重力波の初観測

真貝寿明（大阪工大）

http://www.oit.ac.jp/is/~shinkai/

2016年2月，LIGOが重力波を初めて検出した，と発表した

JAHOU集会2016
2016/3/13

『クーリエ・ジャポン電子版』（講談社）


印刷する
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COURRiER
BUSINESS

2016.3.6

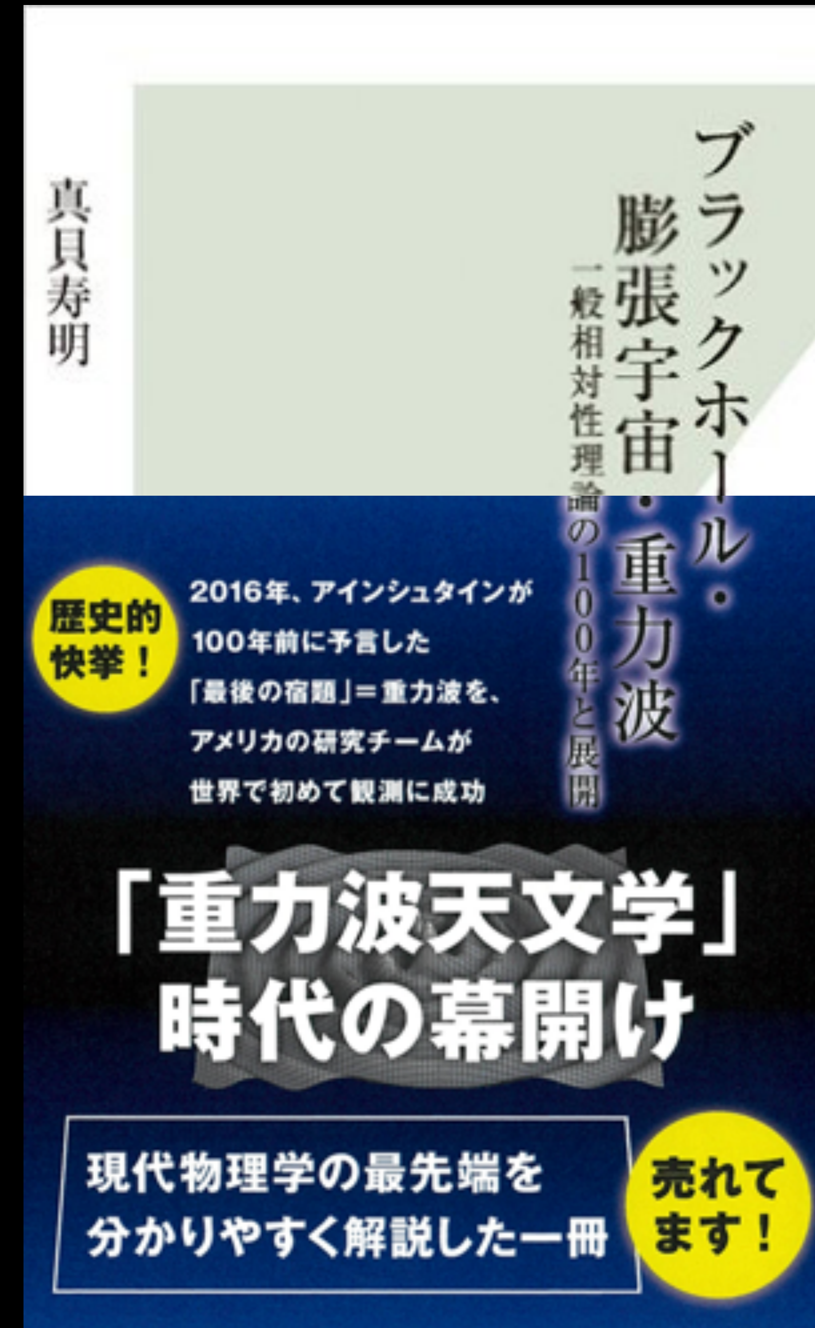
人類が初めて観測した「重力波」を、アインシュタインは100年前に予言していた

Text by Hisaaki Shinkai

CALTECH / MIT / LIGO LABORATORY / REUTERS / AFLO

世界中が喜びに沸いた快挙「初の重力波の観測」。はるか13億光年先から届いた微弱な波を検出したことで、アインシュタインが残した“最後の宿題”はいかに解かれ、宇宙の謎はどう解明されていくのか。宇宙物理学者の真貝寿明さんがわかりやすく解説します。

http://courrier.jp/news/archives/44233/



『ブラックホール・膨張宇宙・重力波
一般相対性理論の100年と展開』
光文社新書
2015年9月刊

重力の正体は？

http://hikingartist.com/

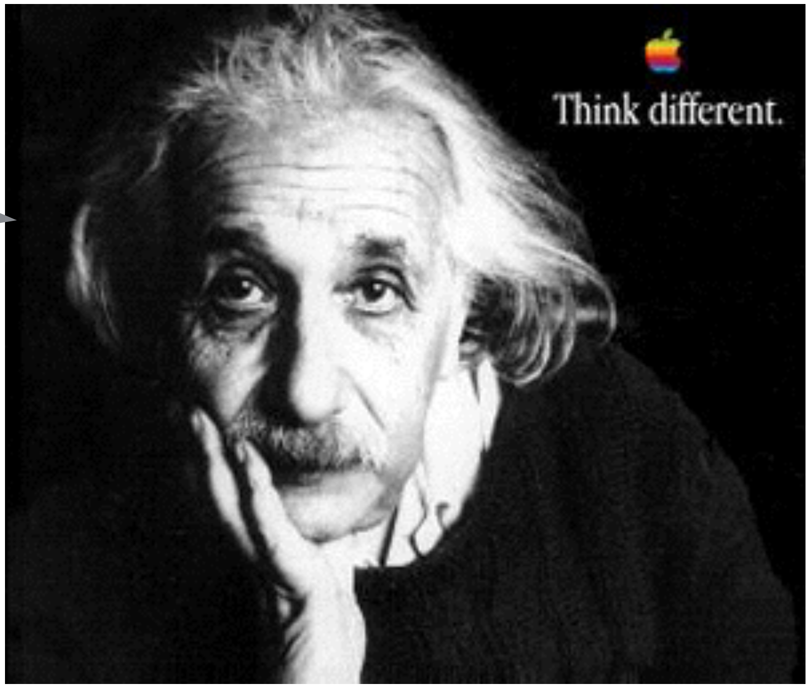
「万有引力があるからだ」（Newton , 1687）

$$F = G\frac{Mm}{r^2} \qquad m\frac{d^2x}{dt^2} = F$$

「時空のゆがみだ」

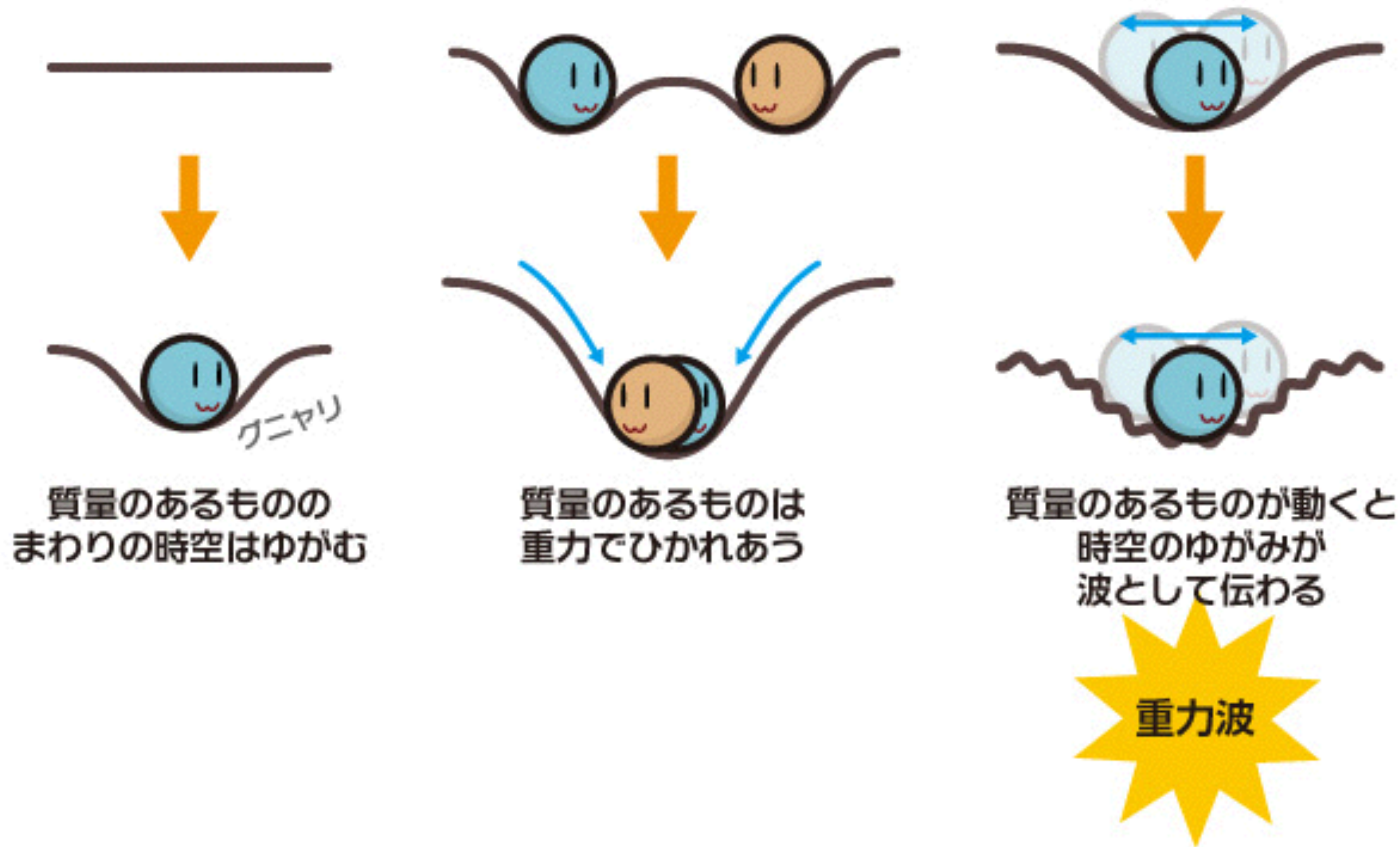
（Einstein , 1915）

一般相対性理論

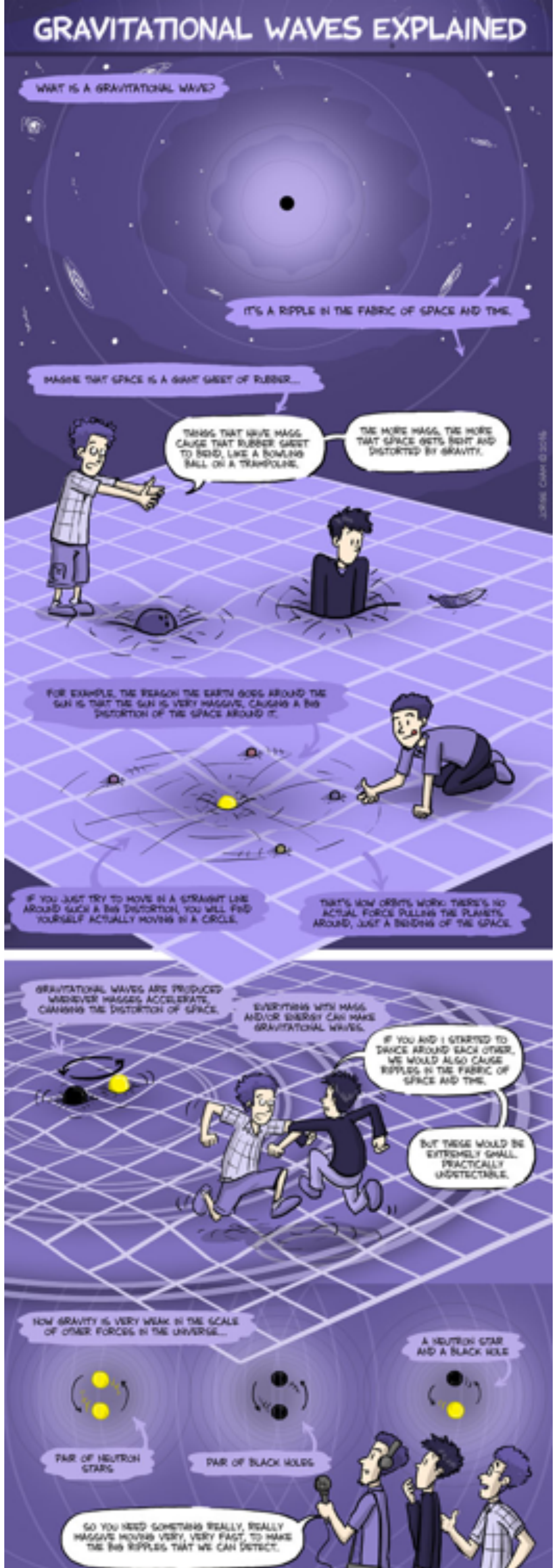


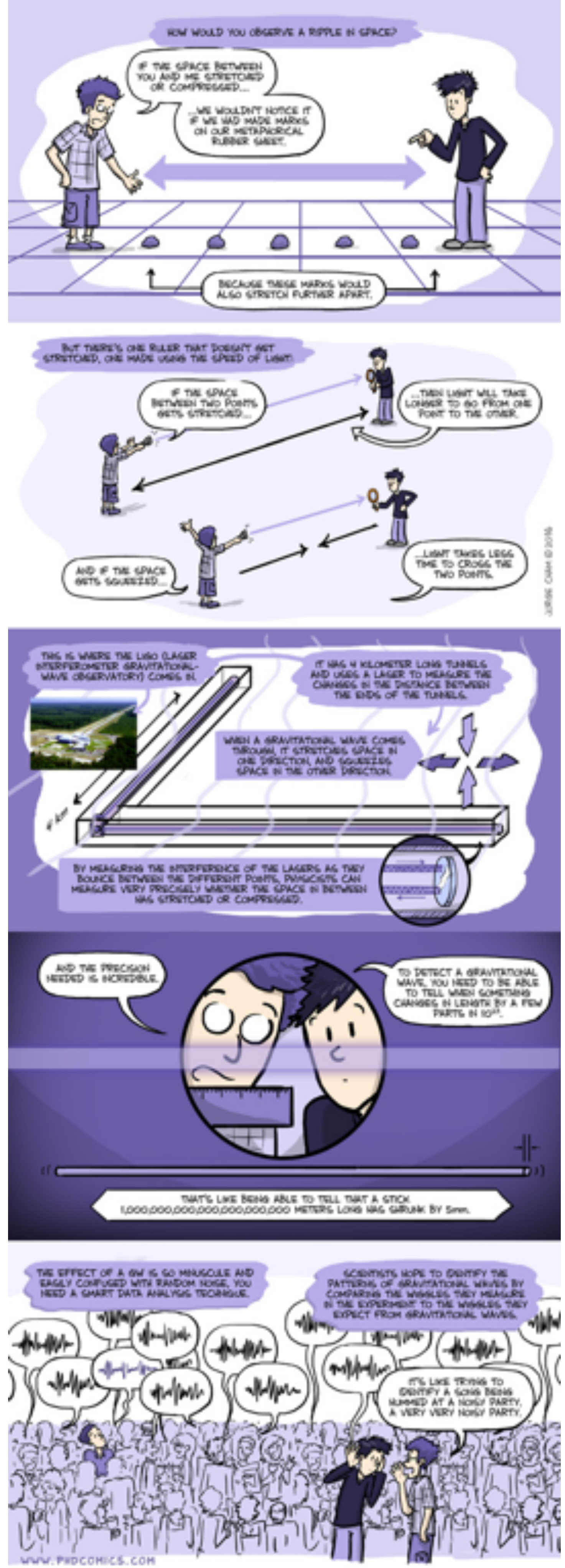
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

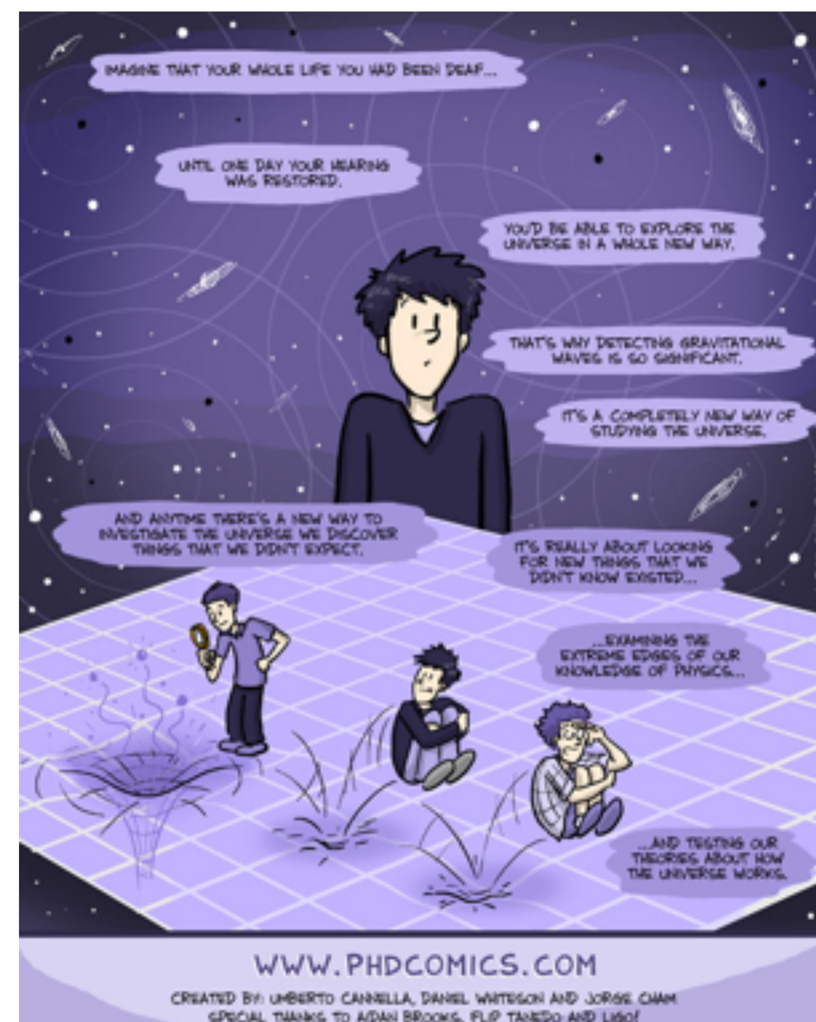
$$\frac{d^2\xi^\mu}{d\tau^2} = R^\mu{}_{\nu\rho\sigma}\frac{d\xi^\nu}{d\tau}\frac{d\xi^\rho}{d\tau}\xi^\sigma$$



秋本 祐希著，洋泉社 http://higgstan.com/2016/02/11/752


GRAVITATIONAL WAVES EXPLAINED
WHAT IS A GRAVITATIONAL WAVE?
IT'S A RIPPLE IN THE FABRIC OF SPACE AND TIME.
IMAGINE THAT SPACE IS A GIANT SHEET OF RUBBER...
THINGS THAT HAVE MASS CAUSE THAT RUBBER SHEET TO BEND, LIKE A BOWLING BALL ON A TRAMPOLINE.
THE MORE MASS, THE MORE THAT SPACE GETS BENT AND DISTORTED BY GRAVITY.
FOR EXAMPLE, THE REASON THE EARTH GOES AROUND THE SUN IS THAT THE SUN IS VERY MASSIVE, CAUSING A BIG DISTORTION OF THE SPACE AROUND IT.
IF YOU JUST TRY TO MOVE IN A STRAIGHT LINE AROUND SUCH A BIG DISTORTION, YOU WILL FIND YOURSELF ACTUALLY MOVING IN A CIRCLE.
THAT'S HOW ORBITS WORK: THERE'S NO ACTUAL FORCE PULLING THE PLANETS AROUND, JUST A BENDING OF THE SPACE.
GRAVITATIONAL WAVES ARE PRODUCED WHENEVER MASSES ACCELERATE, CHANGING THE DISTORTION OF SPACE.
EVERYTHING WITH MASS AND/OR ENERGY CAN MAKE GRAVITATIONAL WAVES.
IF YOU AND I STARTED TO DANCE AROUND EACH OTHER, WE WOULD ALSO CAUSE RIPPLES IN THE FABRIC OF SPACE AND TIME.
BUT THESE WOULD BE EXTREMELY SMALL. PRACTICALLY UNDETECTABLE.
NOW GRAVITY IS VERY WEAK IN THE SCALE OF OTHER FORCES IN THE UNIVERSE...
A NEUTRON STAR AND A BLACK HOLE
PAIR OF NEUTRON STARS
PAIR OF BLACK HOLES
SO YOU NEED SOMETHING REALLY, REALLY MASSIVE MOVING VERY, VERY FAST, TO MAKE THE BIG RIPPLES THAT WE CAN DETECT.


HOW WOULD YOU OBSERVE A RIPPLE IN SPACE?
IF THE SPACE BETWEEN YOU AND ME STRETCHED OR COMPRESSED...
...WE WOULDN'T NOTICE IT IF WE HAD MADE MARKS ON OUR METAPHORICAL RUBBER SHEET.
BECAUSE THESE MARKS WOULD ALSO STRETCH FURTHER APART.
BUT THERE'S ONE RULER THAT DOESN'T GET STRETCHED, ONE MADE USING THE SPEED OF LIGHT.
IF THE SPACE BETWEEN TWO POINTS GETS STRETCHED...
...THEN LIGHT WILL TAKE LONGER TO GO FROM ONE POINT TO THE OTHER.
AND IF THE SPACE GETS SQUEEZED...
...LIGHT TAKES LESS TIME TO CROSS THE TWO POINTS.
THIS IS WHERE THE LIGO (LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY) COMES IN.
IT HAS 4 KILOMETER LONG TUNNELS AND USES A LASER TO MEASURE THE CHANGES IN THE DISTANCE BETWEEN THE ENDS OF THE TUNNELS.
WHEN A GRAVITATIONAL WAVE COMES THROUGH, IT STRETCHES SPACE IN ONE DIRECTION, AND SQUEEZES SPACE IN THE OTHER DIRECTION.
BY MEASURING THE INTERFERENCE OF THE LASERS AS THEY BOUNCE BETWEEN THE DIFFERENT POINTS, PHYSICISTS CAN MEASURE VERY PRECISELY WHETHER THE SPACE IN BETWEEN HAS STRETCHED OR COMPRESSED.
AND THE PRECISION NEEDED IS INCREDIBLE.
TO DETECT A GRAVITATIONAL WAVE, YOU NEED TO BE ABLE TO TELL WHEN SOMETHING CHANGES IN LENGTH BY A FEW PARTS IN 10^{21}.
THAT'S LIKE BEING ABLE TO TELL THAT A STICK 1,000,000,000,000,000,000,000 METERS LONG HAS SHRUNK BY 5mm.
THE EFFECT OF A GW IS SO MINUSCULE AND EASILY CONFUSED WITH RANDOM NOISE, YOU NEED A SMART DATA ANALYSIS TECHNIQUE.
SCIENTISTS HOPE TO IDENTIFY THE PATTERNS OF GRAVITATIONAL WAVES BY COMPARING THE WIGGLES THEY MEASURE IN THE EXPERIMENT TO THE WIGGLES THEY EXPECT FROM GRAVITATIONAL WAVES.
IT'S LIKE TRYING TO IDENTIFY A SONG BEING HUMMED AT A NOISY PARTY. A VERY VERY NOISY PARTY.
WWW.PHDCOMICS.COM


IMAGINE THAT YOUR WHOLE LIFE YOU HAD BEEN DEAF...
UNTIL ONE DAY YOUR HEARING WAS RESTORED.
YOU'D BE ABLE TO EXPLORE THE UNIVERSE IN A WHOLE NEW WAY.
THAT'S WHY DETECTING GRAVITATIONAL WAVES IS SO SIGNIFICANT.
IT'S A COMPLETELY NEW WAY OF STUDYING THE UNIVERSE.
AND ANYTIME THERE'S A NEW WAY TO INVESTIGATE THE UNIVERSE WE DISCOVER THINGS THAT WE DIDN'T EXPECT.
IT'S REALLY ABOUT LOOKING FOR NEW THINGS THAT WE DIDN'T KNOW EXISTED...
...EXAMINING THE EXTREME EDGES OF OUR KNOWLEDGE OF PHYSICS...
...AND TESTING OUR THEORIES ABOUT HOW THE UNIVERSE WORKS.
WWW.PHDCOMICS.COM
CREATED BY: UMBERTO CANNELLA, DANIEL WHITESON AND JORGE CHAM
SPECIAL THANKS TO AIDAN BROOKS, FLIP TANEDO AND LIGO!

重力波　幻の発見 (1968/70)

Joseph Weber

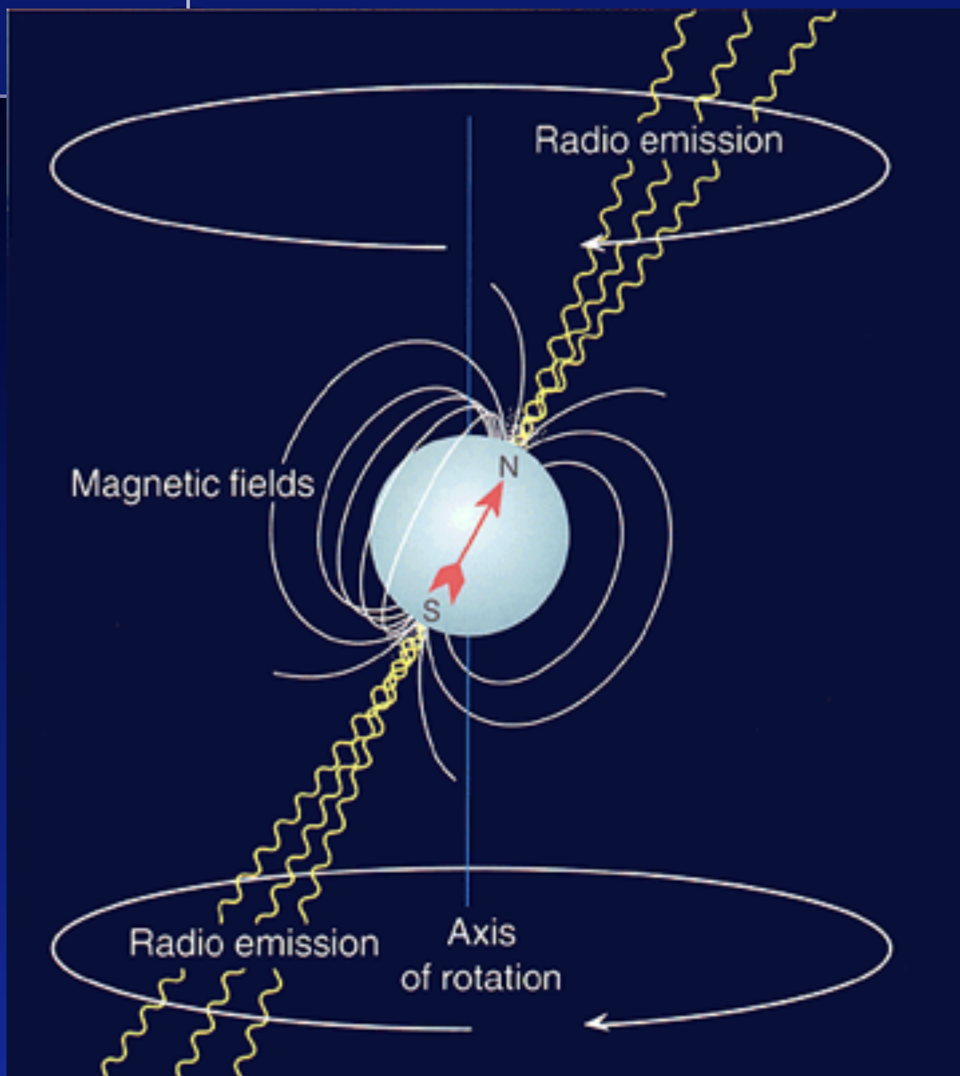
Joseph Weber (**pictured**), a physicist at the University of Maryland in College Park, believed that gravitational waves were real. In 1969, he announced that he had found them with a detector of his own invention: an aluminium cylinder, about 2 metres long and 1 metre in diameter, that ‘rang’ when it was struck by such a wave[2]. His result was never replicated, and was eventually rejected by nearly everyone except Weber himself. Nonetheless, his work drew many other researchers into the gravitational wave field.

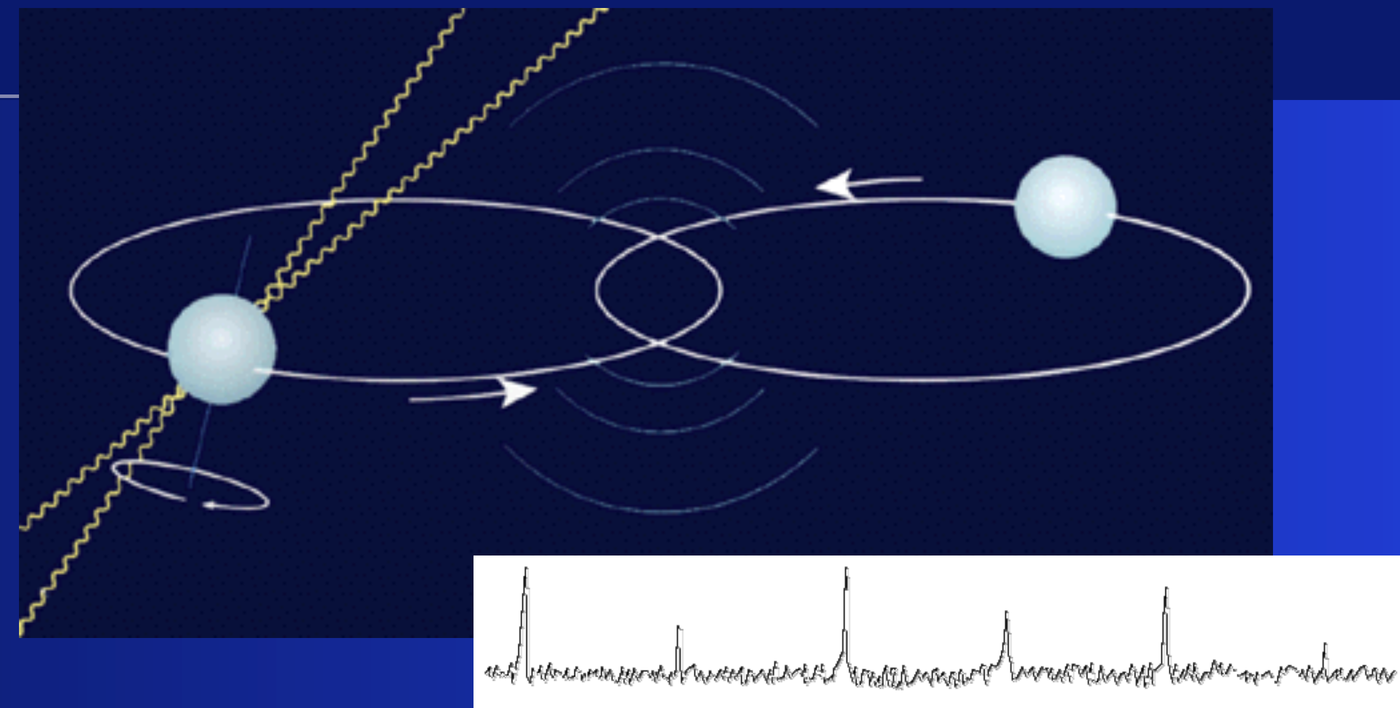
68年に**「２台の装置で同時に重力波信号を検出」**

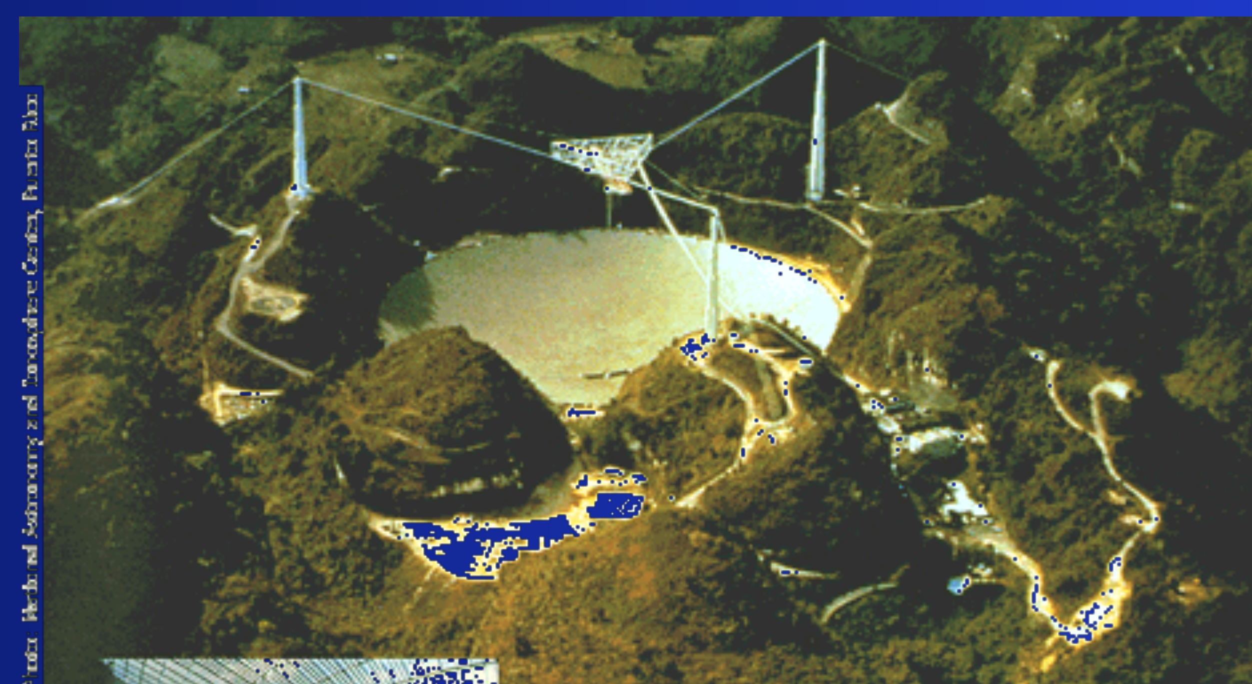
70年に**「重力波信号はおよそ一日に三回の頻度で検出され、検出装置が銀河の中心に対して垂直方向に向いているときに検出率が高い」**

と発表したが，他のグループで追試されず.

