GRADUATE SCHOOL OF
FACULTY OF SCIENCE
KYOTO UNIVERSITY

Impact of gravitational wave detection and its perspective

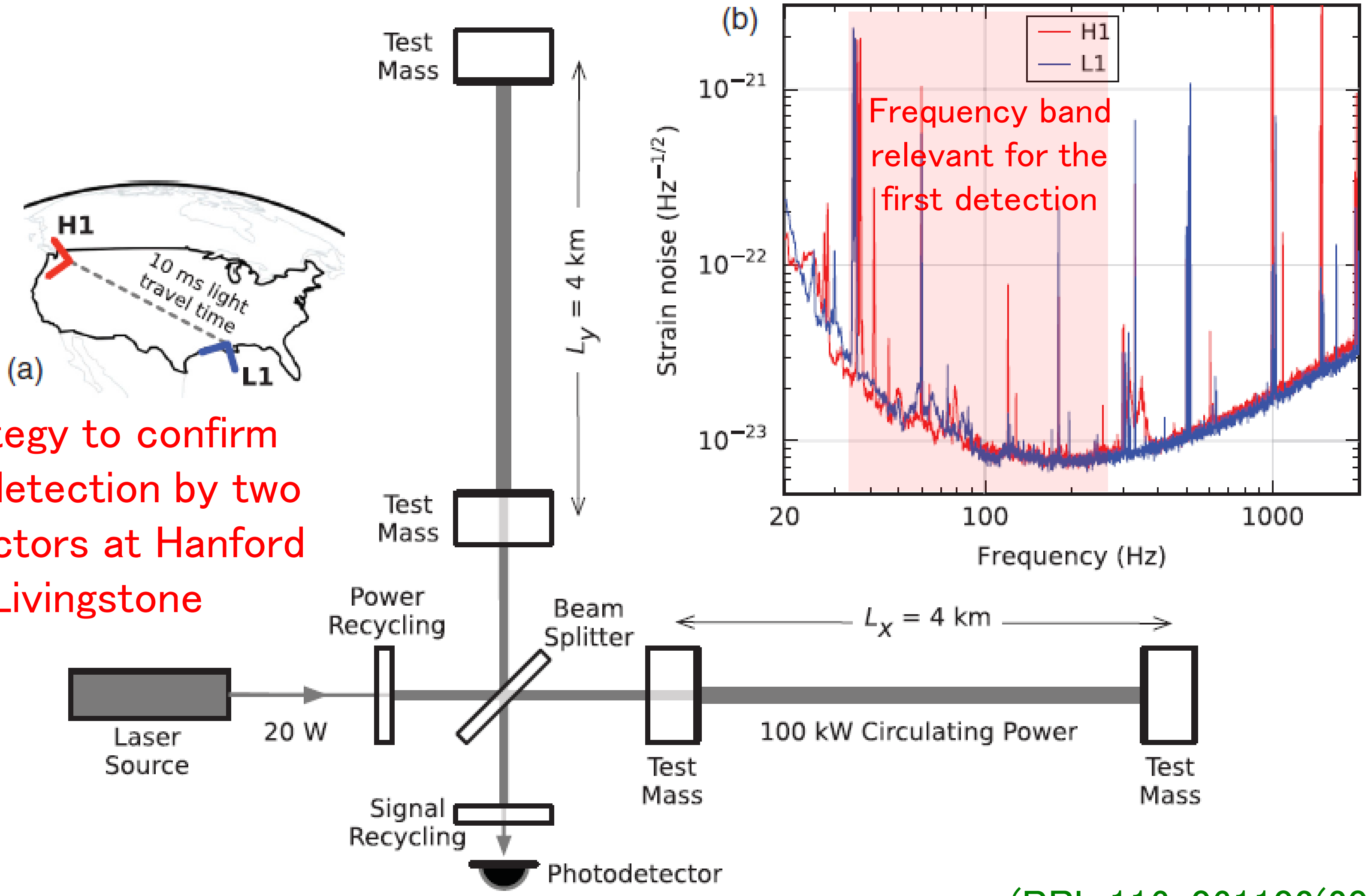
Takahiro Tanaka
(Kyoto university)

First GW detection by LIGO

- 2016 February 11th

  00:30 of Feb. 12th in Japan

  Analysing the data of the first 39days, with 16days long simultaneous observation data by 2 detectors.
- Detection of gravitational waves at 2015 Sep. 14th 09:50:45 UTC, with the amplitude 10^{-21} and S/N~24.
- Masses before merger $36^{+5}_{-4} M_{sol} + 29^{+4}_{-4} M_{sol}$
- Mass after merger $62^{+4}_{-4} M_{sol}$
- Estimated distance $410^{+160}_{-180} Mpc$ $z = 0.09^{+0.03}_{-0.04}$
- Named GW150914

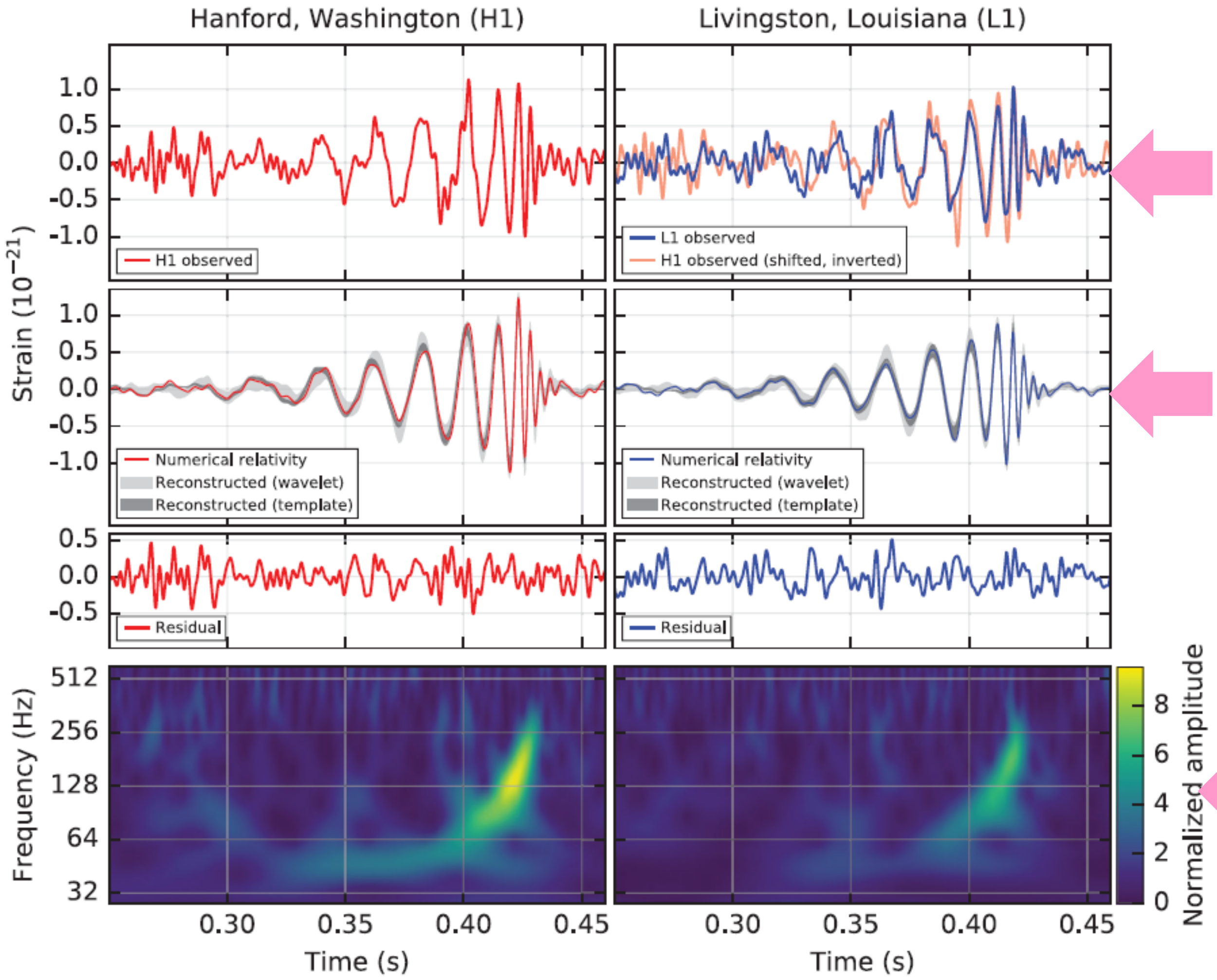


Frequency band relevant for the first detection

Strategy to confirm the detection by two detectors at Hanford and Livingstone

(PRL 116, 061102(2016))

FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). *Inset (a):* Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). *Inset (b):* The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain amplitude. The sensitivity is limited by photon shot noise at frequencies above 150 Hz, and by a superposition of other noise sources at lower frequencies [47]. Narrow-band features include calibration lines (33, 38, 330, and 1080 Hz), vibrational modes of suspension



