Gravitational waves

A new tool for observing the Universe through ripples in spacetime

Daniel Grumiller

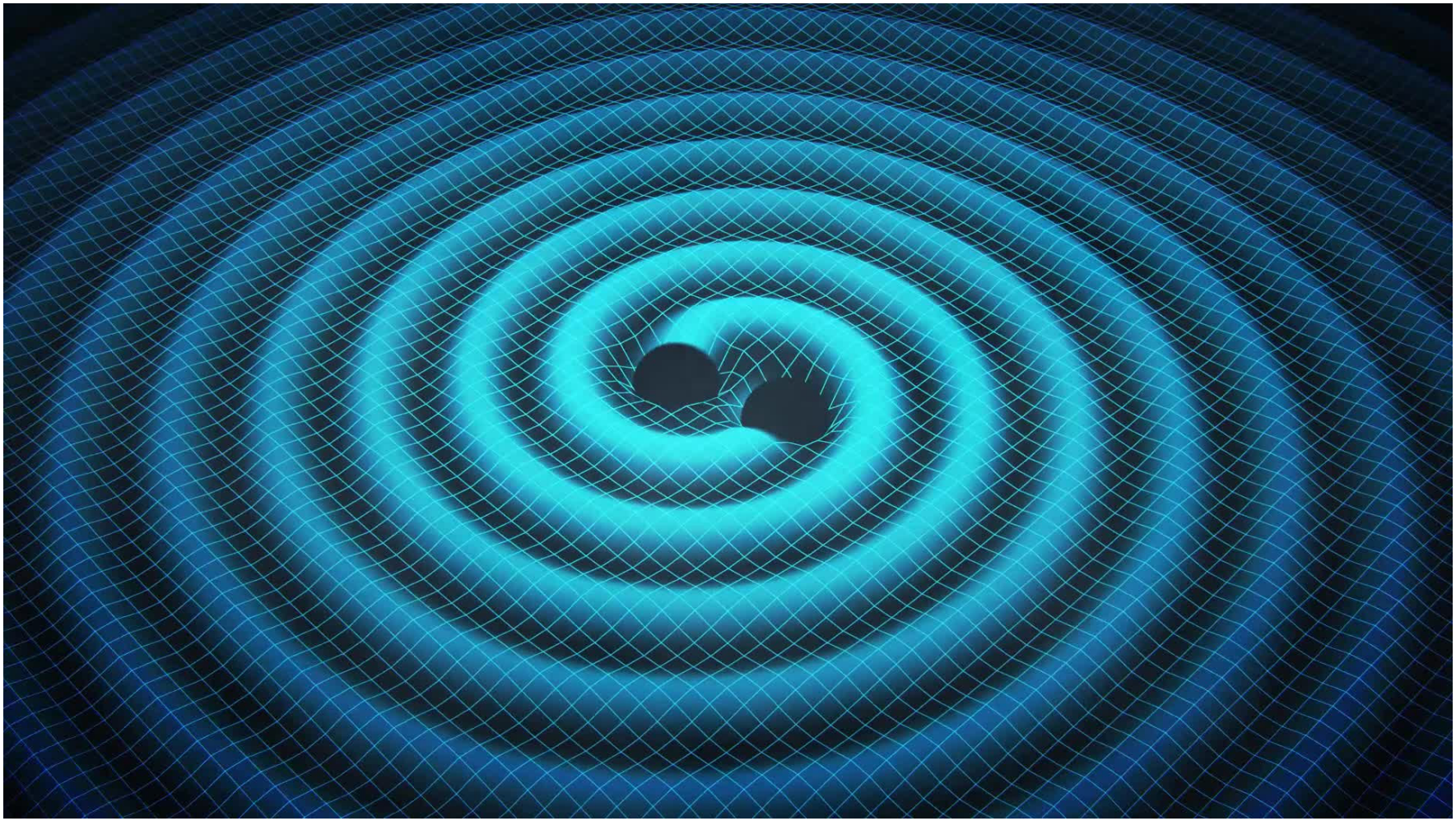
Institute for Theoretical Physics
TU Wien

Based on public lecture for MIT Club Austria
Black Holes I, January 2018

Executive summary

- 1915: Einstein's General Relativity predicts gravitational waves

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



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

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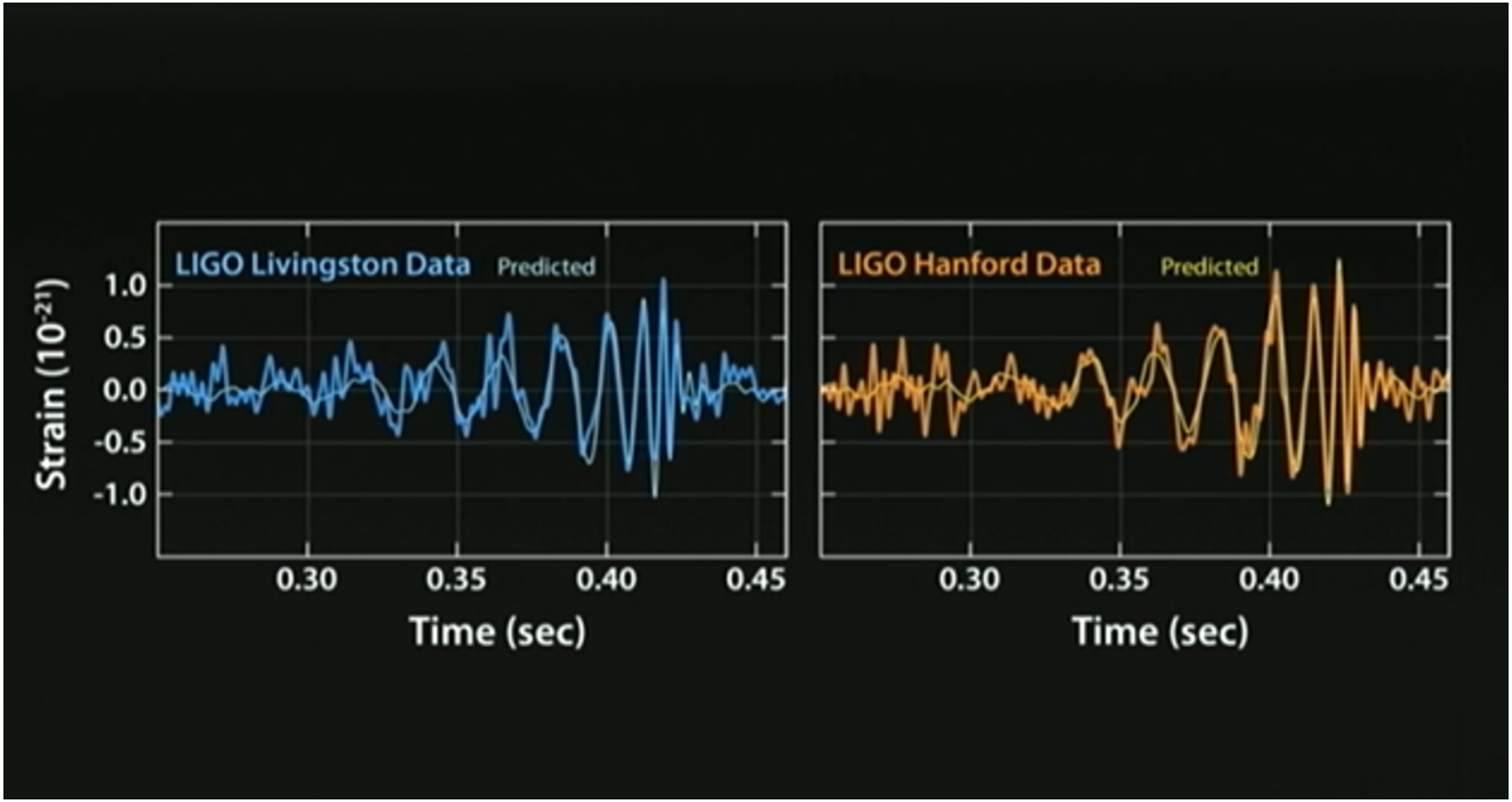

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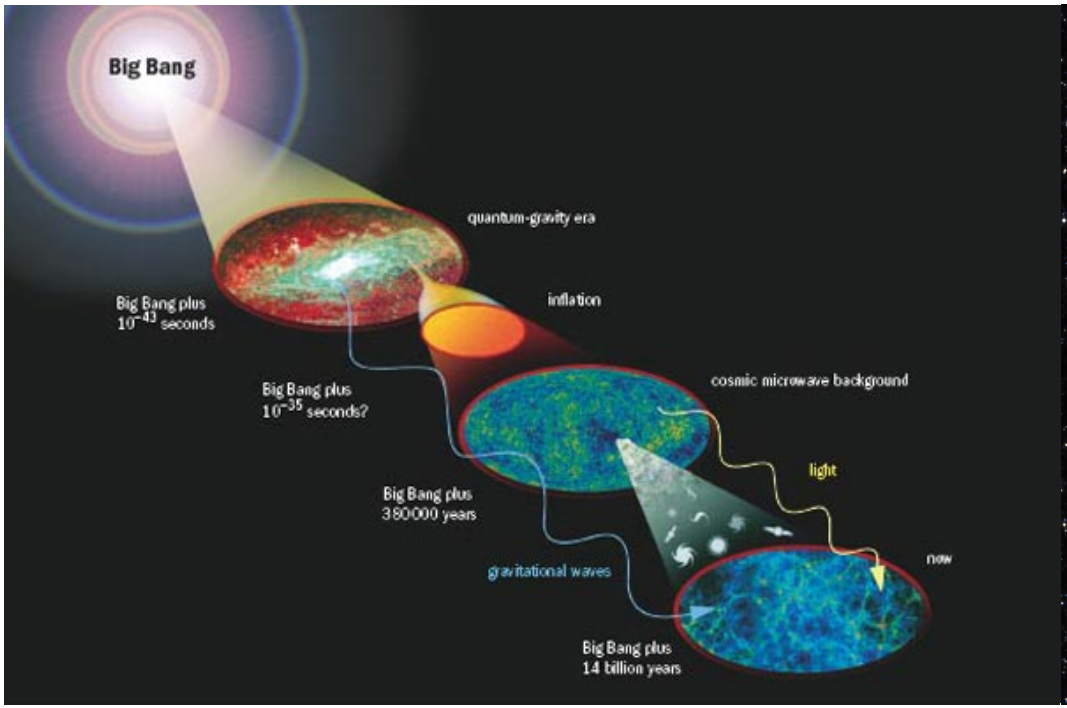

Left: gravitational waves sensitive to early Universe, Right: Supernova

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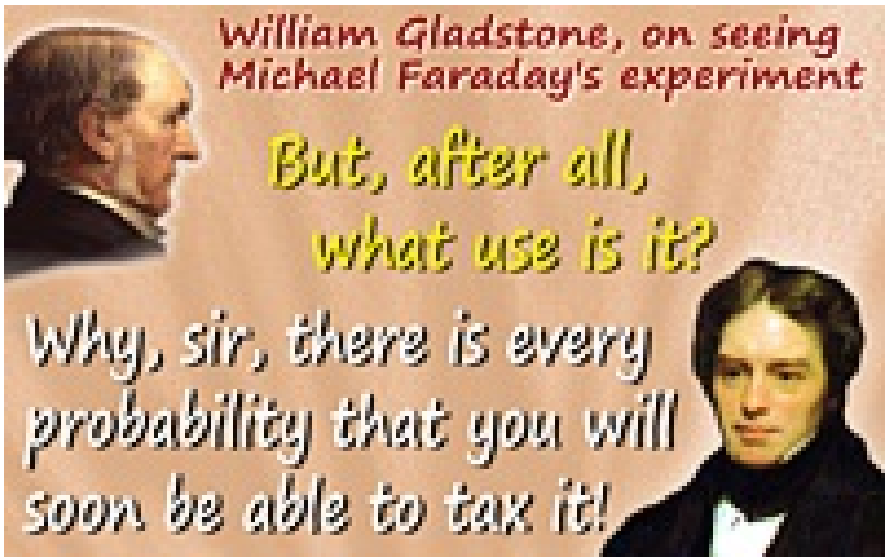
- 2116: someone pays taxes for gravitational waves



