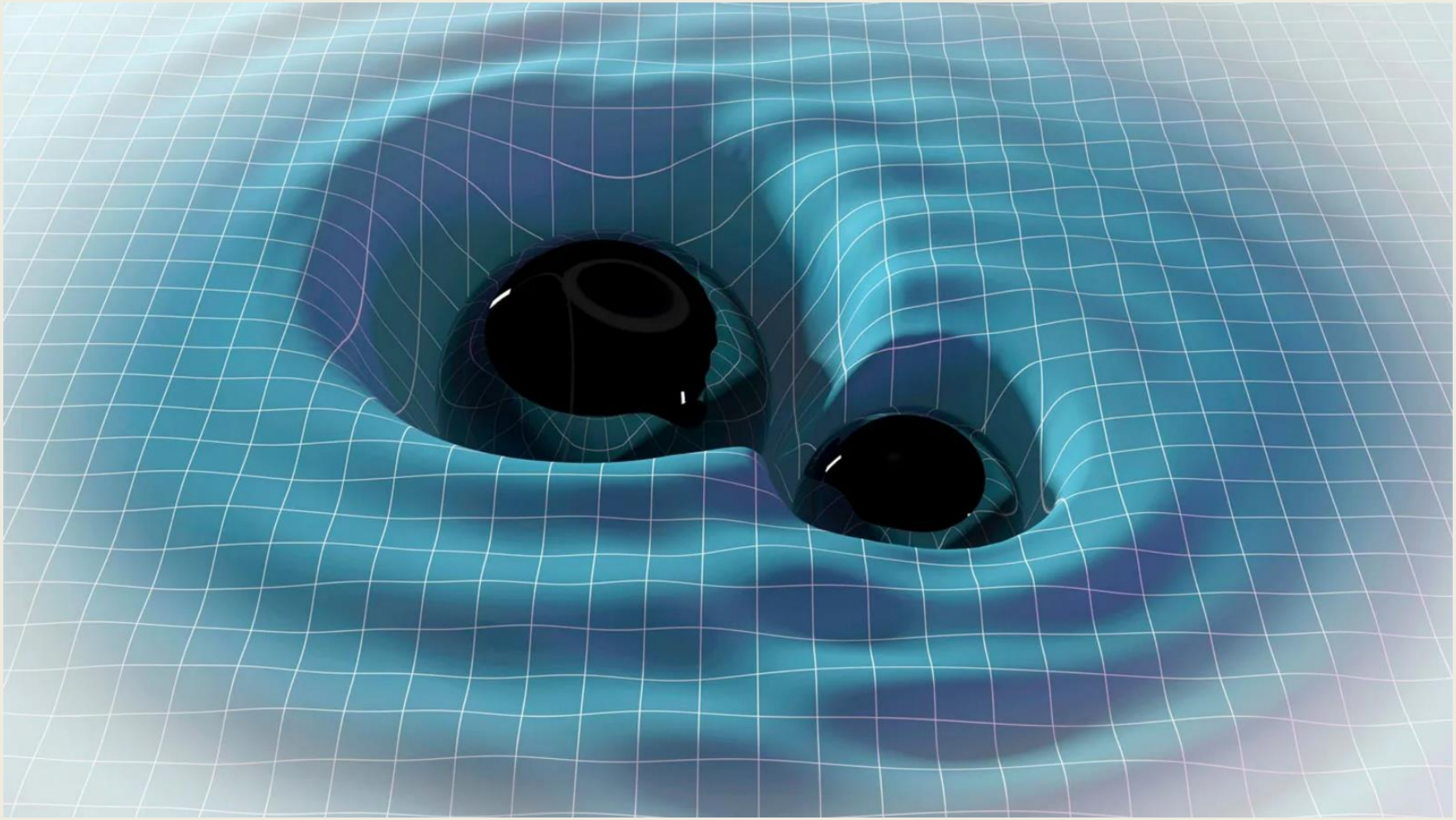
Gravitational Waves



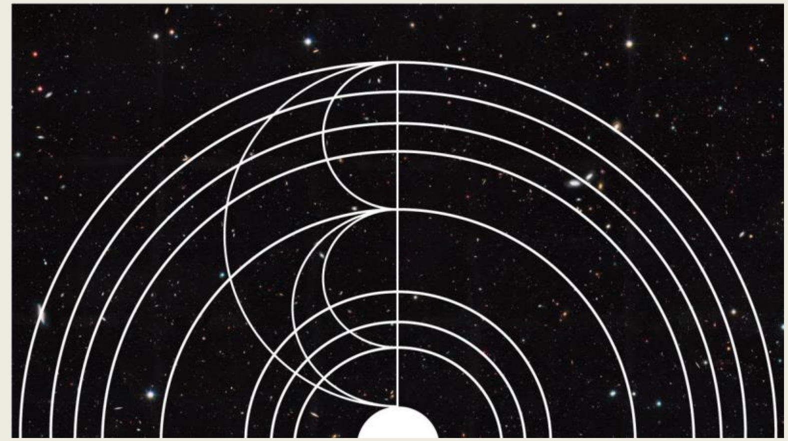
MARK GARLICK/SCIENCE PHOTO LIBRARY/GETTY IMAGES PLUS

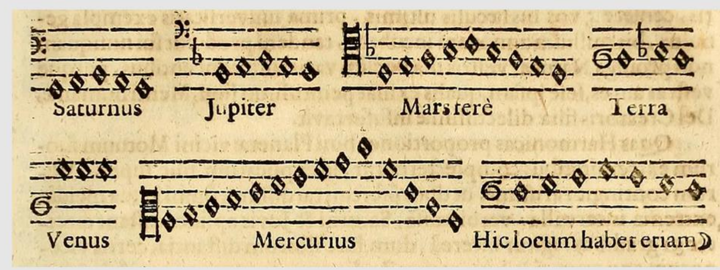
Gravitational Waves

Jorge Luis Borges. The Library of Babel. 1941

$$R^{\nu}_{\mu} - \frac{1}{2}\delta^{\nu}_{\mu}R + \Lambda\delta^{\nu}_{\mu} = T^{\nu}_{\mu}$$

