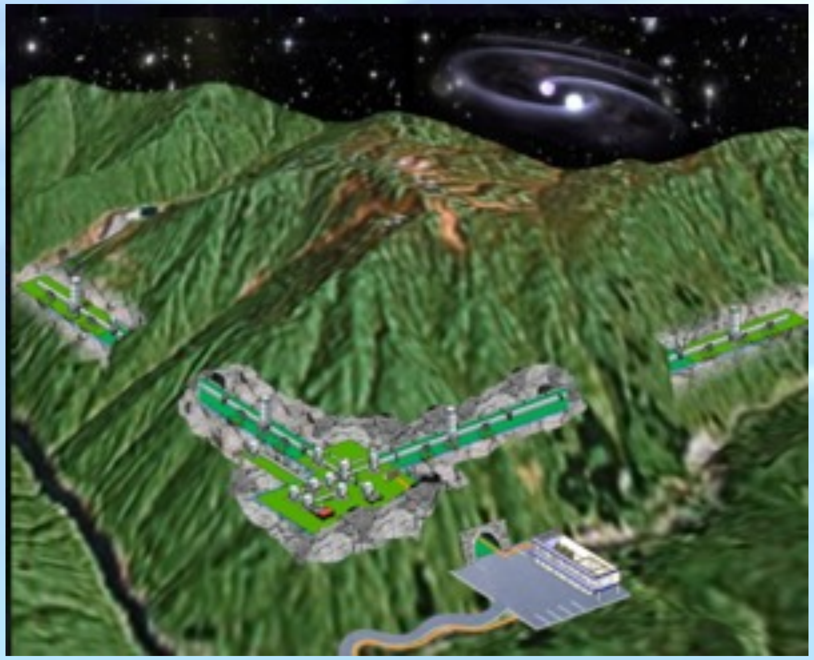
超新星爆発モデルの進展と今後の展望
超新星爆発による重力波の検出

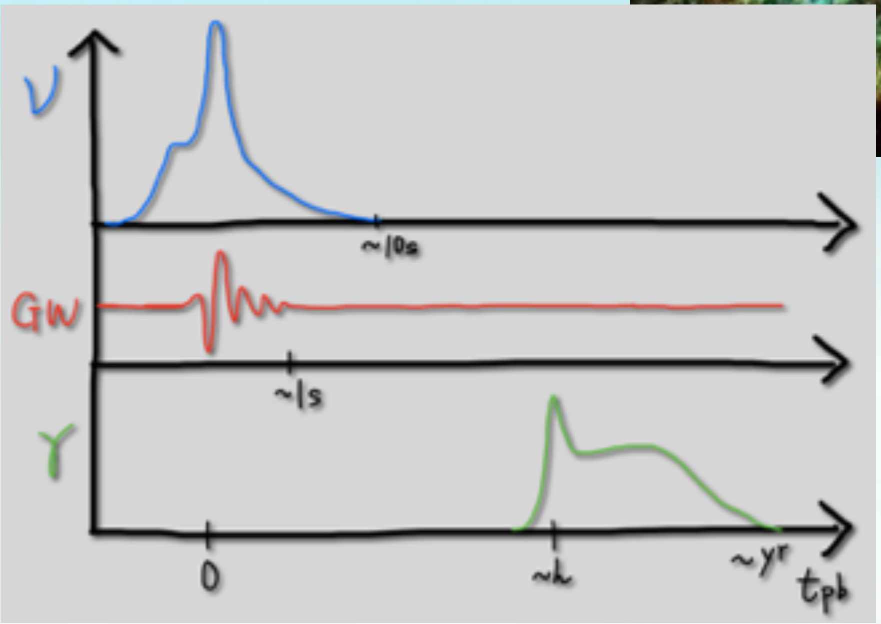
日本物理学会 第70回年次大会
2015/03/24

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

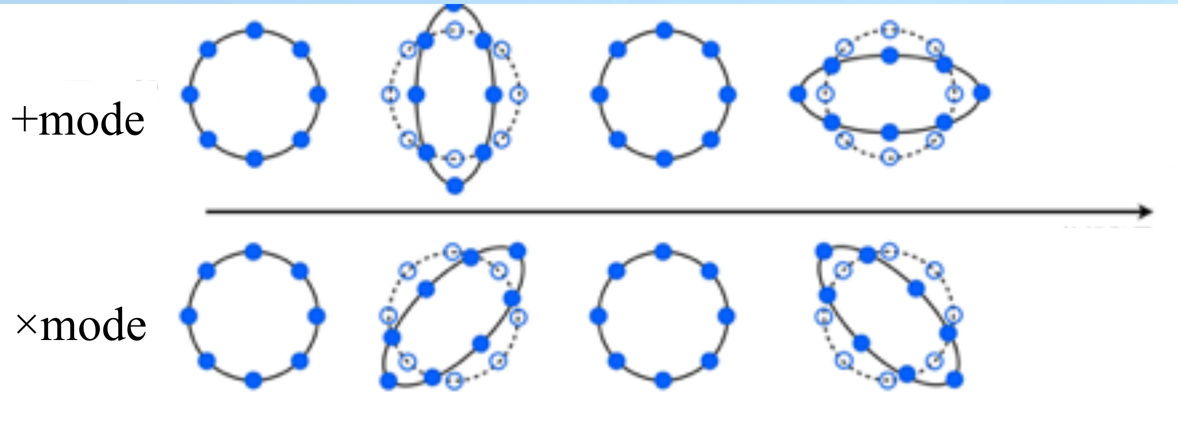
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