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

Outline

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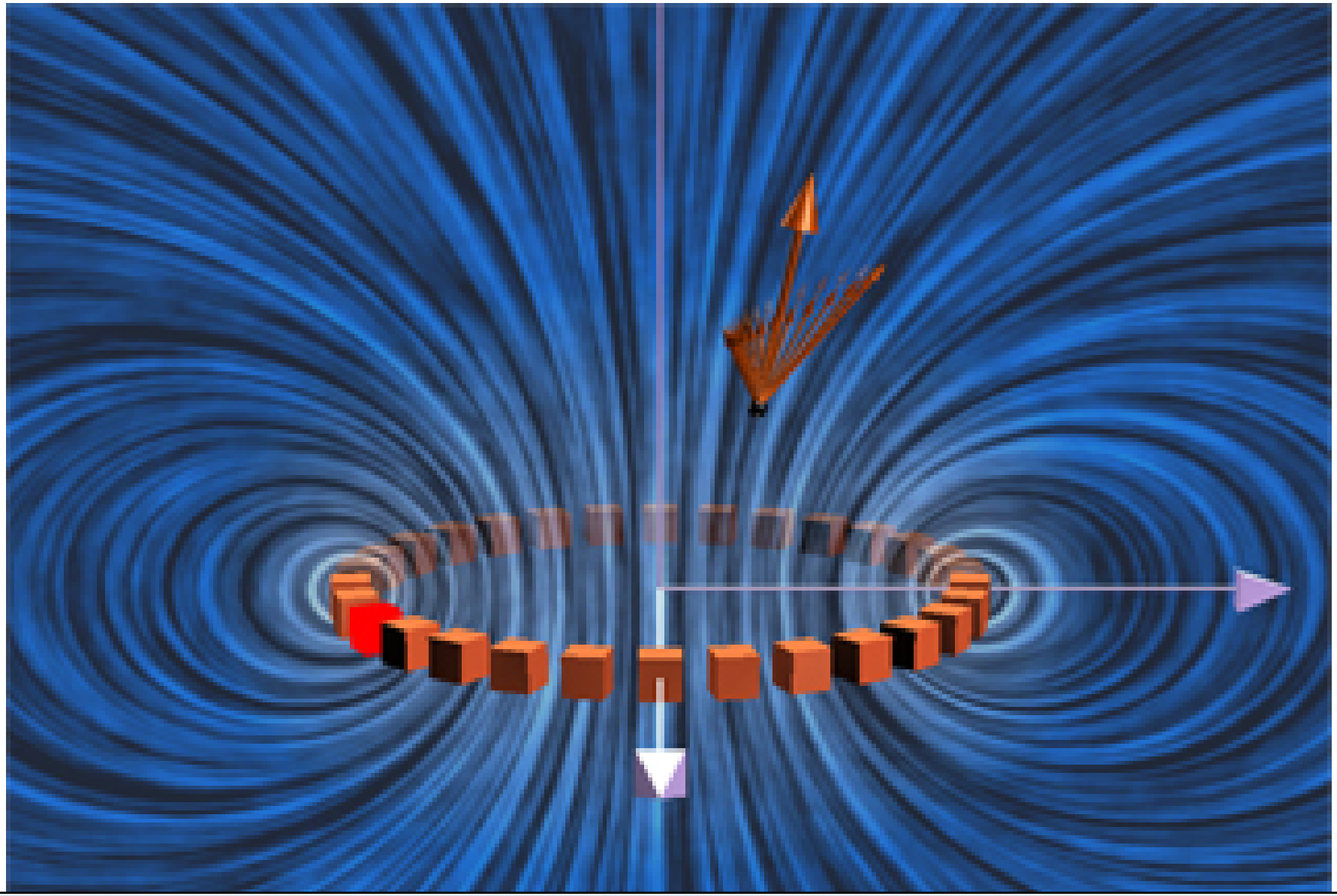
Warm-up: electromagnetism

- Electromagnetism: theory describing dynamics of charges



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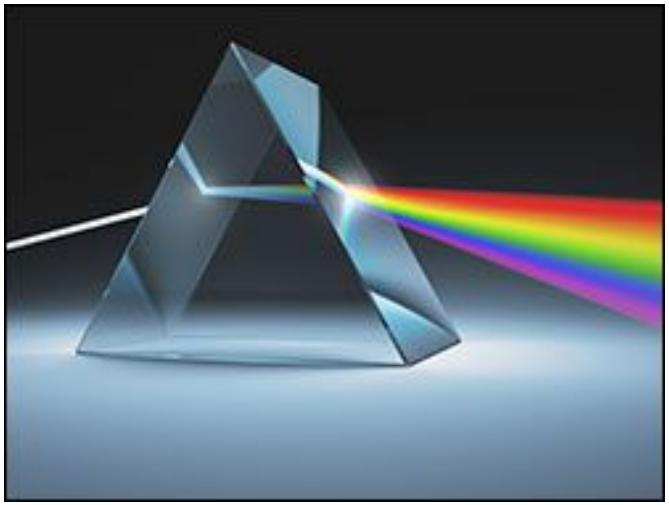
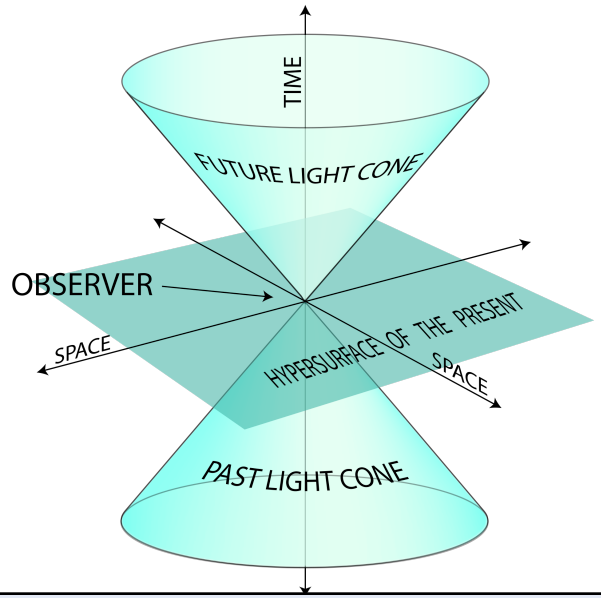


$$E = mc^2$$



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- Quantum electrodynamics tested with amazing precision and accuracy

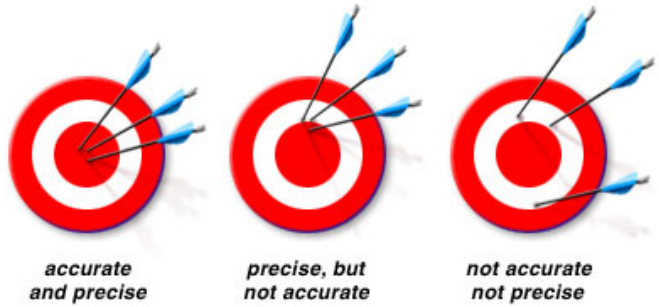
Example: gyromagnetic factor of electron

Experiment (2008):

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

Theory (2012):

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



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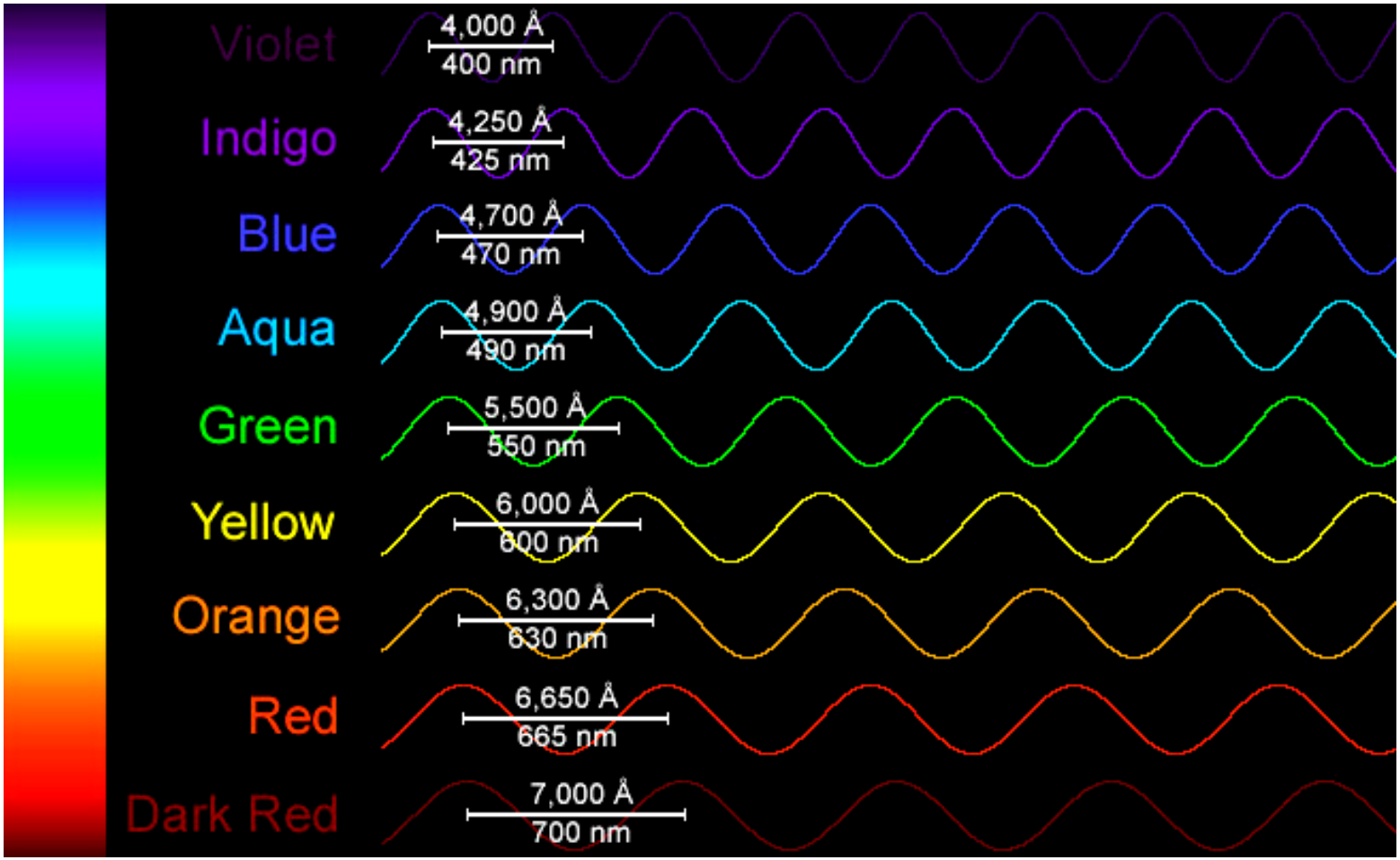

