重力波初観測から考える
今後の重力波研究

神田展行/大阪市立大学/KAGRA

@2016/4/27
神戸大学

今日のお話

1. LIGOによる重力波の初観測
2. 重力波とその源

重力波とは

検出が期待されてきた候補

重力波天文学・重力波物理学の幕開け！？

3. LIGO, Virgoの現状
4. KAGRAの現状
5. 再び、初観測の波形について

おことわり ^^;
いくつかの「内部情報」は、話せないので勘弁してください。

「あと何イベントみつかっているのか？」
「次の論文はいつ？」

重力波の発見

重力波の直接観測がなされました。その結果

０、検出器は原理通りに動いた！

１、一般相対論の重要な予言が検証された

２、ブラックホールが確認された（連星、合体後）

３、重力波天文学、重力波物理学が始まります

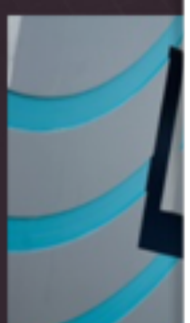
LIGO Laser Interferometer Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT

About | Learn More | News | Gallery | Educational Resources | For Scientists | Study & Work

Gravitational Waves Detected 100 Years After Einstein's Prediction

News Release • February 11, 2016

For the first time, scientists have observed ripples in the fabric of spacetime called gravitational waves, arriving at the earth from a cataclysmic event in the distant universe. This confirms a major prediction of Albert Einstein's 1915 general theory of relativity and opens an unprecedented new window onto the cosmos.



Advanced Run Comes

News Release •

The Advanced L ever official obs a 5-year instrum

Contact LIGO

LIGO Laboratory
MC 100-36
California Institute o
Pasadena, CA 91125

Information: (6

Image Use Policy

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4}M_{\odot}$ and $29^{+4}_{-4}M_{\odot}$, and the final black hole mass is $62^{+4}_{-4}M_{\odot}$, with $3.0^{+0.5}_{-0.5}M_{\odot}c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

GW150914

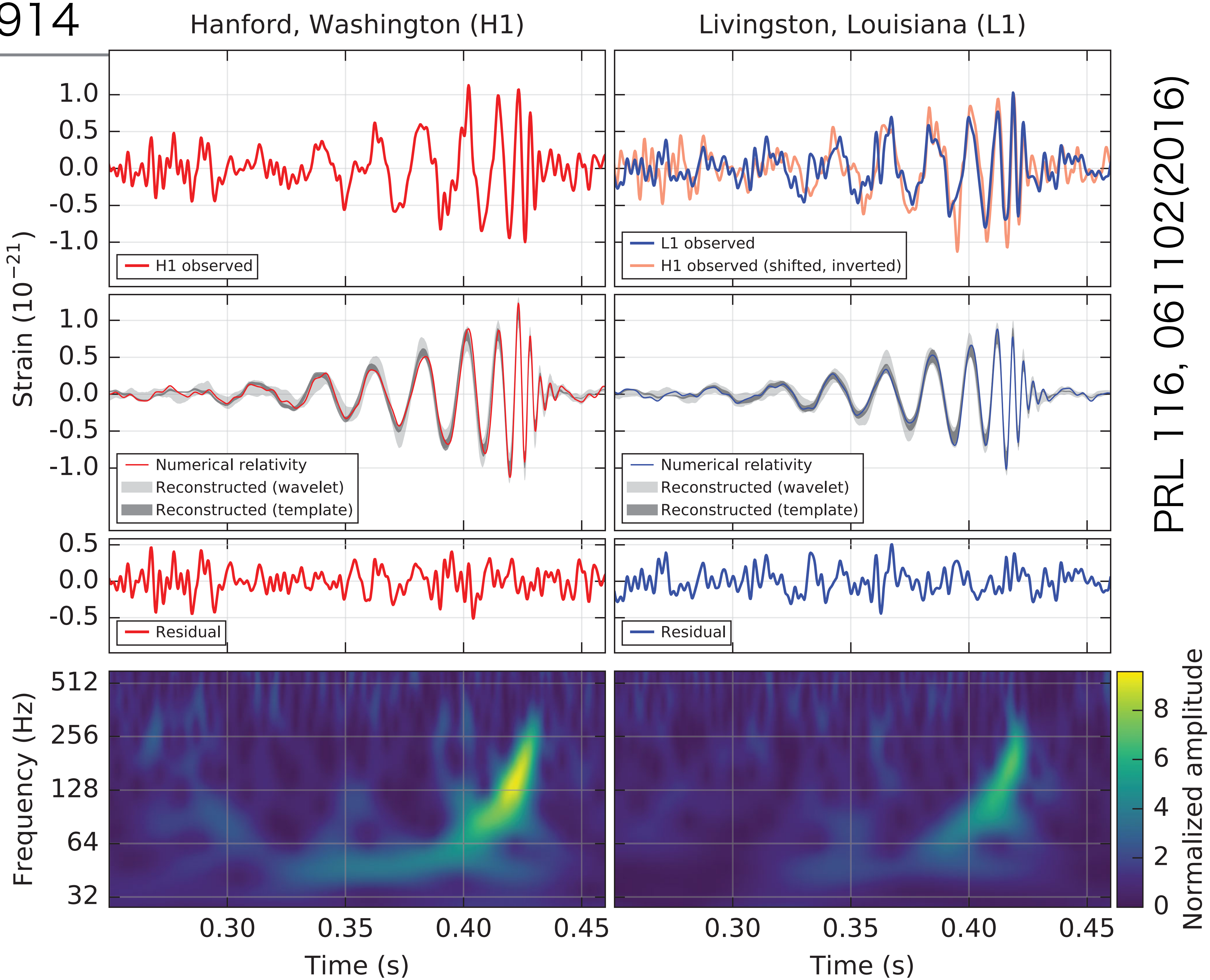
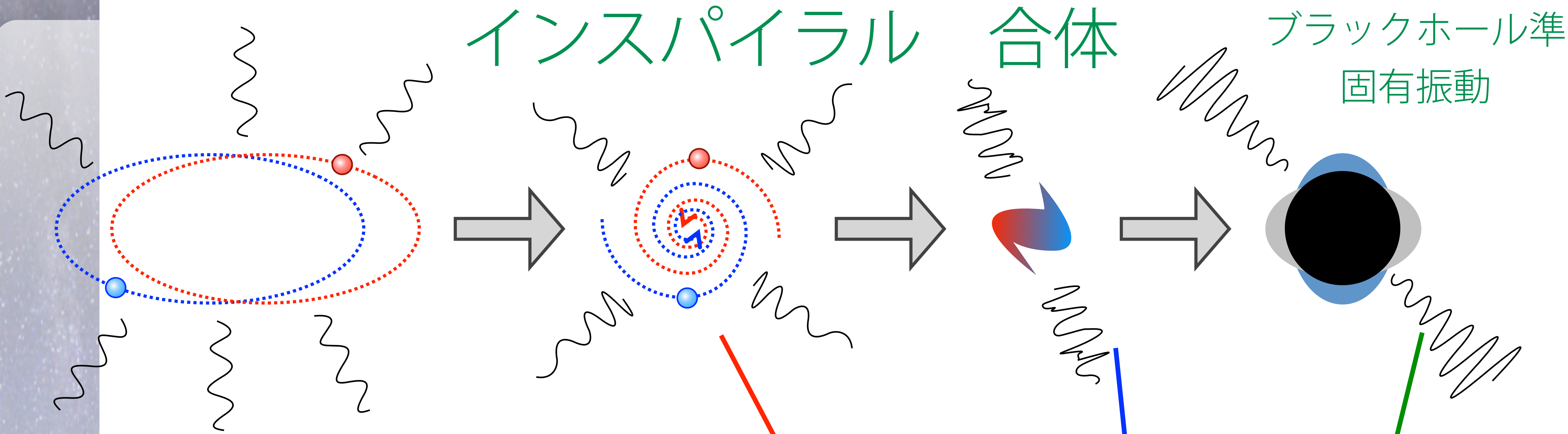
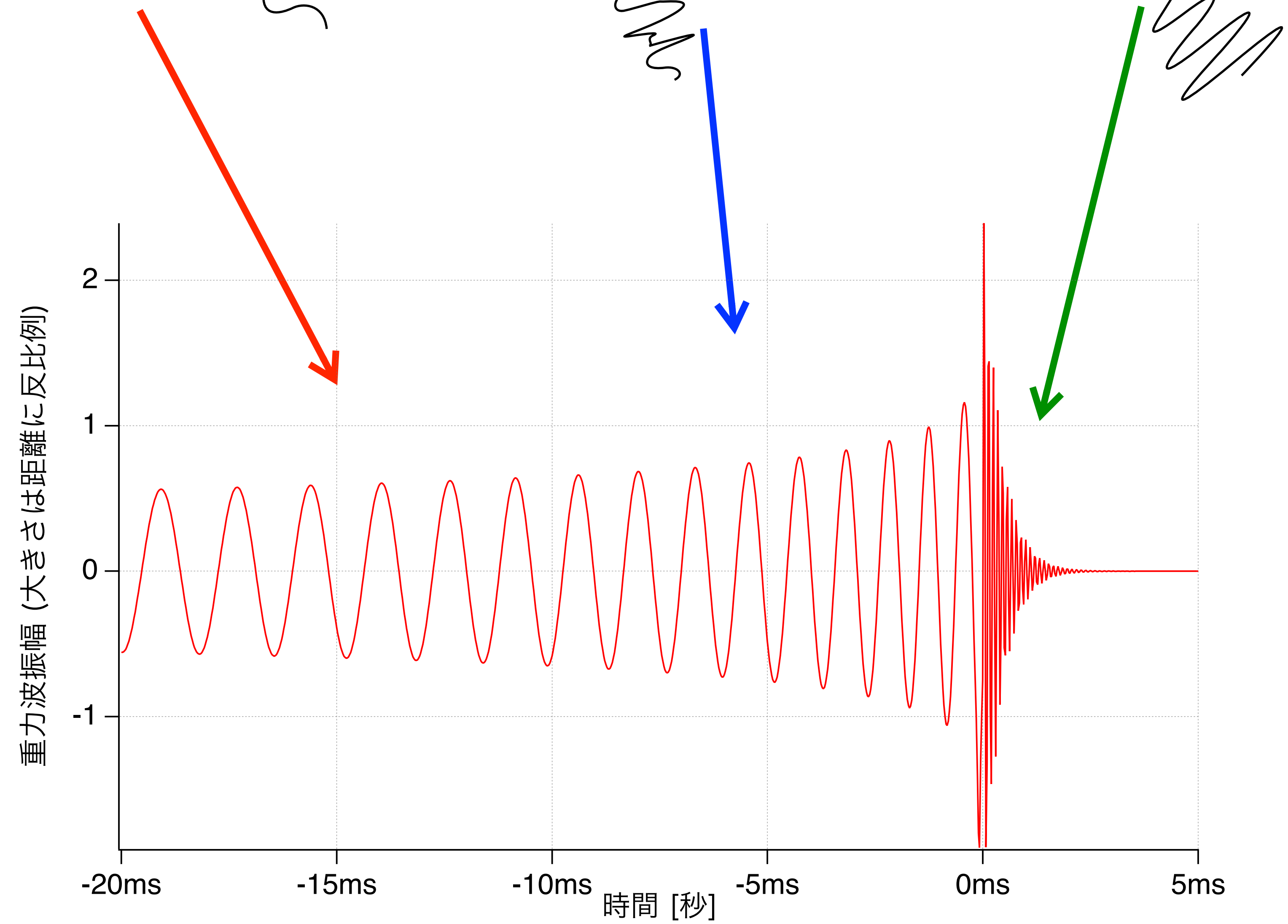


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject

コンパクト連星合体



h ~10^{-24} for NS-NS
at 200Mpc away!



GW150914

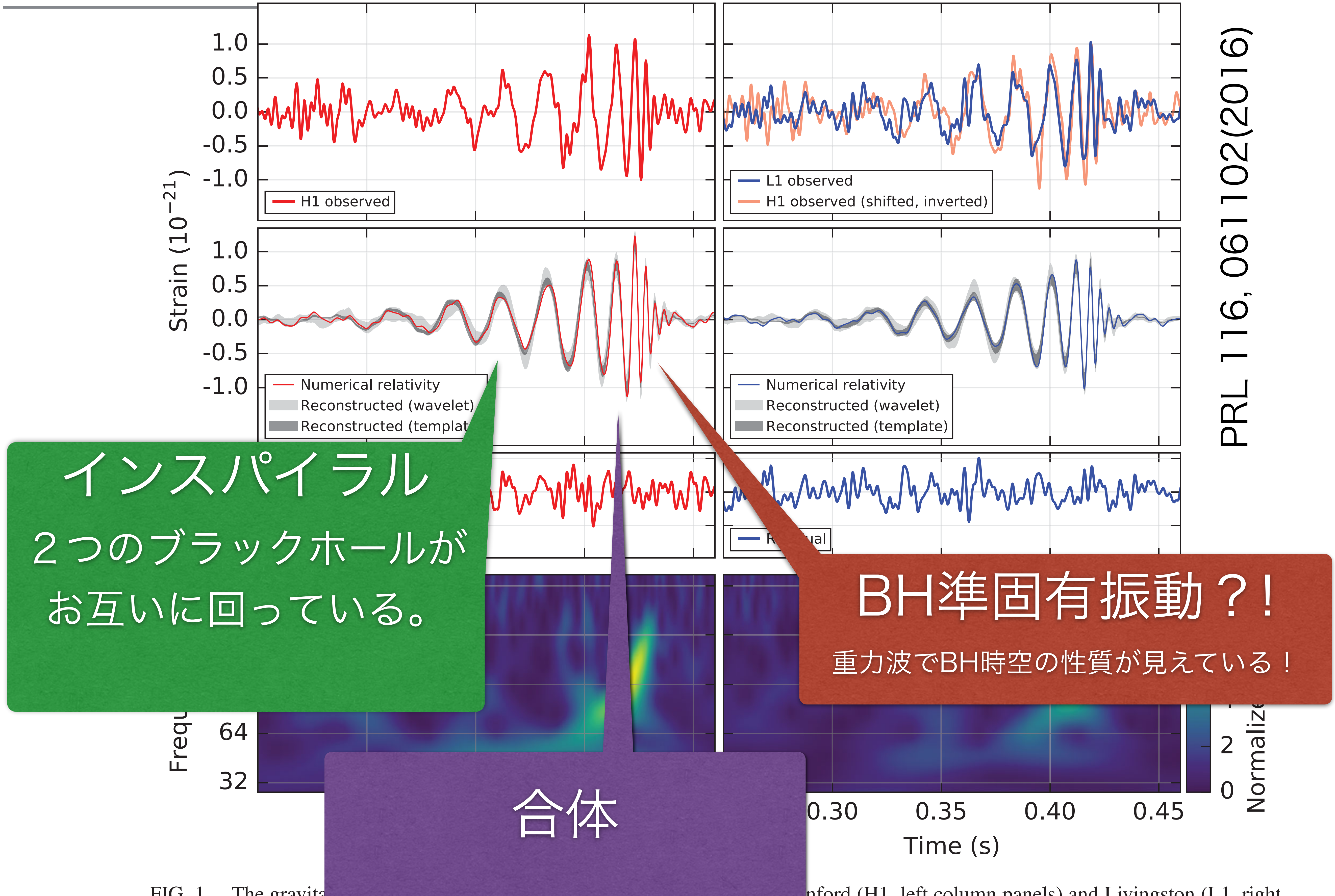


FIG. 1. The gravita ... nford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject

