LIGO Detector and Hardware Introduction

Virtual Open Data Workshop

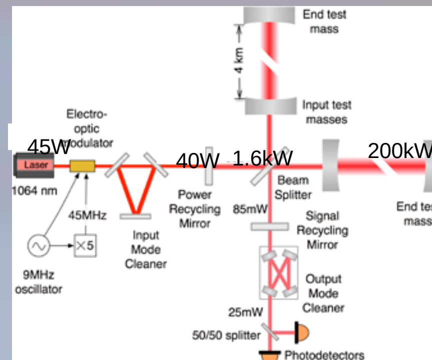
May 2020

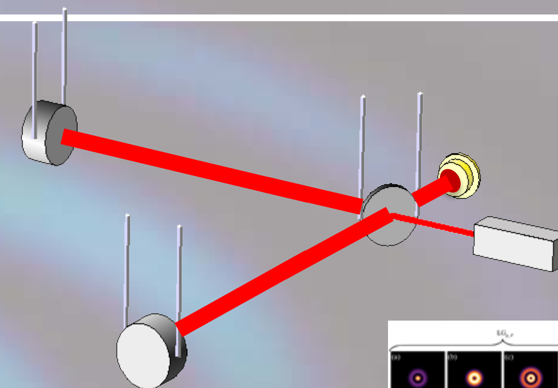
LIGO-G2000795

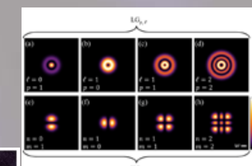
LIGO

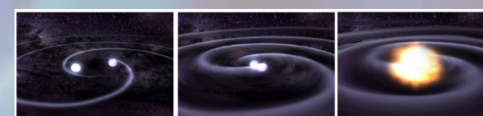
Outline

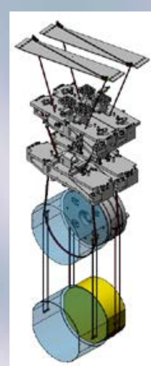
- Introduction
- Interferometry
  - Locking
  - Optical cavities



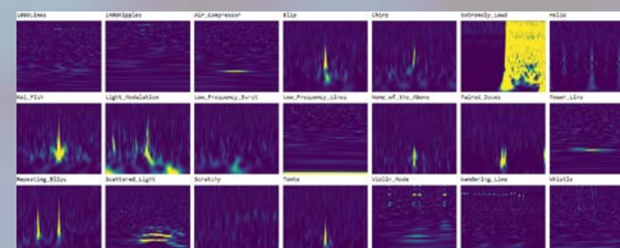


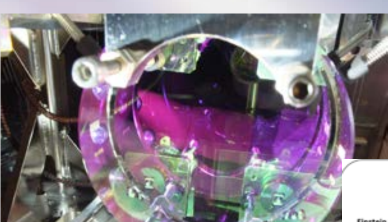


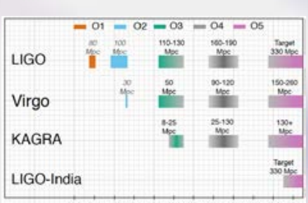


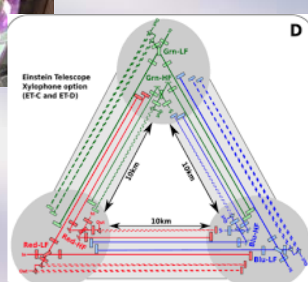


- Hardware
- Noise
  - Fundamental
  - Technical









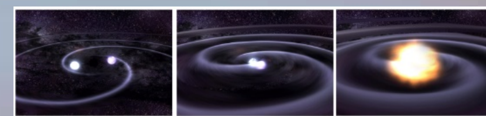
- Commissioning/Observation Runs
- Future Detector Plans
- Bibliography

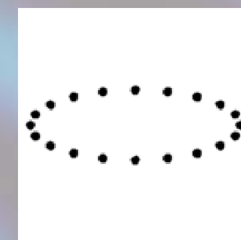
Gravitational Waves

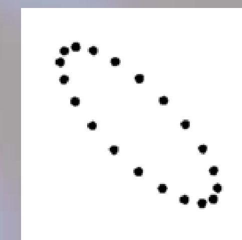
- Metric tensor perturbation in GR $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

  2 polarization in GR

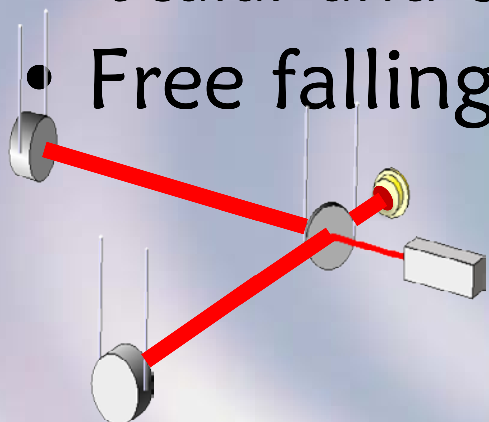
  Scalar and other possible waves







- Free falling masses



  - Change in laser propagation time $\propto h$
  - Phase difference in light $\propto L\, h$
  - Interferometry detects phase difference

- Astronomical Sources

  Modeled vs Unmodeled

  Short vs Long

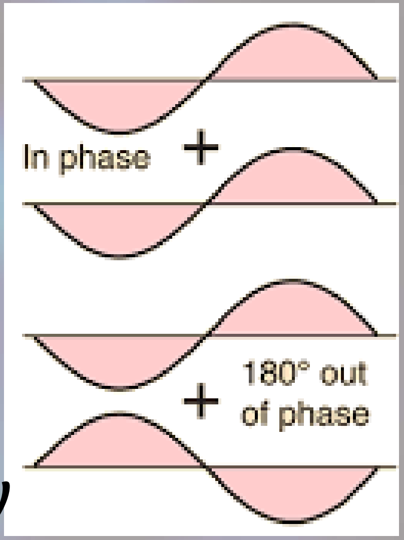
  Known vs Unknown

Modeling /Length	Modeled	Unmodeled
Short	Inspirals (BBH, BNS, BH/NS)	Bursts (Supernova)
Long	Continuous Waves (Pulsars)	Stochastic Background

Sensitivity Estimate

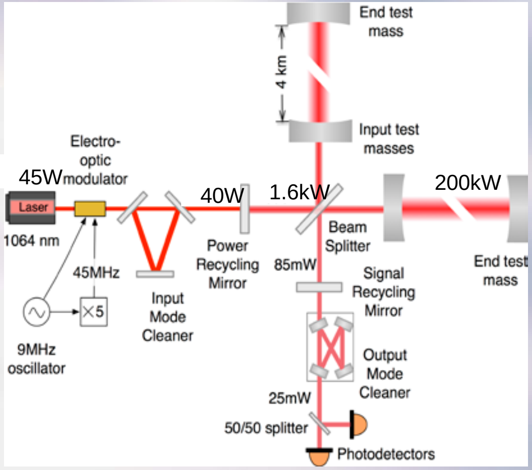
- Strain from single photon: $h \cong \frac{\lambda/_2}{L} = 10^{-10}$
- Need strain 10^{-22}

- Shot noise SNR $\propto N/_{\sqrt{N}} = \sqrt{N}$



- 10^{12} improvement, 10^{24} photons

At 100 Hz equivalent to power of 20 MW



- With 200 W of input laser power, requires power gain of 100,000

Total optical gain in LIGO is ~50,000

Ignores other noise sources

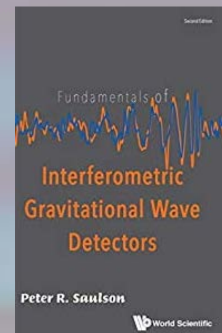
Gravitational Wave Detector Network

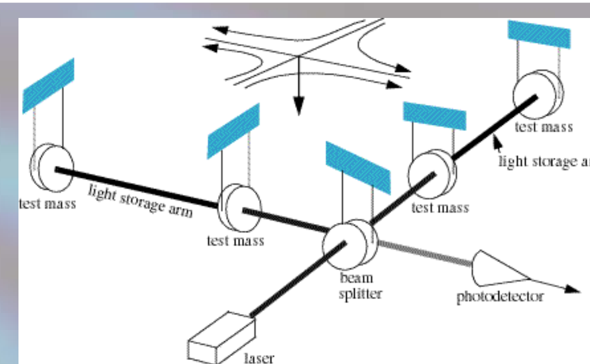
Interferometry

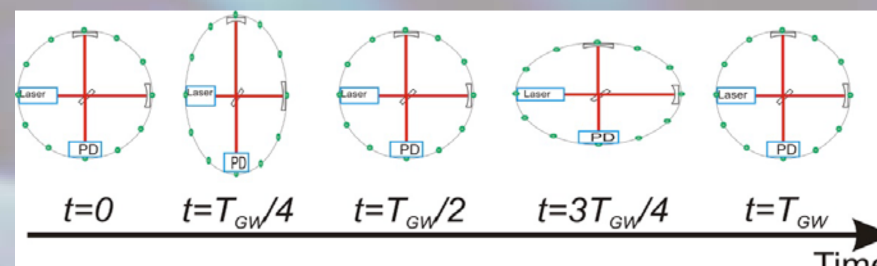
- Book by Peter Saulson
- Michelson interferometer

