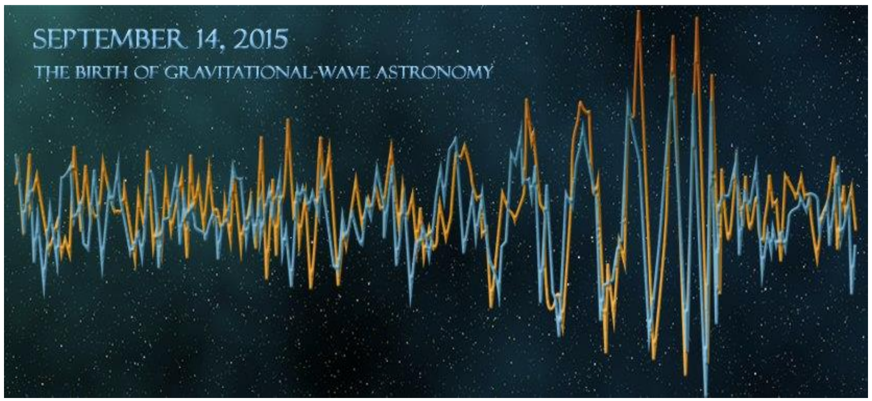


LIGO

Agenda
High Energy Physics Advisory Panel
DoubleTree Bethesda
8120 Wisconsin Ave.
Bethesda, MD 20814
March 31 - April 1, 2016

Barry C Barish
LIGO Laboratory
Caltech
31-March-2016

LIGO-G1600214

Link to our PRL paper

http://www.ligo.org

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$.

Detection Paper Factoids

"the stat that really struck me was that in the first 24 hrs., not only was the page for your PRL abstract hit 380K times, but the PDF of the paper was downloaded from that page 230K times. This is far more hits than any PRL ever, and the fraction of times that it resulted in a download was unusually high. Hundreds of thousands of people actually wanted to read the whole paper! That is just remarkable." Robert Garistro (PRL editor)

Detection-Companion-Papers

https://www.ligo.caltech.edu/page/detection-companion-papers

Discovery Paper

- **"Observation of Gravitational Waves from a Binary Black Hole Merger"** Published in *PRL* **116**, 061102 (2016).

Related papers

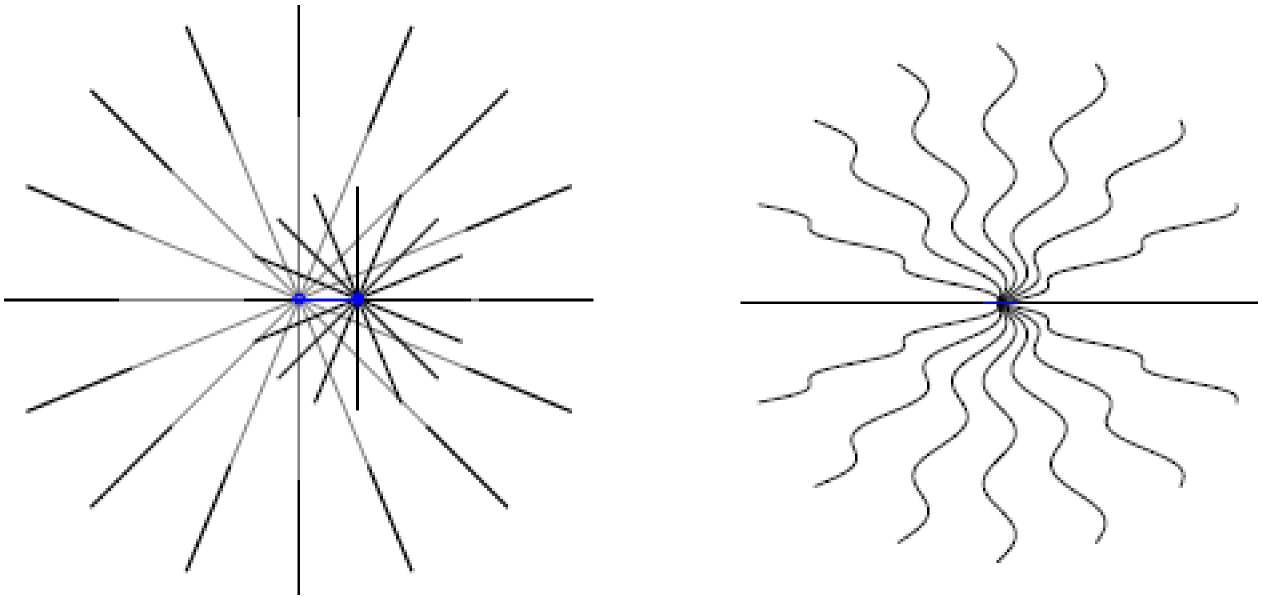
- **"Observing gravitational-wave transient GW150914 with minimal assumptions"**
- **"GW150914: First results from the search for binary black hole coalescence with Advanced LIGO4"**
- **"Properties of the binary black hole merger GW150914"**
- **"The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914"**
- **"Astrophysical Implications of the Binary Black-Hole Merger GW150914"**
- **"Tests of general relativity with GW150914"**

Detection-Companion-Papers *(continued)*

- "GW150914: Implications for the stochastic gravitational-wave background from binary black holes"
- "Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914"
- "Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914"
- "High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES"
- "GW150914: The Advanced LIGO Detectors in the Era of First Discoveries"
- "Localization and broadband follow-up of the gravitational-wave transient GW150914"

- **GW150914 Data Release**
- Data release at LIGO Open Science Center (LOSC) website.

Gravitational Waves



- **Newtonian gravity**: force depends on distance between massive objects and there is instantaneous action at a distance
- **Einstein's gravity**: time dependent gravitational fields propagate like light waves, proportional to quadrupole moment and at speed of light.

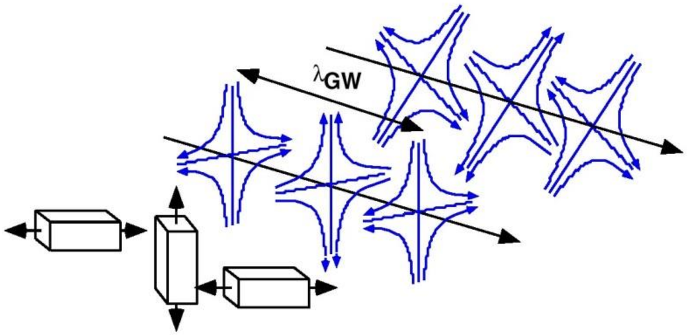
Einstein's Theory of Gravitation

Gravitational Waves

- Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

- The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).

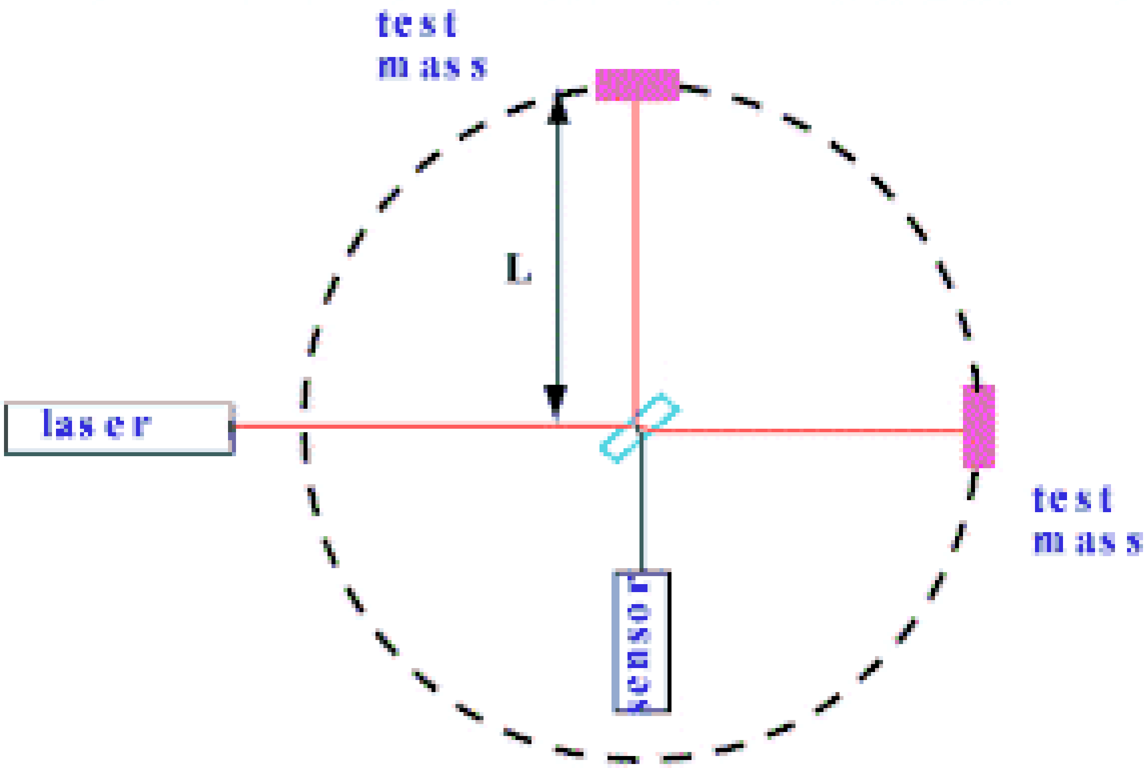


- Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

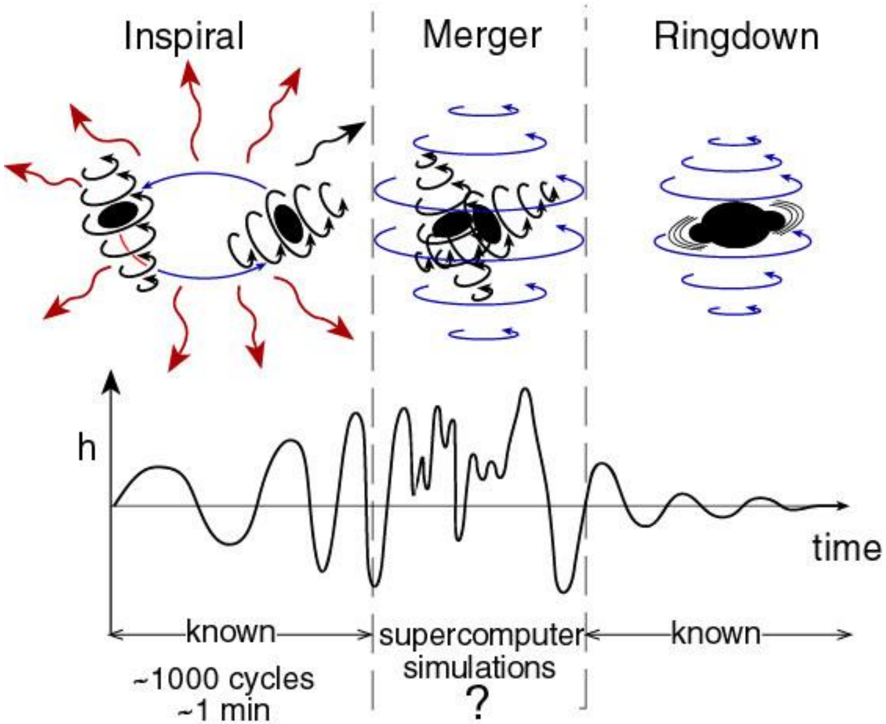
$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

"Direct Detection"

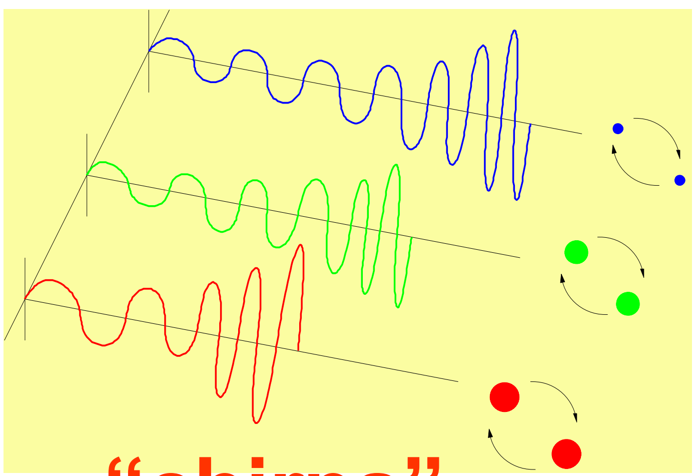
Suspended Mass Interferometers



Compact binary collisions



- Neutron Star – Neutron Star
  - **waveforms are well described**
- Black Hole – Black Hole
  - **Numerical Relativity waveforms**
- Search: *matched templates*

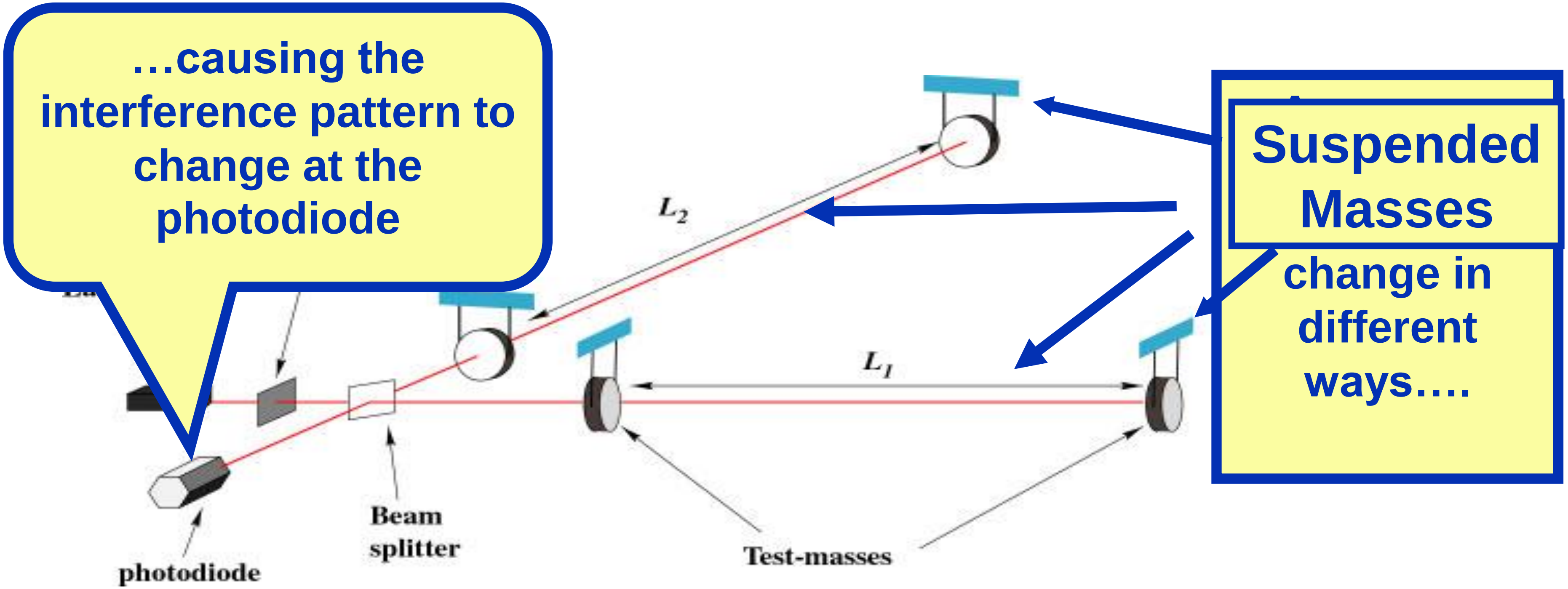


"chirps"

