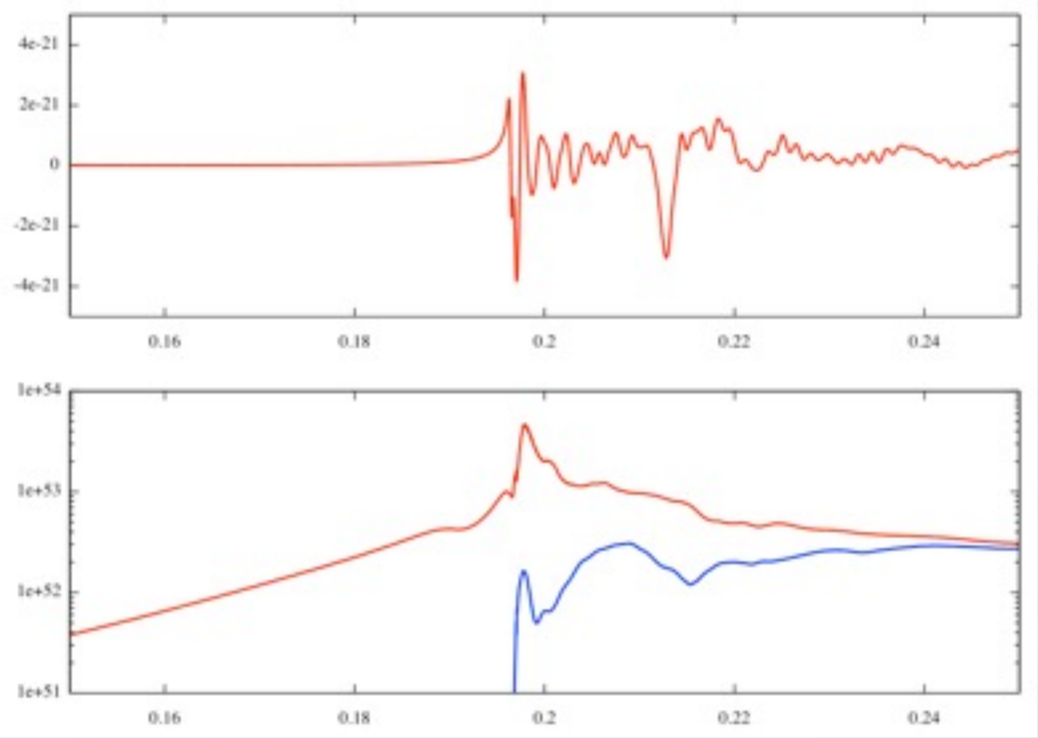




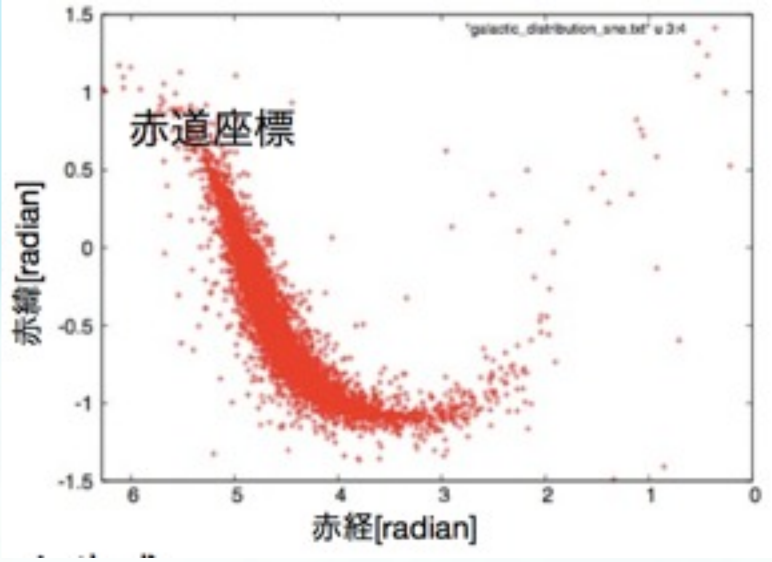
Probing core rotation -result1-

For “Strong” core rotation model:

Preliminary	KAGRA det. eff.[%]	EGADS Nburst[%]	SK+Gd Nburst[%]	Evaluate rotation[%]
0.2kpc uniform	88.0	100	--	98.4
1.0kpc uniform	73.6	40.2	--	80.00
Galactic Center	21.5	--	94.8	75.3
Galaxy distribution	26.7	--	81.7	76.2