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

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

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

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

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

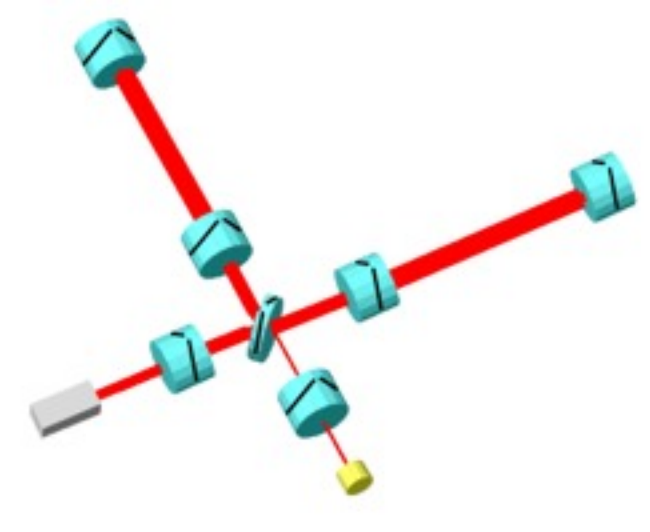
Mass quadruple moment
axis asymmetry

- Laser interferometer

Fabry-perot Michelson interferometer

Observe the optics of interface

Direction dependence

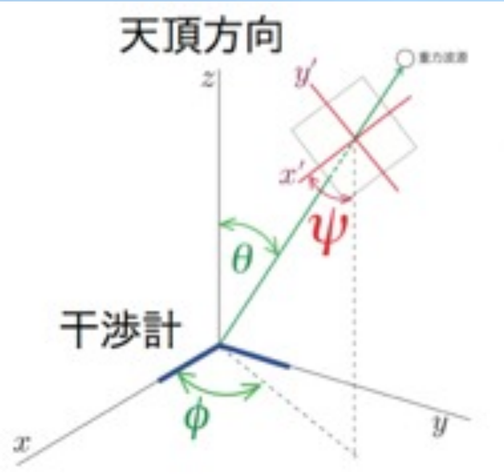


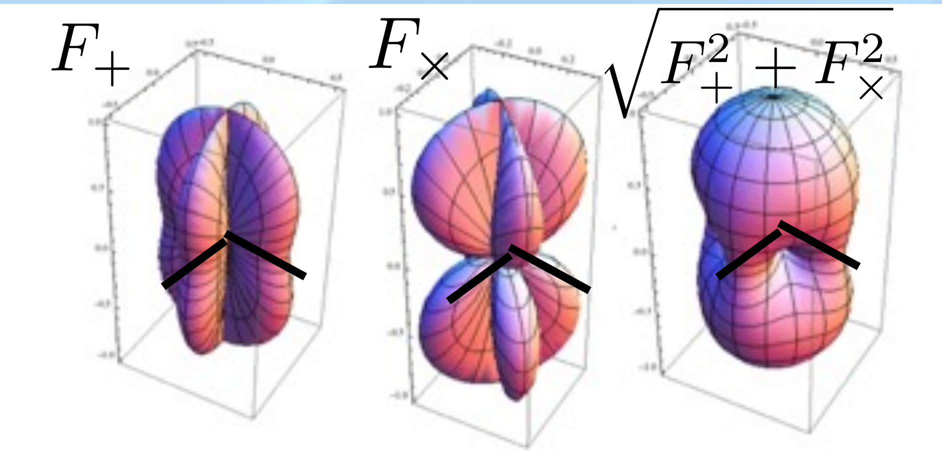
GW and Laser interferometer

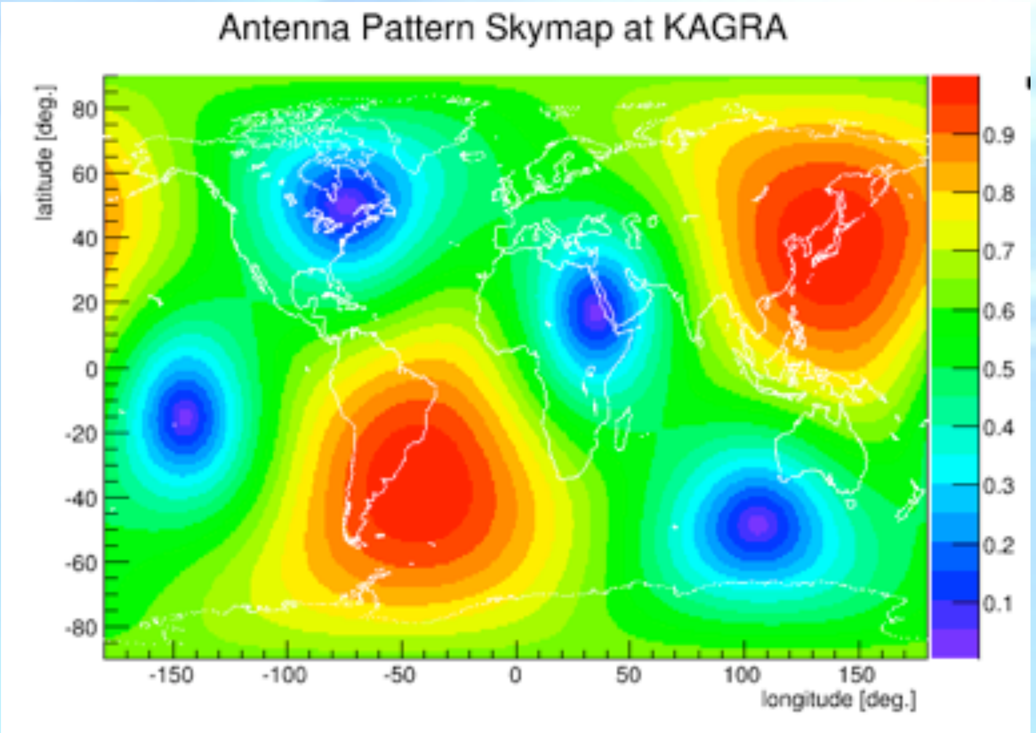
- Antenna pattern

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

θ : Zenith angle
ϕ : Azimuth angle
ψ : Polarization



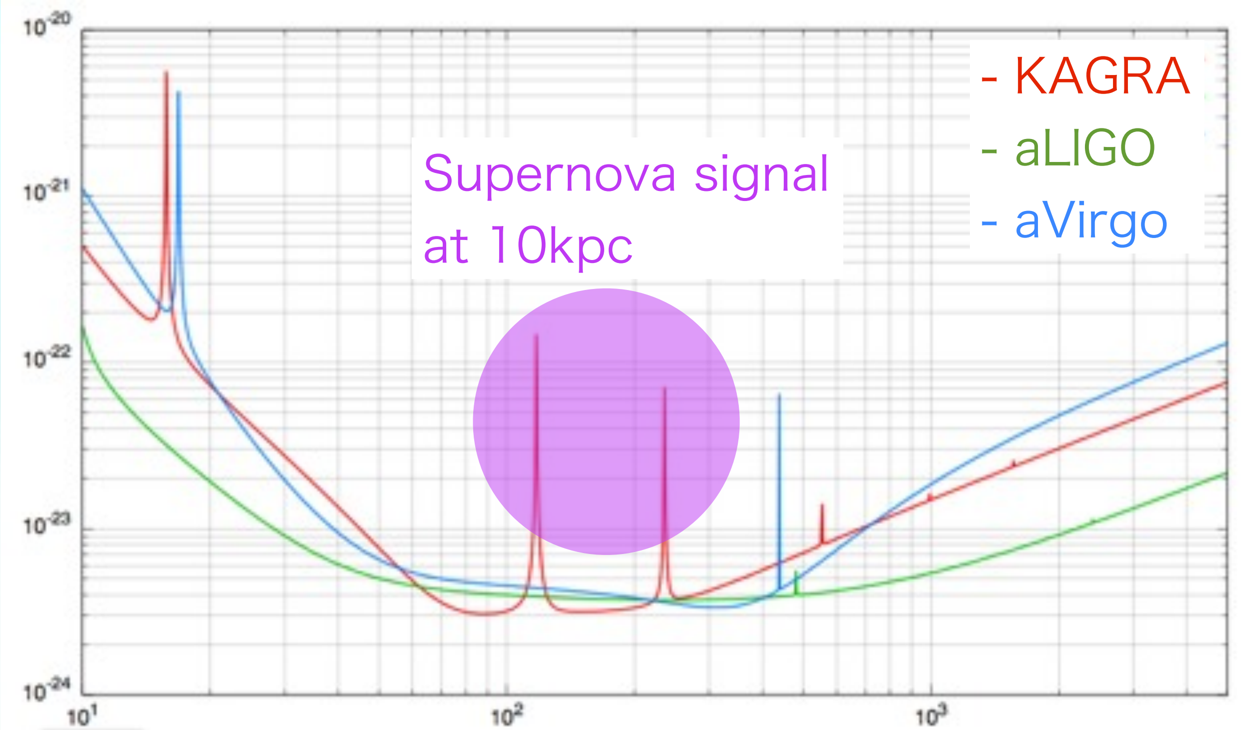




- Detector sensitivity curve

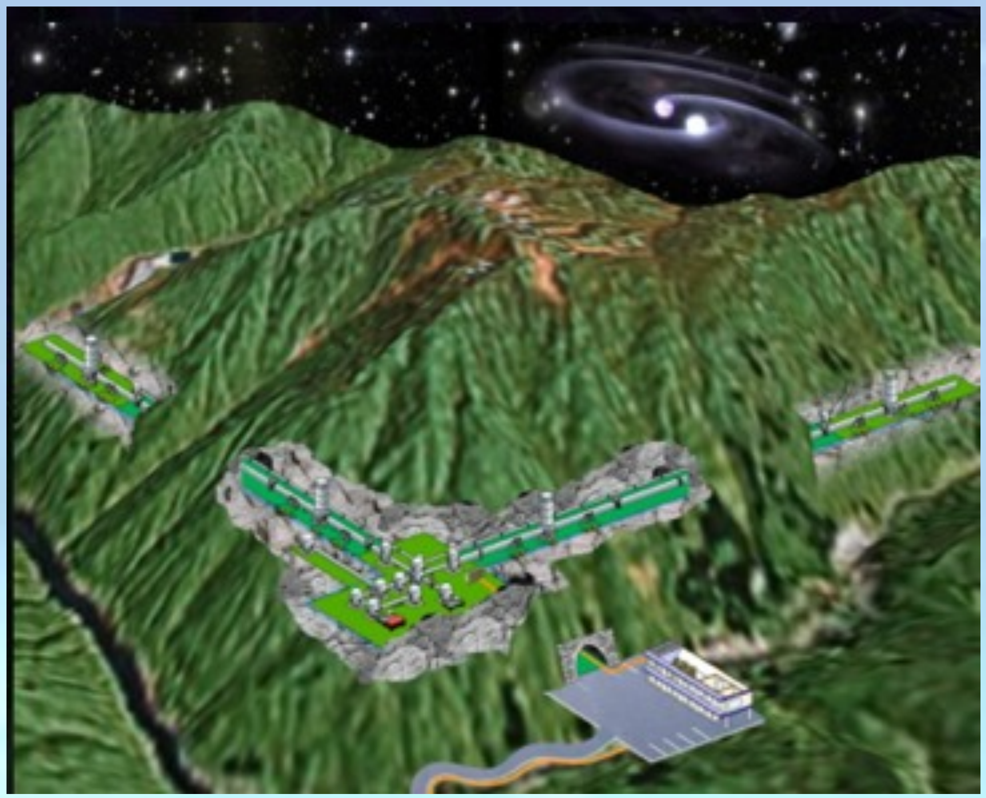
Horizontal axis : Frequency[Hz]
Vertical axis : [1/rHz]
strain equivalent noise spectrum

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



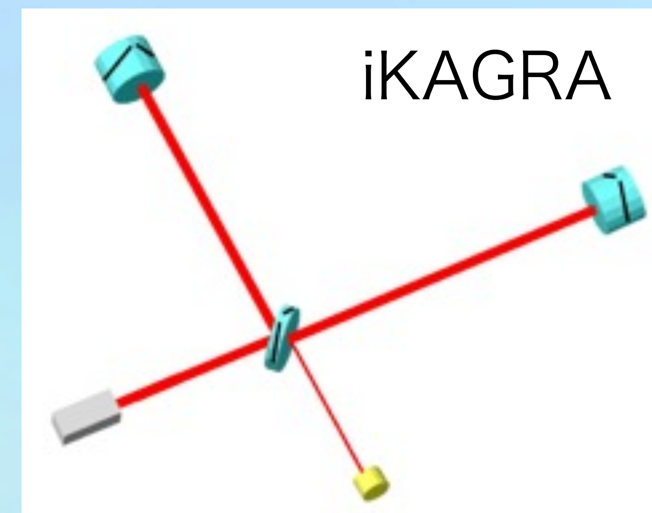
Frequency[Hz]

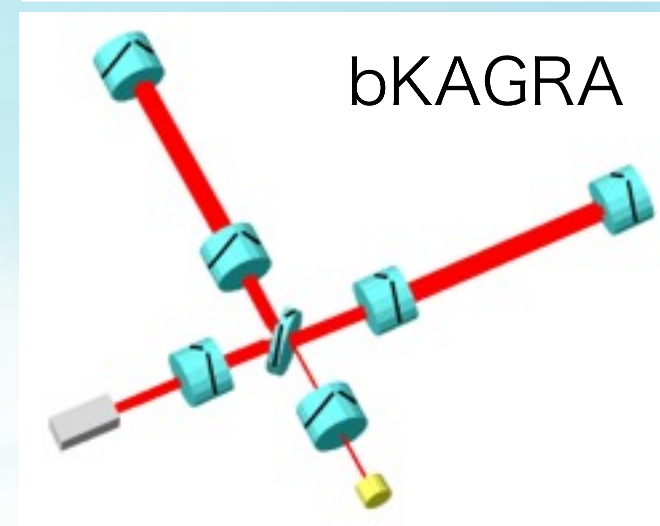
KAGRA : detector overview

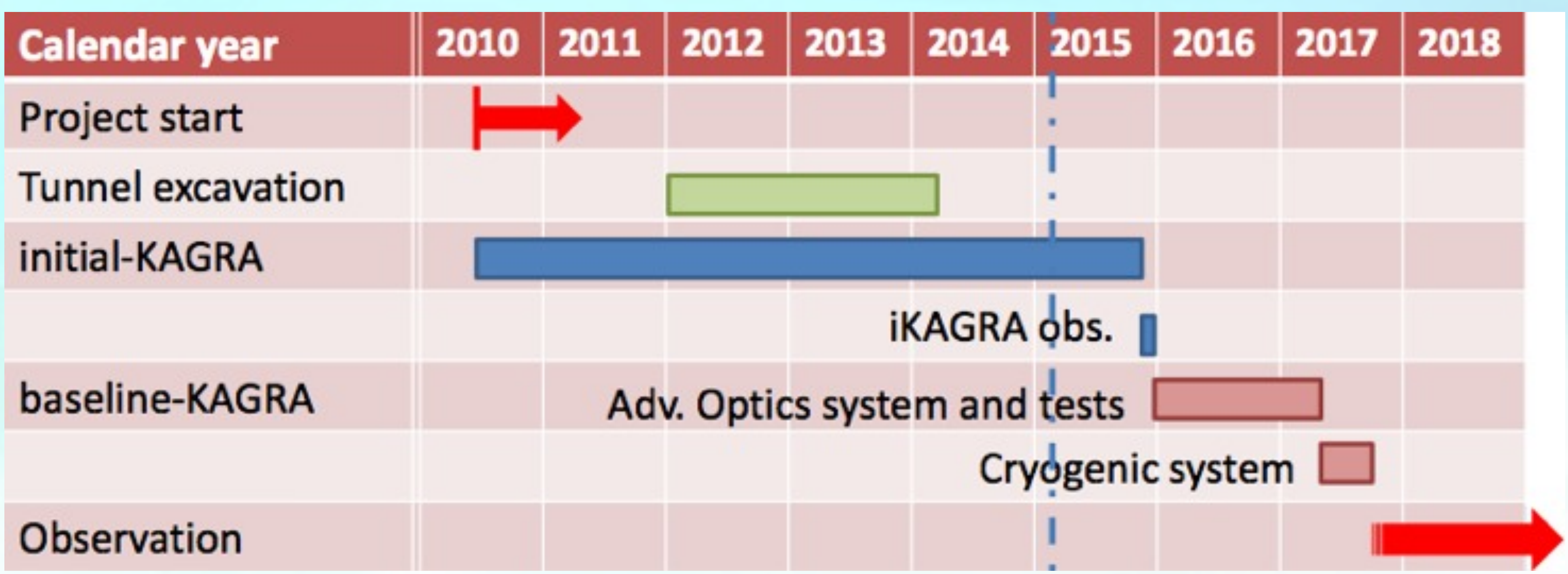


2nd generation GW detector in Japan

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







KAGRA : installation

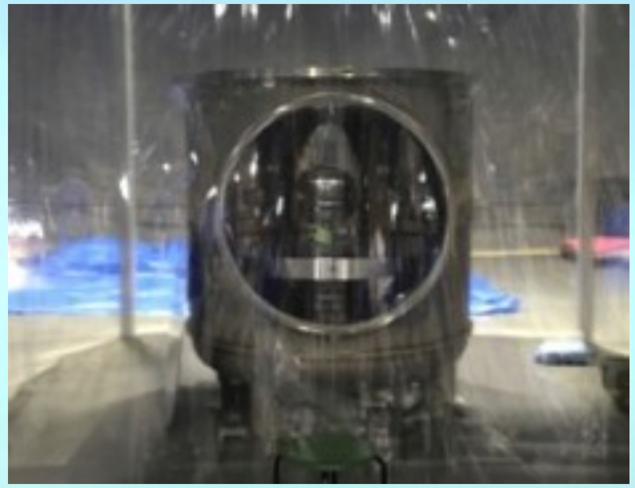
Beam duct :

Cryostat :

Laser booth :

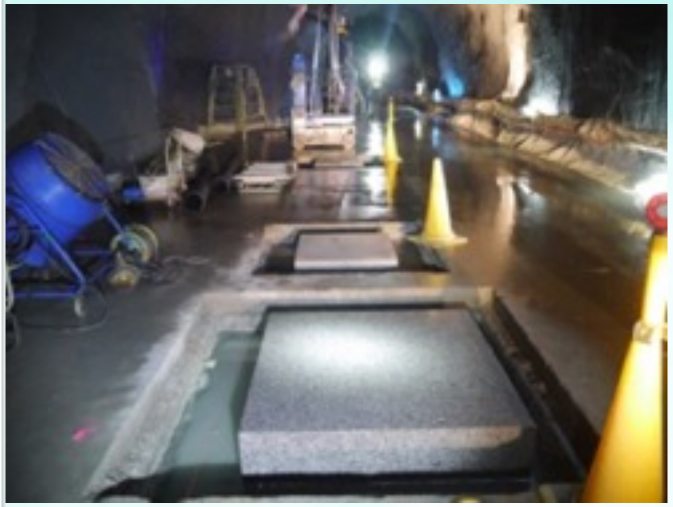
Digital control room :

Stack Vibration :



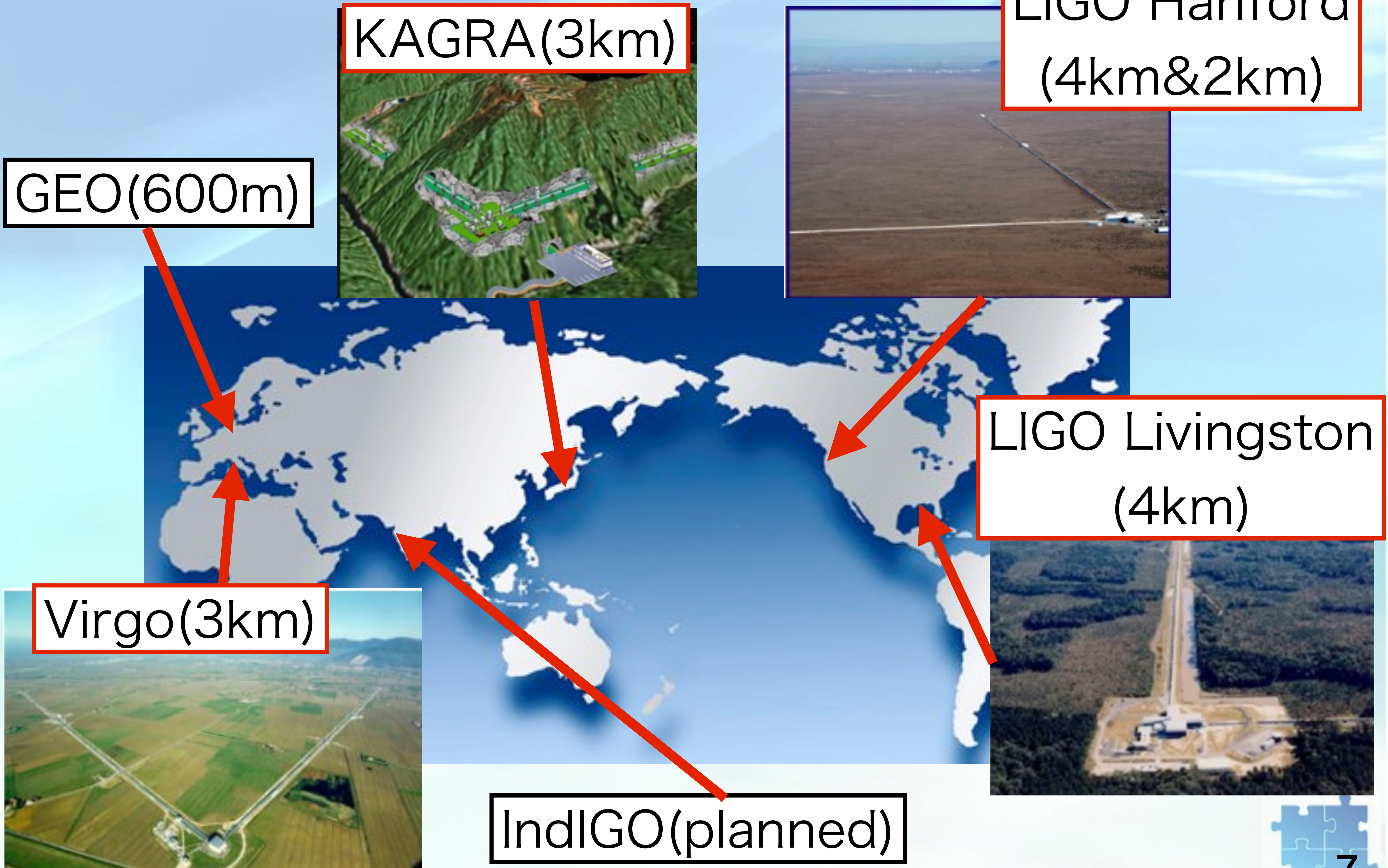
I went to the inside of mine at February : Computer installation

Geophysical interferometer :



