

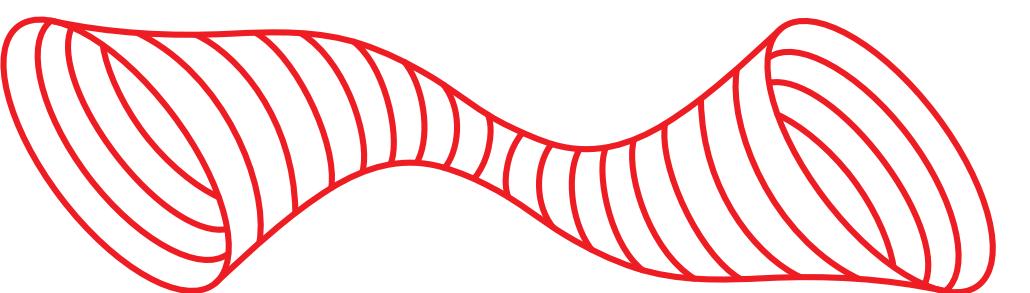


The Next Decade in Gravitational Wave Astronomy

Fysik*, NBI, 2026

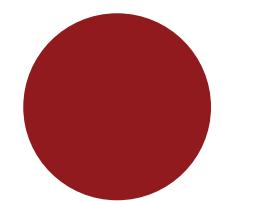
Jose María Ezquiaga

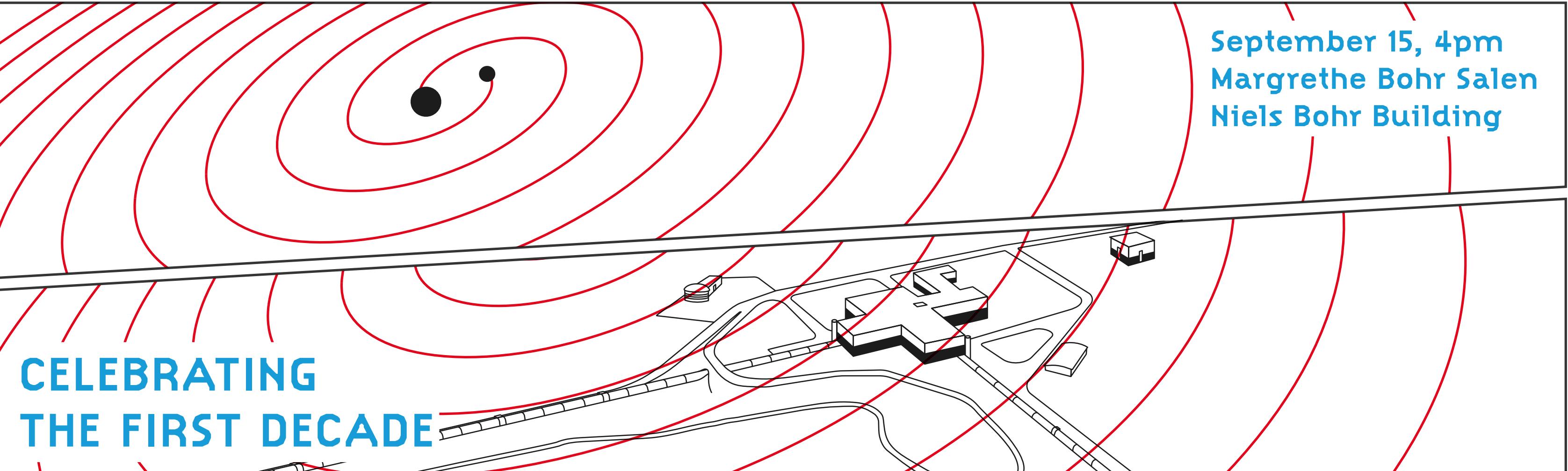
Niels Bohr Institute
ezquiaga.github.io



THE CENTER OF GRAVITY

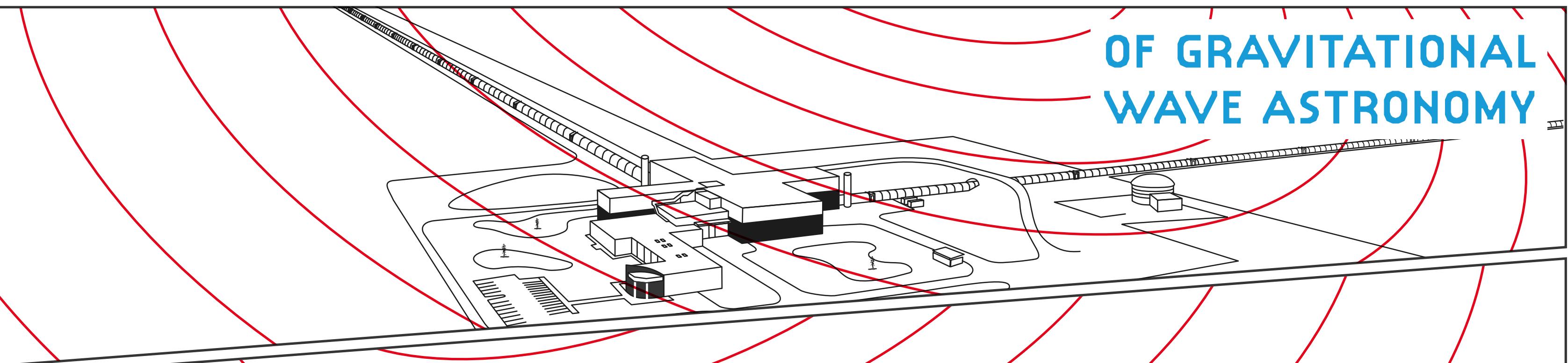
VILLUM FONDEN



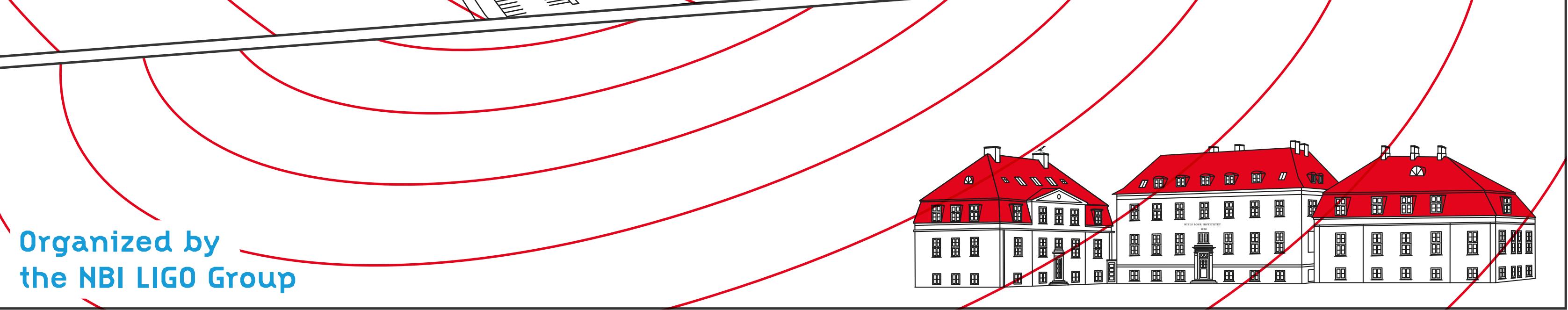


September 15, 4pm
Margrethe Bohr Salen
Niels Bohr Building

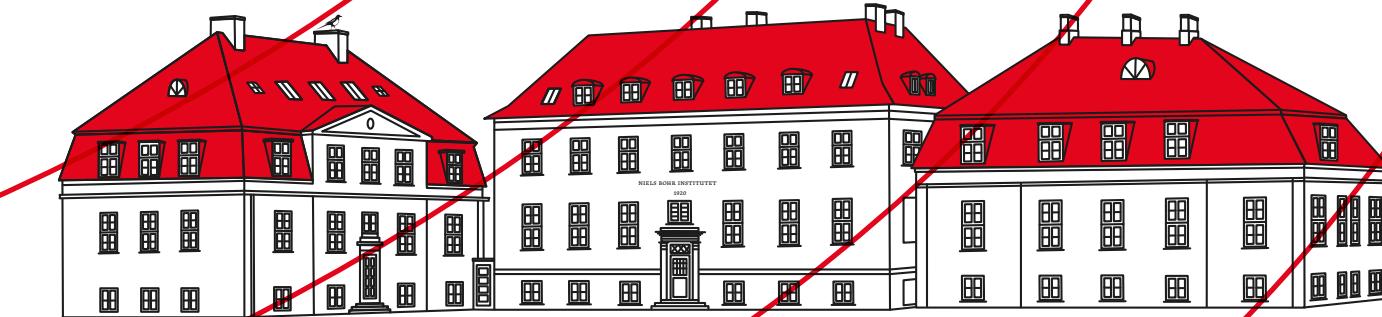
CELEBRATING
THE FIRST DECADE

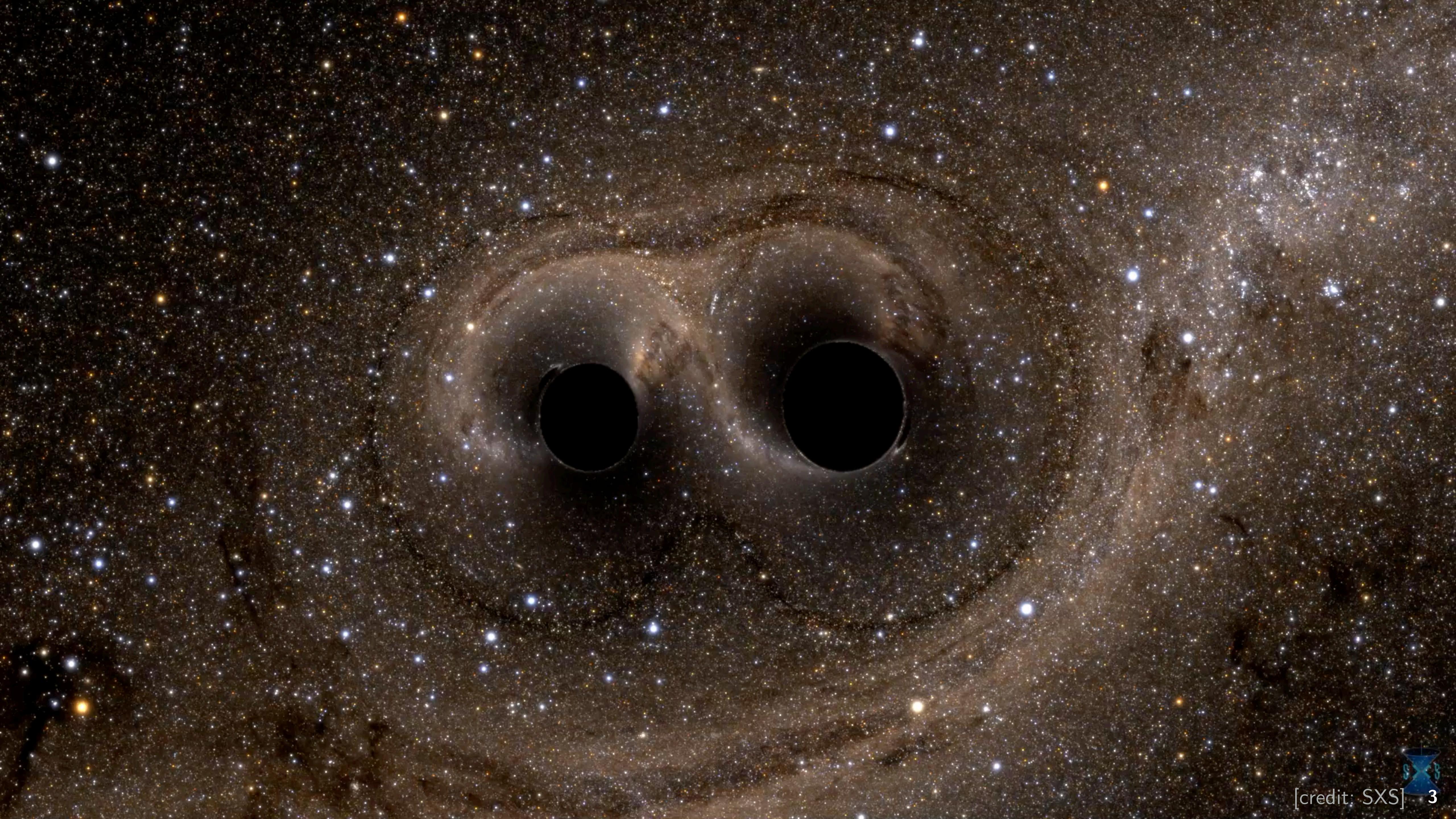


OF GRAVITATIONAL
WAVE ASTRONOMY

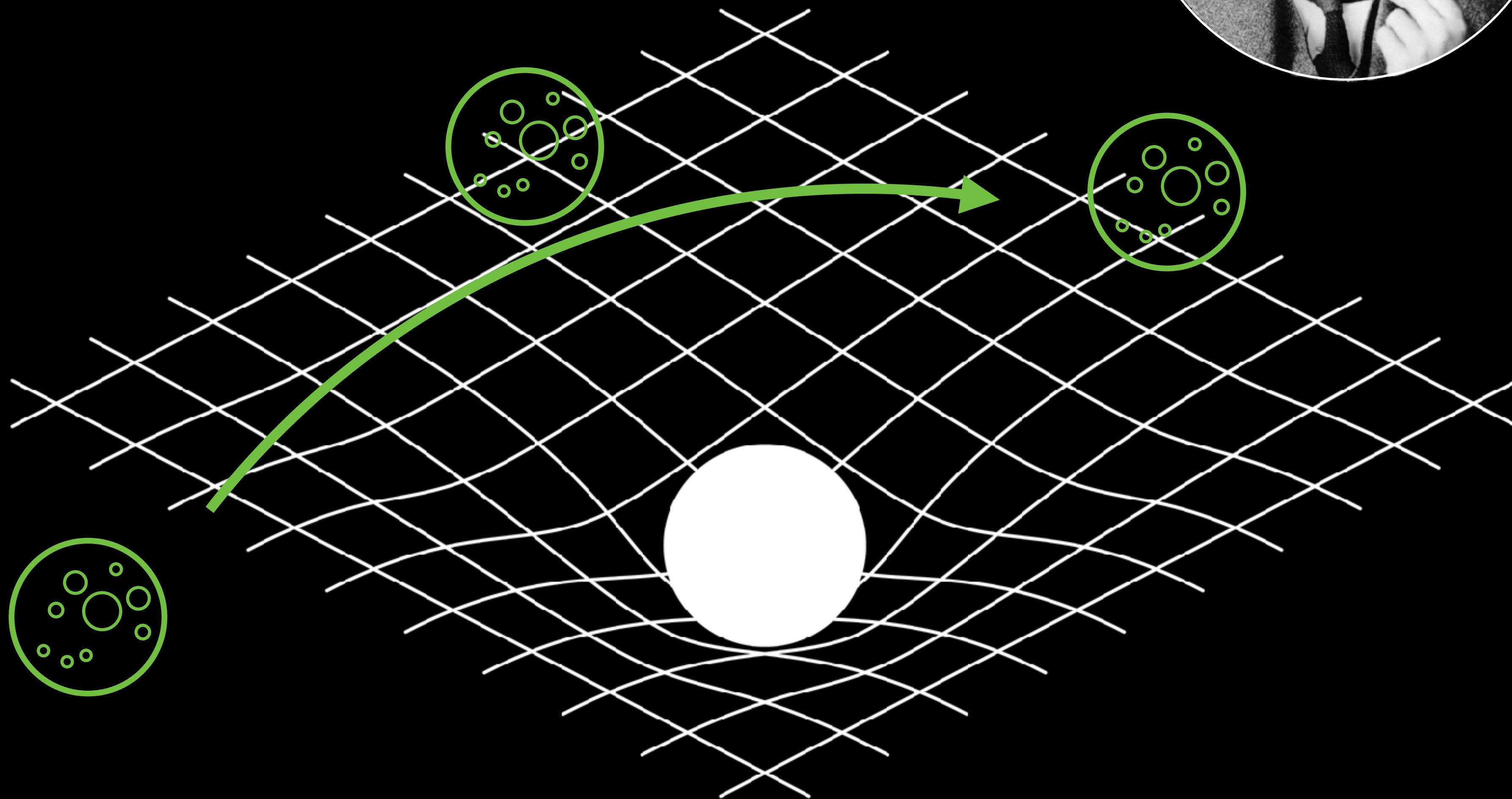
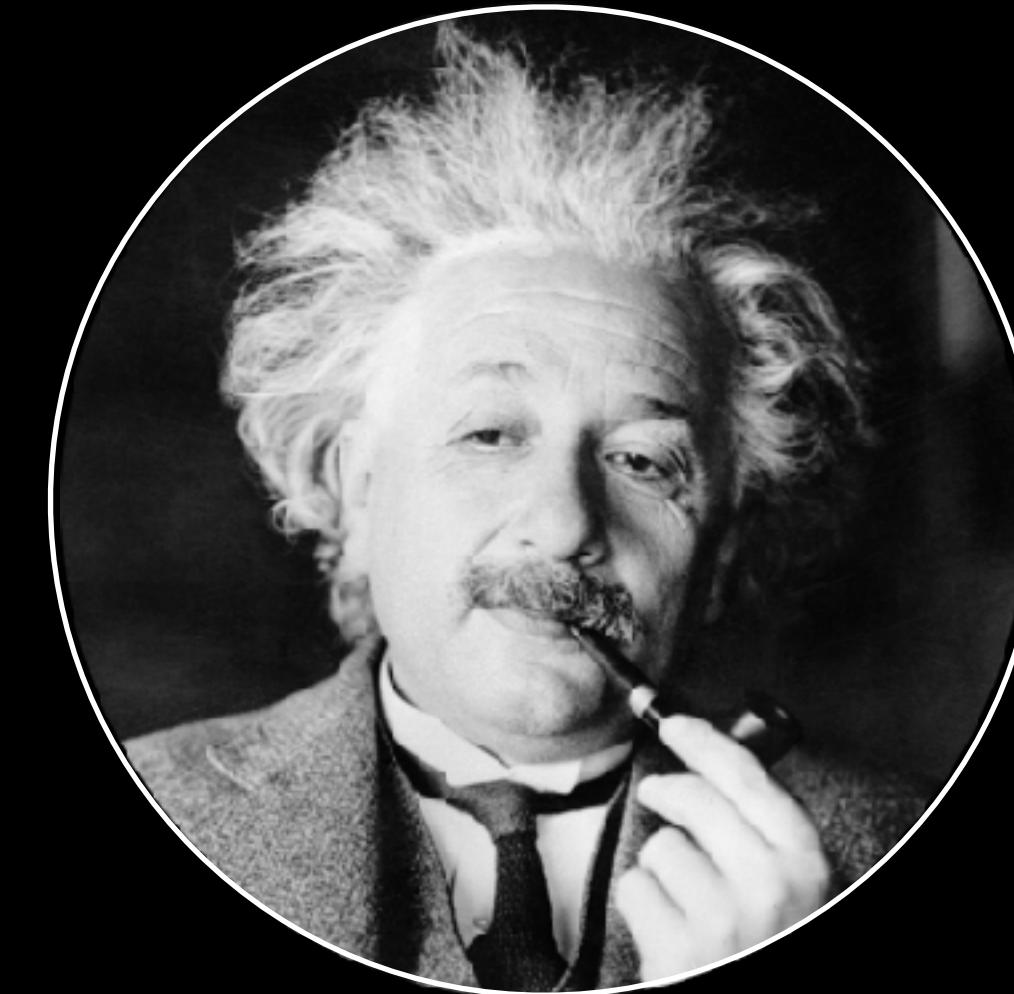


Organized by
the NBI LIGO Group



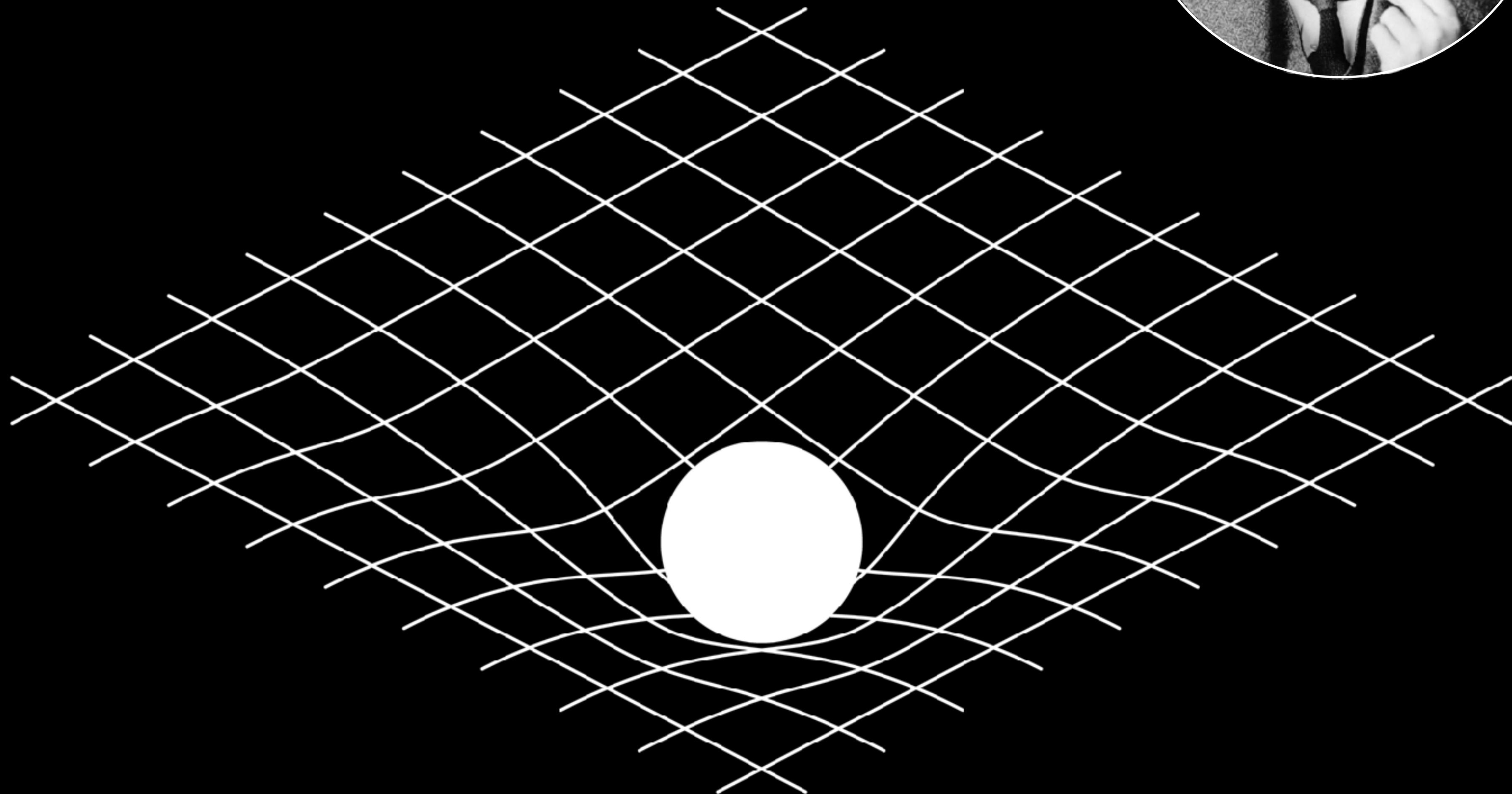
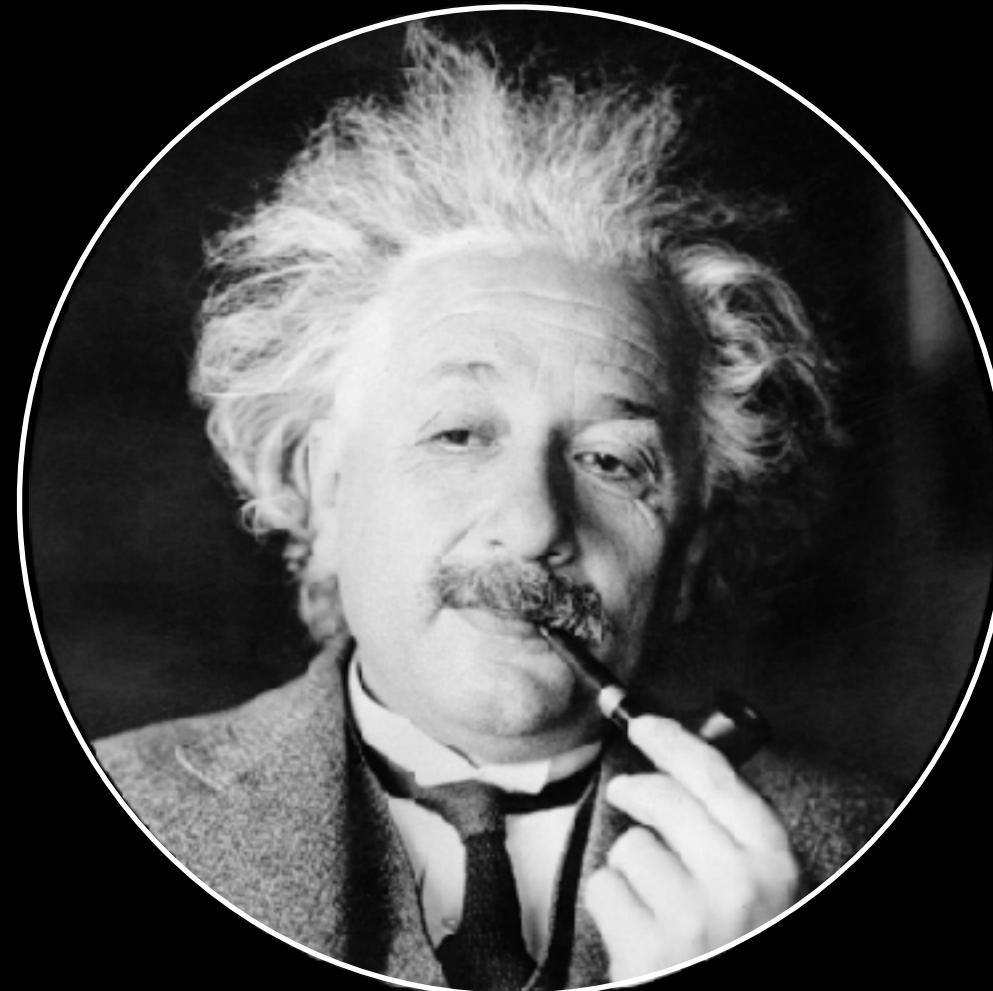