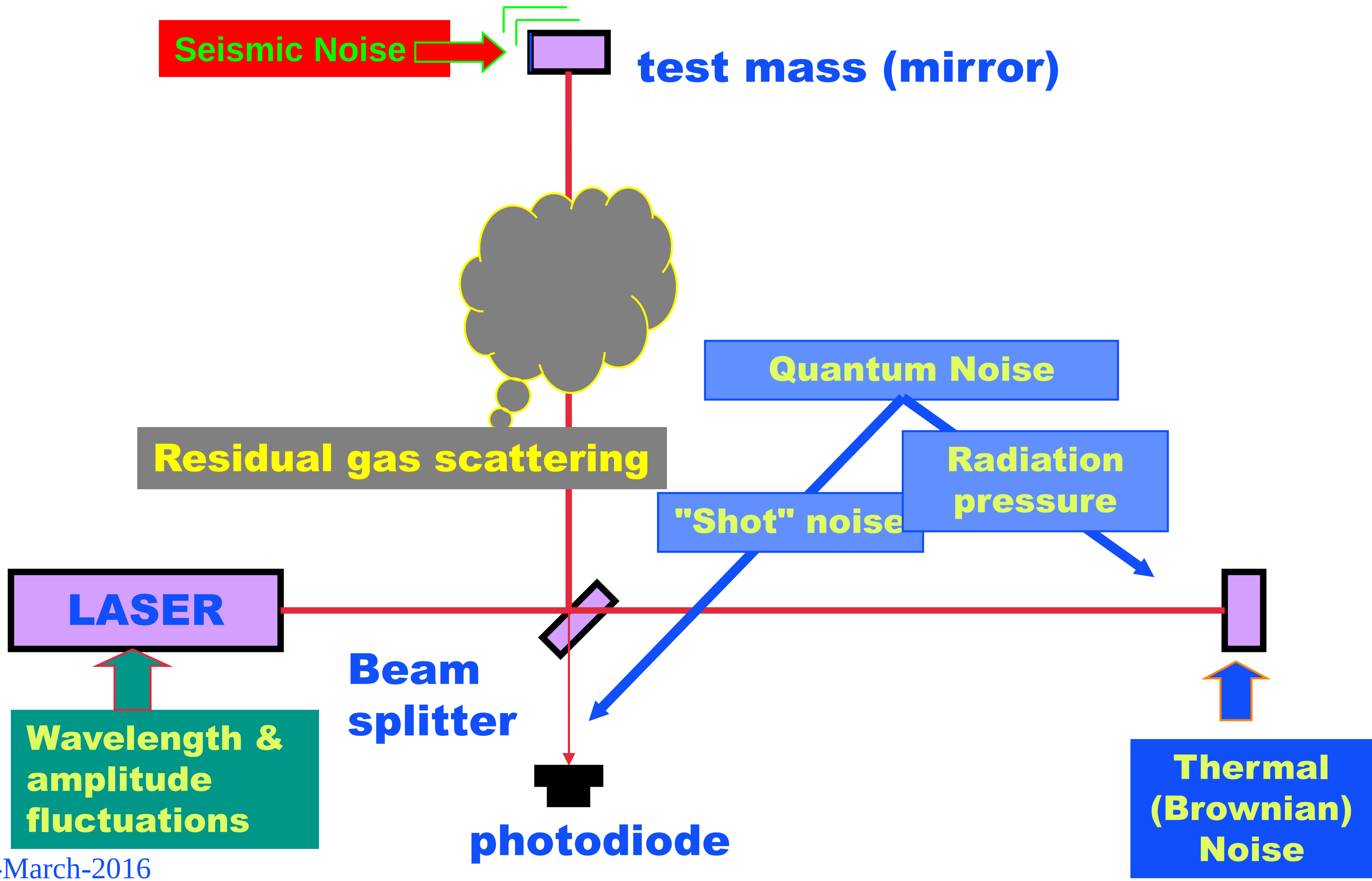
LIGO Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms

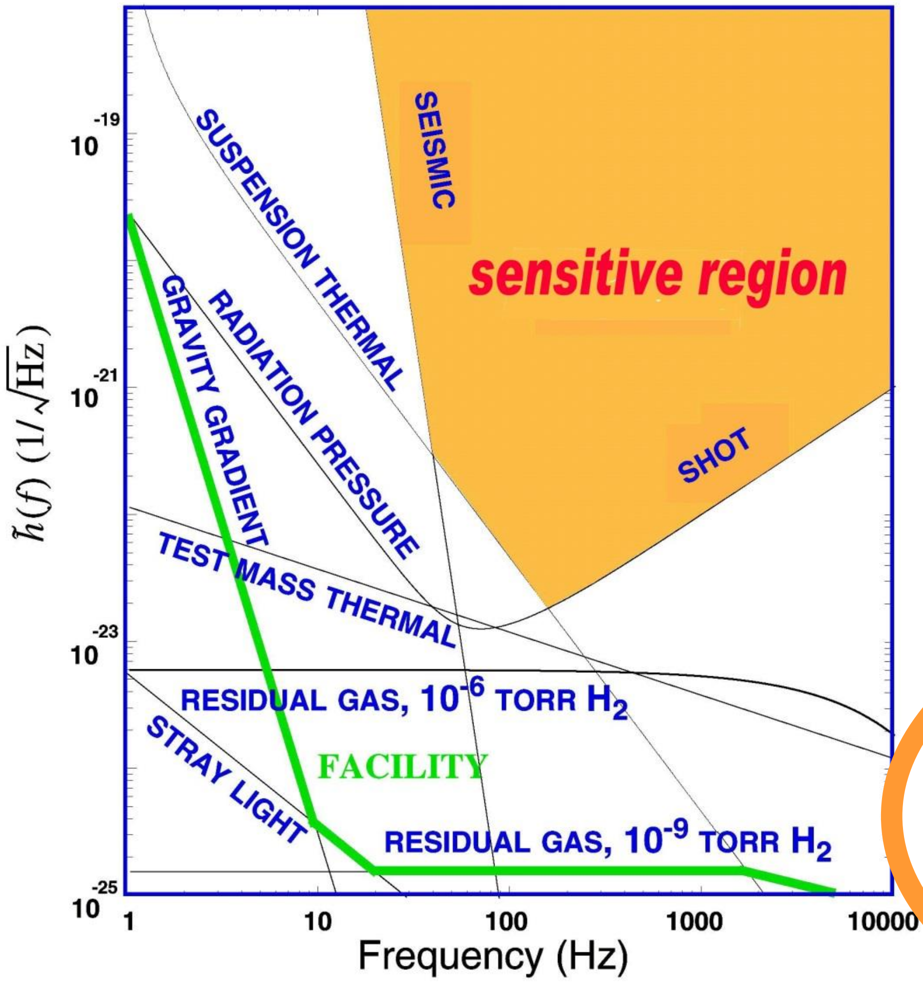
- Arms in LIGO are 4km
- Measure difference in length to one part in 10^{21} or 10^{-18} meters



Interferometer Noise Limits

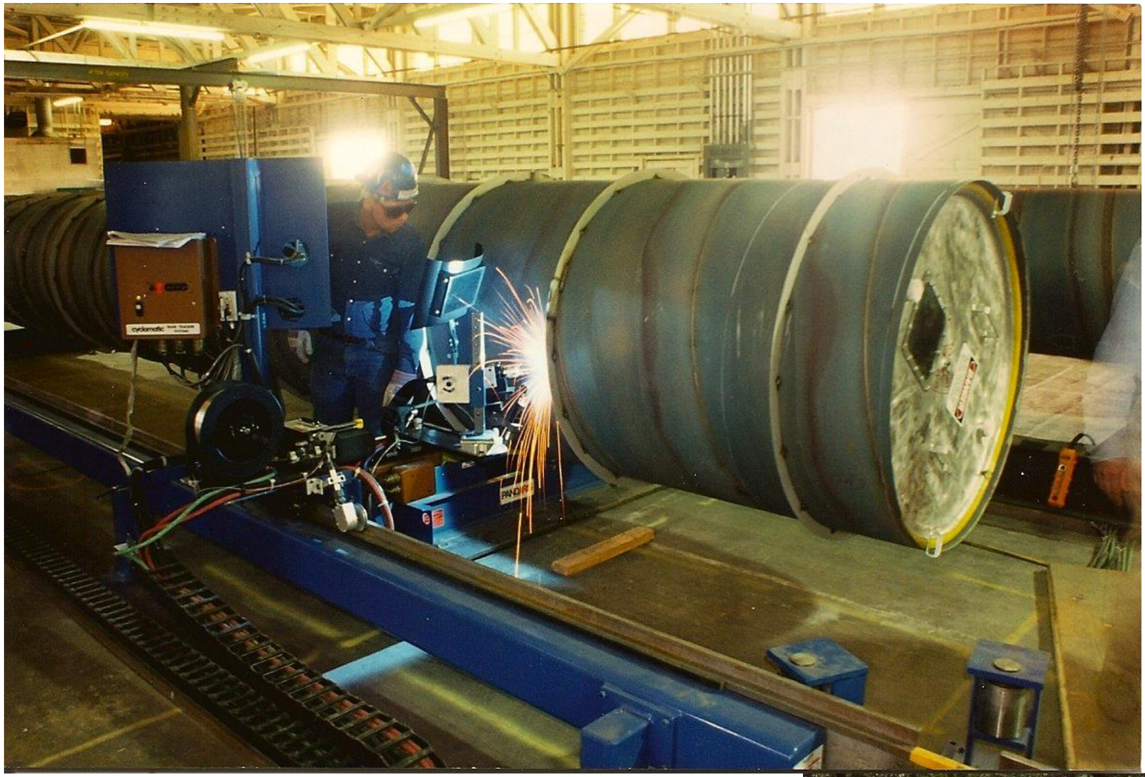


What Limits LIGO Sensitivity?

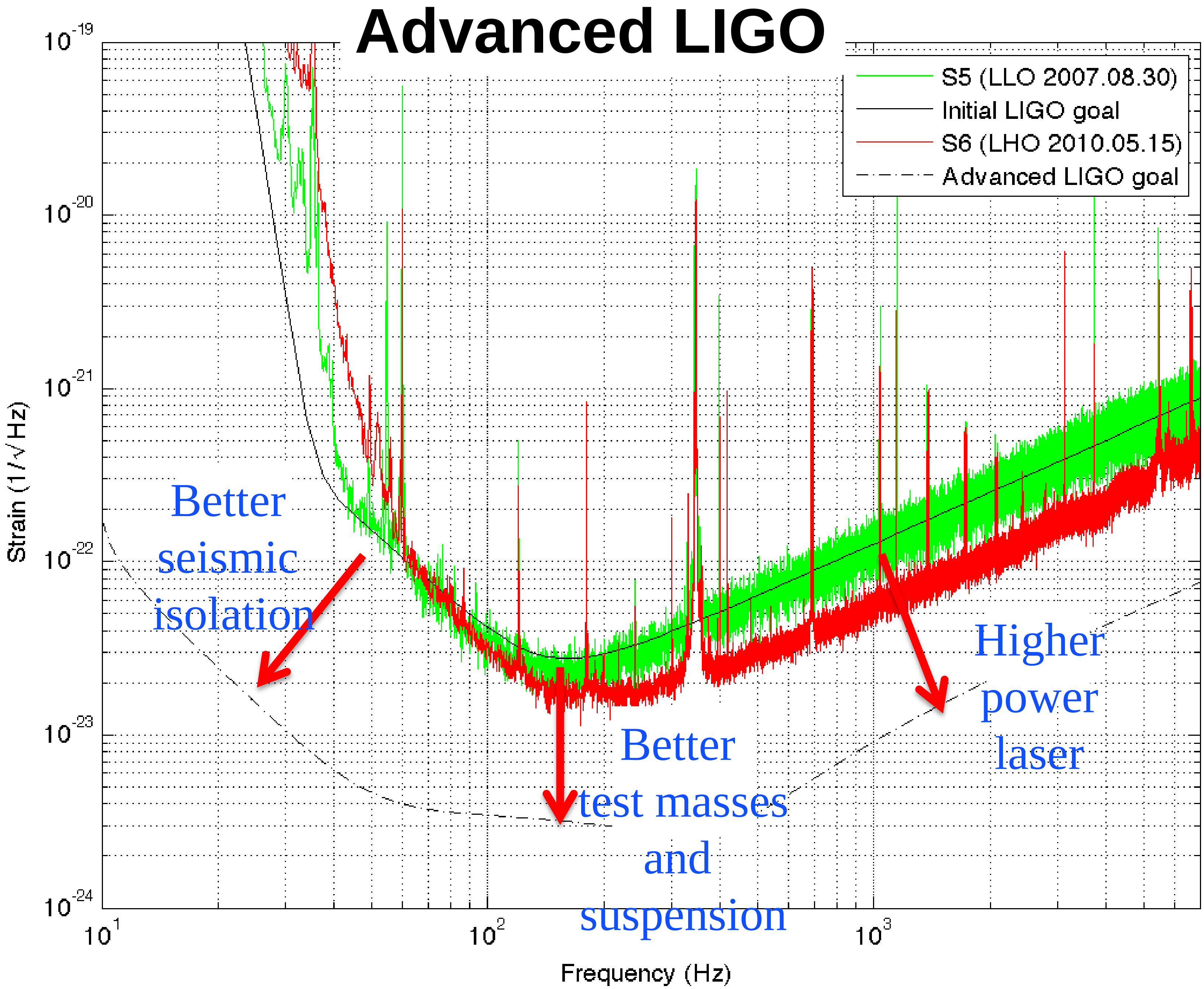


- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals

LIGO
beam tube

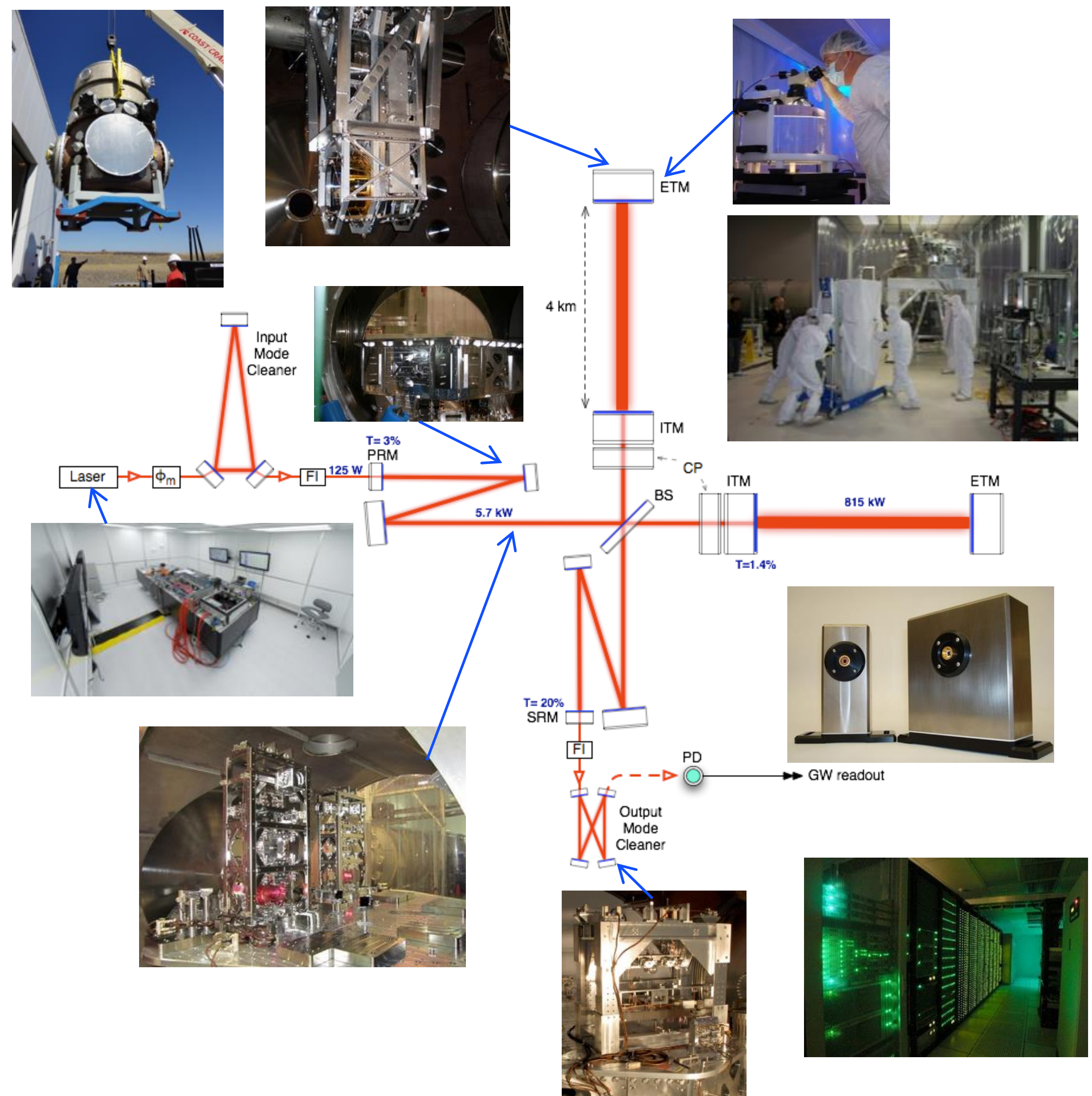


LIGO
vacuum equipment


Advanced LIGO
S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
Better seismic isolation
Better test masses and suspension
Higher power laser

