LASER RANGING IN ANEW 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:



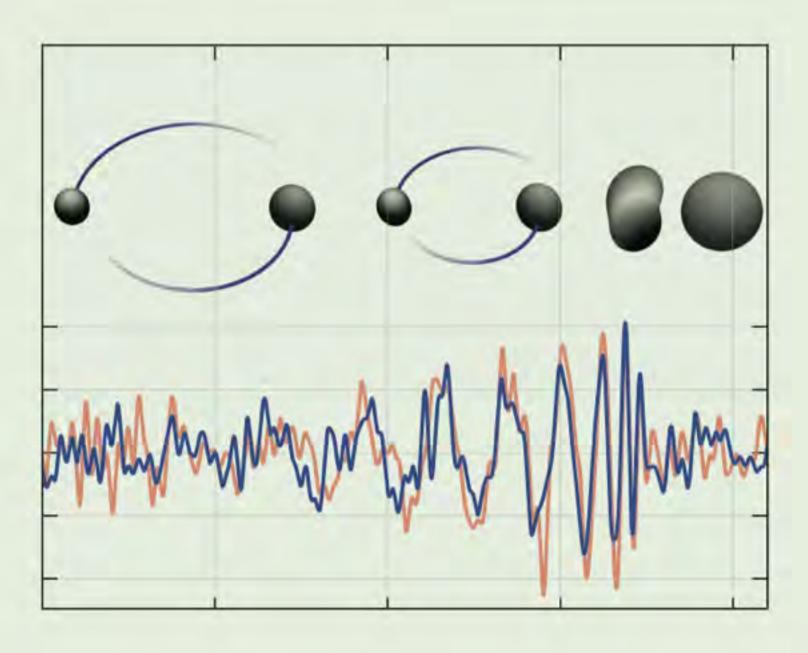


PHYSICAL REVIEW LETTERS

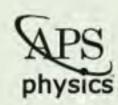
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12 FEBRUARY 2016



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Volume 116, Number 6



Astronomy





Hubble Space Telescope

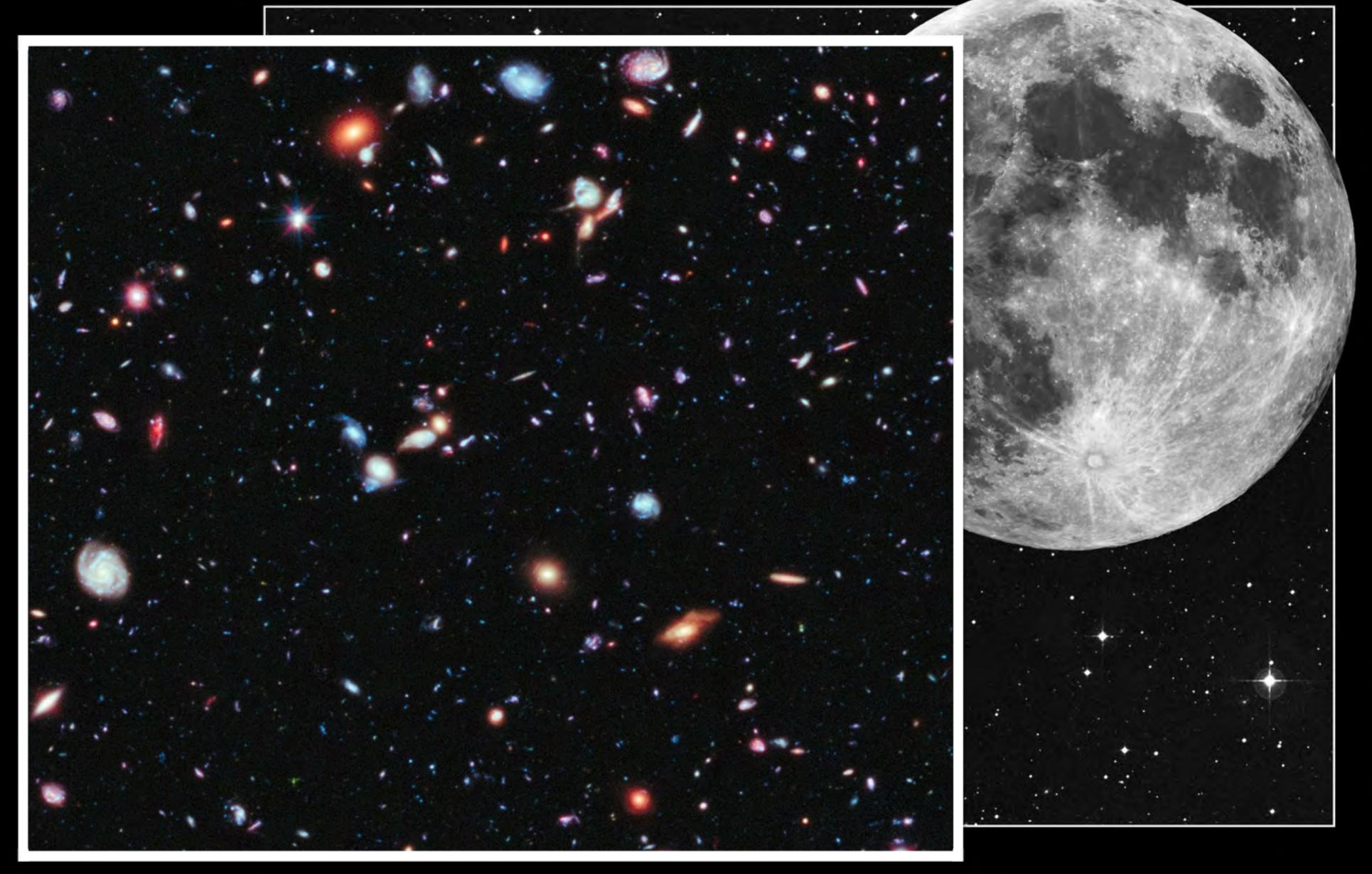






[NASA, ESA, Z. Levay (STScI), T. Rector, I. Dell'Antonio/NOAO/AURA/NSF, G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz), R. Bouwens (Leiden University) and the HUDF09 Team]

