Gravitational waves

A new tool for observing the Universe through ripples in spacetime

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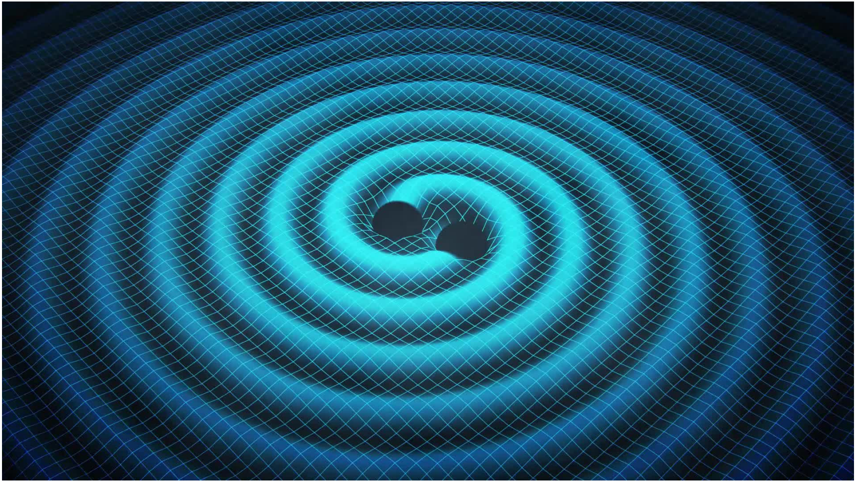
Executive summary

- 1915: Einstein's General Relativity predicts gravitational waves

$$R_{\mu\nu} = 0$$



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- 1915: Einstein's General Relativity predicts gravitational waves
- 1916: Schwarzschild constructs first black hole solution

$$\mathrm{d}s^2 = -(1-2M/r)\,\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{1-2M/r} + r^2\,\mathrm{d}^2\Omega_{S^2}$$

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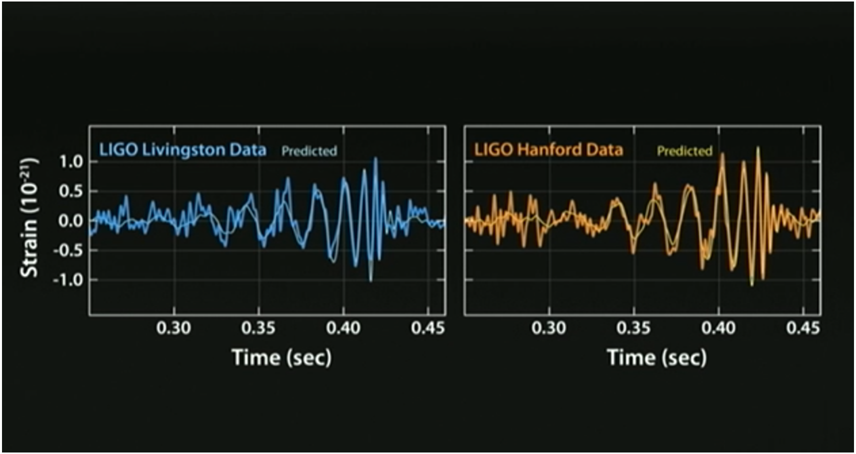

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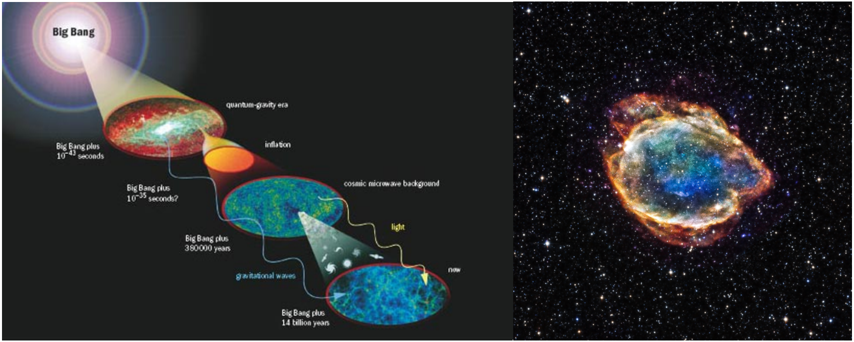
- 2115: gravitational waves standard tool in astrophysics & cosmology



