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LIGO and the Detection of Gravitational Waves

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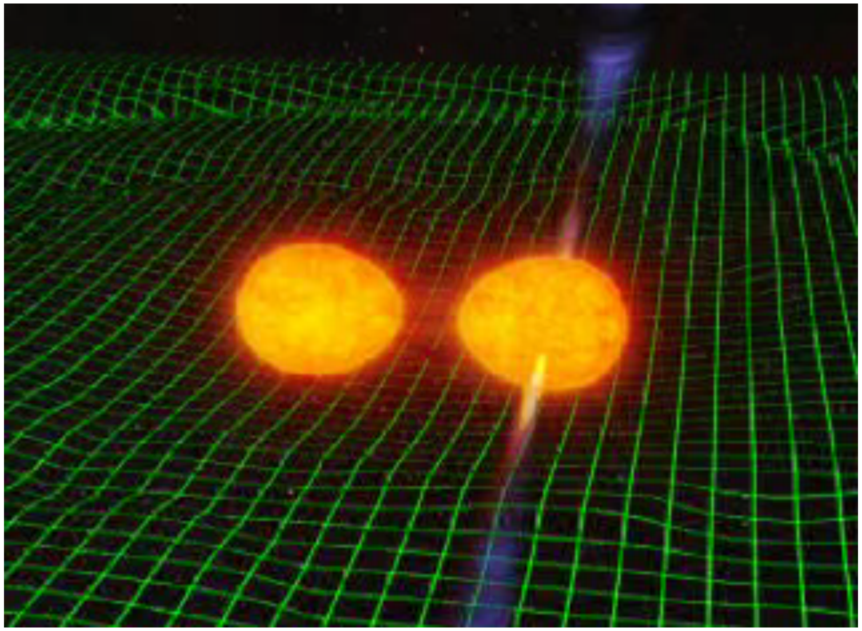
LIGO Livingston Observatory

on behalf of the

LIGO Scientific Collaboration

Gravitational Waves (GWs)

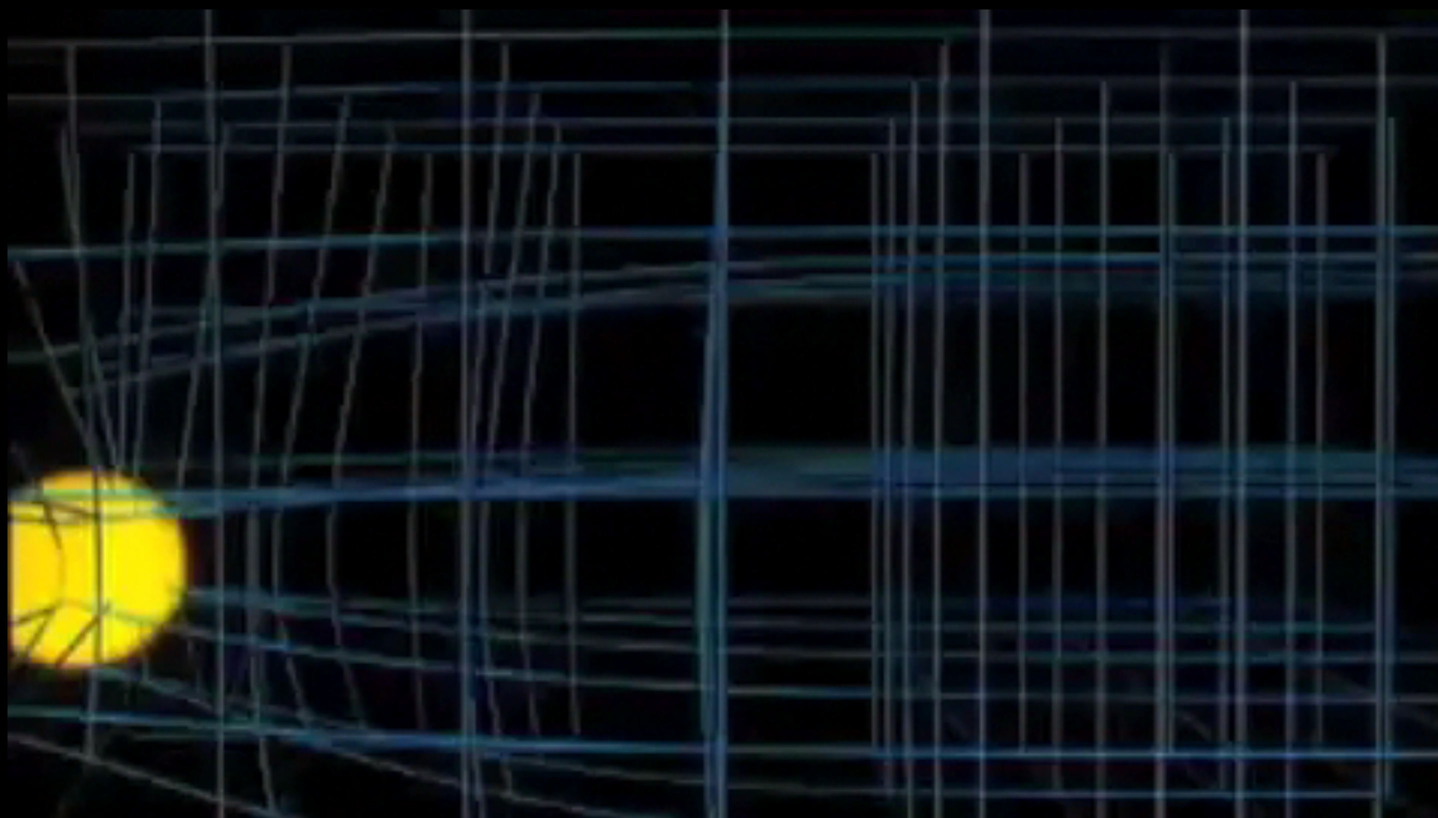
- Ripples on space-time
  - » A propagating change in the gravitational field
- Every mass acceleration creates a gravitational wave
  - » Much like an acceleration of charge creates an EM wave



- Only extremely massive, energetic events will produce detectable gravitational waves
  - » The Big Bang, supernovae, compact binary merger, etc.

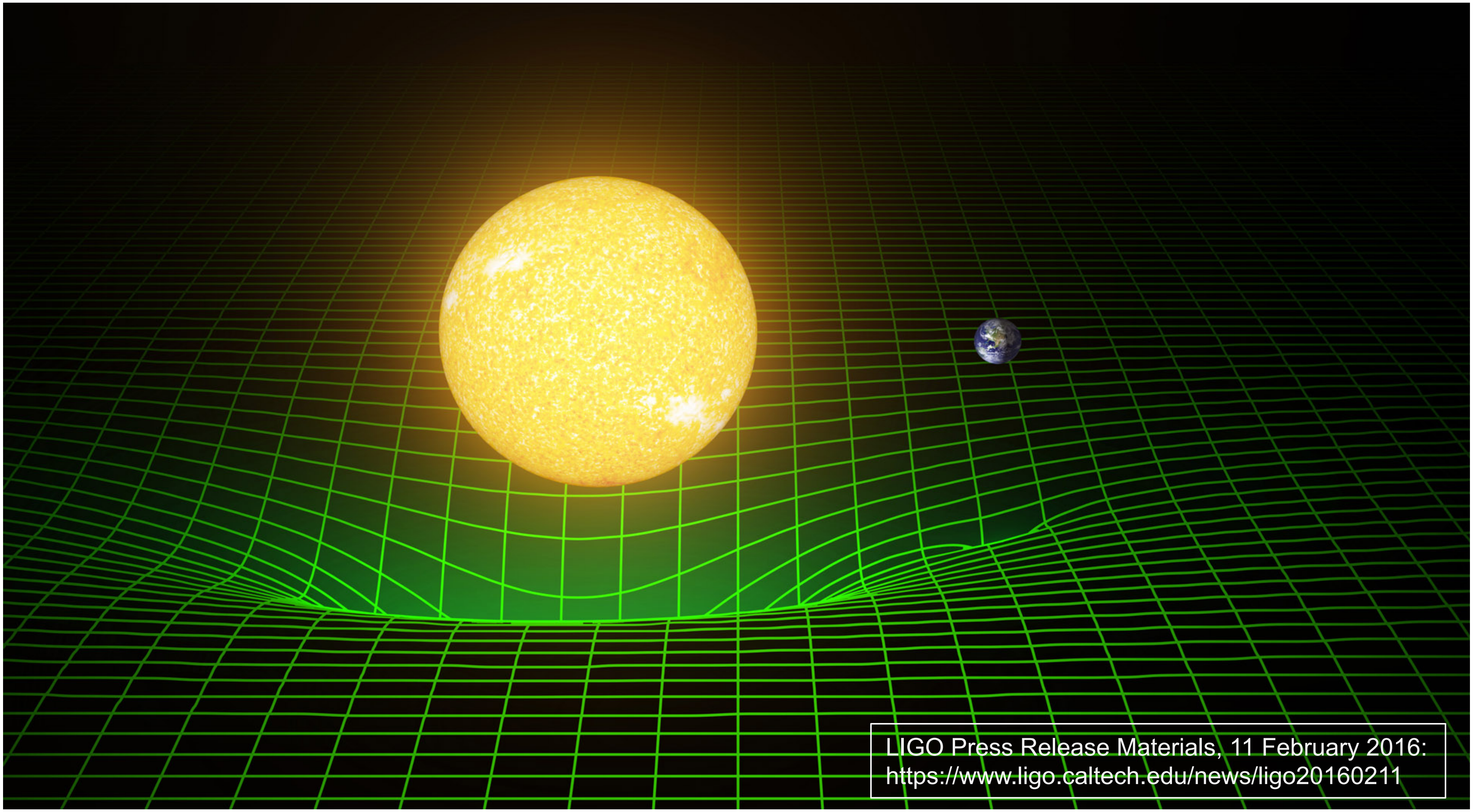
Video from: Jodrell Bank Observatory, 2003