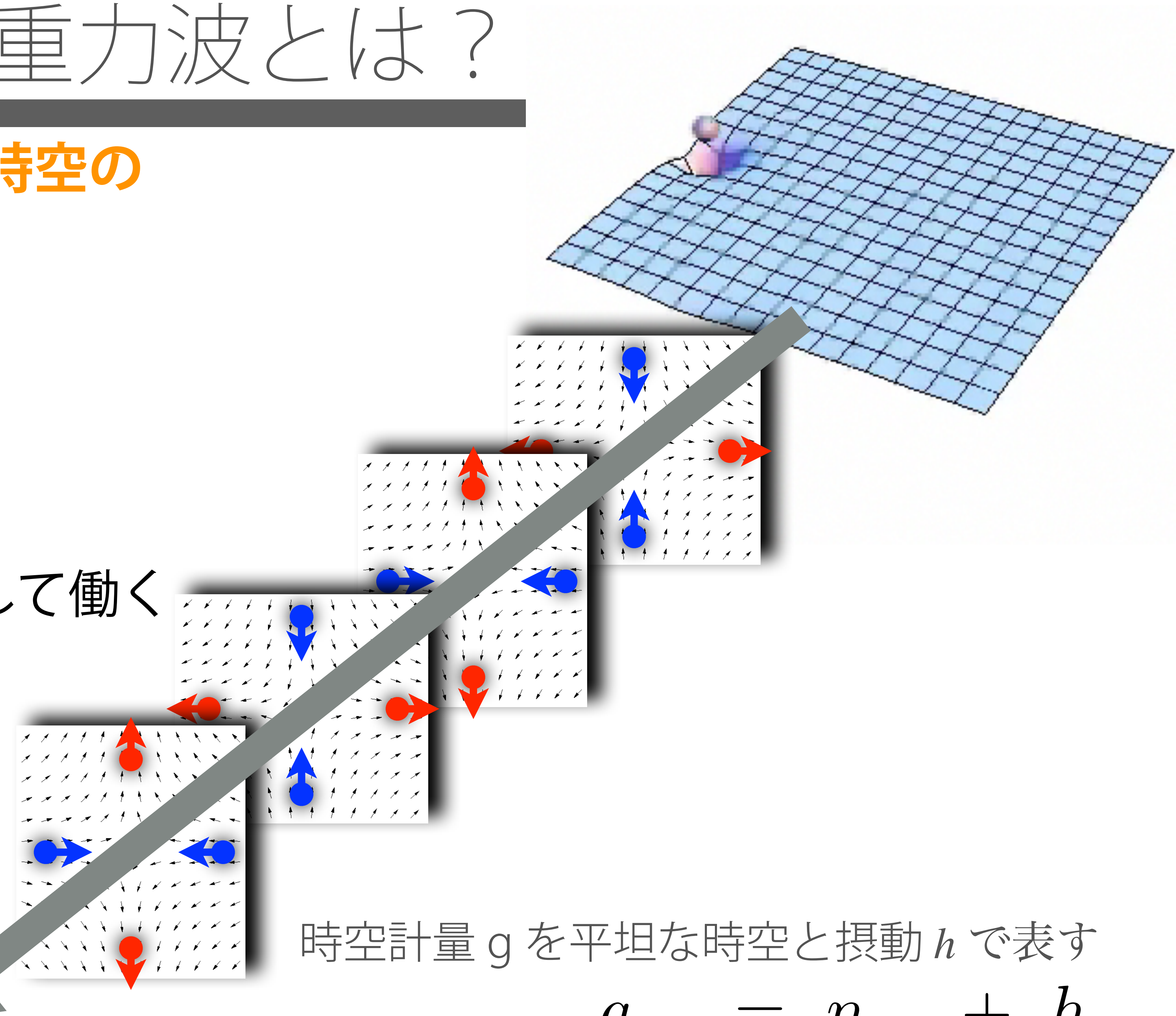
重力波とは？

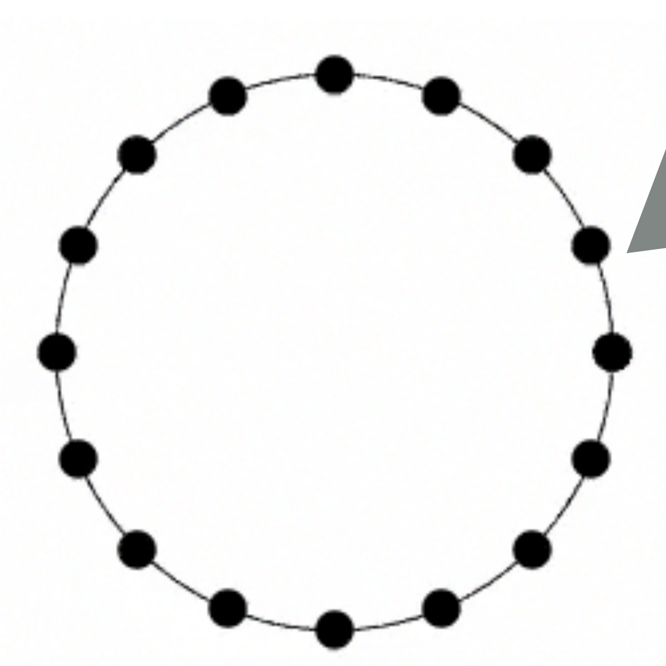
★ **一般相対論による「時空の歪みの波」**

光速度で伝搬

横波

質点間に潮汐力として働く





時空計量 g を平坦な時空と摂動 h で表す

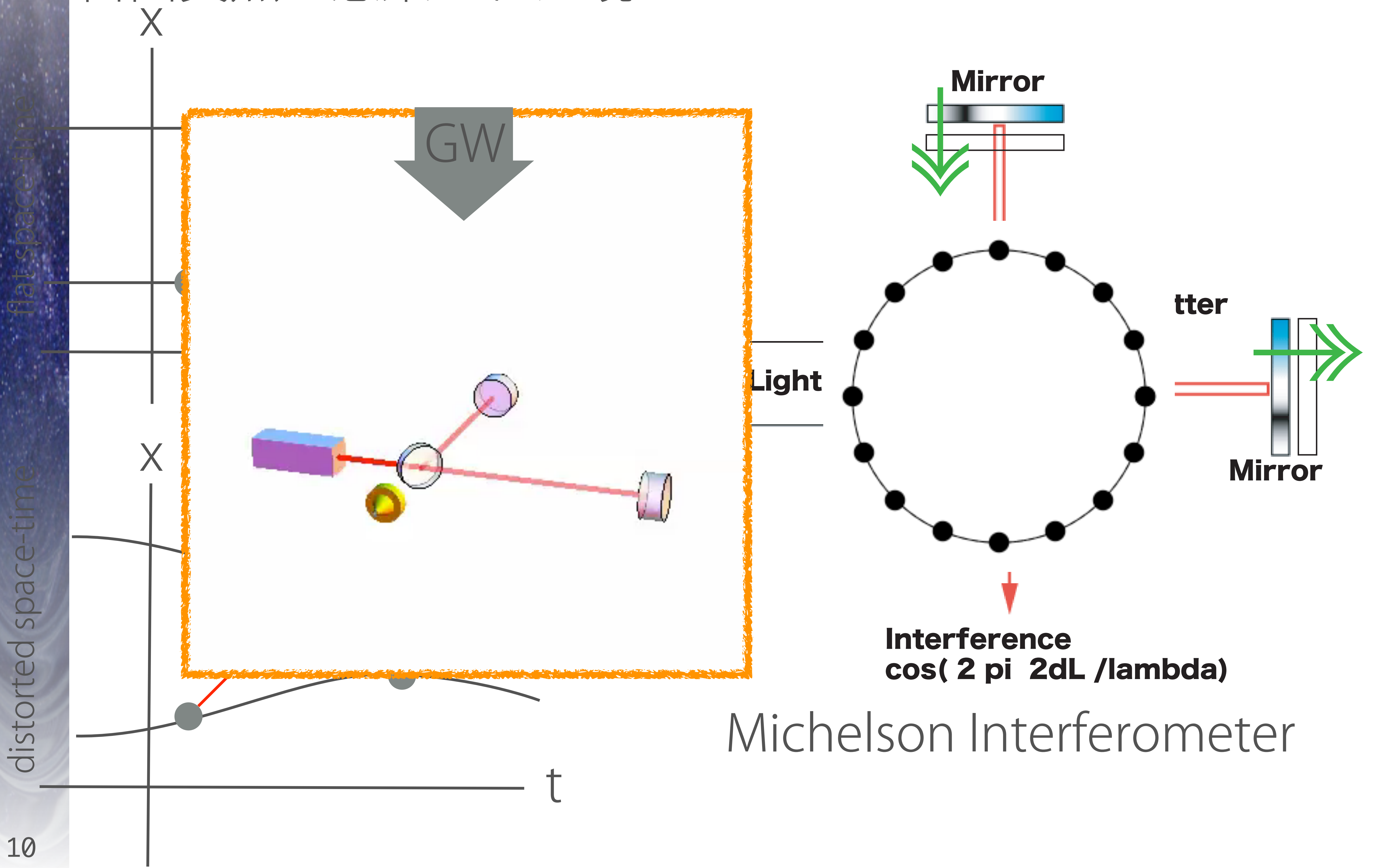
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

摂動 h の満たす波動方程式

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

重力波の検出原理

自由質点＝懸架された鏡

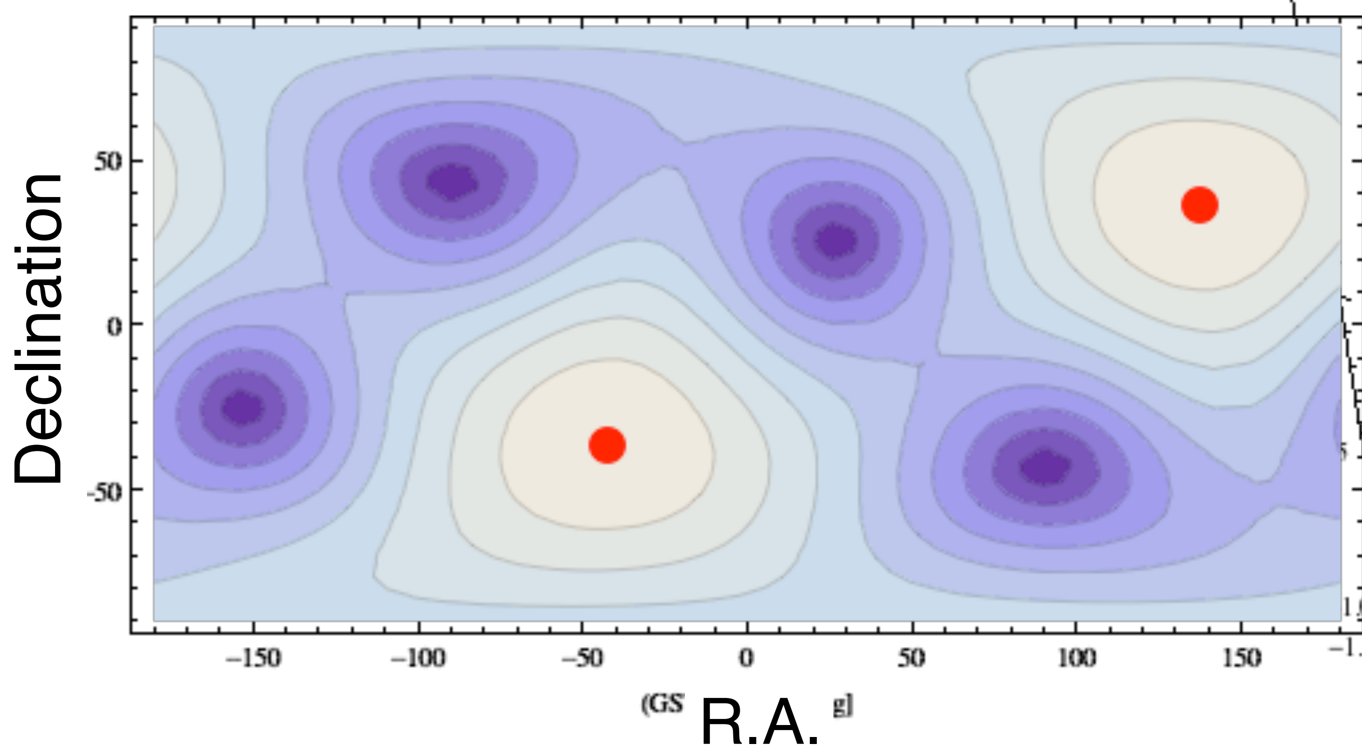


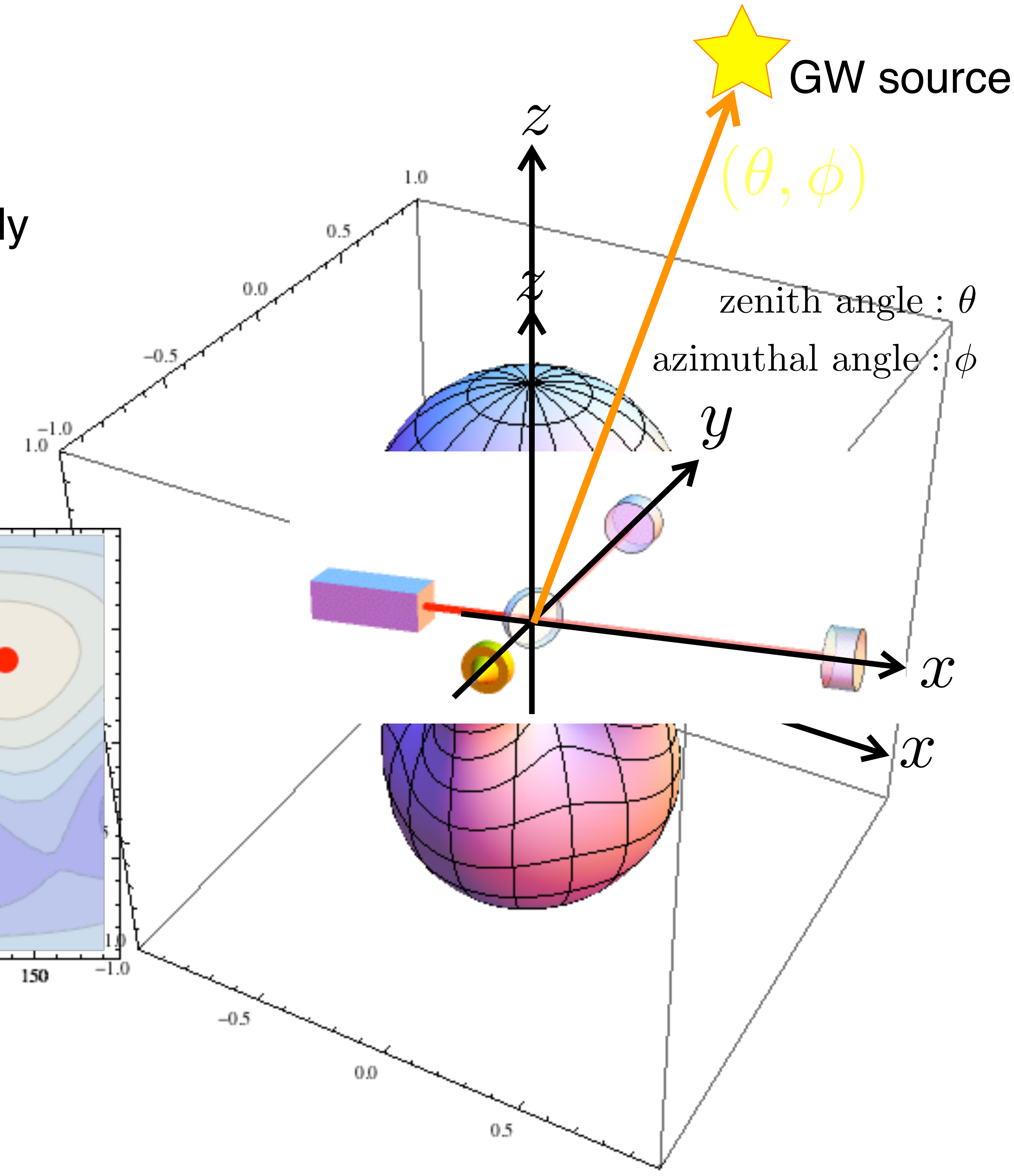
Michelson Interferometer

Antenna Pattern
(Response for source direction and polarization)

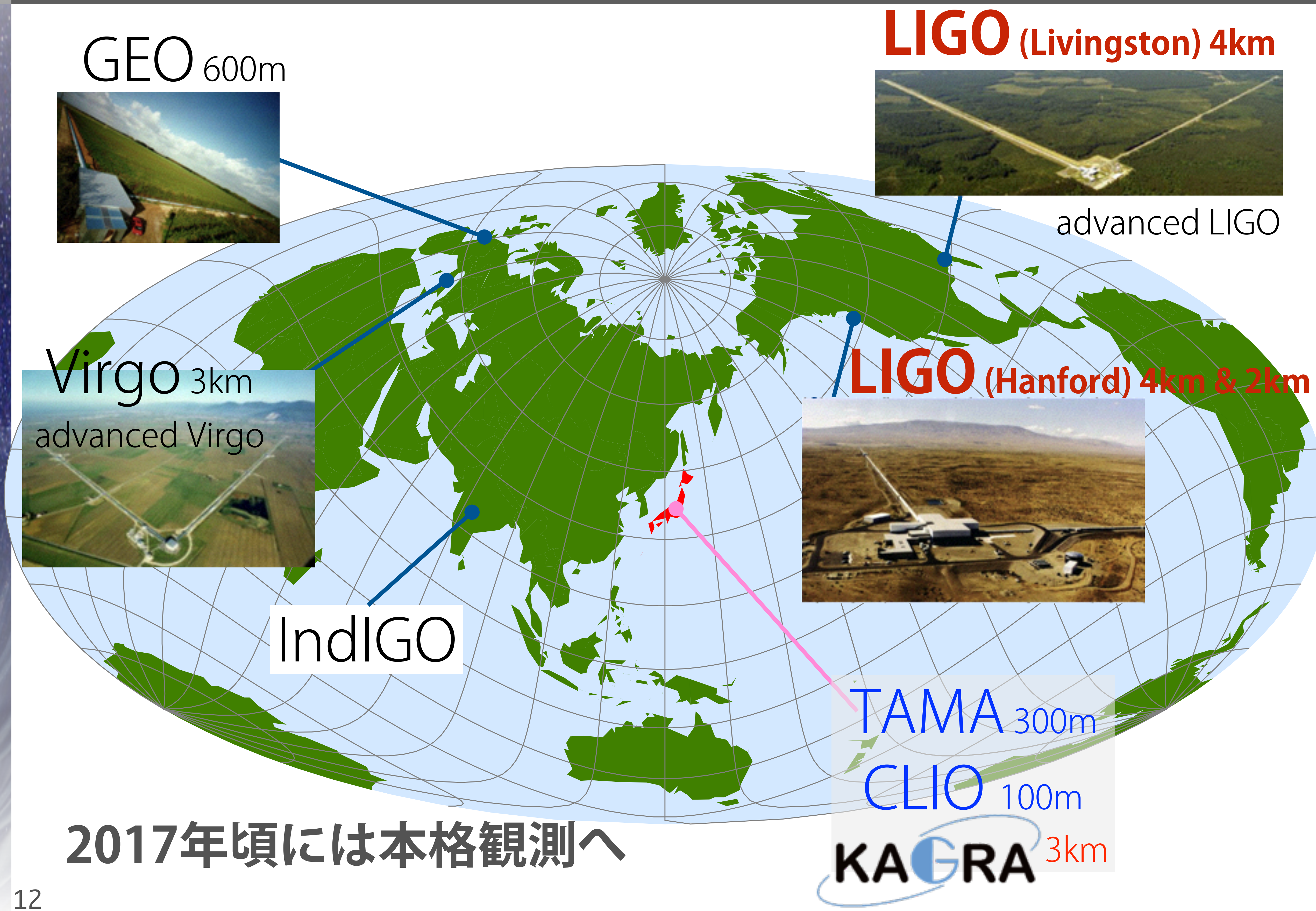
KAGRA

Interferometer's antenna pattern is widely spread as almost '*omni-directional*'.





