LIGO as a Success of Large-scale Science

Coordinating Global Brain Projects
The Rockefeller University

2016-09-19

G1601916

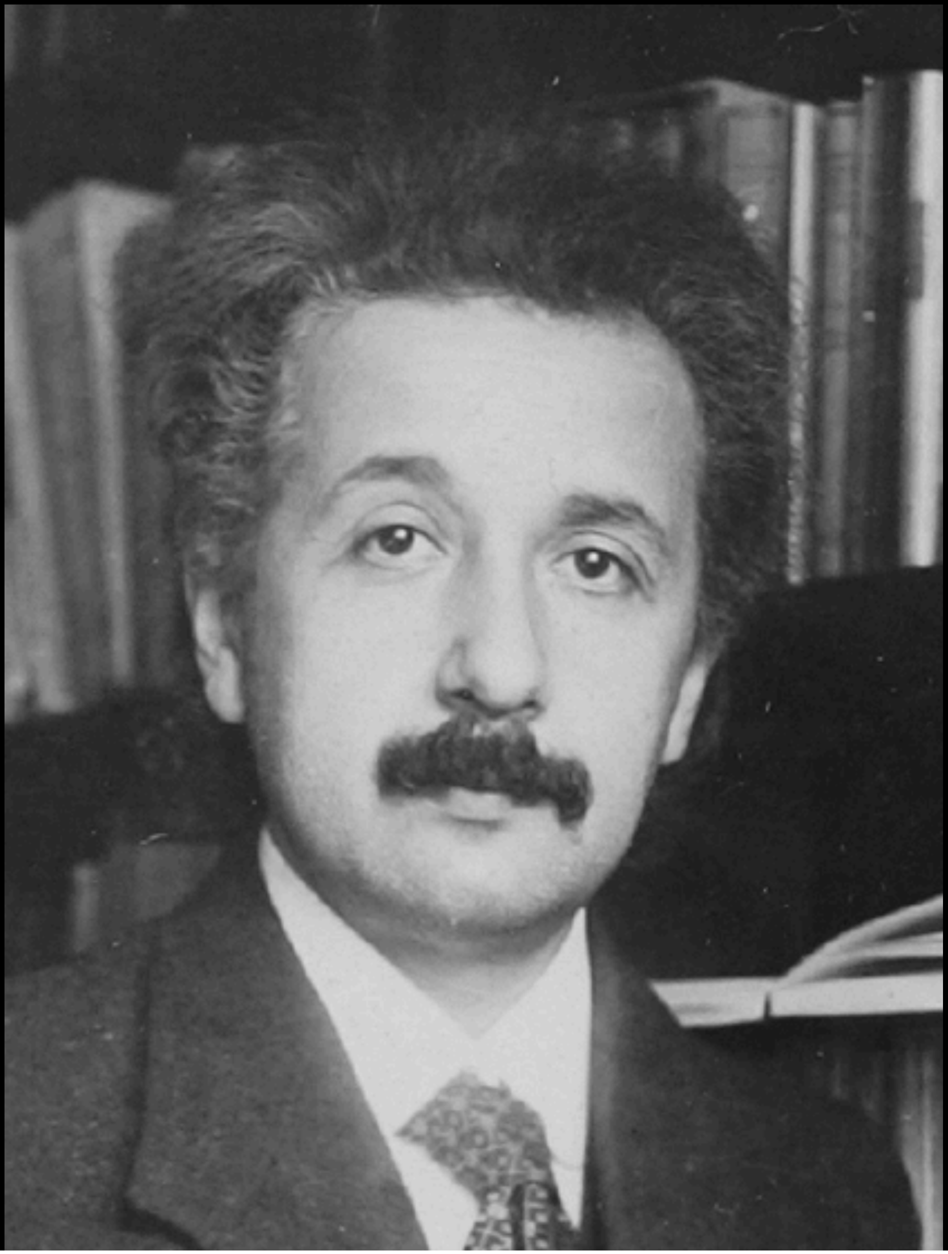
David Shoemaker
For the LIGO and Virgo Scientific Collaborations

Credits
Measurement results: LIGO/Virgo Collaborations,
PRL 116, 061102 (2016); http://arxiv.org/abs/1606.04856
Simulations: SXS Collaboration; LIGO Laboratory
Localization: S. Fairhurst arXiv:1205.6611v1
Photographs: LIGO Laboratory; MIT; Caltech

LIGO

- The LIGO Instruments – and Collaboration – achieved a milestone in physics, just one year ago: The first direct detection of GWs
- To achieve this goal, we needed the
  - instruments,
  - the coherent contribution of 1000 people, and
  - a substantial unifying organization
- Worthwhile to walk through the evolution of the field to show how the GW community evolved to create this synergy

Albert Einstein
1915

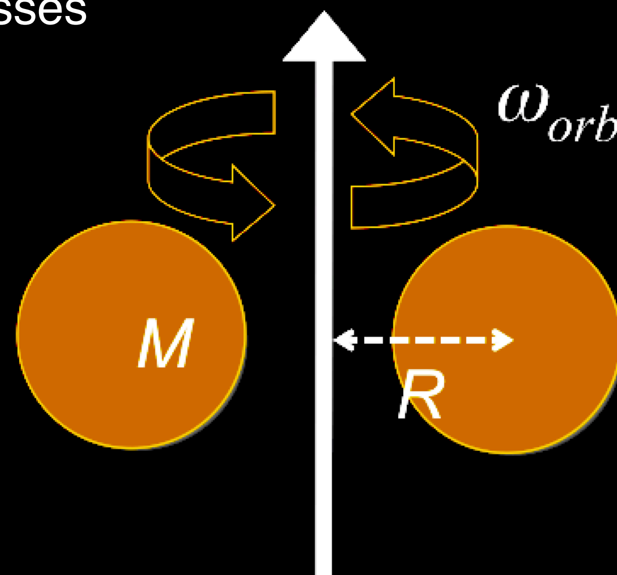


Theoretical basis

- Theory of Special Relativity 1905, which led to….
- Theory of General Relativity 1915
  - » A new vision of the interaction of matter with space-time
- Prediction of Gravitational Waves 1916
  - » Non-spherical element of accelerating masses

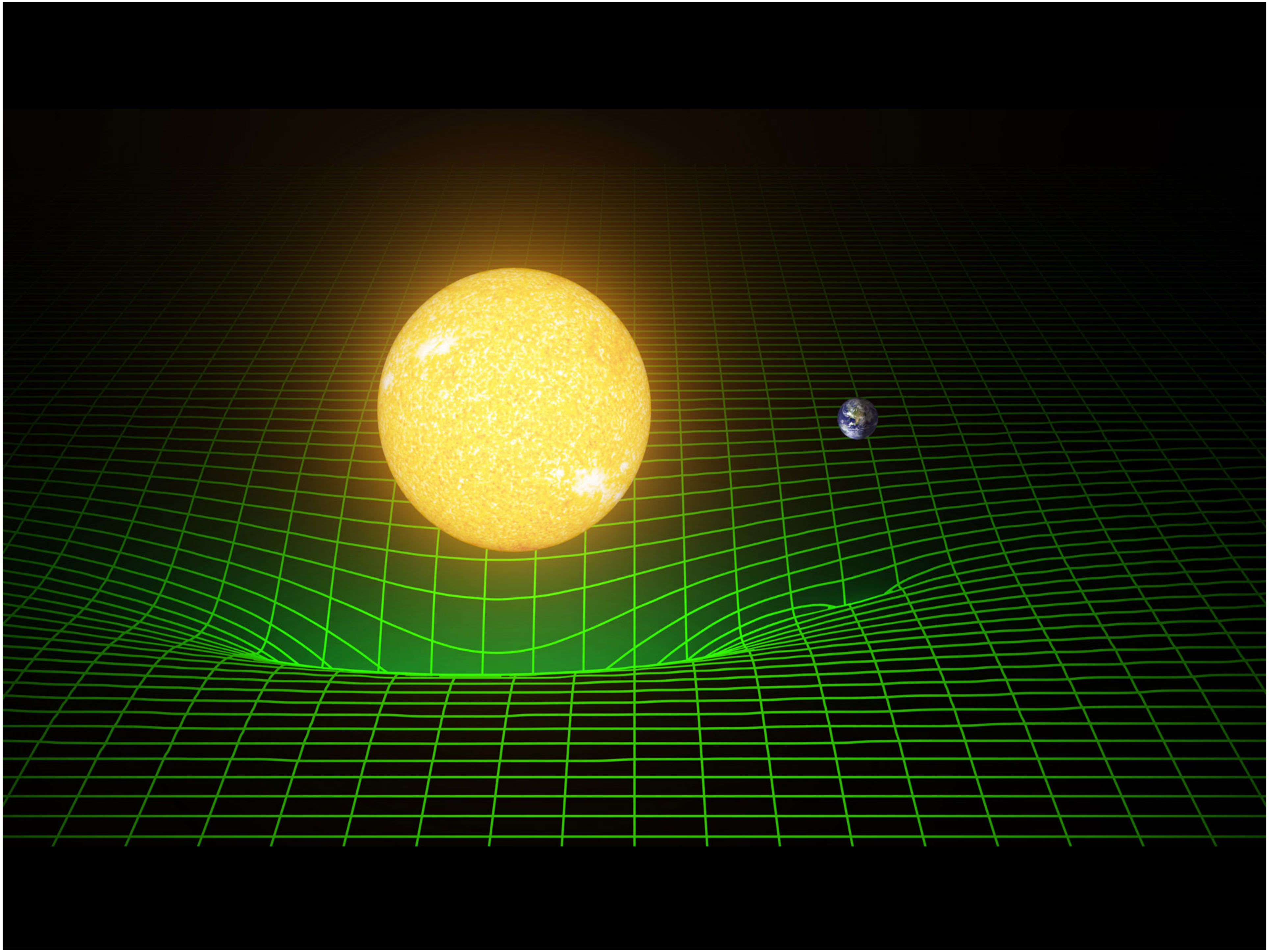
$$h_{\mu\nu} \approx \frac{1}{r}\frac{G}{c^4}\ddot{I}_{\mu\nu}$$

