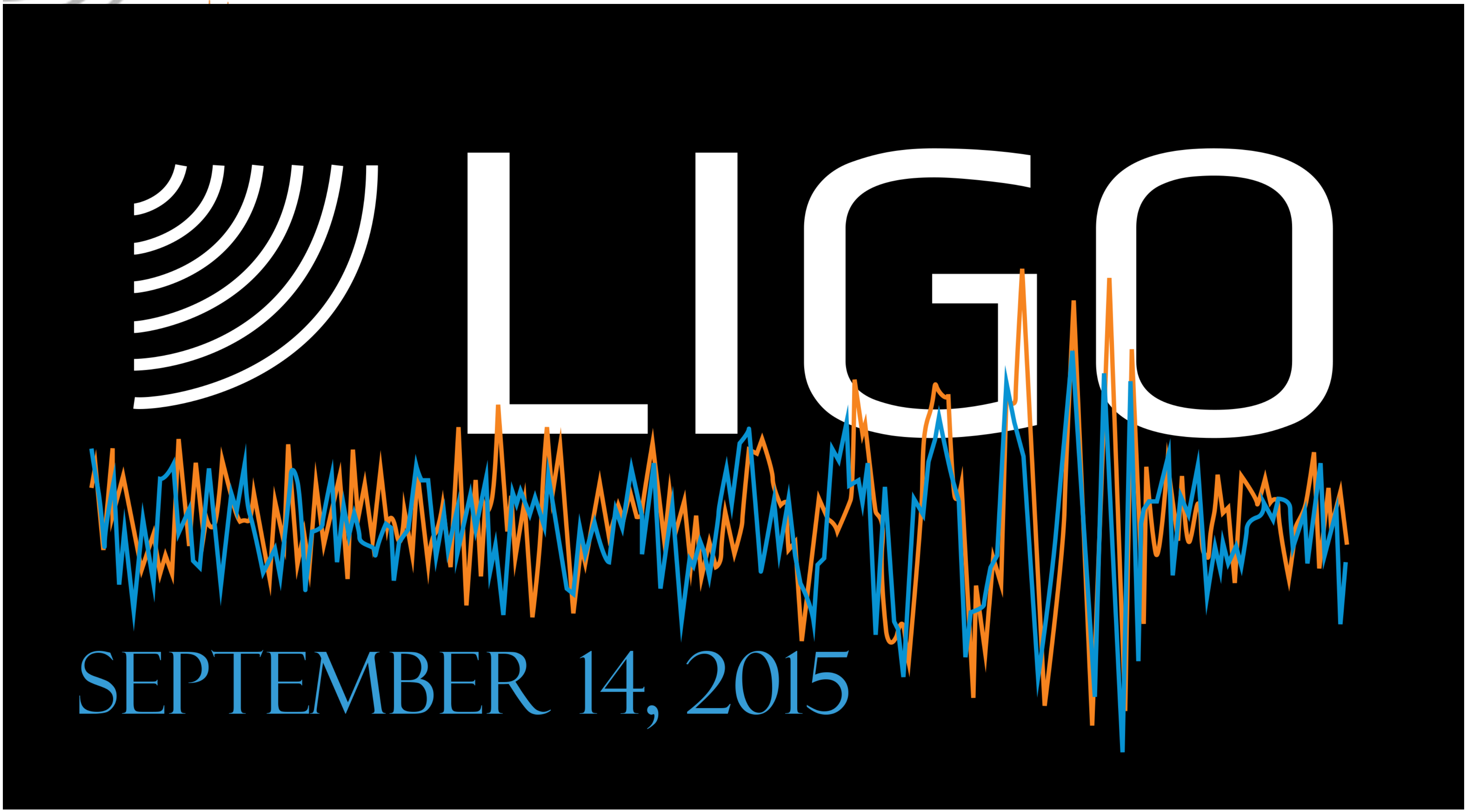
Observation of Gravitational Waves from a Binary Black Hope Merger



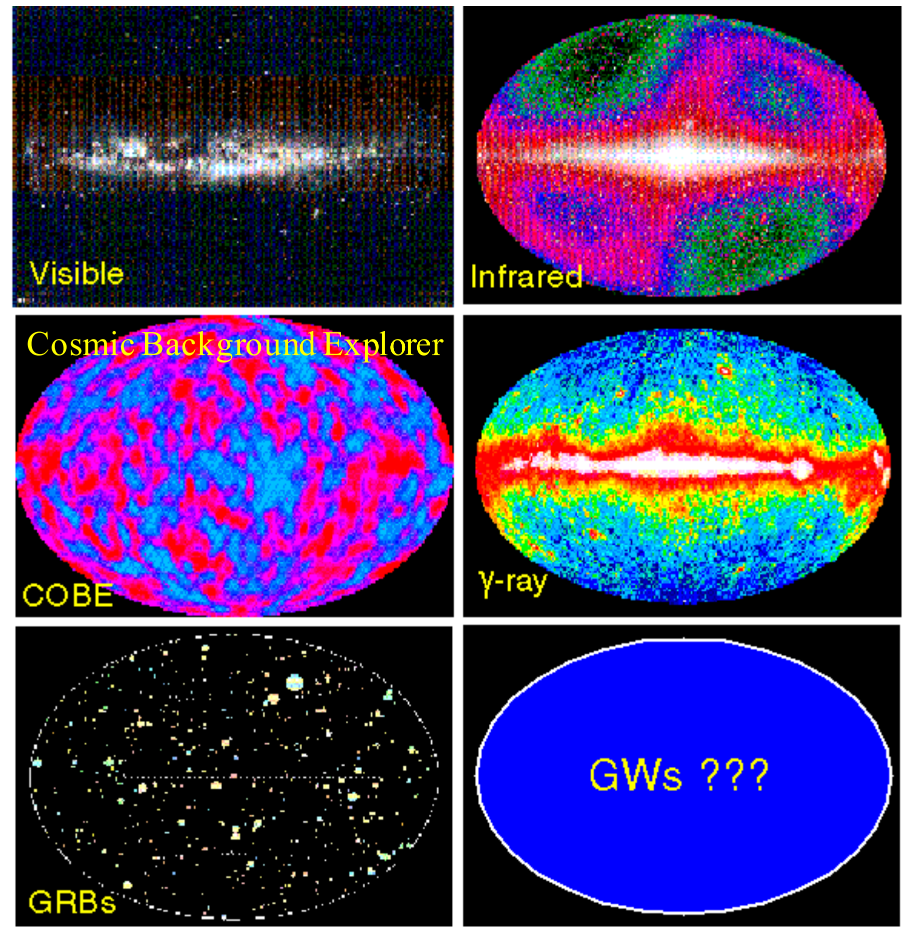
Hiro Yamamoto LIGO Lab / Caltech


National Science Foundation
NSF
NSF

Observation of Gravitational Waves from a Binary Black Hope Merger

Hiro Yamamoto LIGO lab/Caltech

- New Astronomy by gravitational wave signal at the 100^{th} memorial year of general relativity
  - » Just the beginning …
- How the GW signals look like
- Basics of interferometer or how to hear the GW signal?
- GW signal in advanced LIGO
- Scope for the future



LIGO

SEPTEMBER 14, 2015

G1600220-v8

GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

1.3Gly
Redshift = 0.09

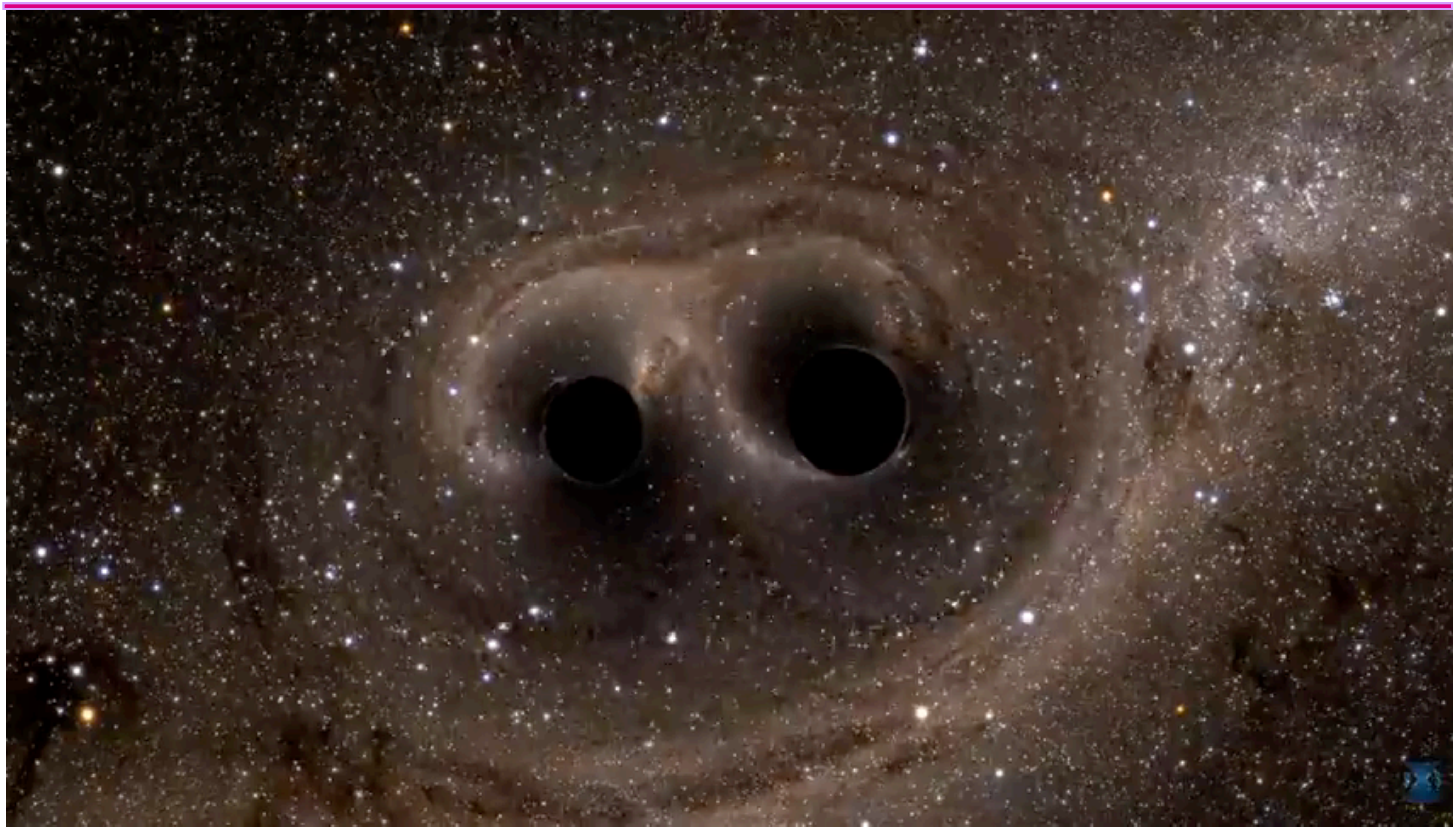
5.1σ
1/200,000 year

M_1=36 M⊙,
M_2=29 M⊙
M_{final}=62 M⊙
3 M⊙ radiated to GW wave

$h=10^{-21}$
h x arm
= 10^{-18} m
= proton / 1000
h x earth = 10^{-14}
= 10 proton

