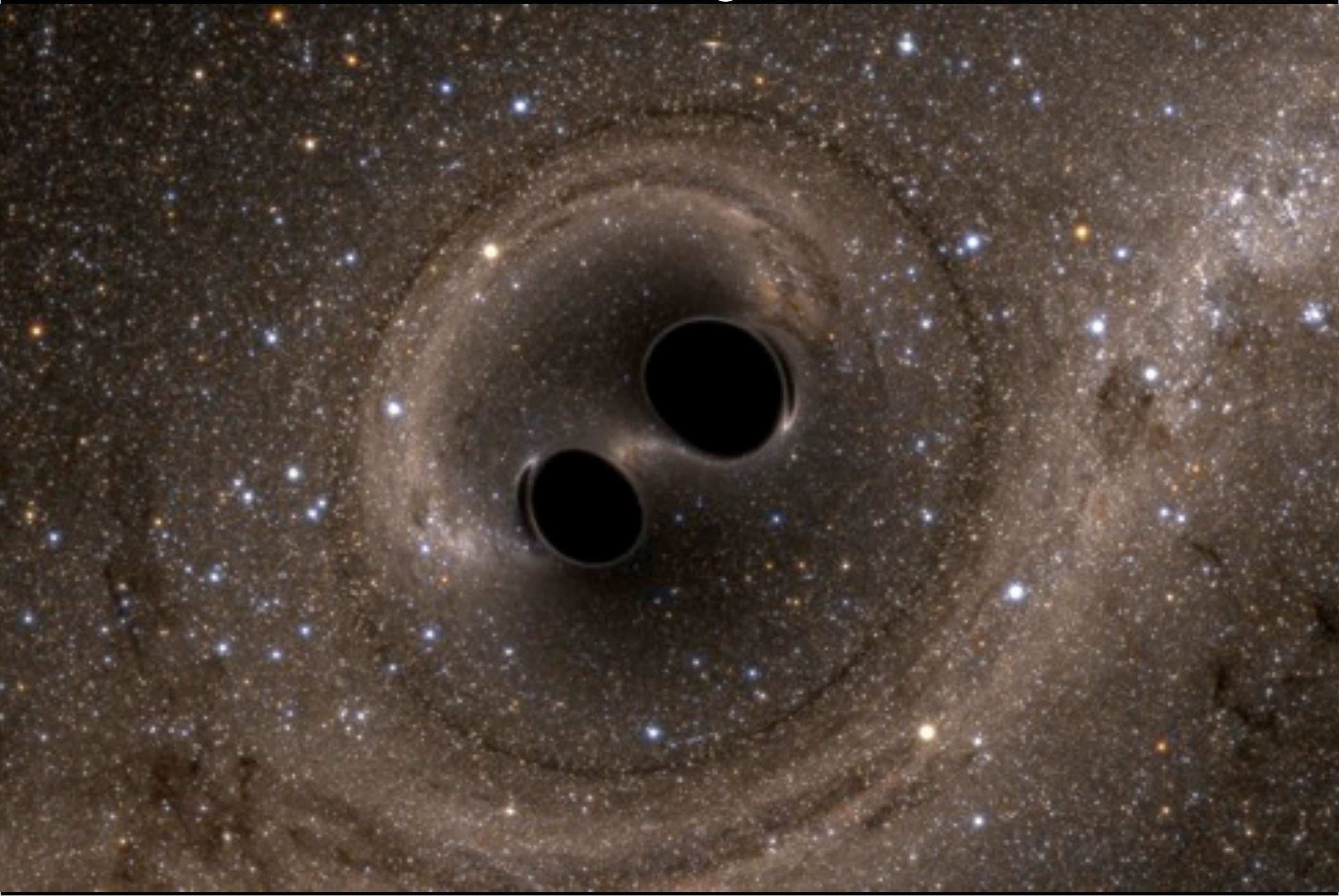
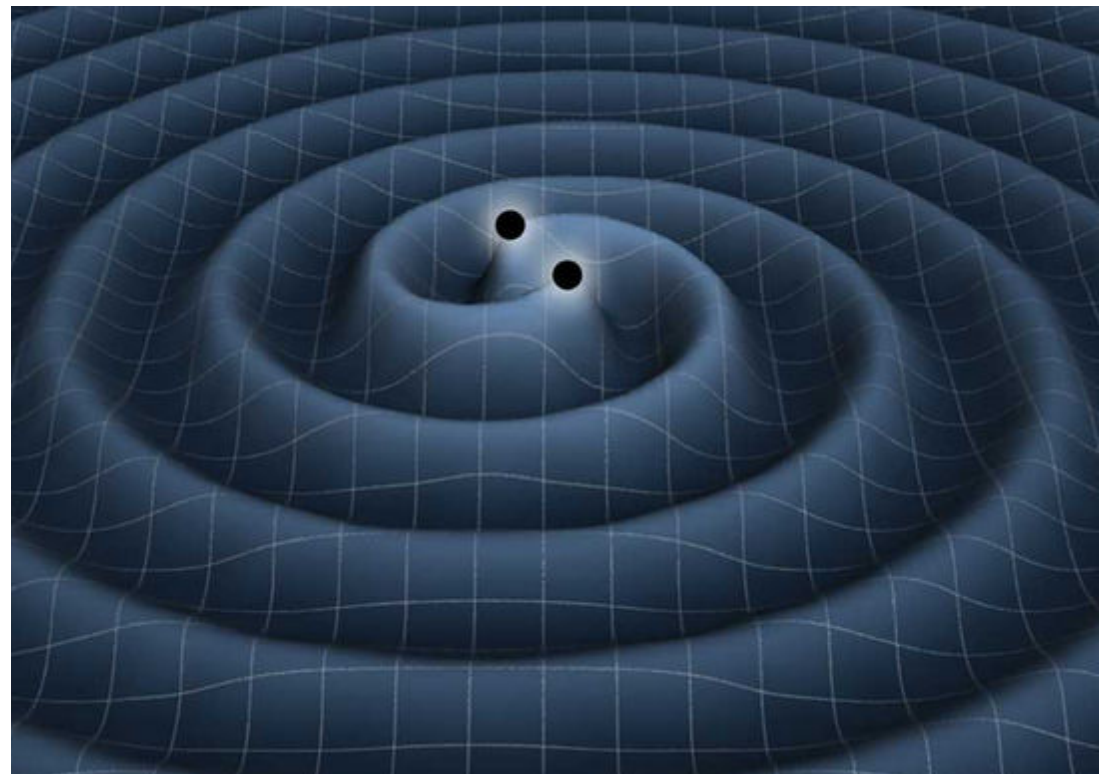
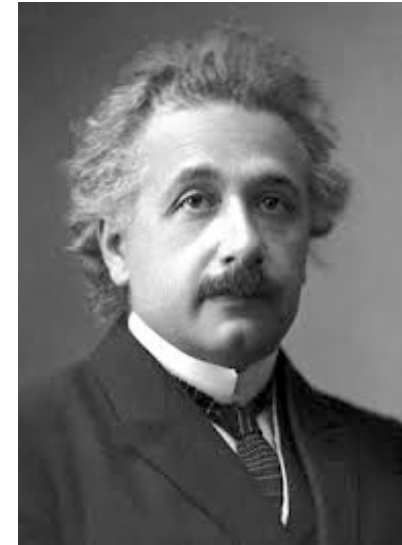


Gravitational Waves from Binary Black Hole Mergers



- The waves of the electromagnetic force are realized as (electric and magnetic) fields which propagate through space and time. [Maxwell, 1865]
- General Relativity describes gravity in terms of a spacetime which is deformable. [Einstein, 1915]
- GWs are oscillations of that spacetime. [Einstein, 1916]
- “ripples in spacetime”



In special relativity:

$$ds^2 = (c dt)^2 - (dx^2 + dy^2 + dz^2) = \sum \eta_{\mu\nu} dx_\mu dx_\nu \quad \text{Einstein, 1905}$$

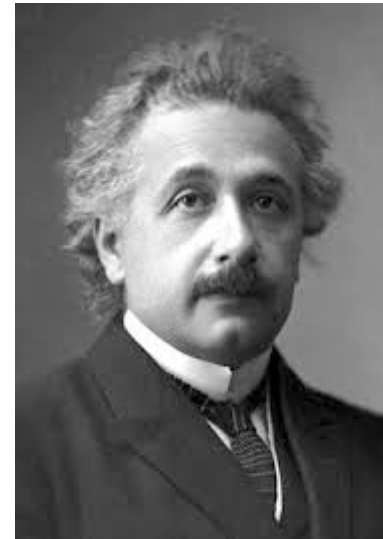
$$\eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

GR:

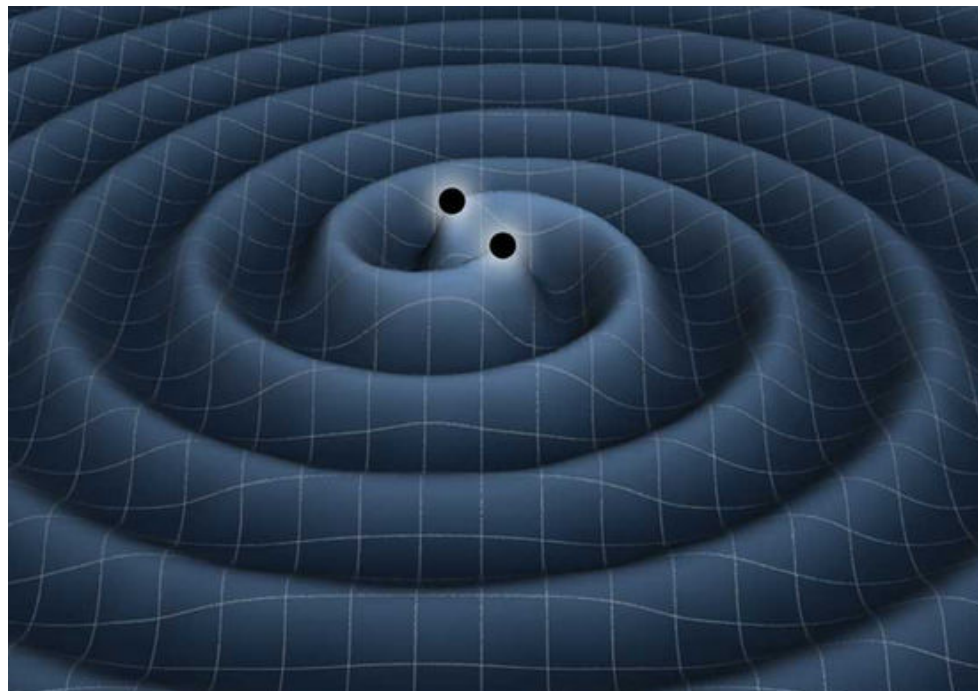
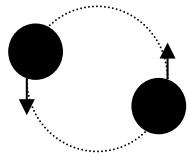
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \quad G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \quad \text{Einstein, 1915}$$

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

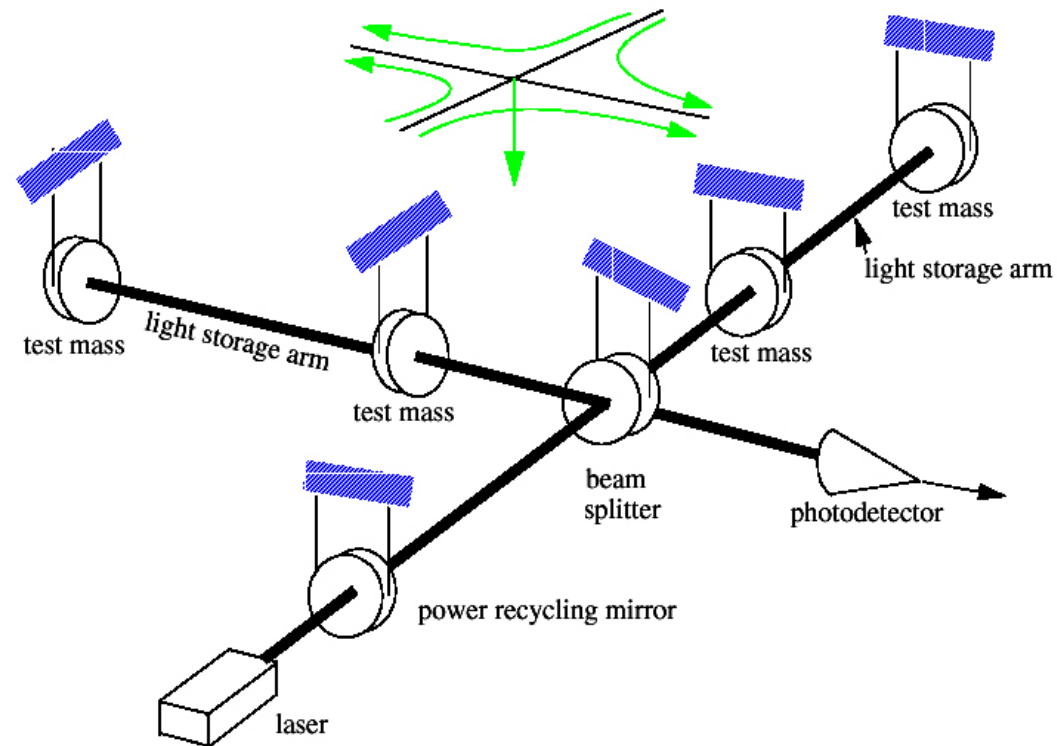
$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = -16\pi T_{\mu\nu} \quad \text{Einstein, 1916}$$



Binary black hole system



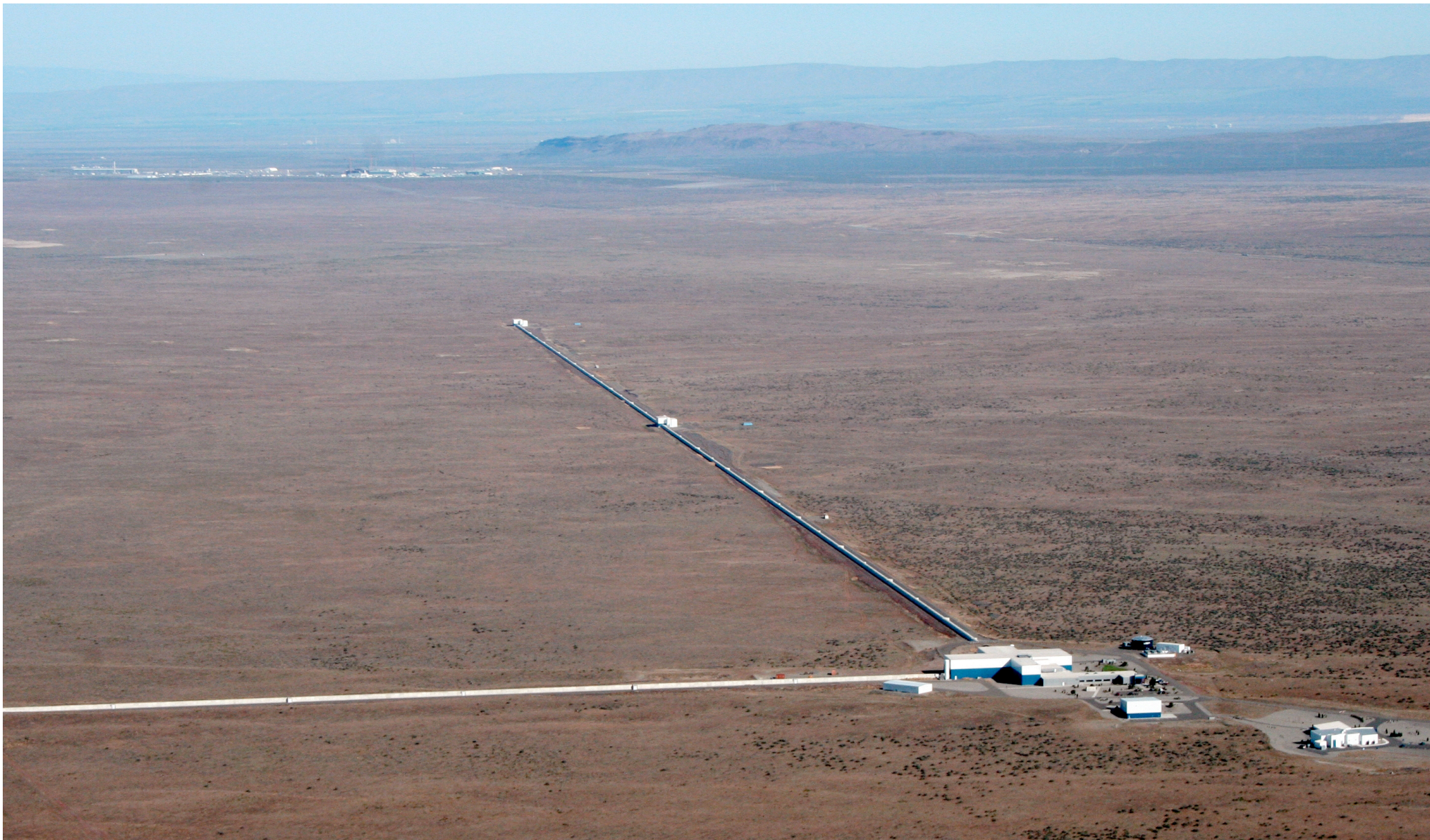
As detected by LIGO:

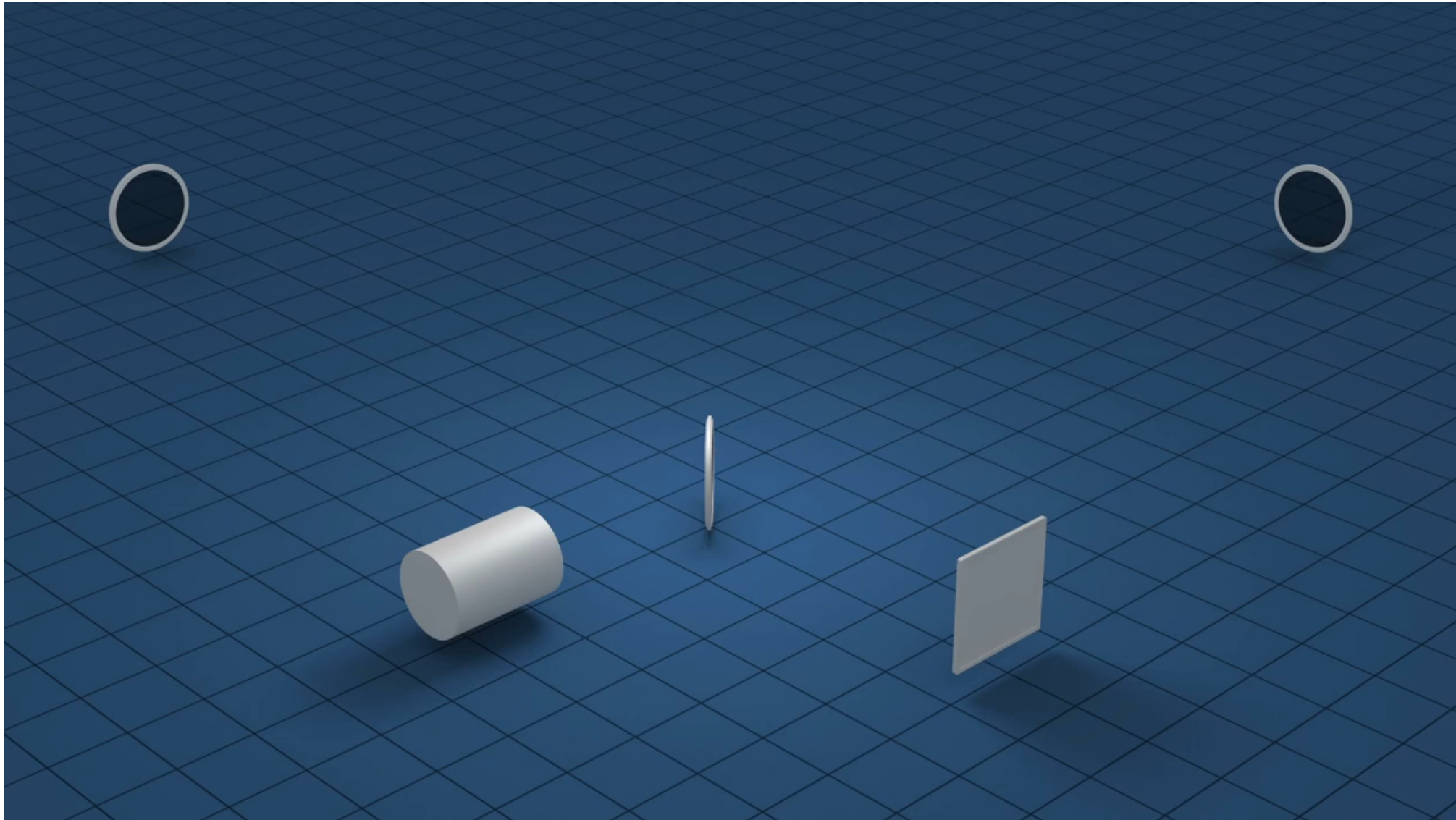


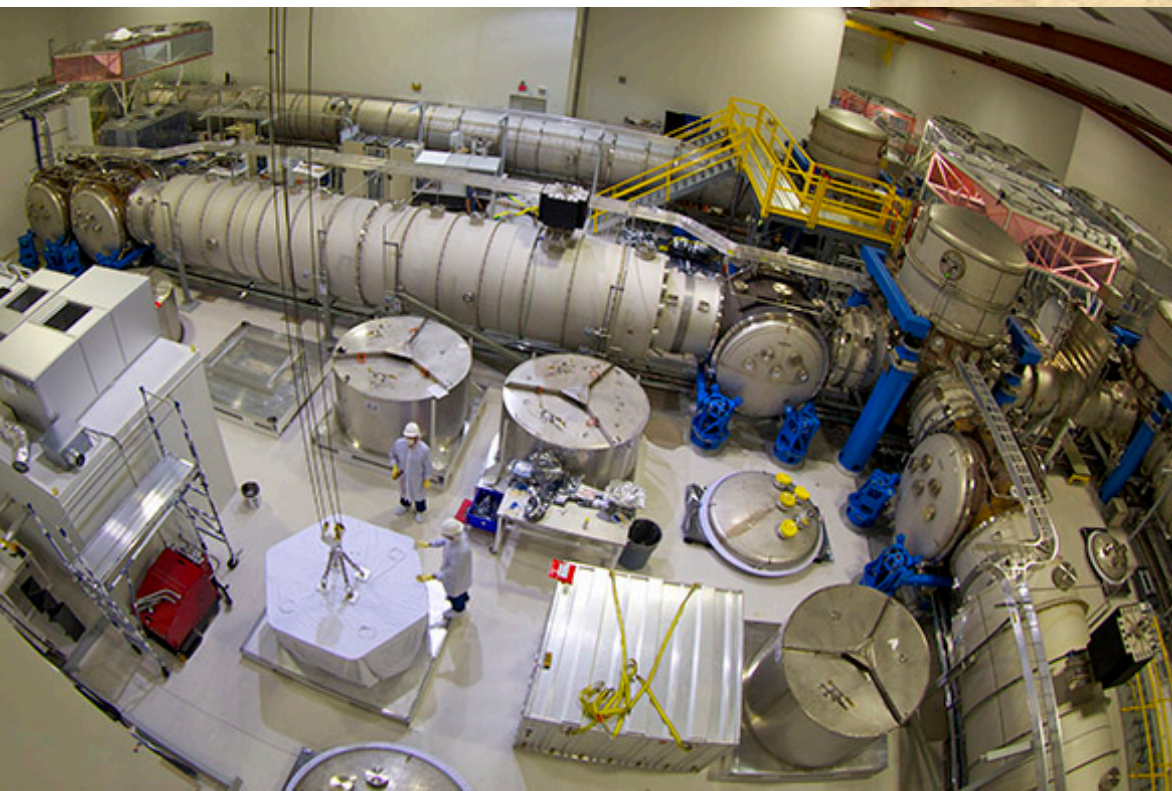
GW ripples are a space strain h ,
where $h = \Delta L / L$

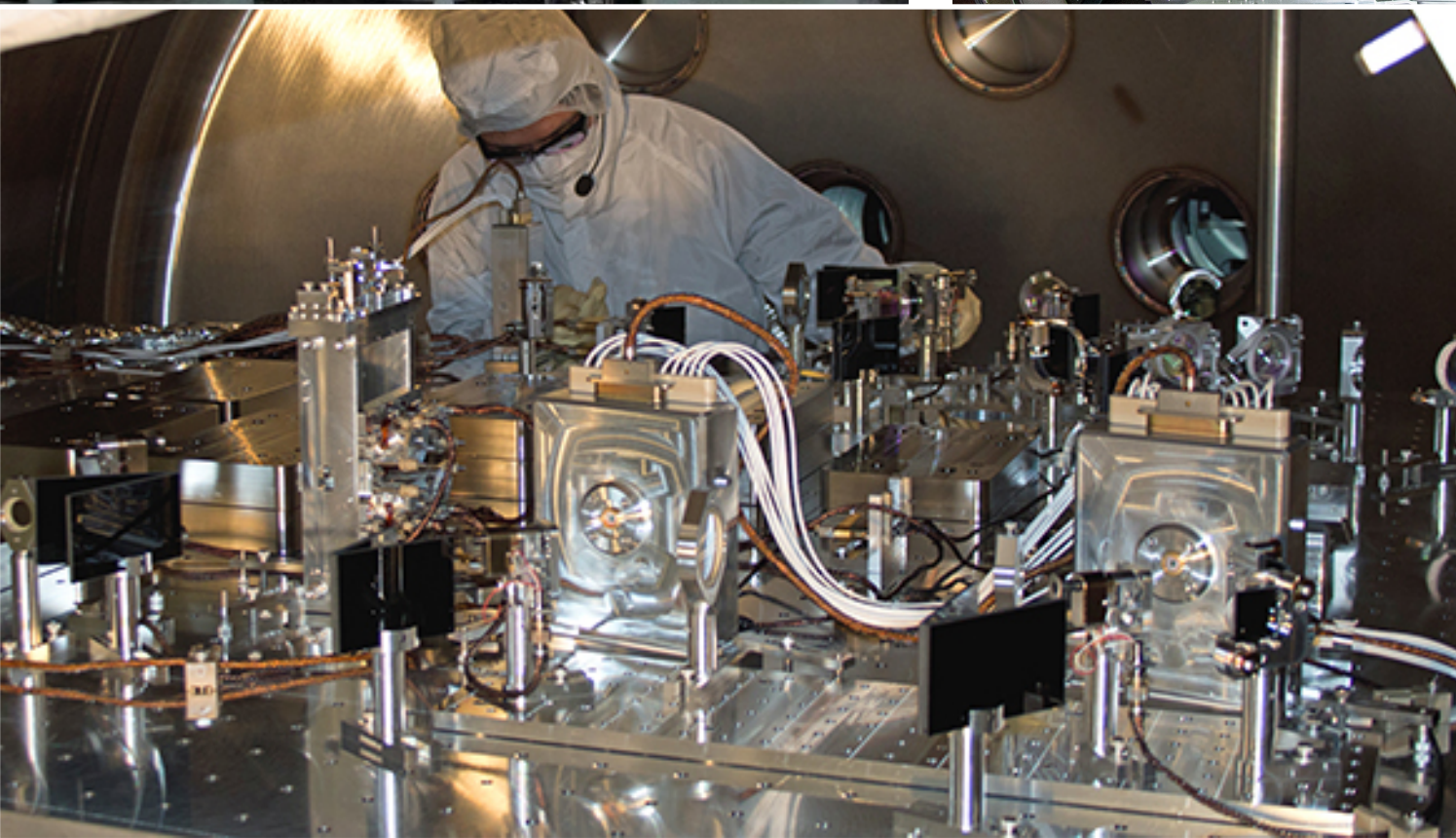
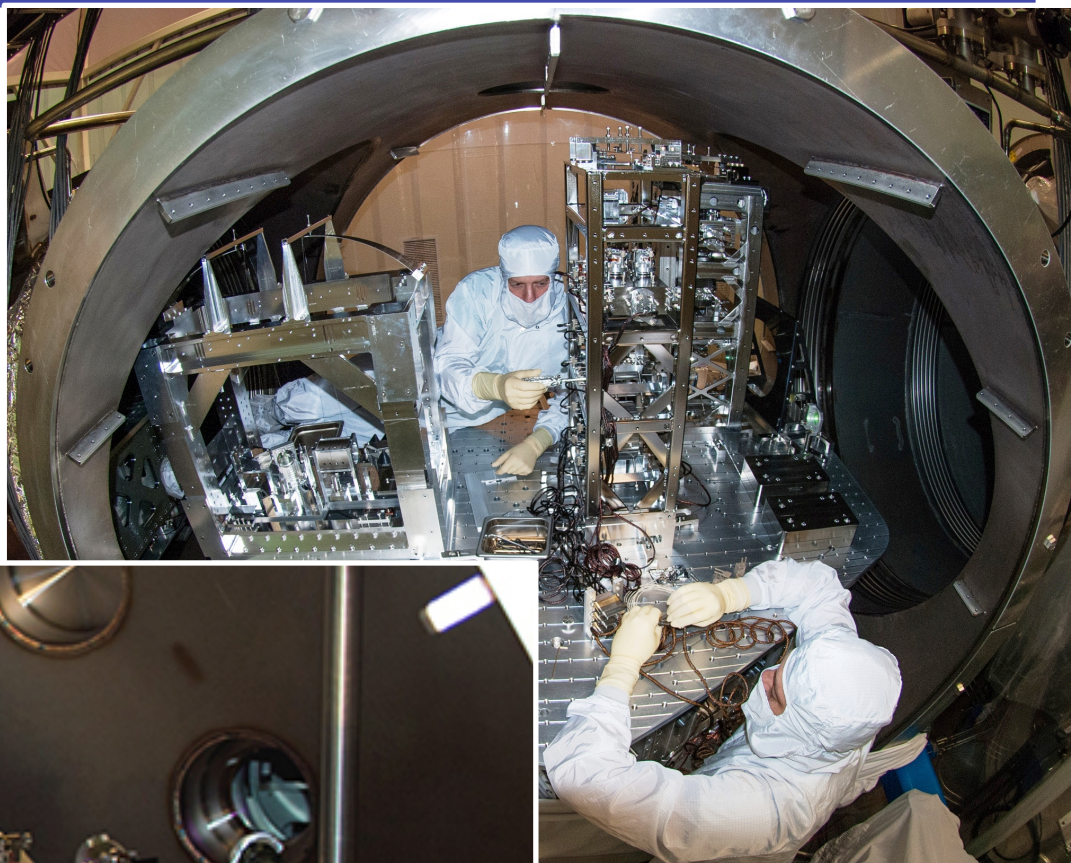
Realistic sources: $h \sim 10^{-23}$