連星中性子星の発見 (1974)







Arecibo, Puerto Rico

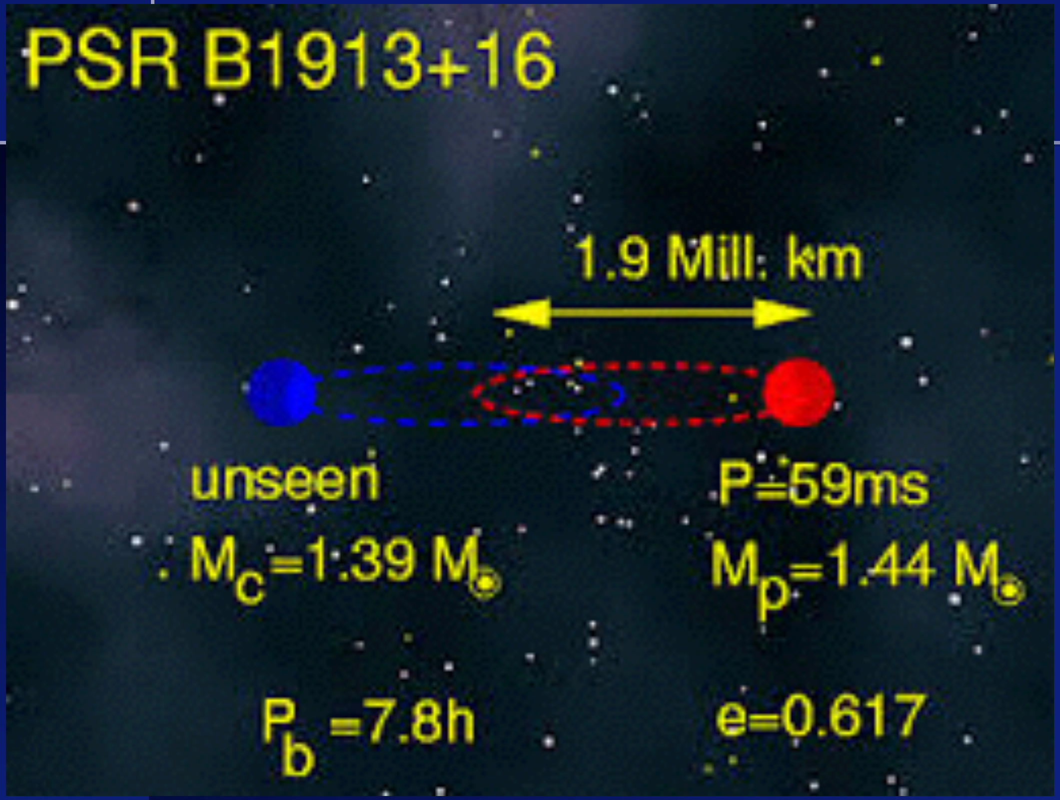
パルサー＝中性子星

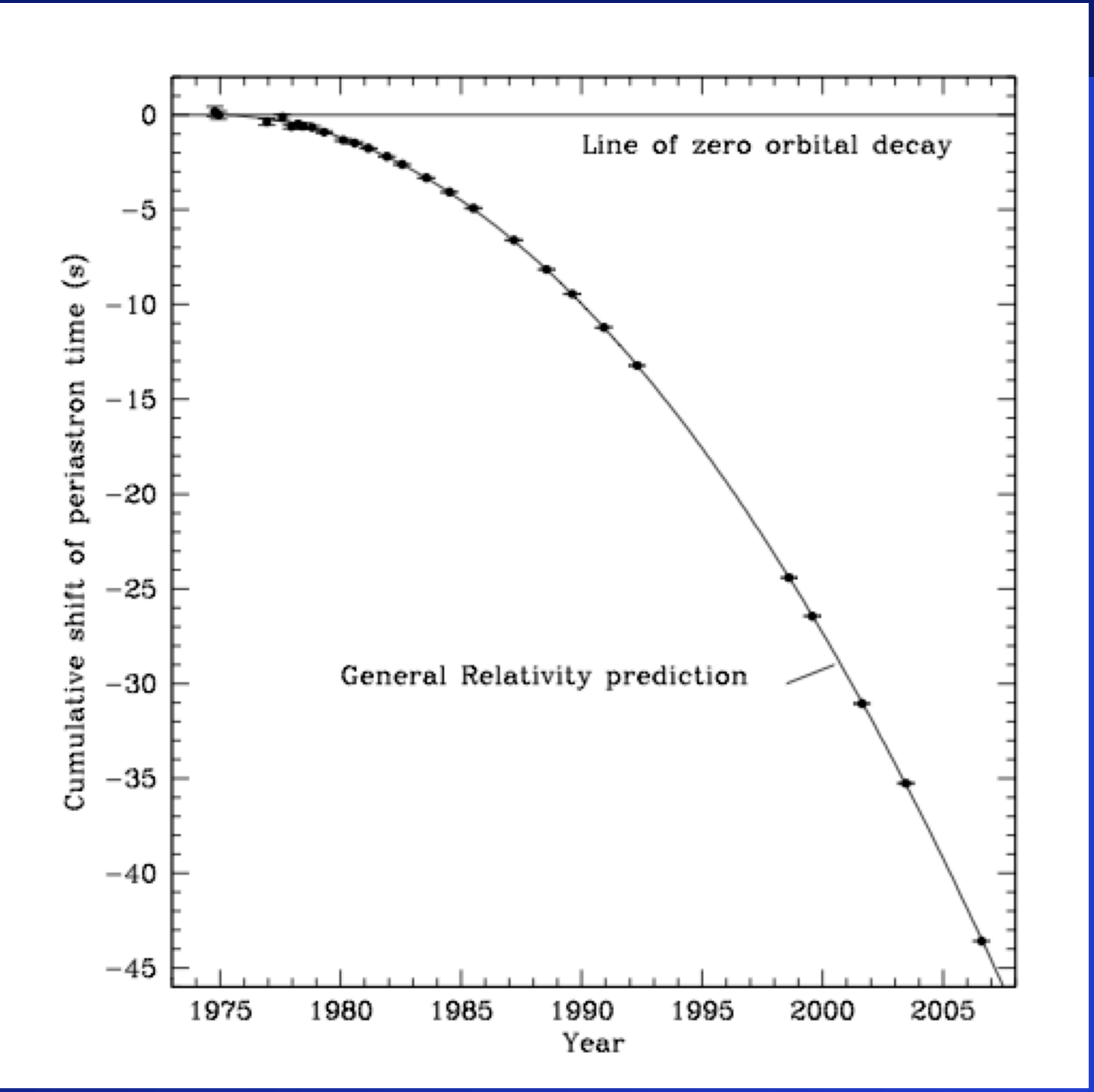
半径 10km位

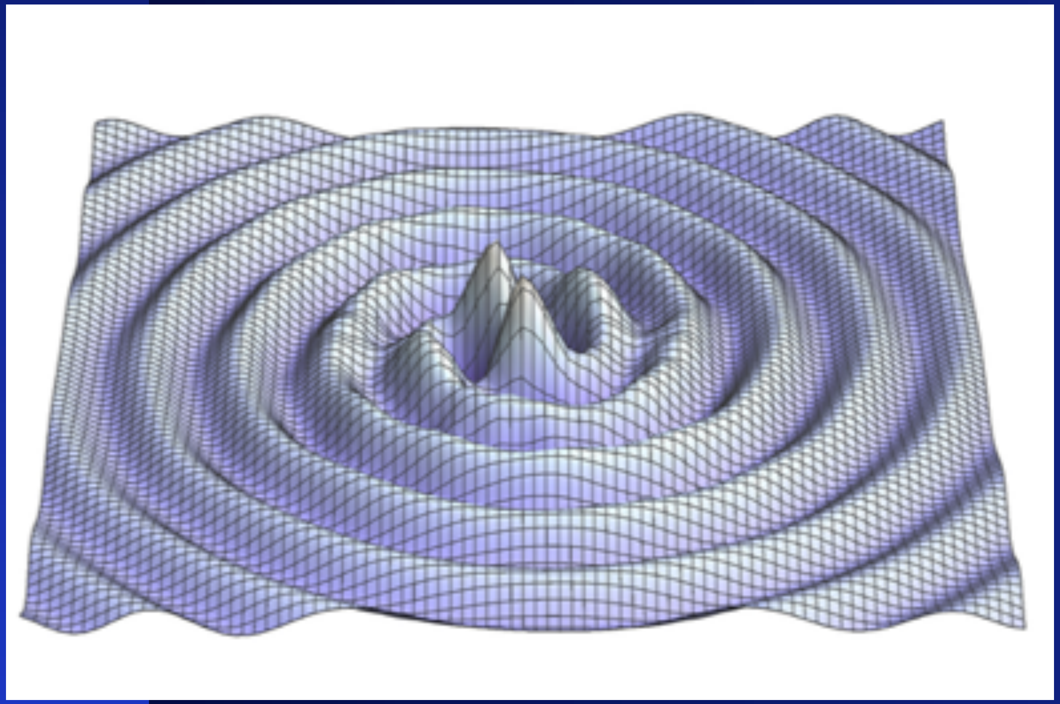
質量 1.4x太陽

http://www.nobelprize.org/nobel_prizes/physics/laureates/1993/illpres/discovery.html

連星中性子星の発見 (1974)



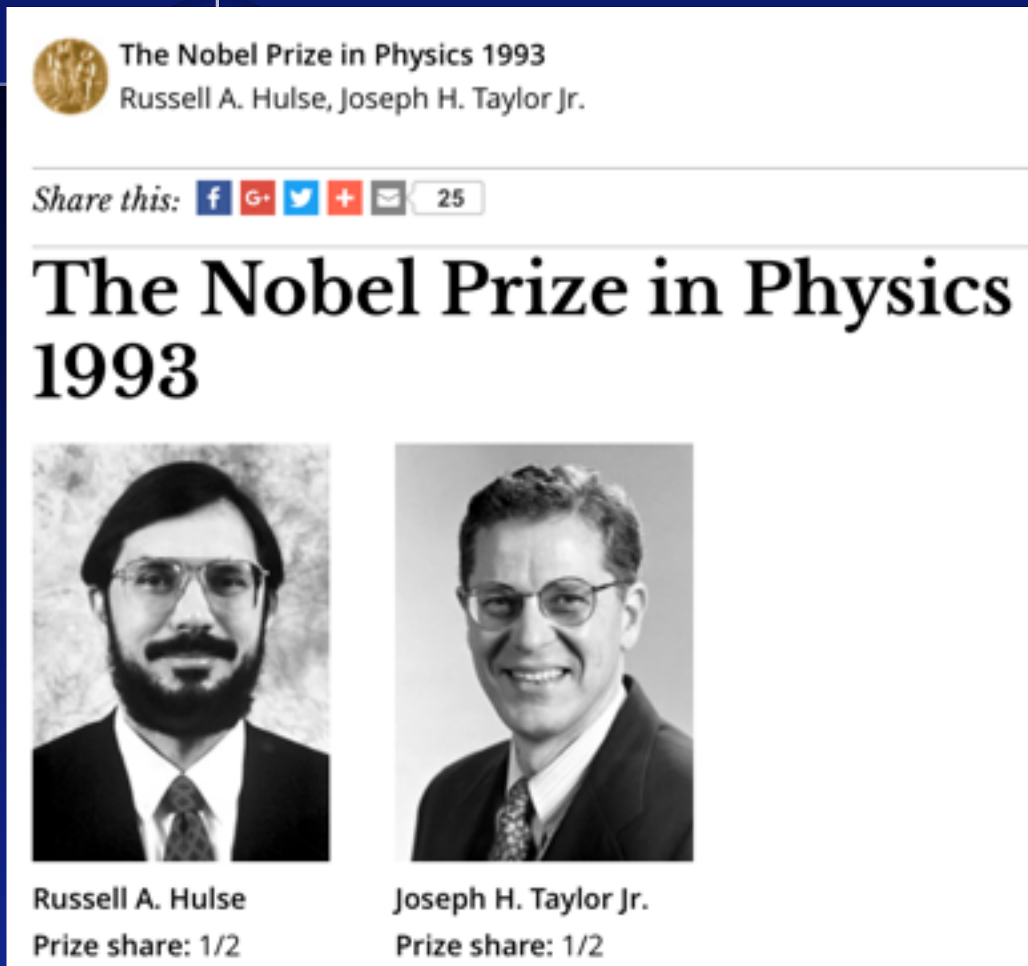


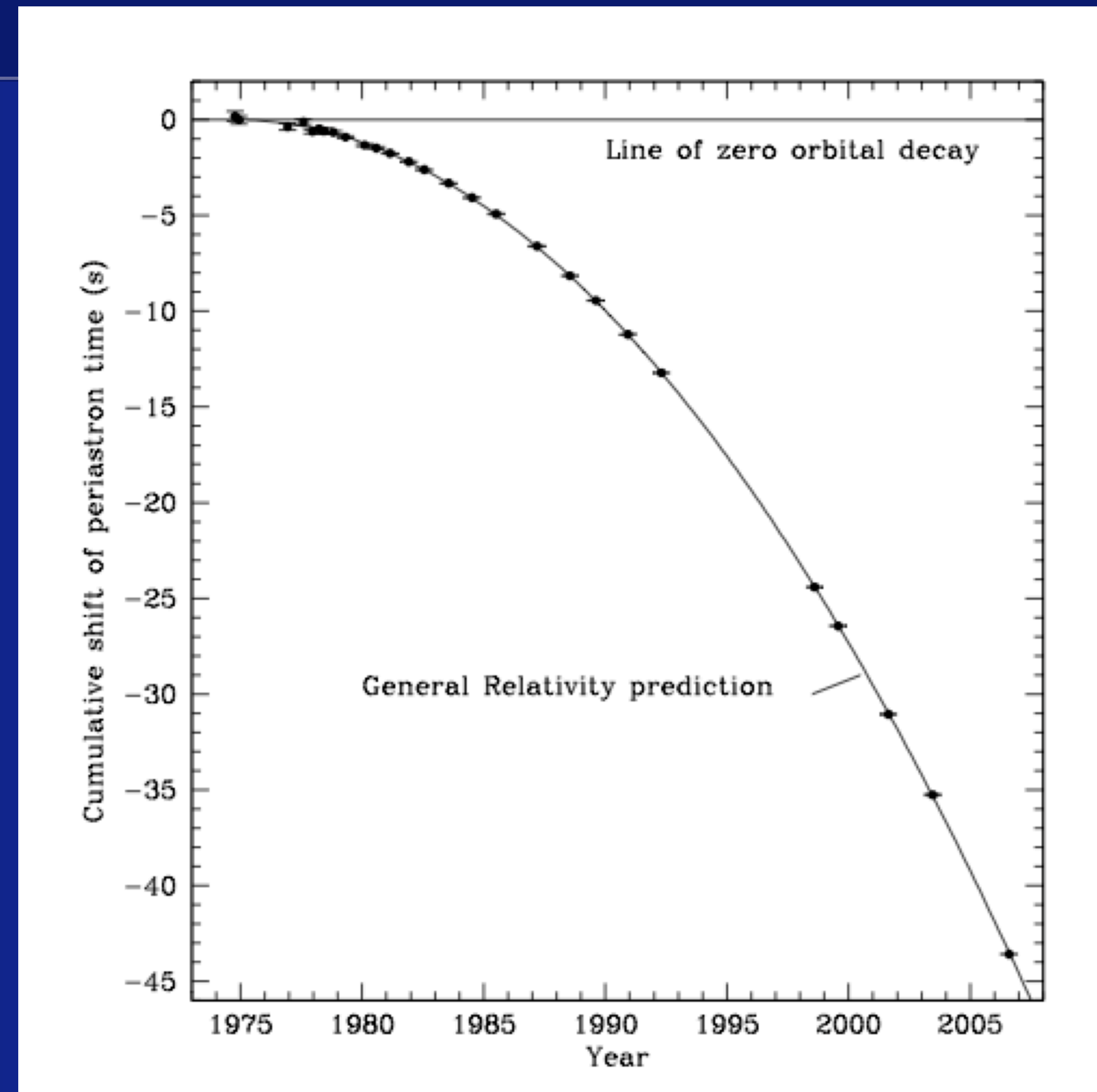


重力波を放出してエネルギーを失うので，星が近づいてゆく.

重力波の存在が間接的に確かめられた.

連星中性子星の発見 (1974)

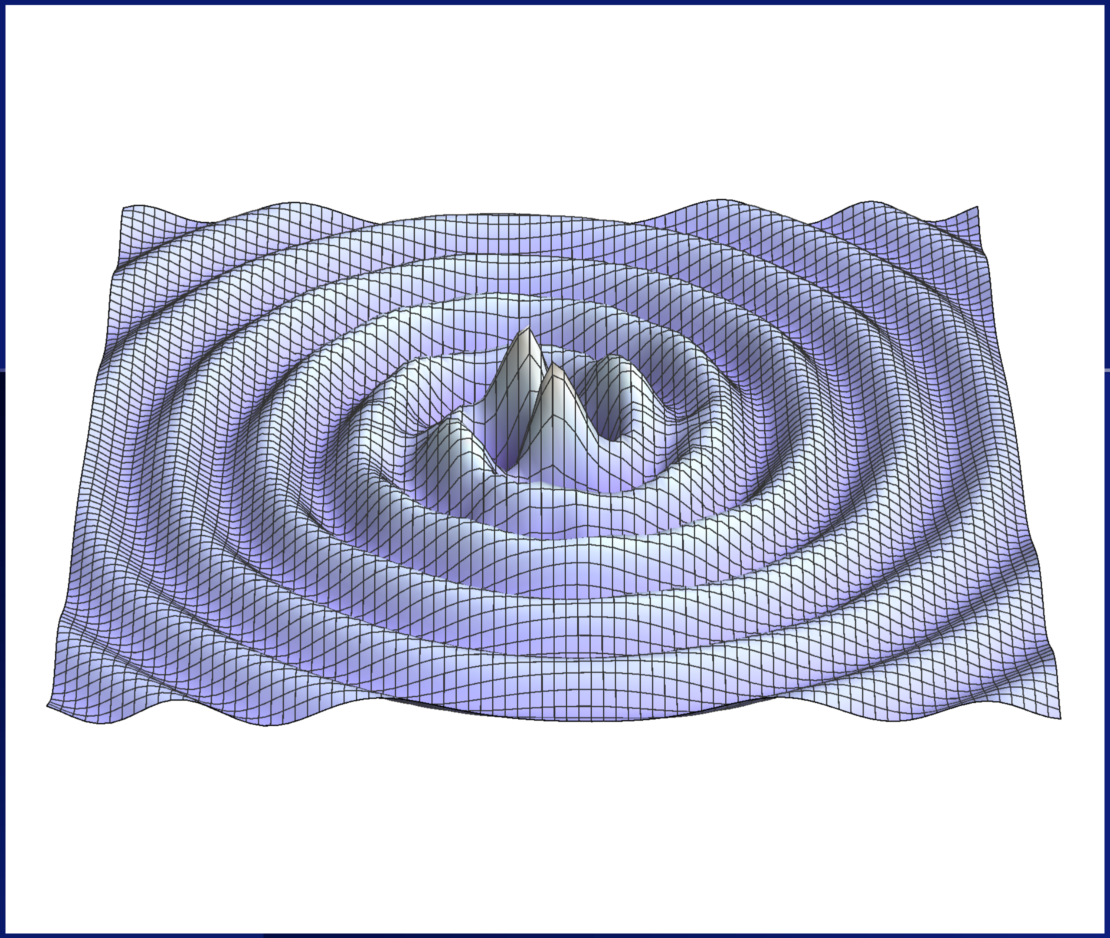




"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

"重力についての新しい研究を開いた，新種のパルサーの発見に対して"

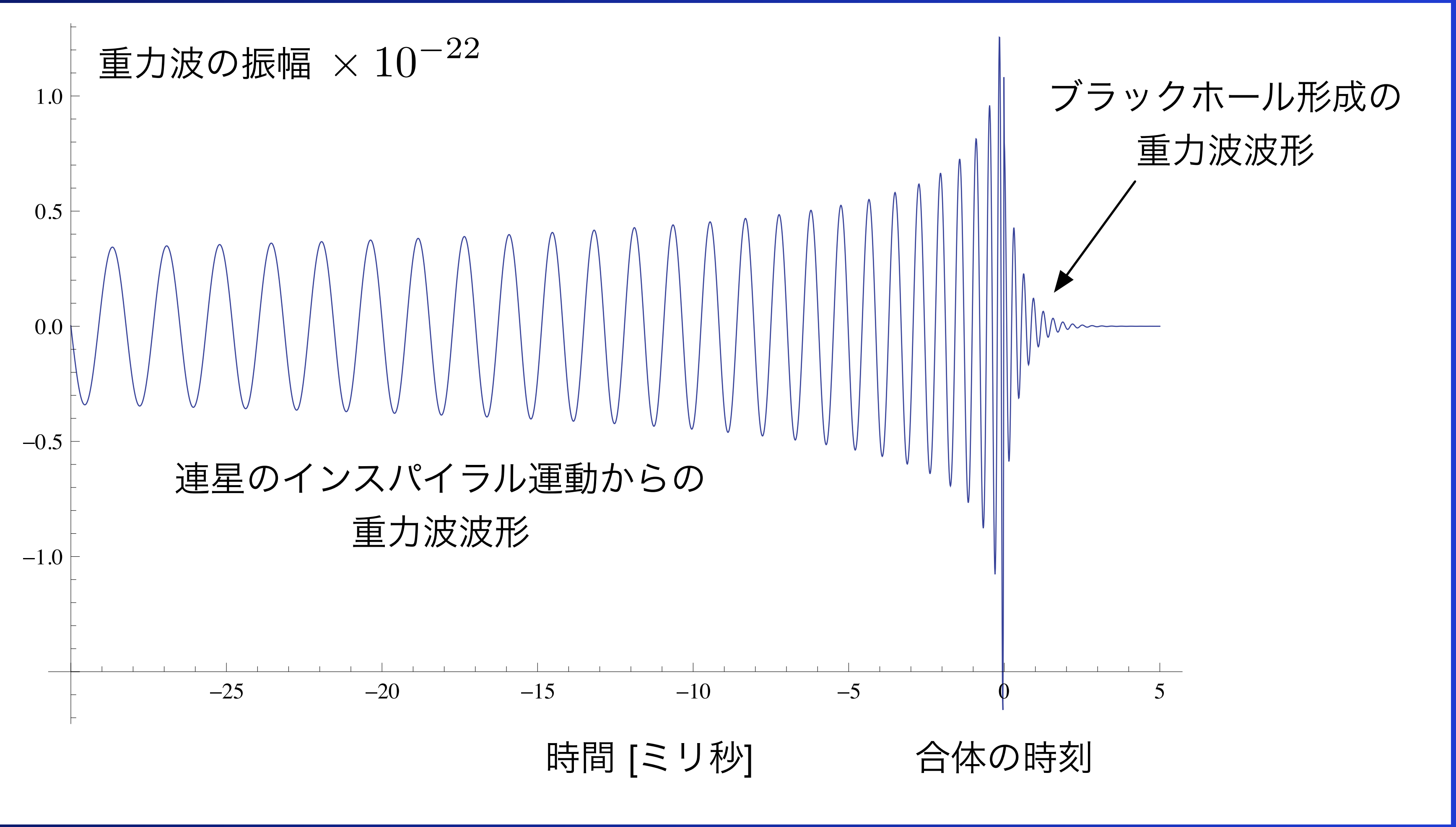
重力波の存在が間接的に確かめられた.



重力波の存在が間接的に確かめられた.

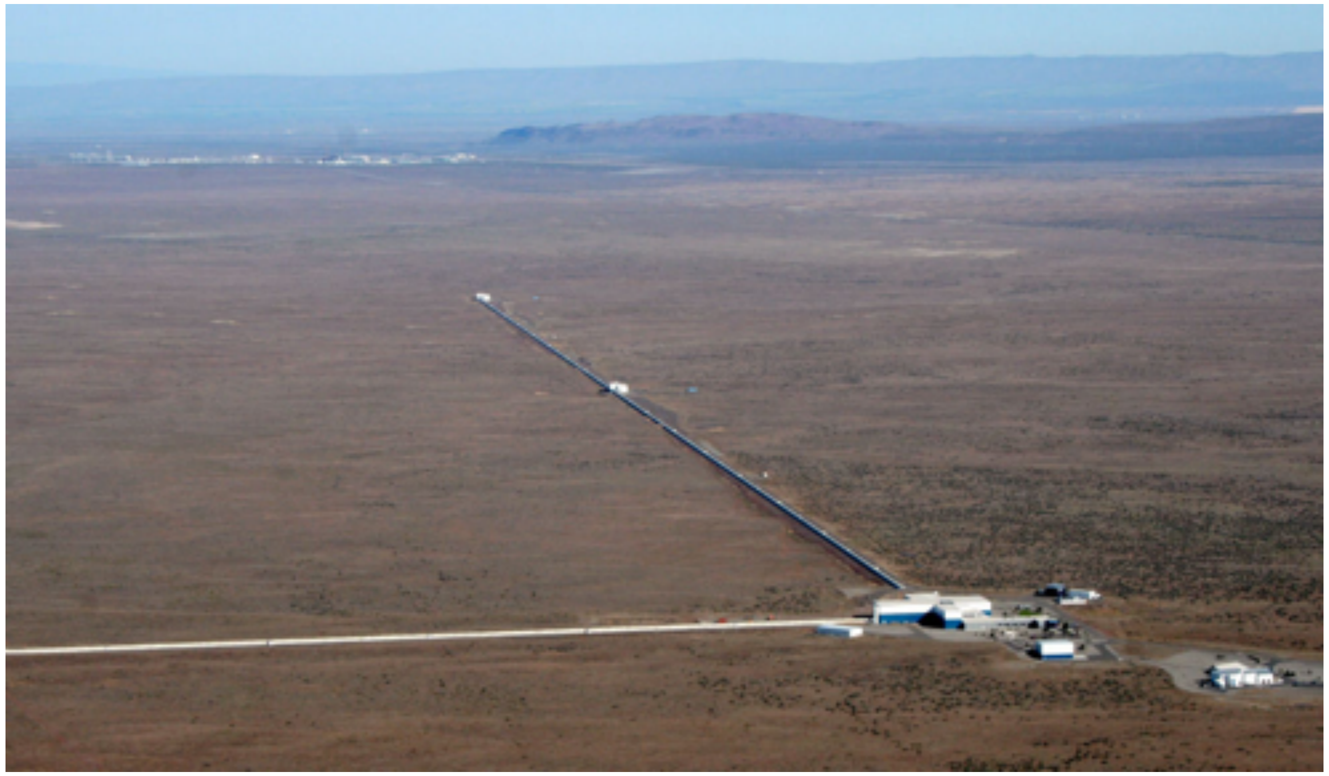
重力波の直接観測をしたい！

連星中性子星(BNS)
連星ブラックホール(BBH)

