

FINDING BLACK HOLES WITH LASERS

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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



an exemplary (personal) story...

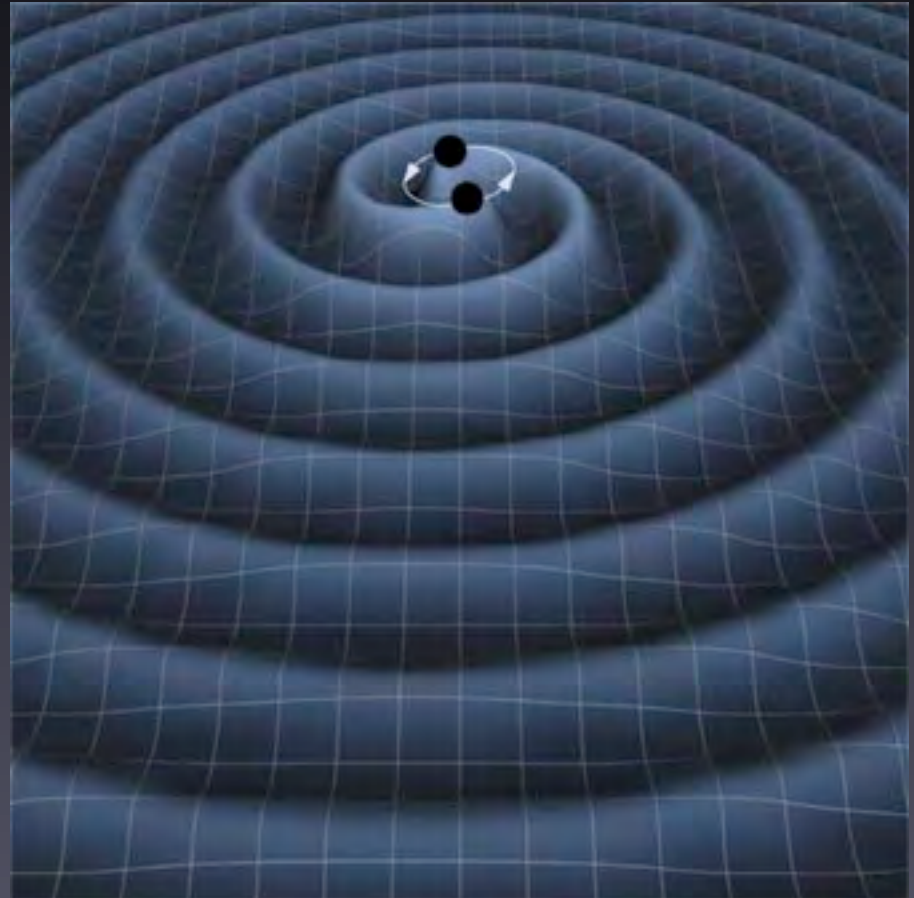
Gravitational what?

