

FINDING BLACK HOLES WITH LASERS

Andreas Freise

LIGO-G1300827

Royal Institute of Great Britain 18.02.2013



[Image shows guide laser at Allgäu Public Observatory in Ottobeuren, Germany. Credit: Martin Kornmesser]



UNIVERSITY OF
BIRMINGHAM

Astronomy



Big Science



ASKAP, part of SKA [<http://www.atnf.csiro.au/projects/askap/>]

LIGO

Laser Interferometer Gravitational wave Observatory



Gravitational Waves!

LIGO

Laser Interferometer Gravitational wave Observatory



Gravitational Waves!

LIGO

Laser Interferometer Gravitational wave Observatory



an exemplary (personal) story...

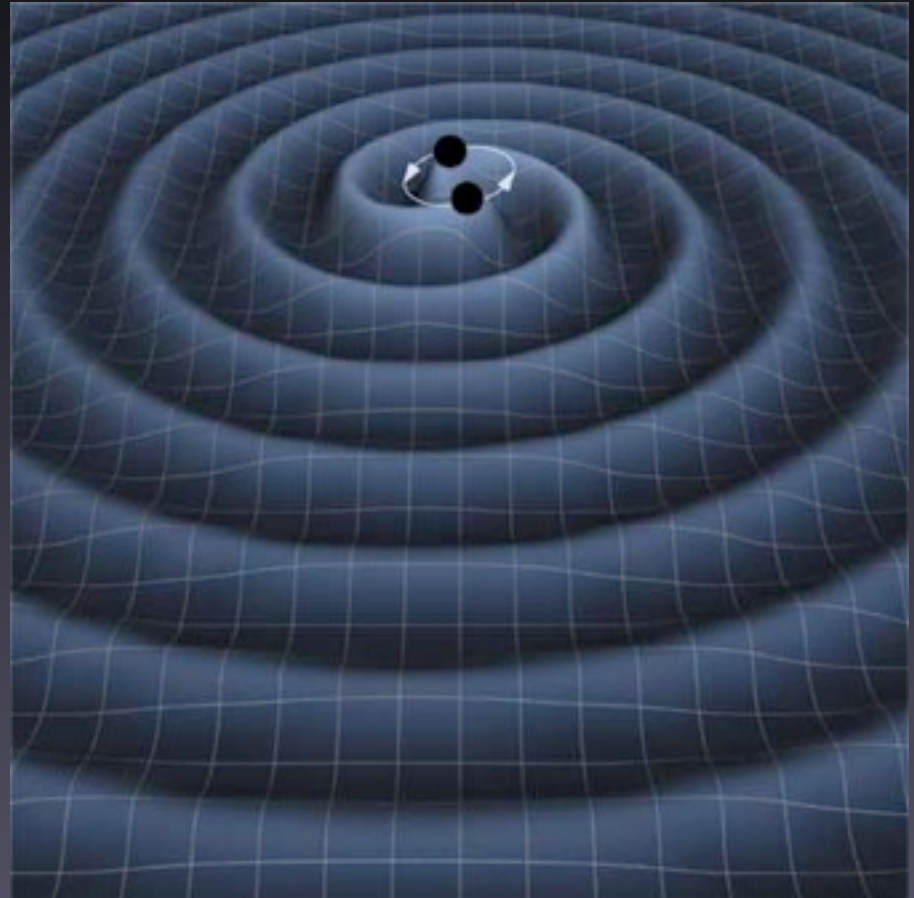
Gravitational what?

96% of the Universe



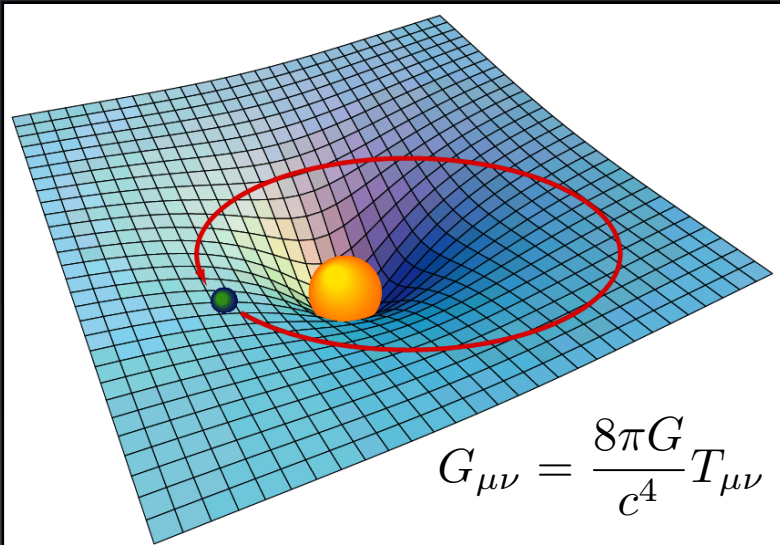
Gravitational Waves

- A fundamental prediction of general relativity
- Ripples of space-time that propagate at the speed of light
- Produced by large, compact and relativistic concentration of mass or energy
- Stretch and squeeze space





Einstein's theory of relativity





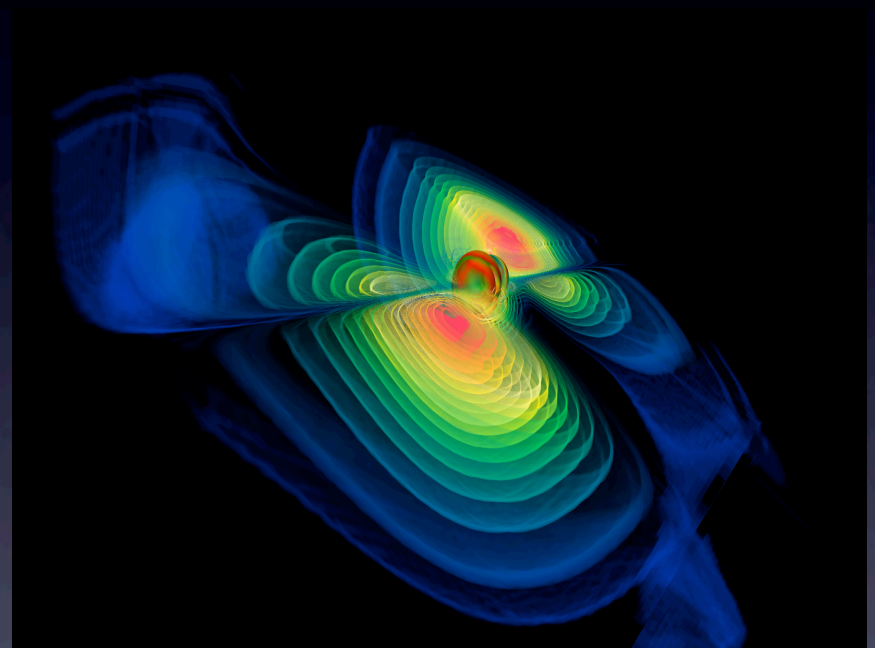
Generation of GWs

The Claw, Dreamworld Australia



$L \sim 0.000\,000\,000\,000\,000\,000$
 $000\,000\,000\,000\,000\,000\,000\,000$
 $000\,1\,W$

Binary black hole merger



$L \sim 10,000,000,000,000,000,$
 $000,000,000,000,000,000,$
 $000,000,000,000,000\,W$



Sources of Gravitational Waves

binary systems



- Any mass distribution that is accelerated in a non-spherically symmetric way (waving hands, running trains, planets in orbit,...)
- Large masses necessary to get any measurable signal

