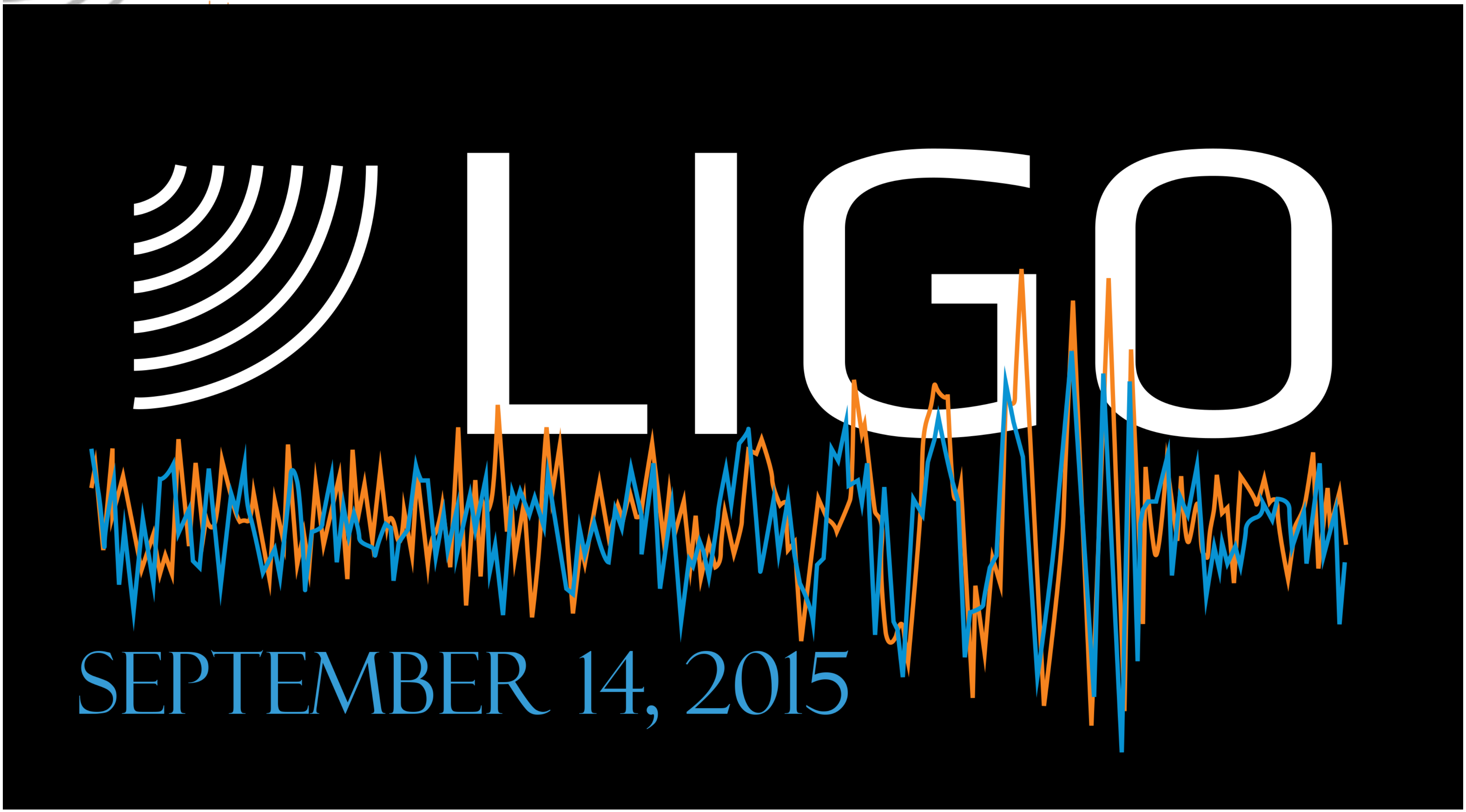
Observation of Gravitational Waves from a Binary Black Hope Merger



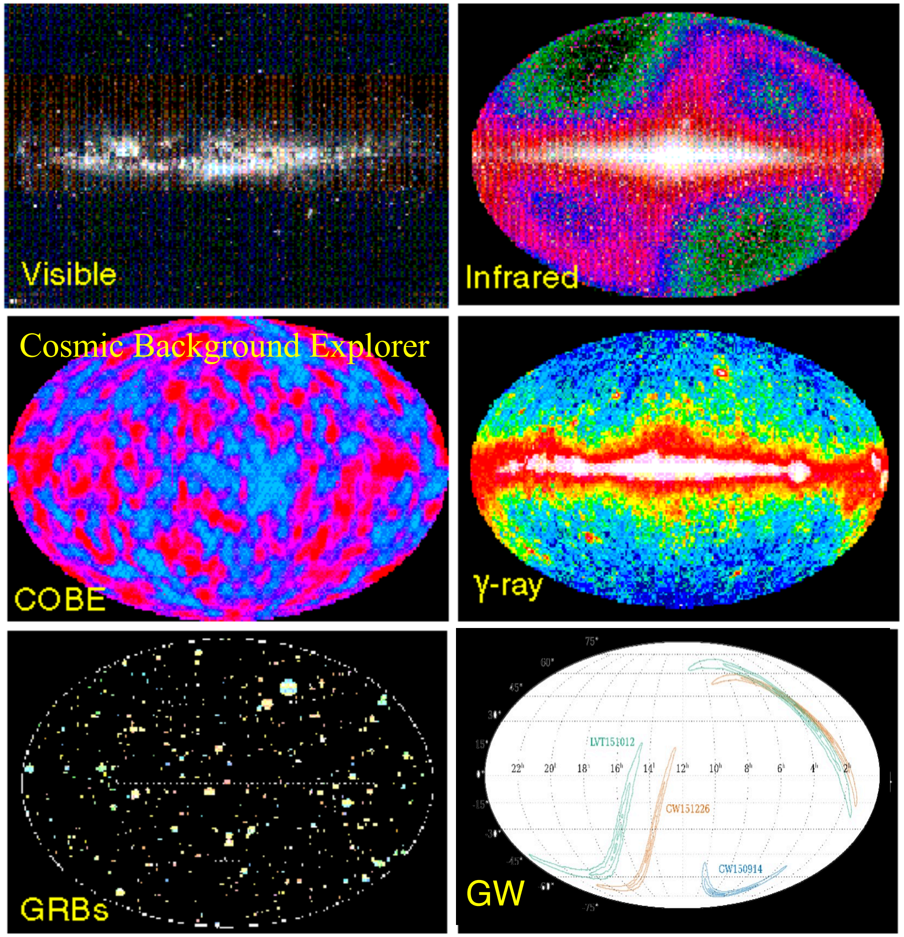
Hiro Yamamoto LIGO Lab / Caltech


National Science Foundation
NSF
NSF

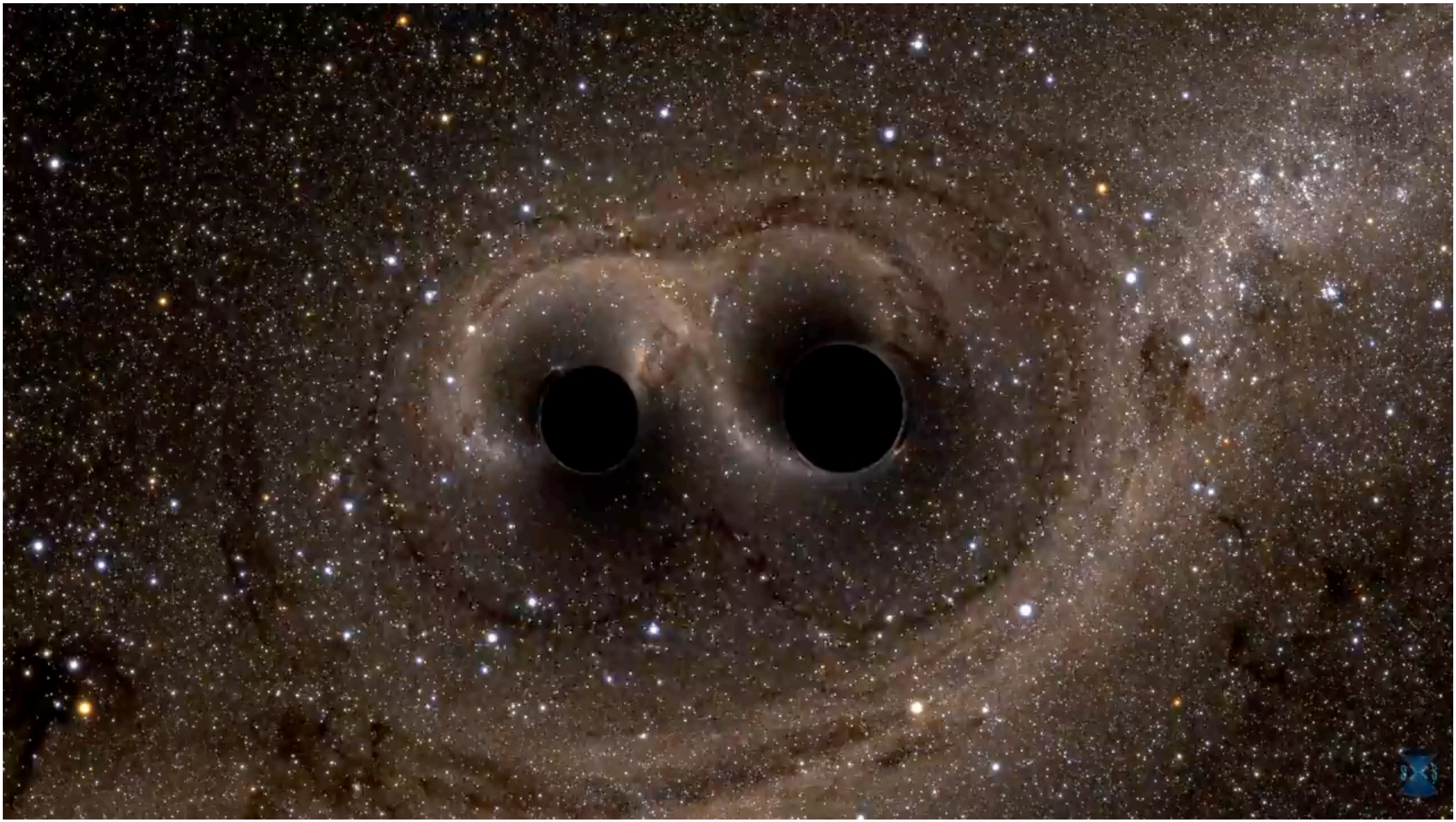
Detection of gravitational wave signals by Advanced LIGO : Past, Present and Future

Hiro Yamamoto LIGO lab/Caltech

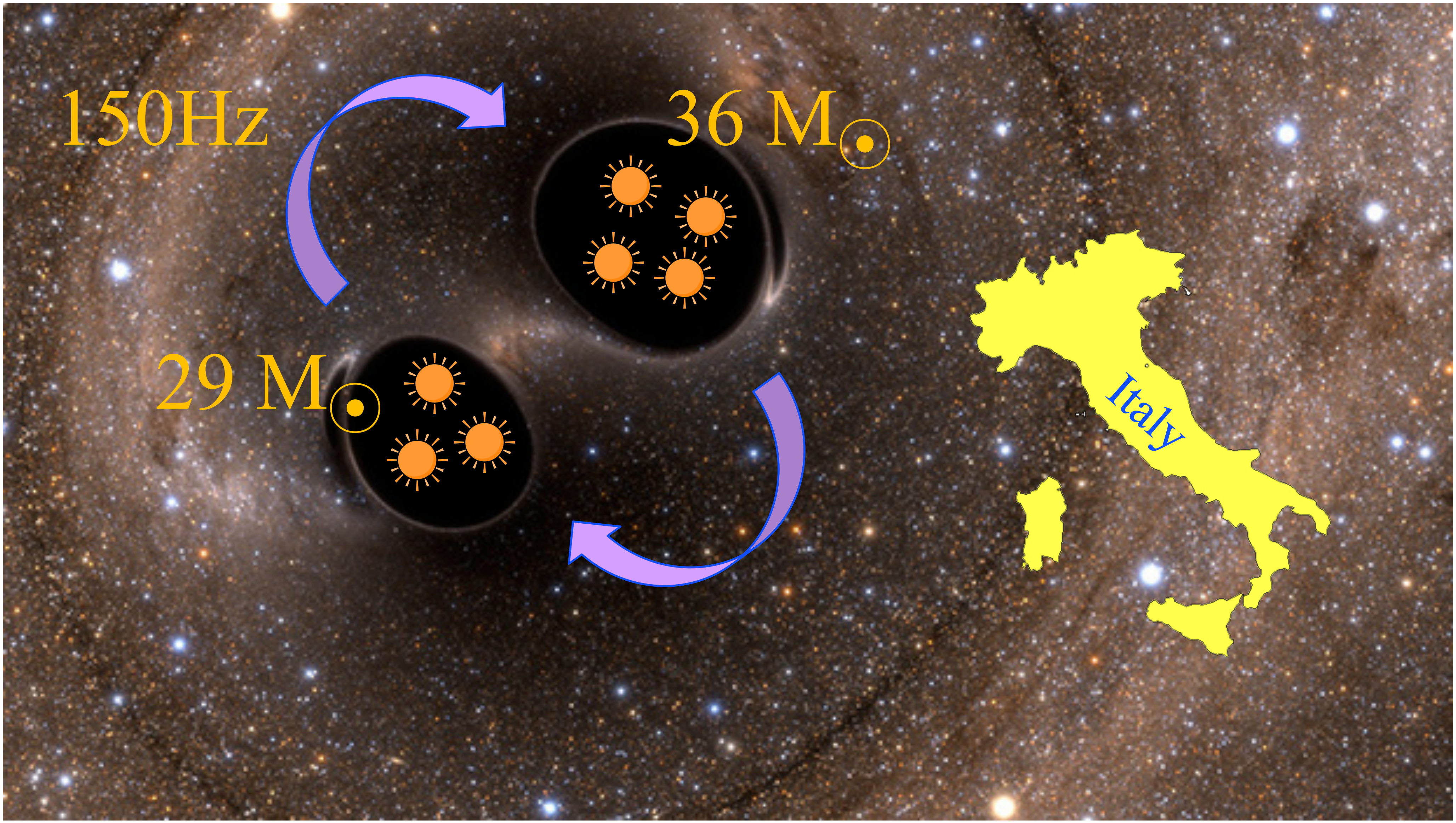
- New Astronomy by gravitational wave signal at the 100th memorial year of general relativity
  - » Just the beginning …
- How the GW signals look like
- Basics of interferometer or how to hear the GW signal?
- GW signal in advanced LIGO
- Scope for the future



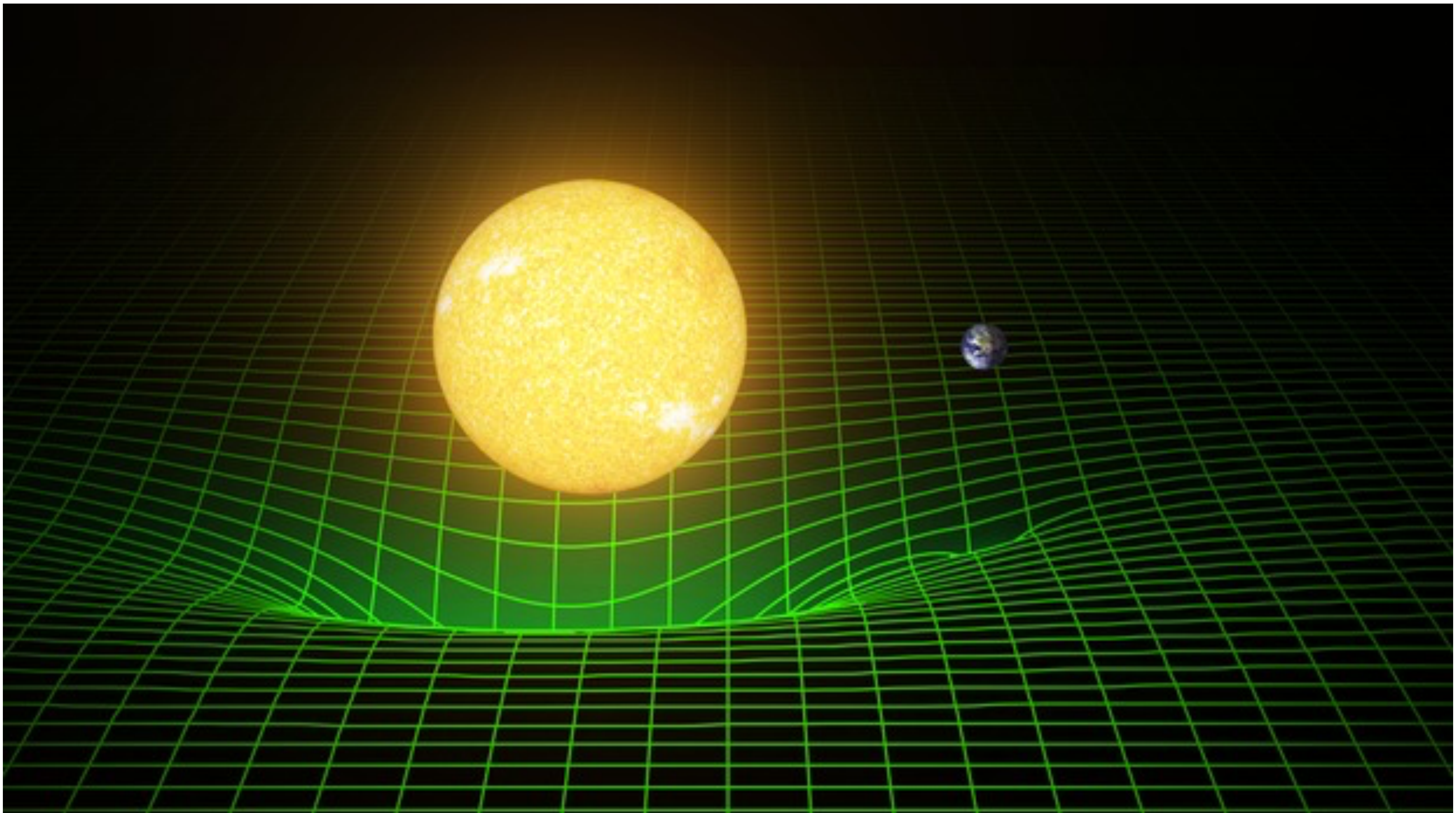
What happened long long time ago
- heavy black hole merger -