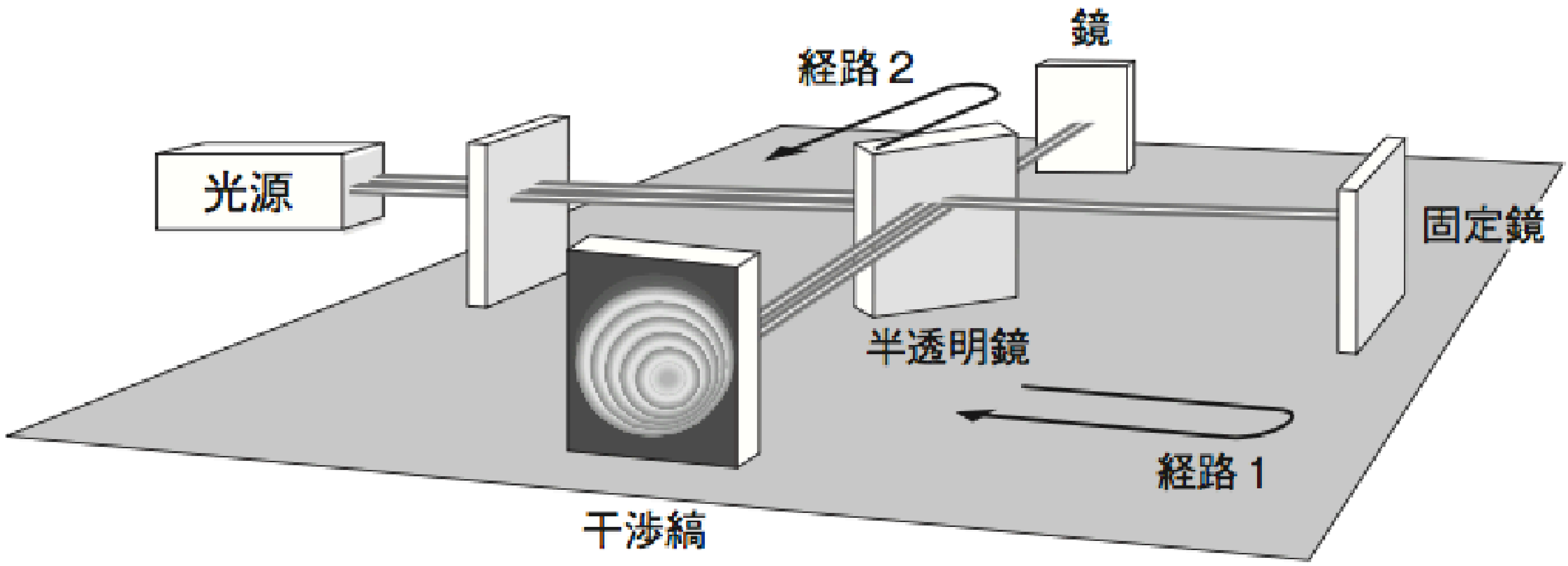


LIGO（レーザー干渉計重力波天文台）

Laser Interferemeter Gravitational-Wave Observatory　（1992年予算承認)



https://mediaassets.caltech.edu/gwave



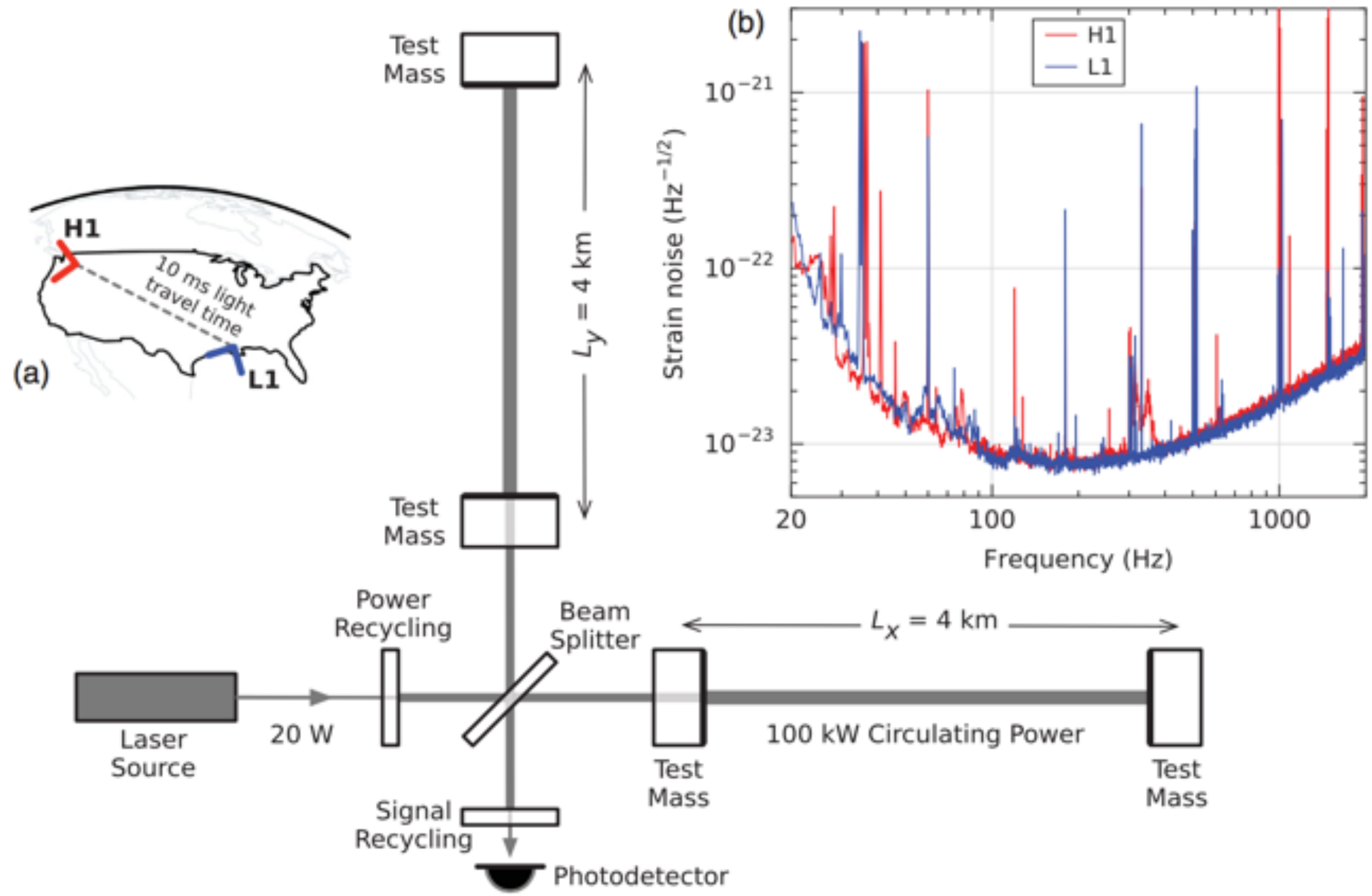
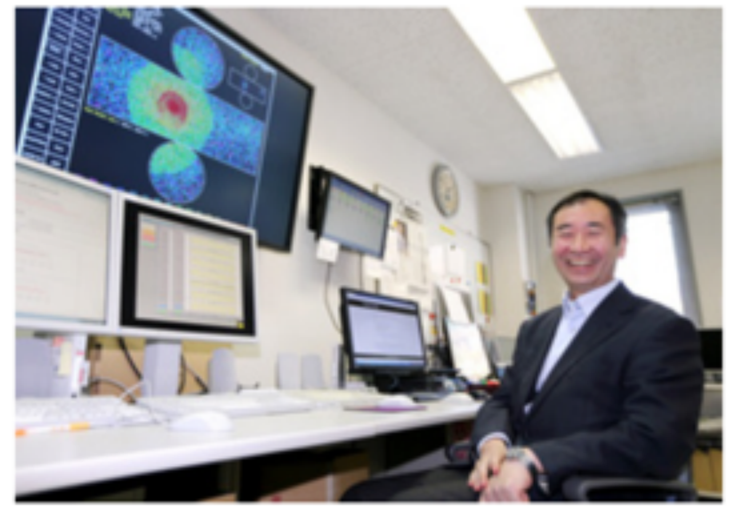


FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the 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 fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

朝日新聞 DIGITAL

ノーベル賞・梶田さん、カミオカ施設訪れ「地域に感謝」

奥村輝　2015年11月5日22時48分



研究棟内の実験監視室を訪れた梶田隆章教授＝5日午後、岐阜県飛騨市、川村直子撮影

ノーベル物理学賞が決まった東京大宇宙線研究所長の梶田隆章教授が5日、受賞決定後初めて、業績につながった大型施設「スーパーカミオカンデ」のある同研究所神岡宇宙素粒子研究施設を訪れた。教員や学生たち約５０人から祝福された梶田教授は「こんなたくさんの人が出迎えてくれるとは。本当にうれしく思います。仲間とともにやってきて良かった」と喜んだ。

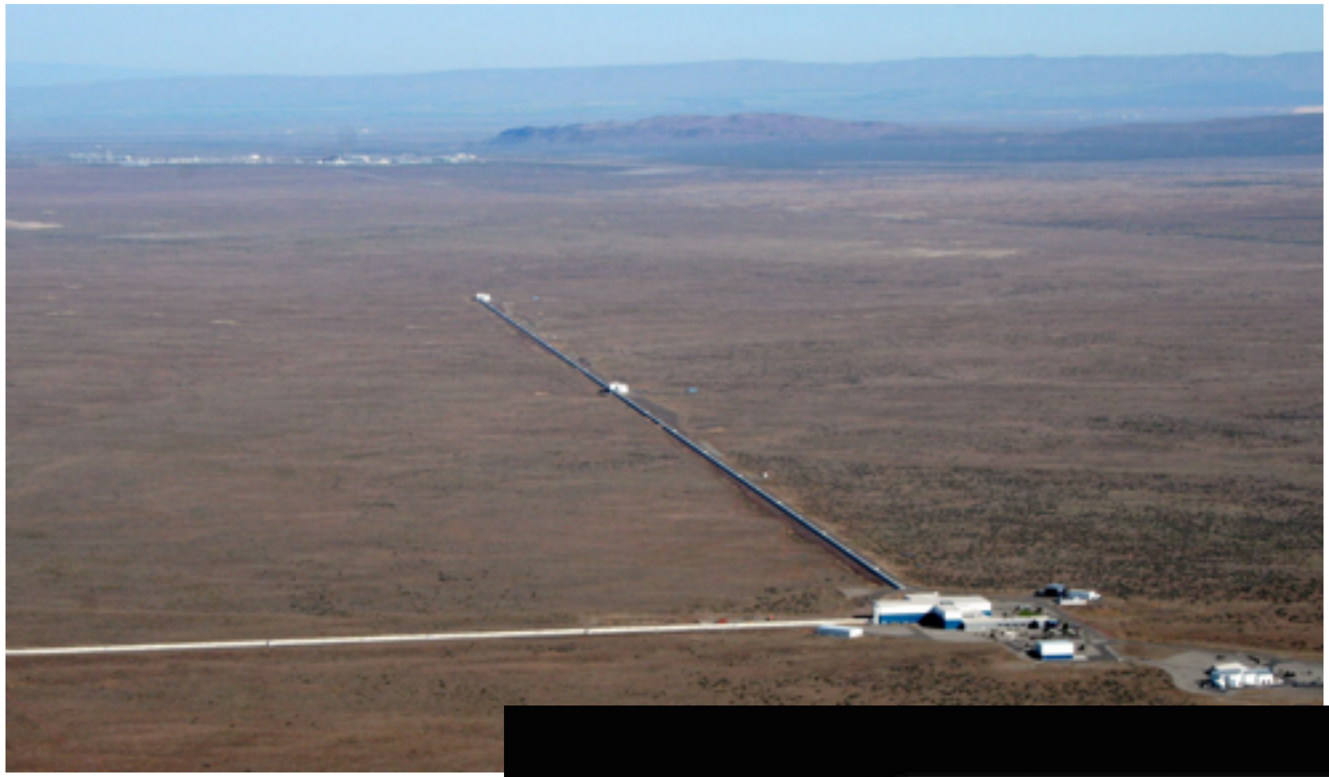
梶田教授は、大学院に入った１９８１年から９９年まで、岐阜県の神岡鉱山にある施設で集中的に研究し、９８年のニュートリノ振動発見の発表に結びつけた。記者会見で、この場所について「研究人生のすべて」と振り返り、「本当に地域の方々のご支援には深く感謝しています」と話した。

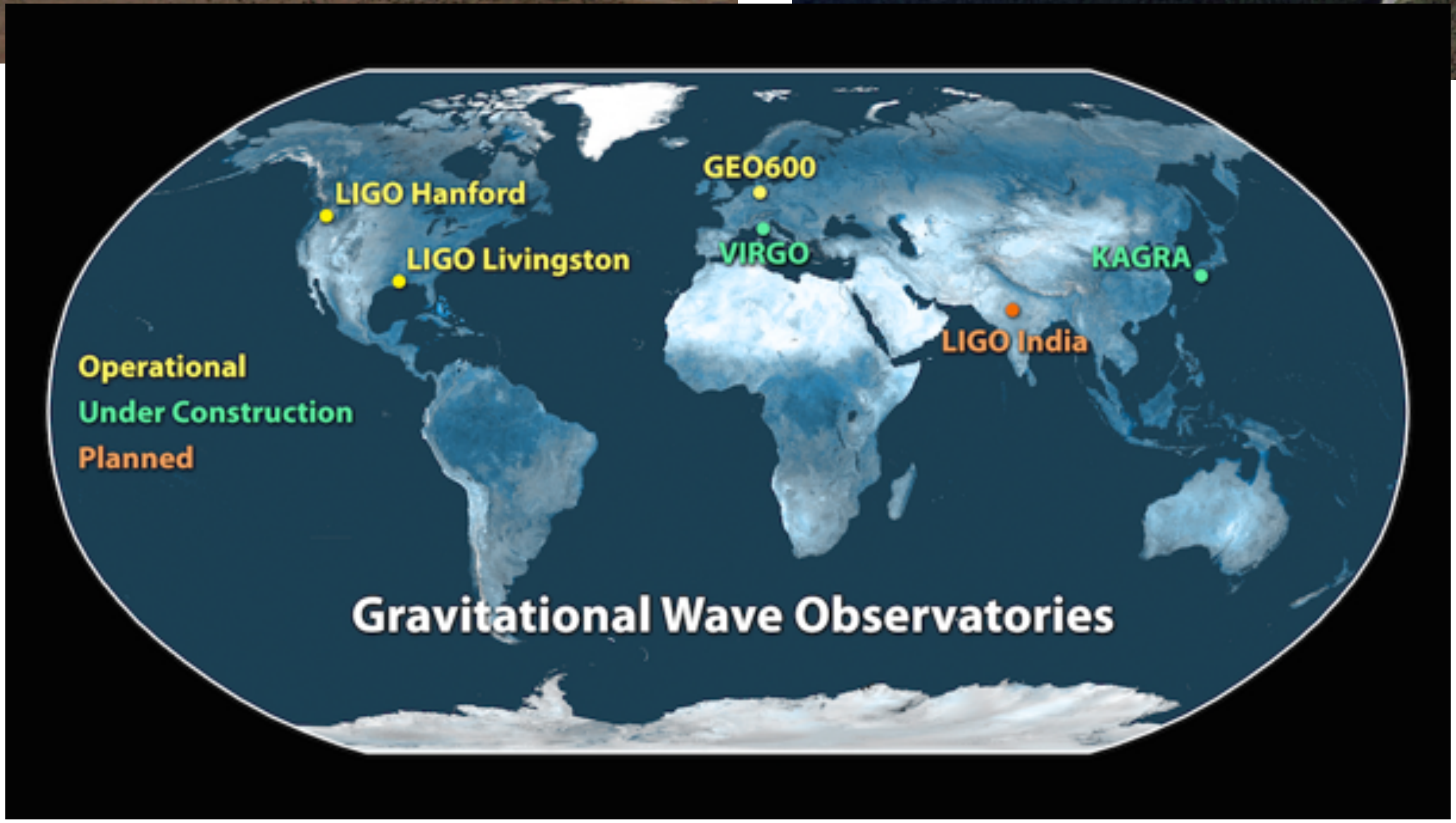
今後の目標には、ニュートリノ振動を詳しく調べることで物質の起源の解明や、建設の進む観測施設「ＫＡＧＲＡ（かぐら）」での重力波天文学の確立を挙げた。

朝日新聞　2015/11/5

LIGO（レーザー干渉計重力波天文台）

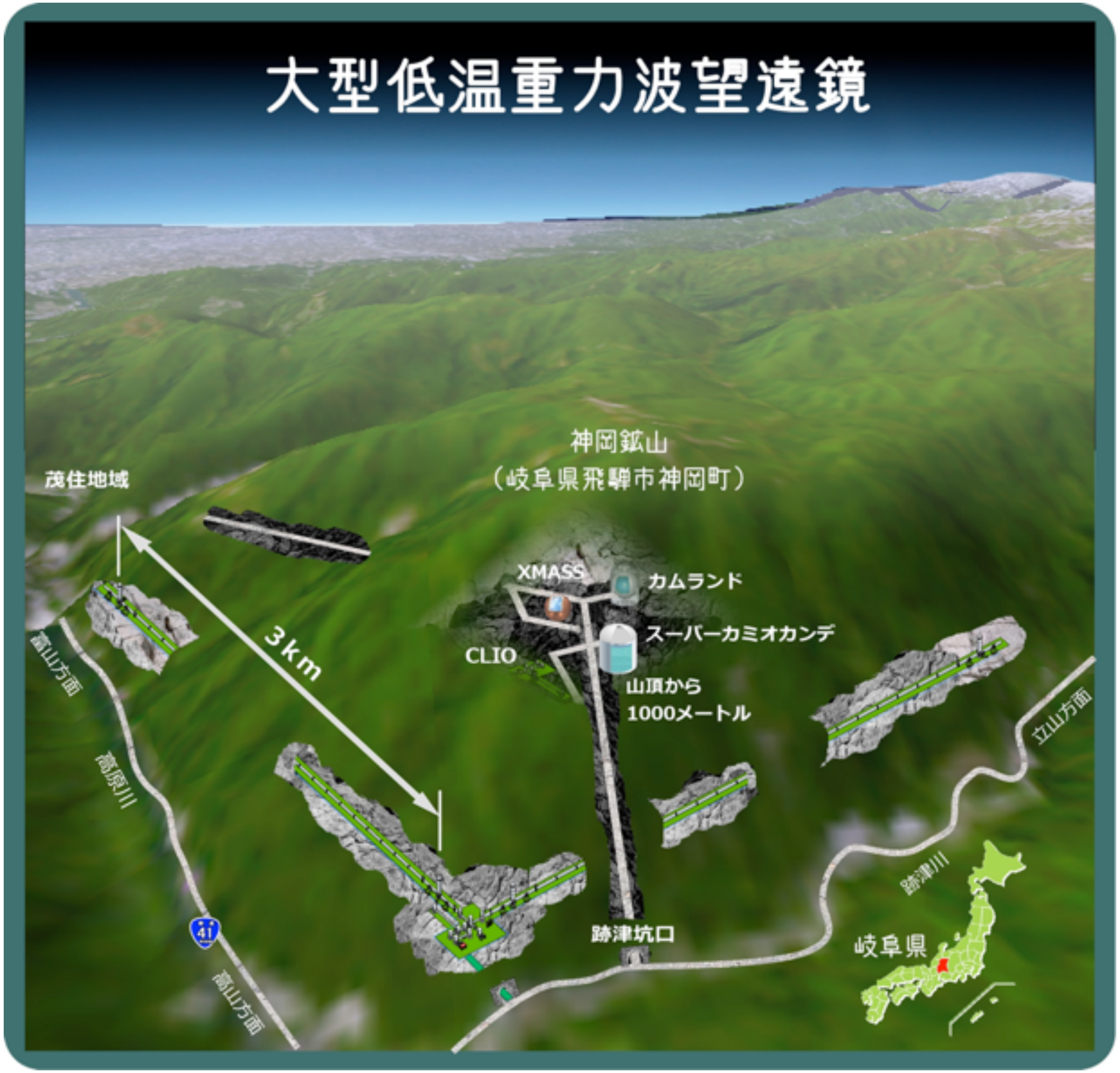
Laser Interferemeter Gravitational-Wave Observatory　（1992年予算承認)





KAGRA（大型低温重力波望遠鏡）

Kamioka Gravitational wave detector, **(Large-scale Cryogenic Gravitational wave Telescope)**



望遠鏡の大きさ：基線長 3km

望遠鏡を神岡鉱山内に建設

地面振動が小さい岐阜県飛騨市にある神岡鉱山

鏡をマイナス250度（20K）まで冷却

熱雑音を小さくするため

鏡の材質としてサファイア

光学特性に優れ、低温に冷却すると熱伝導や機械的損失が少なくなる

http://gwcenter.icrr.u-tokyo.ac.jp/plan/history

2015年8月

Hisaaki Shinkai

Seiji Kawamura Kieran Craig
Martynov Denis

2014年6月、日本が岐阜県に建設している重力波干渉計KAGRA（かぐら）のトンネルが貫通し、マスコミに公開された。KAGRAは、一辺が3kmもあるレーザー干渉計だが、岐阜県神岡鉱山跡の山中にわざわざ建設した理由は何か。

①近くにはスーパーカミオカンデというニュートリノ観測装置があり、実験装置の調整にニュートリノを使うから
②山の中だと地面の振動が少なく、干渉計装置のゆれを押さえることができるから
③山の中だと温度調整が少なくて済むので、レーザー光源のメンテナンスに都合がよいから
④強力なレーザー光の発生や、真空ポンプの稼働で、騒音が激しいから

