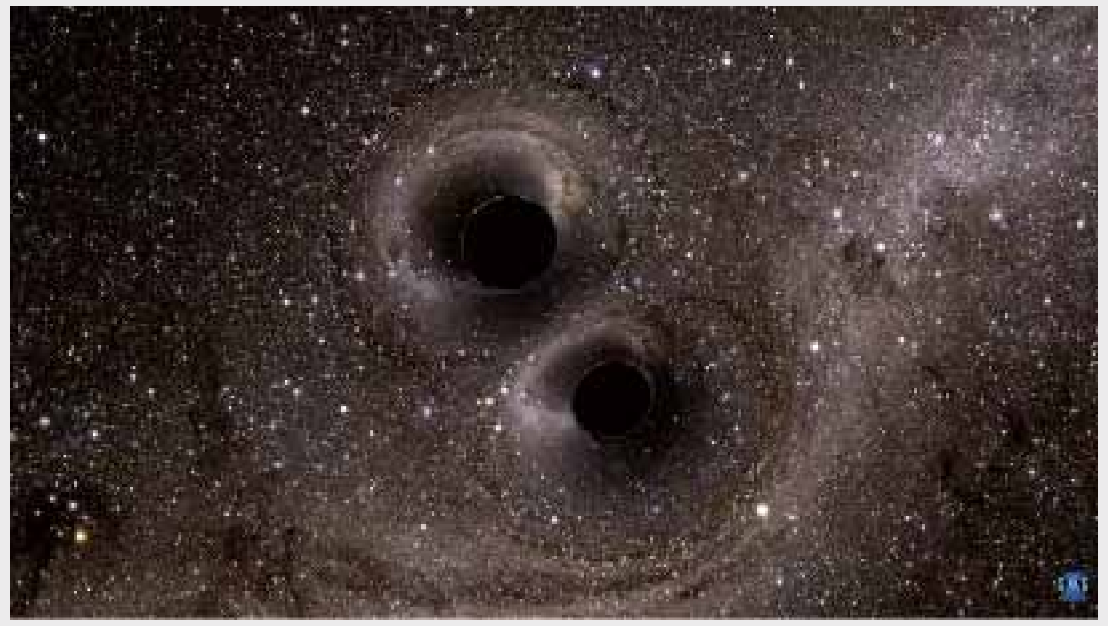
Gravitational wave observation approaching the origin and physics of Black holes

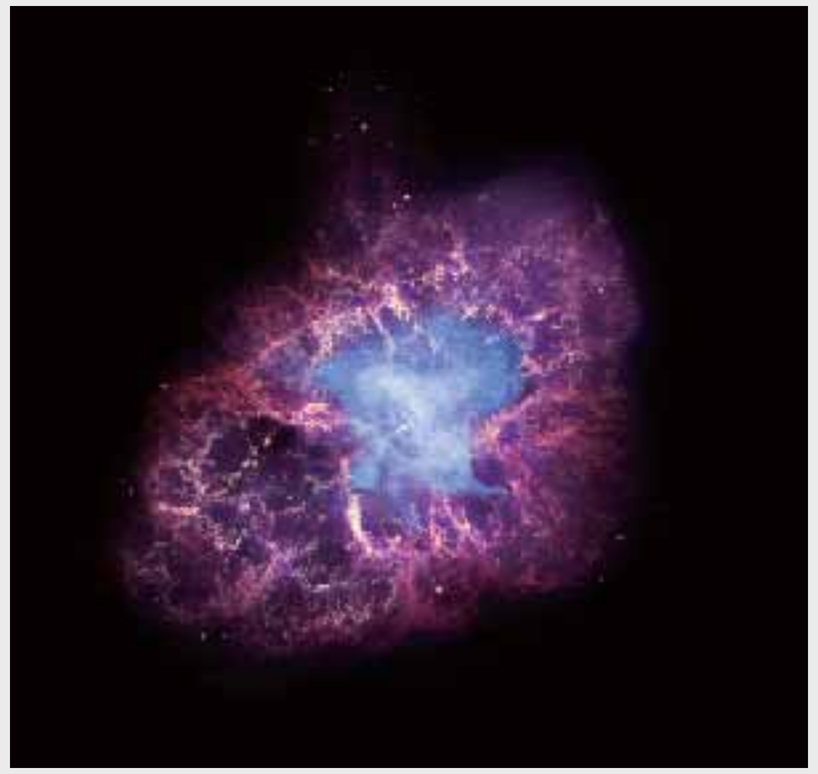
Nobuyuki Kanda (Some viewgraphs are on behalf of KAGRA)
Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP),
Department of Physics, Osaka Metropolitan University

2025/2/8
2nd NTUH-OMU Joint Meeting on Modern Advances in Physics
@NTHU(國立清華大學), Hsinchu, Taiwan

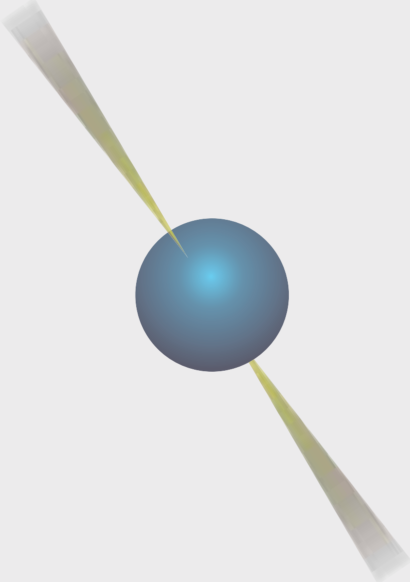
Ground view of Gravitational Wave (GW) observation and its physics



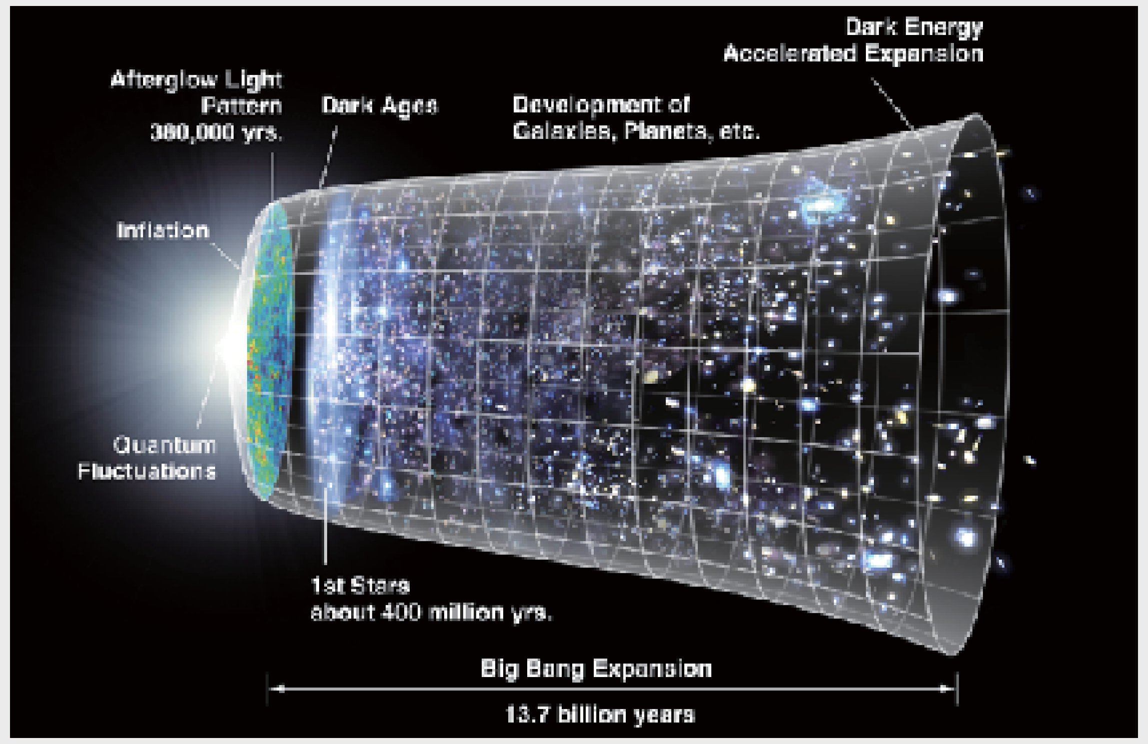
Coalescence of compact binaries:
Black hole (BH) binary,
neutron star (NS) binary, NS-BH



Supernova

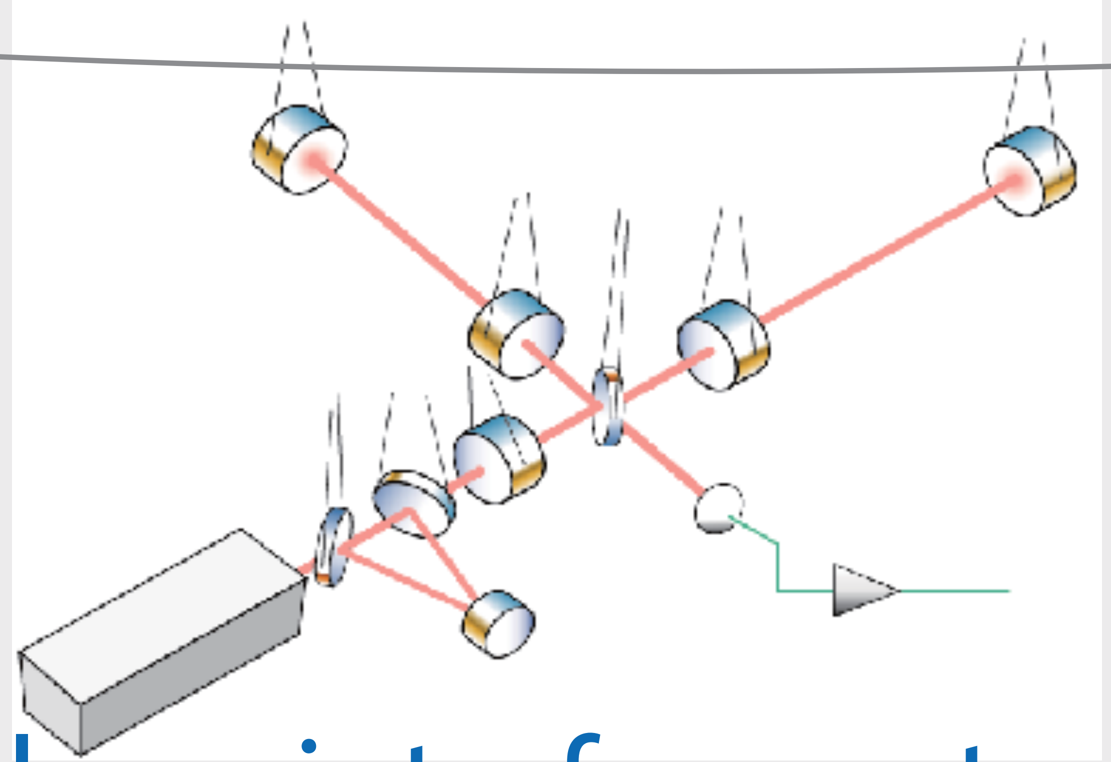


Pulsar



Early universe

Gravitational waves = distortion of space-time



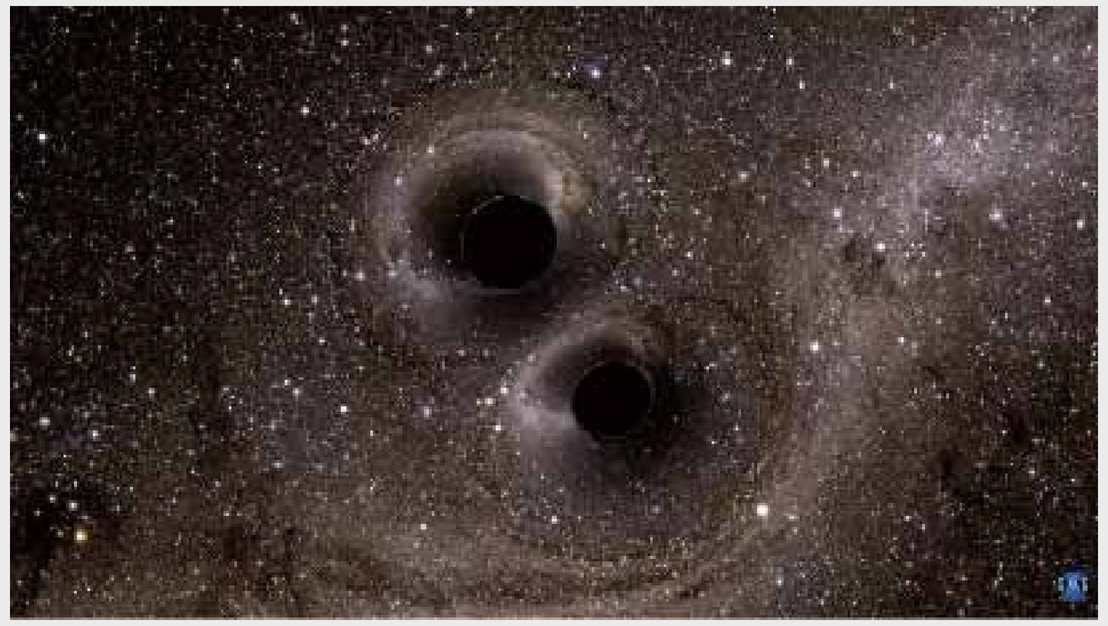
Fundamental physics:
= General relativity
and beyond

Astronomy,
Astrophysics,
Cosmology

laser interferometer

Very high precision measurement of space-time
optics (classical and quantum), electronics, computing, etc...

Ground view of Gravitational Wave (GW) observation and its physics



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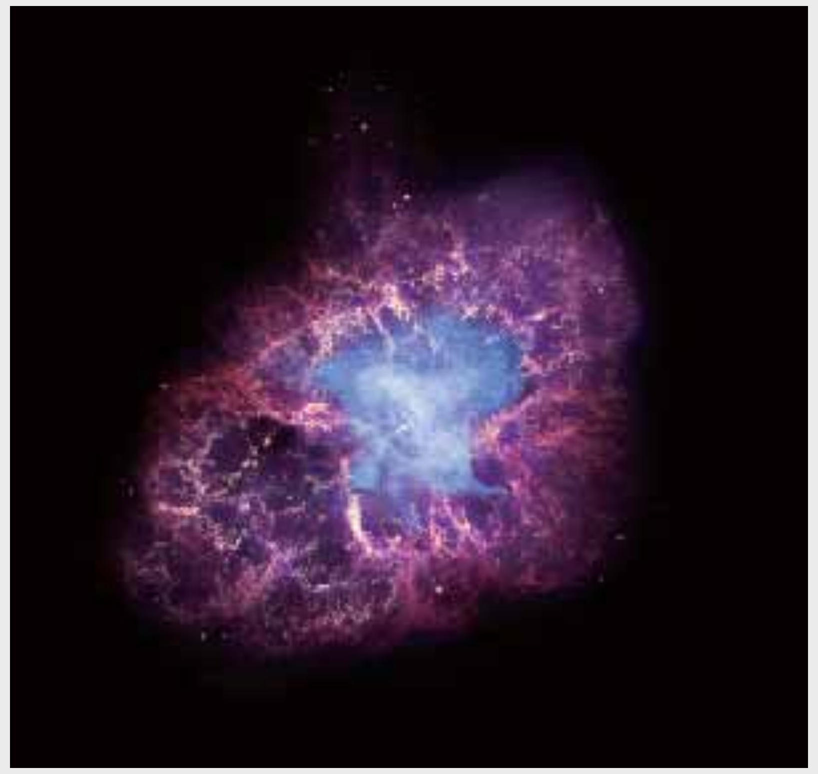

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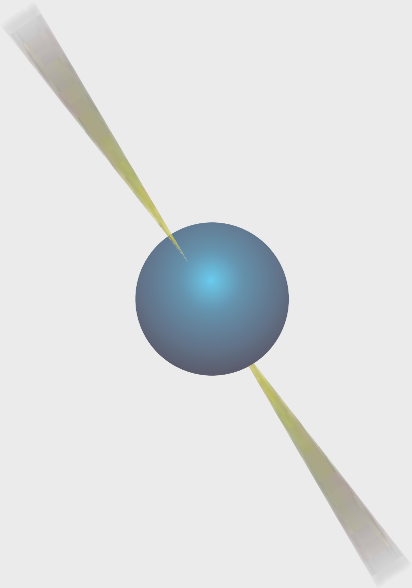

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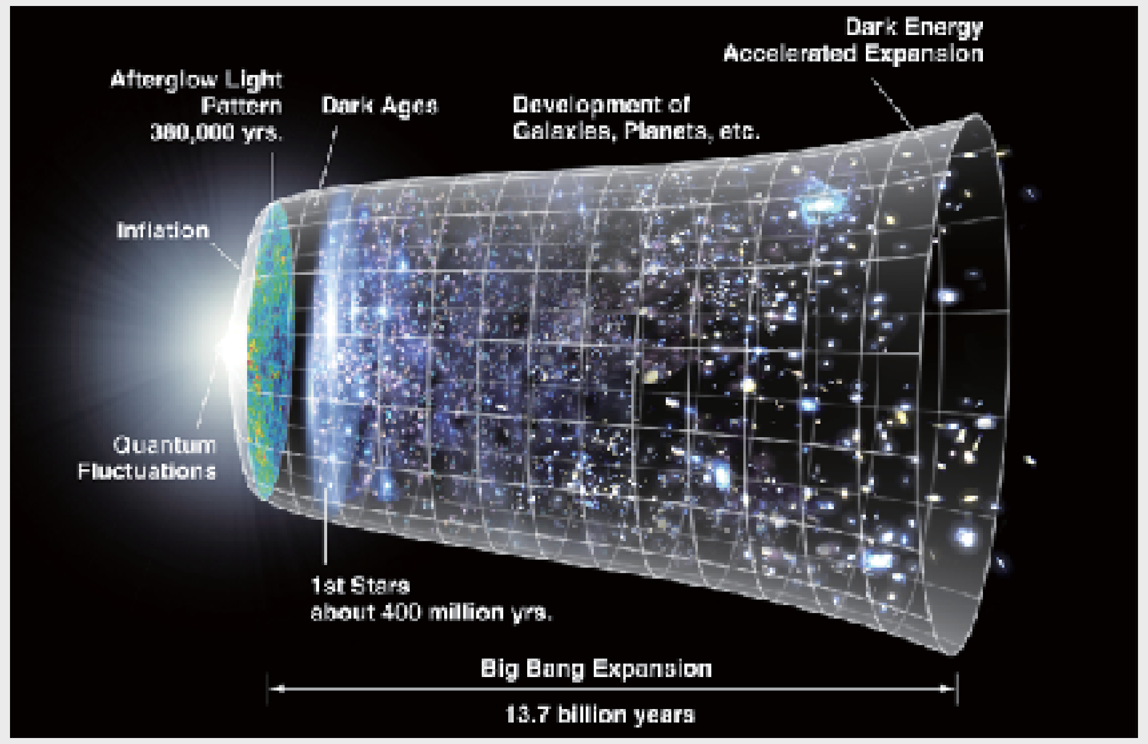

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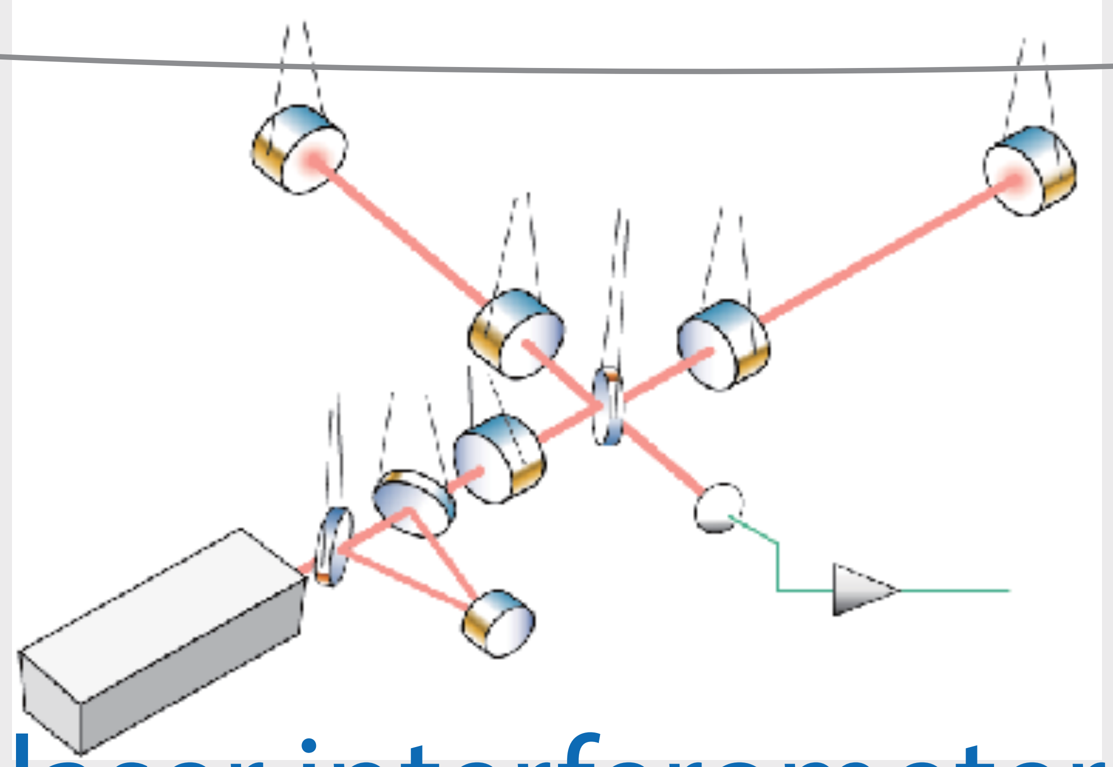

laser interferometer

Astronomy,
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Very high precision measurement of space-time
optics (classical and quantum), electronics, computing, etc...

Gravitational wave physics and Astrophysics Laboratory @ OMU

Research focus : Gravitational Wave observation, Physics/Astronomy of GW

We are dedicated on GW physics.

We are collaborator of KAGRA, large scale laser interferometers. Our laboratory is a one of KAGRA's major data analysis bases.

KAGRA joins the international GW network, so we also worked with LIGO (US) and Virgo(Europa).

- Data analysis, not only for gravitational wave event itself but also many signal processing against noises including methods employing machine learning.
- Data management
- Calibration
- Project management

Staffs :

Nobuyuki Kanda, Yosuke Itoh,
Guo Chin Liu (Tamkang University, NITEP Guest professor)
11 students, 1 secretary in FY2024

Workshop on "還暦" 60th birthday of NK @2024/10/24-25

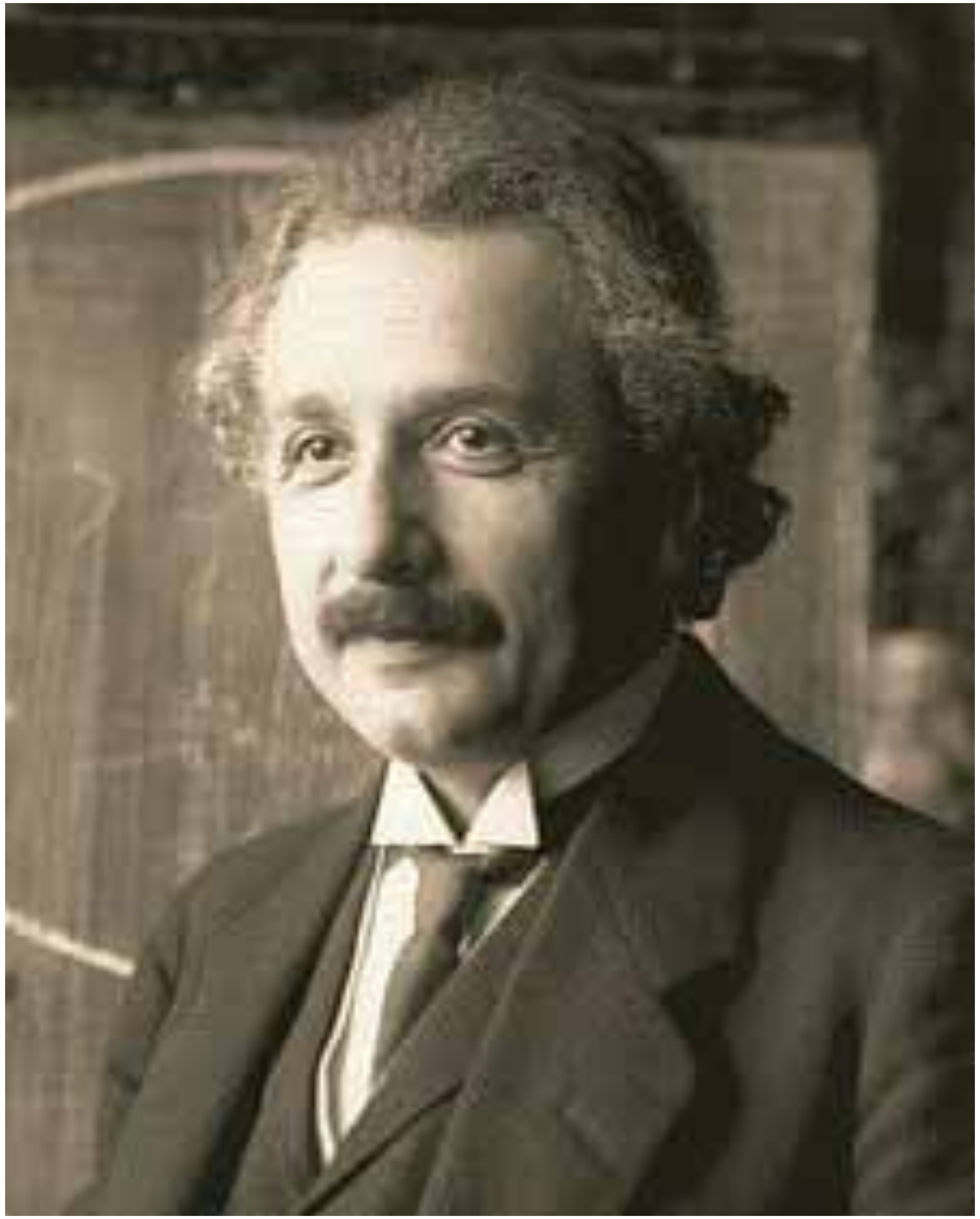
The laboratory has produced many members who are involved in KAGRA, especially in data analysis.

