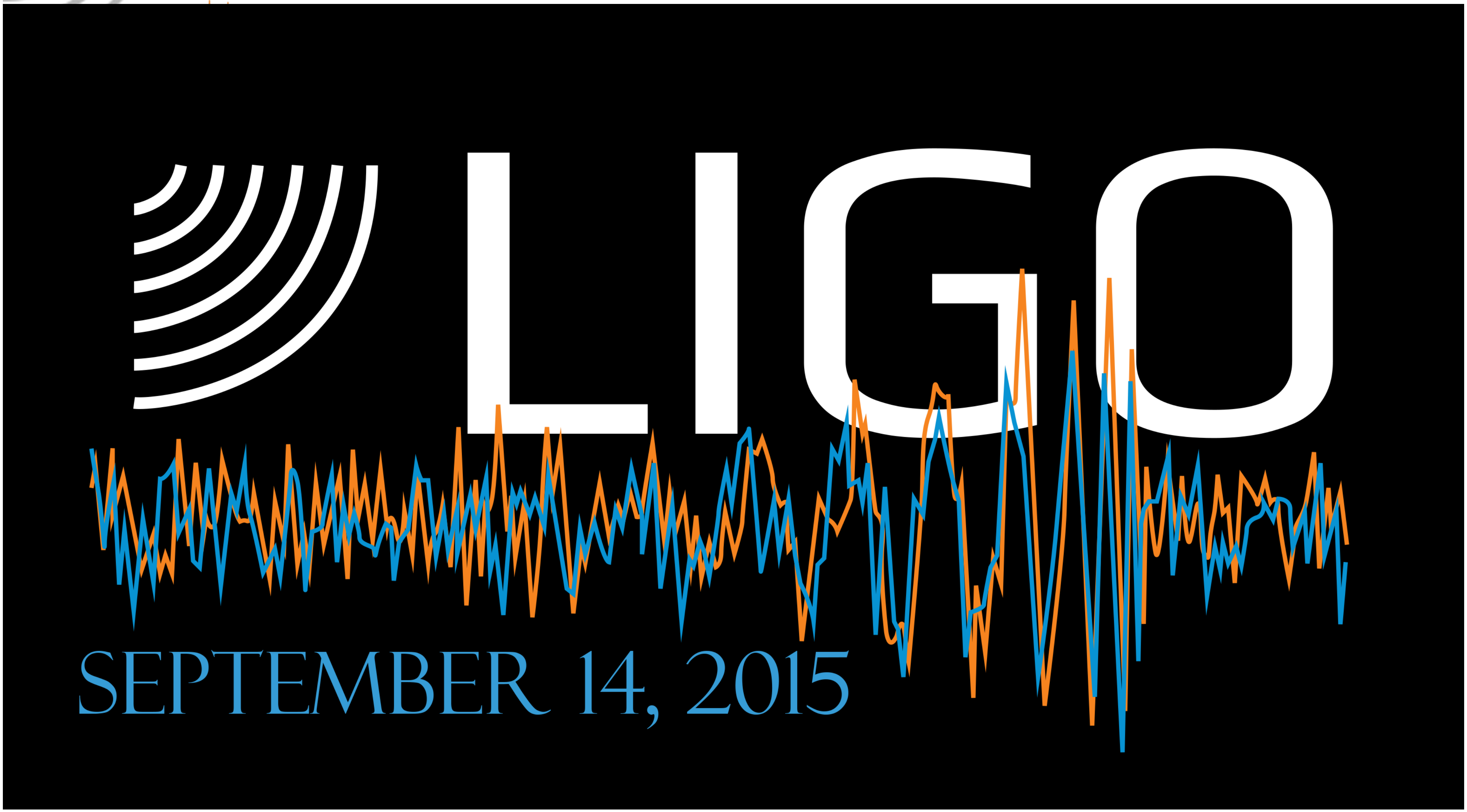
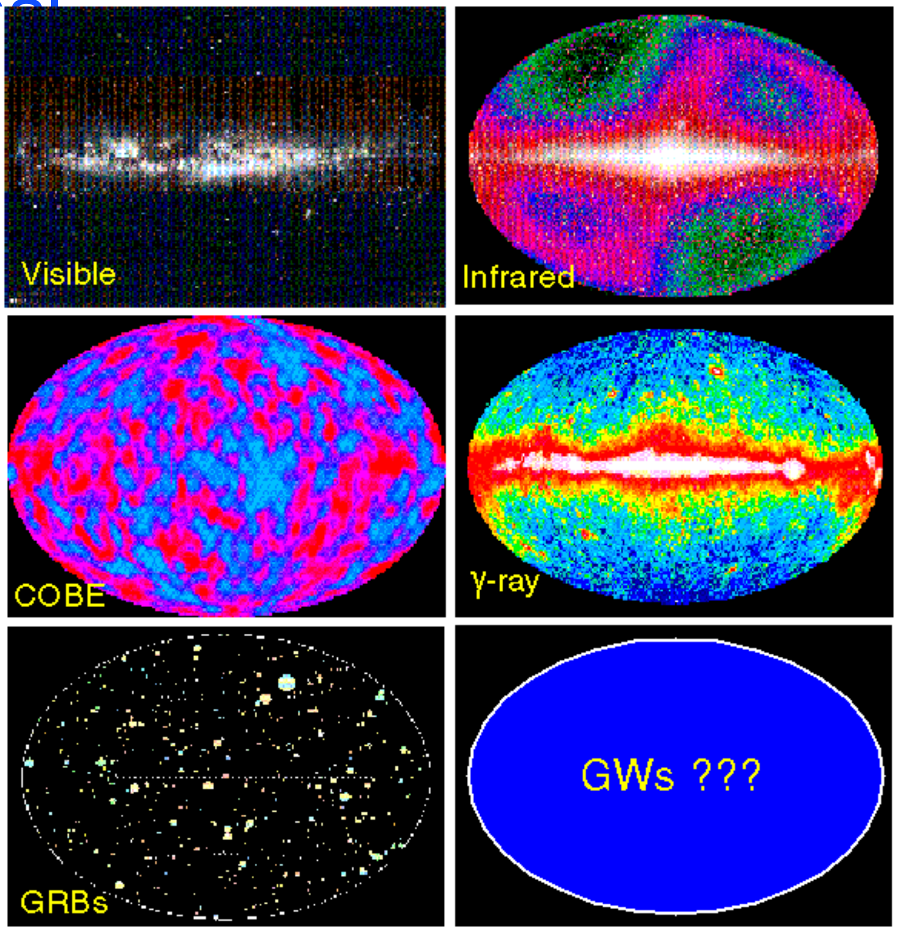

LIGO
SEPTEMBER 14, 2015

Advanced LIGO : Aiming for the detection of the gravitational wave signal, and beyond

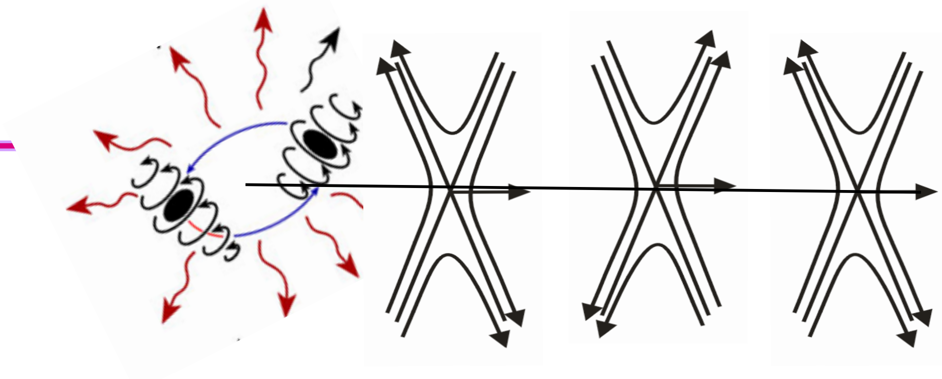
Hiro Yamamoto LIGO lab/Caltech

- New Astronomy by gravitational wave signal at the 100th memorial year of general relativity
  - » In the beginning…
- 2nd generation detector - advanced LIGO
- Observation run 1
- Aiming for the future

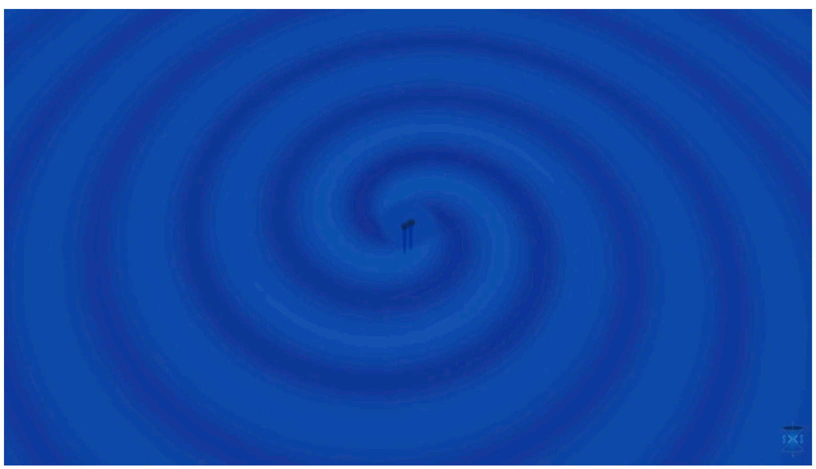


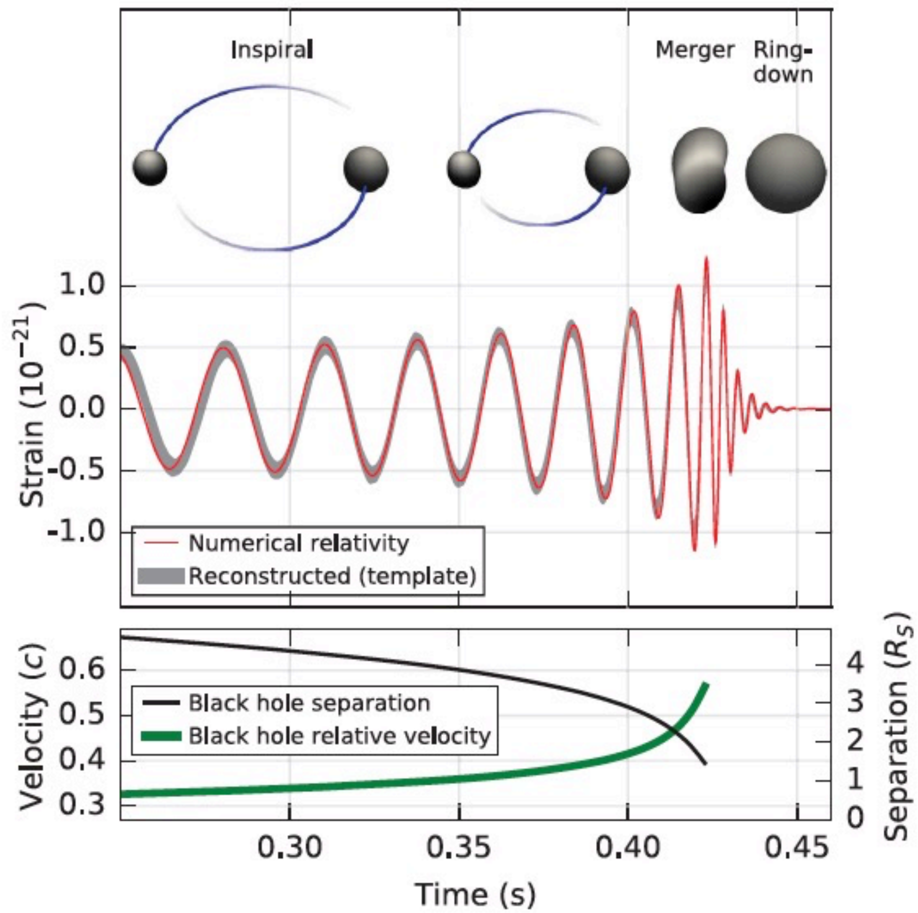
Some slides are copied from talks in 2015 March LVC meeting and from the talk by D. Reitze G1500139

Gravitational waves

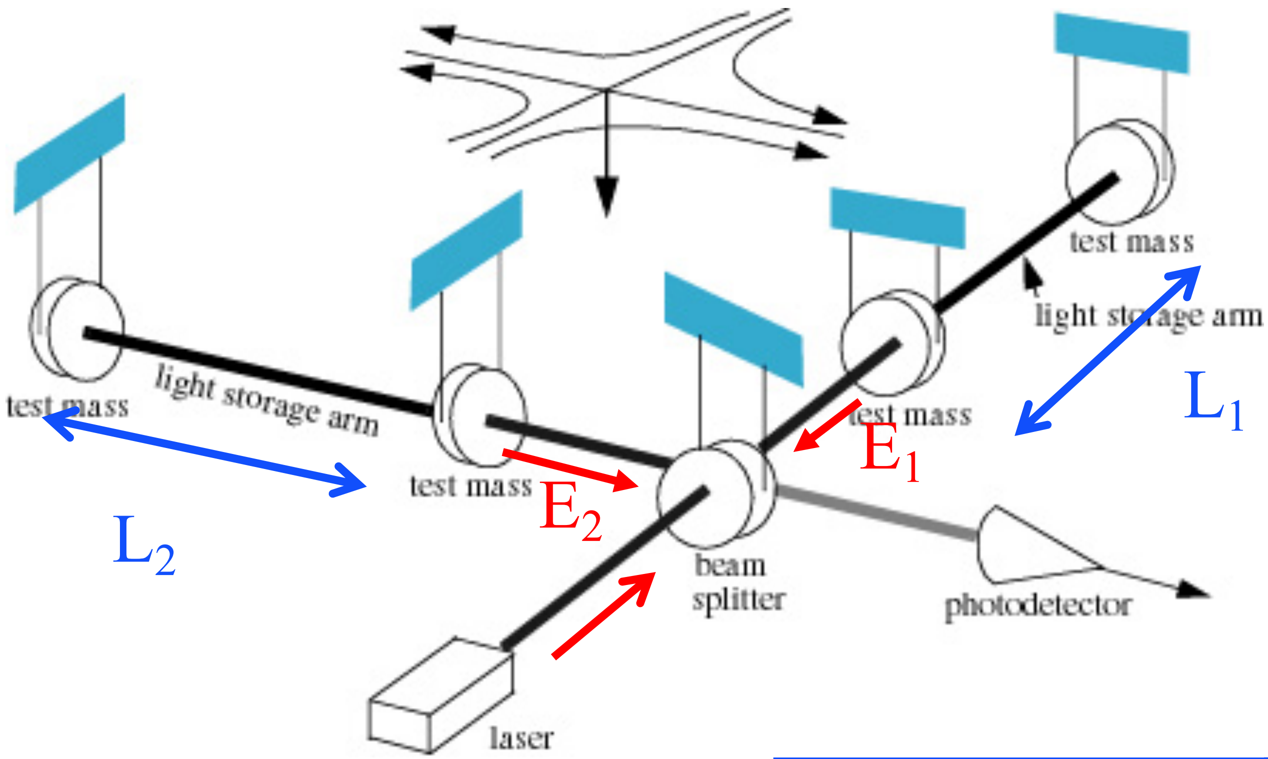


- Gravitational waves are propagating dynamic fluctuations in the curvature of space-time ('ripples' in space-time)
- Emissions from rapidly accelerating non-spherical mass distributions
  - Quadrupolar radiation





Interferometer for Gravitational Wave detection



2 mirrors in the arm effectively lengthen the arm by ~1000

$E_1 - E_2 \propto L_1 - L_2$

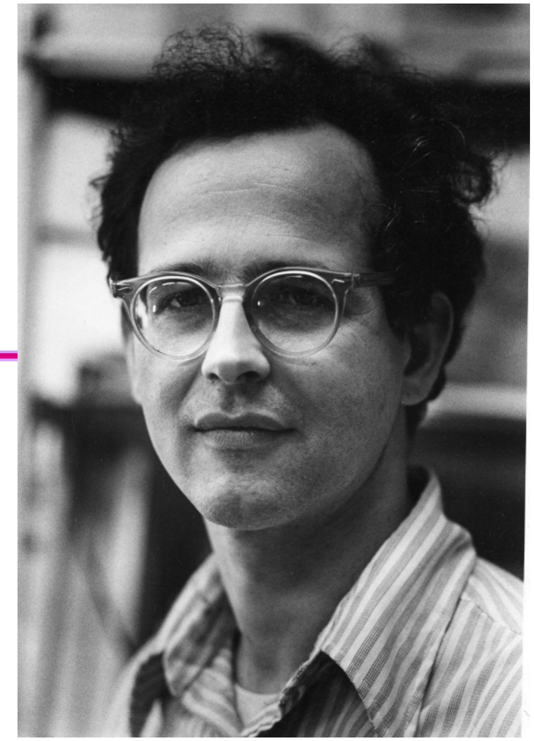
$$h = \frac{L_1 - L_2}{L_1 + L_2}$$

$h \sim 10^{-21}$

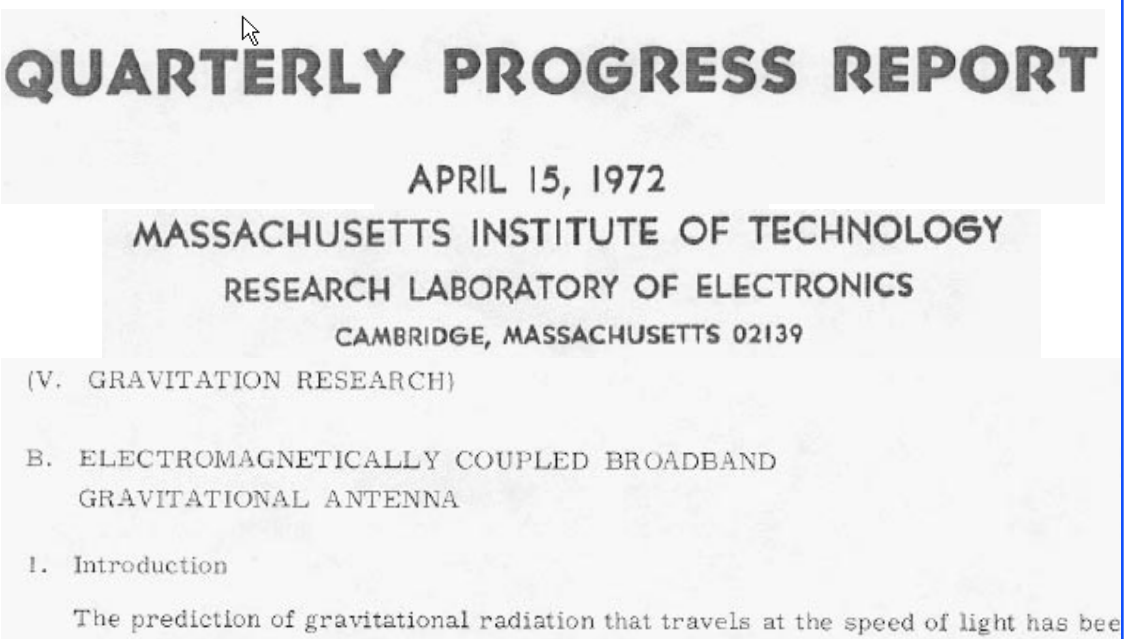
$L_1 - L_2 \sim 10^{-18}$m

From G1101133 by D.H.Shoemaker

In the beginning



- Rai Weiss of MIT was teaching a course on GR in the late '60s
- Wanted a good homework problem for the students
- Why not ask them to work out how to use laser interferometry to detect gravitational waves?
- …led to the instruction book we have been following ever since



