Gravitational Waves

Detection and Detectors

Andreas Freise

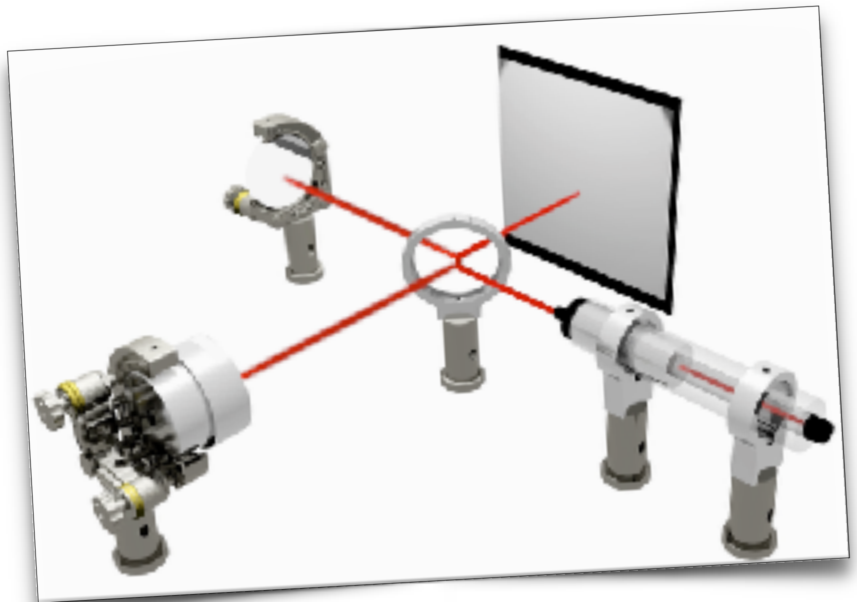
28.11.2017

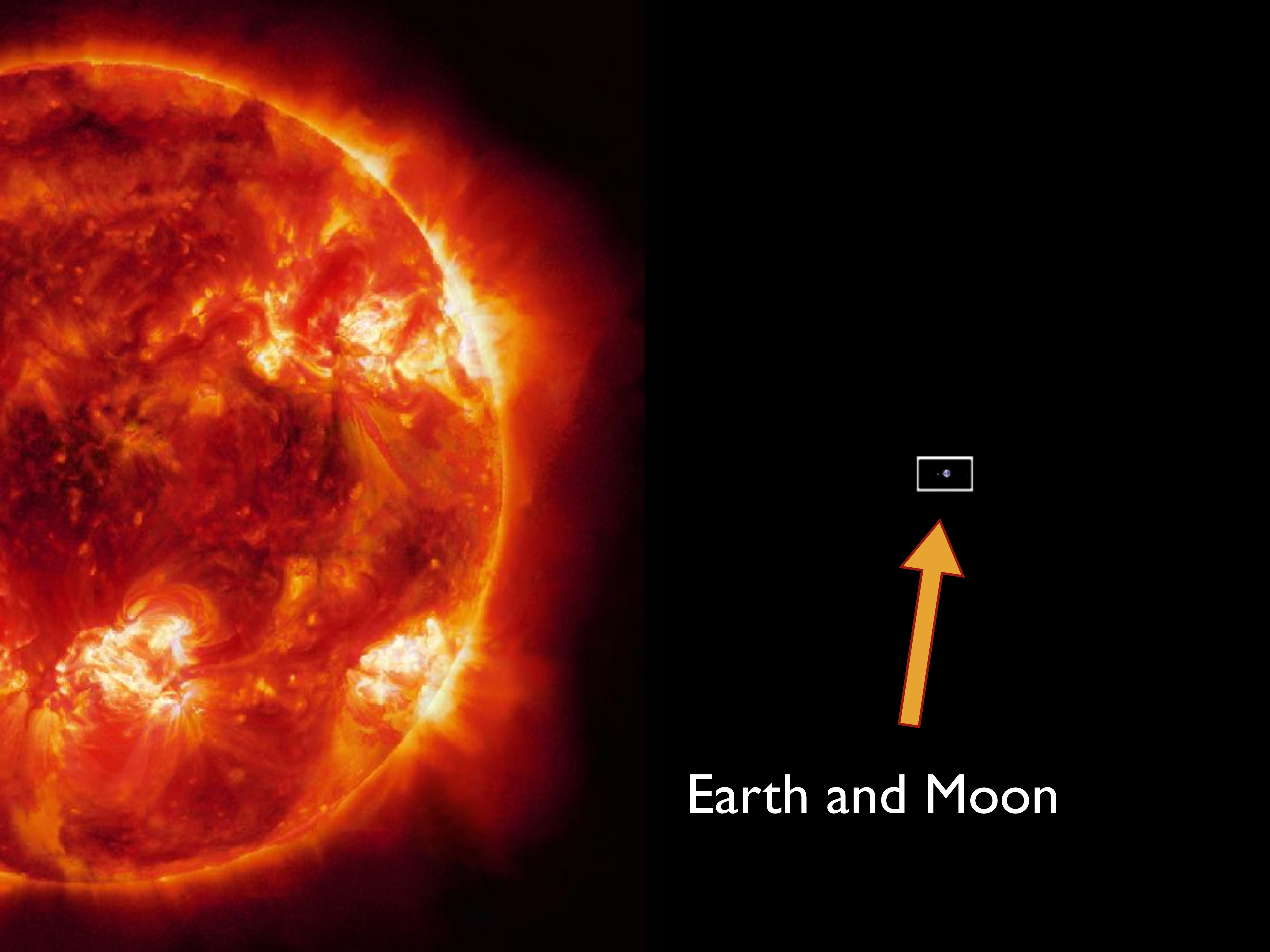
@gwoptics

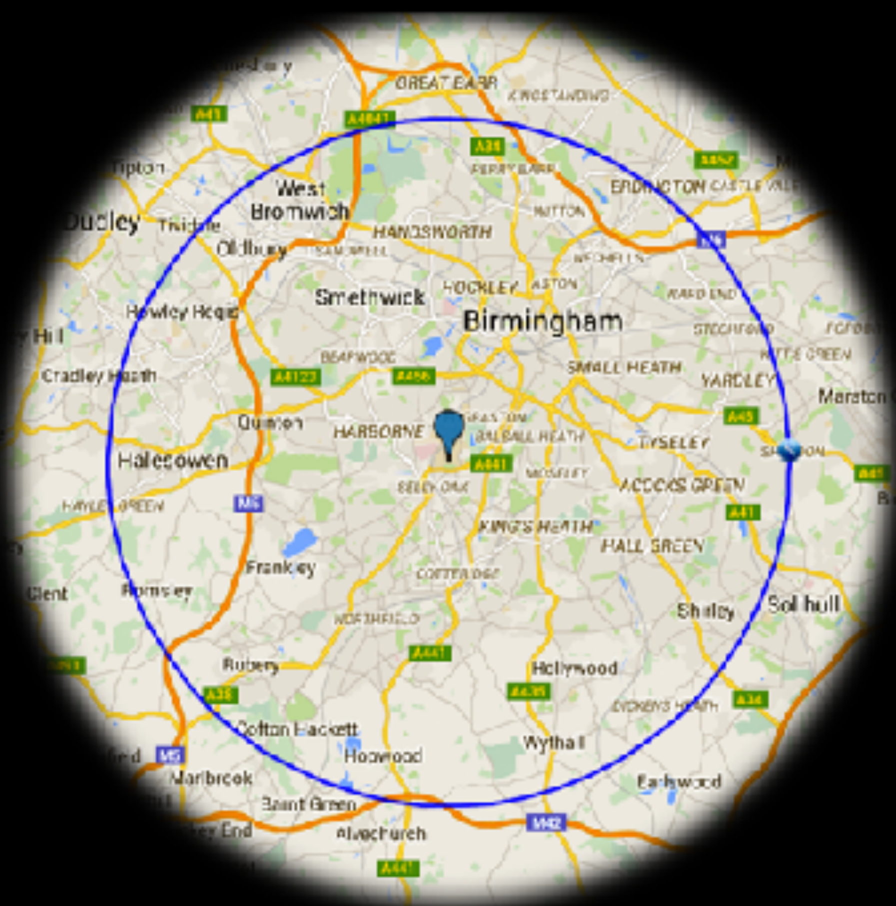
Institute of Gravitational Wave Astronomy

UNIVERSITY OF BIRMINGHAM

Gravitational Wave Astronomy

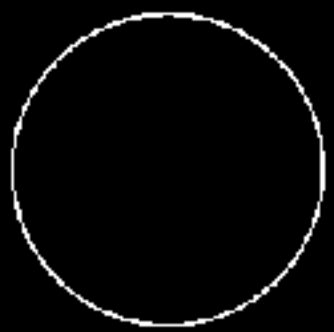



Earth and Moon

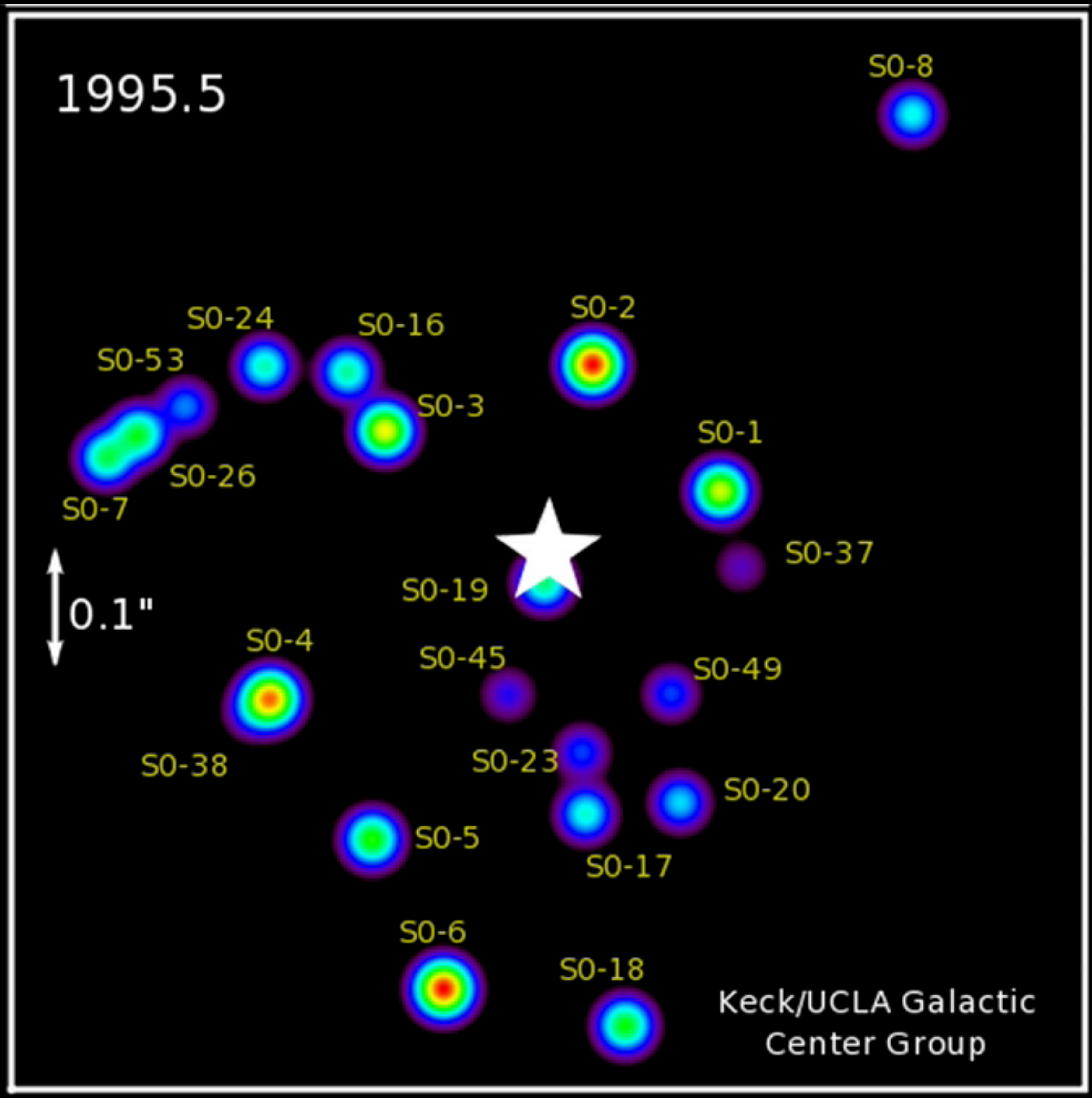


Birmingham

Neutron Star



Black Hole


1995.5
S0-8
S0-24
S0-16
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S0-53
S0-3
S0-26
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S0-45
S0-49
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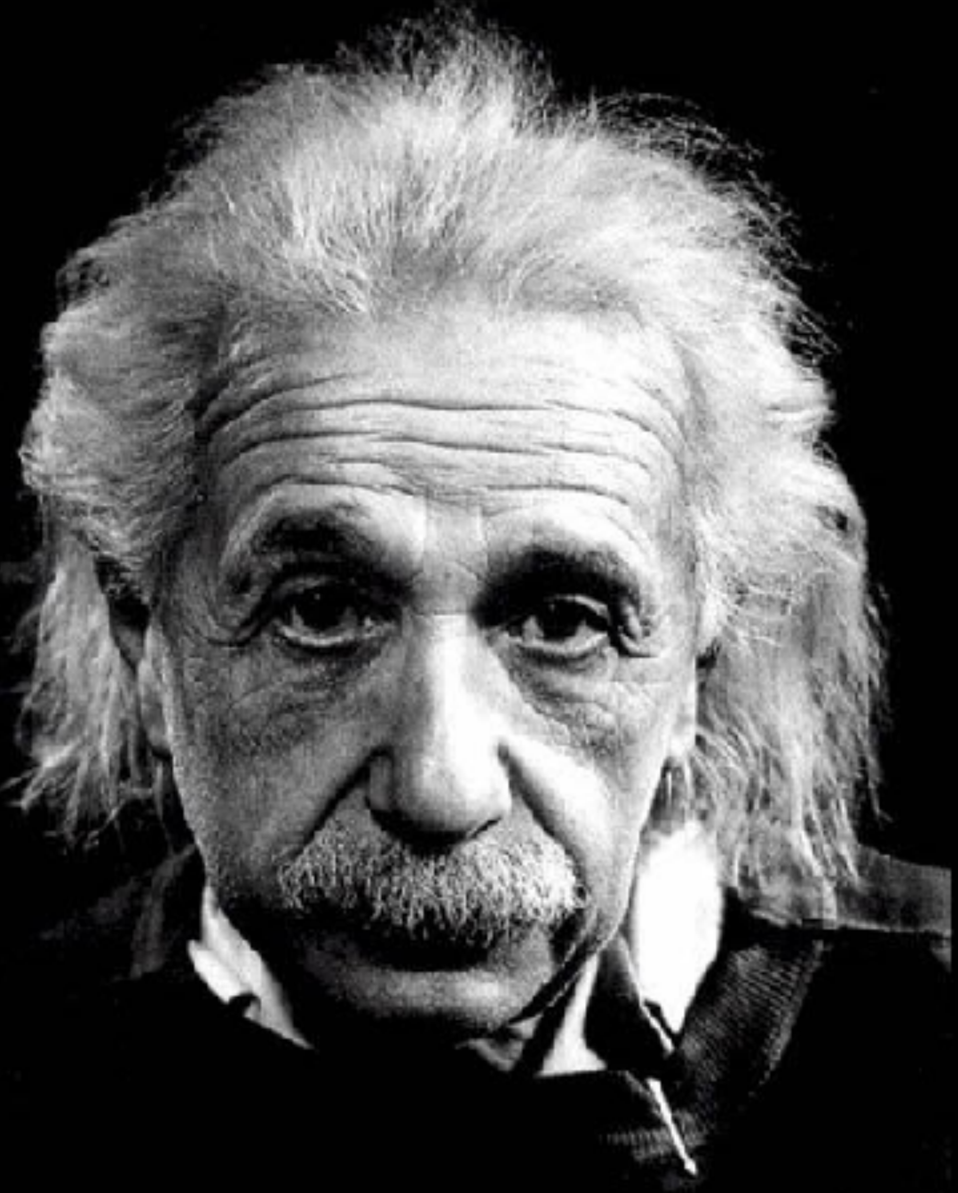
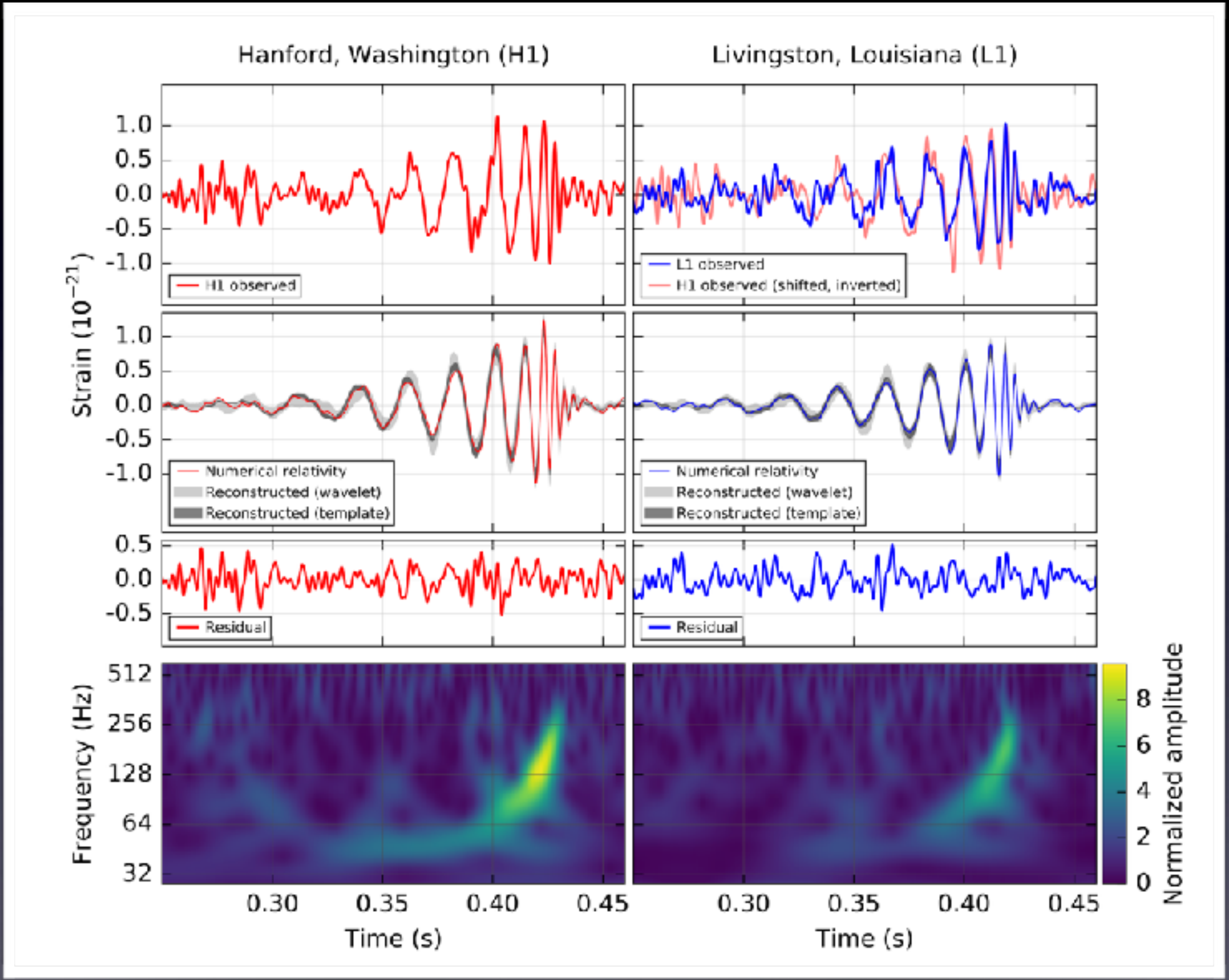
S0-5
S0-17
S0-6
S0-18
Keck/UCLA Galactic
Center Group



Data

... recorded on the
14th of September 2015, at 09:50:45 UTC

GW150914



GW150914

Fact sheet

- About 1 billion years ago (1 billion light years away), two black holes merged
- Before: two black holes of 36 and 29 solar masses
- After: one black hole, 62 solar masses
- Inspiral and merge is a **very violent event**, rotation speed up to 200 Hz
- In 2015 the LIGO mirrors wiggled by 10^{-18} meters for 0.1 seconds

2017 NOBEL PRIZE IN PHYSICS

Rainer Weiss
Barry C. Barish
Kip S. Thorne

Since then…

- GW170608
- GW170817
  (First binary neutron star detection;
  first electromagnetic counterpart)
- GW170814
  (first detection with Virgo)
- GW170104
- GW151226
- GW150914 (First detection)