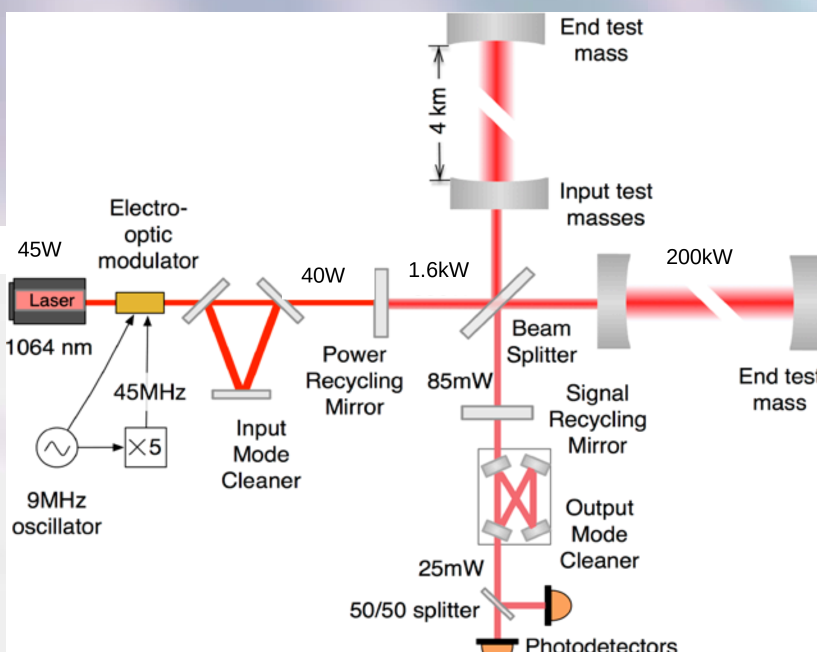
  Fringe splitting
- Fabry-Perot arms

  Cavity pole, $f_c = {}^{c}/_{4L\mathcal{F}}$





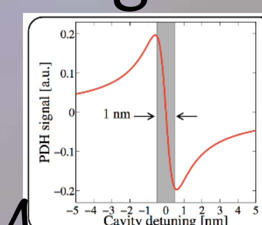




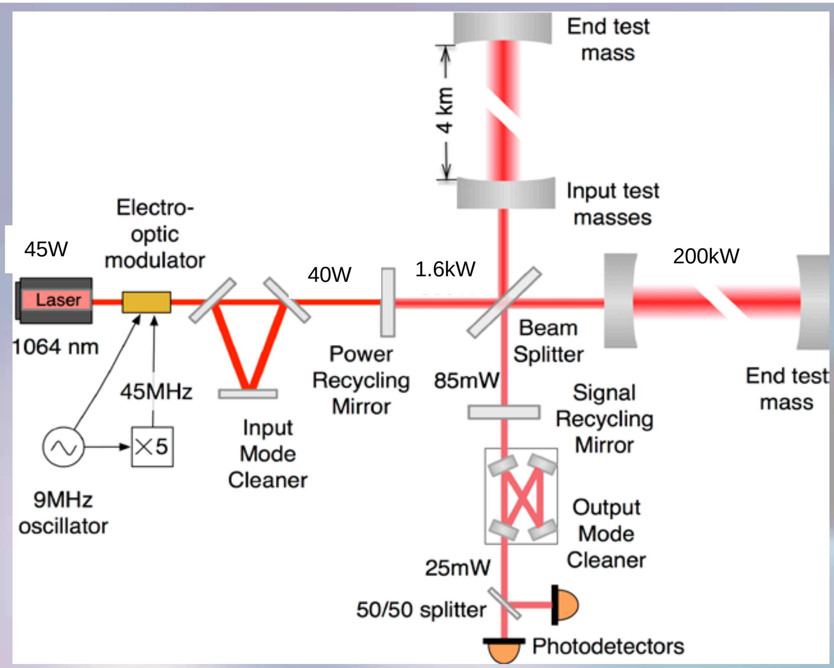
- Pound-Drever-Hall locking

  Match laser frequency to cavity length

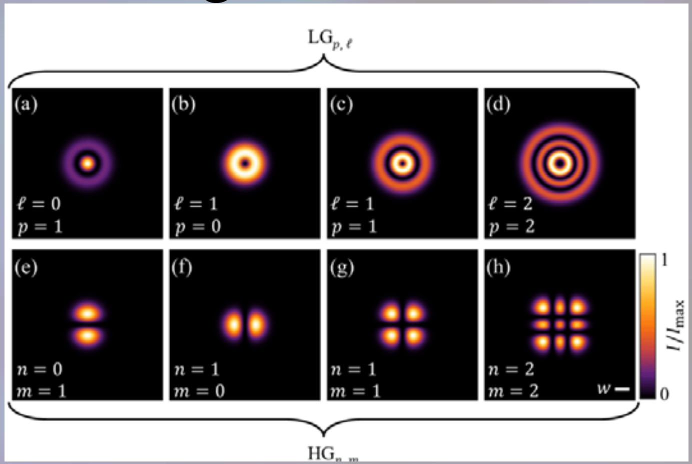
  RF modulation with EOM
- Feedback and controls



Other LIGO Cavities

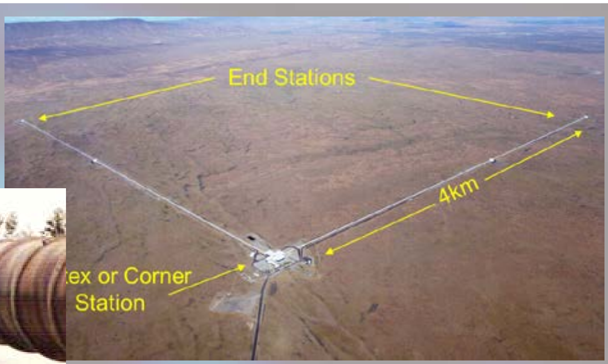


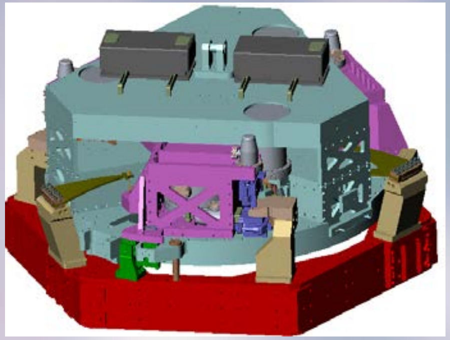
- Mode cleaners
  - Input and output
  - Single Gauss-Laguerre mode
- Power recycling
  - Output dark fringe
  - Reflect light back to IFO
  - Low finesse, gain
- Signal recycling
  - Additional mirror at output port
  - Reflectivity and position tuning of frequency response
- Dual recycled



Hardware

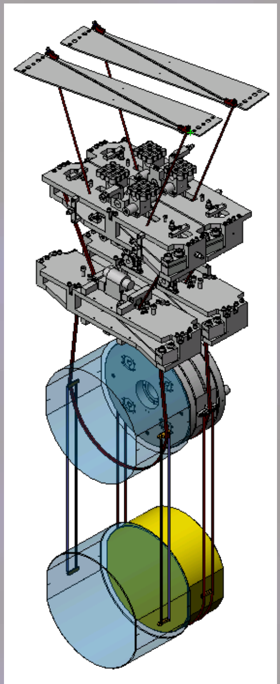
- Arm length, 4 kilometers
  Vert:Horiz coupling $\sim 10^{-4}$ over 4 km
- Vacuum $\sim 10^{-8} - 10^{-9}$ torr
- Same as initial LIGO (2000s)





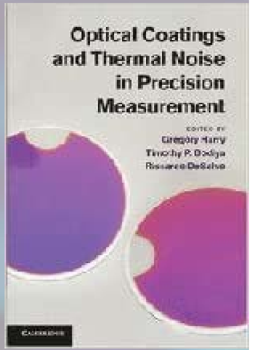
- Seismic isolation: 6 deg of freedom
  Hydraulic actuation, external
  Active isolation, in vacuo
  Lower frequency than iLIGO

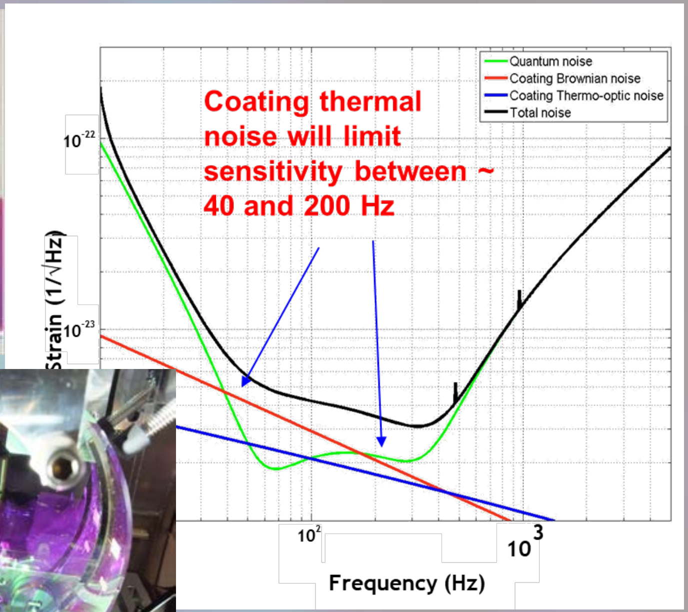
- Suspensions
  Hangs from seismic isolation
  Quadruple pendulums
  Silica fibers in final stage
  Better isolation and lower thermal noise than iLIGO



