

# Gravitational Waves

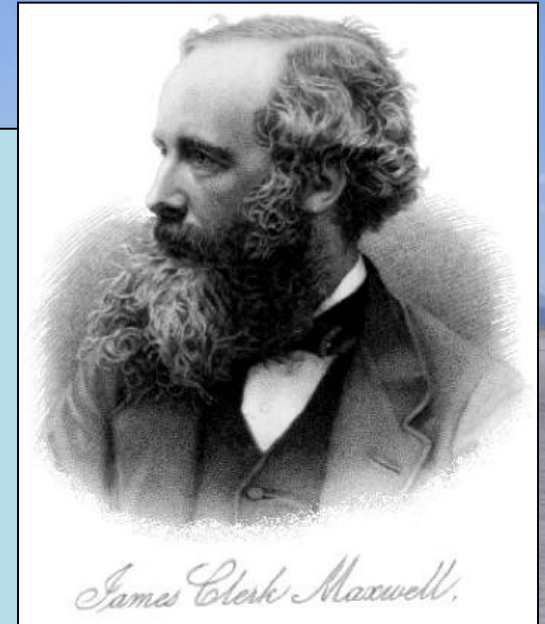
A world-shaking discovery



Earth expands and contracts by the diameter of an atomic nucleus:  $10^{-12}$  cm

# James Clerk Maxwell

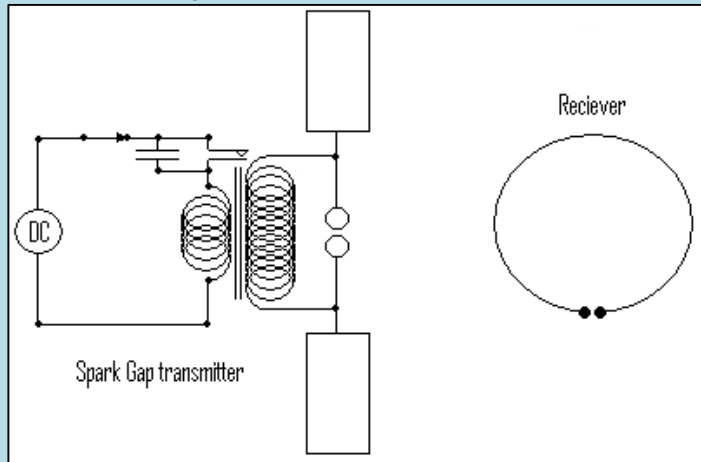
- Professor at King's College  
London: 1860 – 1865
- Unified theory of electricity and  
magnetism
- Predicted electromagnetic waves
- Identified light as due to these waves
- Calculated the velocity of light



**One scientific epoch ended and another began  
with James Clerk Maxwell - Albert Einstein**

# Electromagnetic Waves

- Proposed by Maxwell
- Discovered by Hertz



- A lot to answer for ....
- **Nobody knows where fundamental physics may lead**



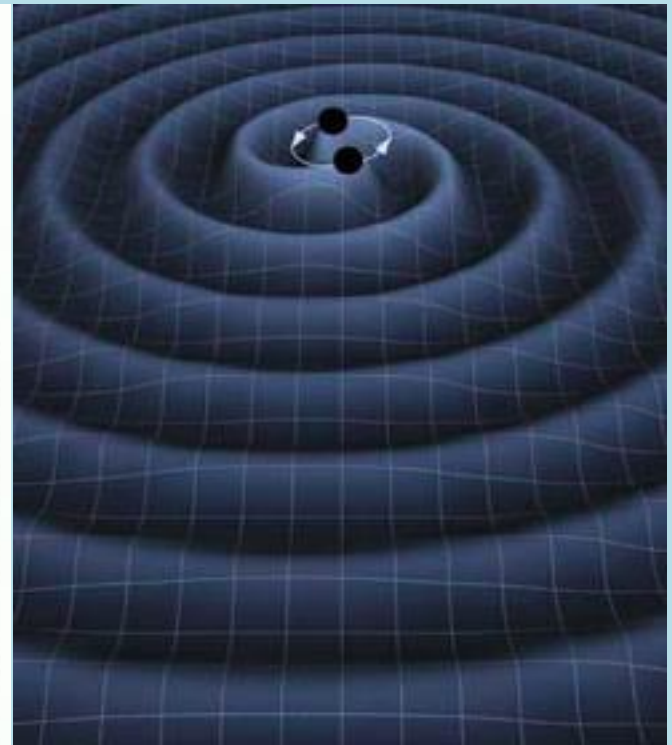


# Gravitational Waves

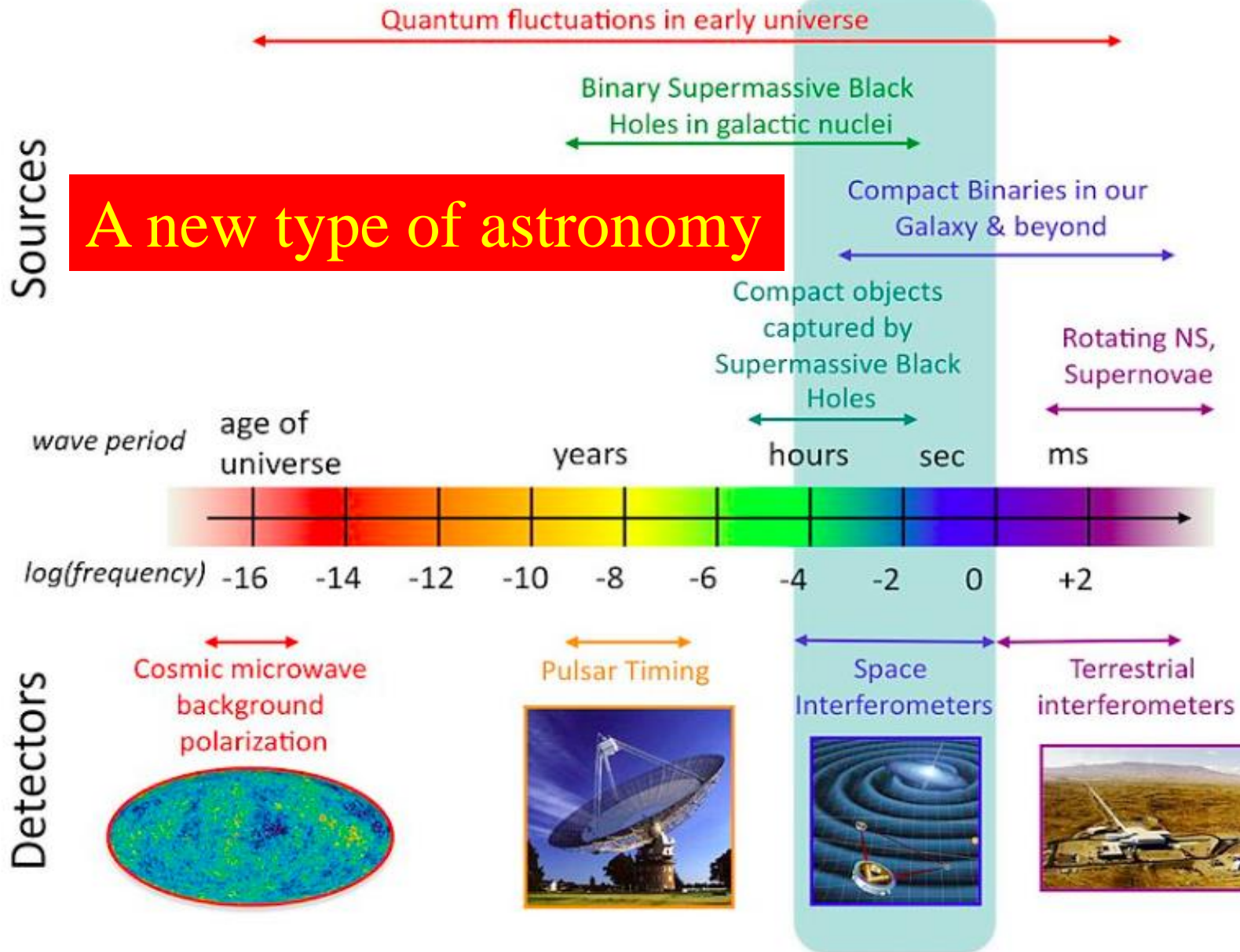
- General relativity proposed by Einstein 1915
- He predicted gravitational waves in 1916



Albert Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 22.6. Berlin 1916



# Gravitational Wave Spectrum



# First Attempts at Detection

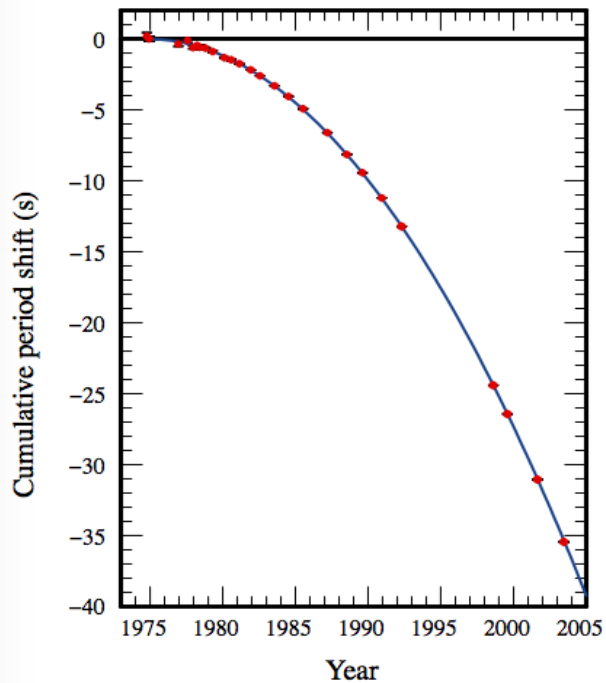
- 1970s: Metal bars  
(Joseph Weber)
- Also Explorer  
experiment at CERN





