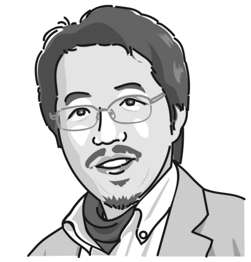
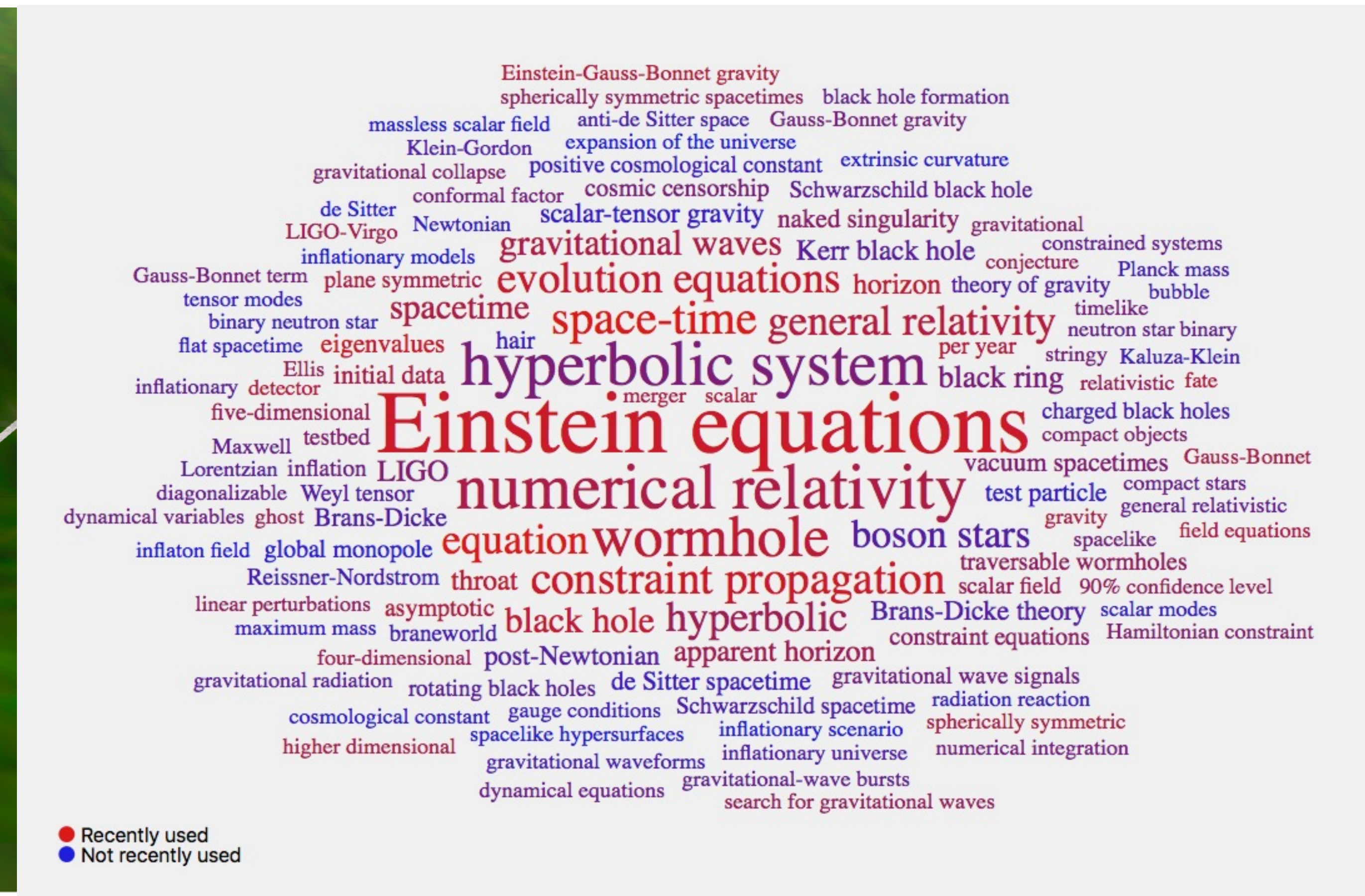
Introduction to Gravitational Wave Physics

真貝寿明　Hisaaki Shinkai

大阪工業大学情報科学部

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





https://scimeter.org says.

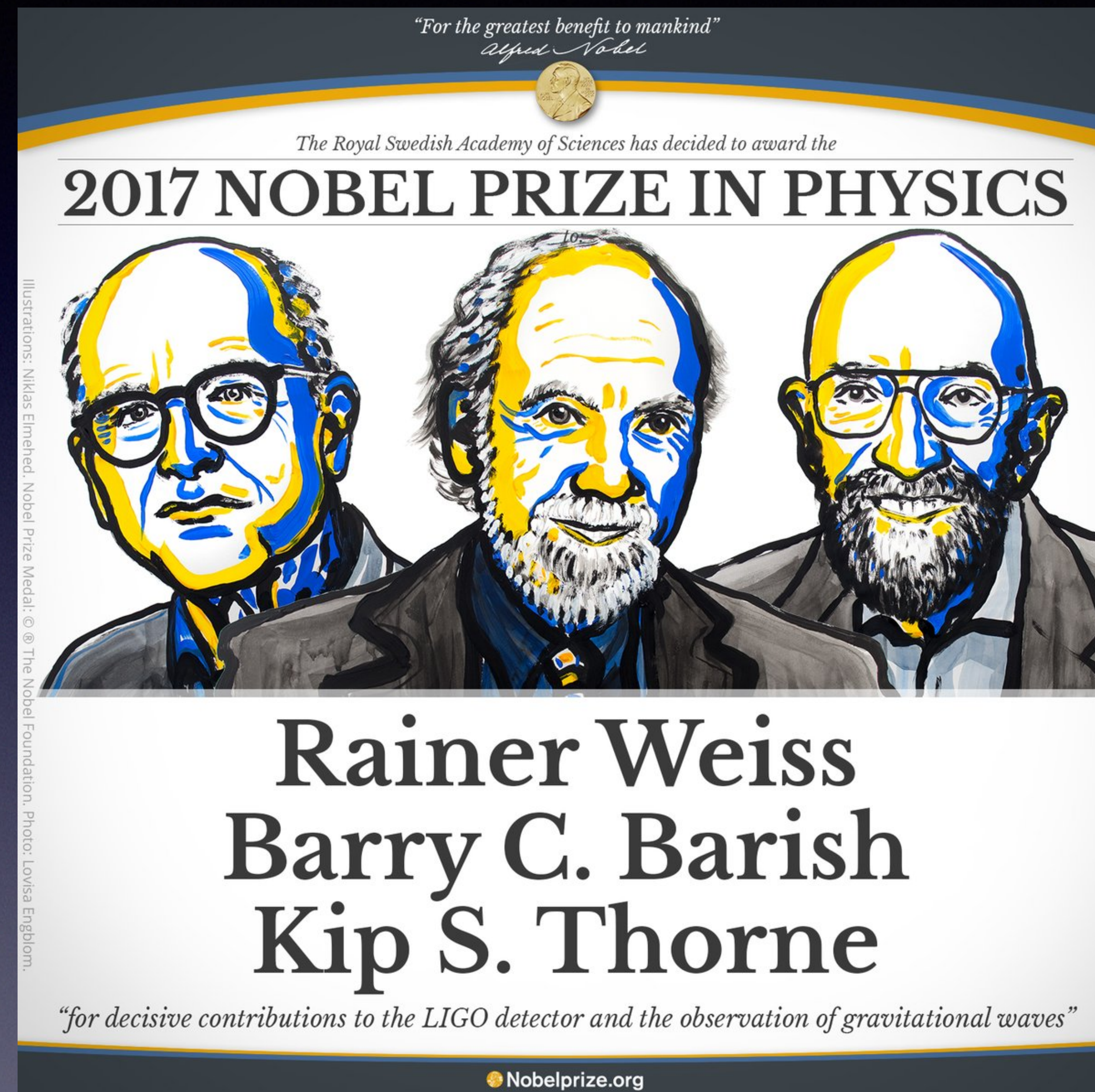
2コマ目は，「Intro to Gravitational Data Analysis」

2020-2-20 山口大学セミナー

First Detection (2015 Sep 14) 2017 Novel Prize

2017年10月，LIGO/Virgo
中性子星連星合体観測を発表
GW170817

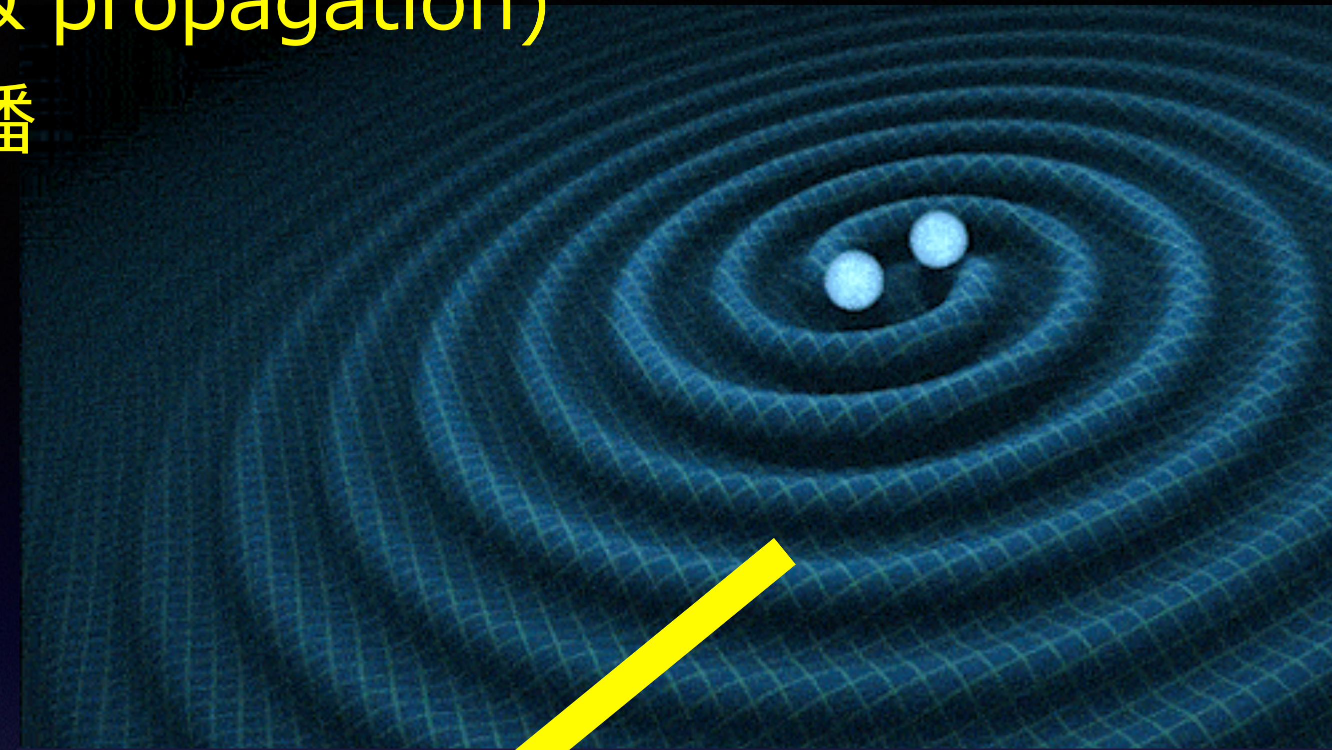
2016年2月，LIGOが重力波を初めて検出した，と発表 GW150914

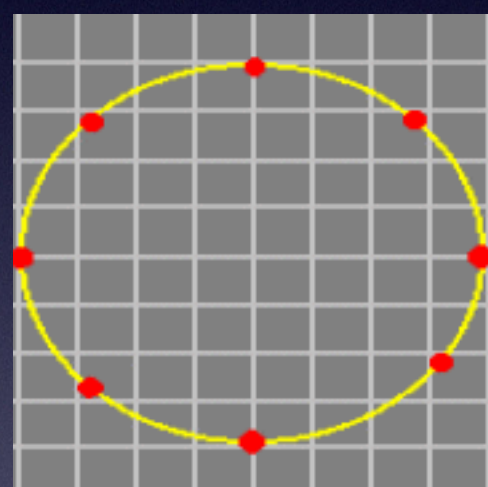


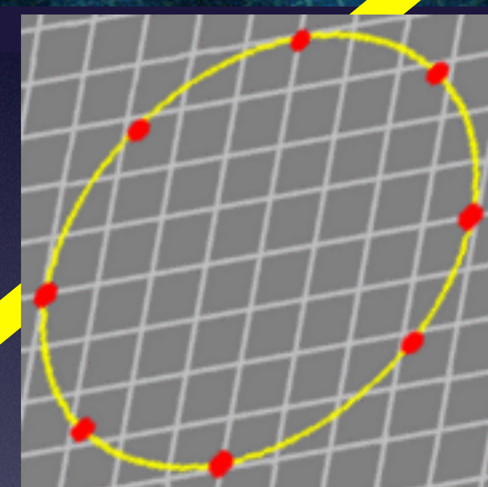
2017年10月，ノーベル財団が，重力波検出に貢献した３名をノーベル物理学賞として顕彰

Gravitational Wave (radiation & propagation)
重力波の発生と伝播

Binary Blackholes,
Binary Neutron Stars
ブラックホール連星や
中性子星連星



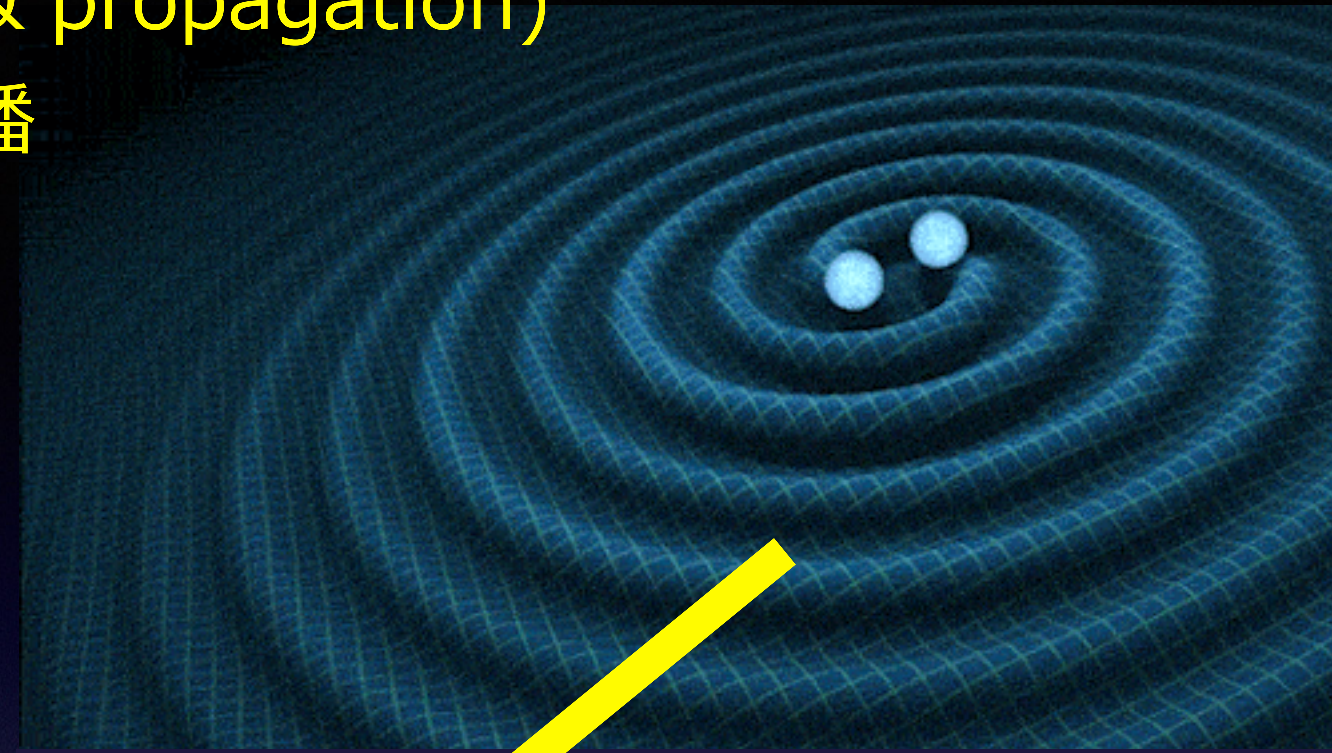




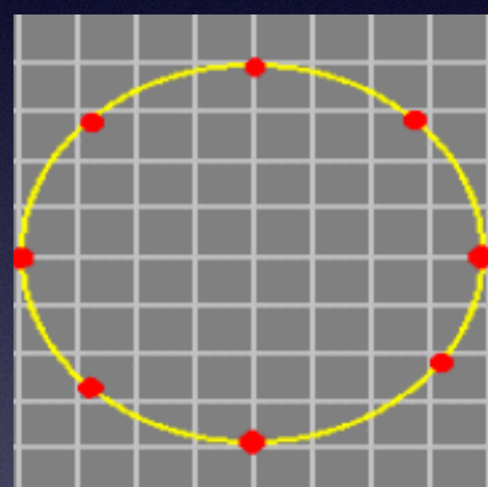
レーザー干渉計

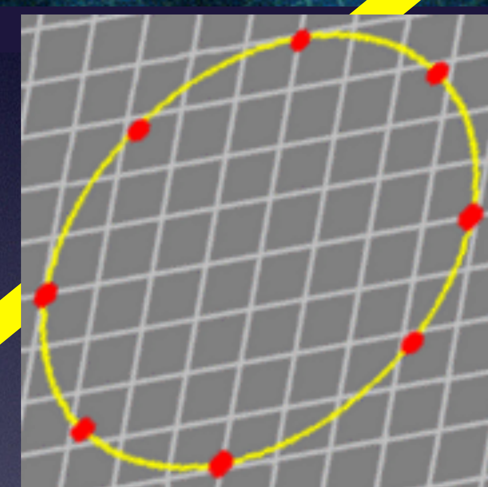
LIGO＝Laser Interferometer
Gravitational-Wave Observatory

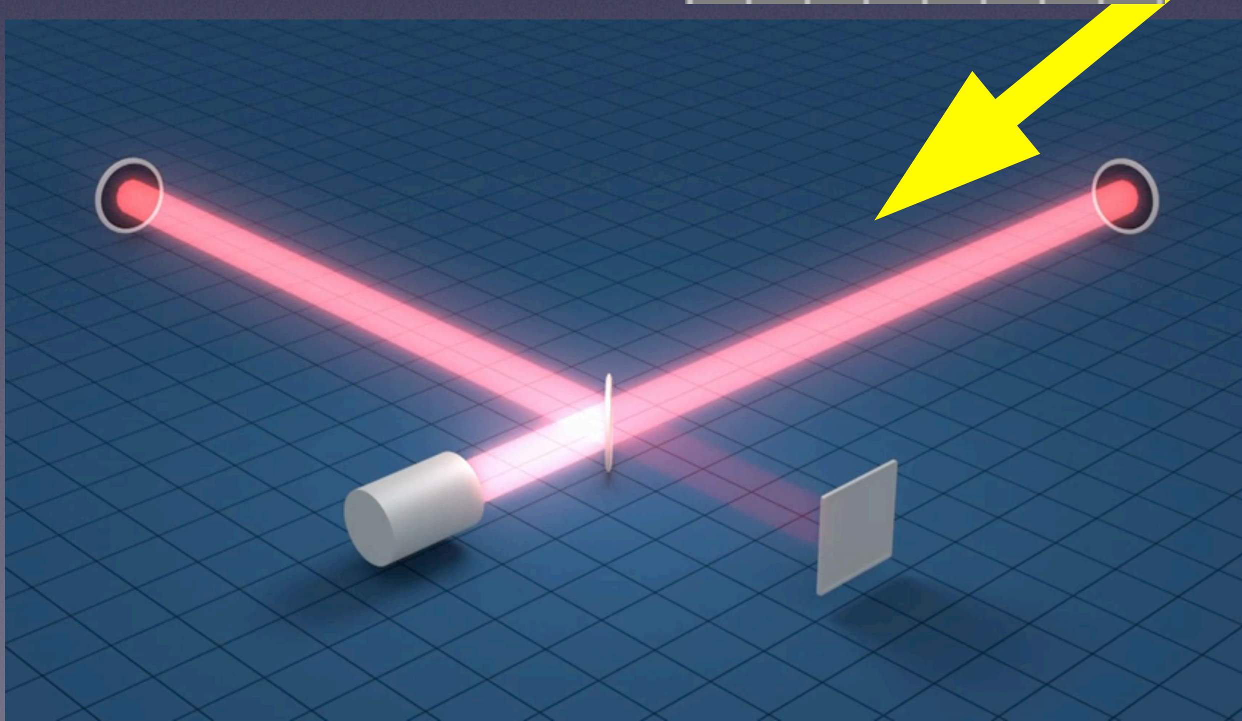
Gravitational Wave (radiation & propagation)
重力波の発生と伝播



Binary Blackholes,
Binary Neutron Stars
ブラックホール連星や
中性子星連星

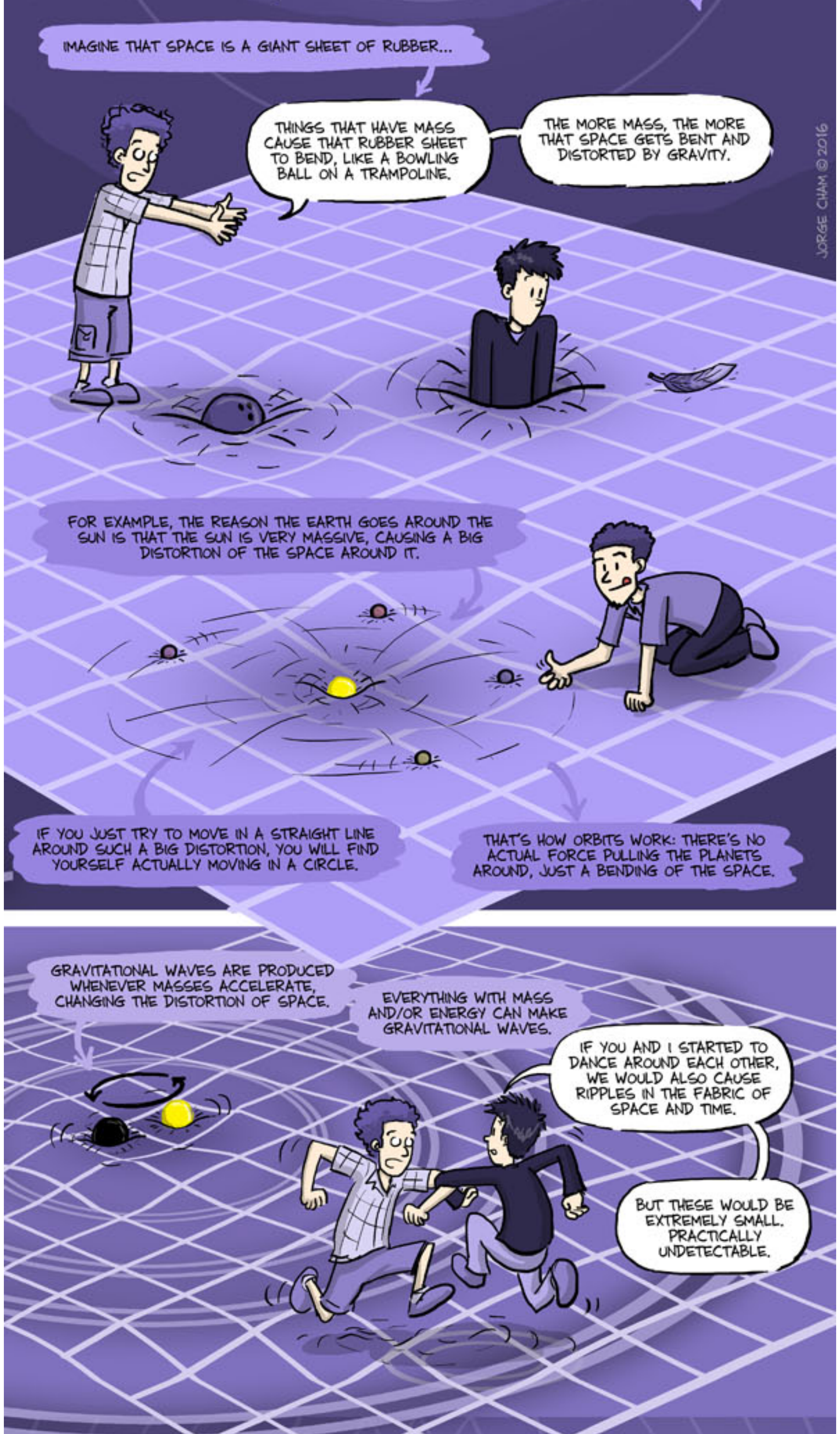






レーザー干渉計

LIGO＝Laser Interferometer
Gravitational-Wave Observatory



重力＝時空のゆがみ

gravitation = space-time warp

質点が加速度運動 ＝ 重力波発生

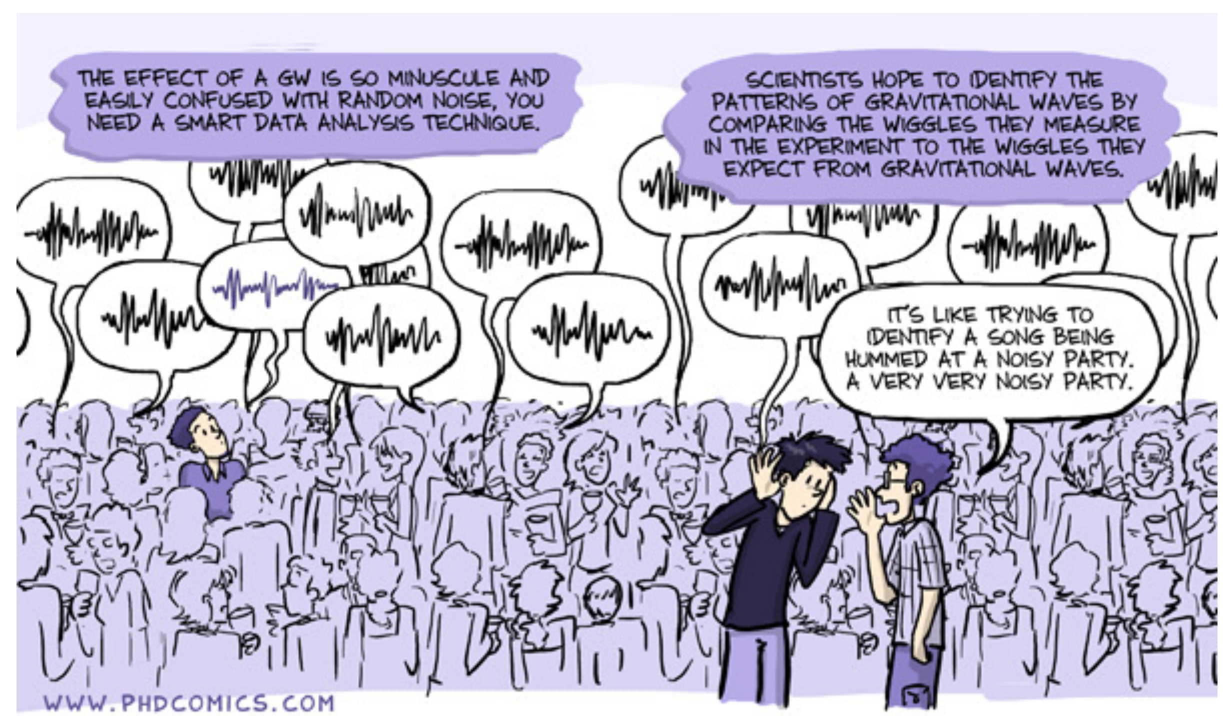
accelerate motion = GW production

大質量の天体が激しく加速度運動

＝ 観測できる重力波が発生

Large-mass astrophysical accel.

= observable GW



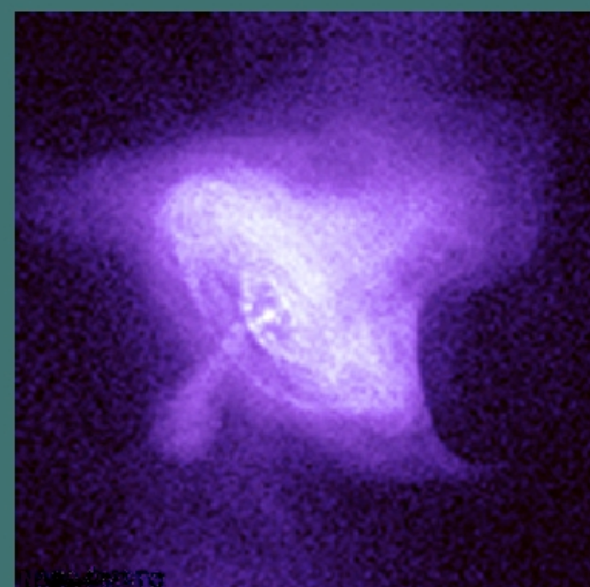
www.phdcomics.com

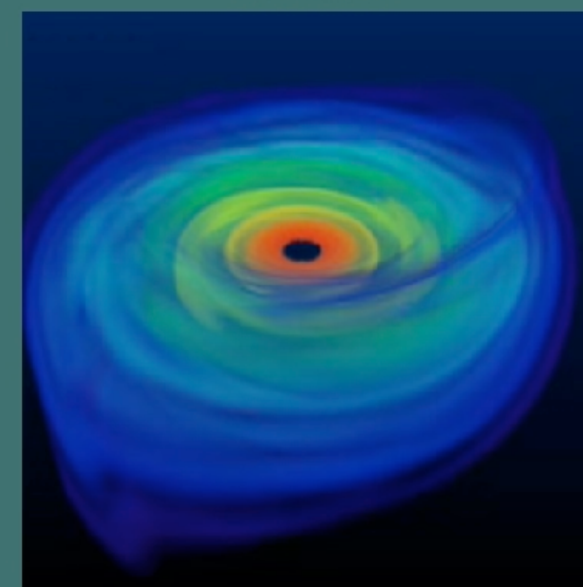
“gravitational waves explained”

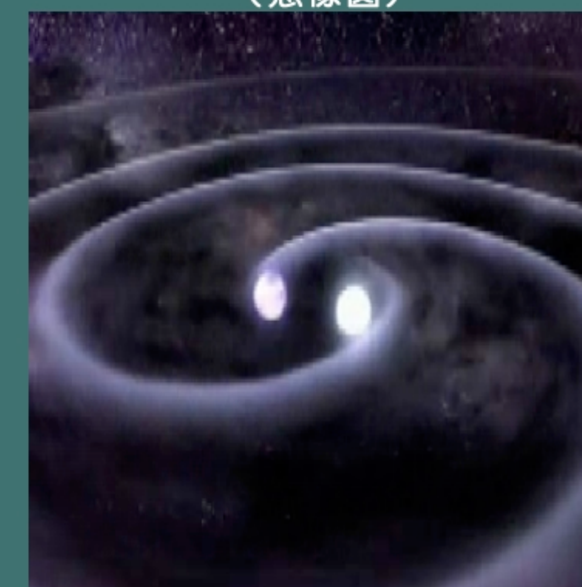
重力波の波源 (GW sources)

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

supernovae	pulsars	black hole	binary neutron stars
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

hard to predict

振幅が小さい

too small amplitude

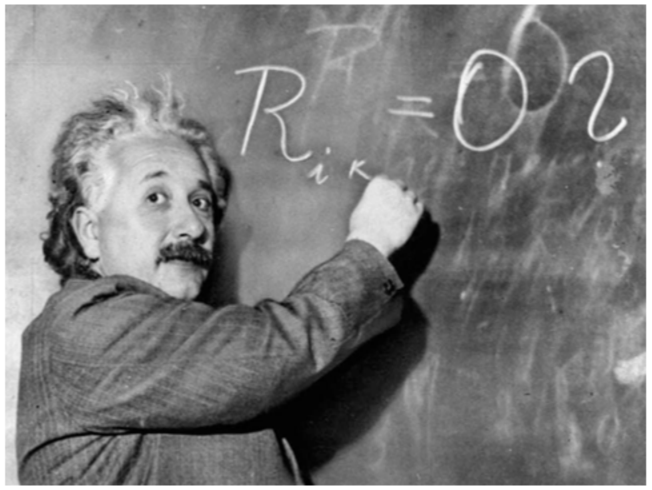
振幅が小さい

too small amplitude

連星合体を ターゲットに

binary coalescence

What we can learn from GW? (重力波観測によって解明できること)



Test of GR at strong gravity region.

一般相対性理論は正しいか？

強い重力場で重力理論の検証ができる

Test of BH no-hair theory

ブラックホール合体後のふるまいは？

no hair になるか.

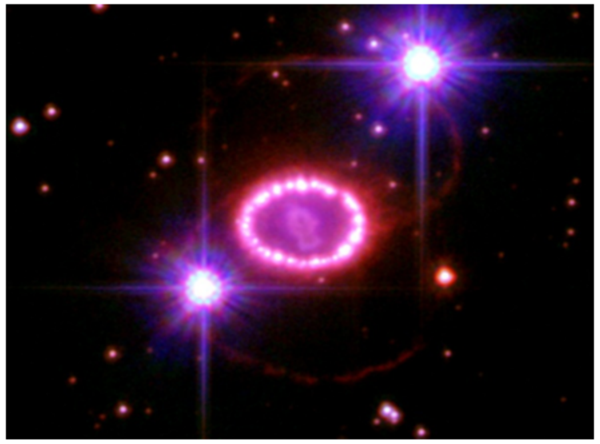
（質量，角運動量，電荷の3物理量のみか？）

Sources of Gamma-ray bursts

ガンマ線バースト現象の起源は？

加速メカニズムは？

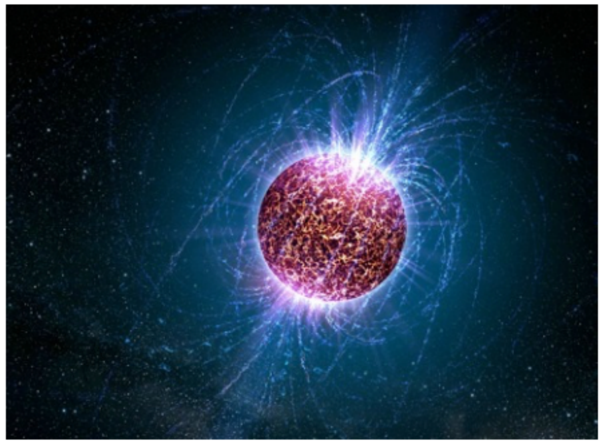
What we can learn from GW? (重力波観測によって解明できること)



Mechanism of Supernovae

超新星爆発のメカニズムは？

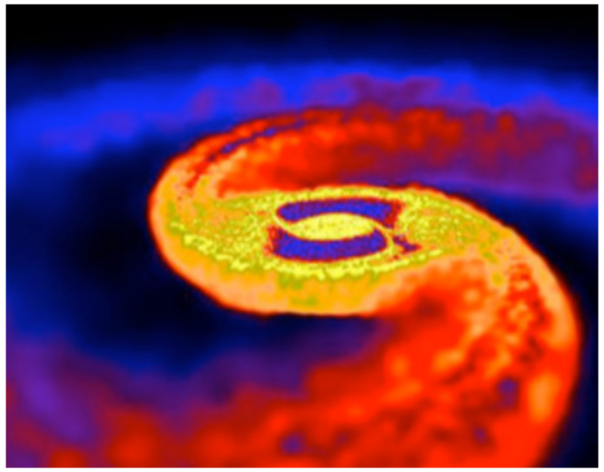
ブラックホールと中性子星の質量差？



Equation of State of nuclear matter

中性子星の最大質量は？

高密度物質の状態方程式は？



Origin of heavy elements

重元素の起源？

r-processは充分に発生するか？

Neutron Star Mass-Radius diagram: Equation of State

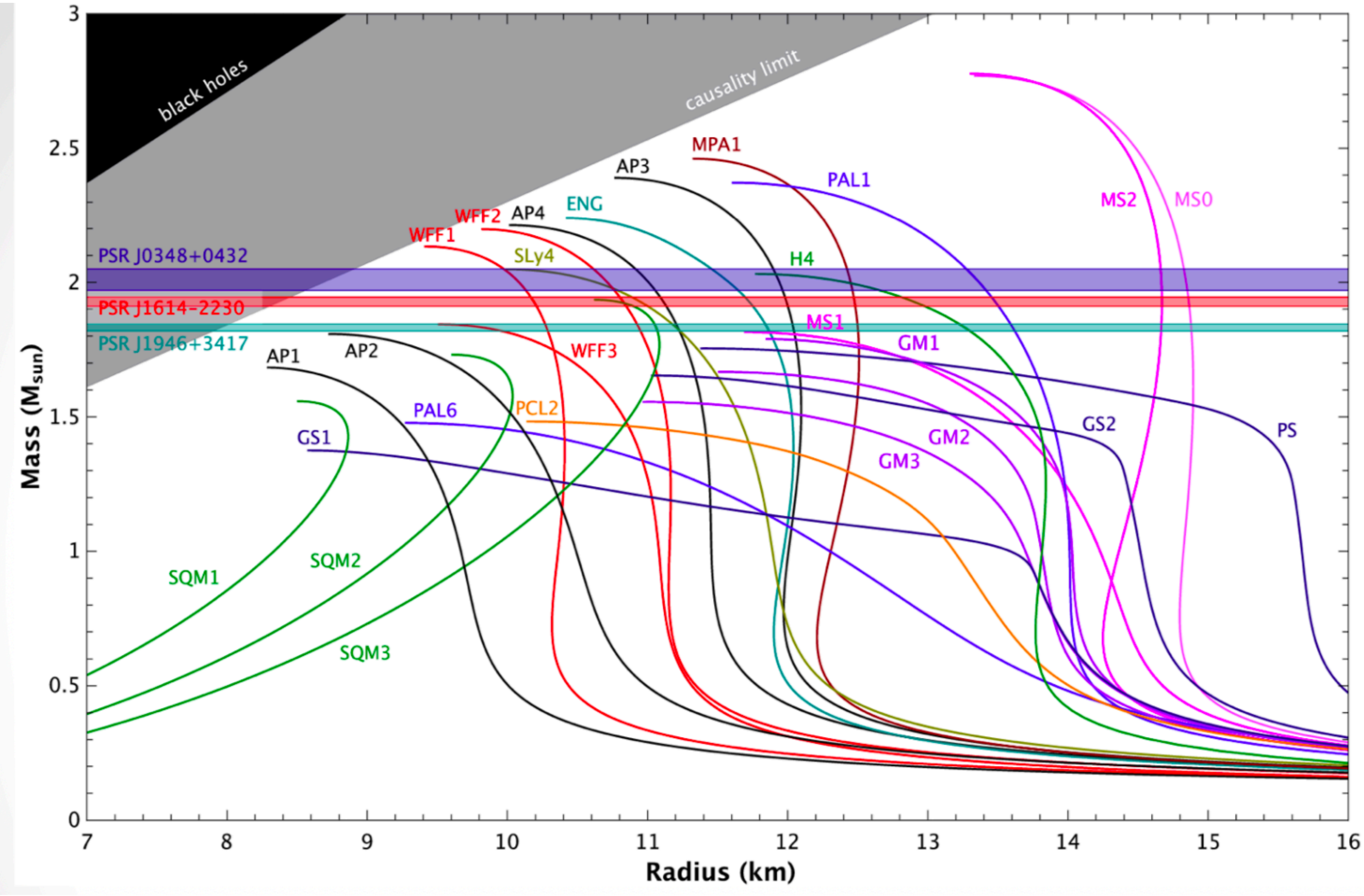


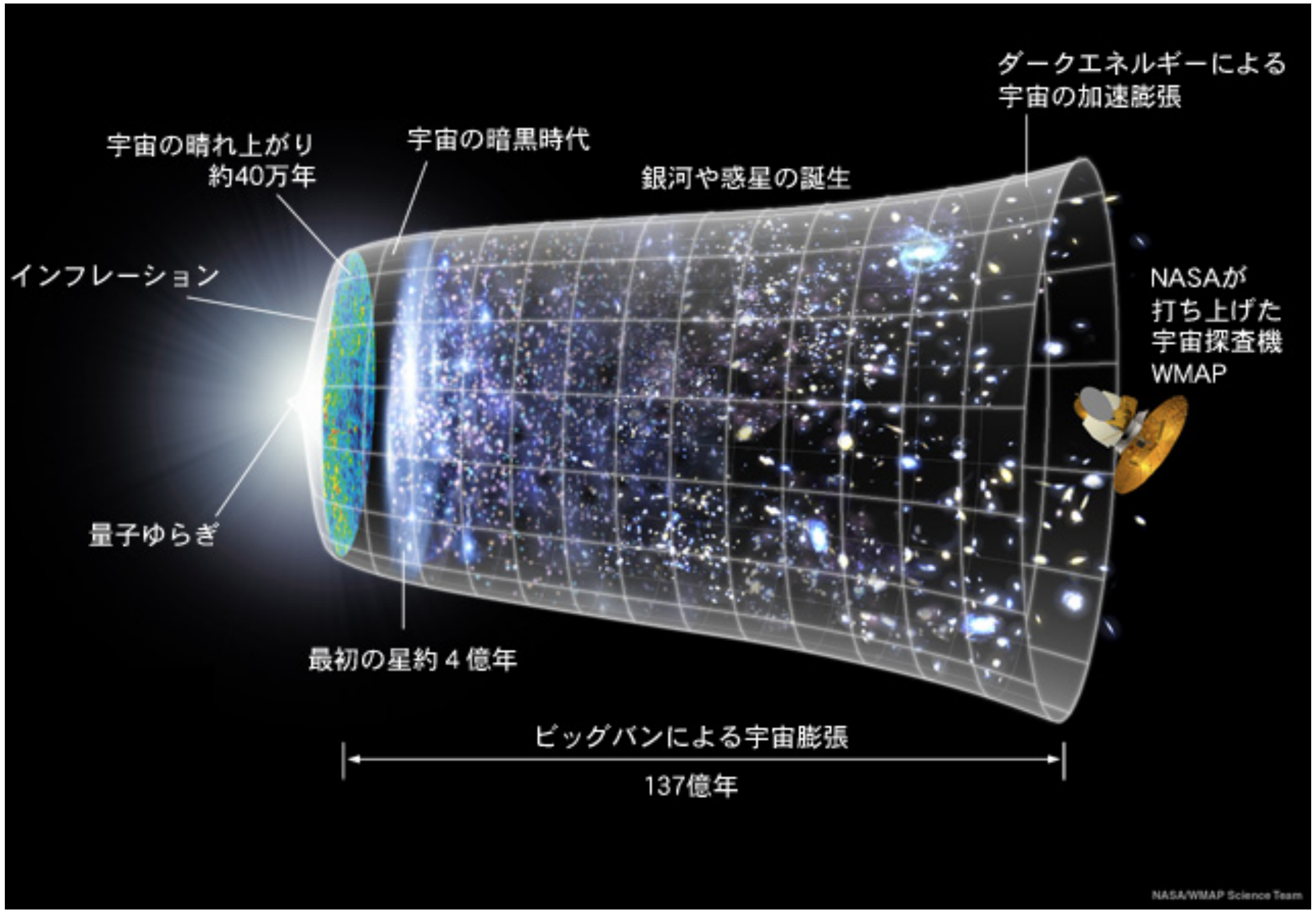
Figure created by Norbert Wex.
EOSs tabulated in Lattimer & Prakash (2001) and provided by the authors.