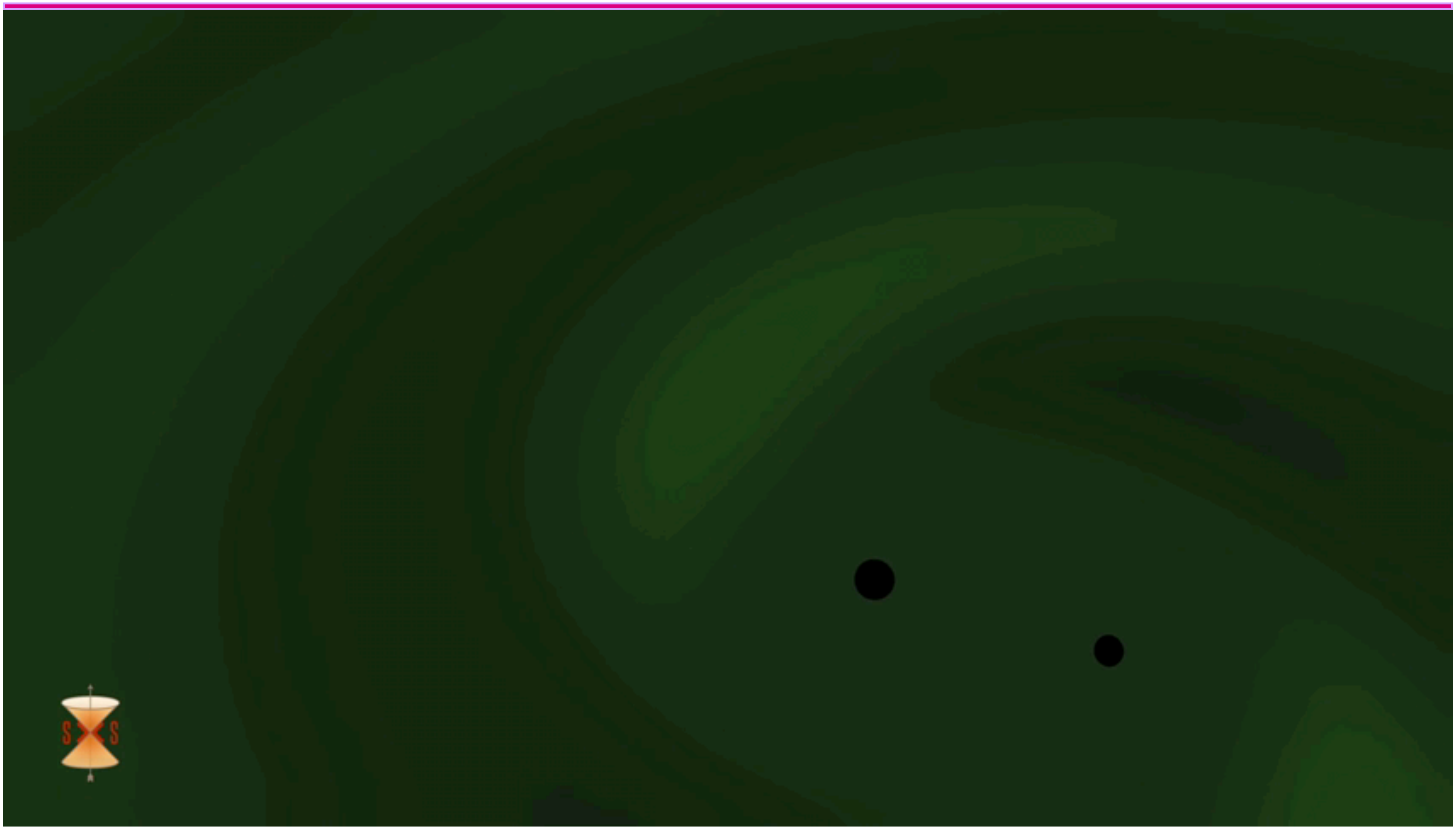
2~400 1/Gpc^3yr

Two Black Holes Merge into One

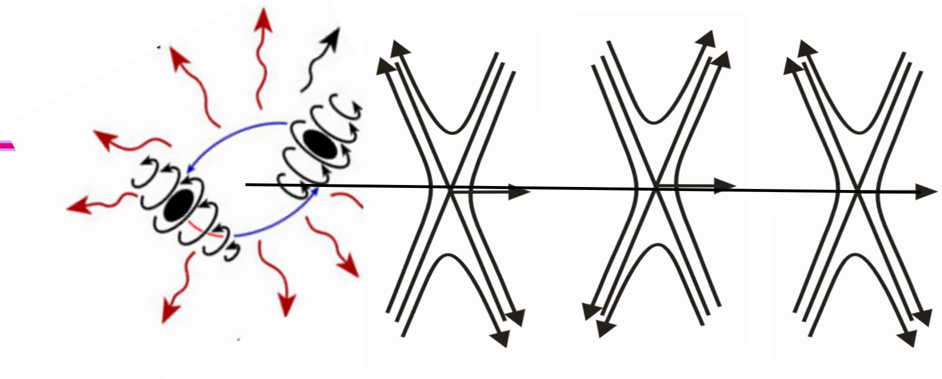


LIGO
SEPTEMBER 14, 2015

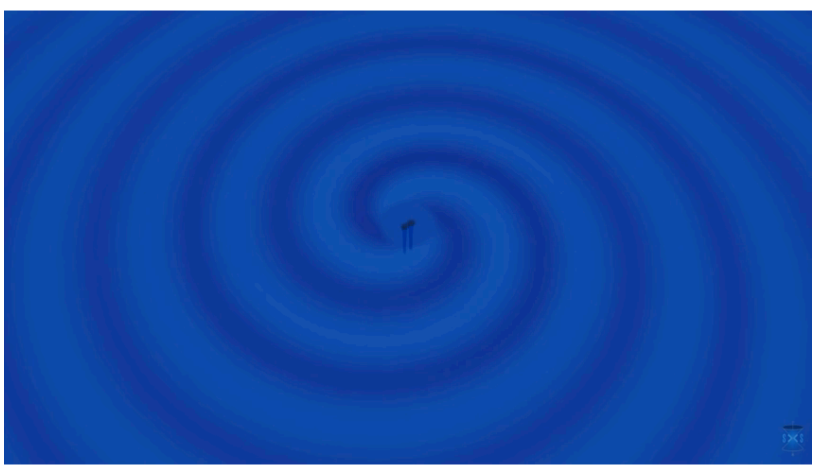
Black Hole Waves Simulation

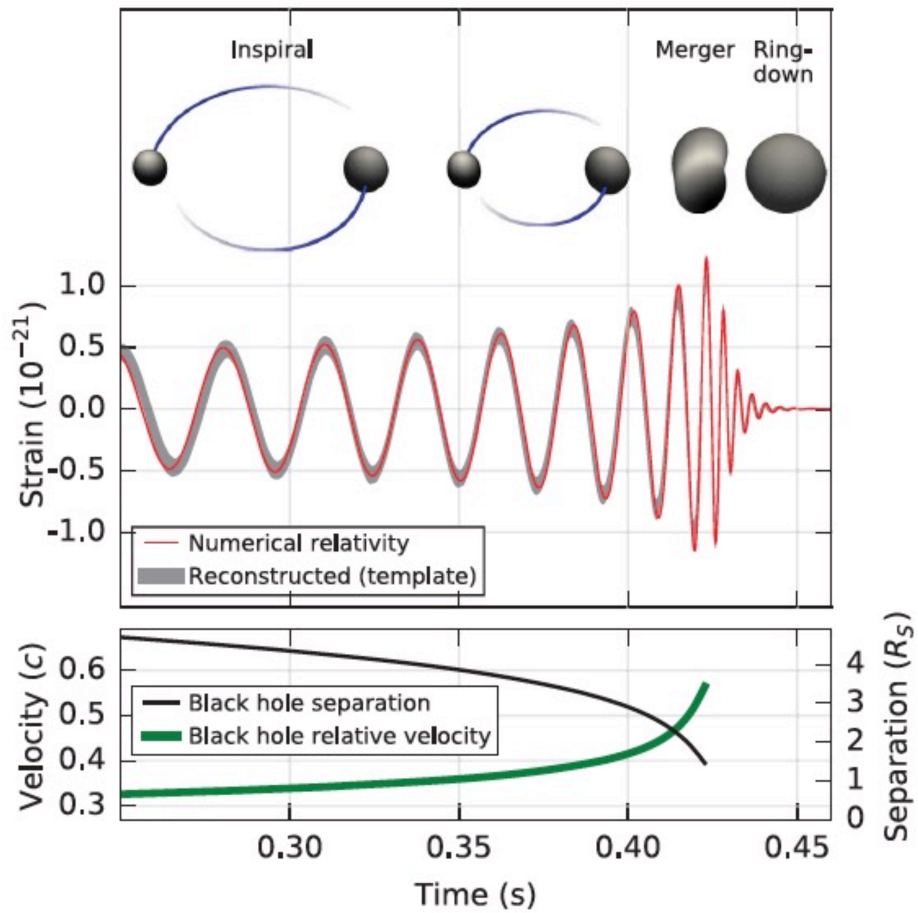


Gravitational waves

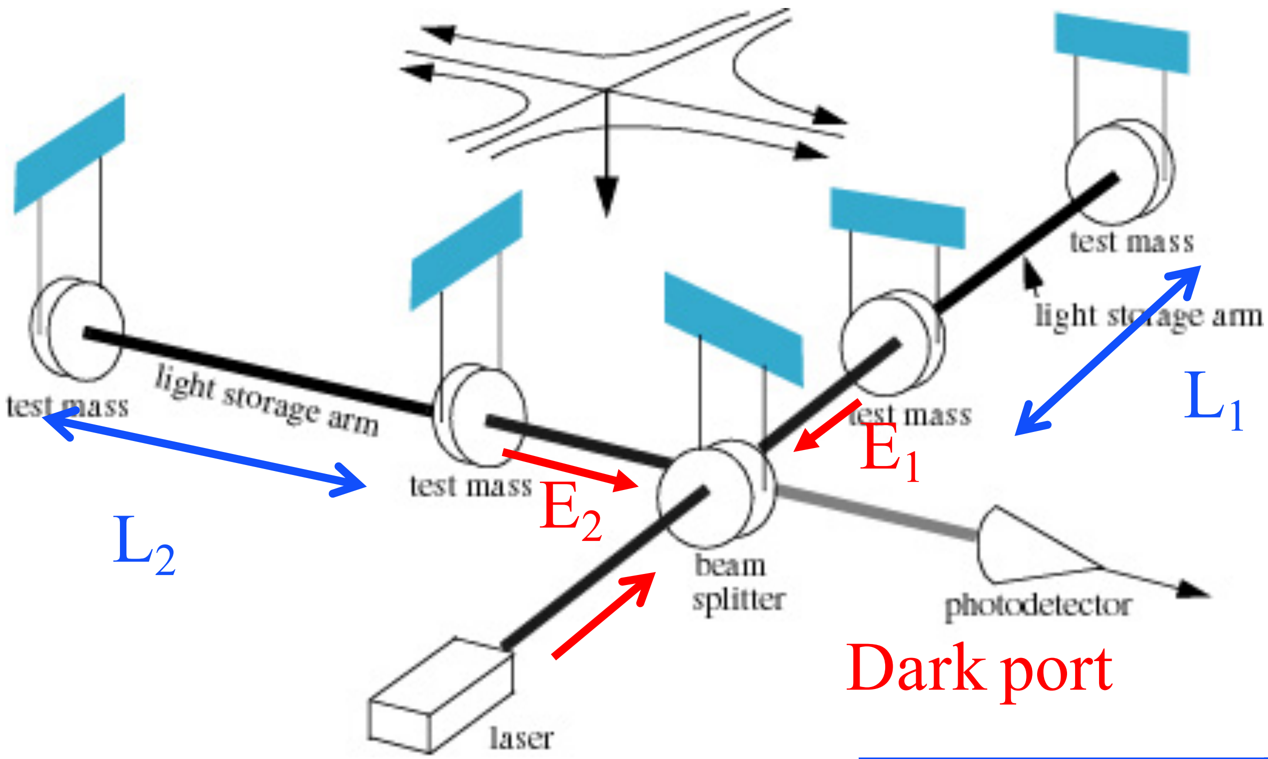


- Gravitational waves are propagating dynamic fluctuations in the curvature of space-time (‘ripples’ in space-time)
- Emissions from rapidly accelerating non-spherical mass distributions
  - Quadrupolar radiation





Interferometer for Gravitational Wave detection



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

$E_1 - E_2 \propto L_1 - L_2$

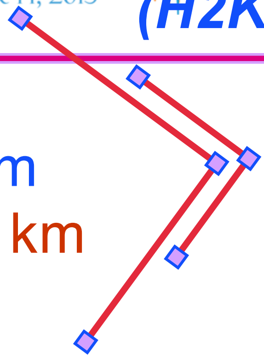
$$h = \frac{L_1 - L_2}{L_1 + L_2}$$

$h \sim 10^{-21}$

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

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

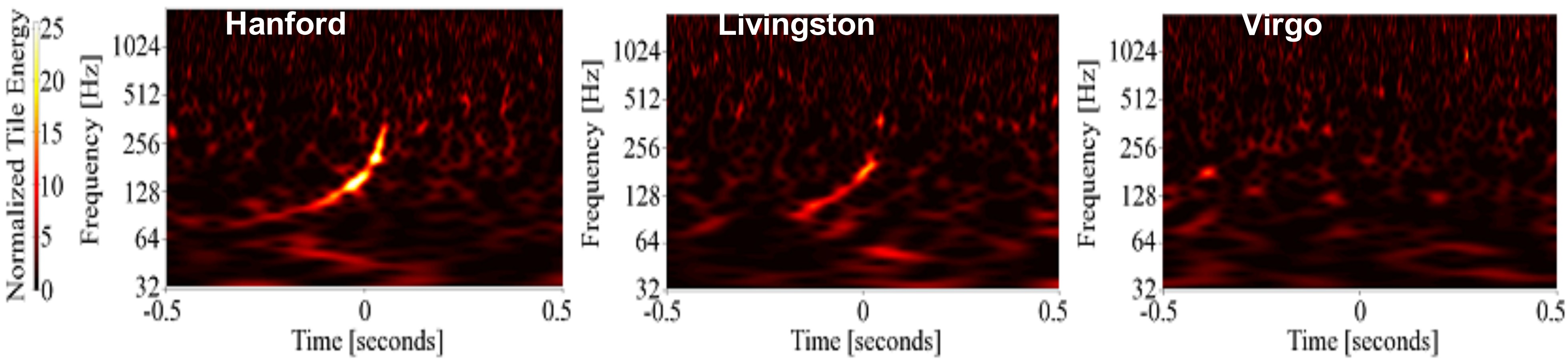
Livingston, LA (LLO)

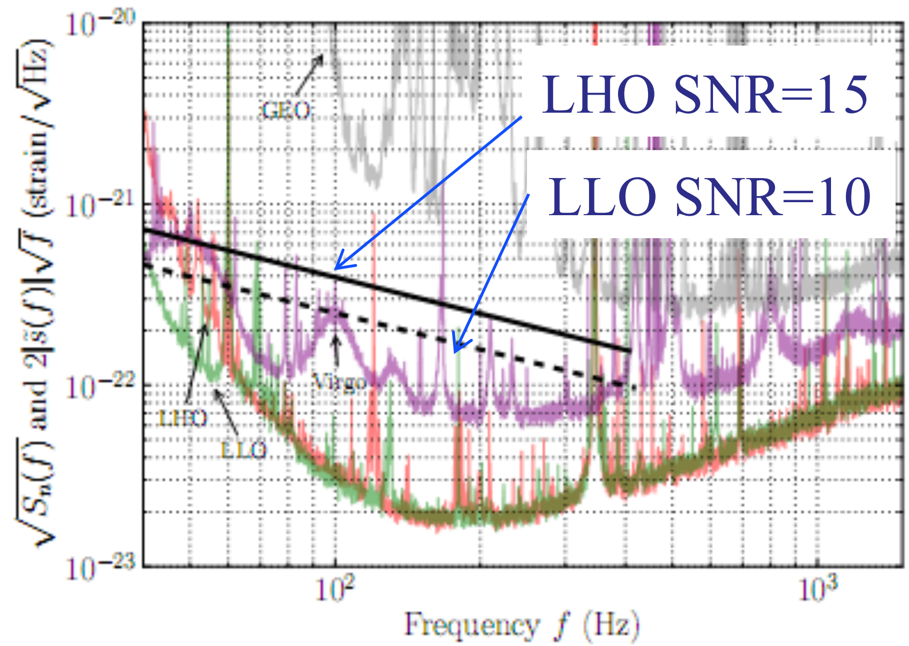
- located in forested, rural area
- commercial logging, wet climate
- 50km from Baton Rouge, LA
- **One L4K IFO**

Livingston Observatory (L4K)

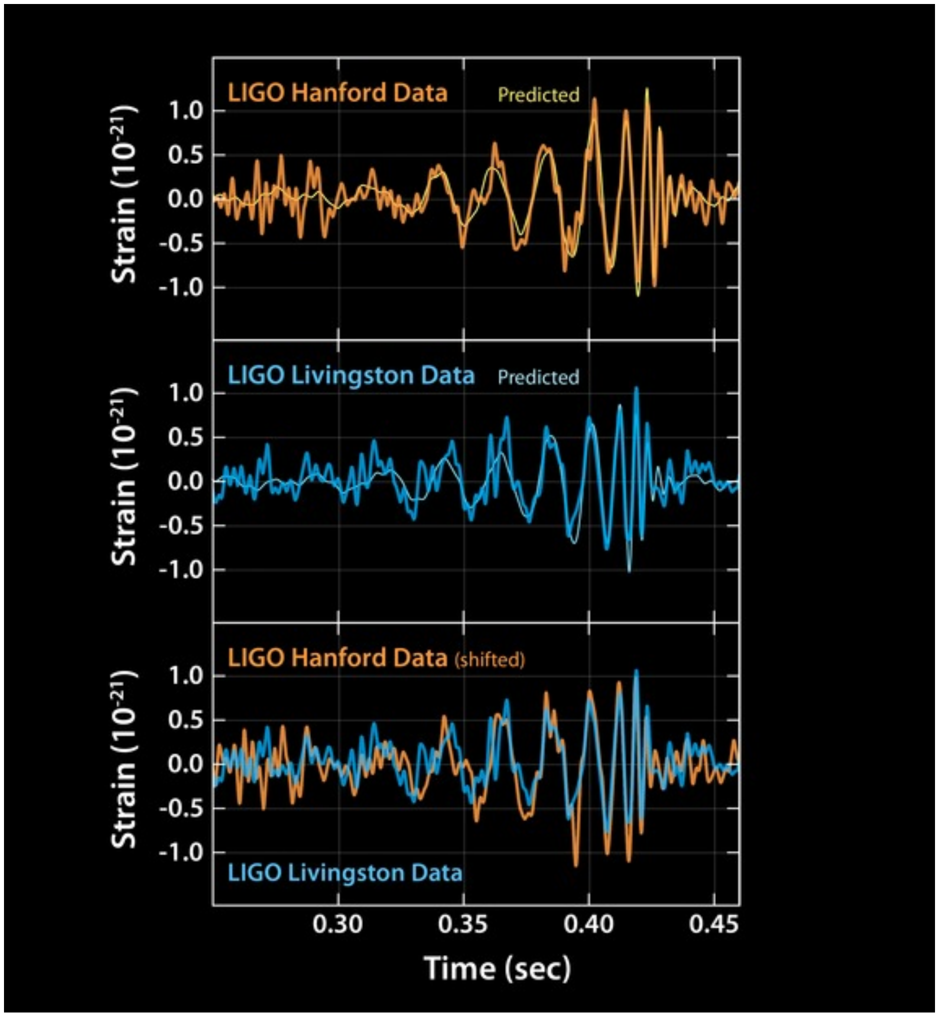
Event GW100916: blind injection FAKE

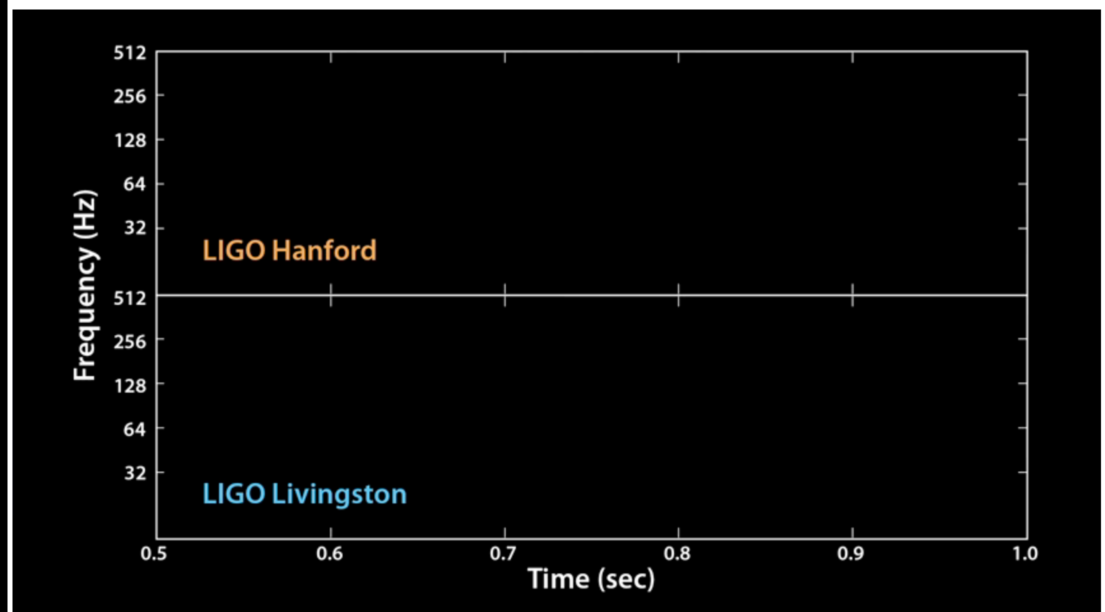
http://www.ligo.org/science/GW100916/ on Sep.16,2010