Space-time curves

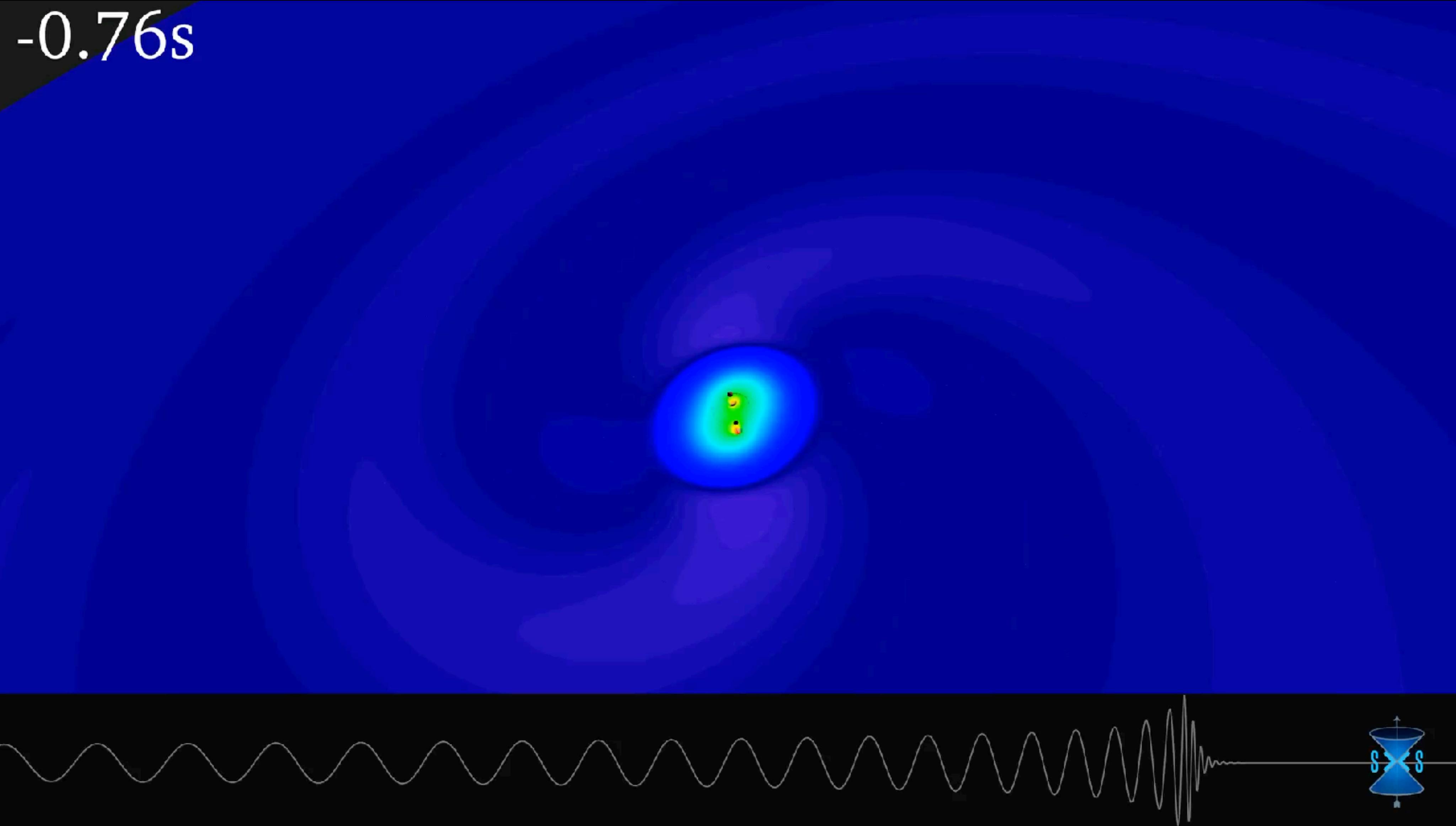


Space-time curves

Space-time is dynamic

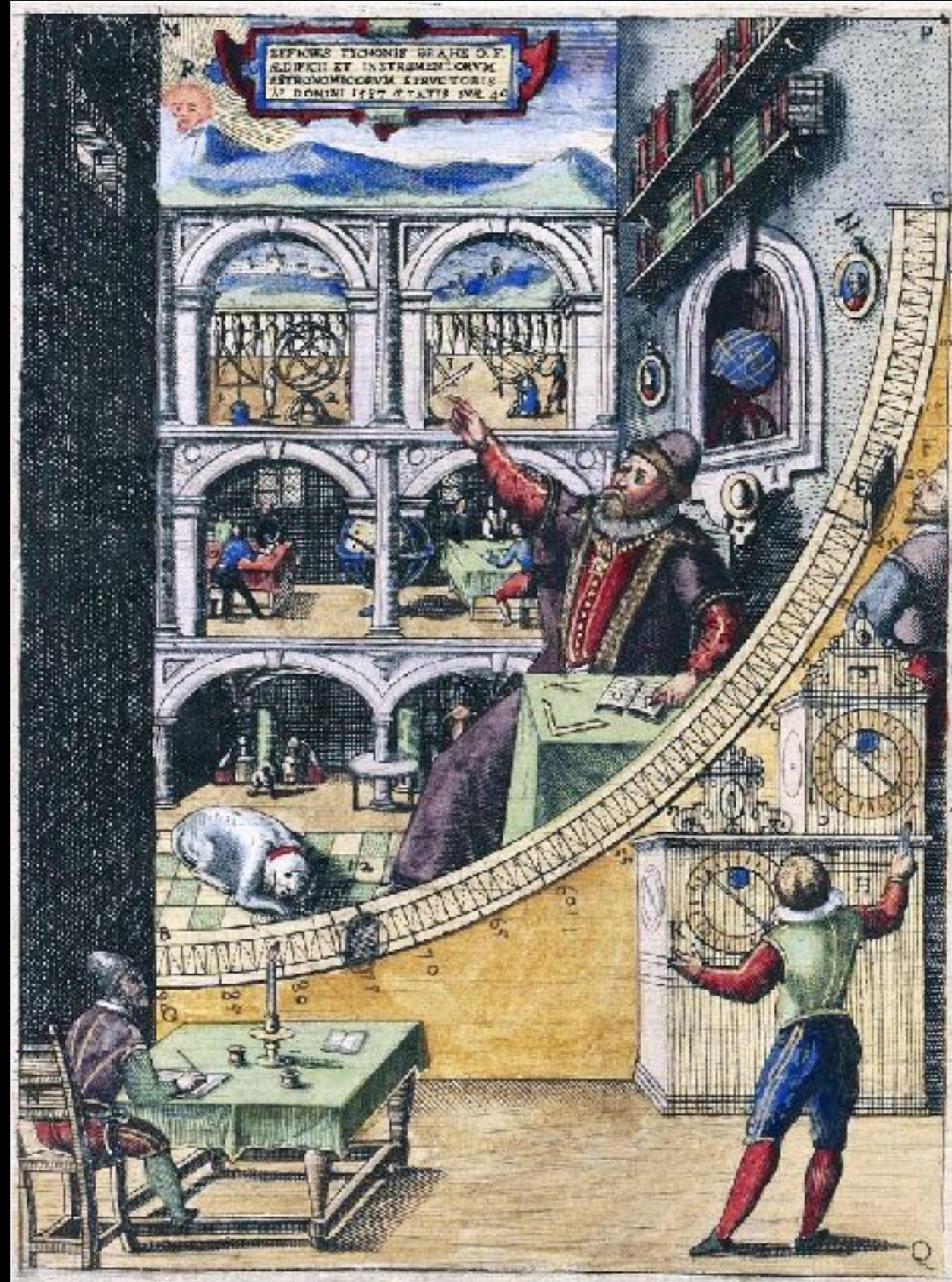


Numerical simulation of a binary black hole merger

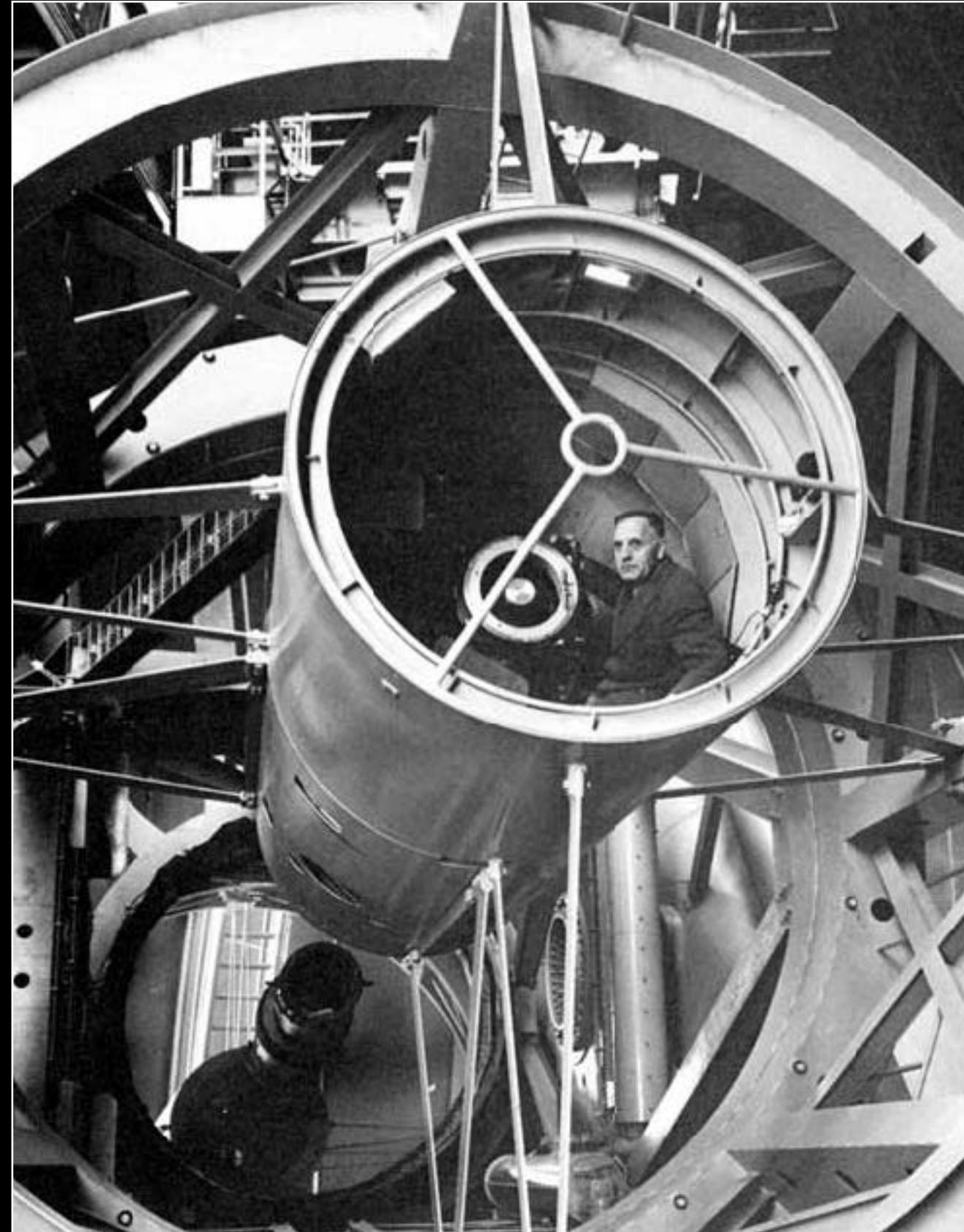


Gravitational waves are new cosmic messengers

Every time that we have been able to look further...



[Tycho Brahe, 16th century]



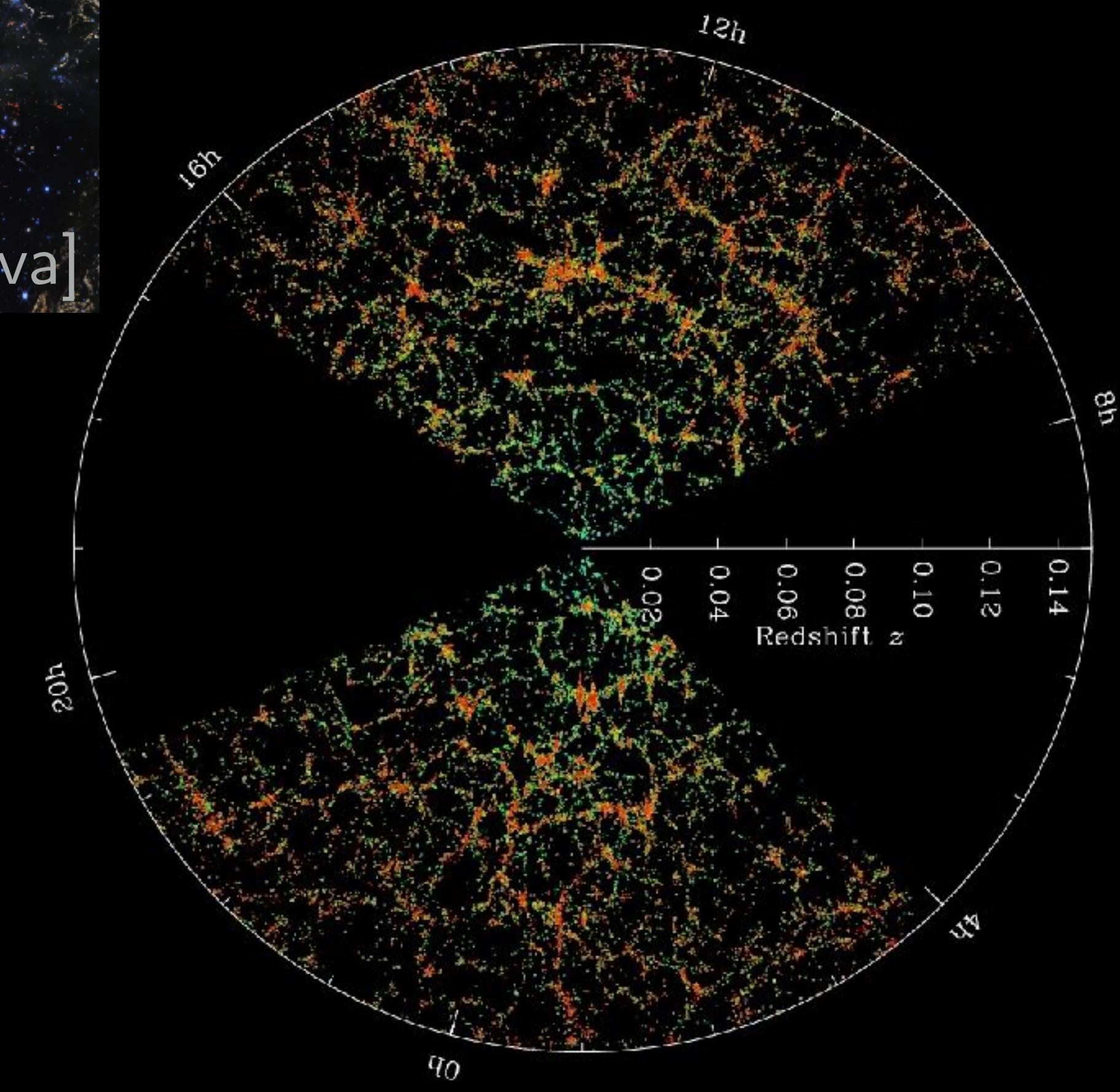
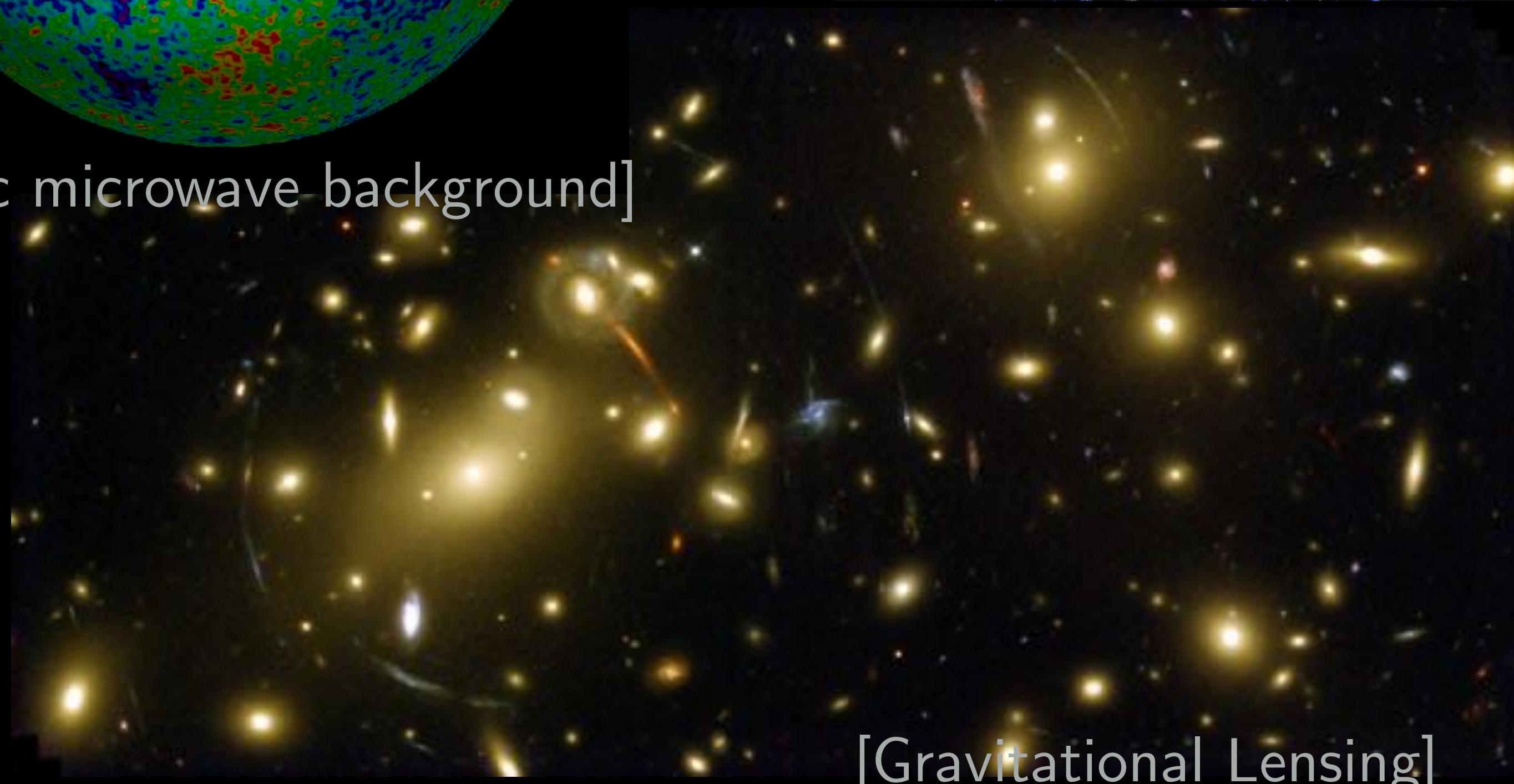
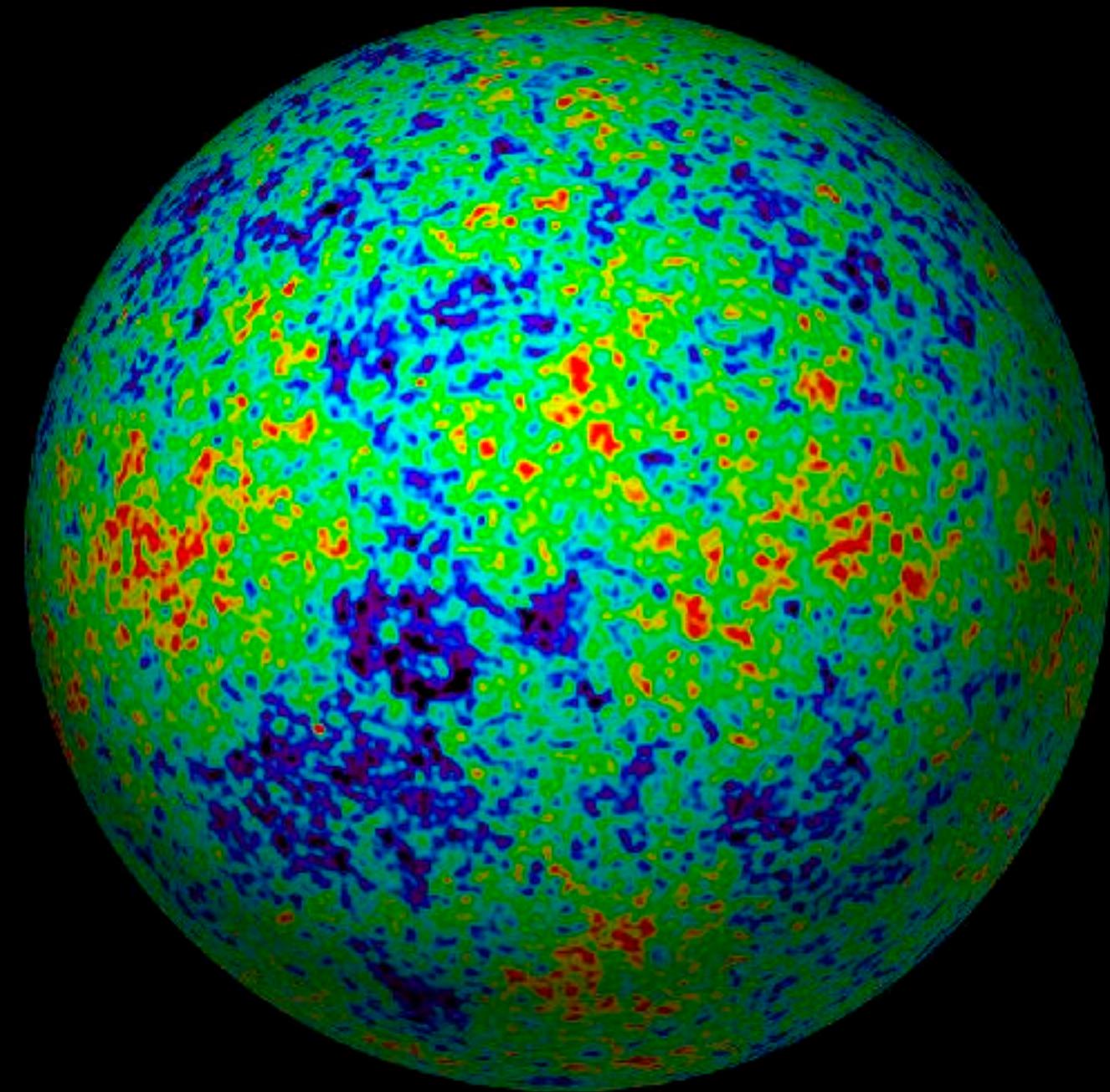
[Edwin Hubble, 20th century]