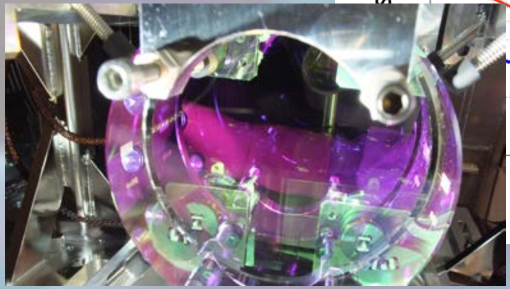
Hardware

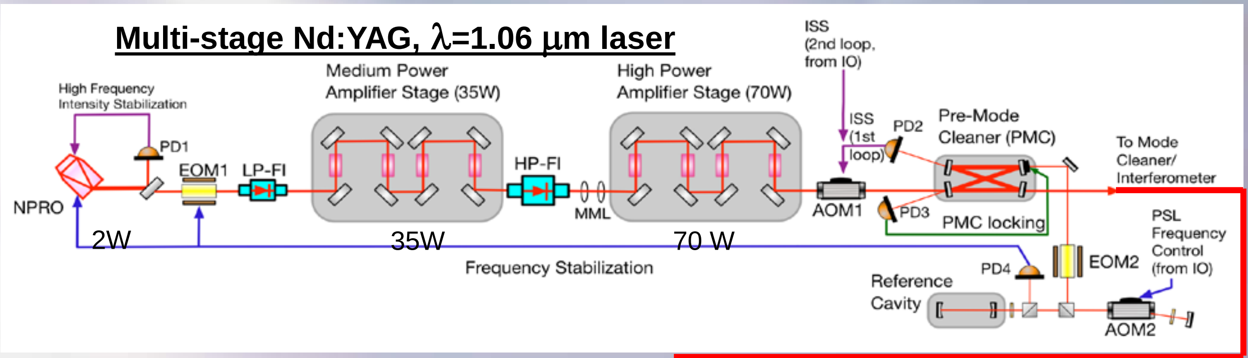
- Optics/Test Masses
  - 40 kg silica, 35 cm diameter
  - Beamsplitter, recycling mirrors
  - Higher mass than iLIGO





- Optical Coating
  - Titania-doped tantala/silica
  - <1 ppm absorption
  - Lower thermal noise than iLIGO





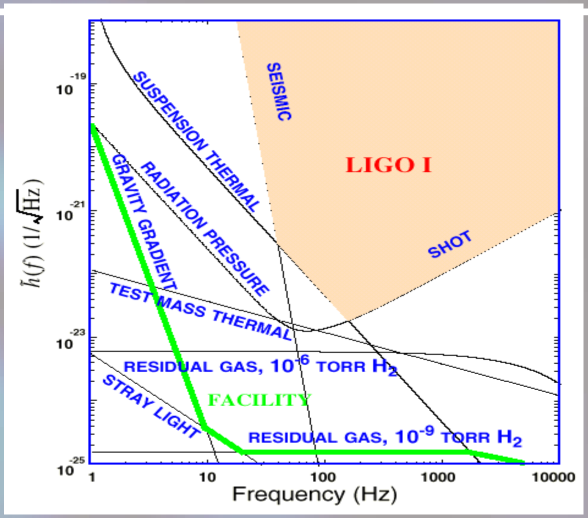
- Laser
  - Nd: YAG, NPRO
  - 1.064 μm, ~150 W
  - Higher power than iLIGO

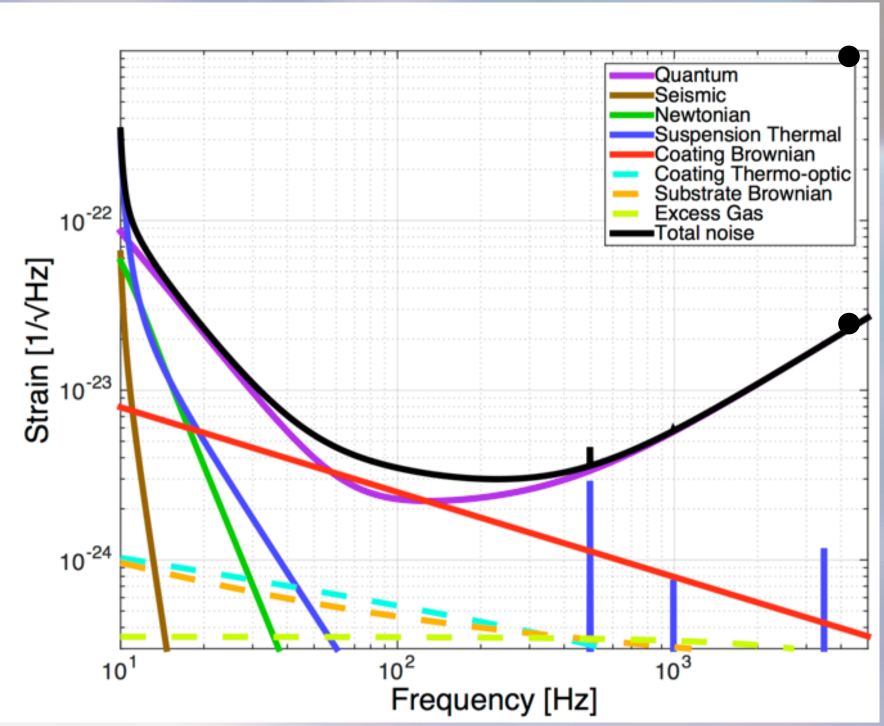
Fundamental Noise

- Sensitive band 10 Hz – 5000 Hz
- Seismic, $\lesssim$ 10 Hz

  Microseism, wind, Earth tides

  Newtonian noise, anthropogenic noise





- Thermal

  Thermodynamics

  Suspensions, coatings, mirrors
- Quantum

  Heisenberg uncertainty of test mass

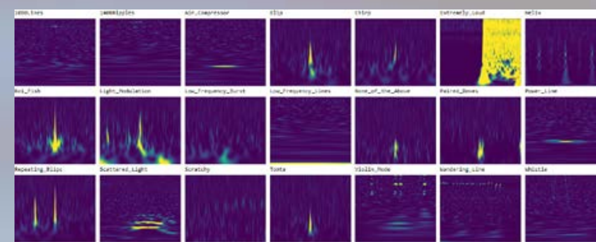
  Shot noise, radiation pressure/back reaction

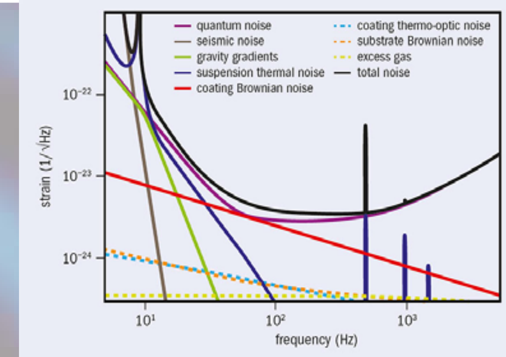
  Squeezed light to get around Heisenberg

Technical Noise

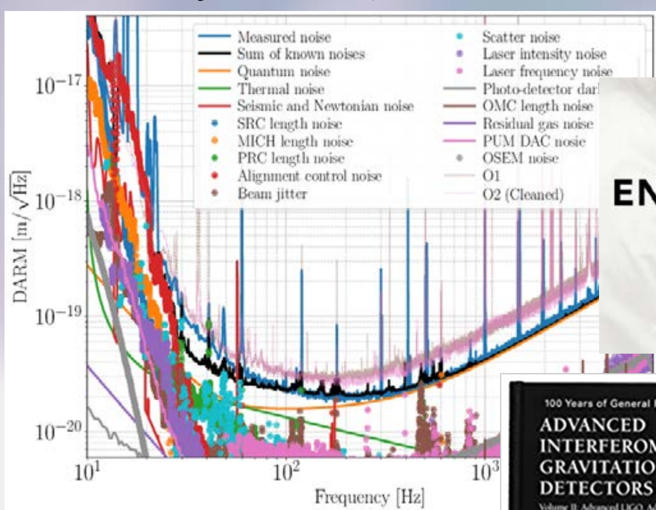
- Residual gas, facility limits
- Non-Gaussian noise