Restricting to 35Hz–350Hz, removing only the frequencies with large noise

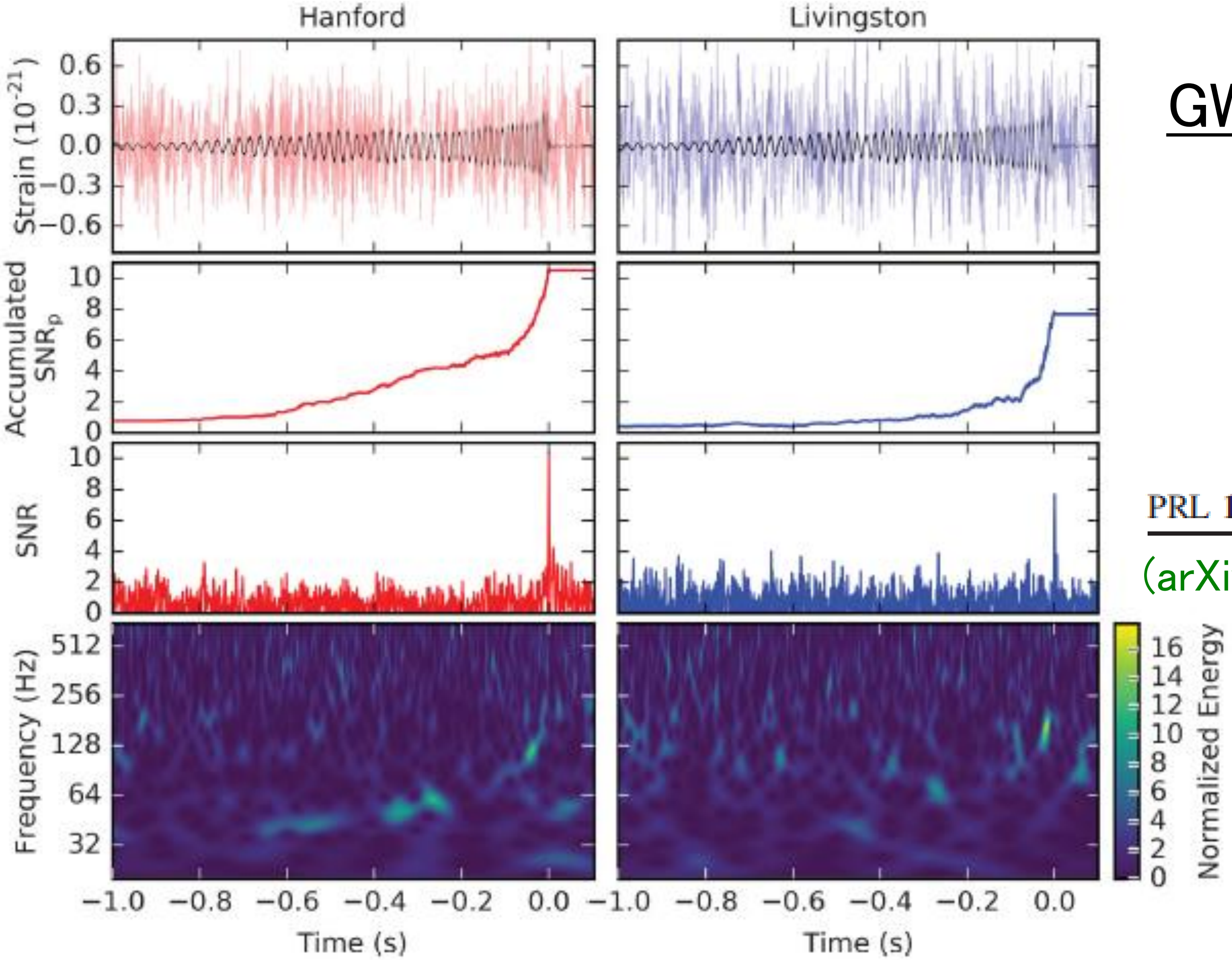
best–fit model based on theoretical prediction

Can be recognized just by looking at time–frequency power spectrum

FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. *Top row, left:* H1 strain. *Top row, right:* L1 strain. GW150914 arrived first at L1 and $6.9^{+0.5}_{-0.4}$ ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors' relative orientations). *Second row:* Gravitational-wave strain projected onto each detector in the 35–350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 [37,38] confirmed to 99.9% by an independent calculation based on [15]. Shaded areas show 90% credible regions for two independent waveform reconstructions. One (dark gray) models the signal using binary black hole template waveforms [39]. The other (light gray) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of sine-Gaussian wavelets [40,41]. These reconstructions have a 94% overlap, as shown in [39]. *Third row:* Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series. *Bottom row:*A time-frequency representation [42] of the strain data, showing the signal frequency increasing over time.

(PRL 116, 061102(2016))

Meanwhile, the second event was announced

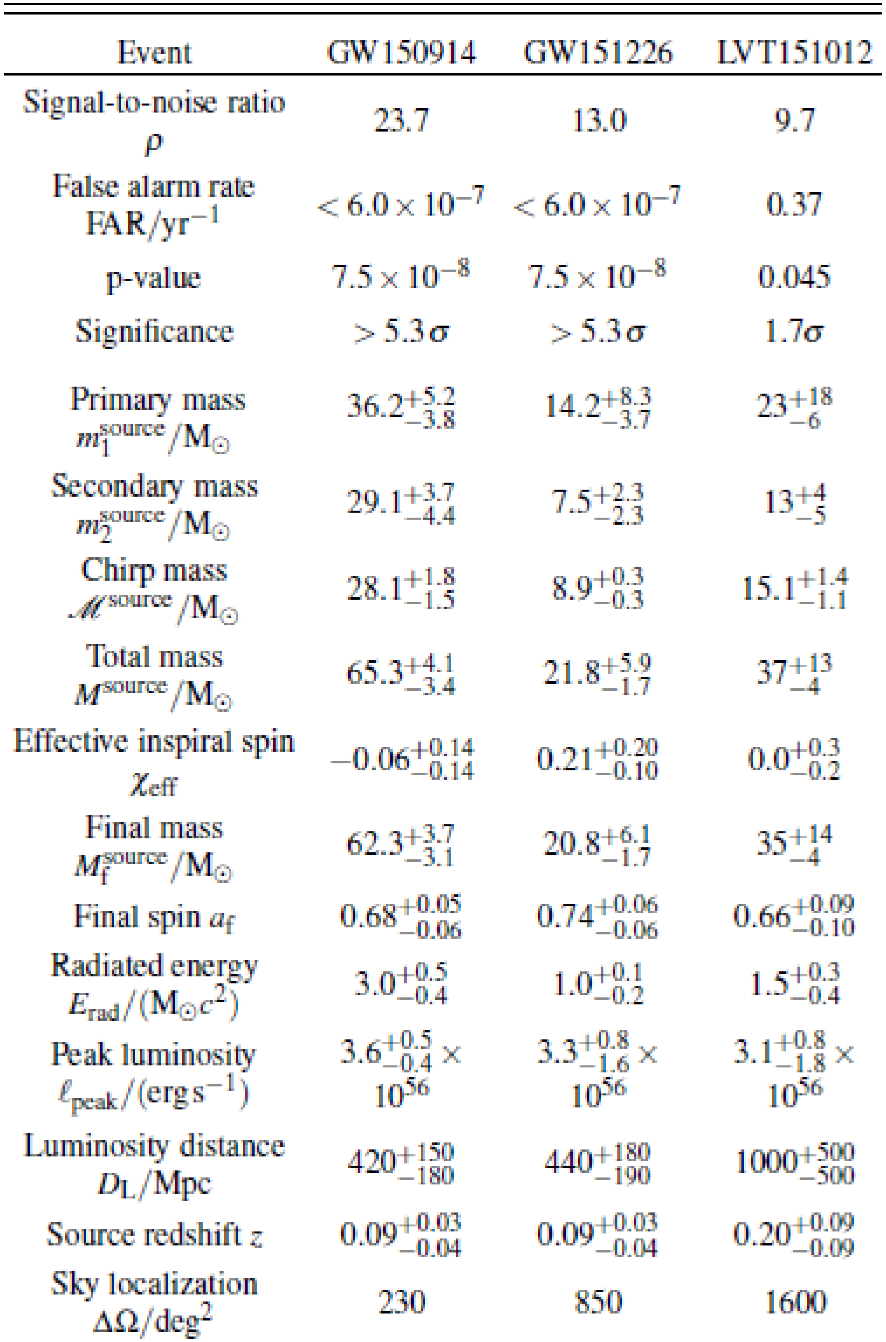


GW151226

PRL 116, 241103 (2016)

(arXiv:1606.04855)

And this time matched filtering analysis was necessary



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR/yr^{-1}}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

GW150914 has extra-ordinarily high S/N.

Showing diversity of constituent masses.

GW151226 suggests the existence of spin before merger.

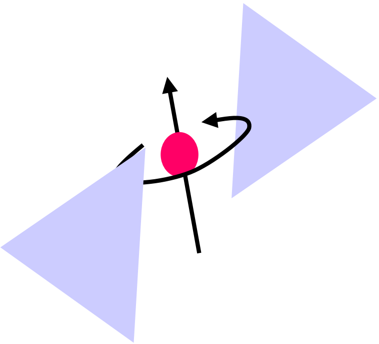
（arXiv:1606.04856）

What we can say from these GW events?

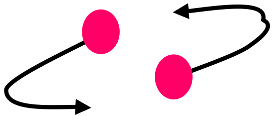
- Direct detection of GWs
  - Really detected
    - GW amplitude of $O(10^{-21})$ means that the displacement is less than 10^{-2} fm for the 4km arm.
    - GWs really propagate.
- Existence of $30M_{\rm sol}$ black holes
  - About 20 black hole candidates of ～$10M_{\rm sol}$ have been known as X-ray binaries, but such the existence of such a high mass BHs was not clear. Moreover, they are rather abundant.
    - 0.6-12events/year/Gpc^3
  - Is GW150914 still a candidate or BH?