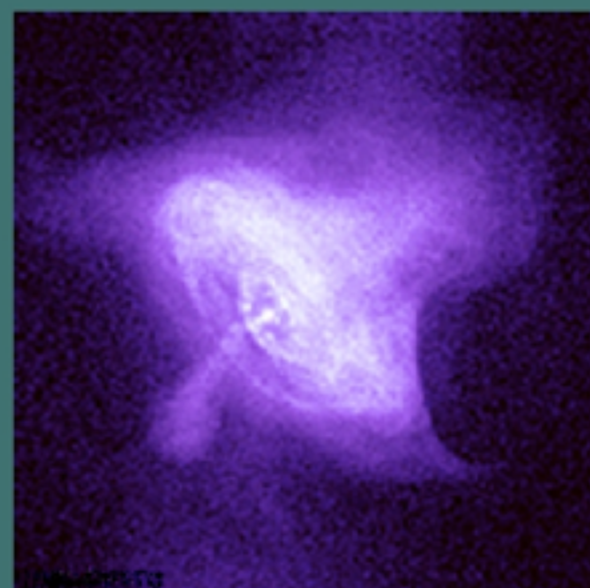
重力波の波源

sources of gravitational wave

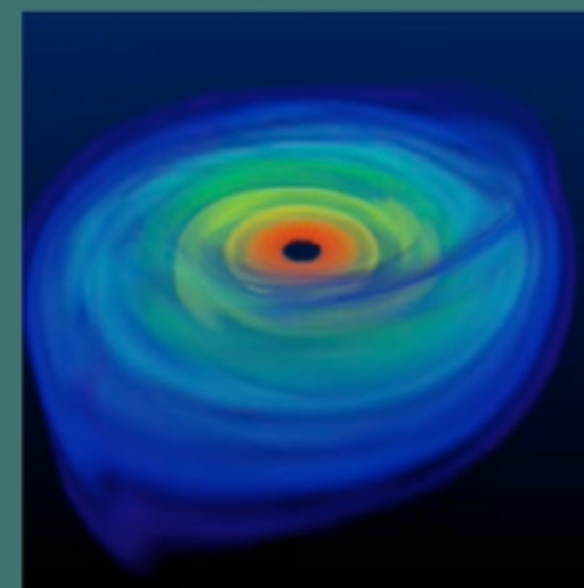
http://gwcenter.icrr.u-tokyo.ac.jp/

超新星爆発（写真出典:NASA）

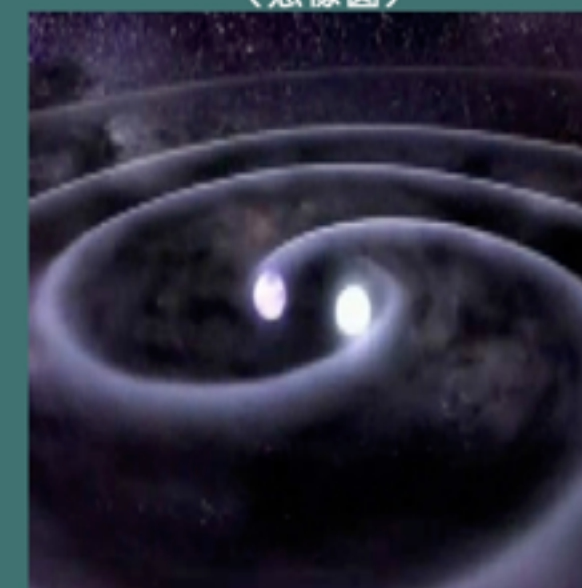
パルサー（写真出典:NASA）



ブラックホール（想像図）



連星中性子星合体（想像図）



予測が難しい

振幅が小さい

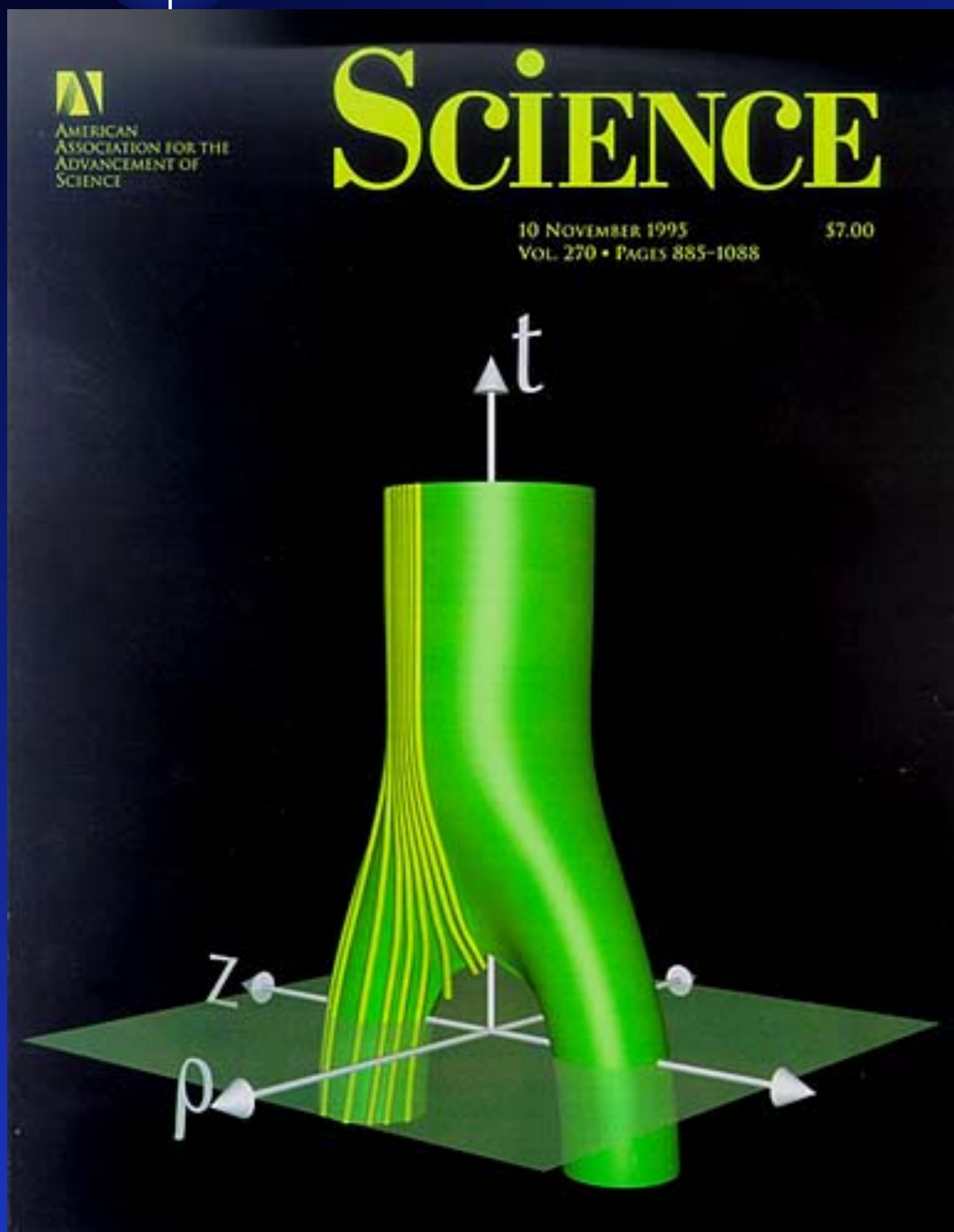
振幅が小さい

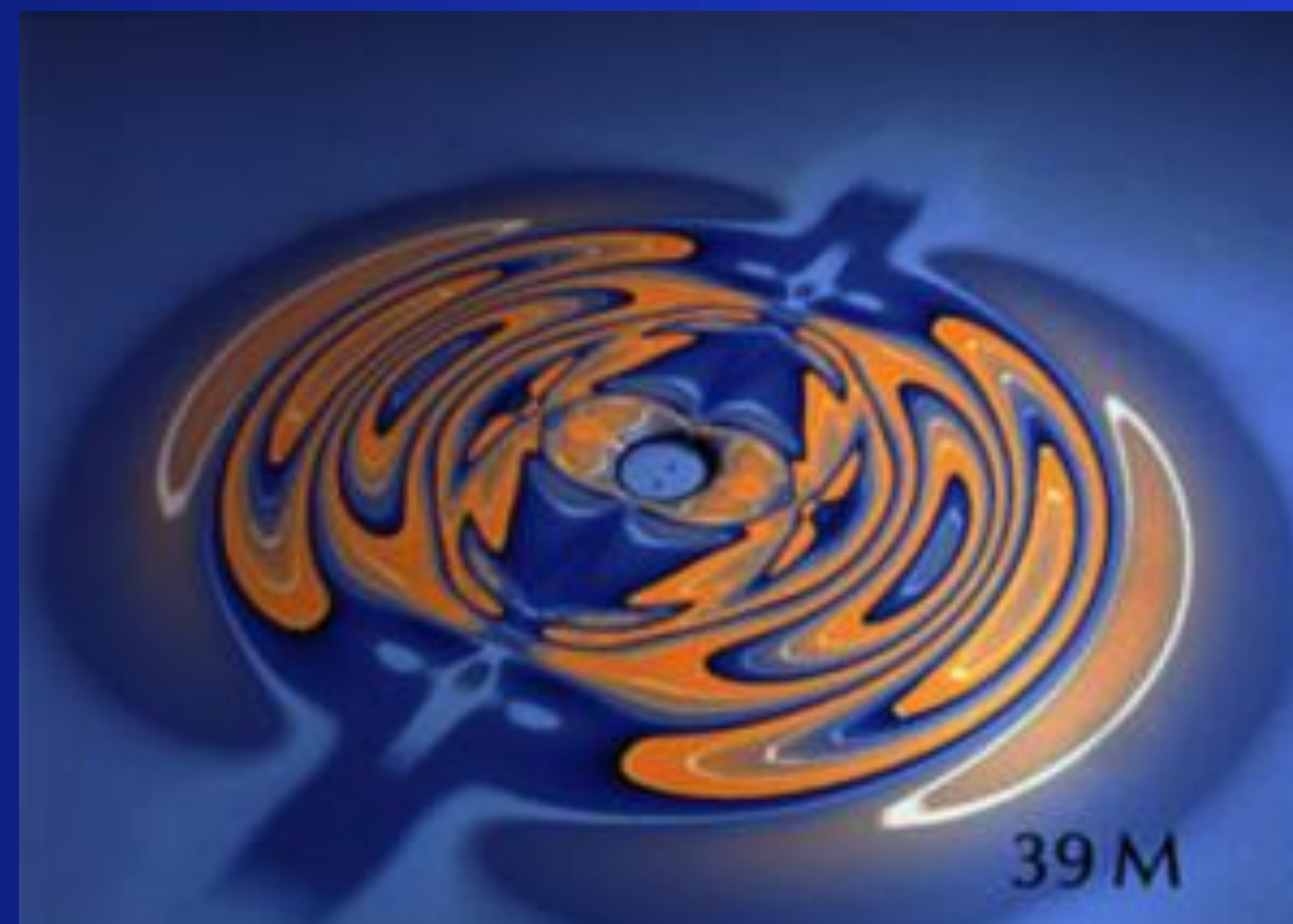
連星合体をターゲットに

重力波は弱いのであらかじめ，波形の予測が必要

ノイズにまみれたデータに，予測した波形があるか探す（matched-filtering method）

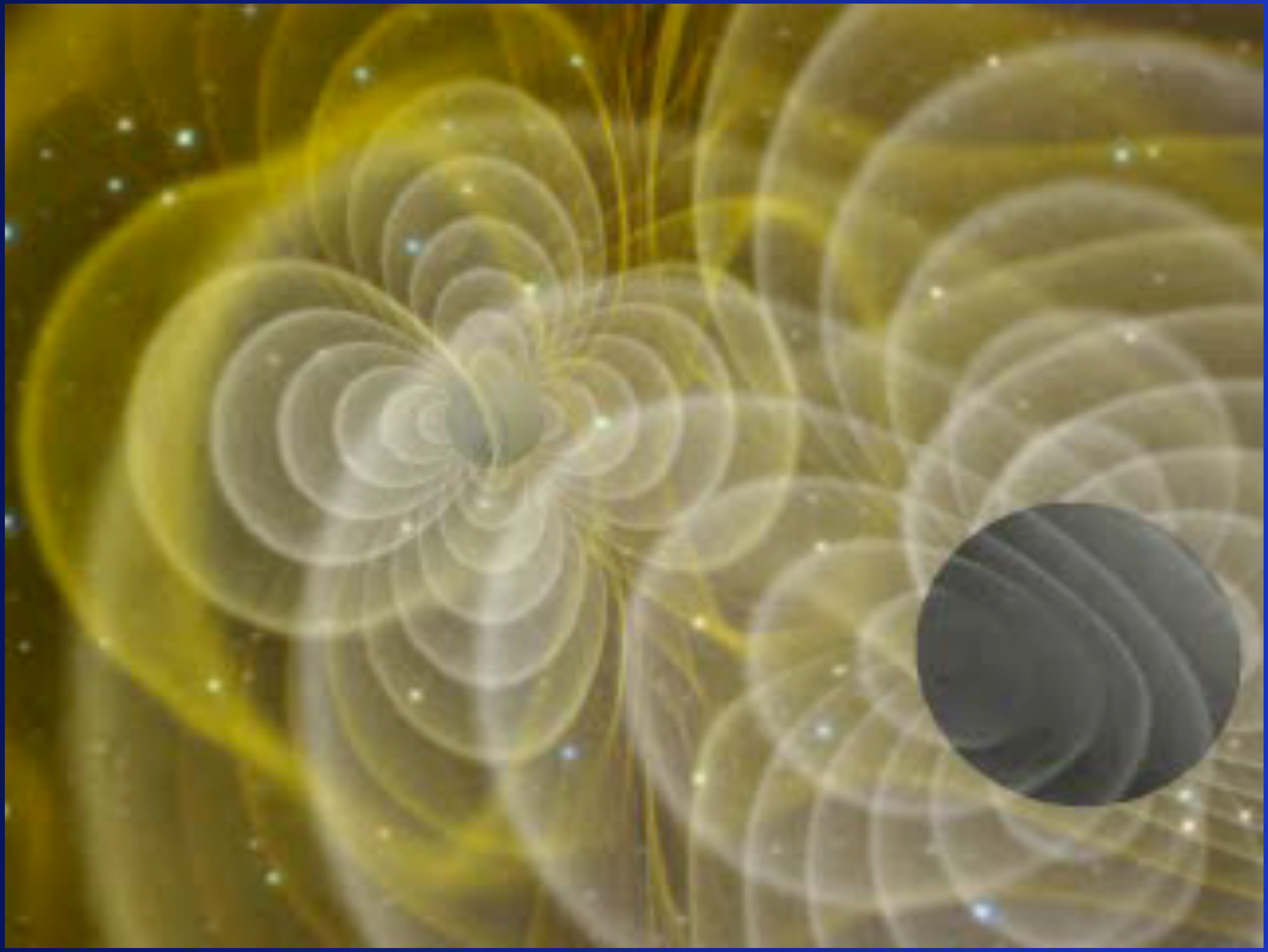
ブラックホールの合体シミュレーション





２つのブラックホールの合体と重力波放出
（90年代，NCSAグループ）

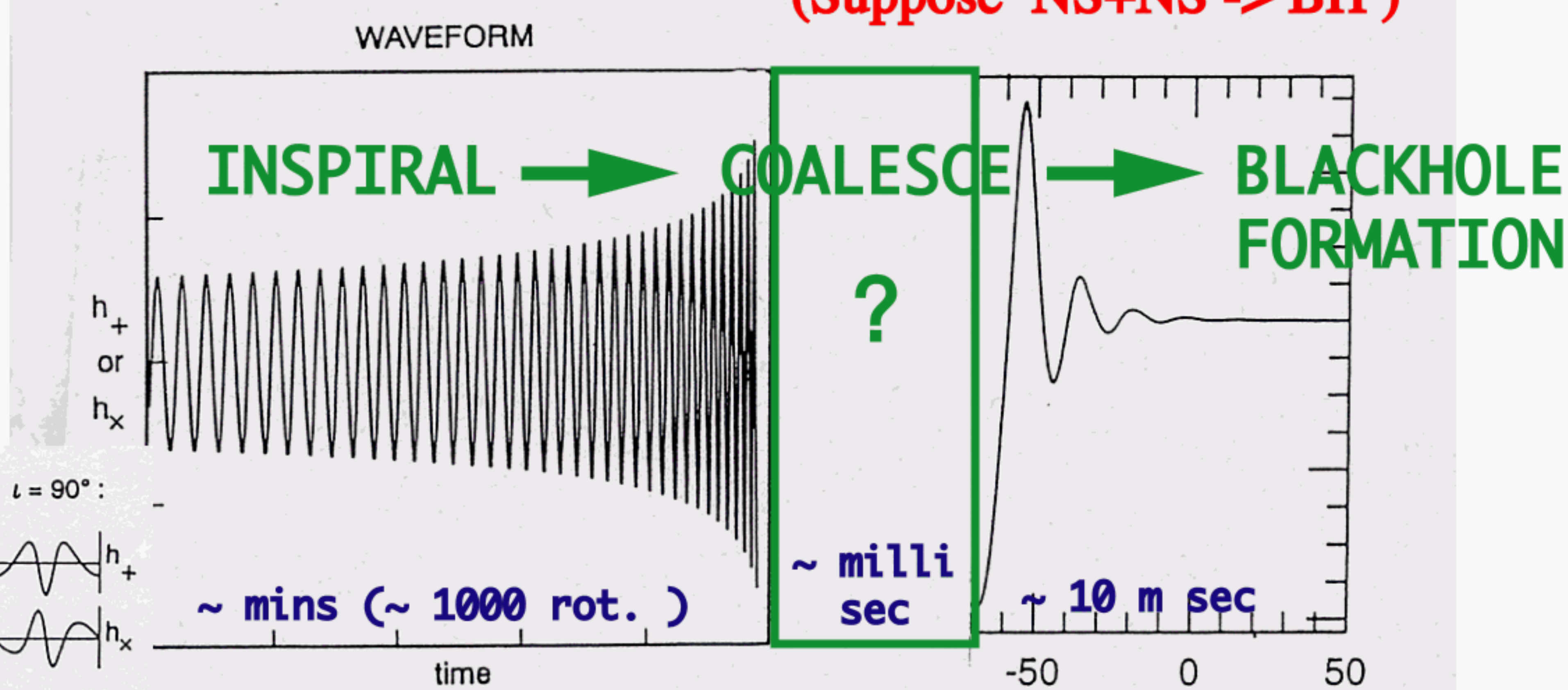
ブラックホールの合体シミュレーション



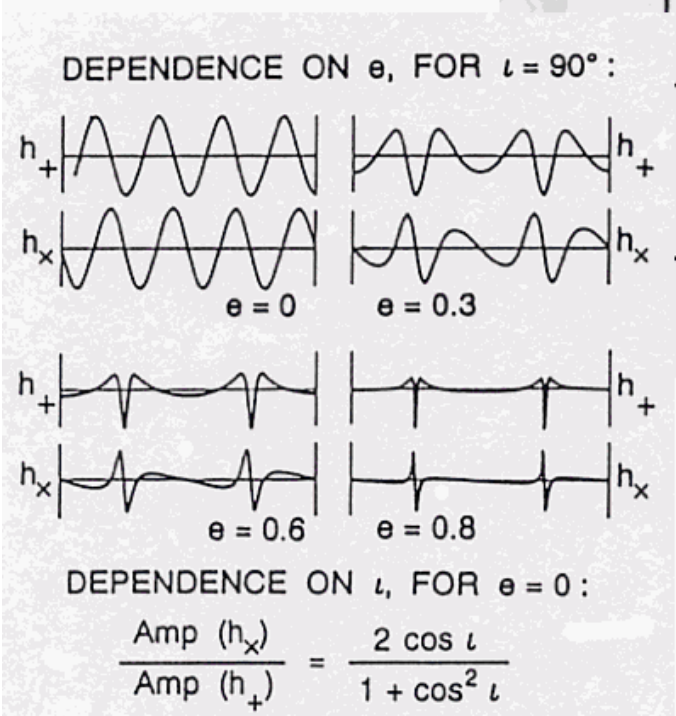
NCSA-AEI group (1998)

What can we learn from gravitational waveform?

(Suppose NS+NS -> BH)



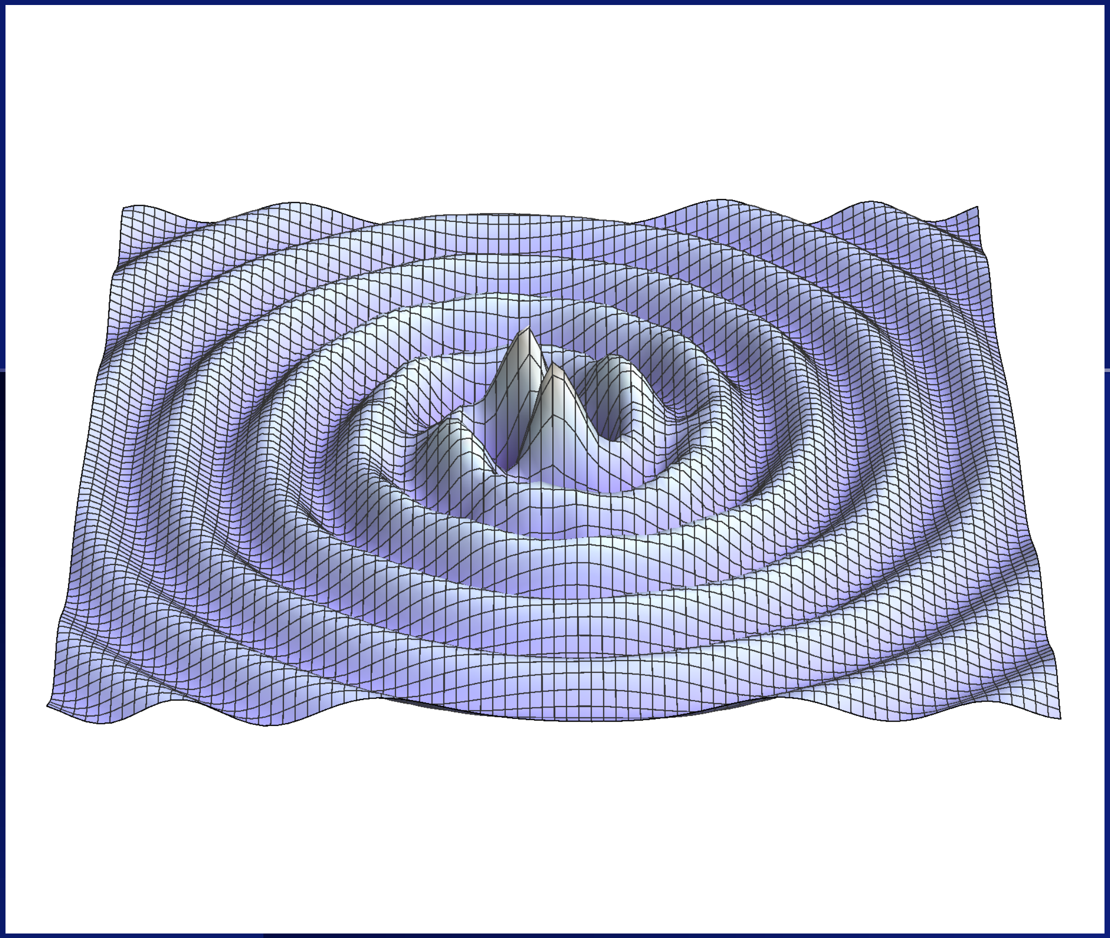
Post Newtonian Approx. | Numerical Relativity | BH. Perturbation



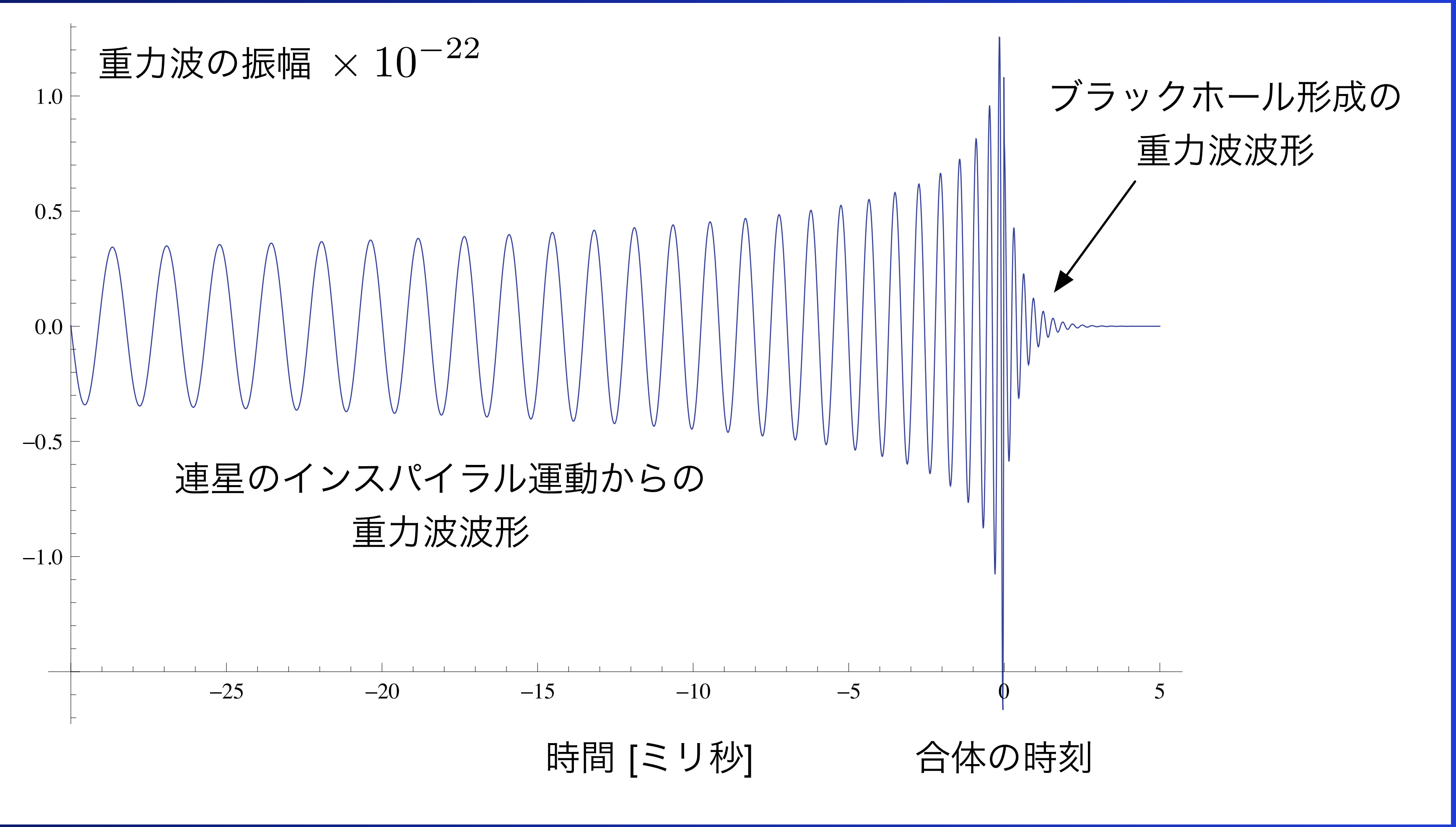
ISCO freq => EoS of NS,
waveform => Formation of BH or NS, BH mass, BH angular momentum,...

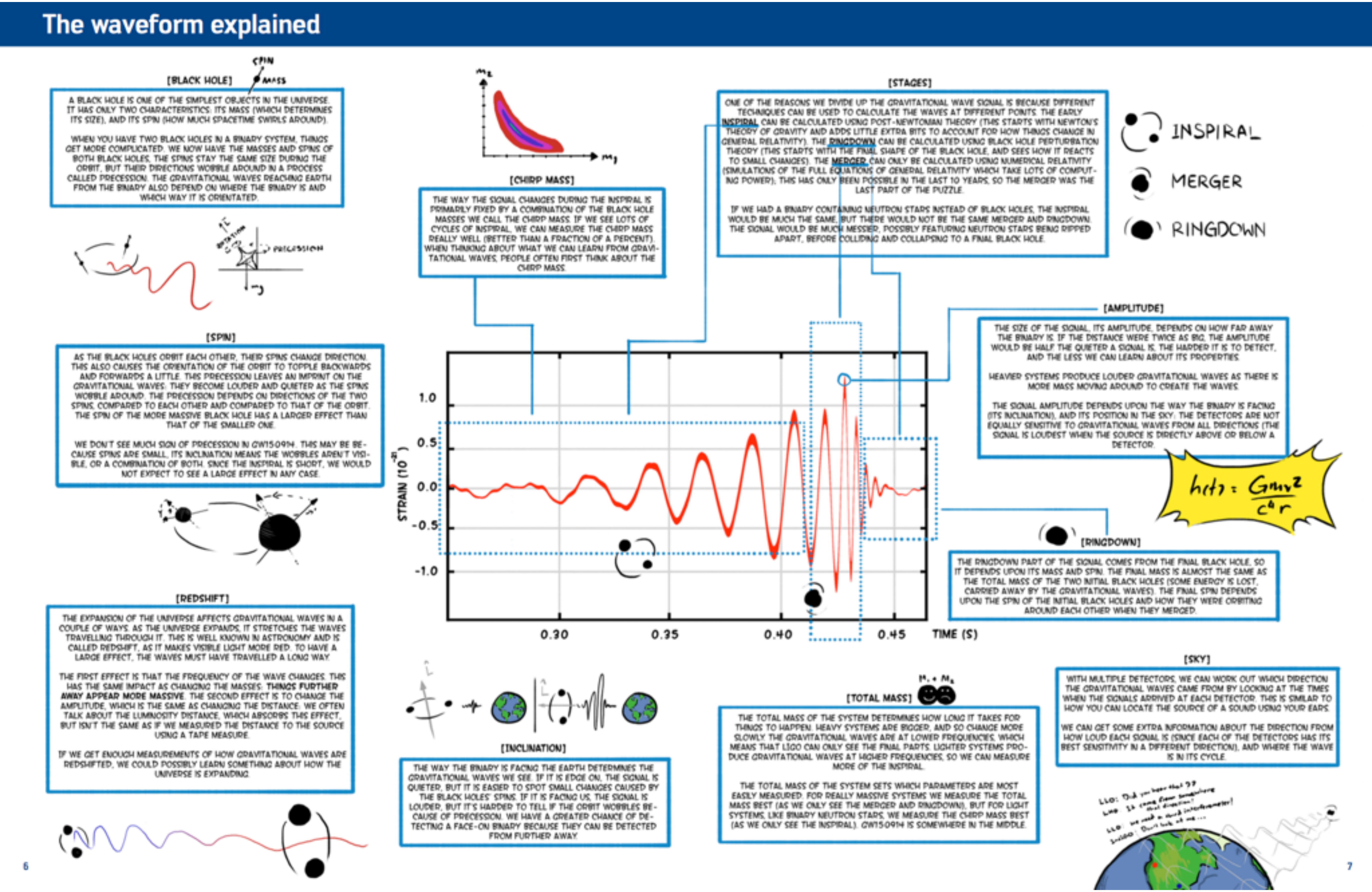
"chirps" df/dt => chirp mass, $M_c = (M_1 M_2)^{3/5} / (M_1+M_2)^{1/5}$
amplitude up => M_c, distance
amplitude $h_+/h_\times$ => inclination
waveform => eccentricity
moduration => spin, ...

statistics => cosmological parameters



連星中性子星(BNS)
連星ブラックホール(BBH)





The waveform explained

[BLACK HOLE]

A BLACK HOLE IS ONE OF THE SIMPLEST OBJECTS IN THE UNIVERSE. IT HAS ONLY TWO CHARACTERISTICS: ITS MASS (WHICH DETERMINES ITS SIZE), AND ITS SPIN (HOW MUCH SPACETIME SWIRLS AROUND).

WHEN YOU HAVE TWO BLACK HOLES IN A BINARY SYSTEM, THINGS GET MORE COMPLICATED. WE NOW HAVE THE MASSES AND SPINS OF BOTH BLACK HOLES. THE SPINS STAY THE SAME SIZE DURING THE ORBIT, BUT THEIR DIRECTIONS WOBBLE AROUND IN A PROCESS CALLED PRECESSION. THE GRAVITATIONAL WAVES REACHING EARTH FROM THE BINARY ALSO DEPEND ON WHERE THE BINARY IS AND WHICH WAY IT IS ORIENTATED.

[SPIN]

AS THE BLACK HOLES ORBIT EACH OTHER, THEIR SPINS CHANGE DIRECTION. THIS ALSO CAUSES THE ORIENTATION OF THE ORBIT TO TOPPLE BACKWARDS AND FORWARDS A LITTLE. THIS PRECESSION LEAVES AN IMPRINT ON THE GRAVITATIONAL WAVES: THEY BECOME LOUDER AND QUIETER AS THE SPINS WOBBLE AROUND. THE PRECESSION DEPENDS ON DIRECTIONS OF THE TWO SPINS, COMPARED TO EACH OTHER AND COMPARED TO THAT OF THE ORBIT. THE SPIN OF THE MORE MASSIVE BLACK HOLE HAS A LARGER EFFECT THAN THAT OF THE SMALLER ONE.

WE DON'T SEE MUCH SIGN OF PRECESSION IN GW150914. THIS MAY BE BECAUSE SPINS ARE SMALL, ITS INCLINATION MEANS THE WOBBLES AREN'T VISIBLE, OR A COMBINATION OF BOTH. SINCE THE INSPIRAL IS SHORT, WE WOULD NOT EXPECT TO SEE A LARGE EFFECT IN ANY CASE.

[REDSHIFT]

THE EXPANSION OF THE UNIVERSE AFFECTS GRAVITATIONAL WAVES IN A COUPLE OF WAYS. AS THE UNIVERSE EXPANDS, IT STRETCHES THE WAVES TRAVELLING THROUGH IT. THIS IS WELL KNOWN IN ASTRONOMY AND IS CALLED REDSHIFT, AS IT MAKES VISIBLE LIGHT MORE RED. TO HAVE A LARGE EFFECT, THE WAVES MUST HAVE TRAVELLED A LONG WAY.

THE FIRST EFFECT IS THAT THE FREQUENCY OF THE WAVE CHANGES. THIS HAS THE SAME IMPACT AS CHANGING THE MASSES: **THINGS FURTHER AWAY APPEAR MORE MASSIVE**. THE SECOND EFFECT IS TO CHANGE THE AMPLITUDE, WHICH IS THE SAME AS CHANGING THE DISTANCE: WE OFTEN TALK ABOUT THE LUMINOSITY DISTANCE, WHICH ABSORBS THIS EFFECT, BUT ISN'T THE SAME AS IF WE MEASURED THE DISTANCE TO THE SOURCE USING A TAPE MEASURE.

IF WE GET ENOUGH MEASUREMENTS OF HOW GRAVITATIONAL WAVES ARE REDSHIFTED, WE COULD POSSIBLY LEARN SOMETHING ABOUT HOW THE UNIVERSE IS EXPANDING.

[CHIRP MASS]

THE WAY THE SIGNAL CHANGES DURING THE INSPIRAL IS PRIMARILY FIXED BY A COMBINATION OF THE BLACK HOLE MASSES WE CALL THE CHIRP MASS. IF WE SEE LOTS OF CYCLES OF INSPIRAL, WE CAN MEASURE THE CHIRP MASS REALLY WELL (BETTER THAN A FRACTION OF A PERCENT). WHEN THINKING ABOUT WHAT WE CAN LEARN FROM GRAVITATIONAL WAVES, PEOPLE OFTEN FIRST THINK ABOUT THE CHIRP MASS.

[STAGES]

ONE OF THE REASONS WE DIVIDE UP THE GRAVITATIONAL WAVE SIGNAL IS BECAUSE DIFFERENT TECHNIQUES CAN BE USED TO CALCULATE THE WAVES AT DIFFERENT POINTS. THE EARLY **INSPIRAL** CAN BE CALCULATED USING POST-NEWTONIAN THEORY (THIS STARTS WITH NEWTON'S THEORY OF GRAVITY AND ADDS LITTLE EXTRA BITS TO ACCOUNT FOR HOW THINGS CHANGE IN GENERAL RELATIVITY). THE **RINGDOWN** CAN BE CALCULATED USING BLACK HOLE PERTURBATION THEORY (THIS STARTS WITH THE FINAL SHAPE OF THE BLACK HOLE, AND SEES HOW IT REACTS TO SMALL CHANGES). THE **MERGER** CAN ONLY BE CALCULATED USING NUMERICAL RELATIVITY (SIMULATIONS OF THE FULL EQUATIONS OF GENERAL RELATIVITY WHICH TAKE LOTS OF COMPUTING POWER). THIS HAS ONLY BEEN POSSIBLE IN THE LAST 10 YEARS, SO THE MERGER WAS THE LAST PART OF THE PUZZLE.

IF WE HAD A BINARY CONTAINING NEUTRON STARS INSTEAD OF BLACK HOLES, THE INSPIRAL WOULD BE MUCH THE SAME, BUT THERE WOULD NOT BE THE SAME MERGER AND RINGDOWN. THE SIGNAL WOULD BE MUCH MESSIER, POSSIBLY FEATURING NEUTRON STARS BEING RIPPED APART, BEFORE COLLIDING AND COLLAPSING TO A FINAL BLACK HOLE.

[AMPLITUDE]

THE SIZE OF THE SIGNAL, ITS AMPLITUDE, DEPENDS ON HOW FAR AWAY THE BINARY IS. IF THE DISTANCE WERE TWICE AS BIG, THE AMPLITUDE WOULD BE HALF. THE QUIETER A SIGNAL IS, THE HARDER IT IS TO DETECT, AND THE LESS WE CAN LEARN ABOUT ITS PROPERTIES.

HEAVIER SYSTEMS PRODUCE LOUDER GRAVITATIONAL WAVES AS THERE IS MORE MASS MOVING AROUND TO CREATE THE WAVES.

THE SIGNAL AMPLITUDE DEPENDS UPON THE WAY THE BINARY IS FACING (ITS INCLINATION), AND ITS POSITION IN THE SKY: THE DETECTORS ARE NOT EQUALLY SENSITIVE TO GRAVITATIONAL WAVES FROM ALL DIRECTIONS (THE SIGNAL IS LOUDEST WHEN THE SOURCE IS DIRECTLY ABOVE OR BELOW A DETECTOR.

[RINGDOWN]

THE RINGDOWN PART OF THE SIGNAL COMES FROM THE FINAL BLACK HOLE, SO IT DEPENDS UPON ITS MASS AND SPIN. THE FINAL MASS IS ALMOST THE SAME AS THE TOTAL MASS OF THE TWO INITIAL BLACK HOLES (SOME ENERGY IS LOST, CARRIED AWAY BY THE GRAVITATIONAL WAVES). THE FINAL SPIN DEPENDS UPON THE SPIN OF THE INITIAL BLACK HOLES AND HOW THEY WERE ORBITING AROUND EACH OTHER WHEN THEY MERGED.

[INCLINATION]

THE WAY THE BINARY IS FACING THE EARTH DETERMINES THE GRAVITATIONAL WAVES WE SEE. IF IT IS EDGE ON, THE SIGNAL IS QUIETER, BUT IT IS EASIER TO SPOT SMALL CHANGES CAUSED BY THE BLACK HOLES' SPINS. IF IT IS FACING US, THE SIGNAL IS LOUDER, BUT IT'S HARDER TO TELL IF THE ORBIT WOBBLES BECAUSE OF PRECESSION. WE HAVE A GREATER CHANCE OF DETECTING A FACE-ON BINARY BECAUSE THEY CAN BE DETECTED FROM FURTHER AWAY.

[TOTAL MASS]

THE TOTAL MASS OF THE SYSTEM DETERMINES HOW LONG IT TAKES FOR THINGS TO HAPPEN. HEAVY SYSTEMS ARE BIGGER, AND SO CHANGE MORE SLOWLY. THE GRAVITATIONAL WAVES ARE AT LOWER FREQUENCIES, WHICH MEANS THAT LIGO CAN ONLY SEE THE FINAL PARTS. LIGHTER SYSTEMS PRODUCE GRAVITATIONAL WAVES AT HIGHER FREQUENCIES, SO WE CAN MEASURE MORE OF THE INSPIRAL.

THE TOTAL MASS OF THE SYSTEM SETS WHICH PARAMETERS ARE MOST EASILY MEASURED. FOR REALLY MASSIVE SYSTEMS WE MEASURE THE TOTAL MASS BEST (AS WE ONLY SEE THE MERGER AND RINGDOWN), BUT FOR LIGHT SYSTEMS, LIKE BINARY NEUTRON STARS, WE MEASURE THE CHIRP MASS BEST (AS WE ONLY SEE THE INSPIRAL). GW150914 IS SOMEWHERE IN THE MIDDLE.

[SKY]

WITH MULTIPLE DETECTORS, WE CAN WORK OUT WHICH DIRECTION THE GRAVITATIONAL WAVES CAME FROM BY LOOKING AT THE TIMES WHEN THE SIGNALS ARRIVED AT EACH DETECTOR. THIS IS SIMILAR TO HOW YOU CAN LOCATE THE SOURCE OF A SOUND USING YOUR EARS.

WE CAN GET SOME EXTRA INFORMATION ABOUT THE DIRECTION FROM HOW LOUD EACH SIGNAL IS (SINCE EACH OF THE DETECTORS HAS ITS BEST SENSITIVITY IN A DIFFERENT DIRECTION), AND WHERE THE WAVE IS IN ITS CYCLE.