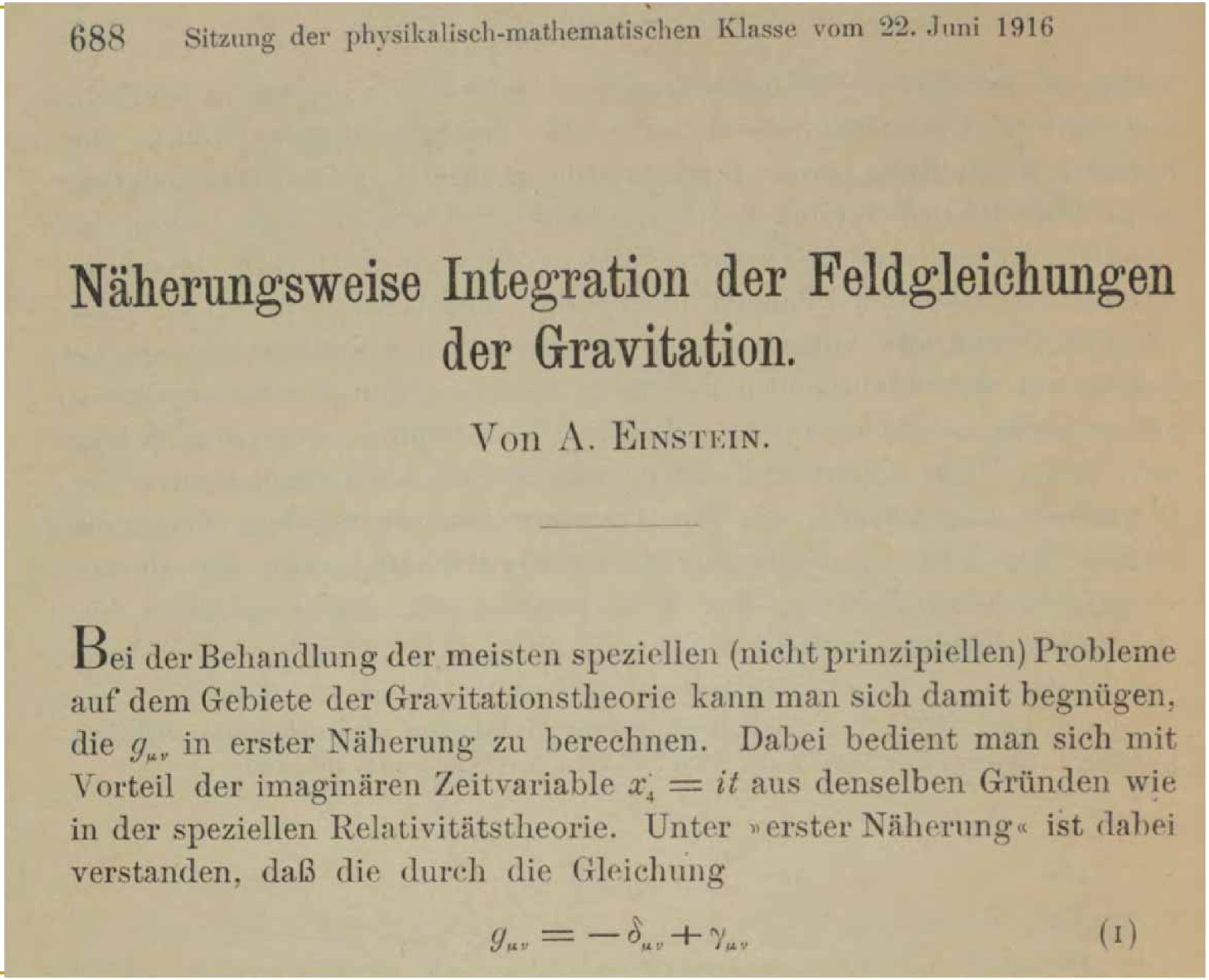
プログラム

Oct. 24	Duration	Speaker	Speaker	Talk title
Chair: 賈				
14:00	10 min.	神田　展行	KANDA Nobuyuki	Opening
14:10	30 min.	藤森　匠	FUJIMORI Takumi	重力波検出器での超軽量暗黒物質探索に向けた最適なデータ解析手法の開発
14:40	30 min.	岩永　響生	IWANAGA Hibiki	深層学習を用いた重力波信号解析による有効スピン推定
15:10	10 min.	休憩		break
Chair: 岩永				
15:20	40 min.	高橋　弘毅	TAKAHASHI Hirotaka	機械学習の重力波データ解析への応用
16:00	25 min.	譲原　浩貴	YUZURIHARA Hirotaka	重力波望遠鏡KAGRAにおける鏡のモニタリングシステム
16:25	15 min.	休憩		break
Chair: 山本				
16:40	20 min.	成川　達也	NARIKAWA Tatsuya	Graviton Oscillations
17:00	20 min.	大原　謙一	OOHARA Ken-ichi	Hilbert Huang Transform
17:20	20 min.	神田　展行	KANDA Nobuyuki	Laplace Transformation for CBC
19:00			懇親会/Banquet	
Oct. 25				
Chair: 川本				
11:00	20 min.	内潟　那美	UCHIKATA Nami	リングダウン解析について
11:20	20 min.	横澤　孝章	YOKOZAWA Takaaki	環境雑音に関する研究
11:40	20 min.	山本　尚弘	YAMAMOTO Takahiro	重力波低遅延探索と検出器特性評価・較正
12:00	1h30min.	昼食		lunch
Chair: 藤森				
13:30	30 min.	川本　竜生	KAWAMOTO Ryuki	重力波望遠鏡KAGRAにおける干渉計制御系の時刻同期精度の評価
14:00	30 min.	賈　依珠美	KAKU Izumi	Gravitational wave radiometry with Stokes parameters
14:30	10 min.	神田　展行	KANDA Nobuyuki	Closing

more 100 years ago...

Einstein's General Relativity and Gravitational Wave (GW) : June 1916





688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

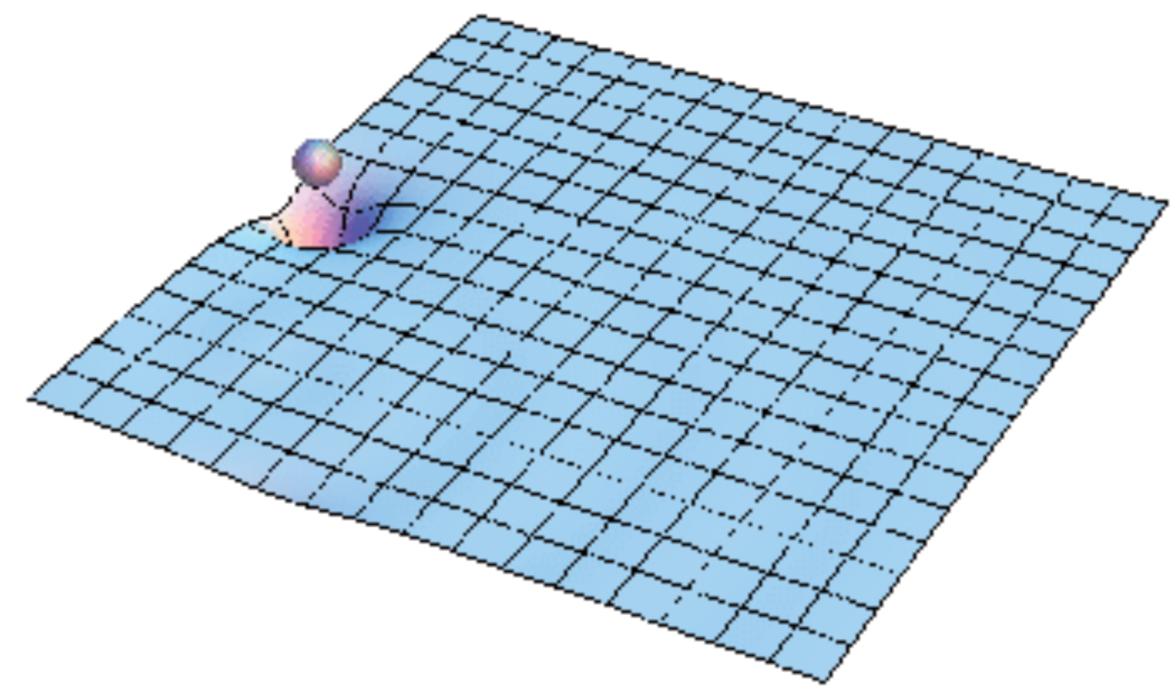
Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

GW from Transient Astronomical Objects



Gravitational Wave

is a wave of distortion of space-time.

strain : *h(t)*

speed of light

transverse

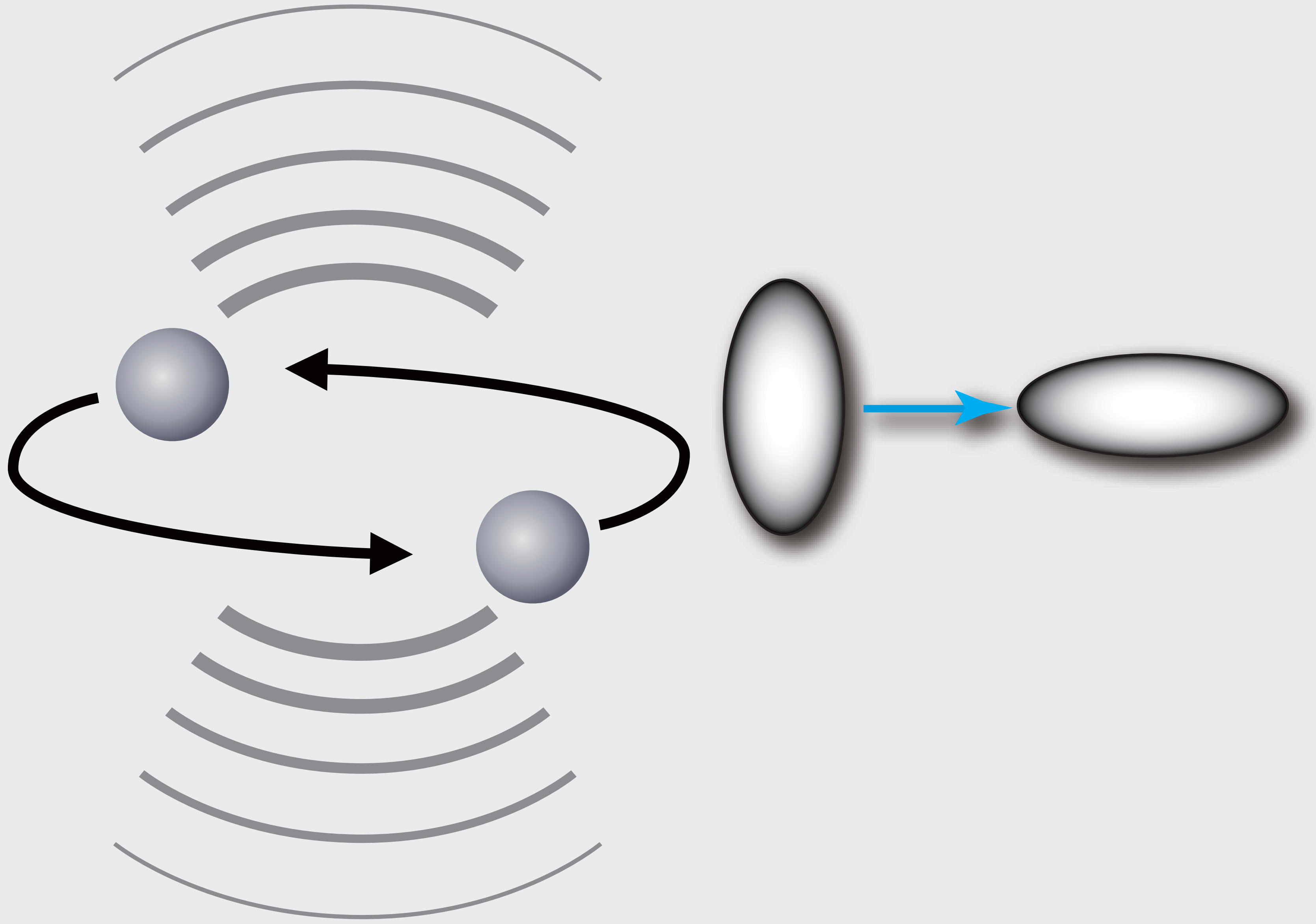
lowest order : mass quadrupole $\ddot{I}_{\mu\nu},\ \dddot{I}_{\mu\nu}$

Possible Sources for current observation : Compact and/or Energetic Object

Compact Binary

Supernovae

Pulsar



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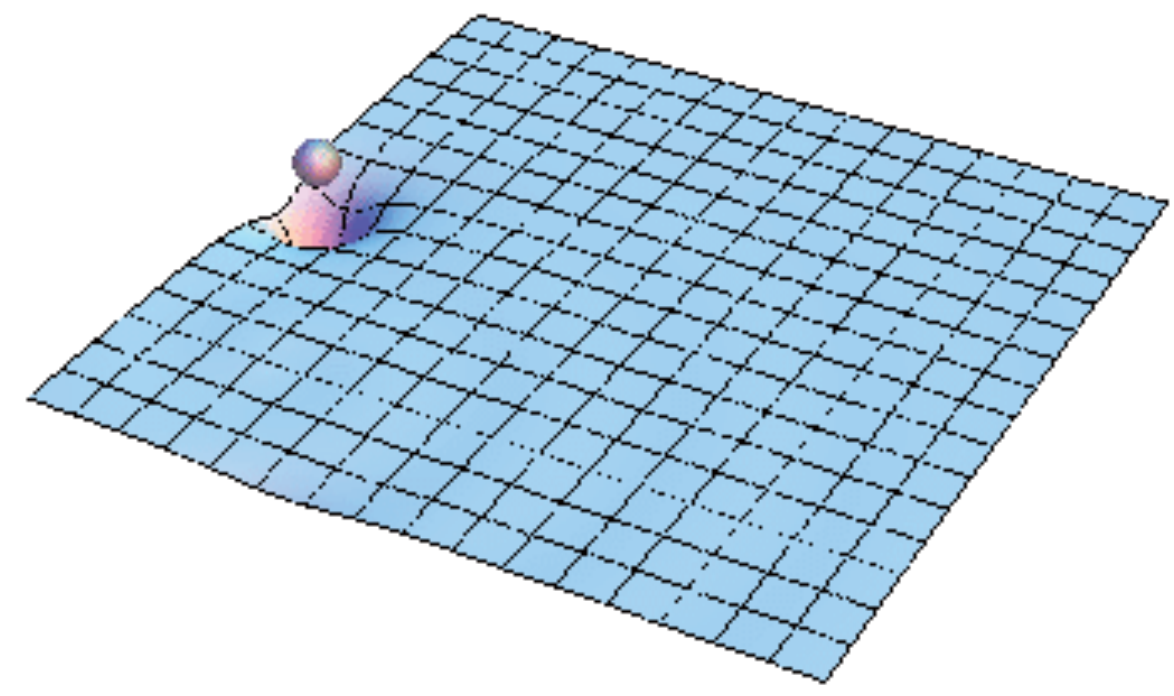

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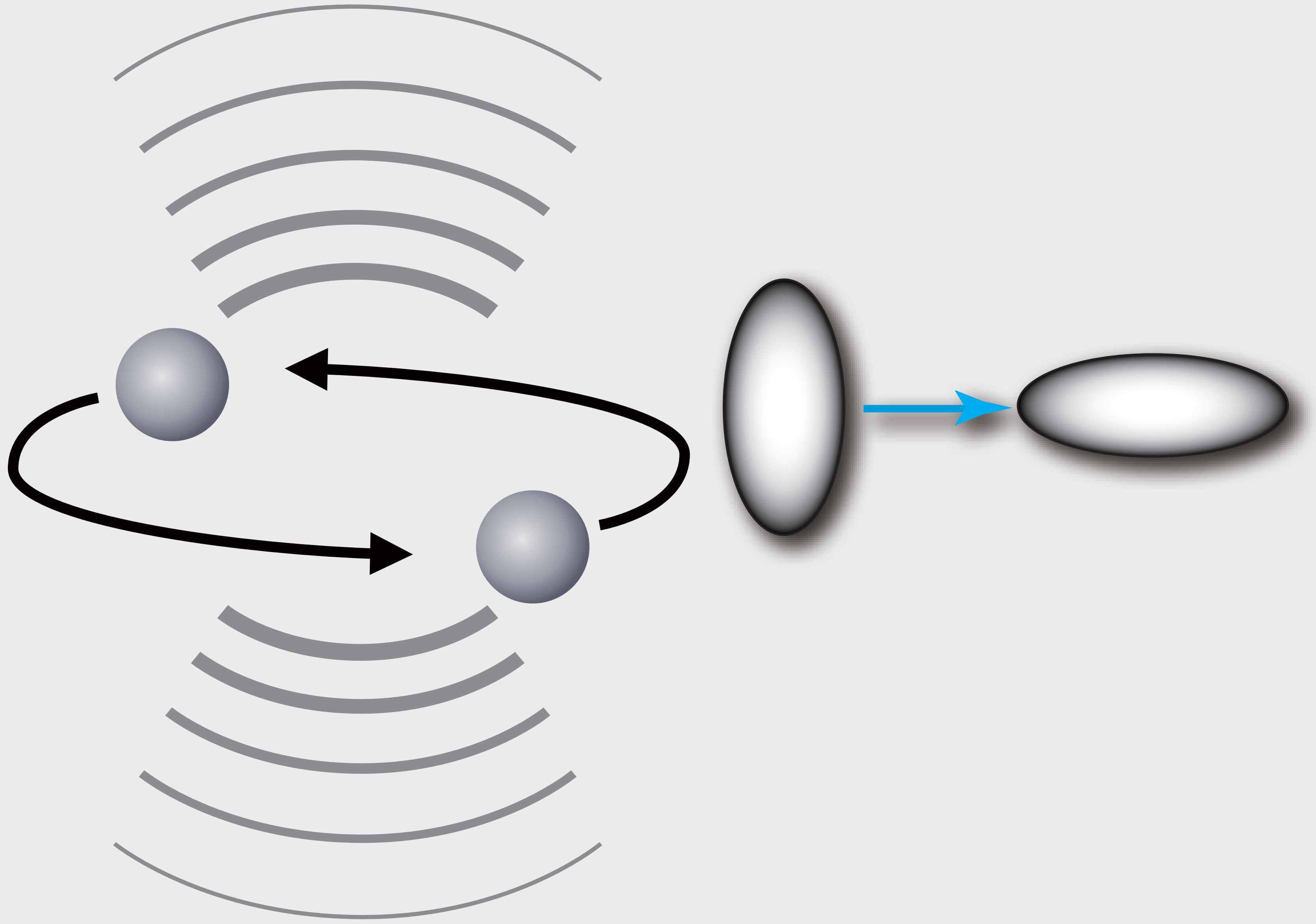
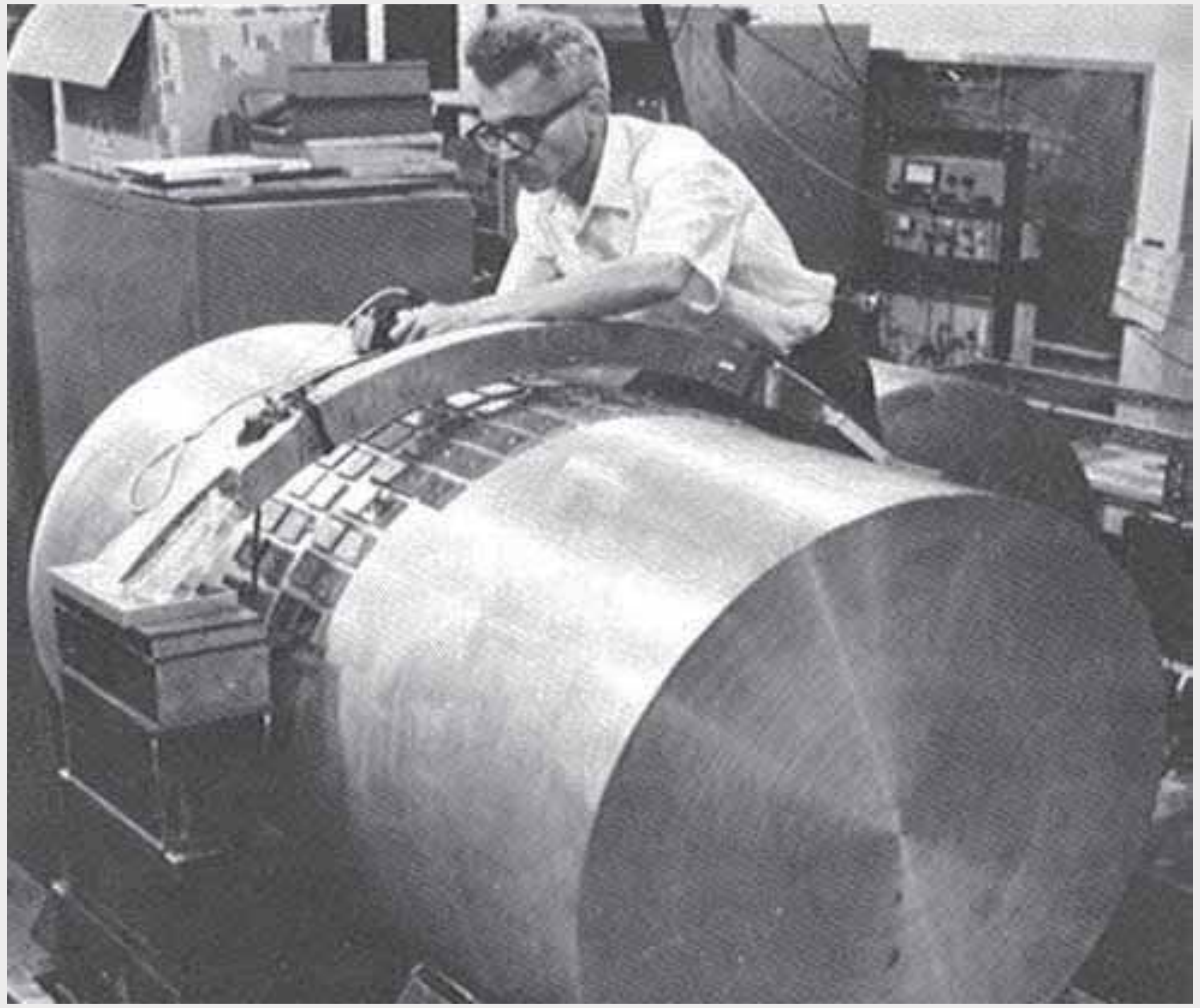


50~60 years ago

in 1960's - 1970's

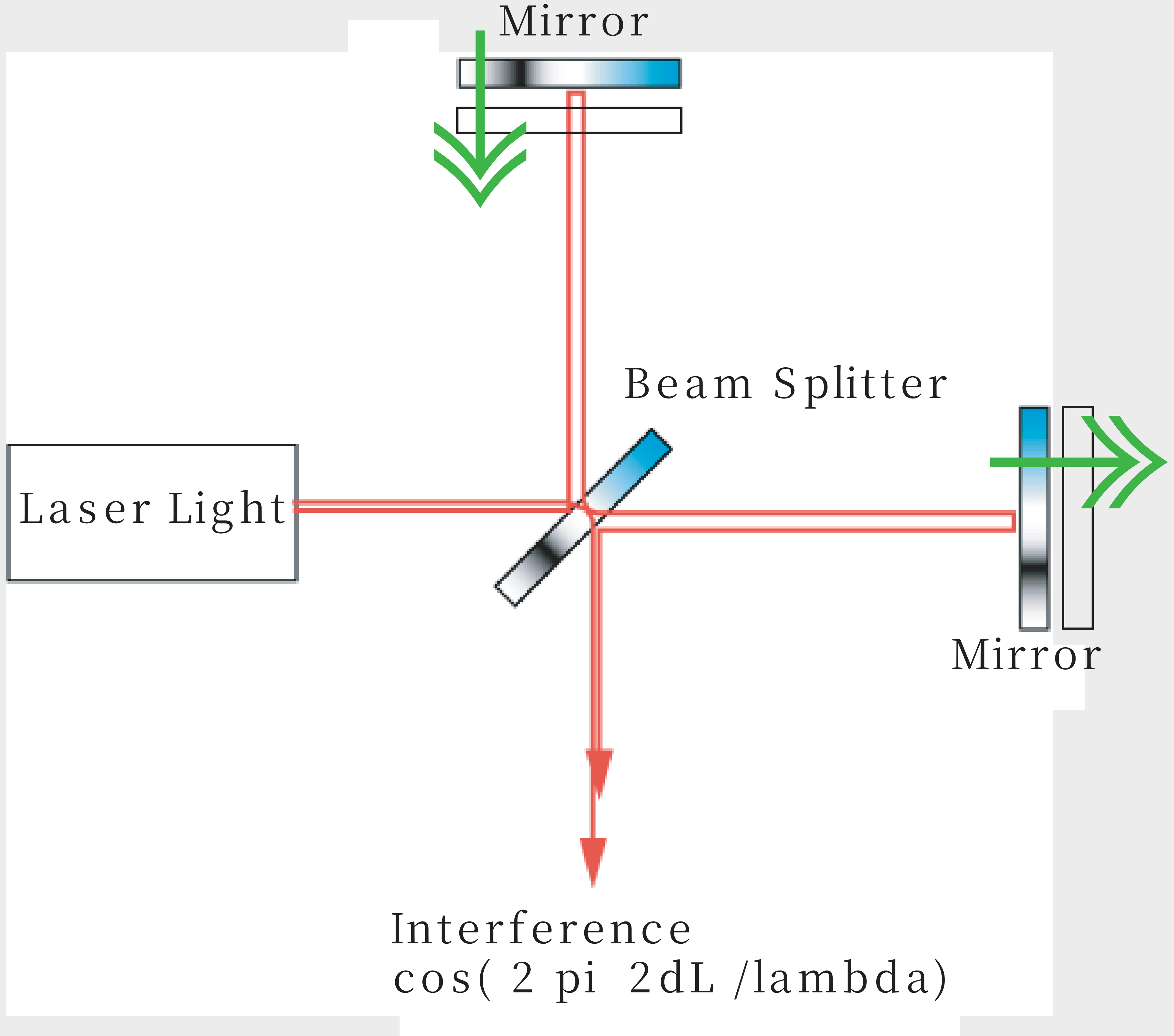
Ideas of GW detection

Resonant mass antenna



Weber “bar”