The Effect of Mass on Space-Time



From: AMNH Bulletin, *Making Waves*

Sun/Earth Spacetime



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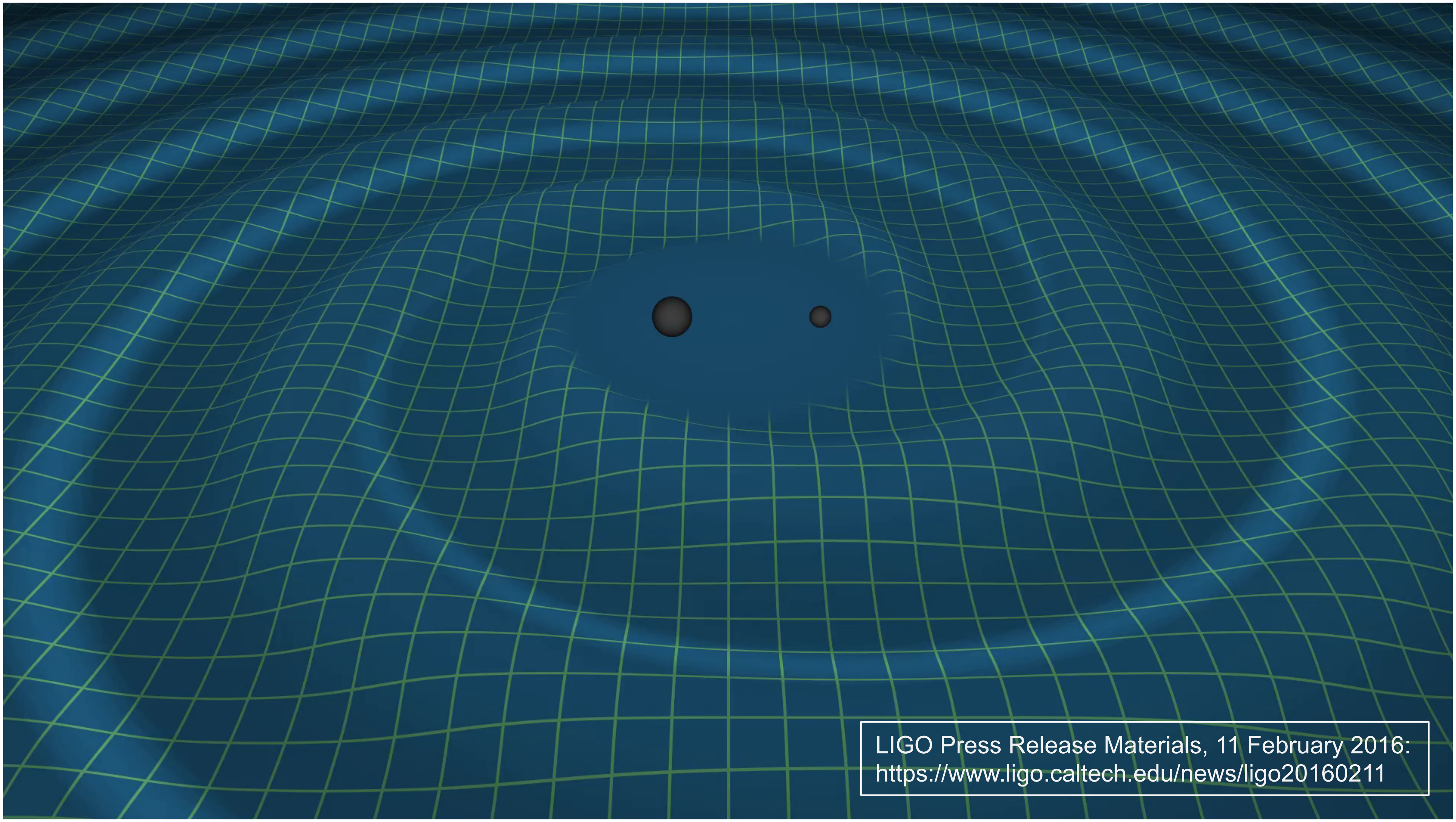
Gravitational Waves Are Ripples on Space-Time



LIGO Press Release Materials, 11 February 2016:
https://www.ligo.caltech.edu/news/ligo20160211

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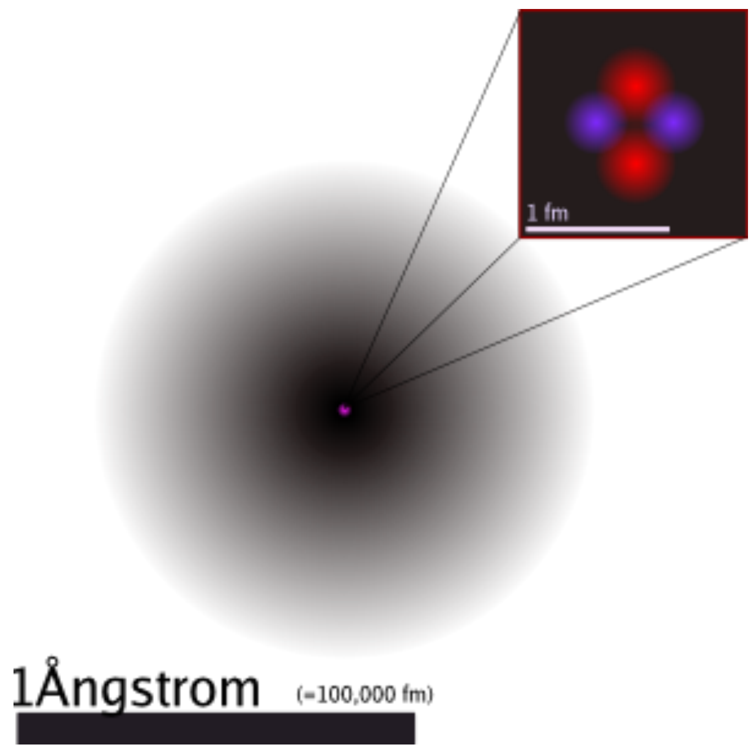
How Big Are Gravitational Waves?

A ‘strong’ gravitational wave is about 1000x smaller than the diameter of a proton.

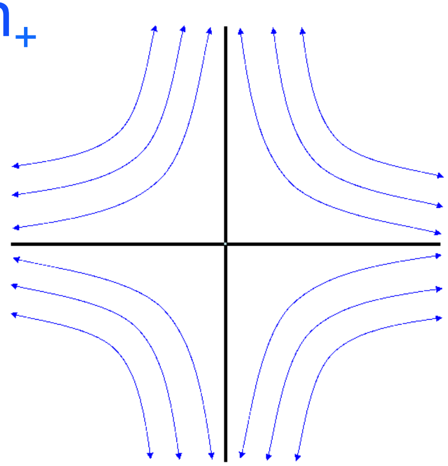
$$10^{-18}\ \mathrm{m} = 0.000000000000000001\ \mathrm{m}$$



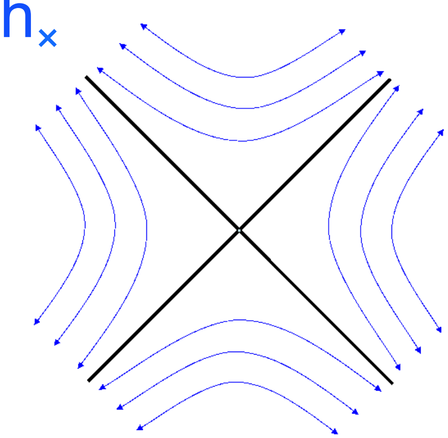
How GWs Affect Space

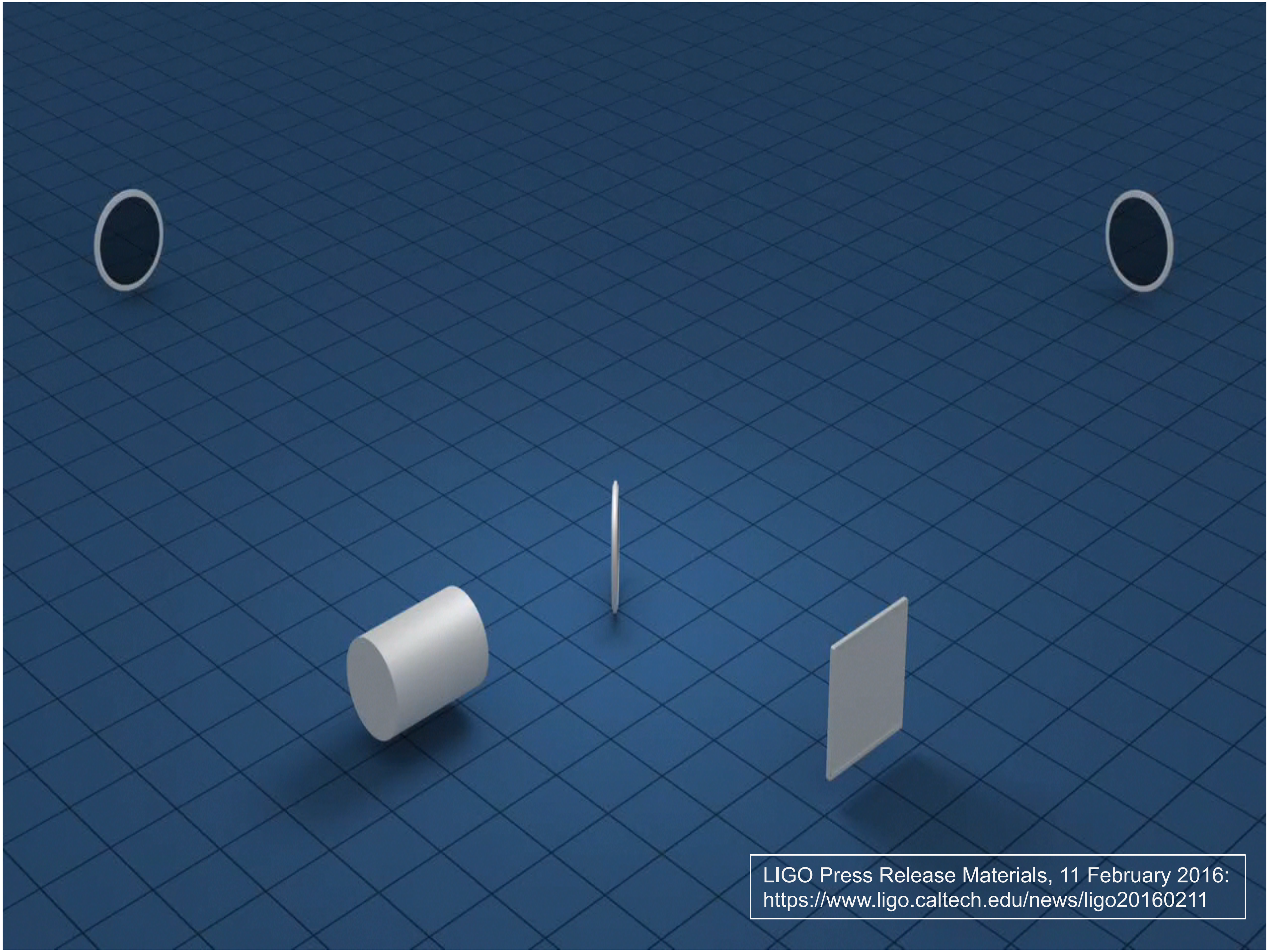
- Since gravity is a tidal force, it will locally compress space in one direction and expand in the orthogonal direction.
- This produces transverse GWs with 2 polarizations:

h_+



$h_\times$





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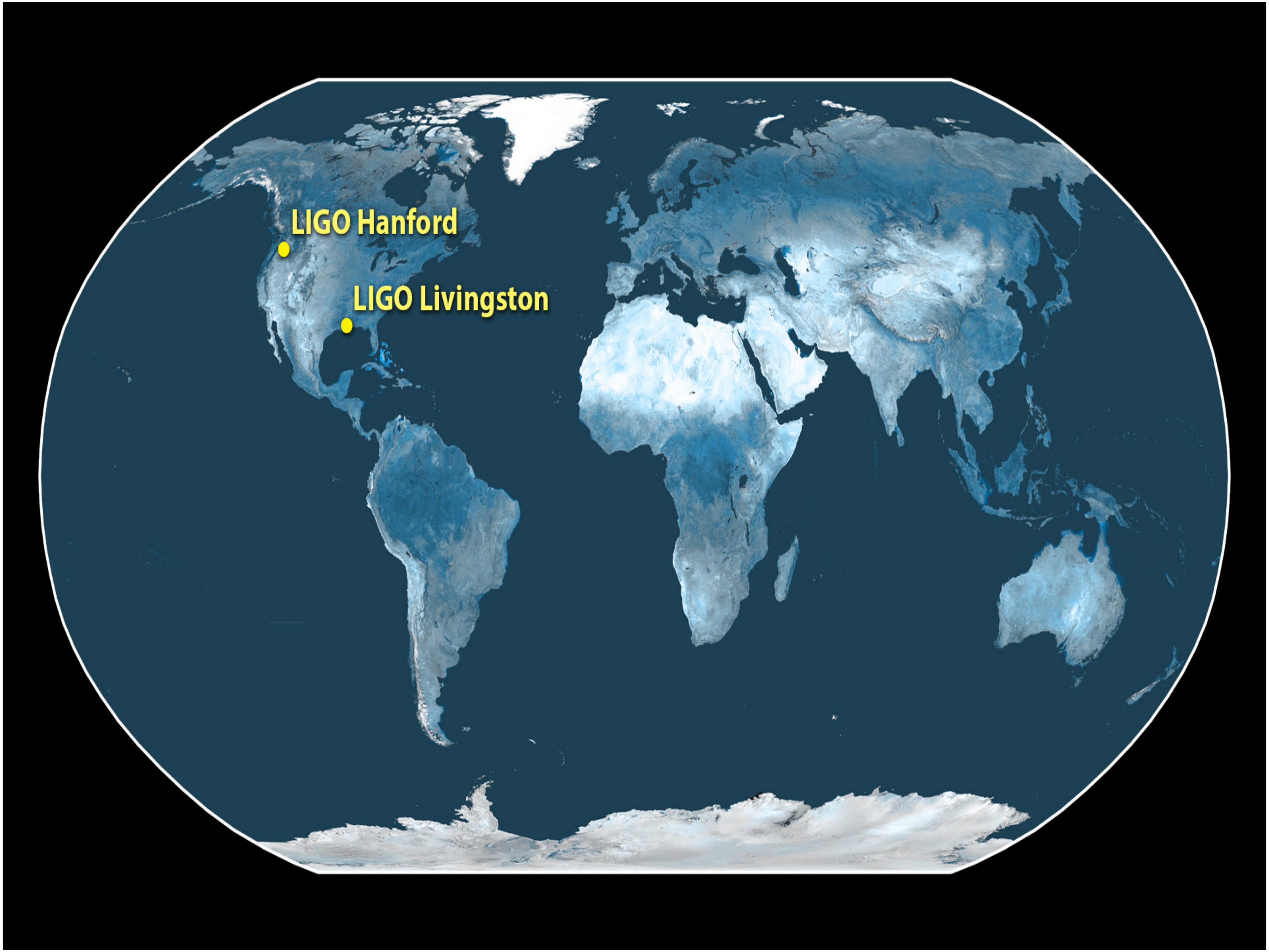
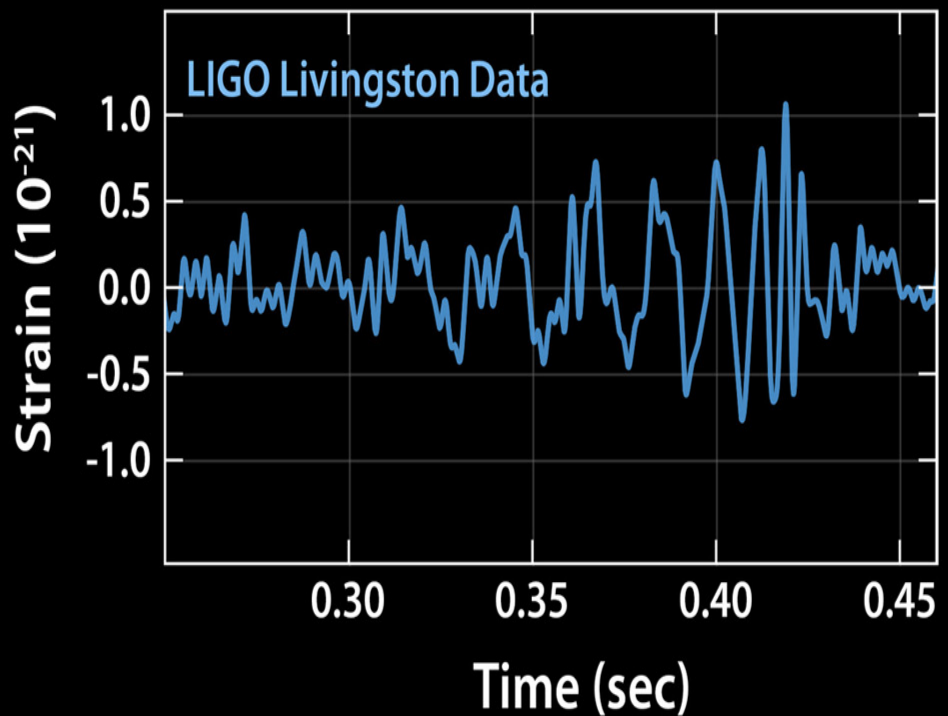

LIGO Hanford
LIGO Livingston

GWs and Astronomy

- A gravitational wave is produced by the bulk motion of mass and will therefore bring us information relating directly to this.
  - » This is something that EM observations rarely do.
  - » This will also allow us to observe objects that do not produce EM radiation.
- Since the universe is essentially transparent to GW, nothing can block a GW from reaching Earth.
- GW will allow us to see farther back into the history of our universe (to 10^{-35} sec) than the CMB can (300,000 years after the Big Bang).

First Detection:
Stellar Mass Binary BH Merger



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. **116**, 061102

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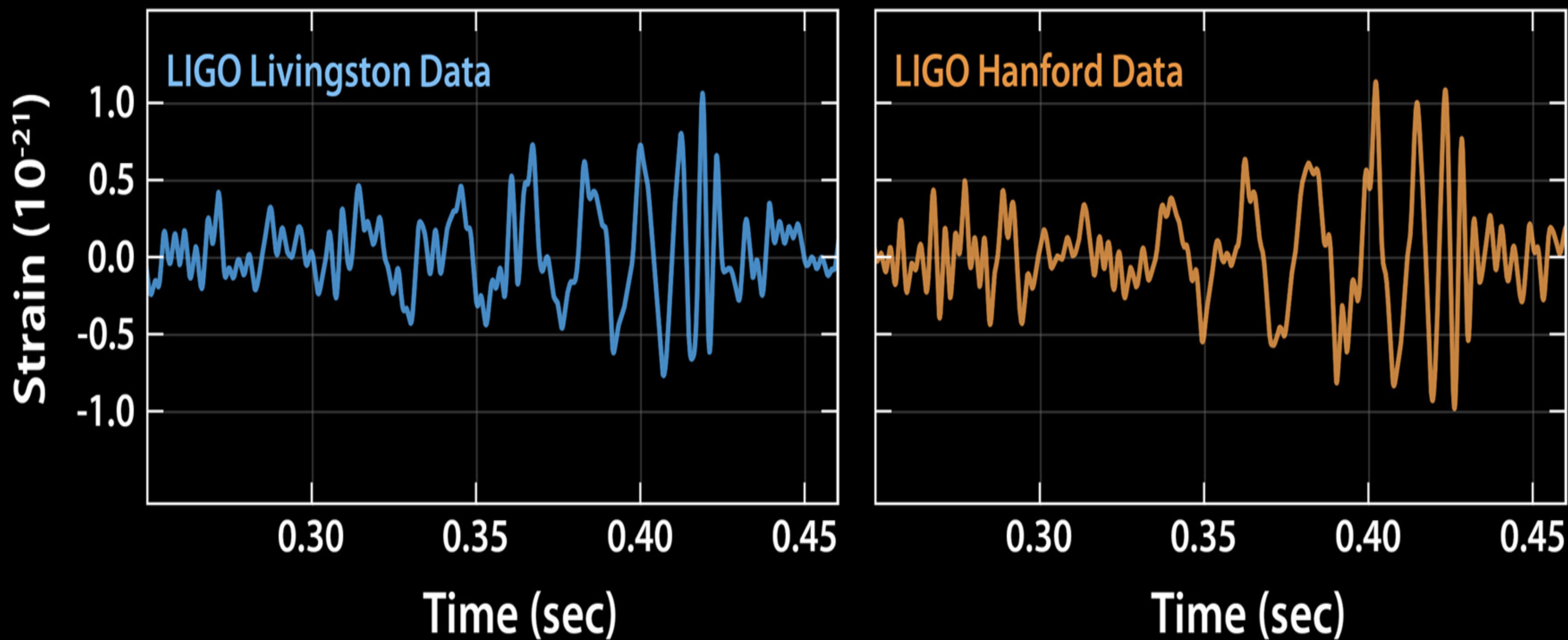

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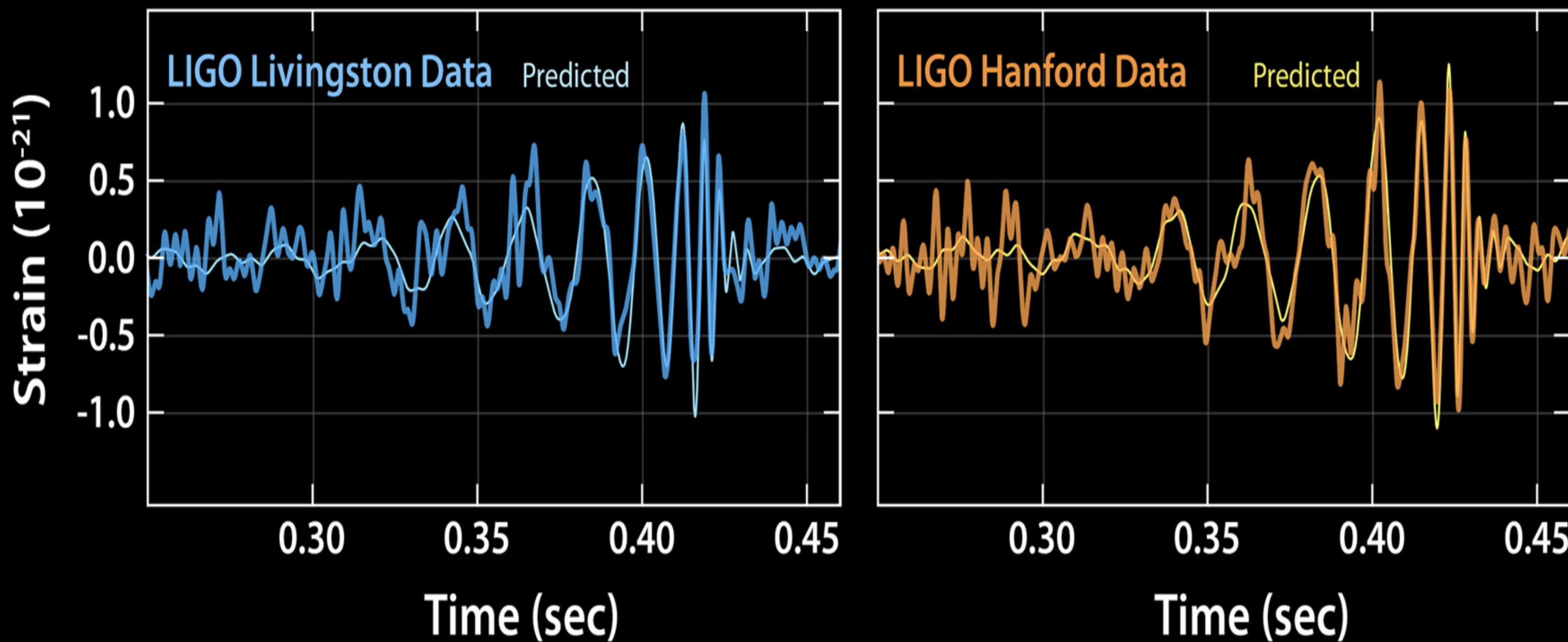