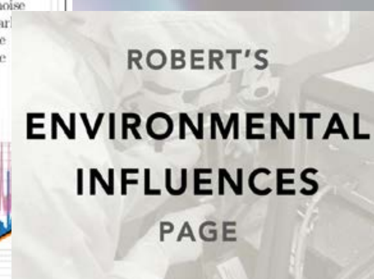
  Glitches





- Frequency and amplitude laser noise





- Environmental noise

  Magnetic fields, RF, acoustic

  Electronics noise

- Parametric instability

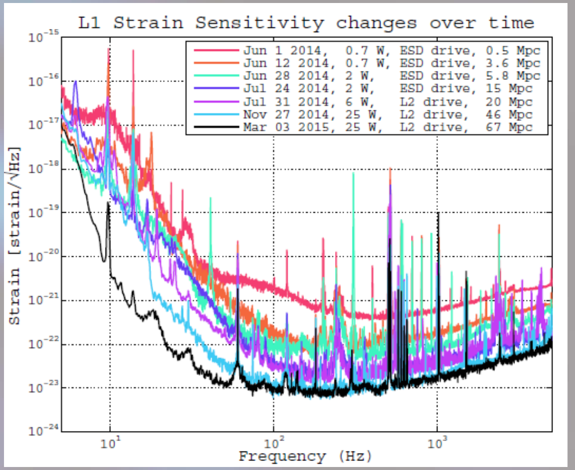
  High optical power can cause loss lock

  Centennial Book

  Reitze, Saulson, Grote

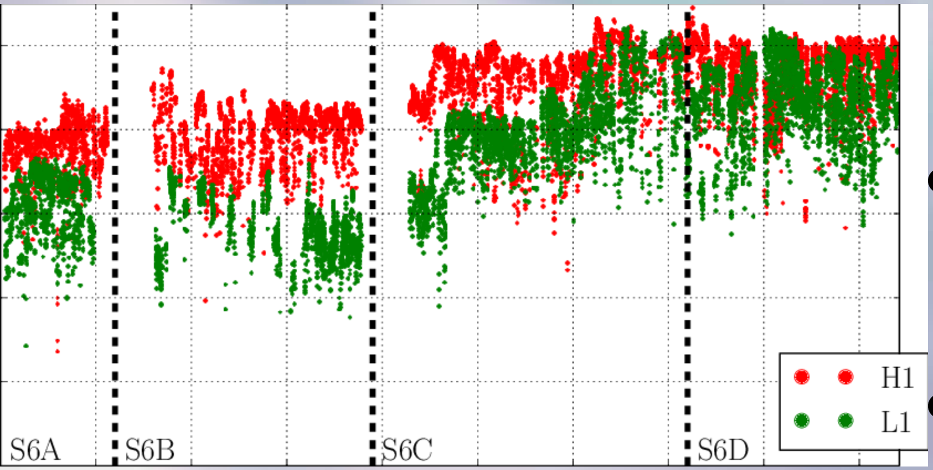
Commissioning

- Commissioning effort gives improvements to noise over time



- Alternate between data taking and commissioning

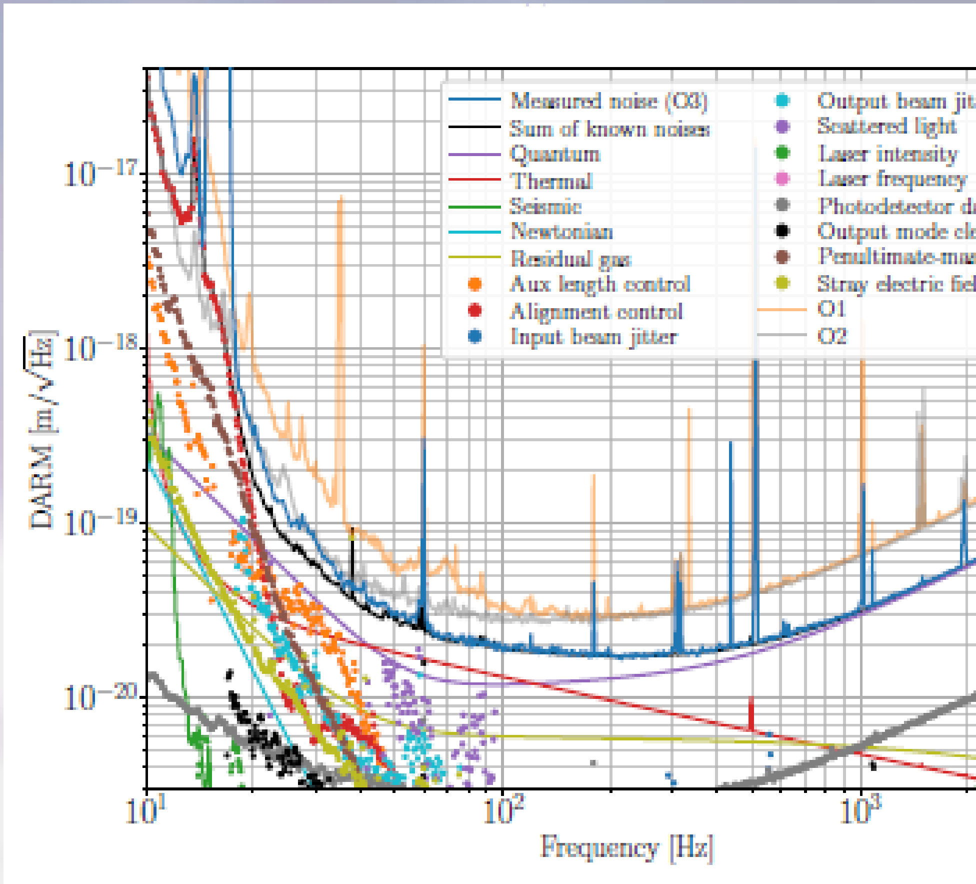
  Fixes and improvements

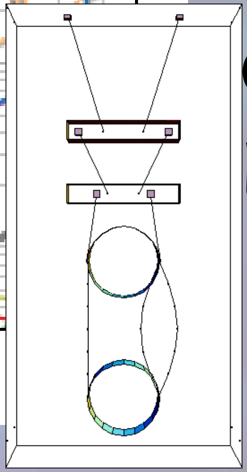


- Often involves increasing laser power
- Managing optical power major challenge
- Causes changes to detectors

Noise Curves

- Optical power increases
- Technical noise in many frequency bands

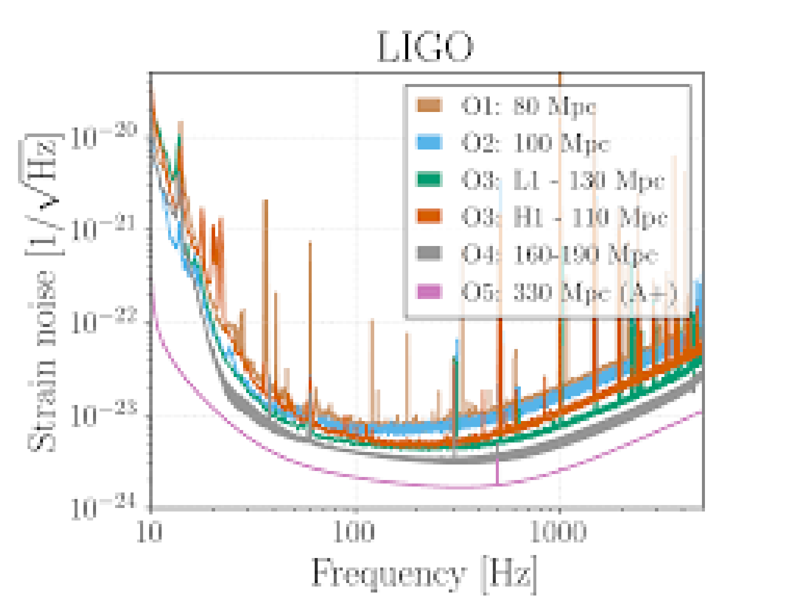


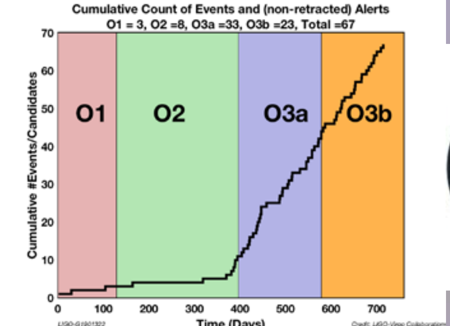


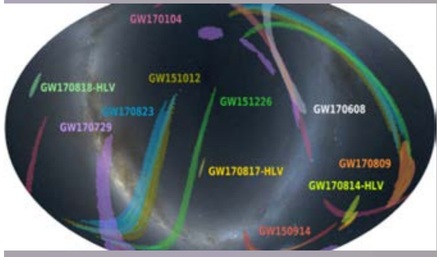
- Narrowband noise
  - Line noise (60 Hz)
  - Calibration lines
  - Violin mode resonances
  - Other resonances
  - Frequency combs

Observation Runs

- Observing run 1: O1 9/2015-1/2016
  BNS L 80 Mpc H 70 Mpc, LIGO Duty cycle 65%
- O2: 11/2016-8/2017
  BNS L 100 Mpc H 80 Mpc
  2 IFO Duty cycle 80%
- O3a: 4/2019-9/2019
  BNS L 140 Mpc H 115 Mpc
  3 IFO Duty cycle 45%
- O3b: 11/2019-3/2020*
  BNS L 135 Mpc H 120 Mpc
  3 IFO Duty cycle 50%

