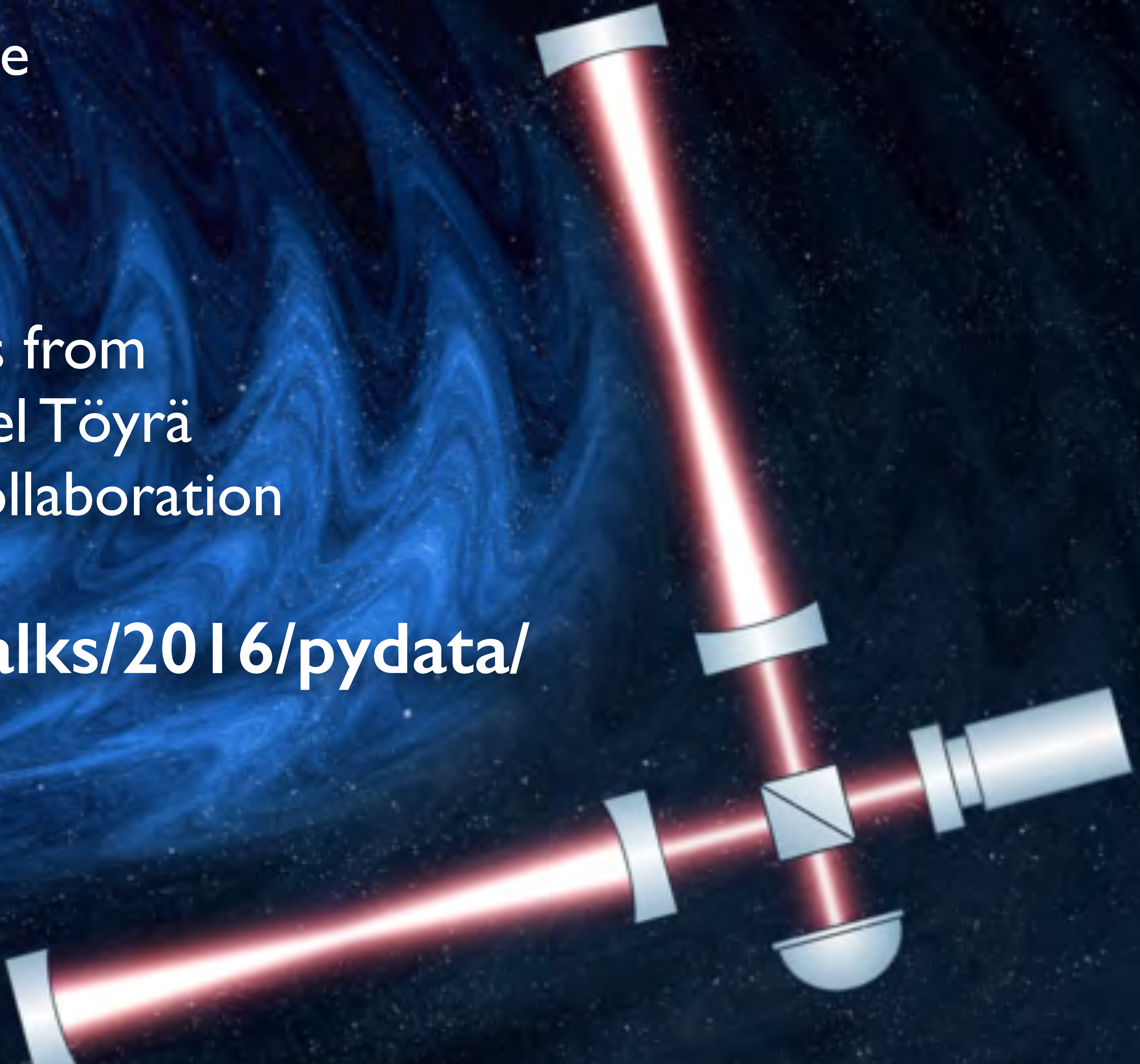
# Laser Ranging in a new Dimension

Andreas Freise
07.05.2016

with contributions from
Daniel Brown, Daniel Töyrä
and the LIGO-Virgo Collaboration

http://www.gwoptics.org/talks/2016/pydata/

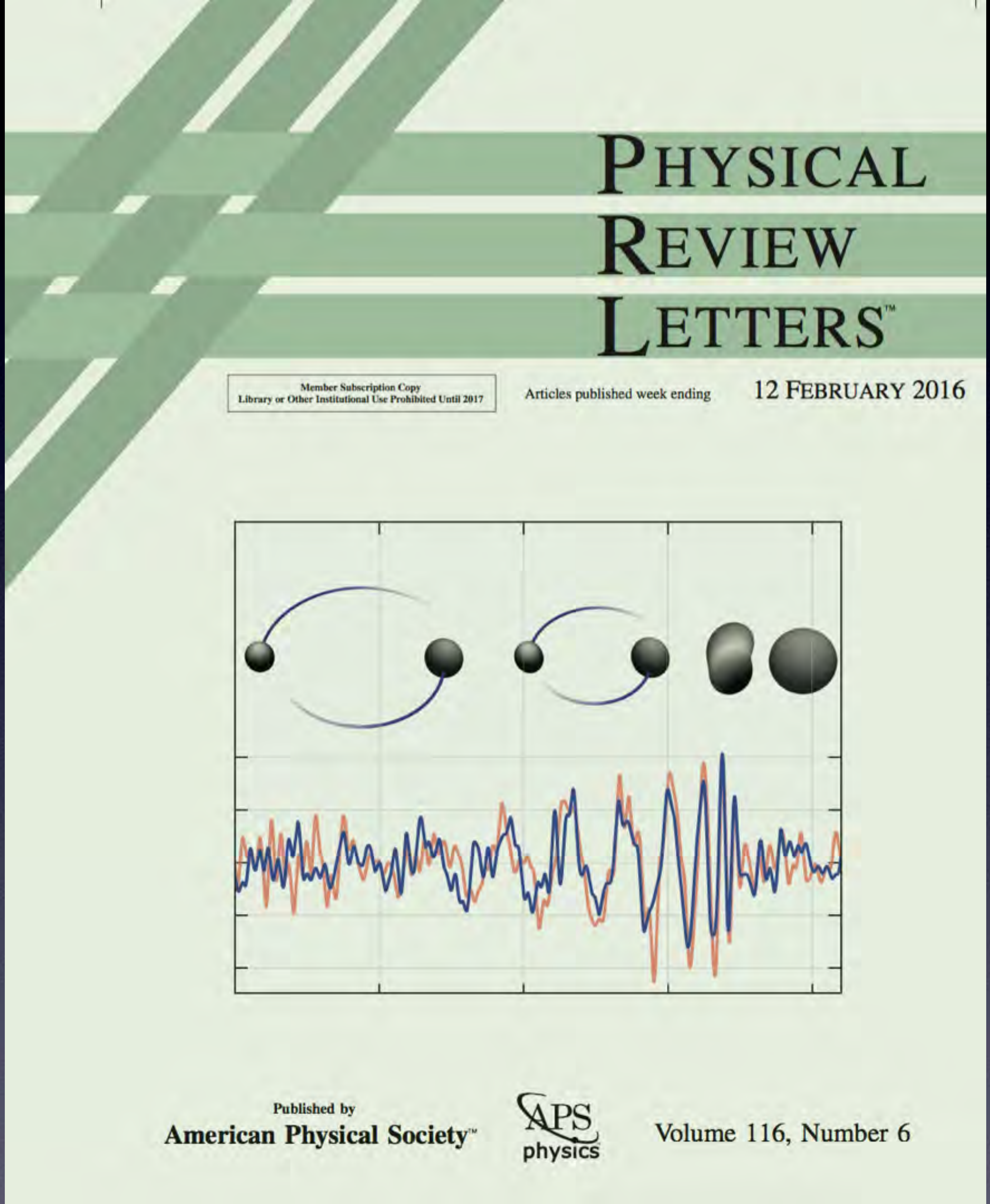


LIGO document number: LIGO-G1601015


Download on the app store (iOS, Android)
or via the webpage: www.laserlabs.org
Tweet a photo with hashtag #PyDataLondon

# In the News:


[Photo by Kate Gushwa, Matt Heintze, Calum Torrie and Liz Natividad]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APS physics

Volume 116, Number 6

UNIVERSITY OF
BIRMINGHAM

# Astronomy

# Hubble Space Telescope

[Image: NASA]


[NASA, ESA, Z. Levay (STScI), T. Rector, I. Dell'Antonio/NOAO/AURA/NSF, G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz), R. Bouwens (Leiden University) and the HUDF09 Team]

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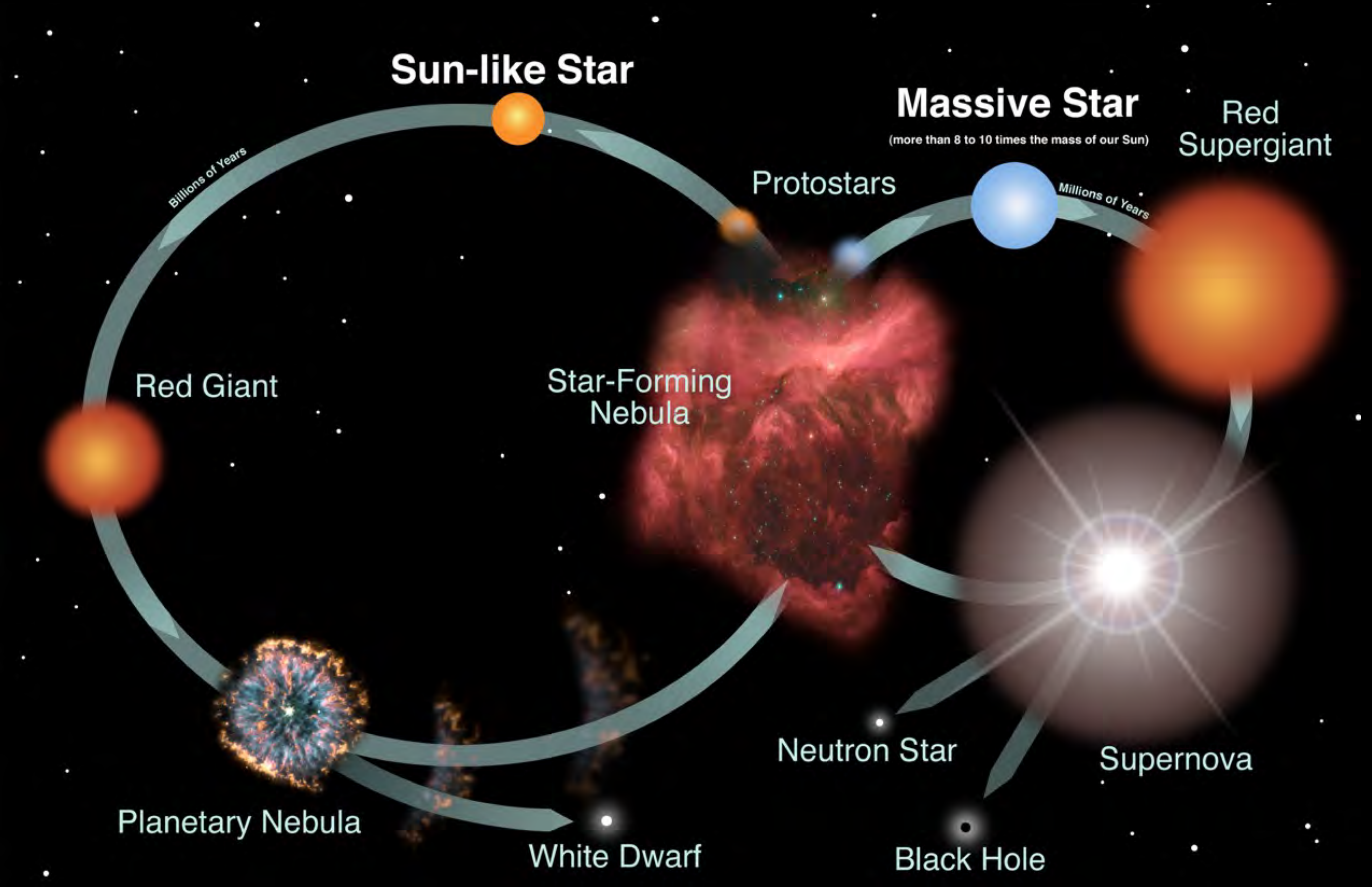
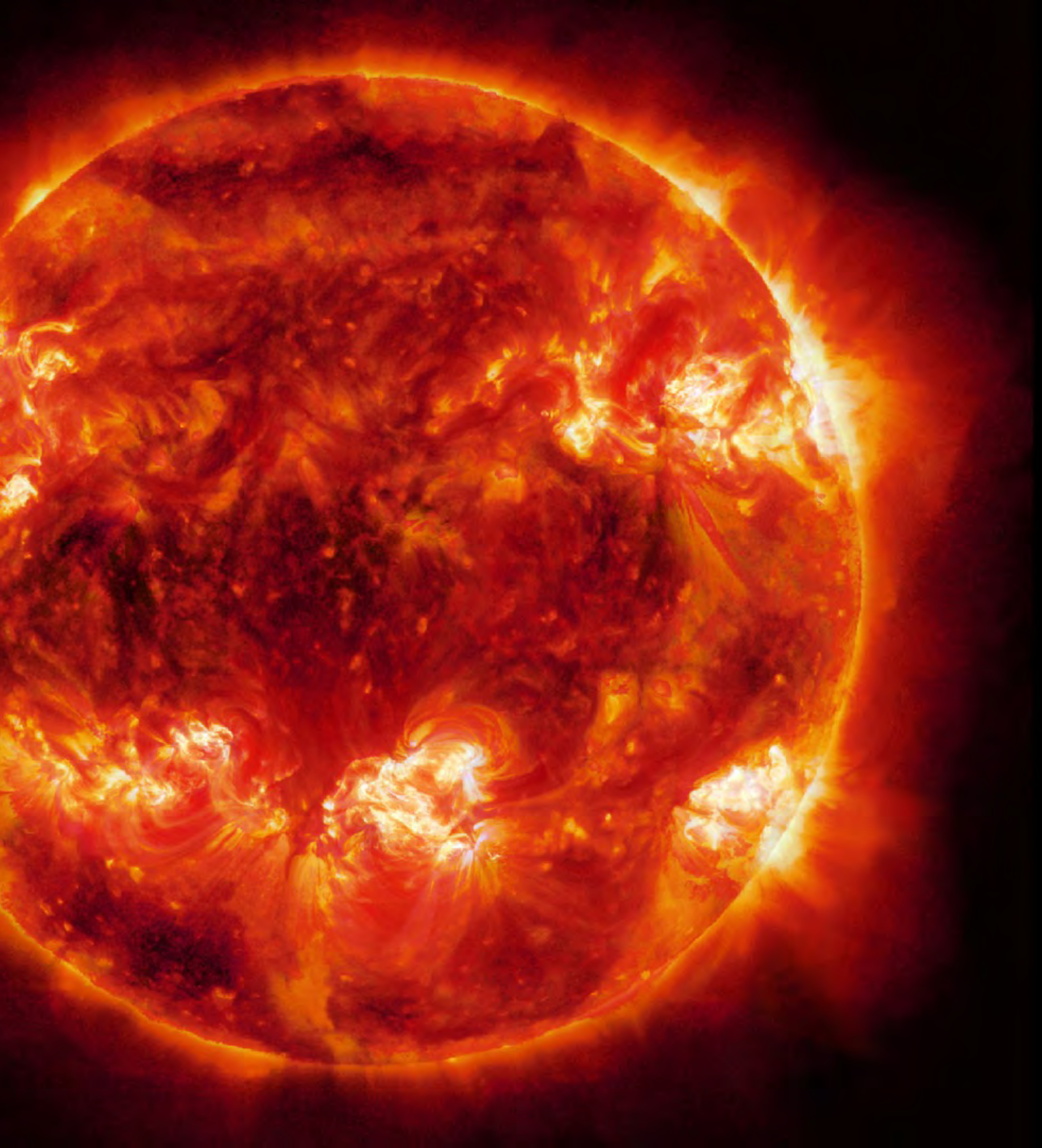
# Life Cycle of Stars



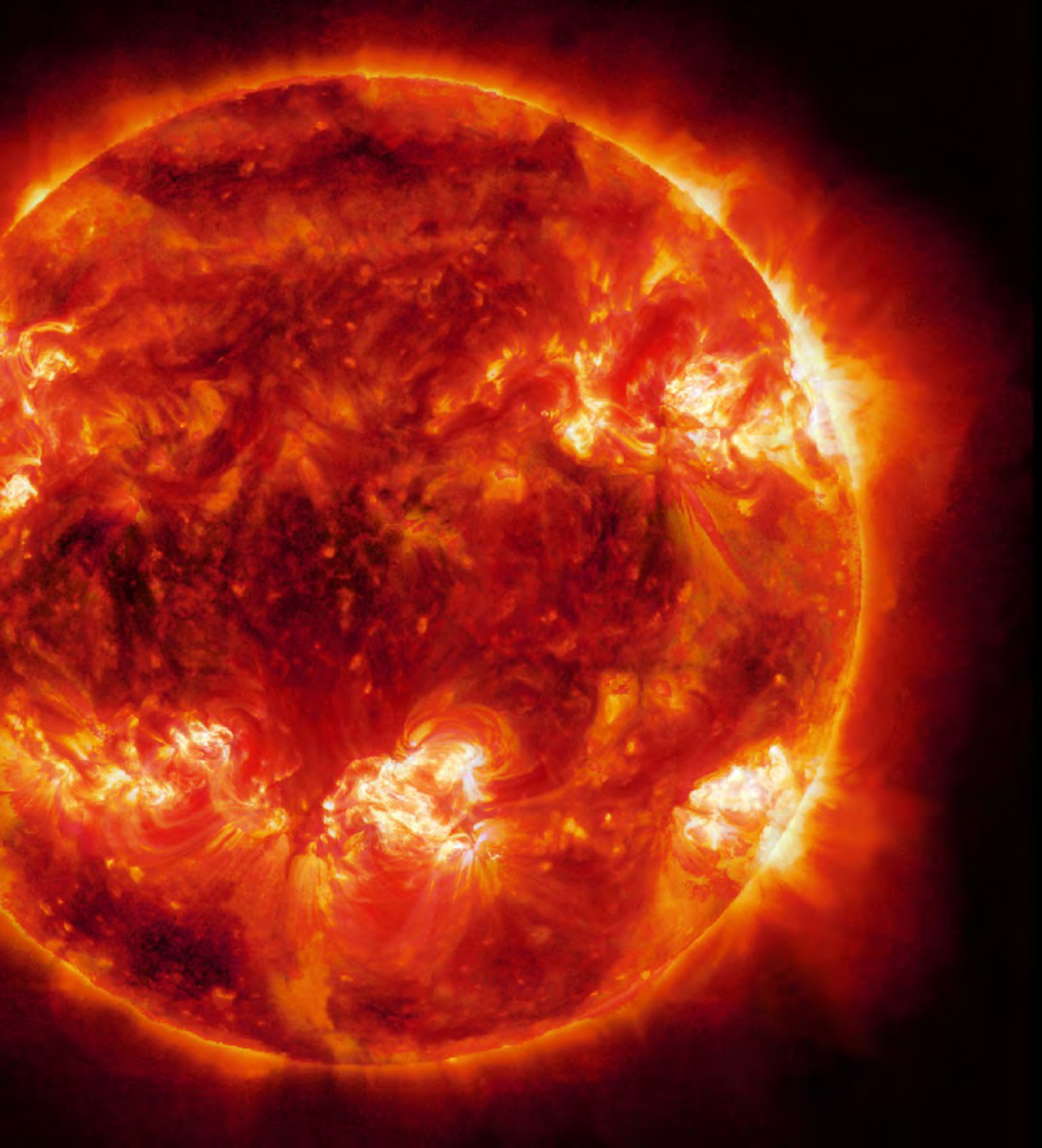

[Credit: NASA and the Night Sky Network]



The Sun

Size = 109 × Earth

Mass = 333000 × Earth

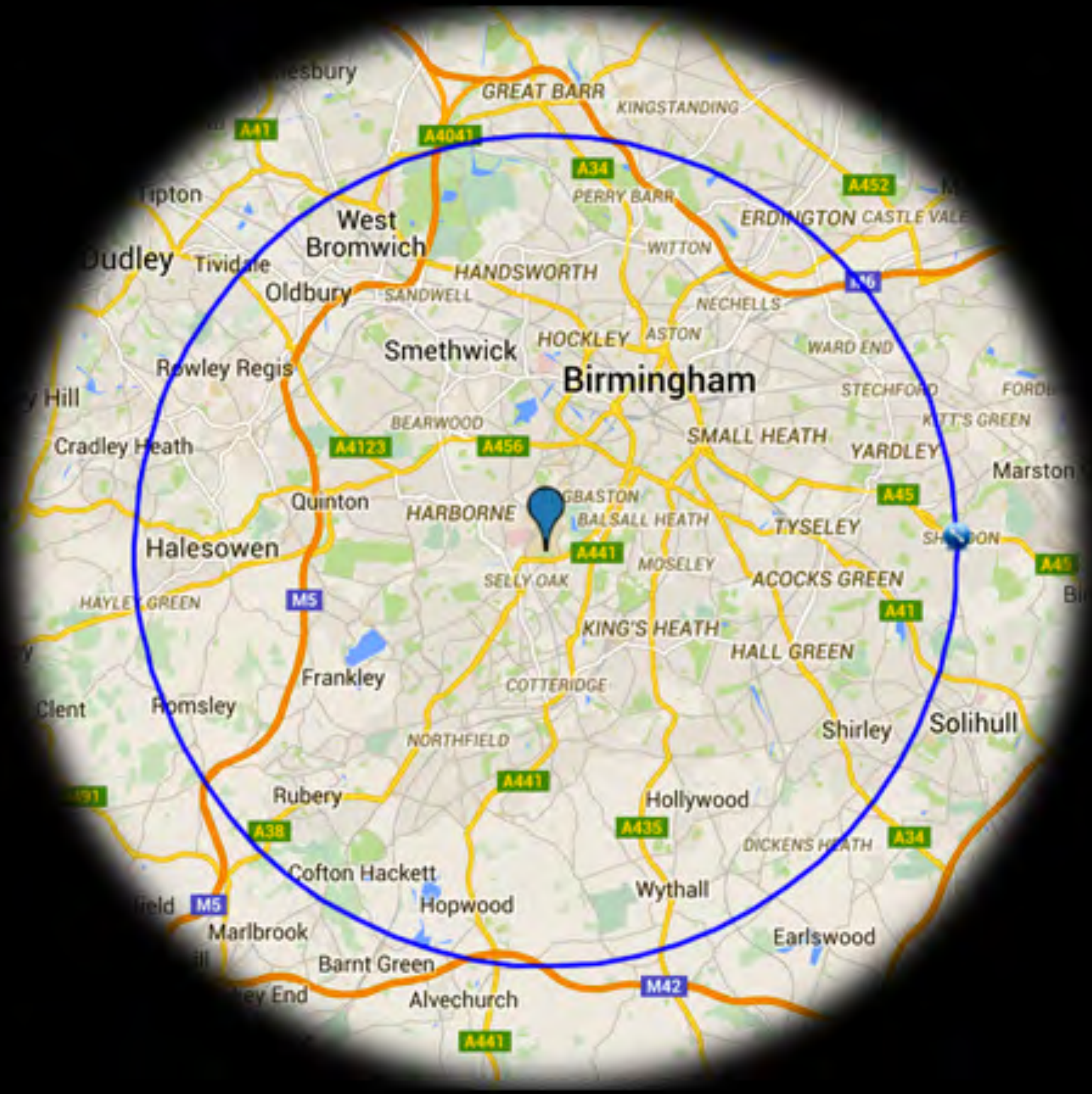


# The Sun

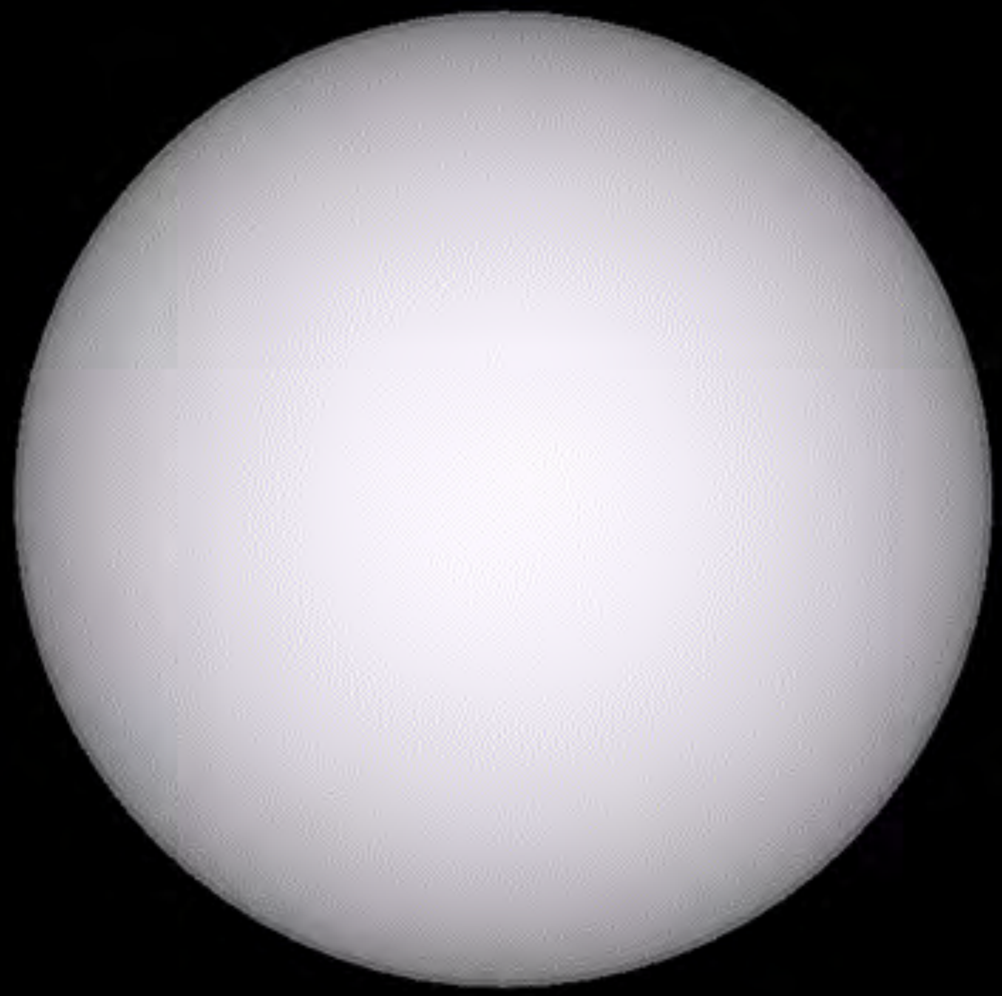
Size = 109 × Earth
Mass = 333000 × Earth

Earth and Moon

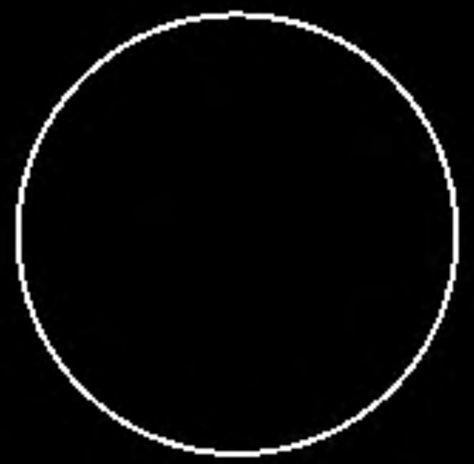
# Neutron Stars and Black Holes




Birmingham

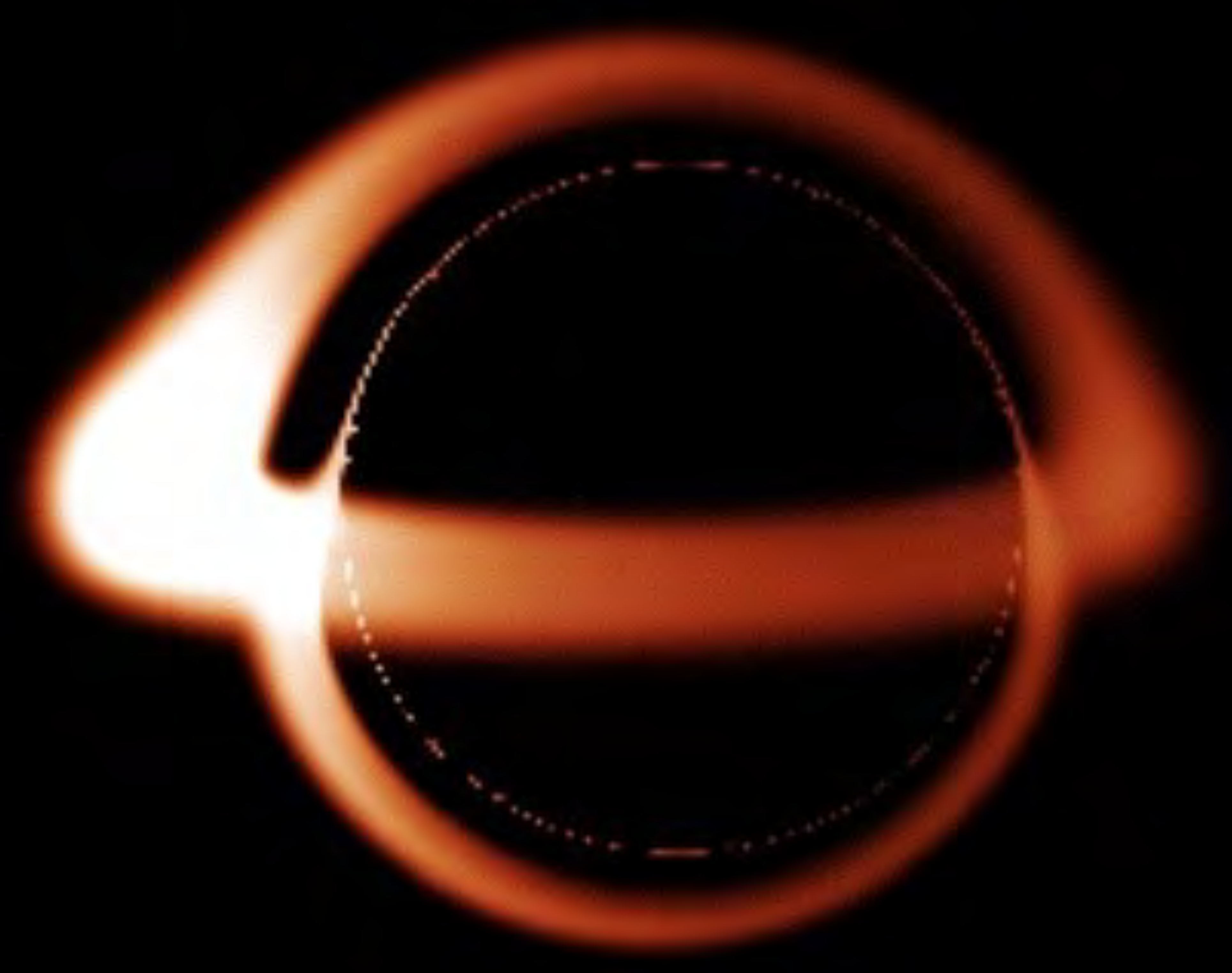


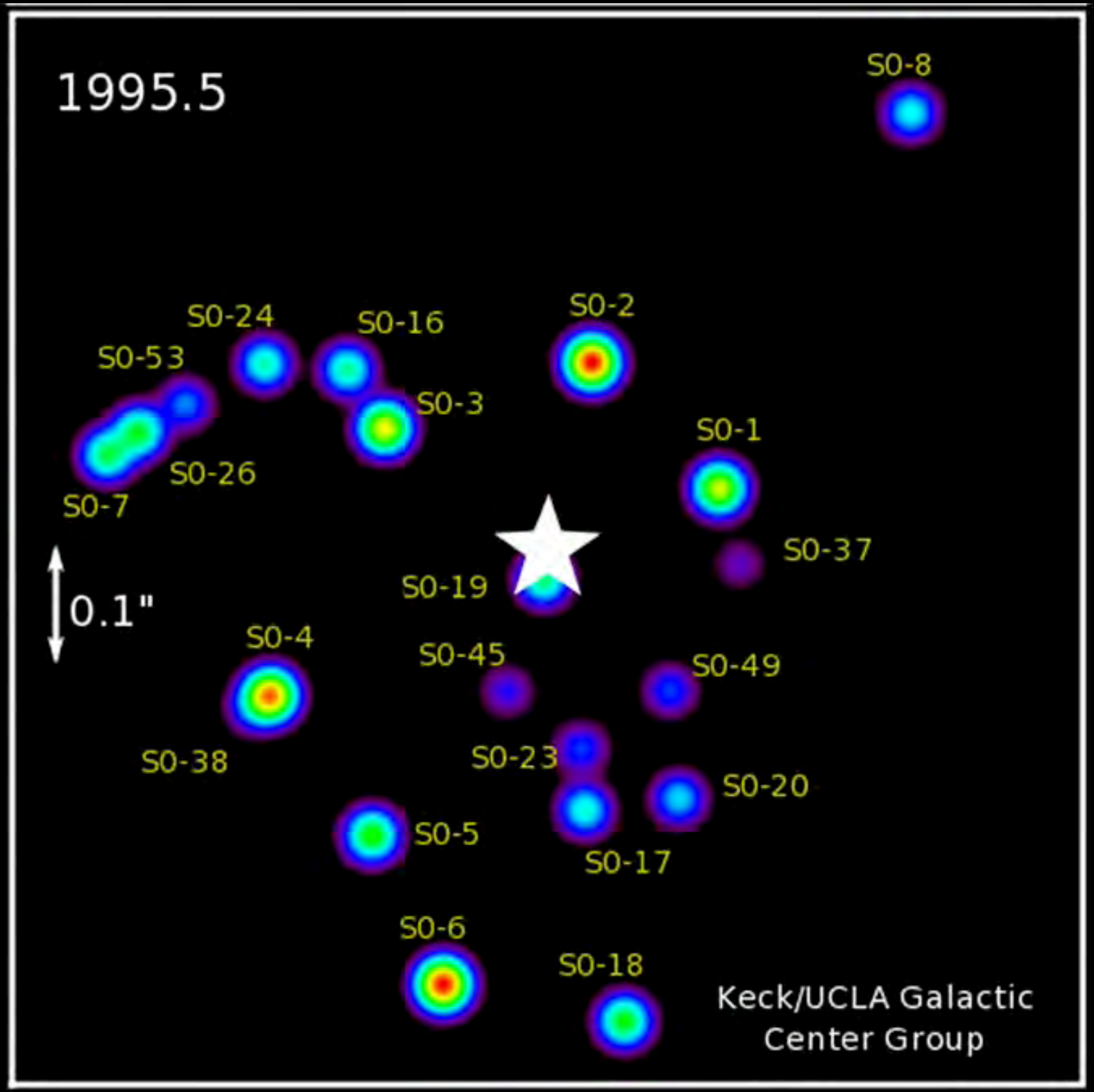
Neutron Star



Black Hole

# What are Black Holes?

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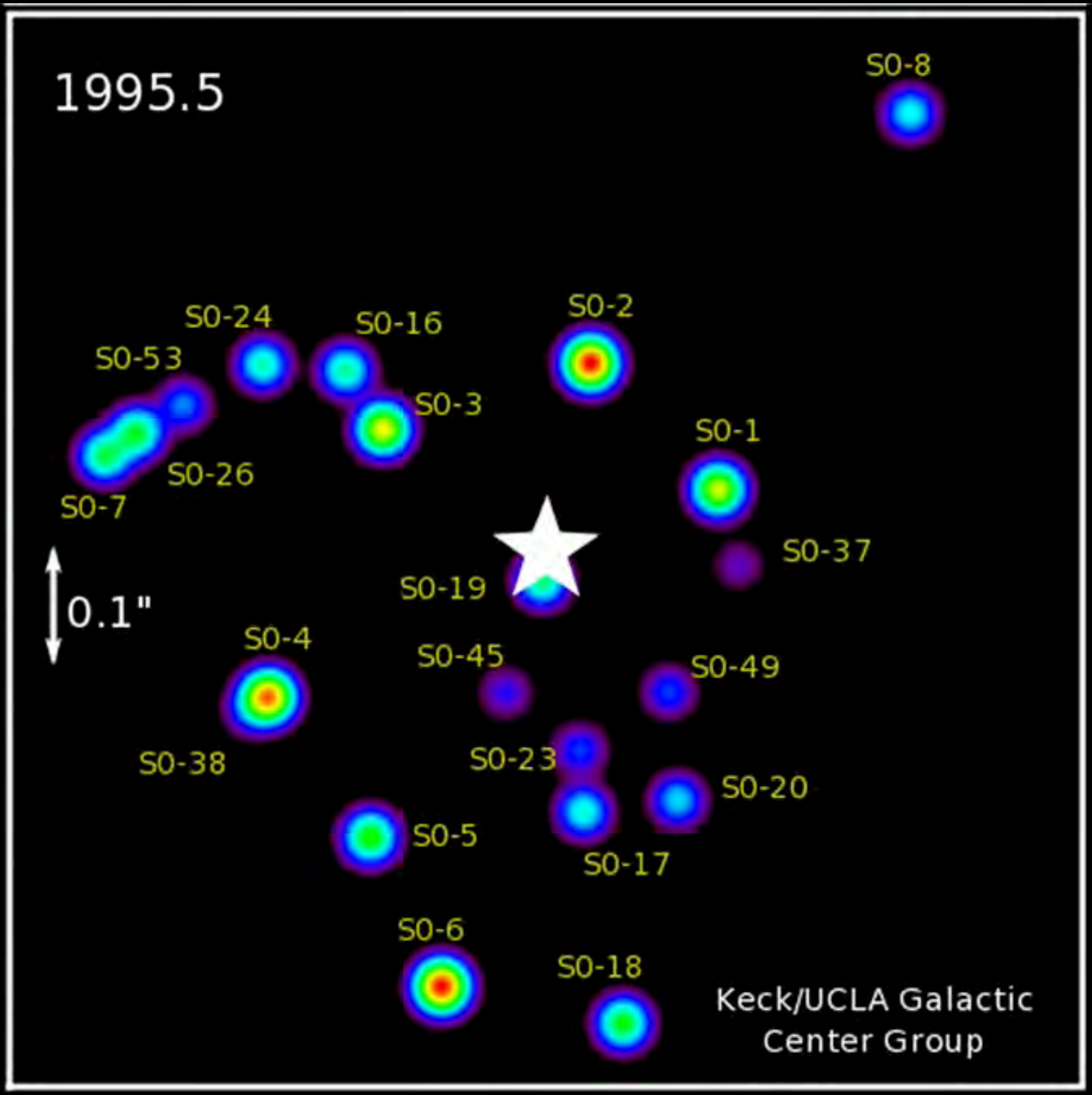
S0-6
S0-18
Keck/UCLA Galactic
Center Group