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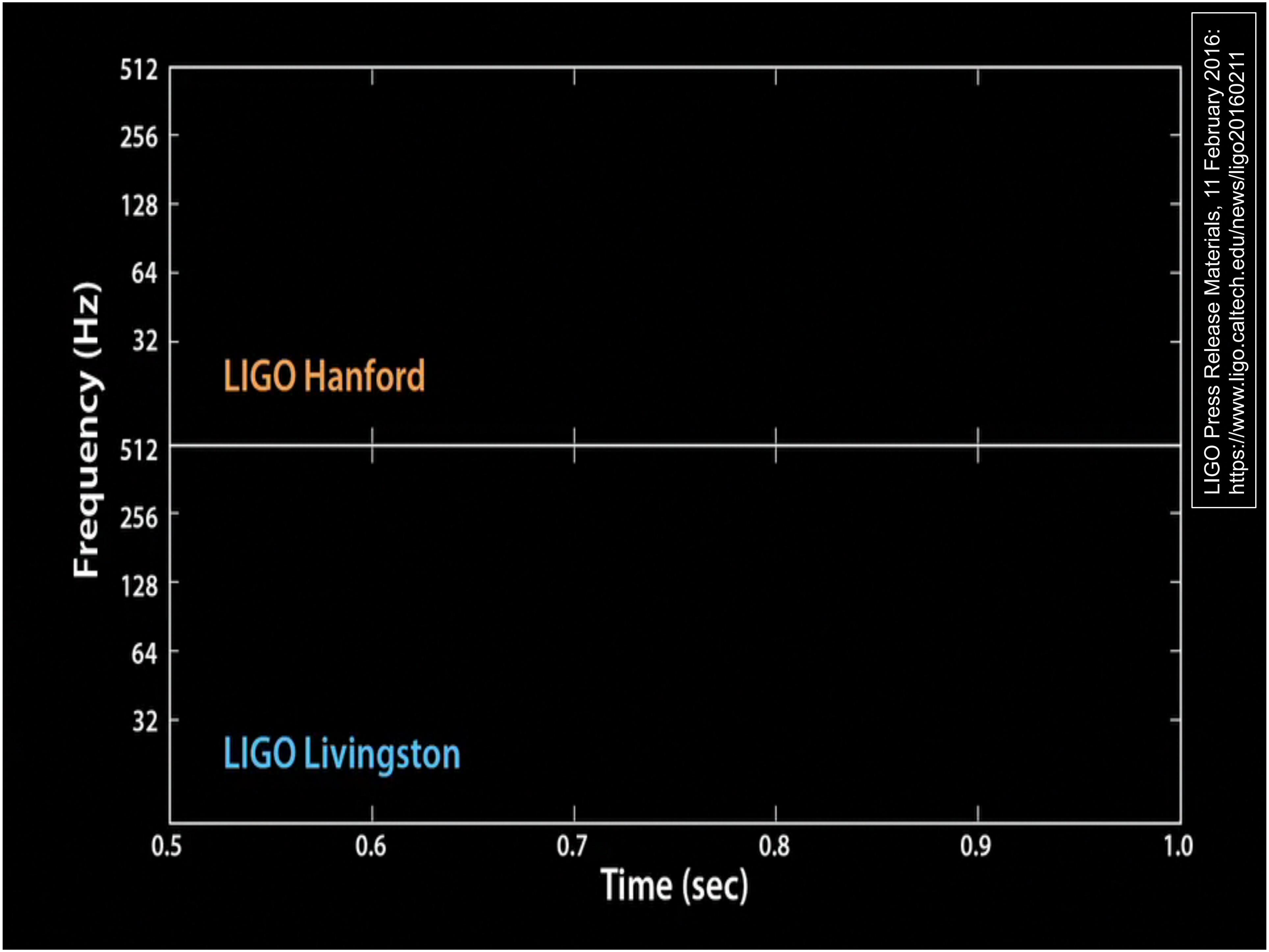
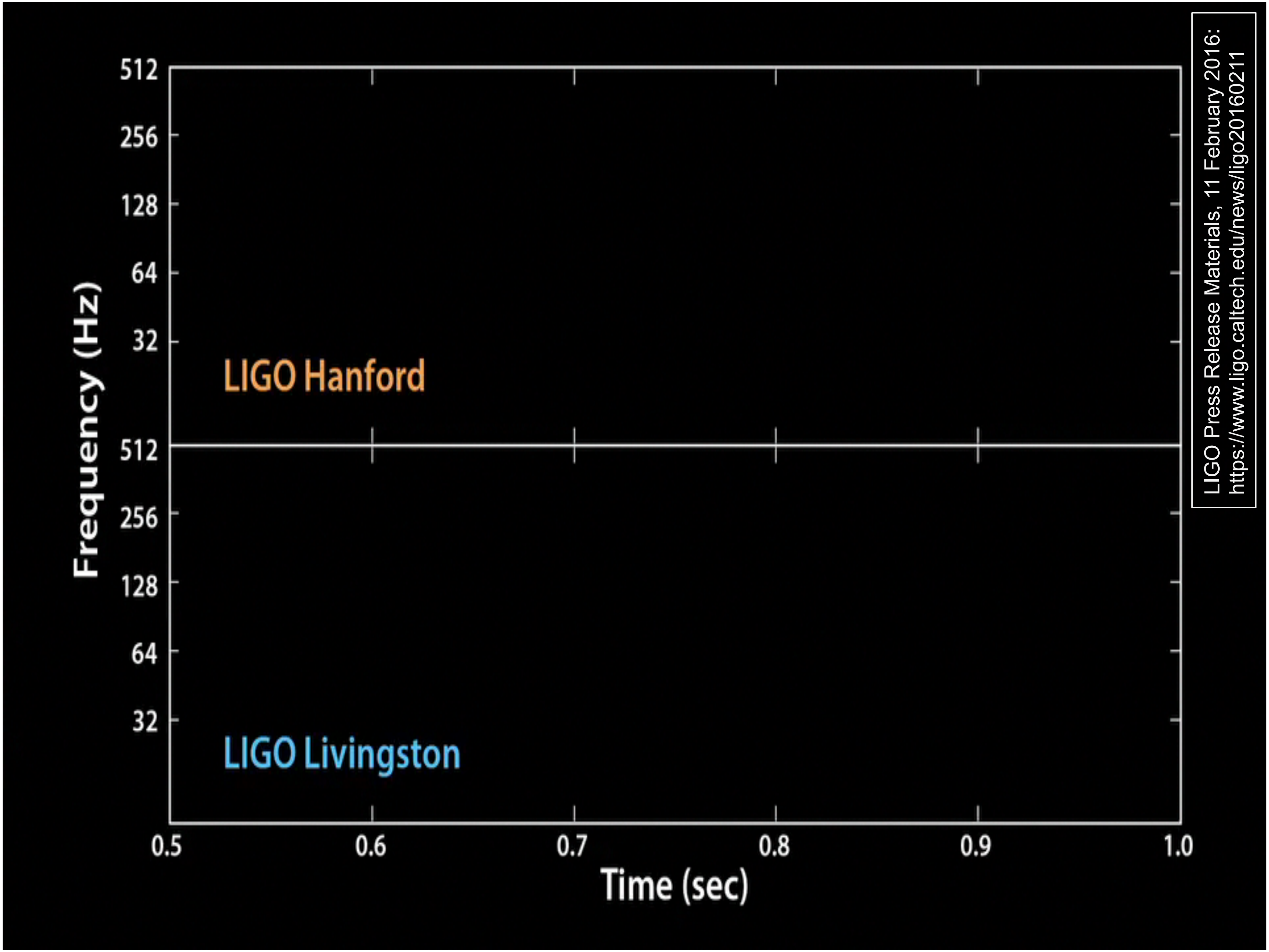

Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)
LIGO Press Release Materials, 11 February 2016:
https://www.ligo.caltech.edu/news/ligo20160211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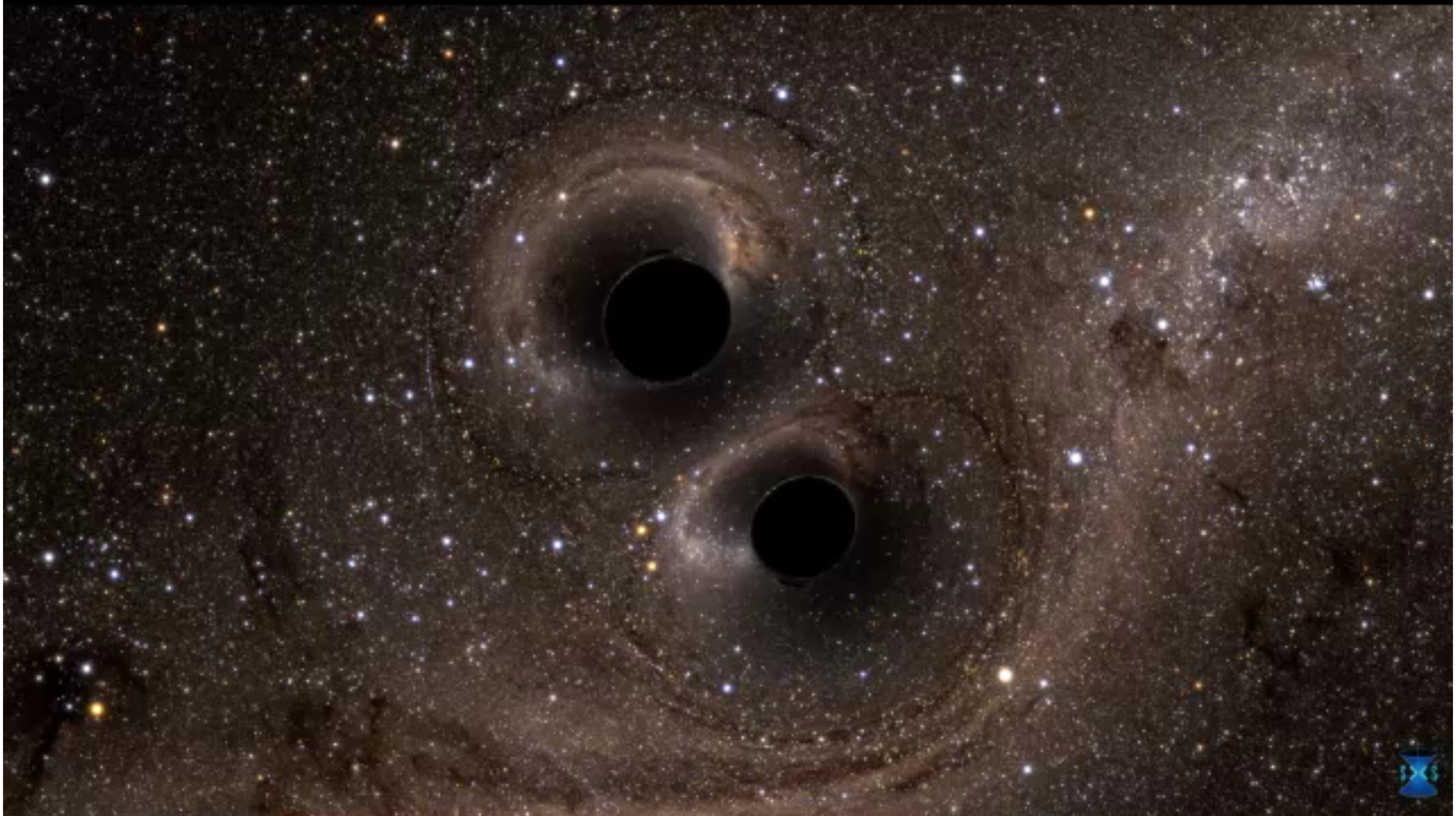