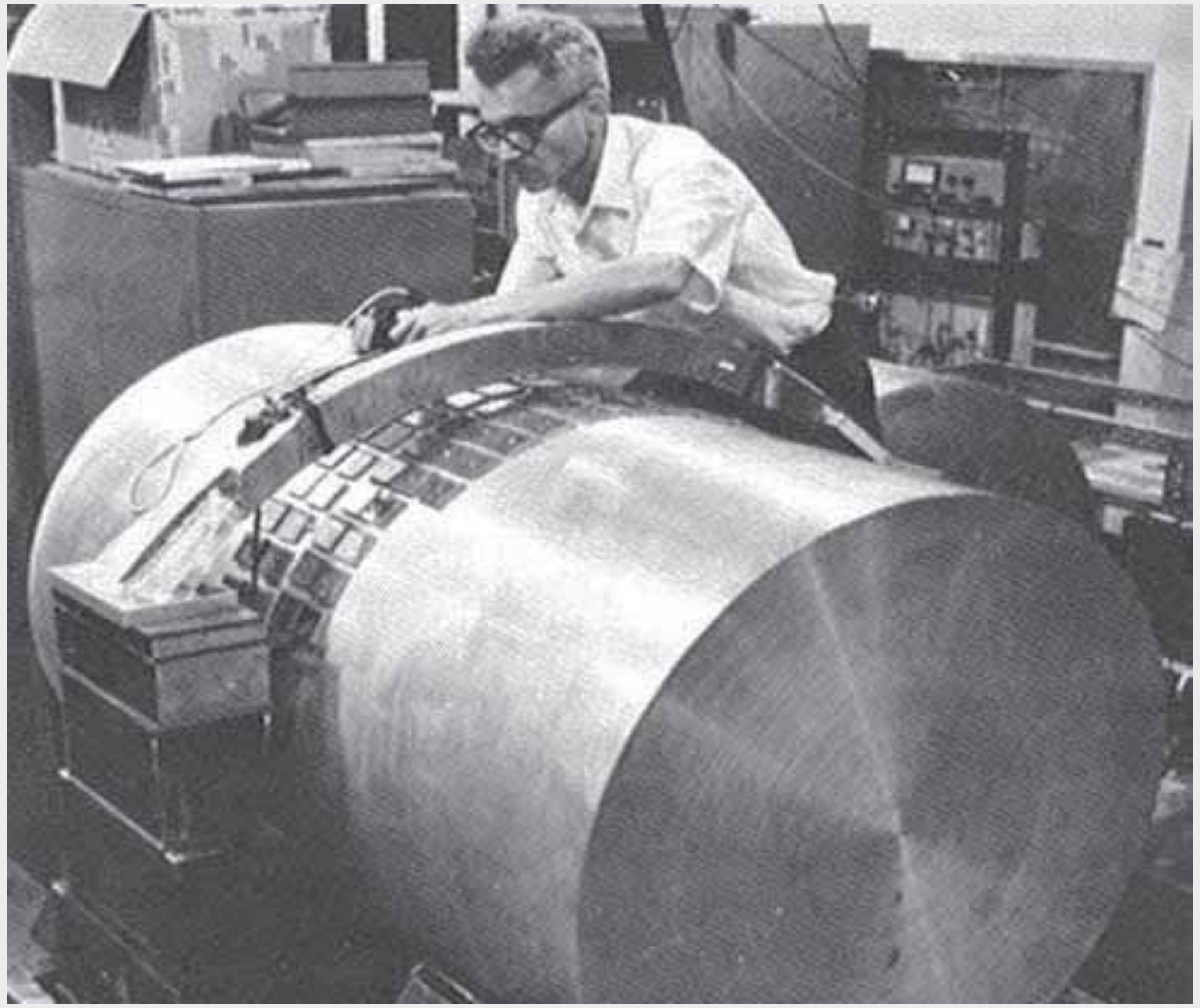
Free test mass type



Michelson interferometer

Ideas of GW detection

Resonant mass antenna



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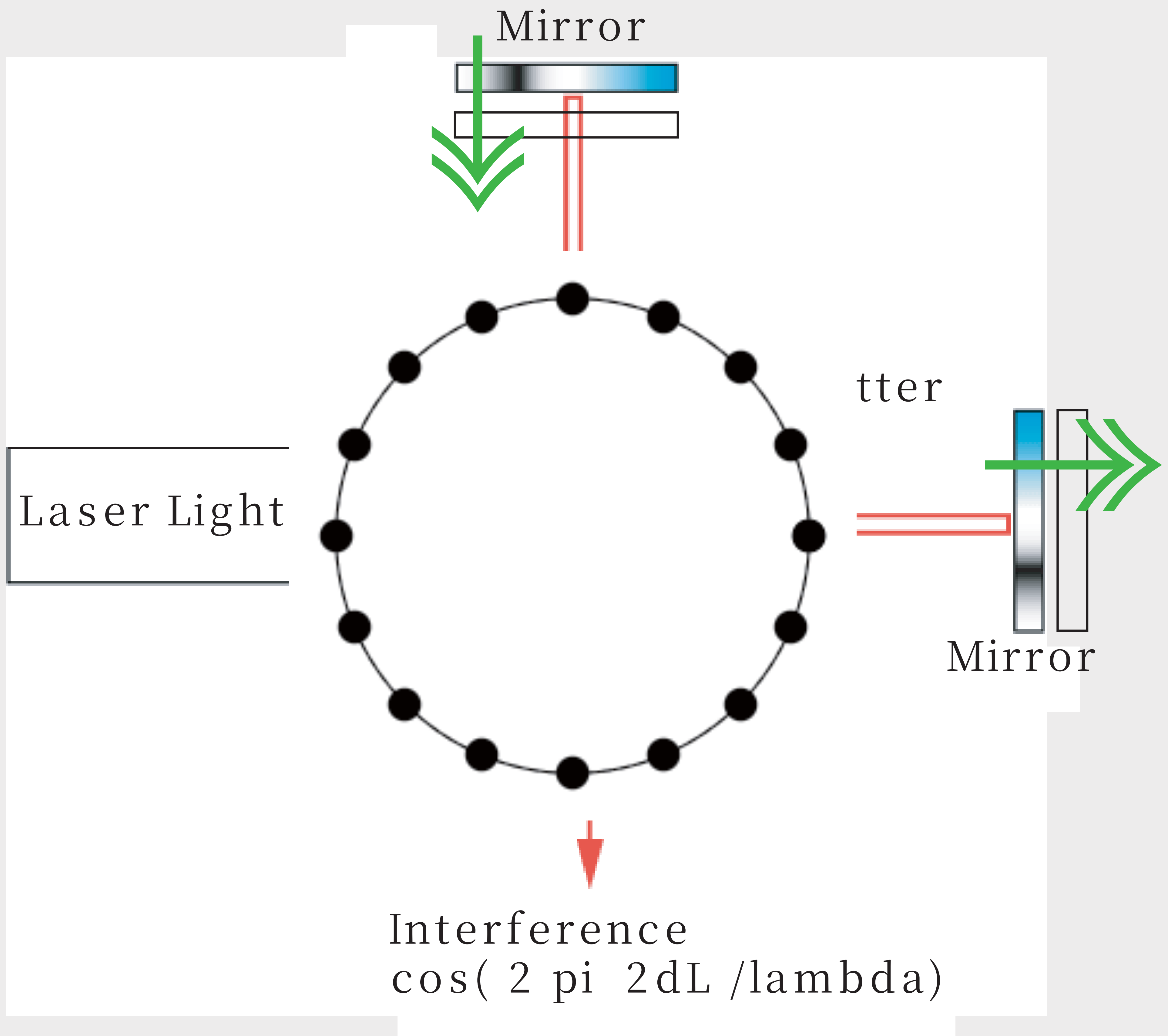
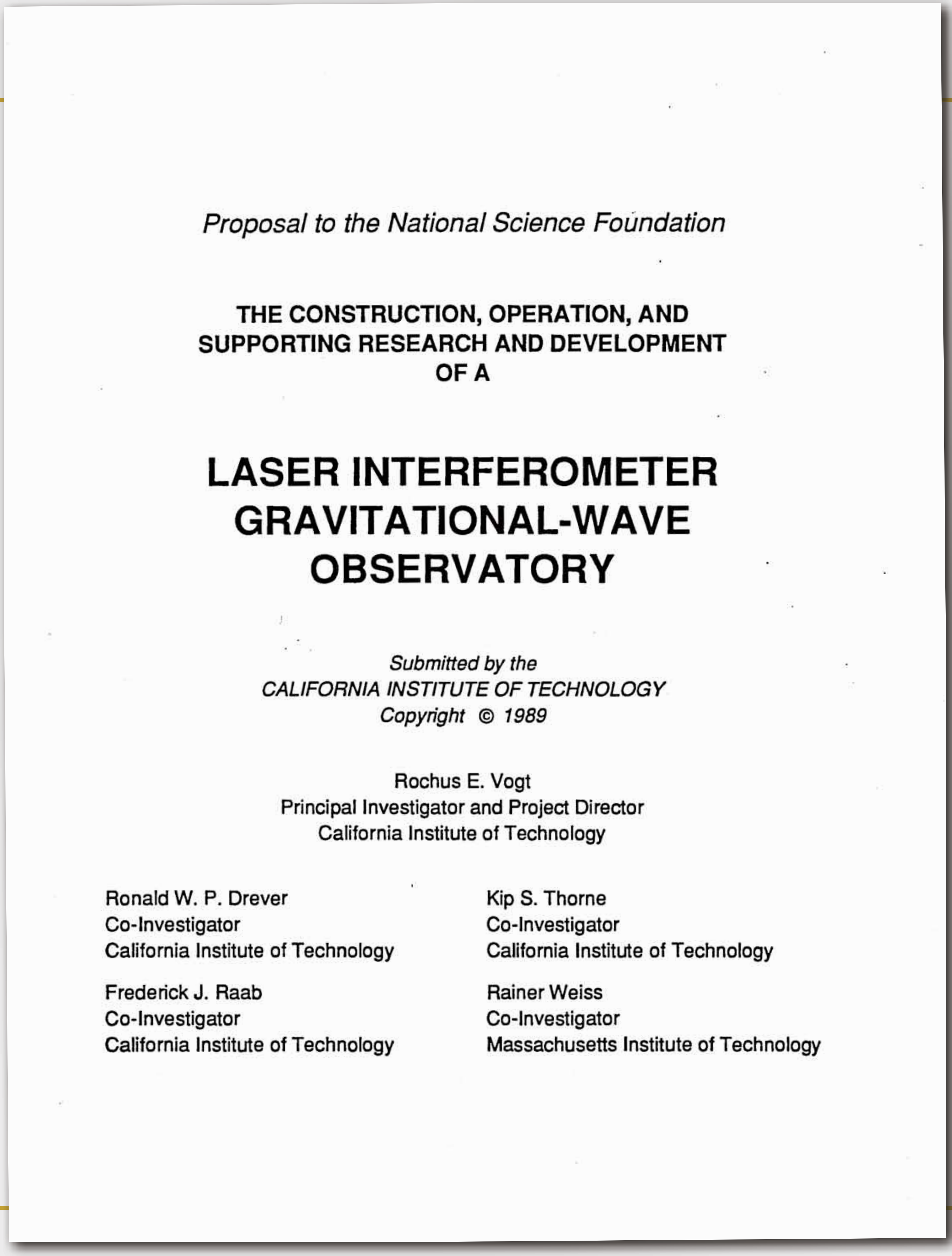


Michelson interferometer

~30 years ago …

The LIGO project was approved and started in US.

Idea of Large-scale Cryogenic Gravitational-Wave Telescope (LCGT) in Japan.



Proposal to the National Science Foundation

**THE CONSTRUCTION, OPERATION, AND
SUPPORTING RESEARCH AND DEVELOPMENT
OF A**

LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY
Copyright © 1989

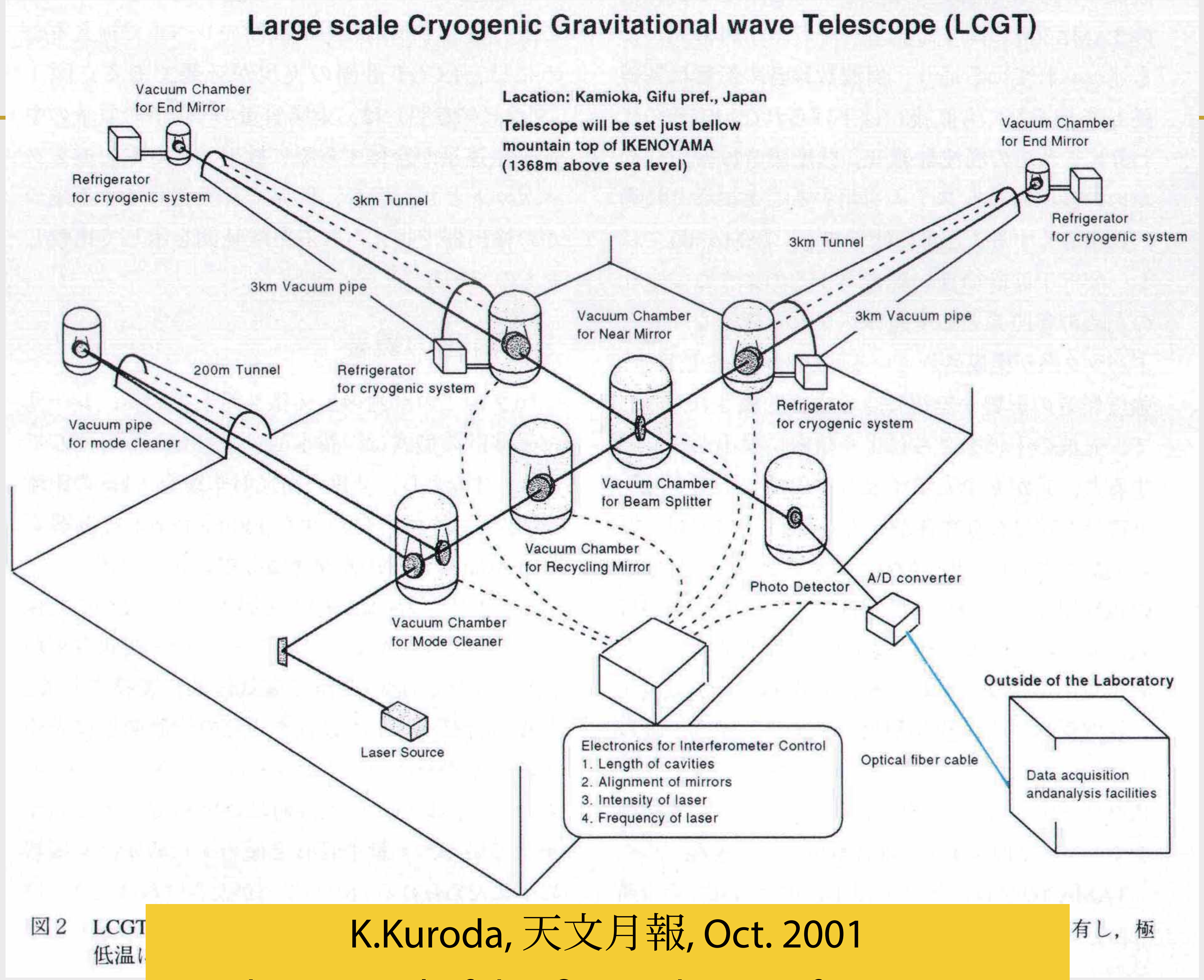
Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology



K.Kuroda, 天文月報, Oct. 2001
(But the original of this figure drawn a few years ago.)

Prof. K.Kuroda of the institute of cosmic ray research, university of Tokyo proposed Large-scale Cryogenic Gravitational-Wave Telescope (LCGT), That is, the current KAGRA.
ICRR GW lab staff was only him and NK.

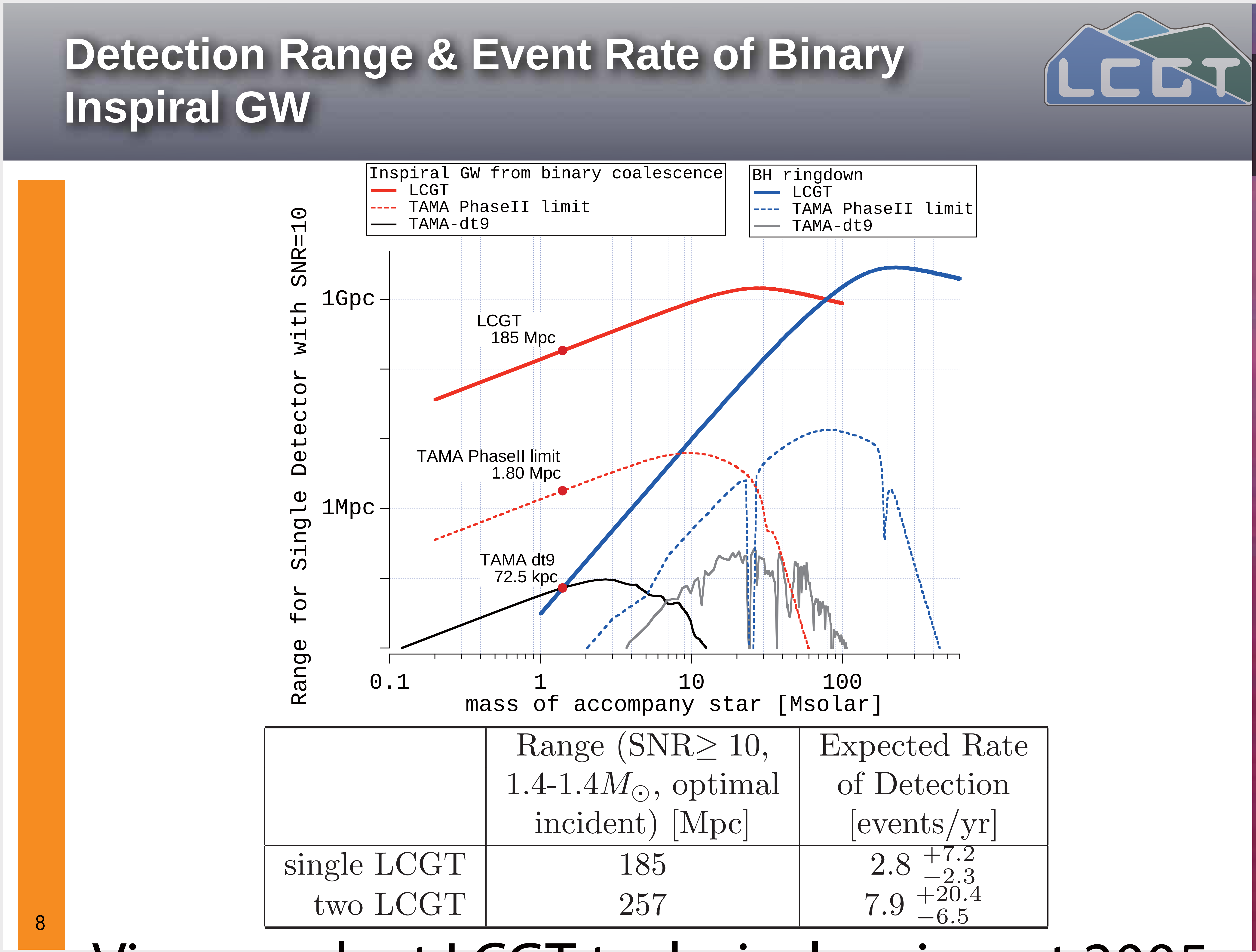
(about) 20 years ago ...

LIGO's first science run S1 : Aug. - Sep. 2002

Kanda moved to Osaka City U. = **beginning of GW experiment lab at our university** : April 2002

LCGT technical review : 2005

LCGT (KAGRA)'s binary detection "range" VS mass

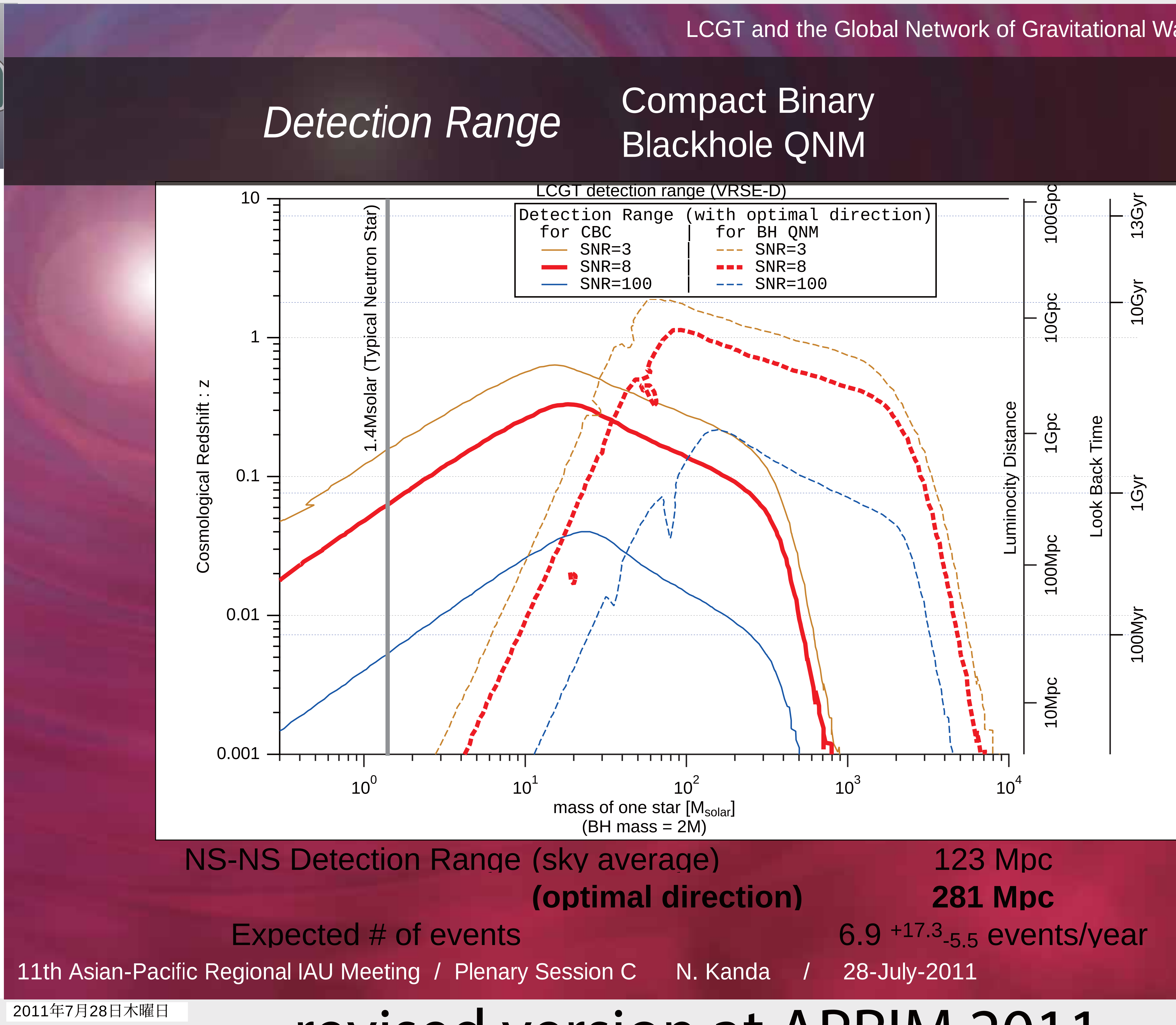


Detection Range & Event Rate of Binary Inspiral GW

	Range (SNR≥ 10, 1.4-1.4$M_\odot$, optimal incident) [Mpc]	Expected Rate of Detection [events/yr]
single LCGT	185	$2.8^{+7.2}_{-2.3}$
two LCGT	257	$7.9^{+20.4}_{-6.5}$

8

Viewgraph at LCGT technical review at 2005.



LCGT and the Global Network of Gravitational Wa

Detection Range Compact Binary Blackhole QNM

NS-NS Detection Range (sky average) 123 Mpc

(optimal direction) 281 Mpc

Expected # of events $6.9^{+17.3}_{-5.5}$ events/year

11th Asian-Pacific Regional IAU Meeting / Plenary Session C N. Kanda / 28-July-2011

2011年7月28日木曜日

revised version at APRIM 2011

Sweet spot is 30 M_solar mass binary. However, it was said as not promising...

