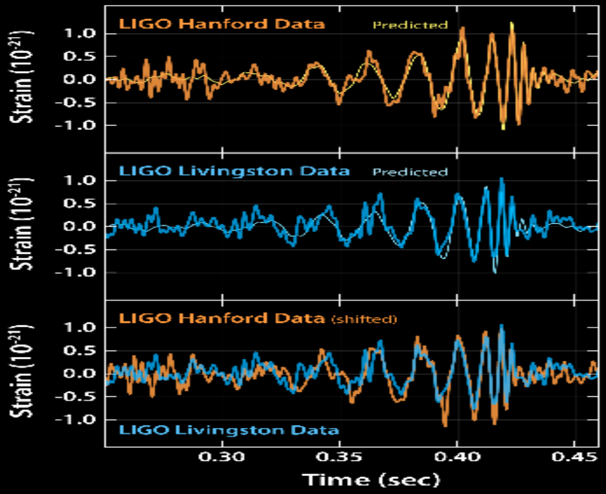
Observation of Gravitational Waves from Binary Black Hole Mergers



102º
Congresso
Della
Societa Italiana di Fisica

Padova

Barry C Barish
Caltech

26-Sept-2016

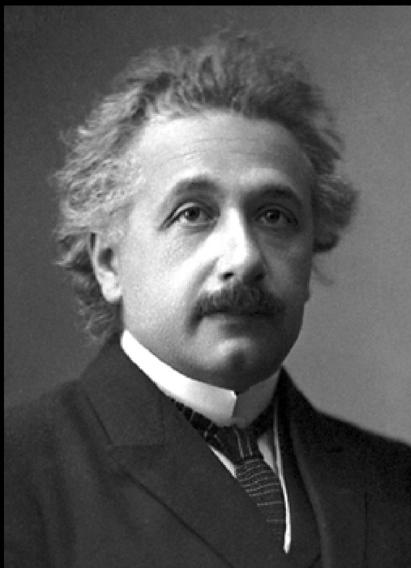
LIGO-G1601663

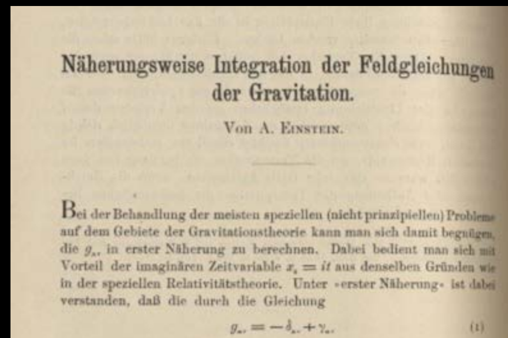
Thanks !!

- Thanks to the *Societa Italiana di Fisica* for the award.
- I am honored to be associated with name of Enrico Fermi, and especially thanks to all my Italian colleagues.
- I am very indebted to my many amazing colleagues on LIGO
- I especially thank my wife and family, who have been tremendously supportive of me and my dedication to physics all these years.
- Lastly, I congratulate my friend and colleague, Adalberto Giazotto.

100 Years Ago -- 1916

Einstein Predicted Gravitational Waves





Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

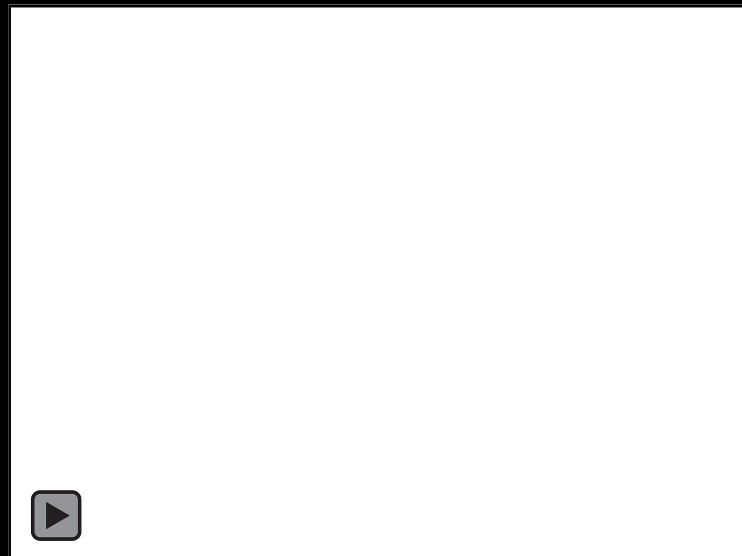
Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