What we can learn from GW? (重力波観測によって解明できること)

Origin of Supermassive Blackholes

銀河中心の超巨大ブラックホールの起源は？

合体成長か，初期にできていたか？



Cosmological Parameters

宇宙の膨張速度の測定

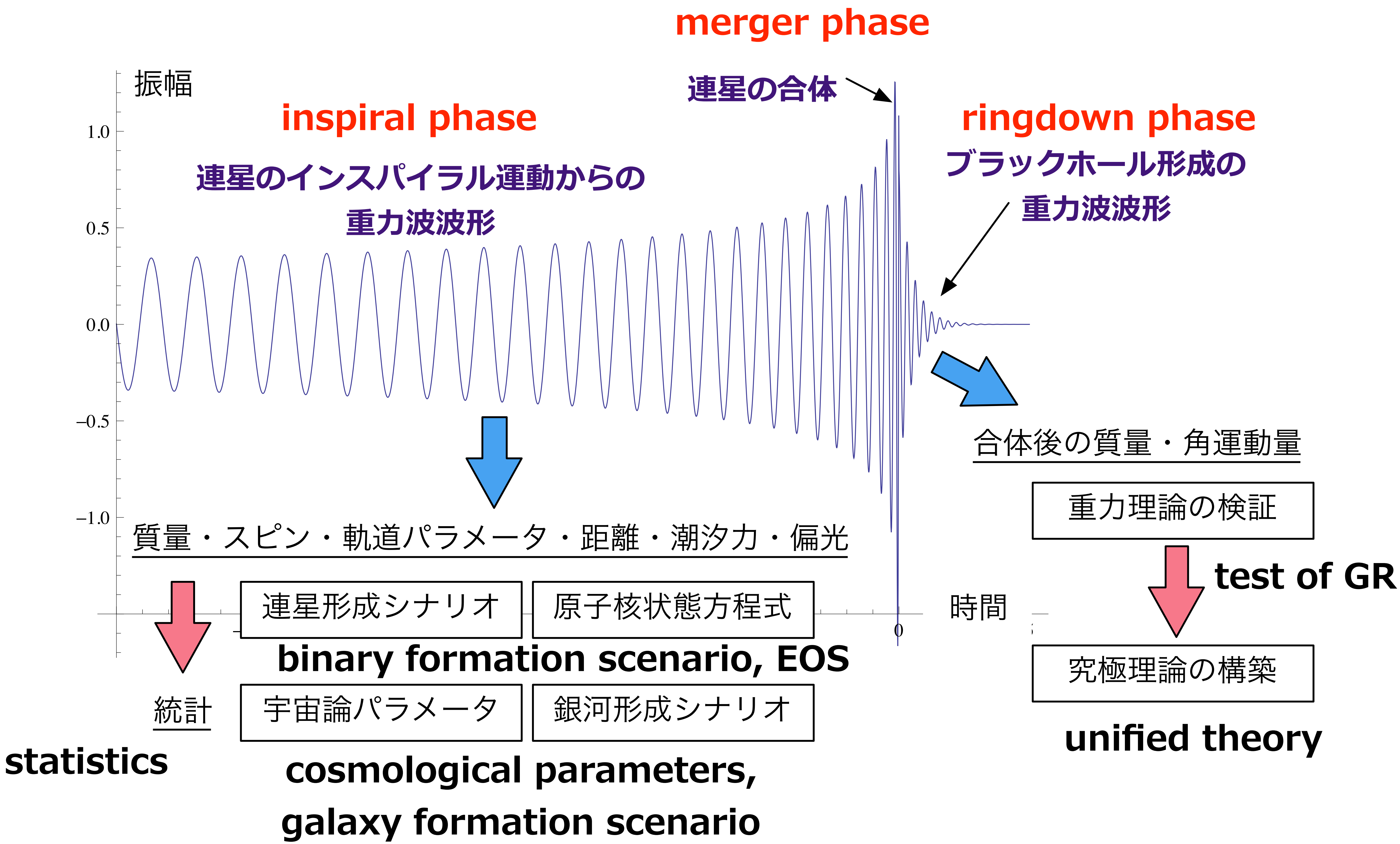
Stellar formation scenario

星形成モデルの特定

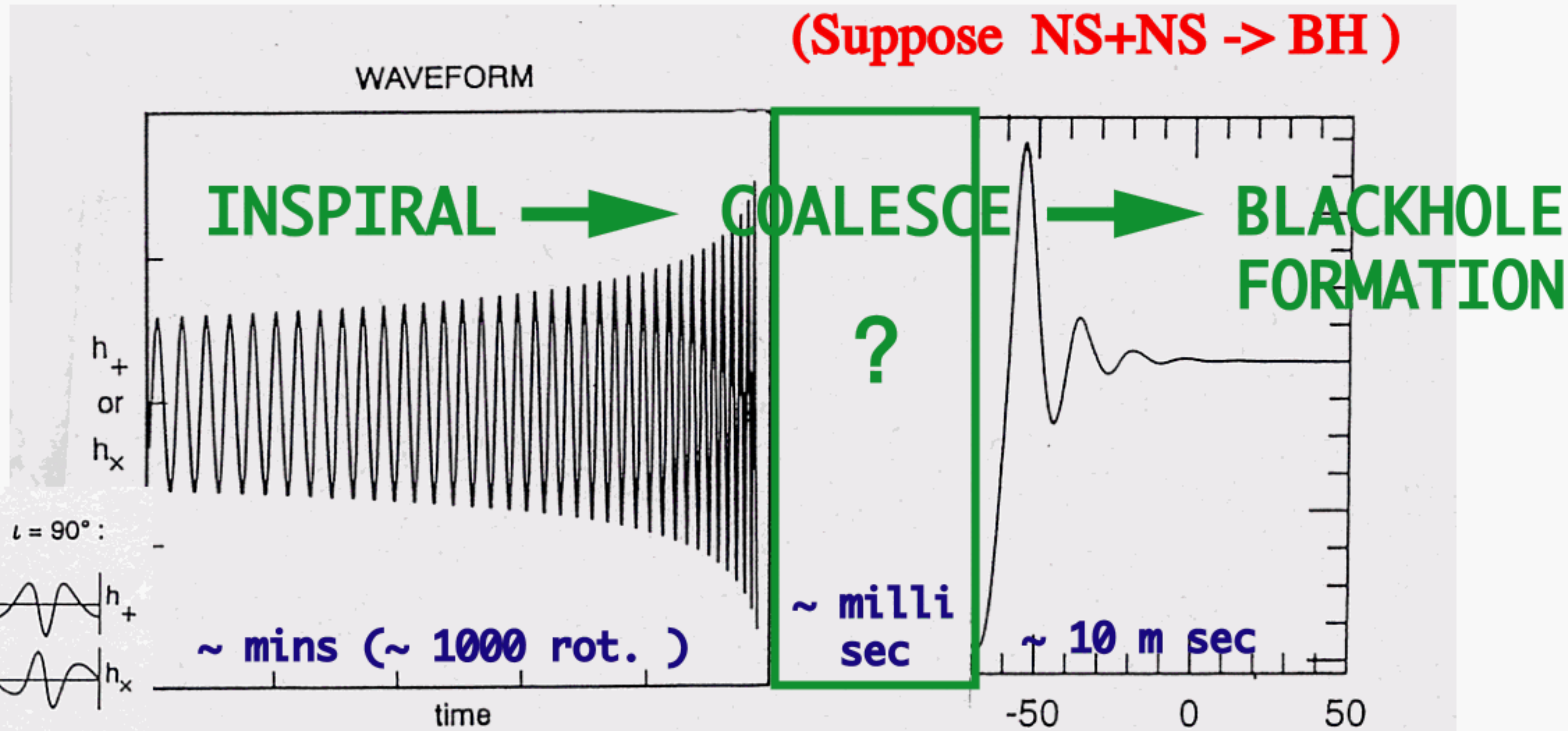
Early Universe before CMB

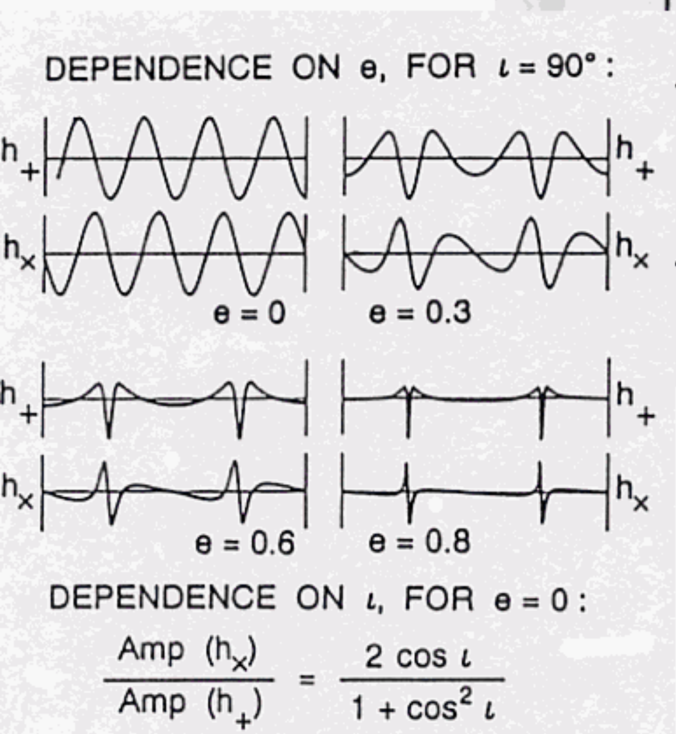
CMB以前の初期宇宙の解明

What we can learn from GW? (重力波観測によって解明できること)



What can we learn from gravitational waveform?





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+/hx => inclination
waveform => eccentricity
moduration => spin, ...

statistics => cosmological parameters

Discoveries end in an illusion (1968/70)

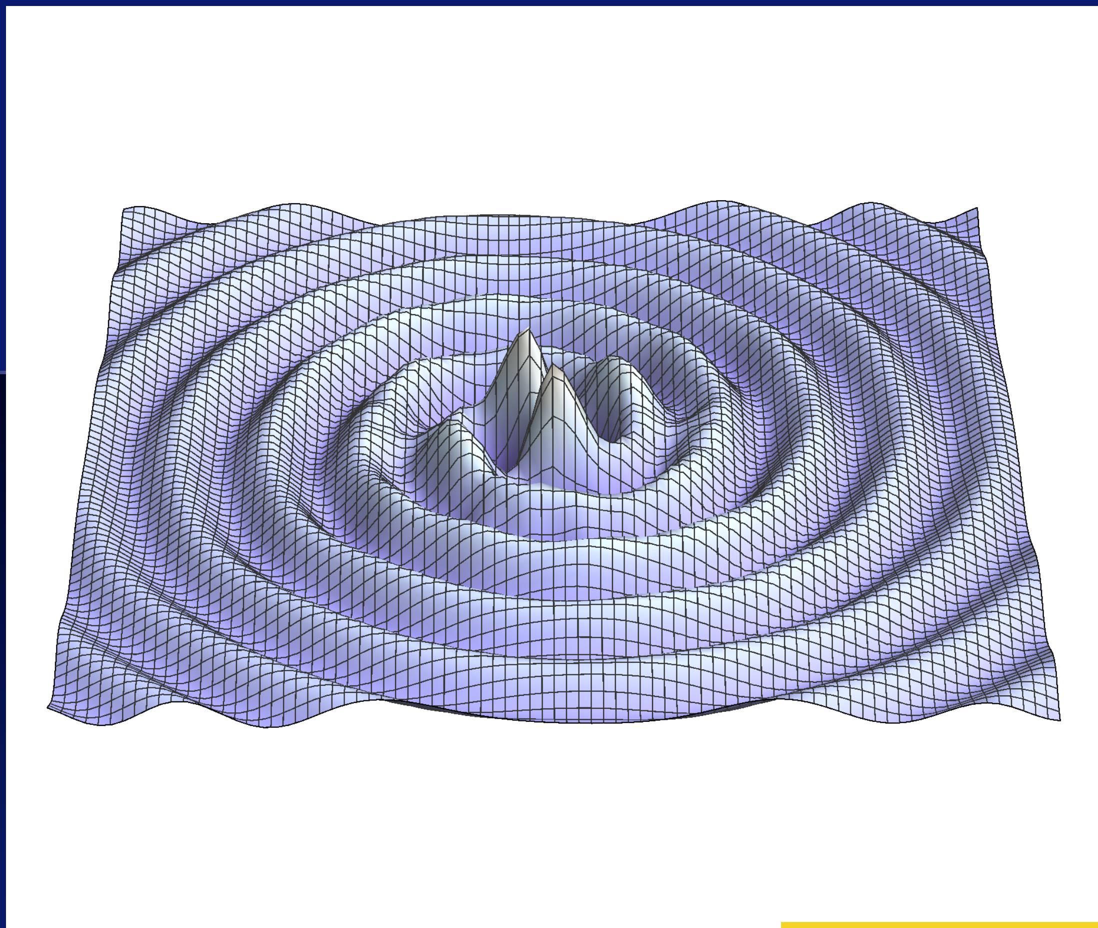
Joseph Weber

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.

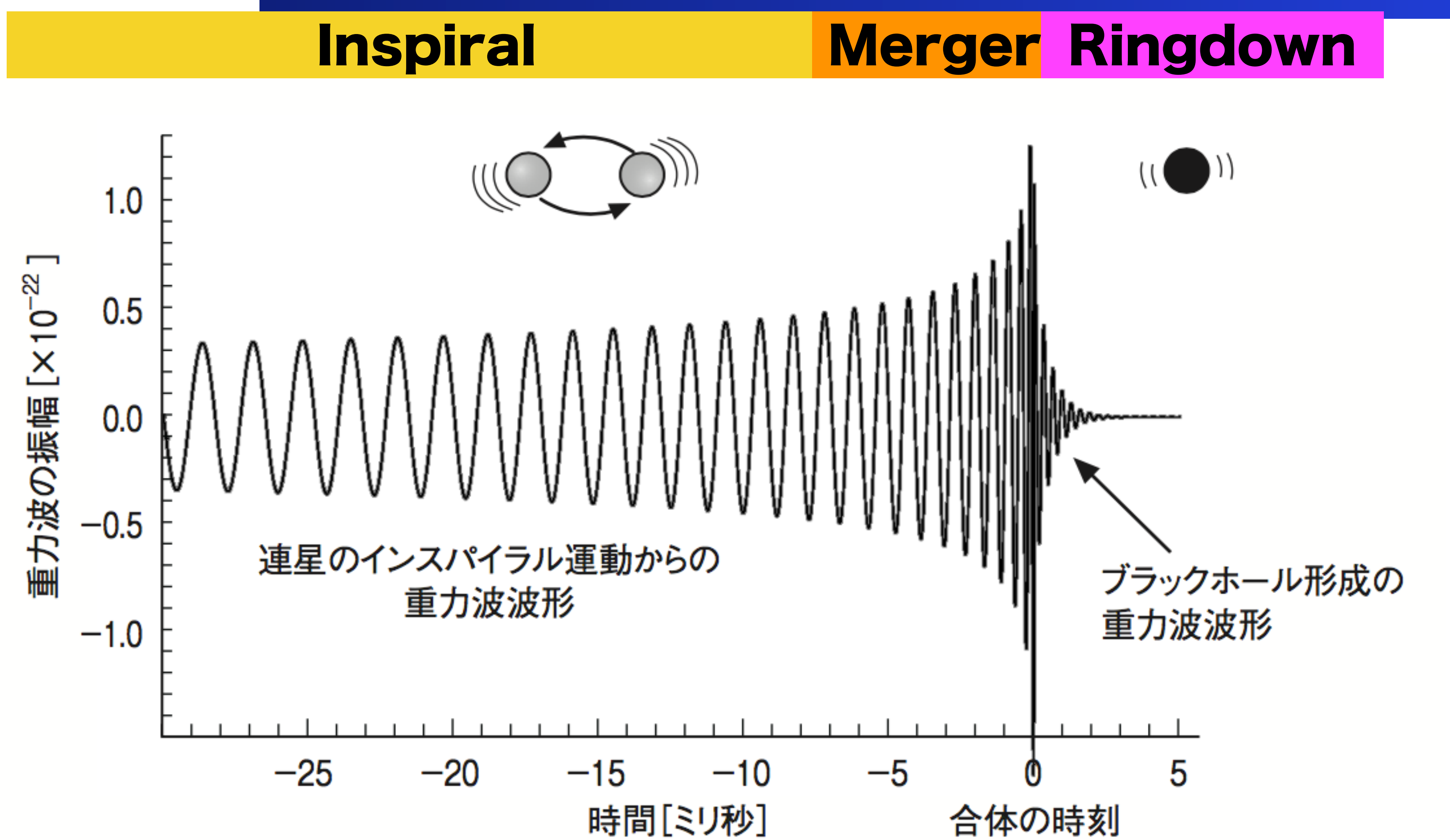


重力波の存在は連星パルサーの発見で，間接的に確かめられていた．

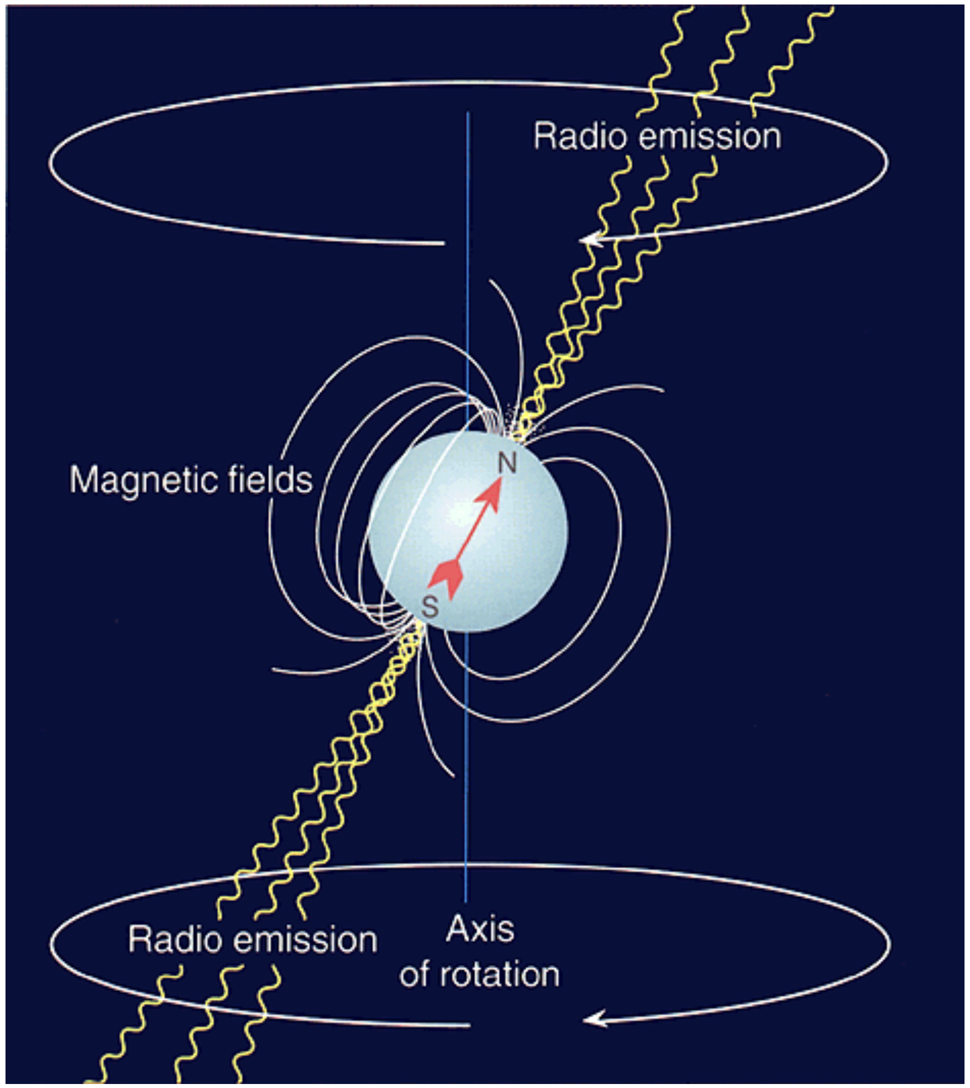
重力波の直接観測をしたい！

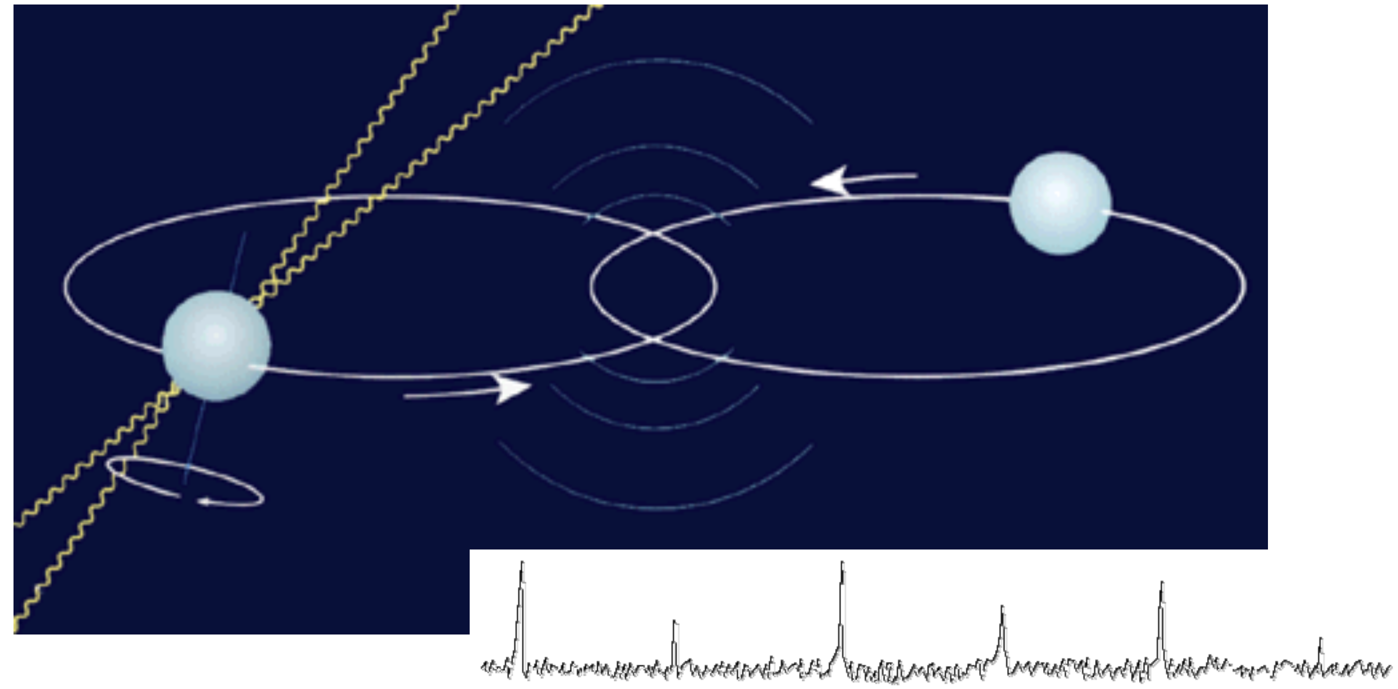
Binary Blackhole

Binary Neutron Stars



Discovery of Binary Neutron Stars (1974)





Arecibo, Puerto Rico

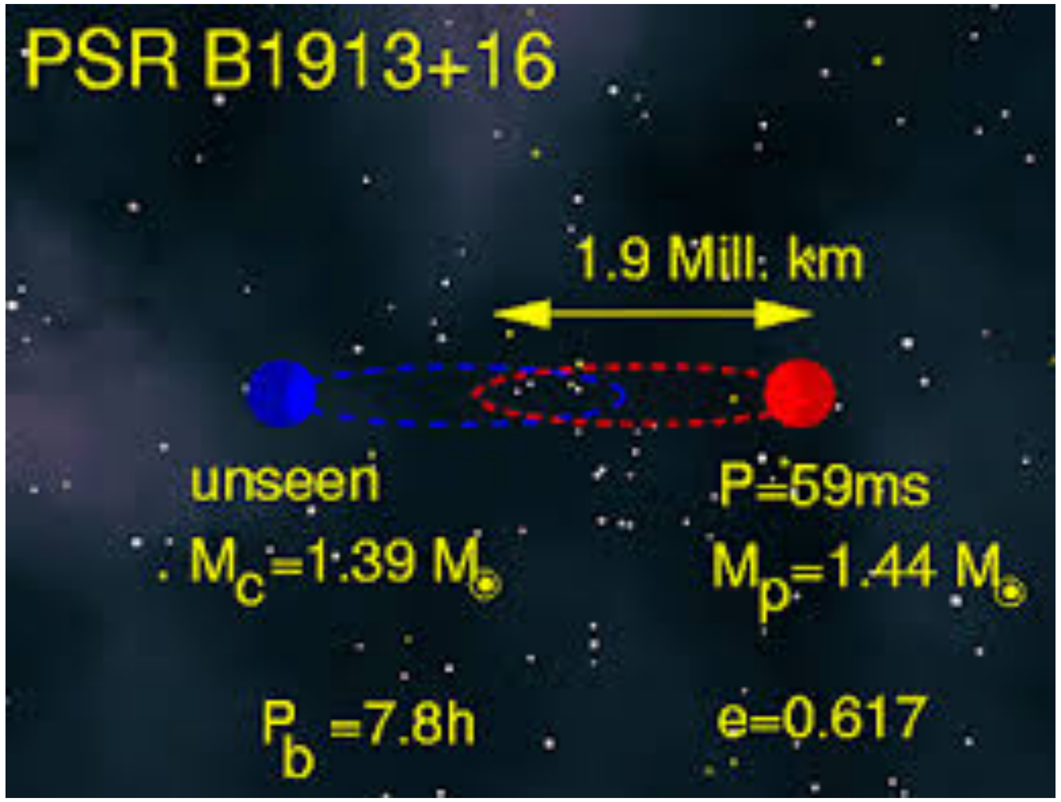
Pulsar = Neutron Star

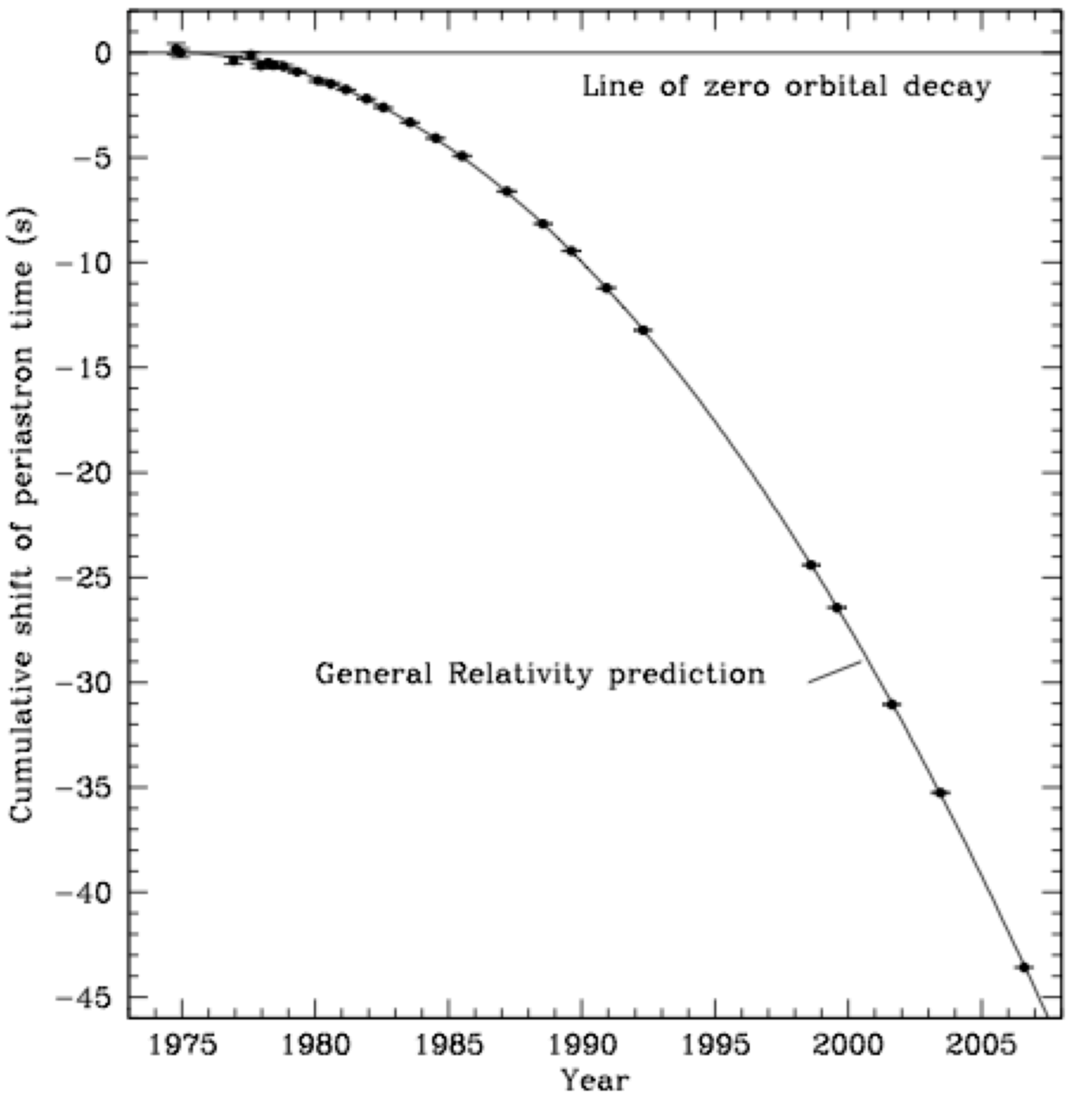
radius 10 km

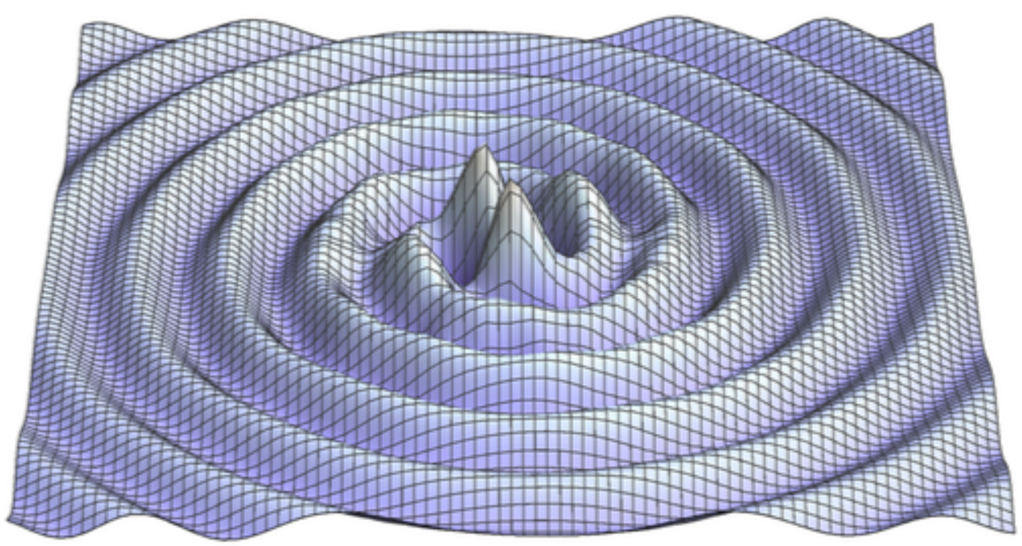
mass 1.4 Msun

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

Discovery of Binary Neutron Stars (1974)



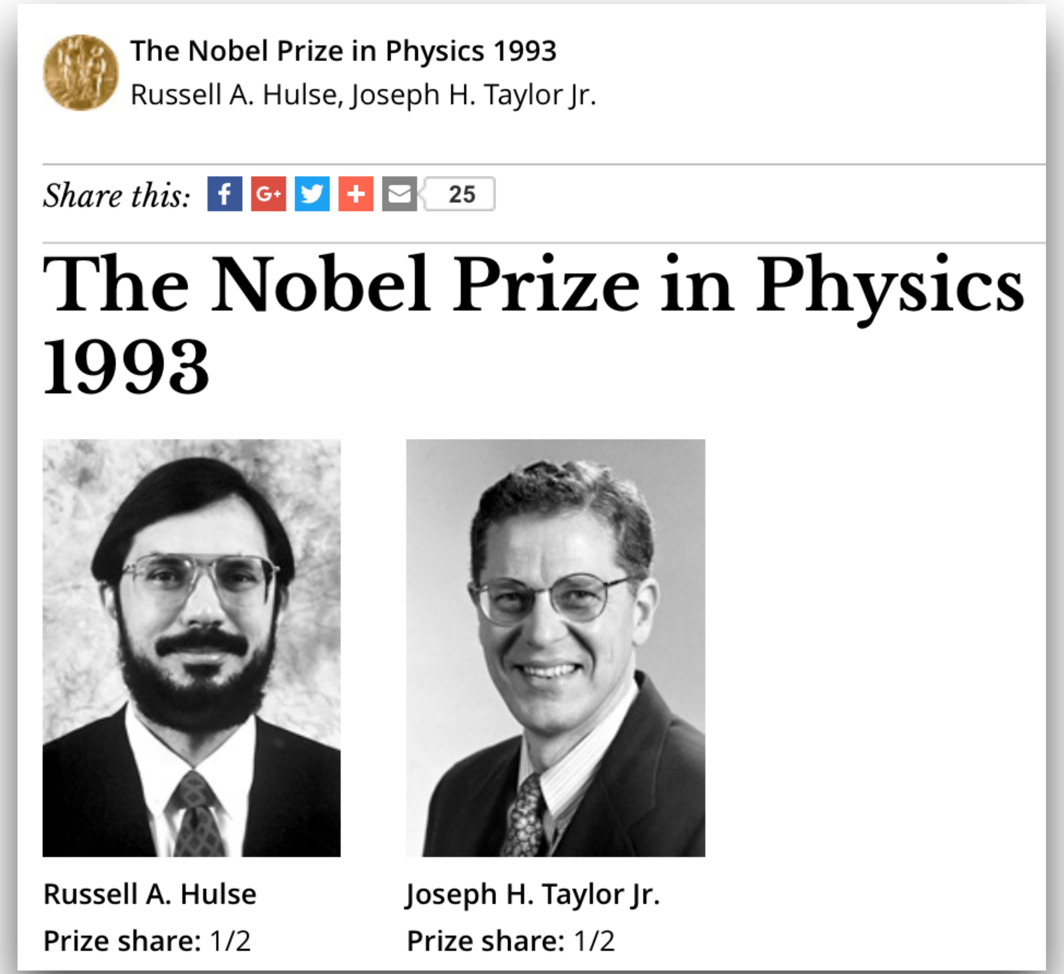




Period reduction by losing energy by GW.
重力波を放出してエネルギーを失うので，星が近づいてゆく．

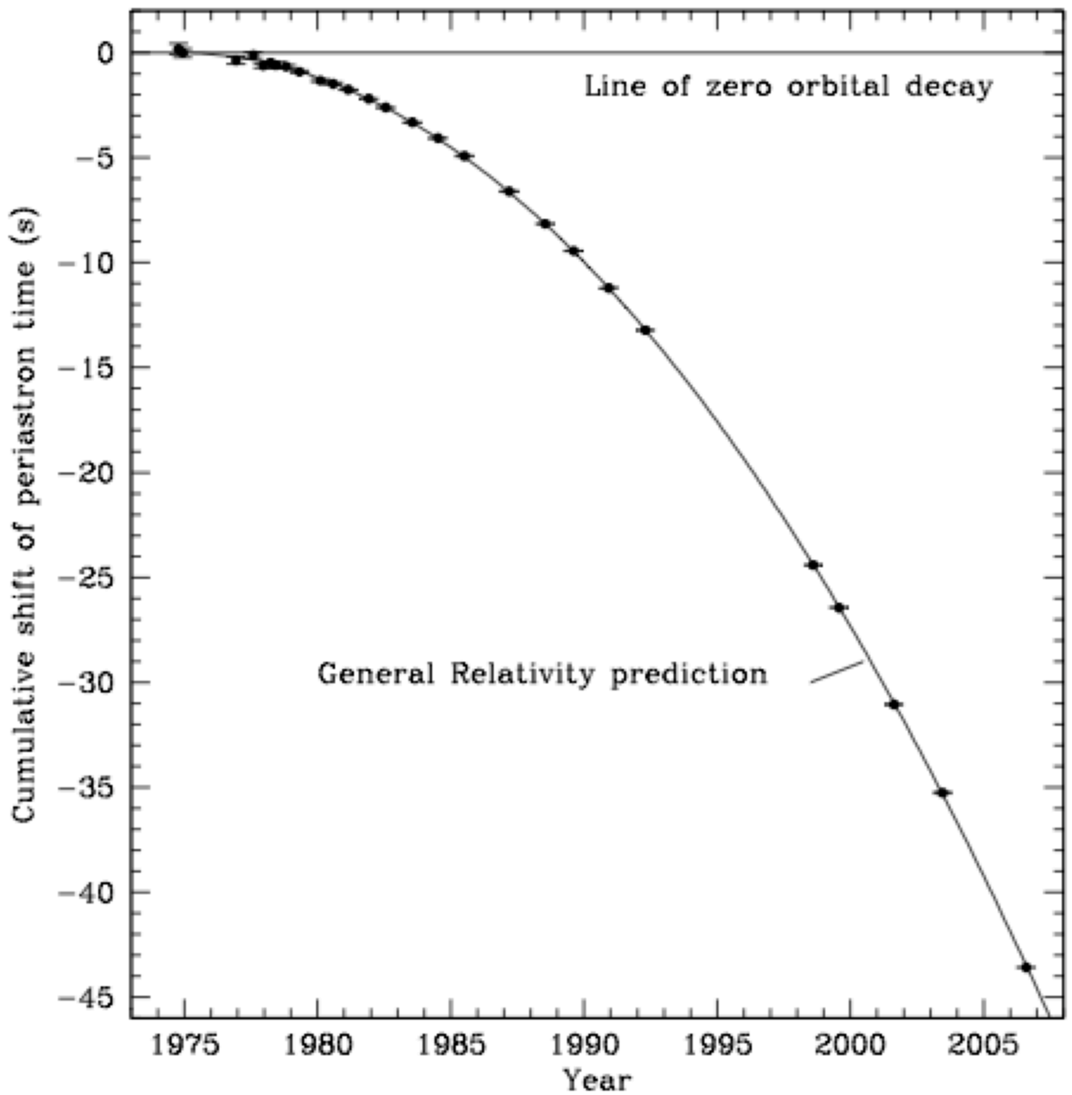
∃ Grav. Wave, indirect proof

Discovery of Binary Neutron Stars (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"