Albert Einstein.
General Relativity Theory.
Gravitational waves.1916

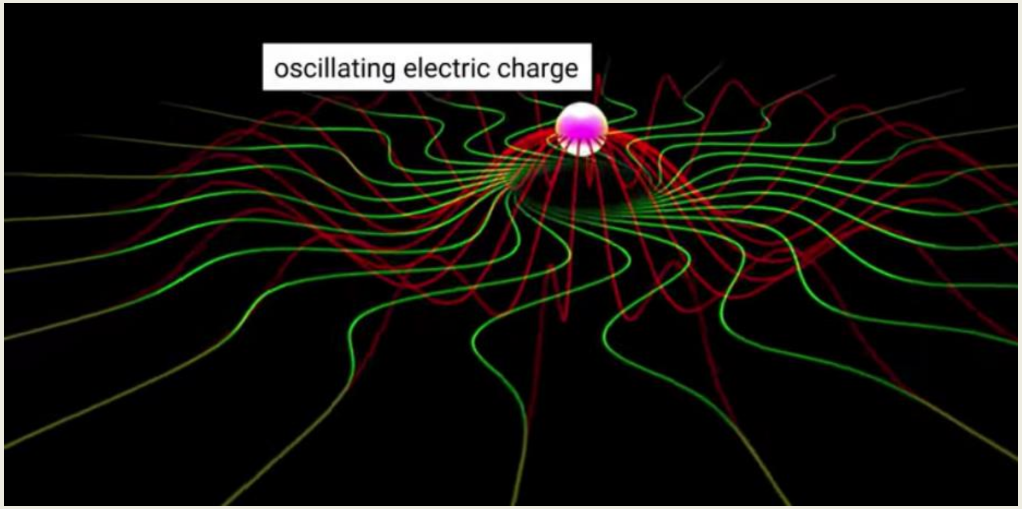




Celestial harmonics of the planets, from *The Harmony of the World* (1619) by Johannes Kepler, based on the Pythagorean concept of the Music of the Spheres.