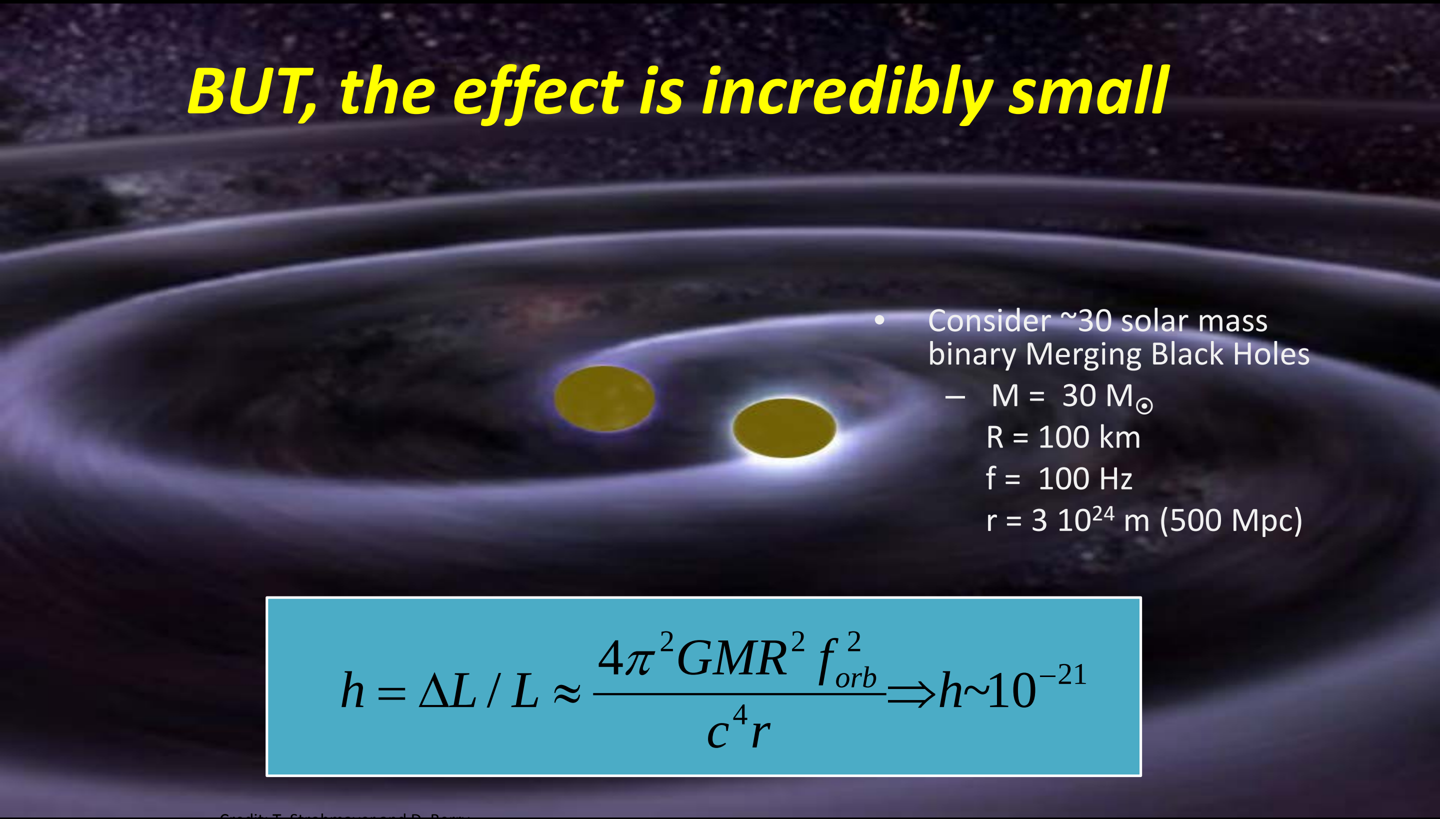
- 1st publication indicating the existence of gravitational waves by Einstein in 1916
  - Contained errors relating wave amplitude to source motions
- 1918 paper corrected earlier errors (factor of 2), and it contains the quadrupole formula for radiating source

Gravitational Wave Source

General Relativity determines exactly what gravitational wave signal merging black holes produce



BUT, the effect is incredibly small



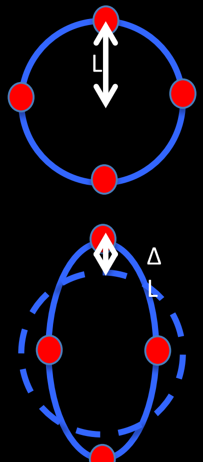
- Consider ~30 solar mass binary Merging Black Holes
  - $M = 30\ M_\odot$
    $R = 100$ km
    $f = 100$ Hz
    $r = 3\ 10^{24}$ m (500 Mpc)

$$h = \Delta L / L \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \Rightarrow h \sim 10^{-21}$$

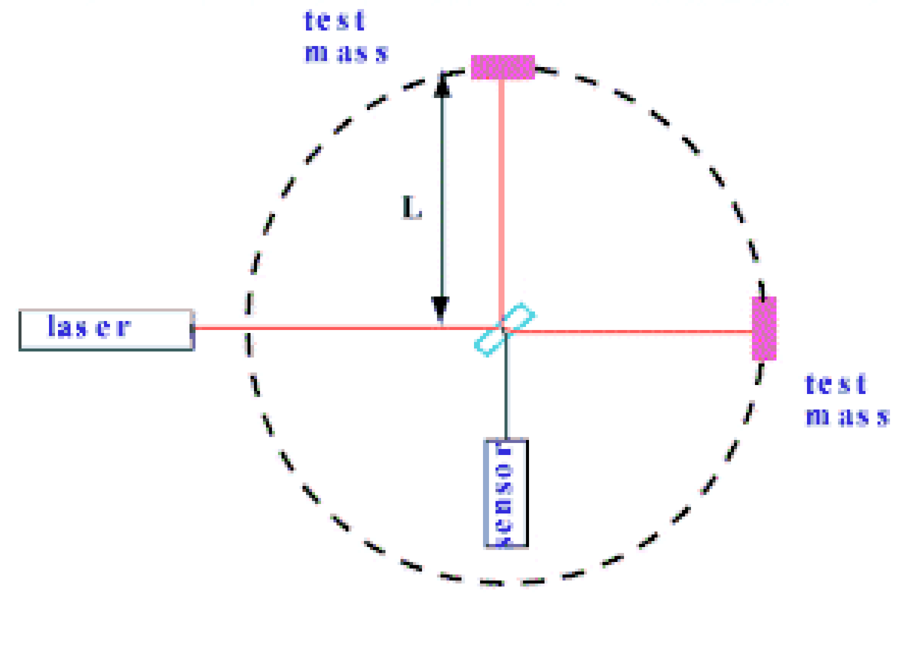
Gravitational waves

- Predicted by Einstein's theory of General Relativity
- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is $h \approx 10^{-21}$
- Change the distance between masses that are free to move by $\Delta L = h \times L$
- Spacetime is "stiff" so changes in distance are very small