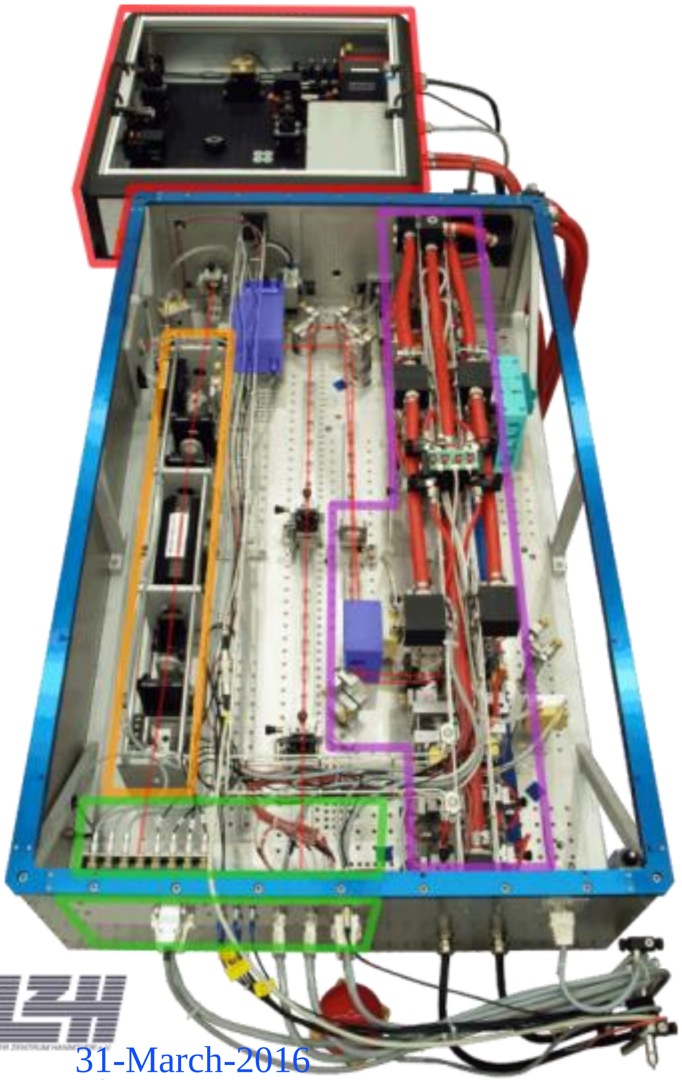
Achieving x10 sensitivity improvement?

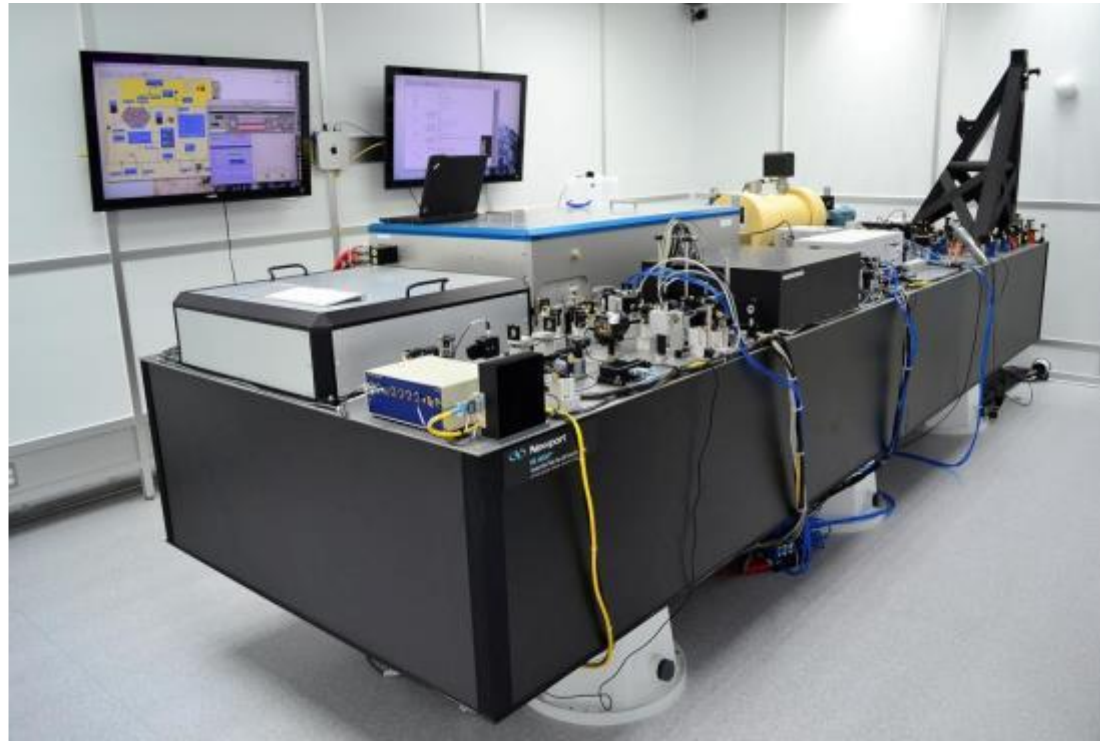
Parameter	***Initial LIGO***	***Advanced LIGO***
Input Laser Power	10 W (10 kW arm)	180 W (>700 kW arm)
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (stable recycling cavities)
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	f_{low} ~ 50 Hz	f_{low} ~ 13 Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum



200W Nd:YAG laser

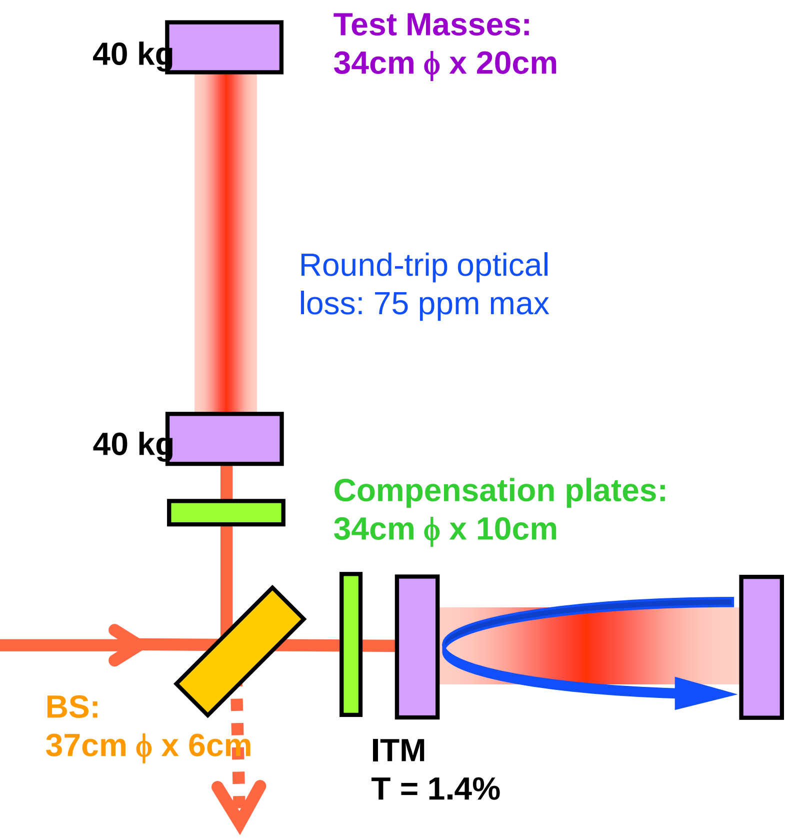
Designed and contributed by Max Planck Albert Einstein Institute

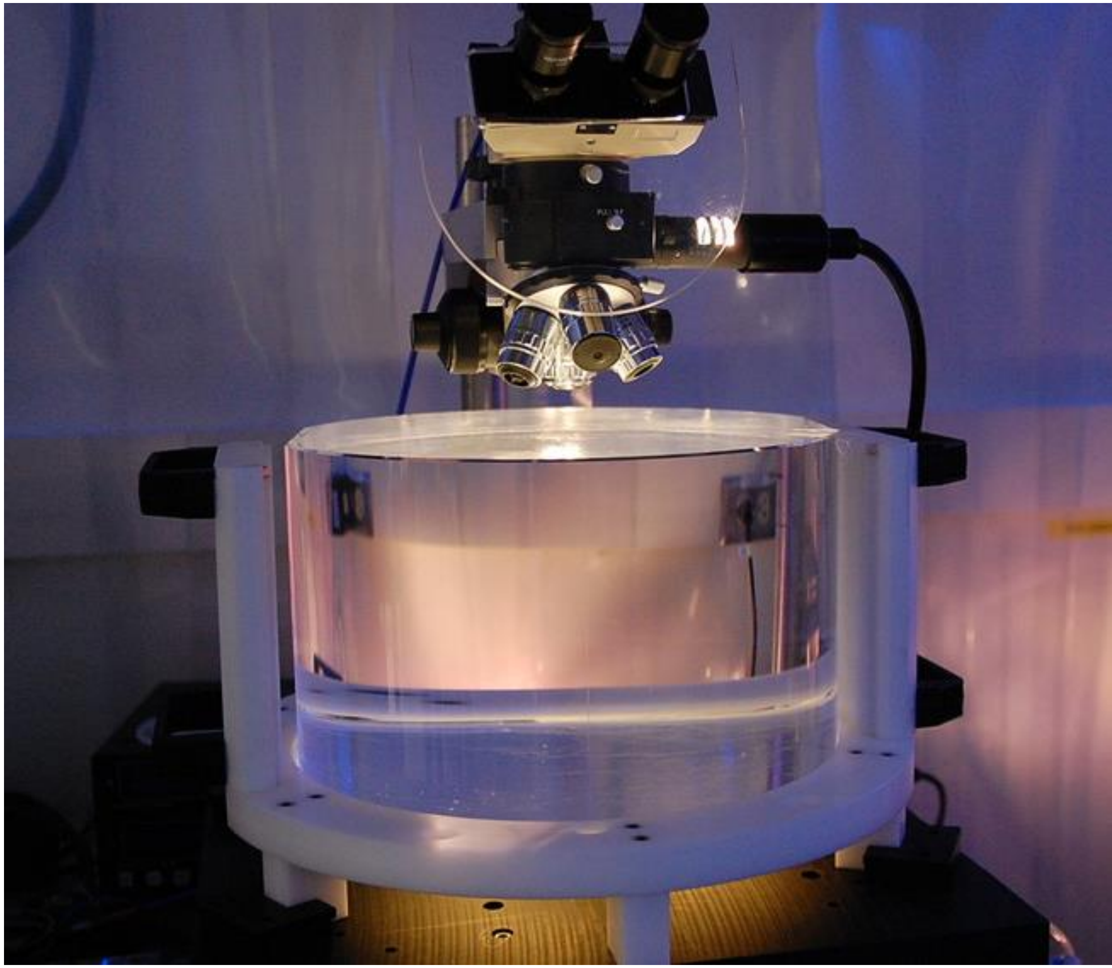




- Stabilized in power and frequency
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

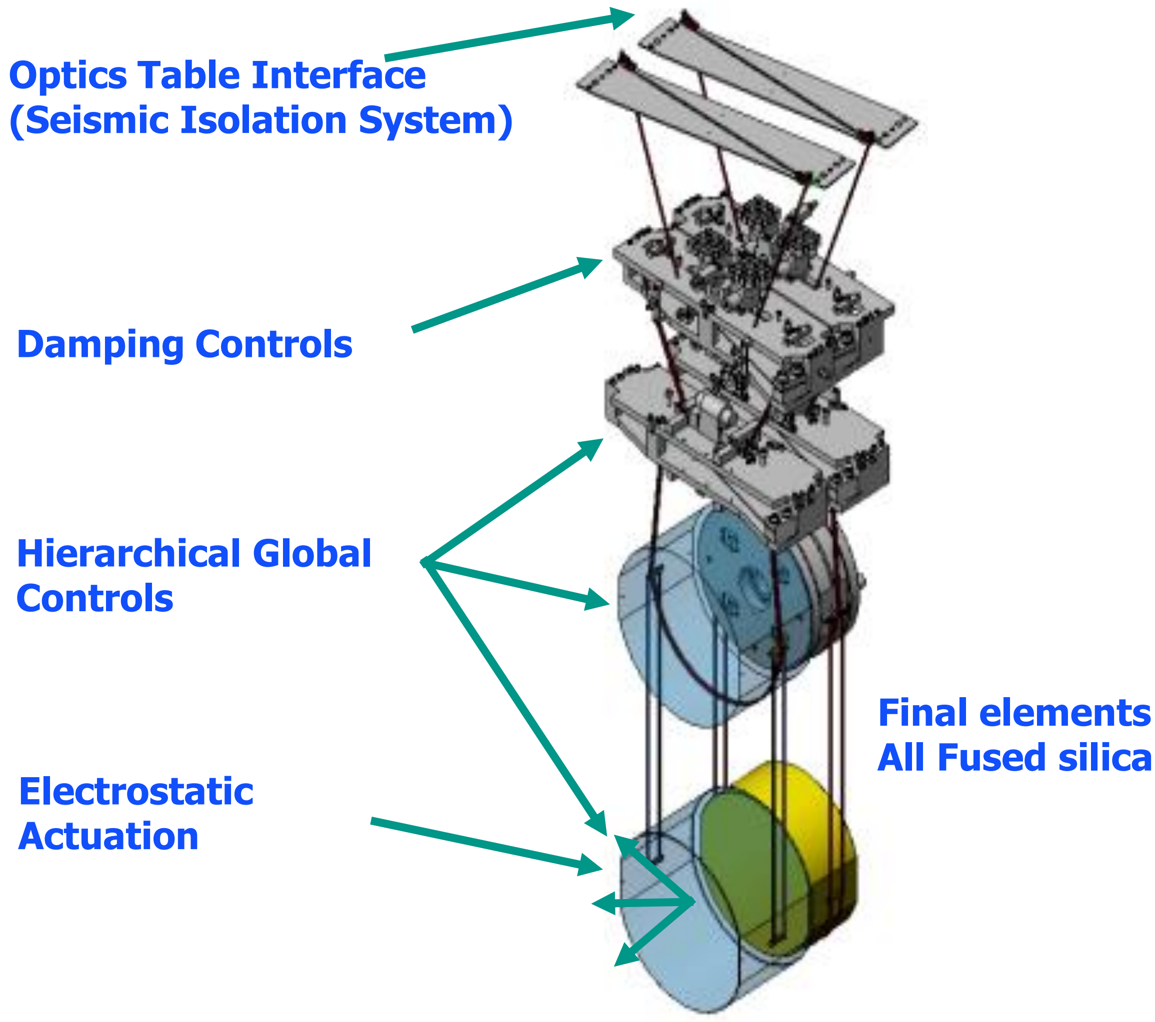
Test Masses


40 kg
Test Masses:
34cm ϕ x 20cm
Round-trip optical
loss: 75 ppm max
40 kg
Compensation plates:
34cm ϕ x 10cm
BS:
37cm ϕ x 6cm
ITM
T = 1.4%