Period reduction by losing energy by GW.
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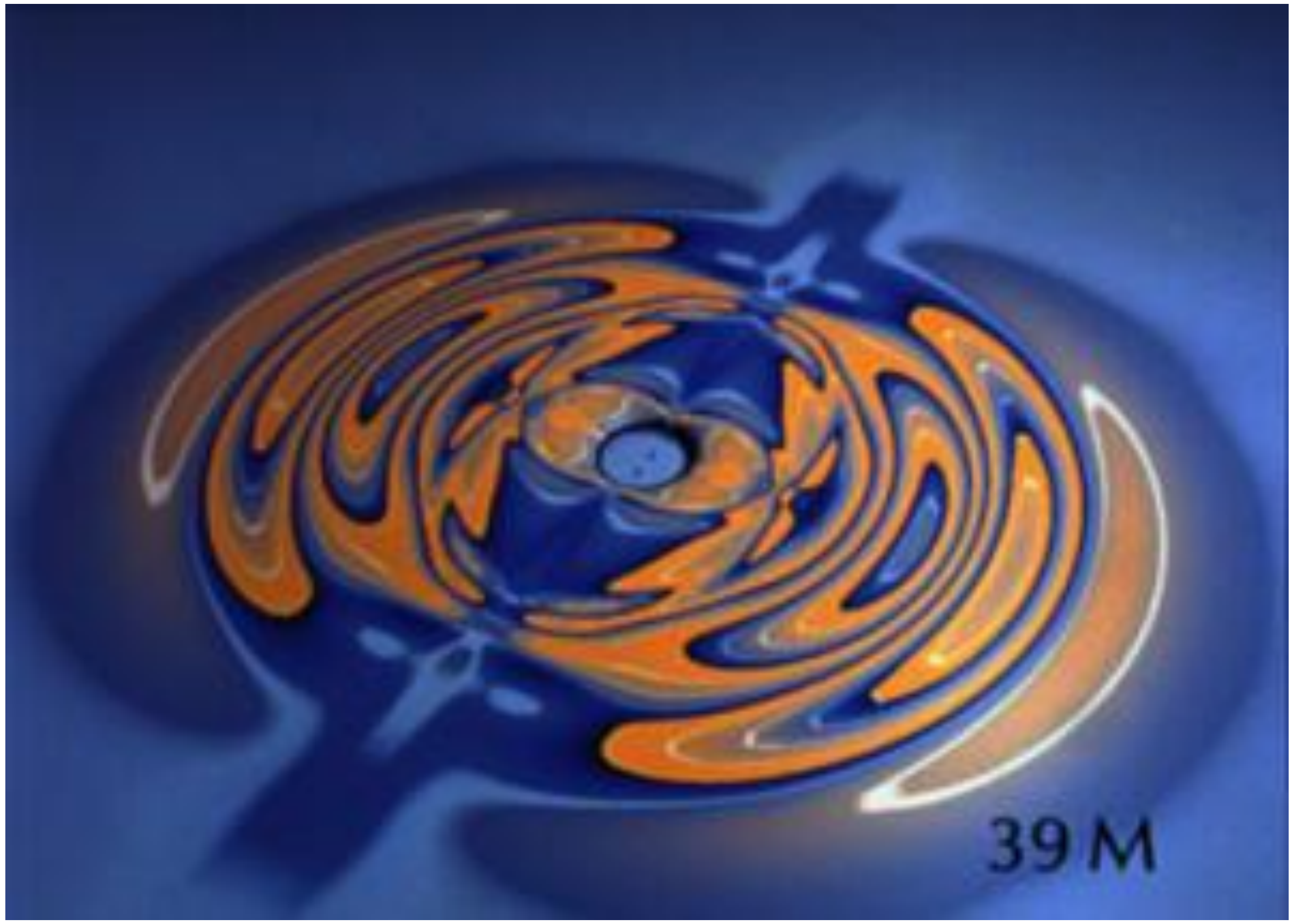
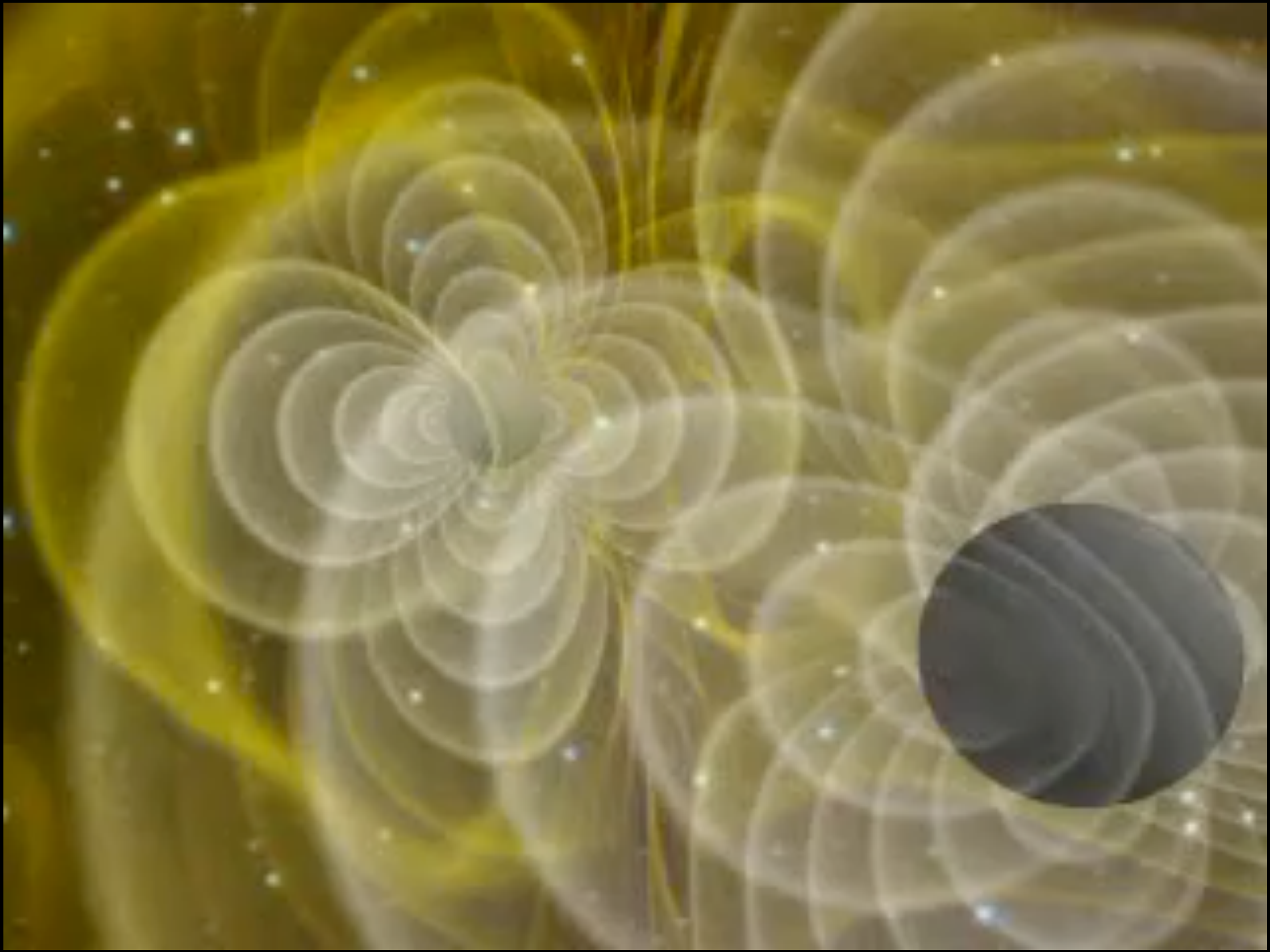
Grand Challenge for Black hole simulation (1990s)



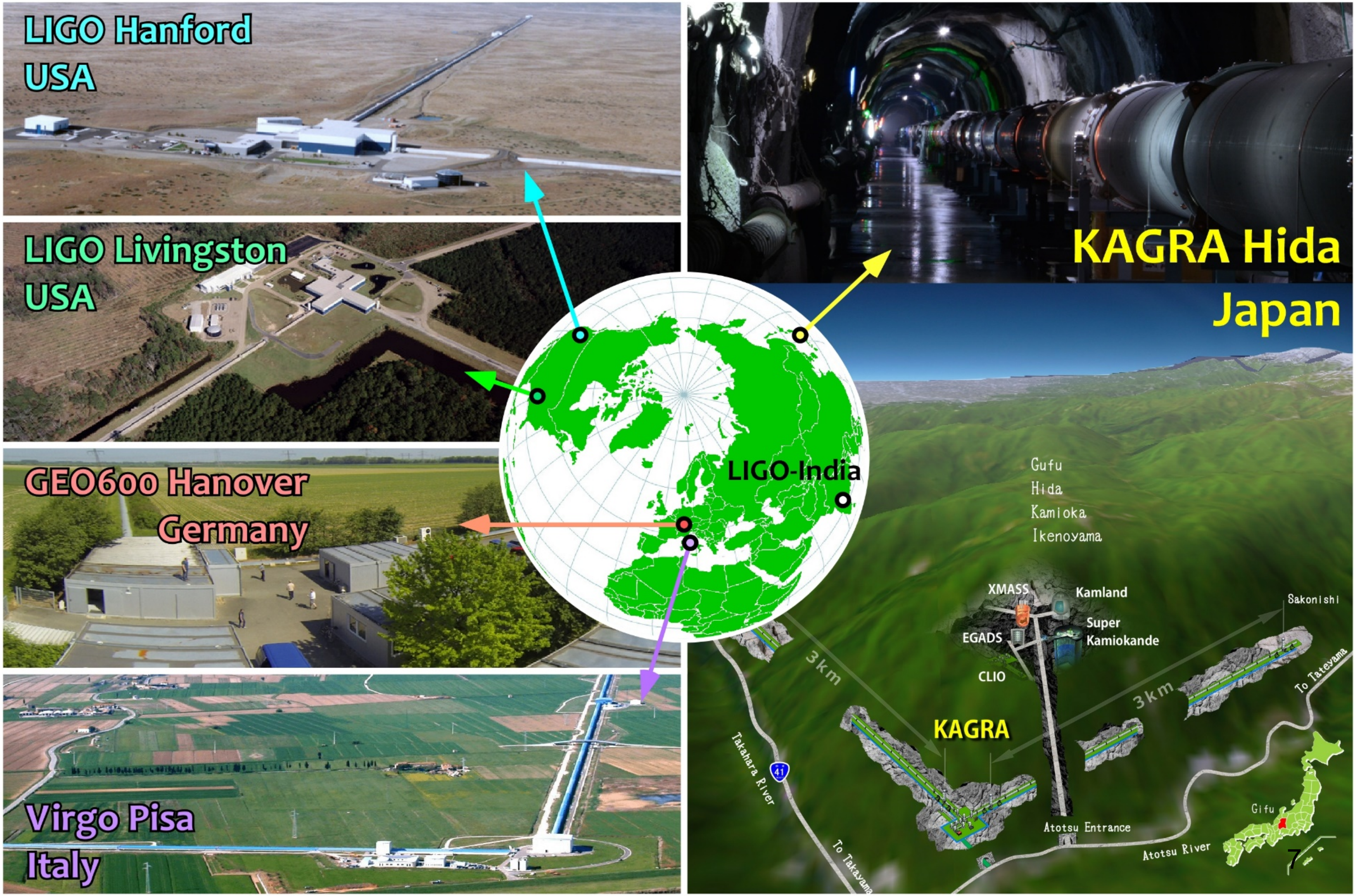
２つのブラックホールの合体と重力波放出
（90年代，NCSAグループ）

Simulation of a Binary BH merger

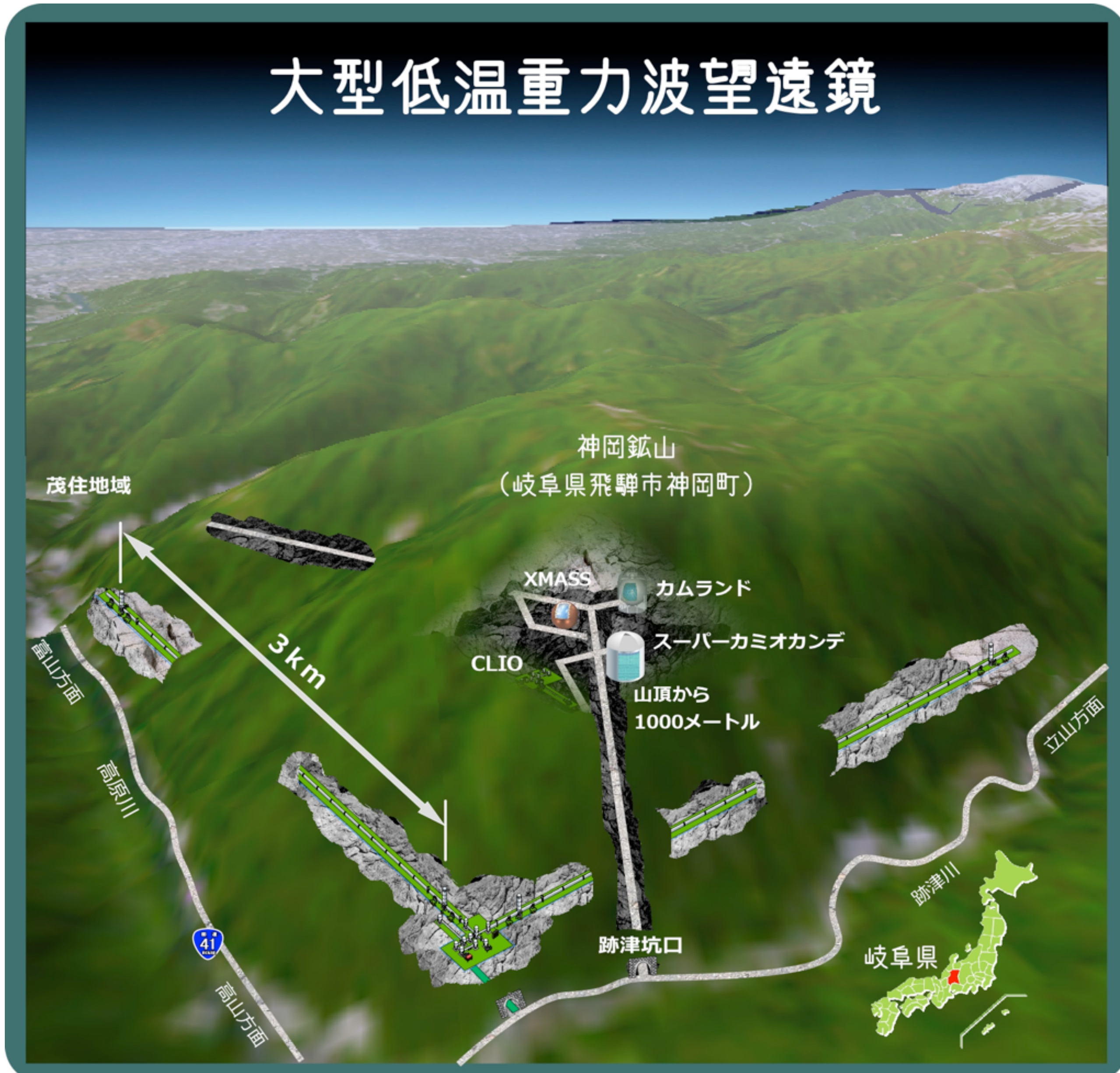


NCSA-AEI group (1998)

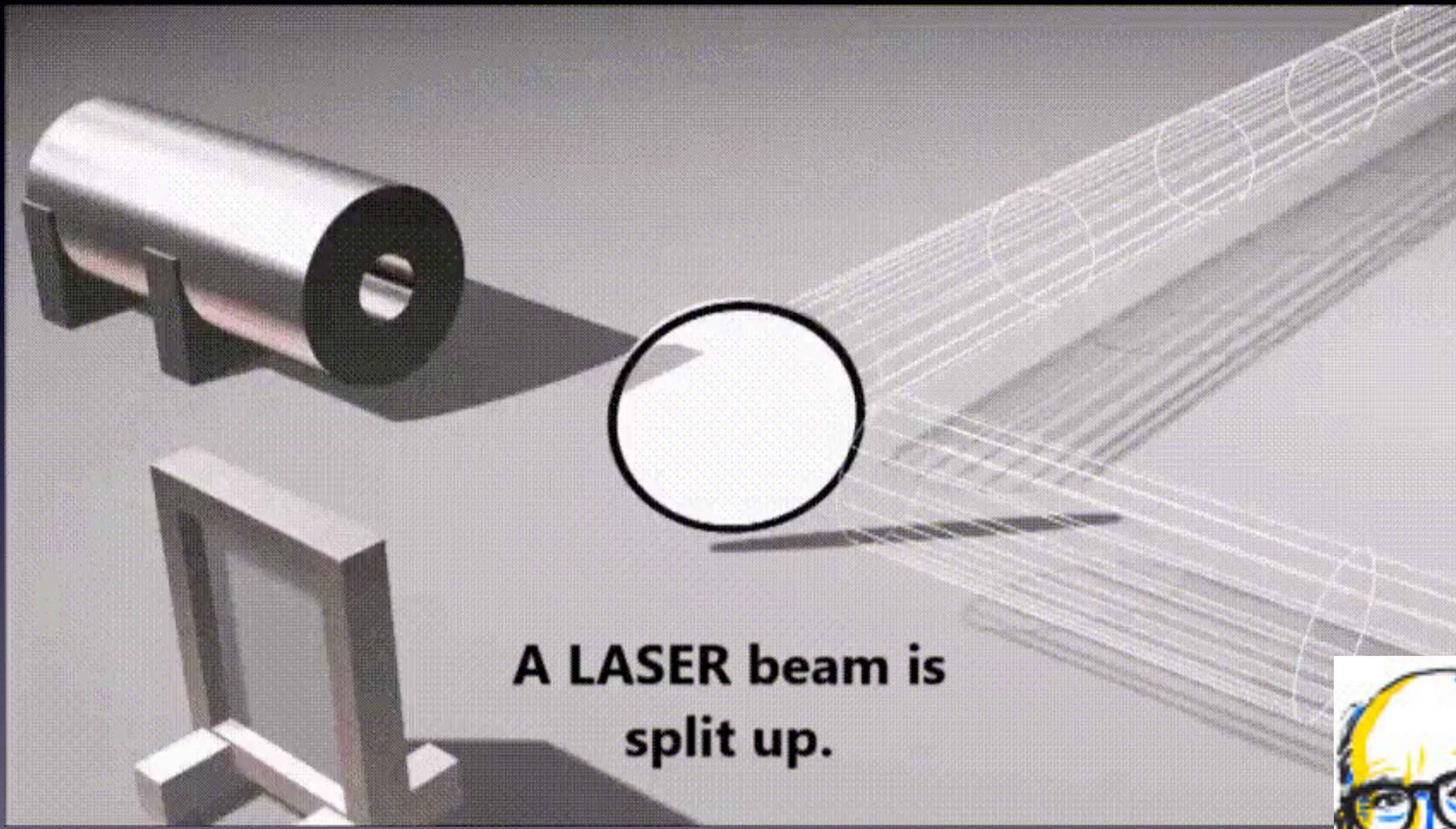
LIGO, Virgo, KAGRA



KAGRA（かぐら：大型低温重力波望遠鏡）



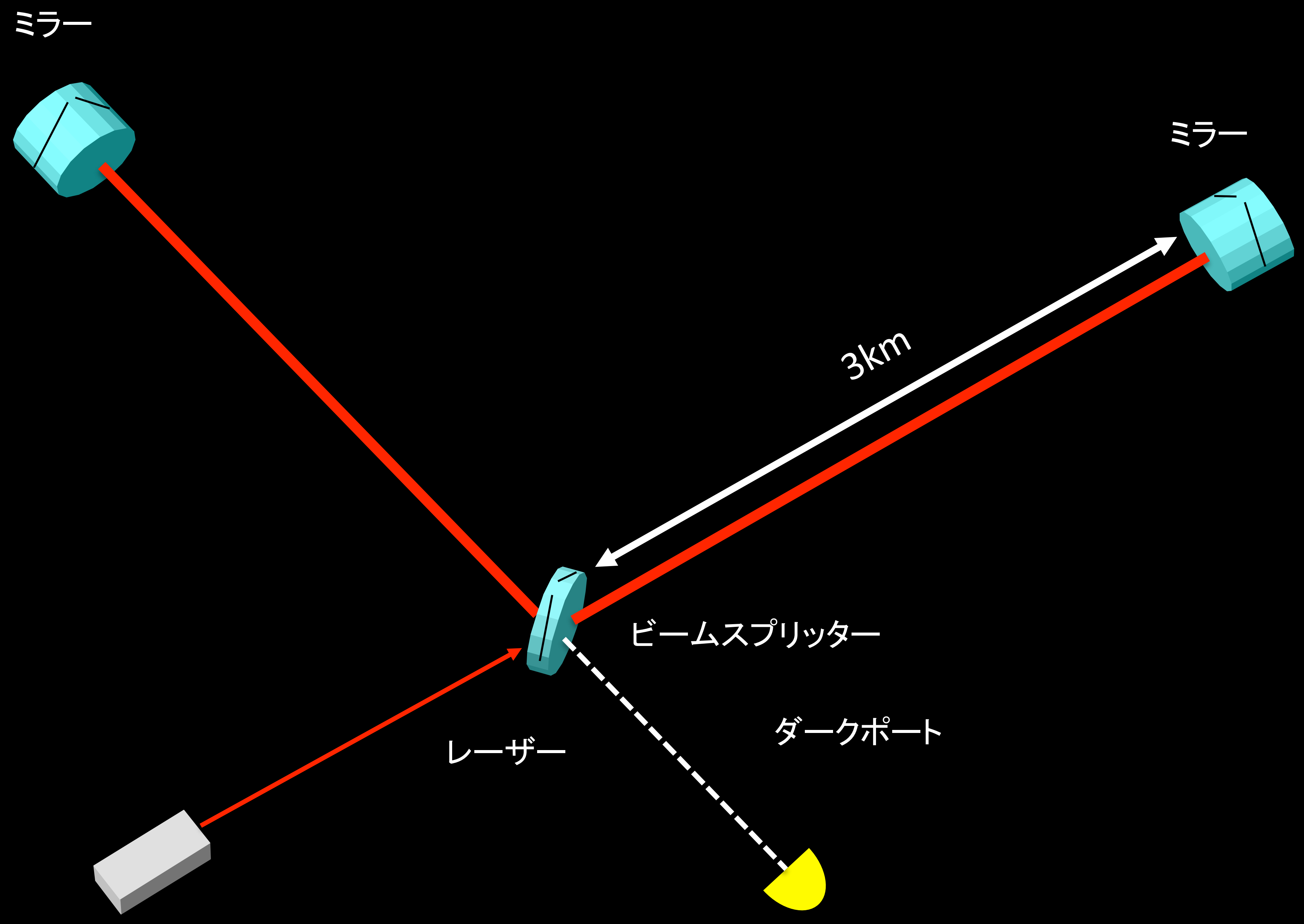
レーザー干渉計による重力波検出のしくみ



https://imgur.com/gallery/0VhrXPV

重力波レーザー干渉計に対する工夫　（1）

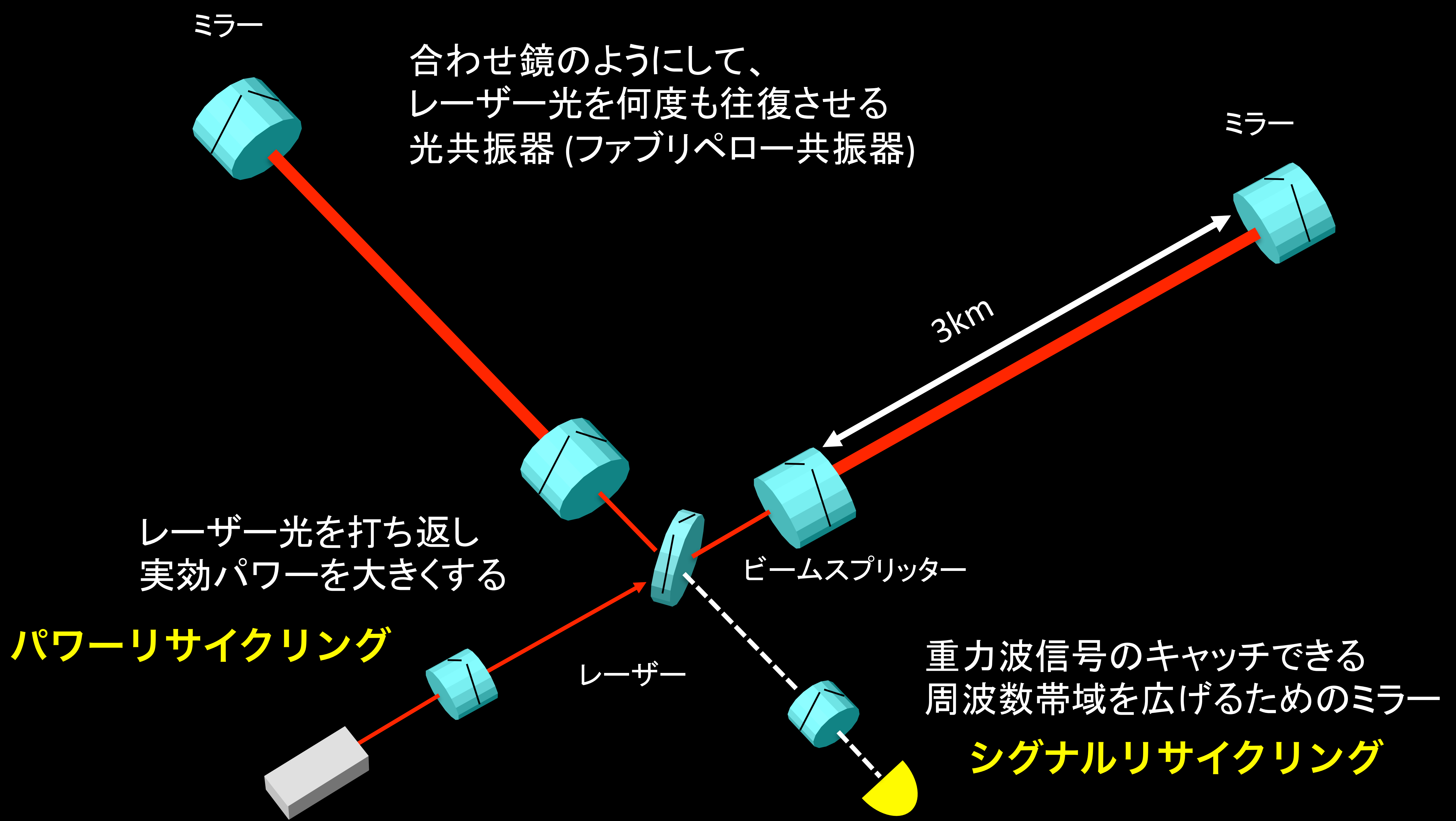
干渉計は，大きければ大きいほどよい．



苔山圭似子氏（東京大宇宙線研究所）のスライドから

重力波レーザー干渉計に対する工夫　（2）

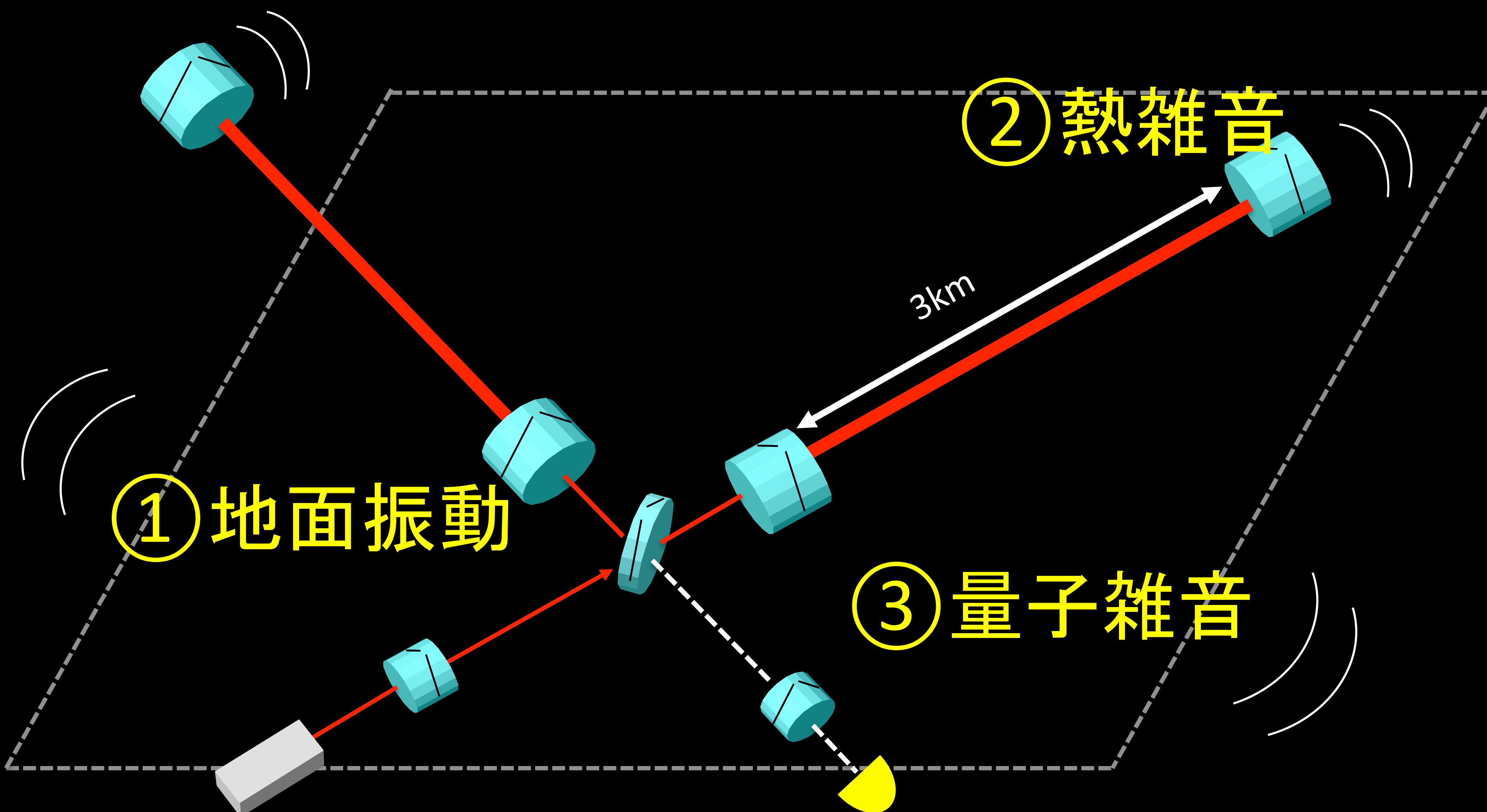
さらに，信号を増幅させる



苔山圭似子氏（東京大宇宙線研究所）のスライドから

重力波レーザー干渉計に対する工夫　(3)

さらに，さらに，雑音を減らす

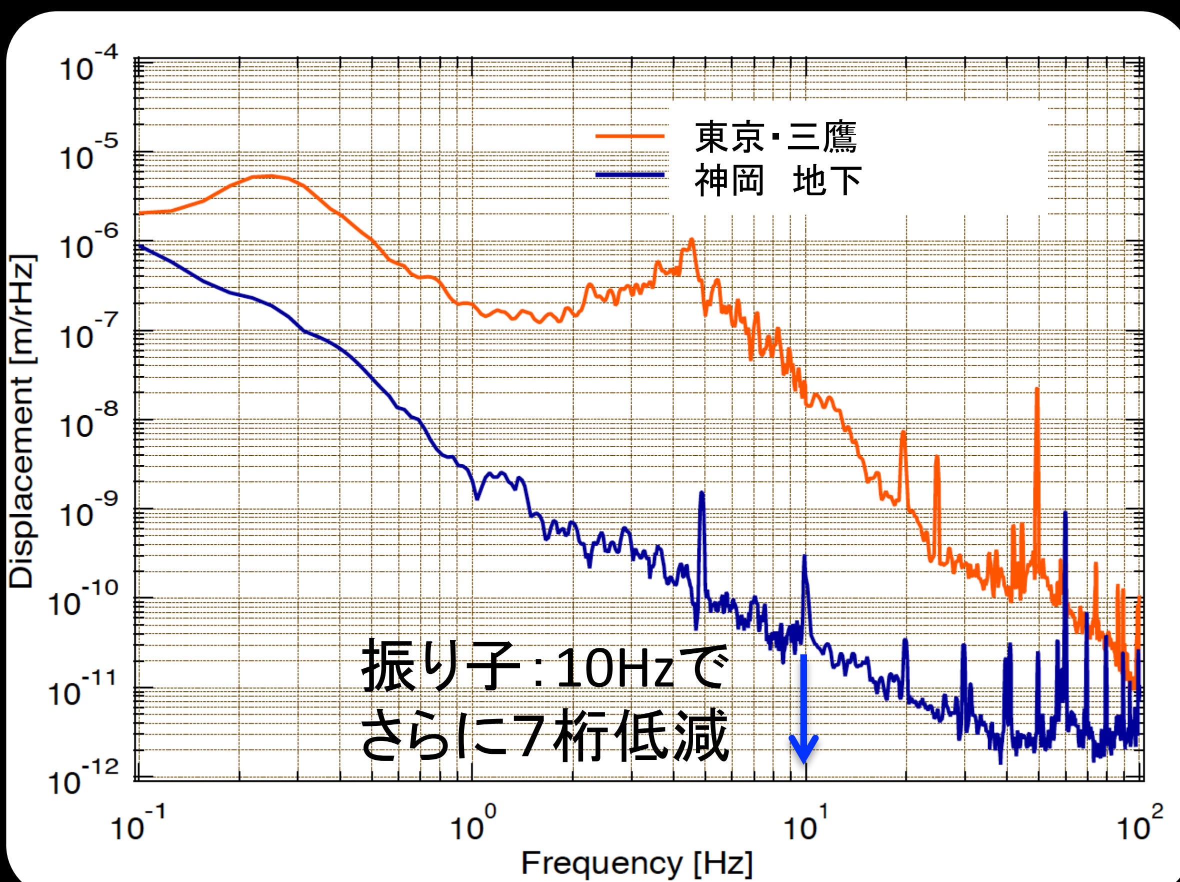


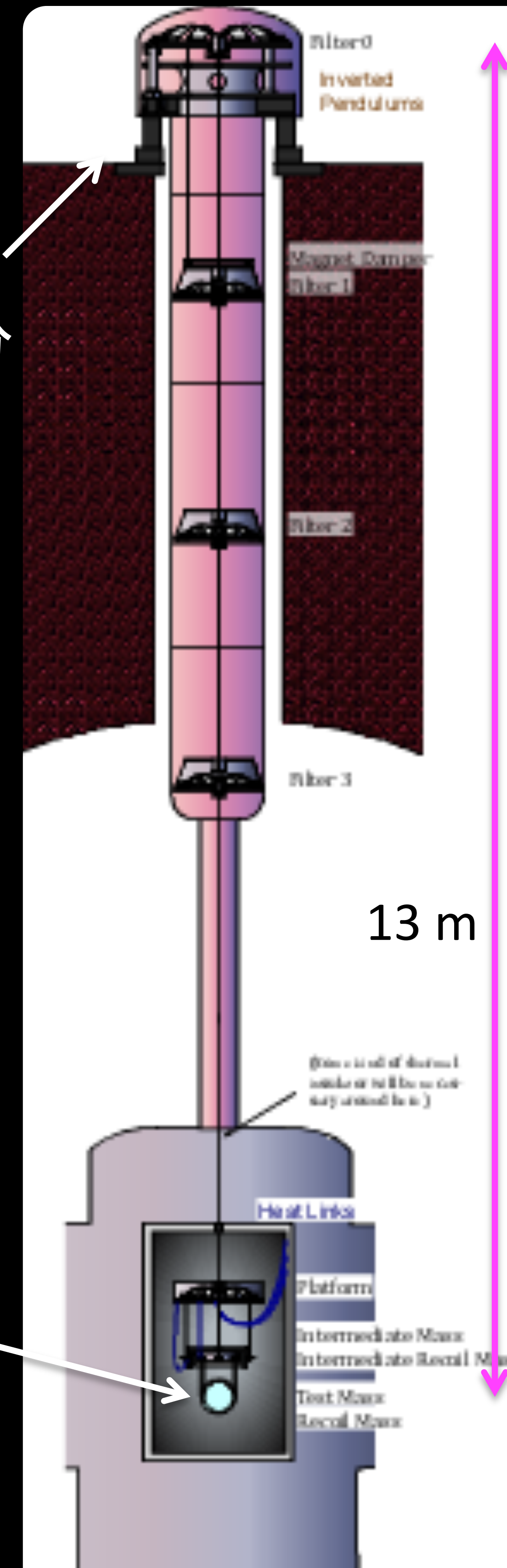
苔山圭似子氏（東京大宇宙線研究所）のスライドから

KAGRAでの雑音対策

①地面振動

- 地下に検出器を設置する
- ミラーを大きな振り子に吊るす





苔山圭似子氏（東京大宇宙線研究所）のスライドから

KAGRAでの雑音対策

②熱雑音

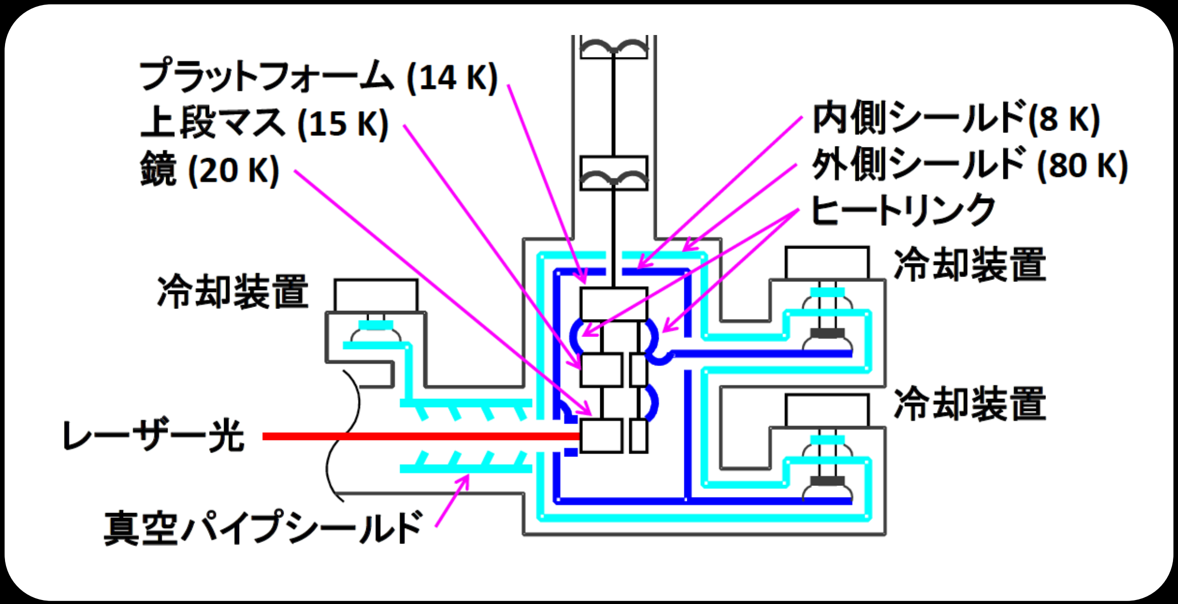
鏡の表面の分子や振り子が熱運動して揺れ、
空間の揺らぎと区別がつかずに雑音となる

$$熱雑音 \propto \sqrt{\frac{T}{Q}}$$

- ミラーをマイナス253℃に冷やす
- サファイアミラーを使う

サファイアミラー

冷却システム

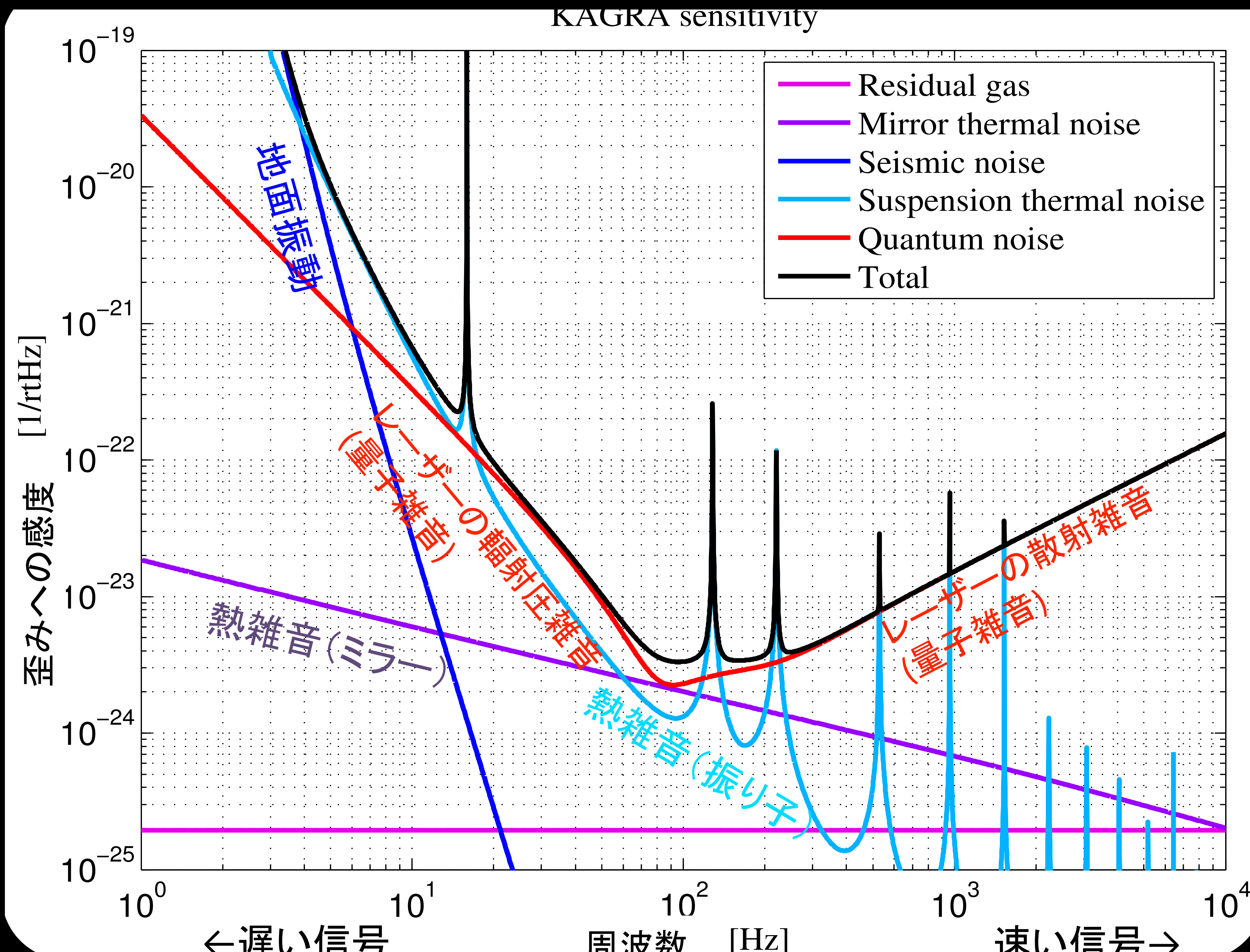


③量子雑音

光子が量子的なふるまいをするせいで起きる雑音

- 180Wのハイパワーレーザーを使う

苔山圭似子氏（東京大宇宙線研究所）のスライドから



苔山圭似子氏（東京大宇宙線研究所）のスライドから

Science 256 (1992) 325

LIGO: The Laser Interferometer Gravitational-Wave Observatory

Alex Abramovici, William E. Althouse, Ronald W. P. Drever, Yekta Gürsel, Seiji Kawamura, Frederick J. Raab, David Shoemaker, Lisa Sievers, Robert E. Spero, Kip S. Thorne, Rochus E. Vogt, Rainer Weiss, Stanley E. Whitcomb, Michael E. Zucker

The goal of the Laser Interferometer Gravitational-Wave Observatory (LIGO) Project is to detect and study astrophysical gravitational waves and use data from them for research in physics and astronomy. LIGO will support studies concerning the nature and nonlinear dynamics of gravity, the structures of black holes, and the equation of state of nuclear matter. It will also measure the masses, birth rates, collisions, and distributions of black holes and neutron stars in the universe and probe the cores of supernovae and the very early universe. The technology for LIGO has been developed during the past 20 years. Construction will begin in 1992, and under the present schedule, LIGO's gravitational-wave searches will begin in 1998.

Einstein's general relativity theory describes gravity as due to a curvature of space-time (*1*). When the curvature is weak, it produces the familiar Newtonian gravity that governs the solar system. When the curvature is strong, however, it should behave in a radically different, highly nonlinear way. According to general relativity, the nonlinearity creates black holes (curvature produces curvature without the aid of any matter), governs their structure, and holds them together against disruption (*2*). Inside a black hole, the curvature should nonlinearly amplify itself to produce a space-time singularity (*2*), and near some singularities the nonlinearity should force the curvature to evolve chaotically (*3*). When an object's curvature varies rapidly (for example, because of pulsations, colli-

The authors are the members of the LIGO Science Steering Group. A. Abramovici, W. E. Althouse (Chief Engineer), R. W. P. Drever, S. Kawamura, F. J. Raab, L. Sievers, R. E. Spero, K. S. Thorne, R. E. Vogt (Director), S. E. Whitcomb (Deputy Director), and M. E. Zucker are with the California Institute of Technology, Pasadena, CA 91125. Y. Gürsel is at the Jet Propulsion Laboratory, Pasadena, CA 91109. D. Shoemaker and R. Weiss are at the Massachusetts Institute of Technology, Cambridge, MA 02129.