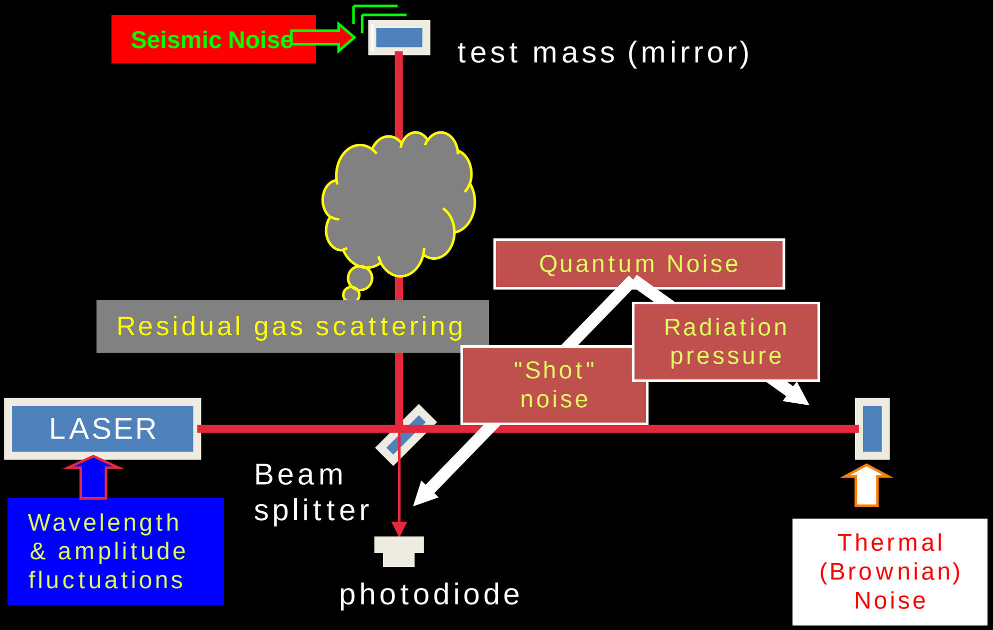
$$\Delta L = h \times L = 10^{-21} \times 1\,\mathrm{m} = 10^{-21}\,\mathrm{m}$$