Left: gravitational waves sensitive to early Universe, Right: Supernova

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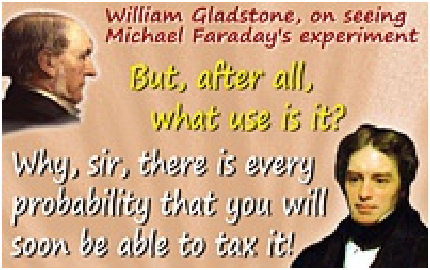
- 2116: someone pays taxes for gravitational waves



Disclaimer: quote above is commonly cited, but probably not authentic

Outline

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Theory

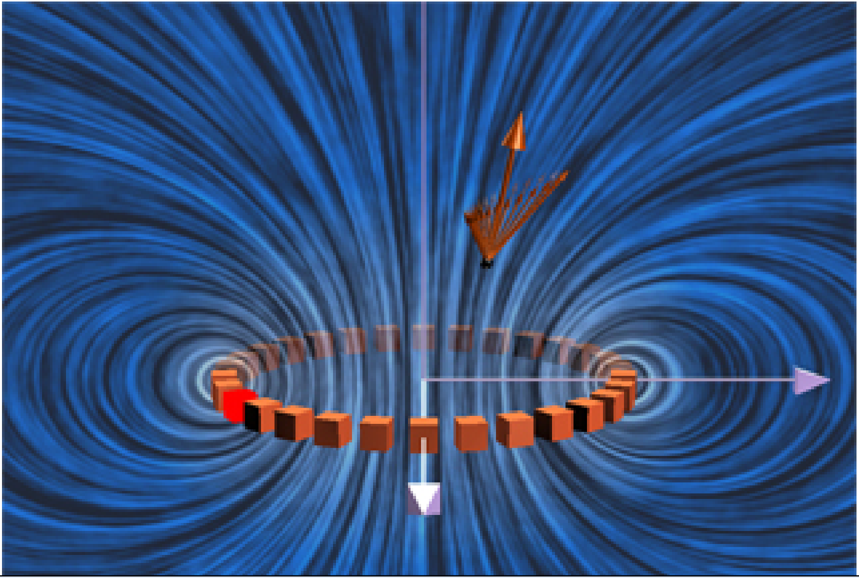
Technology

Observation

Applications

Warm-up: electromagnetism

- Electromagnetism: theory describing dynamics of charges



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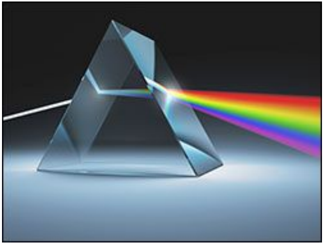
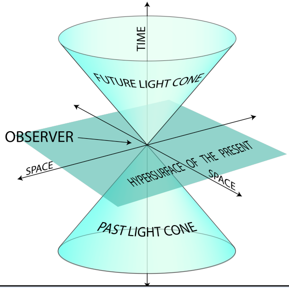
- Electromagnetism: theory describing dynamics of charges
- Unifies electricity, magnetism, optics and special relativity



$$E = mc^2$$



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- Quantum electrodynamics tested with amazing precision and accuracy