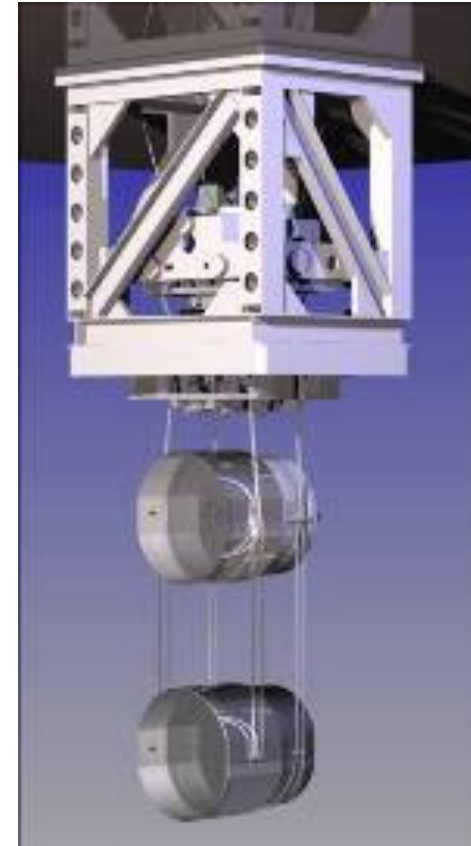
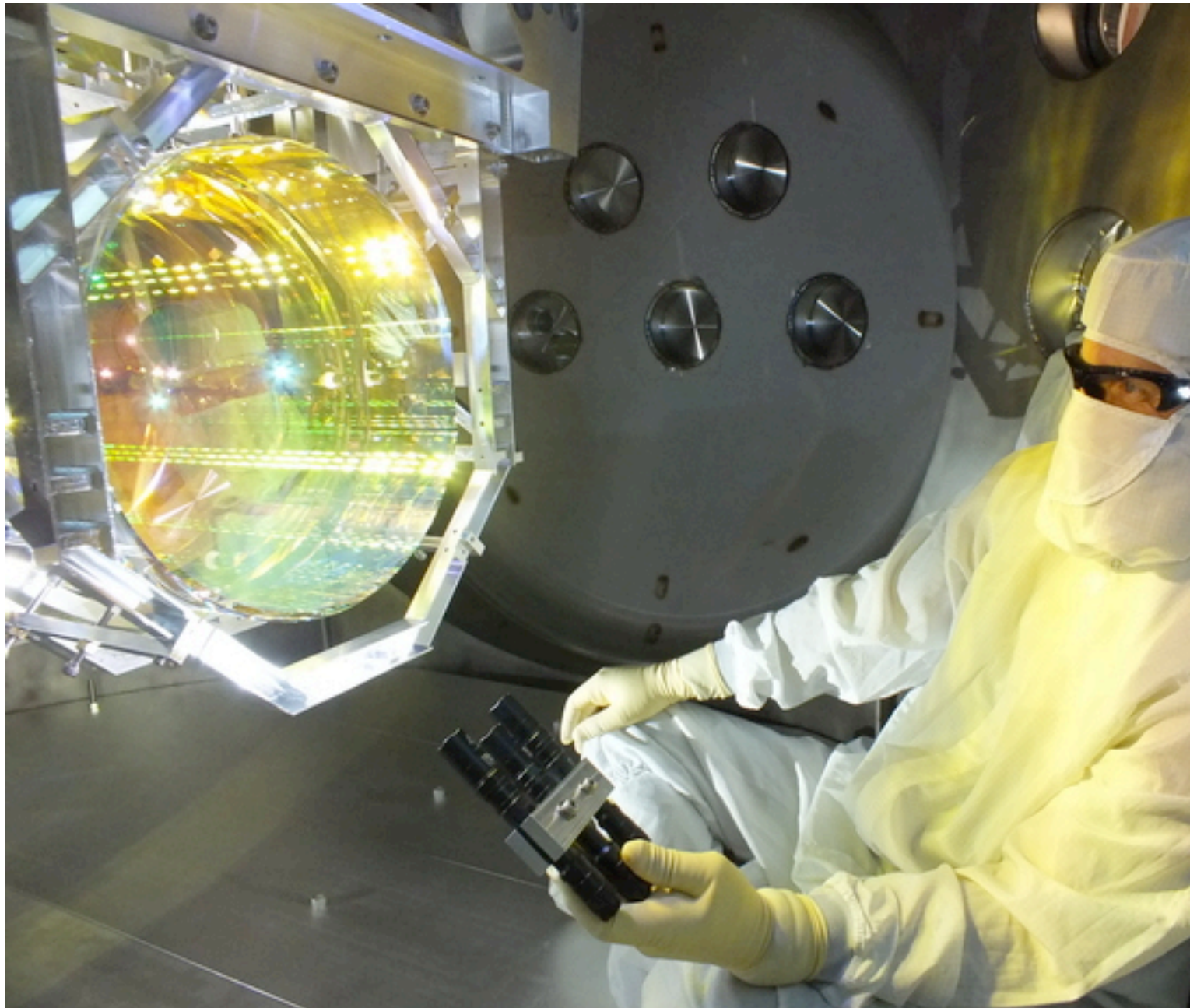
$\Rightarrow \Delta L \sim 10^{-19} \text{ m}$ (Yikes !)

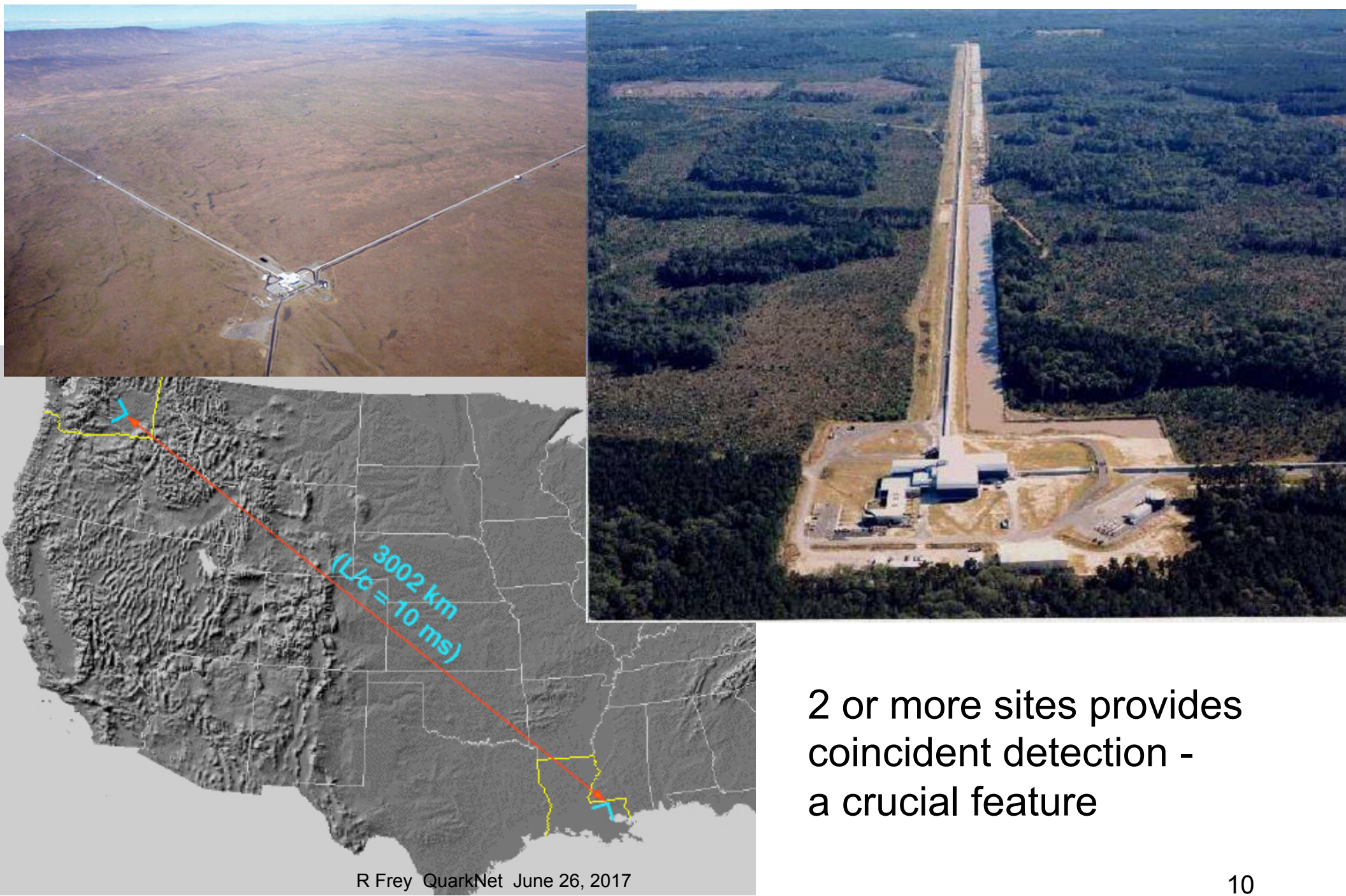






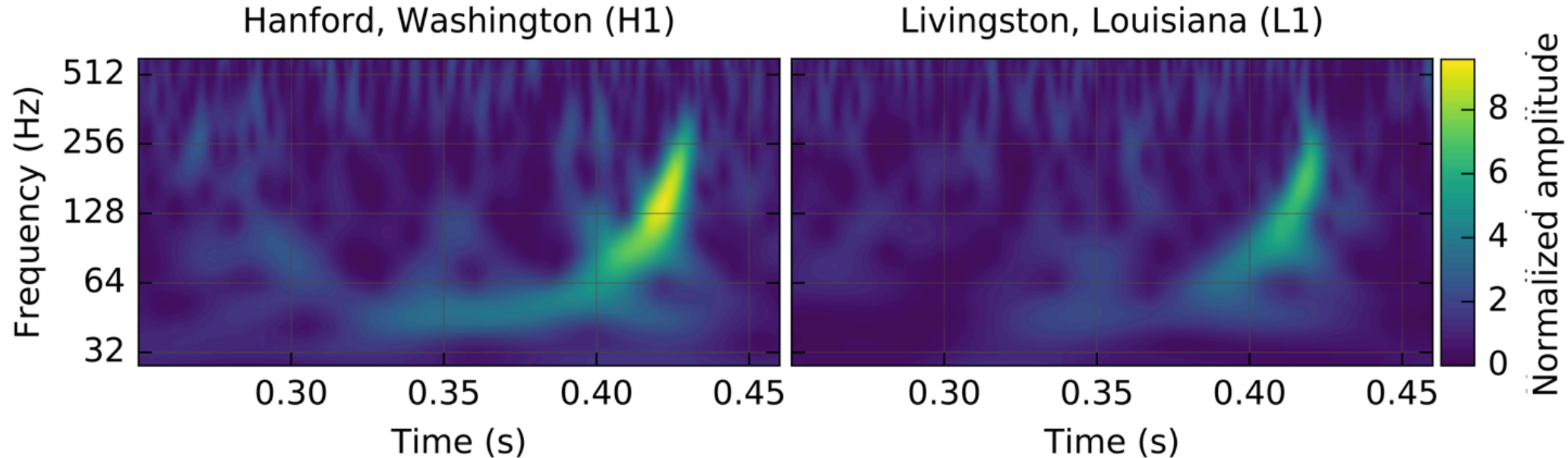






- 1916: Einstein shows gravitational waves would result from General Relativity
- 1960's: Kip Thorne (Caltech) and Rainer Weiss (MIT) predict that gravitational wave detection via laser interferometry is feasible
- 1972: Rainer Weiss (MIT) describes first realistic laser interferometer design
- 1975: Hulse and Taylor show that the decay in the orbit of a binary neutron star system is consistent with energy loss due to gravitational waves
- 1980-81: MIT and Caltech launch construction of first prototype detectors
- 1994: Ground breaking at the Hanford, WA site; 1995 at Livingston, LA
- 1998: UO (+Michigan, LSU, Florida, UW-Milwaukee) – founding members of the LIGO Scientific Collaboration
- 2002-2010: Data taking and development of the scientific program with initial detectors
- Sept 10, 2015: Advanced detectors begin data taking, observing run O1
- Sept 12, 2015: Observation of GW150914, merger of binary black holes
- Dec 26, 2015: Detection of GW151226, a lower mass binary black hole merger
- Dec 2016: Start of observing run O2
- Jan 4, 2017: Detection of GW170104, binary black hole merger
- Run O2 until end of Aug 2017; Virgo may join

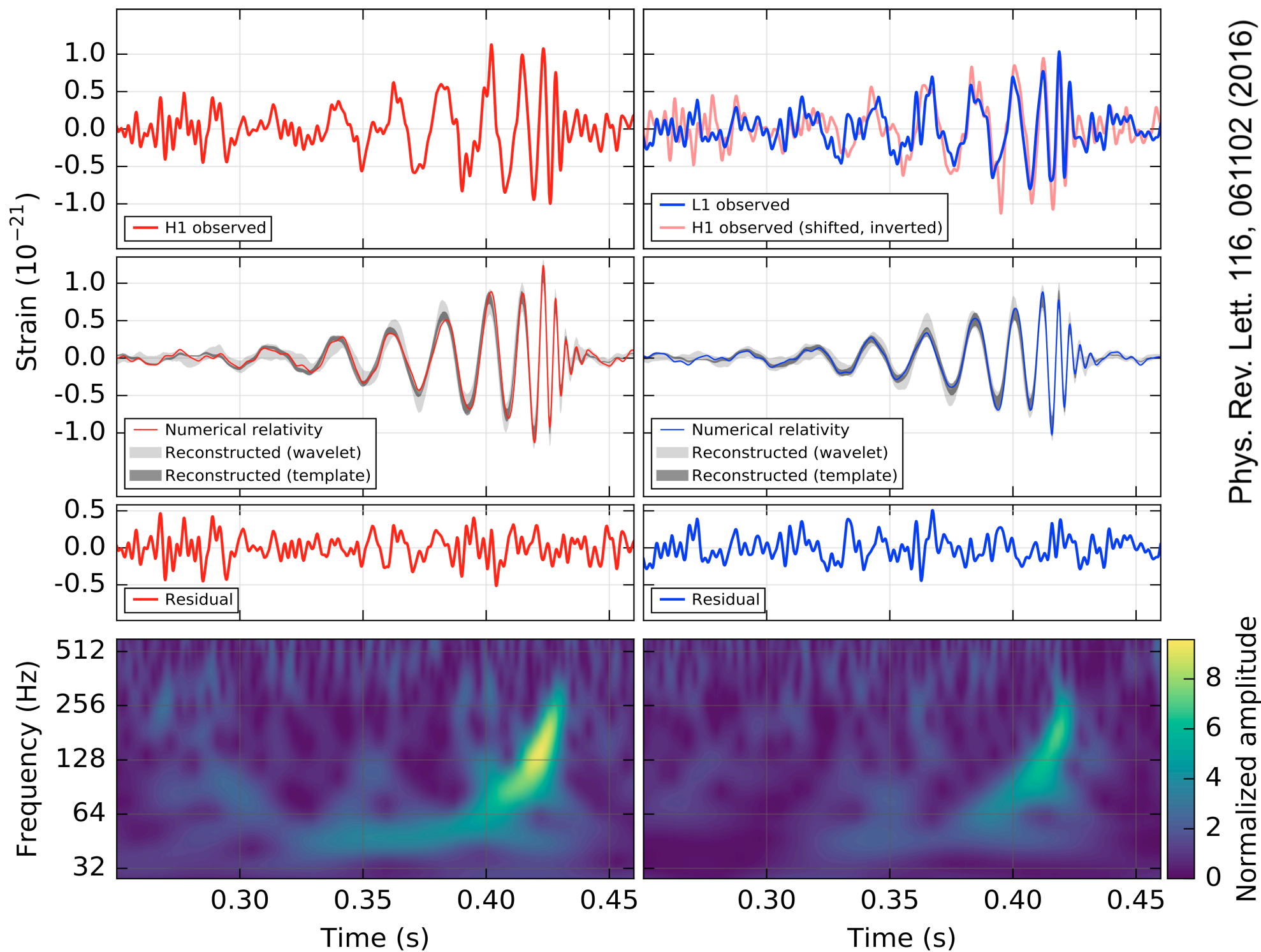
Boom !