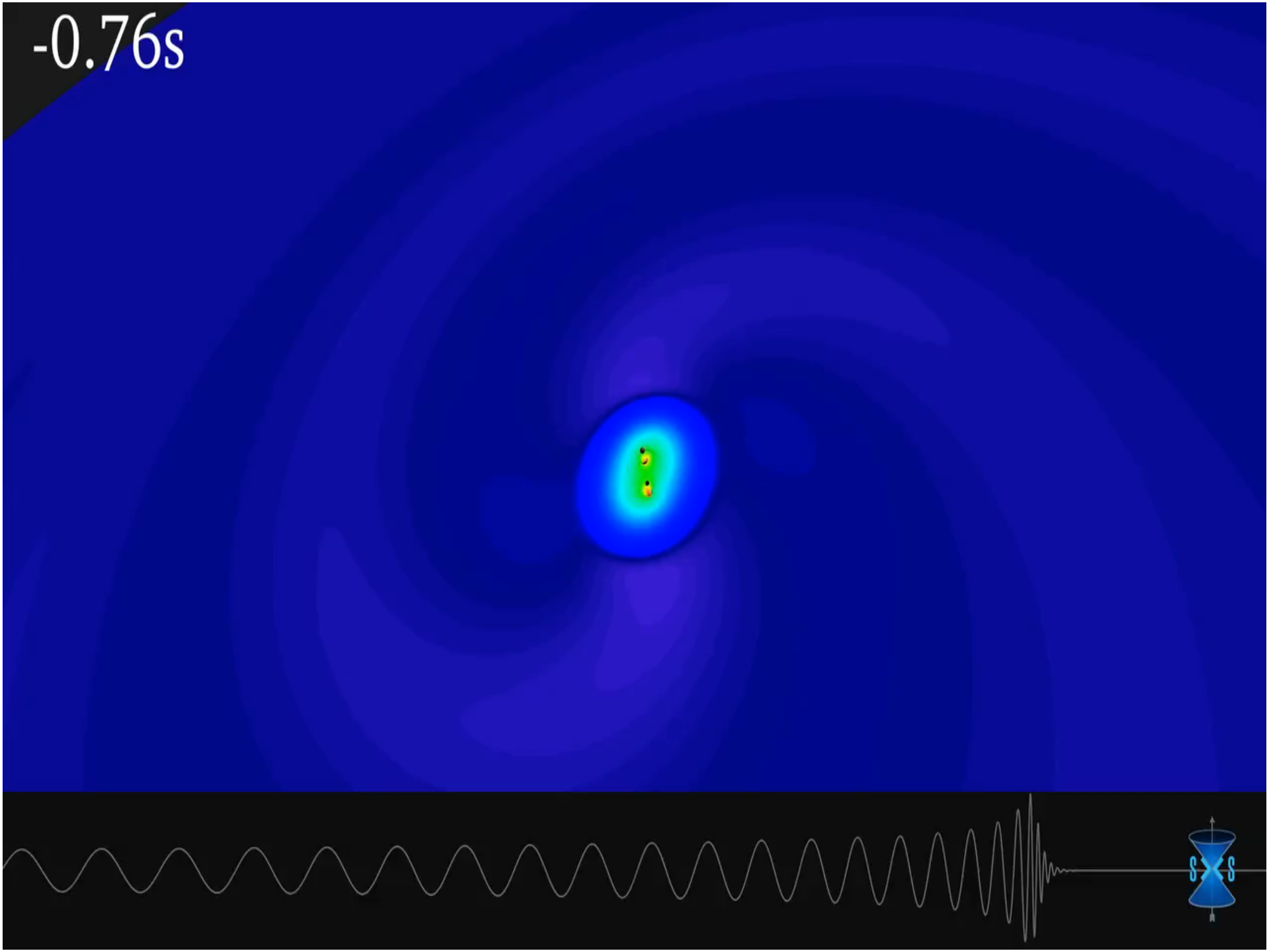
r = distance from the source to the observer



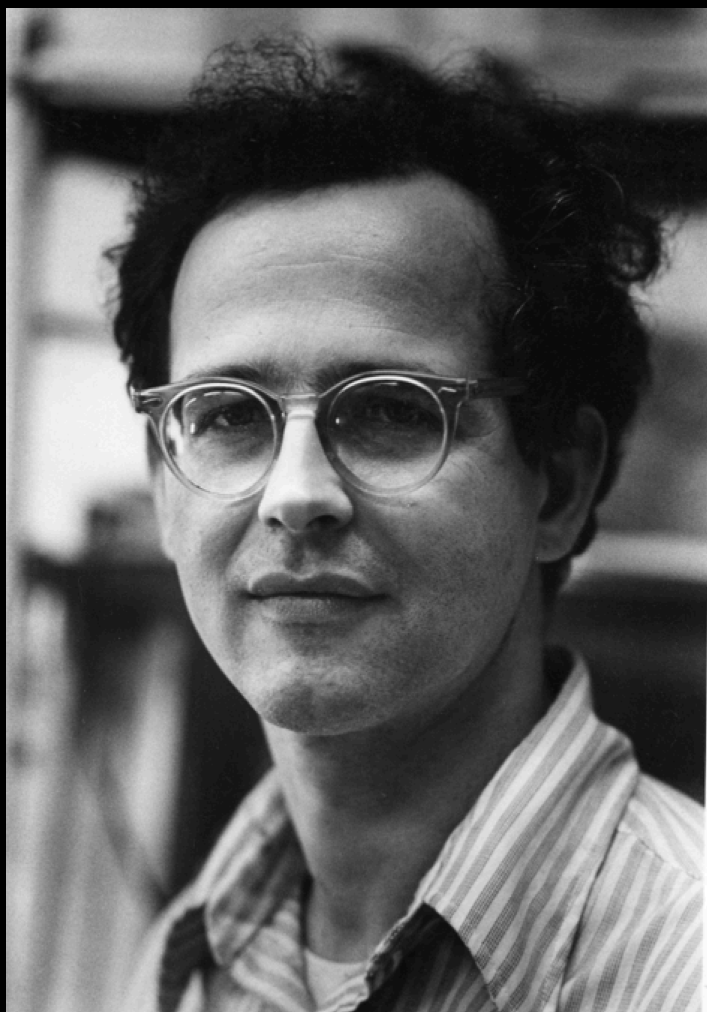
Rotating dumbbell ⟶ $$h \approx \frac{8GMR^2\omega_{orb}^2}{rc^4}$$

- Calculation for Virgo gives $h \sim \Delta L/L \sim 10^{-21}$ – very small strain in space
- Einstein doubted own result, and commented that it was not likely to be observable due to the very small size of the signals




-0.76s
SXS

Rai Weiss, circa 1967



... gravitational wave, and it is assumed that all components ... much smaller than 1. If the plane wave propagates in the x_1 direction, ... is always possible to find a coordinate system in which h_{ij} takes the irreducible fo...

$$h_{ij} = \begin{pmatrix} 0 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & \begin{matrix} h_{22} & h_{23} \\ h_{32} & h_{33} \end{matrix} \end{pmatrix}$$

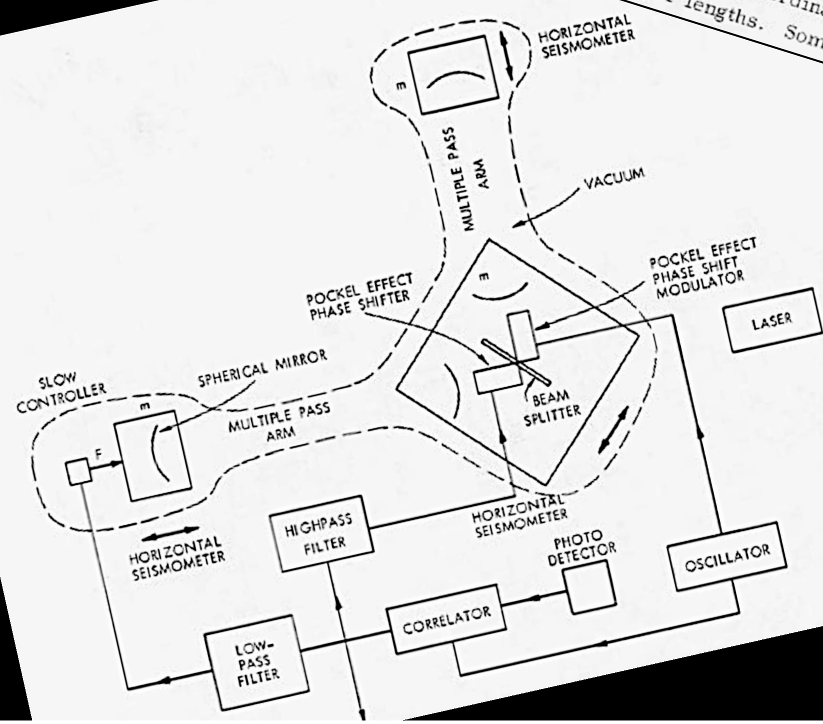
with $h_{22} = -h_{33}$, and $h_{23} = h_{32}$. The tensor components have the usual functional dependence $f(x_1 - ct)$.