[Space Telescopes, 21st century]

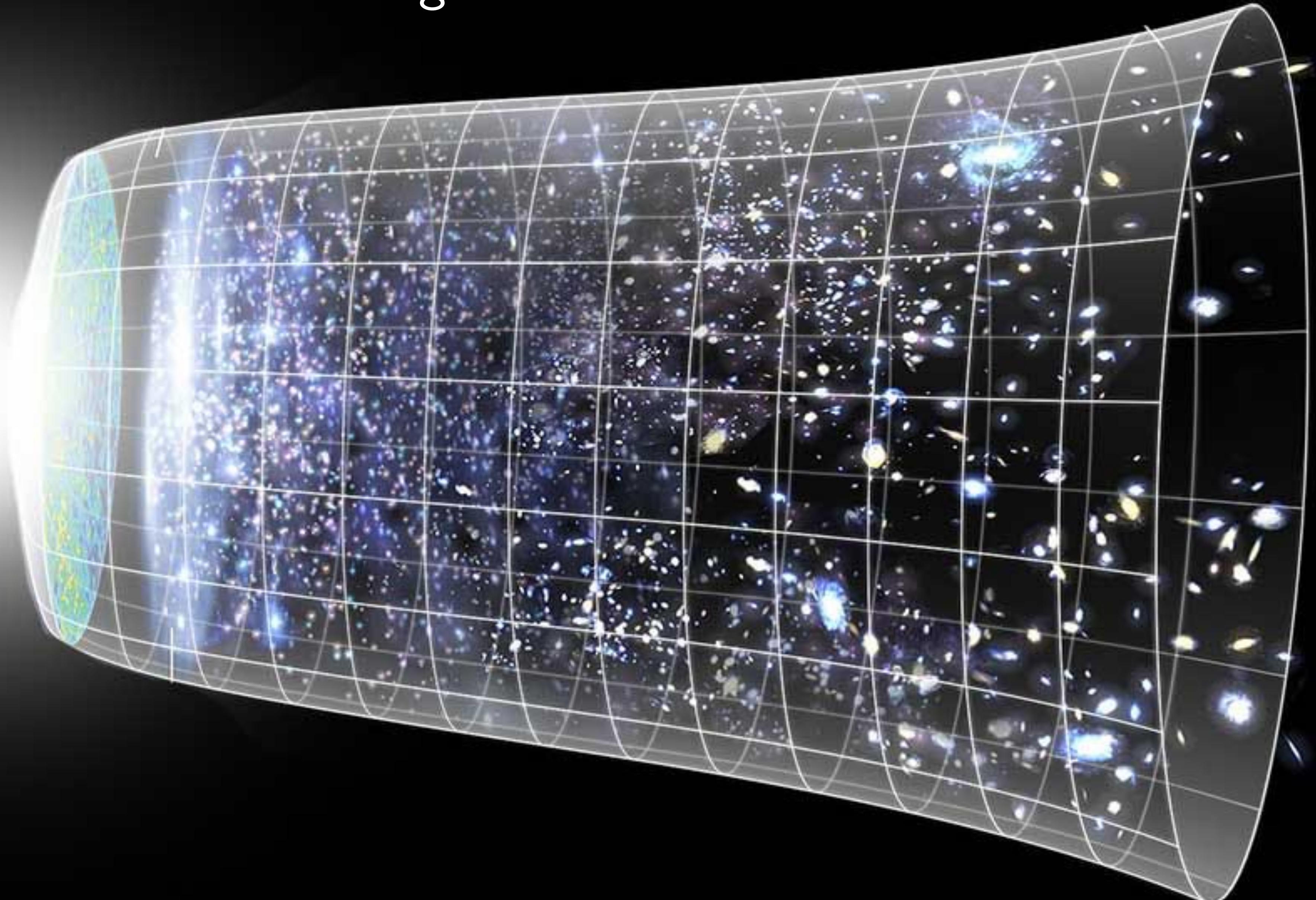
...we have found fascinating surprises

A plethora of cosmological observations



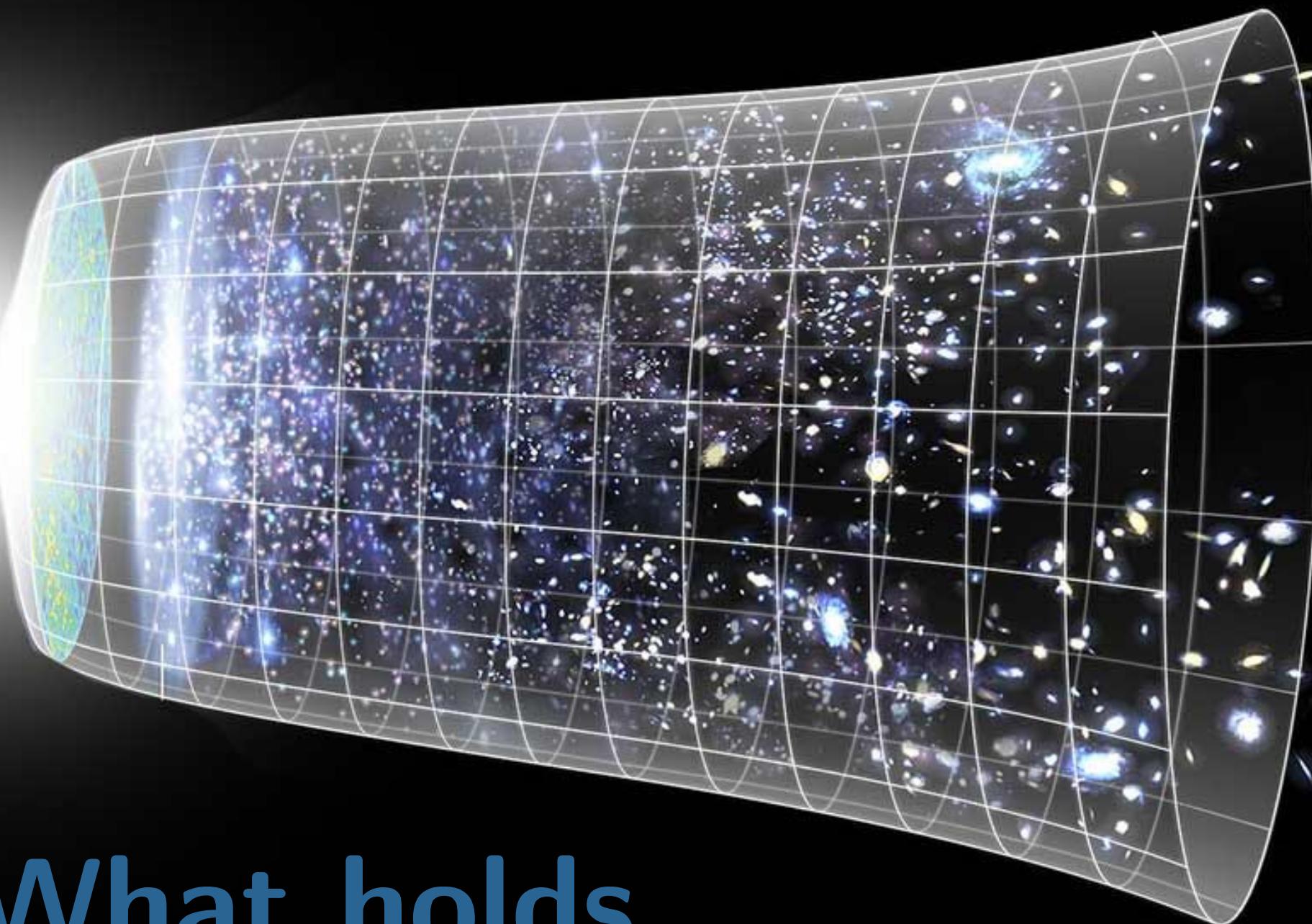
+ many more

The **standard** cosmological model...



...13.8 billion years of cosmic history ¹⁰

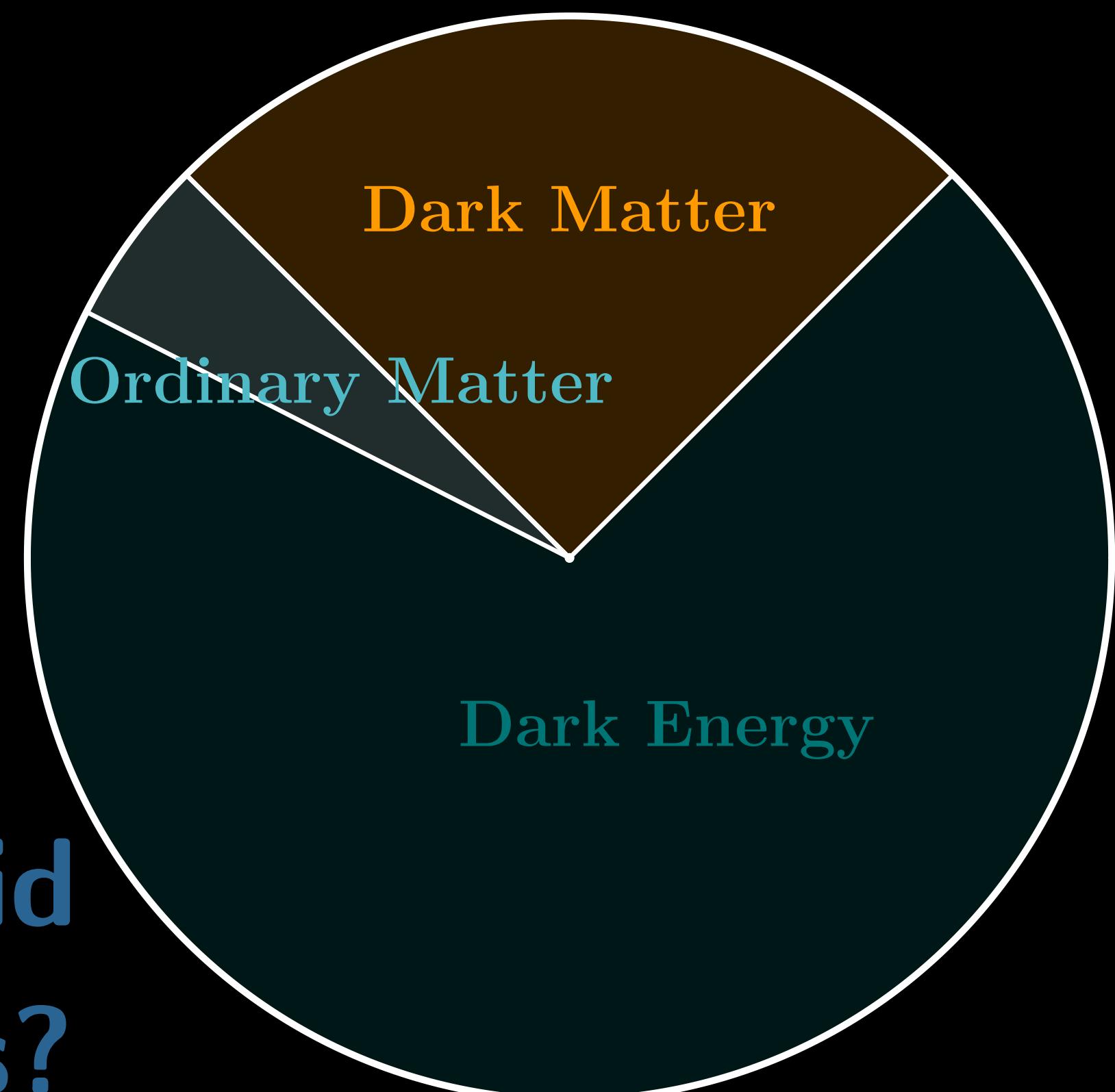
We don't understand the basics of our Universe



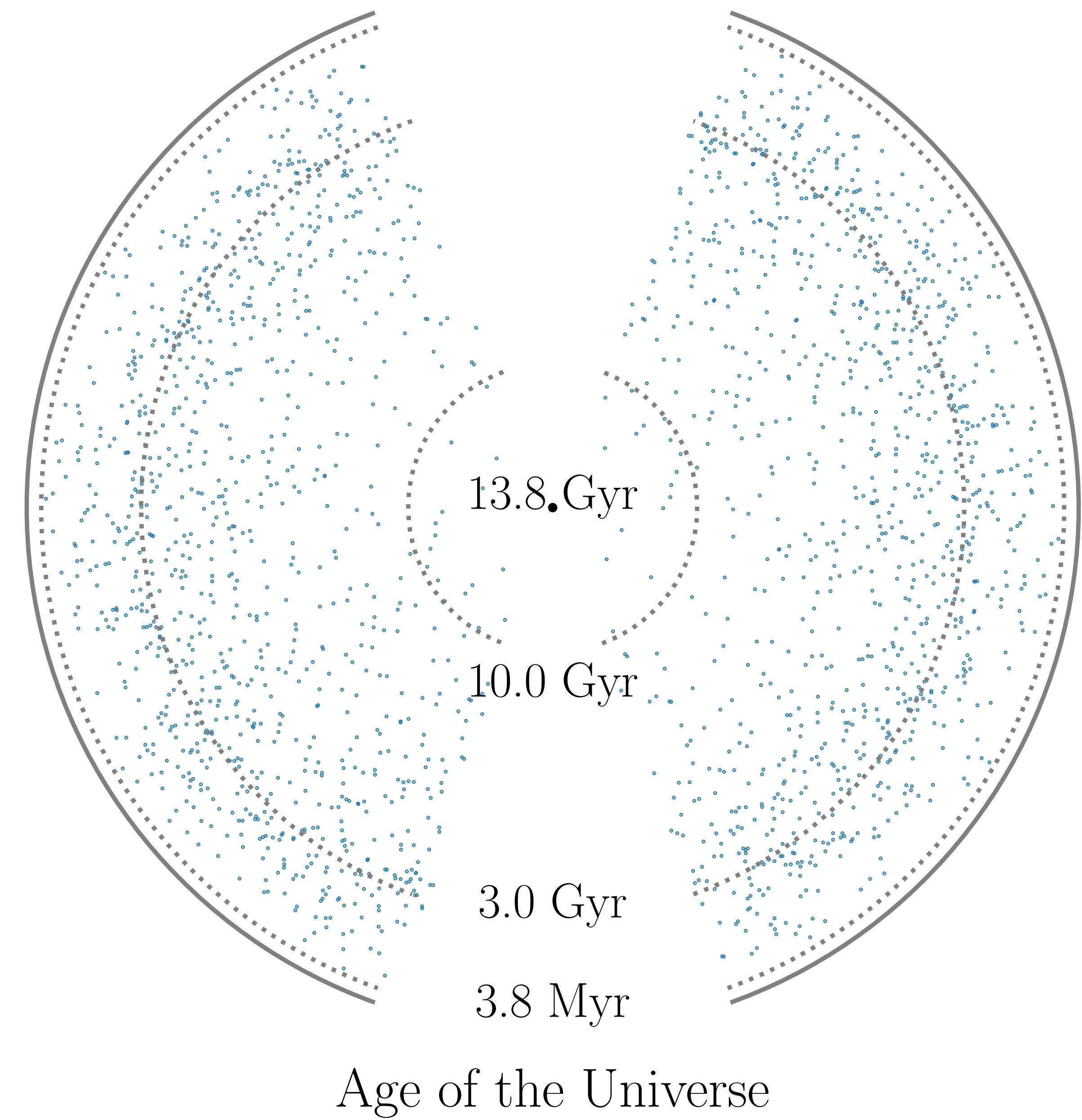
What holds
galaxies together?

Is Einstein gravity valid
at cosmological scales?

Why the Universe
expands ever faster?



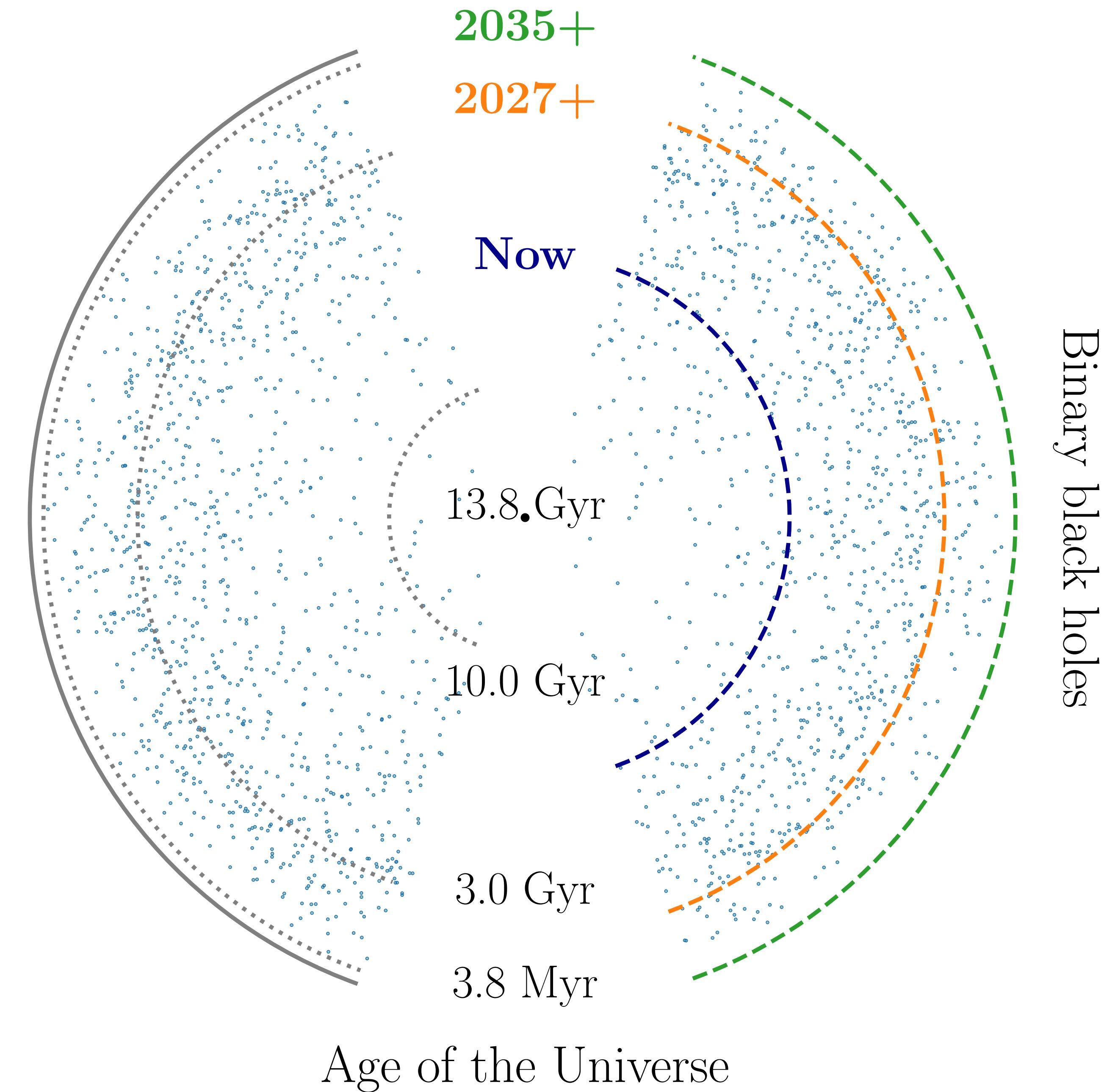
Binary black holes

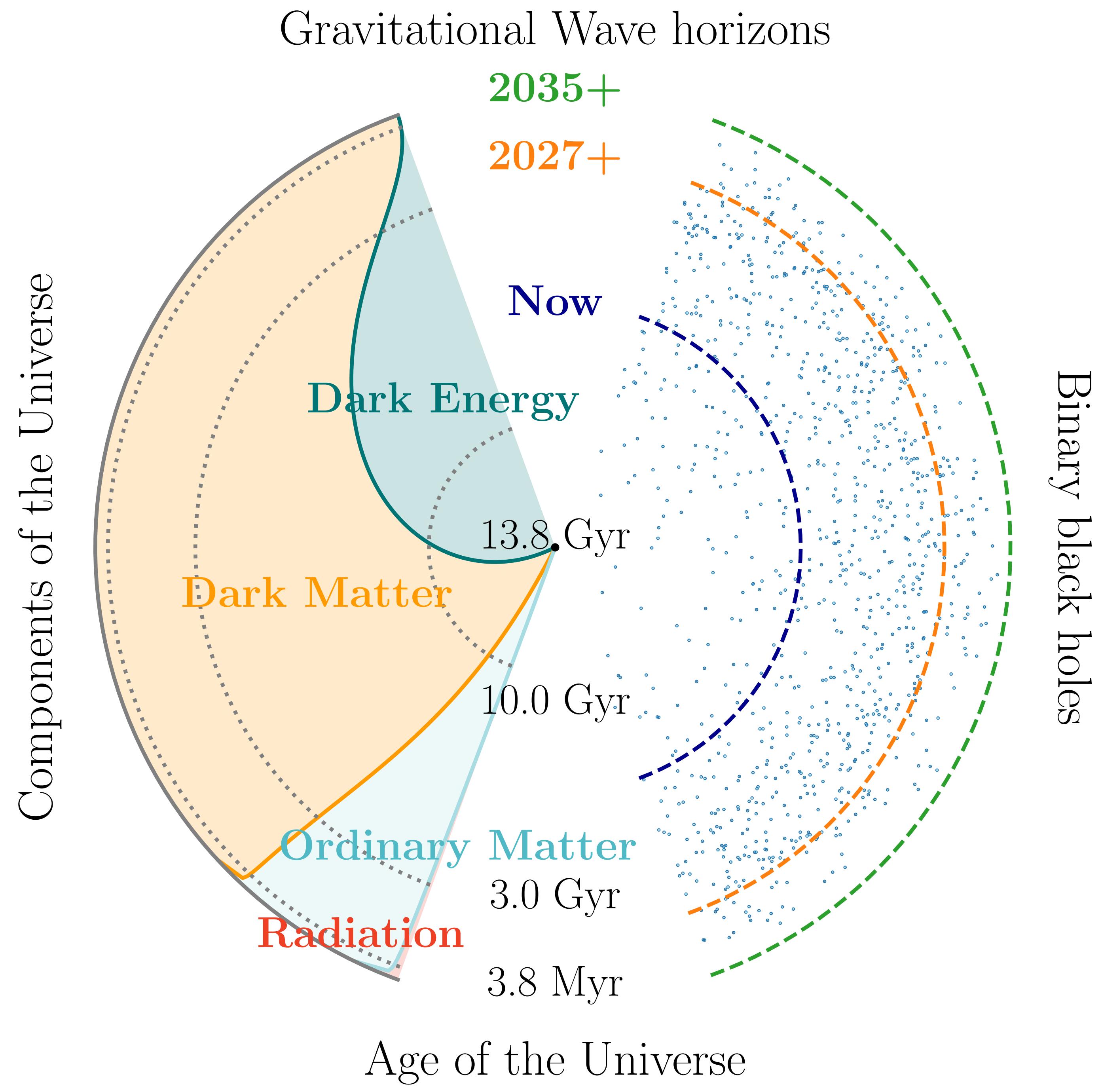


*stellar mass
binary black holes

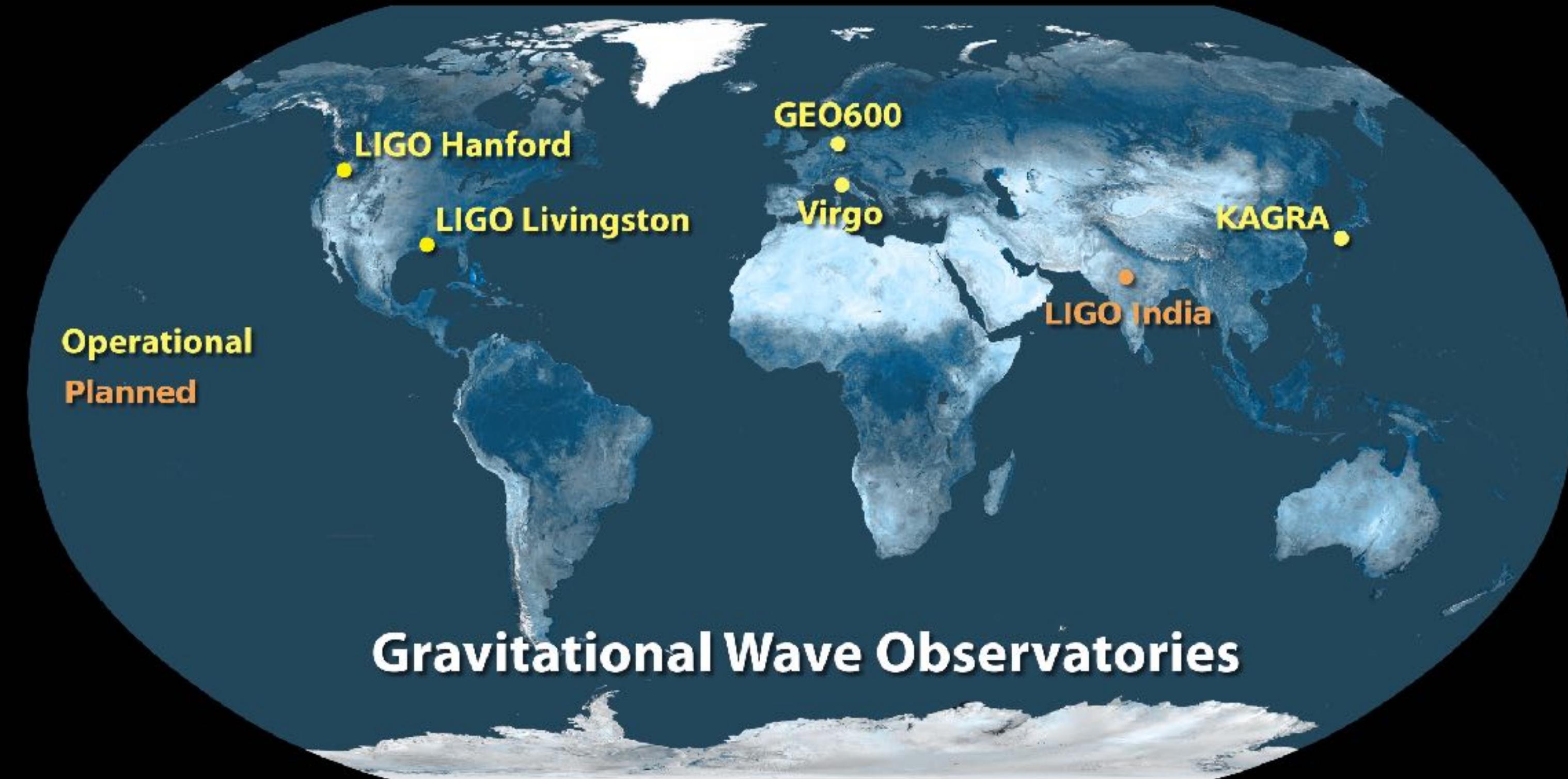
Age of the Universe

Gravitational Wave horizons





The era of gravitational wave astronomy is here!