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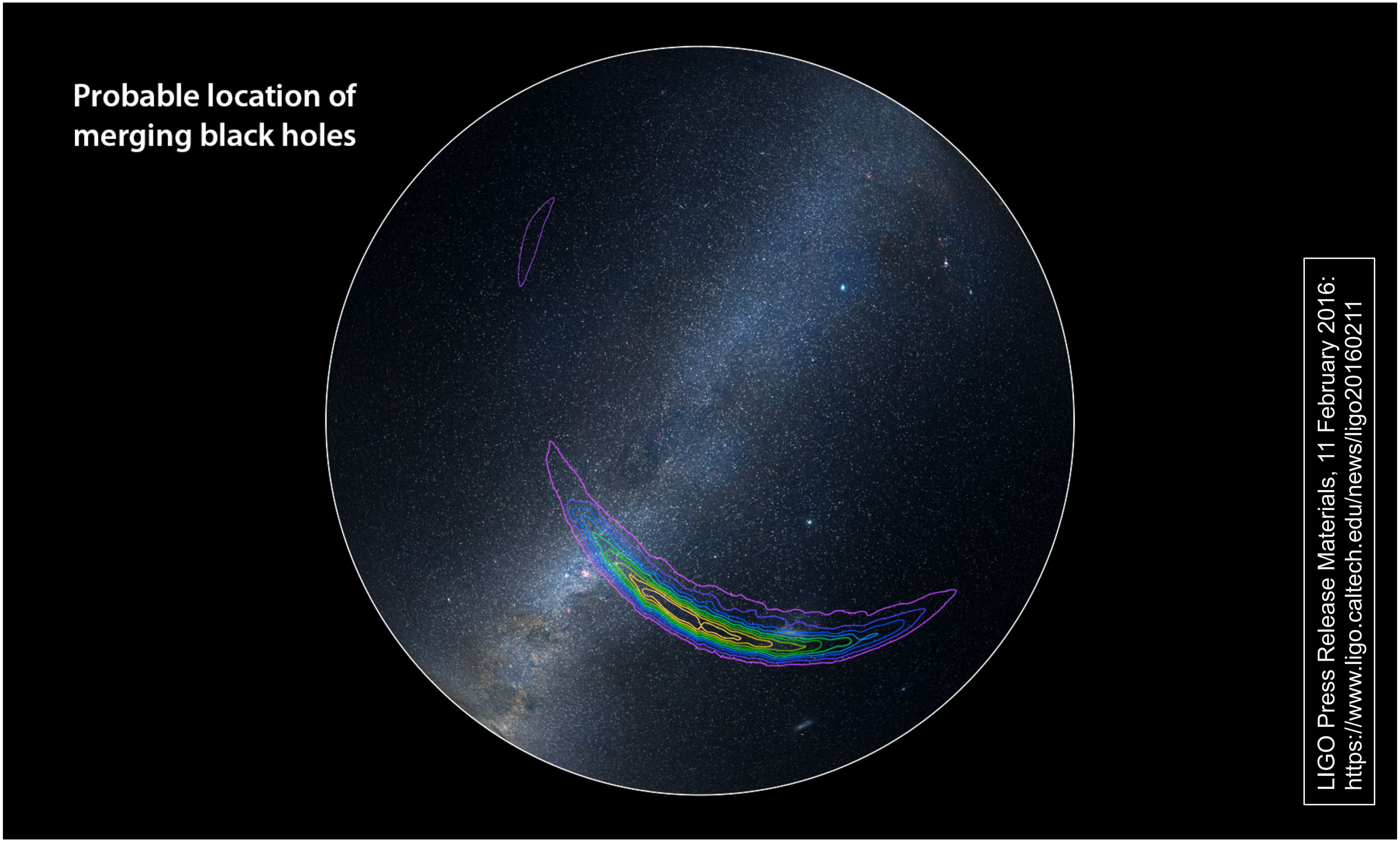
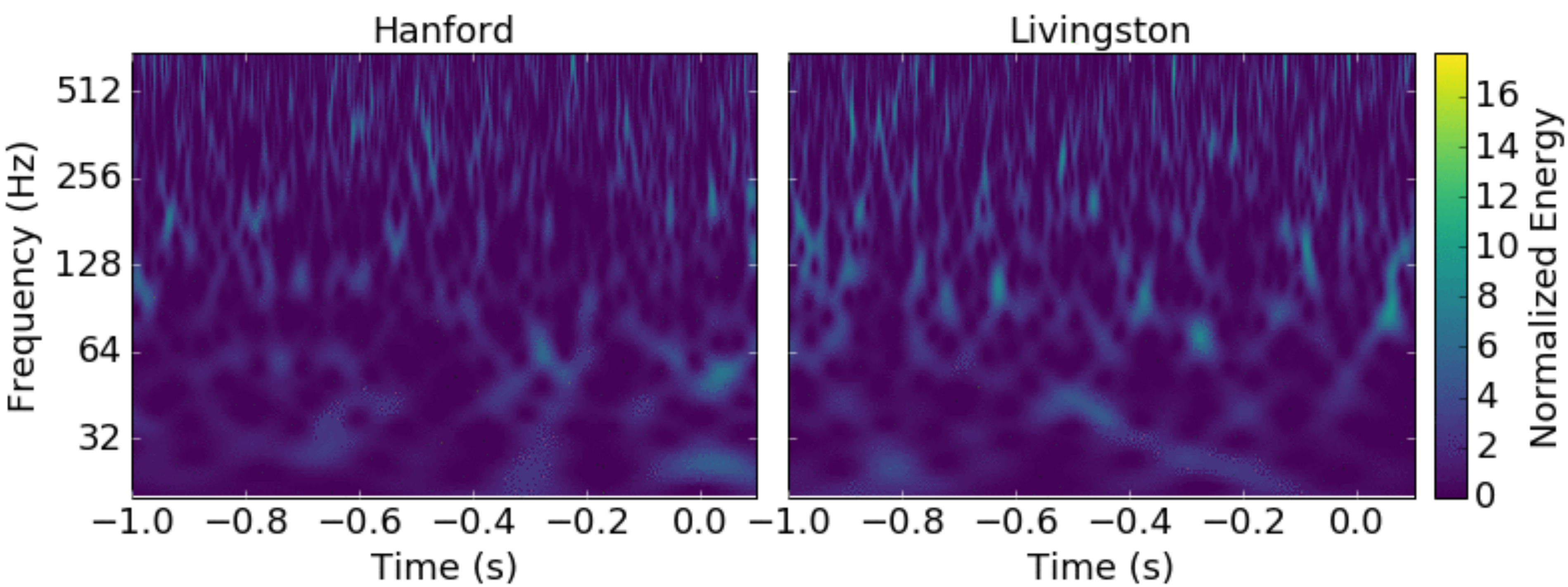
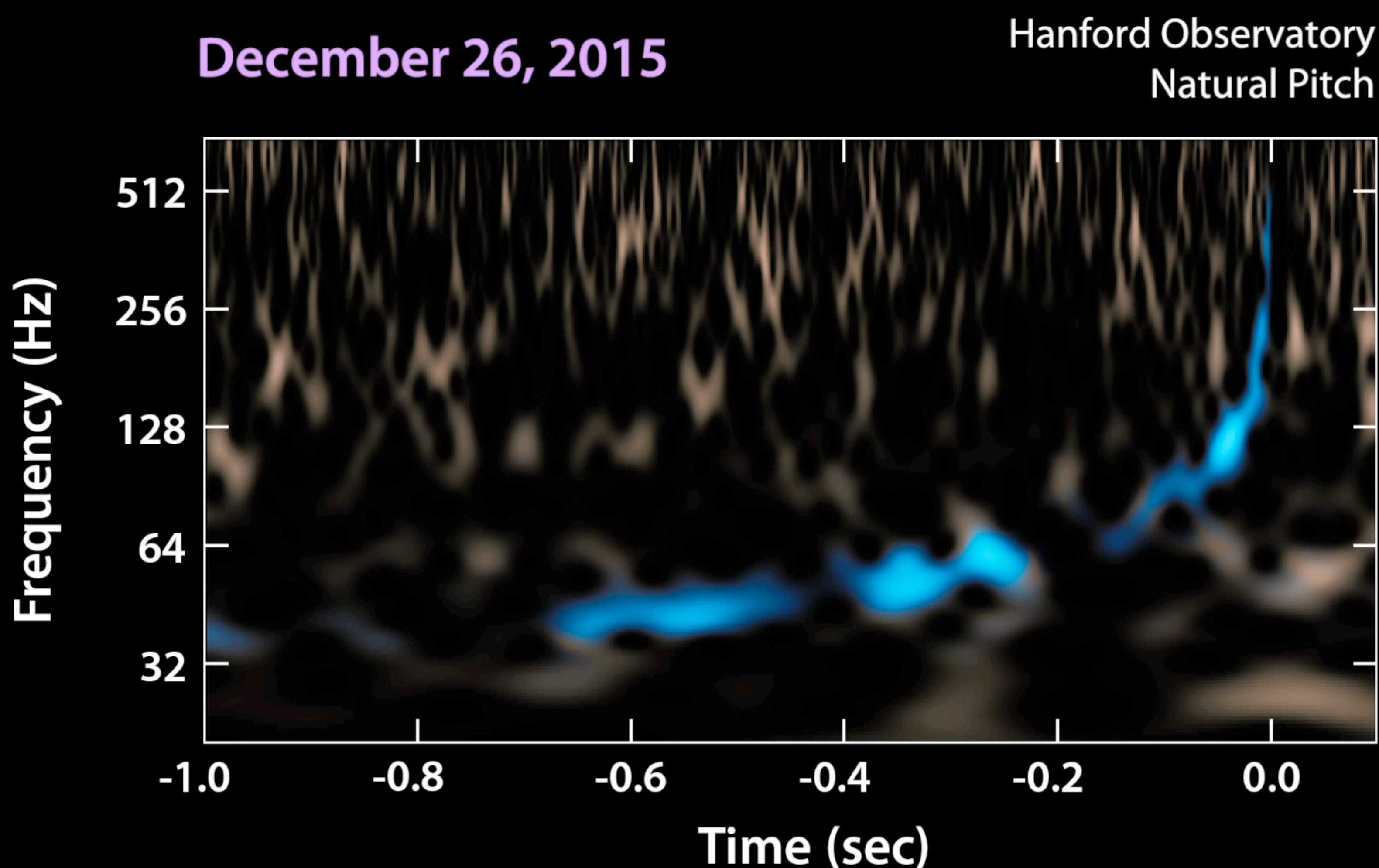
Location of First Detected GW



Seeing the 2nd Signal in the Noise



B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. **116**, 241103



LIGO Press Release Materials, 15 June 2016:
https://www.ligo.caltech.edu/news/ligo20160615