GW170817

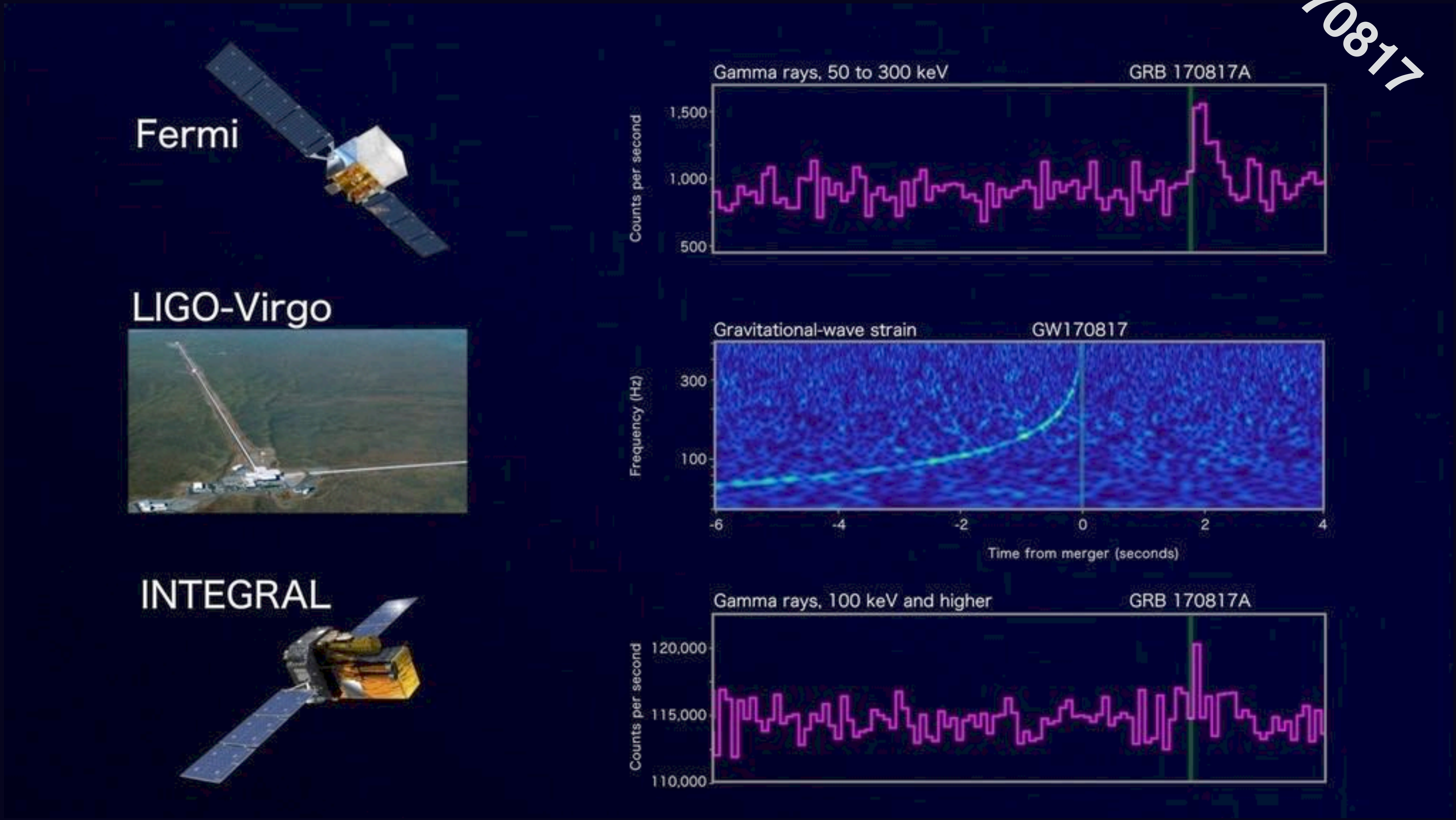
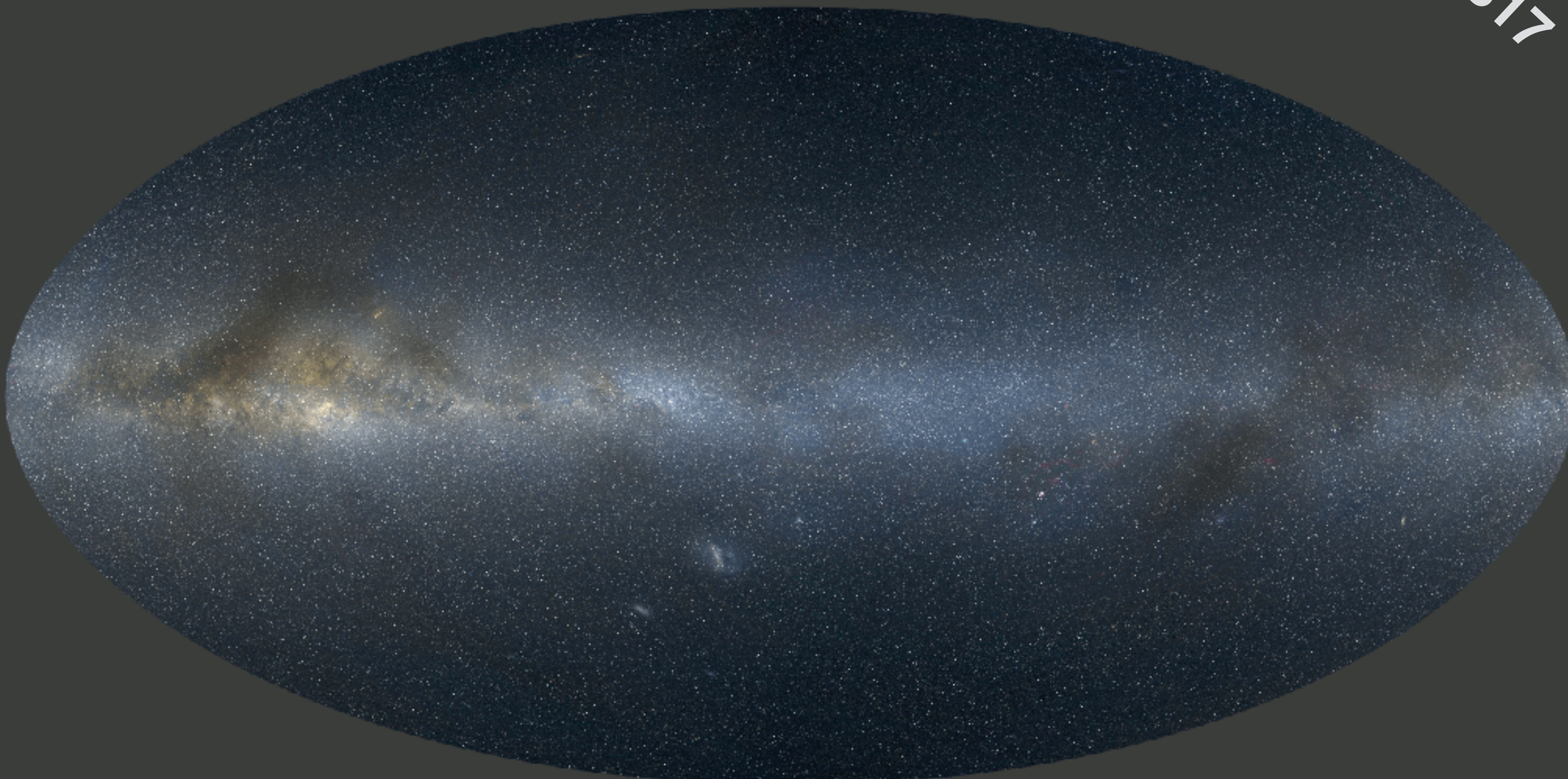


Image: LIGO, AEI, NASA, ESA

GW170817



Hubble observation of galaxy NGC 4993

GW170817

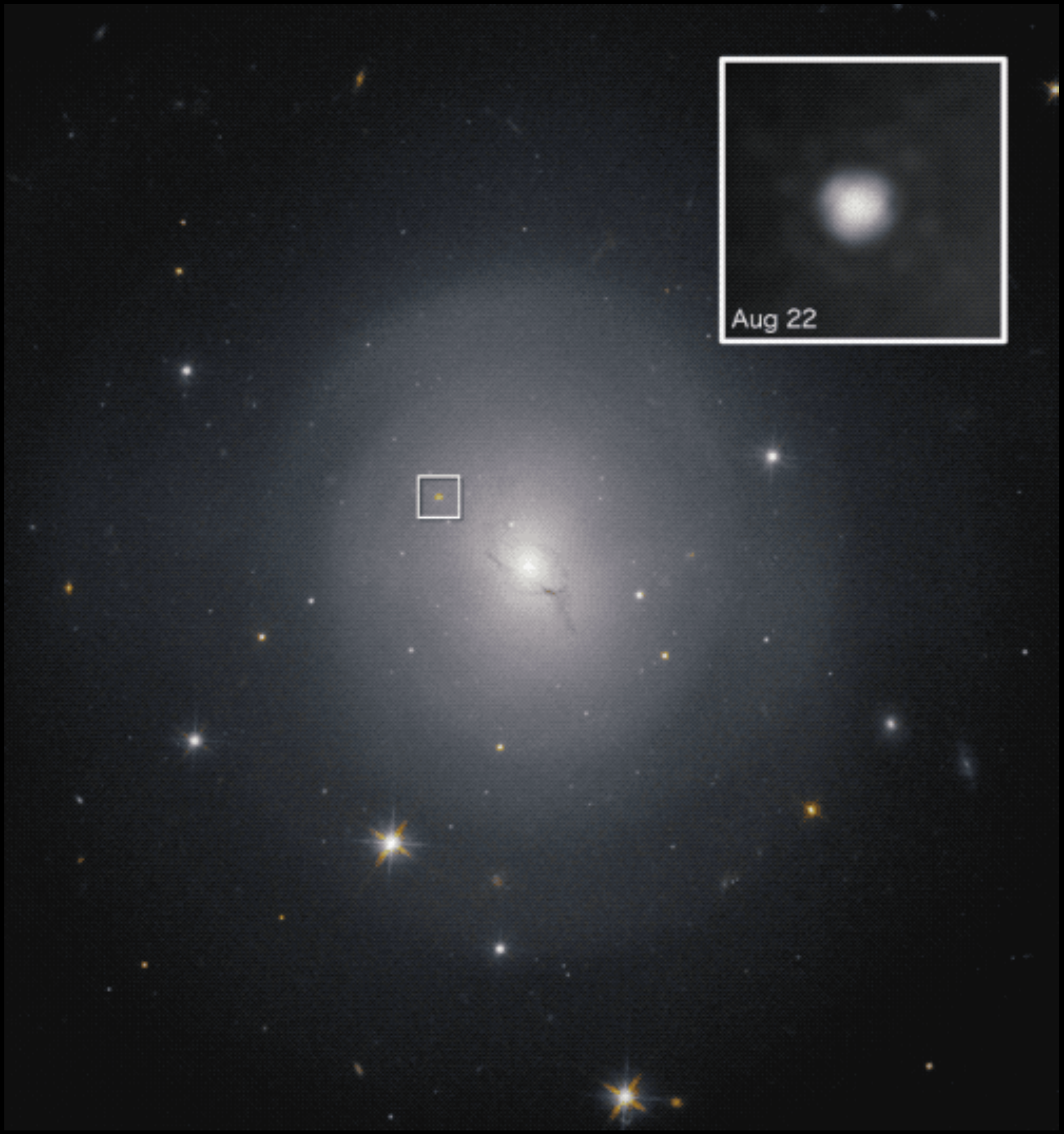


Image: NASA

GW170817

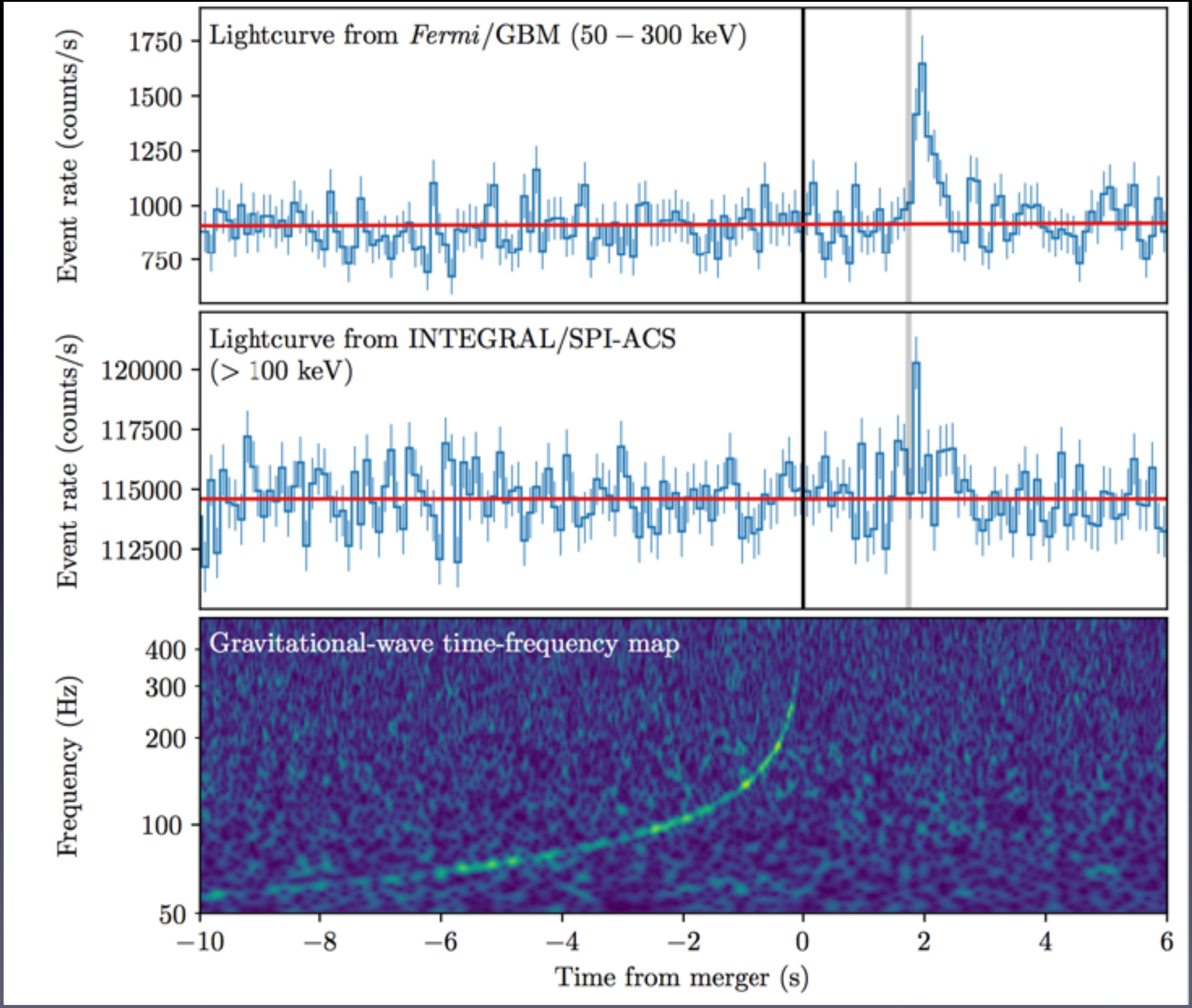
Credit: NASA's Goddard Space Flight Center/CI Lab

GW170817

Measurement of:

- Hubble constant
- speed of gravity = speed of light
- first confirmed ‘kilonova’
  (NS+NS = gold + …)
- …

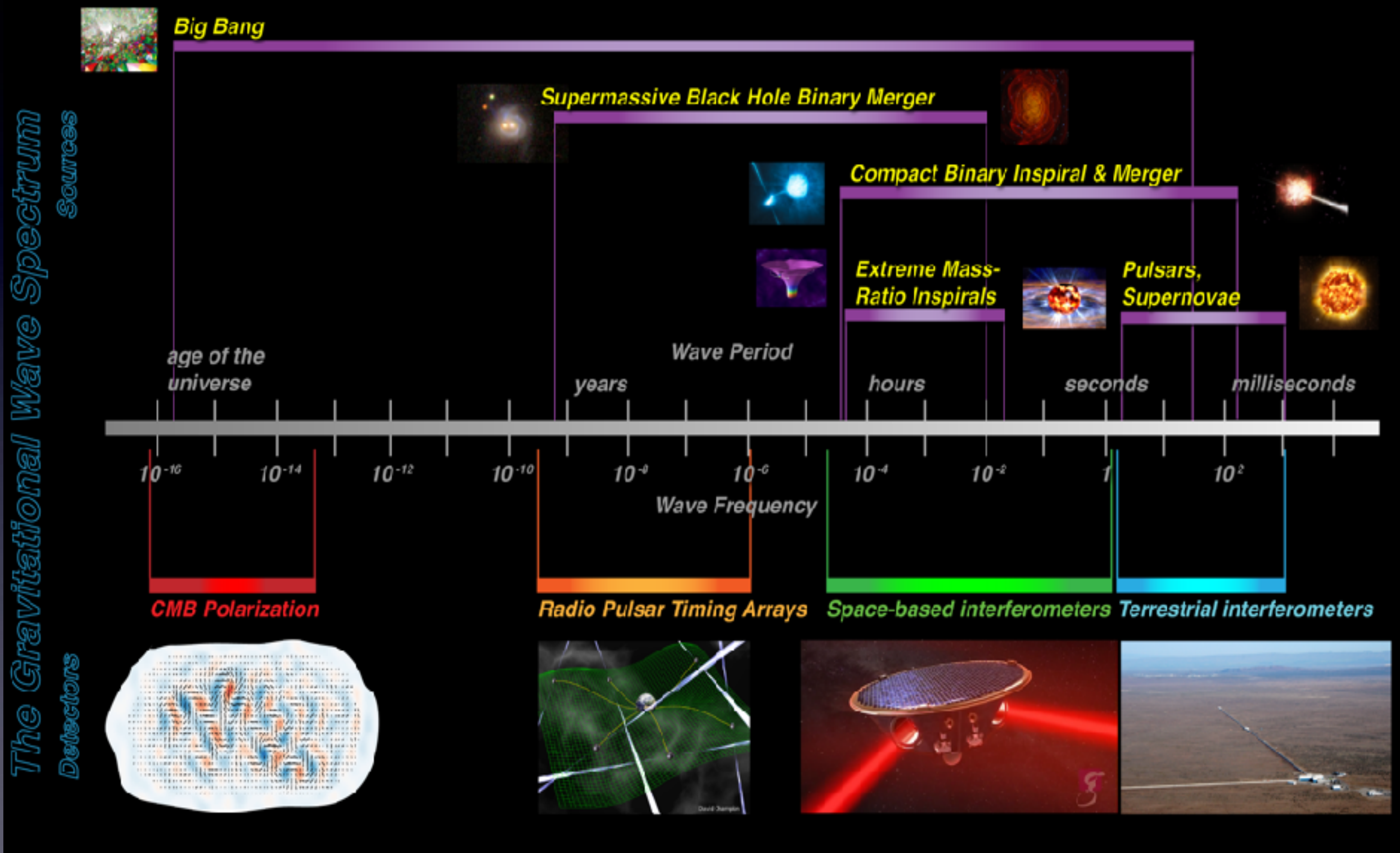
Speed of Gravity



Speed of Gravity

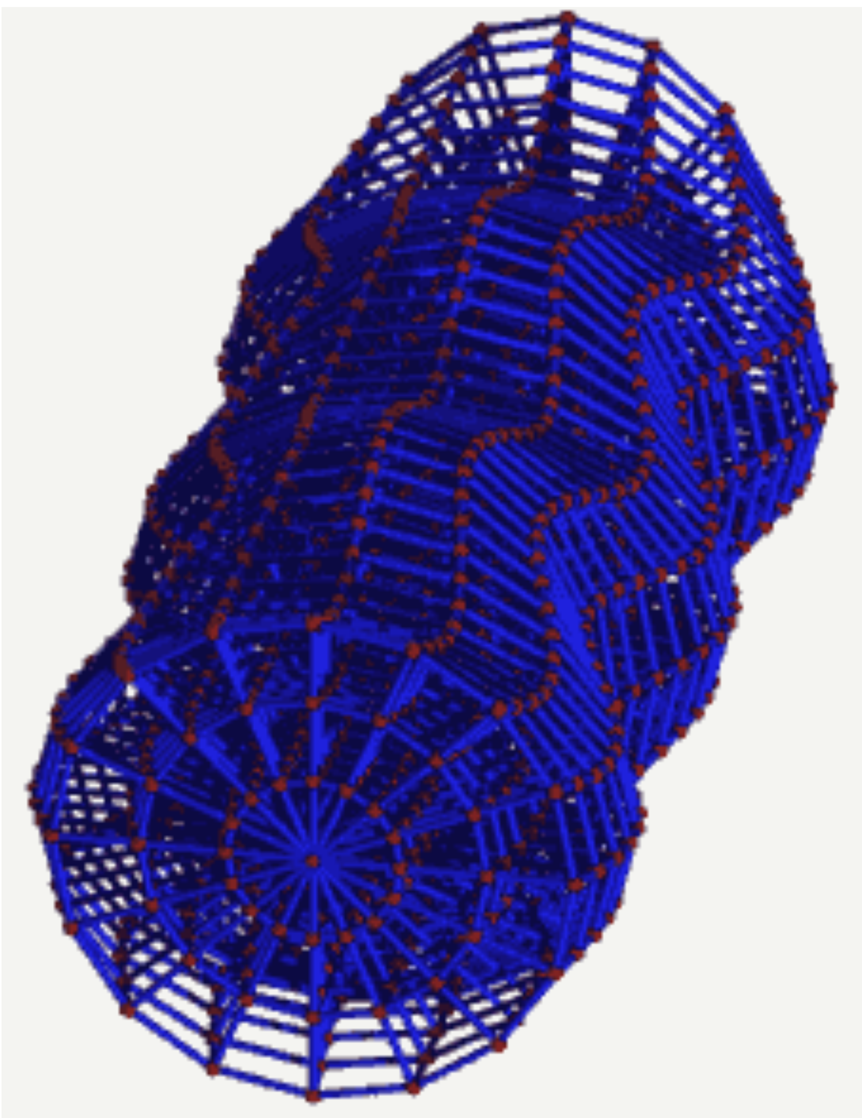
- time delay of +1.74±0.05s between GRB 170817A and GW170817
- difference between the speed of gravity and the speed of light to be between -3×10^{-15} and $+7\times10^{-16}$ times the speed of light