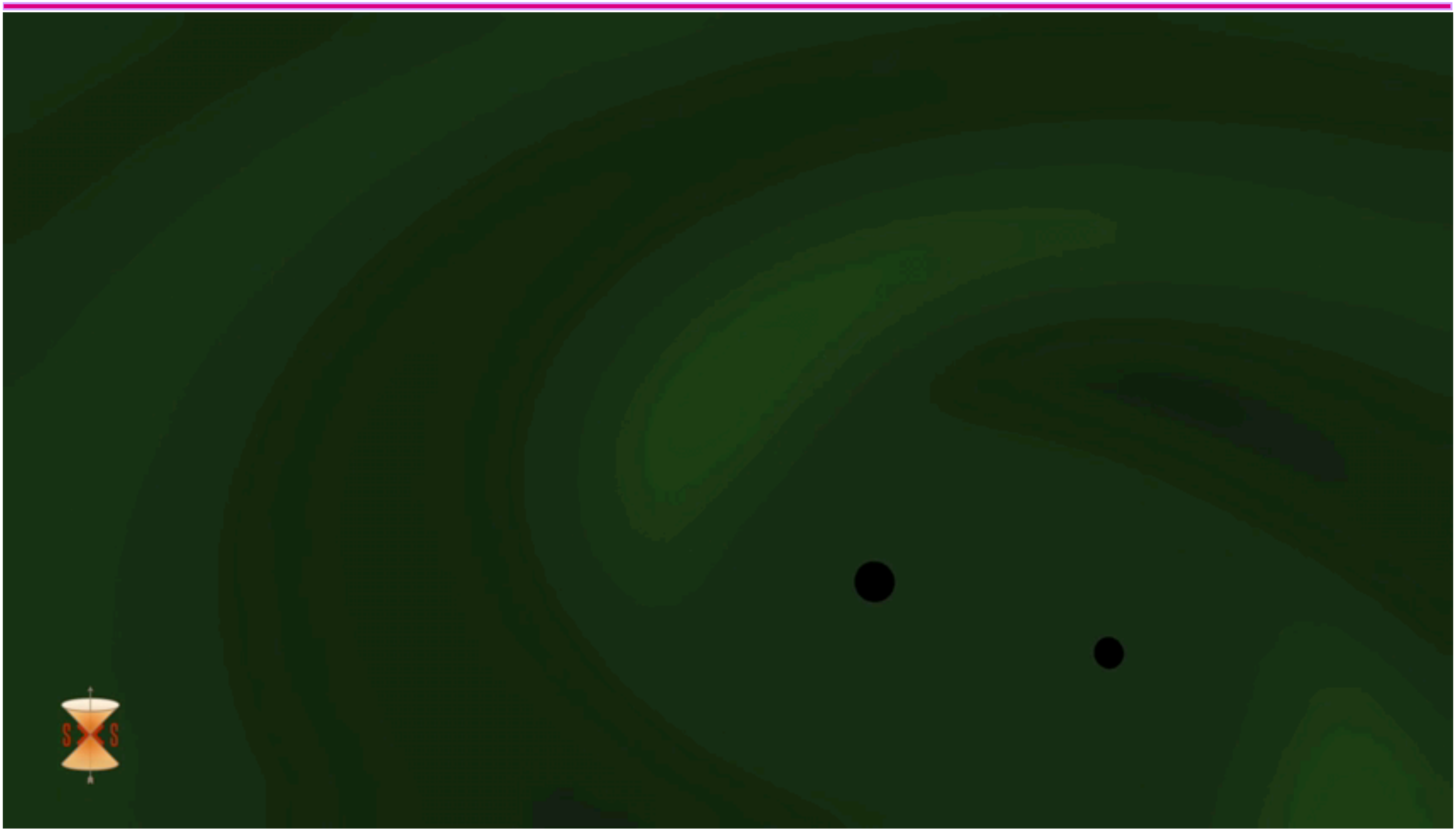
Scale of black hole merger
- 1.3 billion light year or 12000000000000000000000 km away -

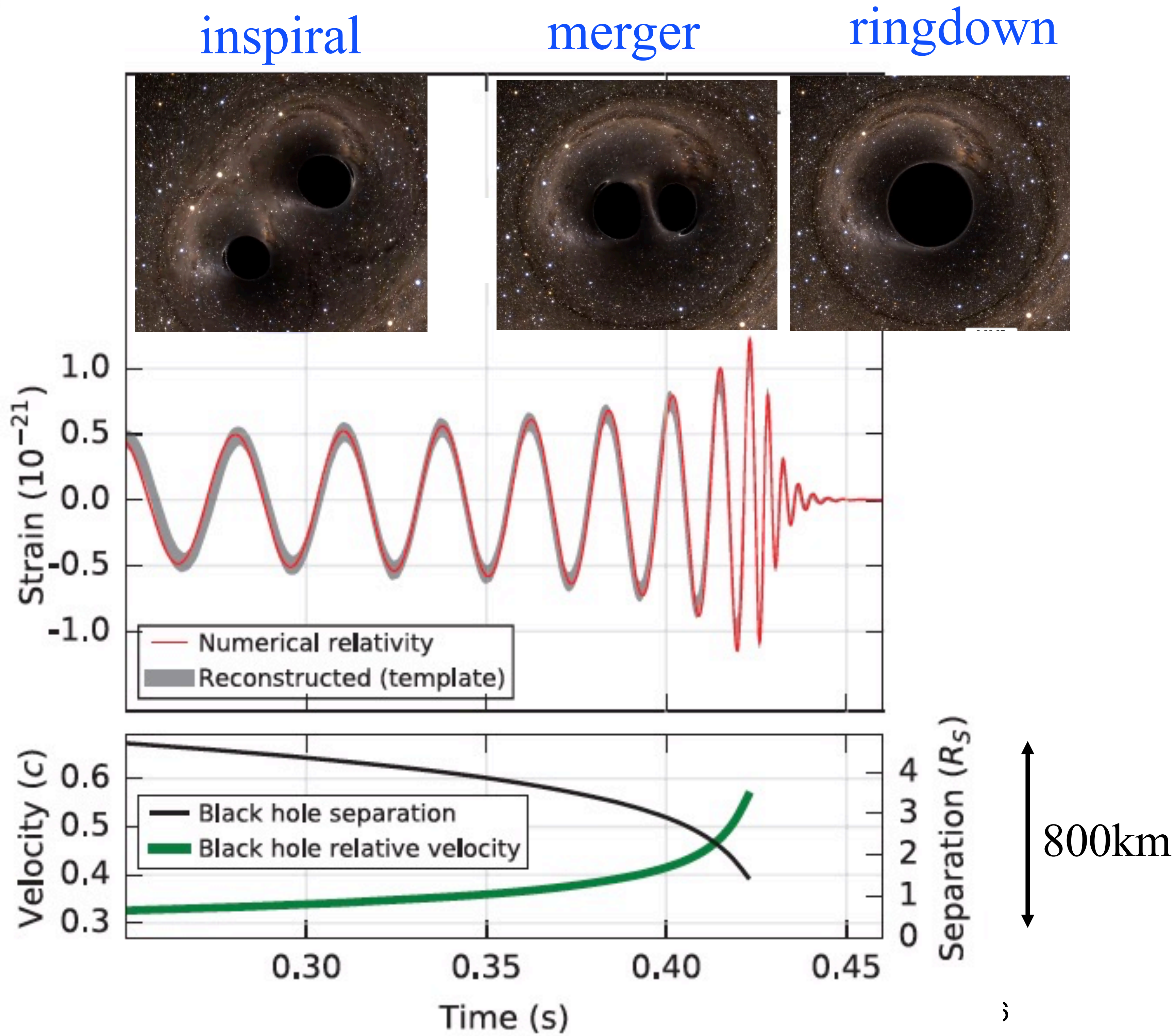


Massive bodies wrap space-time
- General relativities view of gravity -



Black Hole Waves Simulation

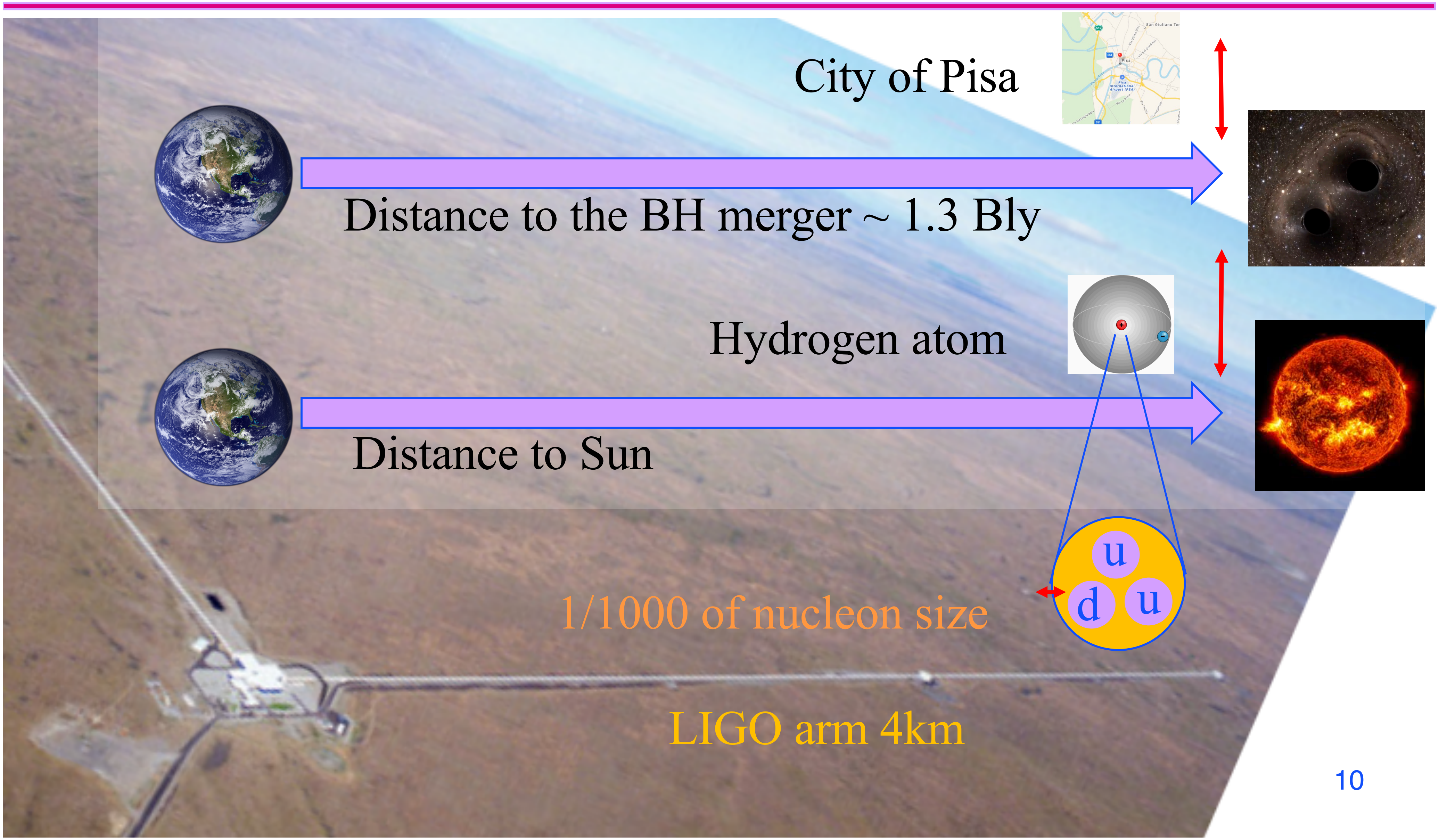



inspiral
merger
ringdown
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
800km
0.30
0.35
0.40
0.45
Time (s)

How much energy emitted

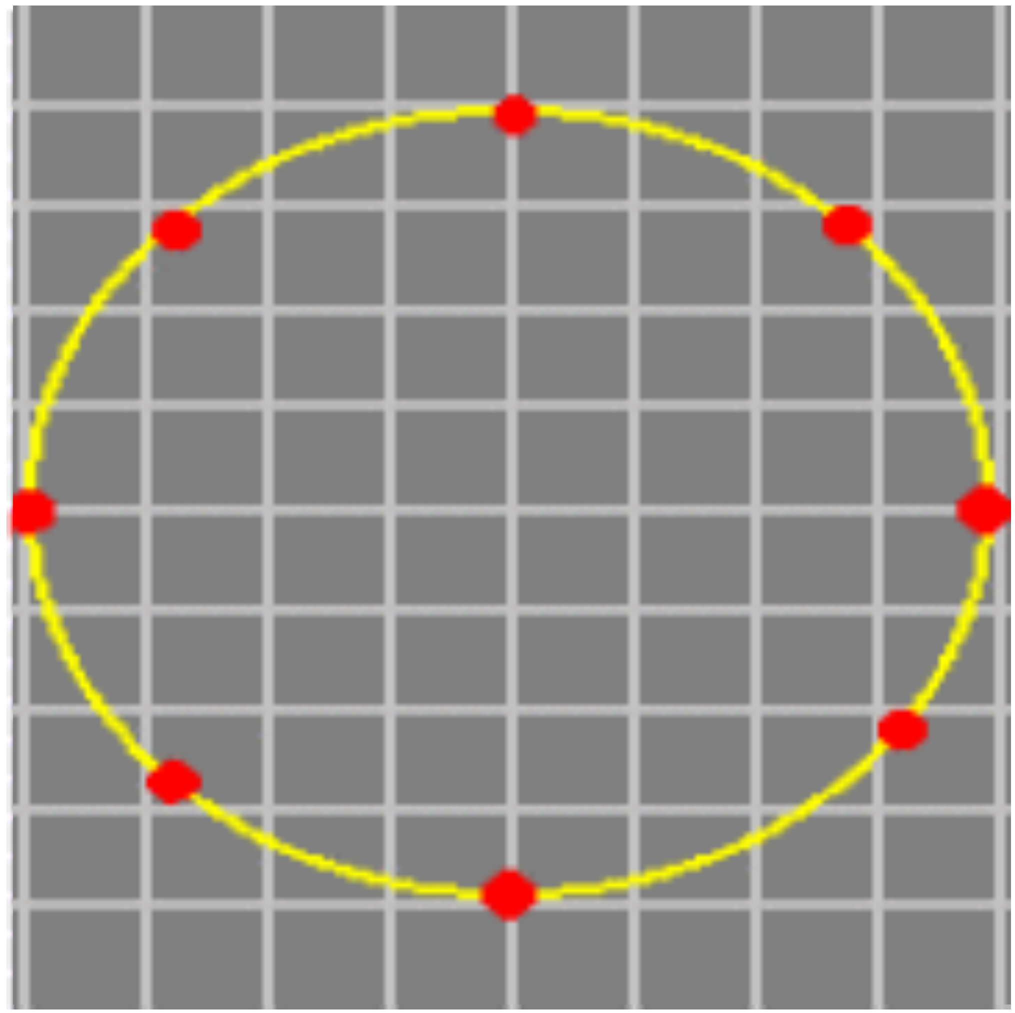
- 36 $M_\odot$ BH and 29 $M_\odot$ BH merged to form 62 $M_\odot$ BH
- Total energy released as GW : 3 $M_\odot$ c^2
- If all energy were released as light
  - » Peak luminosity of 3.6 x 10^{54} erg/s ~ 50 x EM energy output of all the stars in the observable universe
  - » The merger at 1.3 Bly away look as bright as a full moon, located only 1.3 light second away

Size of the effect of the GW on earth
- very very … weak -

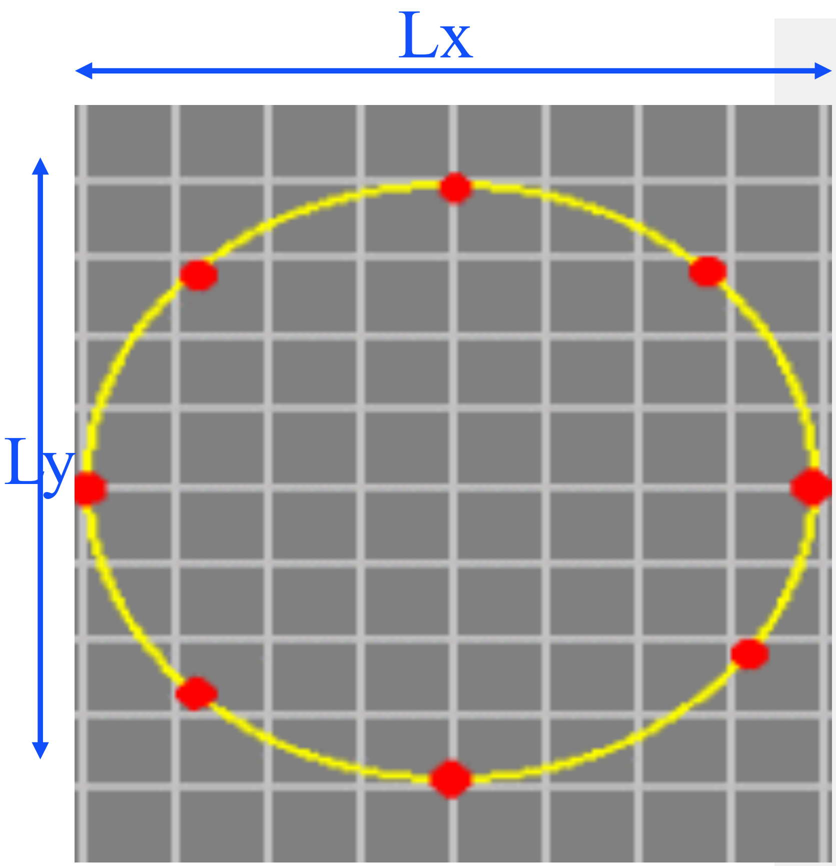


Distortion of space by GW

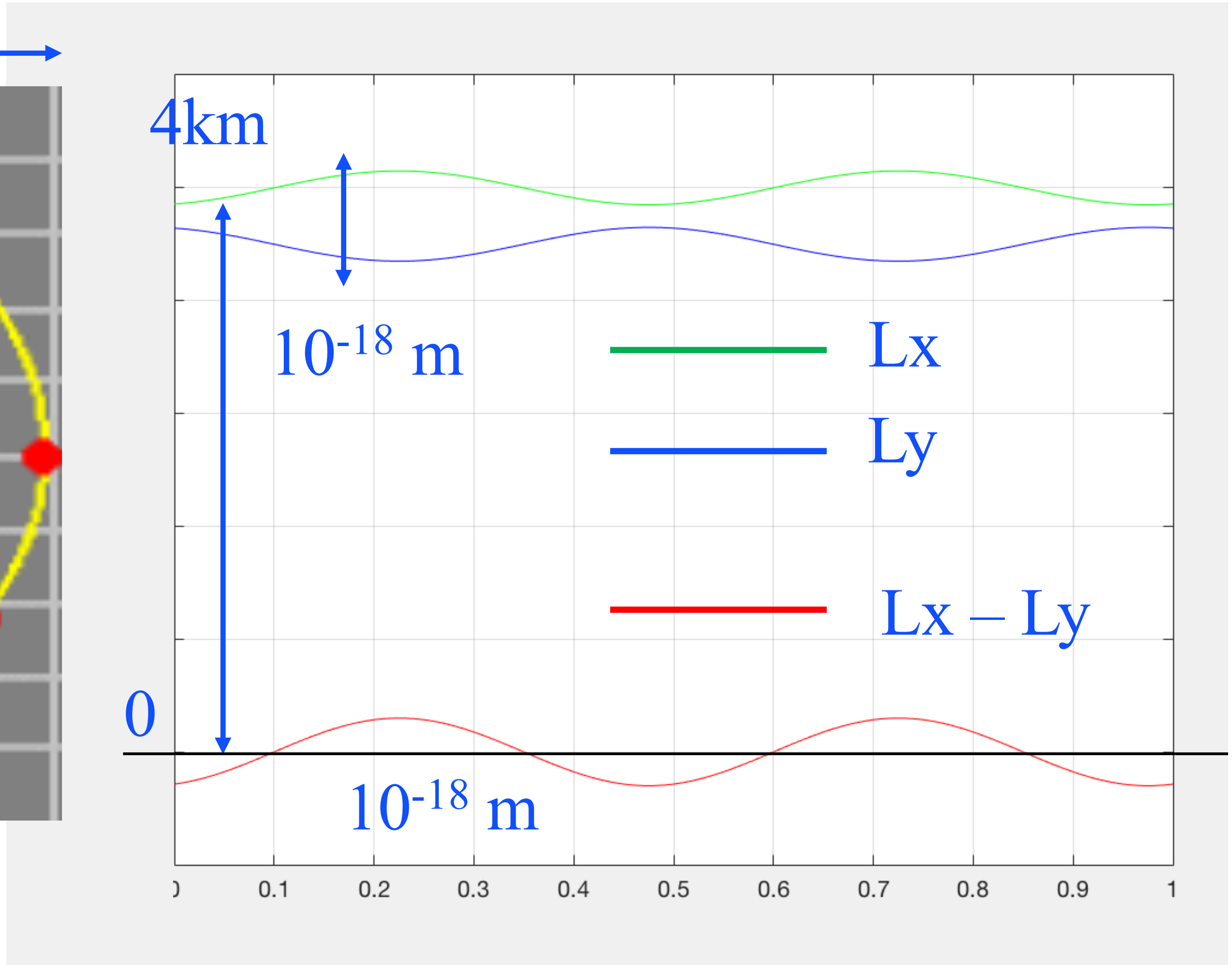
- Gravitational wave traveling into the picture
- Change separation (ΔL) proportional to initial separation (L)
- Expand in one direction and shrink in the orthogonal direction