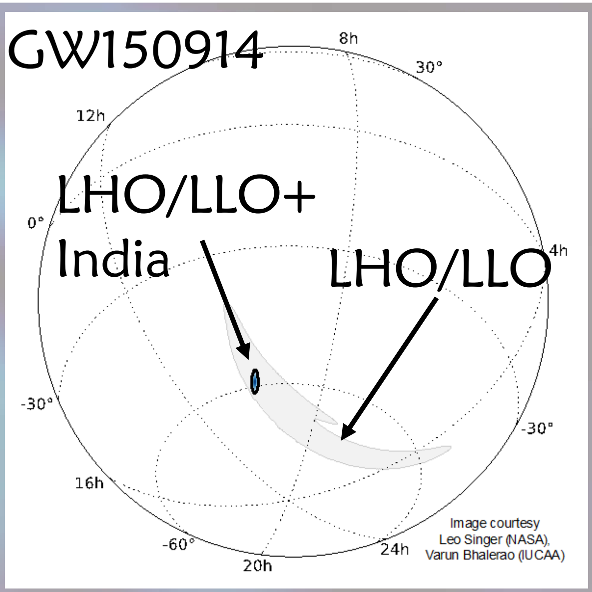






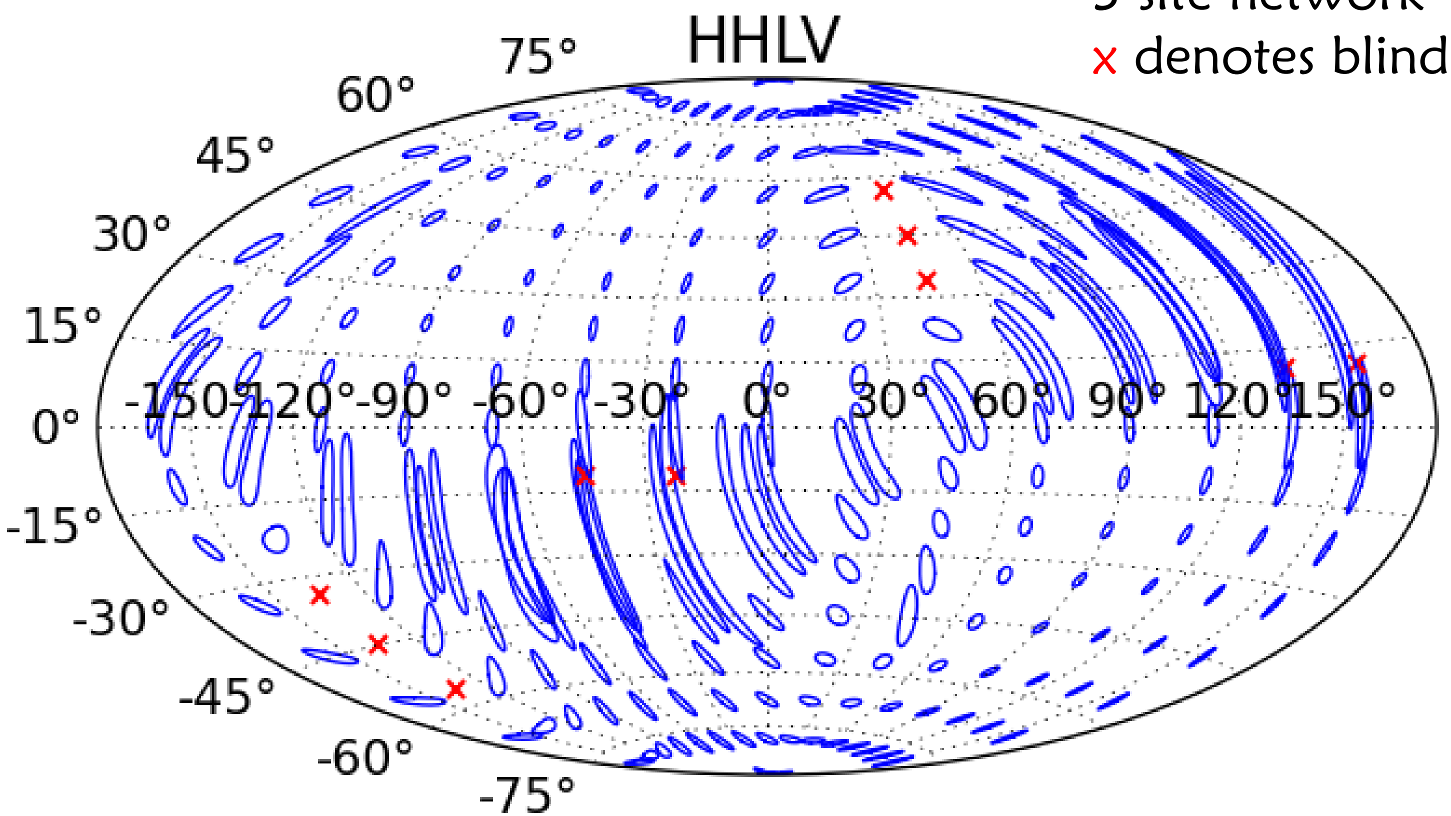
LIGO India

- Spare LIGO hardware
  Built three copies of all hardware
- Localization and triangulation
  More detectors give better source positioning



- Site chosen and being prepared
  Aundha, Maharashtra state
- 2025 operation goal
- Network range
  BNS 330 Mpc

