



# Gravitational Wave Astronomy Begins!

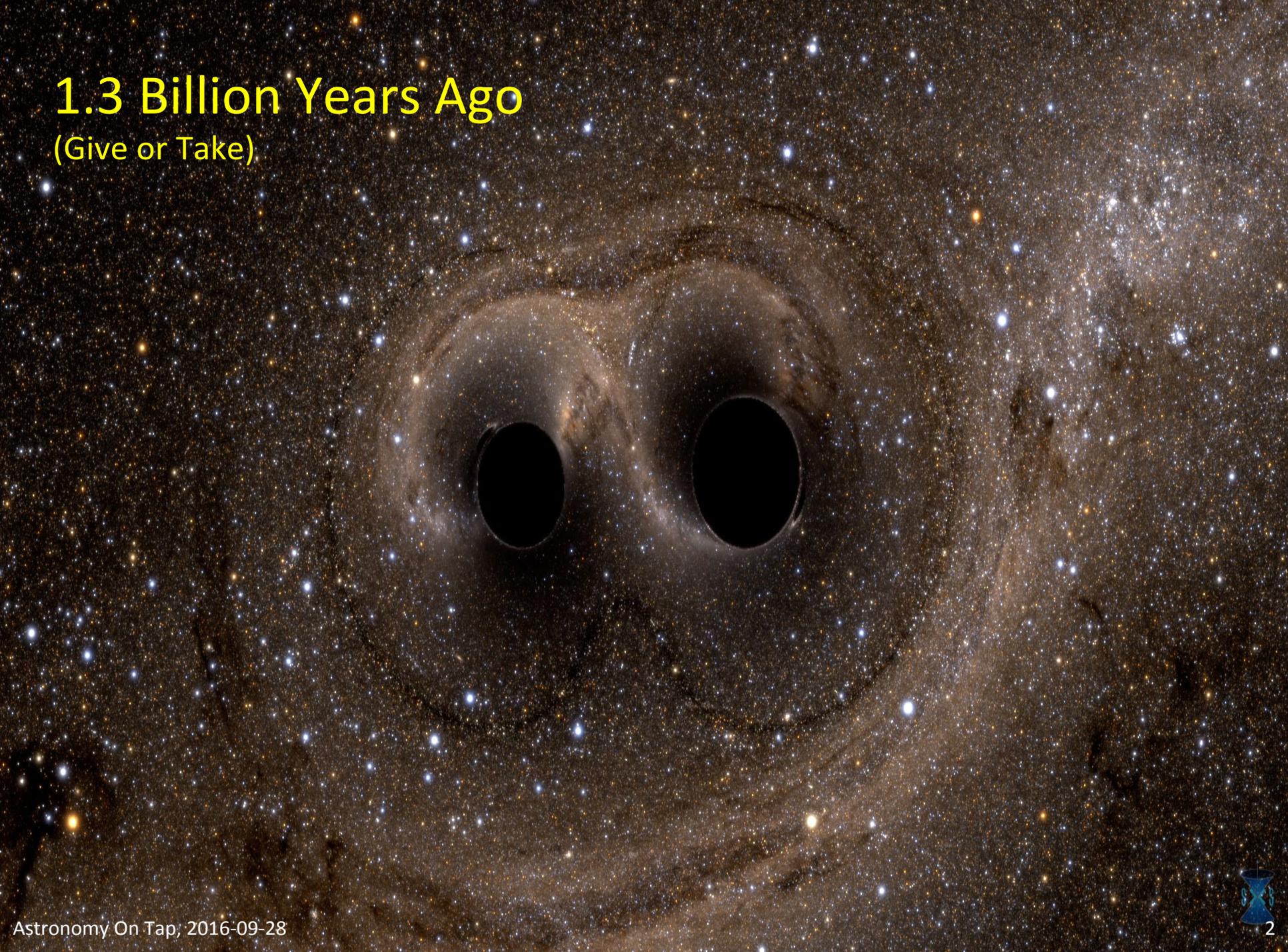
J. Kissel

on behalf of the

LIGO Scientific Collaboration

# 1.3 Billion Years Ago

(Give or Take)