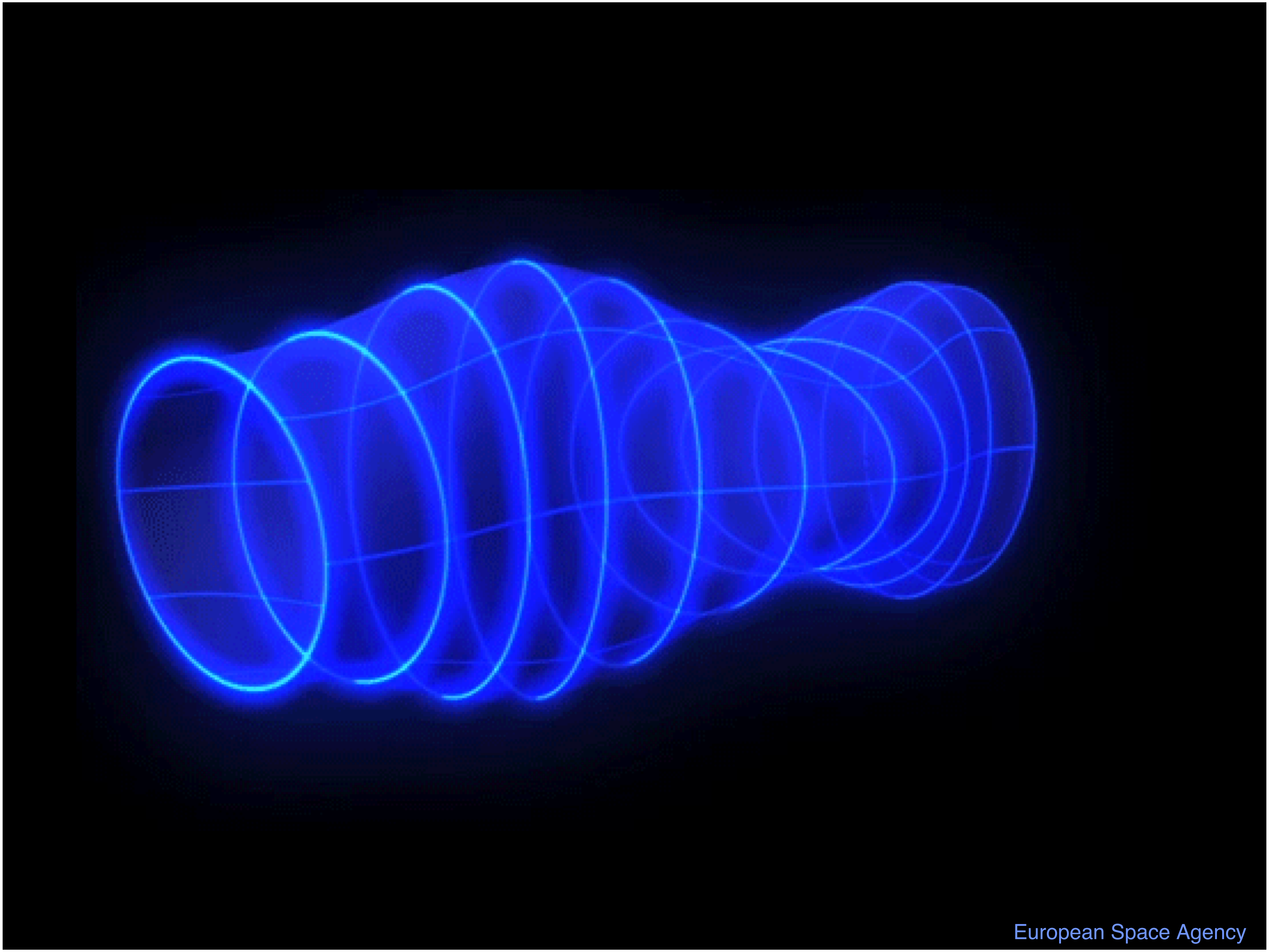
To gain some insight into the meaning of a plane gravitational wave, assume that the wave is in the single polarization state $h_{23} = h_{32} = 0$, and furthermore let $h_{22} = -h_{33} = h \sin (kx_1 - \omega t)$. The interval between two neighboring events is then given by

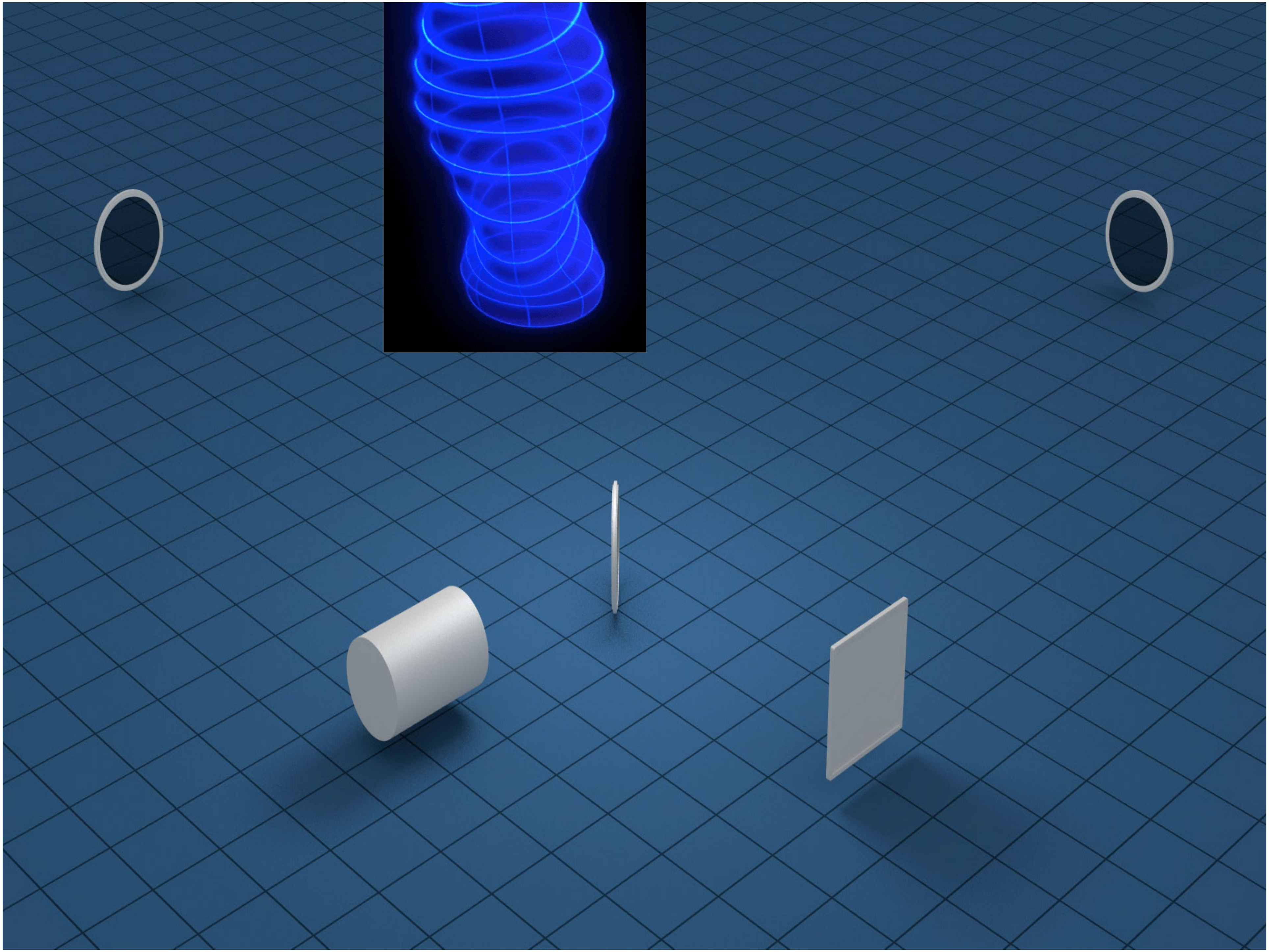
$$ds^2 = g_{ij} dx^i dx^j = c^2 dt^2 - \left[dx_1^2 + (1 + h \sin (kx_1 - \omega t))\, dx_2^2 + (1 - h \sin (kx_1 - \omega t))\, dx_3^2\right].$$