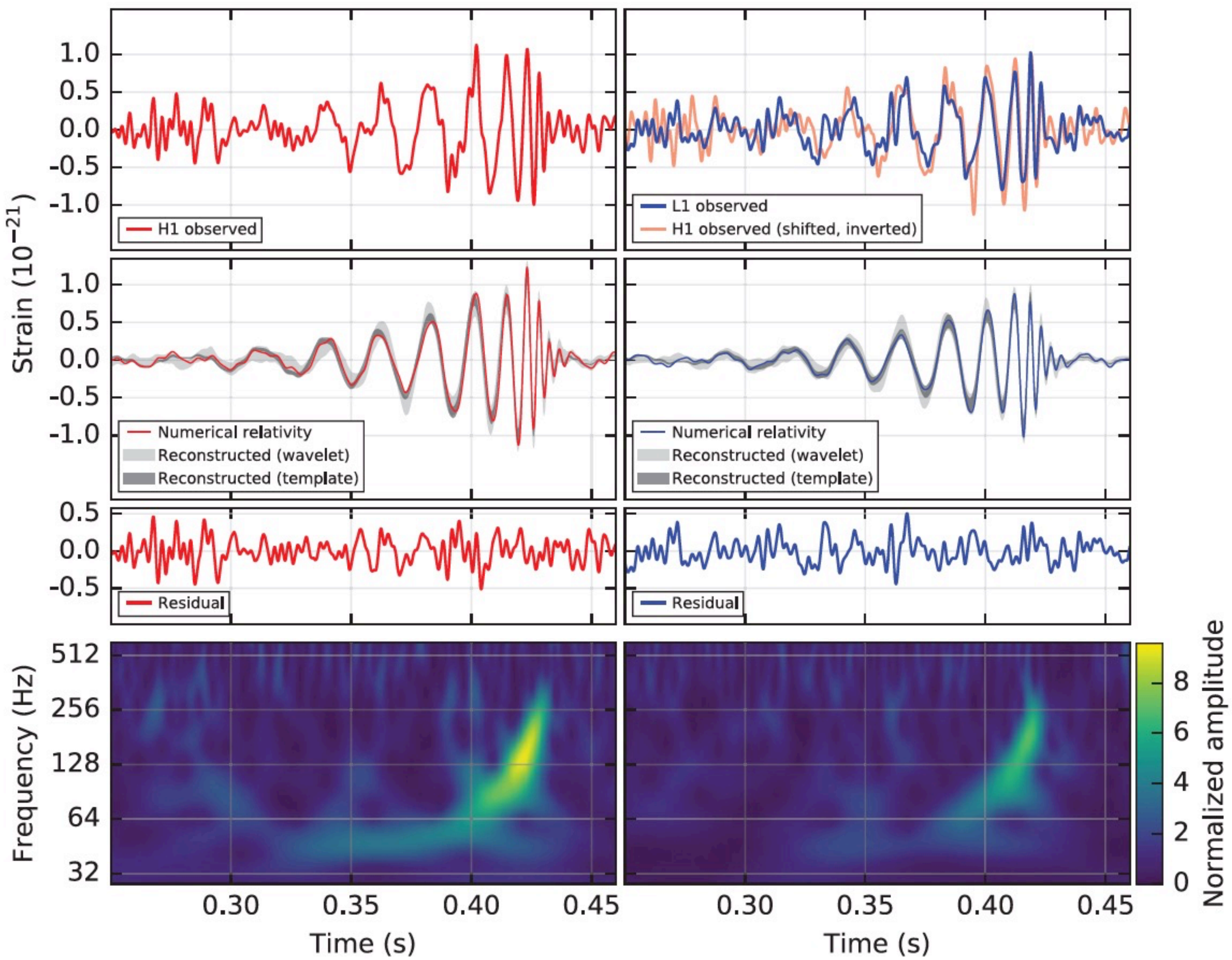
The Chirp of Two Black Holes Colliding : GW150914 REAL





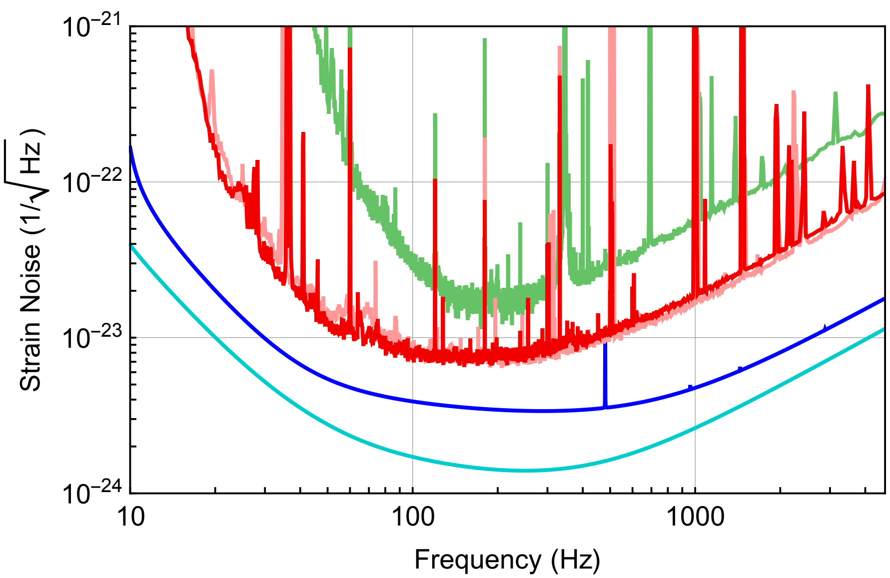
Signal vs GR predictions

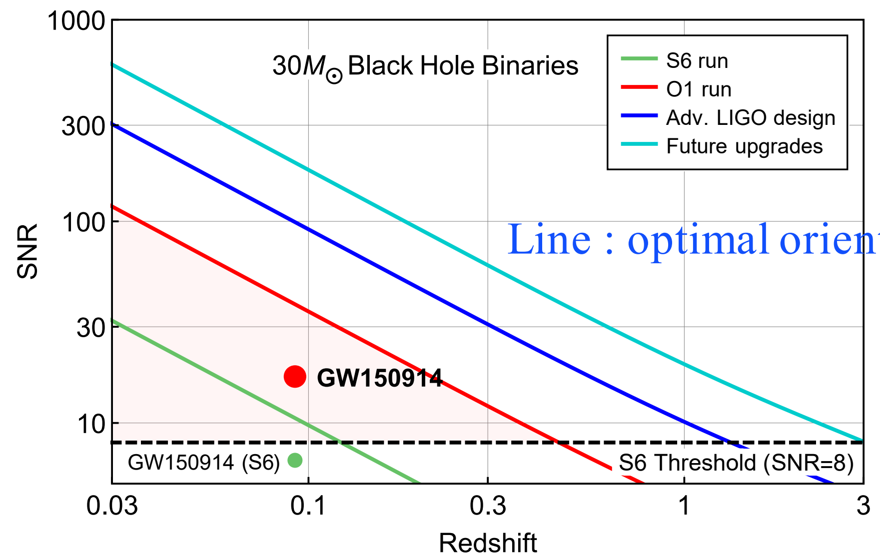
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$



How could we see the signal
1) better sensitivity

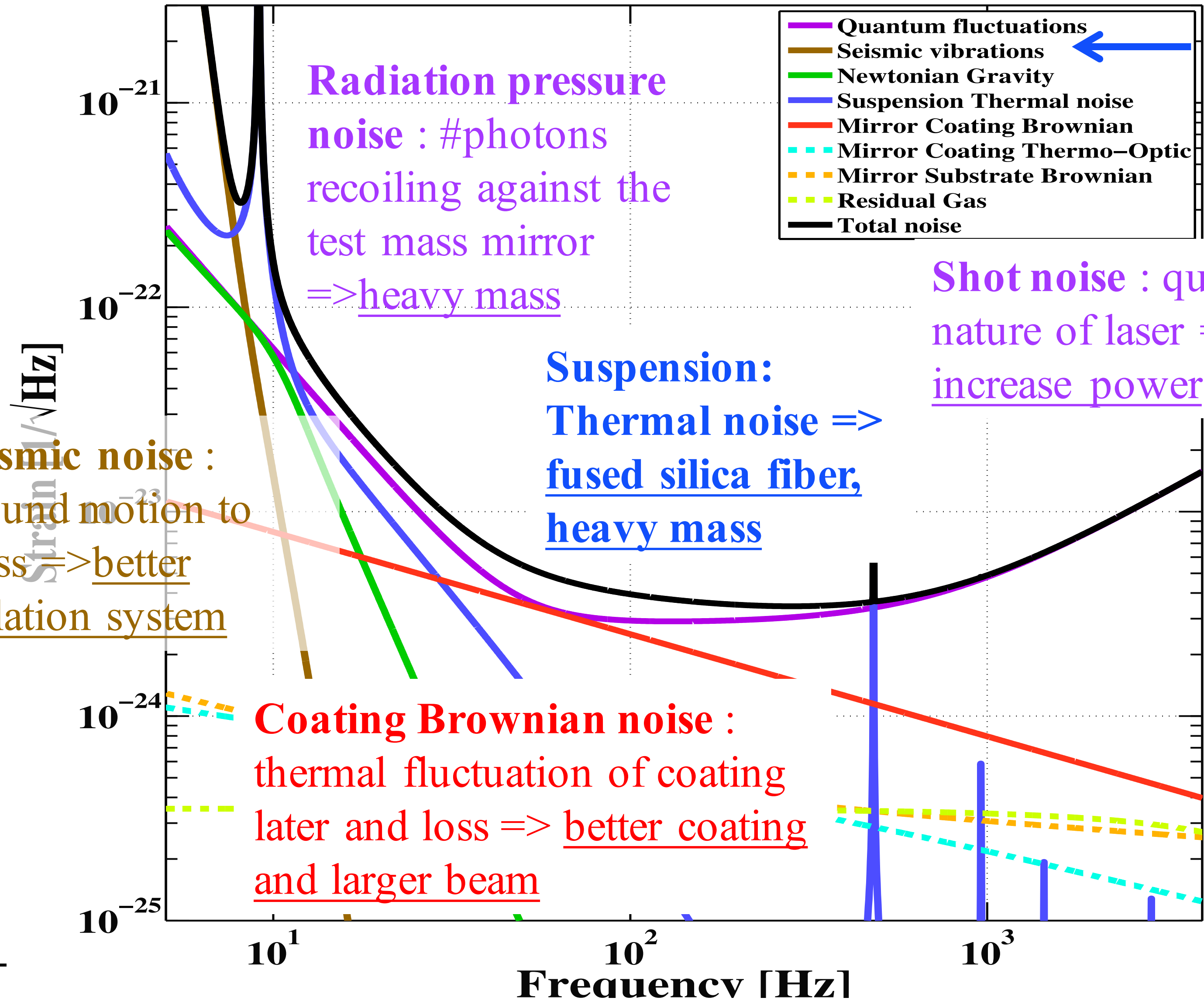
- September 12, 2015 ~ October 20, 2015 (January 12, 2016)
  - » H1:70%, L1:55%, H1+L1:48% => 16 days of data analyzed for data
- Around 100 Hz, h = 8 × 10–24 /√Hz.
- 30 M☉ black holes - 1.3Gpc = 4.1 x iLIGO, rate x70
- 1.4 M☉ neutron star - 70–80Mpc = 3.5 x iLIGO, rate x40