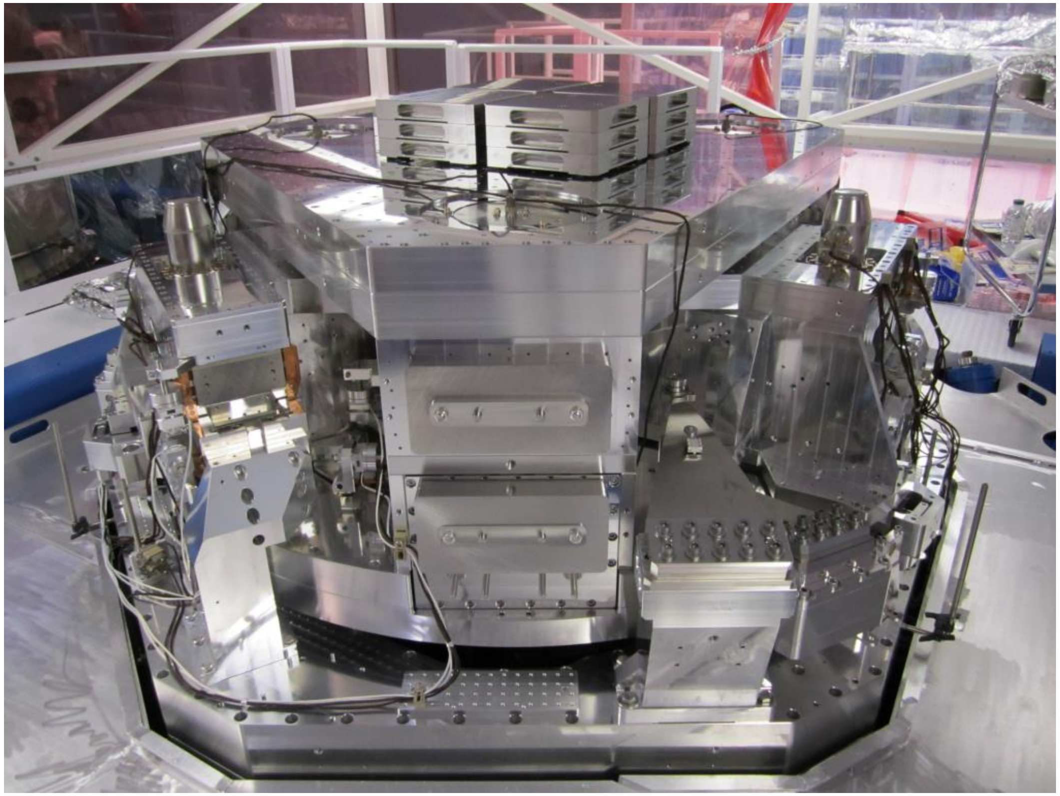


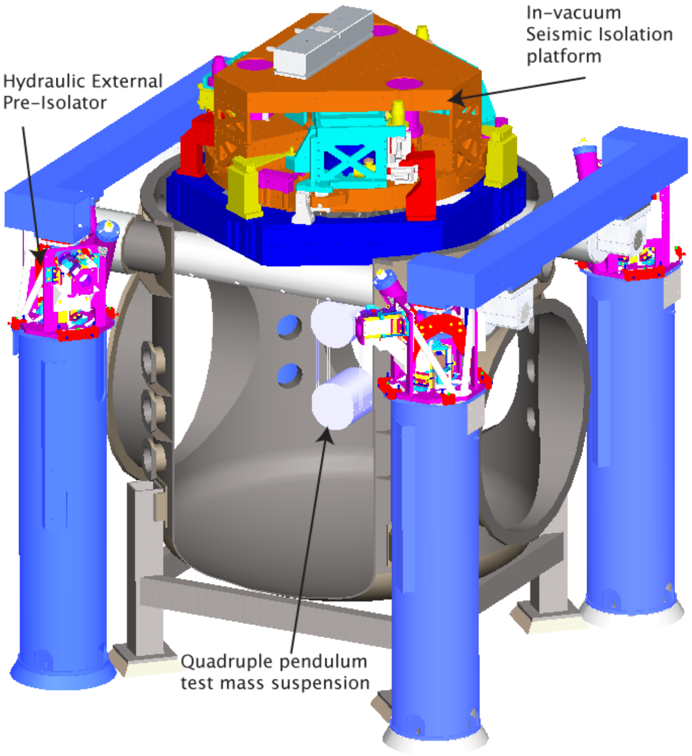
Test Mass

Quadruple Pendulum suspension



Seismic Isolation:
Multi-Stage Solution





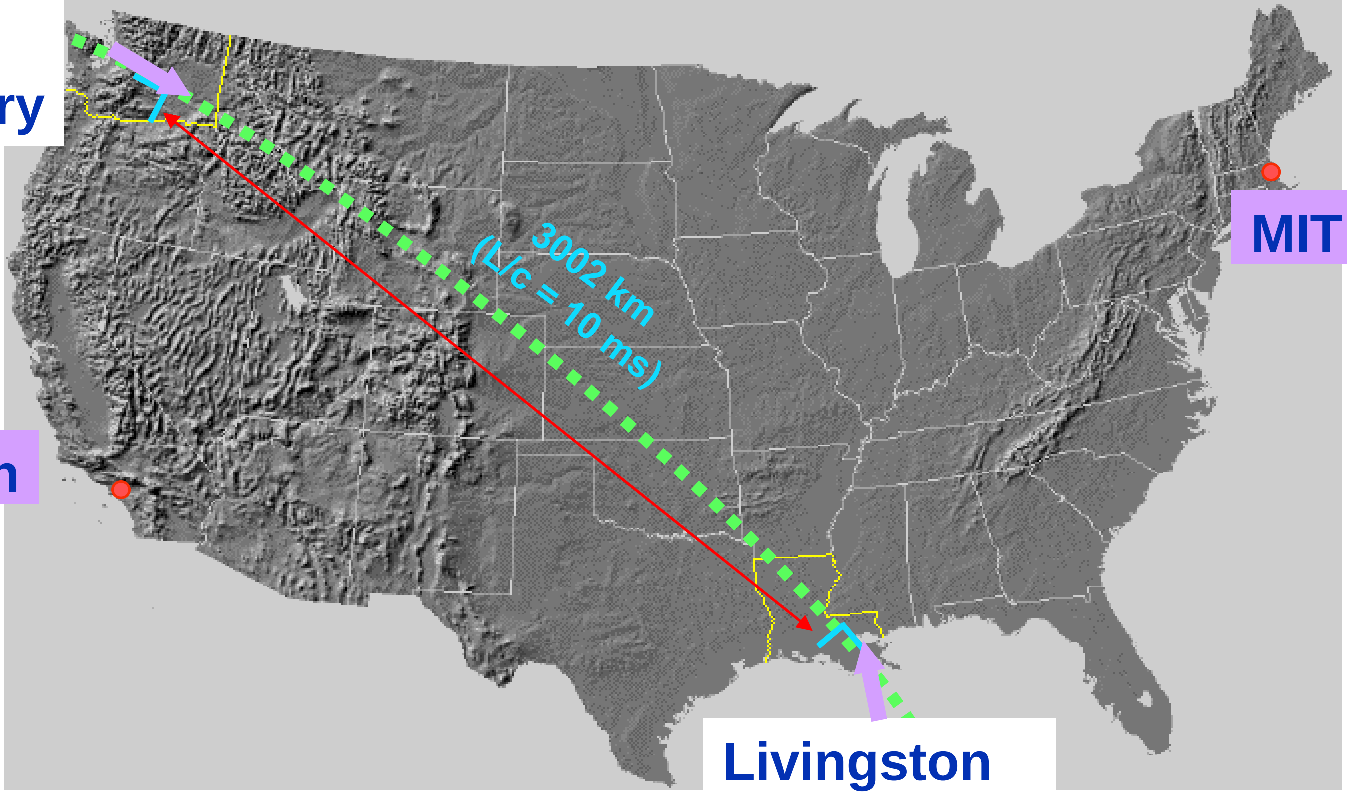
-

LIGO Livingston Observatory

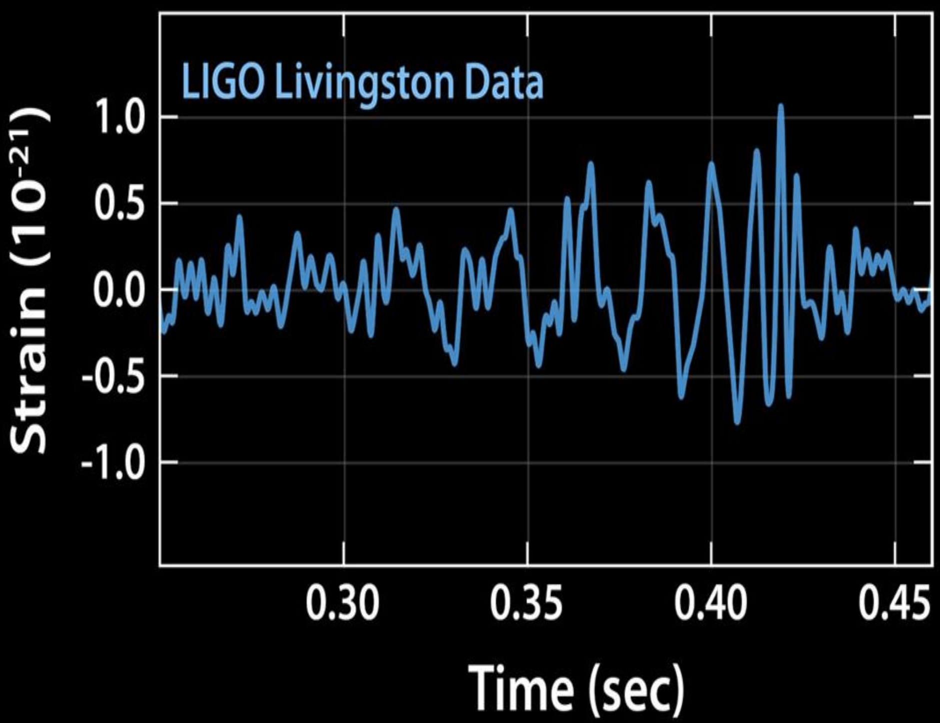
LIGO Hanford Observatory

LIGO

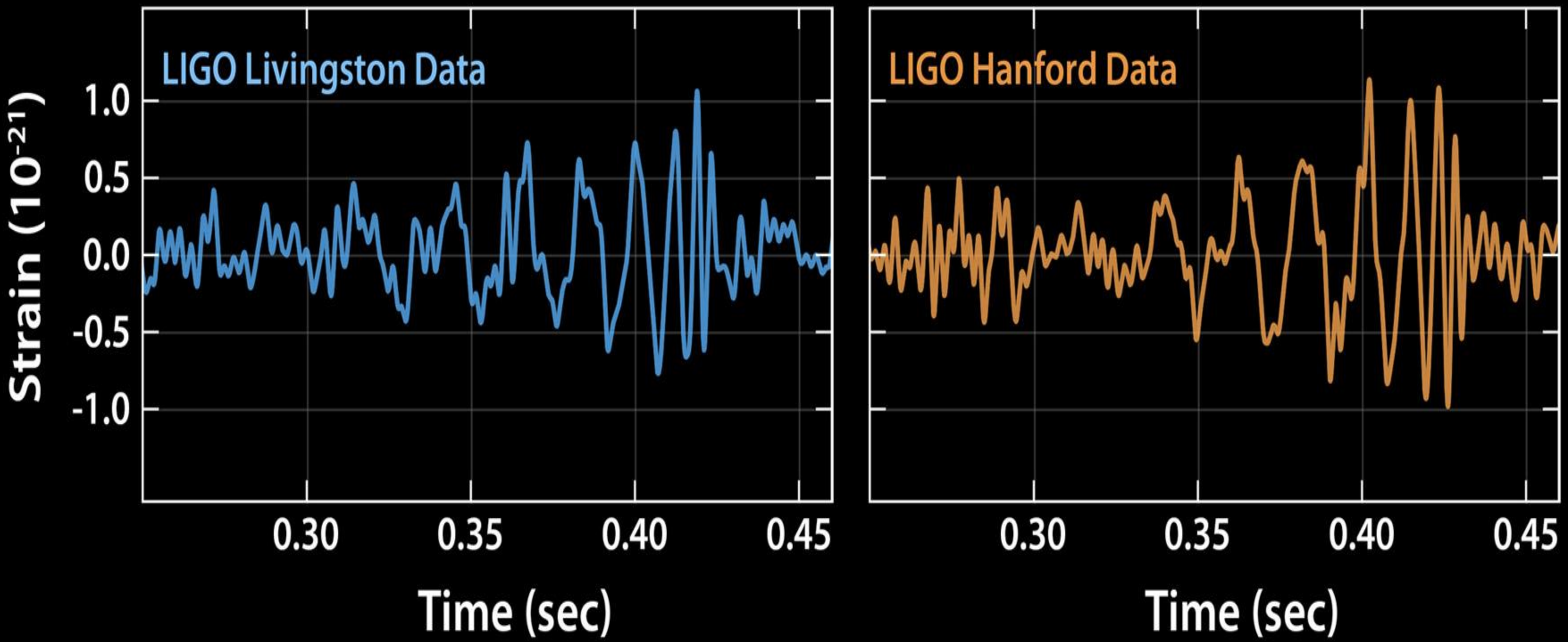
Simultaneous Detection



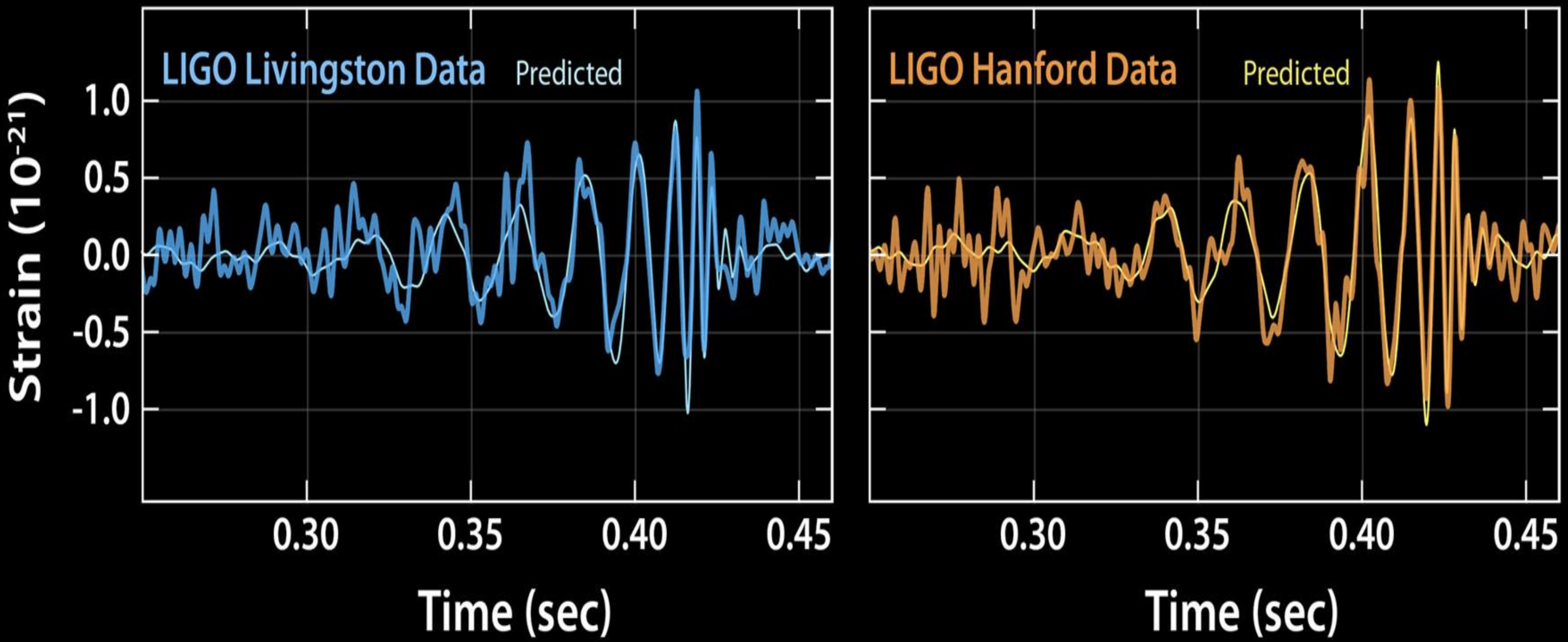
September 14, 2015



September 14, 2015



September 14, 2015



Gravitational Wave Event GW150914

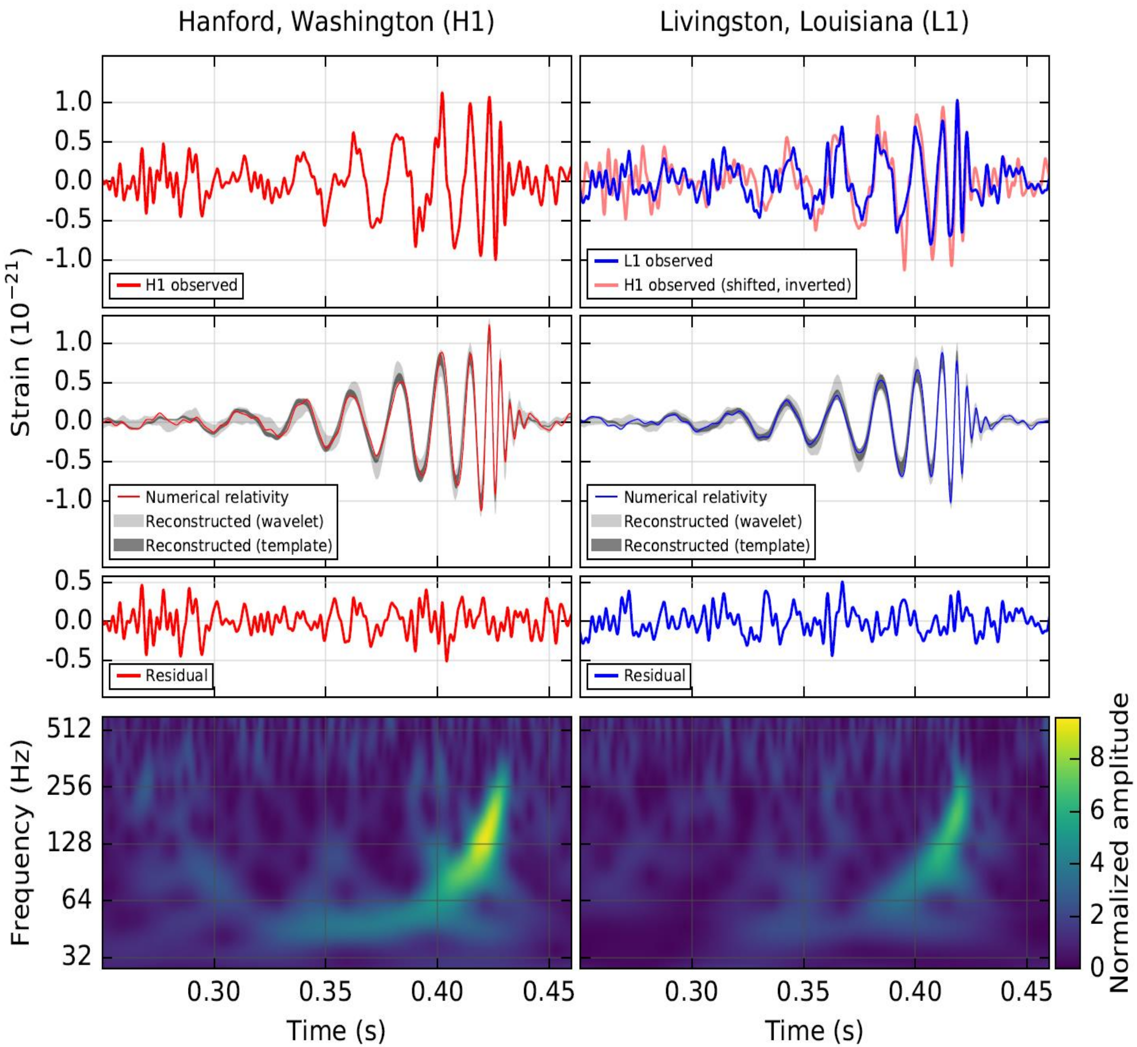
Data bandpass filtered between 35 Hz and 350 Hz

Time difference 6.9 ms with Livingston first

Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

Third Row –residuals

bottom row – time frequency plot showing frequency increases with time (chirp)

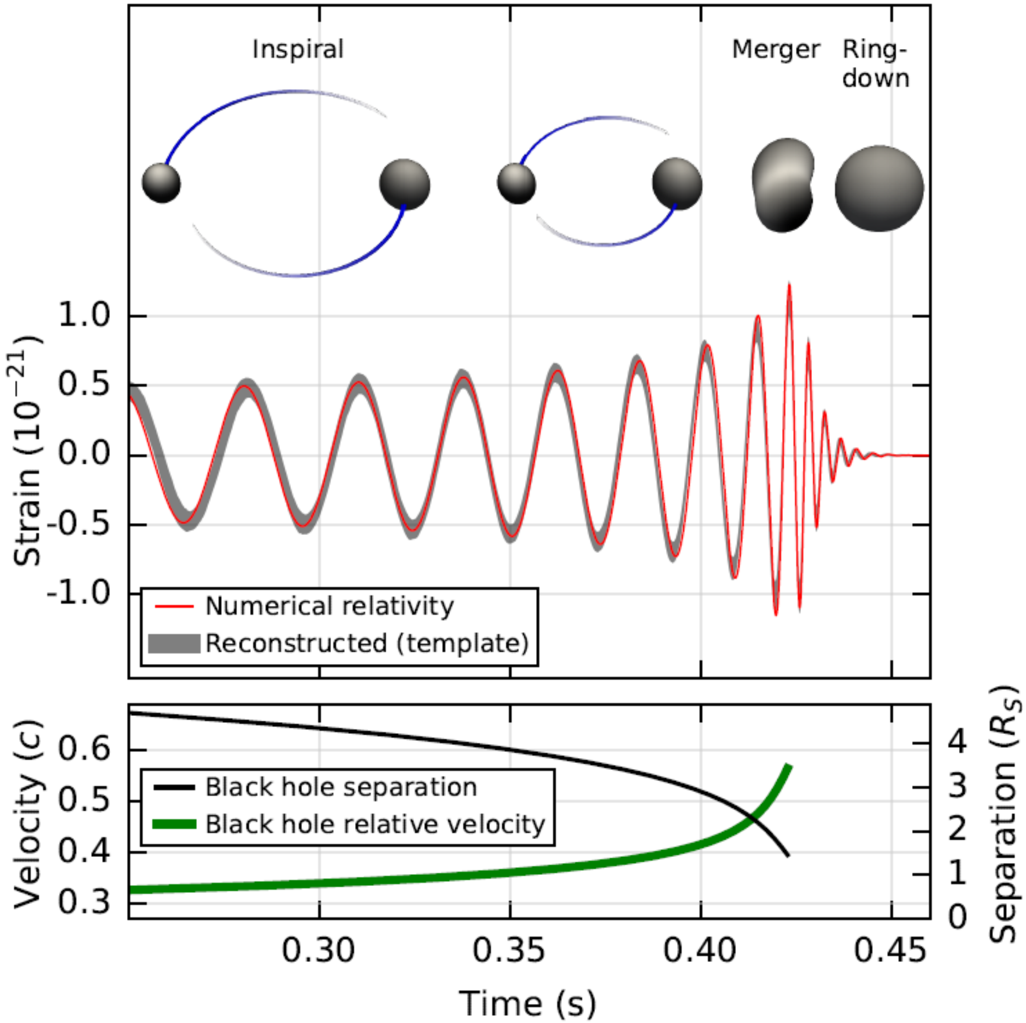


31-March-2016

Estimated GW Strain Amplitude: *GW150914*

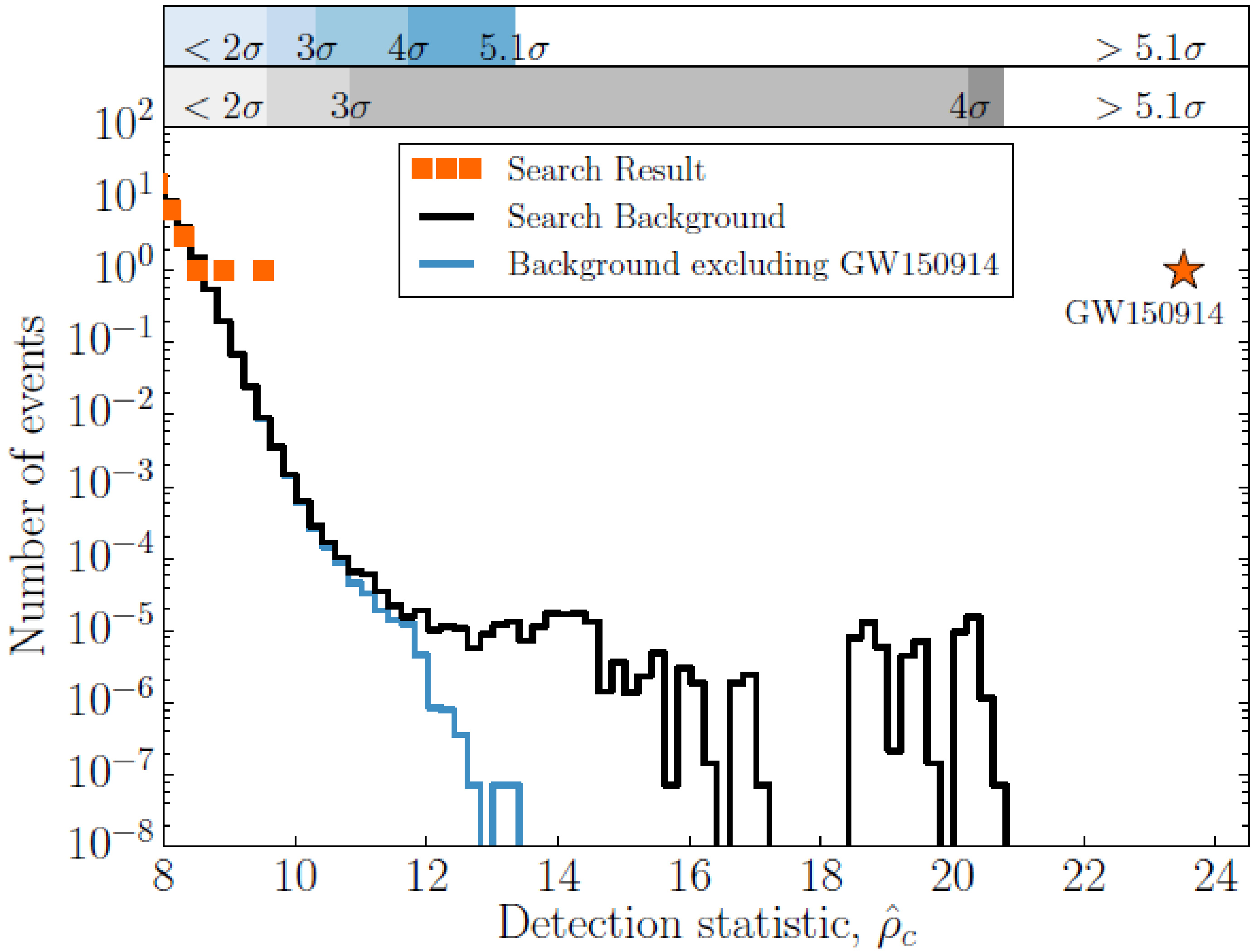
Full bandwidth waveforms without filtering. Numerical relativity models of black hole horizons during coalescence

Effective black hole separation in units of Schwarzschild radius ($R_s = 2GM_f / c^2$); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_f \pi f/c^3)^{1/3}$



Statistical Significance of GW150914

Binary Coalescence Search



31

Measuring the parameters

- Orbits decay due to emission of gravitational waves
  - **Leading order** determined by "chirp mass"

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.
- Sky location, distance, binary orientation information extracted from time-delays and differences in observed amplitude and phase in the detectors

Source Parameters for GW150914

- Use numerical simulations fits of black hole merger to determine parameters, we determine total energy radiated in gravitational waves is $3.0 \pm 0.5\ M_o c^2$. The system reached a peak ~3.6 x10^{56} ergs, and the spin of the final black hole < 0.7 (not maximal spin)