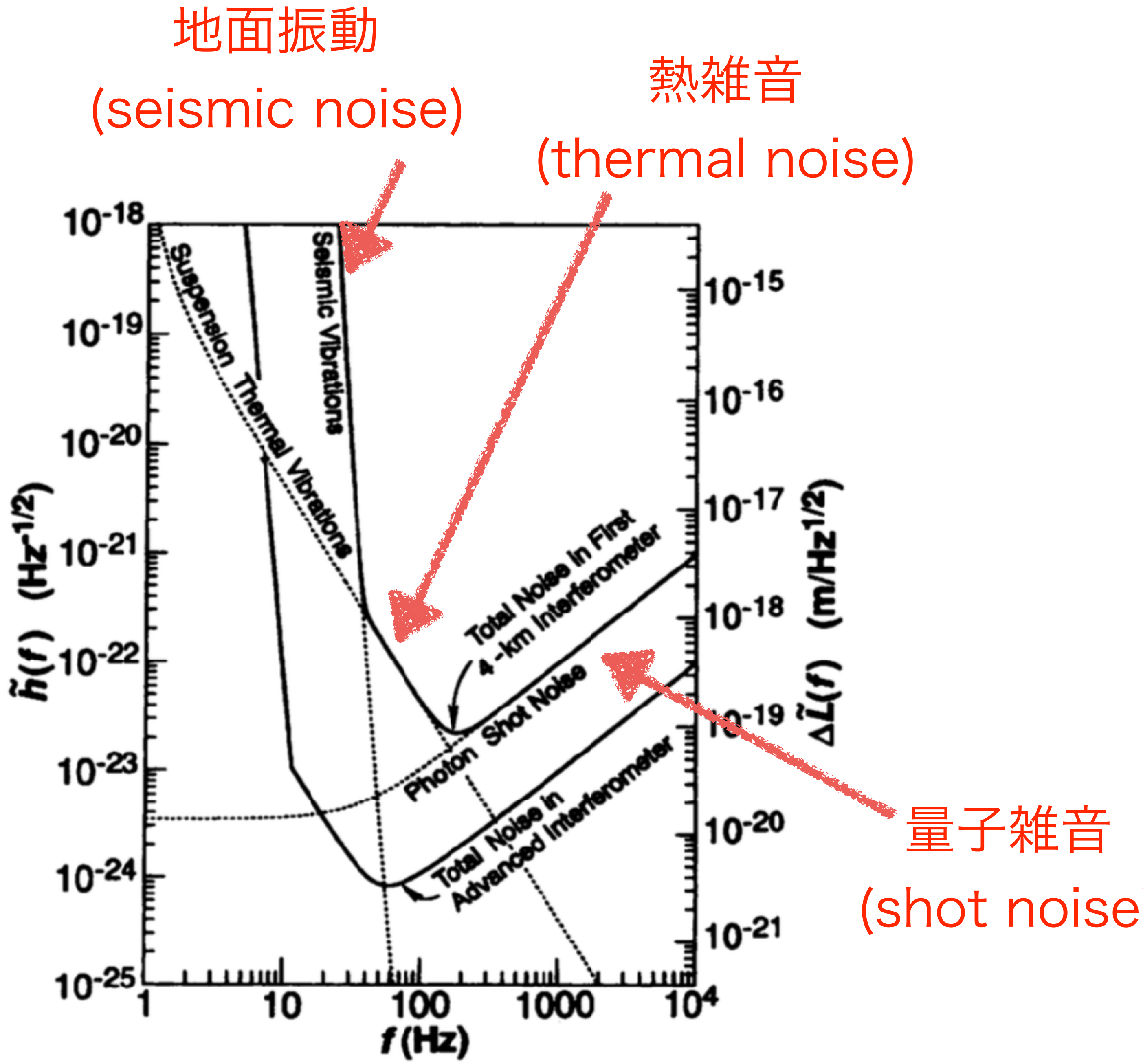
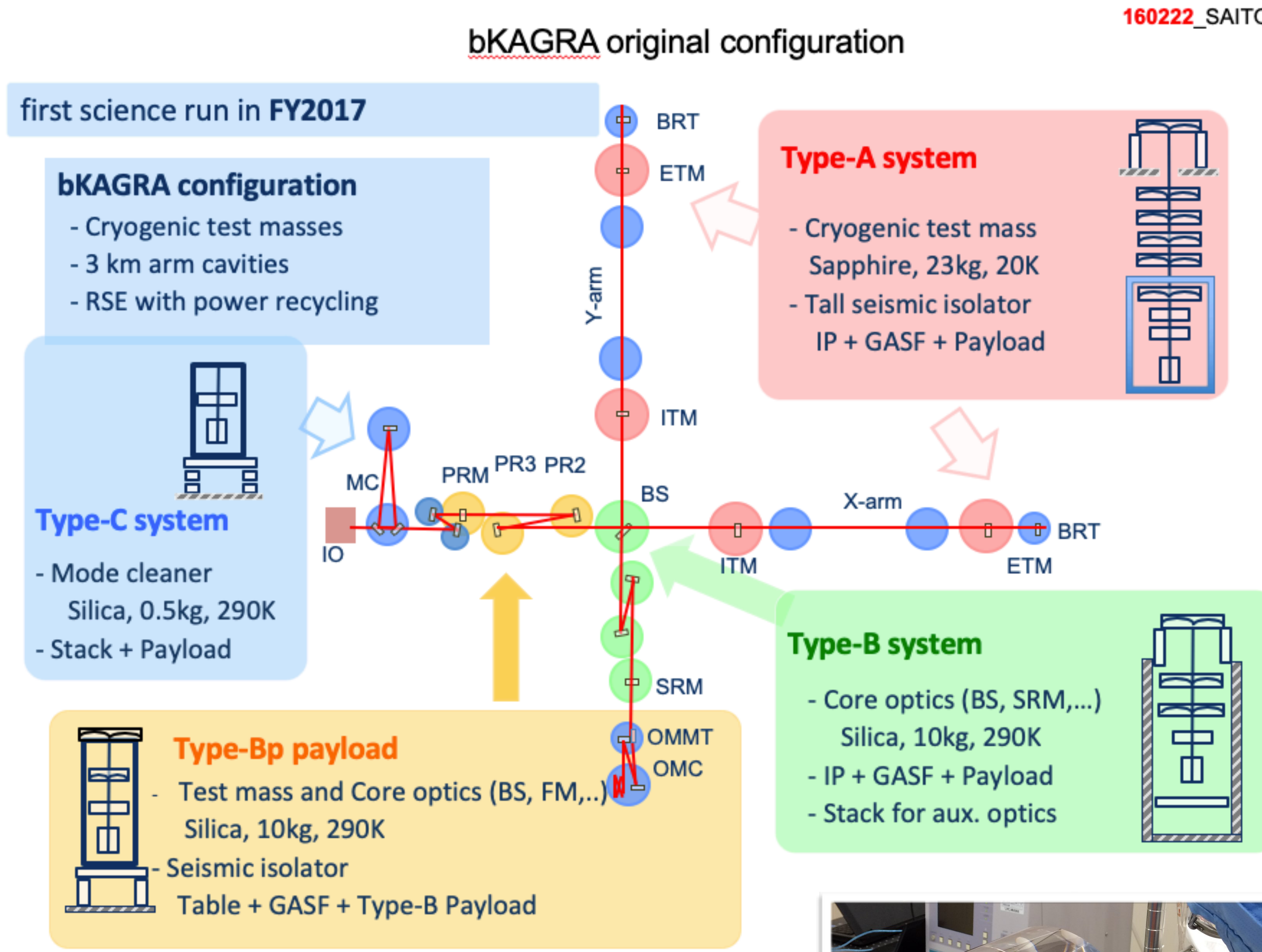
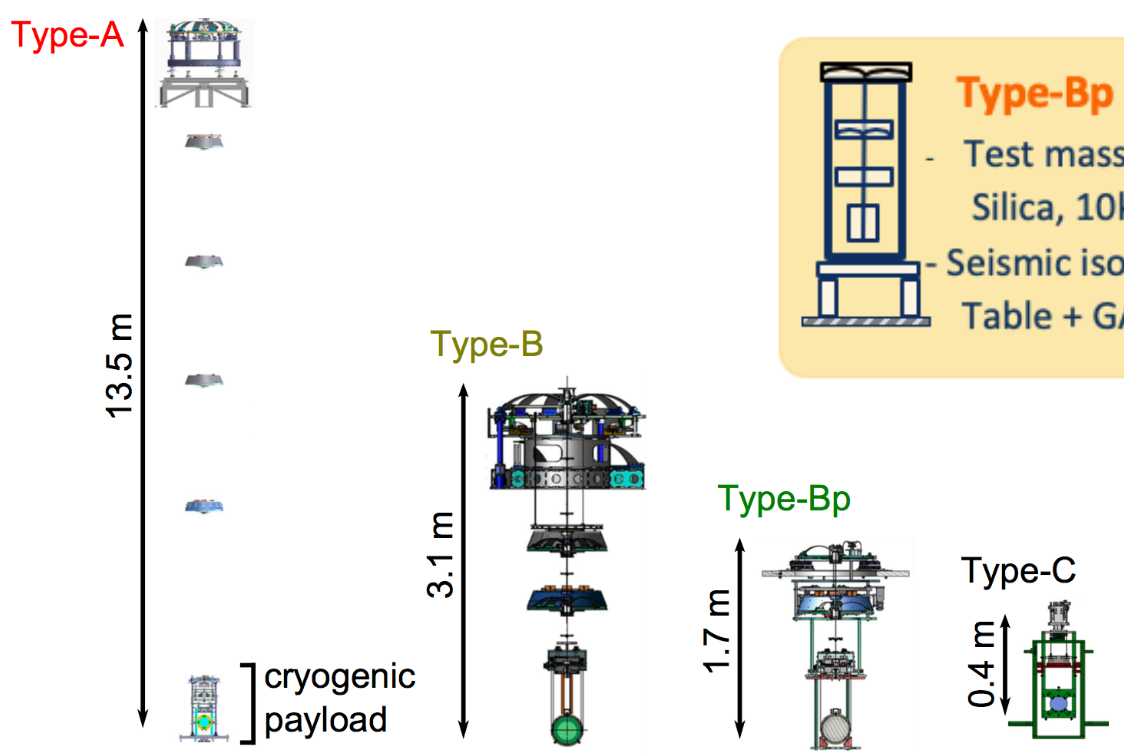
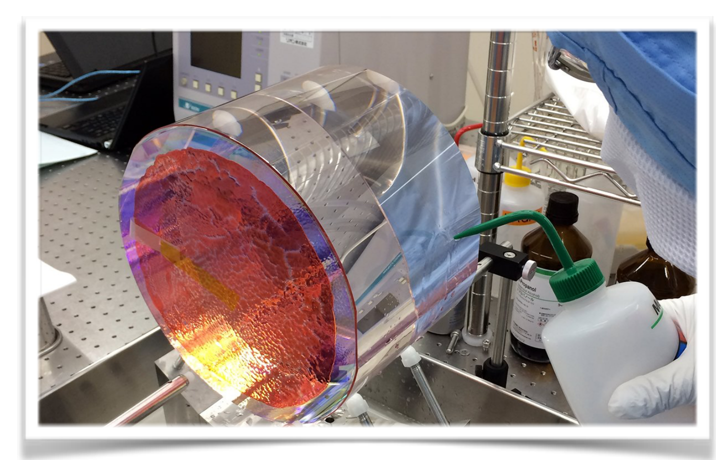


Fig. 7. The expected total noise in each of LIGO's first 4-km interferometers (upper solid curve) and in a more advanced interferometer (lower solid curve). The dashed curves show various contributions to the first interferometer's noise.

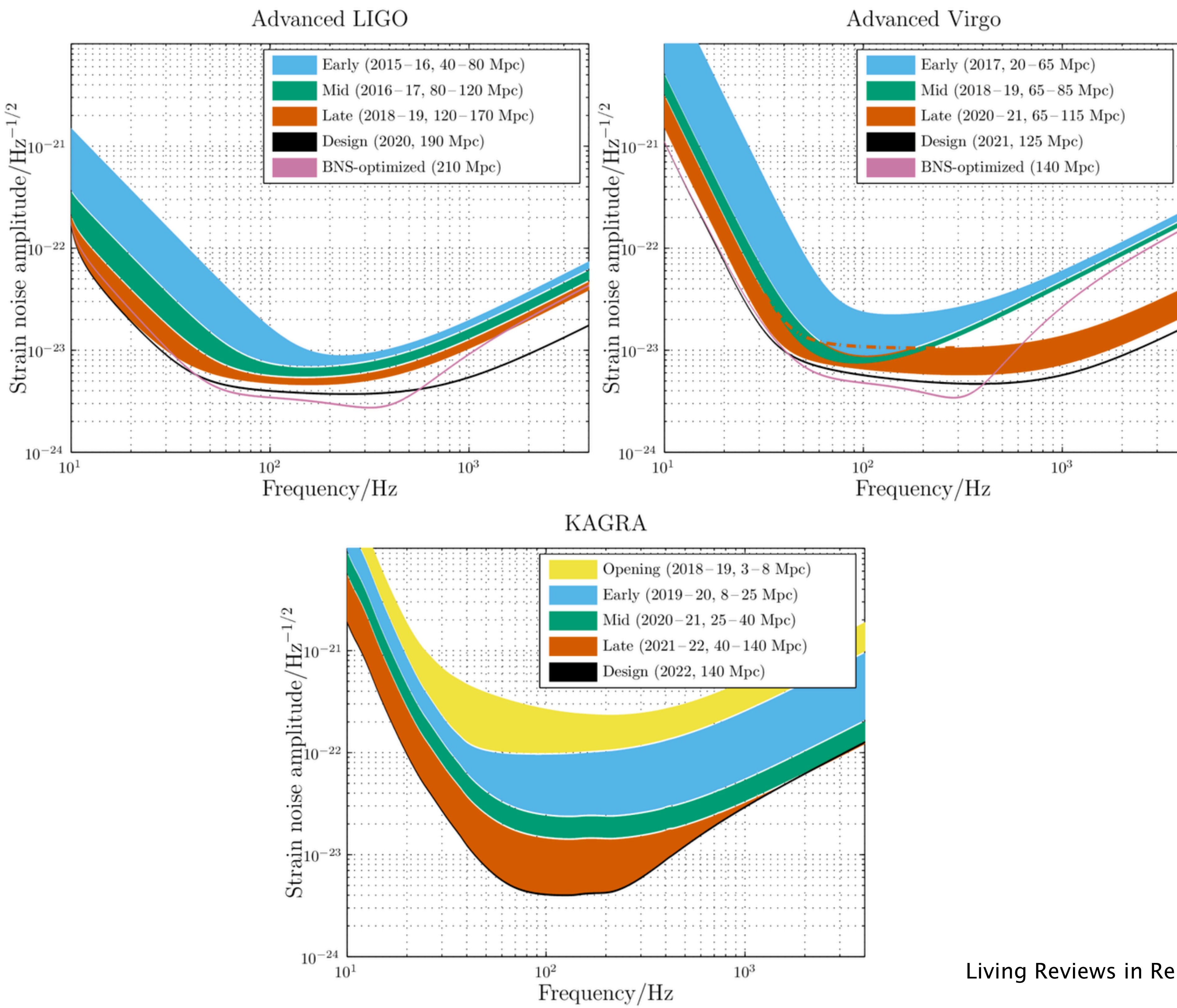
baseline KAGRA 構成図







aLIGO, aVirgo & KAGRA : Target Sensitivity



Living Reviews in Relativity; 21:3; 2018

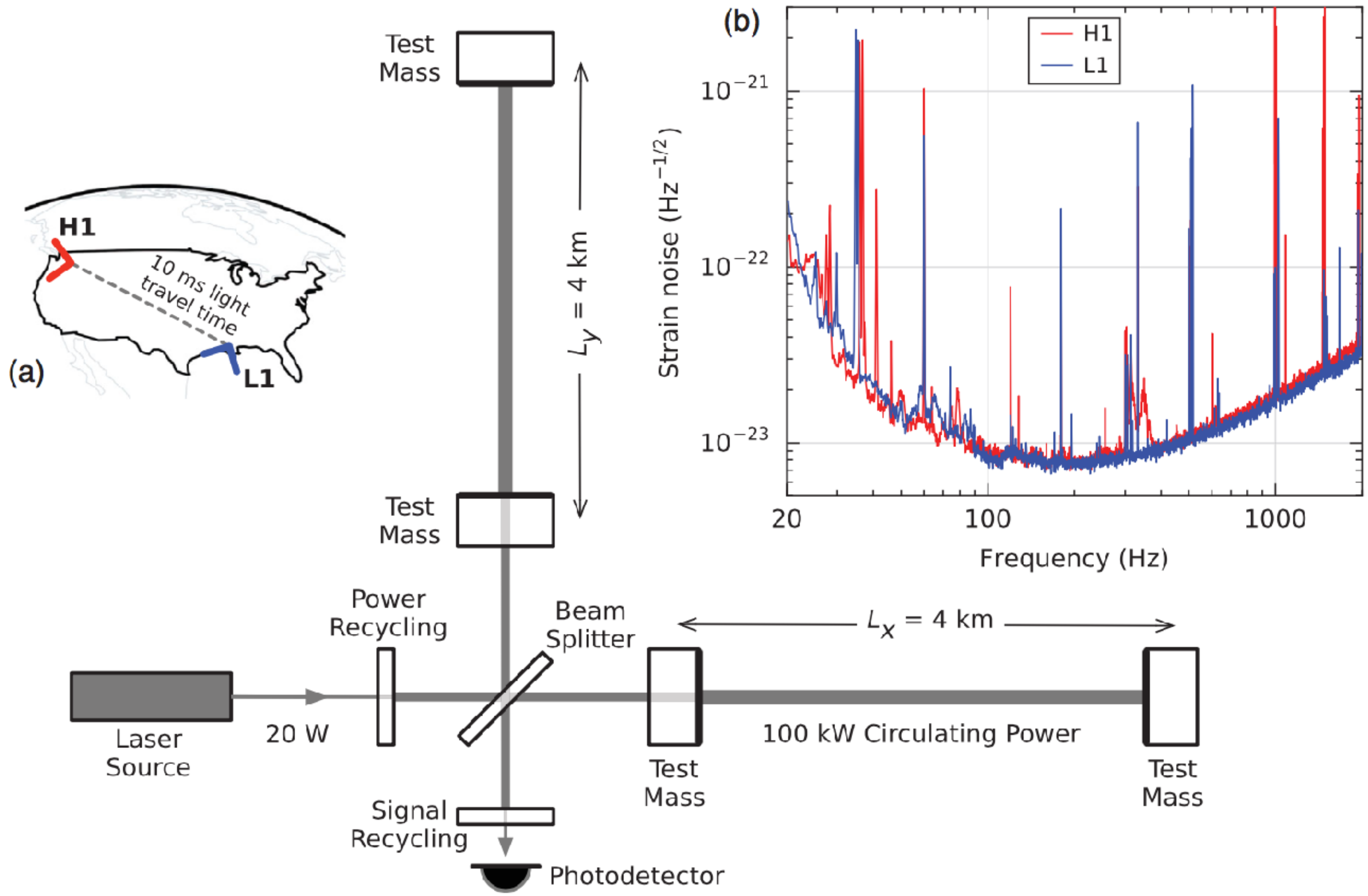


FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the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

重力波初検出を発表するDavid Reitze LIGO所長

2016年2月11日

“We had detected gravitational waves.　We did it. ”

“我々は，重力波を検出した．　やり遂げたのだ. ”

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

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

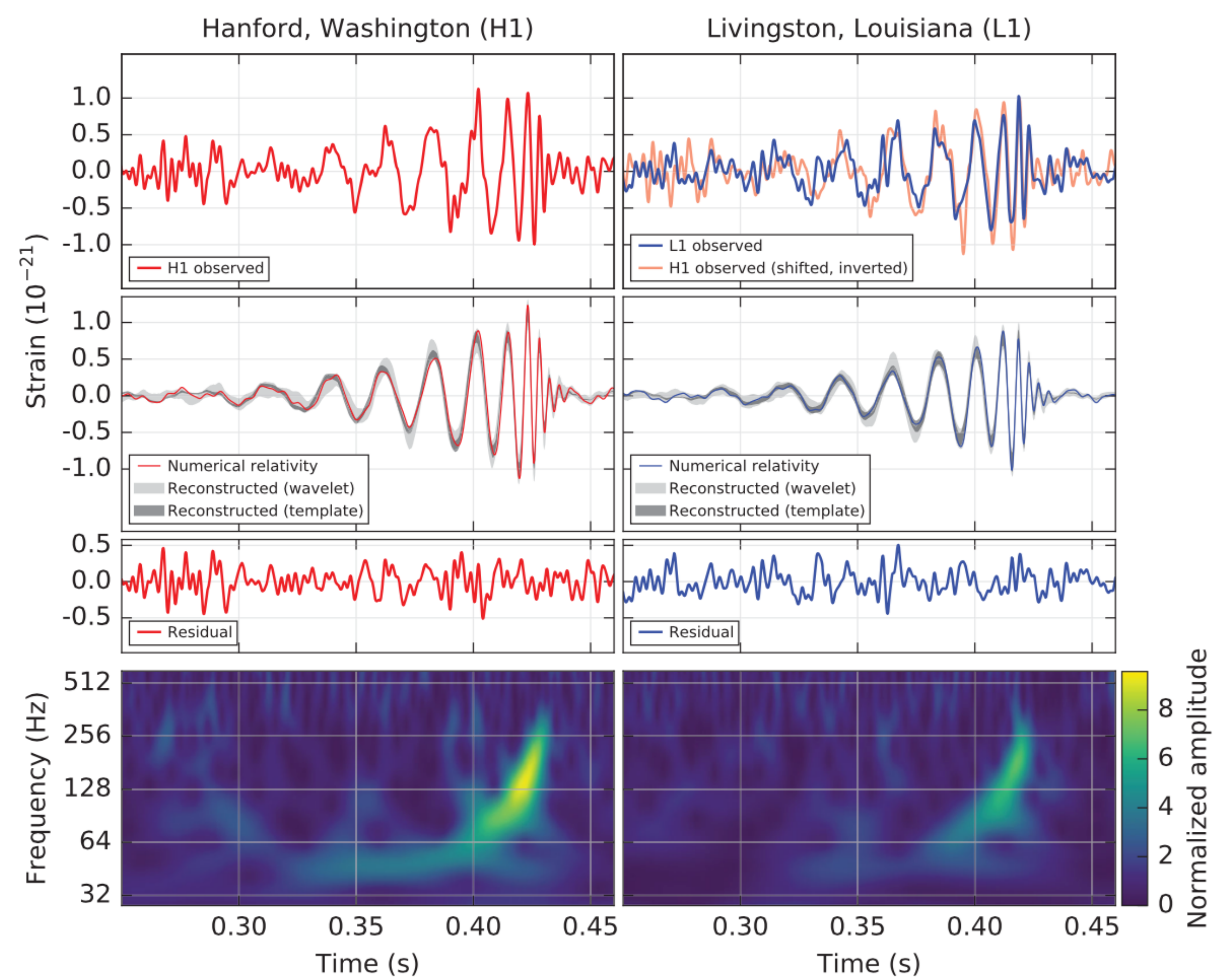


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered


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

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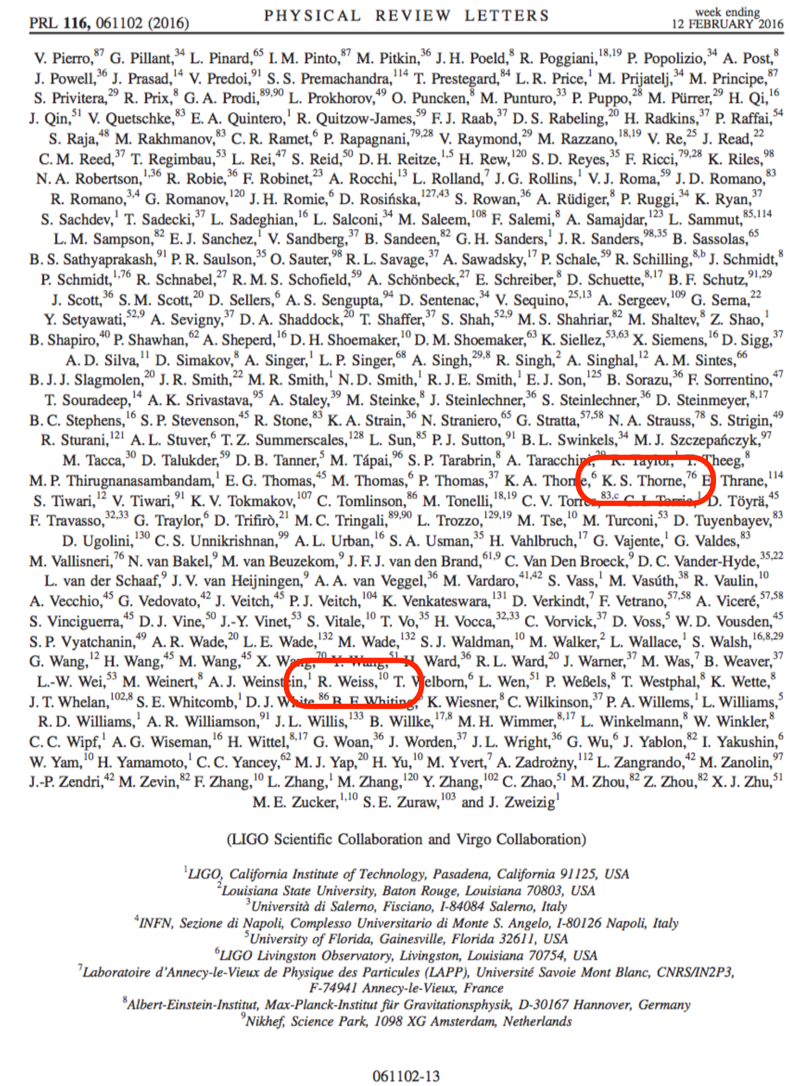
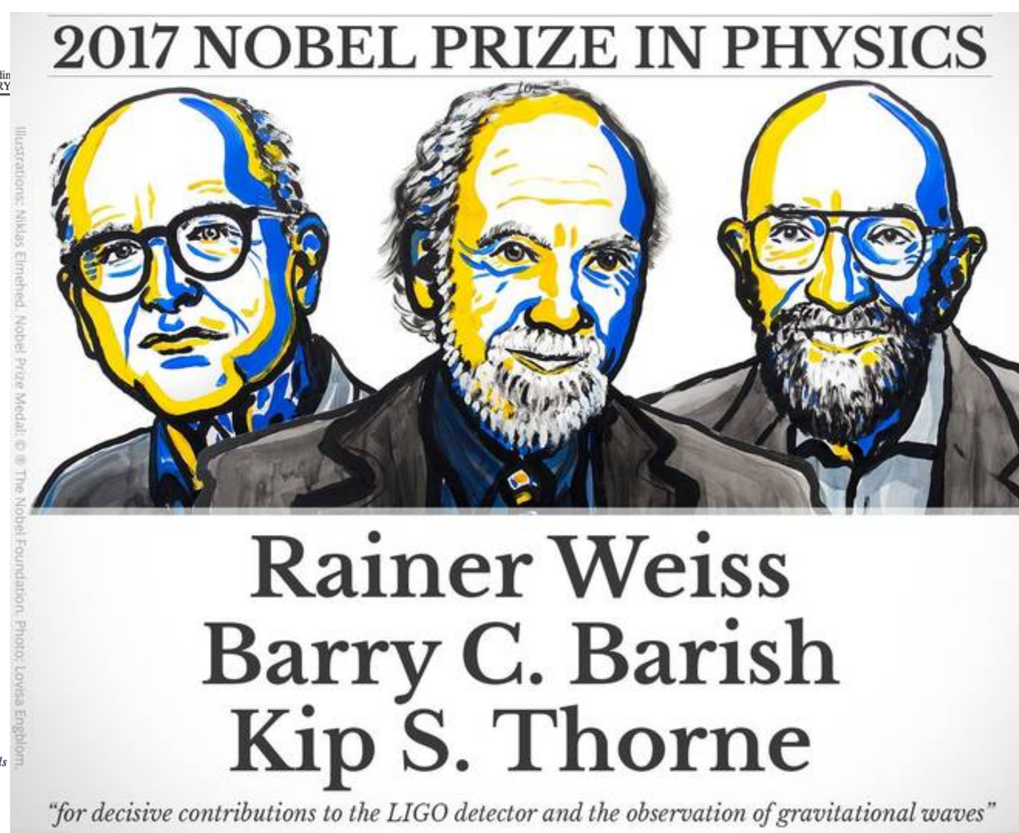

PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

(LIGO Scientific Collaboration and Virgo Collaboration)

061102-13


PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS

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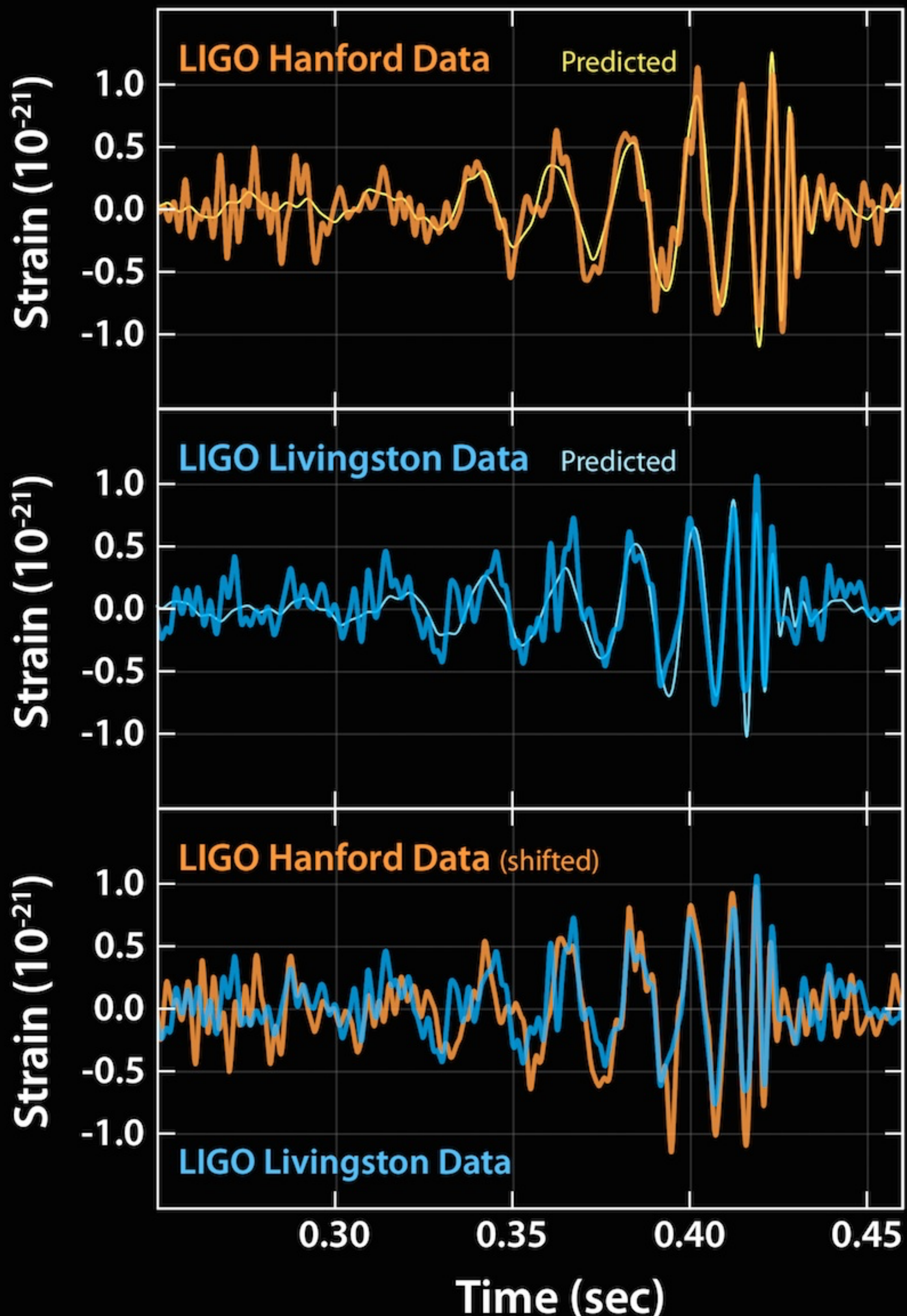
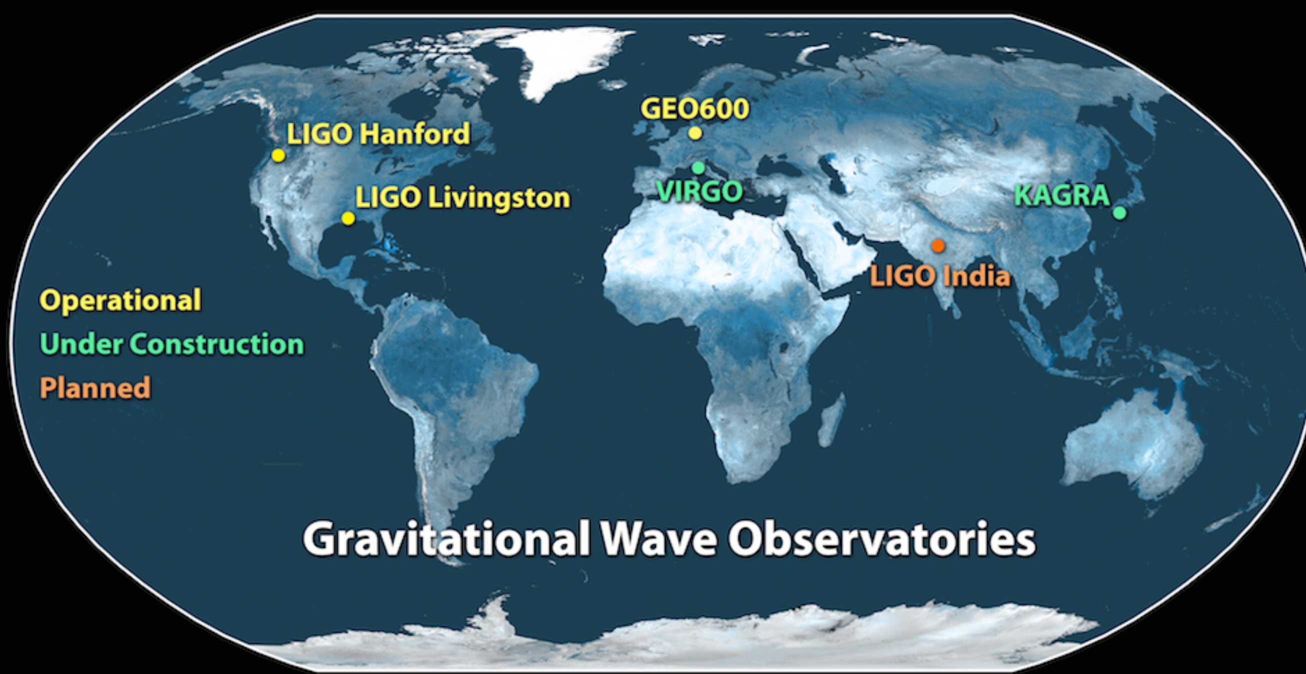
著者1010人

PRL 16ページ

GW150914





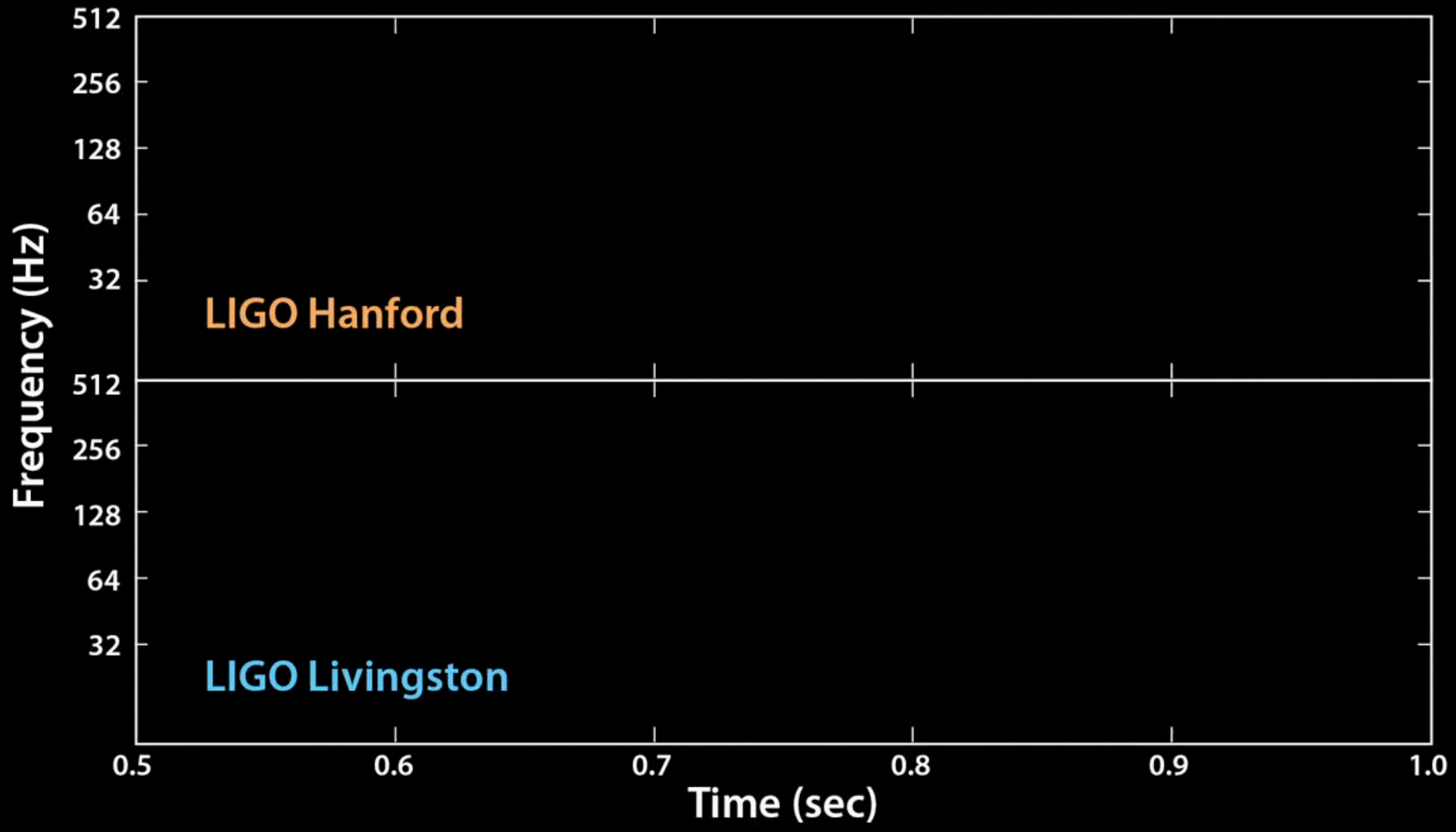
Blackhole merger of
36 Msun + 29 Msun
—> 62 Msun.

Lost 3 Msun

$$E = mc^2$$

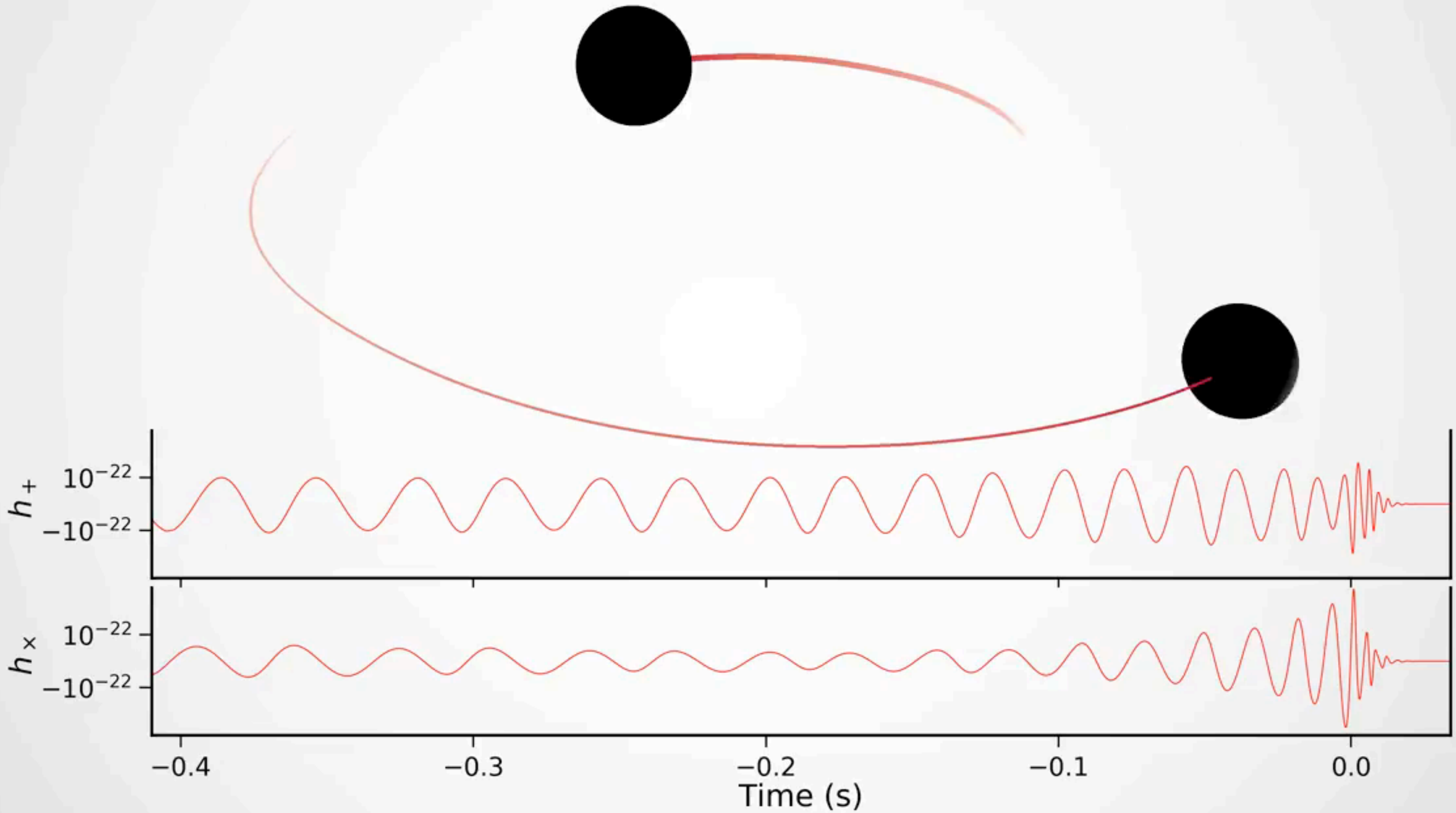
13億光年先（440 Mpc）

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



Animation of the inspiral and collision of two black holes consistent with the masses and spins of GW170104. The top part of the movie shows the black hole horizons (surfaces of "no return"). The initial two black holes orbit each other, until they merge and form one larger remnant black hole. The shown black holes are spinning, and angular momentum is exchanged among the two black holes and with the orbit. This results in a quite dramatic change in the orientation of the orbital plane, clearly visible in the movie. Furthermore, the spin-axes of the black holes change, as visible through the colored patch on each black hole horizon, which indicates the north pole.

