GW170817 and the Rate of Binary Neutron Star Mergers

The Laser Interferometer Gravitational-wave Observatory: a Caltech/MIT collaboration supported by the National Science Foundation

Gregory Mendell, LIGO Hanford Observatory

For the LIGO Scientific and Virgo Collaborations

LIGO-G1800325

Overview

- Astrophysical Rates
- GWs and Advanced LIGO
- Calibration
- GW170817 and the Rate of Binary Neutron Star Mergers
- Future Prospects

LIGO

Astrophysical Merger Rate

$$R = \frac{\Lambda}{VT}$$

Expected number of mergers from counting the observed number.

Time-volume observed by the detector.

$$\langle VT \rangle = T \int \mathrm{d}z\,\mathrm{d}\theta \, \frac{\mathrm{d}V_c}{\mathrm{d}z} \frac{1}{1+z} s(\theta) f(z,\theta)$$

Rate co-moving volume increases with redshift, from standard cosmology.

Distribution of masses and spins.

Detection efficiency found by injecting fake signals via software.

Counting Using All Triggers Above a Low Threshold

1. Bin triggers by ranking statistic, x, and time, t. Find expected number in each bin:

$$\frac{dN}{dxdt}\Delta x\Delta t = [\Lambda_0 p_0(x) + \Lambda_1 p_1(x)]\Delta x\Delta t$$

Λ_0, ρ_0: Expected number and density of terrestrial triggers.

Λ_1 ρ_1: Expected number and density of astrophysical triggers.

2. A product of Poisson Distributions gives the likelihood and posterior:

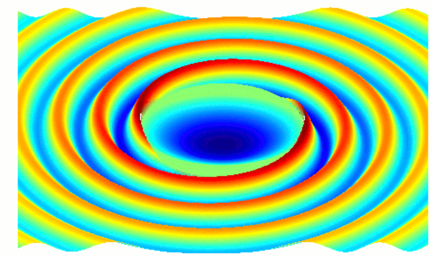
$$L(\{x_j\} \mid \Lambda_0, \Lambda_1) = \prod [\Lambda_0 p_0(x_j) + \Lambda_1 p_1(x_j)]\exp(-\Lambda_0 - \Lambda_1)$$

$$p(\Lambda_0, \Lambda_1 \mid \{x_j\}) \propto p(\Lambda_0, \Lambda_1)L(\{x_j\} \mid \Lambda_0, \Lambda_1)$$

↖ Posterior on Λ_0 and Λ_1. (Can generalize to multiple components, e.g., BNS, NSBH,and BBH.

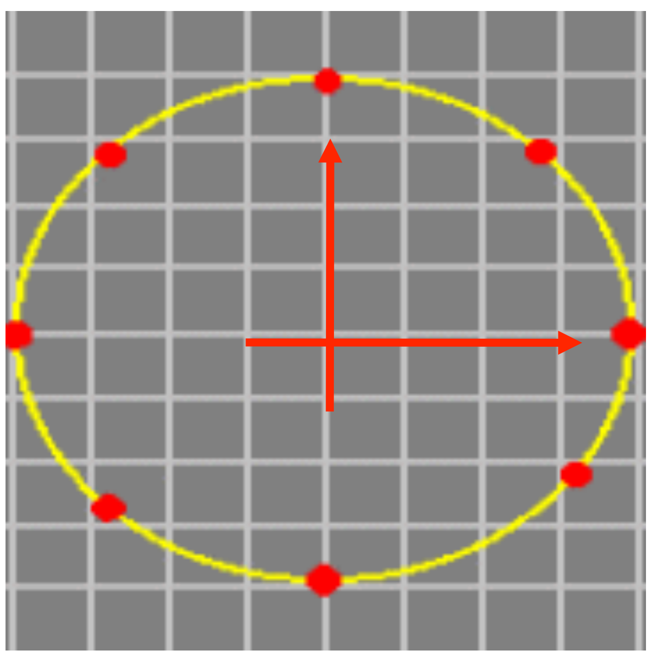
See: B. P. Abbott et al. (LIGO Scientific and Virgo Collaboration) Phys. Rev. Lett. 118, 221101

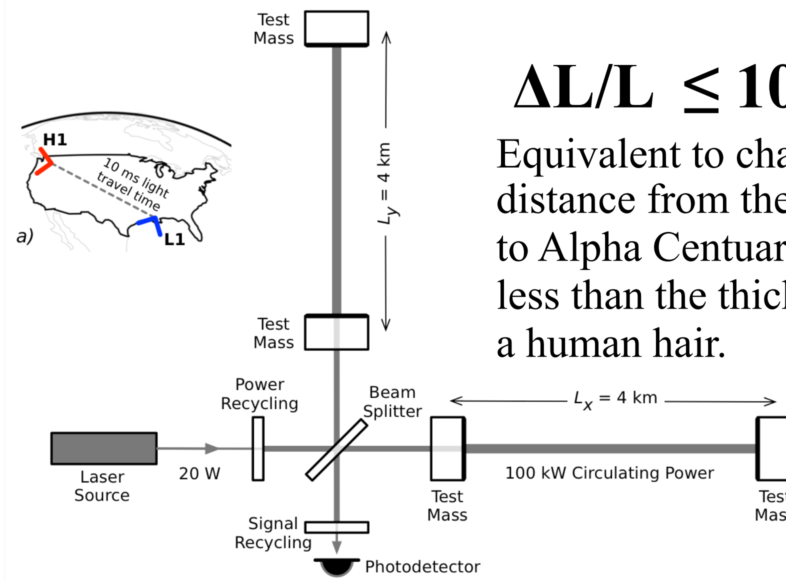
Gravitational Waves



Gravitational waves are ripples in the fabric of spacetime, stirred up by the changing motions of matter and energy. The waves are extremely weak by the times they reach Earth.

$$h_{\mu\nu}^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} e^{2\pi i f(t-z/c)}$$

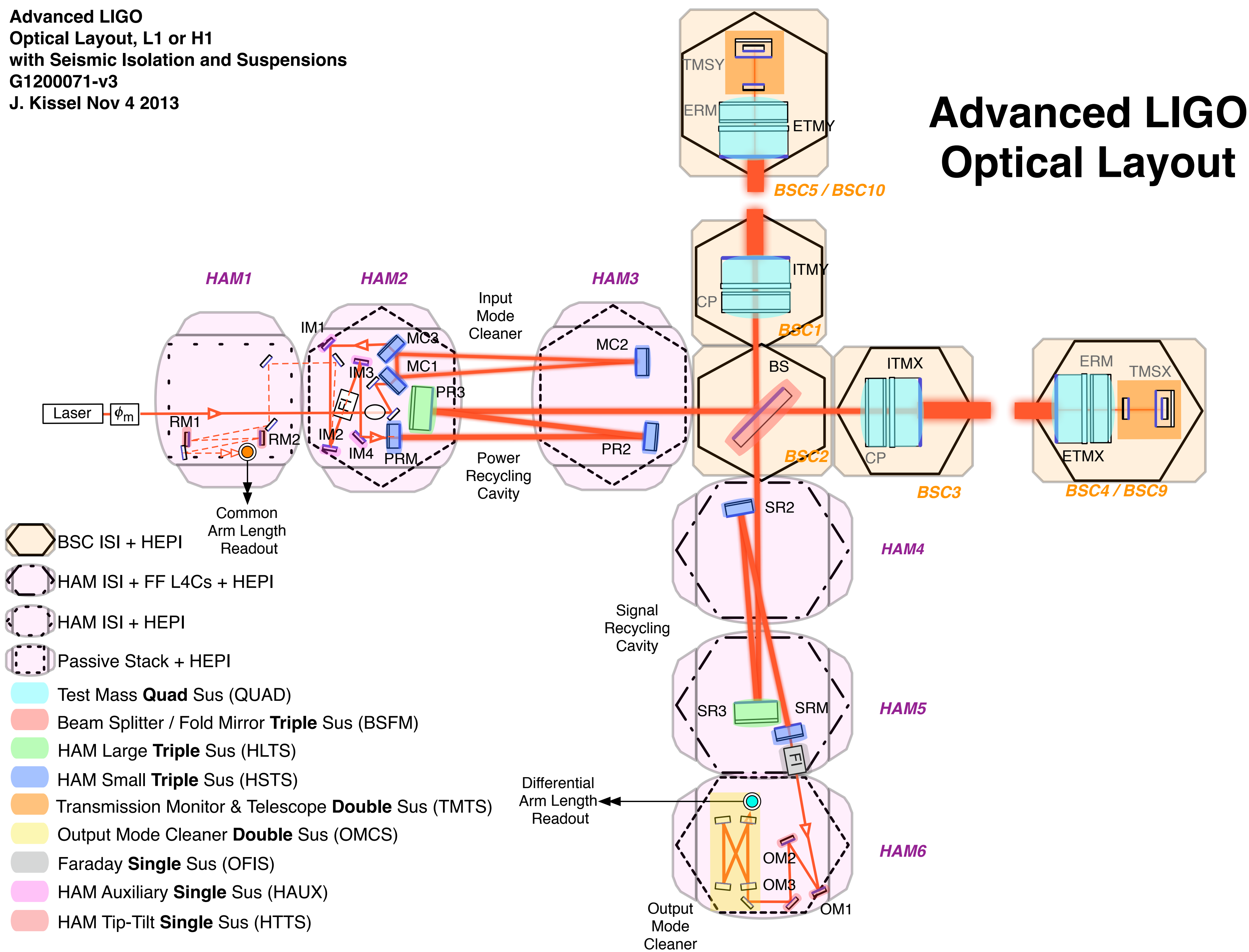




$\Delta L/L \leq 10^{-21}$

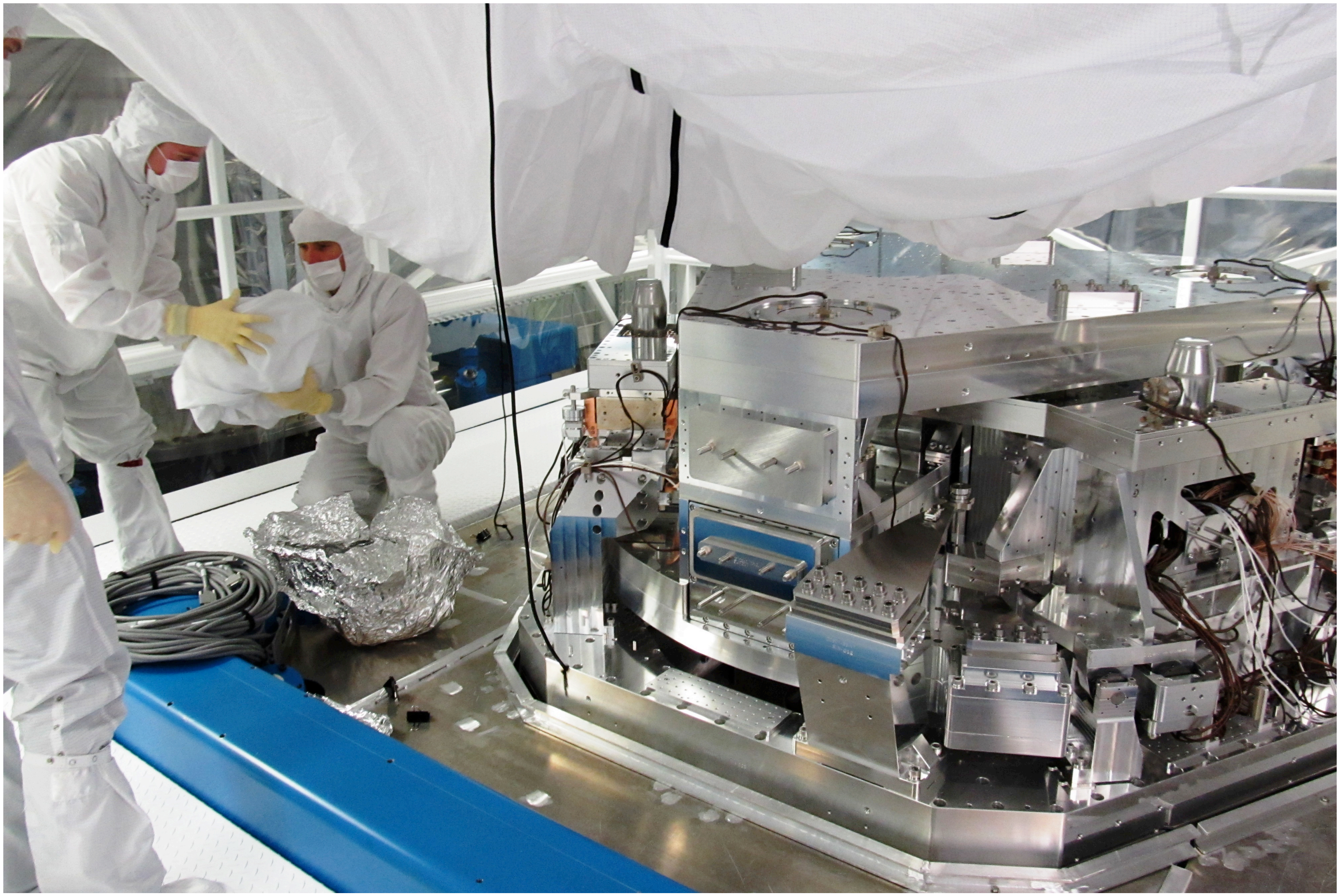
Equivalent to changing distance from the Earth to Alpha Centuari by less than the thickness of a human hair.

Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013



Advanced LIGO

Advanced LIGO

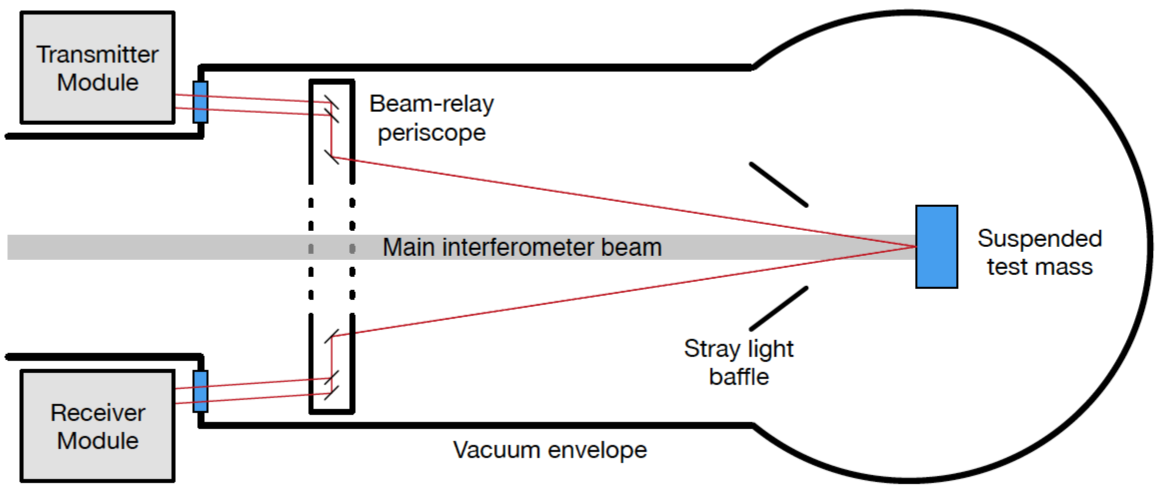


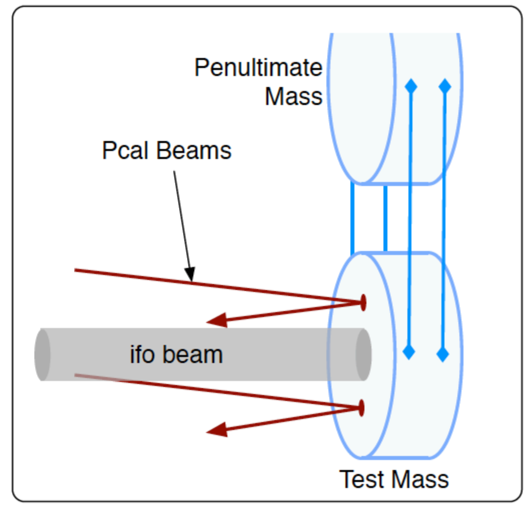
Advanced LIGO

Calibration Measurement

Both **sensing** and **actuation** functions are measured **directly** using a **NIST-traceable auxiliary laser system** near the test mass called a "**Photon Calibrator**"

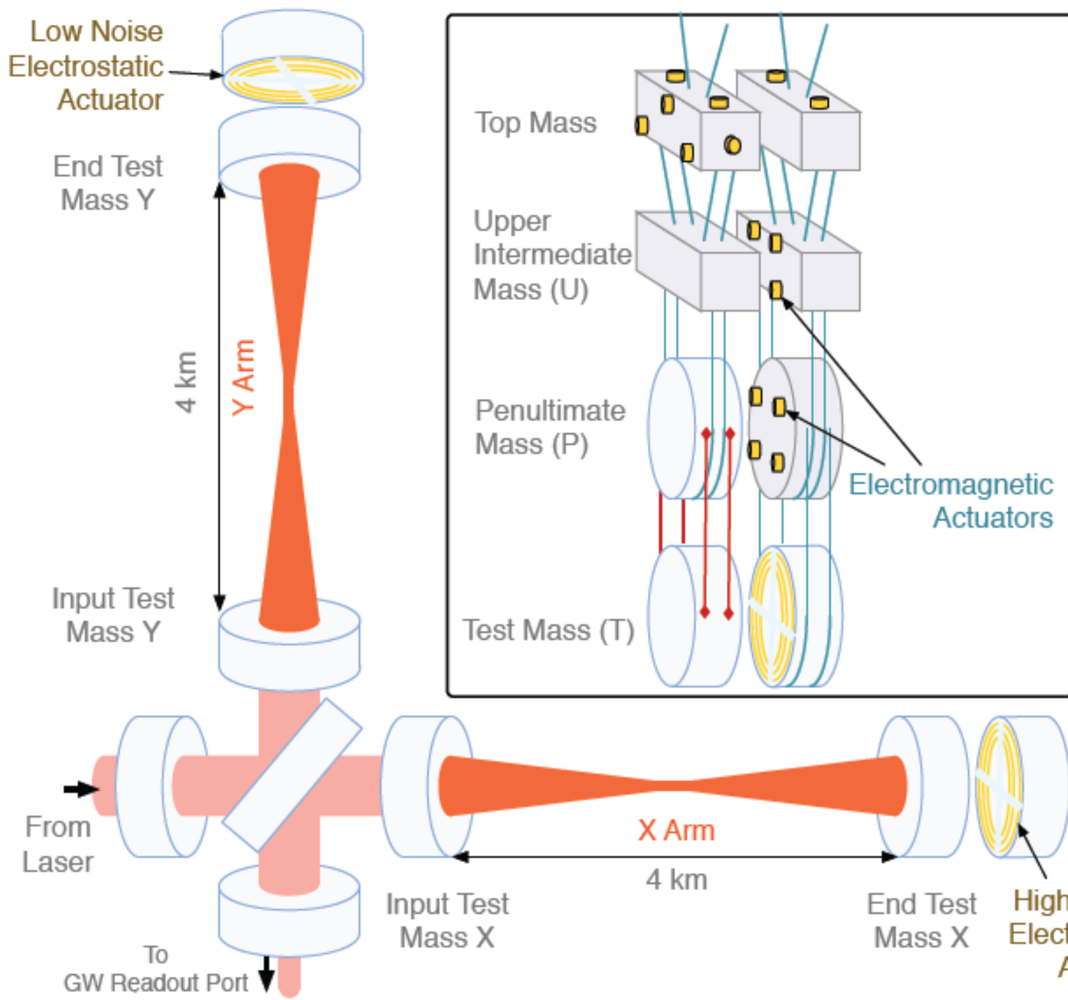
Radiation pressure from the lasers -- whose power is modulated as a function frequency -- **displaces a test mass**, $x_T^{(PC)}$ equivalent to differential arm length changes.

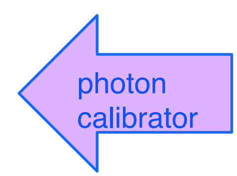




Both **actuation** and **sensing** functions are **mapped as a function of frequency** at the beginning of the run, and monitored for time-dependence throughout the run with single frequency excitations

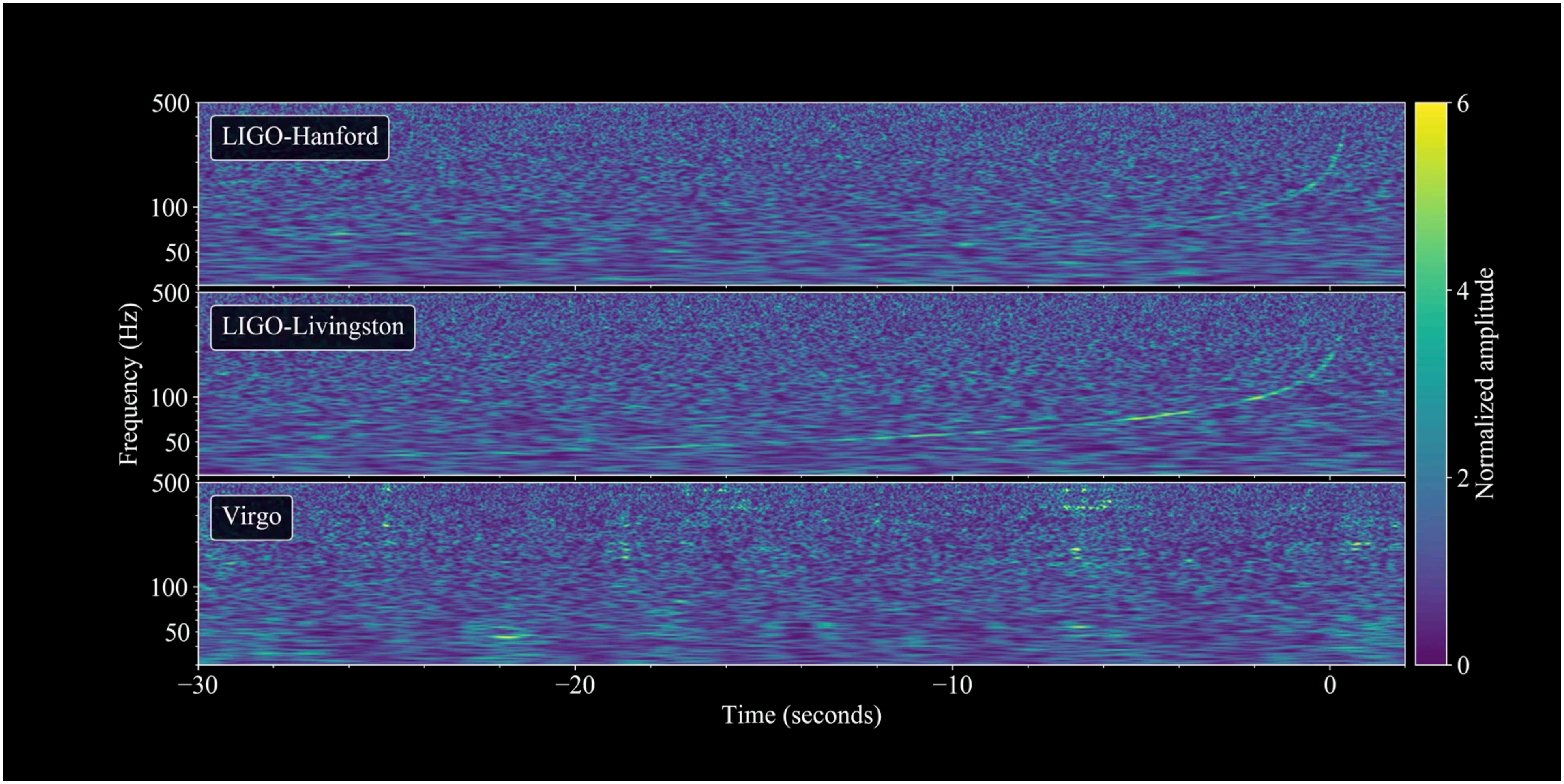
End mirror ("test mass") quadruple-pendulum suspensions





https://dcc.ligo.org/LIGO-P1500248/public/main

August 17, 2017, 5:41 am PDT



LIGO-G1600258

Simple Binary Neutron Star Merger Rate Based On One Detection: GW170817

$$L(N = 1 \mid RVT) \propto \Lambda \exp(-\Lambda)$$

$$p(R \mid N = 1, VT) \propto p(R) RVT \exp(-RVT)$$

Prior = exp(-R/Rscale_prior), where Rscale_prior = R_{UL_90} / 2.302585, chosen to give the O1 90% conf. UL on the BNS rates of 12600.0 Gpc^{-3} yr^{-1} (Astrophysical Journal Letters, 832:L21 2016).