96% of the Universe



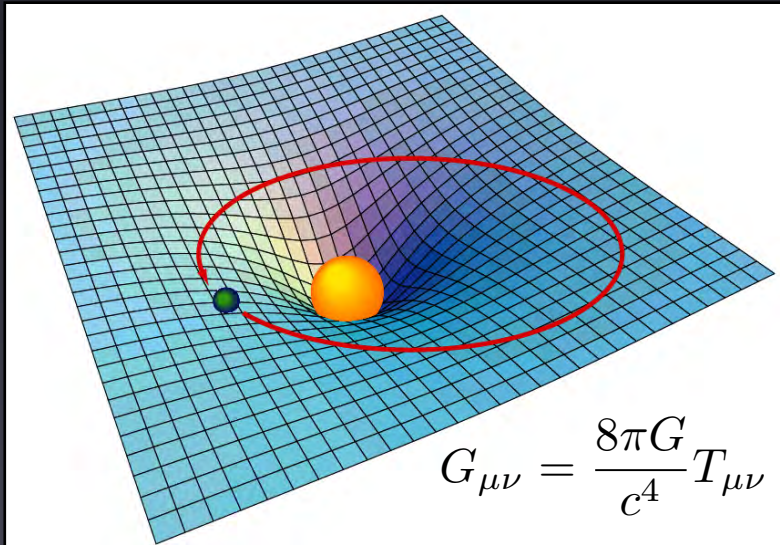
Gravitational Waves

- 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





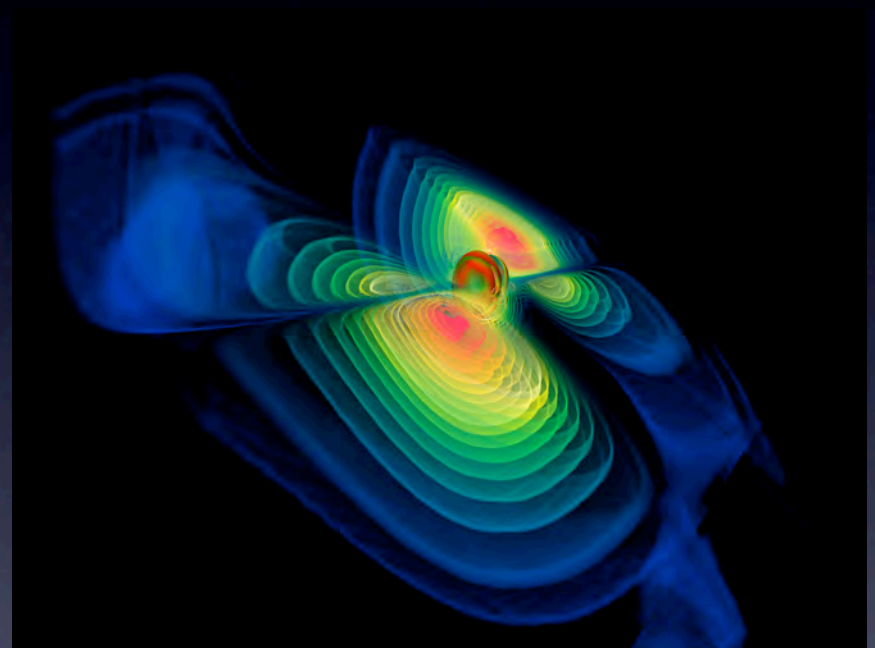
Generation of GWs

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



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



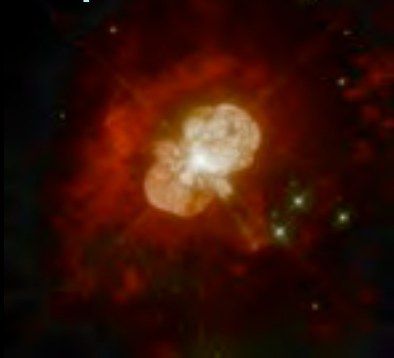
Sources of Gravitational Waves

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

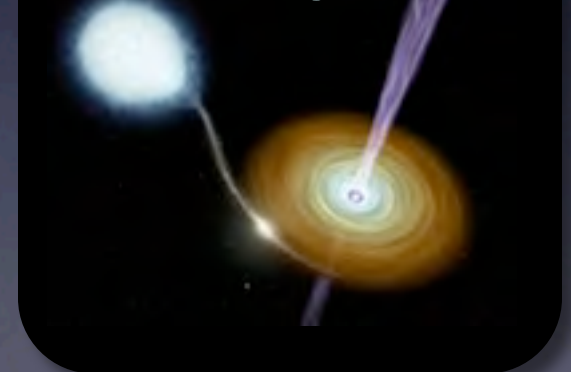
supernovae



pulsars

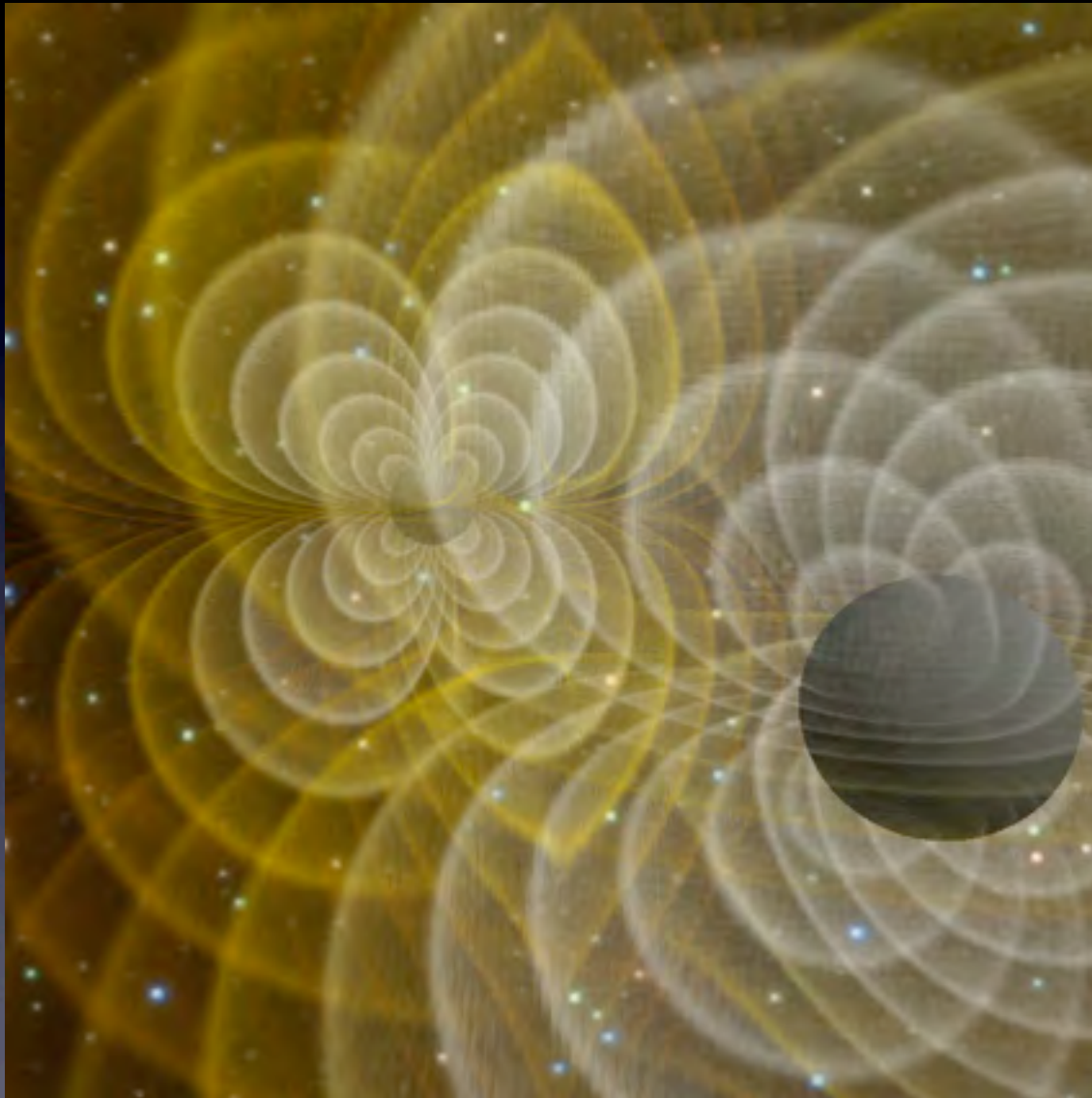


accreting stars



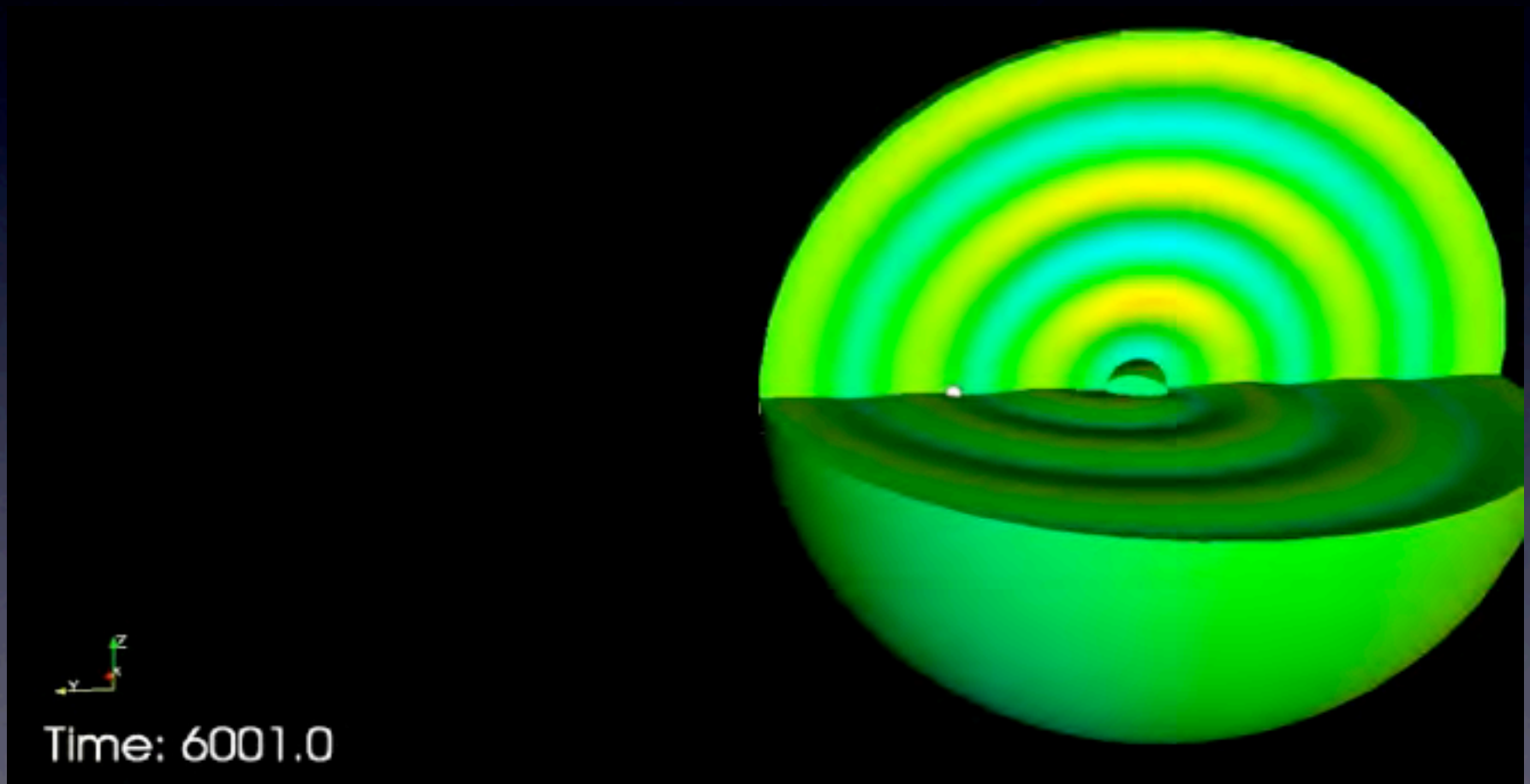


Gravitational waves from merging black holes





Bobbing like a Cork ...



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



And the big question:



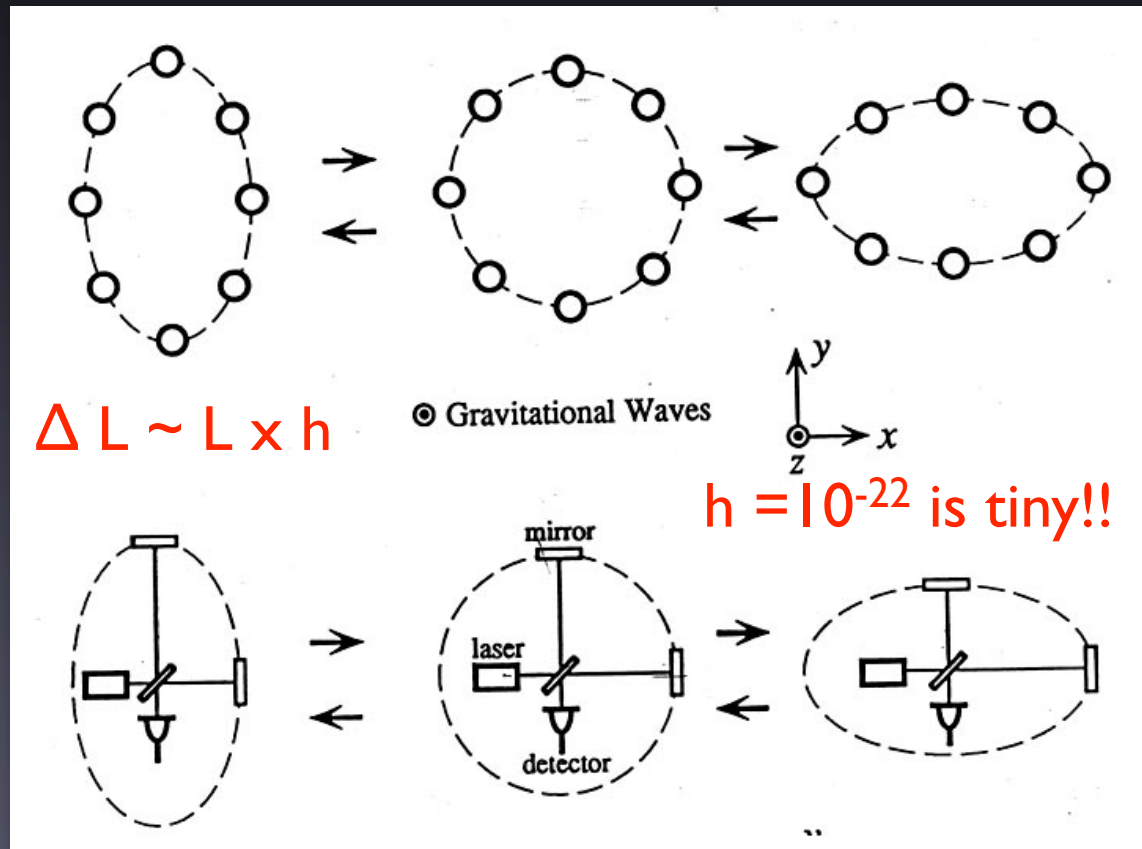
[Credit: <http://www.skyandtelescope.com/>]