# Indirect Detection

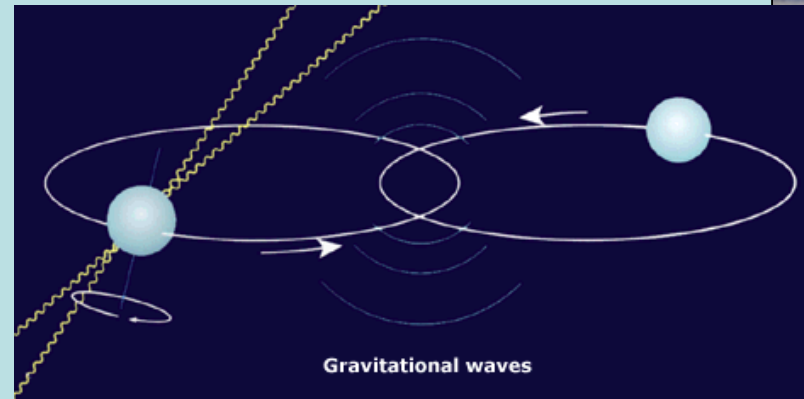
- Binary pulsar discovered 1974 (Hulse & Taylor)
- Emits gravitational waves
- Change in orbit measured



for years

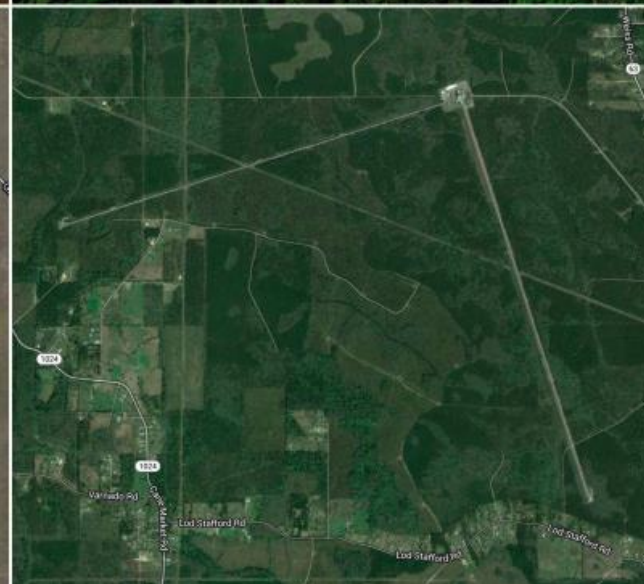
Perfect agreement with Einstein

Nobel Prize 1993



# Discovery of Gravitational Waves

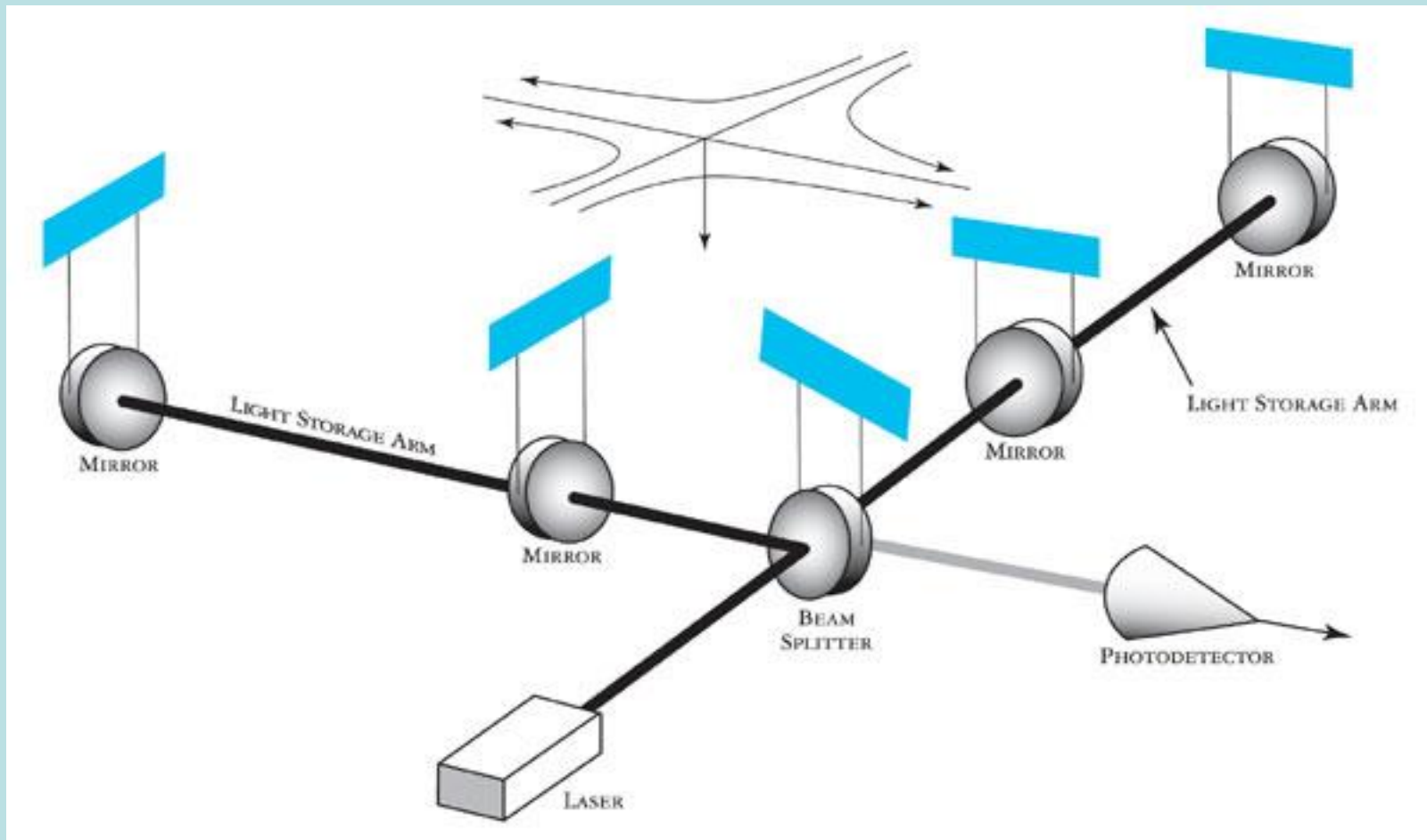
- Measured by the LIGO experiment in 2 locations