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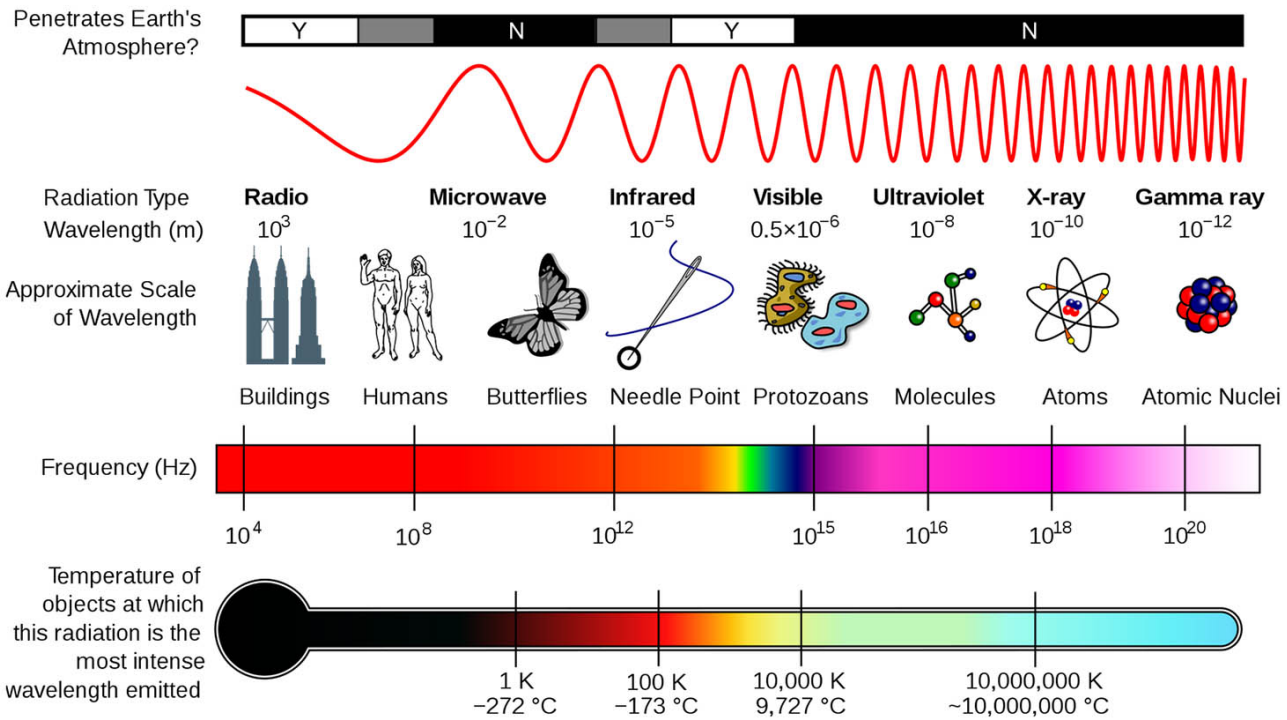

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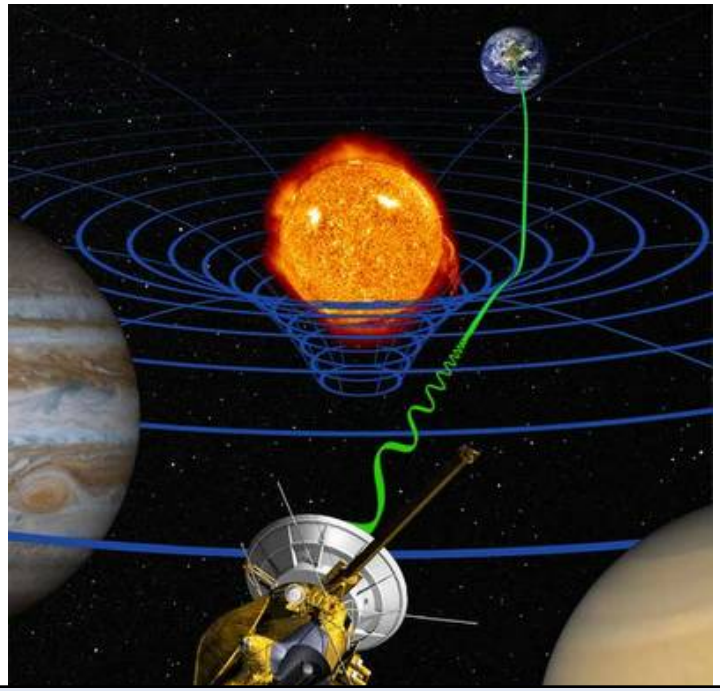

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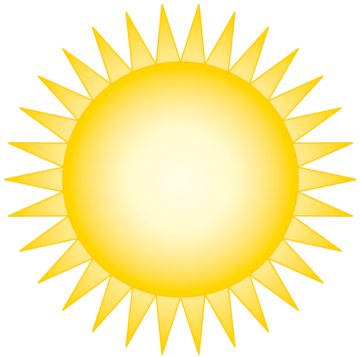
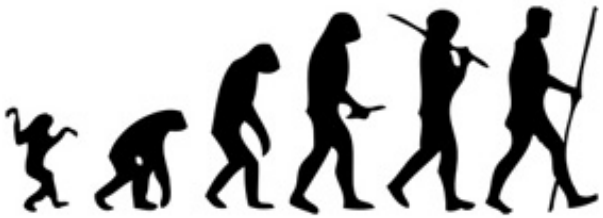
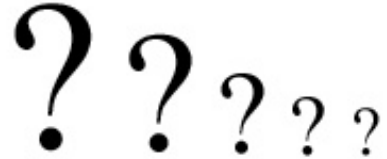
- First observation of light by humankind: about 2 million years ago







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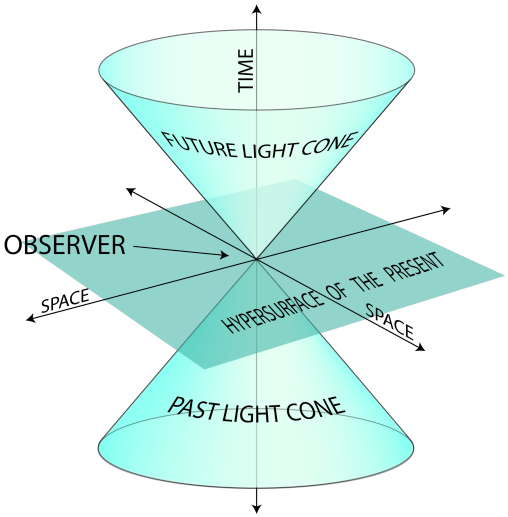

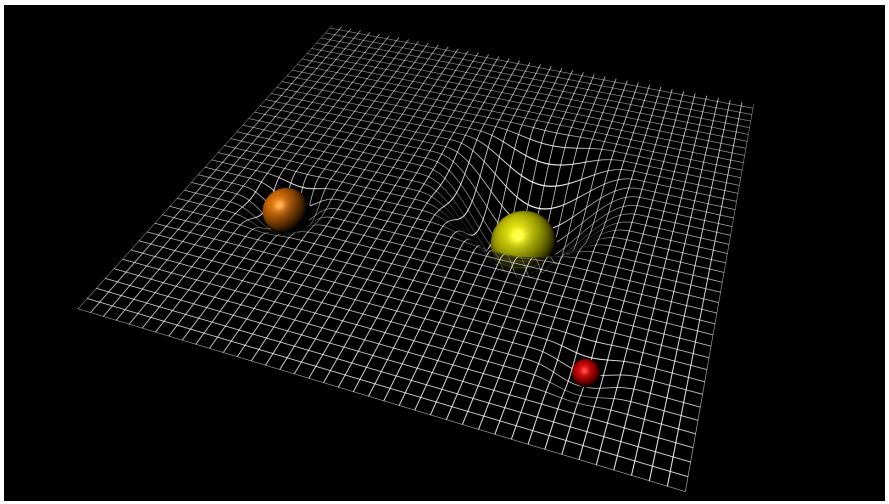

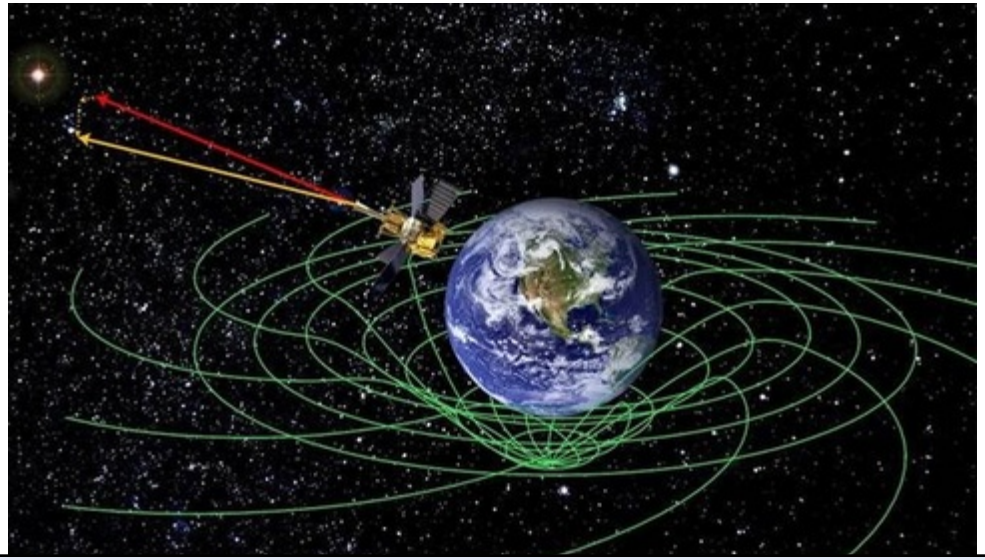

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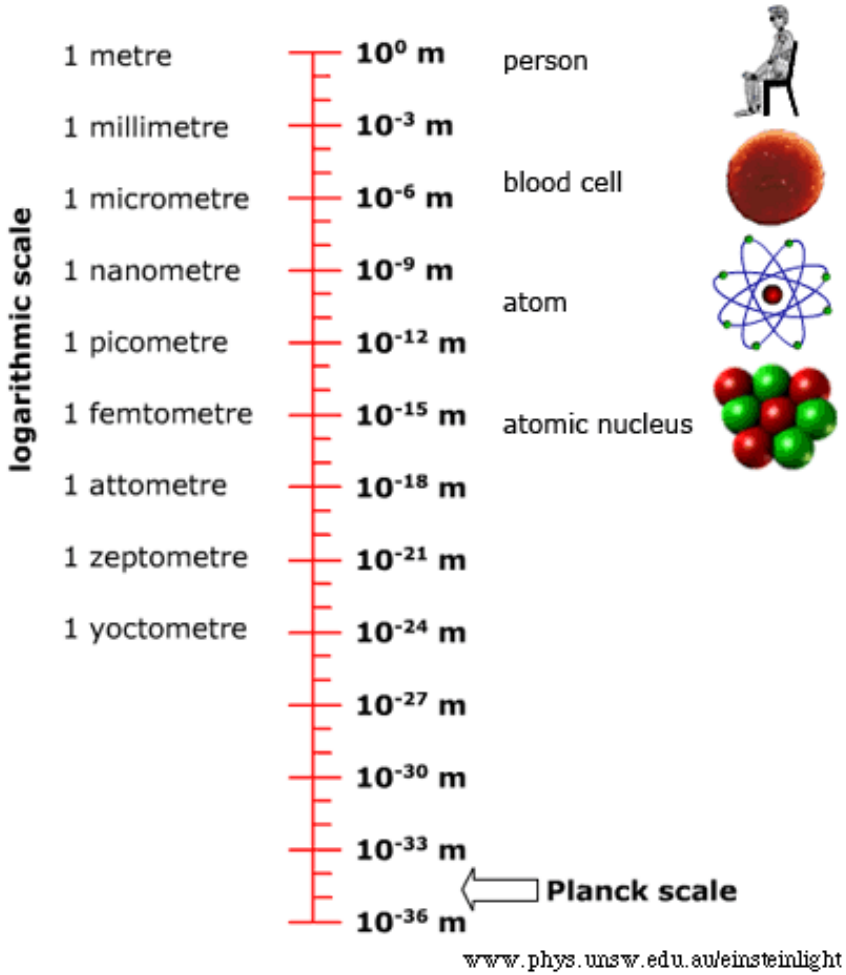