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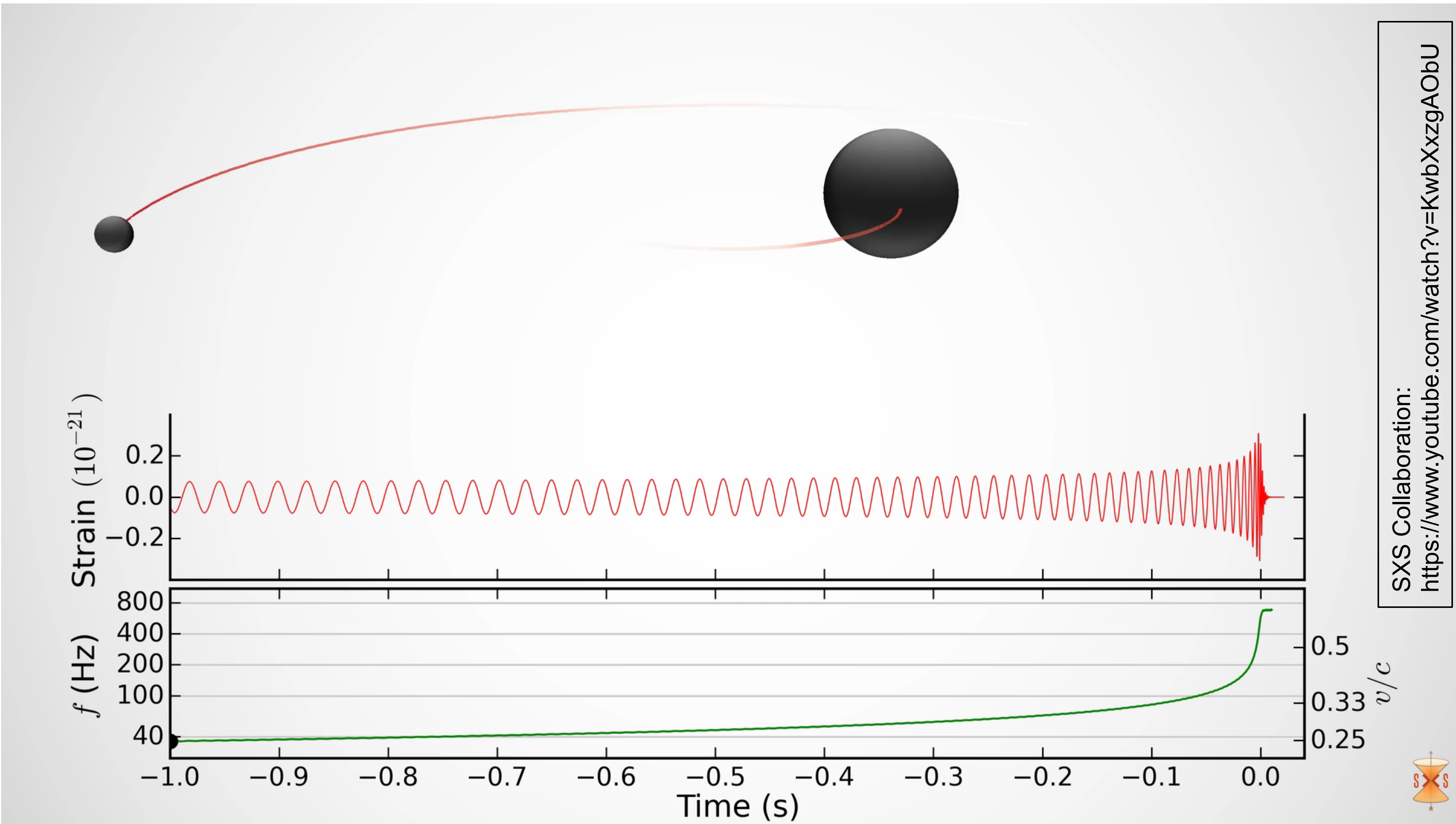
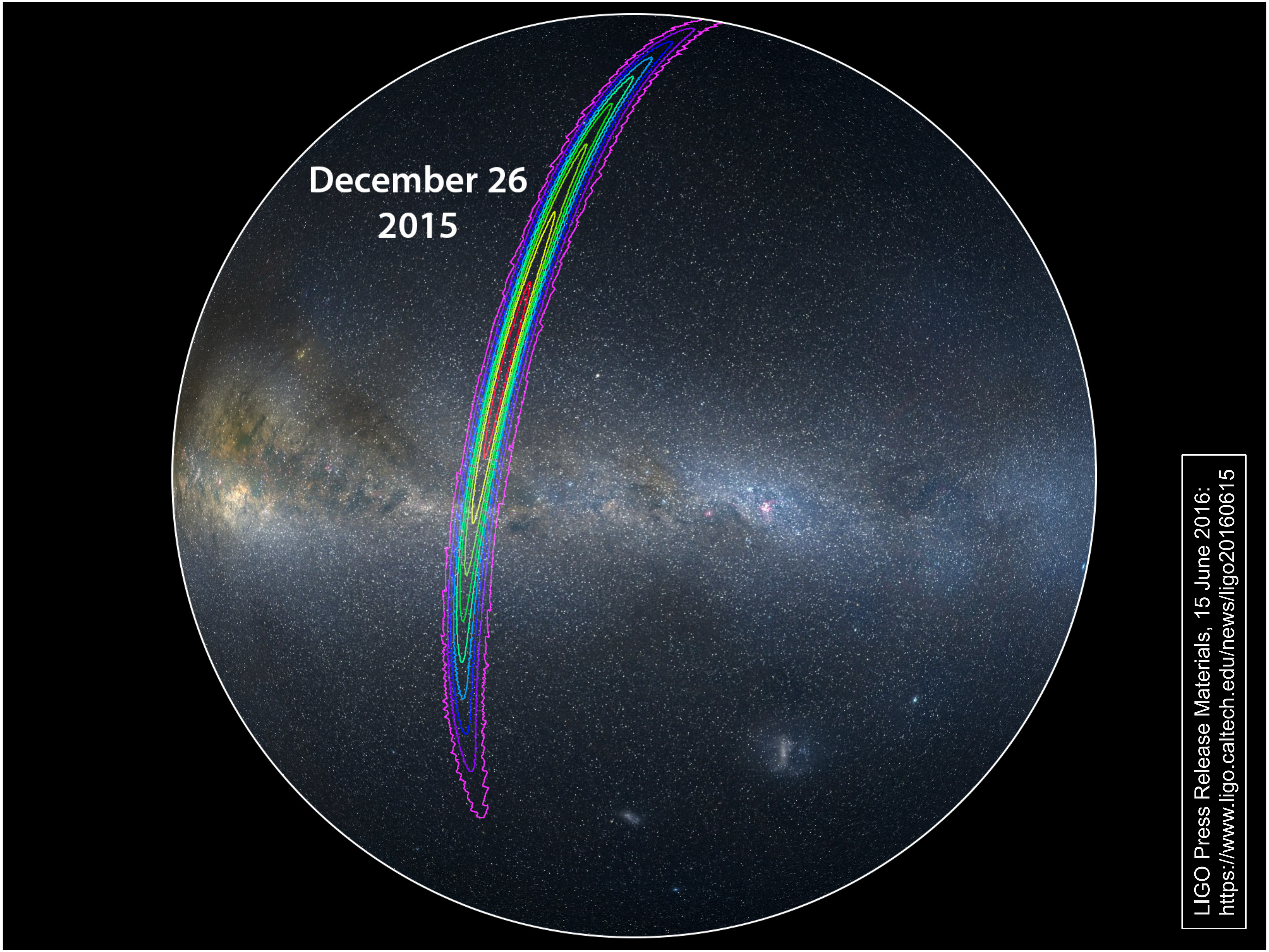
Motion of the Black Holes and the Signal

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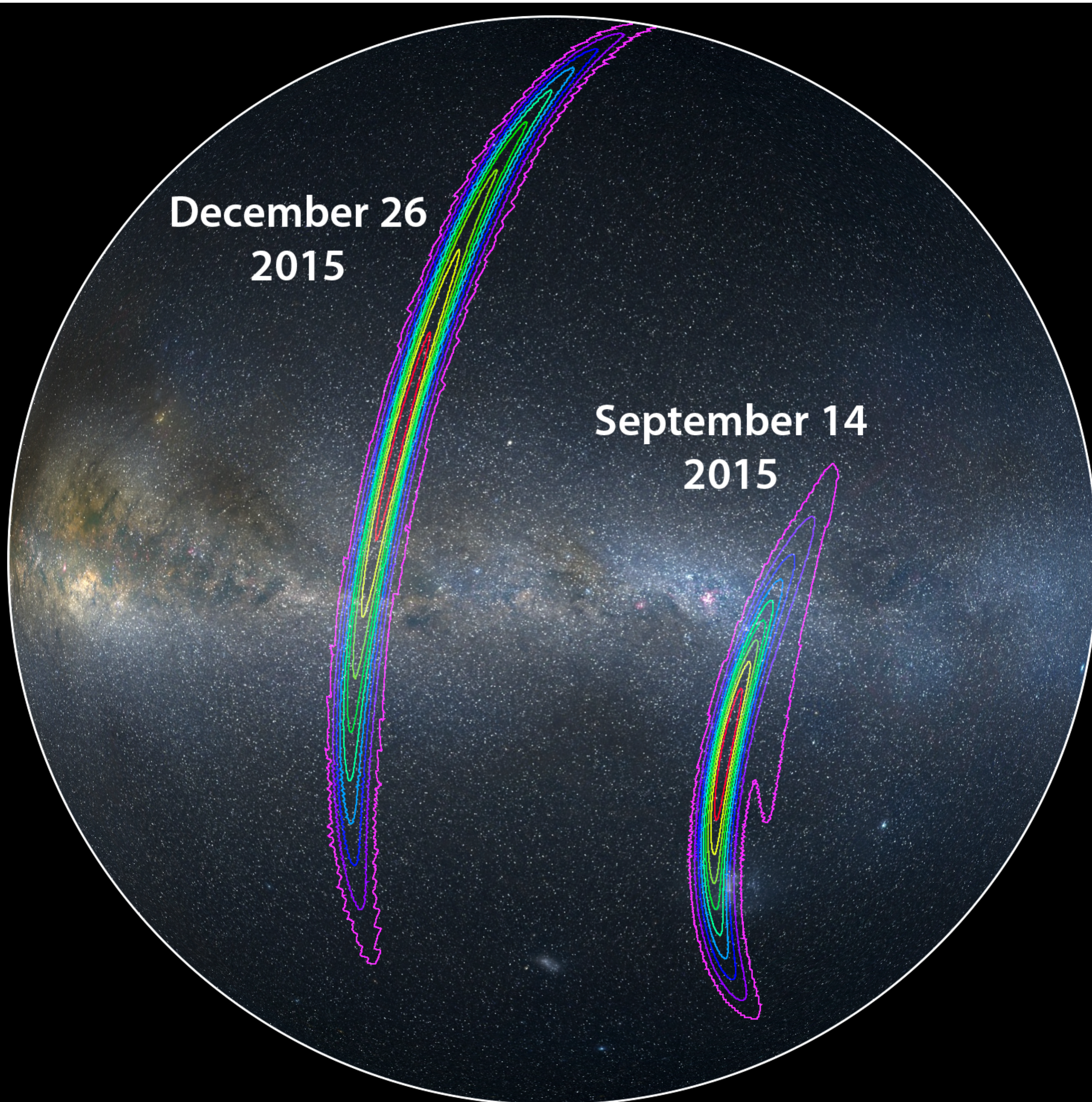
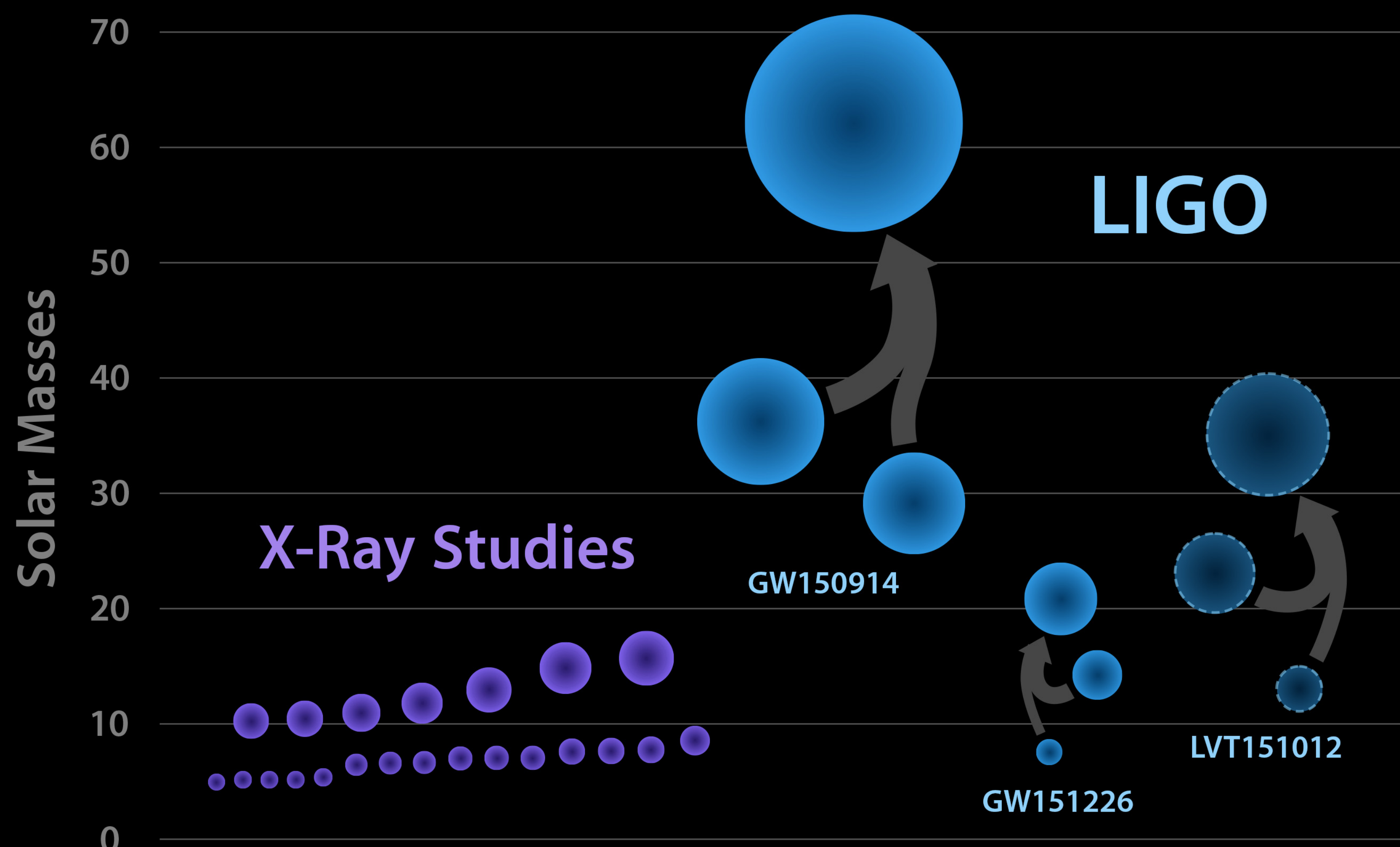
LIGO Press Release Materials, 15 June 2016:
https://www.ligo.caltech.edu/news/ligo20160615