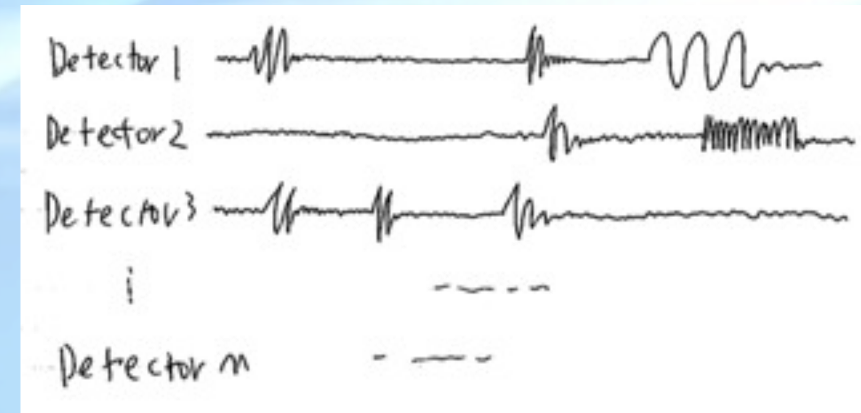
Pictures by T.Uchiyama

World GW detectors

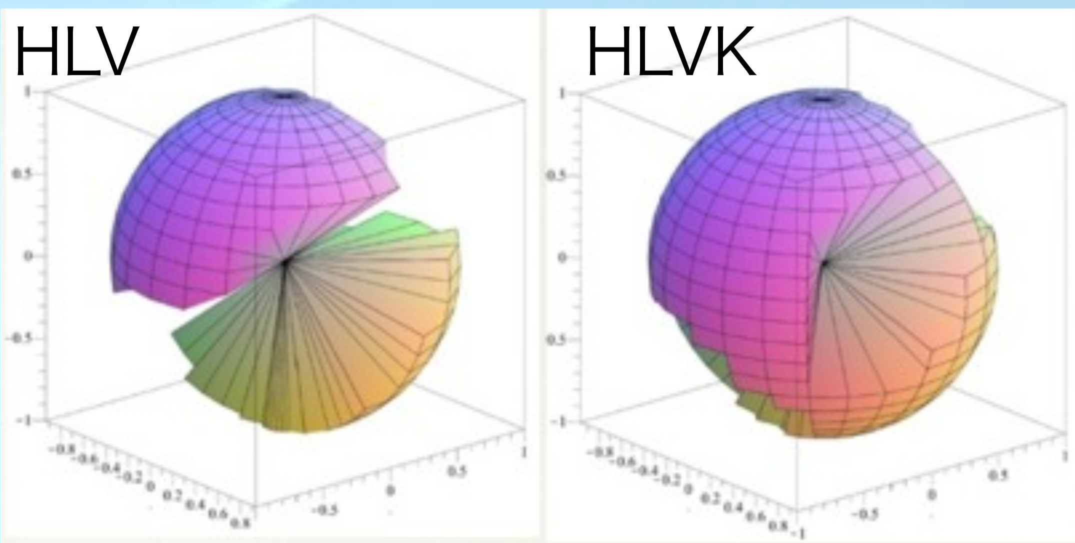


International GW detector network

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



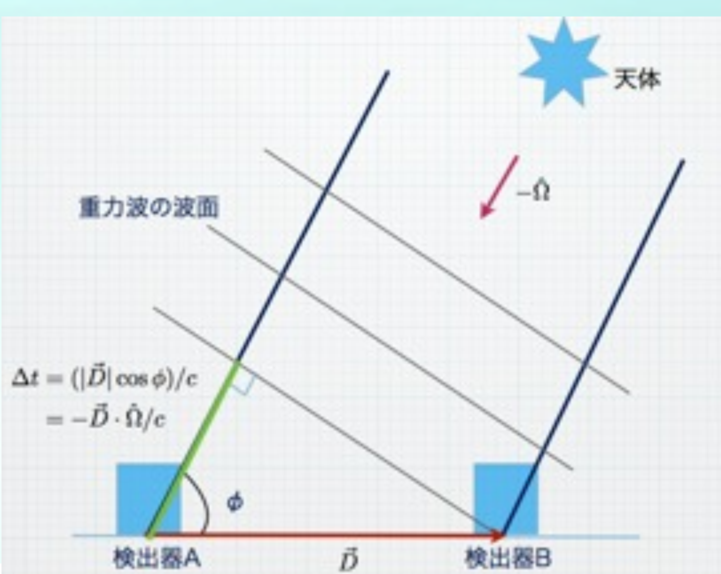
- Expand sky coverage

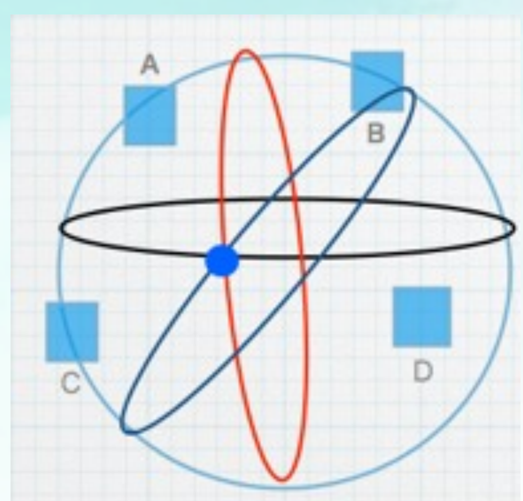


- Coverage of all sky is very important
  - multi detector help it

B.Schutz(2011)

- Estimation of source direction

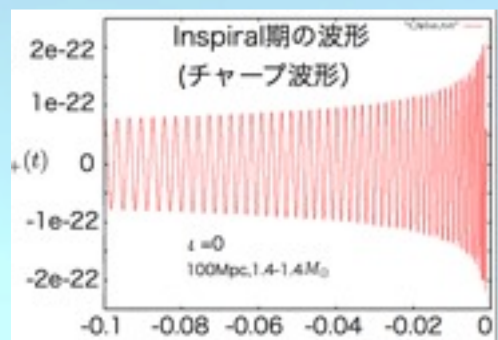
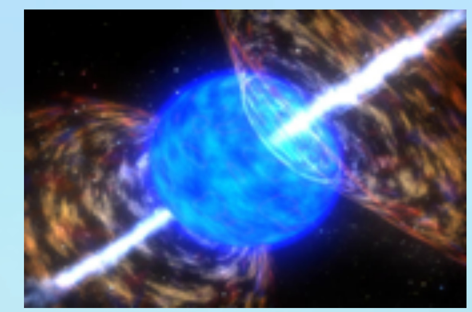
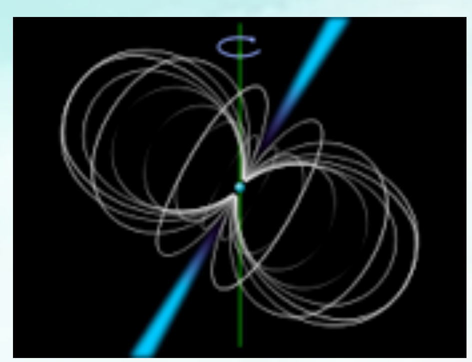
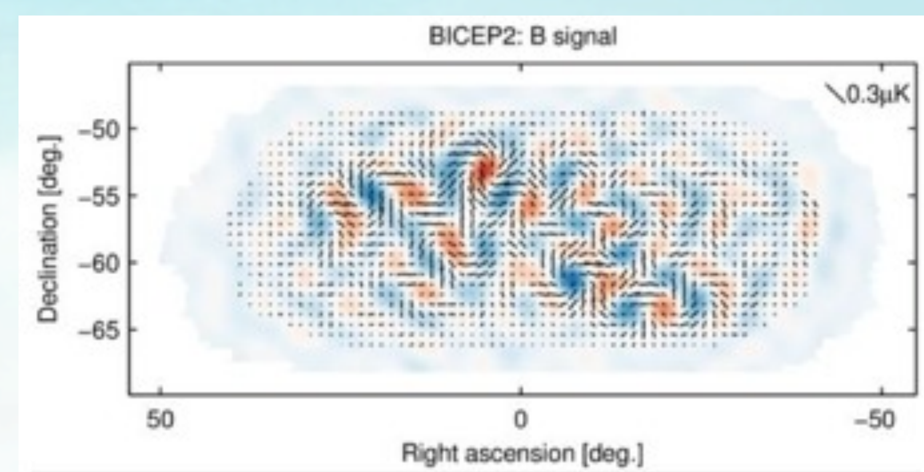




- Need (more than) four detectors
- Coincidence, Coherence

T.Arima

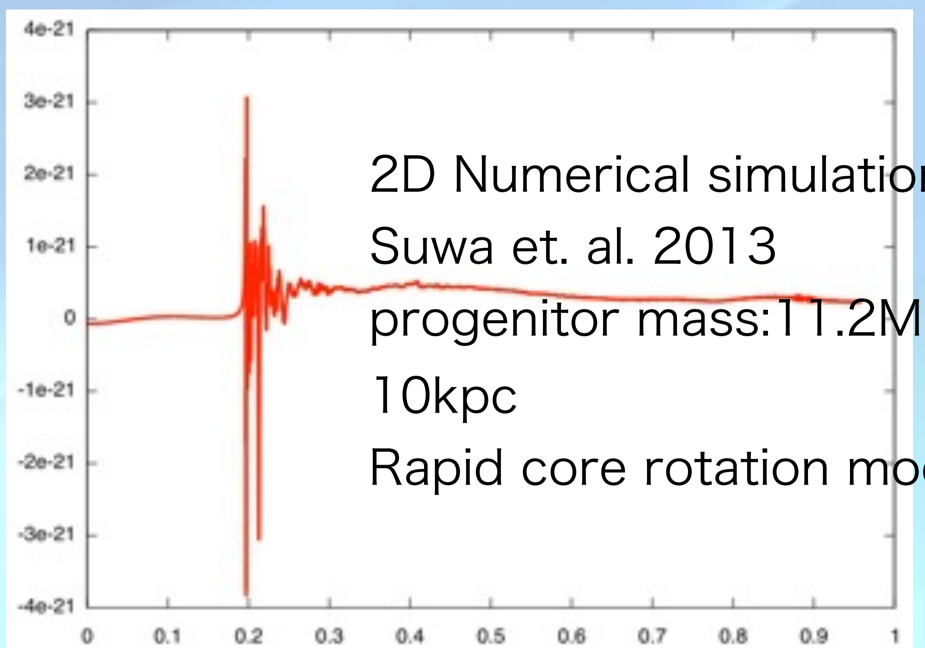
Candidate GW sources

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

Analysis strategy - Observed signal-

$$S_{obs}(t) = (F_+h_+(t) + F_\times h_\times(t)) + n(t)$$

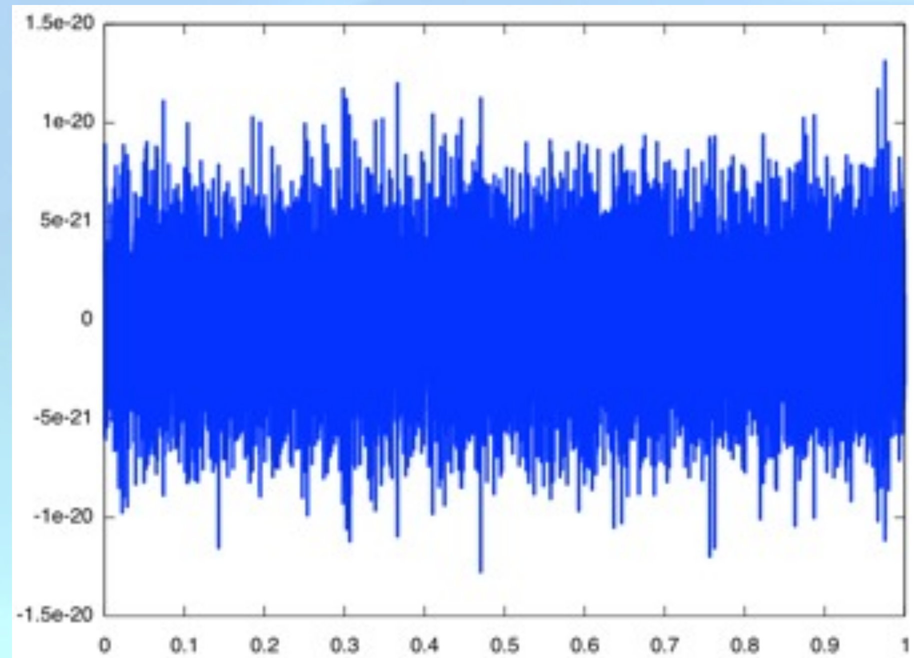
GW signal — Detector noise



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

Time form gravitational collapse[s]

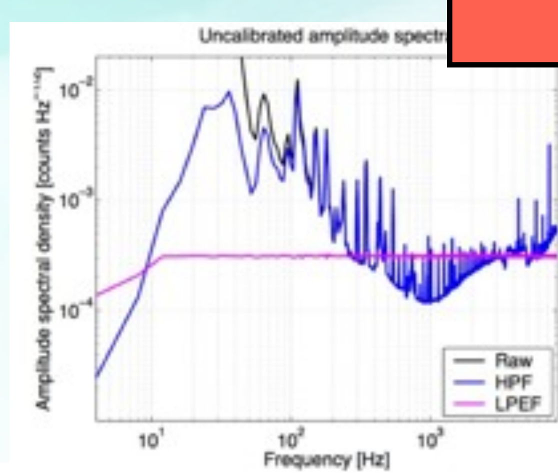
\+



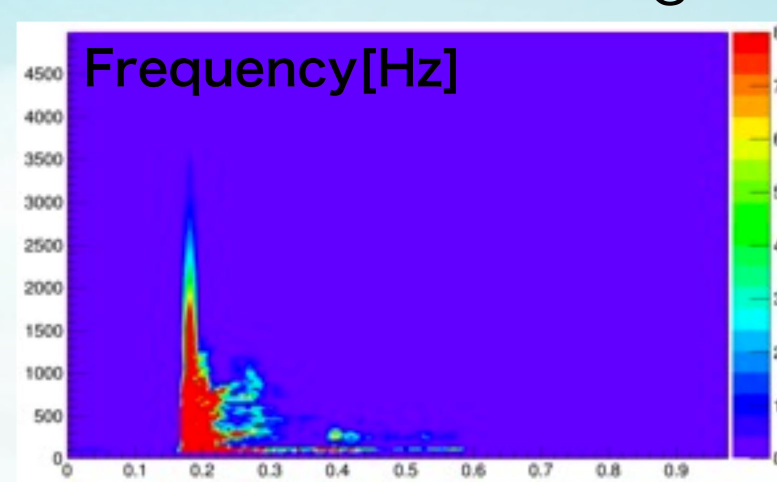
Simulation :
KAGRA noise
Stationary,
Gaussian noise