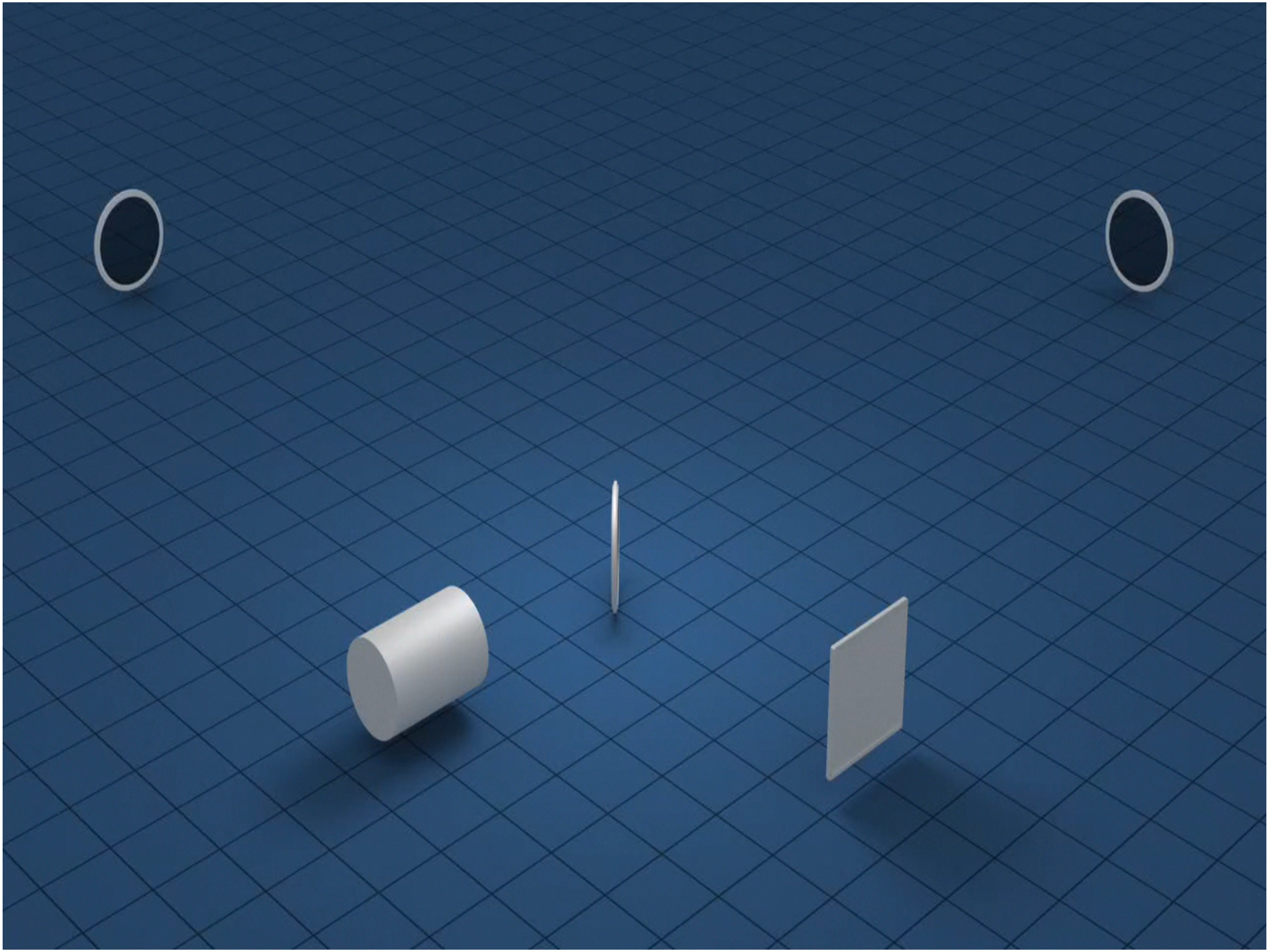
The metric relates coordinate distances to proper lengths. In this metric coordinate time is proper time; however, the spatial coordinates are not proper lengths. Some

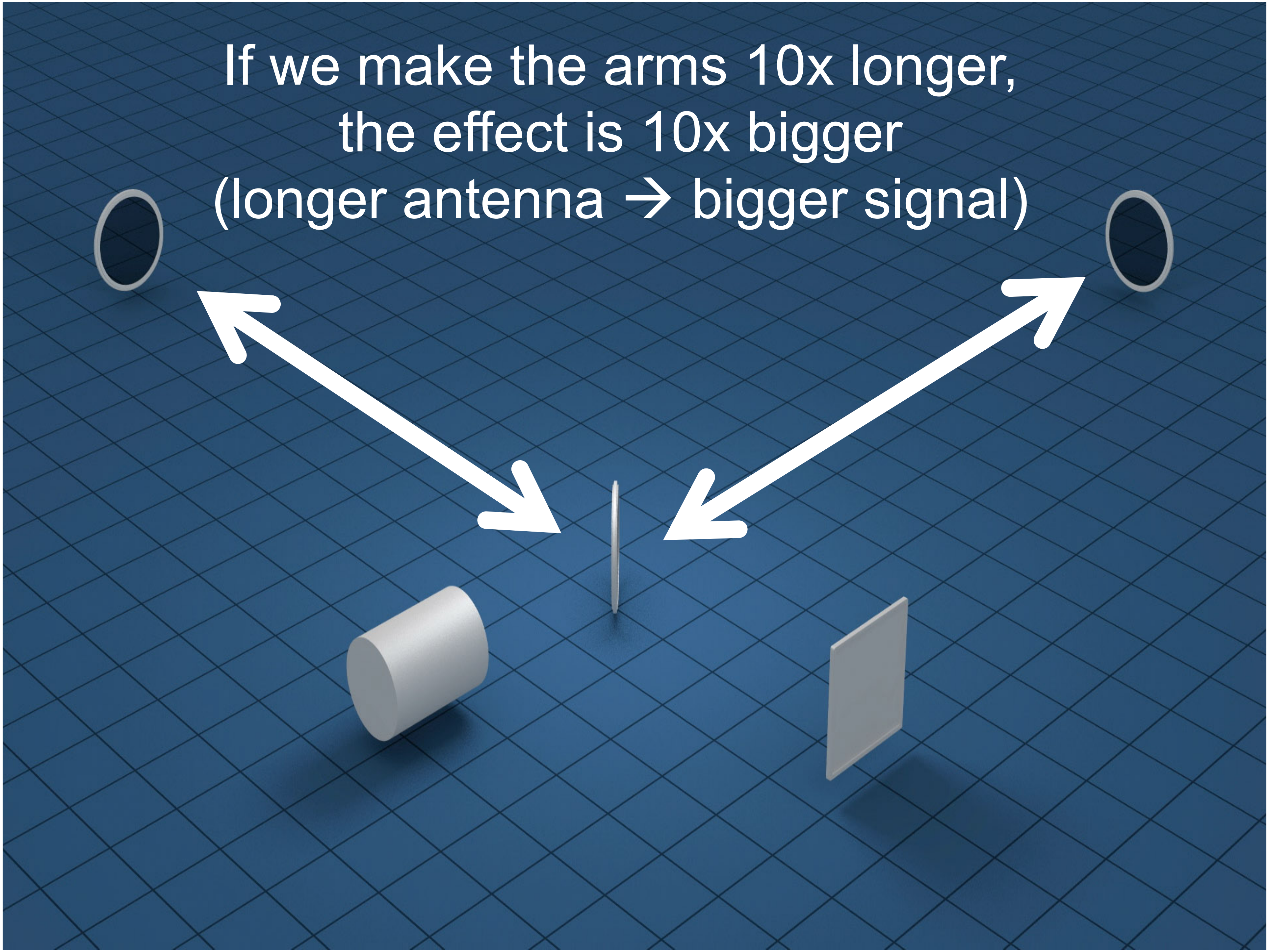
(V. GR...



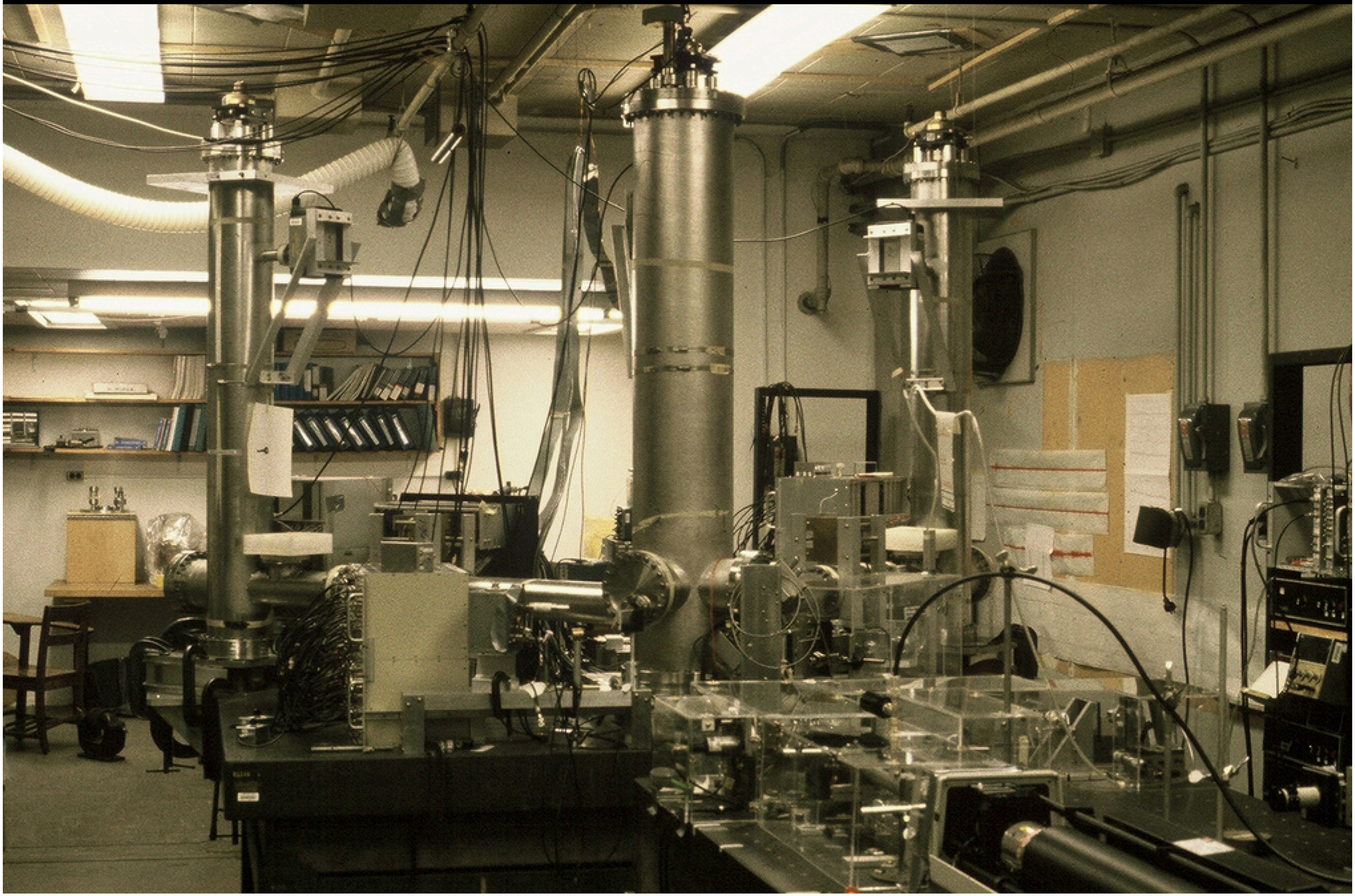

European Space Agency






If we make the arms 10x longer,
the effect is 10x bigger
(longer antenna → bigger signal)