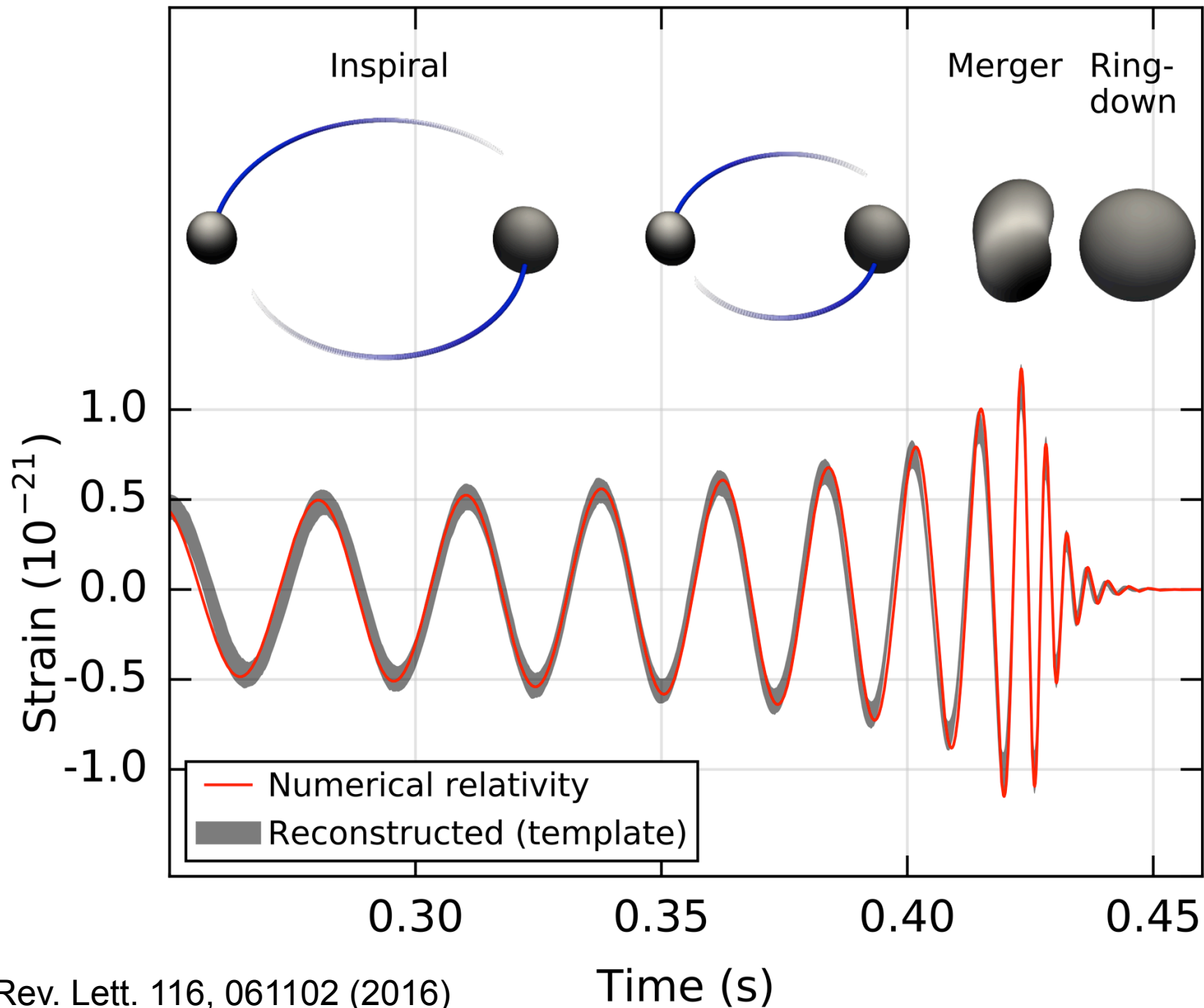


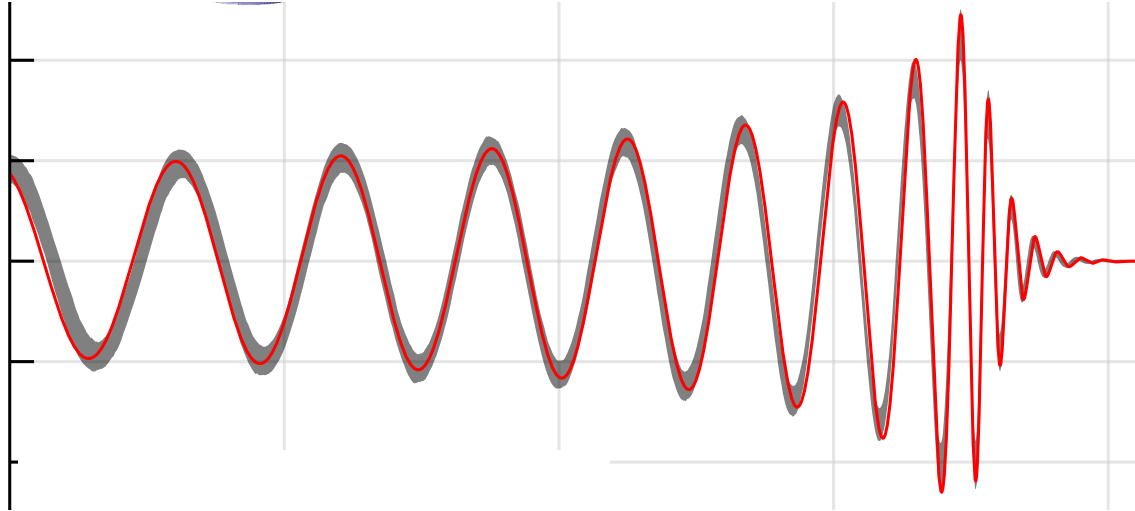
Phys. Rev. Lett. 116, 061102 (2016)

Hanford, Washington (H1)

Livingston, Louisiana (L1)

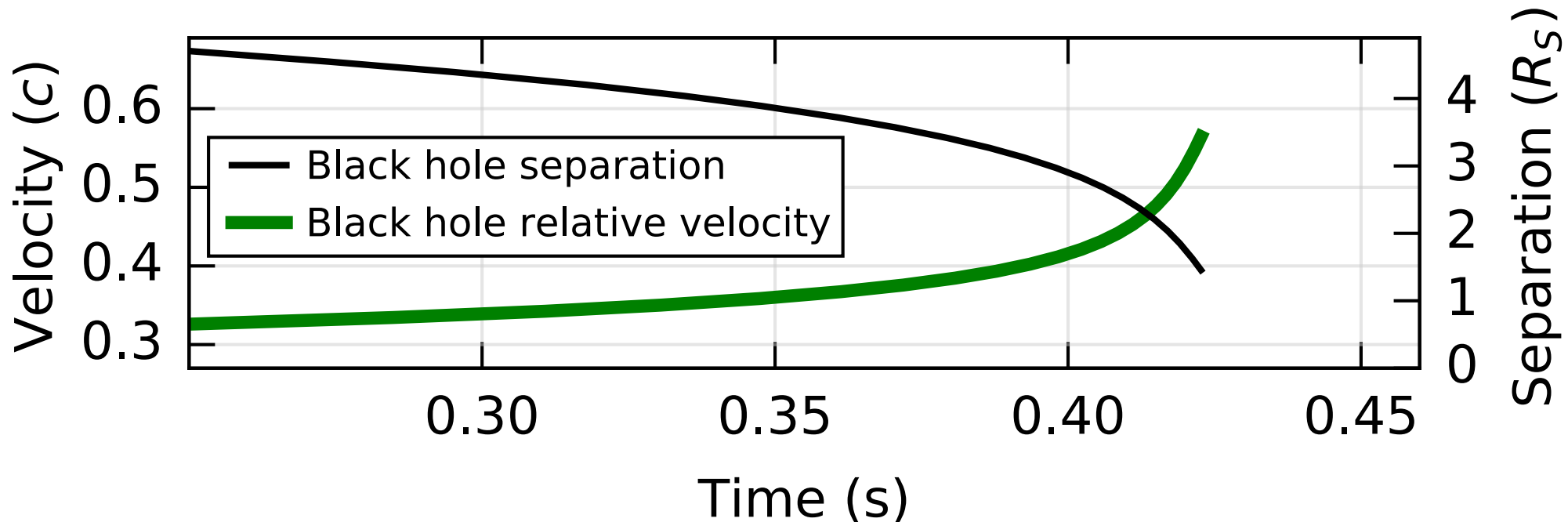






- The chirp function tells us we have 2 objects each of mass about 30 solar masses ($30M_{\odot}$)
- At merger, they are orbiting each other 75 times per second and their separation is about 350 km... *And they are still missing each other!*
- They are indeed black holes.

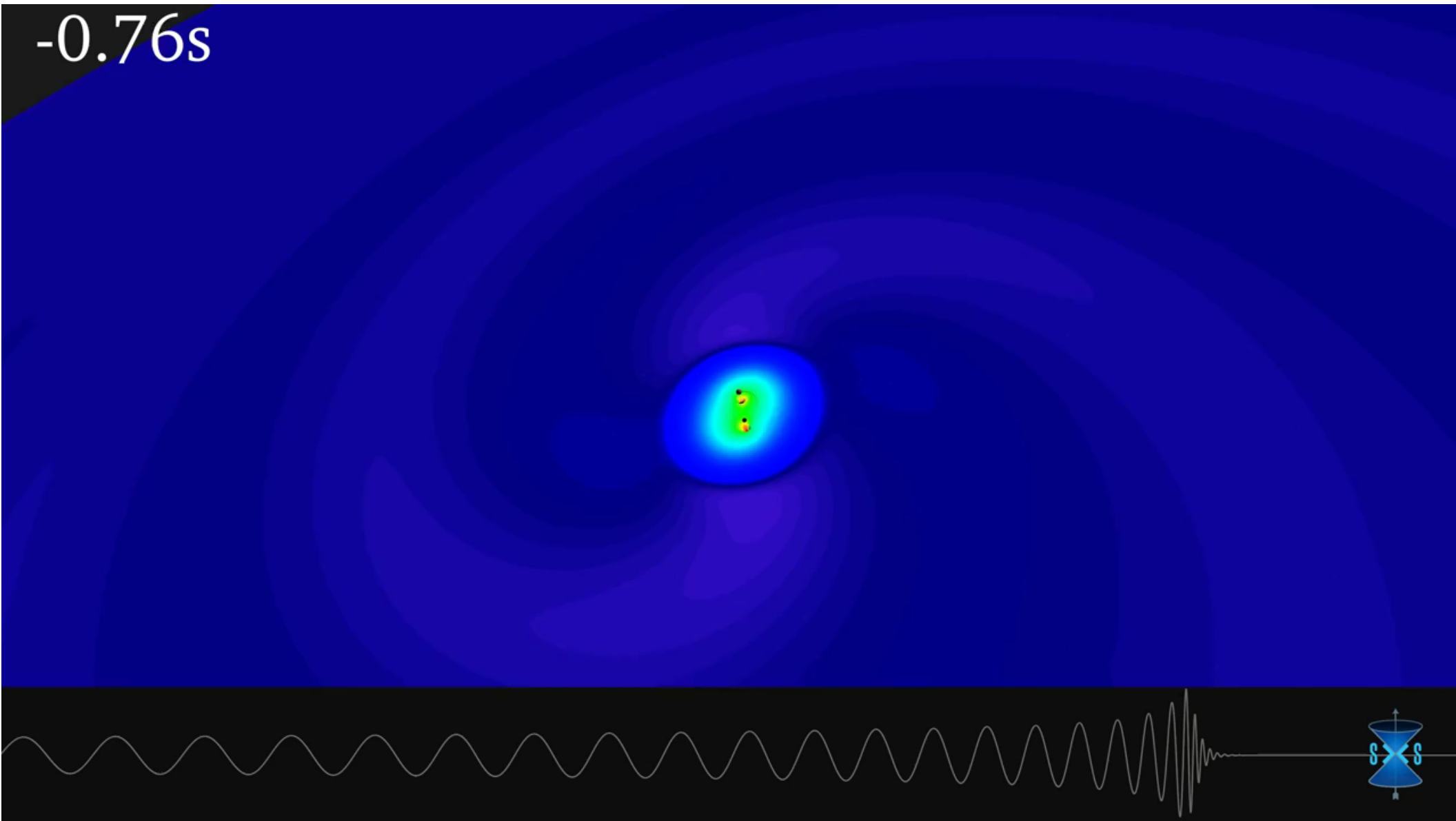
- Predicts gravitational waves... ☒
- Waveforms from GR fit the data beautifully... ☒