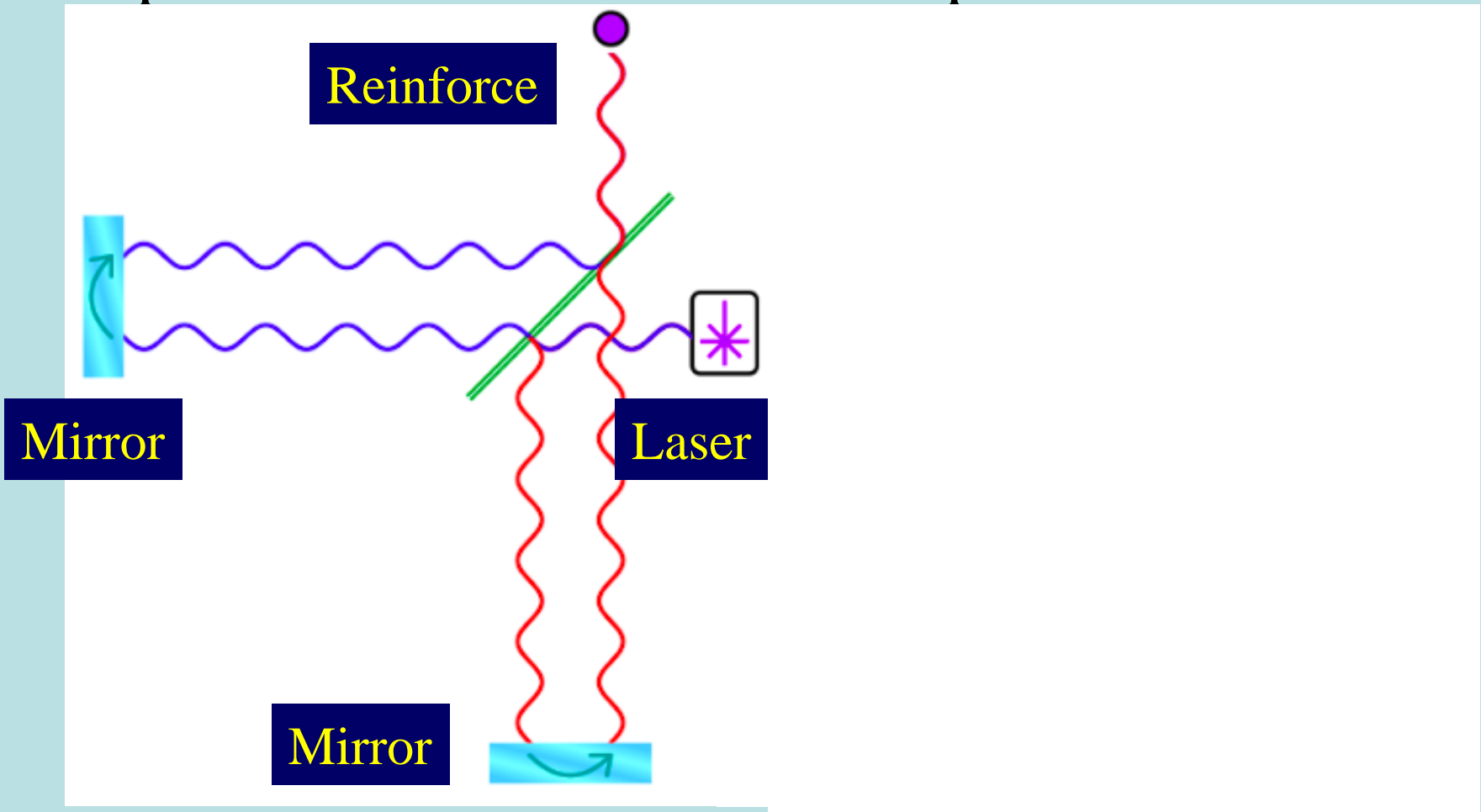
# LIGO experiment

- Inteference between 2 laser beams measures the expansion and contraction of space



# Principle of Laser Interferometer

- Inteferece between 2 laser beams measures the expansion and contraction of space