Indirect evidence of GW emission

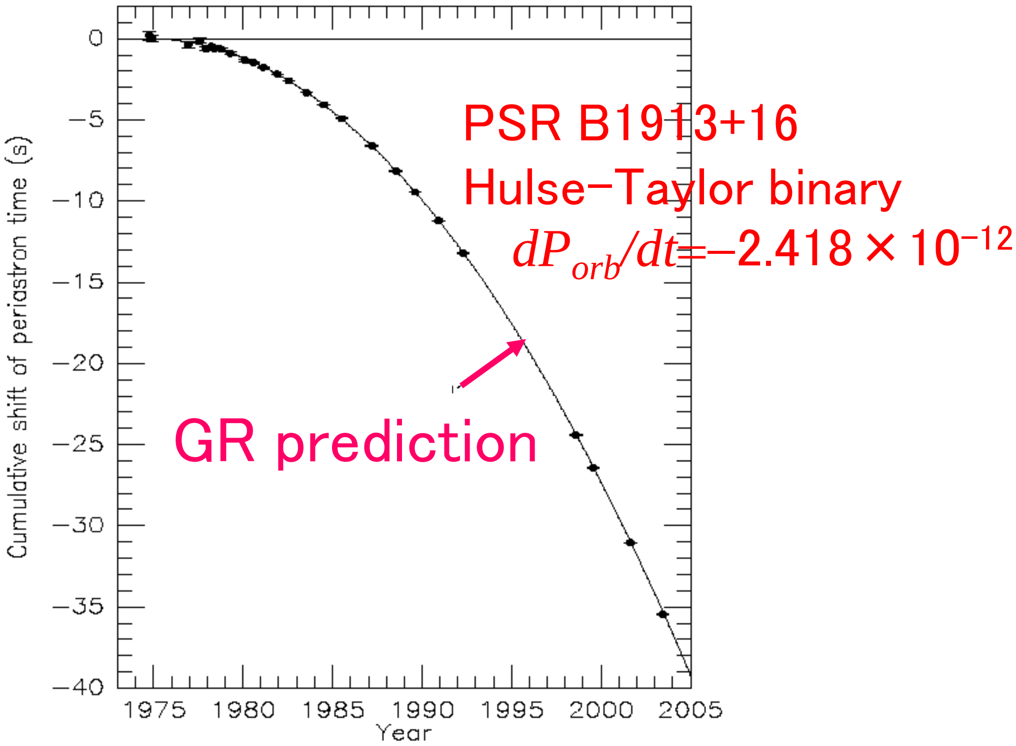
Pulsar is an ideal clock



Binary pulsar can be used to test GR



Periastron time shift due to GW emission



PSR B1913+16

Hulse−Taylor binary

$dP_{orb}/dt = -2.418 \times 10^{-12}$

GR prediction

(J.M. Weisberg and J.H. Taylor, astro−ph/0407149.)

Hulse and Taylor were awarded Nobel prize in 1993

- GW emission was confirmed but its propagation was not.
- It is still uncertain if the propagation is as expected.

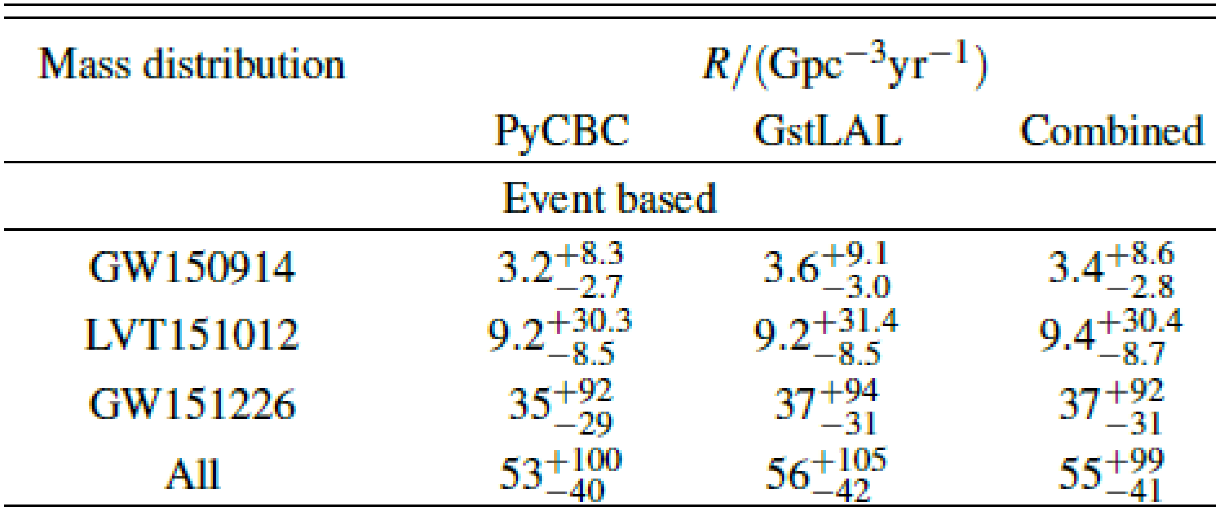
What we can say from these GW events?

- Direct detection of GWs
  - Really detected
    - GW amplitude of $O(10^{-21})$ means that the displacement is 1fm for the 4km arm.
    - GWs really propagate
- Existence of 30M_{sol} black holes
  - About 20 black hole candidates of ～10M_{sol} have been known as X-ray binaries, but the existence of such high mass BHs was not clear. Moreover, they are found to be rather abundant.
    - 0.6-12events/year/Gpc^3
  - Is GW150914 still a candidate or BH?

Observable smaller mass binaries are typically closer

$$\tilde{h}(f) \approx 10^{-21} f^{-1} \left(\frac{f}{10^{5}\,\mathrm{Hz}}\right)^{-1/6} \left(\frac{M_{chirp}}{M_{太陽}}\right)^{5/6} \left(\frac{r}{100Mpc}\right)^{-1} \mathrm{Hz}^{-1}$$

The expected event rate of BBH mergers like GW151226 per unit volume is about 10 times larger than BBH like GW150914.



Mass distribution	$R/(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$		
	PyCBC	GstLAL	Combined
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.4^{+30.4}_{-8.7}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	37^{+92}_{-31}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+99}_{-41}

Various scenarios of massive BBH formation

(ApJ Lett., 818:L22 (2016))

- Binary formation in the metal poor environment

  Weak feedback to the mass accretion

  Low mass loss rate

- Interaction in dense star clusters

  Event rate can be explained

  (For example, arXiv:1604.04254)

- We cannot deny the possibility of scenarios based on primordial BH origin, either.

  (Say, **arXiv:1603.00464, arXiv:1603.05234)**

Primordial black hole scenario for the gravitational wave event GW150914

We also wrote a paper and selected as PRL Editors' Suggestion

Misao Sasaki[a], Teruaki Suyama[b], Takahiro Tanaka[c], and Shuichiro Yokoyama[d]
[a] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[b] *Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan*
[c] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[d] *Department of Physics, Rikkyo University, Tokyo 171-8501, Japan*

arXiv:1603.08338

Abstract

We point out that the gravitational wave event GW150914 observed by the LIGO detectors can be explained by the coalescence of primordial black holes (PBHs). It is found that the expected PBH merger rate would exceed the rate estimated by the LIGO scientific collaboration and Virgo collaboration if PBHs were the dominant component of dark matter, while it can be made compatible if PBHs constitute a fraction of dark matter. Intriguingly, the abundance of PBHs required to explain the suggested lower bound on the event rate, > 2 events/year/Gpc^3, roughly coincides with the existing upper limit set by the non-detection of the CMB spectral distortion. This implies that the proposed PBH scenario may be tested in the not-too-distant future.

What we can say from these GW events?

- Direct detection of GWs
  - Really detected
    - GW amplitude of $O(10^{-21})$ means that the displacement is 1fm for the 4km arm.
    - GWs really propagate
- Existence of 30$M_{\rm sol}$ black holes
  - About 20 black hole candidates of ～10$M_{\rm sol}$ have been known as X-ray binaries, but such the existence of such a high mass BHs was not clear. Moreover, they are rather abundant.
    - 0.6-12events/year/Gpc^3
  - Is GW150914 still a candidate or BH?

Judging if it is a BH or a BH candidate is difficult, but

- Recent development of numerical relativity enabled high precision simulation of BBH coalescence.
- No big discrepancy between theoretical predictions and observations will indicate certainly more than previous observations basically about the matter accretion onto BHs.

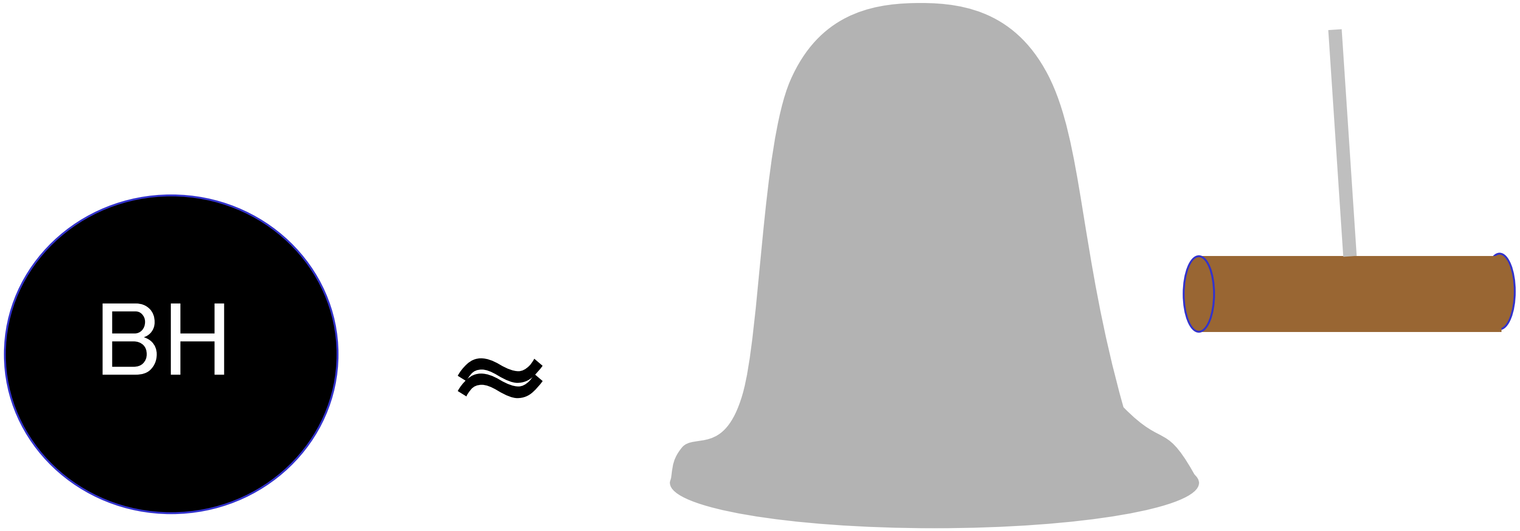
This looks similar to the question about inflation
“Was the inflation paradigm confirmed?”.