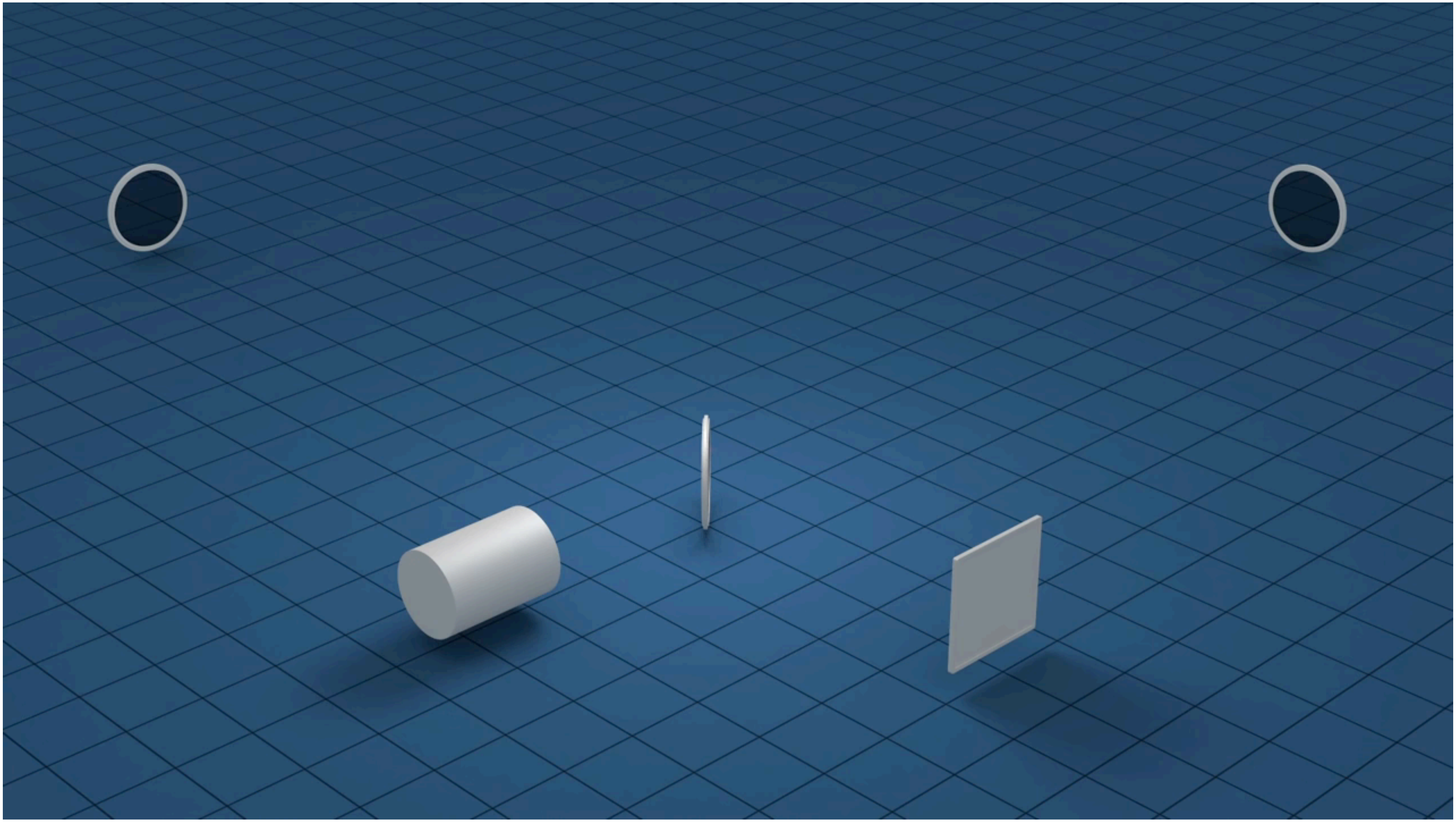
How to detect small variation? Basic idea



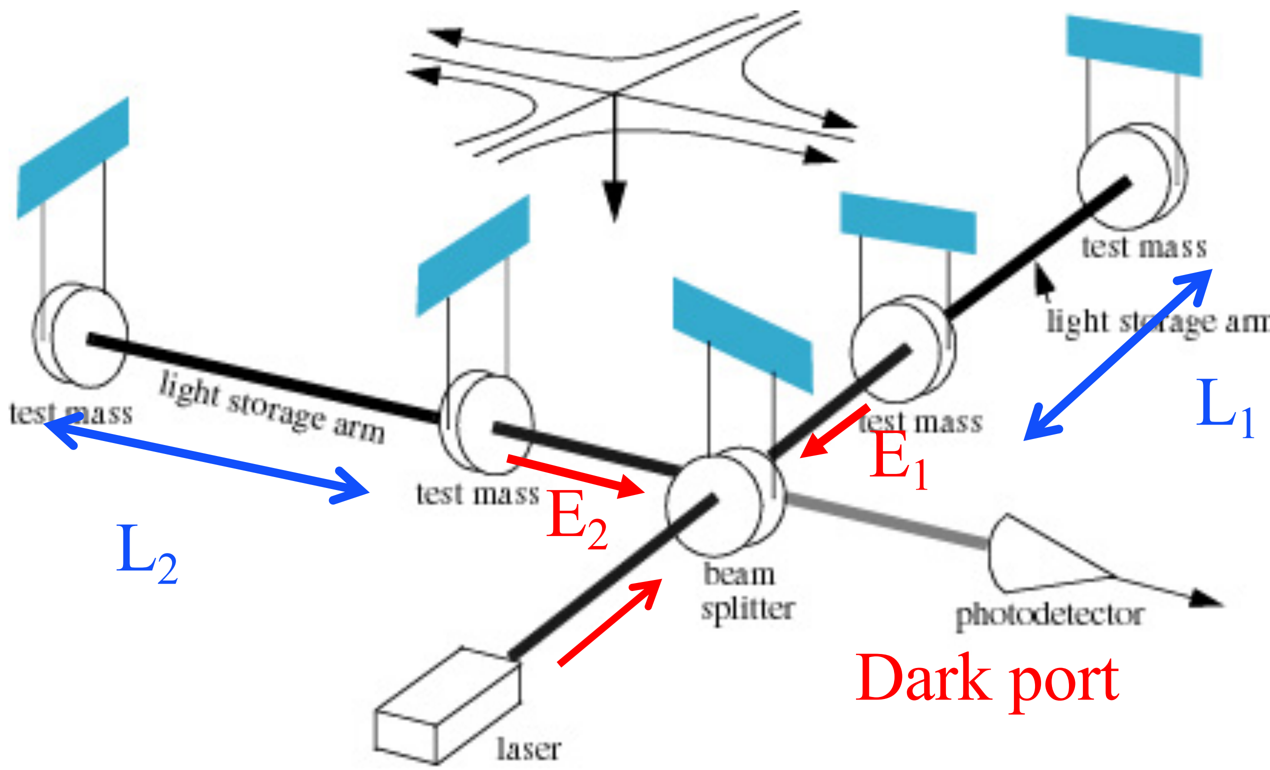
$\Delta L = h\ L$



How to detect small variation?
Interferometer



Interferometer for GW detection



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

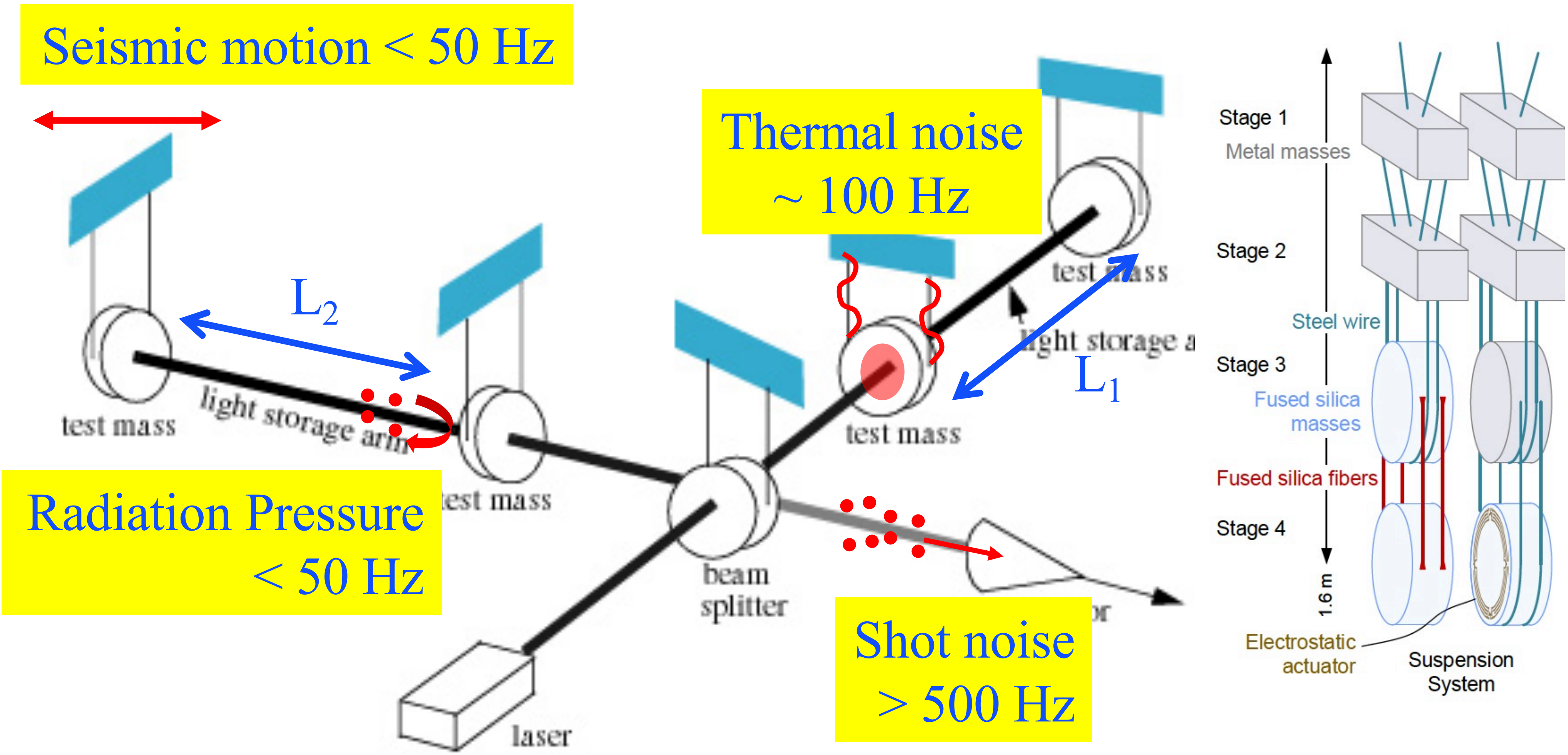
$E_1 - E_2 \propto \quad L_1 - L_2$

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

$h \sim 10^{-21}$

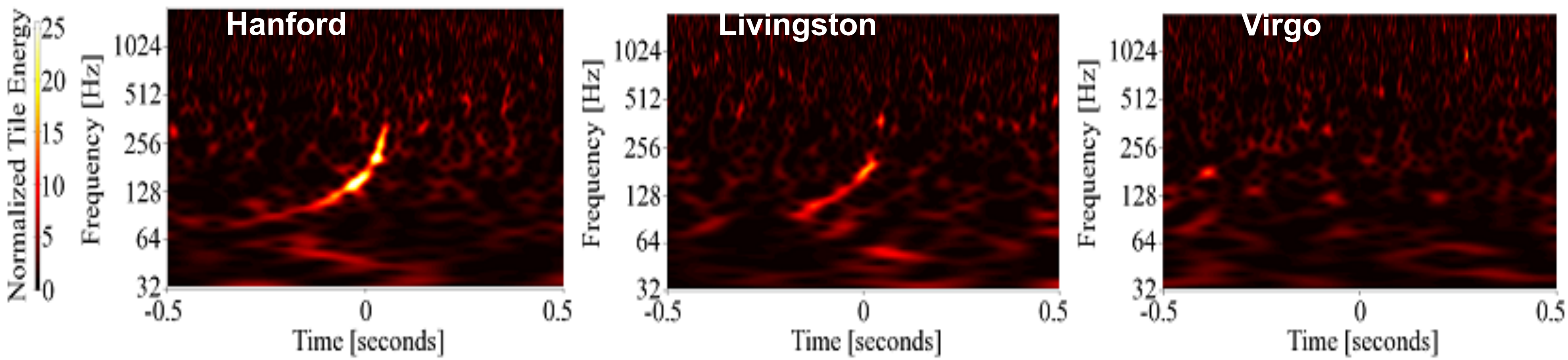
$L_1 - L_2 \sim 10^{-18}$m

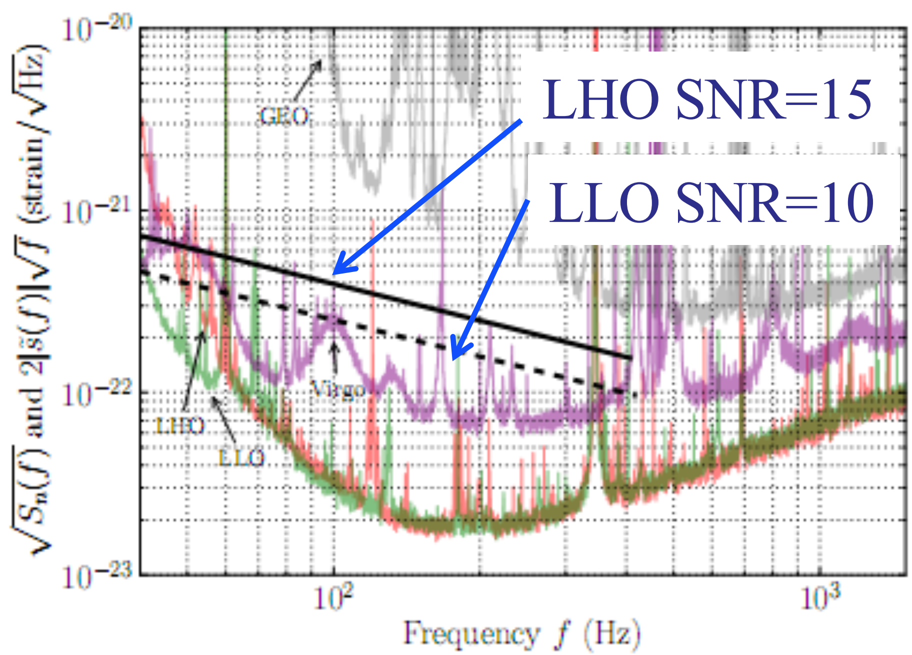
Noise sources of GW detectors - disturbance of L1-L2 -



FAKE Event GW100916: FAKE

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





LIGO sites

Hanford Observatory (H2K and H4K)

Livingston Observatory (L4K)

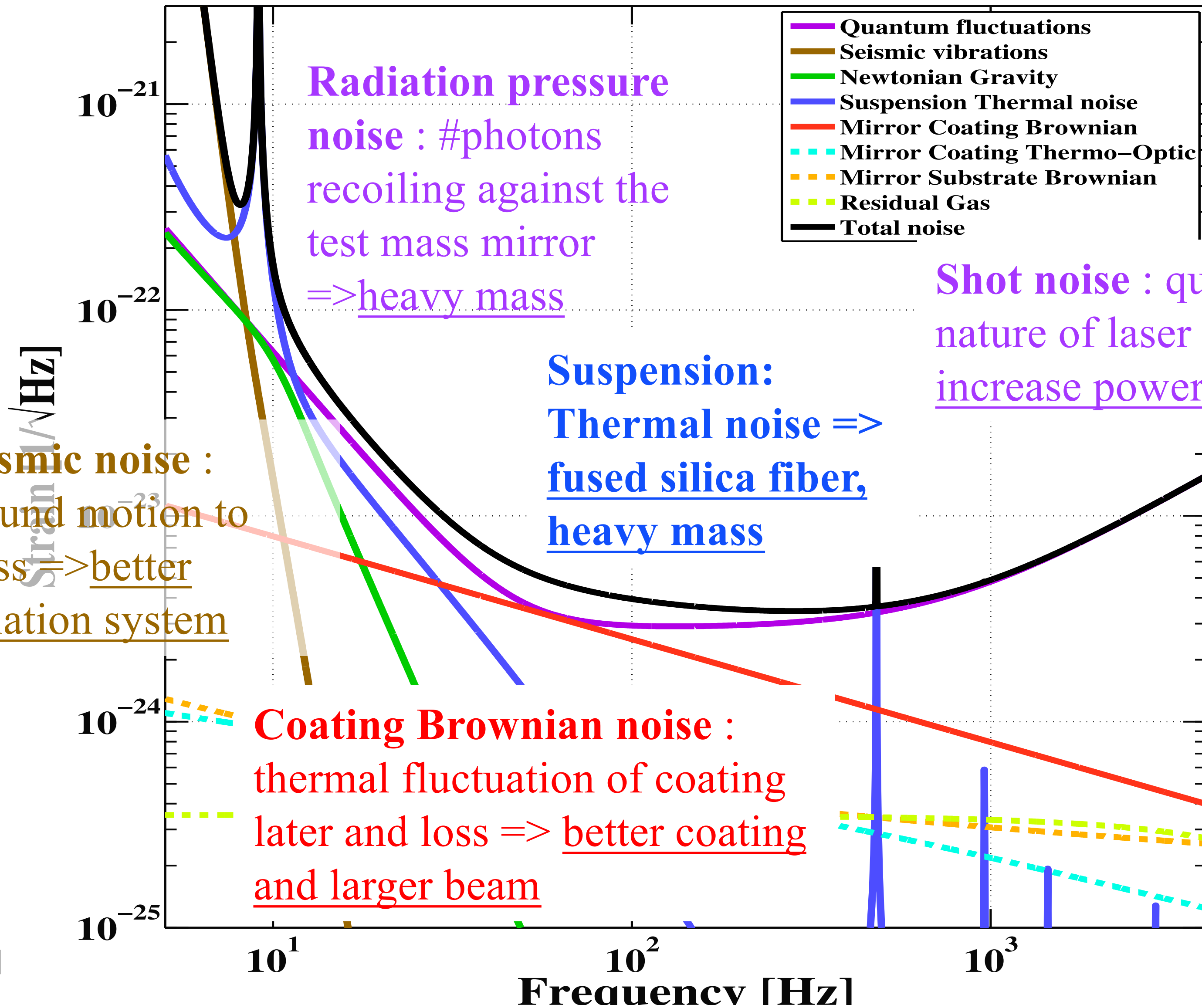
Hanford, WA (LHO)

- 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**

Fundamental Sensitivity Limits in Advanced LIGO



Radiation pressure noise : #photons recoiling against the test mass mirror =>heavy mass

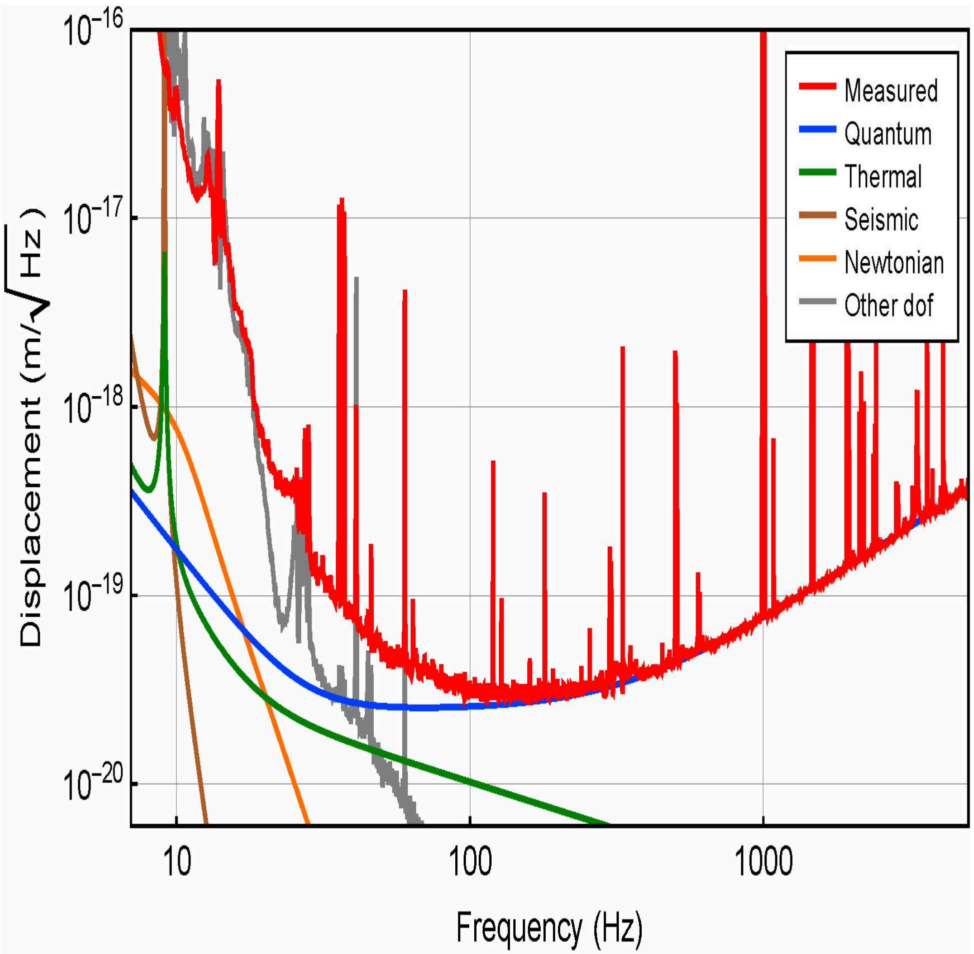
Shot noise : quantum nature of laser => increase power