First prototype detectors in 70's – 80's



GW science up to the early 80's

- Acoustic 'bar' antennas (Joe Weber) pioneered the idea of detection
- Interferometric technique starts to garner interest in mid-'70s
- Widely separated groups, of 5-10 persons
  - Munich, Glasgow, MIT, Caltech
- Precision measurement community worked on relevant problems but independently
- Theory, data analysis techniques advanced in fits and starts
  - Some efforts to join Numerical Relativity into 'challenges'…
- Efforts independent – Exchanging information mostly at conferences
- Some sense of competition and caution in sharing latest tricks
- Growing collection of solutions to
  - key technical problems
  - Predictions of waveforms from potential sources
  - Techniques to extract data
- Most scientists outside of the field – and even many *in* the field – thought detection was probably infeasible
  - Eddington: *"Gravitational waves travel at the speed of thought"*

Broad range of technical development needed

- Optical metrology on a scale and precision beyond the state of the art
- Substantial Optical polishing and coating advances
- High-efficiency ultra-stable single-wavelength lasers
- Interferometer design and readout, understanding of quantum noise
- Multi-input Multi-output servocontrol systems of great complexity and reaching over the 4km-footprint of LIGO
- Seismic isolation systems pushing mechanical design to new limits

And…

- Analytical solutions of Einstein's equations
- Numerical relativity to solve the final coalescence problem
- Development of the data analysis and characterization codes
- Grid computing to harness resources spread around the globe
- Astrophysical interpretation of the signals

US GW science in the late ‘80s

- Rai Weiss (MIT) and Kip Thorne (Caltech): instrumentation and astrophysics were within reach
- …but NSF could not support uncoordinated much less competing efforts
- Not all flowers could be cultivated to bloom if we were to make progress on a concrete goal

- LIGO was proposed as a Caltech-MIT joint effort to build two observatories and use them to search for GWs
- …but honestly the ‘joint effort’ was at yet rocky – different working styles and priorities in the MIT and Caltech groups

Key elements in Initial LIGO's success

- **Scientific leaders**
  - Vision, determination, and complete investment in LIGO
  - They realized they did not have the skills to *lead* the LIGO Project – management, engineering, and communications
- **Programmatic leaders**
  - Several different individuals, different skills suited to phases
  - First: Getting the MIT and Caltech groups to form a single team
  - Then: Providing experience in management of large projects
- **A strong central Laboratory**
  - Providing infrastructure, engineering, management
  - Strong Institutional support at Caltech
  - Enabling groups outside of MIT/Caltech to contribute
- **A funding agency – NSF – inspired and committed to the success of the LIGO Project**

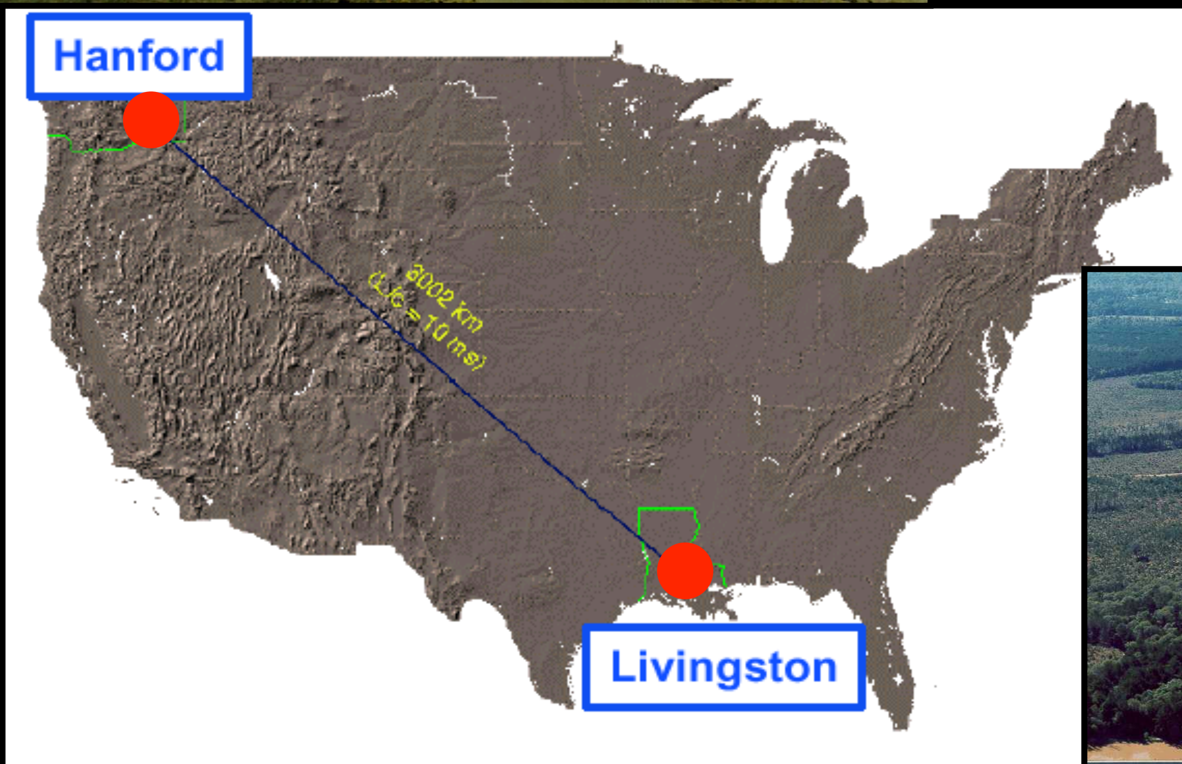
Key early difficulties

- Getting working scientists to
  - Share information freely – things that worked, things that did not
  - Focus on the most important tasks – as determined by leadership
  - Adopt the formalities of reporting progress

- After some bumps in the road, and adapting the organization to a more mature form –

- The NSF supported the proposal to build LIGO.

LIGO Laboratory
– Caltech, MIT –
built observatories in ‘90s, and…



…Observed with the initial detectors 2005-2011, and saw…

nothing

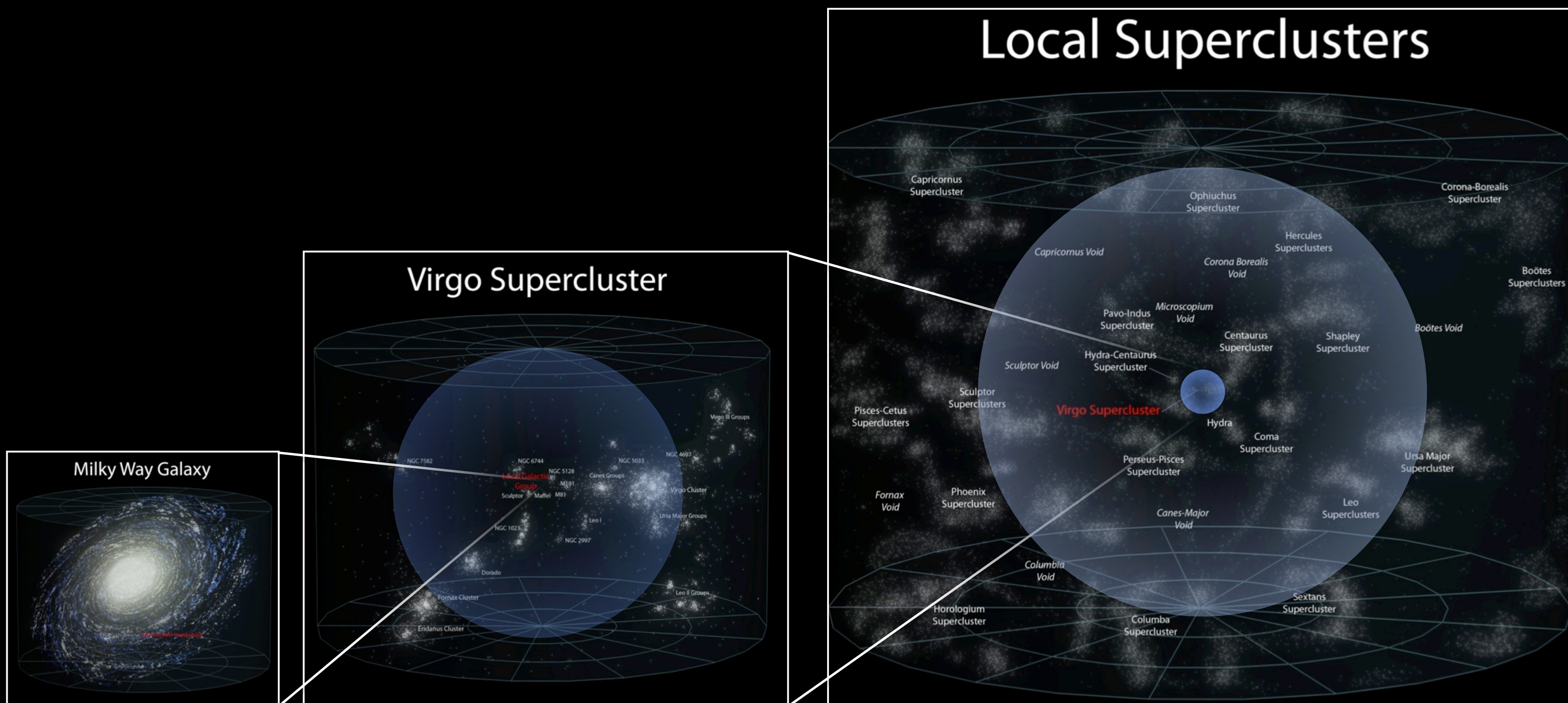
Initial Detectors

- That is to say, we saw no gravitational-wave signals.
  - We learned how to work together – and formed the LIGO Scientific Collaboration to coordinate, plan, and propose coherently to the NSF
  - We learned how to build and commission detectors
  - We learned how to analyze the data
  - We created new upper limits and significant ‘non-detections’

…but it was clear we needed more sensitive detectors.