- For neutrino detector, identification probability of neutronization burst is described
- In 0.2 or 1.0 kpc, current SK DAQ may not work correctly
- In GC, a few of electron neutrino will be observed
- KAGRA analysis
  - First window which satisfied SNR>8
- Galactic Center
  - decl : -28°56'10.23", 10kpc
- Galaxy distribution :



exponential disk model

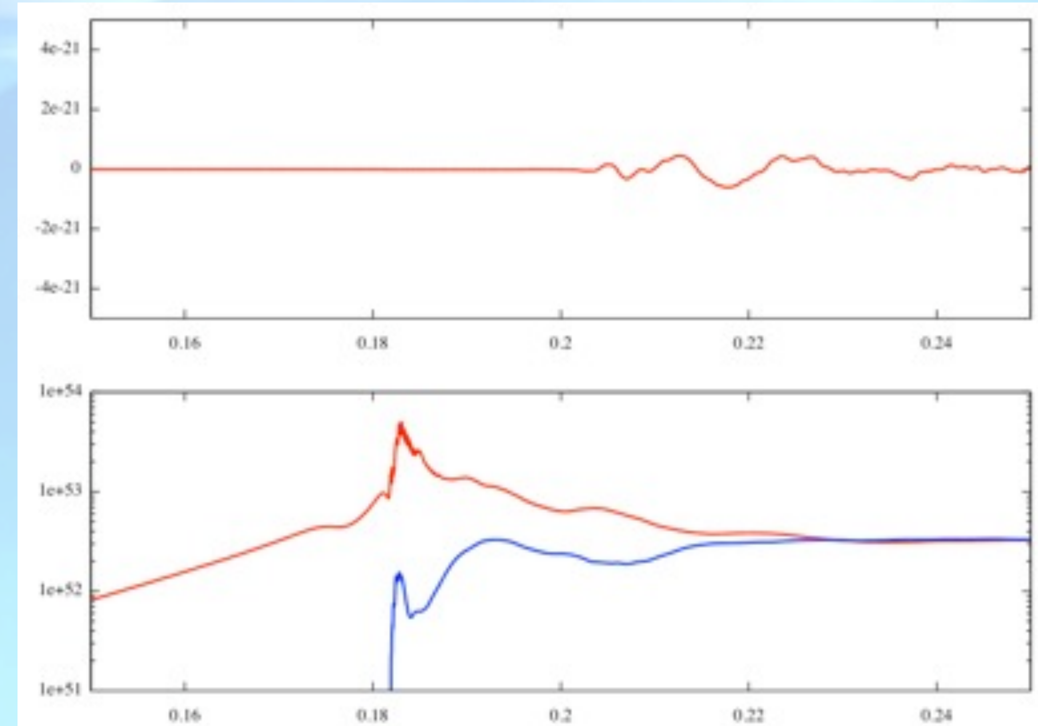
$$dN \propto R\, dR\, dz\, e^{-\frac{R^2}{2R_0^2}} e^{-\frac{|z|}{h}}$$

where, $R_0 \sim 3.5\text{kpc}, h \sim 320\text{pc}$

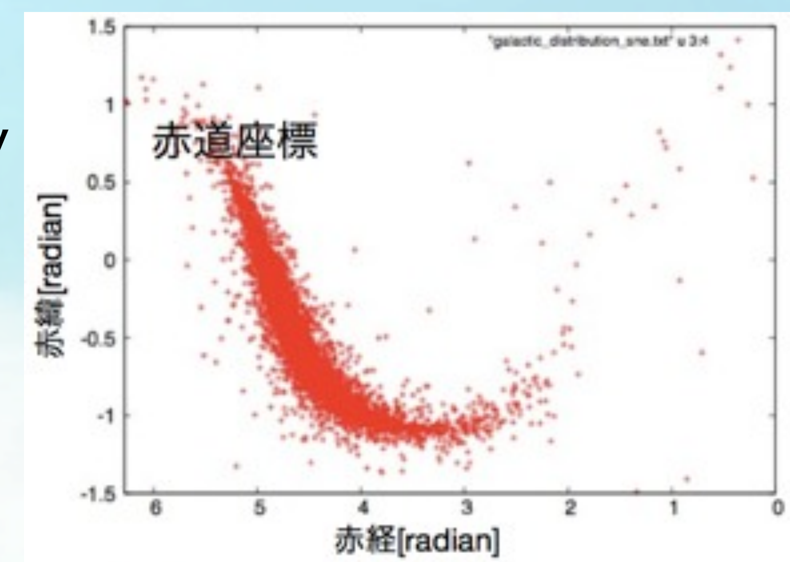
Probing core rotation -result2-

For “No” core rotation model:

Preliminary	KAGRA det. eff.[%]	EGADS det. eff.[%]	SK+Gd det. eff[%]	Evaluate rotation[%]
0.2kpc uniform	74.8	100	--	0.0
1.0kpc uniform	46.5	46.8	--	20.8
Galactic Center	0.0	--	97.5	NaN
Galaxy distribution	1.5	--	84.6	0.2



- For neutrino detector, identification probability of neutronization burst is described
- In 0.2 or 1.0 kpc, current SK DAQ may not work correctly
- In GC, a few of electron neutrino will be observed
- KAGRA analysis
  - First window which satisfied SNR>8
- Galactic Center
  - decl : -28°56'10.23", 10kpc
- Galaxy distribution :

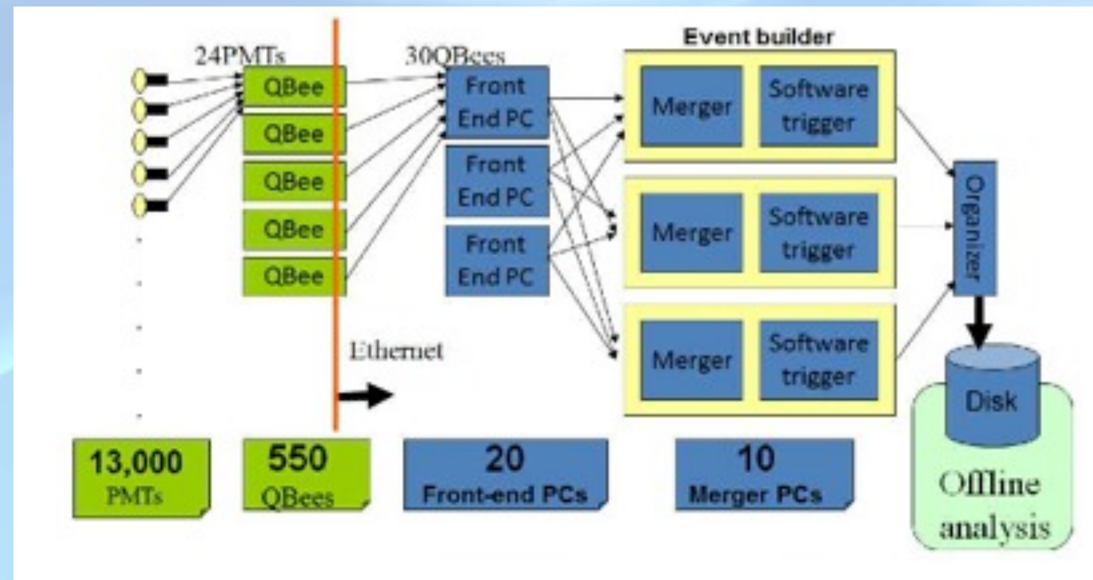


exponential disk model

$$dN \propto R\, dR\, dz\, e^{-\frac{R^2}{2R_0^2}} e^{-\frac{|z|}{h}}$$

where, $R_0 \sim 3.5\text{kpc}, h \sim 320\text{pc}$

Identification SASI motion -tools-



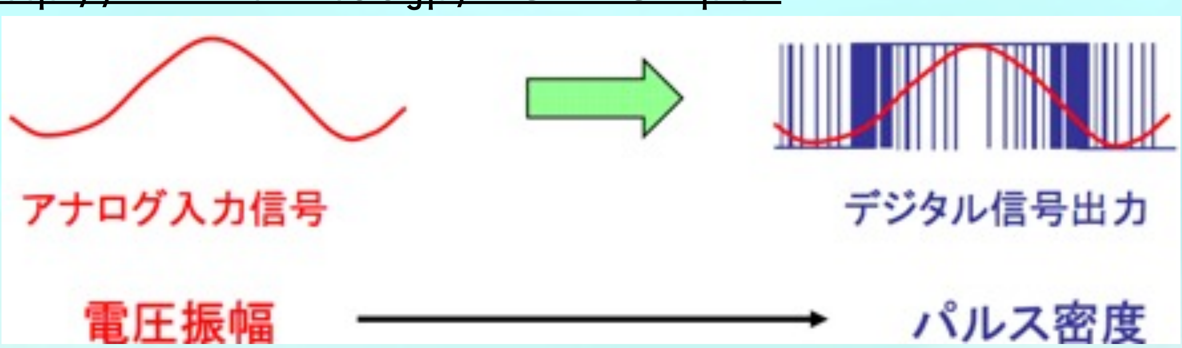
SK trigger information