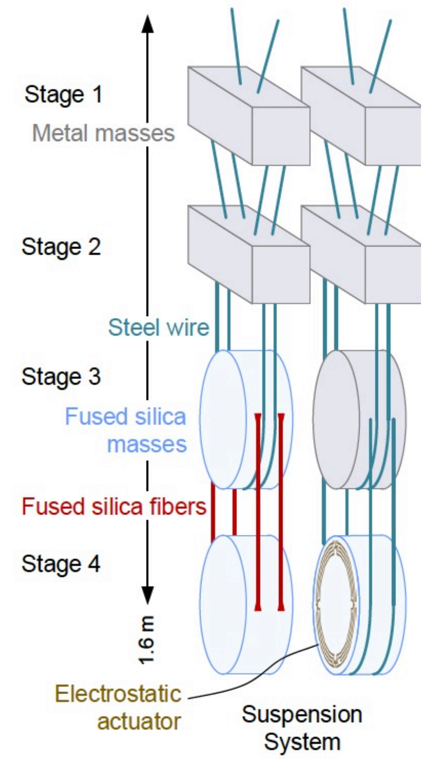




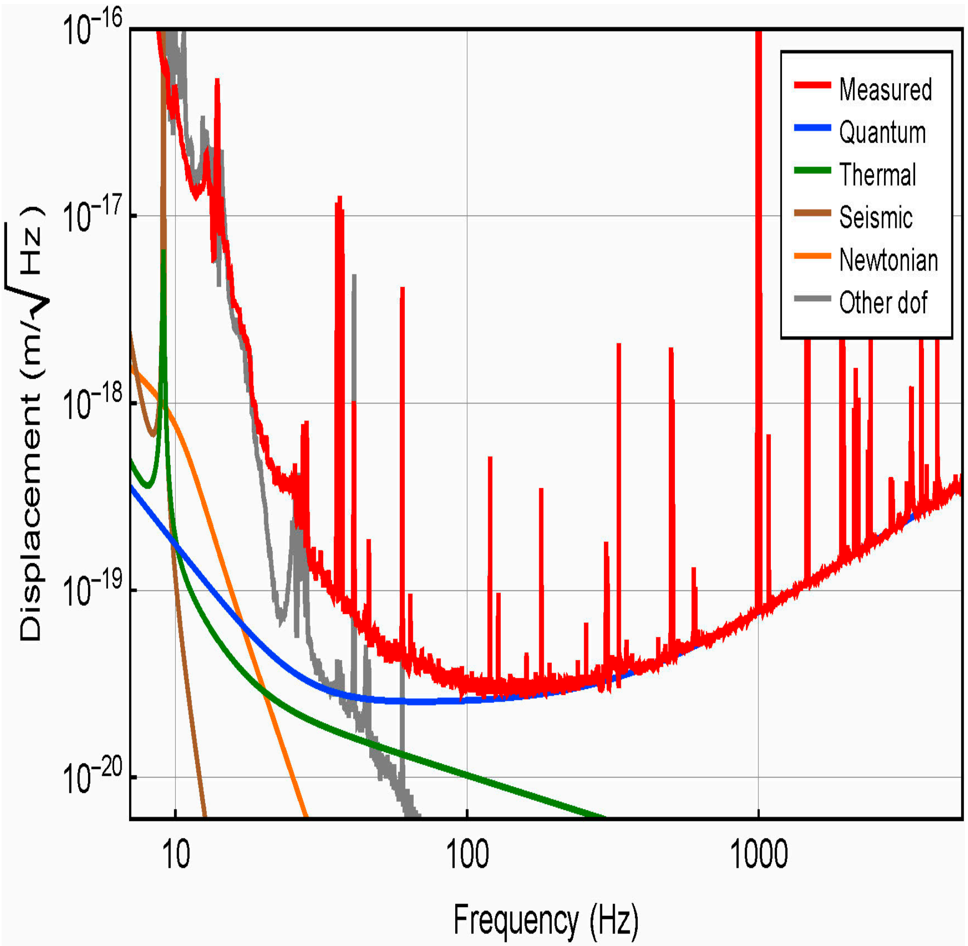
Line : optimal orientation

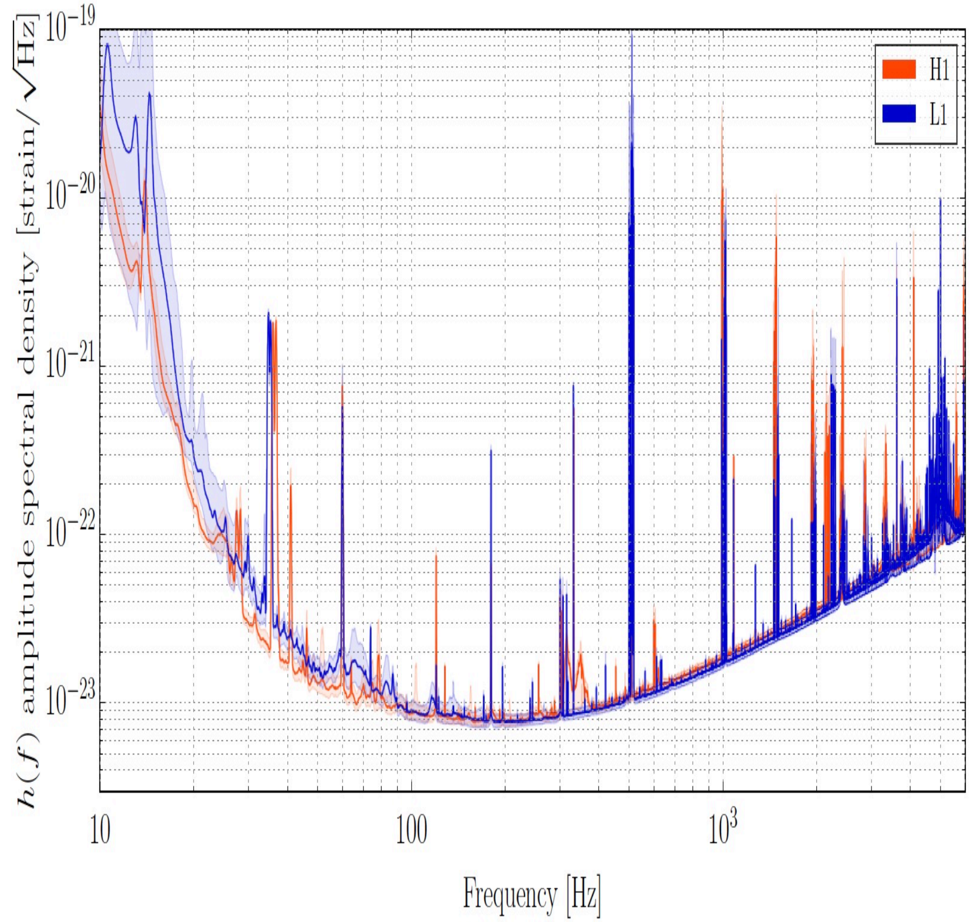
Fundamental Sensitivity Limits in Advanced LIGO



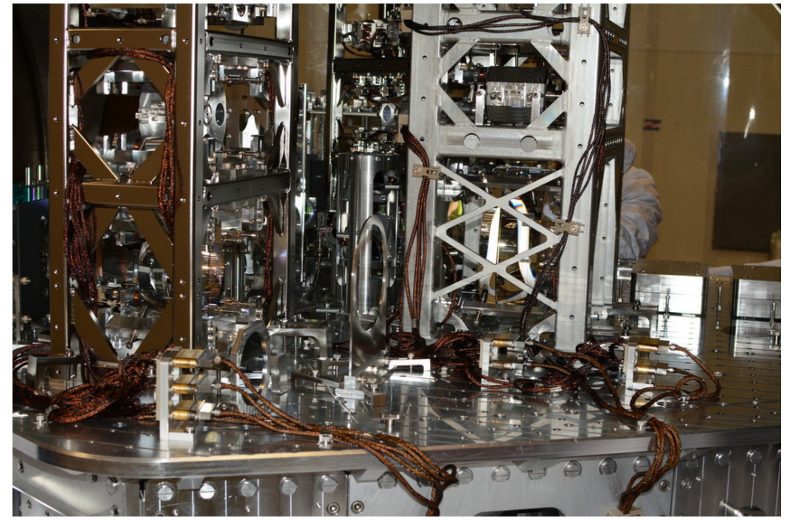


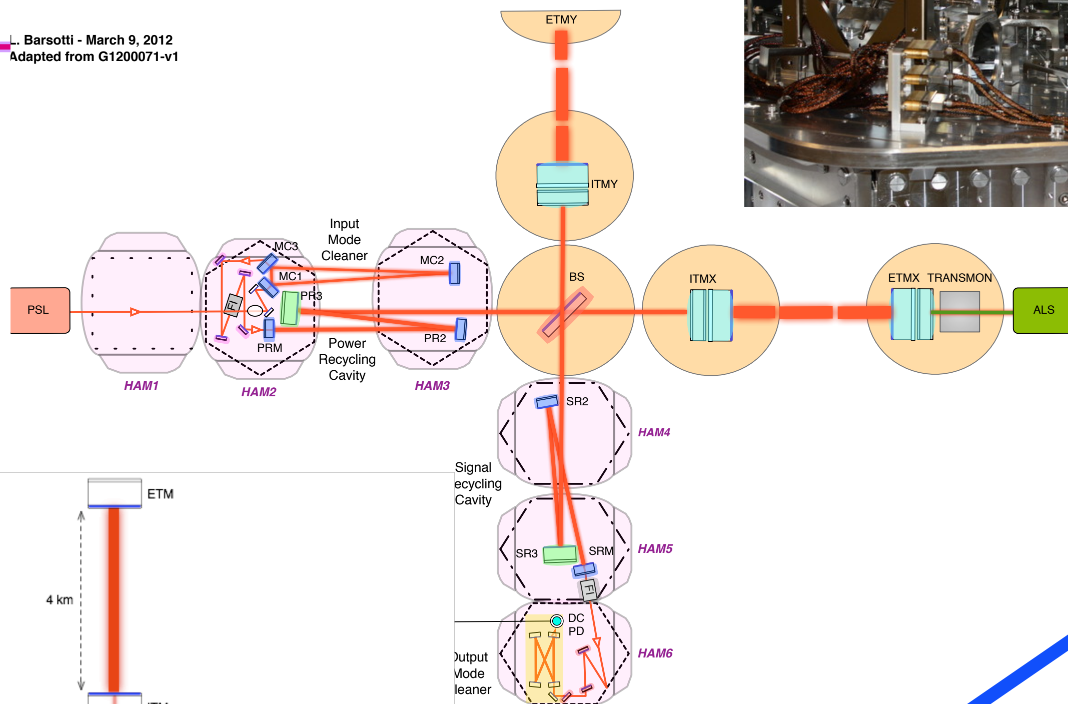
Sensitivities during O1

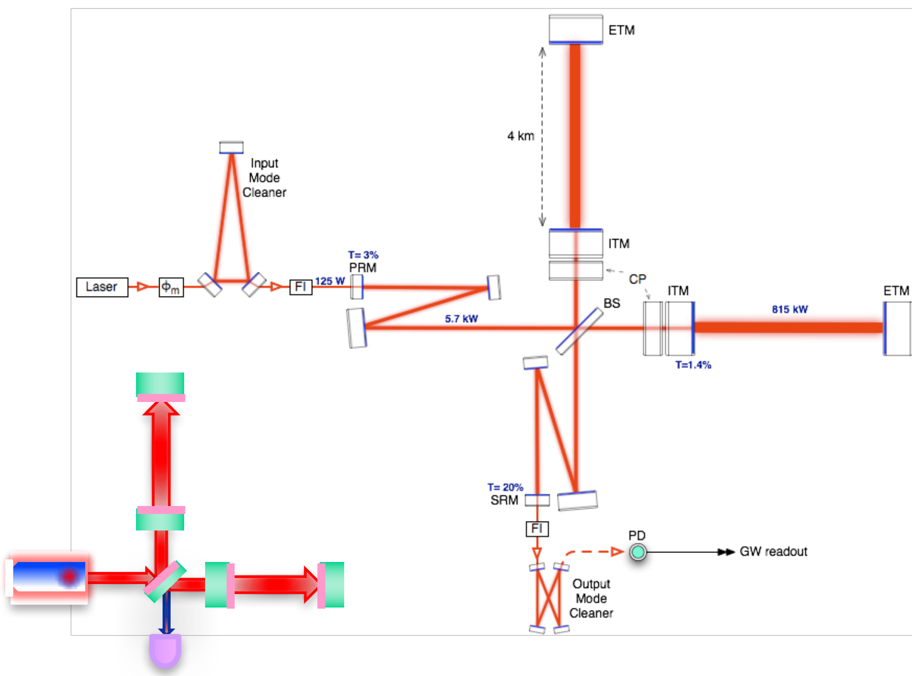




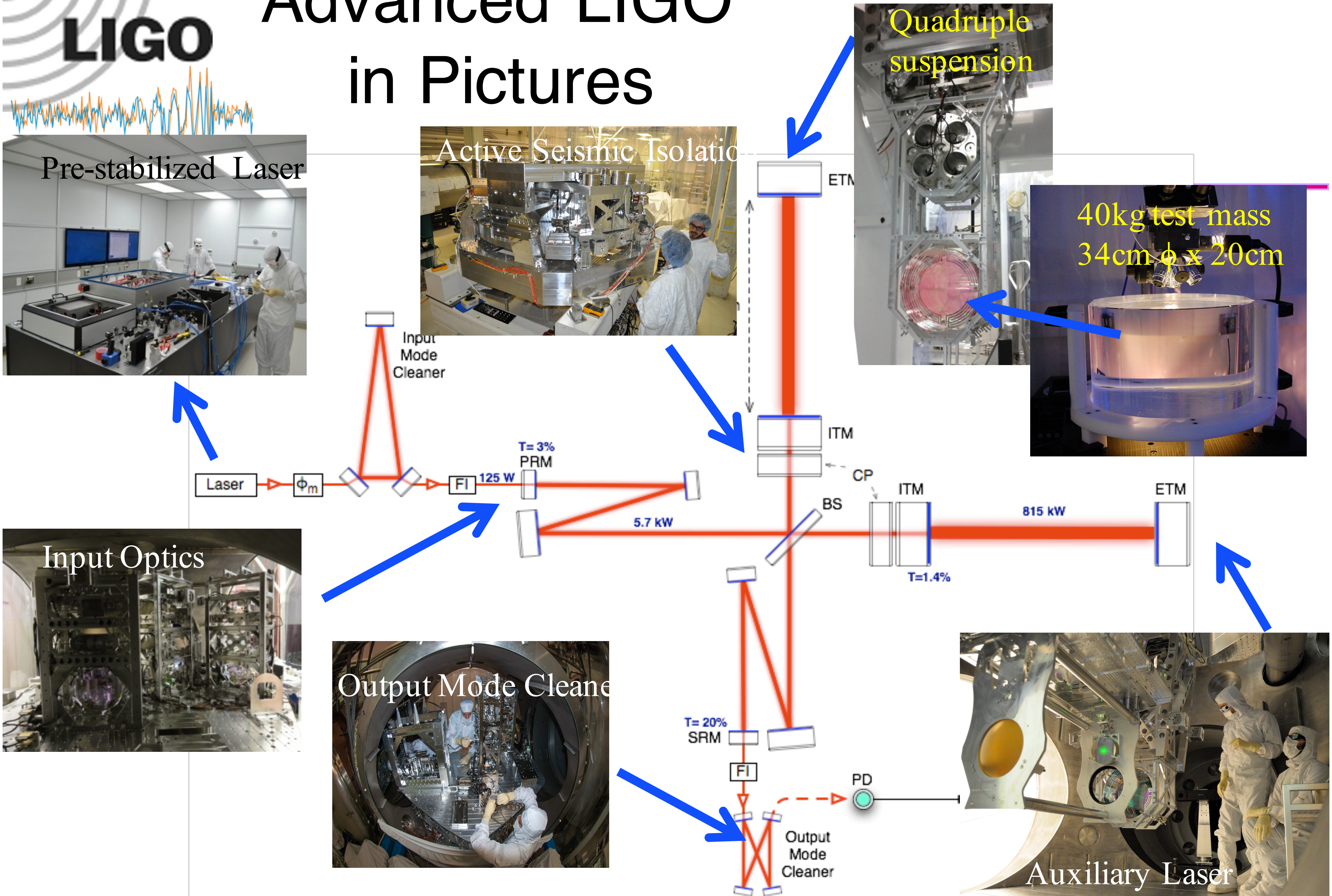
The real instrument is far more complex…







Advanced LIGO in Pictures



Lock acquisition
1µm to 1pm ala iLIGO

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

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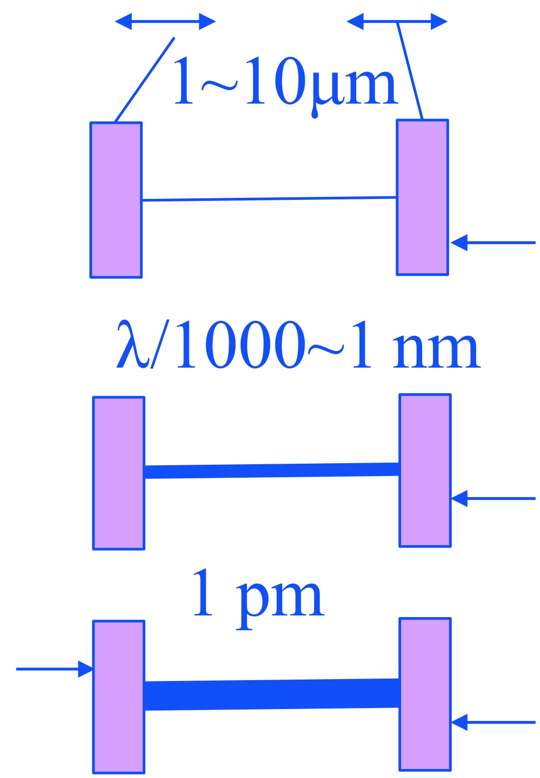