Johannes Kepler feat. Pythagoras.
Music of the Spheres.1619

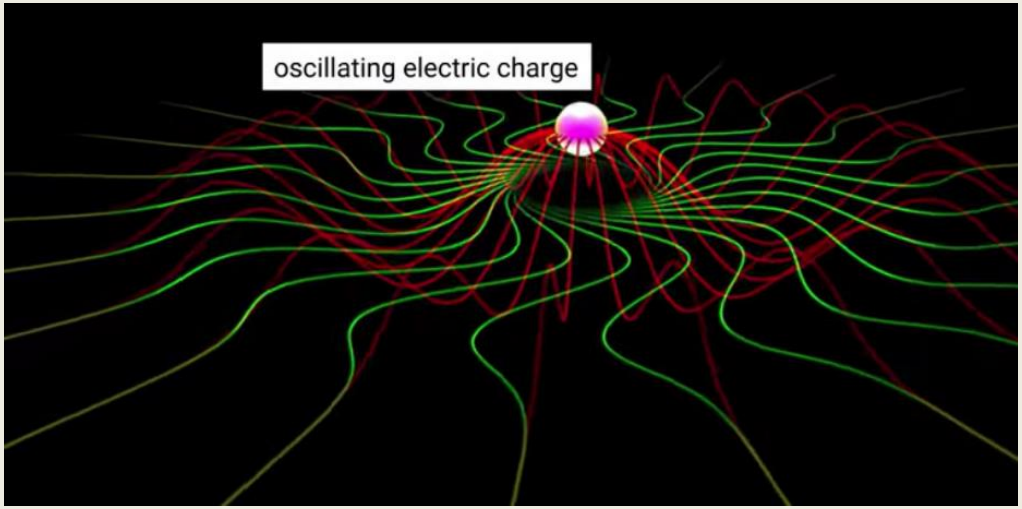
Accelerating charge produces electromagnetic waves



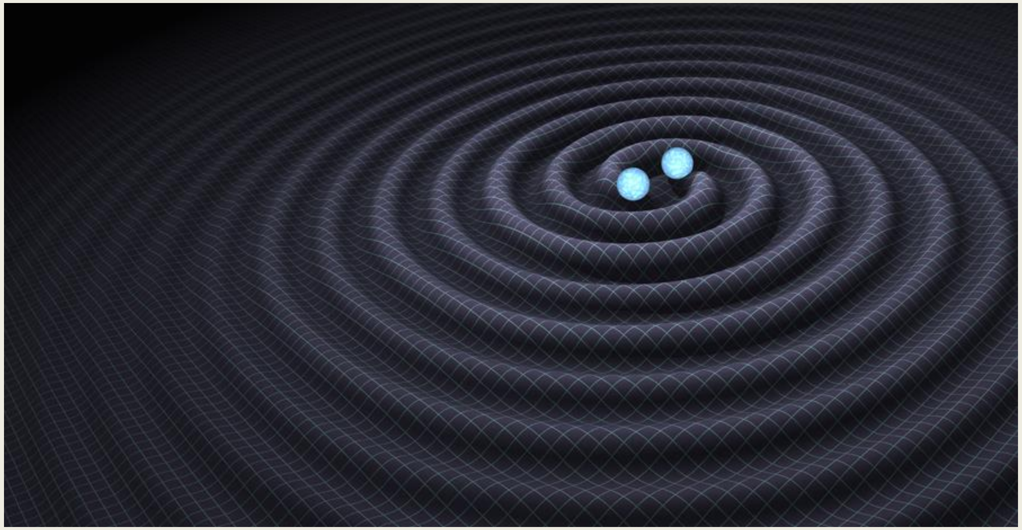
Accelerating mass produces gravitational waves