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	$0.09^{+0.03}_{-0.04}$

Results

Heavy stellar black holes

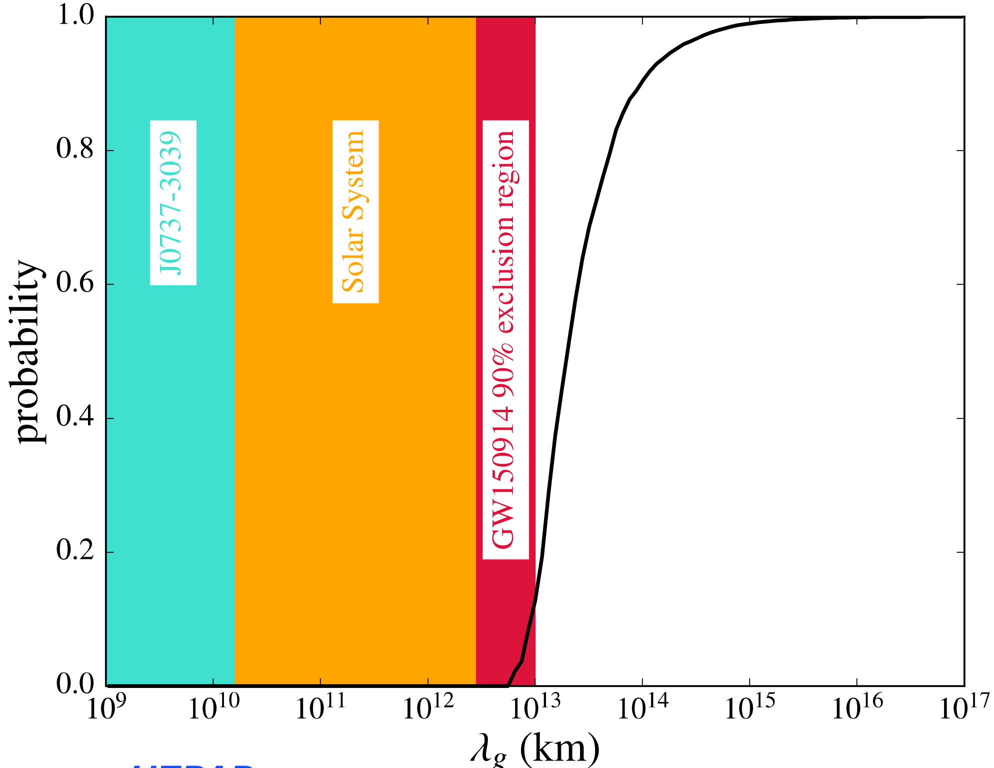
- Stellar binary black holes do exist!
  - **Form** and **merge** in time scales accessible to us
  - Predictions previously encompassed [0 – 10^3] / Gpc^3 / yr
  - Now we <u>exclude</u> lowest end: **rate > 1 Gpc^3 / yr**
- Masses ($M > 20\ M_\odot$) are large compared with *known* stellar mass BHs
- Progenitors are
  - Likely **heavy**, $M > 60\ M_\odot$
  - Likely with a **low metallicity**, $Z < 0.25\ Z_\odot$
- Measured redshift $z \sim 0.1$
- **Low metallicity models can produce low-*z* mergers at rates consistent with our observation**

Upper bound on the graviton mass

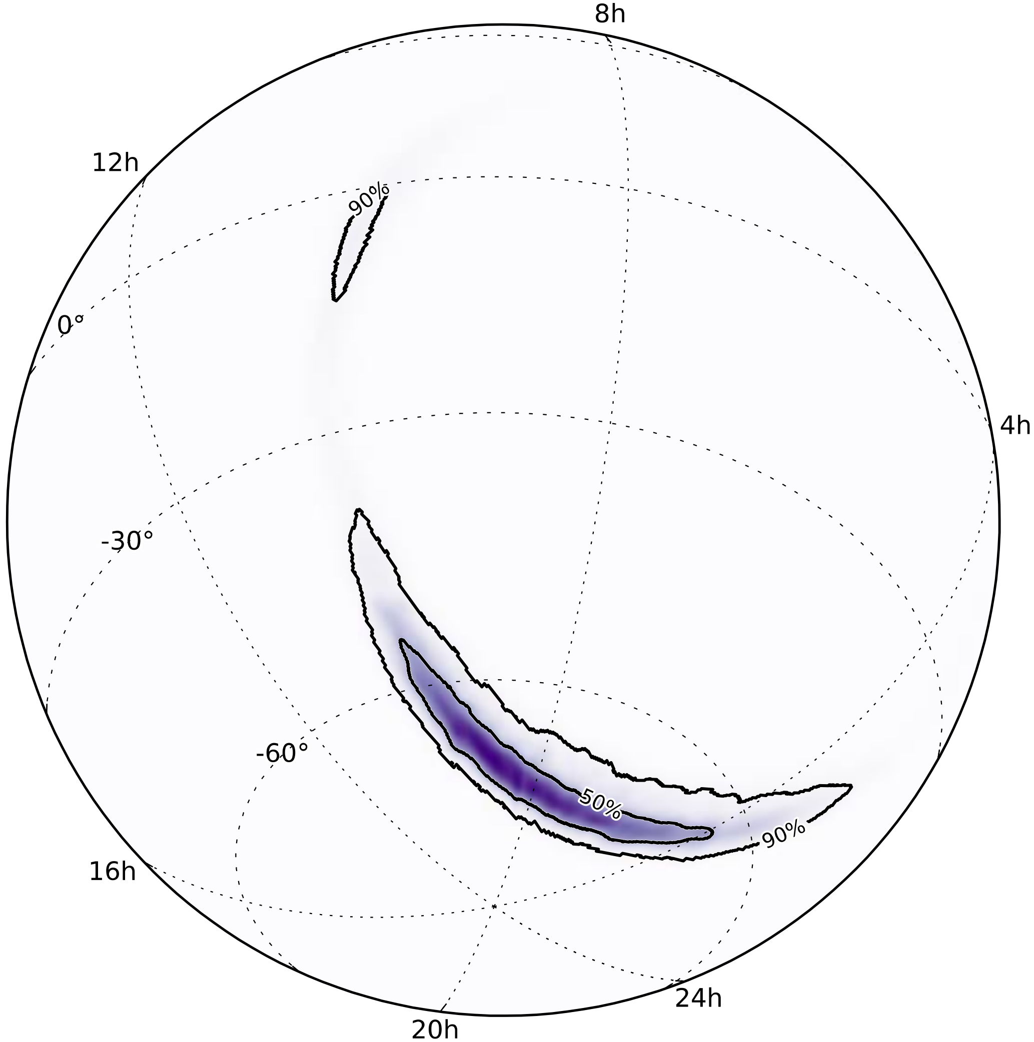
- If $c_{GW} < c$
- ⇔ gravitational waves have a modified dispersion relation
- Findings : at 90 % confidence, $\lambda_g > 10^{13}$ km

or equivalently

$m_g < 1.2 \times 10^{-22}$ eV/c^2



Localization



LIGO: Lesson's Learned

LIGO Project Approved / Funded by NSF in 1994

» **High risk; high scientific payoff !!**

» Unwavering NSF support for 22 years !

» Total NSF Investment to date ~1.2 B$, construction + research

» One major project upgrade (MREFC)

Lessons

» NSF can successfully manage large scientific projects

» Scientists management successful --- on budget, schedule and performance.

» Key strategy: forward looking infrastructure, ongoing R&D and evolving capability

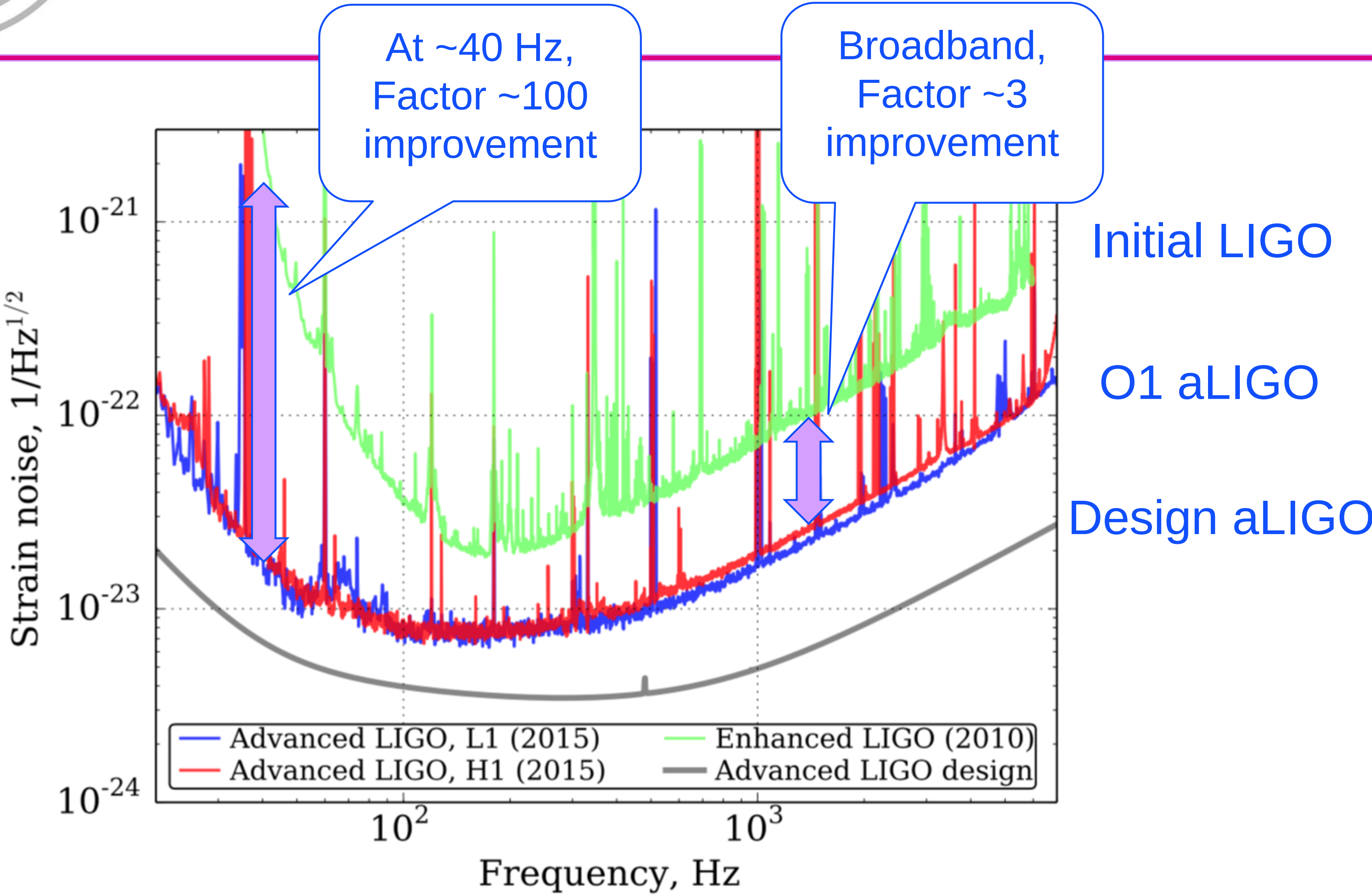
"Open" Scientific Collaboration

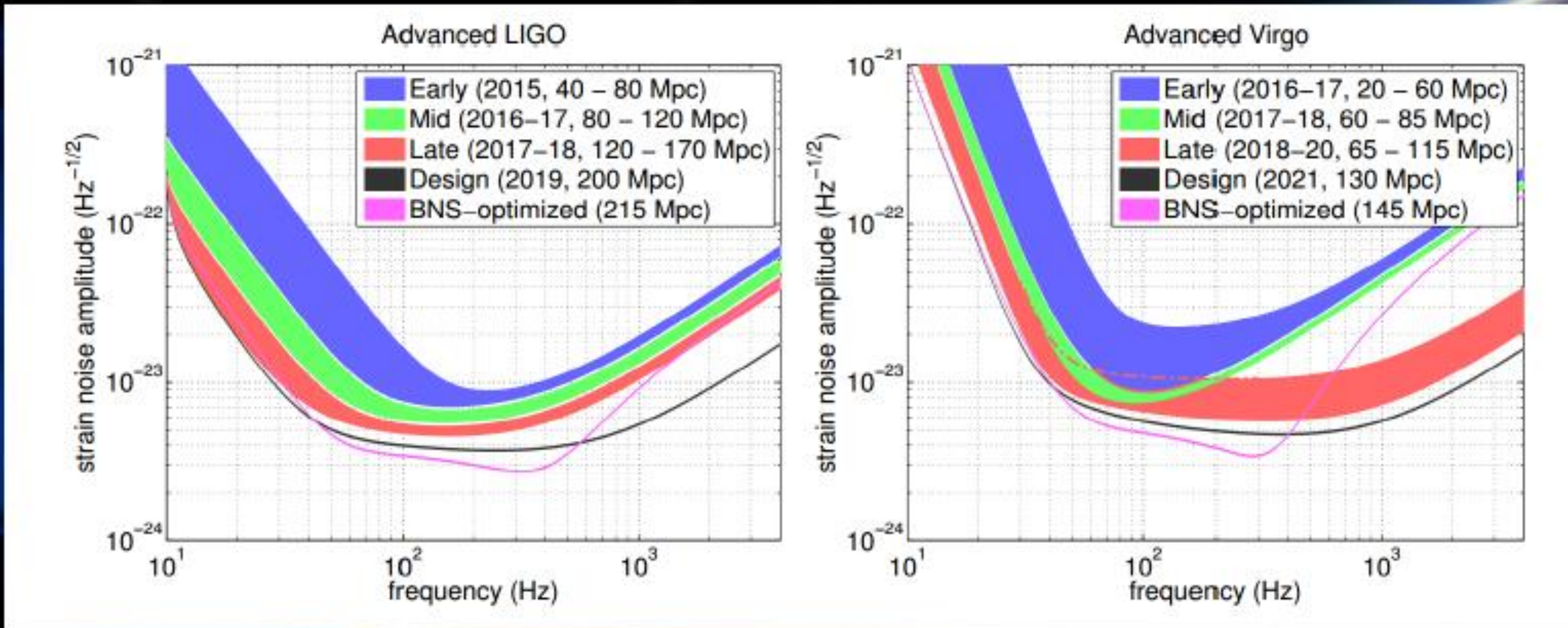
» Open access data – discovery data released on Feb 11

» General policy; all data after 2 years (will shorten) .