[Hanford, US]



[Livingston, US]



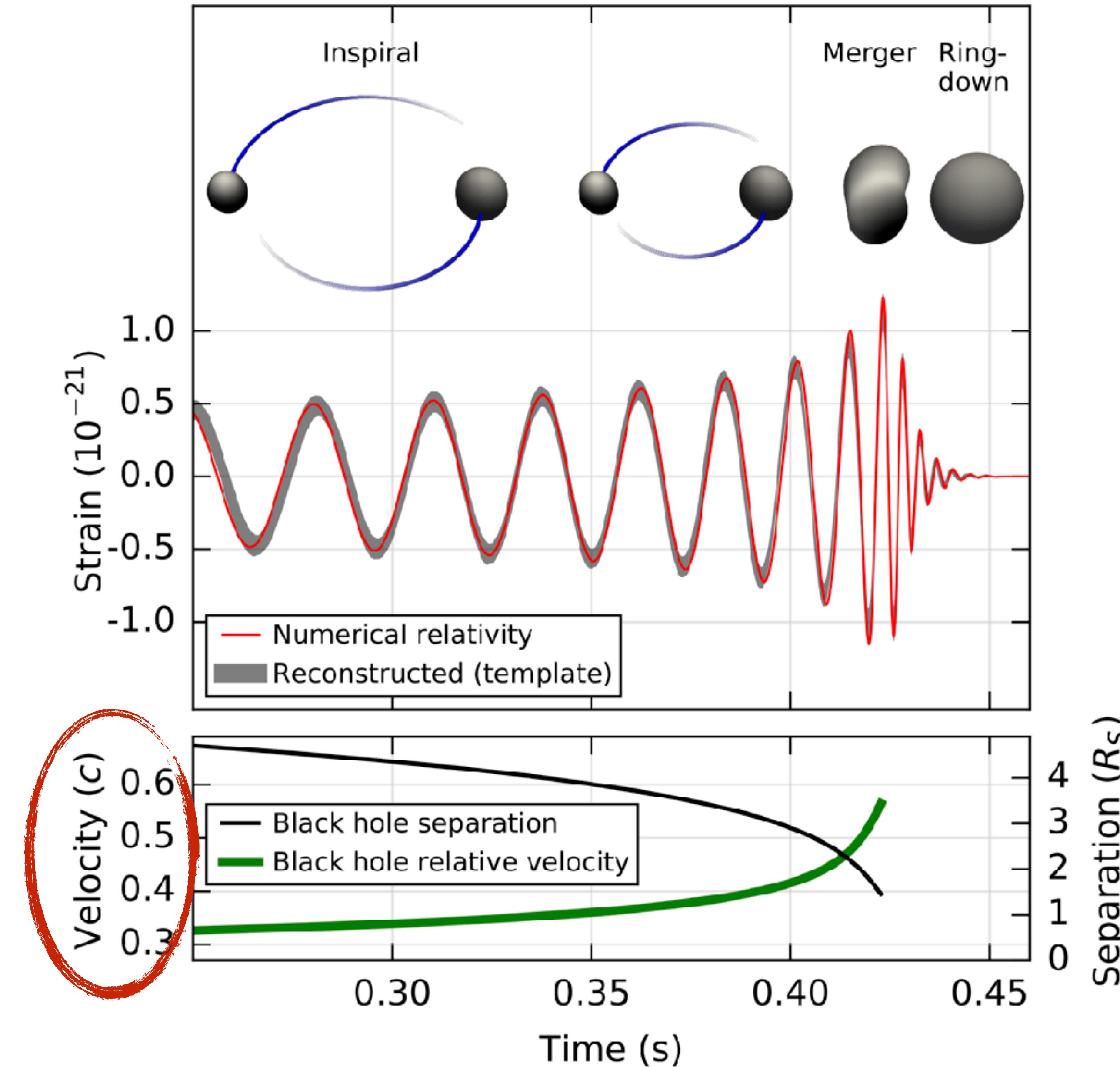
[Virgo, Italy]



[KAGRA, Japan]

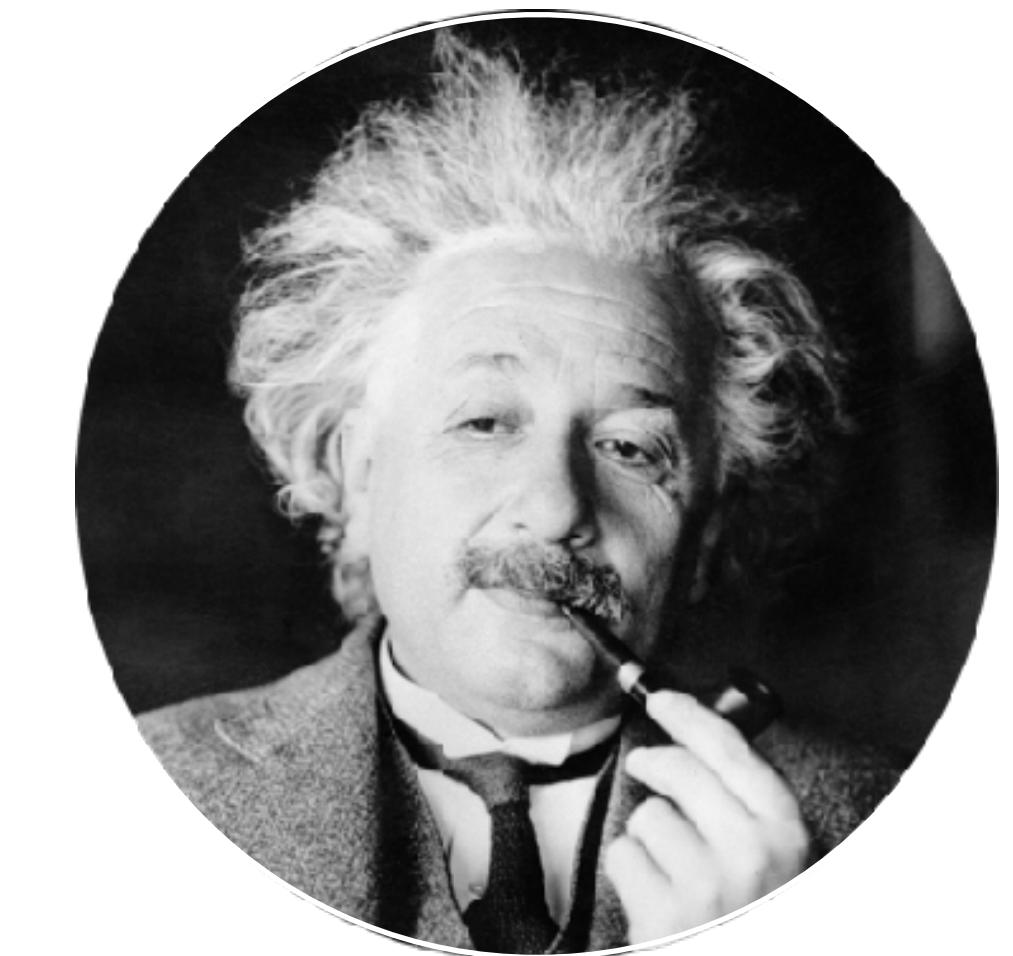
Gravitational waves from stellar-mass **binary black holes**

Strong-field gravity



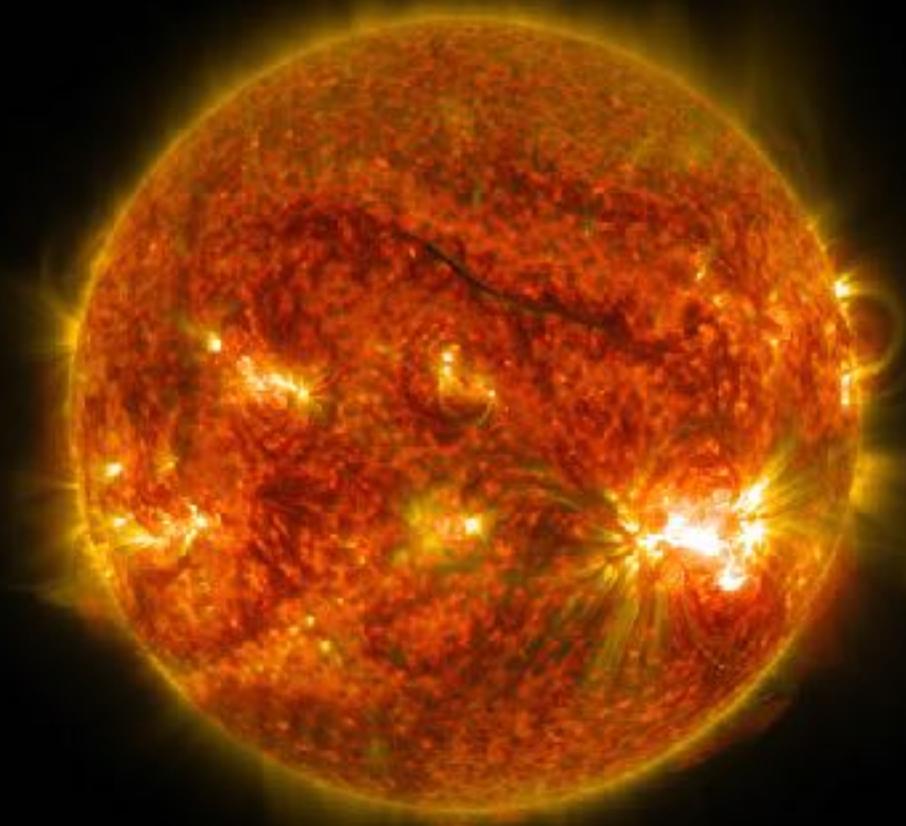
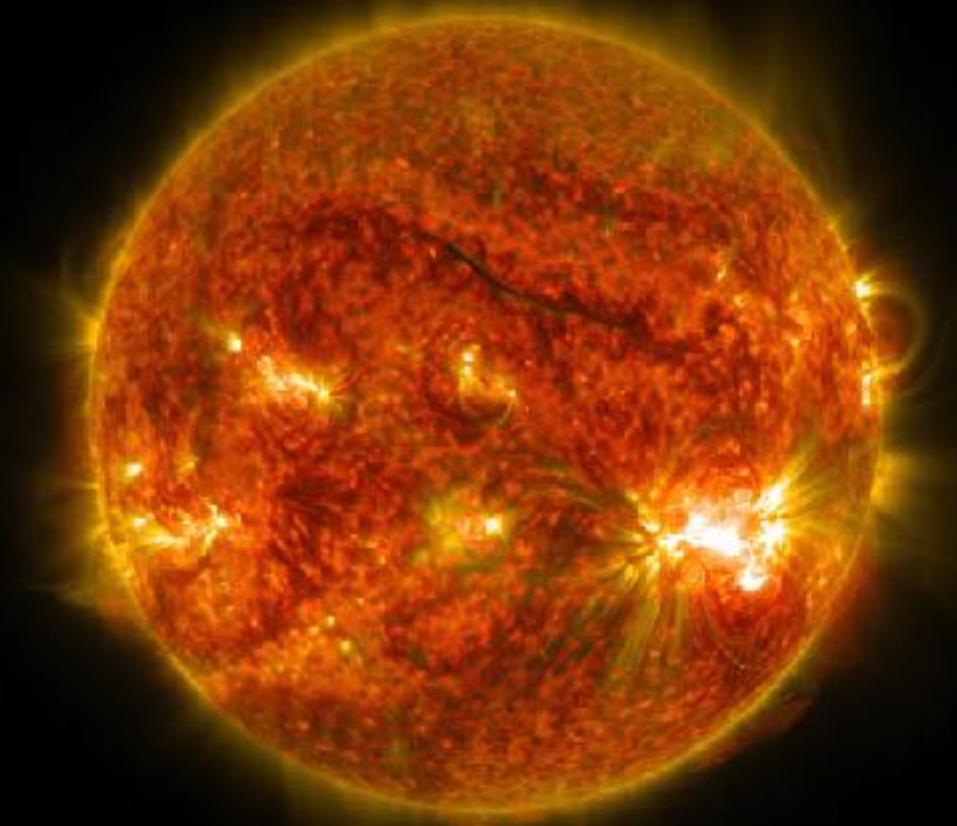
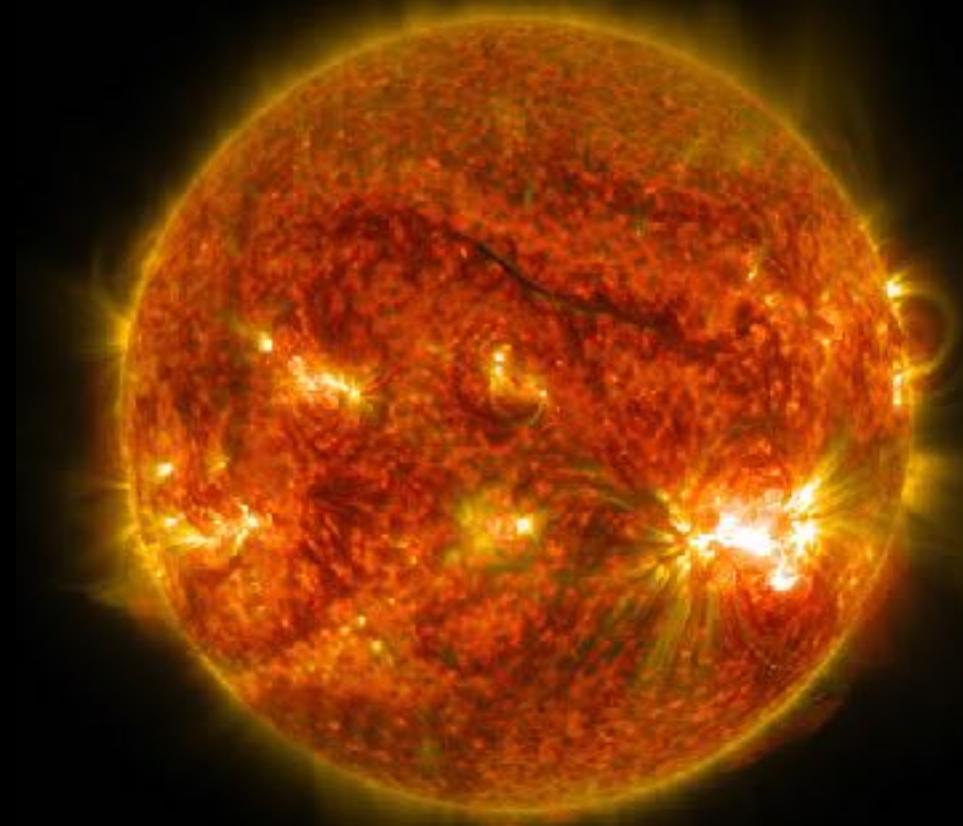
[First detection, GW150914]

16



Energy emitted in gravitational waves

=



>

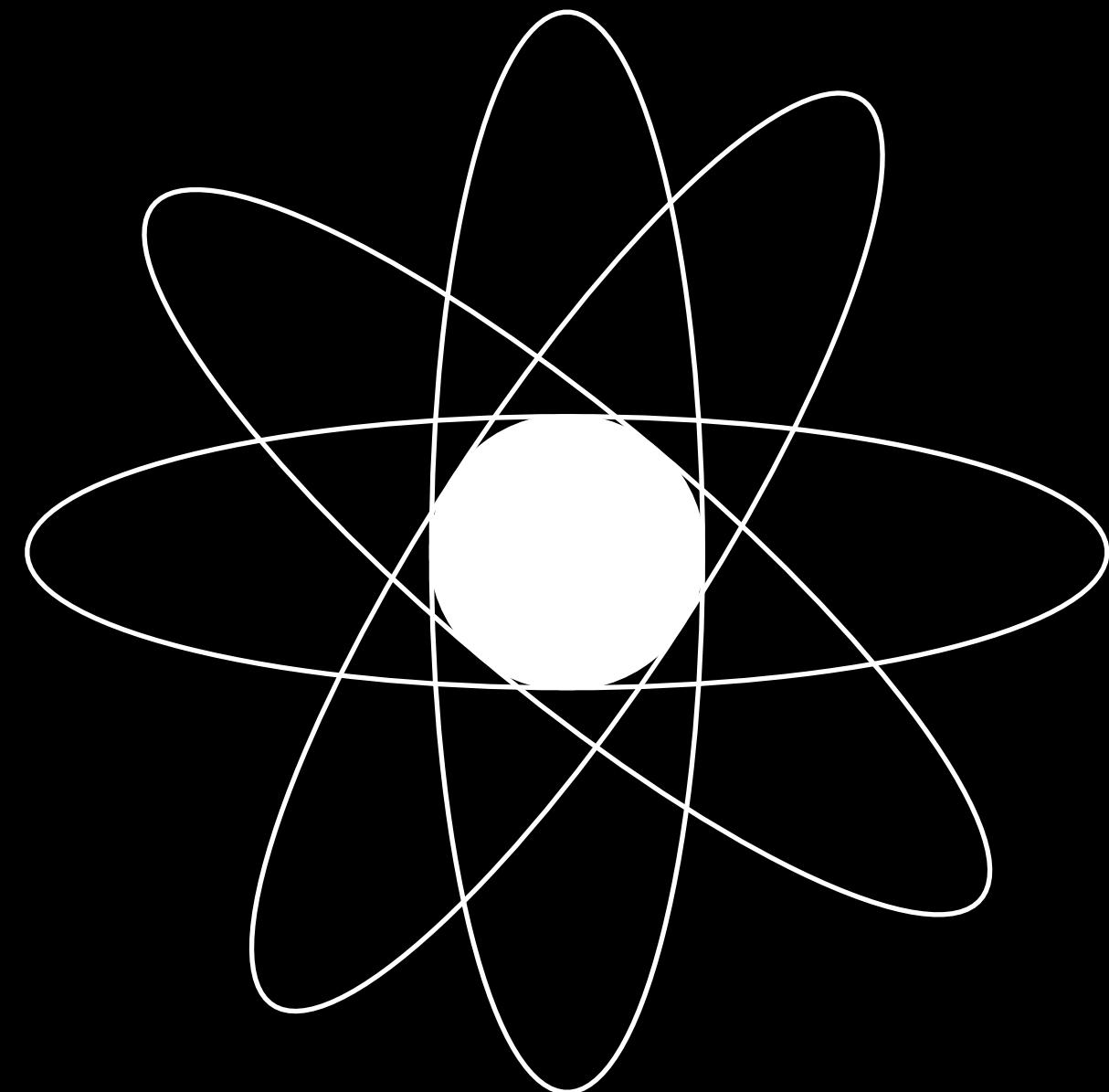


How large is the effect?