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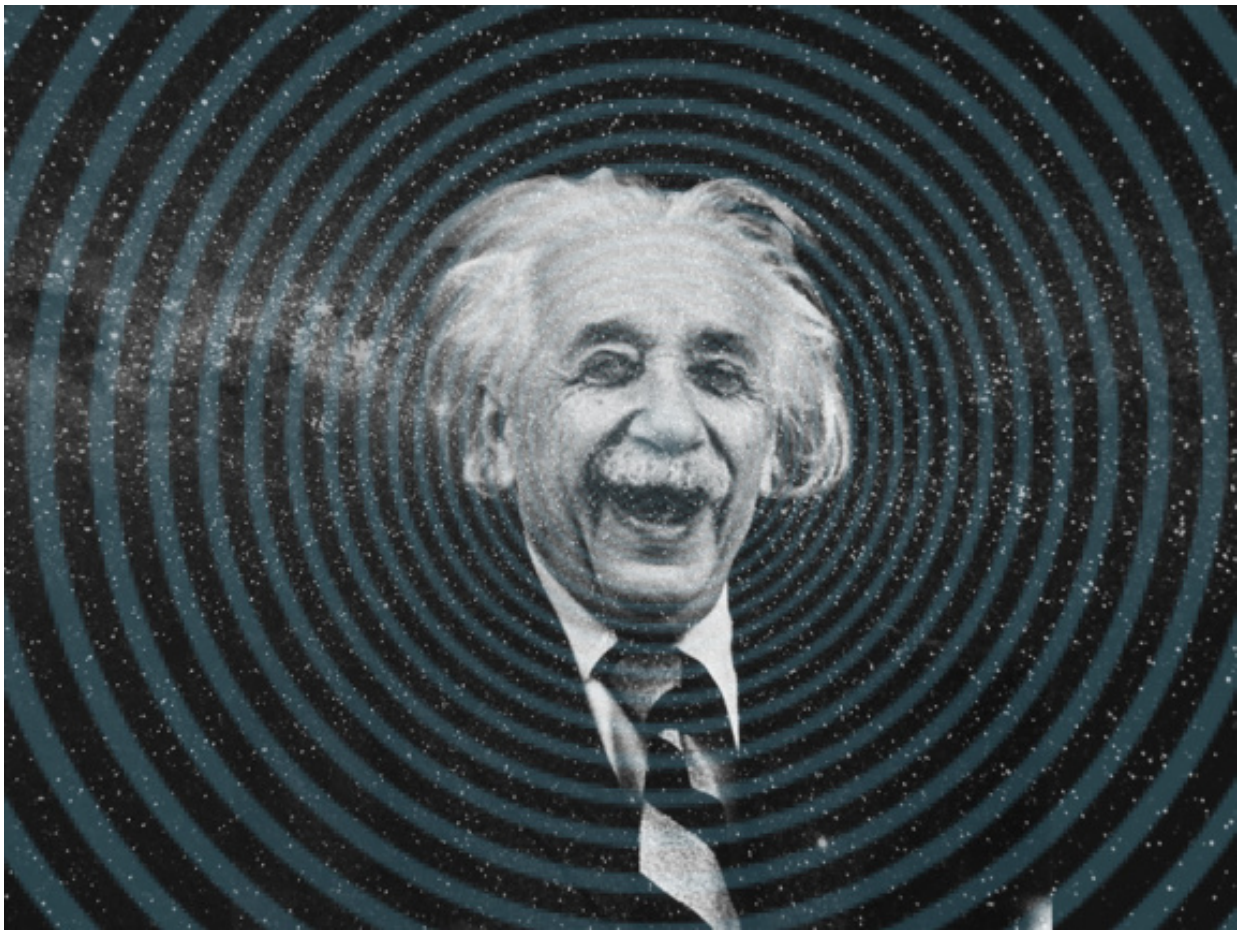

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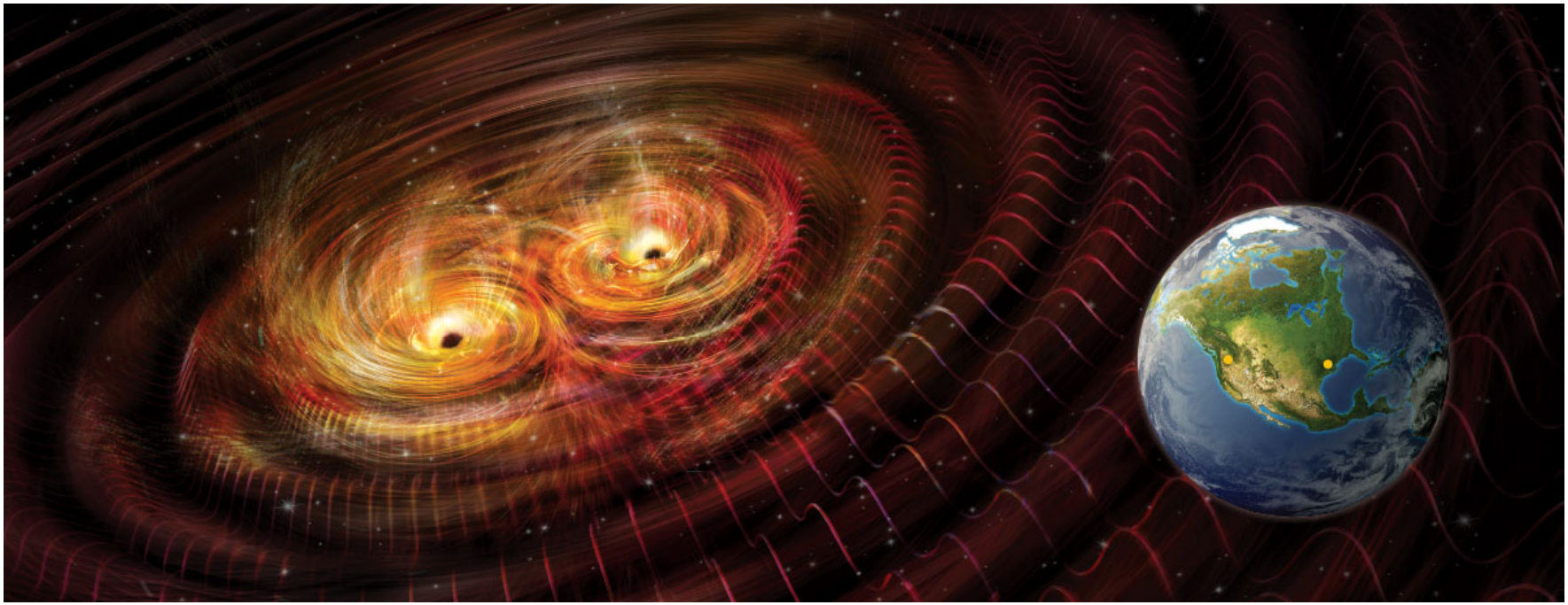

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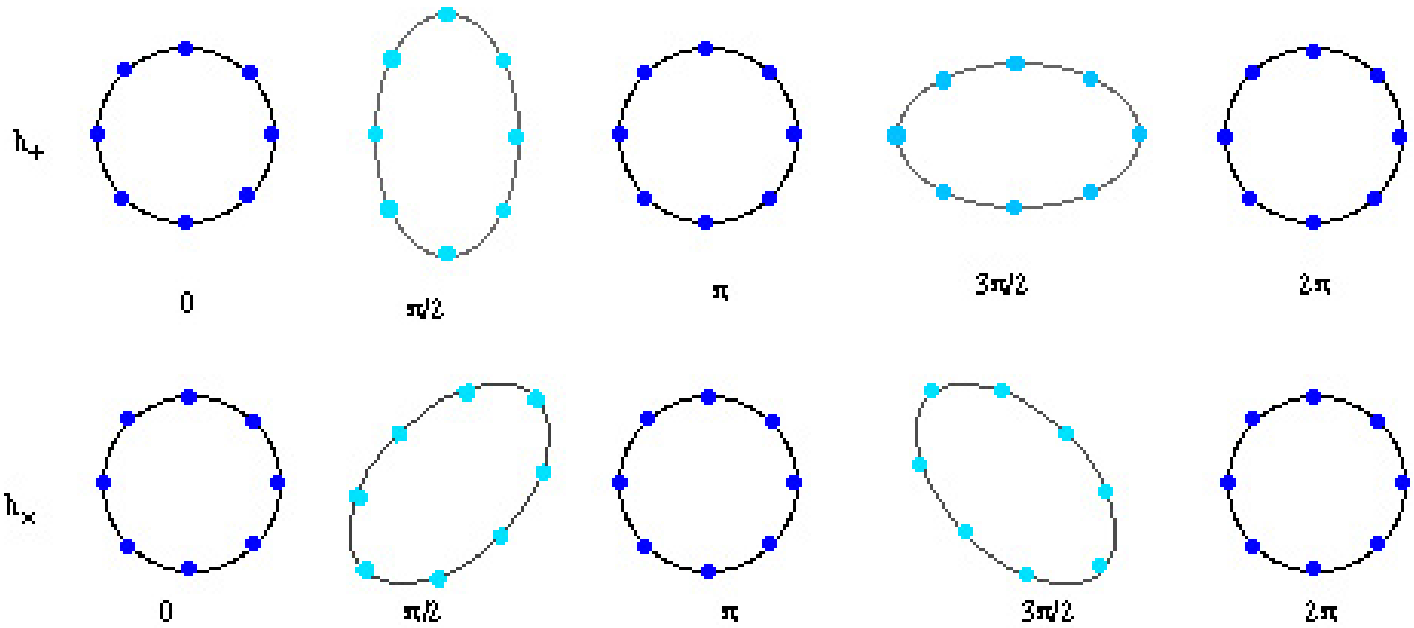