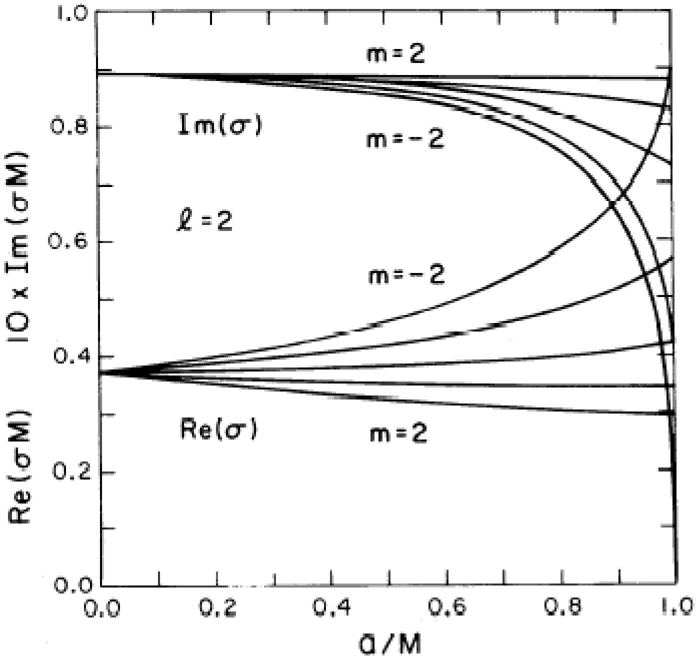
“Many people think so, but it would be more conclusive if tensor B modes are detected. “

⇕

“Many people think so, but it would be more conclusive if QNM modes are detected. ”

BH Quasi-Normal Modes (QNM)

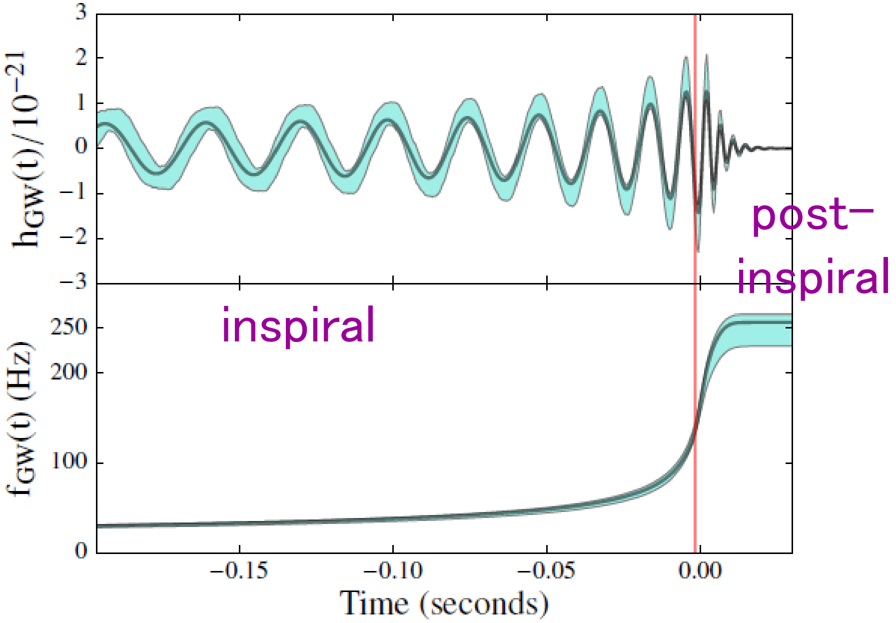


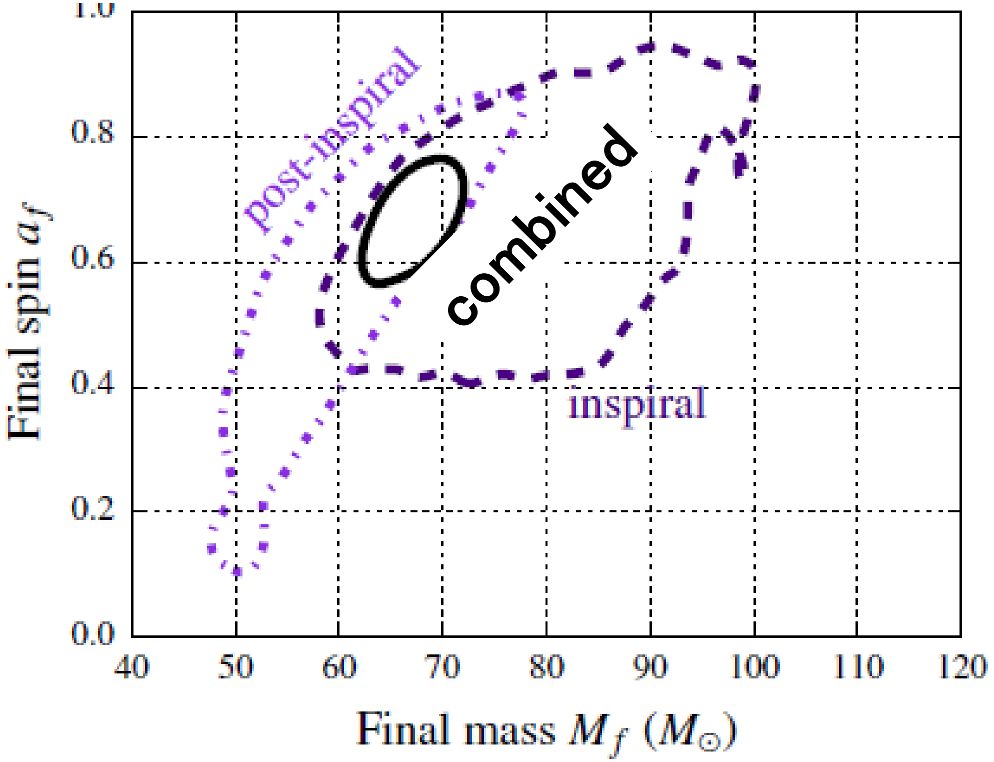


Frequency and decay rate are determined by the BH mass and spin

Decisive evidence of BH formation

(Detweiler ApJ239 292 (1980))





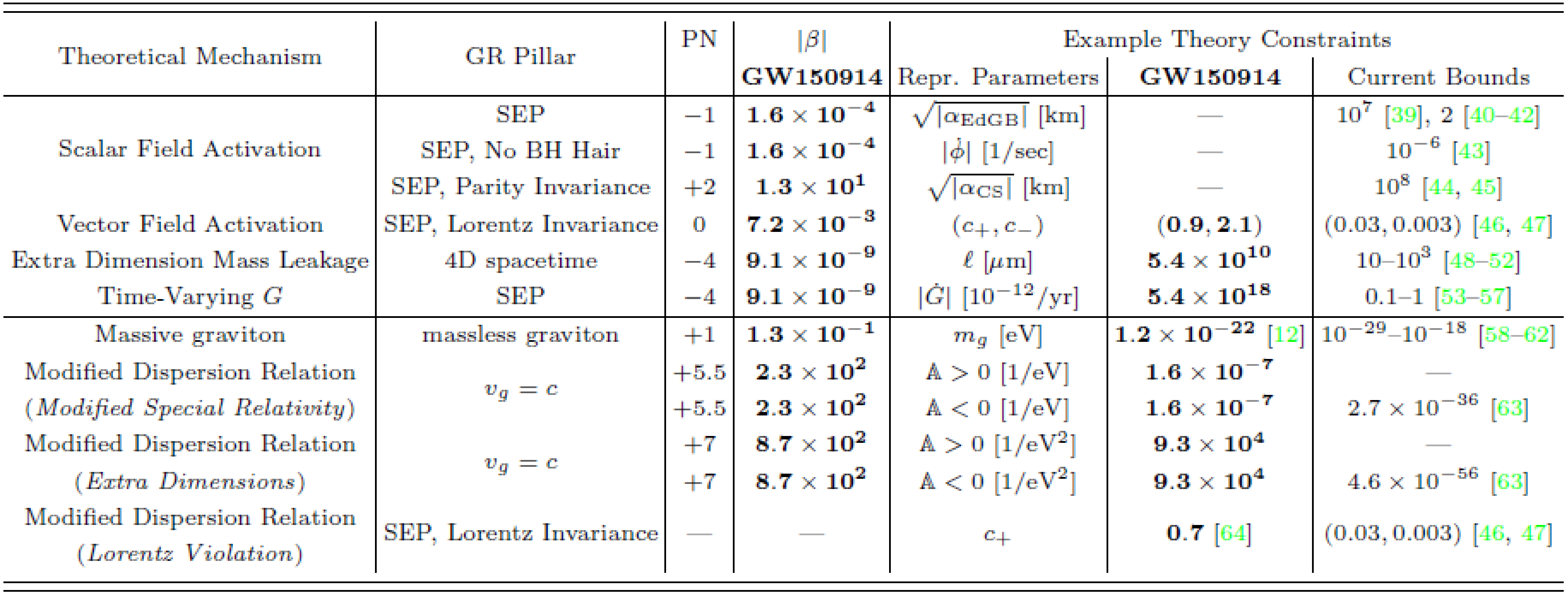
The case of GW150914

The estimated final mass and spin from the respective data of inspiral and post−inspiral contain large errors.

It would be too early to say that the QNM was detected as was predicted.