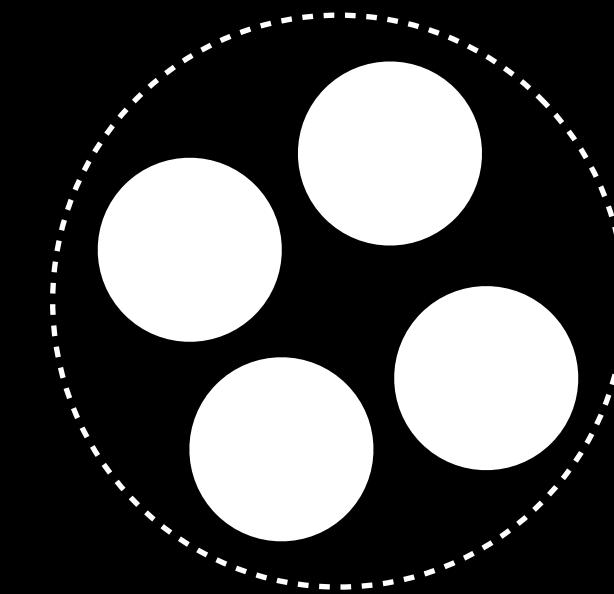


The variation in the distance at the detector is minuscule

0.0000000000000001 meters



atom: 10^{-10} meters

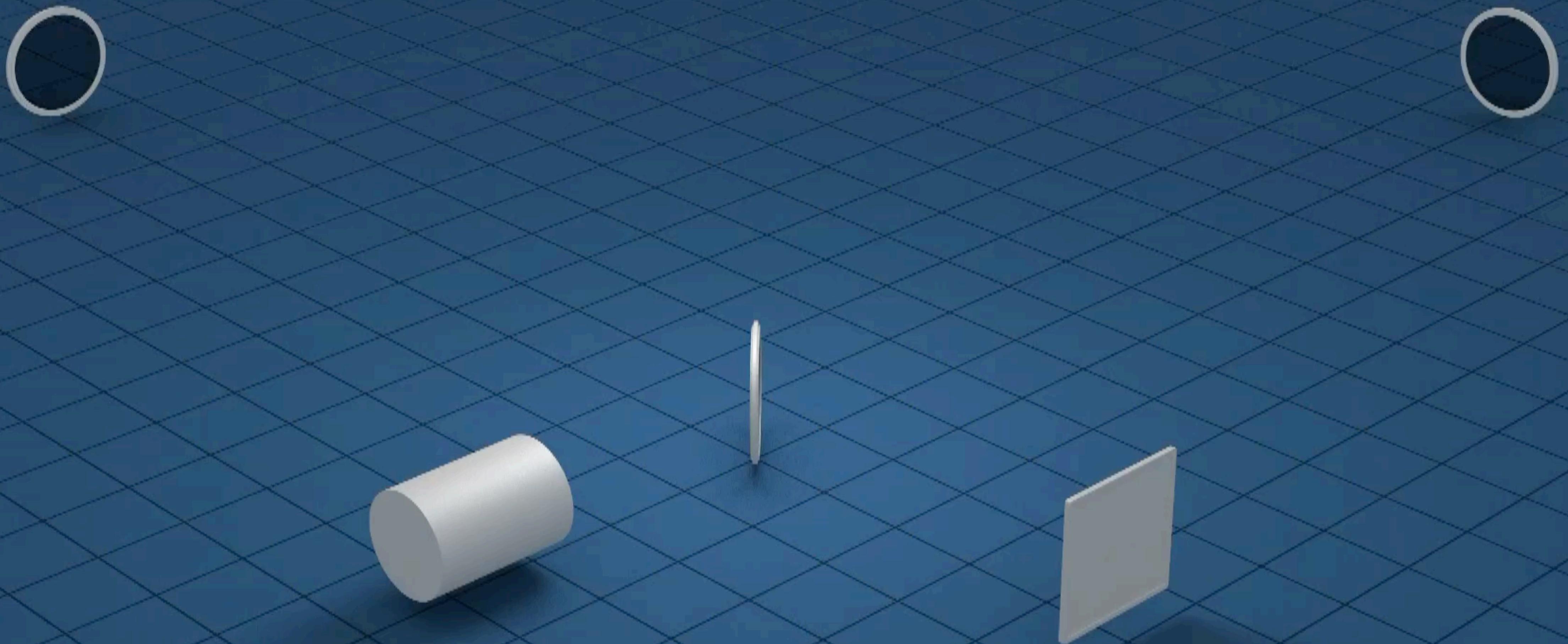


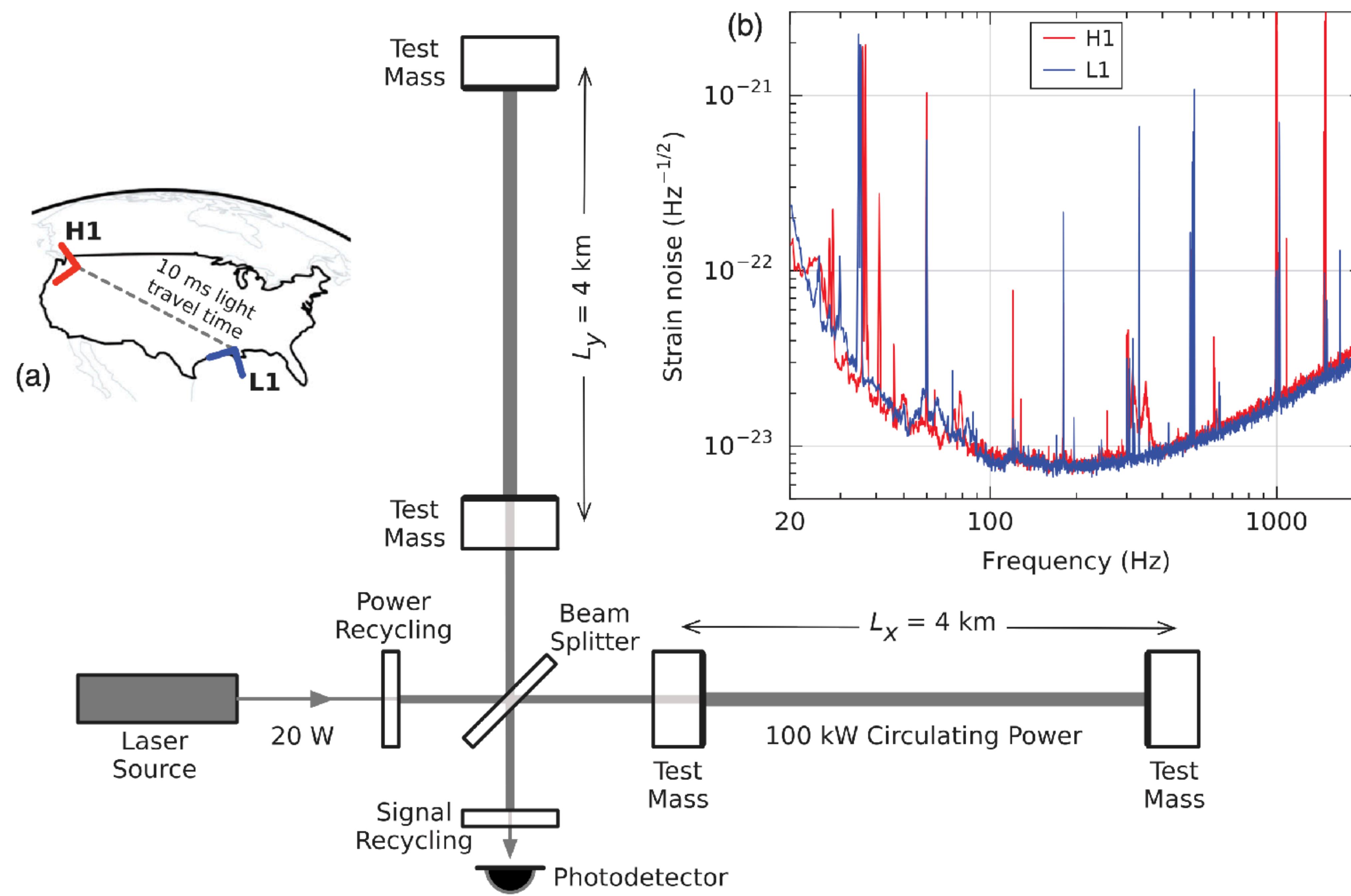
nucleus: 10^{-15} meters



GW effect: 10^{-18} meters

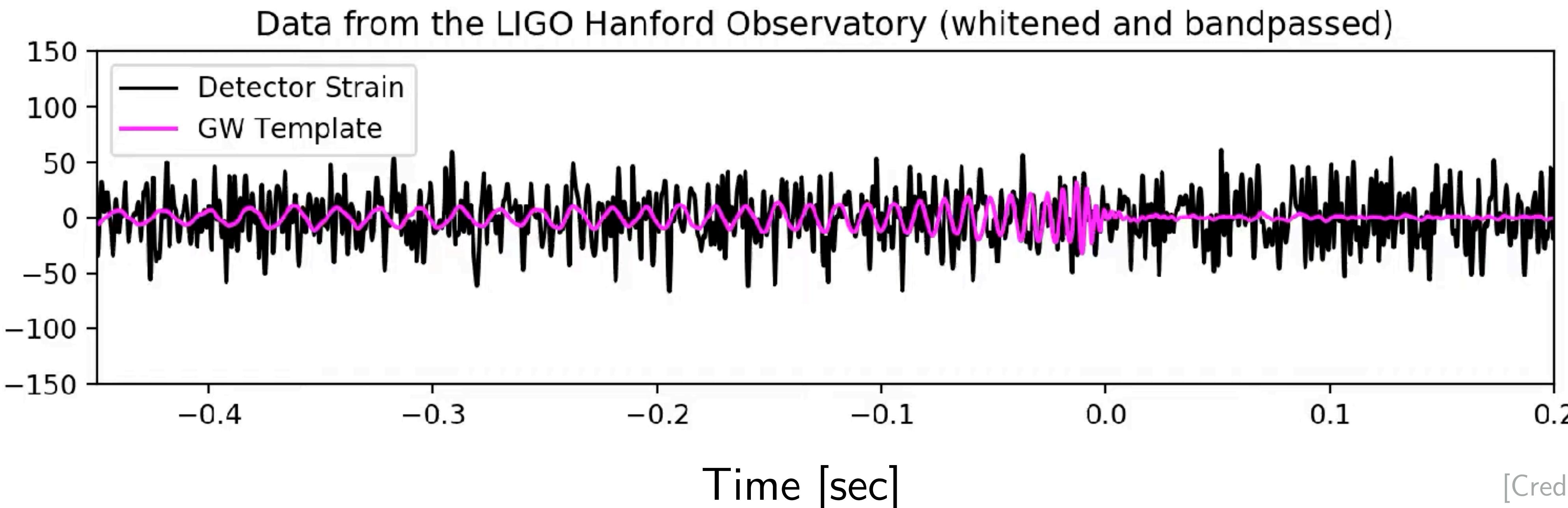
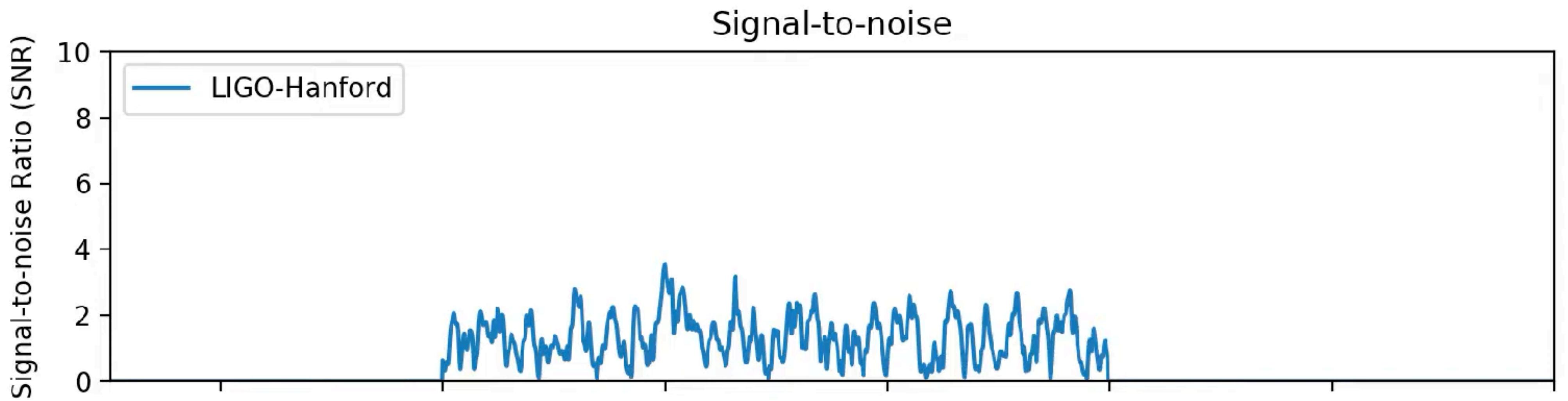
Laser Interferometer Gravitational-wave Observatory (LIGO)

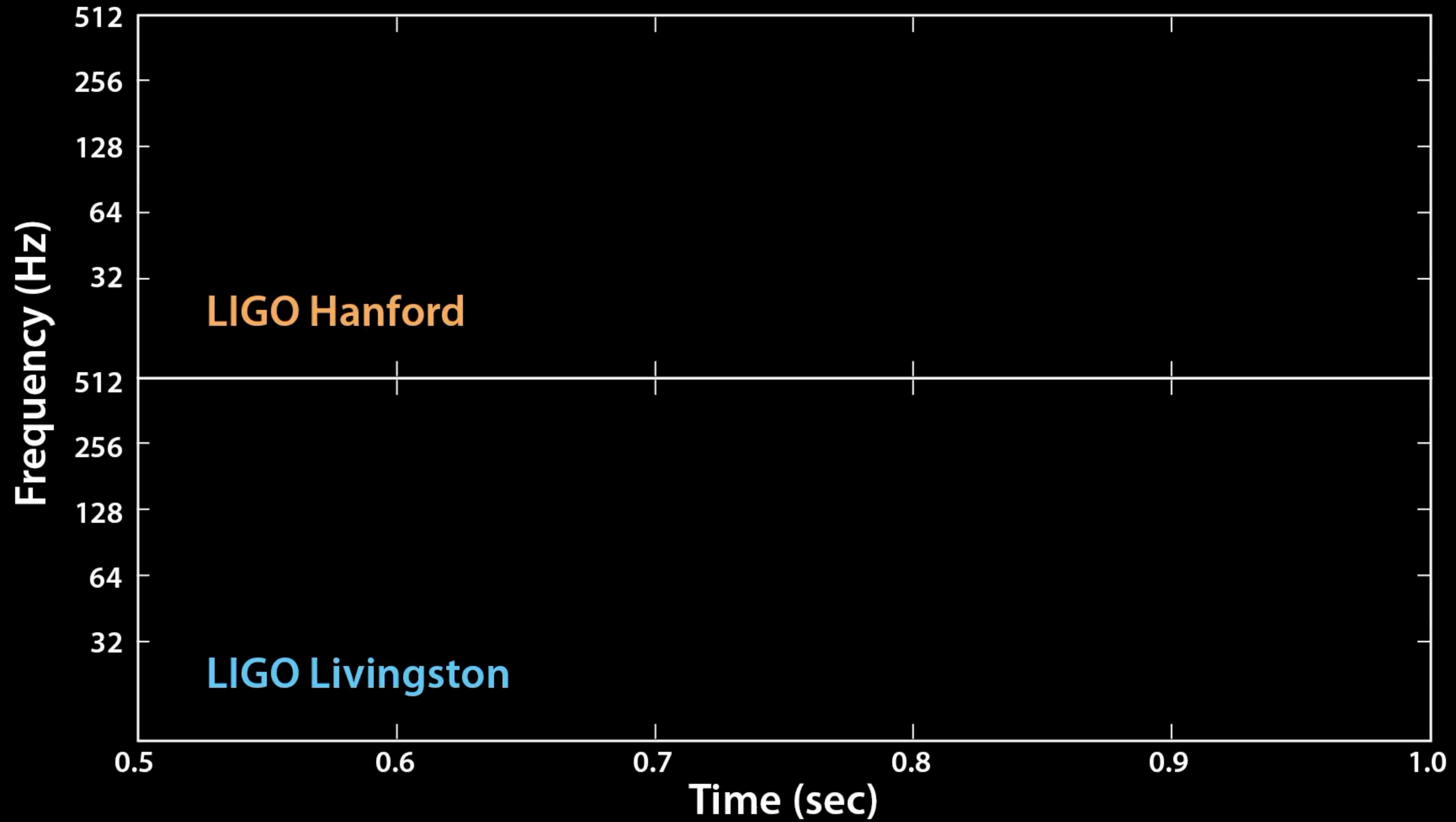




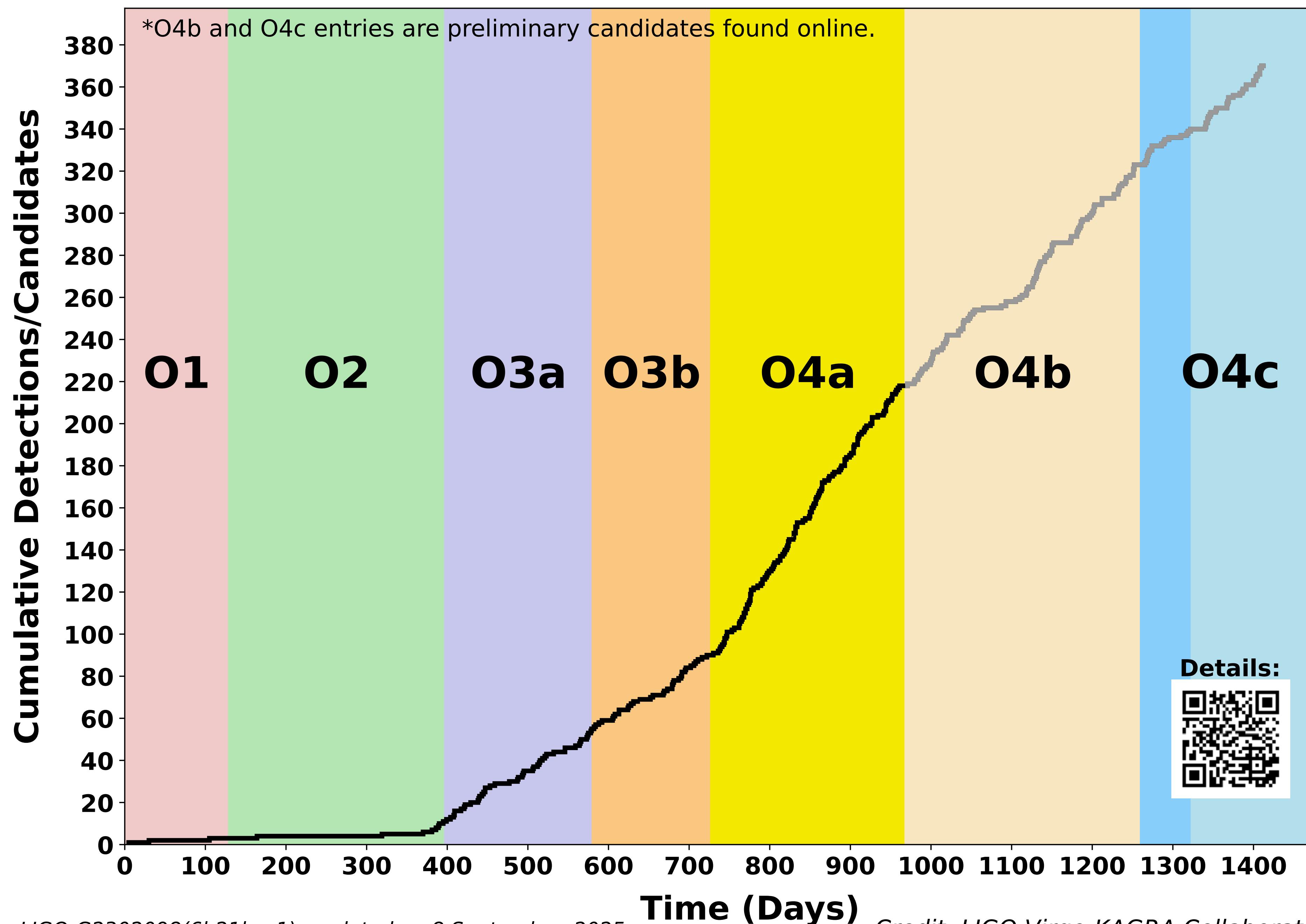
[Credit: LIGO]