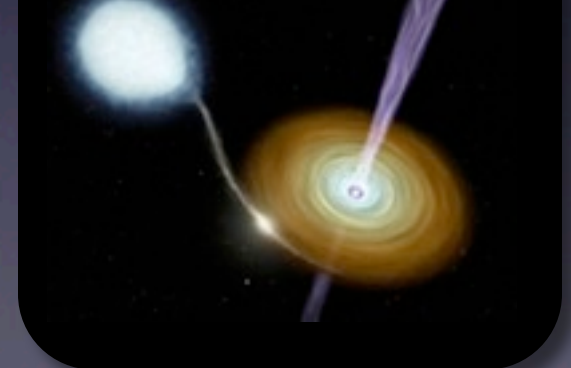
supernovae



pulsars

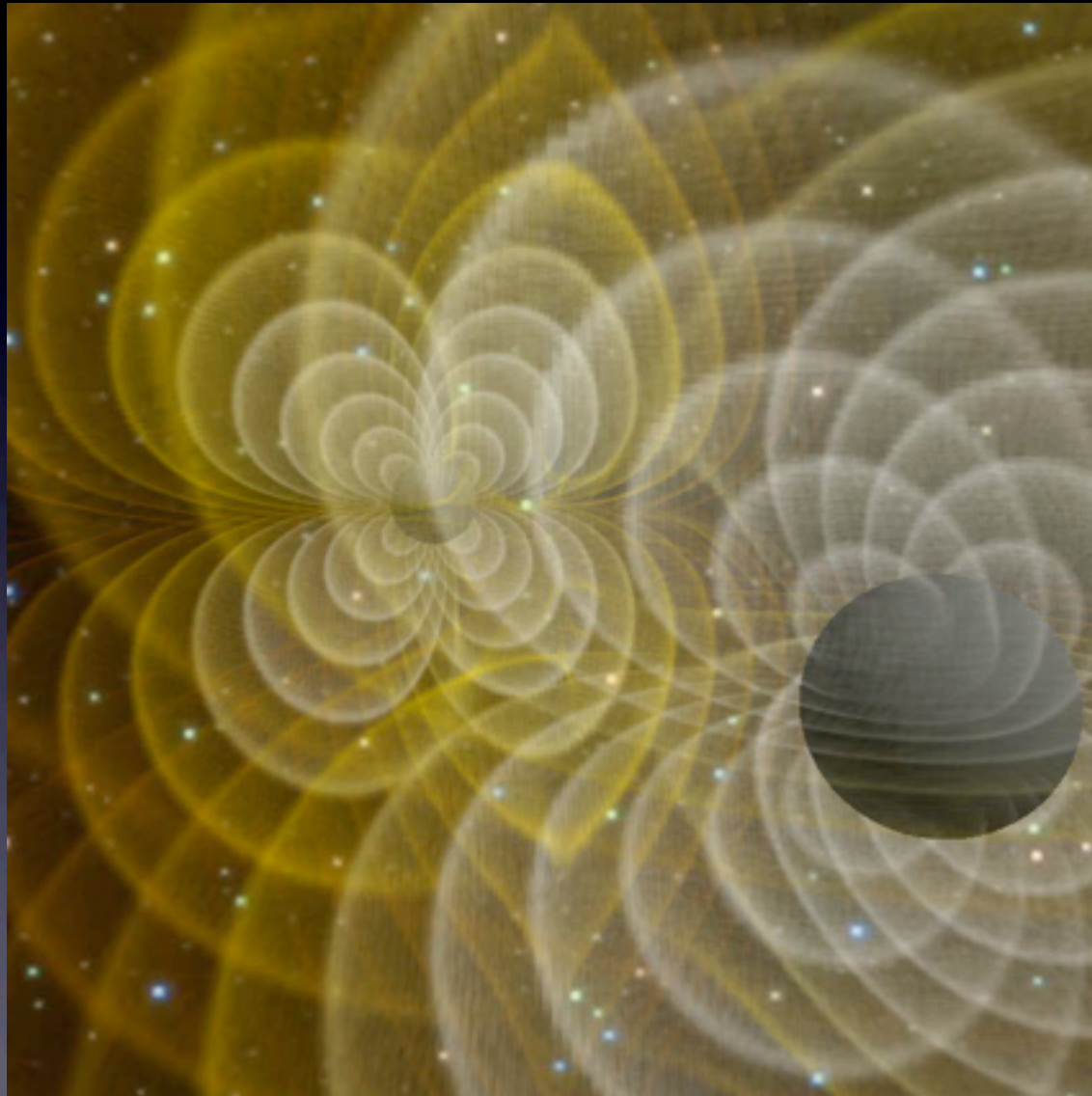


accreting stars





Gravitational waves from merging black holes

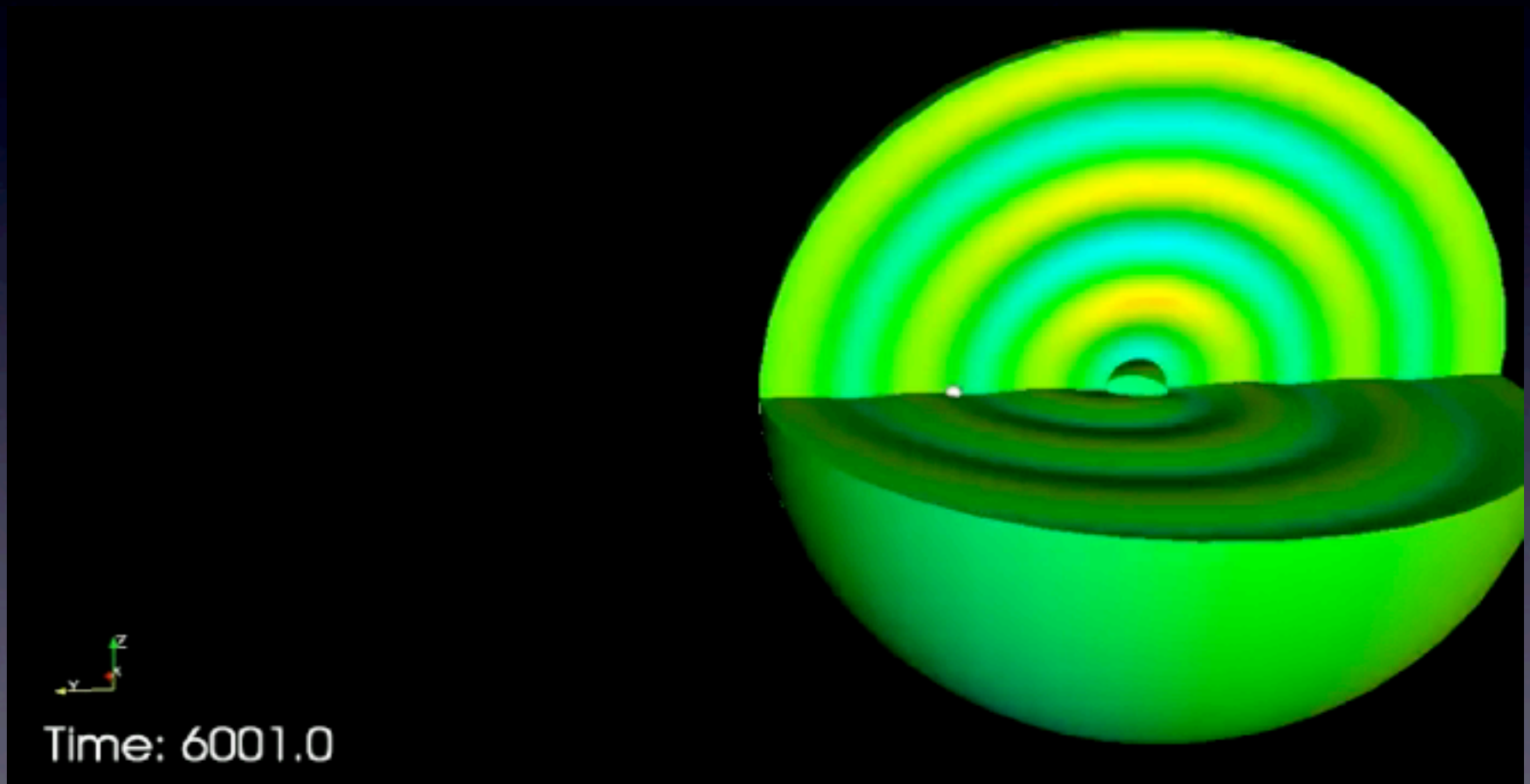




Gravitational waves from merging black holes



Bobbing like a Cork ...



[Credit: <http://www.black-holes.org/>]



And the big question:



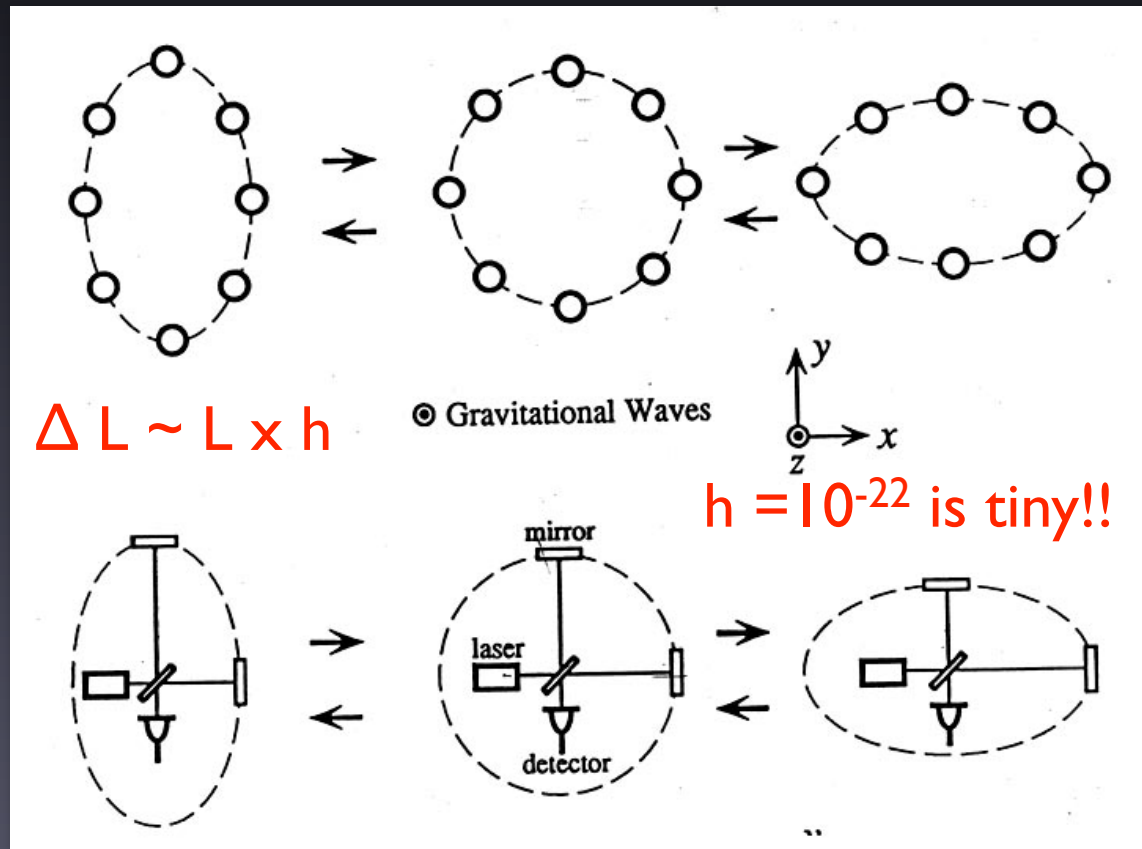
[Credit: <http://www.skyandtelescope.com/>]



Gravitational Wave *Detection!*



Observing Gravitational Waves: *Laser Interferometers*





Interferometry in 1887



Michelson interferometer (ca. 1887)



Sensitivity:
0.01 of a fringe

Interferometry in 1972

ELECTROMAGNETICALLY COUPLED BROADBAND
GRAVITATIONAL ANTENNA

MIT
QUARTERLY PROGRESS REPORT

APRIL 15, 1972

No. 105

Sensitivity:
0.000 000 01
of a fringe

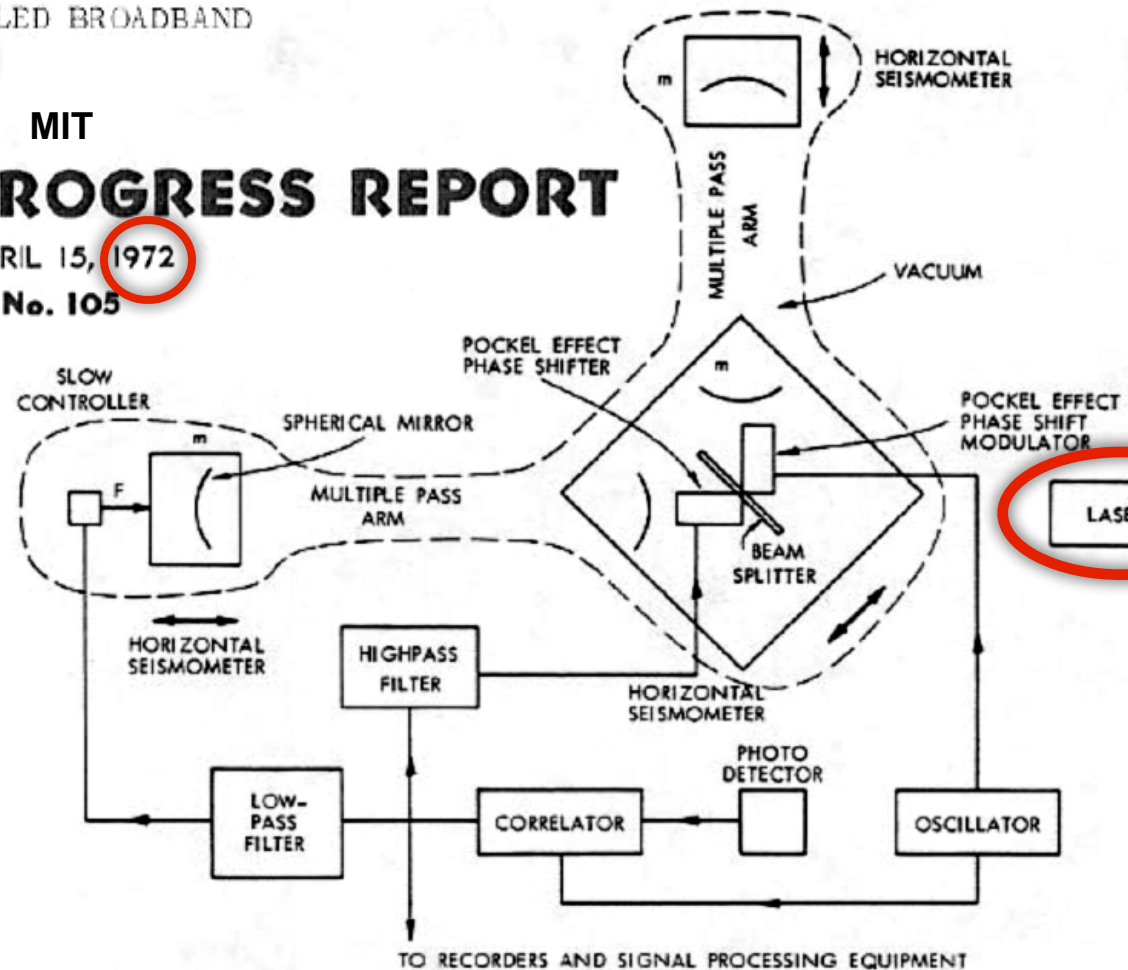
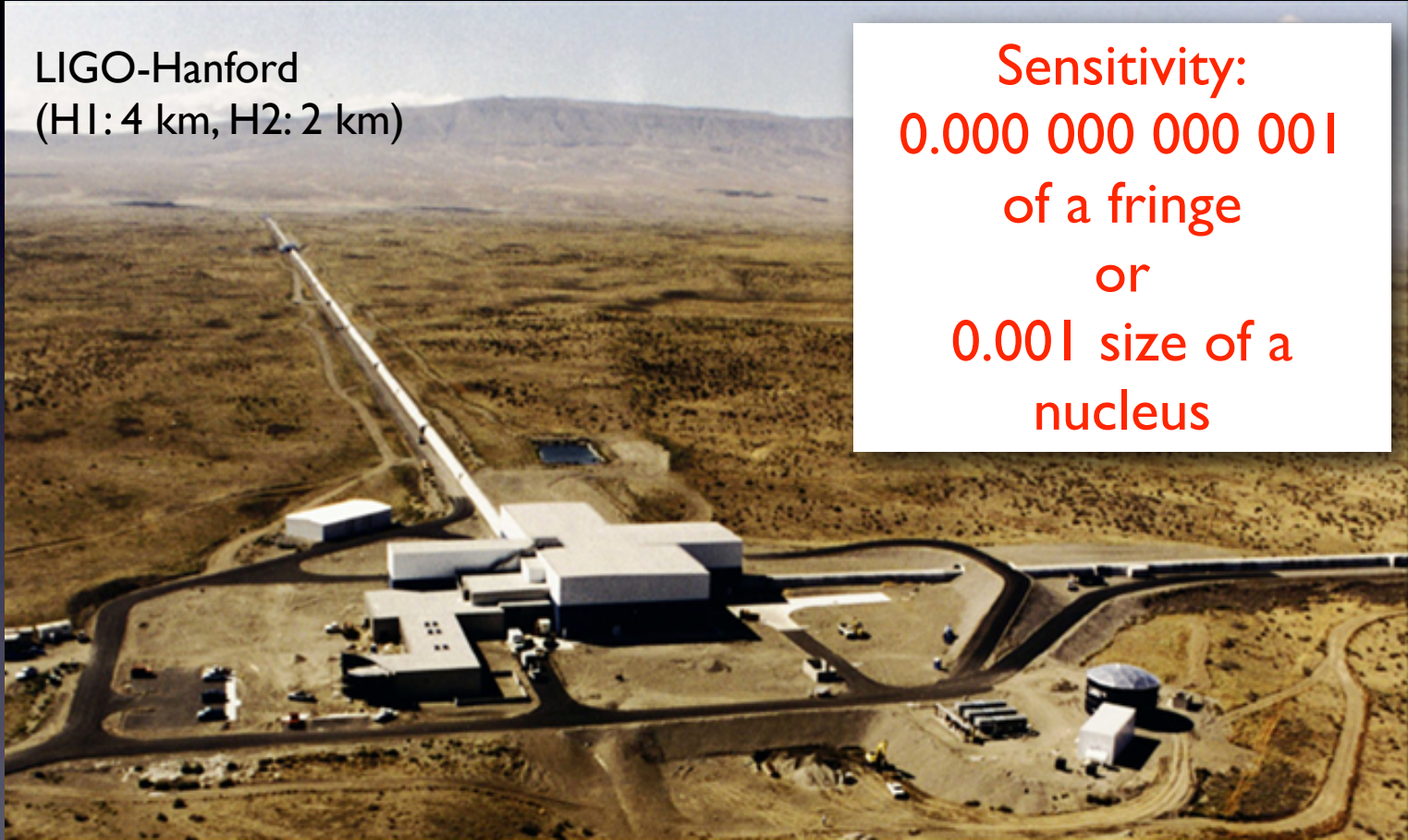