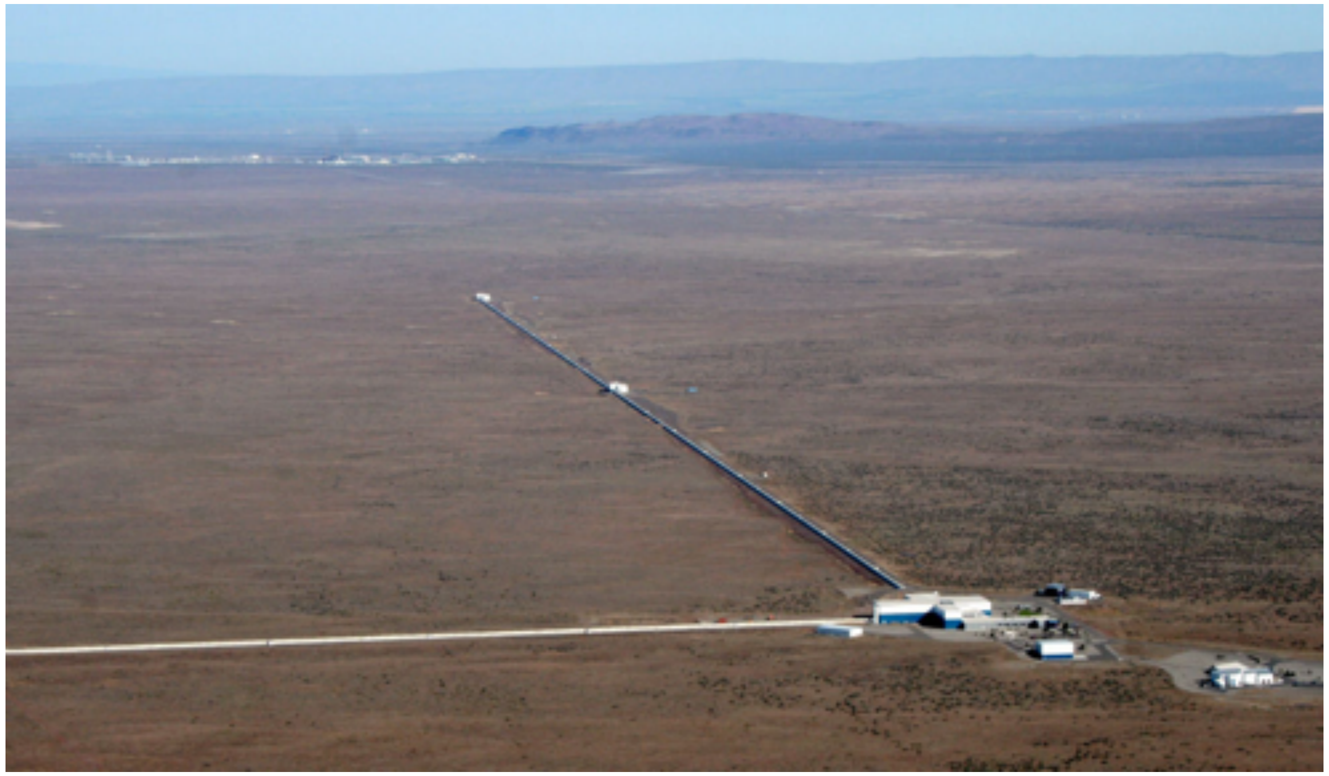
6

7

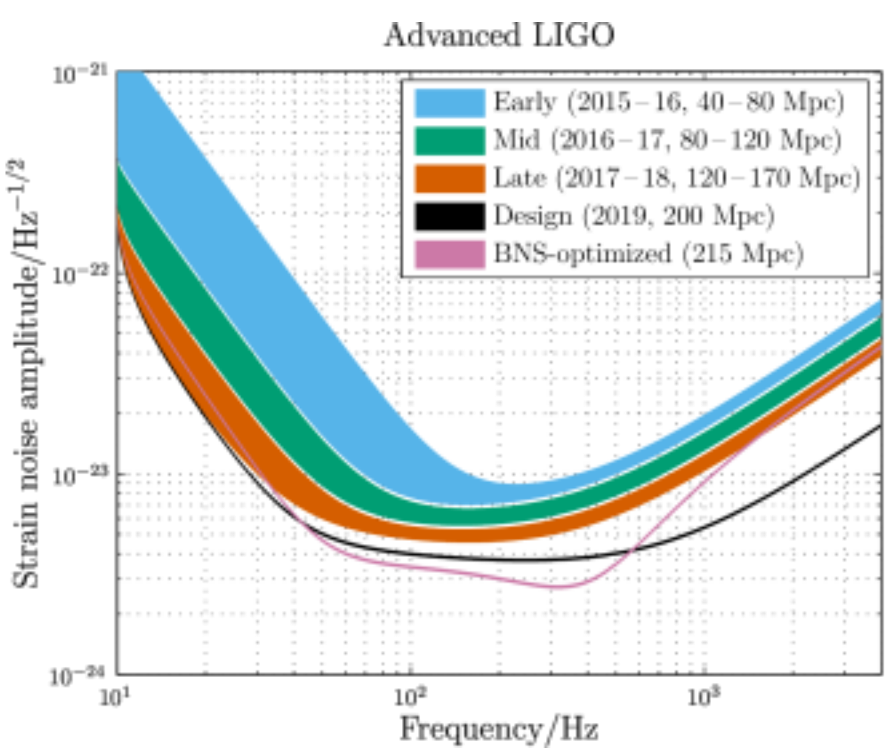
http://www.ligo.org/magazine/LIGO-magazine-issue-8.pdf

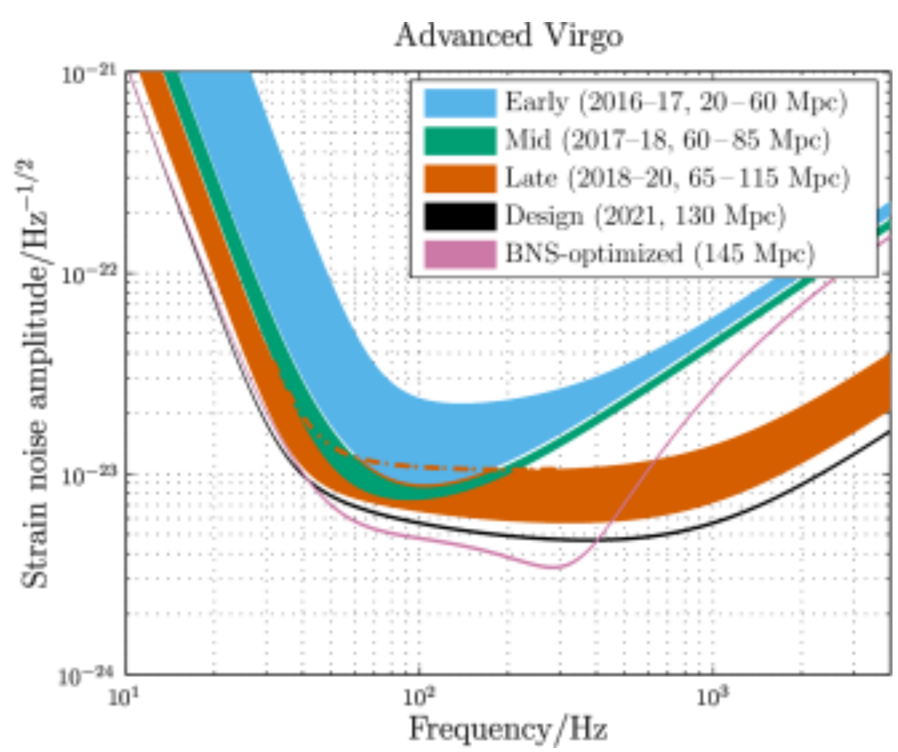
LIGO（レーザー干渉計重力波天文台）

Laser Interferemeter Gravitational-Wave Observatory　（1992年予算承認)



https://mediaassets.caltech.edu/gwave





2015/9/16--2016/1/15
Observation run 1

nature International weekly journal of science

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News & Comment > Column > Muse > 2016 > February > Article

NATURE | COLUMN: MUSE


Alexa Keefe

Has giant LIGO experiment seen gravitational waves?

An improbable rumour has started that the observatory has already made a discovery — but even if true, the signal could be a drill.

Davide Castelvecchi

30 September 2015

Rights & Permissions

On 25 September, a sensational rumour appeared on Twitter: Lawrence Krauss, a cosmologist, reported hearing that the world's largest gravitational-wave observatory had seen a signal, barely a week after its official re-opening.

Lawrence M. Krauss @LKrauss1 フォロー

Rumor of a gravitational wave detection at LIGO detector. Amazing if true. Will post details if it survives.

635 リツイート 666 いいね

13:39 - 2015年9月25日

2015/9/25

Lawrence M. Krauss @LKrauss1 フォロー

My earlier rumor about LIGO has been confirmed by independent sources. Stay tuned! Gravitational waves may have been discovered!! Exciting.

3,563 リツイート 2,888 いいね

7:46 - 2016年1月11日

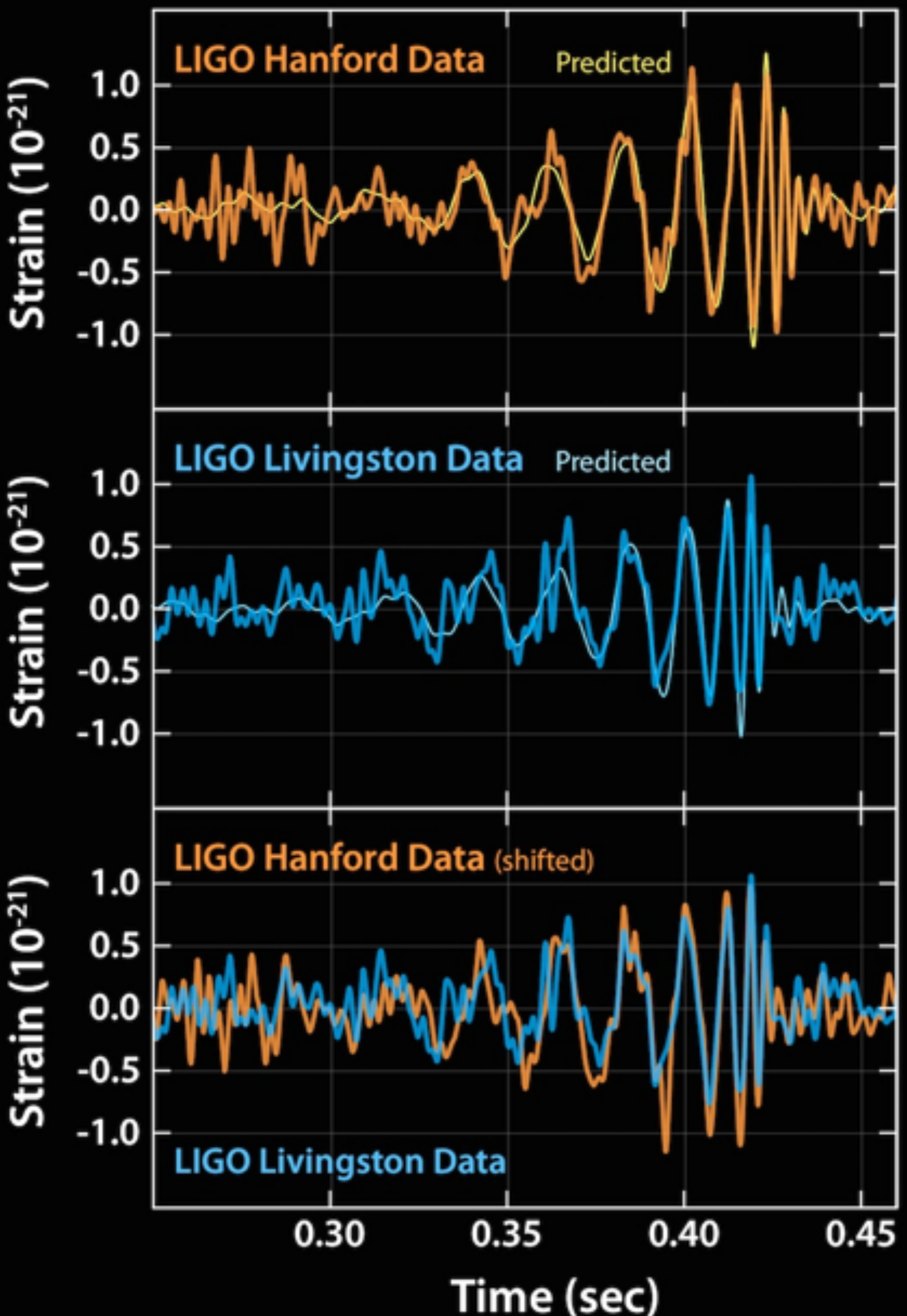
2016/1/11

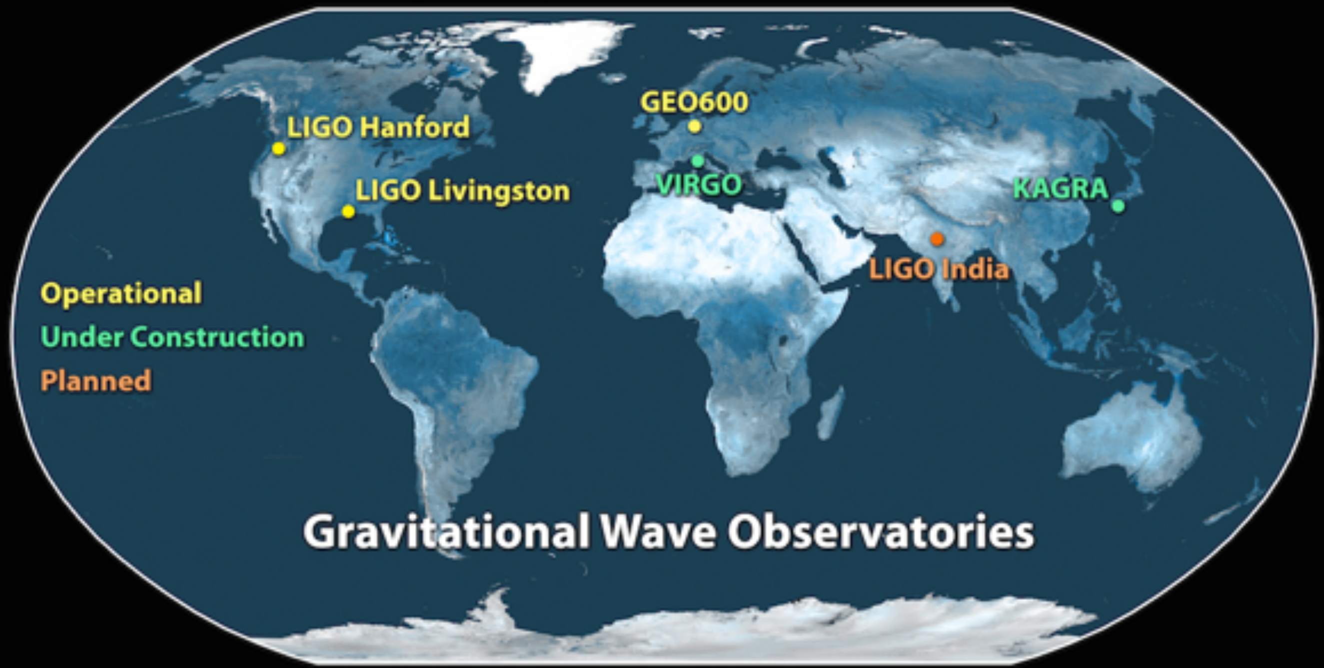
重力波初検出を発表するライツィLIGO所長

2016年2月11日

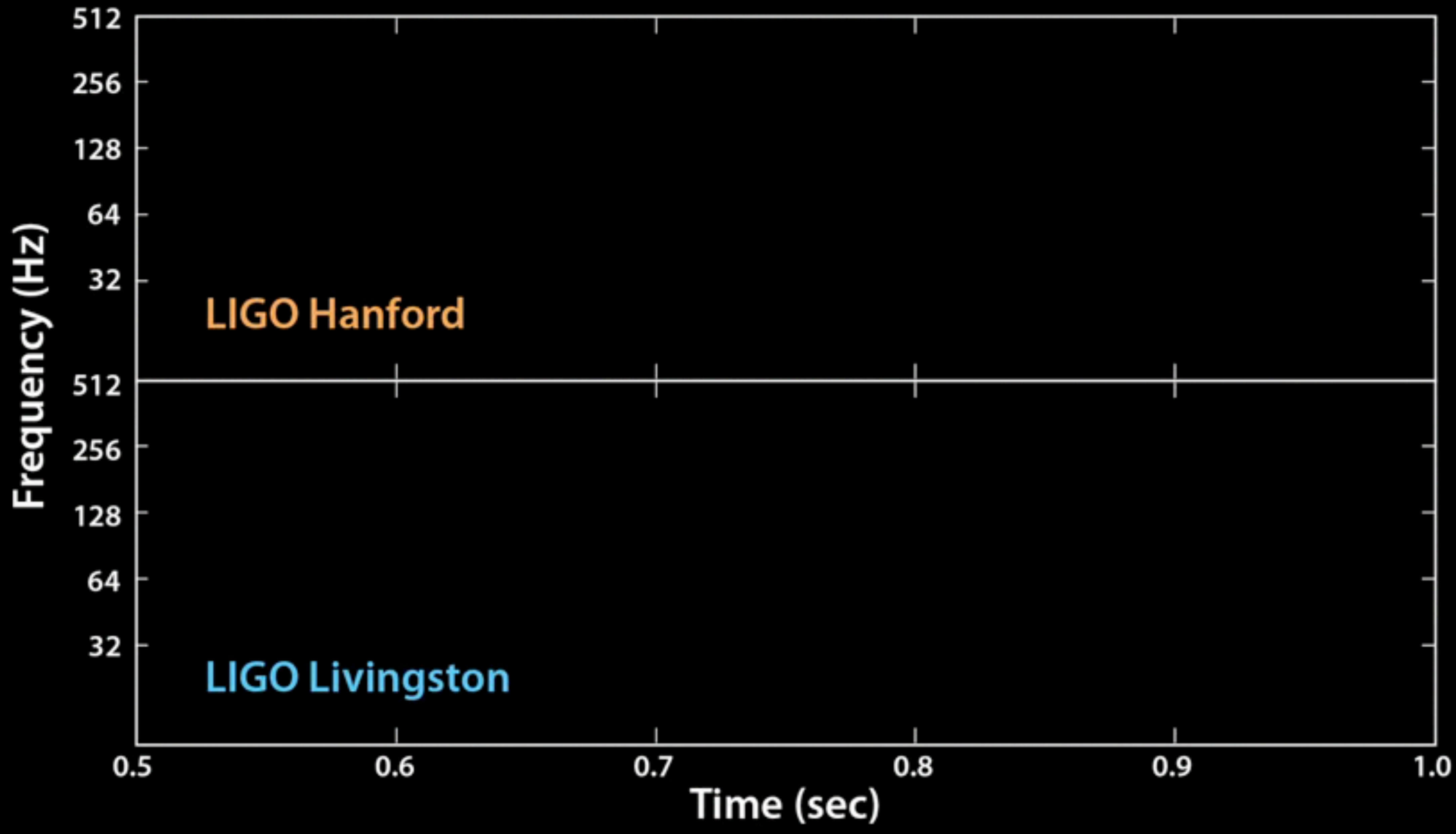
“We had detected gravitational waves.
We did it. ”　(David Reitze)

https://www.youtube.com/watch?v=aEPIwEJmZyE


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

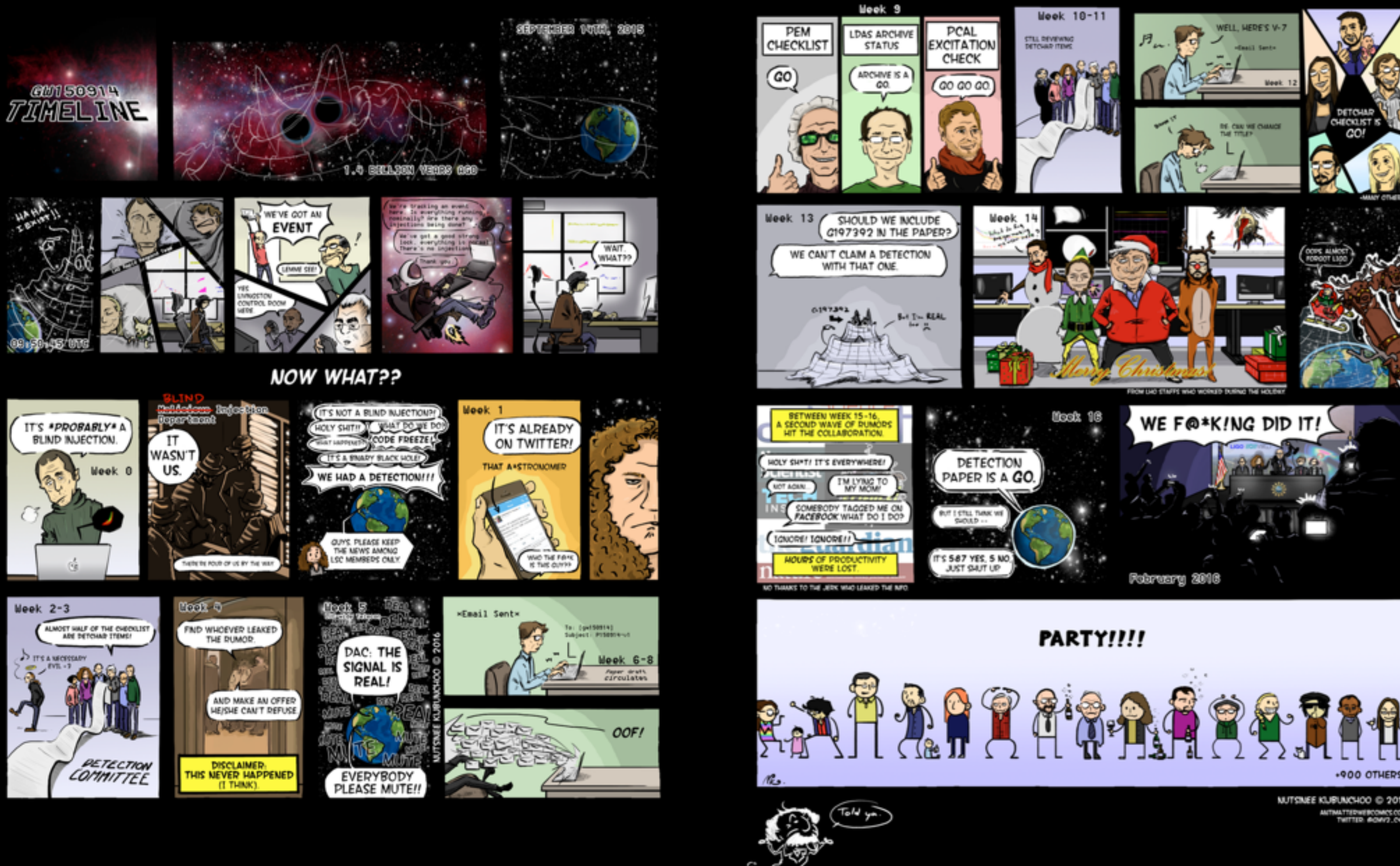

LIGO Hanford
LIGO Livingston
GEO600
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

重力波波形を音にすると．．．



始め2回は実周波数，後の2回は聞えやすいように+400Hz

https://mediaassets.caltech.edu/gwave



www.ligo.org/magazine/LIGO-magazine-issue-8.pdf www.ligo.org/scientists/GW100916/

LIGO Scientific Collaboration - Blind Injection GW100916

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GW-EM alerts | Data releases | LSC Scientific publications

PREFACE - IMPORTANT!

NOTE: This is an EXAMPLE of the data products that the LIGO Scientific Collaboration and Virgo Collaboration might release for their first gravitational wave transient detections. ***This particular event was not a real detection; it was a "blind injection".*** *For more detail and background, see the GW100916 news release.*

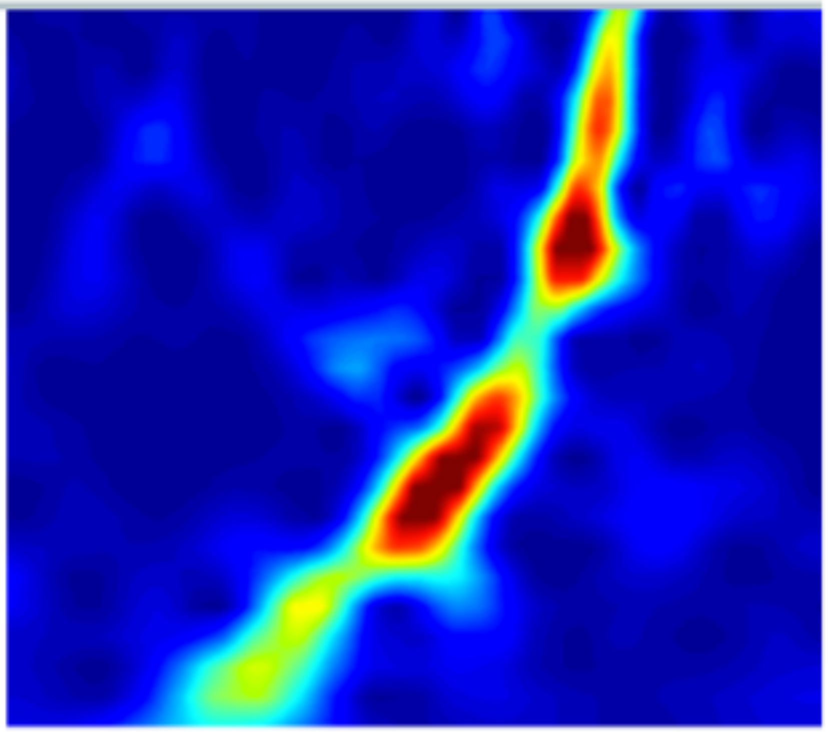
This page, and all the documents and information linked therein, are intended for release to interested scientific colleagues. We welcome your comments on what is useful to have on a page such as this. Please send your feedback to datainfo@ligo.org.

INFORMATION ABOUT GW100916

This page has been prepared by the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration to inform the broader community about an interesting event observed in the gravitational-wave detectors, and to make the data around that time available for others to analyze.

SUMMARY OF OBSERVATION

Data from the gravitational-wave detector network is analyzed in several ways. This page concerns an event identified by multiple analysis pipelines which search for gravitational wave events at all times in the available gravitational-wave data. The event time is 968654557.955 GPS == Sep 16, 2010 06:42:22.955 UTC, and thus it has been assigned the name "GW100916". At that time, the 4-km LIGO Hanford and LIGO Livingston detectors, the 3-km Virgo detector, and the GEO 600-m detector were all collecting data in "science mode" as part of the LIGO-GEO S6 and Virgo VSR3 science runs. Analysis revealed a highly significant event consistent with the coalescence (inspiral and merger) of two black holes or a black hole and a neutron star.



Note: This event was a "blind injection", i.e. a simulated signal inserted into the data streams of the detectors. *This page is provided as an example of how a real gravitational wave event may be presented in the future.*

GW100916 "Big Dog"

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

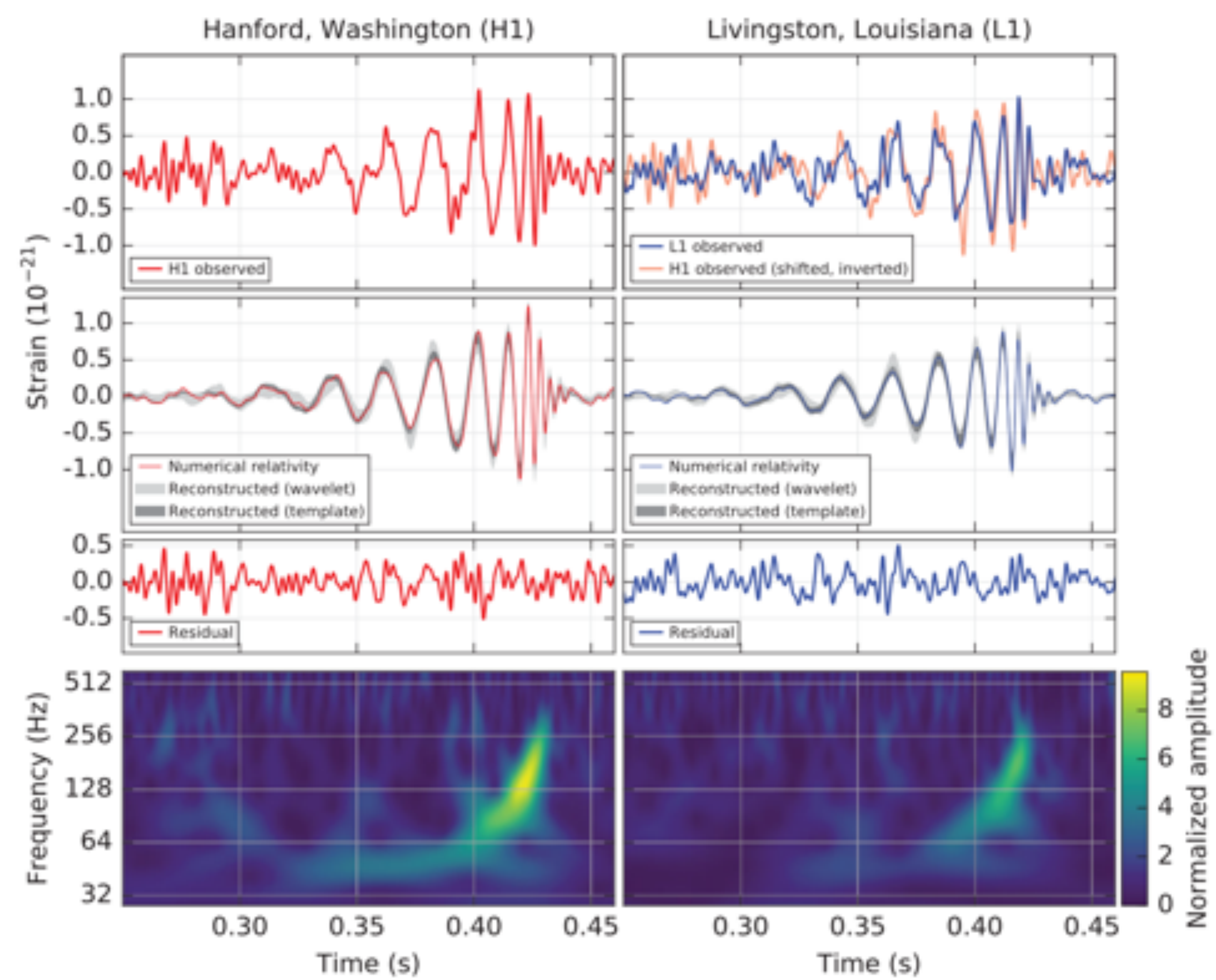
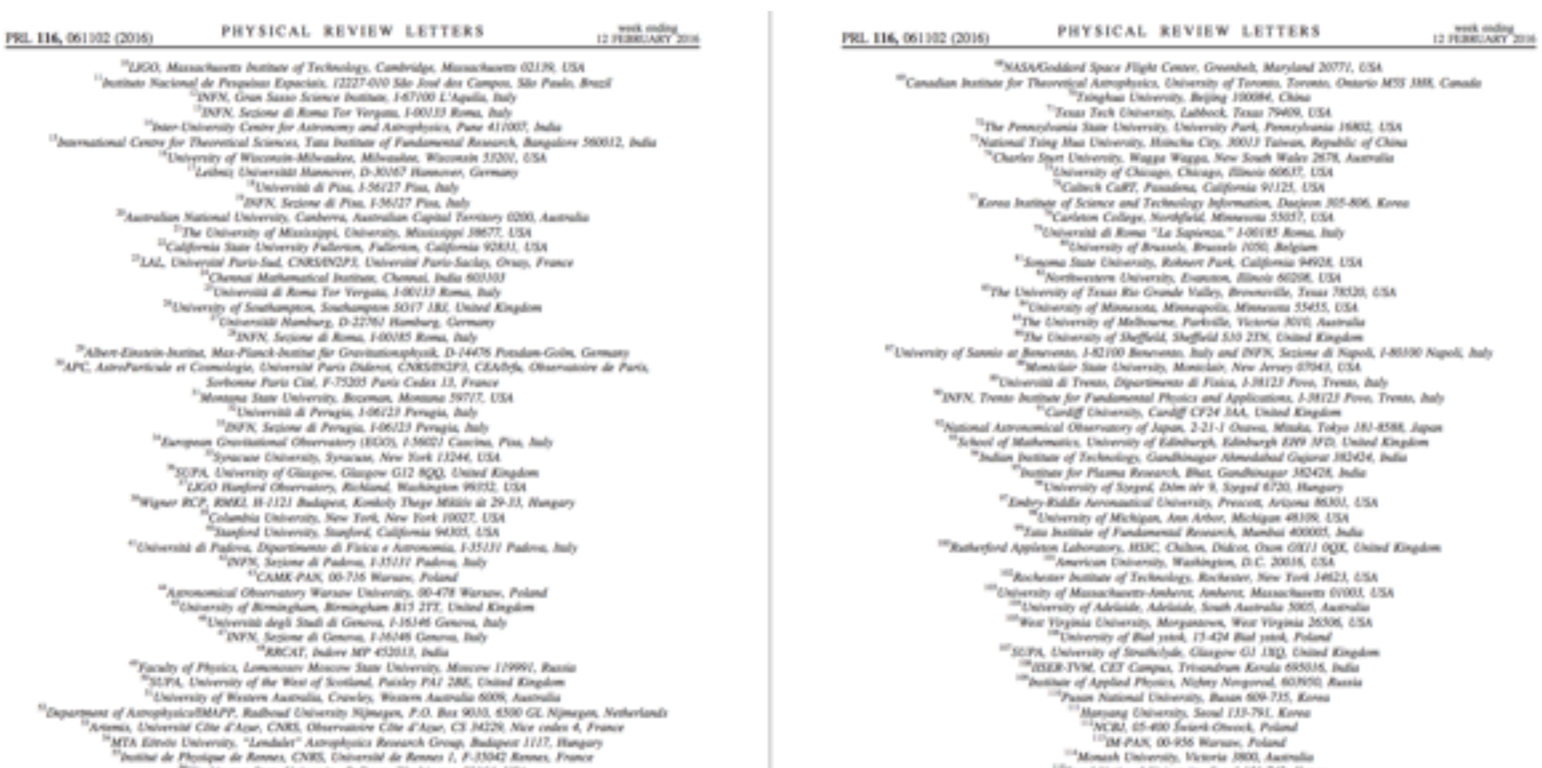