1995.5
S0-8
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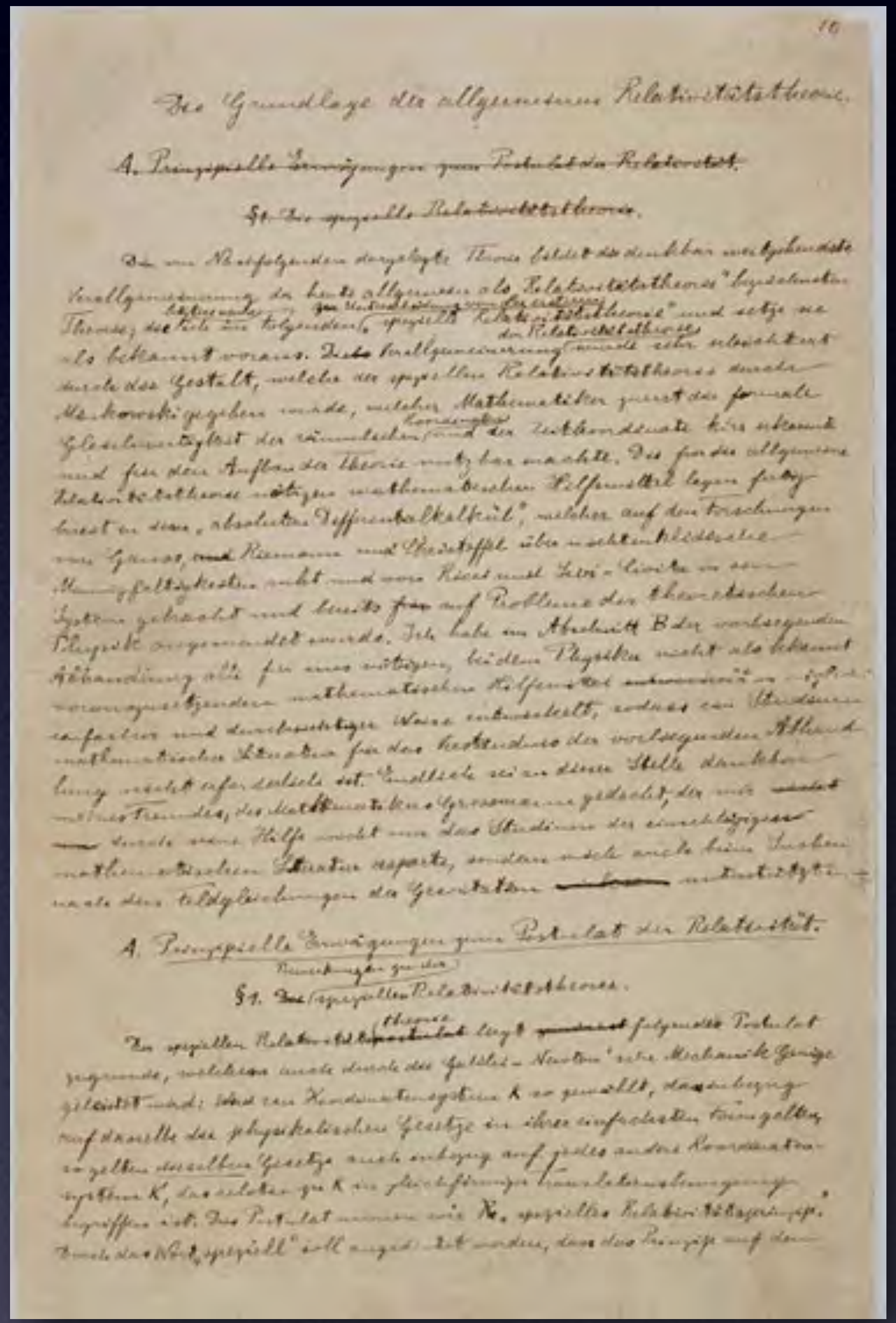
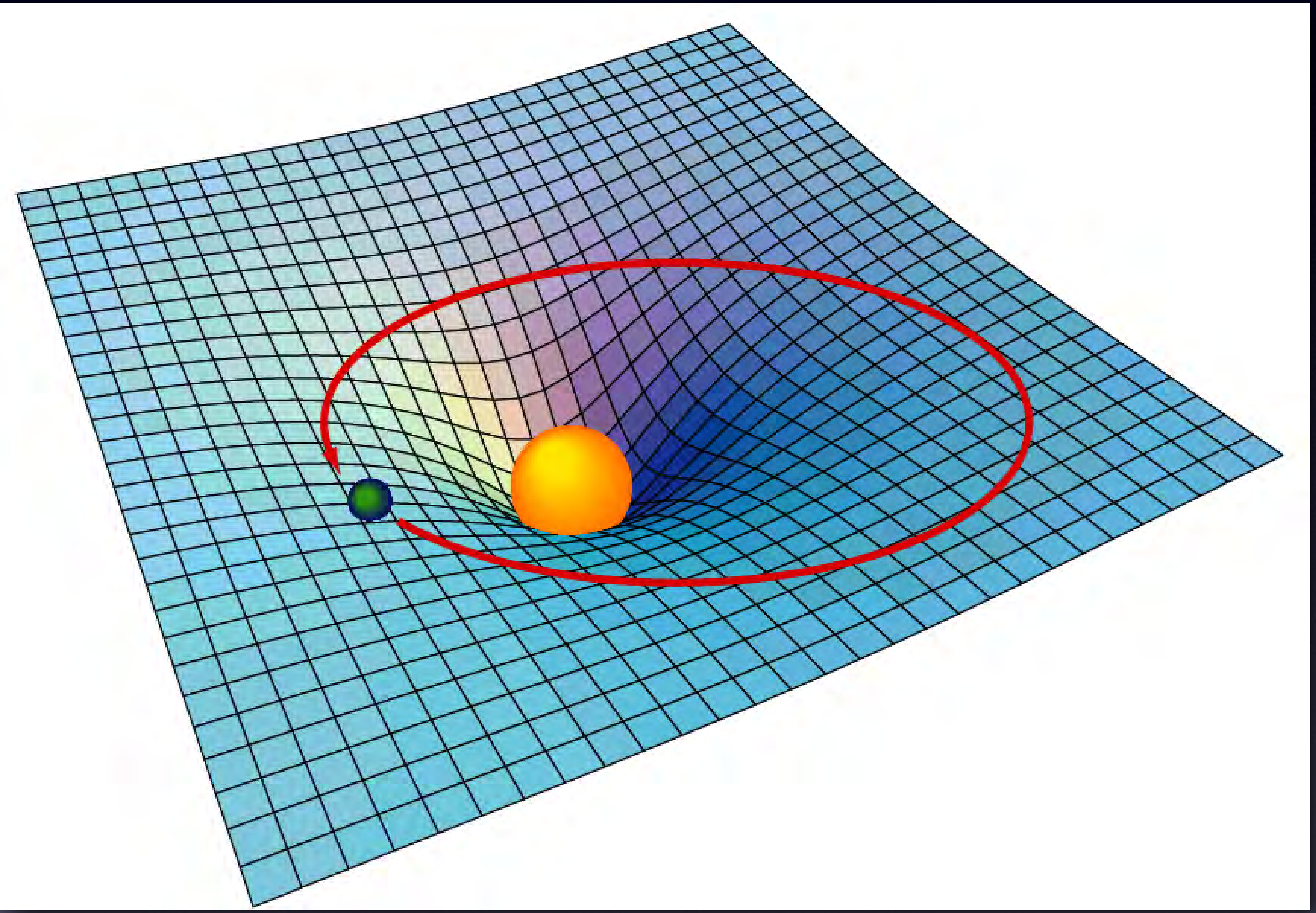
# Einstein's Theory of Relativity



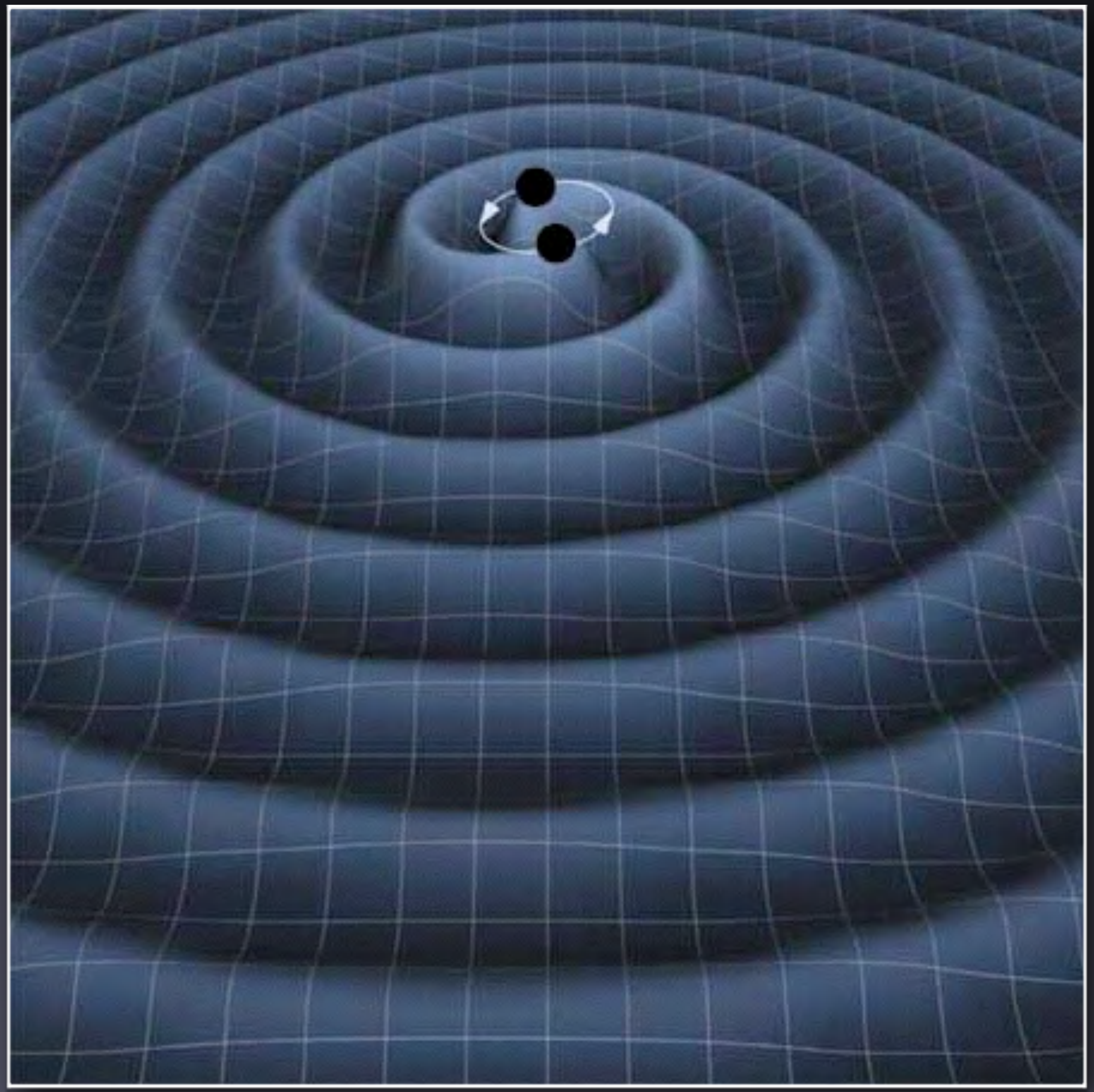
Die Grundlage der allgemeinen Relativitätstheorie.

Einstein, Die Grundlage der allgemeinen Relativitätstheorie



# Gravitational Waves

- Two black holes circling around each other (a ‘binary’ system) ...
- .. create a very strong and quickly varying gravitational field ...
- ... and ripples in space-time that run away at the speed of light.

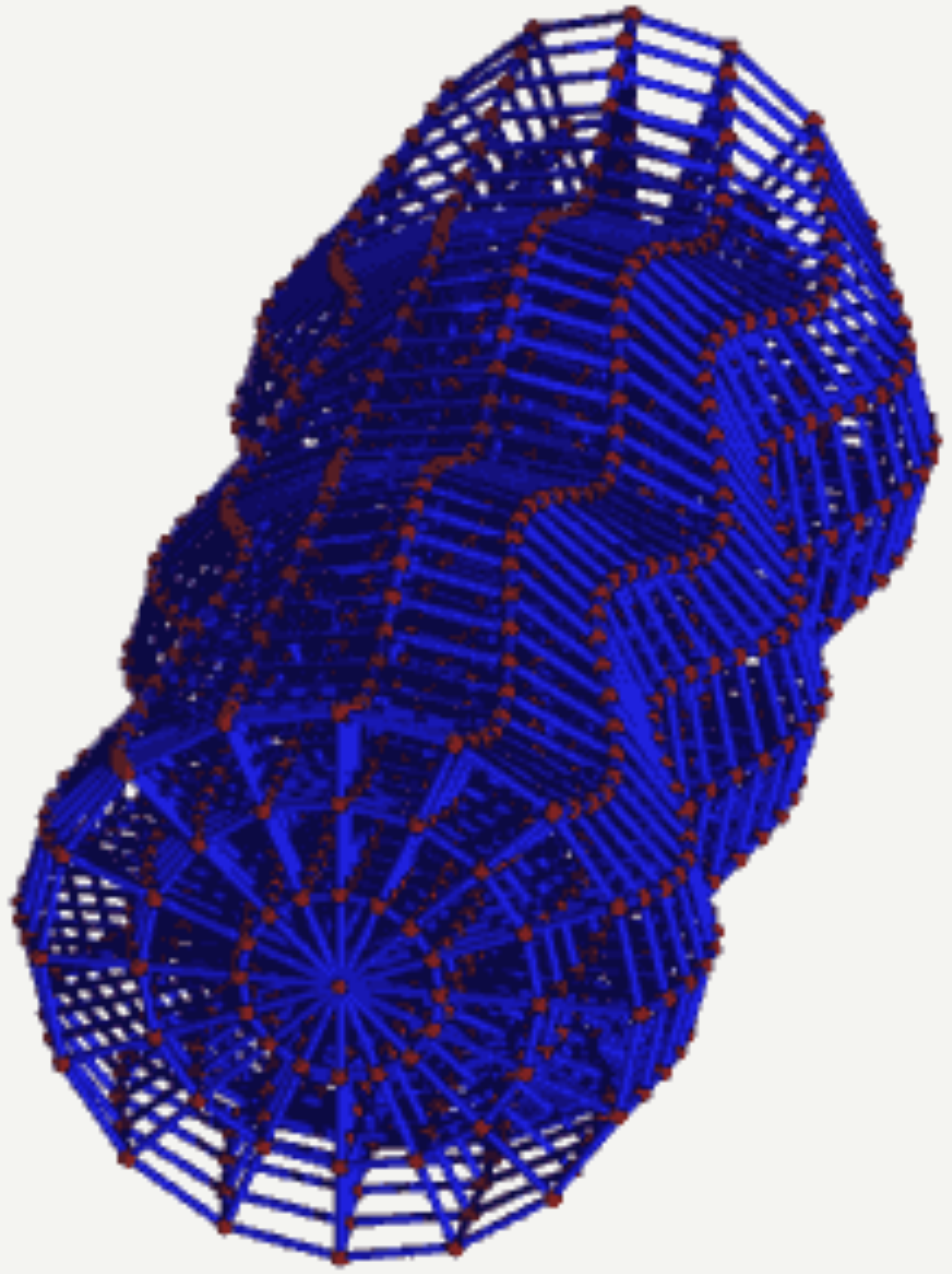


# Astronomy

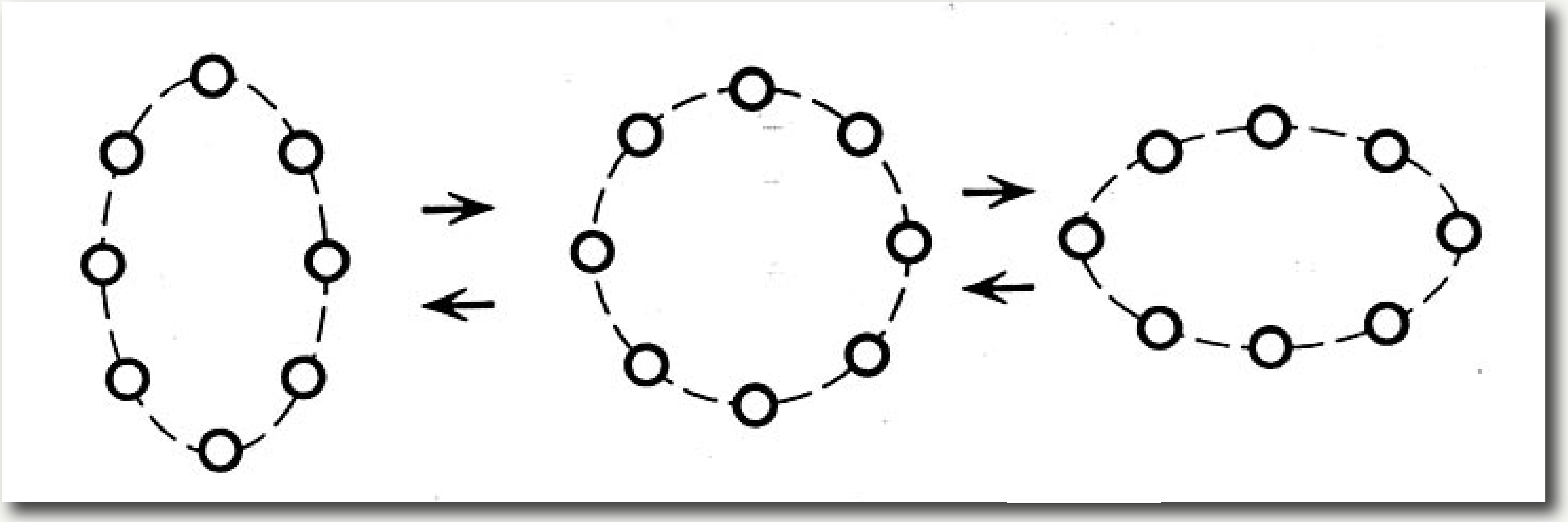
UNIVERSITY OF BIRMINGHAM

# Gravitational Wave
# Astronomy

# Observing Gravitational Waves:

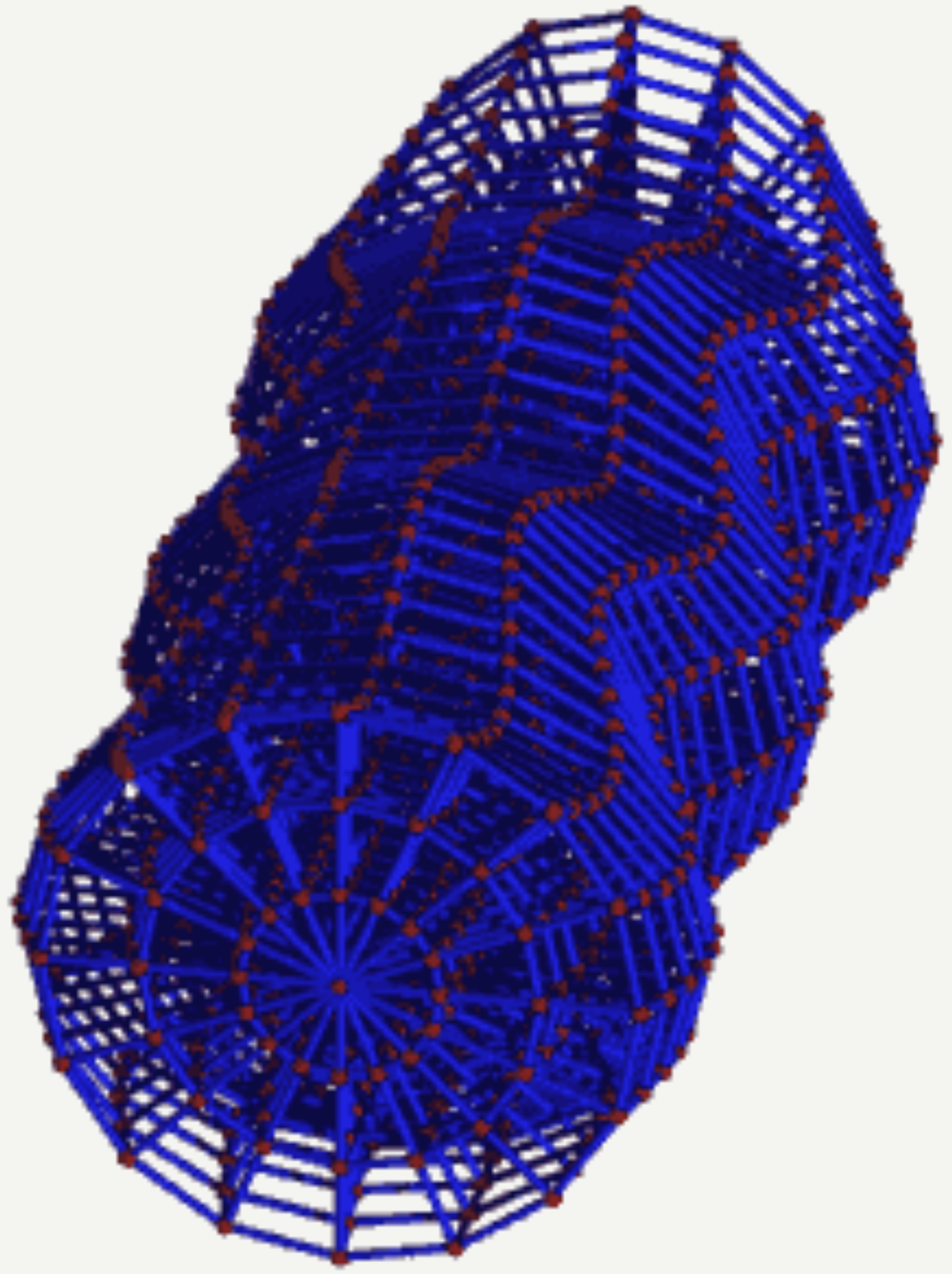


[http://www.einstein-online.info]



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

# Observing Gravitational Waves:



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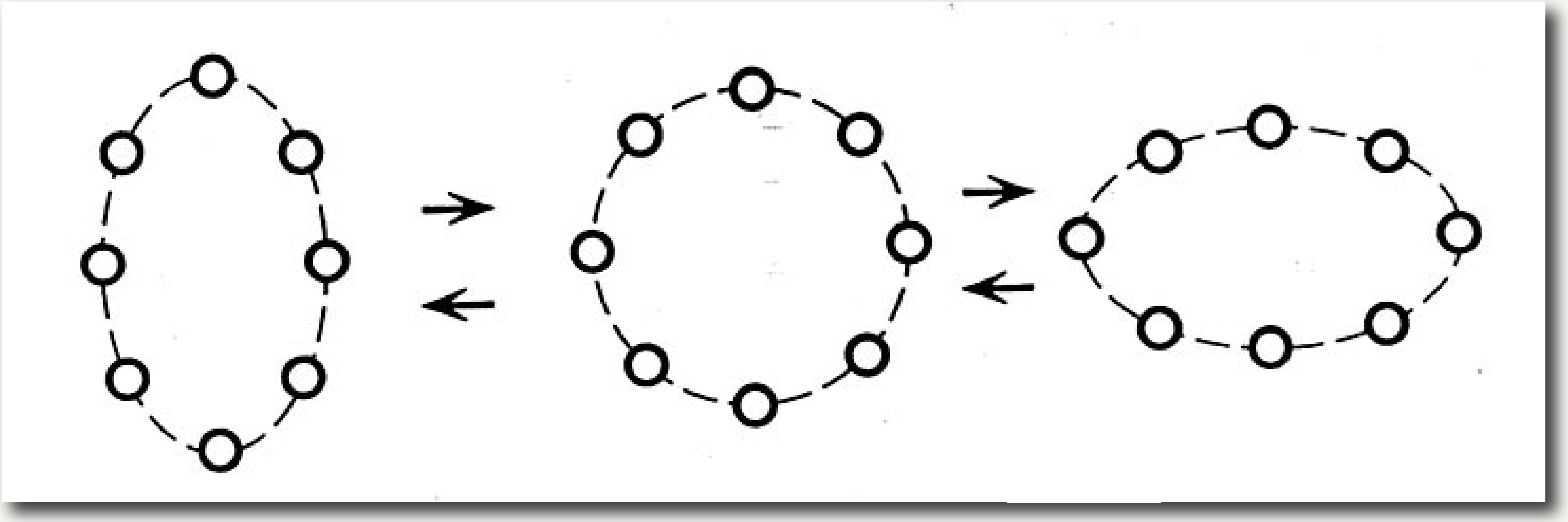

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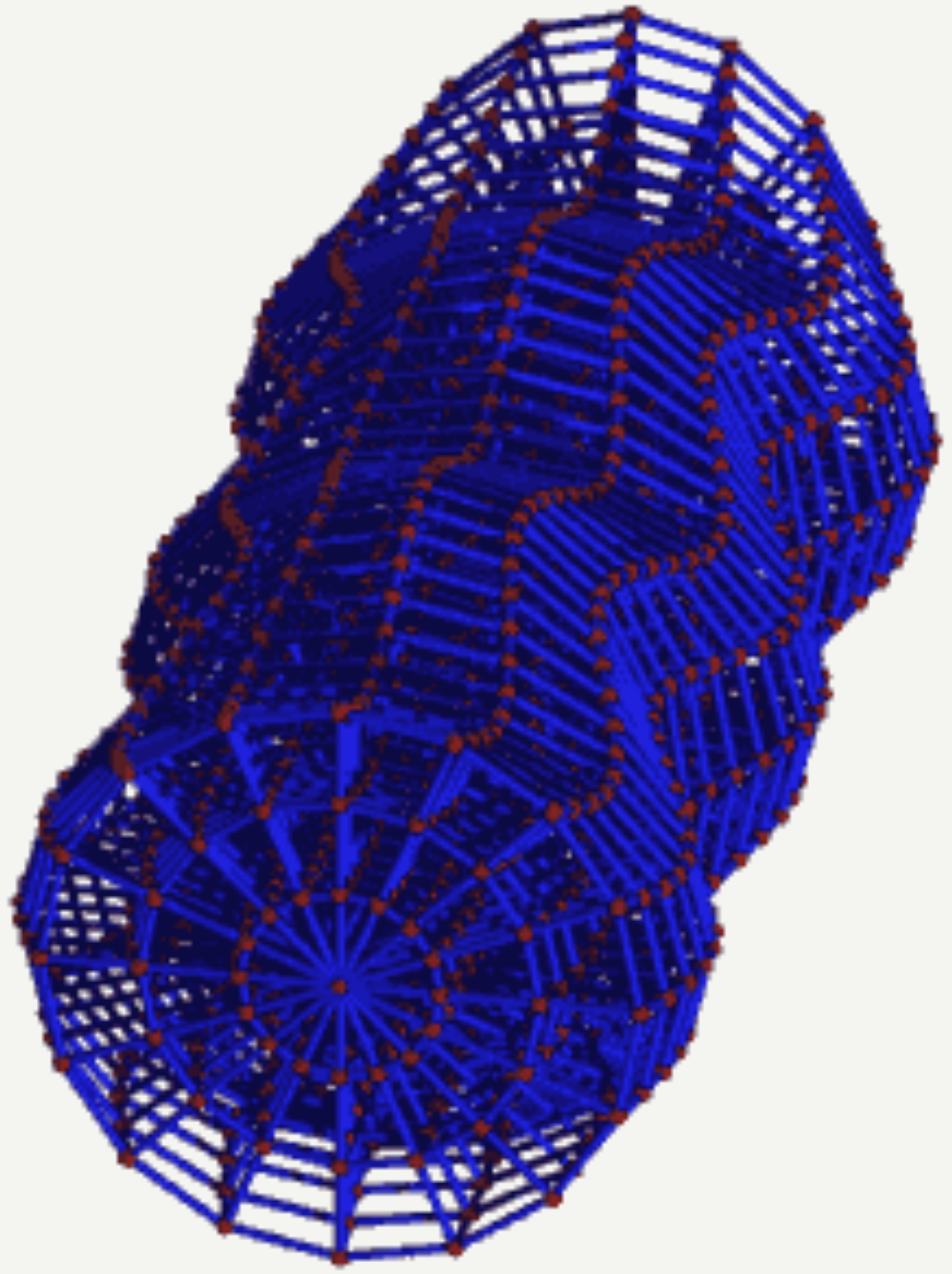

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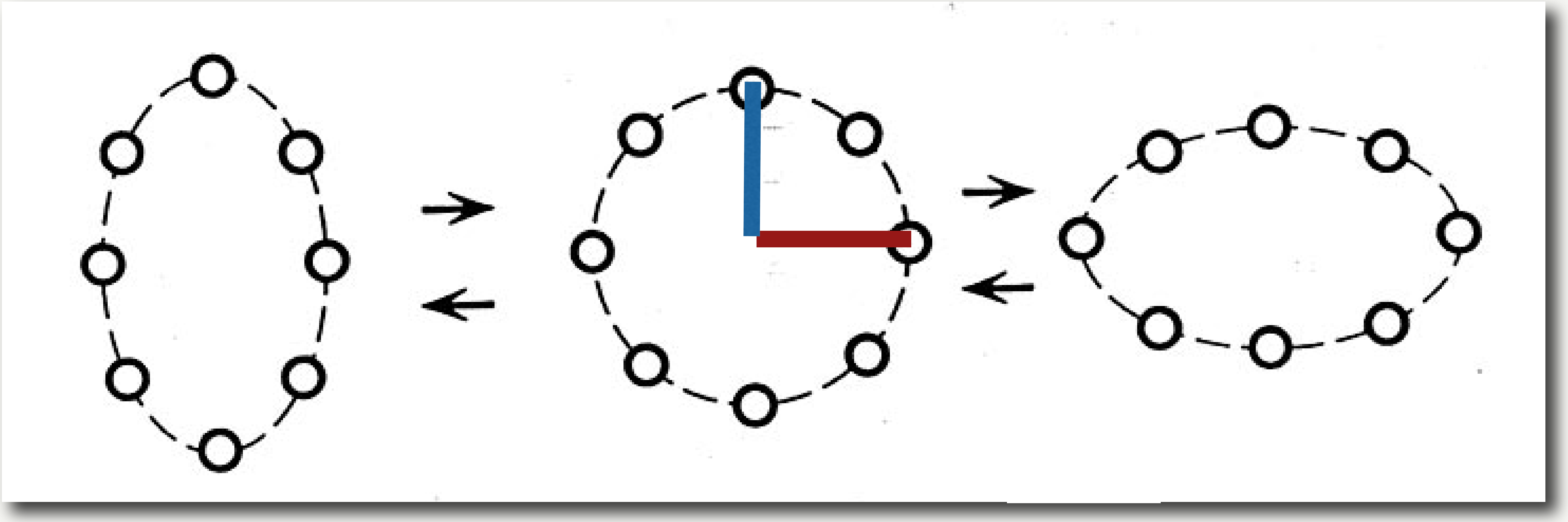
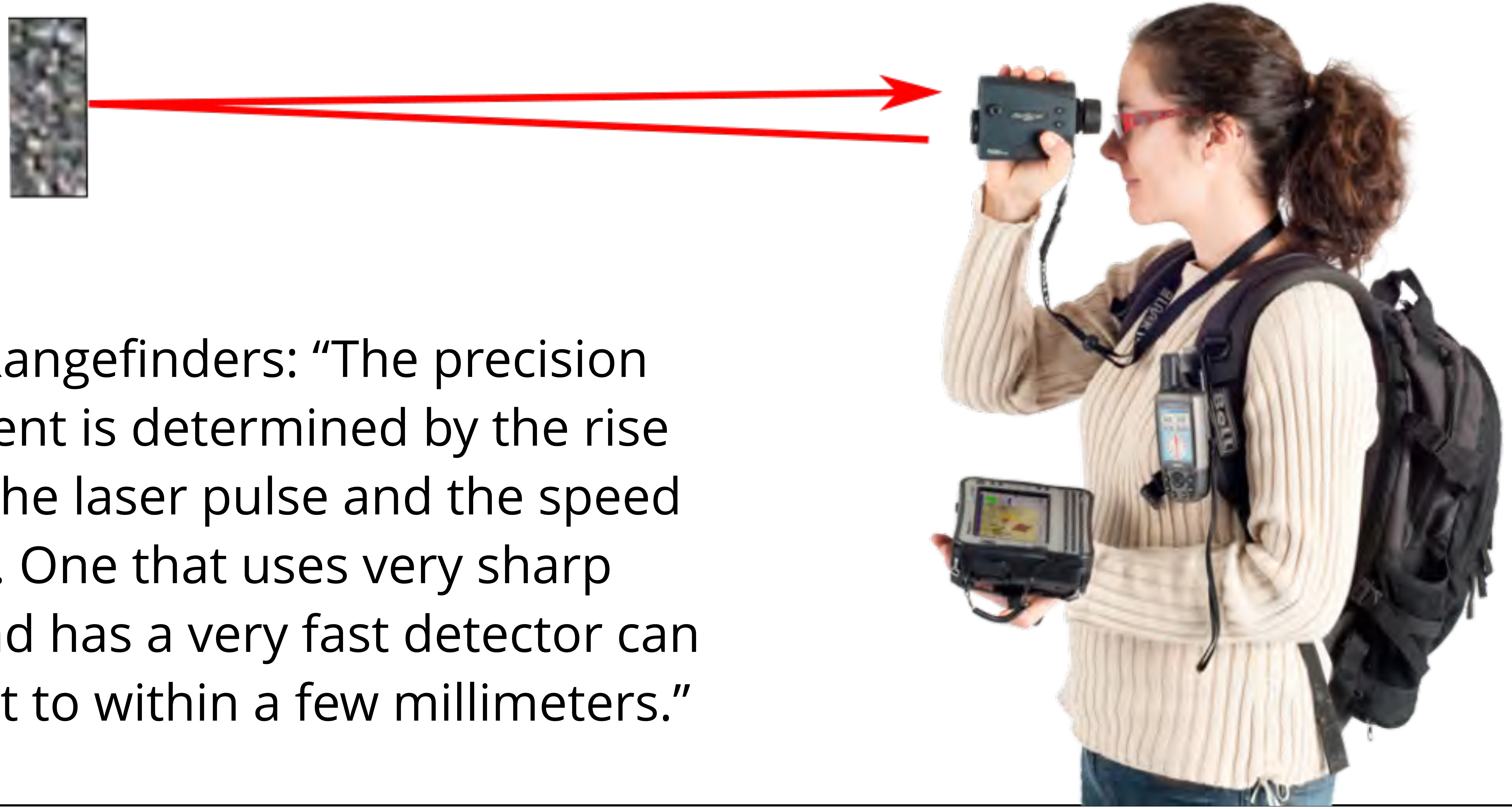


Gravitational waves change
the **distance** between objects.

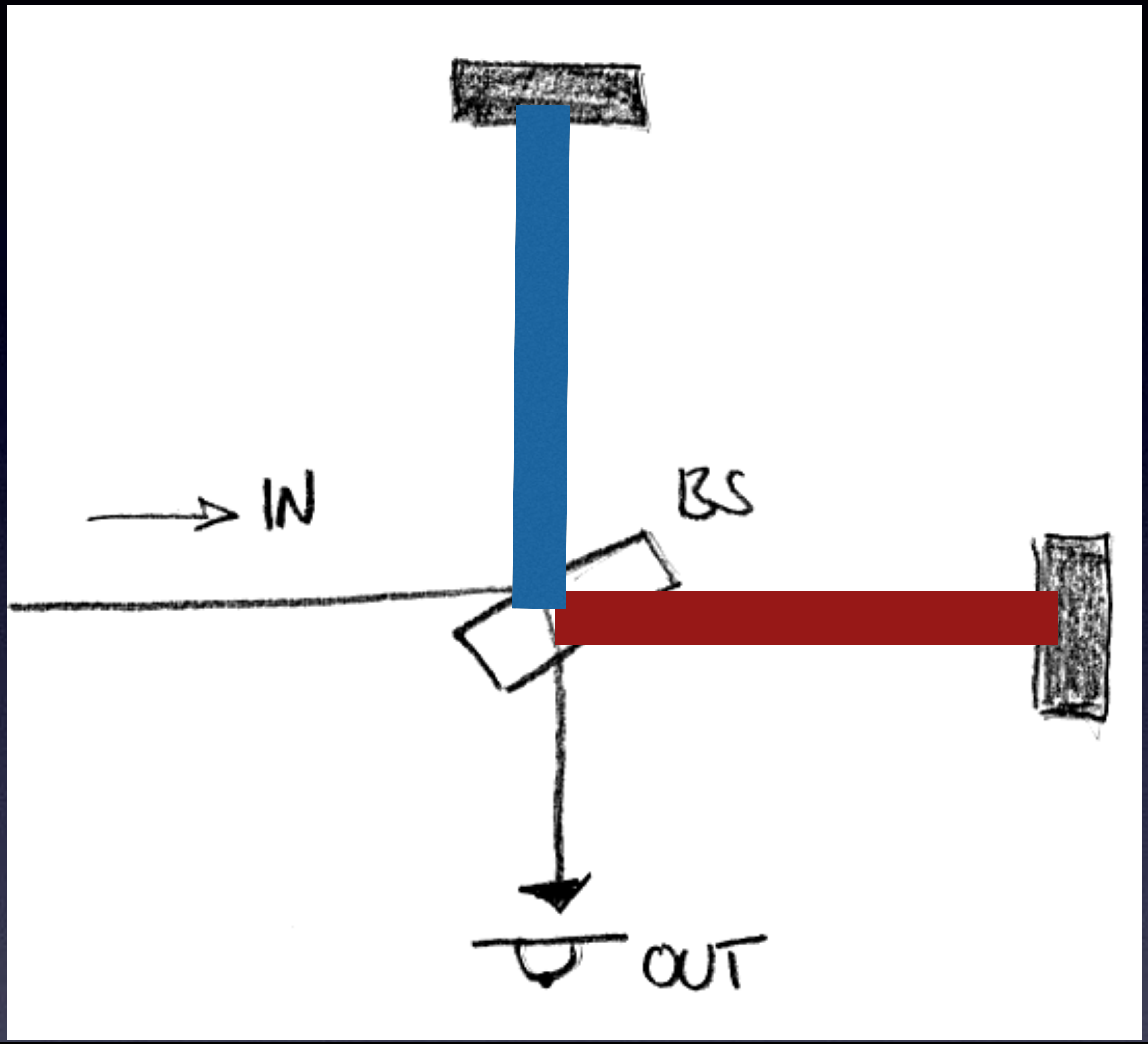
# Laser Rangefinder

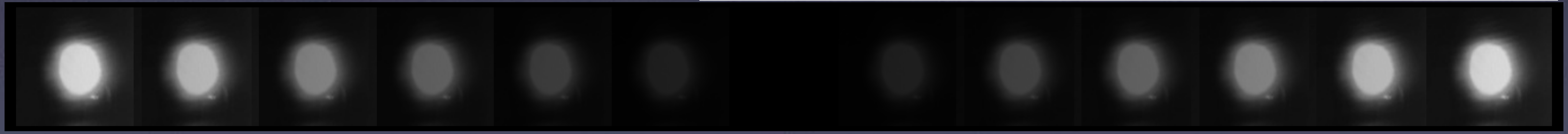


Wikipedia on Rangefinders: “The precision of the instrument is determined by the rise or fall time of the laser pulse and the speed of the receiver. One that uses very sharp laser pulses and has a very fast detector can range an object to within a few millimeters.”