BNS Localization: HLV

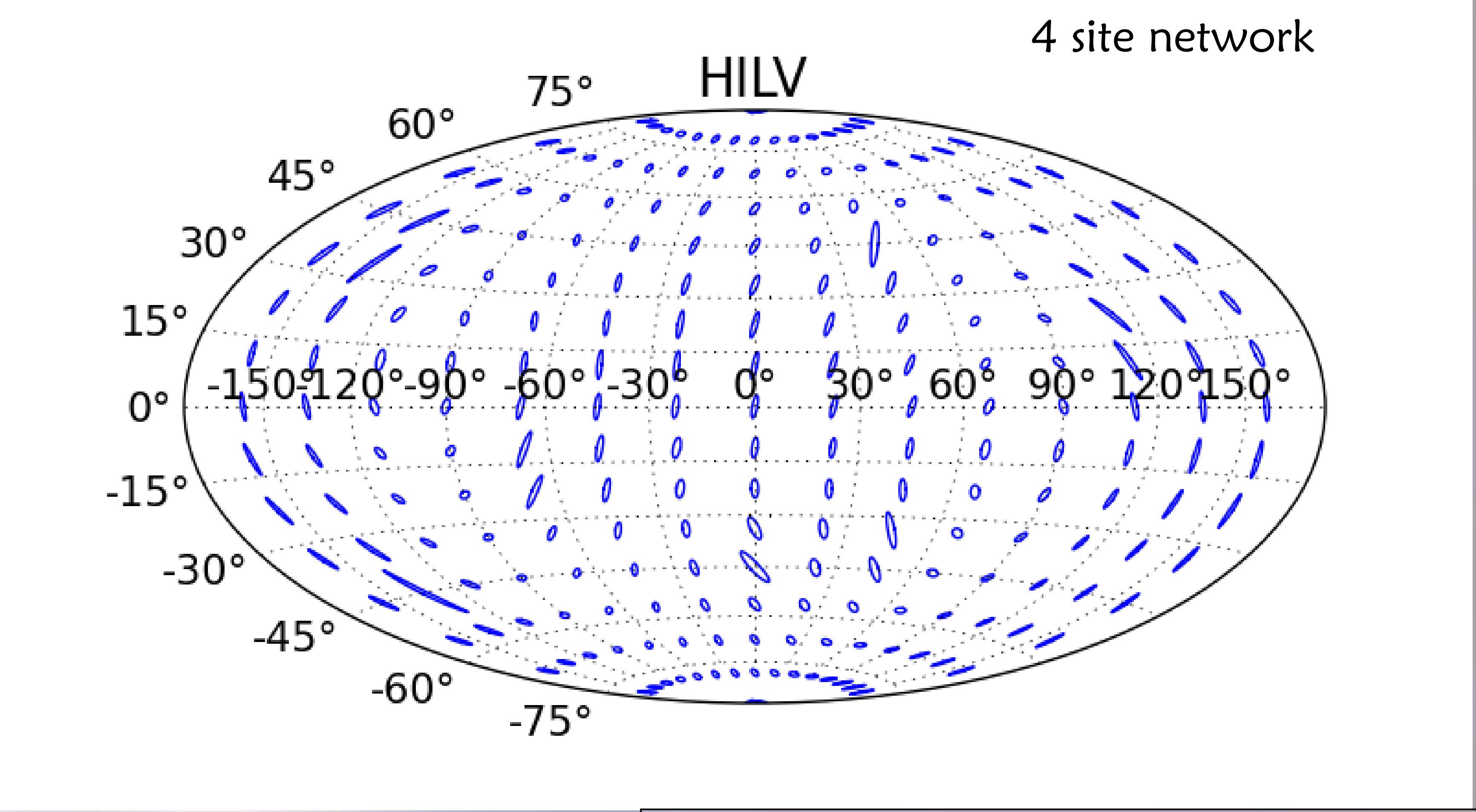


3 site network

x denotes blind spots

S. Fairhurst, "*Improved source localization with LIGO India*", [J. Phys.: Conf. Ser. 484 012007]

BNS Localization: HILV



S. Fairhurst, "*Improved source localization with LIGO India*", J. Phys.: Conf. Ser. 484 012007

Future Advanced LIGO Plans

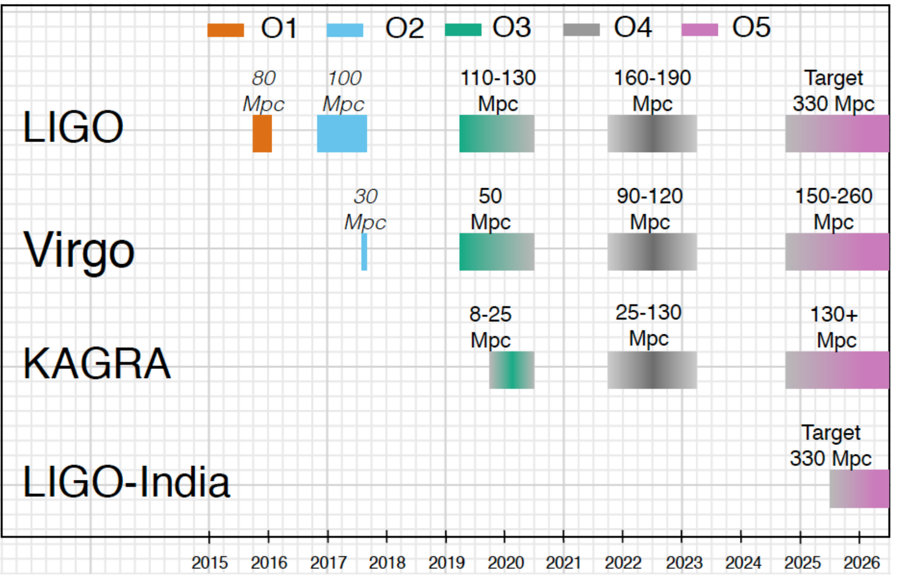
- Further observation runs

  O4 was planned to start January 2022

  Planned/expected BNS 165-190 Mpc

- Commissioning breaks

  Was 20 months starting May 2020

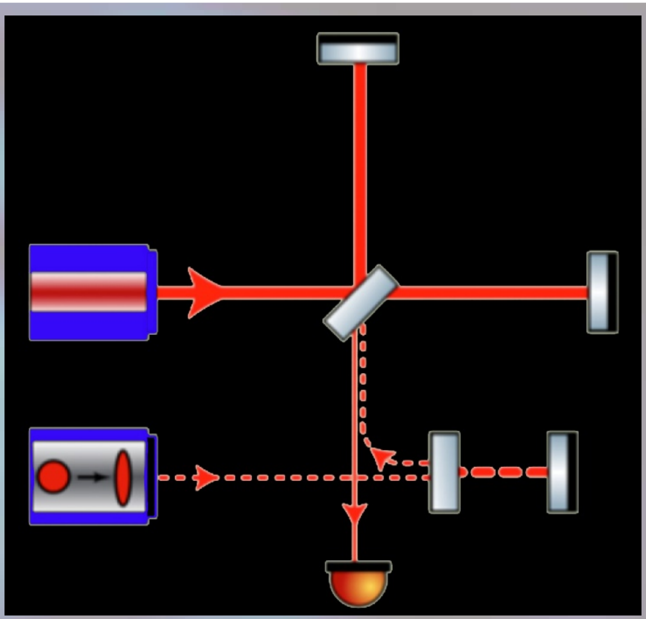


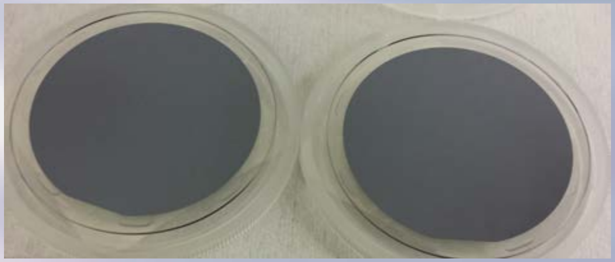
O5 plans

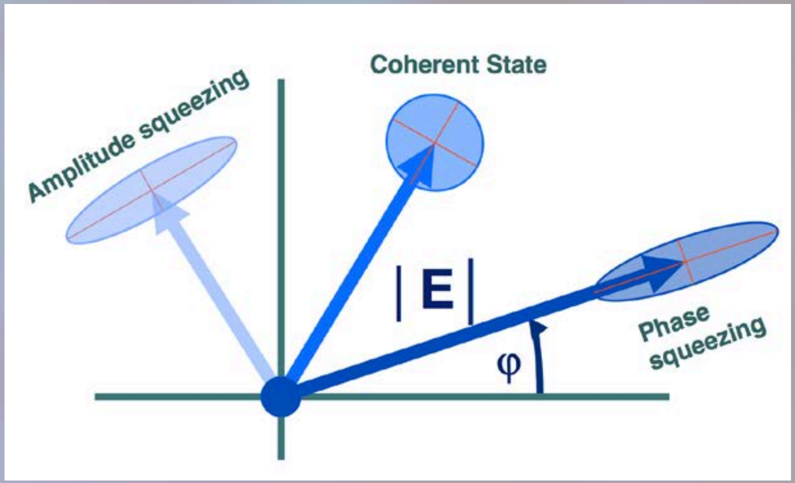
- Was late 2024
- 2 year+ run
- Expect design sensitivity, BNS 200 Mpc
- KAGRA online

Future Detectors

- A+ upgrade
  - Frequency dependent squeezing, 16 m filter cavity
  - Coating upgrade to lower thermal noise
- Was starting May 2020
  - Now, ???
  - Was ending 2023

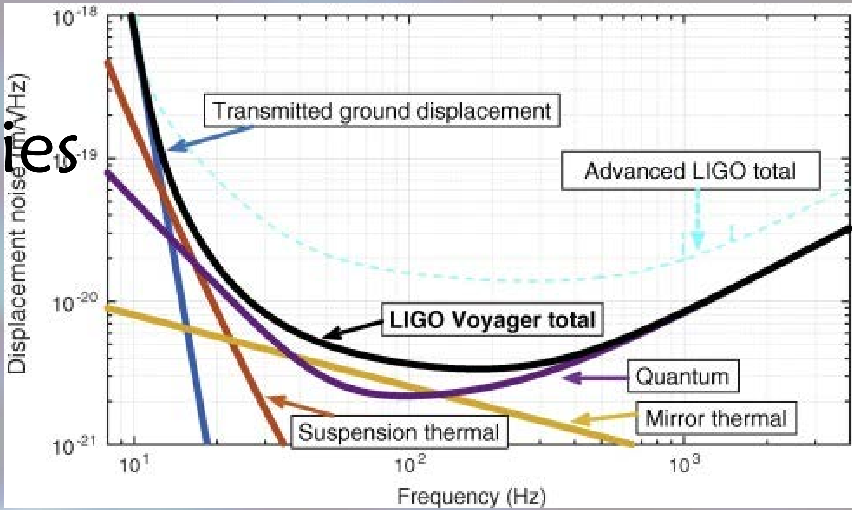


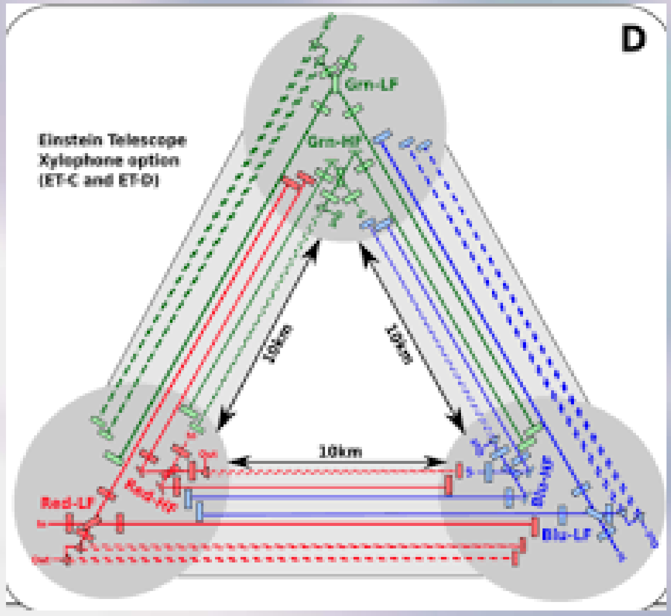




Future Detectors

- LIGO Voyager
  - Best detector in current facilities
  - Cryogenic, silicon mirrors
  - 5X range of O5 LIGO
  - At soonest, 2028





- Cosmic Explorer
  - 10X range of O5 LIGO
  - Mid-2030s, 40 km arms, USA
- Einstein Telescope
  - Triangle geometry, 10 km arms
  - Underground, Europe

Bibliography

Peter Saulson, "Fundamentals of Interferometric Gravitational Wave Detectors", 2nd Edition, World Scientific (2017).