(arXiv:1602.03841)

Constraint on the modification of gravity by GW150914



Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$	Example Theory Constraints		
			GW150914	Repr. Parameters	**GW150914**	Current Bounds
Scalar Field Activation	SEP	-1	$\mathbf{1.6 \times 10^{-4}}$	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km]	—	10^7 [39], 2 [40–42]
	SEP, No BH Hair	-1	$\mathbf{1.6 \times 10^{-4}}$	$\lvert\dot{\phi}\rvert$ [1/sec]	—	10^{-6} [43]
	SEP, Parity Invariance	$+2$	$\mathbf{1.3 \times 10^{1}}$	$\sqrt{\lvert\alpha_{\rm CS}\rvert}$ [km]	—	10^8 [44, 45]
Vector Field Activation	SEP, Lorentz Invariance	0	$\mathbf{7.2 \times 10^{-3}}$	(c_+, c_-)	$\mathbf{(0.9, 2.1)}$	$(0.03, 0.003)$ [46, 47]
Extra Dimension Mass Leakage	4D spacetime	-4	$\mathbf{9.1 \times 10^{-9}}$	ℓ [μm]	$\mathbf{5.4 \times 10^{10}}$	10–10^3 [48–52]
Time-Varying G	SEP	-4	$\mathbf{9.1 \times 10^{-9}}$	$\lvert\dot{G}\rvert$ [10^{-12}/yr]	$\mathbf{5.4 \times 10^{18}}$	0.1–1 [53–57]
Massive graviton	massless graviton	$+1$	$\mathbf{1.3 \times 10^{-1}}$	m_g [eV]	$\mathbf{1.2 \times 10^{-22}}$ [12]	10^{-29}–10^{-18} [58–62]
Modified Dispersion Relation (*Modified Special Relativity*)	$v_g = c$	$+5.5$	$\mathbf{2.3 \times 10^{2}}$	$\mathbb{A} > 0$ [1/eV]	$\mathbf{1.6 \times 10^{-7}}$	—
		$+5.5$	$\mathbf{2.3 \times 10^{2}}$	$\mathbb{A} < 0$ [1/eV]	$\mathbf{1.6 \times 10^{-7}}$	2.7×10^{-36} [63]
Modified Dispersion Relation (*Extra Dimensions*)	$v_g = c$	$+7$	$\mathbf{8.7 \times 10^{2}}$	$\mathbb{A} > 0$ [1/eV^2]	$\mathbf{9.3 \times 10^{4}}$	—
		$+7$	$\mathbf{8.7 \times 10^{2}}$	$\mathbb{A} < 0$ [1/eV^2]	$\mathbf{9.3 \times 10^{4}}$	4.6×10^{-56} [63]
Modified Dispersion Relation (*Lorentz Violation*)	SEP, Lorentz Invariance	—	—	c_+	**0.7** [64]	$(0.03, 0.003)$ [46, 47]

$$\tilde{h}_i(f) = A_i(f) e^{i\Phi_i(f)} . \qquad \delta\Phi_{\rm I,ppE}(f) = \beta \left(\pi \mathcal{M} f\right)^{b/3}$$

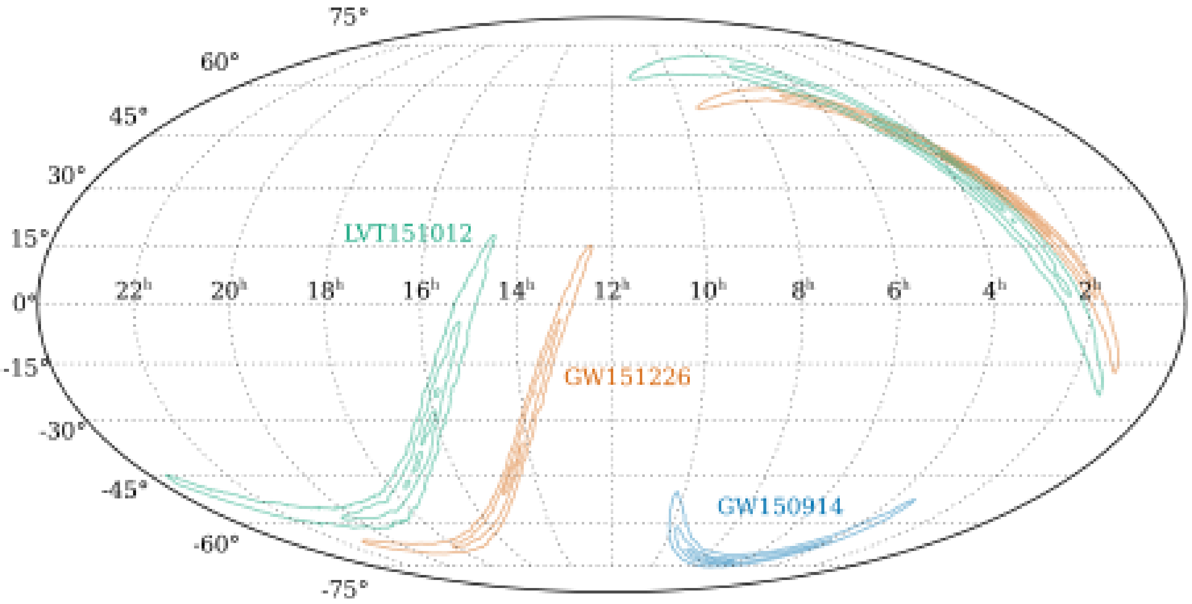
(arXiv:1603.08955)

Constraint on the graviton Compton wavelength is severer than the solar system bounds.

For the improvement of the precision, longer observation in the inspiral phase is necessary ⇒ space interferometer

EM followup observations

- coalescence time
- sky localization



(arXiv:1606.04856)

The case of GW150914

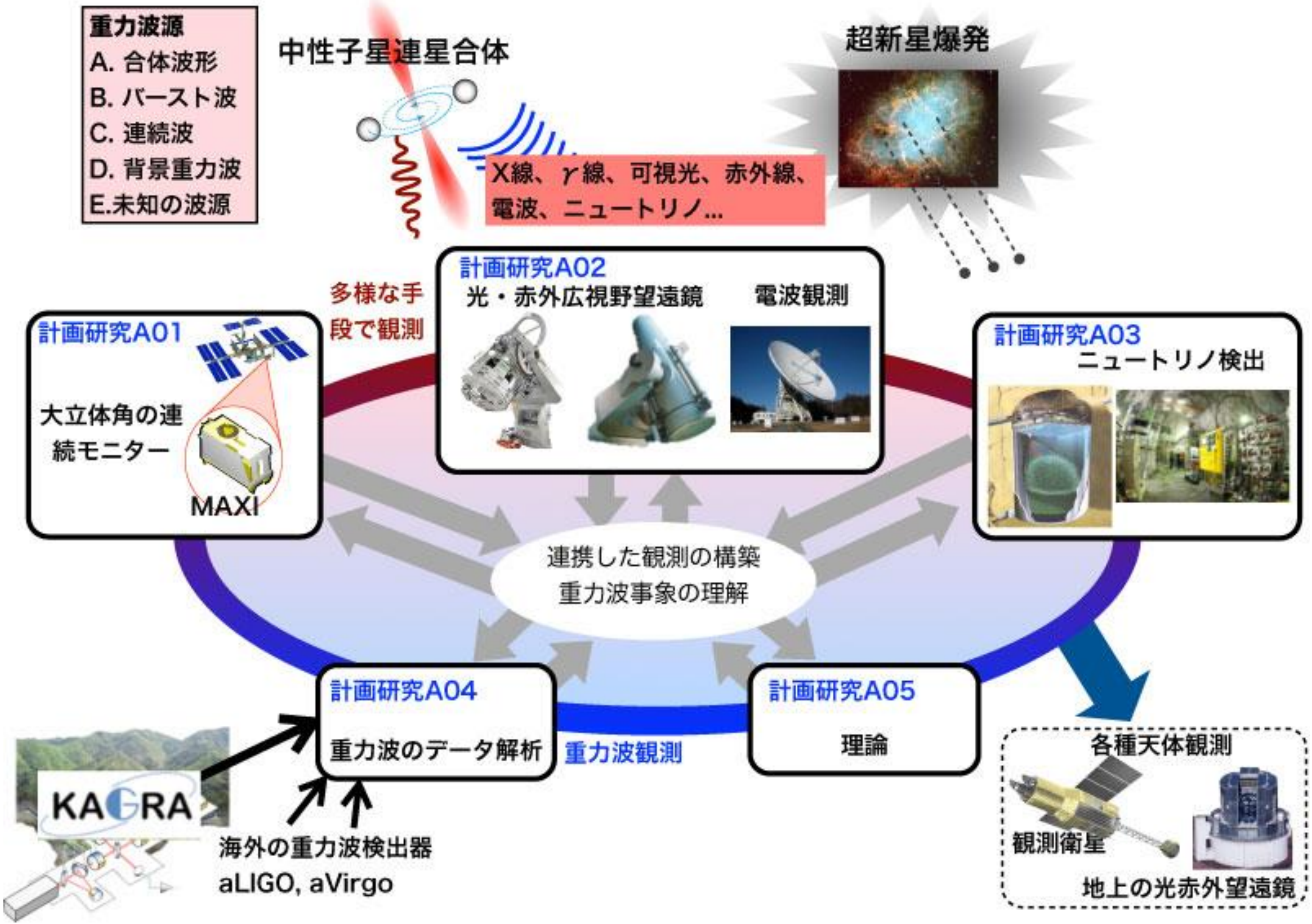
- restricted to the circle determined by the 7msec time difference between 2 detectors
- Antenna pattern matching

⇒ 600deg^2 (90%)
(in Feb. paper)

⇒ 230deg^2 (90%)
(in June paper)

Sky localization of GW151226
is 850deg^2 (90%)

In Japan J-GEM was organized based on the innovative area "New development in astrophysics through multimessenger observations of gravitational wave sources"(2012-2016)