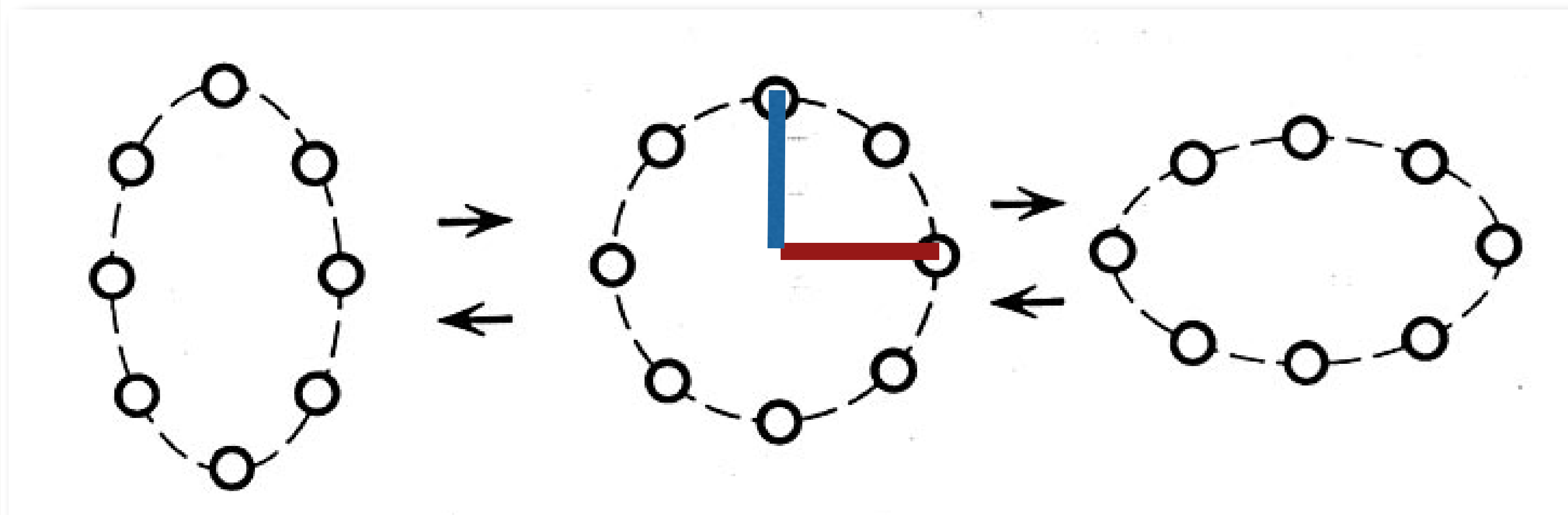
The full GW spectrum



[Credits: Ira Thorpe]

Observing Gravitational Waves





Gravitational waves change the **distance** between objects.

[http://www.einstein-online.info]

Michelson Interferometer

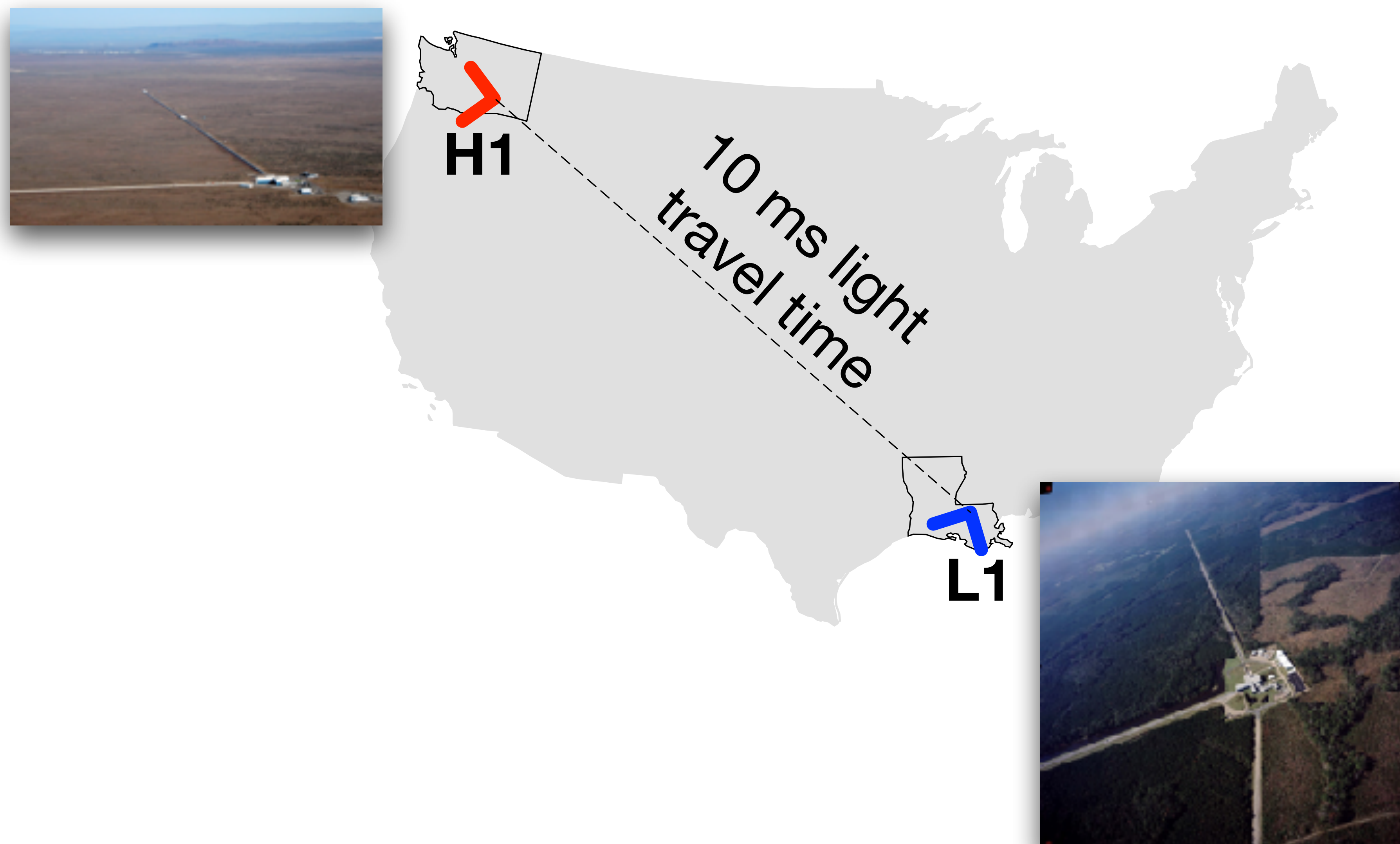
1887:

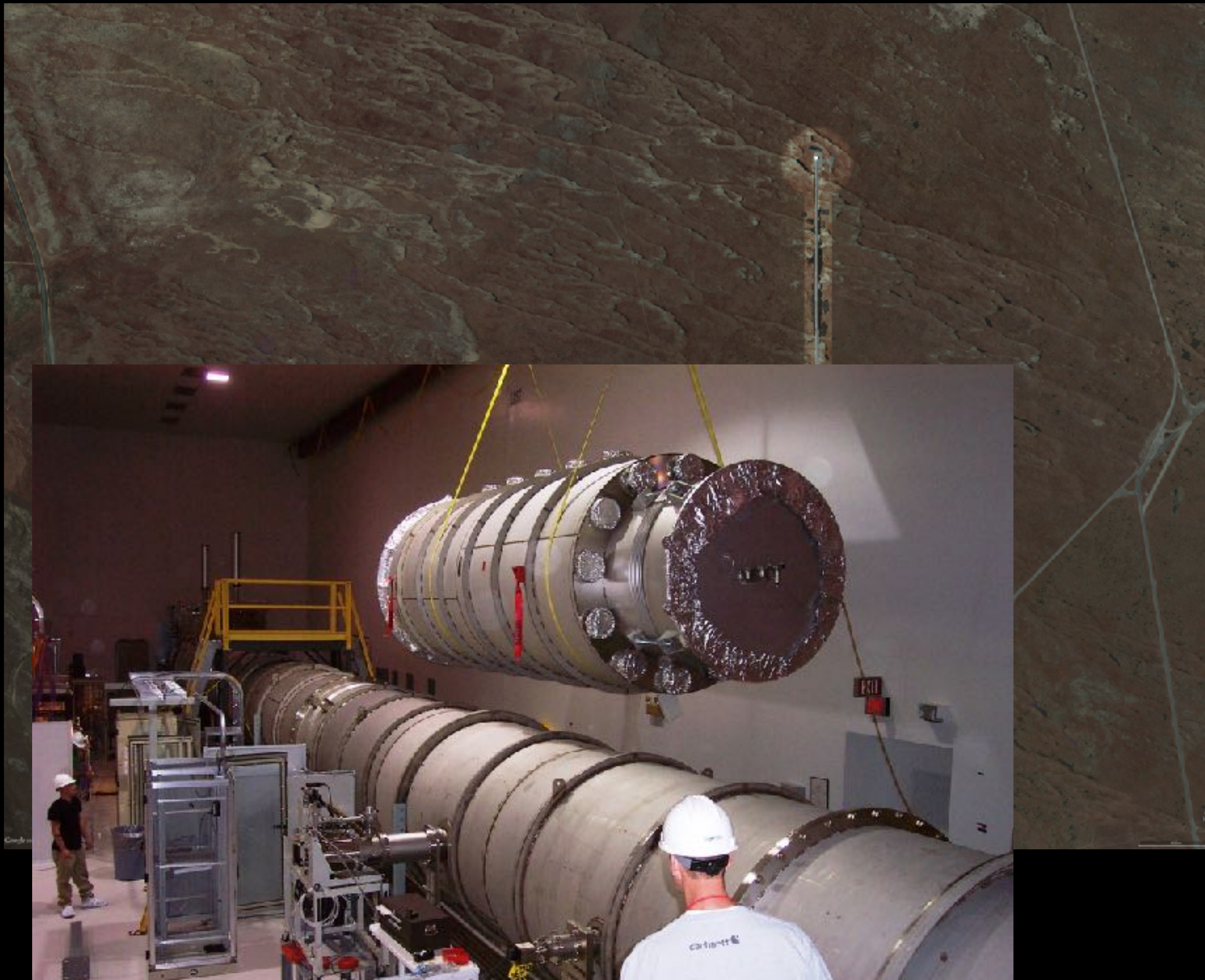
- Michelson Morley Experiment
- Sensitivity: **10^{-2} of a fringe**

Today:

- Advanced LIGO
- Modified Michelson interferometer
- Sensitivity: **10^{-13} of a fringe**

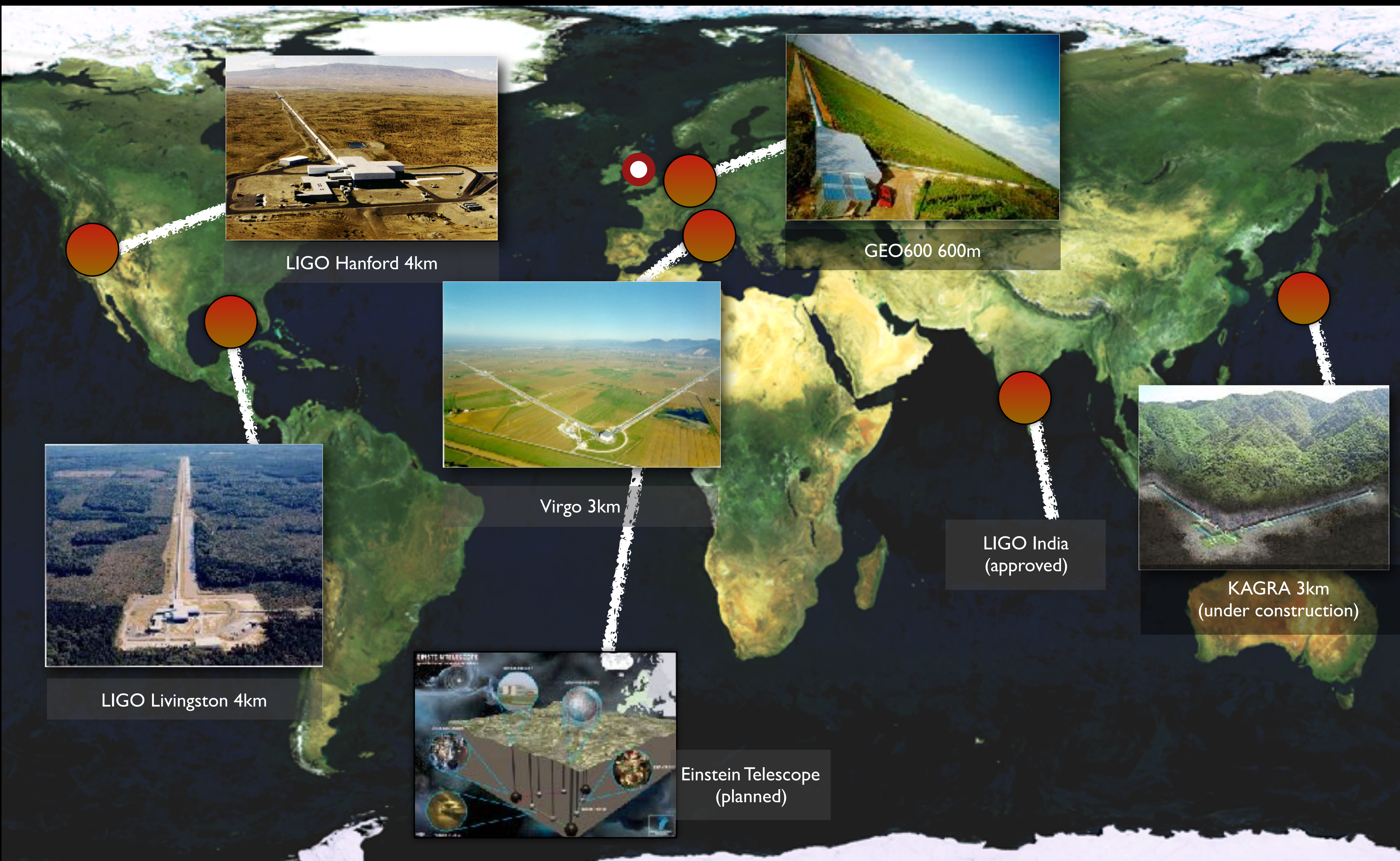
LIGO: Laser Interferometer Gravitational Wave Observatory






5V supply
UNIVERSITY OF BIRMINGHAM
prototype
+14V supply
LIGO-D0901284-v1
S/N 3200701
-14V supply
SATELLITE BOX

Ground-based network



Einstein publishes new theory of gravity, predicting gravitational waves

1916

Joseph Weber constructs resonant bar GW detectors

1960s

Rainer Weiss and Robert Forward start working on interferometric detectors

1970s

LIGO is founded

1992

Nobel Prize for Hulse and Taylor, indirect proof for existence of GWs

1993

6 scientific data taking periods with LIGO, Virgo, GEO and TAMA, **without** a detection

2002 - 2010

Upgrade of LIGO detectors, for a 10-fold increase in sensitivity

2008 - 2014

Bringing LIGO to its new design sensitivity

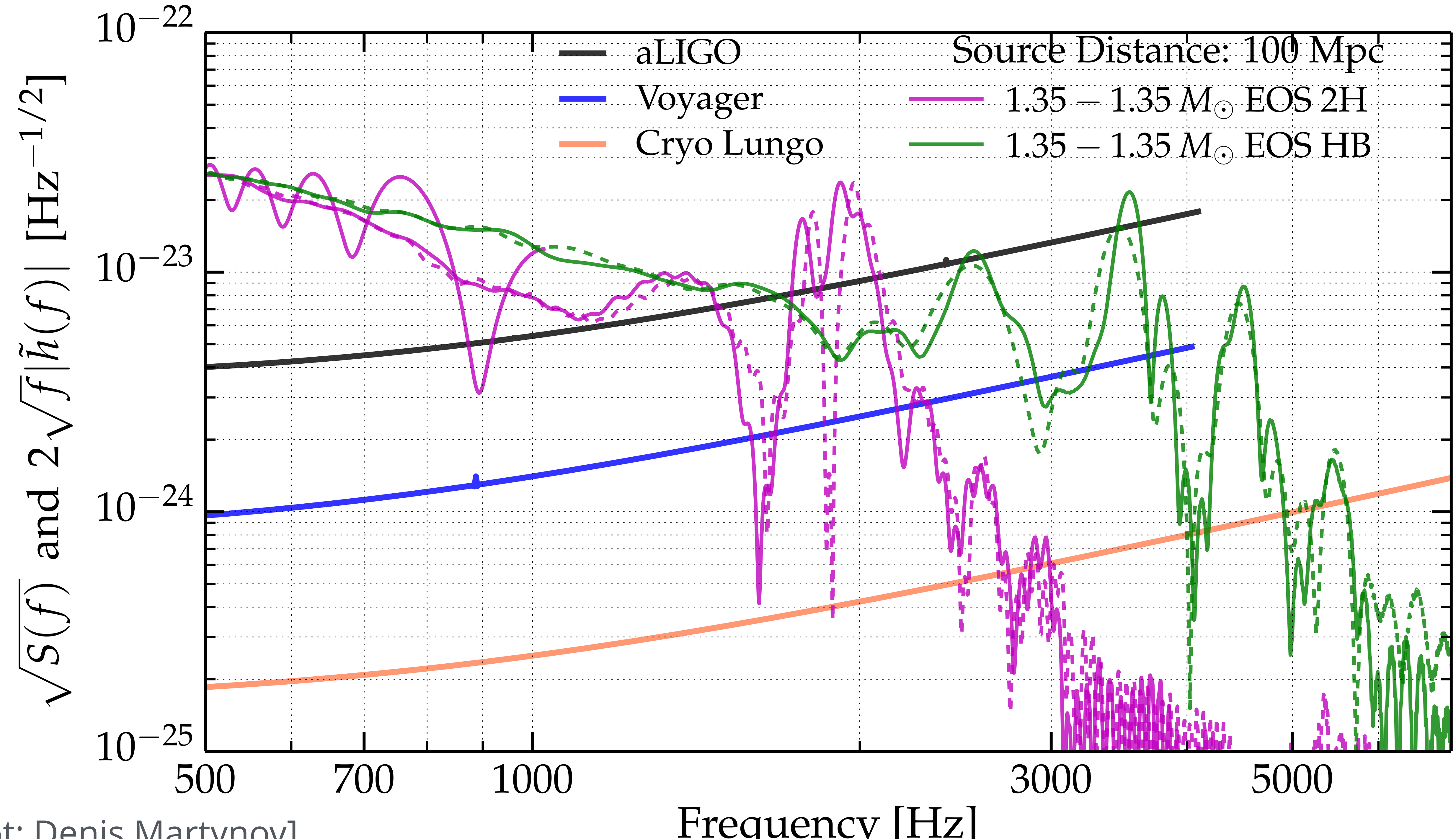
DETECTIONS!