"Optical Coatings and Thermal Noise in Precision Measurement", Ed. G. Harry, T. Bodiya R. DeSalvo, Cambridge University Press (2011).

"Advanced Interferometric Gravitational-Wave Detectors", Vol. 1 and 2, Ed. P. Saulson, D. Reitze, H. Grote, World Scientific (2019).

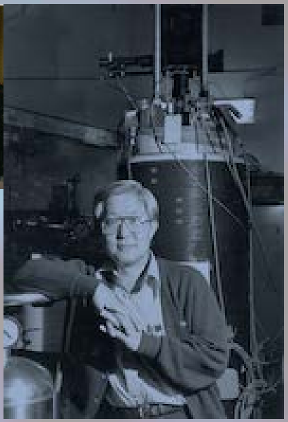
Abbott, B. P., et al. "GW150914: The Advanced LIGO Detectors in the Era of First Discoveries." Physical Review Letters **116.13** (2016): 131103, P1500237.

"Advanced LIGO", The LIGO Scientific Collaboration, Classical and Quantum Gravity, **32** (2015) 074001, P1400177.

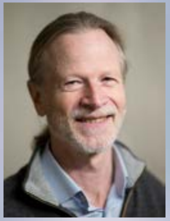
"Advanced Virgo: a second-generation interferometric gravitational wave detector", The Virgo Collaboration, Classical and Quantum Gravity **32**, (2015) 024001.

Personal Introduction

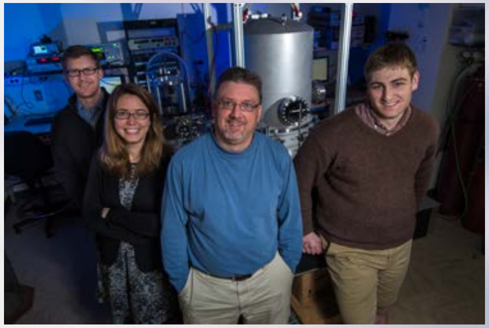
- PhD 1999 University of Maryland
  - Resonant mass detector, ie Weber bar



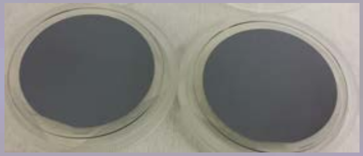
- Postdoc at Syracuse with Peter Saulson
  - Thermal noise, early work on optical coatings



- Postdoc and Research Scientist with LIGO Laboratory at MIT with David Shoemaker
  - Continuing coatings and thermal noise work
  - LASTI prototype, suspensions testing, charging
  - Advanced LIGO Coating Scientist and LSC Optics Chair



- American University faculty
  - AlGaAs coatings for future detectors
  - Stochastic review committee
  - Training of undergraduates

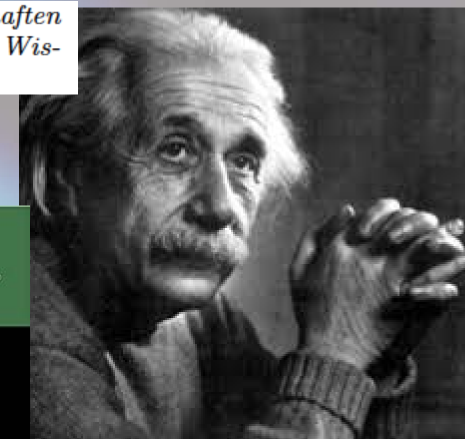


LIGO

Early History of GW Detection

- Einstein

A. Einstein, *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften* (Berlin,1916), 688696; *Sitzungsberichte der Kniglich Preussischen Akademie der Wissenschaften* (Berlin, 1918), 154167.



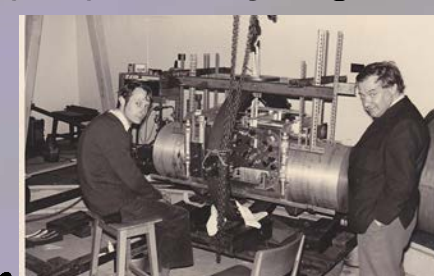
General Relativity 1916, GW 1918

- 1957 Chapel Hill Conference

Possibility of detection

- John Wheeler

- Joe Weber: Resonant mass detectors, unconfirmed detection
- Early interferometry



MIT: Weiss, Glasgow: Drever, Munich: Rudiger

History of LIGO

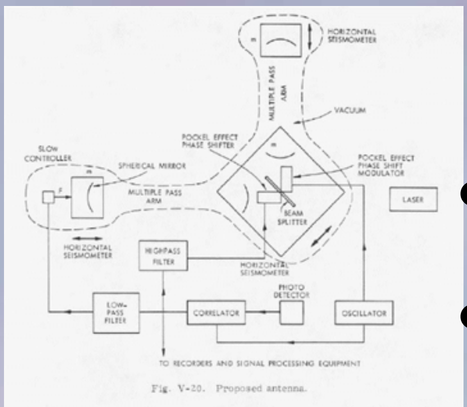
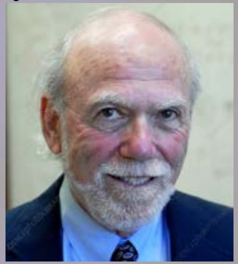


Fig. V-20. Proposed antenna.

- 1970-80s: Separate projects: Caltech (Thorne, Drever) and MIT (Weiss)
- 1983: LIGO design study (Blue Book)
- 1989: LIGO Proposal, Mark I and II
- 1991: Funding for Initial LIGO
- 1997: LIGO Scientific Collaboration (Barish)
- 2001-2007: Initial LIGO Science Runs



- 2010: Decommissioning of Initial LIGO, Beginning of installation for Advanced LIGO
- 2015: First aLIGO observing run, GW150914

Organization of LIGO

- **LIGO Laboratory**

  Campuses: Caltech and MIT

  Sites: Livingston and Hanford

  LIGO India

  Director/Principle Investigator: David Reitze, Al Lazzarini dep.

- **LIGO Scientific Collaboration (LSC)**

  LIGO Laboratory

  GEO 600, OzGrav

  Individual Groups, large and small

  Working groups on hardware, astronomical searches, internal review committees

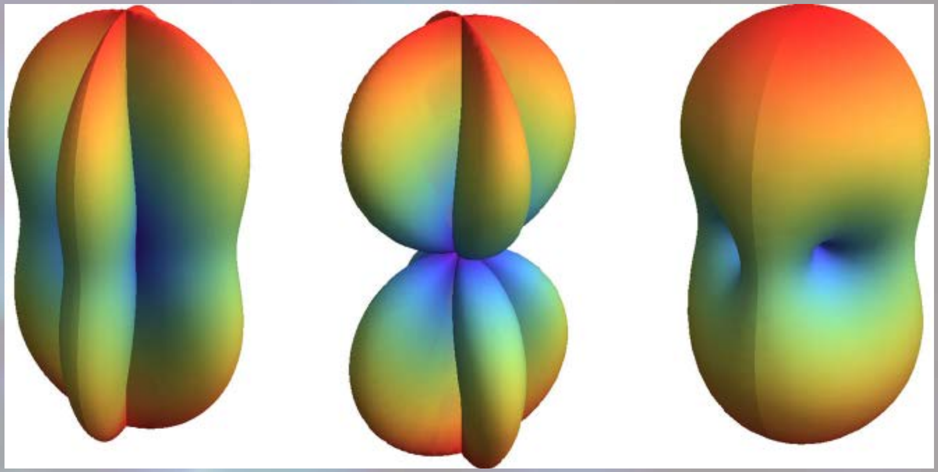
  Spokesperson, Council, hierarchy, structure influenced by high energy and astronomy

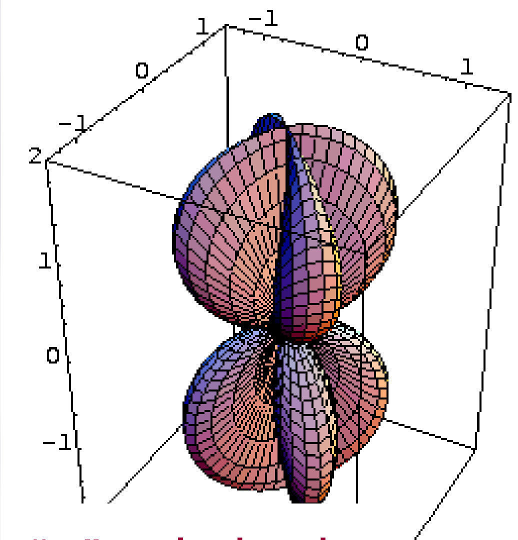
Patrick Brady: UWM

- **Virgo and KAGRA**

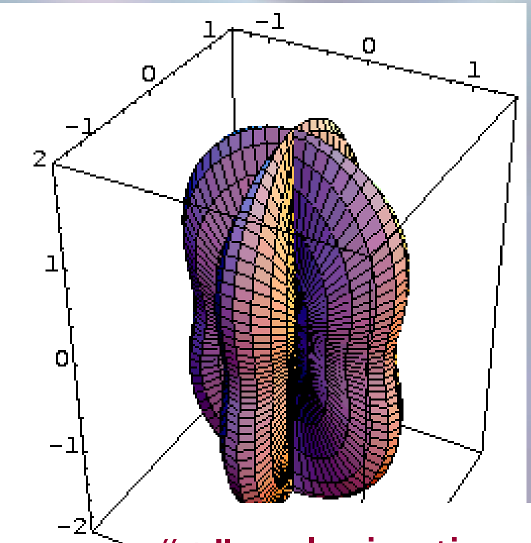
Antenna Pattern

- Source localization not a strength of GW detectors
- Sensitivity dependence on source direction
- Depends on GW polarization and frequency