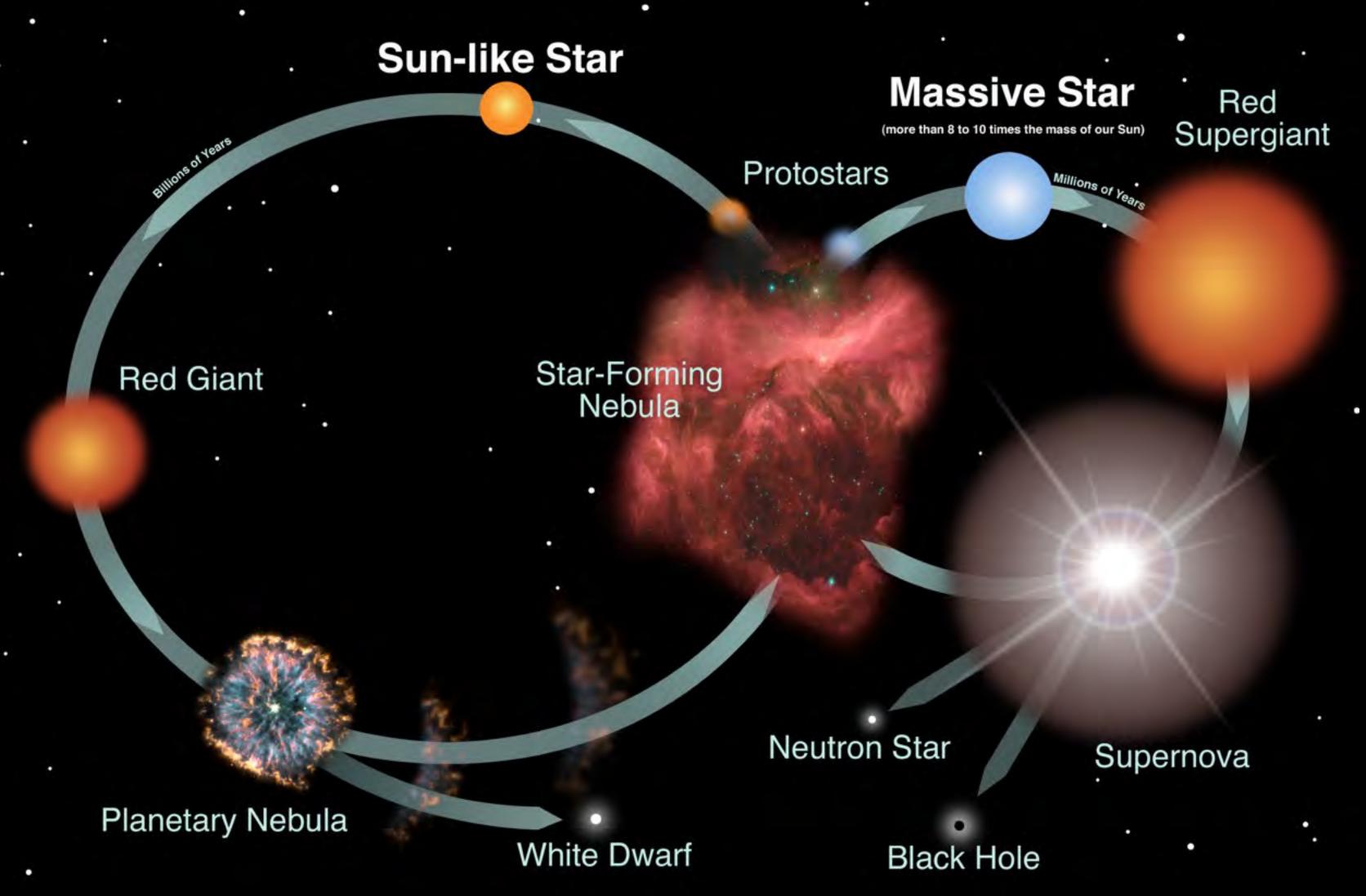


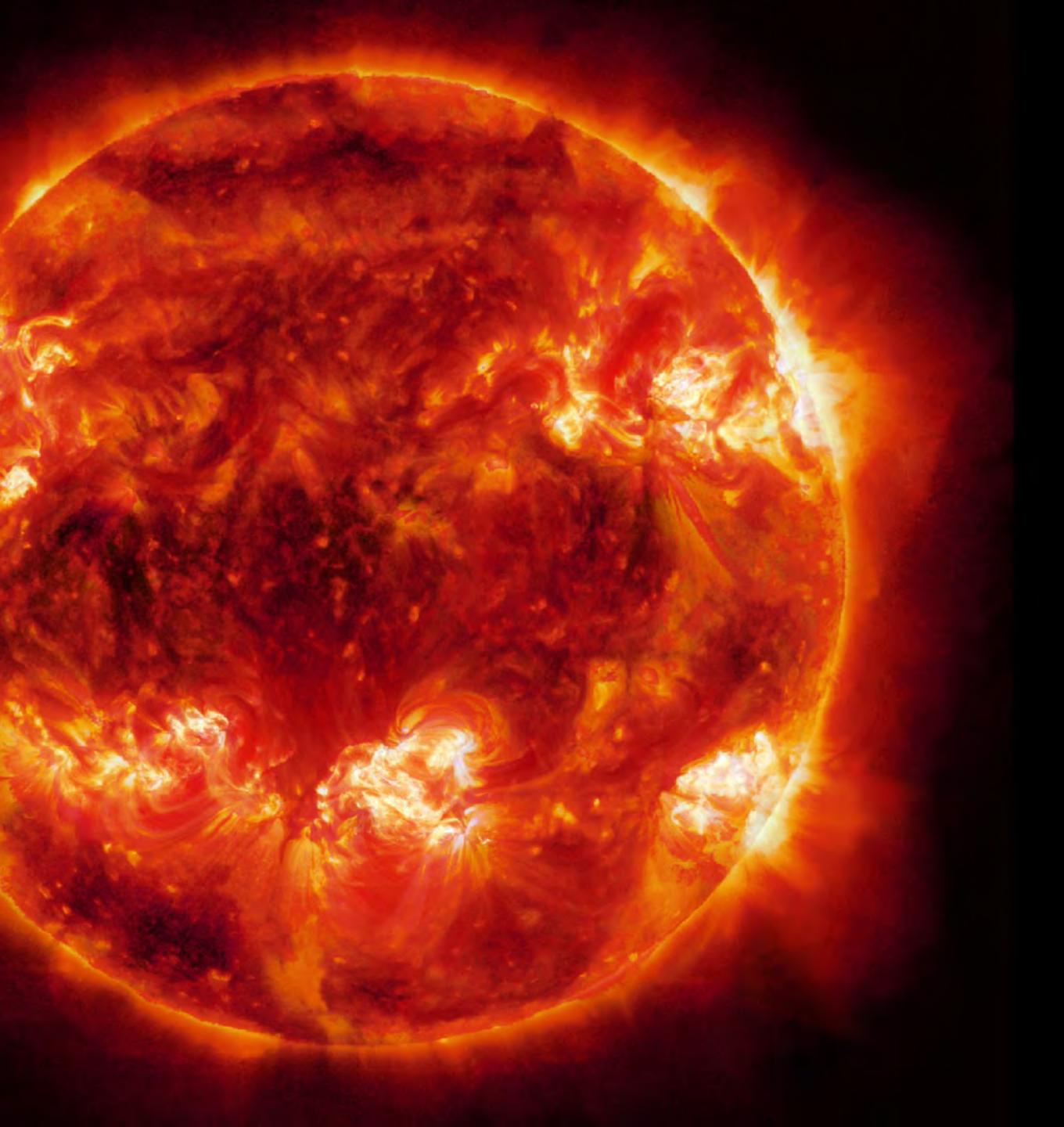


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Life Cycle of Stars

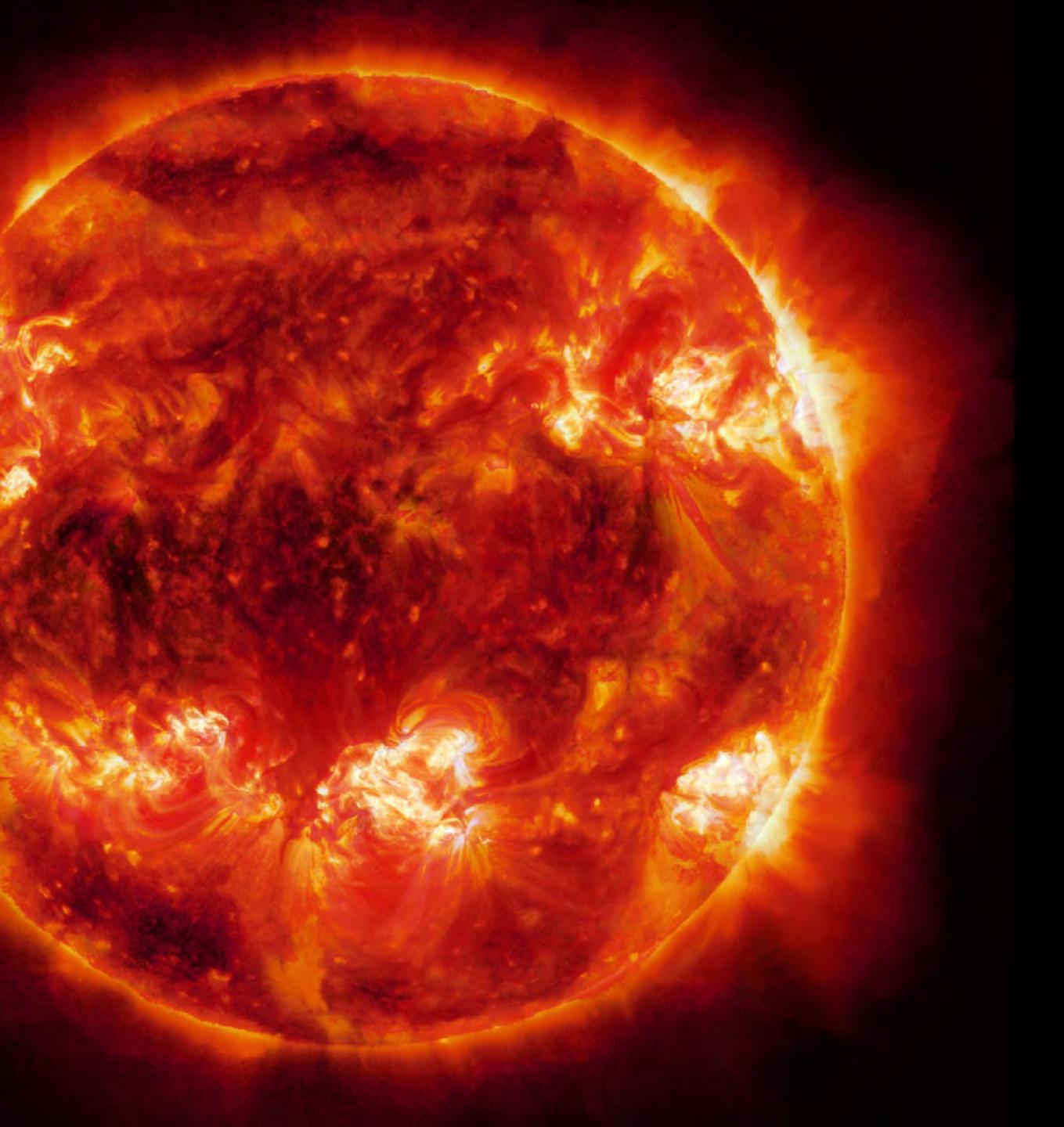




The Sun

Size = 109 × Earth

Mass = 333000 × Earth



The Sun

Size = 109 × Earth

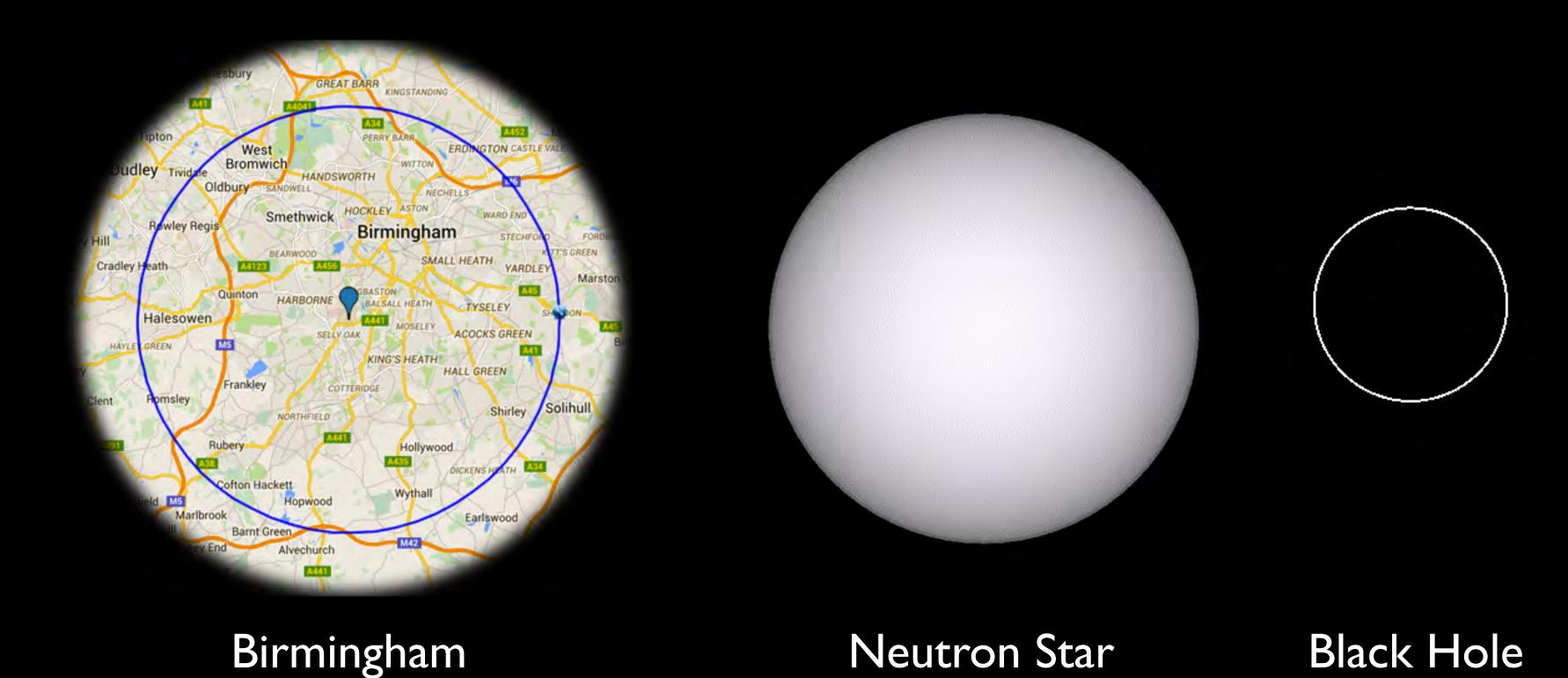
Mass = 333000 × Earth



Earth and Moon

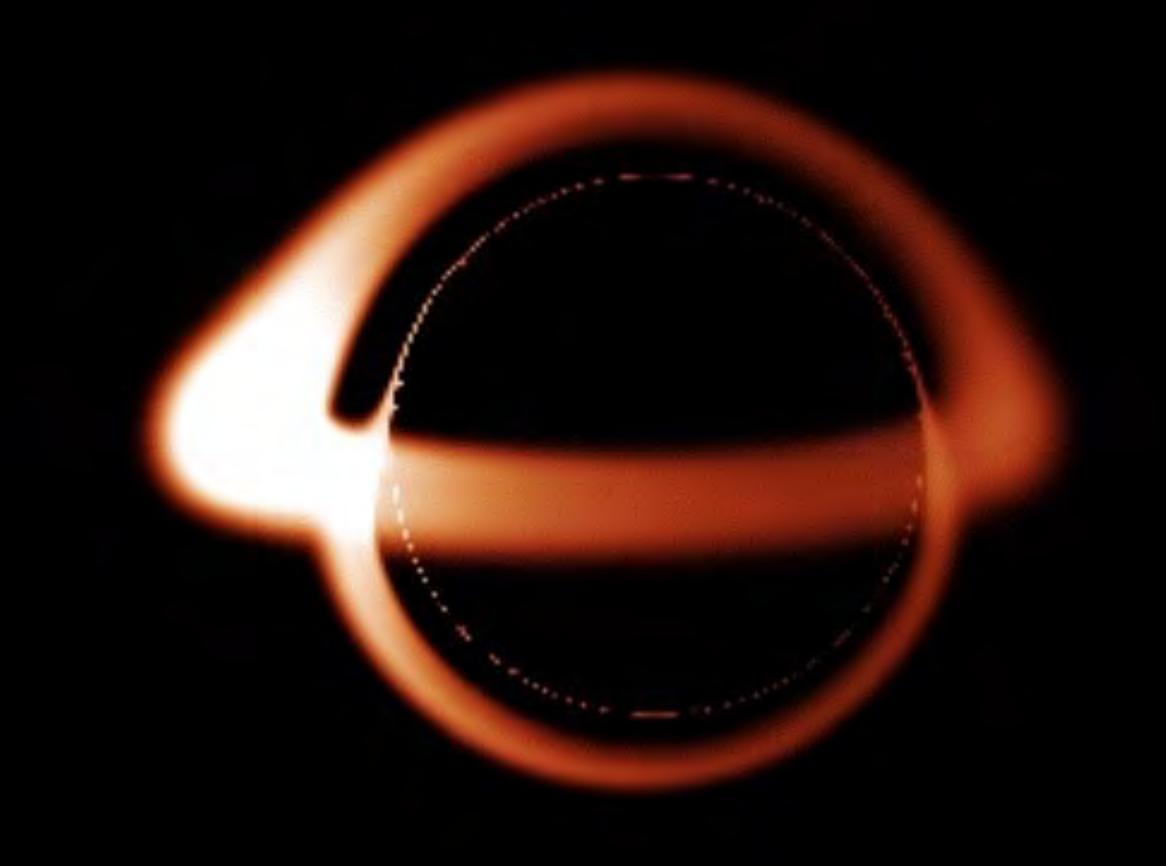


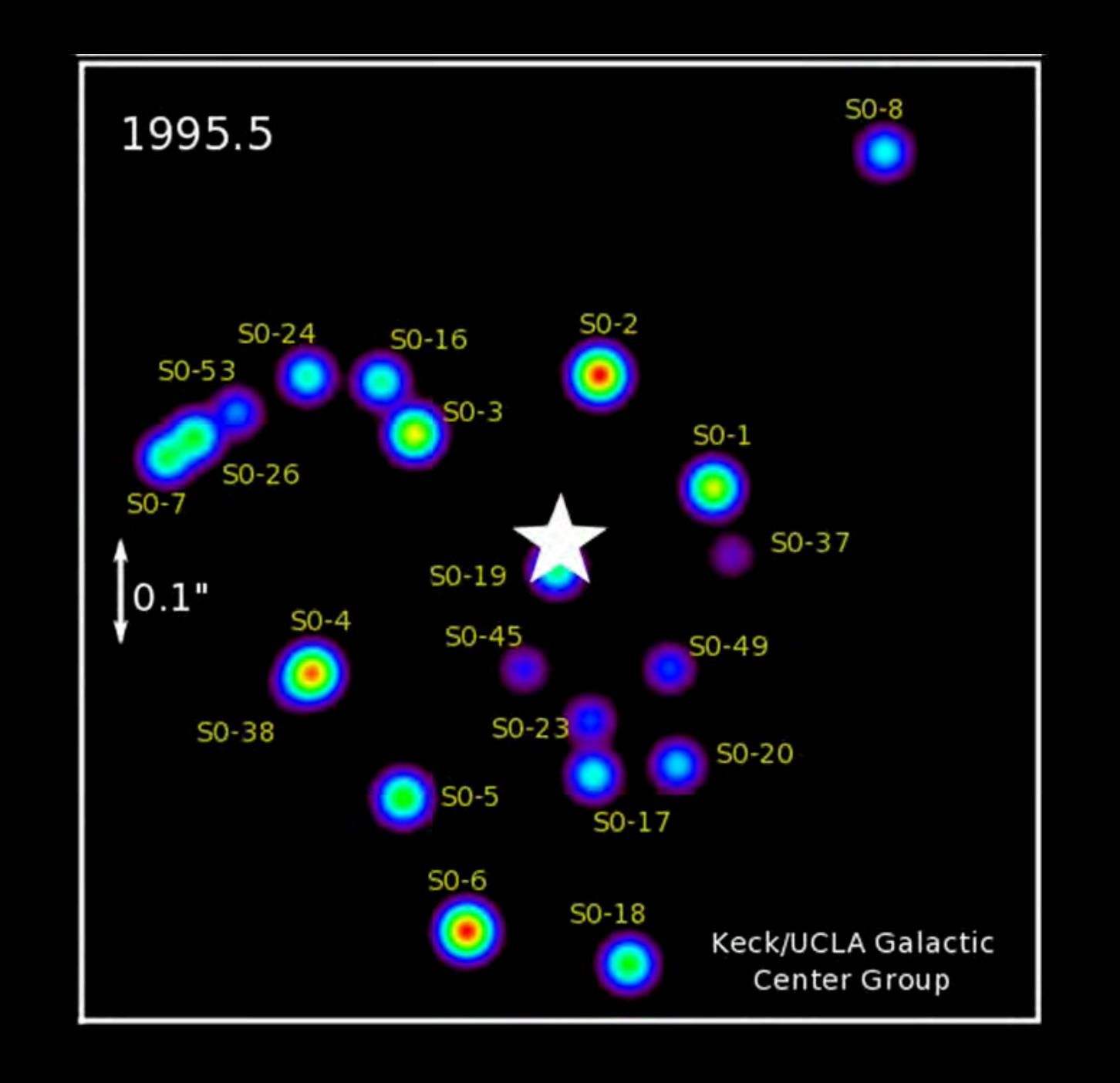
Neutron Stars and Black Holes

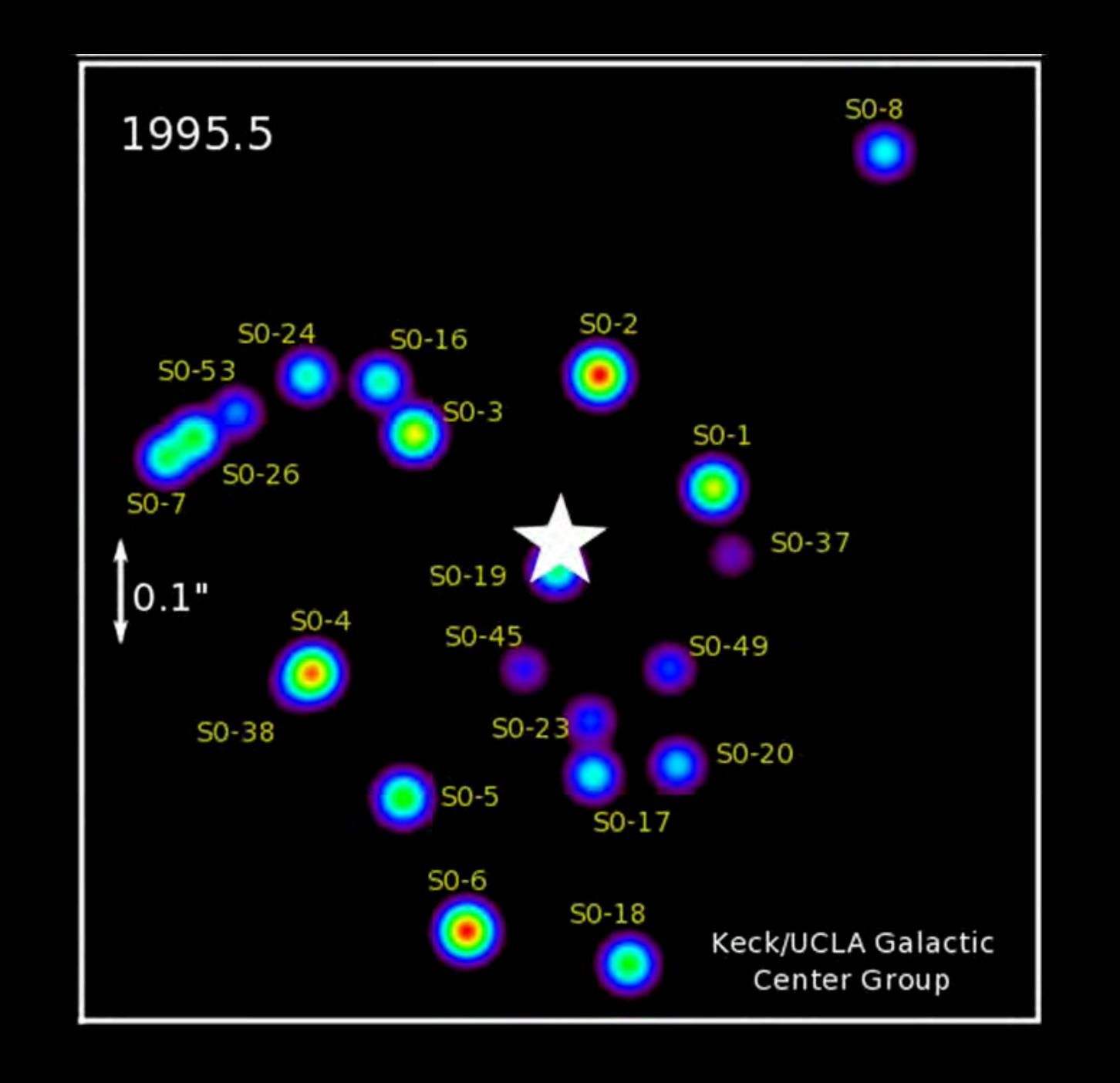




What are Black Holes?









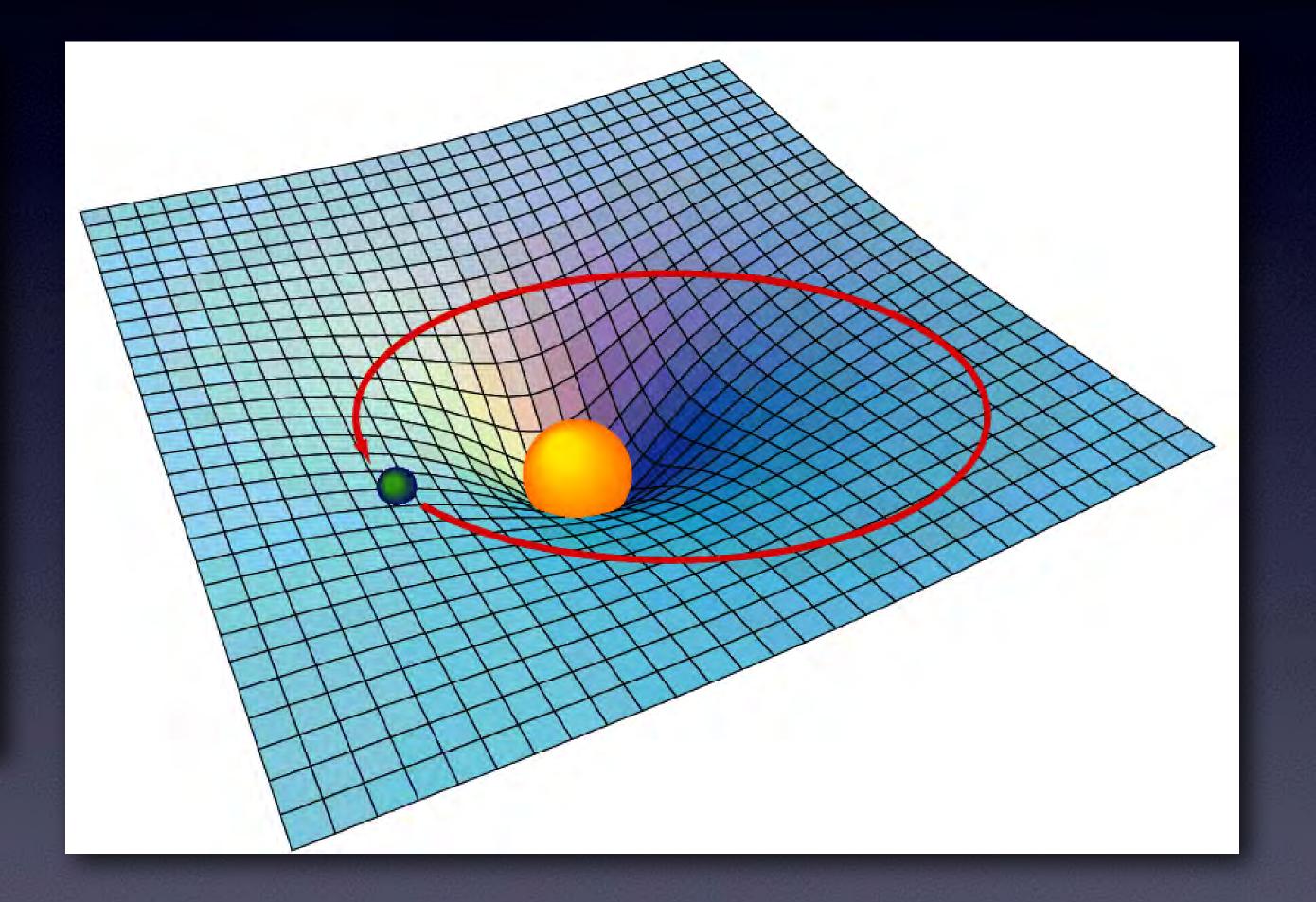
Einstein's Theory of Relativity

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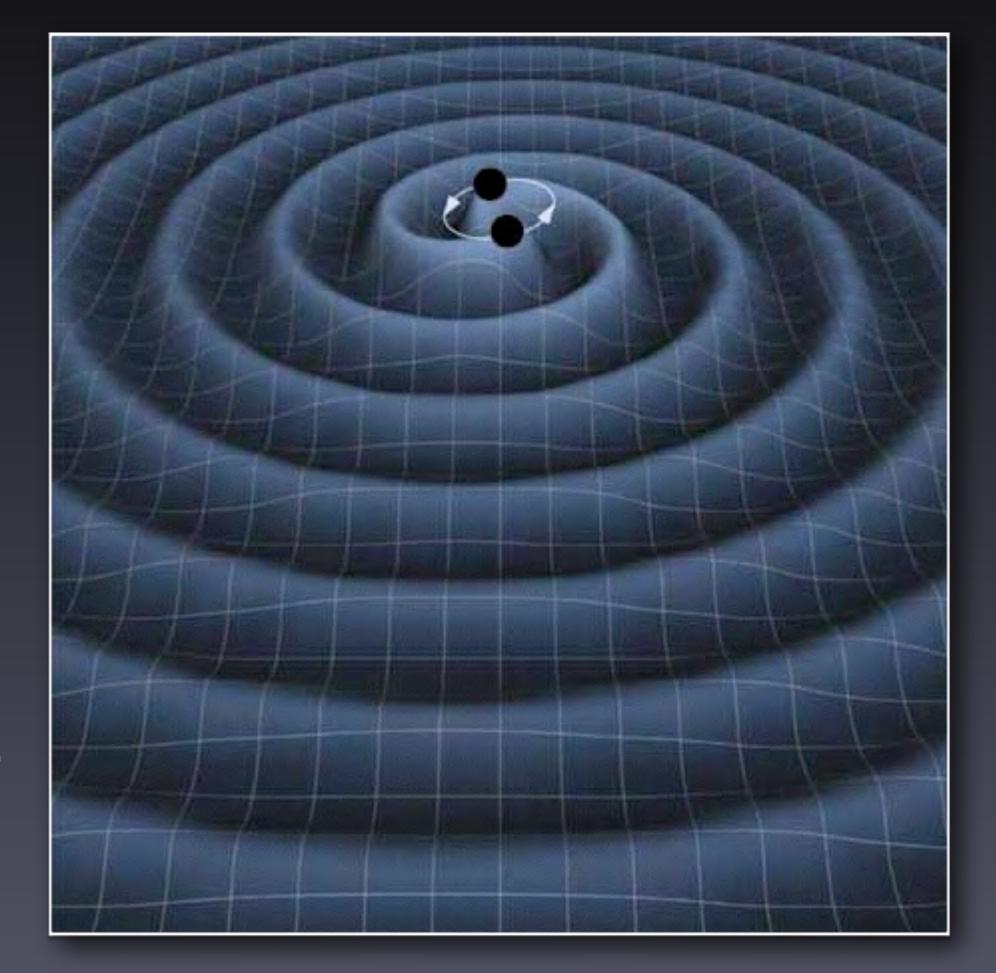
Einstein, Die Grundlage der allgemeinen Relativitätstheorie





Gravitational Waves

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







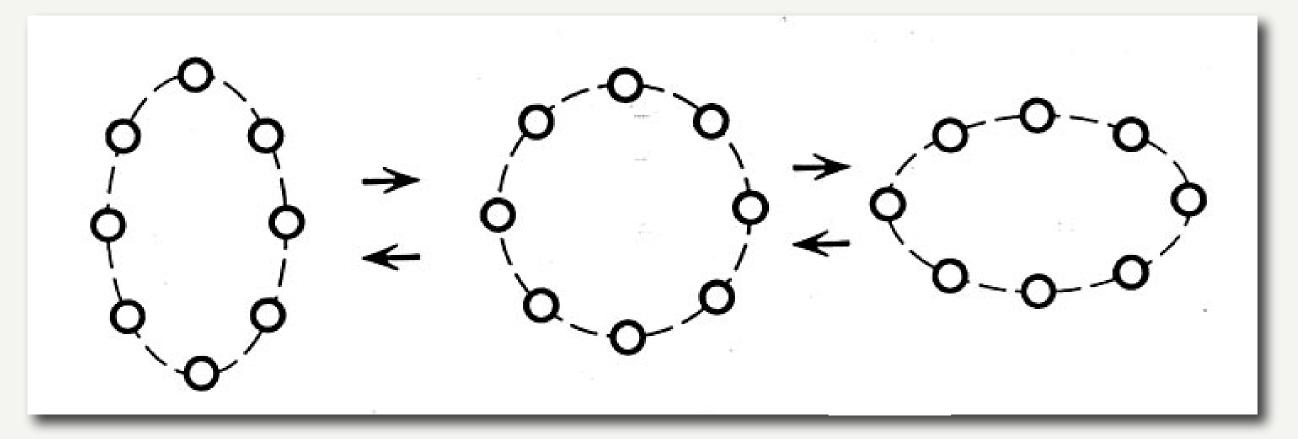






[http://www.einstein-online.info]

Observing Gravitational Waves:



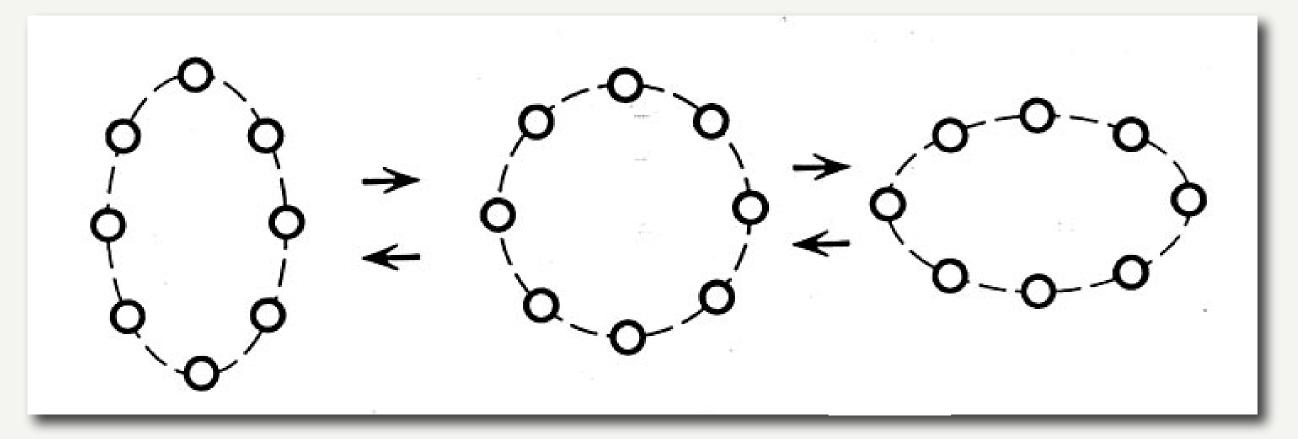
Gravitational waves change the distance between objects.





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

Observing Gravitational Waves:



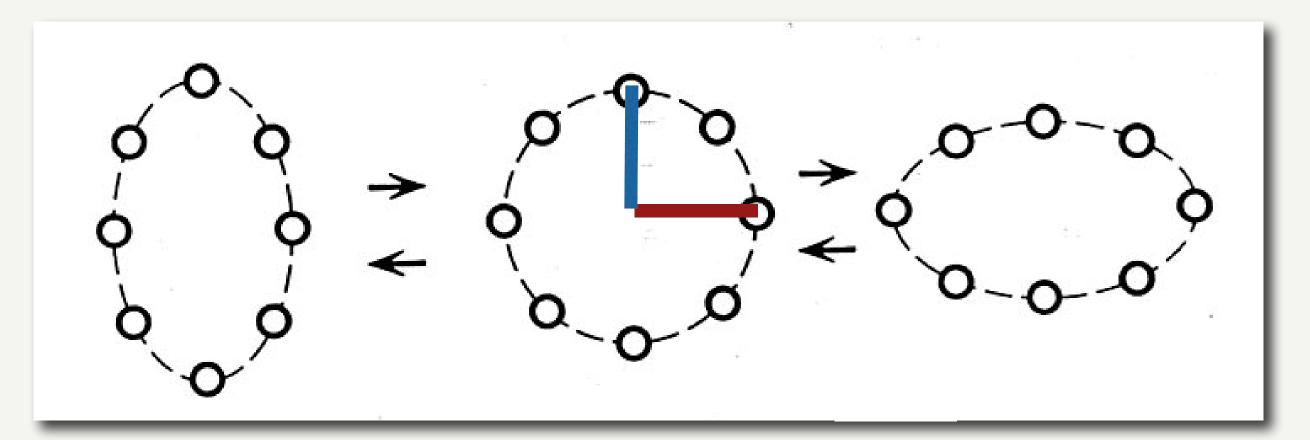
Gravitational waves change the distance between objects.





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

Observing Gravitational Waves:



Gravitational waves change the distance between objects.



Laser Rangefinder



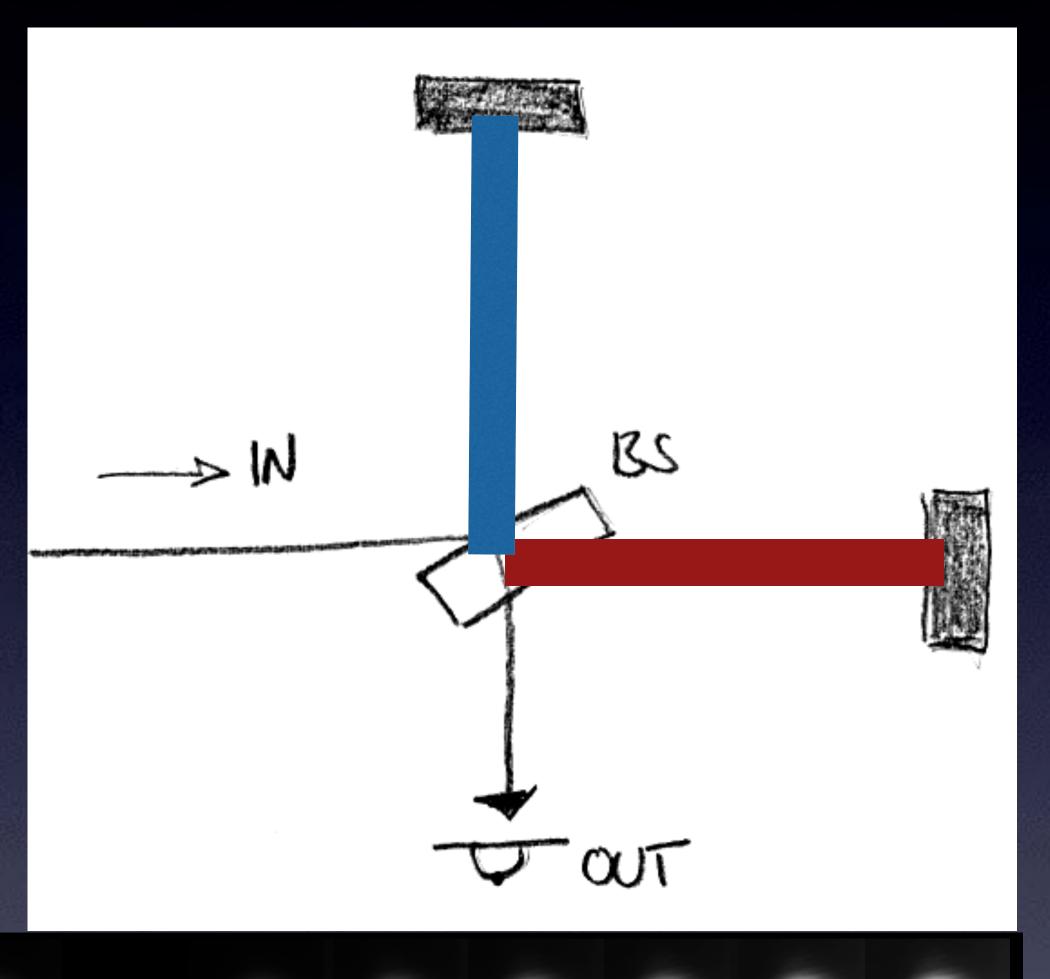
Wikipedia on Rangefinders: "The precision of the instrument is determined by the rise or fall time of the laser pulse and the speed of the receiver. One that uses very sharp laser pulses and has a very fast detector can range an object to within a few millimeters."