1915 1930 1945 1960 1975 1990 2005 2020

Today

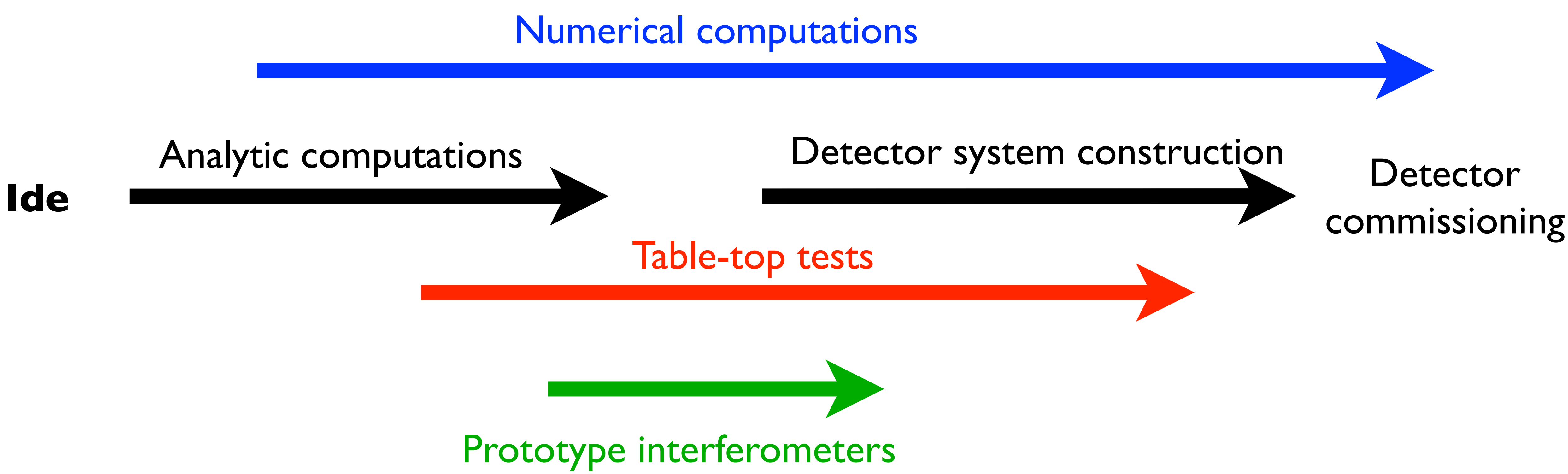
A long journey …

Neutron star equation of state



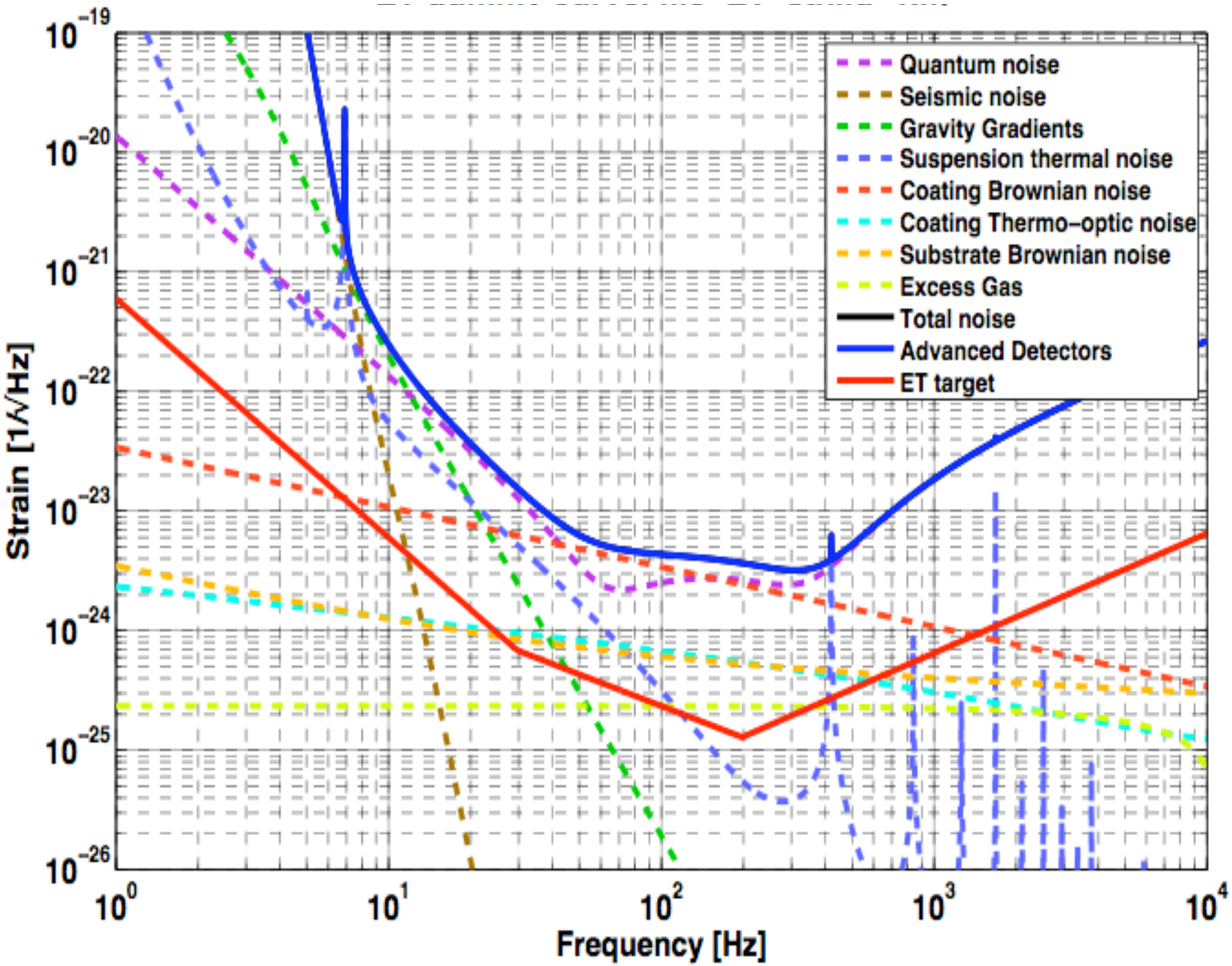
[Plot: Denis Martynov]

From Idea to Implementation



10 to 30 years is a good time scale to go from idea to an implementation/application of a new concept or technology

Noise budget



Quantum Uncertainty

LIGO displacement sensitivity:

$$\Delta x \sim \sqrt{S_h(f) L \Delta f}|_{100\mathrm{Hz}} \sim 10^{-19}\,\mathrm{m}$$

de Broglie wavelength of 40kg test mass:

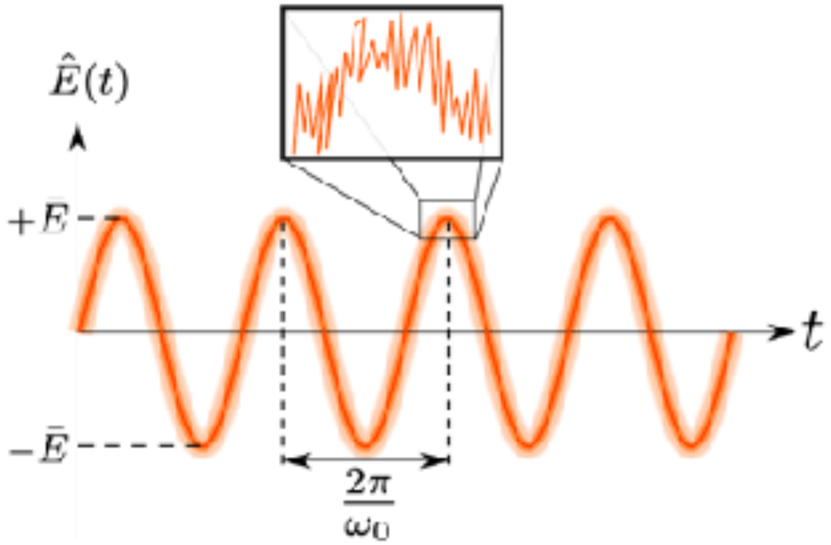
$$\lambda_\mathrm{d} \sim \sqrt{\hbar/(2\pi\, m\, f)}|_{100\mathrm{Hz}} \sim 10^{-19}\,\mathrm{m}$$


LIGO Test Mass

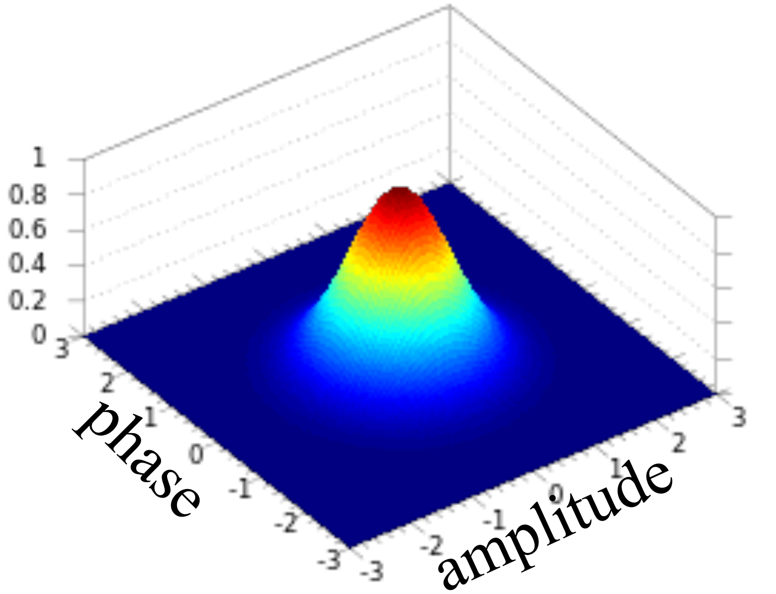
Quantisation of optical field:

Field "position": Phase quadrature

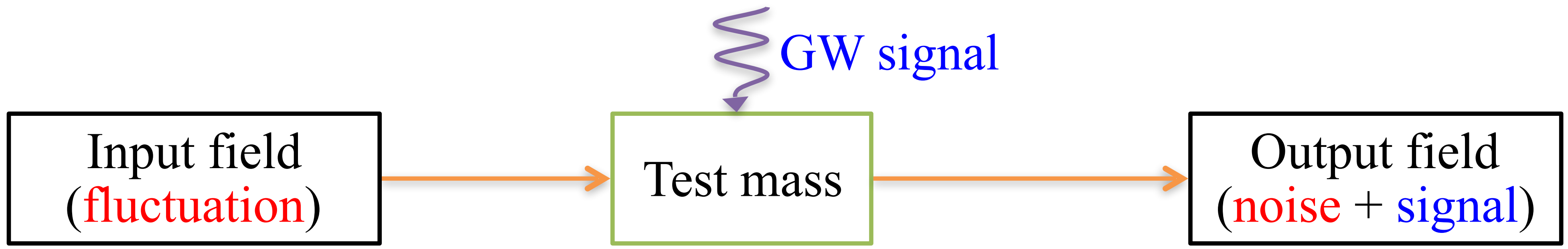
Field "momentum": Amplitude quadrature

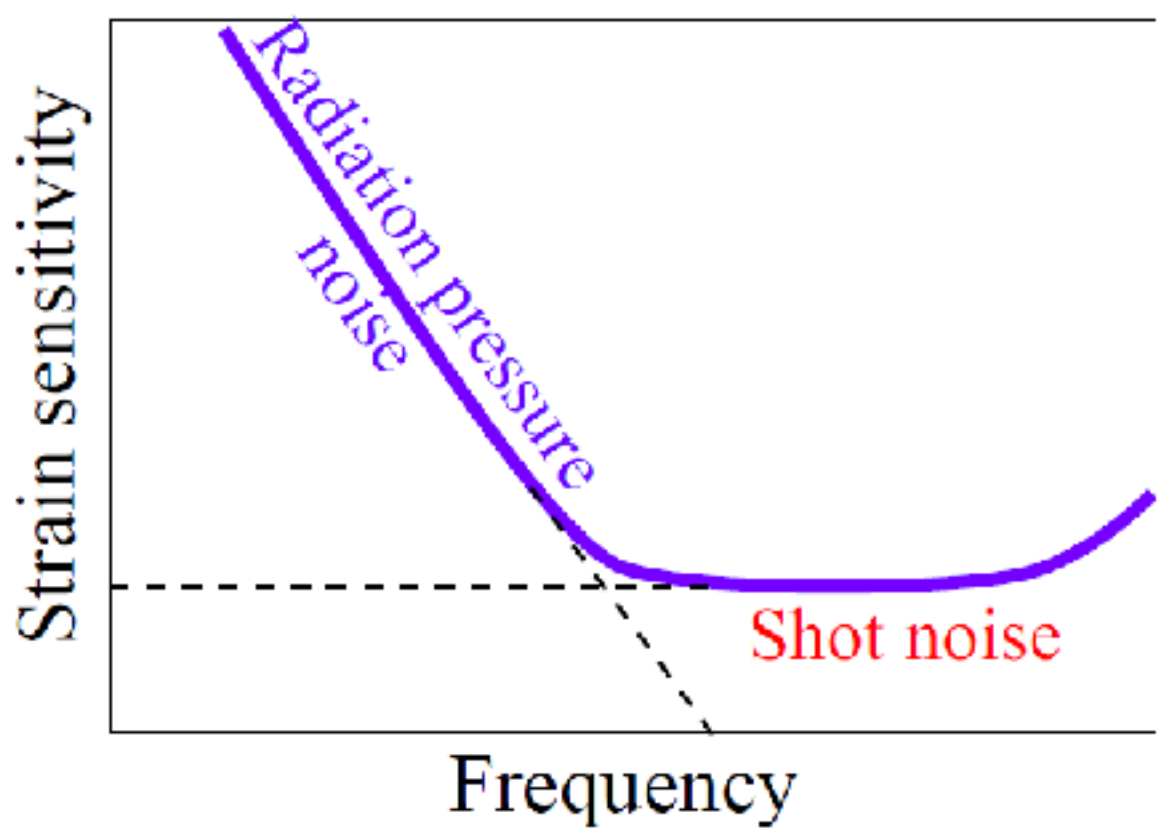


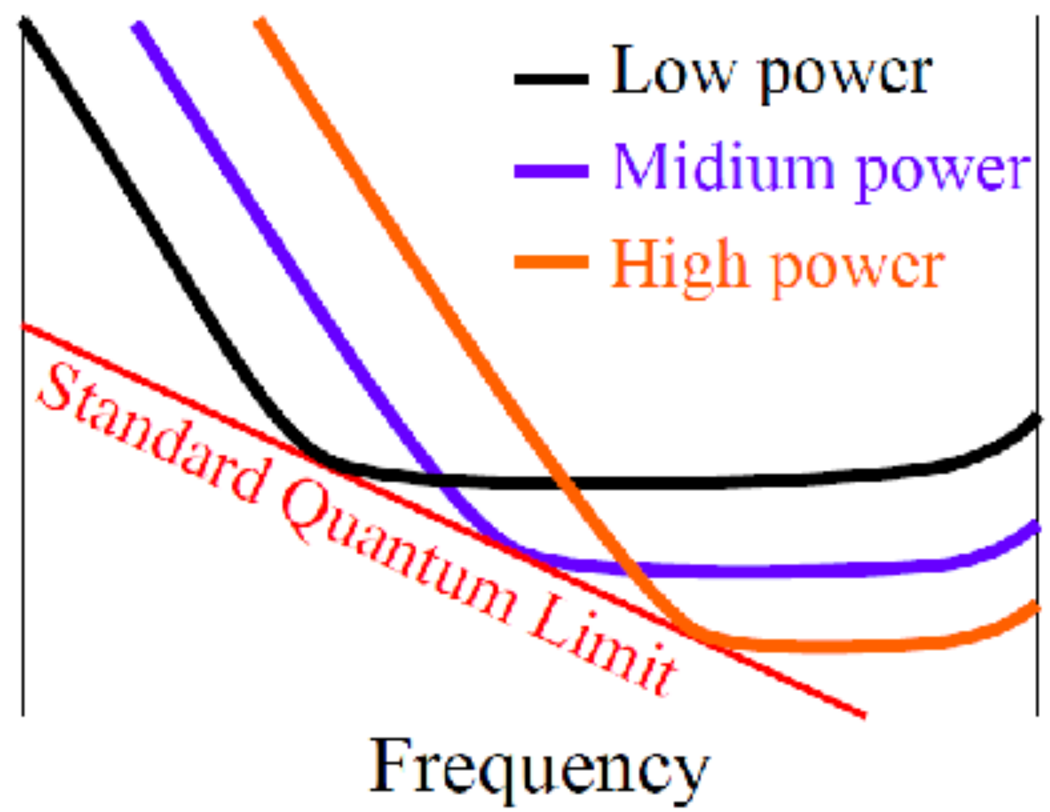
Satisfying Heisenberg Uncertainty



SQL: Standard Quantum Limit







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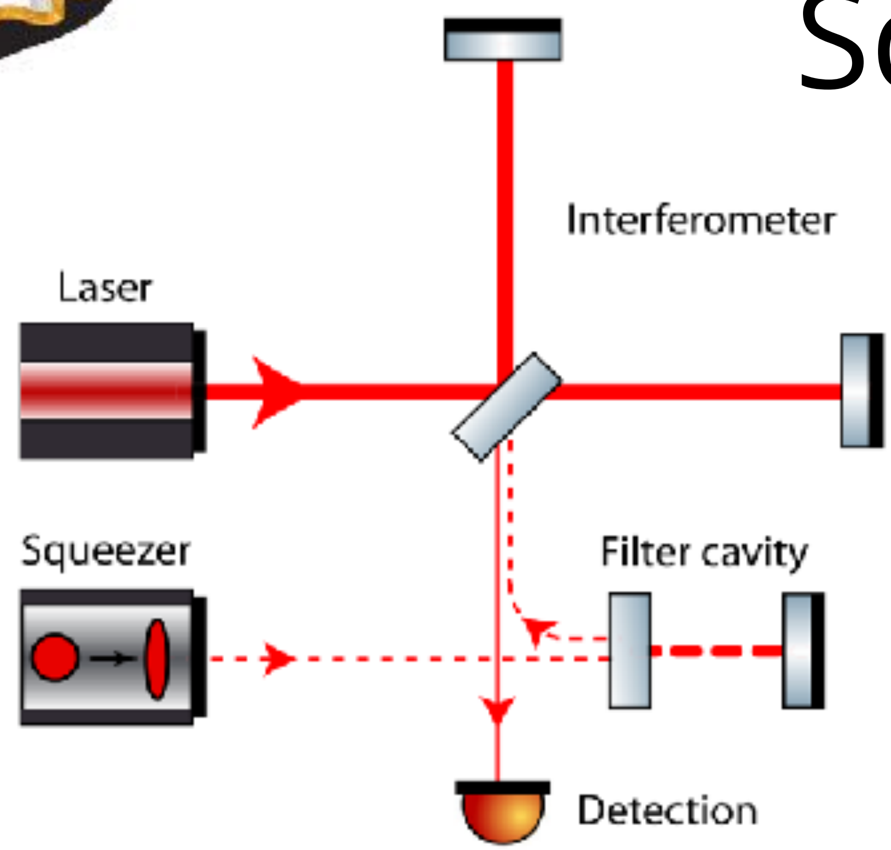
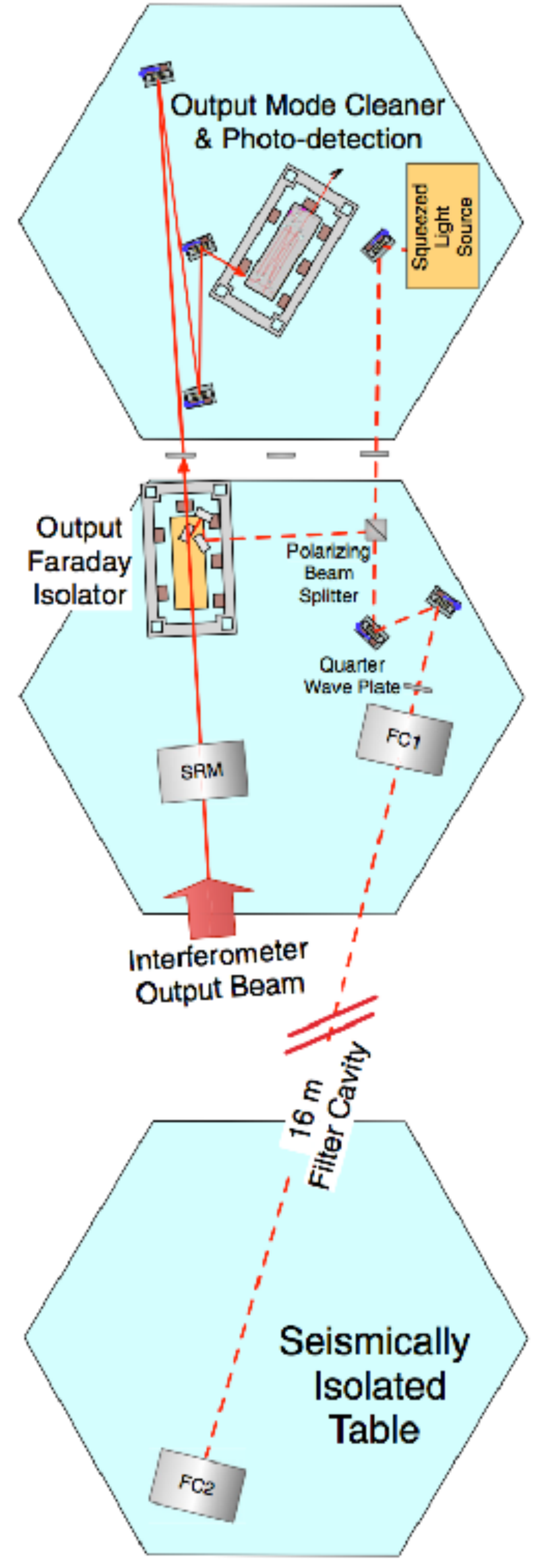
Squeezed Light