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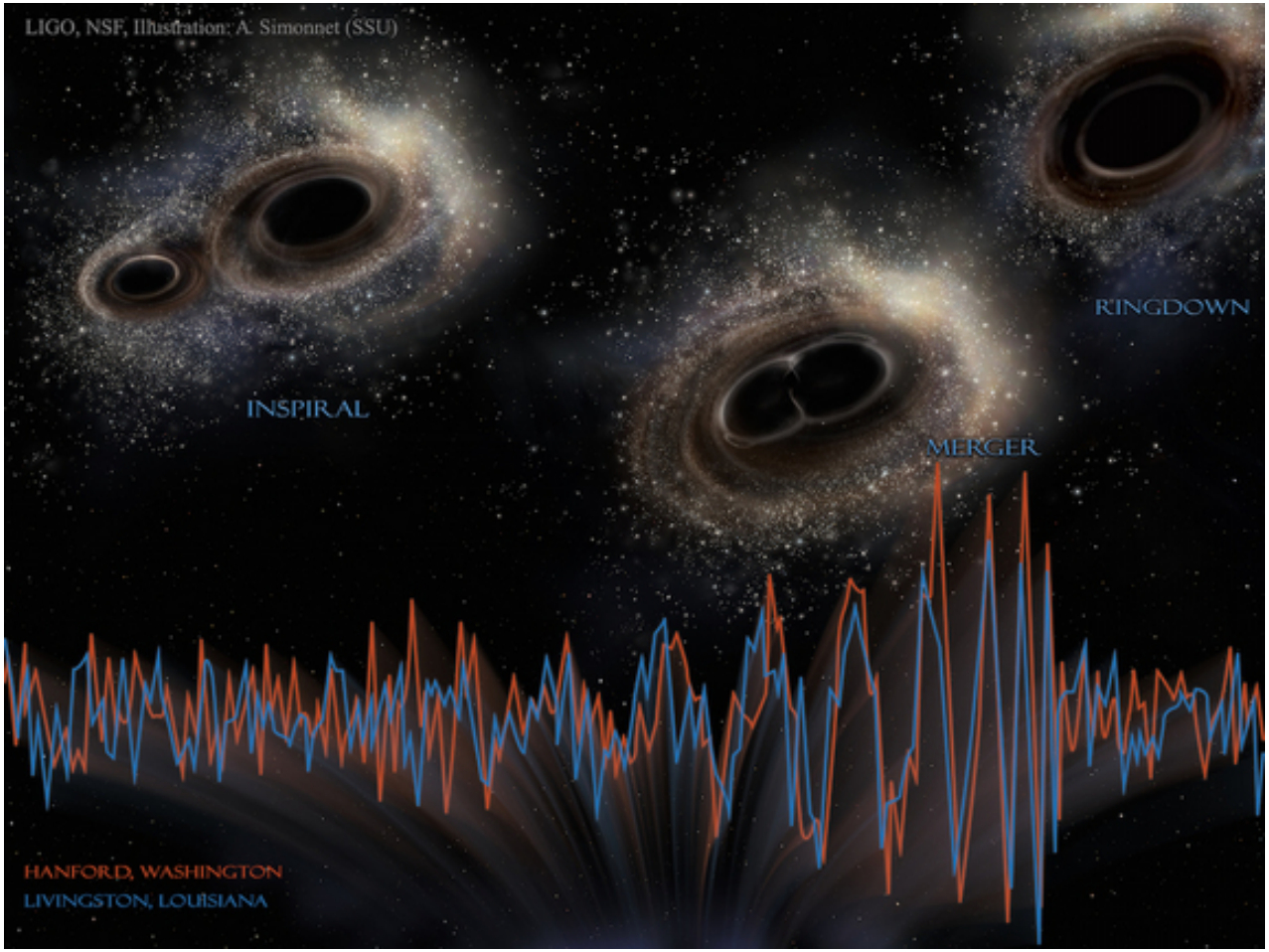

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Get upper bound on gravitational wave energy

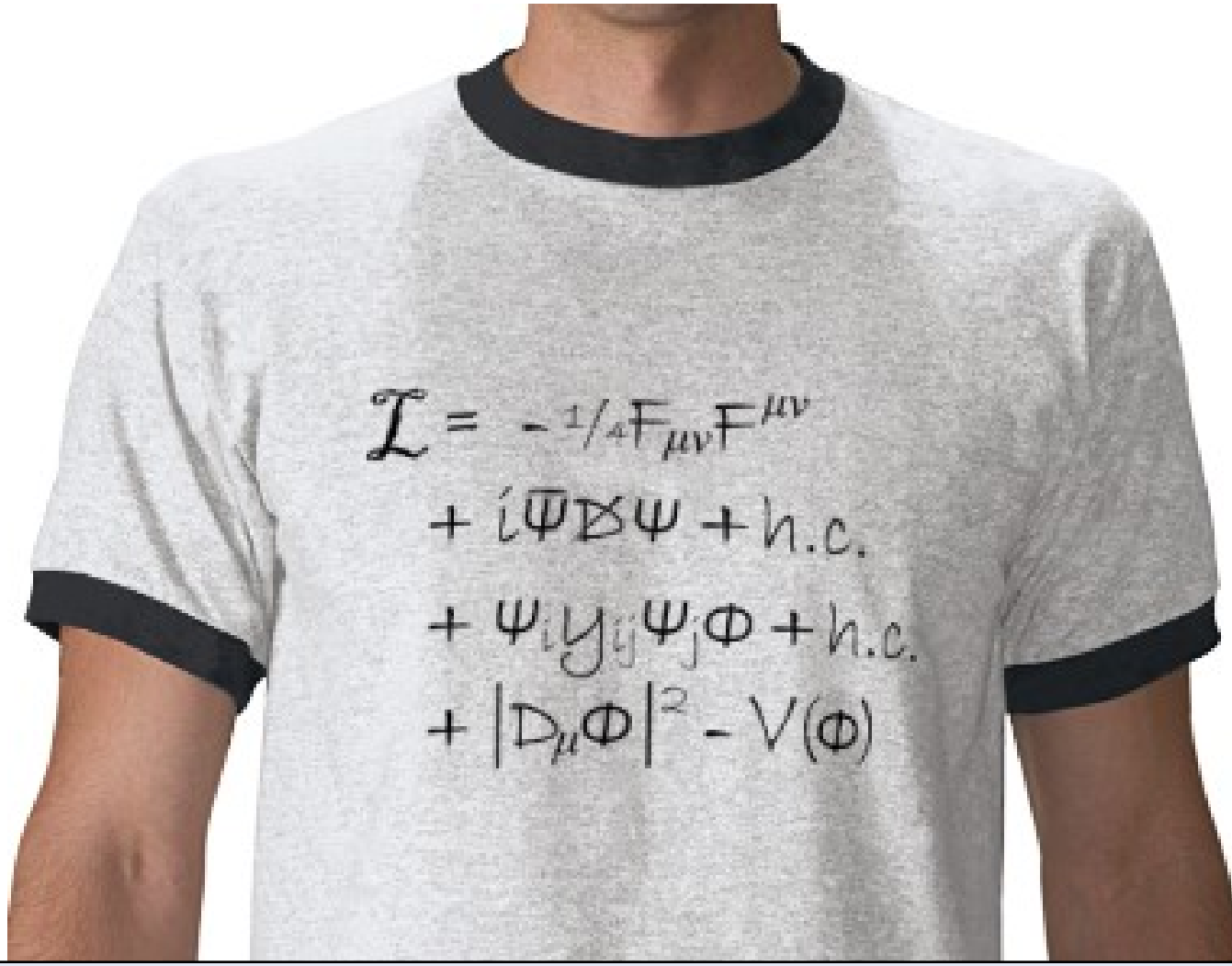
$$E \leq (2 - \sqrt{2})m \approx 29\% \text{ of initial energy}$$

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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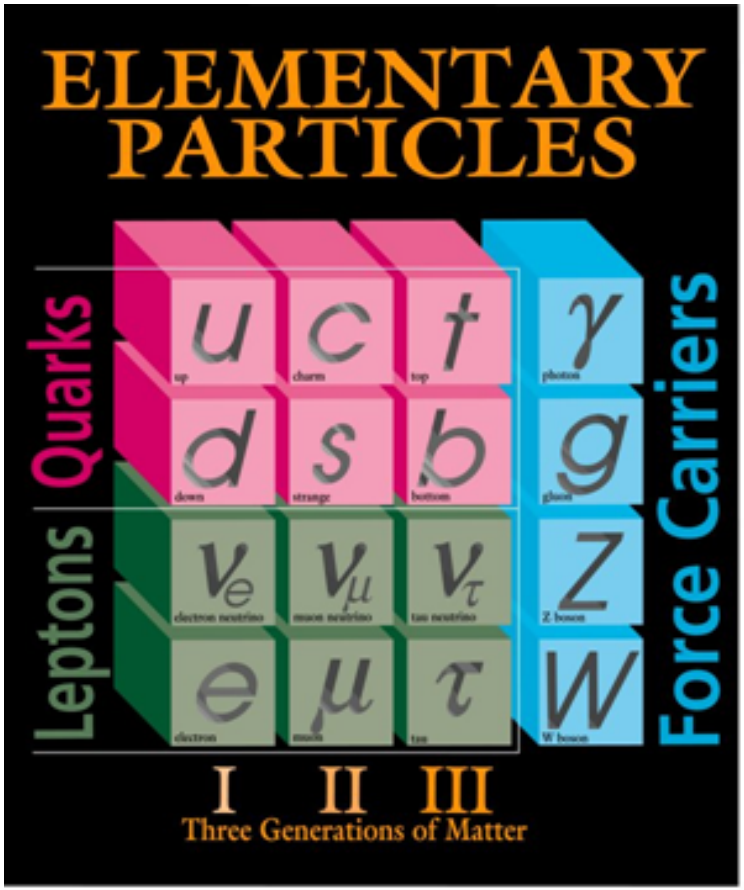

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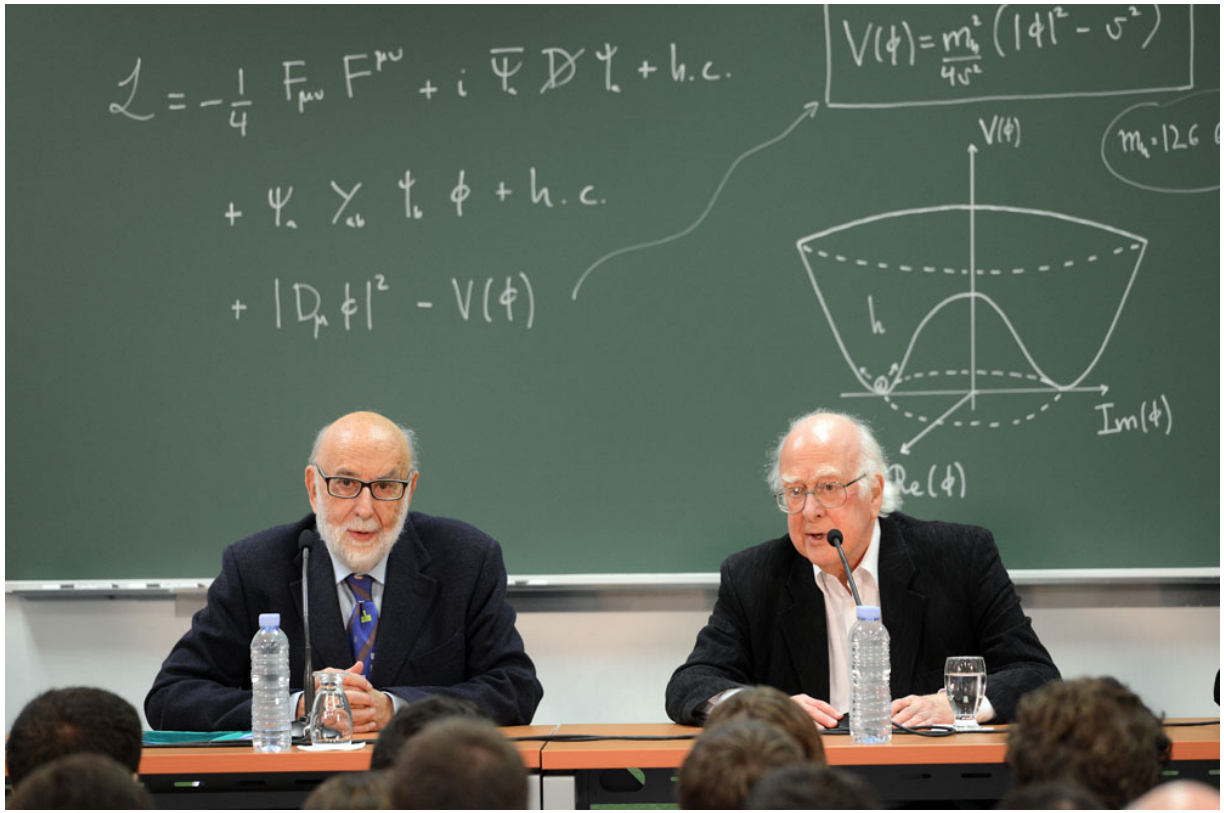