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

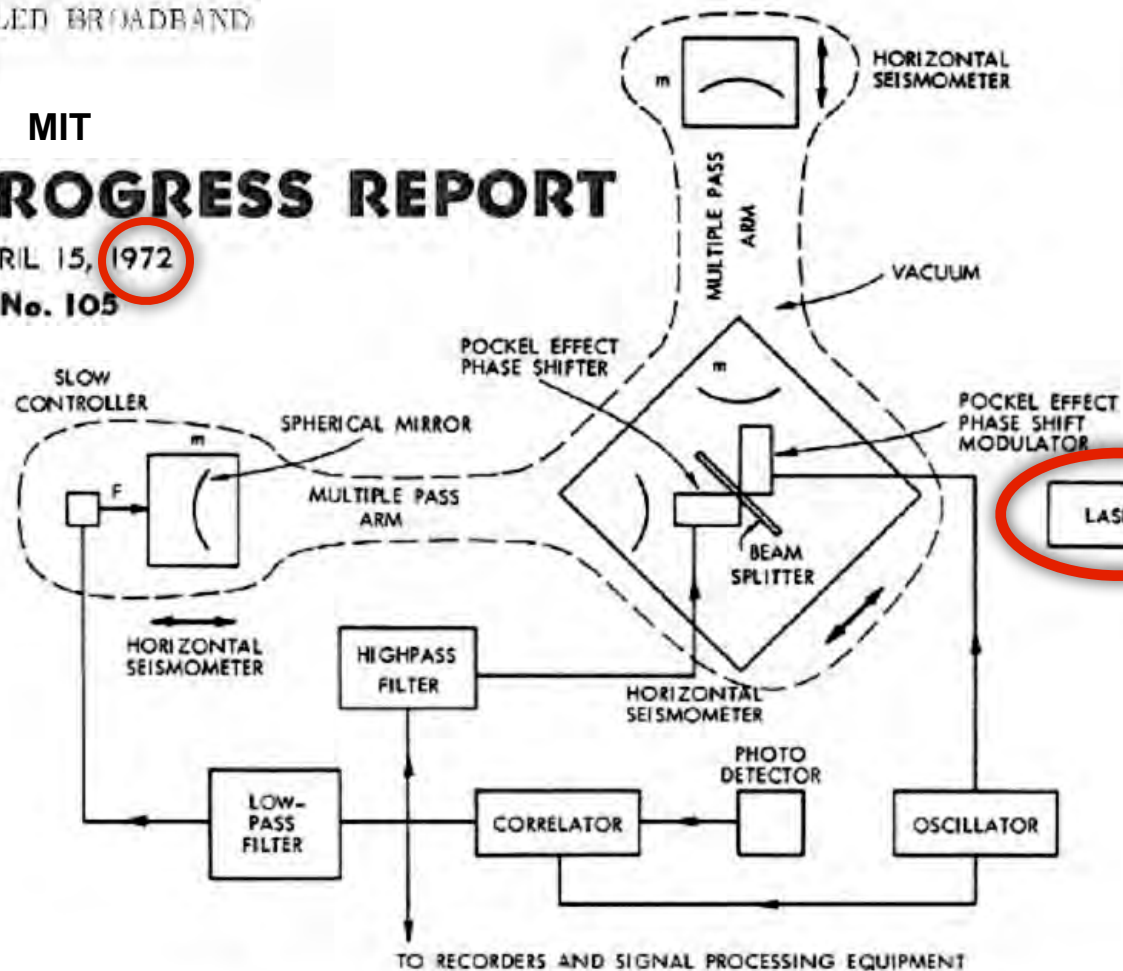
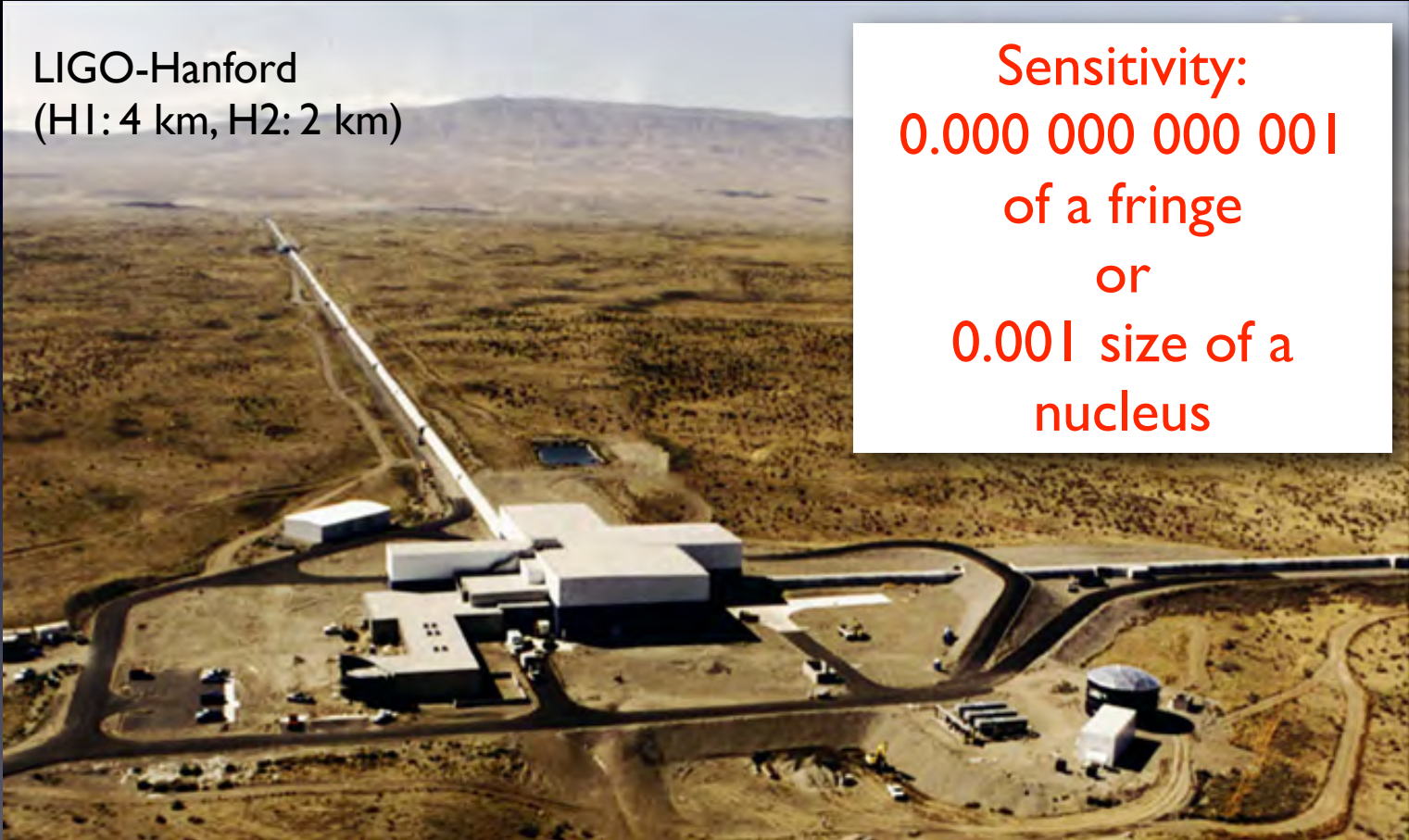


Fig. V-20. Proposed antenna.



GW interferometry today

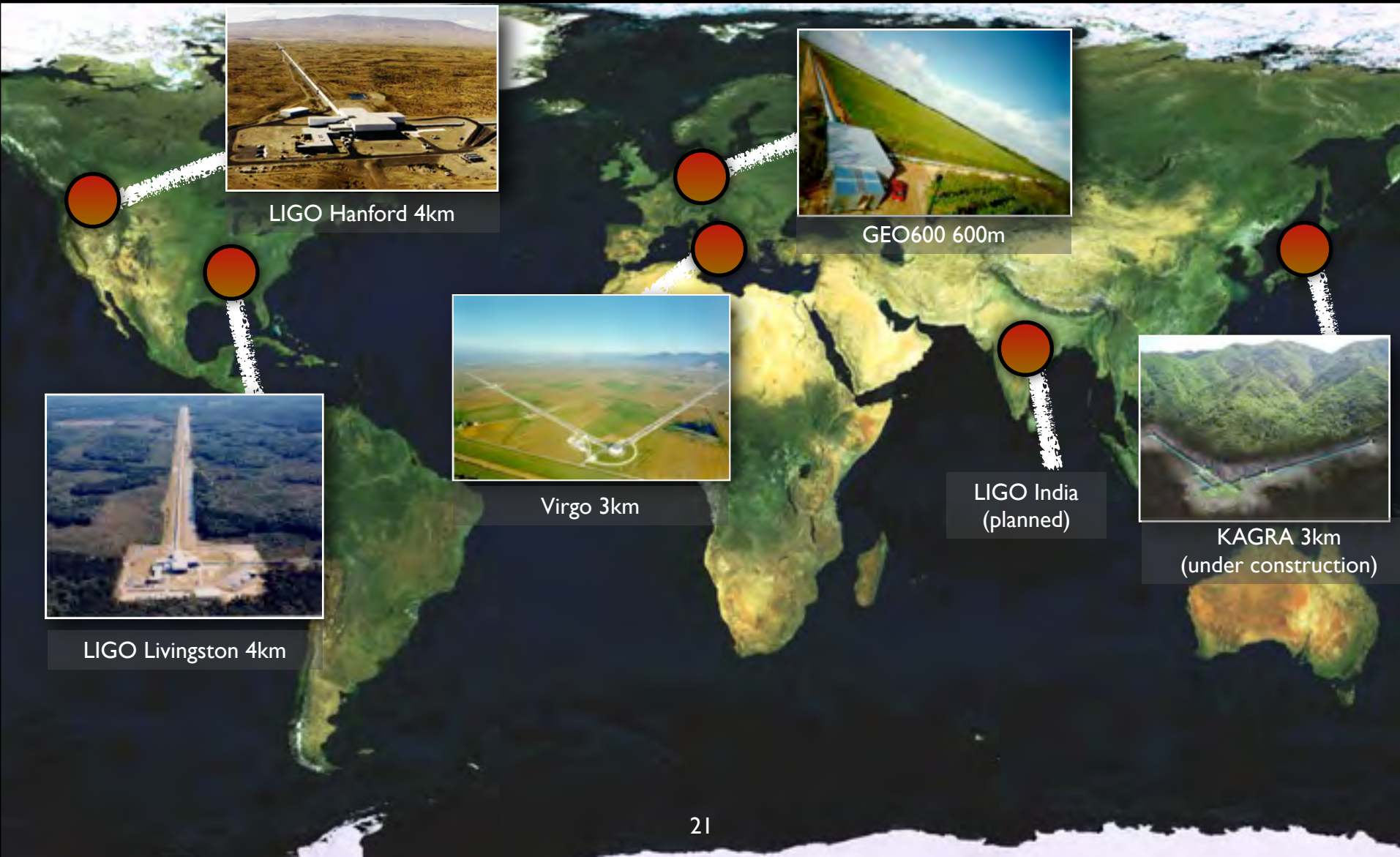
LIGO-Hanford
(H1: 4 km, H2: 2 km)



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



World-wide Network



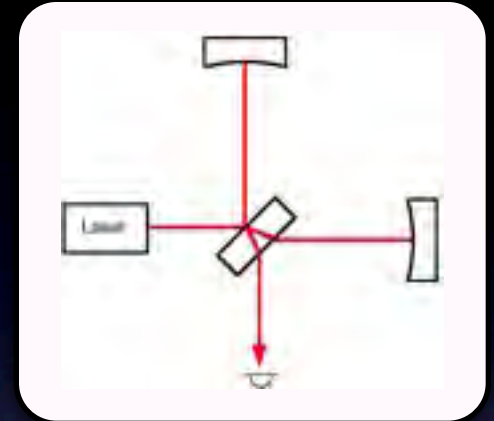


The Emergence of a New Science



The First Generation

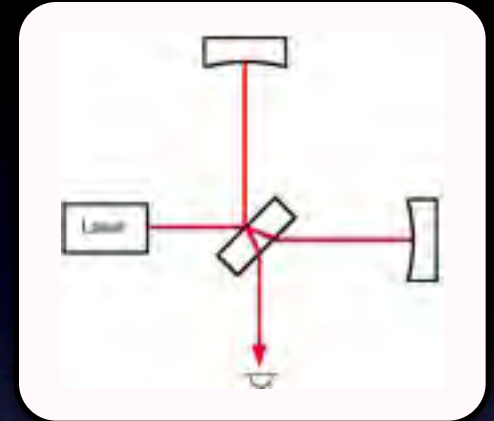
- GEO, TAMA, Virgo, LIGO
- Proposed in the 1980ies
- Development of new technologies
- Detectors build in the 1990ies
- Development of even newer technologies
- Operation and data taking 2002-2010