Example: gyromagnetic factor of electron

Experiment (2008):

$$\frac{g_e^{\text{exp}}}{2} = 1.00115965218073 \pm 0.00000000000028$$

Theory (2012):

$$\frac{g_e^{\text{the}}}{2} = 1.00115965218178 \pm 0.00000000000077$$

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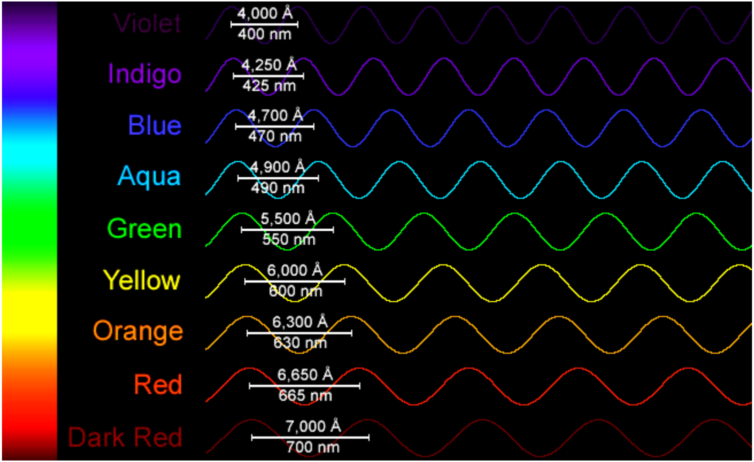

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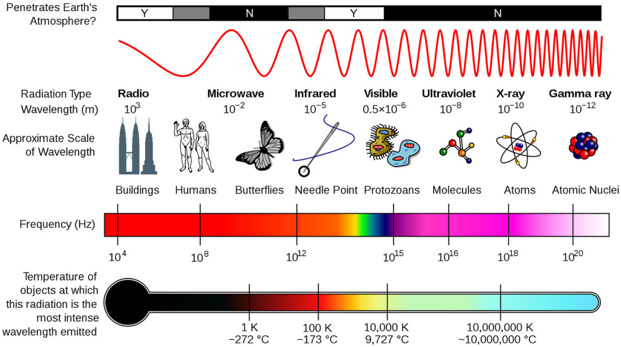

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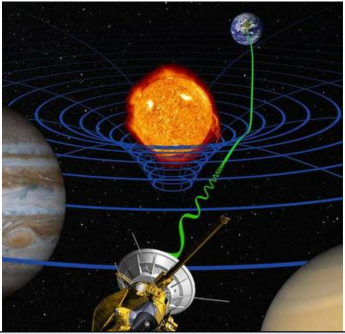

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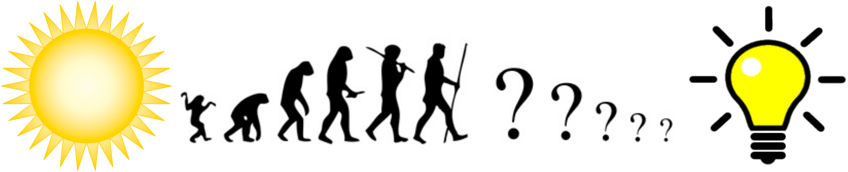
- First observation of light by humankind: about 2 million years ago



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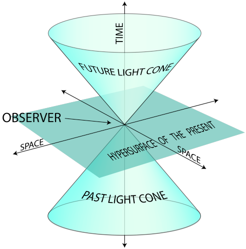

