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"Search for gravitational wave events with KAGRA and the world-wide network of laser interferometers in the advanced detector era"

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Search for gravitational wave events with KAGRA and the world-wide network of laser interferometers in the advanced era

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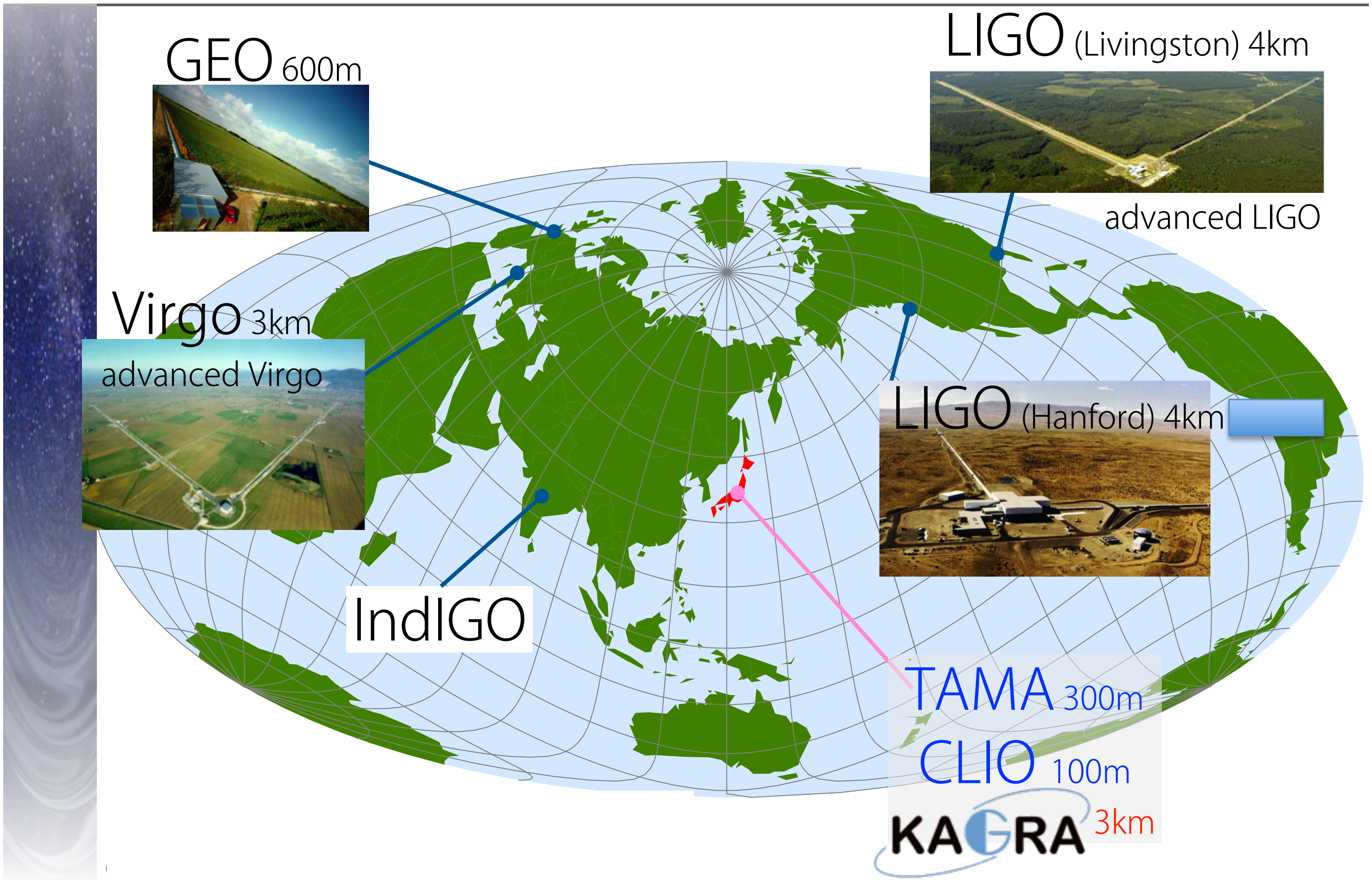

GEO 600m
LIGO (Livingston) 4km
advanced LIGO
Virgo 3km
advanced Virgo
LIGO (Hanford) 4km
IndIGO
TAMA 300m
CLIO 100m
KAGRA 3km

Generation of gravitational waves

In order to produce strong gravitational waves, we need

•Time variation of mass distribution

$$\frac{v}{c} \sim 1 \quad \text{and/or} \quad \left(\frac{v^2}{c^2} \sim\right) \frac{GM}{rc^2} \sim 1$$

high speed **strong gravity field**

•Non-spherically symmetric variation（time variation of quadrupole moment）

These factors restrict the source of strong gravitational waves

Sources of LIGO, Virgo, KAGRA

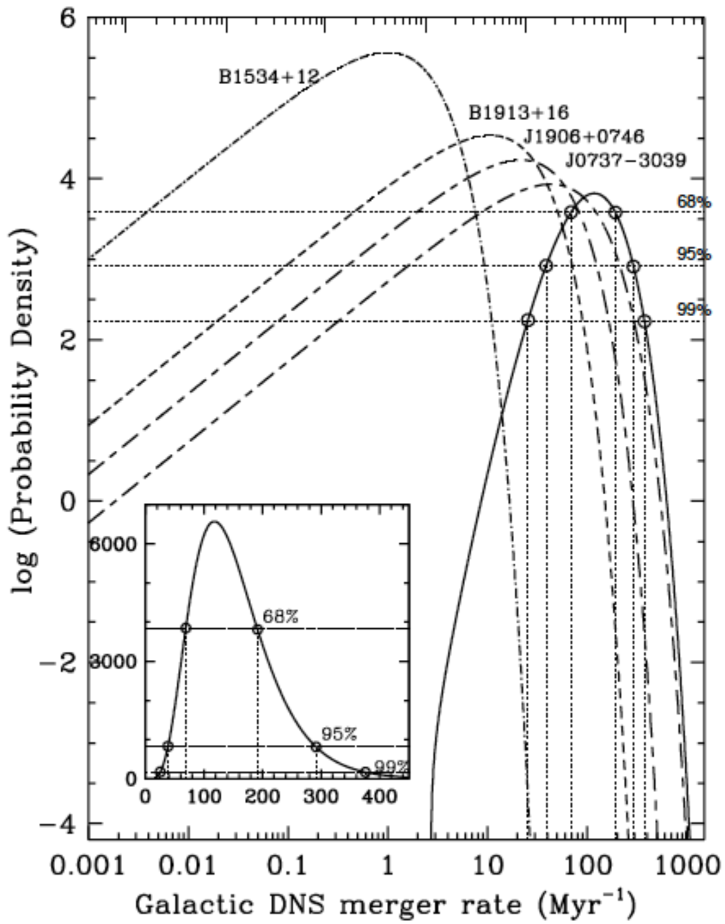
- Compact binary coalescence (CBC)
  neutron star (NS) and/or black hole(BH)
  inspiral, merger, ringdown