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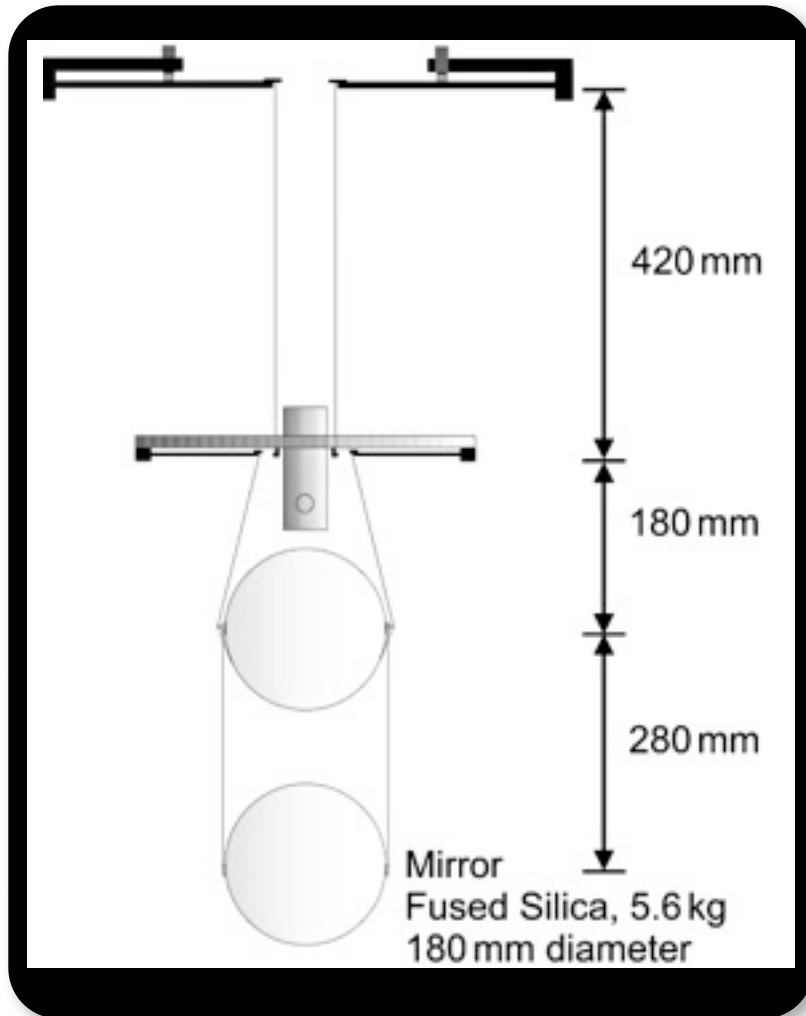
GEO 600 (British/German)



[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



Result?