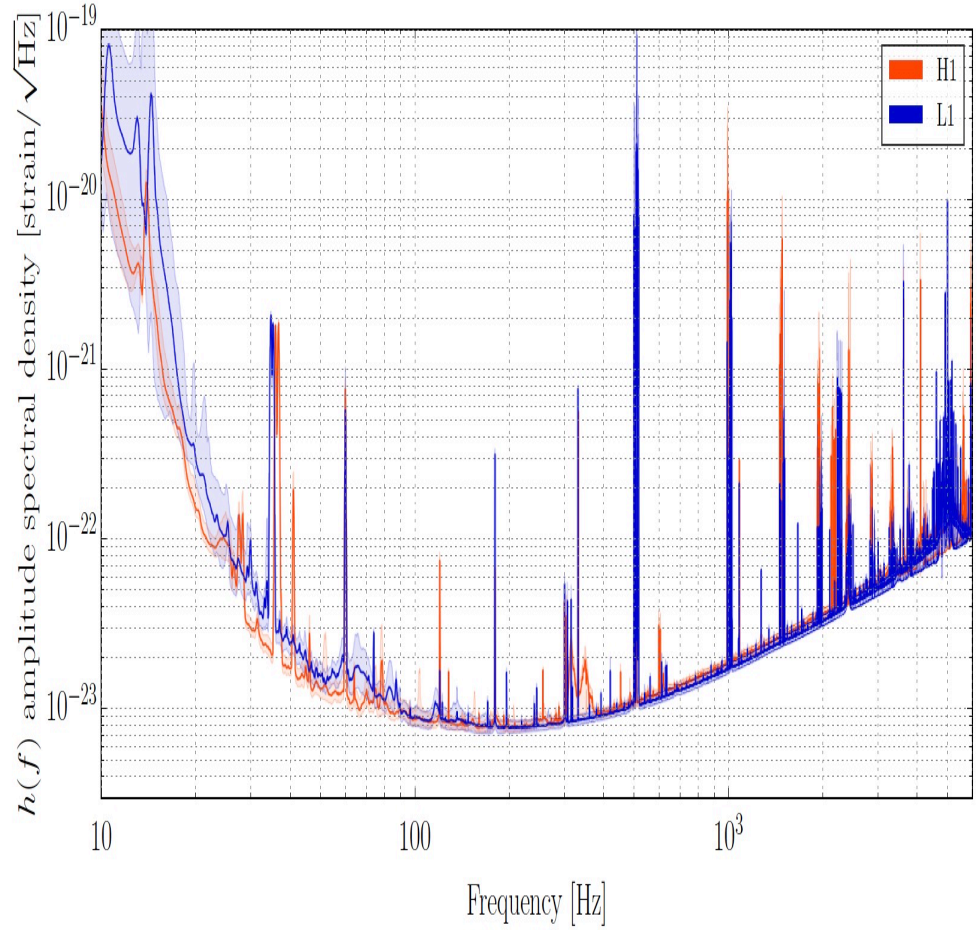
Suspension: Thermal noise => fused silica fiber, heavy mass

Seismic noise : ground motion to mass =>better isolation system

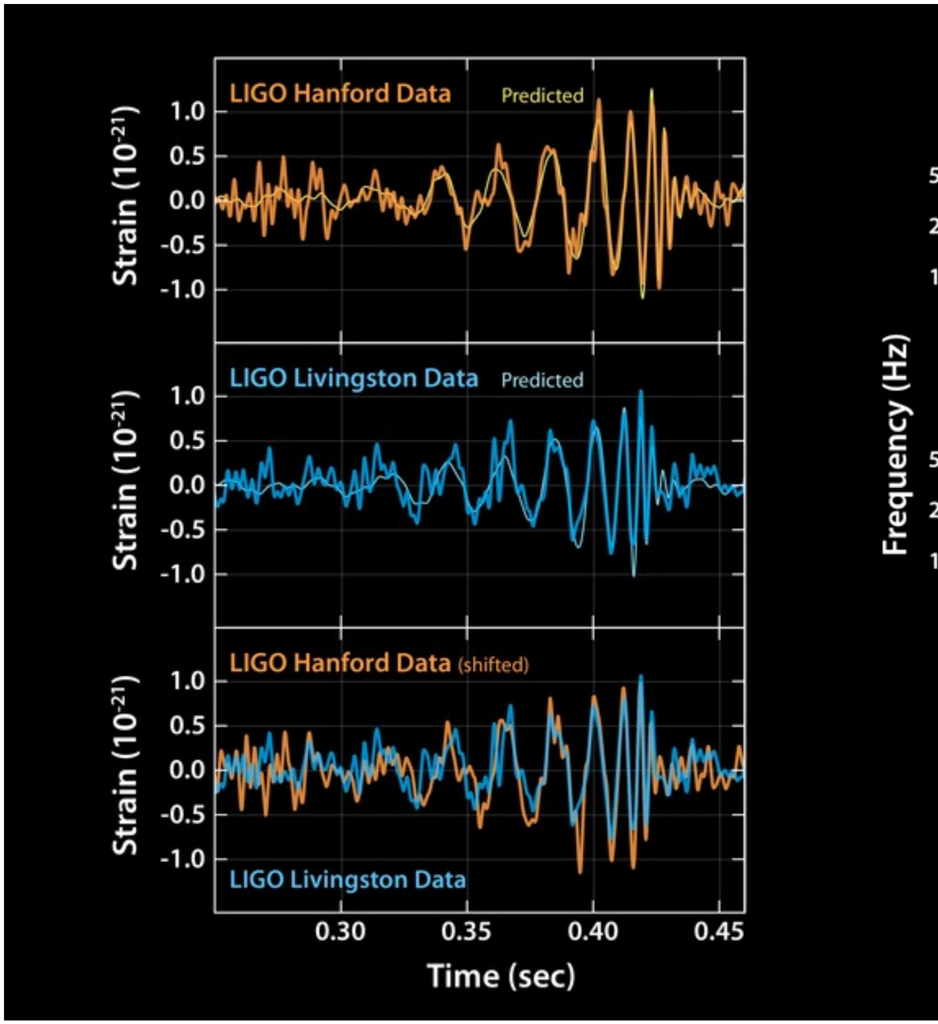
Coating Brownian noise : thermal fluctuation of coating later and loss => better coating and larger beam

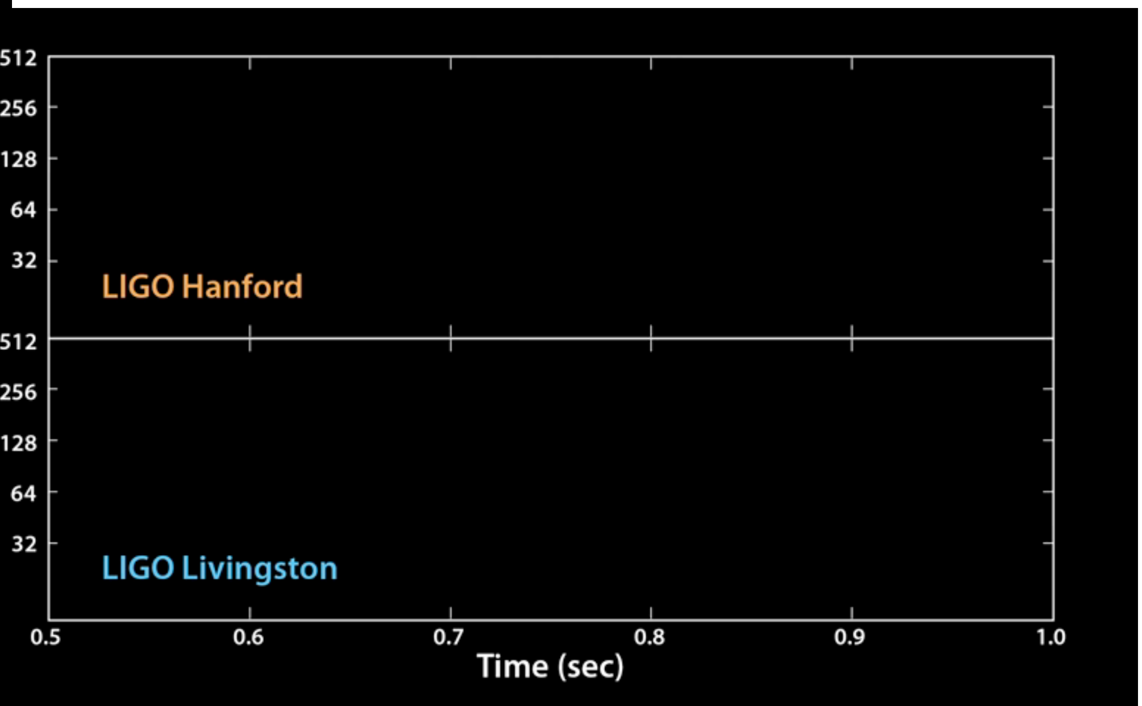
Sensitivities during O1



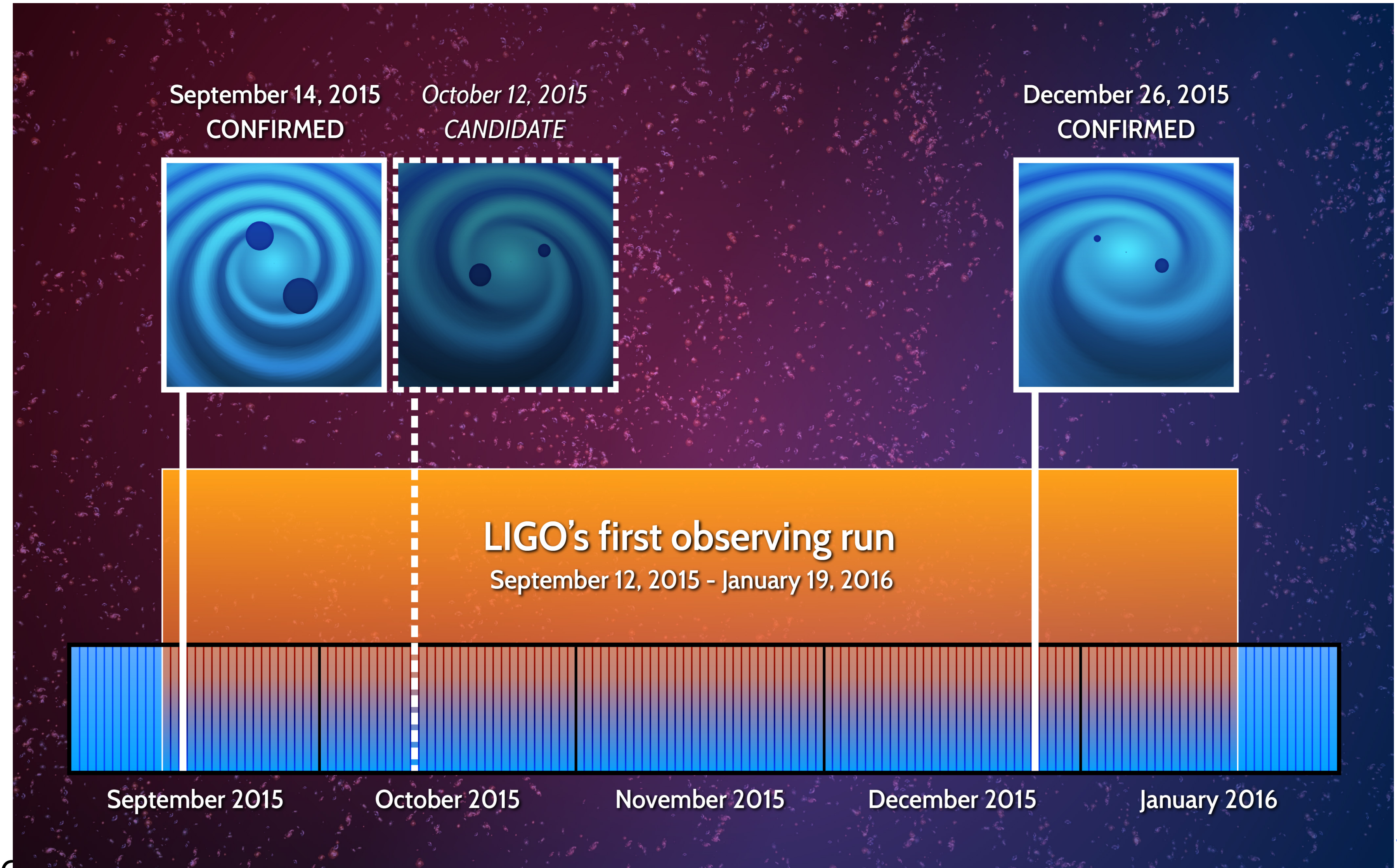


The Chirp of Two Black Holes merger : GW150914 on 2015/9/14



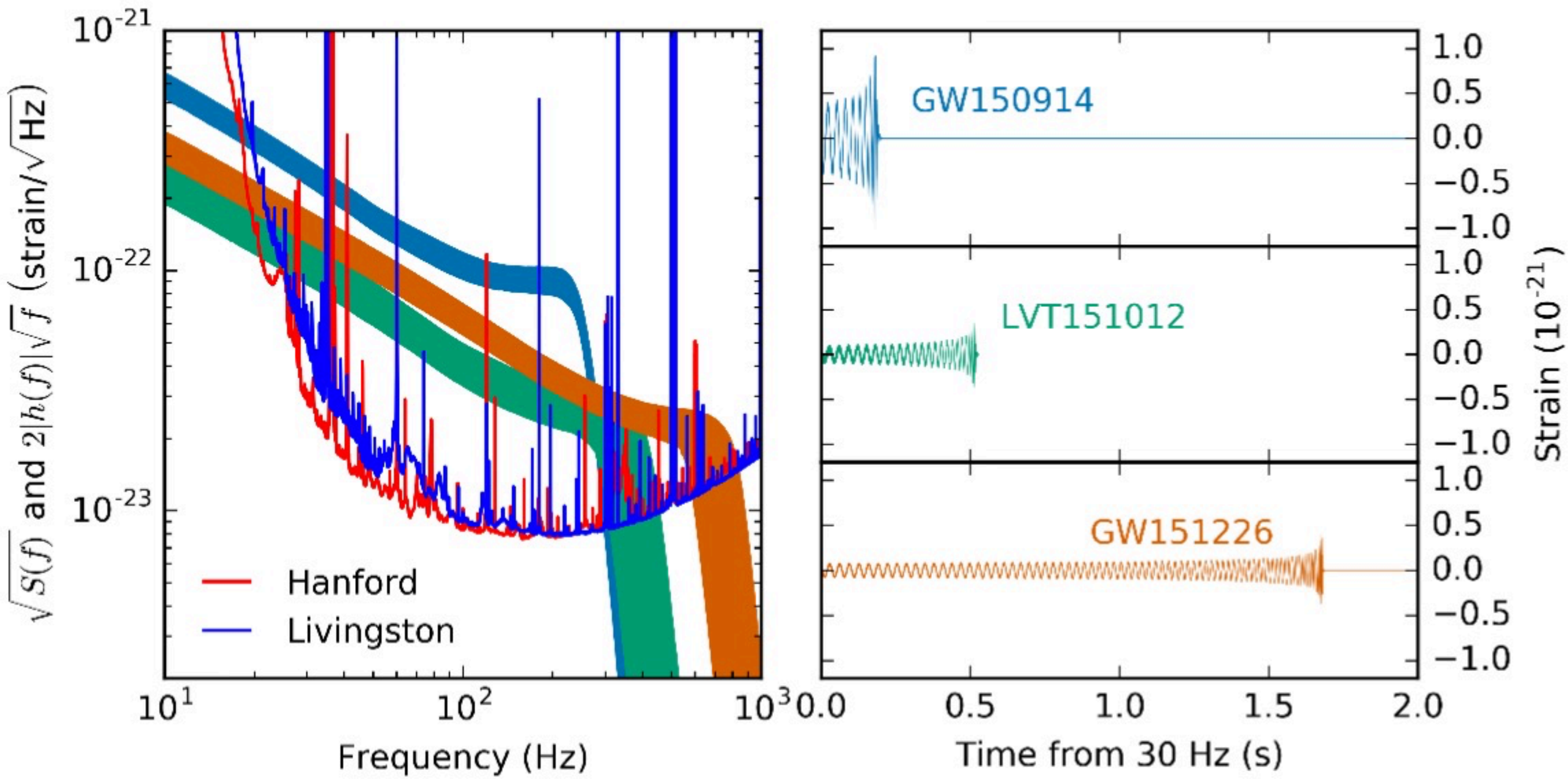


LIGO's First Observing Run

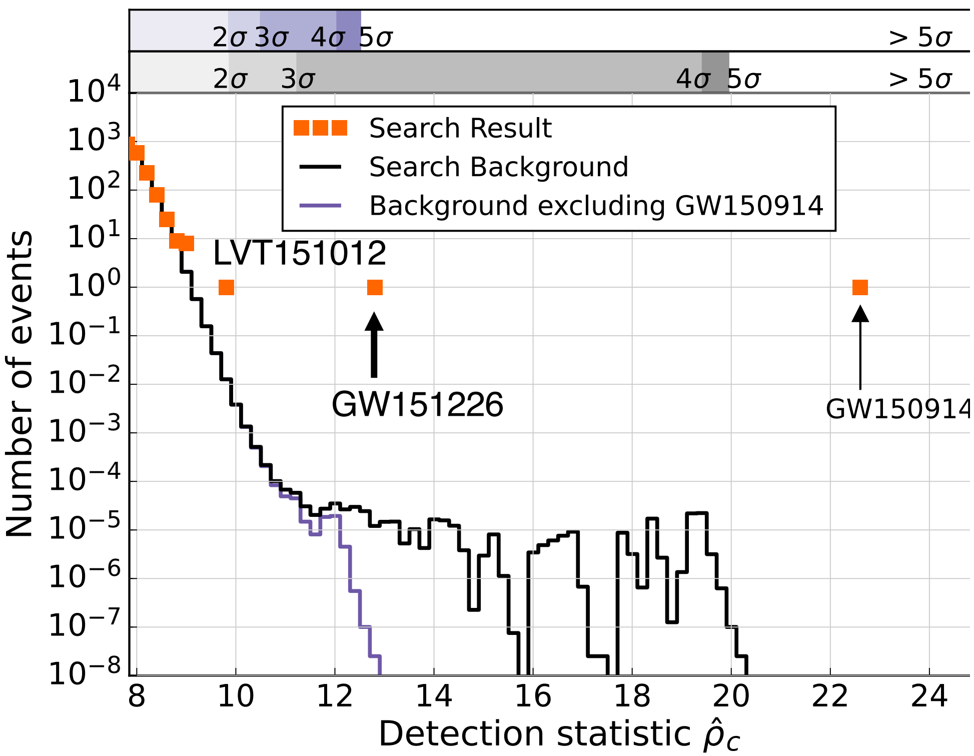


Bandwidth of signals

(arXiv:1606.04856 Binary Black Hole Mergers in the first Advanced LIGO Observing Run)