QUARTERLY PROGRESS REPORT

APRIL 15, 1972

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RESEARCH LABORATORY OF ELECTRONICS

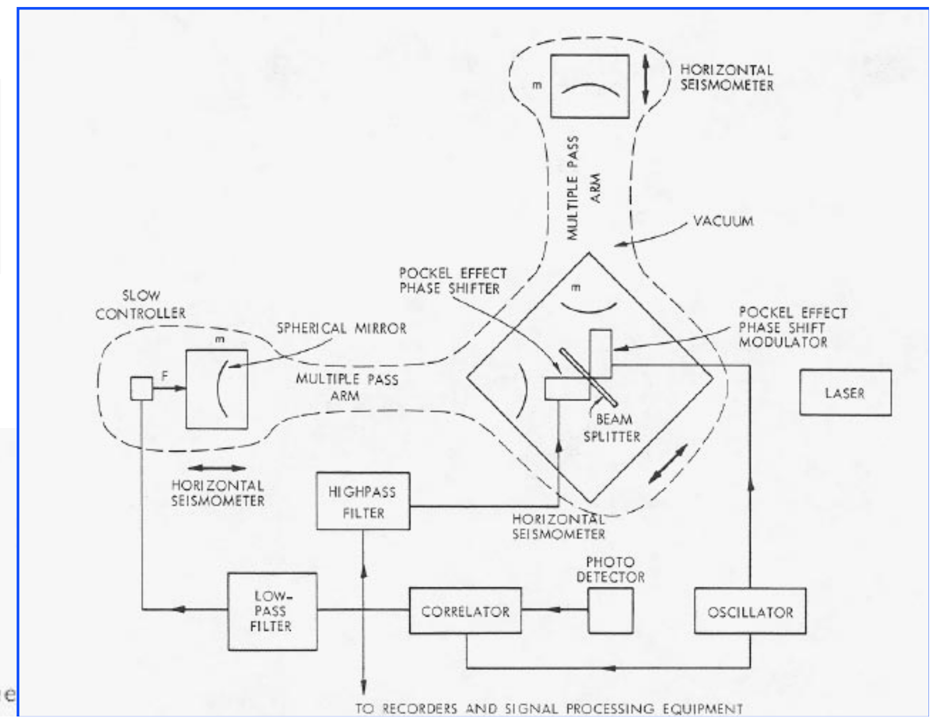
CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

The prediction of gravitational radiation that travels at the speed of light has bee



LIGO Chronology

idea to realization ~ 15 years

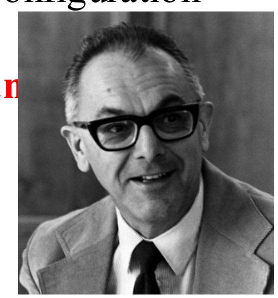

Drever

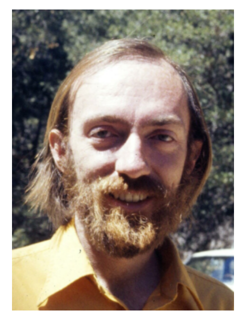

Weiss

Real size R&D for the real detection

Journey for the new astronomy

1970s		Feasibility studies and early work on laser interferometer gravitational-wave detectors
1979		National Science Foundation (NSF) funds Caltech and MIT for laser interferometer R&D
1984		Development of multiple pendulum Advanced LIGO Concept
1989	**December**	**Construction proposal for LIGO submitted to the NSF ($365M as of 2002)**
1990	May	National Science Board approves LIGO construction proposal
1994	July	Groundbreaking at Hanford site
1999		LIGO Scientific Collaboration White Paper on a Advanced LIGO interferometer concept
2000	October	Achieved "first lock" on Hanford 2-km interferometer in power-recycled configuration
2002	August	First scientific operation of all three interferometers in S1 run
2003		**Proposal for Advanced LIGO to the NSF ($205 NSF + $30 UK+German**
2004	October	Approval by NSB of Advanced LIGO
2005	**November**	**Start of initial LIGO Science run, S5, with design sensitivity**
2008	April	Advanced LIGO Project start
2009	July	Science run ("S6") starts with enhanced initial detectors
2014	May	Advanced LIGO Livingston first two-hour lock
2015	March	Advanced LIGO all interferometers accepted
2015	September	Advanced LIGO observation run 1 scheduled


Vogt


Thorn


Executive producer & consultant of movie "Intersteller"

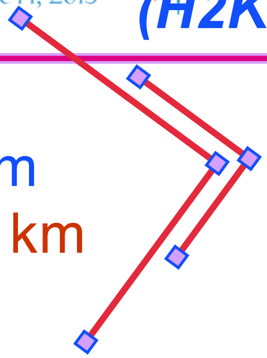
Initial LIGO events

Advanced LIGO events

R&D of aLIGO using iLIGO facility

LIGO sites

Hanford Observatory (H2K and H4K)



Hanford, WA (LHO)

- located on DOE reservation
- treeless, semi-arid high desert
- 25 km from Richland, WA
- **iLIGO : H2K and H4K ⇒**
  aLIGO : 4k LHO + 4k LIGO-India

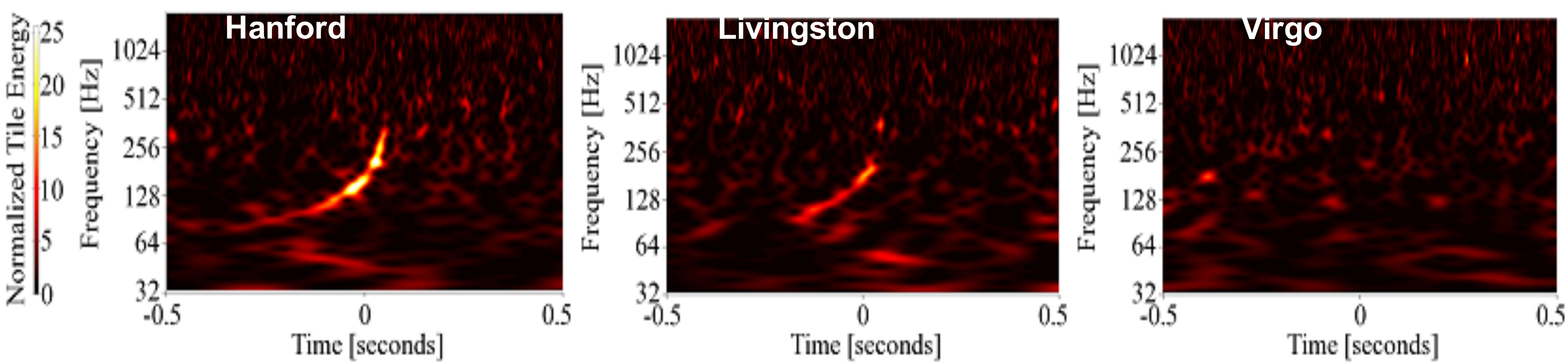
Livingston Observatory (L4K)

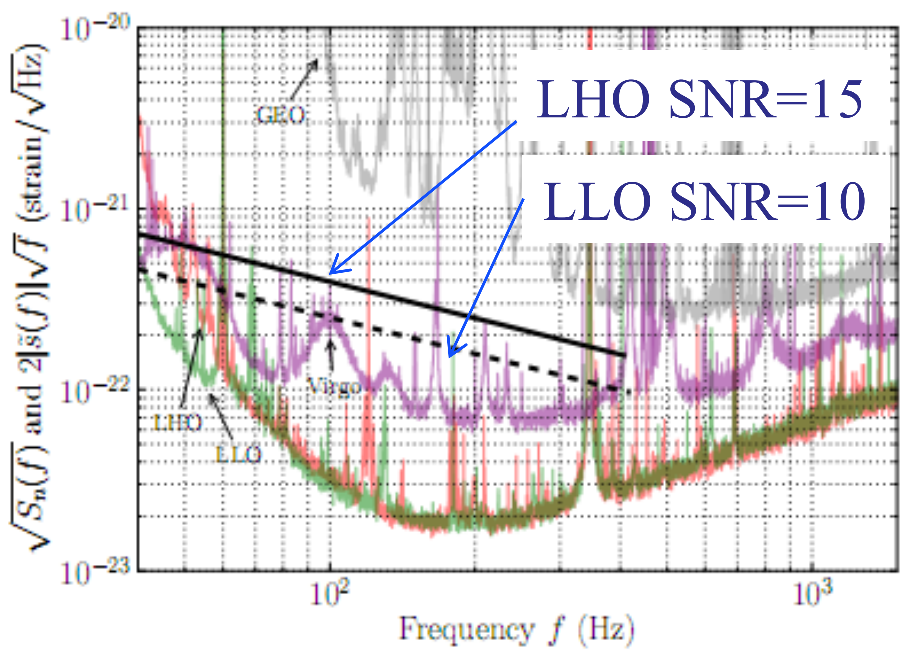
Livingston, LA (LLO)

- located in forested, rural area
- commercial logging, wet climate
- 50km from Baton Rouge, LA
- **One L4K IFO**

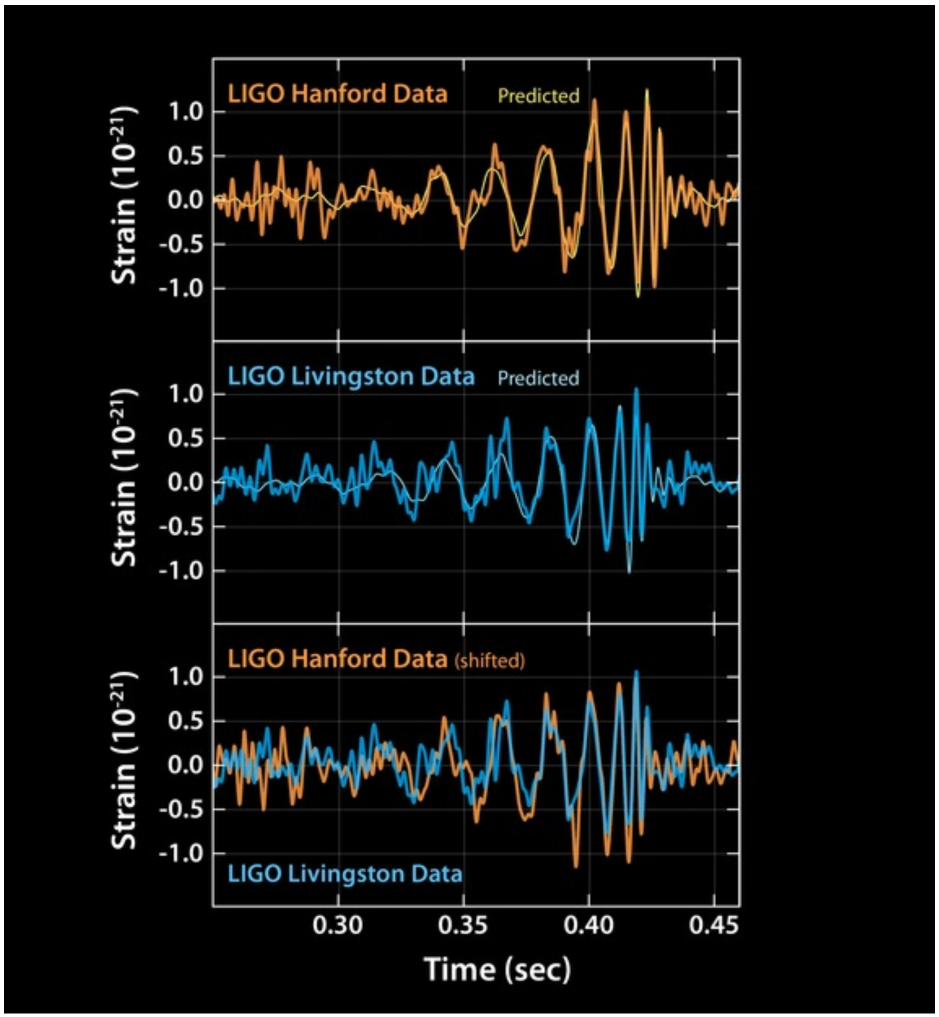
Event GW100916: blind injection

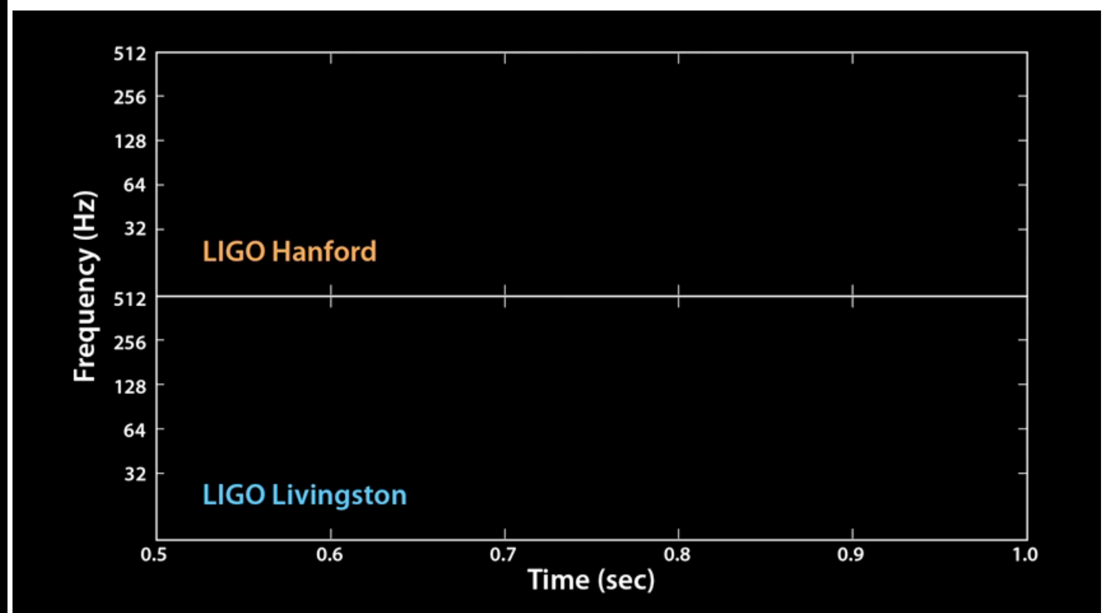
http://www.ligo.org/science/GW100916/





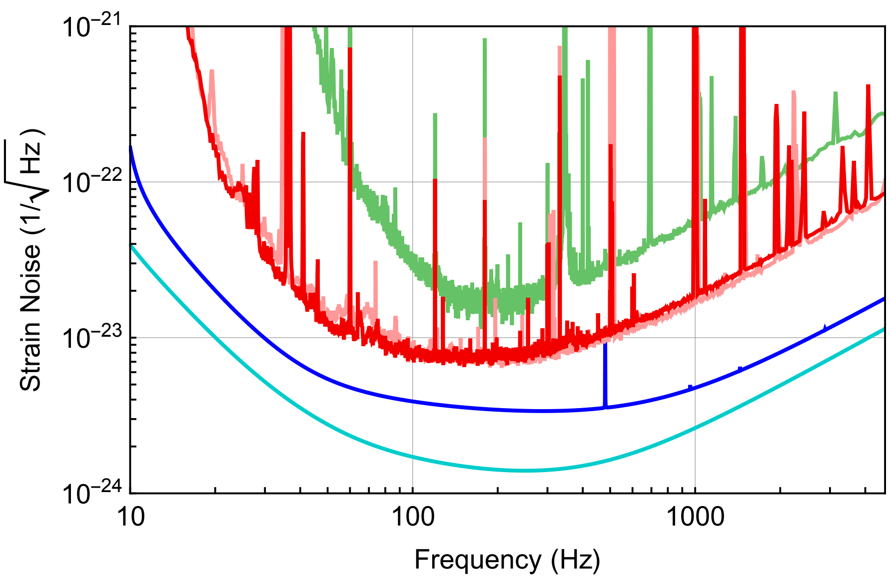
The Chirp of Two Black Holes Colliding : GW150914 REAL