- Burst waves
  stellar core collapse
  pulsar glitches

- Continuous waves
  rotating neutron stars

- Stochastic background
  early universe origin, astrophysical origin

NS-NS merger rate



(Kim ('08), Lorimer ('08))

Galactic merger rate $118^{+174}_{-79}\,\mathrm{Myr}^{-1}$

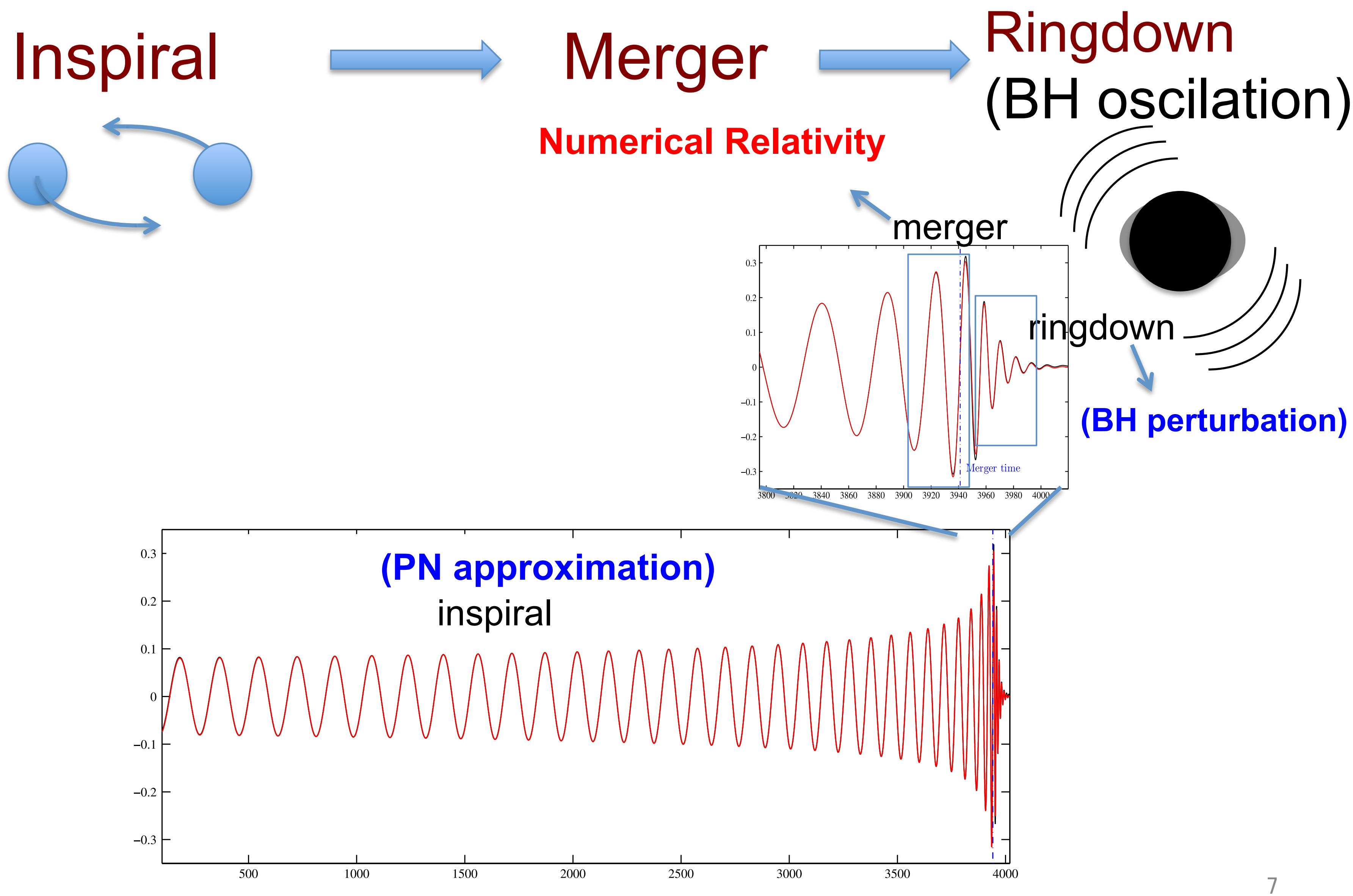
A current official LCGT design (VRSE-D) gives horizon distance (@S/N=8) = 280Mpc (z=0.065)

Event rate for LCGT : $9.8^{+14}_{-6.6}\,\mathrm{yr}^{-1}$

However, systematic errors which are not included in this evaluation may be large.

See also: Abadie et al. CQG27, 173001(2010)