重力波源
A. 合体波形
B. バースト波
C. 連続波
D. 背景重力波
E.未知の波源

中性子星連星合体

超新星爆発

X線、γ線、可視光、赤外線、電波、ニュートリノ…

多様な手段で観測

計画研究A01
大立体角の連続モニター
MAXI

計画研究A02
光・赤外広視野望遠鏡
電波観測

計画研究A03
ニュートリノ検出

連携した観測の構築
重力波事象の理解

計画研究A04
重力波のデータ解析

重力波観測

計画研究A05
理論

KAGRA

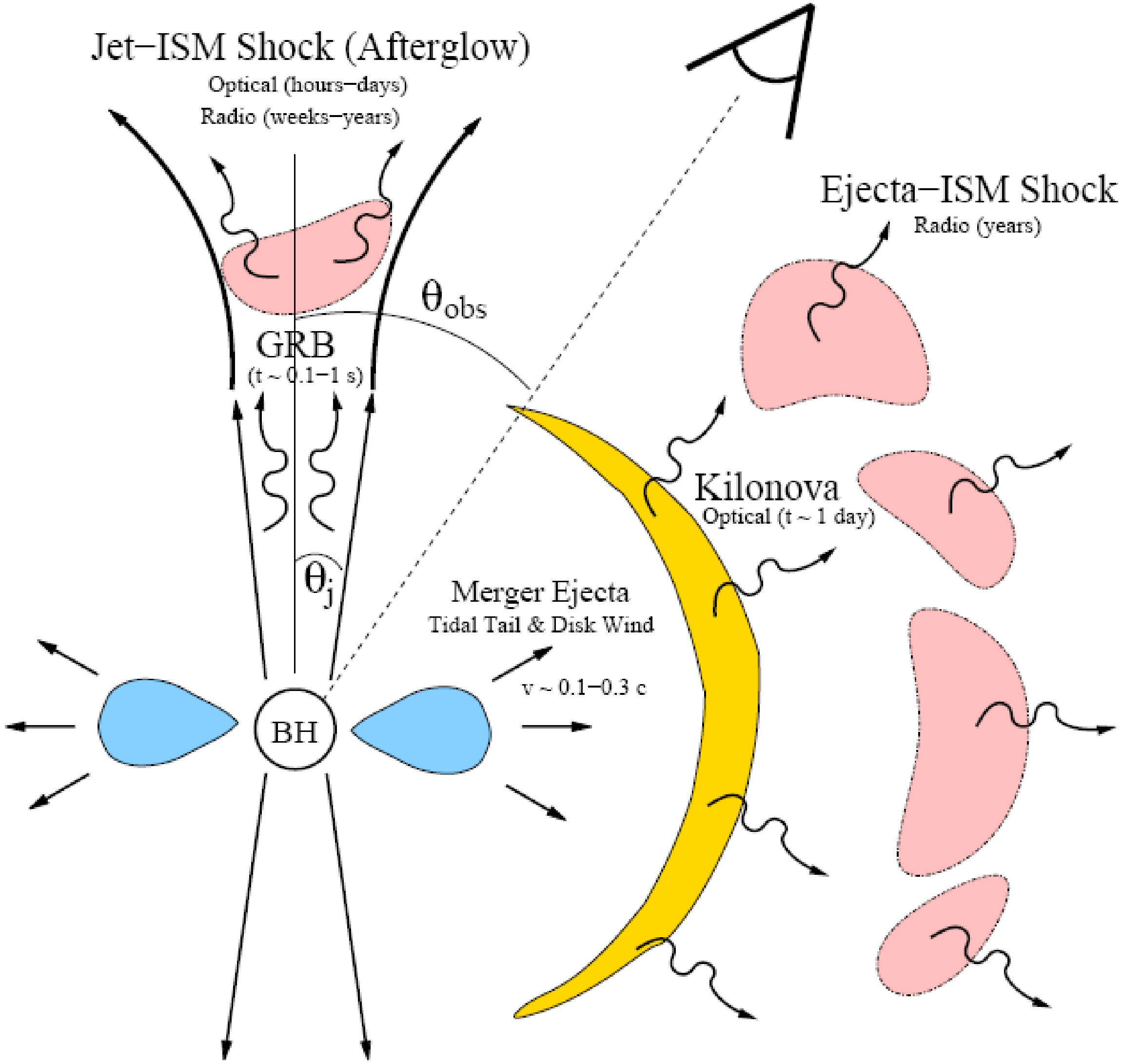
海外の重力波検出器
aLIGO, aVirgo

各種天体観測
観測衛星
地上の光赤外望遠鏡

MOU is exchanged between J-GEM and LIGO/VIRGO

Electromagnetic counterpart

NS−NS, NS−BH merger will given some EM signal. If there must be some associated emission, SGRB of unknown origin is quite likely to be the counterpart.



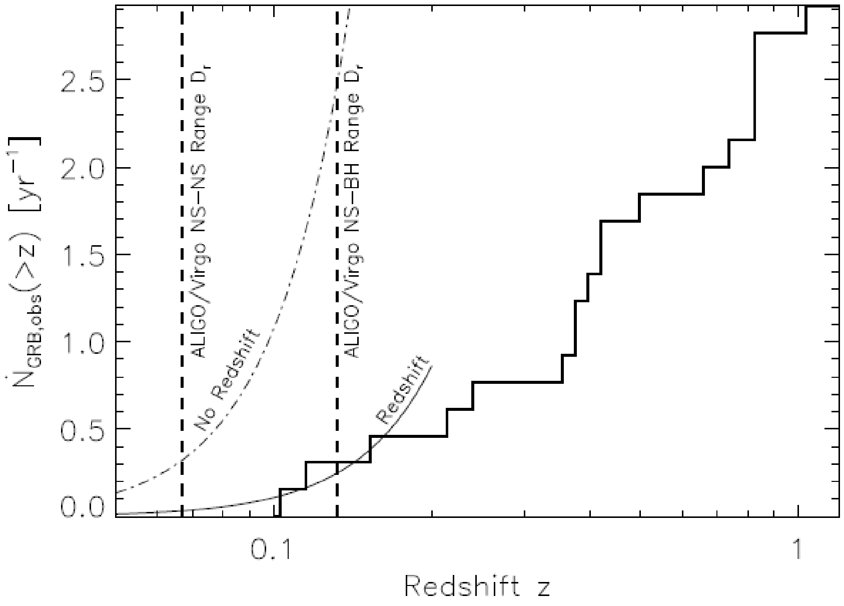
GW event confirmation

New astrophysics

4π emission will be advantageous for follow-up observations

(Metzger and Berger 1108.6056)

NS–NS, NS–BH mergers will emit some electromagnetic signal.
Then, it is likely related to SGRB.



(Metzger and Berger 1108.6056)

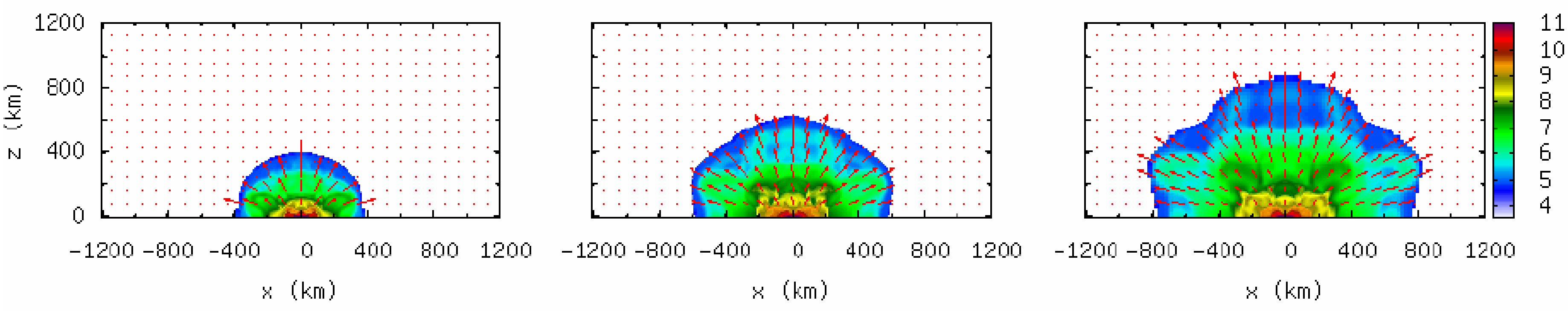
Assuming jet opening angle ～0.12rad, the event rate of SGRBs is consistent with (or slightly larger than) the estimated event rate for NS–NS binary merger, ~$8yr^{-1}$.

from population synthesis simulation and binary pulsar observation

Macronova/Kilonova,

Neutron rich object emitted from NS-NS merger

⇒ nucleosynthesis via r -process(A>130)



$1.35M_\odot + 1.35M_\odot$ with soft EOM but stiff enough to sustain NS of $2M_\odot$

(Hotokezaka et al. 1212.0905)

$\sim 0.2c$

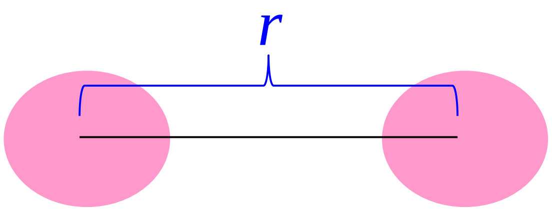
ejecta mass of $\sim 10^{-4}$-$10^{-2}\,M_\odot$

Mass ejection due to tidal disruption (for large radius NS)

& due to shock (for small radius NS)

Small radius NS ⇔ large mass ejection

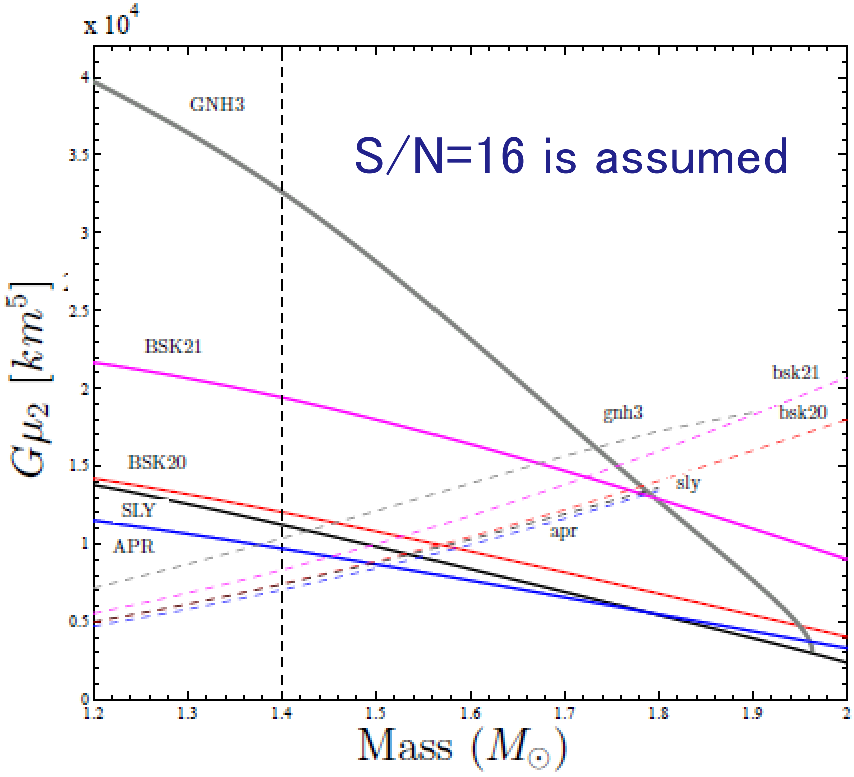
Investigating NS from gravitational wave form



tidal force$(1/r^3)$ × tidal deformation $(1/r^3)$
$\propto$tidal energy $(1/r^6)$

Compared with Newtonian binding energy $(1/r)$, 5PN$(1/r^5)$ order higher

Estimate of the observability of tidal effects on the inspiral wave form.