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



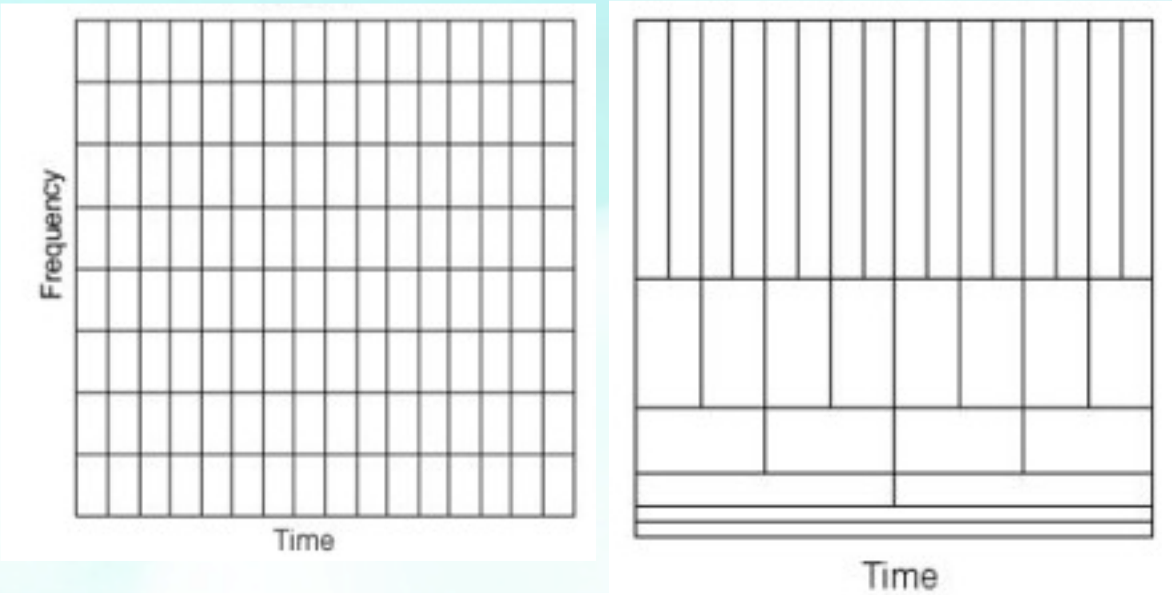
Time[sec]

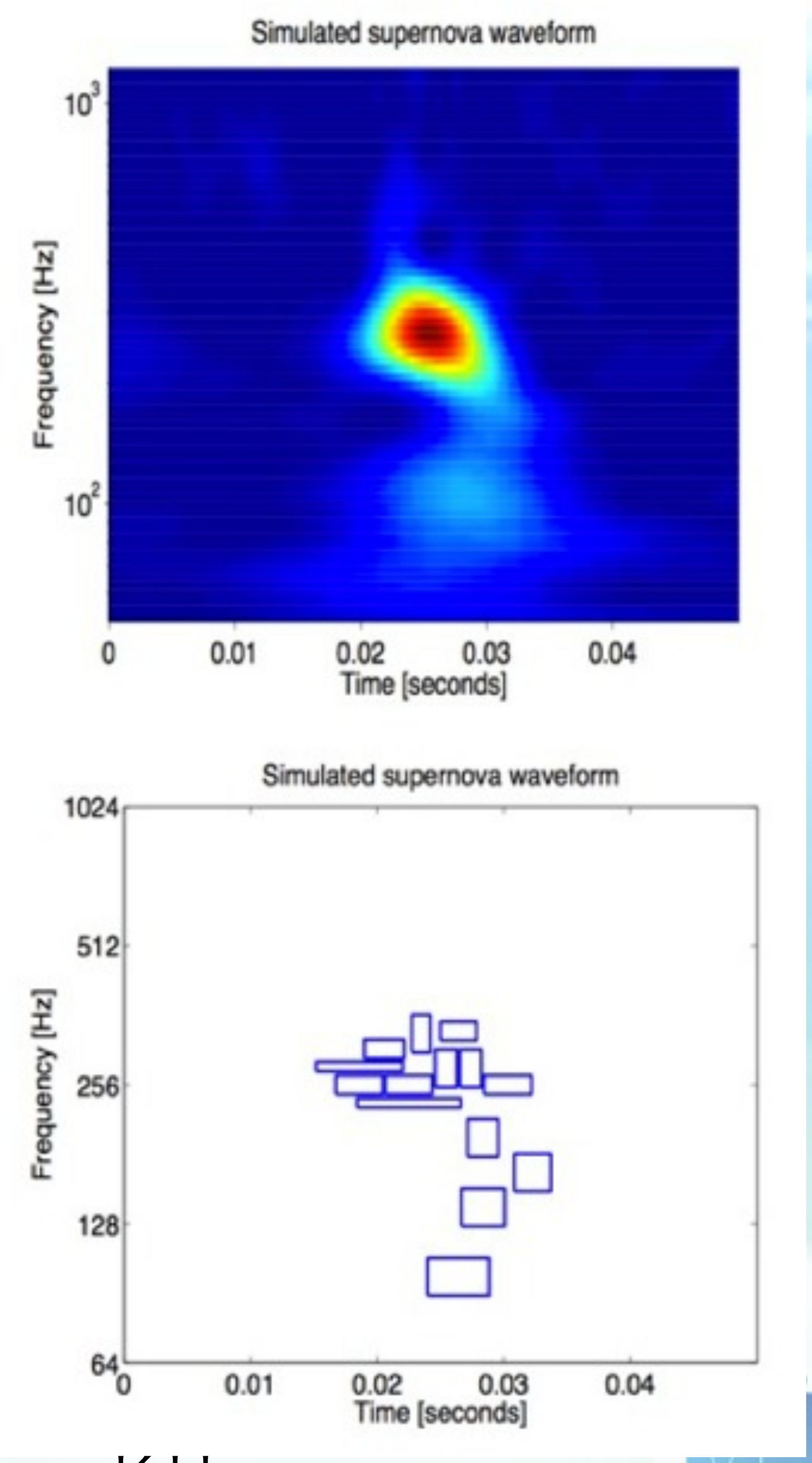
Single detector -TF clustering-

- 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





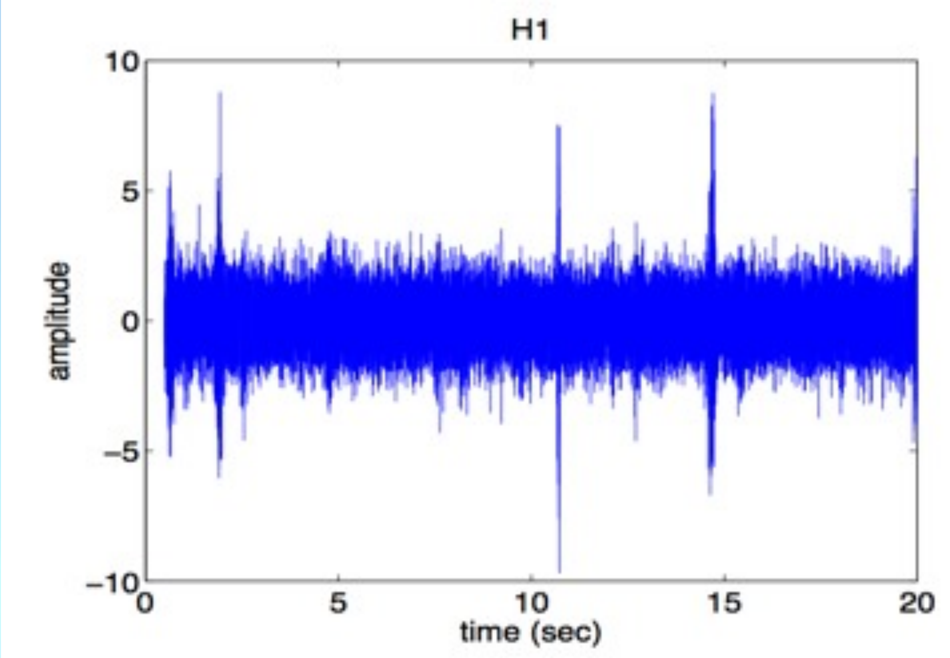
K.Hayama

Analysis strategy -Detector noise-

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

-reduce/identify them (important task)

Example of LIGO S5 data



- 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

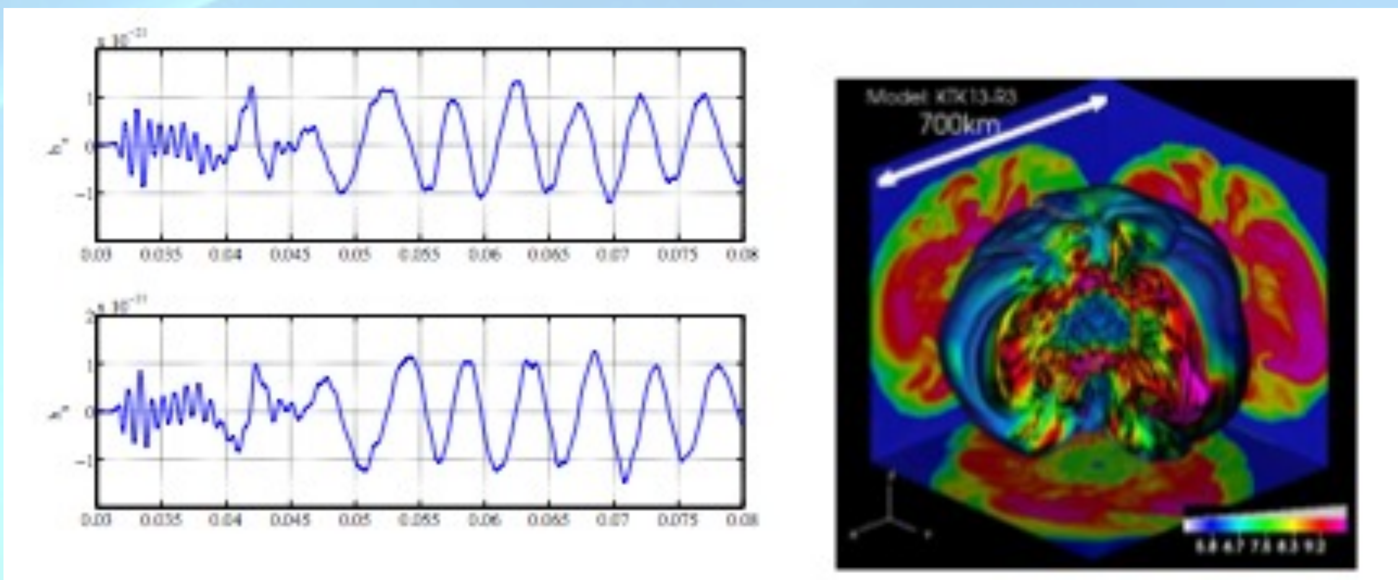
Astrophysics > High Energy Astrophysical Phenomena

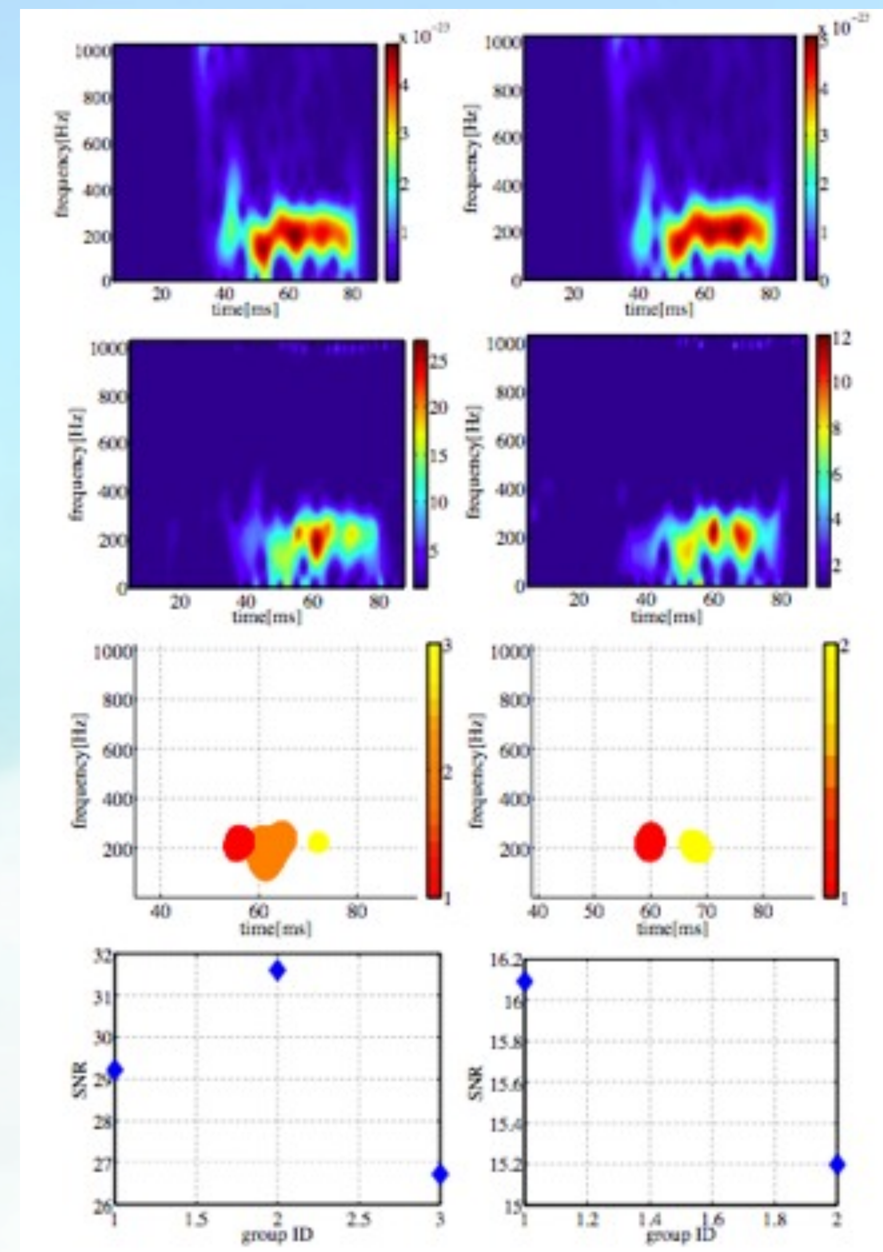
Coherent Network Analysis of Gravitational Waves from Three-Dimensional Core-Collapse Supernova Models