The lower part of the movie shows the two distinct gravitational waves (called 'polarizations') that the merger is emitting into the direction of the camera. The modulations of the polarizations depend sensitively on the orientation of the orbital plane, and thus encode information about the orientation of the orbital plane and its change during the inspiral. Presently, LIGO can only measure one of the polarizations and therefore obtains only limited information about the orientation of the binary. This disadvantage will be remedied with the advent of additional gravitational wave detectors in Italy, Japan and India.

Finally, the slowed-down replay of the merger at the end of the movie makes it possible to observe the distortion of the newly formed remnant black hole, which decays quickly. Furthermore, the remnant black hole is "kicked" by the emitted gravitational waves, and moves upward. (Credit: A. Babul/H. Pfeiffer/CITA/SXS.) - See more at: http://ligo.org/detections/GW170104.php#sthash.NZPaW2LT.dpuf

http://ligo.org/detections/GW170104.php

arXiv:1606.01262

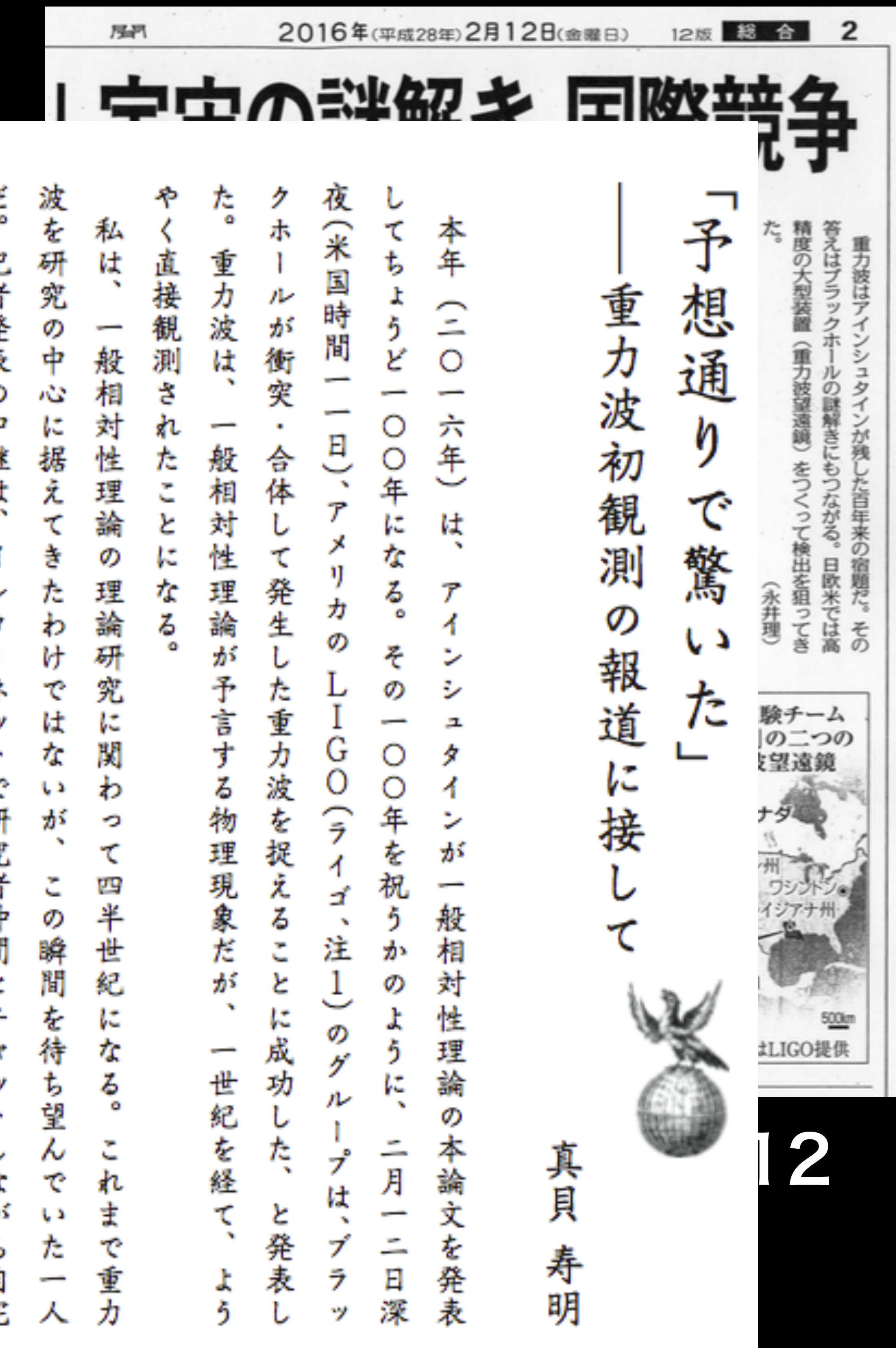
APPENDIX B: SIMULATION RANKINGS

In this appendix, we enumerate the simulations used in this work, ordered by one measure of their similarity with the data ($\ln L$, in Table III). For nonprecessing binaries, Fig. 6 provides a visual illustration of some trends in $\ln L$ versus mass ratio and the two component spins.

TABLE III. *Peak Marginalized* $\ln L$ *I: Consistency between simulations*: Peak value of the marginalized log likelihood $\ln L$ [Eq. (7)] evaluated using a lower frequency $f_{low} = 30$ Hz and all modes with $l \leq 2$; the simulation key, described in Table II [an asterisk (∗) denotes a new simulation motivated by GW150914, and a (+) denotes one of the simulations reported in LVC-detect [1]]; the *initial* spins of the simulation (using – to denote zero, to enhance readability); the initial χ_{eff}; the total (redshifted) mass of the best fit; and the starting frequency (in Hz) of the best fit. Though omitting information accessible to the longest simulations, this choice of low-frequency cutoff eliminates systematic biases associated with simulation duration, which differs across our archive, as seen by the last column.

$\ln L$	Key	q	$\chi_{1,x}$	$\chi_{1,y}$	$\chi_{1,z}$	$\chi_{2,x}$	$\chi_{2,y}$	$\chi_{2,z}$	χ_{eff}	$M_z/M_\odot$	f_{start}(Hz)
272.2	SXS:BBH:0310(∗)	1.221	⋯	⋯	⋯	⋯	⋯	⋯	0.00	73.0	15.1
272.1	D12_q1.00_a-0.25_0.25_n100(∗)	1.0	⋯	⋯	0.250	⋯	⋯	−0.250	−0.00	73.2	20.5
272.1	SXS:BBH:0002[S]	1.0	⋯	⋯	⋯	⋯	⋯	⋯	0.00	73.2	10.0
271.8	D11_q0.75_a0.0_0.0_n100(∗)	1.333	⋯	⋯	⋯	⋯	⋯	⋯	−0.00	72.1	23.1
271.8	SXS:BBH:0305(∗+)	1.221	⋯	⋯	0.330	⋯	⋯	−0.440	−0.02	74.2	14.8
271.6	SXS:BBH:0218	1.0	⋯	⋯	−0.500	⋯	⋯	0.500	0.00	73.3	10.6
271.6	SXS:BBH:0198	1.202	⋯	⋯	⋯	⋯	⋯	⋯	0.00	73.4	12.7
271.6	SXS:BBH:0307(∗)	1.228	⋯	⋯	0.320	⋯	⋯	−0.580	−0.08	70.0	17.0
271.6	GT:BBH:476	1.0	⋯	⋯	−0.200	⋯	⋯	−0.200	−0.20	67.9	24.3
271.6	S0_D10.04_q1.3333_a0.45_-0.80_n100	1.334	⋯	⋯	0.450	⋯	⋯	−0.801	−0.09	71.9	27.9
271.5	D12.00_q0.85_a0.0_0.0_n100(∗)	1.176	⋯	⋯	⋯	⋯	⋯	⋯	−0.00	73.0	20.6
271.5	D12.25_q0.82_a-0.44_0.33_n100(∗+)	1.22	⋯	⋯	0.330	⋯	⋯	−0.440	−0.02	72.9	20.2
271.5	SXS:BBH:0312(∗)	1.203	⋯	⋯	0.390	⋯	⋯	−0.480	−0.00	73.9	14.8
271.4	SXS:BBH:0127	1.34	0.010	−0.077	−0.017	−0.061	−0.065	−0.179	−0.09	71.5	14.3
271.4	SXS:BBH:0115	1.07	0.019	0.013	−0.204	0.243	−0.067	0.291	0.04	74.1	13.8
271.3	SXS:BBH:0213	1.0	⋯	⋯	−0.800	⋯	⋯	0.800	0.00	73.2	11.7
271.3	UD_D10.01_q1.00_a0.4_n100	1.0	⋯	⋯	0.400	⋯	⋯	−0.400	−0.00	73.4	26.7
271.2	D12_q1.00_a-0.25_0.00_n100(∗)	1.0	⋯	⋯	⋯	⋯	⋯	−0.250	−0.12	69.4	21.8
271.2	SXS:BBH:0222	1.0	⋯	⋯	−0.300	⋯	⋯	⋯	−0.15	69.1	12.3
271.2	SXS:BBH:0217	1.0	⋯	⋯	−0.600	⋯	⋯	0.600	0.00	73.2	11.9

2016年2月，LIGOが重力波を初めて検出した，と発表した



2016年(平成28年)2月12日(金曜日) 12版 総合 2

宇宙の謎解き 国際競争

「予想通りで驚いた」
——重力波初観測の報道に接して

真貝 寿明

本年（二〇一六年）は、アインシュタインが一般相対性理論の本論文を発表してちょうど一〇〇年になる。その一〇〇年を祝うかのように、二月一二日深夜(米国時間一一日)、アメリカのＬＩＧＯ(ライゴ、注1)のグループは、ブラックホールが衝突・合体して発生した重力波を捉えることに成功した、と発表した。重力波は、一般相対性理論が予言する物理現象だが、一世紀を経て、ようやく直接観測されたことになる。

私は、一般相対性理論の理論研究に関わって四半世紀になる。これまで重力波を研究の中心に据えてきたわけではないが、この瞬間を待ち望んでいた一人

「窮理」　2016/8

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、岐阜県飛驒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

GW150914

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	$< 1.2 \times 10^{-22}$ 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=9.46×10^{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！

We detected GW !

We could detect GW !

BH exists !

BH binary exists !

GR is right as the 0th order !

Signal-to-Noise Ratio (SNR)

Let the true signal $h(t)$, the function of time, is detected as a signal, $s(t)$, which also includes the unknown noise, $n(t)$:

$$s(t) = h(t) + n(t).$$

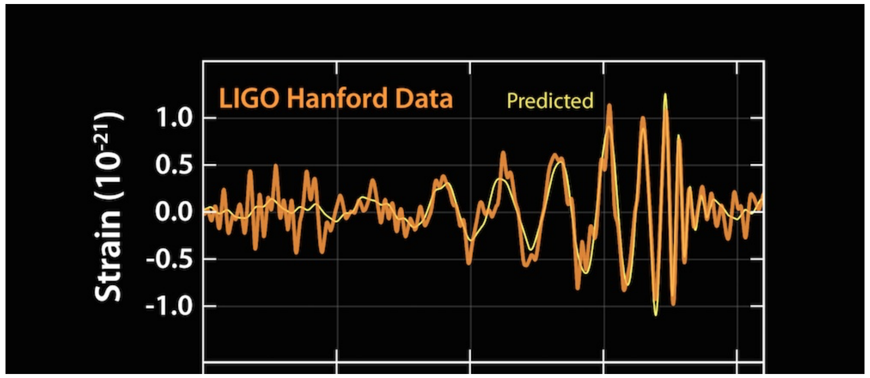
The standard procedure for the detection is judged by the optimal signal-to-noise ratio (SNR), ρ, which is given by

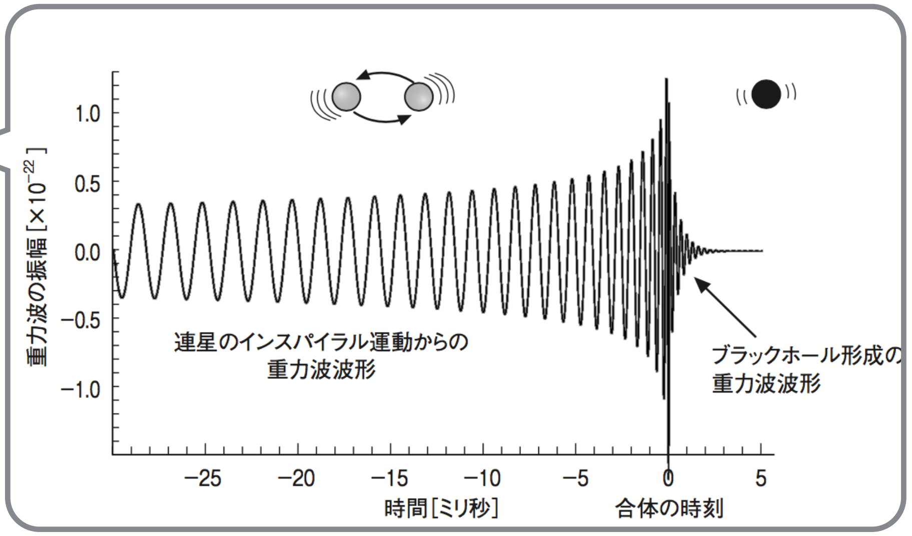
$$\rho = 2\left[\int_0^\infty \frac{\tilde{h}(f)\,\tilde{h}^*(f)}{S_n(f)}\,df\right]^{1/2},$$

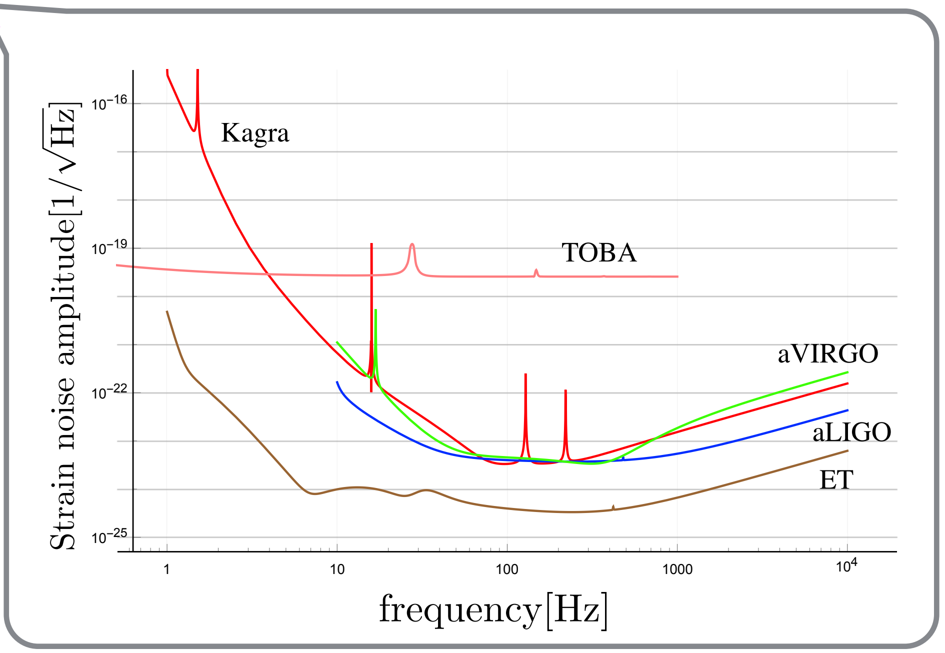
where $\tilde{h}(f)$ is the Fourier-transformed quantity of the wave,

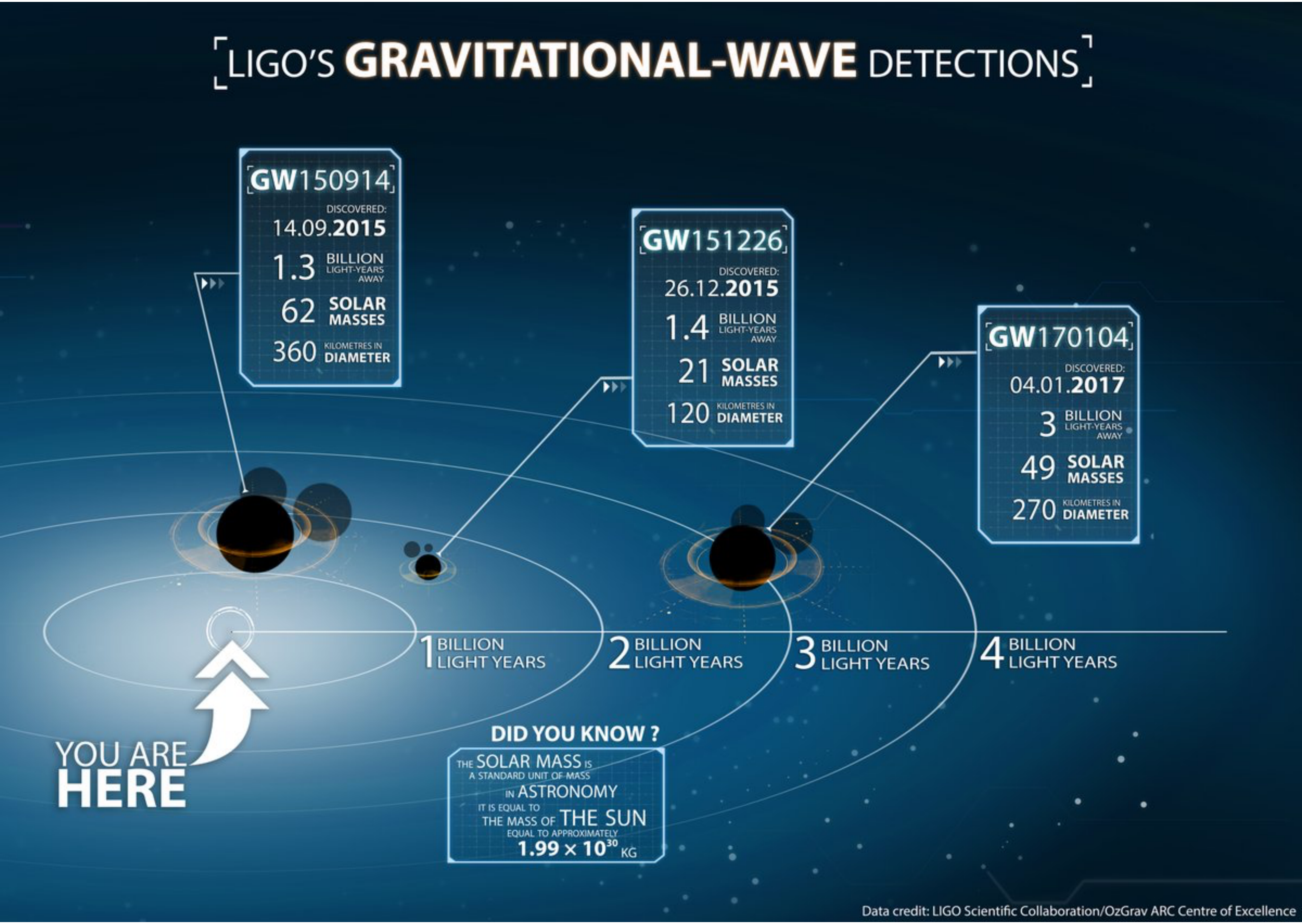
$$\tilde{h}(f) = \int_{-\infty}^{\infty} e^{2\pi i f t}\,h(t)\,dt,$$

and $S_n(f)$ the (one-sided) power spectral density of strain noise of the detector, as we showed in Fig. 1.



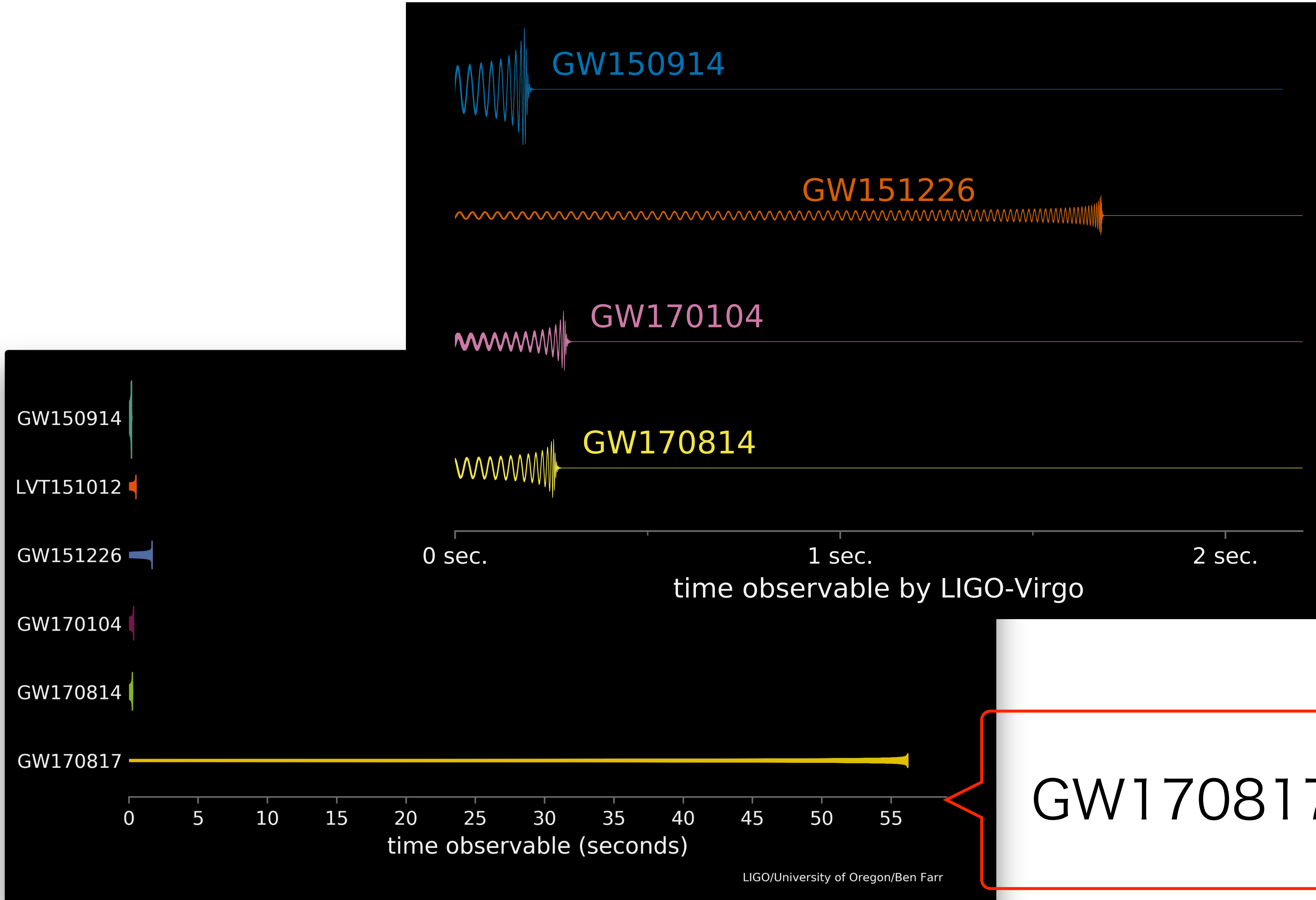





LIGO'S GRAVITATIONAL-WAVE DETECTIONS
GW150914
DISCOVERED: 14.09.2015
1.3 BILLION LIGHT-YEARS AWAY
62 SOLAR MASSES
360 KILOMETRES IN DIAMETER
GW151226
DISCOVERED: 26.12.2015
1.4 BILLION LIGHT-YEARS AWAY
21 SOLAR MASSES
120 KILOMETRES IN DIAMETER
GW170104
DISCOVERED: 04.01.2017
3 BILLION LIGHT-YEARS AWAY
49 SOLAR MASSES
270 KILOMETRES IN DIAMETER
1 BILLION LIGHT YEARS
2 BILLION LIGHT YEARS
3 BILLION LIGHT YEARS
4 BILLION LIGHT YEARS
YOU ARE HERE
DID YOU KNOW ?
THE SOLAR MASS IS A STANDARD UNIT OF MASS IN ASTRONOMY
IT IS EQUAL TO THE MASS OF THE SUN
EQUAL TO APPROXIMATELY 1.99 × 10^30 KG
Data credit: LIGO Scientific Collaboration/OzGrav ARC Centre of Excellence

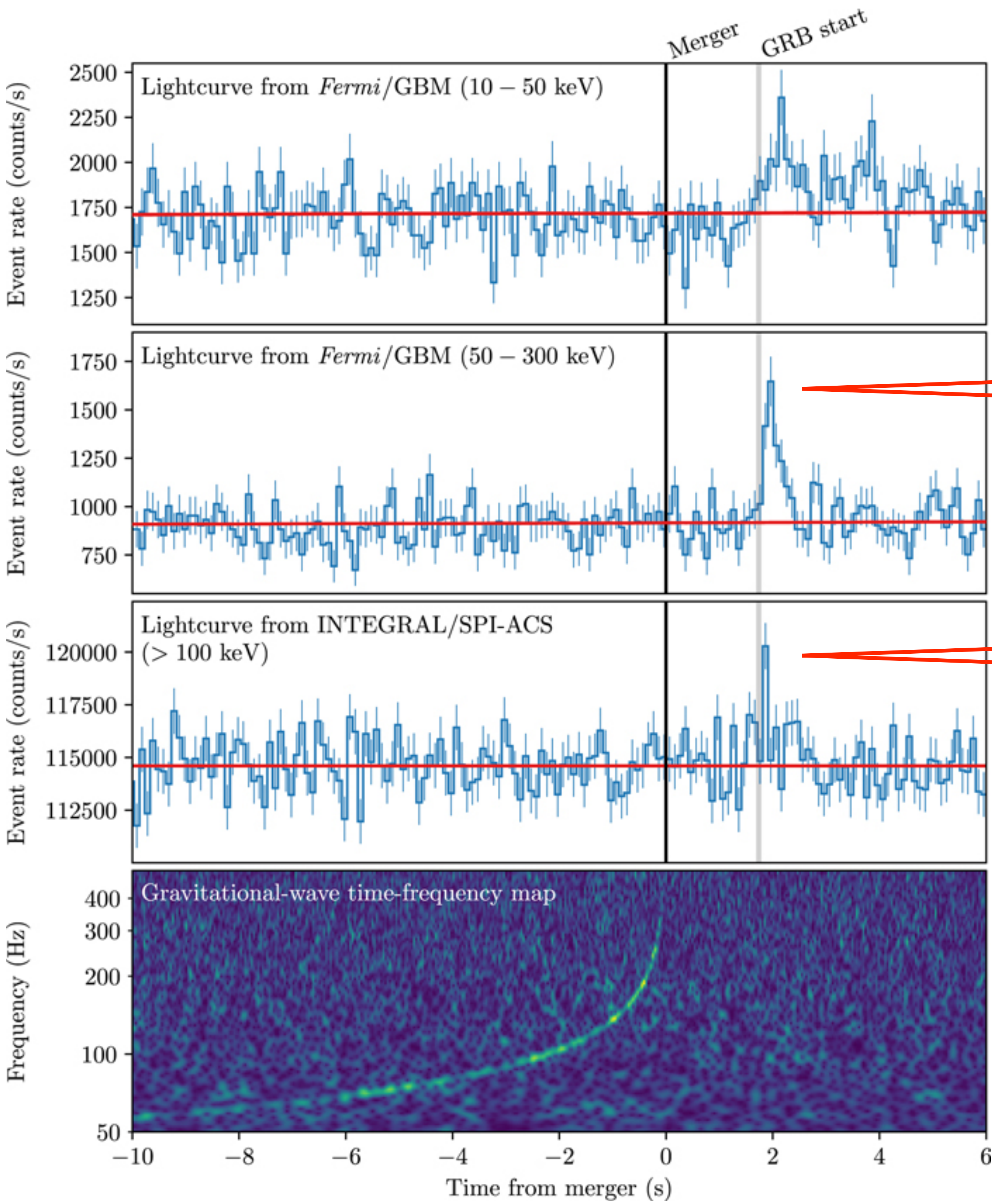
GW170817 : First detection of NSNS merger

連星中性子星合体　重力波検出，多くの天文台が同時観測



GW170817

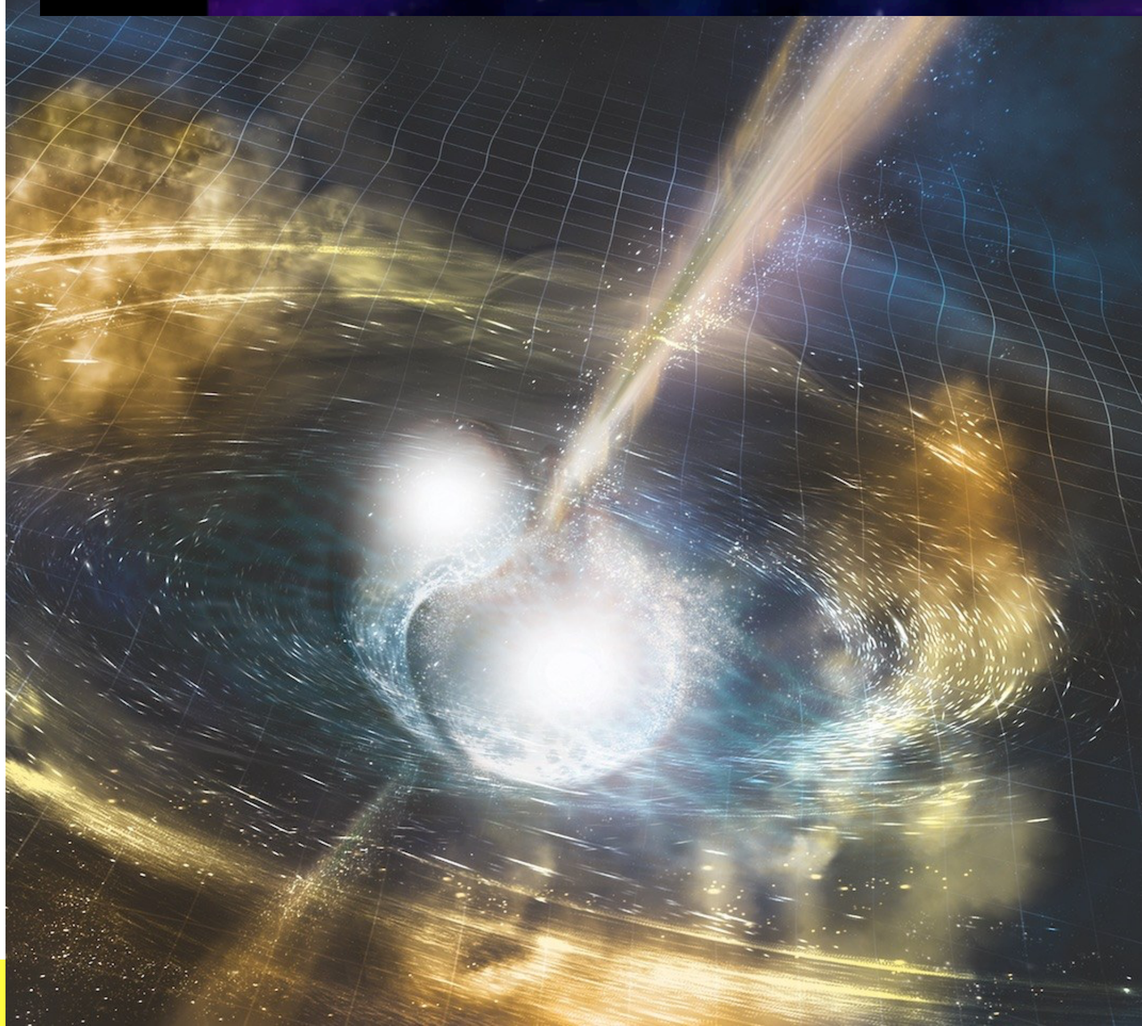
GW170817 : First detection of NSNS merger

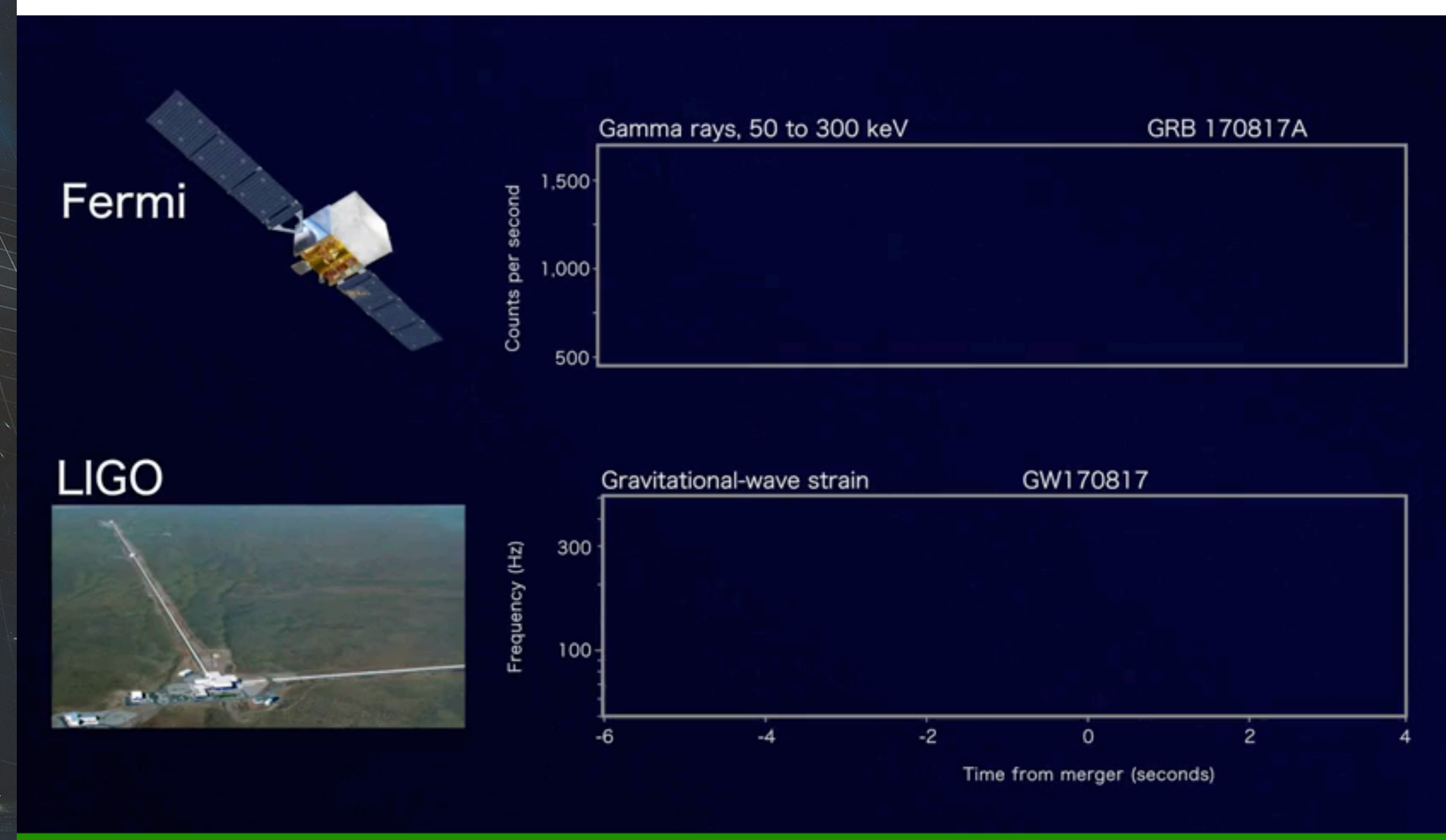


Fermi detected GRB 1.7 sec later the merger.

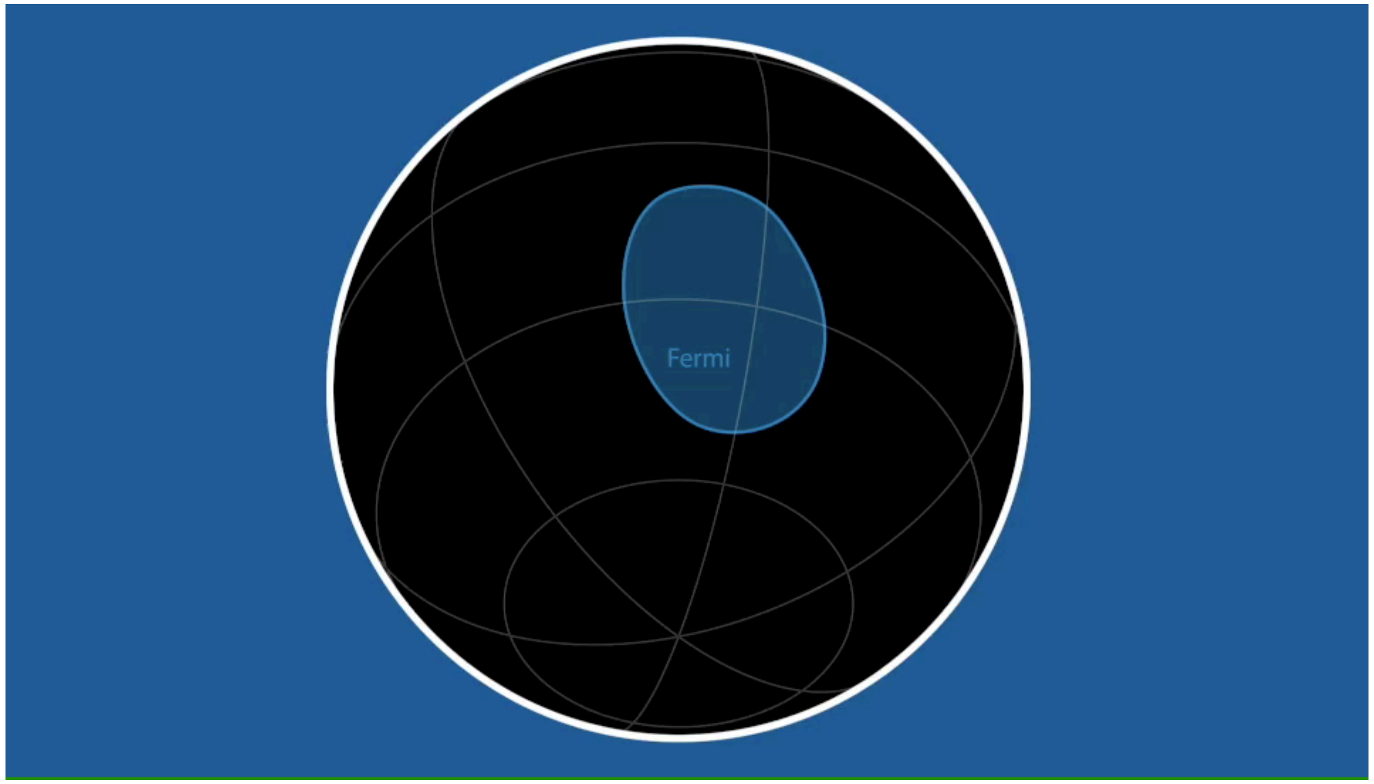
INTEGRAL detected GRB 1.7 sec later the merger.