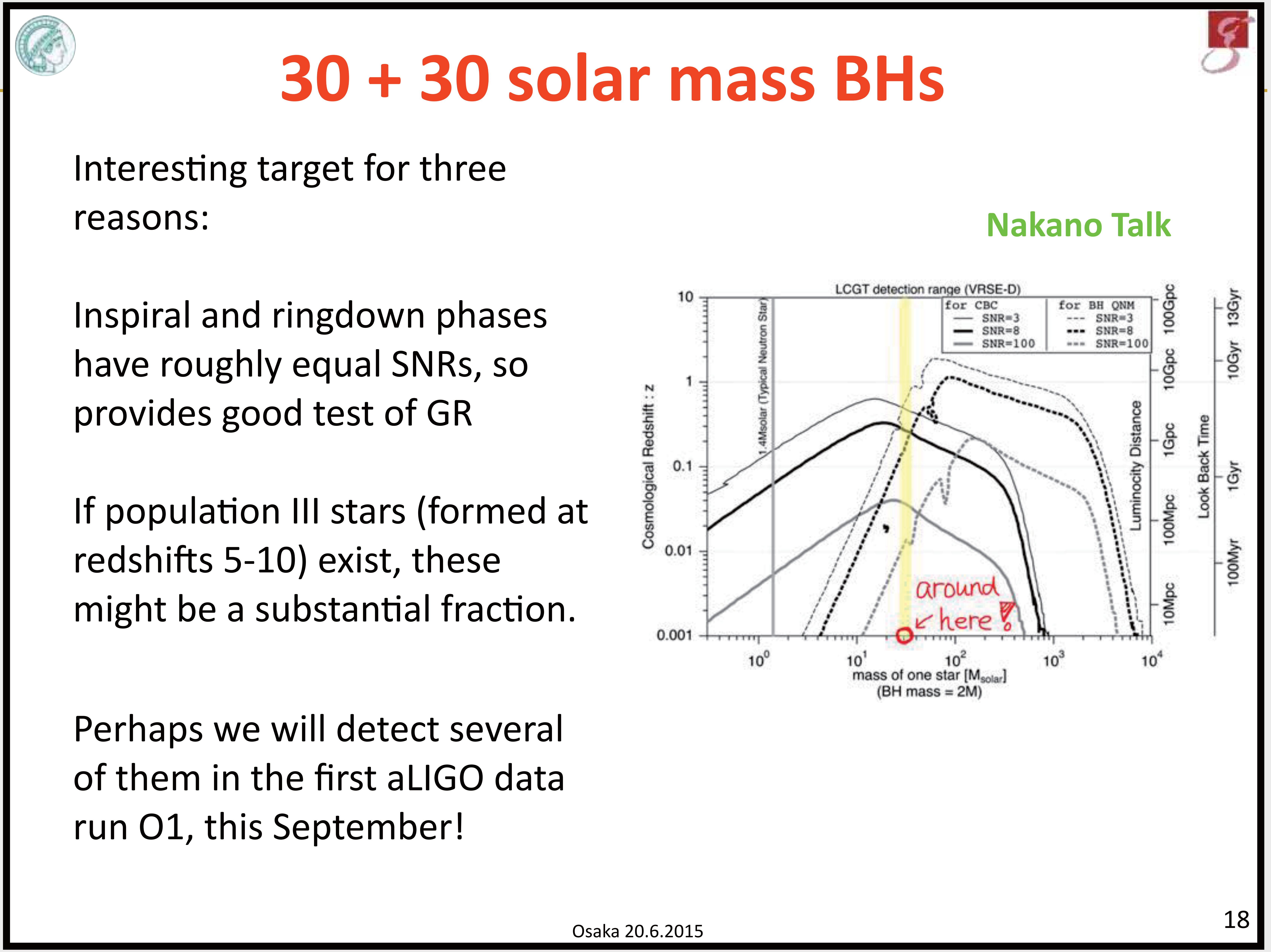
10 years ago …

Gravitational Wave Data Analysis Workshop 2015 at Osaka : *The last workshop of* *without real event data*

GW150914 : The first GW direct observation by humankind !

At June 2015

We expected 30 Msolar Black hole binary, and estimated the detection rate (MNRAS 456, 1093–1114 (2016)) before the first detection.



30 + 30 solar mass BHs

Interesting target for three reasons:

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

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

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

Nakano Talk

Osaka 20.6.2015

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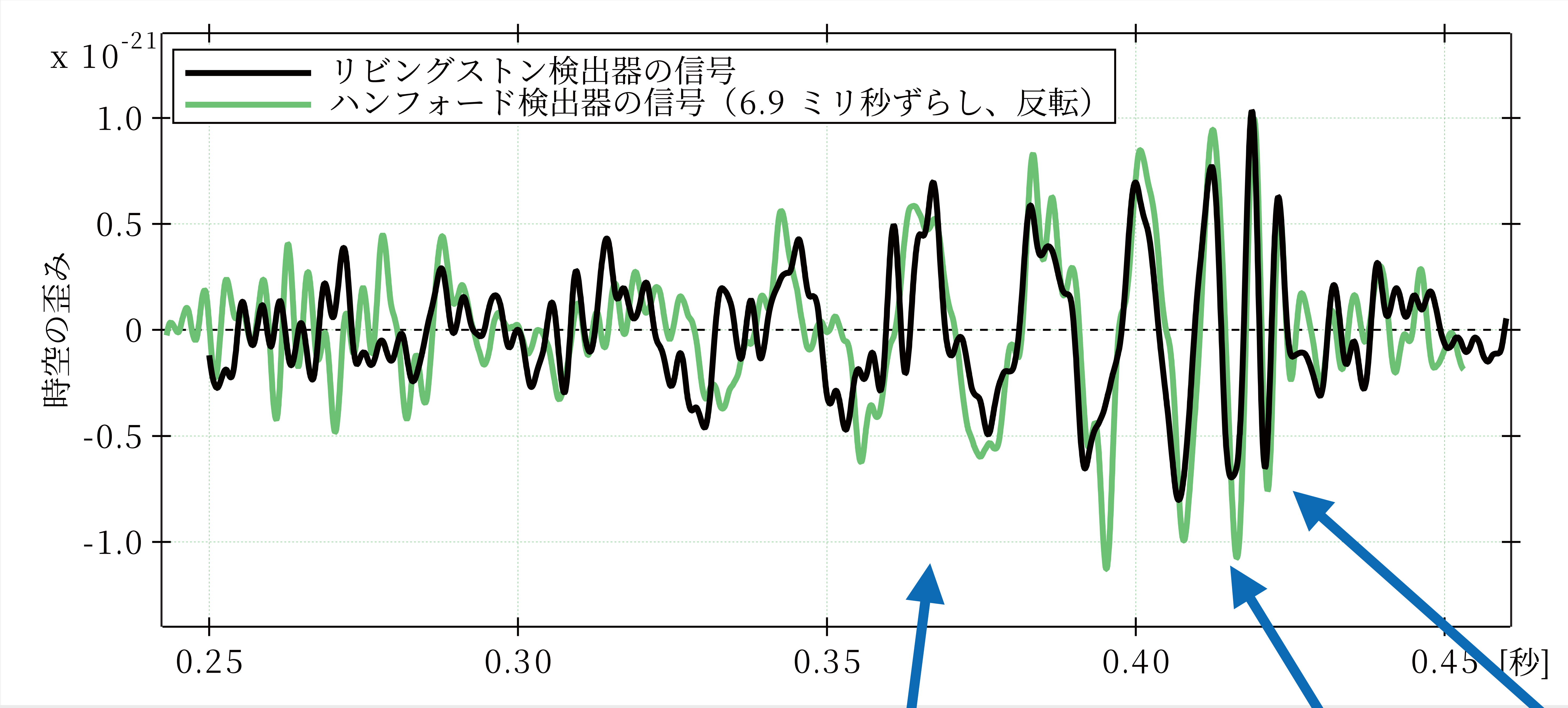
viewgraph edited by Bruce Allen : (Personal) summary of new, novel, and interesting results presented at this workshop
at GWPAW2015 Osaka, June 2015

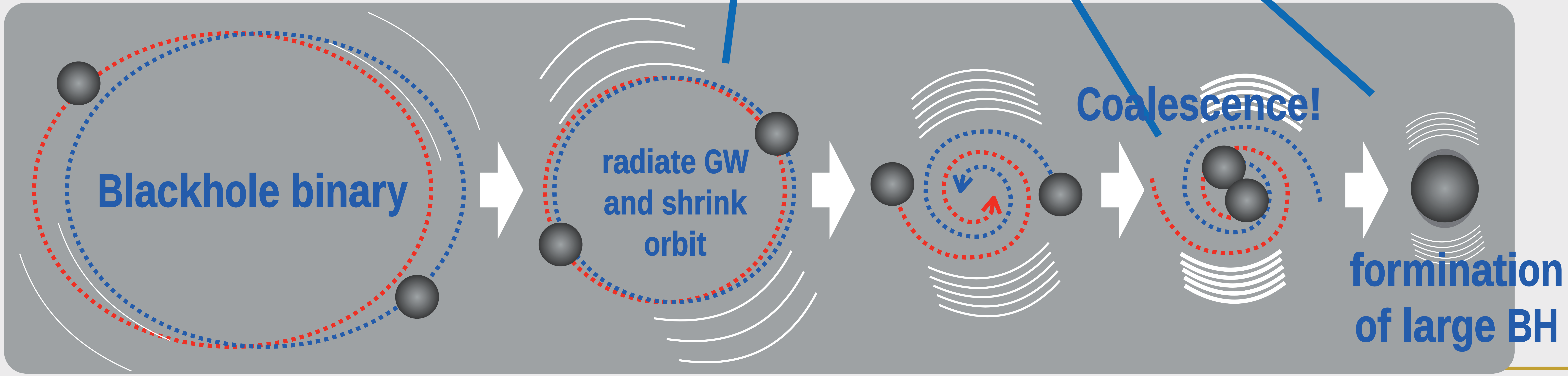
Finally, the first detection event by LIGO at Sep. 15th 2015



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

PRL 116, 061102(2016)

$$36 M_\odot + 29 M_\odot \to 62 M_\odot + E_{GW}$$



Blackhole binary

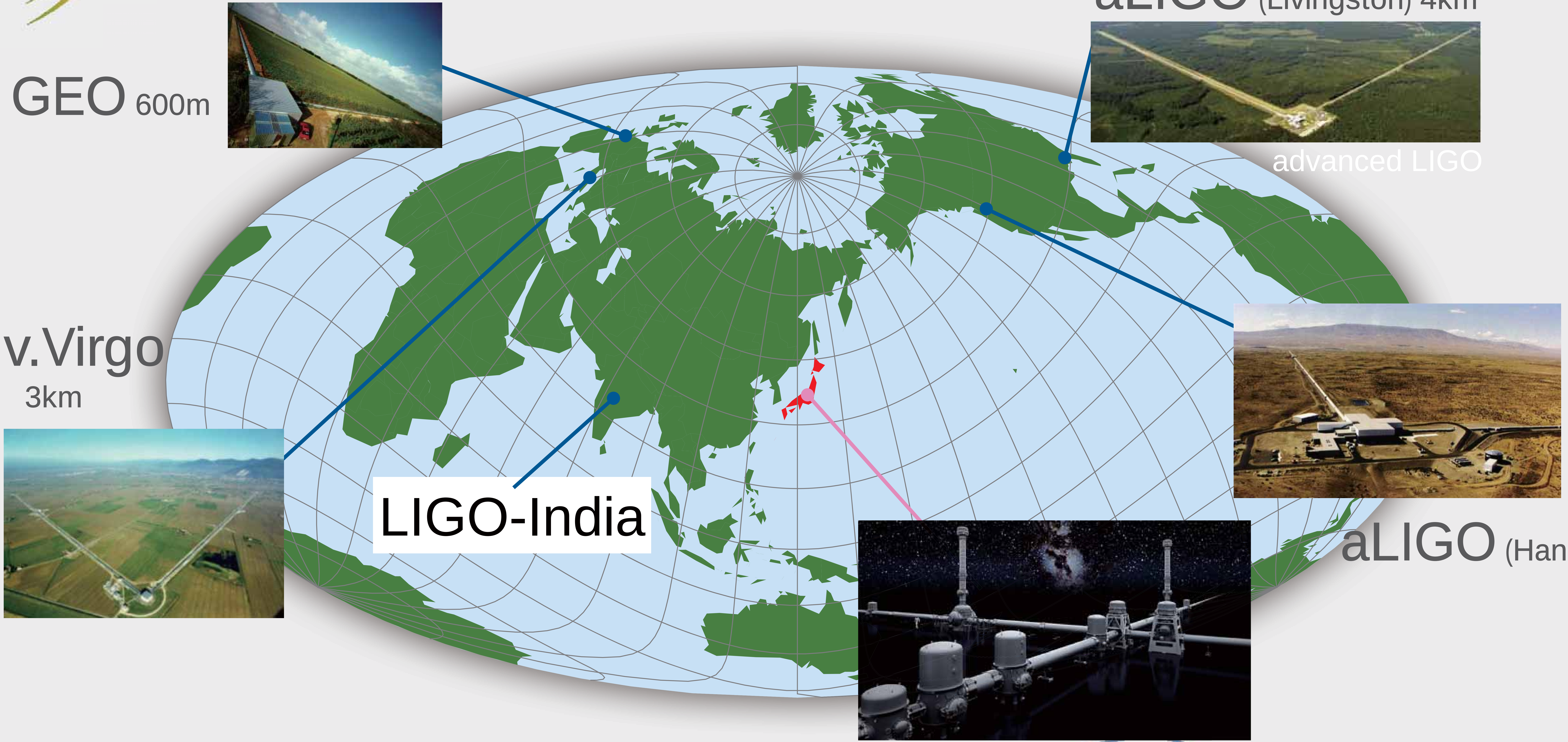
radiate GW and shrink orbit

Coalescence!

formation of large BH

Now : observatories

Laser Interferometric Gravitational Wave Detectors on the Globe



GEO 600m

aLIGO (Livingston) 4km

advanced LIGO

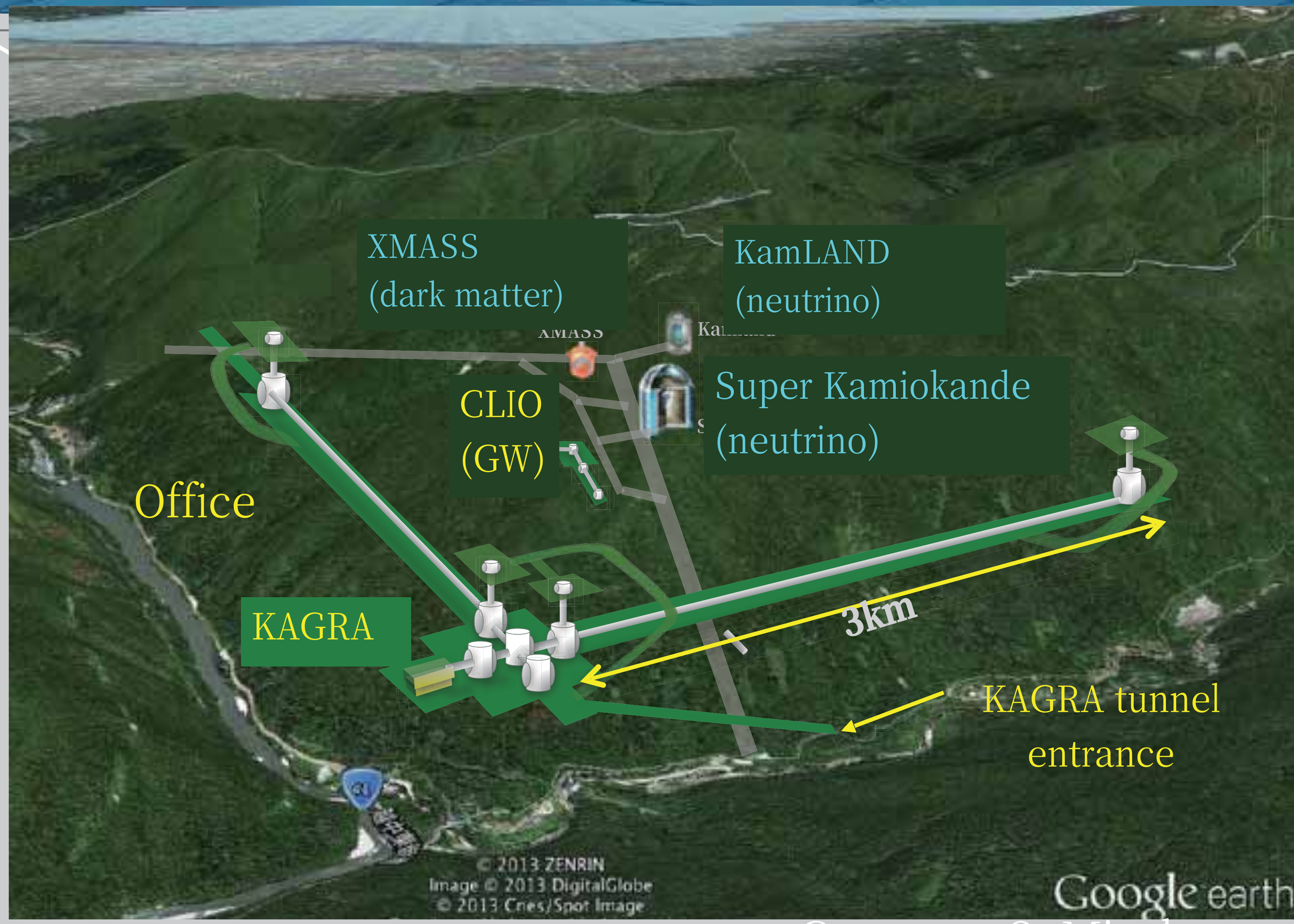
adv.Virgo 3km

LIGO-India

aLIGO (Hanford) 4km

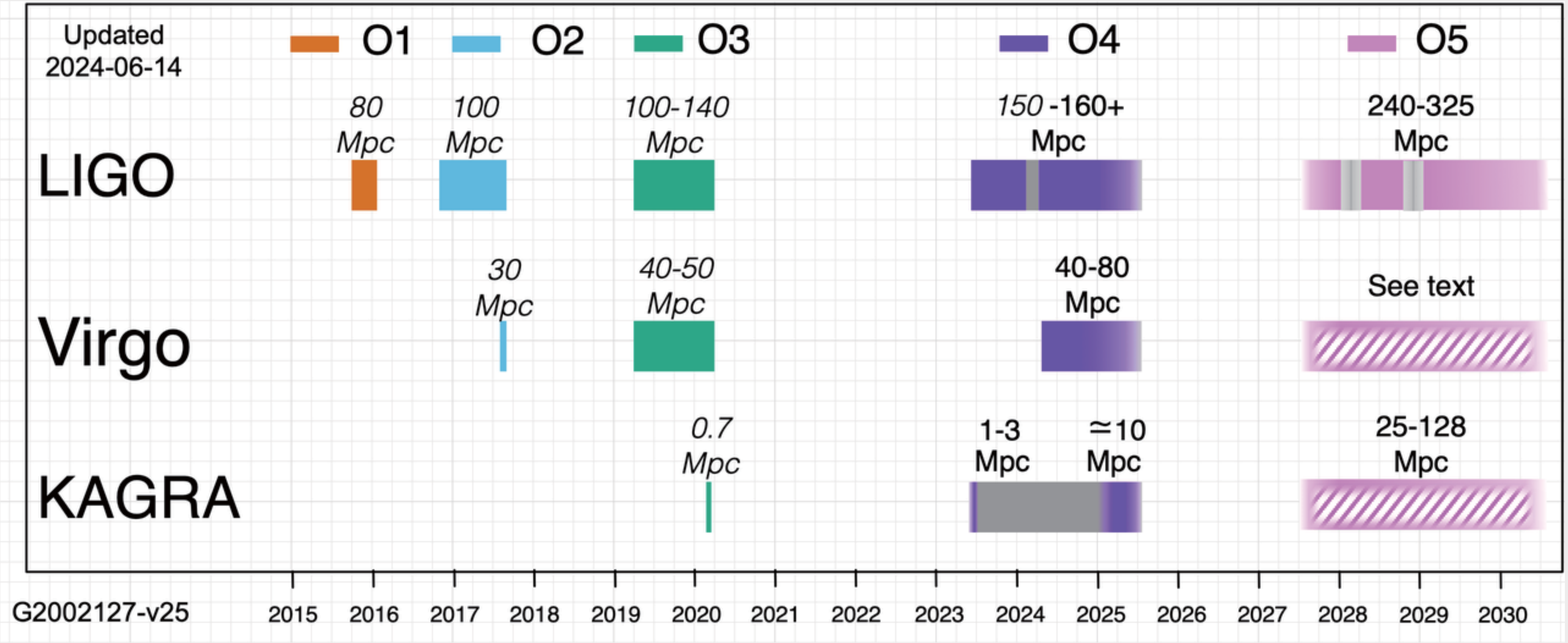
KAGRA

- Undergorund
- long baseline : 3km
- cryogenic (~20K) sapphire mirror



Courtesy: O. Miyakawa

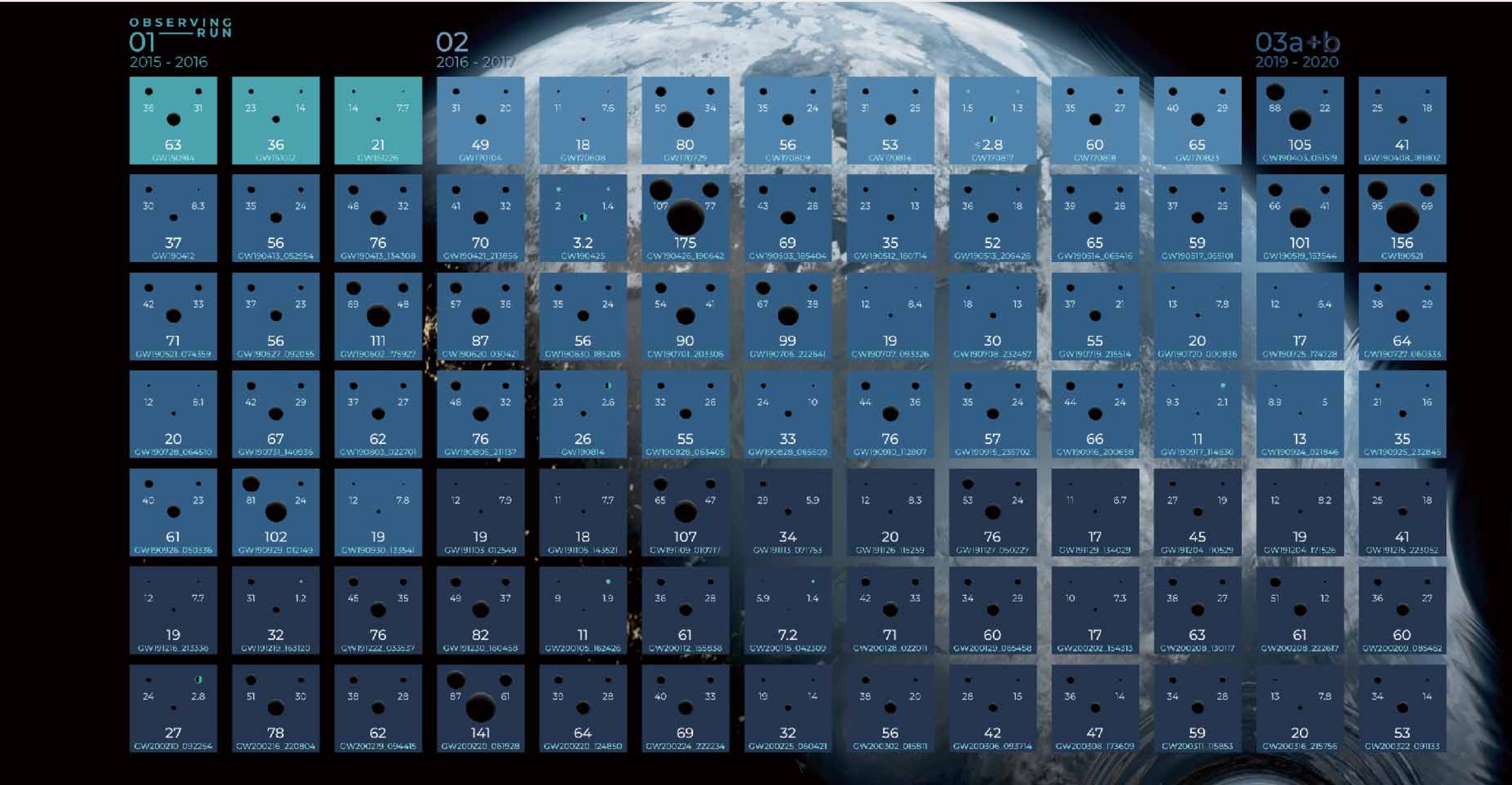
Observation plan



We are currently in O4 (4th observation).