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

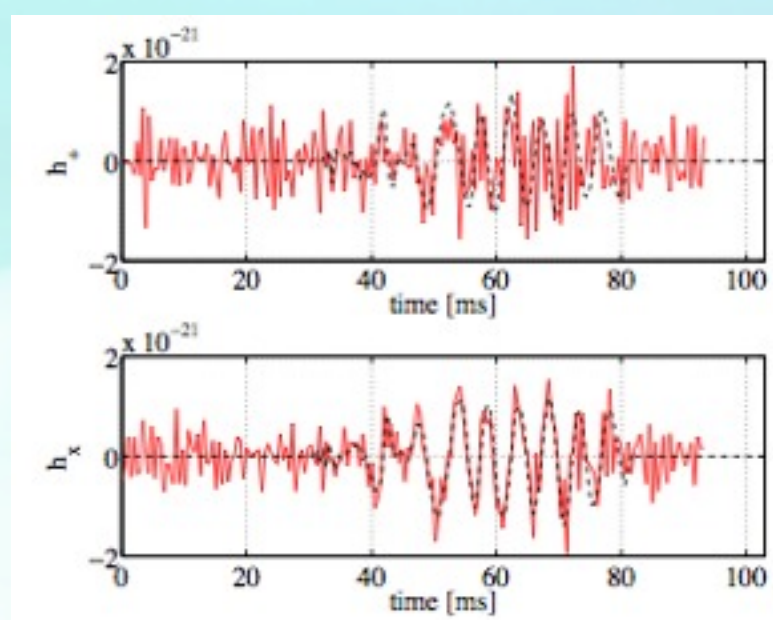




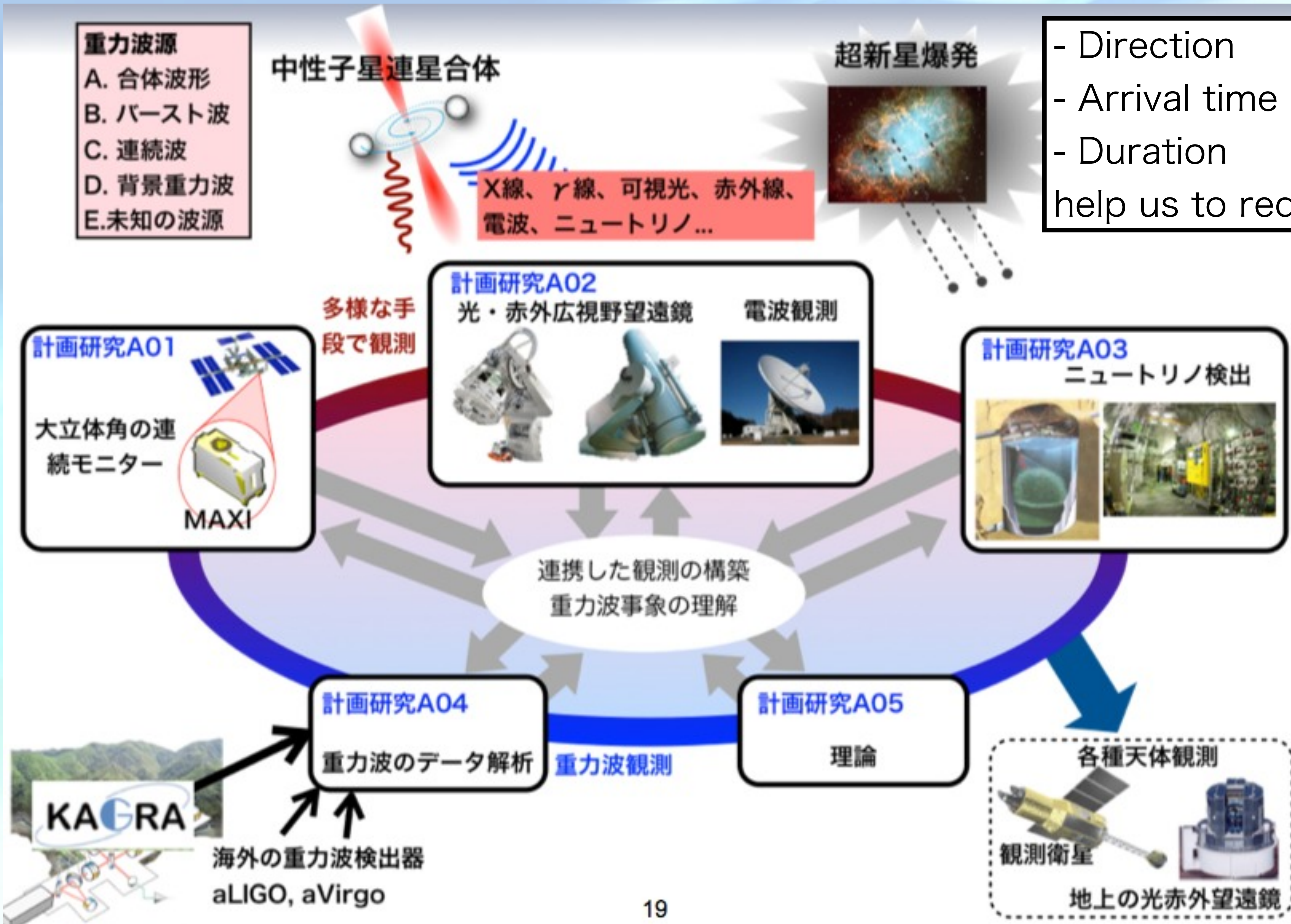
15M⊙ π rad/s angular momentum

Detectors:
aLIGO, aVirgo, KAGRA

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



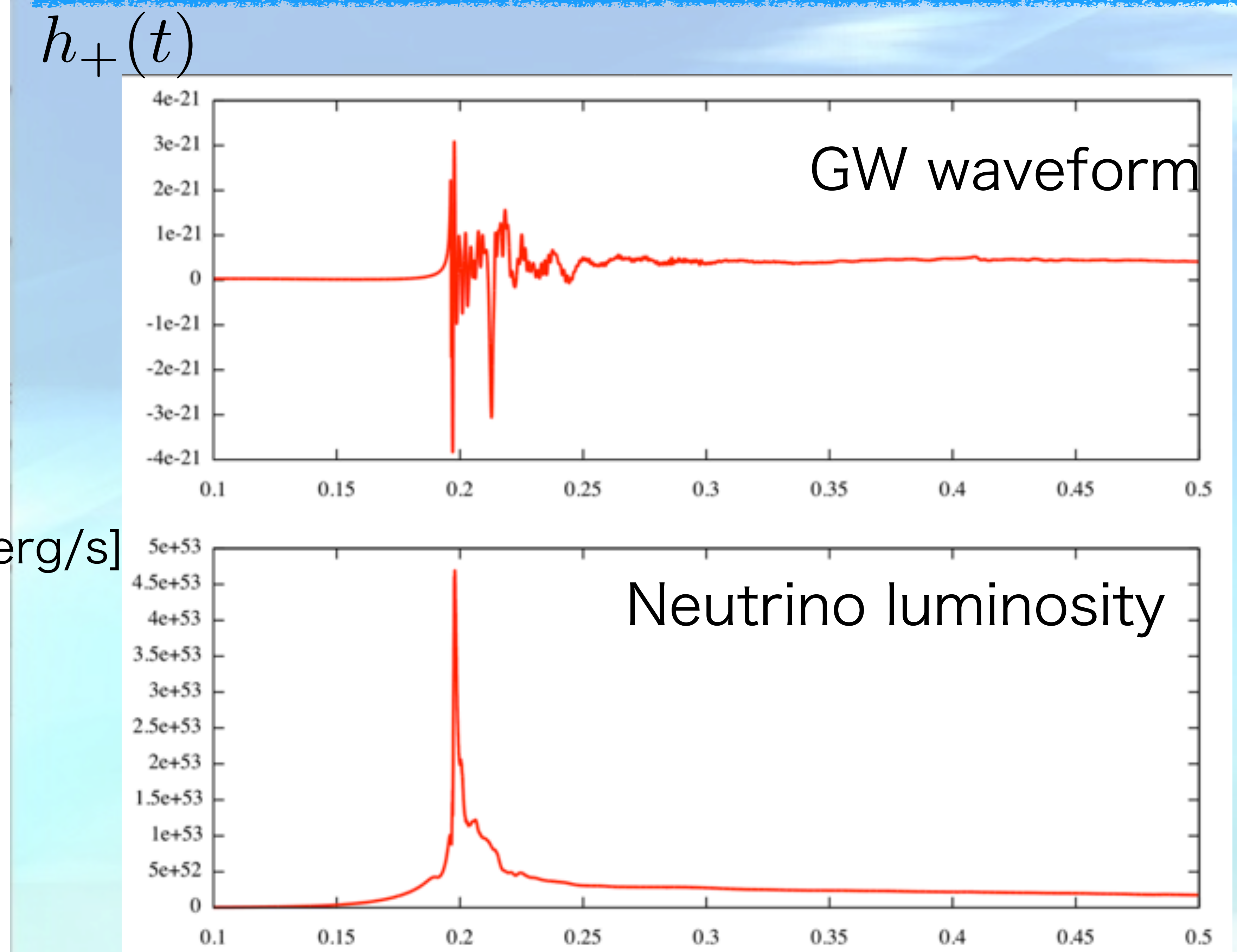
With external trigger



- Direction
- Arrival time
- Duration

help us to reduce FAP

Multi-messenger astronomy



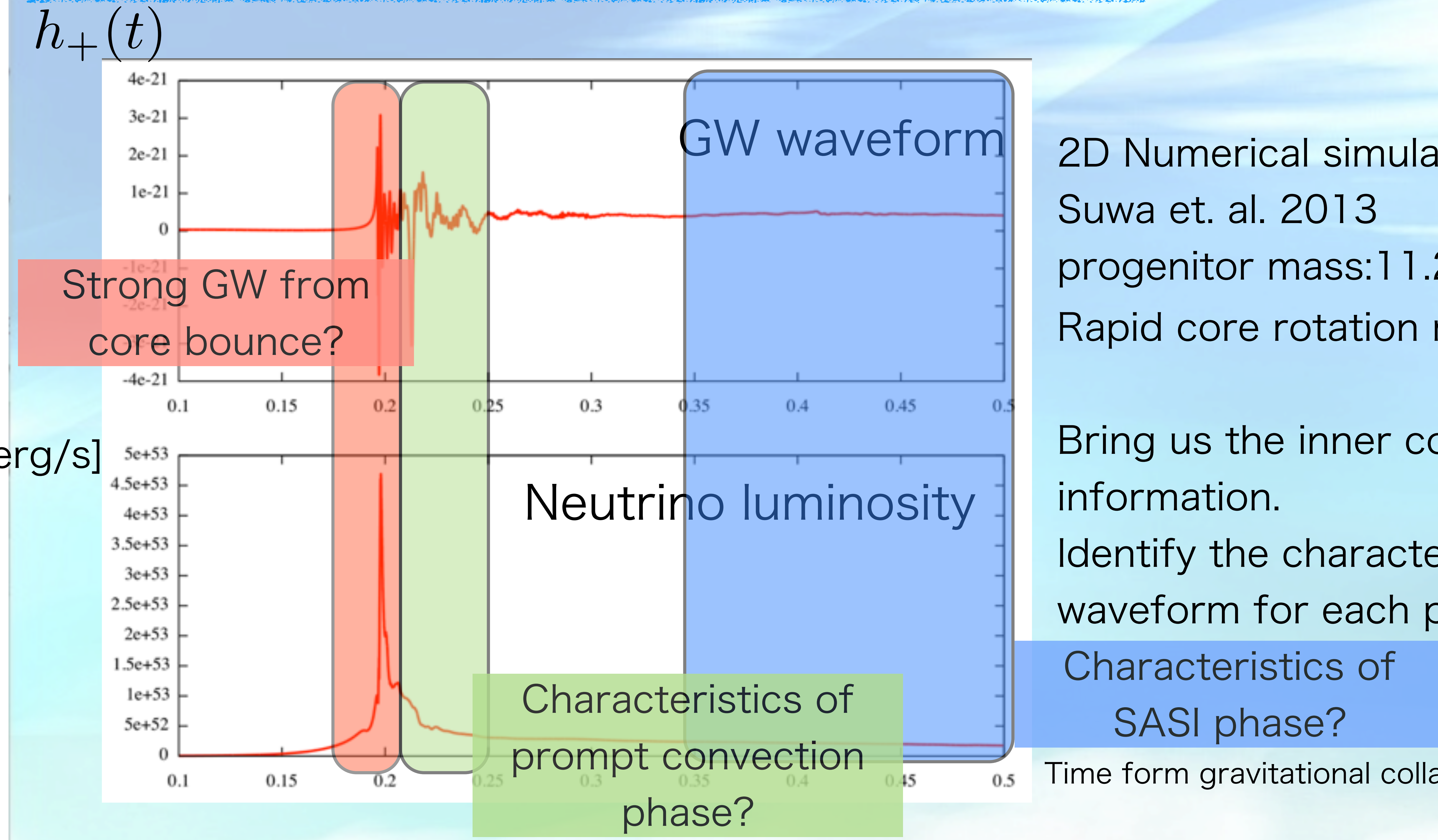
2D Numerical simulation
Suwa et. al. 2013
progenitor mass:11.2M⊙
Rapid core rotation model

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

Time form gravitational collapse[s]

- Time domain astronomy with multi-messanger
- Understand the mechanism from concurrent analysis
  - Inner core information by GW and Neutrino

Multi-messenger astronomy



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- Understand the mechanism from concurrent analysis
  - Inner core information by GW and Neutrino

Core rotation from GW

- Hayama et.al. 2008, E.Abdikamalov et. al. Phys.Rev.D90,044001
- Extraction core rotation condition by preparing many template (~100)

Rotation low :

$$\Omega(\varpi) = \Omega_c \left[1 + \left(\frac{\varpi}{A} \right)^2 \right]$$

where

Ω_c : the initial central angular velocity [rad/s]