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered



著者1010人
PRL 16ページ

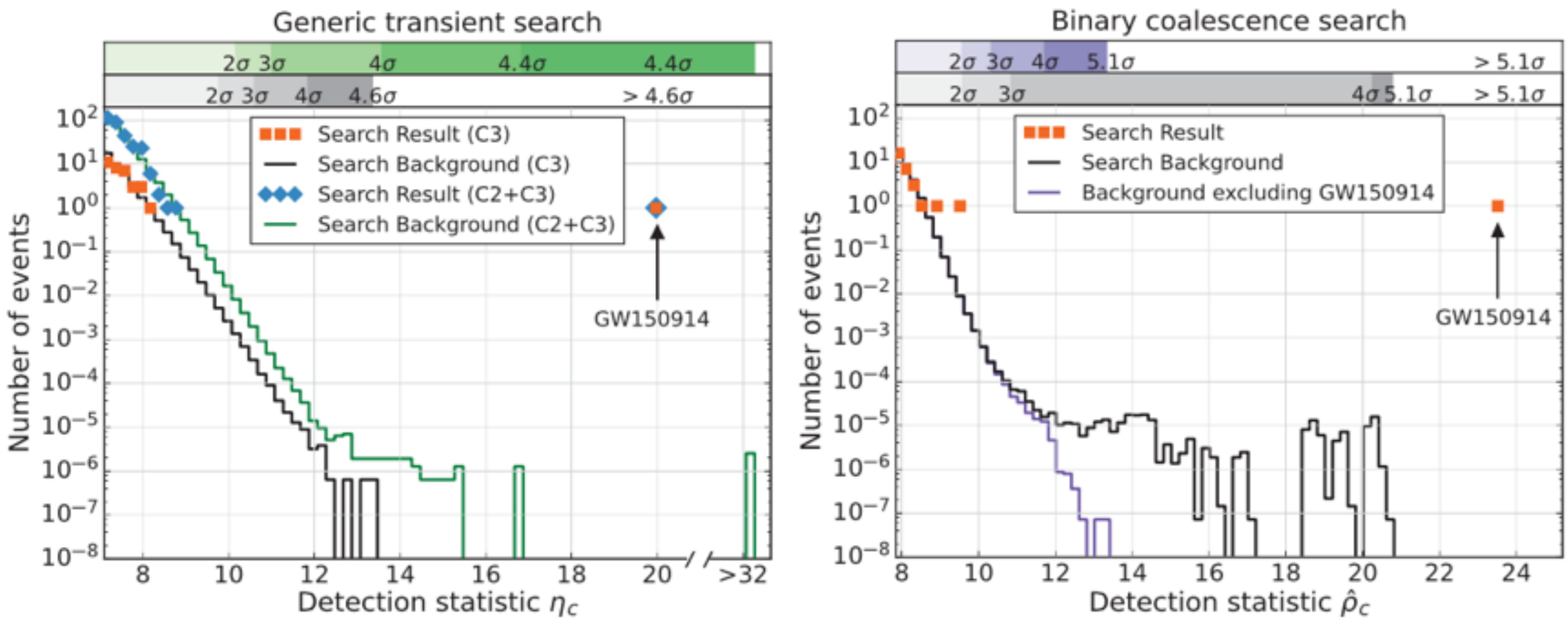
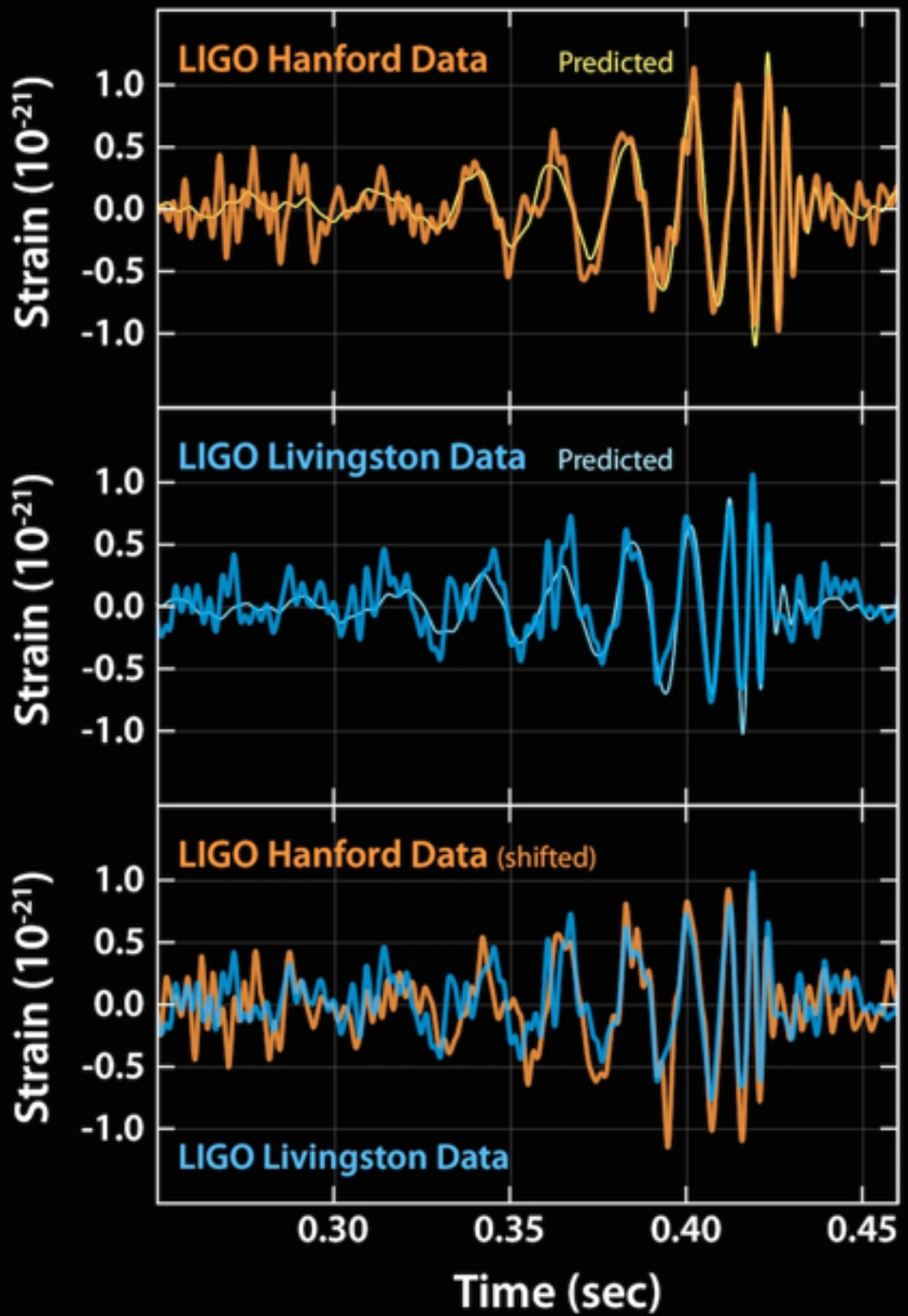
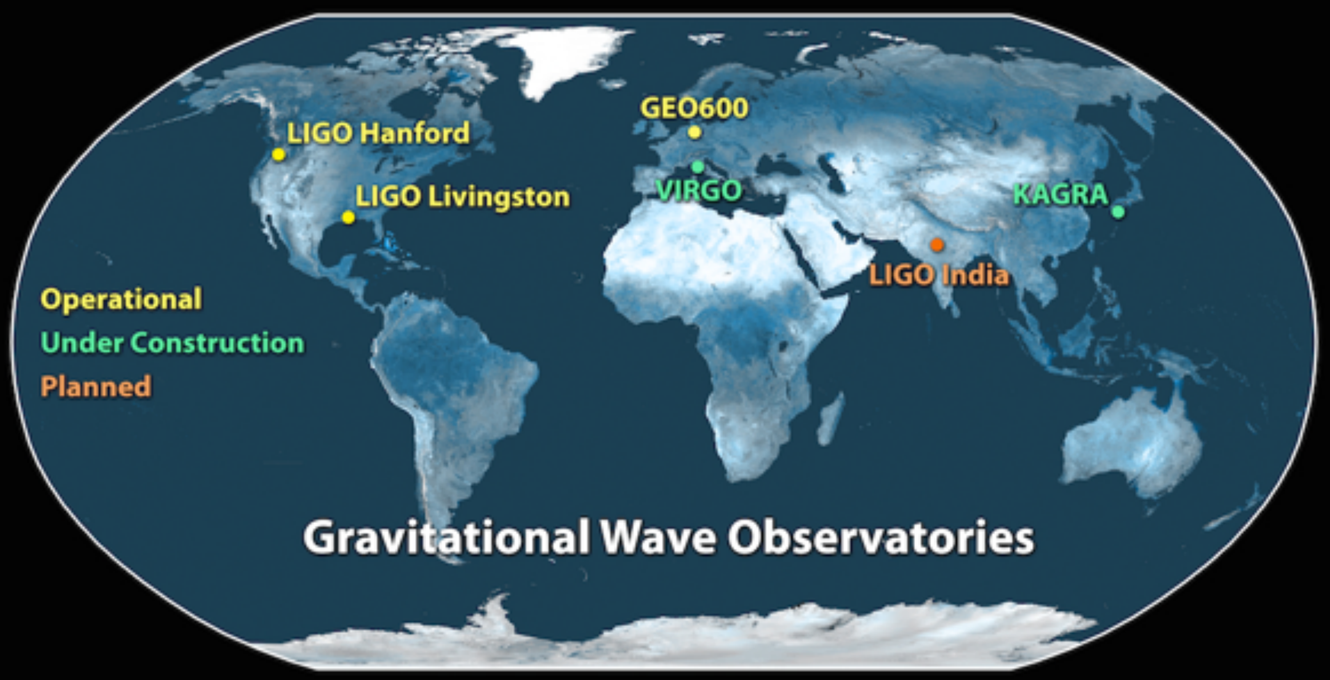
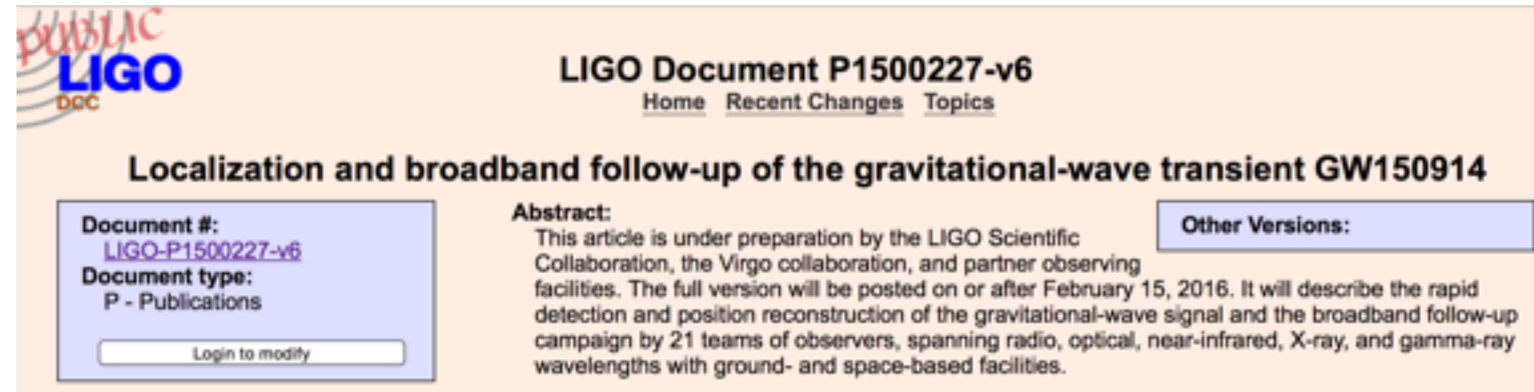
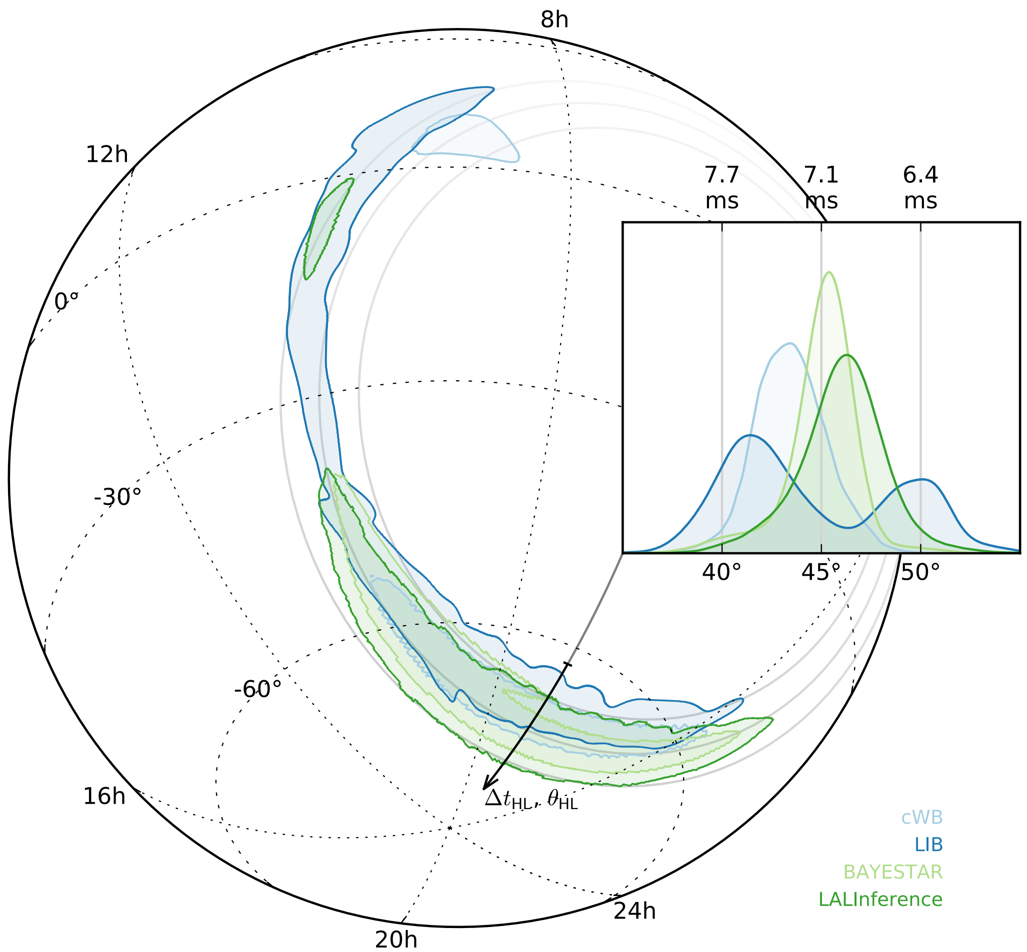


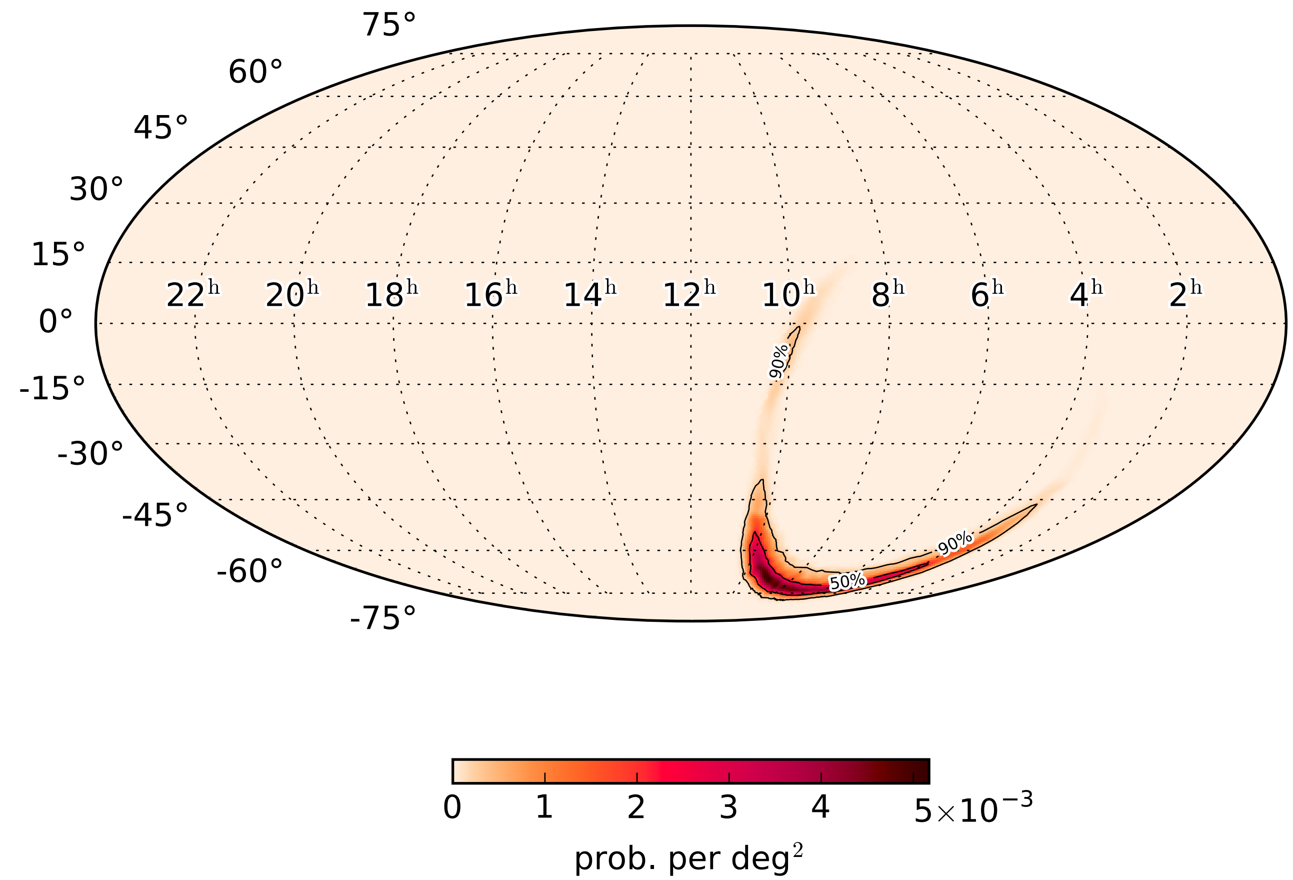
FIG. 4. Search results from the generic transient search (left) and the binary coalescence search (right). These histograms show the number of candidate events (orange markers) and the mean number of background events (black lines) in the search class where GW150914 was found as a function of the search detection statistic and with a bin width of 0.2. The scales on the top give the significance of an event in Gaussian standard deviations based on the corresponding noise background. The significance of GW150914 is greater than 5.1σ and 4.6σ for the binary coalescence and the generic transient searches, respectively. *Left:* Along with the primary search (C3) we also show the results (blue markers) and background (green curve) for an alternative search that treats events independently of their frequency evolution (C2 + C3). The classes C2 and C3 are defined in the text. *Right:* The tail in the black-line background of the binary coalescence search is due to random coincidences of GW150914 in one detector with noise in the other detector. (This type of event is practically absent in the generic transient search background because they do not pass the time-frequency consistency requirements used in that search.) The purple curve is the background excluding those coincidences, which is used to assess the significance of the second strongest event.


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


LIGO Hanford
GEO600
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories





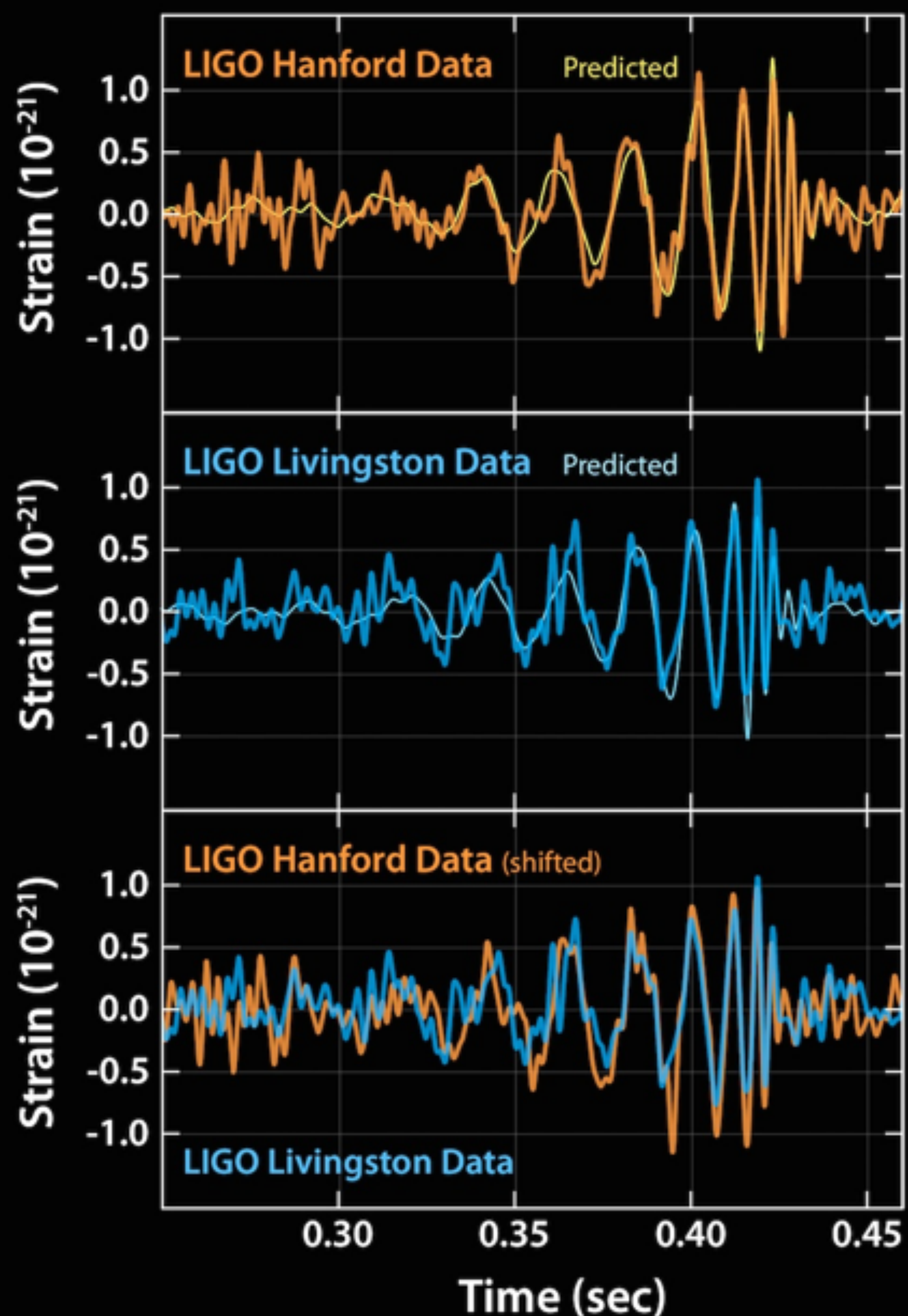


Localization and broadband follow-up of the gravitational-wave transient GW150914

This article is under preparation by the LIGO Scientific Collaboration, the Virgo collaboration, and partner observing facilities. The full version will be posted on or after February 15, 2016. It will describe the rapid detection and position reconstruction of the gravitational-wave signal and the broadband follow-up campaign by 21 teams of observers, spanning radio, optical, near-infrared, X-ray, and gamma-ray wavelengths with ground- and space-based facilities.

LALInference sky map (GCN 18858) Mollweide projection plot

600 square degrees



GW150914:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

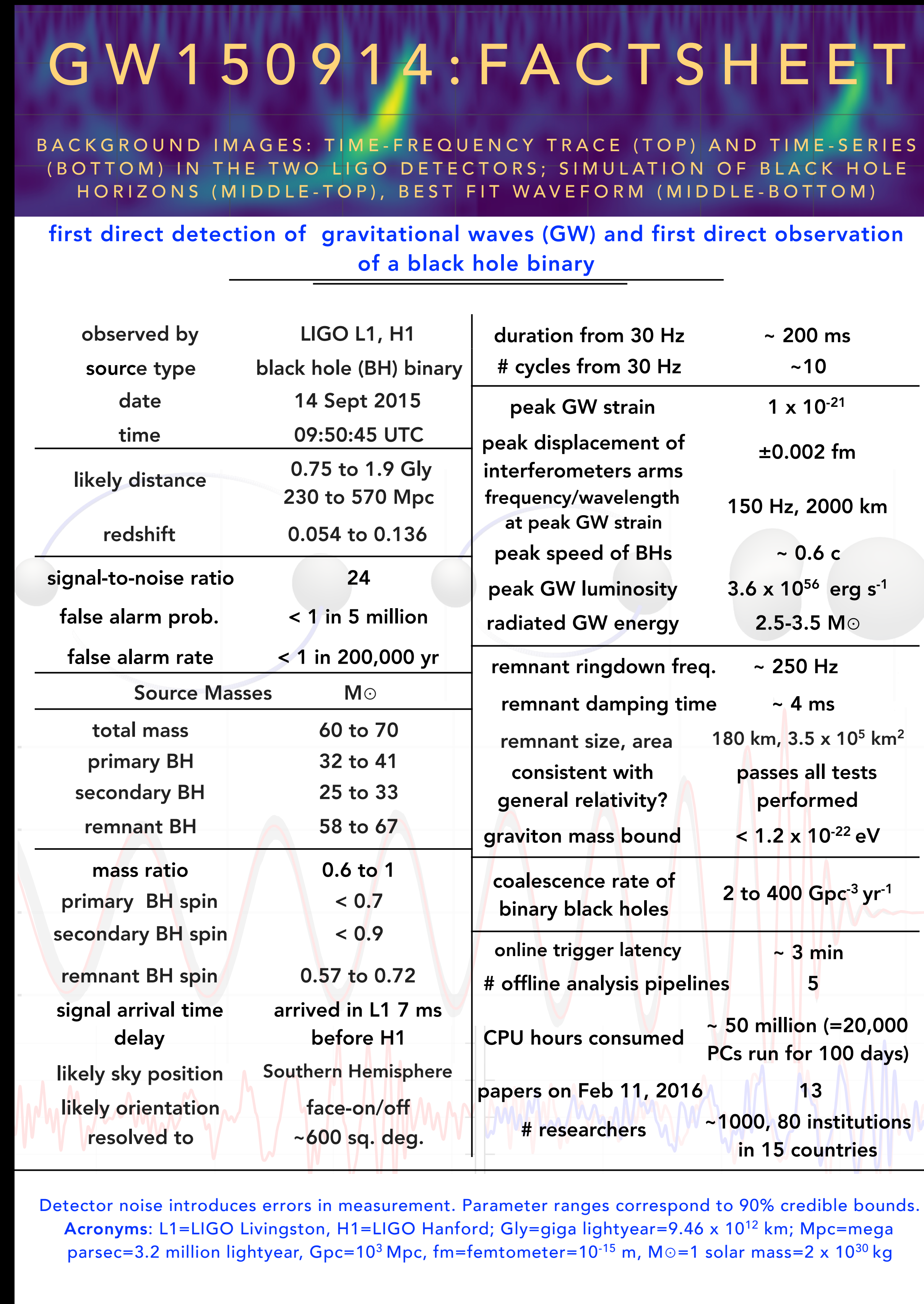
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	< 1.2×10^{-22} eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46 x 10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2 x 10^{30} kg

36Msun + 29 Msun
のBHが合体して 62 Msun
（3 Msun分の質量が消失）

13億光年先
（400±170 Mpc）
（z=0.054—0.136）



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papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds. **Acronyms**: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

重力波が検出された！
重力波が検出できた！
BHが存在した！
BH連星が存在した！
相対論が第0近似として正しい！

ブラックホール 解明に期待

る精度を目指す。実現すれば七億光年の範囲にある連星からの重力波を捉えられる。一年で十回ほどキャッチできる計算だという。

重力波の大きな特徴はブラックホールからも放出されること。連星が合体してブラックホールが生まれる瞬間を観測できると期待される。時間と空間をねじ曲げてすべてをのみ込むブラックホールは、光も電波も出さないため直接には観測できなかった。その謎に迫る強力な手段になる。

また、弱まらずに遠くまで届くので、遠い星の観測や誕生直後の宇宙の姿を知るのにも役立つと期待されている。

大阪工業大の真貝寿明教授（理論物理学）は「重力波を天文学に使うには、発生した場所を割り出す必要がある。それには望遠鏡が四カ所必要だ。KAGRAを含めた世界的なネットワークが重要」と話す。

東京新聞 2016/2/12

重力波 初の直接観測

「研究者勇気づけた」

大阪市大院・神田教授 学生らに解説

米国を中心とした国際研究チームが「重力波」を初めて直接観測したとの発表を受け、重力波の研究が専門の神田展行・大阪市立大大学院教授(51)は12日、発表内容についての説明会を大阪市住吉区の同大杉本キャンパスで開いた。成果を詳しく理解してもらう狙い。学生ら約100人が参加し、真剣な表情で聴き入った。【畠山哲郎】

神田教授は、岐阜県飛騨市の大型低温重力波望遠鏡「KAGRA」のプロジェクトでもデータ管理グループのリーダーを務める。説明会では観測されたデータの見方などを解説し「我々にとっても勇気づけられるものだった」と語った。発表を受けて、研究室の学生が締め切り間際の論文を慌てて書き換えたエピソードを披露すると、会場は笑いに包まれた。

同大大学院理学研究科2年の和知慎吾さん(23)は「重力波だけでなく、ブラックホールも直接観測したことになると分かり、ためになった」と話していた。

重力波は、質量を持った物体が動いた時に周囲の時空にゆがみが生じ、そのゆがみが光速でさざ波のように宇宙空間に伝わる現象。物理学者のアインシュタインが「一般相対性理論」で存在を予言し、世界中の研究者が観測に挑戦していた。

重力波観測について解説する大阪市立大学大学院理学研究科の神田展行教授＝大阪市住吉区で、川平愛撮影

大阪工大 真貝教授 「予想通りで驚いた」

大阪工業大情報科学部の真貝寿明教授（一般相対性理論）は「祝・重力波の直接検出」と題して、研究室のウェブページに一般向けの緊急解説記事を掲載した。昨年には一般向けの解説書「ブラックホール・膨張宇宙・重力波 一般相対性理論の100年と展開」を出版している。「こんなにも予想通りのものが見つかるのかと驚いた。素晴らしい発見だ」と感想を語った。

今後の研究については「日本でもKAGRAを使い、改めて重力波を確認したり、海外のチームと協力して重力波がどこから来たものなのかを調べたりしていくことが重要だ」と話した。【畠山哲郎】