$L \times h = 10^{-18} = 1\ \text{pm}/10^{6}$

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

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

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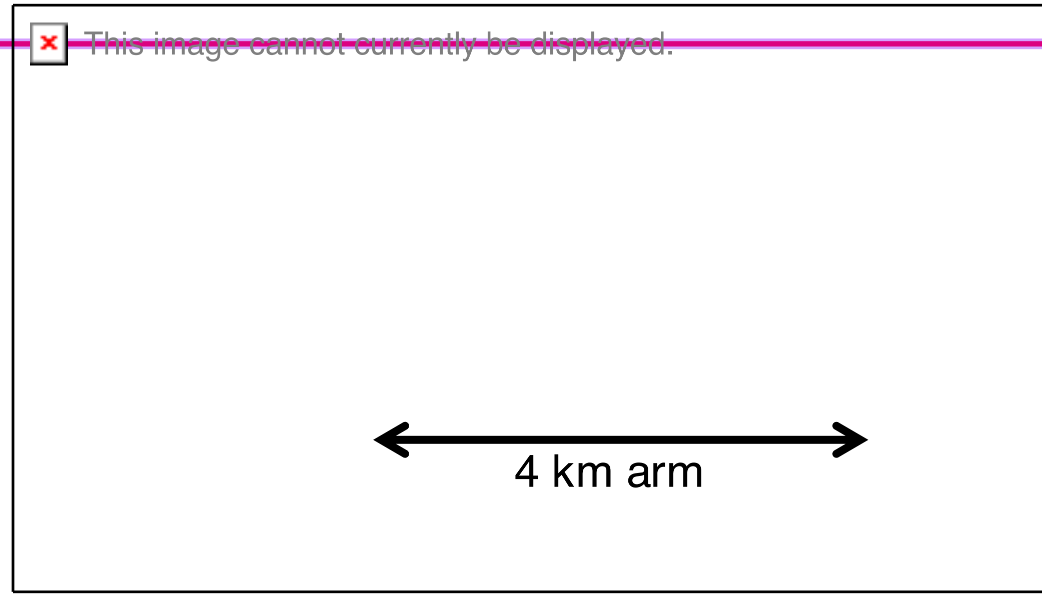
initial LIGO

advanced LIGO

G1400628-v3 by P. Fritschel

Speedier commissioning

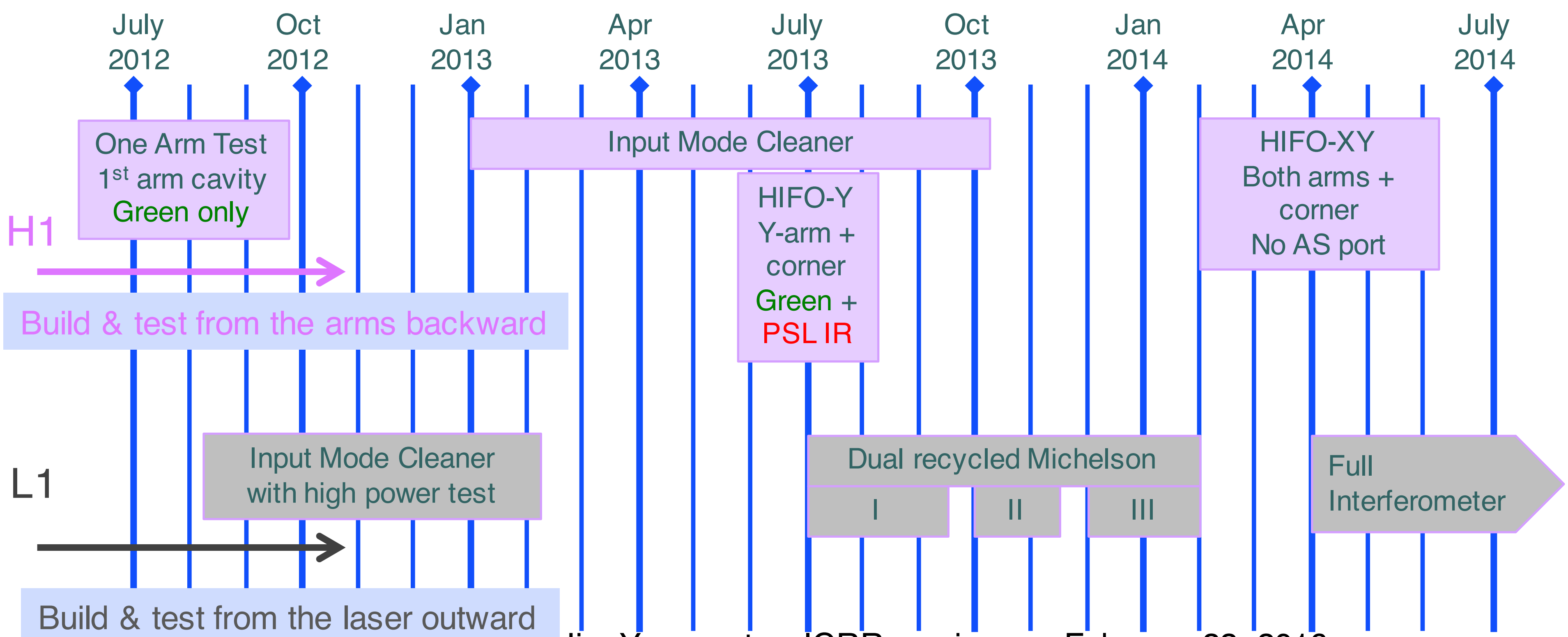


- Lock acquisition strategy designed in from the start, including a new Arm Length Stabilization system
  - Enables a controlled acquisition process

- *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



LIGO
SEPTEMBER 14, 2015


Drever

LIGO Chronology

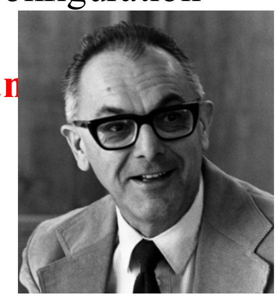
idea to realization ~ 15 years


Weiss

Real size R&D for the real detection

Journey for the new astronomy

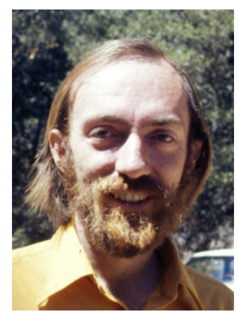
1970s		Feasibility studies and early work on laser interferometer gravitational-wave detectors
1979		National Science Foundation (NSF) funds Caltech and MIT for laser interferometer R&D
1984		Development of multiple pendulum Advanced LIGO Concept
1989	**December**	**Construction proposal for LIGO submitted 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

Initial LIGO events

Advanced LIGO events

R&D of aLIGO using iLIGO facility

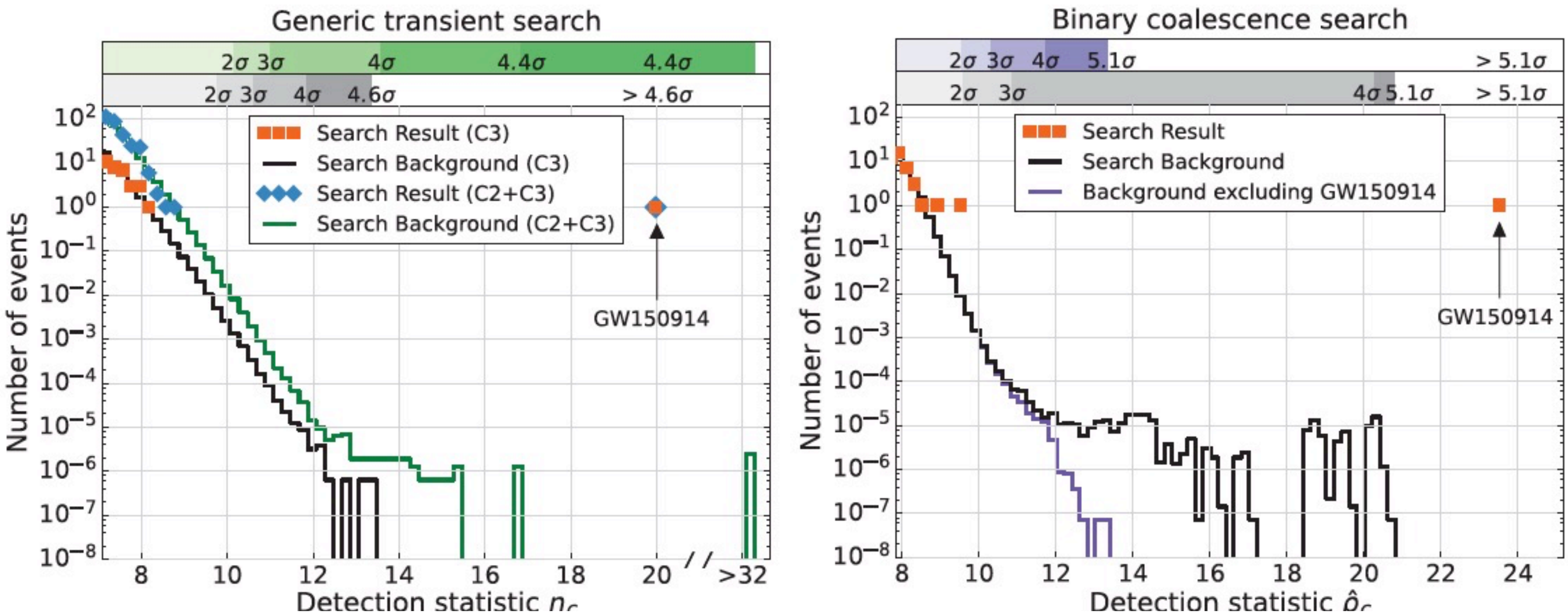

Thorn

Executive producer & consultant of movie “Interstellar”

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 stars
  - » 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

Significance

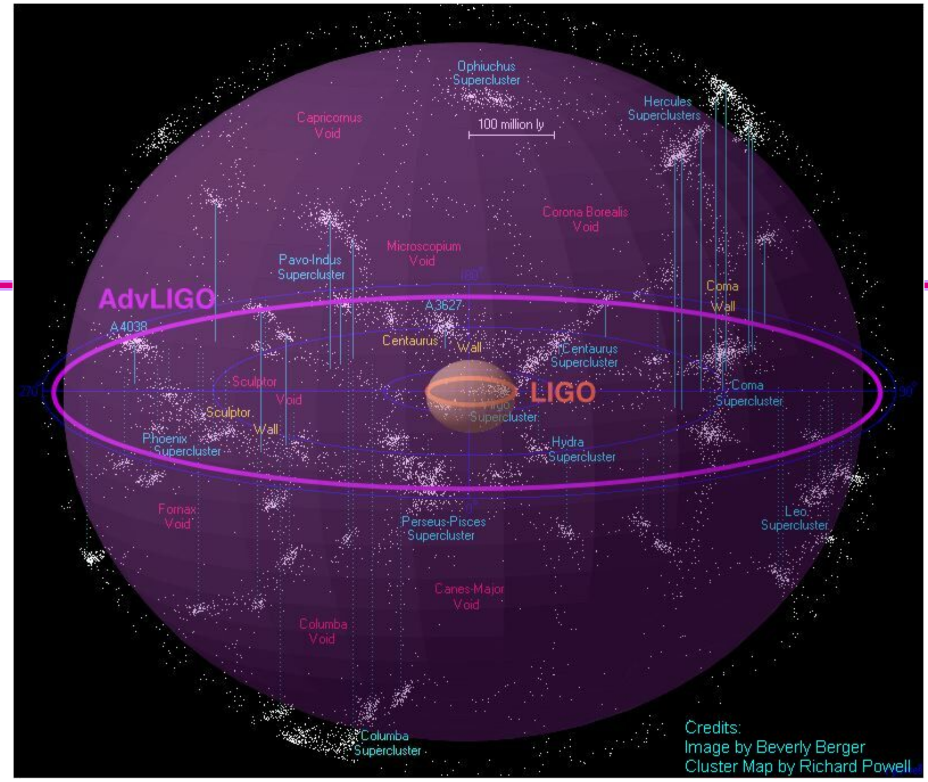


Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ (M$_\odot$)	m_1 (M$_\odot$)	m_2 (M$_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 ($2.1\,\sigma$)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

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
- Long term upgrade
  - » Third IFO to be joined
  - » Voyager – use LIGO facility, cryogenic, Silicon, 2μ laser
  - » Cosmic Explorer – new facility, very long arm

Advanced LIGO ~ BNS rates



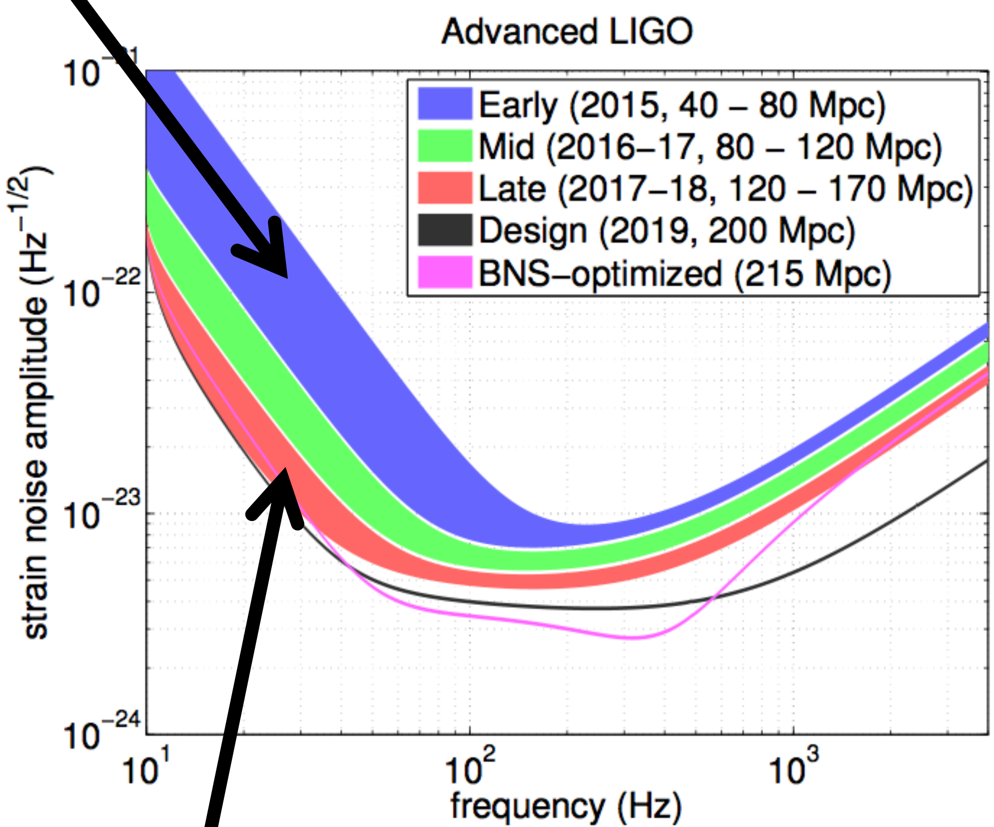
#events by advanced LIGO ~
1000 x #events by initial LIGO

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	BNS Range (Mpc) 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