ϖ : cylindrical radius[km]

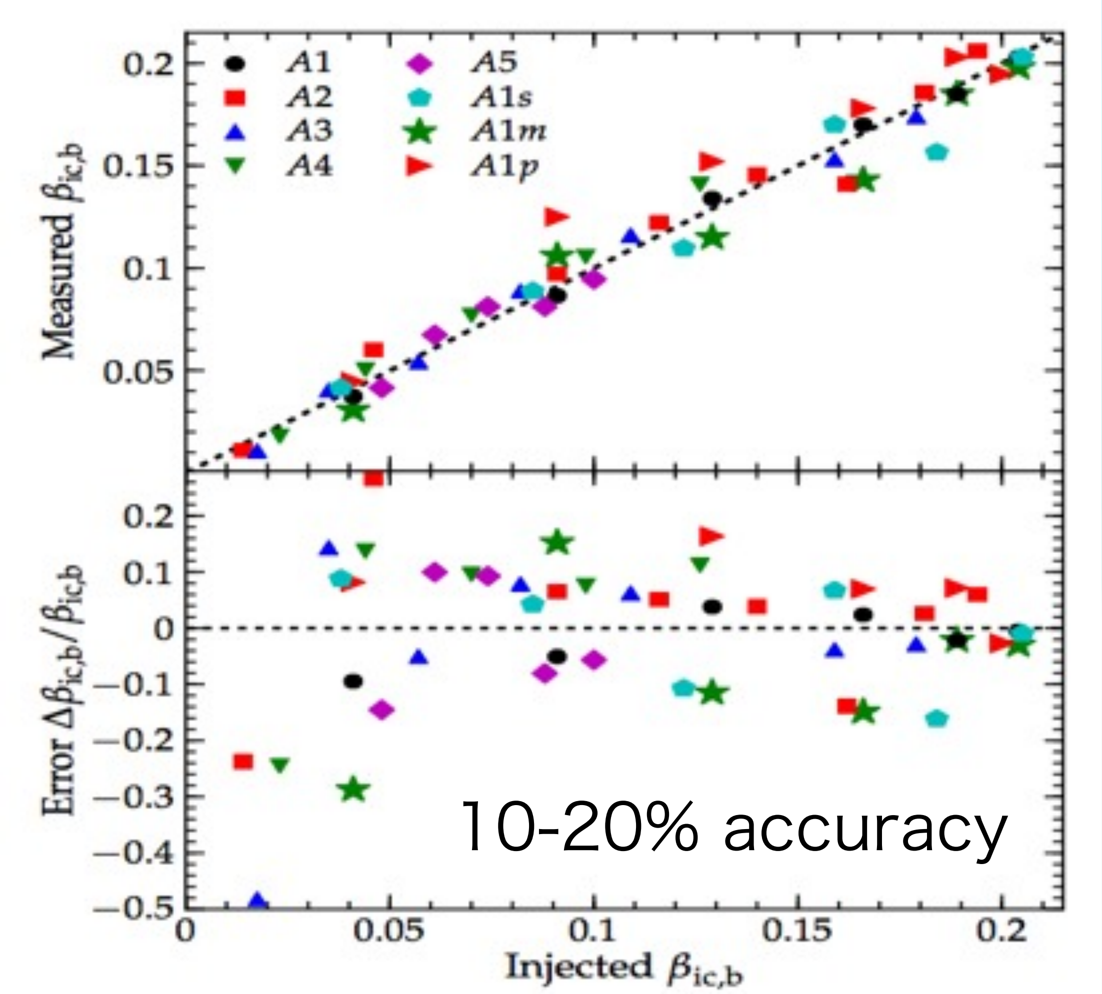
A : Parameter, control the degree of differential rotation[km]

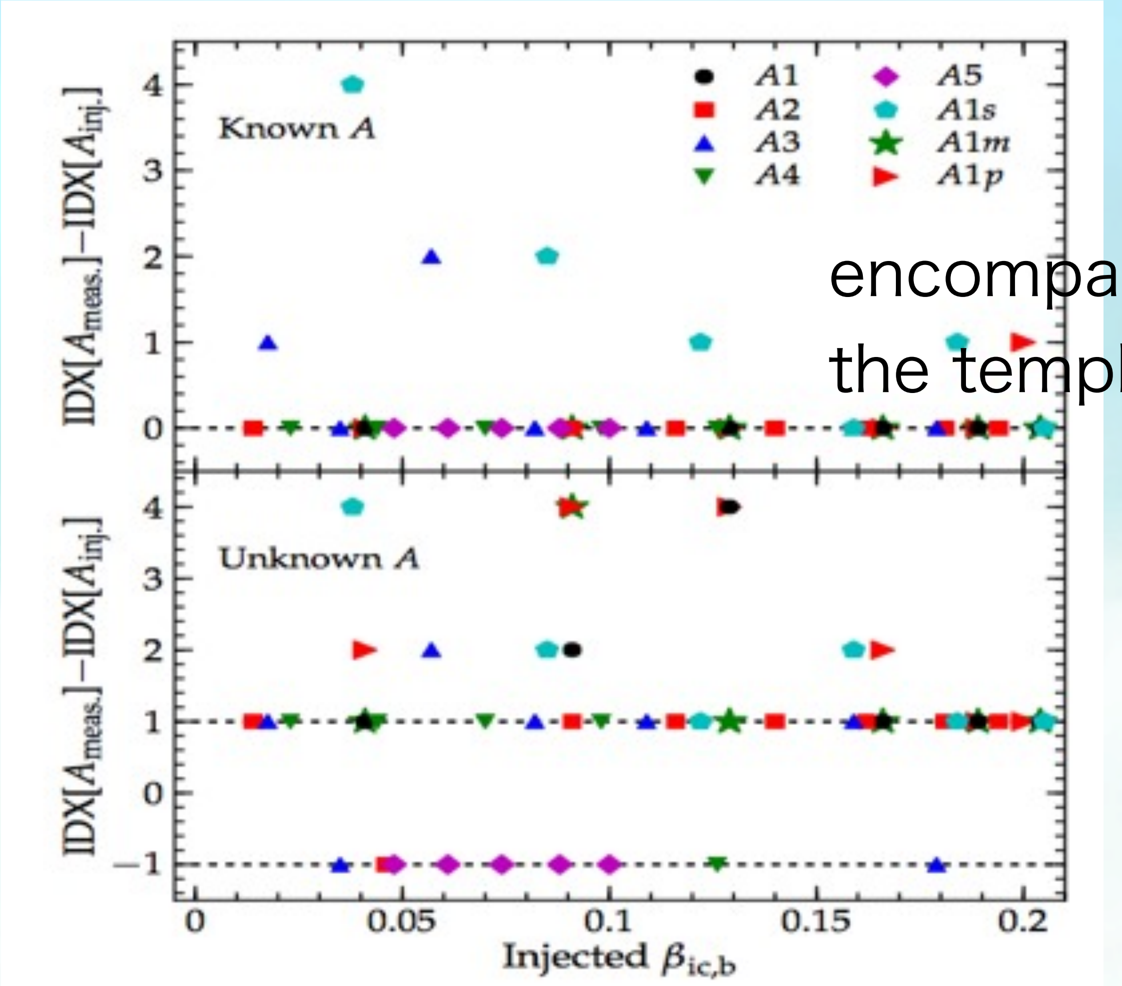
- Search the best-fitting template with given SNR equation

$$< d, x^j >= 2 \int_{-\infty}^{\infty} df \frac{\tilde{d}(f) \tilde{x}^j(f)^* e^{i2\pi f t_0}}{S_h(f)}$$

$$\mathrm{SNR} = \frac{< d, x^j >}{< x^j, x^j >}$$

$\beta_{ic,b}$: ratio of the rotational kinetic energy to the gravitational binding energy



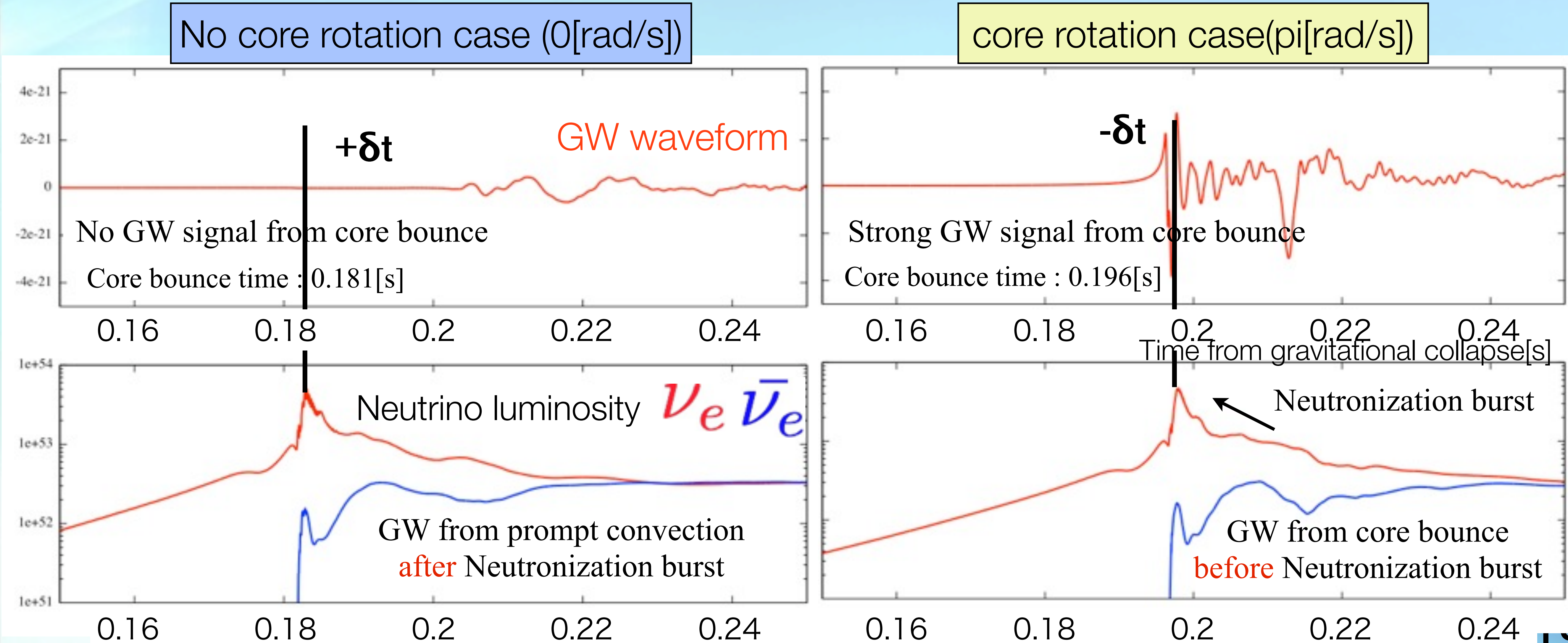


Probing core rotation -motivation-

- 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



Probing core rotation -detectors-

Robust analysis
- Simple search, single detector

Study with KAGRA and EGADS/SK+Gd
- Location -in the same mountain
- Neutron tagging

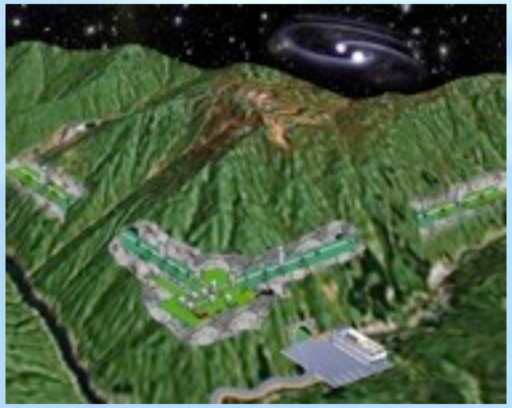
GW analysis
- Excess power filter
- + Short Time Fourier Transform
- Generate signal s(t)=h(t)+n(t)
- Search window which give SNR>8

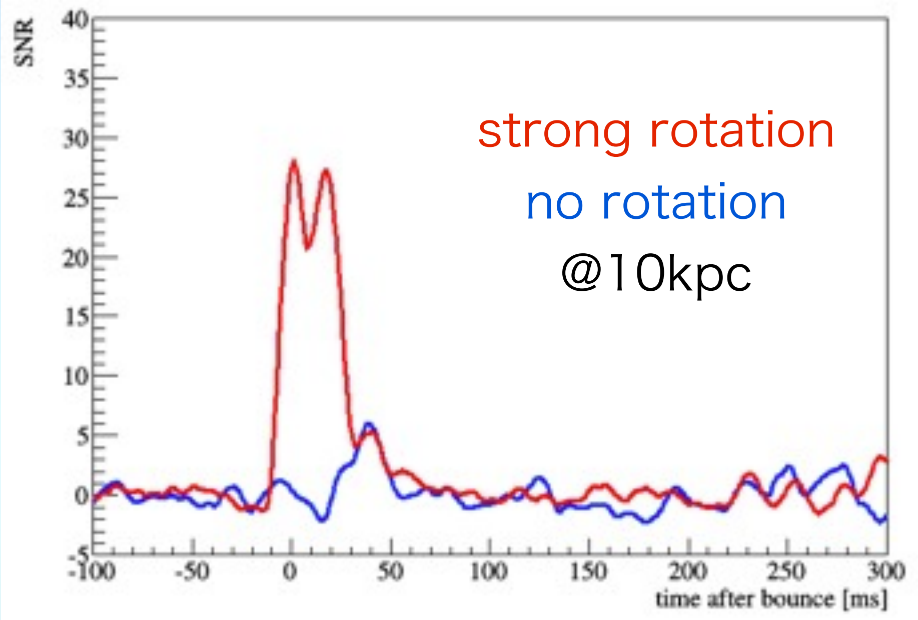
$$\rho = \sqrt{\frac{\int s_w^*(f) \cdot s_w(f) df}{\int < n_w^*(f) \cdot n_w(f) > df}} \qquad \rho_0 = \sqrt{\frac{\int n_w^*(f) \cdot n_w(f) df}{\int < n_w^*(f) \cdot n_w(f) > df}}$$