# Length Measurement with Light

- Use a reference beam instead of a clock
- An interferometer compares two light beams
- Output becomes dark or bright when the light beams shift



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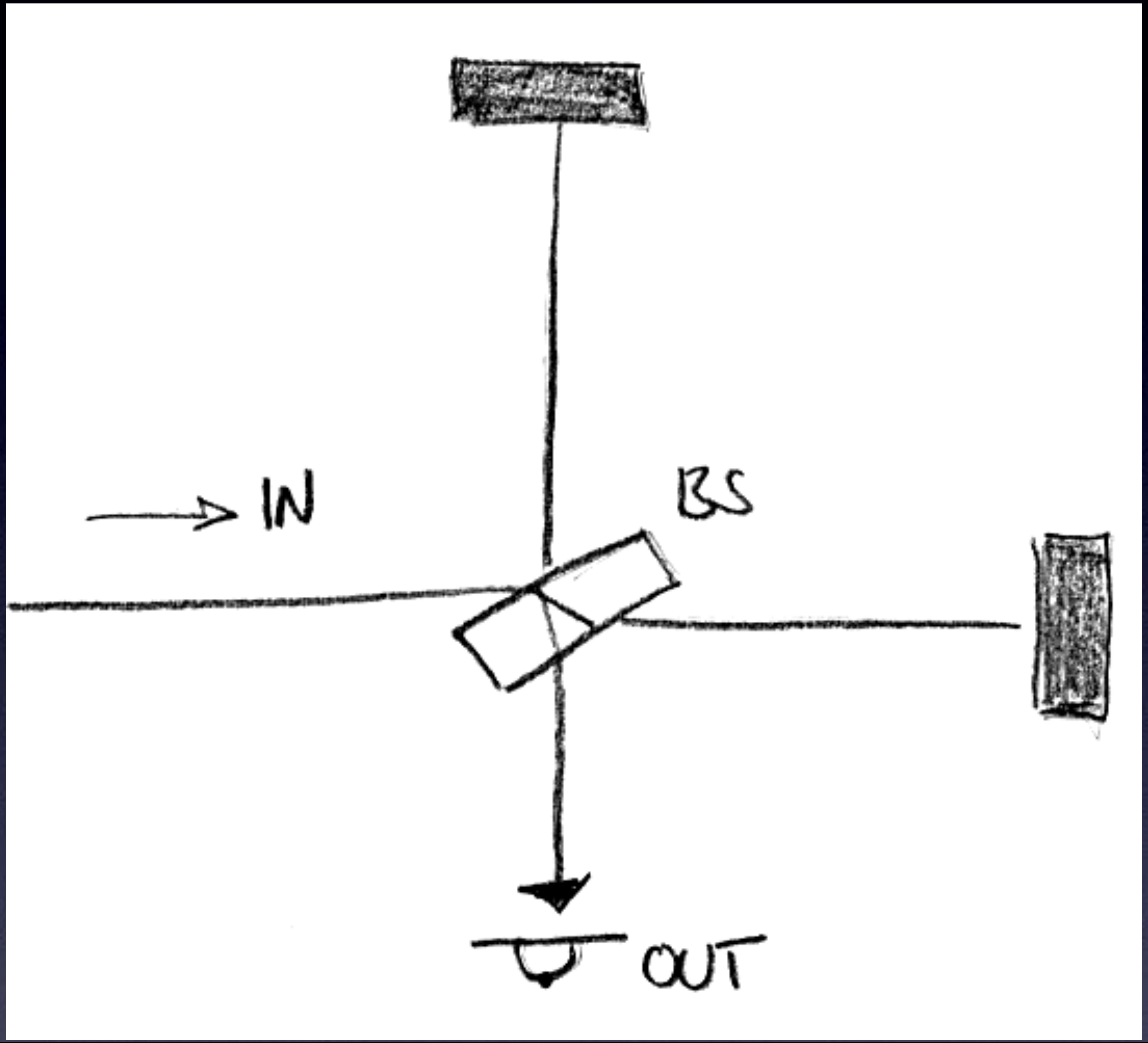
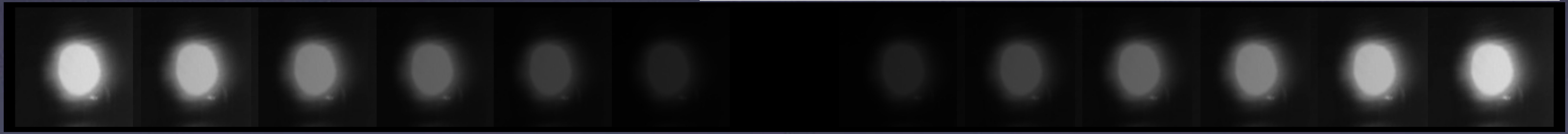
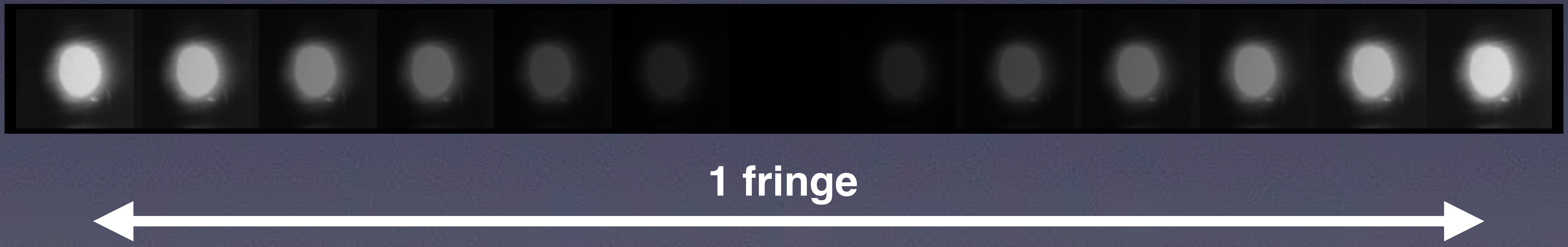


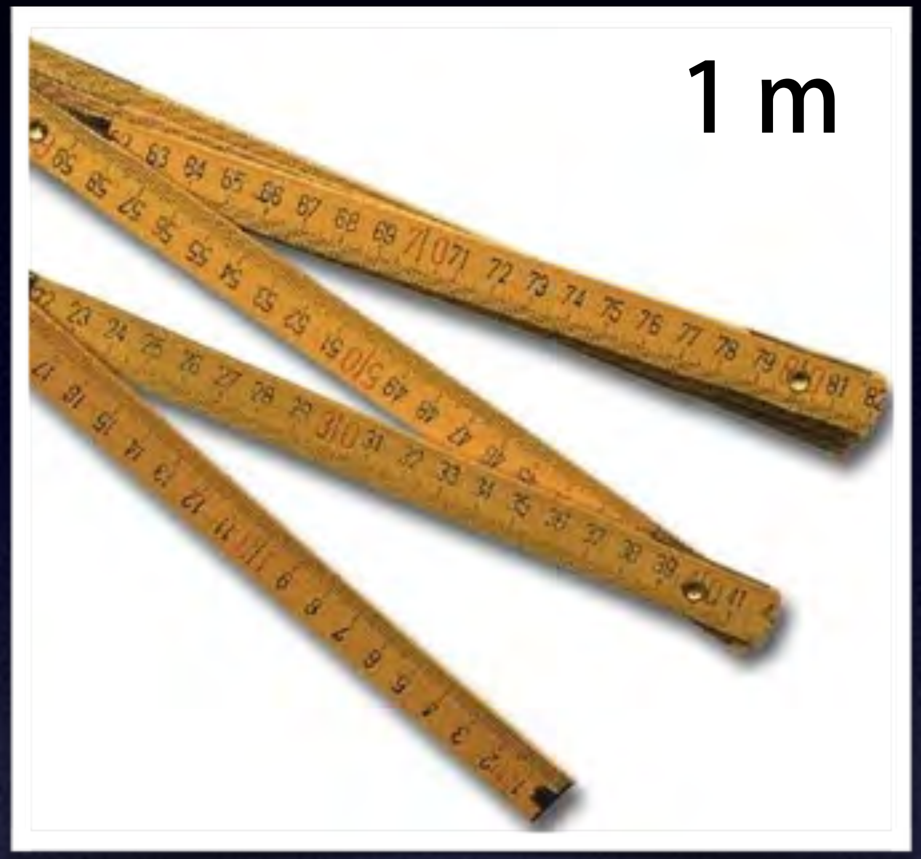
# Interferometry in 1887

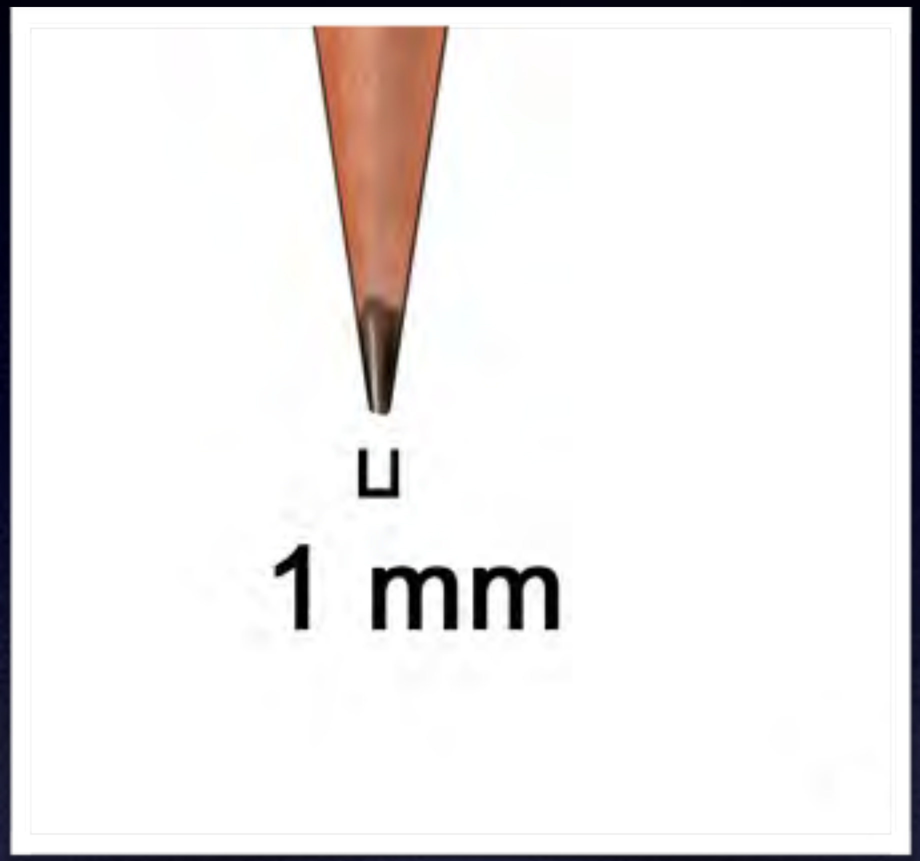
Michelson interferometer (ca. 1887)

Sensitivity: 0.01 of a fringe

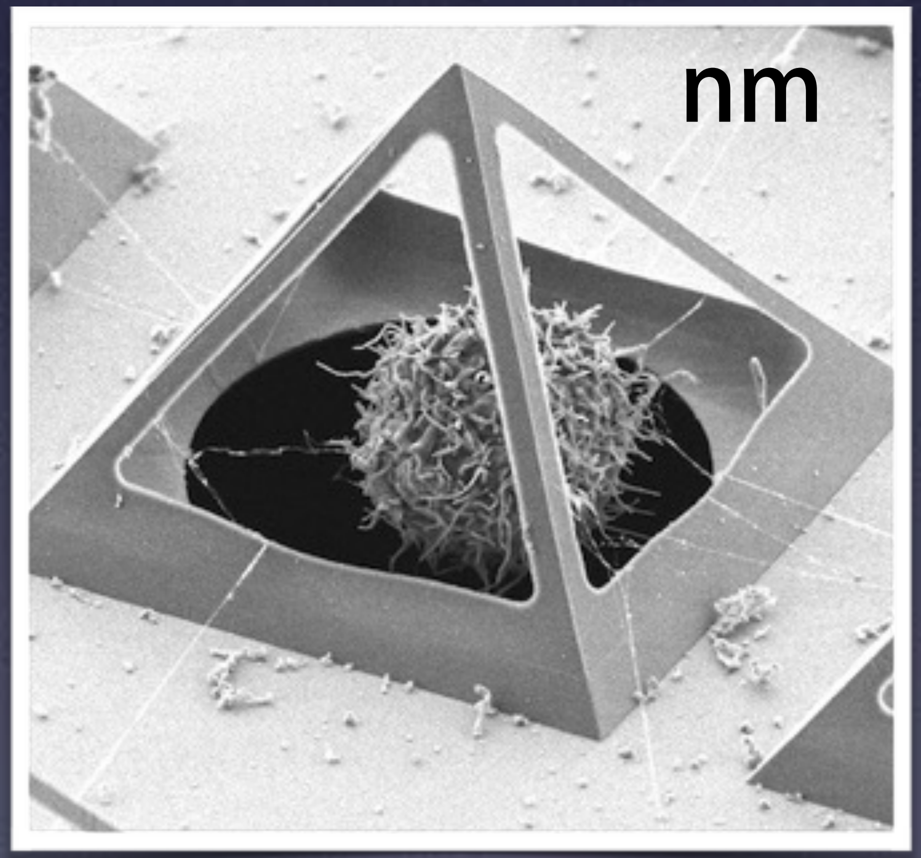


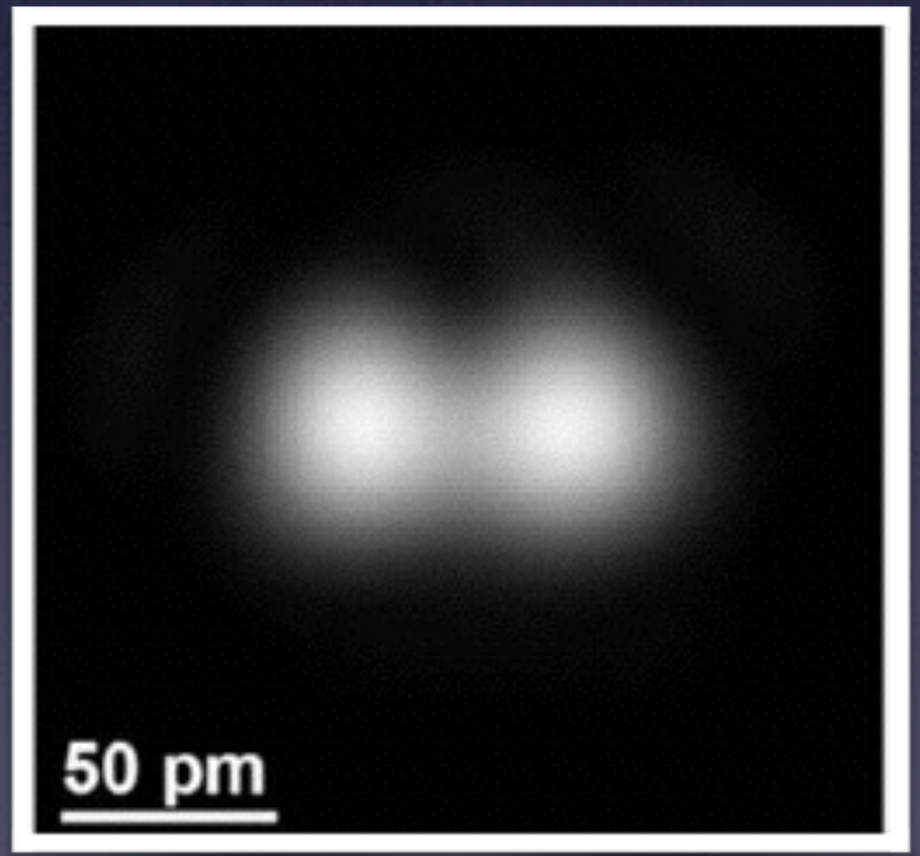
# Length Scales

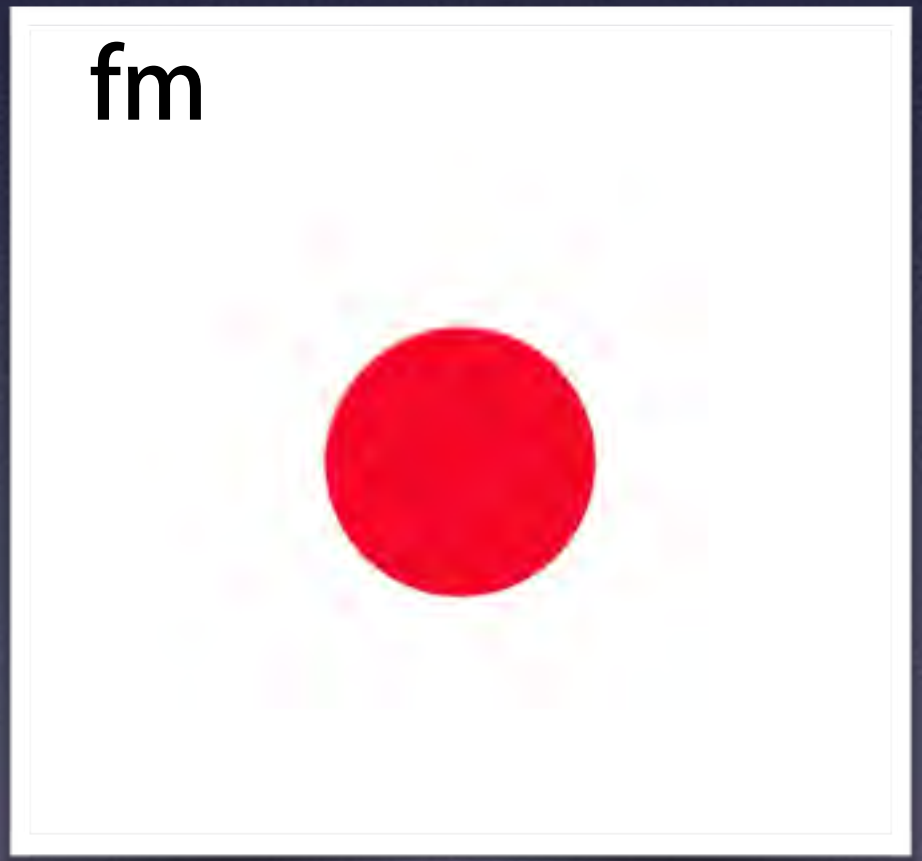


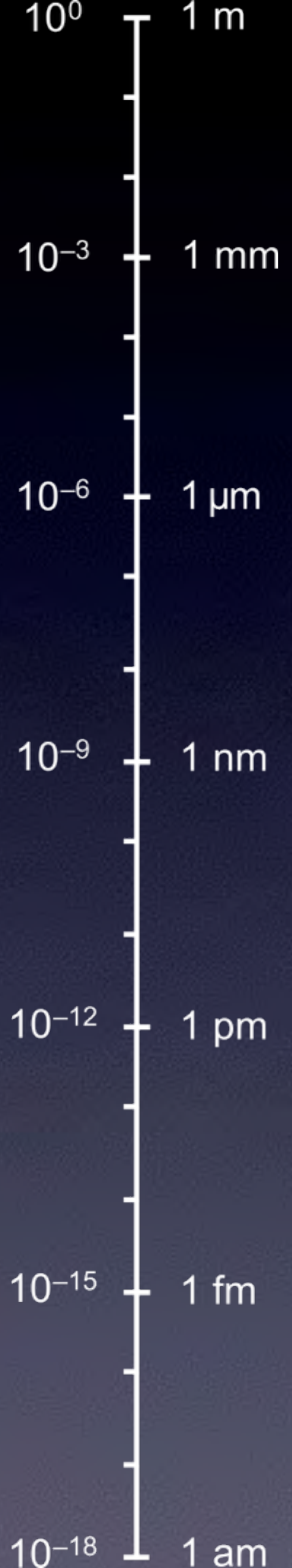







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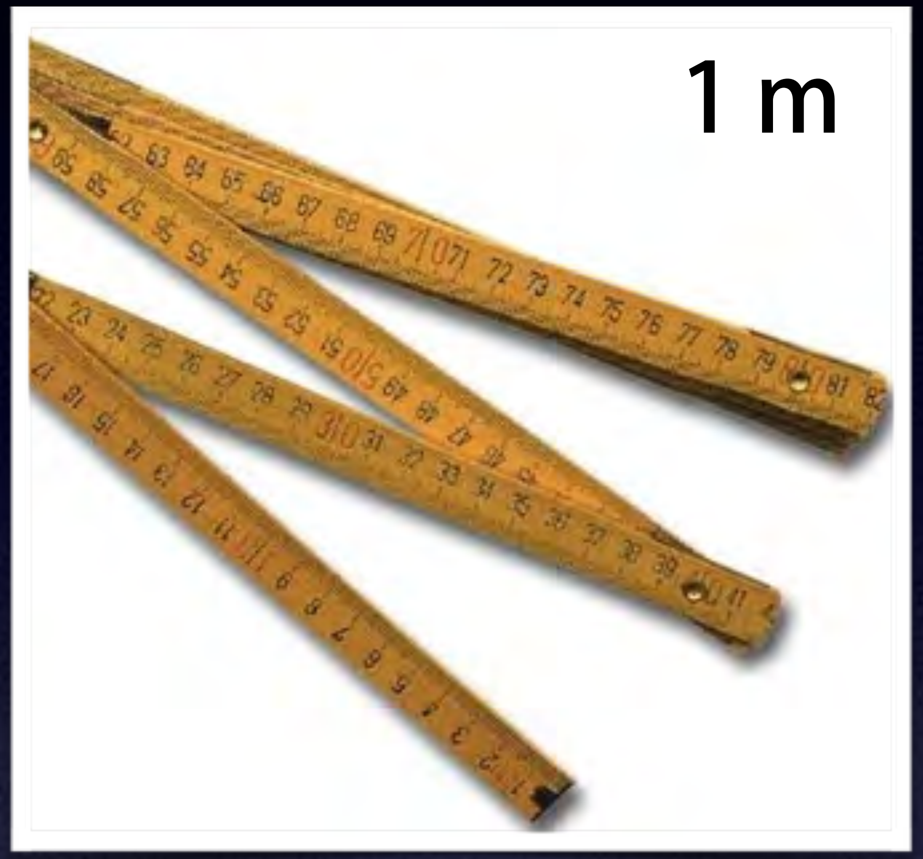


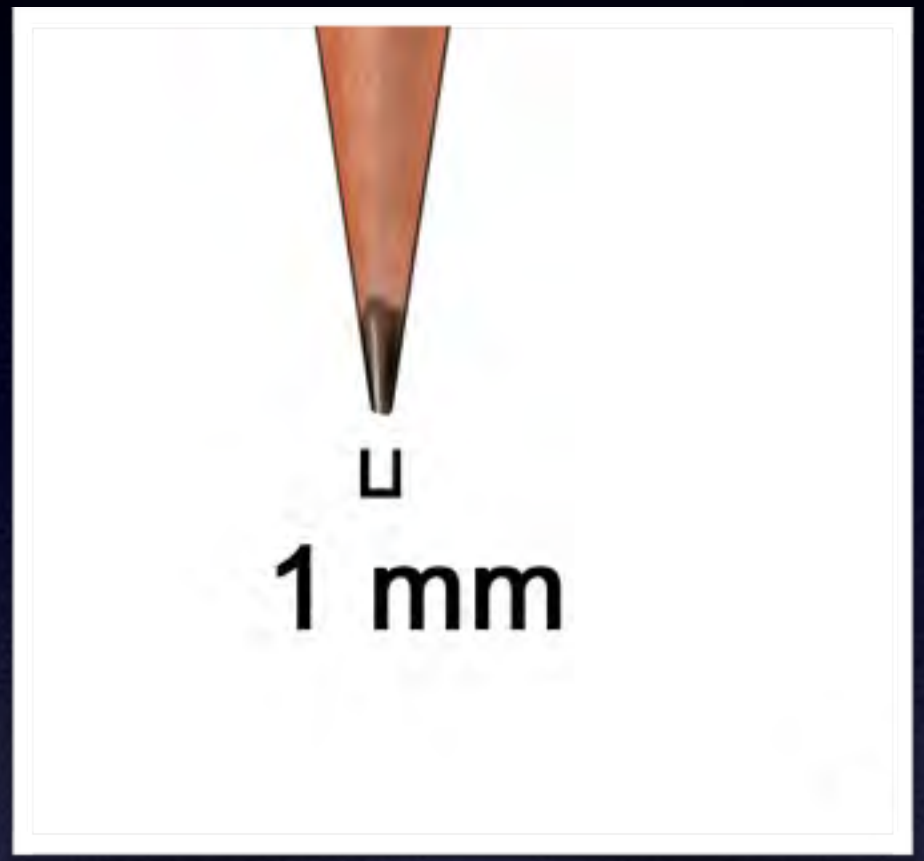



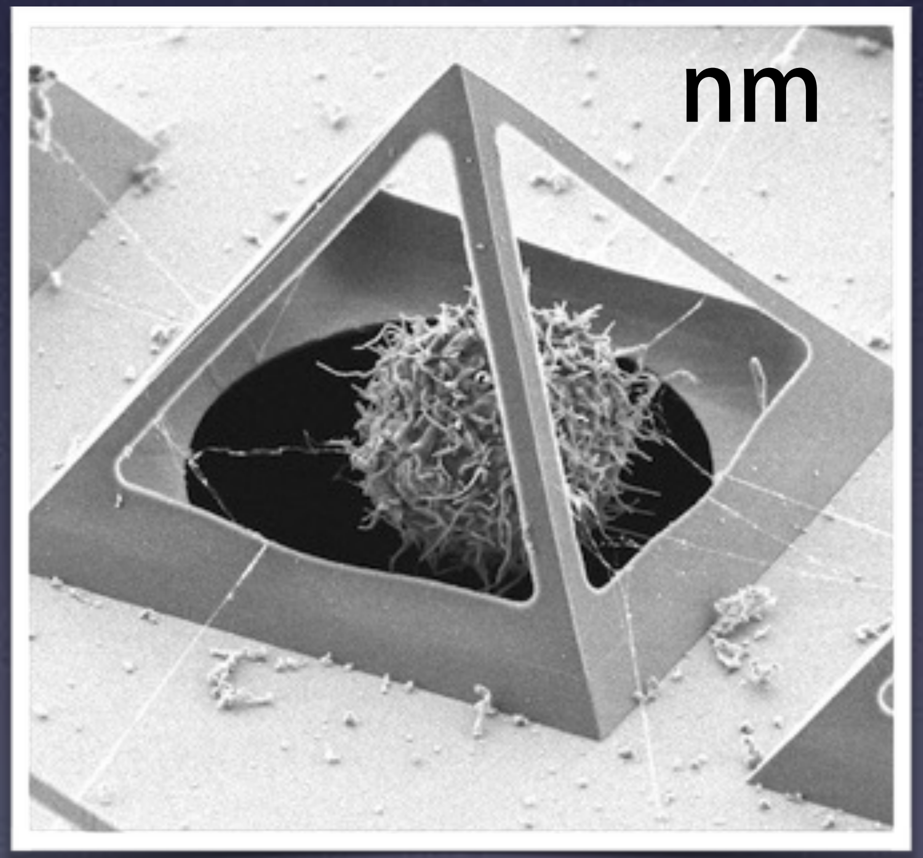


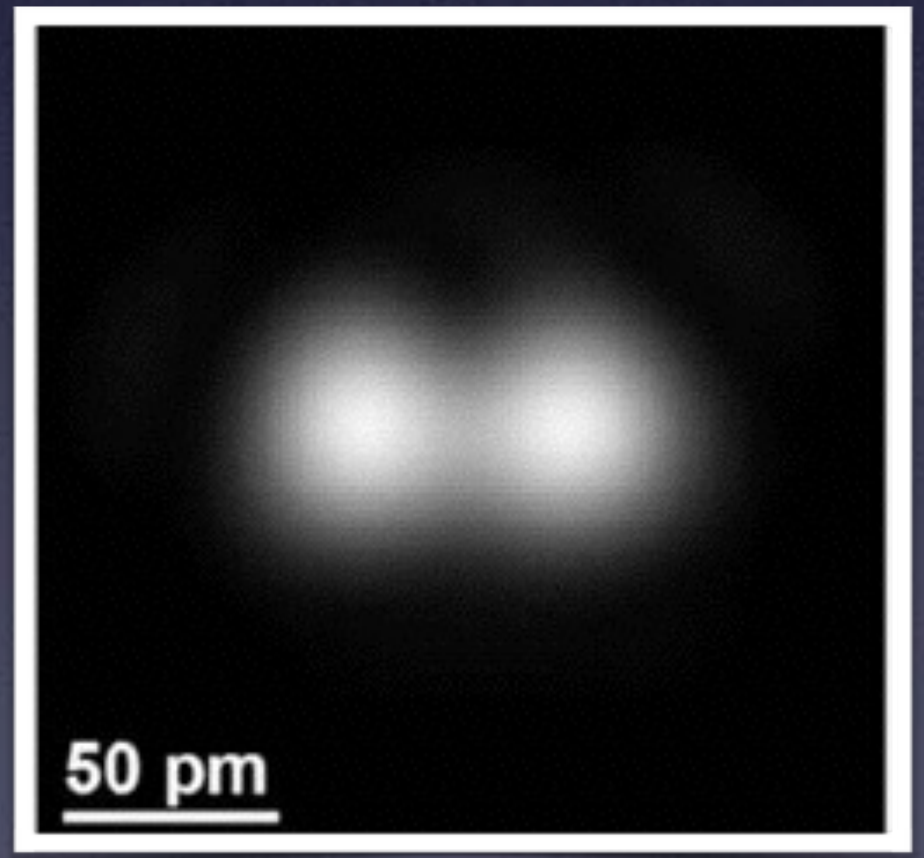



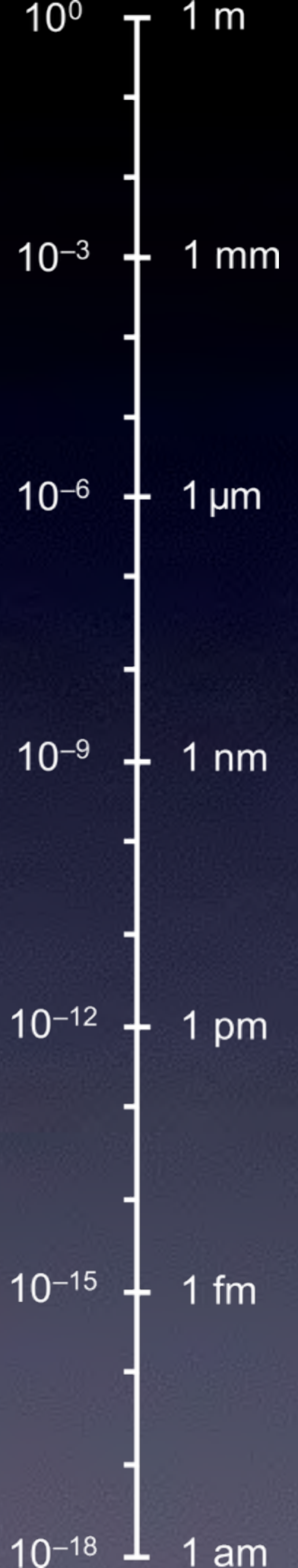

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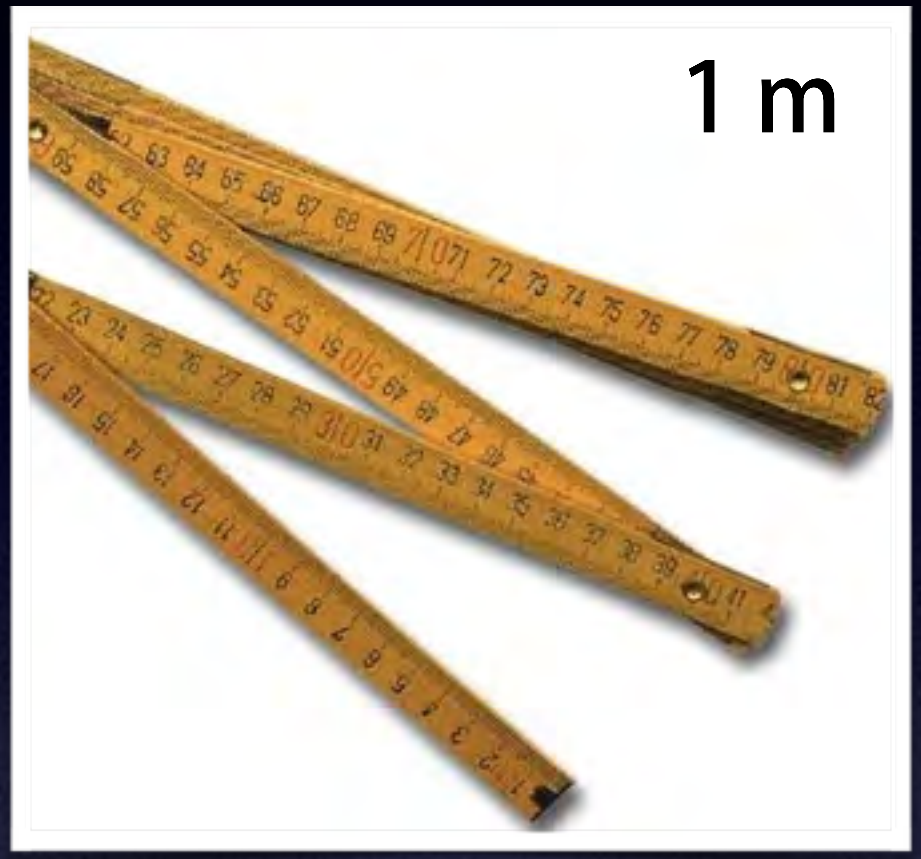
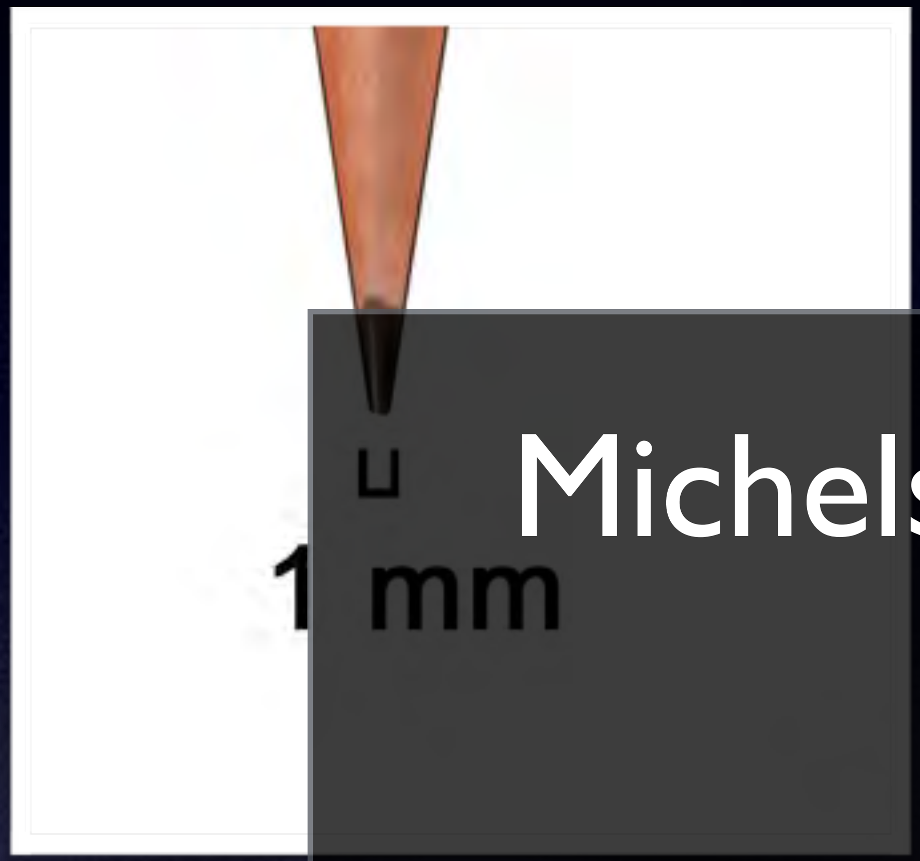
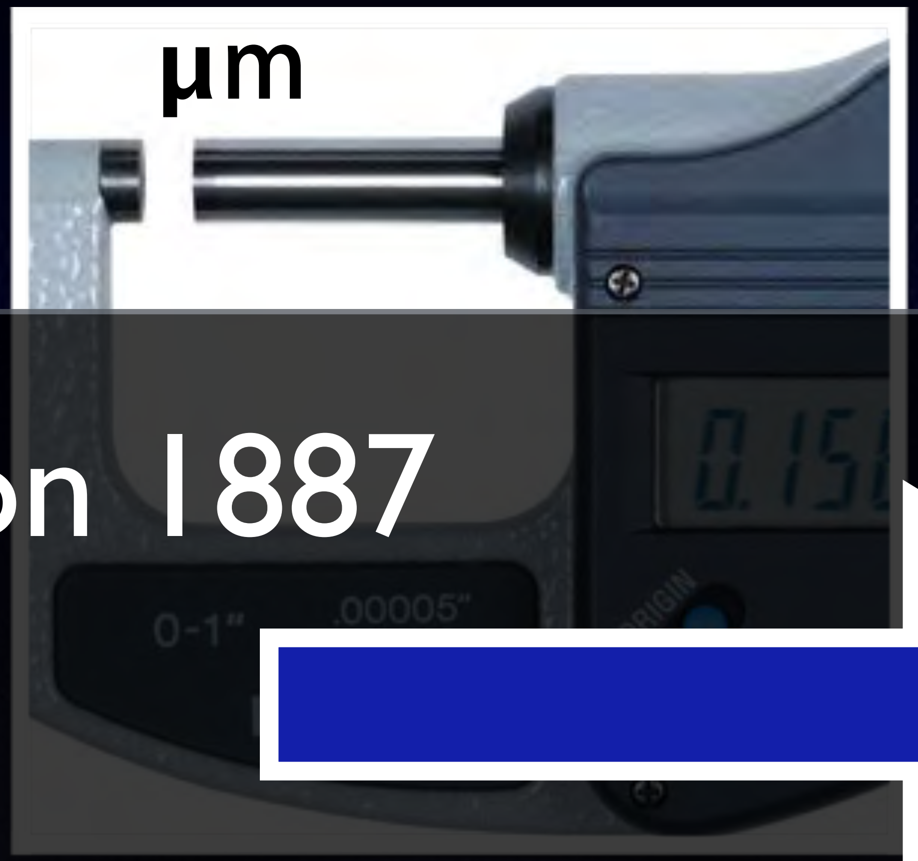
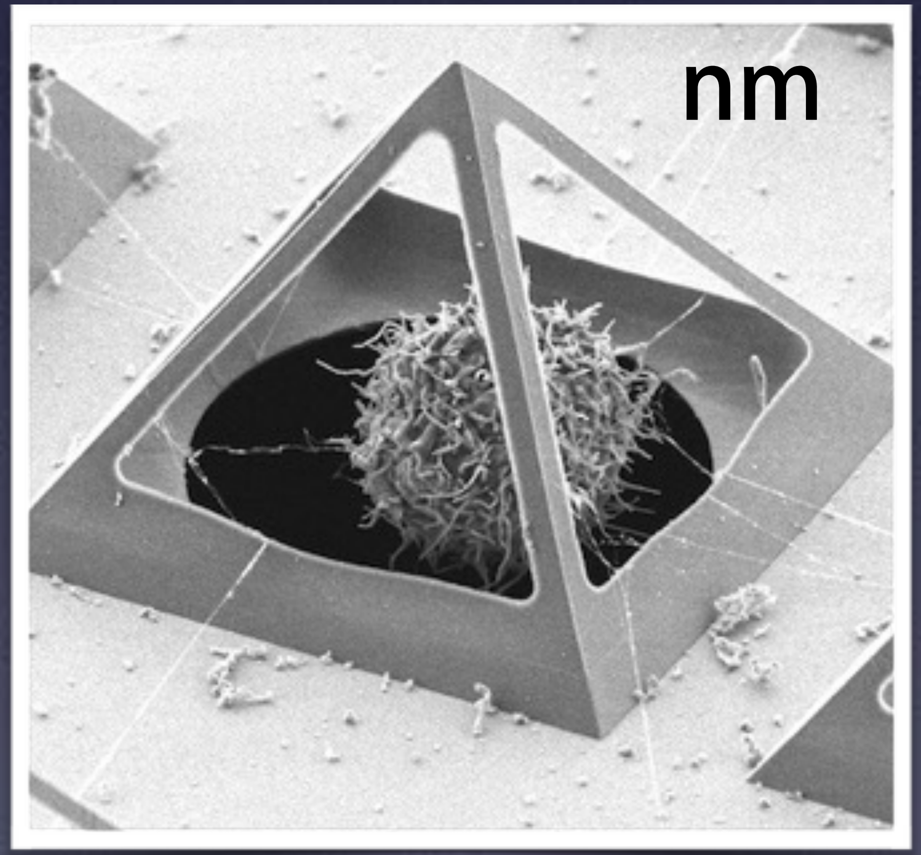
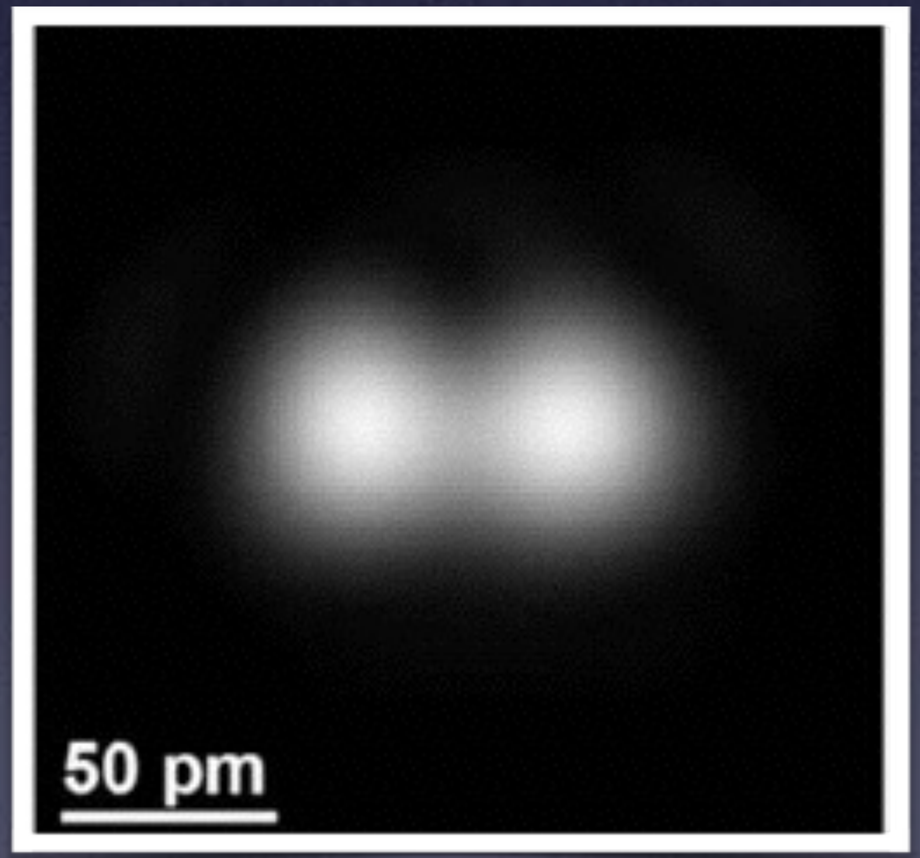