Initial LIGO to Advanced LIGO:

Volume of space grows as the *cube* of sensitivity…
factor of 10 improvement means *1000x* more stars in reach



M. Evans

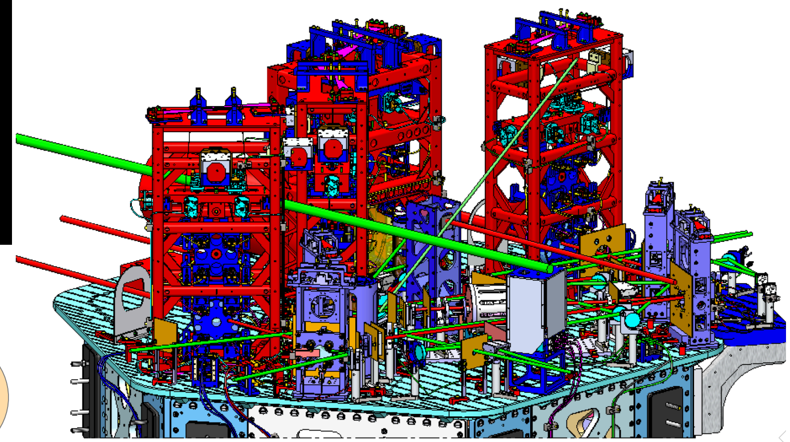
Initial Reach
If we had one
signal here…

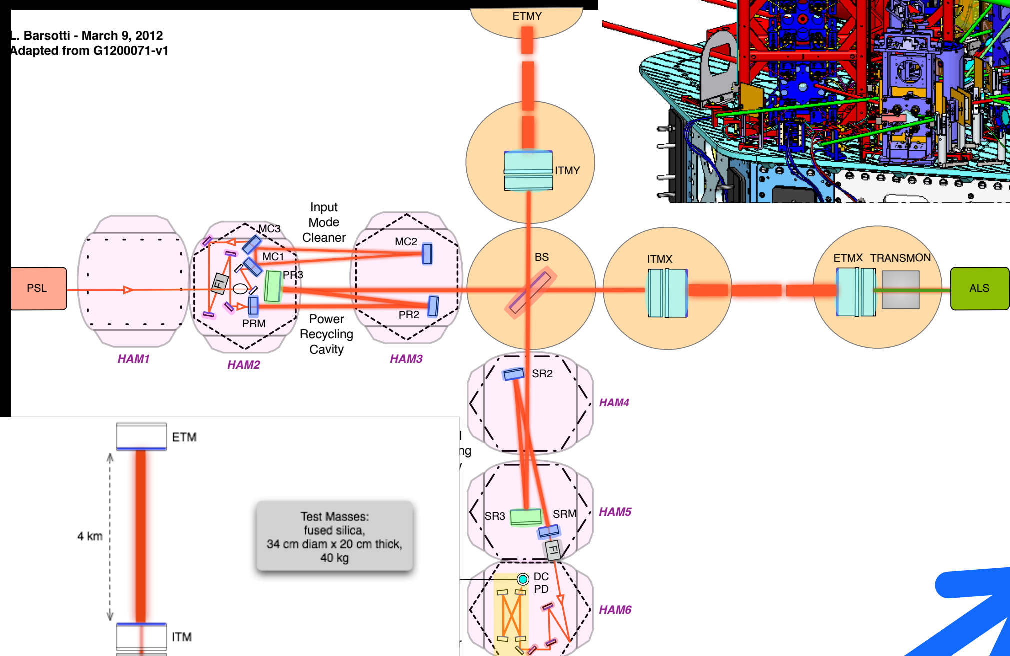
Advanced Reach
…we would have
1000 here!

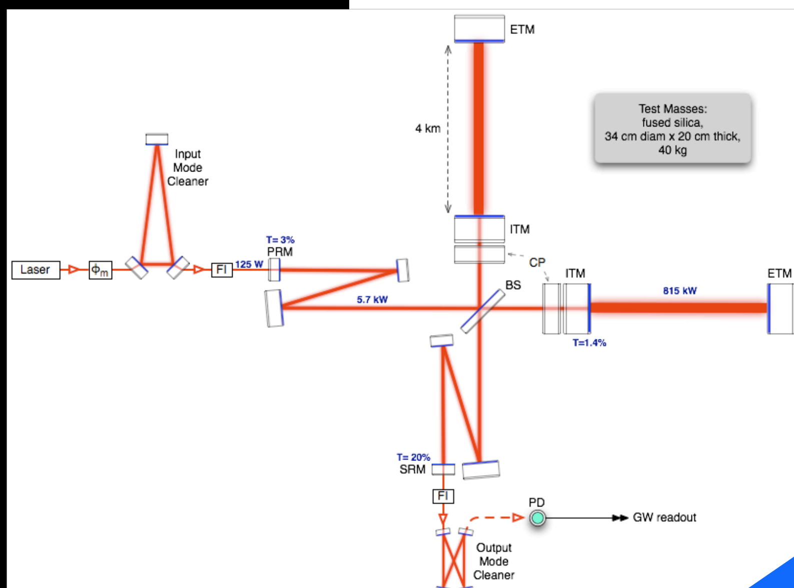
Advanced LIGO

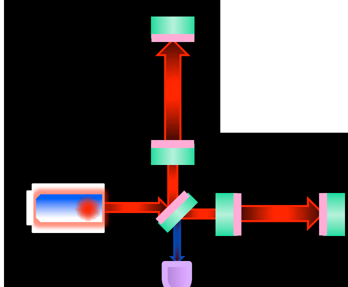
- Better basic science ideas for the detector
  - From an ever larger and more coherent LIGO Scientific Collaboration (well beyond the MIT/Caltech Laboratory)
- Better technology to realize those ideas
- The experience of building initial LIGO
- Really good systems engineering and QA
- 15 years of the scientific life of 100 or so of the best instrument builders on the planet
- Incredible courage, vision, patience on the part of the NSF

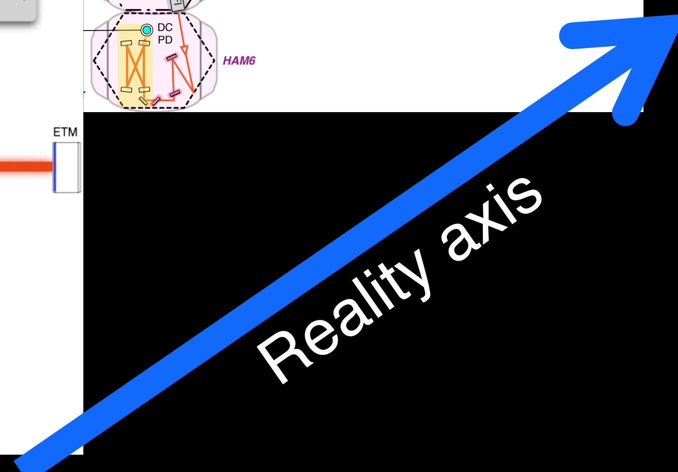
Incredibly complex design, and hardware, needed

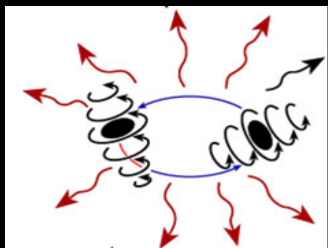


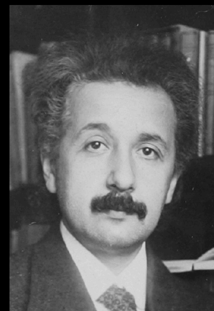


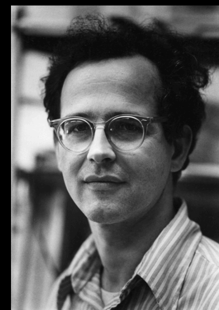


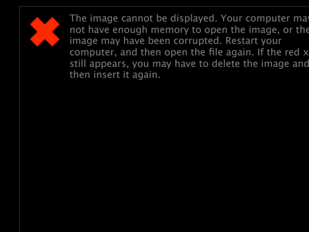












1.3 Billion years after the Black Holes merged..
(and multicellular life started on earth…)

100 years after Einstein predicted gravitational waves…

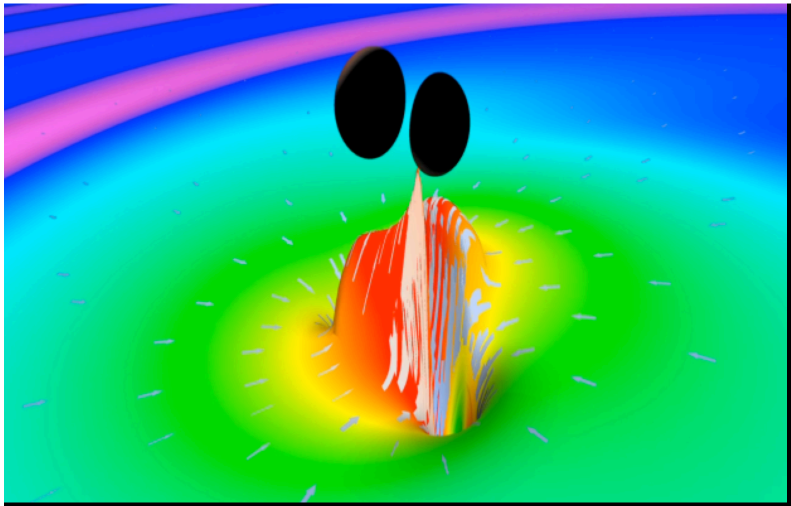
50 years after Rai Weiss invented the detectors...