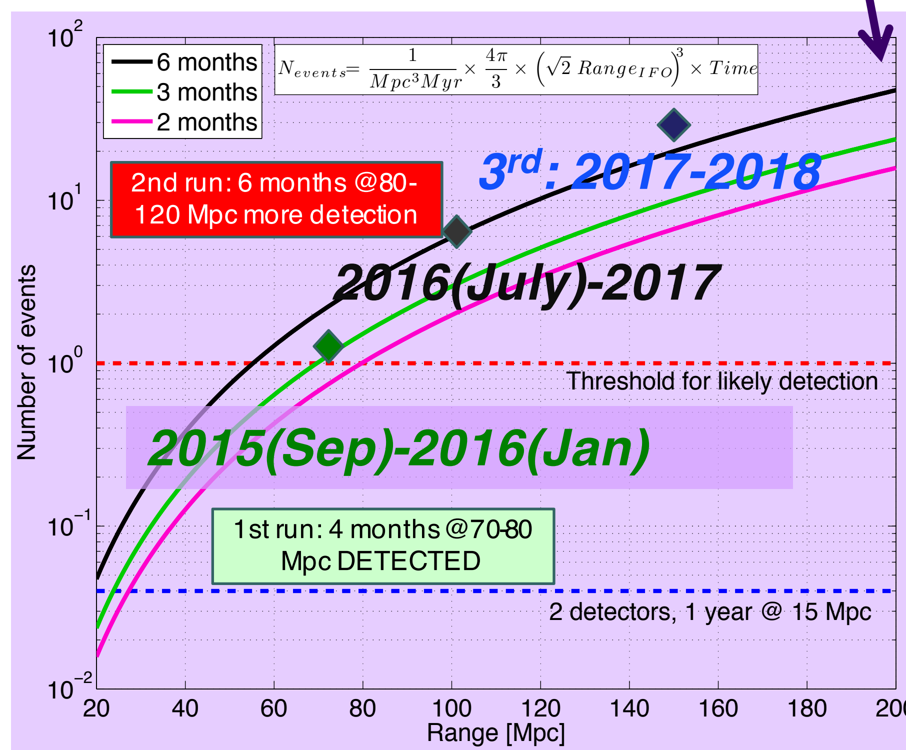
Planning for Advanced LIGO Science

Detected

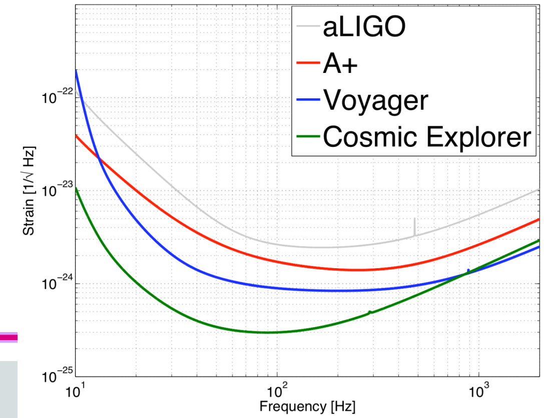


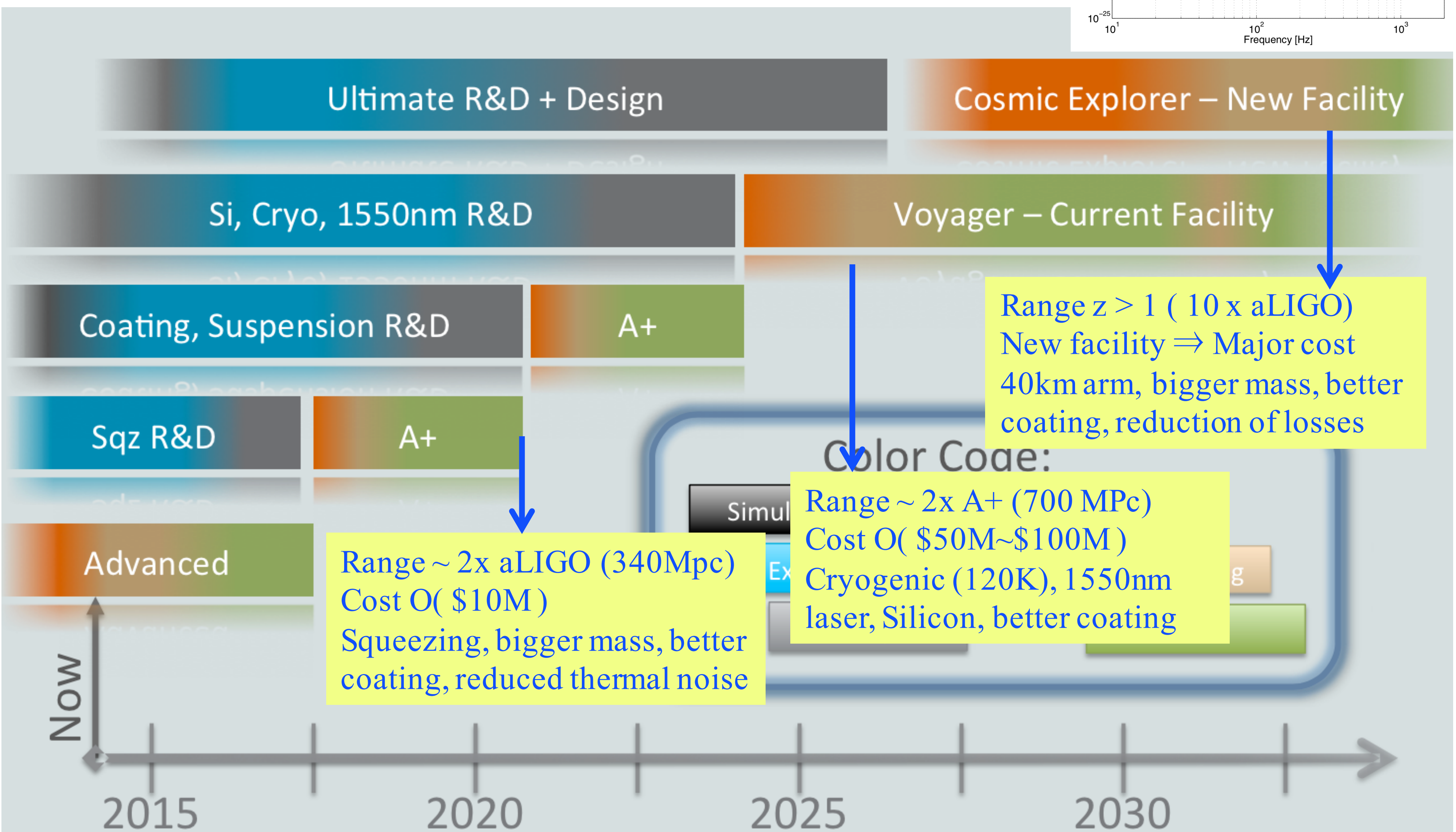
Astronomy

Full sensitivity (200 Mpc): end-2018



Aiming for the future
beyond advanced LIGO





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

- 1006 members, 83 institutions, 15 countries

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

LIGO
SEPTEMBER 14, 2015

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

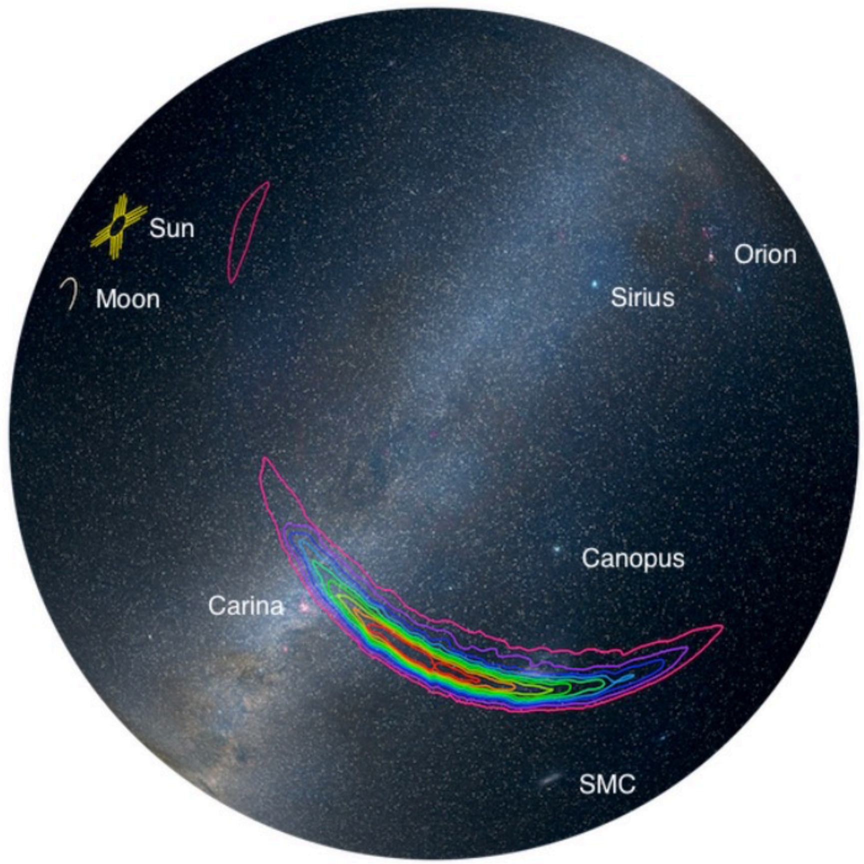
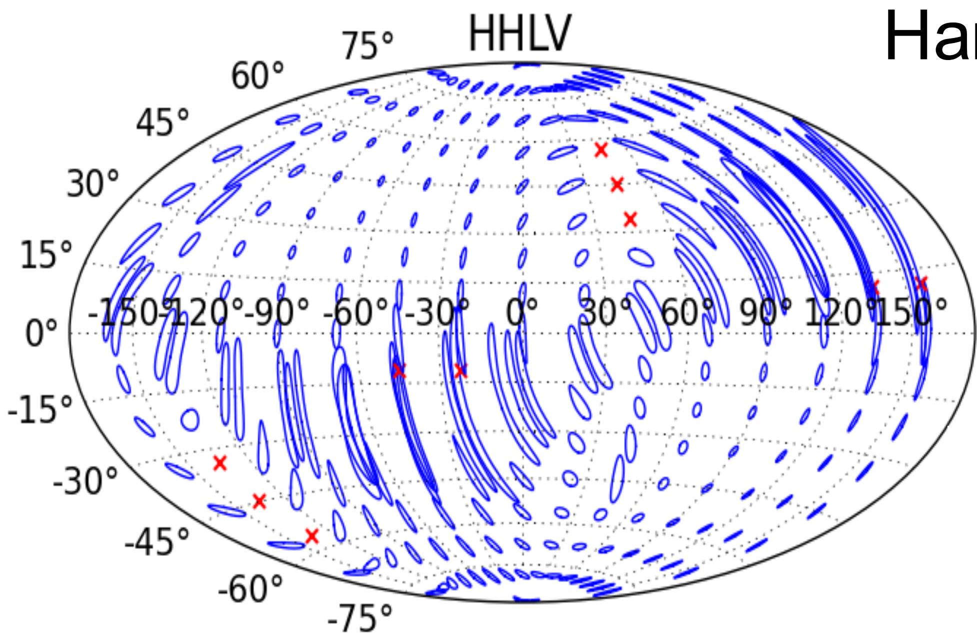


FIG. 4. An orthographic projection of the PDF for the sky location of GW150914 showing contours of the 50% and 90% credible regions plotted over a colour-coded PDF. The sky localization forms part of an annulus, set by the time delay of $6.9^{+0.5}_{-0.4}$ ms between the Livingston and Hanford detectors.

6

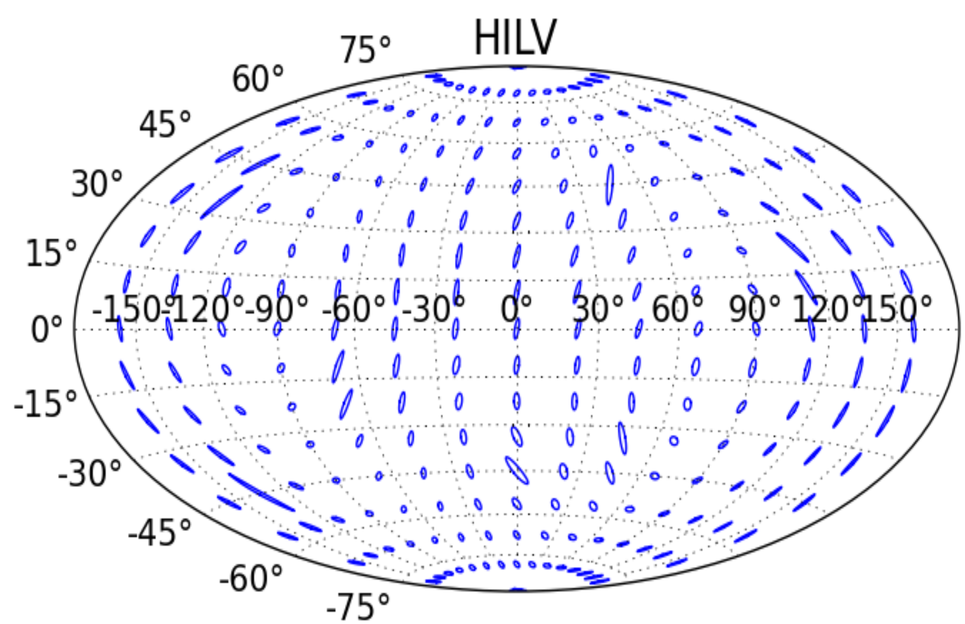
Improvement of Binary Neutron Star Merger Localization by Adding LIGO-India

Hanford+Livingston+one more



x denotes blind spots

Hanford+Livingston+two more



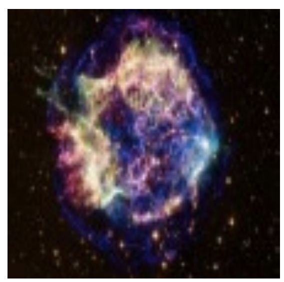
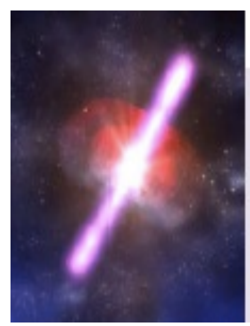
S. Fairhurst, "*Improved source localization with LIGO India*", *J. Phys.: Conf. Ser.* 484 012007

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

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.

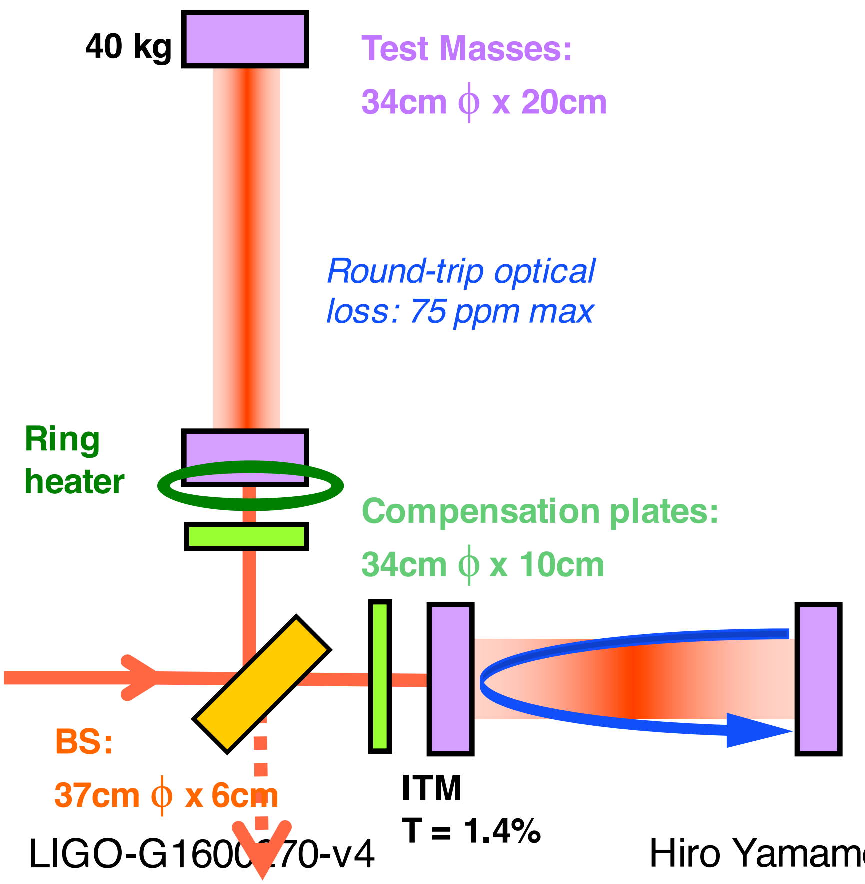

New era may be opening …

- Fermi GBM Observations of LIGO Gravitational Wave event GW150914 (arXiv:1602.03920v2)
  - » With an instantaneous view of 70% of the sky, the Fermi Gamma-ray Burst Monitor (GBM) is an excellent partner in the search for electromagnetic counterparts to gravitational wave (GW) events. GBM observations at the time of the Laser Interferometer Gravitational-wave Observatory (LIGO) event GW150914 reveal the presence of a weak transient source above 50 keV, 0.4 s after the GW event was detected, with a false alarm probability of 0.0022.
  - » Message from Tsune Kamae : FermiのGlastBurstMonitor（NaaIとBGOのシンチレータからなる、簡単にモニター）だけで、受かっています。信号は小さいのですが、タイミングが、ほぼドンピシャリなので、本当に何かあったのだと思います。NS-NSではもっと大量のガンマ線が出ると予想されています。ビーミングでずれていたのかもしれません。BH-BHなら、強いガンマ線が予言されていないのですが、どこまで精密に計算されているのかは判りません。
- ELECTROMAGNETIC COUNTERPARTS TO BLACK HOLE MERGERS DETECTED BY LIGO (non-LSC publication) (A. Loeb, arXiv:1602.04735v1)
  - » Message from Patrick Brady : Welcome to astronomy! This is great.