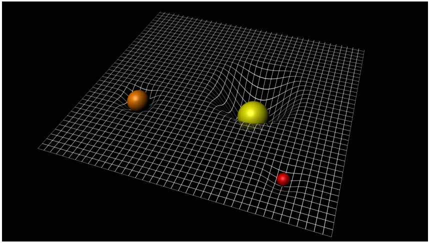

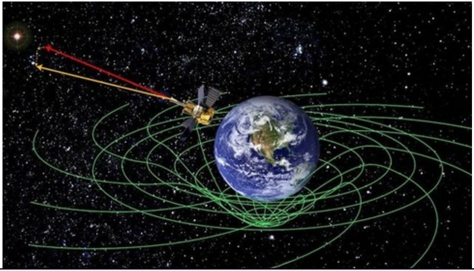

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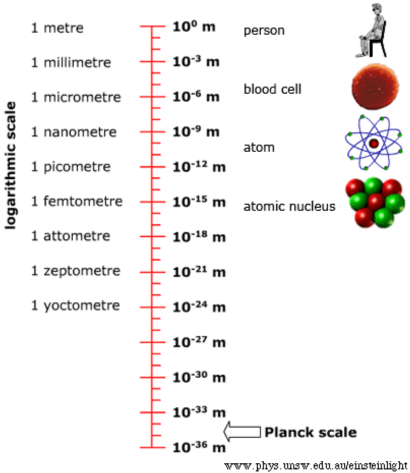

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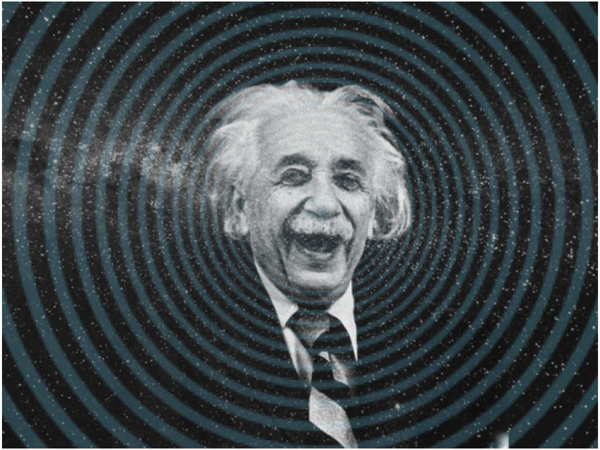

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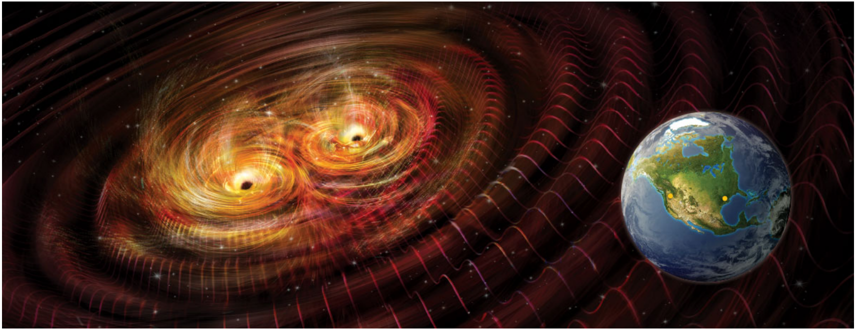

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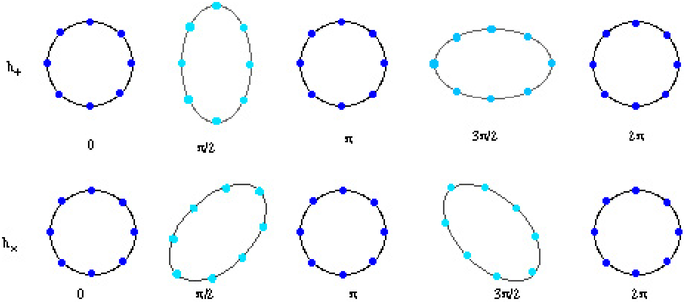

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- First observation of gravitational waves by humankind: about 200 days ago