s(t_i)=0 or 1

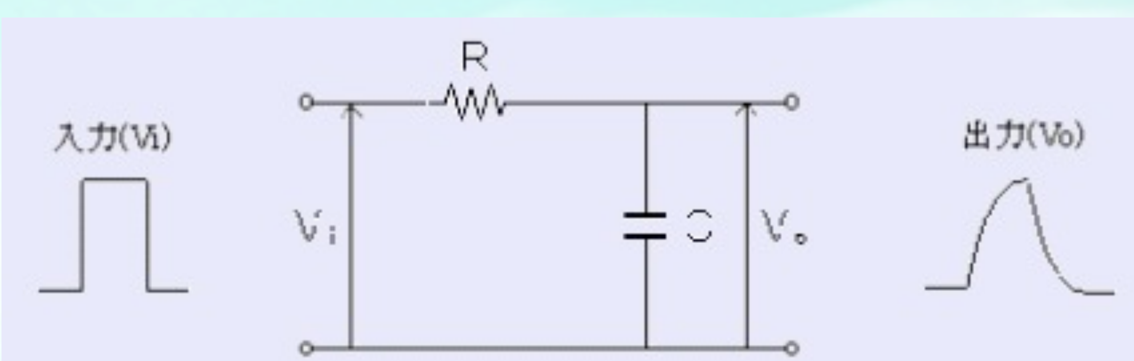
SuperKamiokande detector can save neutrino observe time with high accuracy

Give the signal of 0 or 1 for each time

It will useful to use ΔΣ modulator

http://www.a-r-tec.jp/DSADC2.pdf





SK trigger information s(t_i)=0 or 1

inverse ΔΣ modulator

?

Clear modulation? difficult to identify?

- Check the performance of (inverse) ΔΣ modulator

Identification SASI motion -simulation-

Assume 100Hz modulation with 10 times : 100ms modulation
Number of mean observed neutrino at SuperKamiokande
225[100ms/10kpc/22.5kton] for SASI phase

Signal simulation :

1. Compute # of observed event
   poisson distribution with μ=225
2. With PDF, make trigger event with
   1μs resolution

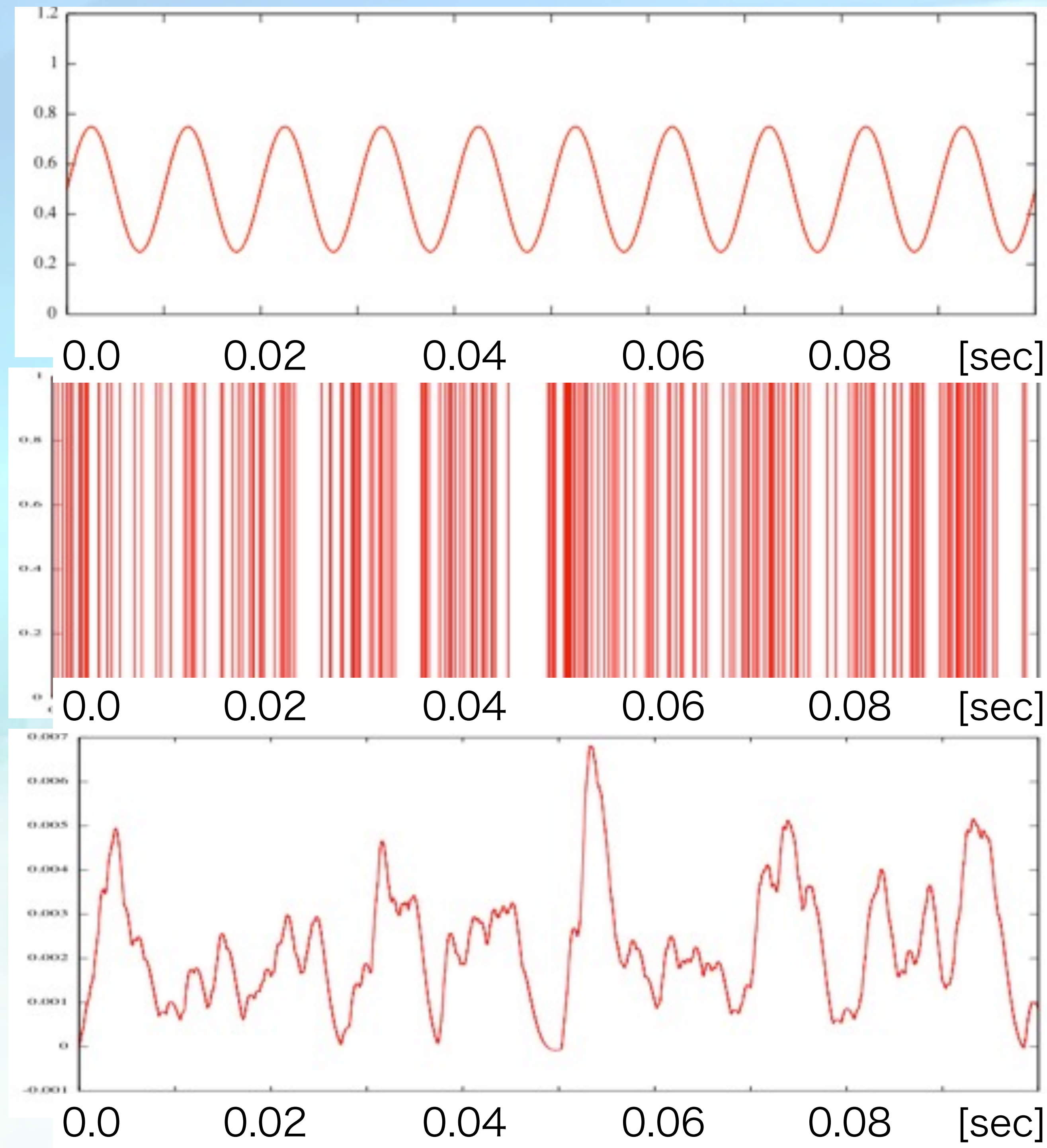
$$\mathrm{PDF} \propto A \times \sin(2\pi f t) + 0.5$$