A unique and important test of GR



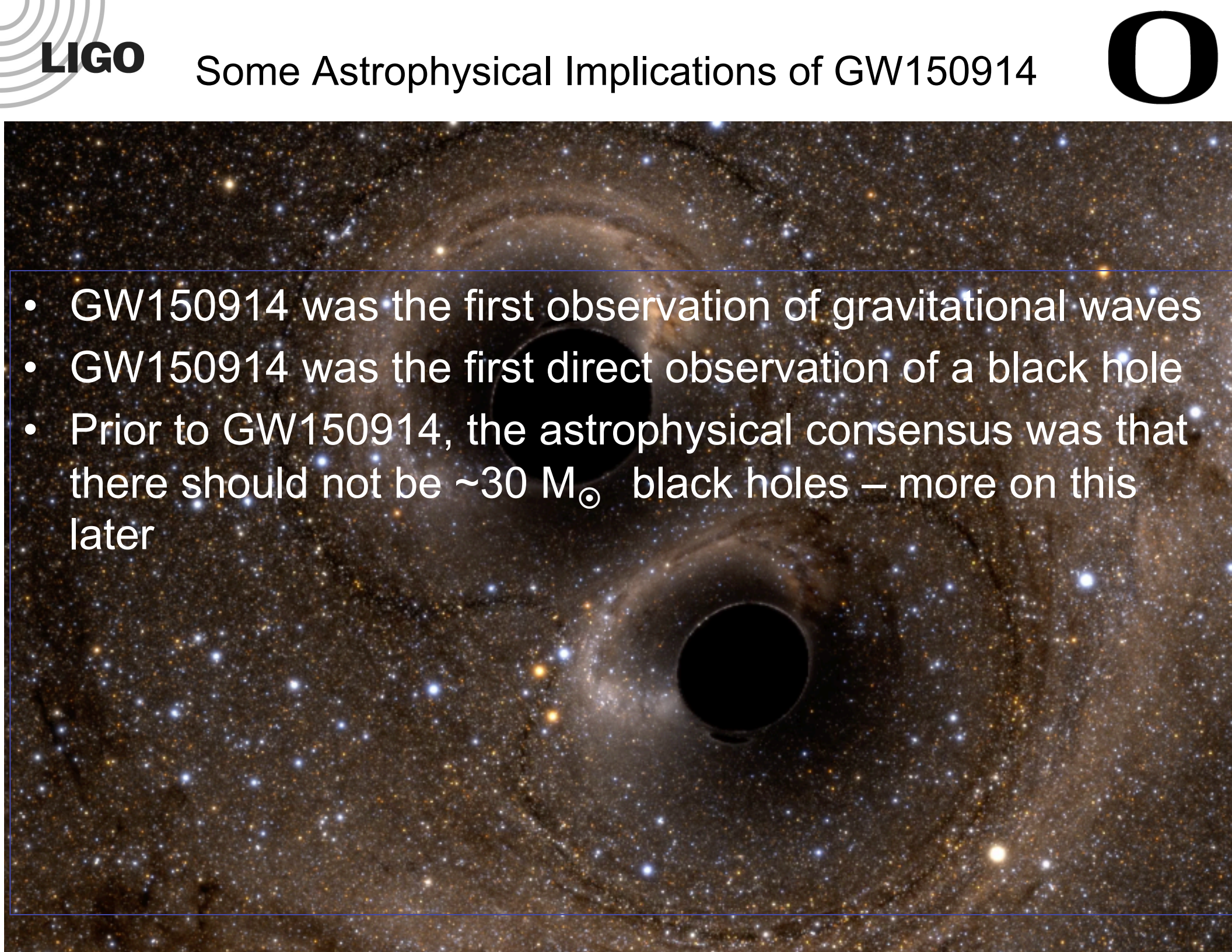
-0.76s



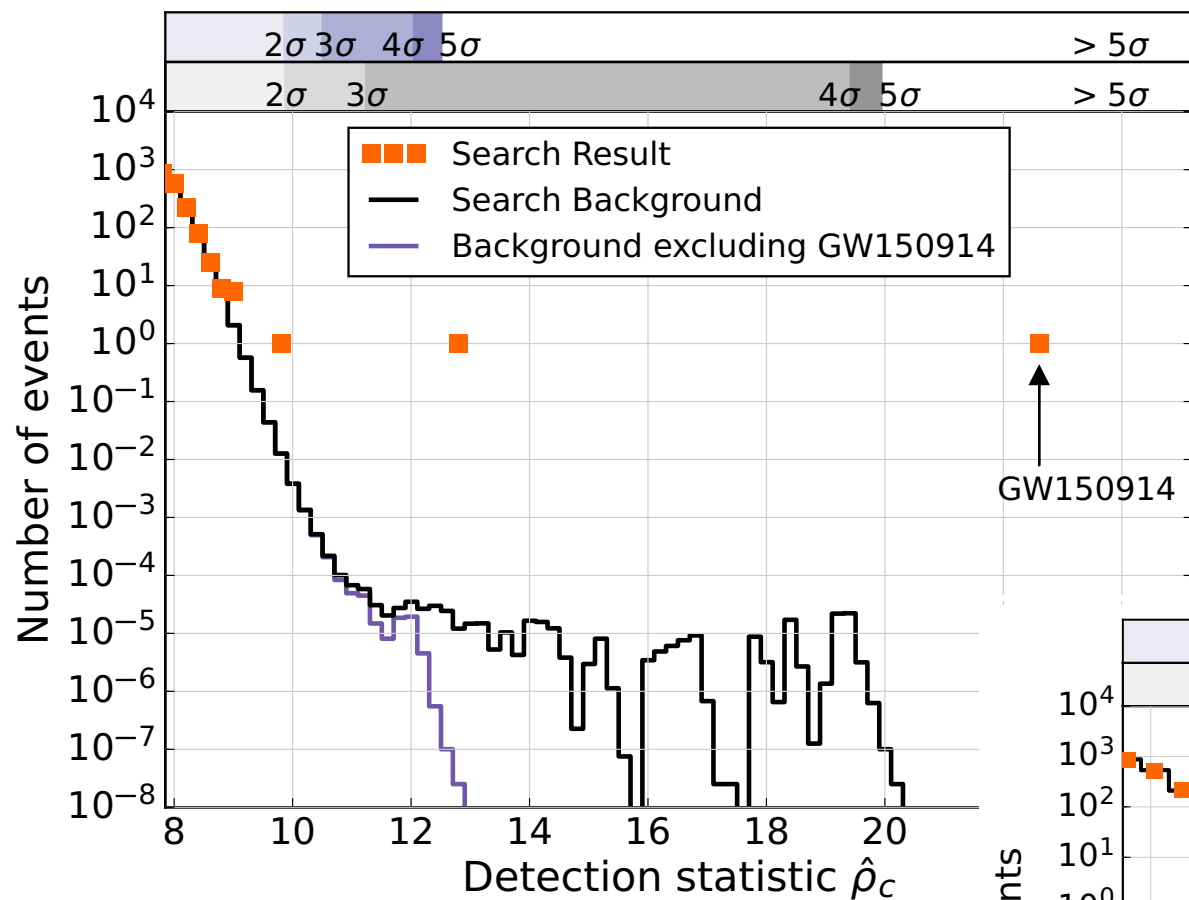
Primary black hole mass	$36^{+5}_{-4} M_{\odot}$
Secondary black hole mass	$29^{+4}_{-4} M_{\odot}$
Final black hole mass	$62^{+4}_{-4} M_{\odot}$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	$410^{+160}_{-180} \text{ Mpc}$
Source redshift, z	$0.09^{+0.03}_{-0.04}$

- Energy radiated in GWs: $3.0^{+0.5}_{-0.5} M_{\odot} c^2$
- Peak GW power: $3.6^{+0.5}_{-0.4} \times 10^{56} \text{ erg/s}$

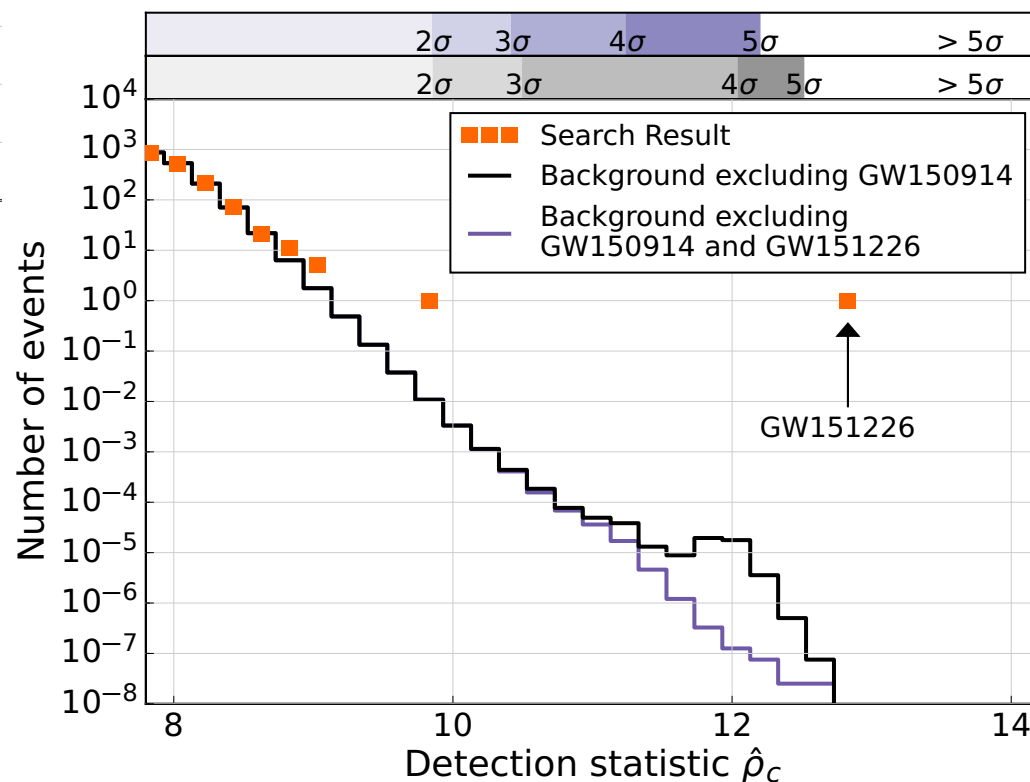
	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/M_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm 0.9}_{-4.5\pm 1.0}$
Detector-frame chirp mass $\mathcal{M}/M_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm 0.4}_{-1.9\pm 0.4}$
Detector-frame primary mass $m_1/M_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm 0.9}_{-4.1\pm 0.3}$
Detector-frame secondary mass $m_2/M_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm 0.1}_{-4.9\pm 0.6}$
Detector-frame final mass $M_f/M_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm 0.8}_{-4.0\pm 0.9}$
Source-frame total mass $M^{\text{source}}/M_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm 1.0}_{-3.9\pm 0.5}$
Source-frame chirp mass $\mathcal{M}^{\text{source}}/M_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm 0.4}_{-1.7\pm 0.2}$
Source-frame primary mass $m_1^{\text{source}}/M_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm 1.1}_{-3.8\pm 0.0}$
Source-frame secondary mass $m_2^{\text{source}}/M_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm 0.2}_{-4.4\pm 0.5}$
Source-frame final mass $M_f^{\text{source}}/M_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm 0.9}_{-3.5\pm 0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm 0.01}_{-0.21\pm 0.03}$
Effective inspiral spin parameter χ_{eff}	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm 0.01}_{-0.18\pm 0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm 0.04}_{-0.28\pm 0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm 0.07}_{-0.42\pm 0.01}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm 0.00}_{-0.07\pm 0.03}$
Luminosity distance D_L/Mpc	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm 20}_{-180\pm 40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm 0.004}_{-0.038\pm 0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_{\text{s/n}}$	288.7 ± 0.2	290.1 ± 0.2	—

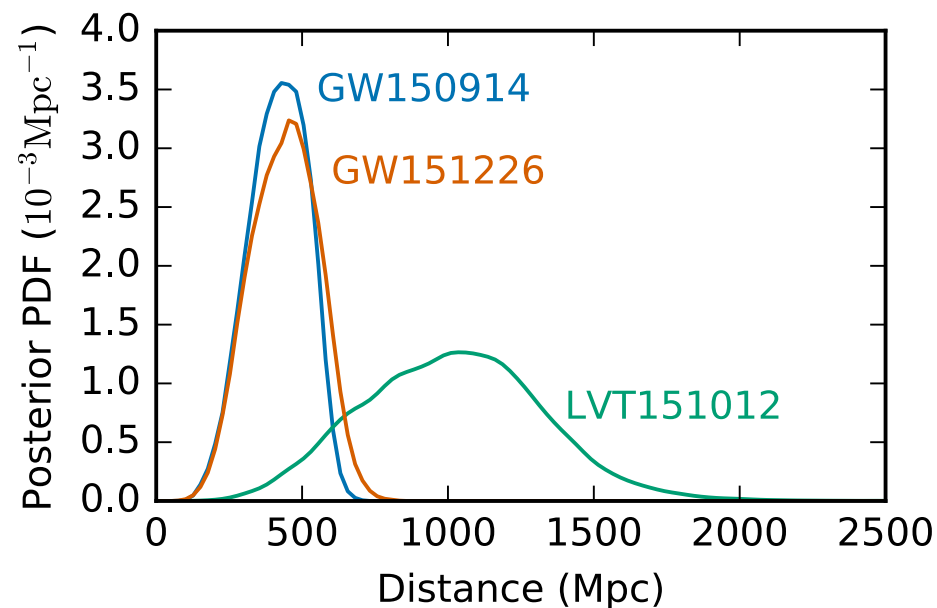
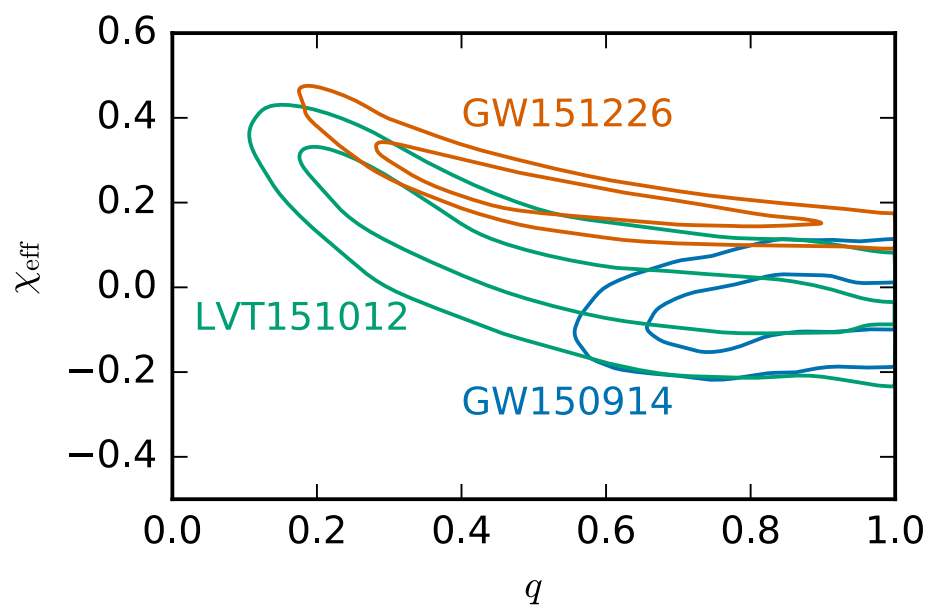
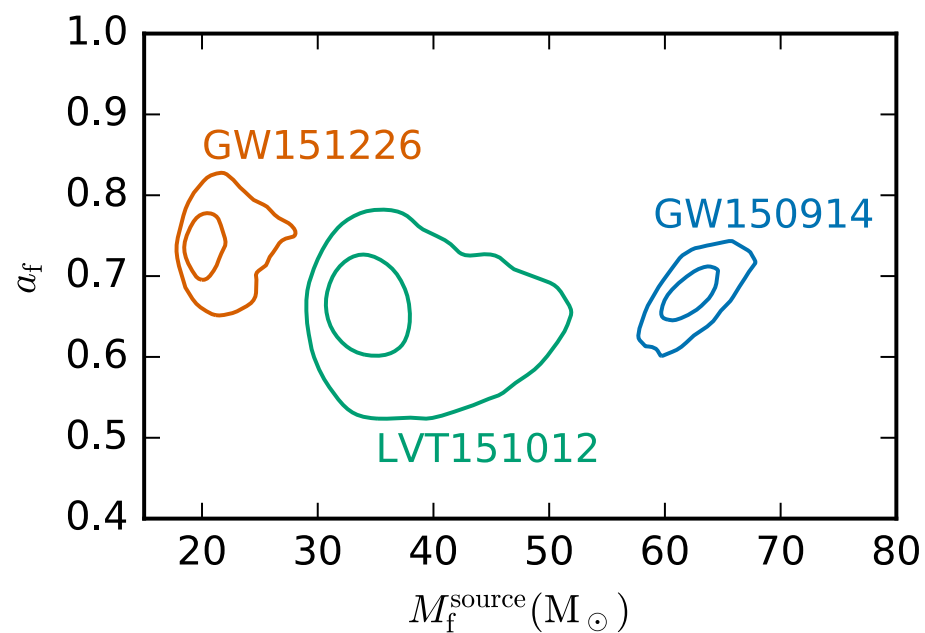
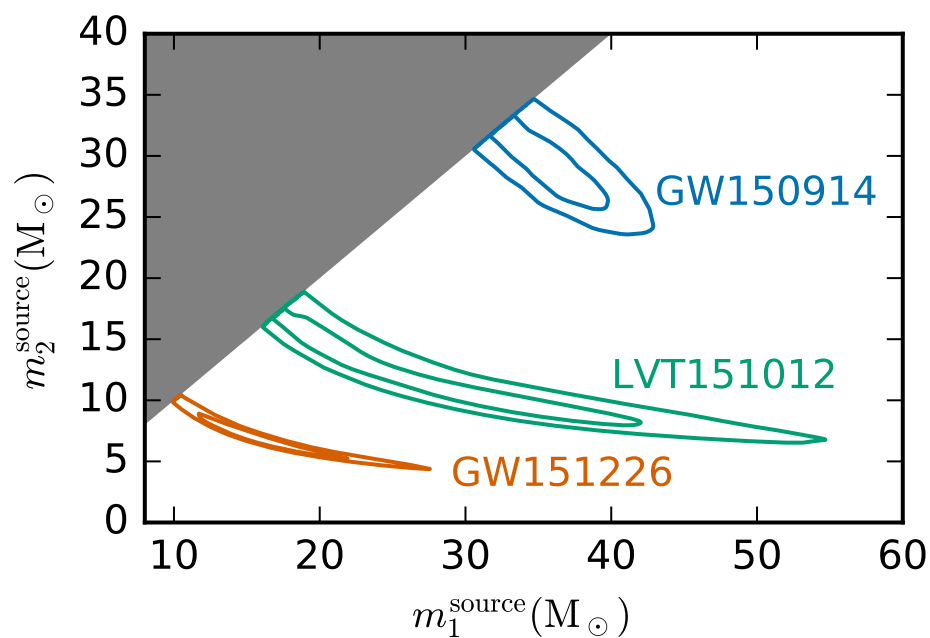
- 
- The background of the slide is a detailed simulation of a black hole merger. It shows two black holes in the process of coalescing, with glowing accretion disks and complex gravitational wave patterns represented by concentric, wavy lines in the surrounding space. The scene is filled with numerous stars of varying colors (white, yellow, orange) against a dark cosmic background.
- GW150914 was the first observation of gravitational waves
 - GW150914 was the first direct observation of a black hole
 - Prior to GW150914, the astrophysical consensus was that there should not be $\sim 30 M_{\odot}$ black holes – more on this later