Length Measurement with Light

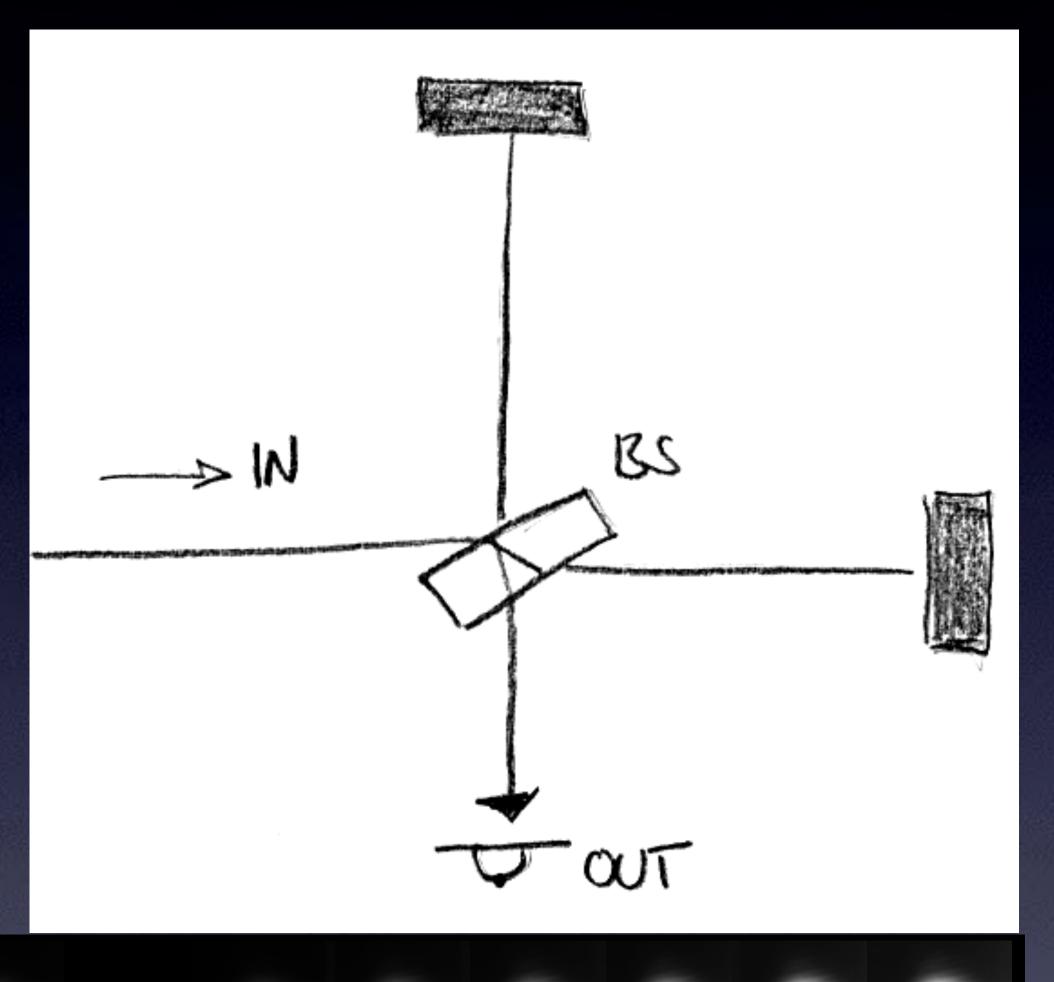
- Use a reference beam instead of a clock
- An interferometer compares two light beams
- Output becomes dark or bright when the light beams shift





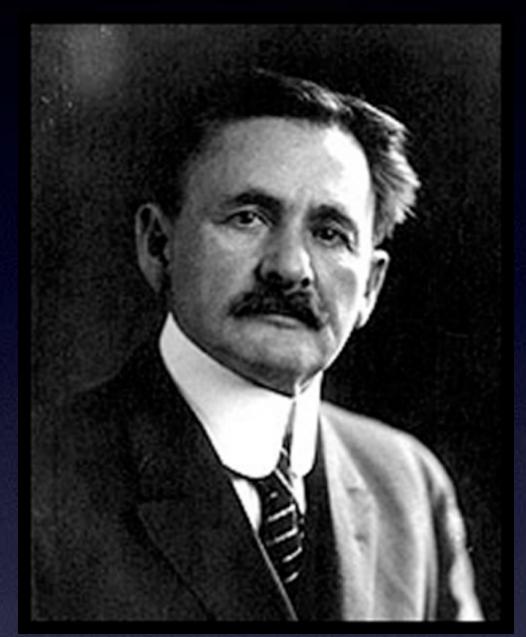
Length Measurement with Light

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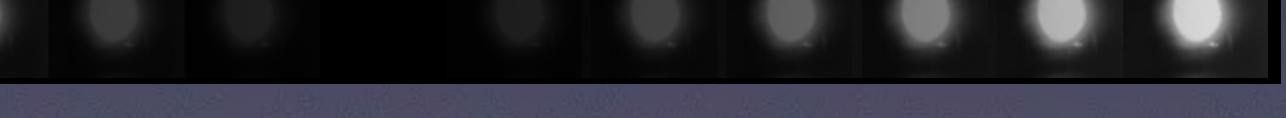
Interferometry in 1887



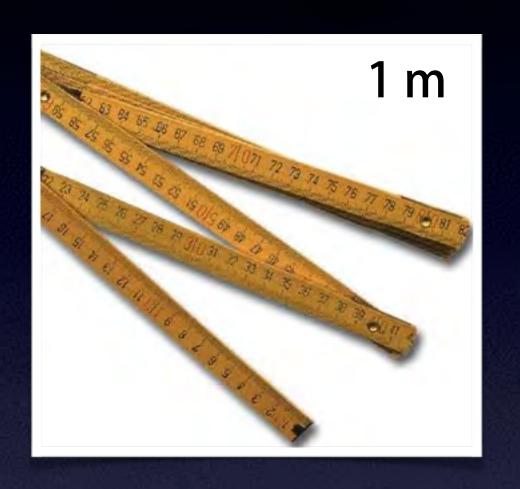
Michelson interferometer (ca. 1887)

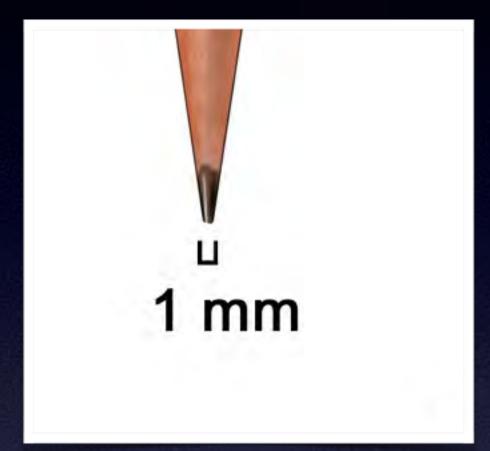
Sensitivity: 0.01 of a fringe



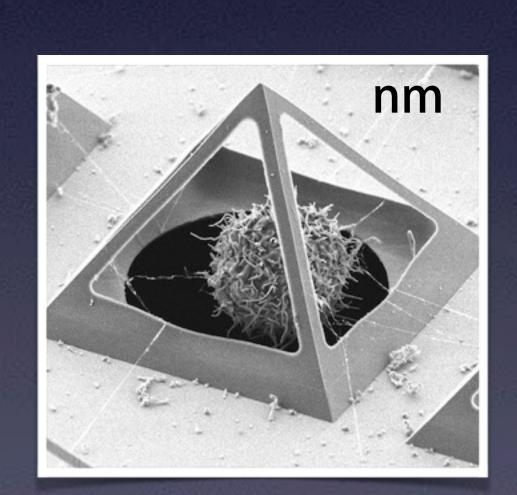


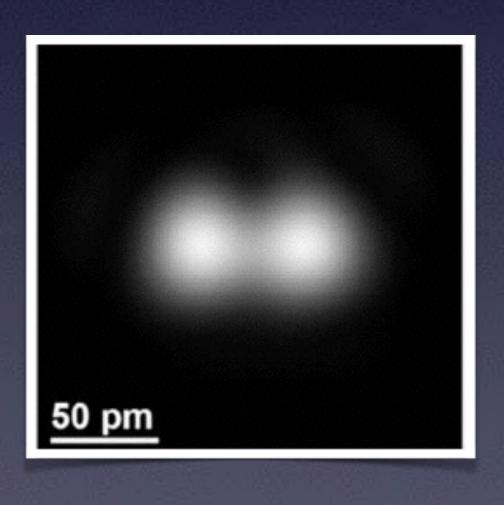




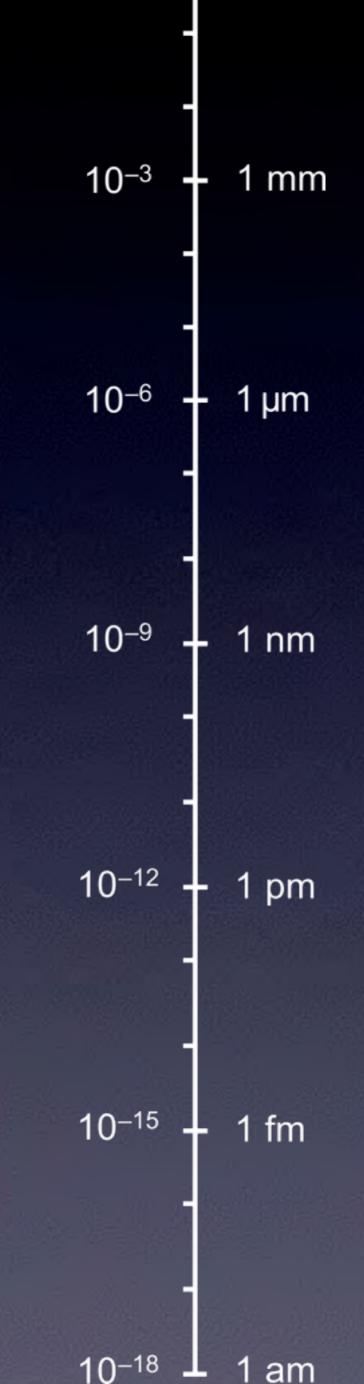










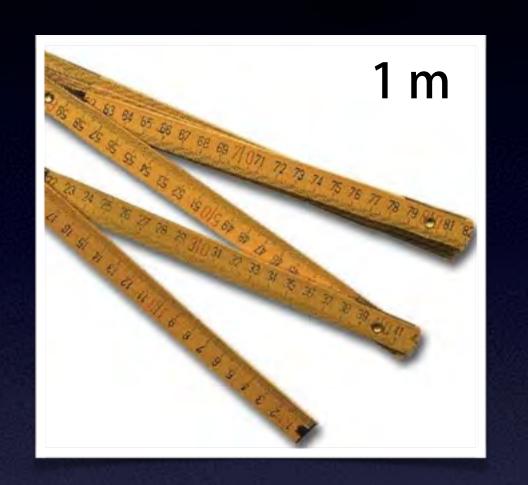


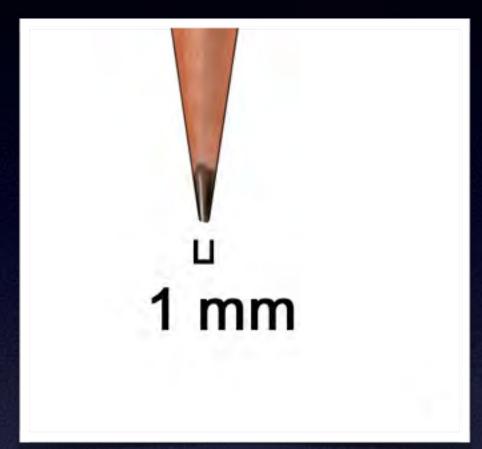
 10^{0} T

A. Freise

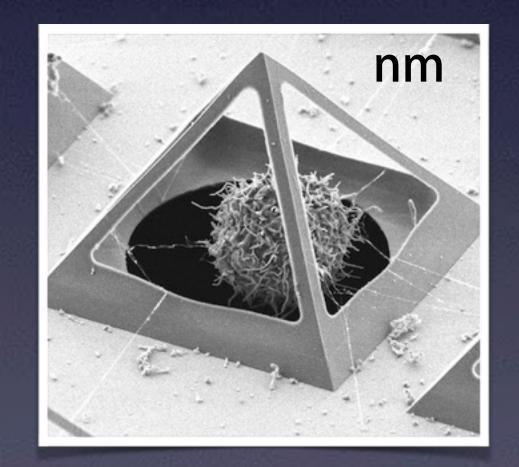
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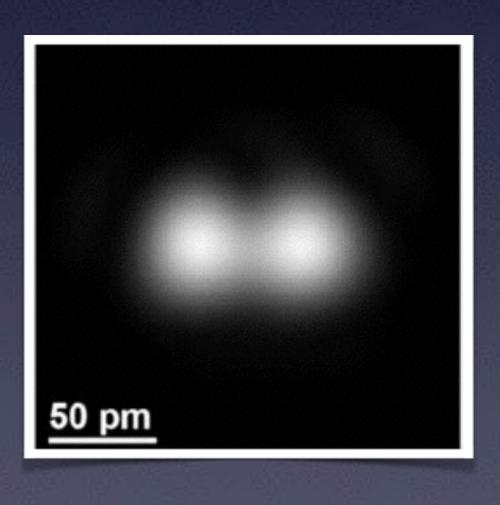




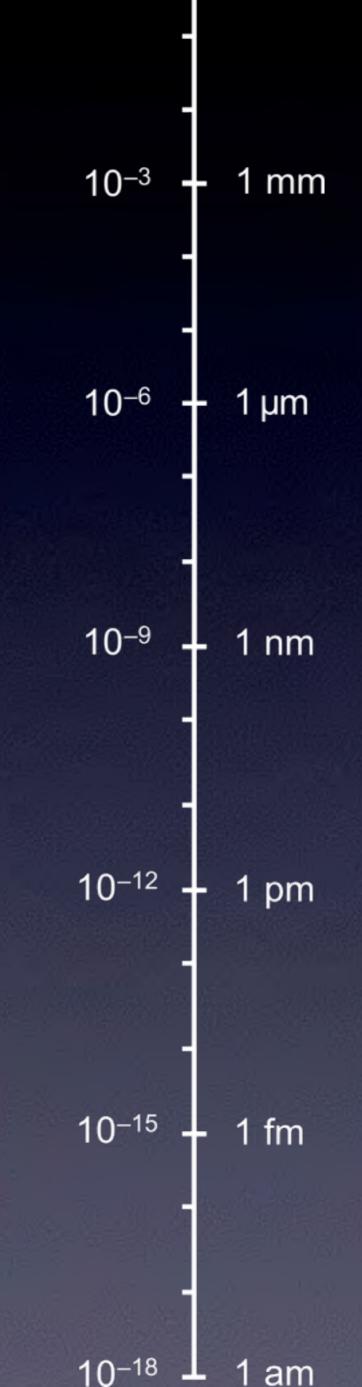








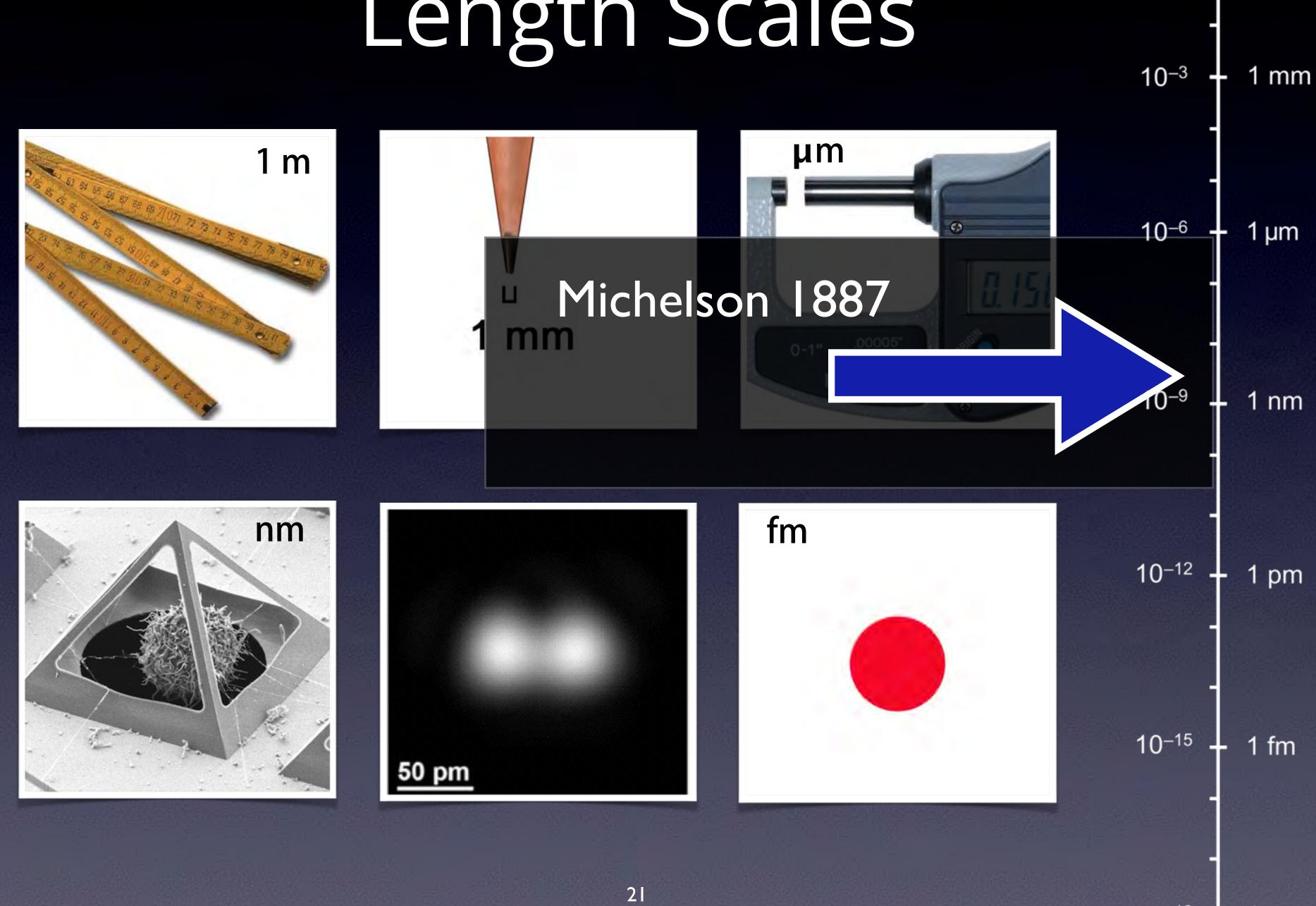




 10^{0} T

A. Freise 21 07.05.2016





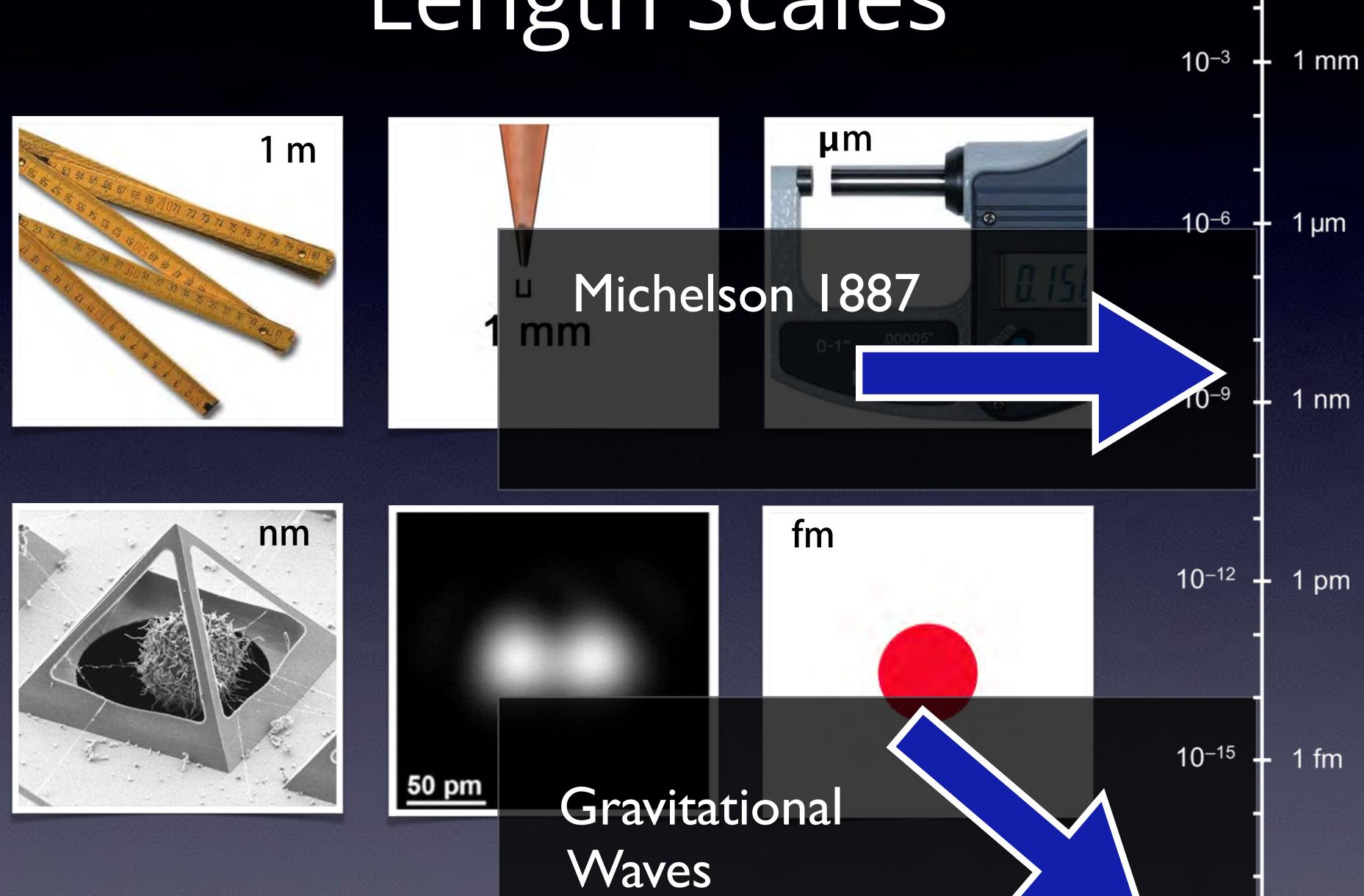
A. Freise

10⁻¹⁸ **⊥** 1 am

 10^{0} T

07.05.2016



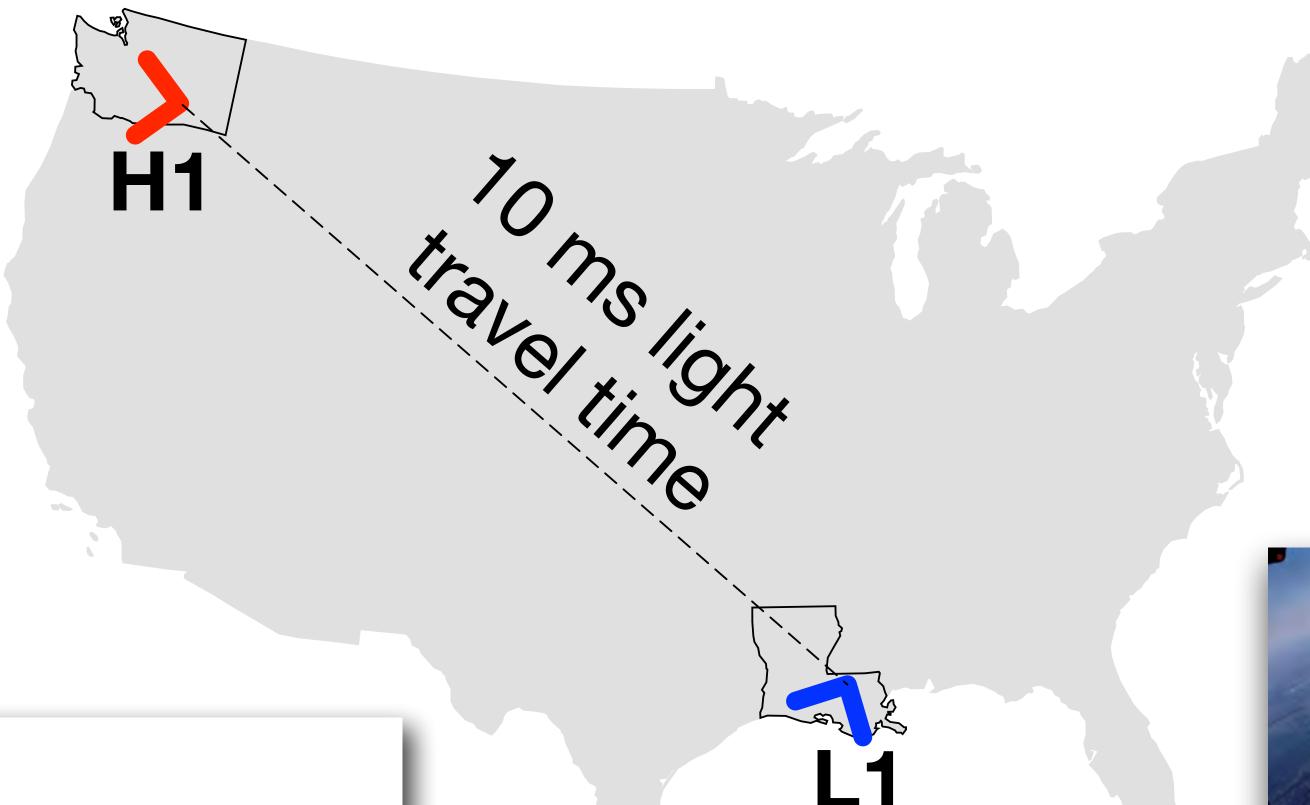


 10^{-18}



Two LIGO Instruments





Sensitivity: 0.000 000 000 000 01 of a fringe or 10⁻²⁰ m





Laser Interferometer

Gravitational-Wave Observatory

Two large Michelson interferometers!