Fig. V-20. Proposed antenna.



GW interferometry today

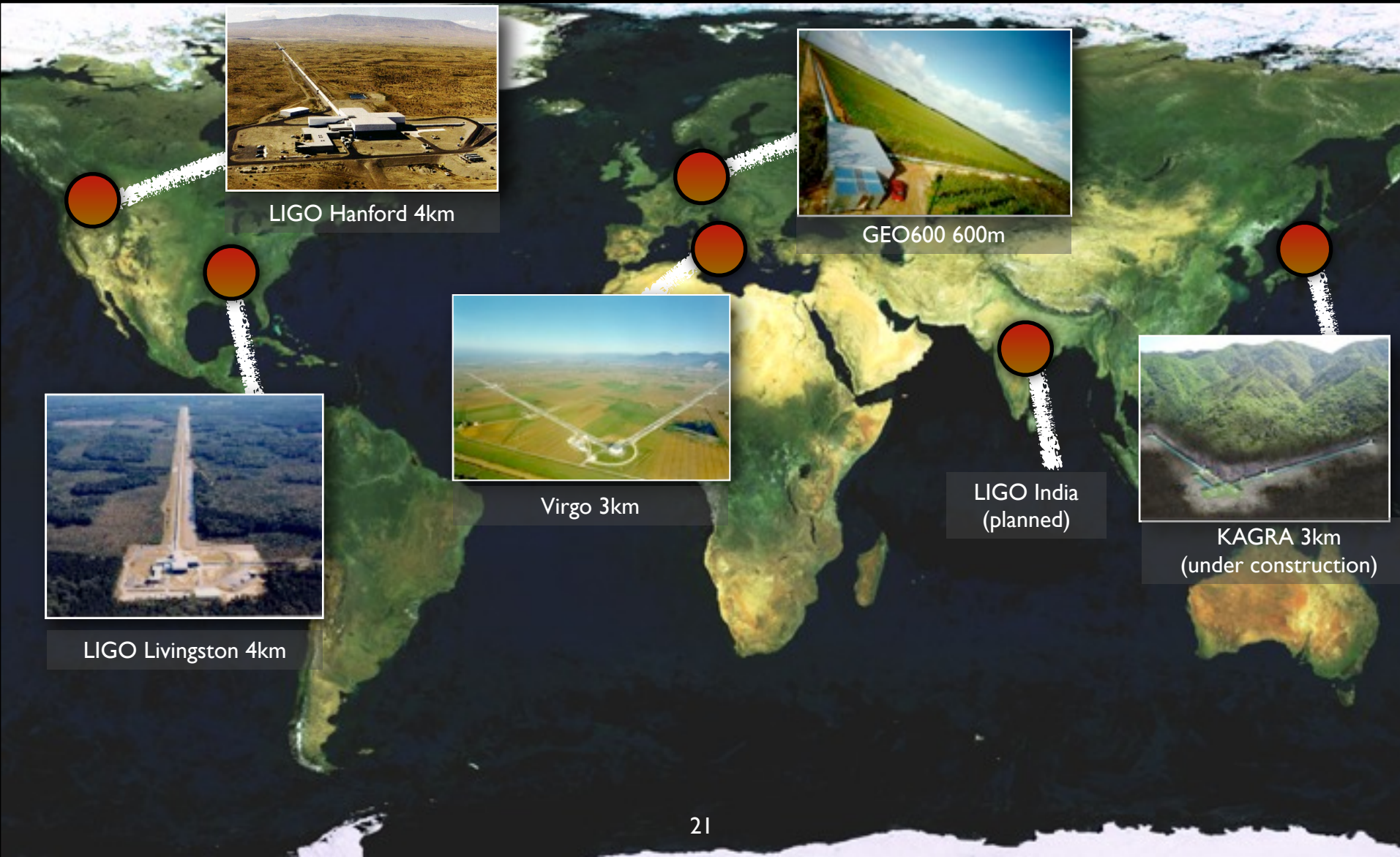
LIGO-Hanford
(H1: 4 km, H2: 2 km)



Sensitivity:
0.000 000 000 001
of a fringe
or
0.001 size of a
nucleus



World-wide Network



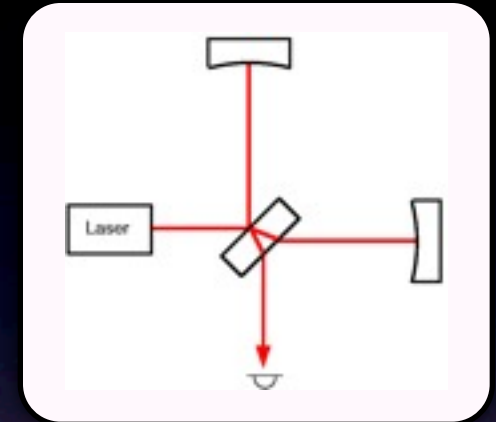


The Emergence of a New Science



The First Generation

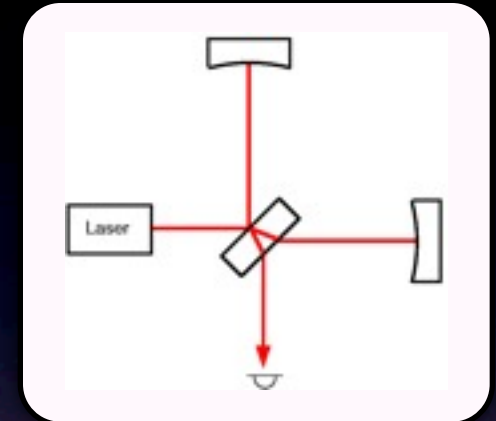
- GEO, TAMA, Virgo, LIGO
- Proposed in the 1980ies
- Development of new technologies
- Detectors build in the 1990ies
- Development of even newer technologies
- Operation and data taking 2002-2010





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- Proposed in the 1980ies
- Development of new technologies
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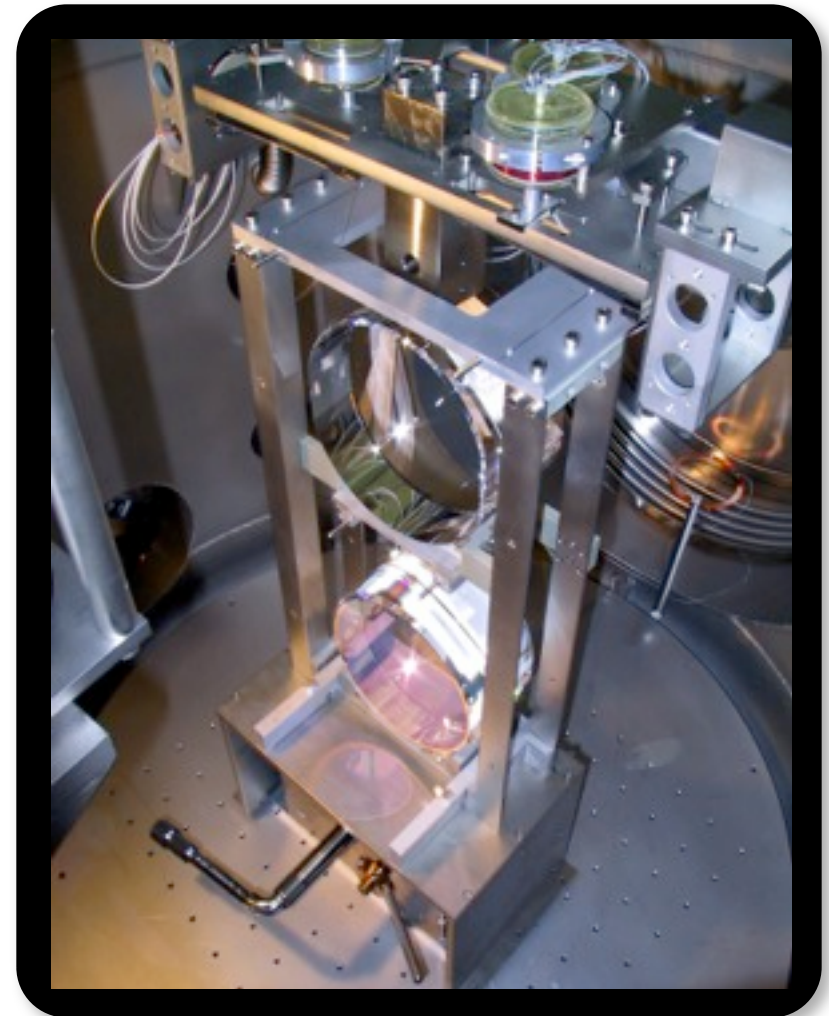
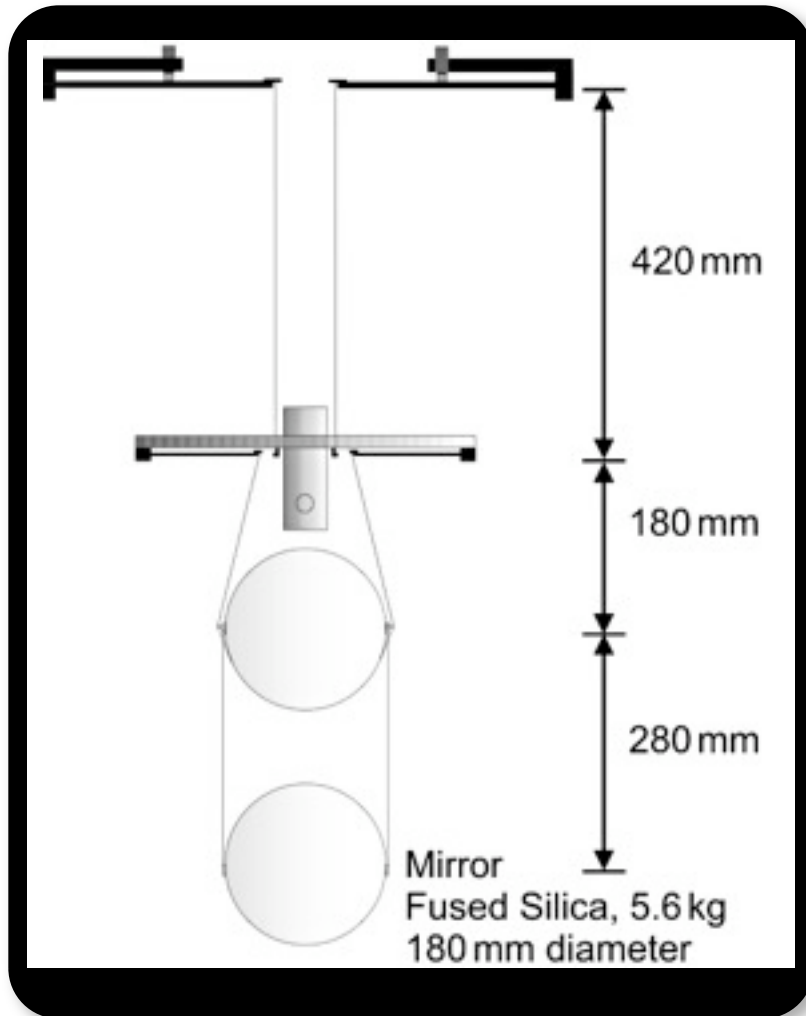


GEO 600 (British/German)



[Credit: Albert-Einstein Institute / GEO 600]

A GEO600 Mirror Suspension





GEO 600 control room (2001)



VIRGO



[Credit: <https://www.cascina.virgo.infn.it/>]



Virgo Main Optics

High quality fused-silica mirrors

- 35 cm diameter, 10 cm thick
- Substrate losses 1 ppm
- Coating losses <5 ppm
- Surface deformation $\lambda/100$
(rms on 150mm)



[Credit: <https://www.cascina.virgo.infn.it/>]



Virgo Control Room (2003)





2012

www.ligo.org/magazine

2012



Welcome to the first issue of the LIGO Magazine!