VT found by injecting BNS systems flat in mass between 1 and 2 Solar Masses, with dimensionless spins below 0.4, out to a distance of 300 Mpc (far enough for detection efficiency to go to ~ 0), using SpinTaylorT2threePointFivePN and SpinTaylorT4threePointFivePN waveforms starting at 25 Hz, the initial calibration, and for a detection threshold corresponding to a False Alarm Rate of 1 per 100 years.

Simple Binary Neutron Star Merger Rate Based On One Detection: GW170817

Result:

$$R = 1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. 119, 161101

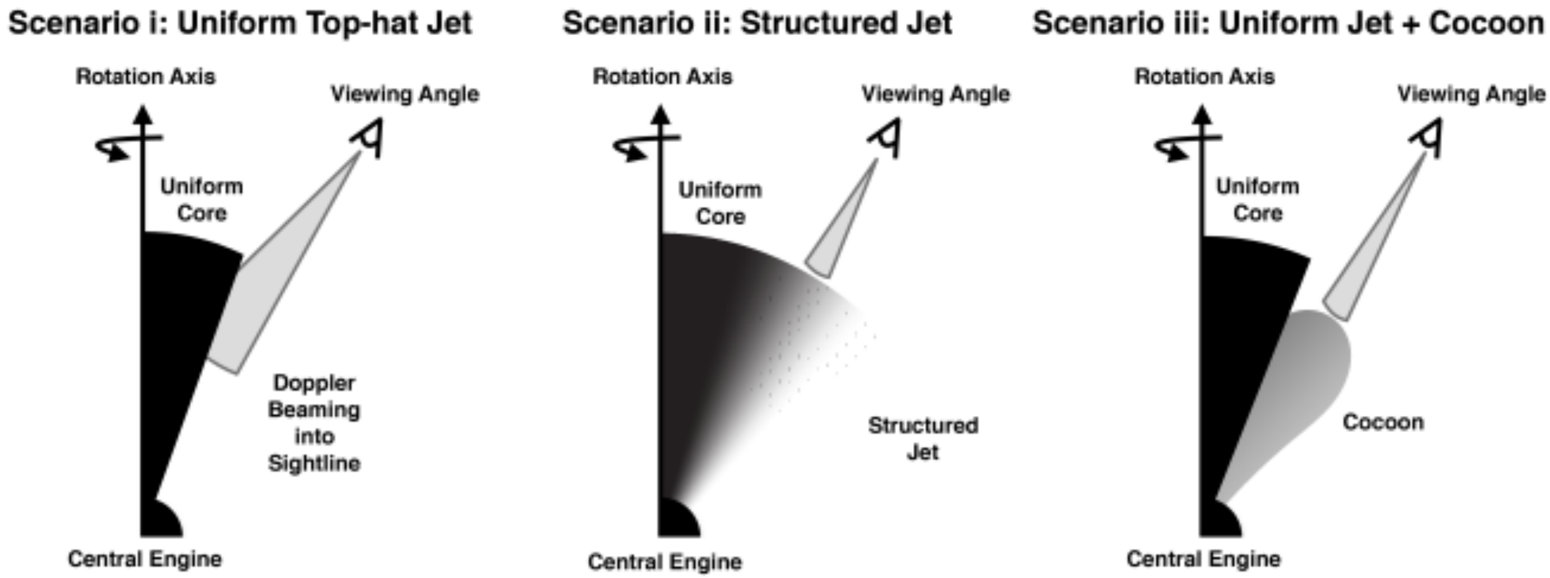
Full O2 results are in progress.

Predicted Binary Neutron Star Merger Rates

	Predicted rates (Gpc^{-3} yr^{-1})			
Source	R_{low}	R_{re}	R_{high}	R_{max}
NS-NS	10	1000	10000	50000
NS-BH	0.6	30	1000	
BH-BH	0.1	5	300	

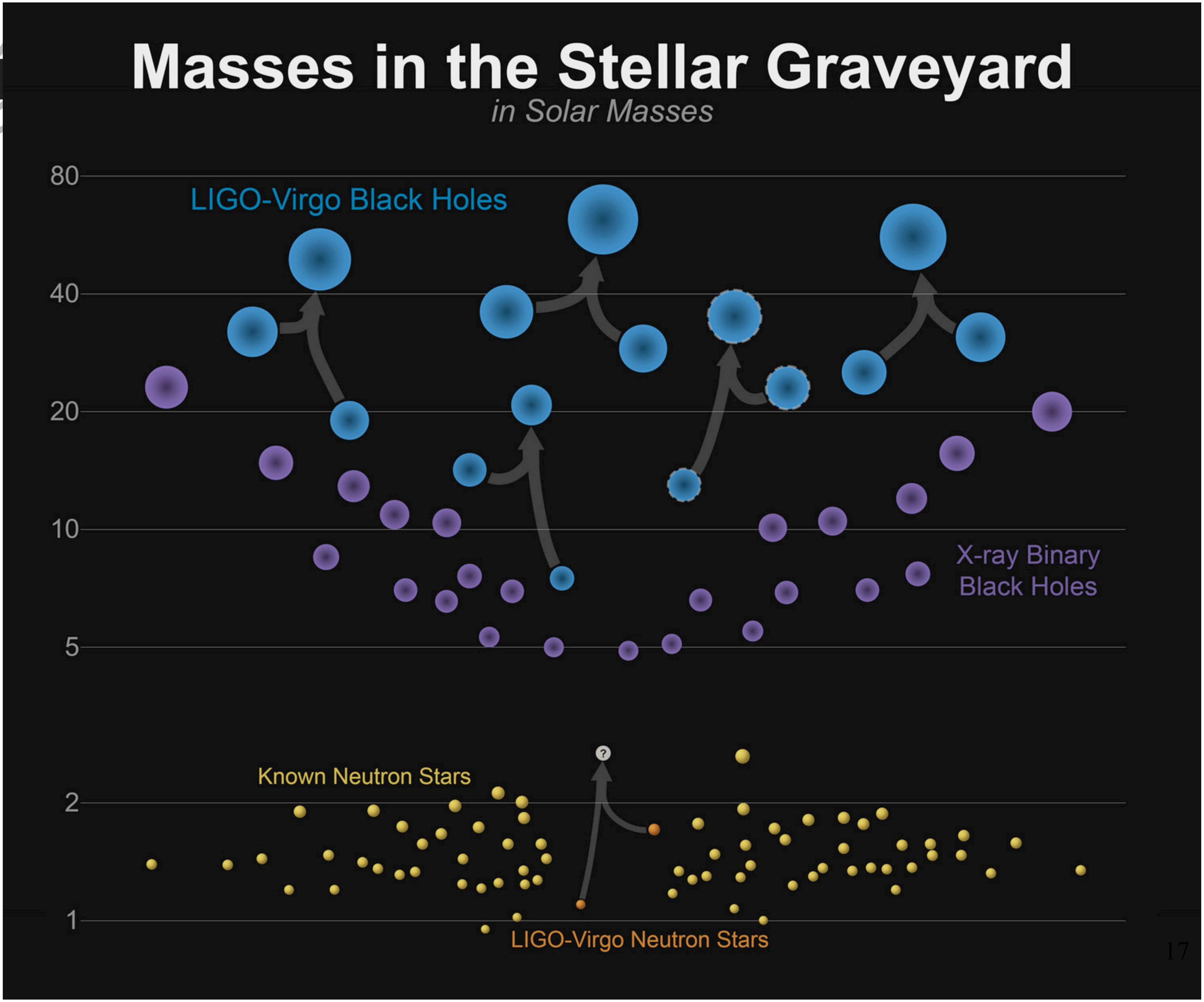
J. Abadie et al. (LIGO Scientific and Virgo Collaboration) Class.Quant.Grav.27:173001, 2010; arXiv: 1003.2480 [astro-ph.HE]

Future Prospects



- "Using the BNS merger volumetric rate estimated from GW170817 ⋯ the LIGO– Virgo detection rate is narrowed down ⋯ to ~ 1– 50 BNS coalescences during the 2018–19 observing run. At design sensitivity, the LIGO and Virgo detectors can expect to detect ~ 6–120 BNS coalescences per year ⋯"
- "Finally, we predict a joint detection rate for the Fermi Gamma-ray Burst Monitor and the Advanced LIGO and Virgo detectors of 0.1– 1.4 per year during the 2018–2019 observing run and 0.3–1.7 per year at design sensitivity."
- The numbers depend on future detection sensitivity and GRB models.

LIGO Scientific Collaboration, Virgo Collaboration, Fermi Gamma-Ray Burst Monitor, INTEGRAL, The Astrophysical Journal Letters, 848:L13 (27pp), 2017 October 20


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary
Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars

The End

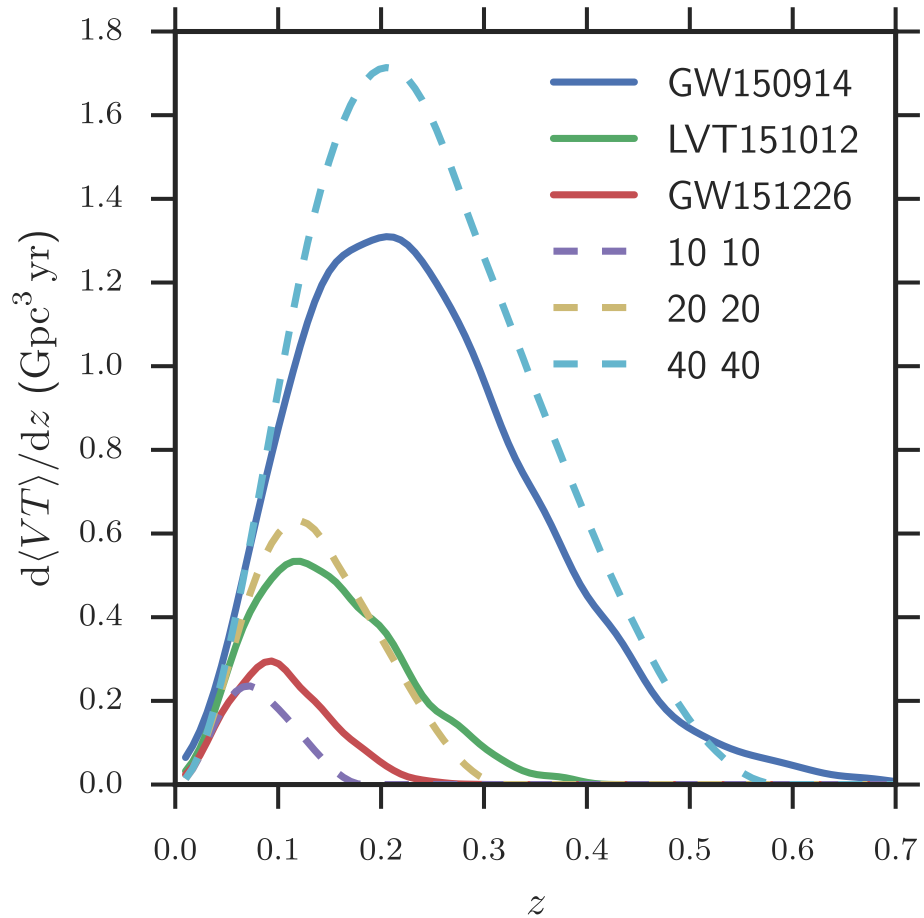
LIGO Scientific Collaboration

LIGO

LSC

- Caltech
- American University
- Andrews University
- Washington State University
- California State University Fullerton
- PennState
- Southern University and Agricultural & Mechanical College
- Massachusetts Institute of Technology
- Leland Stanford Junior University
- The University Of Sheffield
- University of Maryland
- indigo
- Texas Tech University
- Hillsdale College
- Montclair State University
- 清華大学 Tsinghua University
- Université de Montréal
- Monash University
- Universitat de les Illes Balears
- International Institute of Physics
- Cal State LA
- Bellevue College
- Montana State University
- University of Cambridge
- University of Southampton
- Polytechnique Montréal
- The University of Adelaide Australia
- NCSA
- University of Wisconsin Milwaukee
- Trinity University
- Australian National University
- University of the West of Scotland UWS
- University of Strathclyde
- University of Glasgow
- Indian Institute of Technology Madras
- W Bothell
- Michigan
- Columbia University in the City of New York
- Lomonosov Moscow State University
- Syracuse University
- OzGrav
- Cardiff University / Prifysgol Caerdydd
- The University of Western Australia
- R·I·T
- Sonoma State University
- University of Minnesota
- Carleton College
- RRCAT
- Cornell University
- NASA
- The University of Chicago
- IIT Hyderabad
- University of Washington
- Università degli Studi del Sannio
- LSU Louisiana State University
- Colorado State University
- Charles Sturt University
- Marshall Space Flight Center
- Chennai Mathematical Institute
- 東京大学 The University of Tokyo
- ACIGA
- ICTS International Centre for Theoretical Sciences, Tata Institute of Fundamental Research
- University of Birmingham
- Georgia Institute of Technology
- Korean Gravitational Wave Group
- Universität Hamburg — Der Forschung | Der Lehre | Der Bildung
- The University of Melbourne
- Embry-Riddle Aeronautical University
- Villanova University
- Whitman College
- Northwestern
- UF University of Florida
- tifr
- IUCAA
- UTRGV
- University and Institute of Advanced Research — The Puri Foundation for Education in India
- Swinburne University of Technology
- The University of Mississippi
- INPE
- University of Southern California
- GEO 600
- Max Planck Institute for Gravitational Physics, Albert Einstein Institute
- Leibniz Universität Hannover
- University of Zurich
- IISER Thiruvananthapuram
- CITA ICAT
- King's College London
- IISER Kolkata
- NASA Goddard Space Flight Center