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





Advanced LIGO

LIGO

LIGO Scientific Collaboration

LSC

- 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

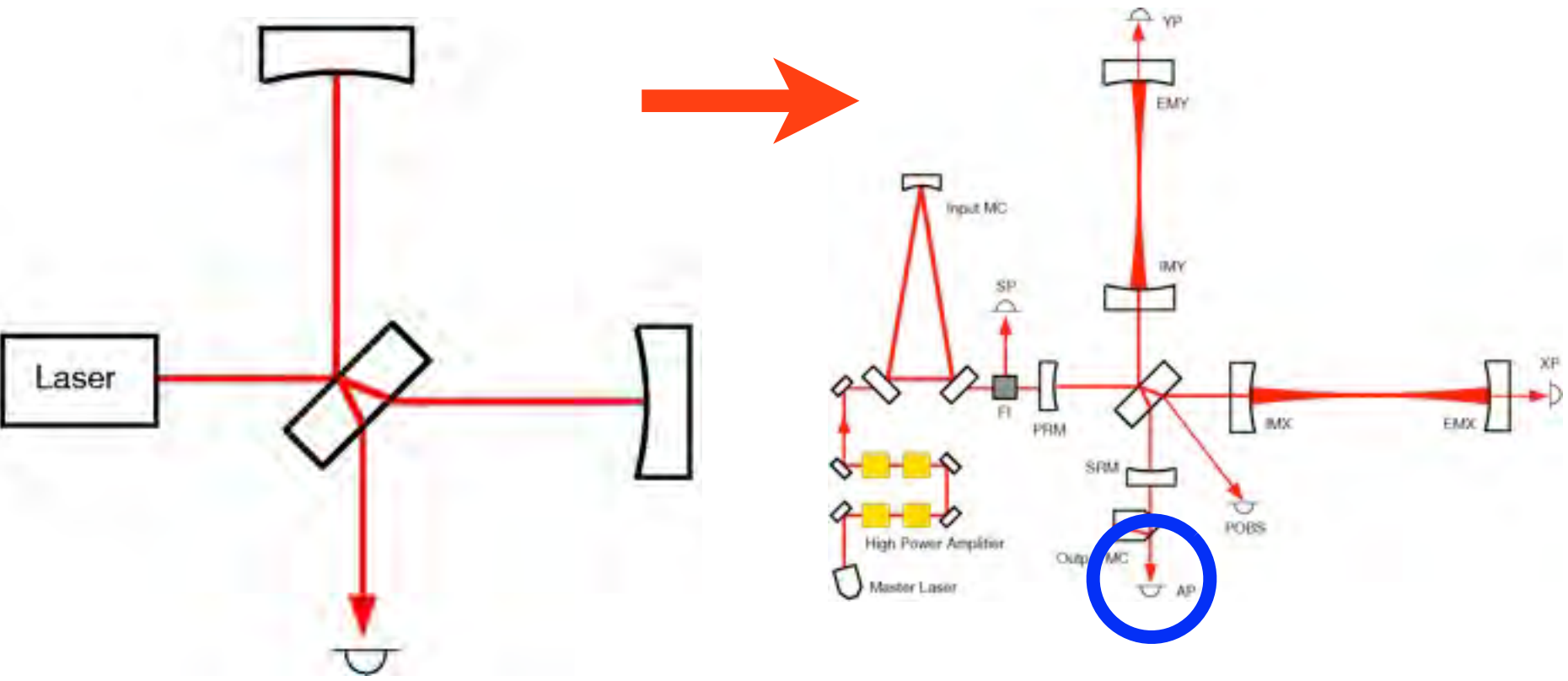


Upgrade of existing LIGO
Start of operation >2015

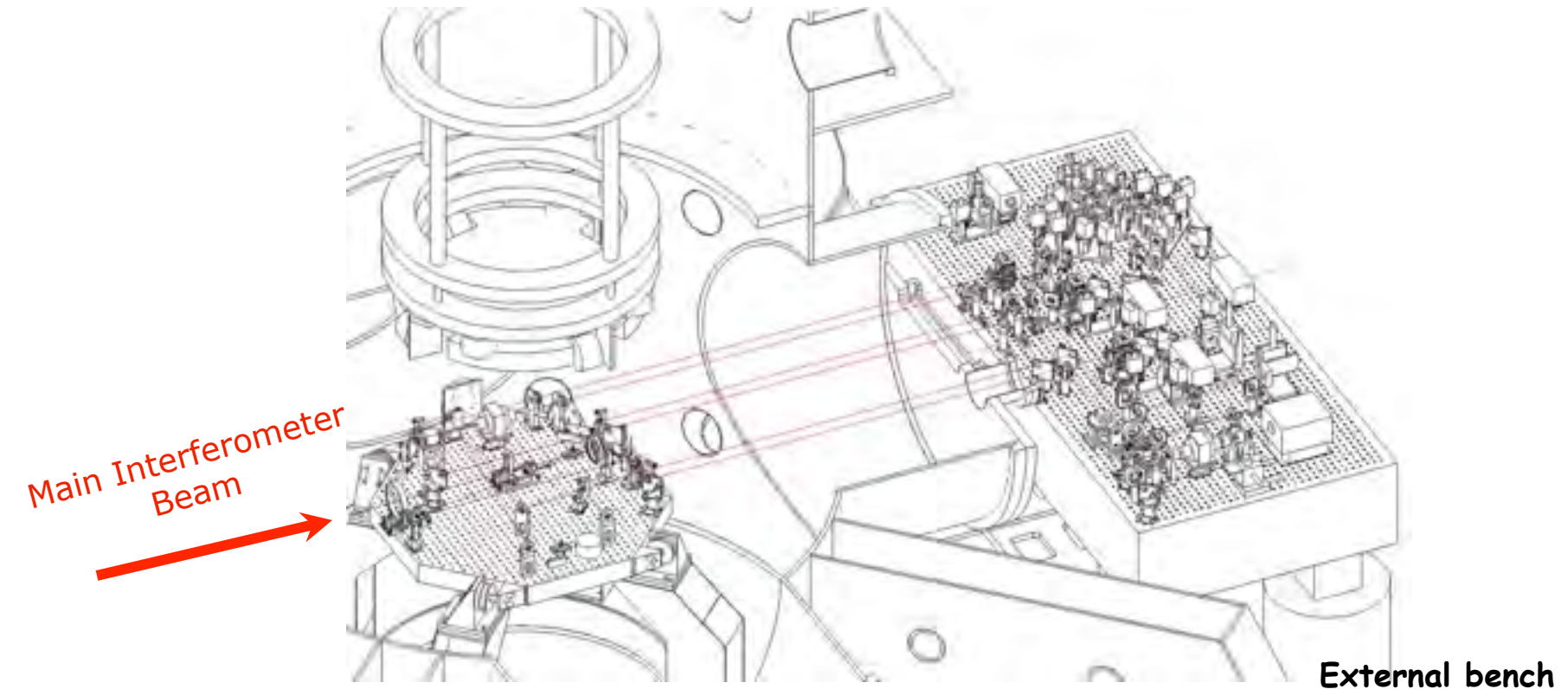


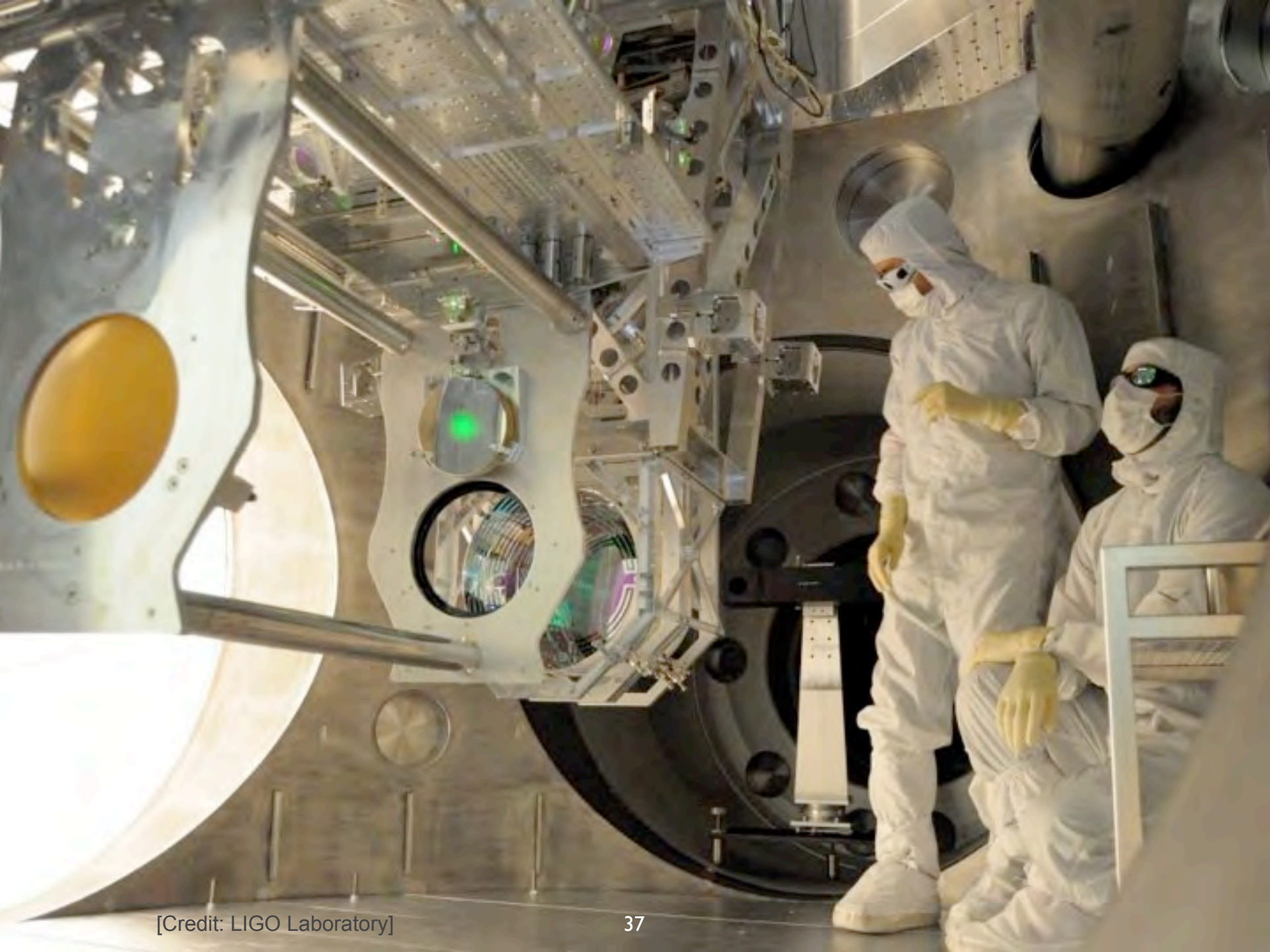


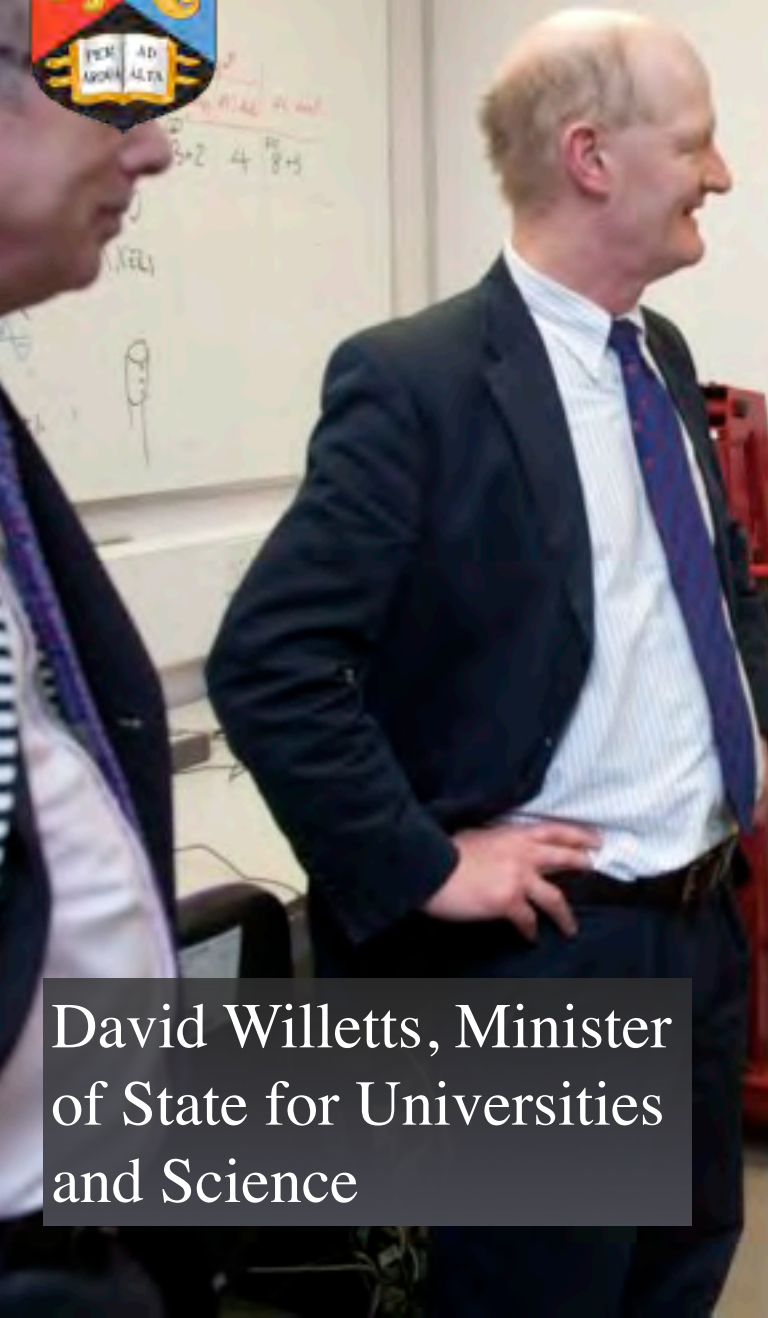
Advanced Interferometry



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!



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]



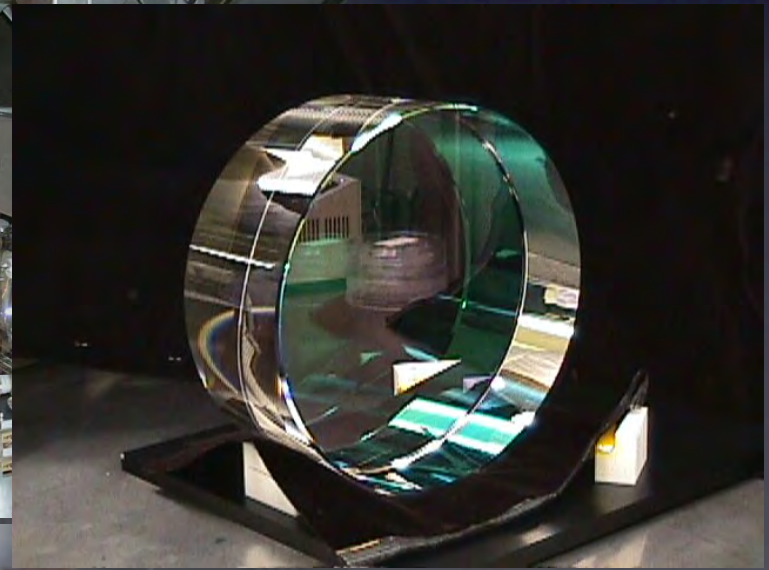
The 'Arm' Cavity



[Images:Virgo, and LIGO Laboratory]



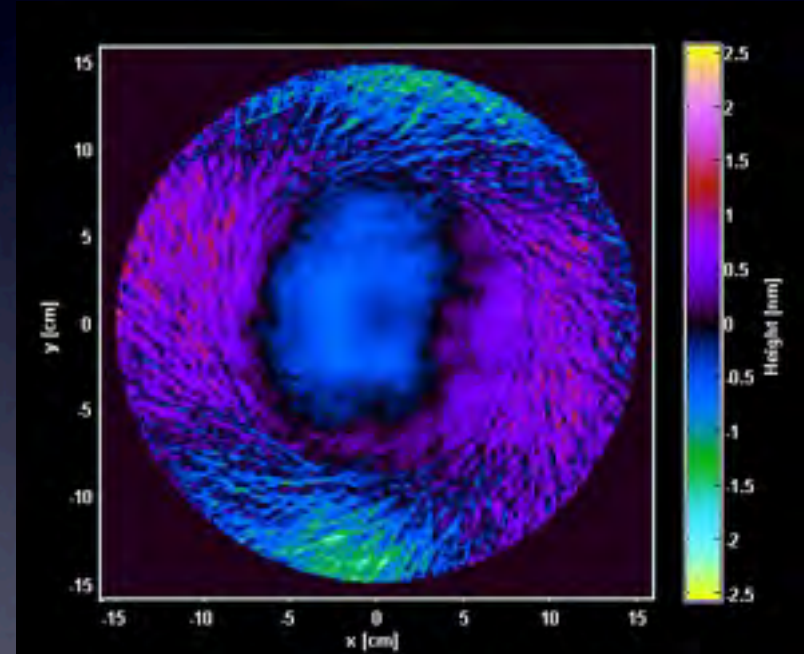
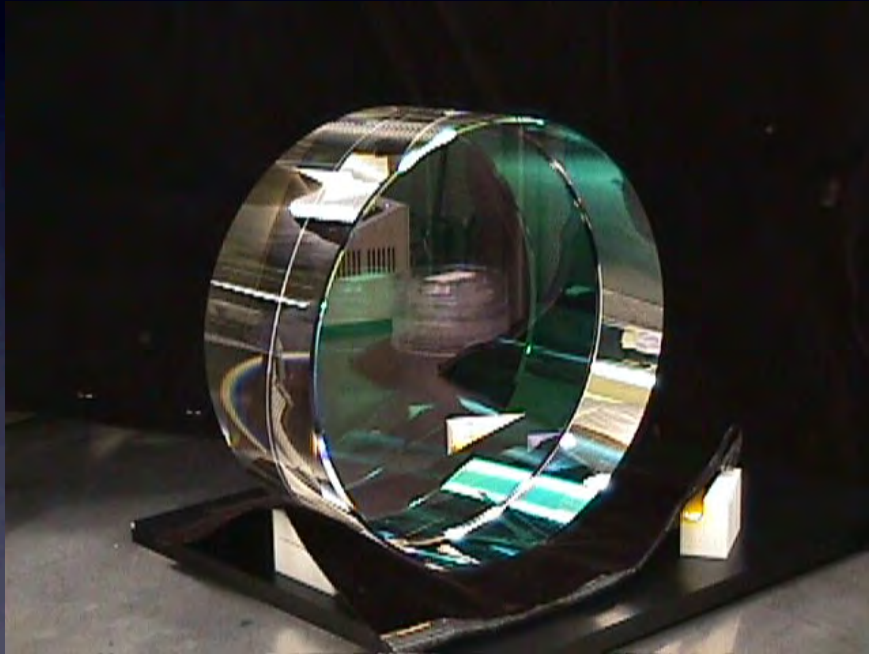
The 'Arm' Cavity