国際観測網

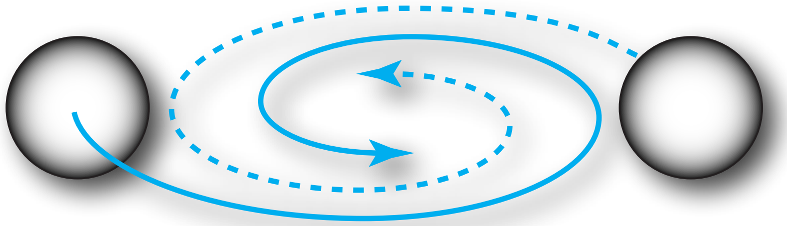


2017年頃には本格観測へ

主な重力波源

★ **突発性のイベント的なもの:**

コンパクト連星 (NS-NS, NS-BH, **BH-BH**)

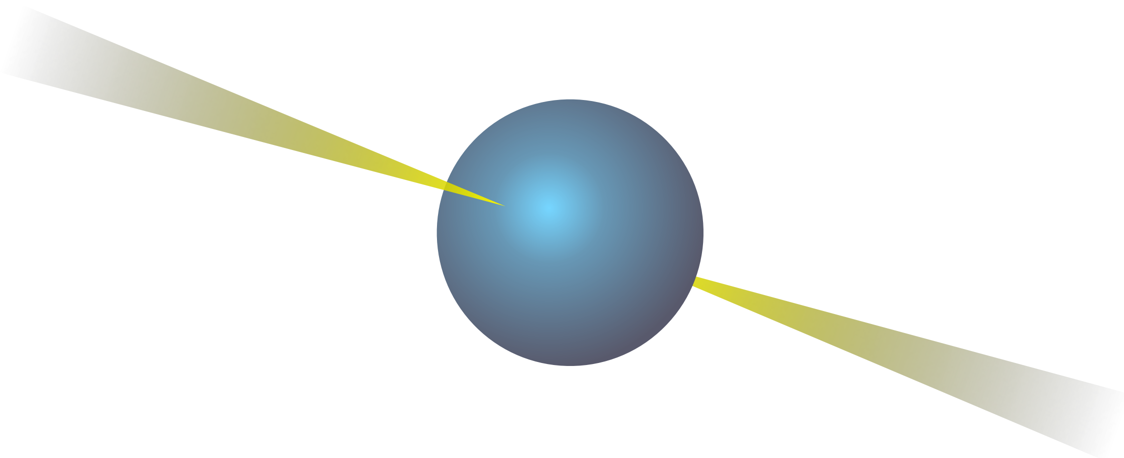


Note: 中性子星 (NS), ブラックホール (BH)

超新星爆発

BH 準固有振動

パルサーのグリッジ



★ **連続波:**

パルサー

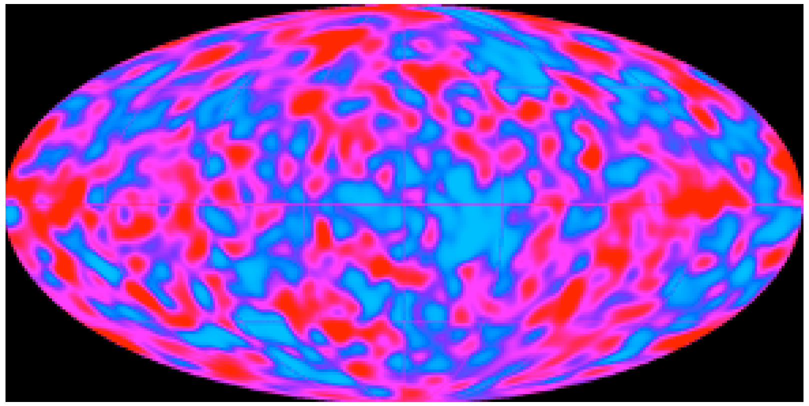
連星

★ **背景輻射重力波**

初期宇宙 (インフレーション起源など)

宇宙紐

天体起源の分離できないもの

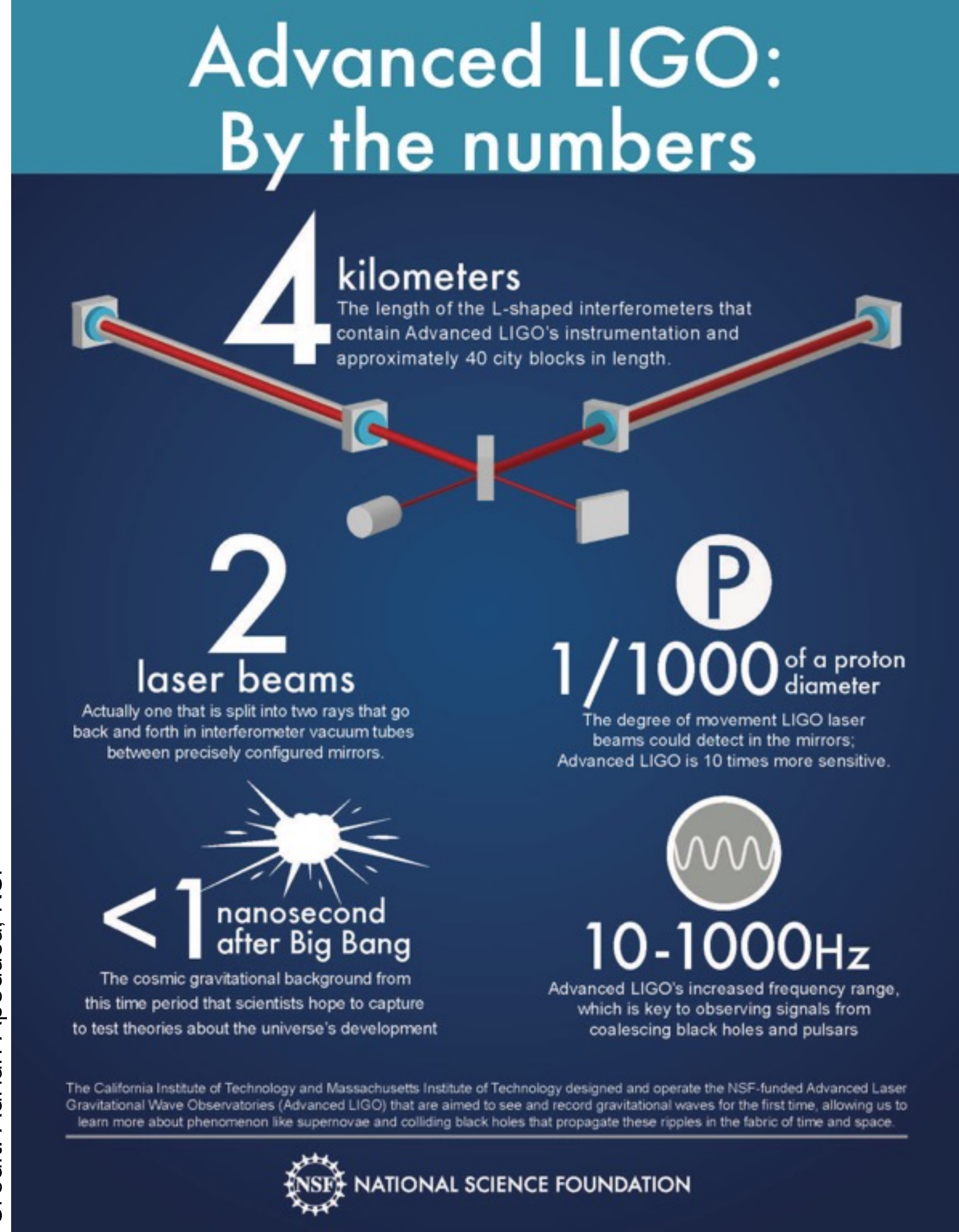


★ **(& 未知の重力波源...)**

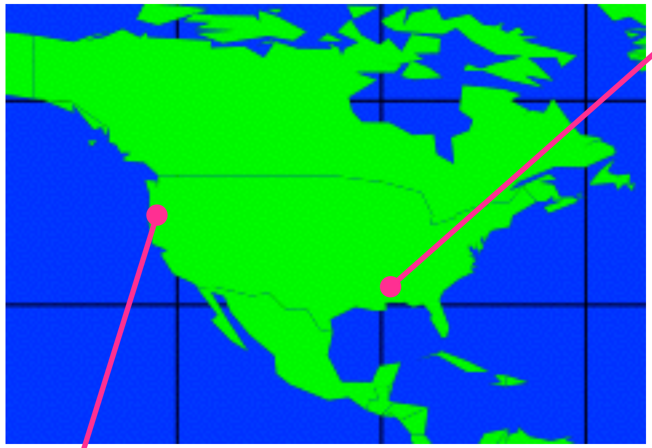
LIGO

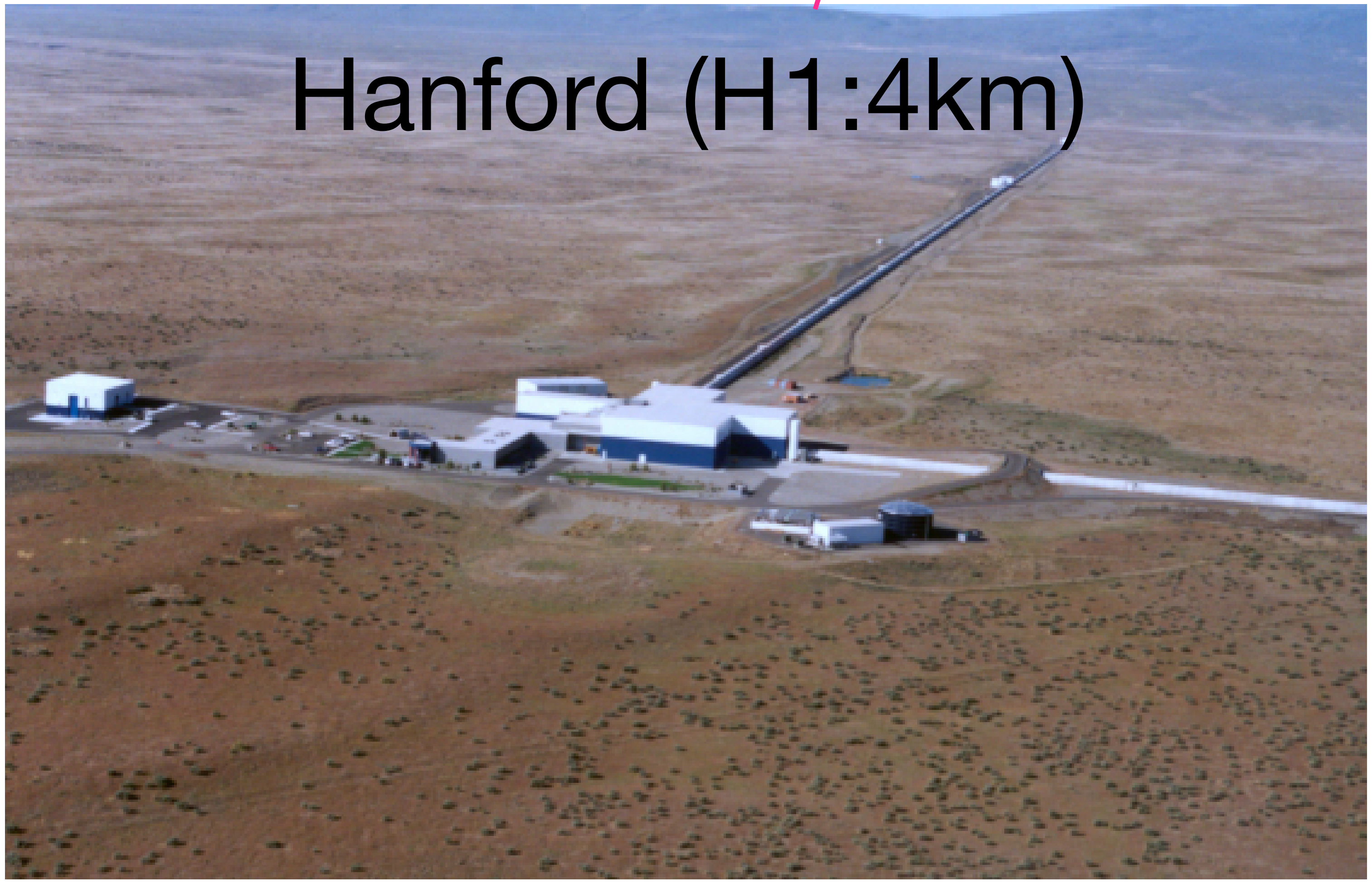
Laser
Interferometric
Gravitational
Observatory

Credit: Adrian Apodaca, NSF



LIGO





O1 観測

2015/9/18 - 2016/1/12
1100時間の２台同時観測

http://www.ligo.org/

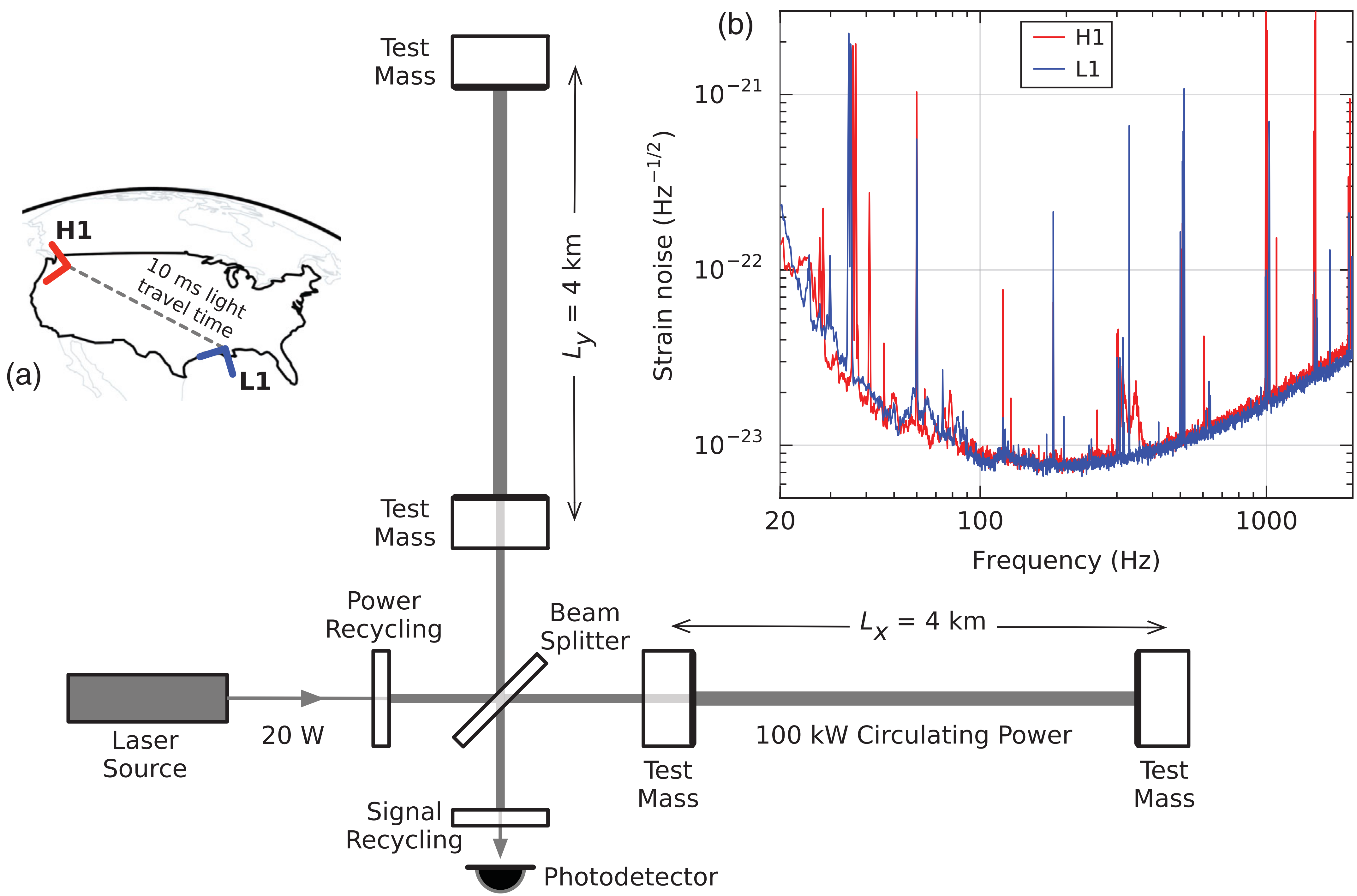
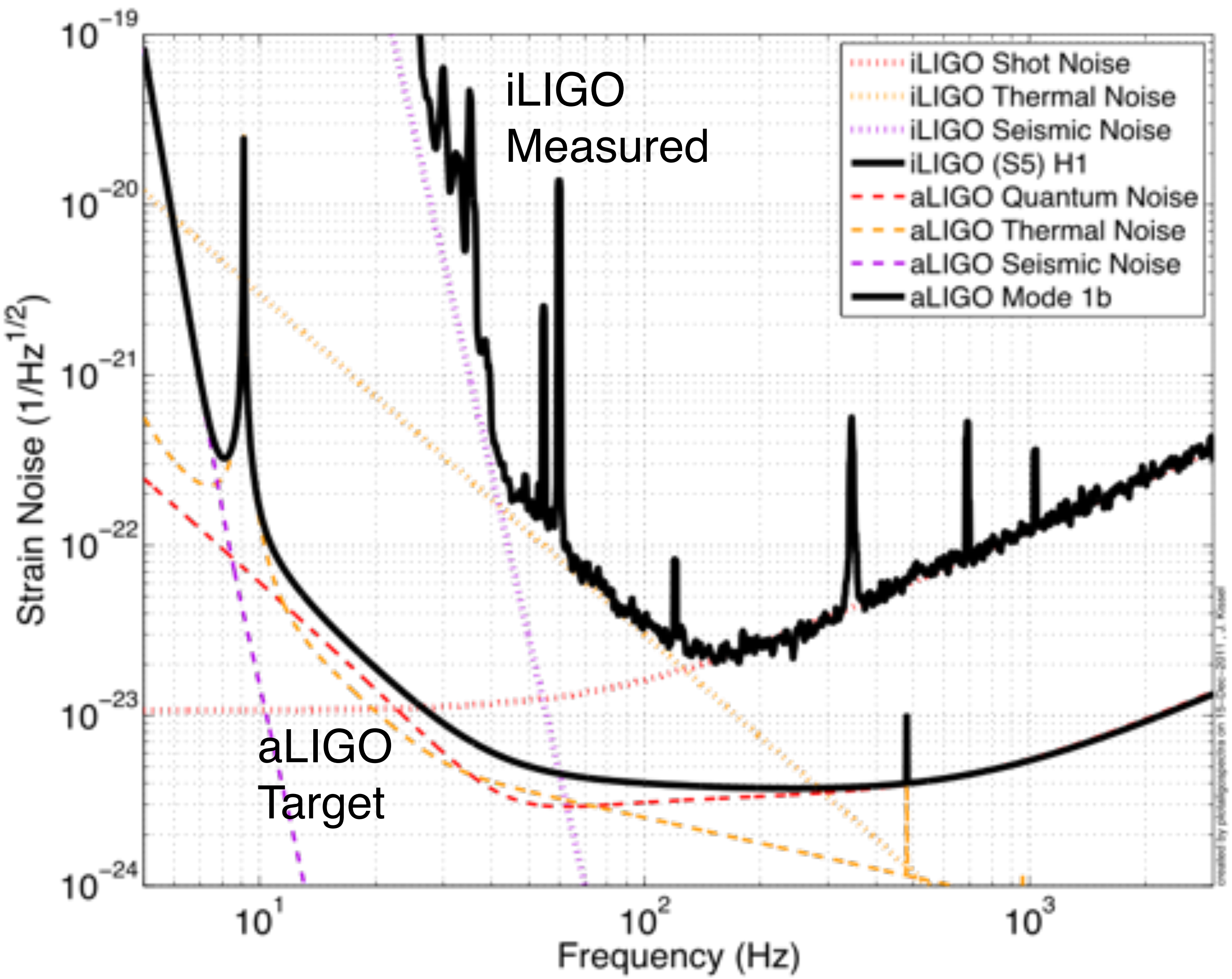


FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the 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

viewgraph by Matthew John Evans : Advanced LIGO: status and plans
at GWPAW2015 Osaka, June 2015

Advanced LIGO vs. Initial LIGO

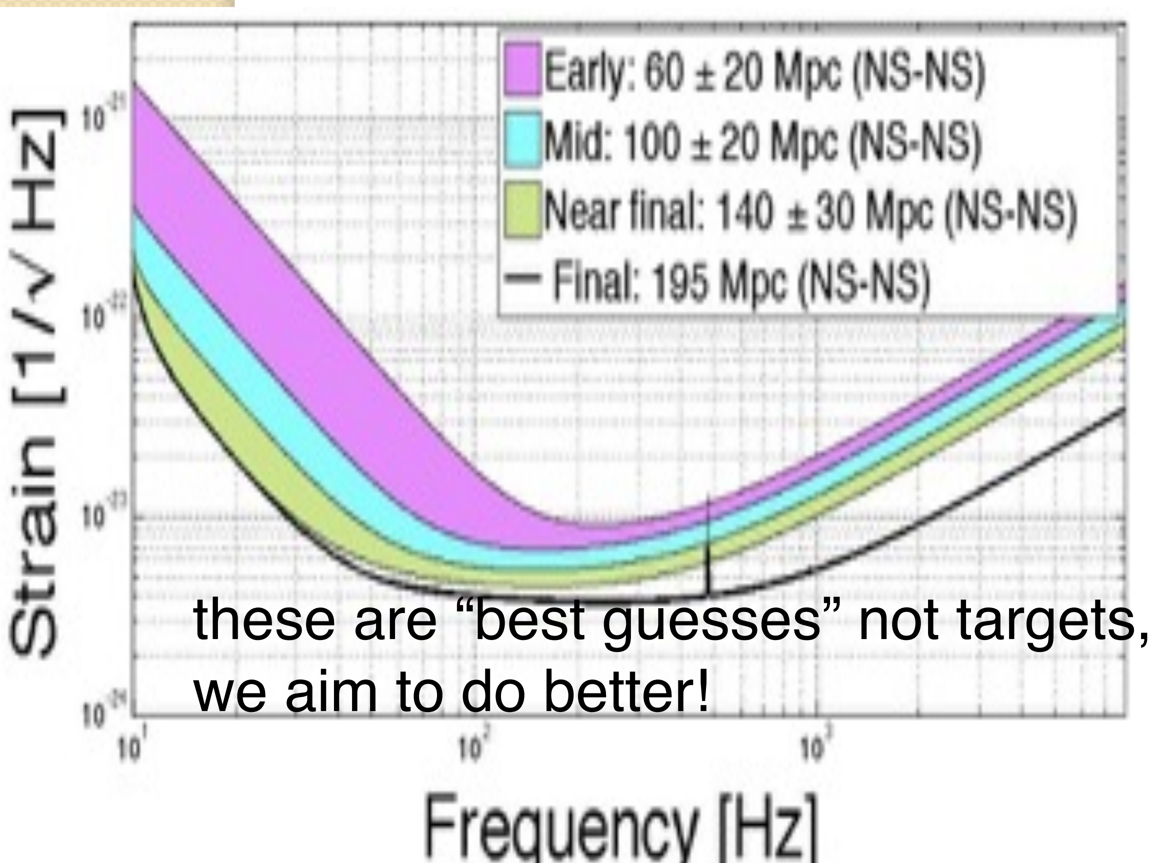


Evans: GWPAW June 2015

viewgraph by Matthew John Evans : Advanced LIGO: status and plans at GWPAW2015 Osaka, June 2015

Detection Rates

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg²	20 deg²
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48



these are “best guesses” not targets,
we aim to do better!

Neutron Star Binaries:

Advanced LIGO: ~ 200 Mpc

“Detection rate” ~ 10/year

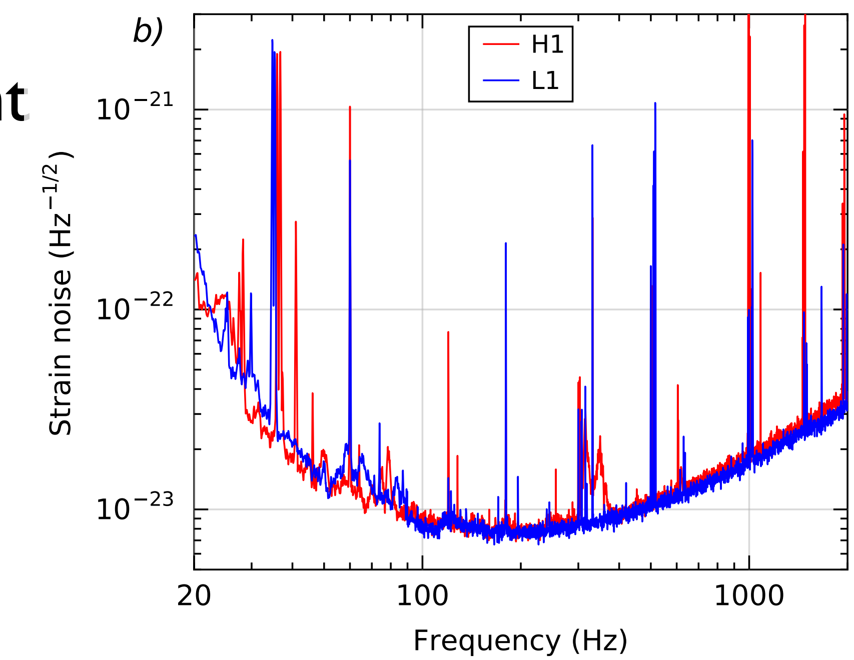
Class. Quant. Grav. **27**, 173001 (2010)

(Initial LIGO: ~15 Mpc, Rate ~1/50years)

viewgraph by Matthew John Evans : Advanced LIGO: status and plans at GWPAW2015 Osaka, June 2015

1st Observing Run

- Official O1: Sept 18th - Jan 12th
  - LIGO Hanford (H1) and Livingston (L1) only
- O1A: Sept 12 - Oct 20th (includes end of ER8) used for dataset presented here
  - Duty cycle: H1 70%, L1 55%, ~50% coincident
  - 16.5 days coincident, good quality data
- BNS range H1: ~80Mpc, L1: ~60 Mpc
- See talk from K. Cannon for search details



viewgraph by John Veitch

O2 は2016年後半。
aVirgoが稼働するのか?

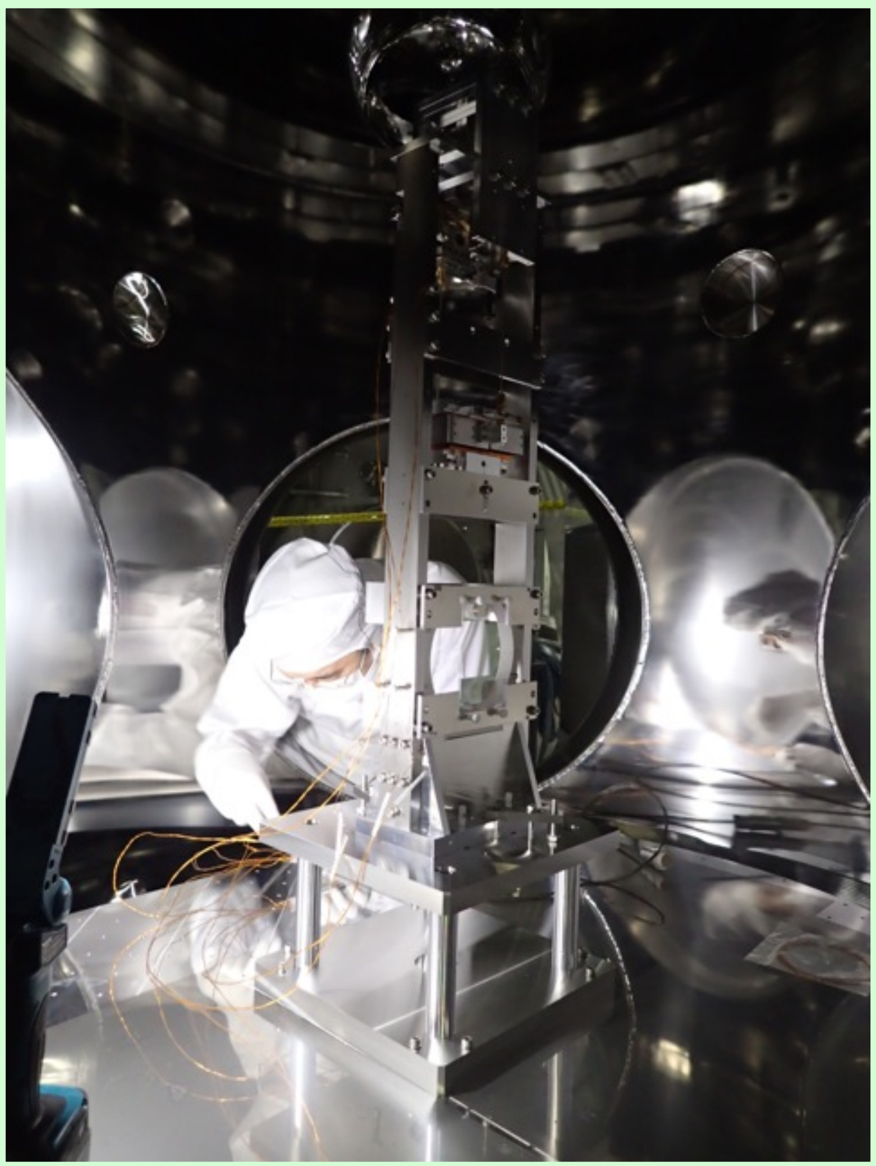
LIGO India の計画が進んでいる。

LIGO India MOU signed

News Release • March 31, 2016

The National Science Foundation's director, France A. Córdova has signed a Memorandum of Understanding with officials in India to officially mark the go-ahead for constructing a third LIGO advanced gravitational wave detector in India.

KAGRA

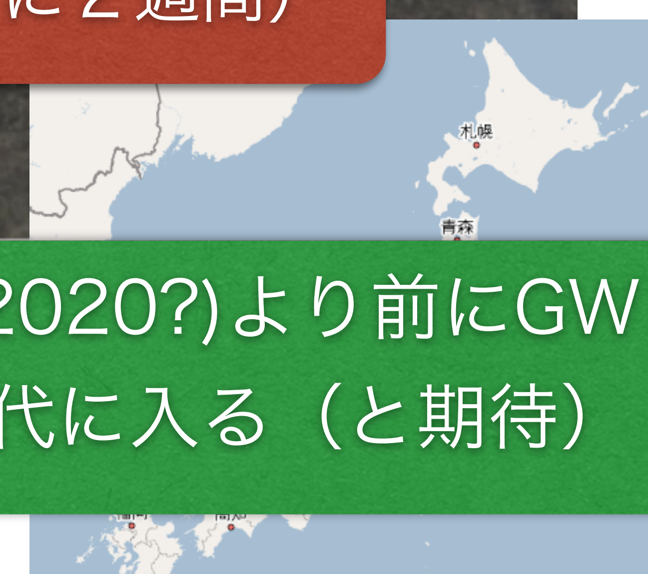


KAGRA

242 persons (78 affiliations) as of May 29, 2015

- 地下
  - 岐阜県神岡鉱山内
  - 静謐で安定な環境
- 低温鏡
  - 20K
  - サファイア基材
- 3km 基線長
- 計画
  - 2010 ：建設開始
  - 2015 ：最初の常温観測
  - 2017年度中：低温鏡での高感度観測

iKAGRA
再来週から初運転
（３月に２週間＋４月に２週間）



LSSTの稼働(2020?)より前にGW検出器４台時代に入る（と期待）

トンネル掘削完成@2014年3月

Photo : KAGRA tunnel, center corner

at July 6, 2015

(from almost same viewpoint of Oct.2014)

optics installation

KAGRA Logbook 3.7

Home | Search | Help

Displaying report 1-1 of 1.

VIS (PR3)

ayaka.shoda - 18:09, Thursday 25 February 2016 (831)

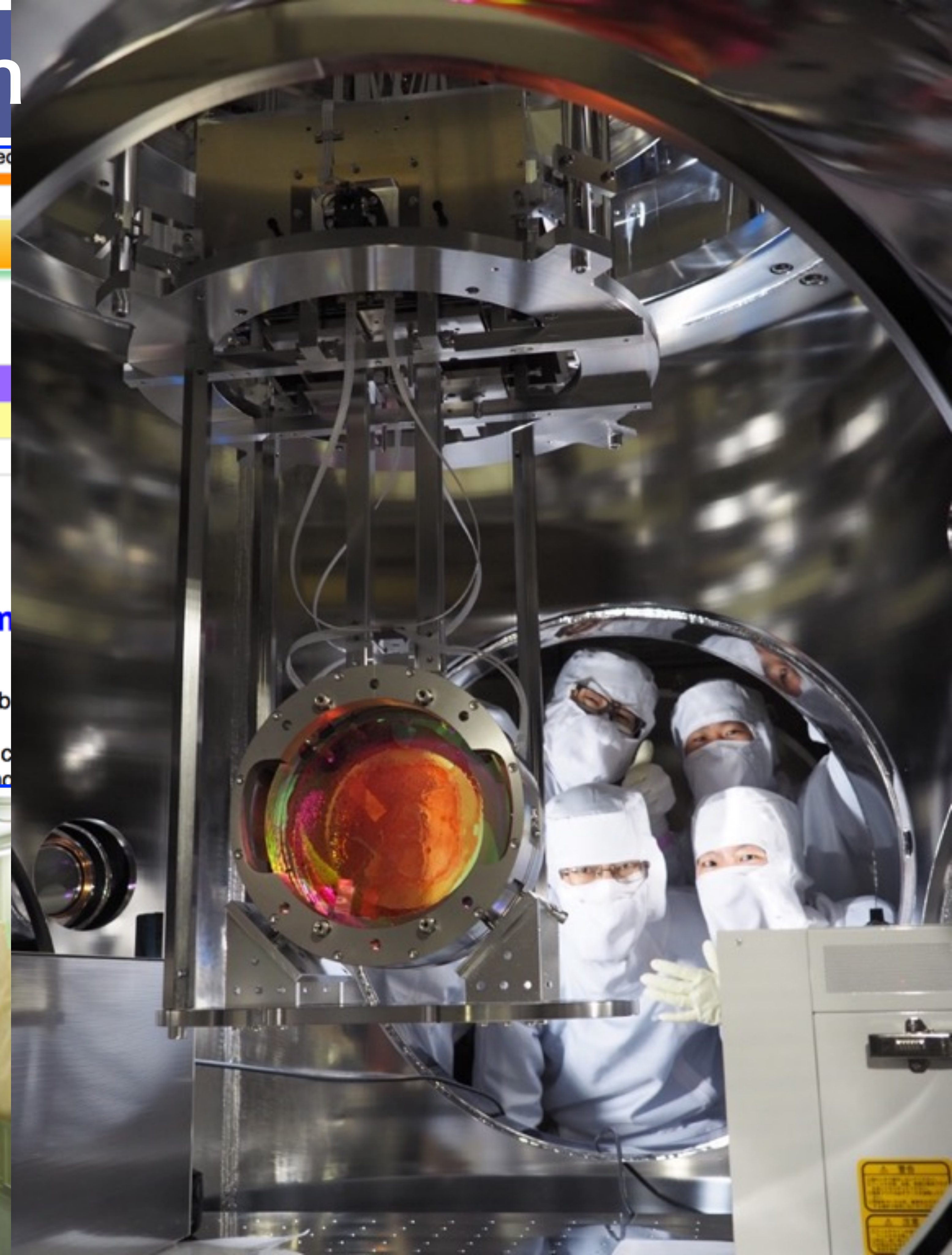
PR3 installed

[Takahashi, Okutomi, Fujii]

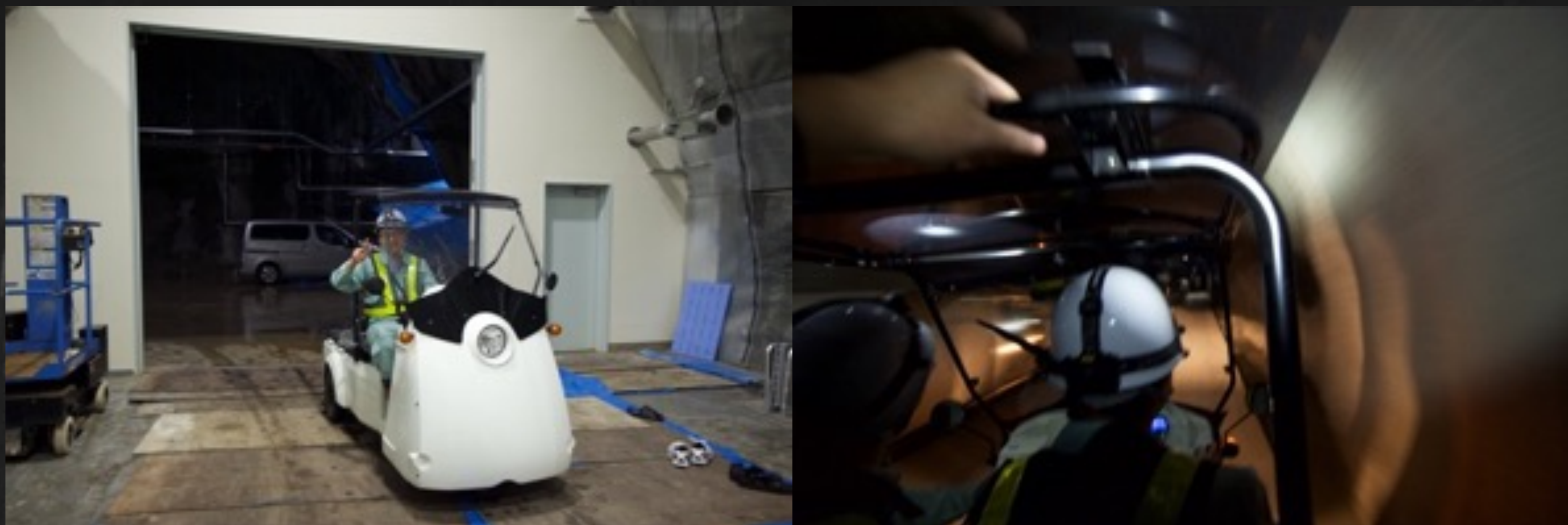
Ladies and gentlemen,

We have installed PR3 mirror into the cham
Yes, we did it!