Physics in Compact Binary Coalescence



Basic value for the inspiral waveform

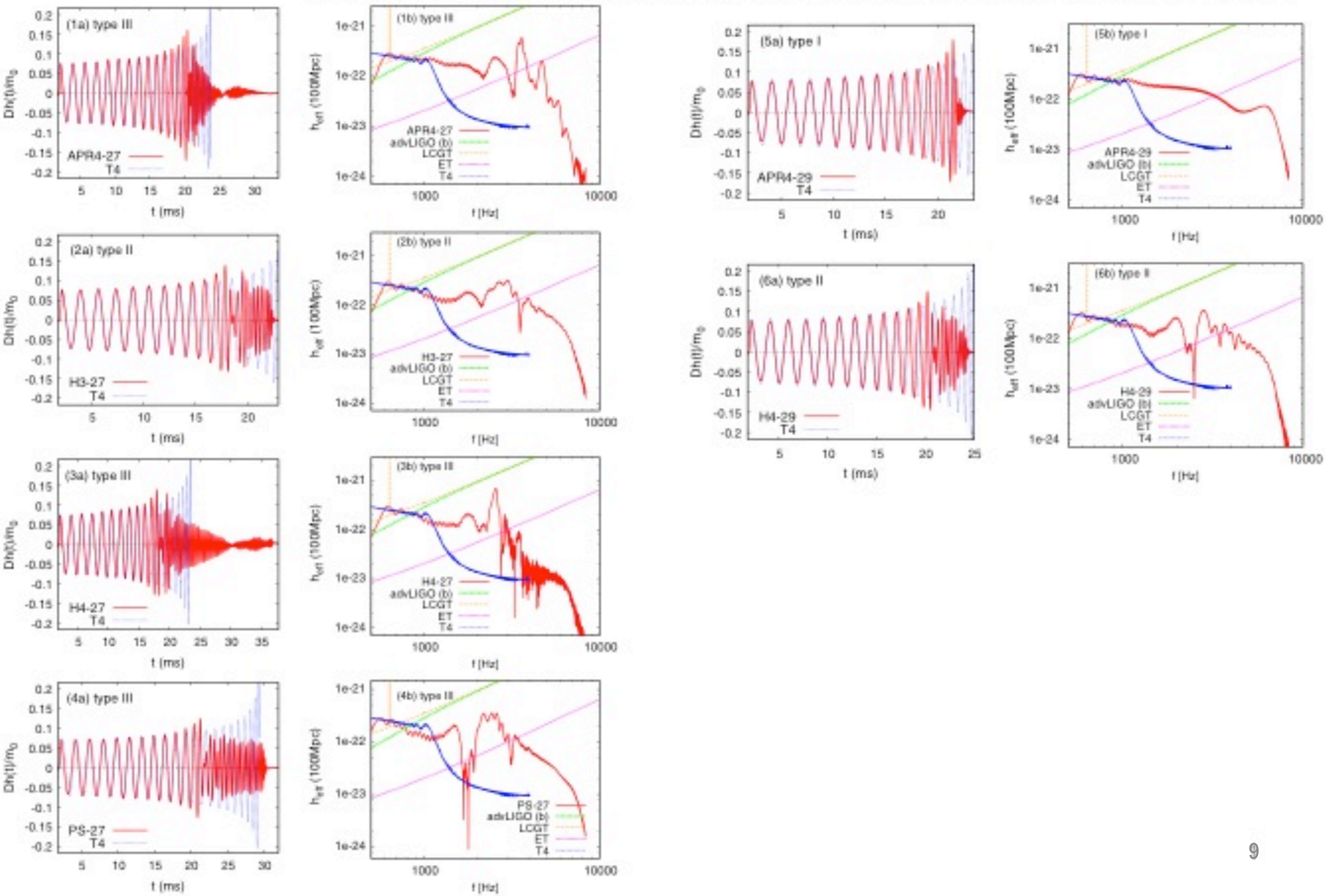
(m_1,m_2) [Msolar]	**(1.4, 1.4)**	(10, 1.4)	(10, 10)	(100, 1.4)
frequency@ISCO[Hz]	1570 Hz	386 Hz	220 Hz	43 Hz
duration(10Hz-ISCO)[sec]	1002 sec	224 sec	38 sec	46 sec
cycle(10Hz-ISCO)	16038	3585	605	743
orb. radius@10Hz[Mt]	174 Mt	68 Mt	47 Mt	16 Mt

$Mt=m_1+m_2$

ISCO: Inner most stable circular orbit.

NS-NS coalescence & HMNS

Hotokezaka, Kyutoku, Okawa, Shibata, Kiuchi, PRD83, 124008 (2011)



NS-NS for KAGRA

NS-NS binary coalescence

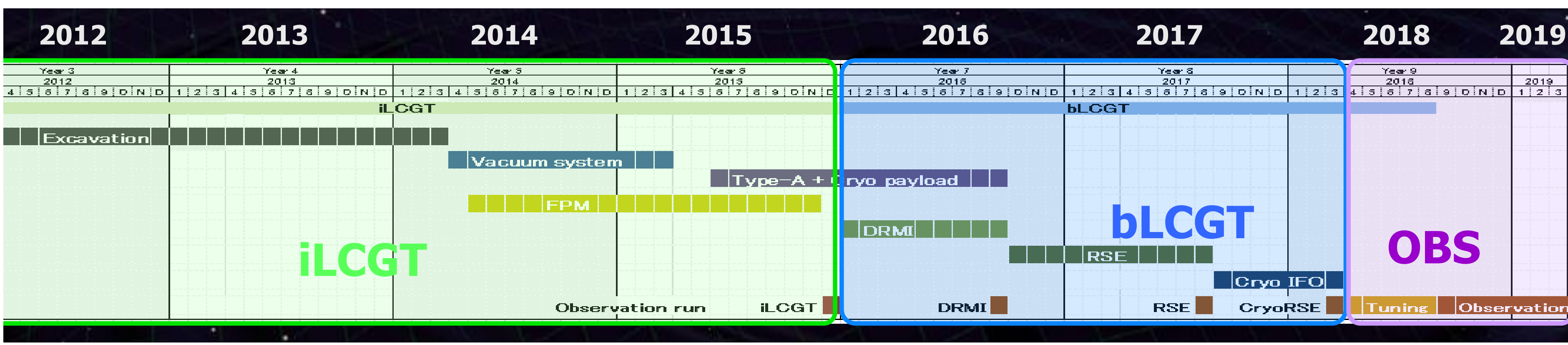
Horizon distance (S/N=8, optimal direction, face-on)

iKAGRA 29Mpc → bKAGRA 280Mpc

(In LIGO's definition, 18Mpc) (173Mpc)

(LIGO's definition)=(KAGRA's definition)x($\sqrt{2}$)x(0.44)

(Assuming phase is measured. Averaged over the sky and inclination angle.)



Event rate for bKAGRA : $9.8^{+14}_{-6.6}\,\mathrm{yr}^{-1}$

(based on Kim ('08), Lorimer ('08))

Supernova (Gravitational Collapse)

Review articles: Ott, CQG, 26, 063001 (2009), Fryer and New, LRR, 14, 1 (2011)

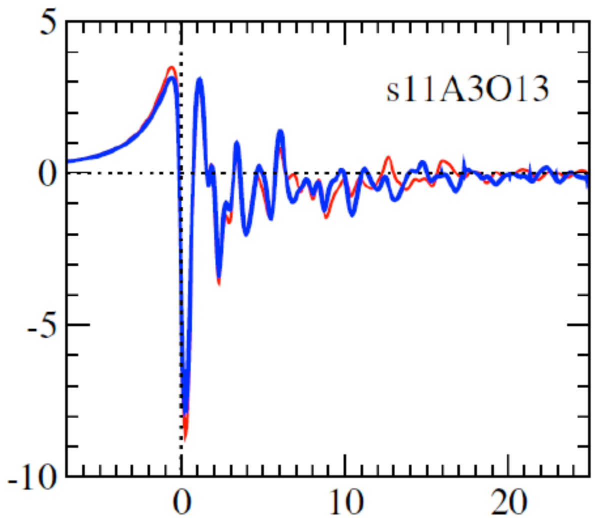
Various possible gravitational wave emission mechanism.