LIGO Scientific Collaboration

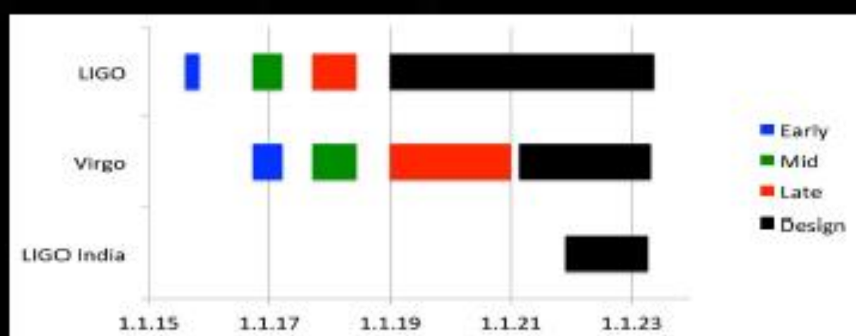
Sensitivity for first Observing run





Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot}c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016 – 2017	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017 – 2018	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Observing scenario



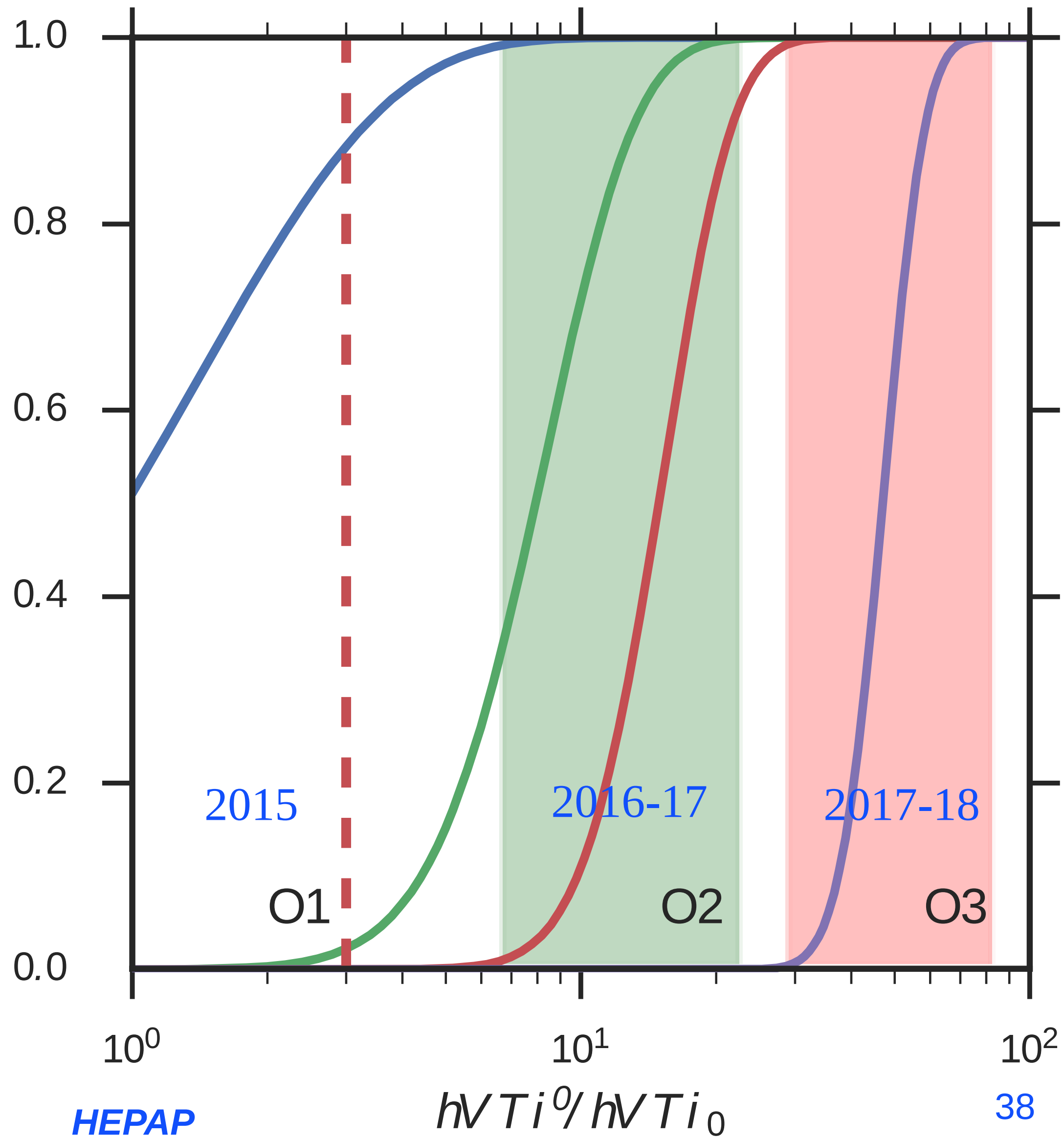
Rate expectations

future running

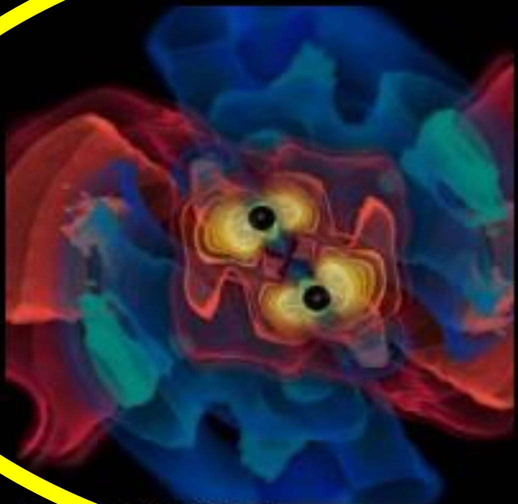
Probability of observing

- N > 0 (blue)
- N > 5 (green)
- N > 10 (red)
- N > 35 (purple)

highly significant events, as a function of surveyed time-volume.



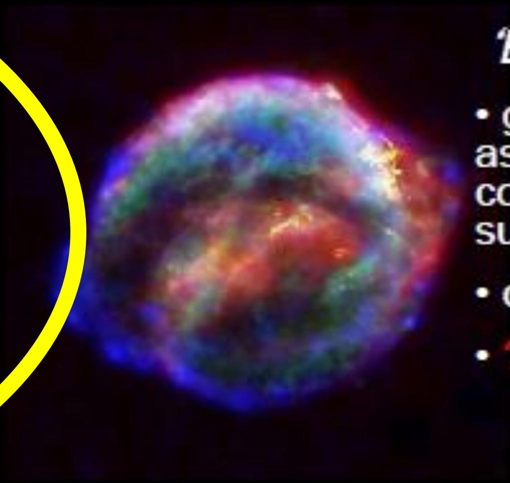
Astrophysical targets for ground-based detectors



Credit: AEI, CCT, LSU

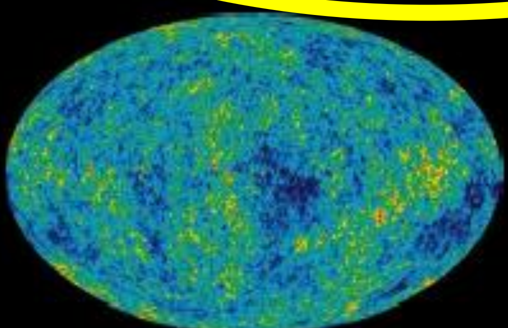
Coalescing Binary Systems

- Neutron stars, low mass black holes, and NS/BS systems



'Bursts'

- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



NASA/WMAP Science Team

Stochastic GWs

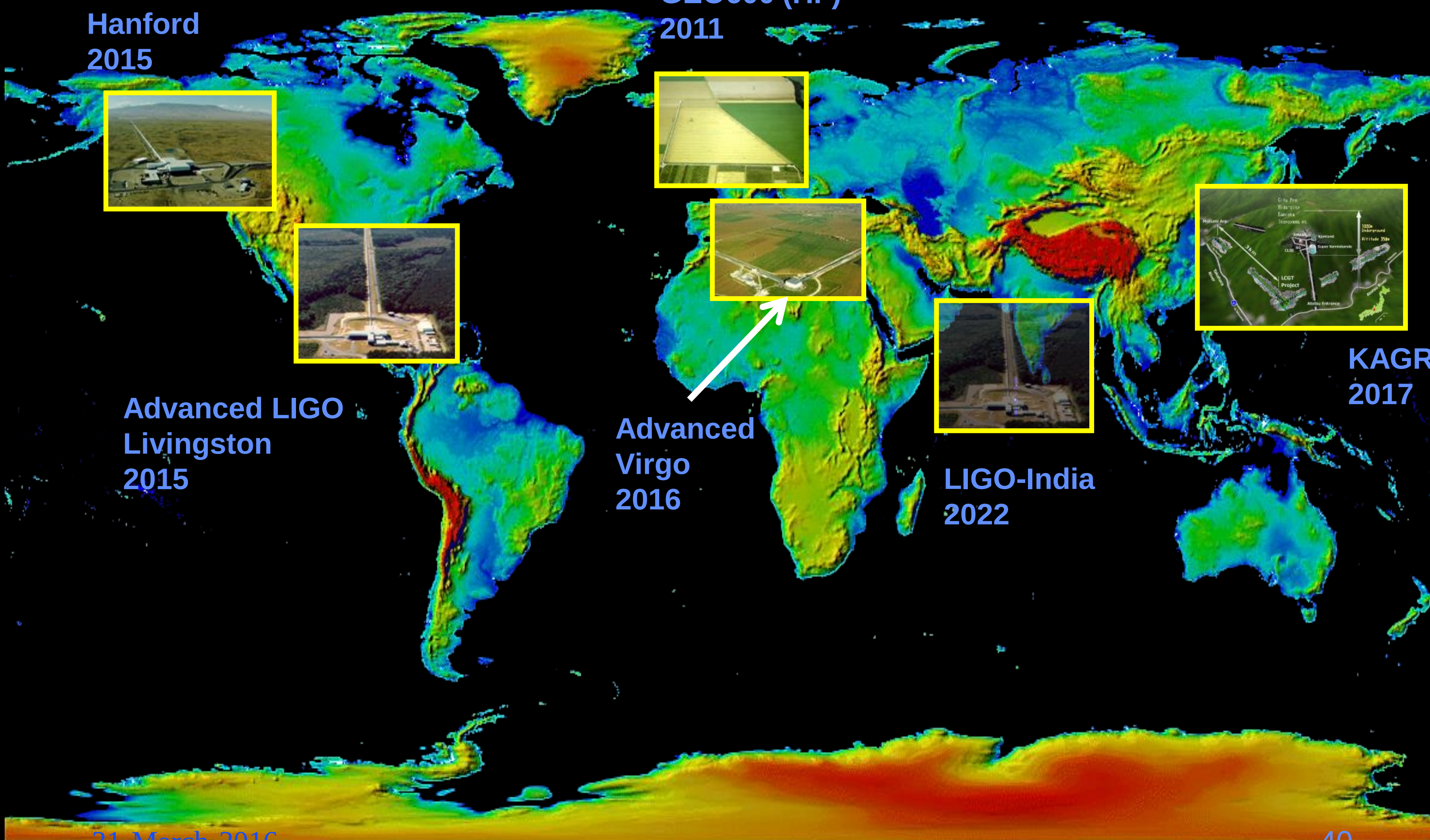
- Incoherent background from primordial GWs or an ensemble of unphased sources
- primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range

Casey Reed, Penn State

Continuous Sources

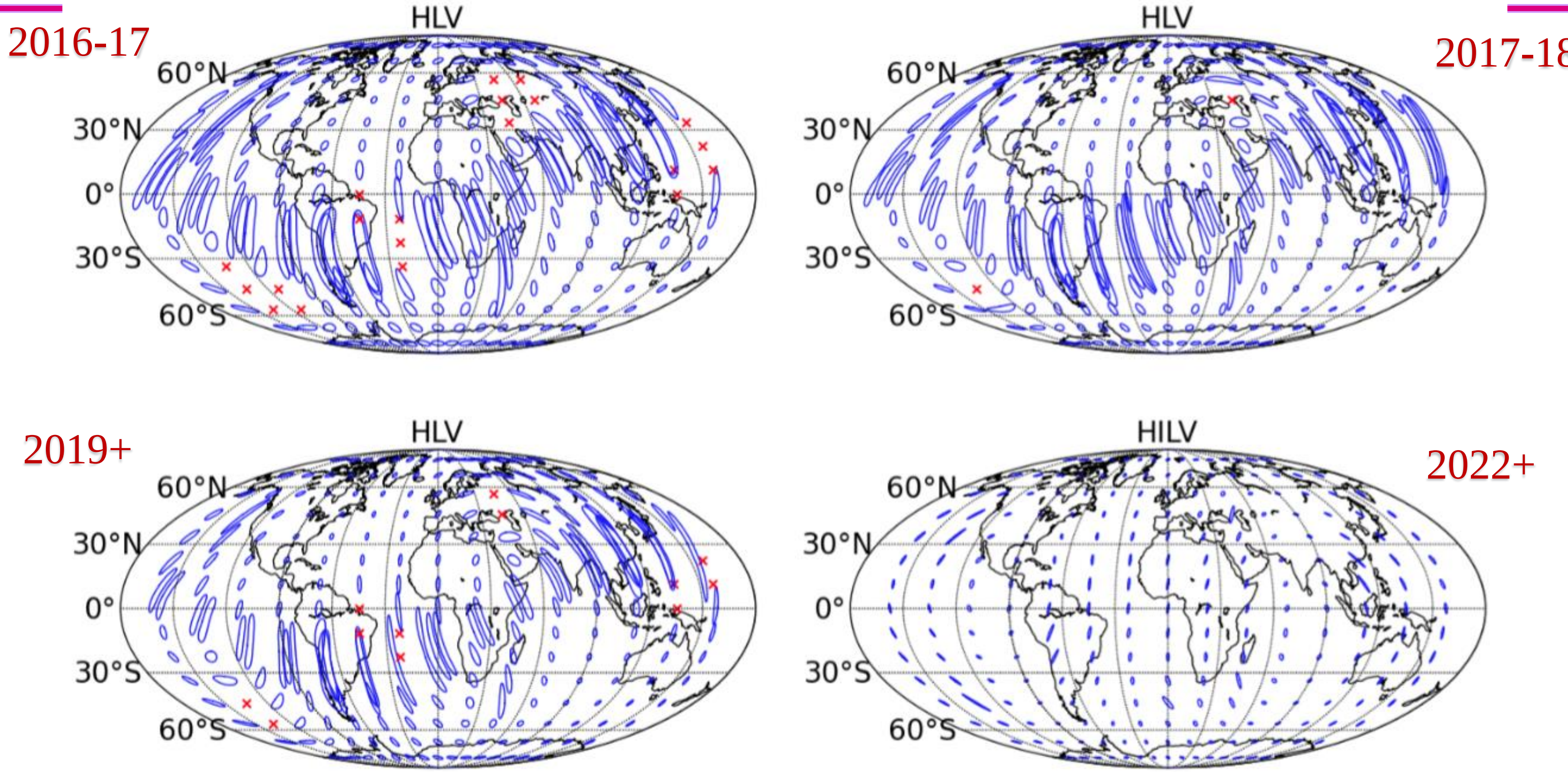
- Spinning neutron stars
- probe crustal deformations, 'EOS, quarki-ness'