Slowed down ~100x: this lasts 1/3 sec in real time

One  $36 M_{\odot}$   
black hole

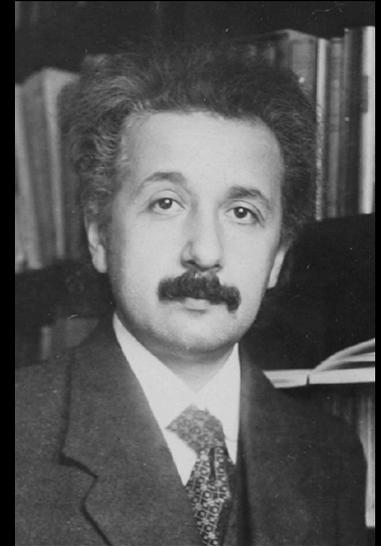
One  $29 M_{\odot}$   
black hole

Final black  
hole  $62 M_{\odot}$

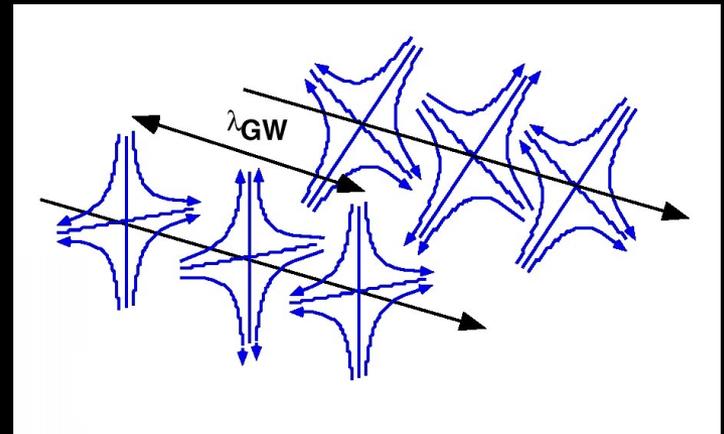


# Gravitational Wave Basics

*Gravitational Waves from binary black hole merger are passing the tip of the handle in the Big Dipper...*



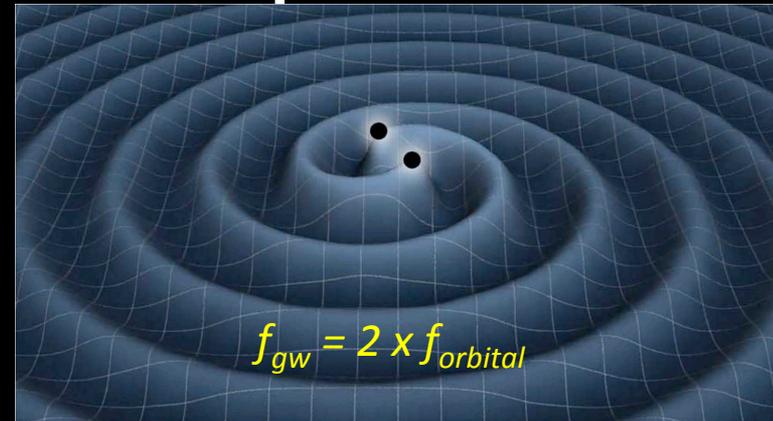
- Einstein, in **1916**, recognized gravitational waves in his theory of General Relativity
  - Necessary consequence of Special Relativity with its finite speed for information transfer
  - Distinctive departure from Newtonian theory
- Time-dependent distortions of space-time created by the acceleration of masses
  - Propagate at the speed of light
  - Pure **quadrupolar waves**, with two orthogonal polarizations



# Gravitational Wave Properties

GW generation: quadrupole formula

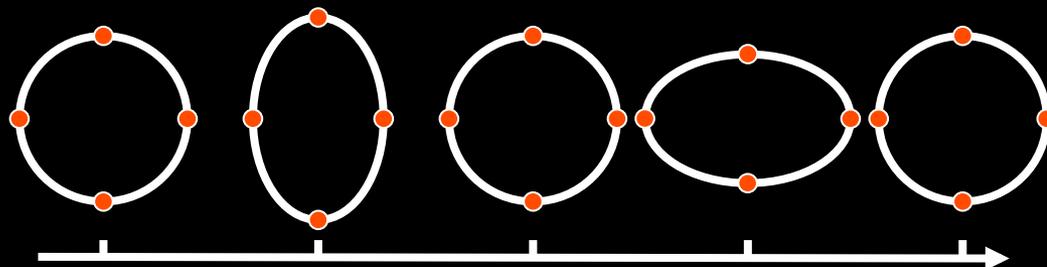
metric perturbation  $h = \frac{2G}{c^4 r} \ddot{I}$  ← quadrupole moment



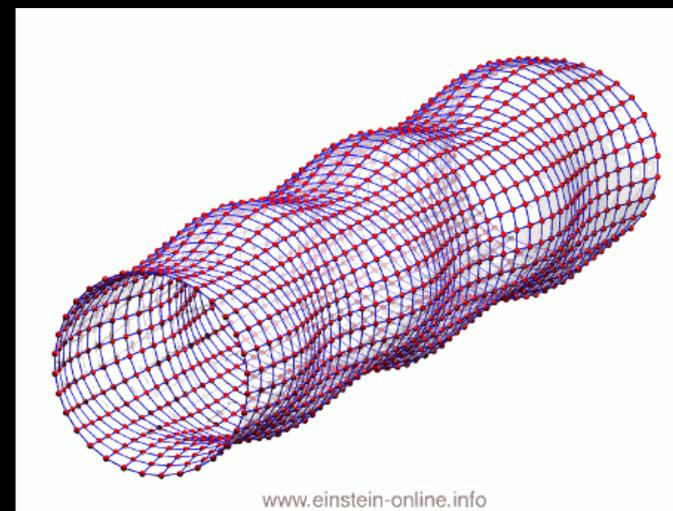
Two **BIG** masses  $m$  in a circular orbit:

$$h = \frac{2Gm}{c^4 r} (2\pi f_{gw})^{2/3} = 1.5 \times 10^{-21} \left( \frac{m}{30M_{\odot}} \right) \left( \frac{400 \text{ Mpc}}{r} \right) \left( \frac{f_{gw}}{50 \text{ Hz}} \right)^{2/3}$$