How does one instrument look like?



LIGO Hanford Site











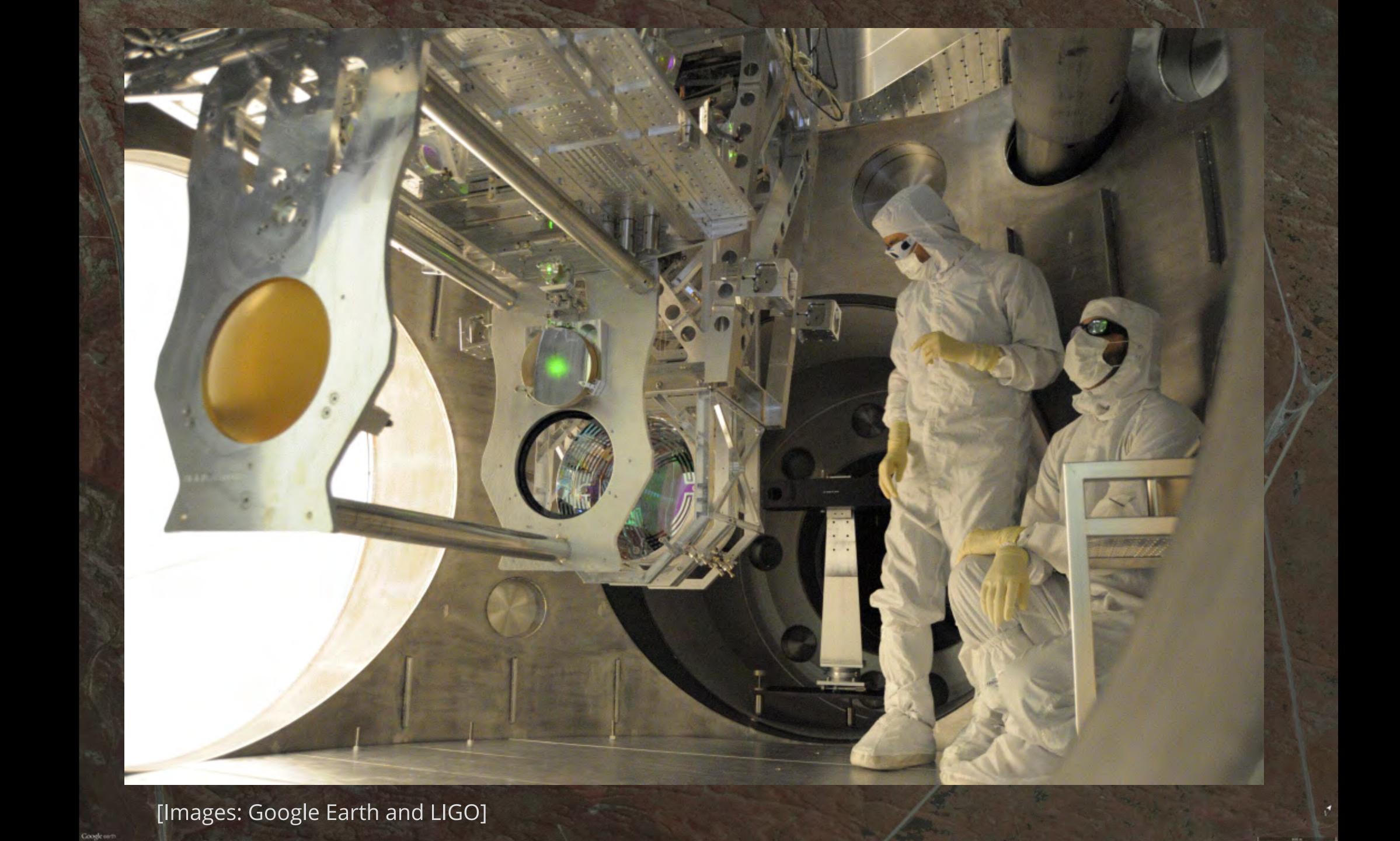












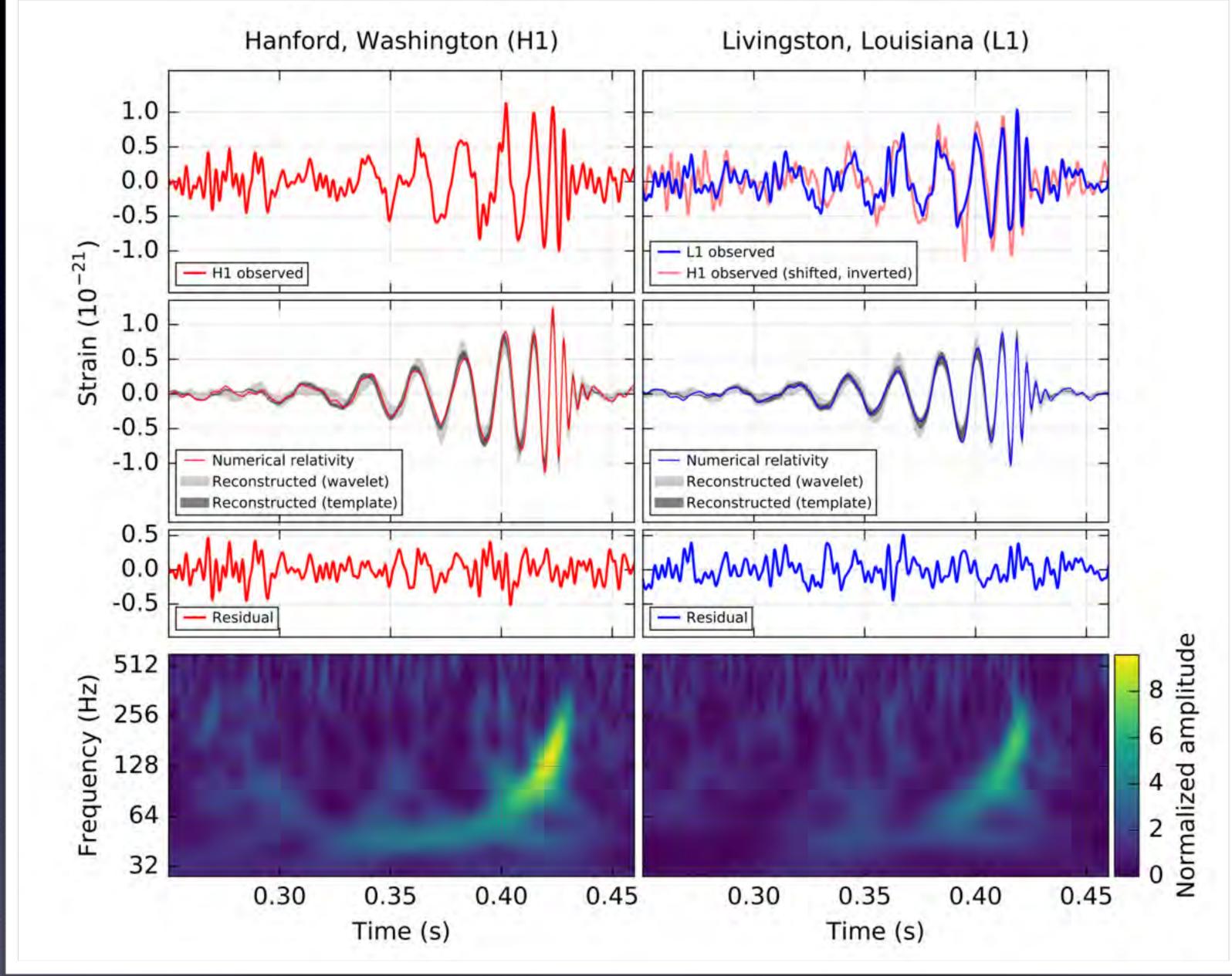


14.09.2015

First Detection of Gravitational Waves

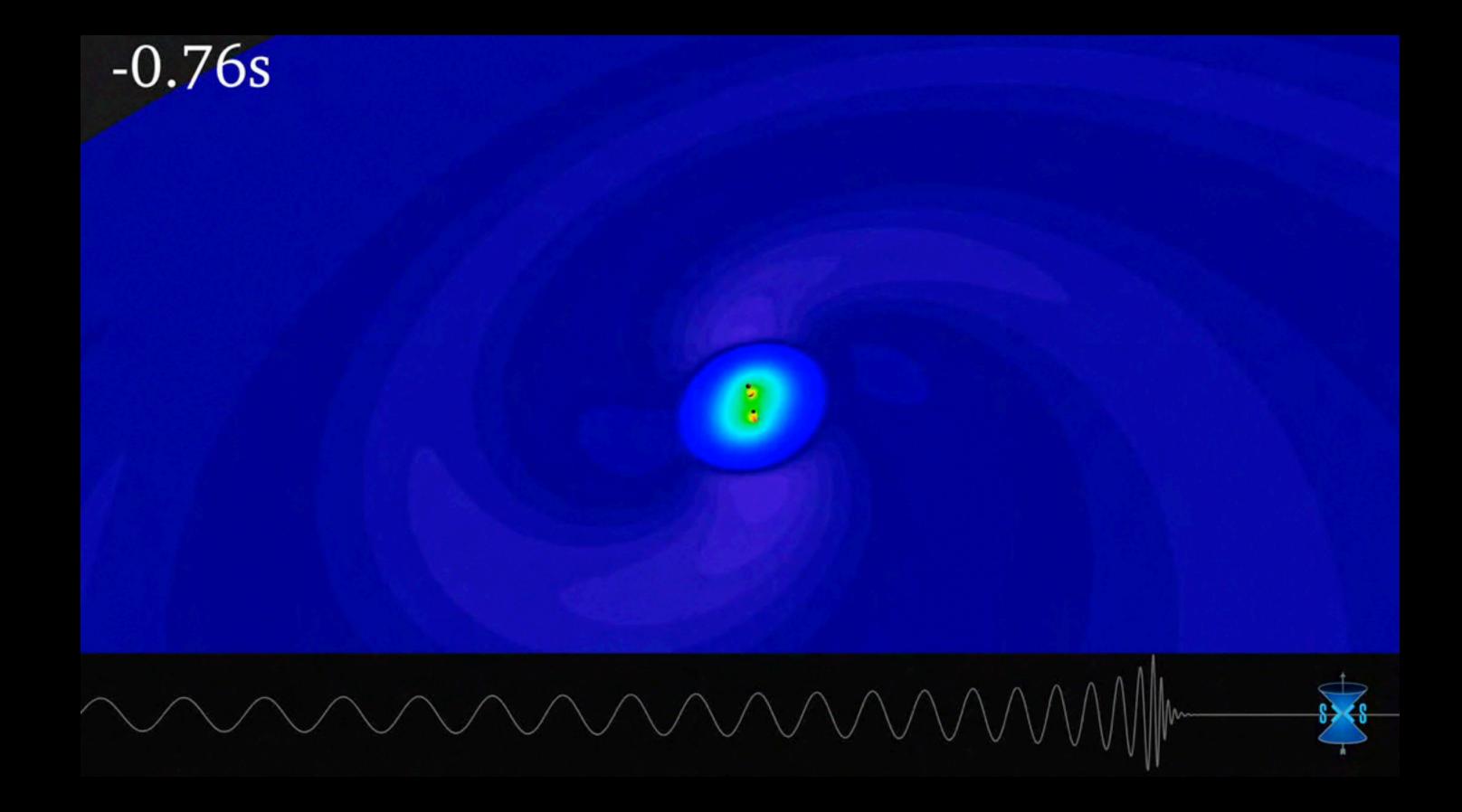
A. Freise 30 07.05.2016

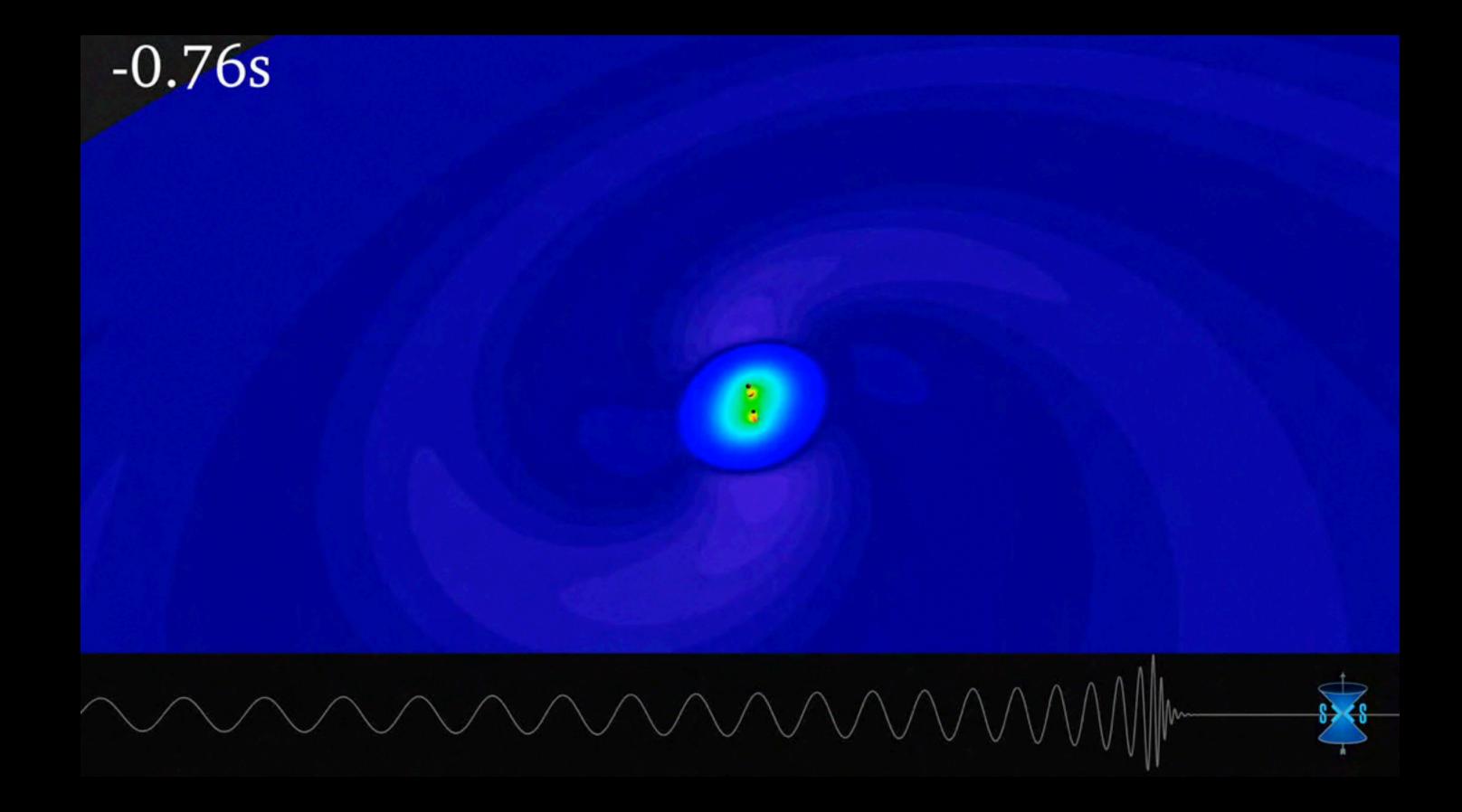




Data

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







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!

A. Freise 34 07.05.2016



Part 2

How to build such an amazingly sensitive laser interferometer?





LIGO Scientific Collaboration





















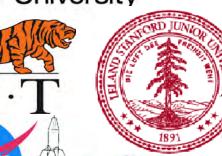
UNIVERSITY OF THE WEST of SCOTLAND





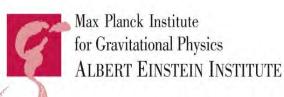
















MONTANA STATE UNIVERSITY











UNIVERSITYOF























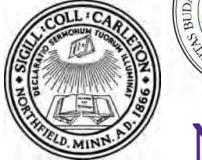






































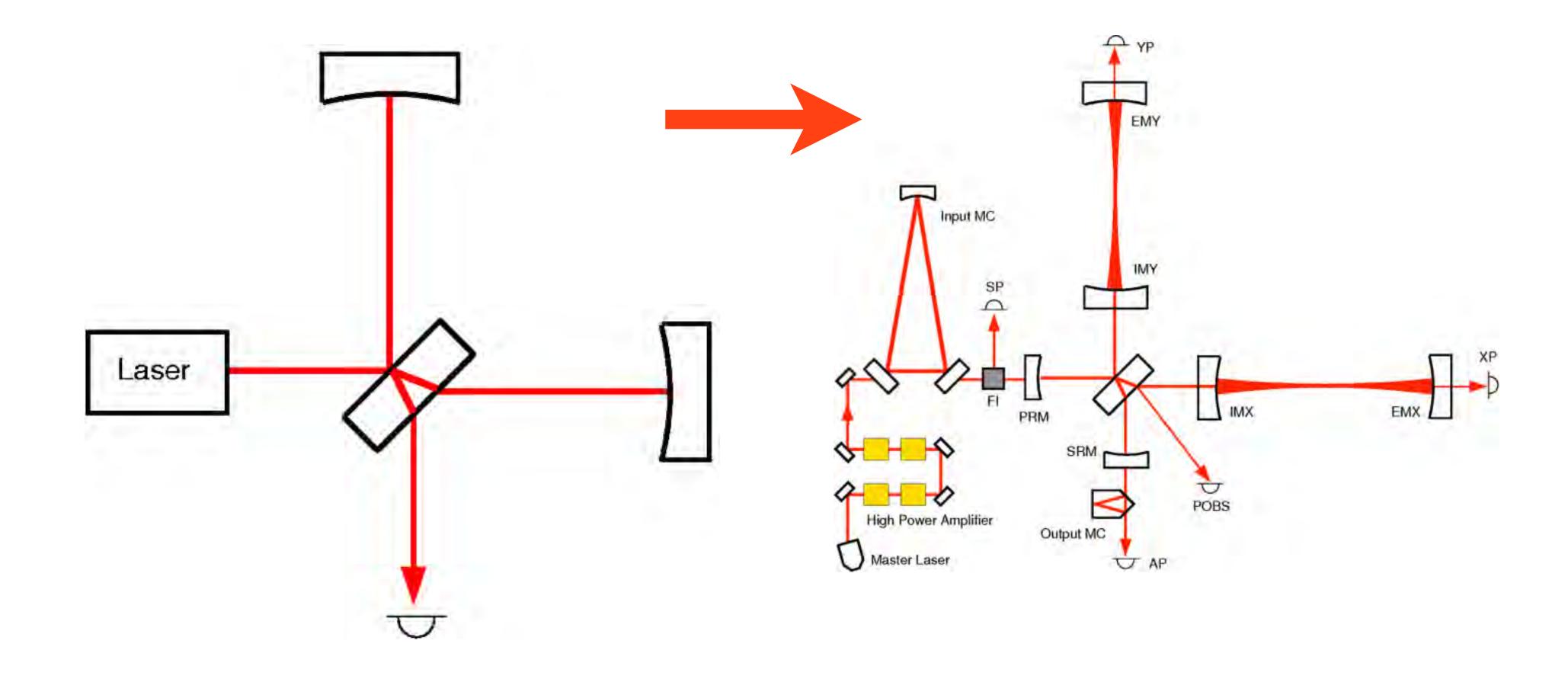








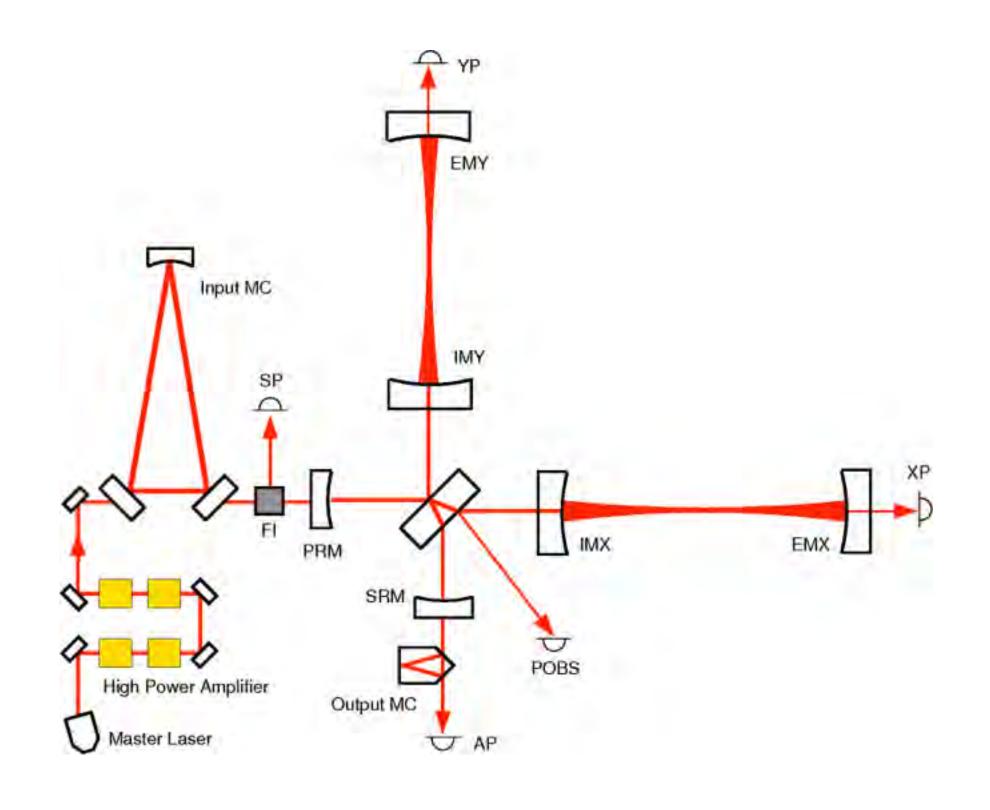
Advanced Interferometry





PER AD ALTA

What Makes it Better?

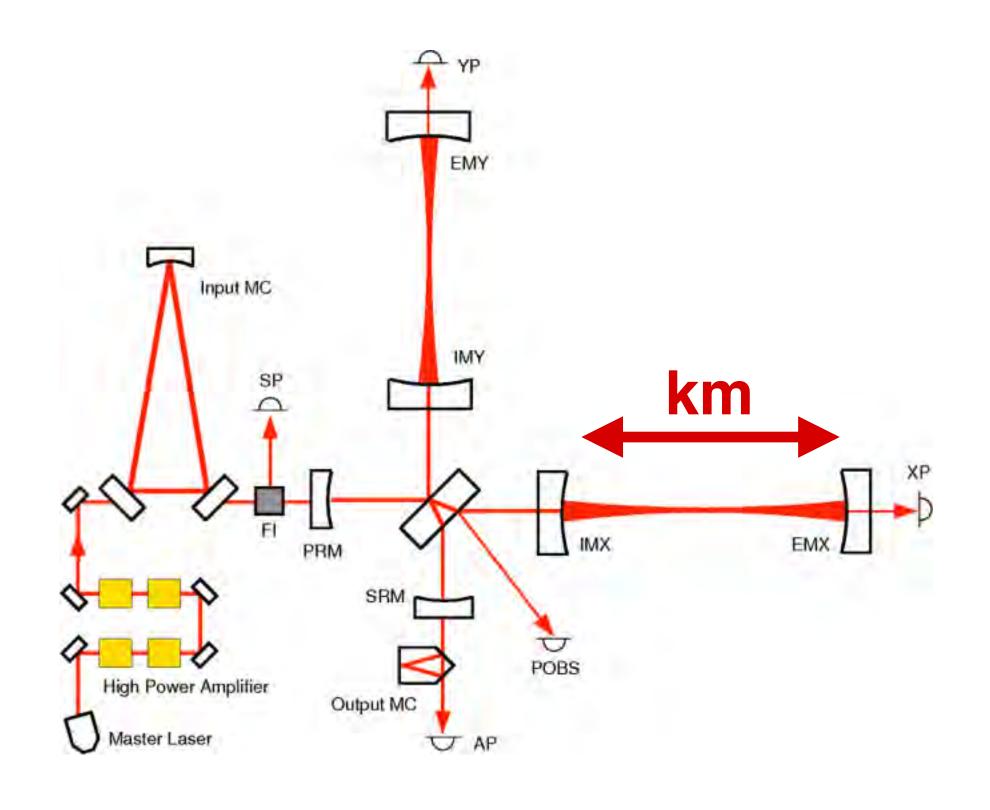


- GW effect scales with arm length: large detectors
- Optical signal scales with light power: high-power laser, optical cavities
- Laser beam fluctuations make noise: filter cavities





What Makes it Better?