We have set the KOACH filters around and inside the vacuum chamb
After that, the top chamber was opened.
Then, we suspended the suspension using the turnbuckles from the c
The suspension can sit on the four legs on the inner frame by aligning



エンド（3kmの端）へ

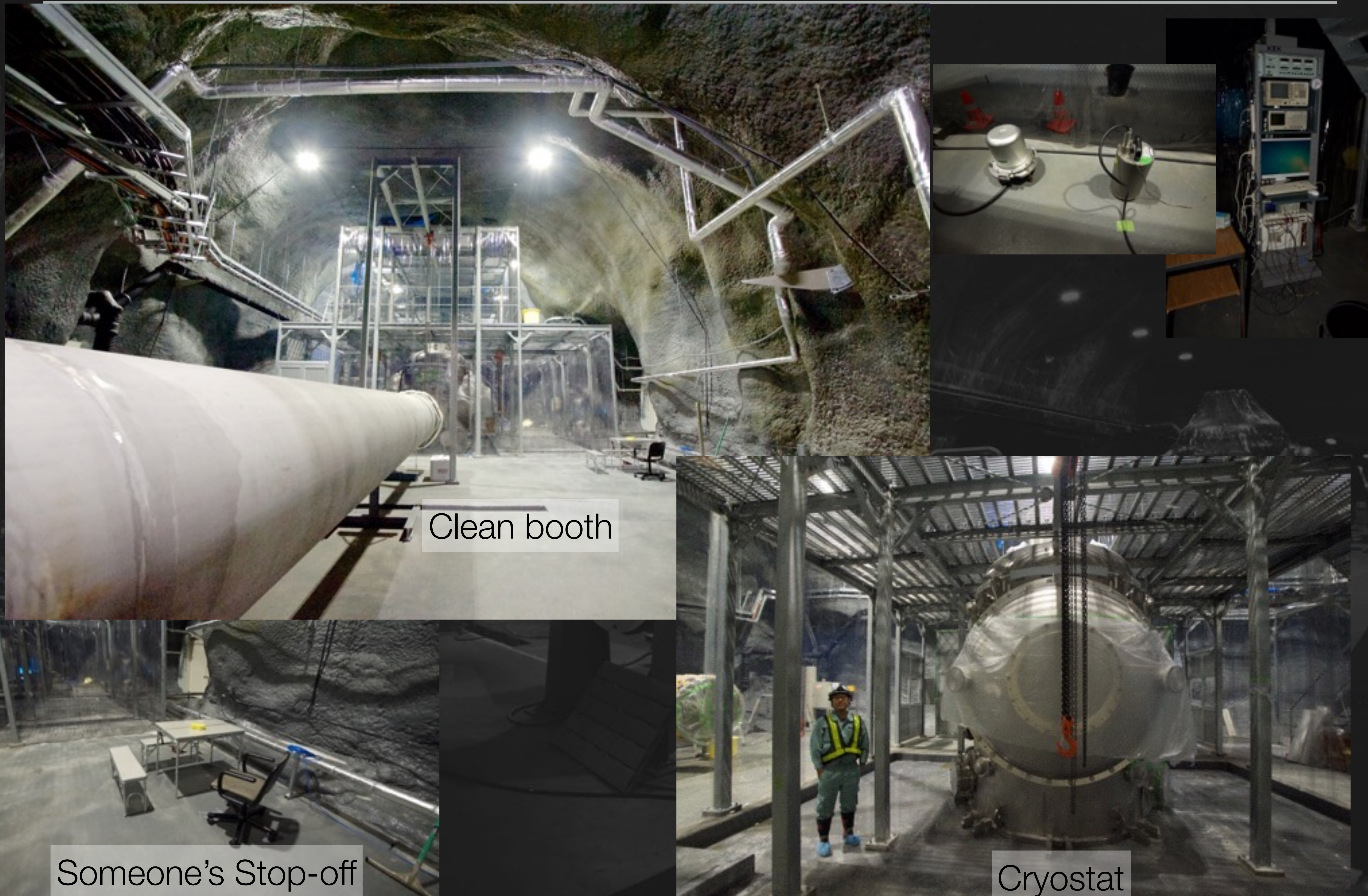


Drive by Electric car

mid of the X-arm

(almost) and of X-arm

X側エンドルーム



データ解析棟　@神岡


at Jan.2014


New office building to be built in 2013. (340m²).
KAGRA office (from Hida-city, since 2012, 140m²)

コントロール室

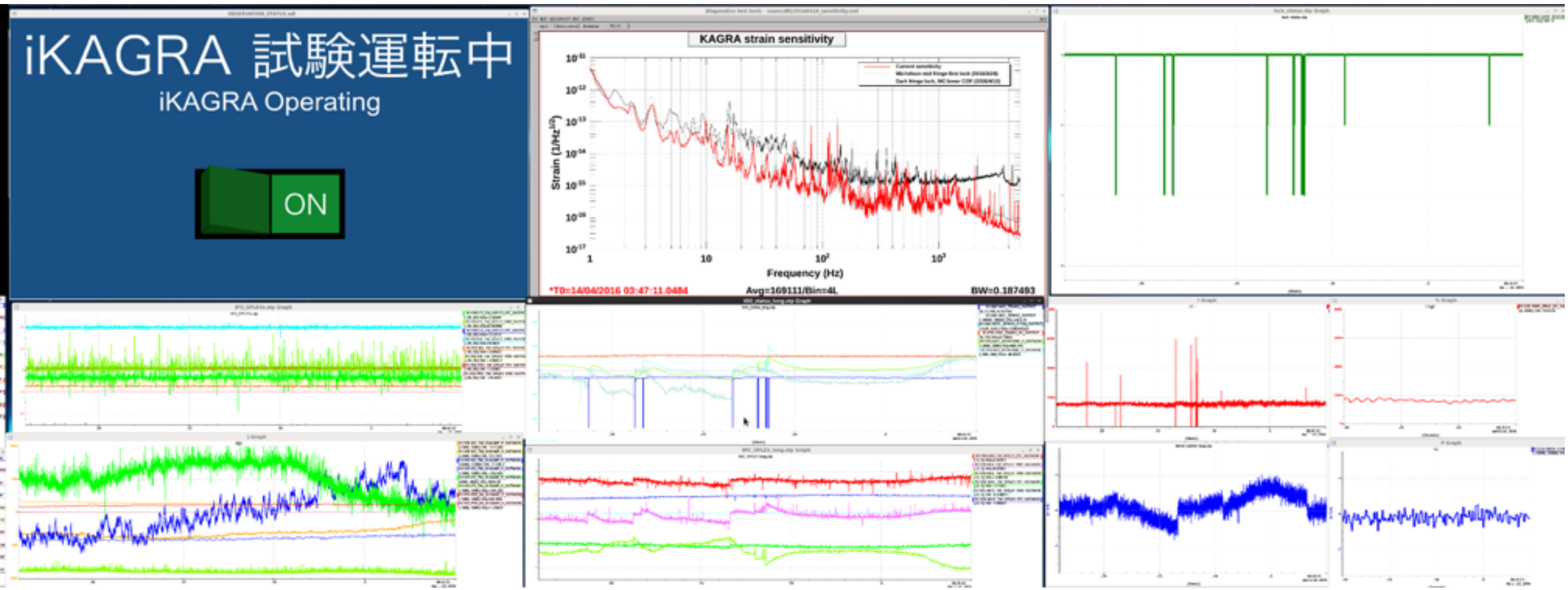
Control room, surface building at Kamioka

Spool data system
in next room

iKAGRA observation

2016/3/25-31

2016/4/11-25



低遅延解析用(low latency analysis)システム

- 観測中にリアルタイムで重力波を探索する
  - フォローアップ観測へのイベント情報も目的
- @大阪市大
  - クラスタ計算機
  - KAGRA（神岡）からデータを転送
  - total 392 cores
  - 288 TiB storage (144 TiB x 2sets)

再び、GW150914について…

イベント名：GW150914

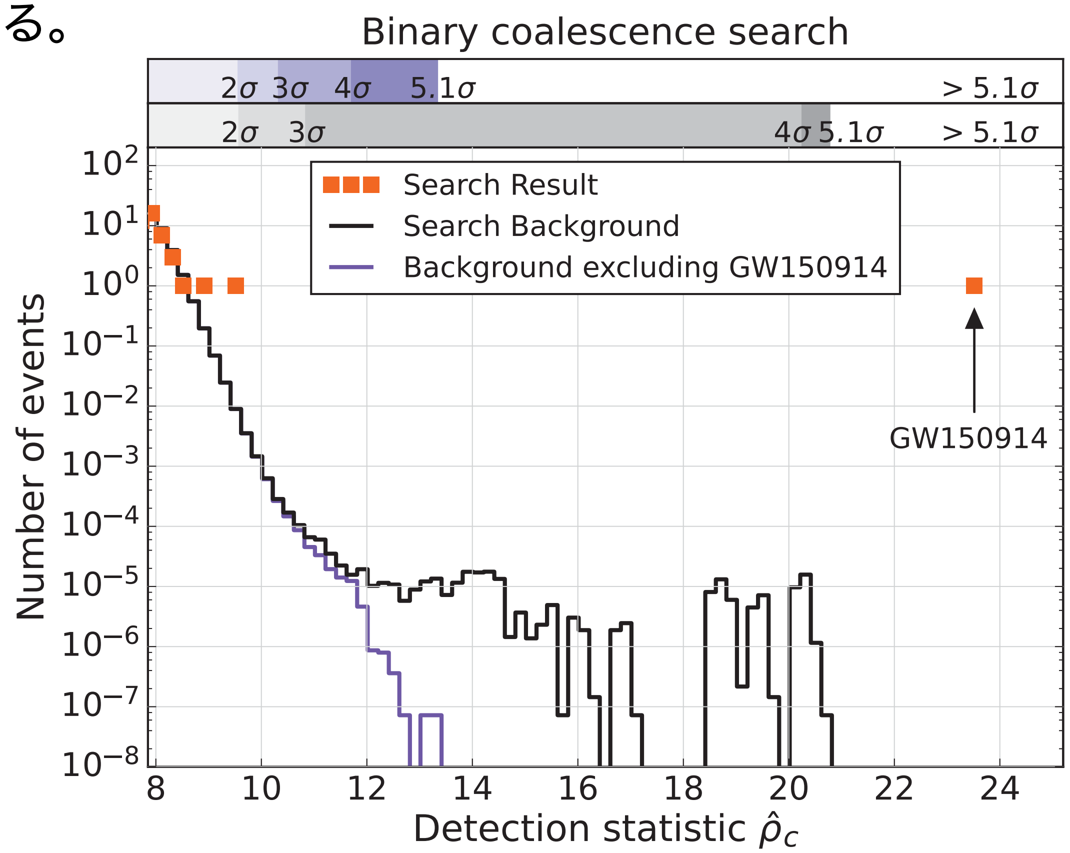
- 番号は見つかった日付 2015年9月14日
- LIGOの２台の検出器(Hanfordサイト、Livingstonサイト)で同時観測した。
- 実はこの日は LIGO o1ランの２日前。

重要な事実

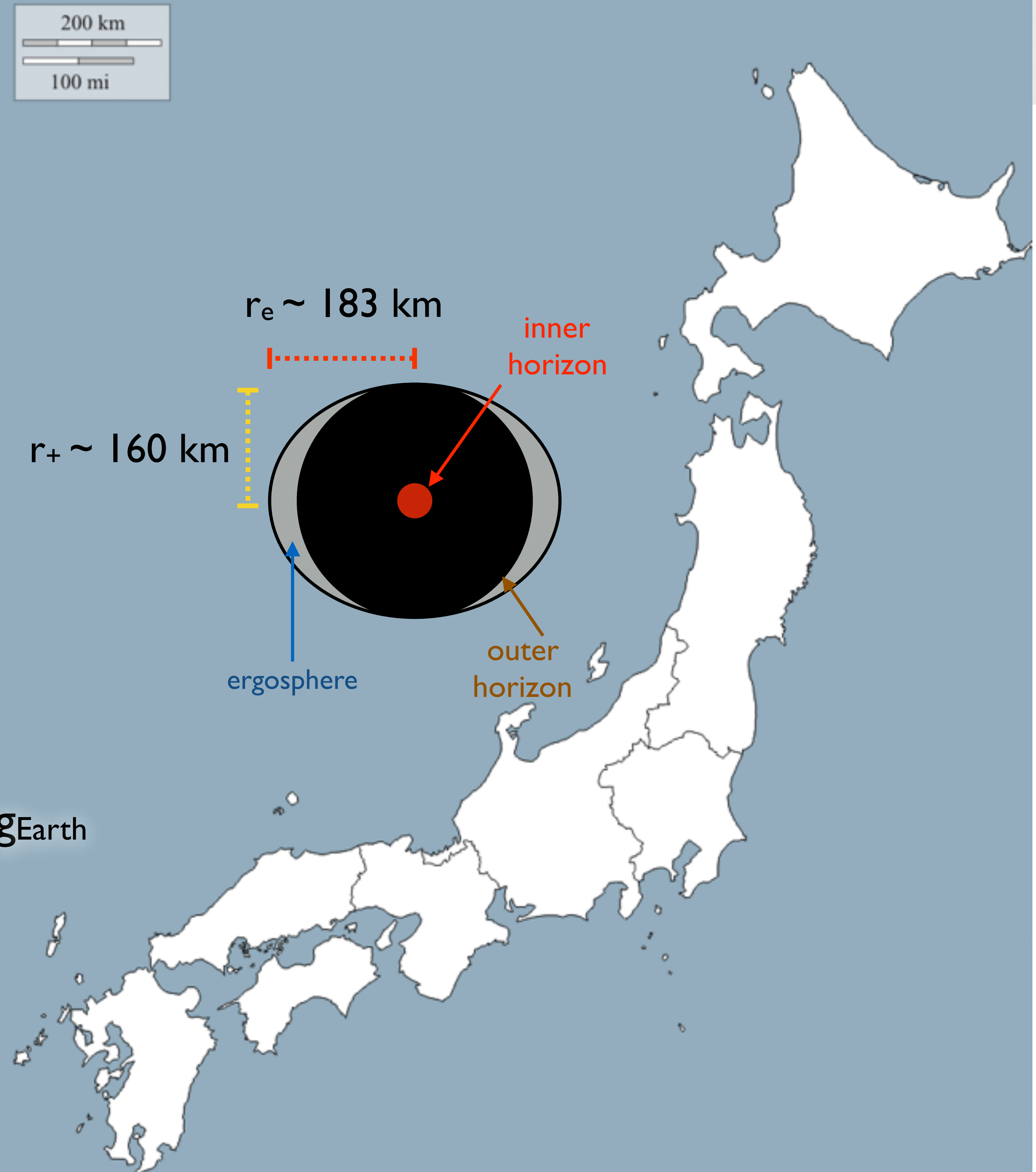
- 連星合体重力波である。
- ２つの星はブラックホールである。 -ブラックホールの初めての直接検出。
- ２つの星が合体してできるさらに大きなブラックホール形成時の、「準固有振動」が確認されている（ように見える）。これはブラックホール時空の基礎的性質である。

シグナルの大きさと有為性

- S/N ~24
    - CBCマッチドフィルターでの値
    - ２つのサイトの"combined"となっている。
- 有為性 5.1 σ
    - FAR < 1回/203000年に一回 (←Binary search)



- $M_f \sim 62 \pm 4\ M_\odot$
  - due to spin $\sim 4\ M_\odot$
  - 20 million Earths
- $f_{rot} \sim 100$ Hz (G_2)
- $f_{22} \sim 250$ Hz (B_3)
- $\tau_{22} \sim 4$ms
- Surface gravity $\sim 2\times10^{10}\ g_{Earth}$
- Equatorial speed ~ 0.4 c
- Area $\sim 3\times10^5$ km