[Images:Virgo, and LIGO Laboratory]



The Mirror Surface

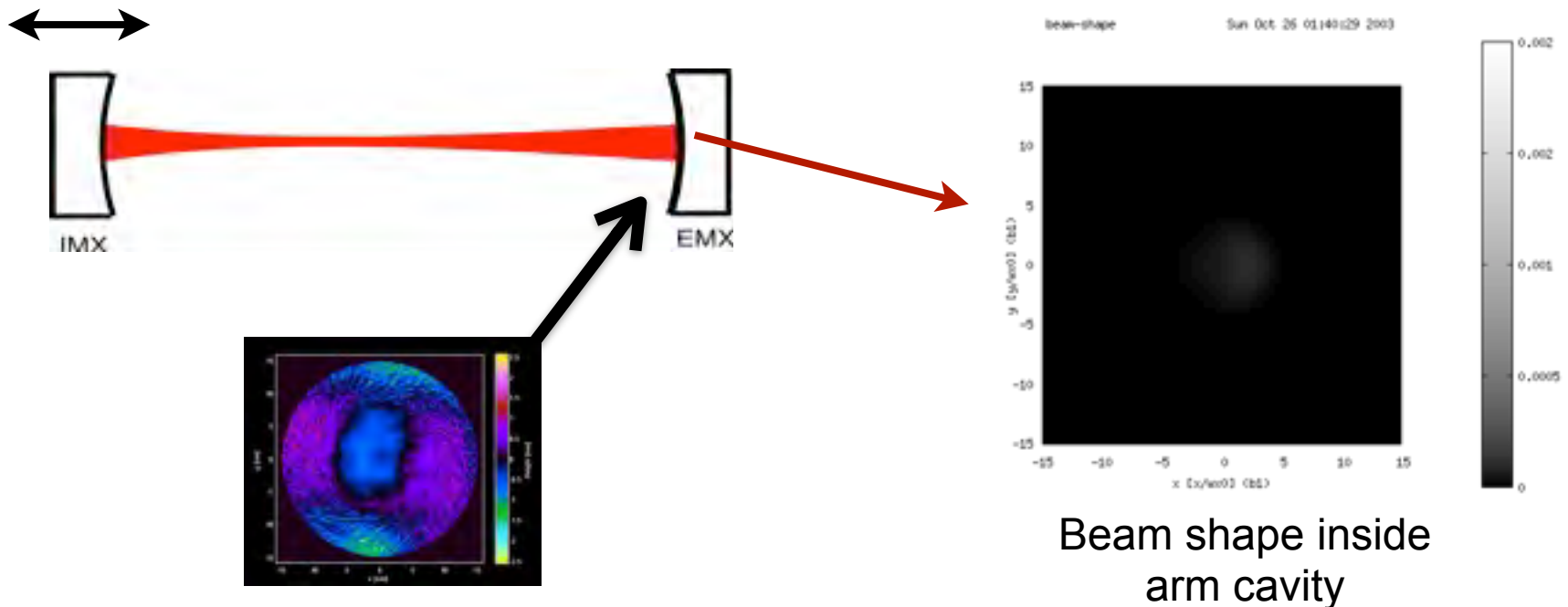


→
Surface measurement

[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:

- Logo: gwoptics
- Tagline: Tools for detecting gravitational waves
- Navigation: HOME, GWEBOOK, SIMULATIONS, PLAY, CONTACT
- 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, Syntax References, User Forums, Single Examples, Complex Examples, History and Impact, Tools, Documentation, Changes, Get the Source, Linux, Redmine page
- Image: Finesse software box
- Text: 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

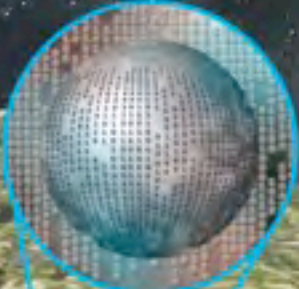
gravitational wave observatory



CENTRAL FACILITY



COMPUTING CENTRE



DETECTOR STATION



END STATION



TUNNEL \varnothing ~5 m

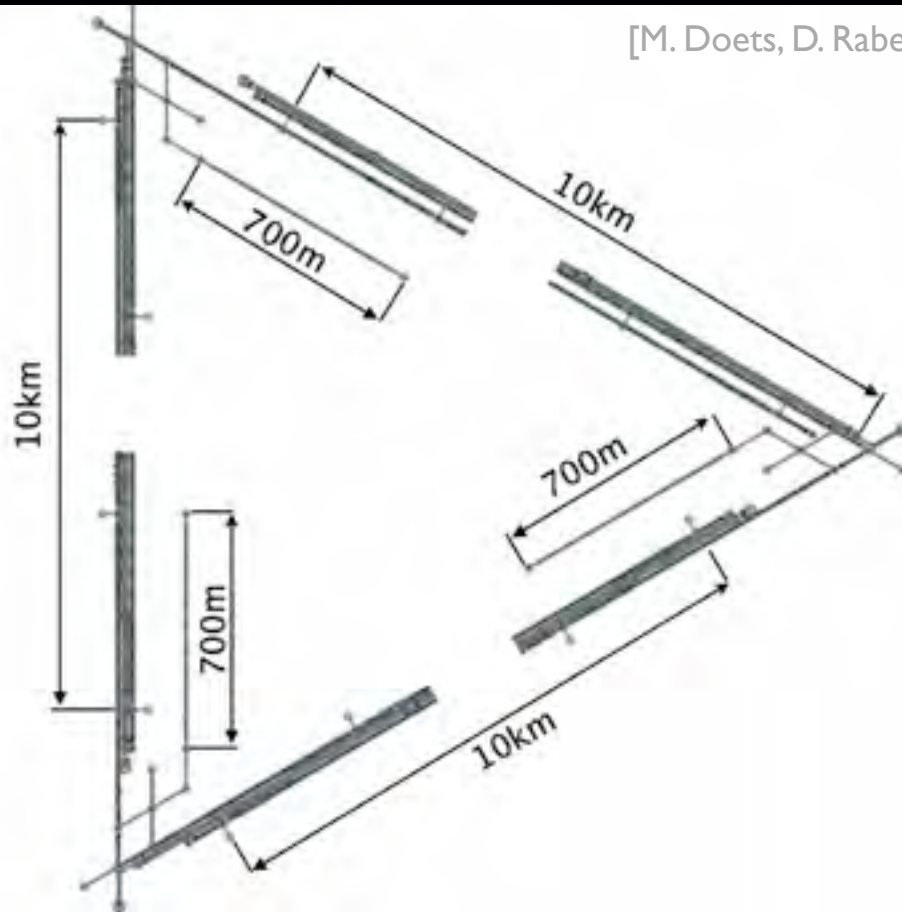
Length ~10 km





Large Infrastructure

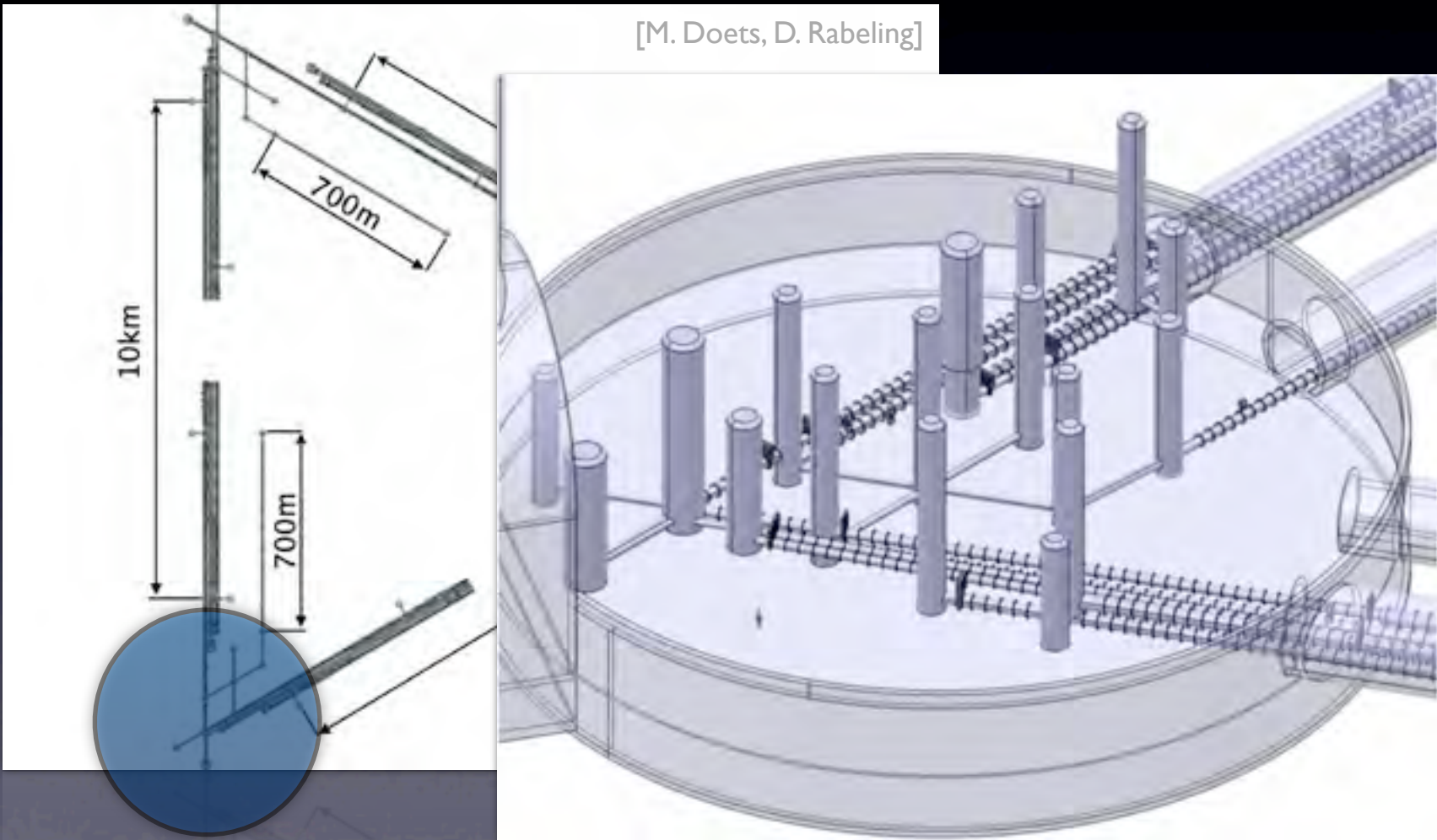
[M. Doets, D. Rabeling]