These pages are an excellent resource for staying abreast of the progress of the LIGO Magazine which will be published online here in this magazine. Many articles and our own LIGO team have already been published. You can also find out more about the magazine in the 'All about us' section. We hope you will find it an interesting and useful read. We would love to hear from you about your comments and feedback. Please email us at ligo@ligo.org or visit our website at www.ligo.org.

Julia Anderson
LIGO Magazine Editor

Chris Dean
LIGO Magazine Editor

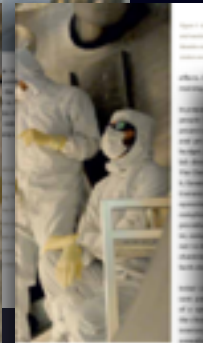
A brief history of the evolution of Advanced LIGO

Since the first LIGO prototype, the Advanced LIGO design has evolved through several stages. The first stage was the LIGO prototype, which was built in the late 1990s and early 2000s. It was a small-scale experiment that demonstrated the feasibility of the LIGO concept. The second stage was the LIGO design study, which was completed in 2002. This study identified the key technologies and design requirements for the Advanced LIGO detector. The third stage was the LIGO design freeze, which was completed in 2005. This freeze established the final design for the detector, including the choice of mirrors, coatings, and optics. The fourth stage was the LIGO design review, which was completed in 2007. This review confirmed the design and identified any remaining issues. The fifth stage was the LIGO design implementation, which is ongoing. This stage involves the construction and testing of the detector components.



Under construction: Advanced LIGO

The Advanced LIGO detector is currently under construction at the LIGO Livingston facility in Louisiana. The detector consists of two identical Michelson interferometers, each with two arms. The arms are 4 km long and contain mirrors that reflect the light back and forth. The mirrors are made of fused silica and are coated with a thin layer of aluminum. The detector is housed in a large underground cavern that has been excavated for the purpose. The construction of the detector is a complex task that involves the use of many different technologies and materials. The detector is expected to be completed in 2015 and will be used to detect gravitational waves.



How does it work? An optical cavity

How does it work? An optical cavity

The optical cavity is a key component of the LIGO detector. It consists of two mirrors that are positioned at the ends of the detector arms. The mirrors are made of fused silica and are coated with a thin layer of aluminum. The cavity is used to store the light for a long time, which allows the light to be amplified and the signal to be measured. The optical cavity is a complex system that involves the use of many different technologies and materials. The cavity is expected to be completed in 2015 and will be used to detect gravitational waves.

Advanced LIGO

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www.ligo.org/magazine

2012



Welcome to the first issue of the LIGO Magazine!

These pages are an excellent introduction to the first issue of the LIGO Magazine, which will be published online in February 2012. The magazine will be published online in February 2012. The magazine will be published online in February 2012.

A brief history of the evolution of Advanced LIGO

Since the first LIGO prototype, the Advanced LIGO design has evolved significantly. The design has evolved significantly. The design has evolved significantly.

The path to the Advanced LIGO design

When LIGO was proposed in the 1990s, it was a simple idea: to build a detector that could identify gravitational waves. The design has evolved significantly.



Under construction: Advanced LIGO

The Advanced LIGO detector is a major step forward in the search for gravitational waves. It is a major step forward in the search for gravitational waves.

How does it work? An optical cavity

When light enters the right-hand mirror, it is reflected back and forth between the mirrors. The light bounces back and forth between the mirrors.

The Advanced LIGO detector is a major step forward in the search for gravitational waves. It is a major step forward in the search for gravitational waves.

What is LIGO?

LIGO is a laser interferometer that measures the strain of spacetime caused by gravitational waves. It is a laser interferometer that measures the strain of spacetime caused by gravitational waves.

How does it work?

The detector consists of two main parts: the interferometer and the control system. The interferometer is a laser interferometer that measures the strain of spacetime caused by gravitational waves.



www.ligo.org/magazine



Result?

- No gravitational wave yet!
- We learned a lot!
- Global gravitational wave community



Result?

- No gravitational wave yet!
- We learned a lot!
- Global gravitational wave community





Advanced LIGO

LIGO

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
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- Univ. of Wisconsin-Milwaukee
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- University of Washington