# Installing LIGO Experiment

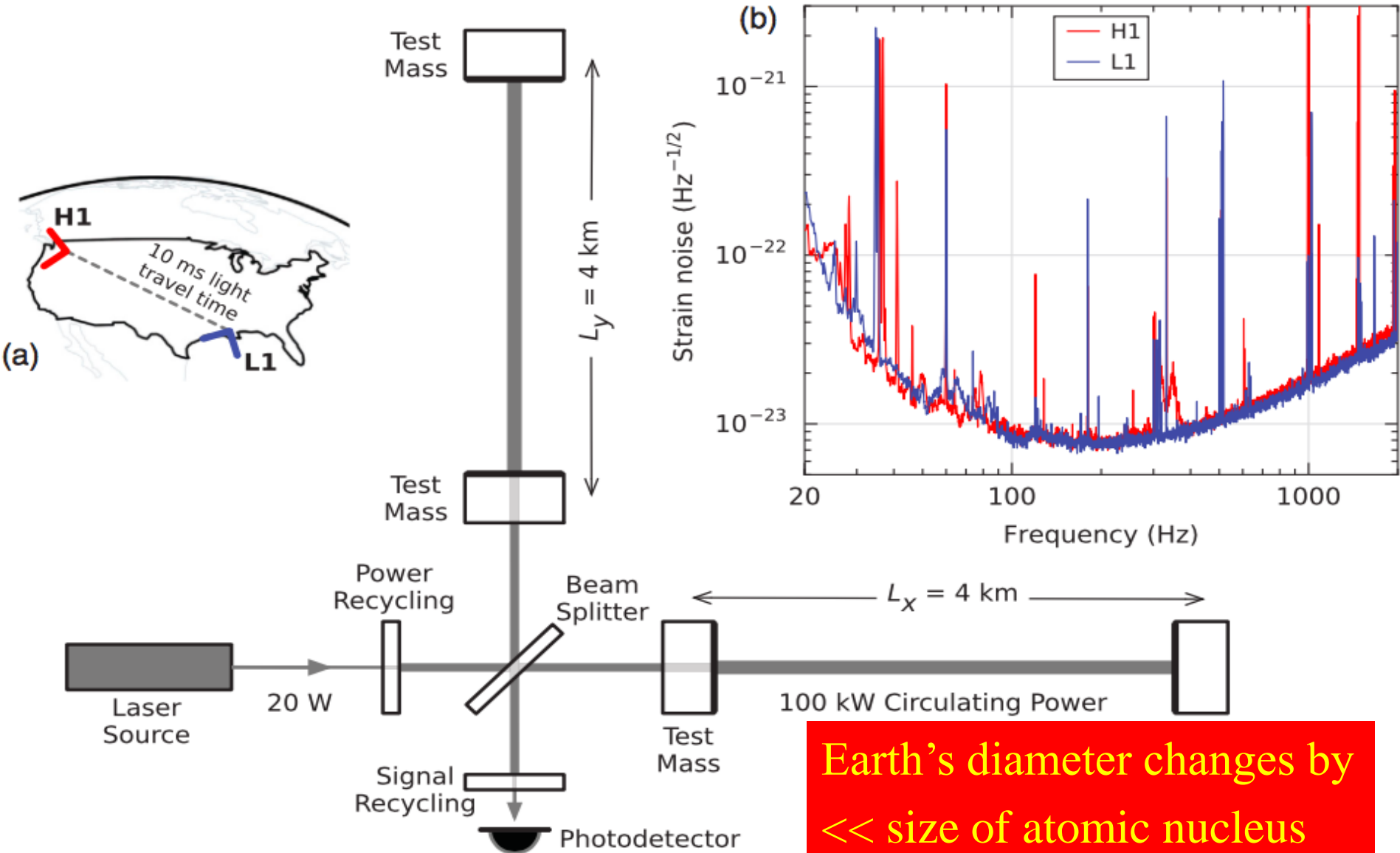




# LIGO Experimental Apparatus



# LIGO Layout & Sensitivity



# Fusion of two massive black holes

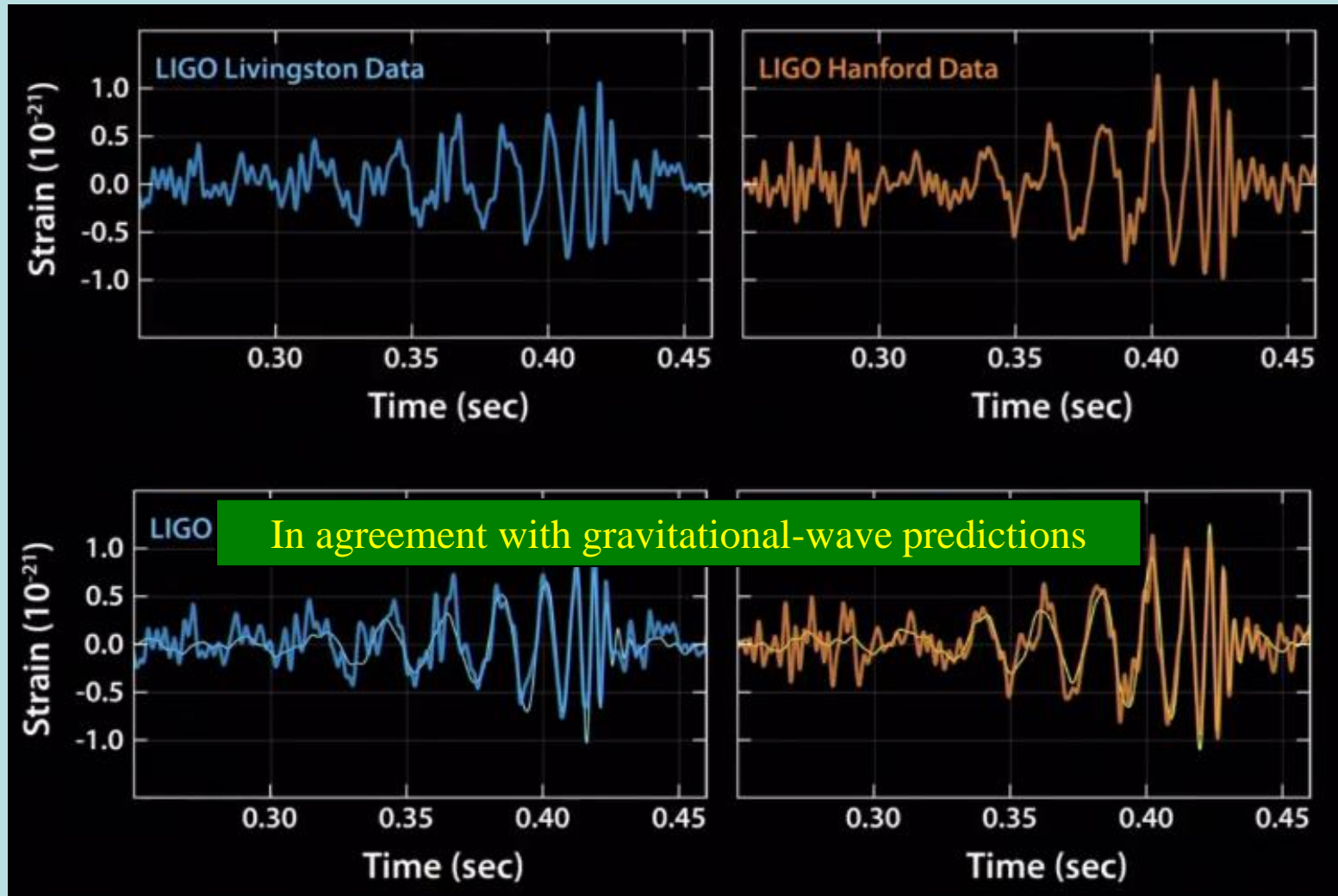


Masses ~ 36, 29 solar masses  
Radiated energy ~ 3 solar masses



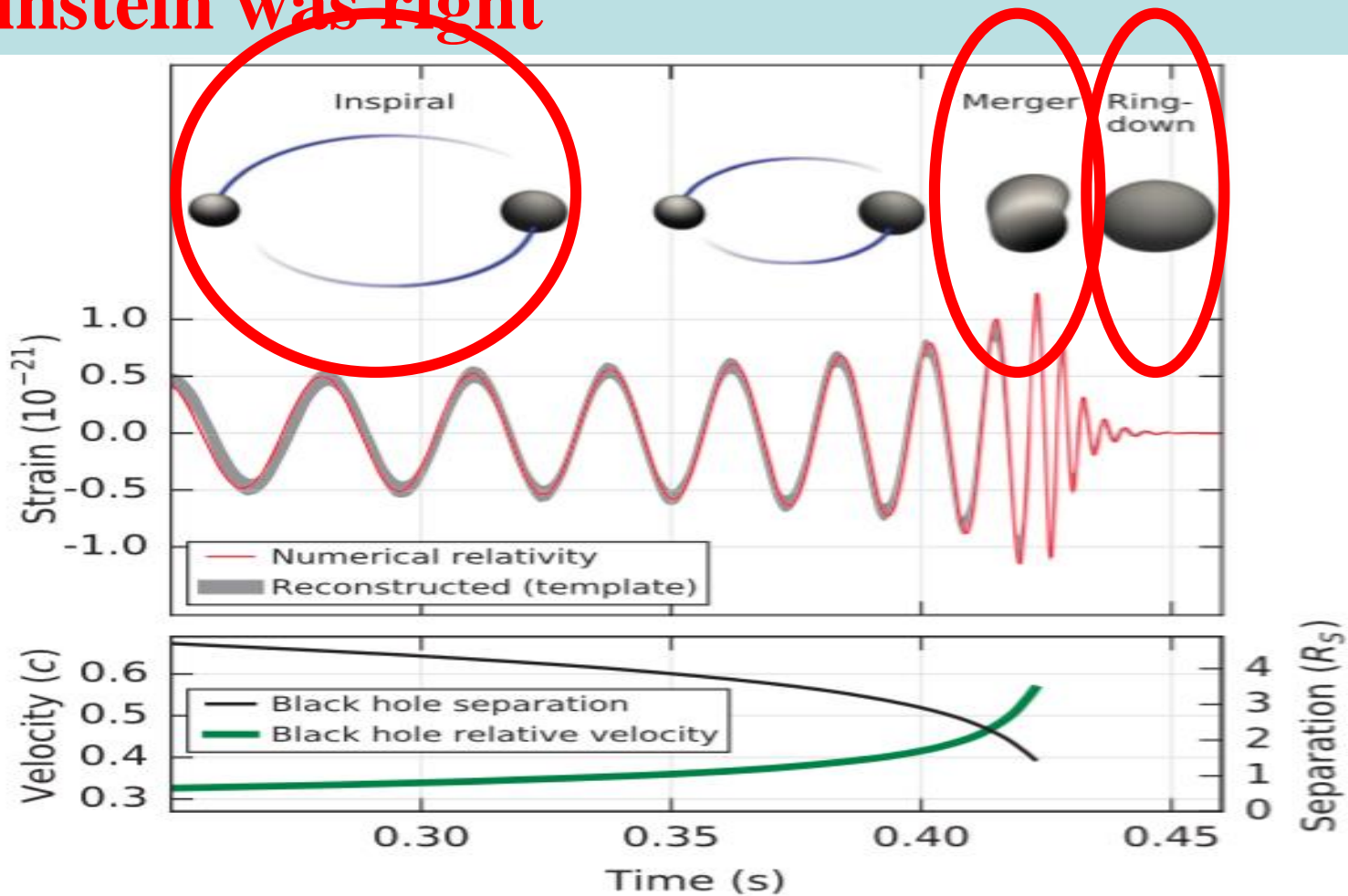
# What was observed

- **Very similar signals in the 2 detectors**