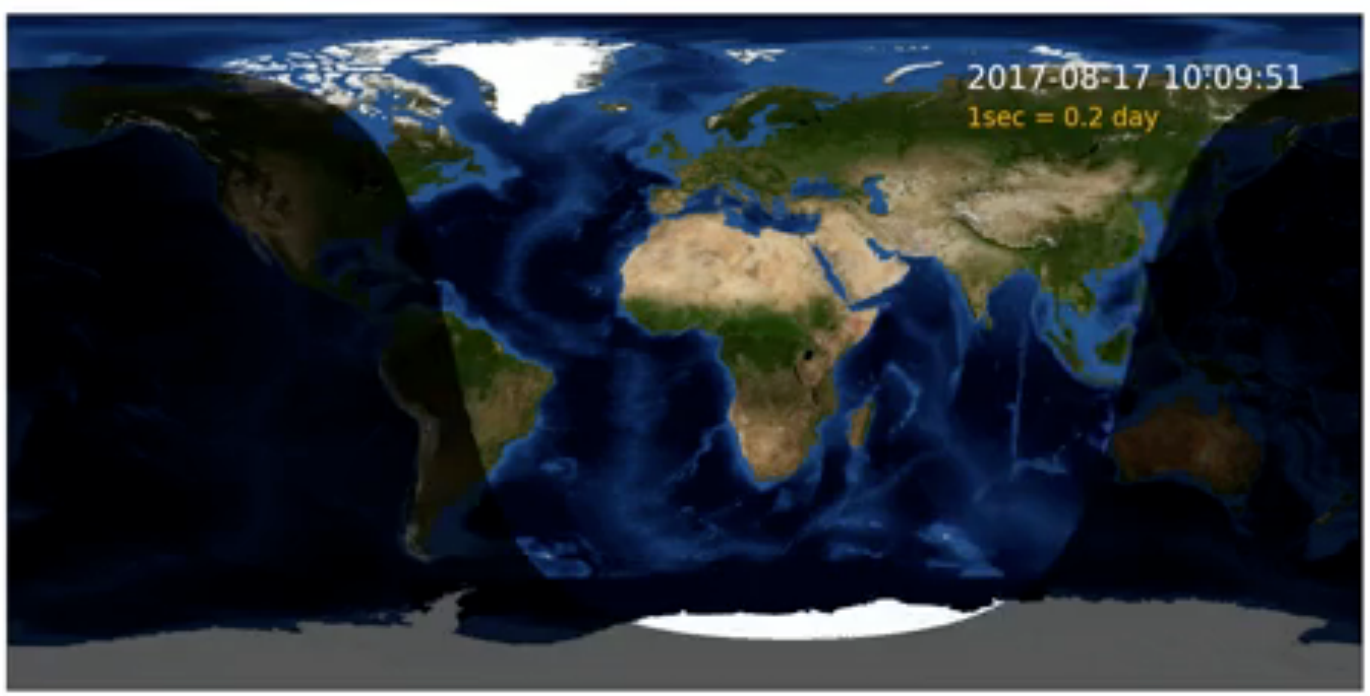
GW170817 : First detection of NSNS merger





GW170817 : First detection of NSNS merger





The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20

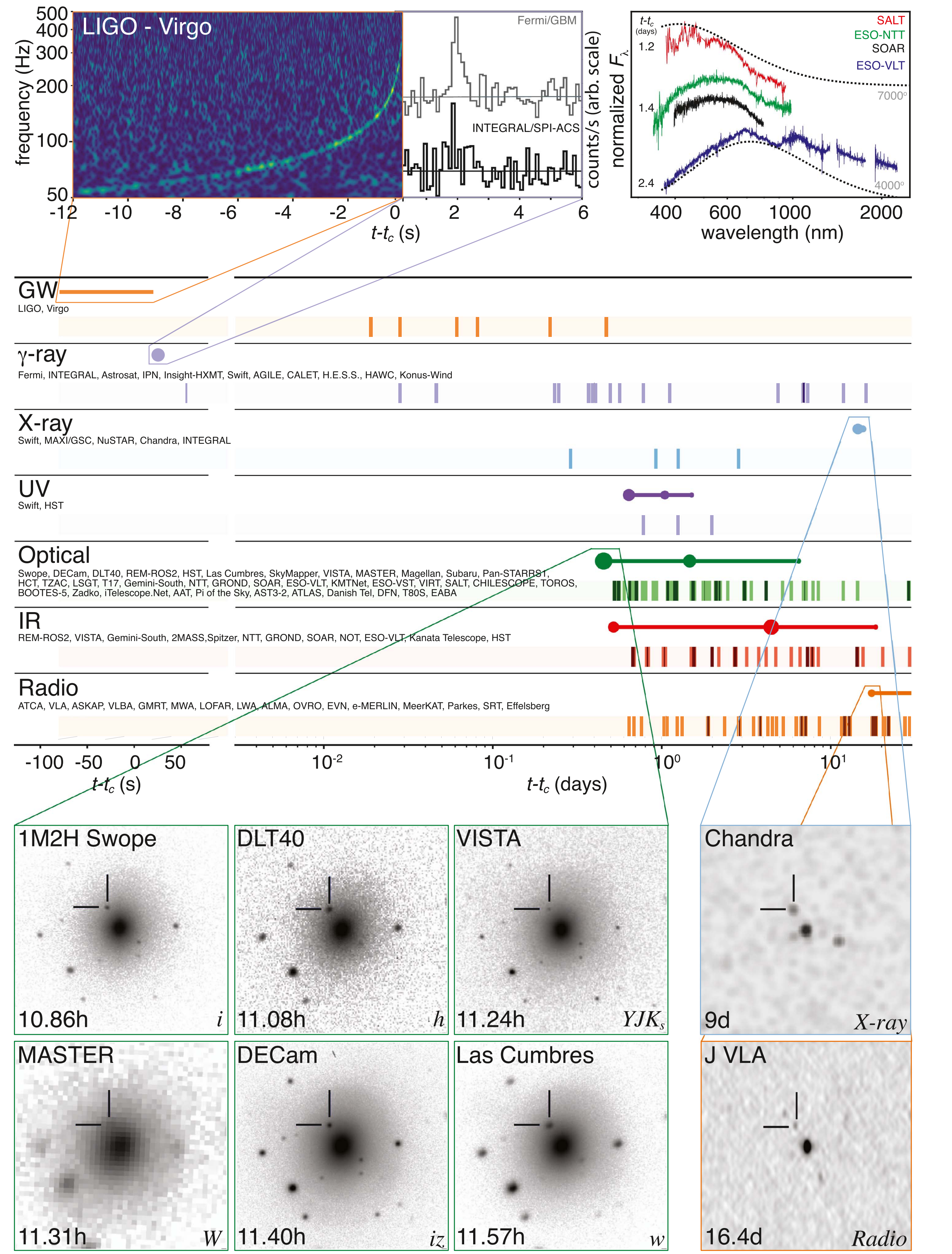
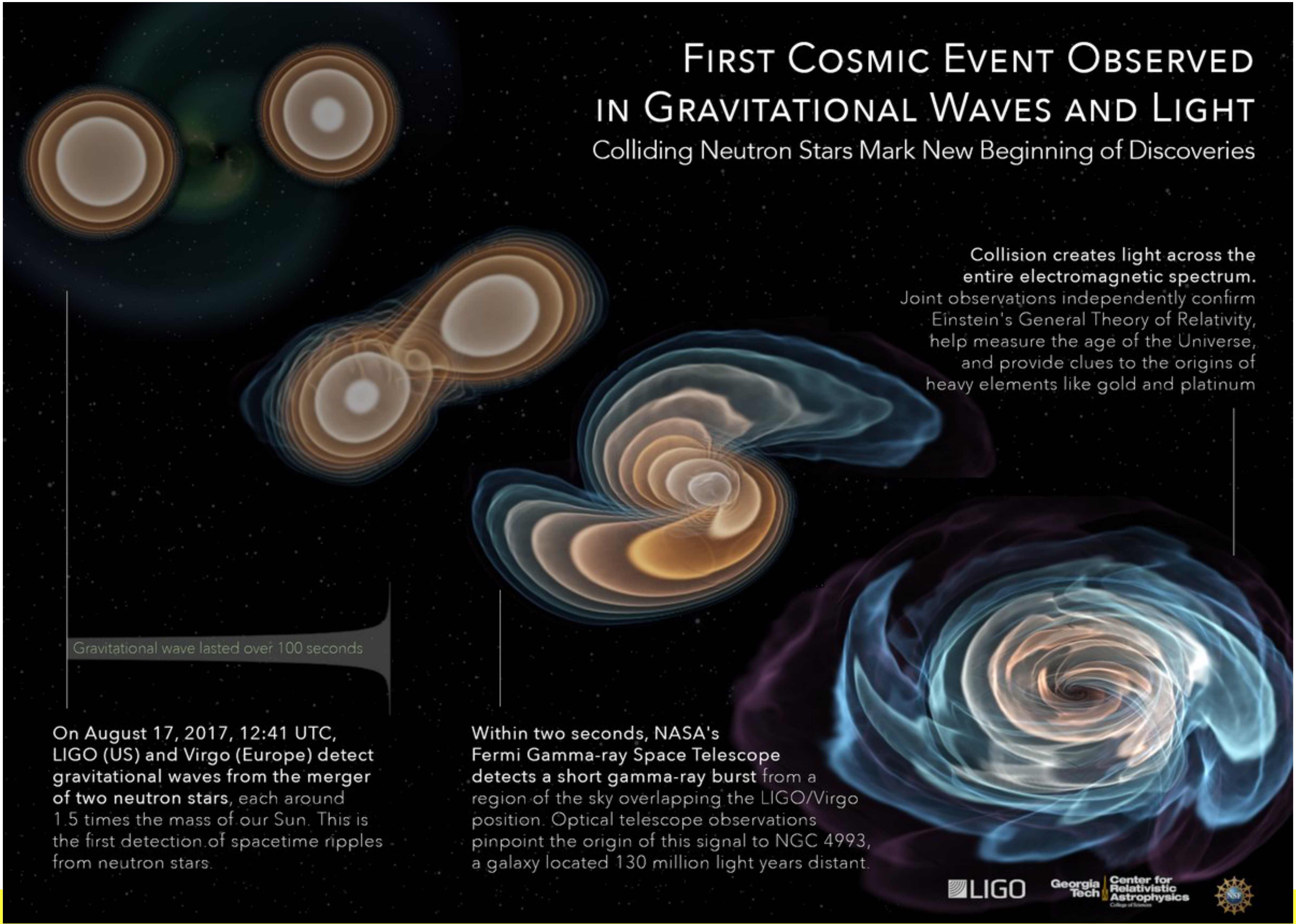


Figure 2. Timeline of the discovery of GW170817, GRB 170817A, SSS17a/AT 2017gfo, and the follow-up observations are shown by messenger and

GW170817 : First detection of NSNS merger



周期表 (periodic table)

原子番号 → 29 +2,1 ← 通常できるイオンの価数
元素記号 → Cu ← 元素記号が灰色のものは人工合成された元素
元素名（日本語）→ 銅
元素名（英語）→ copper
63.55 ←原子量

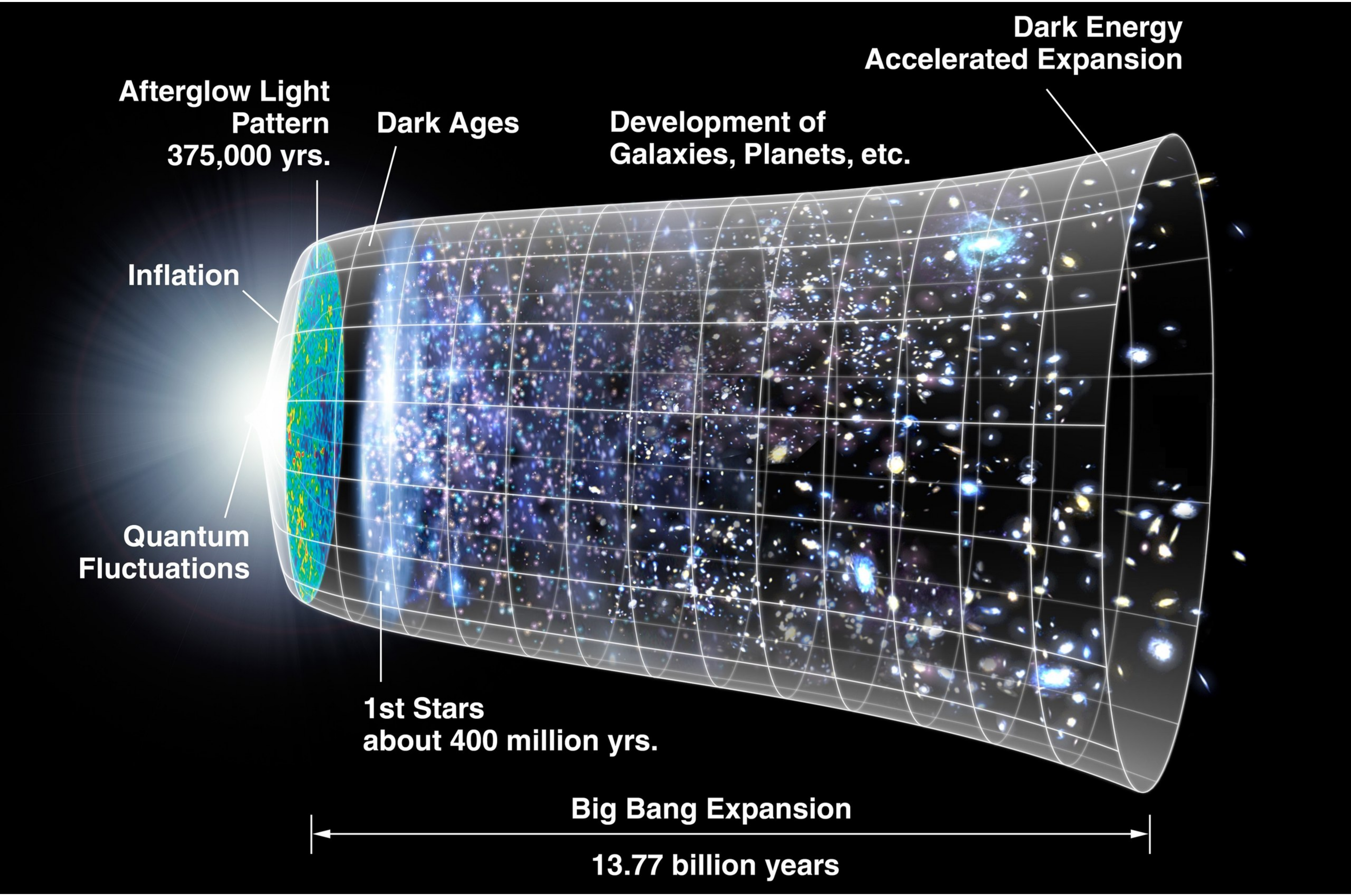
🟨 常温で気体　🟪 単体は半導体
🟩 常温で液体　🟦 単体は強磁性体　🟧 放射性同位体のみからなる元素

↑非金属元素
↓金属元素

Period		1 I A	2 II A		3 III B	4 IV B	5 V B	6 VI B	7 VII B	8 VIII B	9 VIII B	10 VIII B	11 I B	12 II B		13 III A	14 IV A	15 V A	16 VI A	17 VII A	18 VIII A
1	1s	1 ±1 H 水素 hydrogen 1.008																			2 He ヘリウム helium 4.003
2	2s	3 +1 Li リチウム lithium 6.941	4 +2 Be ベリリウム beryllium 9.012												2p	5 +3 B ホウ素 boron 10.81	6 −4 C 炭素 carbon 12.01	7 −3 N 窒素 nitrogen 14.01	8 −2 O 酸素 oxygen 16.00	9 −1 F フッ素 fluorine 19.00	10 Ne ネオン neon 20.18
3	3s	11 +1 Na ナトリウム sodium 22.99	12 +2 Mg マグネシウム magnesium 24.31												3p	13 +3 Al アルミニウム aluminum 26.98	14 −4 Si ケイ素 silicon 28.09	15 −3 P リン phosphorus 30.97	16 −2 S 硫黄 sulfur 32.07	17 −1 Cl 塩素 chlorine 35.45	18 Ar アルゴン argon 39.95
4	4s	19 +1 K カリウム potassium 39.10	20 +2 Ca カルシウム calcium 40.08	3d	21 +3 Sc スカンジウム scandium 44.96	22 +4,3,2 Ti チタン titanium 47.87	23 +5,2,3,4 V バナジウム vanadium 50.94	24 +3,2,6 Cr クロム chromium 52.00	25 +2,3,4,6,7 Mn マンガン manganese 54.94	26 +3,2 Fe 鉄 iron 55.85	27 +2,3 Co コバルト cobalt 58.93	28 +2,3 Ni ニッケル nickel 58.69	29 +2,1 Cu 銅 copper 63.55	30 +2 Zn 亜鉛 zinc 65.41	4p	31 +3 Ga ガリウム gallium 69.72	32 +4,2 Ge ゲルマニウム germanium 72.64	33 −3 As ヒ素 arsenic 74.92	34 −2 Se セレン selenium 78.96	35 −1 Br 臭素 bromine 79.90	36 Kr クリプトン krypton 83.80
5	5s	37 +1 Rb ルビジウム rubidium 85.47	38 +2 Sr ストロンチウム strontium 87.62	4d	39 +3 Y イットリウム yttrium 88.91	40 +4 Zr ジルコニウム zirconium 91.22	41 +5,3 Nb ニオブ niobium 92.91	42 +6,3,5 Mo モリブデン molybdenum 95.94	43 +7,4,6 Tc テクネチウム technetium 98	44 +4,3,6,8 Ru ルテニウム ruthenium 101.1	45 +3,4,6 Rh ロジウム rhodium 102.9	46 +2,4 Pd パラジウム palladium 106.4	47 +1 Ag 銀 silver 107.9	48 +2 Cd カドミウム cadmium 112.4	5p	49 +3 In インジウム indium 114.8	50 +4,2 Sn スズ tin 118.7	51 +3,5 Sb アンチモン antimony 121.8	52 −2 Te テルル tellurium 127.6	53 −1 I ヨウ素 iodine 126.9	54 Xe キセノン xenon 131.3
6	6s	55 +1 Cs セシウム cesium 132.9	56 +2 Ba バリウム barium 137.3	† 5d	57—71 ランタノイド lanthanides	72 +4 Hf ハフニウム hafnium 178.5	73 +5 Ta タンタル tantalum 180.9	74 +6,4 W タングステン tungsten 183.8	75 +7,4,6 Re レニウム rhenium 186.2	76 +4,6,8 Os オスミウム osmium 190.2	77 +4,3,6 Ir イリジウム iridium 192.2	78 +4,2 Pt 白金 platinum 195.1	79 +3,1 Au 金 gold 197.0	80 +2,1 Hg 水銀 mercury 200.6	6p	81 +1,3 Tl タリウム thallium 204.4	82 +2,4 Pb 鉛 lead 207.2	83 +3,5 Bi ビスマス bismuth 209.0	84 +4,2 Po ポロニウム polonium 209	85 At アスタチン astatine 210	86 Rn ラドン radon 222
7	7s	87 +1 Fr フランシウム francium 223	88 +2 Ra ラジウム radium 226	‡ 6d	89—103 アクチノイド actinides	104 Rf ラザホージウム rutherfordium 261	105 Db ドブニウム dubnium 262	106 Sg シーボーギウム seaborgium 266	107 Bh ボーリウム bohrium 264	108 Hs ハッシウム hassium 277	109 Mt マイトネリウム meitnerium 268	110 Ds ダームスタチウム darmstadtium 281	111 Rg レントゲニウム roentgentium 272	112 Cn コペルニシウム copernicium 285	7p	113 Nh ニホニウム nihonium 284	114 Fl フレロビウム flerovium 289	115 Mc モスコビウム moscovium 288	116 Lv リバモリウム livermorium 292	117 Ts テネシン tennessine 293	118 Og オガネソン oganesson 294

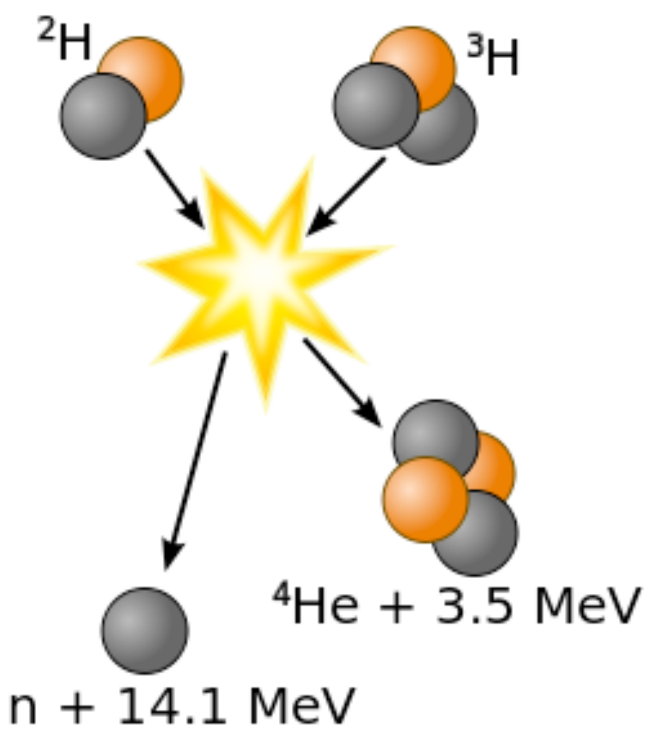
→非金属元素
↓金属元素
↑非金属元素
↓金属元素

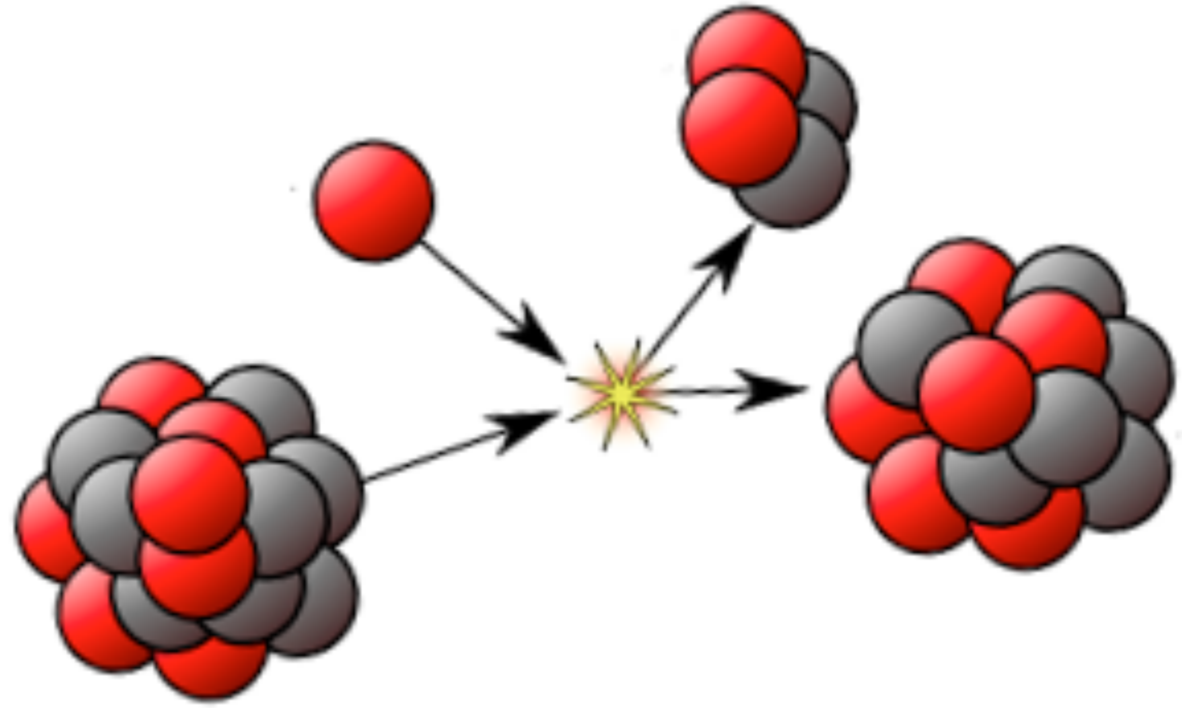
ランタノイド lanthanides （レアアース金属） (rare earth metals)	† 4f	57 +3 La ランタン lanthanum 138.9	58 +3,4 Ce セリウム cerium 140.1	59 +3,4 Pr プラセオジム praseodymium 140.9	60 +3 Nd ネオジム neodymium 144.2	61 +3 Pm プロメチウム promethium 145	62 +3,2 Sm サマリウム samarium 150.4	63 +3,2 Eu ユウロピウム europium 152.0	64 +3 Gd ガドリニウム gadolinium 157.3	65 +3,4 Tb テルビウム terbium 158.9	66 +3 Dy ジスプロシウム dysprosium 162.5	67 +3 Ho ホルミウム holmium 164.9	68 +3 Er エルビウム erbium 167.3	69 +3,2 Tm ツリウム thulium 168.9	70 +3,2 Yb イッテルビウム ytterbium 173.0	71 +3 Lu ルテチウム lutetium 175.0
アクチノイド actinides	‡ 5f	89 +3 Ac アクチニウム actinium 227	90 +4 Th トリウム thorium 232.0	91 +5,4 Pa プロトアクチニウム protactinium 231.0	92 +6,3,4,5 U ウラン uranium 238.0	93 +5,3,4,6 Np ネプツニウム neptunium 237	94 +4,3,5,6 Pu プルトニウム plutonium 239	95 +3,4,5,6 Am アメリシウム americium 243	96 +3 Cm キュリウム curium 247	97 +3,4 Bk バークリウム berkelium 247	98 +3 Cf カリホルニウム californium 251	99 +3 Es アインスタイニウム einsteinium 252	100 +3 Fm フェルミウム fermium 257	101 +3,2 Md メンデレビウム mendelevium 258	102 +2,3 No ノーベリウム nobelium 259	103 +3 Lr ローレンシウム lawrencium 262


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

核反応　原子核の組み替えによって莫大なエネルギーが放出

Nuclear Reactions





$$4\mathrm{p} \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + 2\gamma$$

$${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

核融合

(nuclear fusion)

合体した方が安定
(エネルギー放出)

核分裂

(nuclear fission)

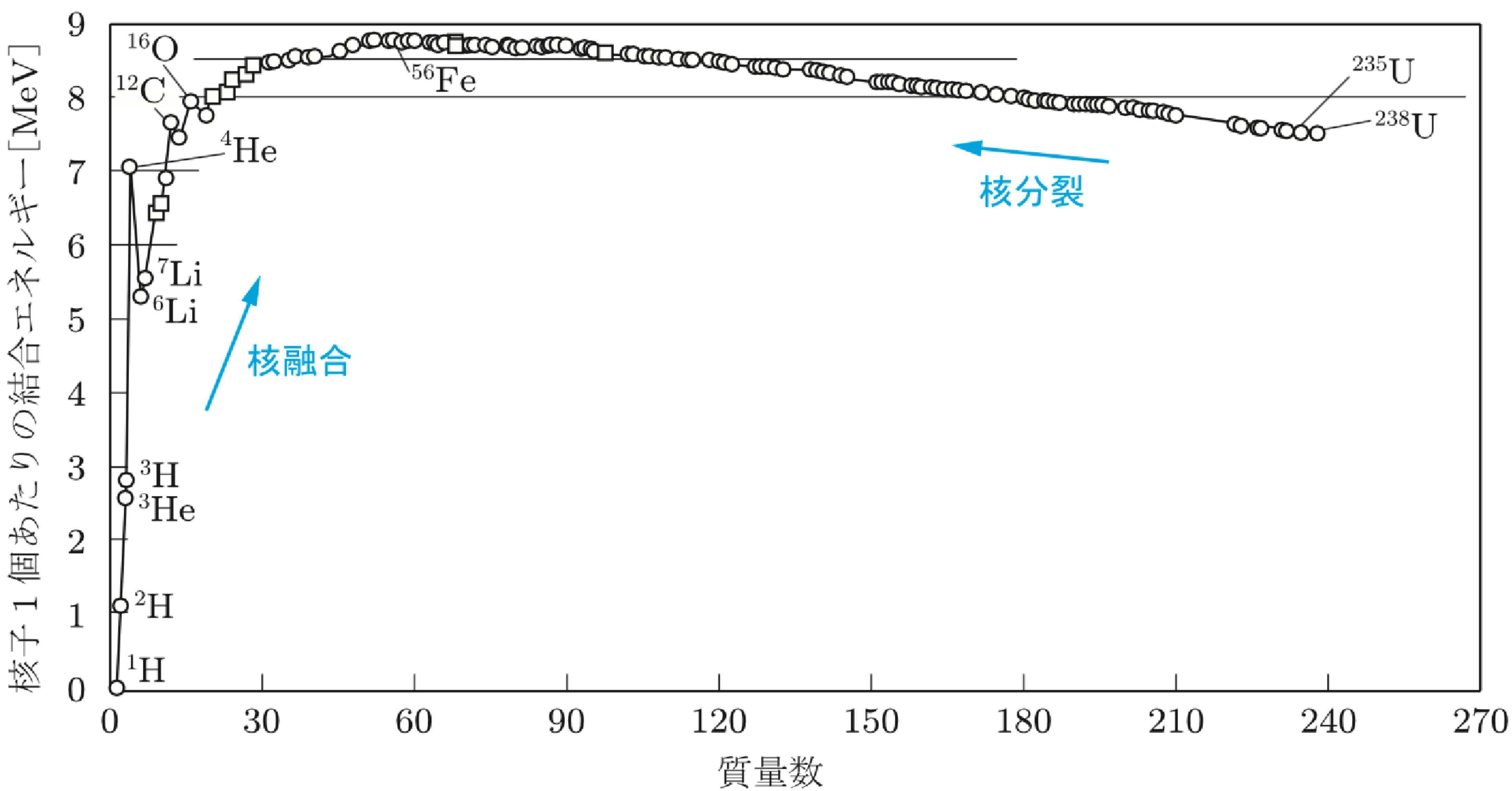
分裂した方が安定
(エネルギー放出)

核融合も核分裂もどちらもおきる理由は何か？

Why both nuclear fusion and fission exist?

結合エネルギー (binding energy)

結合エネルギー（大）→ →



→ → 質量数（大）

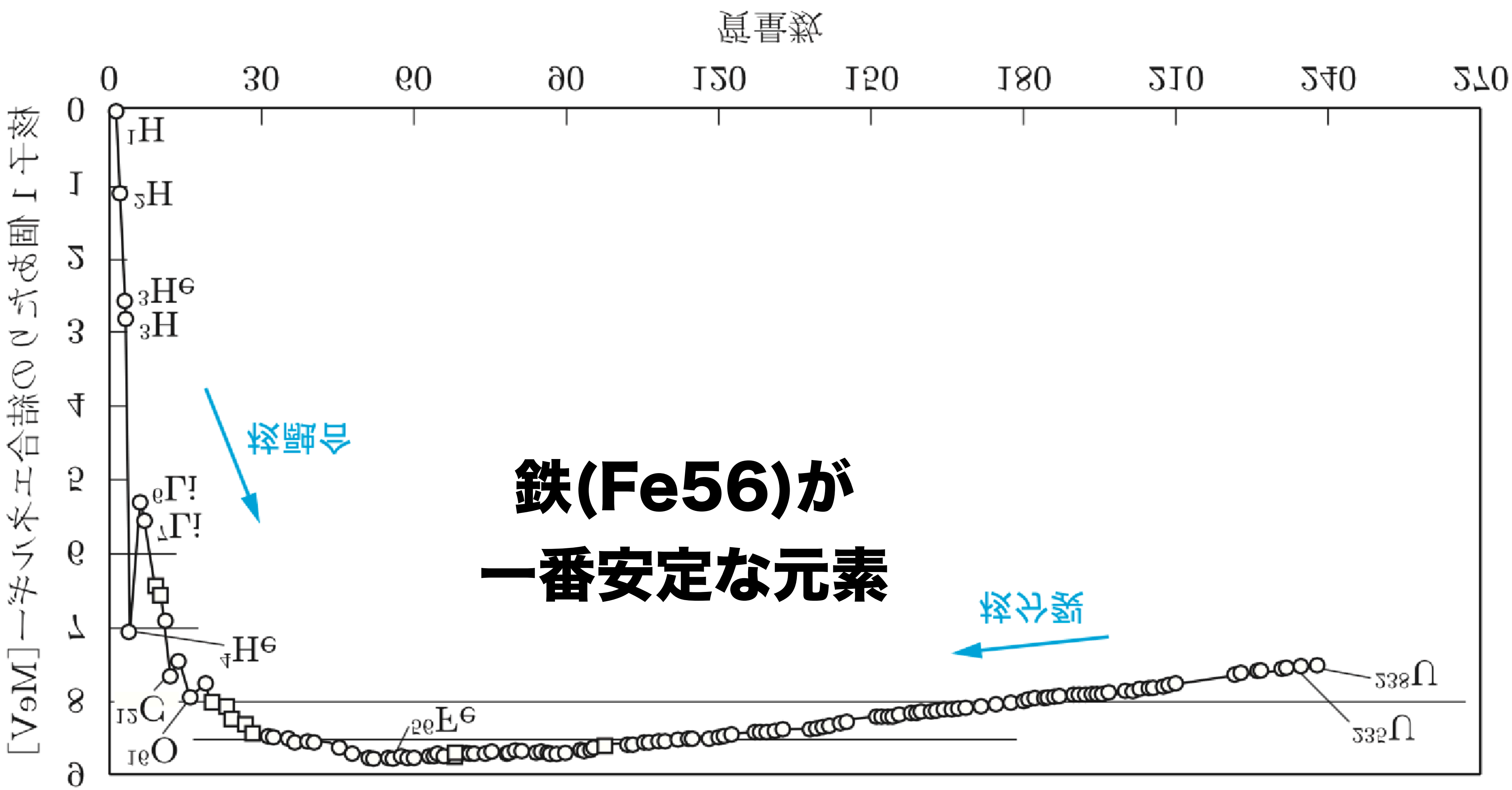
核融合も核分裂もどちらもおきる理由は何か？

Why both nuclear fusion and fission exist?

結合エネルギー (binding energy)

↓↓

結合エネルギー（大）



→ → 質量数（大）

Feよりも重い元素があるのは何故か？

Why there is heavy elements than Fe?

宇宙の始まりは素粒子．

だんだんと冷えるにしたがって水素 (H)が形成．

集まって星ができ，核融合で恒星になる．

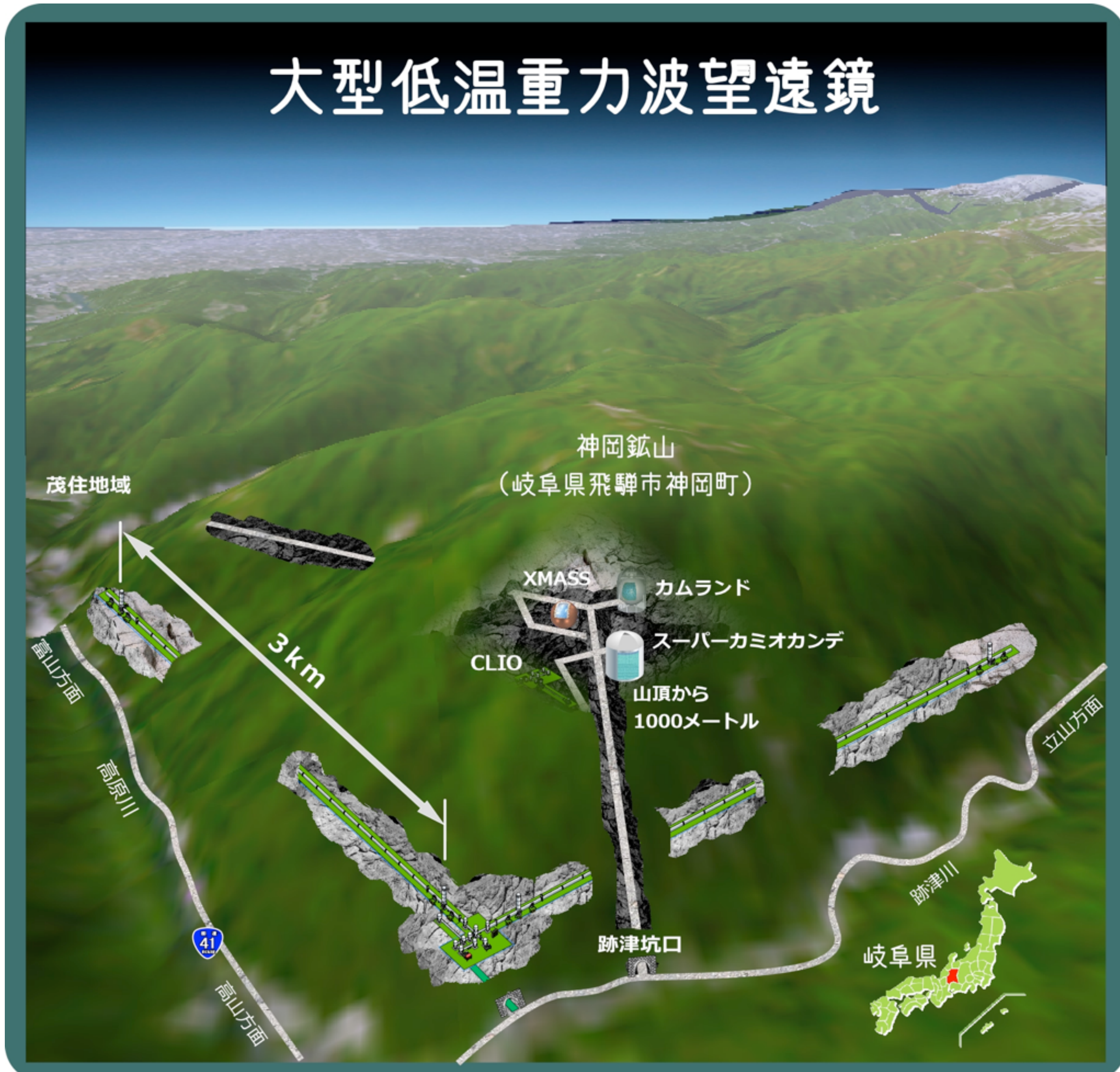
しかし，核融合は，鉄(Fe)までしか進まない．

現在，周期表に Fe より重い元素があるのは何故か？

超新星爆発で作られた！ (by supernovae!)

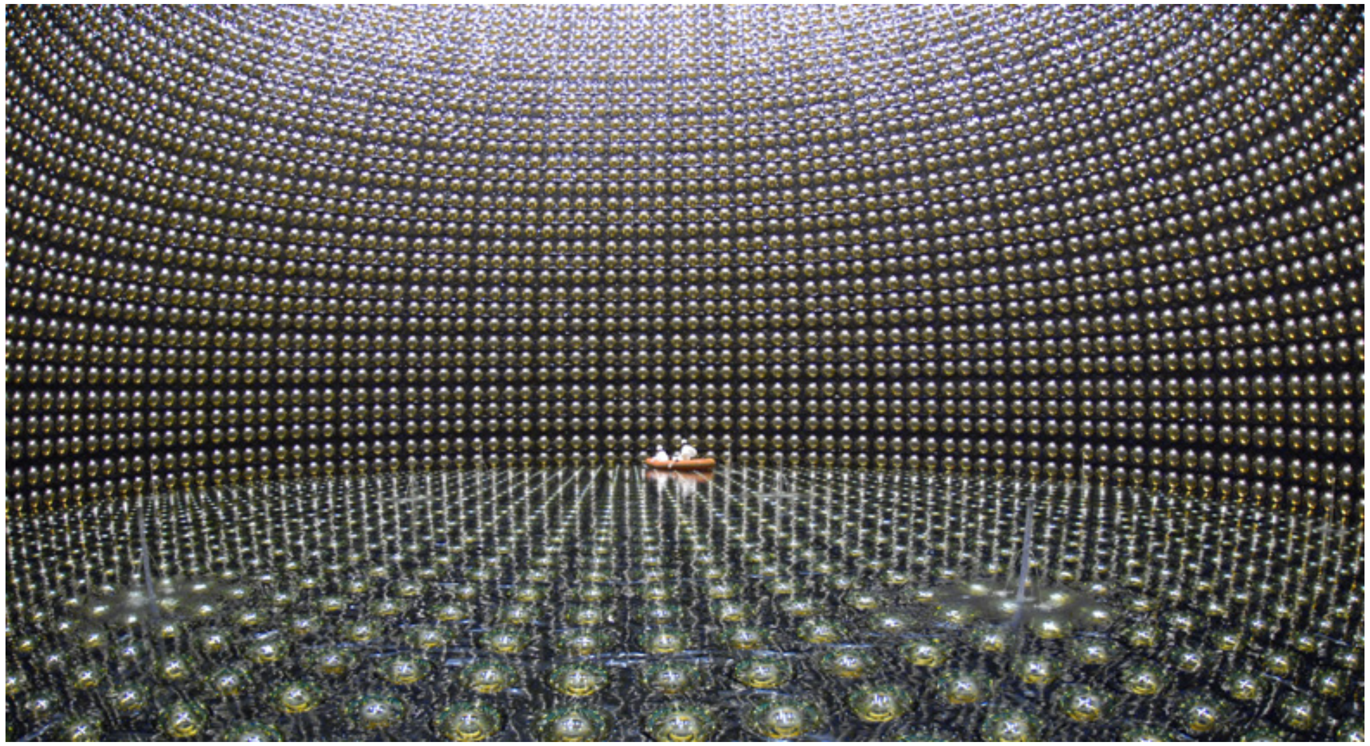
中性子星連星合体で作られた！(by NSNS mergers!)