Astrophysical Reach

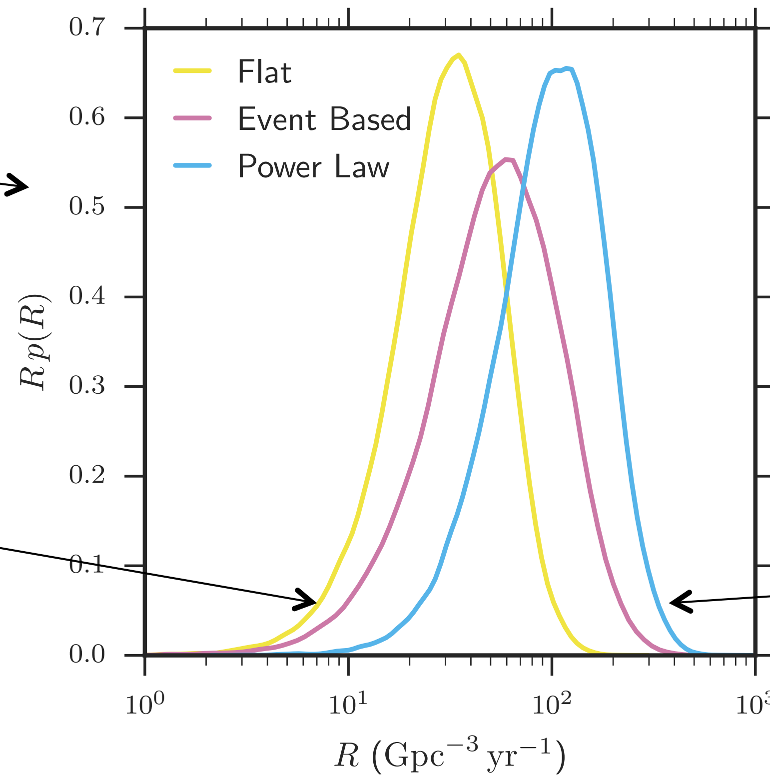


$$\langle VT\rangle = T\int \mathrm{d}z\,\mathrm{d}\theta\,\frac{\mathrm{d}V_c}{\mathrm{d}z}\frac{1}{1+z}s(\theta)f(z,\theta)$$

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. X 6, 041015

Binary Black Hole Merger Rate

O1 Results



9 Gpc^{-3} yr^{-1}

240 Gpc^{-3} yr^{-1}

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. X 6, 041015

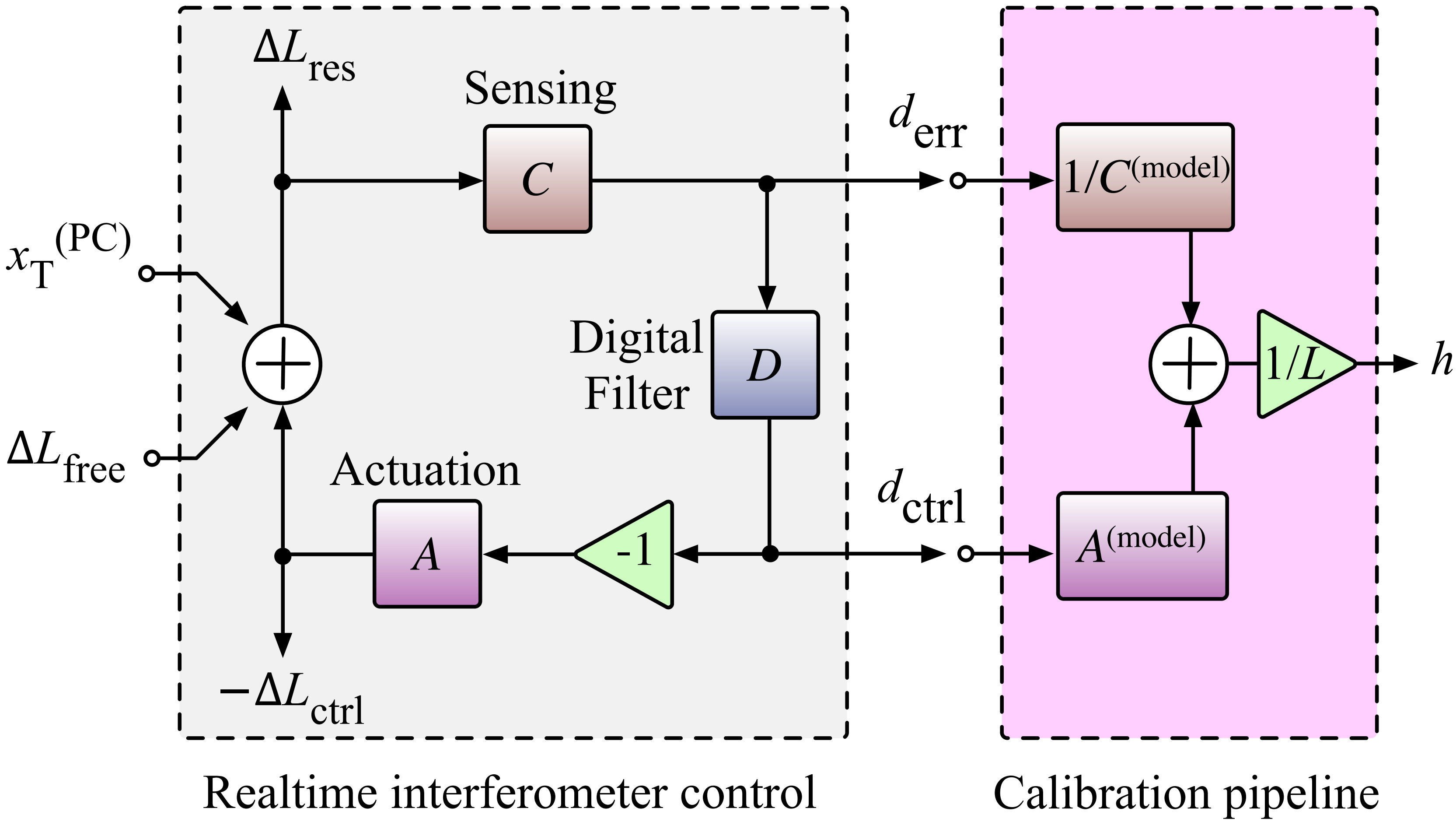
Updated BBH merger rate using data through Jan. 2017: 12-213 Gpc^{-3} yr^{-1}

B. P. Abbott et al. (LIGO Scientific and Virgo Collaboration) Phys. Rev. Lett. 118, 221101

O1 90% conf. ULs: Rate$_{BNS}$ < 12600.0 Gpc^{-3} yr^{-1}; Rate$_{NSBH}$ < 3600.0 Gpc^{-3} yr^{-1}

Astrophysical Journal Letters, 832:L21 2016

Differential Arm Length Control



"**Calibration**" is creating an time-series estimate of $\boldsymbol{h}$ from $\boldsymbol{d}_{\rm err}$ and $\boldsymbol{d}_{\rm ctrl}$ from models of the control loop

$$h = \frac{1}{L}\left[\frac{1}{C^{\rm (model)}} * d_{\rm err} + A^{\rm (model)} * d_{\rm ctrl}\right]$$

Detector Response

$$g_{\mu\upsilon} dx^{\mu} dx^{\upsilon} = 0$$ (Light Travels On Null Geodesics)

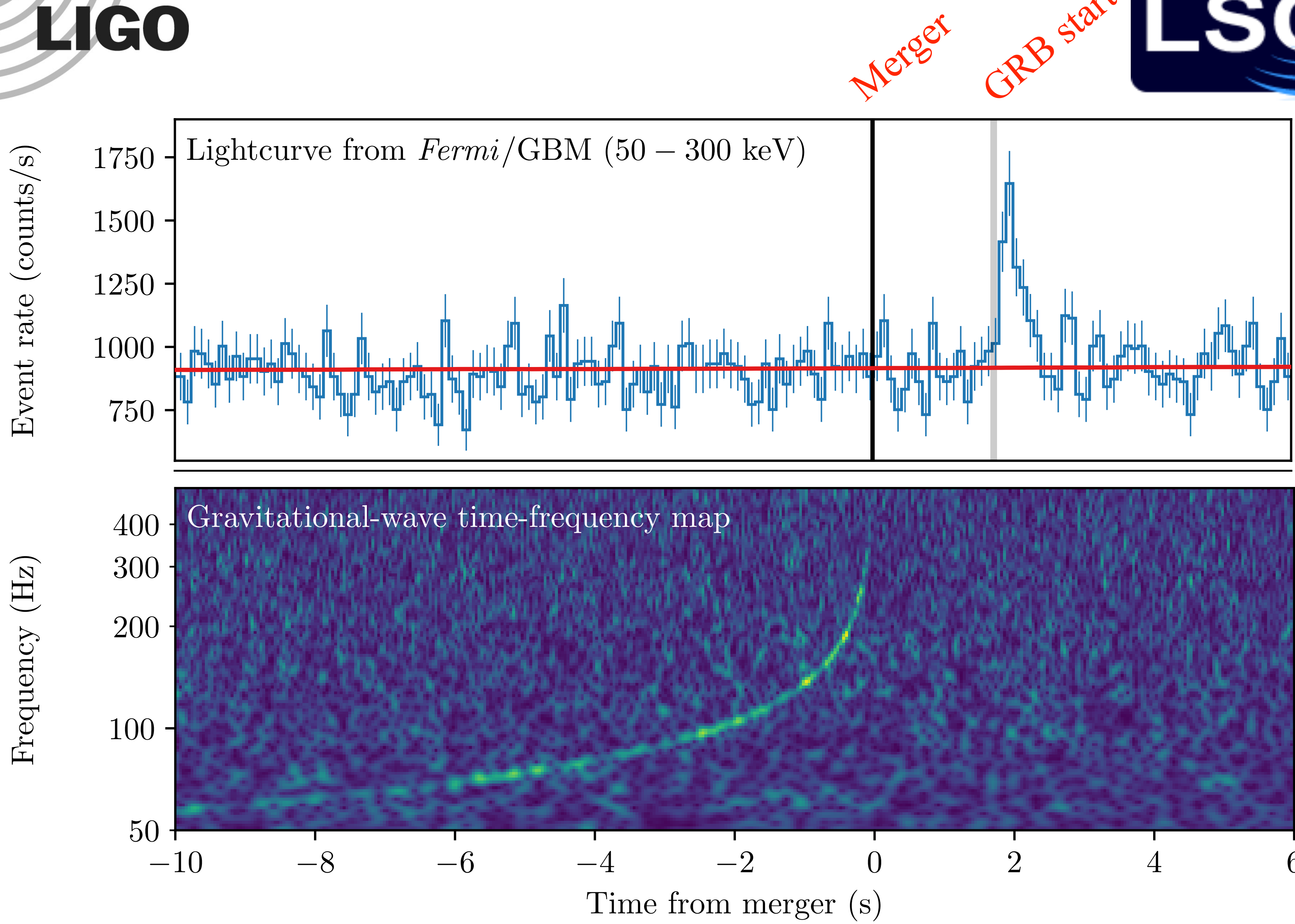
$$c^2 dt^2 - \begin{pmatrix} dx & 0 & 0 \end{pmatrix} \begin{pmatrix} 1+h_{xx} & h_{xy} & h_{xz} \\ h_{yx} & 1+h_{yy} & h_{yz} \\ h_{zx} & h_{zy} & 1+h_{zz} \end{pmatrix} \begin{pmatrix} dx \\ 0 \\ 0 \end{pmatrix} = 0$$