Large Infrastructure

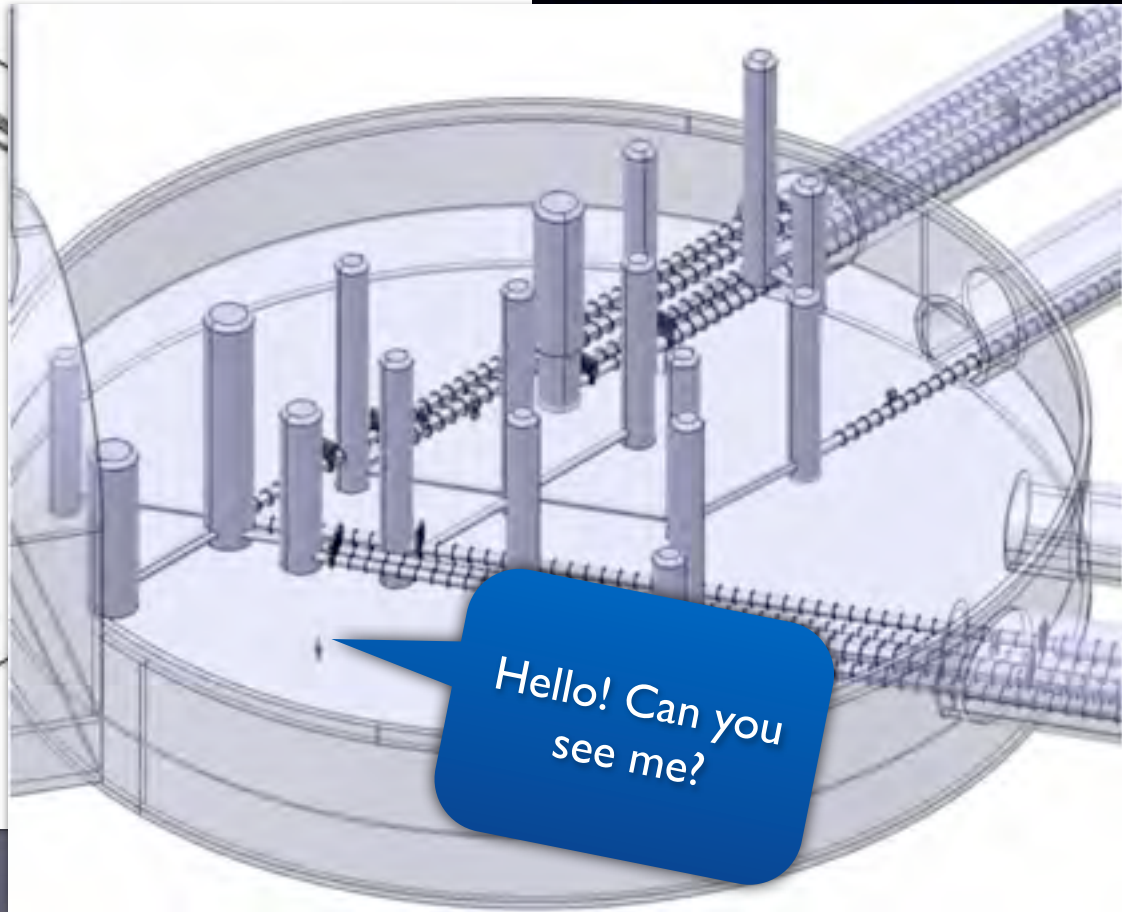
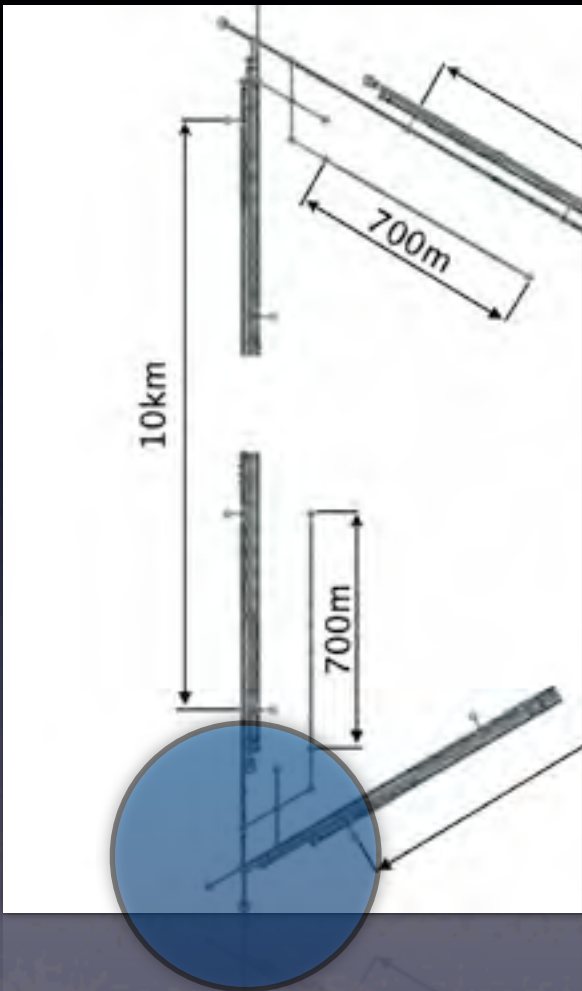
[M. Doets, D. Rabeling]