Matched-filtering



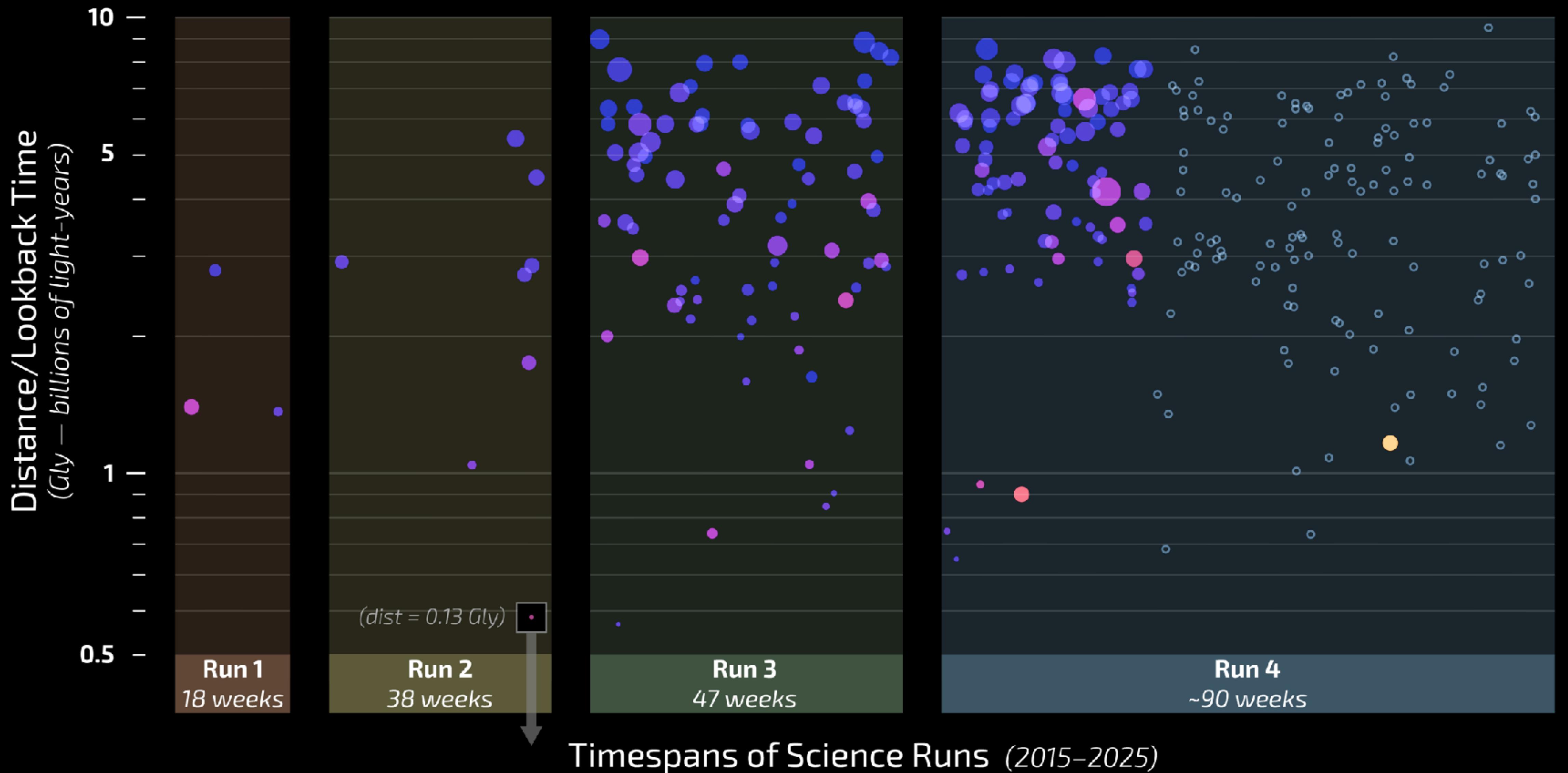


$$O1+O2+O3+O4a = 218, \ O4b^* = 105, \ O4c^* = 47, \ Total = 370$$

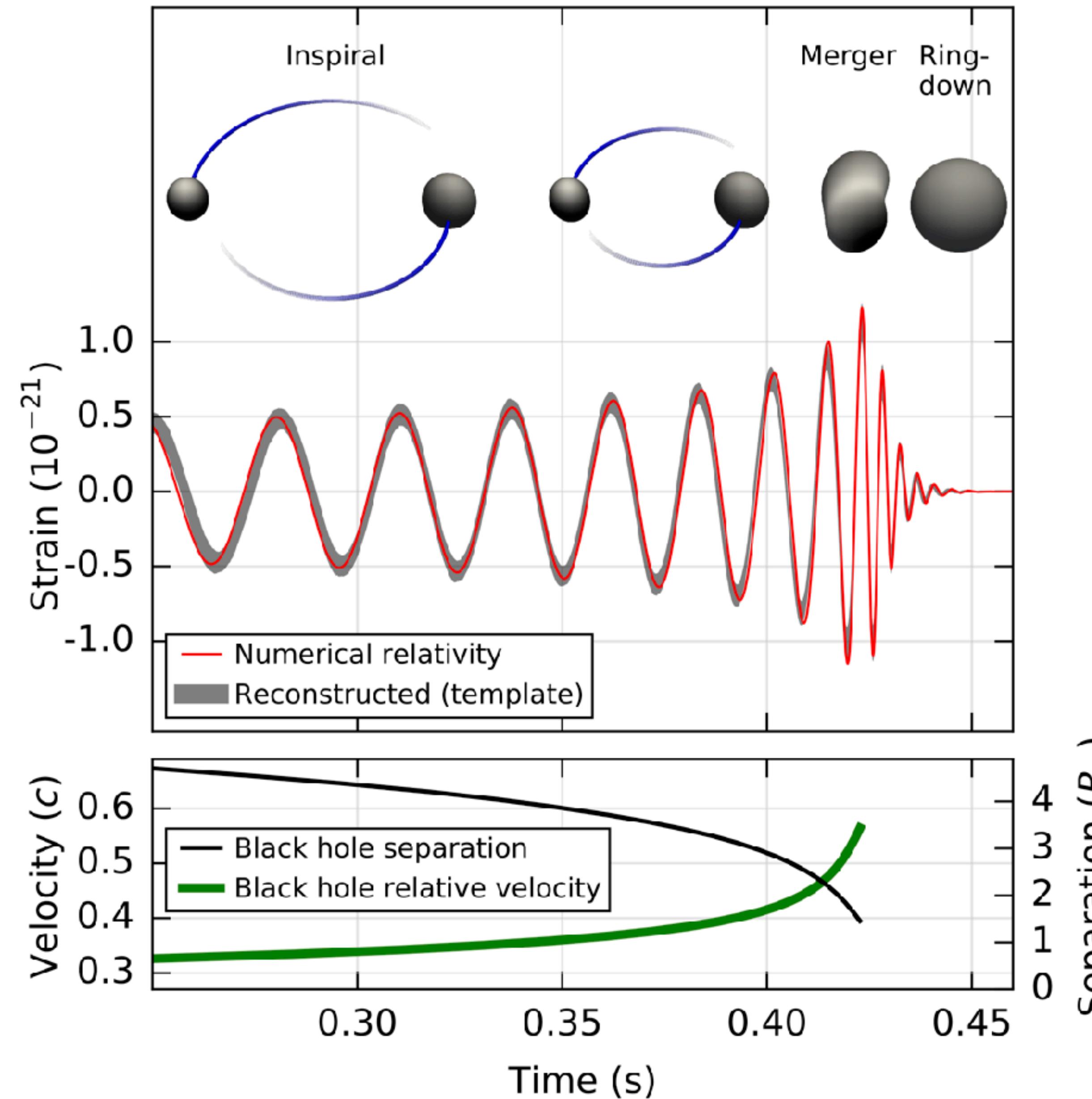


10 Years of LVK Black Hole* Mergers

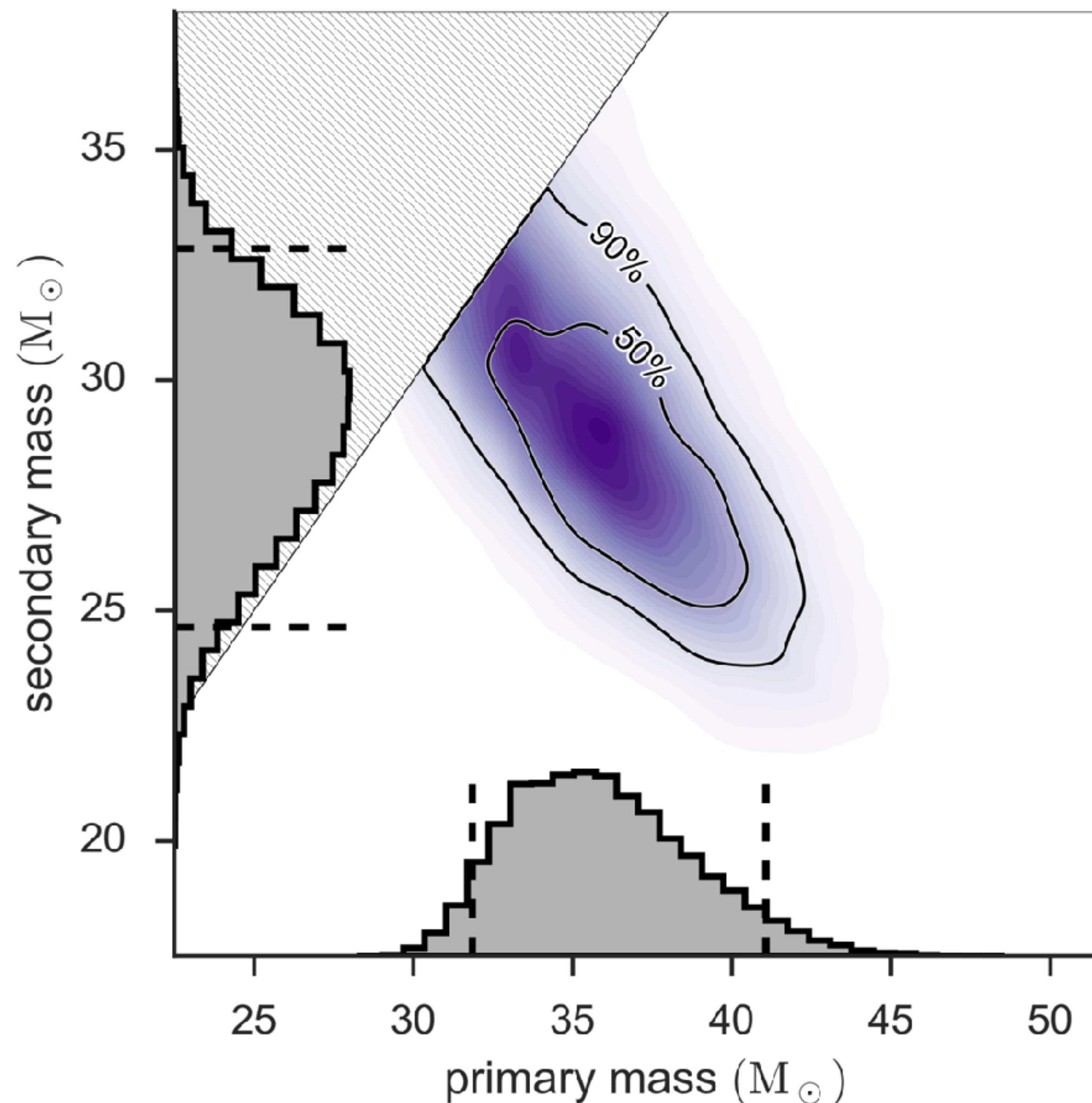
*plus several neutron stars!



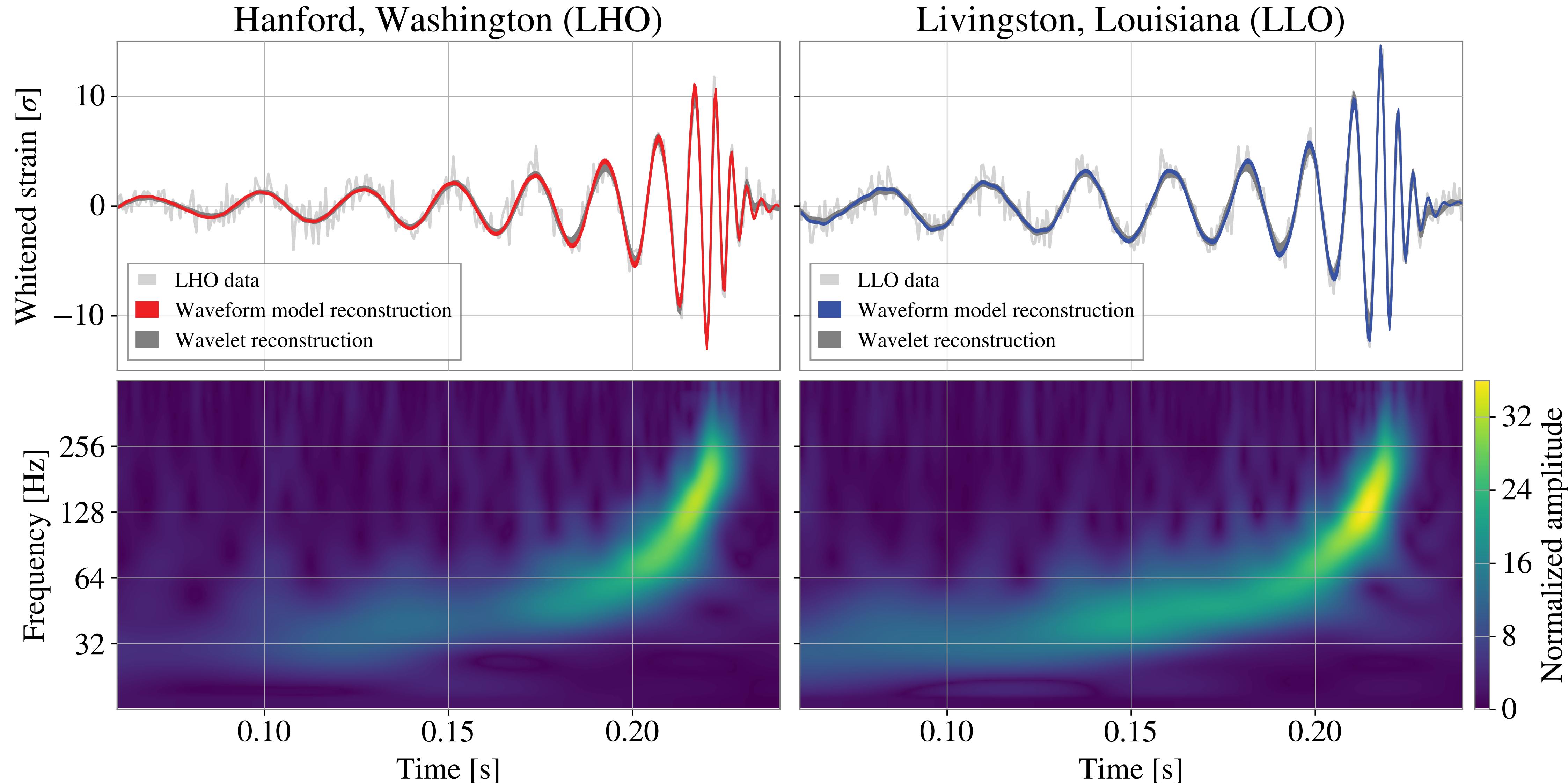
GW150914: the first event!



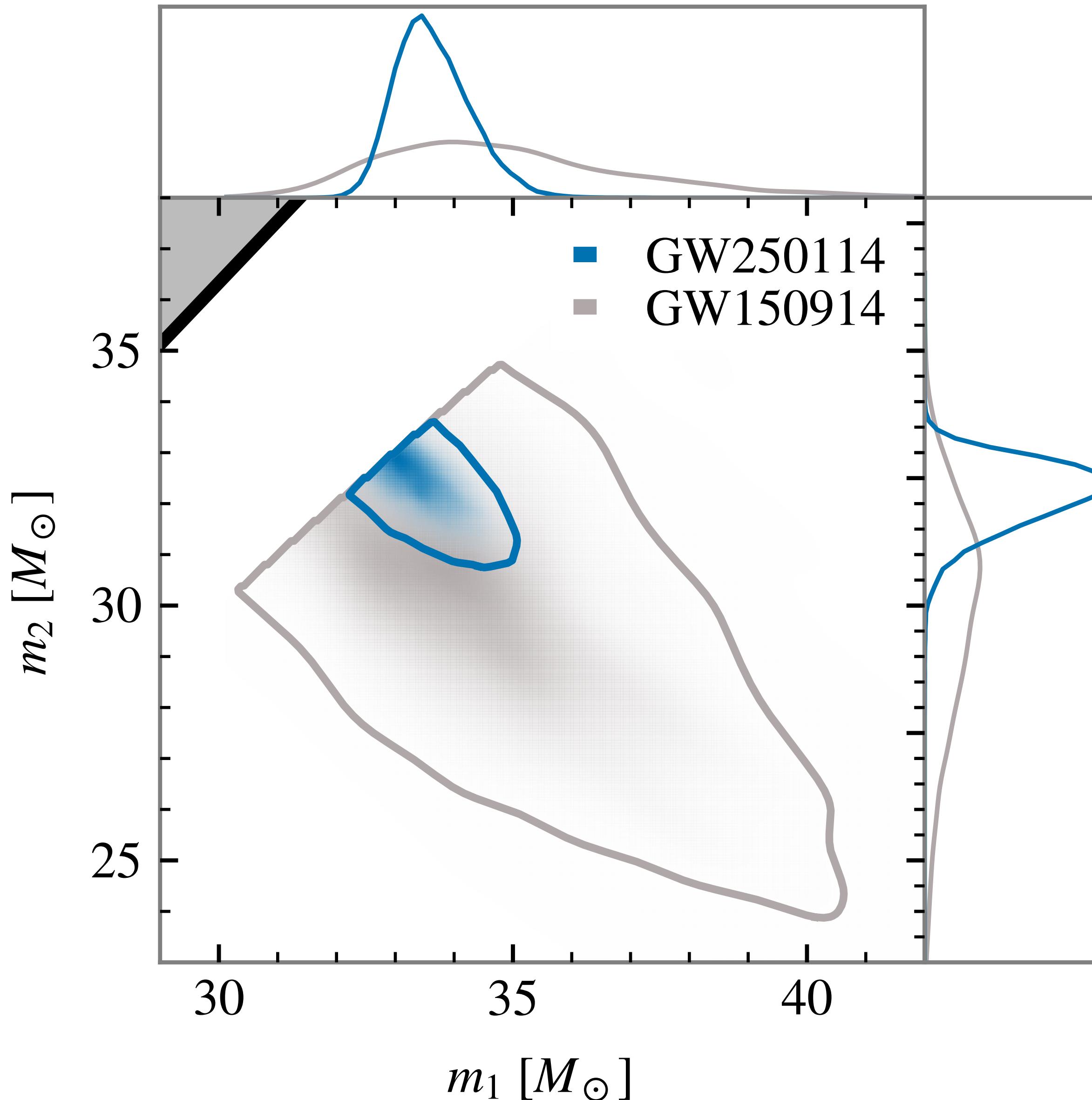
GW150914: learning about the signal properties!



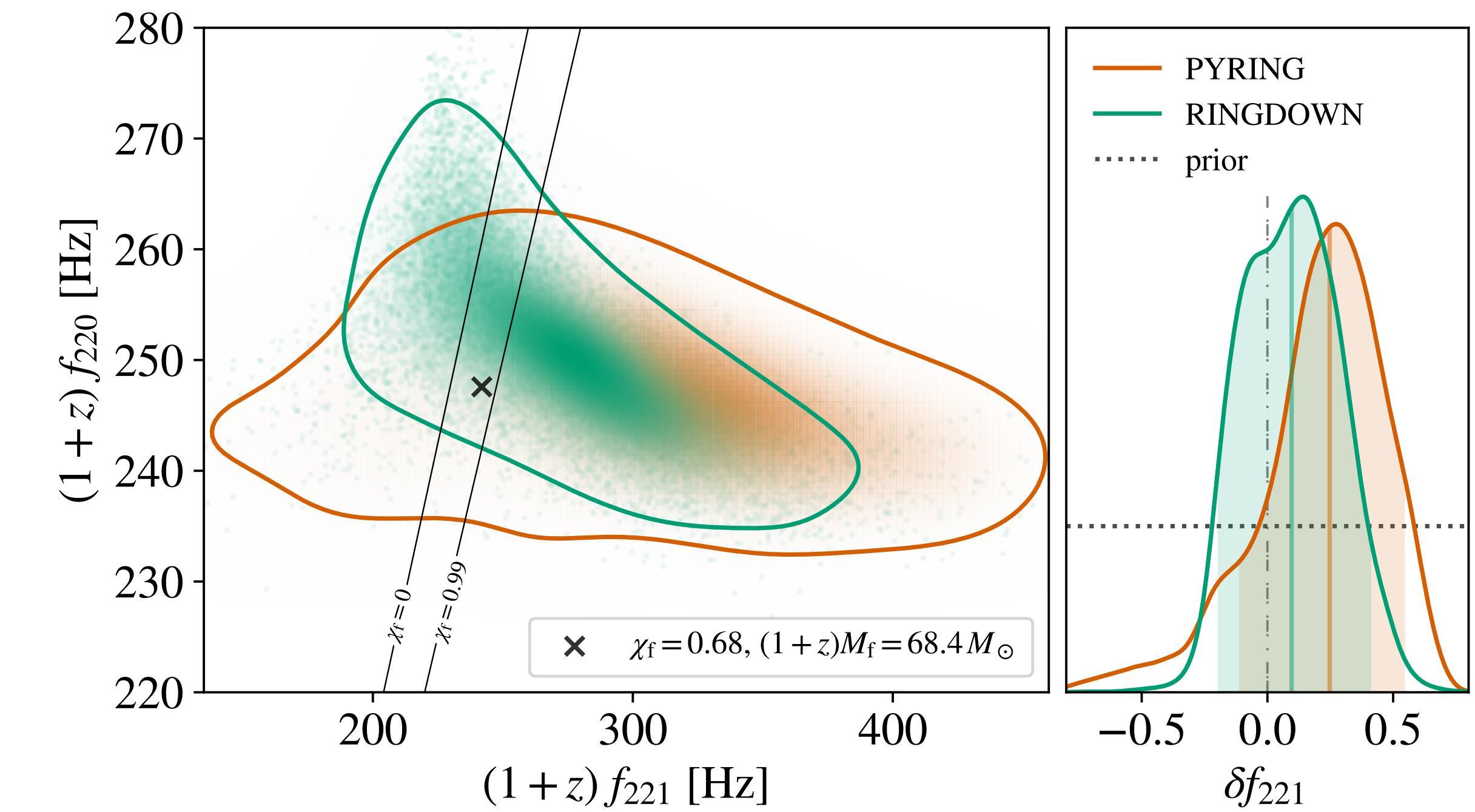
GW250114: the loudest event ever detected (*signal-to-noise* of 80!)



GW250114: precision measurements, even in the ring-down!

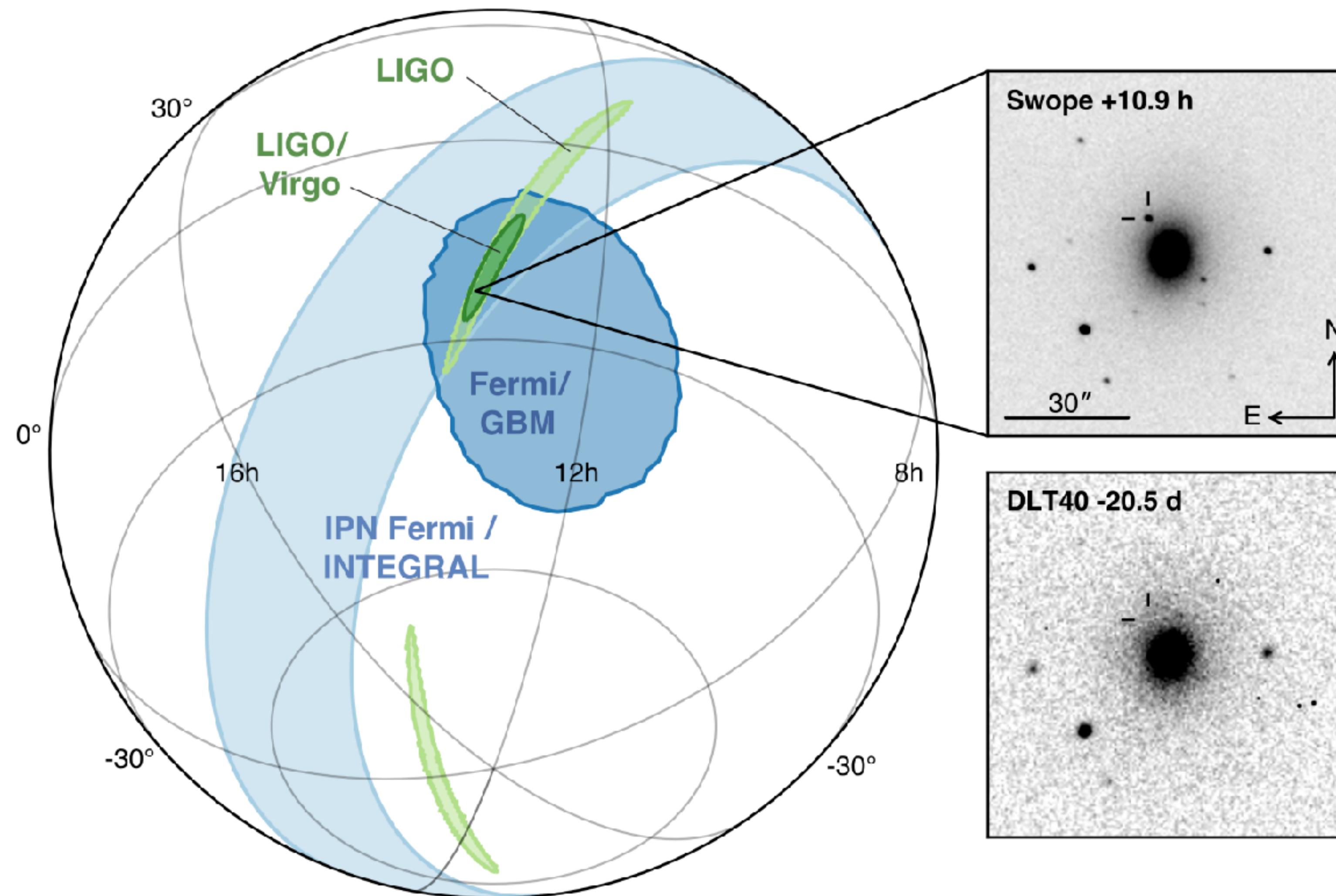


Hawking area law at 4.4σ !