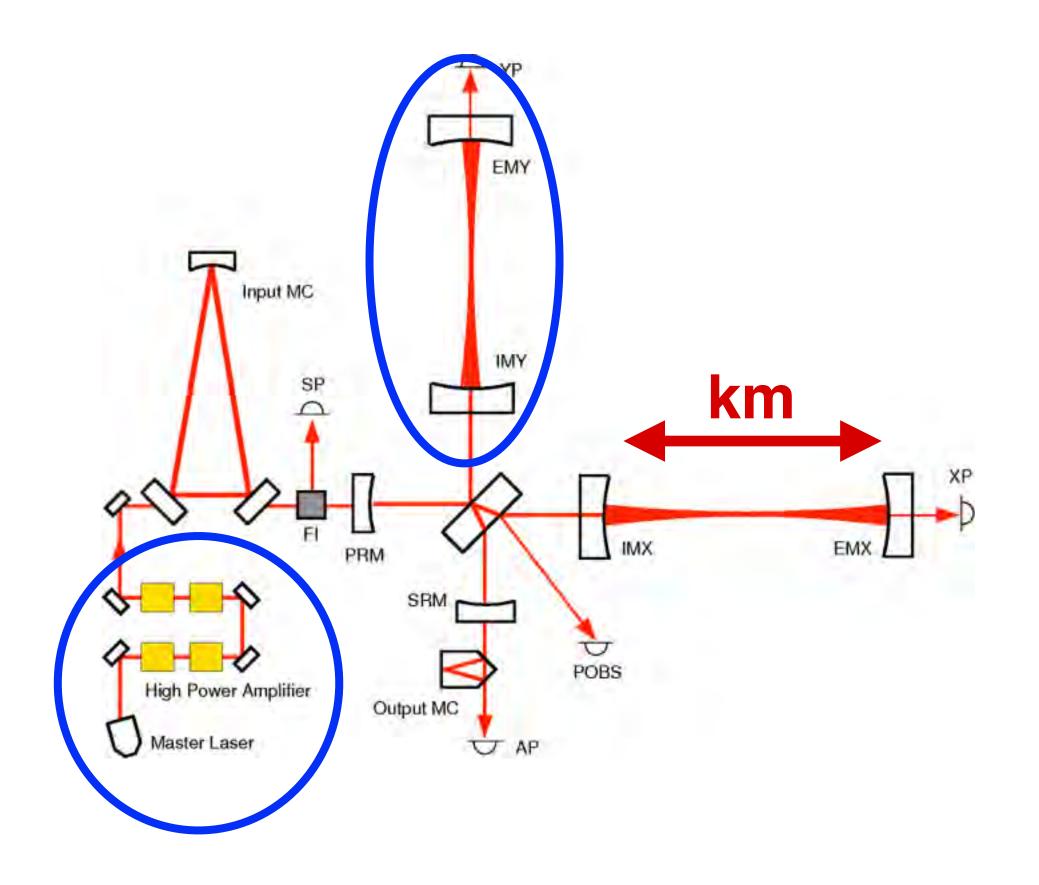


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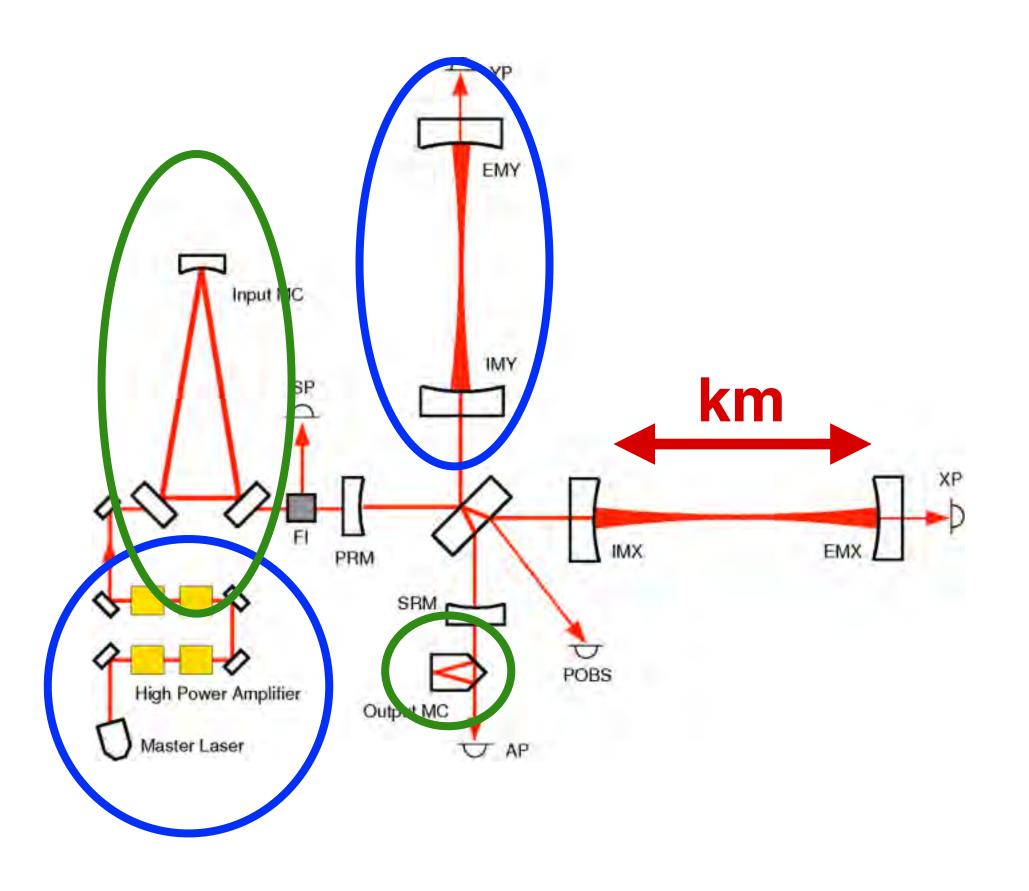


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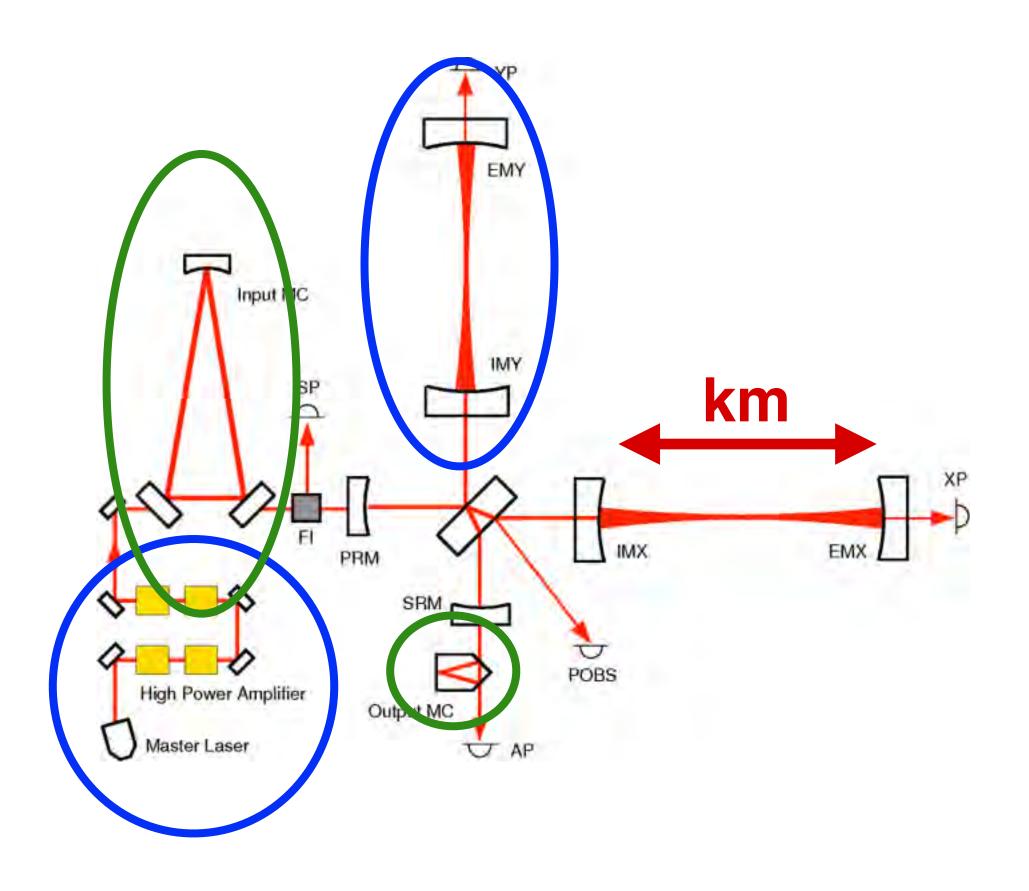
What Makes it Better?



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What Makes it Better?

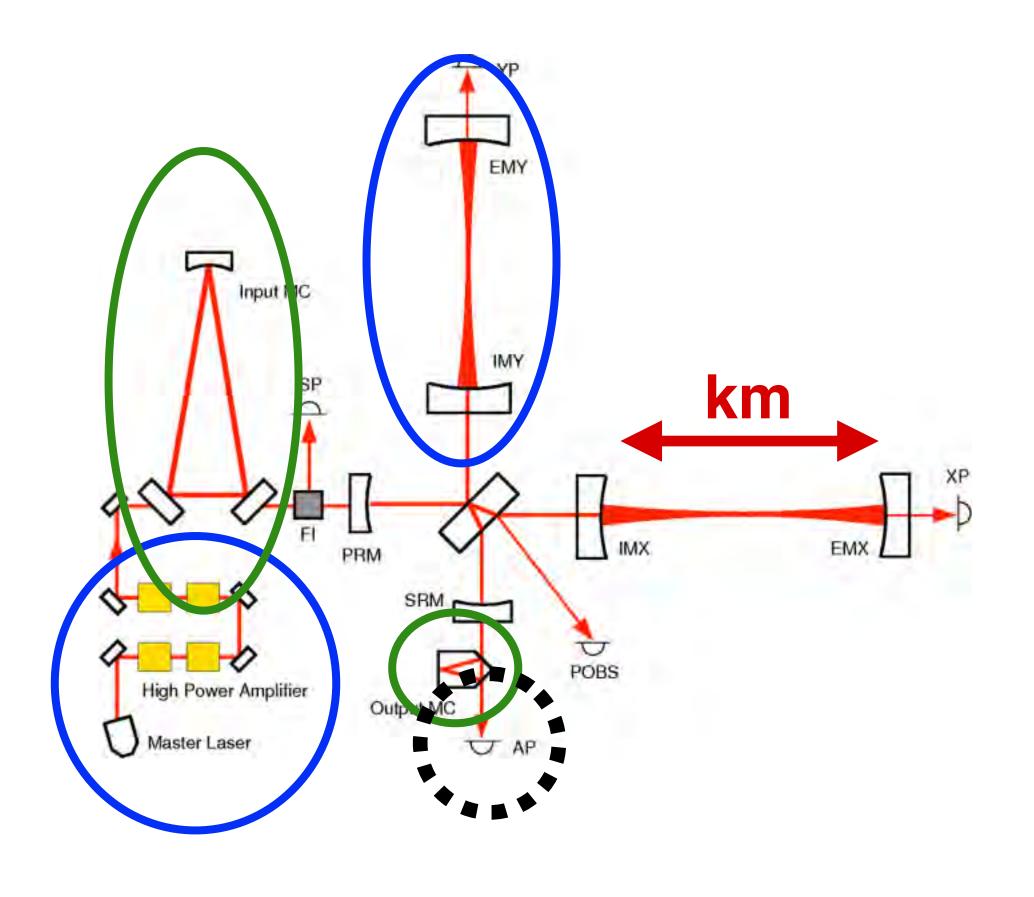


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Stop everything from shaking!



What Makes it Better?

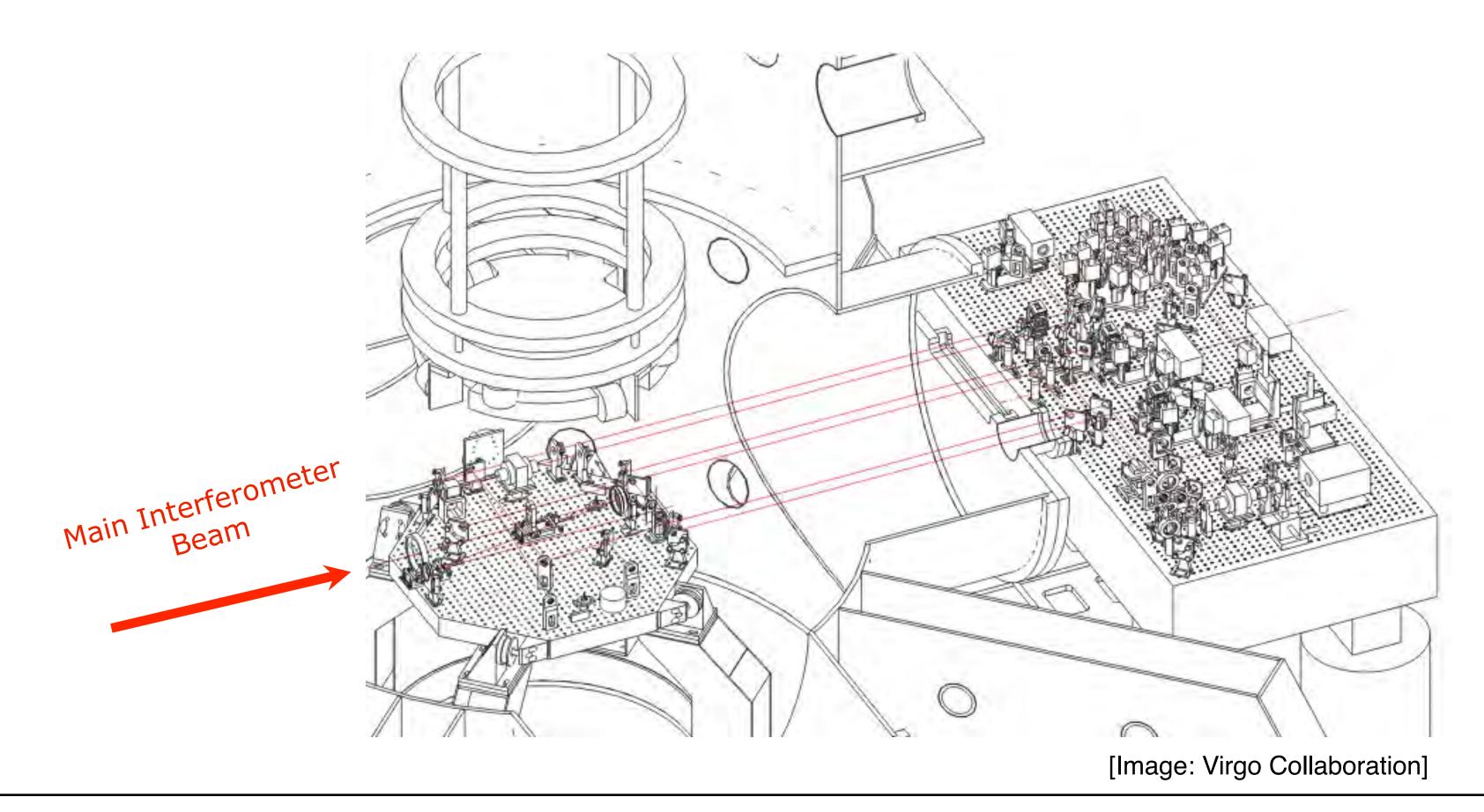


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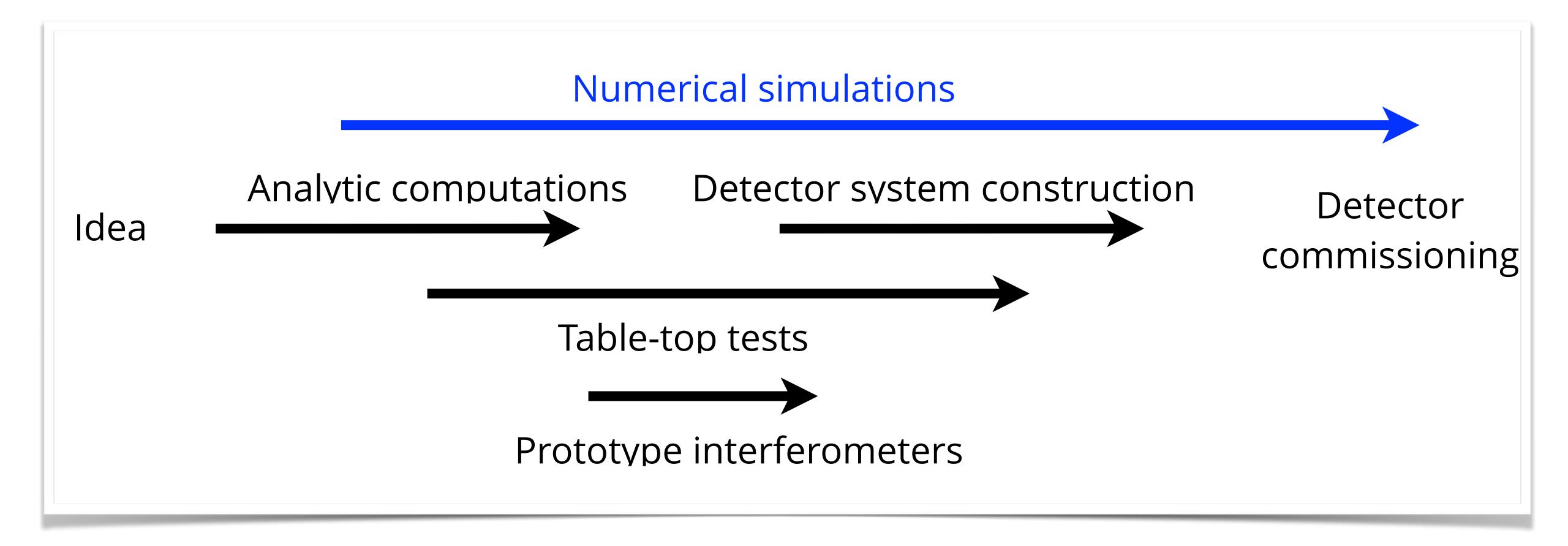
Complexity Increases

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





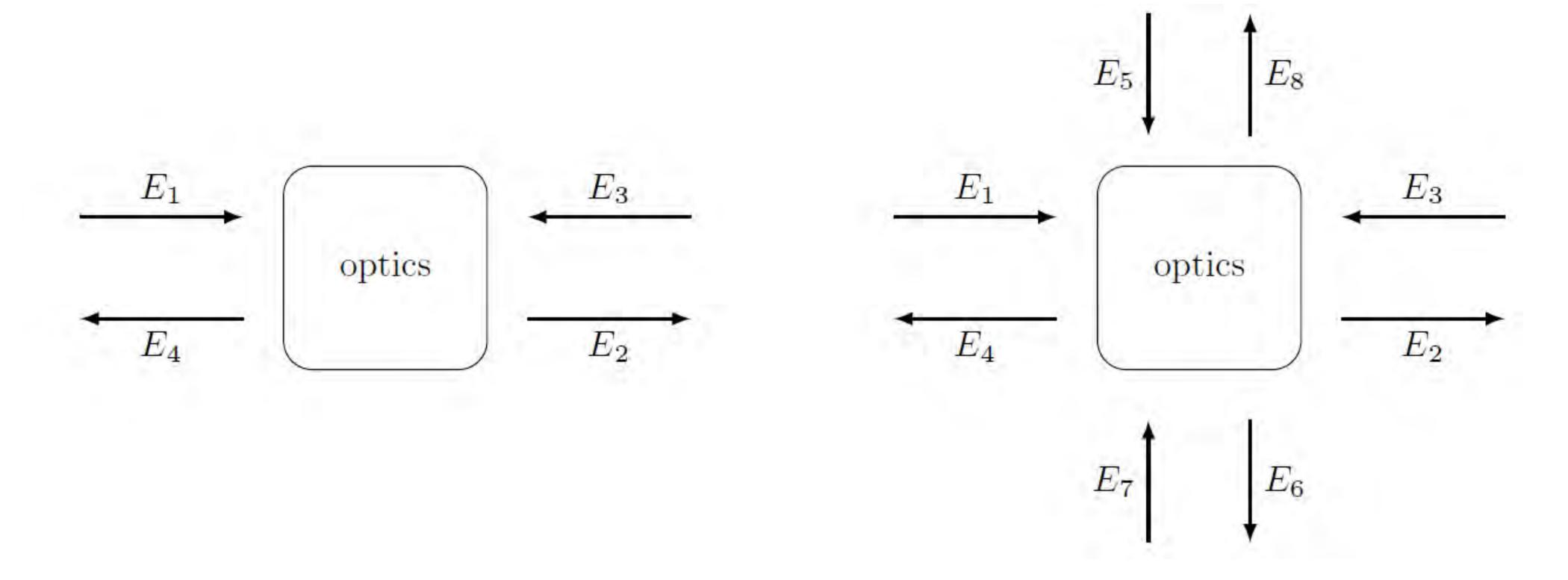
10 to 30 Years from Idea to Application







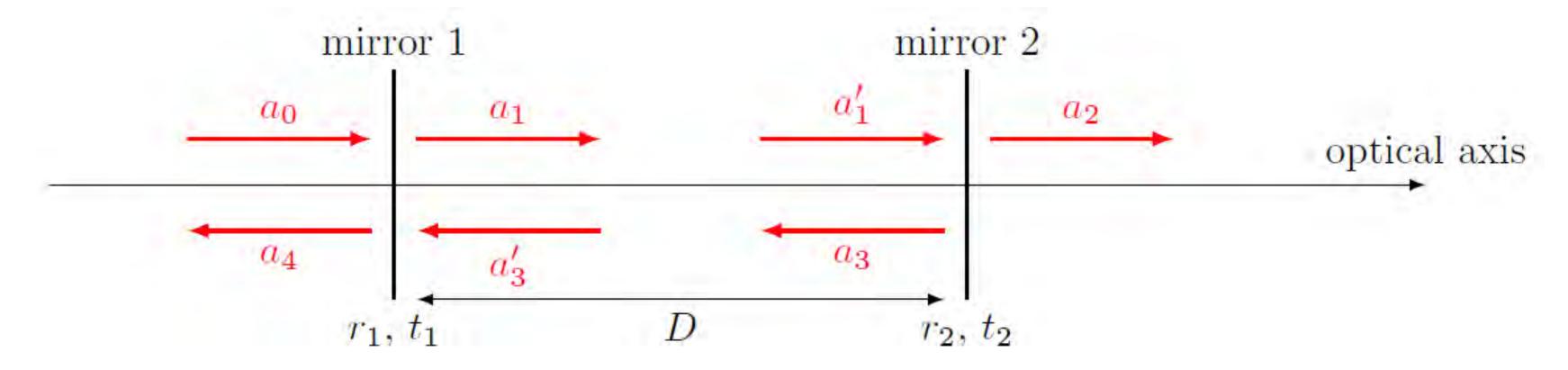
Linear Interaction of Light with Optics







Optical Systems as a Sparse Matrix



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



Play and Evolve

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

- Commercial software is not aimed at optical phase changes of 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!