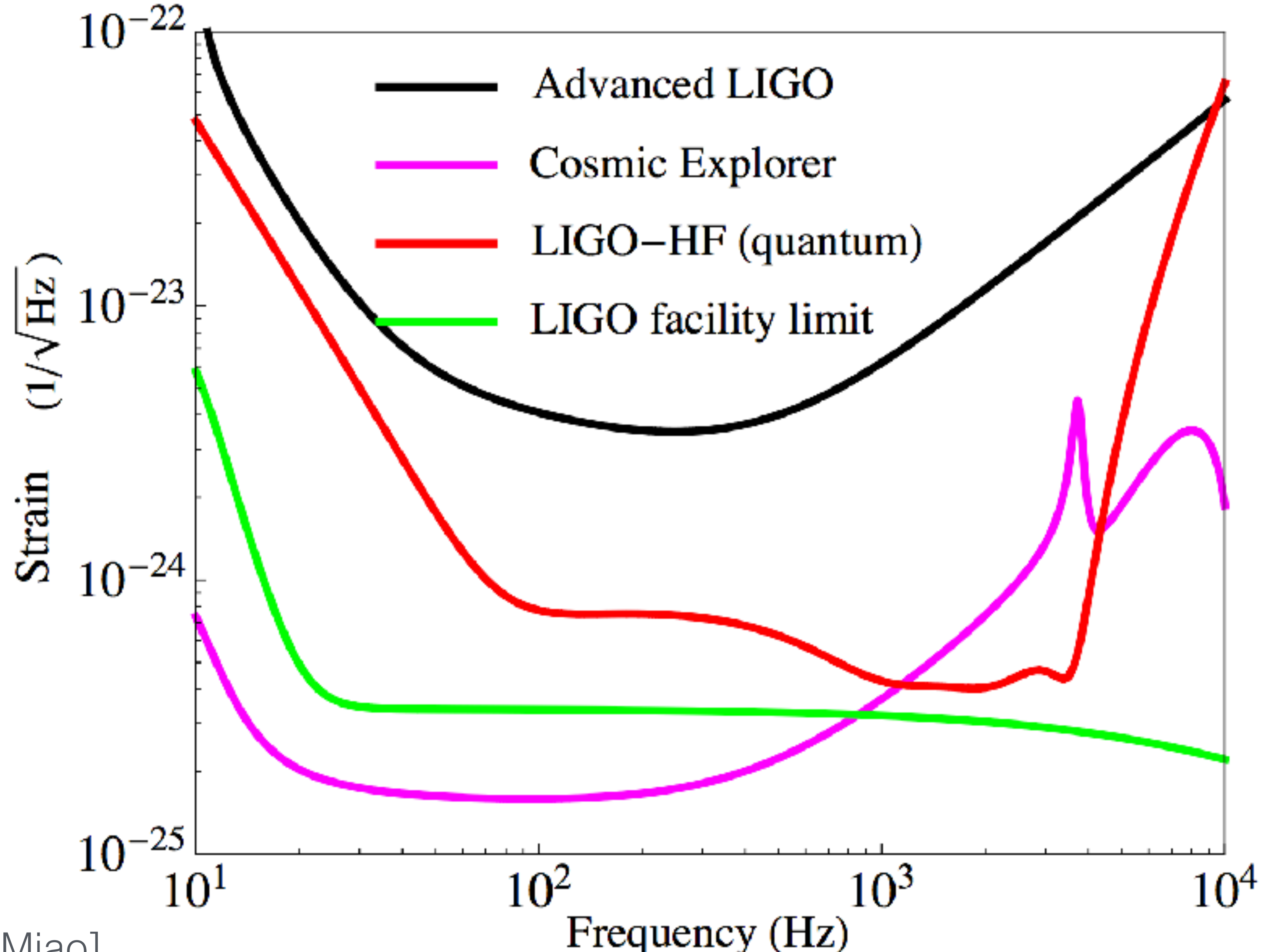




- Planned upgrade for LIGO (A+)
- Frequency-dependent squeezed light
- 16m filter cavity, 6dB squeezing

M. Evans et al.: `Realistic Filter Cavities for Advanced Gravitational Wave Detectors', Phys. Rev. D 88, 022002 (2013), arxiv: 1305.1599

Quantum Potential

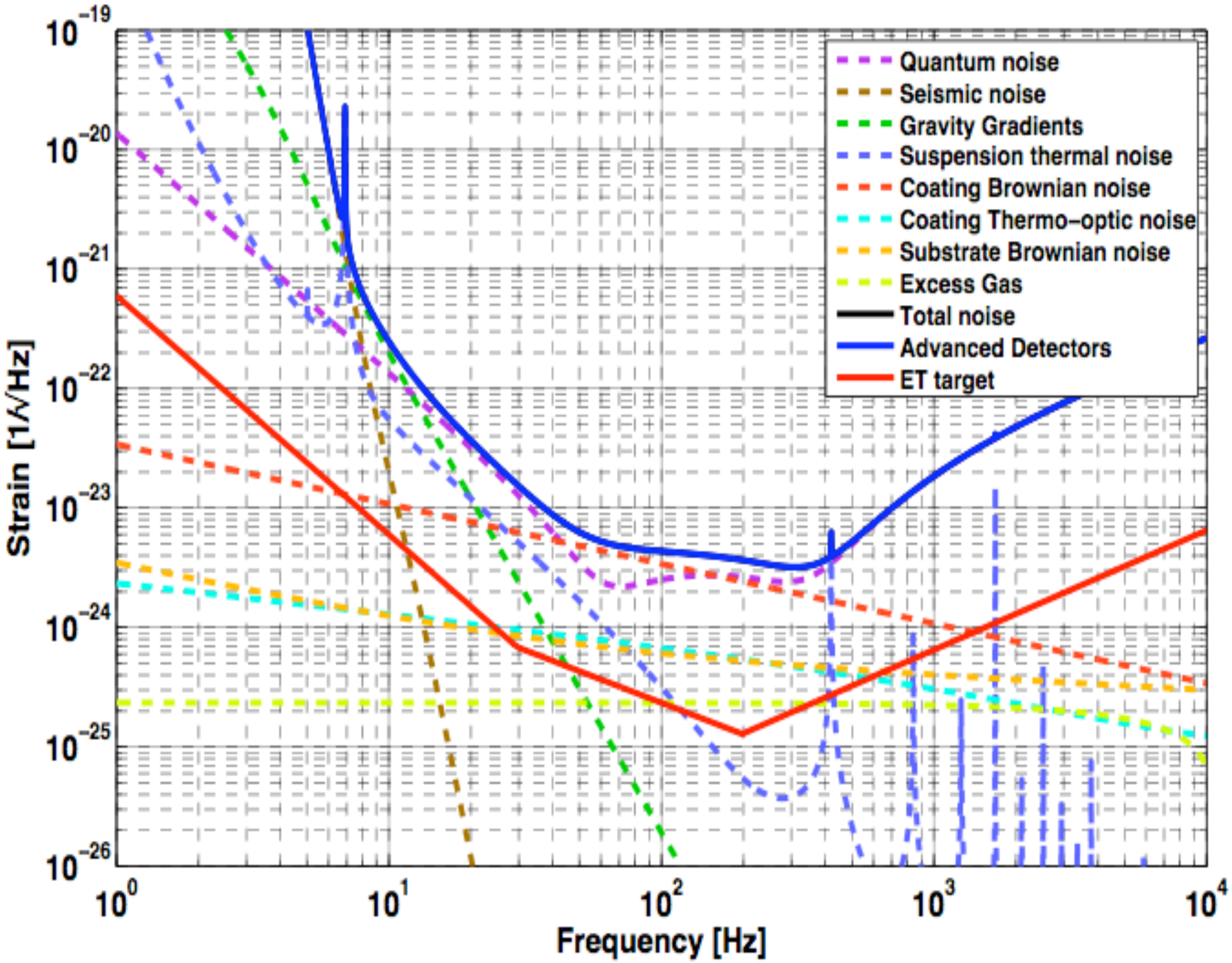


[Image: Haixing Miao]

Quantum Summary

- Quantum noise (of the readout light) poses a limit for gravitational wave detection
- **Standard quantum limit is not a limit**, but gives the sensitivity for a given instrument (length, mass) when no quantum noise correlations are used
- Many **quantum noise reduction schemes** under investigation. They all work well in principle, the challenge is to find the scheme that is **least complex** most **robust to optical losses**

Noise budget

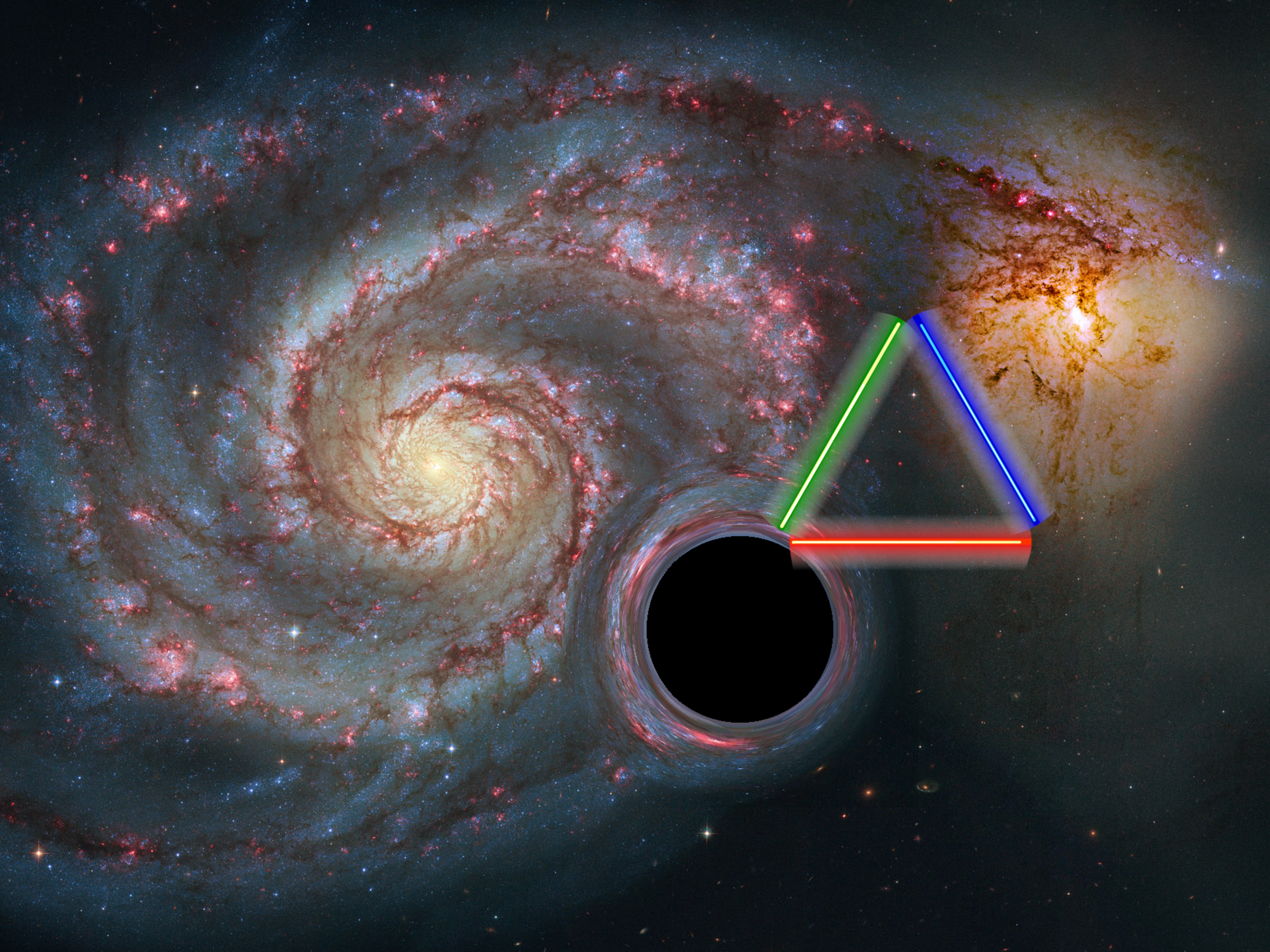


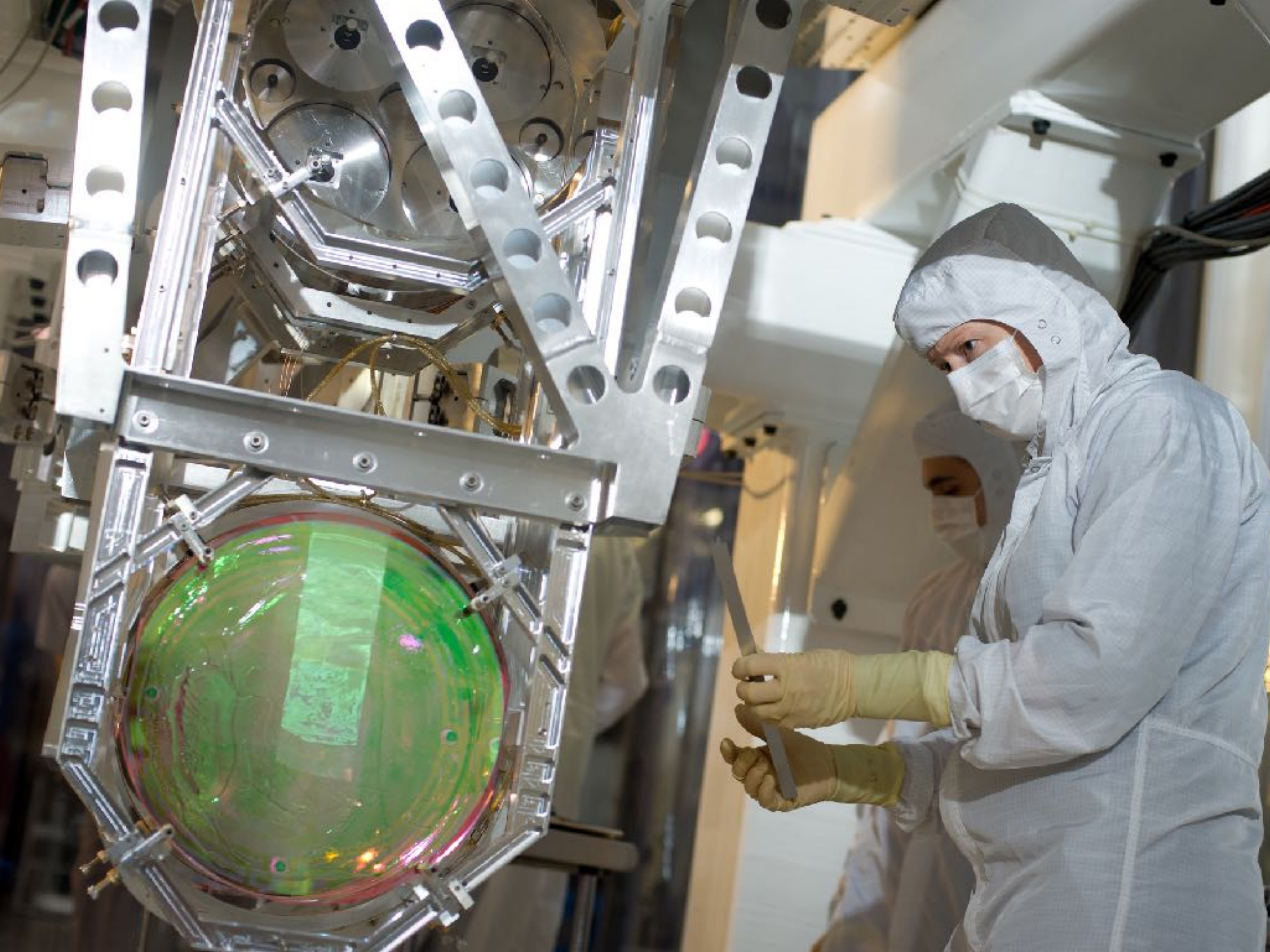
[S. Hild]


BEAT THIS!
1
38
242
1. sam
1
38
242
2. Sam
1e-23
1e-24
1e-25
1e-26
1
10
100
10000
SCIENCE RUN
£18,081,634