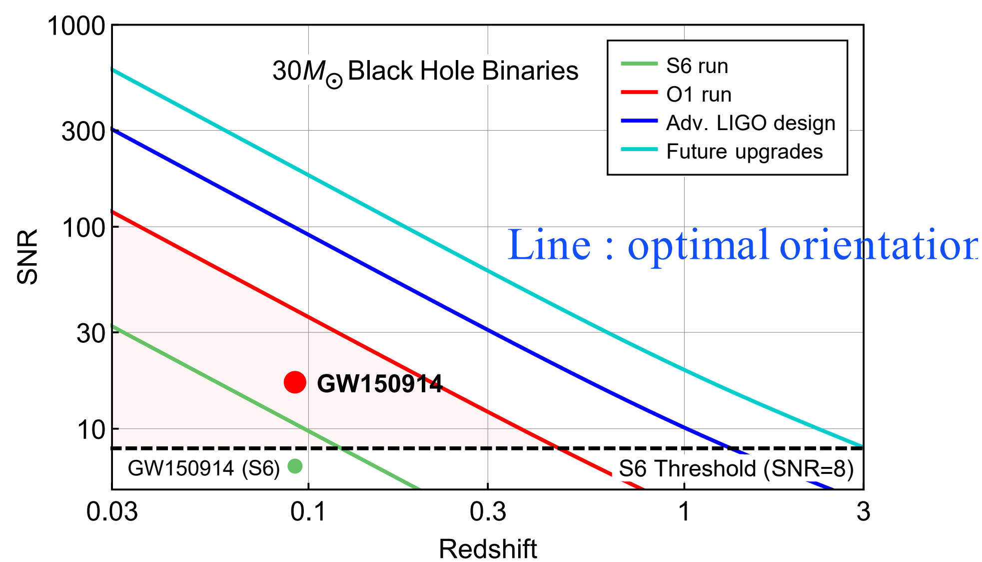




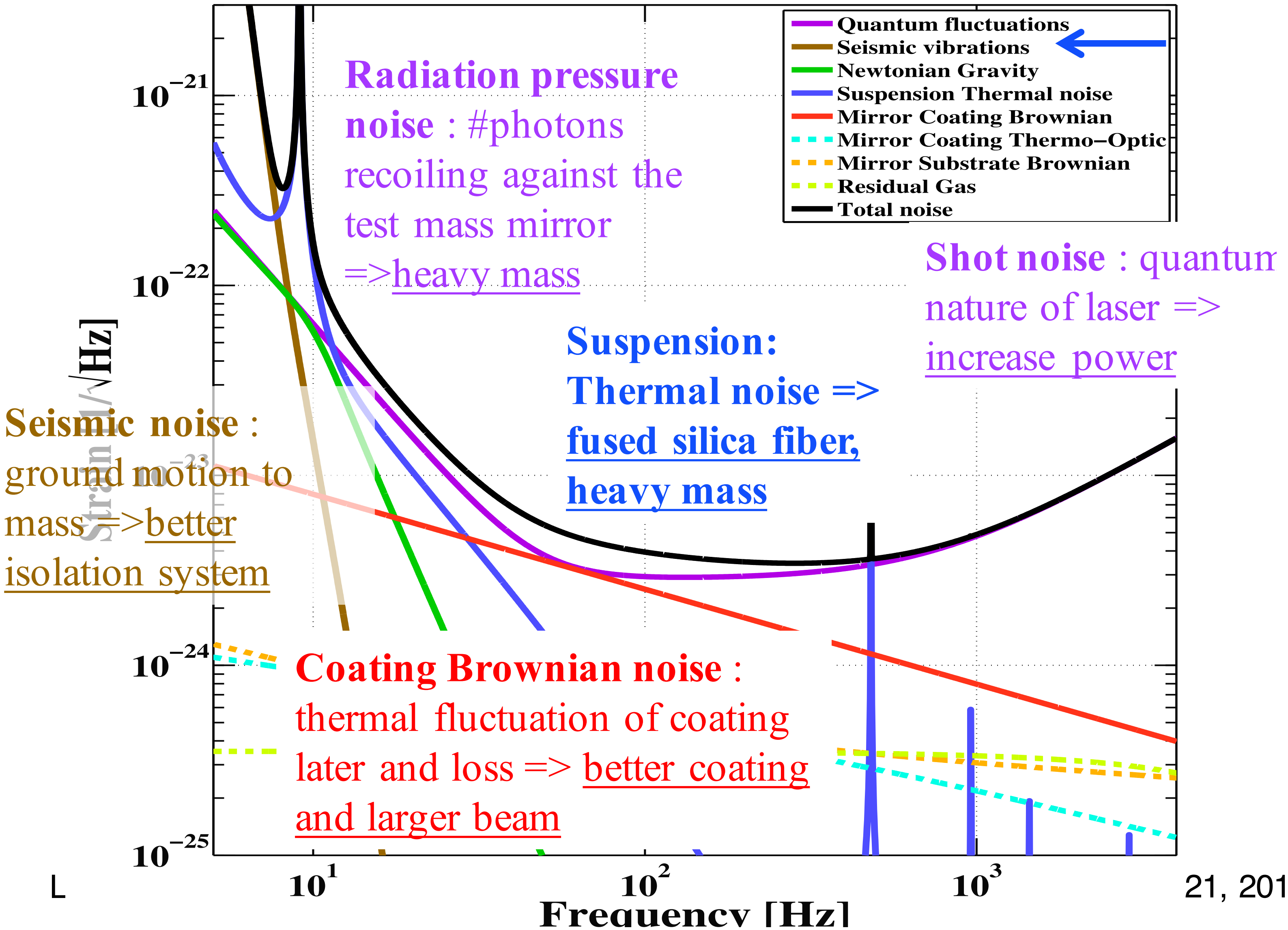
How could we see the signal
1) better sensitivity

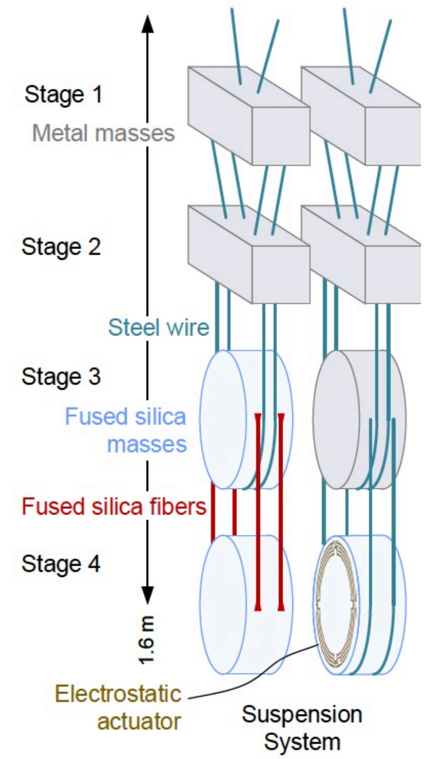
- September 12, 2015 ~ October 20, 2015 (January 12, 2016)
  - » H1:70%, L1:55%, H1+L1:48% => 16 days of data analyzed for data
- Around 100 Hz, h = 8 × 10–24 /√Hz.
- 30 M☉ black holes - 1.3Gpc = 4.1 x iLIGO, rate x70
- 1.4 M☉ neutron star - 70–80Mpc = 3.5 x iLIGO ≃70, rate x40



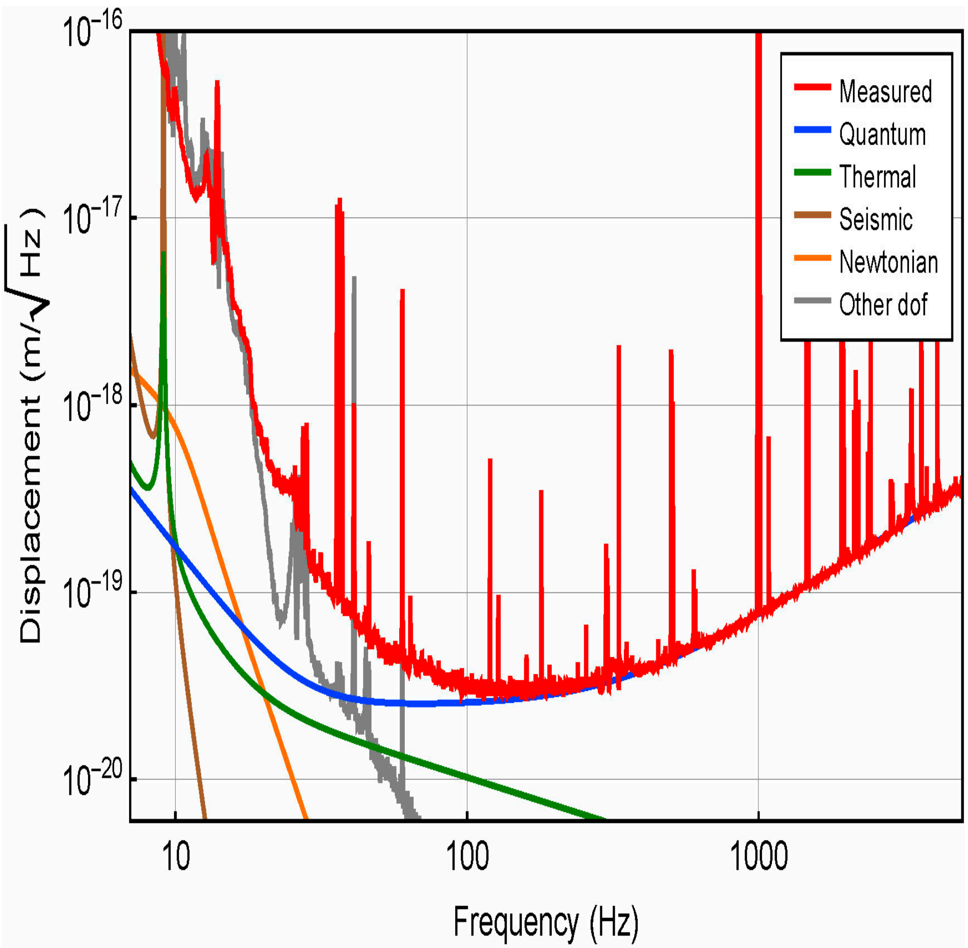


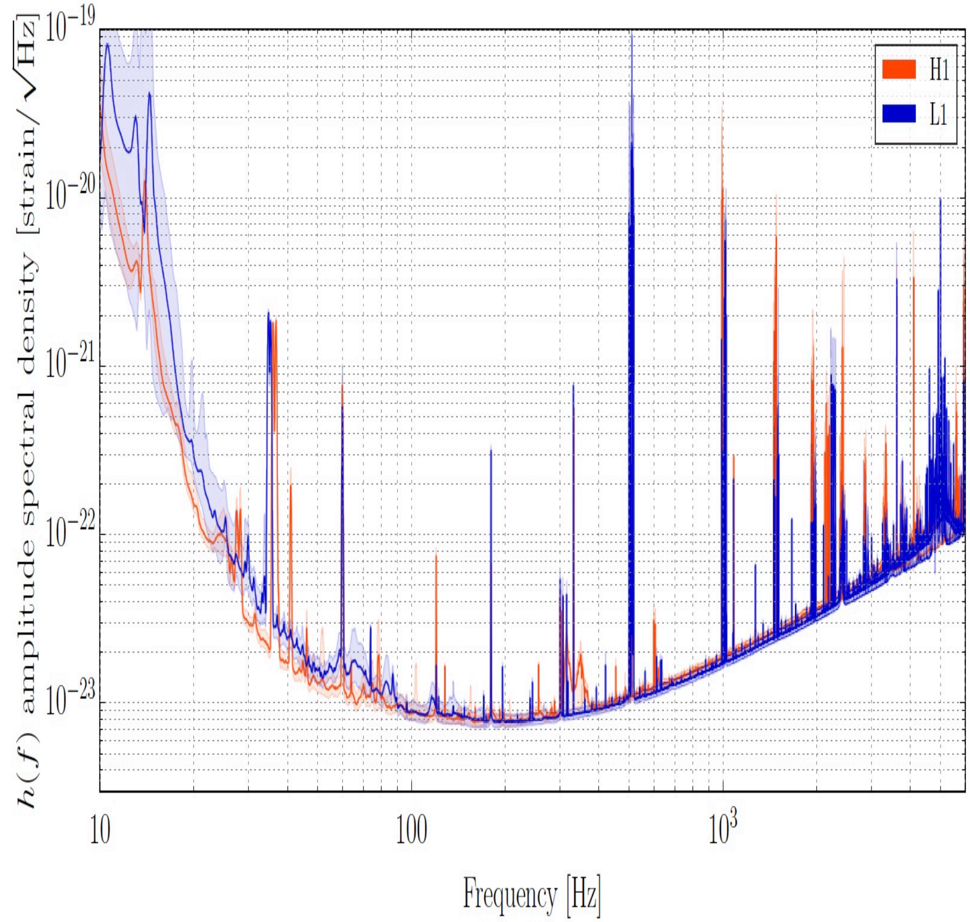
Fundamental Sensitivity Limits in Advanced LIGO