- Core collapse and bounce
- Rotational non-axisymmetric instabilities of proto-neutron star
- Post-bounce convection
- Non-radial pulsations of proto-neutron star

Related to the explosion mechanism

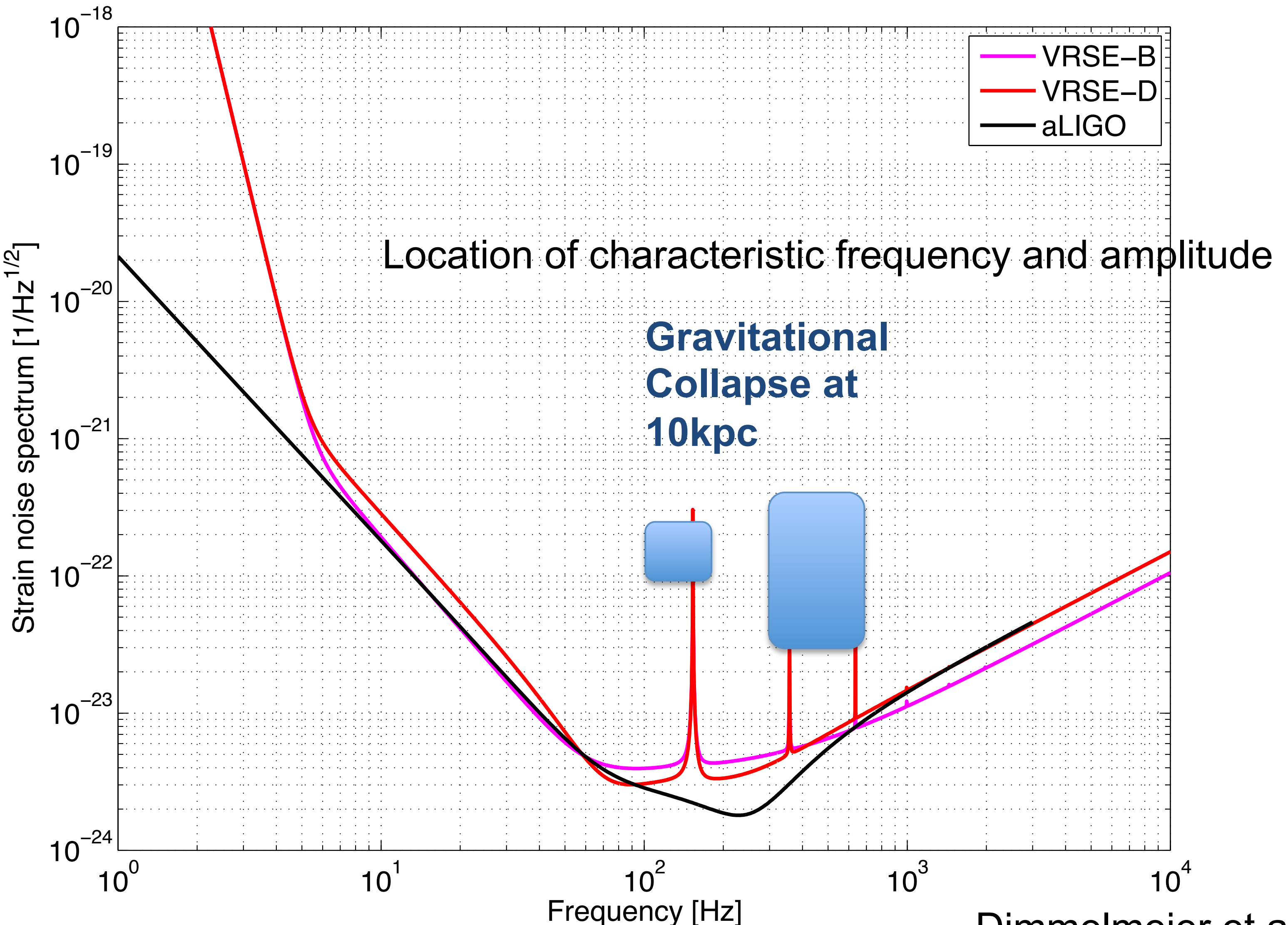
- Anisotropic neutrino emission

etc.



Collapse and bounce wave form from Dimmelmeier et al. 2008 [PRD 78, 064056]