Actually, three BBHs Observed in First Run...



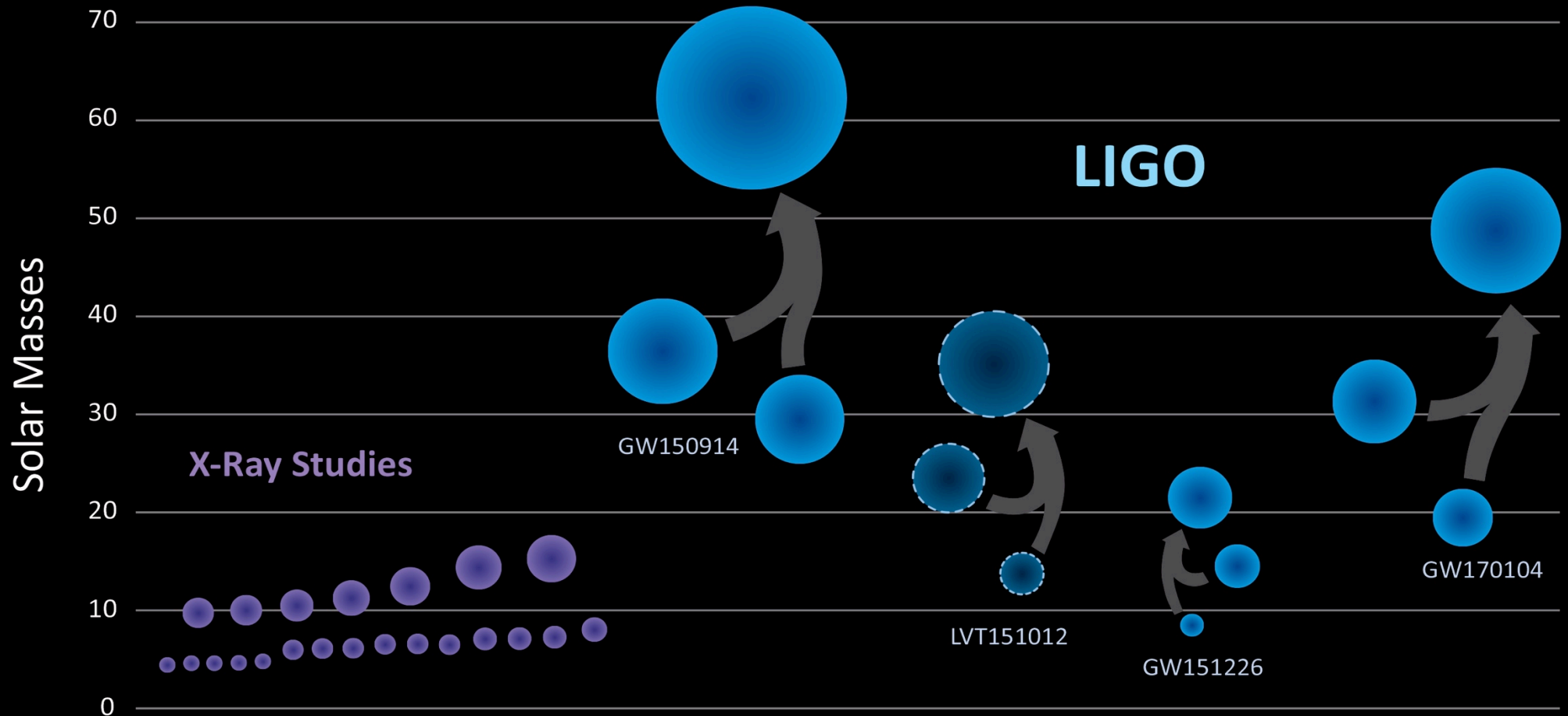
GW150914
LVT151012
GW151226





First event in O2: GW170104

Now we have 3.9 binary black hole mergers



[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

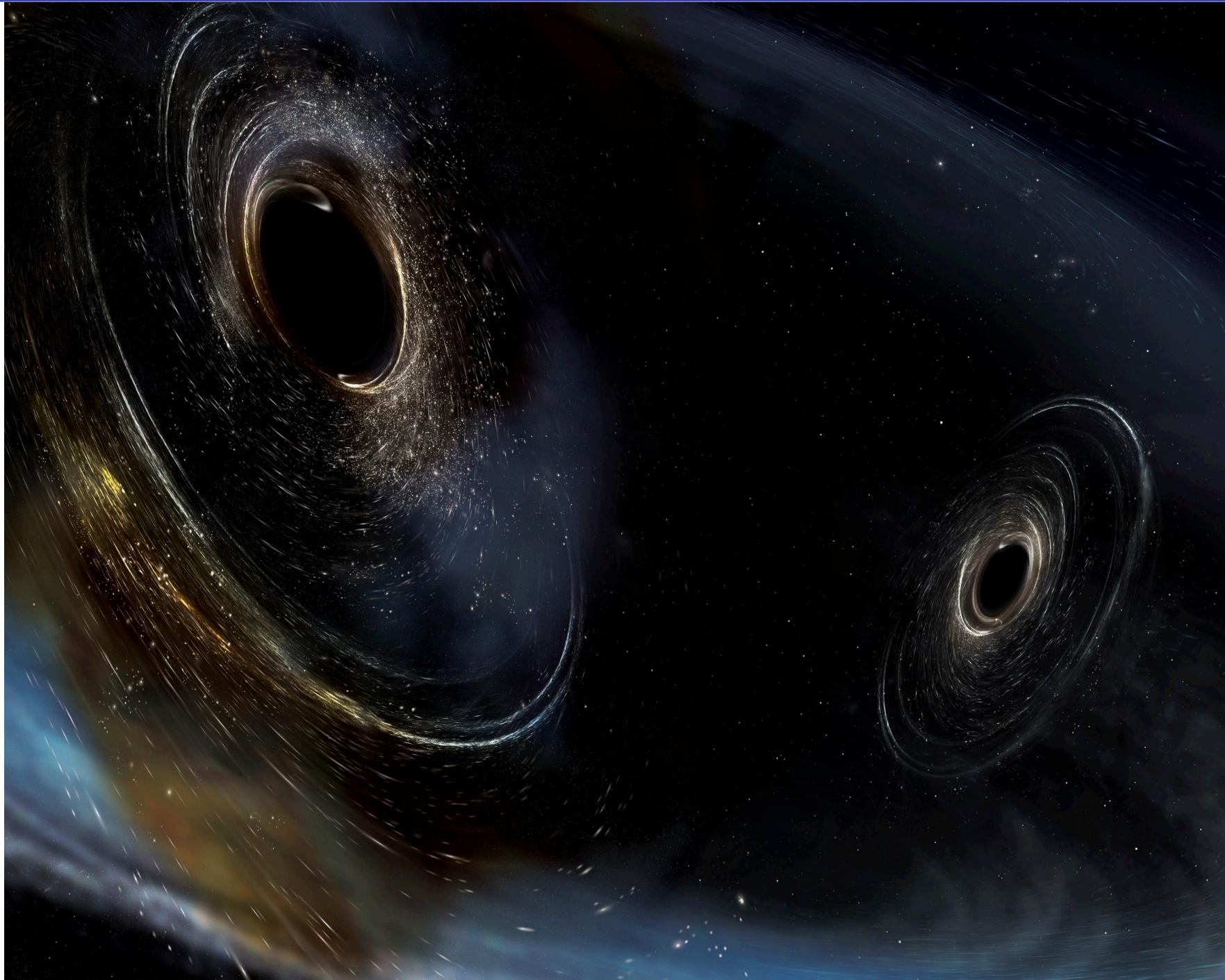
3 BILLION
LIGHT YEARS

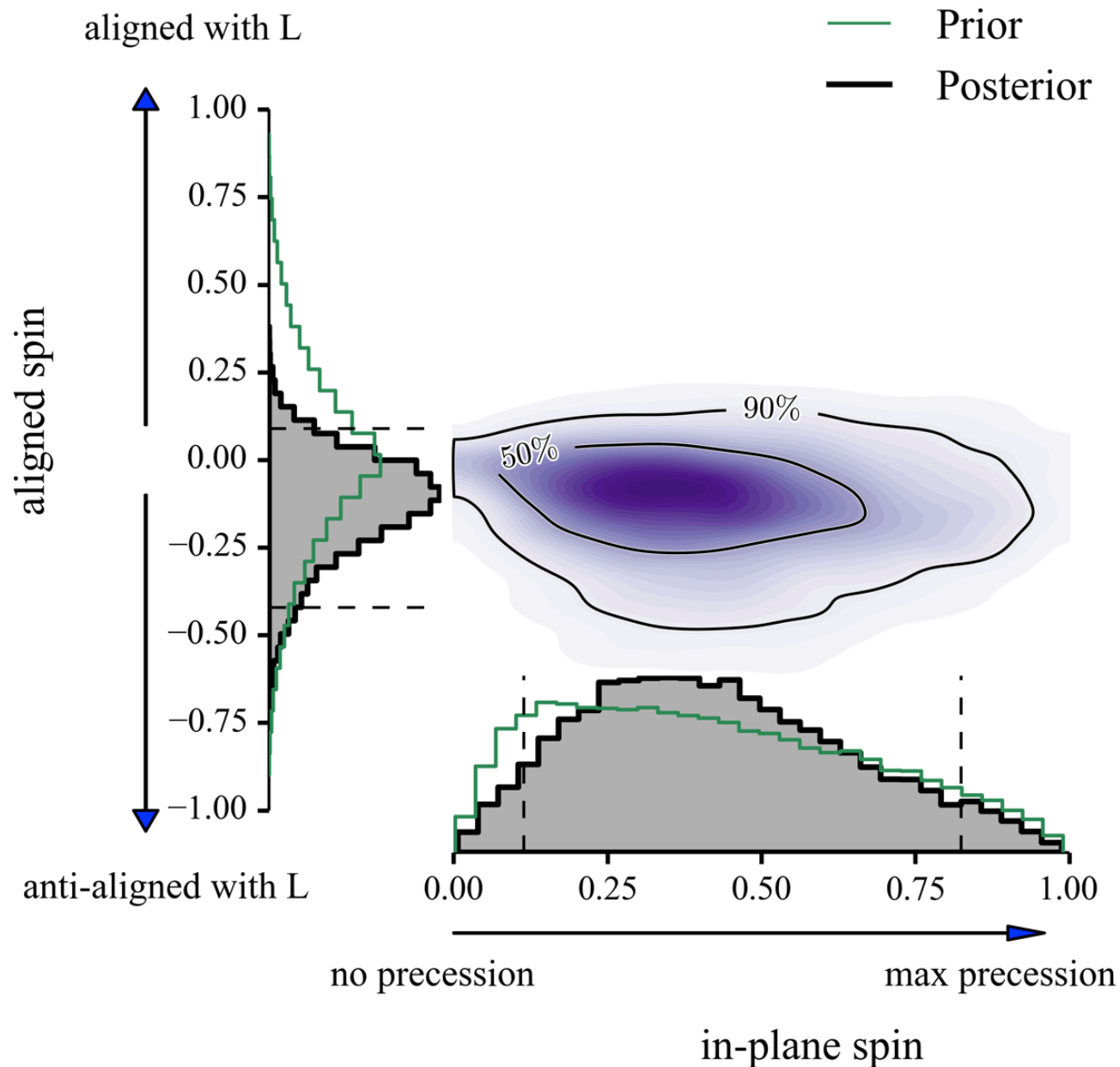
4 BILLION
LIGHT YEARS

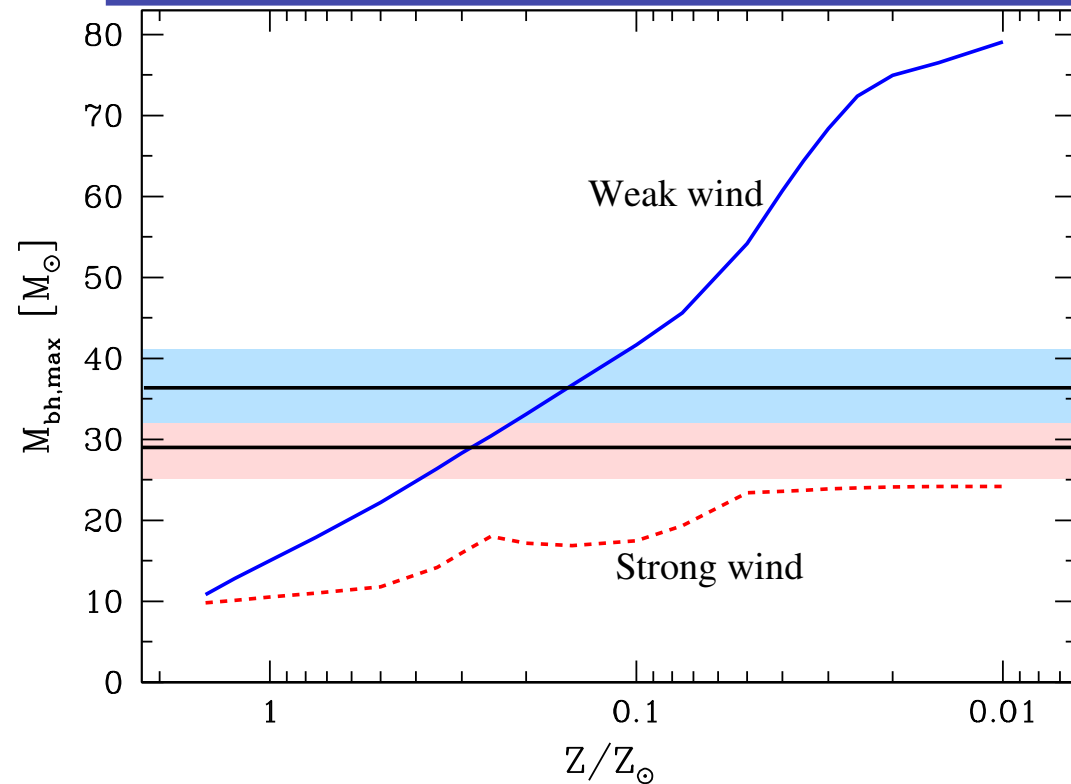
YOU ARE
HERE

DID YOU KNOW ?