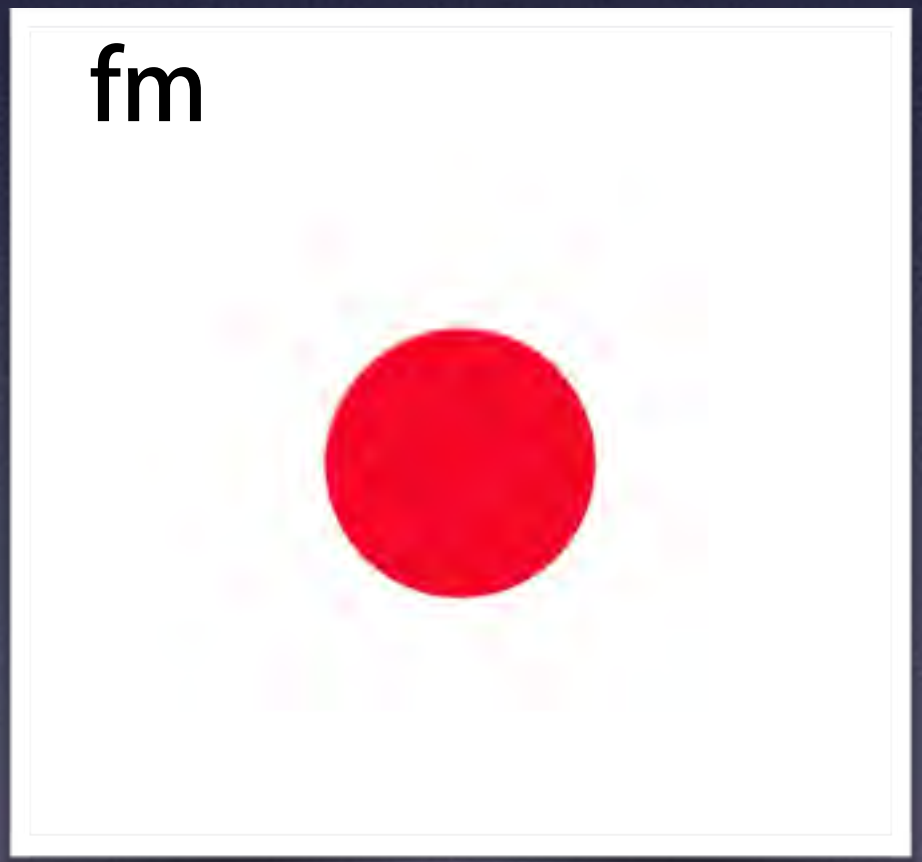



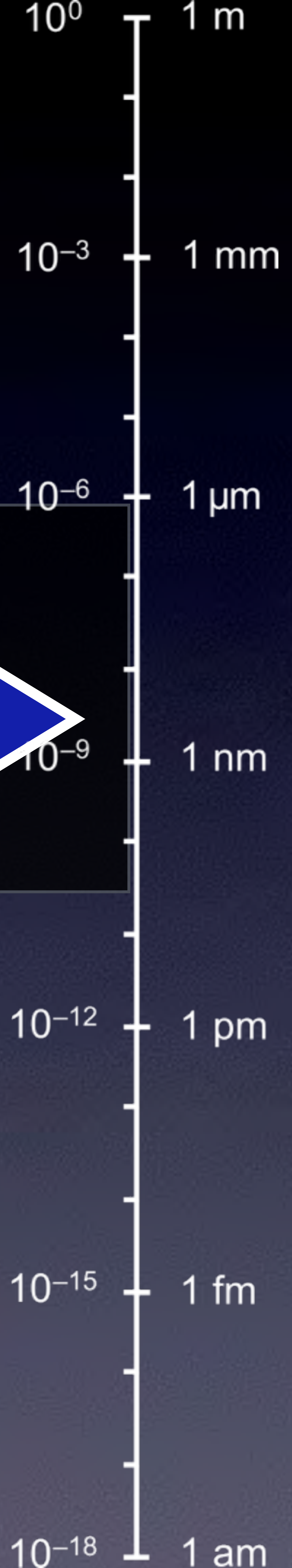




Michelson 1887



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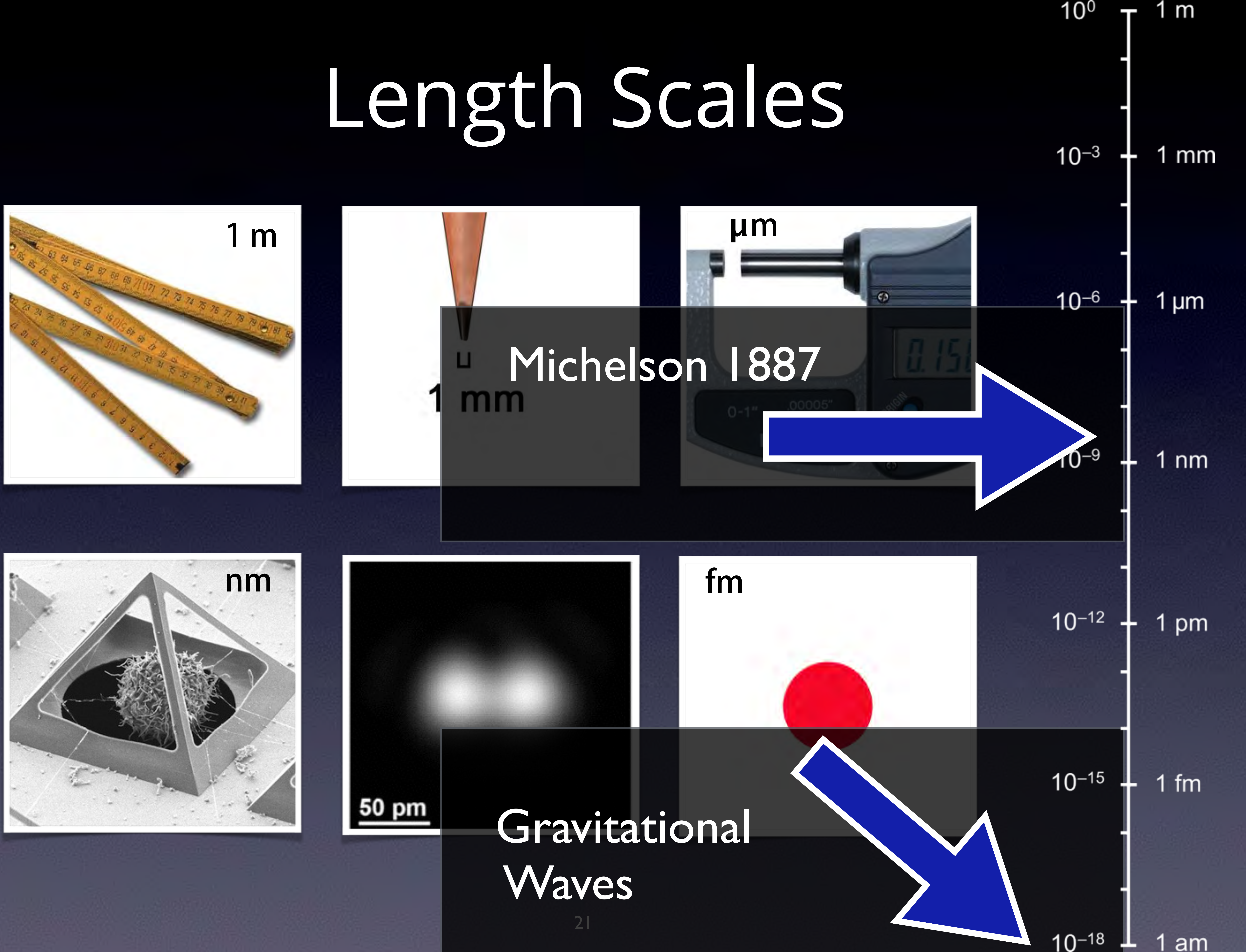
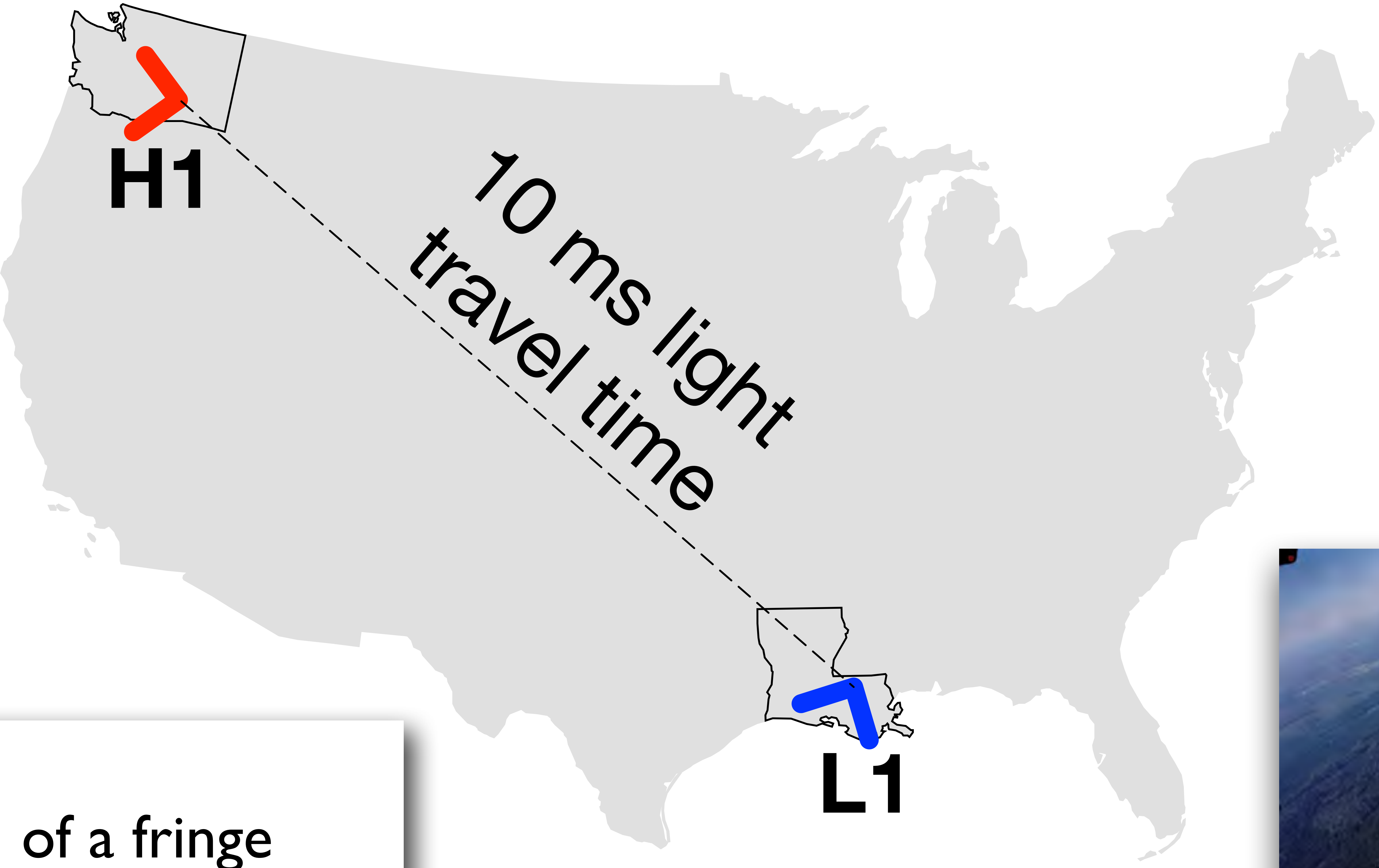


# Two LIGO Instruments




Sensitivity:
0.000 000 000 000 01 of a fringe
or $10^{-20}$ m

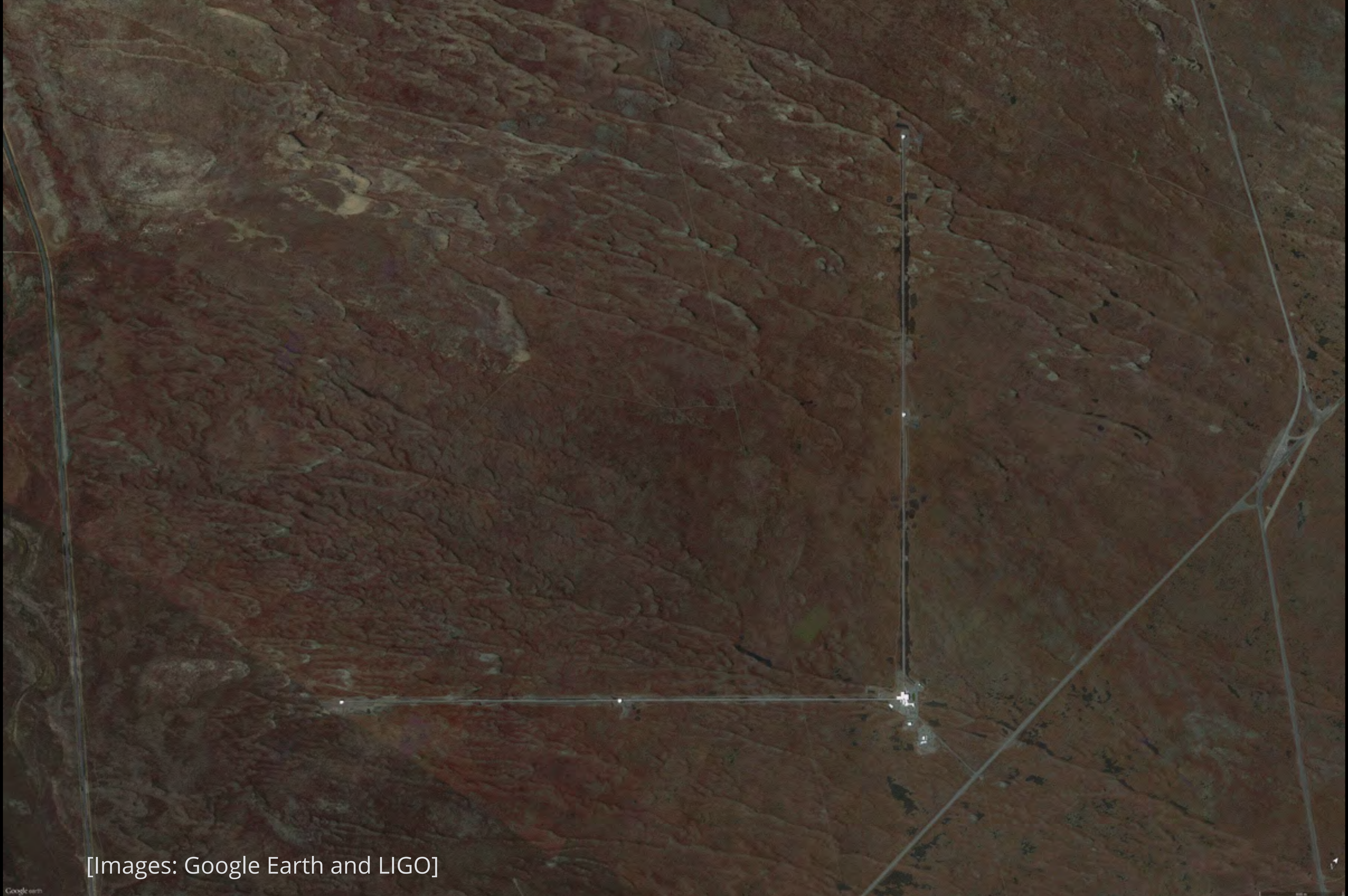
# LIGO

Laser Interferometer
Gravitational-Wave Observatory

Two large Michelson interferometers!

How does one instrument look like?

# LIGO Hanford Site



[Images: Google Earth and LIGO]

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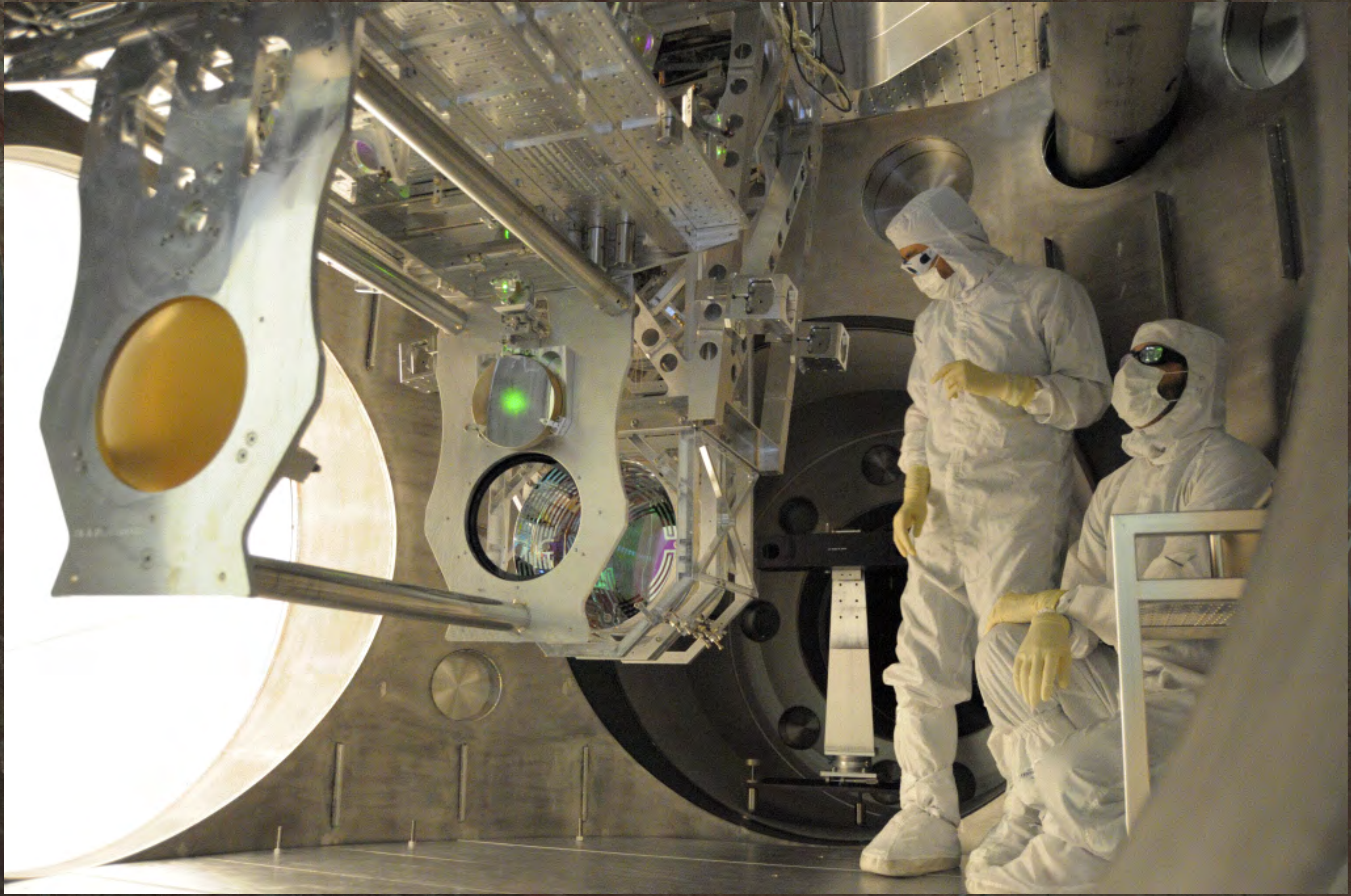
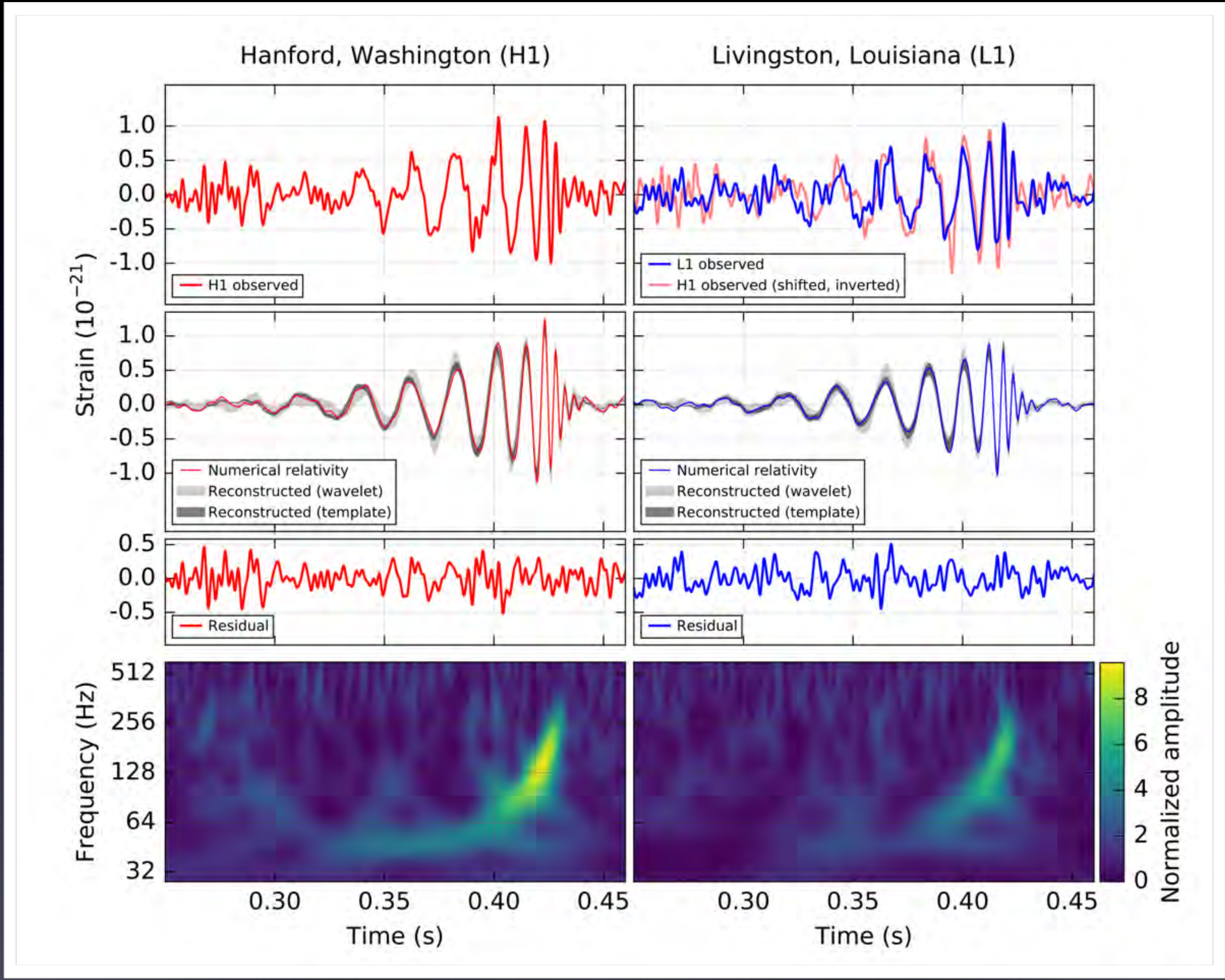


[Images: Google Earth and LIGO]

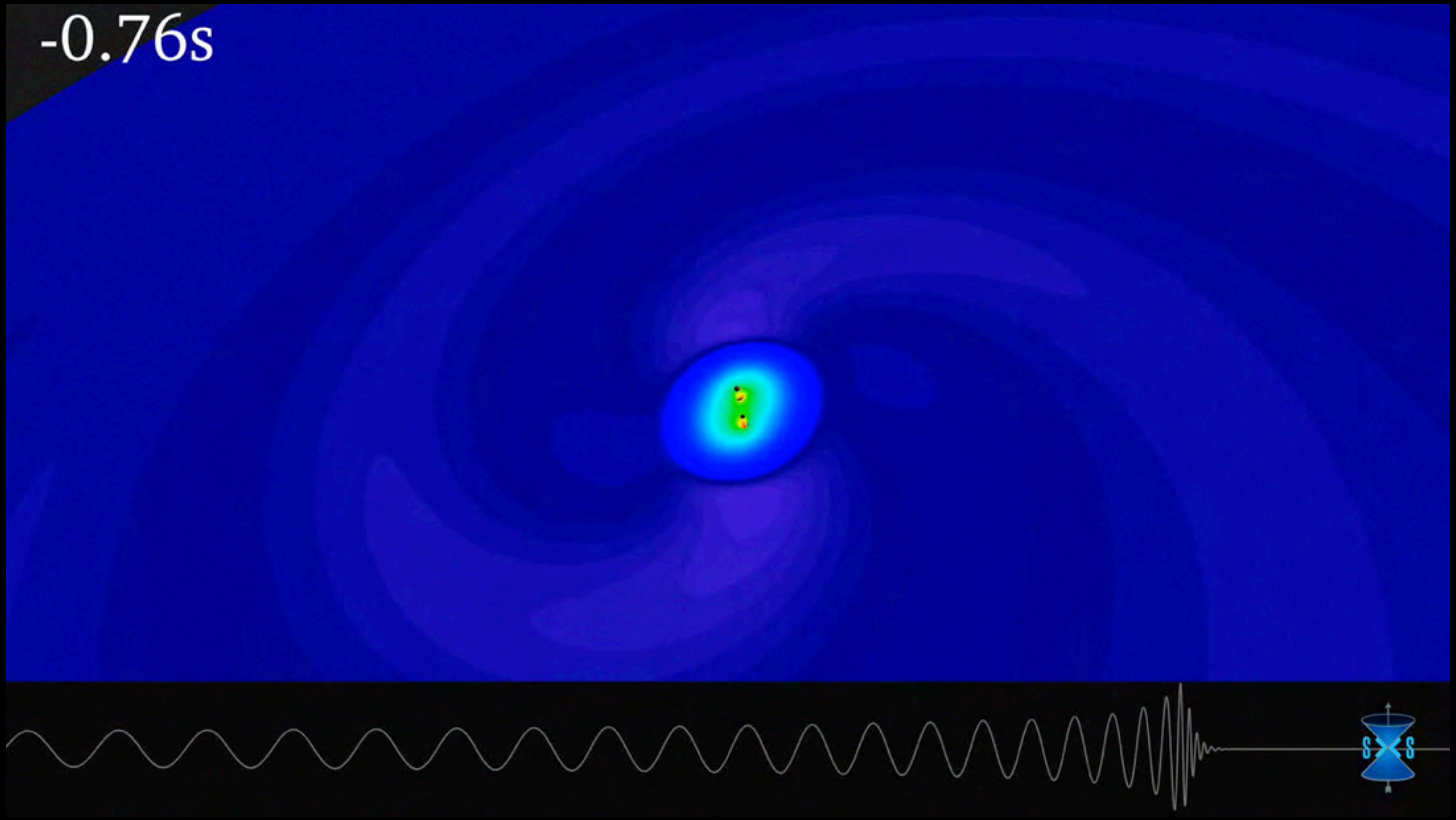
# 14.09.2015

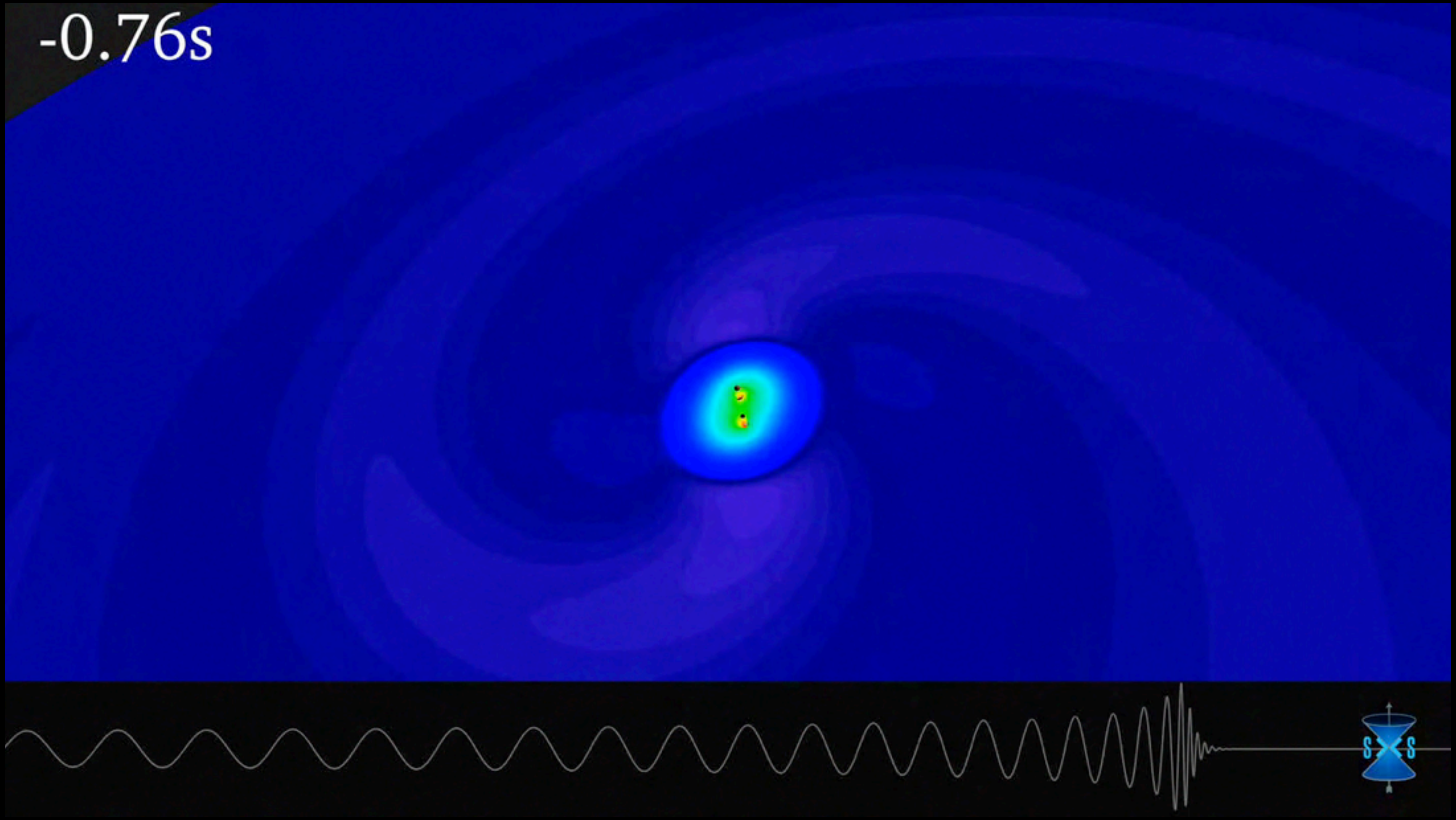
# First Detection of Gravitational Waves

# Data




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


-0.76s


-0.76s

# 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
- Last year the LIGO mirrors wiggled by $10^{-18}$ meters for 0.1 seconds

# Three Key Results

- **First direct detection of a gravitational wave,** confirmation of Einstein's prediction.
- Discovery of the first **binary black hole**.
- Strongest evidence so far that Nature's **black holes** are those described by **general relativity**.

**The start of a new era in astronomy!**

# Part 2

How to build such an amazingly
sensitive laser interferometer?

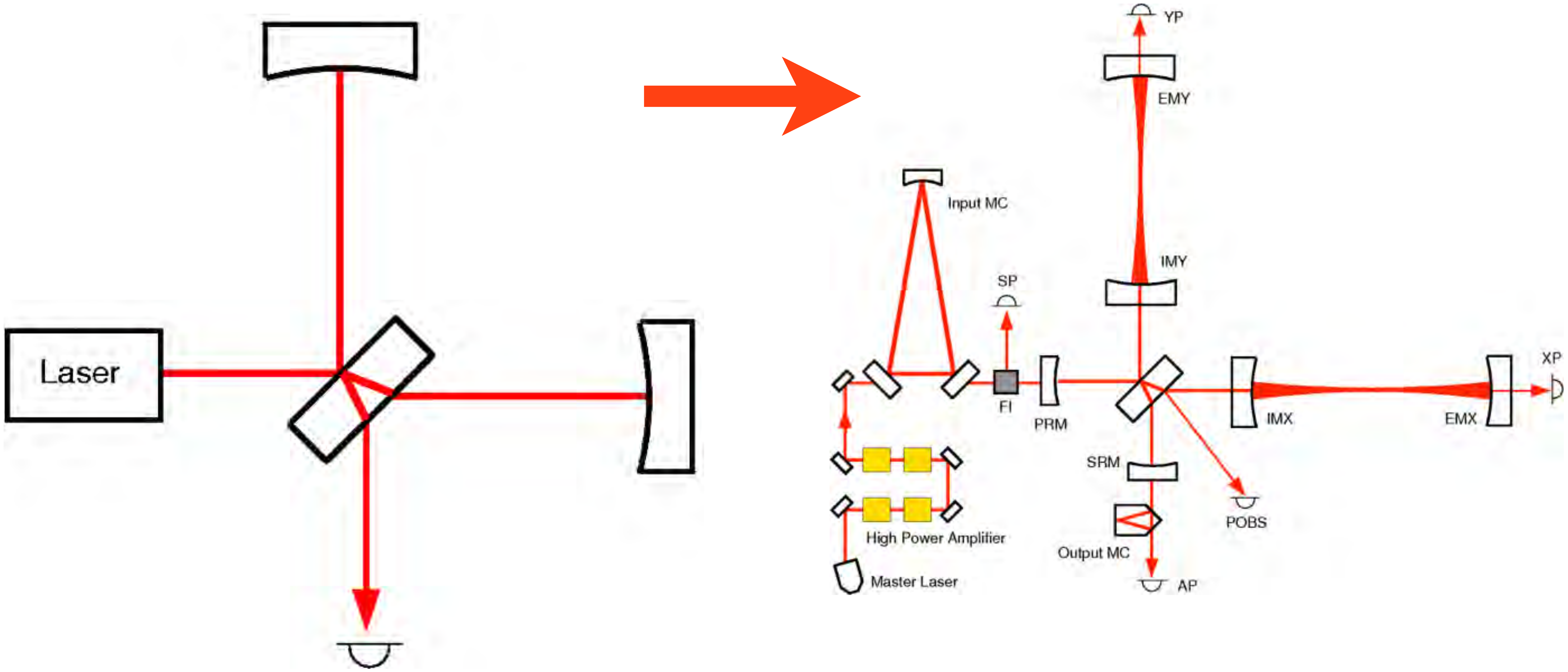
LIGO

# LIGO Scientific Collaboration

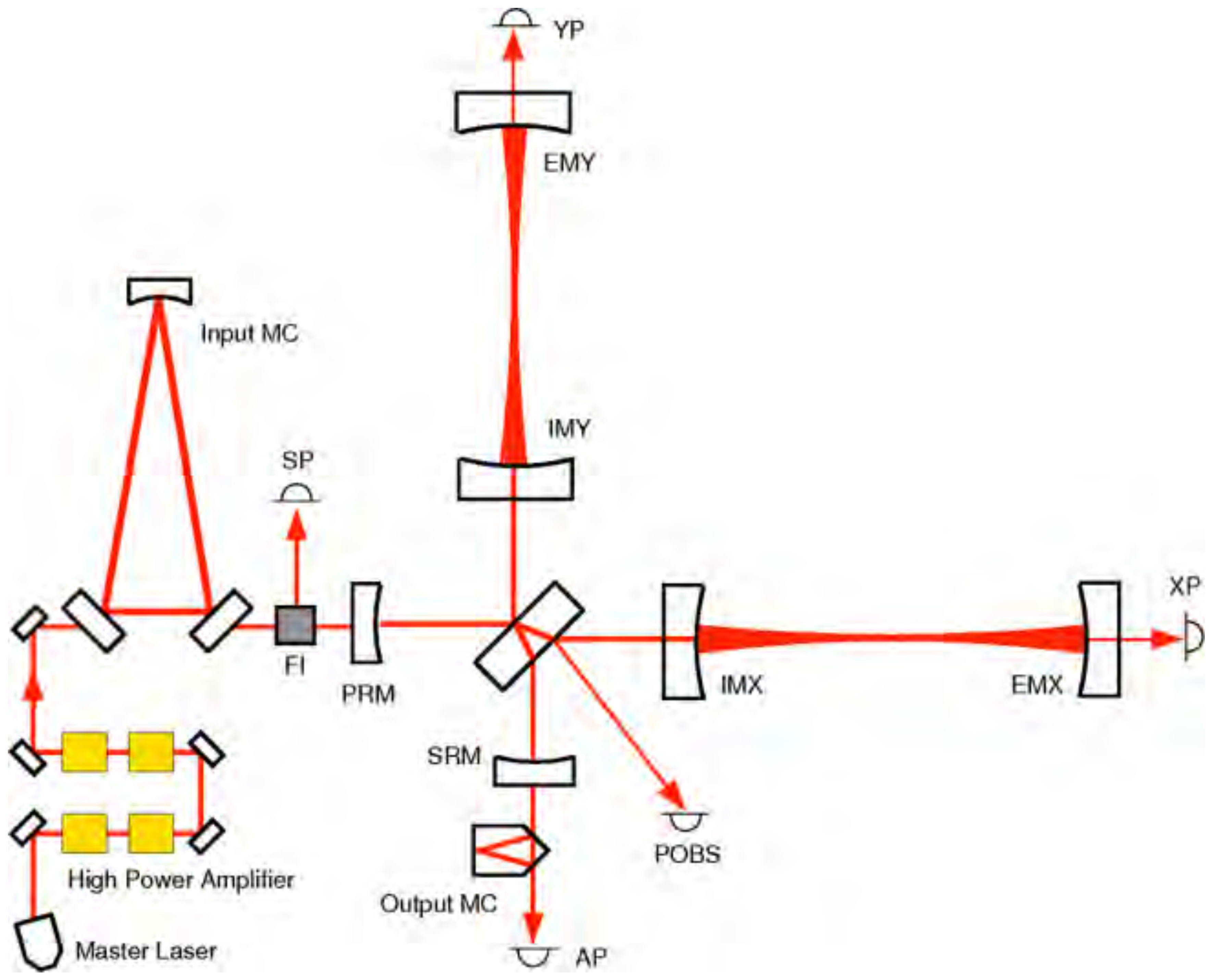
LSC

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
American University Washington, DC
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
University of the West of Scotland UWS
Texas Tech University
Tsinghua University
R·I·T
University of Strathclyde
Michigan
Max Planck Institute for Gravitational Physics Albert Einstein Institute
The University of Western Australia
CITA ICAT
Università degli Studi del Sannio
NASA Goddard Space Flight Center
University of Cambridge
ICTP SAIFR
The University of Chicago
Montana State University
ACU
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
Caltech
University of Minnesota
The University of Mississippi
The University of Adelaide Australia
University of Birmingham
The University of Melbourne
Universitat de les Illes Balears
University of Washington
UTRGV
University of Wisconsin Milwaukee
Northwestern
Cardiff University Prifysgol Caerdydd
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Science & Technology Facilities Council Rutherford Appleton Laboratory

# Advanced Interferometry



# What Makes it Better?




- GW effect scales with arm length: large detectors
- Optical signal scales with light power: high-power laser, optical cavities
- Laser beam fluctuations make noise: filter cavities

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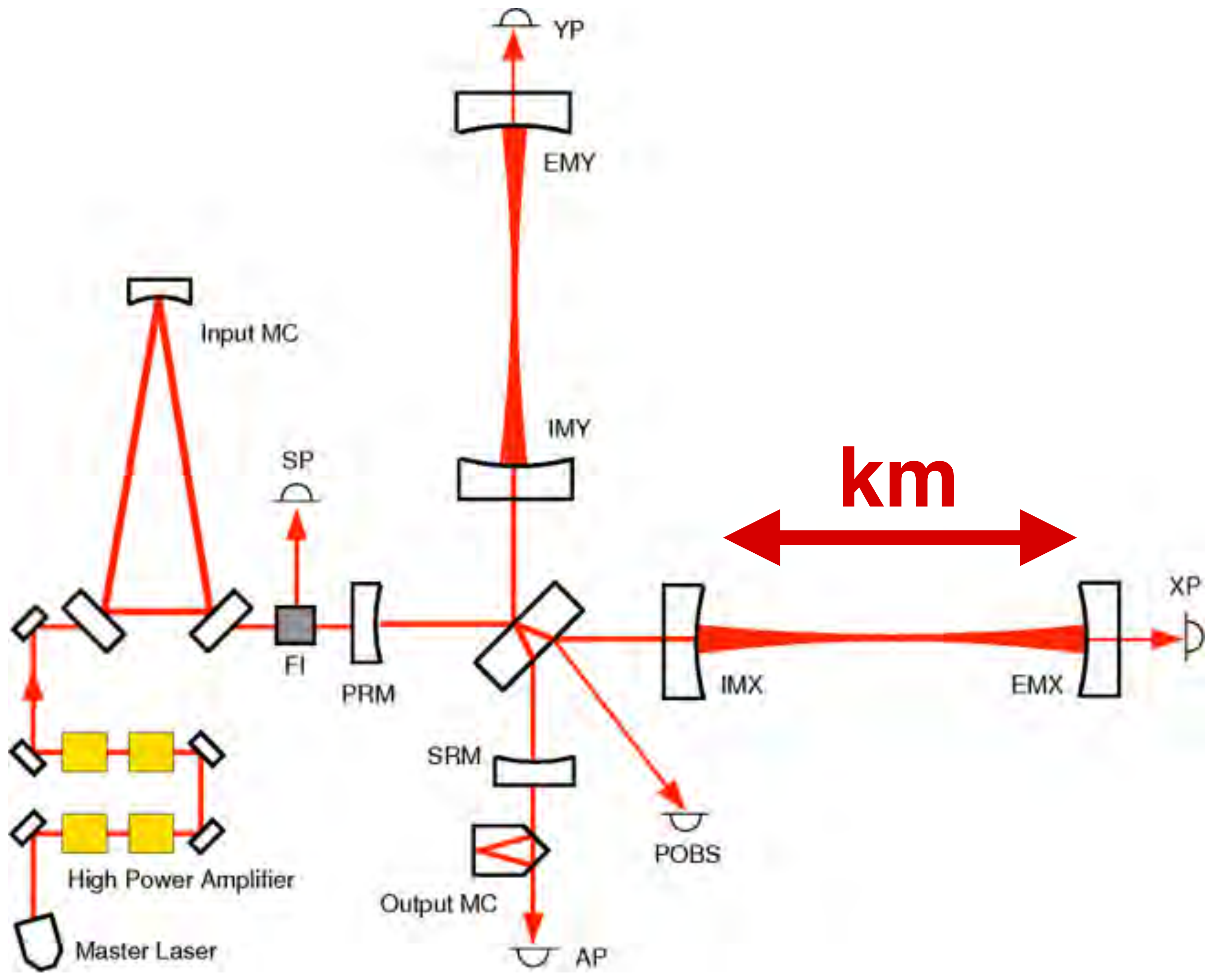


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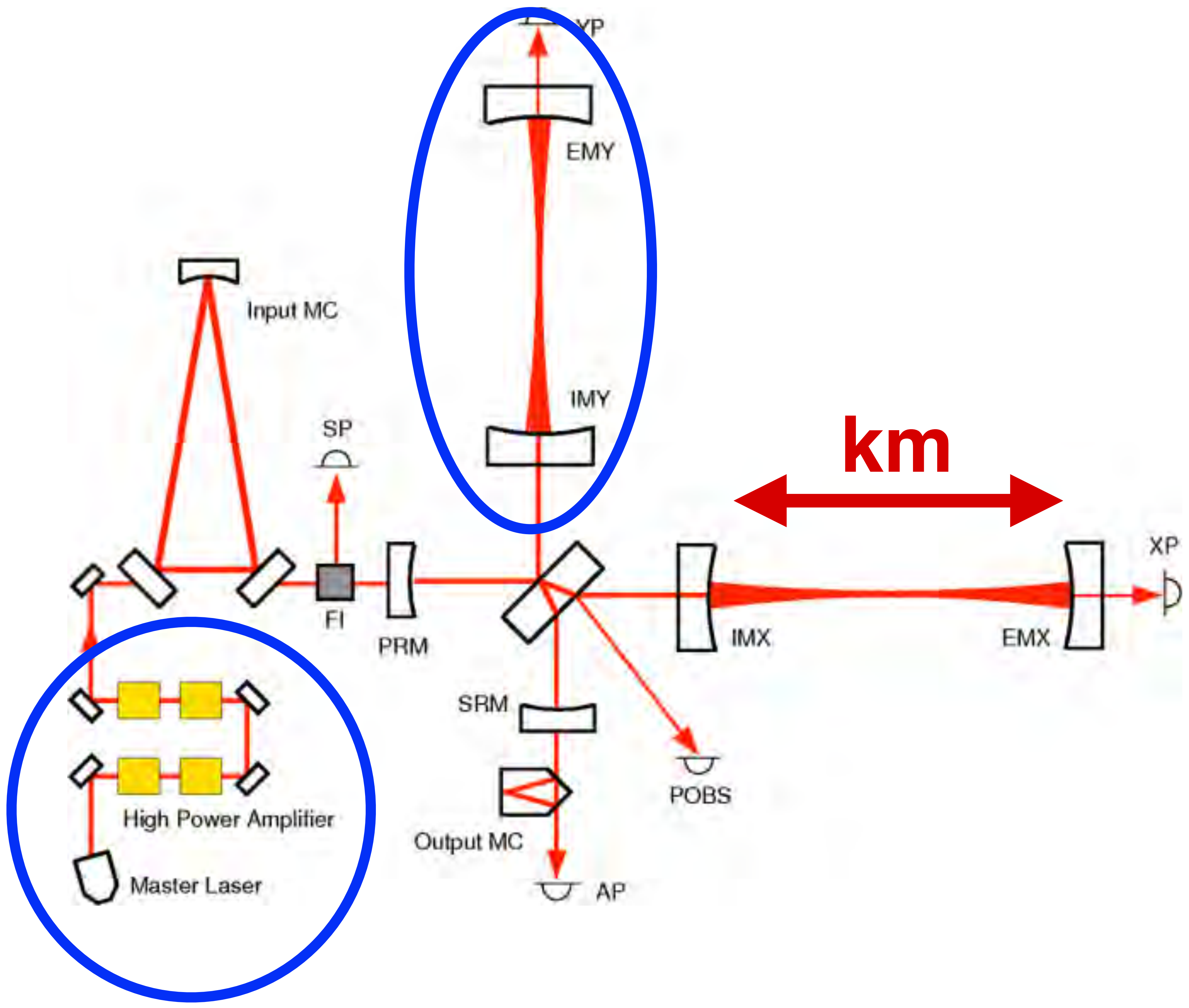