$$c^2 dt^2 = (1 + h_{xx}) dx^2$$

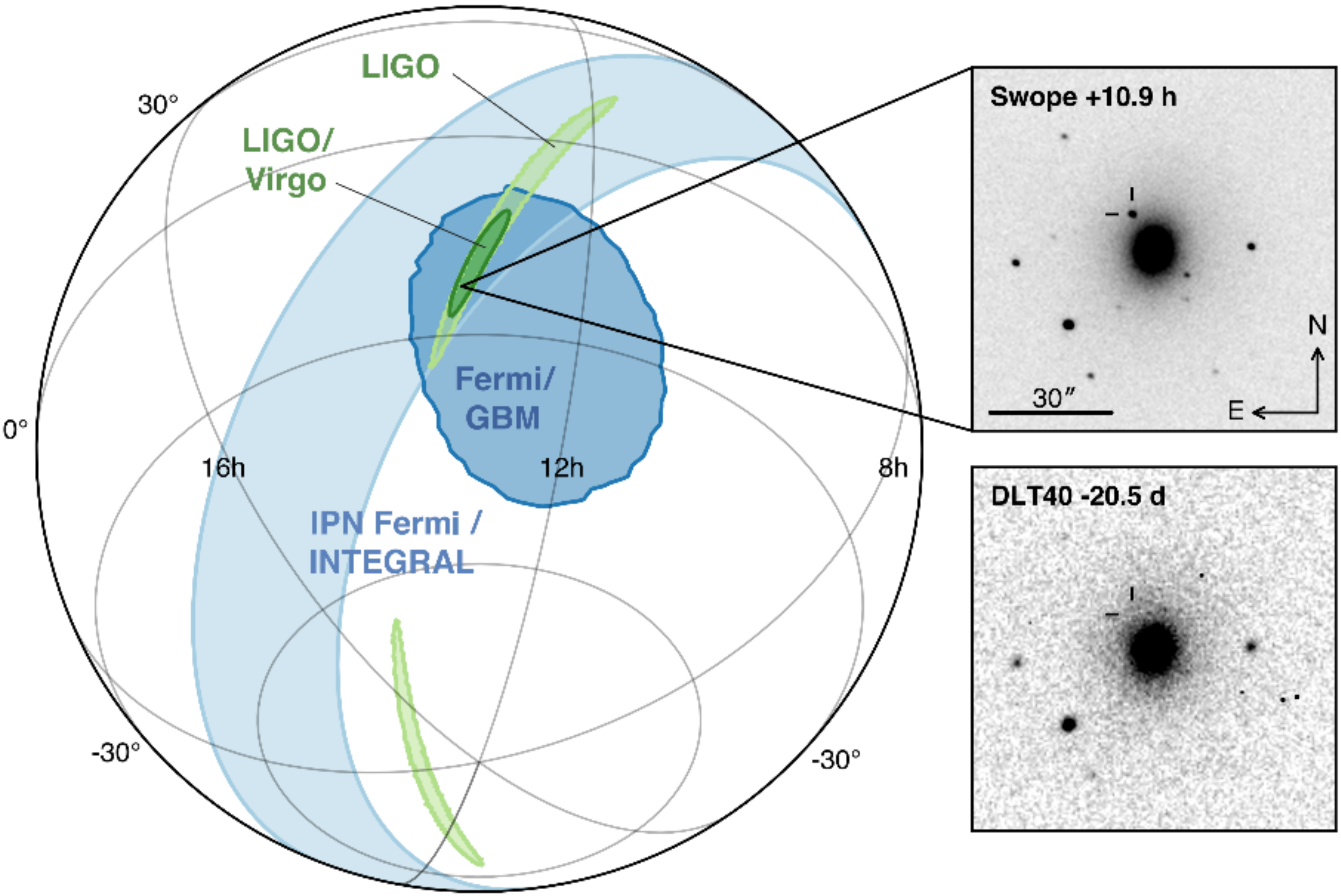
$$c\int_0^{\Delta t} dt = \int_0^L \sqrt{1 + h_{xx}}\, dx \cong \int_0^L \left(1 + \frac{1}{2} h_{xx}\right) dx$$

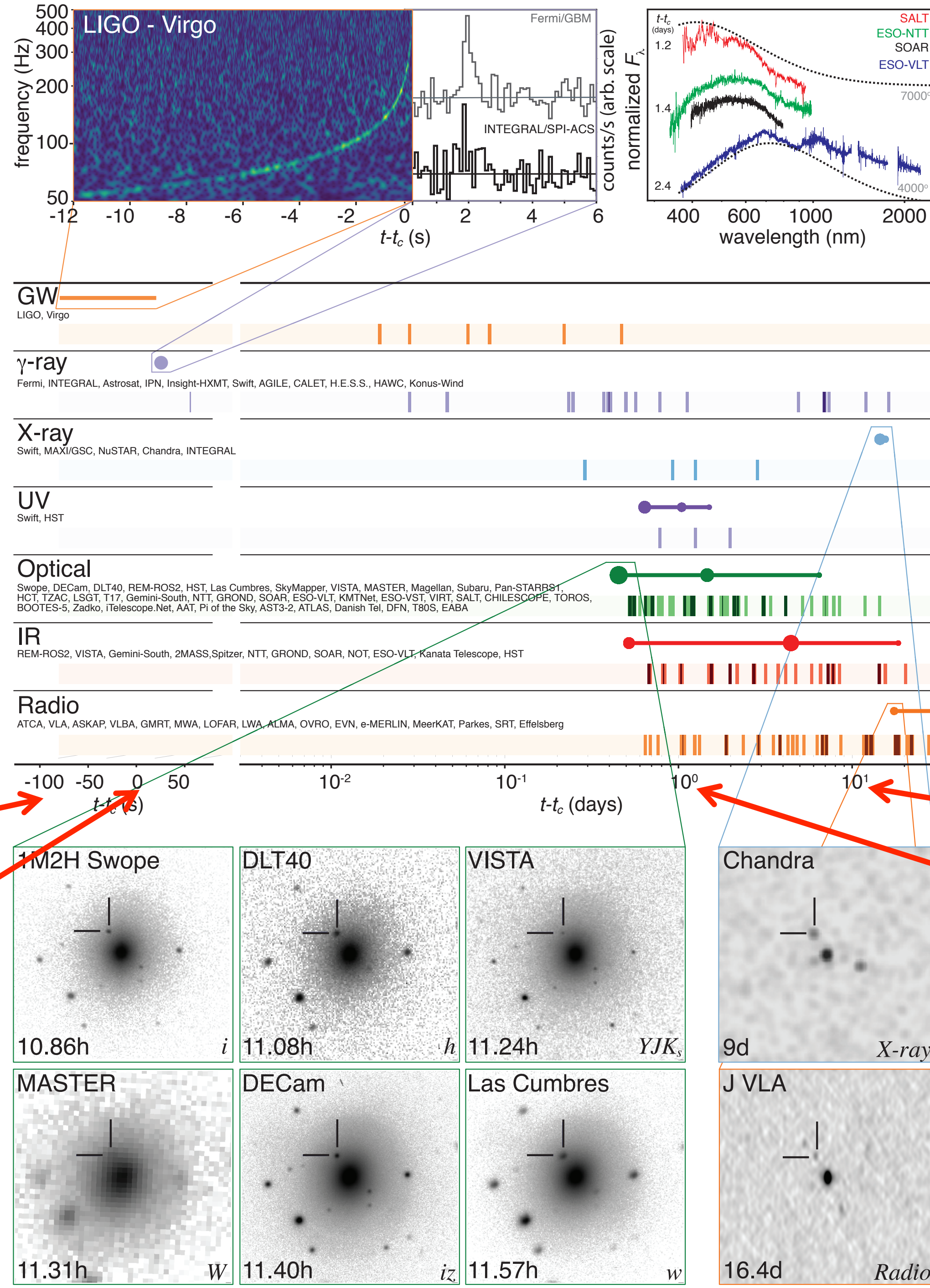
$$c\Delta t = L_x = L + \frac{L}{2} h_{xx}$$

$$\frac{\Delta L}{L} = \frac{1}{2}(h_{xx} - h_{yy}) = F_{+}(\theta,\phi,\psi) h_{+}(t) + F_{\times}(\theta,\phi,\psi) h_{\times}(t)$$



Merger
GRB start
Lightcurve from *Fermi*/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)


LIGO
LIGO/
Virgo
30°
0°
16h
12h
8h
-30°
-30°
Fermi/
GBM
IPN Fermi /
INTEGRAL
Swope +10.9 h
N
E
30″
DLT40 -20.5 d