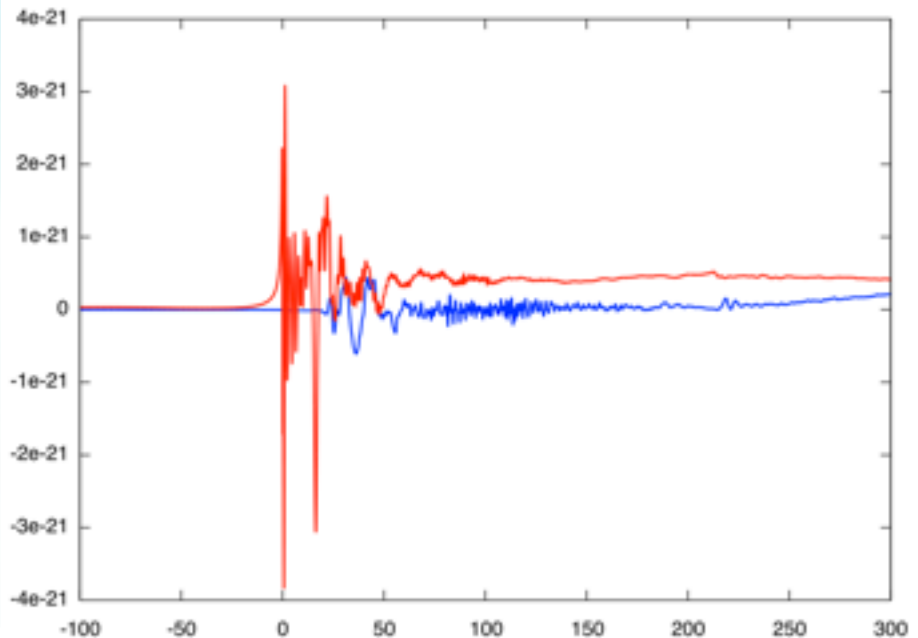
- Estimation of Signal to Noise Ratio

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

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







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Simple search, single detector

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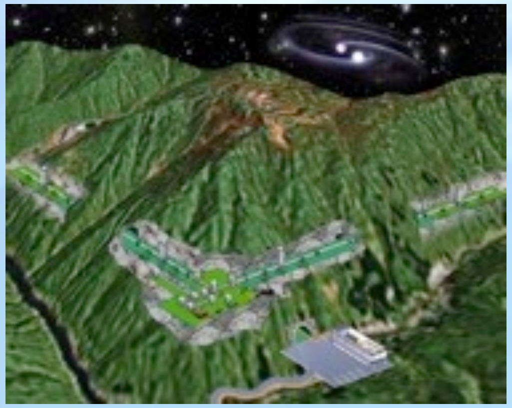
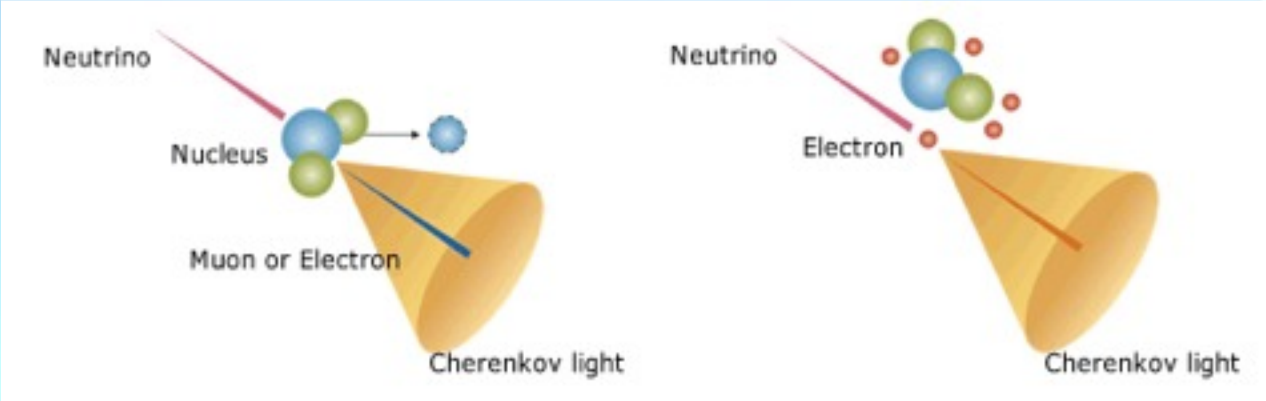
Neutron tagging



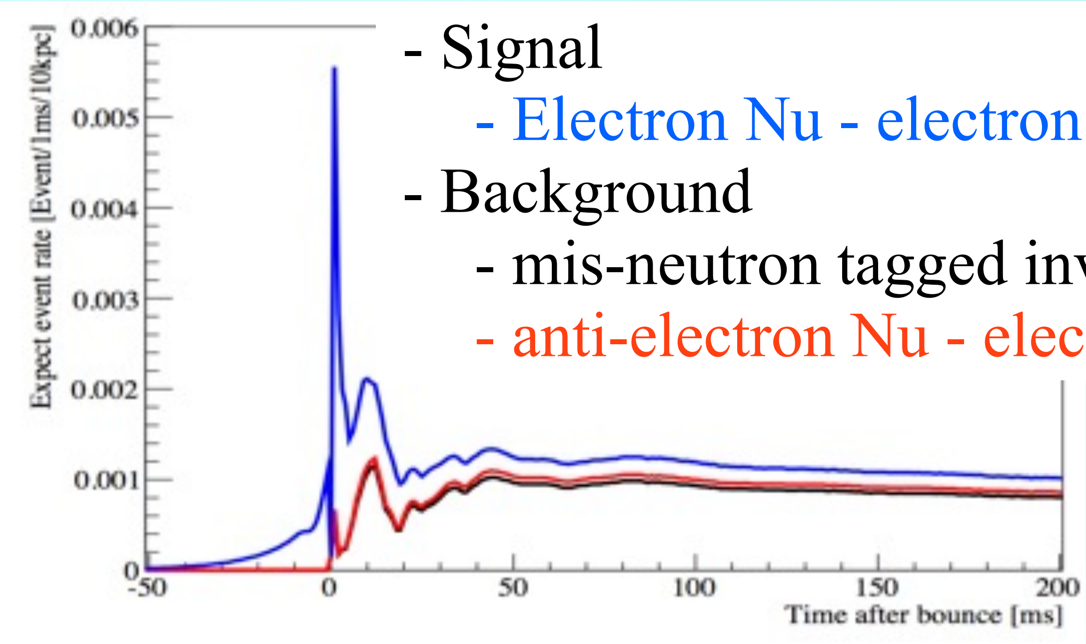


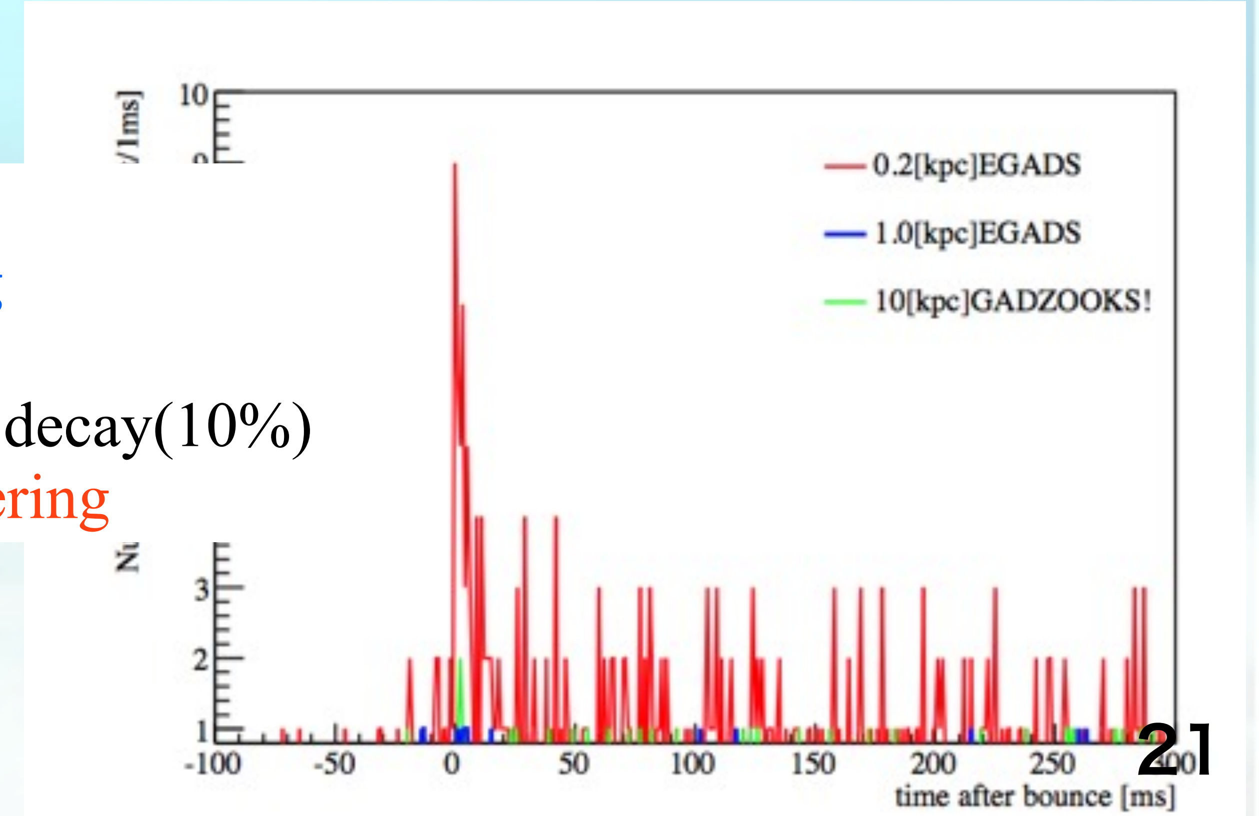
Neutrino analysis

generate signal with Poisson statistics

search window which give max number of observation electron neutrino

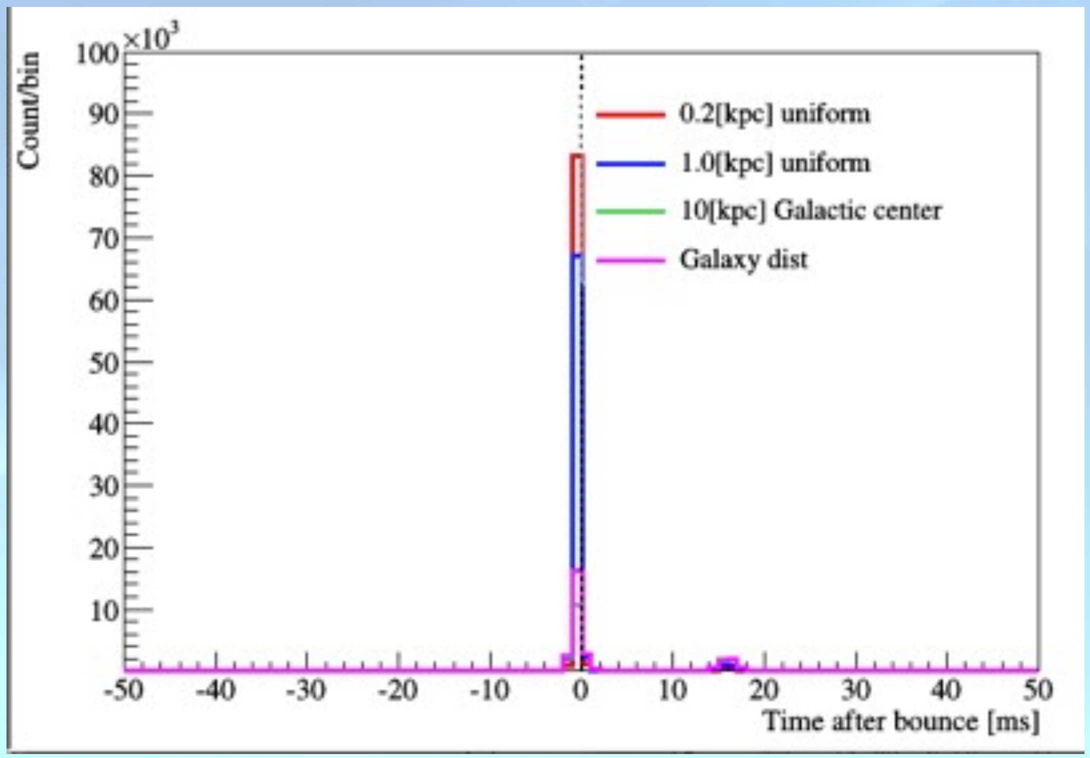
- Signal
  - Electron Nu - electron scattering
- Background
  - mis-neutron tagged inverse beta decay(10%)
  - anti-electron Nu - electron scattering