Suspended Mass Interferometry

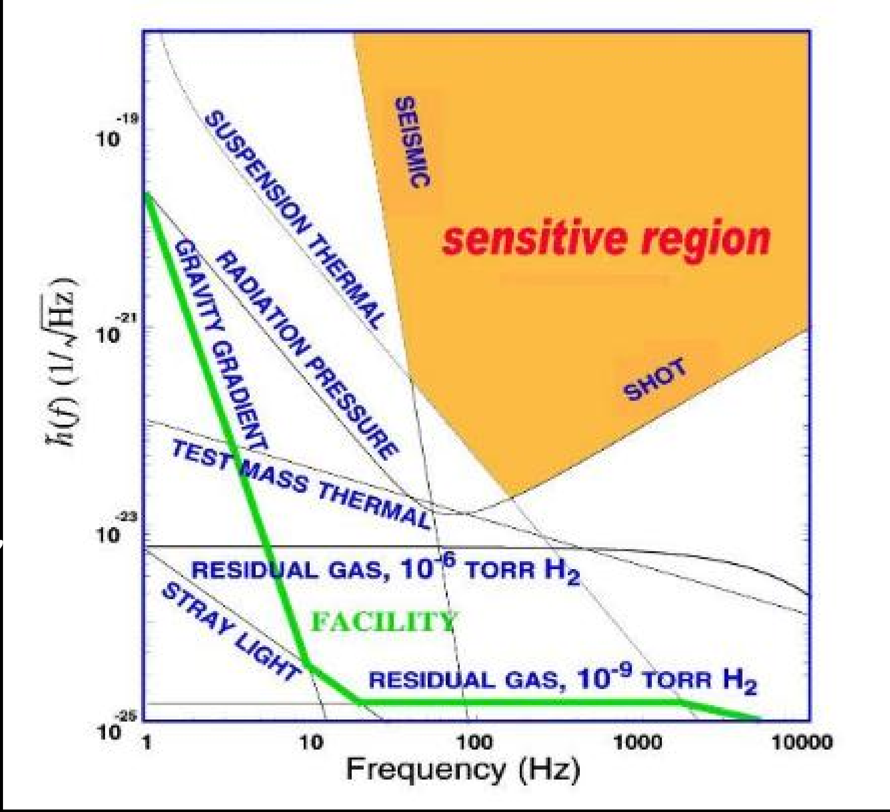


Interferometer Noise Limits



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 Sites


LIGO
Hanford
3002 km
(L/c = 10 ms)
MIT
Caltech
Livingston
Observatory

LIGO Interferometers

Hanford, WA

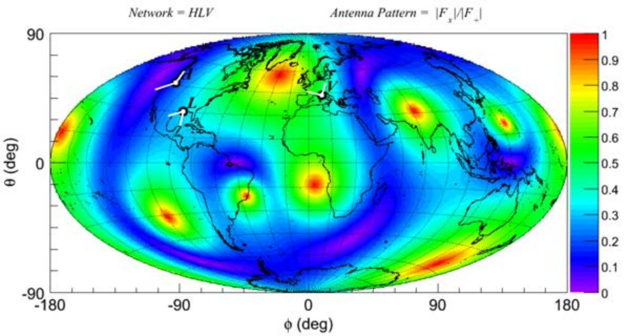
Livingston, LA

Virgo


LIGO
LIGO Scientific Collaboration
LSC
Abilene Christian University
Albert-Einstein Institut
Andrews University
American University
California Institute of Technology
California State Univ., Fullerton
Canadian Inst. Th. Astrophysics
Carleton College
College of William and Mary
Columbia University
Embry-Riddle Aeronautical Univ.
Eötvös Loránd University
Georgia Institute of Technology
Goddard Space Flight Center
Hobart & William Smith Colleges
ICTP-SAIFR
IndIGO
IAP-Russian Acad. of Sciences
Inst. Nacional Pesquisas Espaciais
Kenyon College
Korean Gravitational-Wave Group
Louisiana State University
Montana State University
Montclair State University
Moscow State University
National Tsinghua University
Northwestern University
Penn State University
Rochester Institute of Technology
Sonoma State University
Southern Univ. and A&M College
Stanford University
Syracuse University
Szeged University
Texas Tech University
Trinity University
Tsinghua University
Universitat de les Illes Balears
University of Alabama in Huntsville
University of Brussels
University of Chicago
University of Florida
University of Maryland
University of Michigan
University of Minnesota
University of Mississippi
University of Oregon
University of Sannio
Univ. of Texas-Rio Grande Valley
University of Washington
University of Wisconsin-Milwaukee
Washington State University
West Virginia University
Whitman College
Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):
Australian National University, Charles Sturt University, Monash University, University of Adelaide, University of Melbourne, University of Western Australia
LIGO Laboratory: California Institute of Technology, Massachusetts Institute of Technology, LIGO Hanford Observatory, LIGO Livingston Observatory
German/British Collaboration for the Detection of Gravitational Waves (GEO600):
Cardiff University, Leibniz Universität Hannover, Albert-Einstein Institut, Hannover, King's College London, Rutherford Appleton Laboratory,
University of Birmingham, University of Cambridge, University of Glasgow, University of Hamburg, University of Sheffield,
University of Southampton, University of Strathclyde, University of the West of Scotland
FoF, March 31 2016

LIGO/Virgo Collaboration

- Common Data Formats
  - Agreement in 1997
- MOU Collaboration - 2007
  - Share Data
  - Joint Meeting / Analysis / Publications
- Motivation
  - Three-fold coincidence
  - GW polarization
  - Improve pointing



Elliptical Wave Patterns

Klimenko April 11, 2015, APS meeting, Baltimore, LIGO-1500032

Localization on the sky

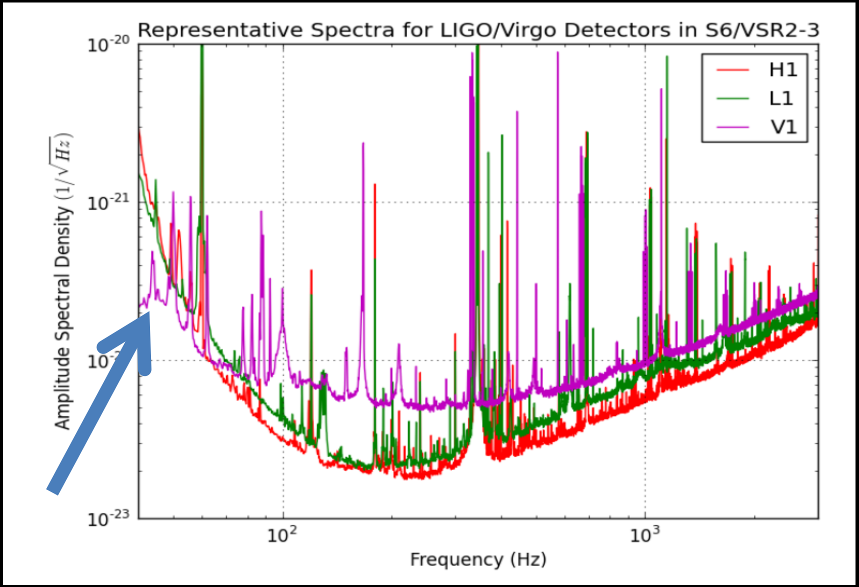
Actual estimates with H1 and L1

Simulated estimates with Virgo

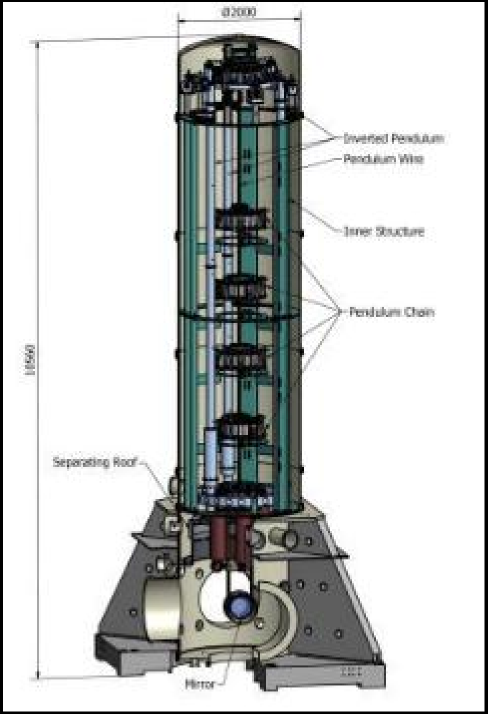
10% to 90% confidence regions

More detectors with large spatially separations
and non-degenerate orientations needed