Gravitational Collapse

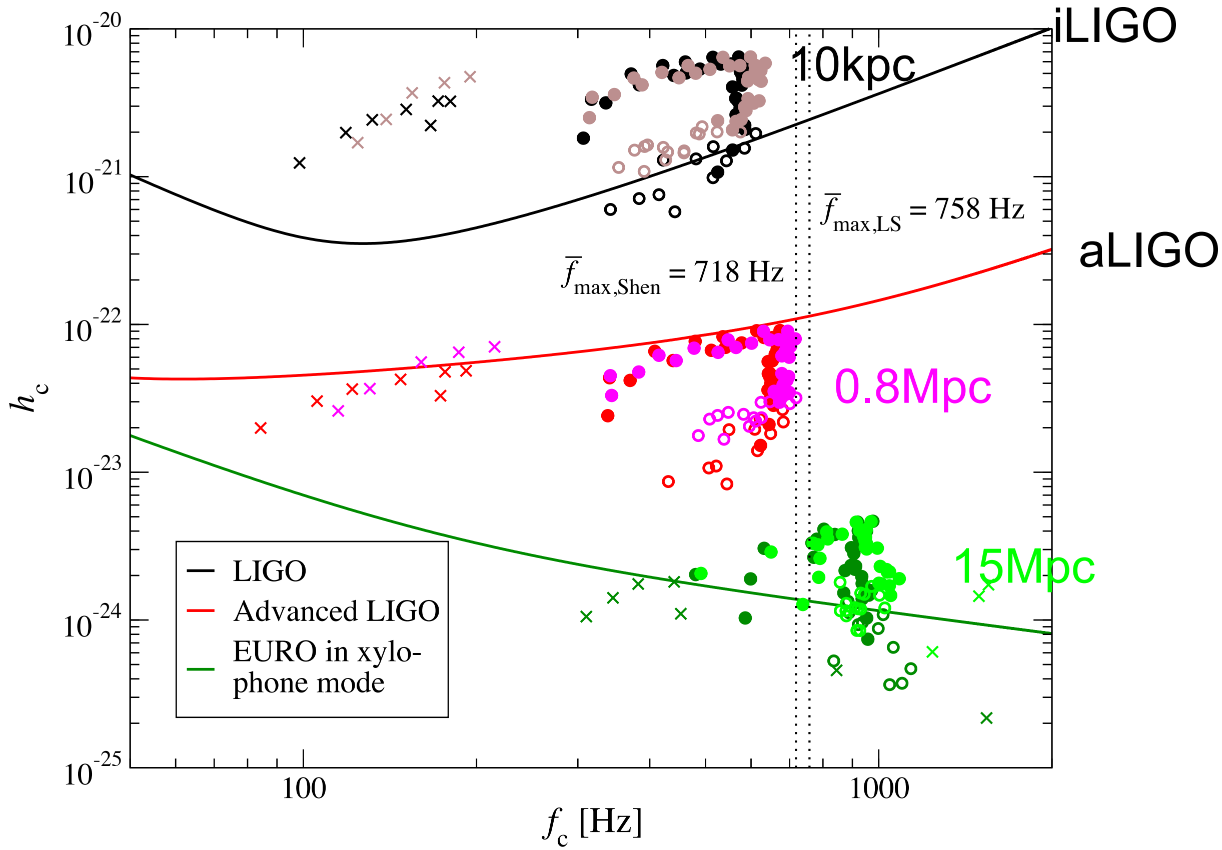


Dimmelmeier et al. ('08)
PRD 78, 064056

～several 100kpc can be seen by KAGRA

GW from core collapse

Dimmelmeier et al. PRD 78, 064056 ('08)

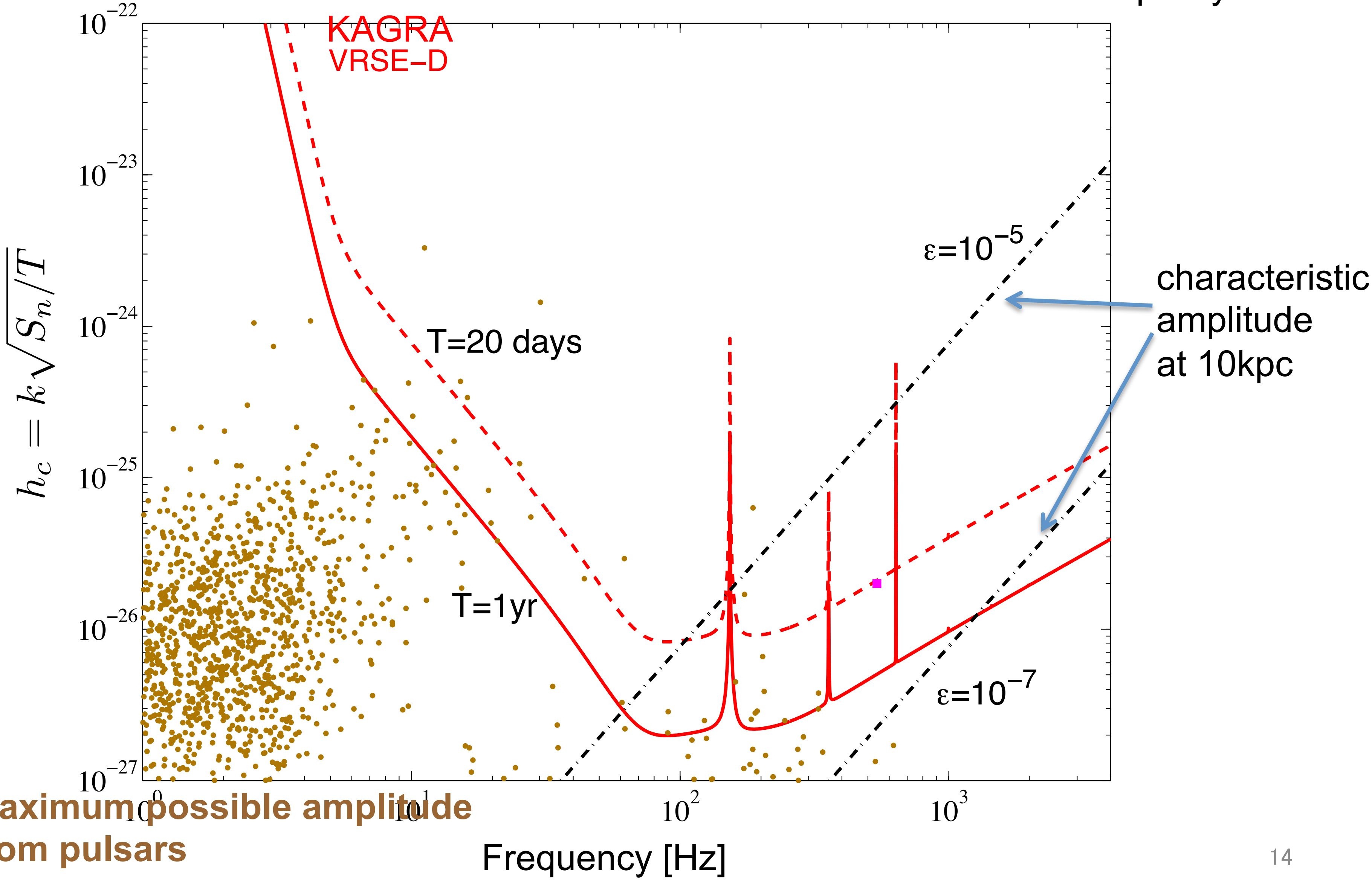


$$f_c = \left(\int_0^\infty \frac{\langle \hat{h}^2 \rangle}{S_h} f\, df\right) \left(\int_0^\infty \frac{\langle \hat{h}^2 \rangle}{S_h} df\right)^{-1}$$

$$h_c = \left(3 \int_0^\infty \frac{S_{h\,c}}{S_h} \langle \hat{h}^2 \rangle f\, df\right)^{1/2},$$

Continuous wave (rotating NS)

ε: ellipticity



Maximum possible amplitude from pulsars

Data analysis method

Gravitational wave data analysis methods are categorized in various ways.

Characteristic of the sources

- ☐ Well-known waveform (expressed by a small number of parameters)
  CBC(inspiral, ringdown), Continuous wave (rotation neutron stars), …
- ☐ Unknown waveform (need complicated numerical simulations)
  Burst（Core collapse supernovae, merger phase of CBC, …)
- ☐ Random waveform (characterized only statistically)
  Stochastic background

Other factors:

- Short duration time（a few 10 minutes） rotation of the earth can be ignored
  CBC, Burst
- Long duration time（more than a few 10 minutes) rotation of the earth affects
  Continuous waves

How to detect the signal

- Know waveform
  "Matched filter"
  Cross-correlate data and templates with weight of inverse of noise power spectrum density
  Look for the parameter which realize the maximum of cross correlation.

- Unknown waveform
  "Excess power"
  Judge the presence of signal from the power excess of data.

How to detect the signal

- **Know waveform**

Multiple detectors' case

"Matched filter"

Cross-correlate data and templates with weight of inverse of noise power spectrum density

Look for the parameter which realize the maximum of cross correlation.