3. Apply inverse $\Delta\Sigma$ modulator(LPF)
4. Apply FFT and extract amplitude, A_{obs}
5. Calculate SNR for 100Hz amplitude

$$\mathrm{SNR} = \frac{A_{obs} - N_m}{N_\sigma}$$

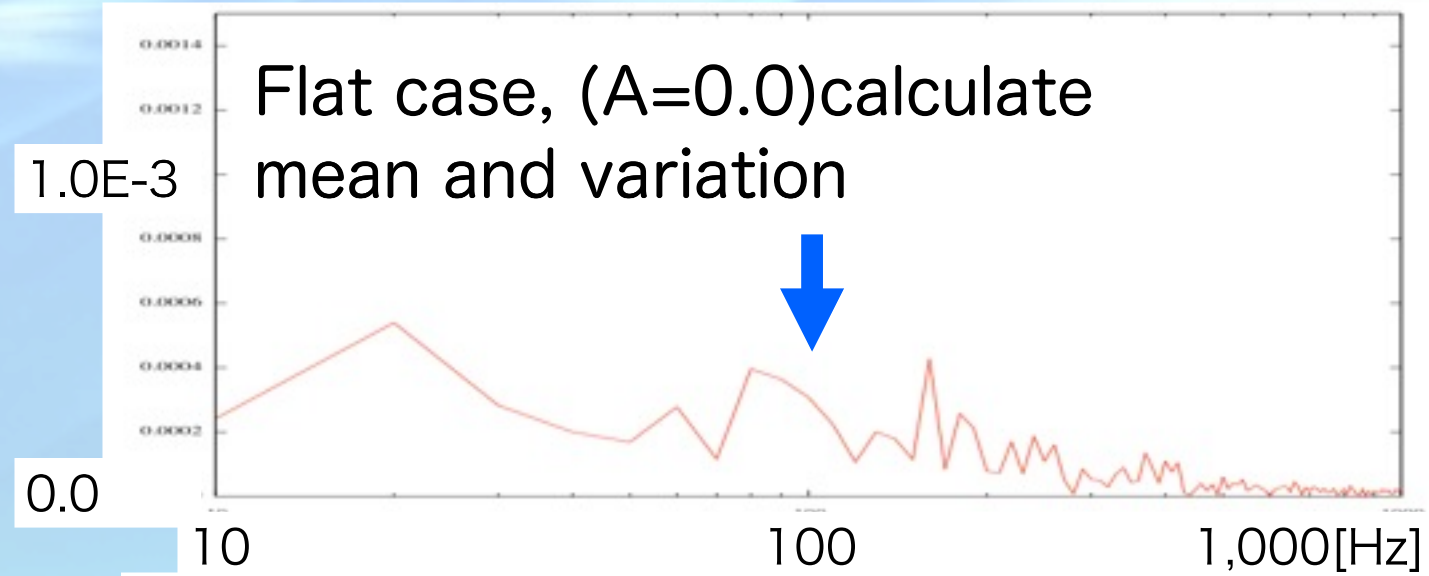
N_m : mean of extracted amplitude for flat PDF