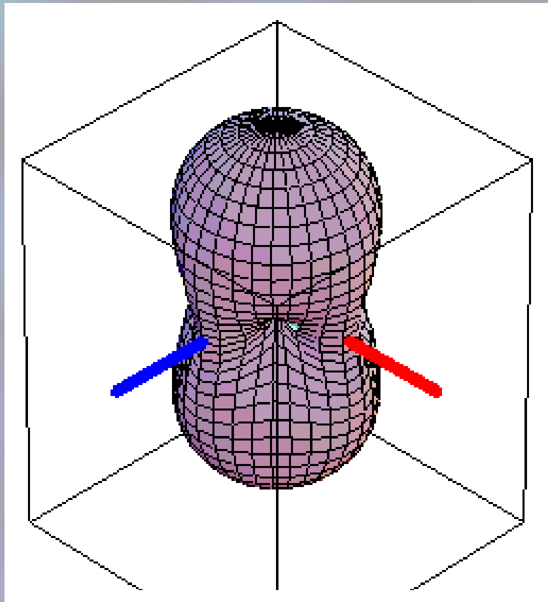




"×" polarization



"+" polarization

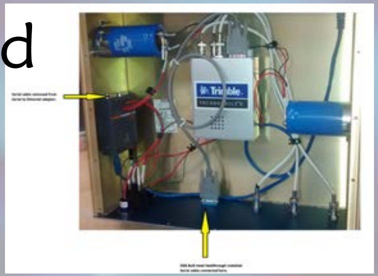


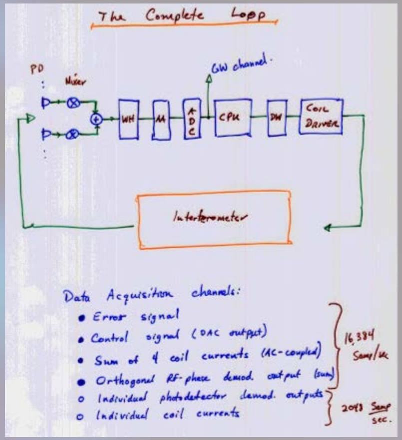
RMS sensitivity

LIGO

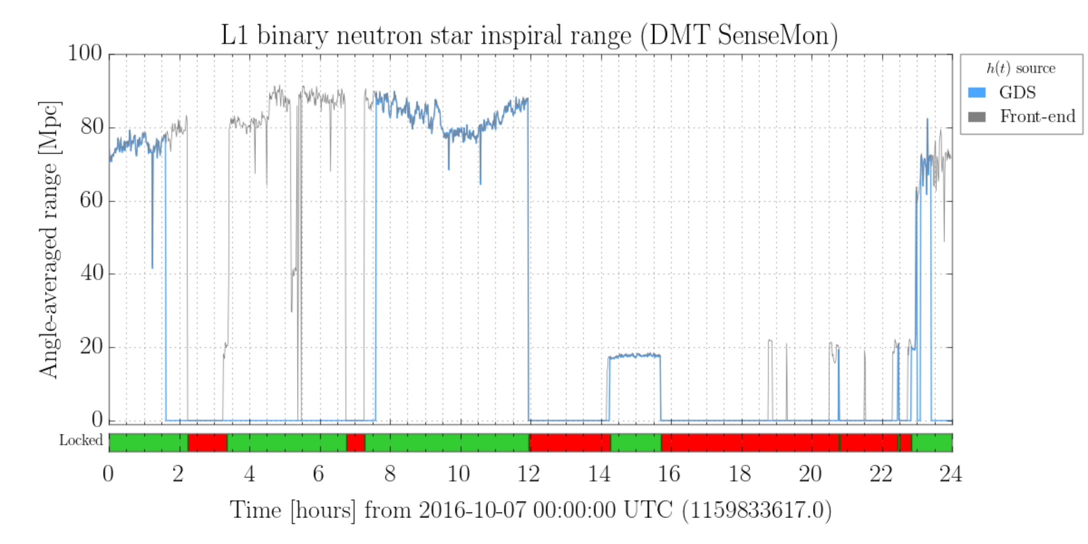
Data

- Most data recorded at 16,384 Hertz
  - LOSC data channel 4096 Hertz
  - Both GW channel and auxiliary and environment monitor channels
  - Some at 2048 Hertz



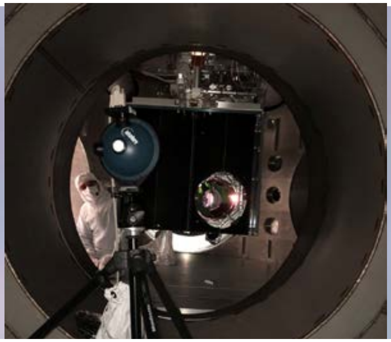


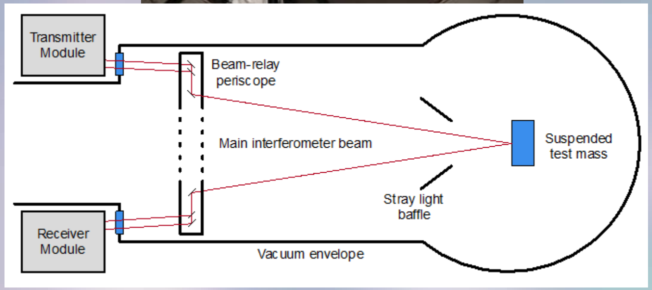
- GPS-locked timing



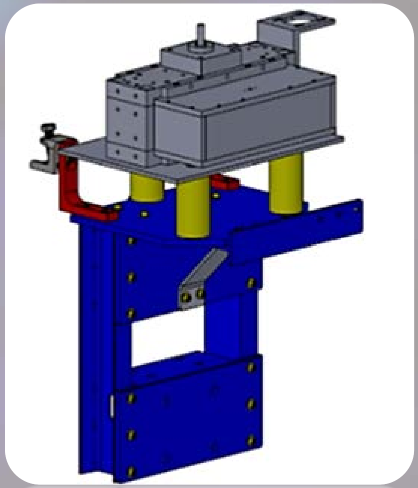
- Science mode flagged, interferometer locked and low noise
  - Data gaps due to lock loss, lock acquisition, etc
  - Data quality talk

Calibration



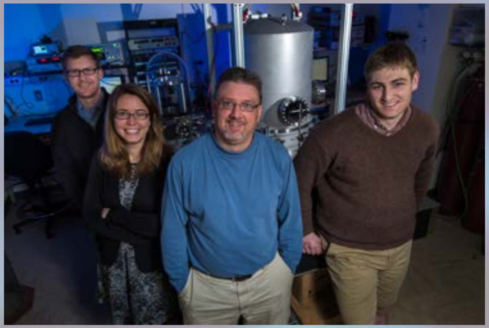
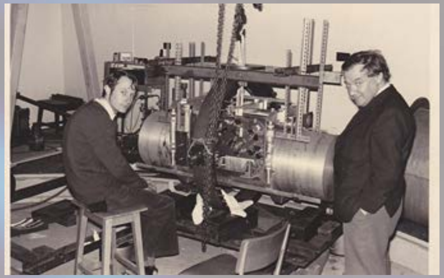
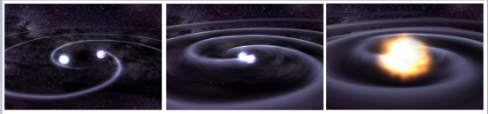


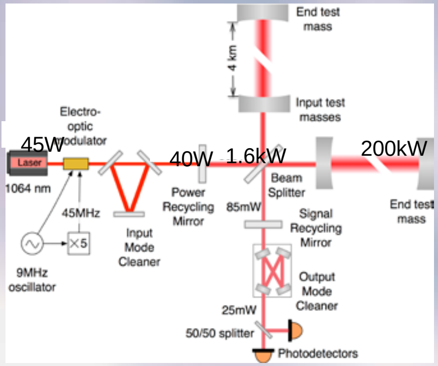
- Feedback response function, magnitude & phase
  - Changes each commissioning step
  - About 1% accuracy
- Photon calibrator, radiation pressure provides calibration
- Continuous calibration lines during data taking update calibration
  - 15 Hz, 430 Hz, 1080 Hz in O3
- Future Newtonian gravity calibrator
  - Prototyping at Hanford

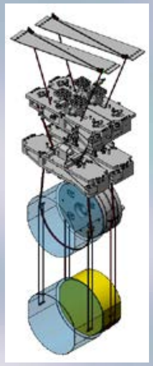


Outline

- Introductions
- History
- Gravitational Waves
- Organization



- Interferometry
- Hardware
- Noise
- Commissioning/Observation Runs
- Future Detector Plans