# Fusion of two massive black holes

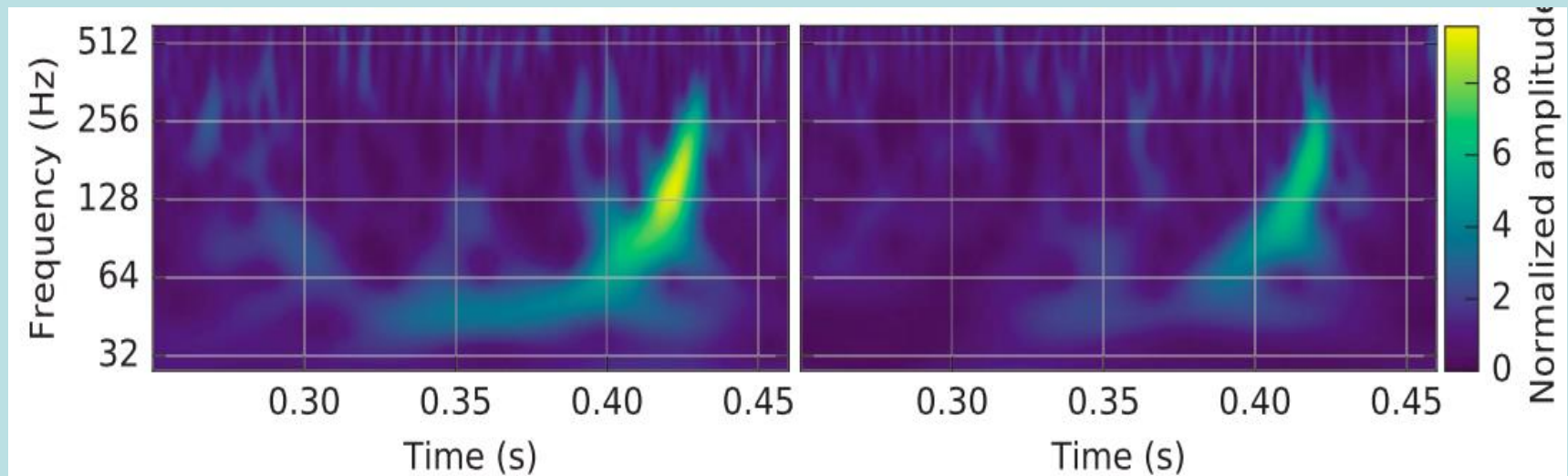
- **Einstein was right**



- **A new way to study the Universe**

# The Gravitational Chirp ...

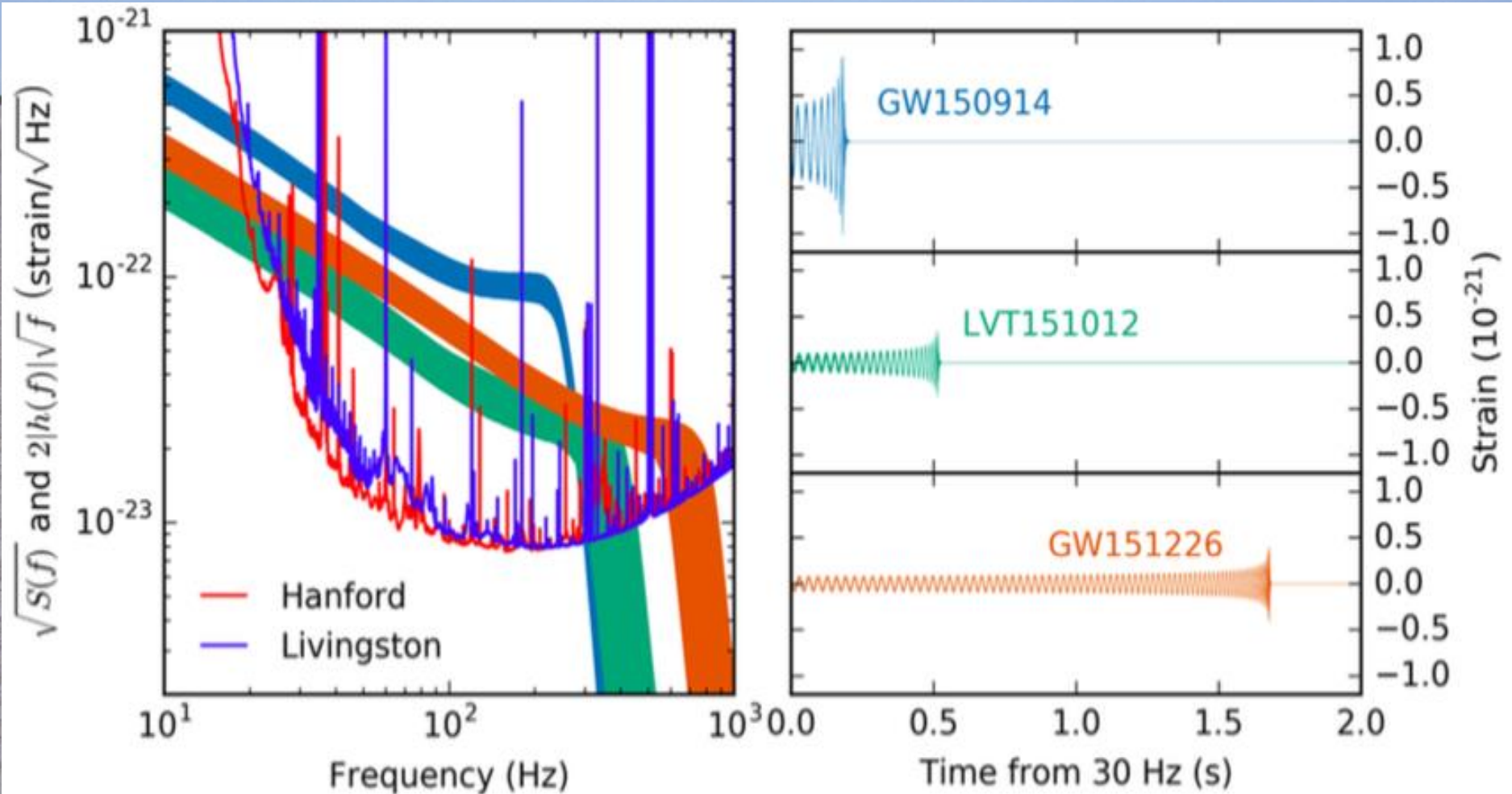
- ... heard around the world



- Frequency increases with time during inspiral
- Followed by ringdown of combined black hole
- Graviton mass  $< 10^{-27} \times$  mass of electron **LIGO**
- Waves of different frequencies have same speed