N_σ : variance of extracted amplitude for flat PDF

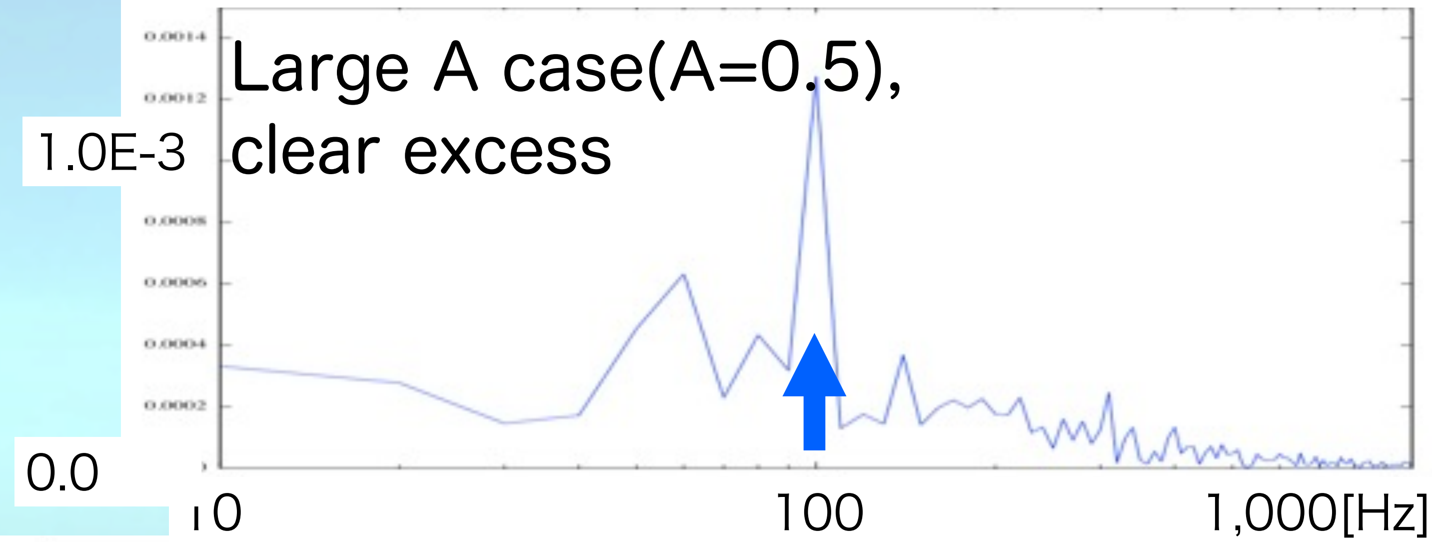


Identification SASI motion -results-

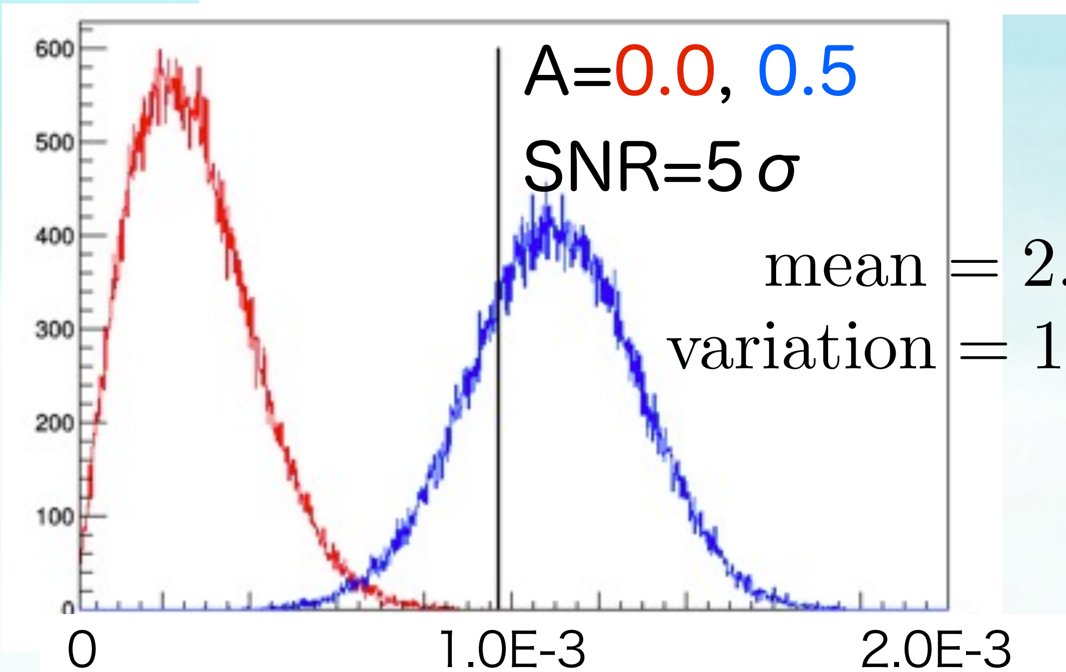
Estimate Flat distribution(noise)
One shot : amplitude-frequency
$A_{ons,flat} = 3.0 \times 10^{-4}$
Apply 1,000,000 times, obtain
$N_m = 2.61 \times 10^{-4}, N_\sigma = 1.34 \times 10^{-4}$
Independent from N_{obs}