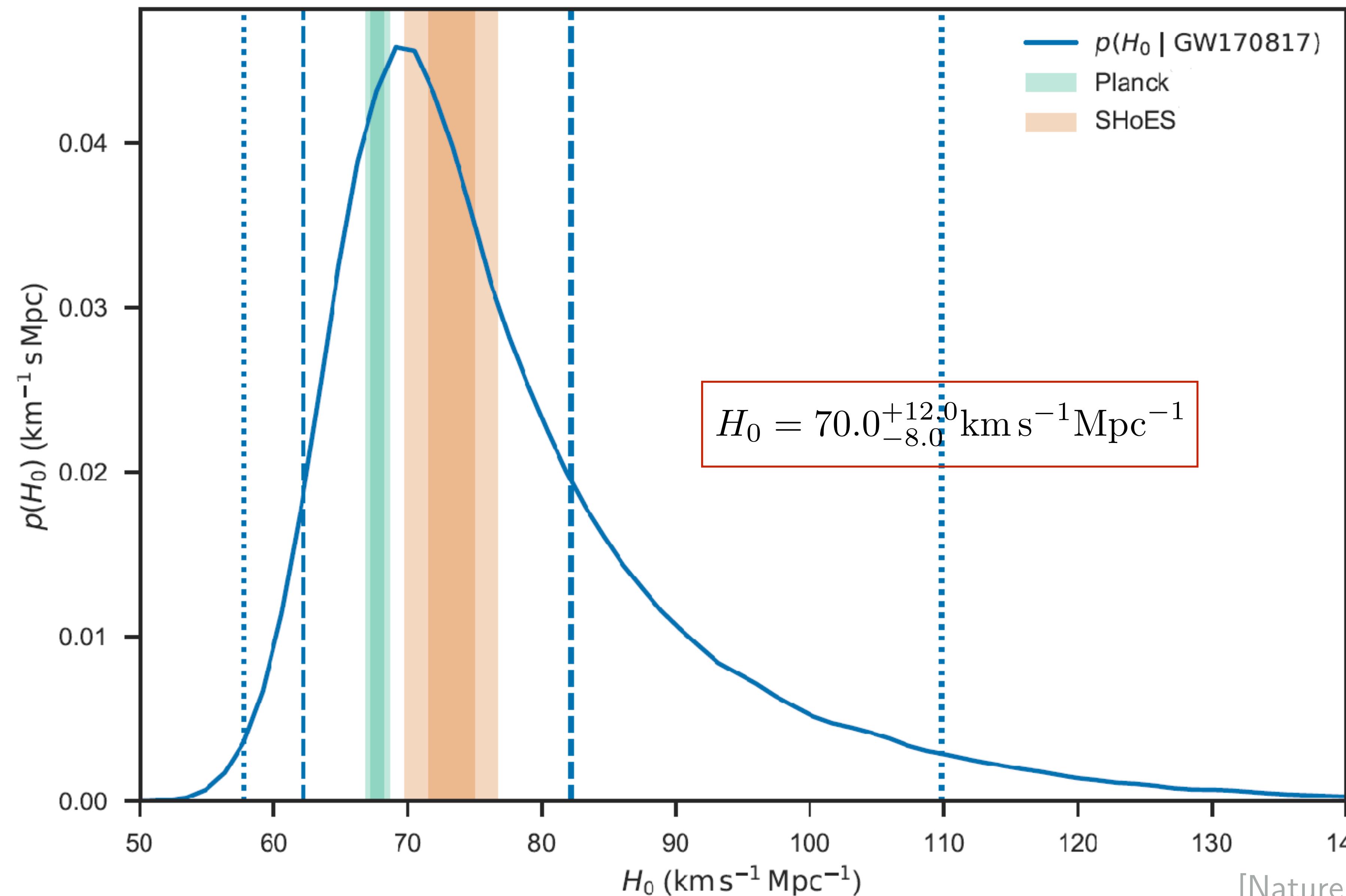


Binary neutron star mergers

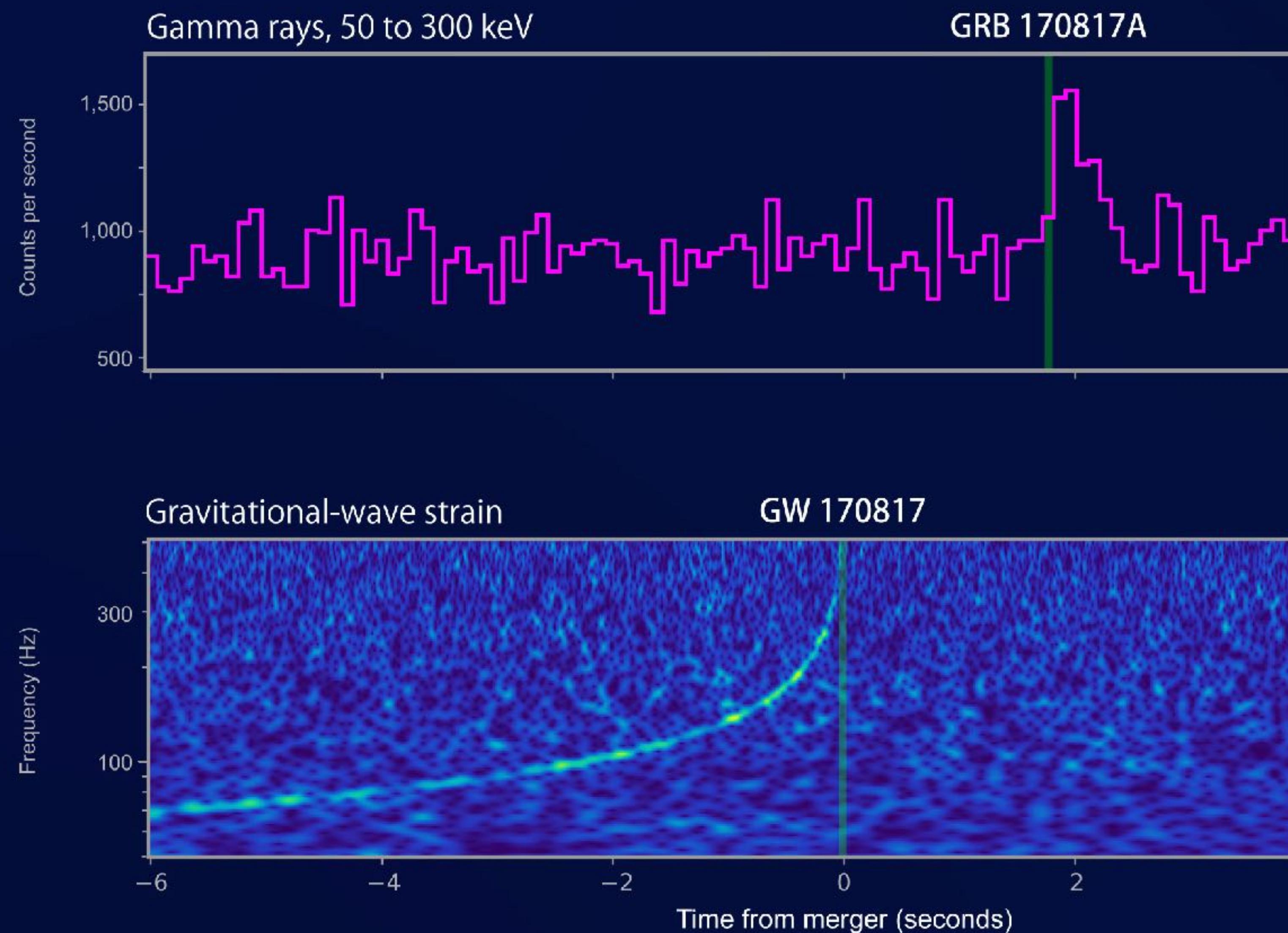
GW170817: first multi-messenger event!



Gravitational waves are standard sirens



Gravitational waves travel at the speed of light!



*Only 1.7s after 100 million light years travelled 33

1	H
3	Li
4	Be
11	Na
12	Mg
19	K
20	Ca
21	Sc
22	Ti
23	V
24	Cr
25	Mn
26	Fe
27	Co
28	Ni
29	Cu
30	Zn
31	Ga
32	Ge
33	As
34	Se
35	Br
36	Kr
37	Rb
38	Sr
39	Y
40	Zr
41	Nb
42	Mo
43	Tc
44	Ru
45	Rh
46	Pd
47	Ag
48	Cd
49	In
50	Sn
51	Sb
52	Te
53	I
54	Xe
55	Cs
56	Ba
72	Hf
73	Ta
74	W
75	Re
76	Os
77	Ir
78	Pt
79	Au
80	Hg
81	Tl
82	Pb
83	Bi
84	Po
85	At
86	Rn
87	Fr
88	Ra

Element Origins

2	He
5	B
6	C
7	N
8	O
9	F
10	Ne
13	Al
14	Si
15	P
16	S
17	Cl
18	Ar
31	Ga
32	Ge
33	As
34	Se
35	Br
36	Kr
49	In
50	Sn
51	Sb
52	Te
53	I
54	Xe

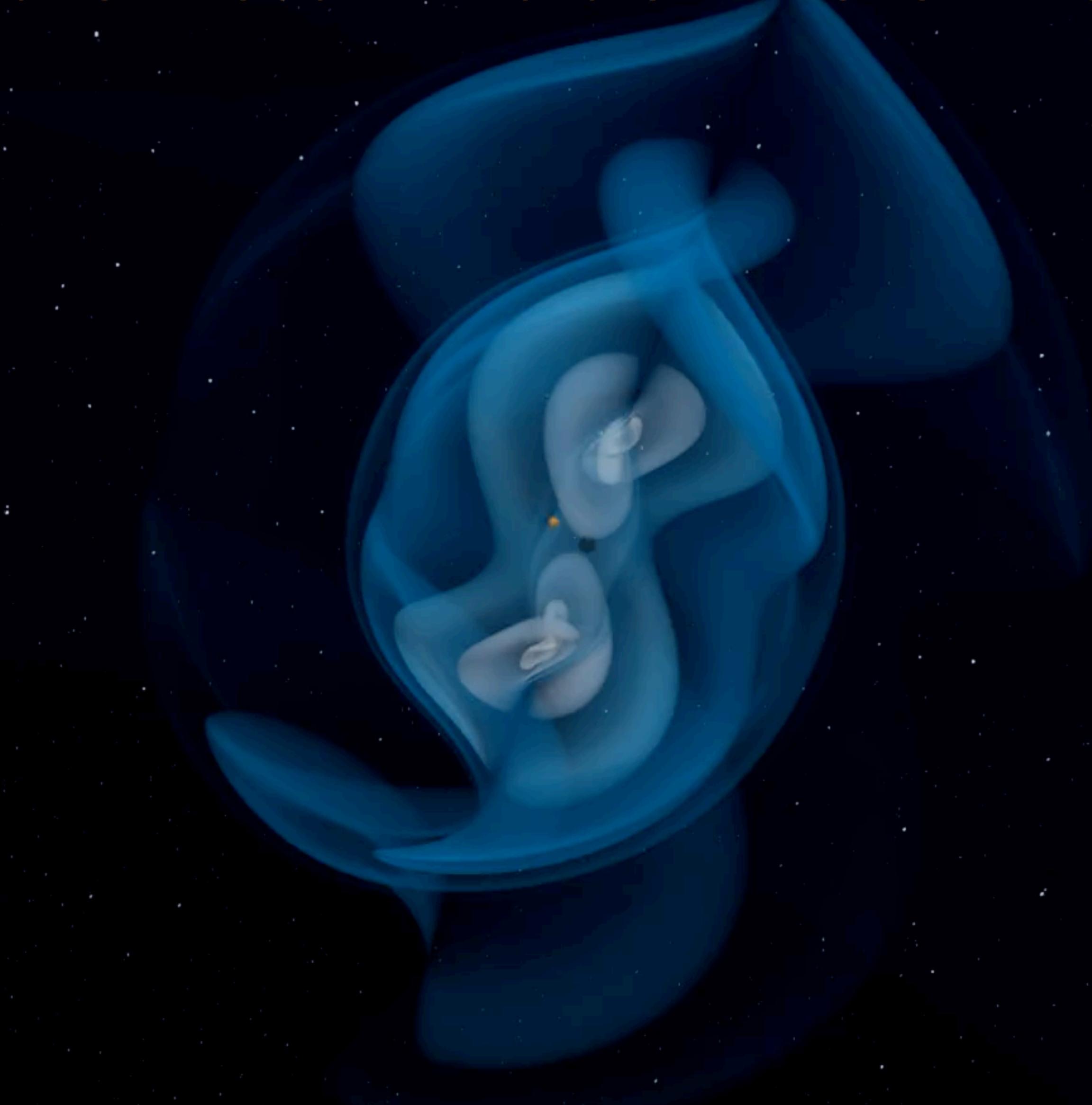
57	La
58	Ce
59	Pr
60	Nd
61	Pm
62	Sm
63	Eu
64	Gd
65	Tb
66	Dy
67	Ho
68	Er
69	Tm
70	Yb
71	Lu

Merging Neutron Stars
Dying Low Mass Stars

Exploding Massive Stars
Exploding White Dwarfs

Big Bang
Cosmic Ray Fission

Neutron star - black hole mergers

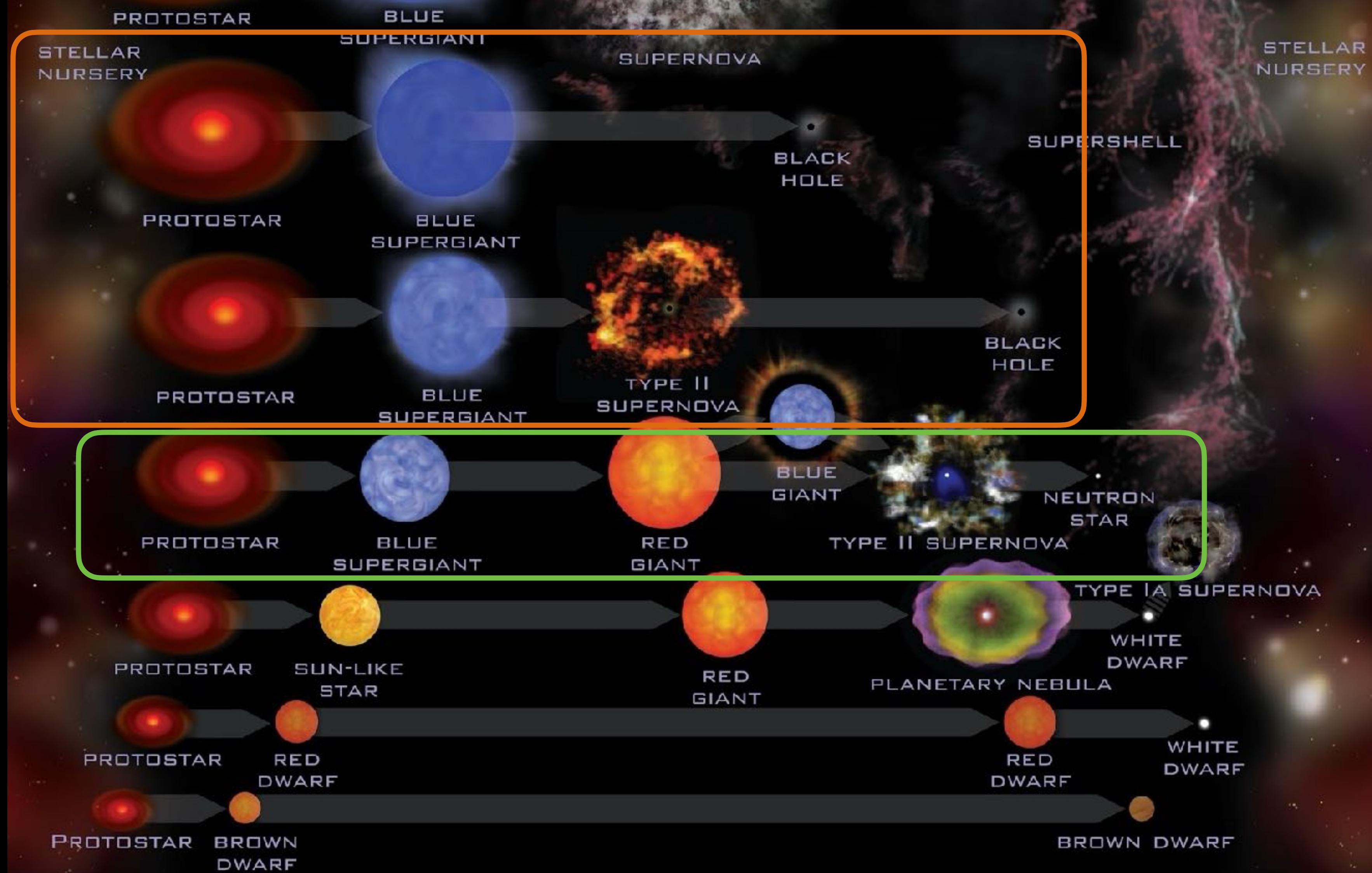


-0.038s



Stellar evolution

How, when, where?

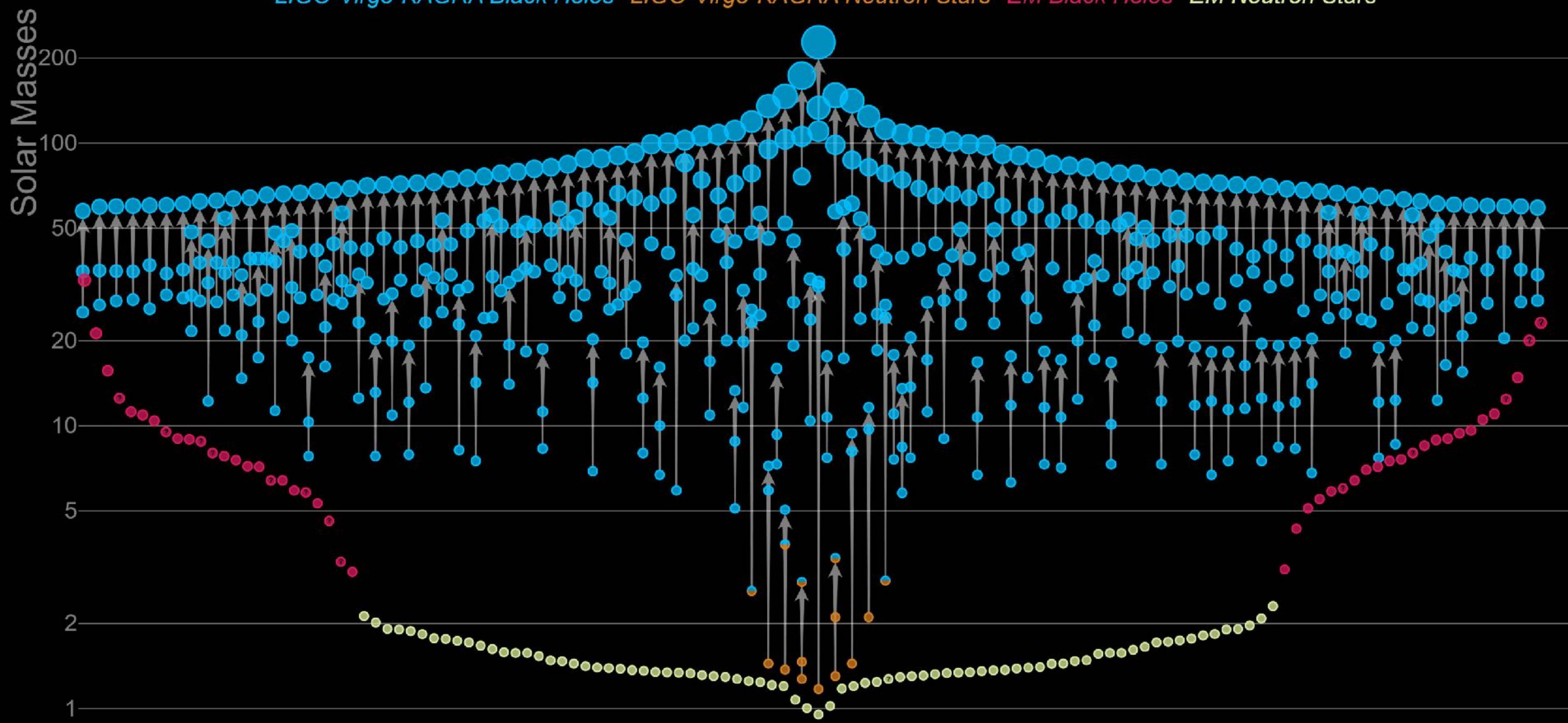


[credit Chandra]

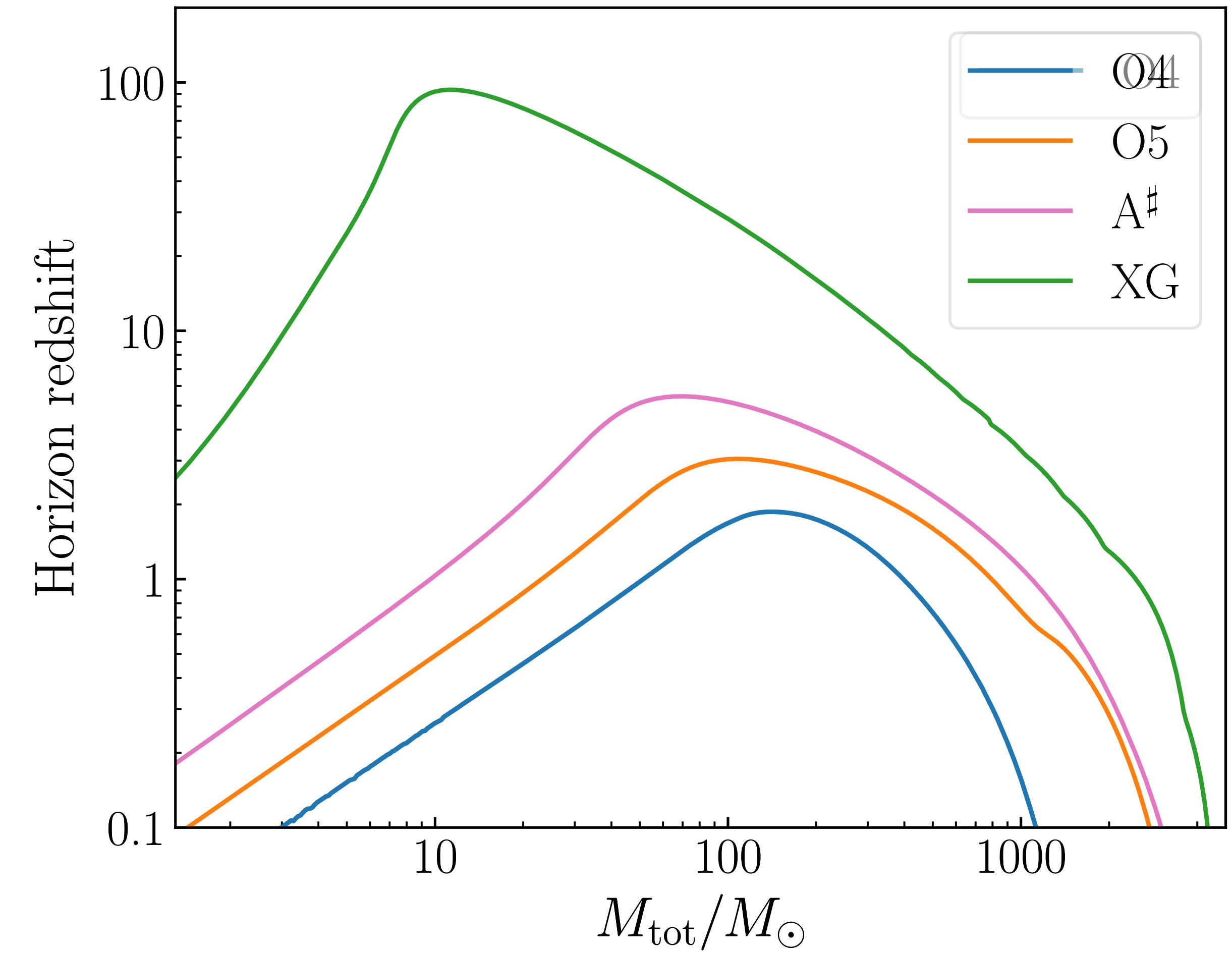
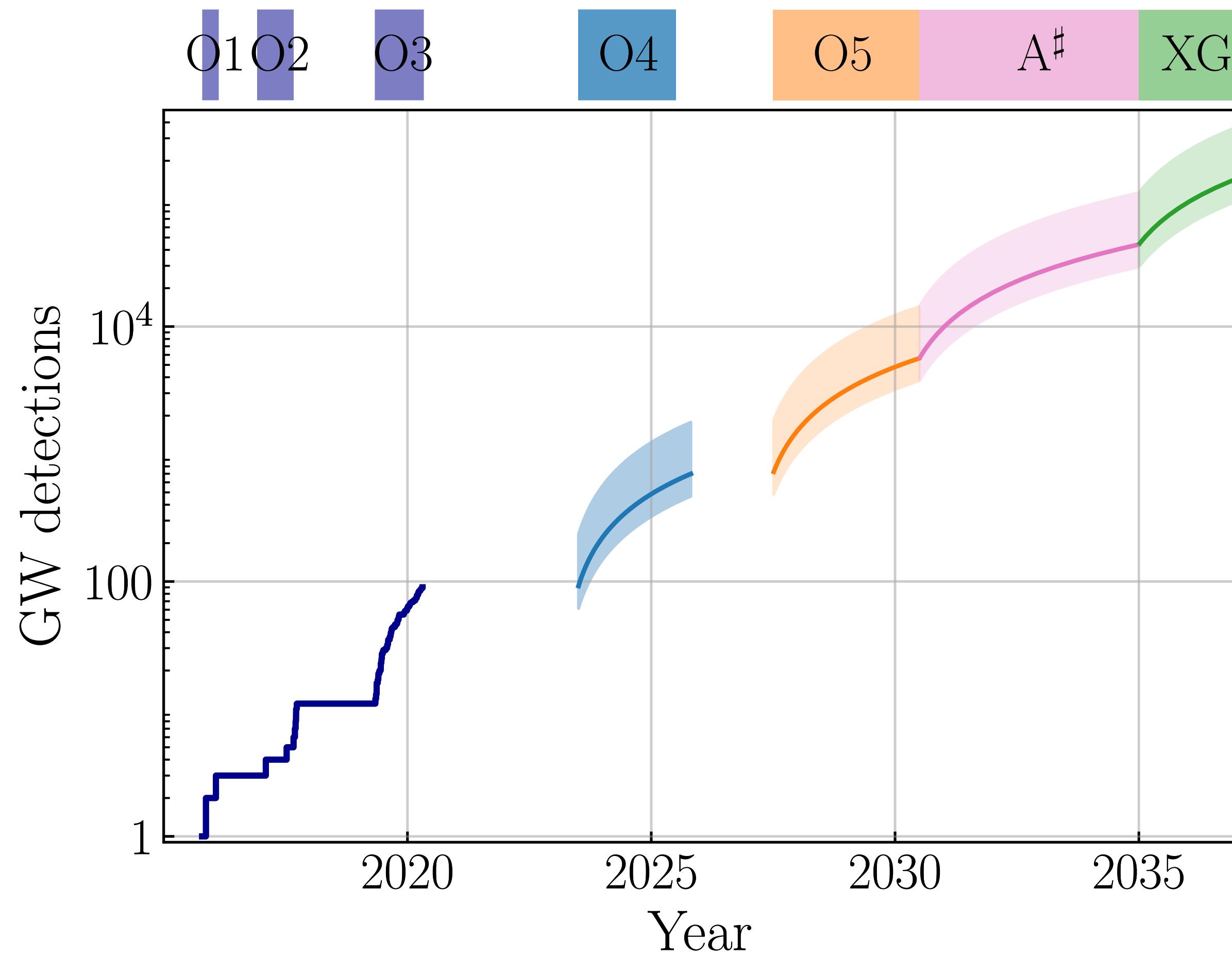
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Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*