20 years after the NSF, MIT, and Caltech Founded LIGO...

10 years after Advanced LIGO got the ok...

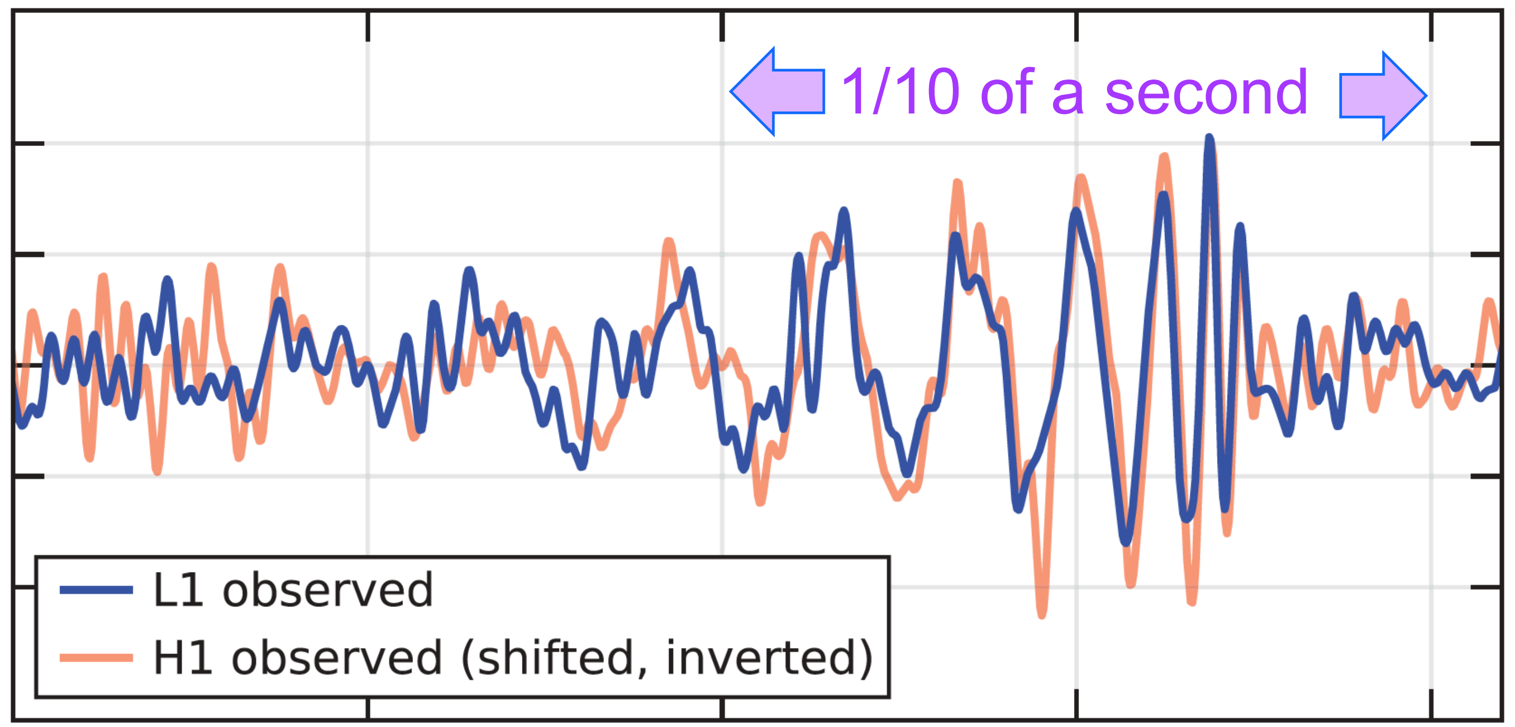
6 months after starting detector tuning...

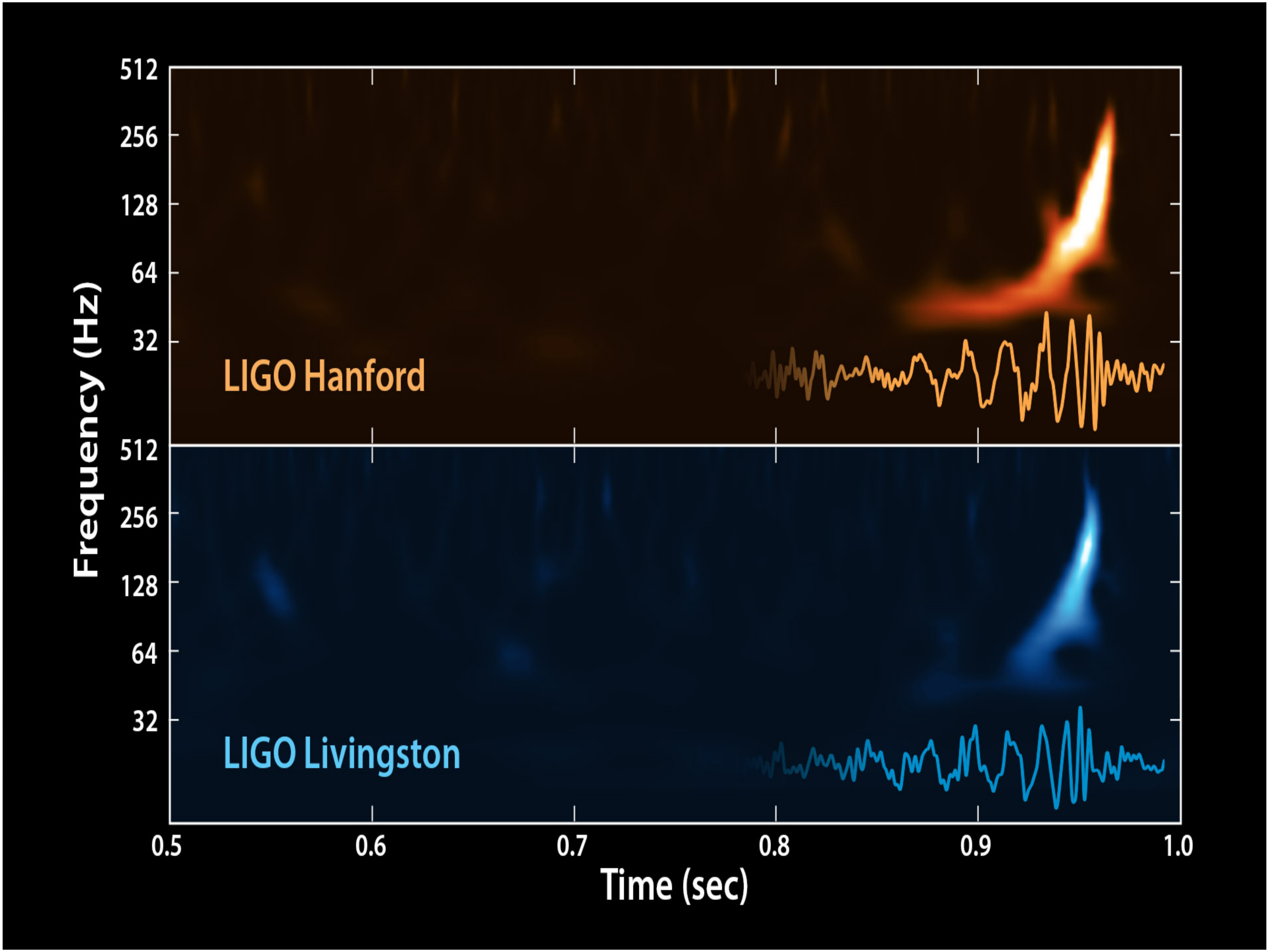
Two days **after we started observing...**