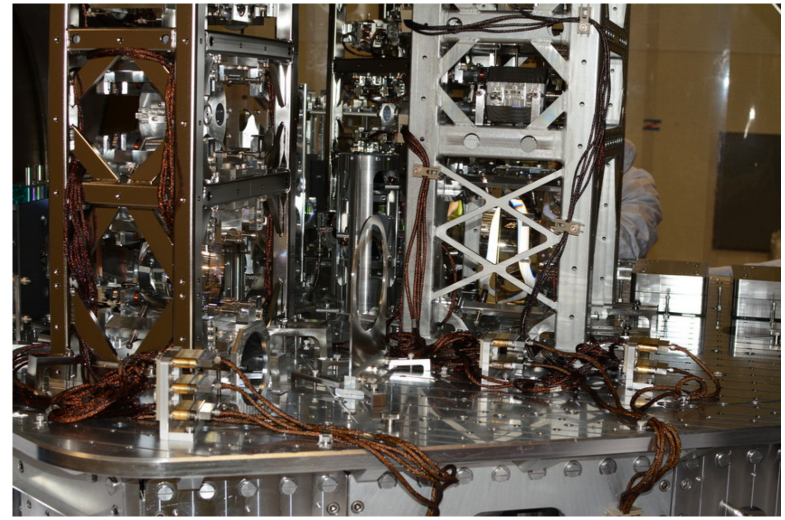


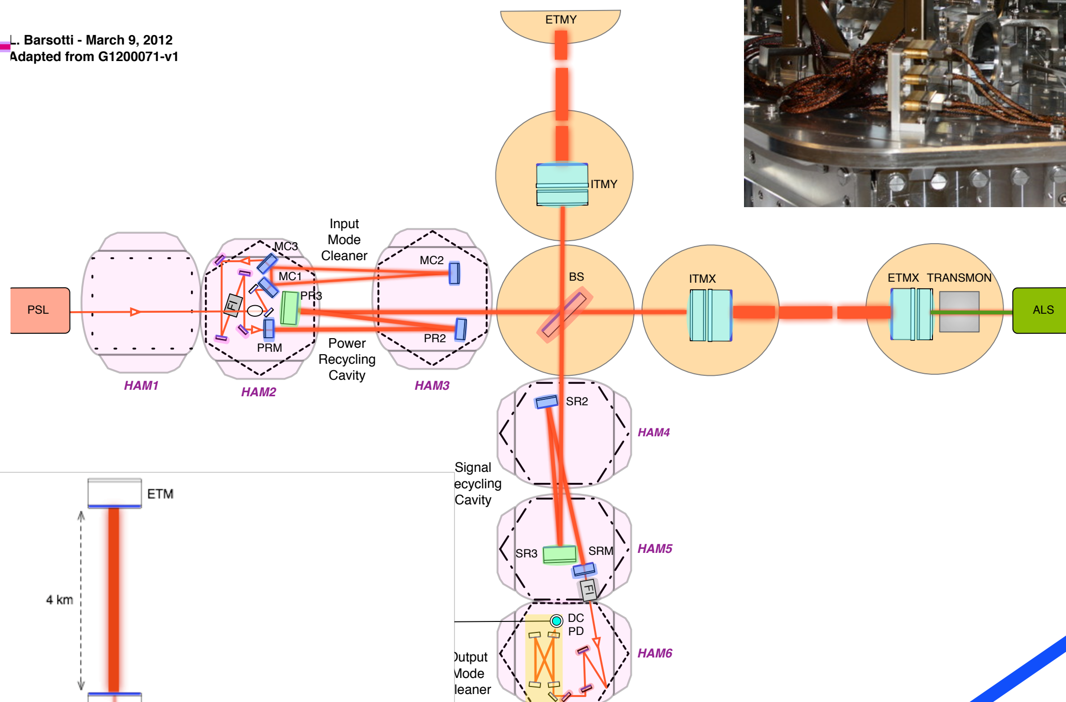
Sensitivities during O1

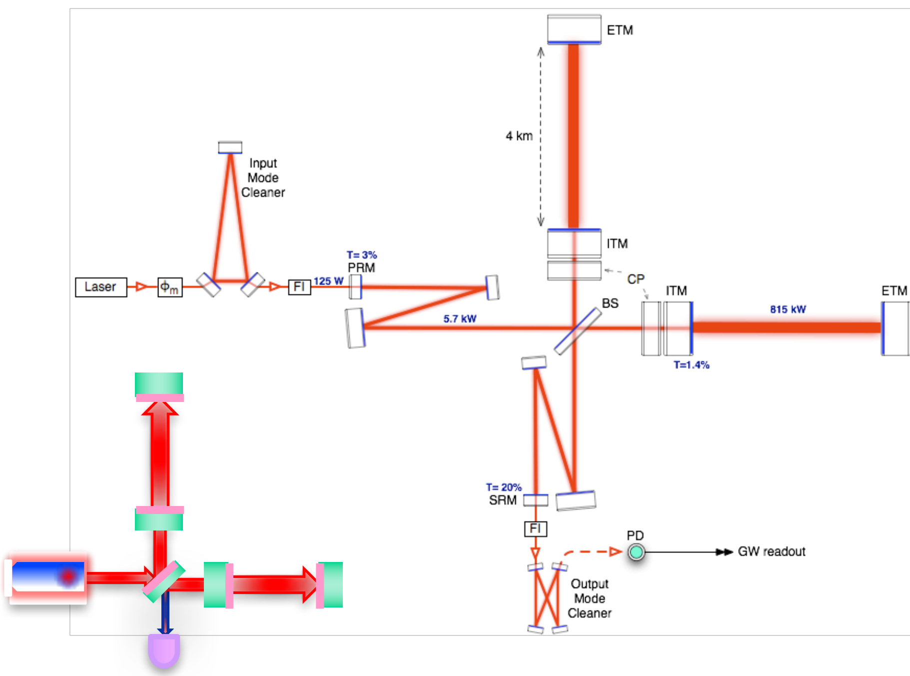




The real instrument is far more complex…

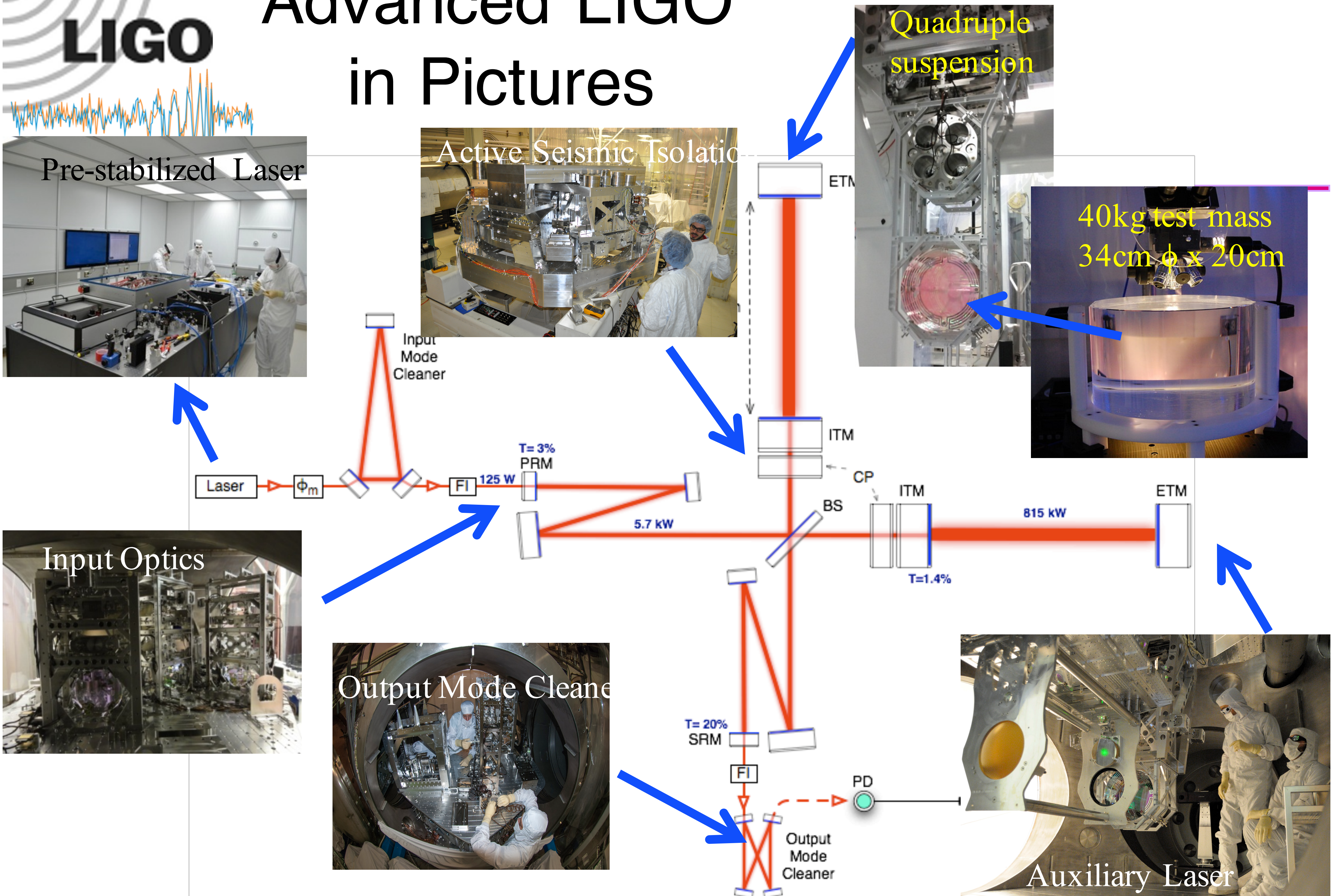






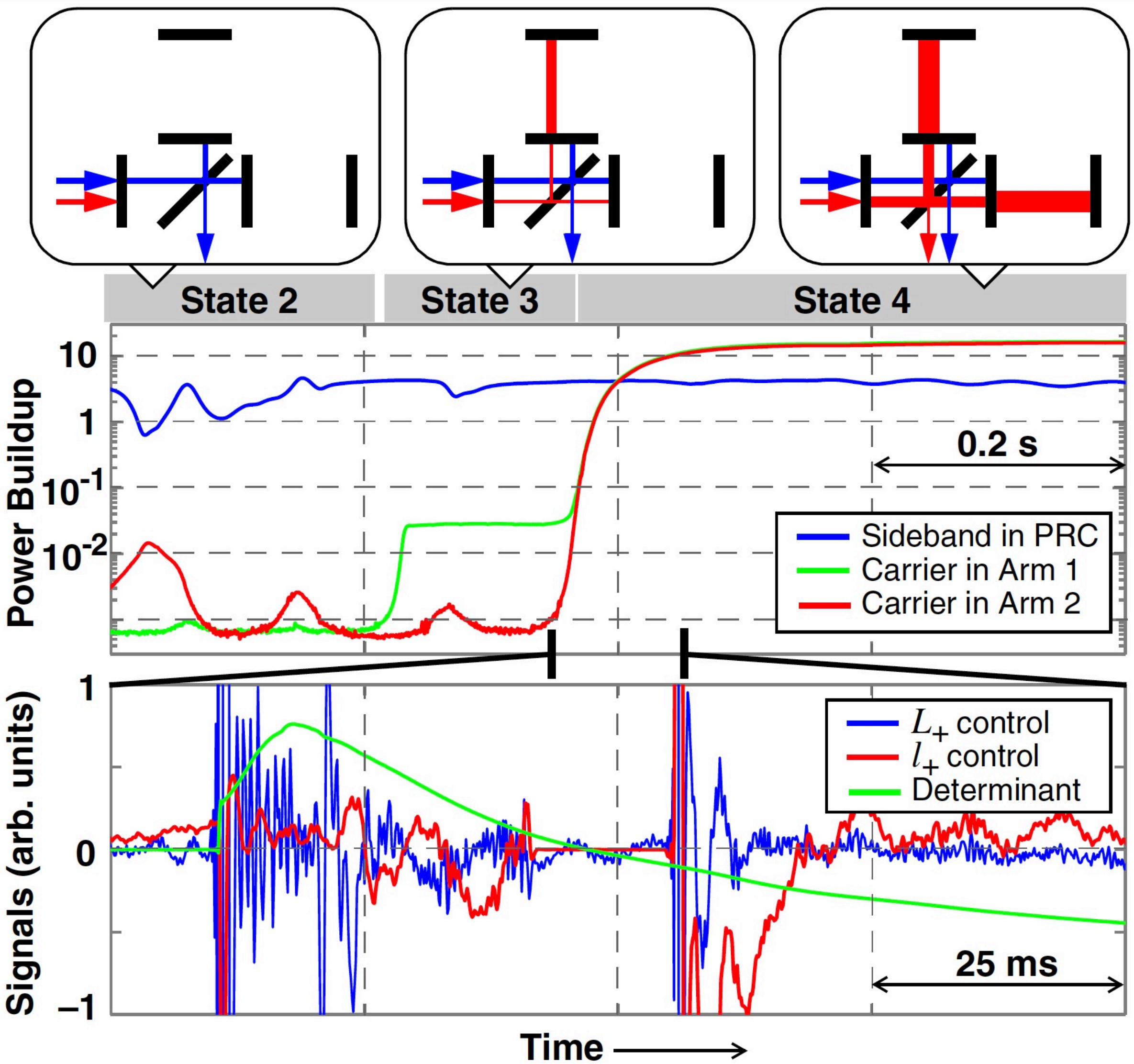
Reality axis

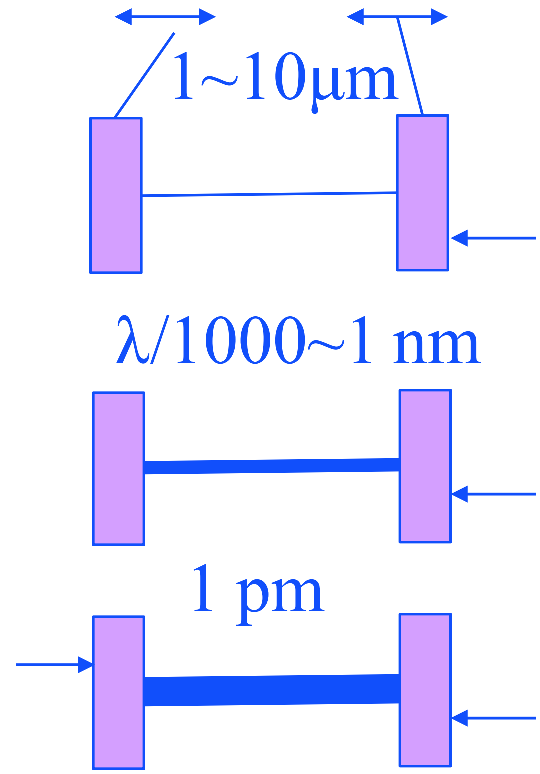
Advanced LIGO in Pictures



Lock acquisition
1µm to 1pm ala iLIGO

Optics Letters Vol. 27, **Issue 8**, pp. 598-600 (2002)

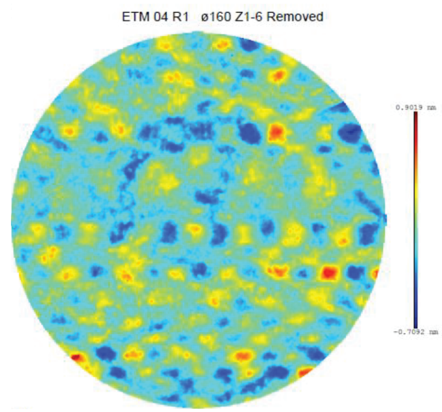




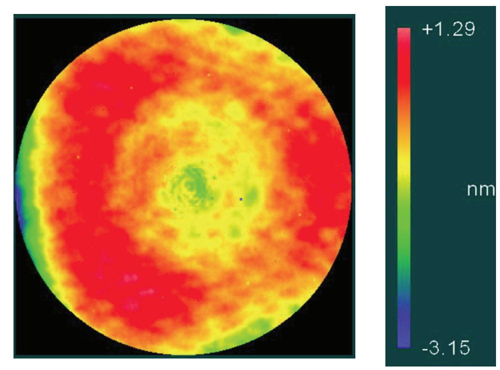
$L \times h = 10^{-18} = 1\ \mathrm{pm}/10^{6}$

Advanced LIGO optics

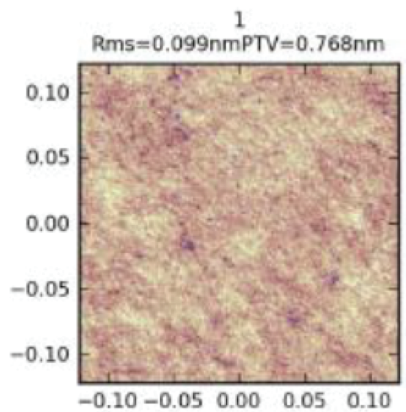
OplusE 1207 特集６
重力波観測用レーザー干渉計における光学設計



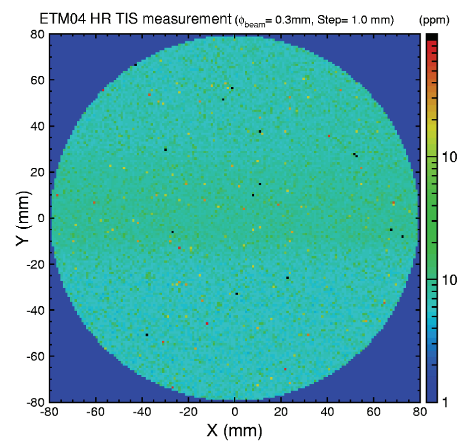
（１）Surface after polishing by ASML
Aperture size 160mm
RMS = 0.1732nm, PV=1.611nm



(2) Surface after multilayer coating by ison spattering
Aperture160mm
RMS = 0.563nm, PV=4.436nm

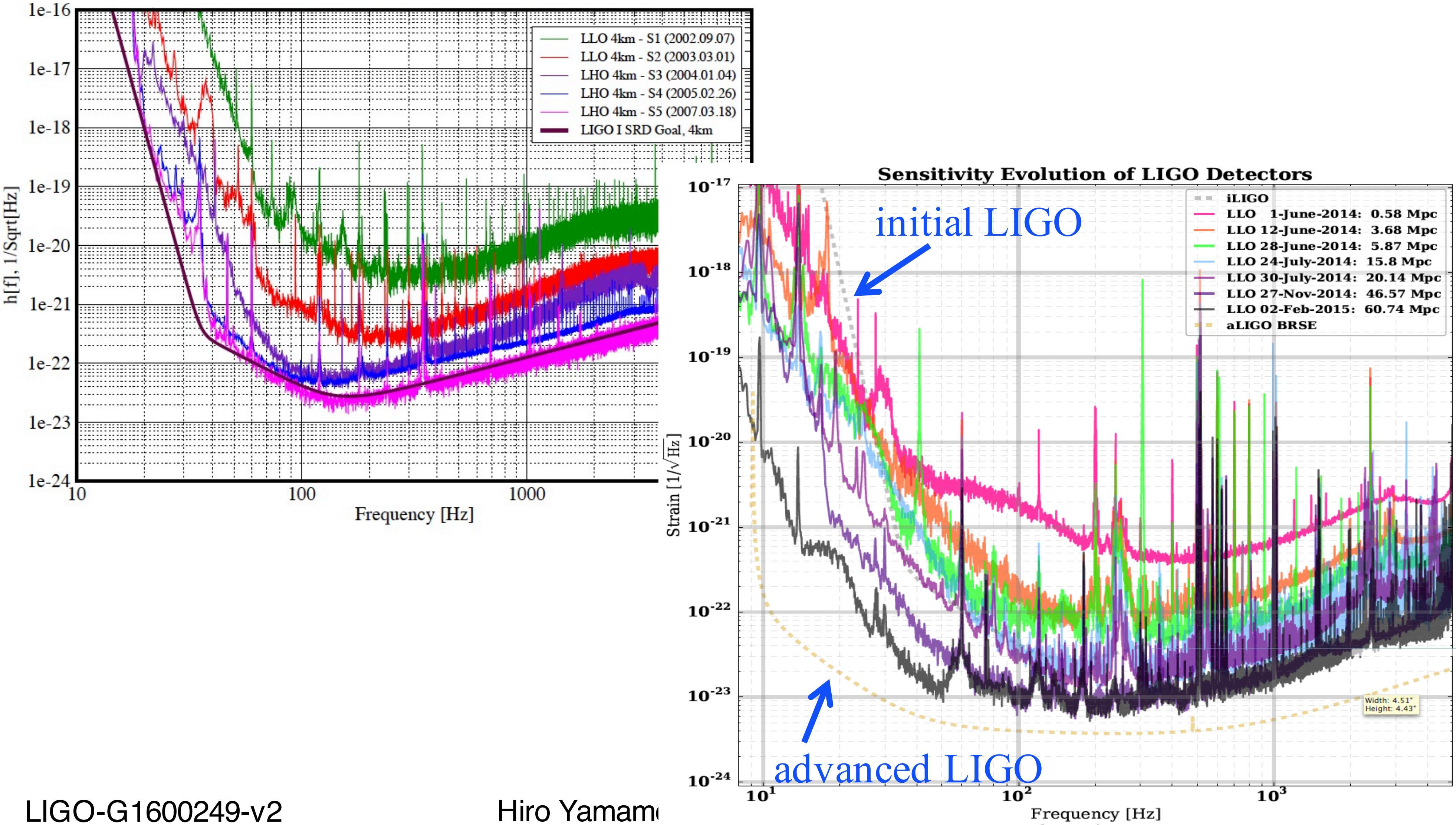


(3) Surface after polishing measured by PMM(phase measuring microscope) with magnification of 50.
0.25mm x 0.25mm square near center.
RMS = 0.099nm, PV=0.768nm.



(4) Reflectance measured by an integrating sphere with the scattering angle larger than 1°. The size of the laser is 0.3mm, with spacing 1mm.
RMS using all data points is 98ppm. RMS is 20ppm after excluding 15 points with reflectance > 1000ppm.