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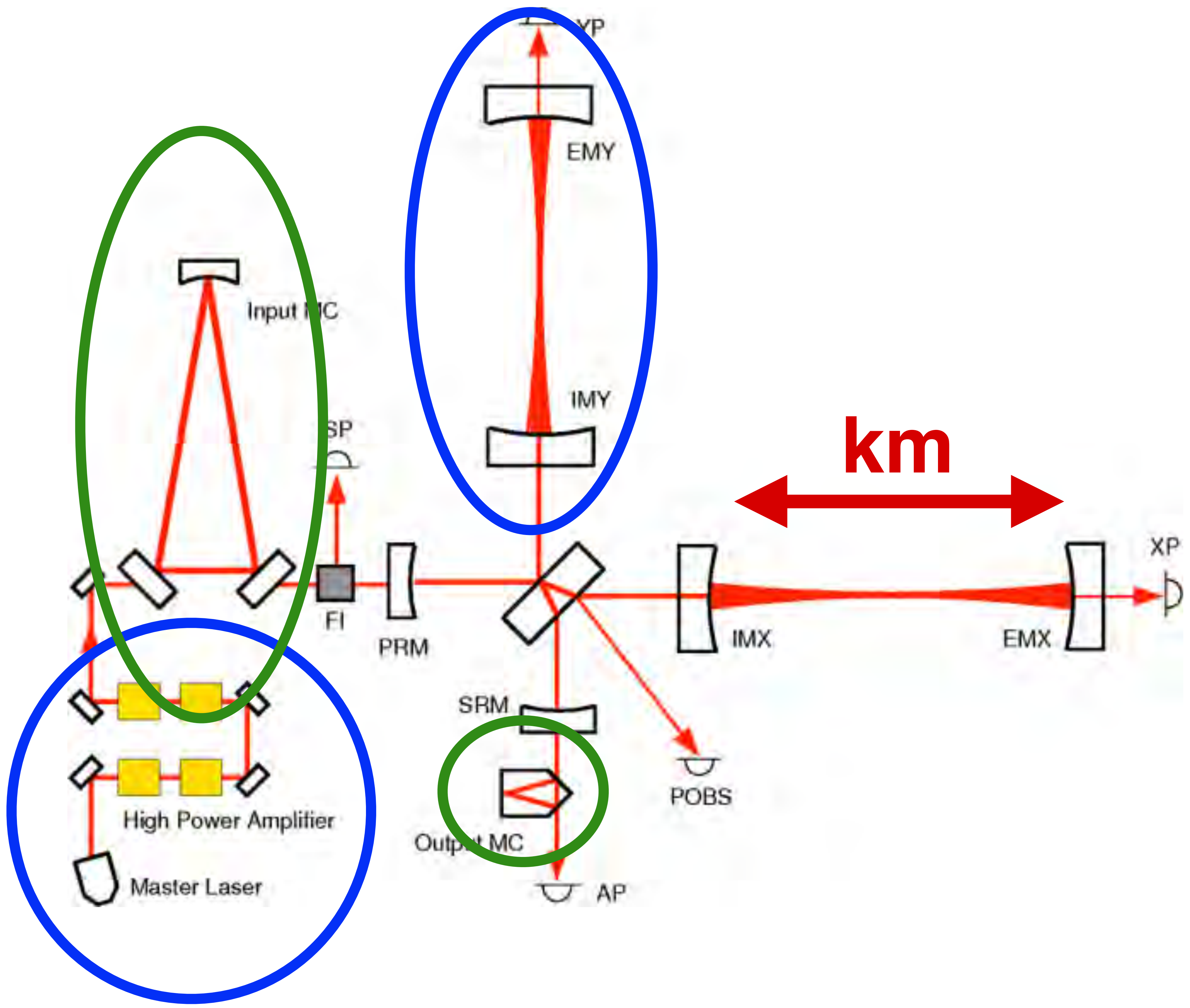


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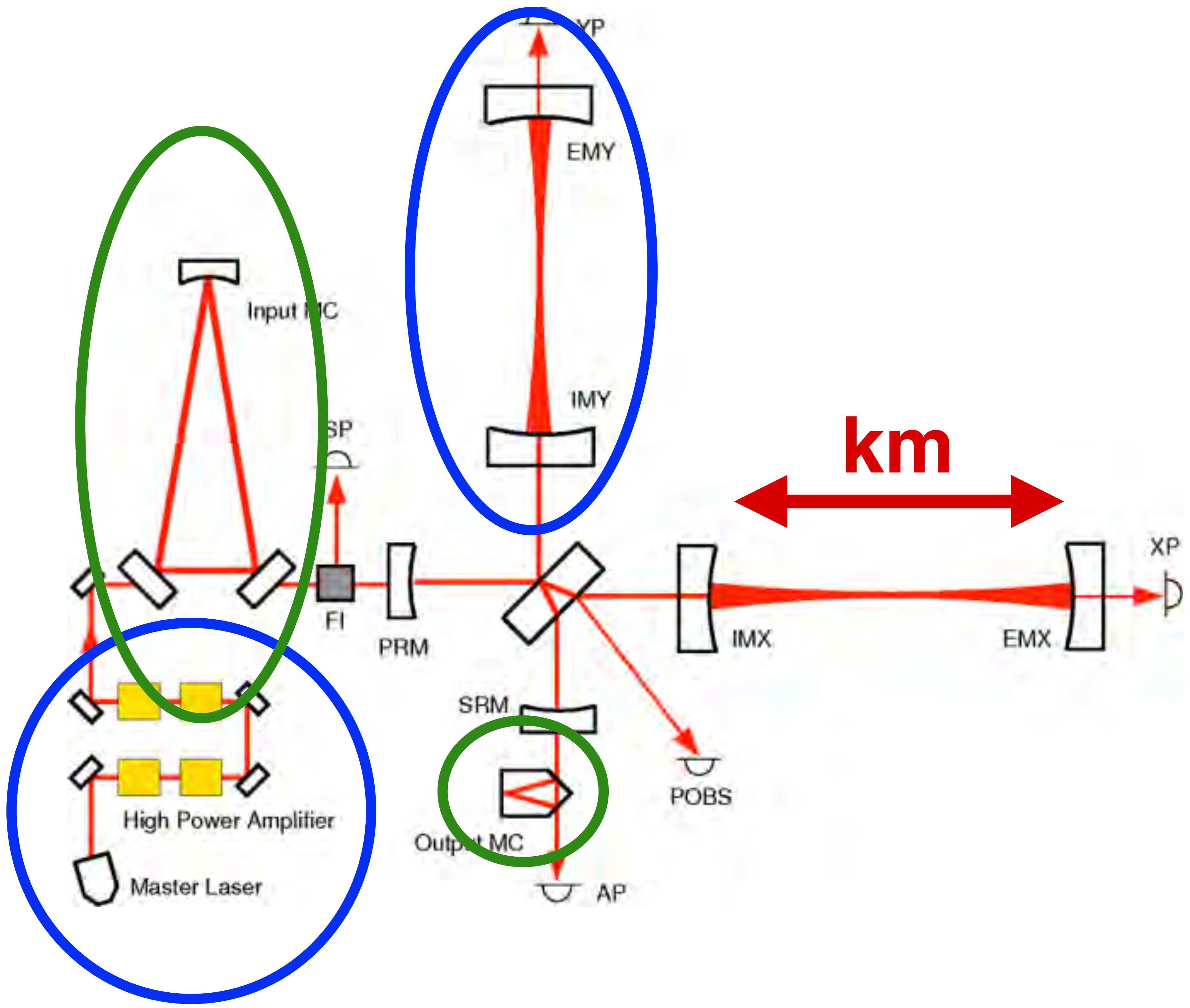
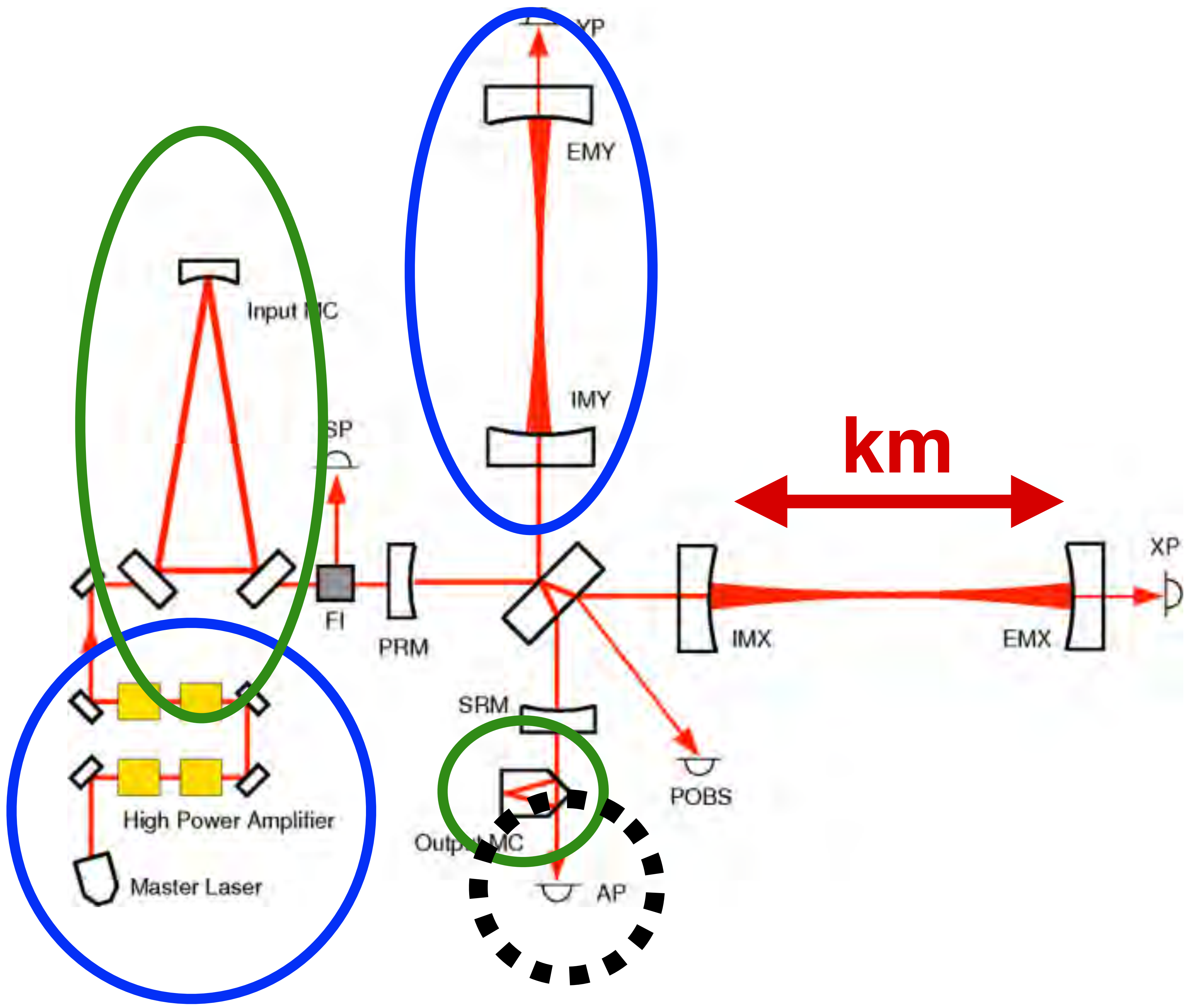
# What Makes it Better?




- GW effect scales with arm length: large detectors
- Optical signal scales with light power: high-power laser, optical cavities
- Laser beam fluctuations make noise: filter cavities

- Stop everything from shaking!

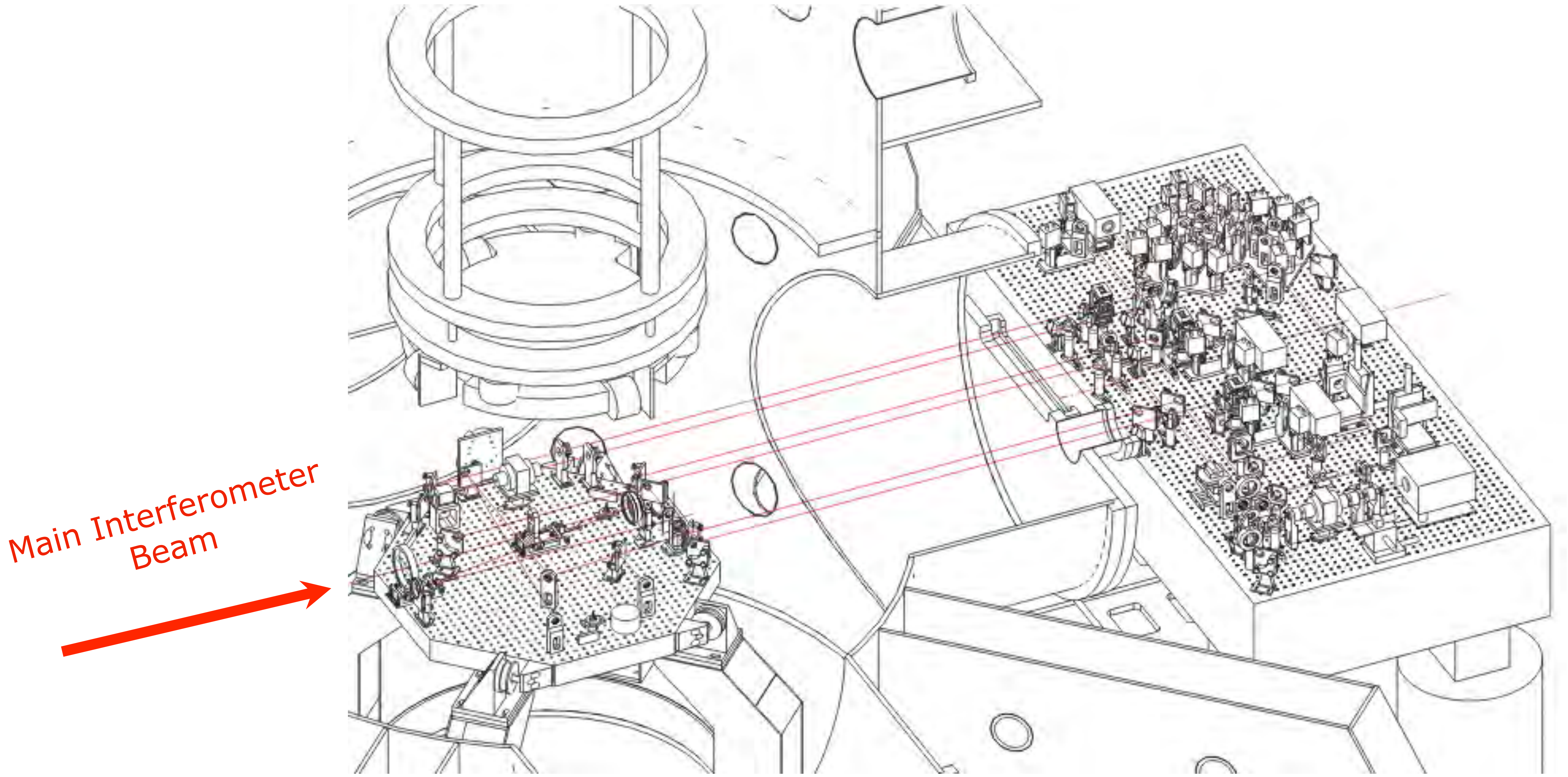
# What Makes it Better?




- GW effect scales with arm length: large detectors
- Optical signal scales with light power: high-power laser, optical cavities
- Laser beam fluctuations make noise: filter cavities
- Stop everything from shaking!

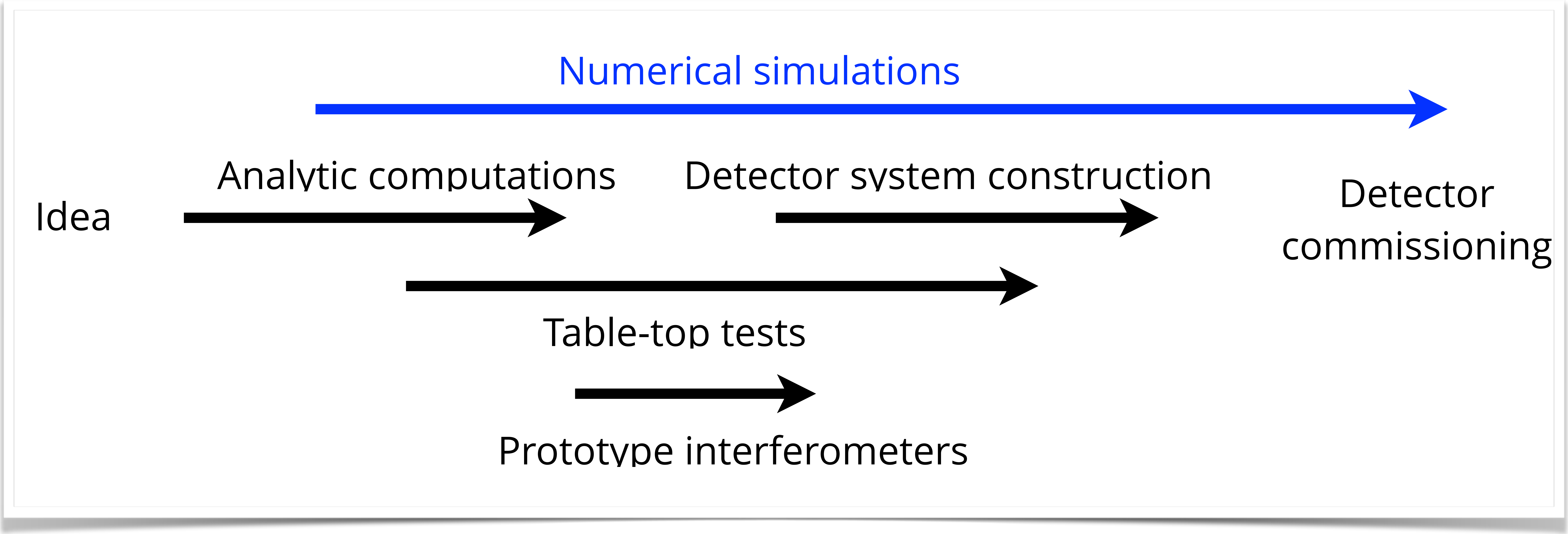
# Complexity Increases

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

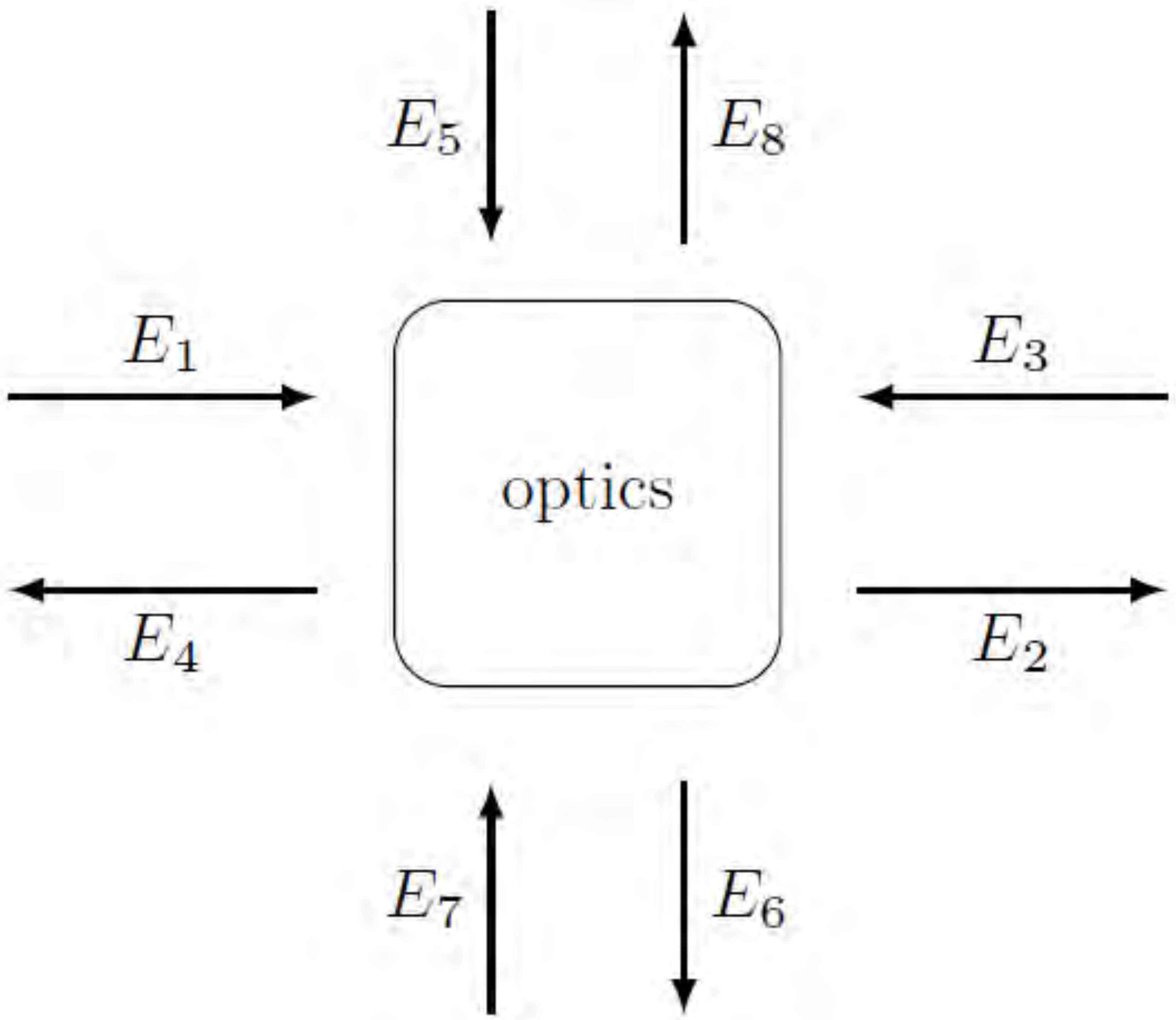



[Image: Virgo Collaboration]

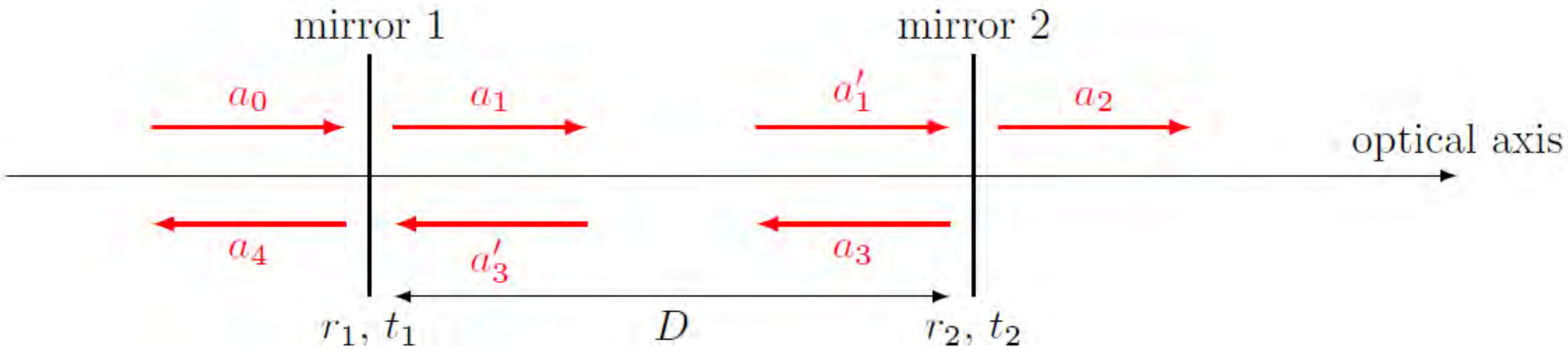
# 10 to 30 Years from Idea to Application



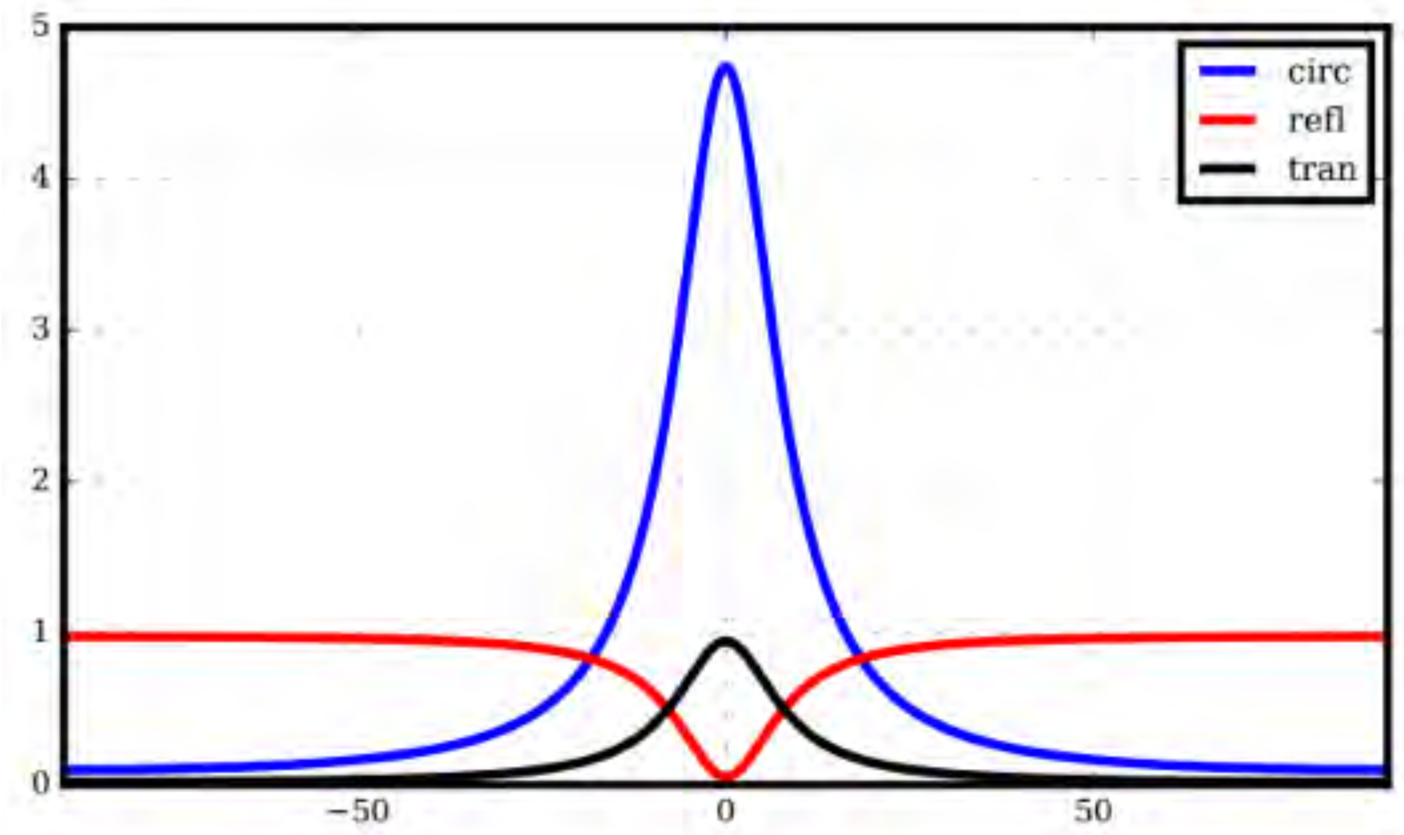
# Linear Interaction of Light with Optics

# Optical Systems as a Sparse Matrix




$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\mathrm{i}\,t_1 & 1 & 0 & -r_1 & 0 & 0 & 0 \\ -r_1 & 0 & 1 & -\mathrm{i}\,t_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & -e^{-\mathrm{i}\,kD} \\ 0 & -e^{-\mathrm{i}\,kD} & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\mathrm{i}\,t_2 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -r_2 & 1 \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ a_4 \\ a_3' \\ a_1' \\ a_2 \\ a_3 \end{pmatrix} = \begin{pmatrix} a_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$



# Play and Evolve

Spare matrix solvers are available, so what is the problem?

- Commercial software is not aimed at optical phase changes of $\mathbf{10^{-13}}$ and interference effects at that level
- We are building a **completely new class of device**, there is no manual, everything is new, we learn as we go along
- It is easy to make plots of interferometer signals, but it is **hard to ask the right questions**
- A LIGO detector is a **strongly coupled** assembly of many optical parts, the interplay between different parts caused surprises!

# Adapt Complexity Correctly

- Model everything in detail to replicate your experiment in the computer? No, model output as difficult to understand as real experiment.
- Use fundamental concepts only? No, your model will not reproduce the behaviour that you want to investigate.

- **Use the right level of abstraction and allow to add or remove details? Yes, your model mimics the real instrument, but has less complexity!**

# Invented here

- Software developed as side project by scientist working on non-code tasks
- Developer is its own user, often the only one
- Code quality is low, best practises are not known or not followed
- Difficult to make impact in teams or projects
  `real physicists don't use simulations'

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# FINESSE

www.gwoptics.org/finesse

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  ~~ \)-'   '
     / |
----'--'----------------------------------------
```

- Started 1997 as a PhD side project
- Stand-alone binary, written in C
- > 40.000 lines of code
- Open sourced in 2012
- Under active development
- Used extensively worldwide

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# User interface

optical_spring_mechTF.kat — kats

optical_spring_mechTF.kat

```
tf sus 1 0 p 1 100000

l l1 3 0 n1
m ITM 0.9937 0.0063 0 n1 n2
s cav1 1 n2 n3
m ETM 1 0 -0.048 n3 n4

attr ITM M 0.25 zmech sus
attr ETM M 0.25 zmech sus

fsig aforce ETM Fz 1 0 1

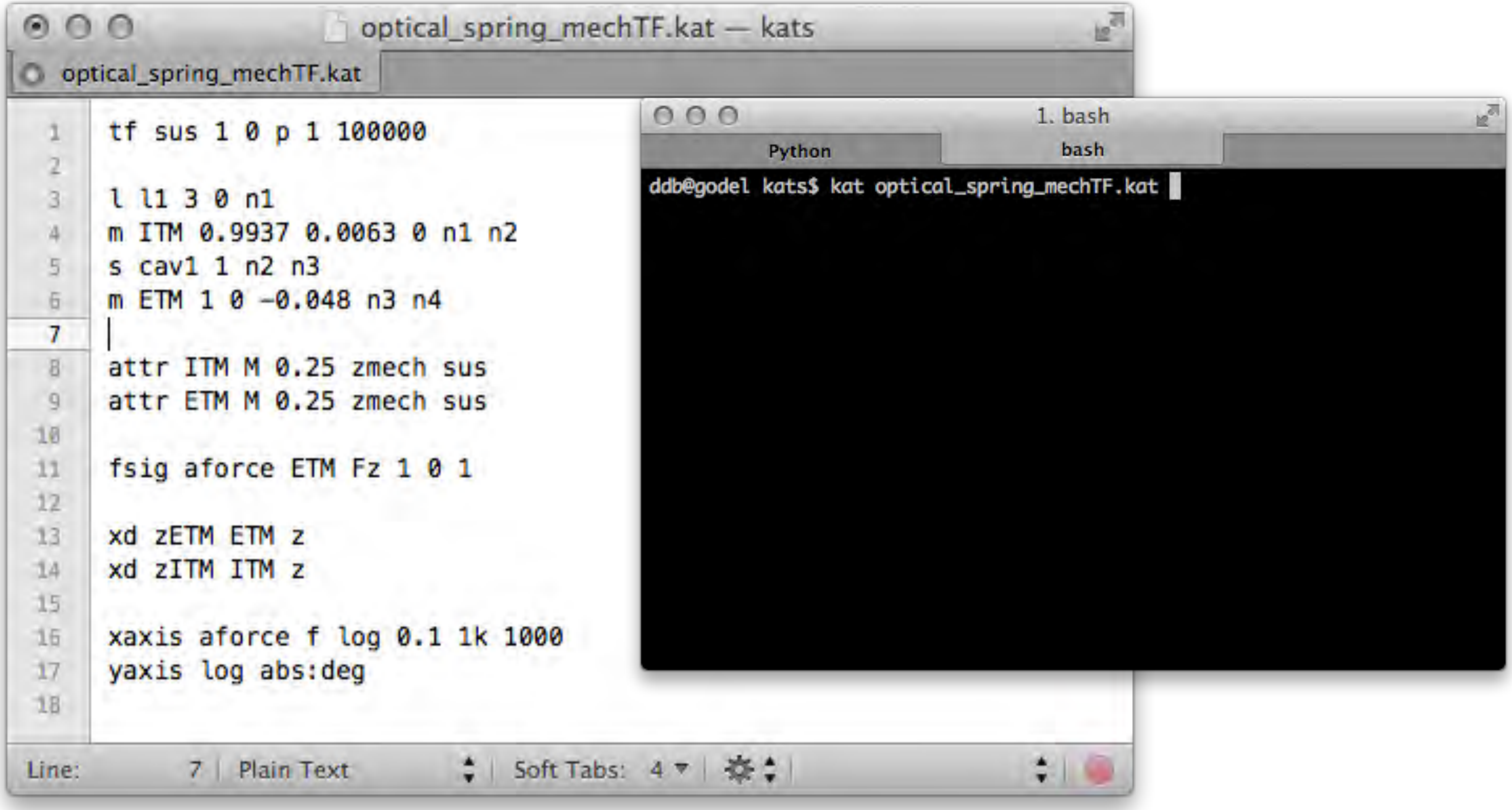
xd zETM ETM z
xd zITM ITM z

xaxis aforce f log 0.1 1k 1000
yaxis log abs:deg
```

Line: 7 | Plain Text | Soft Tabs: 4

Measurement of radiation-pressure-induced optomechanical dynamics in a suspended Fabry-Perot cavity
Corbitt, et. al. 2006. http://pra.aps.org/abstract/PRA/v74/i2/e021802

# User interface




Measurement of radiation-pressure-induced optomechanical dynamics in a suspended Fabry-Perot cavity
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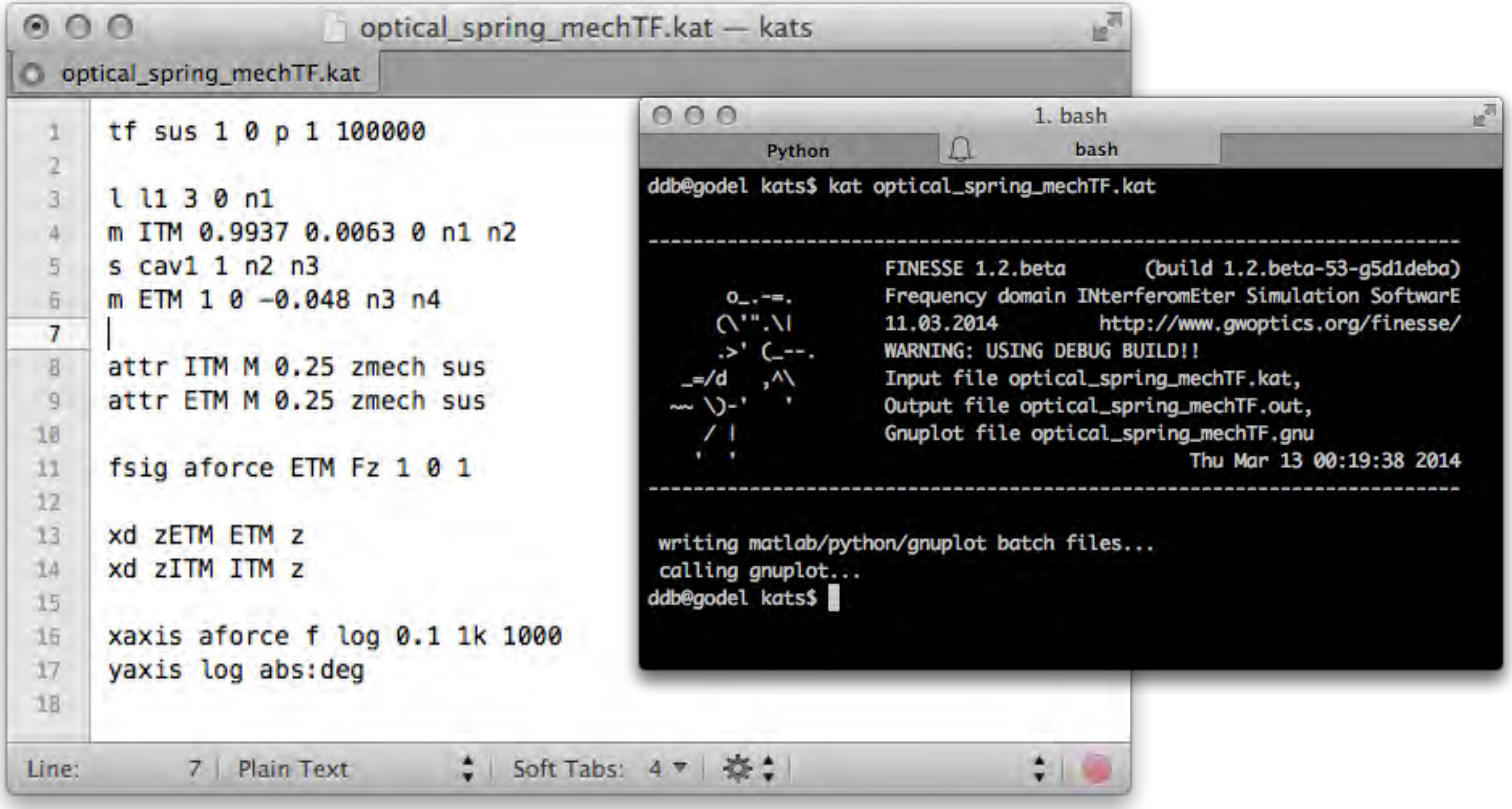
# User interface




Measurement of radiation-pressure-induced optomechanical dynamics in a suspended Fabry-Perot cavity
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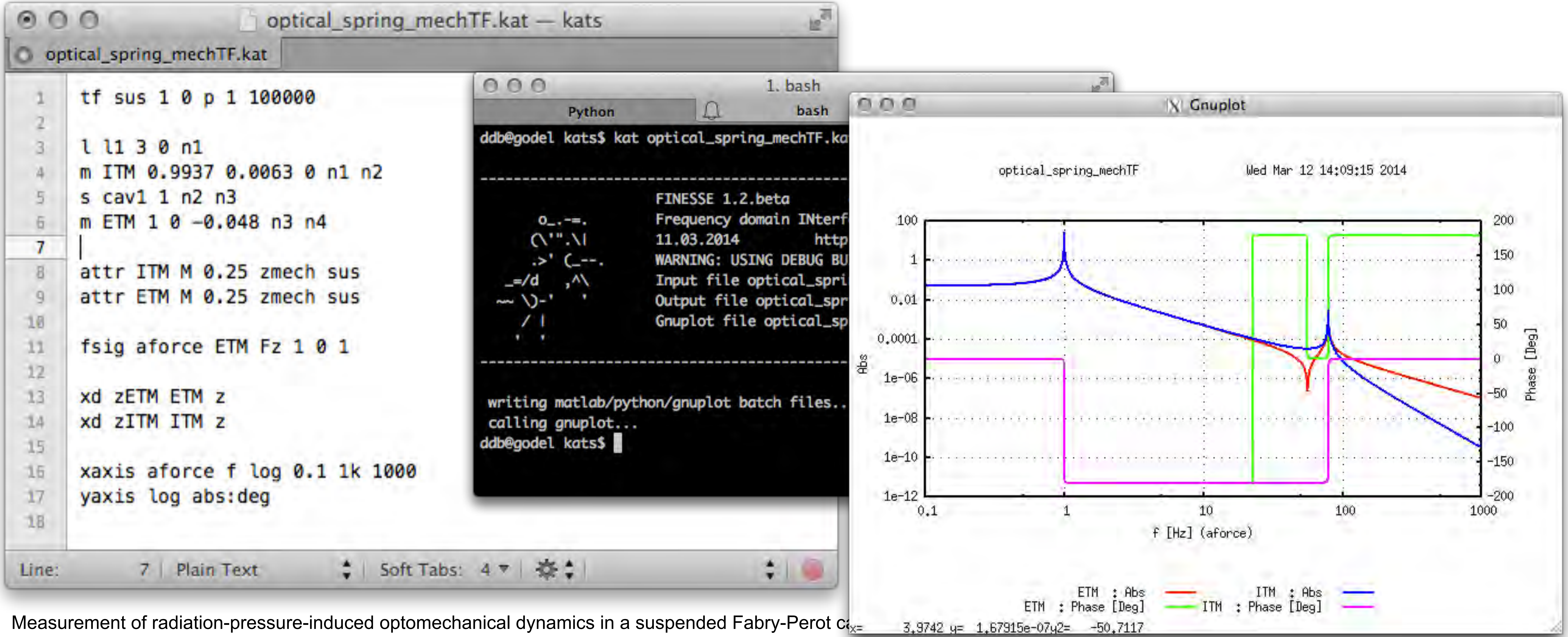
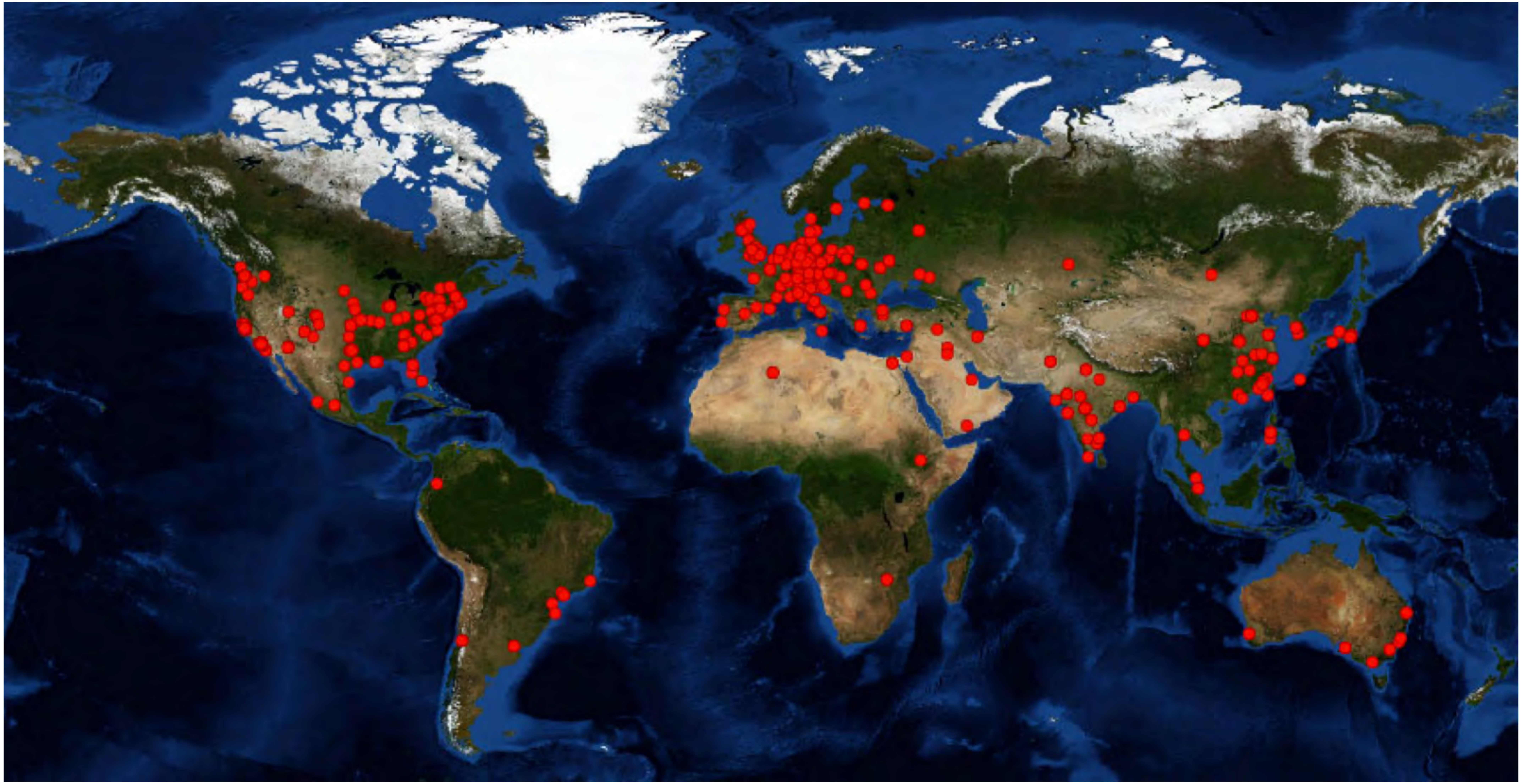
# User interface




Measurement of radiation-pressure-induced optomechanical dynamics in a suspended Fabry-Perot ca
Corbitt, et. al. 2006. http://pra.aps.org/abstract/PRA/v74/i2/e021802

# FINESSE 1.0 download locations



# From Matlab to Python

- We needed a scripting environment to support the stand-alone simulation software to:
  - automate simulation tasks
  - pre- and post-processing of data
  - present results of complex tasks

- 2006 developed a set of tools to run FINESSE from Matlab
- 2013 started to develop PyKat, a Python-based replacement

# Why Python?

Originally used Matlab because is has been chosen as the standard tool of the project, but...

- Matlab **licenses are expensive**, artificially limits the reach of our software
- Many features of the framework require **text parsing**, which is difficult in Matlab
- **Python is cool**, students want to use it
- Python (now) provides the right mixture of **stability and playground**

# PyKat

www.gwoptics.org/pykat