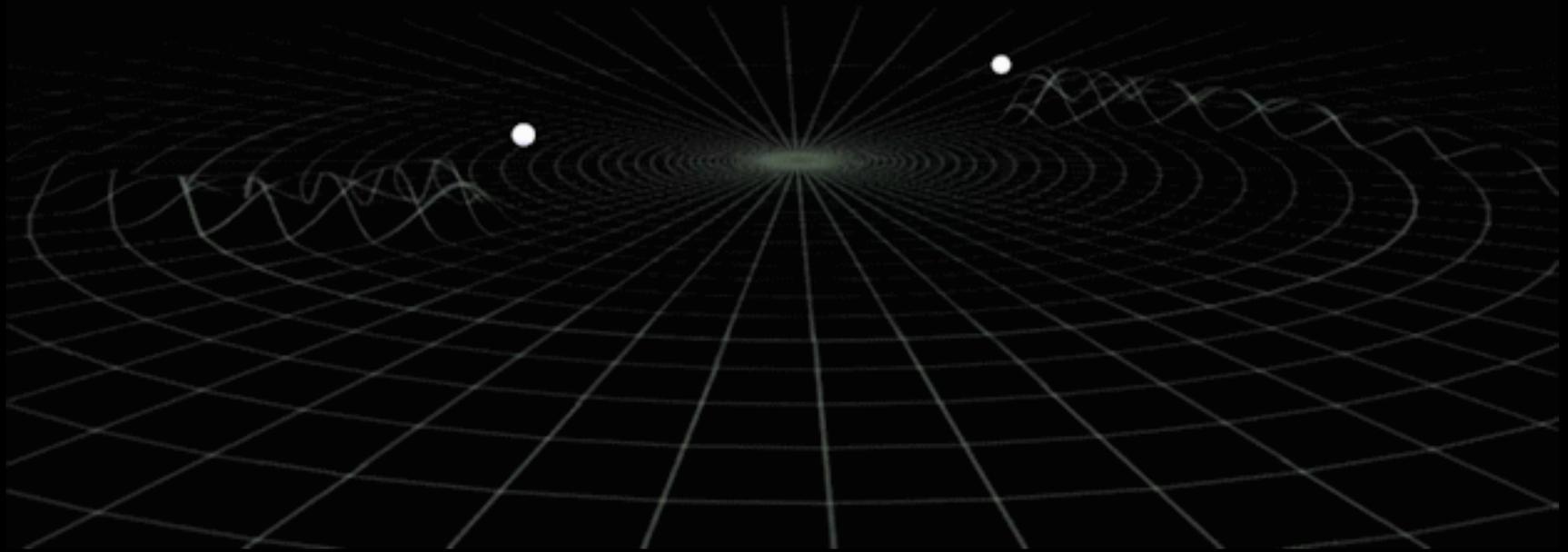
**Typical  $h = 1.5e-21$  !!**  
**1/1000 of proton diameter!!**



Here, strain  
 $h = 0.4$  !