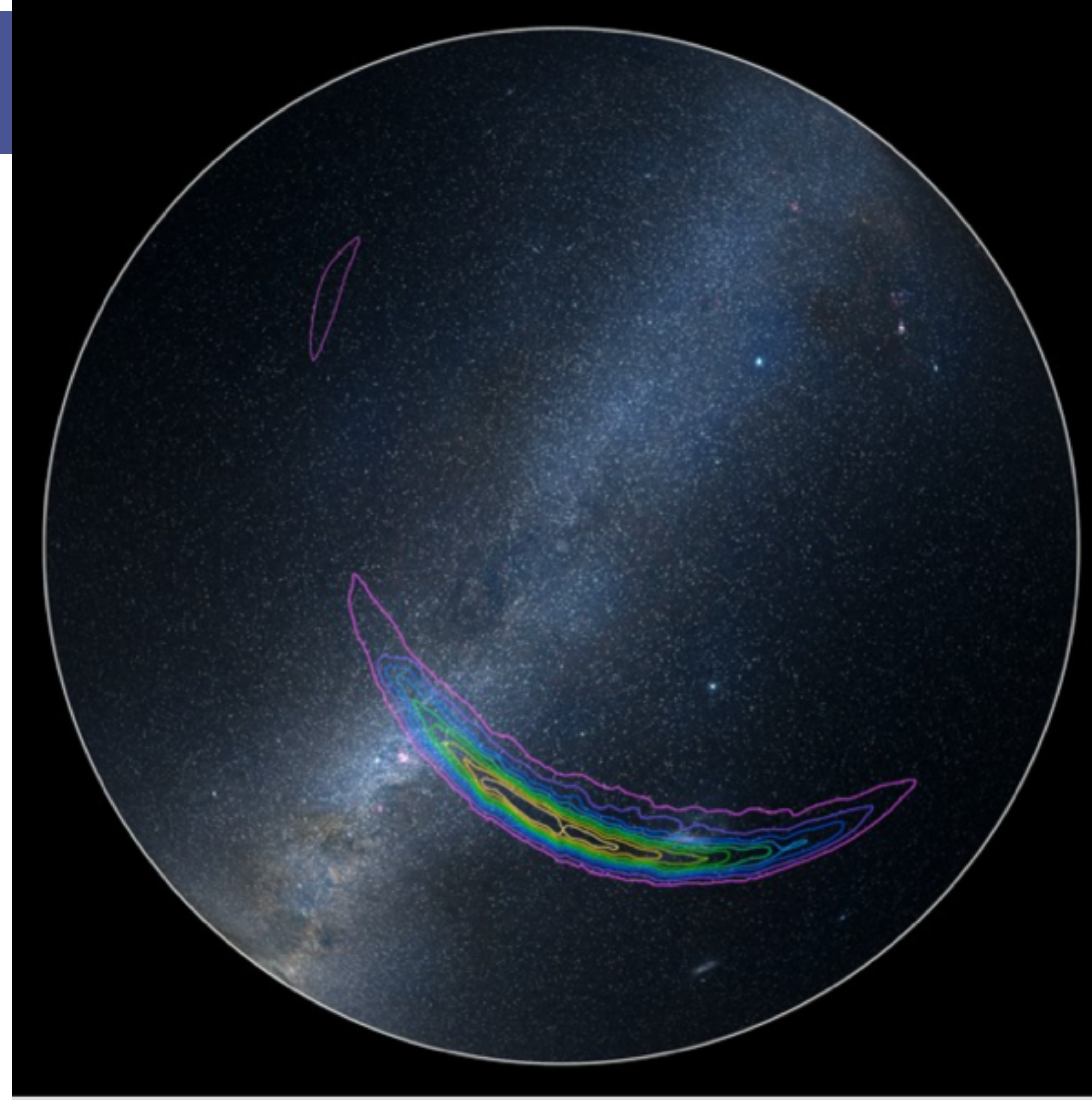


viewgraph by John Veitch

到来方向

検出器の時間差

２台の信号の振幅比

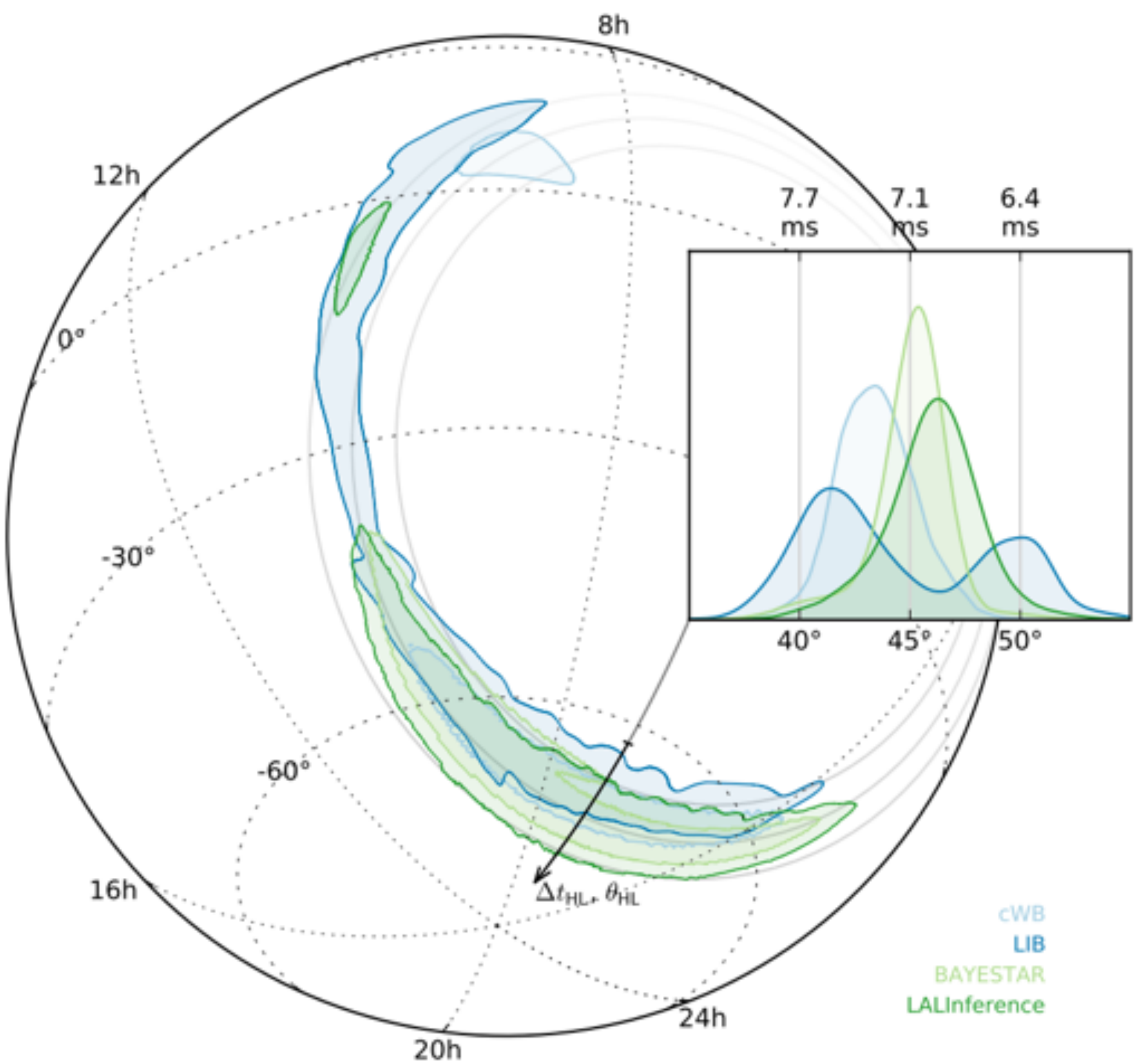


Where the Gravitational Waves Came From

Image Credit: LIGO/Axel Mellinger

The approximate location of the source of gravitational waves detected on September 14, 2015, by the twin LIGO facilities is shown on this sky map of the southern hemisphere. The colored lines represent different probabilities for where the signal originated: the purple line defines the region where the signal is predicted to have come from with a 90 percent confidence level; the inner yellow line defines the target region at a 10 percent confidence level.

Future Outlook
Localisation



LSC

22

VIRGO

viewgraph by John Veitch

Parameter Estimation

arXiv:1602.03840

Properties of the binary black hole merger GW150914

The LIGO Scientific Collaboration and The Virgo Collaboration

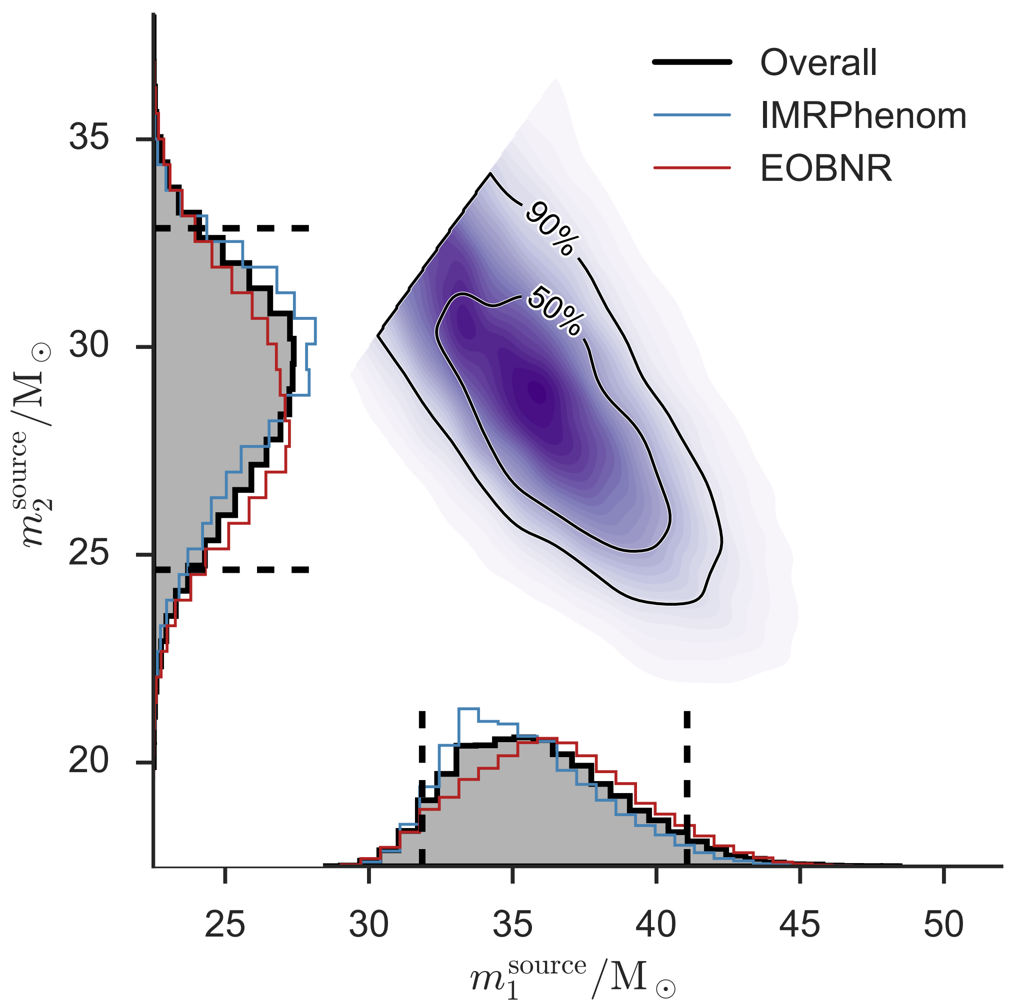


FIG. 1. Posterior PDFs for the source-frame component masses $m_1^{\rm source}$ and $m_2^{\rm source}$, where $m_2^{\rm source} \leq m_1^{\rm source}$. In the 1-dimensional marginalised distributions we show the Overall (solid black), IMRPhenom (blue) and EOBNR (red) PDFs; the dashed vertical lines mark the 90% credible interval for the Overall PDF. The 2-dimensional plot shows the contours of the 50% and 90% credible regions plotted over a colour-coded posterior density function.

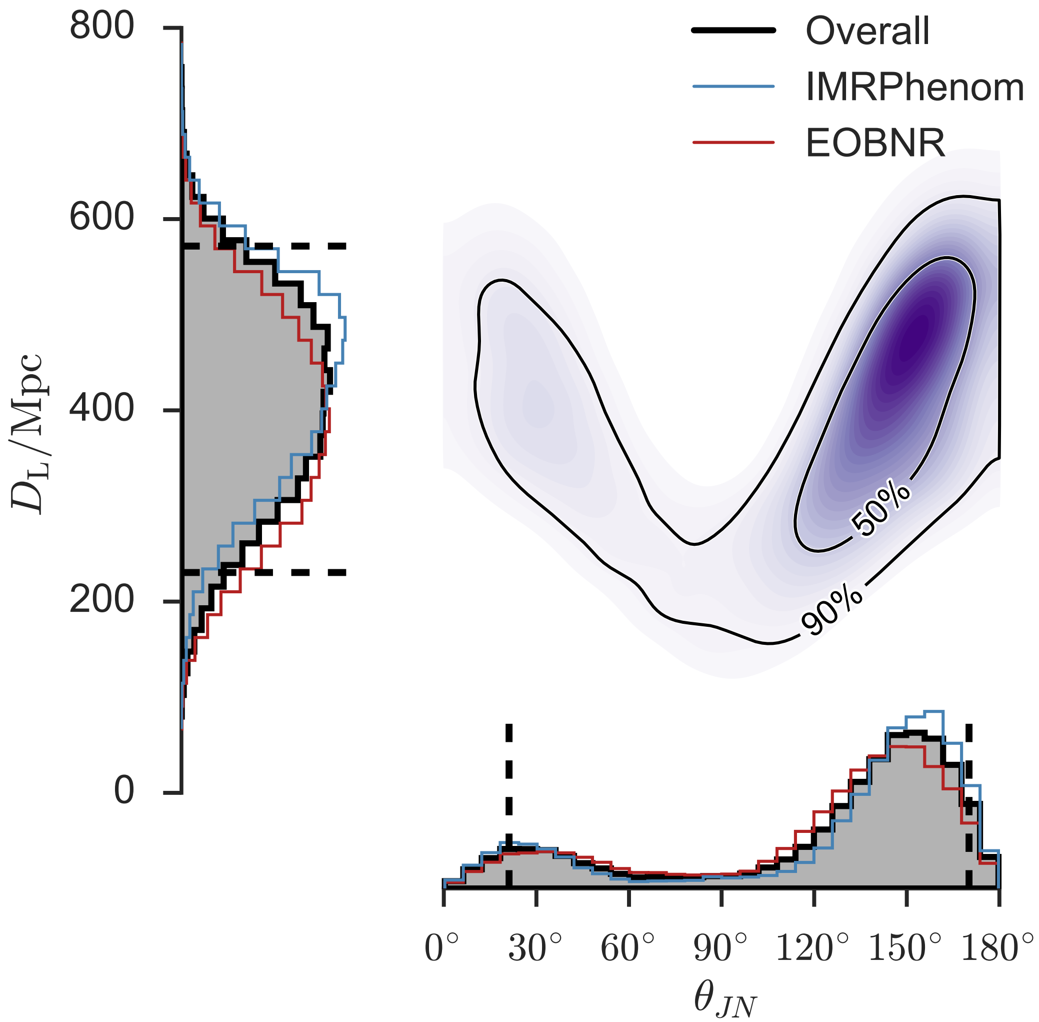
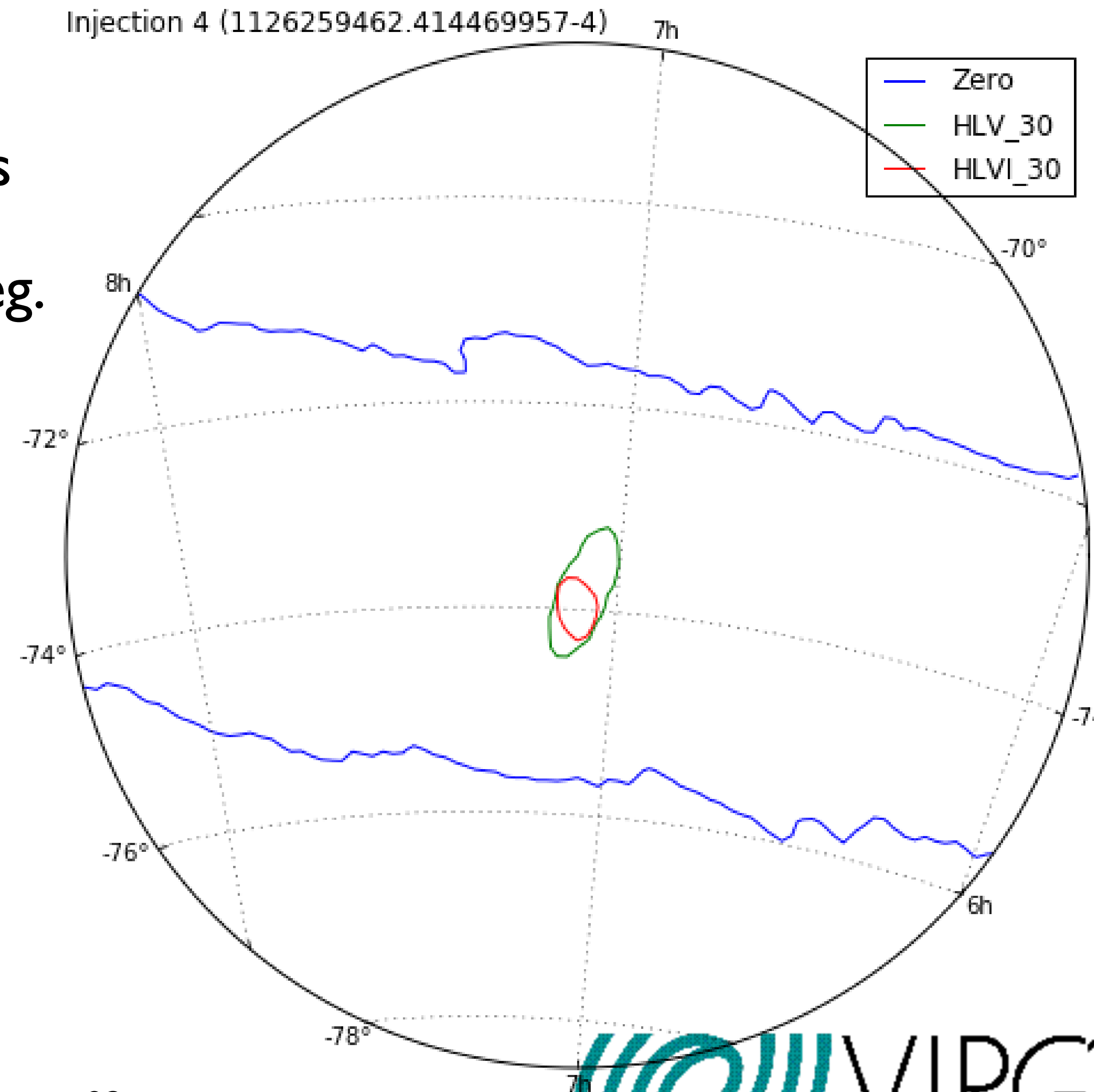


FIG. 2. Posterior PDFs for the source luminosity distance $D_{\rm L}$ and the binary inclination θ_{JN}. In the 1-dimensional marginalised distributions we show the Overall (solid black), IMRPhenom (blue) and EOBNR (red) PDFs; the dashed vertical lines mark the 90% credible interval for the Overall PDF. The 2-dimensional plot shows the contours of the 50% and 90% credible regions plotted over a colour-coded PDF.