Now, we are in the observational era of GW

Events in O1,O2,O3



Carl Knox (OzGrav, Swinburne University of Technology)

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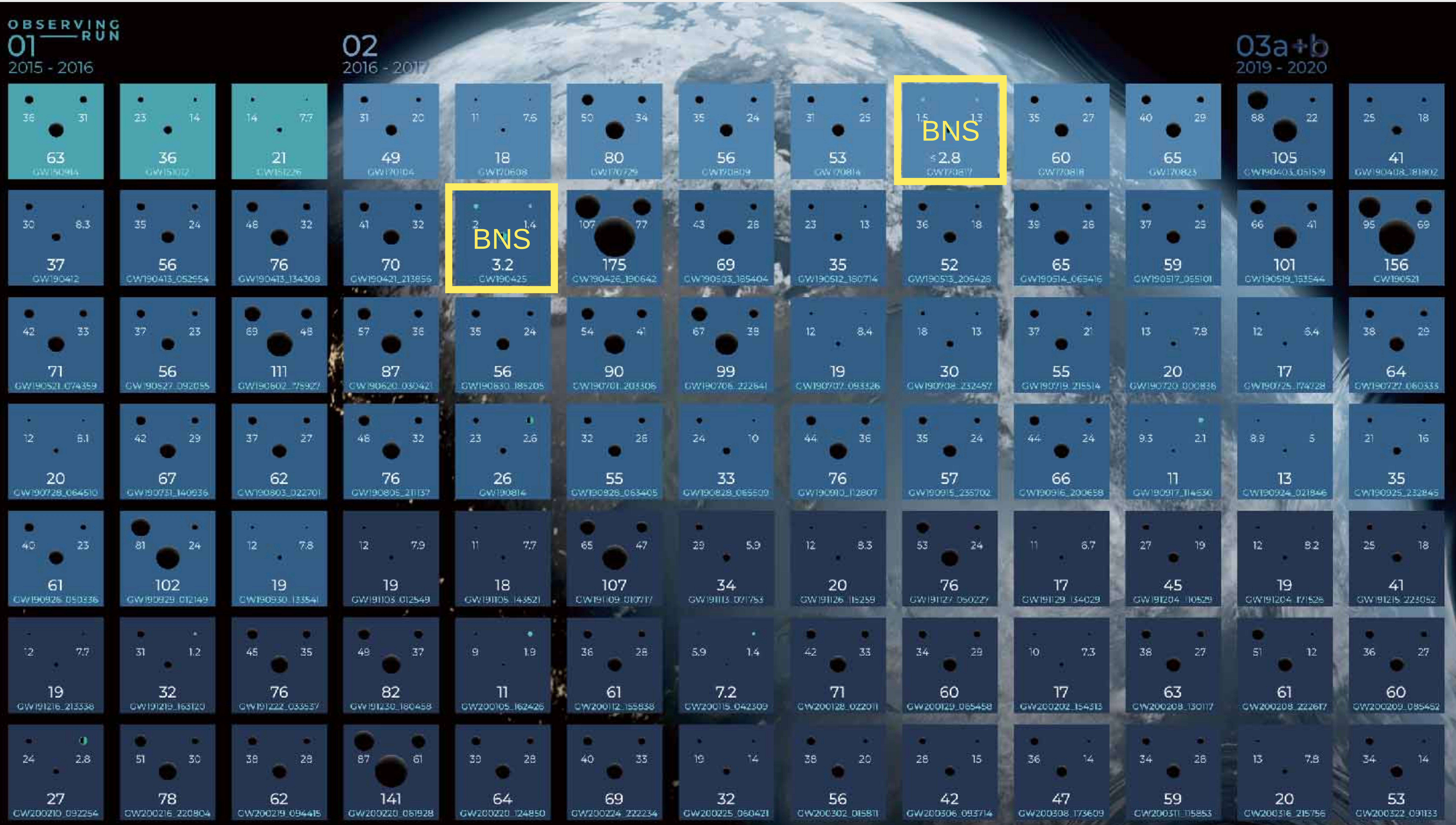

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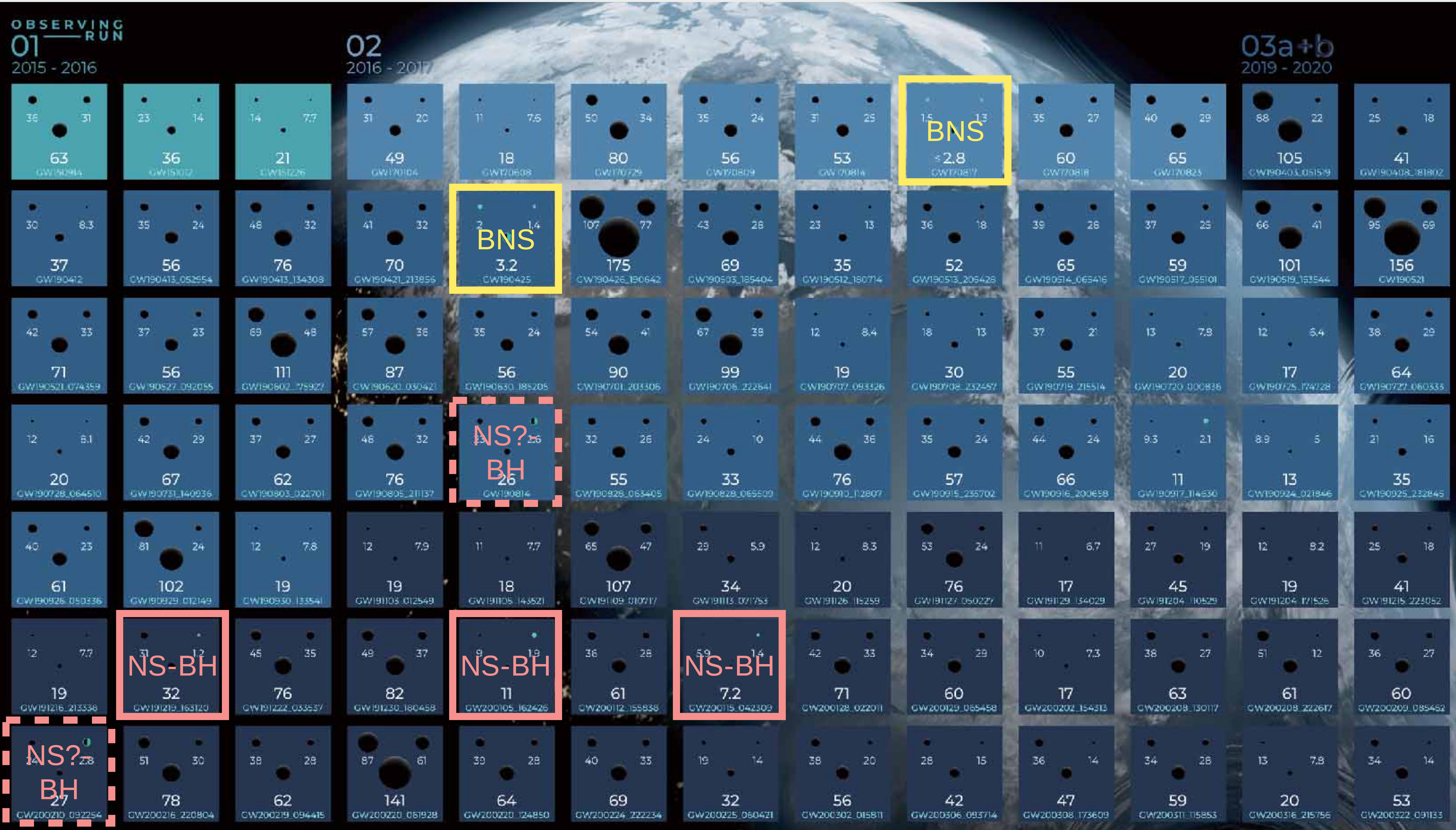

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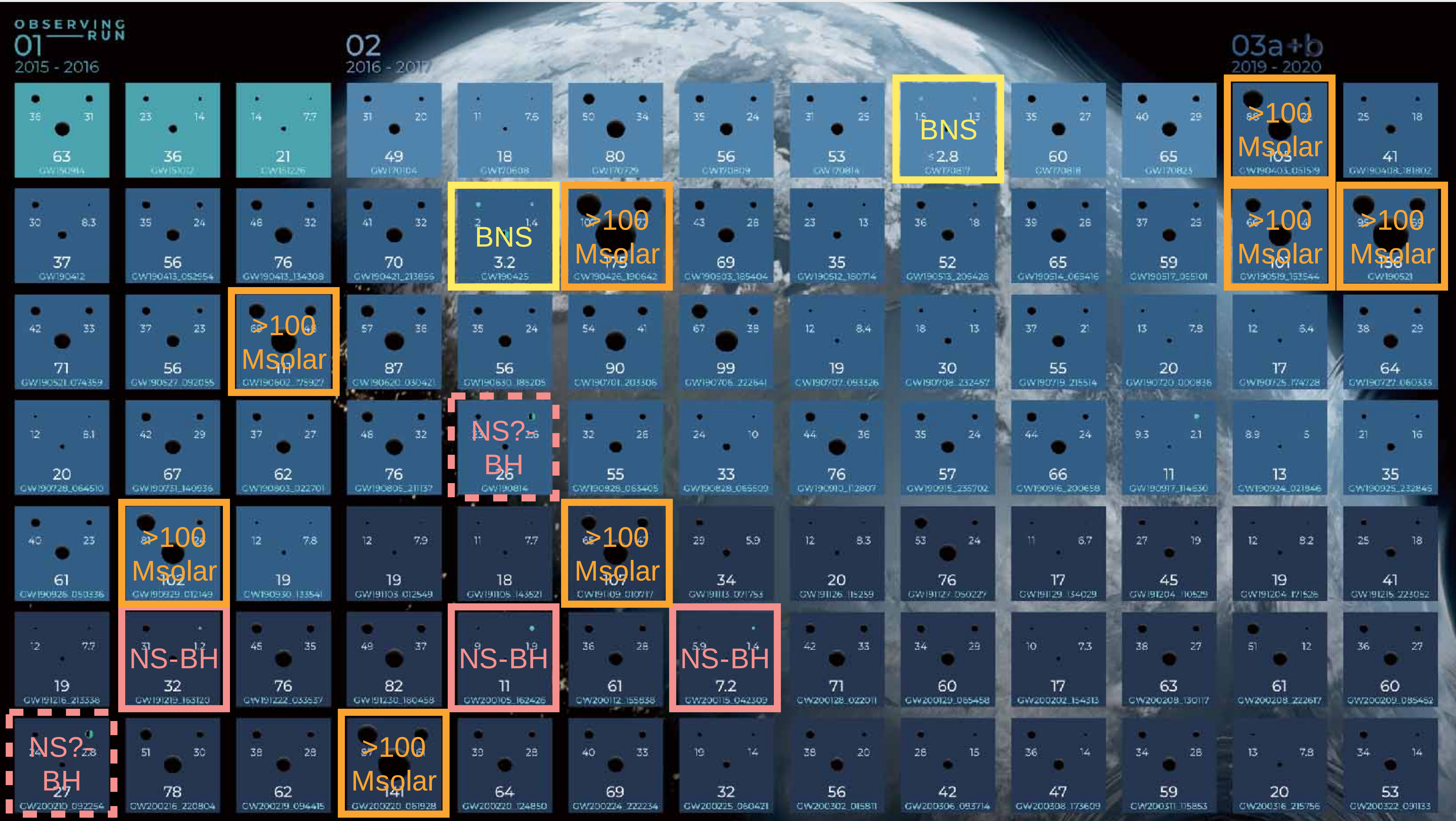

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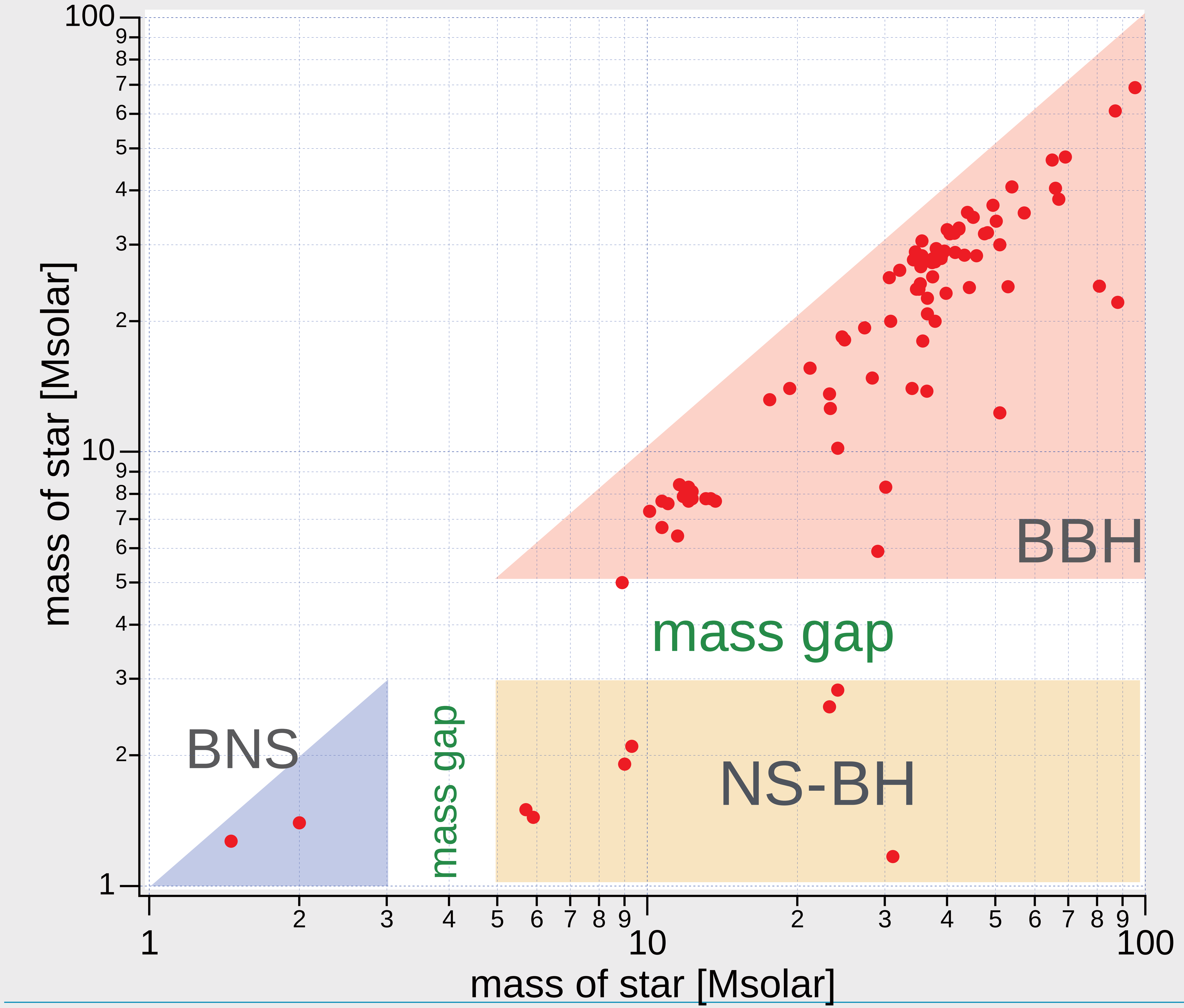
Events in O1,O2,O3

GWTC-2, -3 events



based on the data in
https://www.gw-openscience.org/eventapi/html/allevents/

Various events appear:

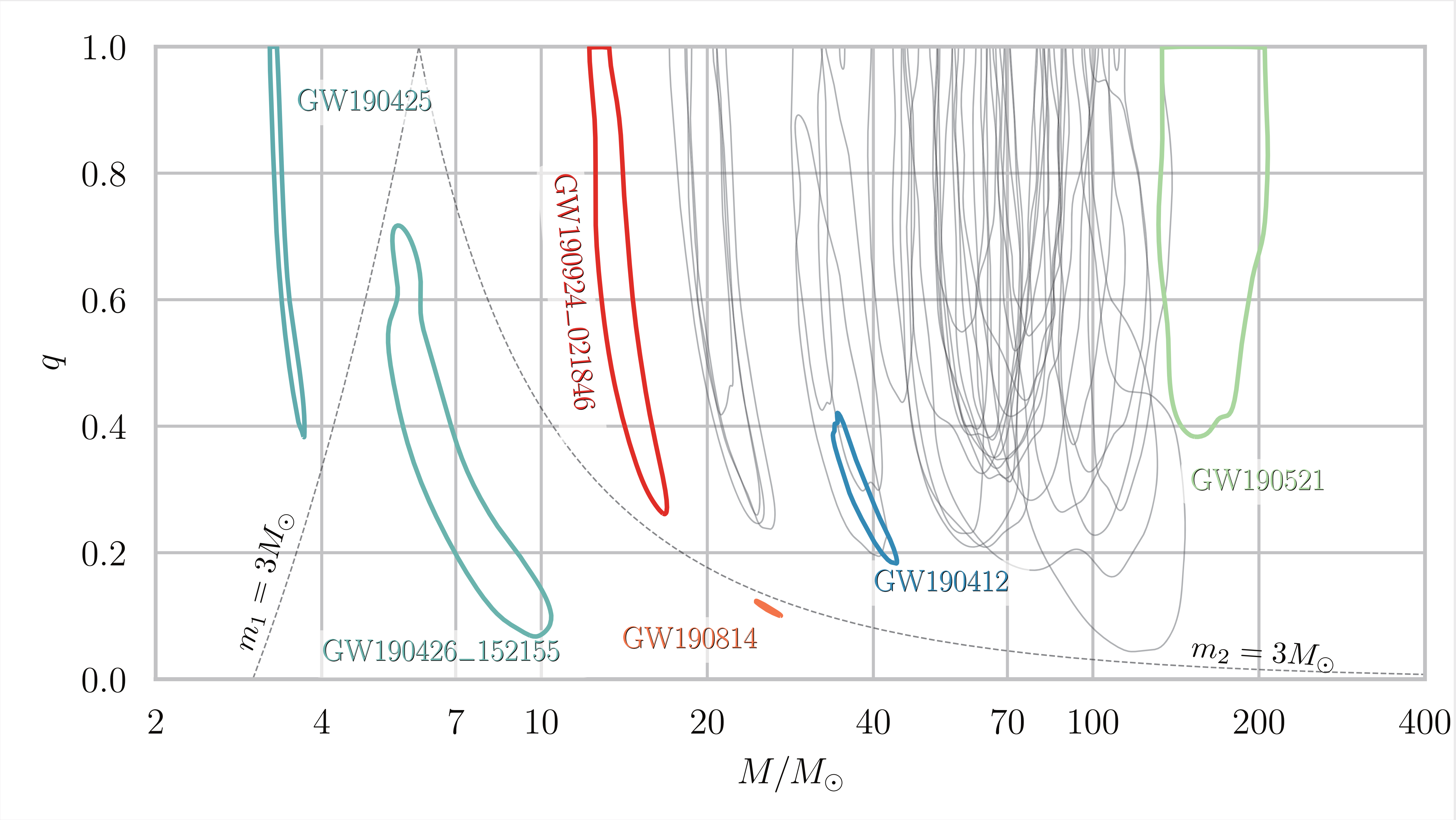
binary blackhole (BBH)
around 10-30 Msolar,
~100 Msolar,
binary neutron star (BNS)
neutron star - blackhole (NS-BH)

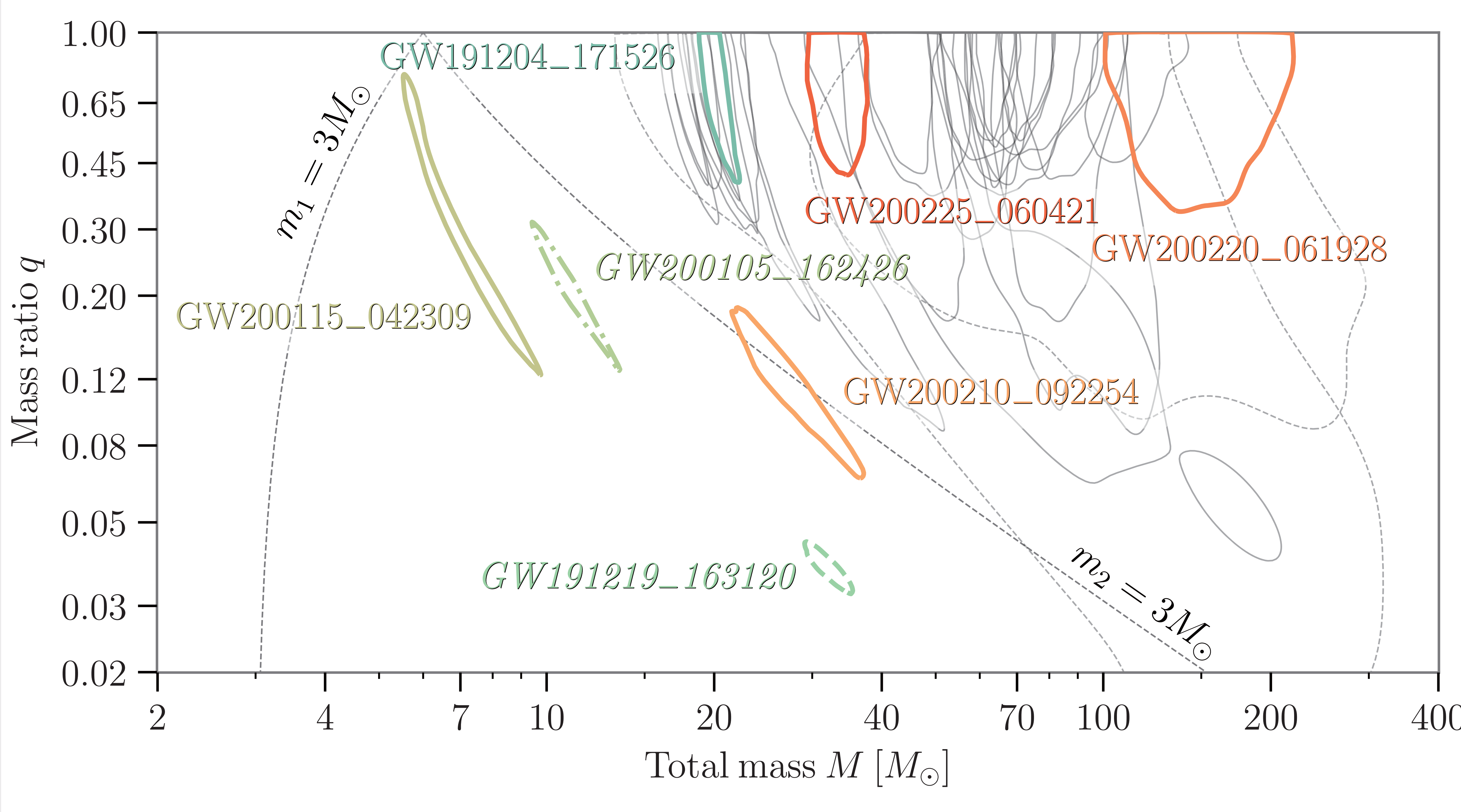
High mass ratio,
Edge at mass gap region,

GWTC-2, -3 binaries

Almost are "BH-BH

There some extreme mass ratio binaries, heave (>100Msol), etc.