O1 BBH search

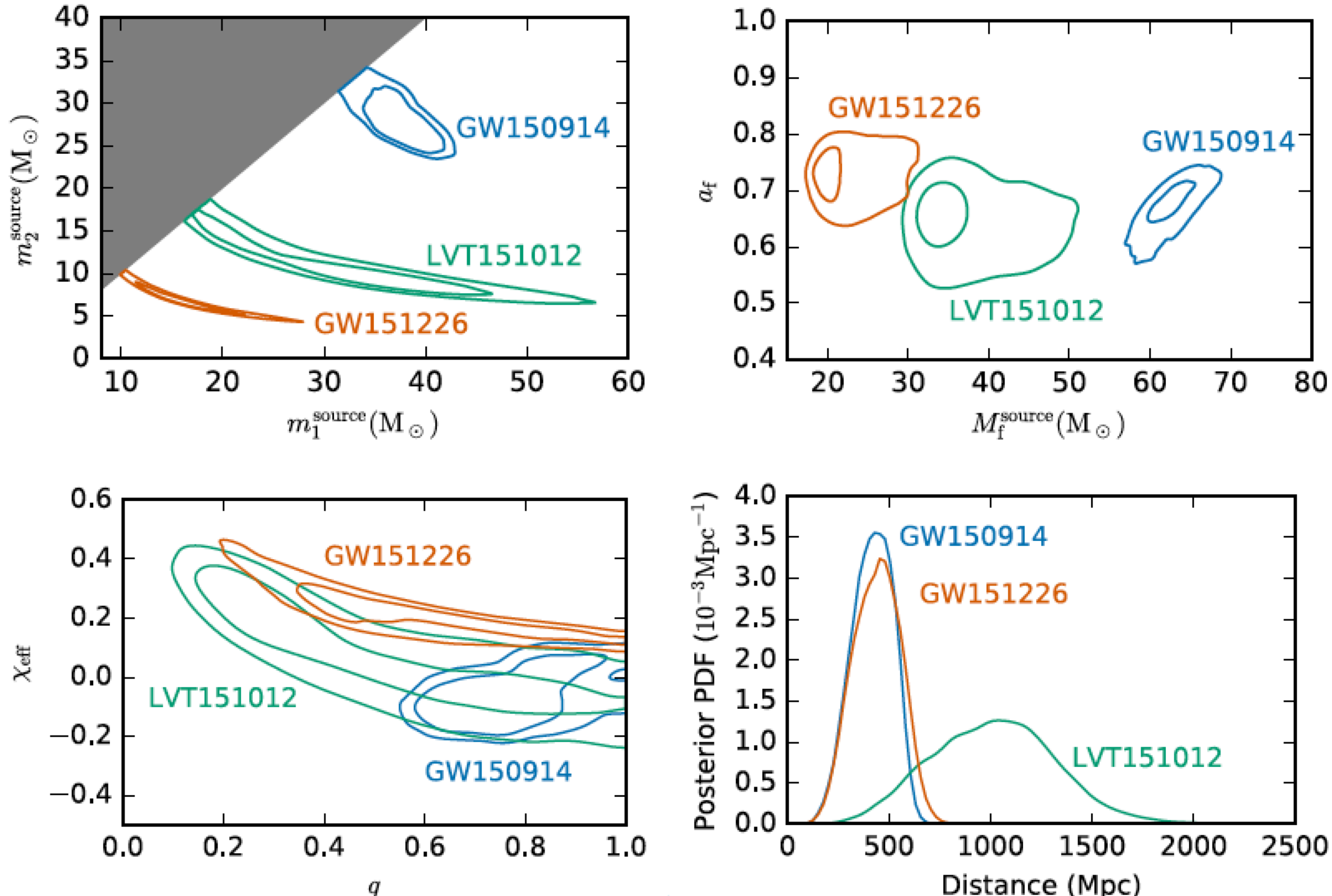


Search for binary black holes systems with black holes larger than 2 $M_\odot$ and total mass less than100 $M_\odot$, in O1 (Sep 12, 2015-Jan 19, 2016, ~48 days of coincident data)

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\rm source}/M_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/M_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\rm source}/M_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\rm source}/M_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin $\chi_{\rm eff}$	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_f^{\rm source}/M_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\rm rad}/(M_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_L/{\rm Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/{\rm deg}^2$	230	850	1600

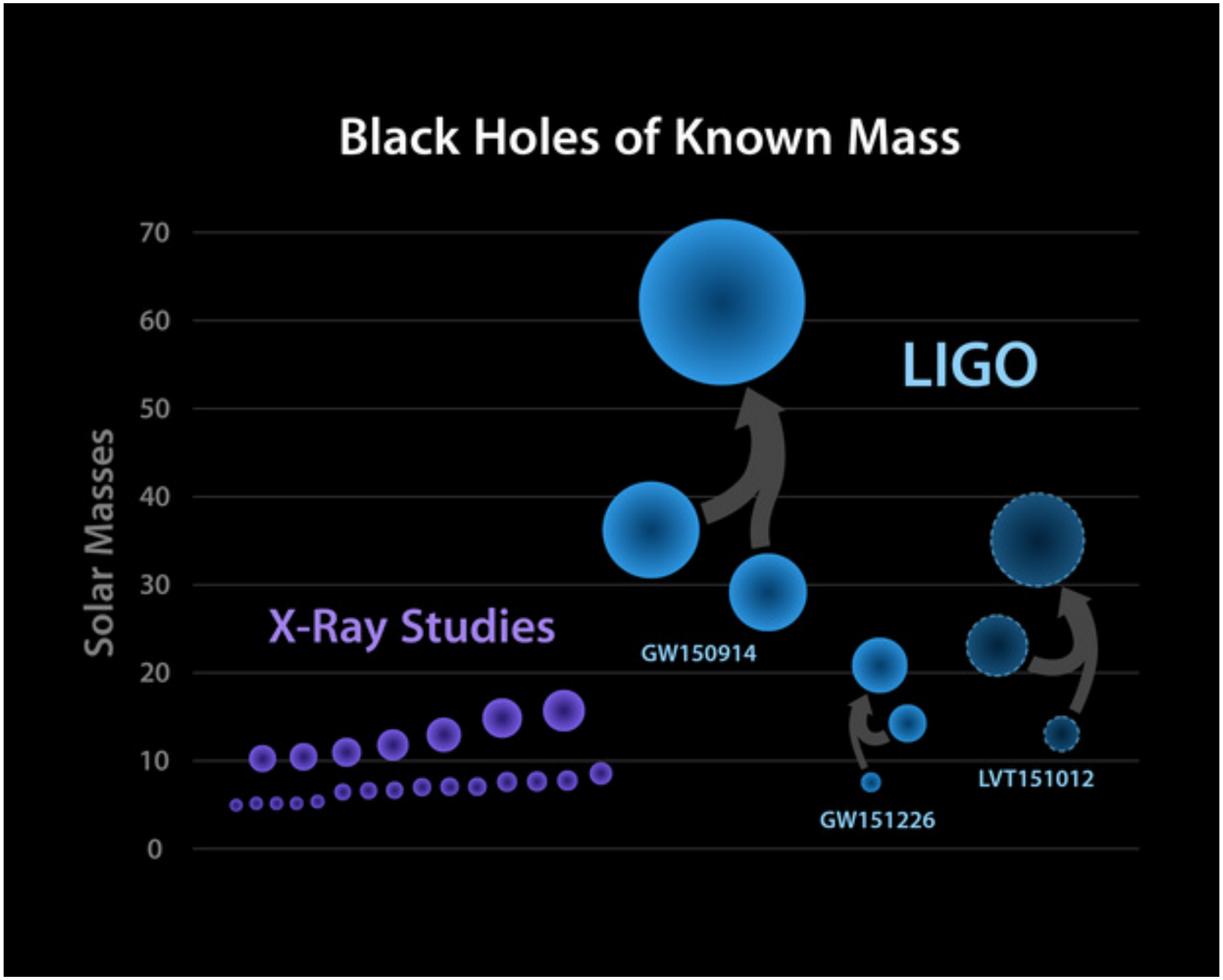
arXiv:1606.04856

Parameters of BBH systems



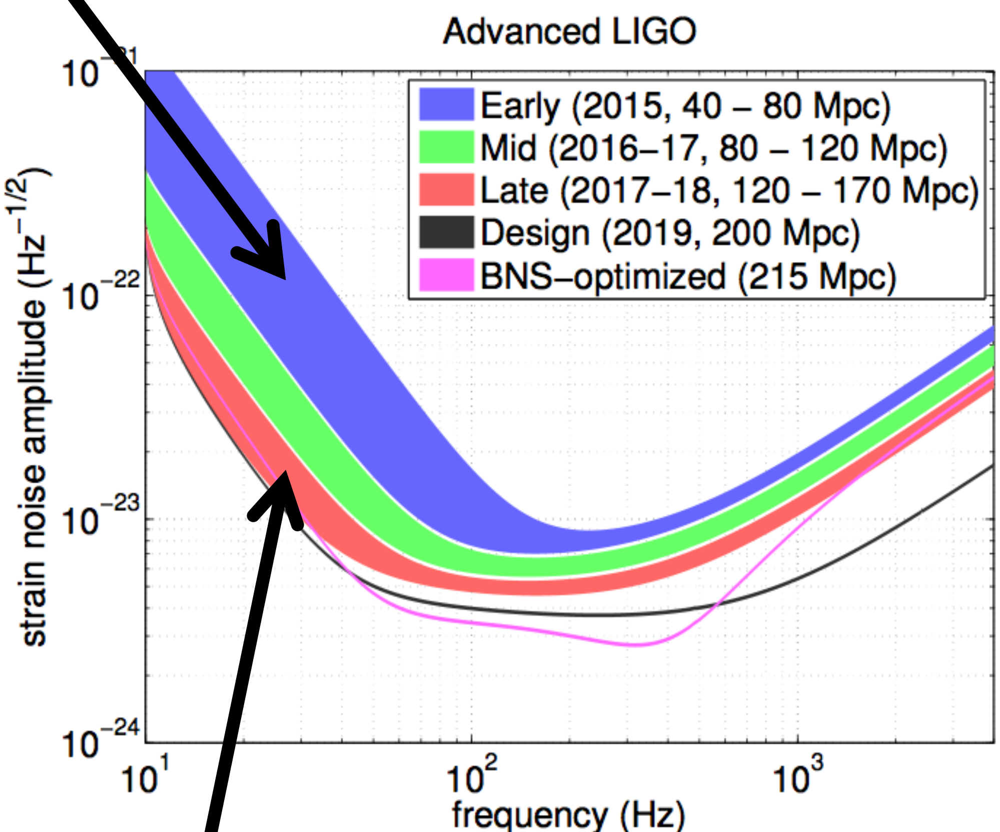
Top left: Component masses. Top right: The mass and dimensionless spin magnitude of the final black holes.
Bottom left: The effective spin and mass ratios of the binary components. *Bottom right:* The luminosity distance to the three events.