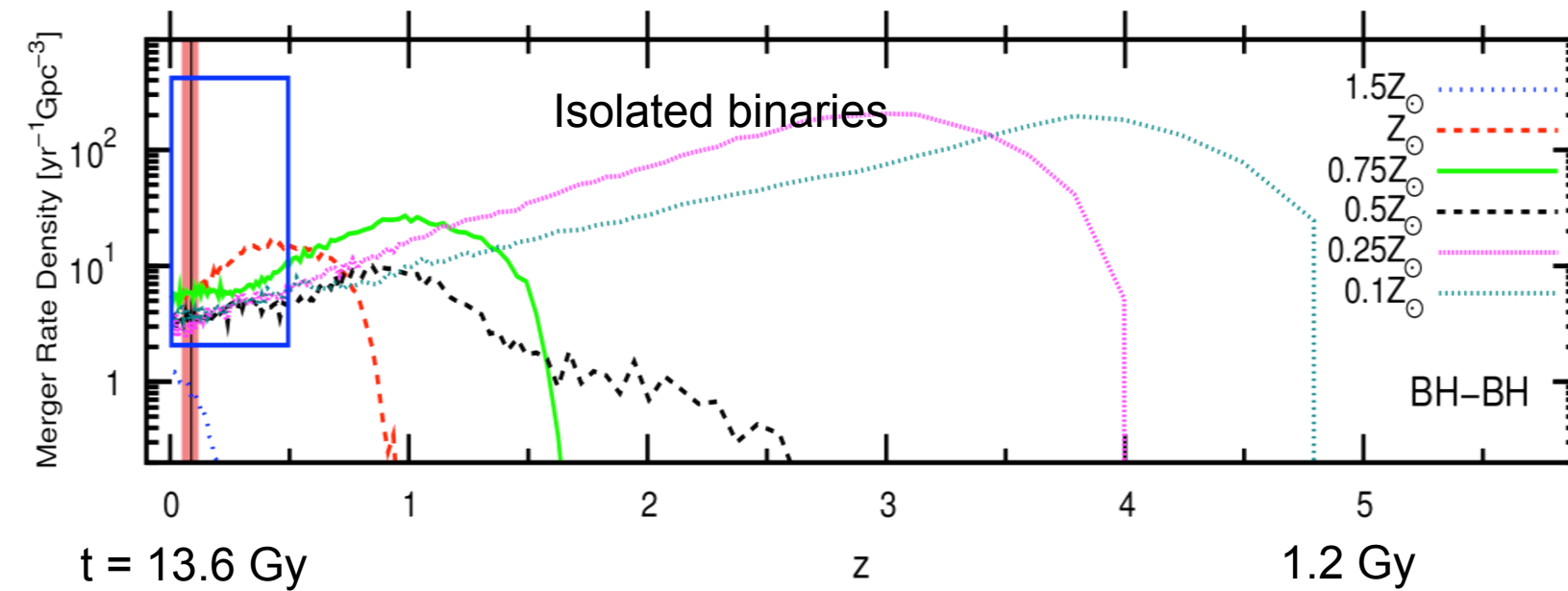
THE **SOLAR MASS** IS
A STANDARD UNIT OF MASS
IN ASTRONOMY
IT IS EQUAL TO
THE MASS OF THE SUN
EQUAL TO APPROXIMATELY
 1.99×10^{30} KG







- Implies low metallicity and weak winds; Pop III stars?
- Rate may require dynamical formation



The LIGO logo, consisting of several concentric circles of varying line thicknesses, creating a ripple effect.

An explanation for the observations which also explains other mysteries

O

BLACK HOLES

from the Beginning of Time

COSMOLOGY

A hidden population of black holes born less than one second after the big bang could solve the mystery of dark matter

By Juan García-Bellido and Sébastien Clesse

Illustration by Kevin Brown, Mandel White Studios

More than a billion years ago two black holes in the distant universe spiraled around each other in a deathly dance until they merged. This spiraling collision was so violent that it shook the fabric of spacetime, sending perturbations—gravitational waves—rippling outward through the cosmos at the speed of light. In September 2015, after traveling more than a billion light-years, those ripples washed over our planet, registering as a “chirp” in the sensors of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO).

This was the first direct detection of gravitational waves, and the observation confirmed Albert Einstein’s century-old prediction of their existence. Yet the chirp revealed that each of the merger’s progenitor black holes was 30 times heavier than the sun. That is, their masses were two to three times larger than ordinary black holes born from supernova explosions of massive stars. These black holes were so heavy, it is hard to explain how they formed from stars at all. Furthermore, even if two such black holes did independently form from the deaths of very massive stars, they would have then had to find each other and merge—an event with an exceedingly low

IN BRIEF

The nature of dark matter—the invisible material that holds galaxies together by its gravity—is a deep cosmic enigma. Many researchers suspect dark matter is made of weakly interacting massive particles and have been seeking them in experiments. But to date, no such “WIMPs” have been found. “Primordial” black holes that may have

formed shortly after the big bang are an alternative candidate for dark matter. Yet these, too, have so far eluded detection. More evidence for primordial black holes may emerge in new data from gravitational-wave detectors and other observatories. If confirmed to exist, these objects could solve the mystery of dark matter and several other cosmic conundrums.

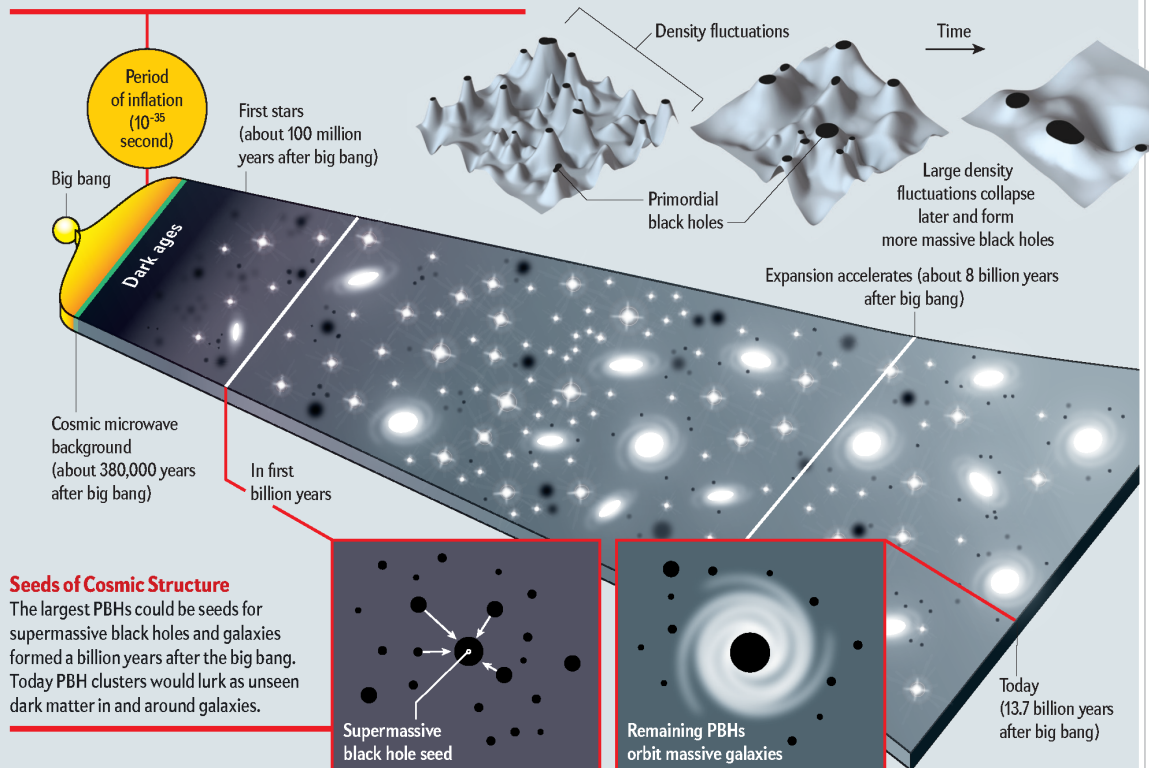
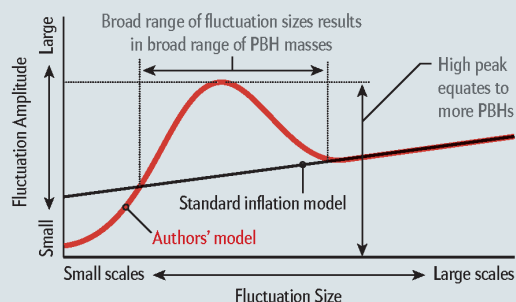
Black Holes Birthed by the Big Bang

The universe's first black holes may have been born in the earliest moments of cosmic time, when all was a seething, thick fog of fundamental particles. In the 1970s theorists realized that dense regions of that fog could collapse under their own gravity

just a second after the big bang, forming so-called primordial black holes (PBHs) that would then shape the structure of the evolving, expanding universe. Emitting no light, PBHs would be a natural—albeit difficult to detect—candidate for dark matter.

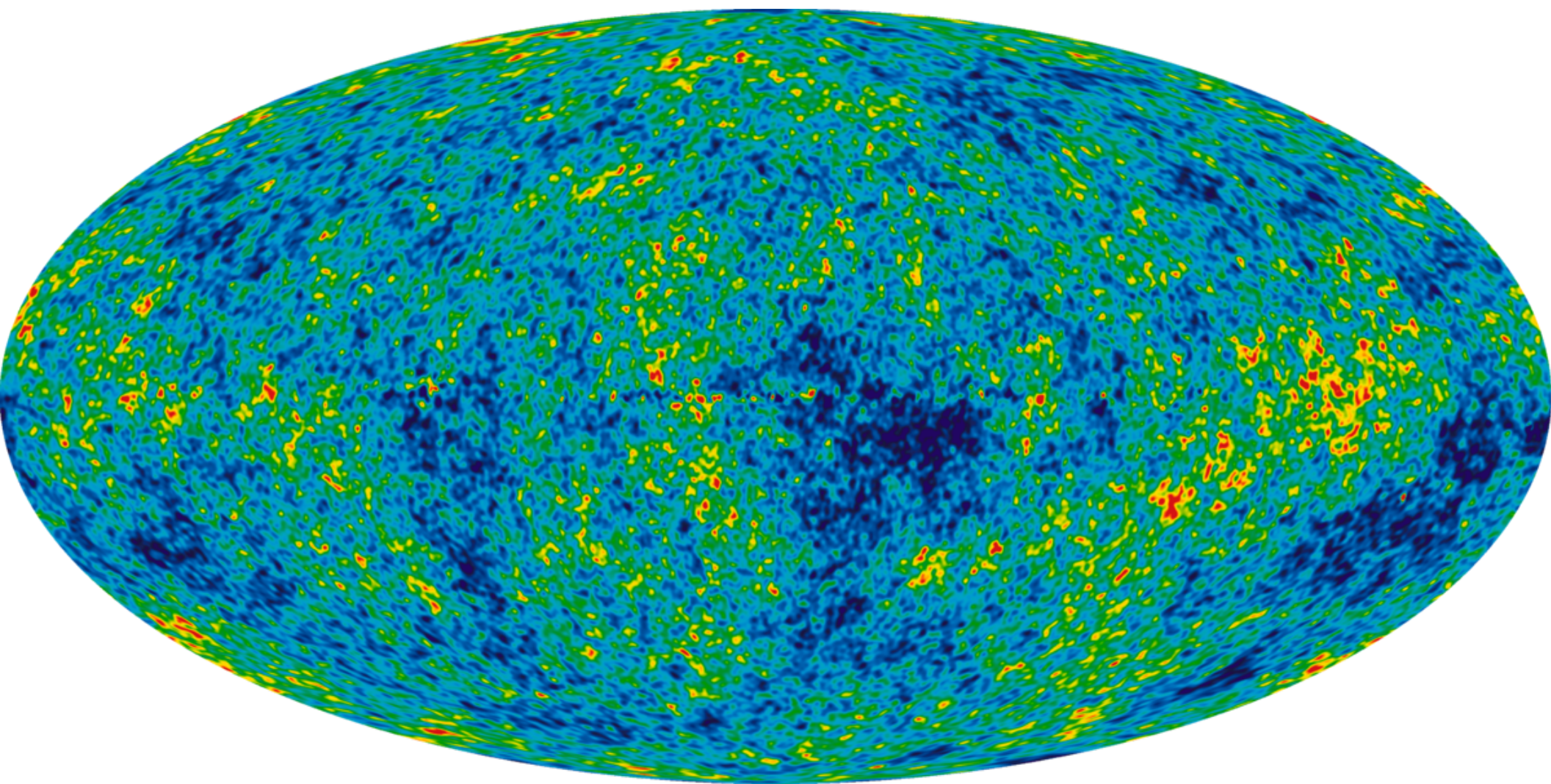
Primordial Black Holes Form in Clusters

Inflation—a proposed acceleration to the universe's expansion less than a second after the big bang—would form PBHs by magnifying quantum fluctuations to immense scales. As inflation ended, these fluctuations would create density perturbations that then form PBHs. Larger, more powerful fluctuations would create more massive and numerous PBHs. The authors' inflationary model predicts a broad peak of magnified fluctuations and a range of density perturbations, producing PBHs in clusters, with each PBH ranging from one 100th to 10,000 times the mass of our sun. Half a million years after the big bang, a cluster might span hundreds of light-years and contain millions of PBHs. As the PBHs within such clusters merged together, scattered apart, and fed on ordinary gas and dust, they would guide the growth of galaxies and galactic clusters.