```
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```

- Python-based tools for optical simulations
- Primary use: IPython notebooks to run FINESSE simulations
- Python 2/3 compatible
- main packages used: NumPy, Matplotlib, SciPy, SymPy

# Finesse at work

[Logbook page 2292, 15.12.2011, Holger Wittel]

# Simulations during operations

- Availability of well tested, `realistic' models
- Modelling interferometer response to signals and to noise for calibration and noise budget
- **Identifying unexpected features, to make use of them as diagnostic tools**
- **Capability to investigate proposed changes before hardware changes**

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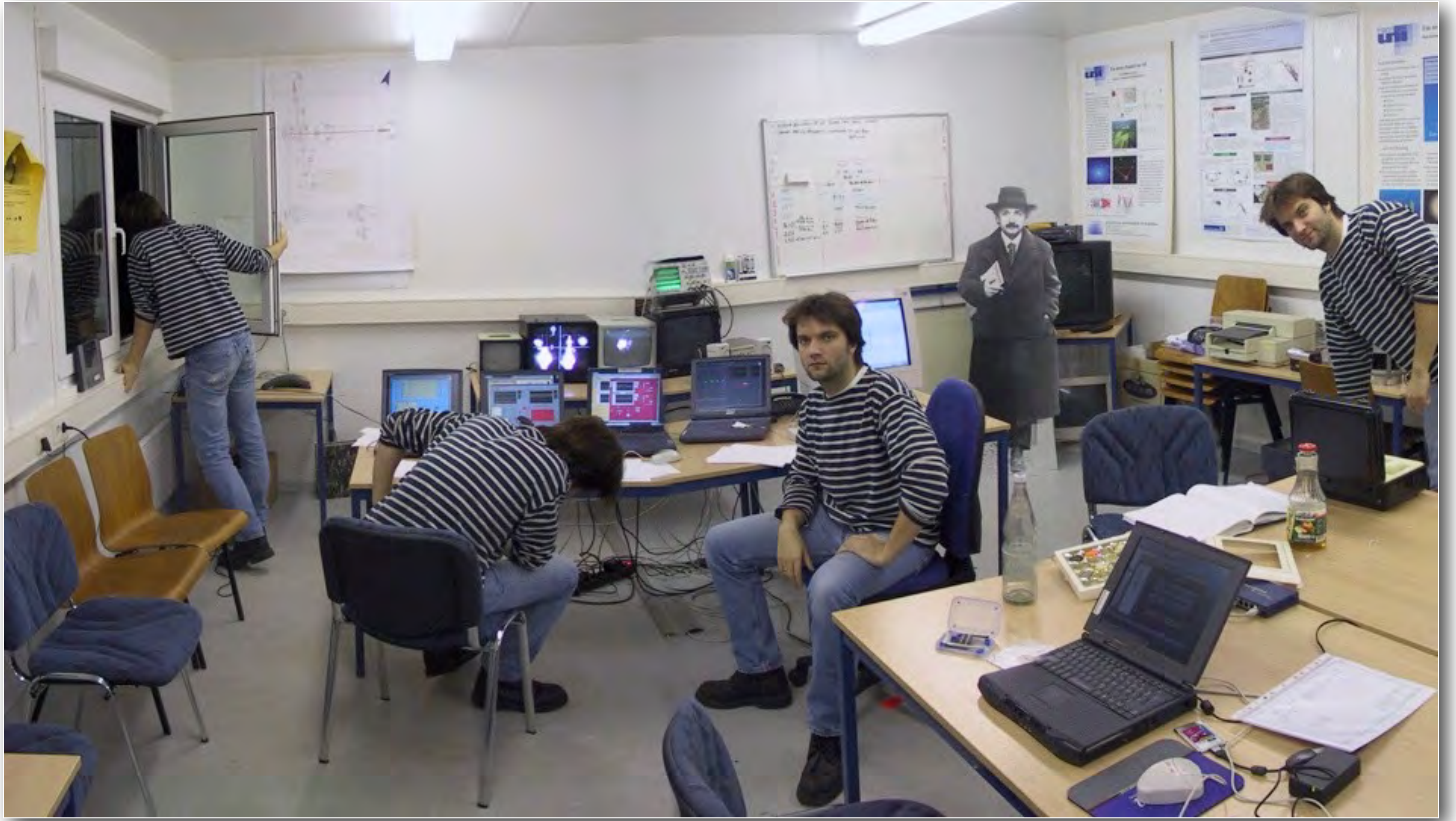
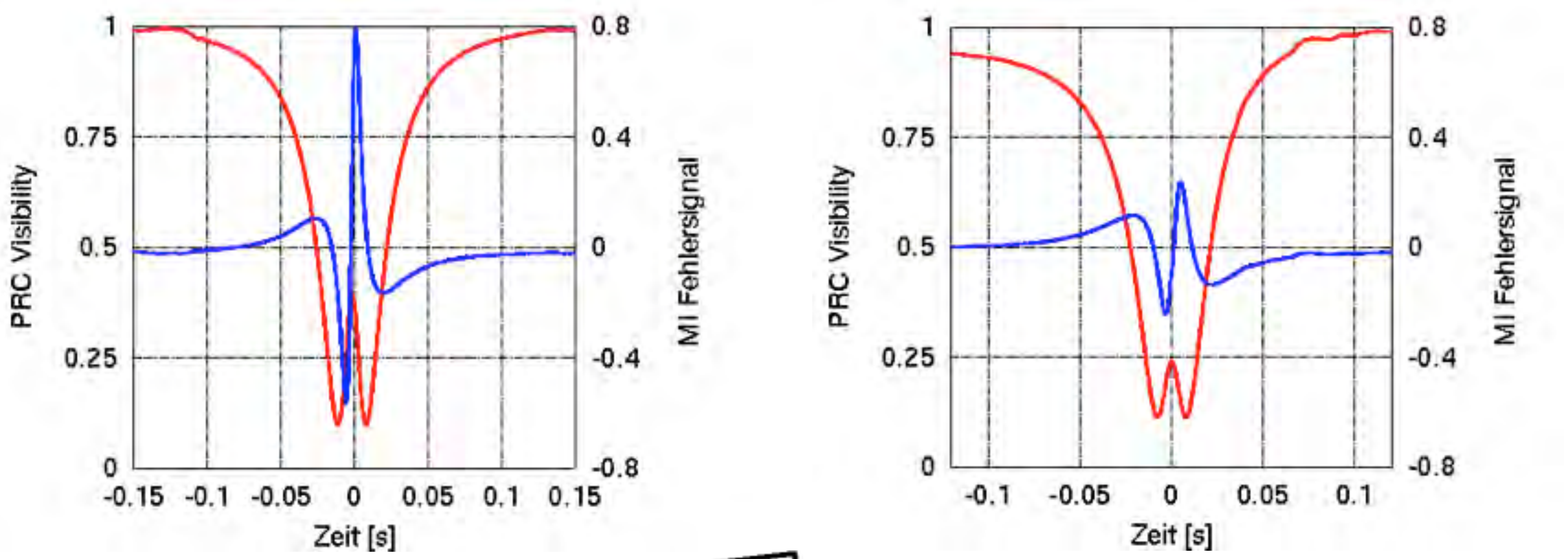
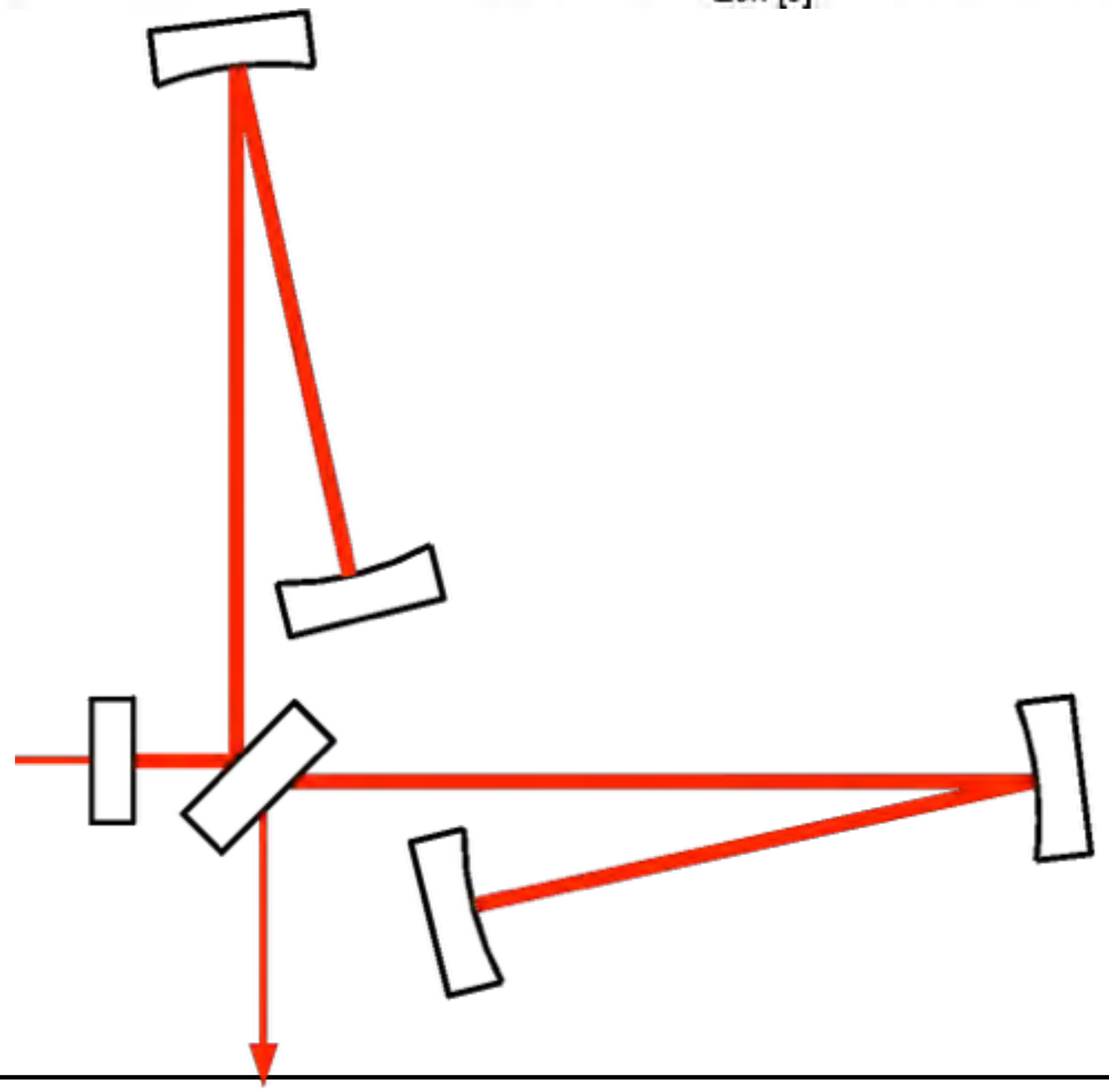
# A long time ago, in the GEO 600 control room ...