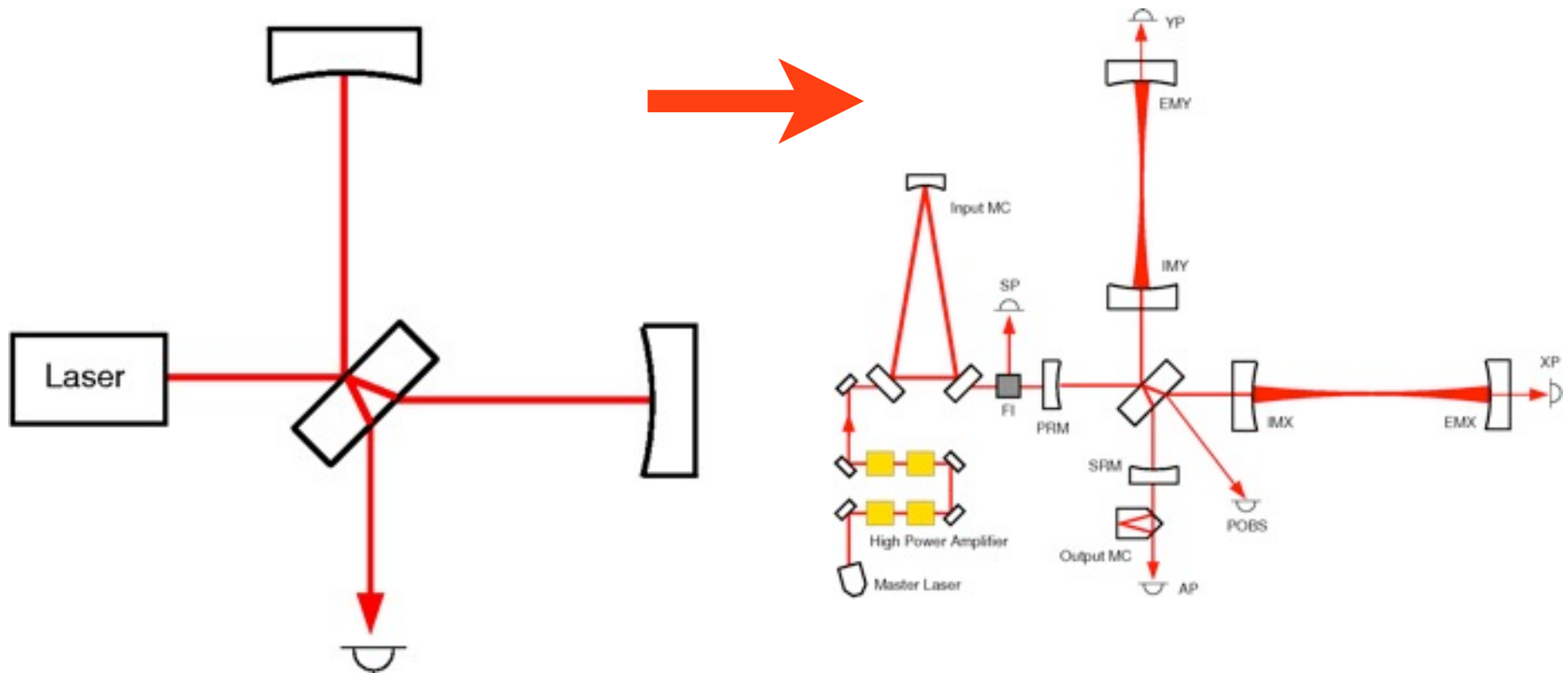


Upgrade of existing LIGO
Start of operation >2015



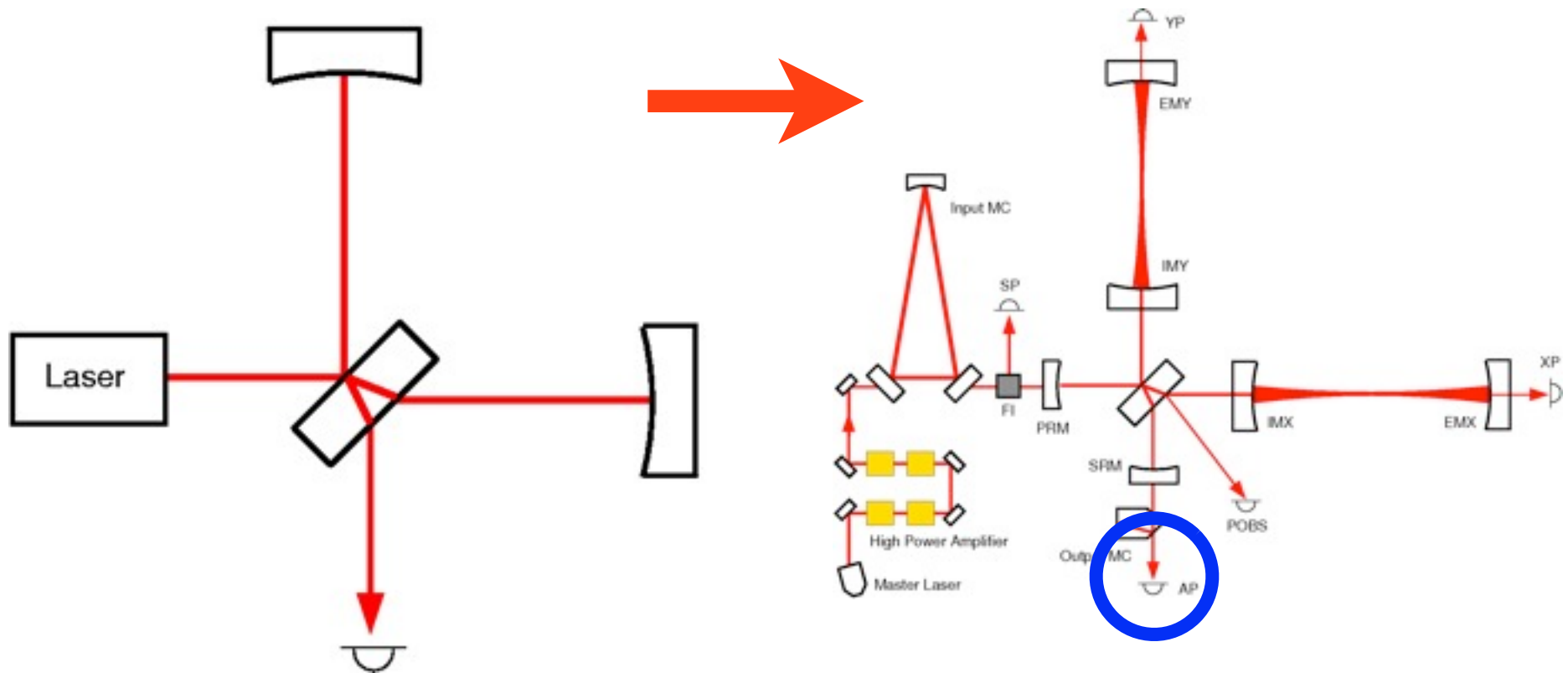


Advanced Interferometry

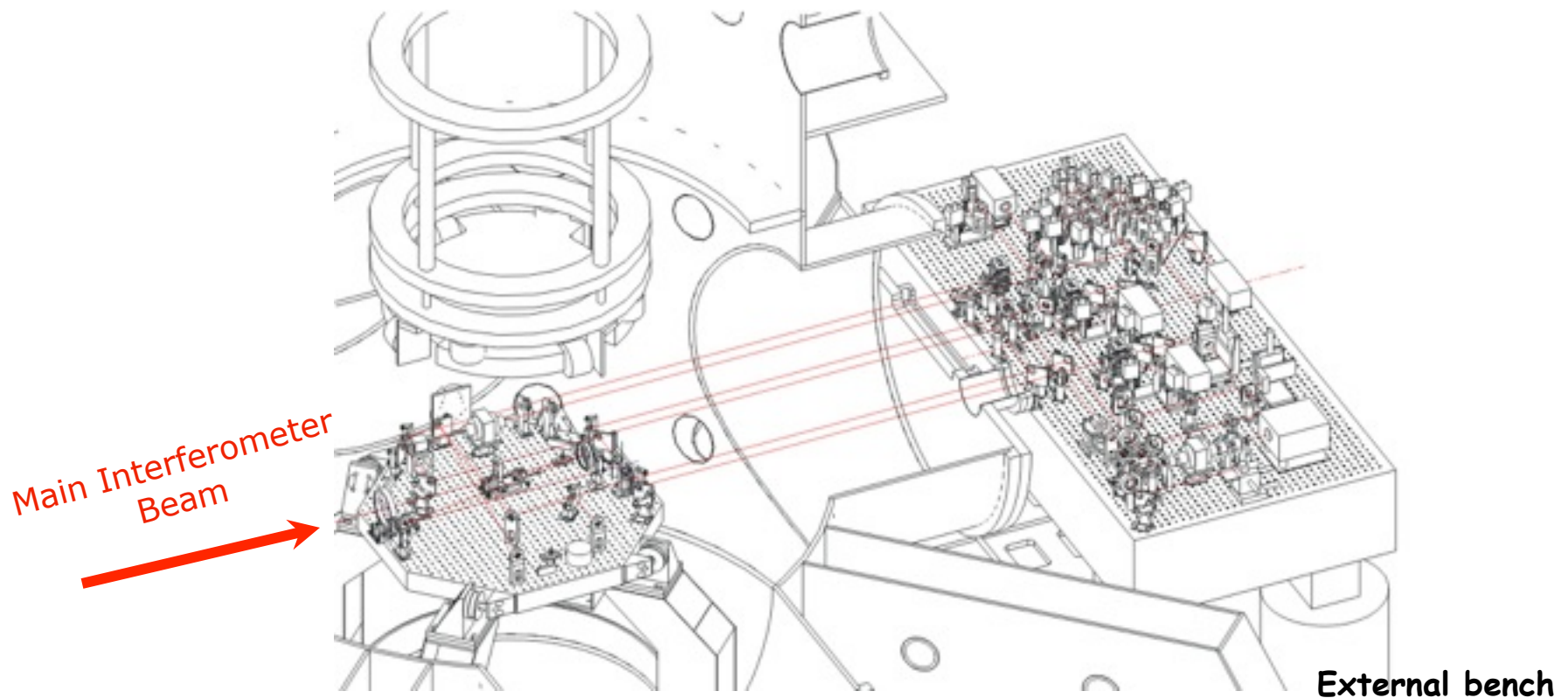


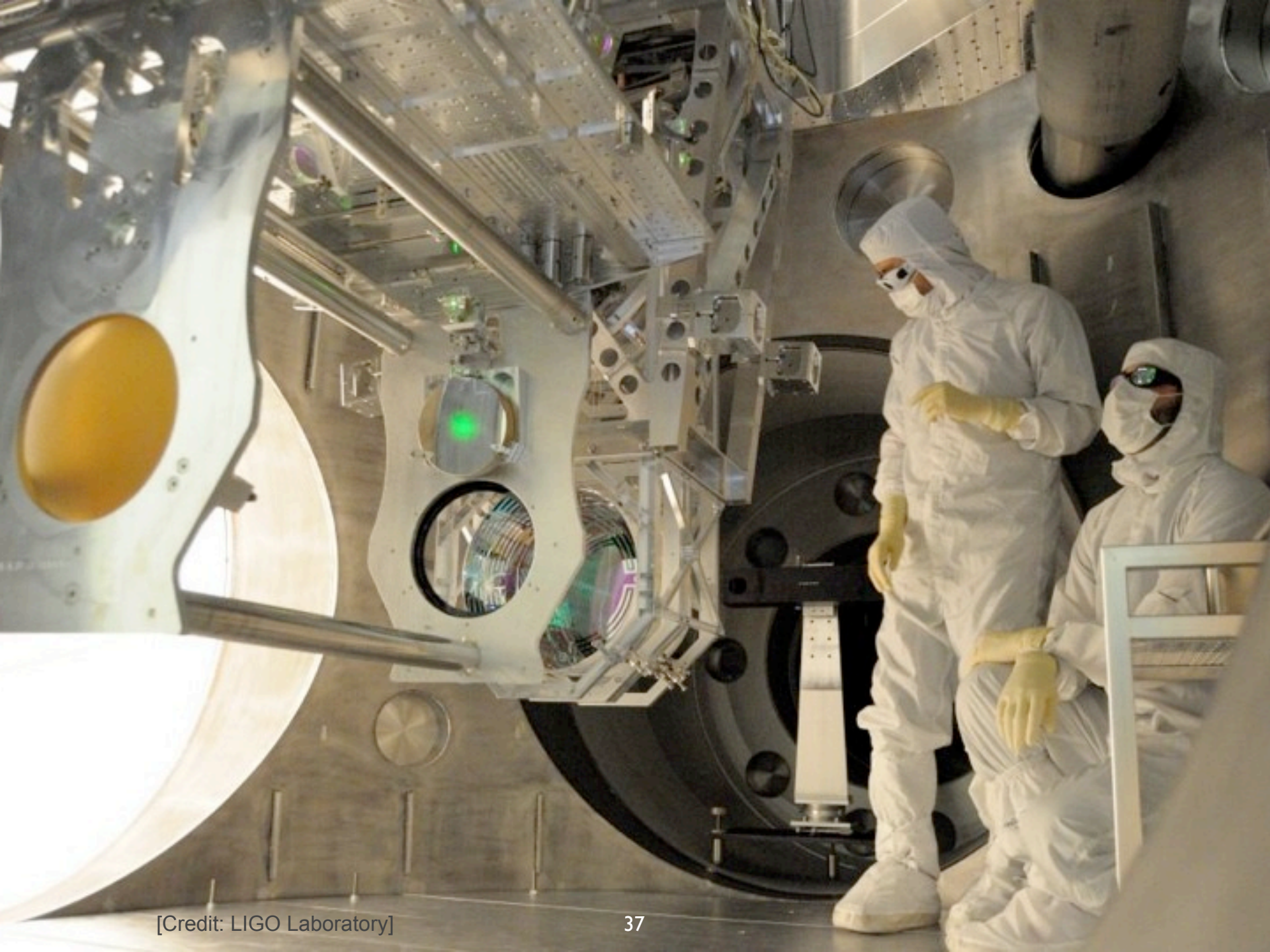


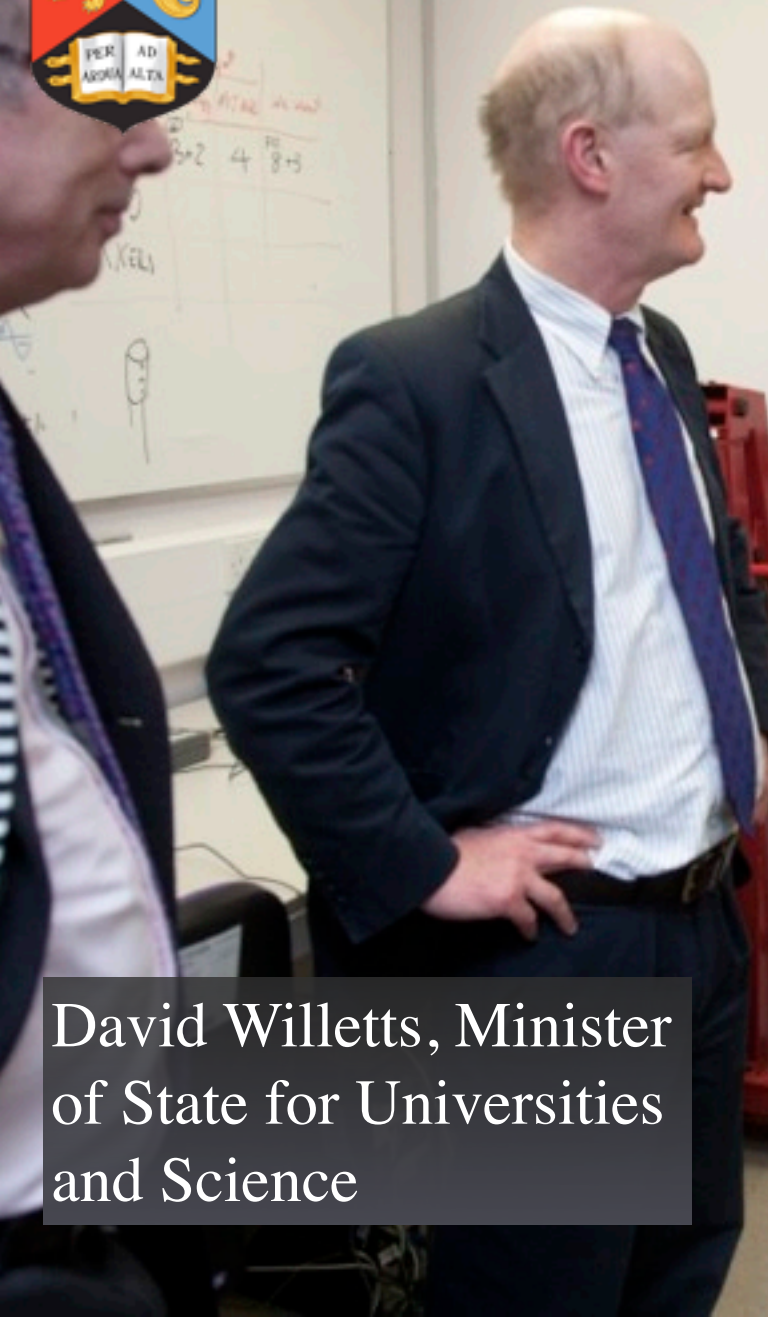
Advanced Interferometry



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







David Willetts, Minister of State for Universities and Science

Advanced LIGO is expected to achieve first detection!



Advanced LIGO is expected to achieve first detection!



What shall we do then?