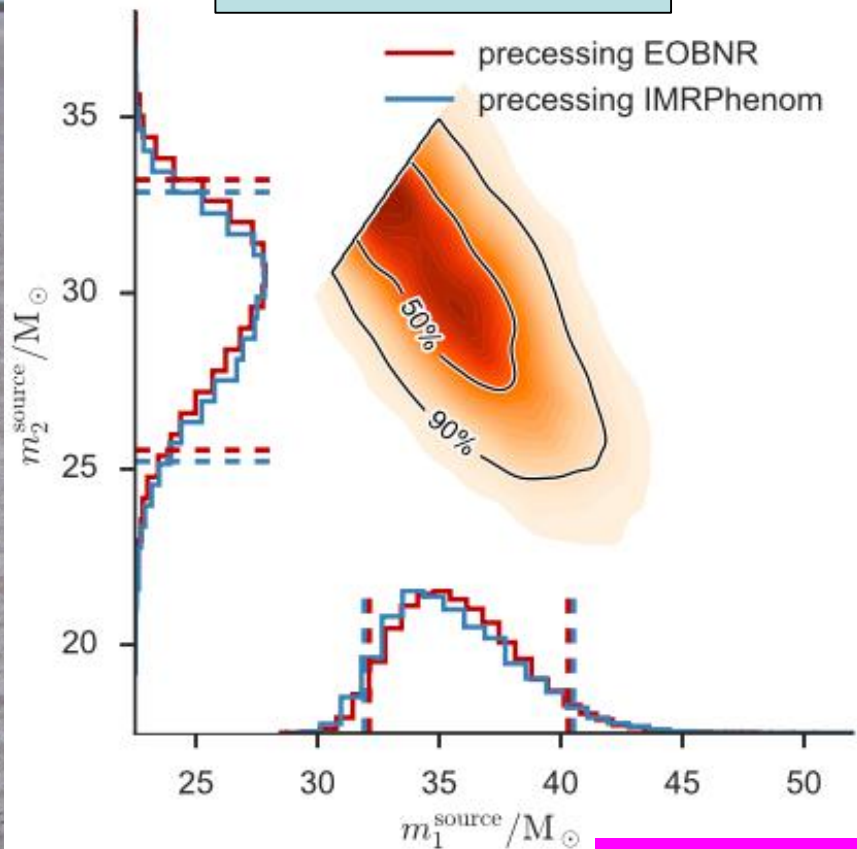


# GW150914, GW131226 & LVT151012

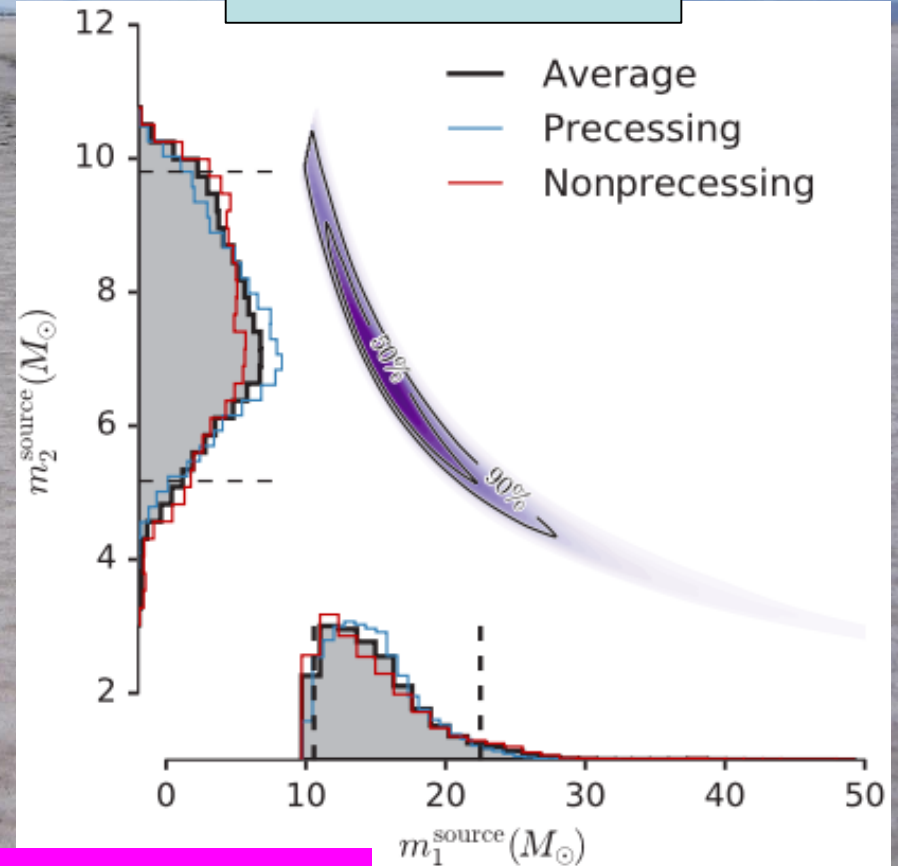


# Inferred Black-Hole Masses

## GW150914

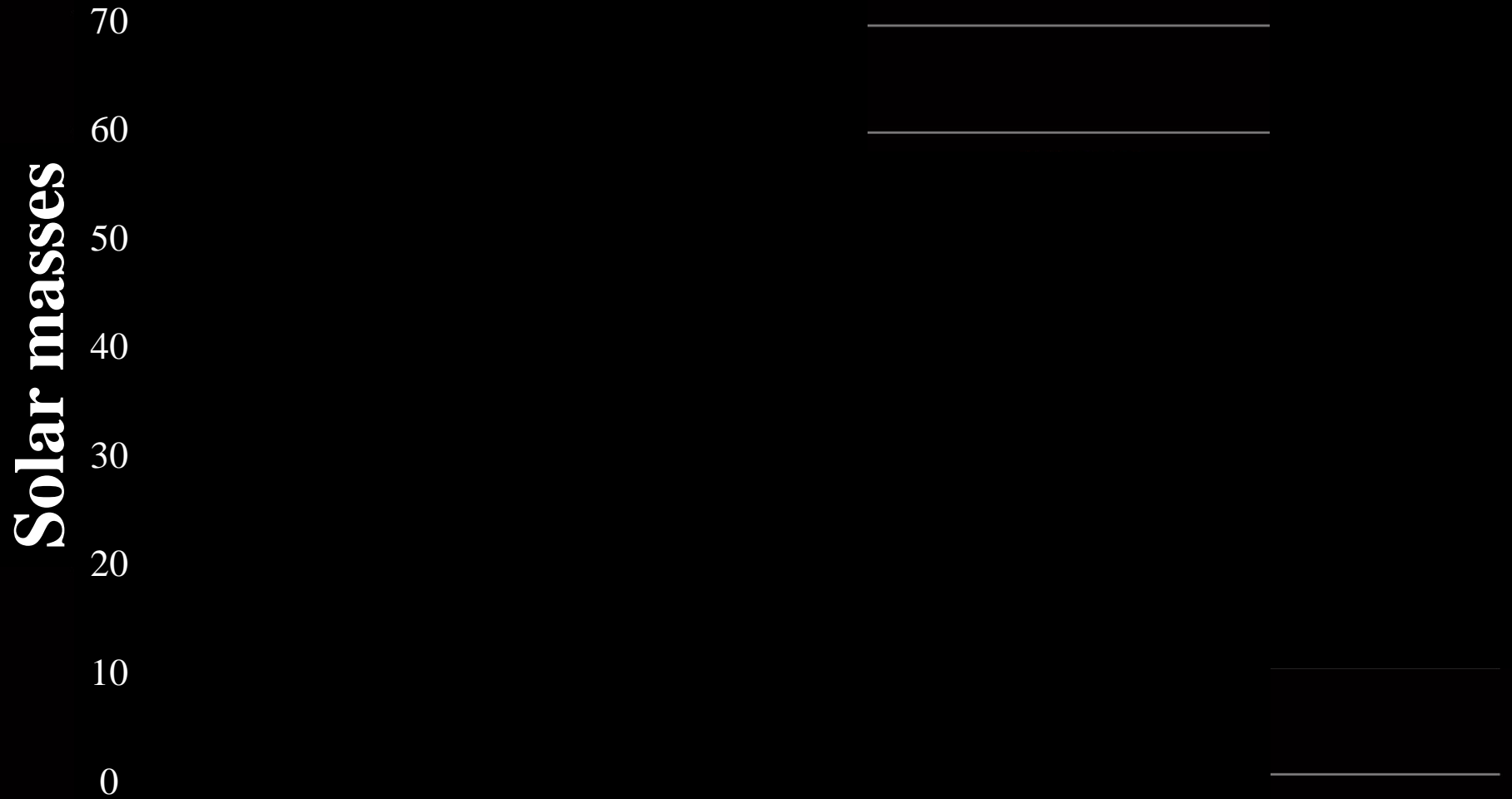


## GW151226



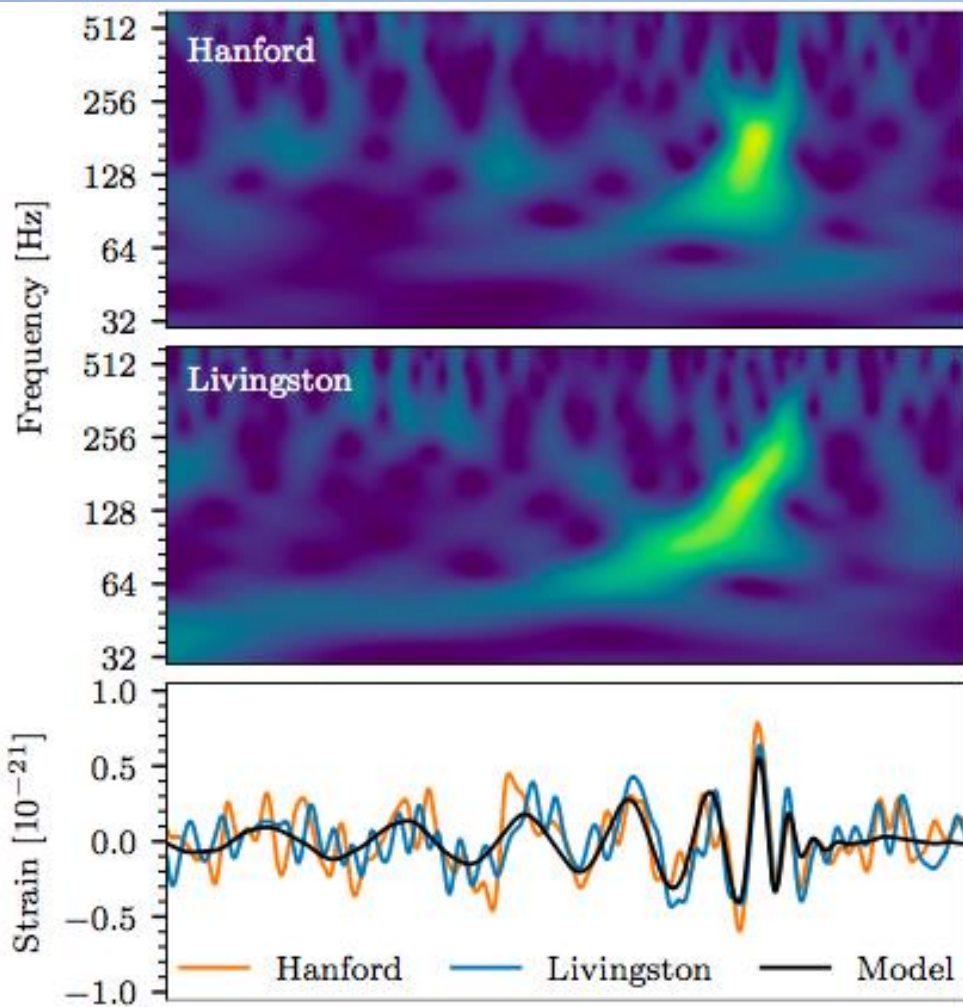
LIGO & Virgo, arXiv:1606.04764

# Measured Black Hole Masses





# The Chirp from GW170401



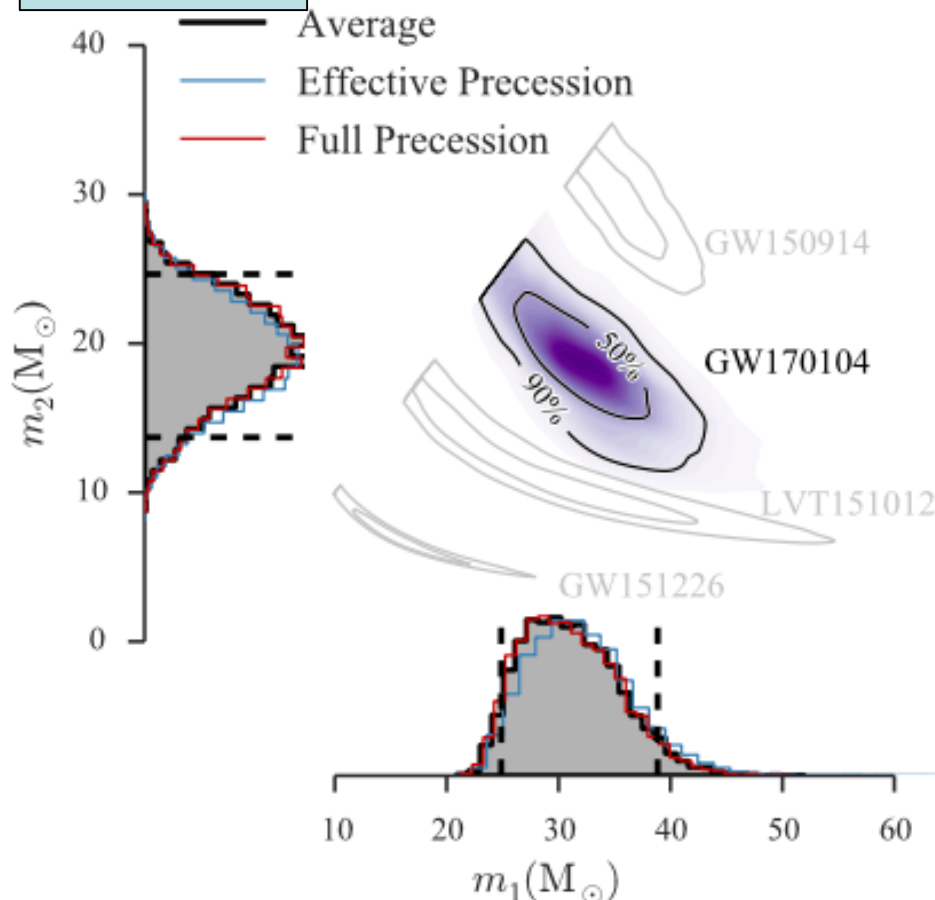
- Frequency increases with time (inspiral)
- Similar signals in both detectors  $\sim$  GW model
- Combined limit on graviton mass
- $< 1.5 \times 10^{-28} m_{\text{electron}}$