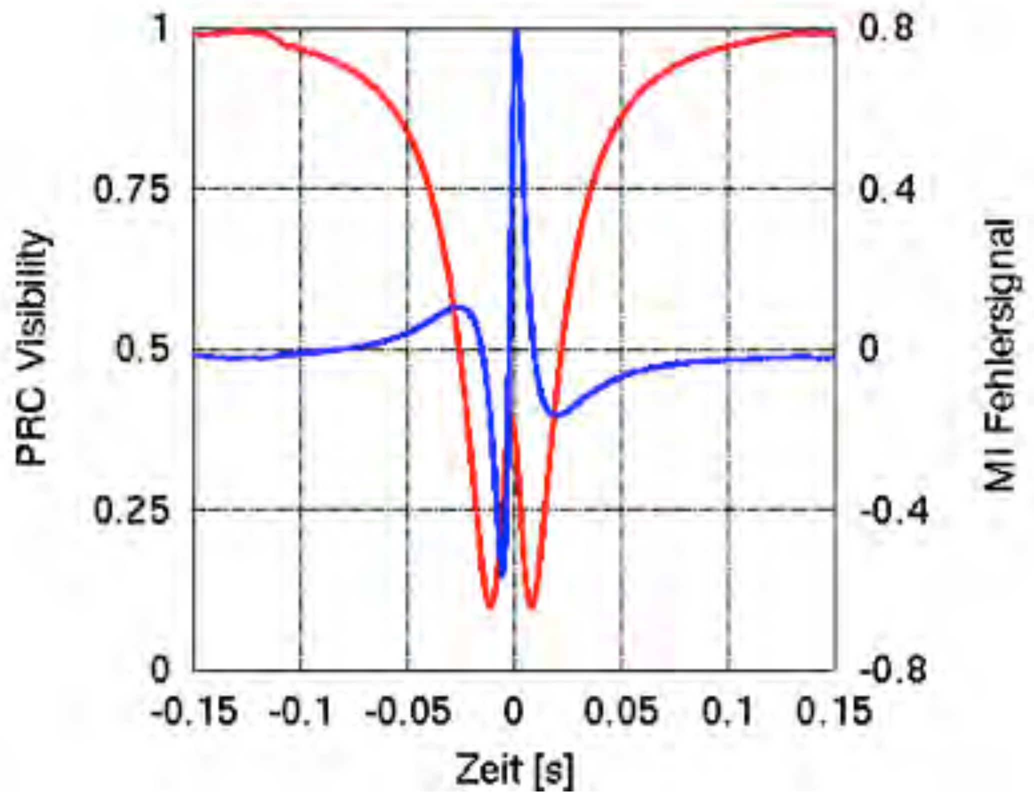


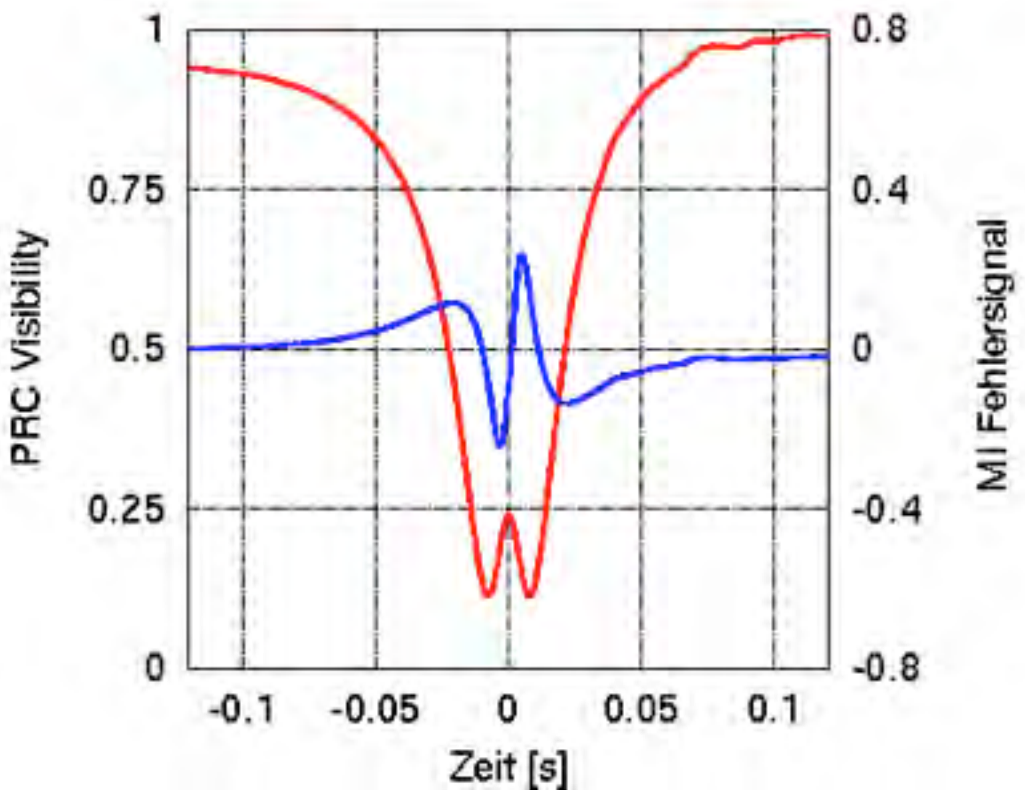
# Distorted Control Signals



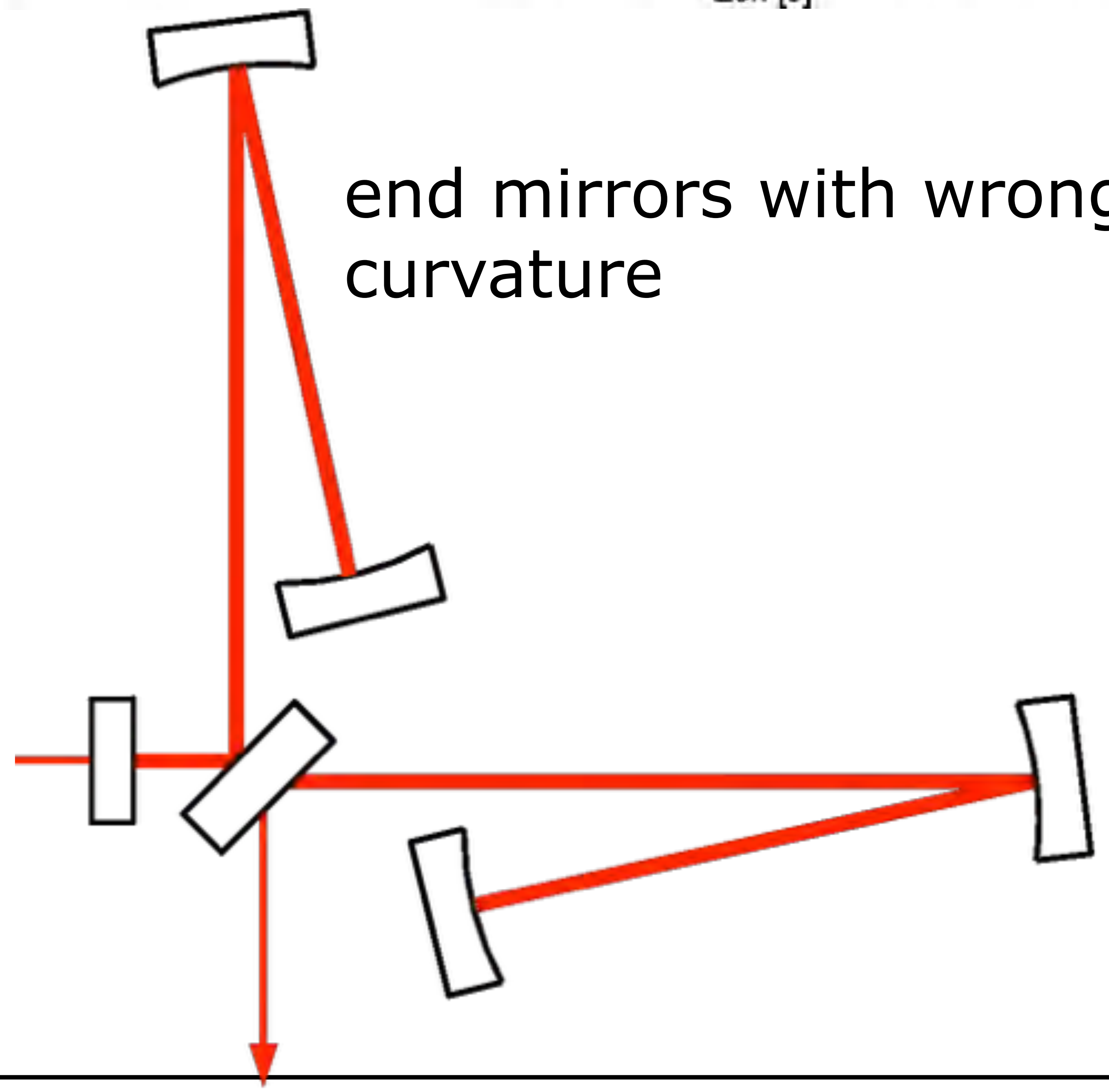



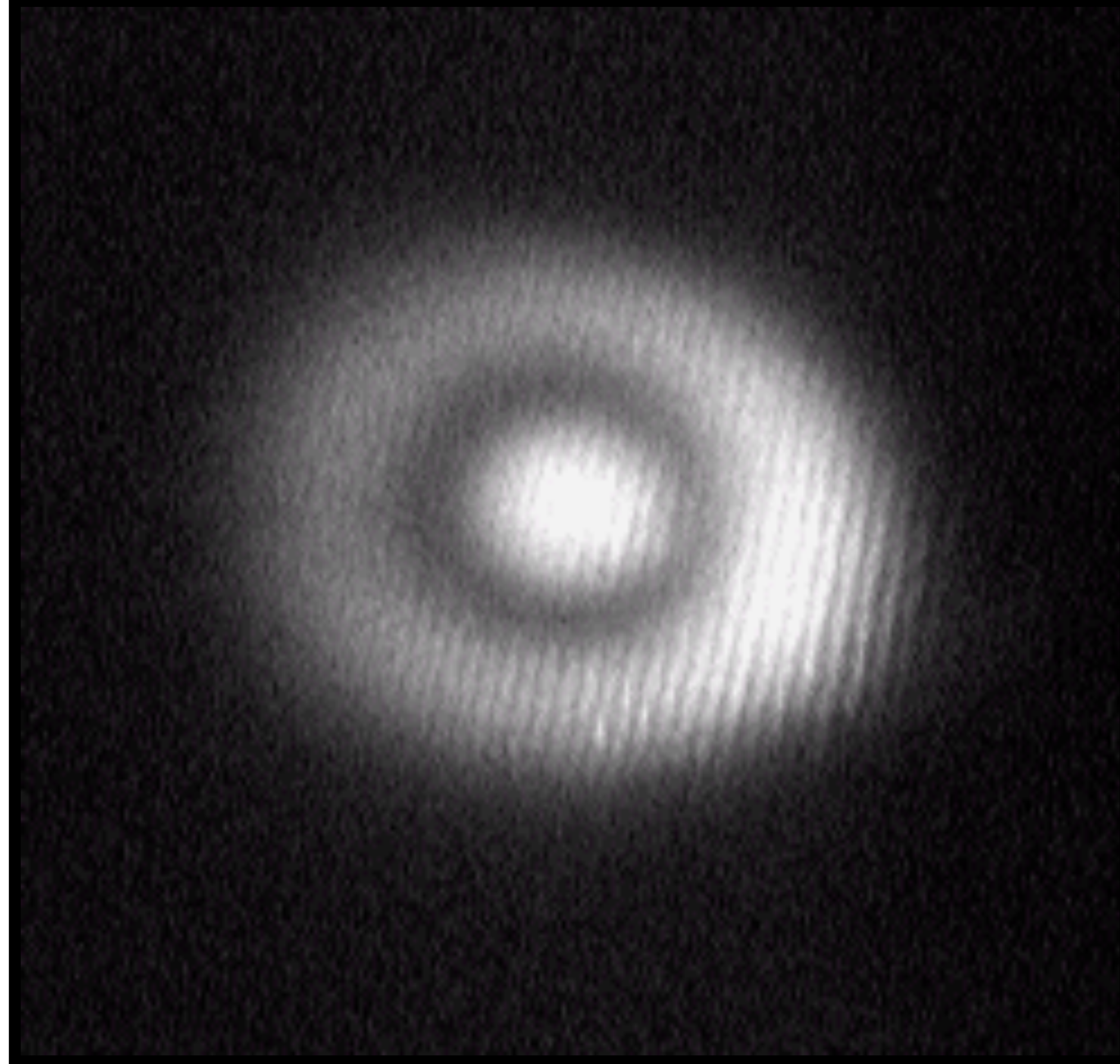
# Distorted Control Signals



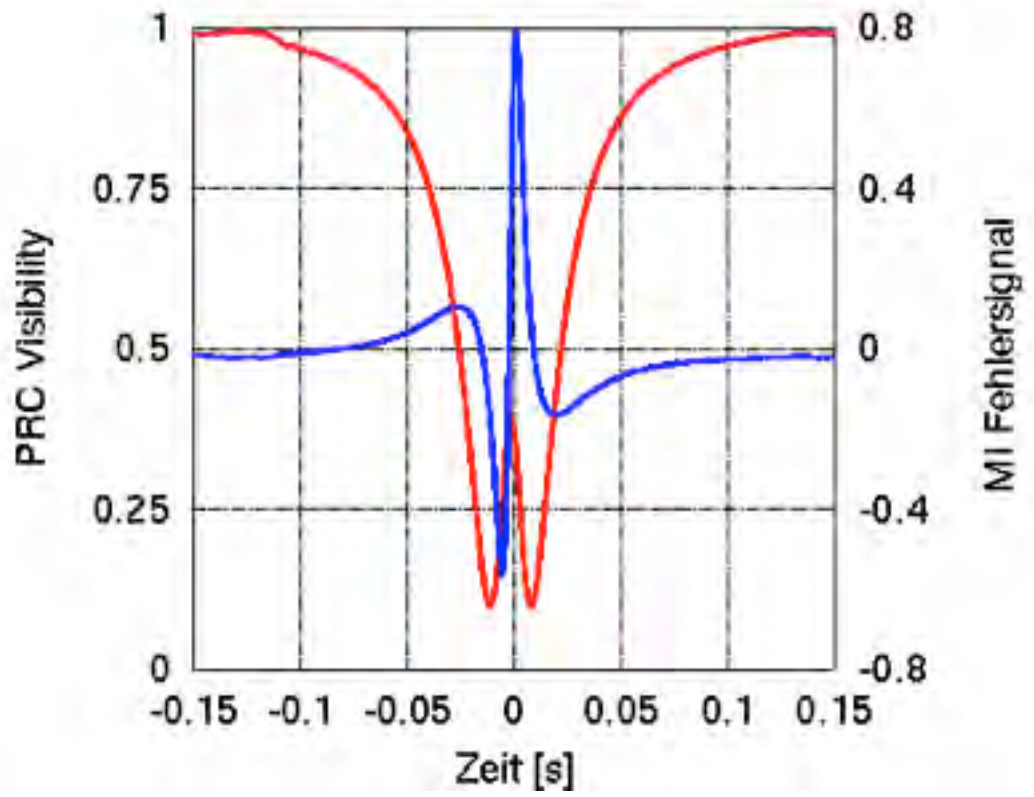



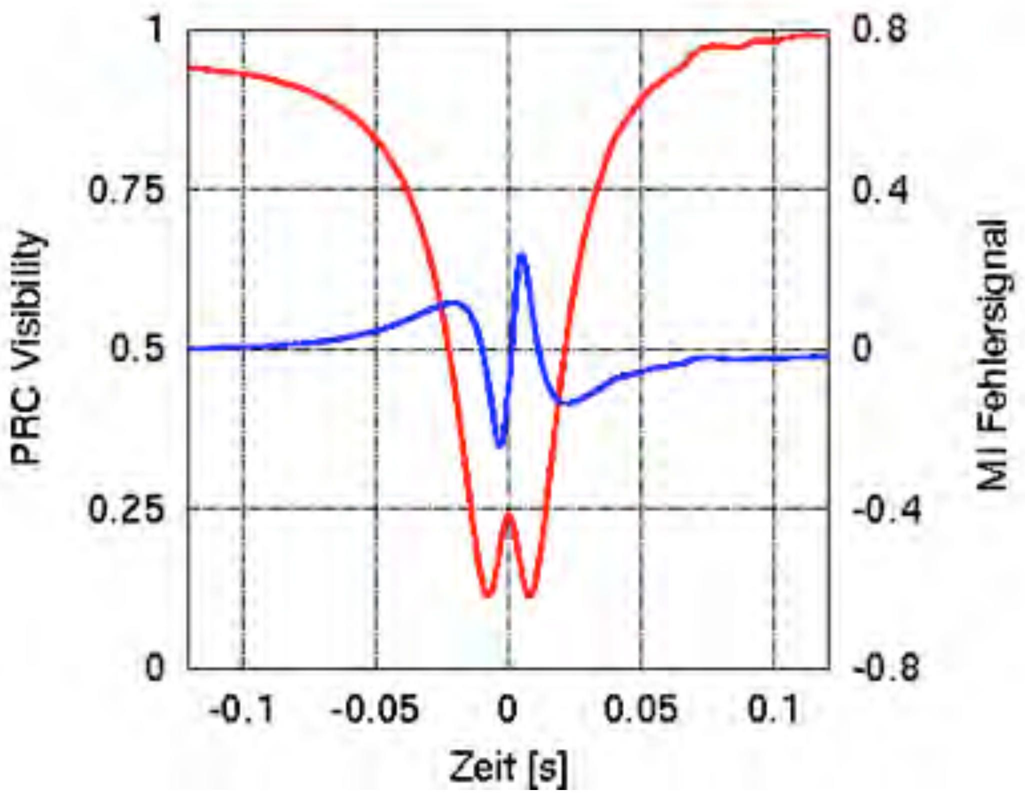

end mirrors with wrong curvature

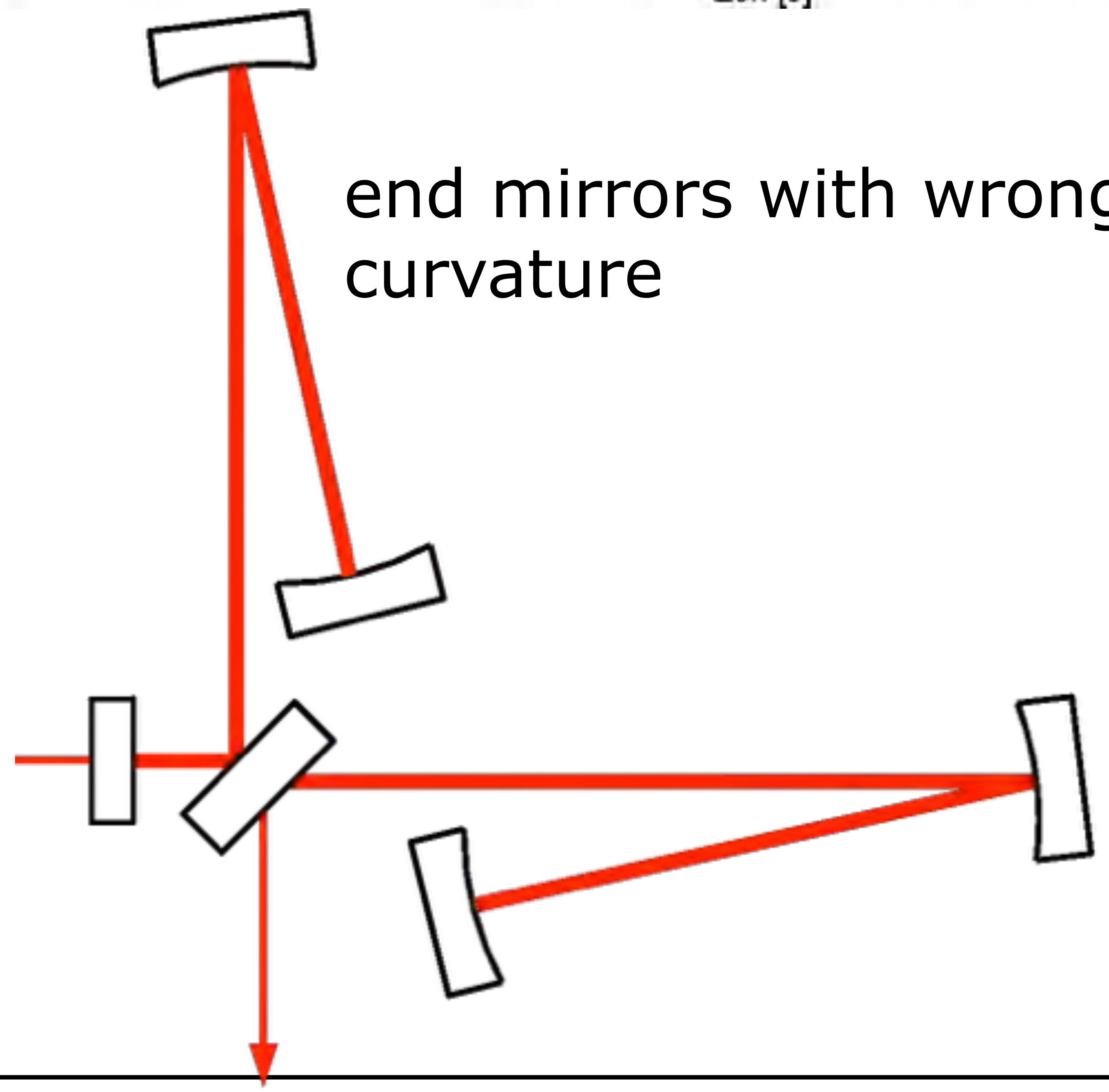




# Distorted Control Signals



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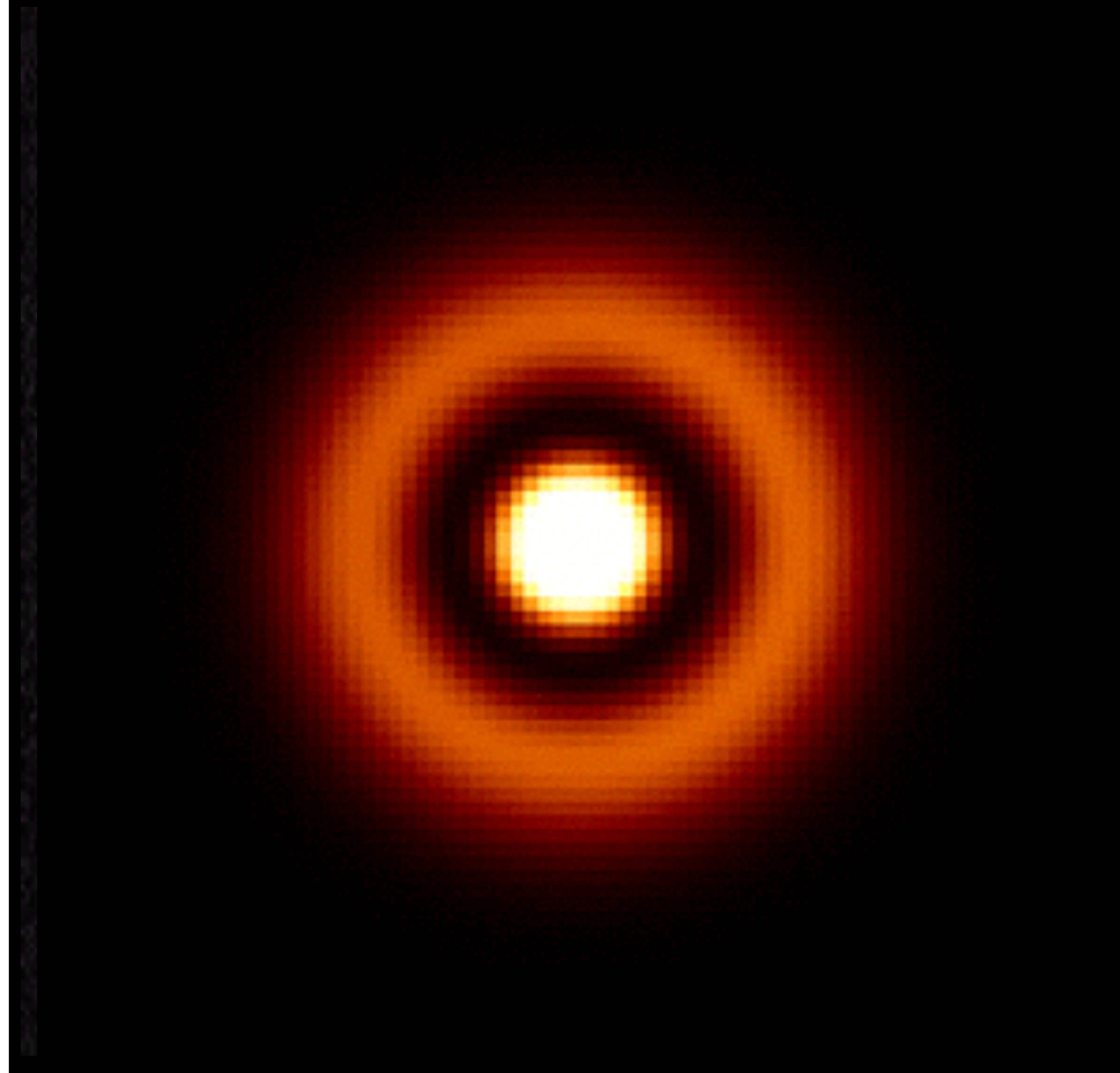
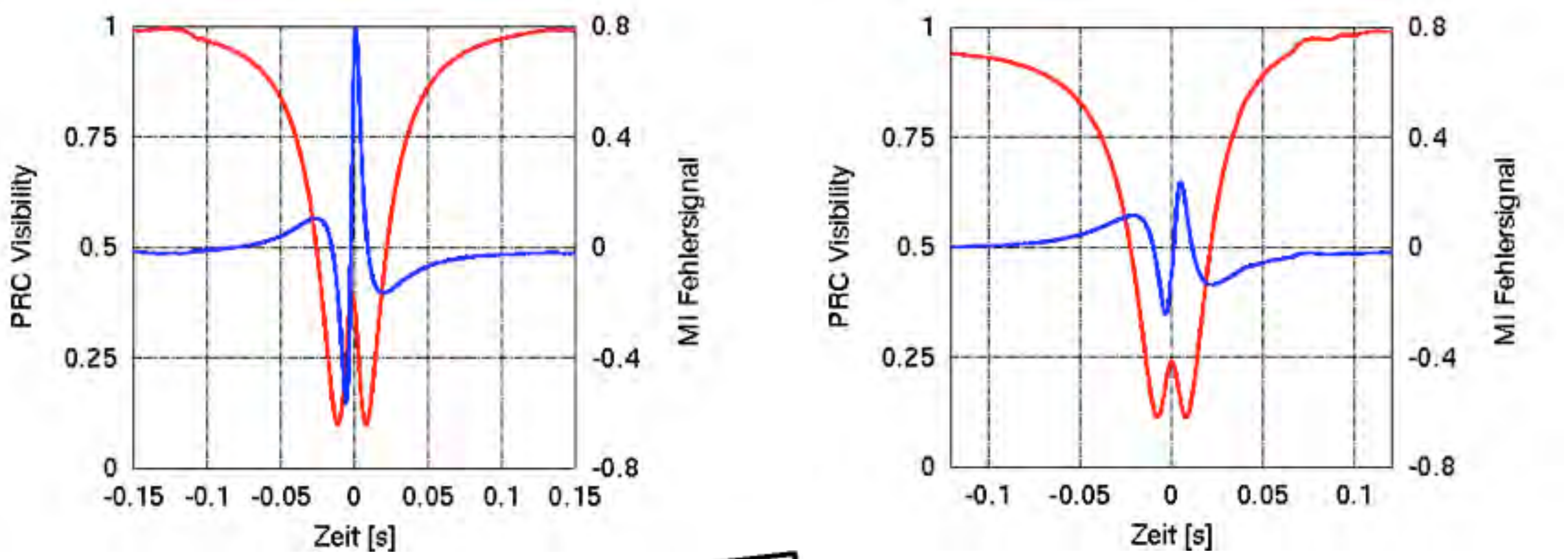
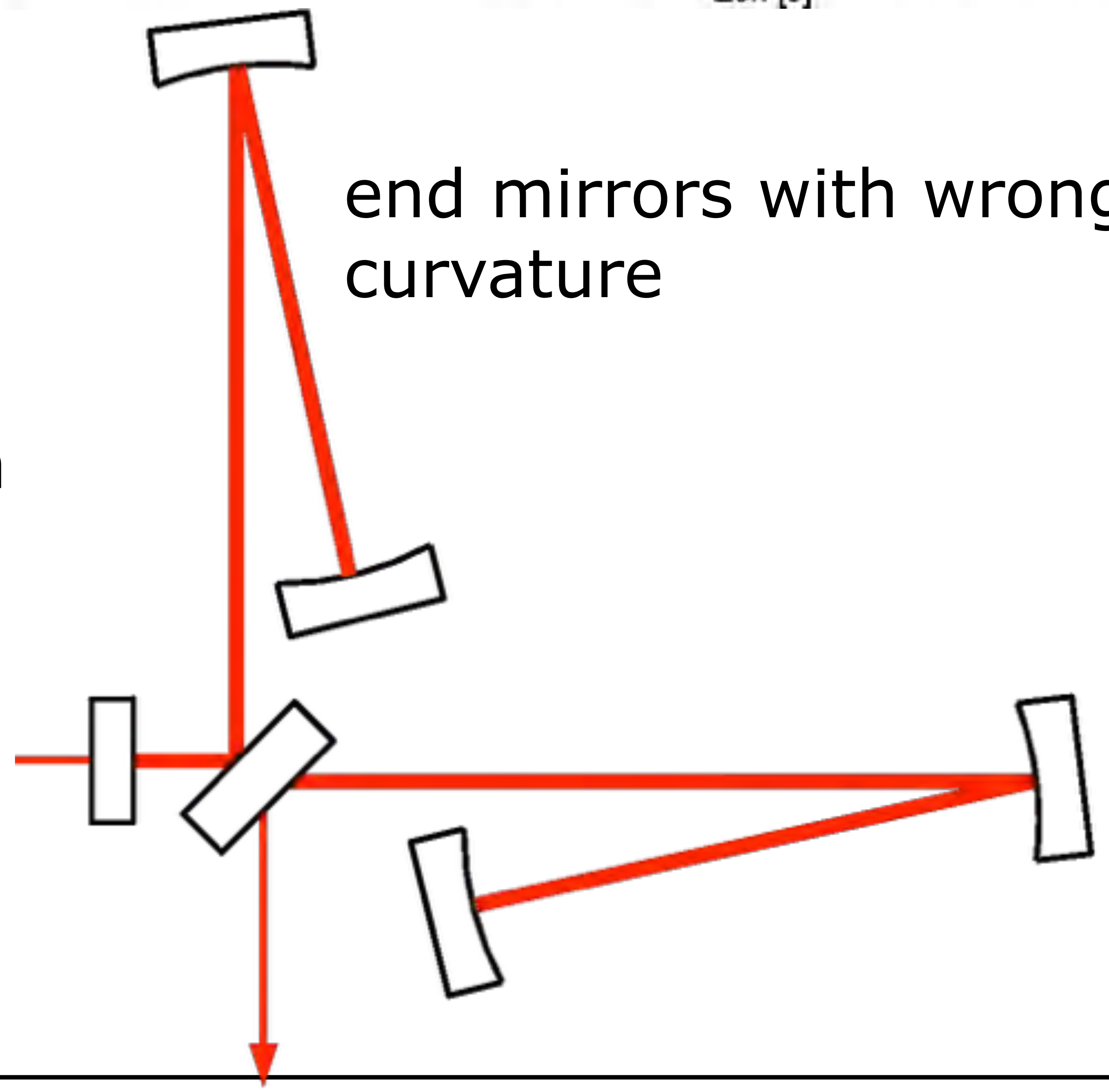
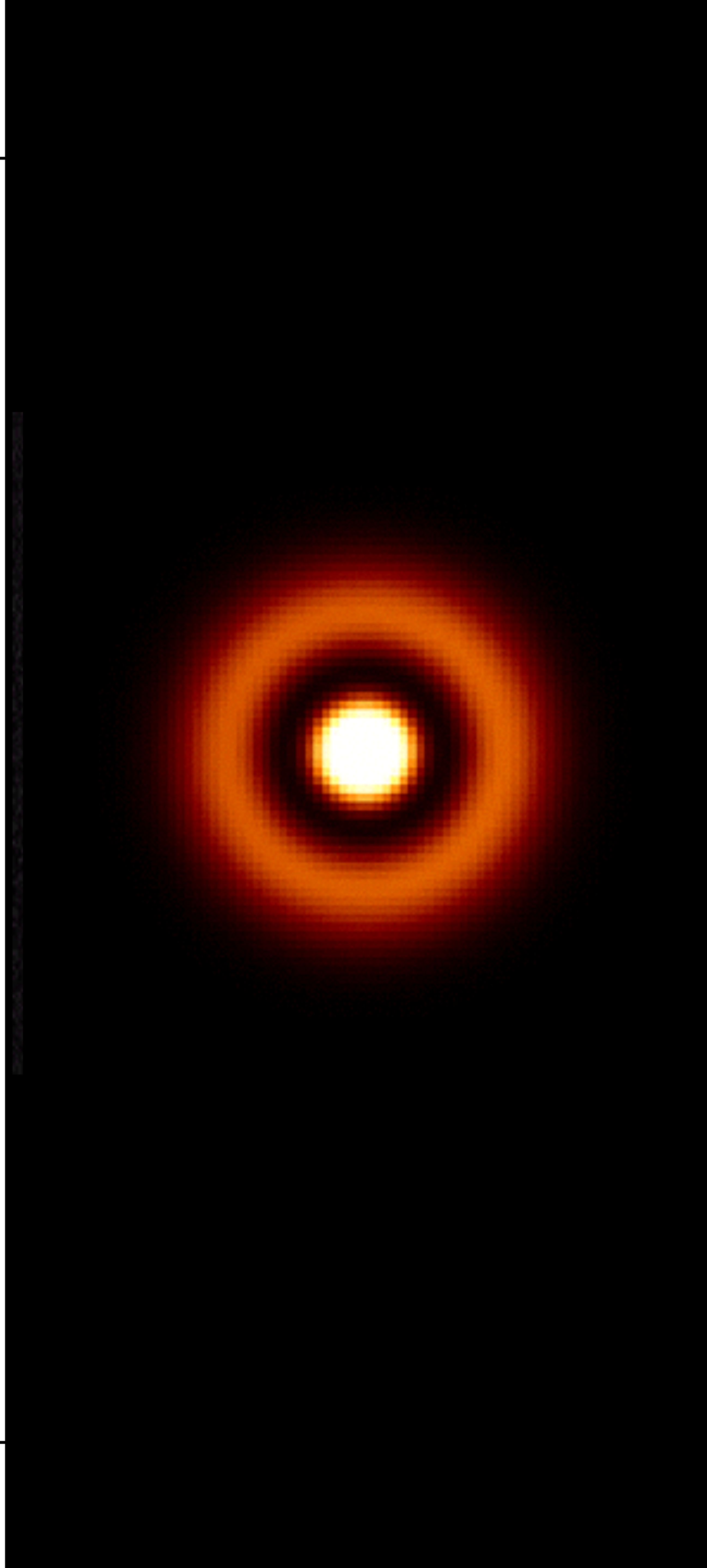


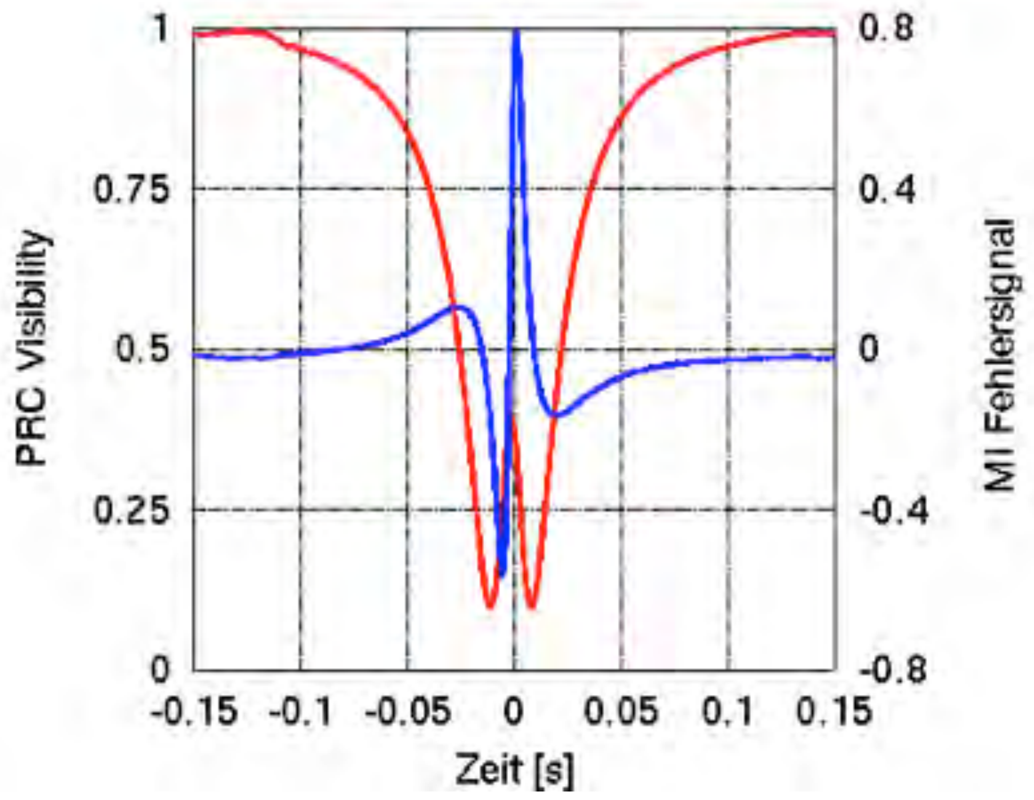
# Distorted Control Signals

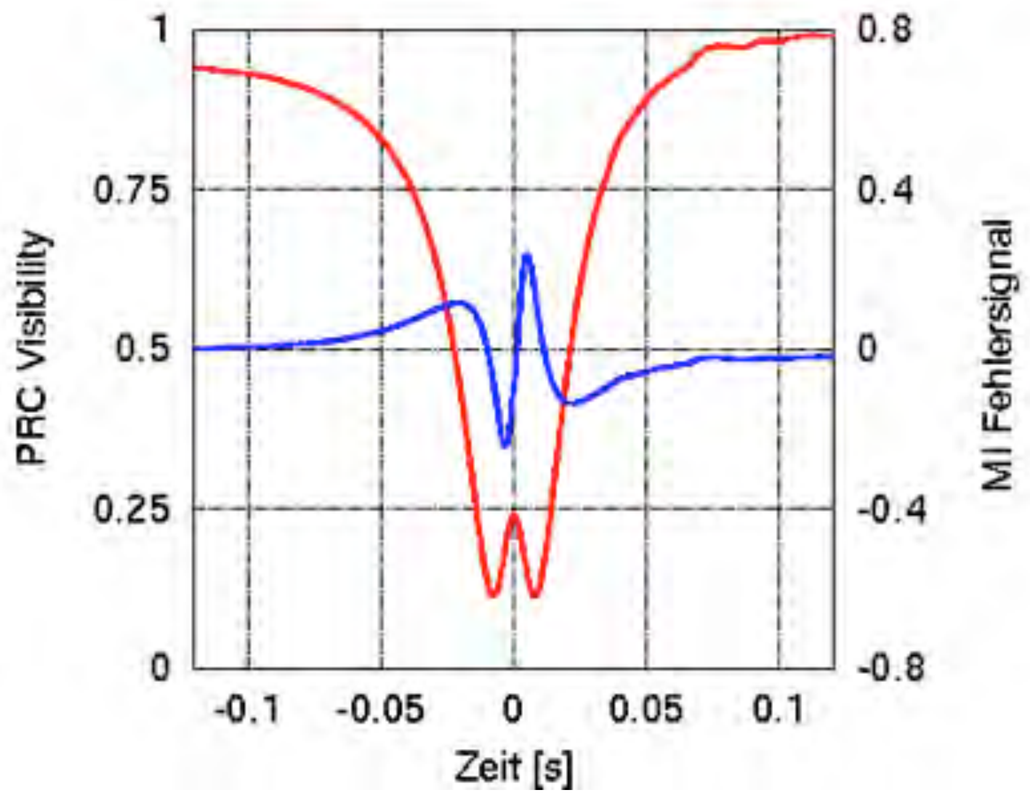


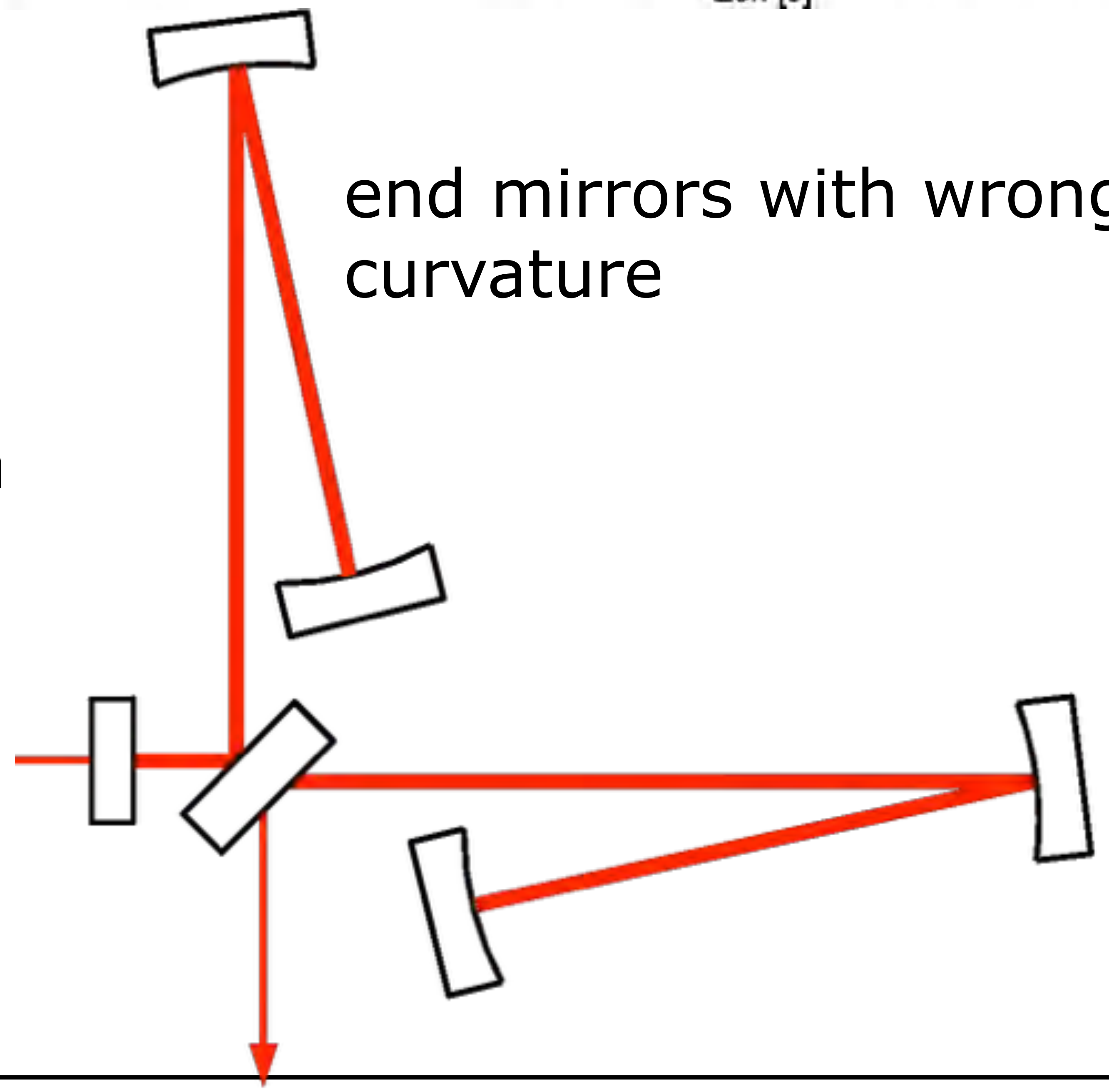



# Distorted Control Signals

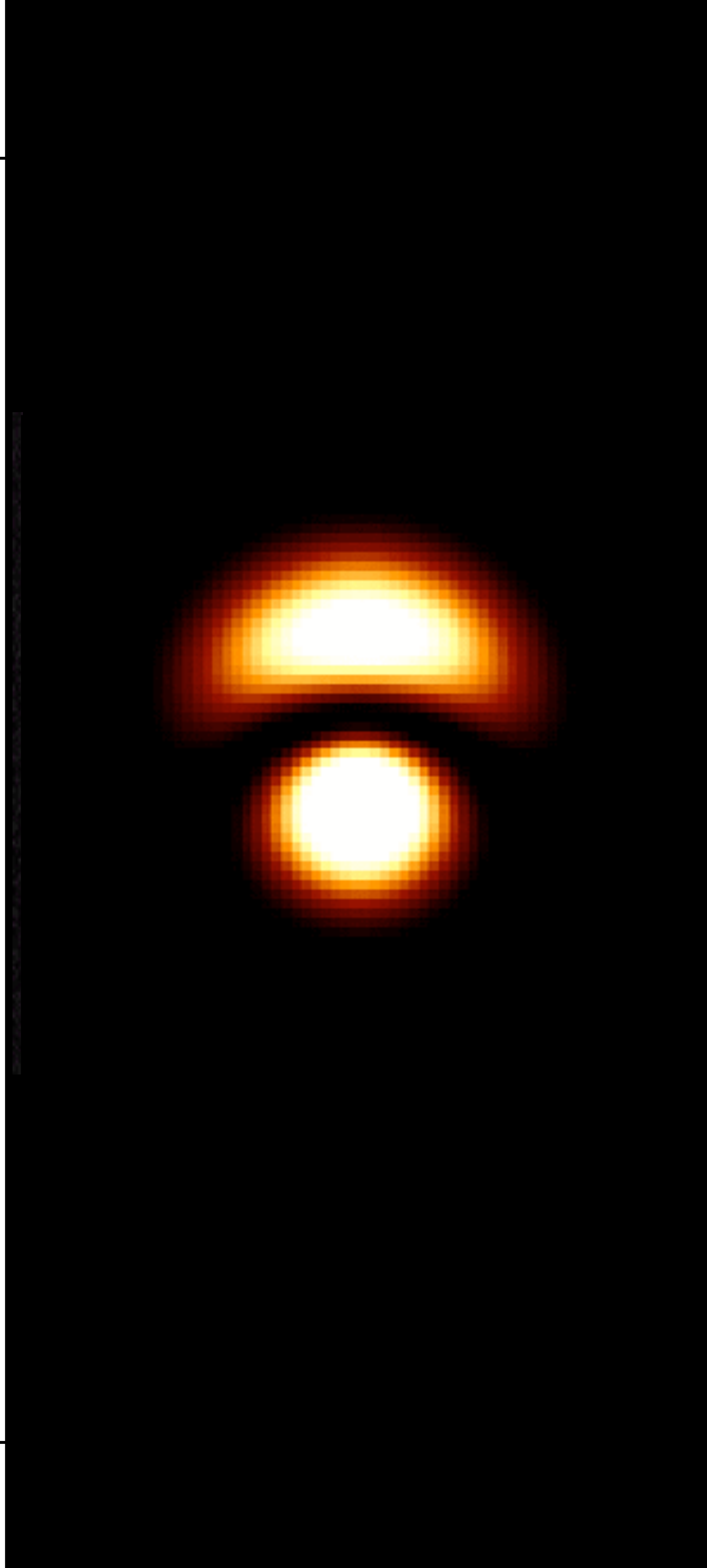


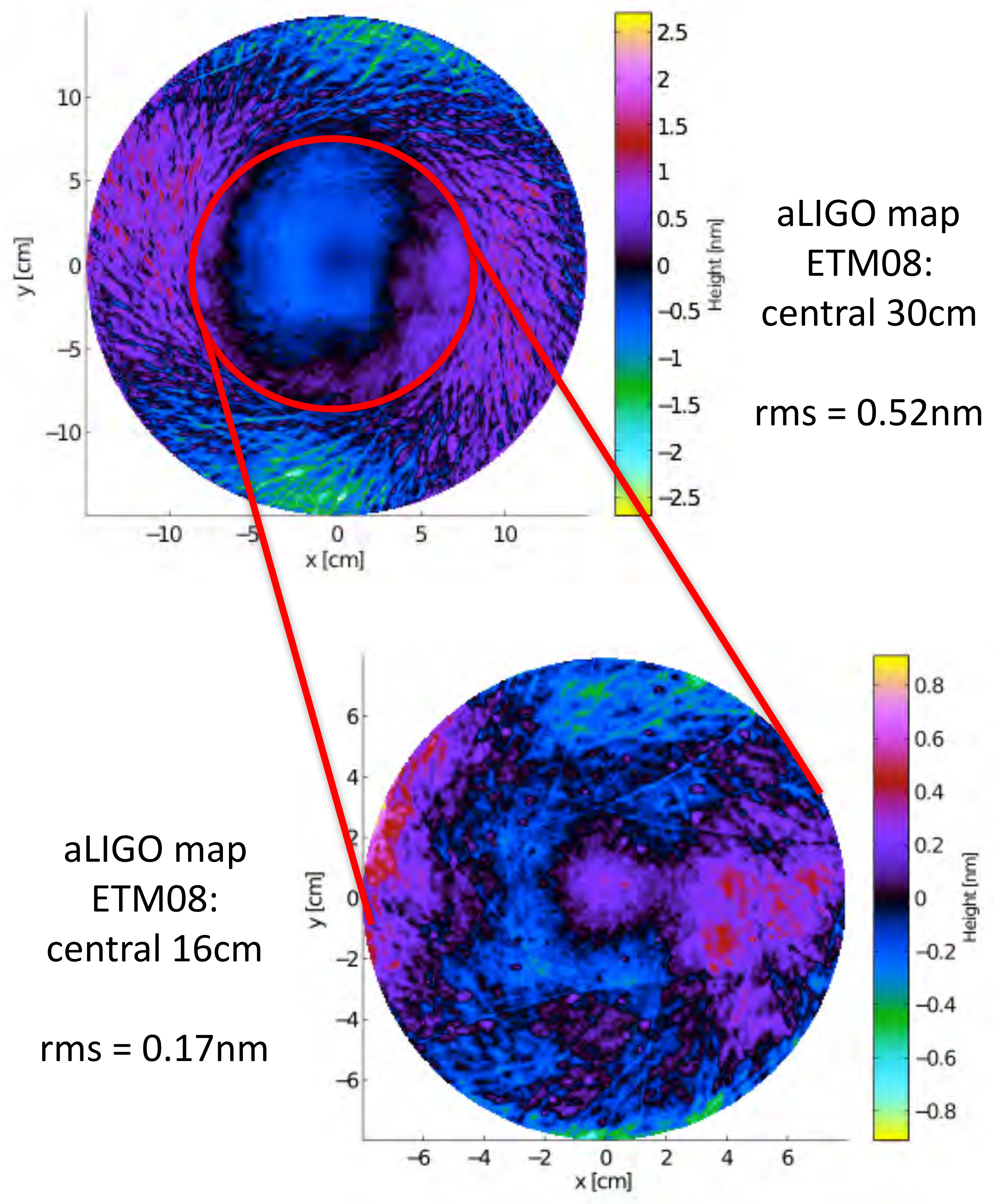
end mirrors with wrong curvature

BS `tilt' motion excited




LIGO Mirrors

# LIGO Mirror Surface Quality




- LIGO mirrors require extremely flat surfaces
- Surface roughness or distortions cause optical loss, details depend on the type and shape of the distortions
- Surface measurement are available from manufacturer
- Numerical modelling is used to predict optical loss to determine if mirrors can be accepted

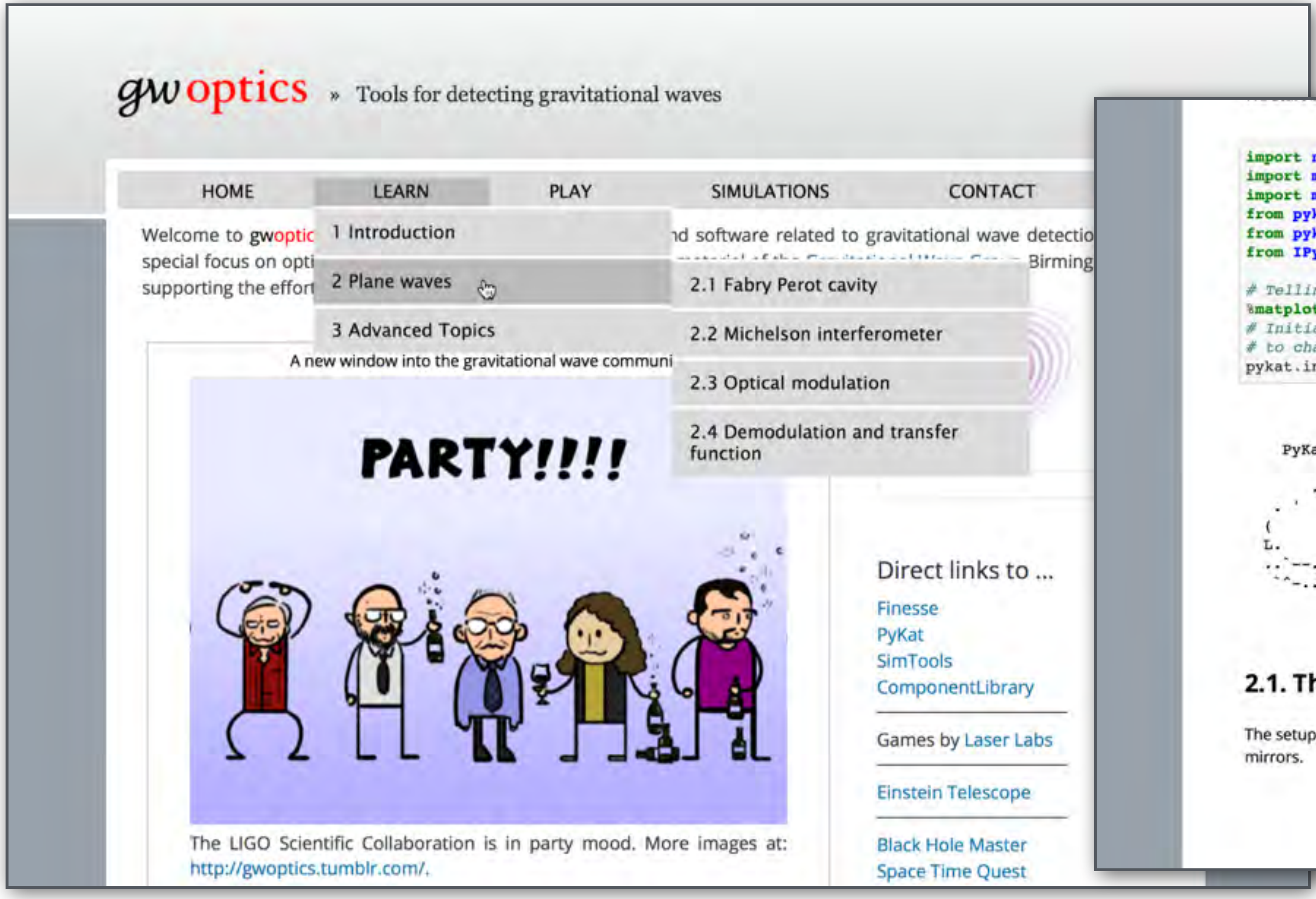
# Teaching and Training

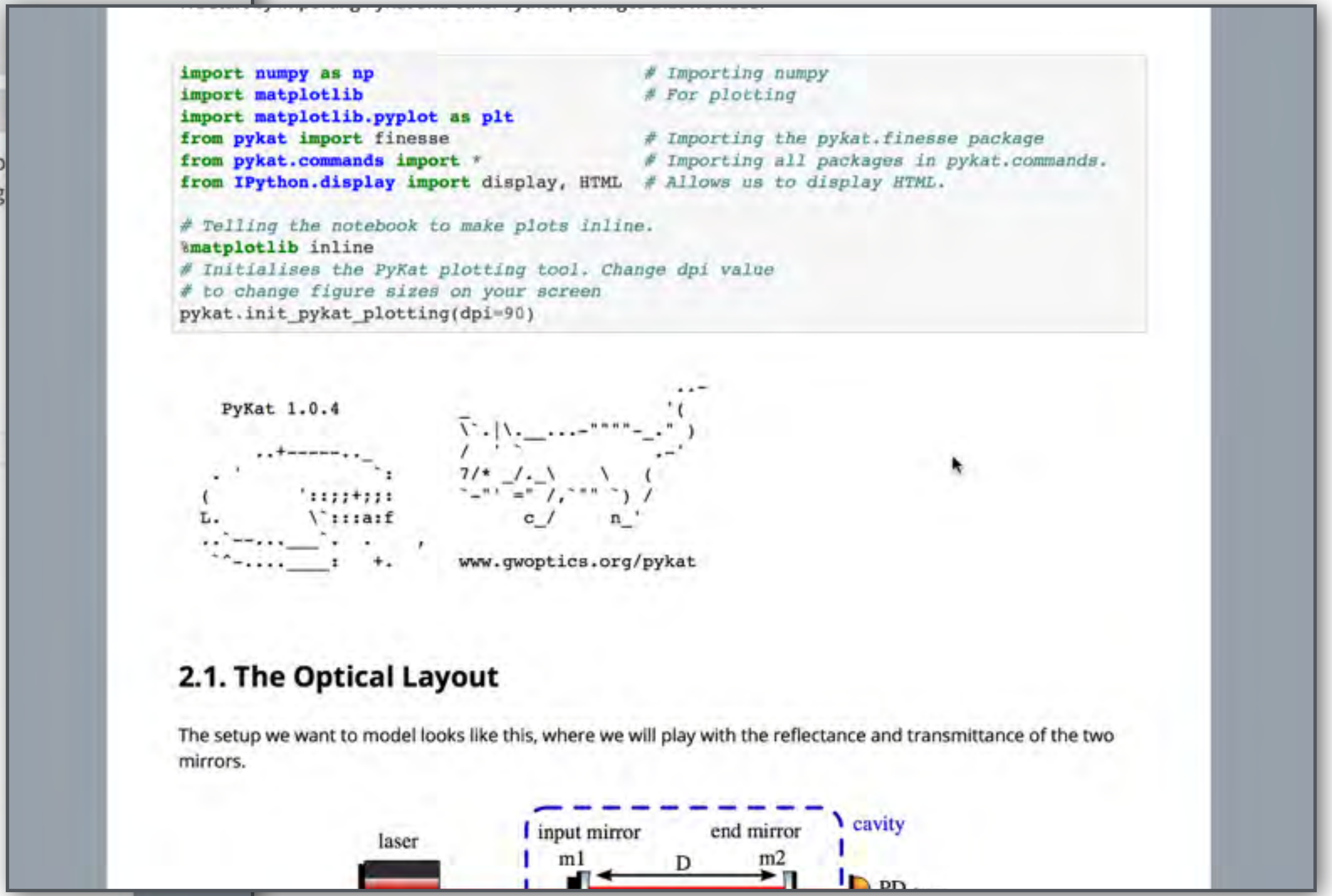
# Teaching a New Generation

- In 2015/2016 we ran two successful summer school for post-graduate students
- Teaching material entirely based on IPython notebooks
- Installed all software on user-owned laptops, using Anaconda
- teaching **laser interferometry**, **quantum optics**, **modelling**
- Now moving this material online

# http://www.gwoptics.org/learn/

# https://github.com/gwoptics/learn_laser_interferometry



# Does Python work for us?

Pros:

- Easy to learn, fun to use
- Free, cross platform
- Powerful and flexible
- Facilitates transparency, sharing, and teaching

Cons:

- Installation not trivial, often the show stopper for new users
- Variants of documentation and packages are confusing
- Lack of specific Matlab package **Simulink** for control systems

# More Python in LIGO

- **Automation and control of the LIGO detectors**: J.G. Rollins `Distributed State Machine Supervision for Long-baseline Gravitational-wave Detectors', https://arxiv.org/abs/1604.01456
- **Data analysis**, see for example the IPython notebook in the **open data release** of the first detection: https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.html

[Image from the film 'LIGO, A Passion for Understanding' by Kai Staats]

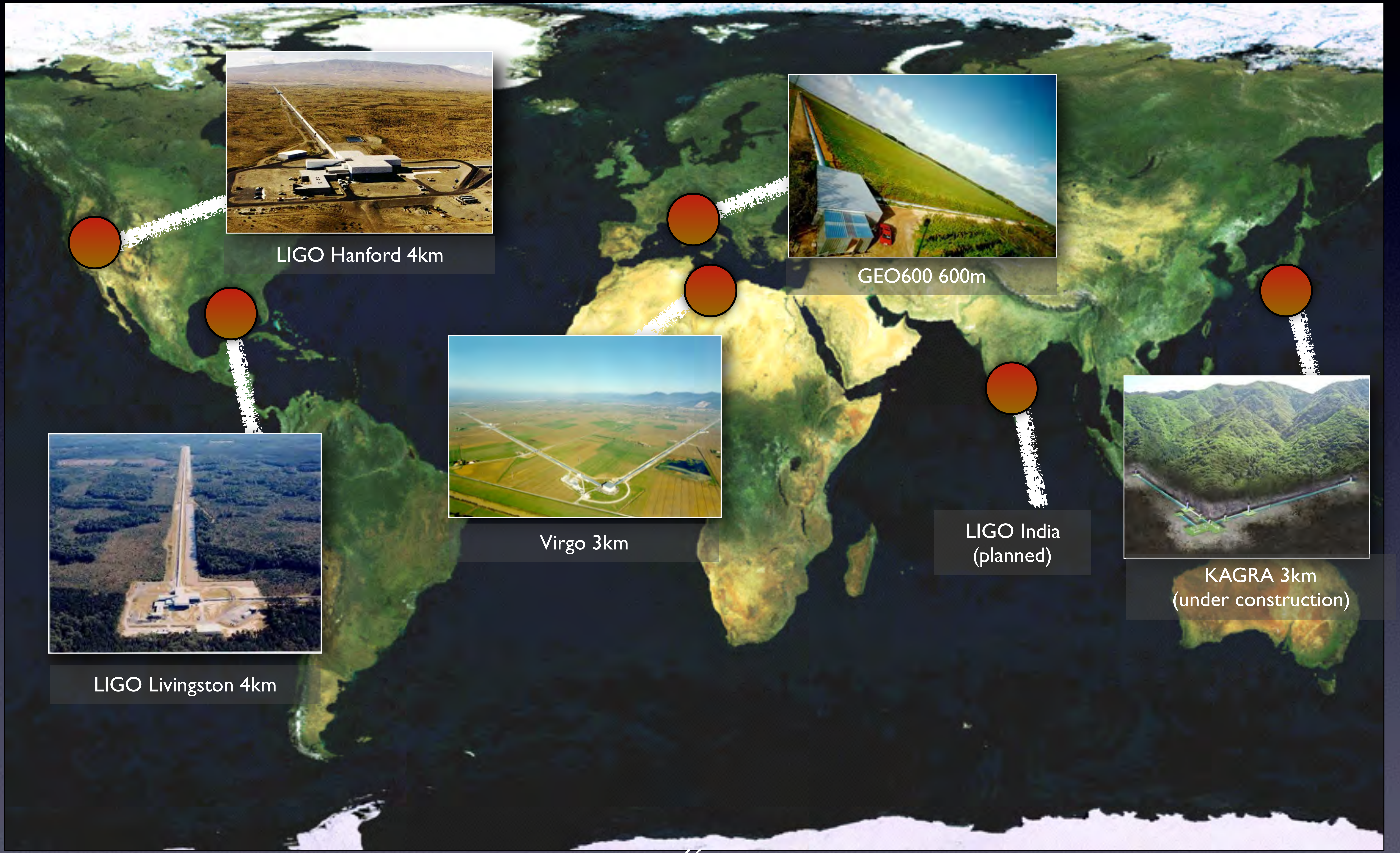

# Find out more!

www.ligo.org/magazine

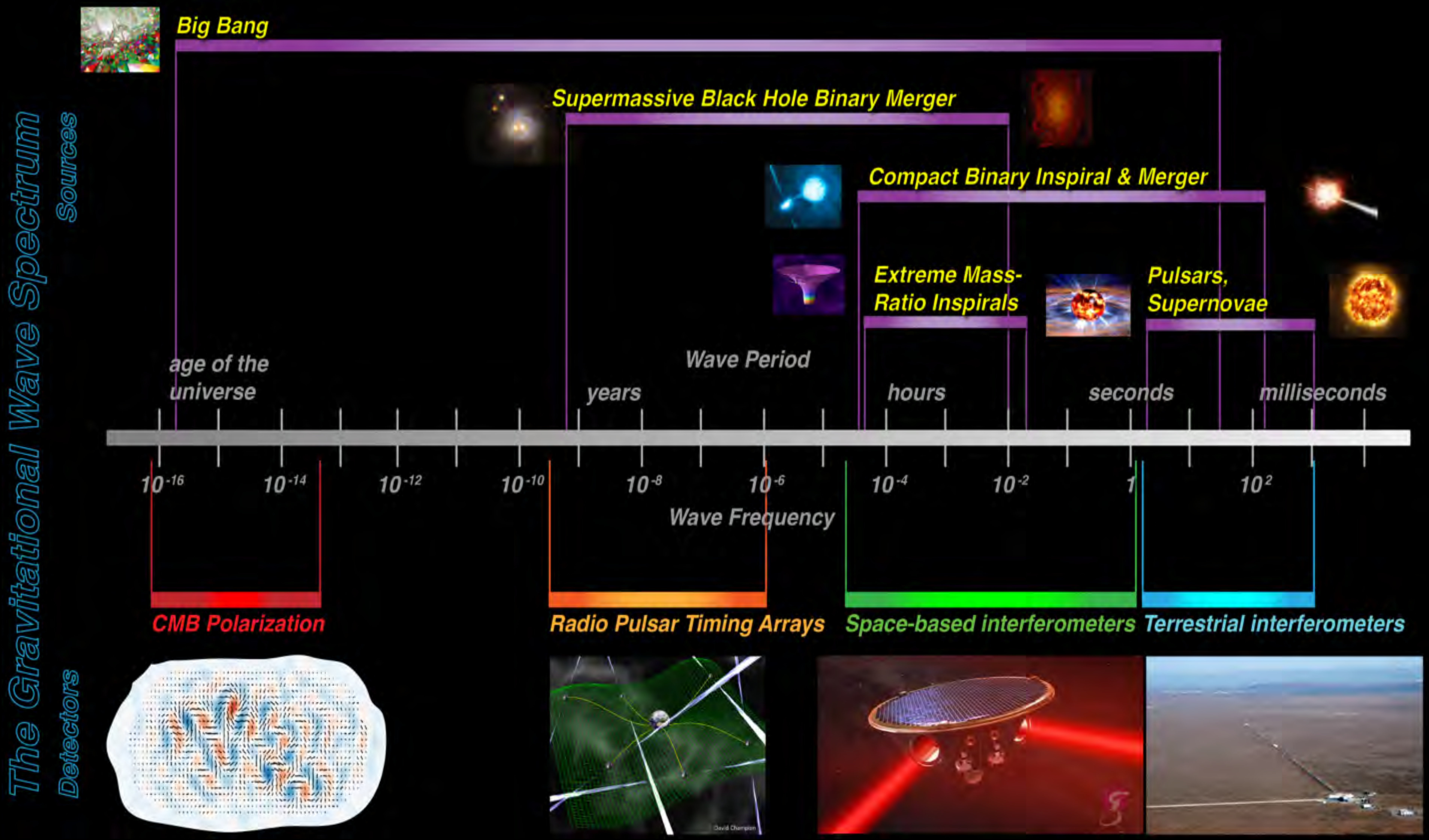
# Find out more!