Future Outlook Localisation

- Studied simulated replicas with different network configurations
- HL Design sensitivity: ~50 sq. deg.
- HLV Design: ~4.6 sq. deg.
- HLVI Design: ~3.9 sq. deg.
- KAGRA!
- SNR goes from
  - 25→70→87→97



LSC

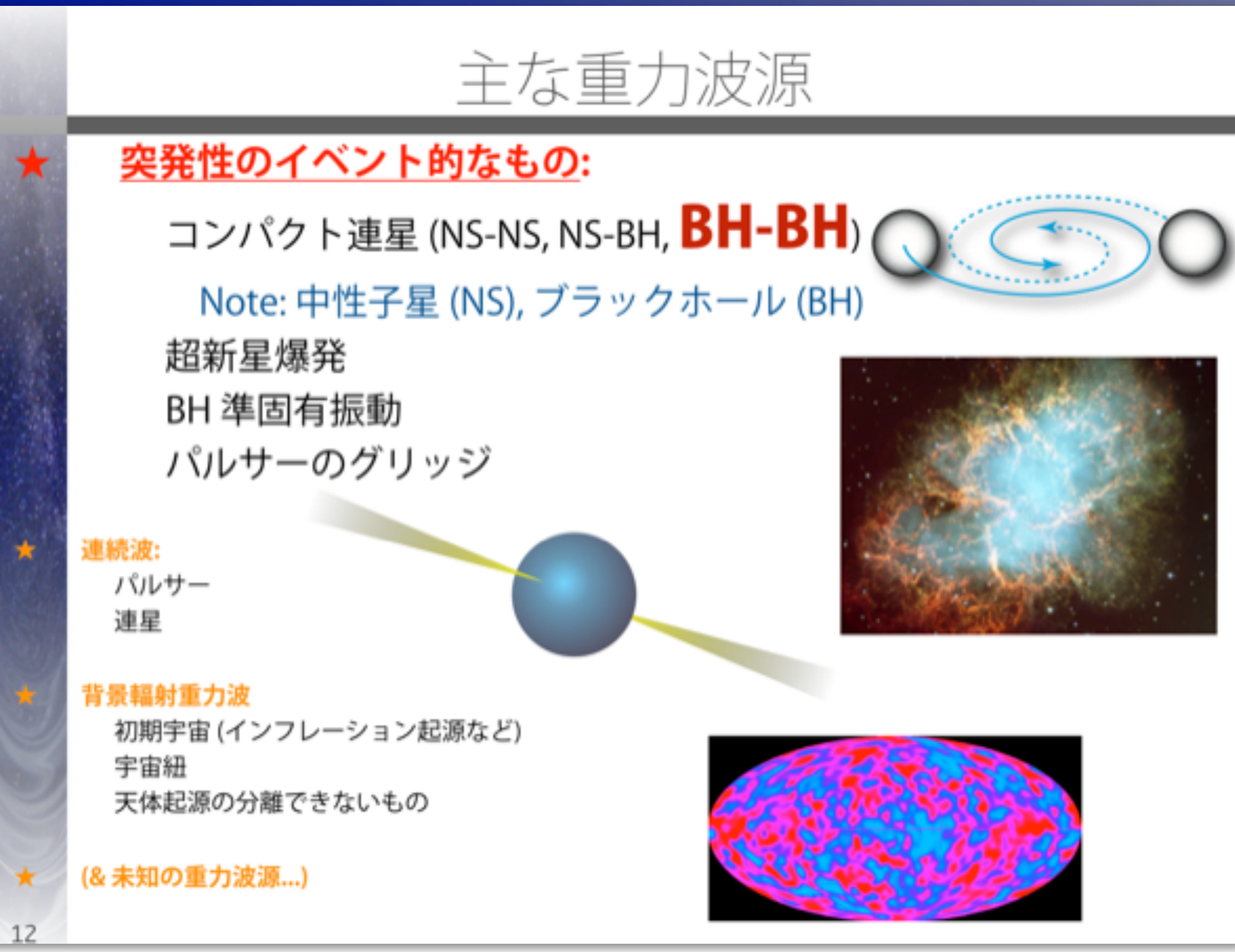
VIRGO

23

viewgraph by John Veitch

重力波天文学・重力波天体物理学の幕開け?!

KAGRA



長らく、NS-NSが本命であるとされてきた。また超新星爆発も重力波源として有望視されてきた。これらの重力波源は、依然として興味深い対象であることは間違いない。

しかし、今回いきなり<u>BH-BHからの重力波</u>が見つかった。

NS-NSと違って、以下のことがすぐに物理の問題として浮上した。

数値相対論波形の活躍

（NS-NSであれば、おそらく長いPN波形での話題になったのではないか？）

ブラックホール準固有振動は見えているか、否か？

→基礎物理の問題の研究対象になる。

LIGOはイベント付近の検出器信号を公開しています。

https://losc.ligo.org/events/GW150914/

LIGO

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

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- Timelines
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- Data Analysis Projects
- Acknowledgement

Data release for event GW150914

This page has been prepared by the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration to inform the broader community about a confirmed astrophysical event observed by the gravitational-wave detectors, and to make the data around that time available for others to analyze. There is also a **technical details** page about the data linked below, and feel free to **contact us**. This dataset has the Digital Object Identifier (doi) http://dx.doi.org/10.7935/K5MW2F23

Summary of Observation

The event occurred at GPS time 1126259462.39 == September 14 2015, 09:50:45.39 UTC. The false alarm rate is estimated to be less than 1 event per **203,000 years**, equivalent to a significance of **5.1 sigma**. The event was detected in data from the LIGO Hanford and LIGO Livingston observatories.

- There are Science Summaries, covering the information below in ordinary language.
- There is a one page factsheet about GW150914, summarizing the event.

How to Use this Page

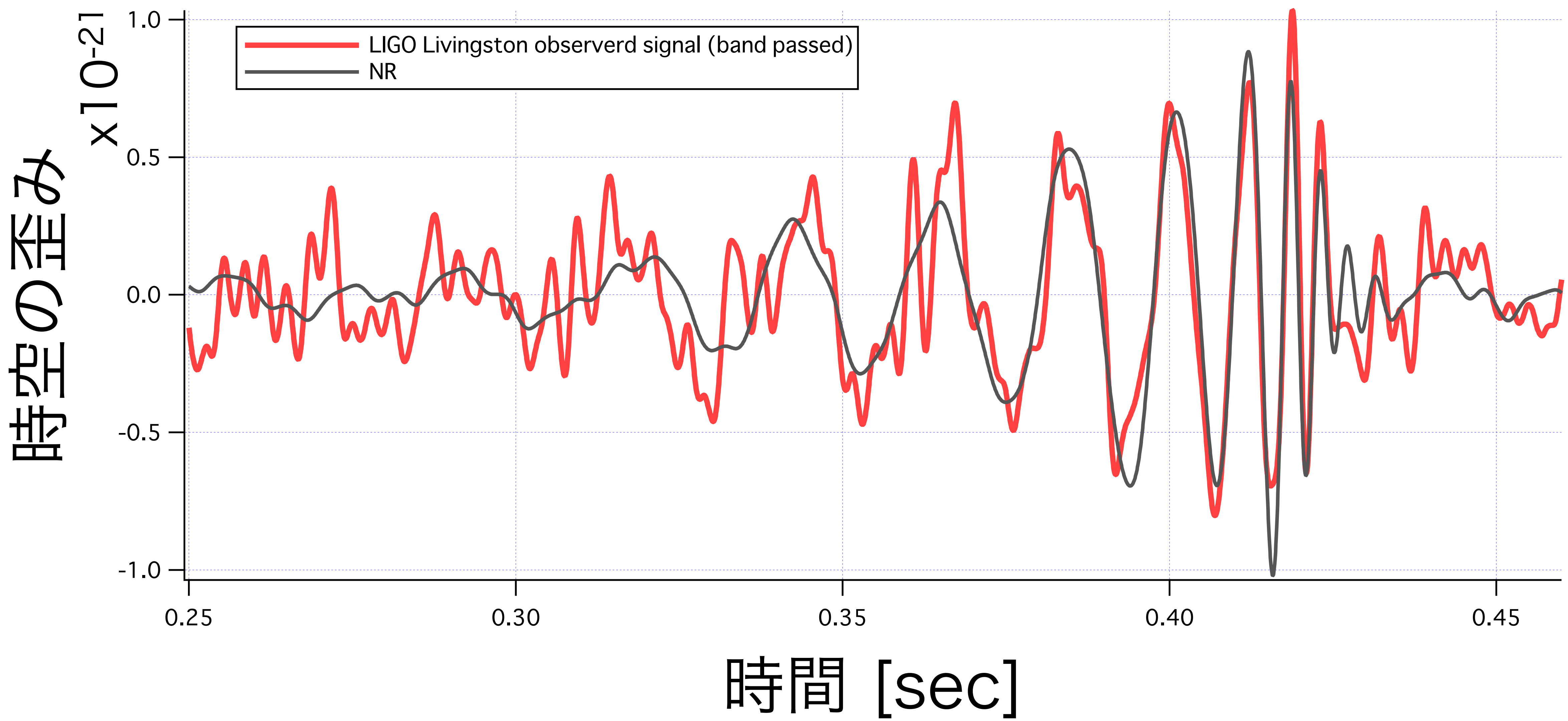
- **Click on the section headings below to show available data files.**
  - (click to Open/Close all sections)
- There are lots of data files available in the sections below, look for the word **DATA**.
- Click on each thumbnail image for larger image.
- See the papers linked below for full information, references, and meaning.
- Many of the data files linked below have heterogeneous formatting; if you have any questions, please contact us.

The G150914 detection paper:

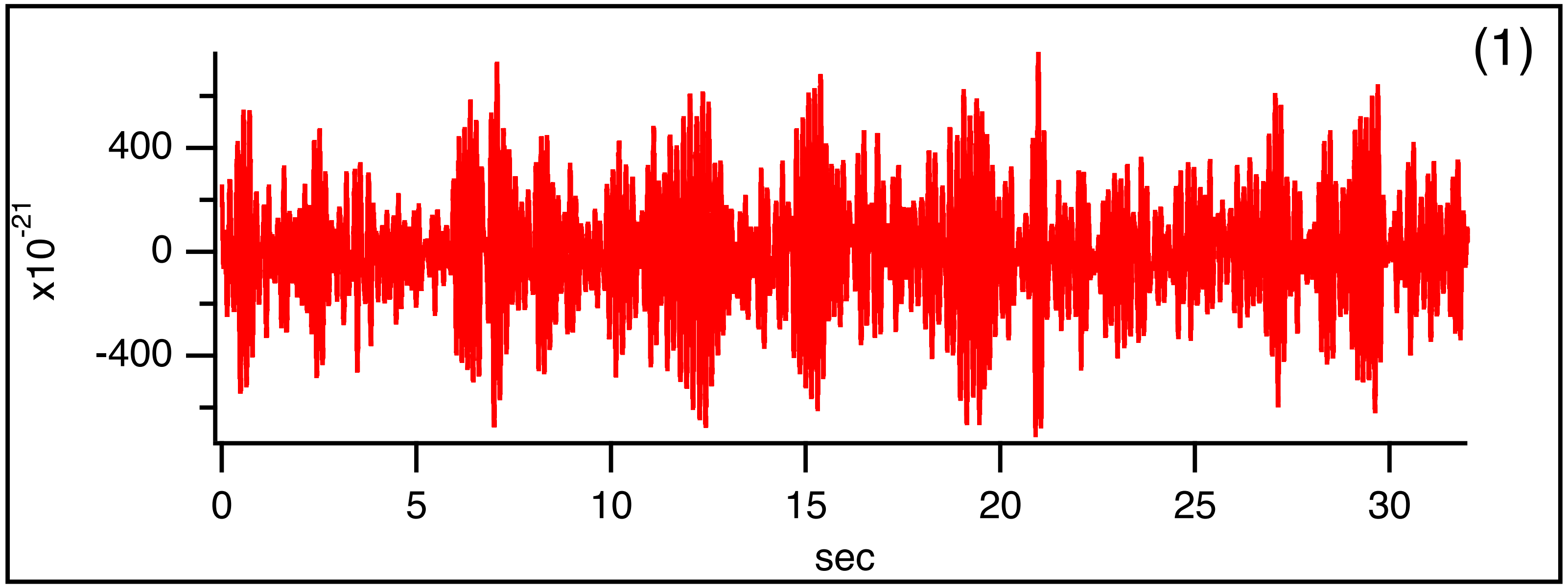
Observation of Gravitational Waves from a Binary Black Hole Merger

For full details see LIGO DCC, arXiv, or Phys. Rev. Letters

波形を読む



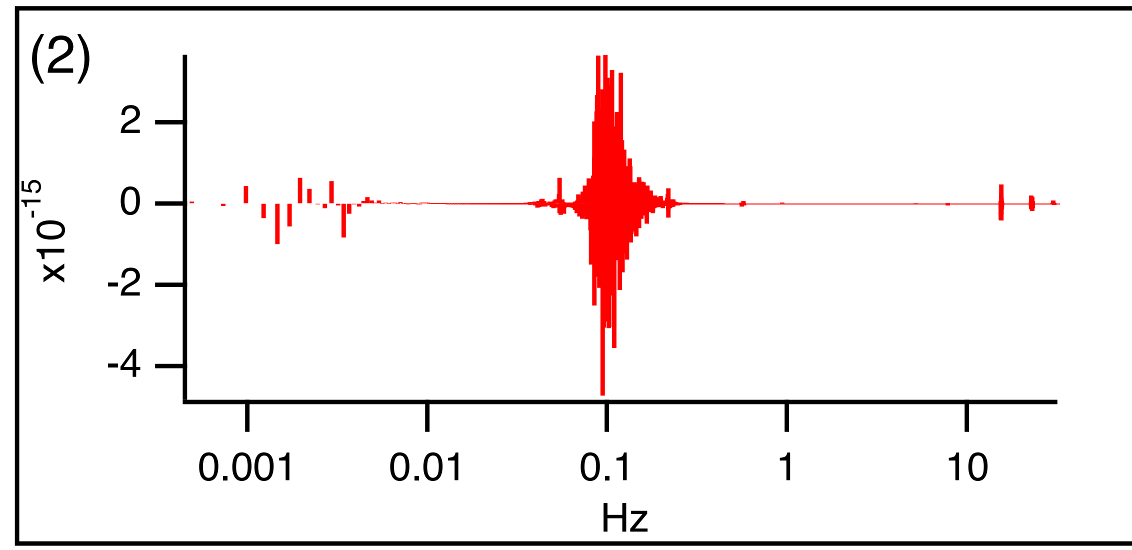
LIGOが配布している観測波形データと、パラメタ推定に用いた数値相対論波形



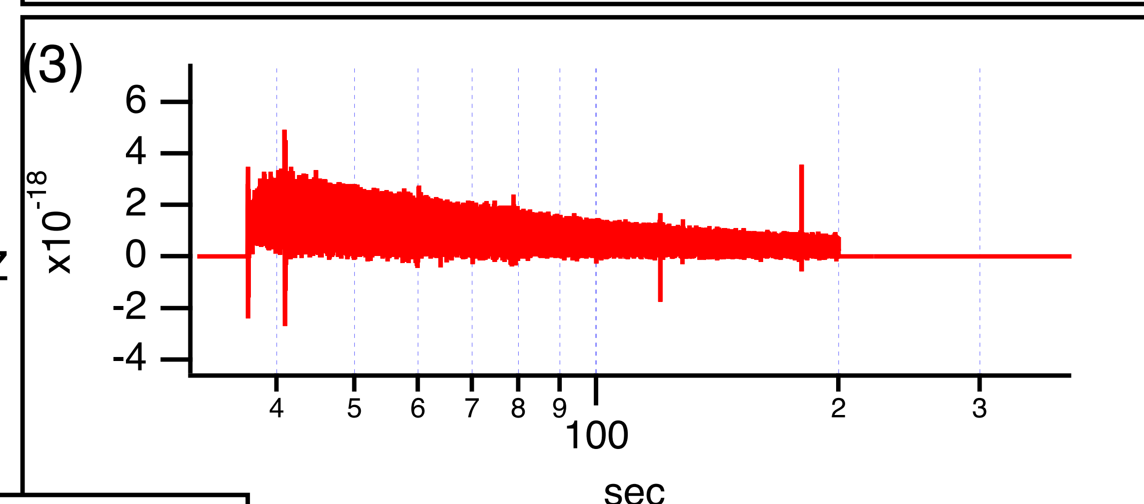
LIGO配布のデータ
合体付近32sec, 4096Hzサンプリング

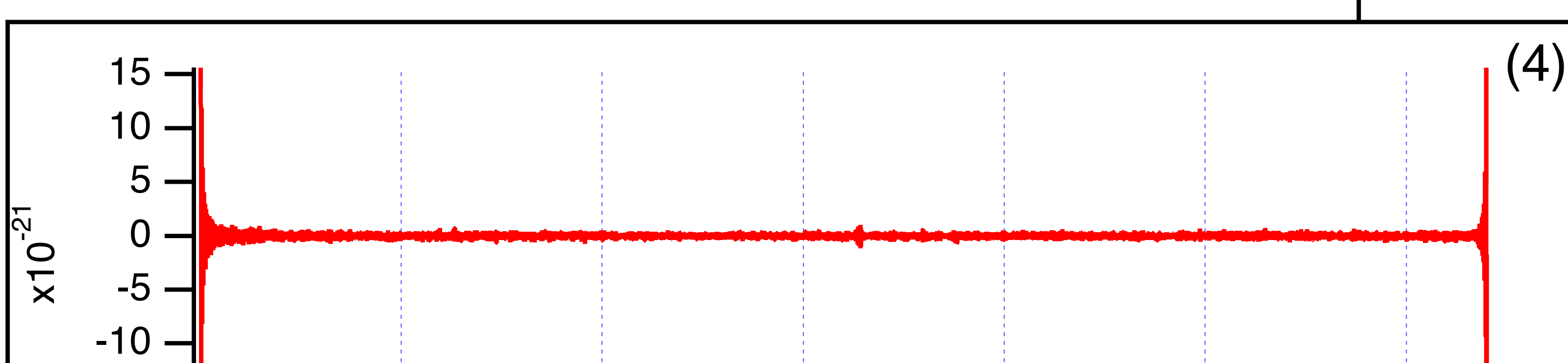
FFT

(FFTは実部虚部両方グラフにしてある)