# Gravitational Wave Signature For Colliding Black Holes...



# Brief History of LIGO

*Gravitational wave from the merger pass...*

*Arcturus  
in Bootes*

- **1972**  
Original concept:, Rai Weiss

- **1994 – 2000**  
Two LIGO observatories  
constructed

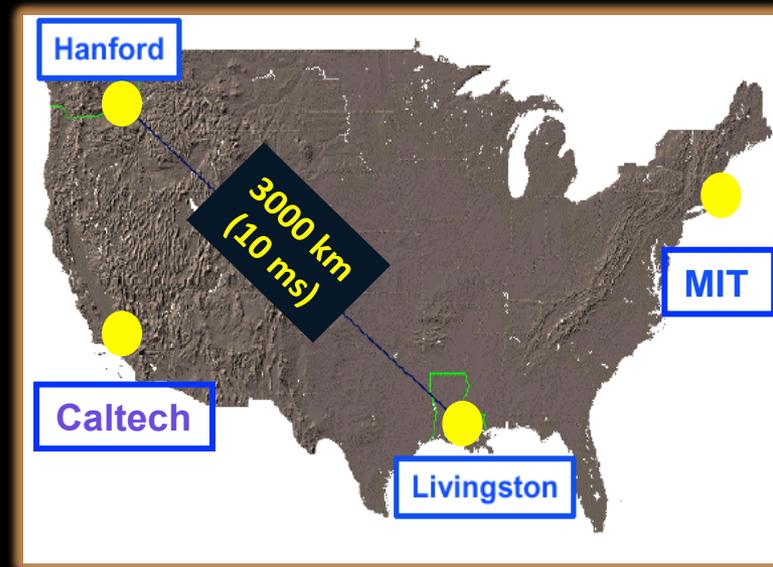
*Sirius A&B  
in Canis Major*

- **2002 – 2007**  
**Initial LIGO**

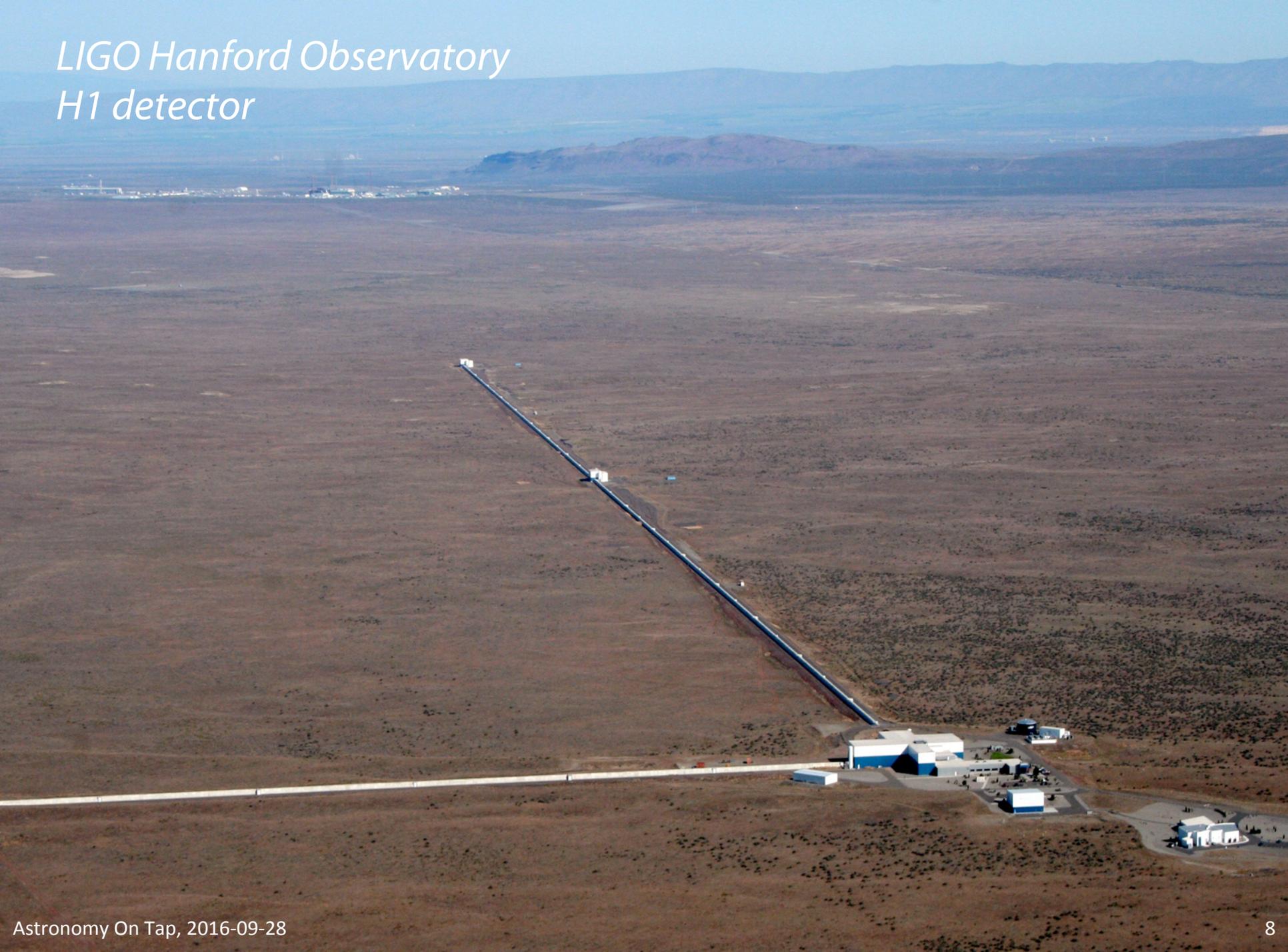
*Proxima Centauri*

- **2008 – 2010**  
Enhanced LIGO operated

- **2014**  
Advanced LIGO upgrade  
construction completed



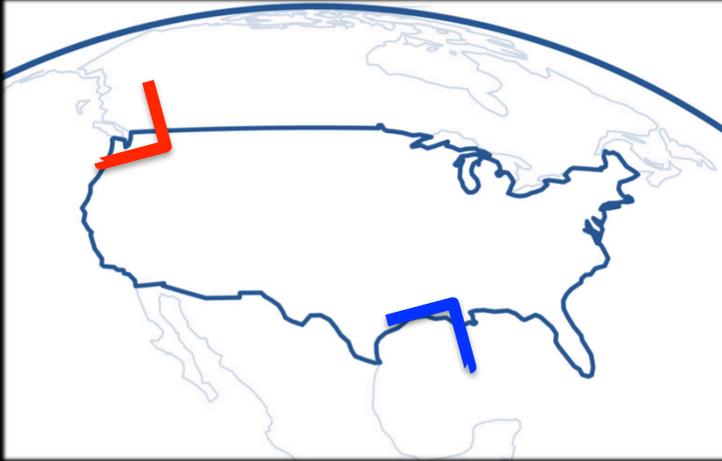
*LIGO Hanford Observatory  
H1 detector*