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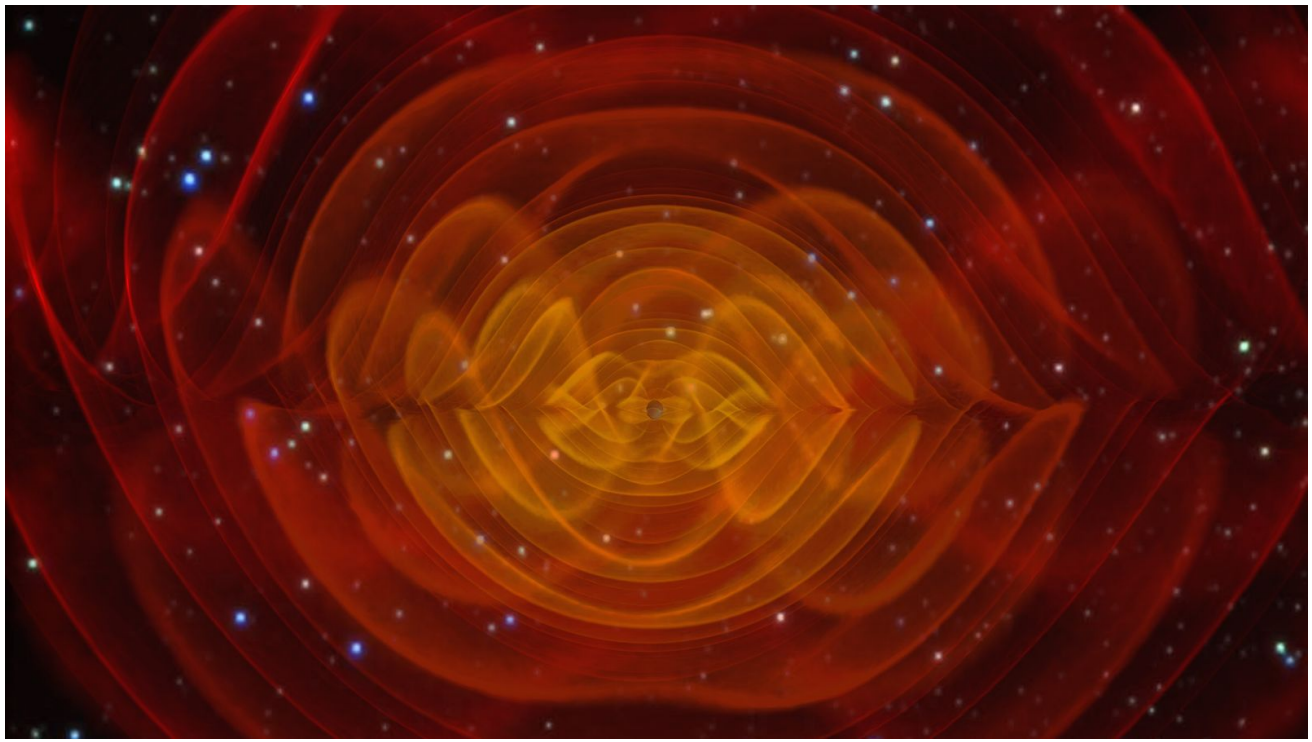

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Amazing achievement of humanity from late 1600 till early 2000!

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- 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!

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

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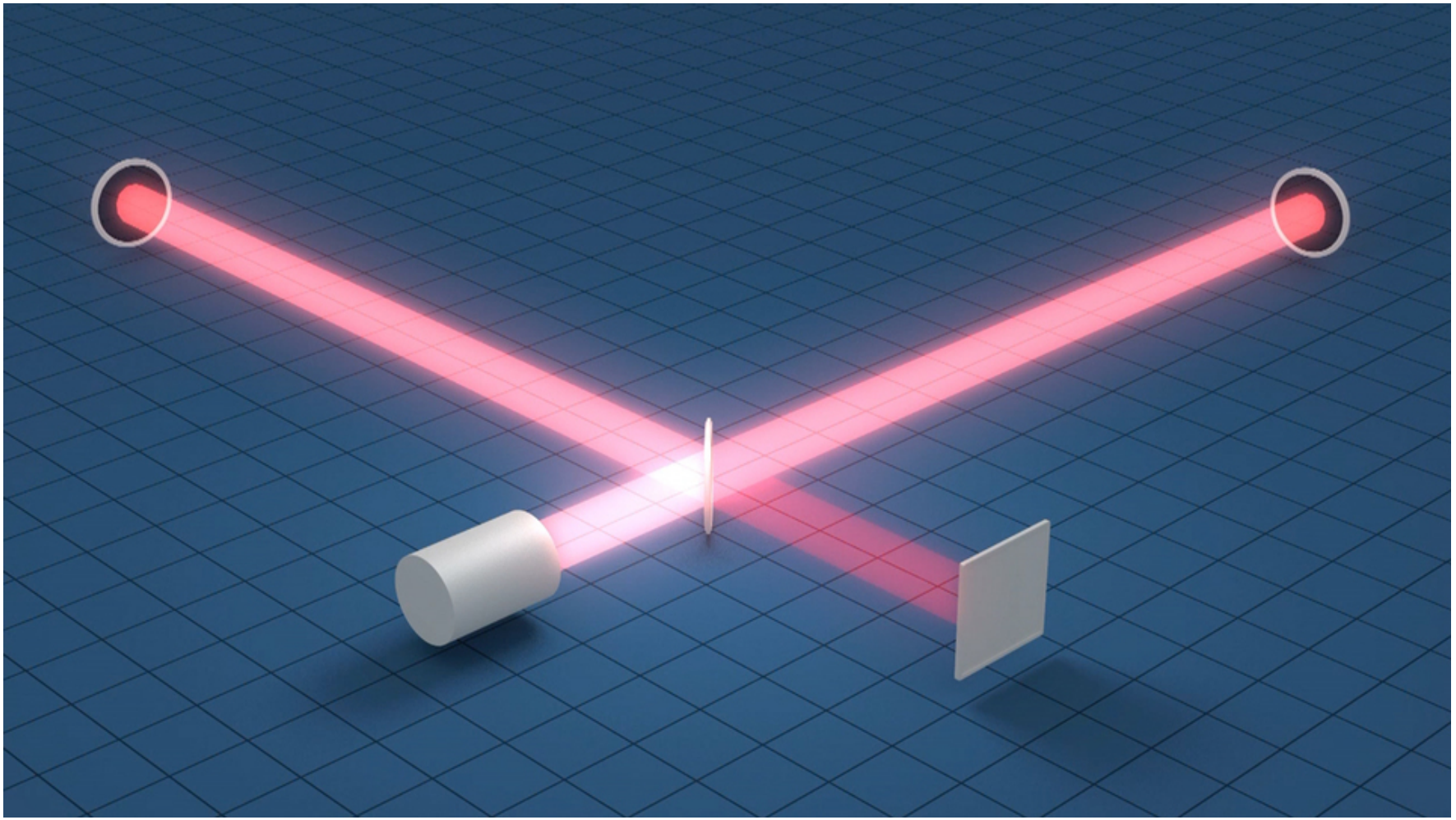

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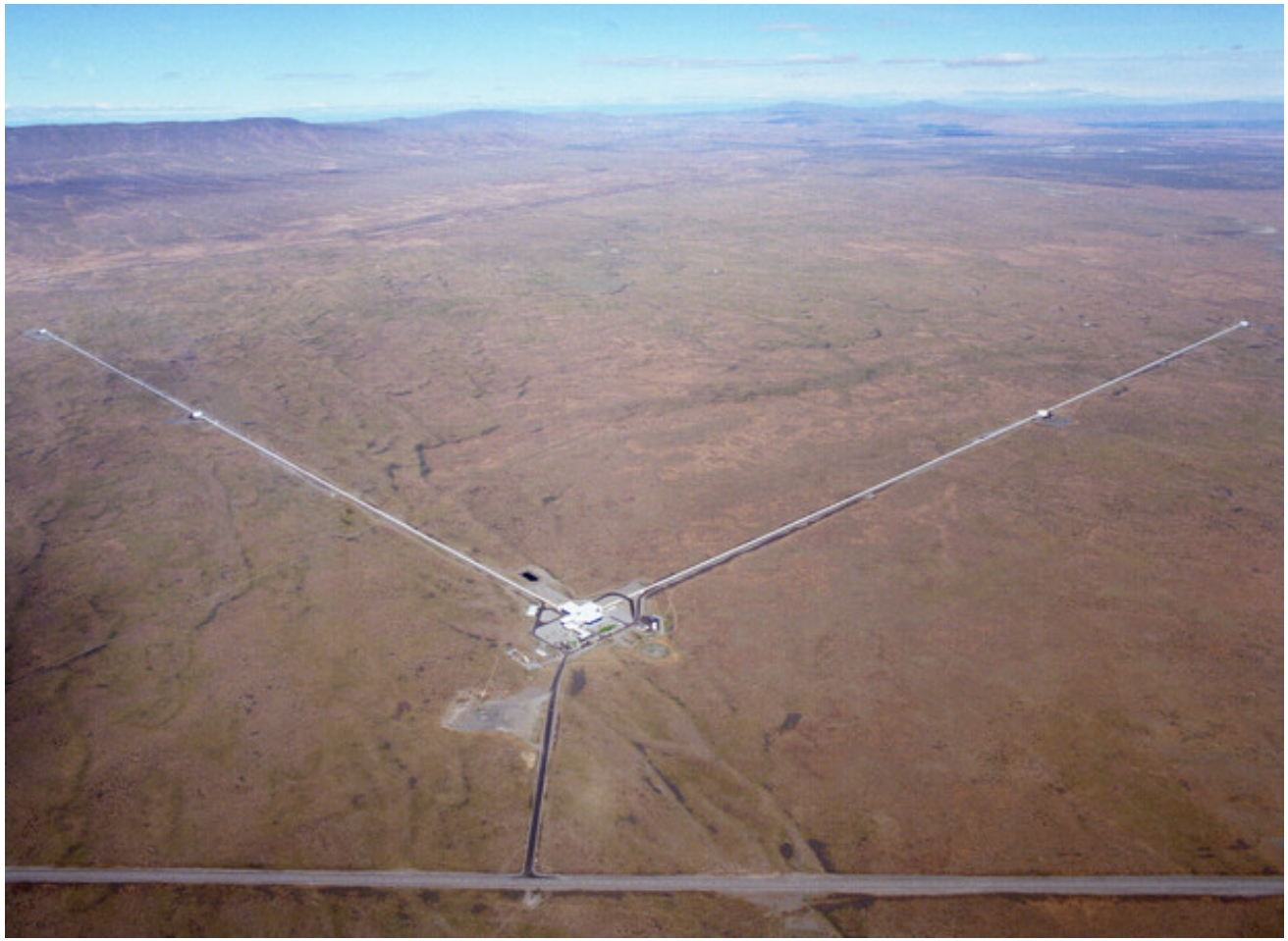