$$R_\mu^\nu - \frac{1}{2}\delta_\mu^\nu R + \Lambda\delta_\mu^\nu = T_\mu^\nu$$

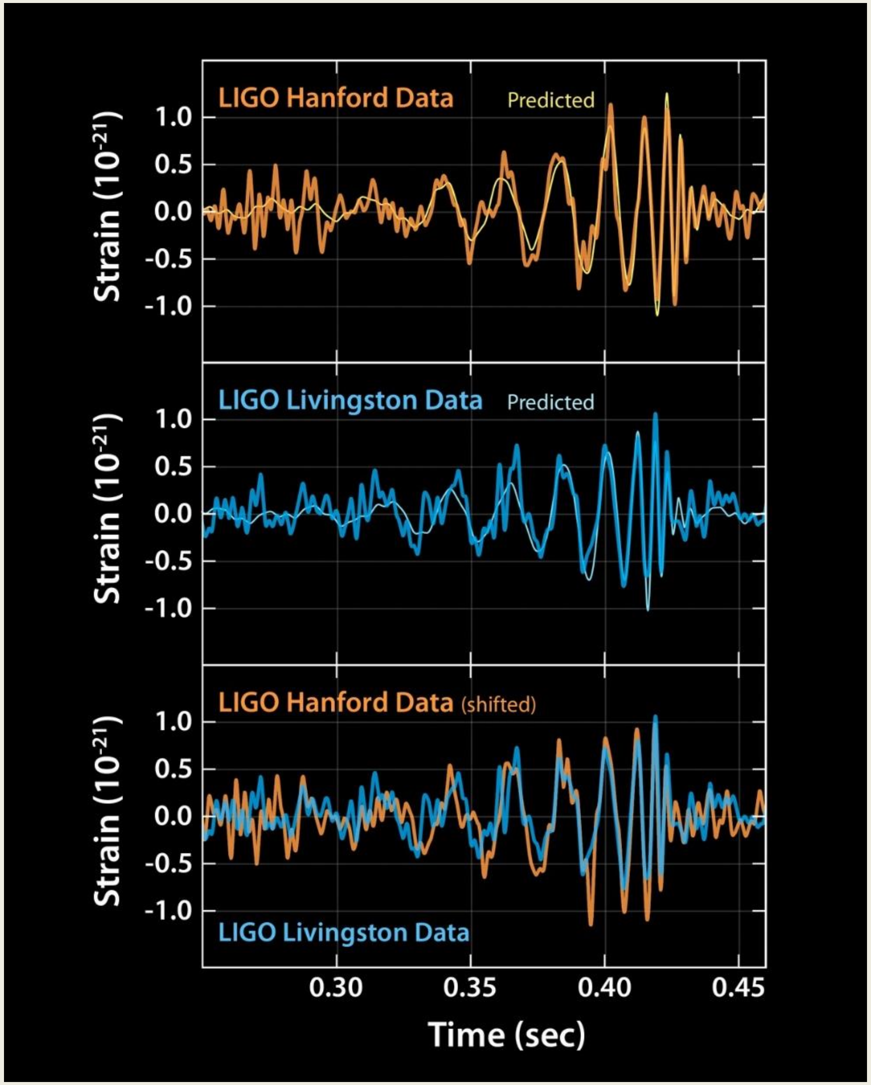
Accelerating charge produces electromagnetic waves



Accelerating mass produces gravitational waves



The First Event



September 14, 2015, the Laser Interferometer Gravitational Wave Observatory (LIGO) made the first direct detection of gravitational waves. These waves were produced by the merger of two black holes about 1.3 billion light-years away.

Strain

$$h \sim \frac{GM}{c^2}\frac{(v/c)^2}{d}$$

https://youtu.be/QyDcTbR-kEA

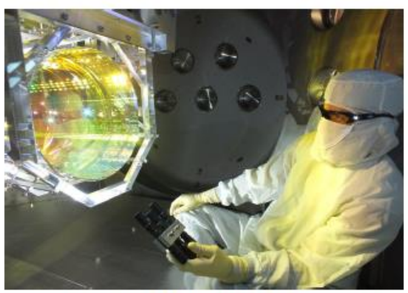
Strain

$$h \sim \frac{GM}{c^2}\frac{(v/c)^2}{d}$$

M **is the binary's total mass,**
v **its velocity near merger and**
d **its luminosity distance to Earth**

- change in distance: $\frac{\Delta L}{L} \sim \frac{GM}{c^2}\frac{(v/c)^2}{d} \approx 10^{-21}$
- e.g.:
  - L(London - NY) $\sim 5500km \Rightarrow \Delta L \sim$ proton
  - L(Earth - Proxima Centauri) $\sim 4.2ly \Rightarrow \Delta L \sim$ human hair
- "tricks:"

really sensitive microphone | make microphone enourmous | keep everthing really quiet