In agreement with gravitational-wave predictions

LIGO, arXiv:1706.01812

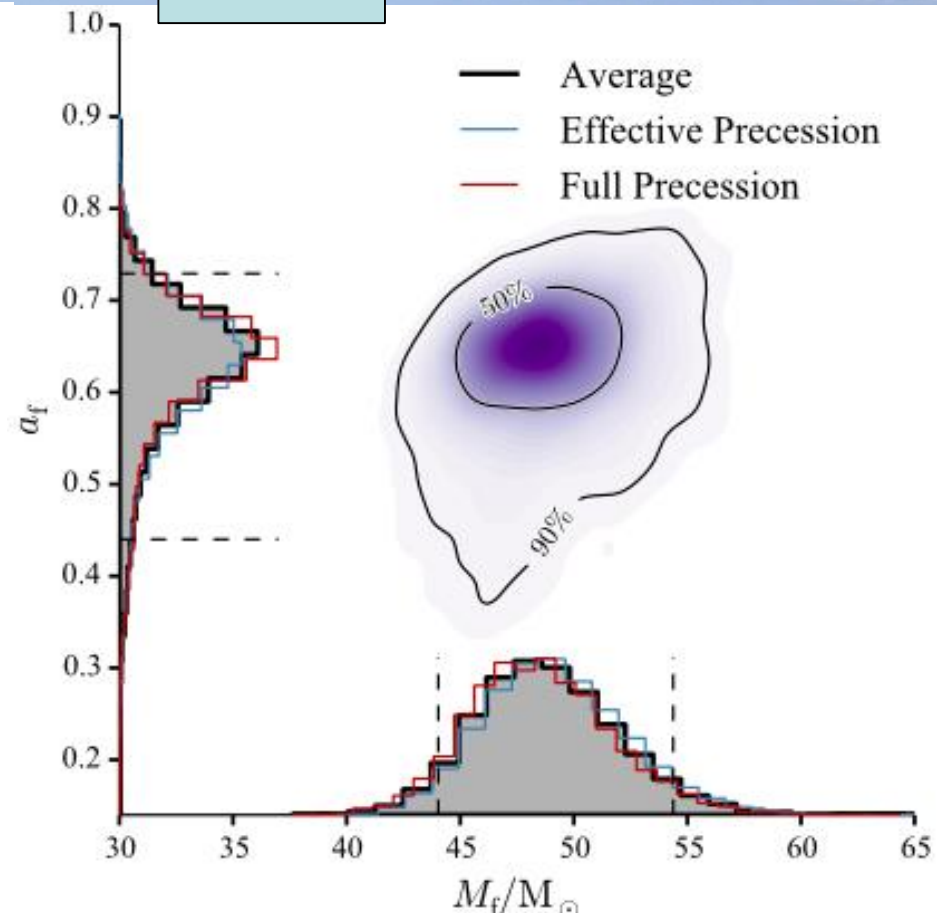
# GW170104 Black Hole Masses

Before



~ 31.2, 19.4 solar masses

After



~ 48.7 solar masses

# Ground-Based GW Detectors

Advanced LIGO  
Hanford  
2015



GEO600 (HF)  
2011

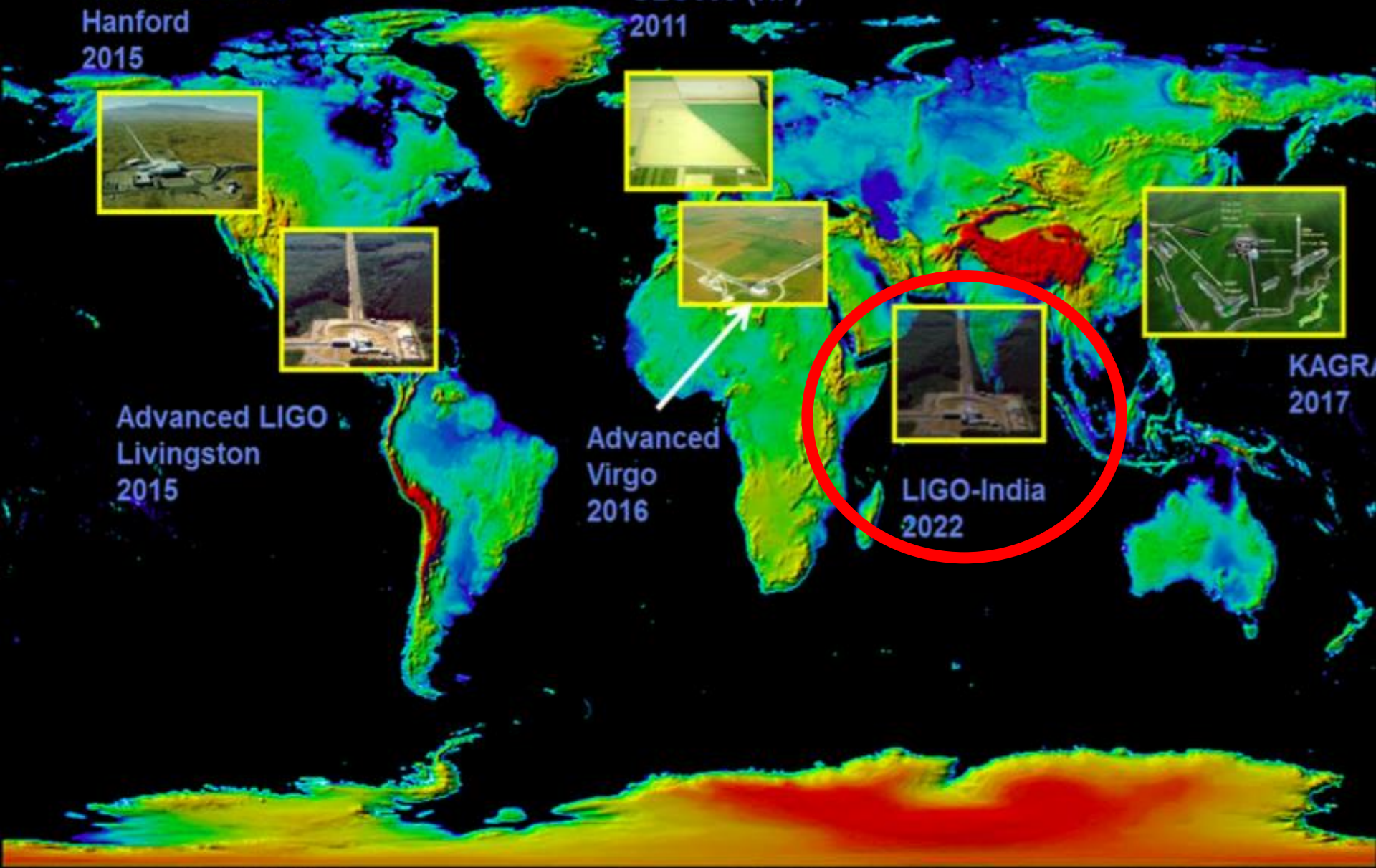


KAGRA  
2017

Advanced LIGO  
Livingston  
2015

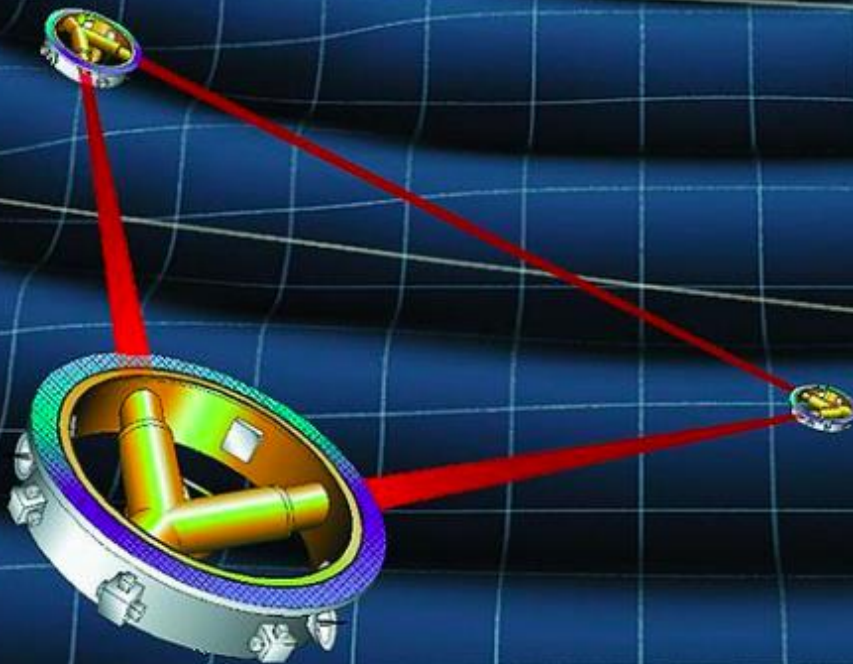
Advanced  
Virgo  
2016