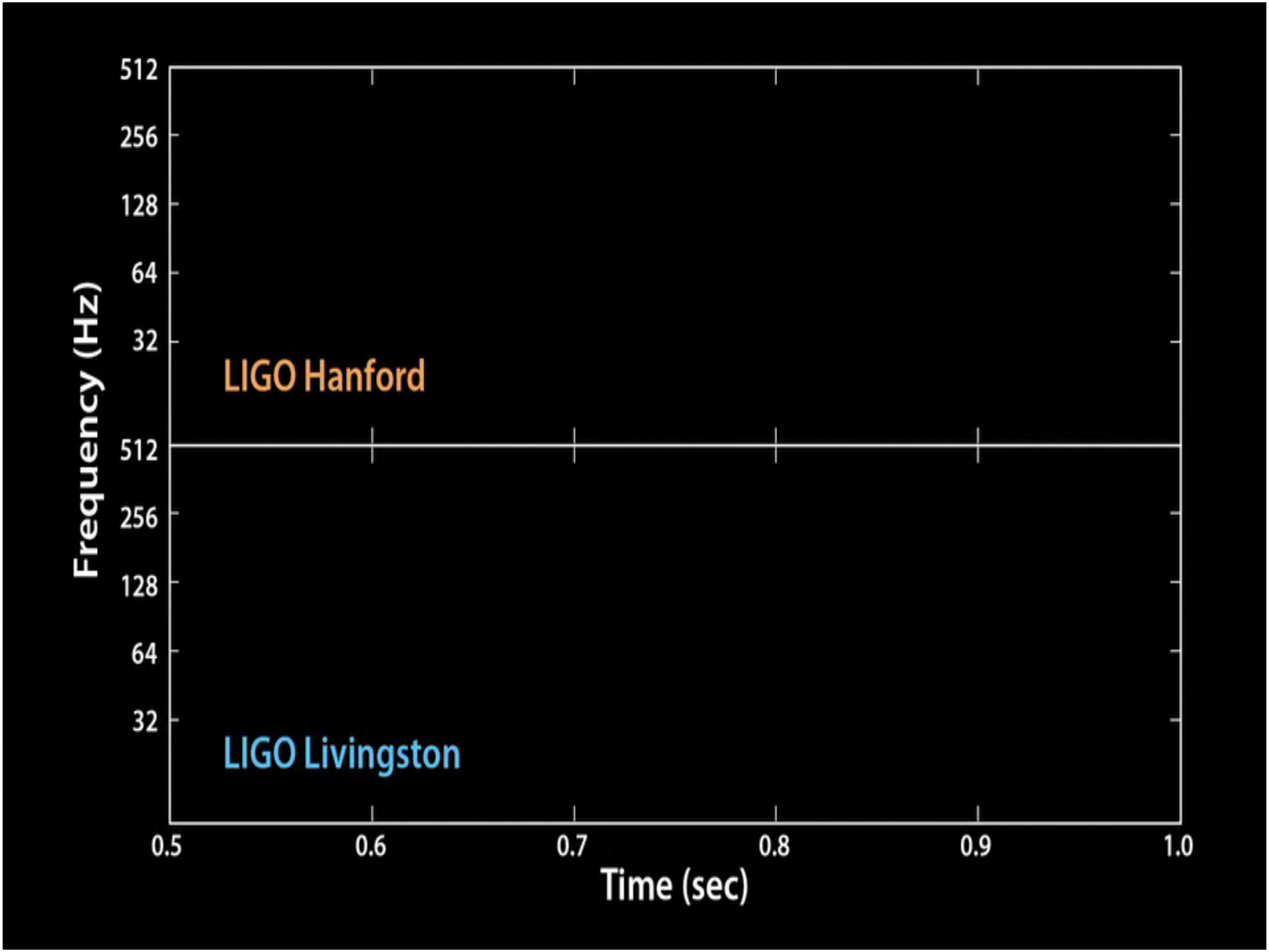


September 14, 2015 at 05:51 EDT:

Cosmic Rendezvous




512
256
128
64
32
Frequency (Hz)
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



Frequency (Hz)
512
256
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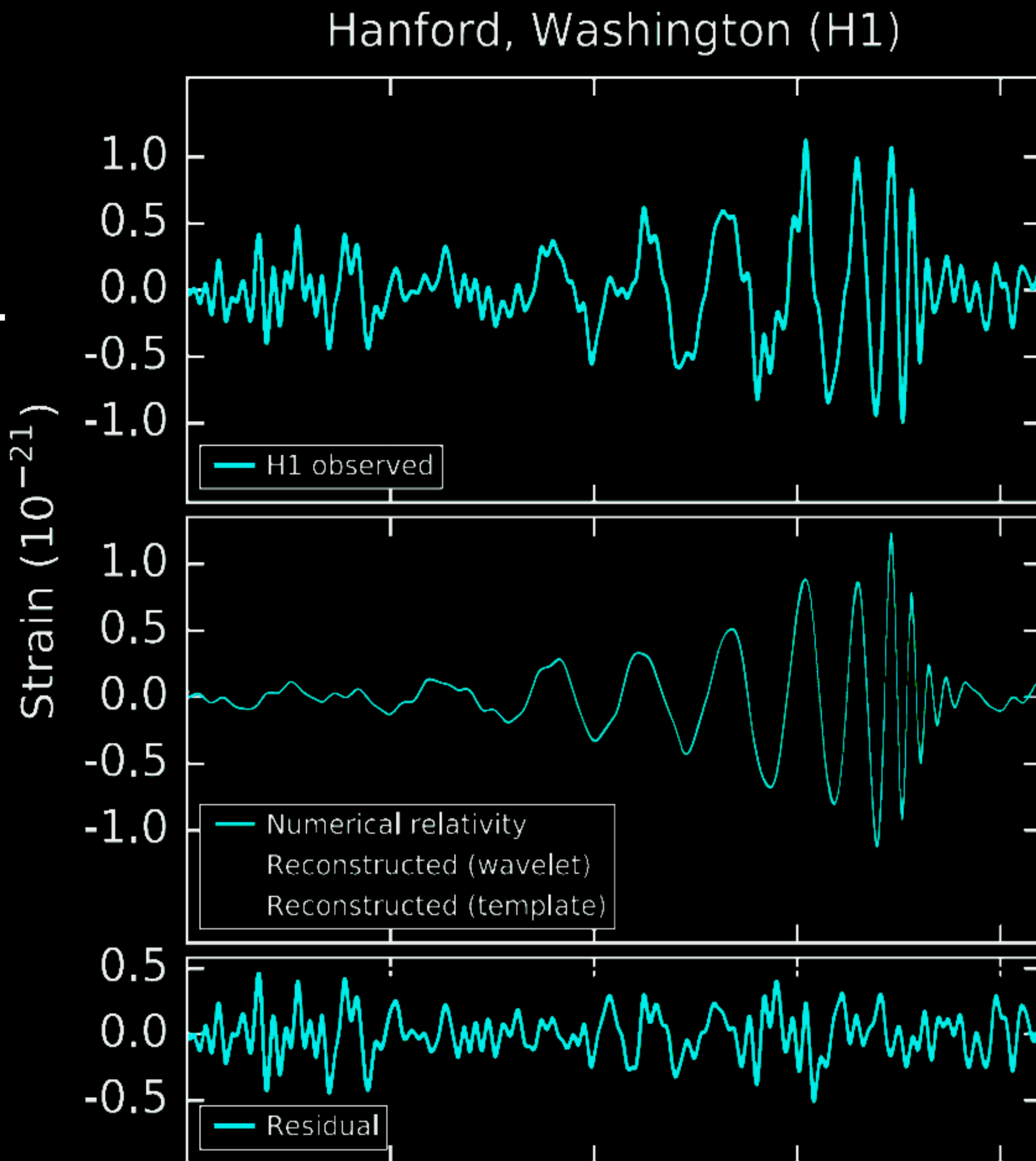
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

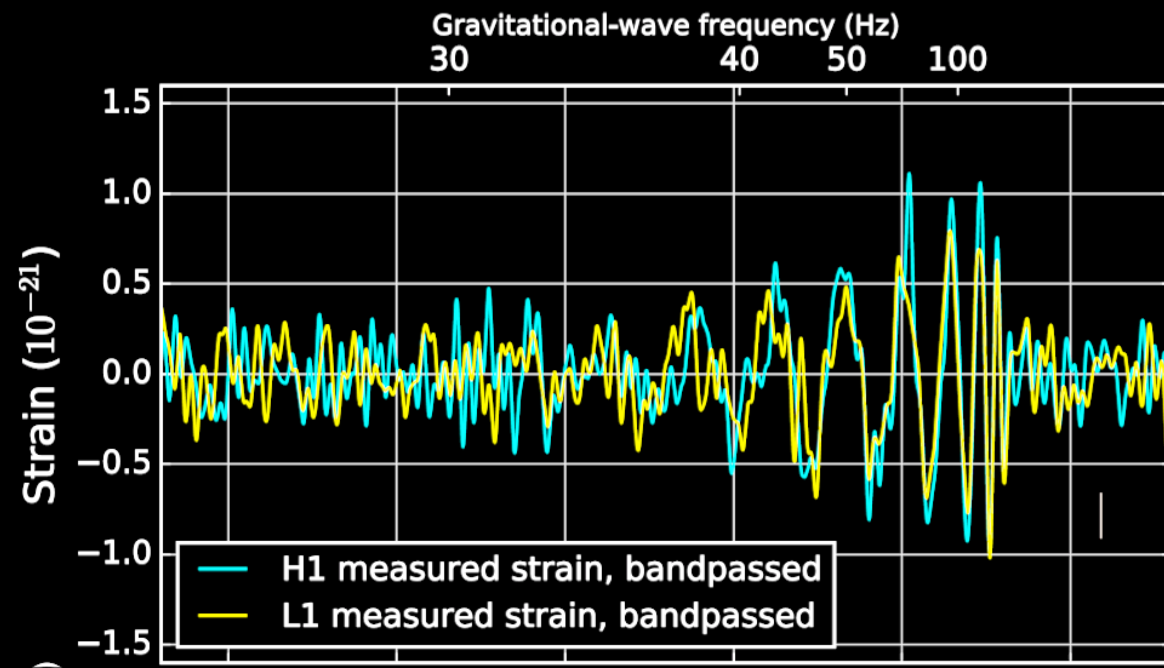
This measured signal…

…minus Einstein's prediction…

…equals noise



LIGO can actually measure the change in distance between our optics, due to a passing space-time ripple



An astonishingly tangible connection between:

the most cataclysmic conditions of space and time,

– and –

stuff we make with our own hands

And…

- We were ready, due to the nature of the LIGO Laboratory and the LIGO Scientific Collaboration.

Key features of our collaboration

- **Strong central LIGO Laboratory - ~150 persons**
  - The LIGO Instruments and the Observatories housing them
  - Engineering and computing resources
  - Scientific and engineering Management
- **LIGO Scientific Collaboration - ~1000 persons**
  - Elected spokesperson, Working group structure with leadership
  - International membership
  - Rewards of membership:
    - immediate access to data
    - Access to expertise and central infrastructure
    - Leverage of small group effort by larger group effort
- **Collaboration tools**
  - Common Document repository (with access controls)
  - ‘Telecon’ voice and document sharing to bridge continents
  - Closed meetings for entire collaboration, 2x year
- **Shared data and expertise with European Virgo Collaboration**
- **Supportive funding agency in the form of the NSF**

LIGO Scientific Collaboration

The LSC is the organization the conducts the science of LIGO

www.ligo.org 1000+ members, 90 institutions, 16 countries

Slide: Gabriela González

The advanced GW detector network