Gravitational wave sources

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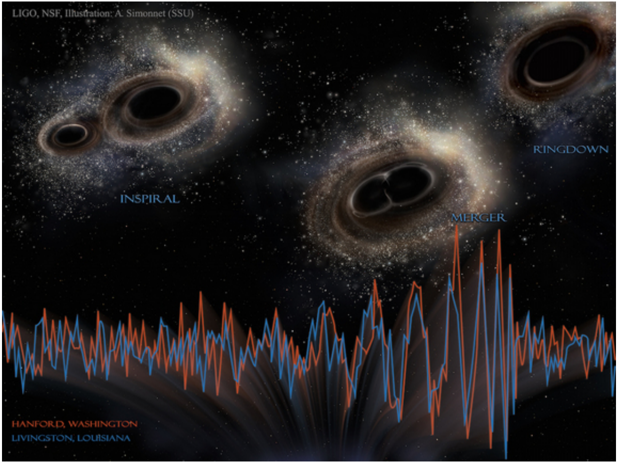

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- Simple calculation to estimate gravitational wave energy
  Take two Schwarzschild black holes of equal mass m
  Call final black hole mass M and gravitational wave energy E
  Energy conservation:

$$M + E = m + m \Rightarrow E = 2m - M$$

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Get upper bound on gravitational wave energy

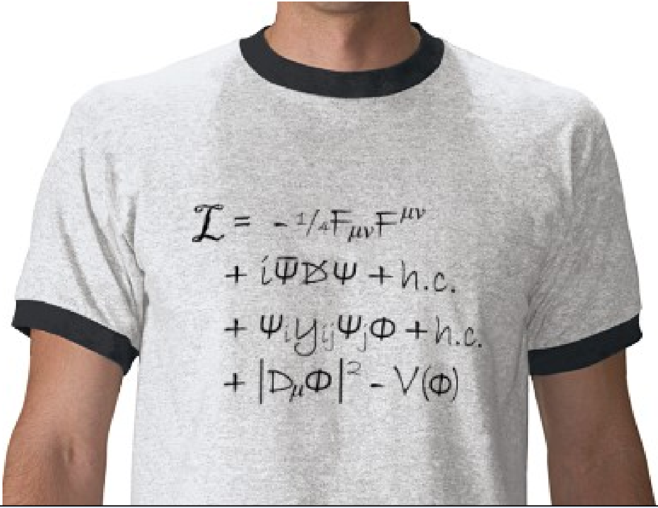
$$E \leq (2 - \sqrt{2})m \approx 29\% \text{ of initial energy}$$

Energy released by $10^{34} - 10^{36}$ Nagasaki bombs!

Gravitational waves as the last known puzzle piece

Big questions: what is the Universe made of? what are the fundamental forces?

- All known forces of Nature described with amazing precision through the Standard Models of particle physics and Cosmology



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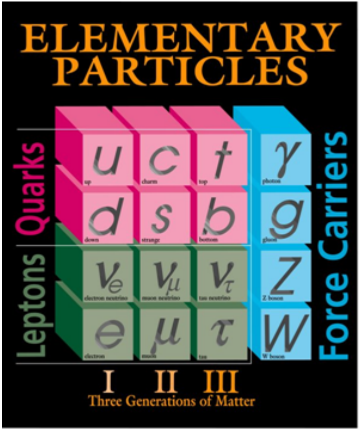

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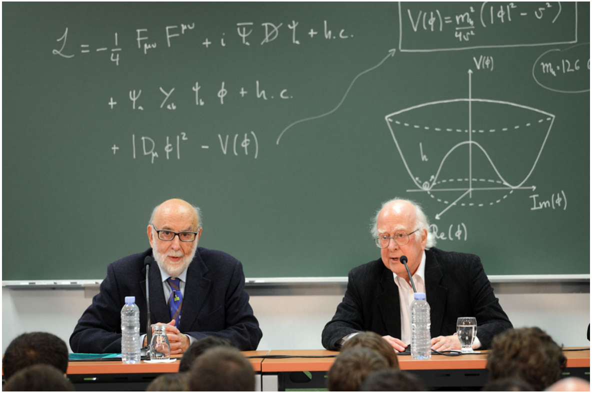