LIGO-India  
2022

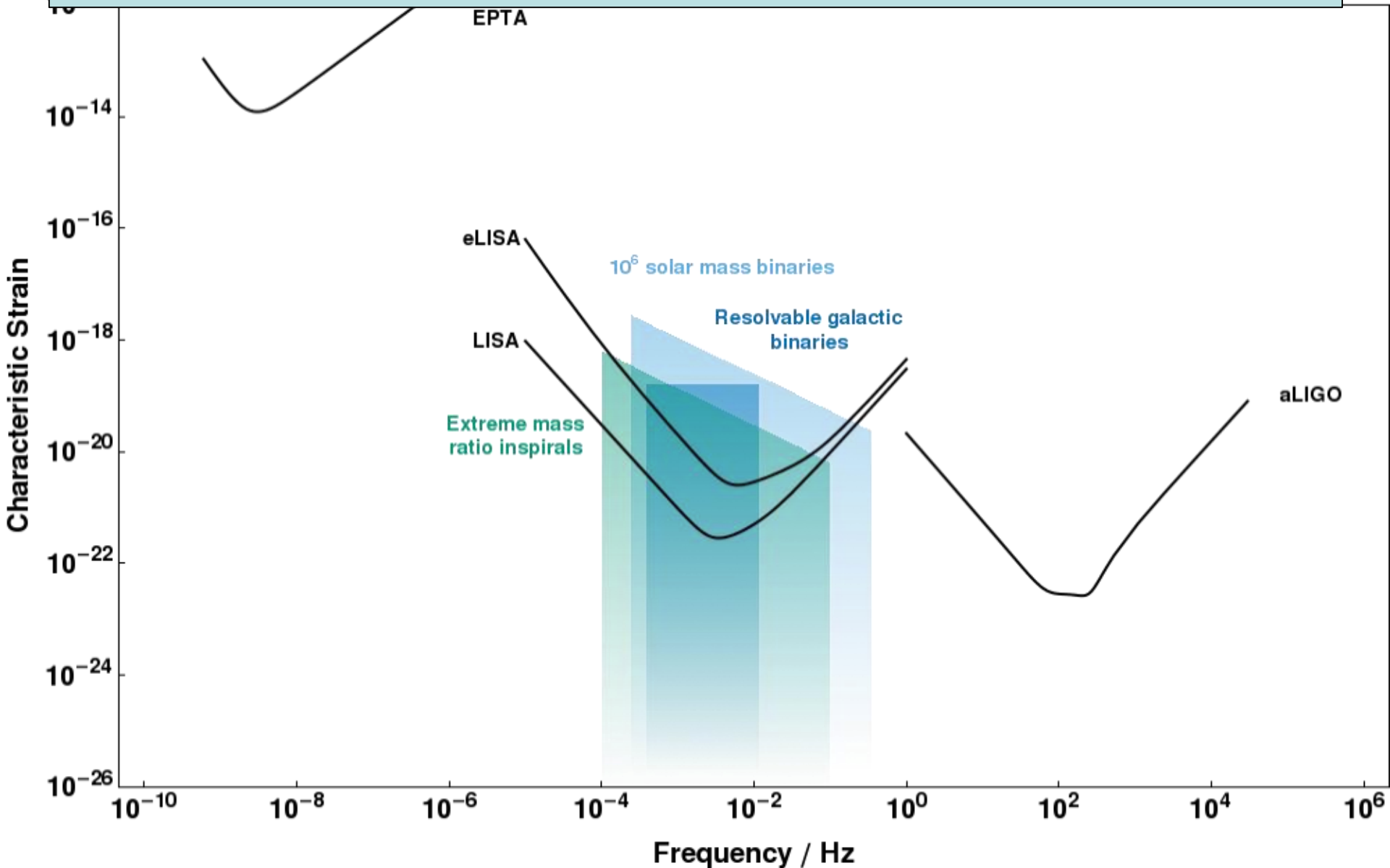


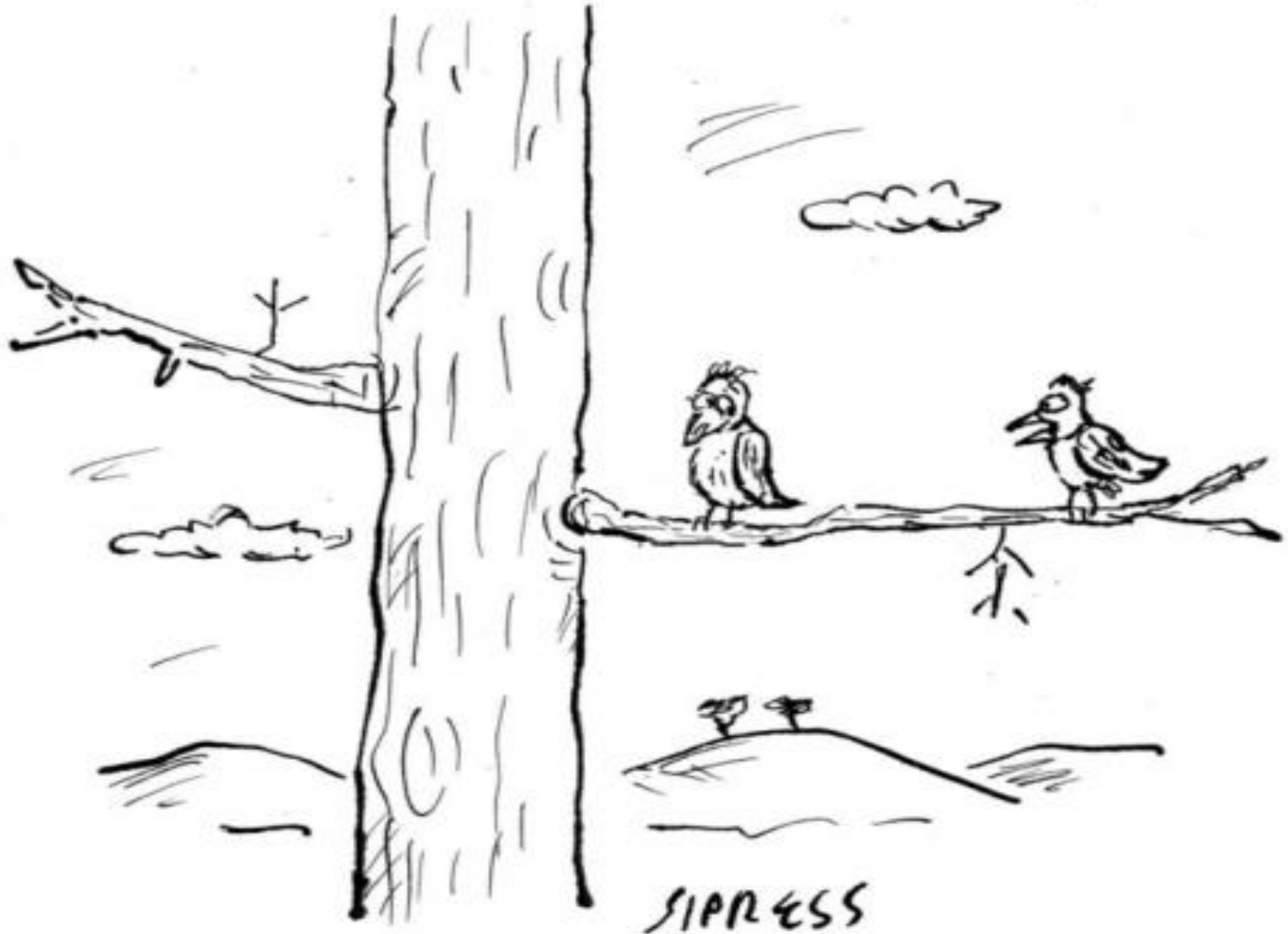


# Future Step: Interferometer in Space



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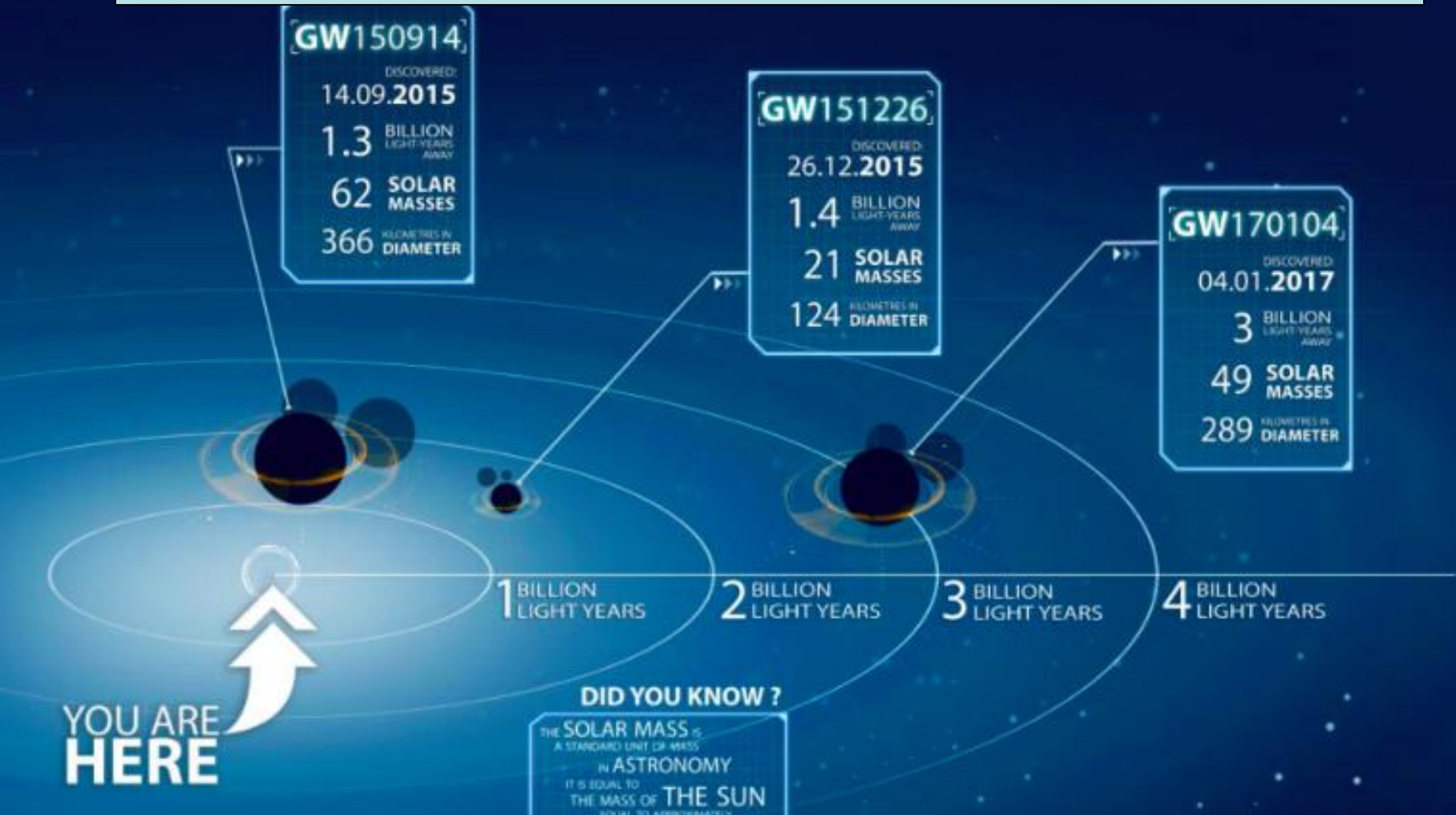




**Was that you I heard just now, or was it two black holes colliding?**



# LIGO GW detections



Excellent video explanation:

<http://motls.blogspot.ch/2016/02/brian-greenes-ligo-colbert-lecture-was.html>