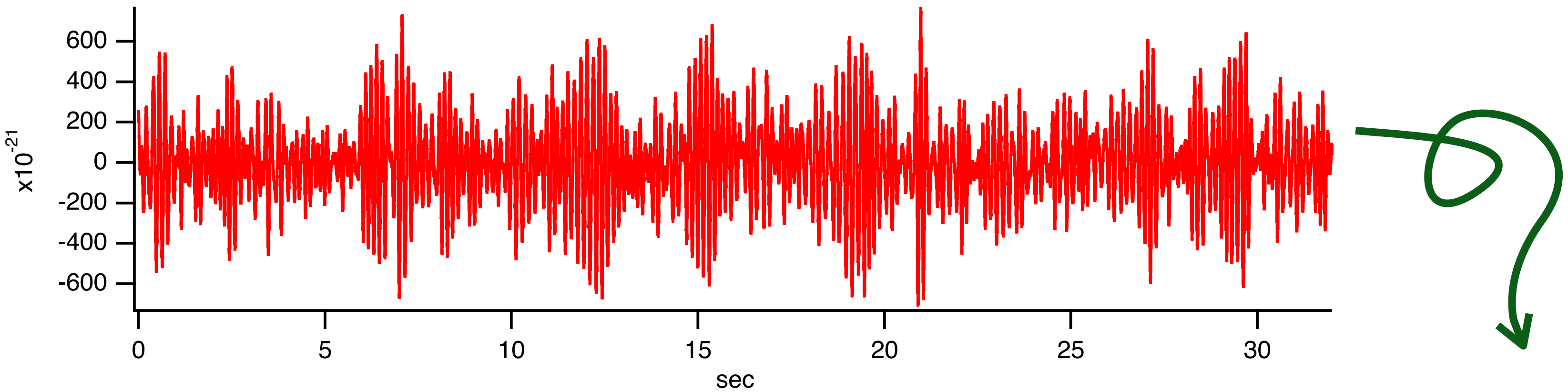
バンドパス操作
いまは時間が無いので簡単のため、
下記の周波数の値を0にするだけ。
1, 電源ラインの雑音 59.98 - 60.02 Hz
2, 低周波 36.8以下
3, 高周波 200Hz以上

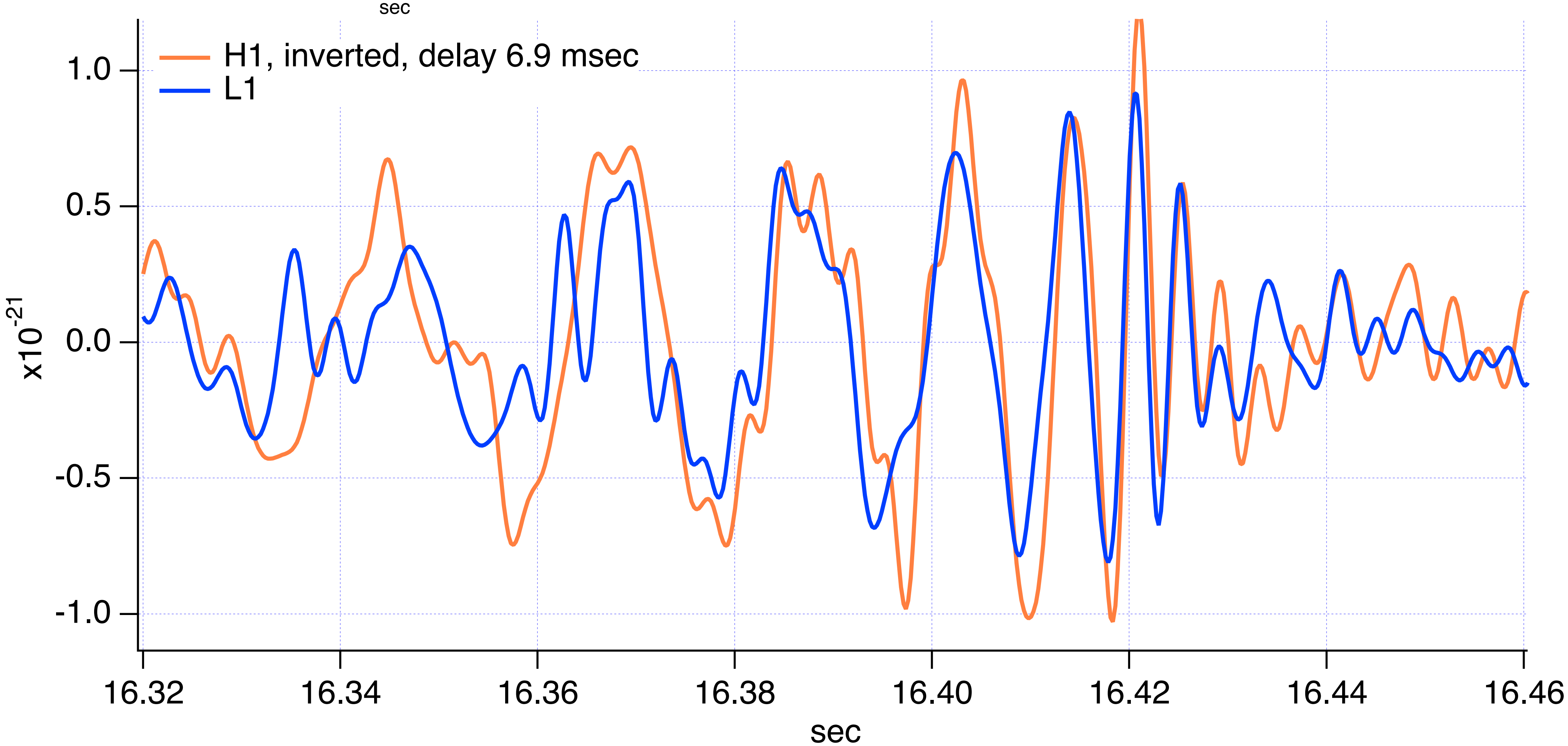




逆FFT

せっかくなので元データ(h(t))から、フィルタを変えて試す





なんとなく…！？

しかし、このデータでリングダウン部分のみから、SchwarzschildかKerrかの区別がつくとは思えない。

（日本の解析Gに、もっと面白いt-f分解の解析をやっている人がいるので、そのうち発表するはずです…)

フォローアップ観測

光学観測　見つかっていない

日本では、J-GEM グループがフォローアップ観測した。（木曽シュミット、すばる望遠鏡、MOAほか）

X線・ガンマ線

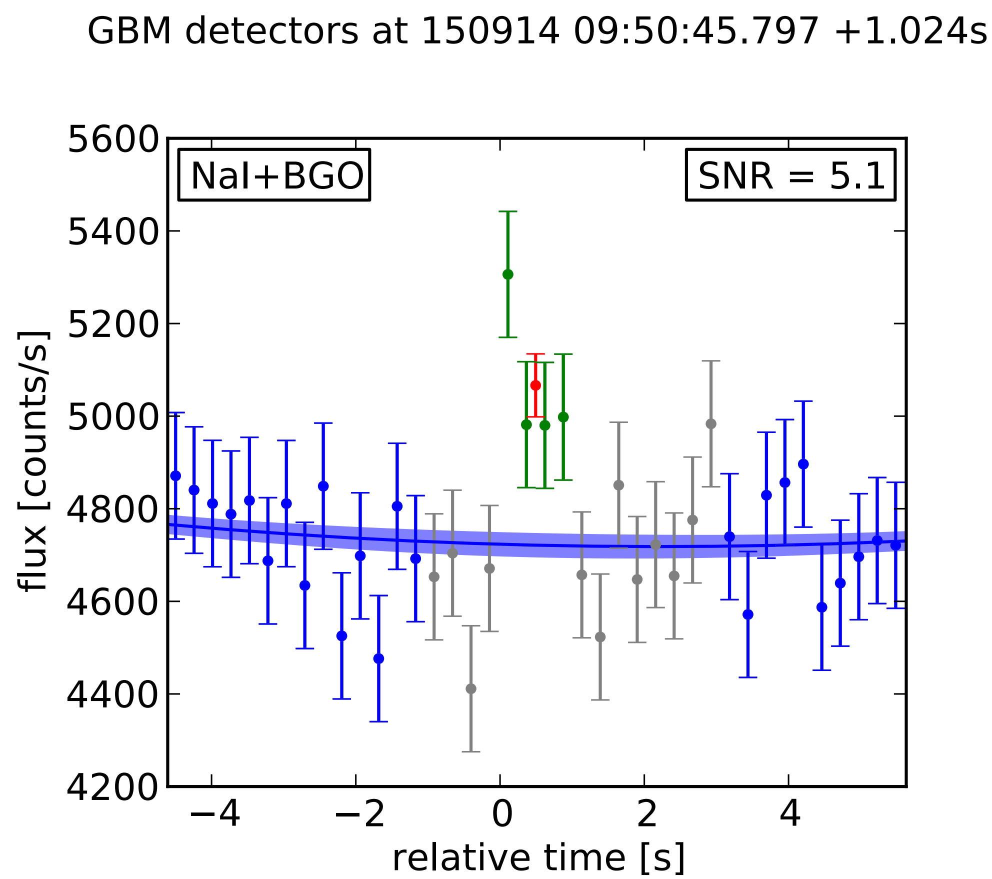
Fermi ：なにかあったと主張

INTEGRAL : ない

Swift : ない

ニュートリノ

IceCube, ANTARES : IceCubeで当該時刻にイベントはあるが、方向は整合していない。



Fermi GBM Observations of LIGO Gravitational Wave event GW150914

V. Connaughton[*,1], E. Burns[2], A. Goldstein[+,3], L. Blackburn[4], M. S. Briggs[5], B.-B. Zhang[6] C. M. Hui[3], P. Jenke[6], J. Racusin[7], C. A. Wilson-Hodge[3], P. N. Bhat[6], W. Cleveland[1], G. Fitzpatrick[6], M. M. Giles[8], M. H. Gibby[8], J. Greiner[9], A. von Kienlin[9], R. M. Kippen[10], S. McBreen[11], B. Mailyan[6], C. A. Meegan[6], W. S. Paciesas[1], R. D. Preece[5], O. Roberts[10], L. Sparke[12], M. Stanbro[2], K. Toelge[9], P. Veres[6], H.-F. Yu[9,13]

and other authors

重力波の発見

KAGRA

重力波の直接観測がなされました。その結果

0、検出器は原理通りに動いた！

1、一般相対論の重要な予言が検証された

時空の「波動」の直接測定、強い重力場での検証

次なる検証は？相対論を超える範囲？重力子？

2、ブラックホールが確認された（連星、合体後）

BH自体から出る重力波！

BH時空(Kerr時空)そのものの性質に根ざす放射

したがって、基礎物理学的にも極めて興味深い対象

3、重力波天文学、重力波物理学が始まります

統計的になにかを探る時代が、予想していたより

も早く訪れるかもしれない。

さらに…

KAGRA

BH-BHが見つかったとはいえ、中性子星連星や超新星爆発も期待されている。

これらでできる物理や天文学は、BHの物理とはまたちょっと違う。

もう一点…

３０太陽質量のブラックホールはどうやって生まれたか？

考えられるものはいくつかある。

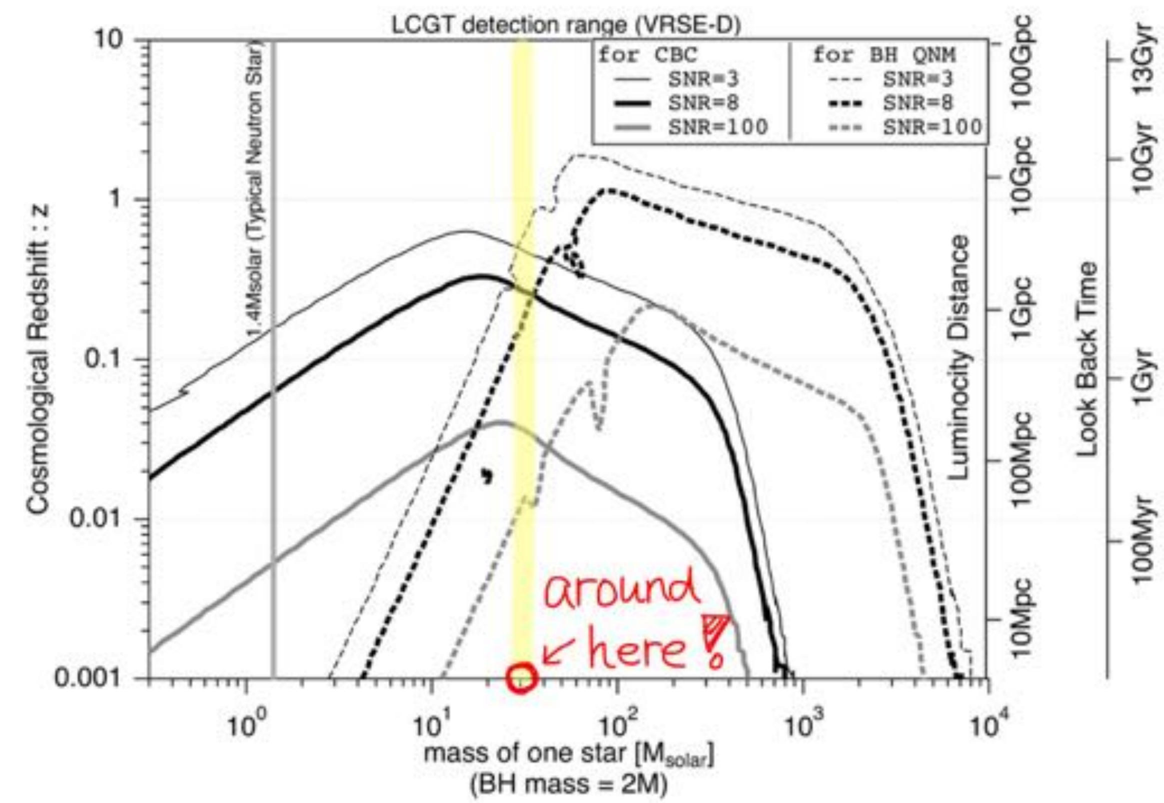
星形成の問題になる。

Population III 星起源という可能性もある。

30 + 30 solar mass BHs

Interesting target for three reasons:

Nakano Talk



Inspiral and ringdown phases have roughly equal SNRs, so provides good test of GR

If population III stars (formed at redshifts 5-10) exist, these might be a substantial fraction.

Perhaps we will detect several of them in the first aLIGO data run O1, this September!

viewgraph edited by Bruce Allen : (Personal) summary of new, novel, and interesting results presented at this workshop at GWPAW2015 Osaka, June 2015

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **456,** 1093–1114 (2016) doi:10.1093/mnras/stv2624

The detection rate of inspiral and quasi-normal modes of Population III binary black holes which can confirm or refute the general relativity in the strong gravity region

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ABSTRACT

Using our population synthesis code, we found that the typical chirp mass defined by $(m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$ of Population III (Pop III) binary black holes (BH–BHs) is $\sim$30 $M_\odot$ with the total mass of $\sim$60 $M_\odot$ so that the inspiral chirp signal as well as quasi-normal mode (QNM) of the merging black hole (BH) are interesting targets of KAGRA. The detection rate of the coalescing Pop III BH–BHs is $\sim$180 events yr^{-1} $(SFR_{\rm p}/(10^{-2.5}\,M_\odot\,{\rm yr}^{-1}\,{\rm Mpc}^{-3}))([f_{\rm b}/(1 + f_{\rm b})]/0.33)Err_{\rm sys}$ in our standard model, where $SFR_{\rm p}$, $f_{\rm b}$ and $Err_{\rm sys}$ are the peak value of the Pop III star formation rate, the binary fraction and the systematic error with $Err_{\rm sys} = 1$ for our standard model, respectively. To evaluate the robustness of chirp mass distribution and the range of $Err_{\rm sys}$, we examine the dependence of the results on the unknown parameters and the distribution functions in the population synthesis code. We found that the chirp mass has a peak at $\sim$30 $M_\odot$ in most of parameters and distribution functions as well as $Err_{\rm sys}$ ranges from 0.046 to 4. Therefore, the detection rate of the coalescing Pop III BH–BHs ranges about 8.3-720 events yr$^{-1}(SFR_{\rm p}/(10^{-2.5}\,M_\odot\,{\rm yr}^{-1}\,{\rm Mpc}^{-3}))([f_{\rm b}/(1 + f_{\rm b})]/0.33)$. The minimum rate corresponds to the worst model which we think unlikely so that unless $(SFR_{\rm p}/(10^{-2.5}\,M_\odot\,{\rm yr}^{-1}\,{\rm Mpc}^{-3}))([f_{\rm b}/(1 + f_{\rm b})]/0.33) \ll 0.1$, we expect the Pop III BH–BHs merger rate of at least one event per year by KAGRA. Nakano, Tanaka & Nakamura show that if signal-to-noise ratio (S/N) of QNM is larger than 35, we can confirm or refute the general relativity (GR) more than 5σ level. In our standard model, the detection rate of Pop III BH–BHs whose S/N is larger than 35 is 3.2 events yr^{-1} $(SFR_{\rm p}/(10^{-2.5}\,M_\odot\,{\rm yr}^{-1}\,{\rm Mpc}^{-3}))([f_{\rm b}/(1 +$

重力波観測時代へようこそ！