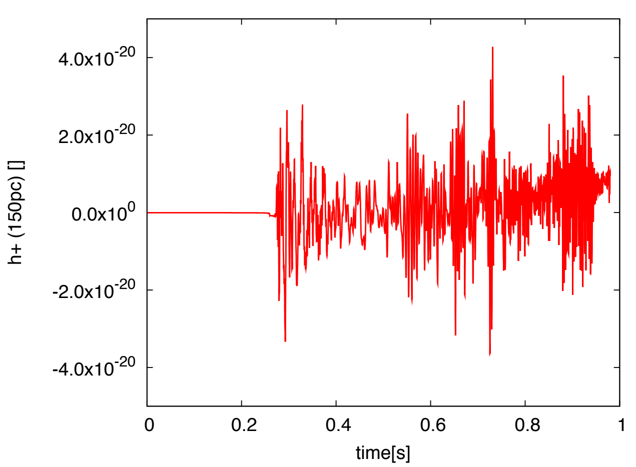
Estimate A dependence(signal)
One shot : amplitude-frequency
$N_{obs} = 225$
$A_{obs,0.5} = 1.2 \times 10^{-3}, \mathrm{SNR} = 7.7$
Set observation threshold = 5 σ

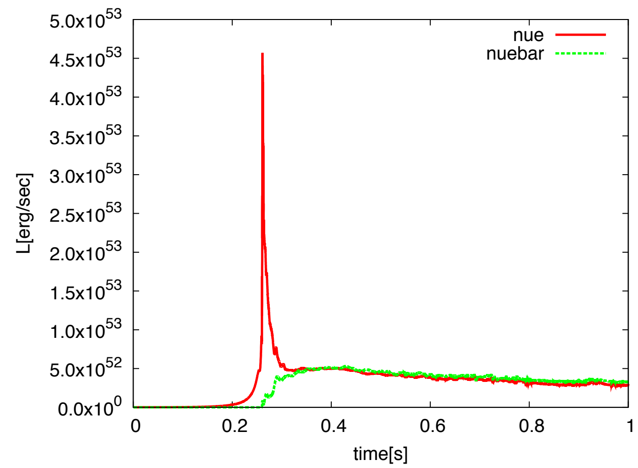


A	Det. Eff.
0.5	86%
0.4	45%
0.3	14%
0.2	2%
0.1	<1%



time epoch -preliminary- M.Asano

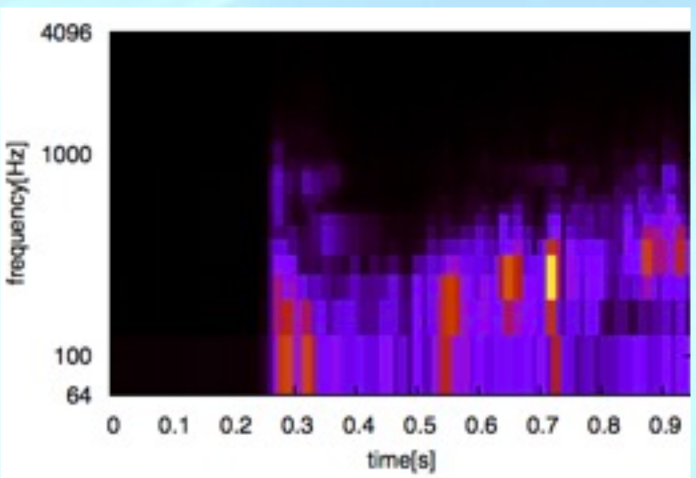


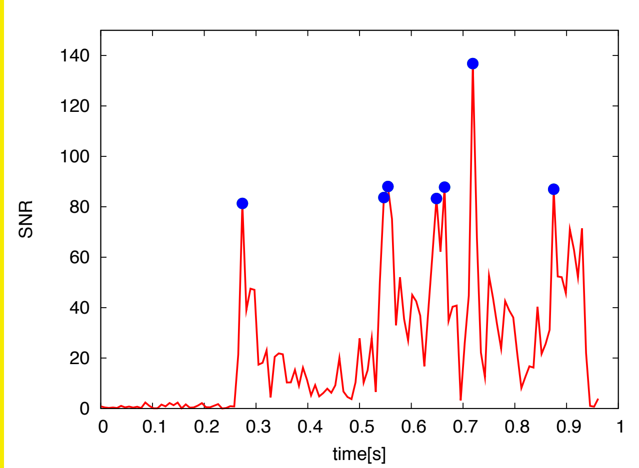


Investigate the method to extract the characteristic epoch
- prompt convection
- shock stall
- SASI, neutrino-driven convection etc..