Filling in the black hole catalog



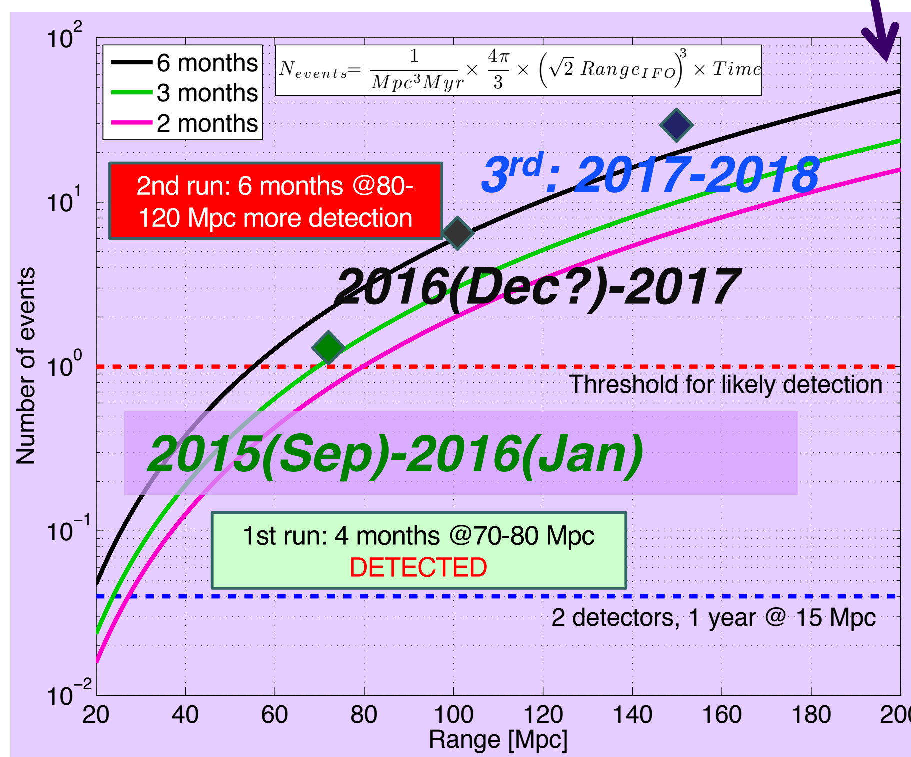
Planning for Advanced LIGO Science

Detected

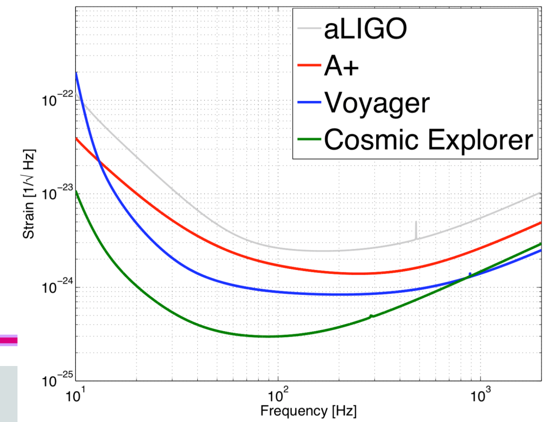


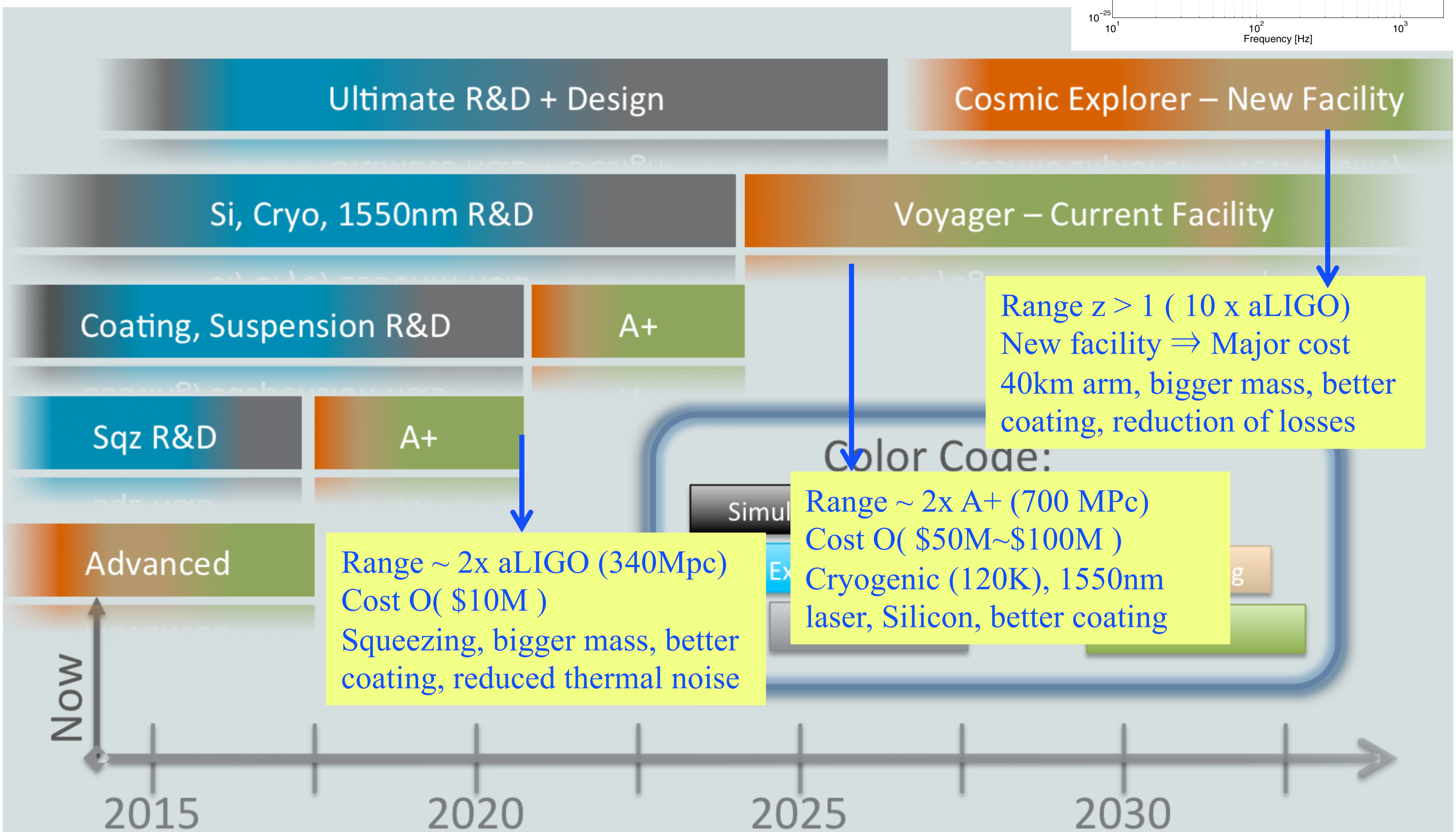
Astronomy

Full sensitivity (200 Mpc): end-2018

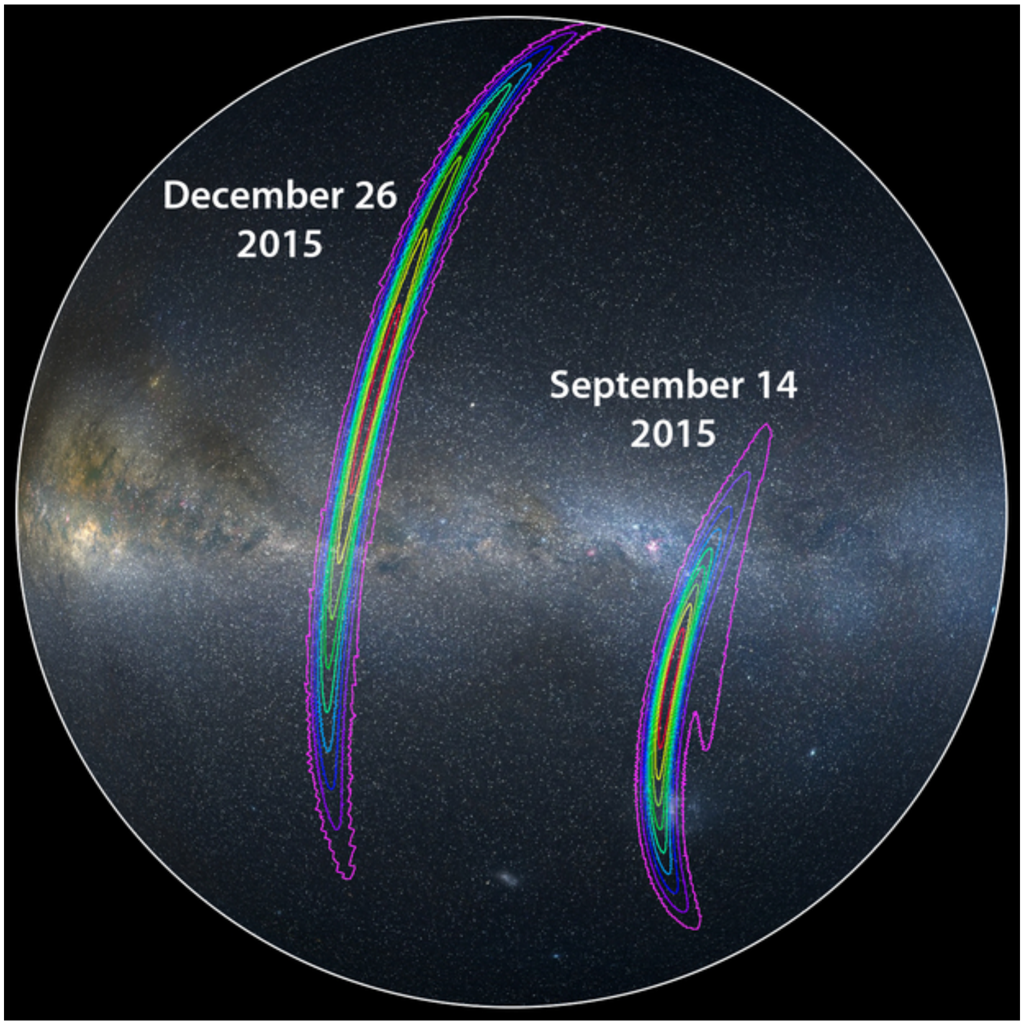


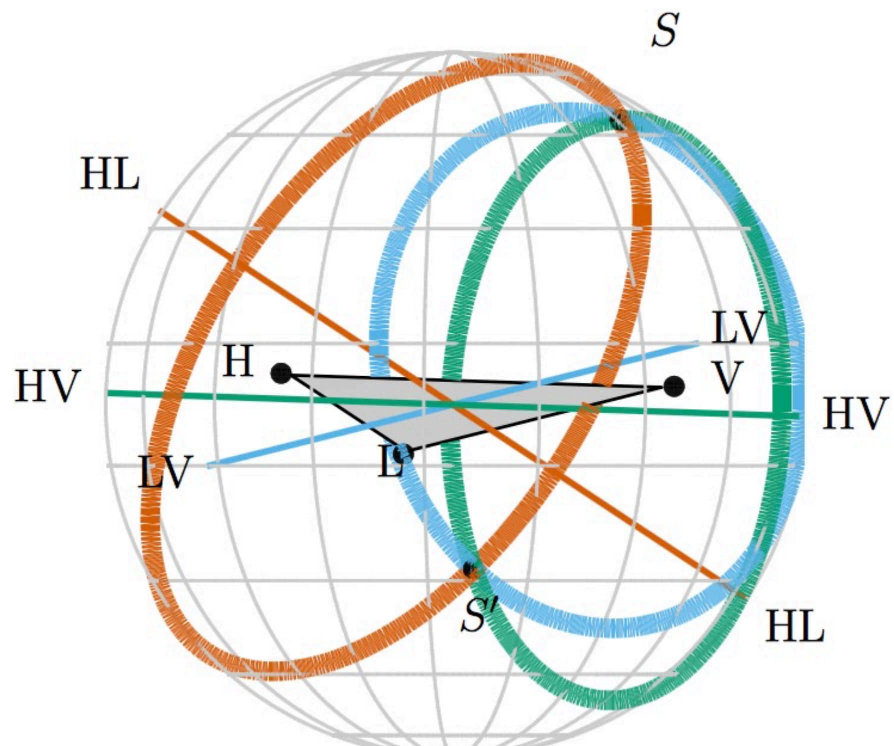
Aiming for the future
beyond advanced LIGO





Localization poor because of only 2 IFOs





Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo

Abbott, B. P. et al.
The LIGO Scientific Collaboration and the Virgo Collaboration
(The full author list and affiliations are given at the end of paper.)
email: lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.it

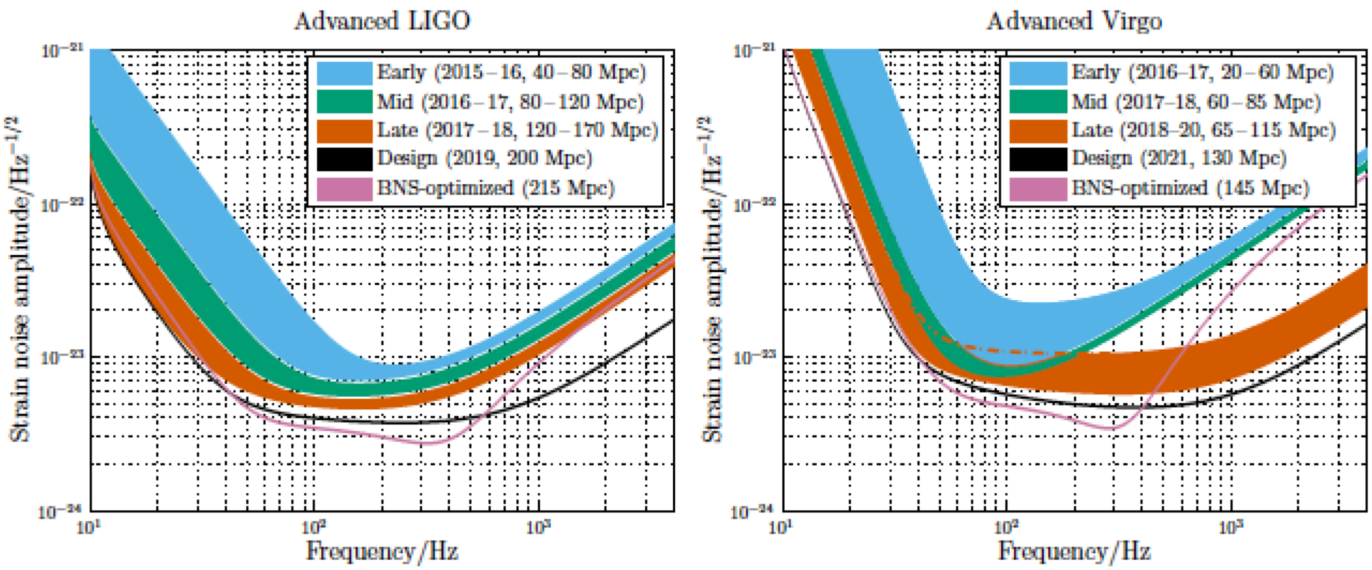


Figure 1: aLIGO (*left*) and AdV (*right*) target strain sensitivity as a function of frequency. The binary neutron-star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates.

2015 – 2016 (O1) A four-month run (beginning 18 September 2015 and ending 12 January 2016) with the two-detector H1L1 network at early aLIGO sensitivity (40 – 80 Mpc BNS range).

2016 – 2017 (O2) A six-month run with H1L1 at 80 – 120 Mpc and V1 at 20 – 60 Mpc.

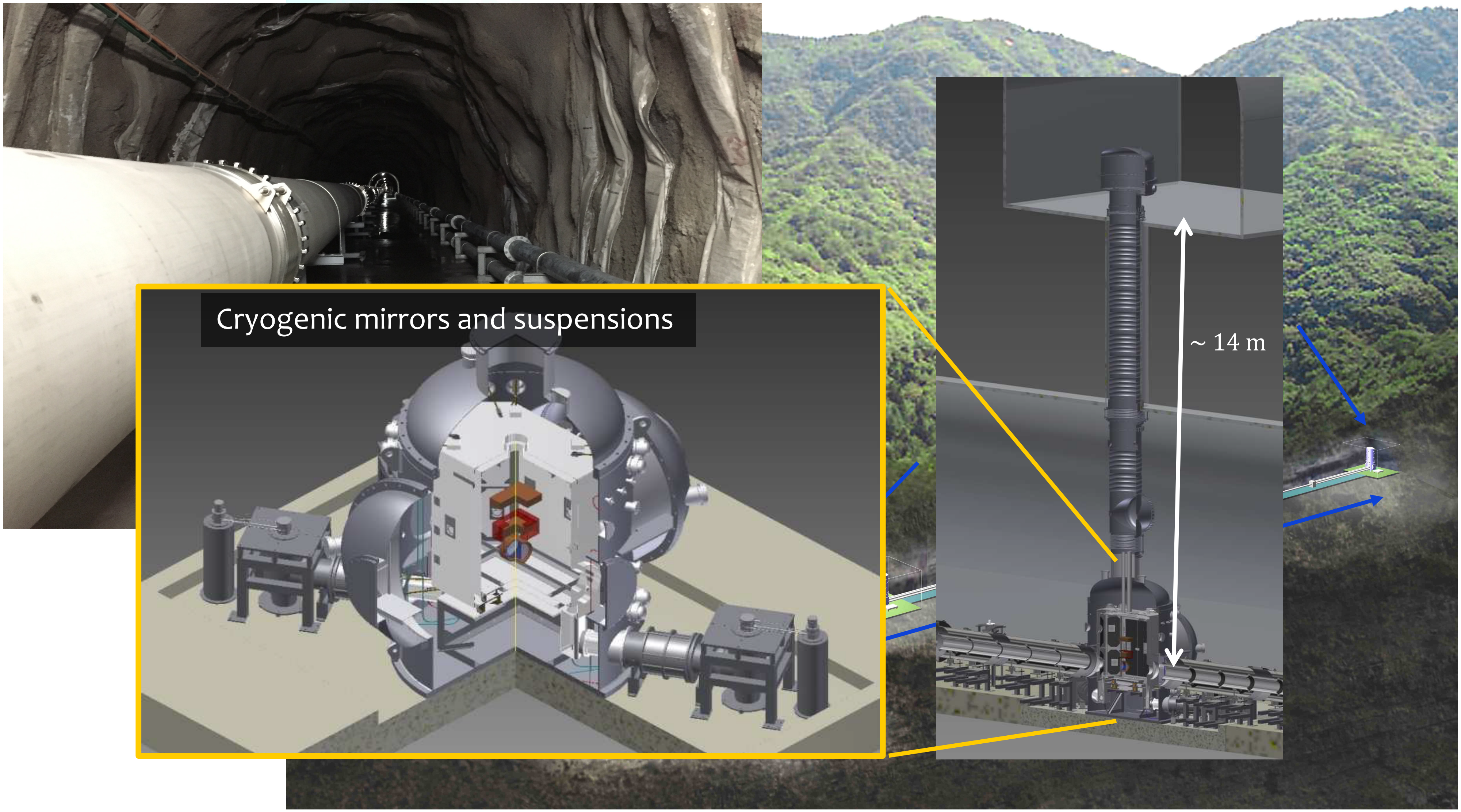
2017 – 2018 (O3) A nine-month run with H1L1 at 120 – 170 Mpc and V1 at 60 – 85 Mpc.

2019+ Three-detector network with H1L1 at full sensitivity of 200 Mpc and V1 at 65 – 115 Mpc.

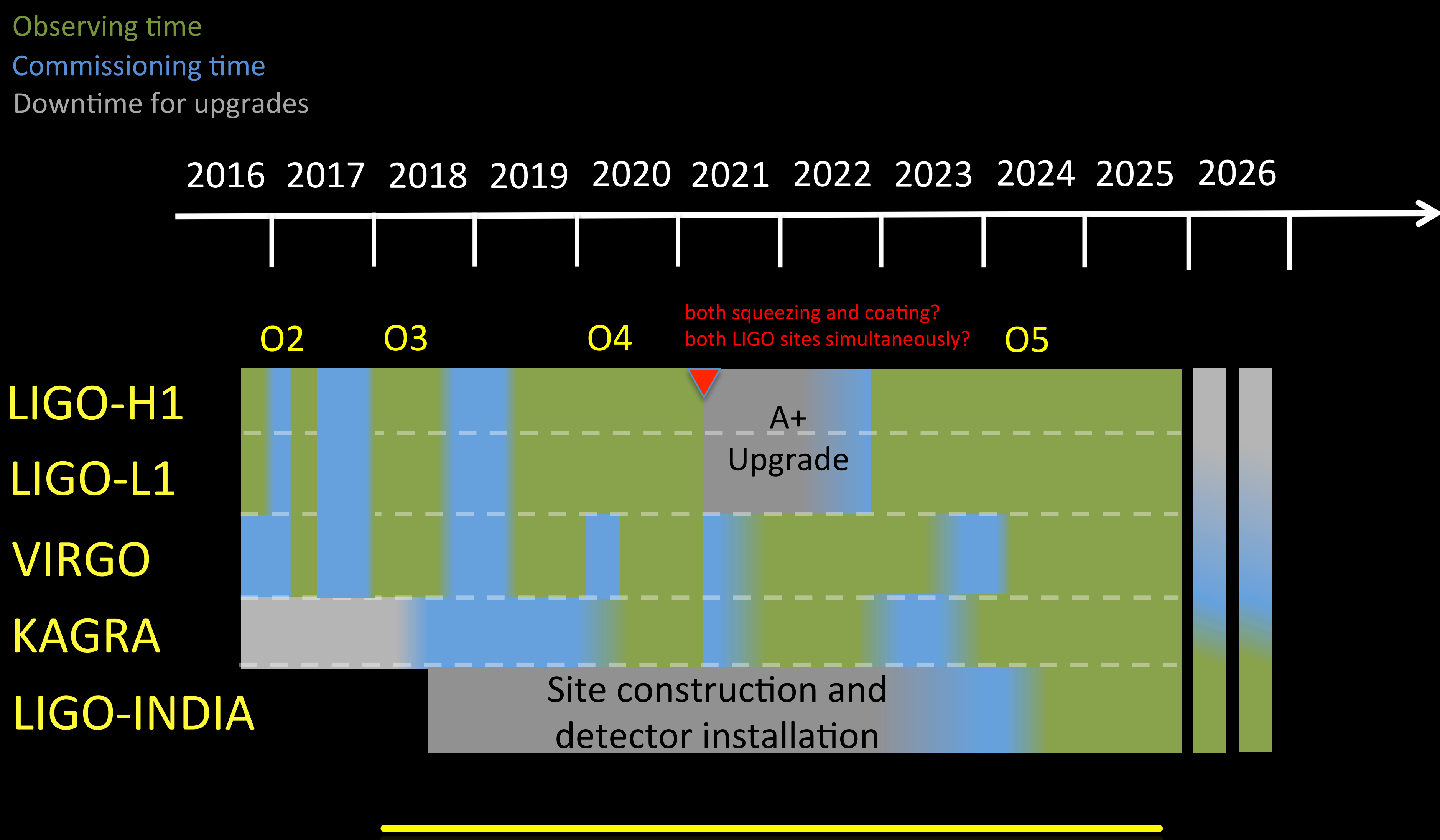
International network

- 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!**

KAGRA
- Underground and Cryogenic -



Plausible world-wide observing scenario for the next decade

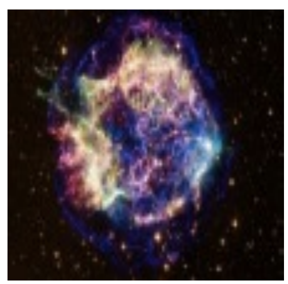
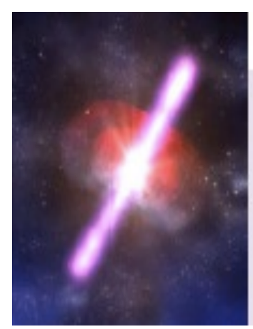


LIGO = LIGO Lab (CIT,MIT,UFL) + LSC (LIGO Science Collaboration)

- 1006 members, 83 institutions, 15 countries

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.


LIGO Open Science Center

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

- Getting Started
- Tutorials
- Data
  - Events
  - Bulk Data
- Timelines
- My Sources
- Software
- GPS ↔ UTC
- About LIGO
- Data Analysis Projects
- Acknowledgement

Welcome to the LIGO Open Science Center

About LIGO
Get Started with LIGO data
Join the E-mail list for updates
For general information on LIGO, please visit ligo.org
If you have LSC credentials, you may go to the development site

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More discoveries from LIGO!

Data Releases from two events and a candidate event

released 2016 June 15:
Event of December 26, GW151226: Chirp mass 9

released 2016 June 15:
Candidate event of October 12, LVT151012: Chirp mass 15

released 2016 Feb 11:
Event of September 14, GW150914: Chirp mass 30

The LIGO Laboratory's Data Management Plan describes the scope and timing of LIGO data releases.

Jupyter notebook

See the new tutorial on signal processing with LIGO data, as a Jupyter (iPython) notebook.
Tutorial on Binary Black Hole Signals in LIGO Open Data

URL : https://losc.ligo.org

Getting Started

Welcome! The LIGO Open Science Center (LOSC) provides access to LIGO data, as well as documentation, tutorials, and online tools for finding and viewing data.

What's LIGO!?

The LIGO Scientific Collaboration Home Page provides a general introduction to LIGO.

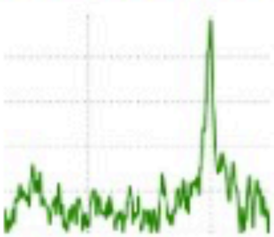
Where's the data?

The Data Page allows you to download LIGO data.

The main data are a time series sampled at 4096 Hz.

Data are calibrated so that gravitational wave signals have units of dimensionless strain (ΔL / L).

How do I work with LIGO data?



The Tutorials Page gives examples of how to work with LIGO data. If you are a student, this is a great place to start.

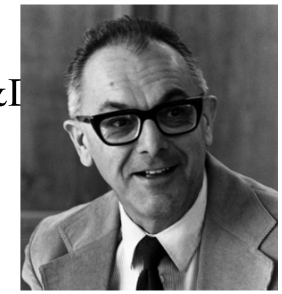

Drever

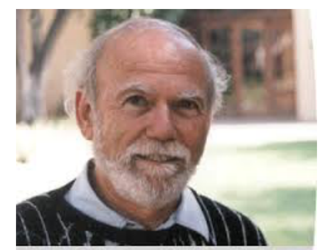
LIGO Chronology

idea to realization ~ 20 years

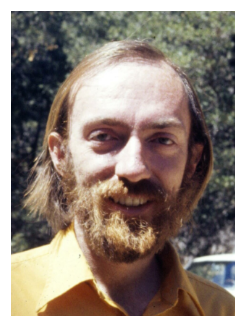

Weiss

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		Barish becomes the PI of LIGO
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+Germany)**
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


Barish

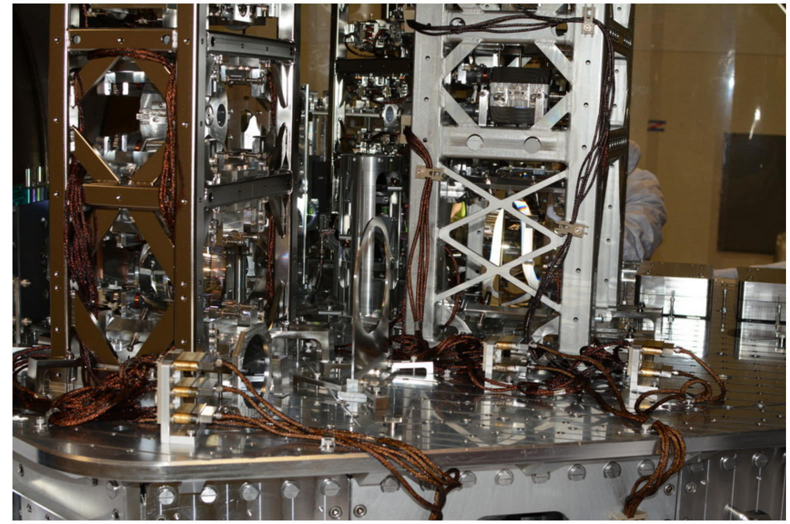
Initial LIGO events
Advanced LIGO events
R&D of aLIGO using iLIGO facility