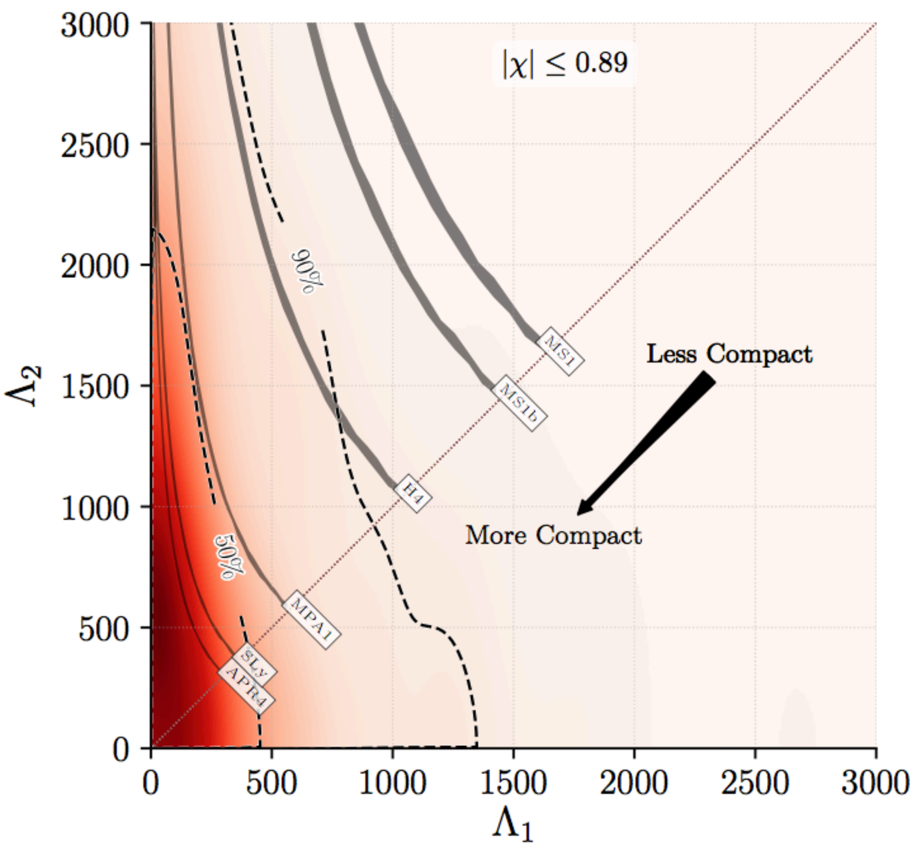
-100s

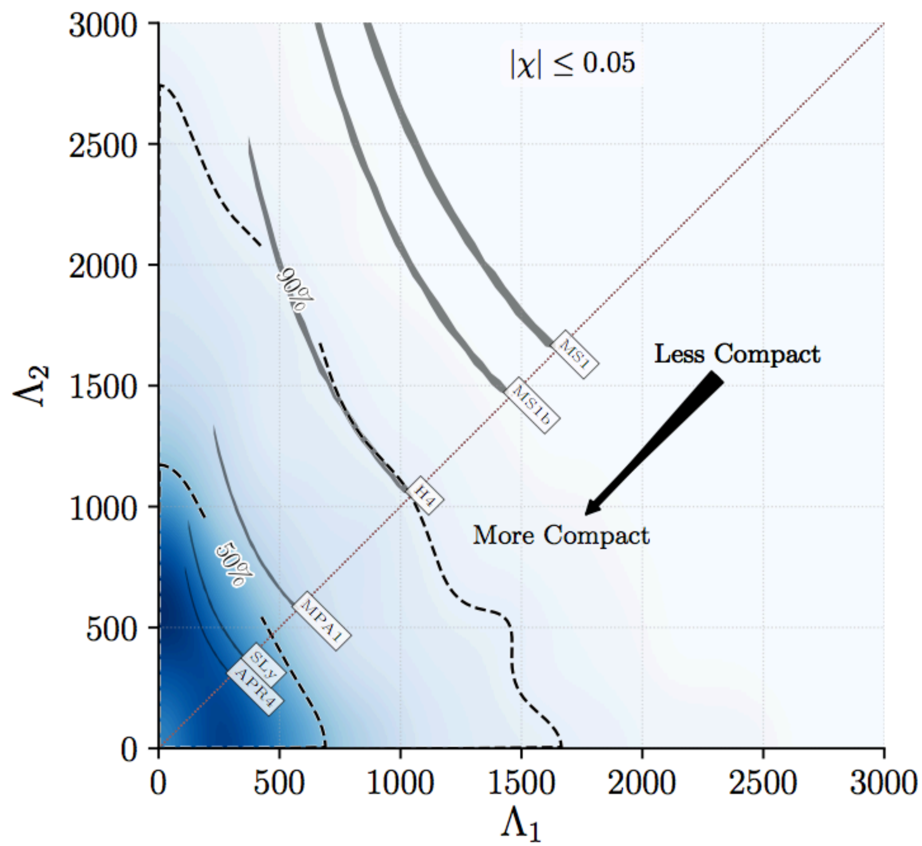
Merger

10 days

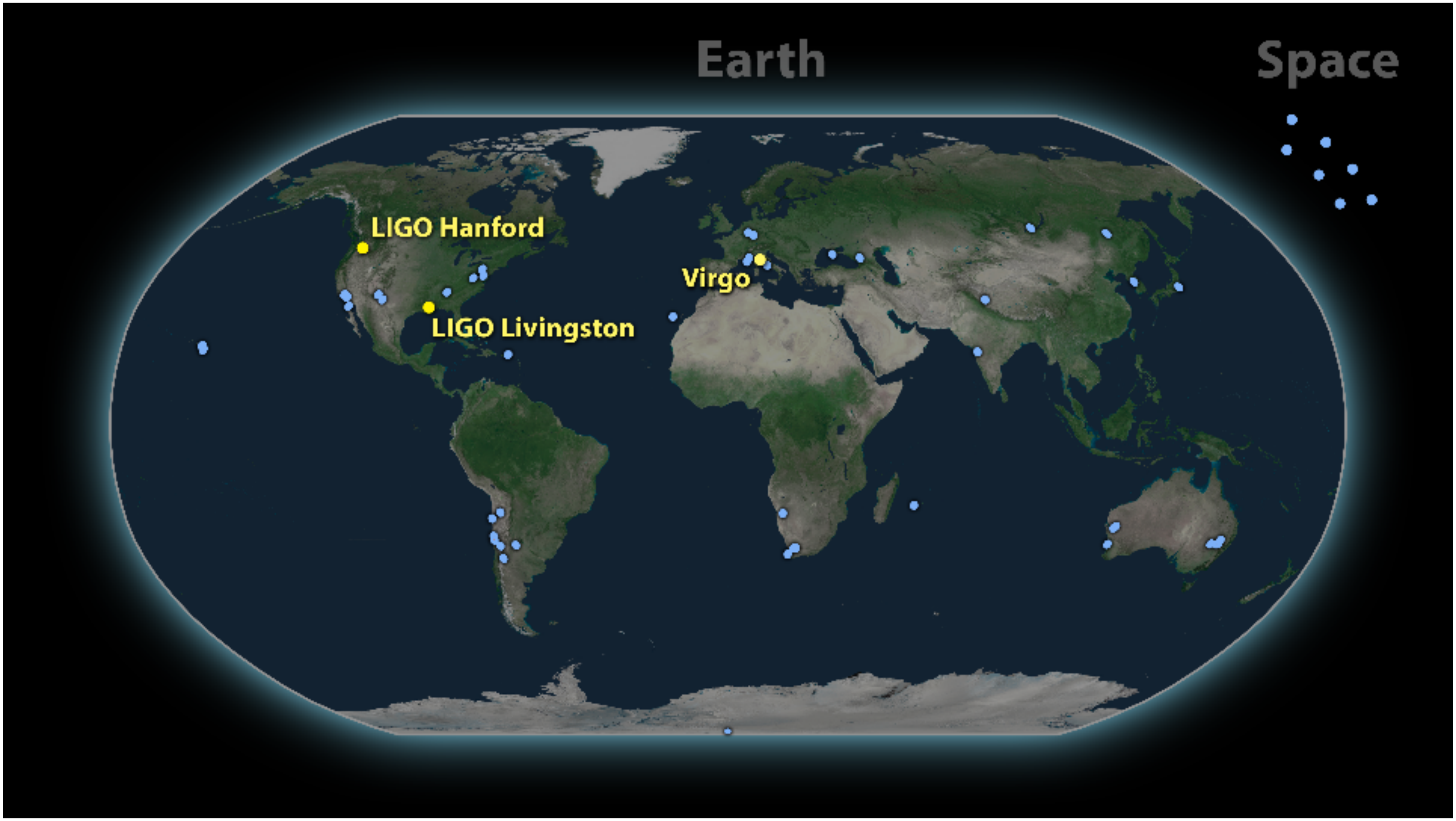
1 day

Limits on Neutron Star Tidal Deformation and Equation of State

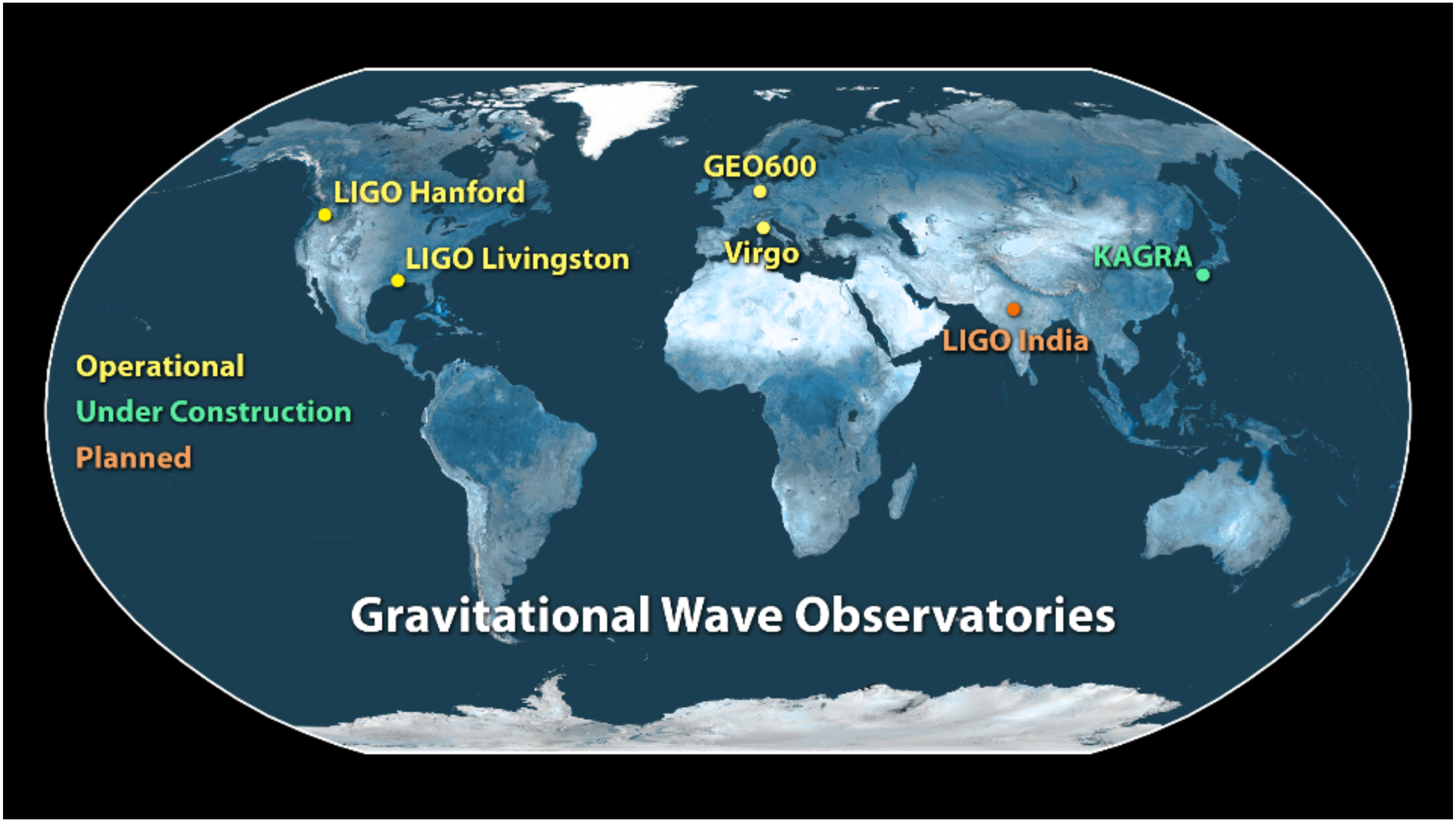




These figures show the "tidal deformability" of the stars. Each axis corresponds to one of the two stars, and how deformable it might be. The GW170817 system lies somewhere on this plot. The dashed lines marked 90% and 50% represent the chance the system is below and to the left of the dashed line. The high spin cases are shown on the left, and the low spin cases are shown on the right. (Credit: https://www.ligo.org/science/Publication-GW170817BNS/index.php; GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, PRL 119, 161101, 2017.)