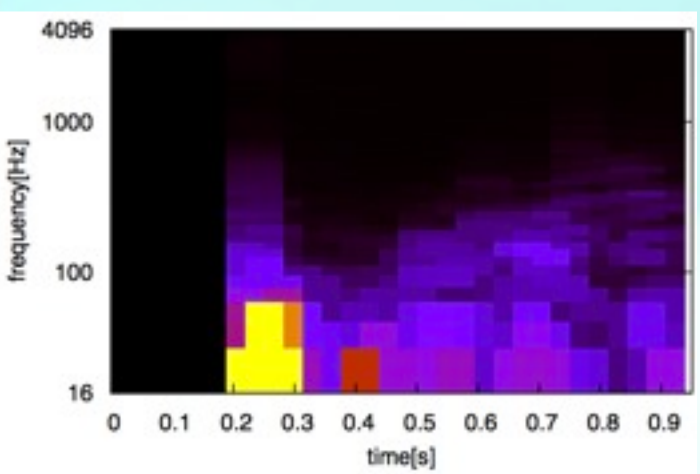
s80 model (Suwa et al) GW and neutrino

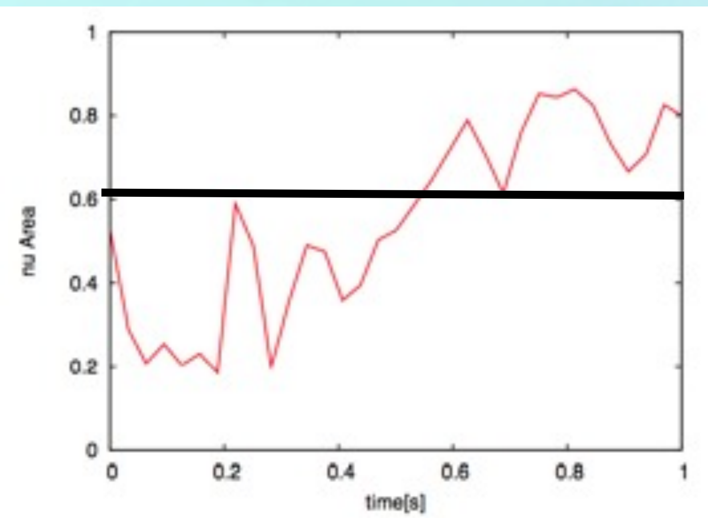
- GW (extract projecting SNR)
  - first : prompt
  - after : SASI etc.
- neutrino (extract high frequency component)





s80 model's epoch
prompt GW's epoch : 274ms,
delayed GW's epoch : 547~875ms
start time of delayed phase : 563ms





Model \ Physical process	prompt convection[ms]	shock stall[ms]	SASI,Neutrino-driven-convection,PNS convection etc.[ms]	
typical	200	300 ∼ 500		500 ∼
	epoch of GW			epoch of $\bar{\nu}_e$
s80	274	na	547∼875	563
s50	234	na	609∼921	563
s15	na	na	547∼657	500
s20	na	na	705∼783	682
s30	337	na	744∼1275	470
s40	na	na	773∼1289	789
s100	na	na	654∼1240	647

Summary

- KAGRA status
  - iKAGRA observation will start end of this year
  - Installation work is going on
- Analysis strategy
  - Single detector : Expand to TF plane and search clustering
  - Multi detectors : Coherent Network Analysis
- Messages from Supernova
  - Core bounce from GW
    - Template tuning and extract the rotation power
    - Coincidence analysis with neutrino and GW

GWPAW 2015@ Osaka

Date: 17-20 June, 2015

Venue: INTEX-Osaka International Conference Hall

Invited speakers:

Status of Gravitational Wave detectors

Matthew Evans (LIGO), Francesco Piergiovanni (Virgo), Takaaki Kajita (KAGRA)
Martin Hewitson (eLISA & LPF), Masaki Ando (DECIGO), Dick Manchester (PTAs)

Counterpart/follow-up

Edo Berger (Short GRB), Shrinivas Kulkarni (Optical-Infrared-radio)
Peter Meszaros (X, Gamma), Mark Vagins (Neutrino)

GW Data Analysis and Theory

Alessandra Buonanno (GW modeling), Maria Alessandra Papa (Data analysis)
David Merritt (Sources for low frequency GW)
Bruce Allen (Summary talk and organizer of discussion)