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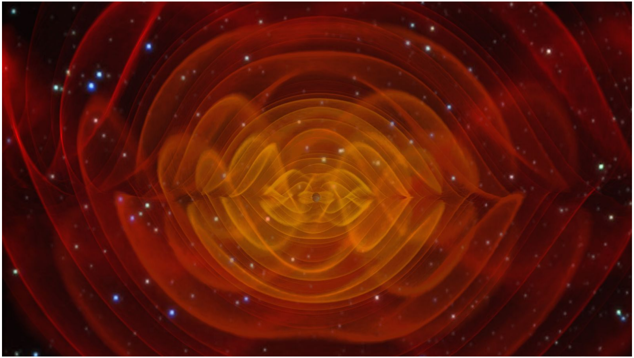

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Amazing achievement of humanity from late 1600 till early 2000!

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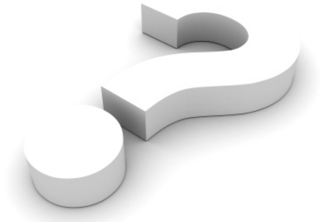

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- Yes: the dark side of the Universe! (dark matter, dark energy)
  Understanding the dark side may take a couple of decades — interesting times for fundamental physics!

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> We may be lucky and witness not only the completion of the Standard Models, but also a first glimpse into the dark side of the Universe within our lifetimes!

Outline

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Typical gravitational waves change spatial distances by a small fraction of the size of a proton!

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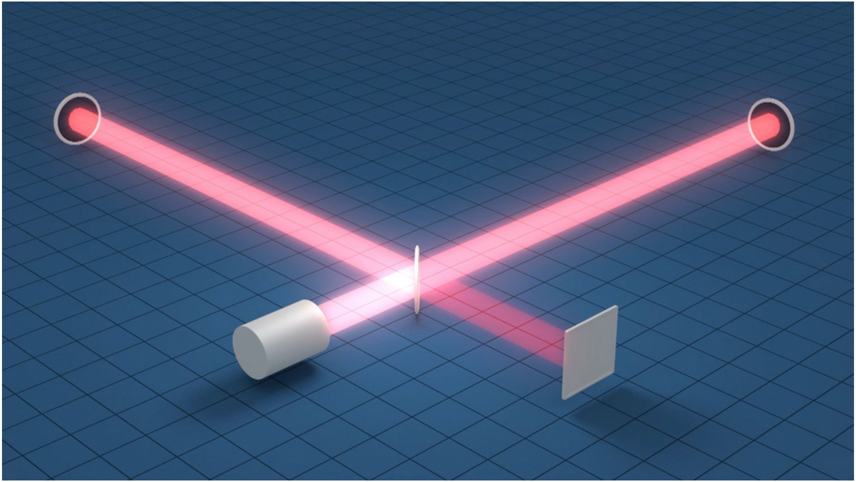

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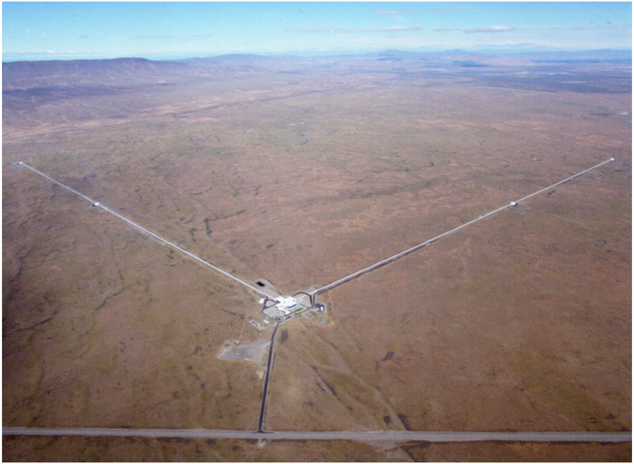