SPACE-TIME QUEST

LASER LABS





GW

↓

Mirror

↓

Light

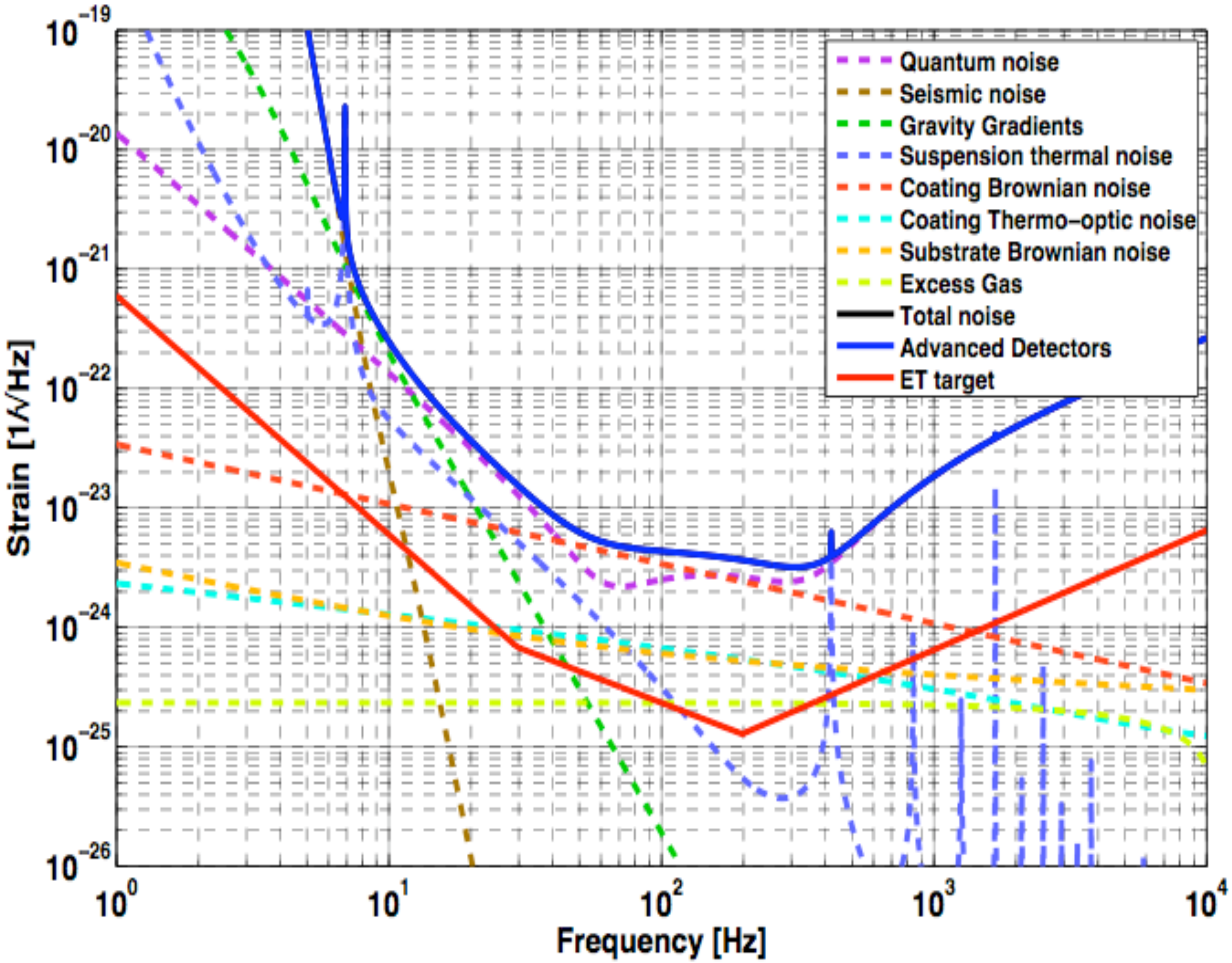
→

Electronic Signal

LIGO Scientific Collaboration

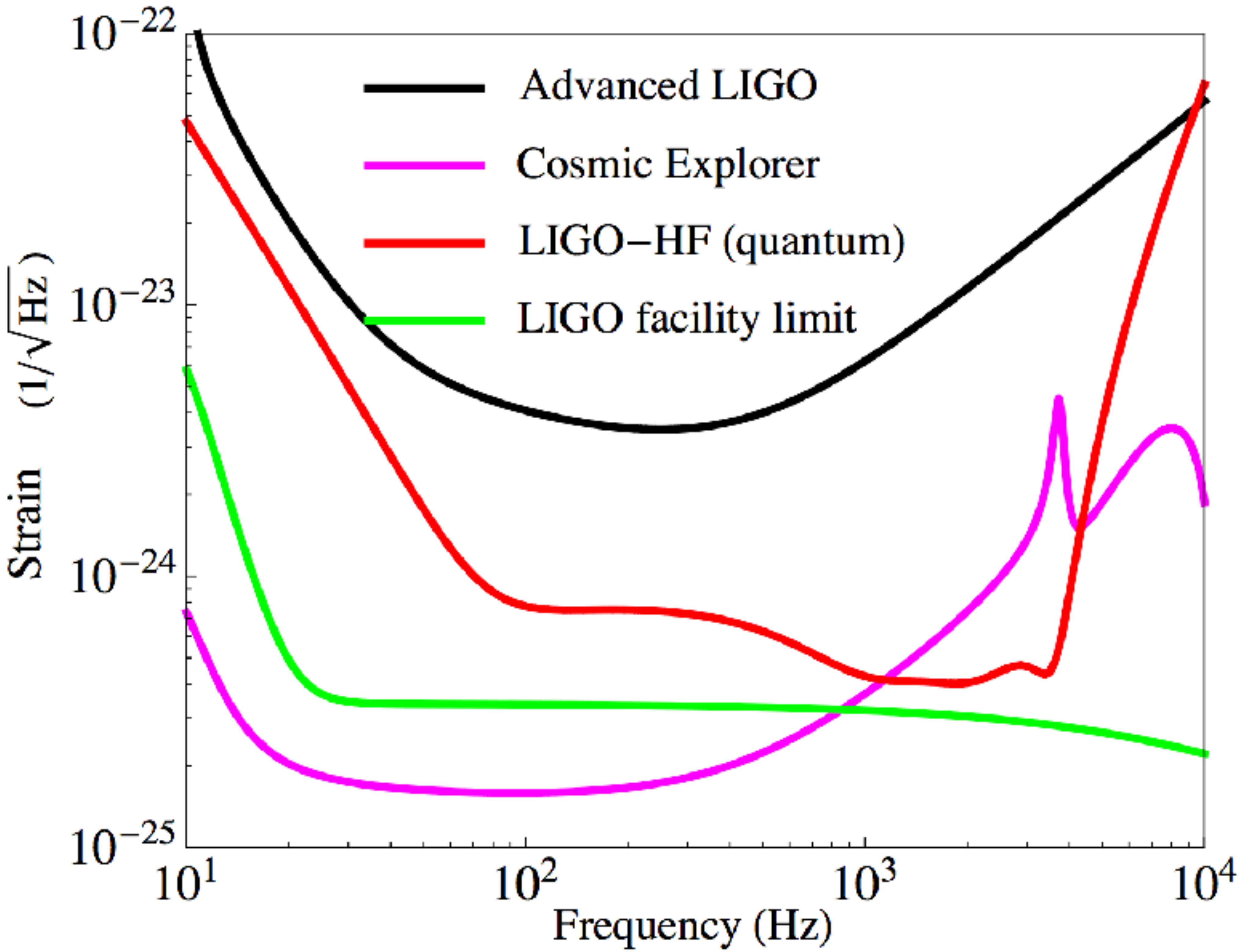
- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

Noise budget



[S. Hild]

Quantum Potential



Quantum model of GW detector

Quantization of test mass (center-of-mass motion):

$$\omega_{\rm CM}/2\pi \approx 1{\rm Hz}$$

$$k_B T \approx 10^{13}\hbar\,\omega_{\rm CM}$$

Suspension thermal noise
(thermal energy
concentrated at low frequencies)

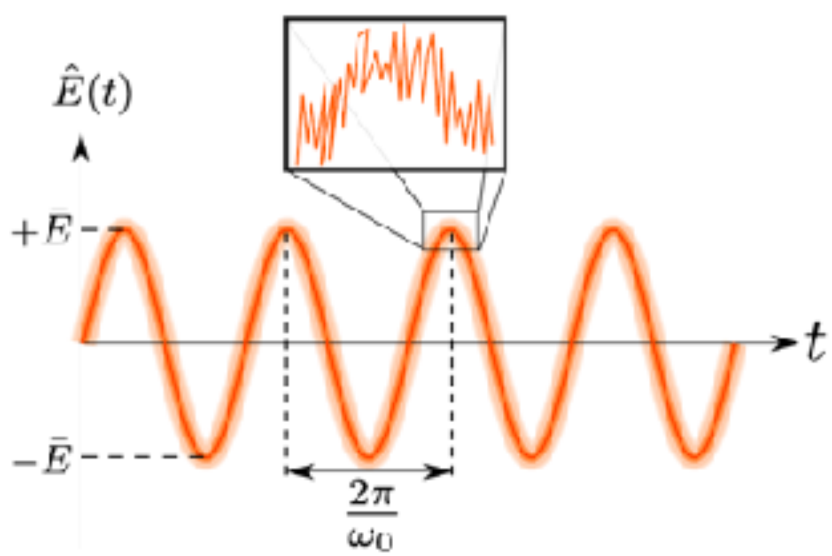
Quantization of optical field:

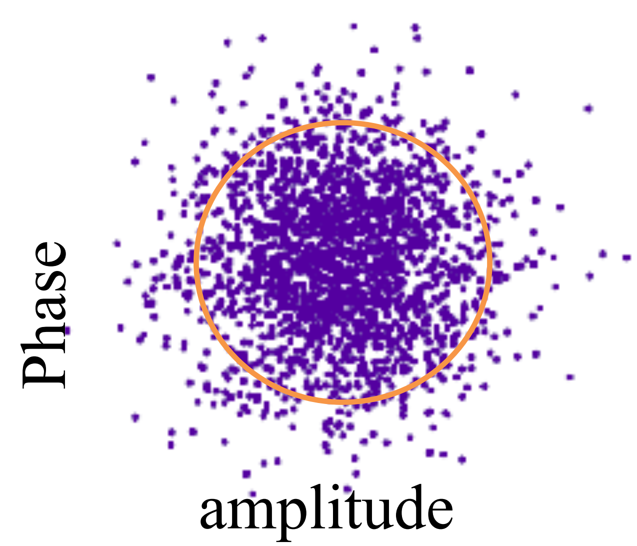
$$\omega_{\rm opt}/2\pi \approx 10^{14}{\rm Hz} \qquad k_B T \approx 10^{-2}\hbar\,\omega_{\rm opt}$$ (Quantum-limited)

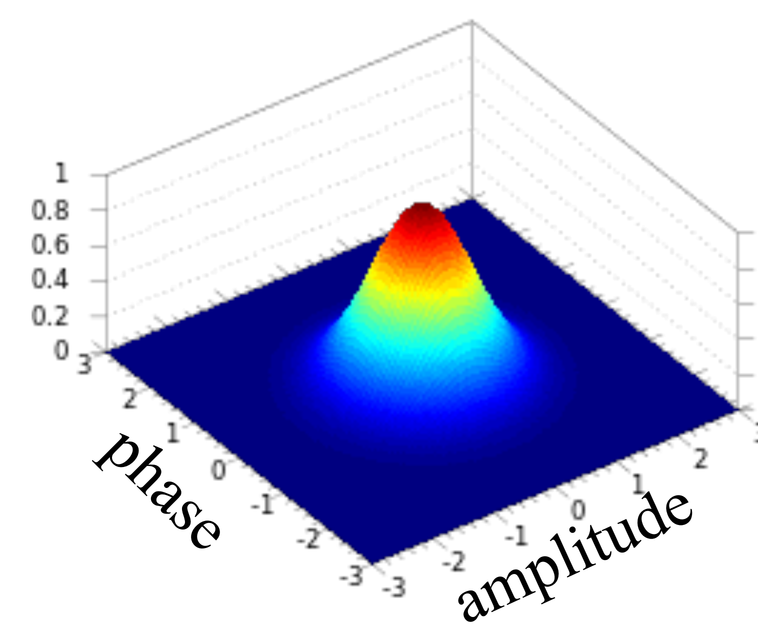
Field "position": Phase quadrature

Field "momentum": Amplitude quadrature

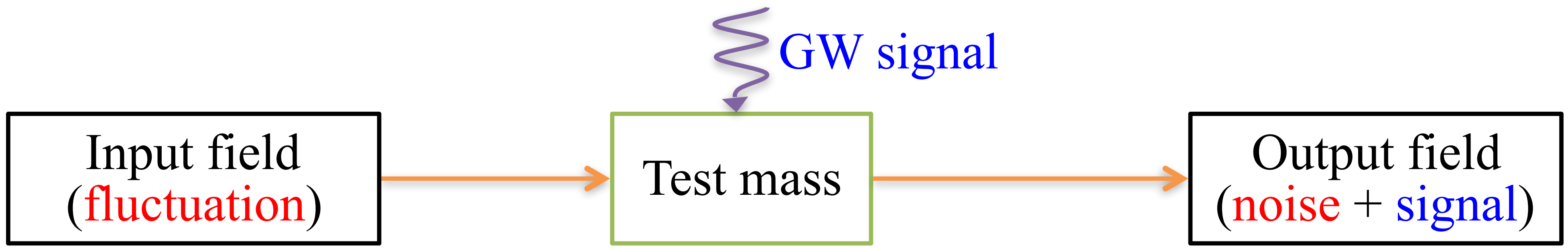
Satisfying
Heisenberg Uncertainty





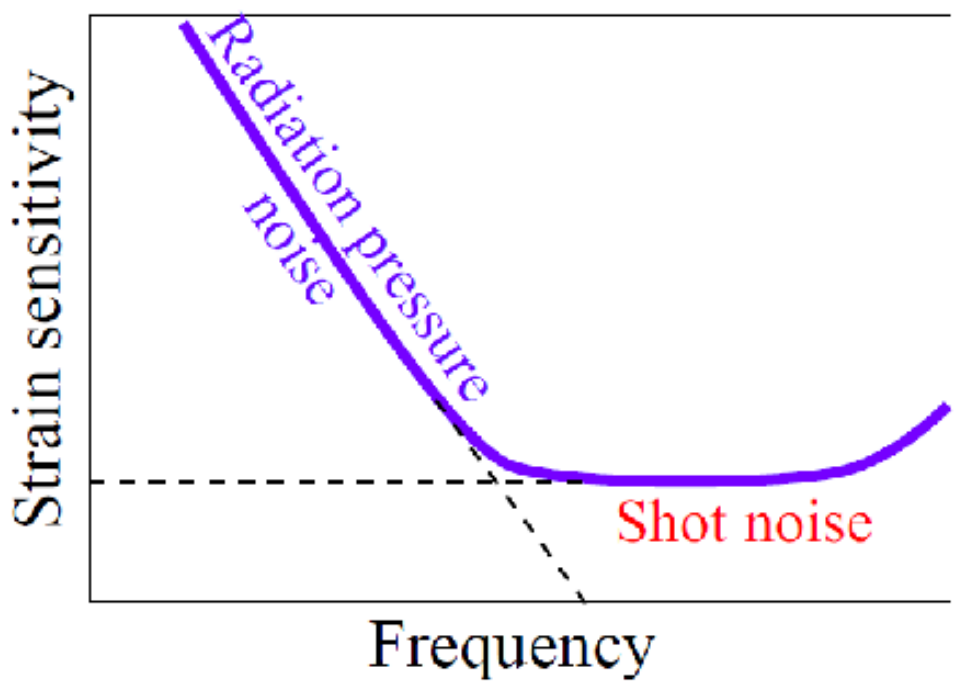


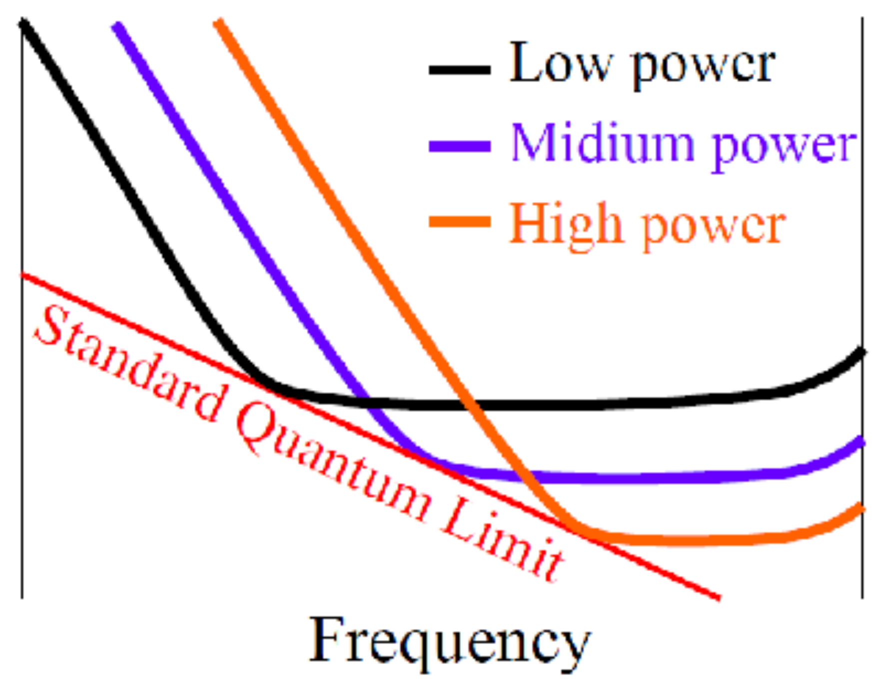
Standard Quantum Limit and beyond



Quantum fluctuation in phase ⇨ **Shot noise**

in amplitude ⇨ **Radiation pressure noise**





We are studying different approaches to surpass the SQL and understanding the fundamental quantum limit

Collaborative Work

- Our code is modern, open source and under continuous development
- We use the right tools for collaboration with people around the world:
  - git repositories for simulations files
  - chat channels for quick questions
  - joint papers and LIGO DCC notes to document our work

Open Tasks

- Modelling in support of detector commissioning
  - mode-matching, parametric instabilities, ...
- Modelling designs for future detectors
  - LIGO upgrades, Einstein Telescope, ...
- Code development of current software
  - implement/test advanced features
  - improve user interface

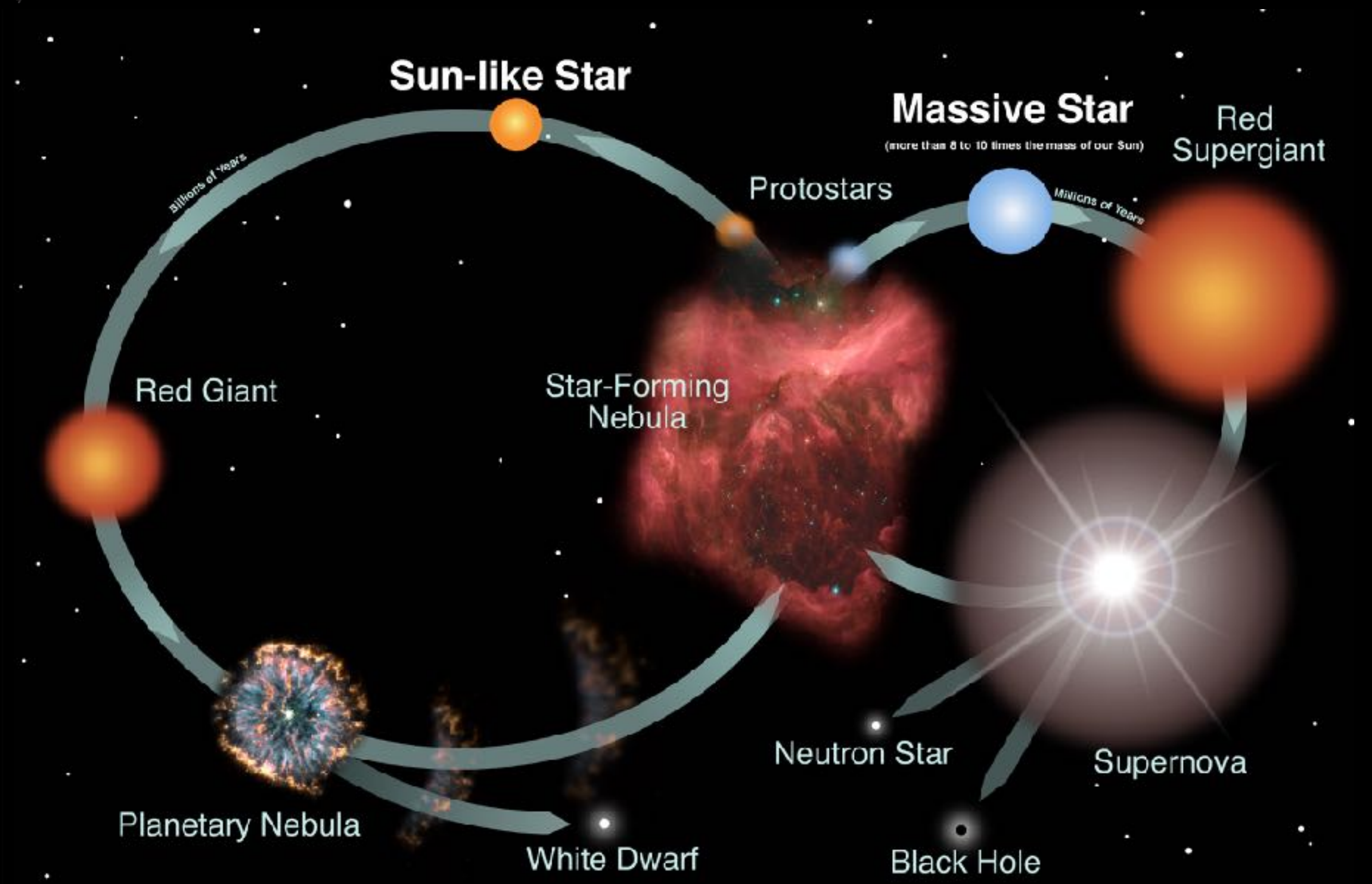
Resources

- Interferometer techniques for gravitational wave detection, Living Rev. Relativity (2017) https://link.springer.com/article/10.1007/s41114-016-0002-8
- FINESSE, numerical modelling software for interferometers http://www.gwoptics.org/finesse/
- Learn Laser Interferometry, a self-study course on interferometry for precision measurements http://www.gwoptics.org/learn/
- **Installation instructions and example files:** www.gwoptics.org/learn/schools/St_Andrews_2017