GWTC-2 arXiv:2010.14527

GWTC-3 arXiv:2111.03606

GWTC-2, -3 binaries

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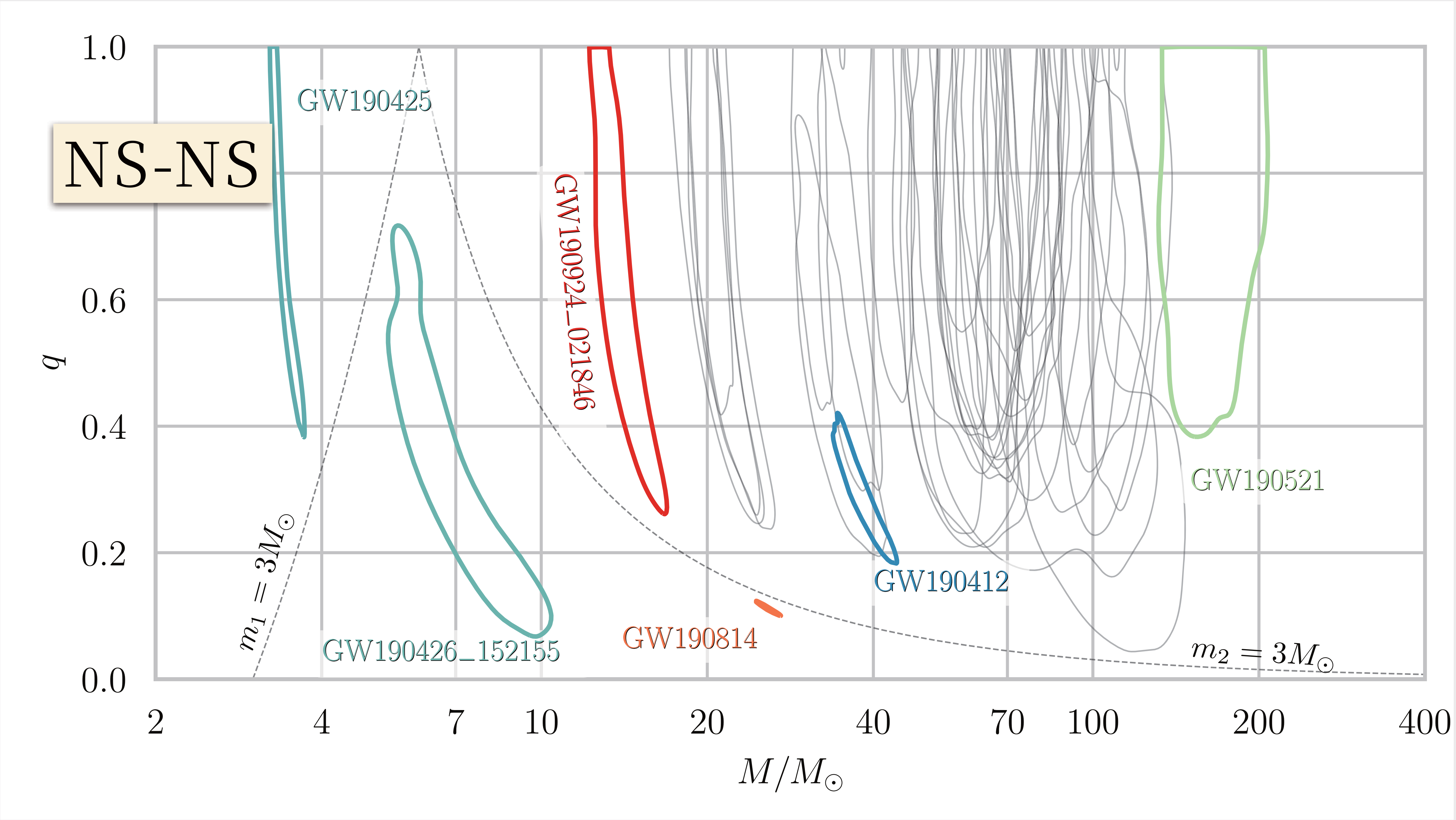

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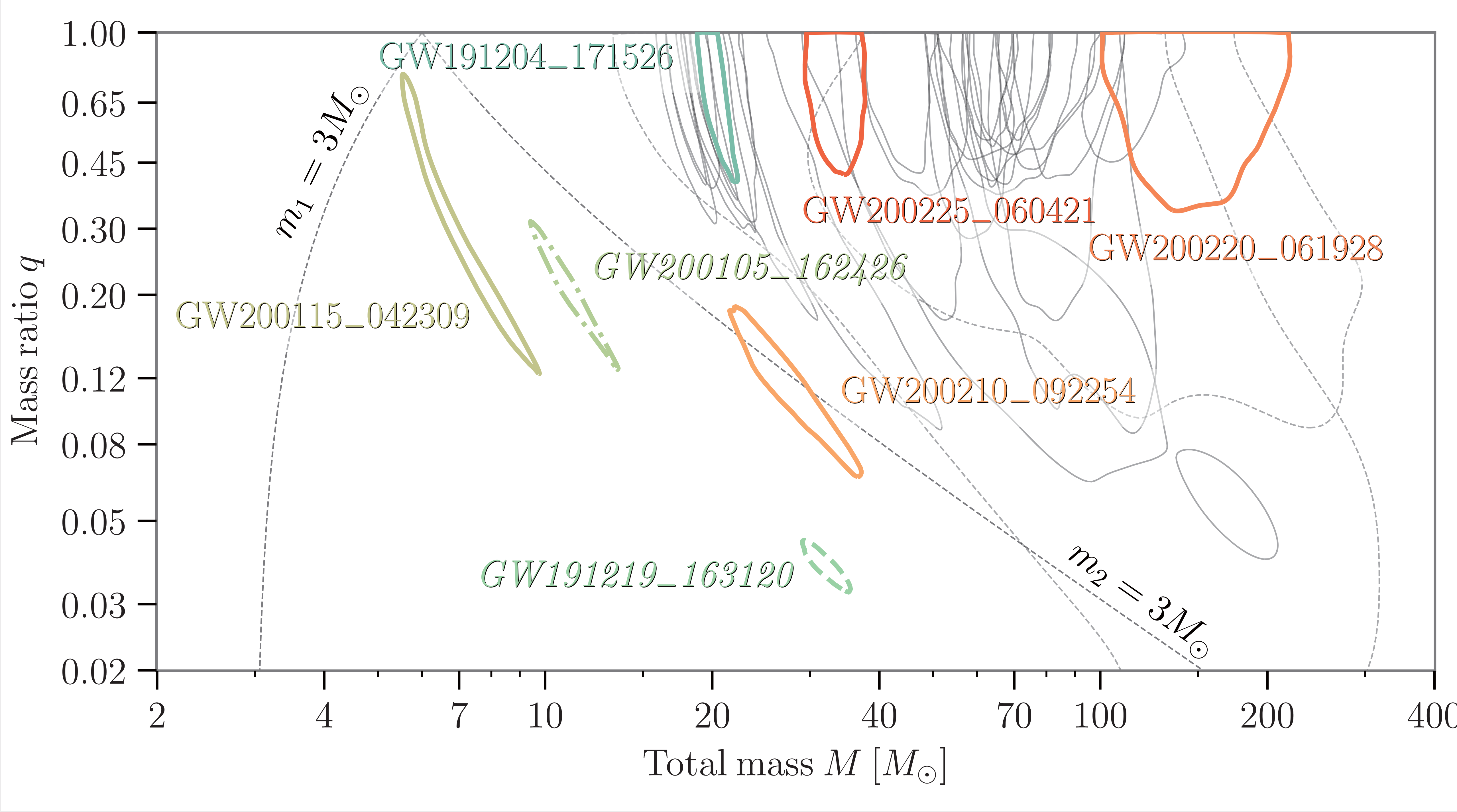

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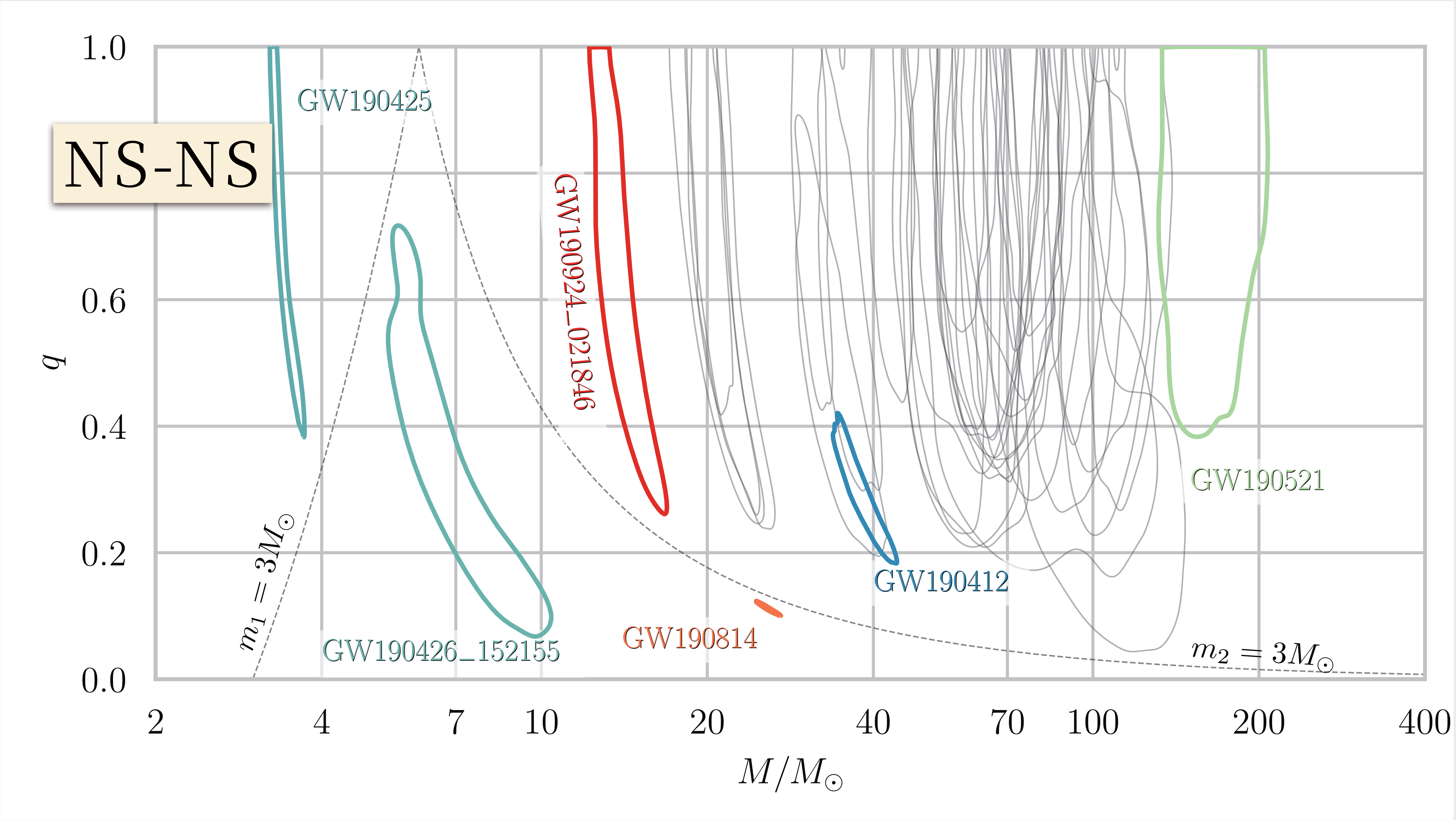

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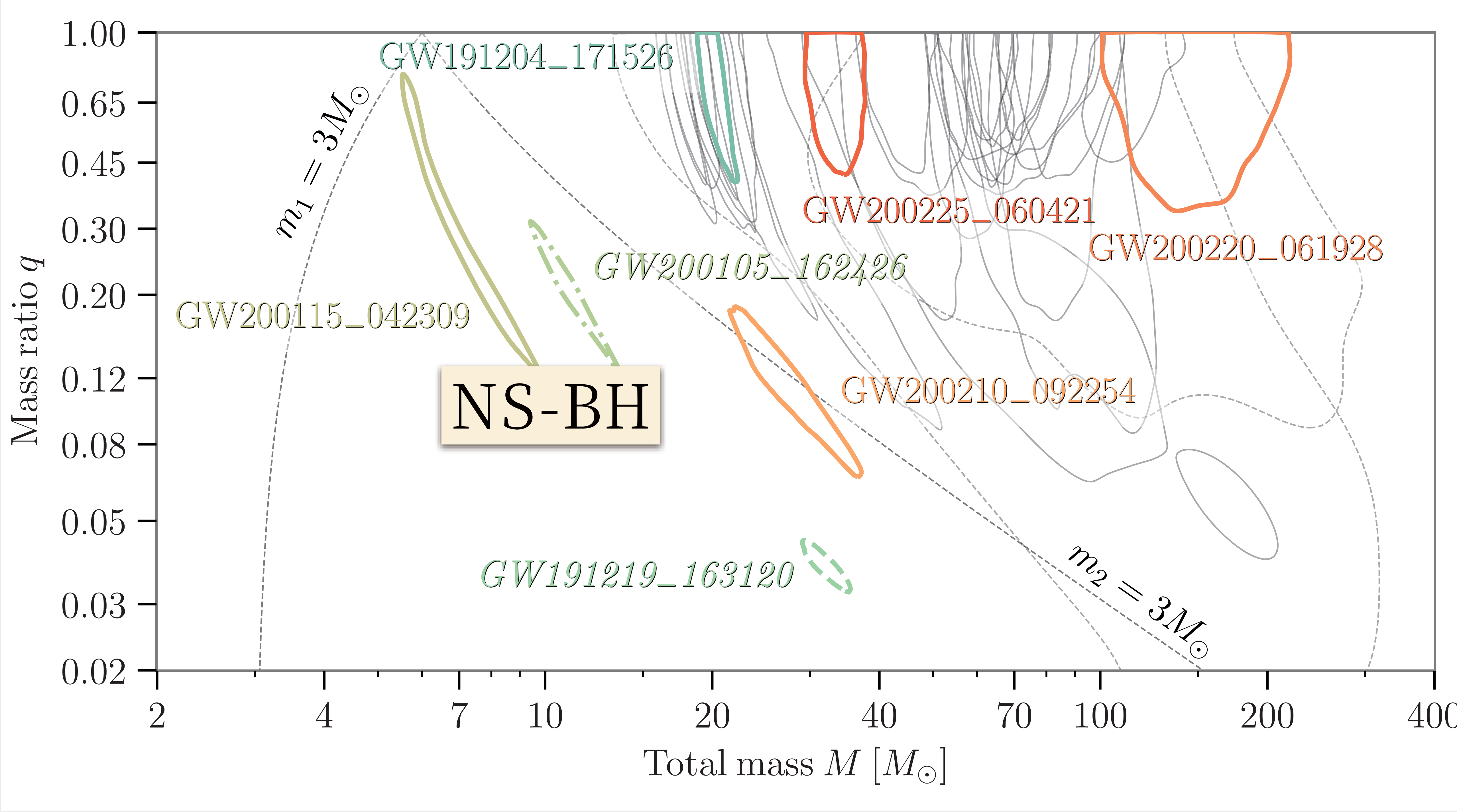

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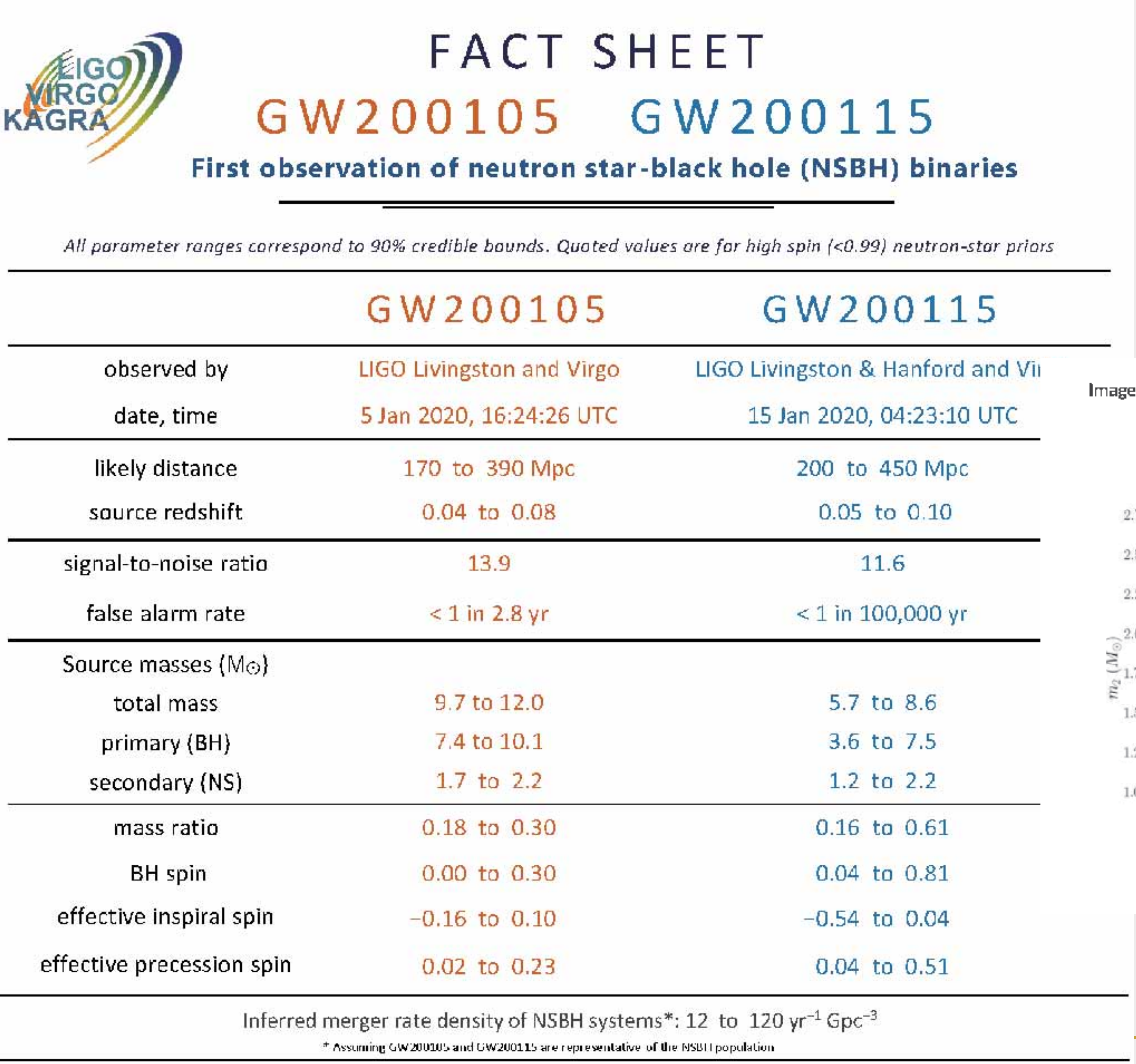
NS-BH



LIGO VIRGO KAGRA

FACT SHEET

GW200105 GW200115

First observation of neutron star-black hole (NSBH) binaries

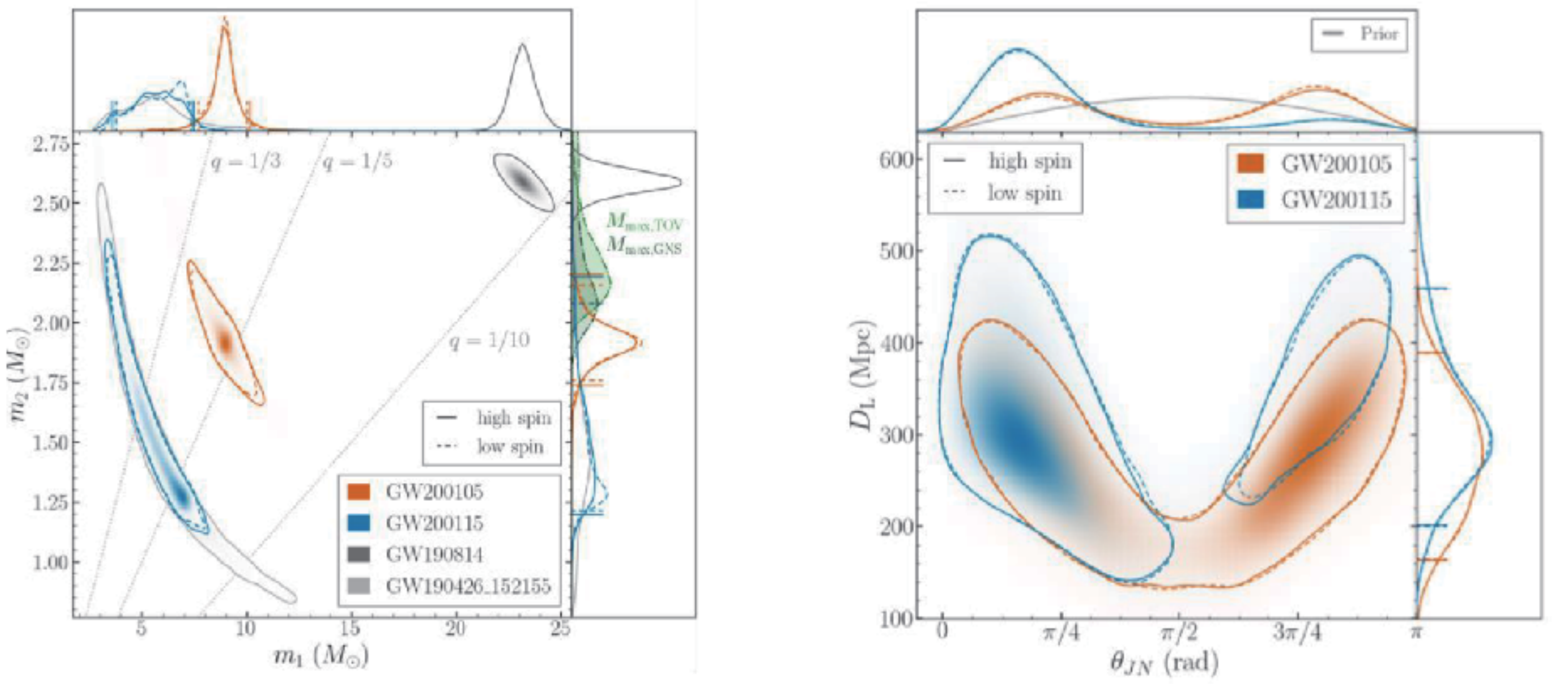
All parameter ranges correspond to 90% credible bounds. Quoted values are for high spin (<0.99) neutron-star priors

	GW200105	GW200115
observed by	LIGO Livingston and Virgo	LIGO Livingston & Hanford and Vi
date, time	5 Jan 2020, 16:24:26 UTC	15 Jan 2020, 04:23:10 UTC
likely distance	170 to 390 Mpc	200 to 450 Mpc
source redshift	0.04 to 0.08	0.05 to 0.10
signal-to-noise ratio	13.9	11.6
false alarm rate	< 1 in 2.8 yr	< 1 in 100,000 yr
Source masses ($M_\odot$)		
total mass	9.7 to 12.0	5.7 to 8.6
primary (BH)	7.4 to 10.1	3.6 to 7.5
secondary (NS)	1.7 to 2.2	1.2 to 2.2
mass ratio	0.18 to 0.30	0.16 to 0.61
BH spin	0.00 to 0.30	0.04 to 0.81
effective inspiral spin	−0.16 to 0.10	−0.54 to 0.04
effective precession spin	0.02 to 0.23	0.04 to 0.51

Inferred merger rate density of NSBH systems*: 12 to 120 $\mathrm{yr}^{-1}\,\mathrm{Gpc}^{-3}$

* Assuming GW200105 and GW200115 are representative of the NSBH population

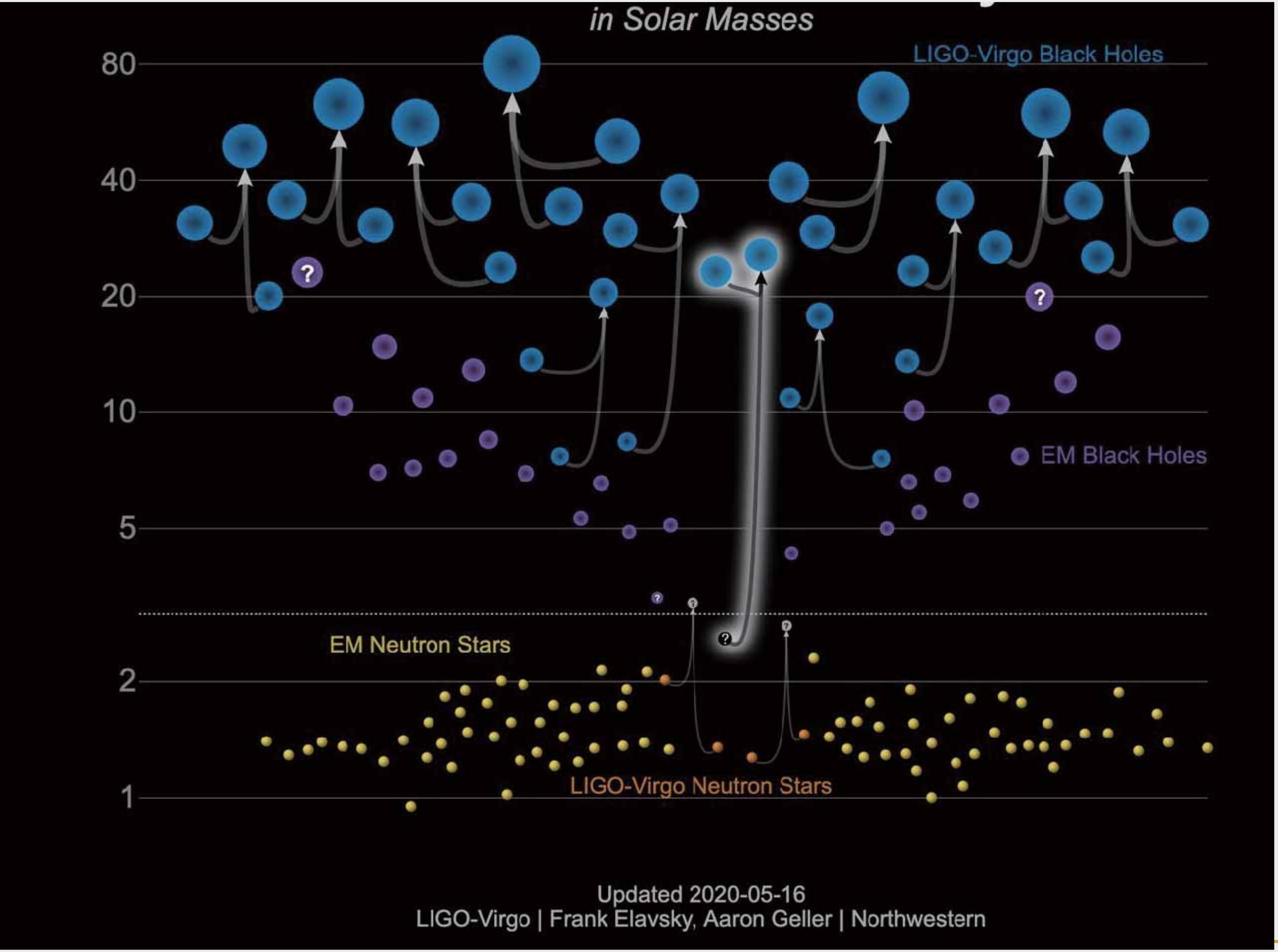
Images: companion masses (left), distance vs inclination (right), both with low (<0.05) and high (<0.99) spin priors for the neutron stars



Credits: B.S. Sathyaprakash, Penn State and Cardiff Unive

https://www.ligo.caltech.edu/news/ligo20210629

Extream mass ratio



Updated 2020-05-16
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW190814

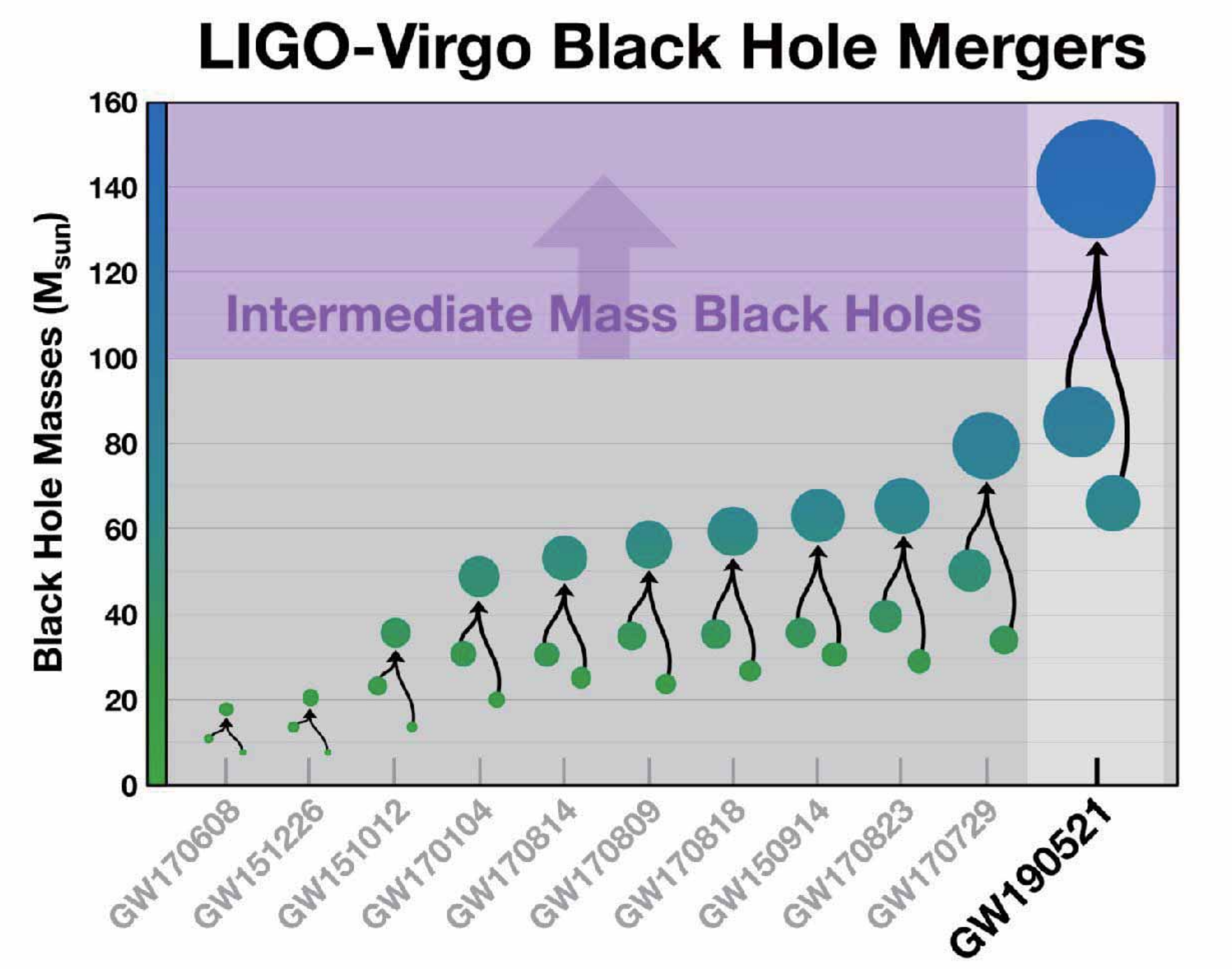
m_1 $(M_\odot)$	m_2 $(M_\odot)$
$23.2^{+1.1}_{-1.0}$	$2.59^{+0.08}_{-0.09}$

2.6 Msol ... What ?

lightest BH ?

or heaviest NS ?