LIGO Press Release Materials, 15 June 2016:
https://www.ligo.caltech.edu/news/ligo20160615

Black Holes of Known Mass



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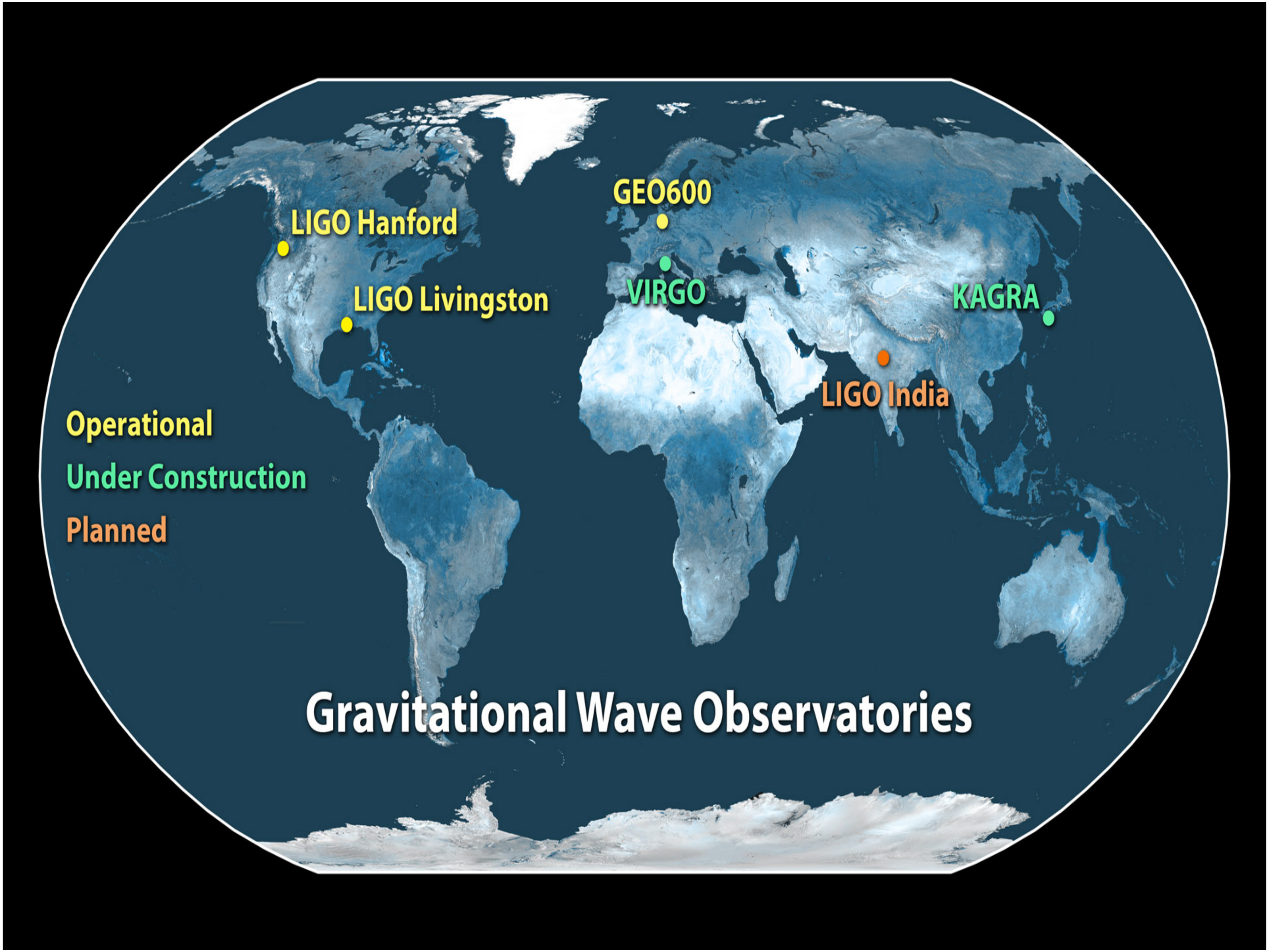
GEO600
LIGO Hanford
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

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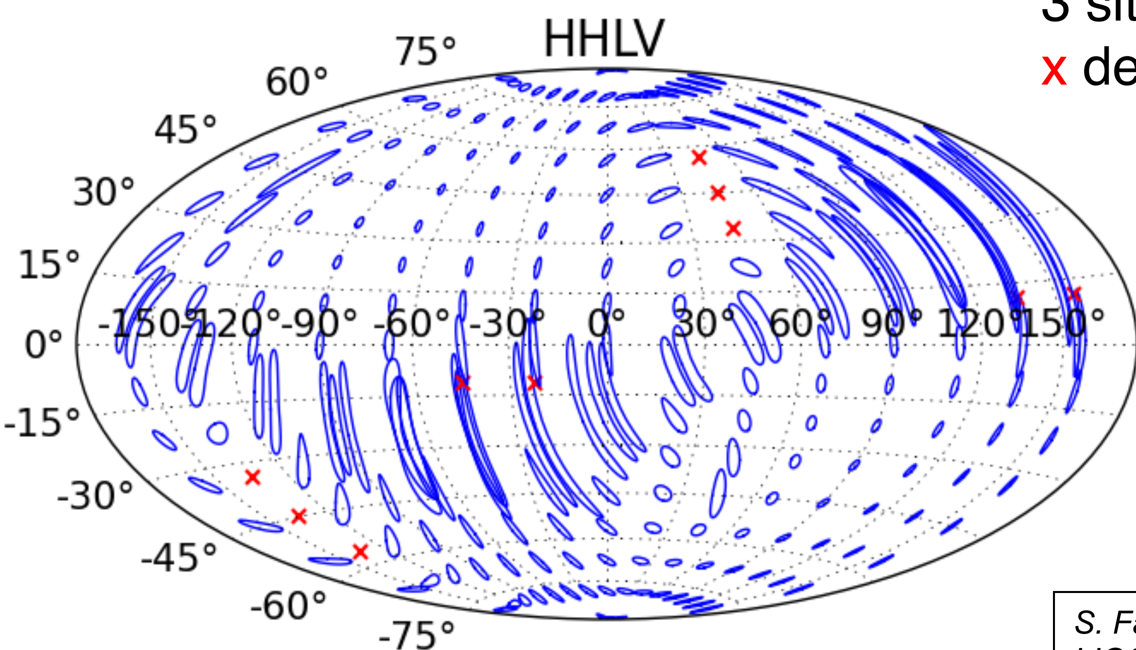
Future: LIGO-India

- The arrangement of the existing advanced detectors along a near plane makes it difficult to localize a source around the equator.