↓ multiple detectors' case

"Coherent matched filter" (Maximum likelihood method)

- **Unknown waveform**

"Excess power"

Judge the presence of signal from the power excess of data.

↓ multiple detectors' case

e.g., "Coherent WaveBurst" of LSC.

"Coherent excess power" (Maximum likelihood method)

- **Random waveform**

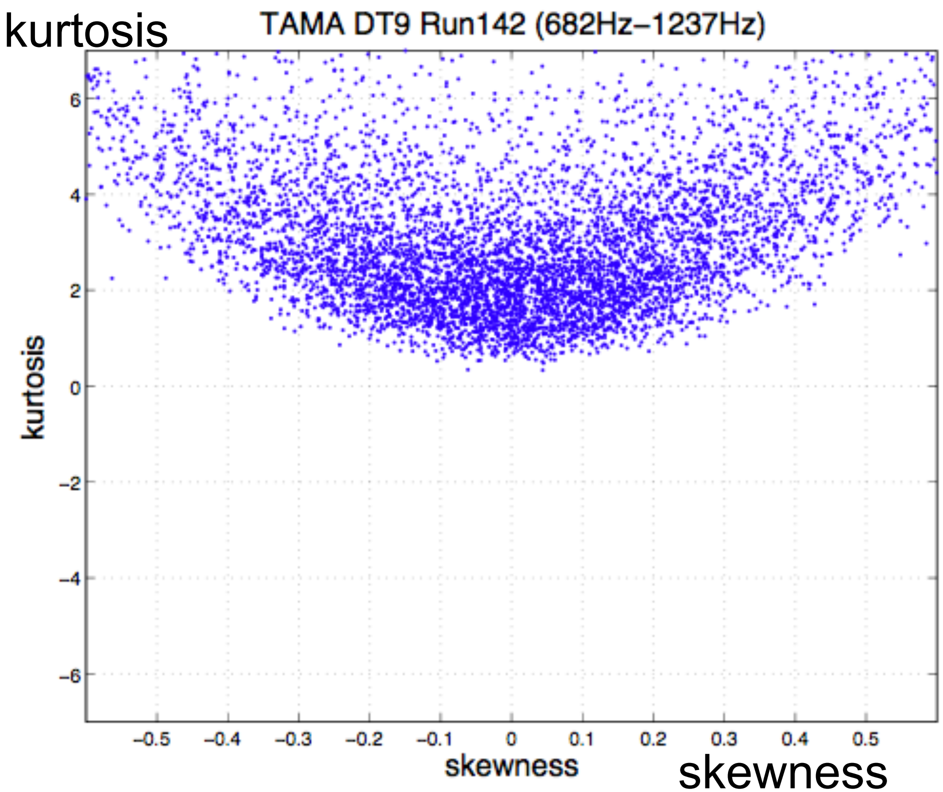
"Cross correlation"

Cross correlation of data from different detectors.

Noise veto

In any laser interferometer detectors, the presence of non-stationary, non-Gaussian noise can not be ignored (at least so far, and probably in the future too).

In order to veto the fake events produced by such noise, noise veto scheme are introduced (case by case).



Non Gaussianity of TAMA data

Importance of network

For the gravitational wave astronomy, multiple detector network is important.

Why network?

needless to say but

- Improvement of S/N
- Improvement of reliability of detection

at the same time

- To determine the direction of the source,
- To determine two polarization mode of GW,
- To cover whole sky,

we need global network of (3 or more) detectors.

Accuracy of direction

NS-NS coalescence @180Mpc

L:LIGO-Livingston
H:LIGO-Hanford
V: Virgo
K: KAGRA
I:LIGO-India

median of $\delta\Omega$ [Deg^2]	LHV	LHVK	LHVI
(1.4, 1.4) Msolar	30.25	9.5	9.0

(95%CI)

e.g., J.Veitch et al., PRD85, 104045 (2012)
(Fisher matrix & simulation)

direction, inclination, polarization angle are given randomly

Source localization accuracy is 10 - 30 Deg^2 (@180Mpc, 95%CI).

see also Wen and Chen (2010)
Fairhurst (2011)

Importance of astronomical observation

•Triggered search

If we know the time and direction from other astronomical observation (EM, neutrino), it is a great benefit to the detection of the gravitational wave signal, since we can reduce the threshold.

(e.g., Kochanek,Piran (1993))

e.g, : GRB: Core collapse or CBC
Neutrino from Supernovae in nearby galaxies
Wide field optical/IR telescope monitoring SNe and GRB

- In fact, in the LIGO-Virgo analysis of 2009-2010 data,

the triggered search using 154 GRBs information (time and direction), the threshold becomes 2 times lower than that which does not use such information.

This means 2 times longer distance of detection range.

(arXiv:1205.2216)

Importance of astronomical observation

- Follow up observation by astronomical telescopes

This is more challenging.
First, we detect GW signal.
Next, with the informaiton of time and direction, astronomical observation are done.

- This useful for the improvement of the significance of detection, and for the detailed investigation of the physical process of the source.

- Since gravitational wave detectors are extremely wide fieldtelescope, this approach should also be a standard tool as a multi-messenger astronomy.

Low latency

For the follow-up search by the EM observatories,
low latency analysis is important.

For inspiral analysis, if we have 1Tflops computing power,
we can finish the analysis within 10 minutes (=length of template).

But 10 minutes are not very short if we consider, e.g., short gamma ray burst (the earlier, the better!).

In such case, we can reduce the mass range for the search.