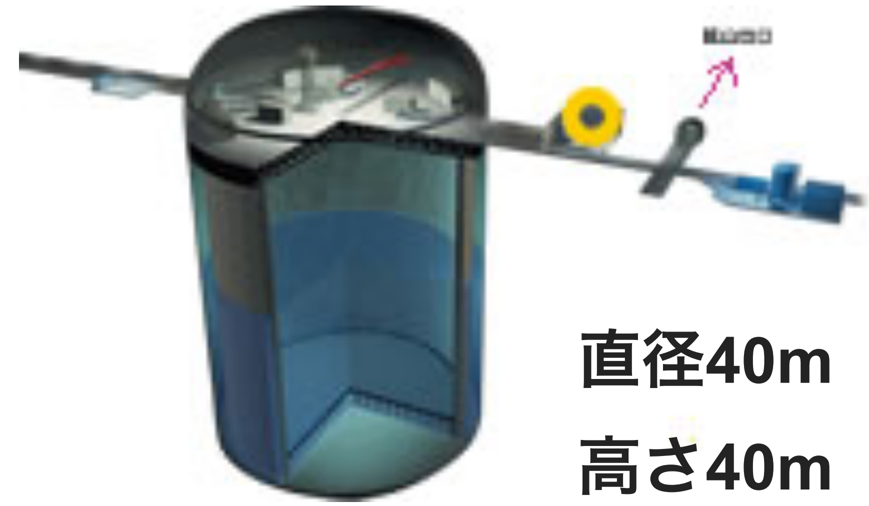
KAGRA（かぐら：大型低温重力波望遠鏡）



スーパー・カミオカンデ（ニュートリノ観測装置）

Super-Kamiokande　http://www-sk.icrr.u-tokyo.ac.jp/sk/





直径40m
高さ40m

岐阜県・神岡の鉱山跡の空洞に巨大な水槽をつくり，
宇宙から飛来するニュートリノを観測する．

ノーベル物理学賞を受賞

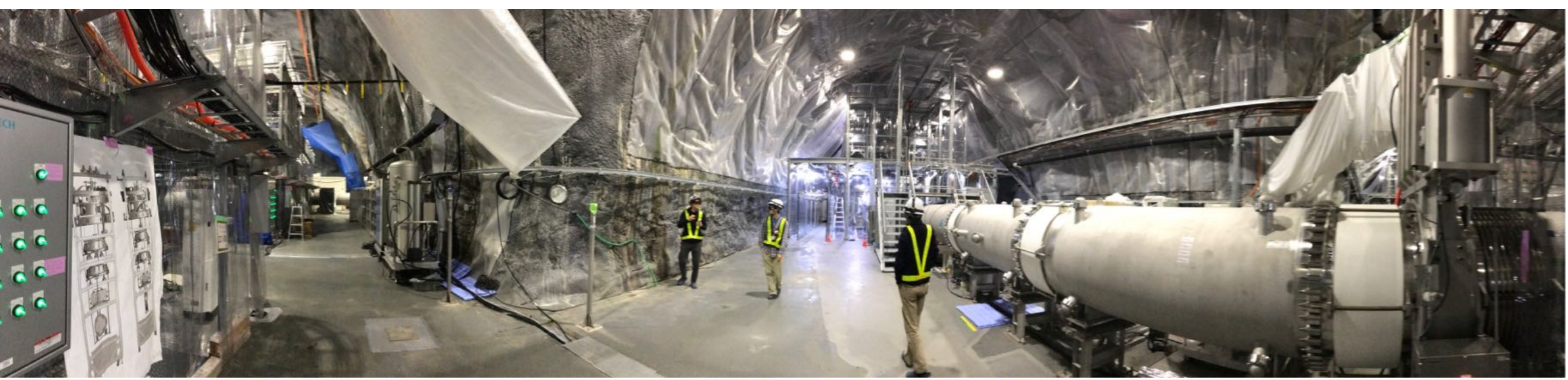
小柴昌俊（2002年）

梶田隆章（2015年）

KAGRA（かぐら：大型低温重力波望遠鏡）

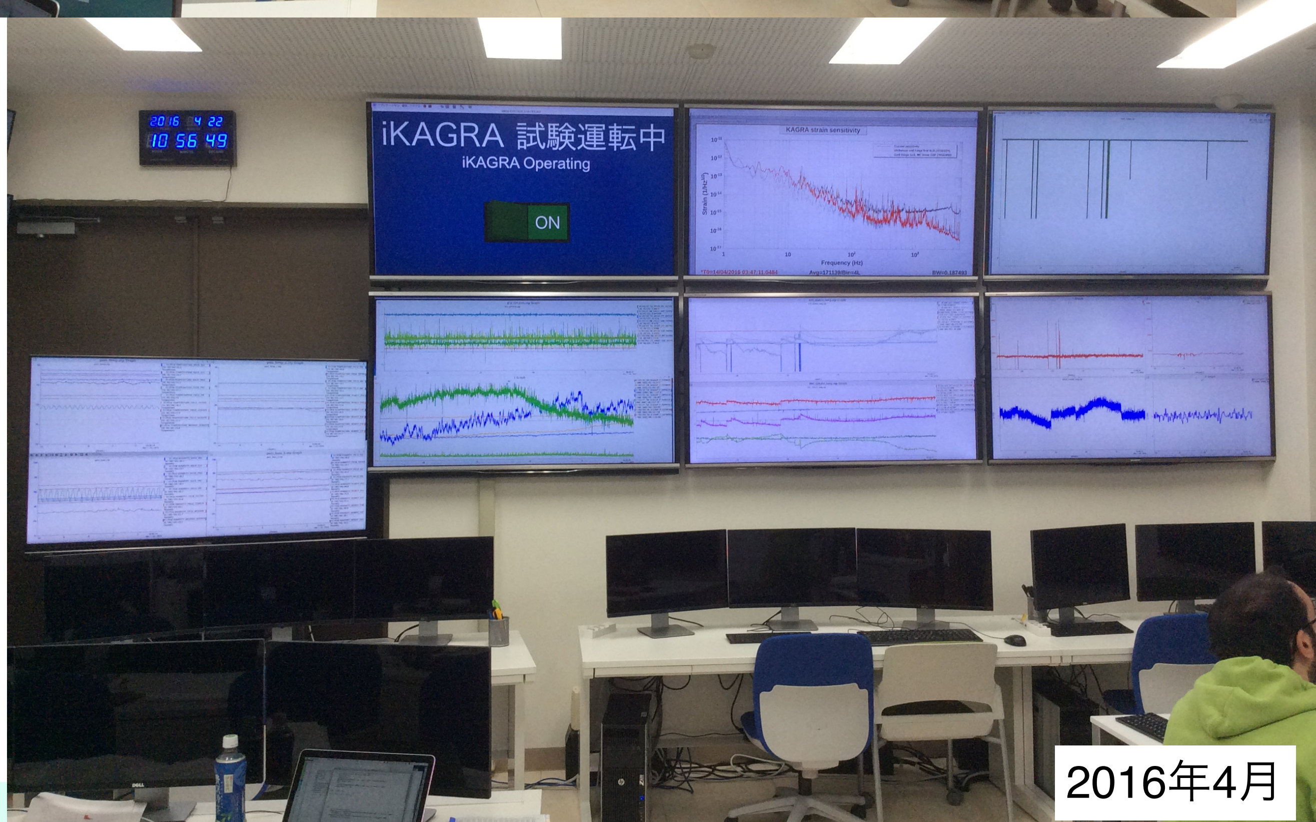
Hisaaki Shinkai

Seiji Kawamura　　Kieran Craig
Martynov Denis



KAGRA（かぐら：大型低温重力波望遠鏡）

KAGRA（かぐら：大型低温重力波望遠鏡）



KAGRA SCIENTIFIC CONGRESS: COLLABORATORS' INFORMATION EXCHANGE 2018/08/01

KSC Newsletter

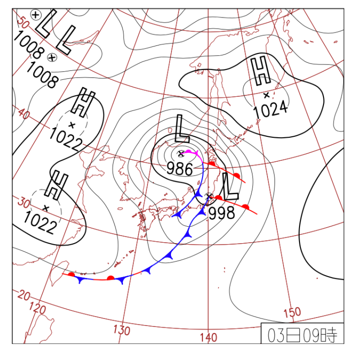
Second Issue

From Phase 1 to Phase 2

Nine-day operation with wild weather & earthquakes

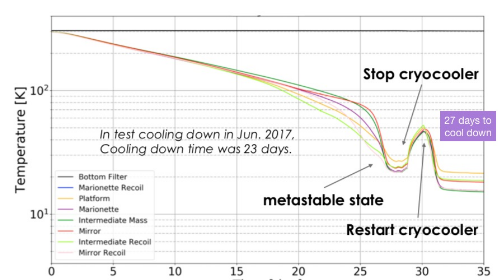
KAGRA now has the world's tallest vibration isolation systems (13.5 m) which help to reduce seismic noise at low frequencies. The volume of the vacuum system is third largest in the world. Two 23-kg sapphire mirrors have been installed at each end, and one of them was kept for 30 days at cryogenic temperature (18K).

A leakage of the vacuum system was found in April 2018, therefore the Phase-1 experimental activity was delayed for 5 days. Despite the difficulties, the phase-1 operation was a success: it lasted from April 28 to May 6, 2018, and during this period many injection tests were performed.

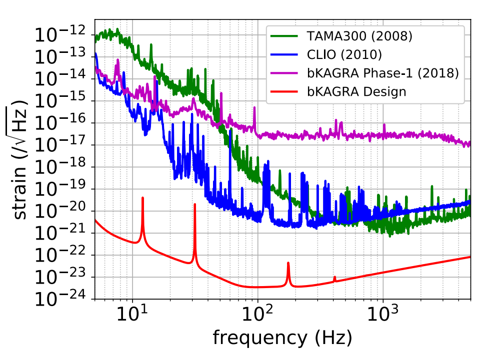


Weather map of May 3, 2018.

The interferometer duty cycle during the Phase-1 operation reached 88.6% between April 28 and May 2, while it dropped to 26.8% on May 3 and 4. Finally it slightly improved to 59.8% over the final days (May 5 & 6). The longest lock was over 10 hours. The low duty cycle on May 3 and on the following days was mainly attributed to the high micro-seismic noise caused by a heavy storm, local earthquakes, volcano eruptions in Hawaii, and visits of theorists.



The achieved sensitivity during Phase 1 was still worse than the final sensitivities of TAMA and CLIO, except at the lower frequencies (40 Hz), where KAGRA's sensitivity was better than that of TAMA. KAGRA started Phase 2 from May 7: the final installation work before the real observation run.

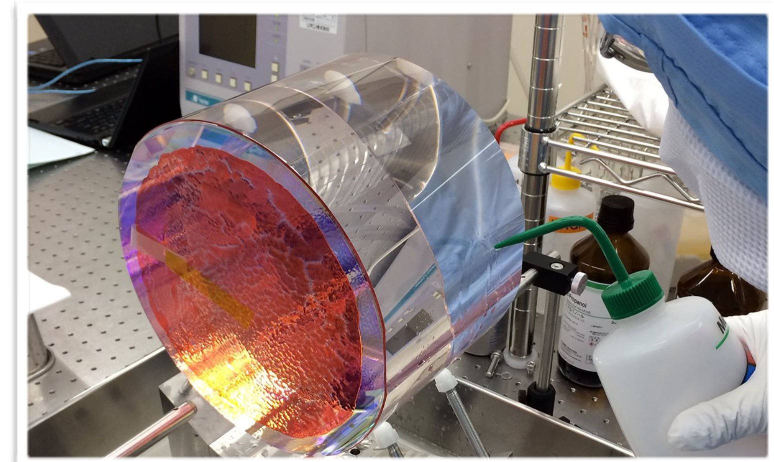


Contents of this issue

KAGRA SCIENTIFIC CONGRESS: COLLABORATORS' INFORMATION EXCHANGE 2018/04/01

KSC NewsLetter

The premiere issue



Phase-1 operation starts on April 23

First cryogenic interferometer test will start soon.

After two years from the iKAGRA run, we will start phase-1 operation on April 23 to May 6. Due to the tight schedule for our upcoming real observation, system engineering office (SEO) decided to operate phase-1 with one cryogenic mirror (Y-arm), and the other at normal temperature. We do not know what will be the outcomes. So it might become a sort of fun. A detail list of tests planned during the run is at page-3.

The above photo, taken in a clean room in the University of Toyama, is our 23kg-Sapphire mirror for X-end, which is now under installation. The installation of the cryo-payload at X-end is almost done and the main beam is coming back to the center now 😀.

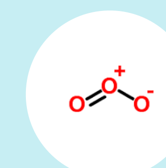
Three words you should not miss in our conversation.

1 GW
Find GW.
Here GW is not "Gravitational Wave", but "Golden Week".

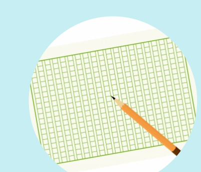
2 CRYOGENIC
Buy refrigerator, set freezing chamber, feel chilly, but try not to catch a cold.

3 O3
Not an oxygen-allotrope. Not a pathogenic *Vibrio Parahaemolyticus*.

What is this NewsLetter?
Nobody knows if this is the first issue of a series of information letters, or just a April fool's day joke.



O3=Ozone.
We are in a rush for O3 this year. Let's finish looking for O2.



We call for volunteers
We welcome your editorial participation to this journal. It will give you a career update definitely.

http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/KAGRA

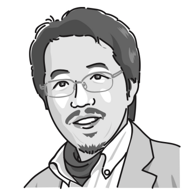
Organization of KSC (KAGRA Scientific Congress)

Takaaki Kajita
(PI)

Masatake Ohashi
(vice PI)

Yoshio Saito
(SEO proj. manager)

KAGRA Scientific Congress (KSC) organization chart 2019/August 24

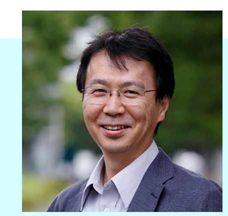


- PI
- EO — sharing information & idea — KSC board
- SEO

KSC board

- * Hisaaki Shinkai
- * Shinji Miyoki
- * Chunglee Kim
- Hideyuki Tagoshi
- Tomotada Akutsu
- Zhoujian Cao
- Hyung-Won Lee
- Ray-Kuang Lee
- Hirotaka Yuzurihara
- Tomohiro Yamada

◀ **New Board (2019/8-2021/8)**



Data Analysis Committee (DAC)

- * Hideyuki Tagoshi
- + WGs chairs/vice chairs
- + Hisaaki Shinkai (board)

Compact Binary Coalescence	Continuous Wave	Burst Wave	Stochastic Wave	Computing & Software	Calibration	Detchar
* Hideyuki Tagoshi Kipp Cannon Hyung-Won Lee Tjonnie Li	* Yousuke Itoh	* Kazuhiro Hayama	* Guo-Chin Liu Sachiko Kuroyanagi	* Ken-ichi Oohara Hirotaka Takahashi Kazuki Sakai	* Yuki Inoue	* Keiko Kokeyama

Joint Editorial board	Joint Run Planning Committee	LVC-KAGRA taskforce	Joint Meeting Committee	Joint Detection Committee
* TBD	Yousuke Itoh Shinji Miyoki	Yoshio Saito (leader, project manager) Hideyuki Tagoshi (Data analysis) Takahiro Yamamoto (Calibration) Osamu Miyakawa (commissioning) Hisaaki Shinkai (MoU)	* TBD	* TBD

KAGRA SCIENTIFIC CONGRESS: COLLABORATORS' INFORMATION EXCHANGE 2019/12/01

KSC Newsletter

Issue 6

2019/10
LVK MoA signed

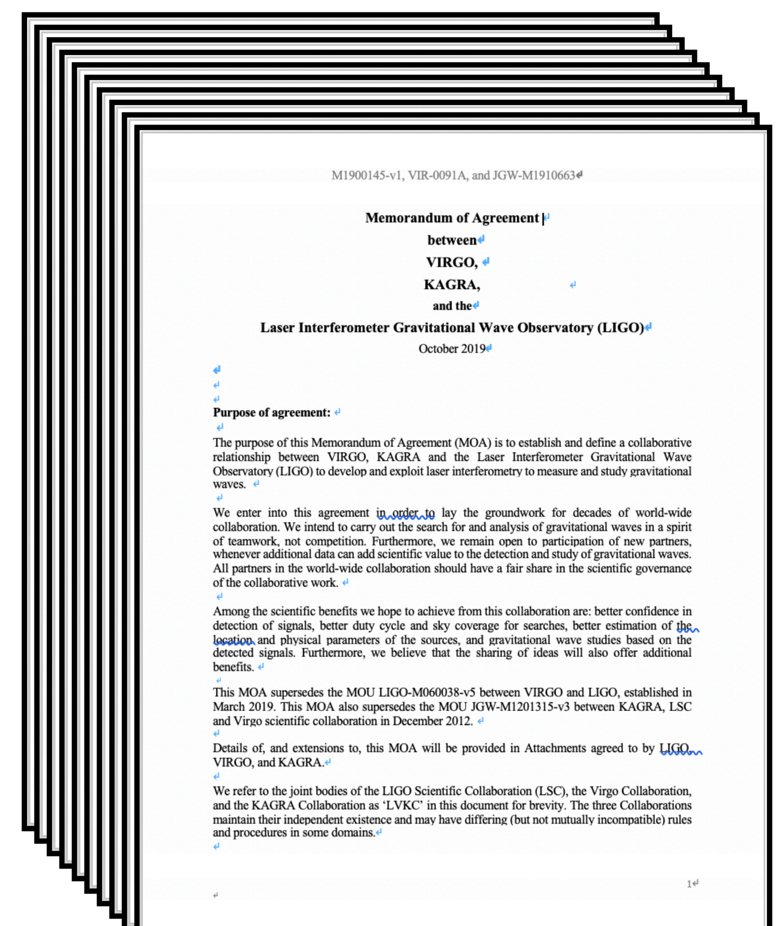
KAGRA joined International GW Network

Signed up LIGO-Virgo-KAGRA MoA for joint observation

On October 4, 2019, KAGRA held a ceremony to mark the completion of the detector. The ceremony was in the site, and after the play of the music of *kagura* (the traditional Shinto-style ritual music) by local children's musical group, Takaaki Kajita, our PI, pushed a button with U Tokyo Executive Vice President Kohei Miyazono to demonstrate the detector in motion. In the evening of the day, the signing ceremony of a memorandum of agreement (MoA) on a research collaboration between KAGRA, LIGO and Virgo were held.

This MoA makes KAGRA an equal partner of LIGO and Virgo, and once KAGRA satisfied the criteria for joining observation then all the scientific achievements will be presented as LIGO-Virgo-KAGRA collaboration. KAGRA is definitely close to the production phase after the ten-year construction and installation period. 🍏

(Above) Pose for photos after signing a MoA. (from left) EGO vice president Christian Olivetto, Virgo spokesperson Jo van den Brand, KAGRA principal investigator Takaaki Kajita, LIGO Executive Director David Reitze, KSC board chair Hisaaki Shinkai, and KAGRA vice PI Masatake Ohashi. At ANA Crowne Plaza hotel Toyama, October 4, 2019. [Photo courtesy of Hida City]



M1900145-v1, VIR-0091A, and JGW-M1910663

Memorandum of Agreement
between
VIRGO,
KAGRA,
and the
Laser Interferometer Gravitational Wave Observatory (LIGO)
October 2019

Purpose of agreement:

The purpose of this Memorandum of Agreement (MOA) is to establish and define a collaborative relationship between VIRGO, KAGRA and the Laser Interferometer Gravitational Wave Observatory (LIGO) to develop and exploit laser interferometry to measure and study gravitational waves.

We enter into this agreement in order to lay the groundwork for decades of world-wide collaboration. We intend to carry out the search for and analysis of gravitational waves in a spirit of teamwork, not competition. Furthermore, we remain open to participation of new partners, whenever additional data can add scientific value to the detection and study of gravitational waves. All partners in the world-wide collaboration should have a fair share in the scientific governance of the collaborative work.

Among the scientific benefits we hope to achieve from this collaboration are: better confidence in detection of signals, better duty cycle and sky coverage for searches, better estimation of the location and physical parameters of the sources, and gravitational wave studies based on the detected signals. Furthermore, we believe that the sharing of ideas will also offer additional benefits.

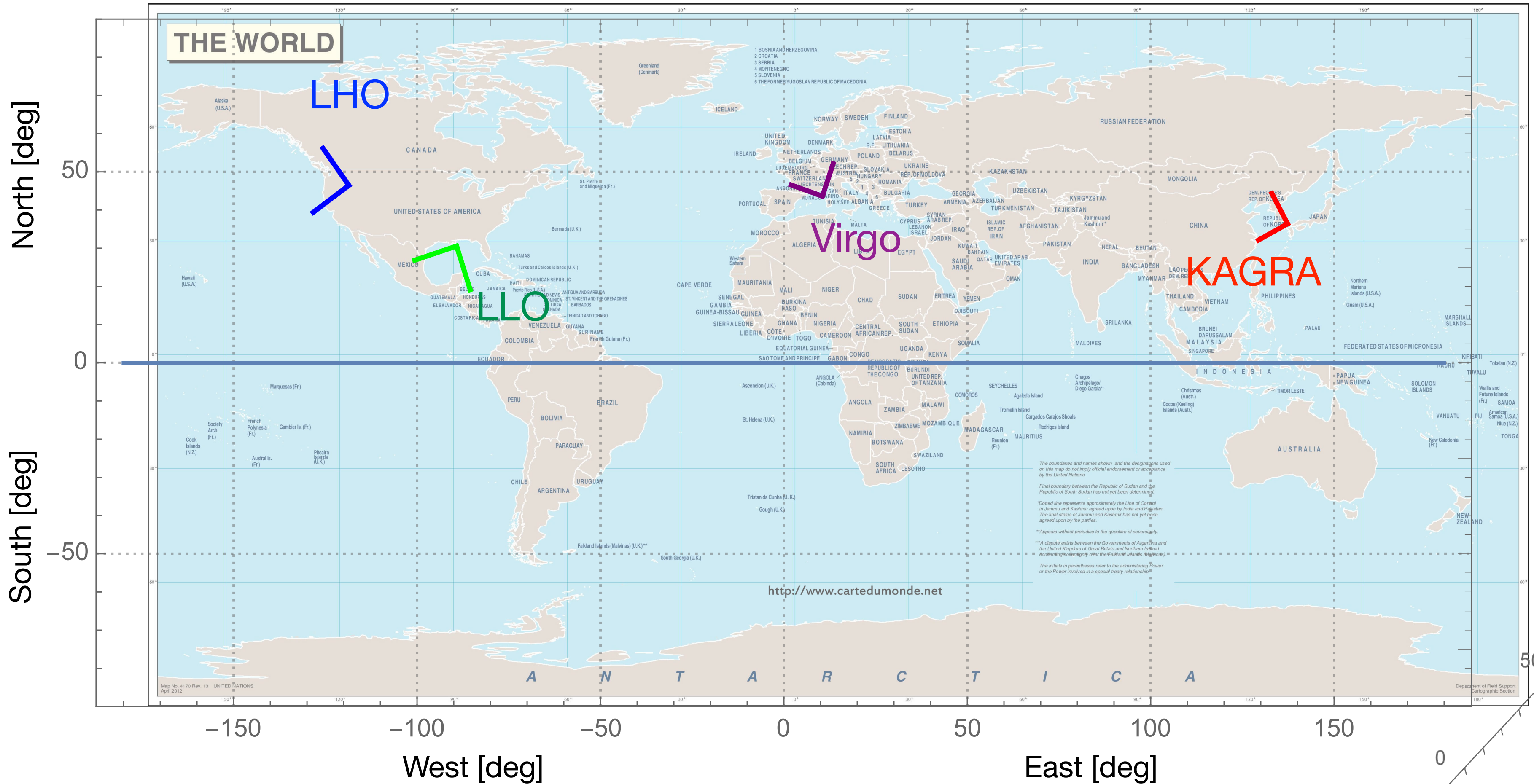
This MOA supersedes the MOU LIGO-M060038-v5 between VIRGO and LIGO, established in March 2019. This MOA also supersedes the MOU JGW-M1201315-v3 between KAGRA, LSC and Virgo scientific collaboration in December 2012.

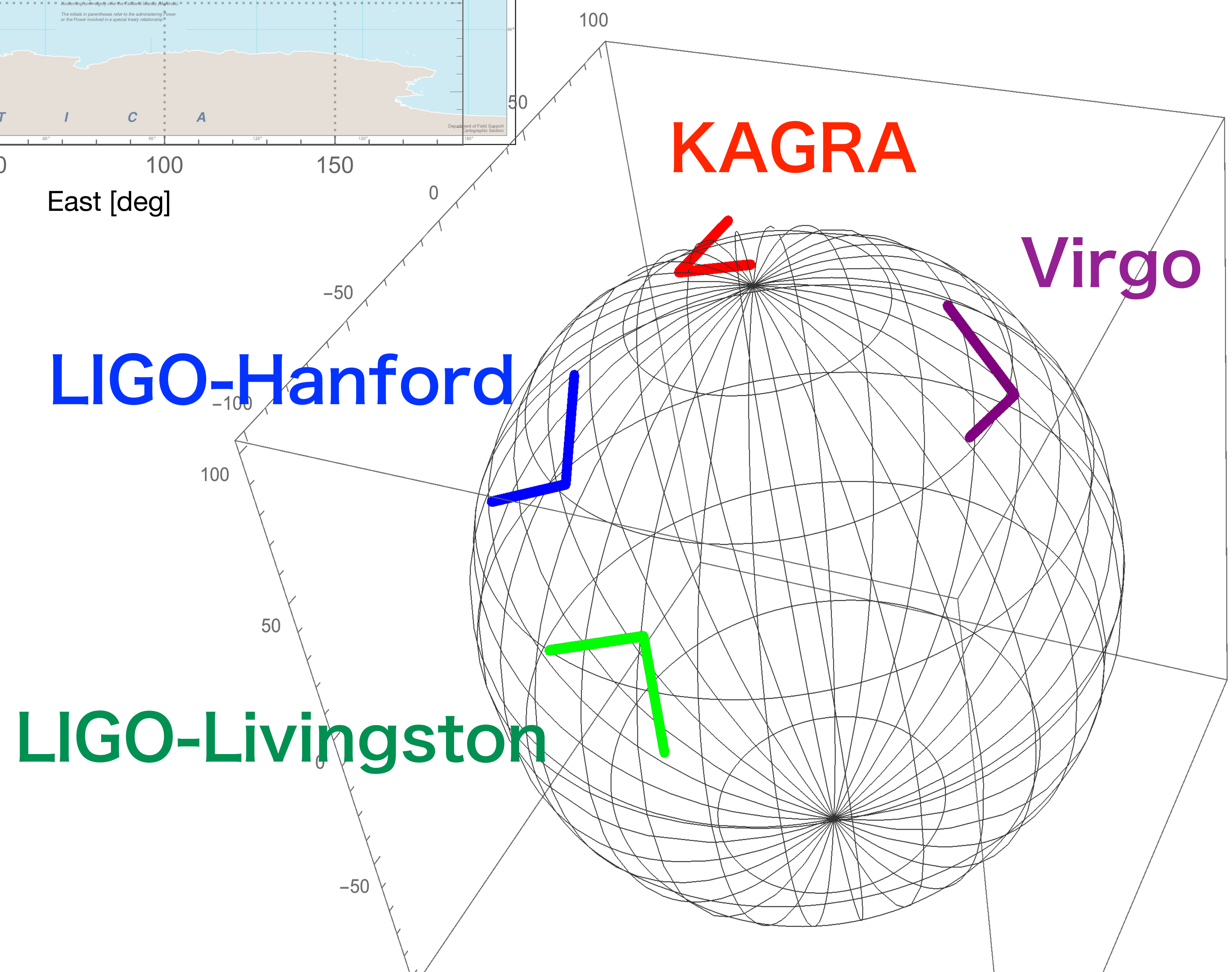
Details of, and extensions to, this MOA will be provided in Attachments agreed to by LIGO, VIRGO, and KAGRA.

We refer to the joint bodies of the LIGO Scientific Collaboration (LSC), the Virgo Collaboration, and the KAGRA Collaboration as 'LVKC' in this document for brevity. The three Collaborations maintain their independent existence and may have differing (but not mutually incompatible) rules and procedures in some domains.

1

International GW network （国際重力波観測ネットワーク）

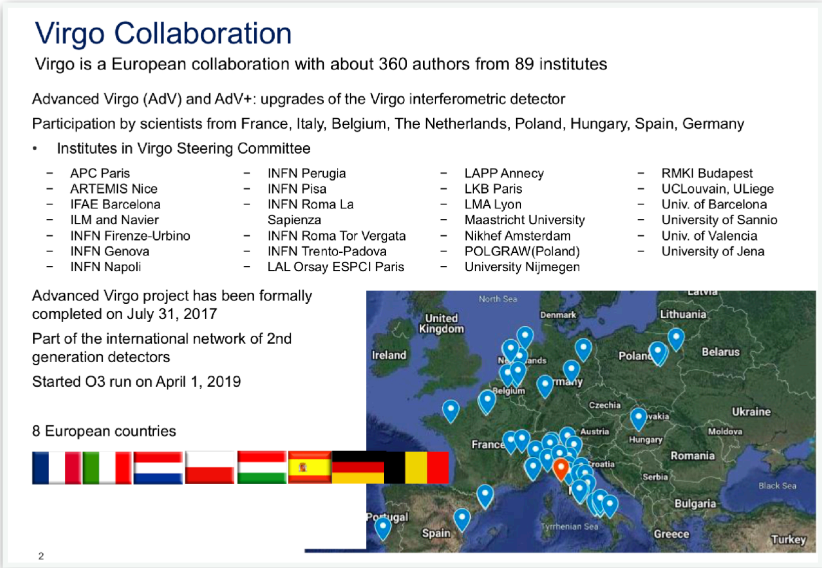




International GW network （国際重力波観測ネットワーク）

LIGO

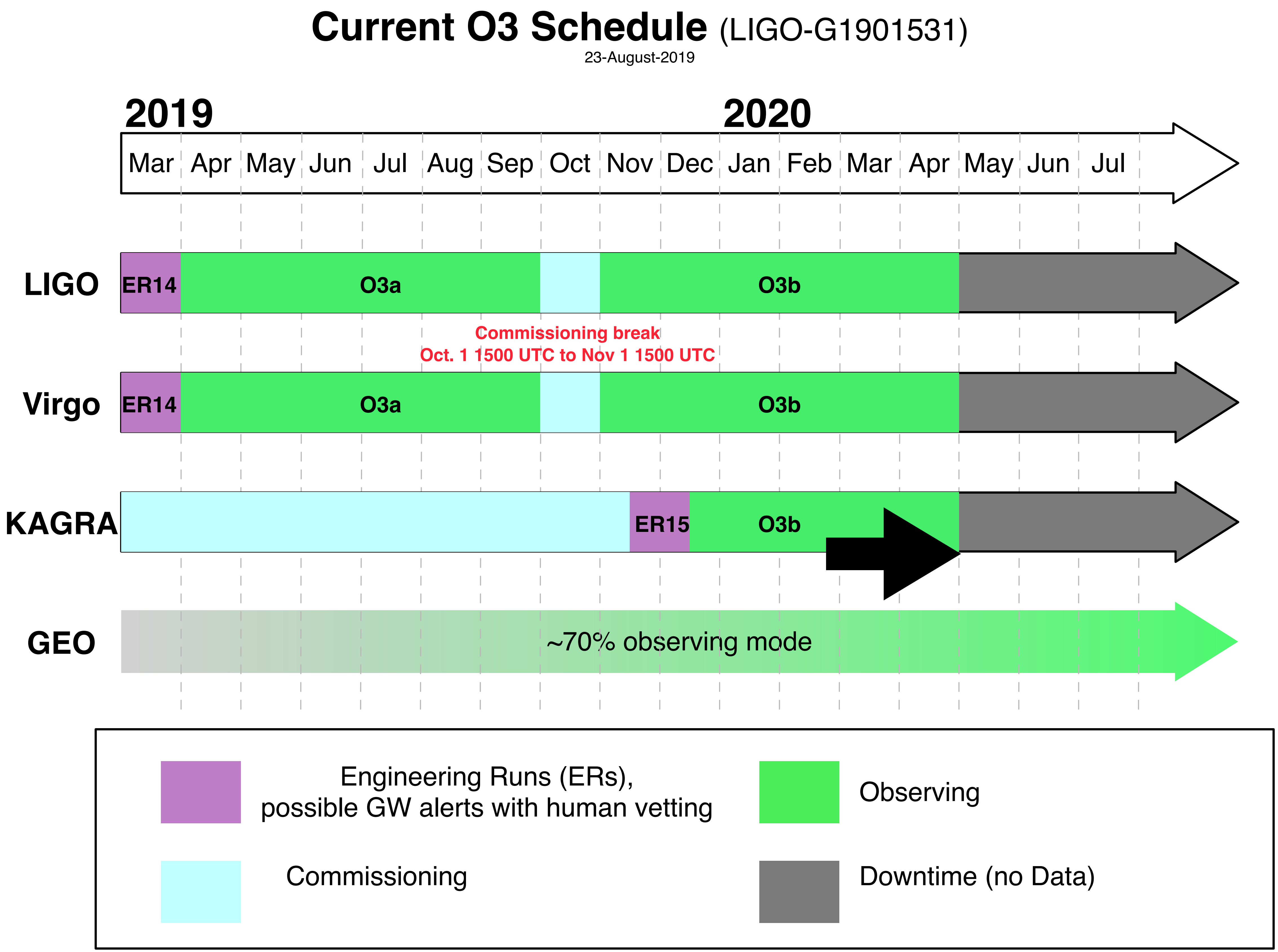
VIRGO



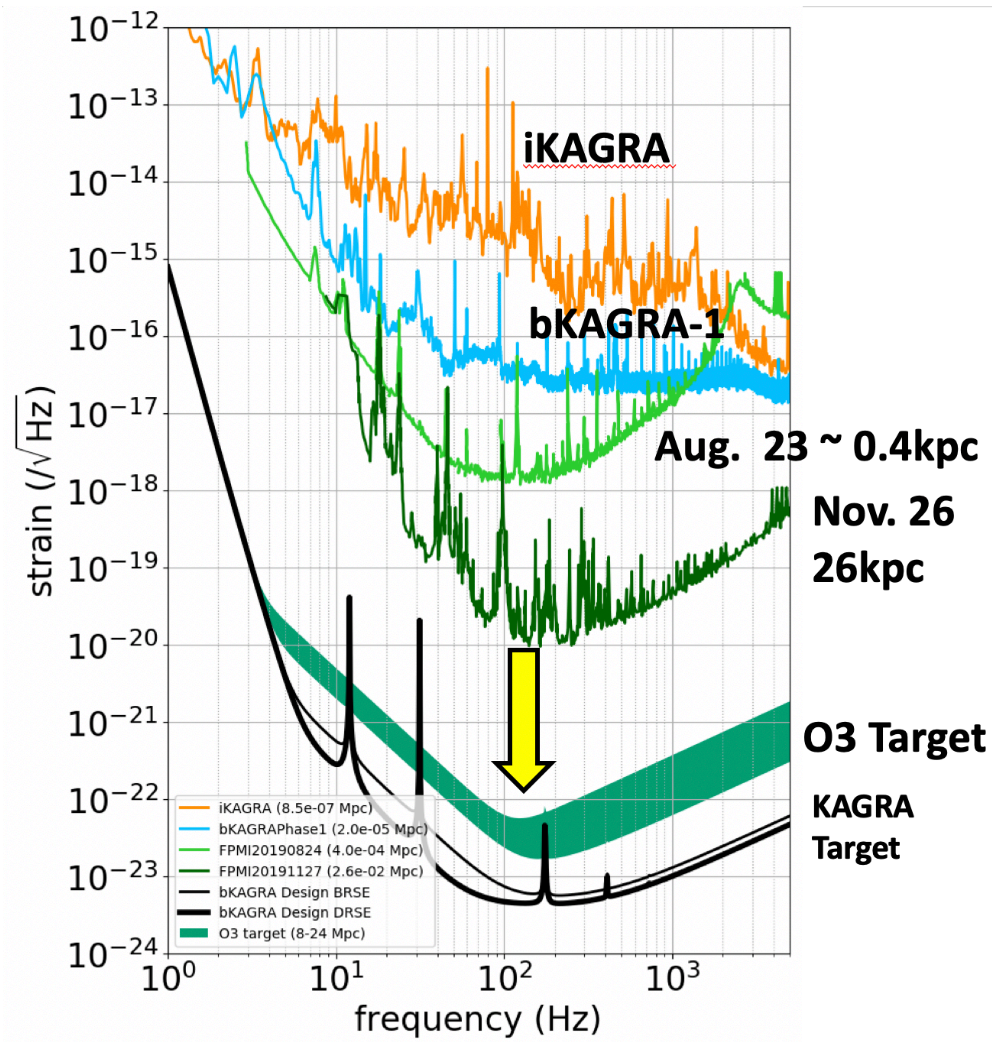
KAGRA

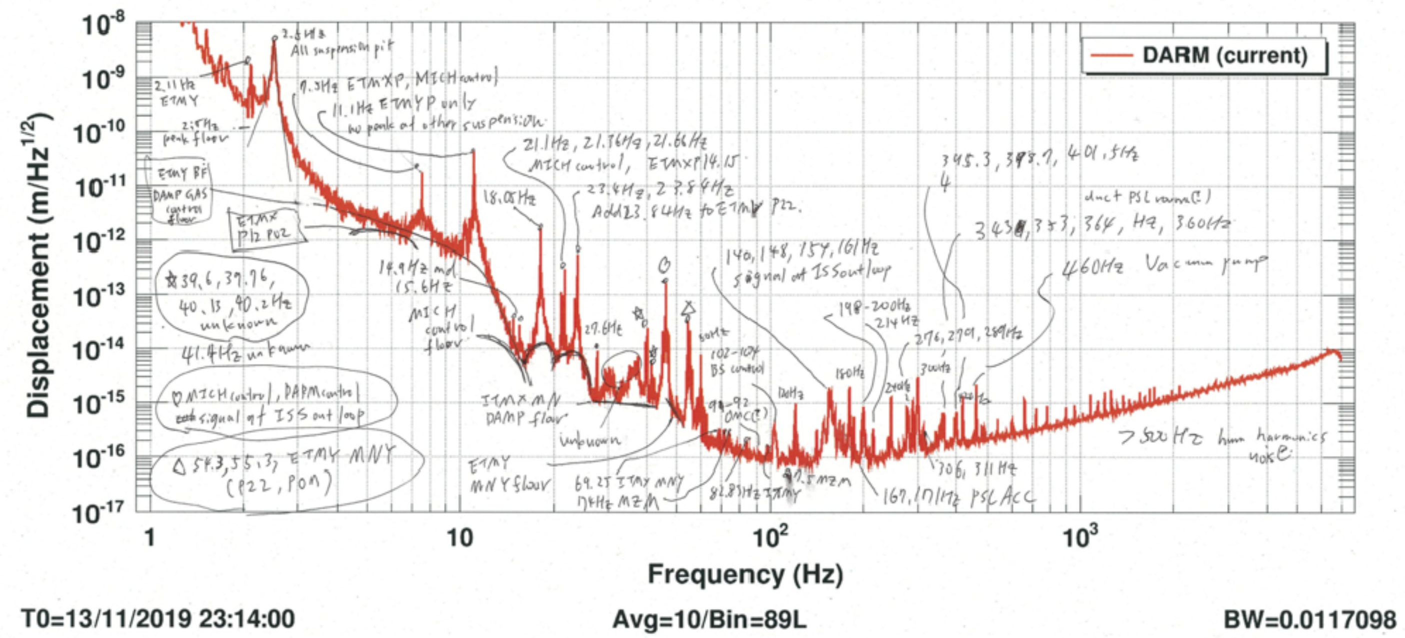
LIGO	VIRGO	KAGRA
1330 members	465 members	360 members
860 authors	360 authors	200 authors
101 groups	96 groups	110 groups
20 countries	8 countries	14 regions

Observation 3



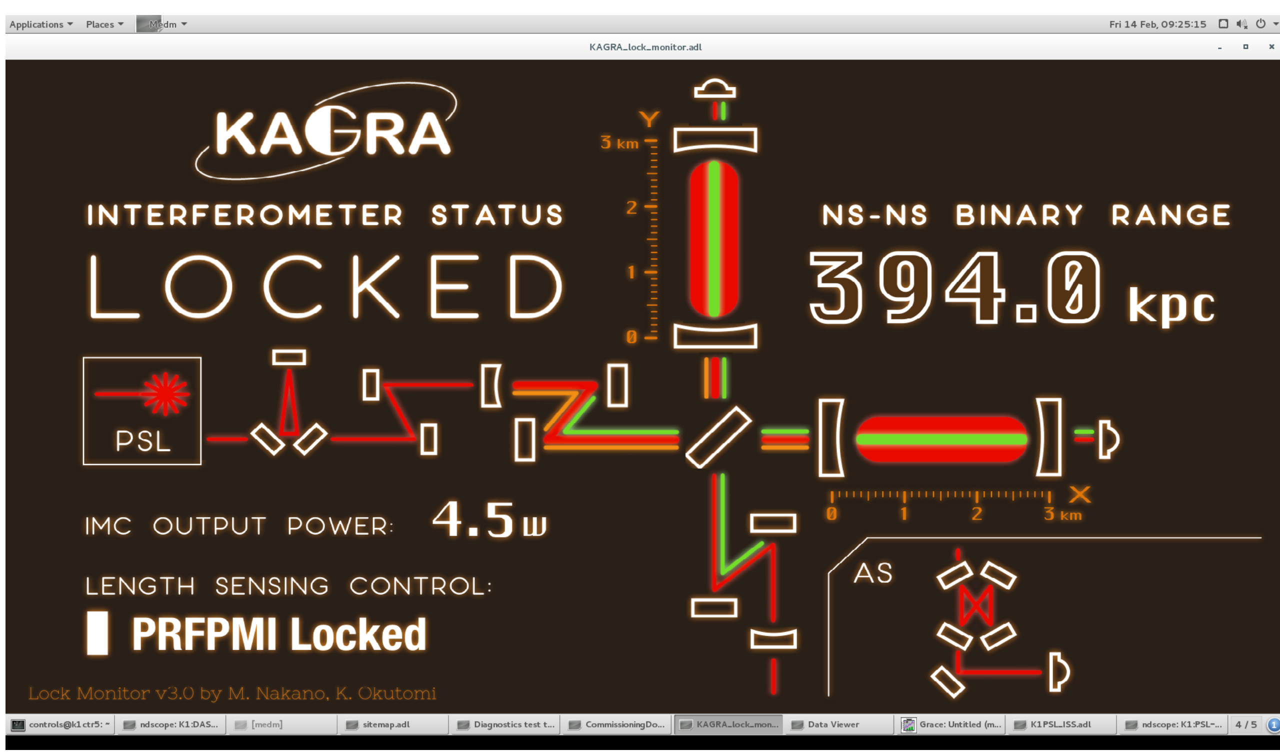
Rush to 1 Mpc by February 25, 2020

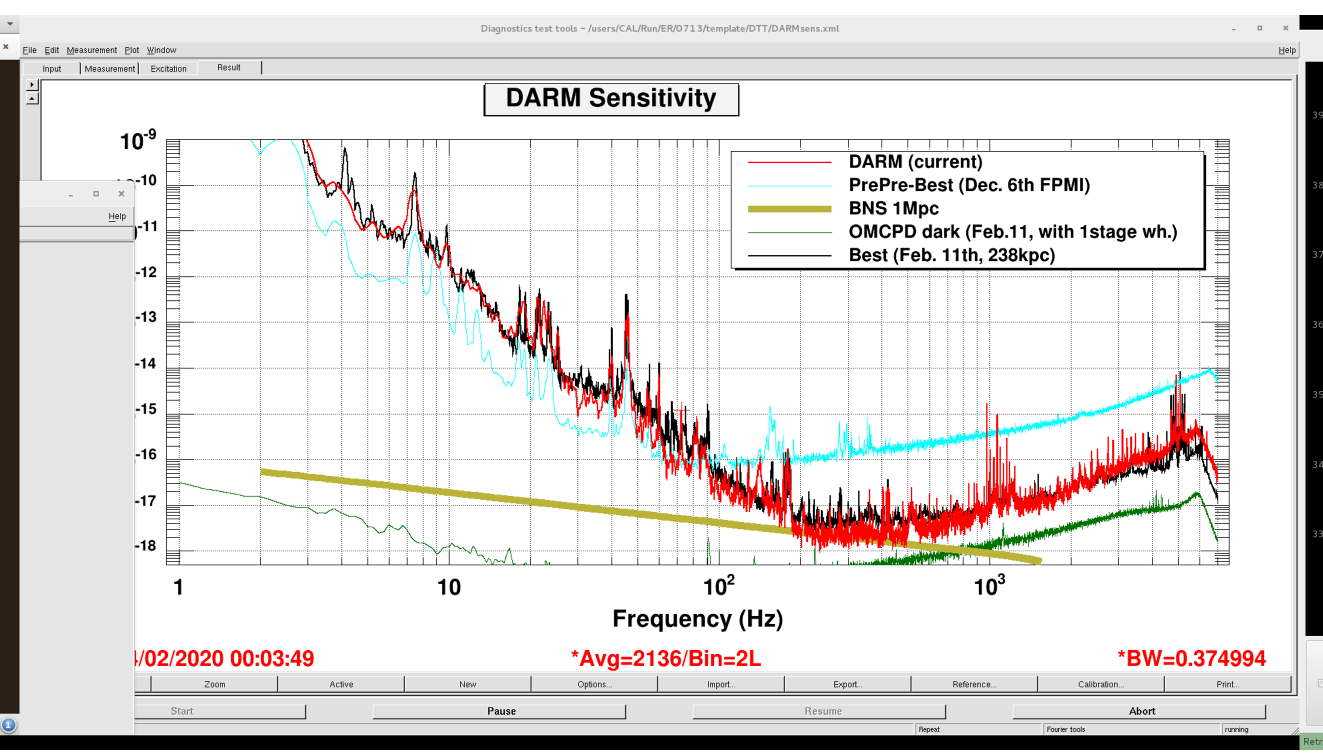




2020/2/13

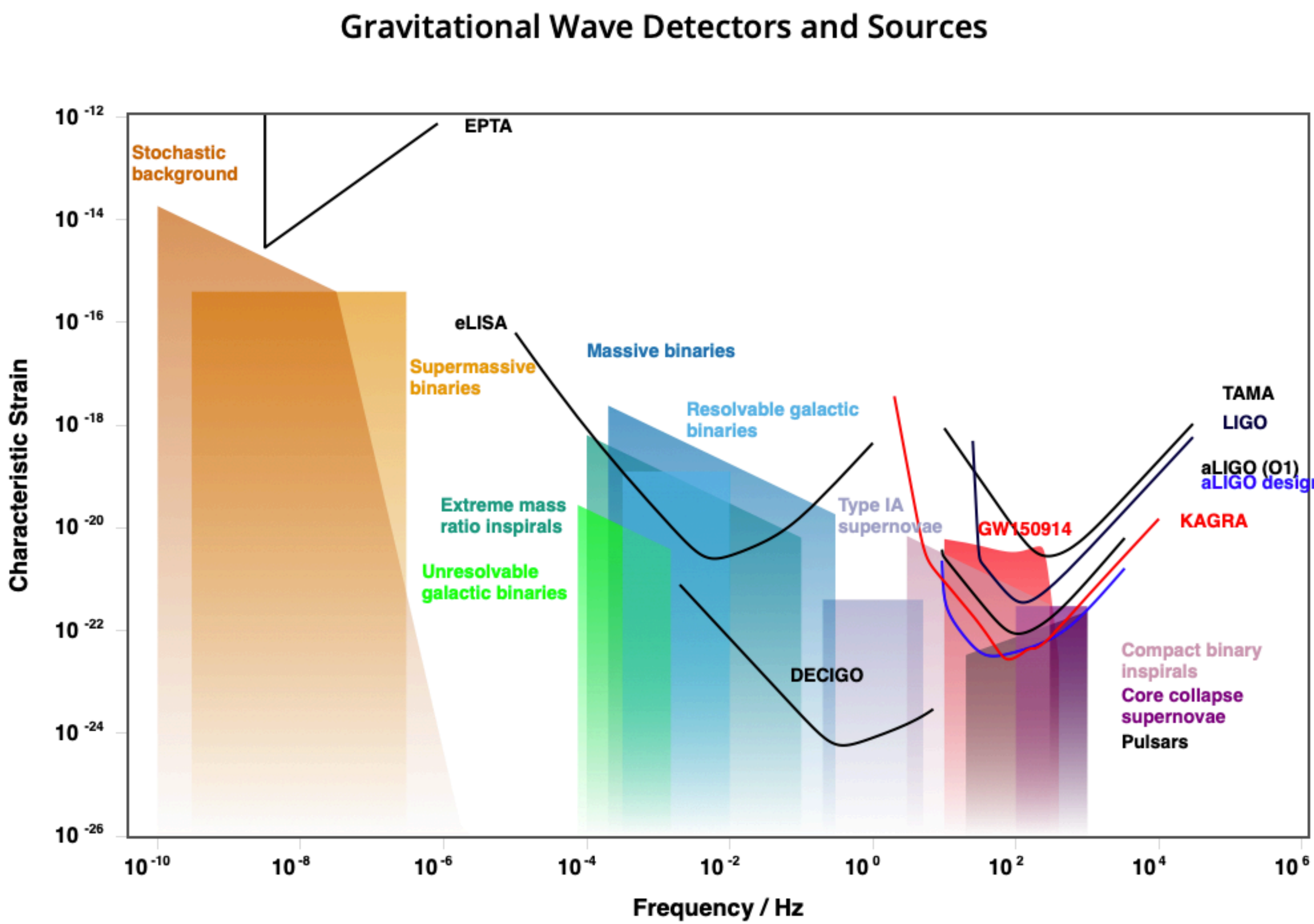
http://klog.icrr.u-tokyo.ac.jp/osl/?r=12961