S/N=16 is assumed

Solid curves are tidal deformability for various EOS

Dashed curves are 1σ level of design sensitivity of advLIGO

(Damour, Nagar and Villain 1203.4352)

Future of gravitational wave physics

国立天文台HPより

Improvement in sky localization

Error in the estimated NS-NS binary sky position

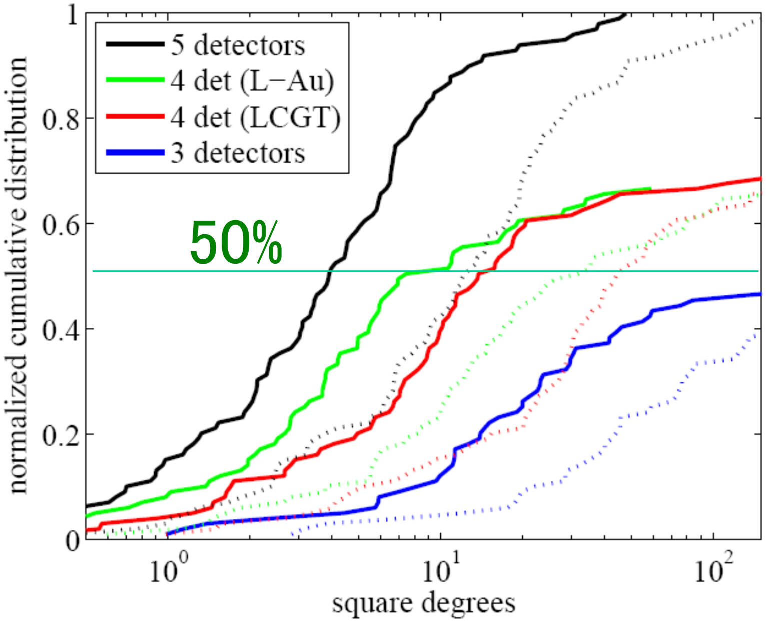


FIG. 3.— Normalized cumulative distributions as a function of the sky-error area (square degrees) of a sample of NS-NS binaries in Case I detection scenario. Key: Solid/dotted lines denote 68% and 95% confidence regions respectively. Black: LIGO+Virgo+LAu+LCGT network, green: LIGO+Virgo+LAu, red: LIGO+Virgo+LCGT, and blue: LIGO+Virgo only.

(Nissanke,Sievers, Dalal, Holz **arXiv:1105.3184**)

Simultaneous detection by the detector network can reduce the error box.

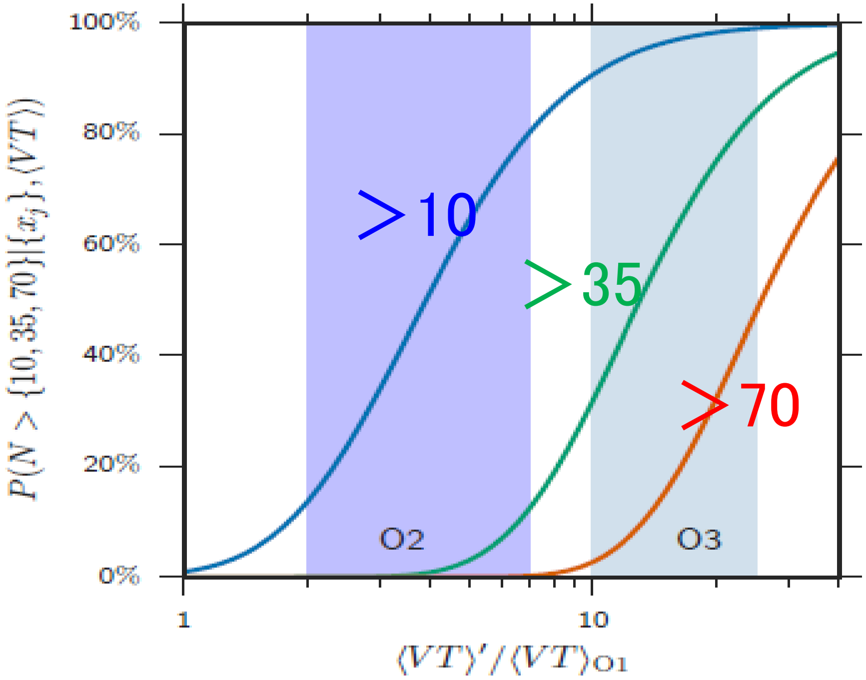
Data analysis group will become able to send alert after 5-10 mins after events.

KISS (1.05m) 4deg^2
PTF (1.2m) 7deg^2
Subaru-HSC(8.2m) 1.75deg^2
LSST (8.4m) 9.4deg^2

We can expect high event rate

AdvLIGO will improve the sensitivity ～3 times better.
The number of detectors will become 4 or 5.
Long-term stable operation.

⇒ S/N >100 events might be expected

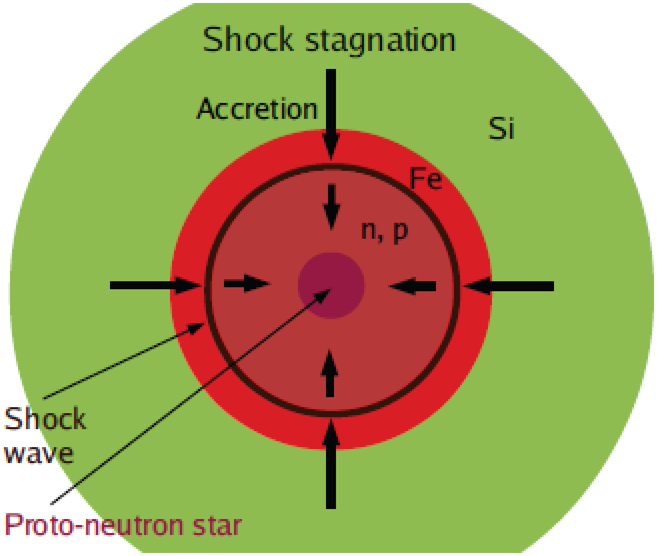


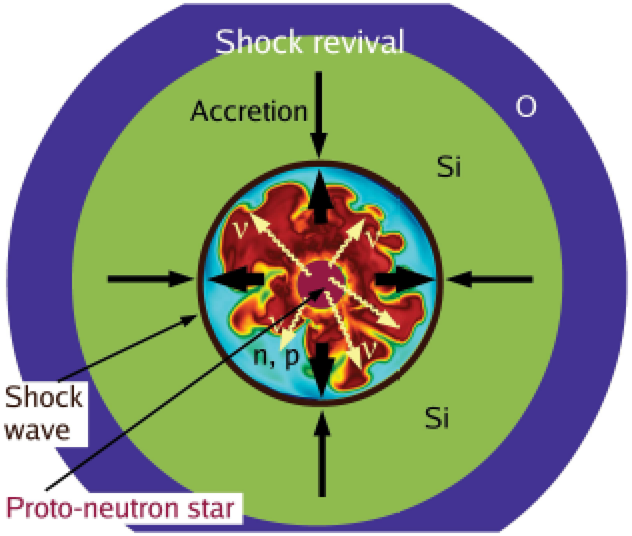
(arXiv:1606.04856)

Supernovae

Core collapse supernovae are going to be realized by numerical simulation.

Shock heating by neutrinos
Assisted by multi-dimensional instabilities

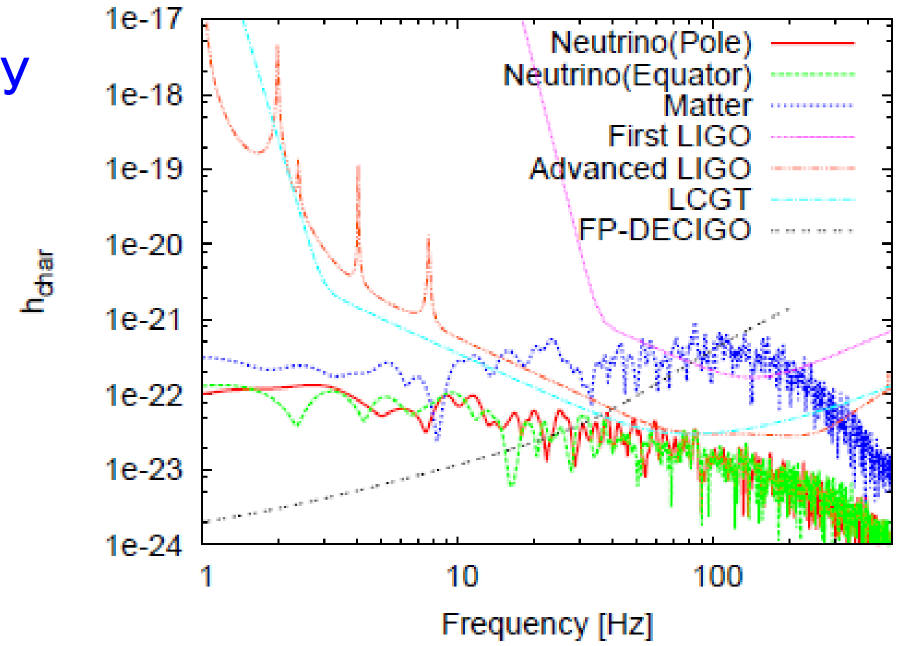




(Janka et al. 1211.1378)