(credit: Caltech/MIT/LIGO Laboratory)

detector network

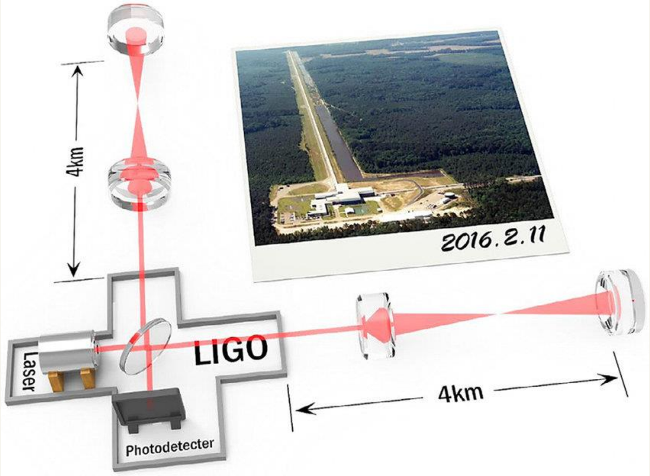
LIGO Livingston

[a] $M = 60M_\odot$, $v/c \sim 0.5$, $d \sim 1.4$billionly; $M_\odot \sim 2 \cdot 10^{30} kg$; $1ly = 9.4 \cdot 10^{12} km$

Credit: Helvi Witek. Lectures for King's College London

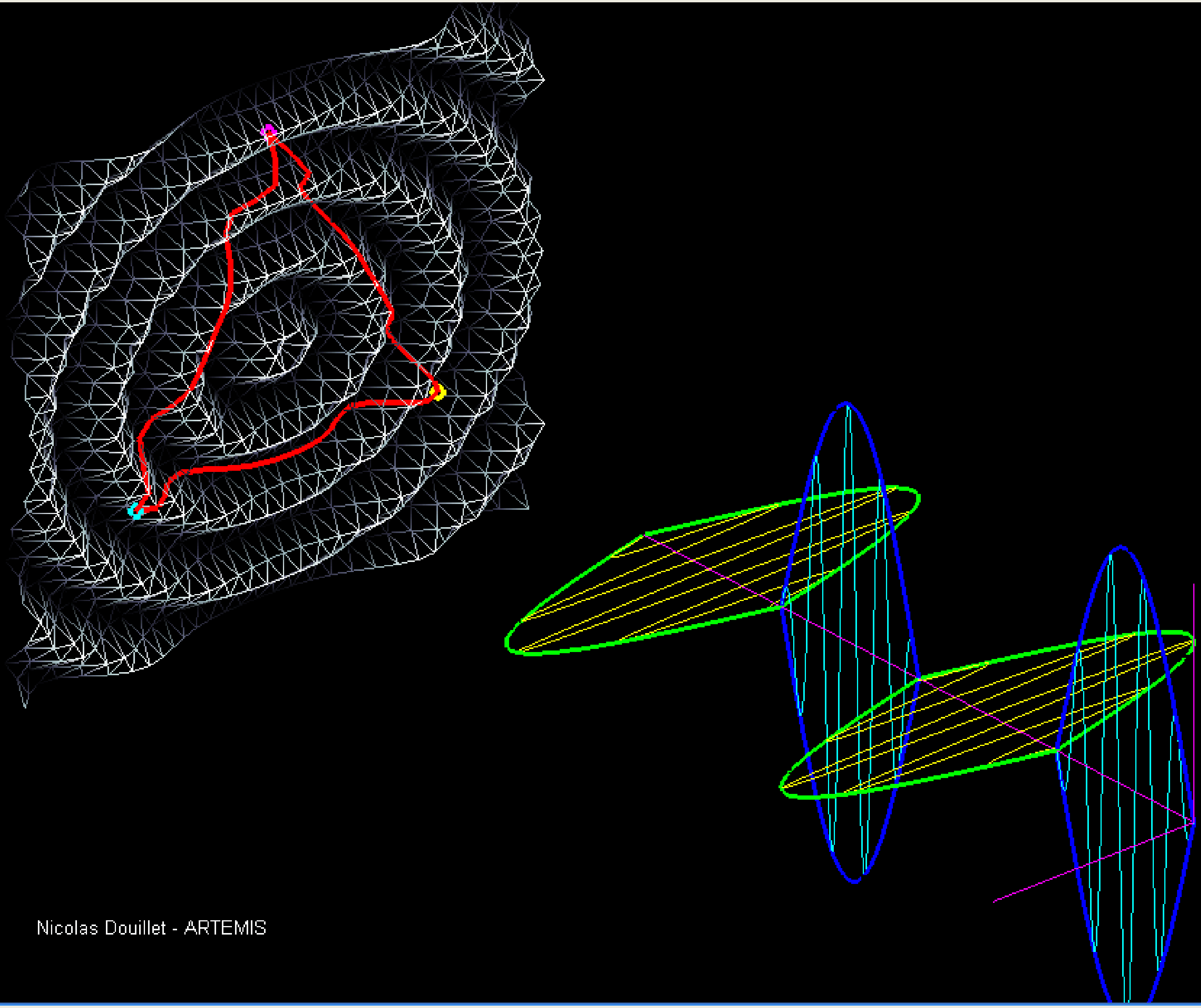
How can we detect it at all?