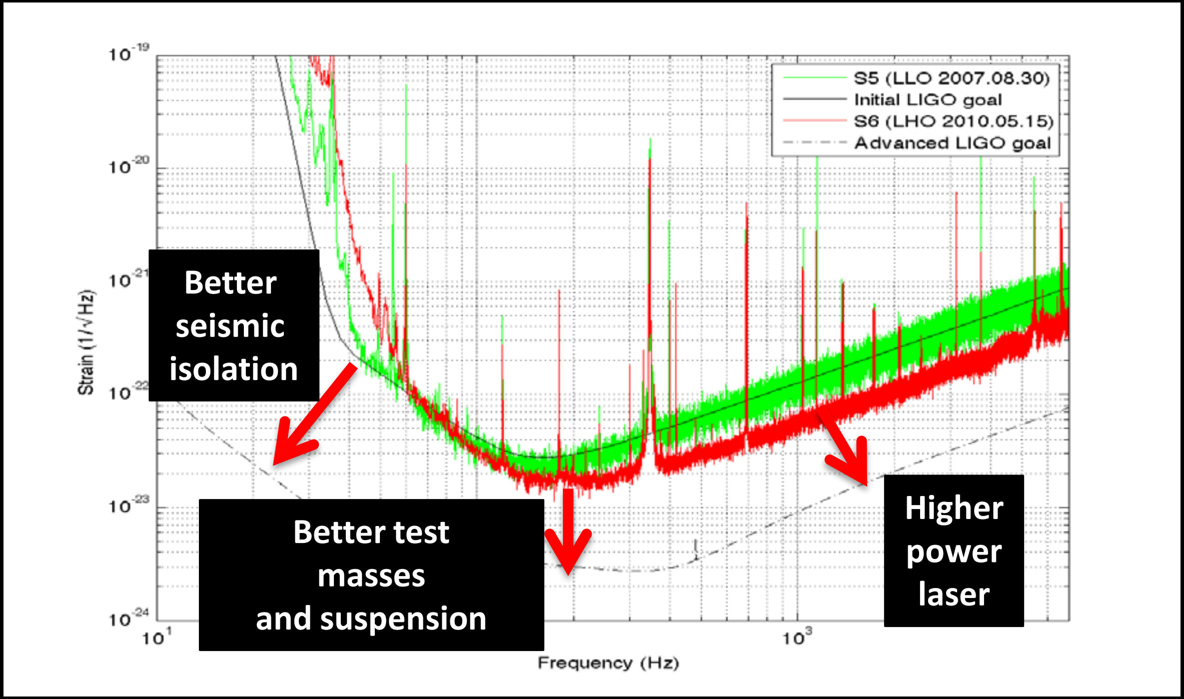
Initial LIGO/Virgo Sensitivities



Virgo Pendulum Chain



Advanced LIGO



LIGO-G1601663

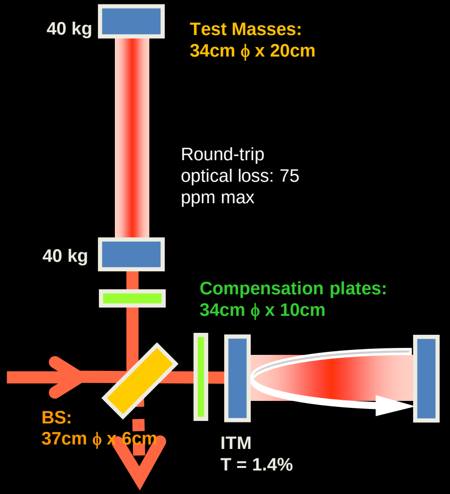
200W Nd:YAG laser

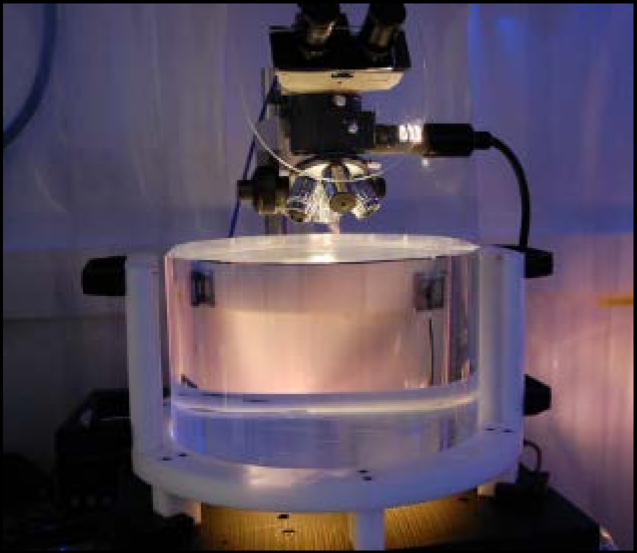
Designed and contributed by Max Planck Albert Einstein Institute