Deviation from spherical symmetry
⇒GW radiation

- bounce
- convective matter motions, SASI
- anisotropic neutrino emission



SN at 10kpc

(Kotake et al. 1106.0544)

Explosion mechanism

Simultaneous observation of neutrino and GWs

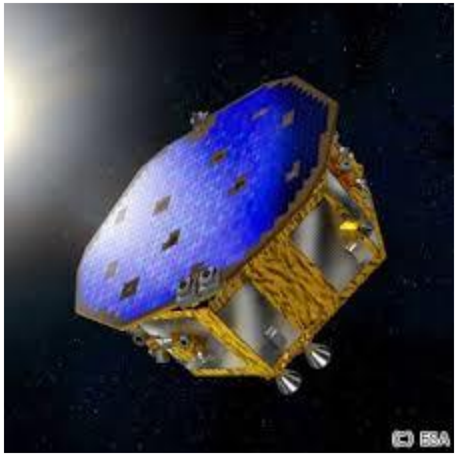
Spike of ν_e at the neutronization burst ⇔ GWs form bounce

Large GW ⇔ large core rotation (Yokozawa et al. 1410.2050)

Propagation speeds of GWs and ν_e

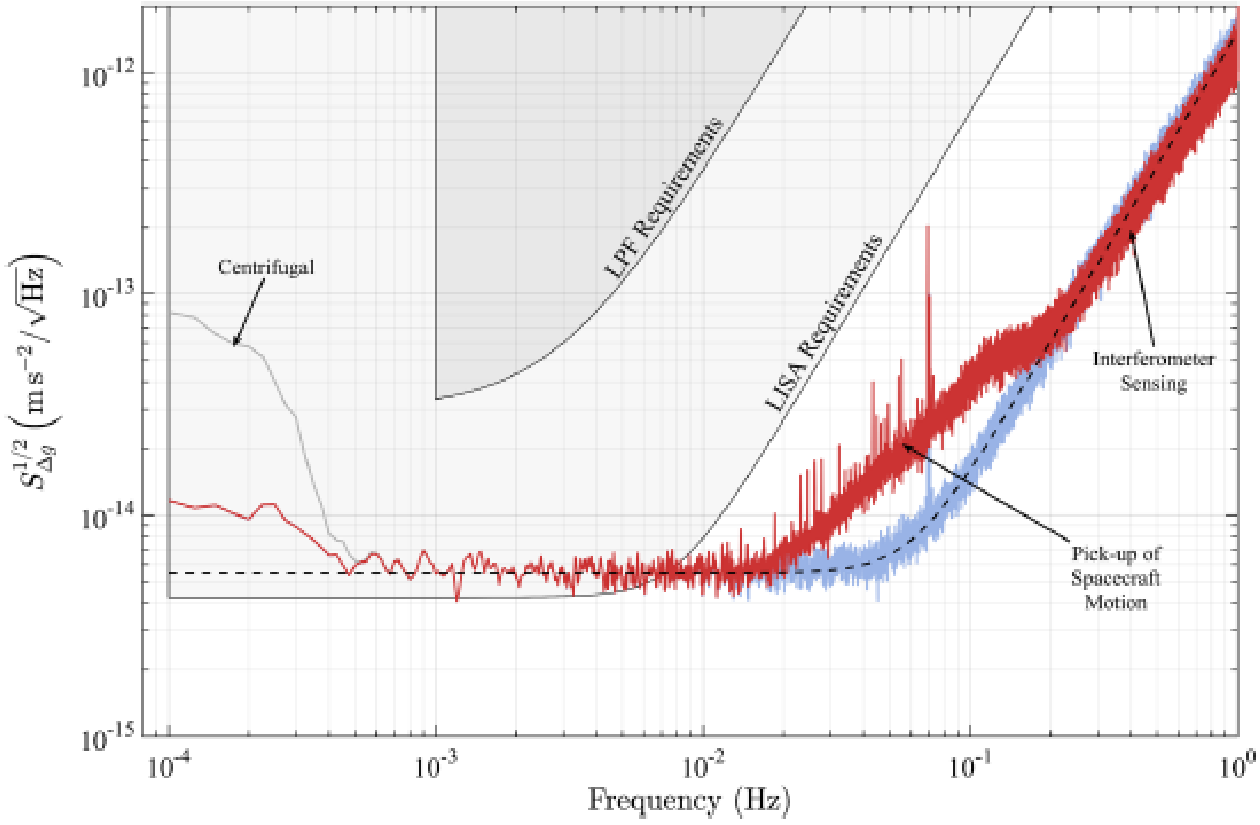
c_{GW} is constrained to ~ 10^{-15} (Nishizawa et al. 1405.5544)

LISA pathfinder



Launched on Dec. 3, 2015

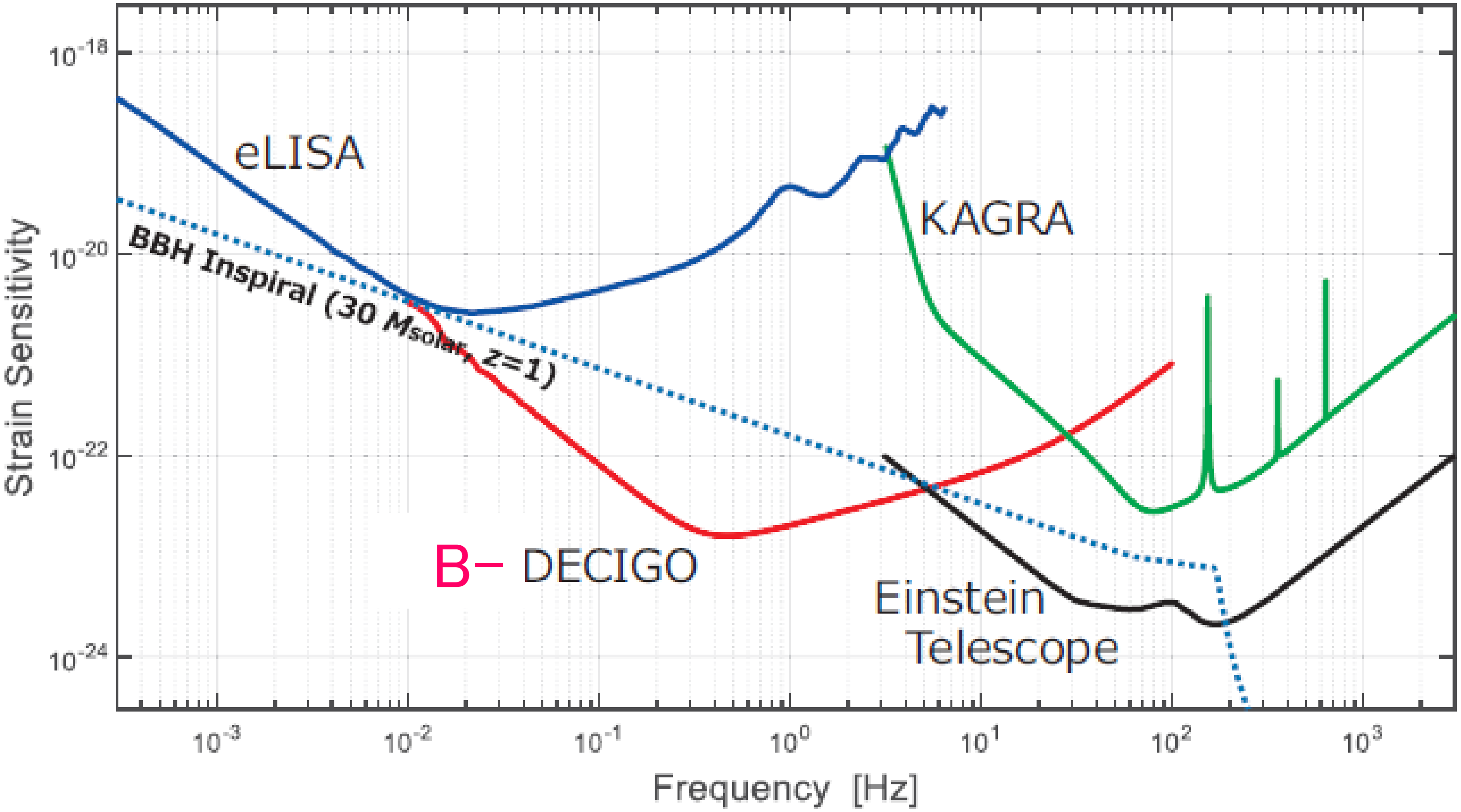
Proof of drag free technology for LISA



Measured acceleration noise level is almost at the LISA requirement level. (PRL 116, 231101 (2016))

Re-definition of the Pre-DECIGO mission

（arXiv:1607.00897 ）



$$h_c = 1.89 \times 10^{-21} (1+z)^{5/6} \left(\frac{M_c}{26.1 M_\odot}\right)^{5/6} \left(\frac{\nu}{0.1\,\mathrm{Hz}}\right)^{-1/6} \left(\frac{d_L(z)}{1\,\mathrm{Gpc}}\right)^{-1} \propto (1+z)^{-1/6}$$

for $z >> 1$

$30 M_{\mathrm{sol}}$ BBH is detectable even at z=30

⇒ Formation scenarios are distinguishable from redshift distribution

Sky position can be determined well in advance before merger.

Summary

- Gravitation waves are directly detected
- The existence of $30M_{\mathrm{sol}}$ BH was uncovered
  - can be Pop III origin
  - BH-QNM will be used to confirm BH spacetime
- Dawn of GW physics/astronomy
  - Multi-messenger and multi-detectors are important
  - Origin of SGRB
  - Detection of BNS is also expected
    - EOS of high density nuclear matter
    - *r*-process element(Au,Pt,etc.)Tests of GR
  - Space missions targeted at Low frequencies and pulsar timing array