Preparing for Advanced LIGO



Commissioning and Simulation Workshop, LIGO Livingston 28.01. - 01.02.2013



The 'Arm' Cavity



[Images:Virgo, and LIGO Laboratory]



The 'Arm' Cavity



[Images: Virgo, and LIGO Laboratory]



The 'Arm' Cavity



[Images:Virgo, and LIGO Laboratory]



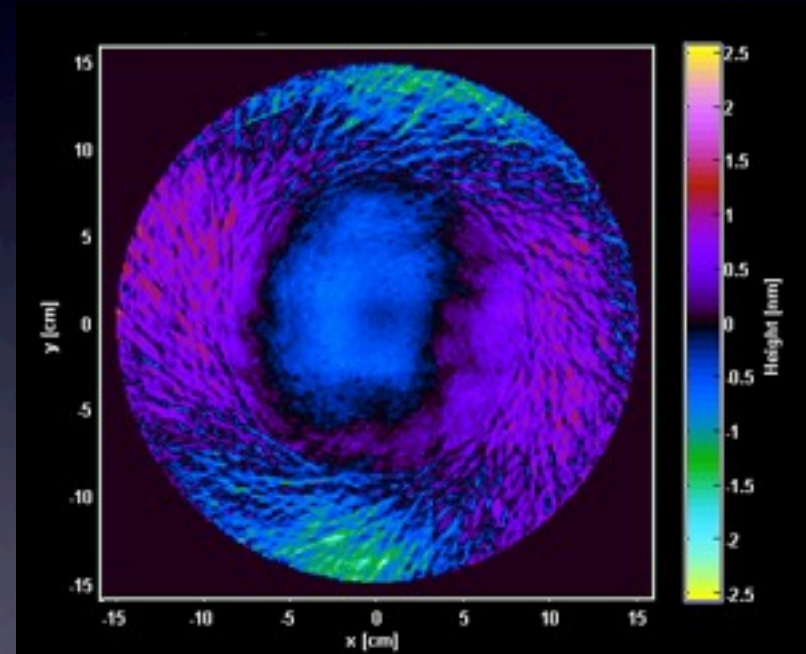
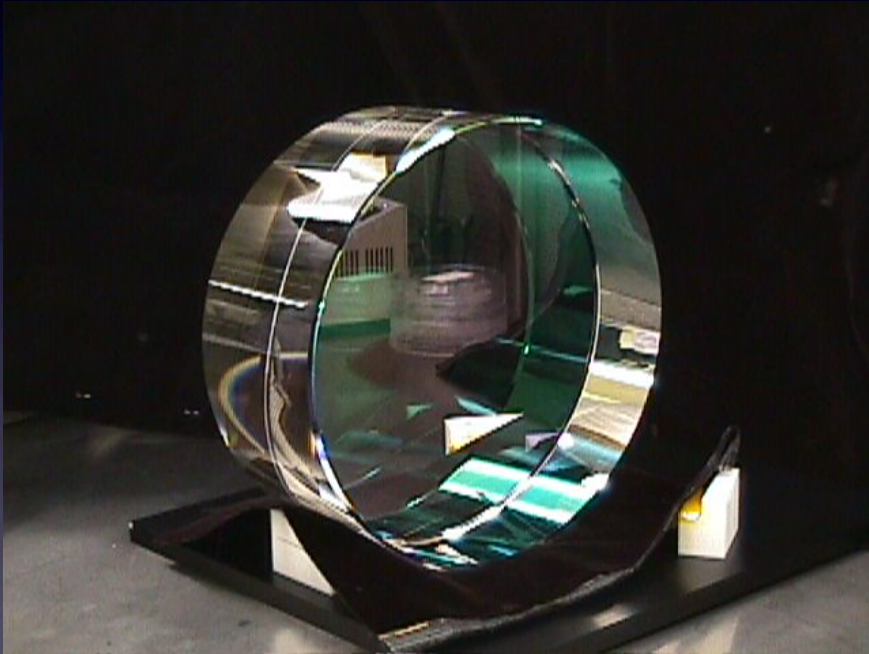
The 'Arm' Cavity



[Images:Virgo, and LIGO Laboratory]



The Mirror Surface

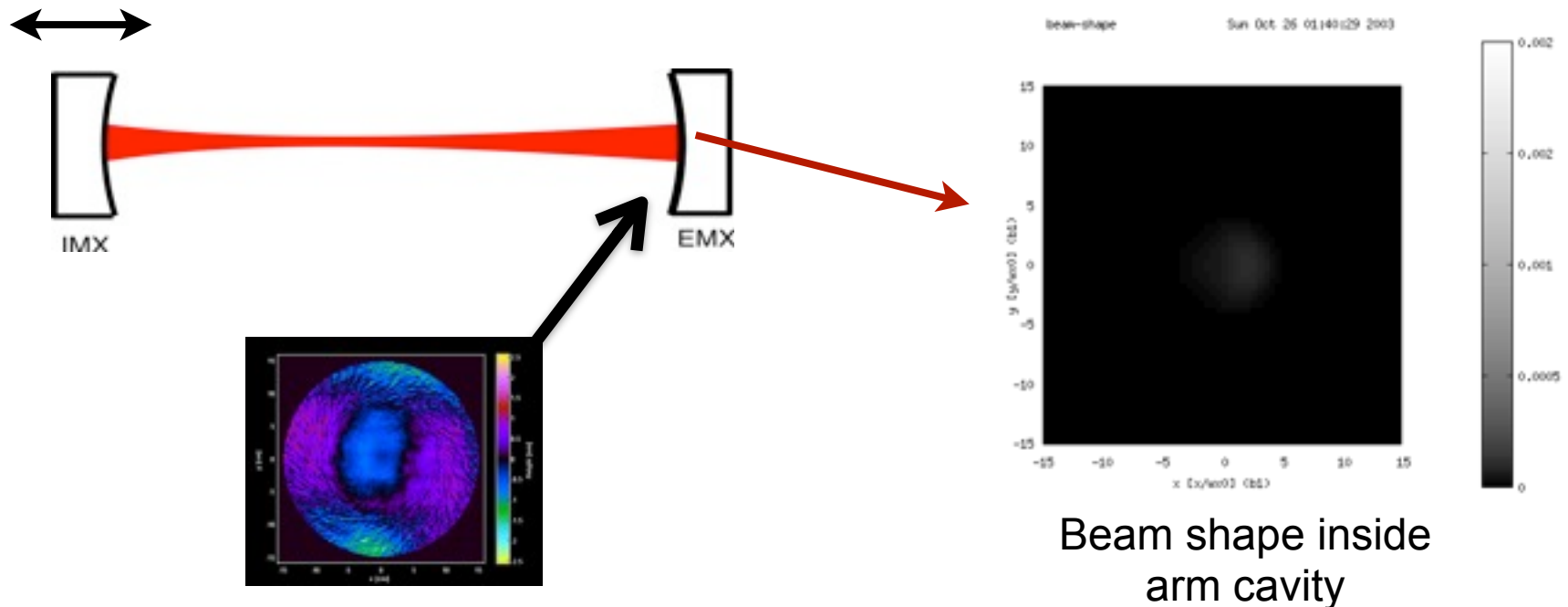


→
Surface measurement

[Images:Virgo, and LIGO Laboratory]

Beam shape distortions

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





FINESSE: Open Source Simulation

- Started in 1997 and developed as my PhD side project, used extensively worldwide
- Versions available for **Windows**, **Linux** and **Mac OSX**, open source, download at www.gwoptics.org/finesse

The screenshot shows the gwoptics website with the following content:

- Header: gwoptics » Tools for detecting gravitational waves
- Navigation: HOME, GW EBOOK, SIMULATIONS, PLAY, CONTACT, Twitter icon
- Section: FINESSE (Frequency domain INTERferometer Simulation Software)
- Text: "At GEO 600 we have created a fast and easy to use interferometer simulation. We want to design and debug laser interferometers with a simple but powerful tool. We want to be able to simulate many different user-defined optical setups and we would like to playfully teach and learn more about laser optics. FINESSE has a long pedigree and has benefited from years of real-life employment by the optics groups of gravitational wave detectors. While some of the code is ten years old we are committed to adapting the code to new challenges posed by new types of interferometry in future projects, maintaining the code and the trust which has been built through years of testing against experimental results."
- Links: Download, Simple Examples, Complex Examples, History and Impact, Tools, Documentation, Changes, Get the Source, Luxor, Redmine page
- Image: Finesse software box
- Footer: Getting started with FINESSE!

A red arrow points to the 'Download' link.