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

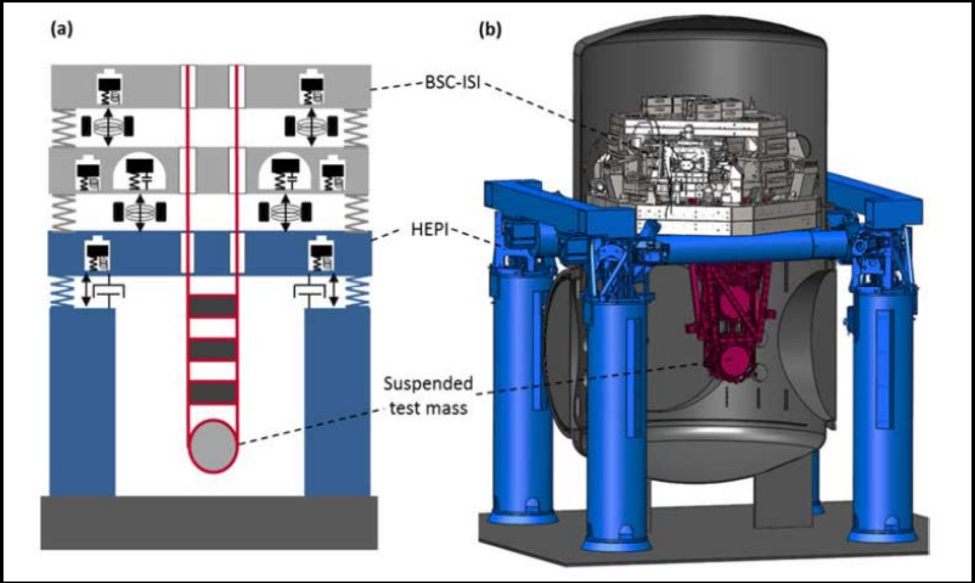
Mirror / Test Masses

- **Mechanical requirements: bulk and coating thermal noise, high resonant frequency**
- **Optical requirements: figure, scatter, homogeneity, bulk and coating absorption**

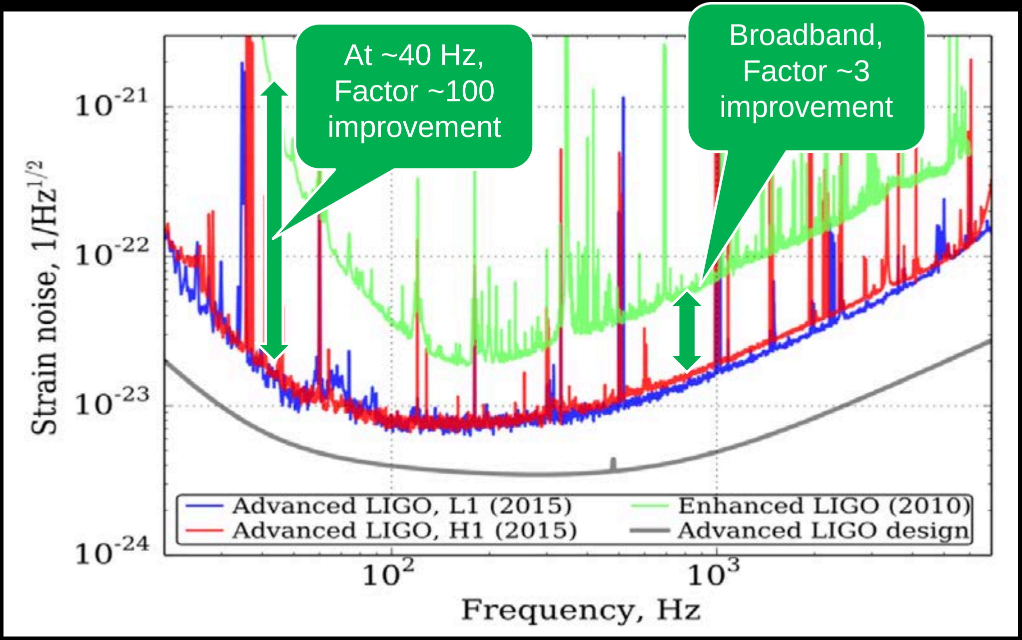




Seismic Isolation
Passive / Active Multi-Stage



Sensitivity for first Observing Run



Initial LIGO

O1 aLIGO

Design aLIGO

Gravitational Wave Event

GW150914

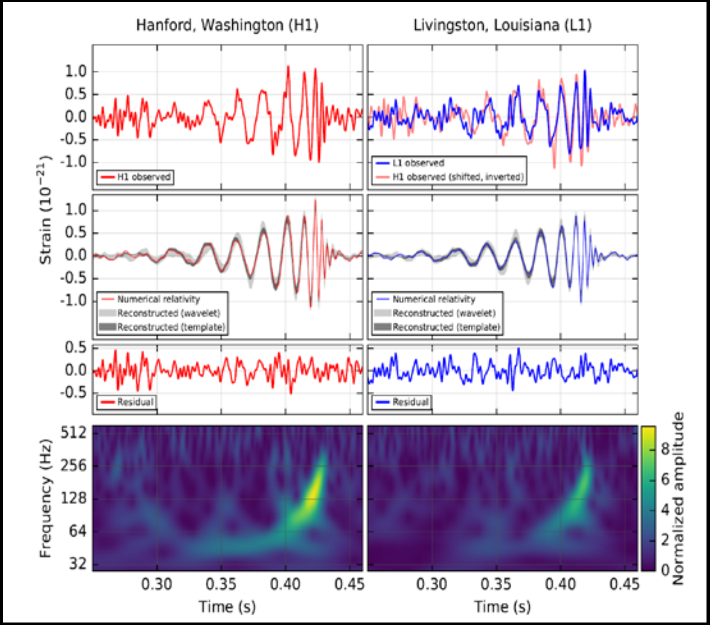
Data bandpass filtered between 35 Hz and 350 Hz

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)