A. Freise 44 07.05.2016



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'

FINESSE

www.gwoptics.org/finesse

- 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



User interface

```
000
                    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
 10
     fsig aforce ETM Fz 1 0 1
     xd zETM ETM z
     xd zITM ITM z
 15
     xaxis aforce f log 0.1 1k 1000
     yaxis log abs:deg
18
                                 Soft Tabs: 4 ▼
Line:
           7 | Plain Text
```

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

```
000
                     optical_spring_mechTF.kat - kats
optical_spring_mechTF.kat
                                            000
                                                                       1. bash
      tf sus 1 0 p 1 100000
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                                                    Python
                                            ddb@godel kats$ kat optical_spring_mechTF.kat
     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
 10
      fsig aforce ETM Fz 1 0 1
 12
      xd zETM ETM z
      xd zITM ITM z
 15
      xaxis aforce f log 0.1 1k 1000
      yaxis log abs:deg
18
                                  Soft Tabs: 4 ₹
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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



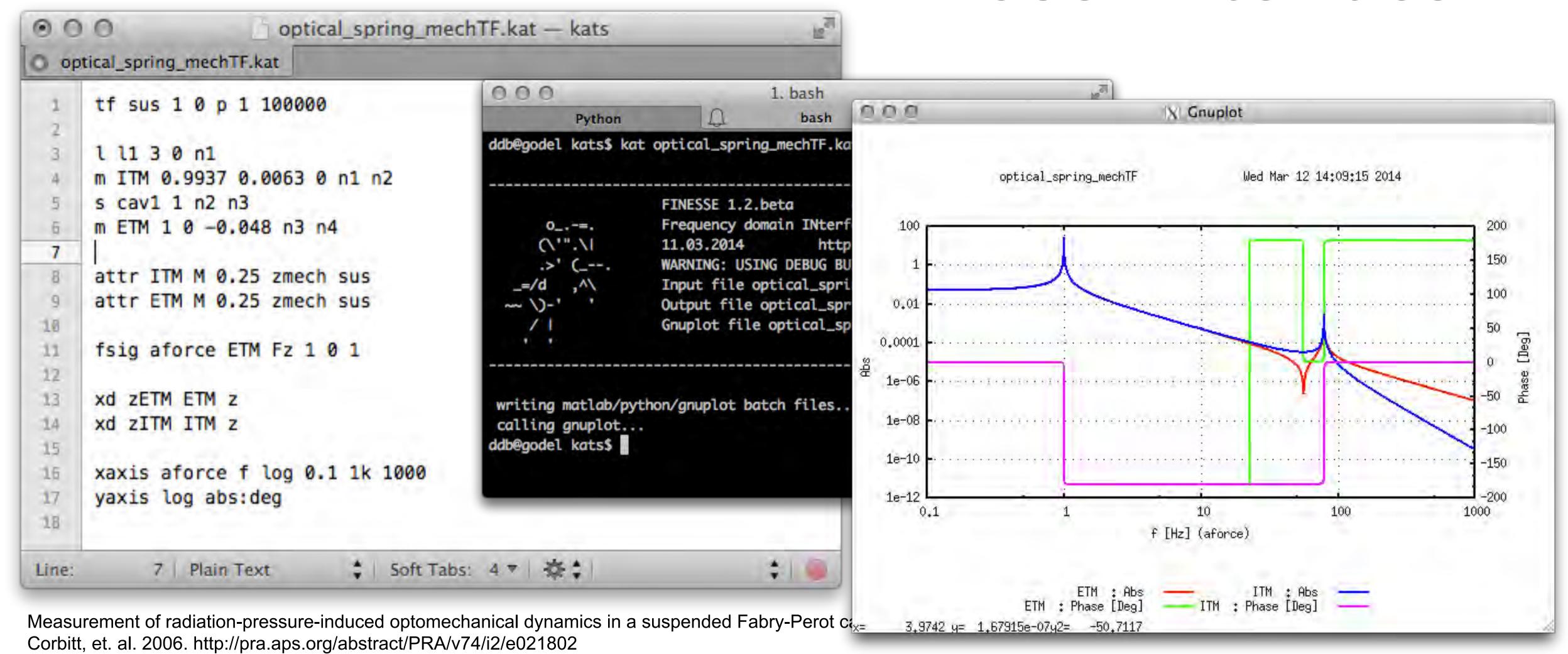
User interface

```
000
                       optical spring mechTF.kat - kats
optical_spring_mechTF.kat
                                                 000
                                                                               1. bash
      tf sus 1 0 p 1 100000
                                                                                  bash
                                                          Python
                                                 ddb@godel kats$ kat optical_spring_mechTF.kat
      l l1 3 0 n1
      m ITM 0.9937 0.0063 0 n1 n2
      s cav1 1 n2 n3
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                                                                   Frequency domain INterferomEter Simulation SoftwarE
      m ETM 1 0 -0.048 n3 n4
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                                                                                    http://www.gwoptics.org/finesse/
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      attr ITM M 0.25 zmech sus
                                                                   Input file optical_spring_mechTF.kat,
      attr ETM M 0.25 zmech sus
                                                                   Output file optical_spring_mechTF.out,
                                                  ~ V-'
                                                                   Gnuplot file optical_spring_mechTF.gnu
 10
                                                                                           Thu Mar 13 00:19:38 2014
      fsig aforce ETM Fz 1 0 1
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      xd zETM ETM z
                                                  writing matlab/python/gnuplot batch files...
      xd zITM ITM z
                                                  calling gnuplot...
                                                 ddb@godel kats$
 15
      xaxis aforce f log 0.1 1k 1000
      yaxis log abs:deg
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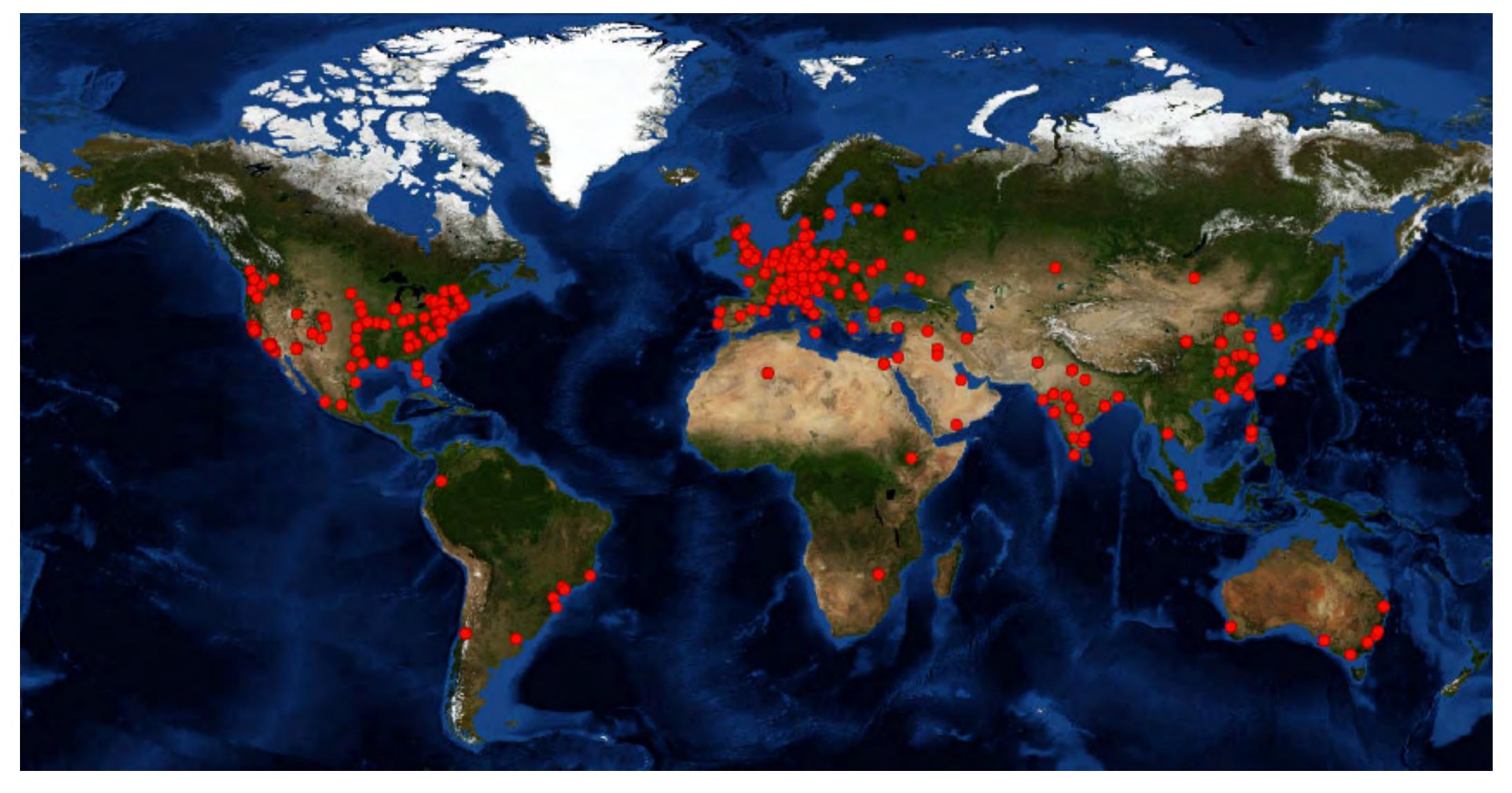
Measurement of radiation-pressure-induced optomechanical dynamics in a suspended Fabry-Perot cavity Corbitt, et. al. 2006. http://pra.aps.org/abstract/PRA/v74/i2/e021802



User interface









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

A. Freise 50



PyKat

www.gwoptics.org/pykat

- 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







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

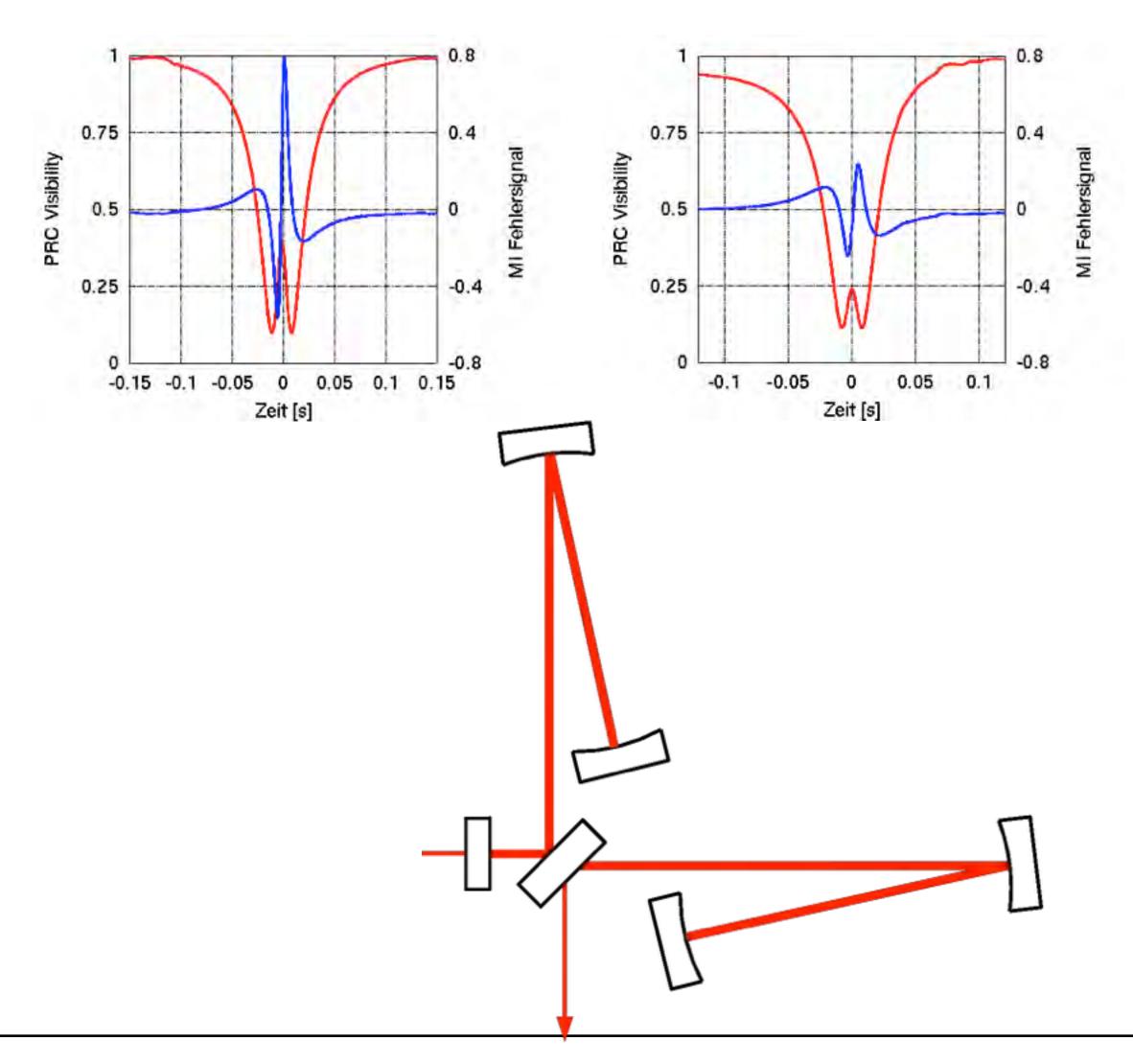
A. Freise 53



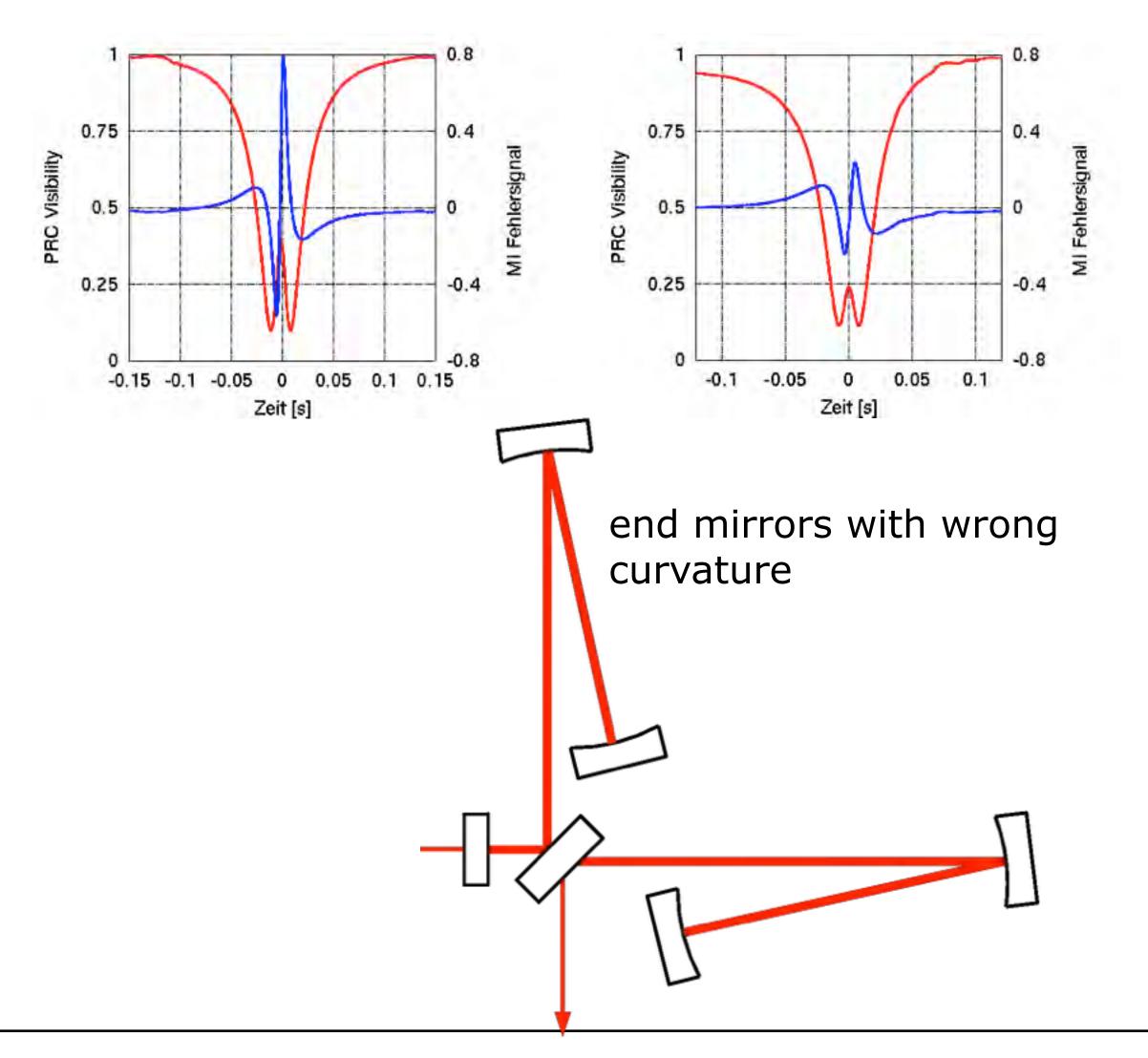
A long time ago, in the GEO 600 control room ...