IMBH (Intermediate mass black-hole)



LIGO-Virgo Black Hole Mergers

M $(M_\odot)$	$\mathcal{M}$ $(M_\odot)$	m_1 $(M_\odot)$	m_2 $(M_\odot)$	M_f $(M_\odot)$
$163.9^{+39.2}_{-23.5}$	$69.2^{+17.0}_{-10.6}$	$95.3^{+28.7}_{-18.9}$	$69.0^{+22.7}_{-23.1}$	$156.3^{+36.8}_{-22.4}$

Enigma : Origins

30 solar mass BH is hard to be formed by stars as our sun in some reason, typically small progenitor mass.

Pop III star

First generation stars was made from H,He = low metal. Thus these stars may form larger mass comparing with PopI,II.

Dynamical formation

Primordial BH

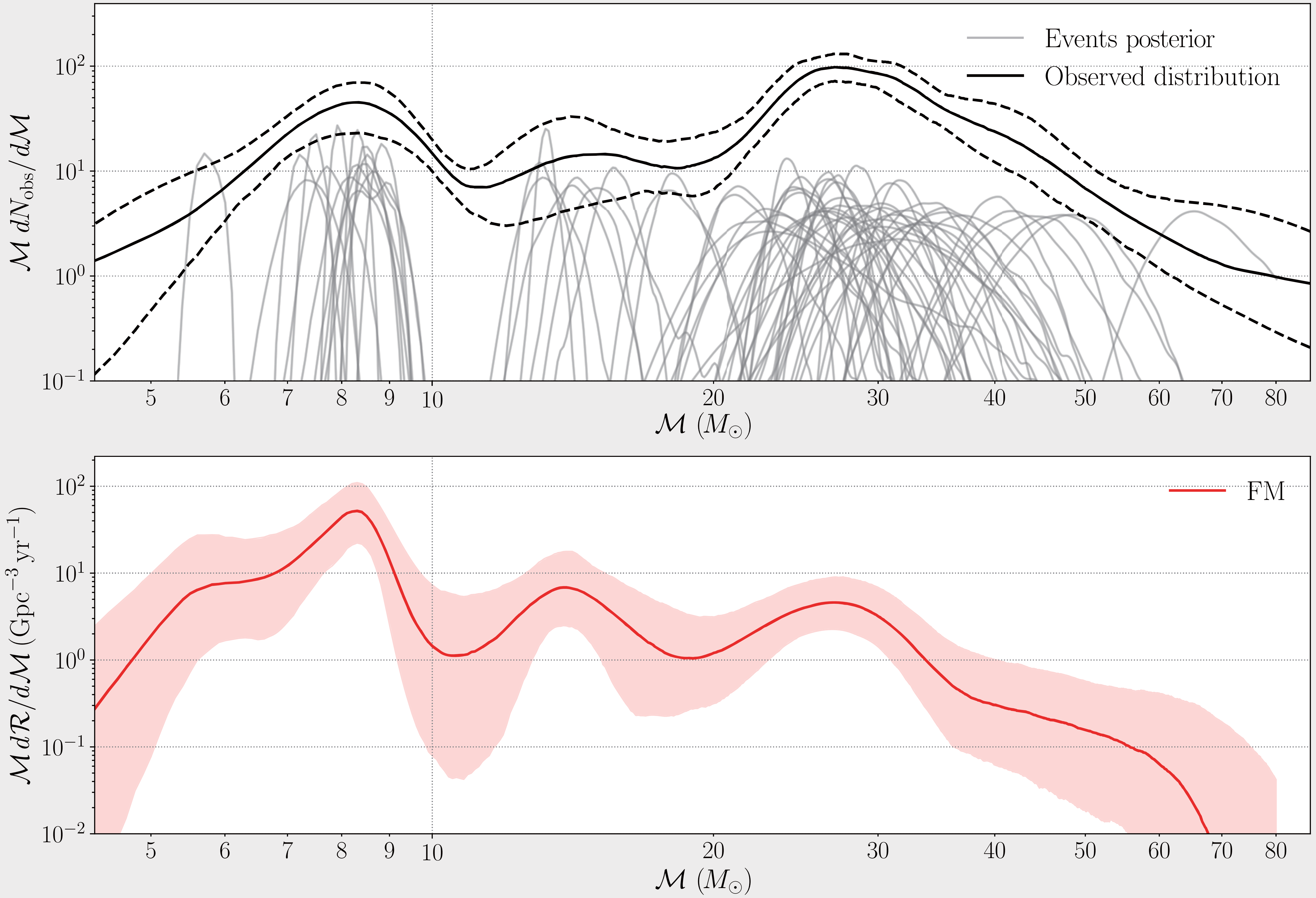


FIG. 2. Illustrating substructure in the source chirp-mass distribution for a BBH (with FAR $< 1\ \mathrm{yr}^{-1}$, excluding GW190814, as in Sec. VI). All event inferences shown adopt the same fiducial PE priors shown in Fig. 1 and described in the text. Top: the individual-event observations versus chirp mass (gray) and an inferred distribution of the observed chirp-mass distribution (black solid) using an adaptive kernel density estimator [115,116]. The kernel bandwidth is optimized for the local event density and a 90% confidence interval (black dashed) is obtained by bootstrapping [117]. Bottom: the solid curve is the predicted underlying source chirp-mass distribution obtained using the flexible mixture model framework (FM); see Sec. III for details. Unlike the top panel, this panel accounts for our selection effects. The distribution shows three clusters at low masses and a relative deficit of mergers in the chirp-mass range $10-12M_\odot$.

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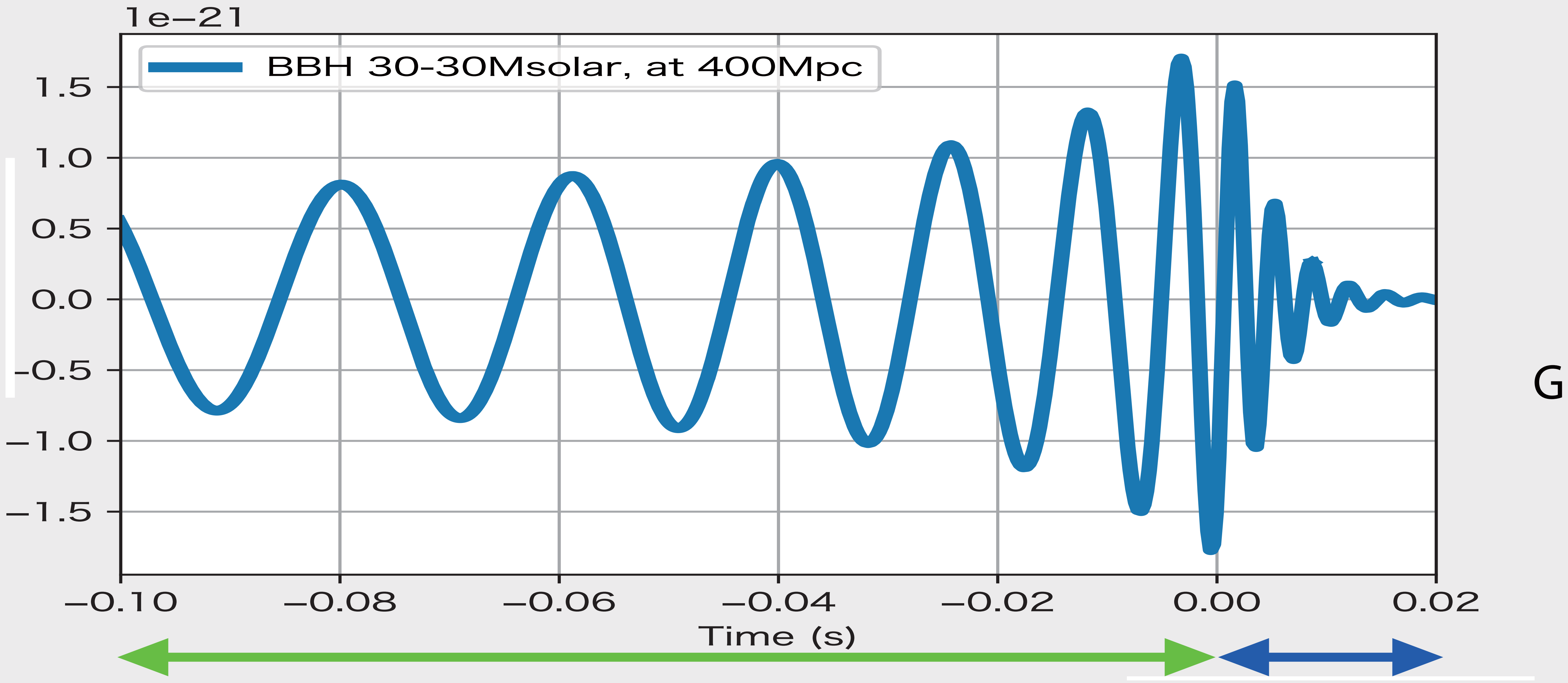
Quest : Space-time of BH

Quasi-normal mode

Blackhole Quasinormal modes (BH-QNMs) are dumped-sinusoidal ("ringdown") gravitational wave (GW) form.

BH mass and angular momentum determine its frequency and decay time.

How to identify QNM, especially higher modes(index l,m) and overtones(n) are interested problem.



BH QNM

Ergoshere of BH

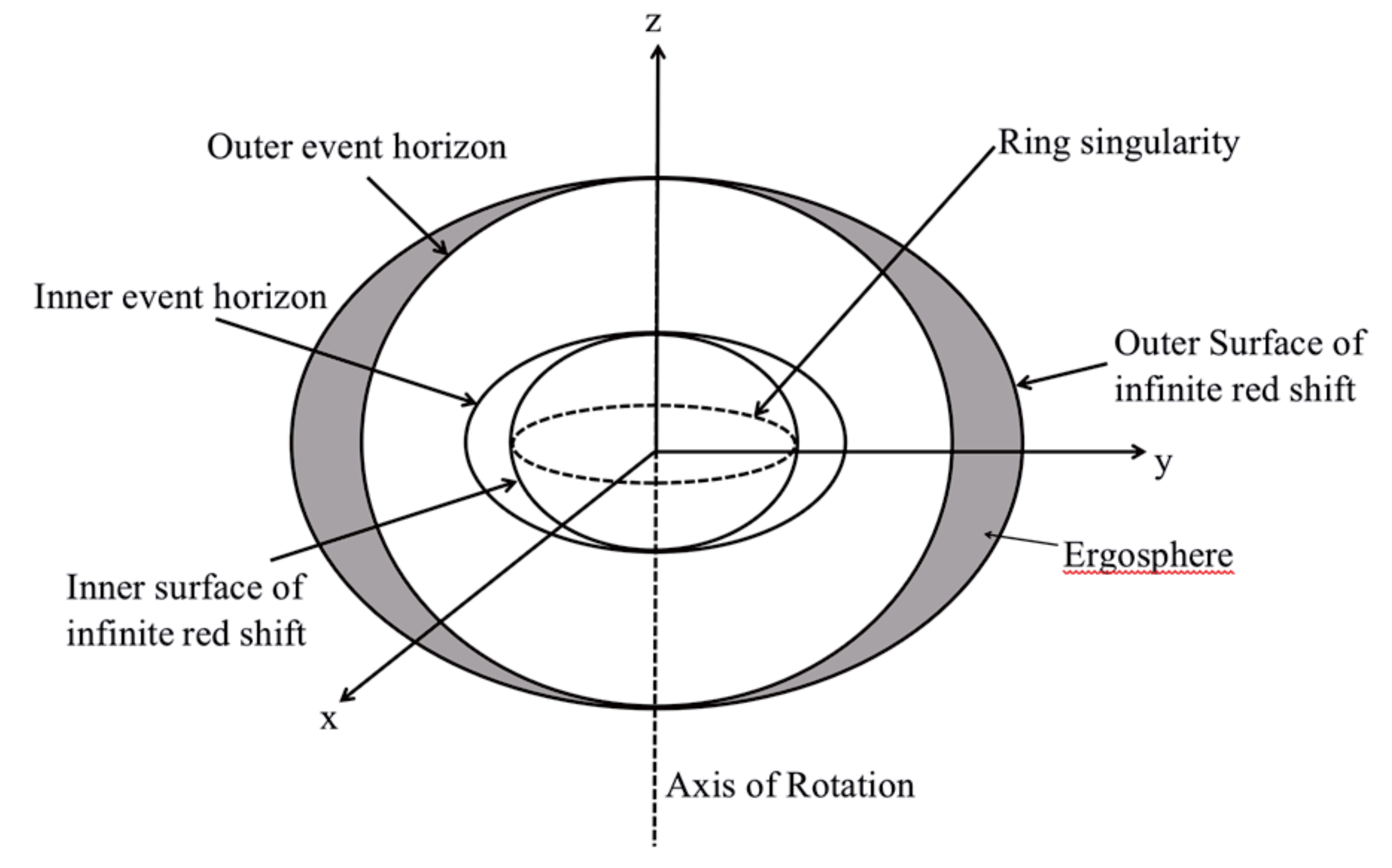
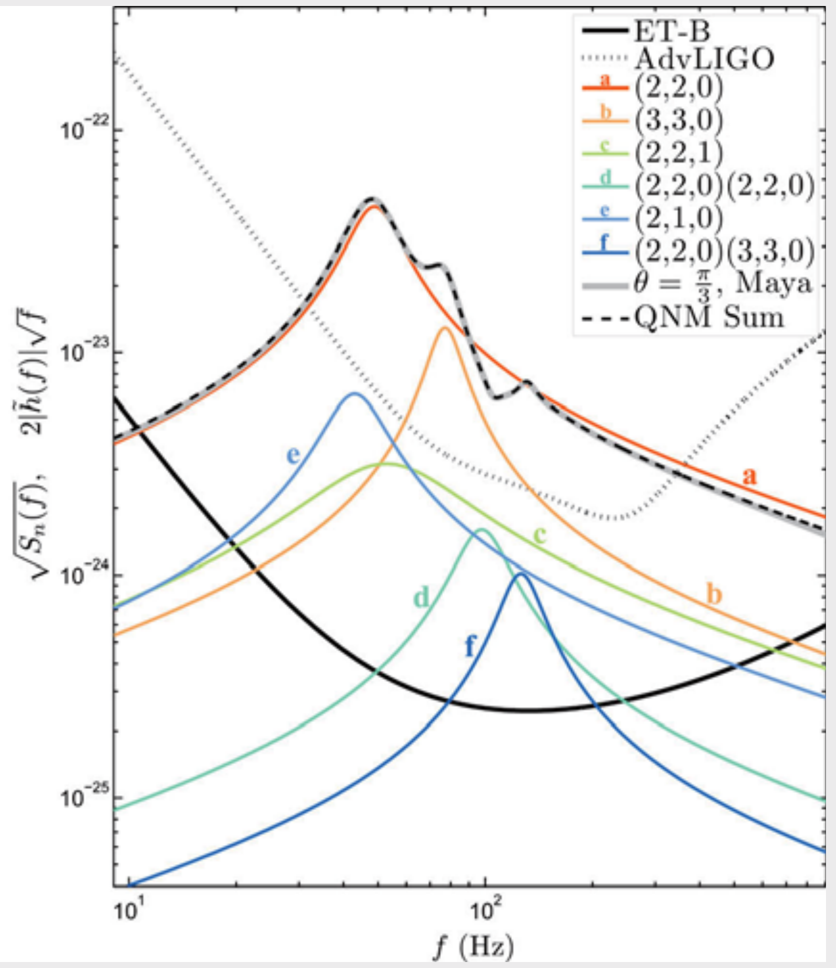


Figure 4. A sketch of Kerr black hole.

Guan, Lingyan & Tang, Xianzhe & Tian, Jialing & Wu, Jiayi. (2022). Journal of Physics: Conference Series. 2364. 012053. 10.1088/1742-6596/2364/1/012053.

BH quasi-normal mode

$$h(f_c, Q, t_0, \phi_0; t) = e^{-\frac{\pi f_c (t-t_0)}{Q}} \cos(2\pi f_c (t - t_0) - \phi_0)$$



Laplace Transform : Idea & Motivation

Laplace Transform : time series in real ==> complex frequency domain

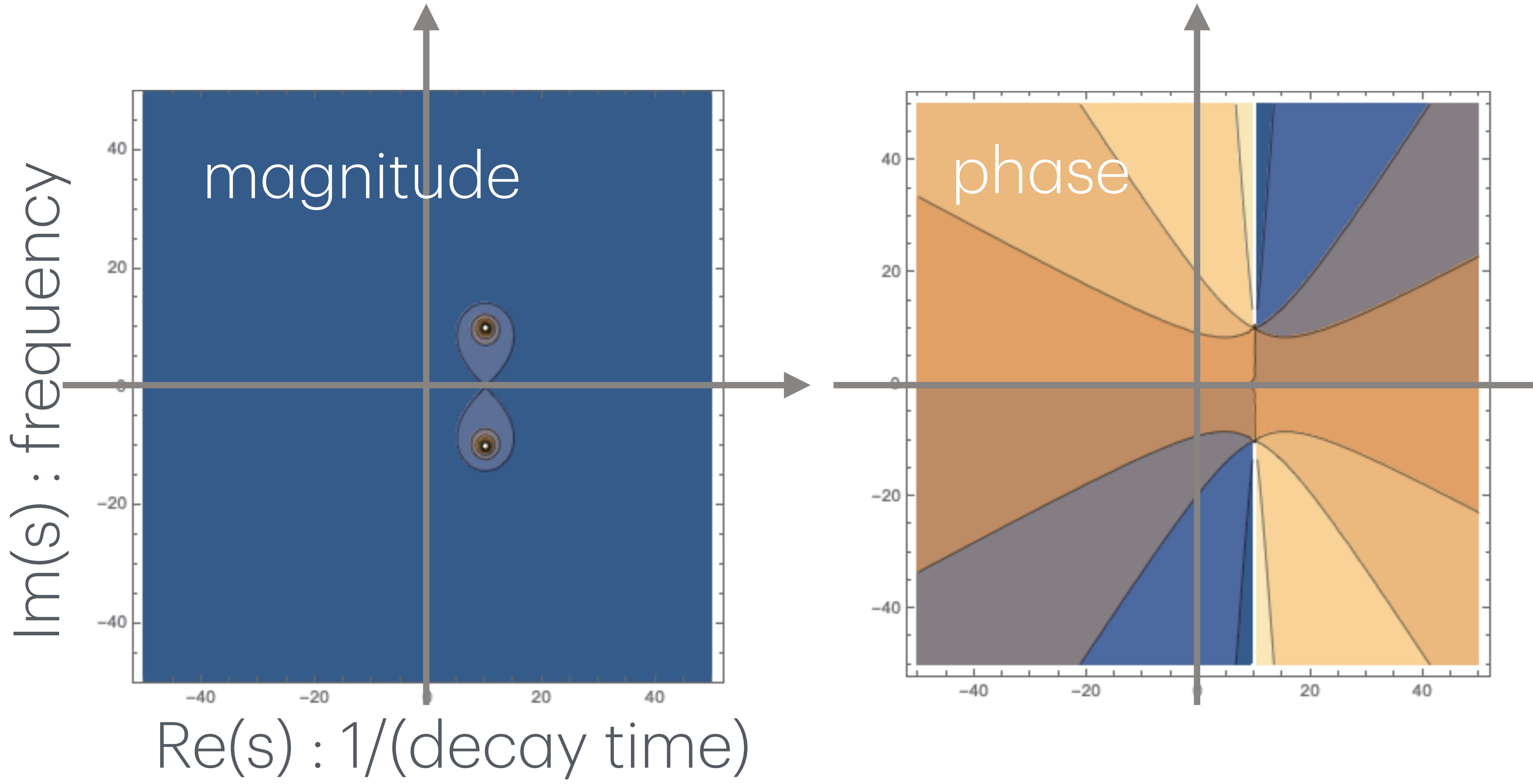
$$H(s) = \mathcal{L}[h](s) = \int_0^\infty h(t)e^{-st}dt$$

$$= \int_0^\infty h(t)e^{-(b+i\omega)t}dt$$

h(t) : time series
H(s) : Laplace transform of *h(t)*
s : complex frequency
b : Re(s), ω : Im(s)

- clear and simple definition,
- well known its behavior for typical time signals in electric circuit.

Dumped sinusoidal wave will be represented as 'pole' in complex plane.



This property is expected to be **suitable for viewing BH QNM**.