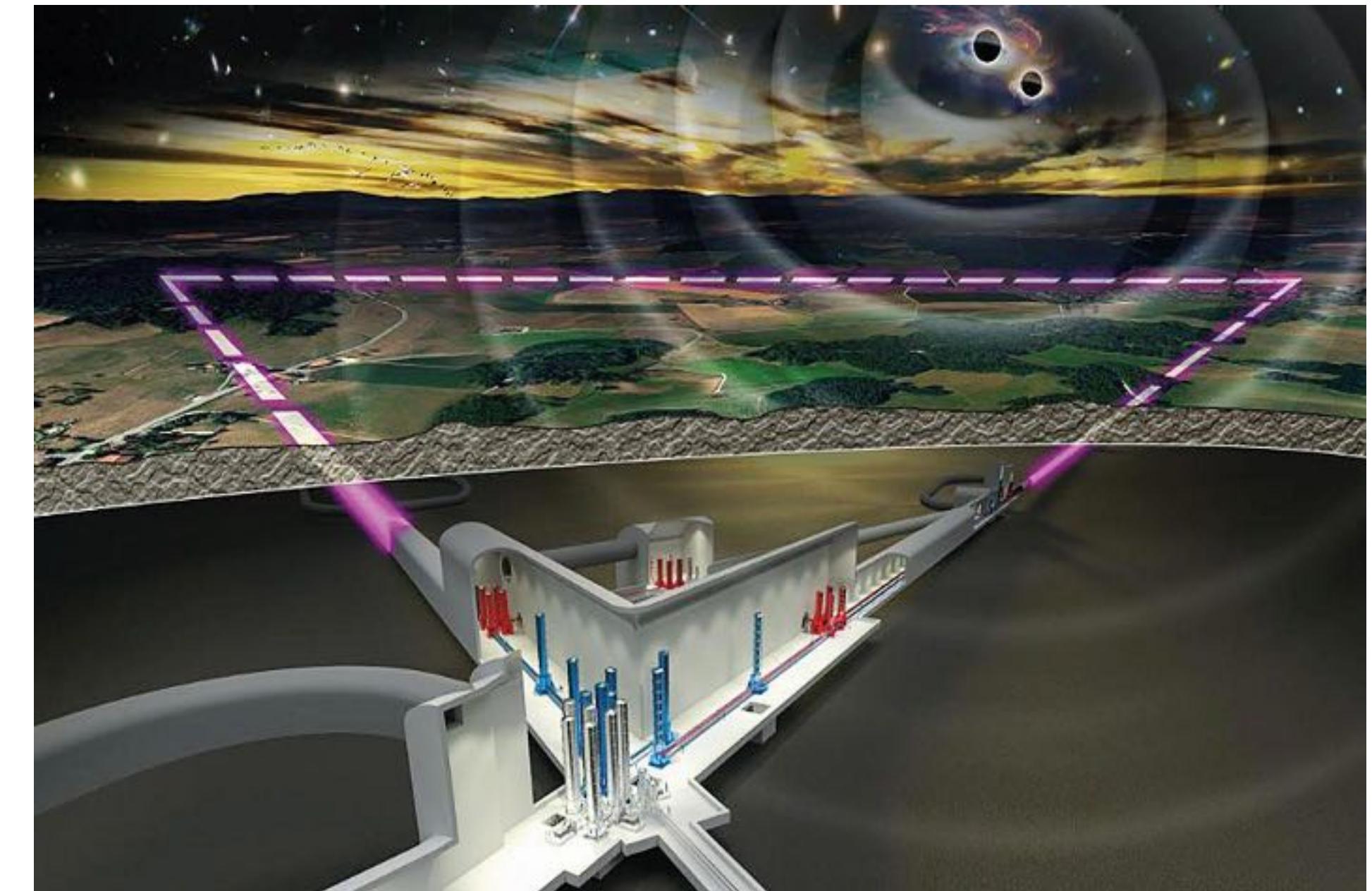


The future: big data & distant Universe!



Next-generation ground-based observatories:

Cosmic Explorer, US

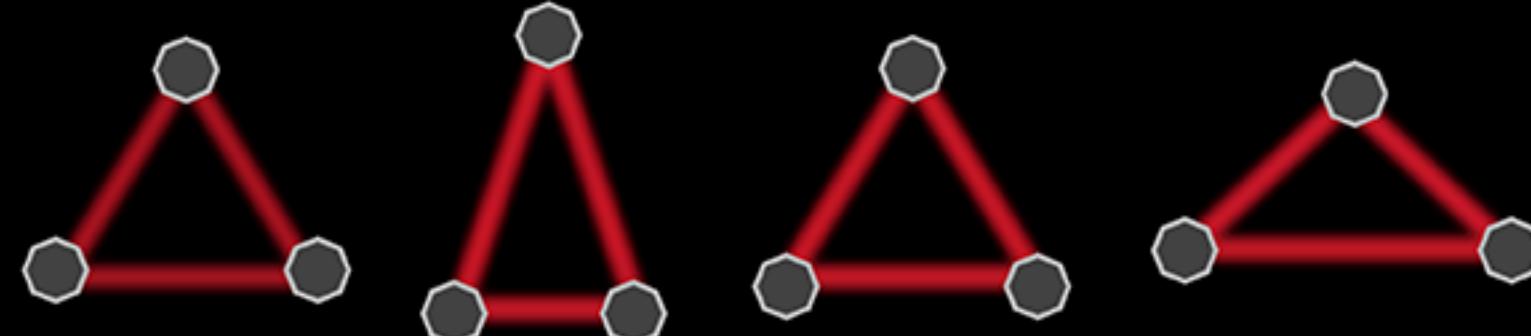


Einstein Telescope, Europe

LISA - LASER INTERFEROMETER SPACE ANTENNA

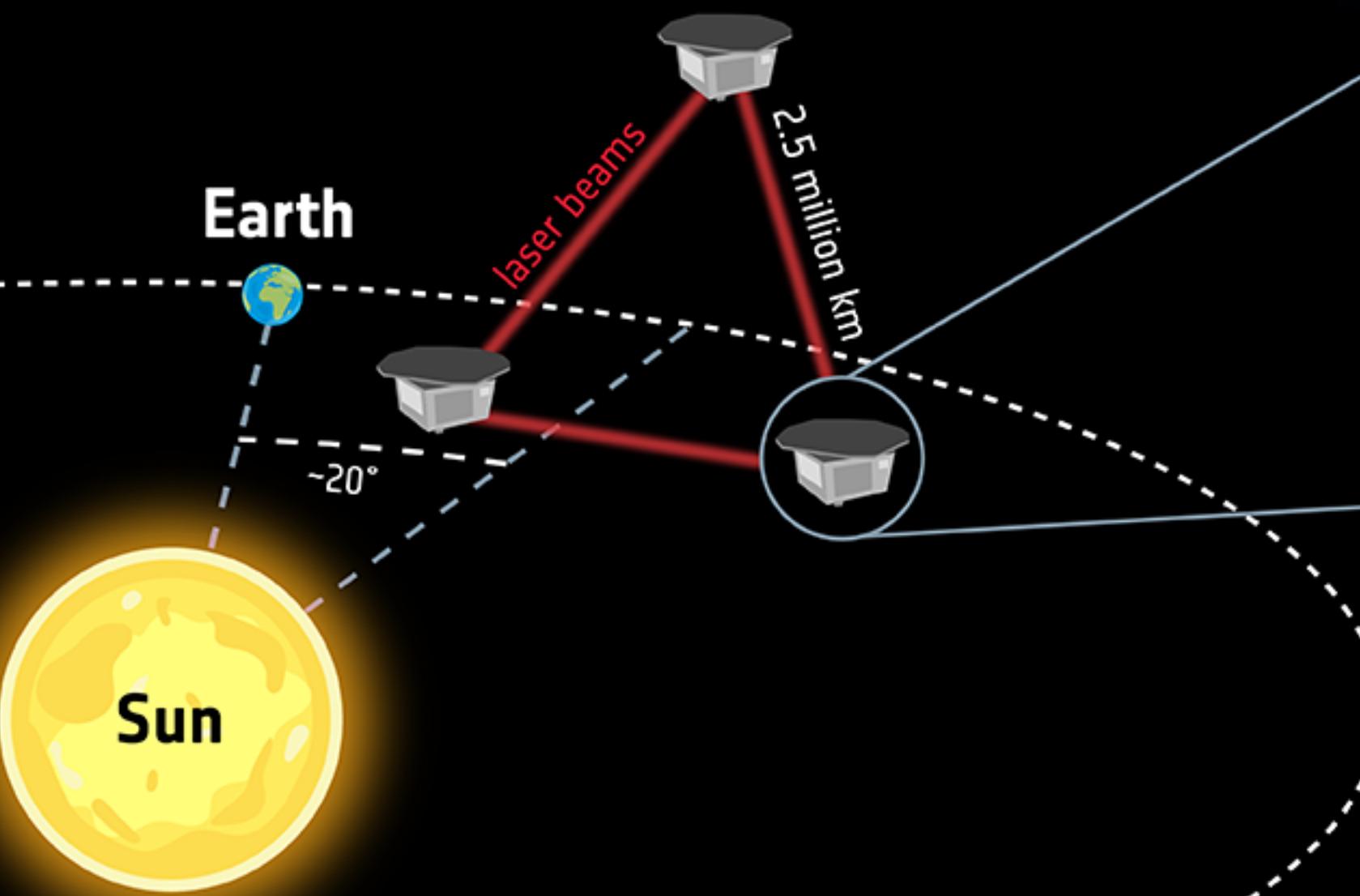
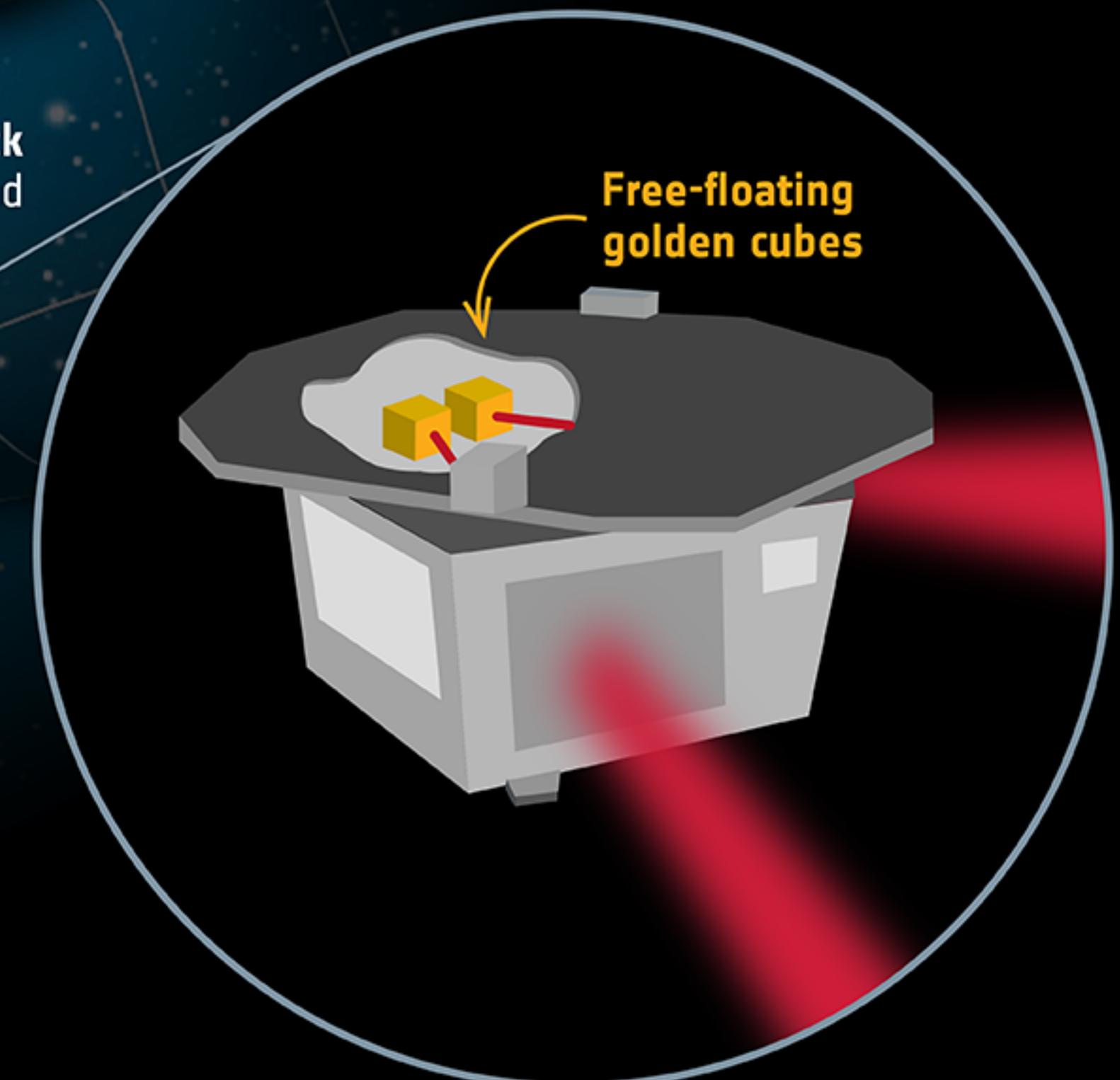
Gravitational waves are ripples in spacetime that alter the distances between objects. LISA will detect them by measuring subtle changes in the distances between **free-floating cubes** nestled within its three spacecraft.

③ **identical spacecraft** exchange **laser beams**. Gravitational waves change the distance between the **free-floating cubes** in the different spacecraft. This tiny change will be measured by the laser beams.



* Changes in distances travelled by the laser beams are not to scale and extremely exaggerated

Powerful events such as **colliding black holes** shake the fabric of spacetime and cause gravitational waves



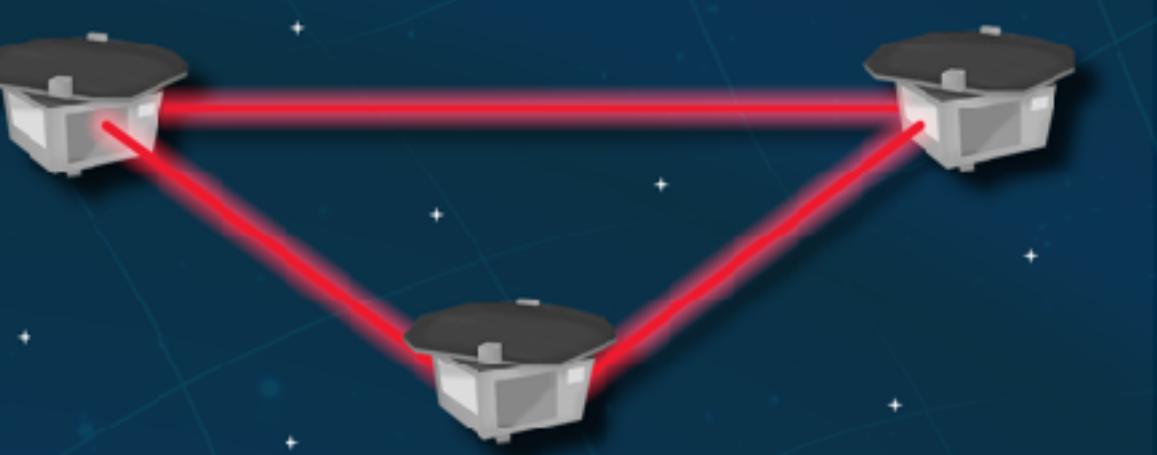
THE SPECTRUM OF GRAVITATIONAL WAVES

Observatories & experiments

Ground-based experiment



Space-based observatory



Pulsar timing array



Cosmic microwave background polarisation



Timescales

milliseconds

seconds

hours

years

Frequency (Hz)

100

1

10^{-2}

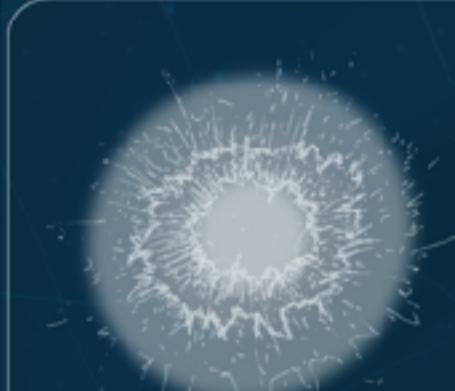
10^{-4}

10^{-6}

10^{-8}

10^{-16}

Cosmic sources



Supernova



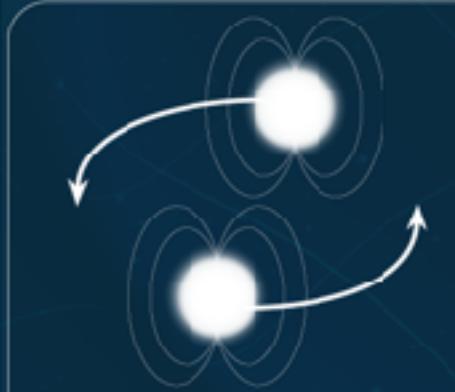
Pulsar



Compact object falling onto a supermassive black hole



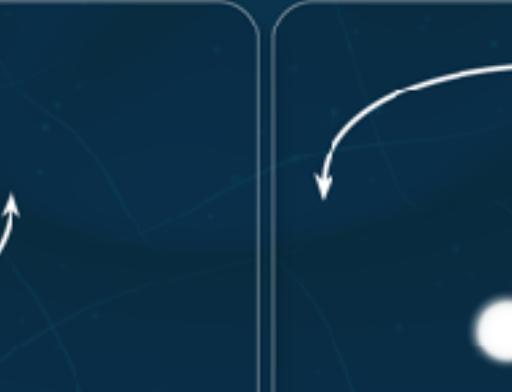
Merging supermassive black holes



Merging neutron stars in other galaxies

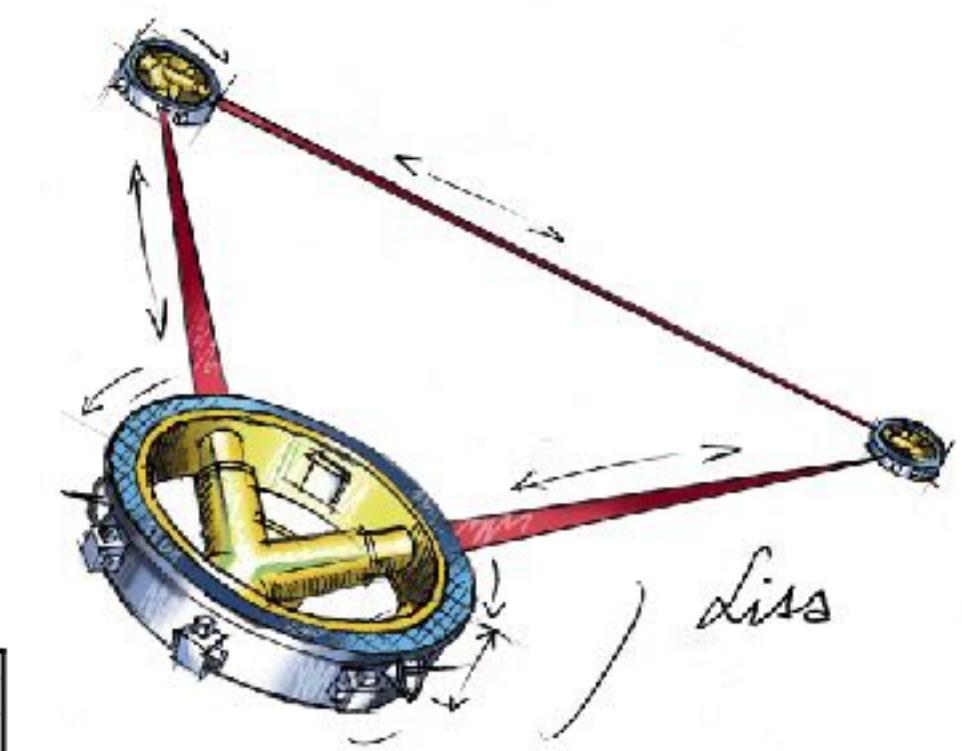
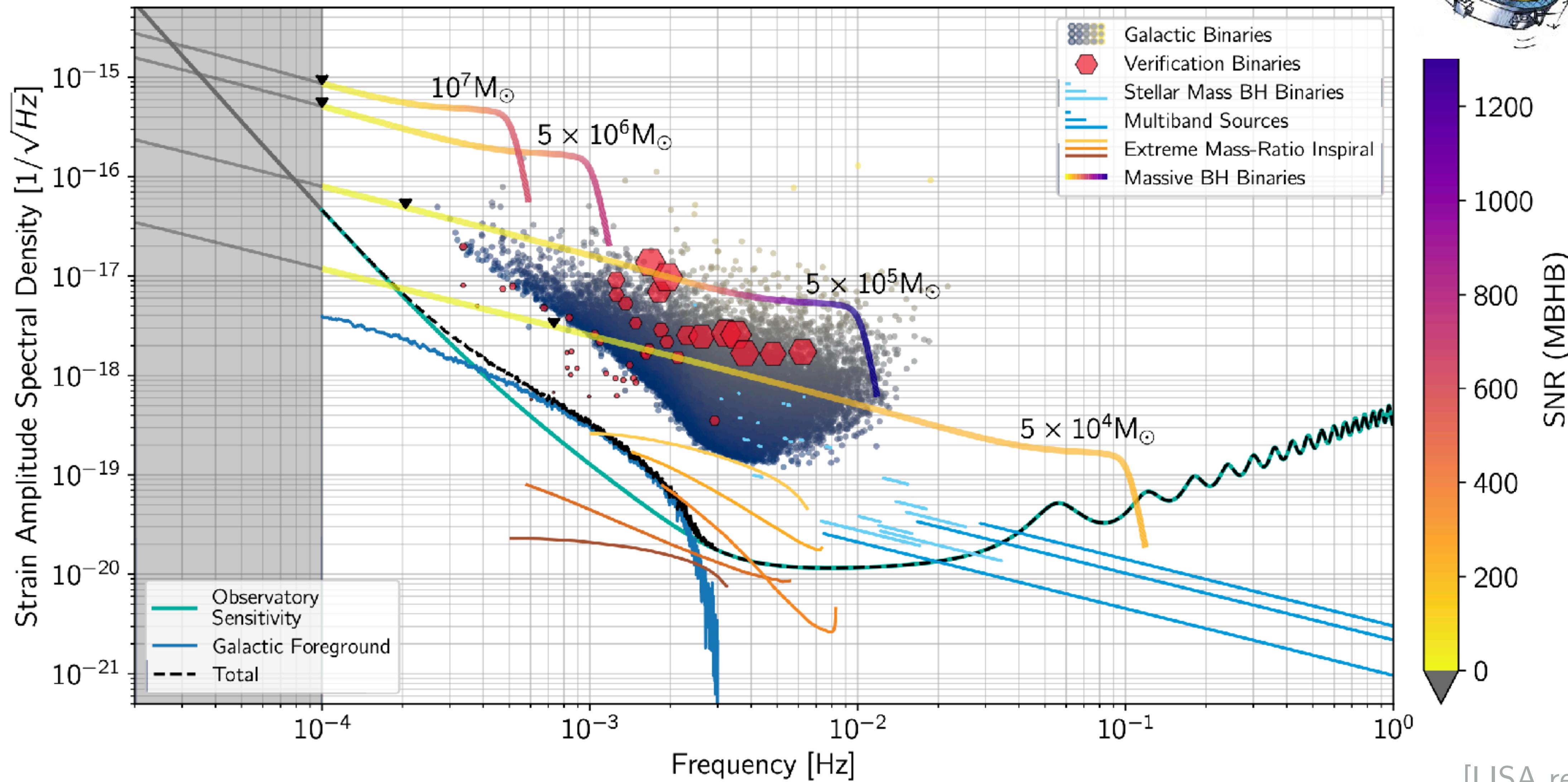


Merging stellar-mass black holes in other galaxies



Merging white dwarfs in our Galaxy

LISA perspective from space: super massive black holes + galactic binaries



Join us!

NBI LIGO group

MSc PUK course: “Black holes & Gravitational Waves”
Student resources @ The Center of Gravity



[slides w/ links!]



jose.ezquiaga@nbi.ku.dk