Reflection from the Advanced LIGO pre-Modecleaner cavity, image by Kate Dooley



The Einstein Telescope

EINSTEIN TELESCOPE

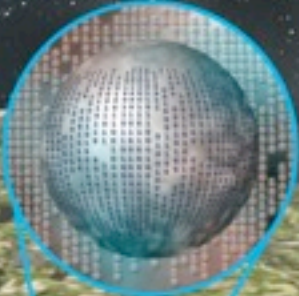
gravitational wave observatory



CENTRAL FACILITY



COMPUTING CENTRE



DETECTOR STATION



END STATION



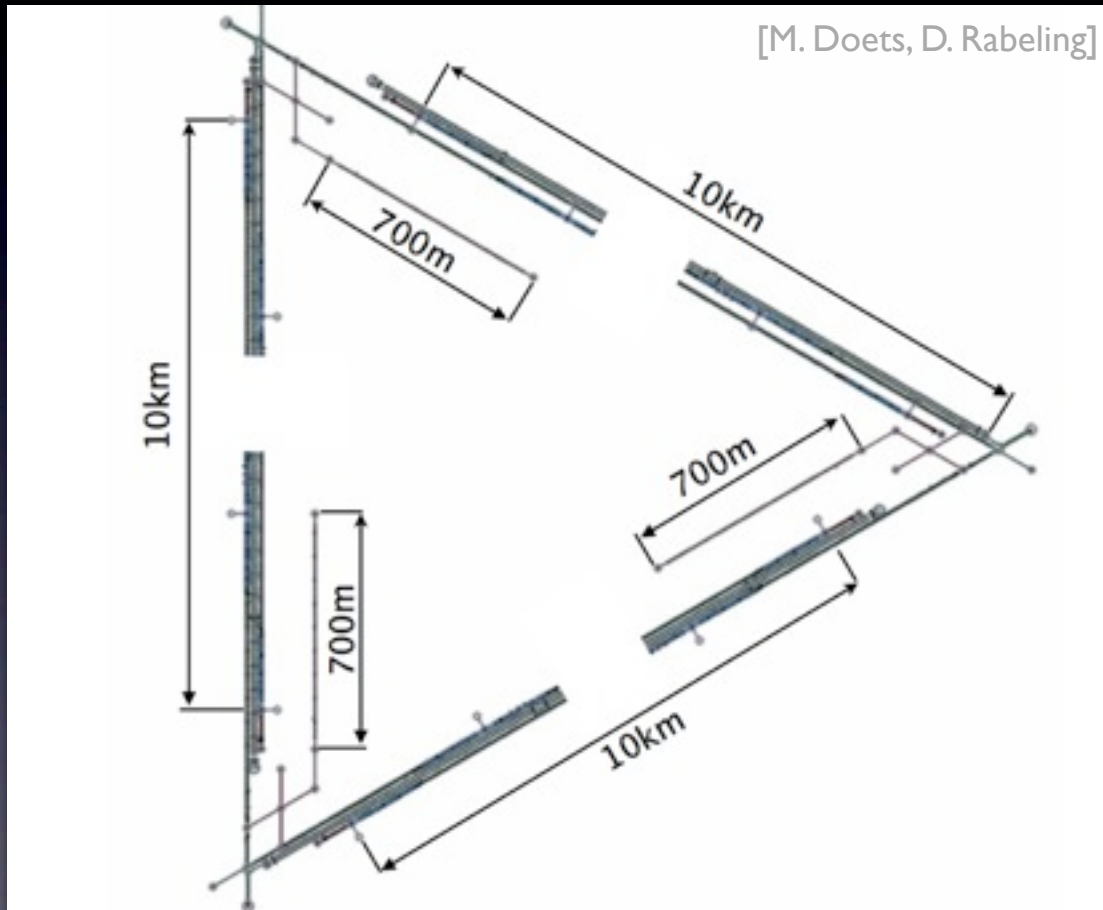
TUNNEL \varnothing ~5 m

Length ~10 km





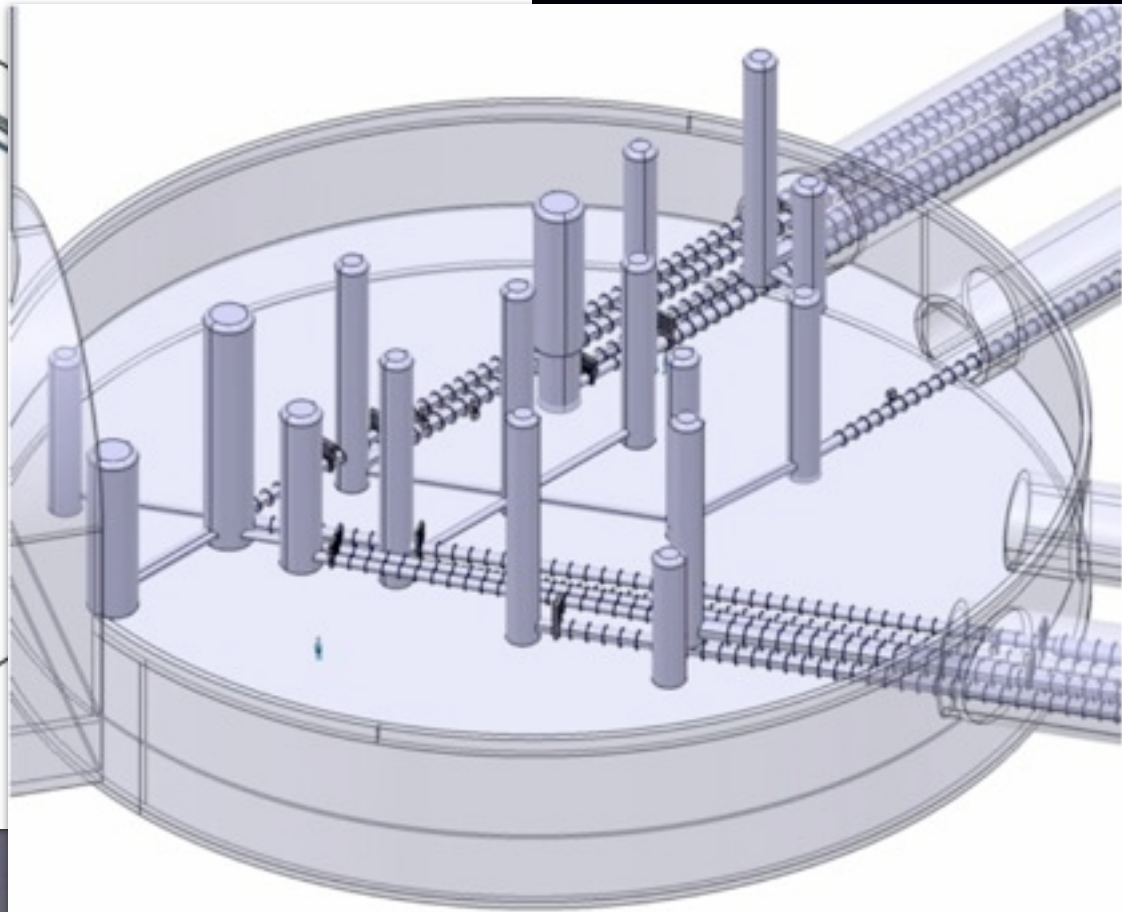
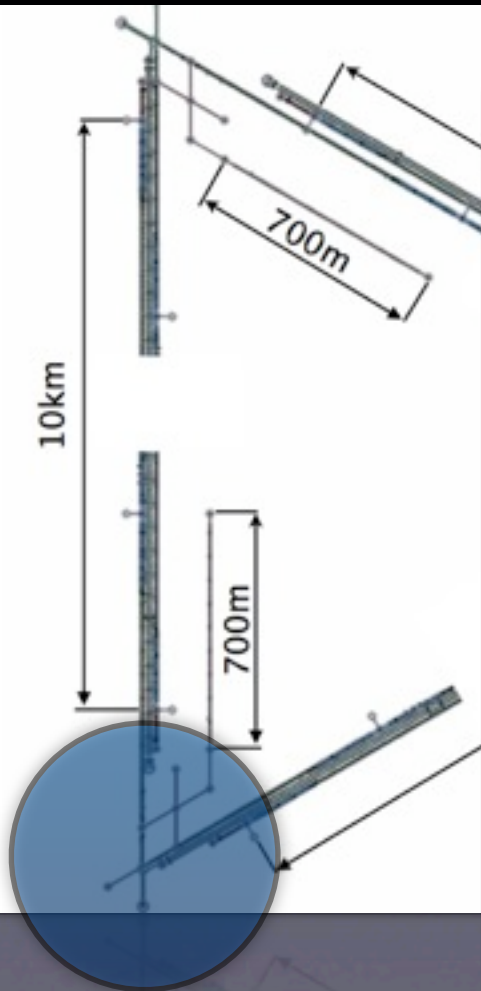
Large Infrastructure





Large Infrastructure

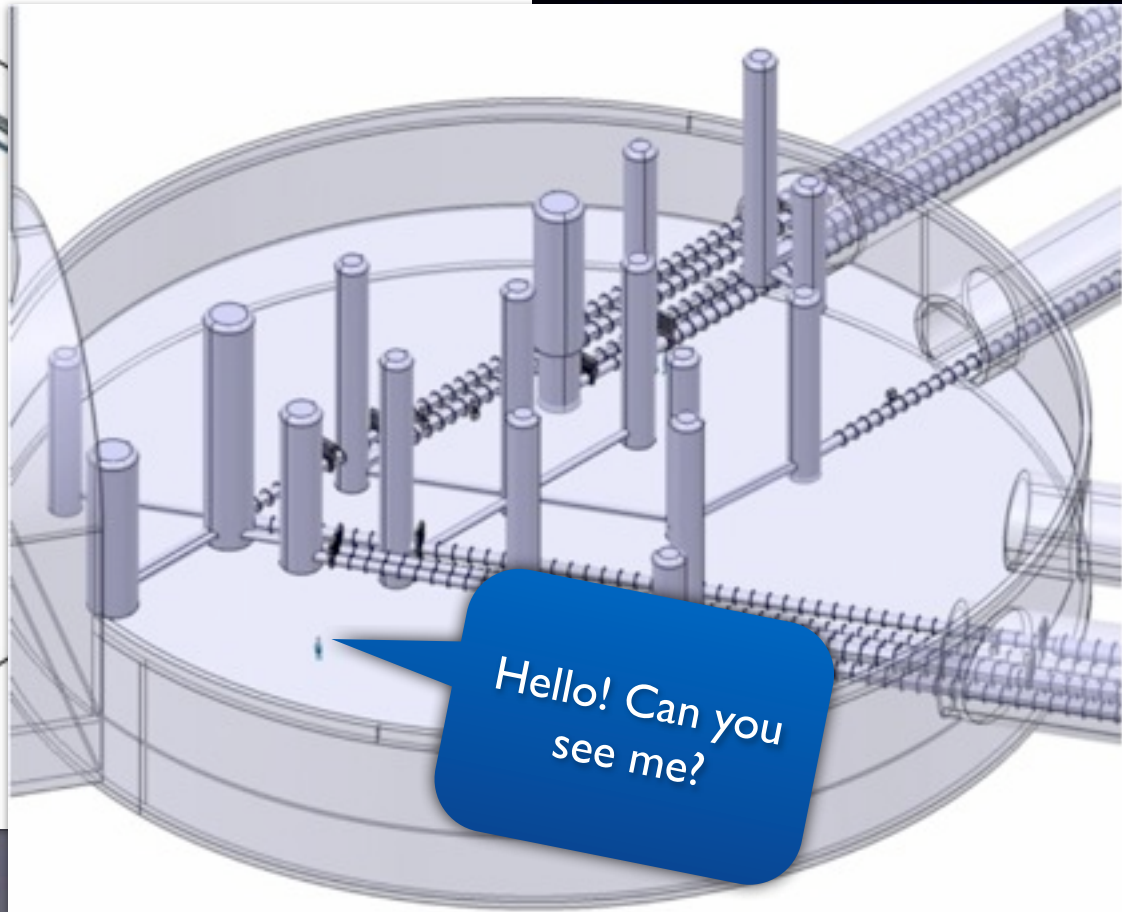
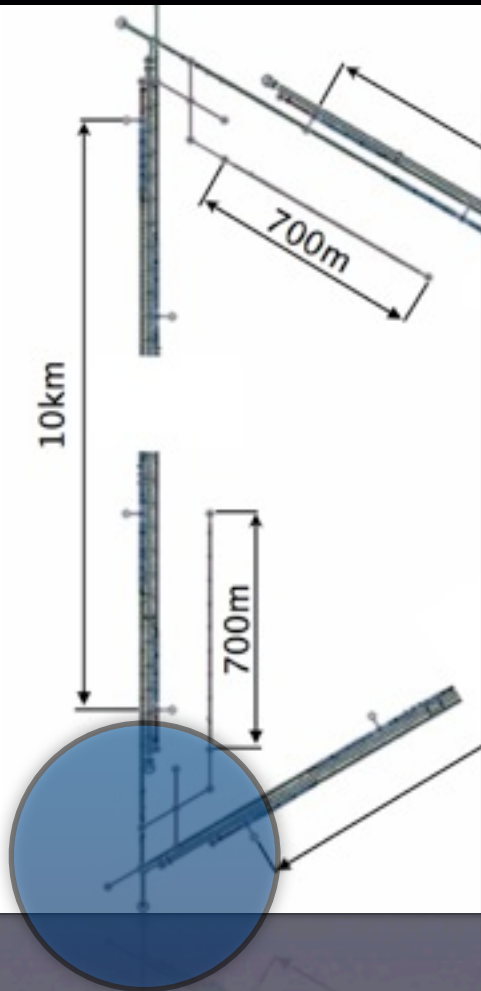
[M. Doets, D. Rabeling]