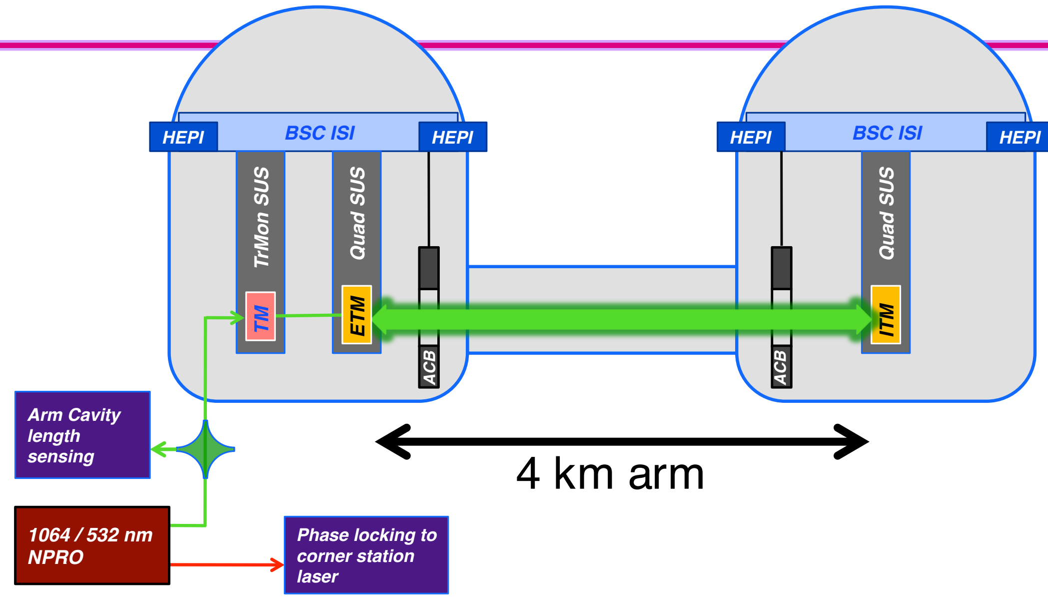
How could we see the signal
2) better understanding of IFO



G1400628-v3 by P. Fritschel

Speedier commissioning

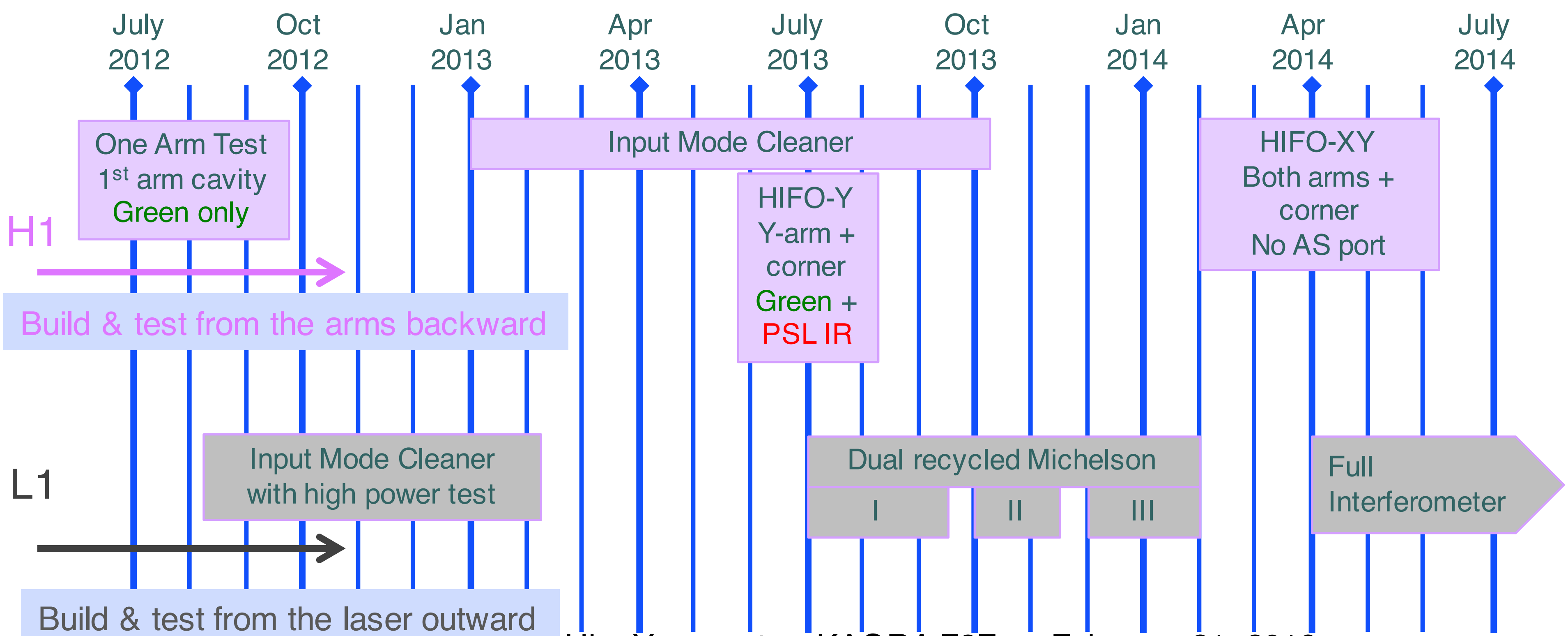
- Lock acquisition strategy designed in from the start, including a new Arm Length Stabilization system
  - Enables a controlled acquisition process



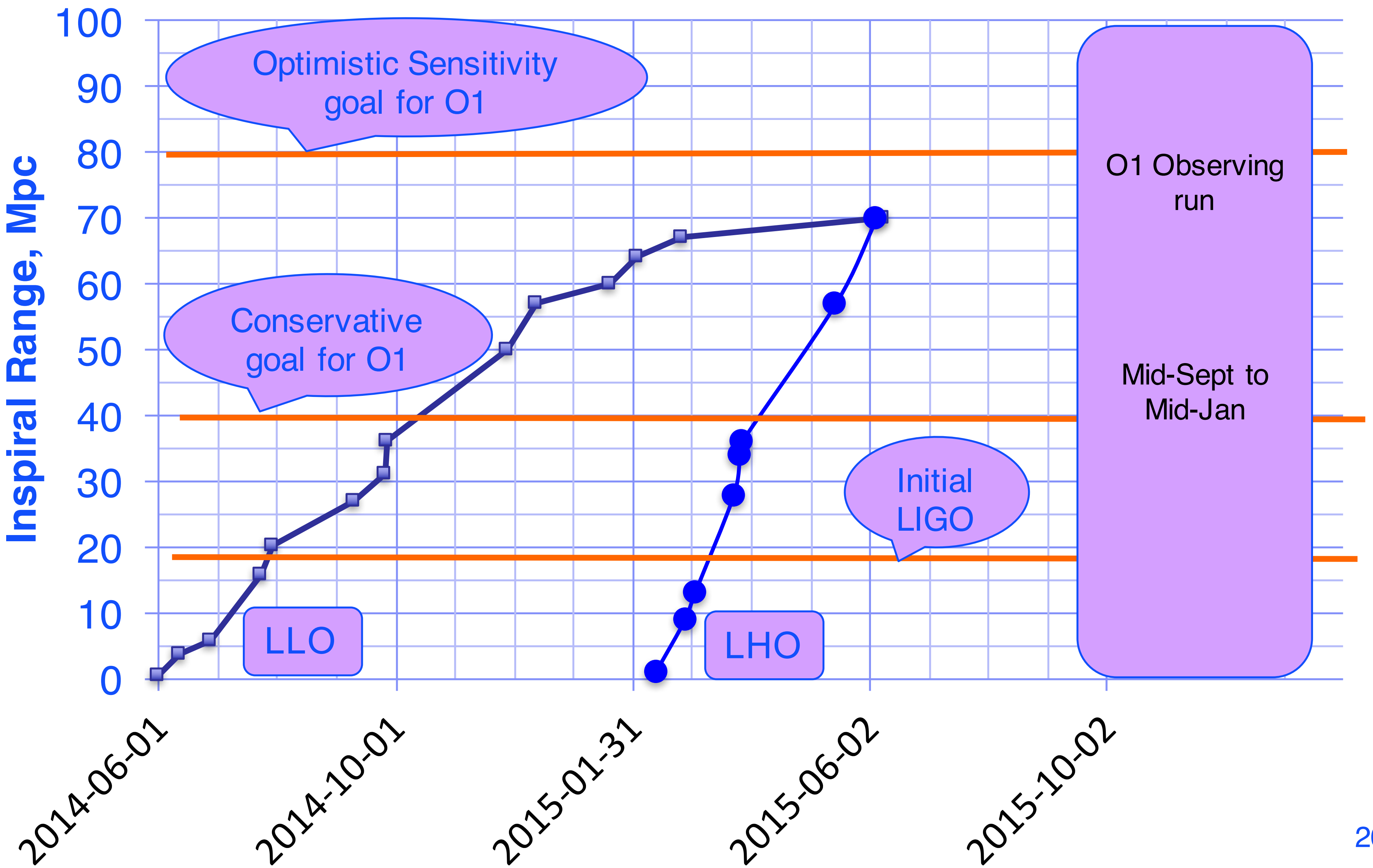
- *Better teams* on hand
  - More people and with more experience
  - Observatory staff, including operators, involved from the beginning
- *Better support structure* in place
  - Software tools in place
  - Online web tools in place
- Having been there before helps a lot!

Project Integrated Testing Plan

- Integrated testing phases interleaved with installation
- Complementary division between LHO and LLO
  - » Designed to address biggest areas of risk as soon as possible
  - » H1 focused on long arm cavities; L1 worked outward from the vertex



Commissioning progress

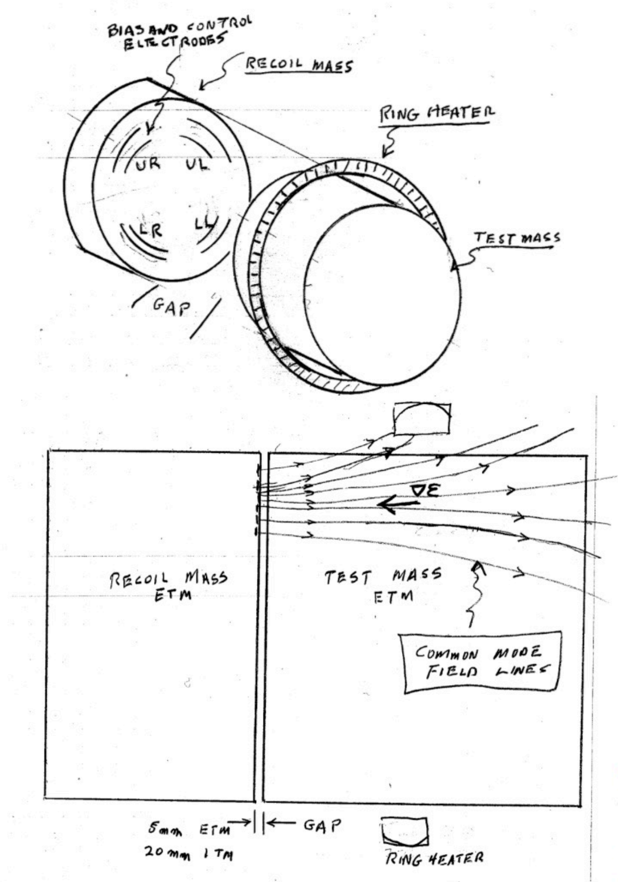


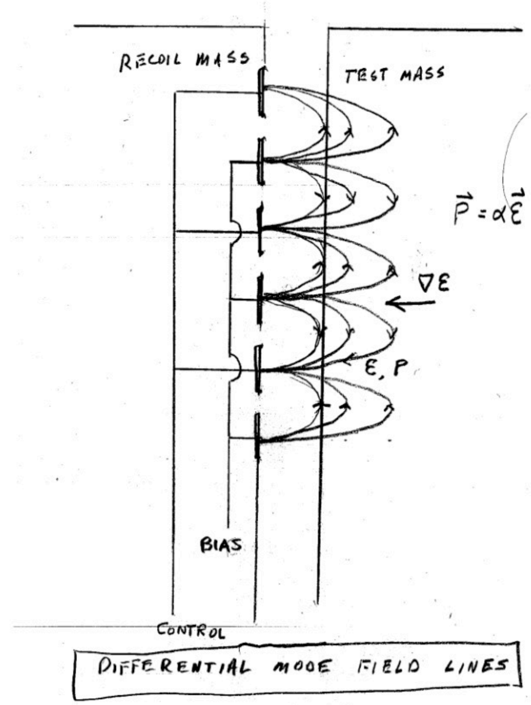
Improving sensitivity

- Near term upgrade
  - » So far so good – based on past experience
    - – More challenges waiting
  - » Thermal compensation
  - » Parametric instability – mirror vibration couples to field mode excitation
  - » Gas dumping
  - » Charge fluctuation in mass
  - » Low frequency unknown noise
  - » O2 starts in July 2016, ~100Mpc-120Mpc
- Long term upgrade
  - » Waiting for third IFO to be joined
  - » Voyager – use LIGO facility, cryogenic, Silicon, 2μ laser
  - » Cosmic Explorer – new facility, very long arm

Three major issues
(1) Charging

Basics





$$\vec{F} = \iiint \nabla(\vec{P}\cdot\vec{E})dv + \iiint \rho\vec{E}\,dv$$

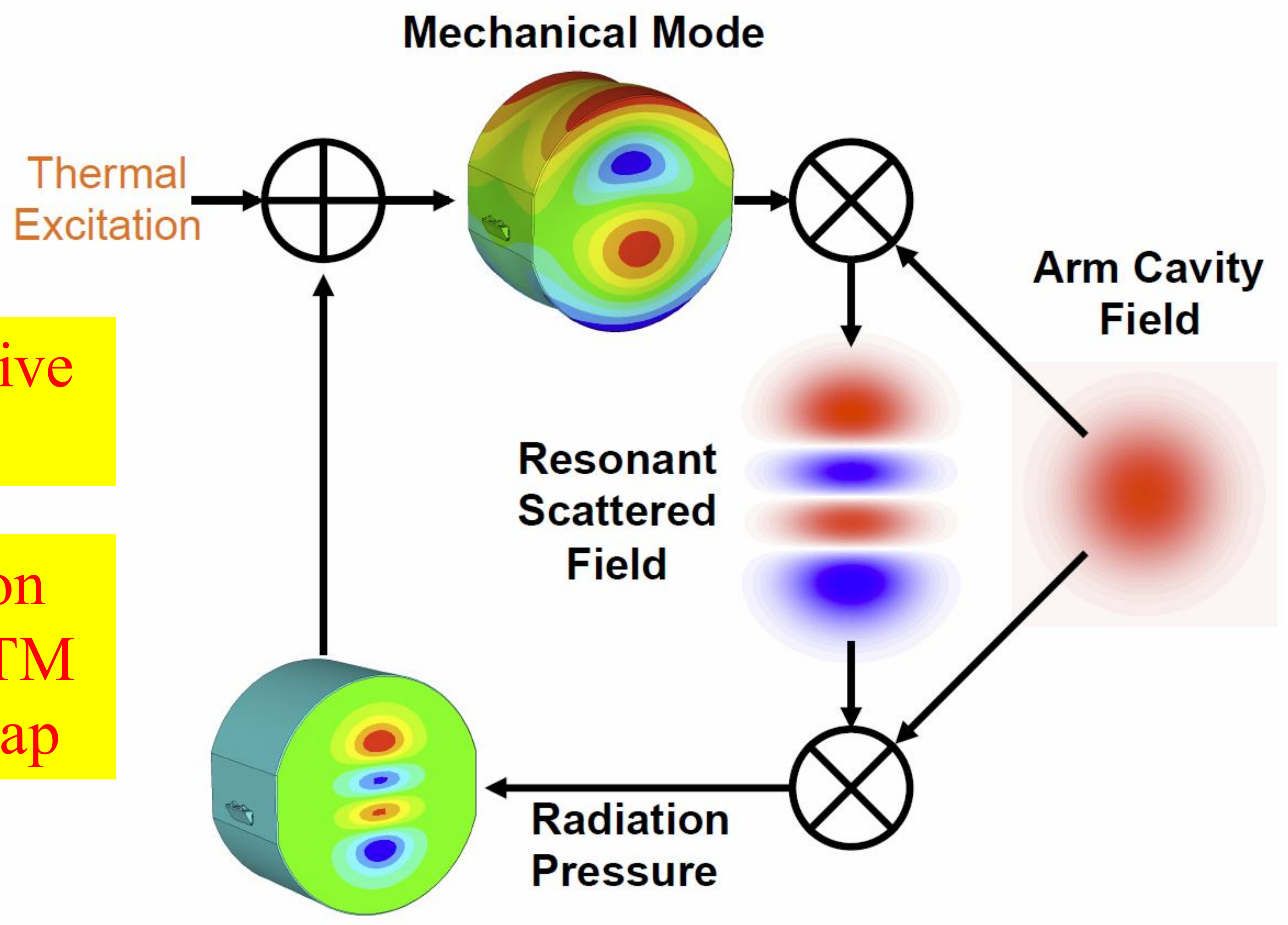
$$\nabla(\vec{P}\cdot\vec{E}) = (\vec{P}\cdot\nabla)\vec{E} + (\vec{E}\cdot\nabla)\vec{P} + \vec{E}\times(\nabla\times\vec{P}) + \vec{P}\times(\nabla\times\vec{E})$$

$P_i = \alpha_{ij}E_j$ Limit of isotropic material $\vec{P} = \alpha\vec{E}$

$\vec{E}_{total} = \vec{E}_{esd} + \vec{E}_{ambient}$ $F_{esd} = a(V_{bias} - V_{control})^2 + b(V_{bias} + V_{control})^2 + c(V_{bias} + V_{control})$

$$b/a \sim 1/3$$

Three major issues
(2) Parametric Instabilities



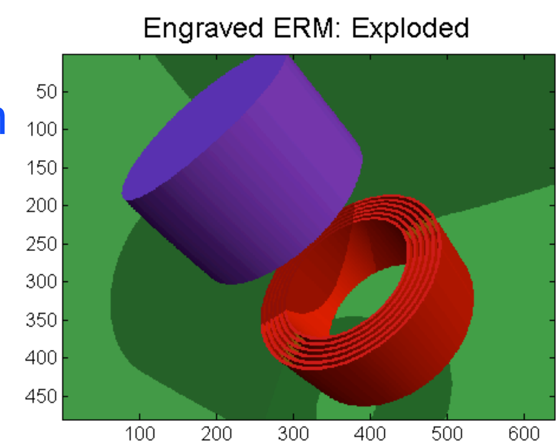
Passive and active dumping

High voltage on ETD to drive ITM with a 1.5cm gap

Evans et al., Phys. Rev. Lett. 114, 161102 (2015)

Three major issues
(3) Squeeze film damping

- Small gap (5 mm) between ETM and its reaction mass increased damping from residual gas
  - » Current poor vacuum level at LLO end station means this is a significant thermal noise term below ~60 Hz
  - » At expected vacuum level, squeeze film damping noise will compete with radiation pressure noise at full power
- Beyond lower vacuum, the solution is a new, annular reaction mass (hole in the middle)
  - » Provides same amount of electro-static drive actuation
  - » Reduces damping force by a factor of 2.5x
  - » Working towards possible retrofit in early 2016