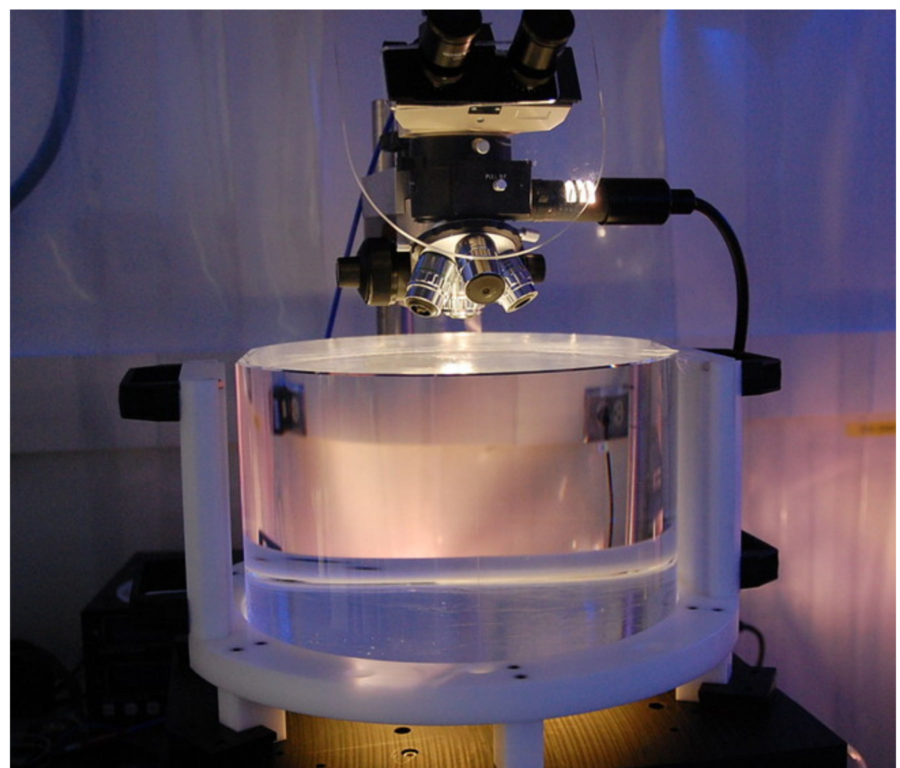
End of slides

Test Masses with thermal compensation system

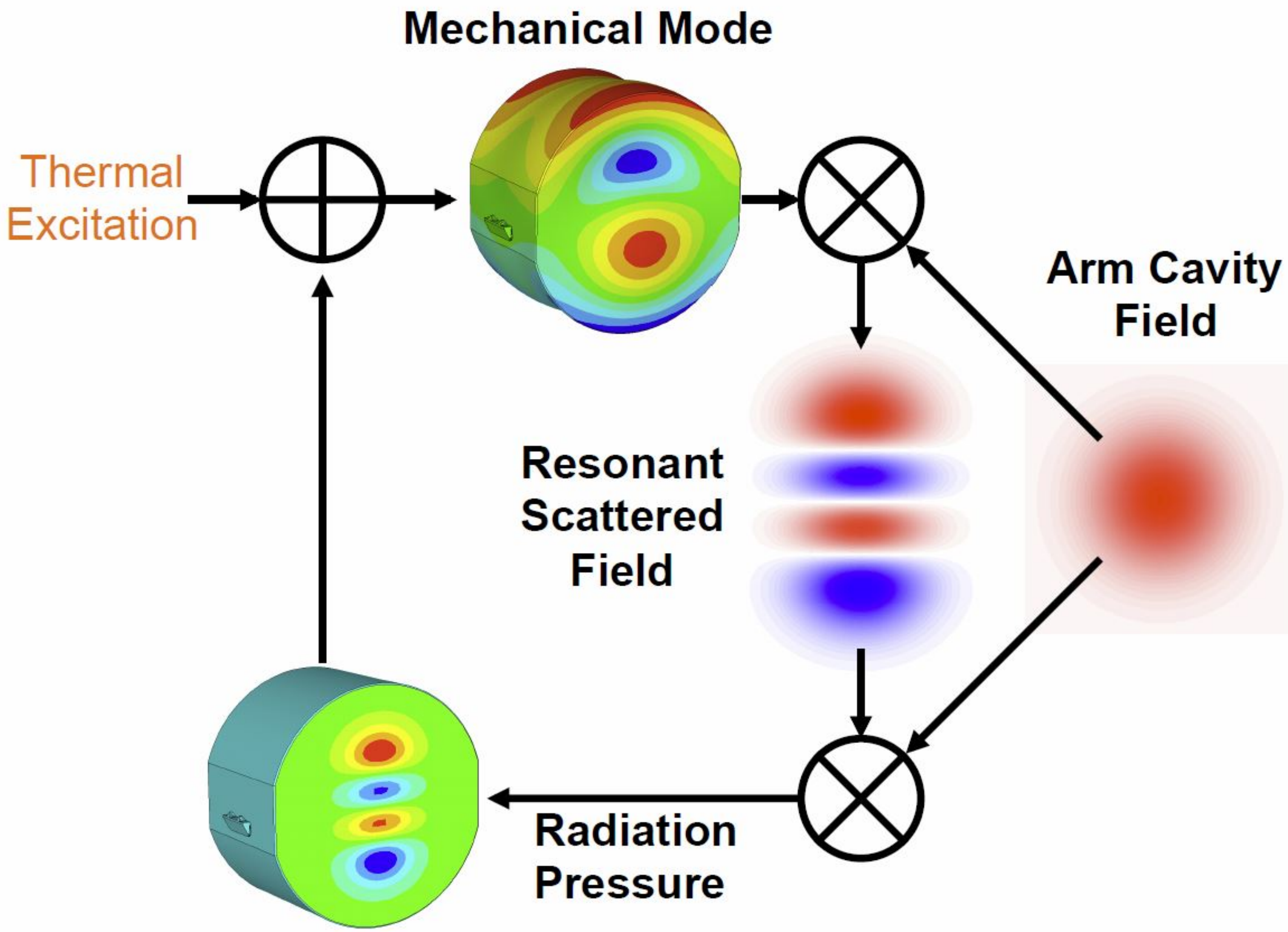
- Requires the state of the art in substrates, polishing and coating
  - » Fabri-Perot cavity is used to measure arm length or space distortion



- 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



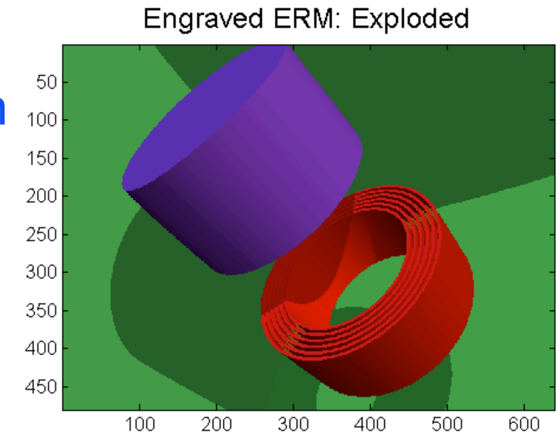
Three major issues
(2) Parametric Instabilities