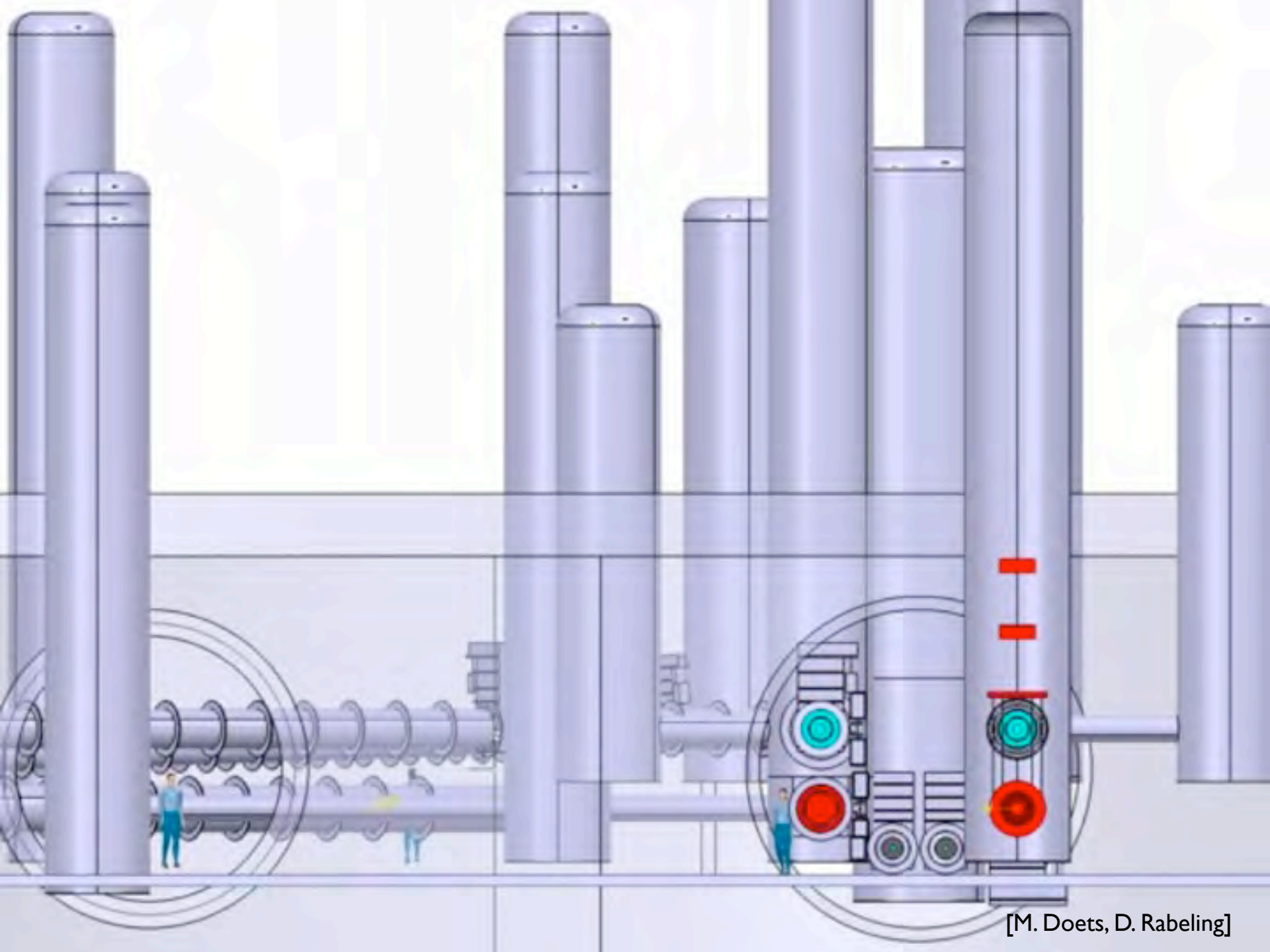


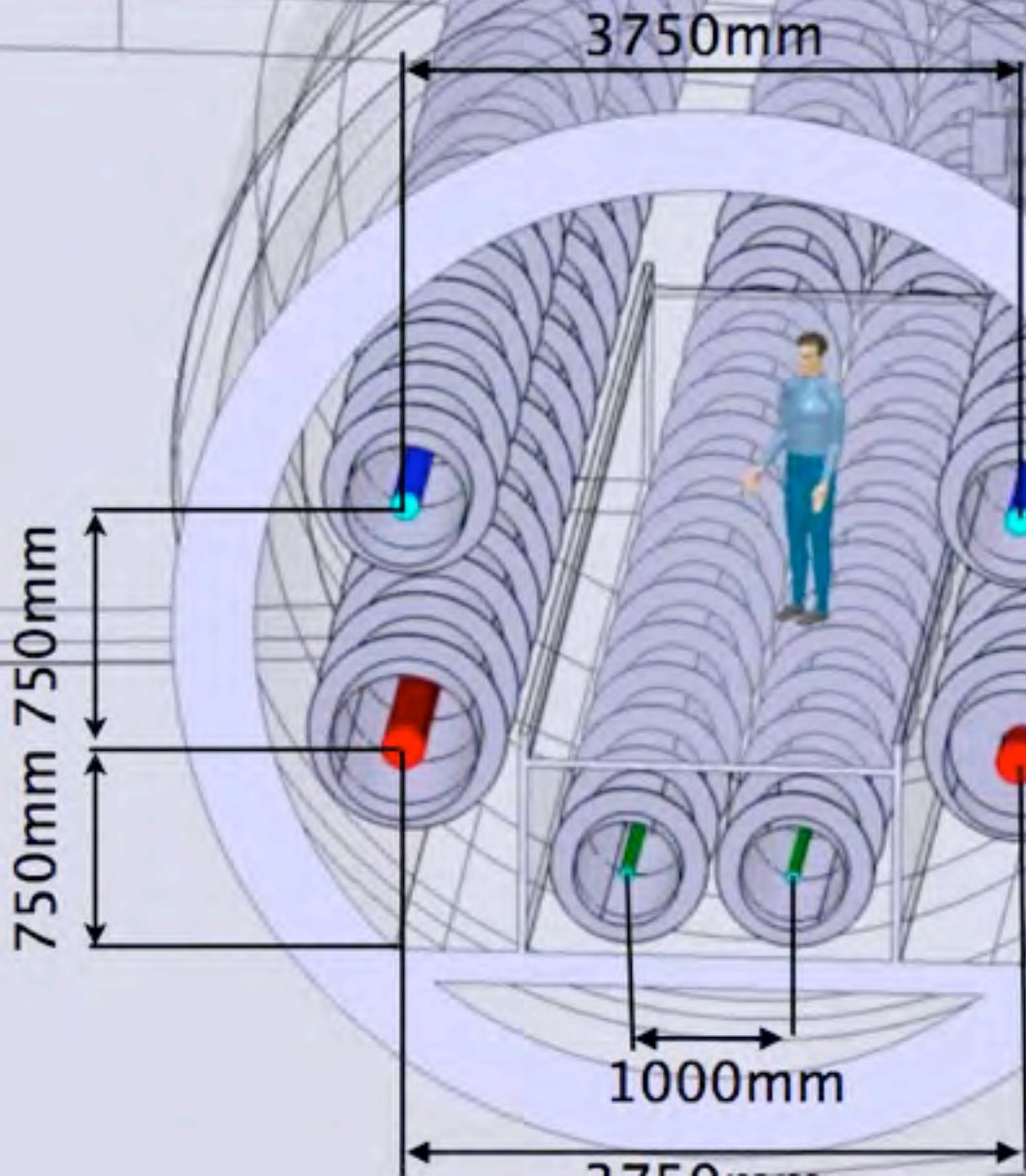


Large Infrastructure

[M. Doets, D. Rabeling]

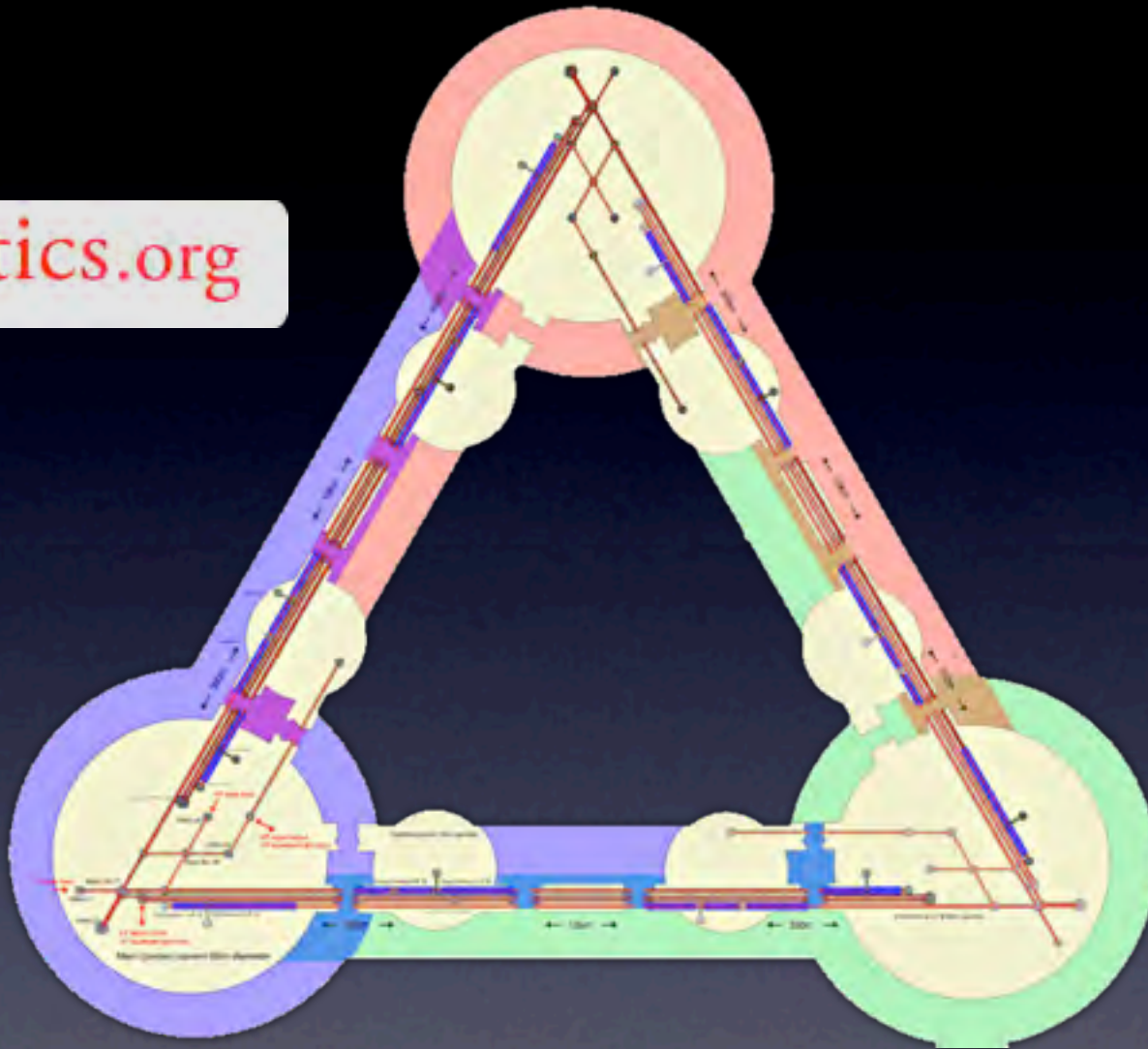








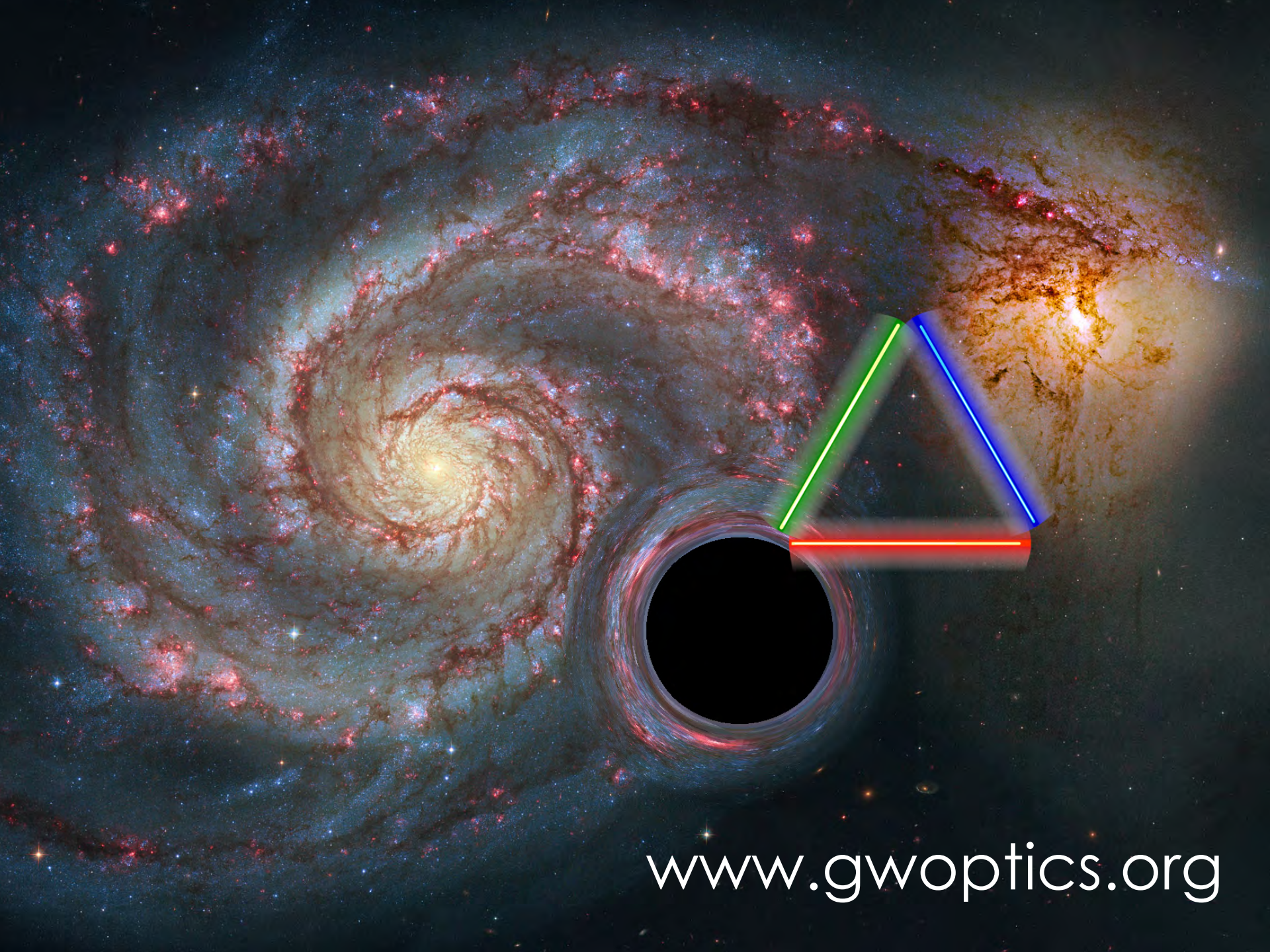
gwoptics.org





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/>
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 - 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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- Lainey Bird
- Sky and Telescope Magazine
- John James
- Kate Dooley (LIGO/GEO)
- Martin Doets, David Rabeling (Nikhef)