Thorn

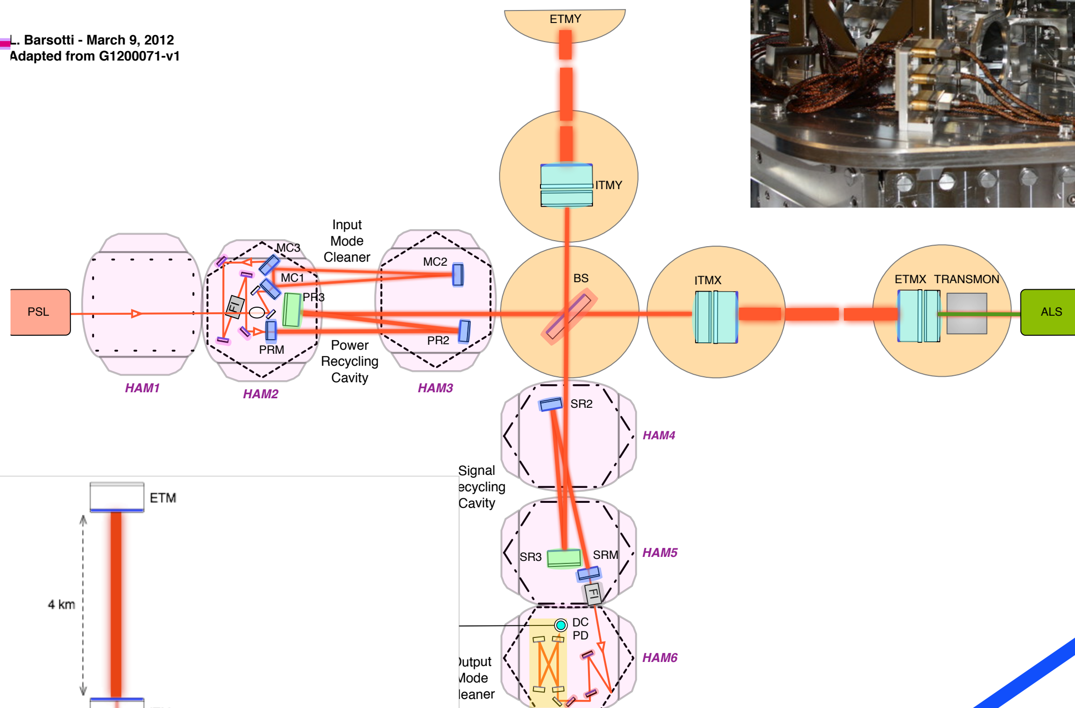

Executive producer & consultant of movie “Intersteller”

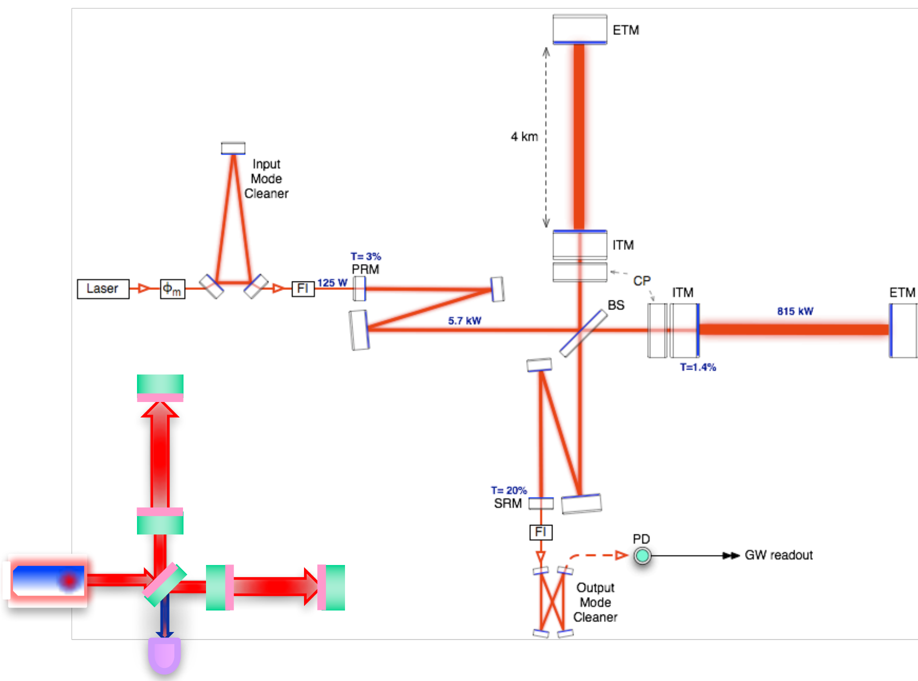
The real instrument is far more complex…

SEPTEMBER 14, 2015

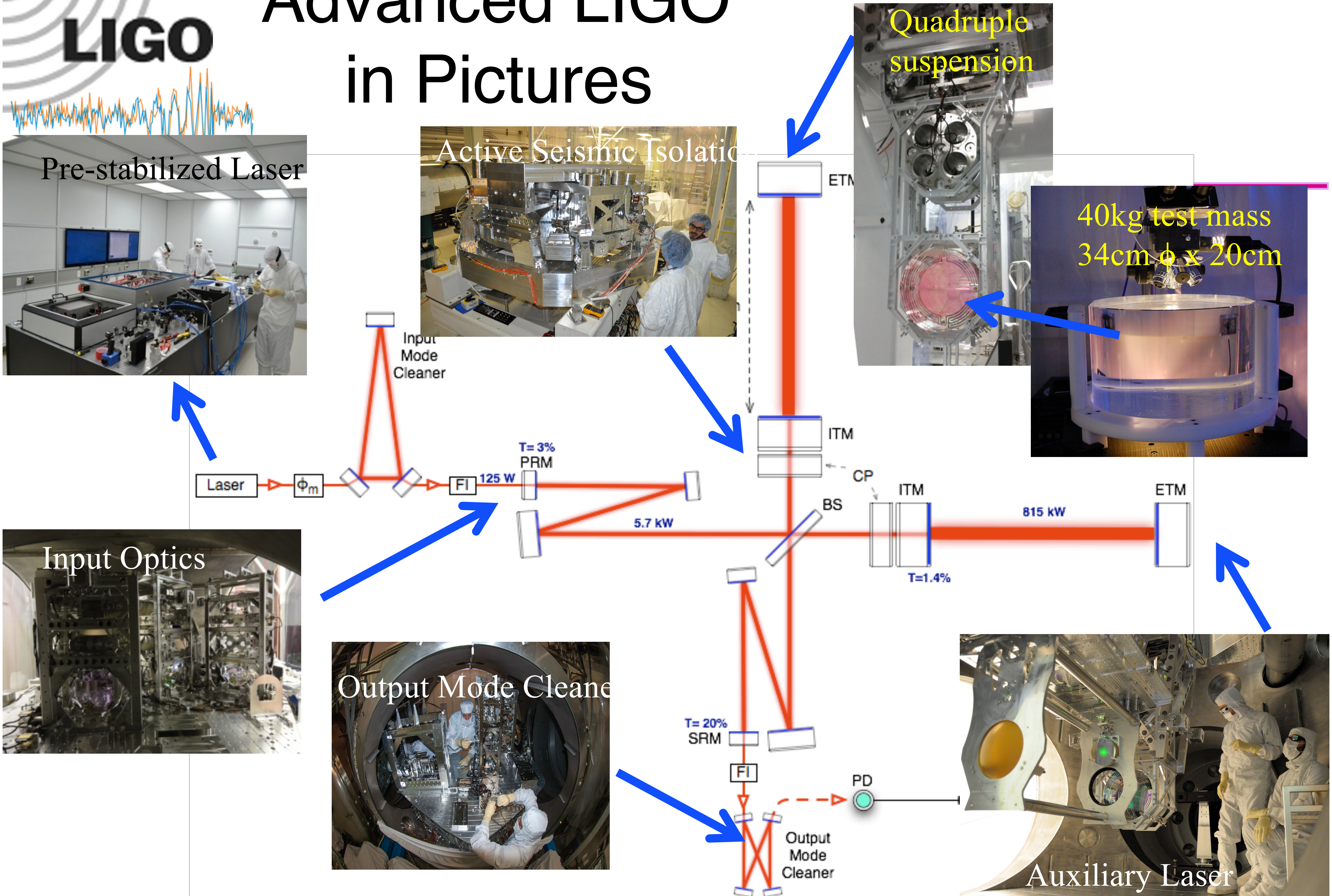


L. Barsotti - March 9, 2012
Adapted from G1200071-v1





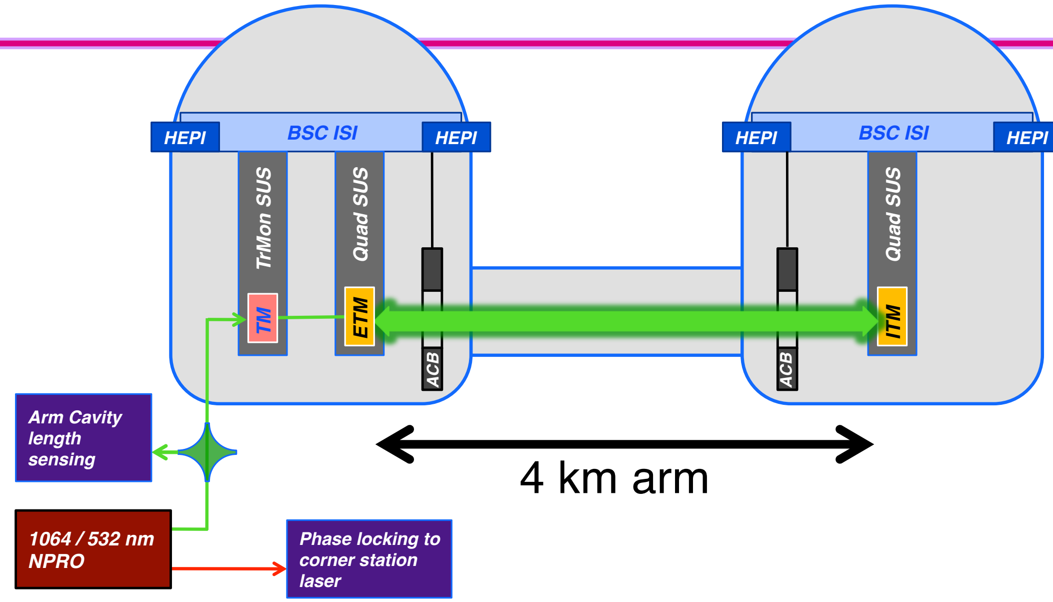
Advanced LIGO in Pictures



G1400628-v3 by P. Fritschel

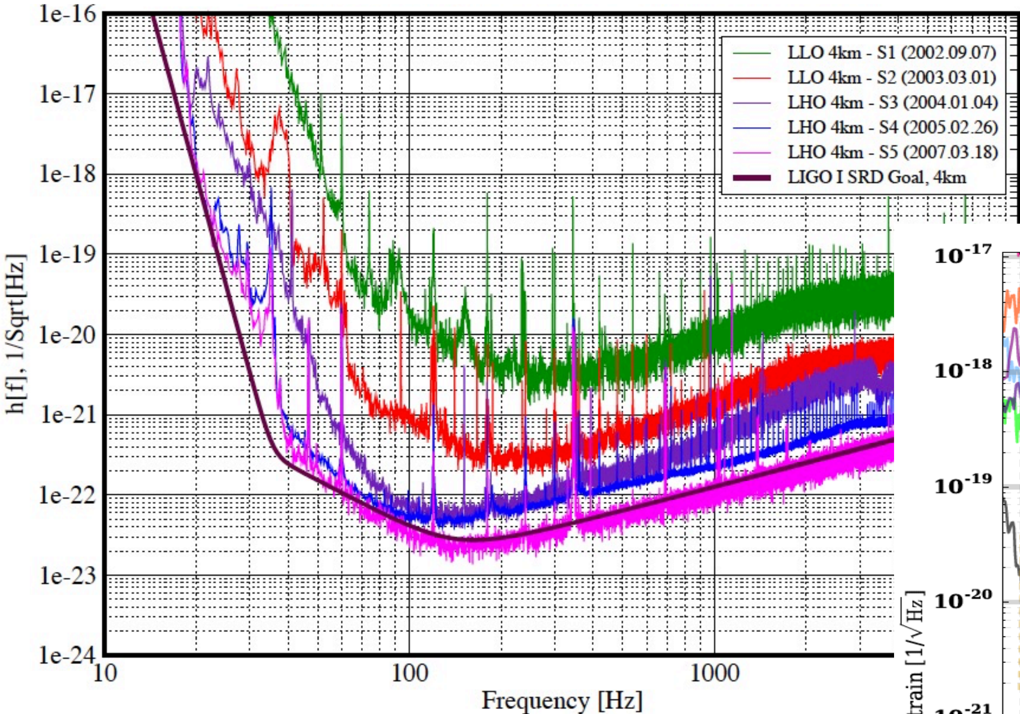
Speedier commissioning

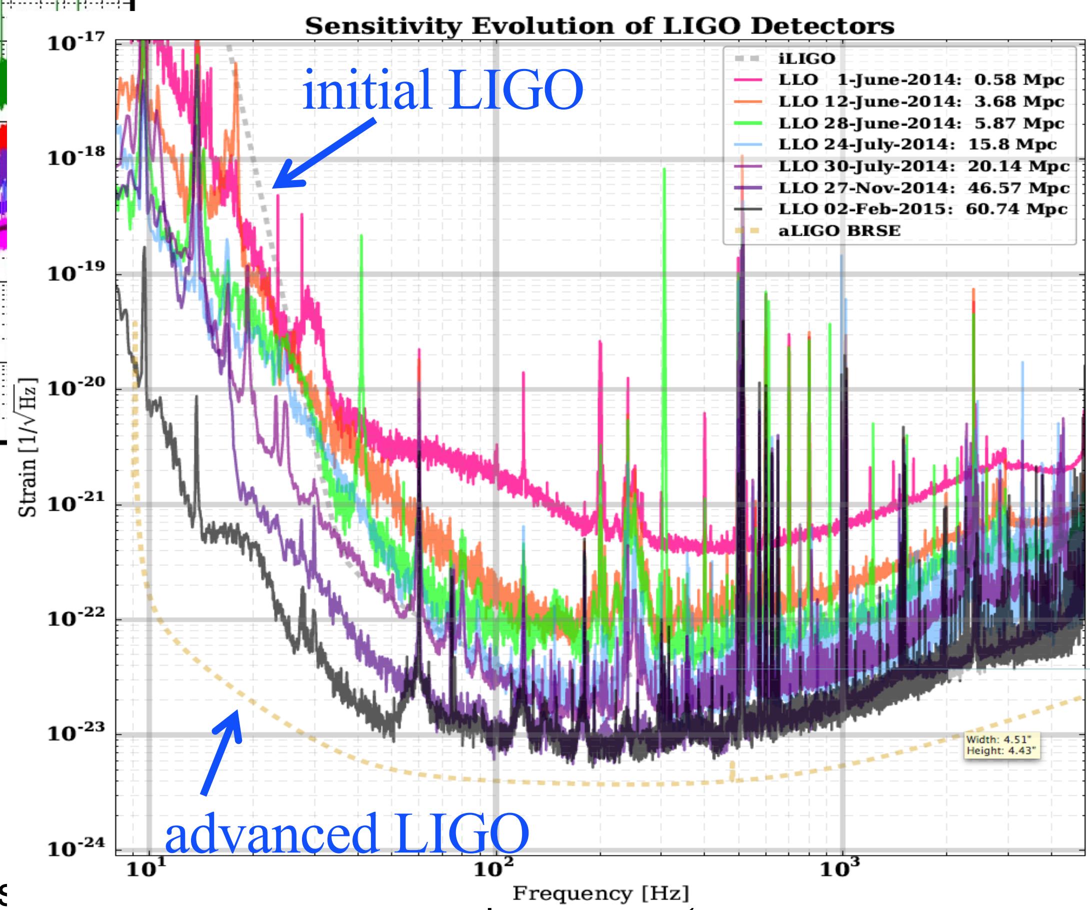
- Lock acquisition strategy designed in from the start, including a new Arm Length Stabilization system
  - Enables a controlled acquisition process



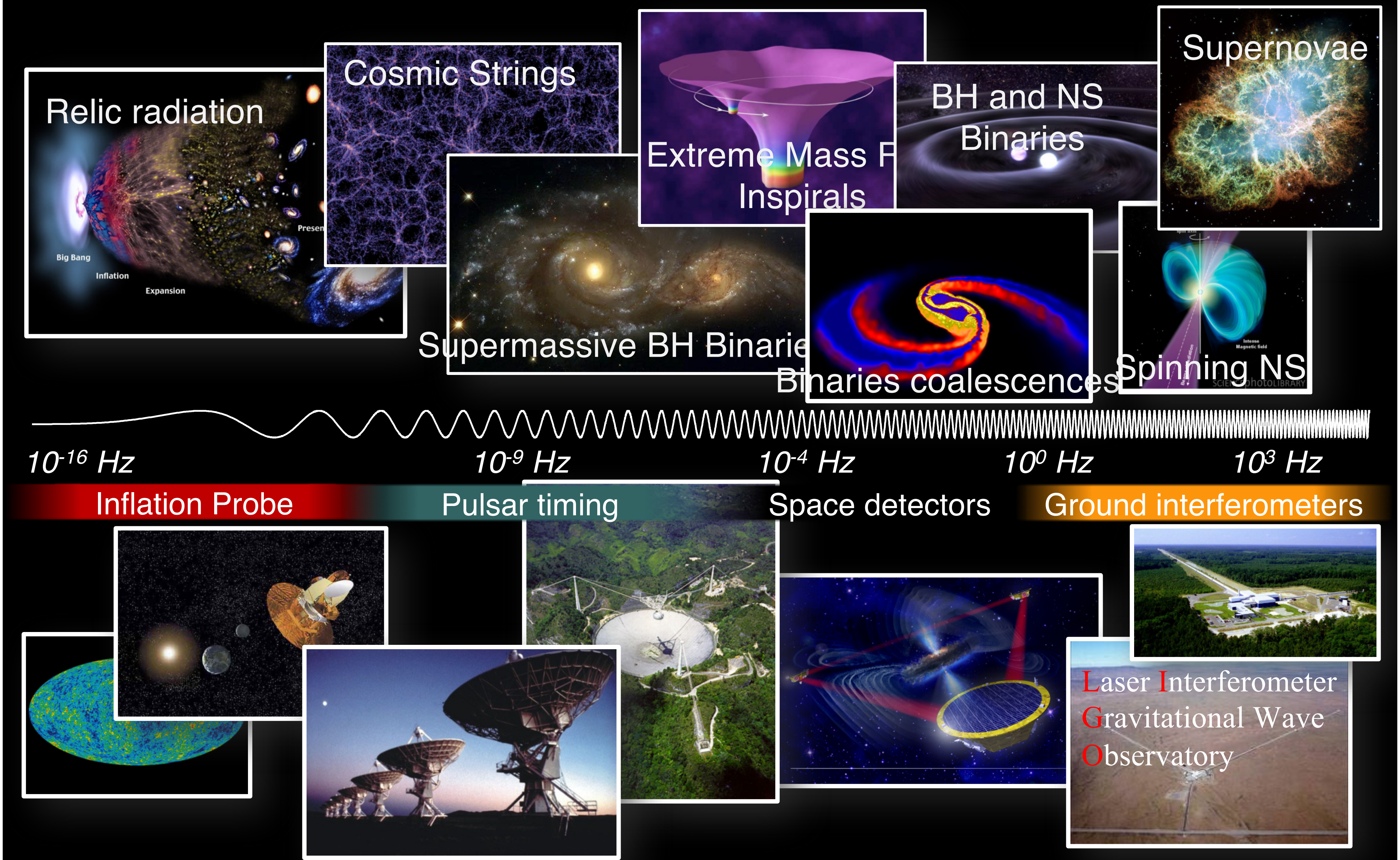
- *Better teams* on hand
  - More people and with more experience
  - Observatory staff, including operators, involved from the beginning
- *Better support structure* in place
  - Software tools in place
  - Online web tools in place
- Having been there before helps a lot!