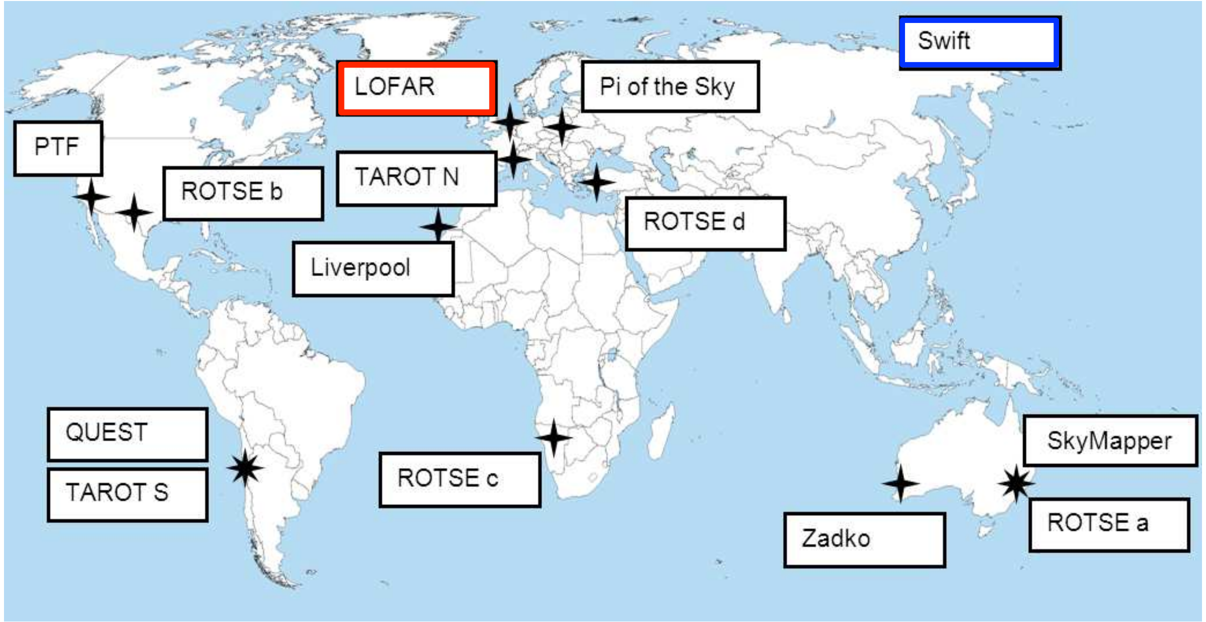
If mass range between 1-2M_{solar}, the number of template is around 5000.
Then, if computing power is 1Tflops,
the computation time is less than1 second.
This is only for matched filtering computation.
Data transfer, calibration etc. must be tuned for this special purpose.

(See Kanda-san's talk)

Example of LIGO – Virgo

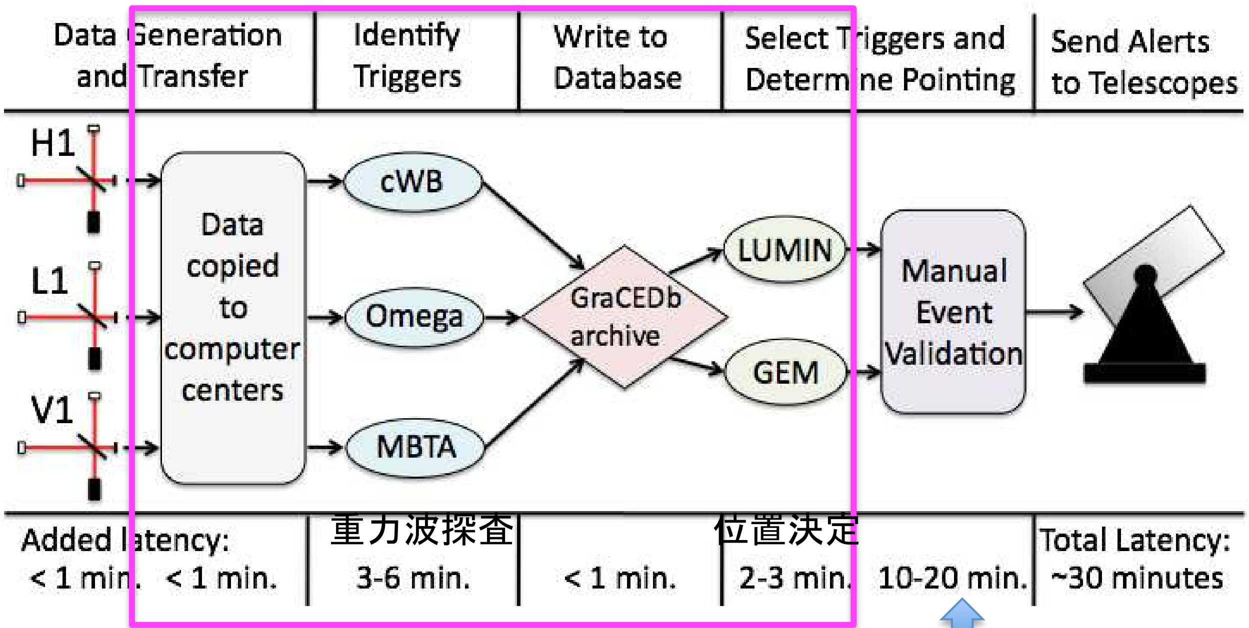
Ref. A&A 539, 124 (2012), A&A 541, 155 (2012

LIGO S6, Virgo VSR2 (12/17/2009-1/8/2010, 9/2-10/20/2010)

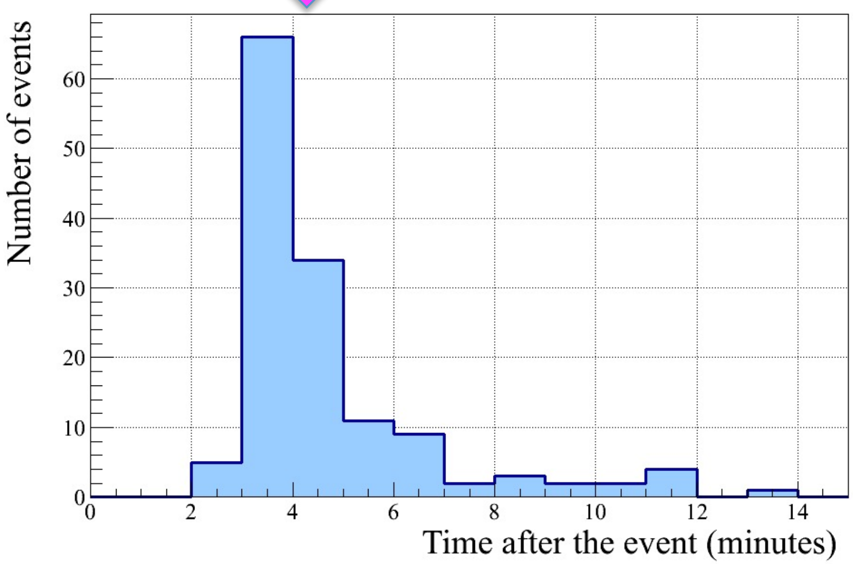


Participated observatories

Example of LIGO – Virgo



Check by human



Automated part of MBTA(CBC) analysis was finished in 4 minutes typically.

A&A 541, 155 (2012)

Example of LIGO – Virgo

- Source localization accuracy is several 10～100sq. deg. (since these are by initial LIGO,Virgo).
Bigger than FOV of astronomical instruments.