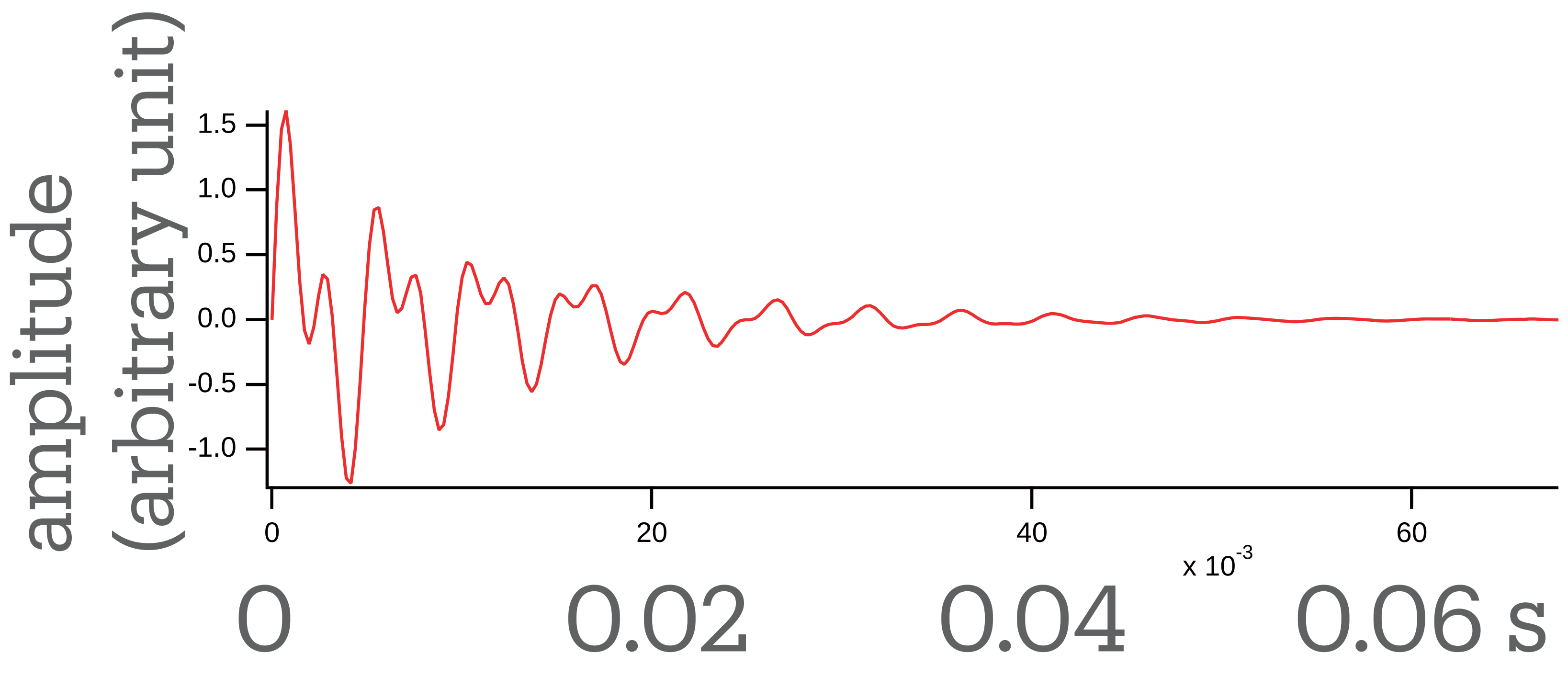
Implementation of Laplace transform for Numerical Analysis of Gravitational Waveform

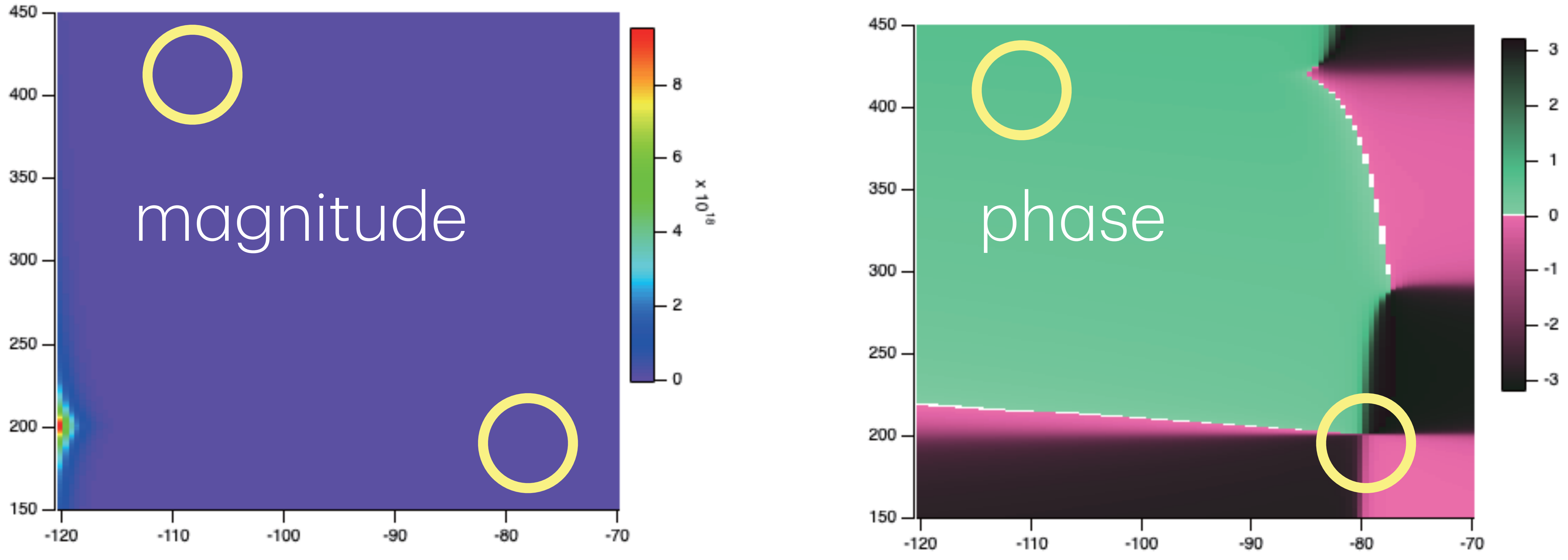
$$H(s) = \mathcal{L}[h](s) = \int_0^\infty h(t)e^{-st}dt$$

$$= \int_0^\infty h(t)e^{-(b+i\omega)t}dt$$

- Laplace transform is implemented as Fourier transform of $h(t)e^{bt}$.
- We employ fast Fourier transform (FFT) for numerical calculation.
- With scanning parameter b (= inverse of decay time = real part of complex frequency s), we got Laplace transform.

example : double exponential decay time series



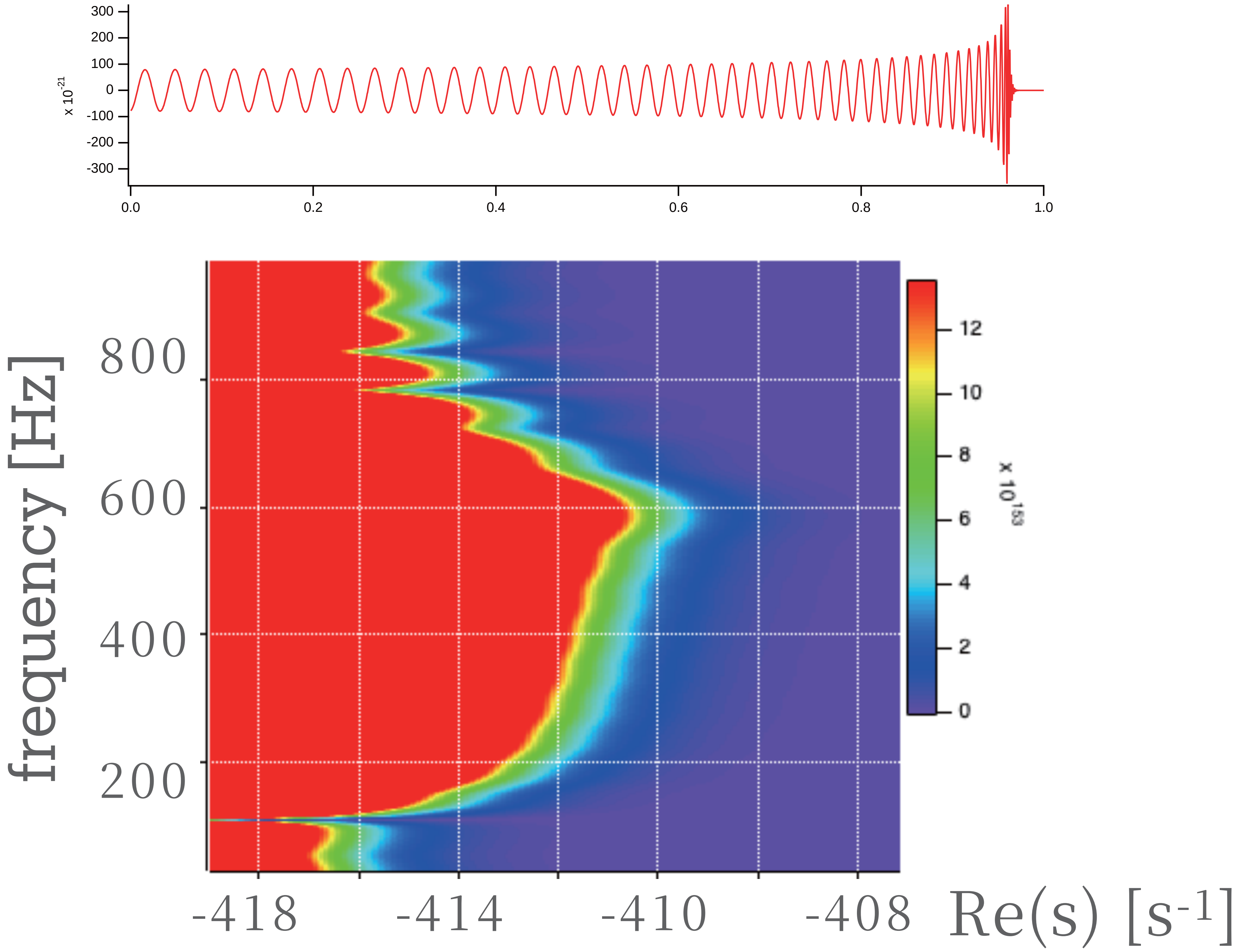


Pole that has smaller b is hard to find in this example, but phase map suggest two poles.

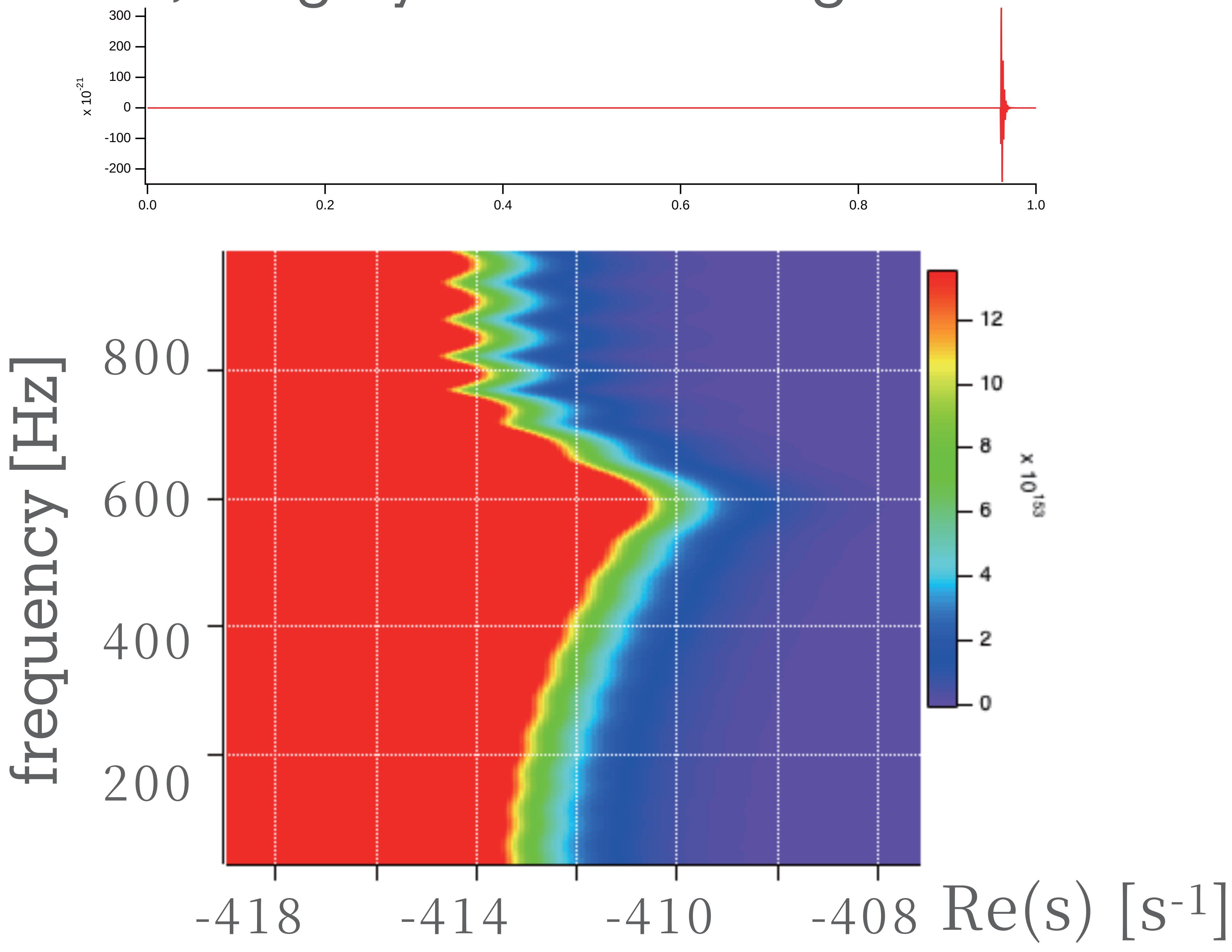
Short-time Laplace Transform

- With time slice, we can supress waveform components of non-QNM (i.e, chirp, merger).
- However, no longer needed to cut-out strictly around QNM.

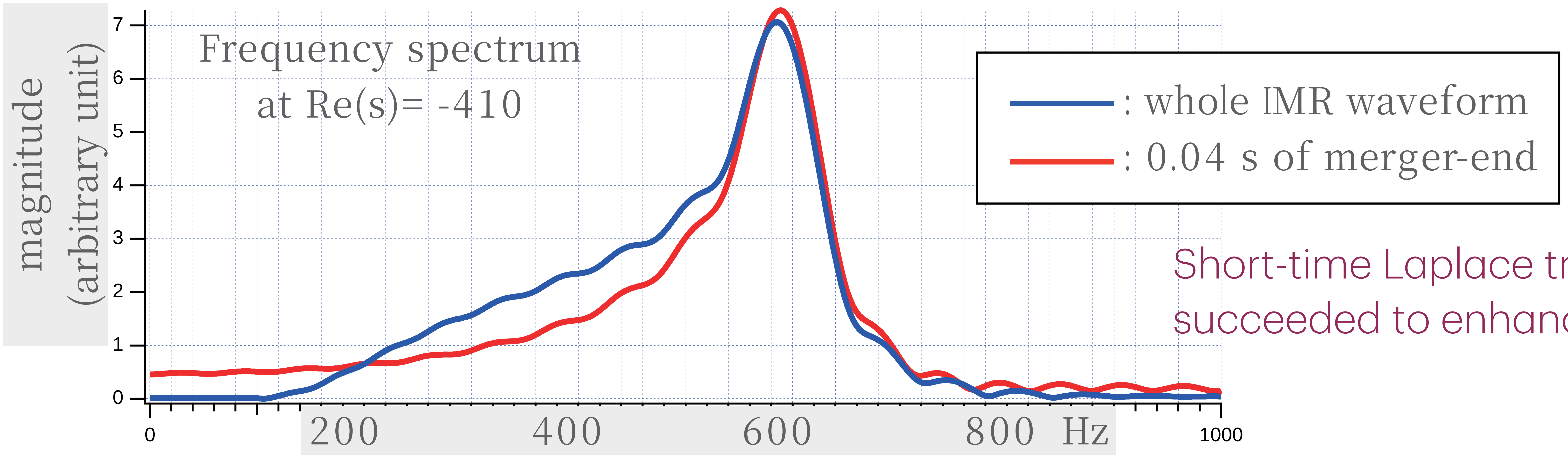
1sec whole IMR waveform



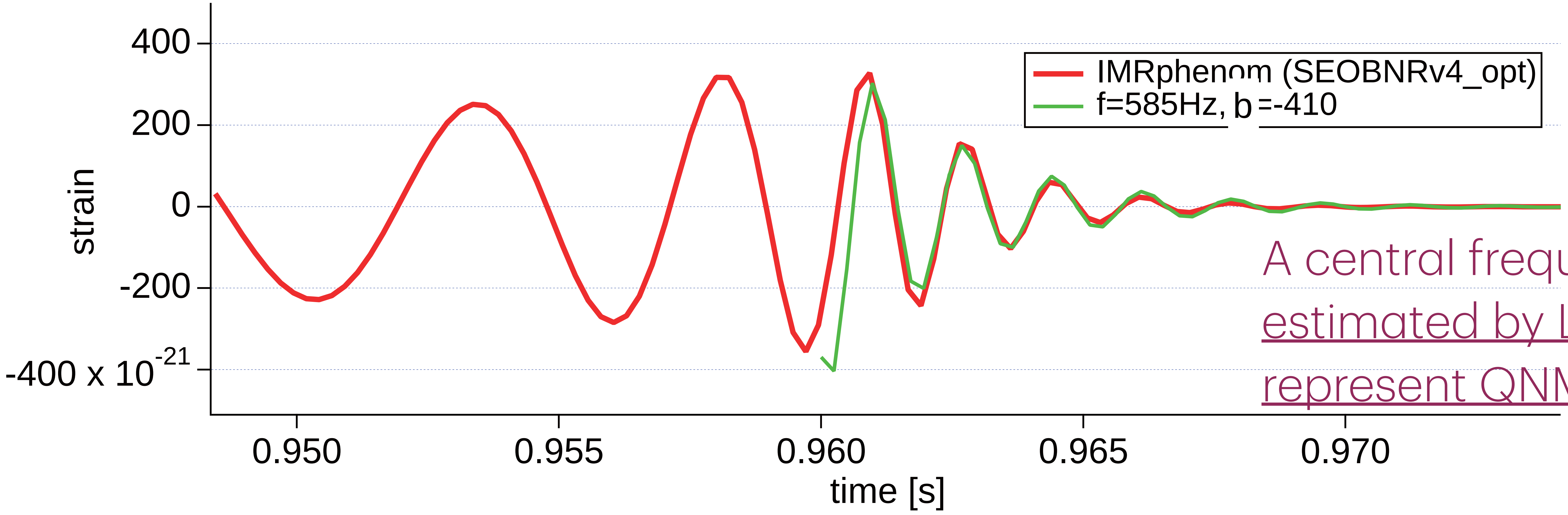
0.04 sec, roughly cut from merger to the end



Short-time Laplace Transform (cont'd)



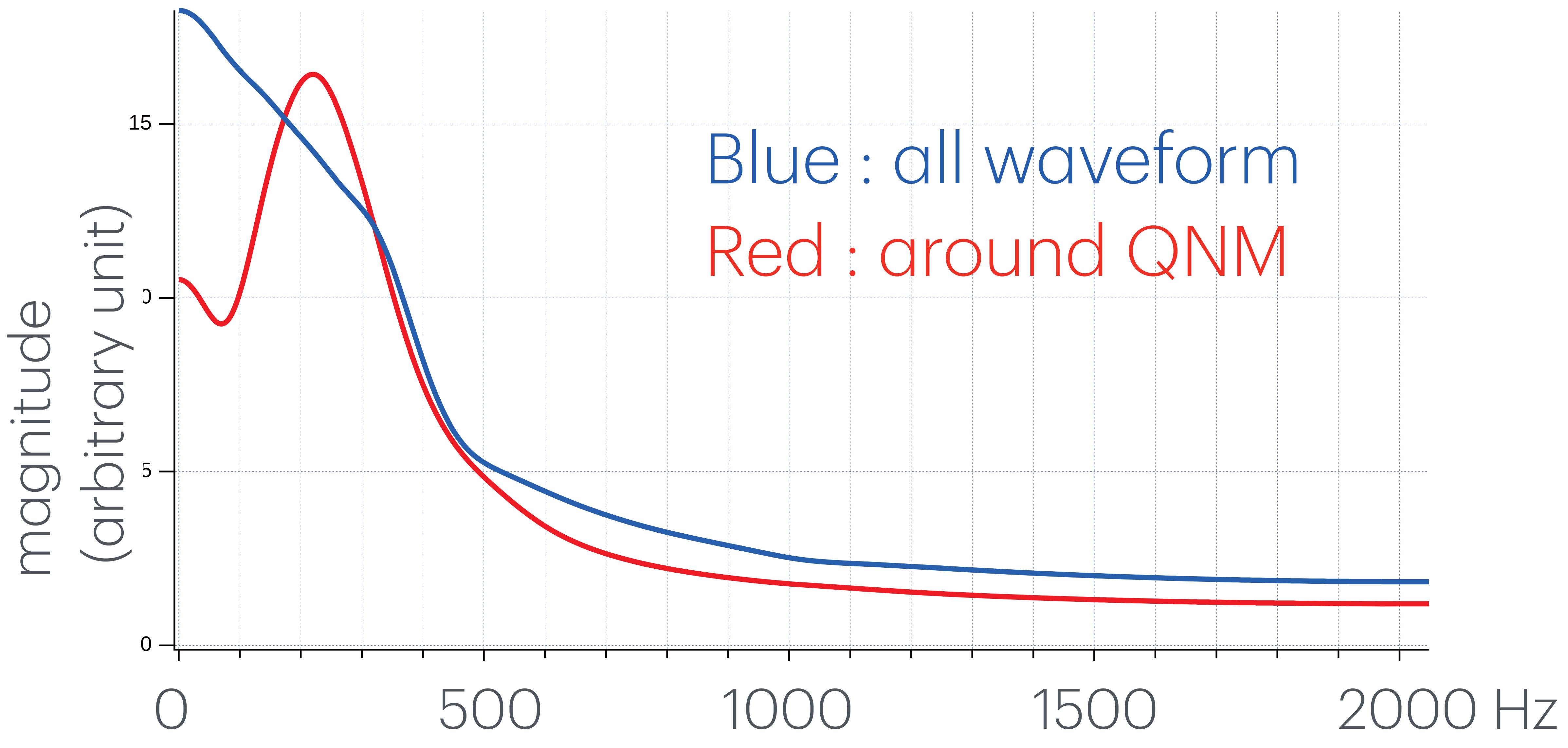
Short-time Laplace transform succeeded to enhance QNM.



A central frequency and decay time estimated by Laplace transform can represent QNM mode in time series.

Real observed gravitational waveform : GW150914 (cont'd)

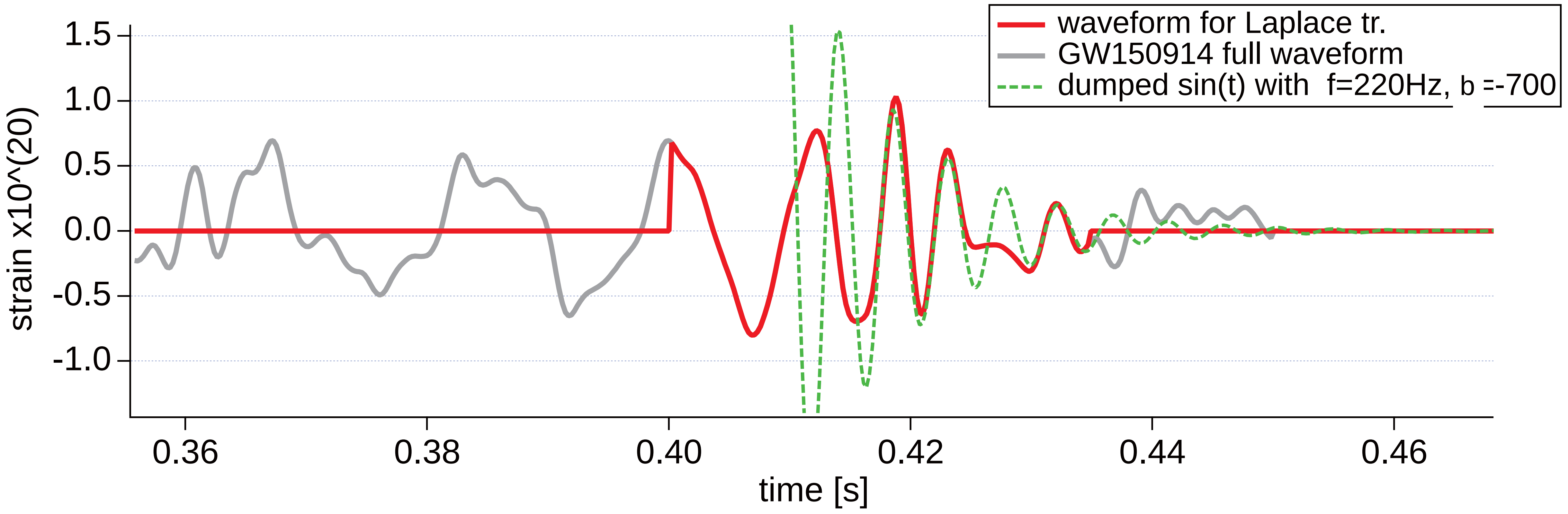
Spectrum at Re(s)=-700



Blue : all waveform

Red : around QNM

Time series of original GW150914 and estimated QNM



central frequency : $f_0 \sim 220\text{Hz}$

1/(decay time) : $Re(s) \sim -700$

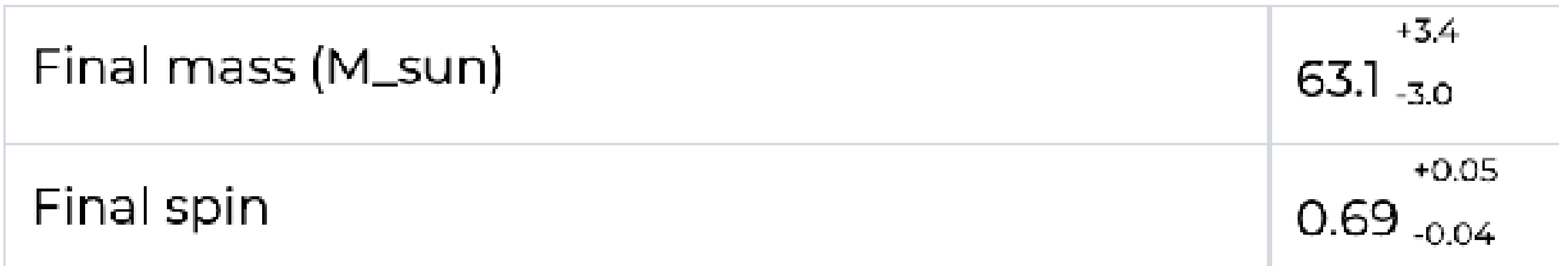
Quality factor : $Q \sim 3.1$

Kerr parameter : $\alpha \sim 0.65$

Total mass at detector frame :

$M(1+z) \sim 75.7M_\odot$

-> $M \sim 68.4M_\odot$ with redshift 0.107



Final mass (M_sun)	$63.1^{+3.4}_{-3.0}$
Final spin	$0.69^{+0.05}_{-0.04}$

GWTC-1 PE for GW150914

Summary

Gravitational waves were predicted about 100 years ago and were successfully observed for the first time in human history 10 years ago.

These 30 years or so of "We couldn't find it, but we kept trying" were very important.

Gravitational wave physics and Astrophysics Laboratory at OMU started from 2002. We have been taken important role of KAGRA design and kick-up of data analysis in Japan.

In the observational era of GW, we hope to execute GW data analysis, development of new method and future plan also.

Personally, NK strongly interested in BH's origin and its space-time.