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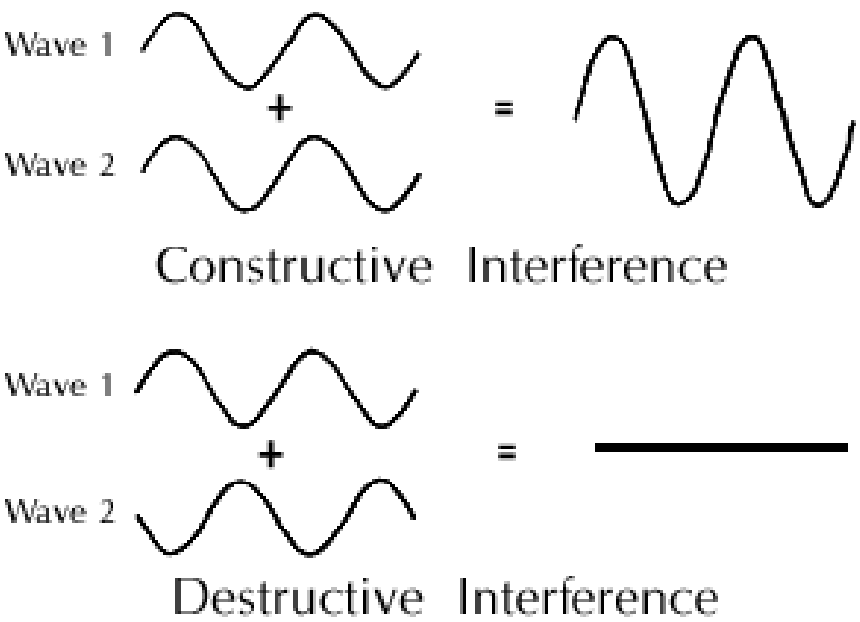

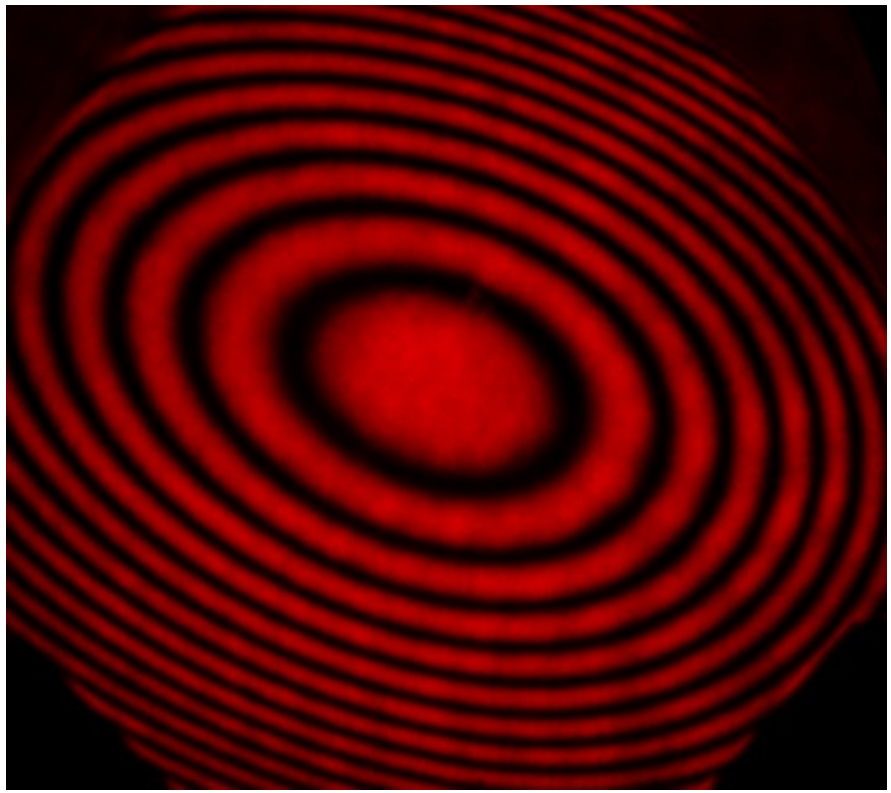

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(Advanced) LIGO needed 25 years of development and 500 million $ investment, involving more than 900 scientists and engineers

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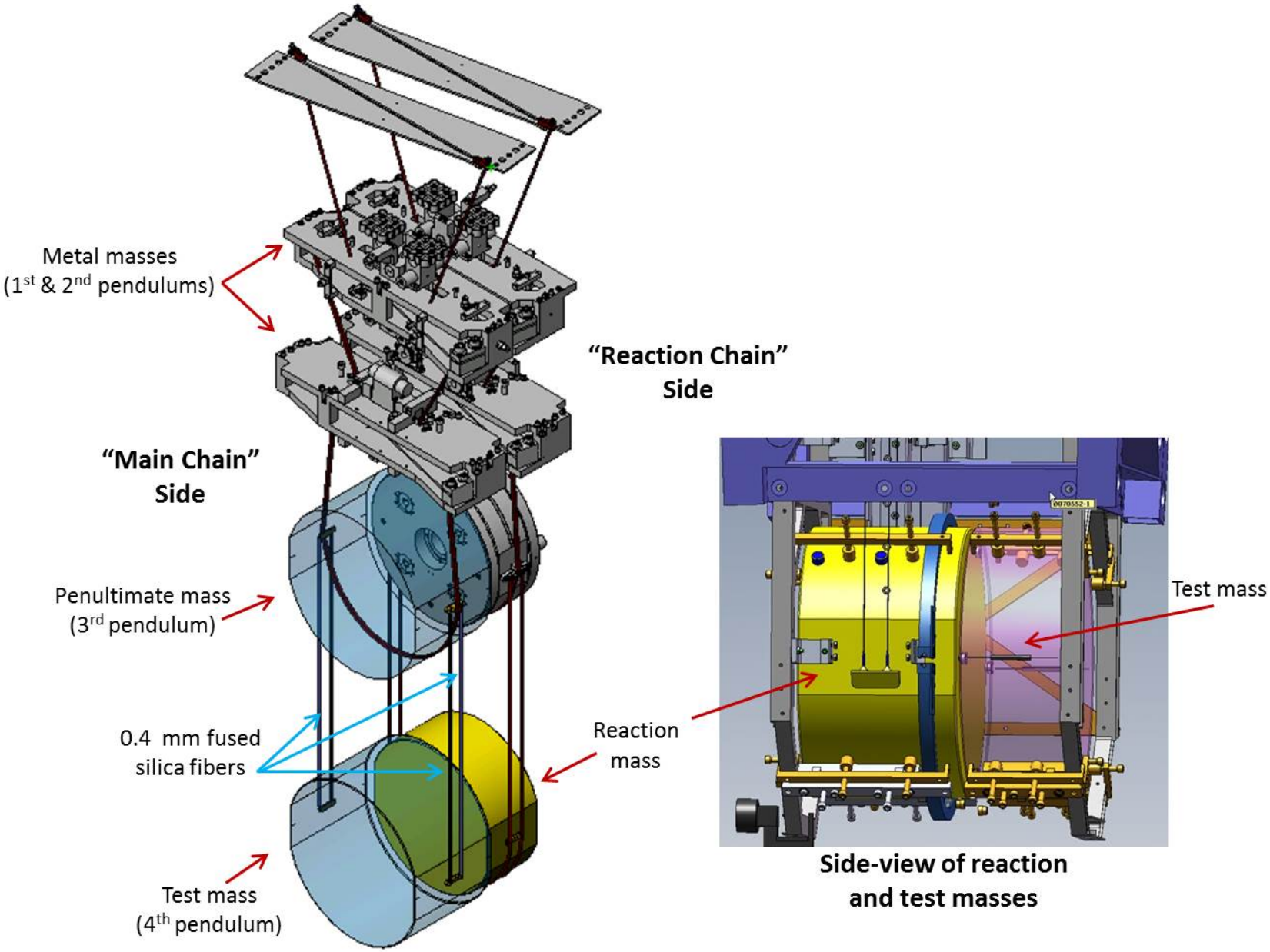
- Reduce local errors by suspension system to isolate mirrors from shaking