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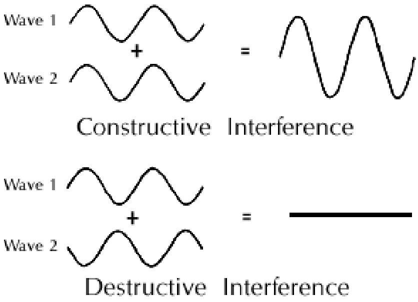

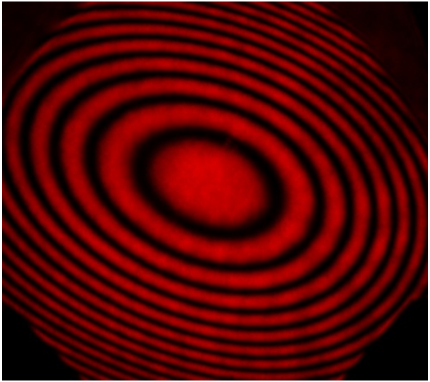

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(Advanced) LIGO needed 25 years of development and 500 million $ investment, involving more than 900 scientists and engineers

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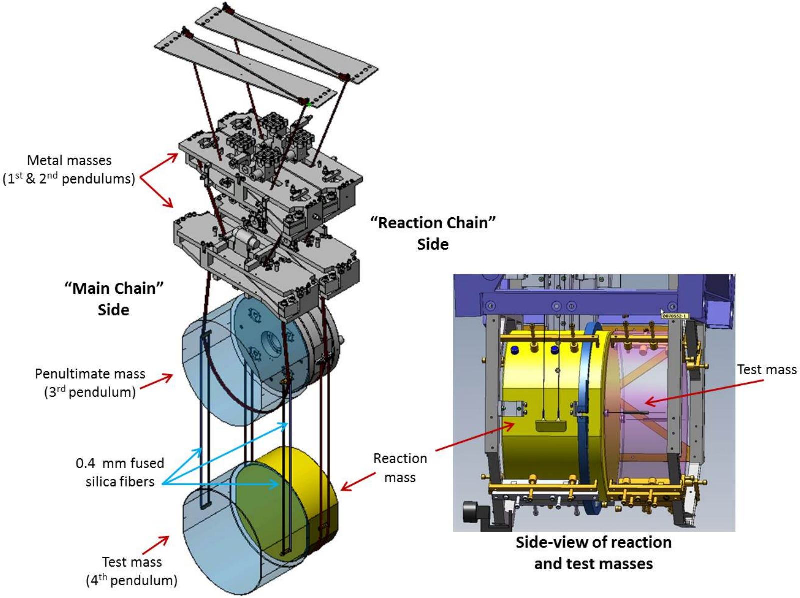
- Reduce errors by having two identical experiments, one at West coast (Hanford, Washington), one at East coast (Livingston, Louisiana)
- Reduce local errors by suspension system to isolate mirrors from shaking

  Suspension system works (in principle) like that of a (very advanced) car — wheels feel bumps, but are decoupled from car

LIGO suspension system



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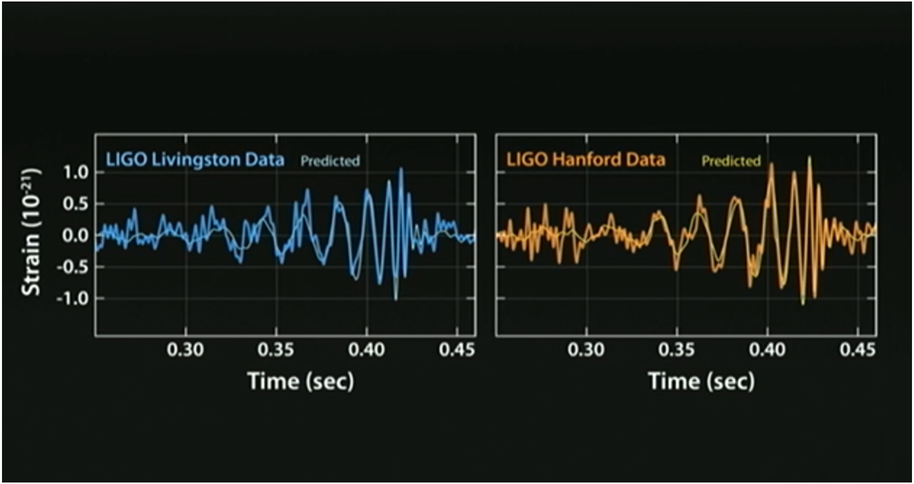
September 14, 2015, 5:51am (Boston time)