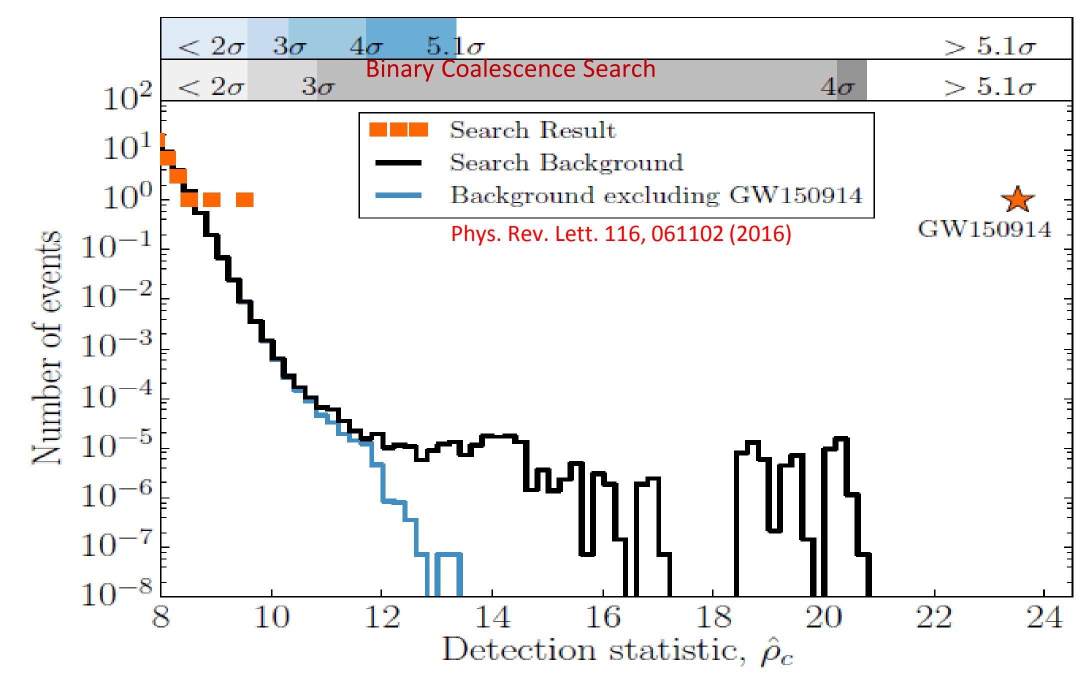
Third Row –residuals

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



Phys. Rev. Lett. 116, 061102 (2016)

Statistical Significance of GW150914

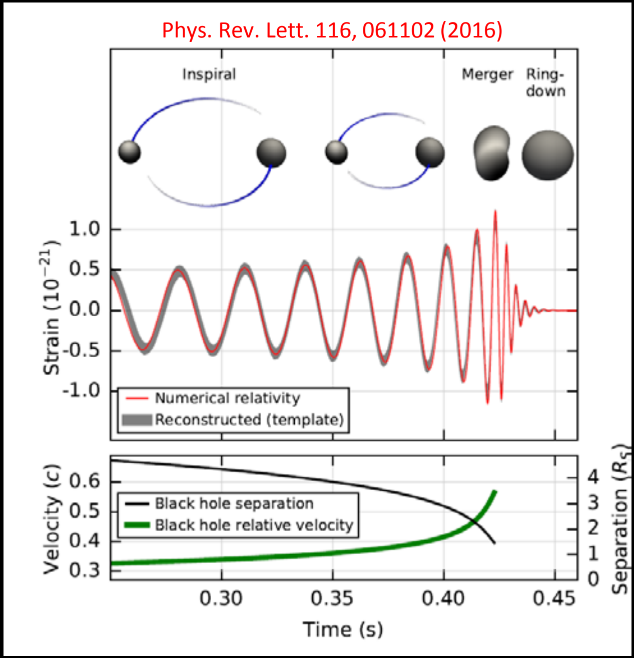


Fermi Prize

Black Hole Merger: 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 $v/c = (GM_f \pi f / c^3)^{1/3}$

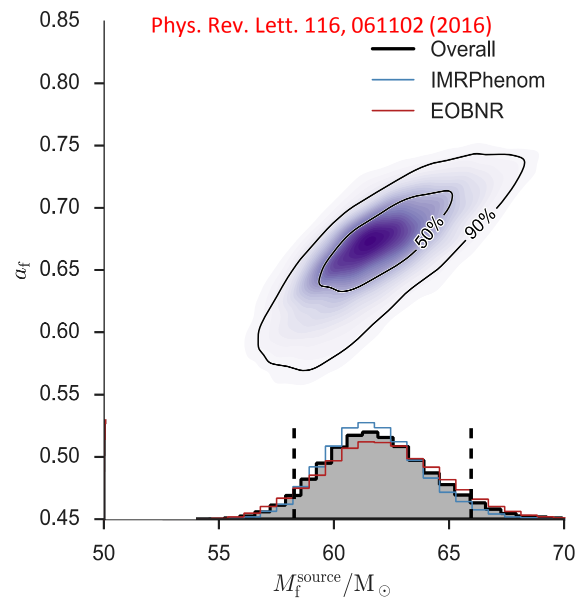


Black Hole Merger Parameters for GW150914

- Use numerical simulations fits of black hole merger to determine parameters; determine total energy radiated in gravitational waves is 3.0±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	$0.09^{+0.03}_{-0.04}$

Phys. Rev. Lett. 116, 061102 (2016)



More Events?