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

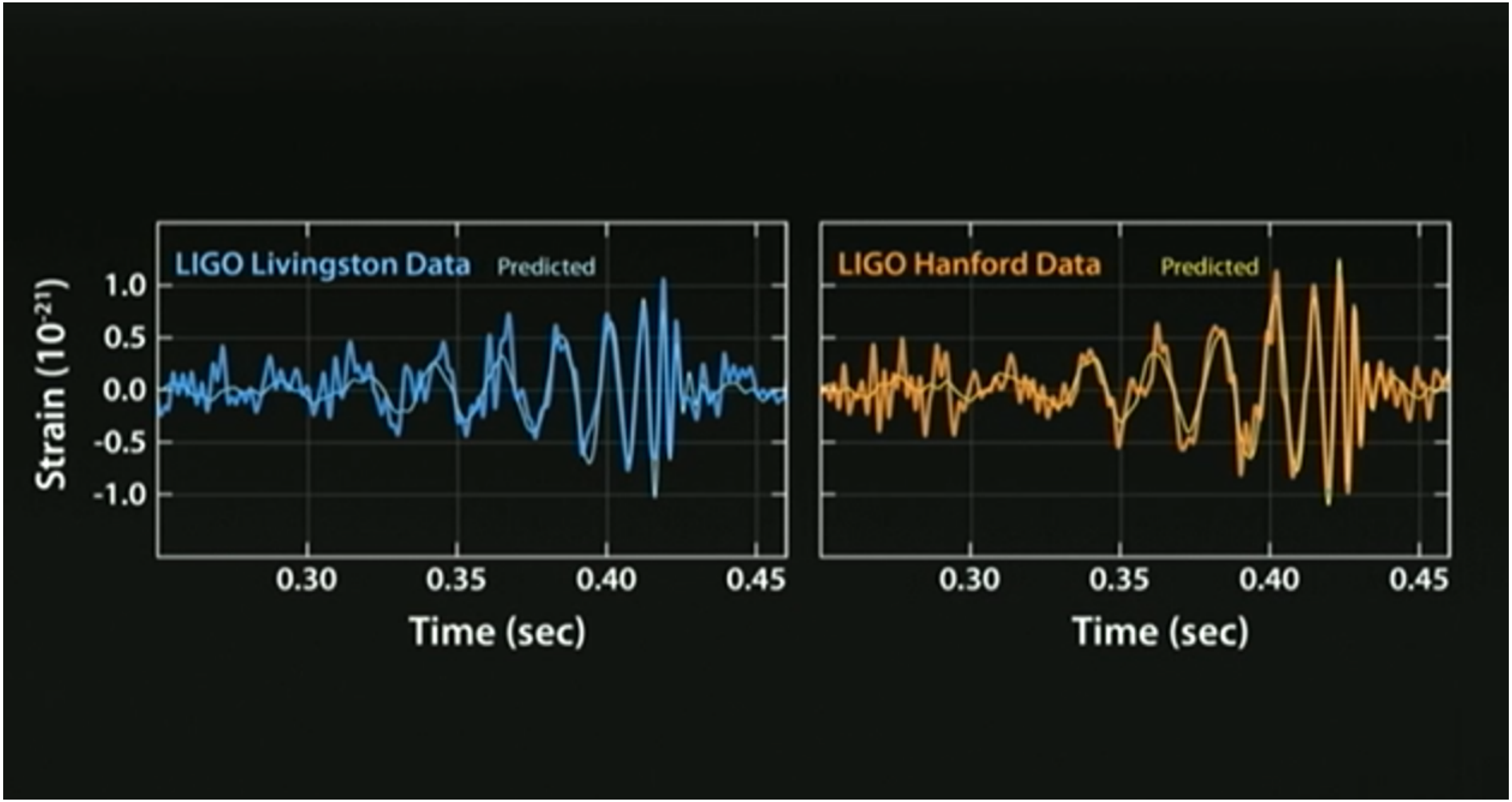
LIGO suspension system



Side-view of reaction and test masses

Outline

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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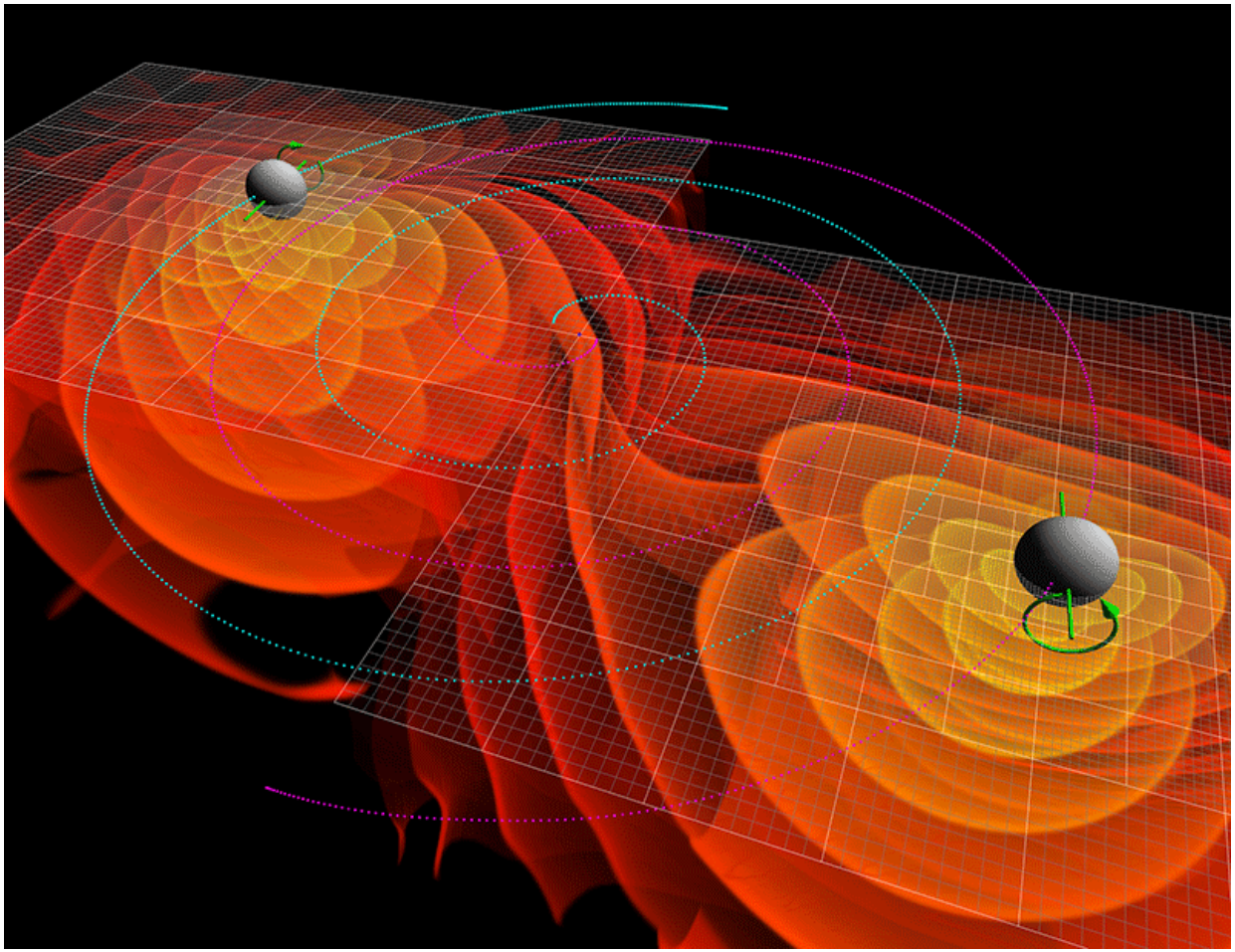

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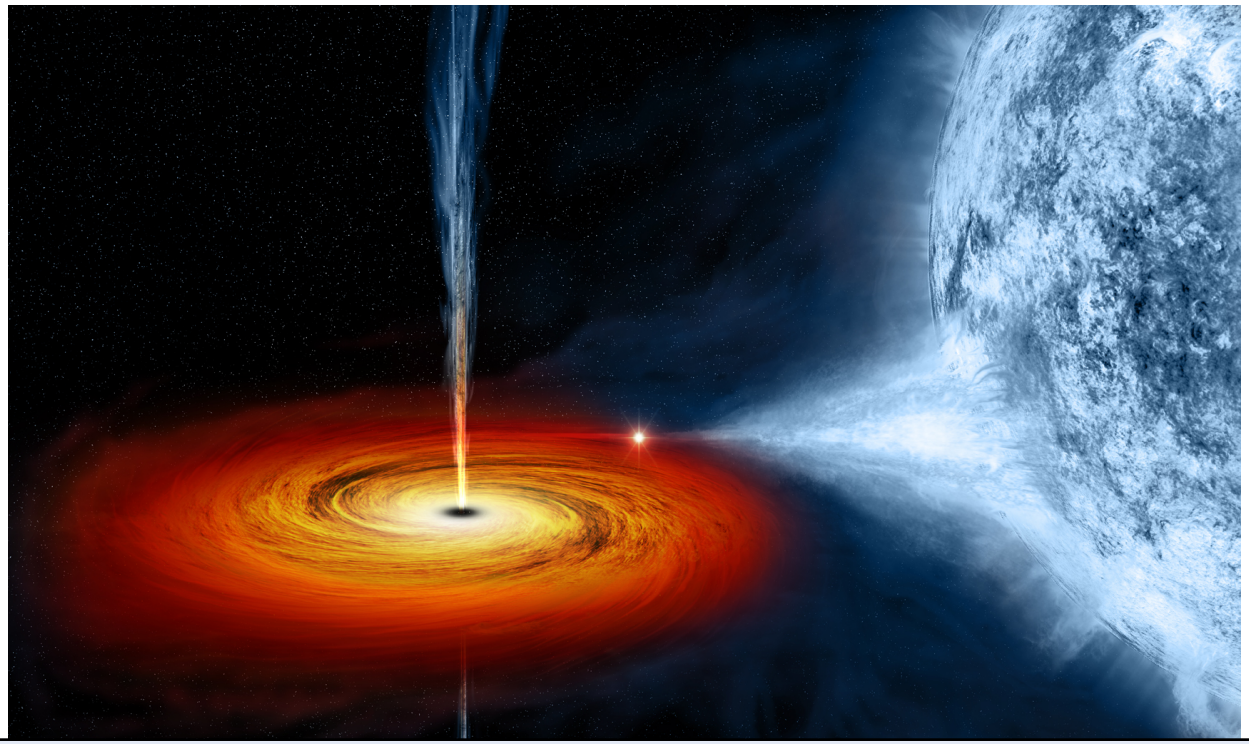

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Having said all this:

- gravitational waves were expected to exist
- interest therefore mostly in experimental applications!

Experimental applications: gravitational wave astronomy

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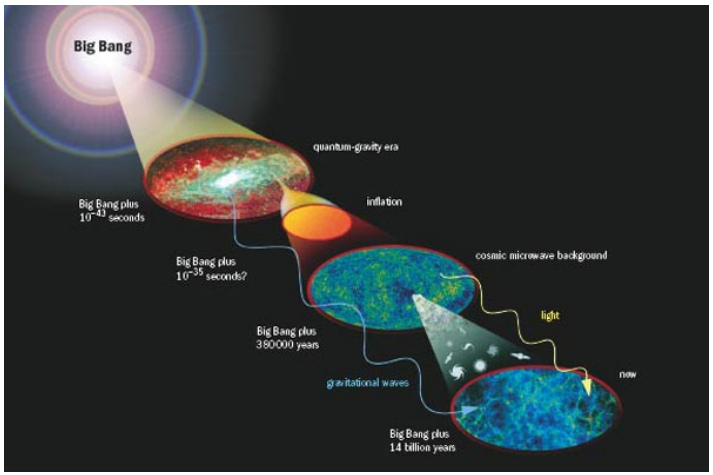
- Example 3: early Universe (light blind to anything before Universe was 370.000 years old)



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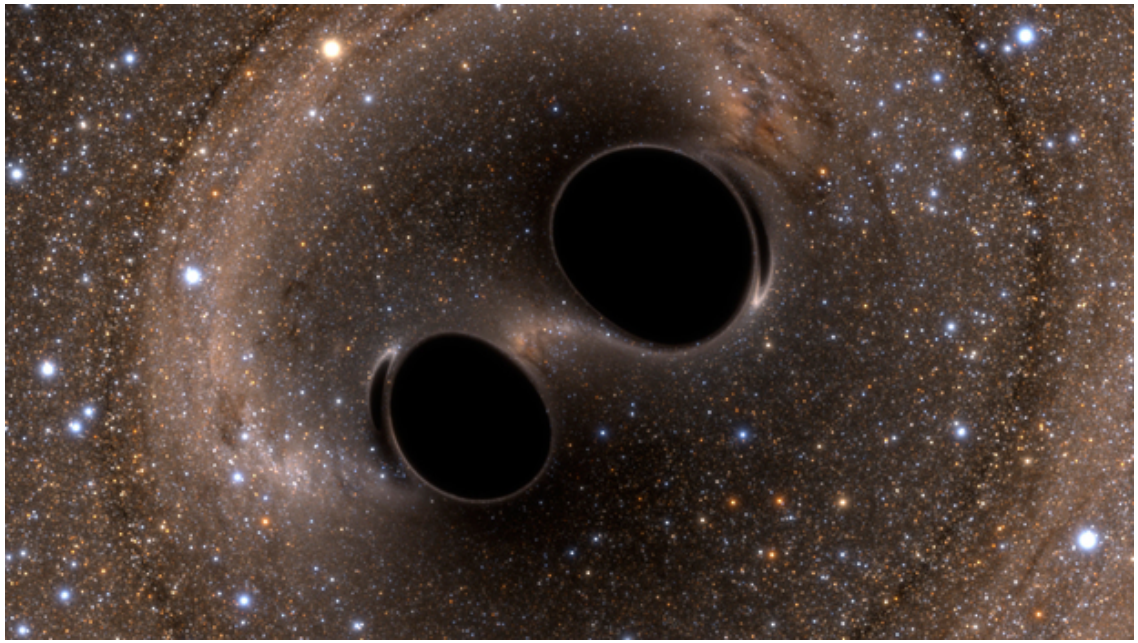
- Patience needed in fundamental research on big questions
- Funding must come from public sources, not from industry
- Conversely: Public funding should go to fundamental research, not to industry (Austrian funding agency FWF in dire straits)

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