www.ligo.org/magazine

# Ground-based detectors today



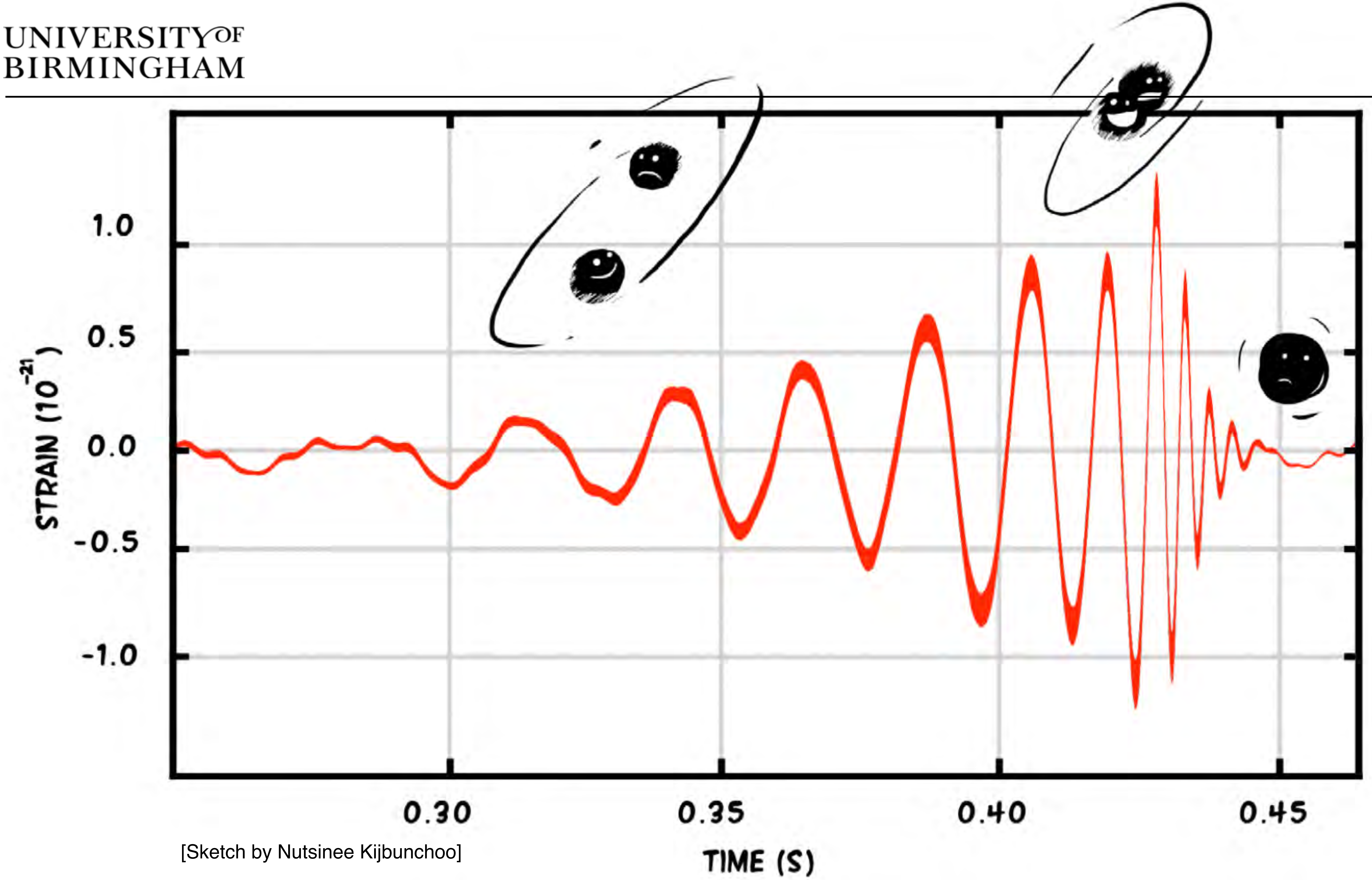
# The full GW spectrum



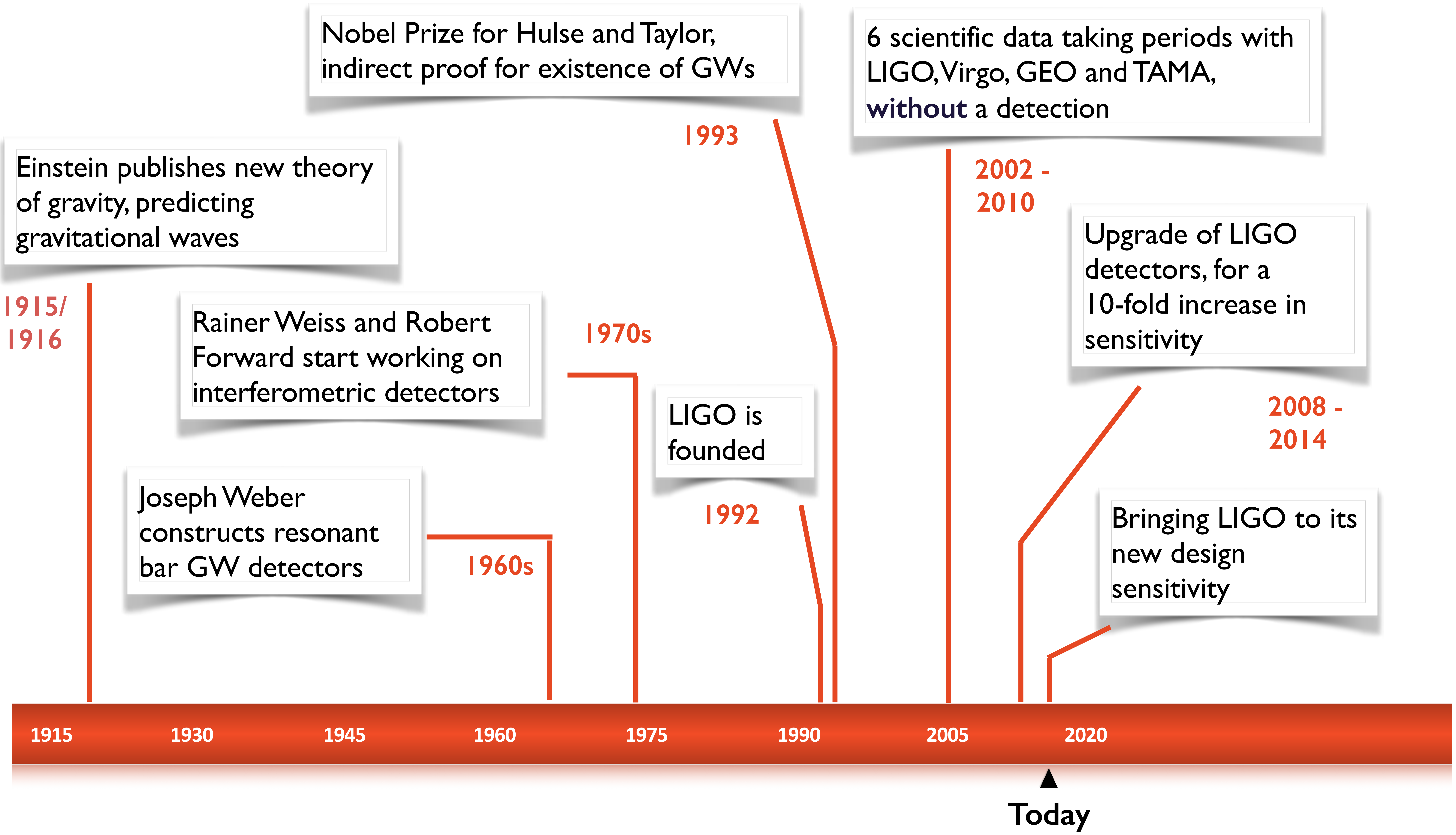

·(Credits: Ira Thorpe)

# Advanced LIGO Parameters

| Parameter | Value | Unit |
| --- | --- | --- |
| Laser wavelength | 1064 | nm |
| Arm cavity length, $L_0$ | 3994.5 | m |
| Power recycling cavity length, $l_{p,+}$ | 57.66 | m |
| Signal recycling cavity length, $l_{s,+}$ | 56.01 | m |
| Michelson asymmetry, $l_-$ | 8 | cm |
| Input mode cleaner length (round trip) | 32.95 | m |
| Output mode cleaner length (round trip) | 1.13 | m |
| Input mode cleaner finesse | 500 | |
| Output mode cleaner finesse | 390 | |
| Round trip loss in arm cavity, $Y_{arm}$ | 85–100 | ppm |
| Arm cavity build–up, $G_{arm}$ | 270 | |
| Power recycling gain, $G_{prc}$ | 38 | |
| Signal recycling attenuation, $1/G_{src}$ | 0.11 | |
| Common coupled cavity build–up, $G_+$ | 5000 | |
| Differential coupled cavity build–up, $G_-$ | 31.4 | |
| Common coupled cavity pole, $f_+$ | 0.6 | Hz |
| Differential coupled cavity pole, $f_-$ | 335–390 | Hz |
| RF modulation index | 0.13–0.26 | rad |
| Test mass diameter | 34 | cm |
| Test mass thickness | 20 | cm |
| Beam size at end test mass | 6.2 | cm |
| Beam size at input test mass | 5.3 | cm |
| Mass of the test mass, $M$ | 40 | kg |




[Sketch by Nutsinee Kijbunchoo]


Einstein publishes new theory of gravity, predicting gravitational waves
1915/ 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
1915
1930
1945
1960
1975
1990
2005
2020
Today

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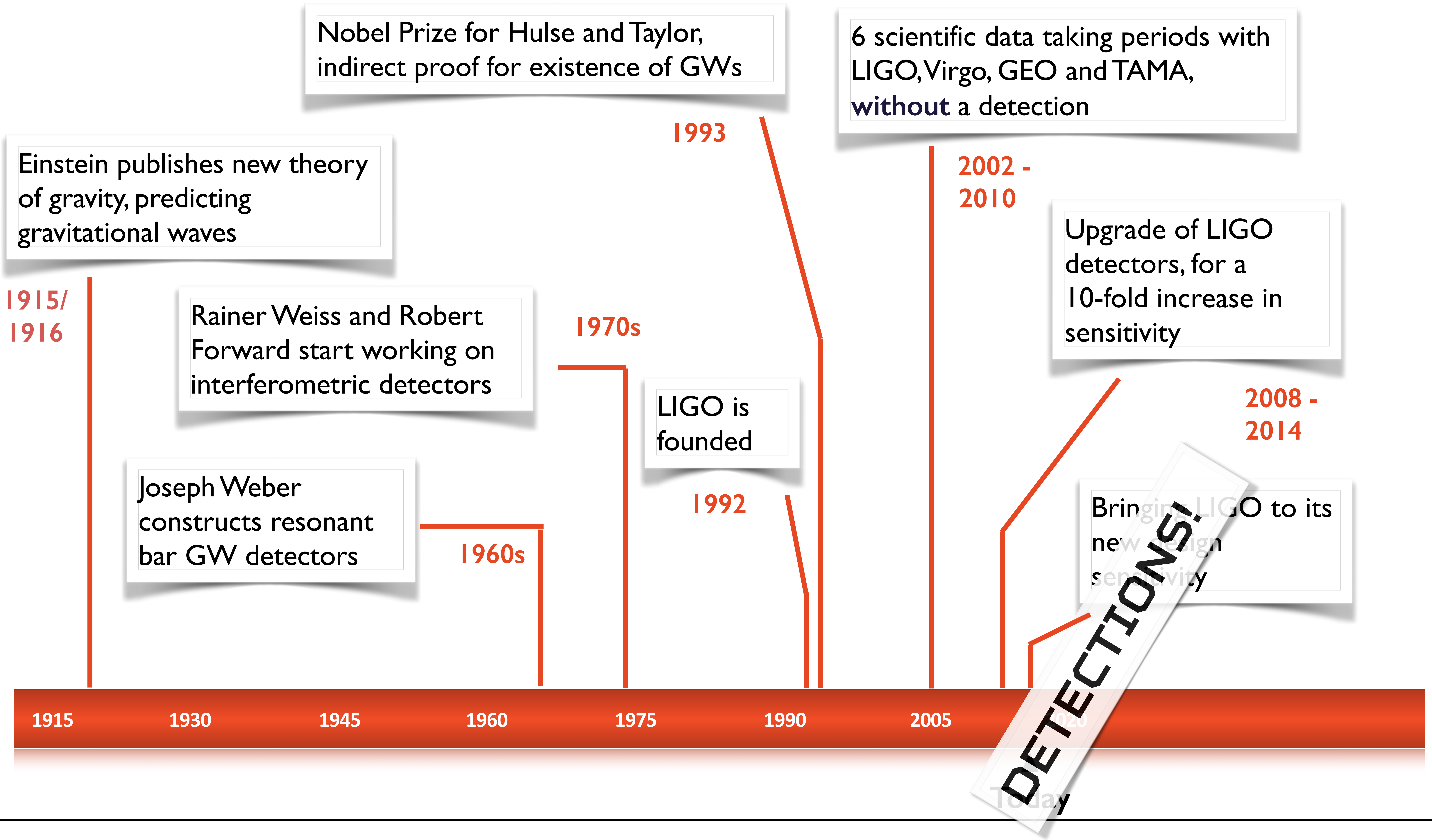
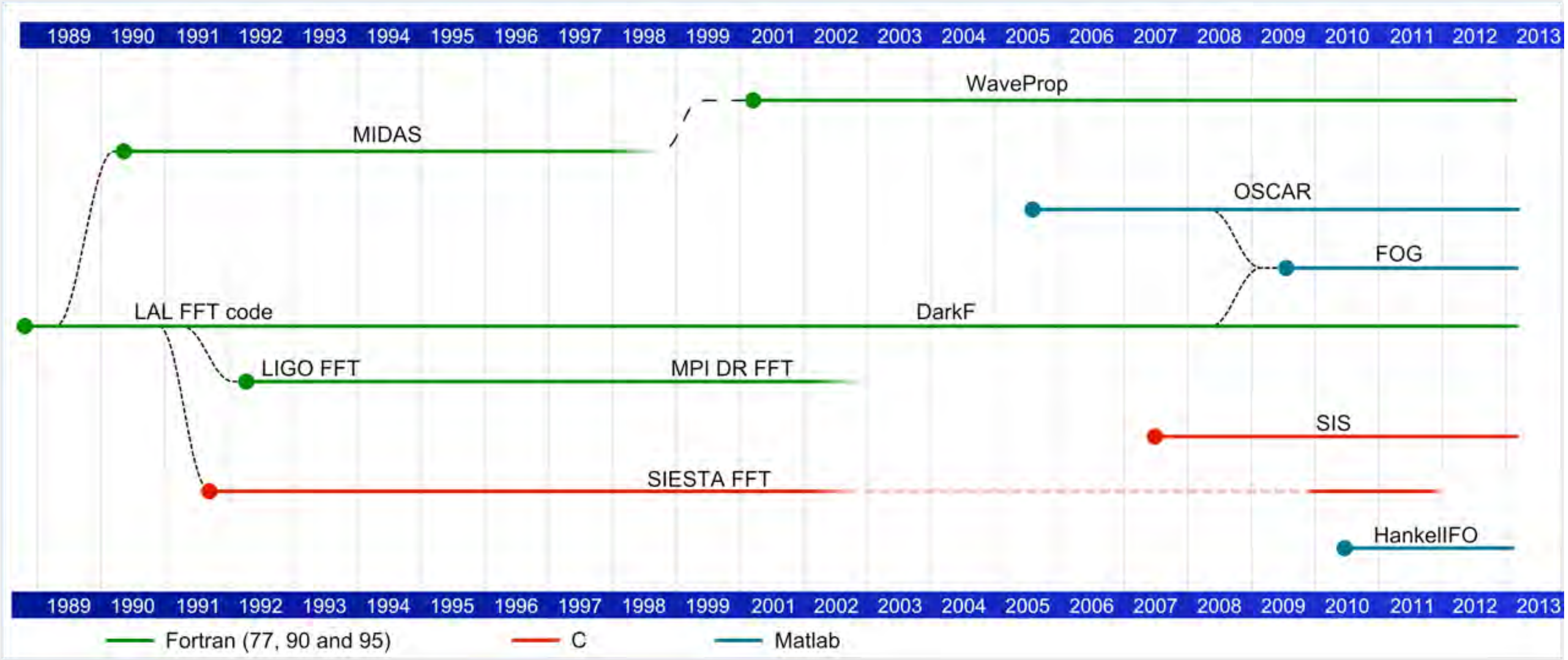
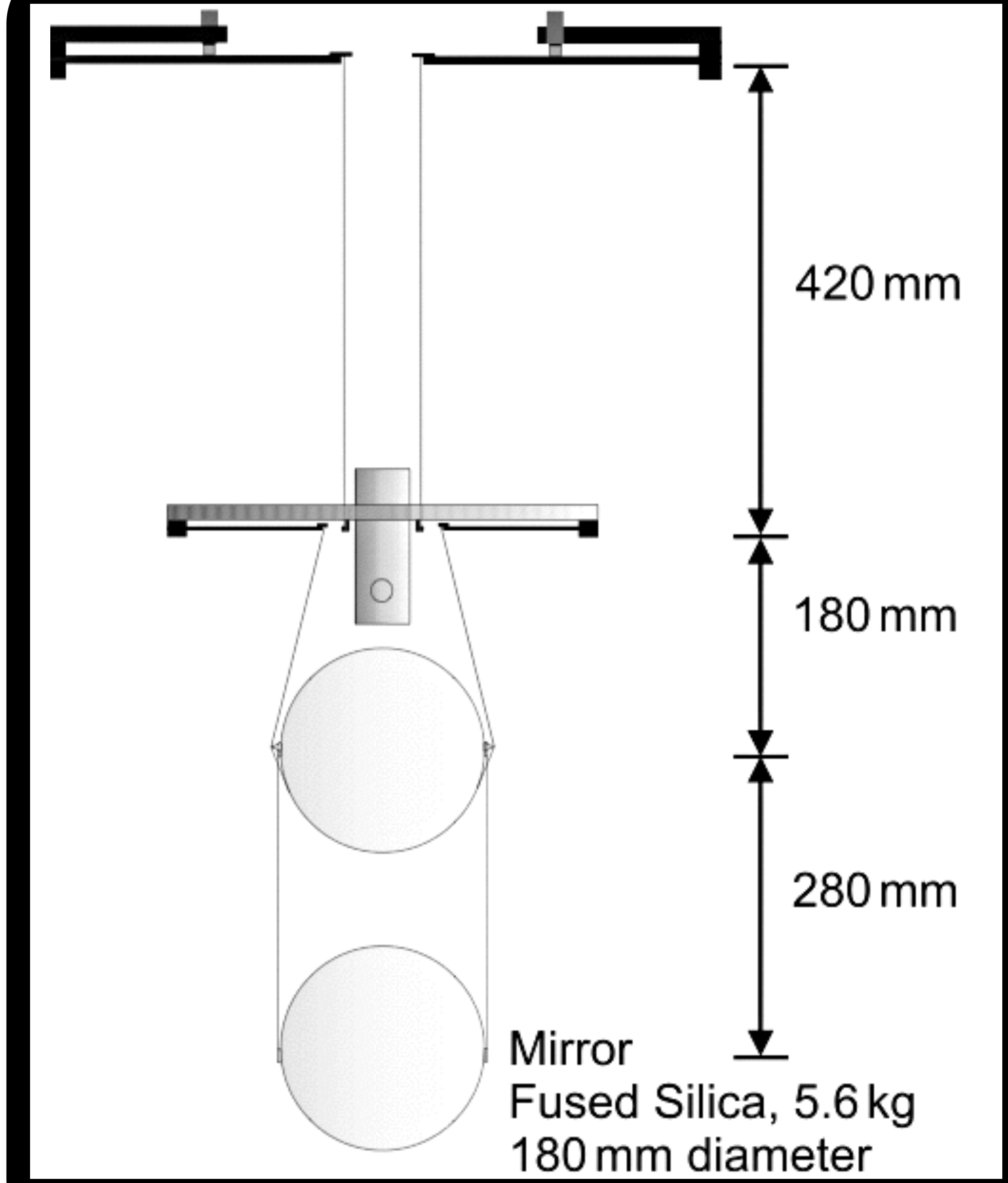


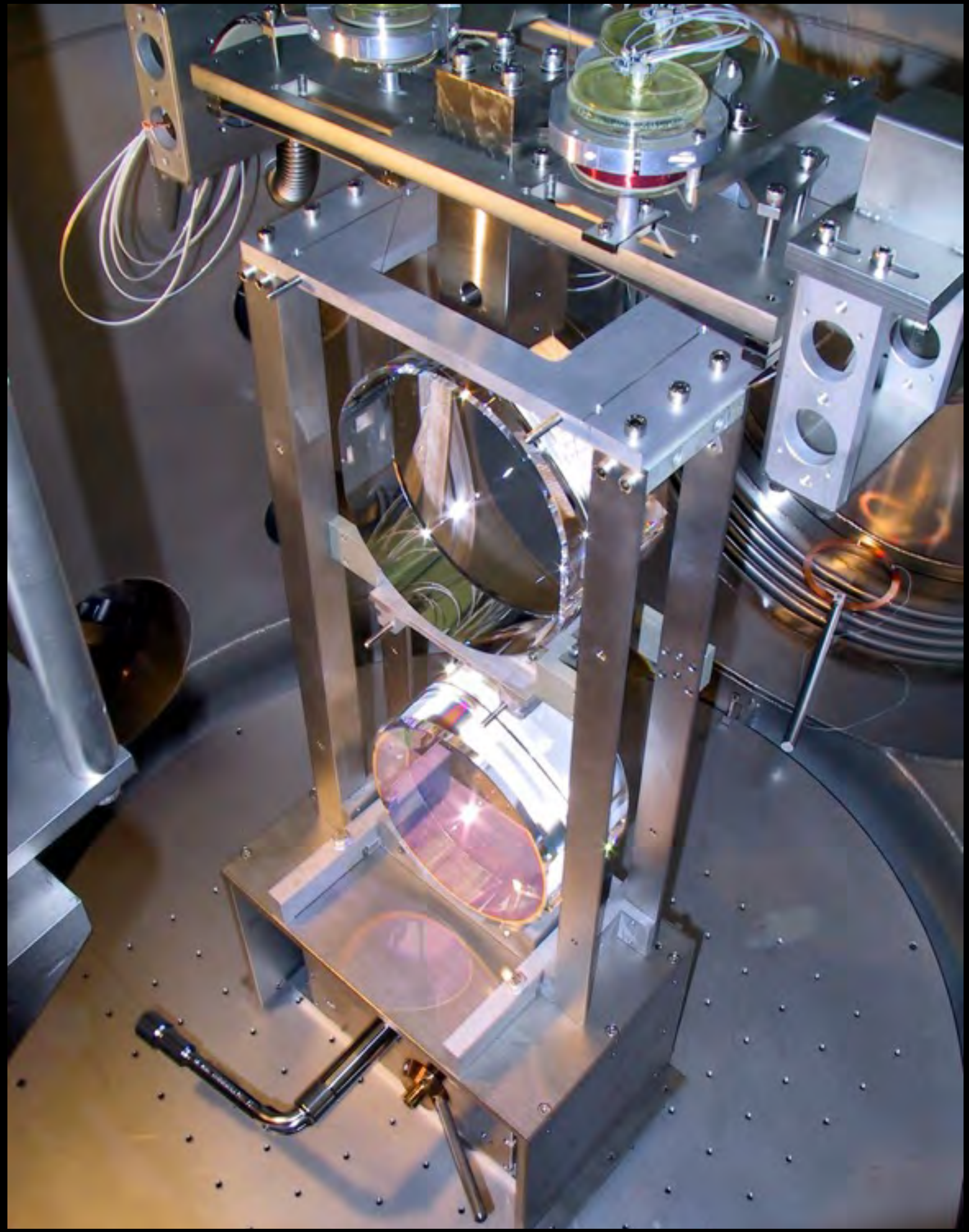
# Life and Death of Simulations




[Talk by Jerome Degallaix, LIGO commissioning and simulation workshop, Feb. 2013]

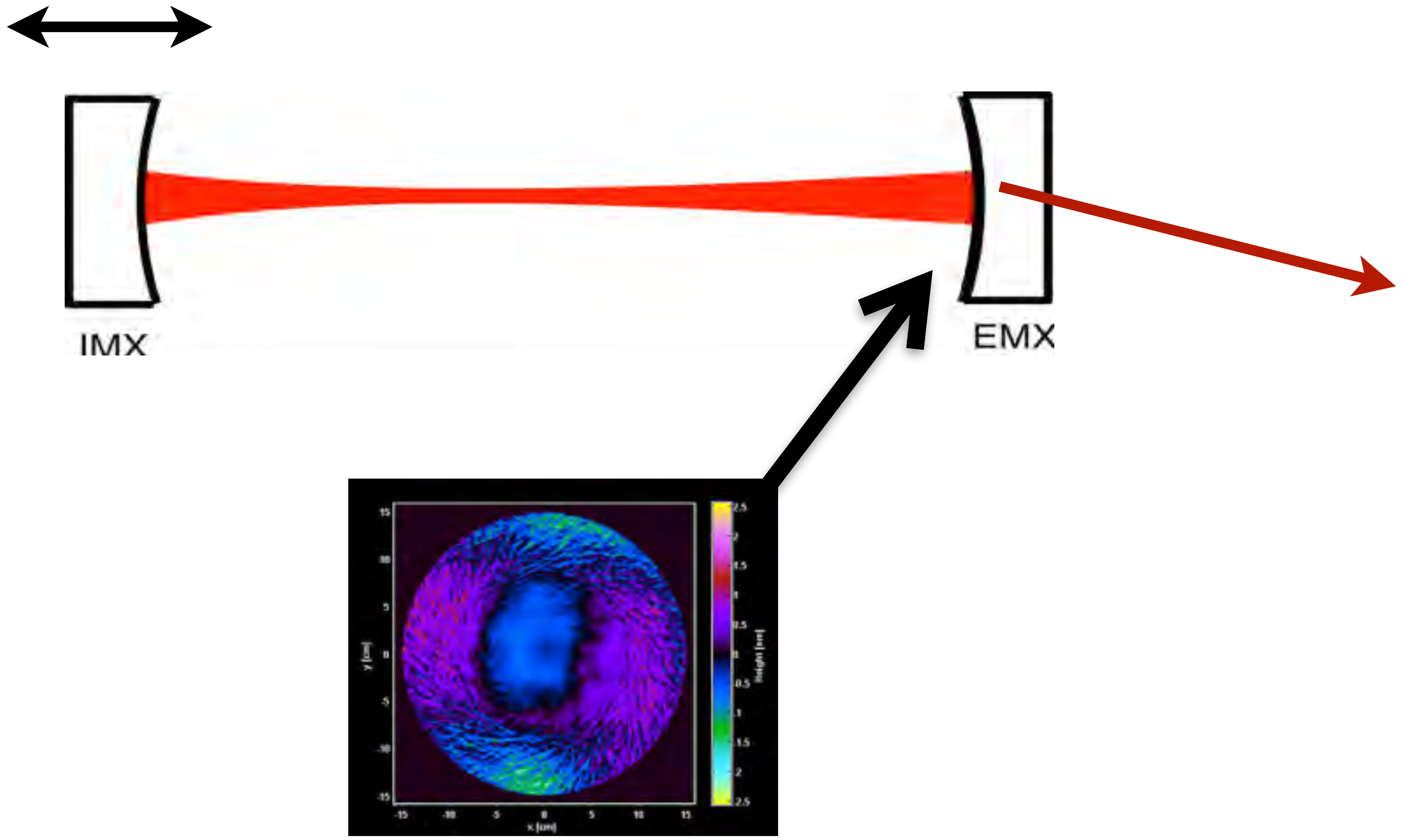
# A GEO600 Mirror Suspension

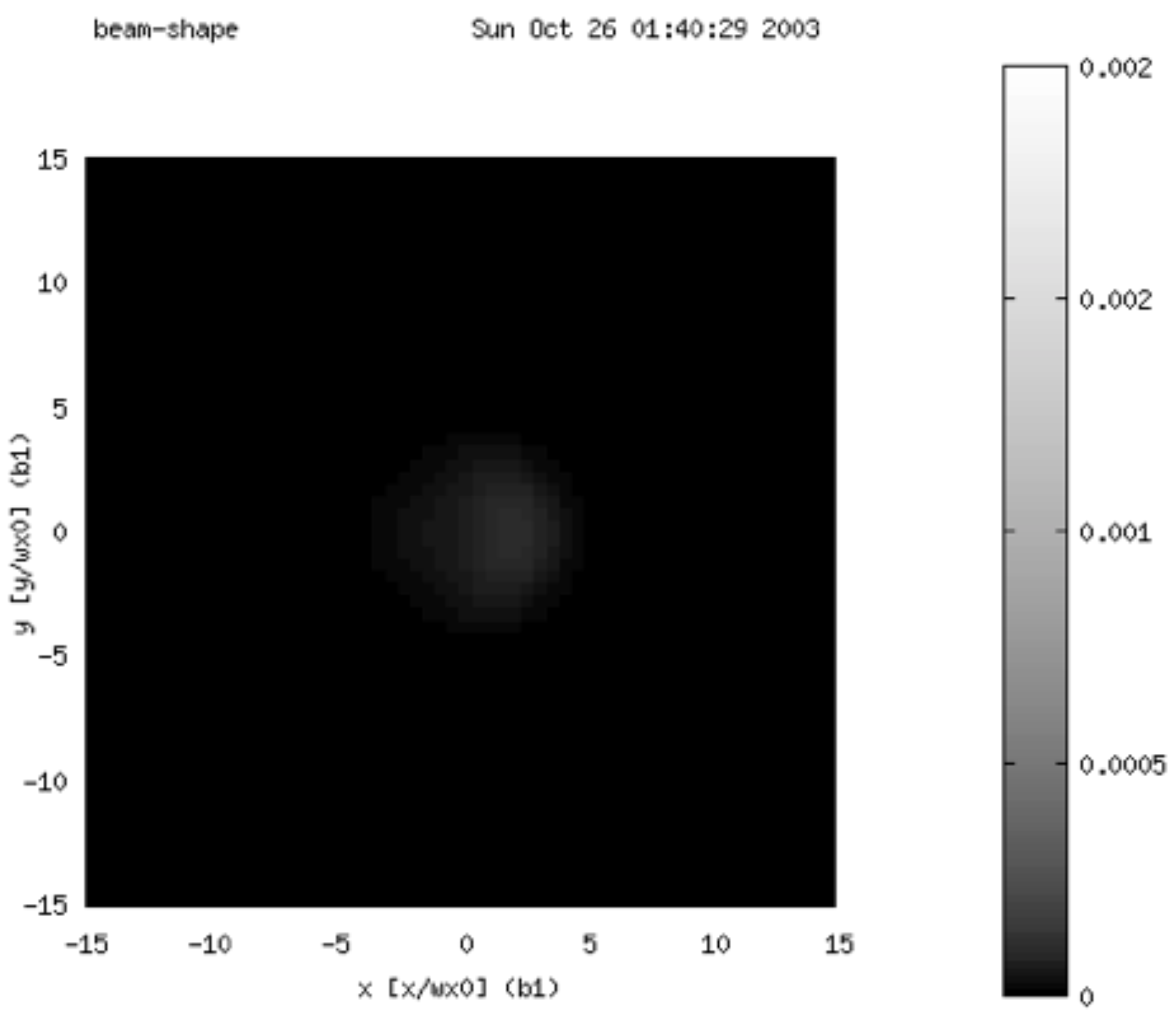


# Beam Shape Distortions

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

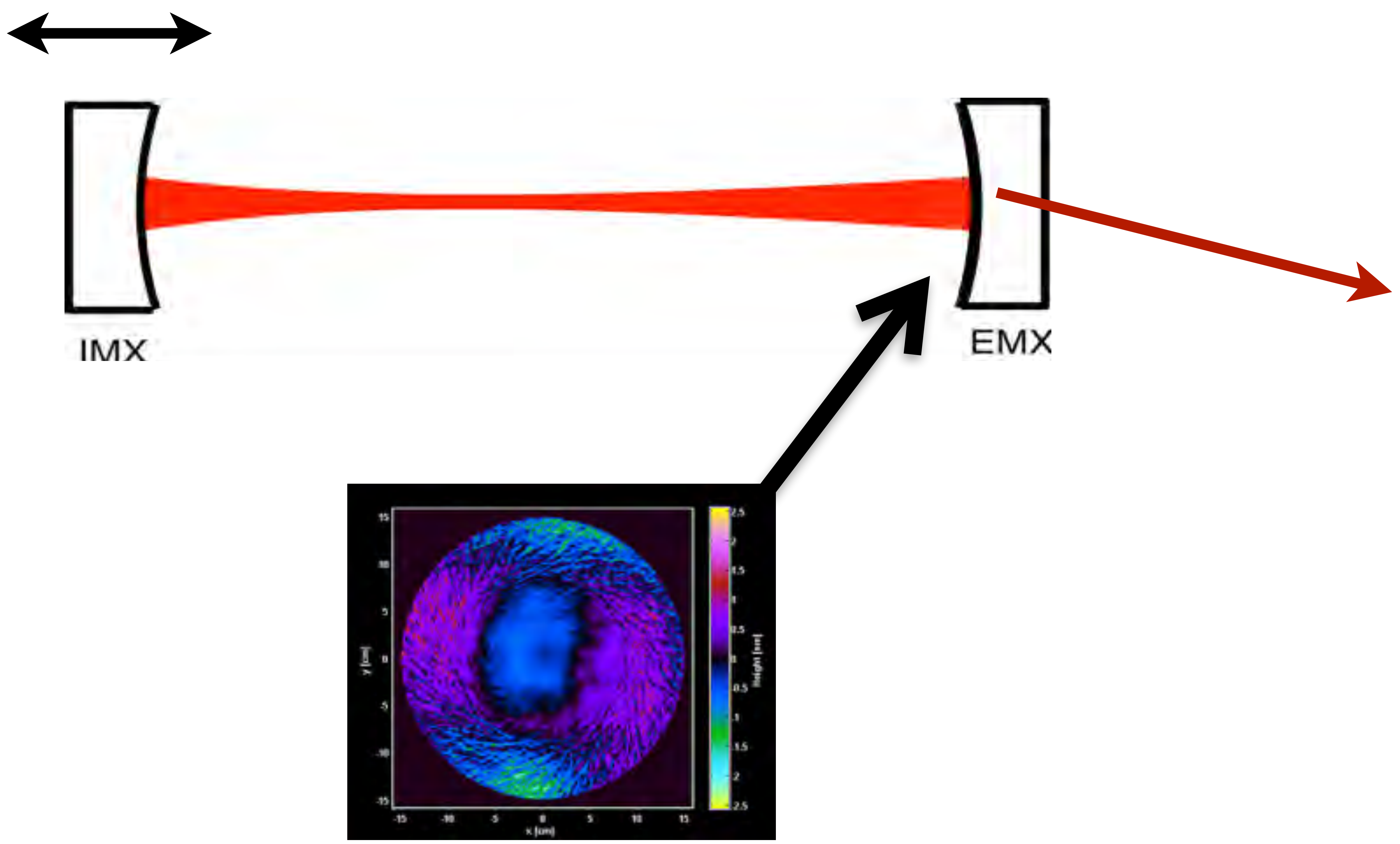


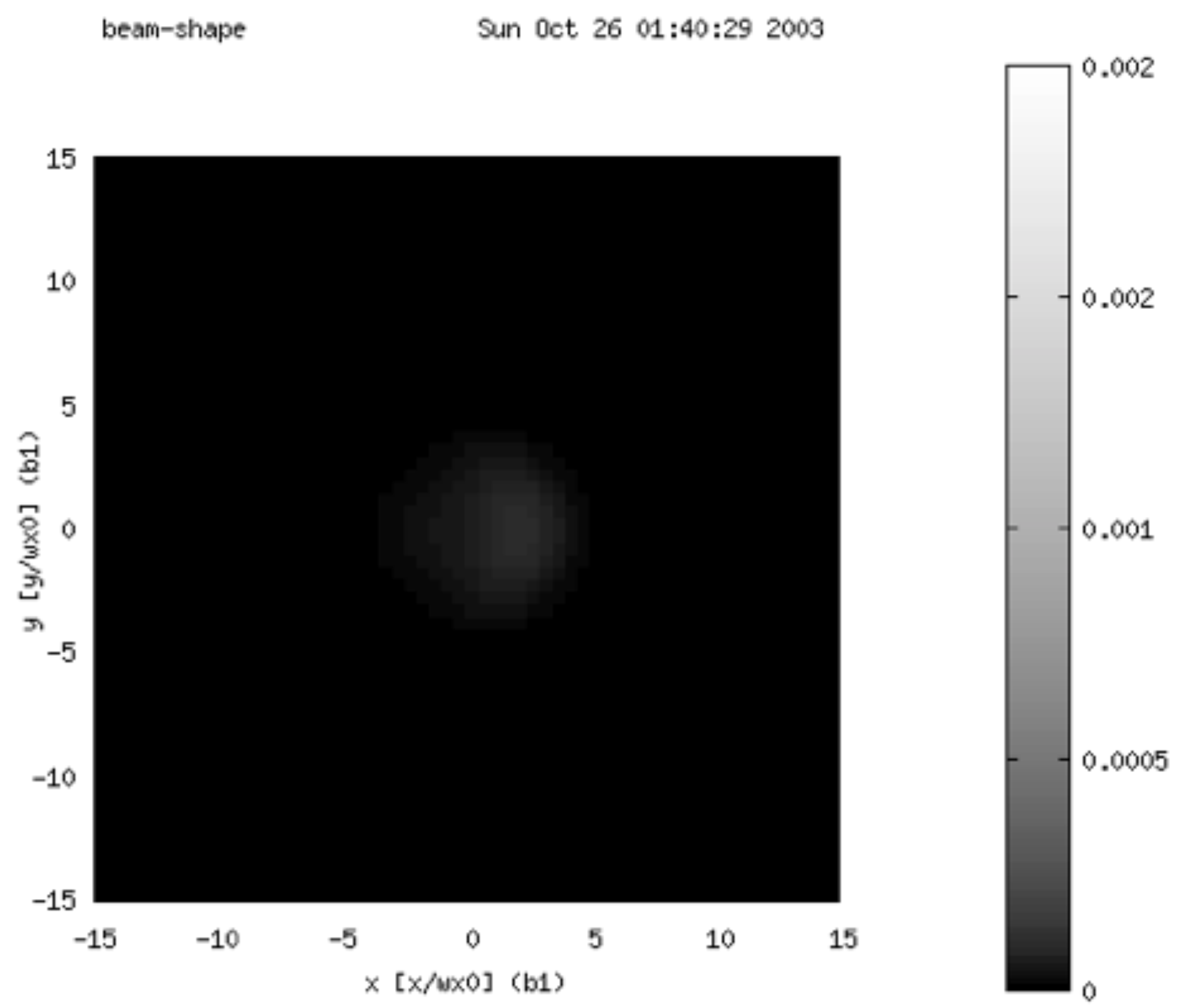




Beam shape inside arm cavity

# Beam Shape Distortions

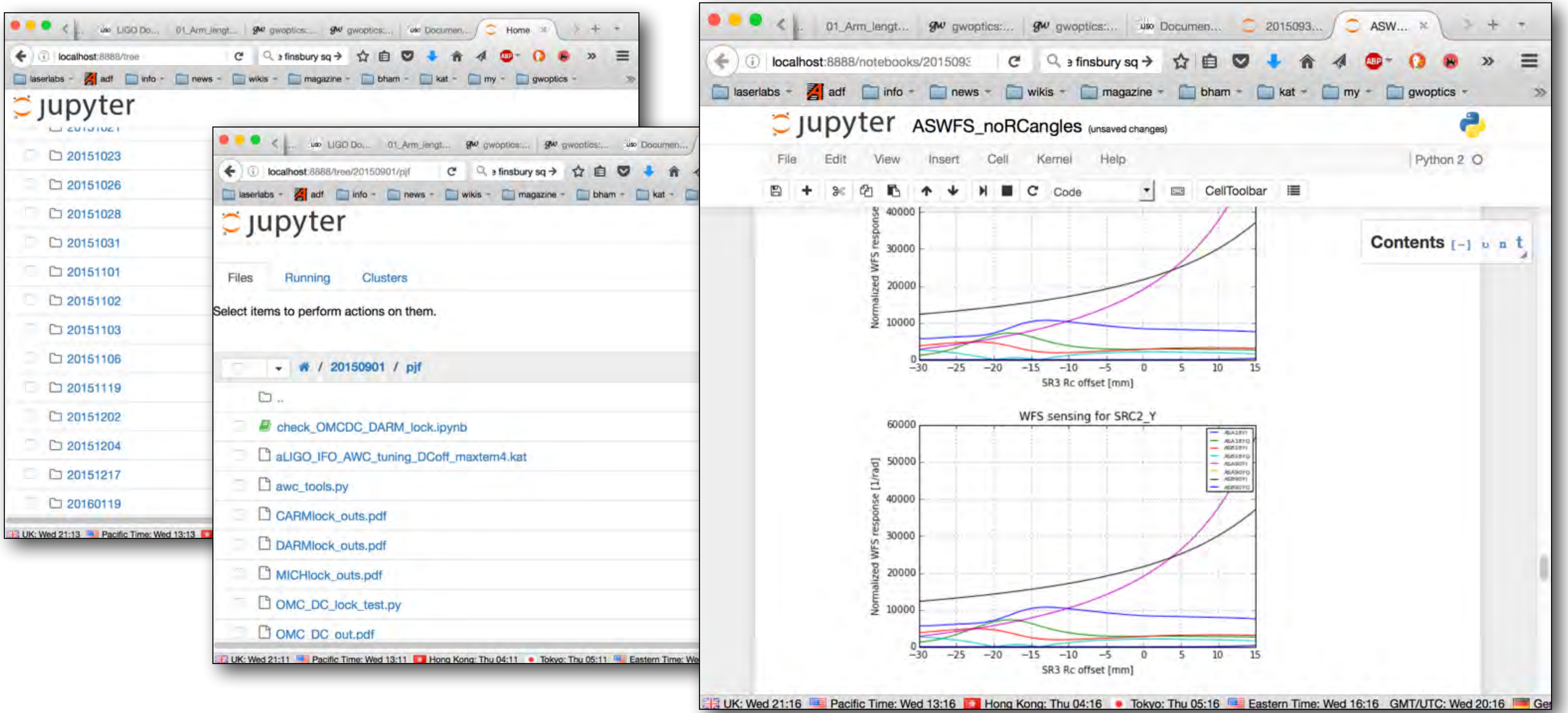
Acceptance of mirrors from manufacturer: Computer models are used to estimate the optical distortions due to the measured mirror distortions.




Beam shape inside arm cavity

# LIGO commissioning, task sharing and recording



# Why Interferometer Simulations?

- Investigation of **new interferometry techniques**, or **new optical technologies**
- **Optical design** of the gravitational wave detectors, computation of **requirements** for optical components
- **Commissioning** of the detectors