毎日新聞 2016/2/13

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重力波天文学で何がわかる？

対応する天体の姿

→ 天体物理学

ブラックホールの存在する強い重力場

→ 一般相対性理論の検証

中性子星連星合体のふるまい

→ 原子核の状態方程式

イベント頻度・統計

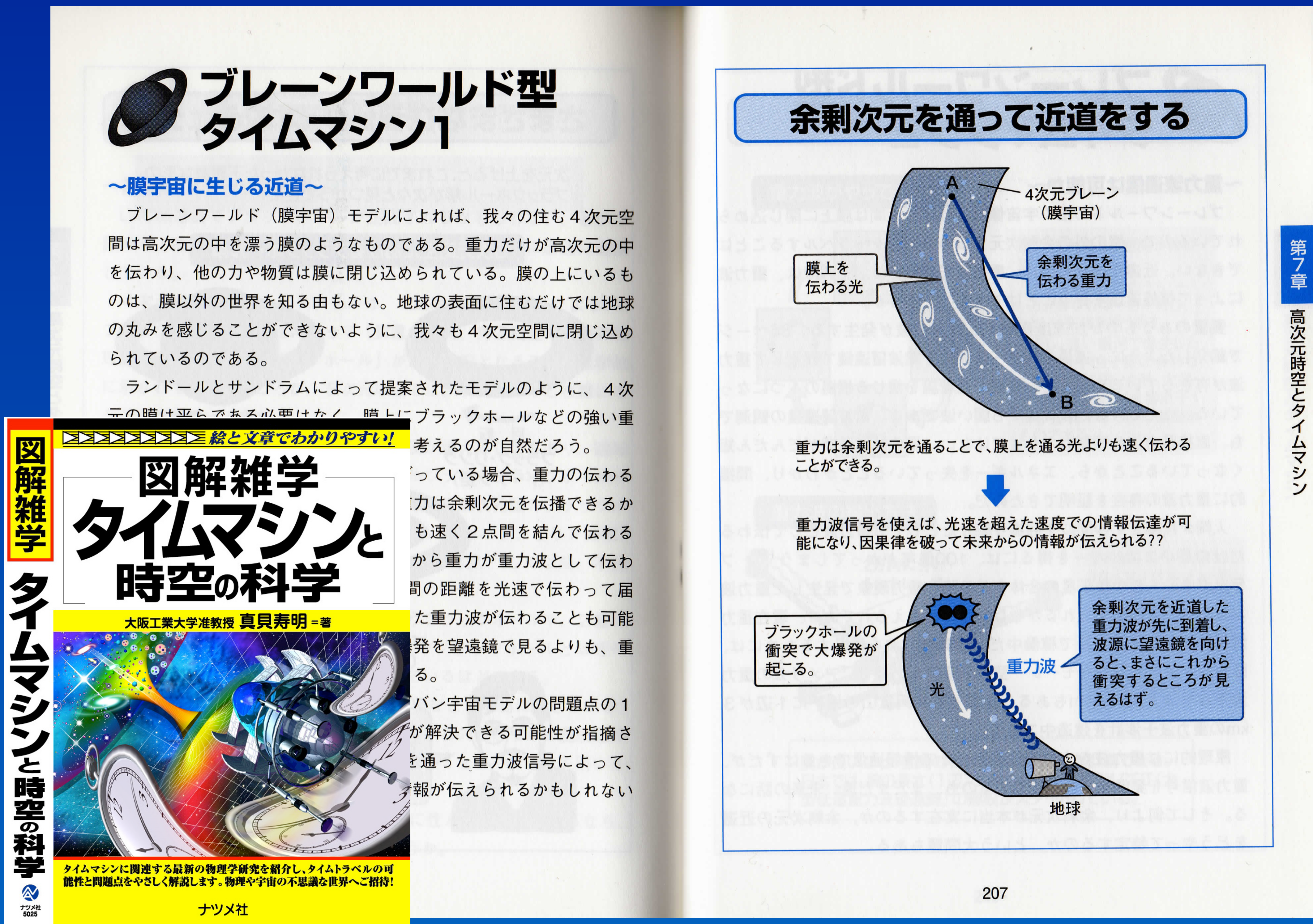
→ 星形成モデル・銀河中心ブラックホール
宇宙論パラメータ

背景重力波の存在

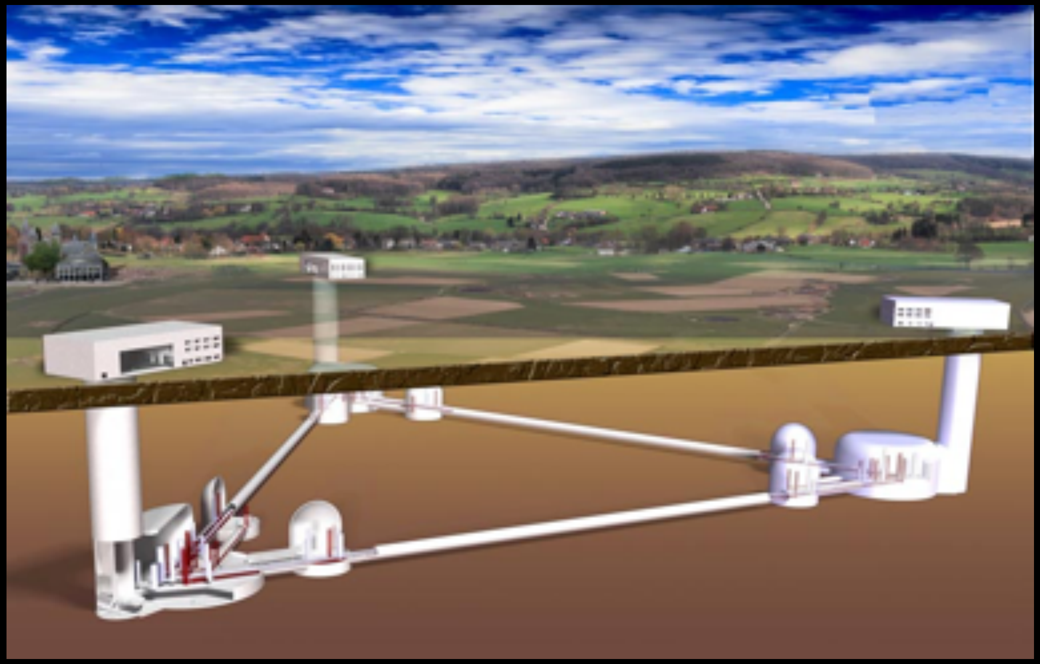
→ 星形成モデル・宇宙初期モデル

重力波天文学で何がわかる？

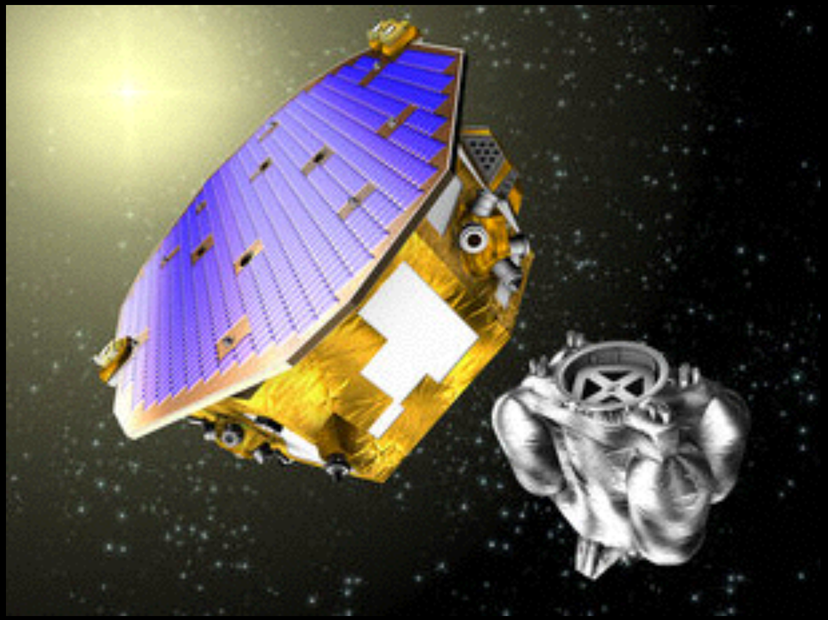
とんでもないこと？ → 世の中，実は5次元．．とか



重力波天文学の幕開け



Einstein Telescope (10kmx3)



LISA Pathfinder

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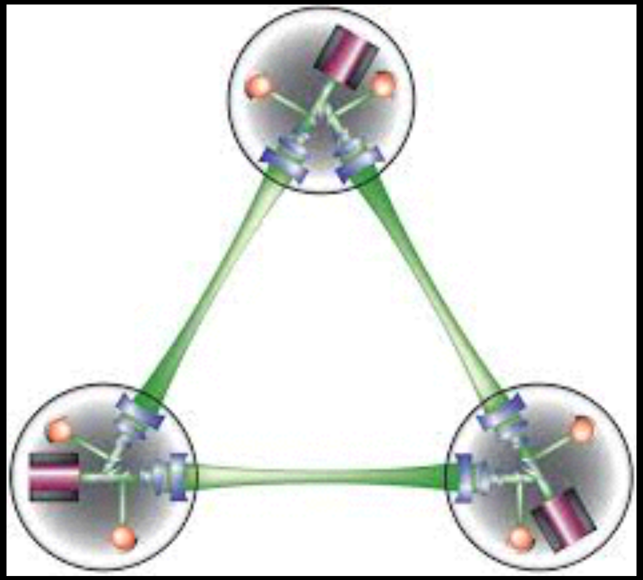


DECIGO Pathfinder

以下，バックアップ

PRL **116,** 061102 (2016)

Selected for a Viewpoint in *Physics*

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

PRL116（2016）061102

PRL116 (2016) 061102

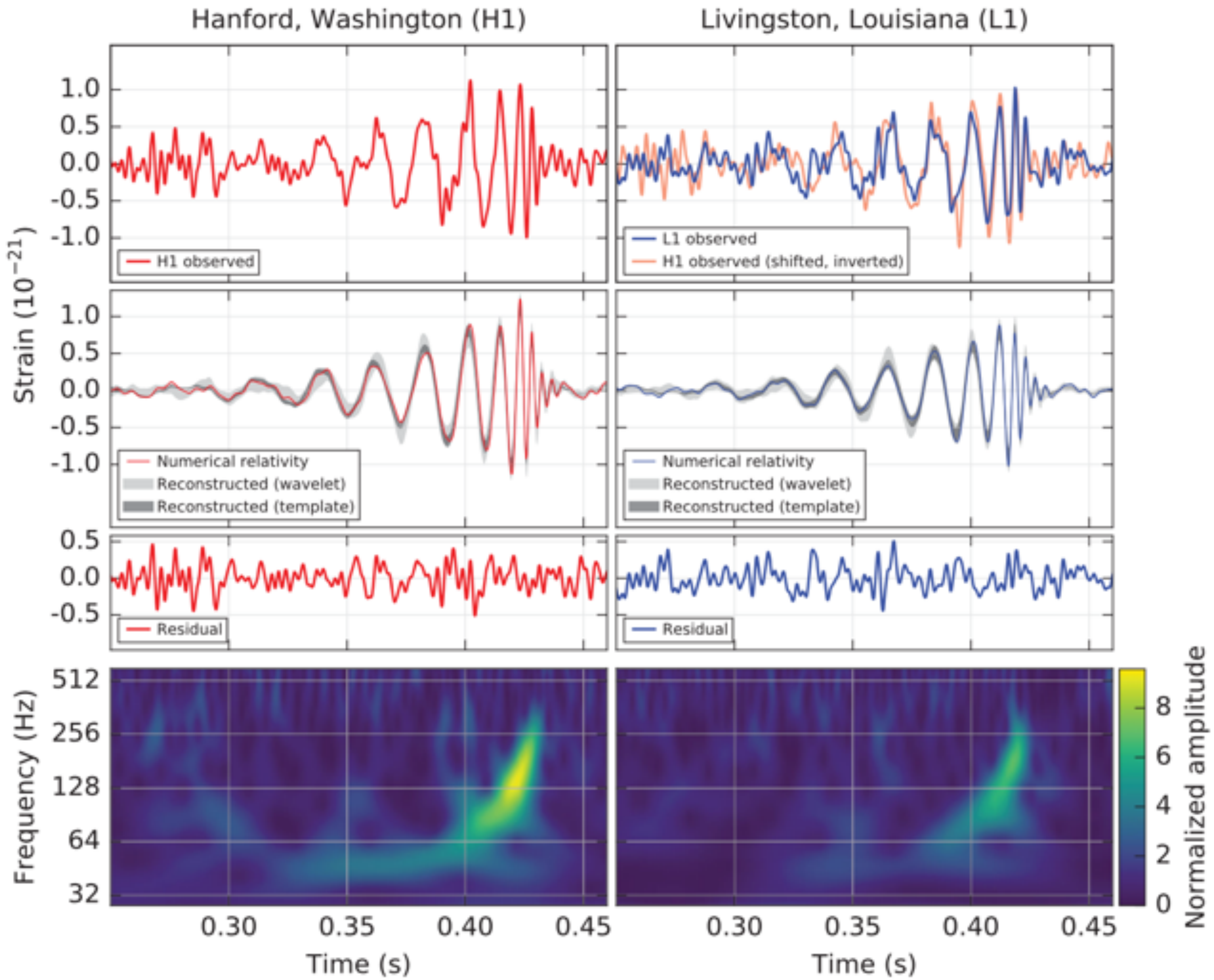


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress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

PRL116 (2016) 061102

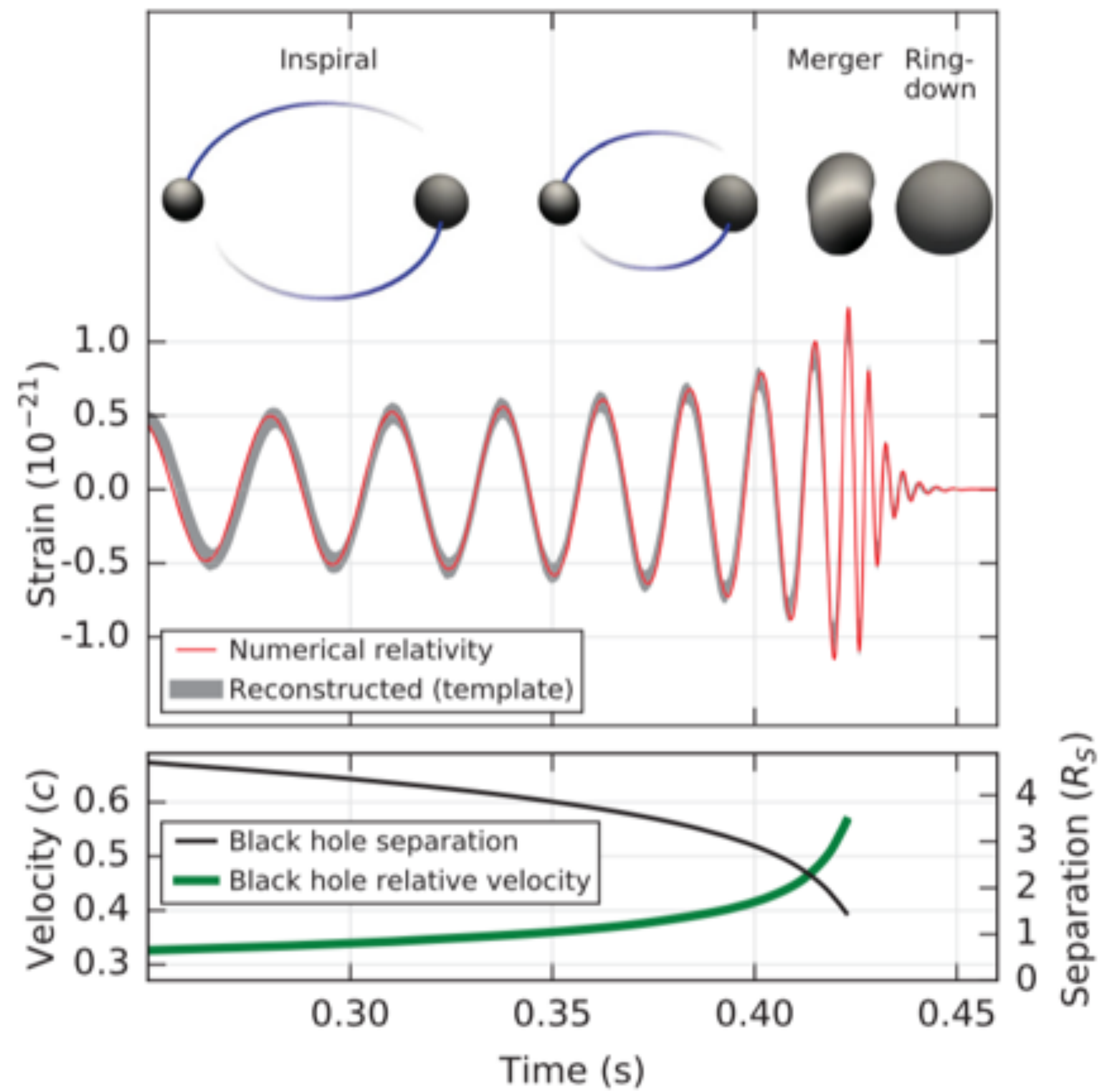


FIG. 2. *Top:* Estimated gravitational-wave strain amplitude from GW150914 projected onto H1. This shows the full bandwidth of the waveforms, without the filtering used for Fig. 1. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. *Bottom:* The Keplerian effective black hole separation in units of Schwarzschild radii ($R_S = 2GM/c^2$) and the effective relative velocity given by the post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$, where f is the gravitational-wave frequency calculated with numerical relativity and M is the total mass (value from Table I).

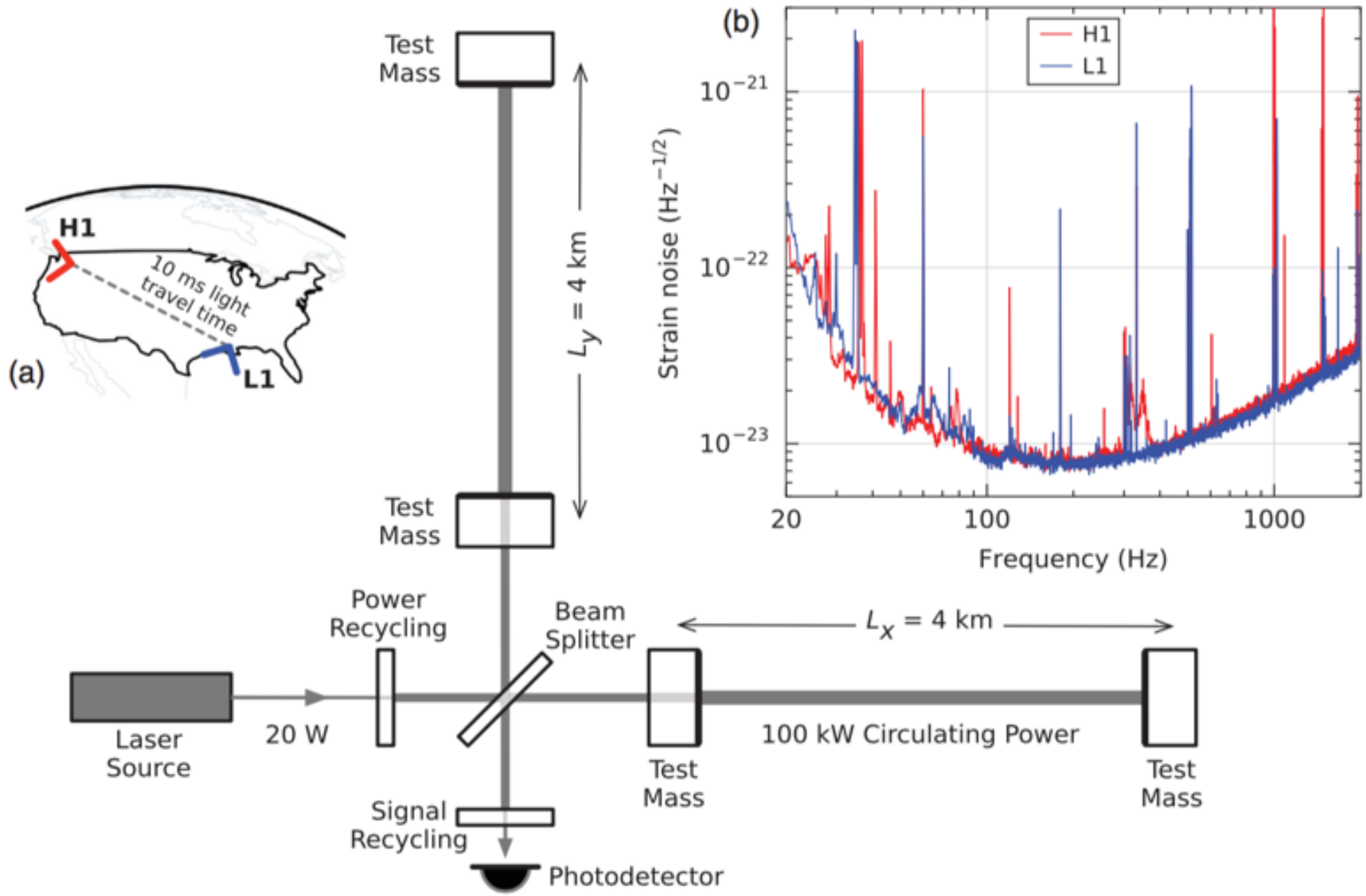


FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the 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 fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 ($2.1\,\sigma$)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

TABLE I. Parameters of the two most significant events. The false alarm rate (FAR) and false alarm probability ($\mathscr{F}$) given here were determined by the PyCBC pipeline; the GstLAL results are consistent with this. The source-frame chirp mass $\mathscr{M}$, component masses $m_{1,2}$, effective spin χ_{eff}, and luminosity distance D_L are determined using a parameter estimation method that assumes the presence of a coherent compact binary coalescence signal starting at 20 Hz in the data [90]. The results are computed by averaging the posteriors for two model waveforms. Quoted uncertainties include both the 90% credible interval and an estimate for the 90% range of systematic error determined from the variance between waveform models. Further parameter estimates of GW150914 are presented in Ref. [18].

1602.03839

論文紹介　GW150924のSwiftフォロー　2016/2/14　真貝

P.A. Evans +, arXiv:1602.03868 (submitted to MNRAS Lett.)
Swift follow-up of the Gravitational Wave source GW150914

結論　対応天体はなかった

P.A. Evans +, MNRAS 455(2016) 1522 [arXiv:1506.01624]
Optimisation of the Swift X-ray follow-up of Advanced LIGO and Virgo gravitational wave triggers in 2015--16

ガンマ線バーストを探す

素早く向きを変える様子から「Swift」(和名アマツバメ)

2015 September 14 at 09:50:45 UT

‘Coherent WaveBurst’ (cWB) pipeline for ALIGO triggered

2015 September 16 at 06:39 UT

This event was announced to the EM follow-up partners

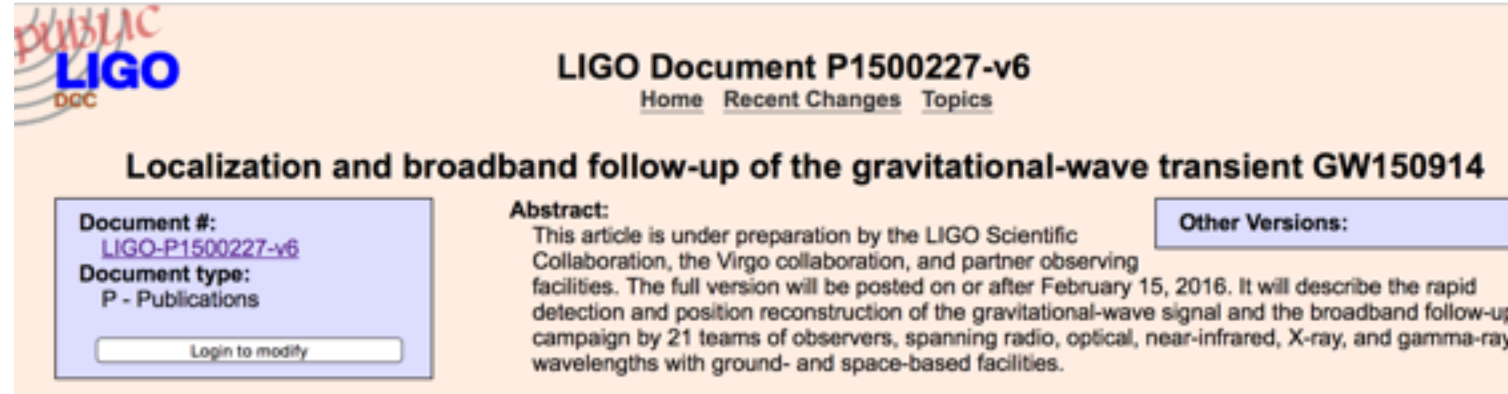
The 90% confidence errore region in the initially-released skymap ‘LIB skymap’ covered 750 square degrees (this was later reduced to 600 square degrees in the ‘LALInterence’ skymap)

この論文では

☑XRT and UV/Optical telescope (UVOT; Roming et al. 2005)

☑Burst Alert Telescope (BAT; Barthelmy et al. 2005) data for any sign of hard X-ray emission at the time of the trigger.

他のフォローアップ・サーチについては別の論文にまとめる予定


PUBLIC LIGO DCC

LIGO Document P1500227-v6

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Localization and broadband follow-up of the gravitational-wave transient GW150914

Document #: LIGO-P1500227-v6

Document type: P - Publications

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Abstract:
This article is under preparation by the LIGO Scientific Collaboration, the Virgo collaboration, and partner observing facilities. The full version will be posted on or after February 15, 2016. It will describe the rapid detection and position reconstruction of the gravitational-wave signal and the broadband follow-up campaign by 21 teams of observers, spanning radio, optical, near-infrared, X-ray, and gamma-ray wavelengths with ground- and space-based facilities.

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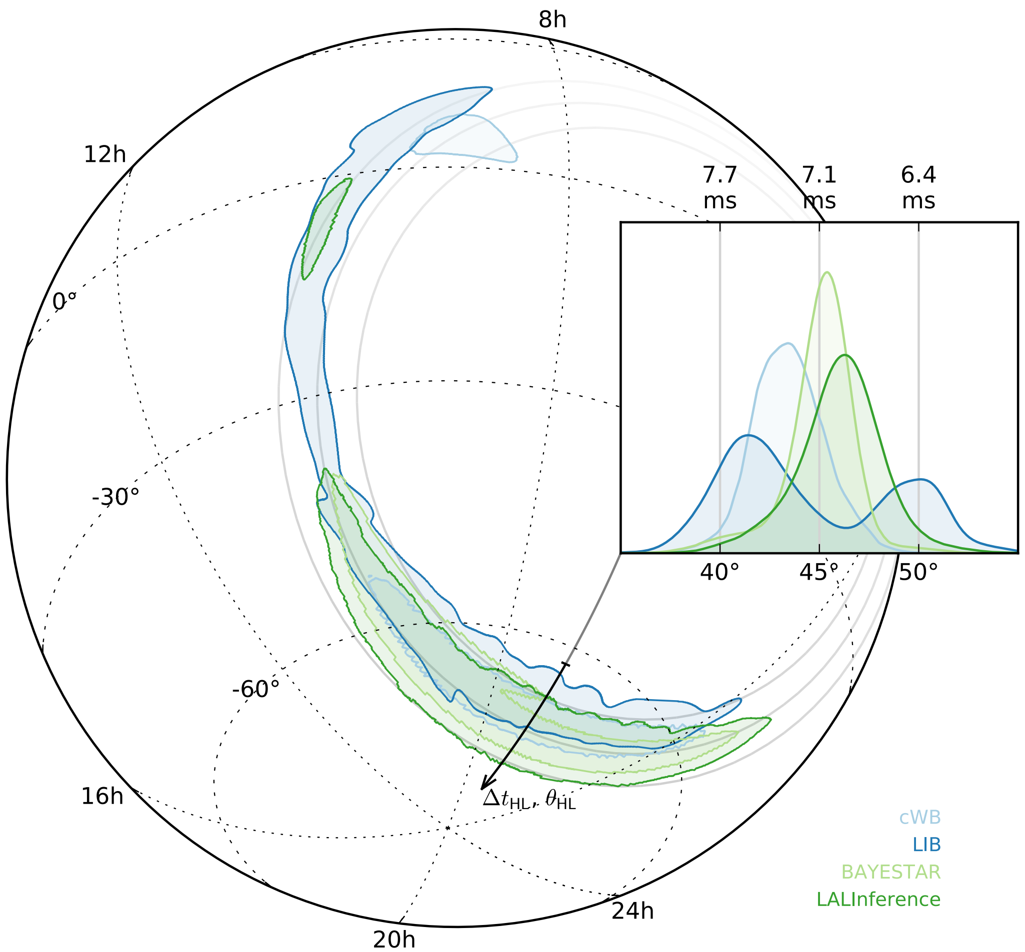

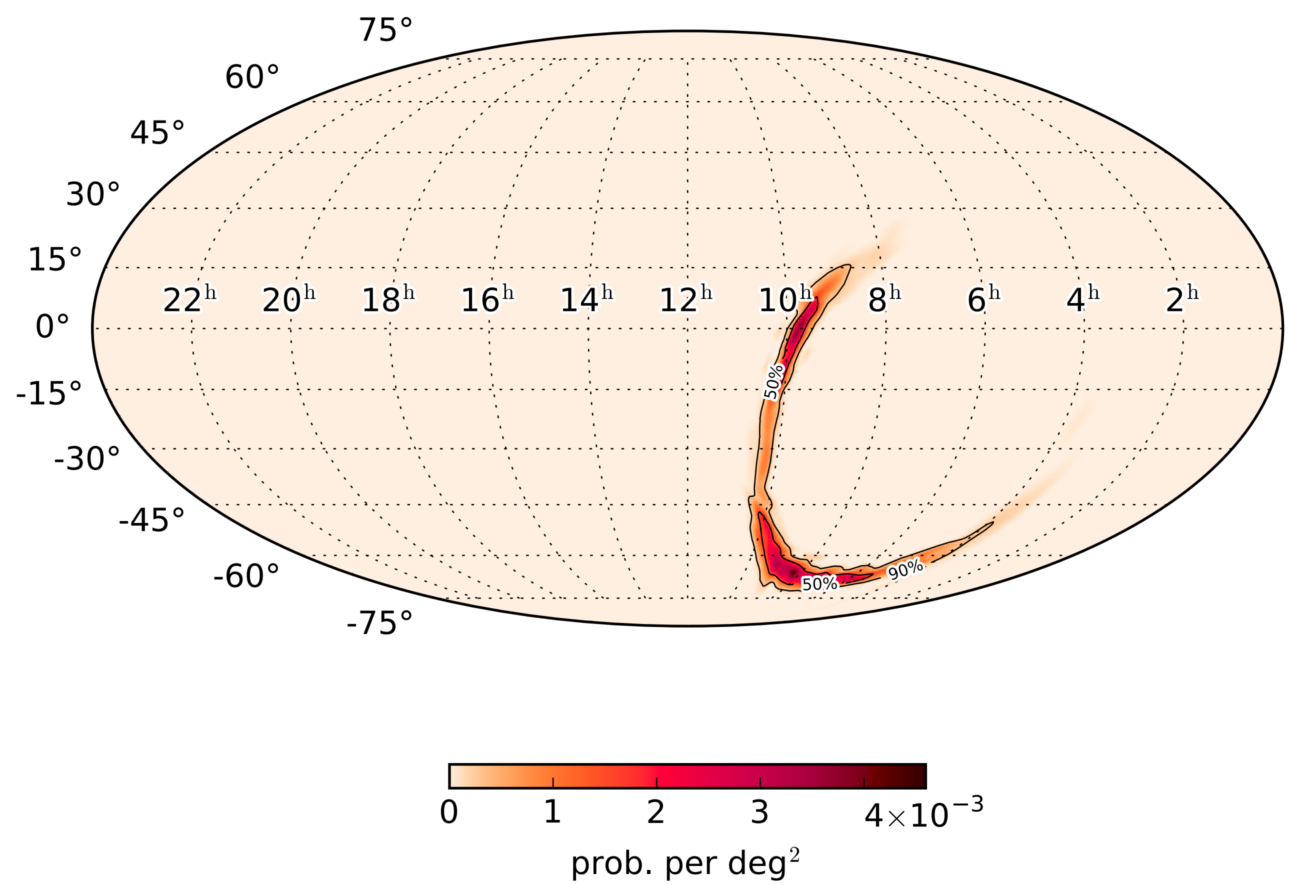

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LIB sky map (GCN 18330) Mollweide projection plot