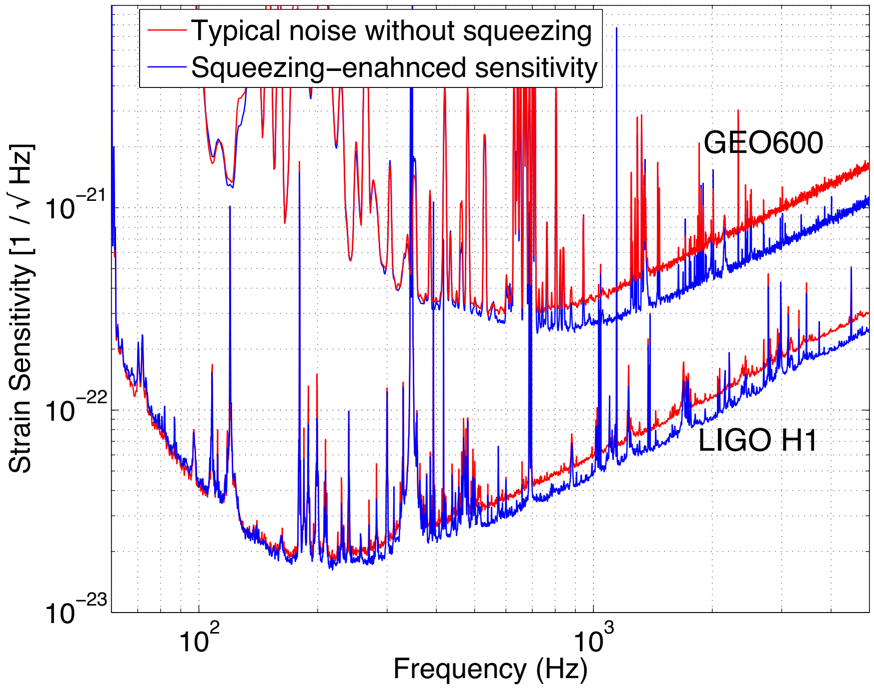
Squeezed Light in LIGO

suppressing quantum noise without increasing power

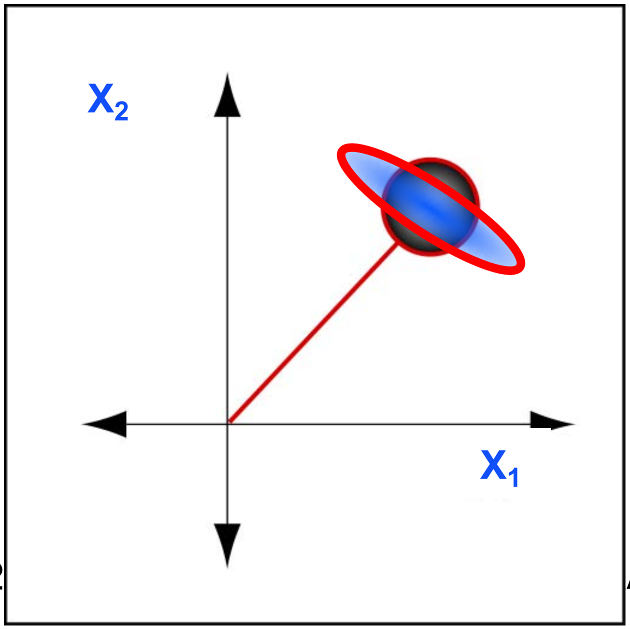
- Heisenberg Uncertainty Principle

$$\langle(\Delta\hat{X}_1)^2\rangle\,\langle(\Delta\hat{X}_2)^2\rangle \geq 1$$

- Squeezed state
  - Reduce noise in one quadrature at the expense of the other
  - Shot noise - phase, radiation pressure - amplitude

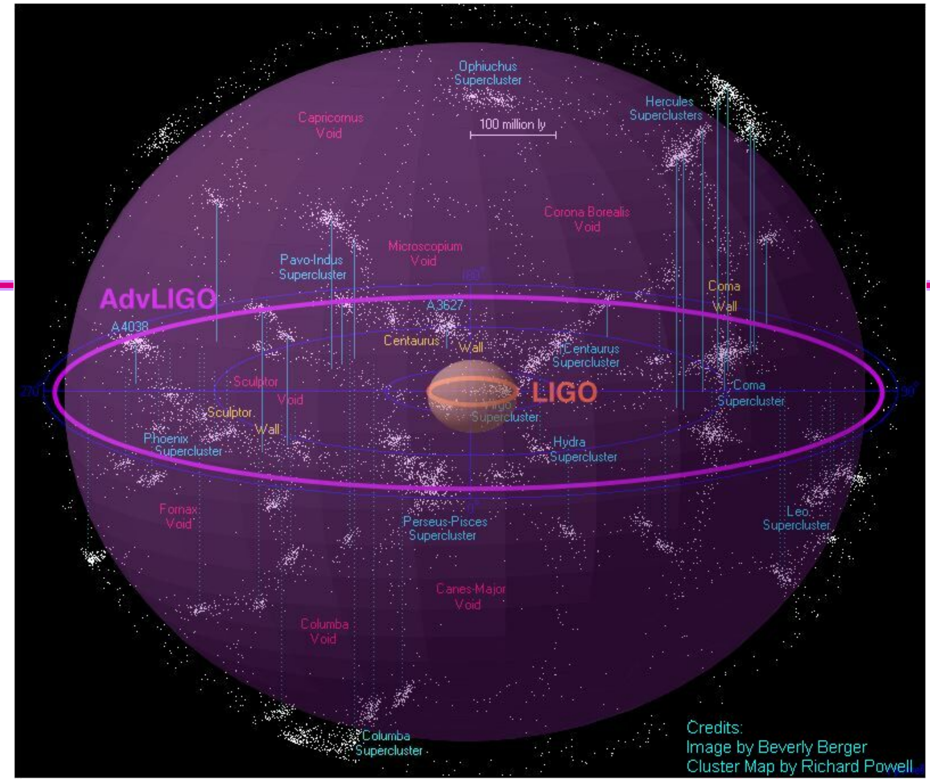


X_1 and X_2 associated with amplitude and phase



Aasi, et al., (LIGO Scientific Collaboration), Nature Physics, 7, 962 (2011); Nature Photonics 7 613 (2013).

Advanced LIGO ~ event rates



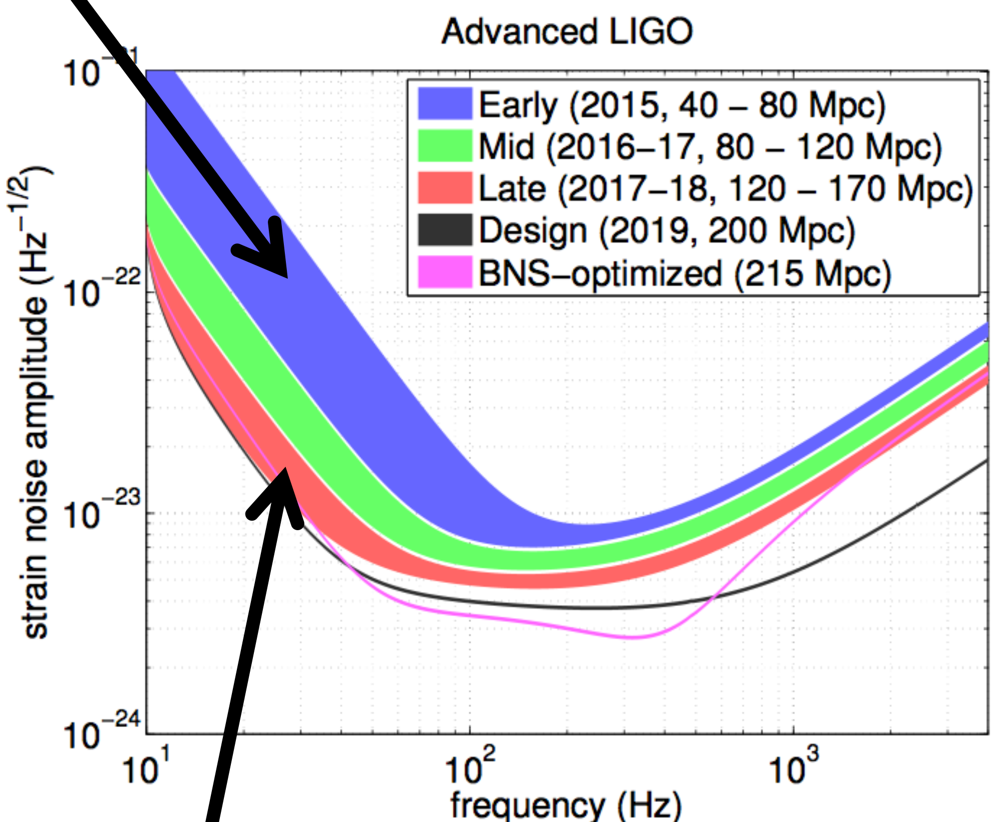
#events by advanced LIGO ~
1000 x #events by initial LIGO

Assumes NS-NS rate between 10^{-8} $Mpc^{-3}yr^{-1}$ and 10^{-5} $Mpc^{-3}yr^{-1}$

Observation run	Epoch	Estimated Run Duration	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections
1	2015	3 months	40 – 80	–	0.0004 – 3
2	2016–17	6 months	80 – 120	20 – 60	0.006 – 20
3	2017–18	9 months	120 – 170	60 – 85	0.04 – 100
	2019+	(per year)	200	65 – 130	0.2 – 200
	2022+ (India)	(per year)	200	130	0.4 – 400