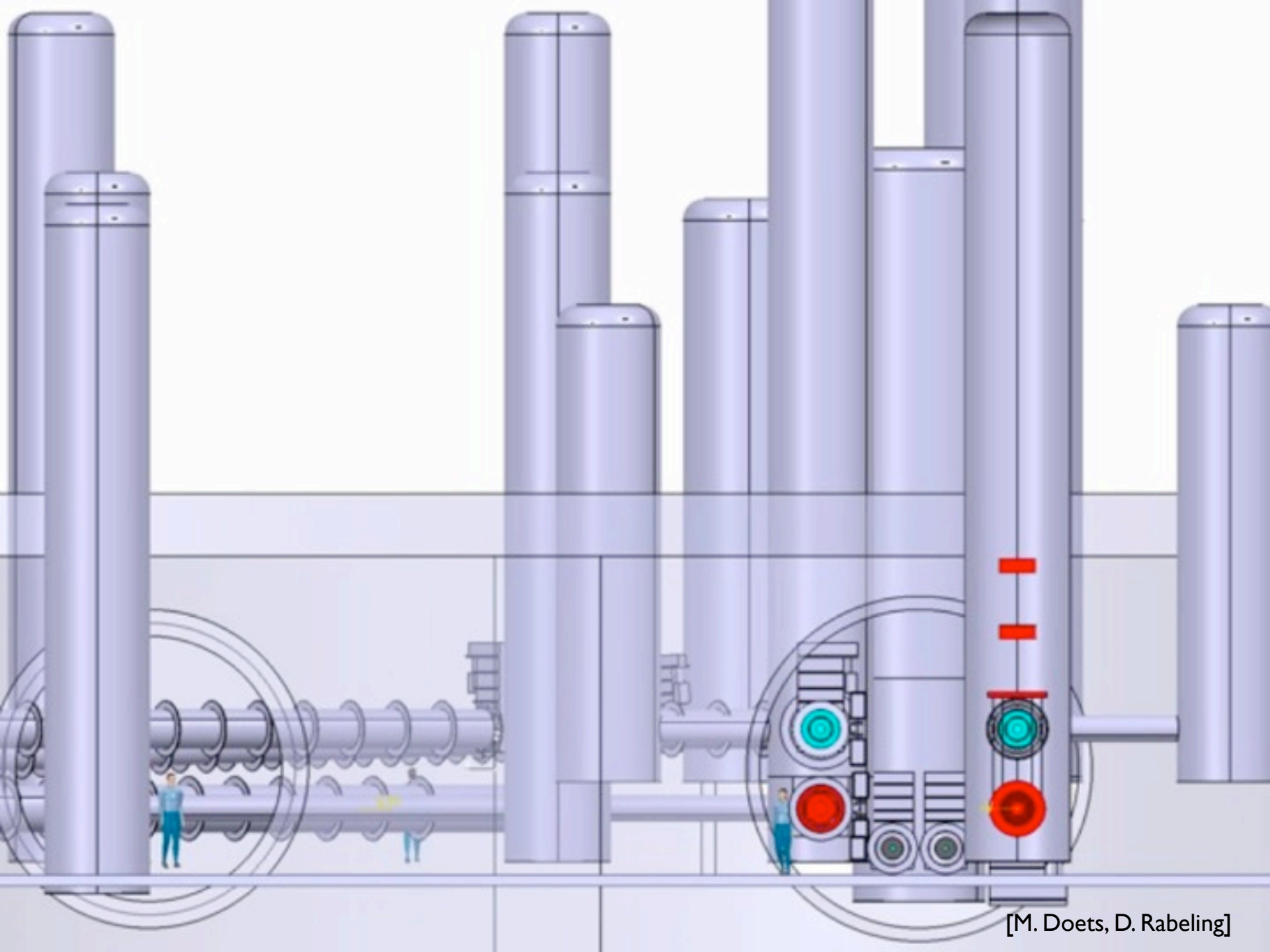


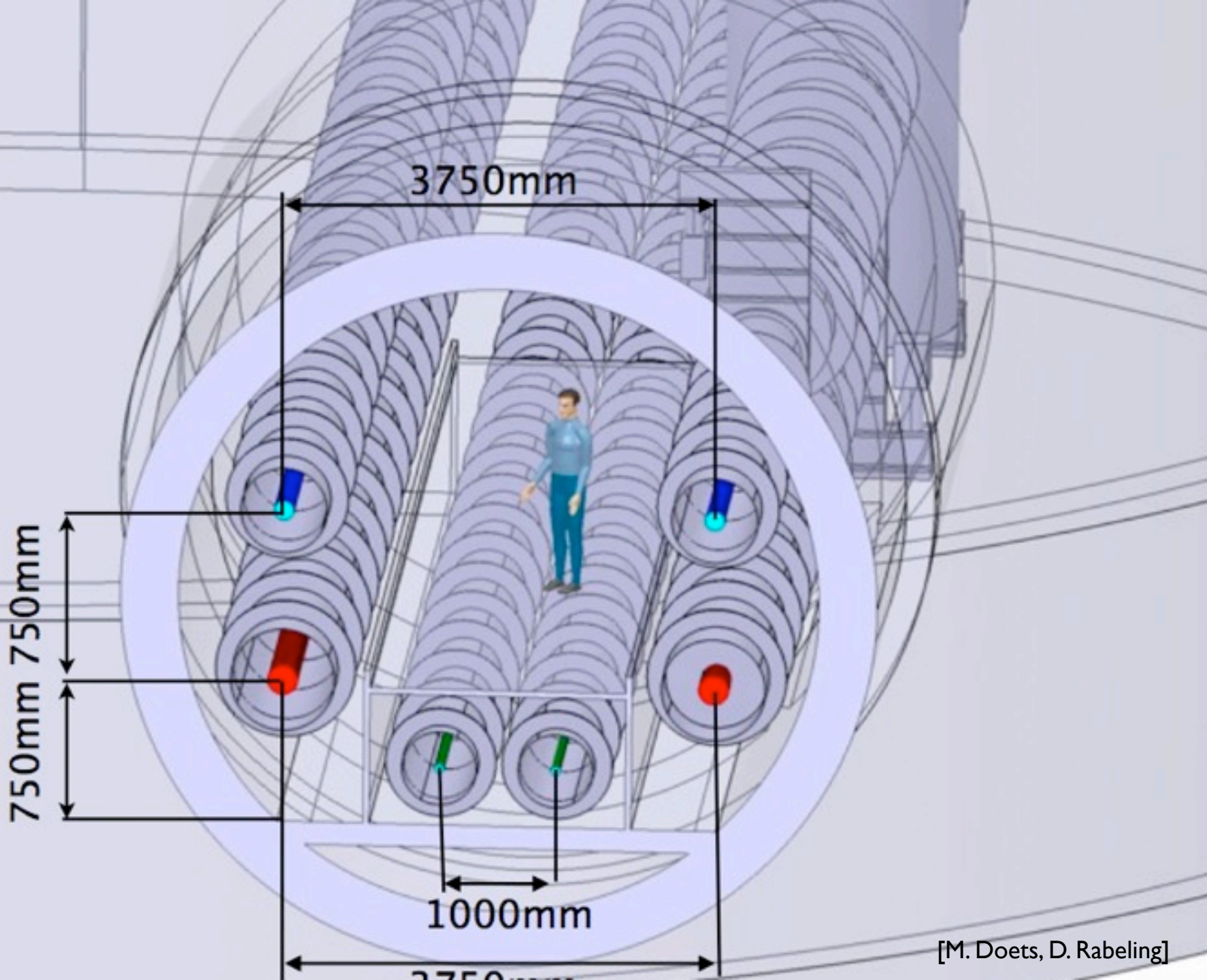


Large Infrastructure

[M. Doets, D. Rabeling]

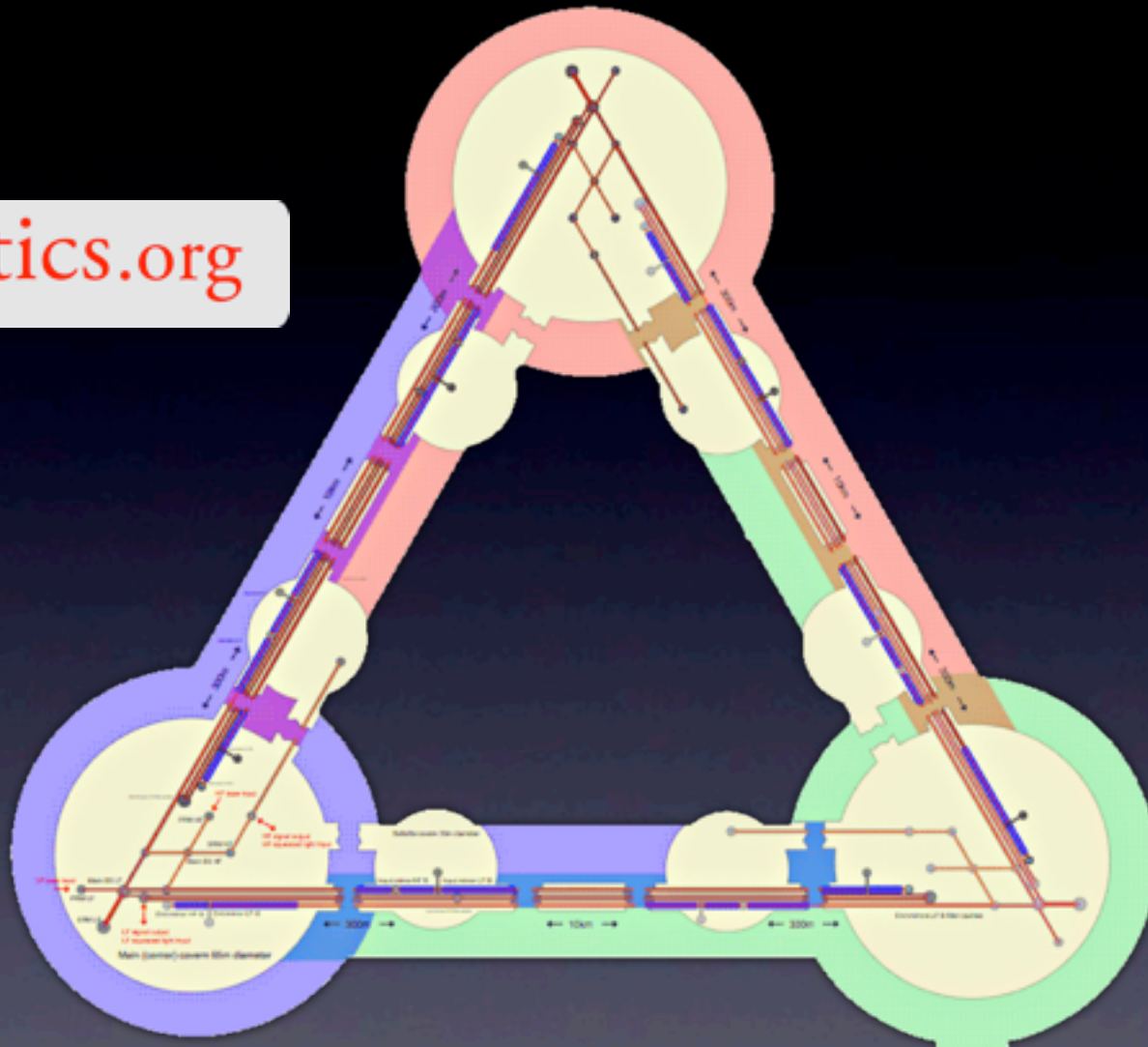








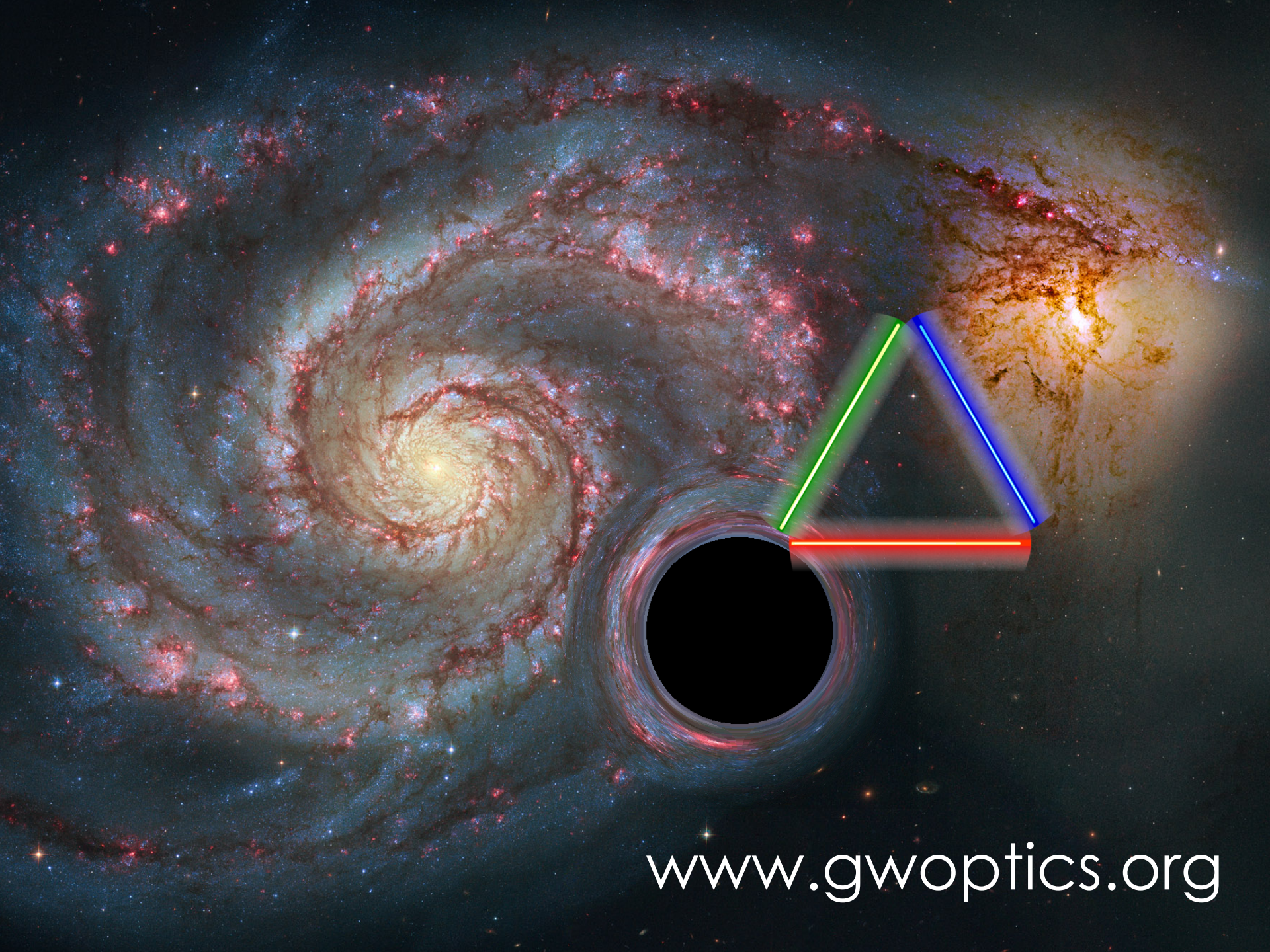
gwoptics.org





Science is a slow process

You can have a big impact



www.gwoptics.org



Acknowledgements

- Some of the images and media shown were produced by these gravitational wave projects:
 - LIGO Laboratory and the LIGO Scientific Collaboration, <http://ligo.org/>
 - GEO 600, <http://www.geo600.org/>
 - Virgo, <http://wwwcascina.virgo.infn.it/>
 - Einstein Telescope, <http://www.et-gw.eu/>
 - LISA, <http://lisa.nasa.gov/>
 - KAGRA, <http://gwcenter.icrr.u-tokyo.ac.jp/>
- Further support and material has been provided by the following institutions:
 - Gravitational Wave Group University of Birmingham, <http://www.sr.bham.ac.uk/gwgroup/>
 - Albert Einstein Institute, <http://www.aei.mpg.de/>
 - NIKHEF, <http://www.nikhef.nl/>
 - Numerical Relativity group, FSU Jena, <https://www.tpi.uni-jena.de/>
 - NASA, GSFC, <http://www.nasa.gov>
 - Caltech-Cornell, <http://www.black-holes.org/>



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- John James
- Kate Dooley (LIGO/GEO)
- Martin Doets, David Rabeling (Nikhef)