Laser
Interferometer
Gravitational wave
Observatory!



https://www.ligo.org/detections/GW150914.php

https://youtu.be/tQ_teIUb3tE



Nicolas Douillet - ARTEMIS

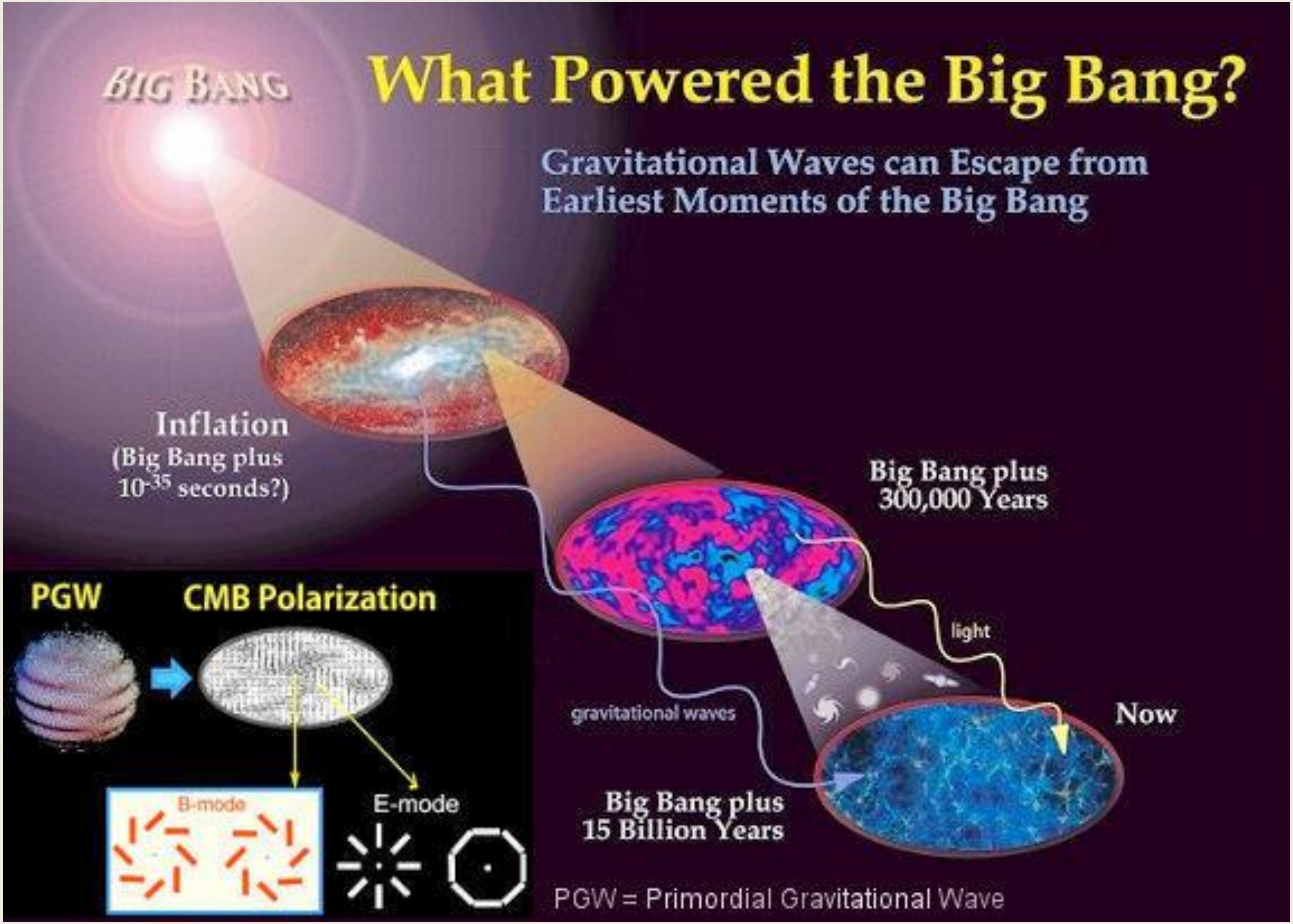
What can we find from gravitational waves?