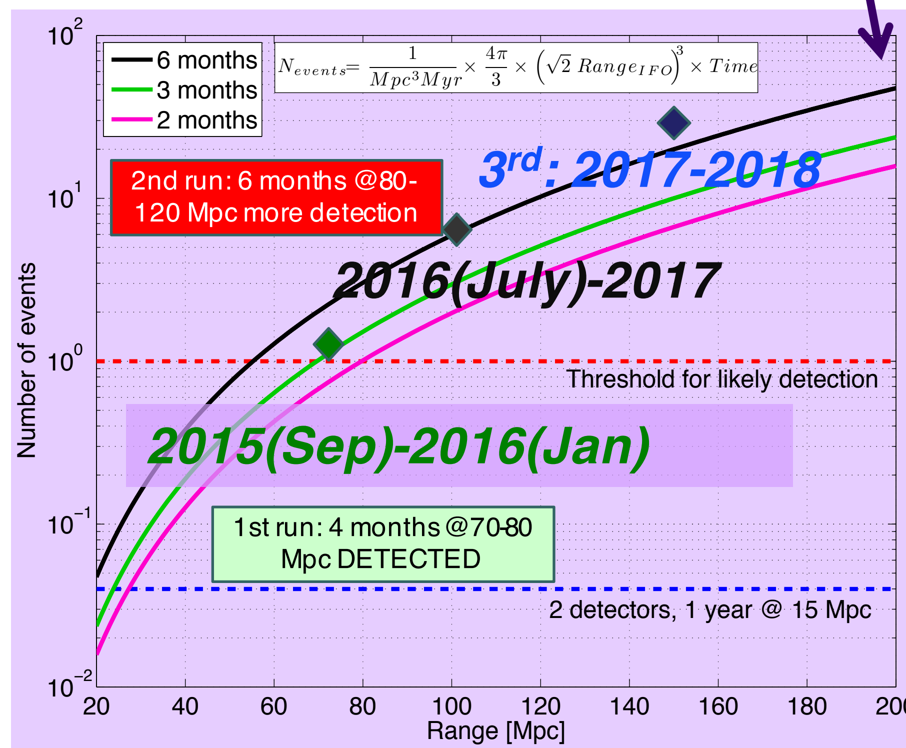
Planning for Advanced LIGO Science

Detected

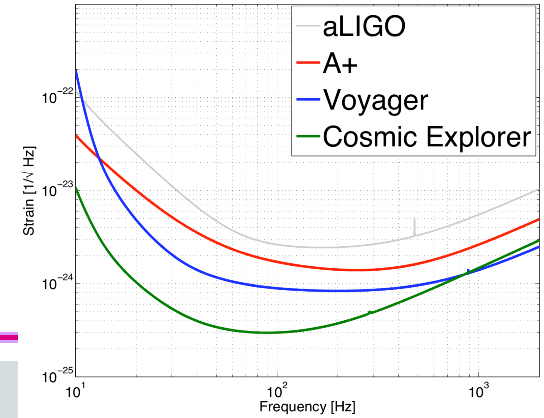


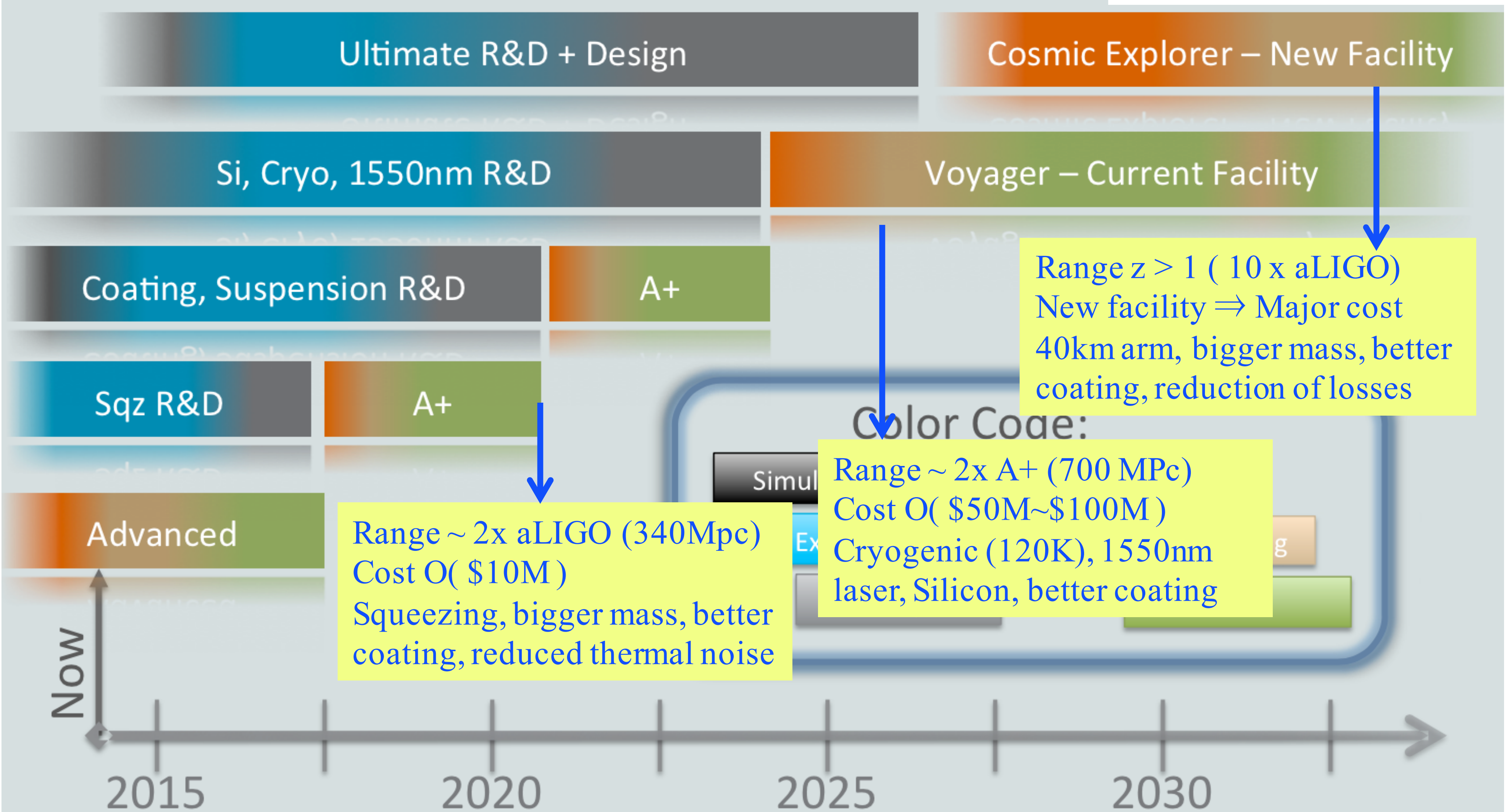
Astronomy

Full sensitivity (200 Mpc): end-2018

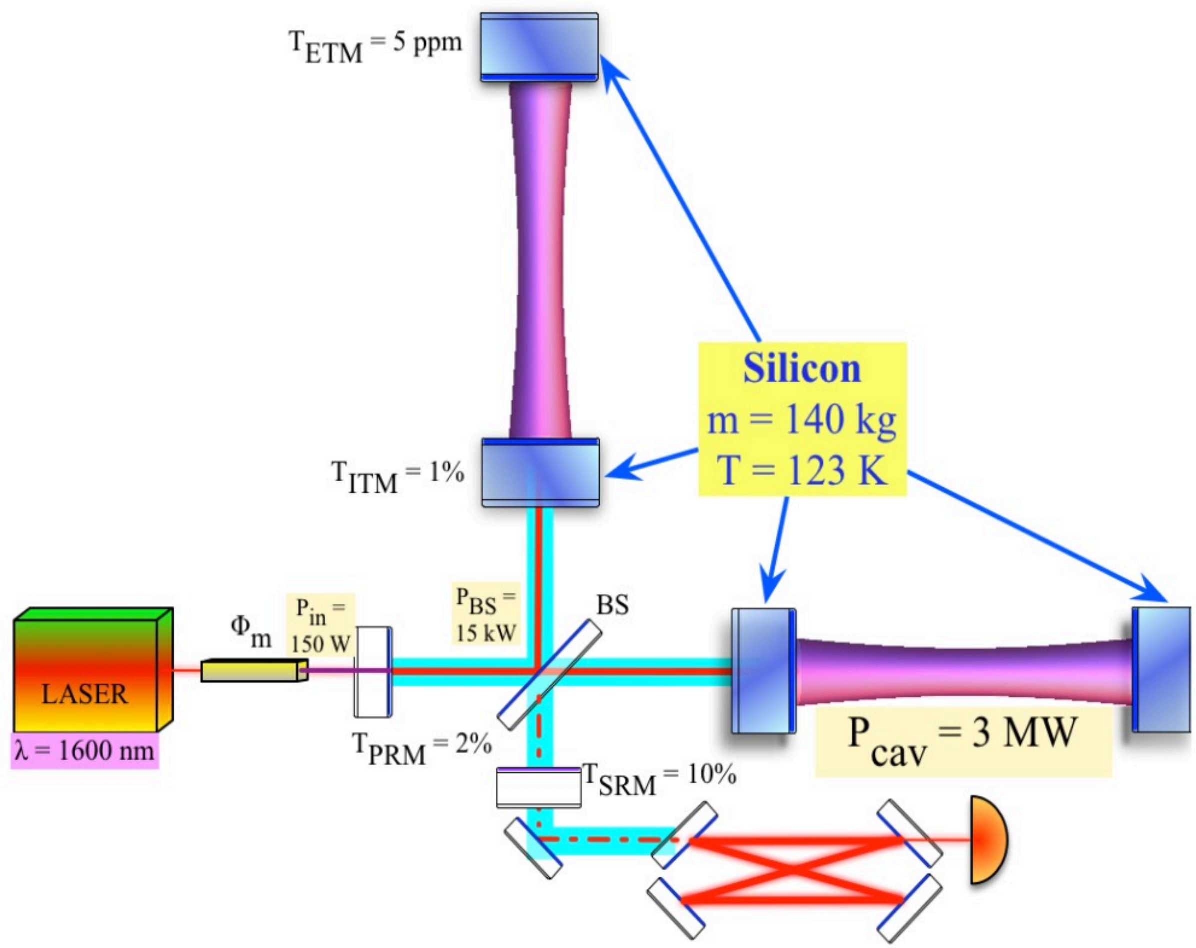


Aiming for the future
beyond advanced LIGO





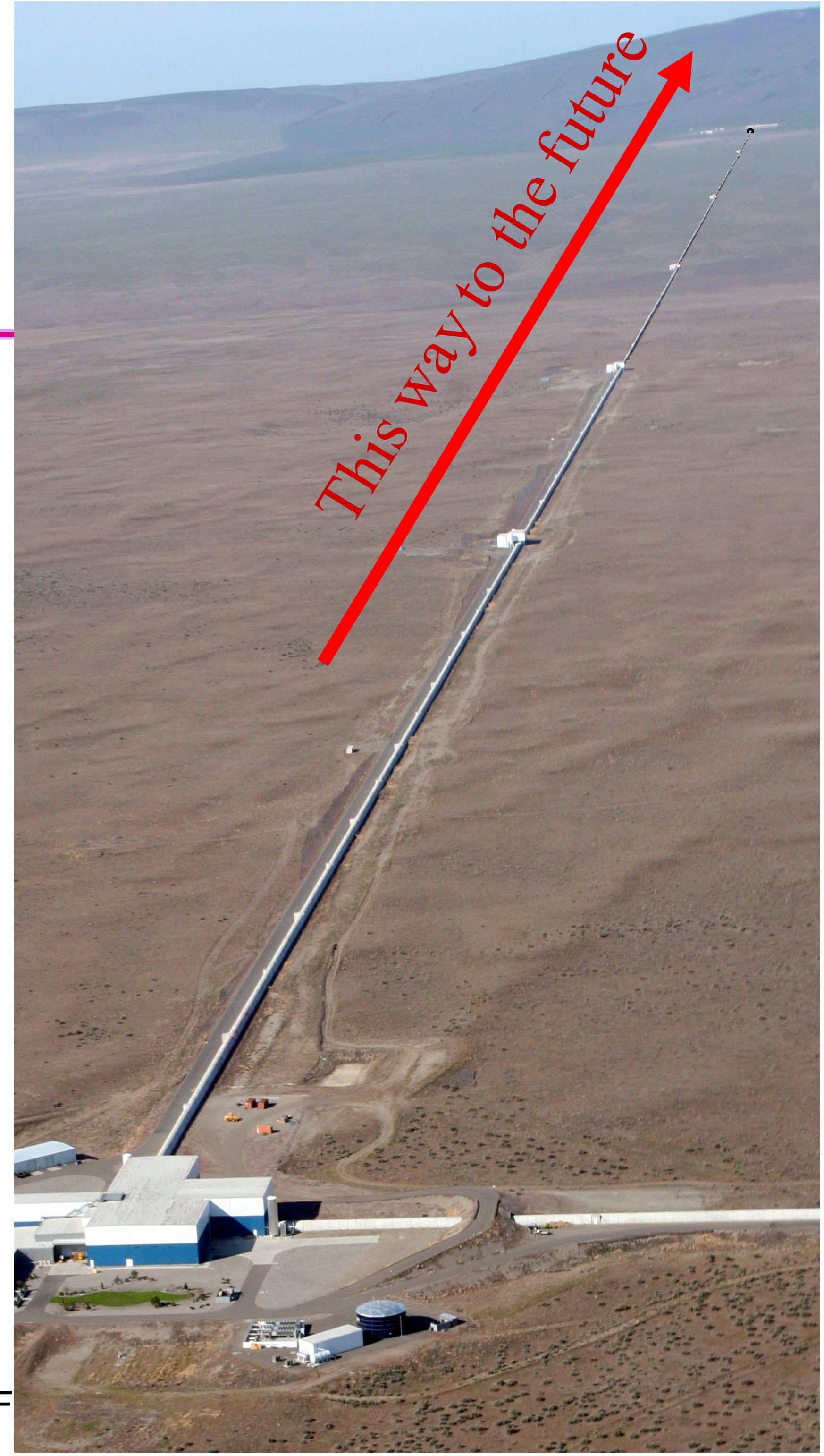
Cryogenic in Voyger



Cosmic Explorer : Long is good

SEPTEMBER 14, 2015

- Coating noise
  - » Gain: $L^{1.5}$
  - » Cryogenic/Crystal: no need
- Displacement noise
  - » Gain: L
  - » Newtonian N. irrelevant
- Radiation pressure
  - » Becomes irrelevant
- Shot noise
  - » Gain: ~sqrt(L)
  - » Freq. indep. Squeezing
- Vertical susp. Thermal
  - » Gain: constant



LIGO = LIGO Lab (CIT,MIT,UFL) + LSC (LIGO Science Collaboration)

- 1006 members, 83 institutions, 15 countries

International network

Dave: I am positively delighted to inform you that yesterday, LIGO-India was formally approved as an official Mega-Science project by the government of India!

- detection confidence
- locate the sources
  - all detectors should have comparable sensitivity (~factor 2)
- decompose the polarization of gravitational waves
- open up a new field of astrophysics!

Localization
poor because of only 2 IFOs

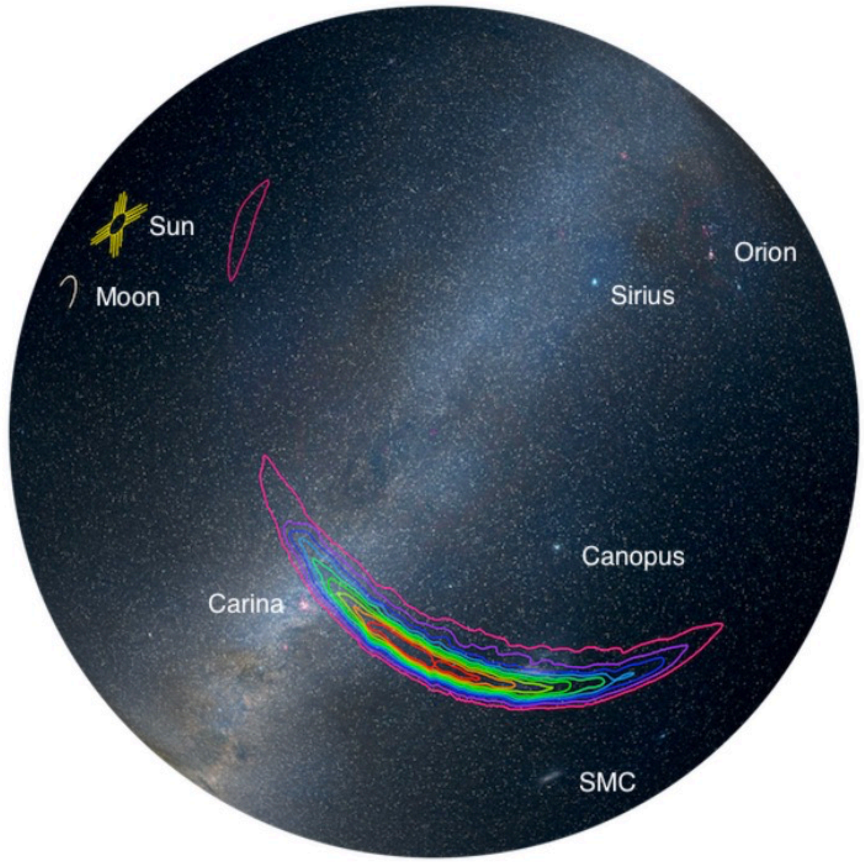
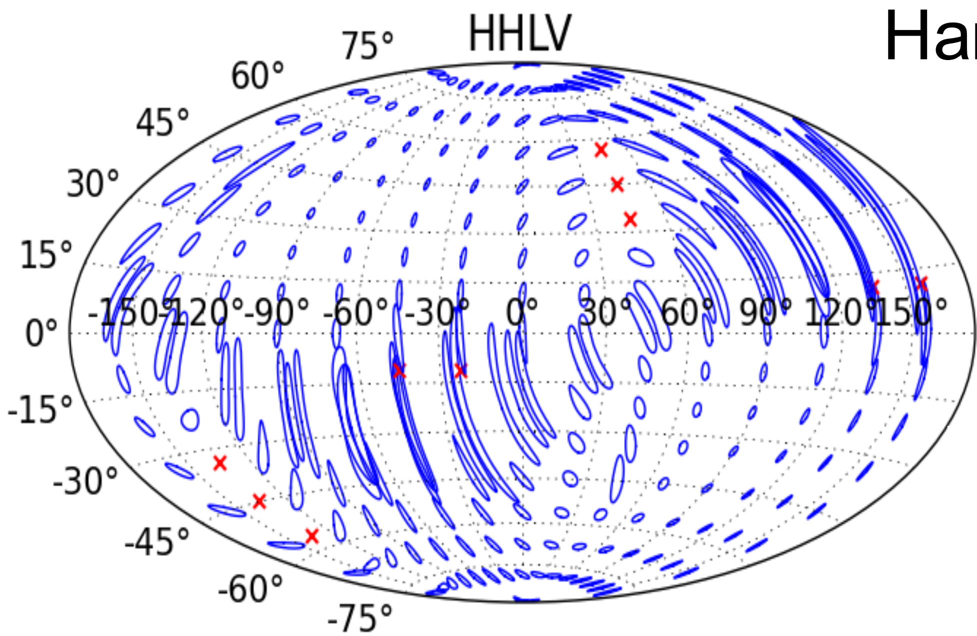


FIG. 4. An orthographic projection of the PDF for the sky location of GW150914 showing contours of the 50% and 90% credible regions plotted over a colour-coded PDF. The sky localization forms part of an annulus, set by the time delay of $6.9^{+0.5}_{-0.4}$ ms between the Livingston and Hanford detectors.

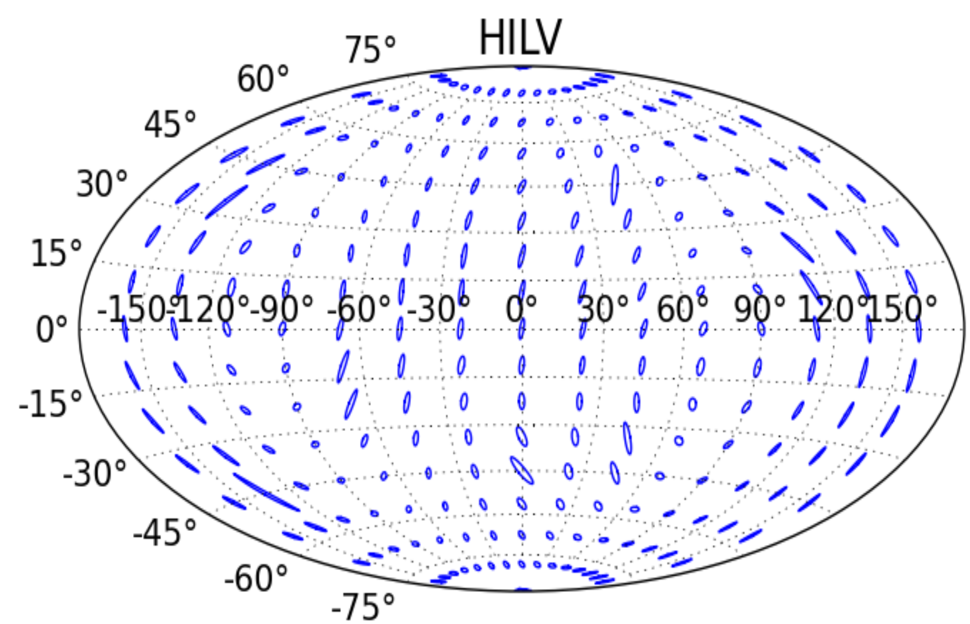
Improvement of Binary Neutron Star Merger Localization by Adding LIGO-India



Hanford+Livingston+one more

x denotes blind spots

Hanford+Livingston+two more



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

LIGO needs partner GW detectors with similar sensitivity

- LIGO is seriously seeking for third/fourth good IFOs
  - » AdVirgo is trying to join O2, but still have some problems to solve
  - » LIGO-India has been approved, many years to come
- To improve sky coverage, sensitivity > 0.5 of LIGO
  - » < 20 Mpc is useless
- To KAGRA
  - » Eagerly waiting to join the international GW network
  - » Good sensitivity is a must as a good partner
  - » Sooner the better
    - – Simpler configuration need to be considered

End of slides

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the National Science Foundation of the United States.

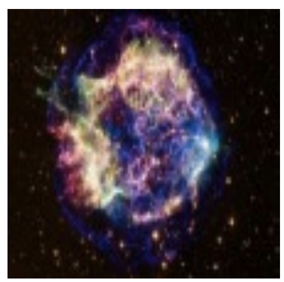
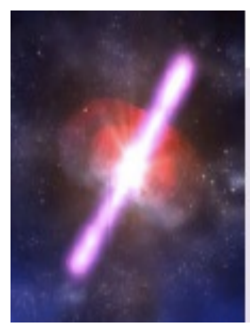
Welcome! The LIGO Open Science Center (LOSC, https://losc.ligo.org) provides access to a variety of LIGO data products, as well as documentation, tutorials, and online tools for finding and viewing data.

Gravitational-Wave Strain Data

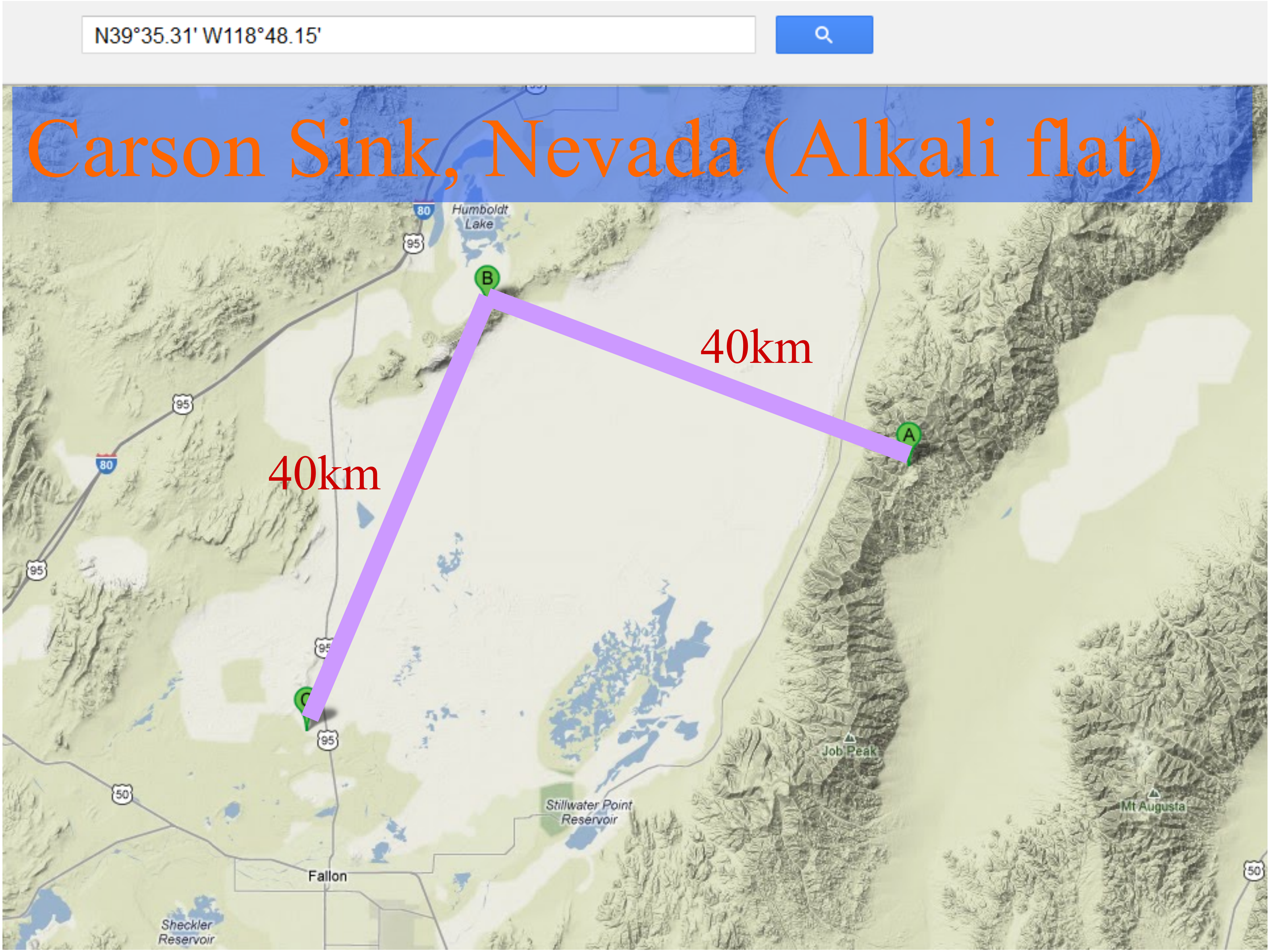
- Tutorial on Signal Processing with Gravitational-Wave Strain Data
- About the Instruments and Collaborations
- Observing Gravitational-Wave Transient GW150914 with Minimal Assumptions
- GW150914: First Results from the Search for Binary Black Hole Coalescence with Advanced LIGO
- Properties of the binary black hole merger GW150914
- The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914