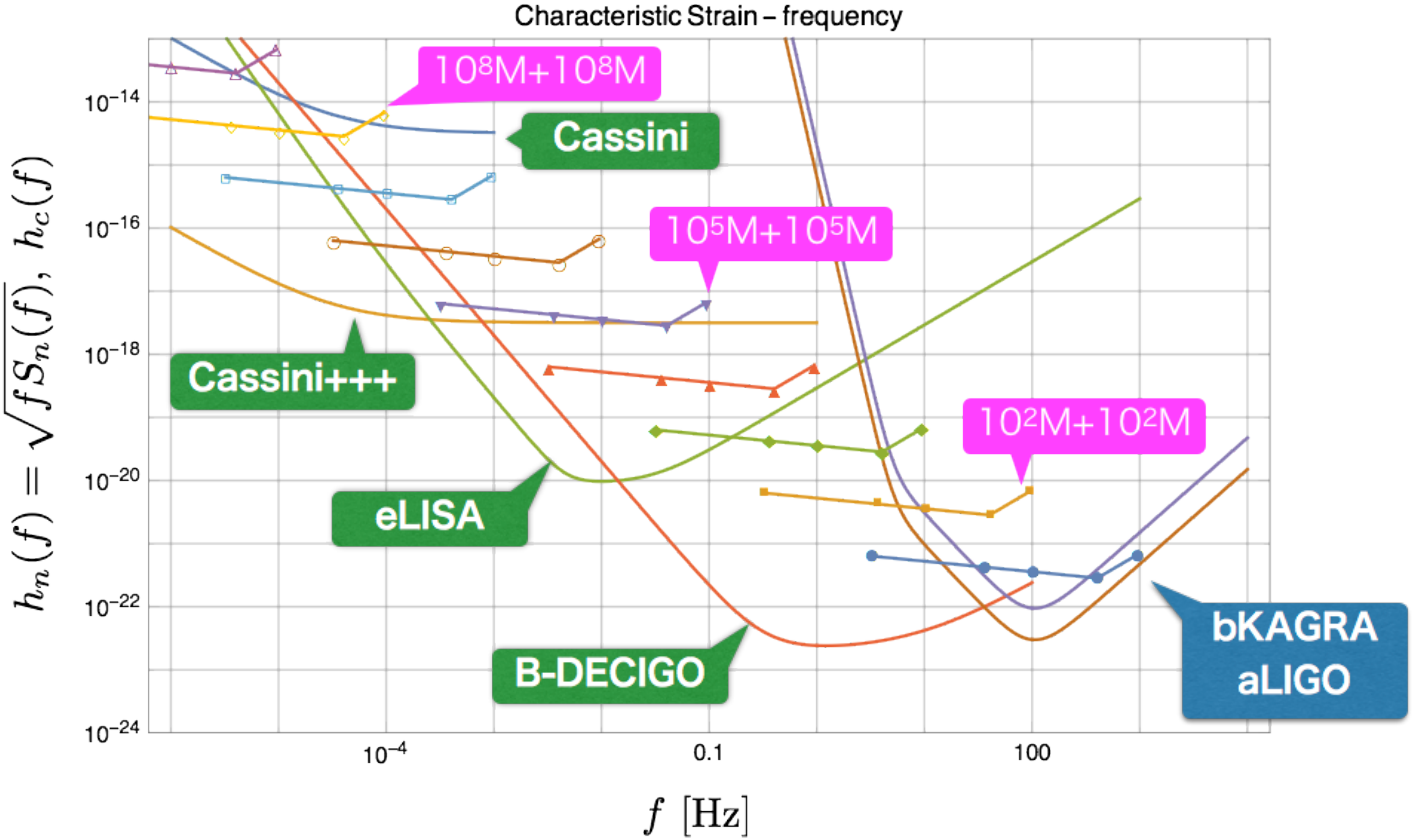


GW observatory plans in space

http://gwplotter.com



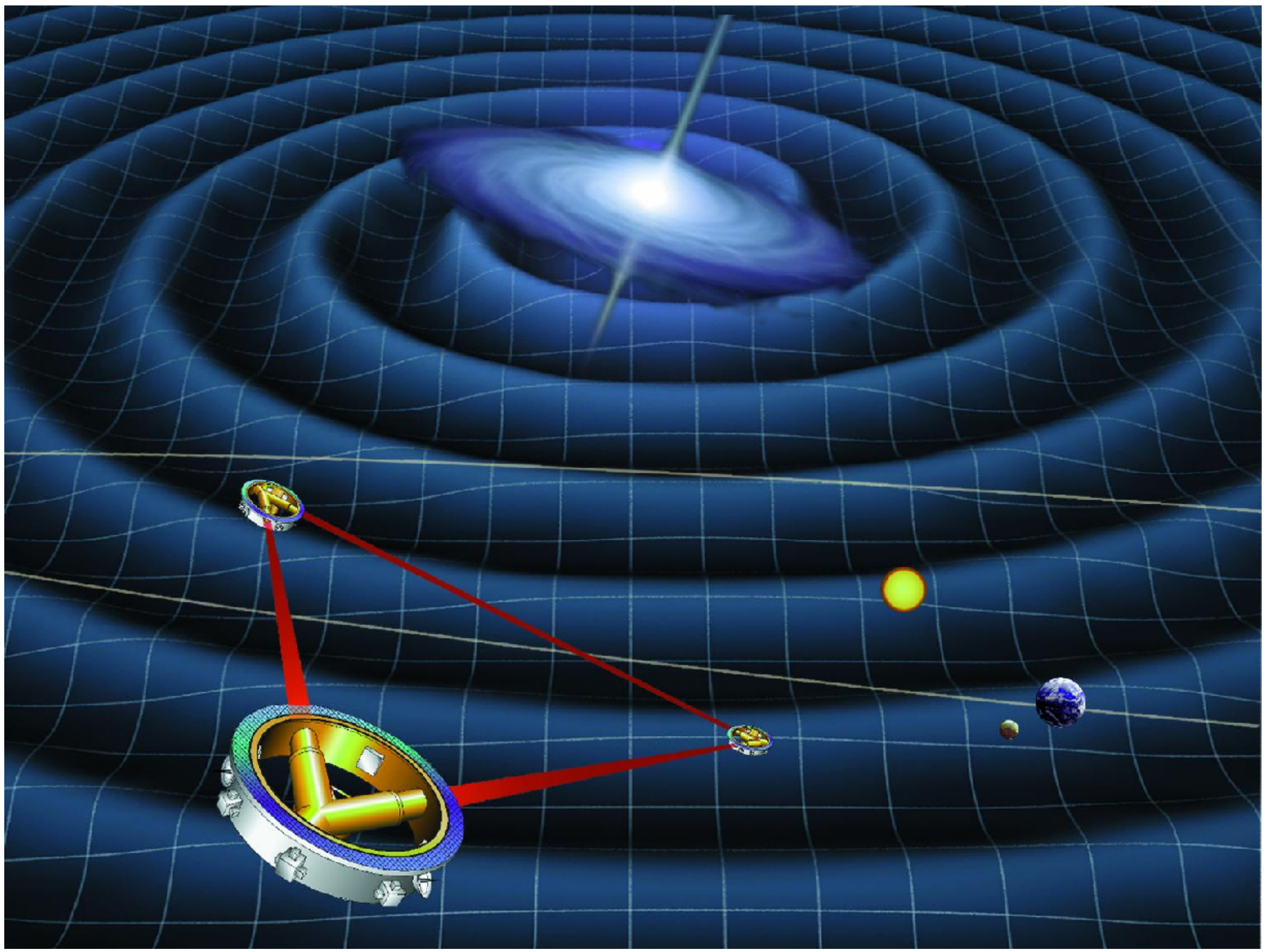
GW observatory plans in space



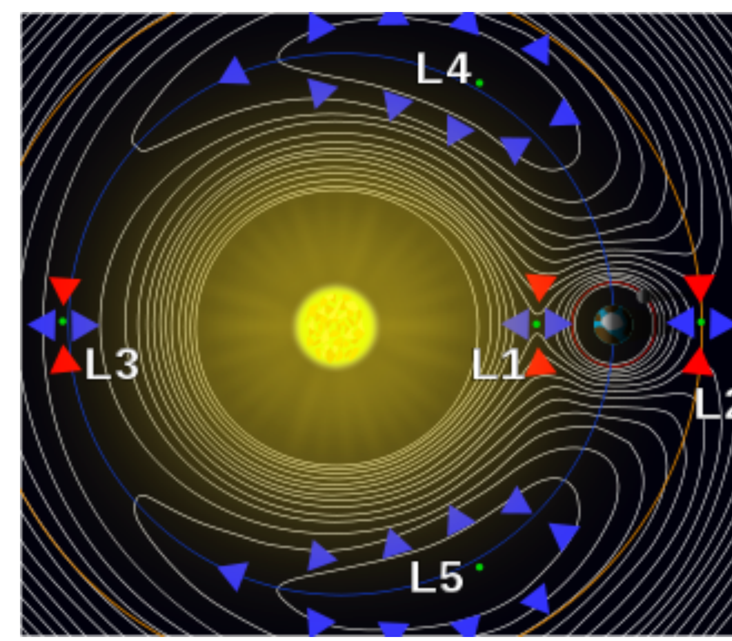
重力波宇宙干渉計LISA（リサ）　ESA予算承認

2017/6/20

Laser Interferometer Space Antenna

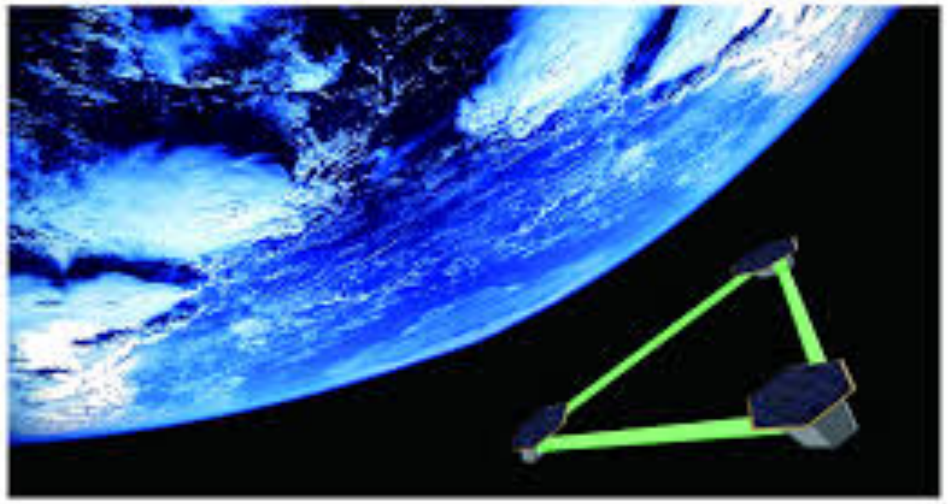


2034年に打ち上げ予定
250万kmの腕の長さ
地球の公転軌道のL4
低周波数帯（mHzからHz帯）



重力波宇宙干渉計DECIGO（ディサイゴ）

Deci-hertz Interferometer Gravitational wave Observatory



1000kmの腕の長さ
低周波数帯（deciHzからHz帯）

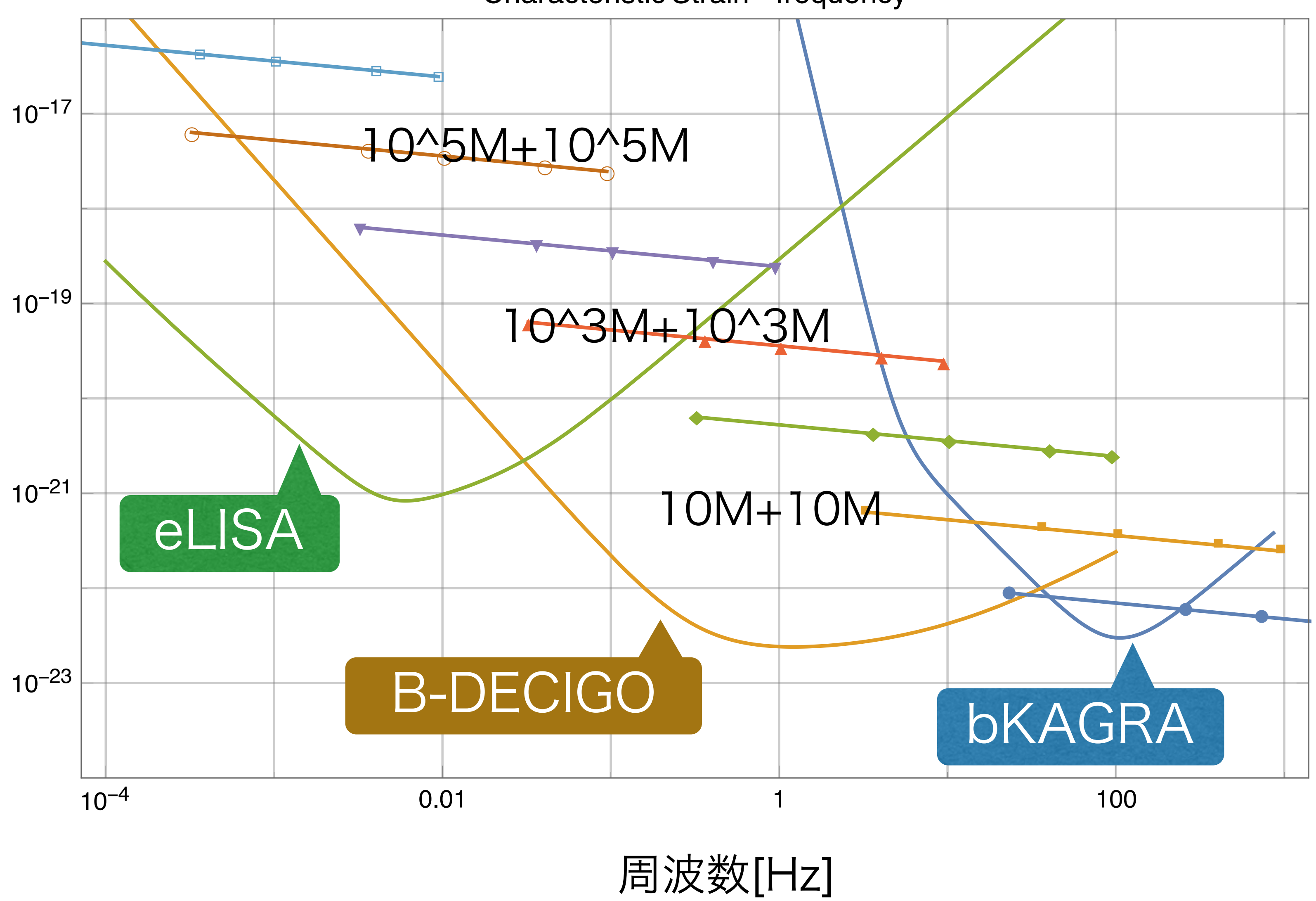
宇宙全体スケールで
巨大ブラックホール連星合体の
重力波が検出できる

↓

銀河中心の超巨大ブラックホール
形成過程がわかる

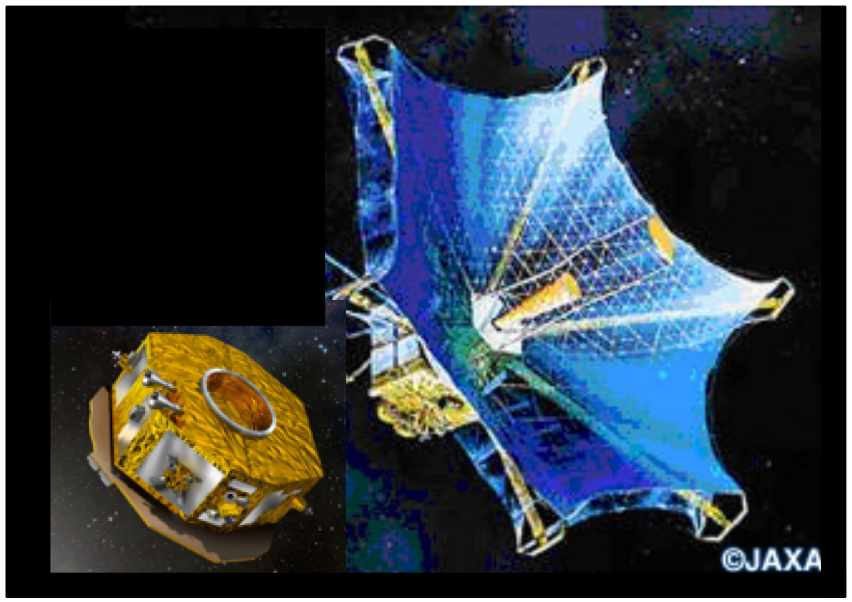
宇宙の膨張速度がわかる

重力波の検出感度



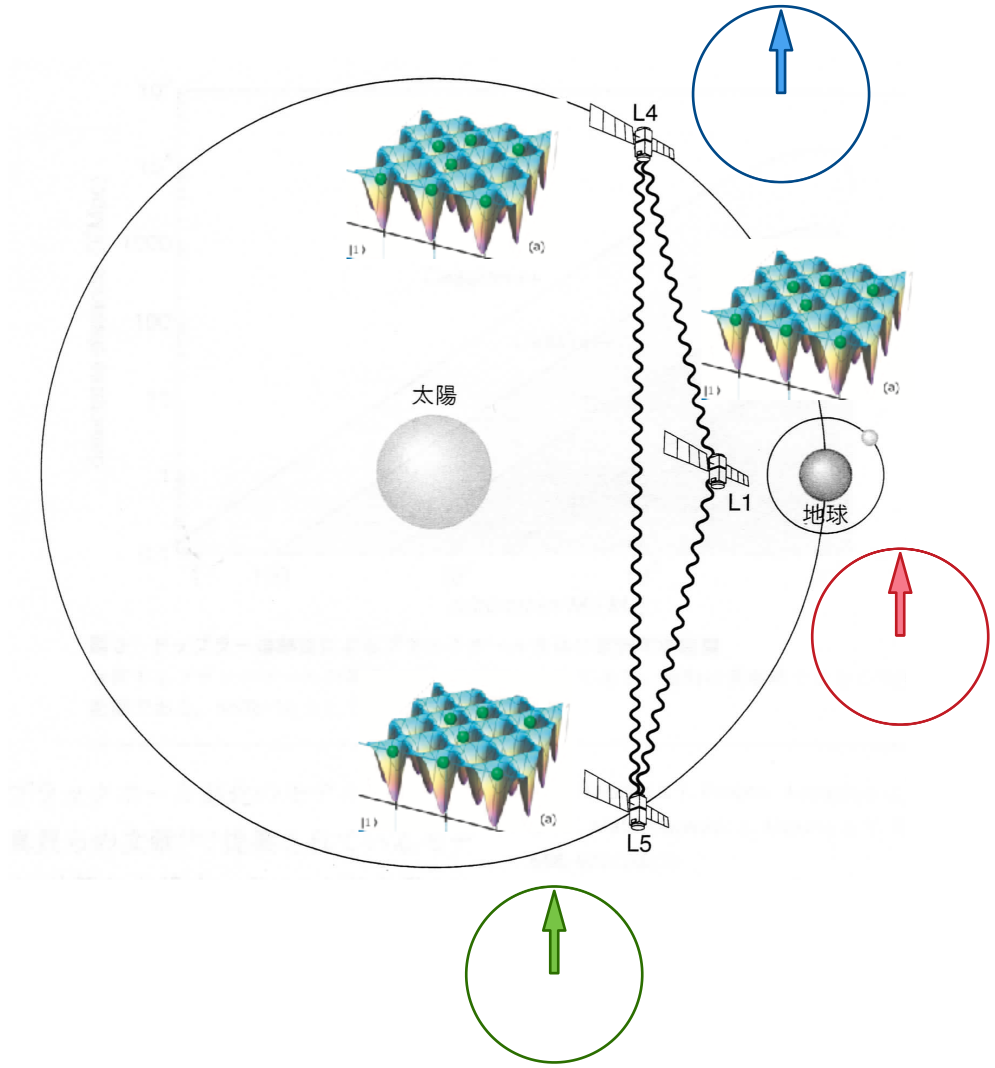
宇宙空間光格子時計ネットワーク INO

Interplanetary Network of Optical Lattice Clocks



宇宙全体スケールで
巨大ブラックホール連星合体の
重力波が検出できる

銀河中心の超巨大ブラックホール
形成過程がわかる



「数理科学」2018-12
「科学」2017-12
Int. J. Mod. Phys.
D 28 (2019) 1940002
[arXiv:1809.10317]

伊能忠敬

江戸時代，日本中で
精密な測量をして地図を作成

BH連星合体から銀河中心SMBHの形成シナリオを決める

★BH連星合体が繰り返されて，SMBHが形成されると考える
★1つの銀河にいくつBH連星合体があるかを数える
★宇宙にいくつ銀河があるかを数える
★LIGOやKAGRAの検出器感度で，1年にいくつ観測できるのか予想する

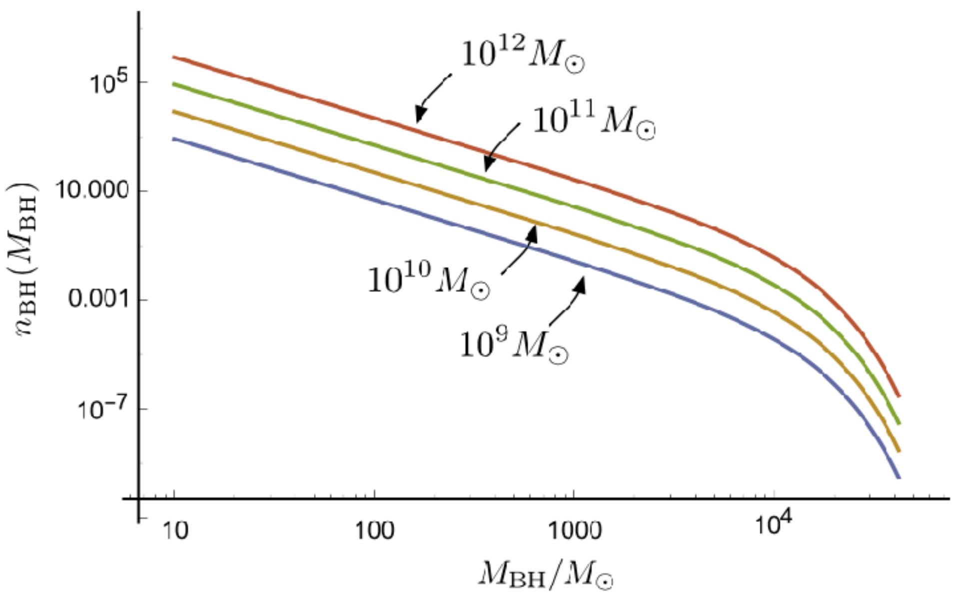


Figure 5. Number density of BHs per galaxy as a function of BH mass for different total mass of galaxies $M_{galaxy} = 10^9 M_\odot, \cdots, 10^{12} M_\odot$.

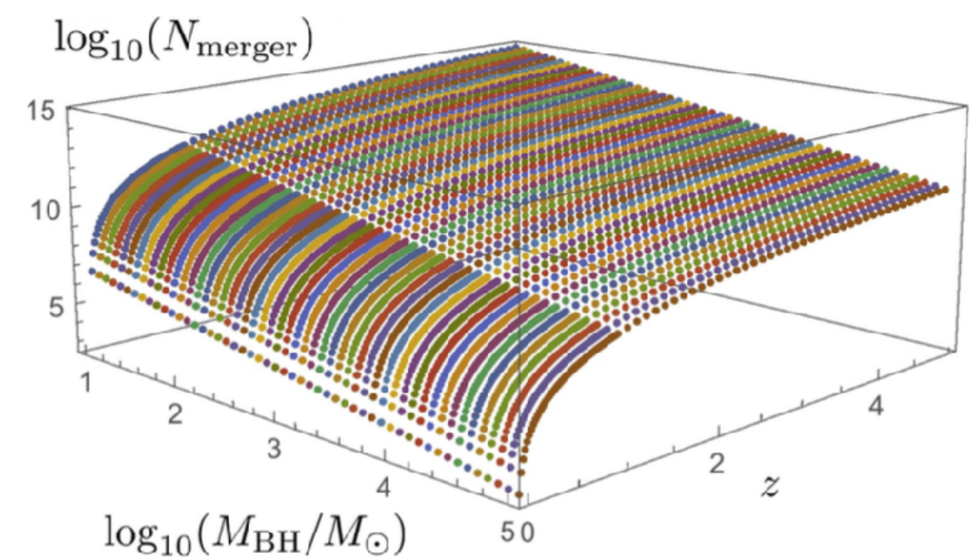


Figure 6. Cumulative distribution function of the number of BH mergers $N_{merger}(M_{BH})$ as a function of the redshift z. N_{merger} is expressed with binned one, of which we binned 20 for one order in M_{BH}.

The Astrophysical Journal, 835:276 (8pp), 2017 February 1
doi:10.3847/1538-4357/835/2/276

CrossMark

Gravitational Waves from Merging Intermediate-mass Black Holes. II. Event Rates at Ground-based Detectors

Hisa-aki Shinkai[1], Nobuyuki Kanda[2], and Toshikazu Ebisuzaki[3]

BH連星合体から銀河中心SMBHの形成シナリオを決める

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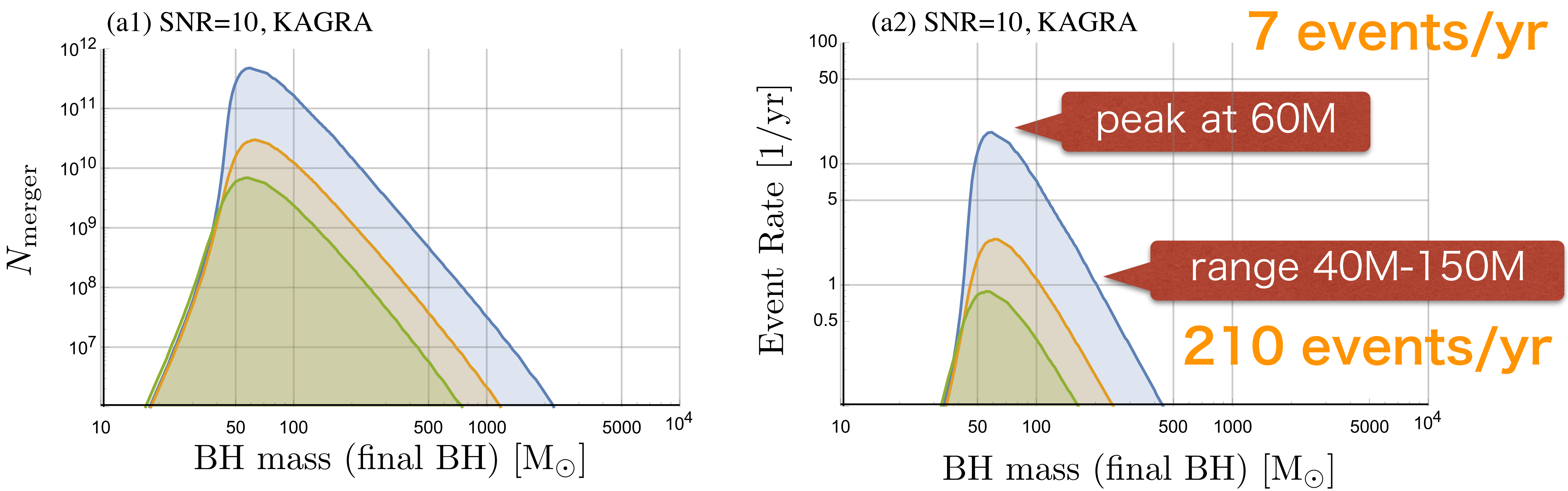
★LIGOやKAGRAの検出器感度で，1年にいくつ観測できるのか予想する



The Astrophysical Journal, 835:276 (8pp), 2017 February 1
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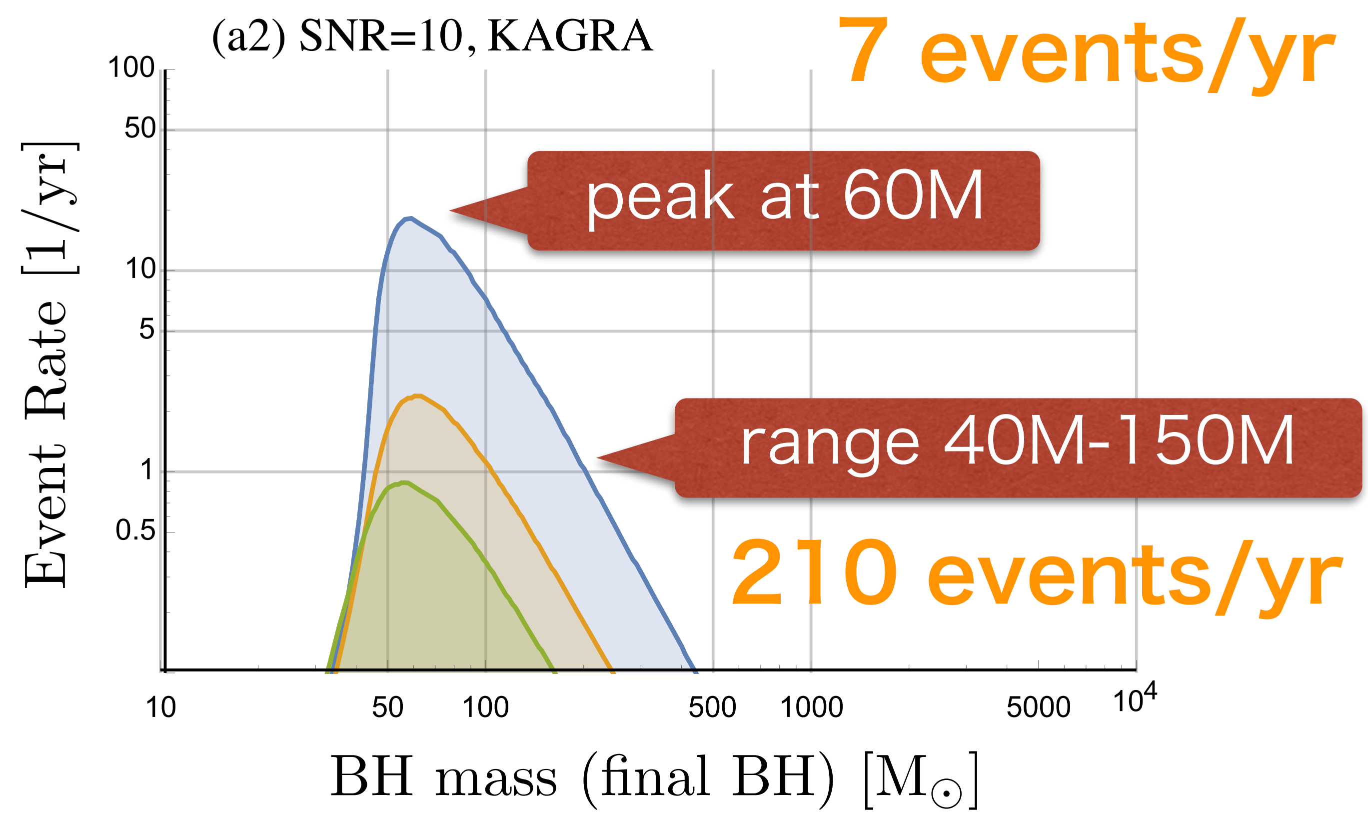
Gravitational Waves from Merging Intermediate-mass Black Holes. II. Event Rates at Ground-based Detectors

Hisa-aki Shinkai[1], Nobuyuki Kanda[2], and Toshikazu Ebisuzaki[3]

Event Rates at bKAGRA/aLIGO

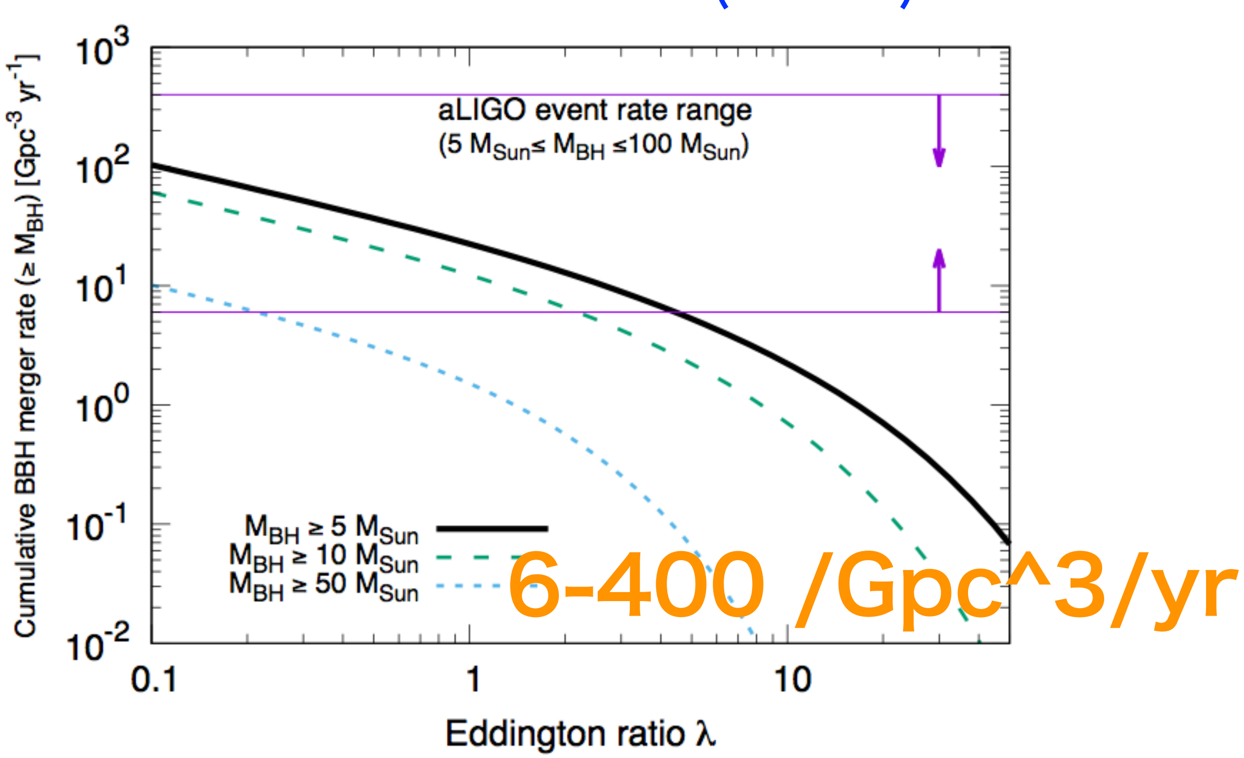
Mass distribution	PyCBC	GstLAL	Combined
	$R/(\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1})$		
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.8}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.1^{+31.0}_{-8.5}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	36^{+95}_{-30}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+103}_{-41}
	Astrophysical		
Flat in log mass	31^{+43}_{-21}	29^{+43}_{-21}	31^{+42}_{-21}
Power law (−2.35)	100^{+136}_{-69}	94^{+137}_{-66}	97^{+135}_{-67}

LIGO group PRX6(2016)041015

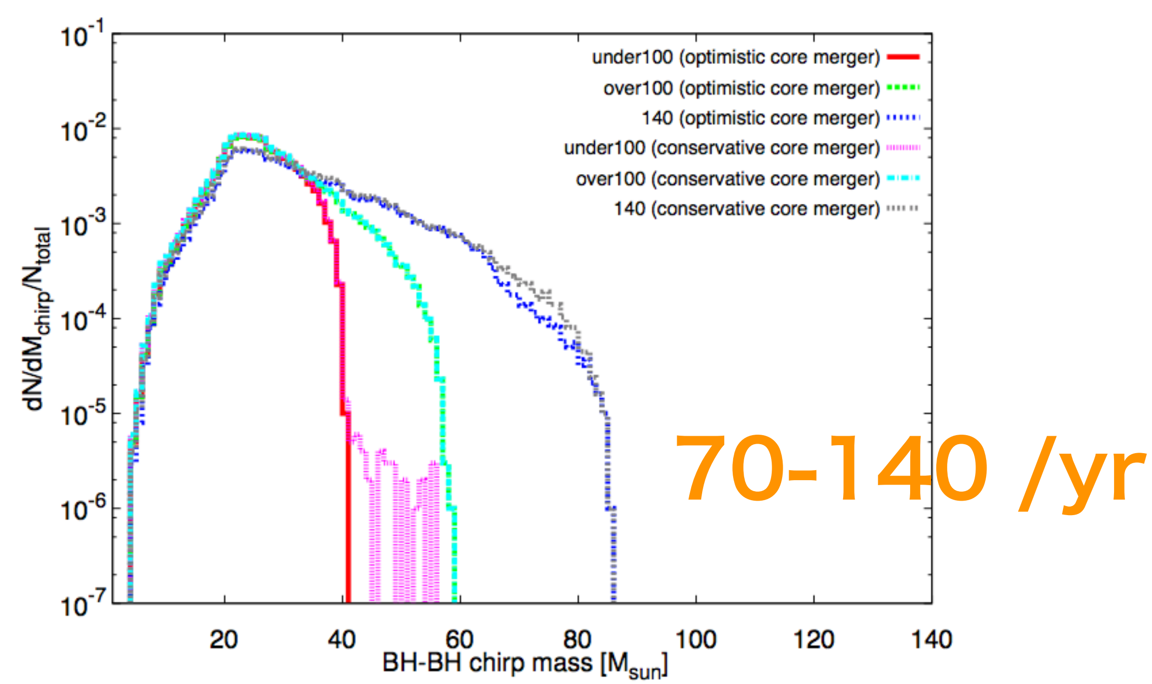


Shinkai+ ApJ 835(2017)276

Inoue+ MNRAS461(2016)4329



Kinugawa+ MNRAS456(2015)1093



	宇宙線	ガンマ線	X線	光			電磁波					
				紫外線	可視光線	赤外線	マイクロ波	超短波	短波	中波	長波	超長波
波長[m]	10^{-13}	10^{-10}	10^{-9}	3.8×10^{-7}	7.7×10^{-7}	10^{-4}	1	10	10^2	10^3	10^4	
波長[nm]				380	770							
振動数[Hz]		3×10^{18}	3×10^{17}			3×10^{12}	3×10^8	3×10^7	3×10^6	3×10^5	3×10^4	
利用例		医療／食品照射	医療／X線写真	殺菌	光学機器	赤外線写真	電子レンジ 携帯電話	FMラジオ テレビ	短波ラジオ	AMラジオ	飛行機の通信 電波時計	

ガンマ線　X線　可視光　赤外　電波

重力波