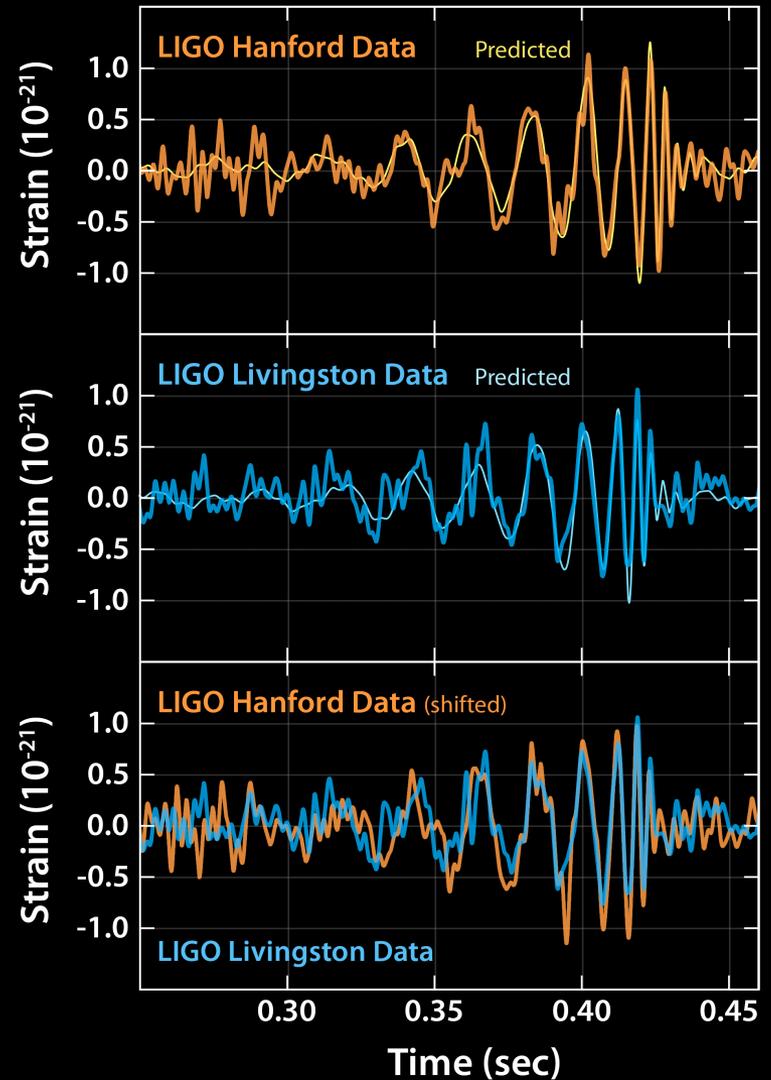
*LIGO Livingston Observatory  
L1 detector*