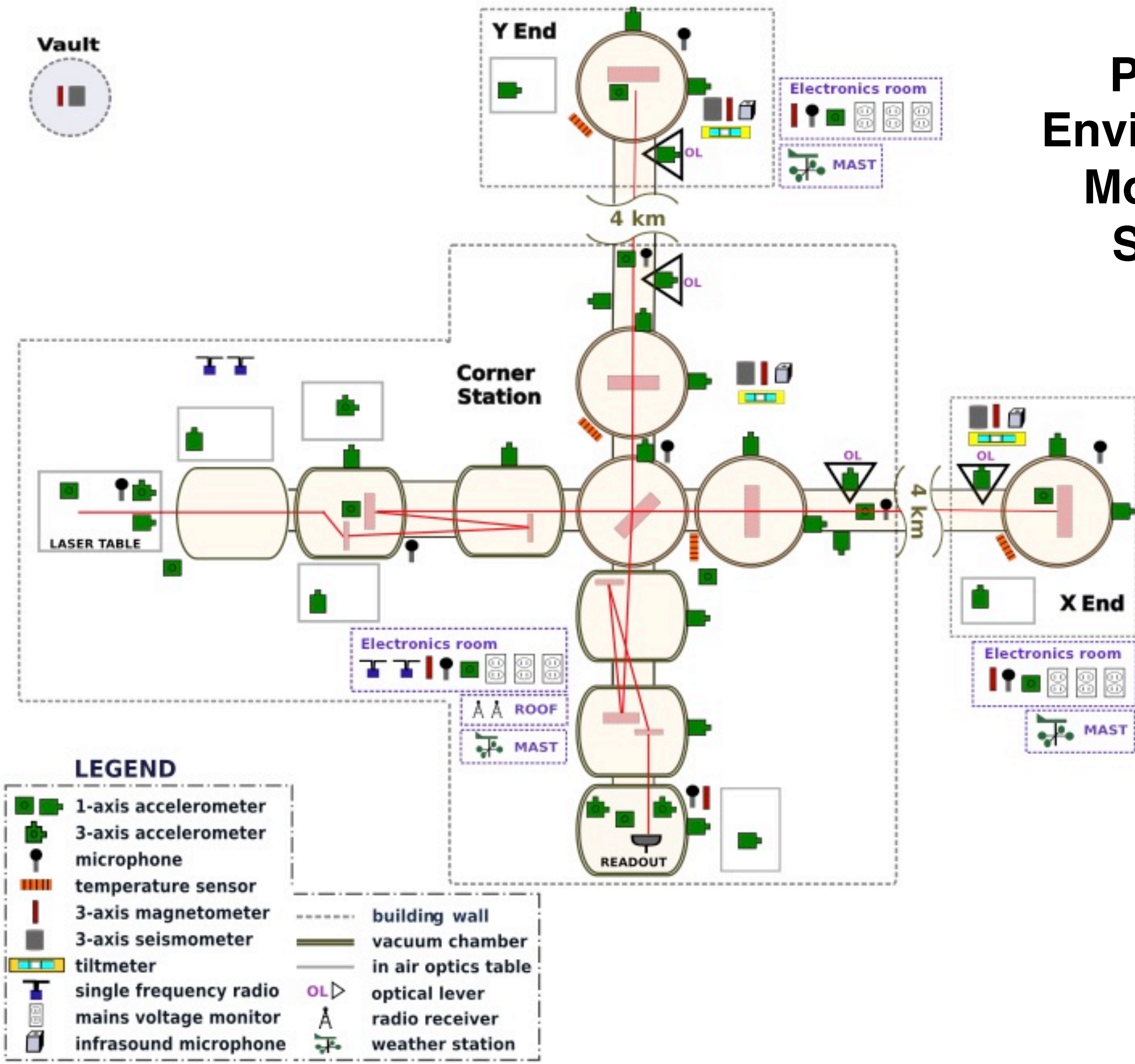


LIGO-G1600258

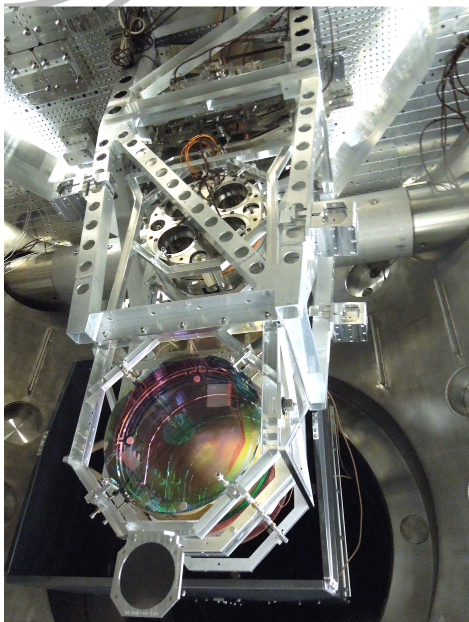


LIGO-G1600258

Physical Environmental Monitoring Sensors



Seismic Isolation

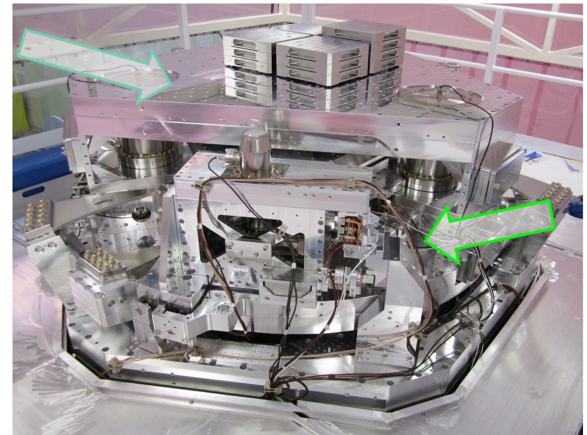


Ground Motion at 10 [Hz] ➔ 10^{-9} [m/rtHz]

$$\Delta L = h\ L \rightarrow 10^{-19}\, m / Hz^{1/2}$$

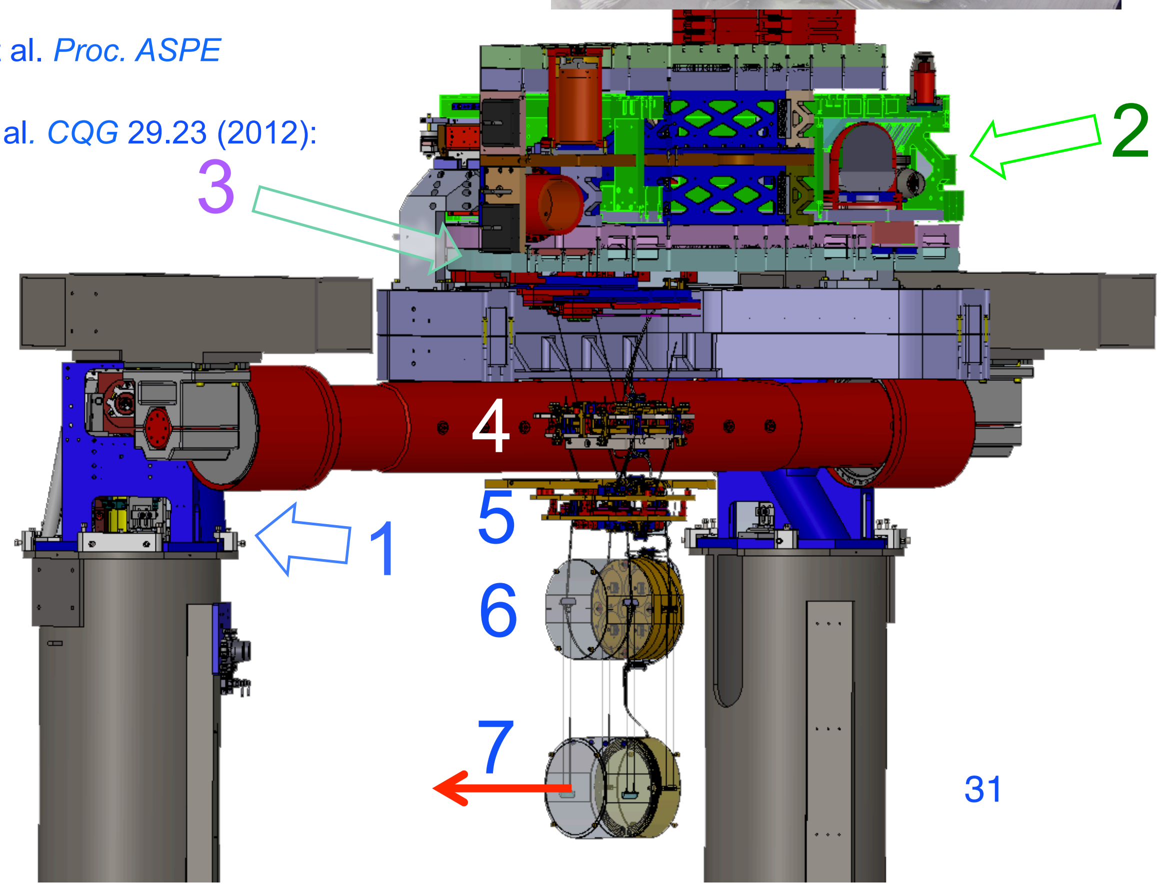
Need 10 orders of magnitude

Test masses are suspended from 7 stages of active and passive vibration isolation

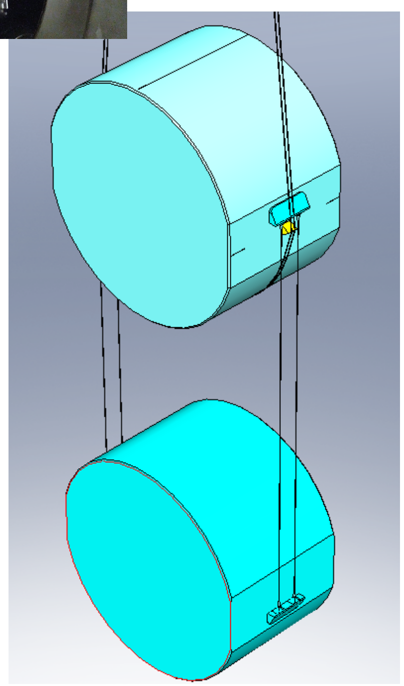


Matichard, F., et al. *Proc. ASPE* (2010)

Aston, S. M., et al. *CQG* 29.23 (2012): 235004.



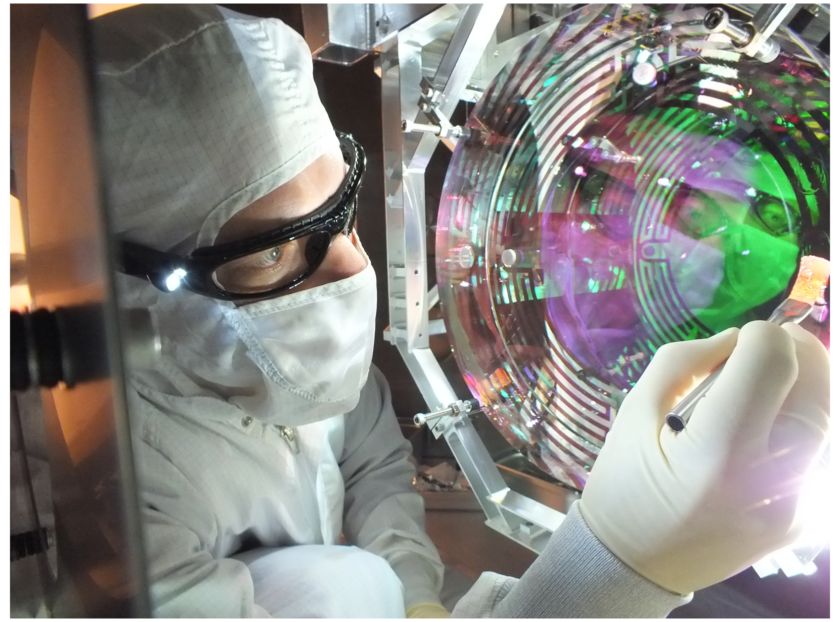
Last two stages are monolithic to improve Brownian noise



Cumming, A. V., et al. *CQG* 29.3 (2012): 035003.

Test Masses

- Heavy Mirrors → Insensitive to photon pressure from high power
- Test mass coating brownian noise dominates strain sensitivity in the most sensitive region (~100 [Hz])
- Larger Mirrors → Increase Spot Size: Average over more surface area