750 square degrees

LIGO Document P1500227-v6

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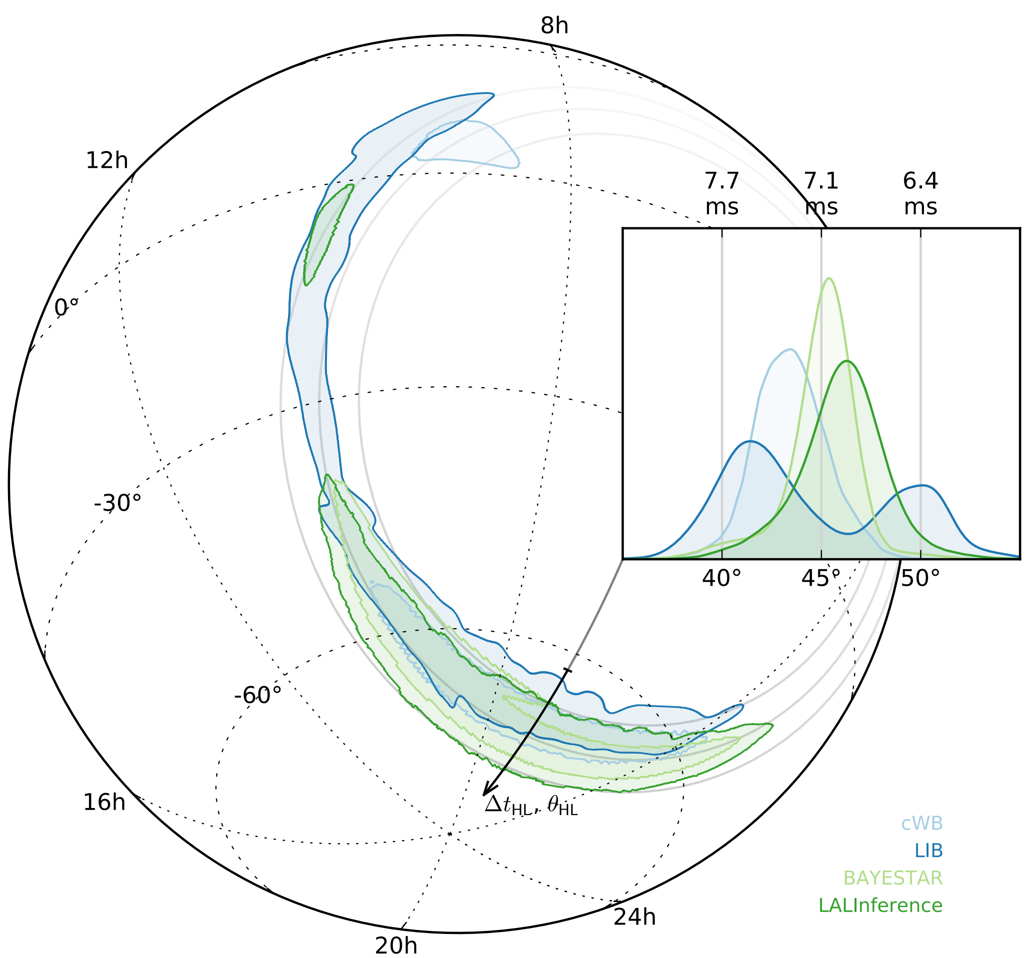

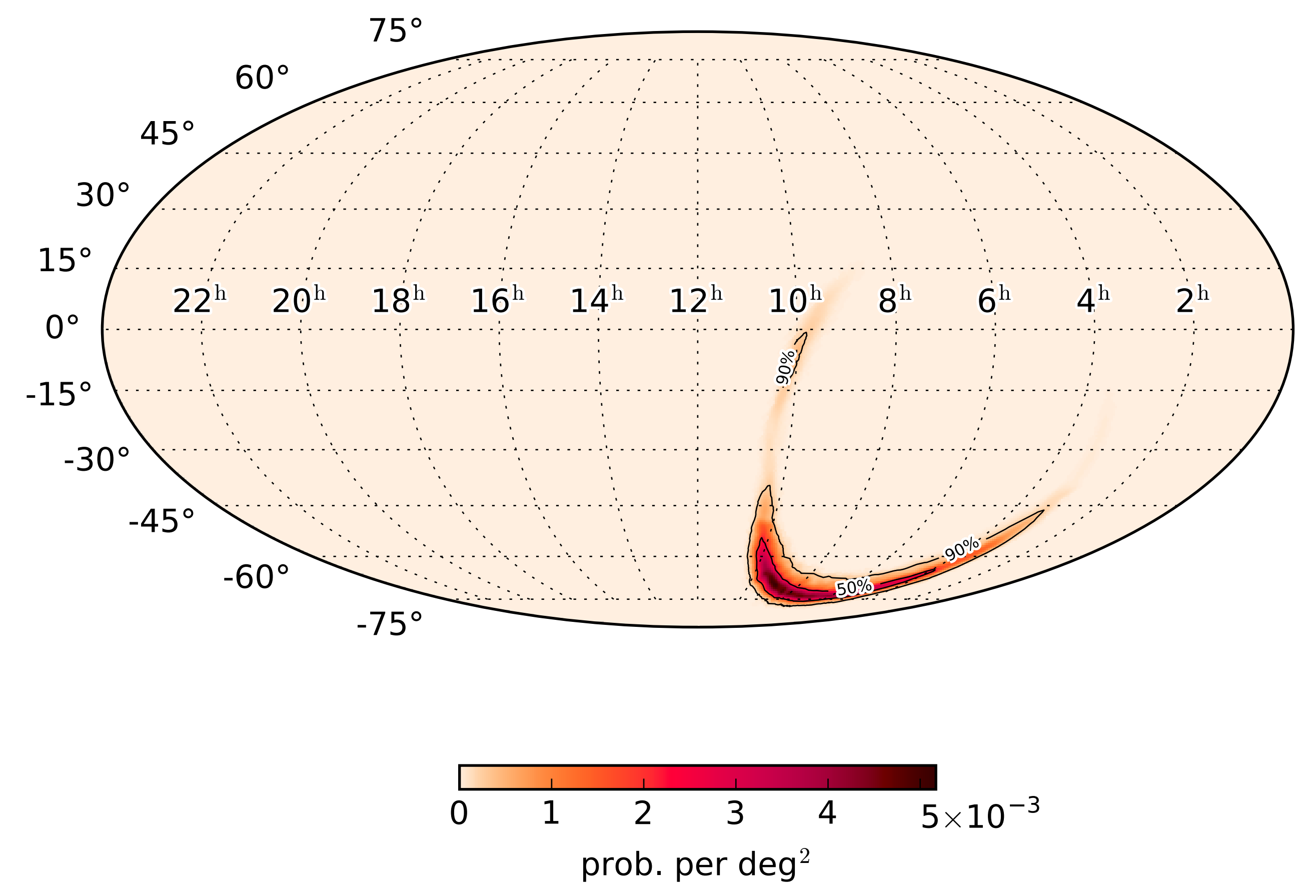

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LALInference sky map (GCN 18858) Mollweide projection plot

600 square degrees

LIB_skymap
by LVC team
on 2015 Sep 15

luminosity-weighted
GWGC map

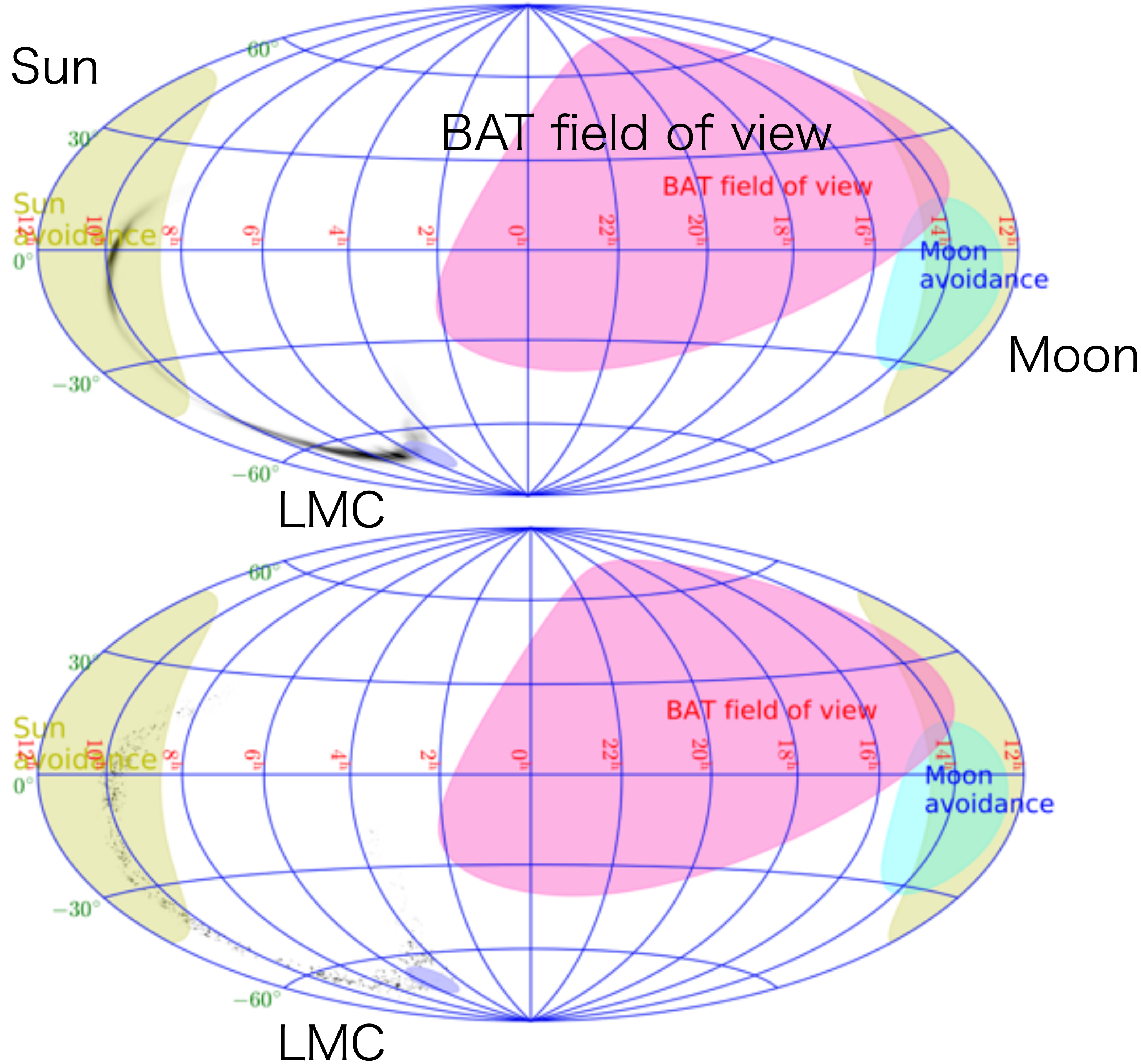


Figure 1. The 'LIB_skymap' GW localisation map produced by the LVC team on 2015 September 15 (top), convolved with our luminosity-weighted GWGC map (bottom). Coordinates are equatorial, J2000. The yellow and cyan circles show the regions of the sky which *Swift* could not observe due to the presence of the sun and moon respectively, calculated at the time of the first *Swift* observations. The small, pale lilac ellipse marks the LMC. The large purple region approximates the BAT field of view at the time of the GW trigger.

P.A. Evans +, arXiv:1602.03868

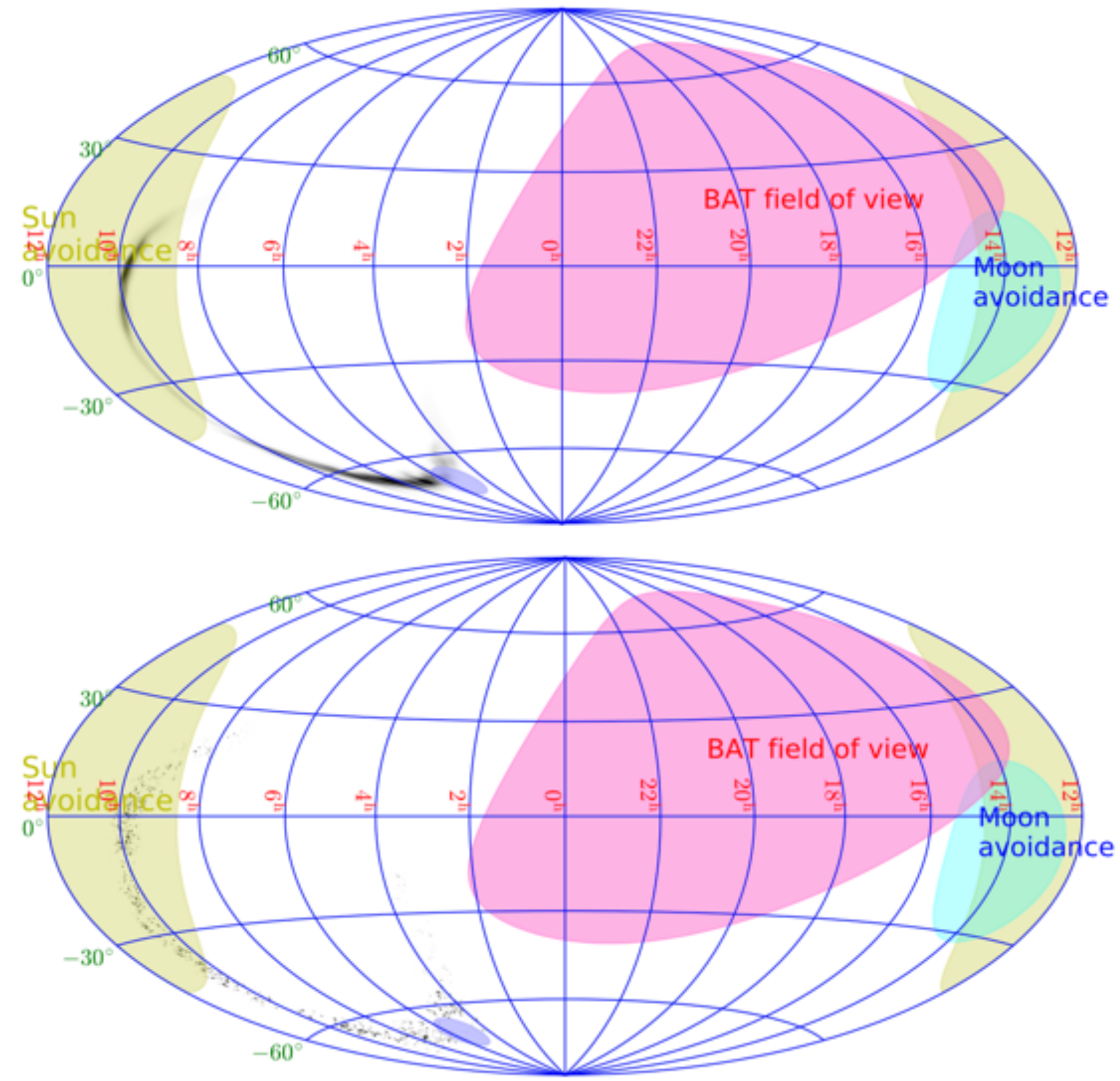
Table 1. *Swift* observations of the error region of GW150914

GW group 2015 September 16 at 06:39 UT

Pointing direction (J2000)	Start time[a] (UTC)	Exposure (s)
$09^h13^m29.65^s, -60^\circ43'37.4''$	Sep 16 at 15:19:27	777
$08^h16^m30.77^s, -67^\circ38'06.7''$	Sep 16 at 16:54:41	987
$07^h28^m42.38^s, -66^\circ59'43.1''$	Sep 16 at 18:28:32	970
$08^h03^m23.72^s, -67^\circ37'17.2''$	Sep 16 at 20:05:37	970
$08^h57^m17.34^s, -65^\circ26'34.1''$	Sep 16 at 21:42:15	985
LMC Observations		
$06^h55^m30.59^s, -68^\circ18'44.3''$	Sep 17 at 18:26:54	20
$06^h59^m13.43^s, -68^\circ18'29.7''$	Sep 17 at 18:28:03	42
$06^h57^m21.25^s, -68^\circ36'12.8''$	Sep 17 at 18:29:12	20
$06^h53^m42.84^s, -68^\circ36'04.4''$	Sep 17 at 18:30:21	22
$06^h51^m53.97^s, -68^\circ18'16.7''$	Sep 17 at 18:31:29	32
$06^h53^m45.48^s, -68^\circ00'43.4''$	Sep 17 at 18:32:38	22
$06^h57^m25.10^s, -68^\circ01'02.6''$	Sep 17 at 18:33:46	25
$07^h01^m1.84^s, -68^\circ01'05.6''$	Sep 17 at 18:34:54	35
$07^h02^m52.89^s, -68^\circ18'56.6''$	Sep 17 at 18:36:02	72
$07^h01^m0.50^s, -68^\circ36'16.1''$	Sep 17 at 18:37:09	82
$06^h59^m11.14^s, -68^\circ53'42.6''$	Sep 17 at 18:38:17	37
$06^h55^m32.45^s, -68^\circ53'32.4''$	Sep 17 at 18:39:25	25
$06^h51^m54.75^s, -68^\circ53'32.0''$	Sep 17 at 18:40:33	65
$06^h50^m5.28^s, -68^\circ35'51.8''$	Sep 17 at 18:41:40	52
$06^h48^m15.62^s, -68^\circ18'20.6''$	Sep 17 at 18:42:47	65
$06^h50^m6.94^s, -68^\circ00'54.0''$	Sep 17 at 18:43:53	60
$06^h51^m56.98^s, -67^\circ43'22.9''$	Sep 17 at 18:44:59	67
$06^h55^m34.08^s, -67^\circ43'36.1''$	Sep 17 at 18:46:04	72
$06^h59^m13.52^s, -67^\circ43'33.4''$	Sep 17 at 18:47:10	55
$07^h02^m51.97^s, -67^\circ43'41.4''$	Sep 17 at 18:48:15	62
$07^h04^m42.41^s, -68^\circ01'15.1''$	Sep 17 at 18:49:21	75
$07^h06^m30.83^s, -68^\circ18'50.4''$	Sep 17 at 18:50:27	70
$07^h04^m41.09^s, -68^\circ36'37.2''$	Sep 17 at 18:51:32	60
$07^h02^m50.35^s, -68^\circ53'43.9''$	Sep 17 at 18:52:38	60
$07^h01^m1.00^s, -69^\circ11'19.8''$	Sep 17 at 18:53:43	62
$06^h57^m21.83^s, -69^\circ11'05.0''$	Sep 17 at 18:54:49	67
$06^h53^m43.60^s, -69^\circ11'06.9''$	Sep 17 at 18:55:55	42
$06^h50^m4.65^s, -69^\circ11'01.6''$	Sep 17 at 20:02:45	20
$06^h48^m14.61^s, -68^\circ53'22.8''$	Sep 17 at 20:03:54	32
$06^h46^m25.66^s, -68^\circ35'44.9''$	Sep 17 at 20:05:02	20
$06^h44^m35.32^s, -68^\circ18'21.1''$	Sep 17 at 20:06:11	25
$06^h46^m27.88^s, -68^\circ00'48.6''$	Sep 17 at 20:07:19	35
$06^h48^m17.47^s, -67^\circ43'23.8''$	Sep 17 at 20:08:27	60
$06^h50^m7.30^s, -67^\circ25'50.9''$	Sep 17 at 20:09:34	70
$06^h53^m44.83^s, -67^\circ26'05.6''$	Sep 17 at 20:10:41	77
$06^h57^m24.51^s, -67^\circ26'04.1''$	Sep 17 at 20:11:48	67
$07^h01^m2.66^s, -67^\circ26'08.1''$	Sep 17 at 20:12:54	57

[a] All observations were in 2015.

Sep 16 at 15:19 UT



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Sep 17 at 20:12 UT

P.A. Evans +, arXiv:1602.03868

判定基準を4つに分けた

Rank 1: Good GW counterpart candidate.　**良いGW対応候補天体**　カタログの銀河に接近

Sources which lie within 200 kpc of a GWGC galaxy, and are either uncatalogued and brighter than the 3-σ catalogue limit, or catalogued but brighter than their catalogued flux. In both cases, 'brighter than' means that the measured and historical values (or upper limits) disagree at the 5-σ level. For uncatalogued sources, the comparison is to the RASS, or to 1SXPS or the XMM catalogues, if an upper limit from those catalogues is available and deeper than the RASS limit.

Rank 2: Possible counterpart.　**GW対応候補天体の可能性あり**

The criteria for this are similar to those above, except that 'brighter' is determined at the 3-σ level, and there is no requirement for the source to be near a known galaxy.

Rank 3: Undistinguished source.　**判定できず**

Sources which are uncatalogued, but are fainter than existing catalogue limits, or consistent with those limits at the 3-σ level. i.e. sources which cannot be distinguished from field sources.

Rank 4: Not a counterpart.　**対応候補天体ではない**

Sources which are catalogued, and which have fluxes consistent with (at the 3-σ level) or fainter than their catalogued values.

P.A. Evans +, arXiv:1602.03868

Gravitational Wave Galaxy Catalogue (GWGC)

Quantum Grav. 28 (2011) 085016 D J White *et al*

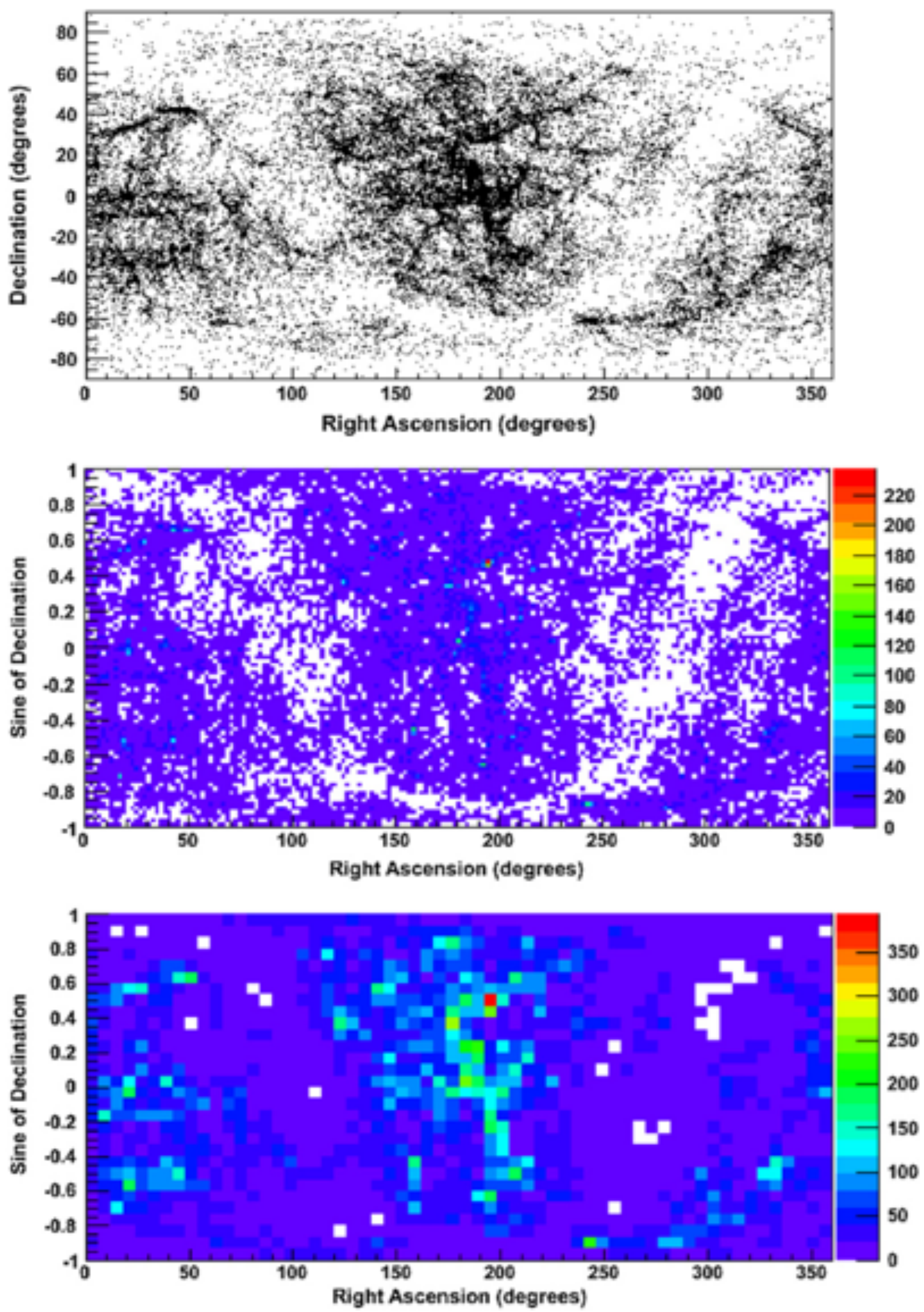

Figure 1. Scatter plot showing the distribution of galaxies in the GWGC on the sky (top), and the distribution in ~ 2° bins (middle) and 6° bins (bottom). The choice of bin size represents the best and median localization of error circles on the sky, obtainable with the LIGO/Virgo network of detectors (Fairhurst 2009). This highlights the importance of using an available list of galaxies, as we must choose the best fields within a LIGO/Virgo error circle to observe.

A list of galaxies for gravitational wave searches
Darren J White, E J Daw and V S Dhillon
CQG 28 (2011) 085016

既存の4カタログを統合

- Tully Nearby Galaxy Catalog
- Catalog of Neighboring Galaxies
- V8k catalogue
- HyperLEDA

53000個の銀河
150個のMilky Way 球状星団
100Mpc以内のもの

Gravitational Wave Galaxy Catalogue (GWGC)

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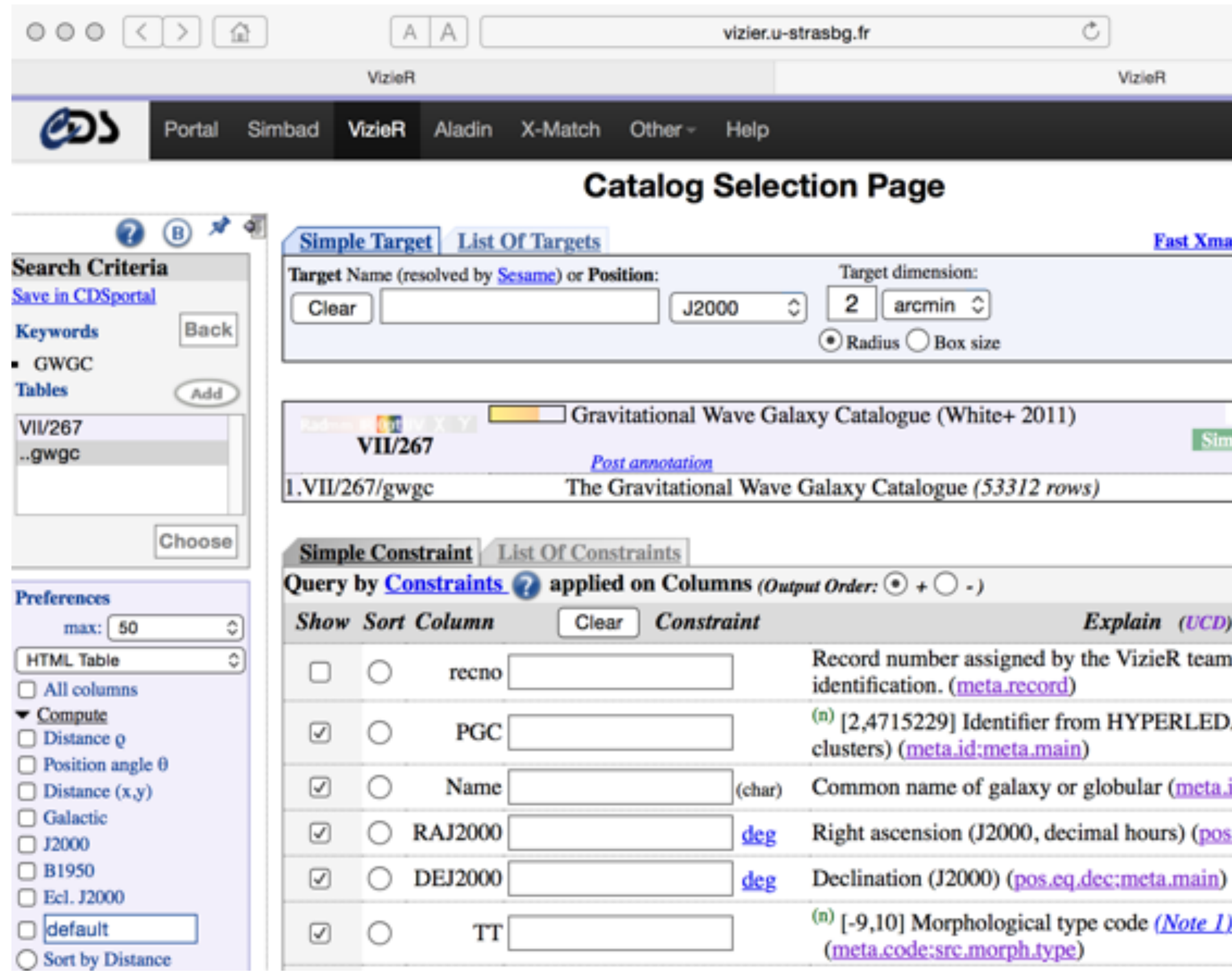
Table 1. Completeness of the GWGC, based on fig. 5 of White, Daw & Dhillon (2011).

Distance (Mpc)	Completeness (%)
$\leq$40	100
50	70
60	65
70	65
80	60
90	58
100	55
>100	0^a

[a] The GWGC only includes galaxies within 100 Mpc, hence the sudden cut-off.

P.A. Evans +,
MNRAS 455(2016) 1522
[arXiv:1506.01624]



http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=GWGC
http://vizier.nao.ac.jp/viz-bin/VizieR-2

結果

3つ見つかったが **Rank 4: Not a counterpart.** **対応候補天体ではない**

Table 2. Sources detected by *Swift* follow-up of GW150914

P.A. Evans +, arXiv:1602.03868

RA (J2000)	Dec (J2000)	Error 90% conf.	Flux 0.3–10 keV, erg cm^{-2} s^{-1}	Magnitude AB mag	Catalogued name
09h 14m 06.54s	-60°32′ 07.7″	4.8″	$(1.9 \pm 0.5) \times 10^{-12}$	N/A	XMMSL1 J091406.5-603212
09h 13m 30.24s	-60°47′ 18.1″	6.1″	$(5.3 \pm 2.0) \times 10^{-13}$	15.44±0.02[a]	ESO 126-2 = 1RXS J091330.1-604707
08h 17m 60.62s	-67°44′ 03.9″	4.7″	$(8.9 \pm 2.4) \times 10^{-13}$	17.53±0.05	1RXS J081731.6-674414

[a] Magnitude of the core. The galaxy as a whole (removing foreground stars) has a *u* magnitude of 14.15±0.02.

議論と結論

★XRTでは，4.7 平方度を調べた（LALInterenceの2%の領域）

★合体の瞬間に，BATは，その方向を向いていなかった．時折，そのような場合でもバーストを引っ掛けるが，今回は±100secに，なし．

★BH-BHならばガンマ線バーストあるかどうか不明，しかも500Mpcであれば銀河カタログになく，「対応なし」は驚くべきことではない．

★triggerのアナウンスがされてから，15時間以内にGW-EMグループに，結果を伝えることができた．

★GWグループには，距離や質量などを添えて，もっと狭い範囲でアラートを．