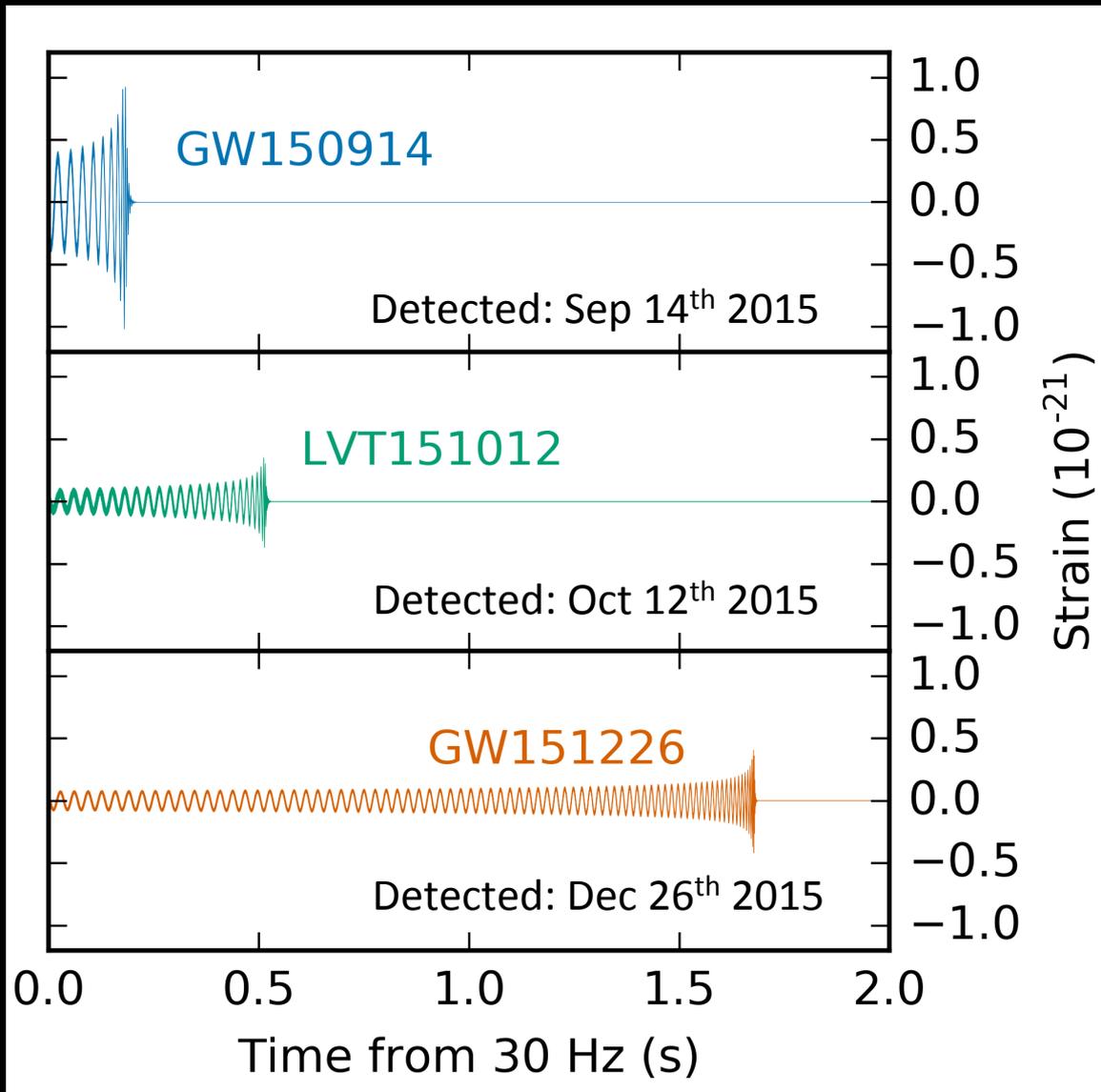
# Then, on 14 September 2015 ...



The gravitational waves from this merger passed through the LIGO detectors!



# Then Again (Twice!) in 4 months



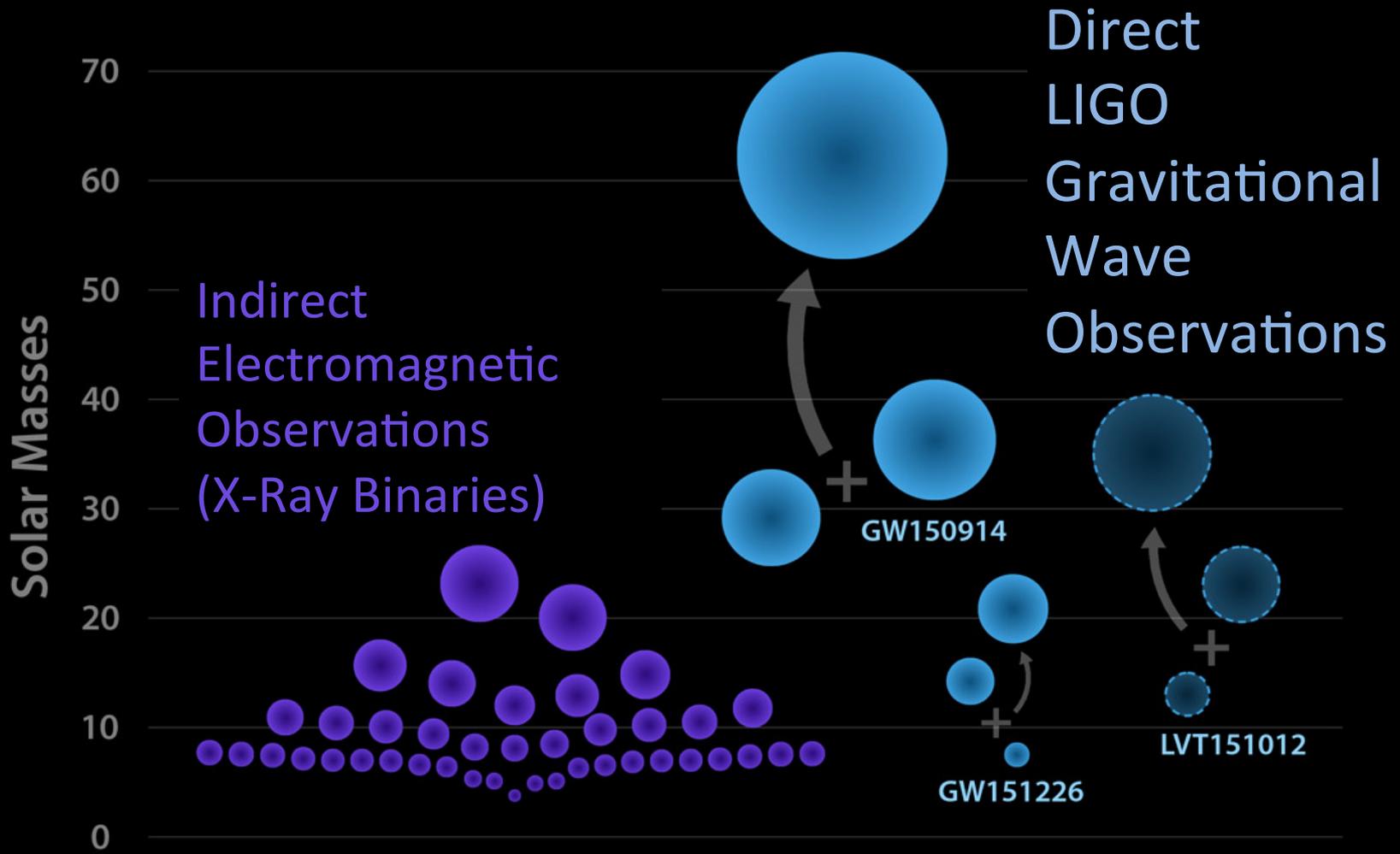
**36  $M_{\odot}$  + 29  $M_{\odot}$   
1.3 billion ly away**