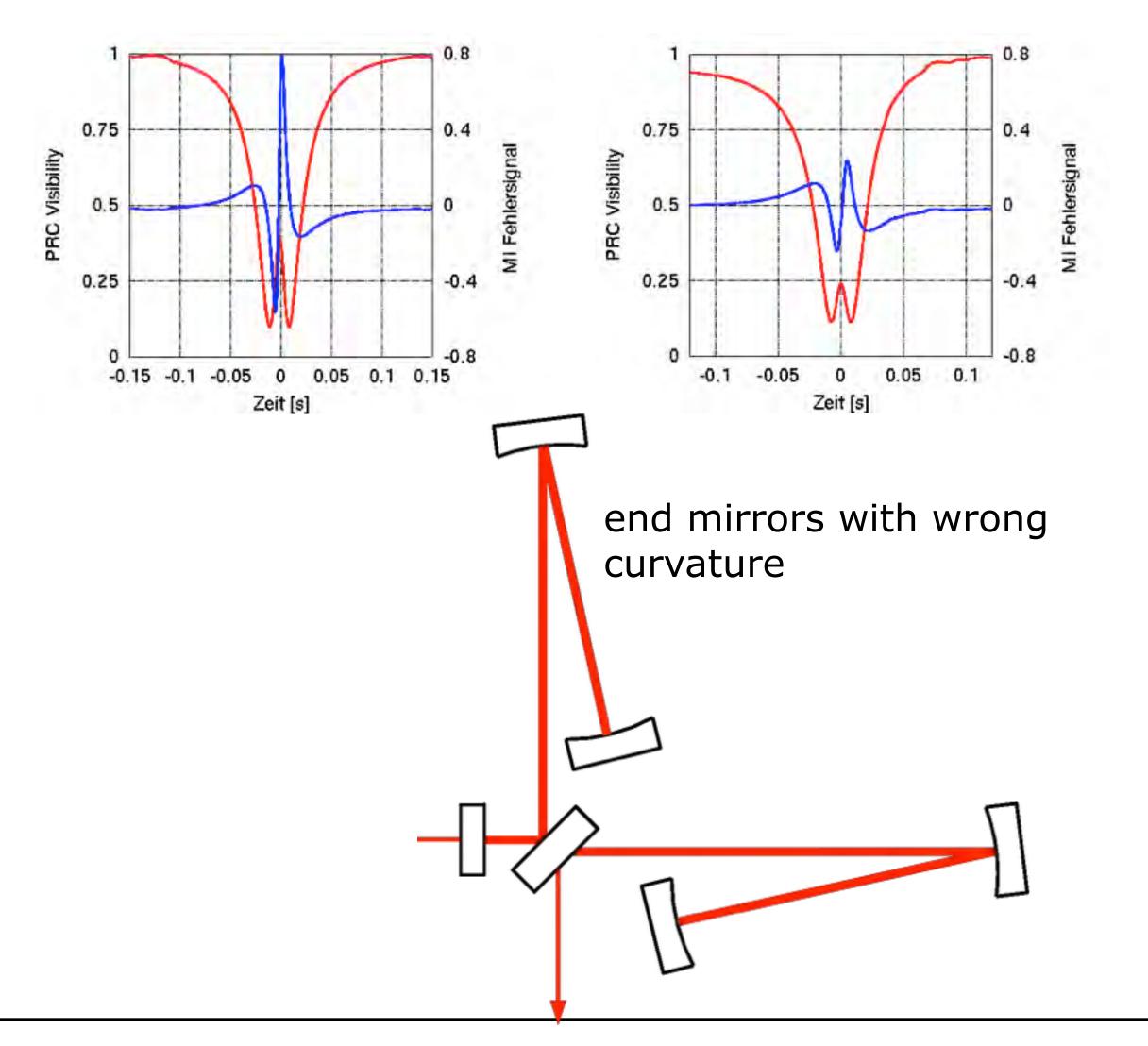




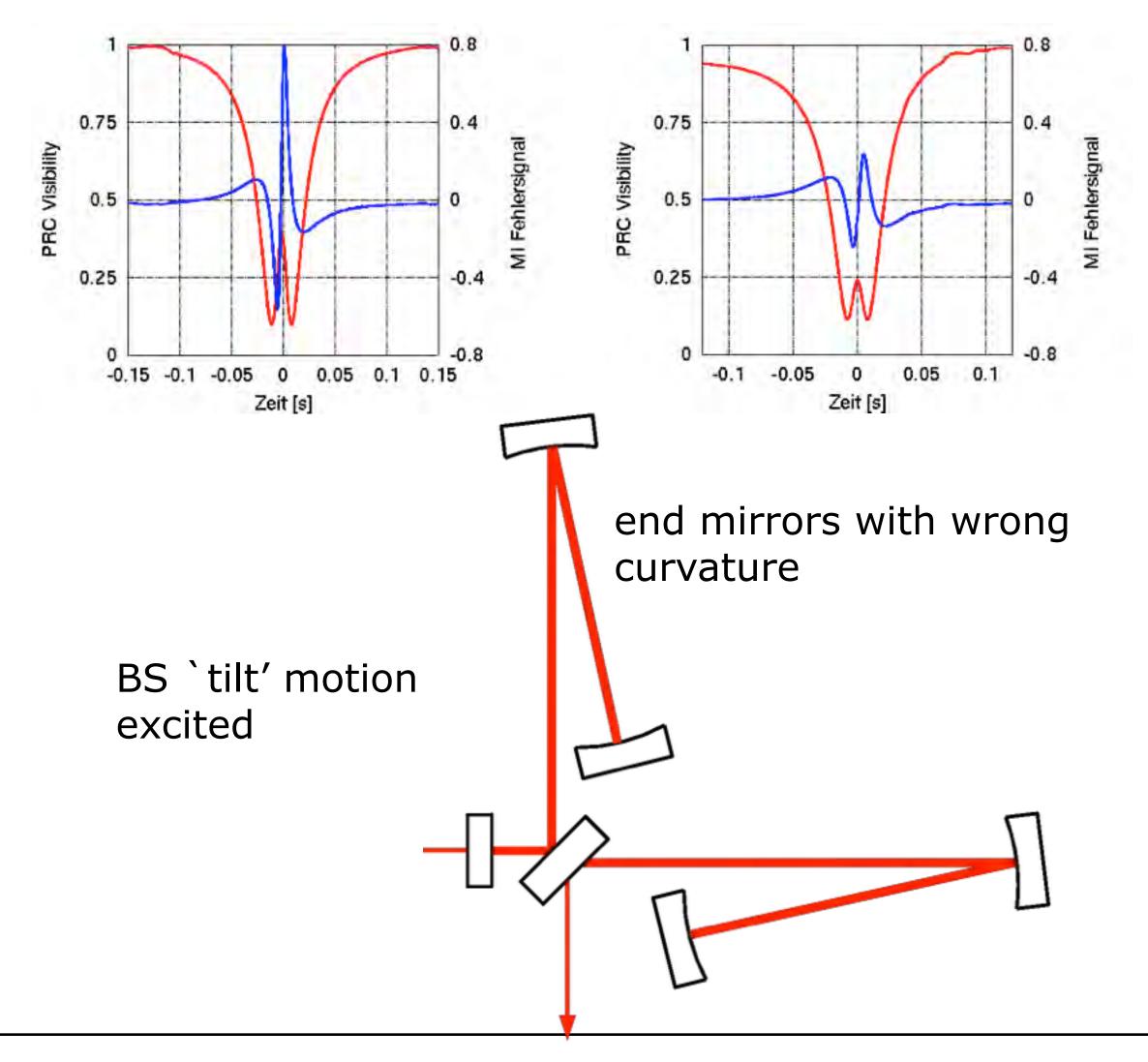




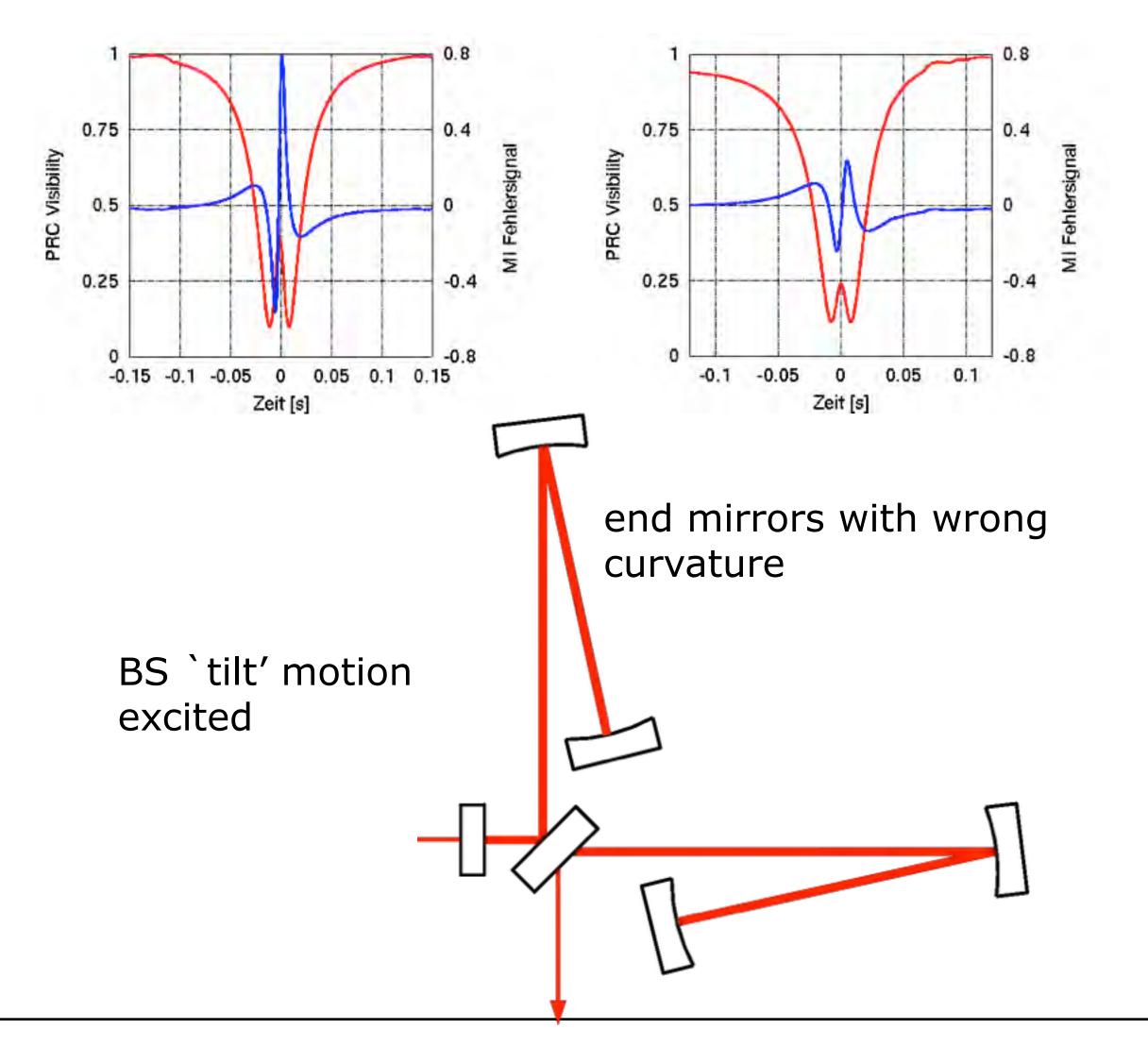








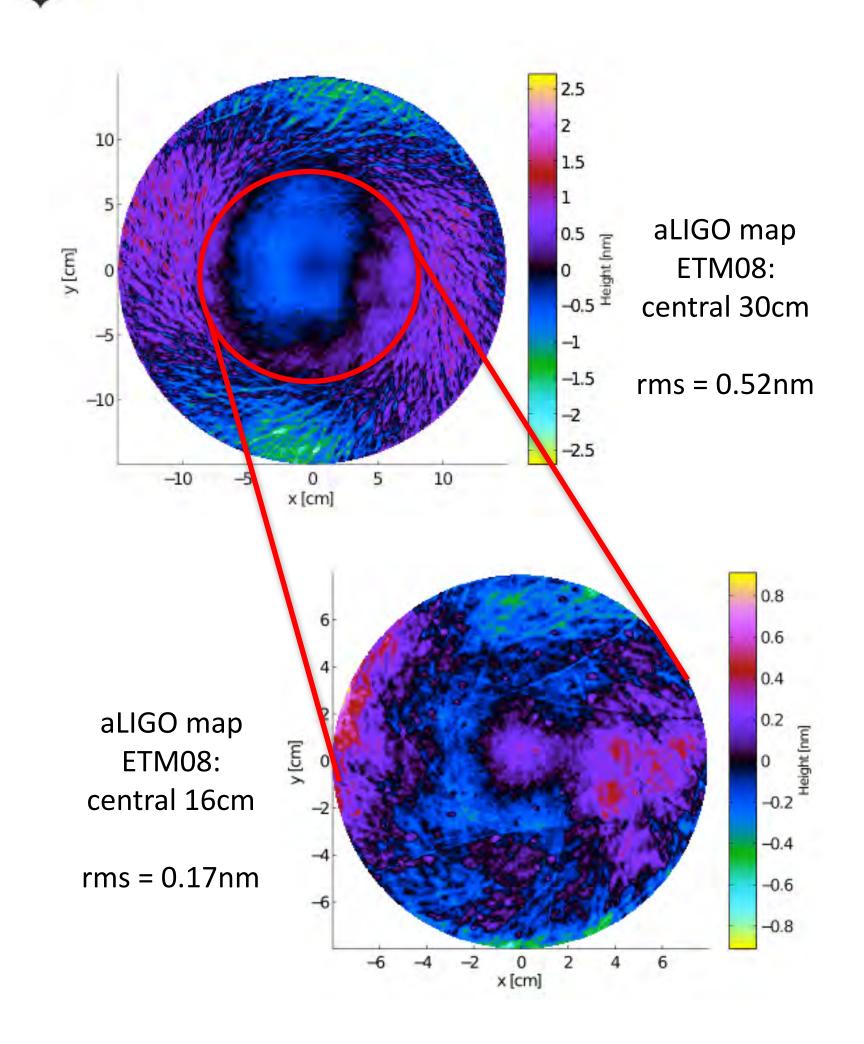








LIGO Mirror Surface Quality



- 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 a New Generation

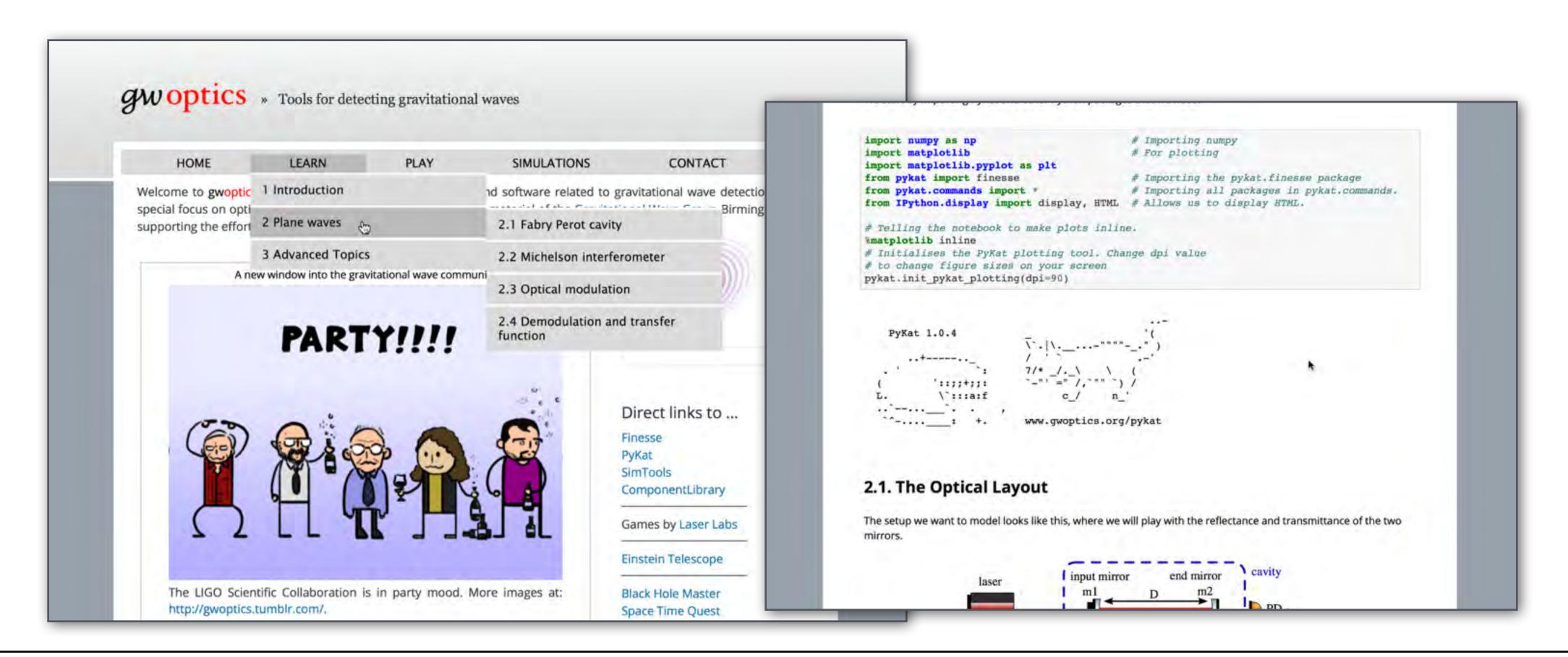
- In 2015/2016 we ran two successful summer school for post-graduate students
- Teaching material entirely based on IPython notebooks
- Installed all software on user-owned laptops, using Anaconda
- teaching laser interferometry, quantum optics, modelling
- Now moving this material online

A. Freise 59





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

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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



Welcome to the first issue of the LIGO Magazine!

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A brief history

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Find out more!



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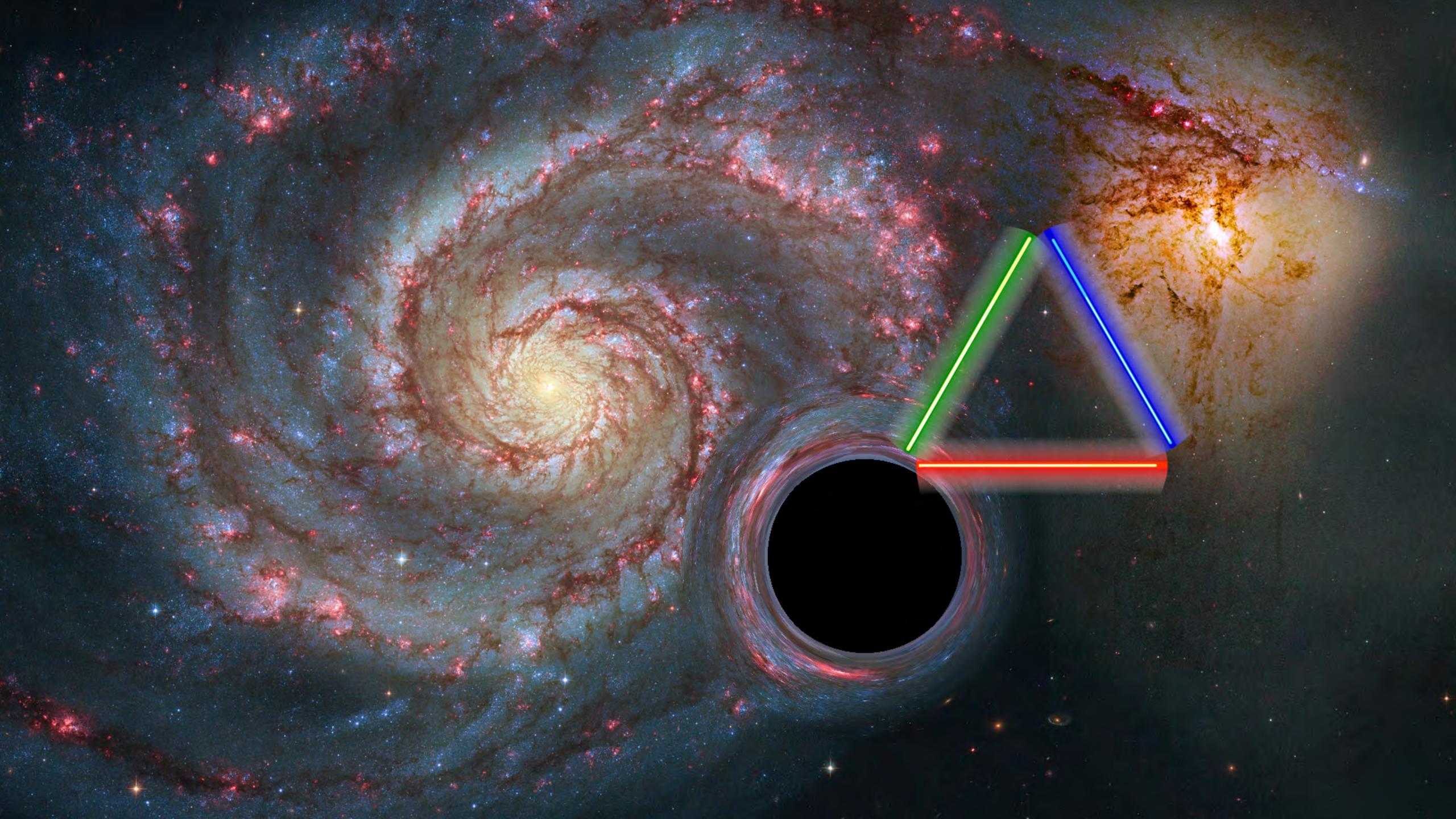
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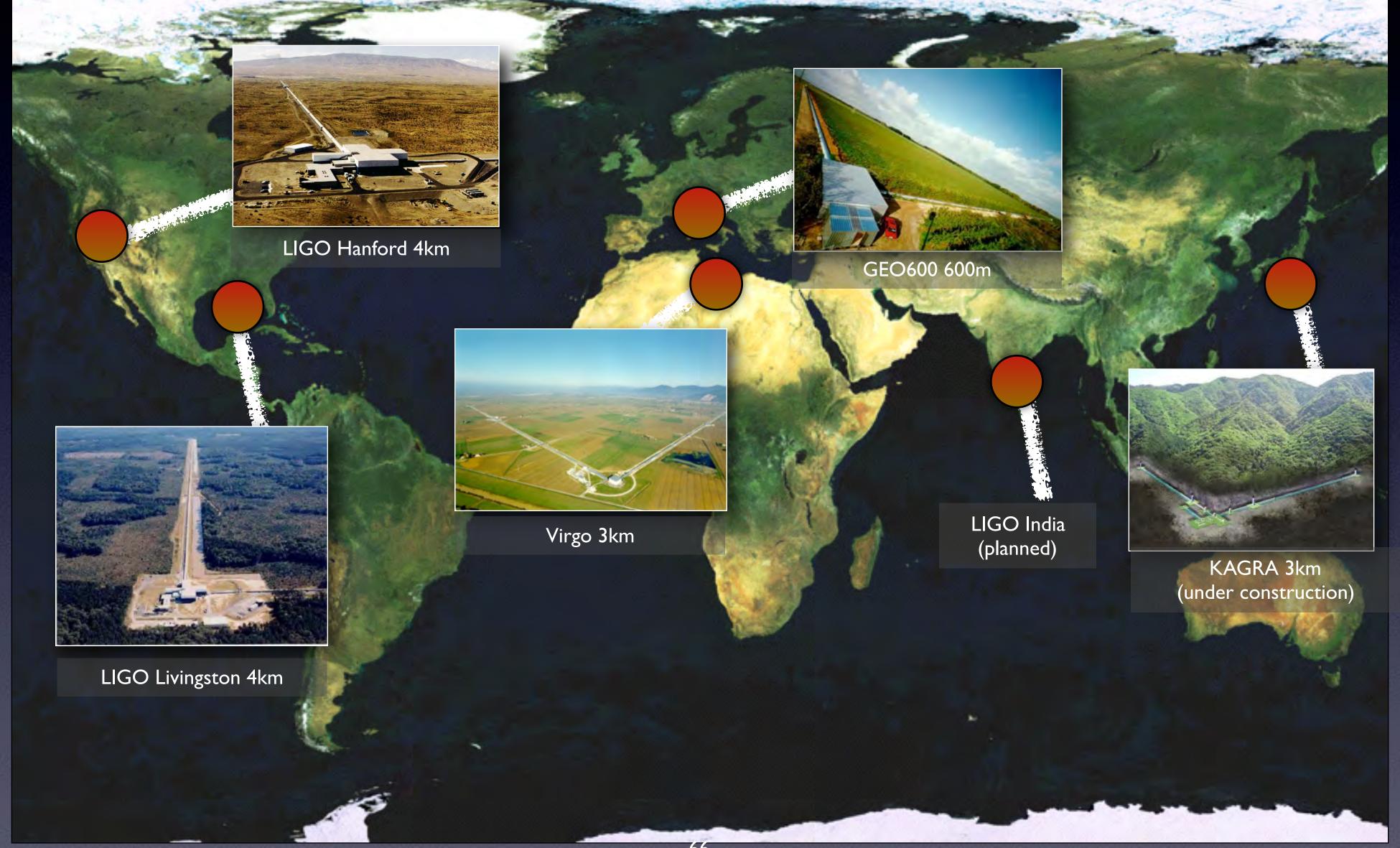
www.ligo.org/magazine







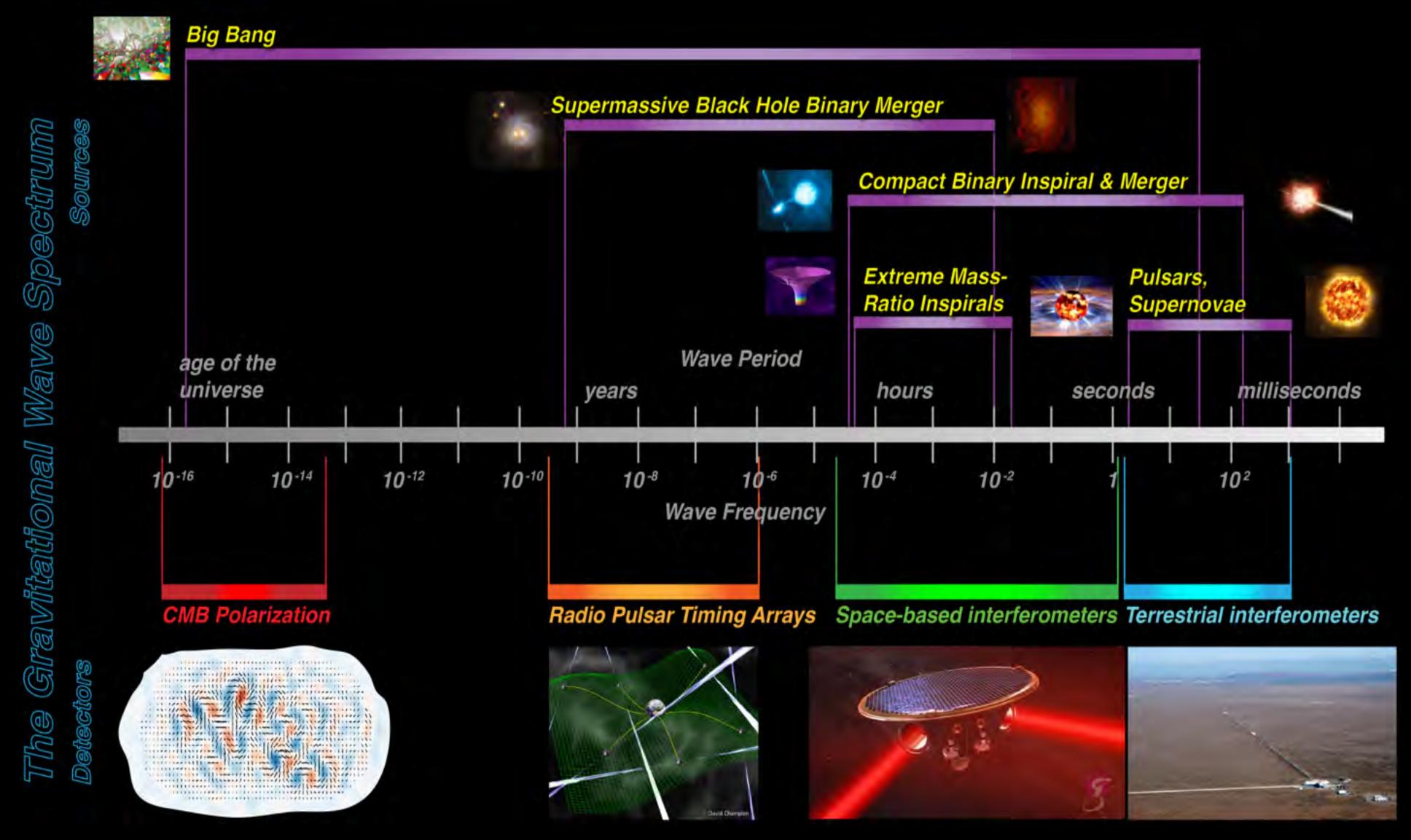
Ground-based detectors today



A. Freise 66 07.05.2016



The full GW spectrum



·(Credits: Ira Thorpe)