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



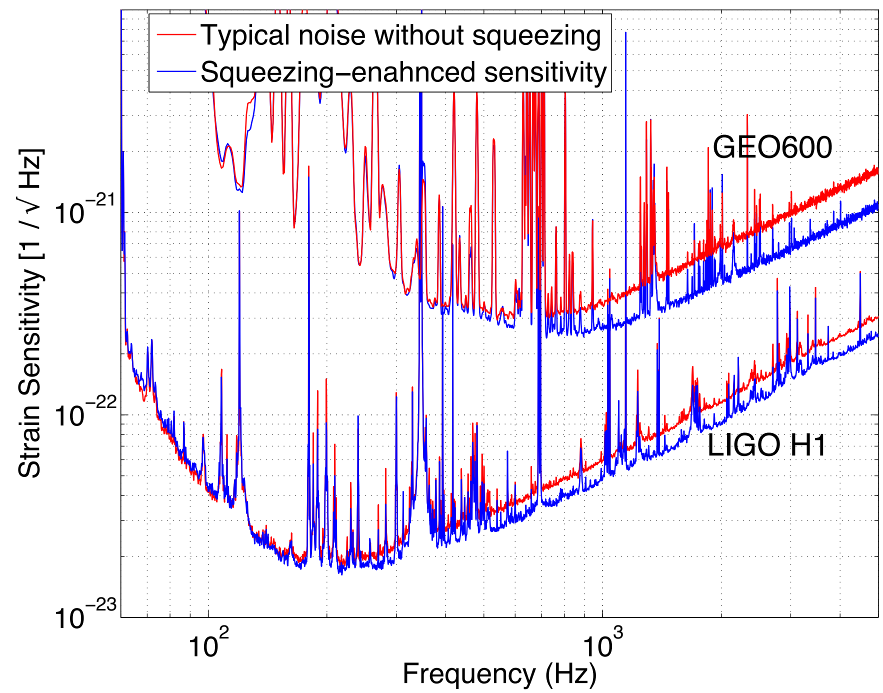
Squeezed Light in LIGO

suppressing quantum noise without increasing power

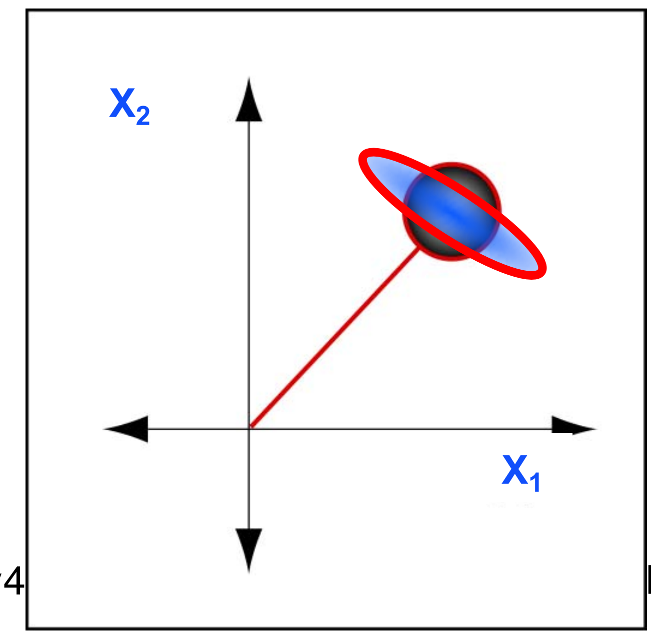
- Heisenberg Uncertainty Principle

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

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

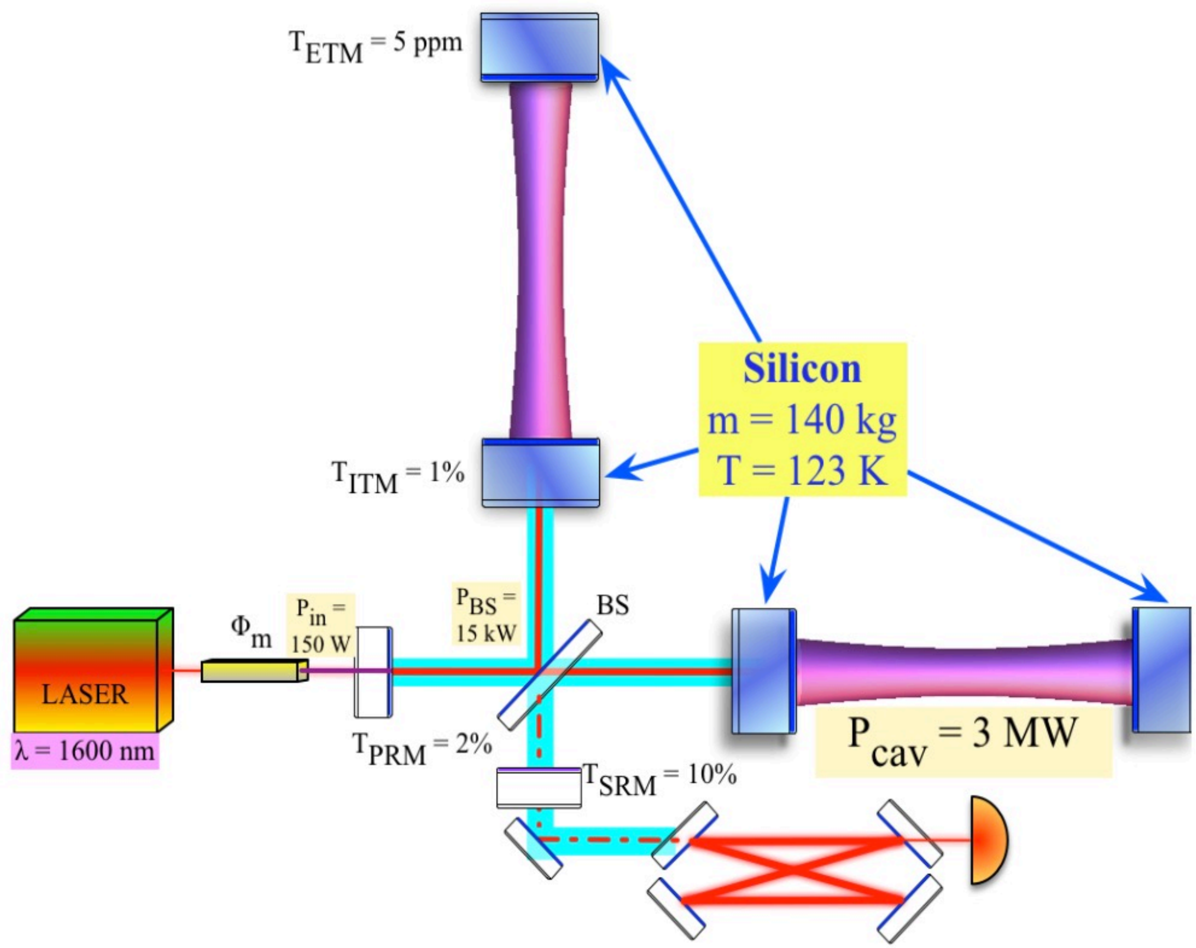


X_1 and X_2 associated with amplitude and phase



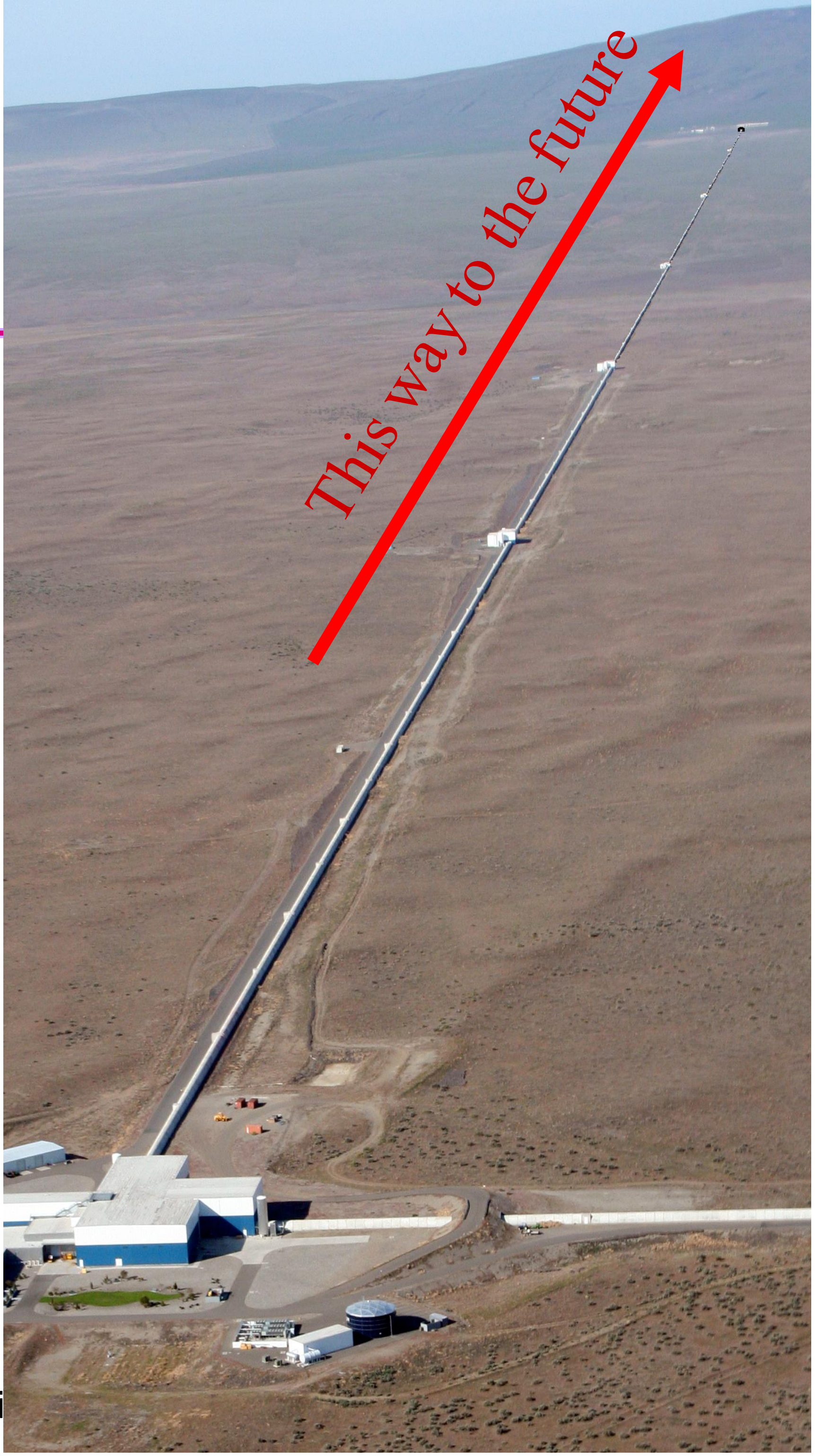
Aasi, et al., (LIGO Scientific Collaboration), Nature Physics, 7, 962 (2011); Nature Photonics 7 613 (2013).

Cryogenic in Voyger

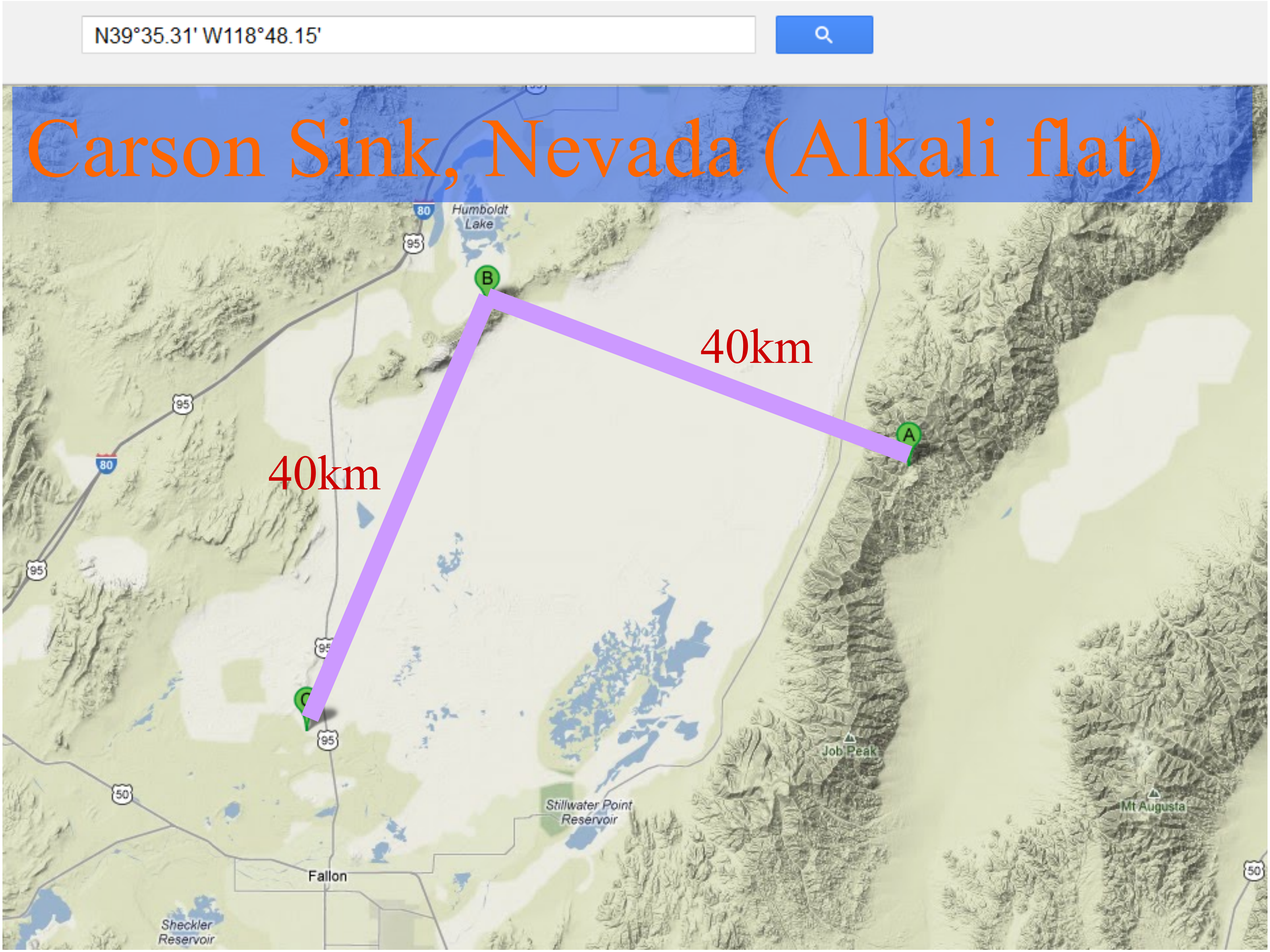


Cosmic Explorer : Long is good

- 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

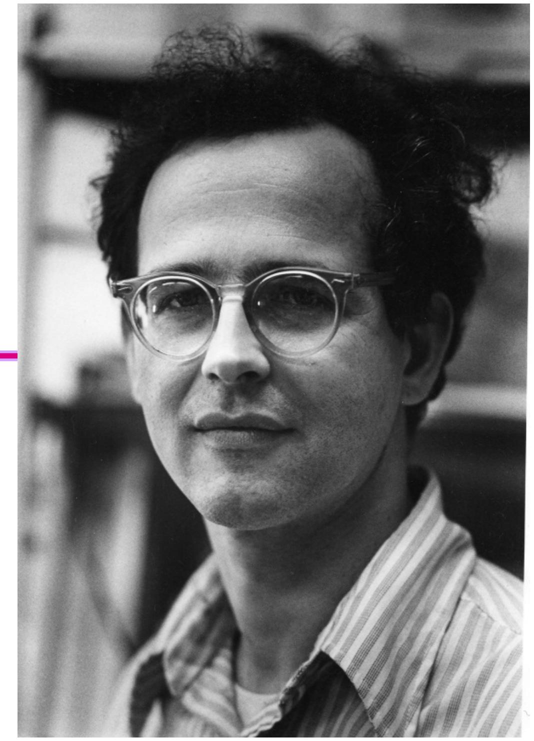


Carson Sink, Nevada (Alkali flat)



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

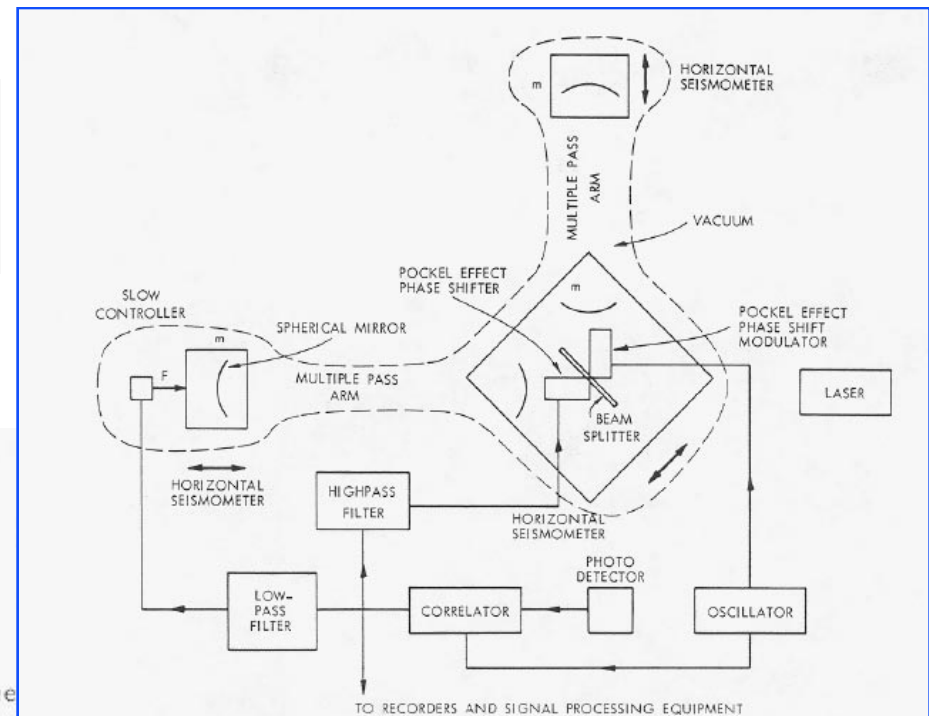
CAMBRIDGE, MASSACHUSETTS 02139

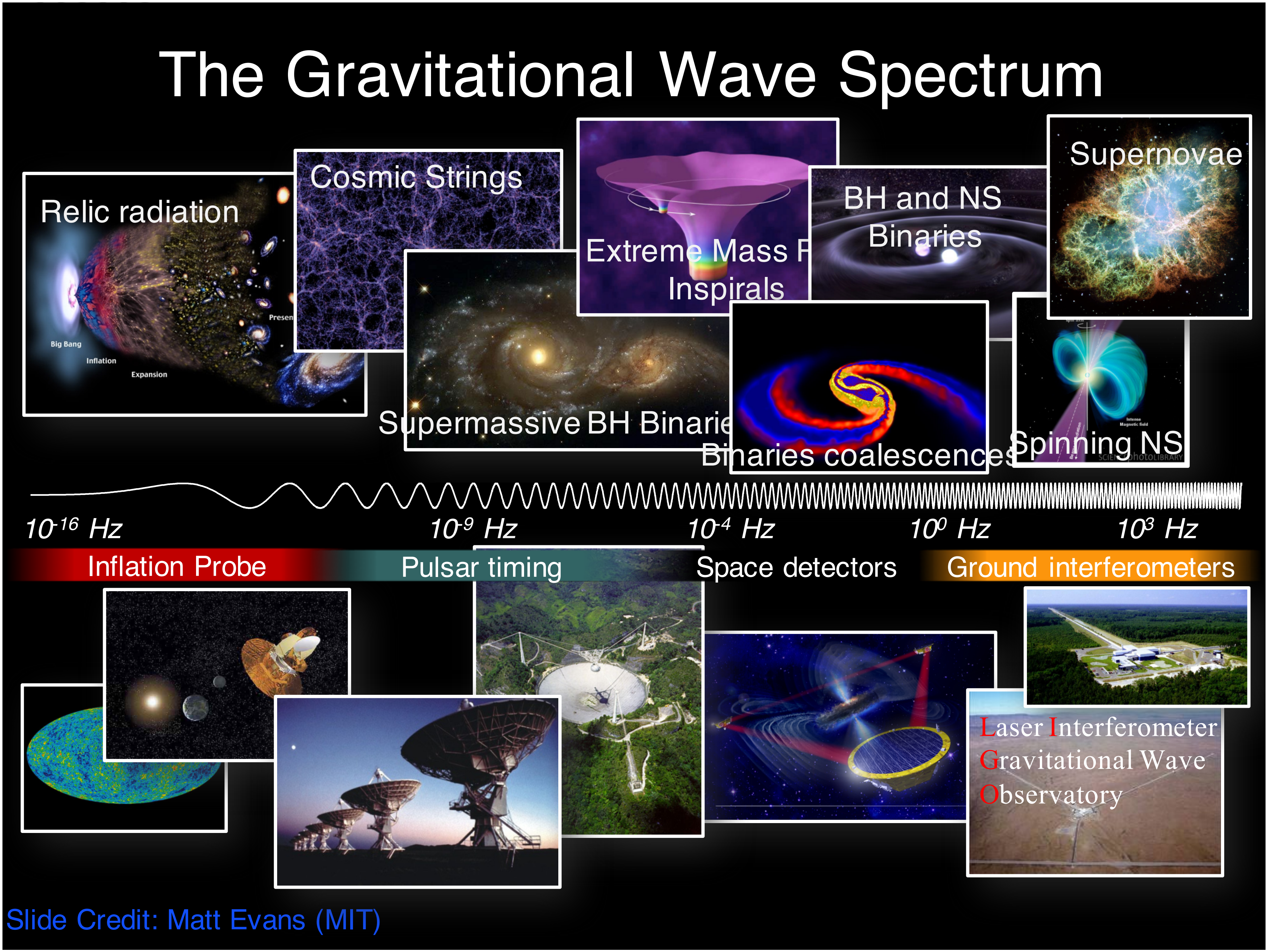
(V. GRAVITATION RESEARCH)

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

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




The Gravitational Wave Spectrum
Relic radiation
Big Bang
Inflation
Expansion
Cosmic Strings
Extreme Mass R
Inspirals
BH and NS
Binaries
Supernovae
Supermassive BH Binaries
Binaries coalescences
Spinning NS
10-16 Hz
10-9 Hz
10-4 Hz
100 Hz
103 Hz
Inflation Probe
Pulsar timing
Space detectors
Ground interferometers
Laser Interferometer
Gravitational Wave
Observatory
Slide Credit: Matt Evans (MIT)