**23  $M_{\odot}$  + 13  $M_{\odot}$   
3.3 billion ly away**

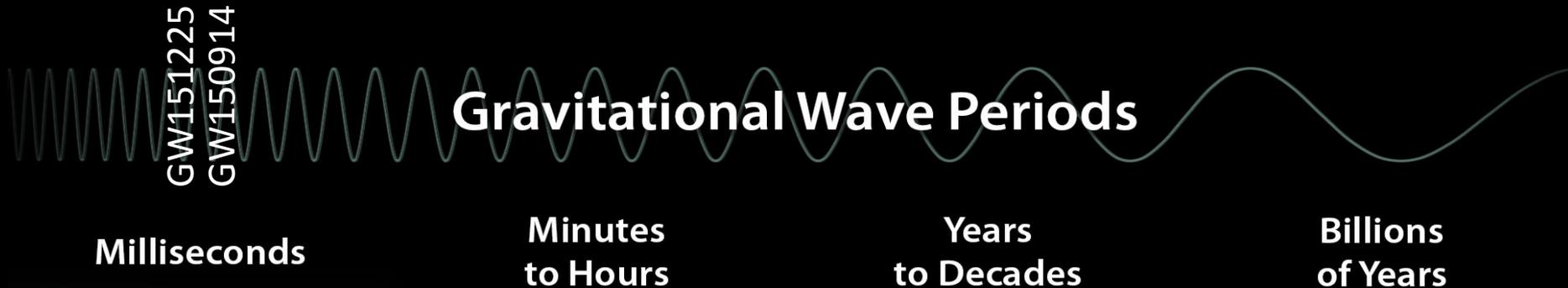
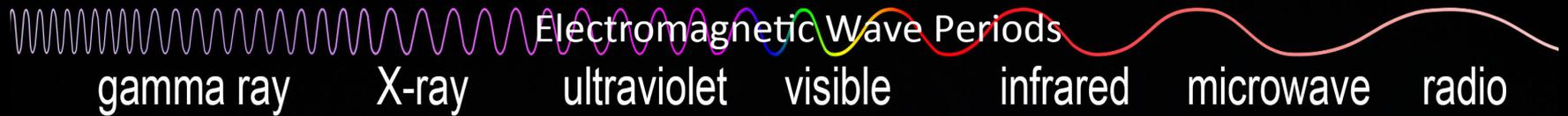
**14  $M_{\odot}$  + 7.5  $M_{\odot}$   
1.4 billion ly away**

<https://dcc.ligo.org/LIGO-P1600088/public>

# Gravitational Wave Astronomy Has Begun! Black Holes of Known Mass



# The Future of Gravitational Wave Astronomy



Merging  $\sim$ solar mass compact stars and **black holes**, galactic supernovae and pulsars

Galactic Nuclei swallowing  $\sim$ solar mass stars

Supermassive Black Holes in Galactic Nuclei

Quantum Fluctuations of the Early Universe

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Quantum Fluctuations of the Early Universe