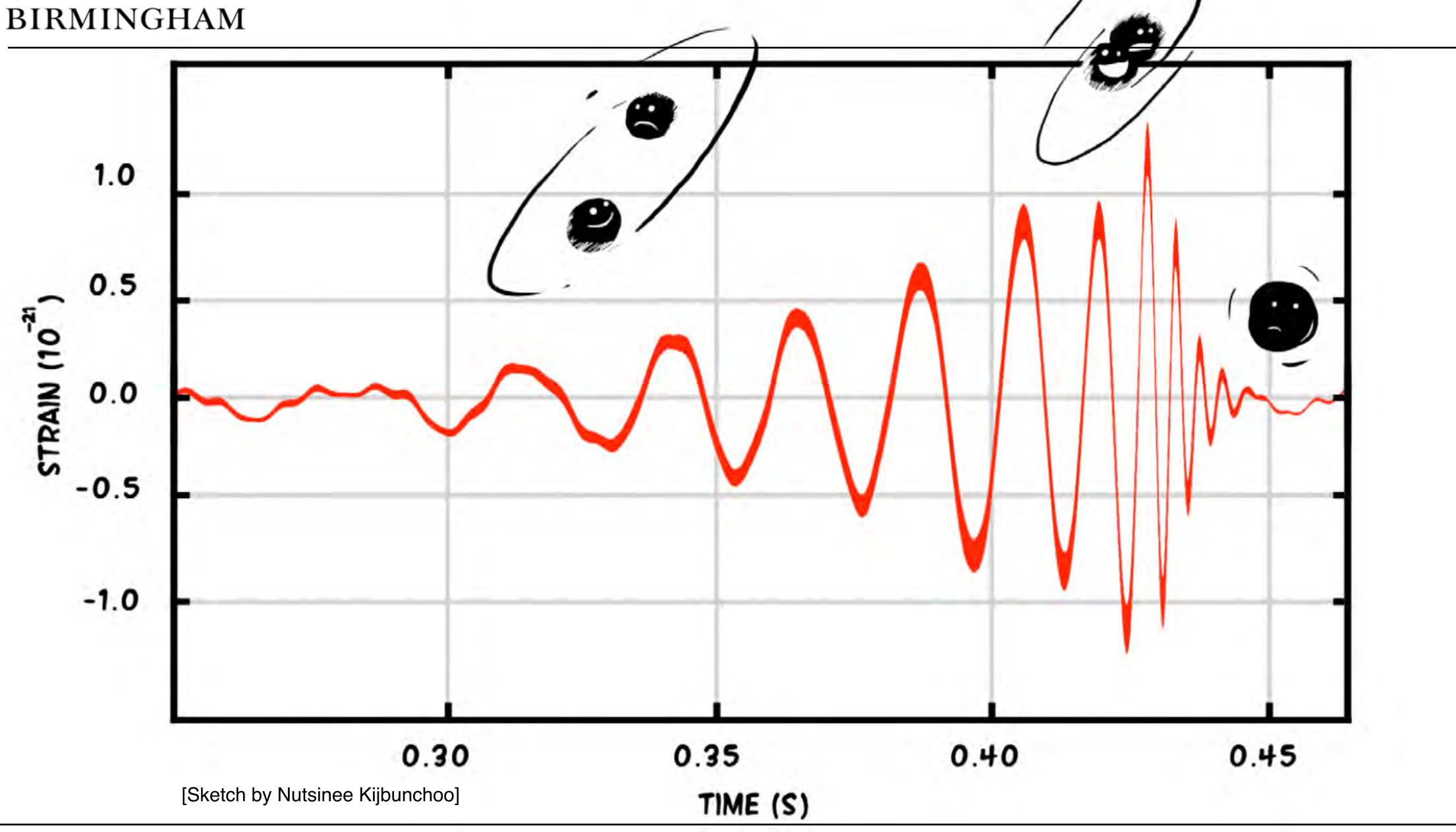


Advanced LIGO Parameters

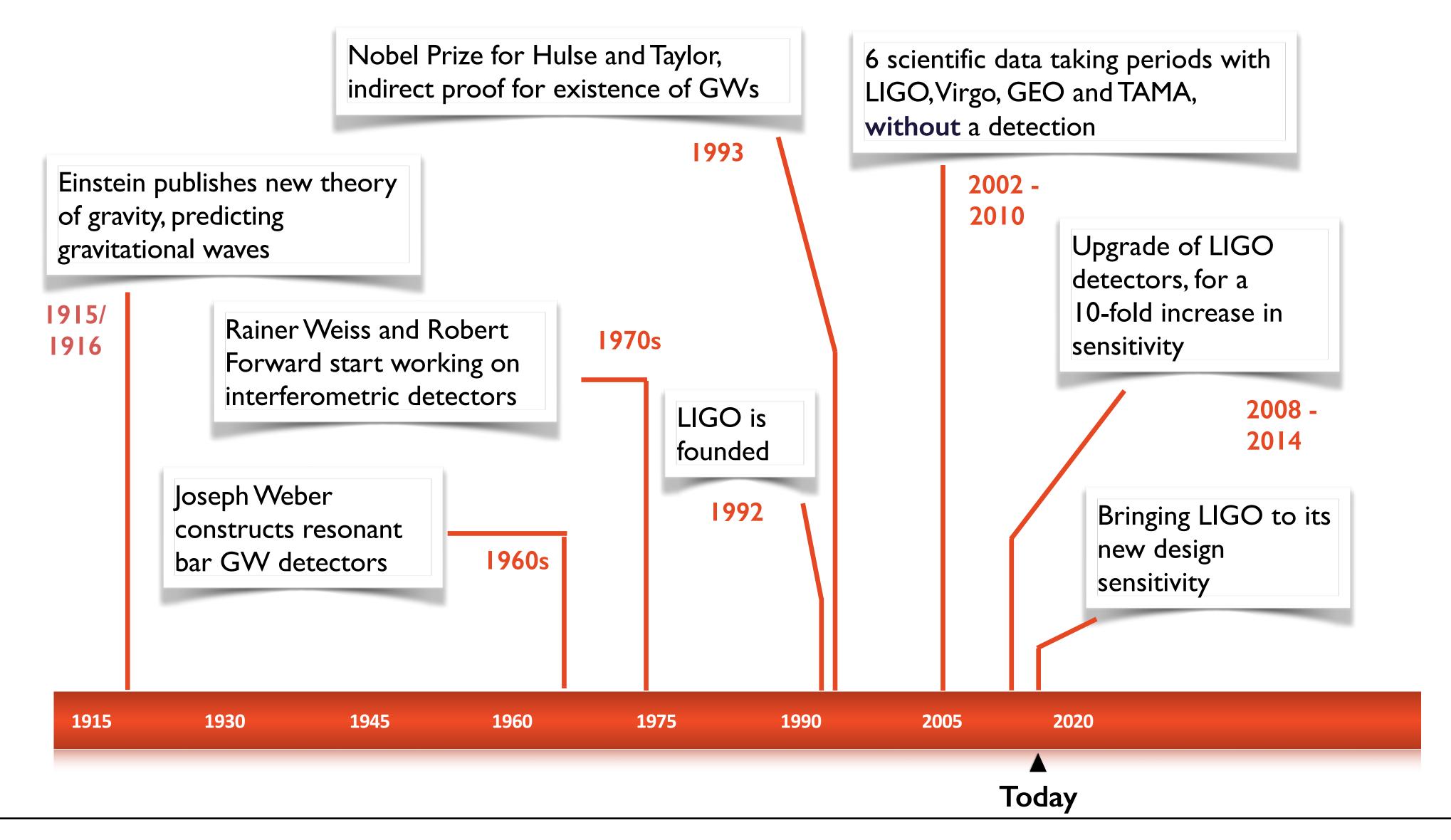
Parameter	Value	Unit
Laser wavelength	1064	nm
Arm cavity length, L_0	3994.5	m
Power recycling cavity length, $l_{p,+}$	57.66	m
Signal recycling cavity length, $l_{s,+}$	56.01	m
Michelson asymmetry, l_{-}	8	cm
Input mode cleaner length (round trip)	32.95	m
Output mode cleaner length (round trip)	1.13	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

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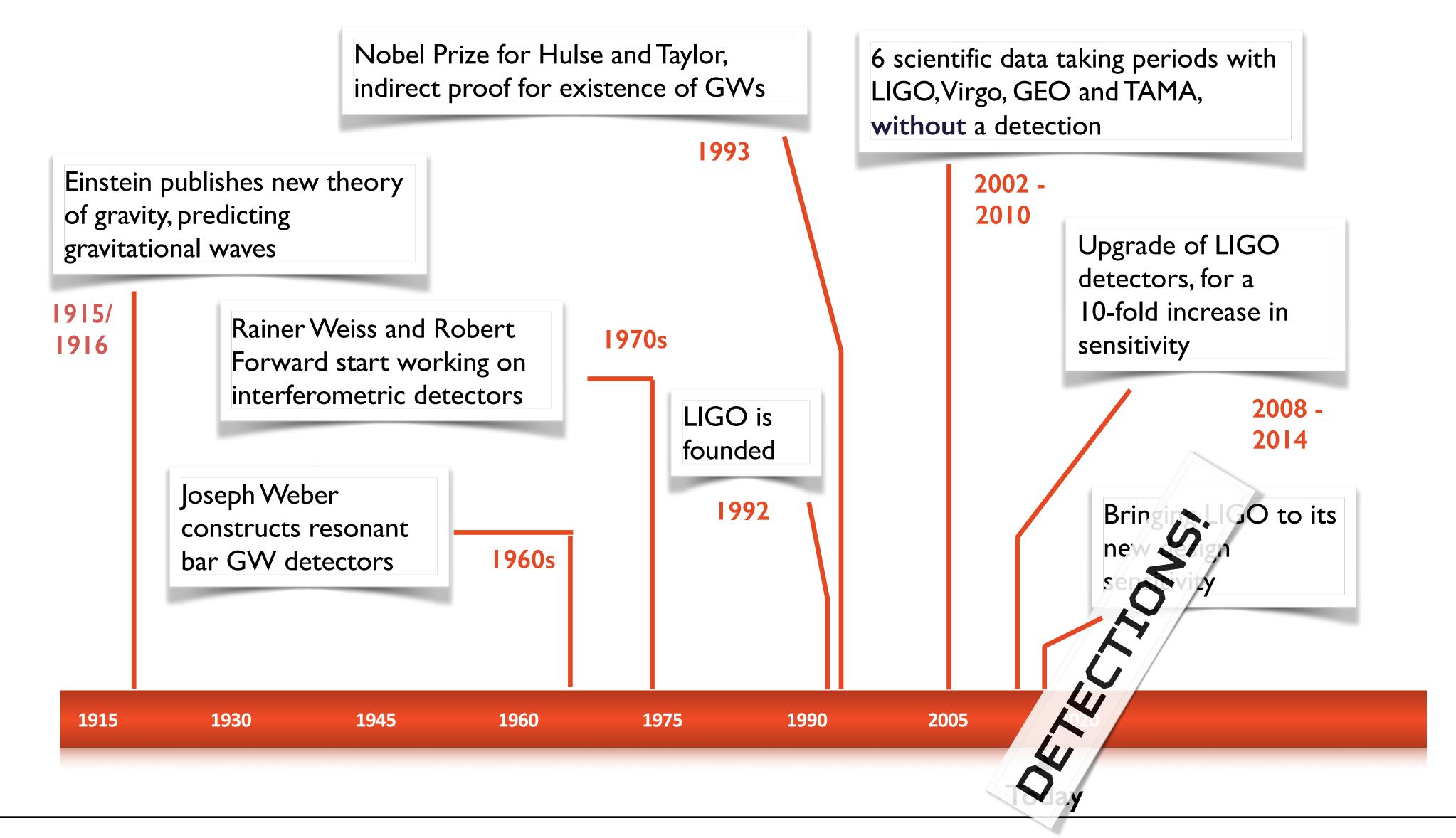






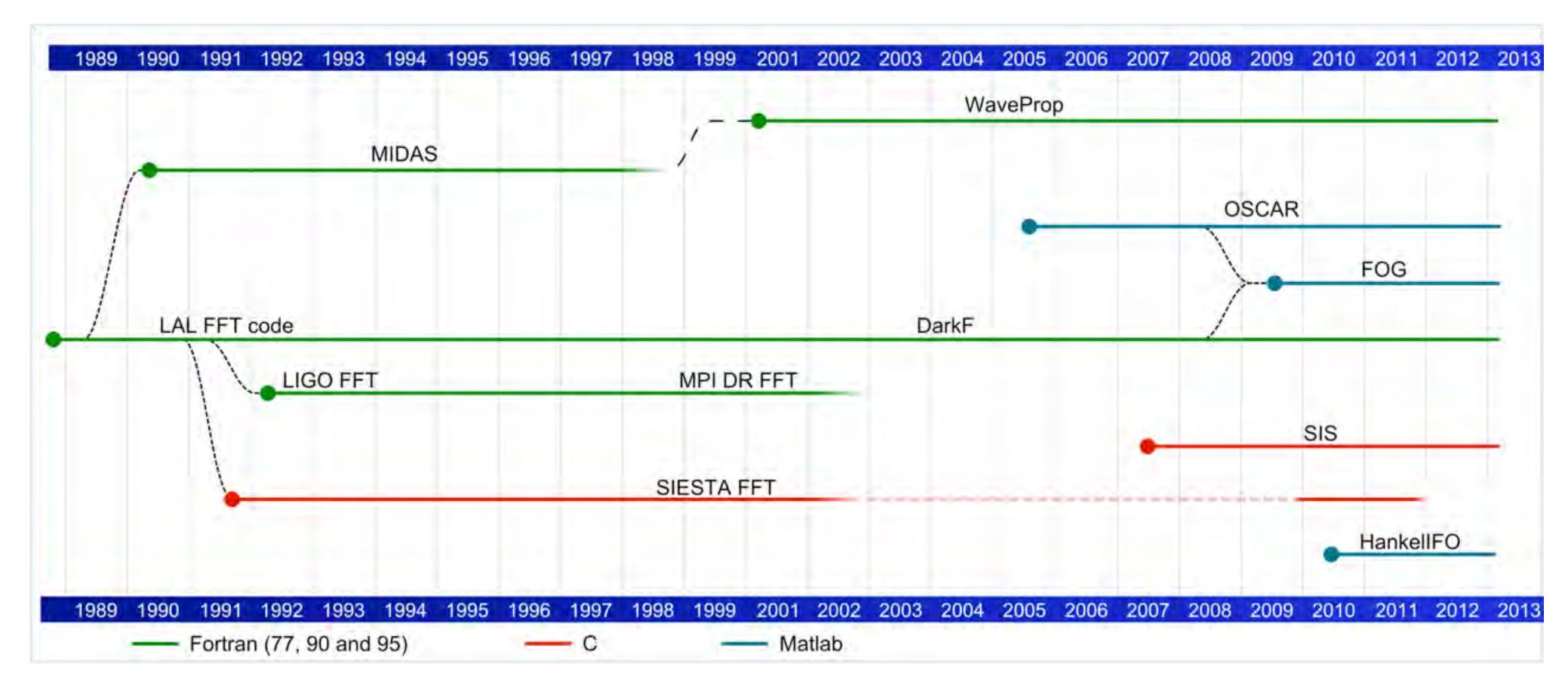








Life and Death of Simulations

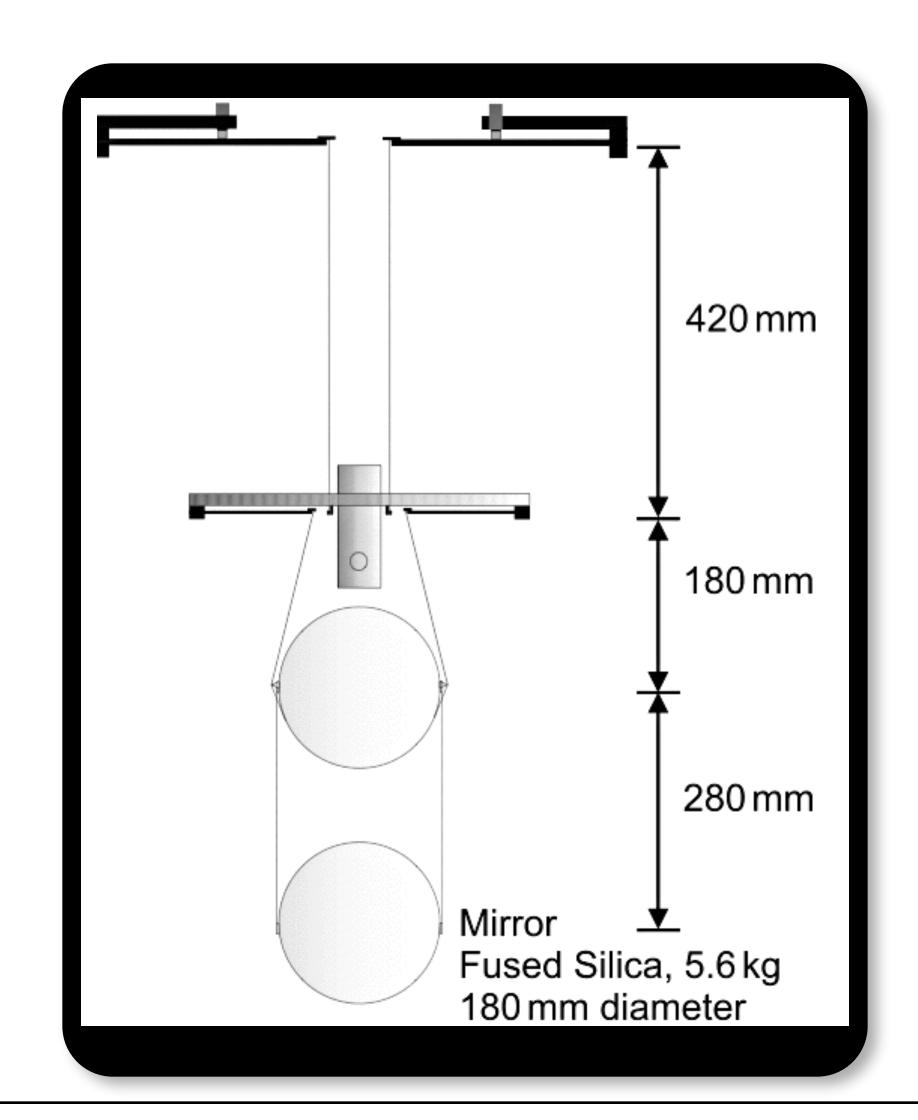


[Talk by Jerome Degallaix, LIGO commissioning and simulation workshop, Feb. 2013]



A GEO600 Mirror Suspension



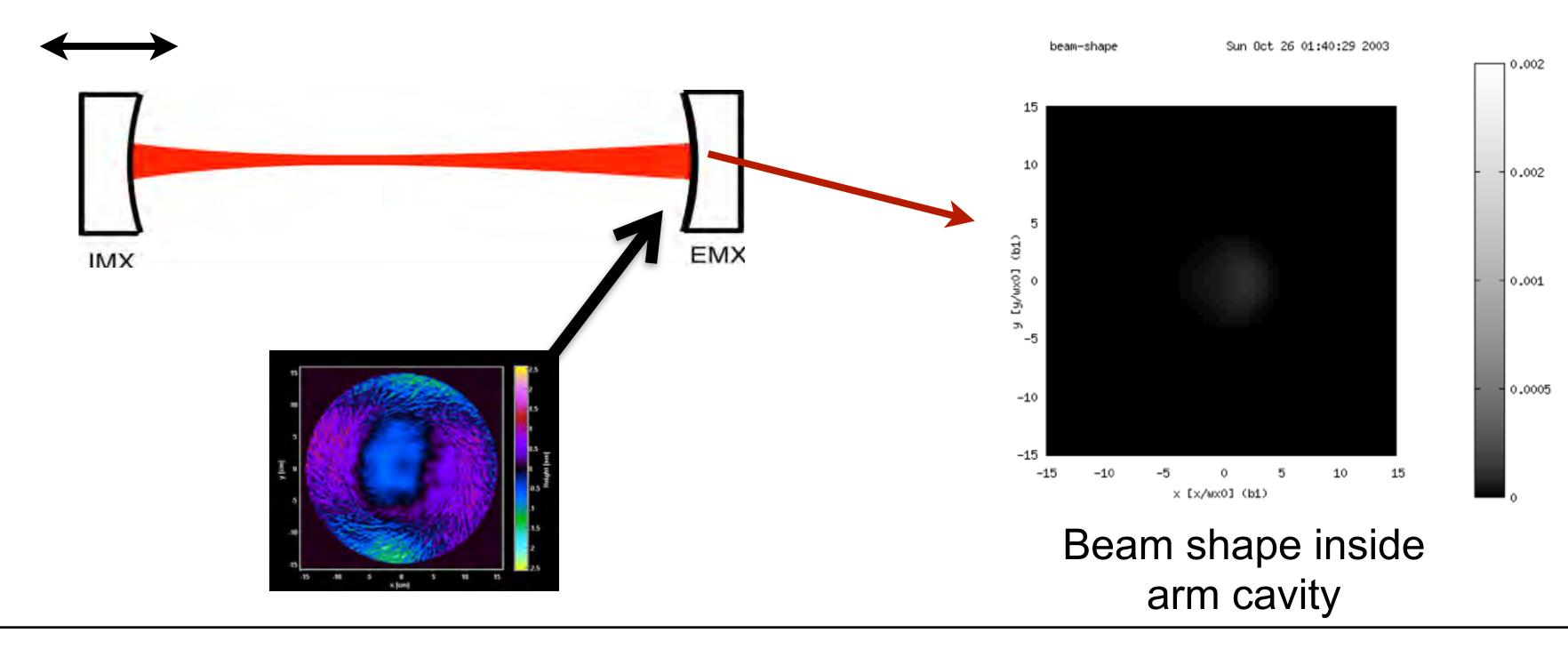






Beam Shape Distortions

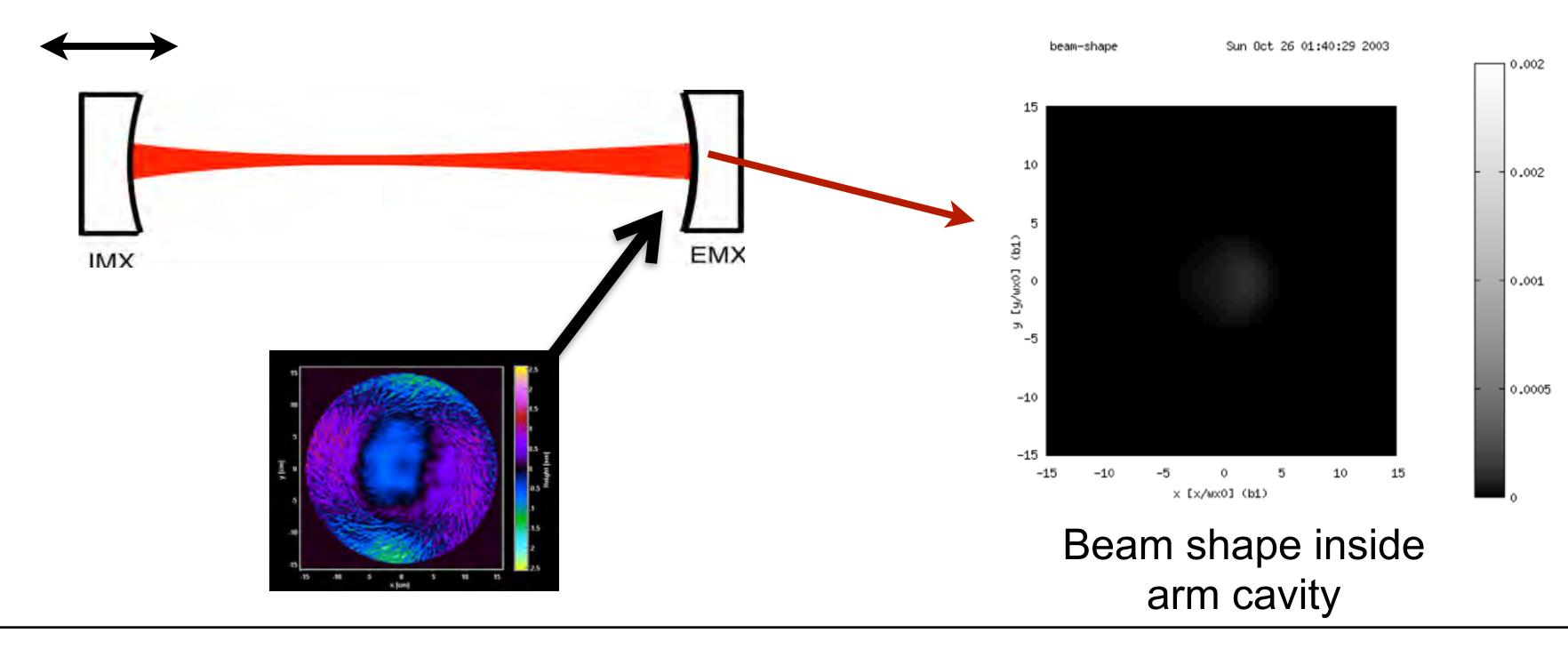
Acceptance of mirrors from manufacturer: Computer models are used to estimate the optical distortions due to the measured mirror distortions.





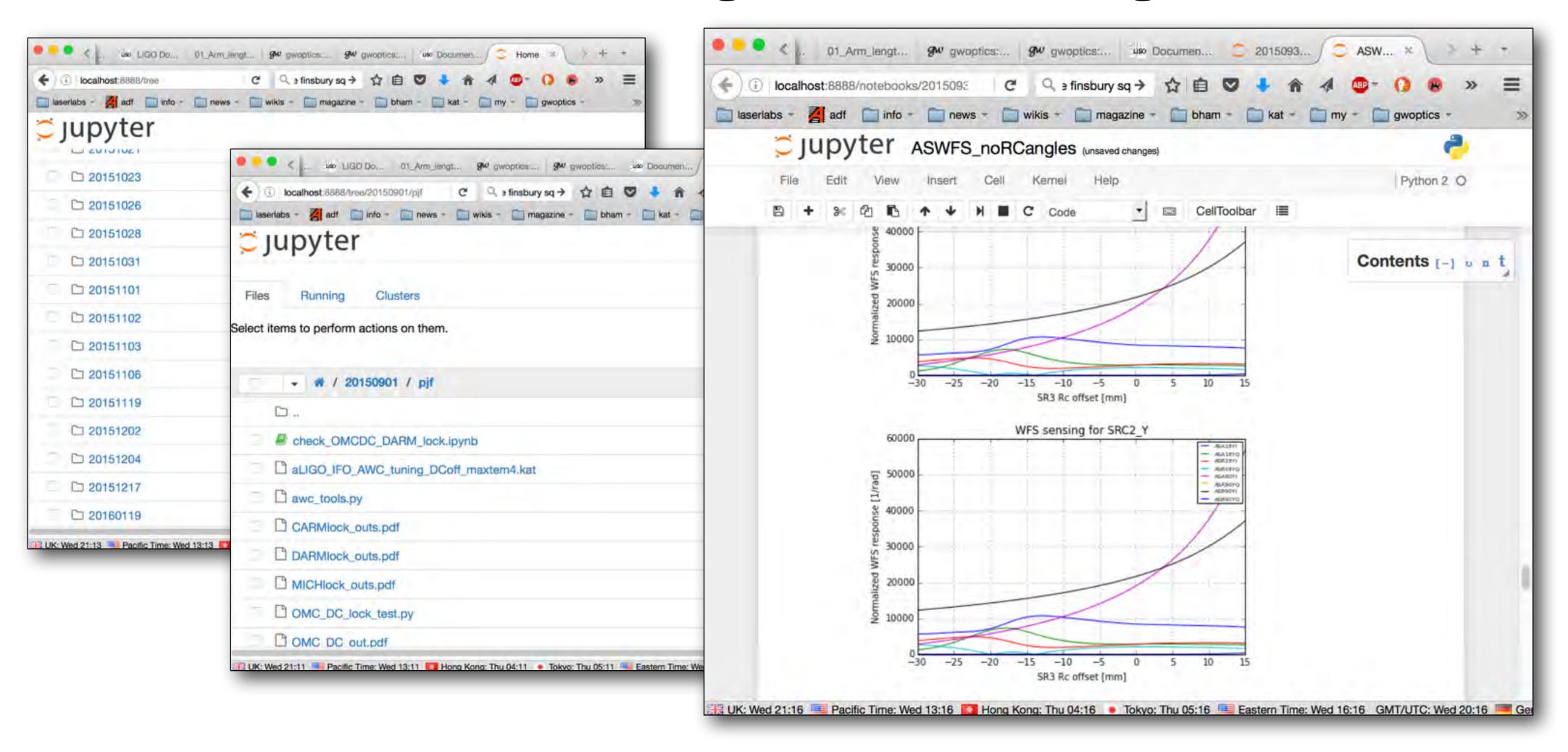
Beam Shape Distortions

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





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