The advanced GW detector network: 2015-2025



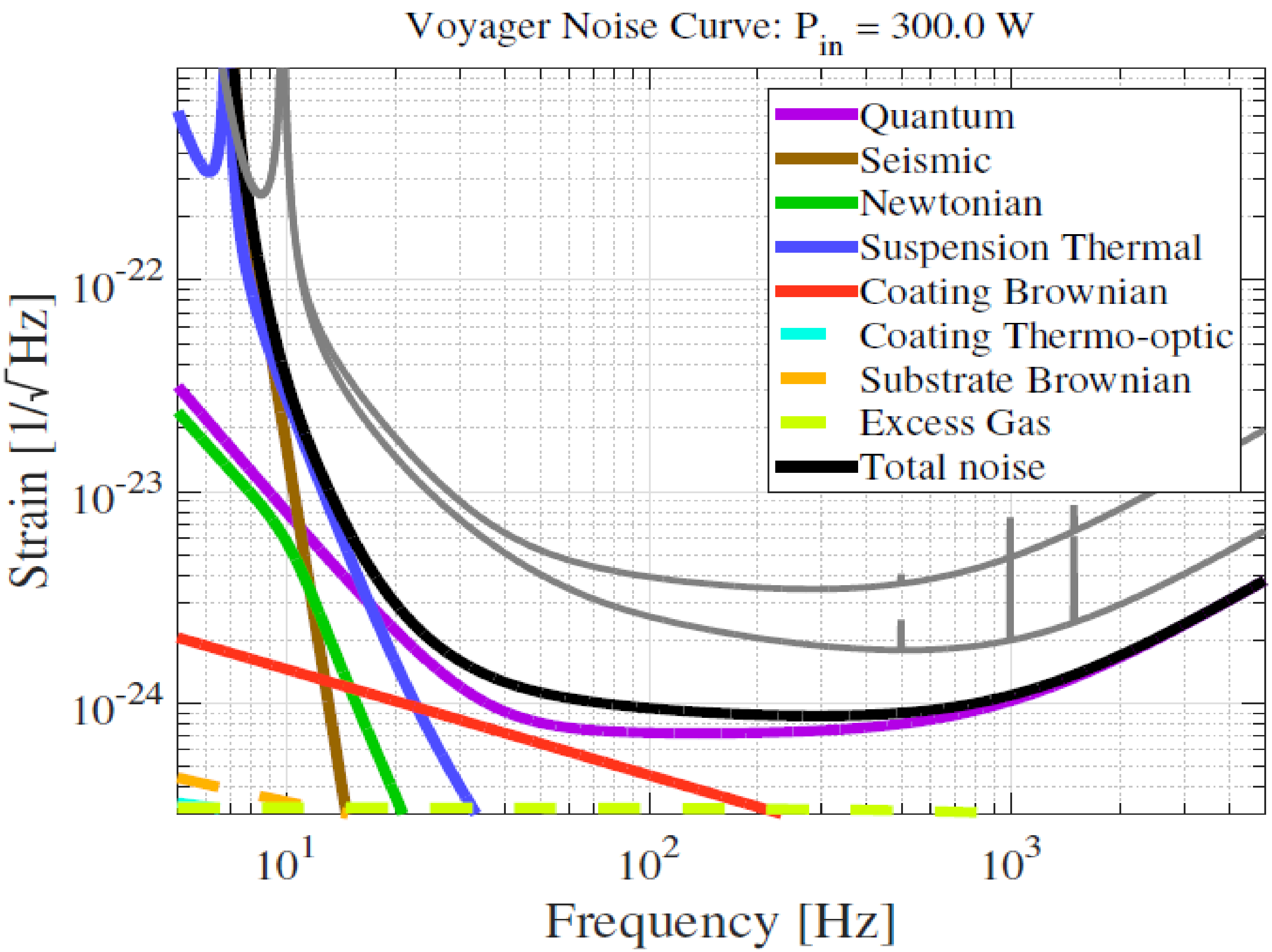
Localization of the Source

future: more precise



- Adding Virgo will break the annulus
- As sensitivity progresses, so does the localization. In the design LIGO-Virgo network, GW150914 could have been localized to less than 20 deg^2
- LIGO India will lead to a further impressive improvement

Fully Exploiting LIGO Infrastructure

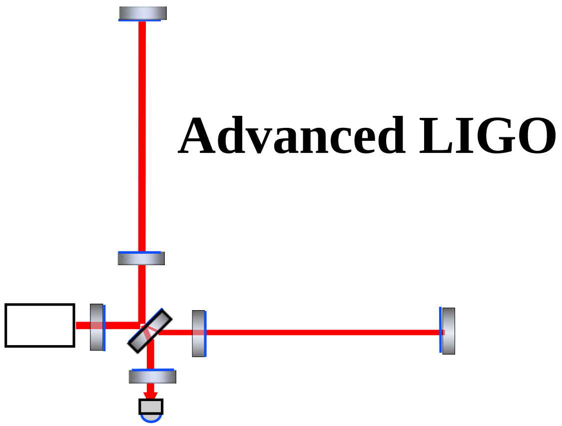


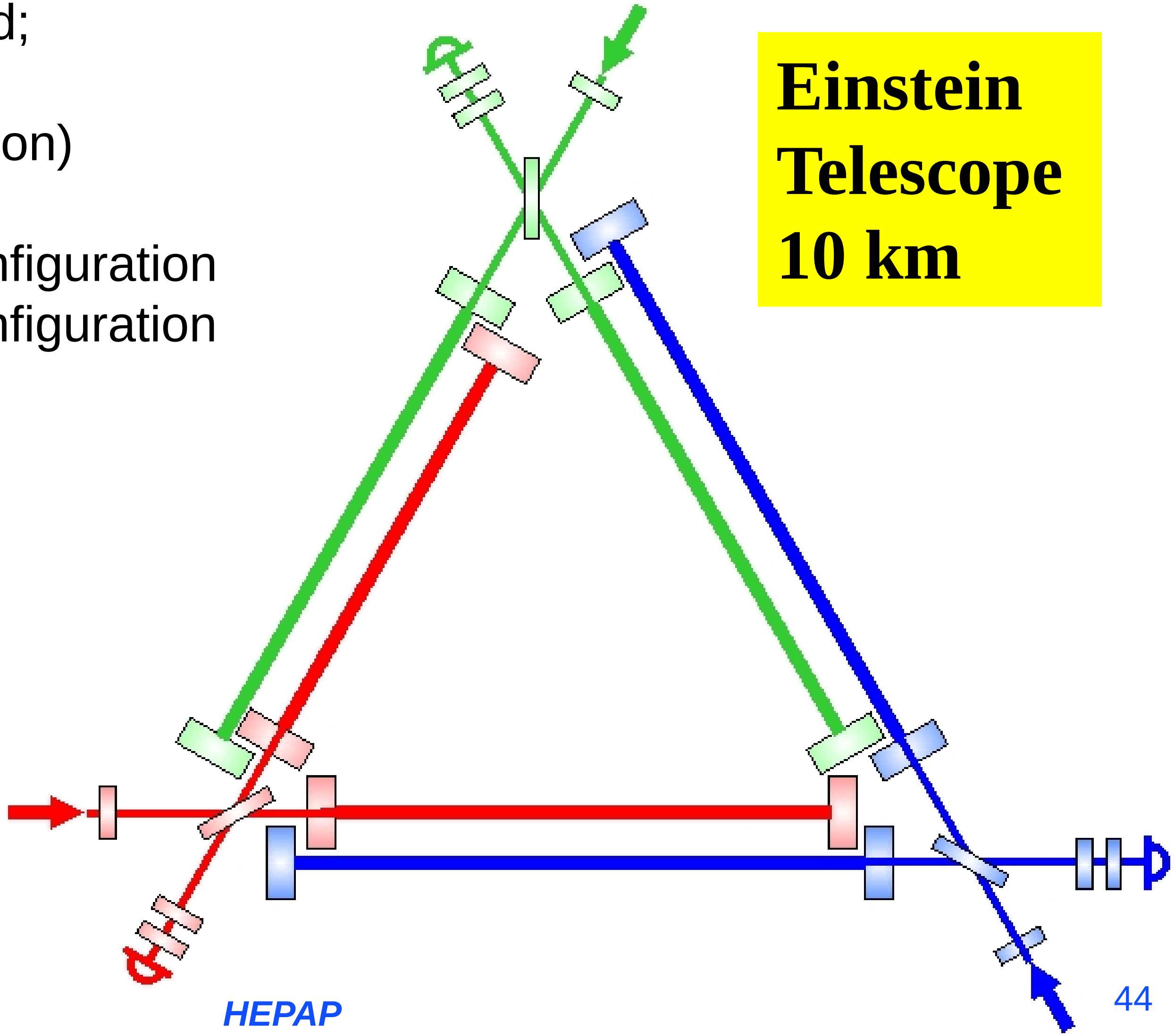

Cryogenic Mirror
KAGRA
Kamioka Mine
Underground
Technologies crucial for next-generation detectors;
KAGRA can be regarded as a 2.5-generation detector.

ASPERA: Future European Detector

The Einstein Telescope: x10 aLIGO

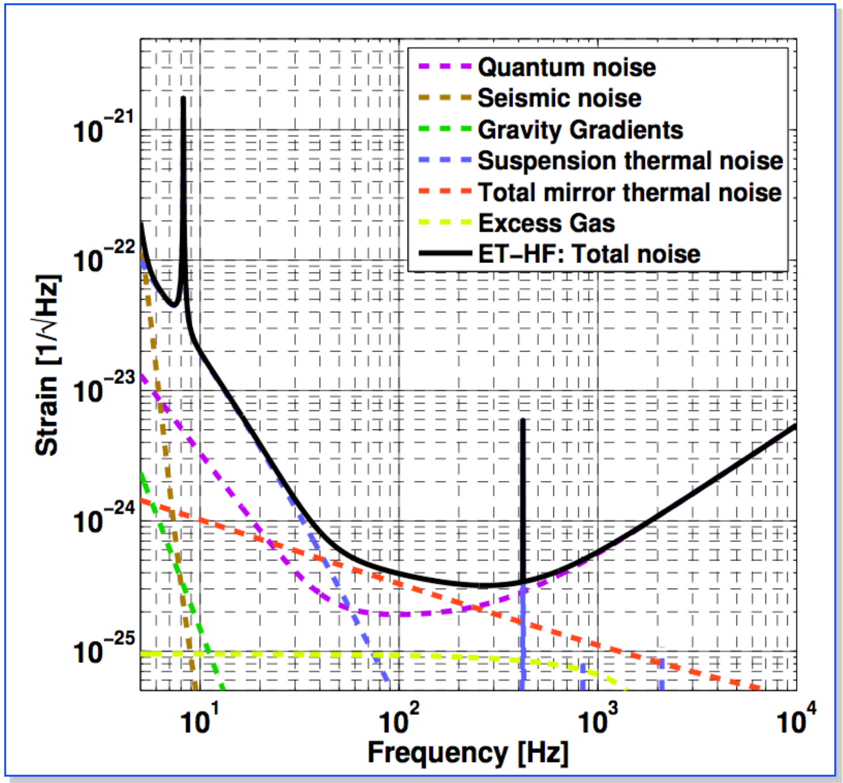
- Deep Underground;
- 10 km arms
- Triangle (polarization)
- Cryogenic
- Low frequency configuration
- high frequescy configuration



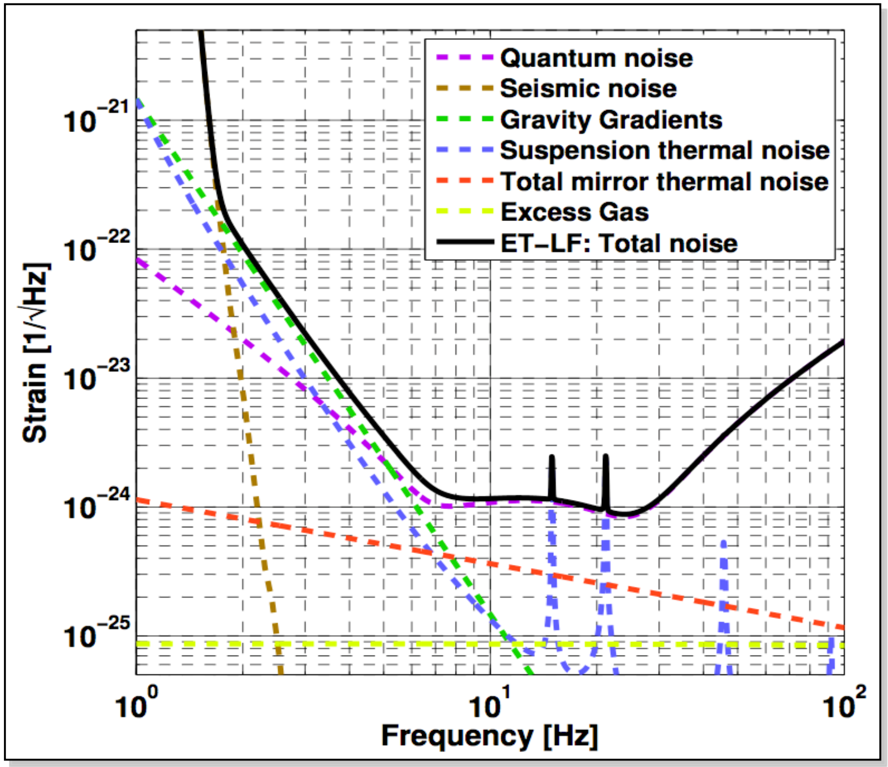


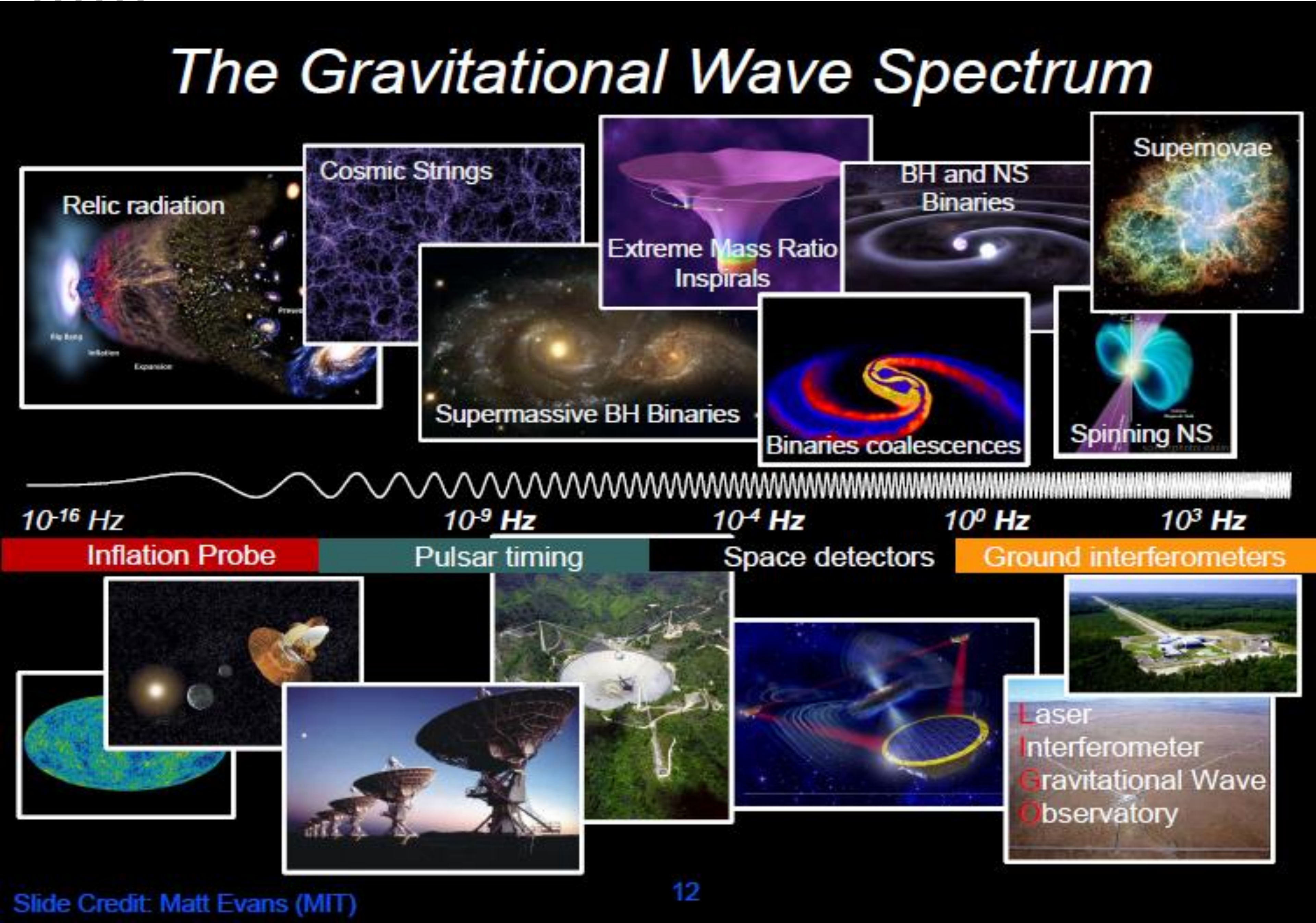
Einstein Telescope (Europe)

ET High Frequency



ET Low Frequency




The Gravitational Wave Spectrum
Relic radiation
Cosmic Strings
Extreme Mass Ratio 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)
12

End