## Gravitational Wave Periods

Milliseconds

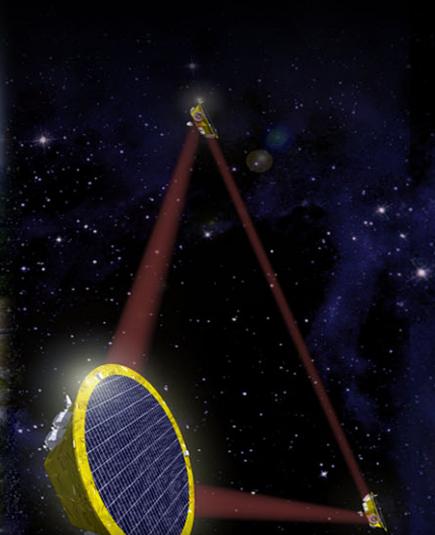
Minutes to Hours

Years to Decades

Billions of Years



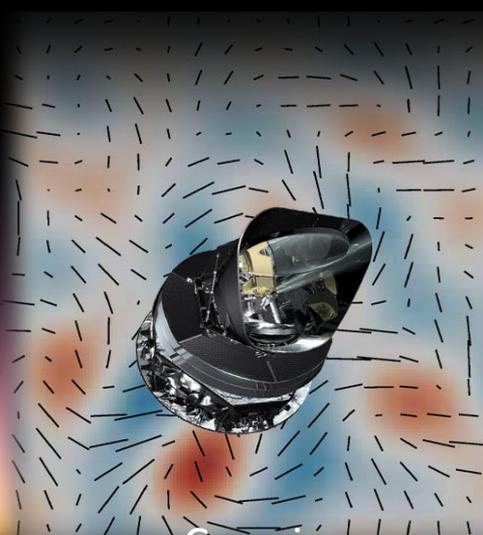
Ground-based Interferometers



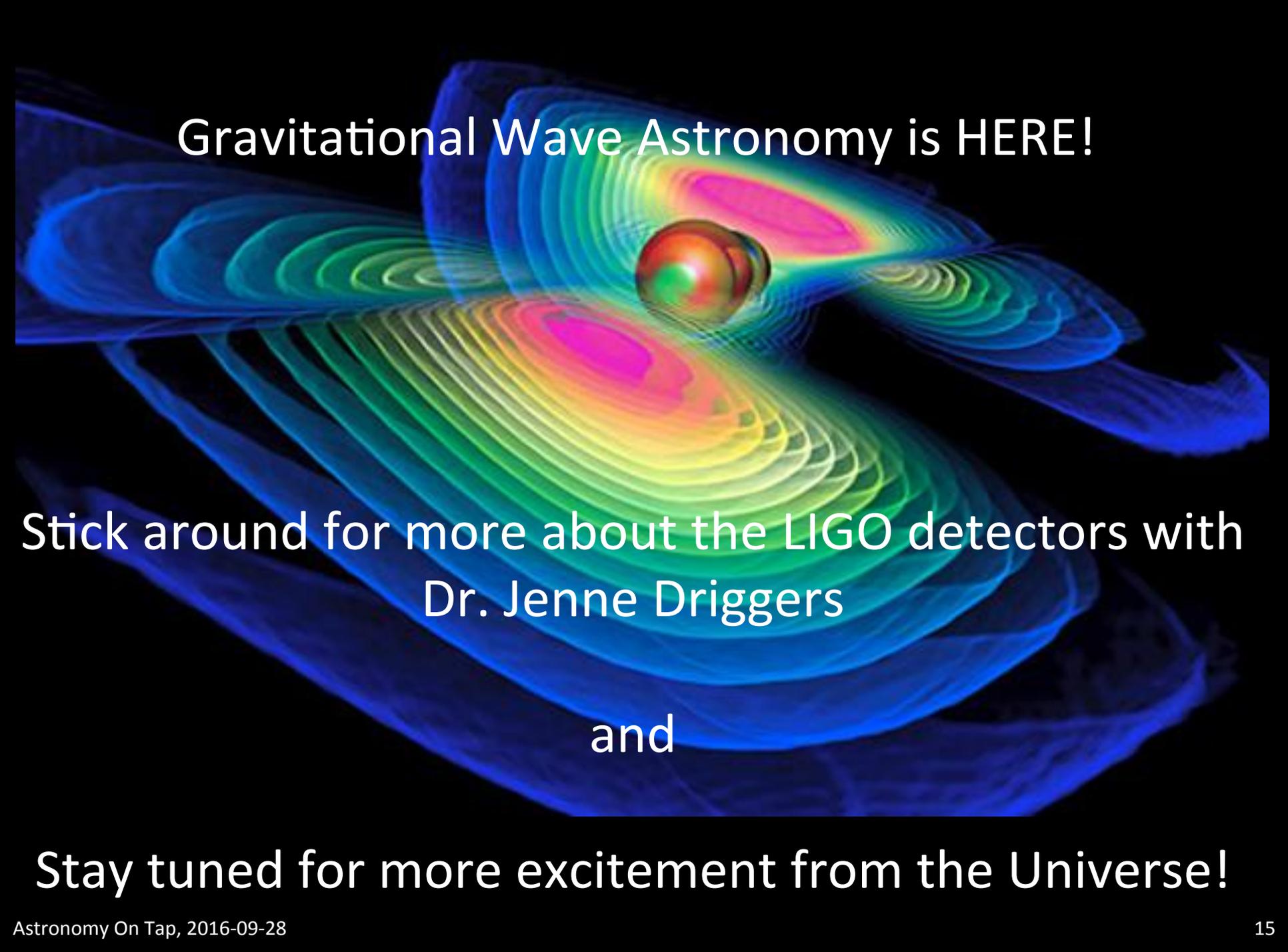
Space-based Interferometers



Pulsar Timing Arrays



Cosmic Microwave Background



Gravitational Wave Astronomy is HERE!

Stick around for more about the LIGO detectors with  
Dr. Jenne Driggers

and

Stay tuned for more excitement from the Universe!