- East and West coast data compatible with each other
- Gravitational wave signal significantly above background
- Matches very precisely predictions from black hole merger

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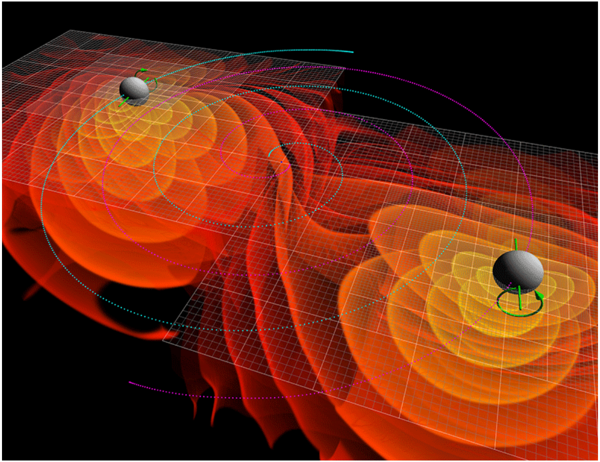

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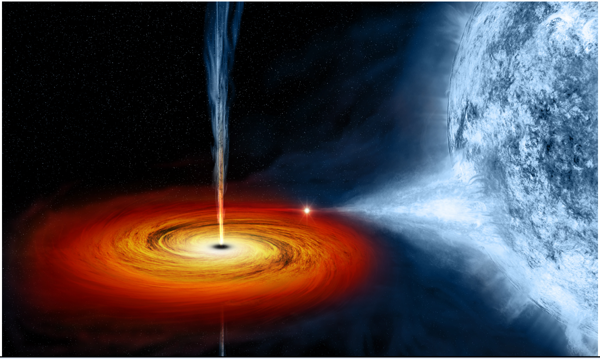

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> Having said all this:
>
> - gravitational waves were expected to exist
> - interest therefore mostly in experimental applications!

Experimental applications: gravitational wave astronomy

A new way to experience the Universe!

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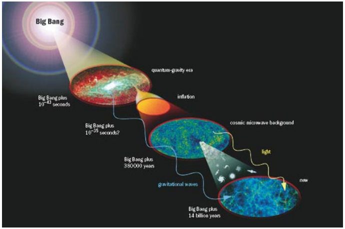
- Example 3: early Universe (light blind to anything before Universe was 370.000 years old)



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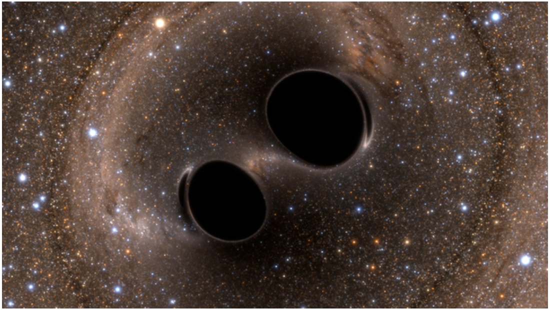
> - Conversely: Public funding should go to fundamental research, not to industry (Austrian funding agency FWF in dire straits)

Congratulations to the Advanced LIGO team at MIT and 90 other institutions!



I hope you enjoyed my talk!

... any questions?

Backup slide
Educational video by LIGO