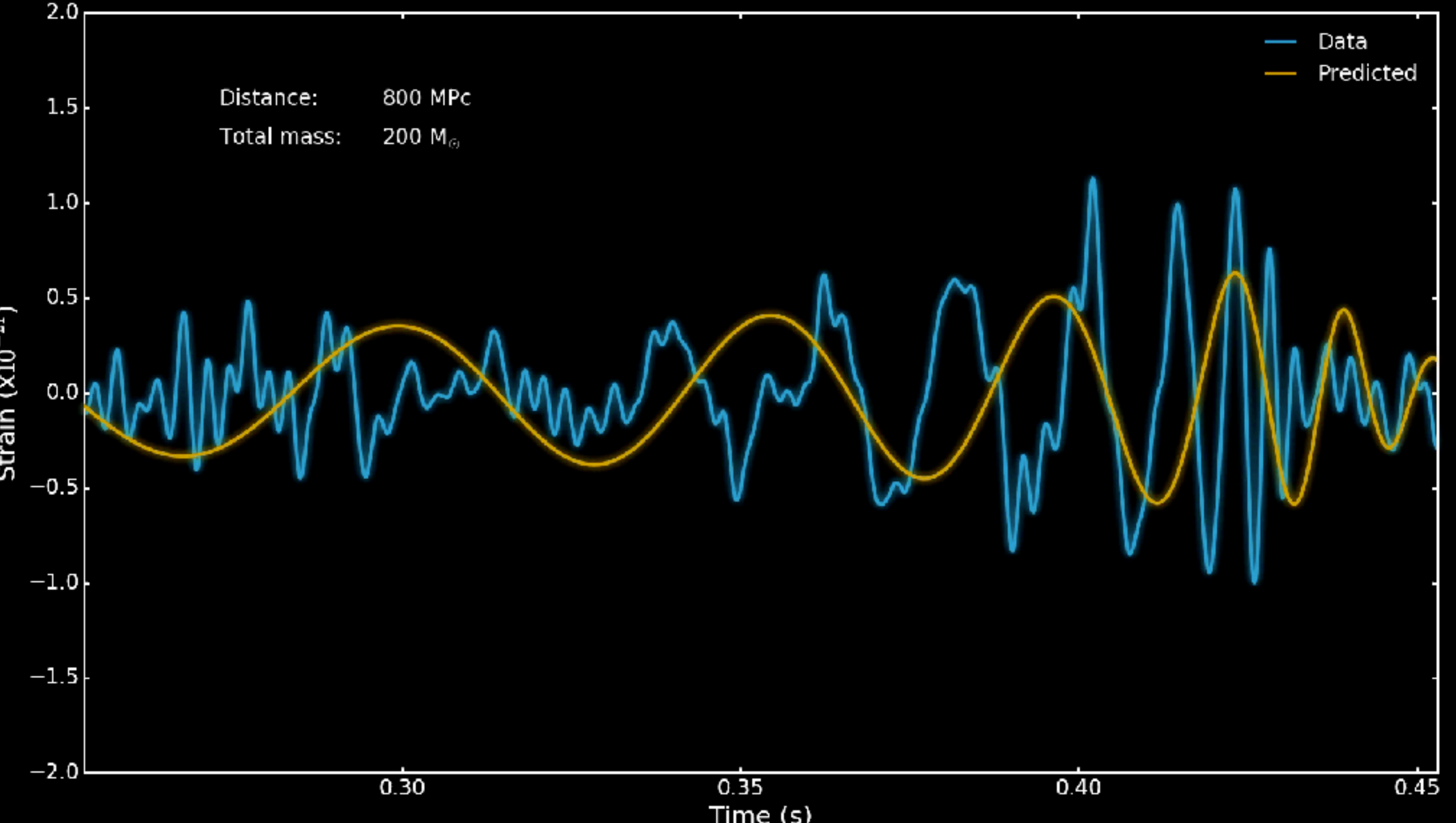
Apps for iOS, Android (or PC and Mac):

www.laserlabs.org

Life Cycle of Stars



[Credit: NASA and the Night Sky Network]



Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Ca

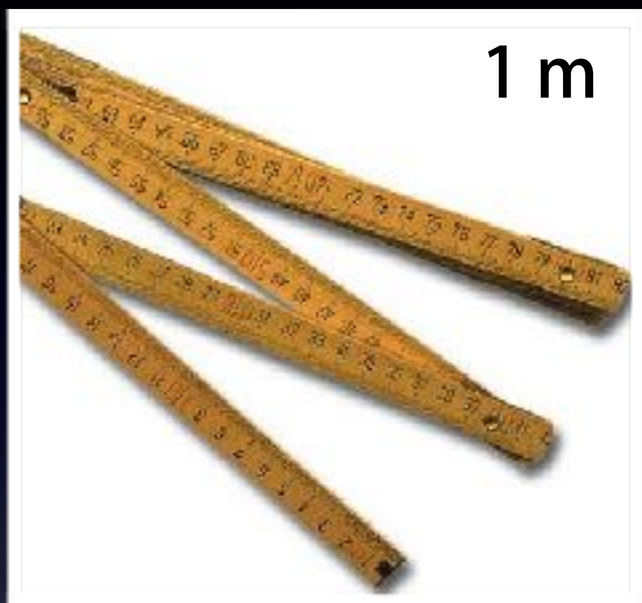
GW150914

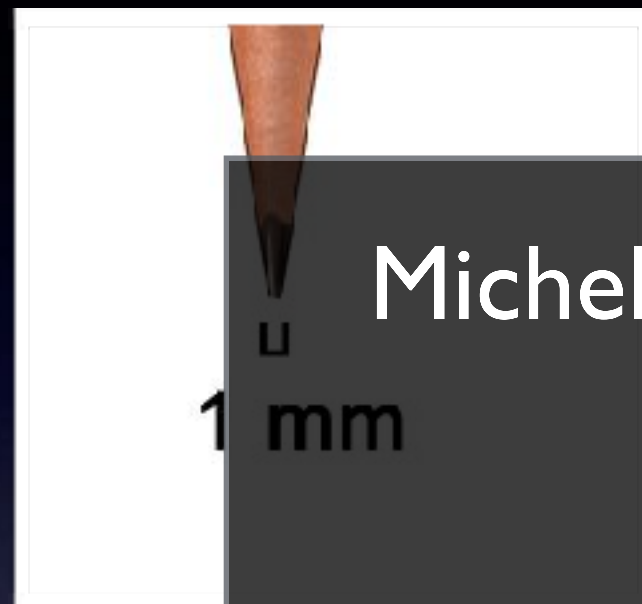
2017 Nobel Prize in Physics


DRAGOFOL

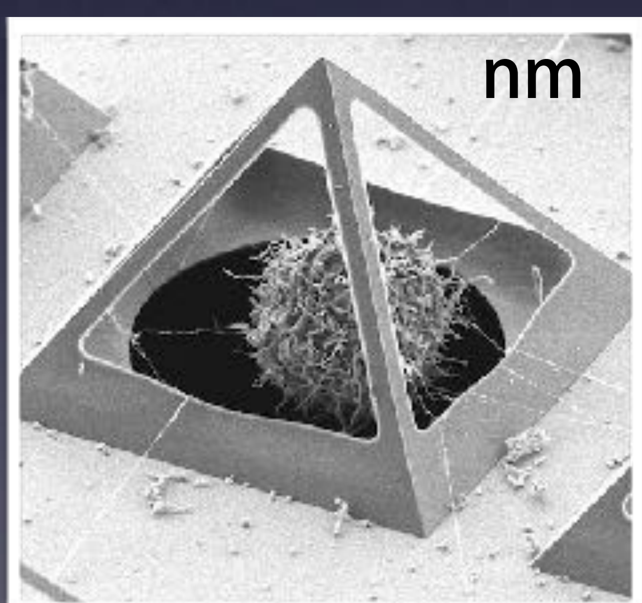
David Willets, Minister of State for Universities and Science (2012)

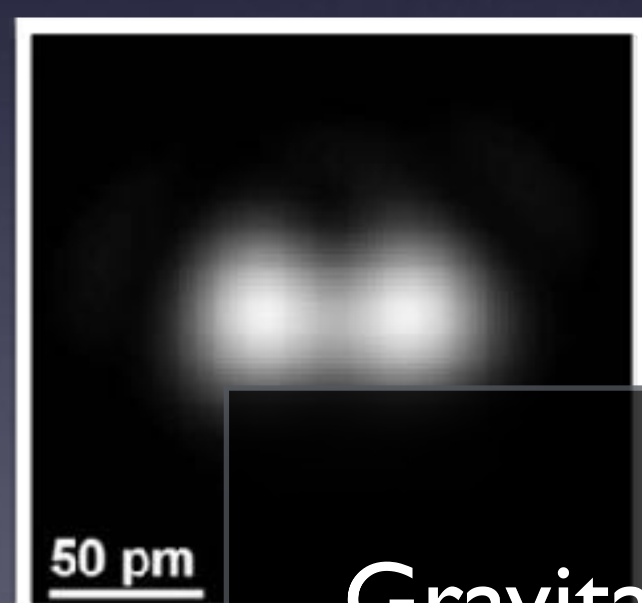
Length Scales



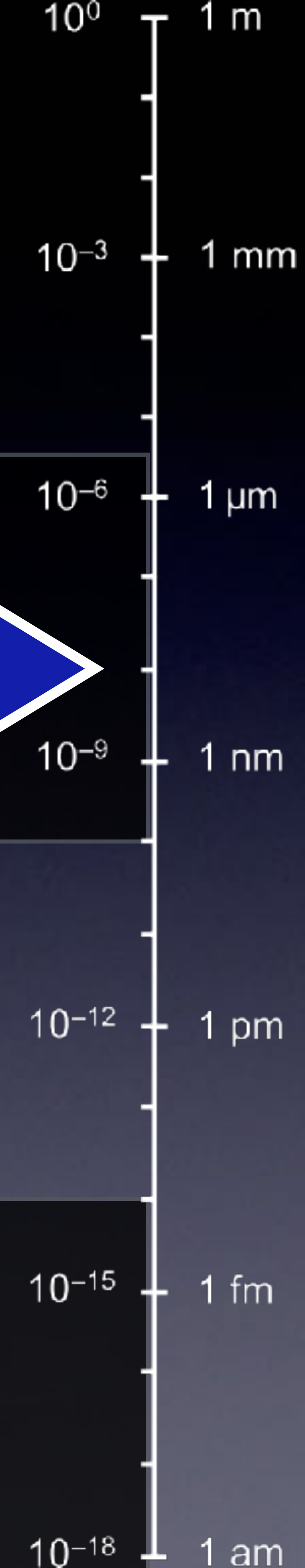


Michelson 1887



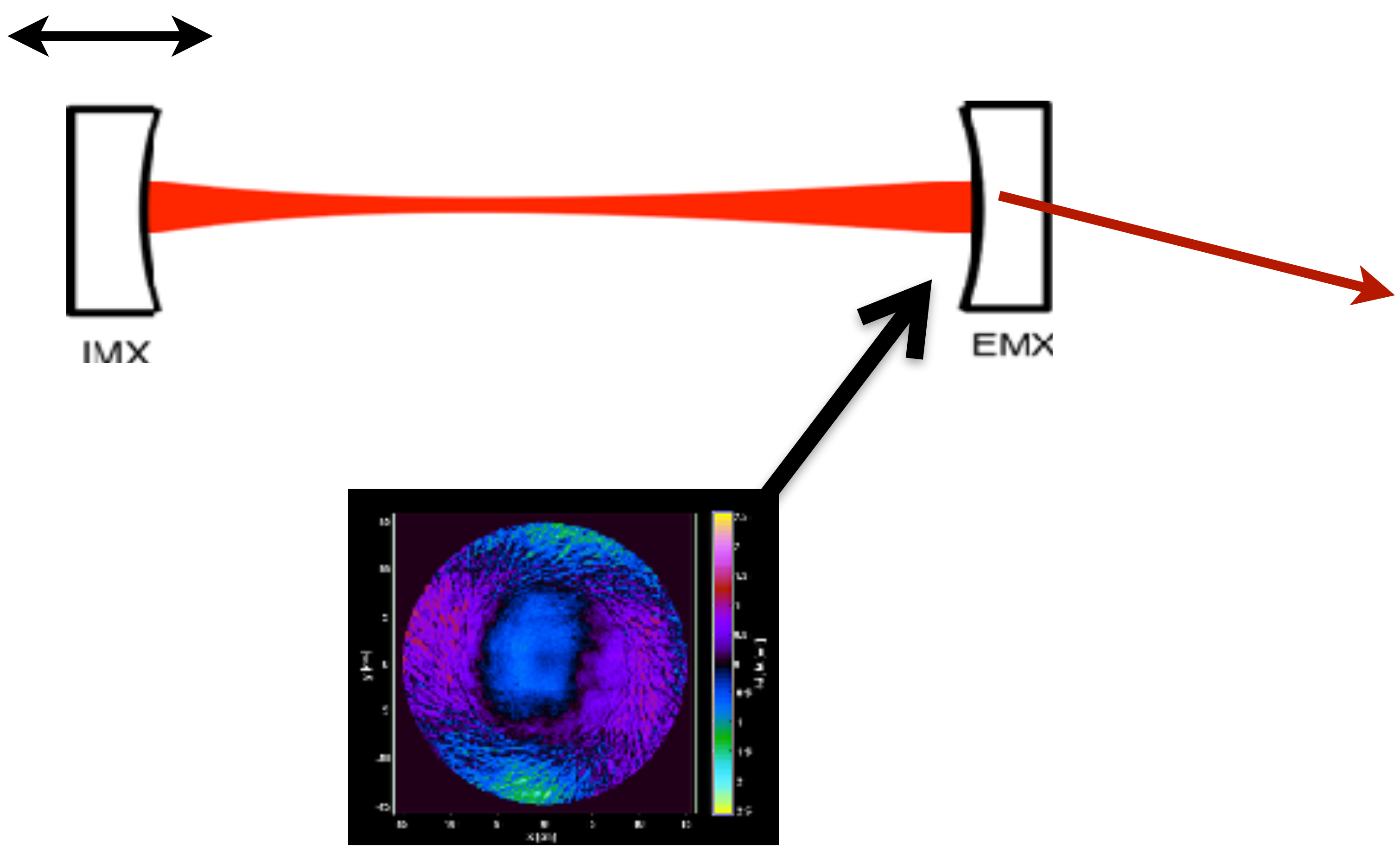


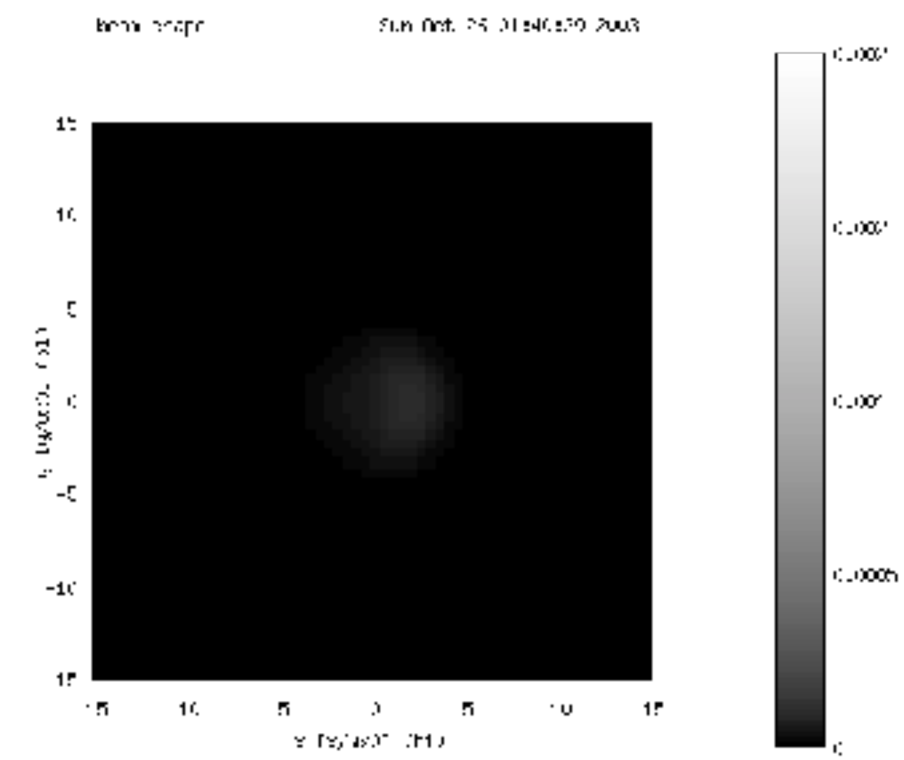
Gravitational Waves



Beam Shape Distortions

Acceptance of mirrors from manufacturer: Computer model is used to estimate the optical distortions due to the measured mirror distortions.





Beam shape inside arm cavity

UNIVERSITY OF BIRMINGHAM

Learn Laser Interferometry

gw optics » Tools for detecting gravitational waves

HOME LEARN PLAY SIMULATIONS CONTACT

Course: Learn Laser Interferometry

Learn Laser Interferometry

A self-study course on interferometry for precision measurements, using IPython notebooks.

This page provides resources and self-study material on laser interferometry. In particular we cover the topics related to the use of optical systems for gravitational wave detectors such as LIGO. At the same time this is a collection of reference examples for using PyKat.

Daniel Töyrä
Daniel Brown
Andreas Freise
and others
since 2016

Table of Contents

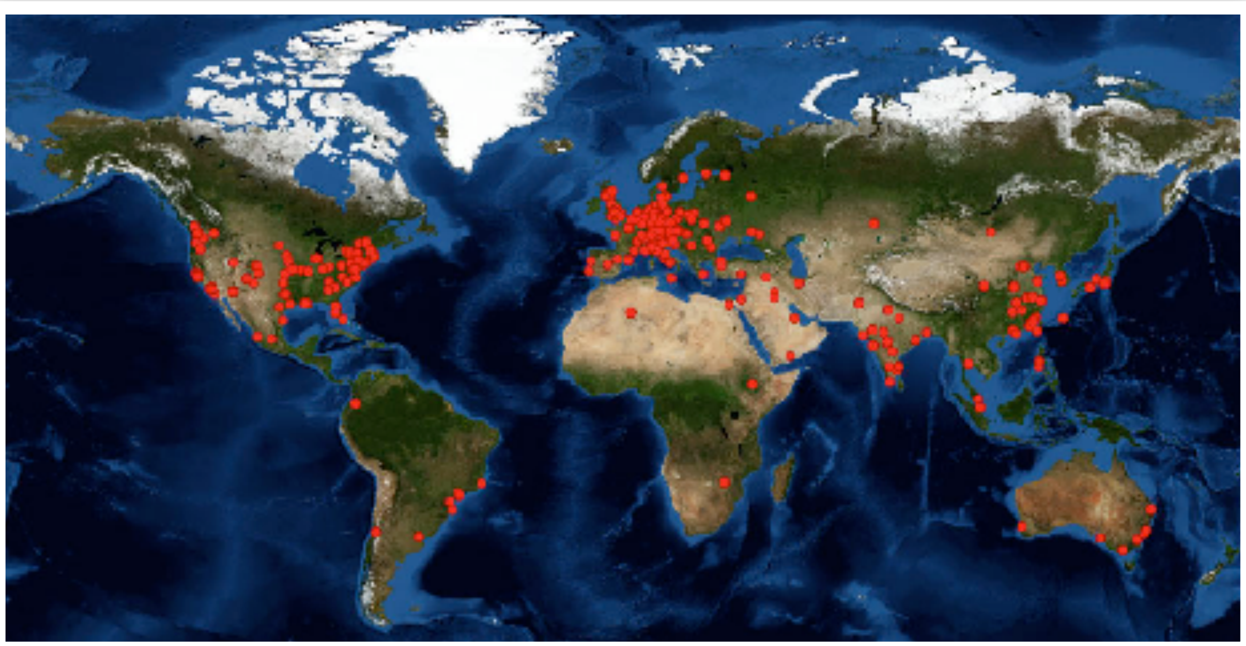
Modelling is not Theory

- Numerical simulations are different from other theoretical work:

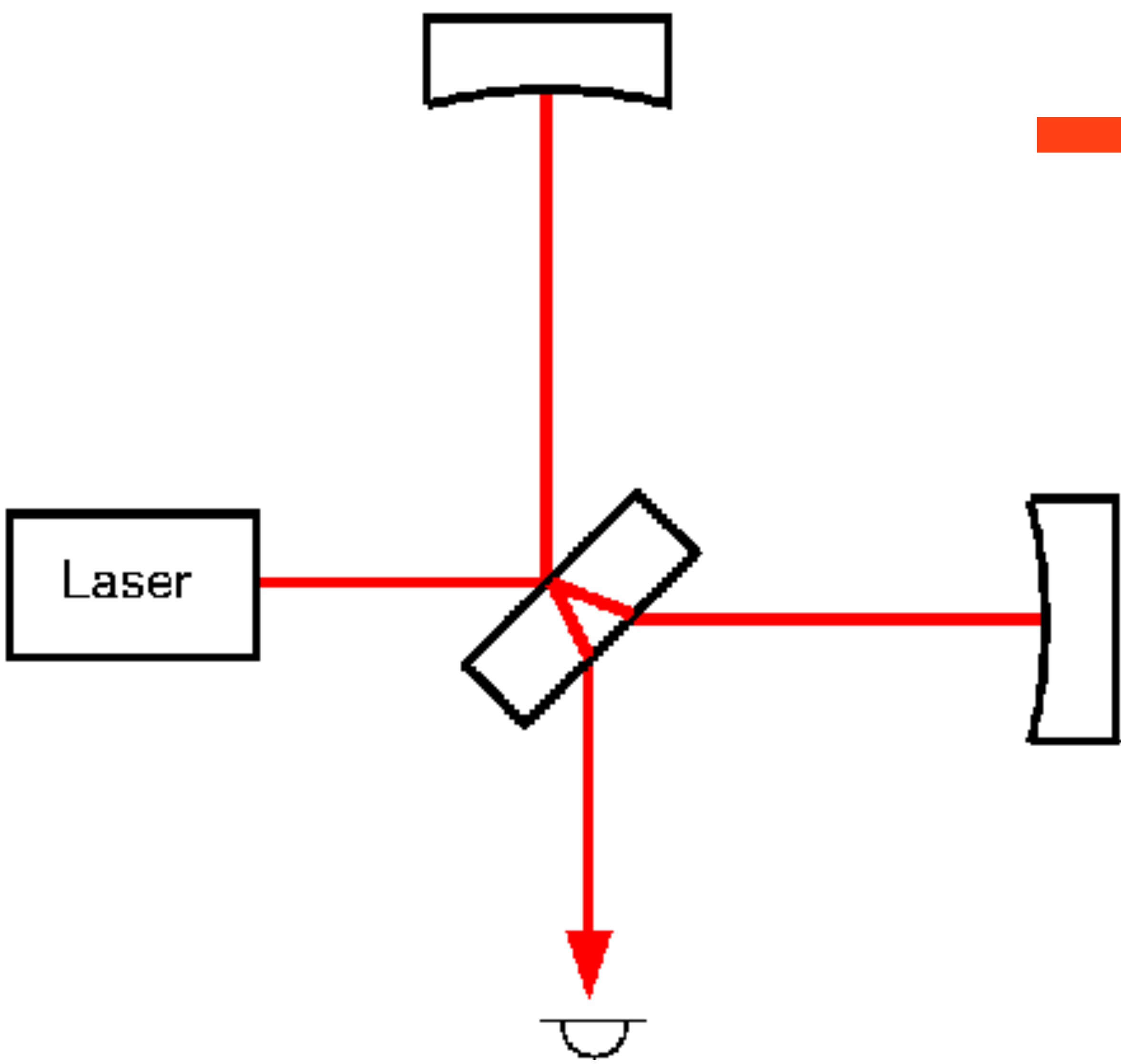
  - Write your own software? Probably not.
  - Do it alone? Definitely not!
  - Solving elegant problems? Not very often.