How could we see the signal
- better understanding of IFO -





The Gravitational Wave Spectrum



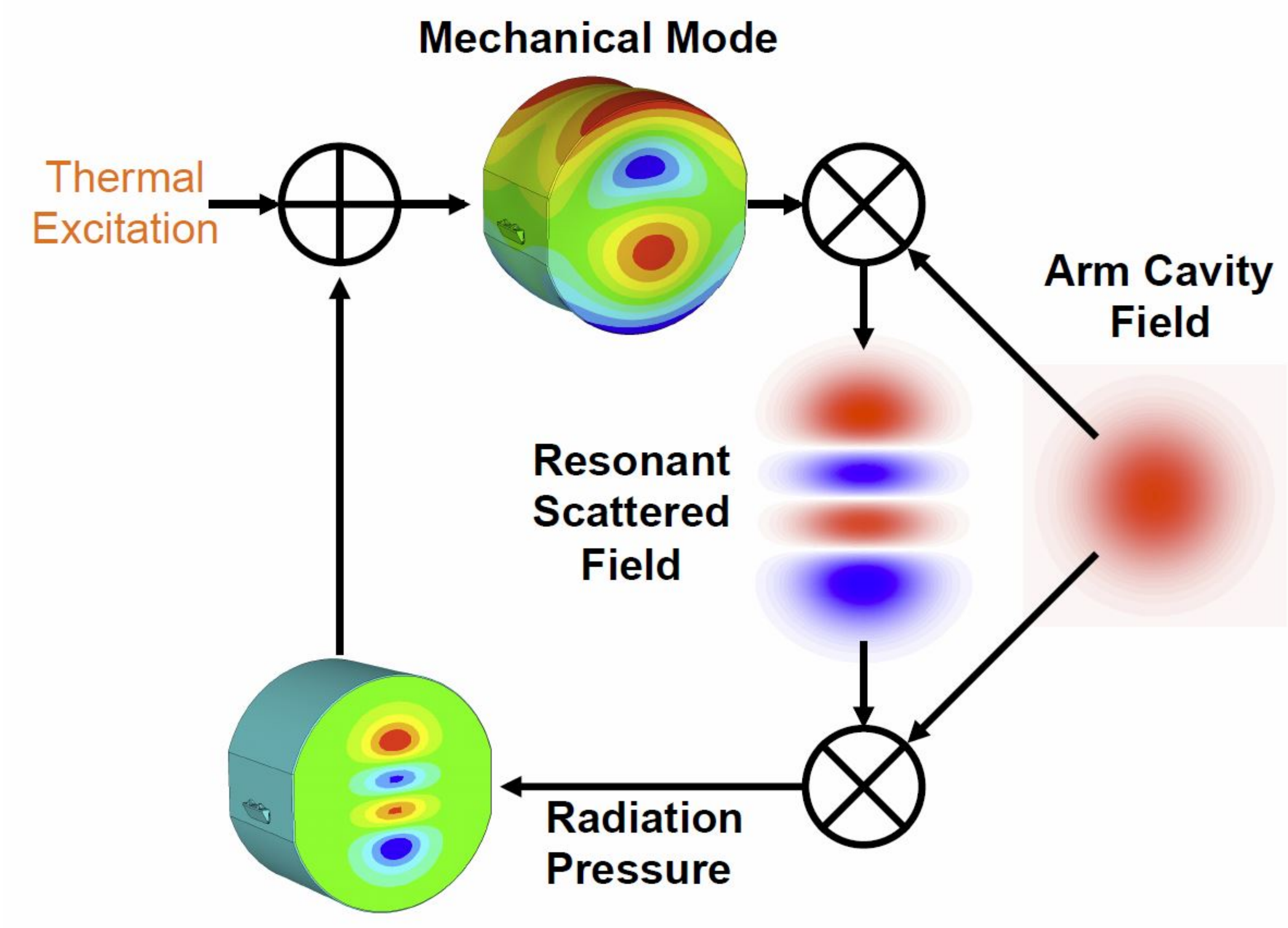
Slide Credit: Matt Evans (MIT)

Summary

- First direct observation of gravitational signals.
  - » Strict test of the general relativity, both weak field and strong field
  - » Discovery of heavy black holes, new theories of heavy steller mass BH formation
- New astronomy using GW signals, just beginning
  - » International network for better sky coverage
  - » Multi messenger astronomy
  - » Another revolutionary new detectors to have better sensitivities and to over different frequency ranges

End of slides

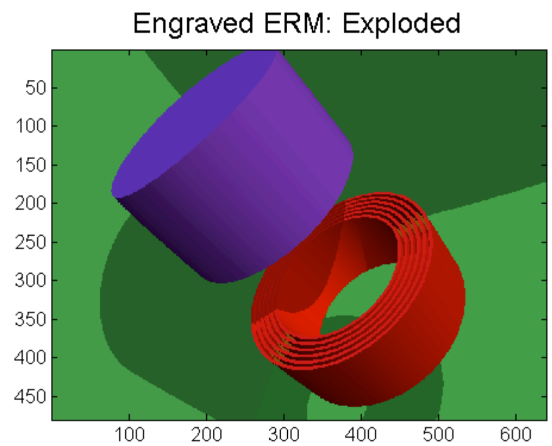
major issues
Parametric Instabilities



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

major issues
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



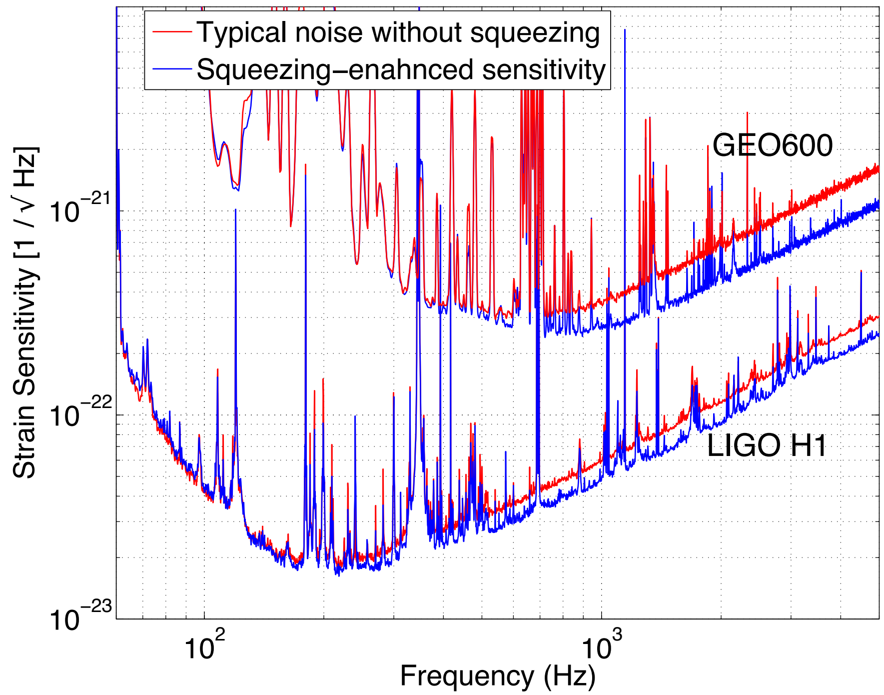
Squeezed Light in LIGO

suppressing quantum noise without increasing power

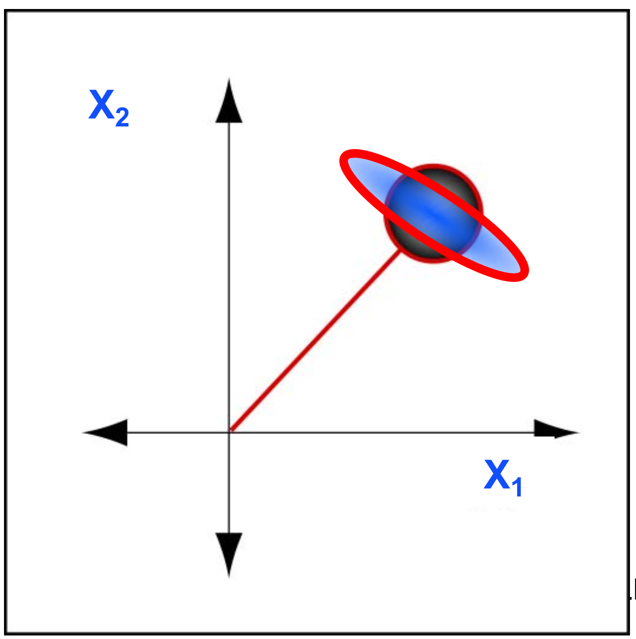
- Heisenberg Uncertainty Principle

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

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

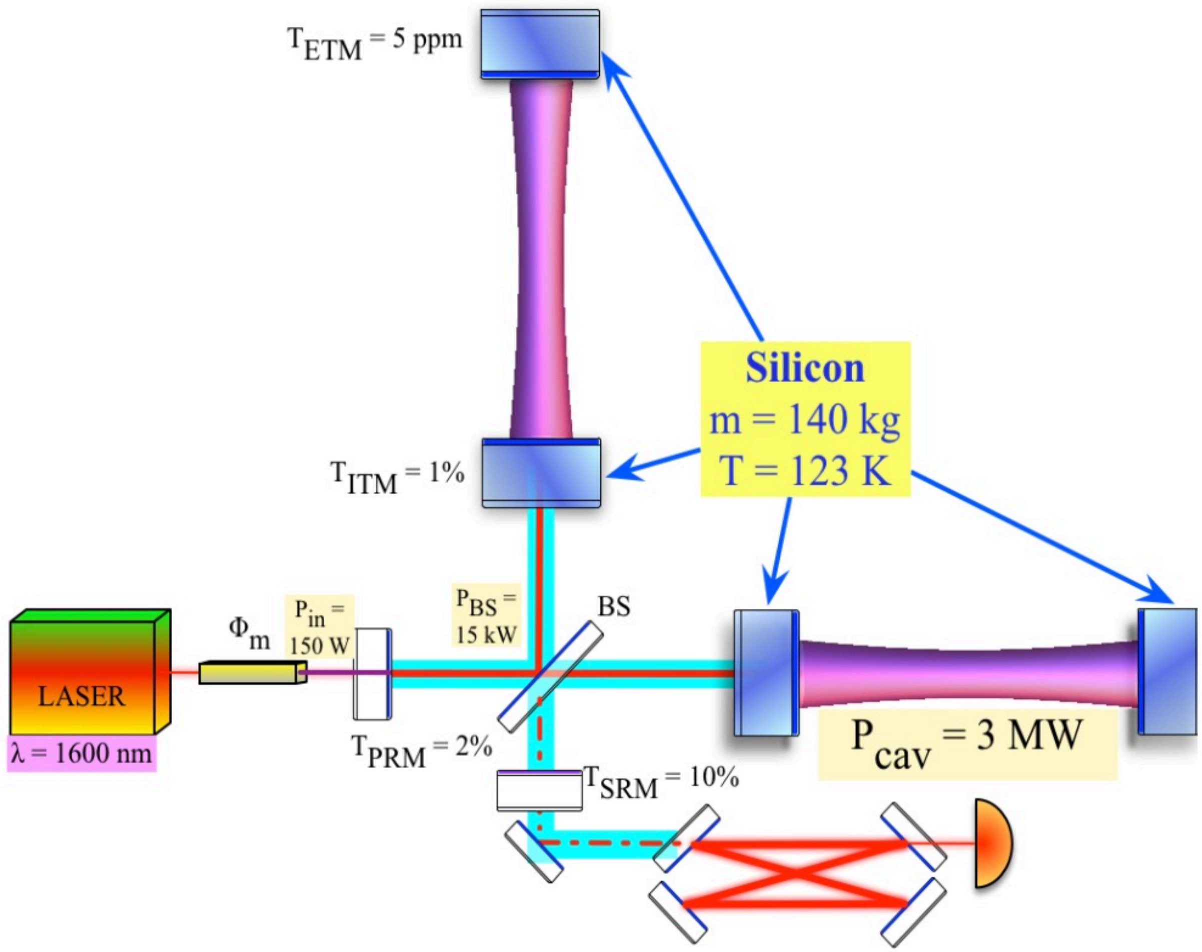


X_1 and X_2 associated with amplitude and phase



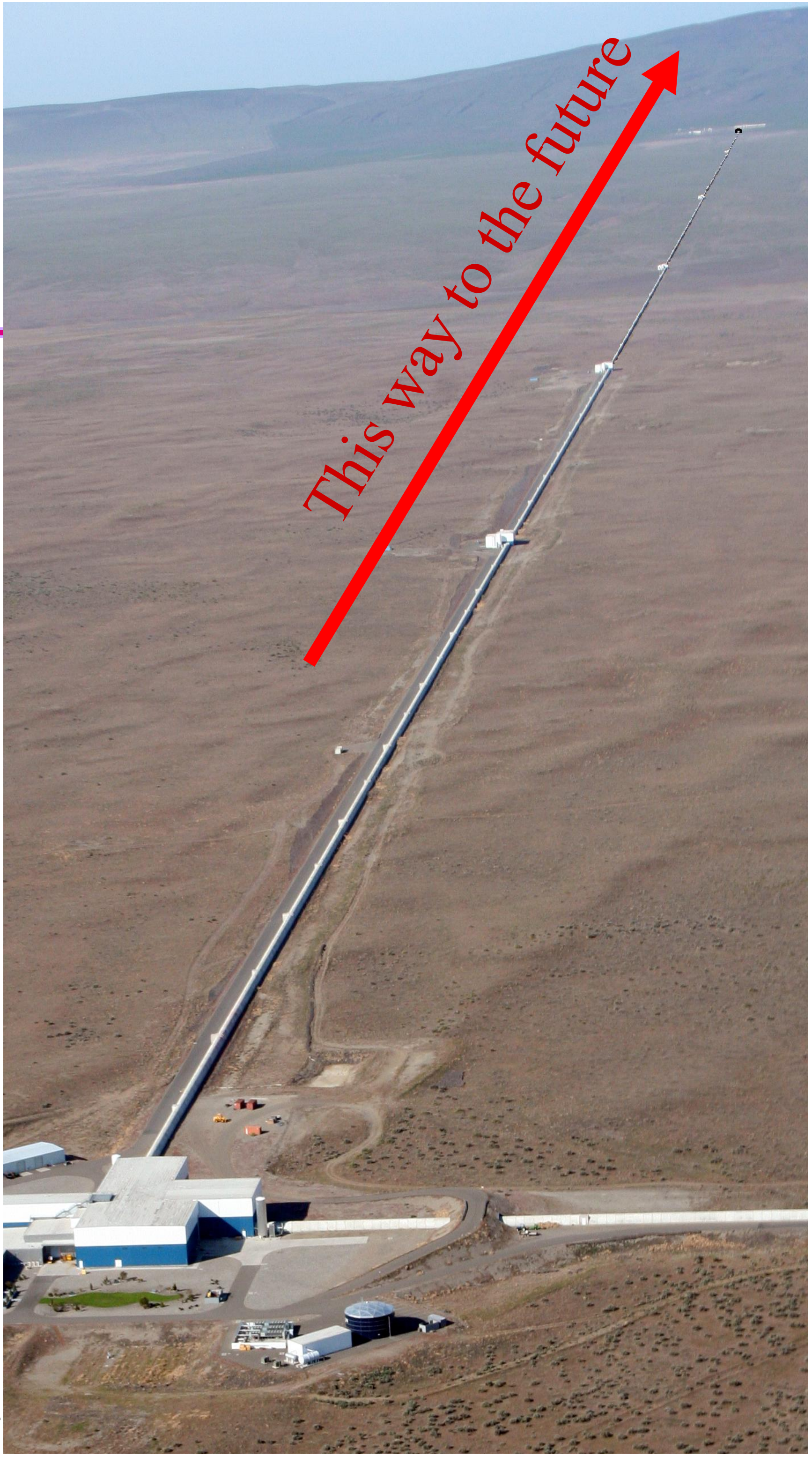
Aasi, et al., (LIGO Scientific Collaboration), Nature Physics, 7, 962 (2011); Nature Photonics 7 613 (2013).

Cryogenic in Voyger

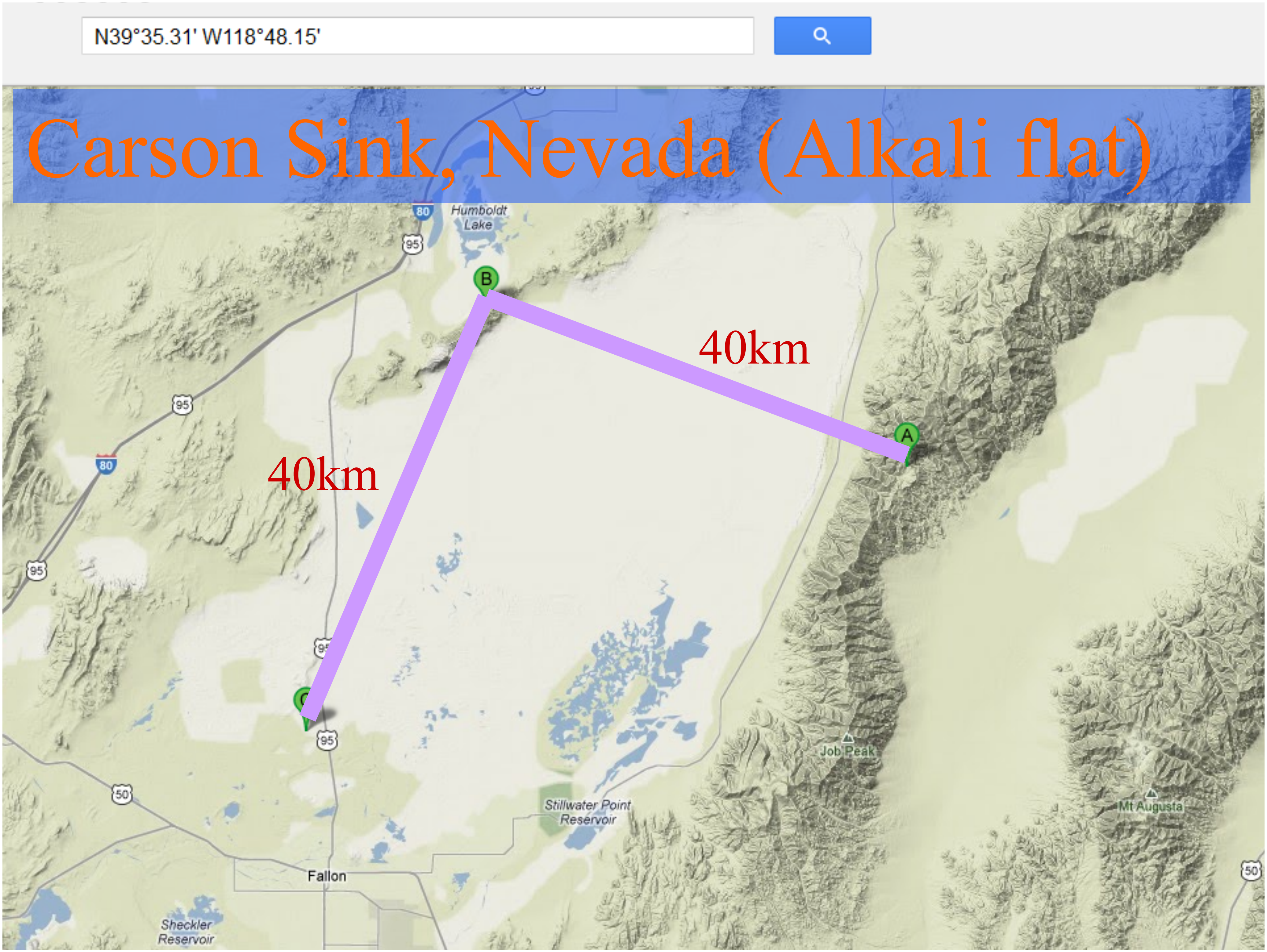


Cosmic Explorer : Long is good

- 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

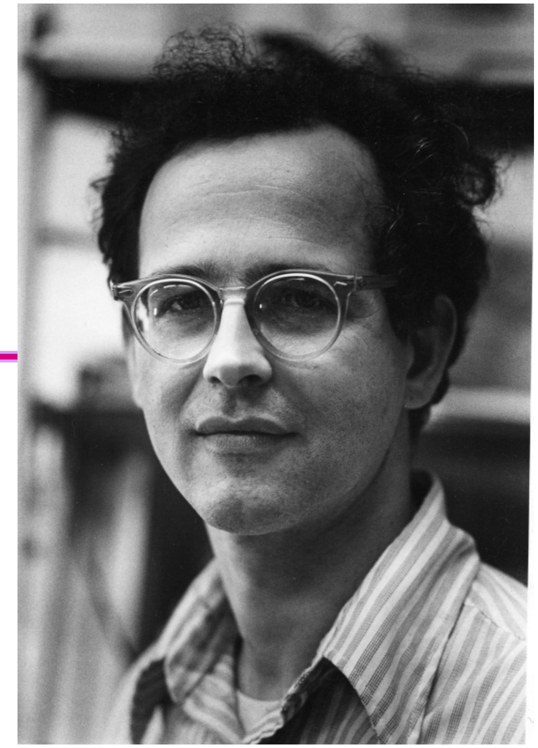


Carson Sink, Nevada (Alkali flat)



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