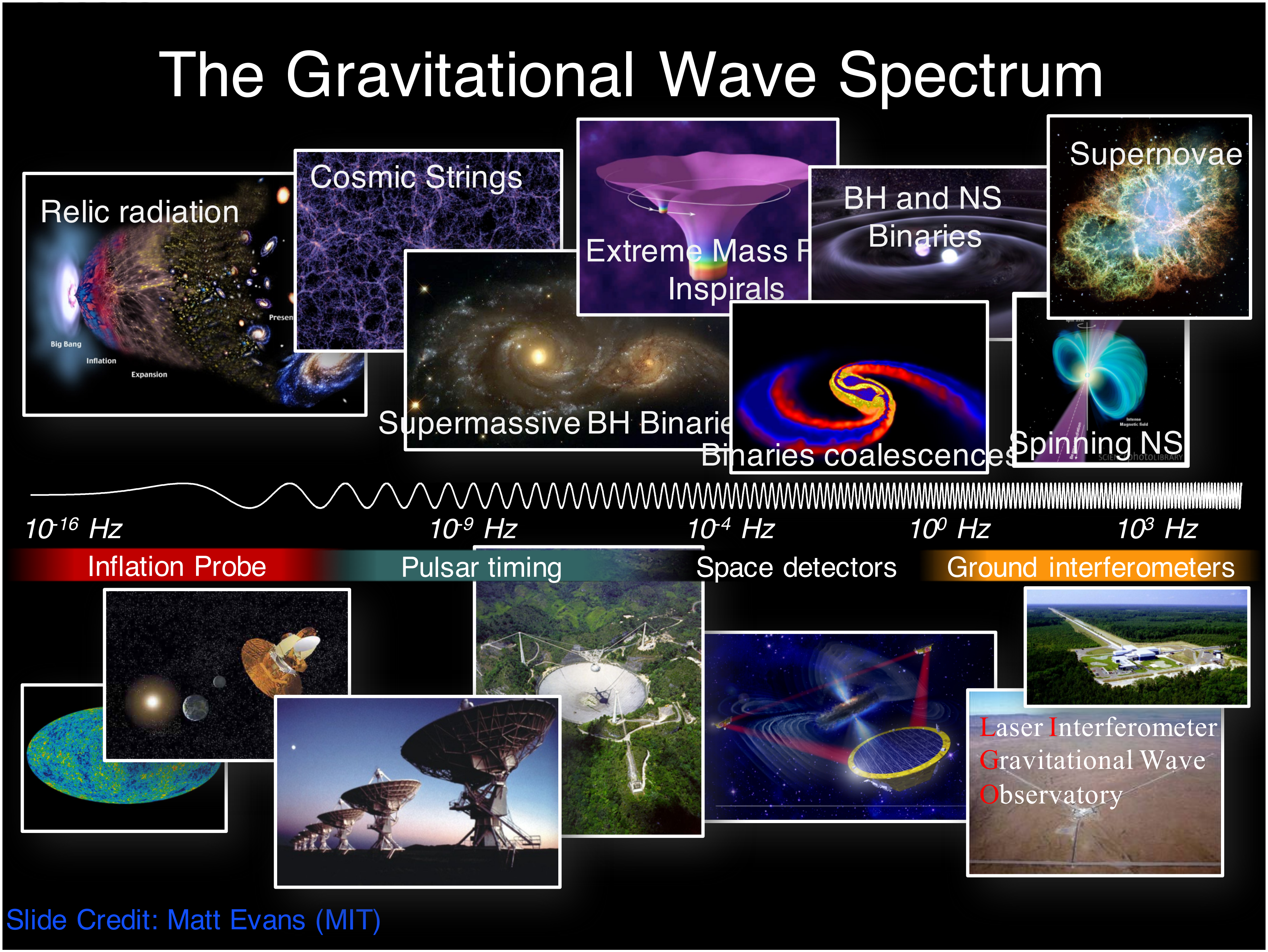
Multi-messenger astronomy
collaborations with Groups Detecting other signals

- Discussions going toward the new astrophysical era
- Complementary alert system
- Complementary and supplemental information about the source
- Many MOUs exchanged with EM partners, covering the whole EM spectrum.


Carson Sink, Nevada (Alkali flat)





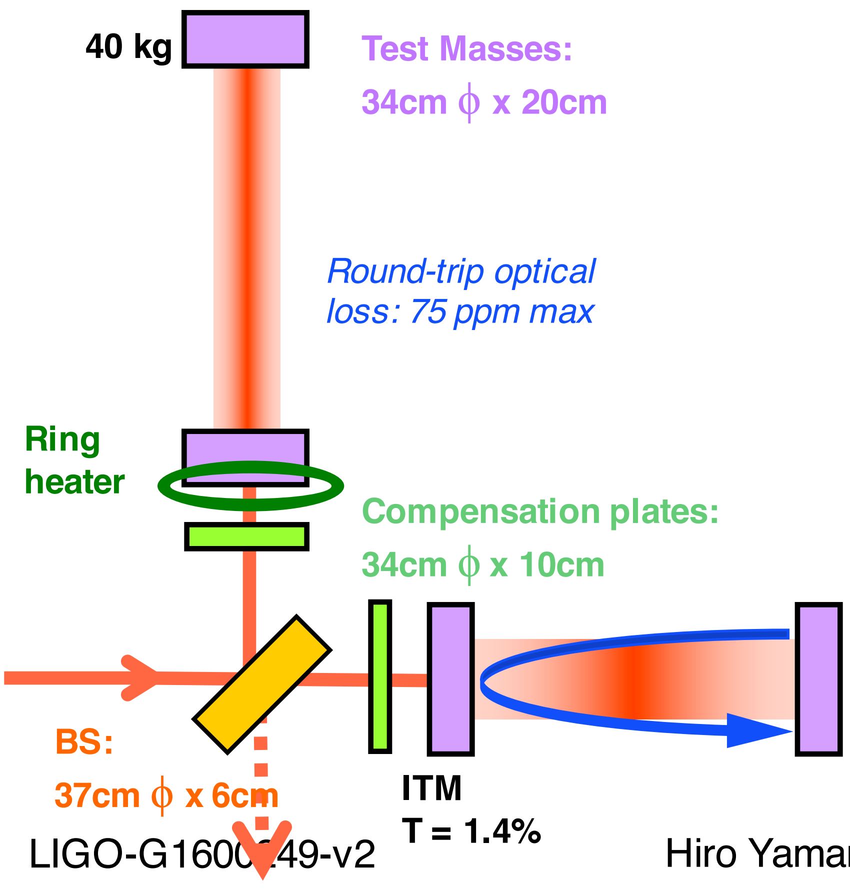
Slide Credit: Matt Evans (MIT)

Advanced LIGO Data analysis

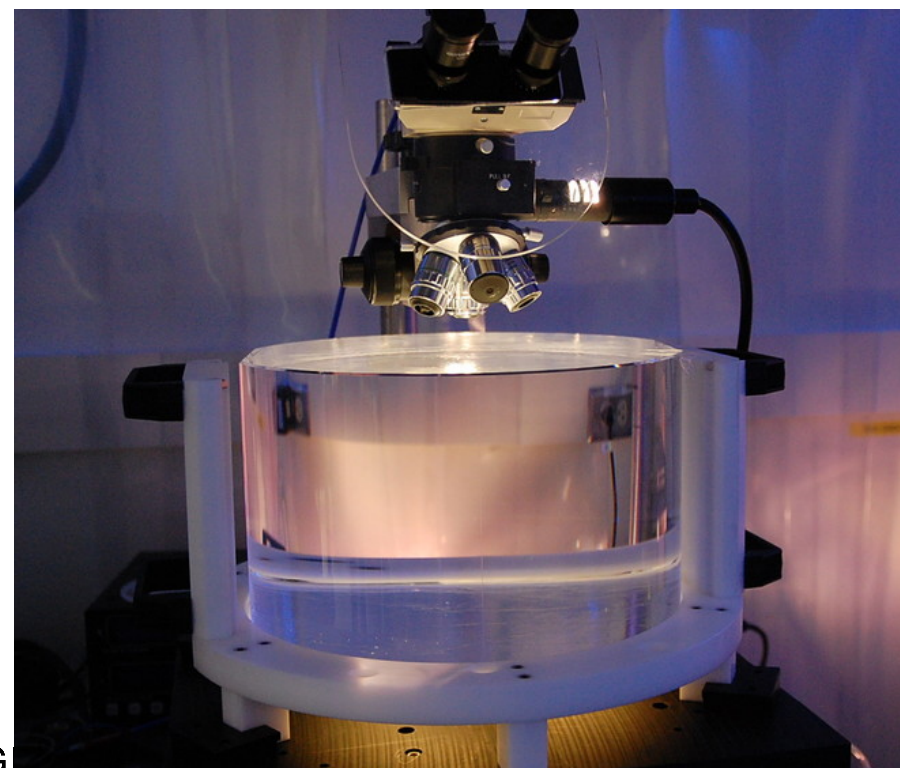
- Burst (generic transient search)
  - P1500229: Observing gravitational-wave transient GW150914 with minimal assumptions
  - All-sky search for generic GW transients, in low latency for EM follow up and deep, offline for 4σ detection confidence
- Compact Binary Coalescence Search
  - P1500269 : GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
  - Low latency, all-sky search for BNS and NS-BH systems
  - Search for binary neutron-star and black-hole systems (BNS, BHNS, BBH)
- Continuous Wave
  - All-sky deep/broad search for isolated starts
  - Targeted search for high value, known pulsars
- Stochastic Gravitational Wave background
  - P1500222: GW150914: Implications for the stochastic gravitational-wave background from binary black holesDirectional and isotropic search for stochastic gravitational wave background
  - Constraints of a detected background of astrophysical origin with long transients

Test Masses with thermal compensation system

- Requires the state of the art in substrates, polishing and coating
  - » Fabri-Perot cavity is used to measure arm length or space distortion



- Half-nm flatness over 300mm diameter
- 0.2 ppm absorption at 1064nm
- Coating specs for 1064 and 532 nm
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency

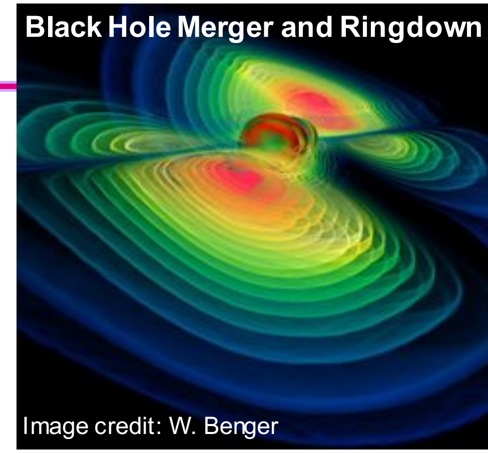


LIGO vacuums

Beam light path must be high vacuum to minimize “phase noise”. The 4km arm is the world’s biggest UHV vacuum system, and is straighter than earth’s curvature

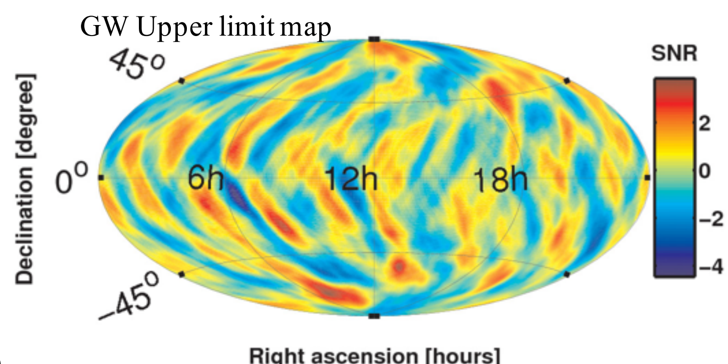
All optical components must be in high vacuum, so mirrors are not “knocked around” by gas pressure

Some Questions Gravitational Waves May Be Able to Answer



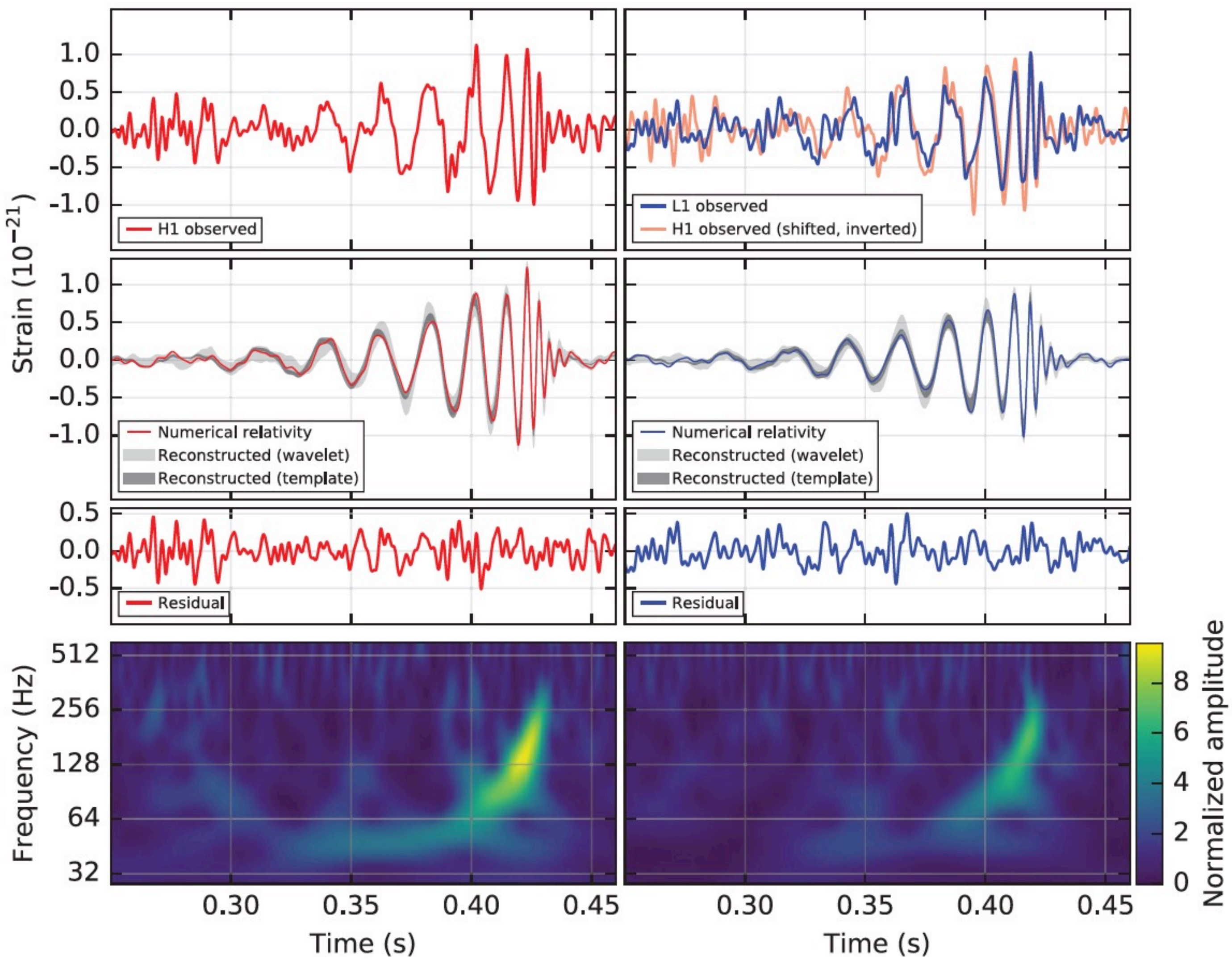
- **Fundamental Physics**
  - » *Is General Relativity the correct theory of gravity?*
  - » *How does matter behave under extreme conditions?*
  - » *What equation of state describes a neutron star?*

- **Astrophysics, Astronomy, Cosmology**
  - » *Do compact binary mergers cause GRBs?*
  - » *What is the supernova mechanism in core-collapse of massive stars?*
  - » *How many low mass black holes are there in the universe?*
  - » *Do intermediate mass black holes exist?*
  - » *How bumpy are neutron stars?*
  - » *Is there a primordial gravitational-wave residue?*



Signal vs GR predictions

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$



Advanced LIGO Data analysis

- Burst
  - » All-sky search for generic GW transients, in low latency for EM follow up and deep, offline for 4σ detection confidence
- Compact Binary Coalescence
  - » Low latency, all-sky search for BNS and NS-BH systems
  - » Search for binary neutron-star and black-hole systems (BNS, BHNS, BBH)
- Continuous Wave
  - » All-sky deep/broad search for isolated starts
  - » Targeted search for high value, known pulsars
- Stochastic Gravitational Wave background
  - » Directional and isotropic search for stochastic gravitational wave background
  - » Constraints of a detected background of astrophysical origin with long transients

✓ Search for GW signals using alerts by other signals

✓ Parameter estimation for the astrophysical interpretation of detected events