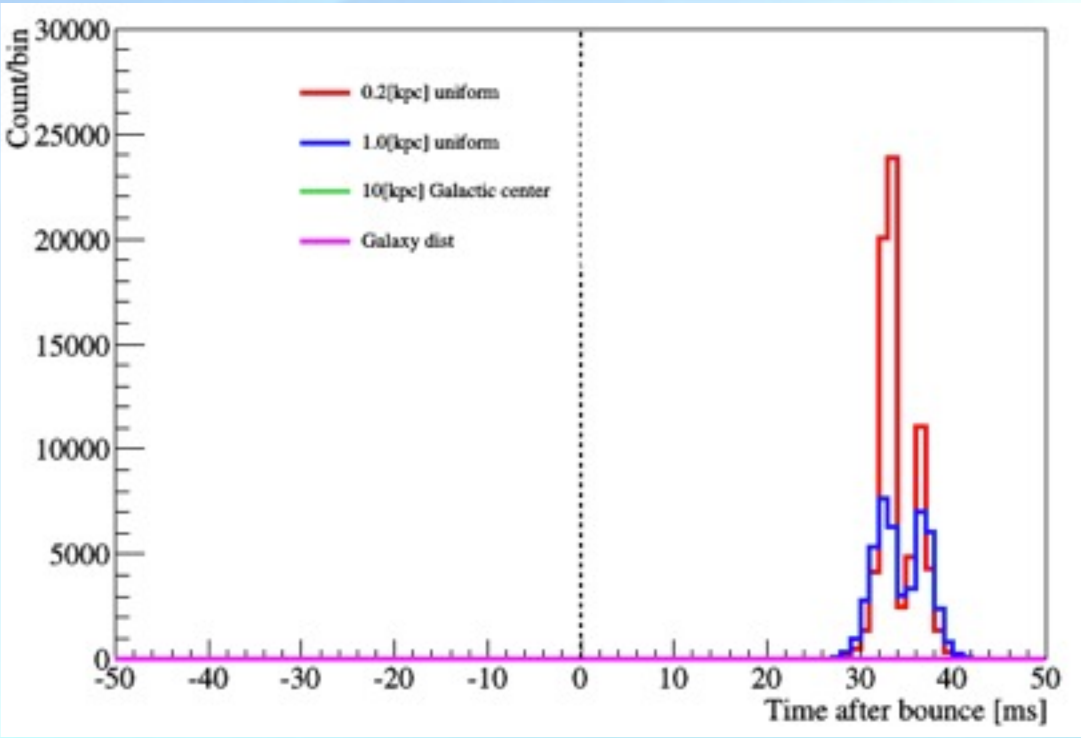




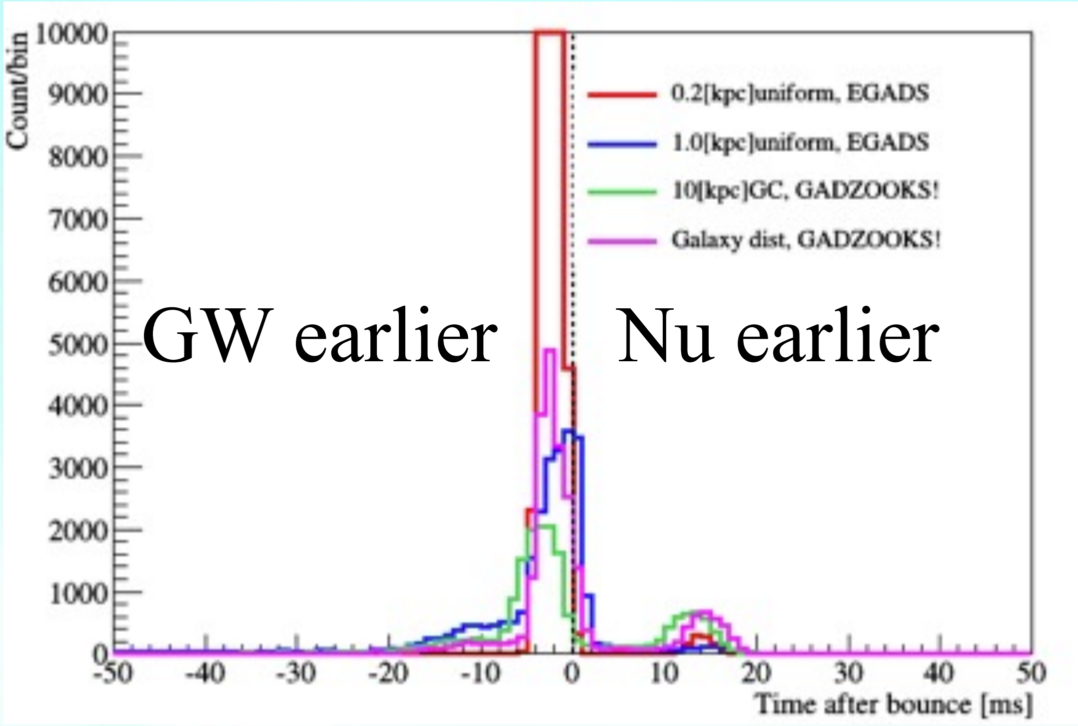
Probing core rotation -time epoch-

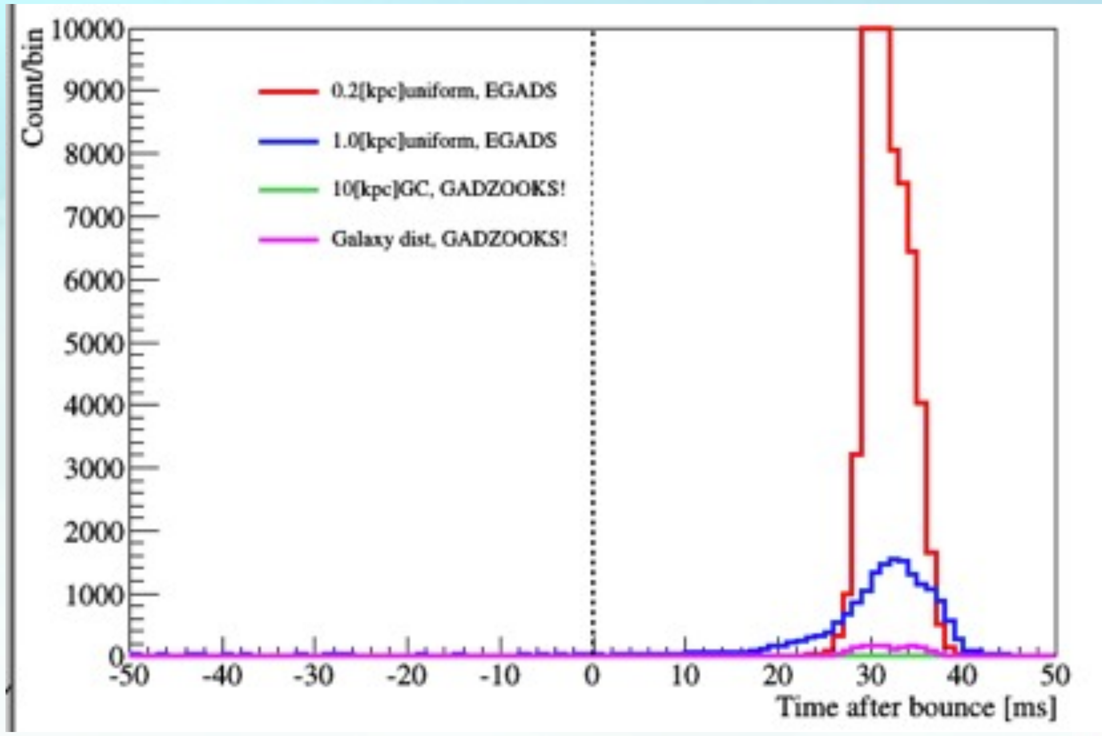
GW epoch : 1.0 pi rad/s 0.0 pi rad/s





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

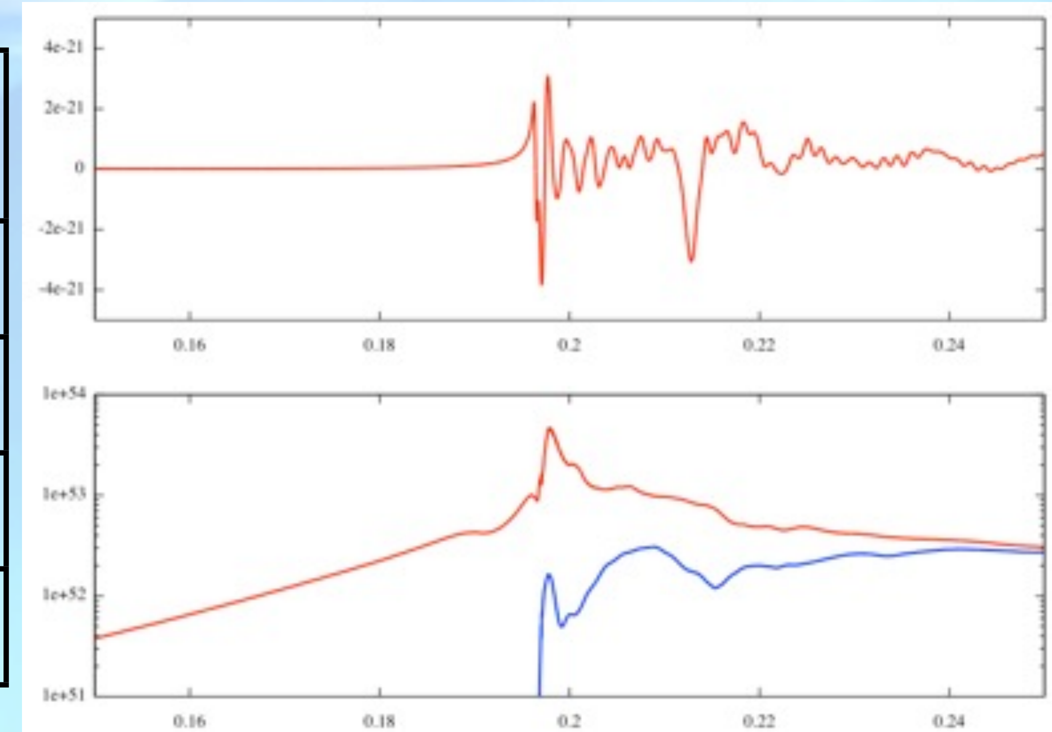




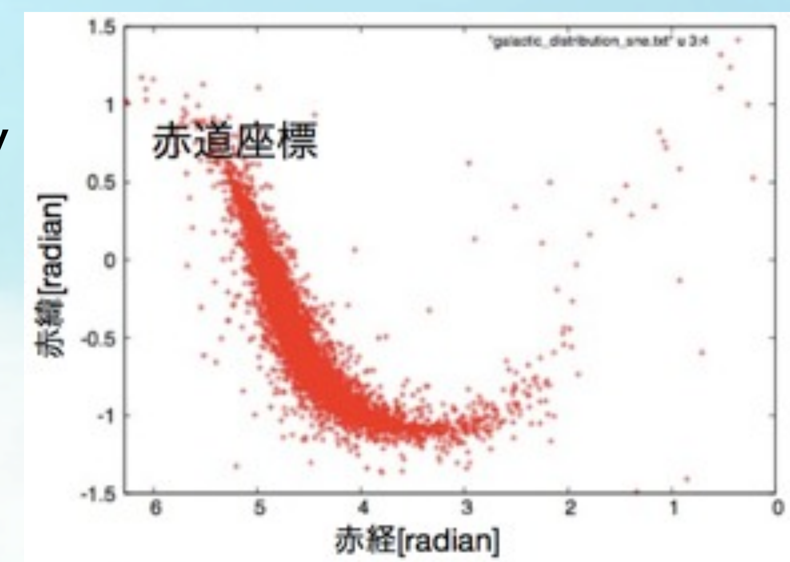
Probing core rotation -result1-

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

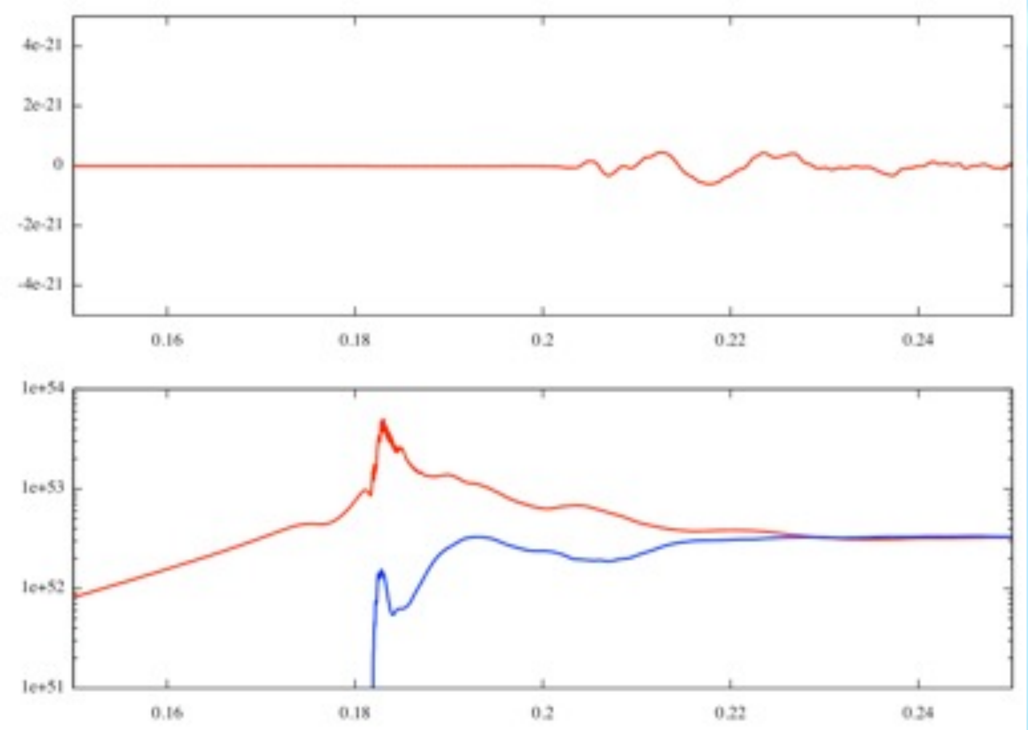
$$dN \propto R\, dR\, dz\, e^{-\frac{R^2}{2R_0^2}} e^{-\frac{|z|}{h}}$$

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

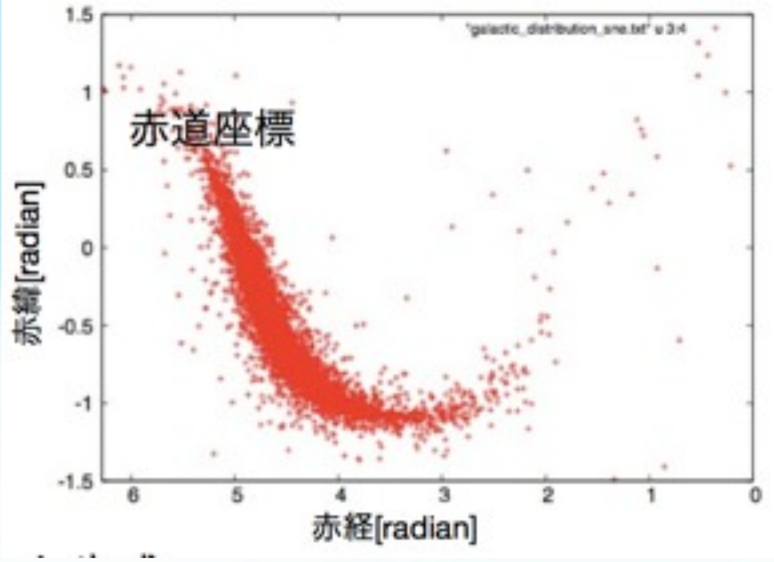
Probing core rotation -result2-

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

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

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

Summary

- KAGRA status
  - iKAGRA observation will start at the end of this year
  - Installation work is going on
- Analysis strategy
  - Event reconstruction : Expand to TF plane and 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)