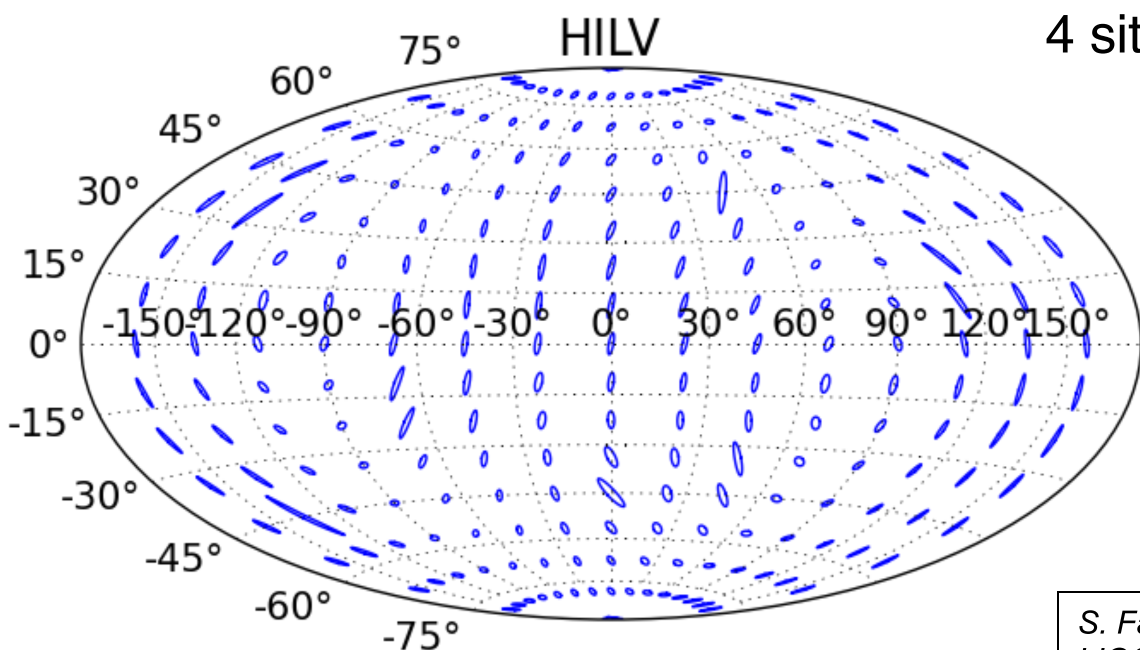
3 site network

x denotes blind spots

S. Fairhurst, "Improved source localization with LIGO India", J. Phys.: Conf. Ser. 484 012007

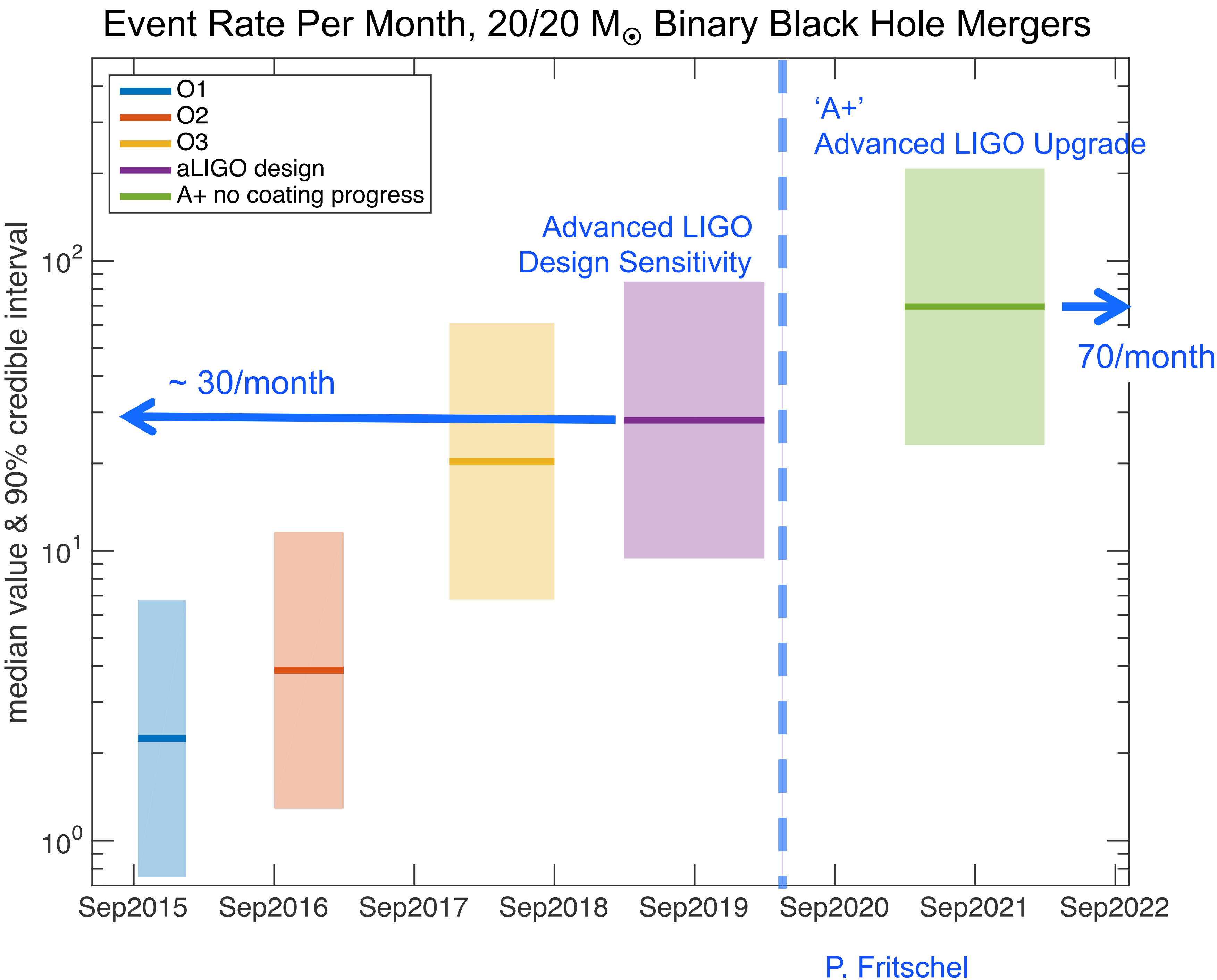
Future: LIGO-India

- A detector located south of the plane of the other detectors will increase source localization.
- This project is currently in development.



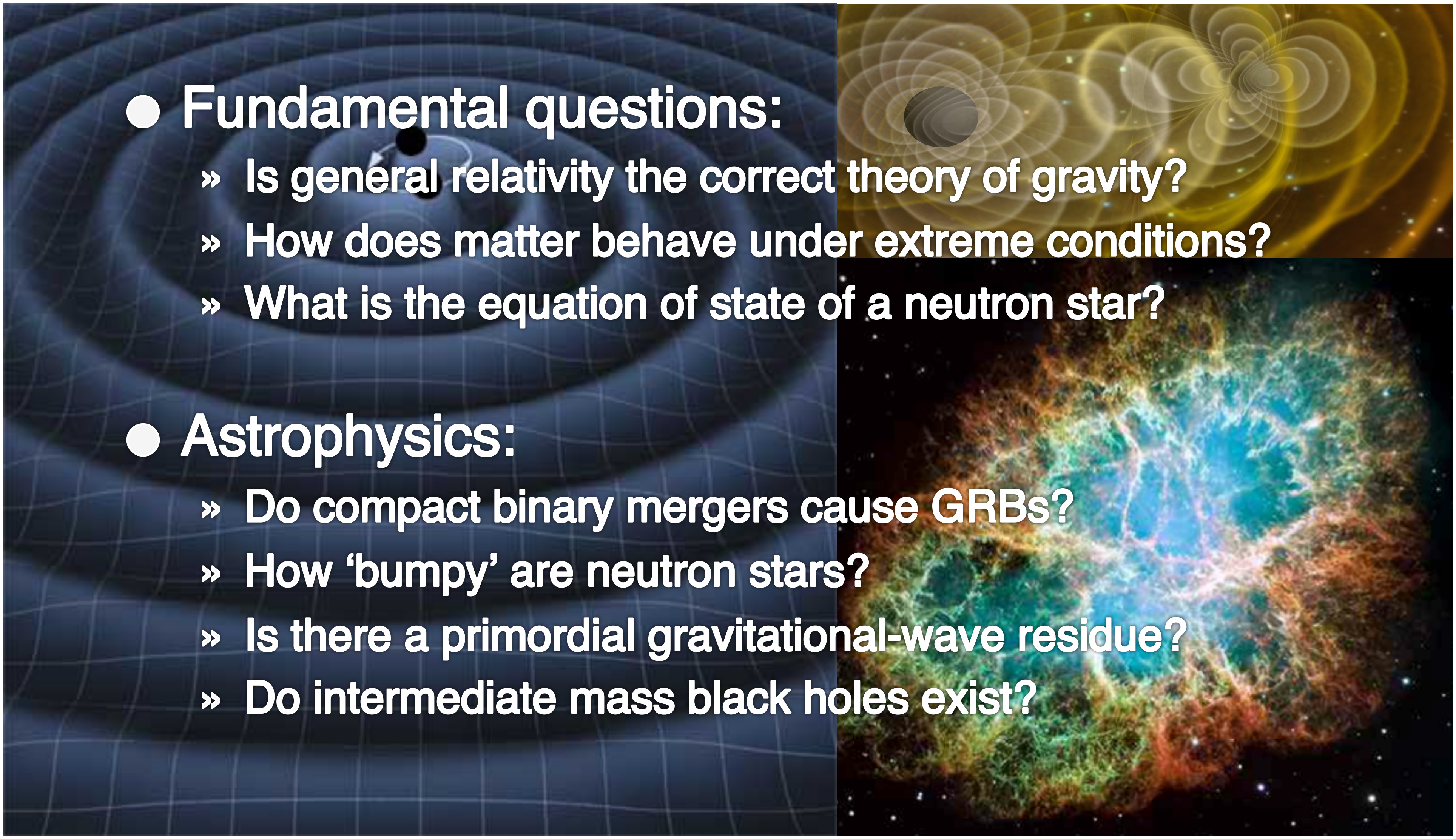
4 site network

S. Fairhurst, "Improved source localization with LIGO India", J. Phys.: Conf. Ser. 484 012007



Event Rate Per Month, 20/20 M☉ Binary Black Hole Mergers
O1
O2
O3
aLIGO design
A+ no coating progress
'A+'
Advanced LIGO Upgrade
Advanced LIGO
Design Sensitivity
~ 30/month
70/month
median value & 90% credible interval
10^2
10^1
10^0
Sep2015
Sep2016
Sep2017
Sep2018
Sep2019
Sep2020
Sep2021
Sep2022
P. Fritschel

What Questions May GWs Answer?



- **Fundamental questions:**
  - Is general relativity the correct theory of gravity?
  - How does matter behave under extreme conditions?
  - What is the equation of state of a neutron star?
- **Astrophysics:**
  - Do compact binary mergers cause GRBs?
  - How ‘bumpy’ are neutron stars?
  - Is there a primordial gravitational-wave residue?
  - Do intermediate mass black holes exist?

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End

This colloquium will discuss what gravitational waves are and how they are used to observe the universe in a new way. The history of the search for gravitational waves will be reviewed leading up to today's advanced detectors and how they operate. Most sources of detectable gravitational waves are some of the most violent, energetic events in the universe from the earliest moments after the Big Bang to the supernova death of a star. Each class of gravitational-wave sources requires unique search methods, which will also be discussed with a special focus on the binary black hole systems that were the sources of both of the first gravitational wave detections.


LVEA WALL 1
07:56:26PM 07/12/2008

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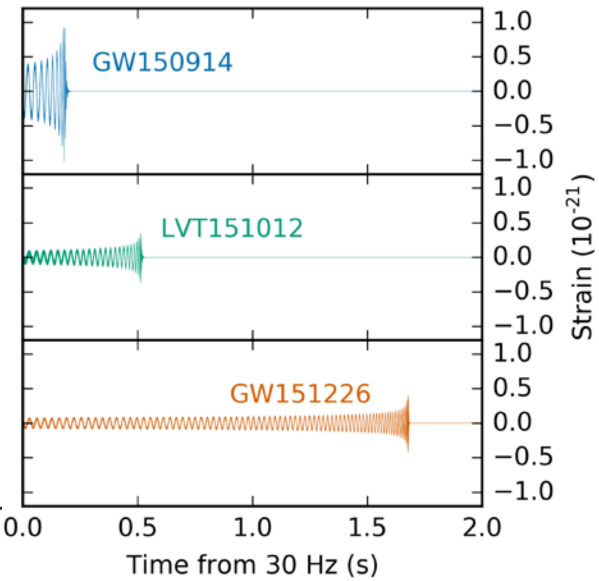
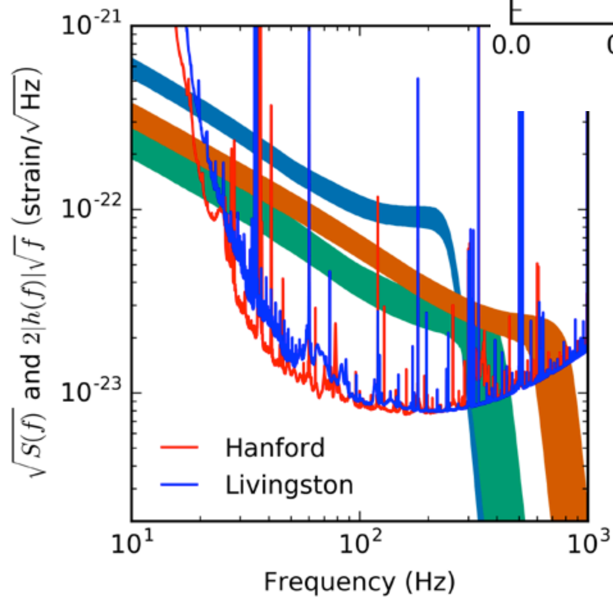
What We Learned from the First Detections

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR/yr^{-1}}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_f^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600





Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", arXiv:1606.04856.