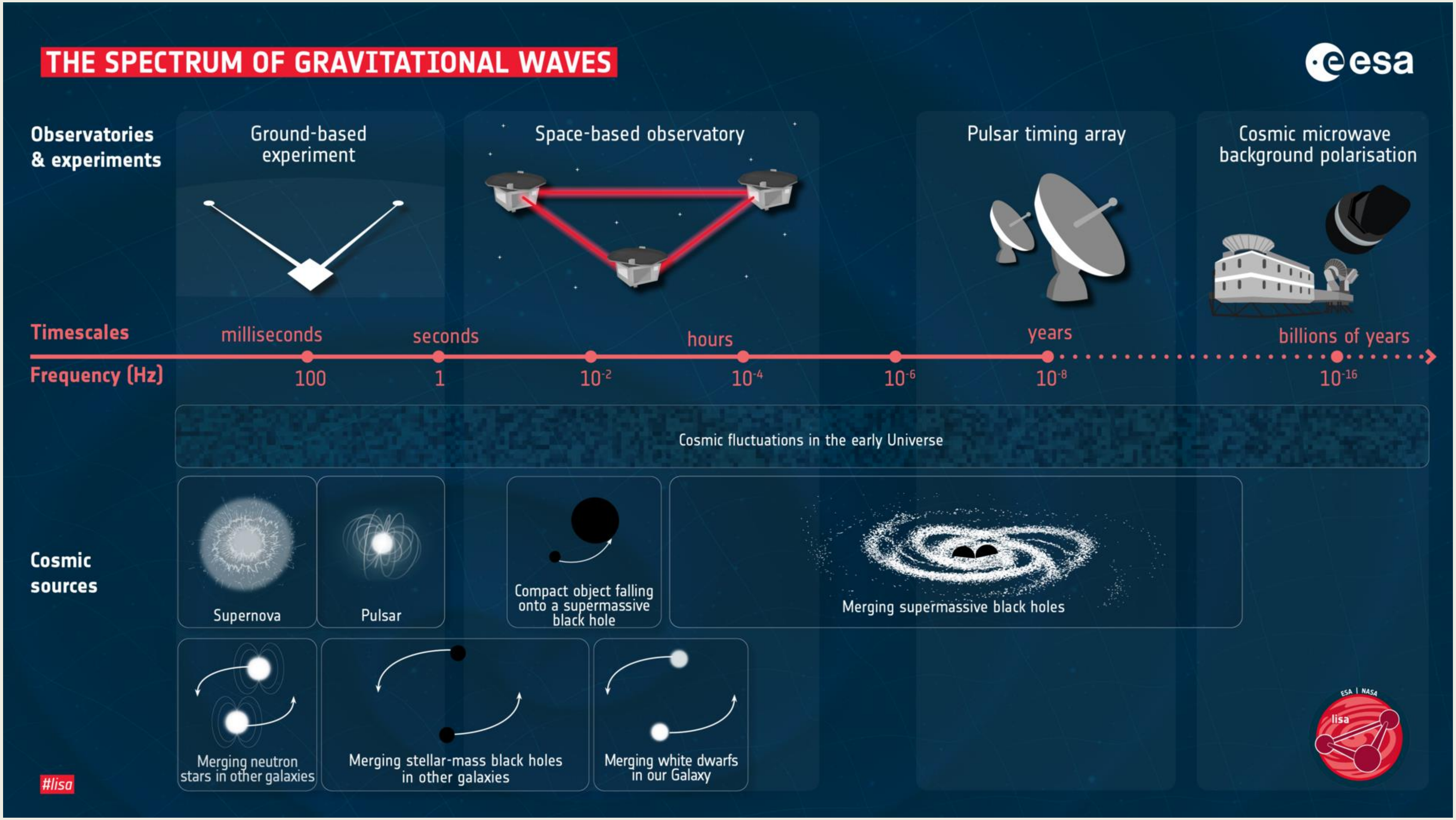
Cosmology

- **Primordial Gravitational Waves**
- **Cosmic Microwave Background (CMB) Polarization**
- **Large-Scale Structure of the Universe**
- **Phase Transitions**
- **Cosmic Strings**