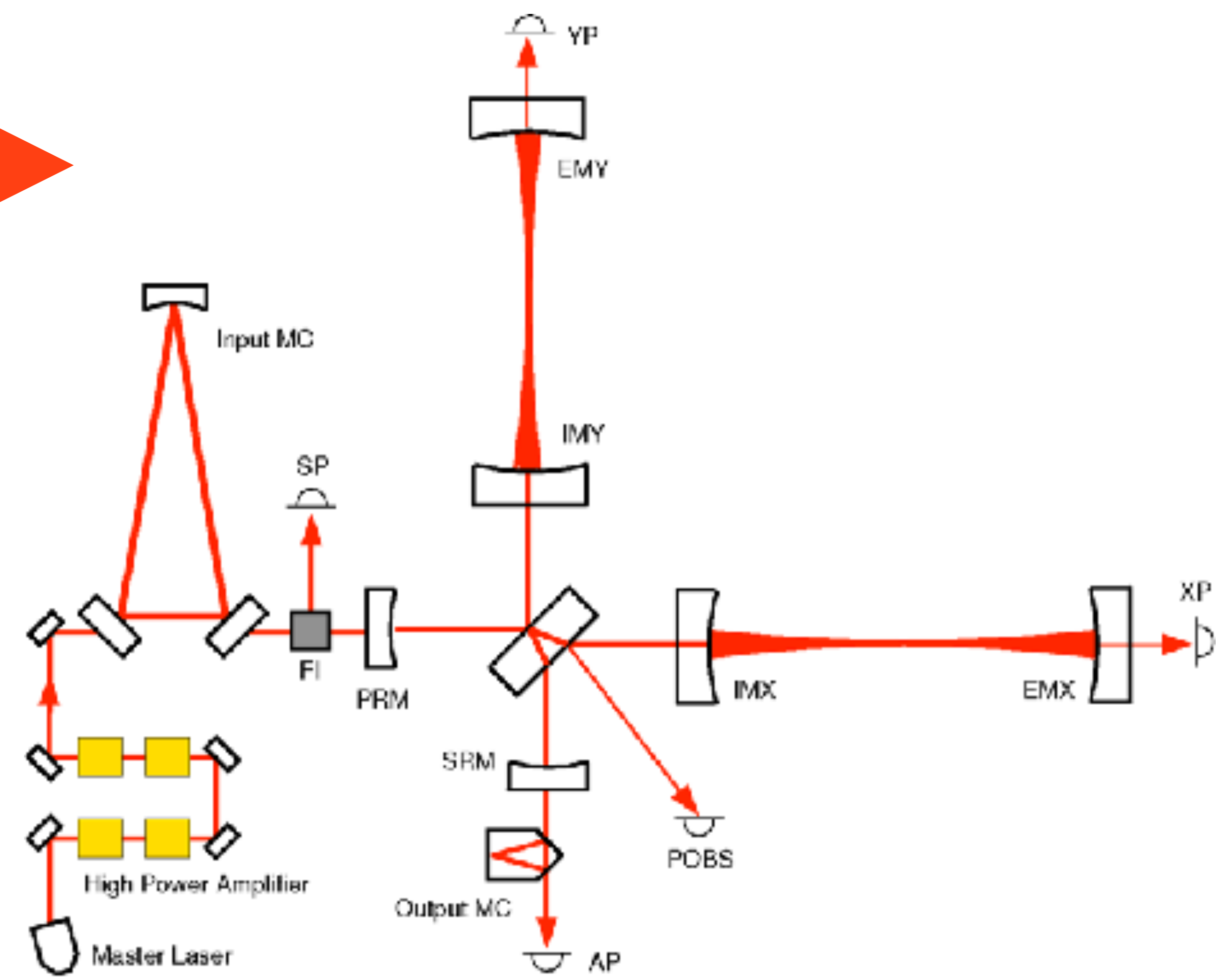
Interferometer simulation: FINESSE

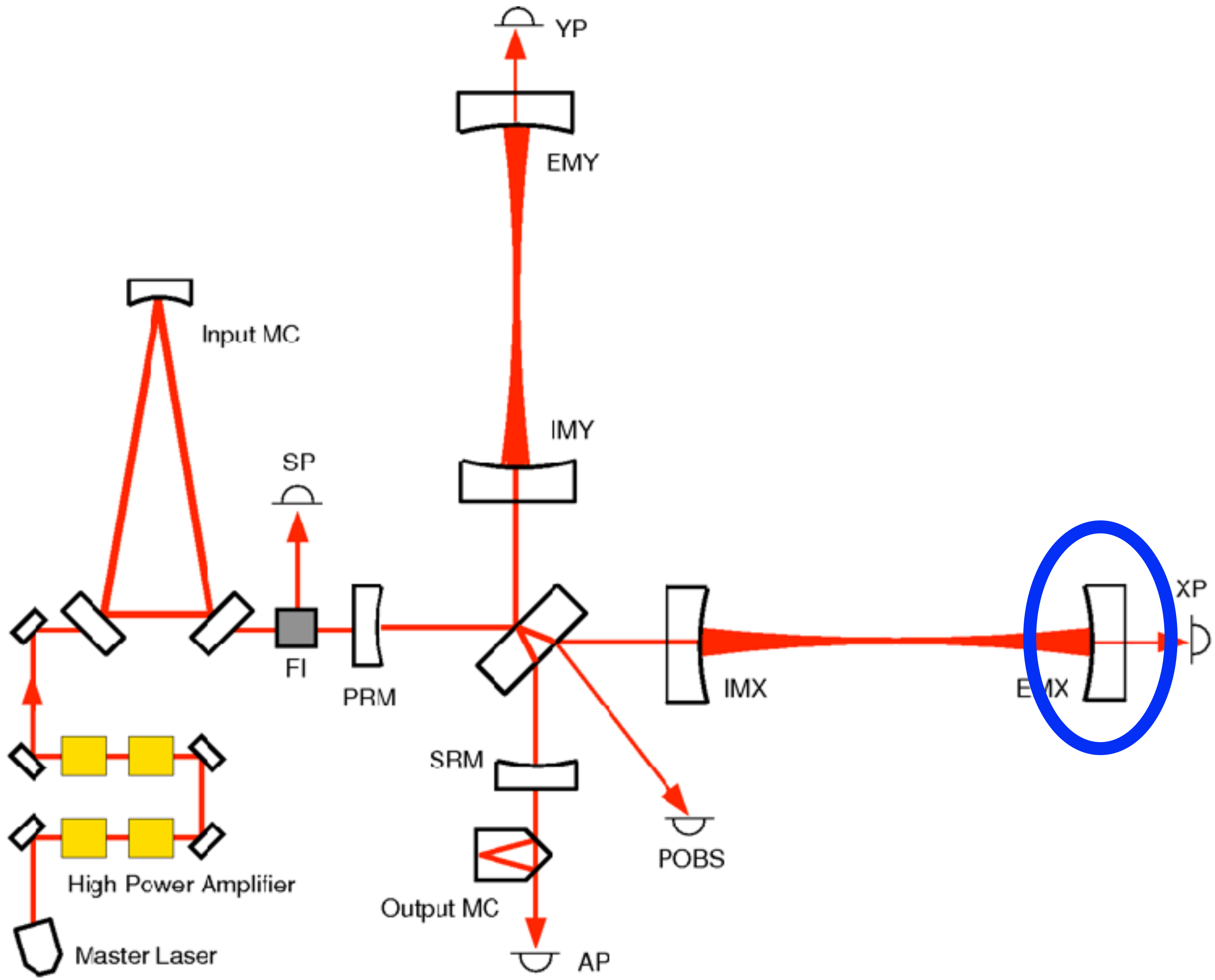
- Started1997, PhD side project
- Used extensively worldwide
- Open sourced in 2012
- Continuously used and developed



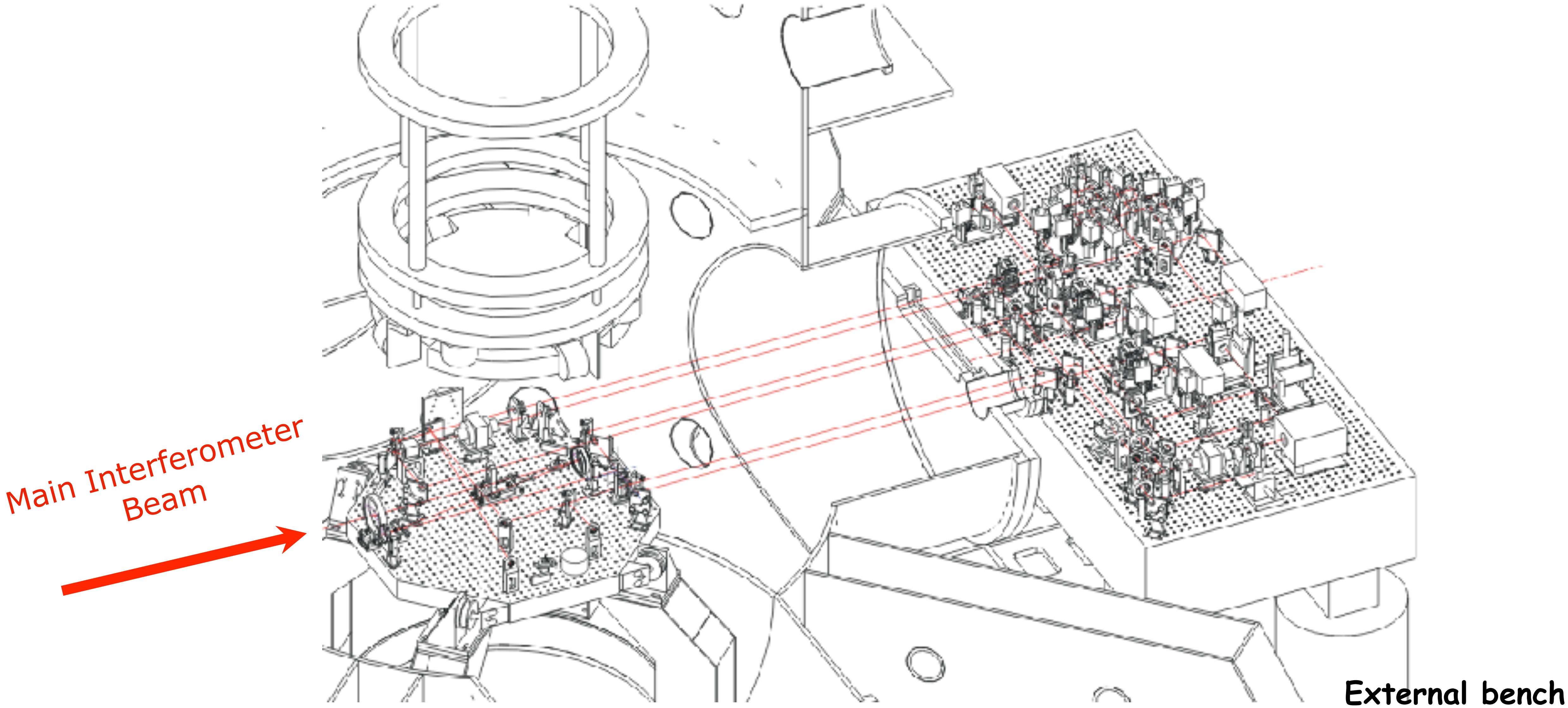
Advanced Interferometry

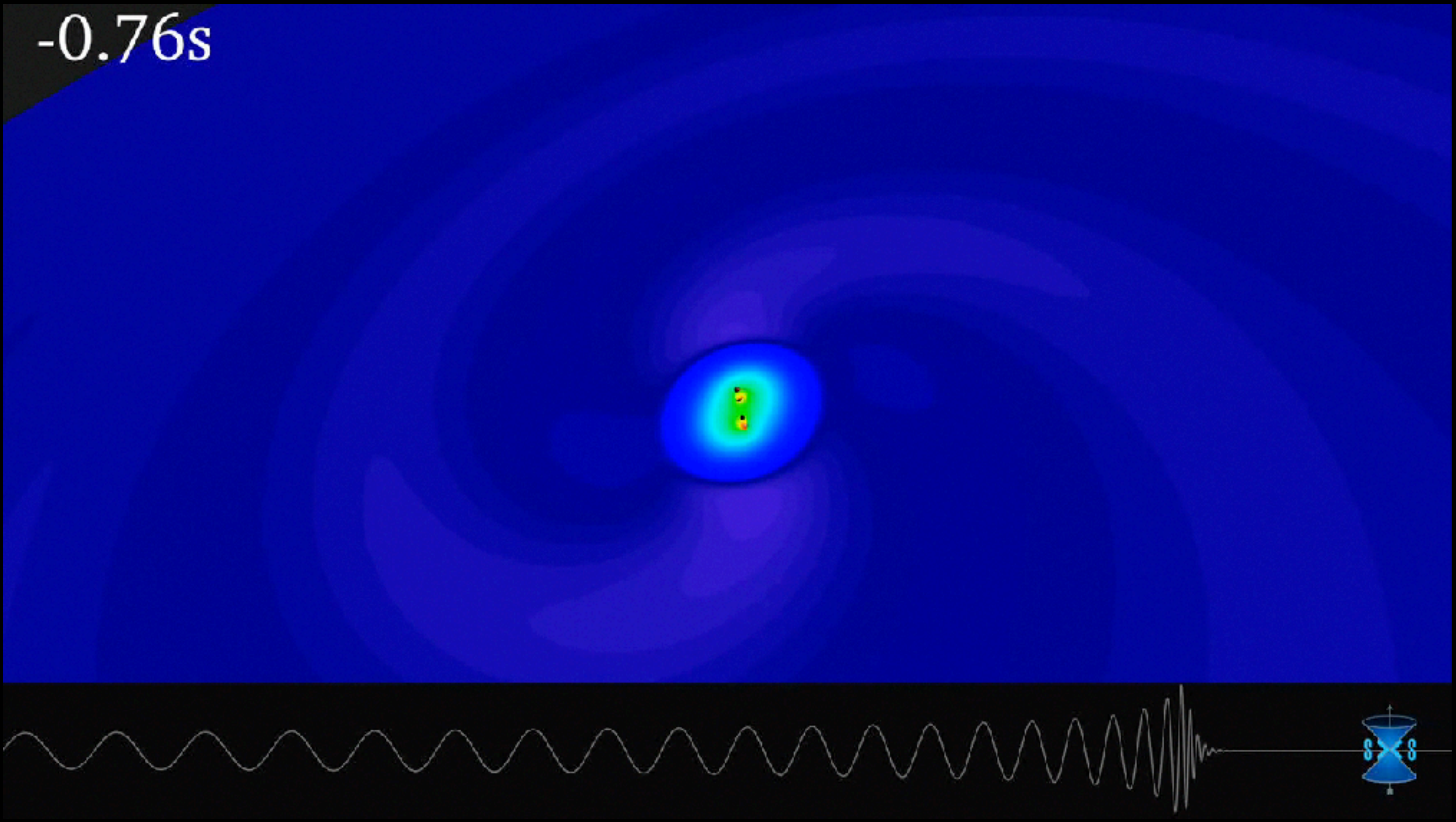





YP
EMY
Input MC
IMY
SP
XP
FI
PRM
IMX
EMX
SRM
POBS
High Power Amplifier
Output MC
Master Laser
AP

Michelson used his eye to measure the light, this is how one photo detection port looks today:





GW150914


[Images: Google Earth and LIGO]

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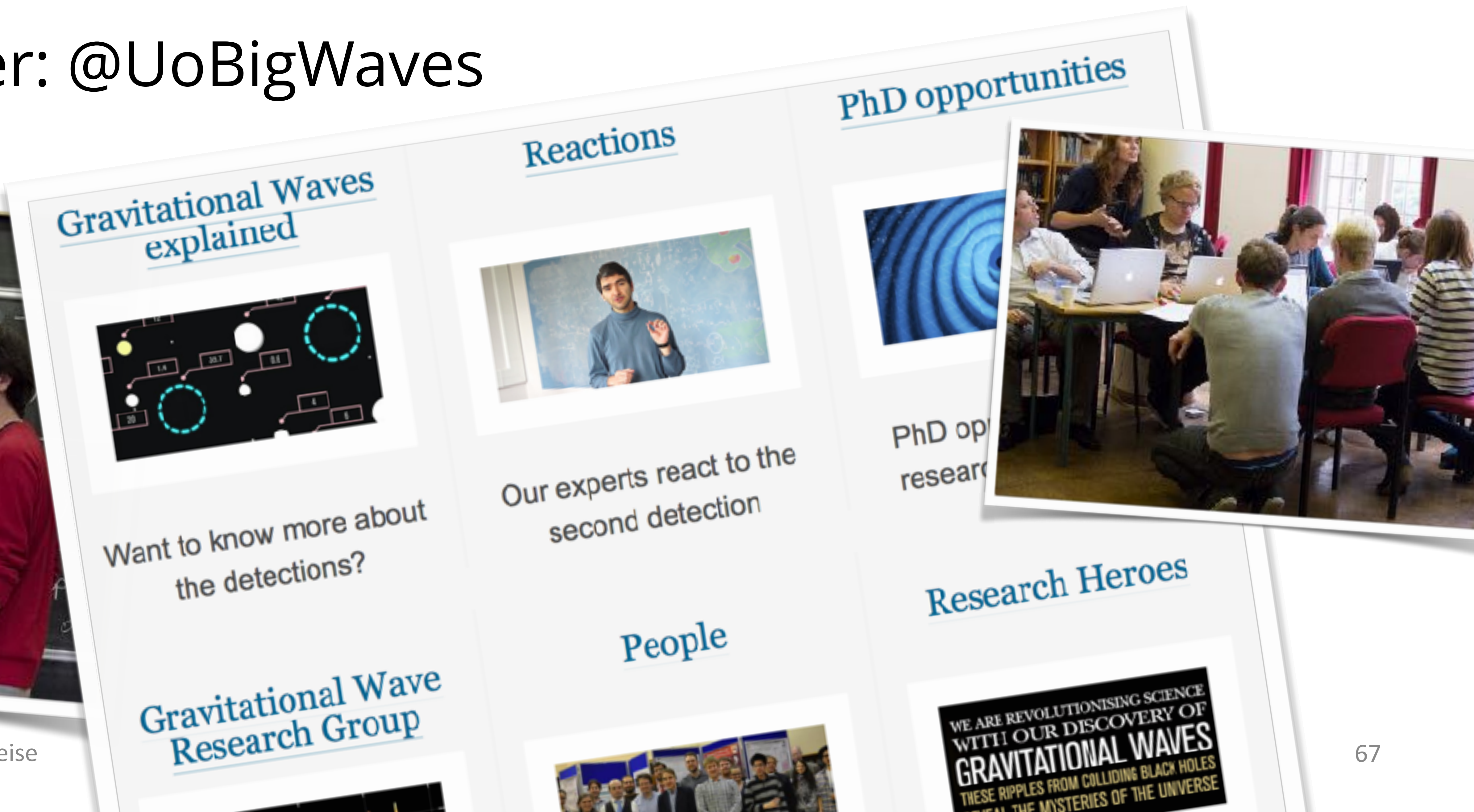
[Images: Google Earth and LIGO]

Institute of Gravitational Wave Astronomy

Founded: 4th October 2016

Web: birmingham.ac.uk/gravitational-waves

Twitter: @UoBigWaves



How to Play?

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