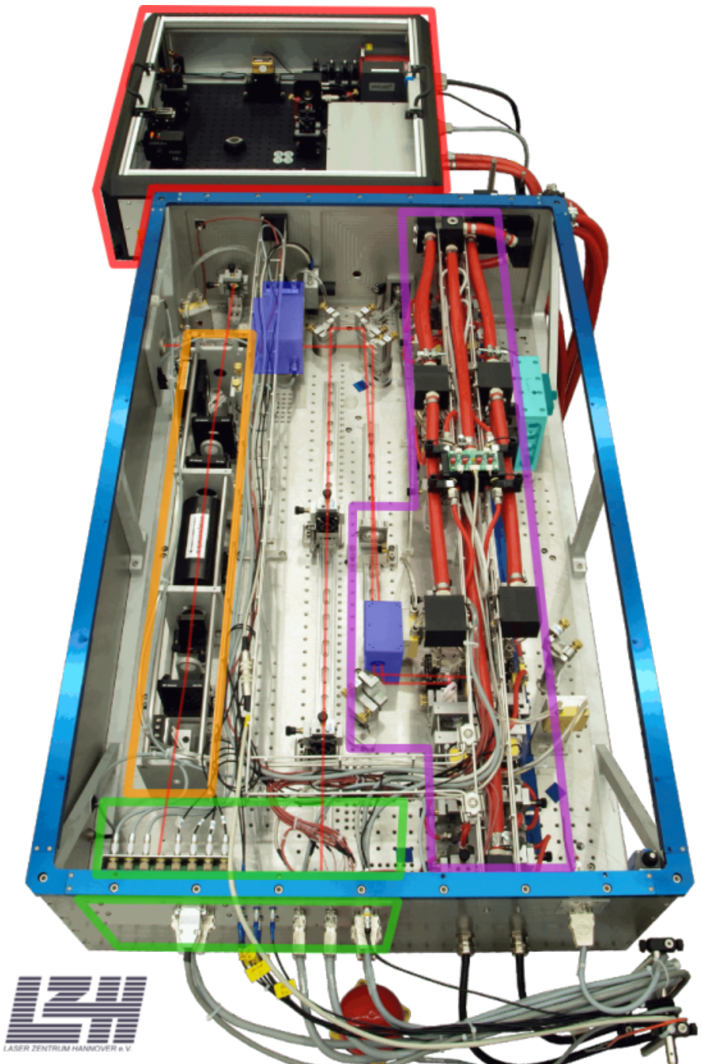


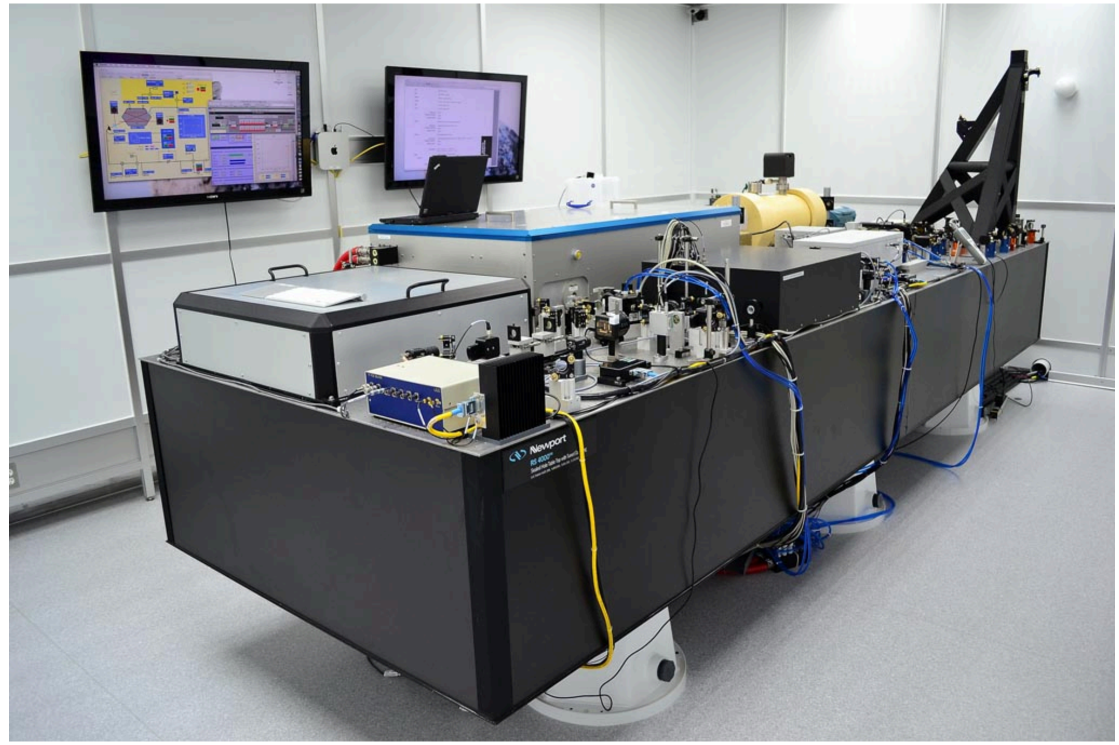
Diameter	**34 cm**
Thickness	**20 cm**
Mass	**40 kg**
$1/e^2$ Beam Size	**5.3-6.2 cm**

Harry, G. M., *et al.* *CQG* 27.8 (2010) 084006

200W Nd:YAG laser

Designed and contributed by Max Planck Albert Einstein Institute





- Stabilized in power and frequency – using techniques developed for time references
- Uses a monolithic master oscillator followed by injection-locked rod amplifier
- Delivers the required shot-noise limited fringe resolution

The Control Model: Actuation

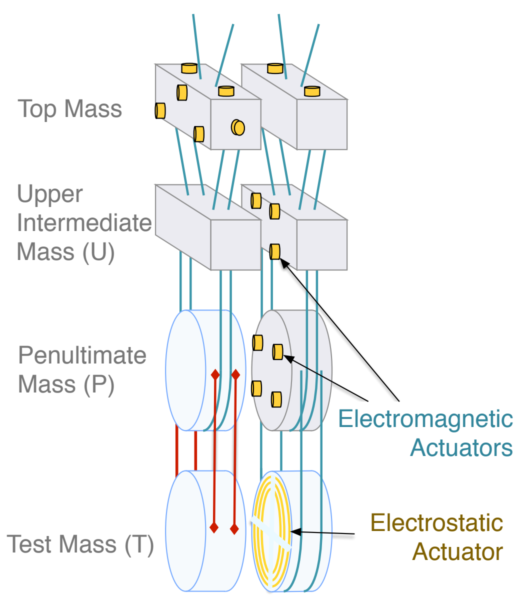
Actuation Function:
The resulting differential arm length displacement ΔL_{ctrl} response as a result of the digital control signal d_{ctrl}

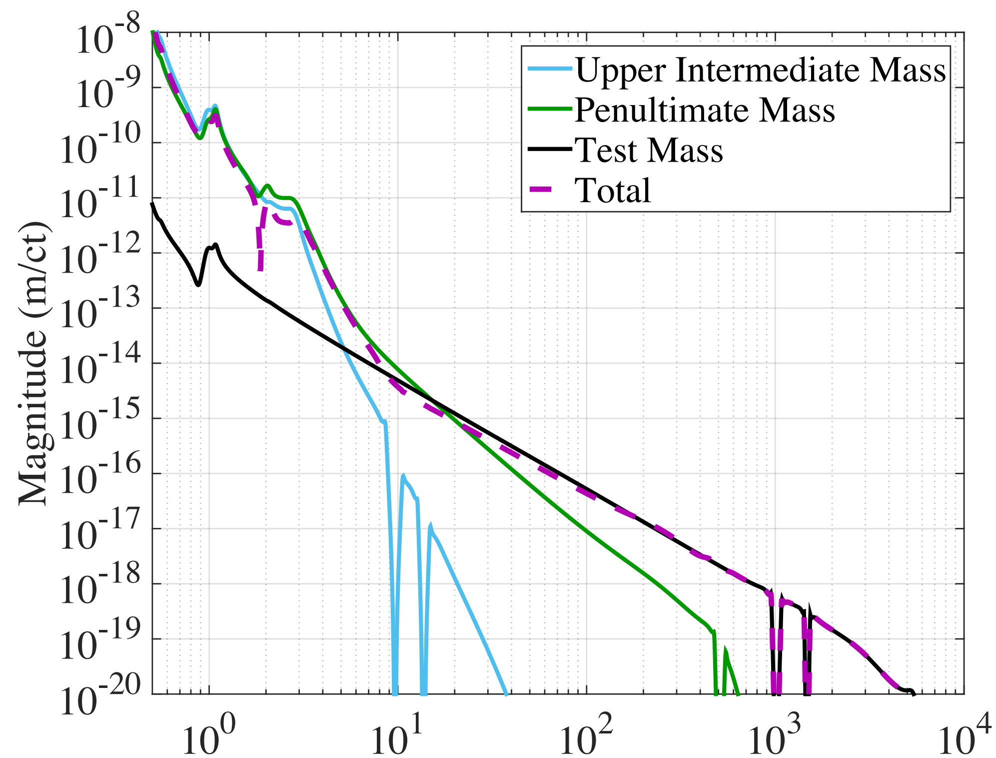
A

$$\Delta L_{ctrl} \equiv A(f) d_{ctrl}$$

For each stage U, P, and T:

- a gain
- mechanical pendulum response
- digital control distribution filters



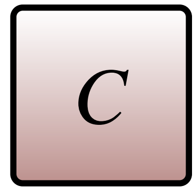


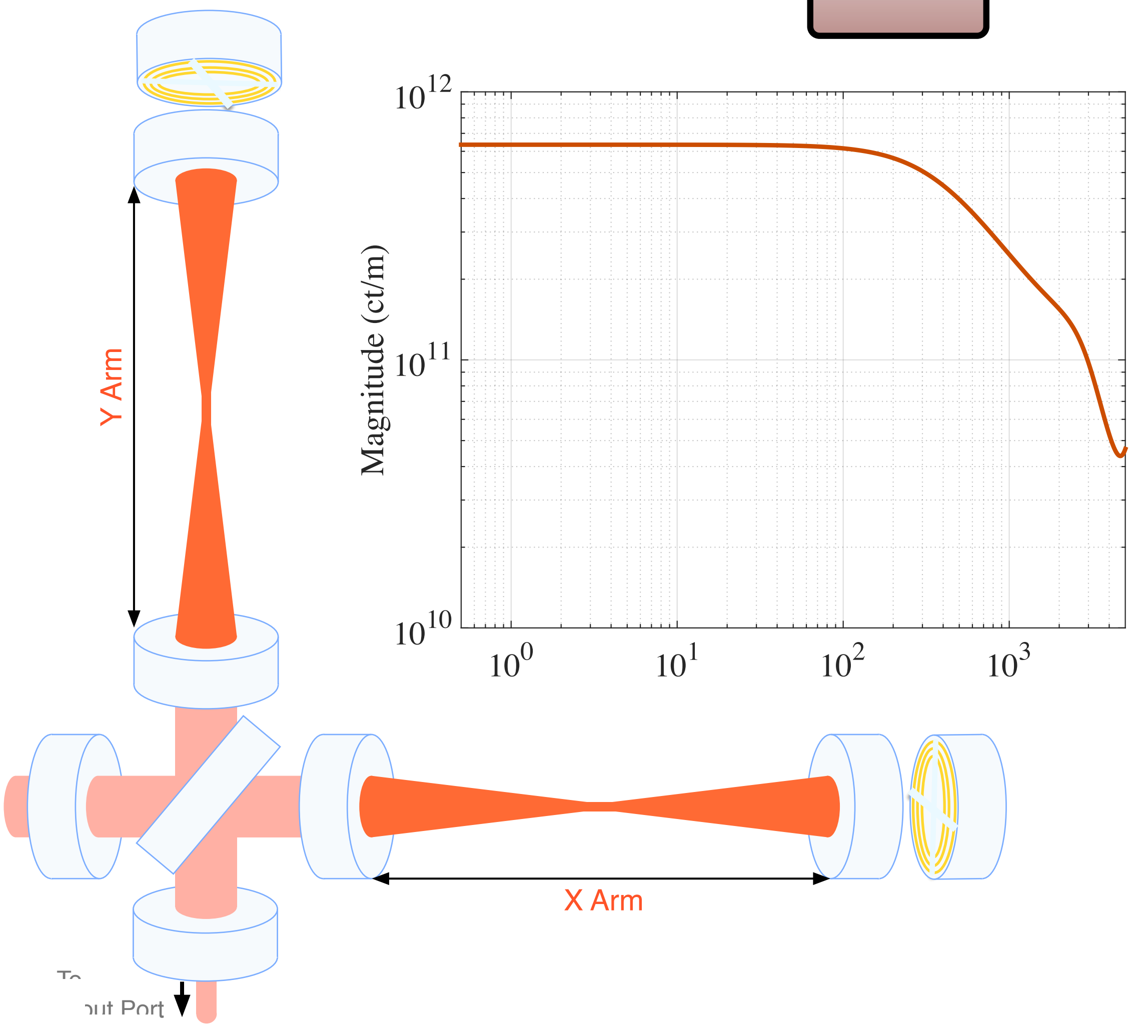
$$A = K_U A_U + K_P A_P + K_T A_T$$

J. Kissel, 2016 Apr APS Meeting, arXiv:1602.03845 (2016)

The Control Model: Sensing

$$d_{err} \equiv C(f)\Delta L_{res}$$





Sensing Function:
The interferometer's response to differential arm length displacement $\boldsymbol{\Delta L_{res}}$ as measured by the digitized photodetector signal $\boldsymbol{d_{err}}$

Dual-Recycled Fabry-Perot Michelson response well-approximated* by:

- a single pole low-pass filter,
- a gain, and
- a time-delay

** J. Mizuno et al., Phys. Lett. A 175, 273 (1993)*
M. Rakhmanov et al., CQG 25, 184017 (2008)

Minor effects of the photodiodes' electronics and digitization, are well-understood and included