Compact Objects

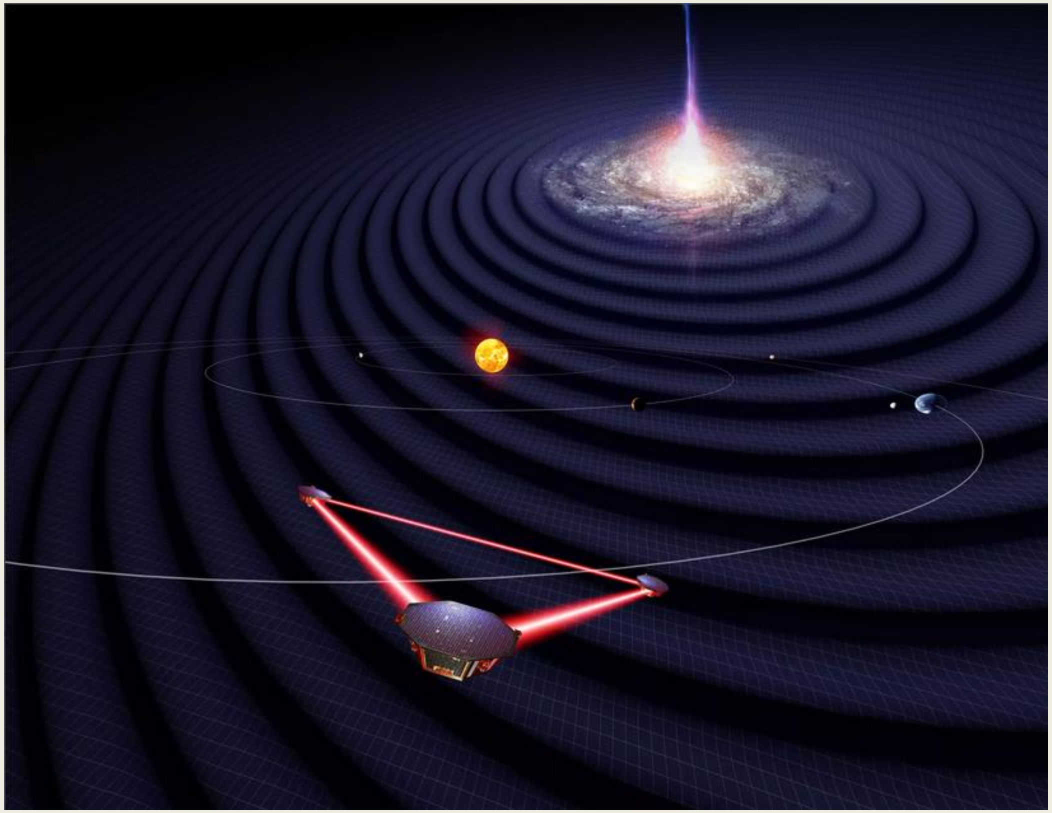
- **Astrophysical Sources**
- **Black Holes**
- **Neutron Stars**
- **Stellar Evolution**
- **Modified Gravity Theories**


BIG BANG
What Powered the Big Bang?
Gravitational Waves can Escape from
Earliest Moments of the Big Bang
Inflation
(Big Bang plus
10-35 seconds?)
Big Bang plus
300,000 Years
light
gravitational waves
Now
Big Bang plus
15 Billion Years
PGW
CMB Polarization
B-mode
E-mode
PGW = Primordial Gravitational Wave



Credit: European Space Agency

What's then?



Credit: University of Florida / Simon Barke (CC BY 4.0)

The Laser Interferometer Space Antenna (LISA) concept features three spacecraft arranged in an equilateral triangle with each side 2.5 million kilometers long, flying in an Earth-like heliocentric orbit. Launch date 2035 (planned).