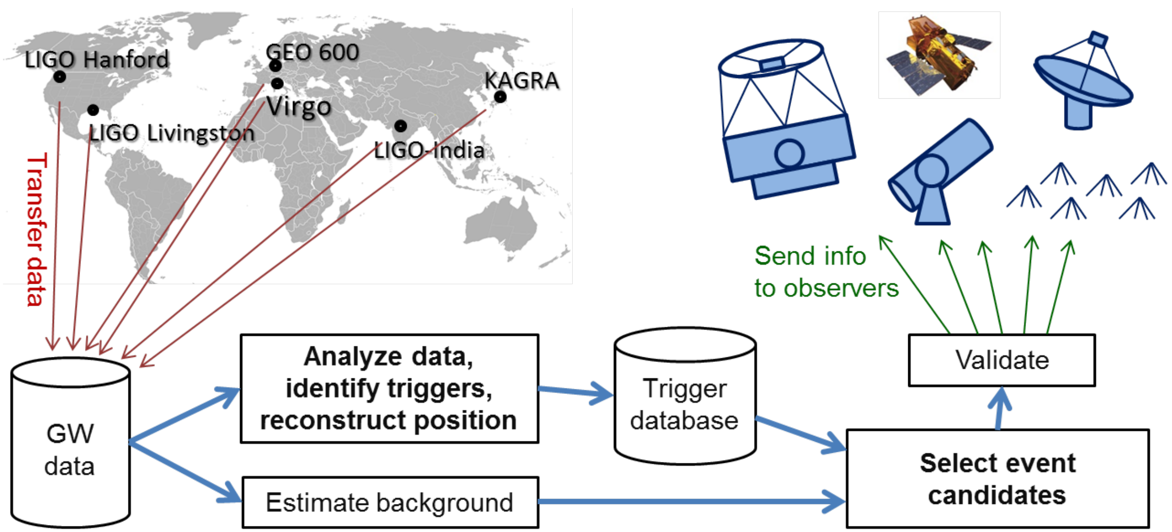
↓

- Use galactic catelog (GWGC)
and restrict the search region (up to 3-4deg^2).

GWGC: The Gravitational Wave Galaxy Catalog

Low latency search in KAGRA

- In KAGRA, we also plan to develop the high speed data analysis system and to establish the alert system to the astronomical observatories.
- Possible source direction must be restricted by using galactic catalog?
- In order to do this, we need to collaborate LIGO and Virgo.



taken from arxiv:1206.6163

GW data analysis in advanced detector era

"Real detection"

Global network analysis
Collaboration of astronomers

all of these are good for the detection

"GW astronomy and astrophysics" will begin as soon as GW is detected.

For astronomy and astrophysics, extraction of physical parameters are necessary.

Parameter estimation

- Known waveform (matched filter):
  Since theoretical waveform is done for the detection, parameter estimation is basically done at the same time of detection.

- Unknown waveform
  Theoretical waveform is not used. Reconstruction of buried signals, and extraction of physical parameters are necessary. This requires multiple detectors' data.

GW signal reconstruction・・・Gursel, Tinto (1989), Klimenko+ ('05,'08)
Supernova waveform model selection
・・・Summerscales+ (2008), Rover+ (2009), Logue+ (2012).

Time frequency analysis

For unmodeled burst signals, because of the lack of the accurate theoretical waveform, it also seems to be useful to employ some time-frequency representation of the data itself.

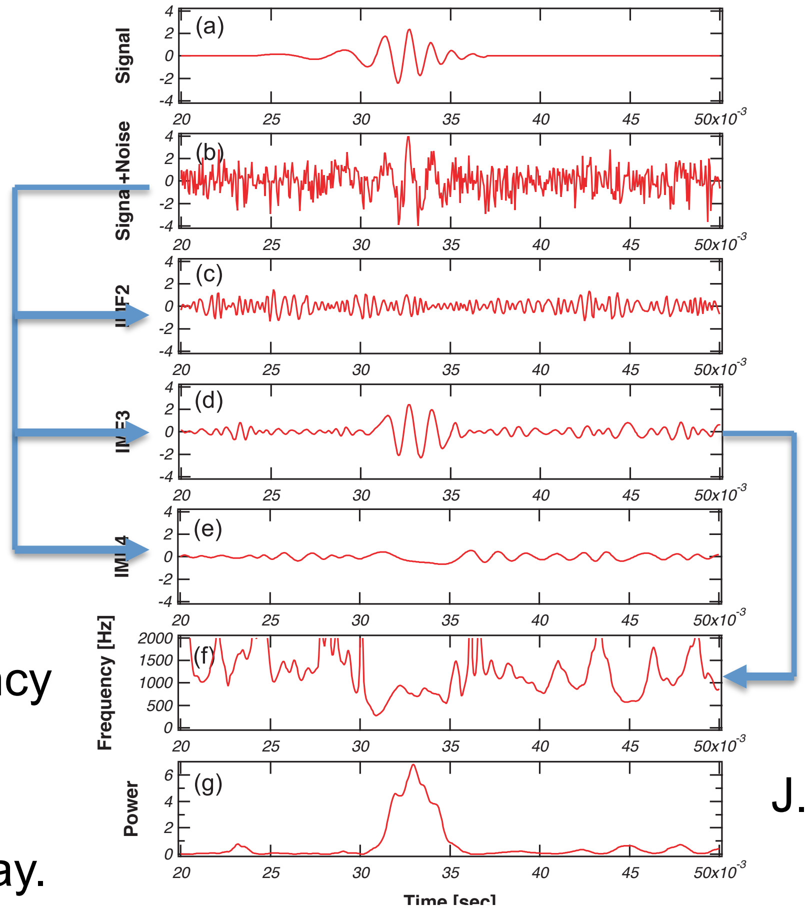
"plot of the energy distribution on the time-frequency plane"

- Spectrogram with STFT
- Wigner-Ville distribution
- Wavelet transform
- etc.

Other new methods

"Hilbert-Huang transform" (Huang+ ('98))
Empirical mode decomposition
+ instantaneous frequency by Hilbert transform

J.B.Camp et al.
H.Takahashi, K.Oohara et al.



Instantaneous frequency

J.B.Camp+ ('07)

Analysis of HMNS is now underway.

KAGRA data analysis

- We need to have our own data analysis software in order to perform data analysis smoothly.
- We just started the development of the data analysis package for KAGRA.
- This should be compatible with existing software package of LIGO and Virgo.
- At the same time, we have to develop the package better than those of LIGO and Virgo's package at, at least, some points, since we develop new one from now.

incorporate new technology,
faster computation speed,
better accuracy, …

e.g., Fast computation with GPGPU
(K.Tanaka, N.Kanda,…)

KAGRA data analysis subsystem

- Core members: H.Tagoshi, Y.Itoh, H. Takahashi,
  N.Kanda (DMG), K.Hayama(DetChar), K.Oohara

+ graduate students

Clearly, we need more man power.

There are 4 postdoc positions at Osaka U. (2) and Osaka City U. (2).
If you are interested in, please contact us.

End