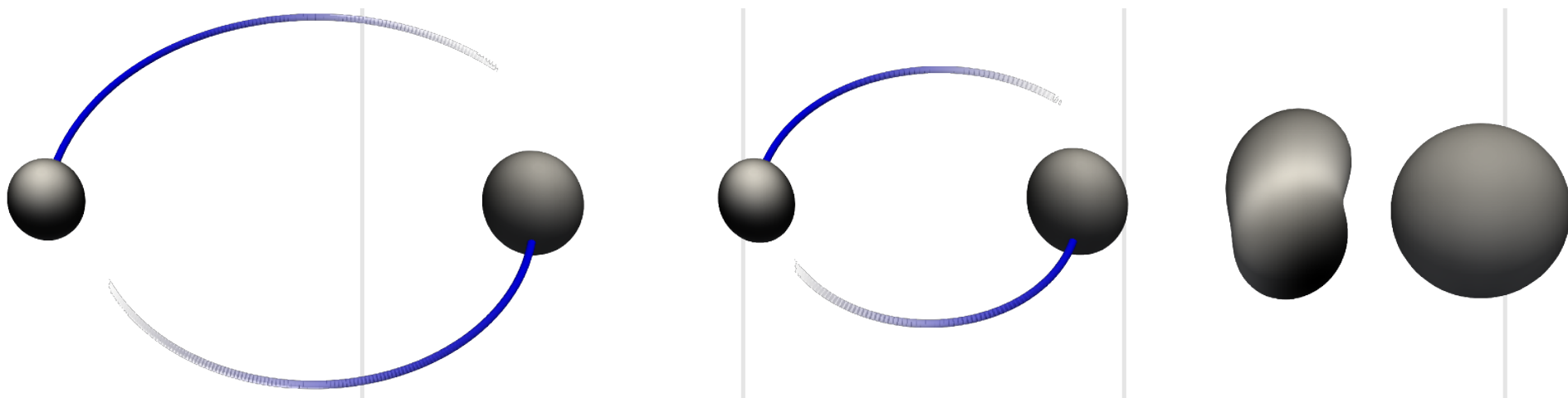


- Conjectured by Hawking in the 1970s
- Quantum fluctuations amplified by inflation
- Black hole masses from 1% of solar mass to 10,000 times solar mass
- Could explain:
- Dark matter
- LIGO enhanced rate of black holes
- Lack of dwarf galaxies
- Supermassive black holes

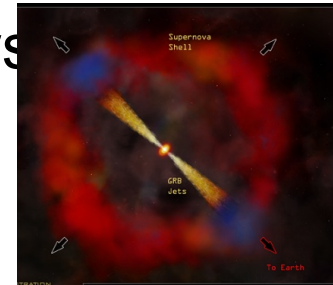
$t = 300,000 \text{ y}$



- Short Answer: “Yes”
- Longer Answer:
 - The ~3 months of run O1 yielded 3 BBH events.
 - For O1, LIGO was at ~30% of its design sensitivity
 - Expect improved sensitivity for O2, O3, ... until 100% reached 2019-ish
 - O2 in progress – started Nov 2016
 - At design: 1 event/month $\rightarrow$ 1 event/day



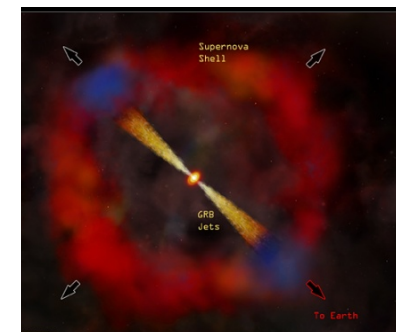
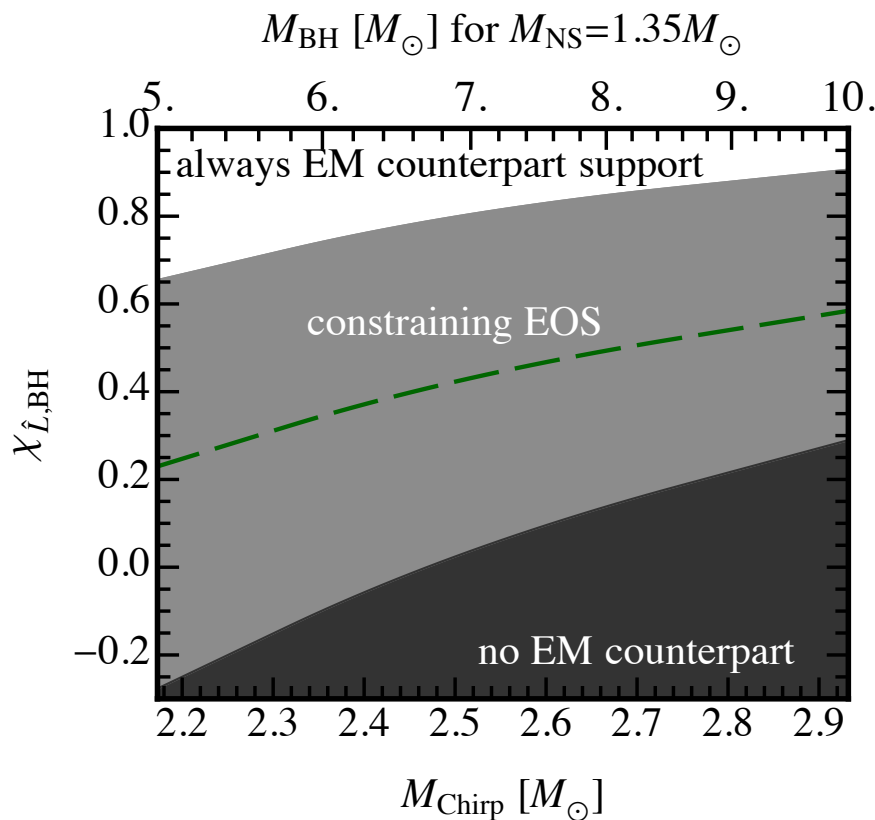
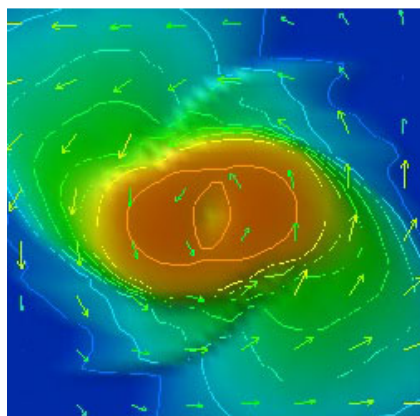
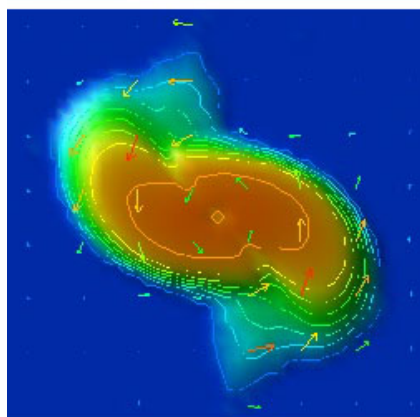
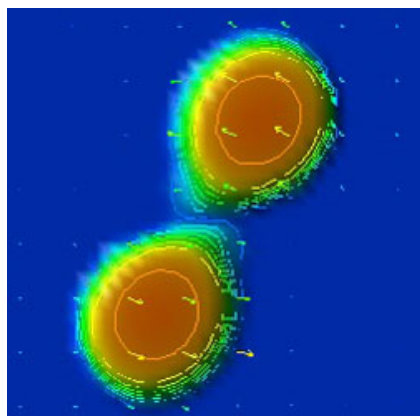
- population of BBH events; systems with hundreds of solar mass?
- stellar formation and evolution; cosmology
- Primordial black holes?
- GWs from NS-BH or NS-NS binary mergers
- associated with gamma-ray bursts (GRBs), EM afterglows
- cosmology (Hubble), neutron star EOS, ...
- GWs from stellar collapse
- associated with Long GRBs, supernovae, afterglows, neutrinos
- GWs from (galactic) single neutron stars: magnetar x-ray flares, pulsars
- GWs from inflation, cosmic strings, ??



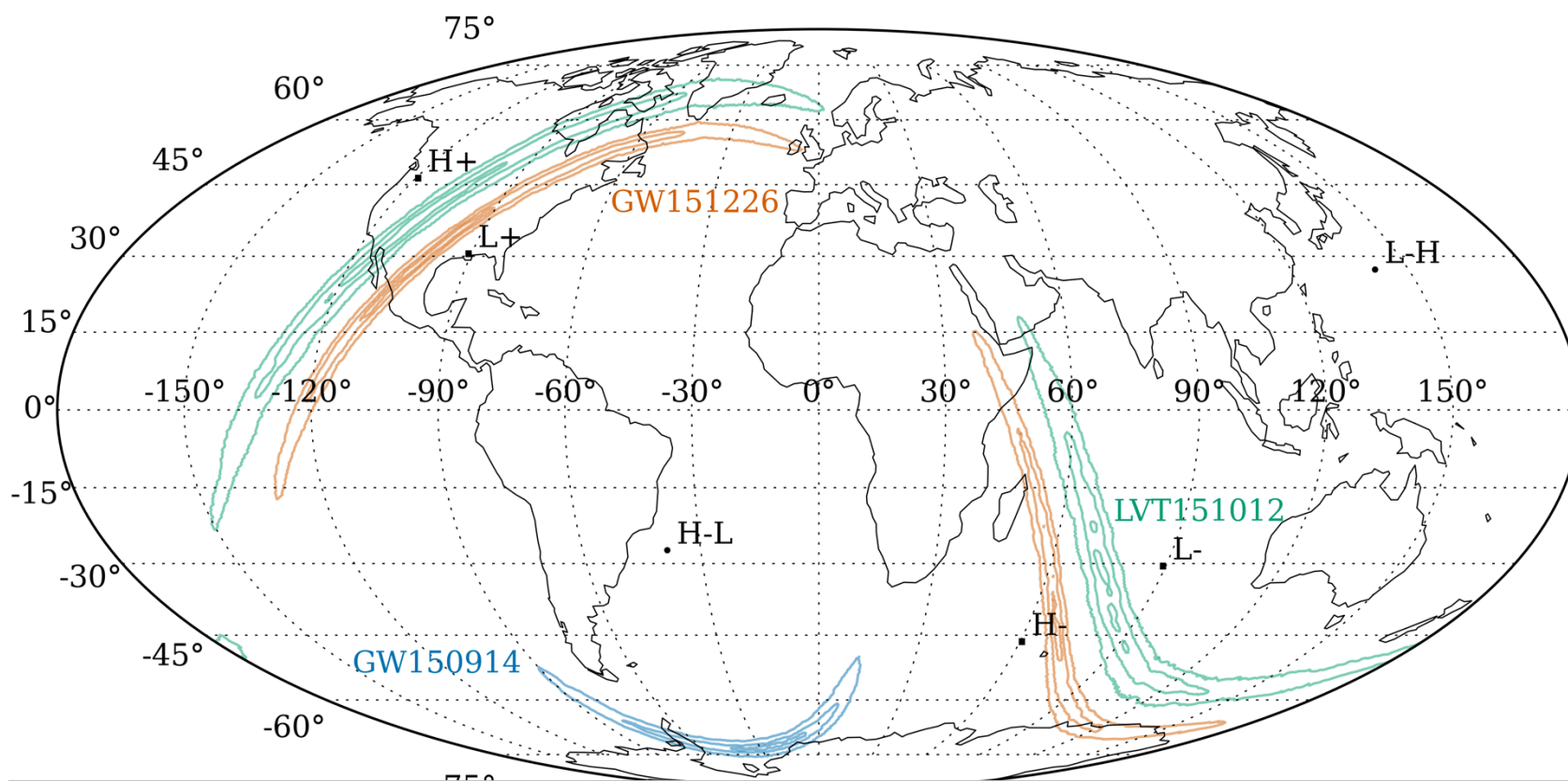
NS-NS mergers, NS equation of state, EM afterglows (kilonova), R-process elements

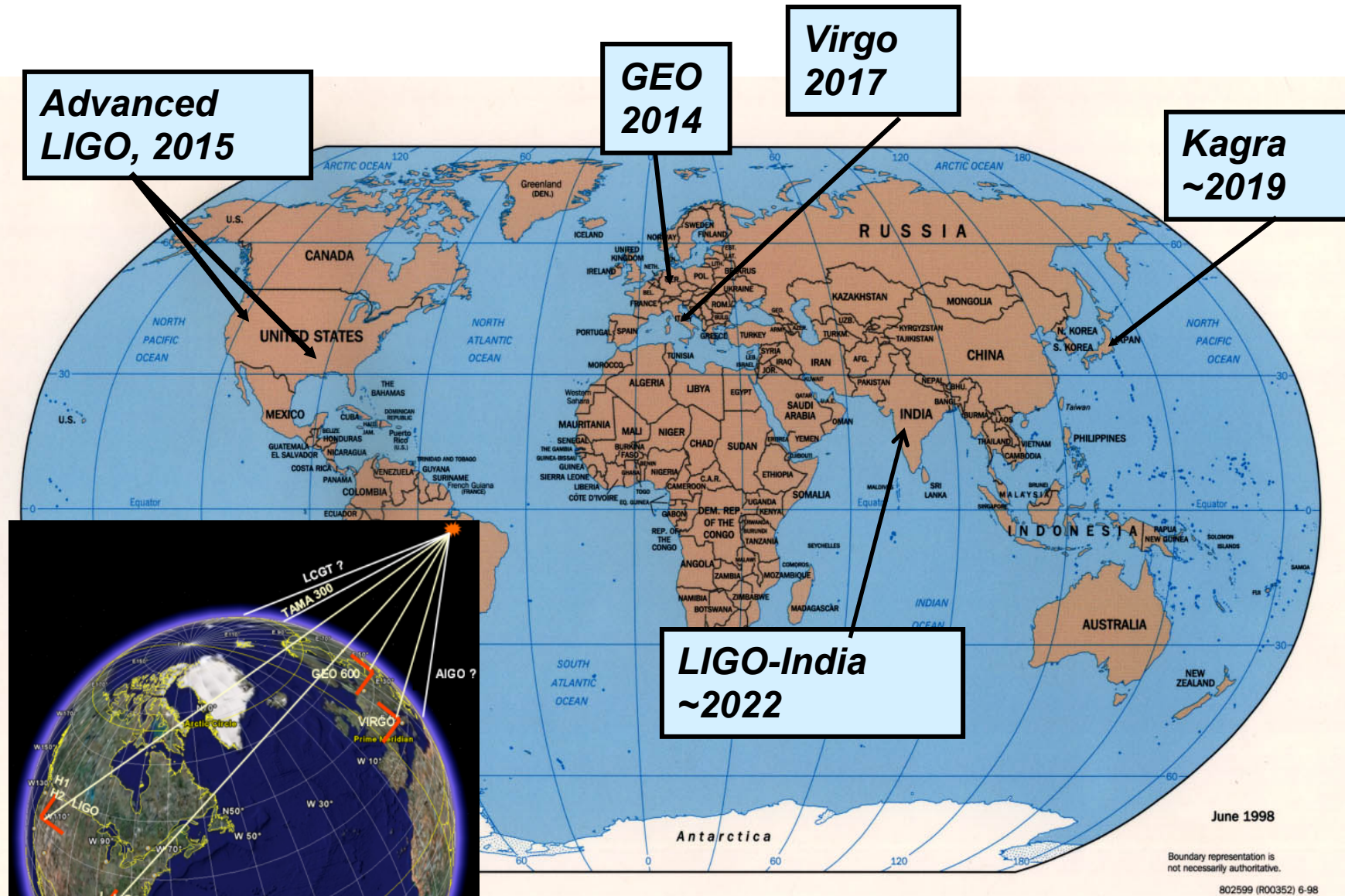


Shibata



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra																
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	



The 2nd generation GW detector network

3 or more detectors: localization from
~100 square degrees to ~10 sq degrees

- Gravitational Waves discovered!
- General Relativity (still) looks good.
- A lot of science from the first few events
- The (really) exciting part:
A new window on the Universe...
The fun is just beginning!