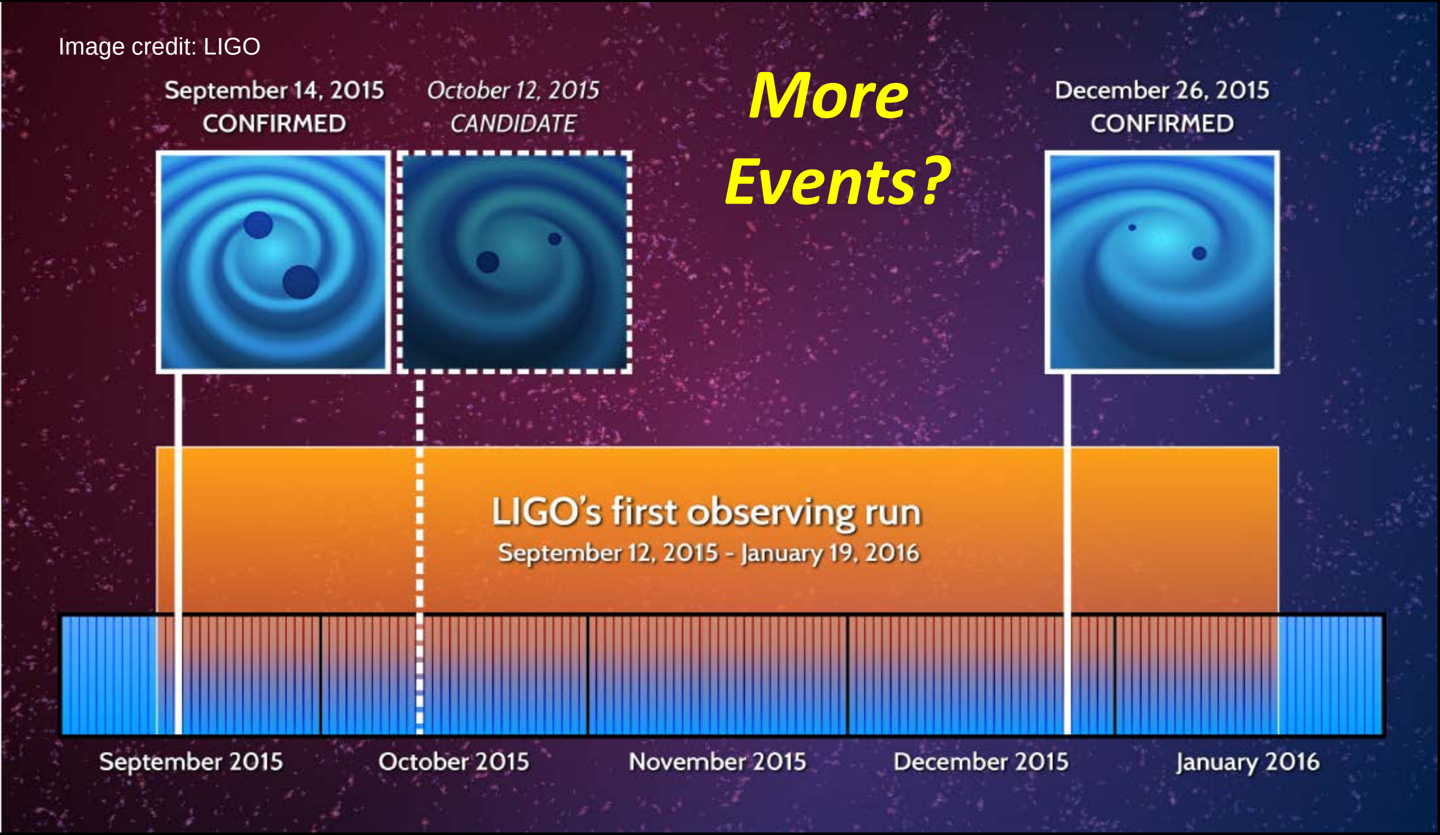
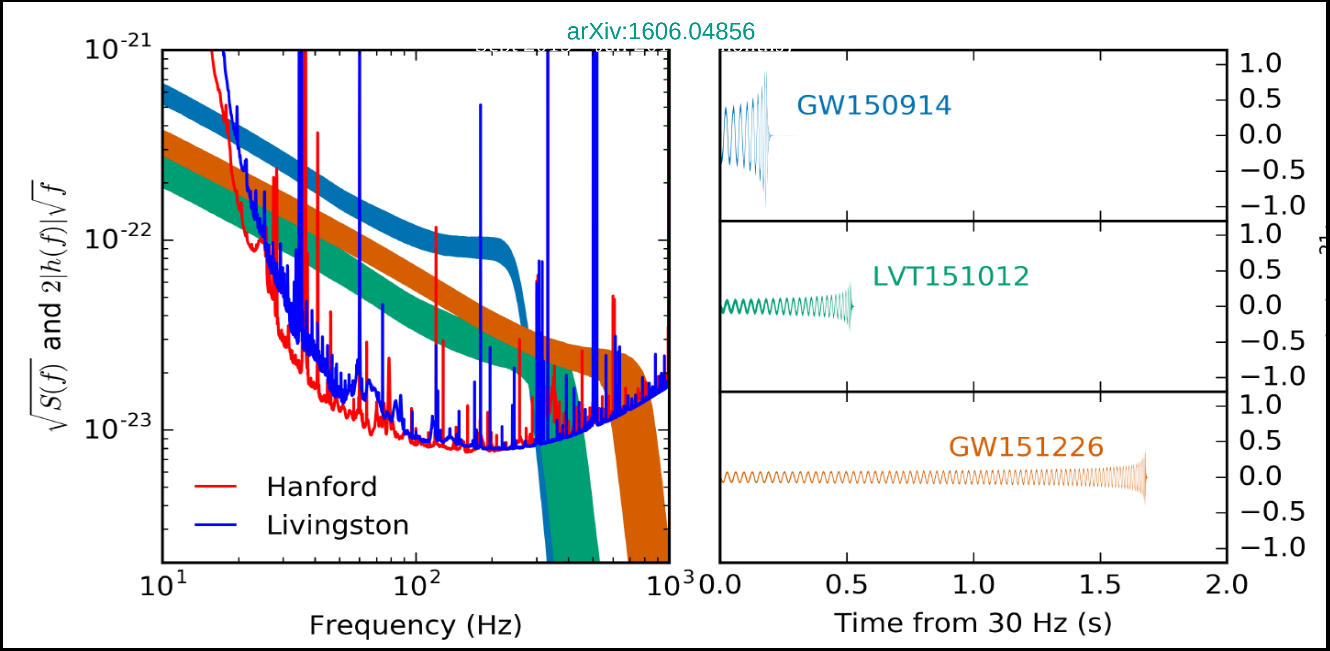
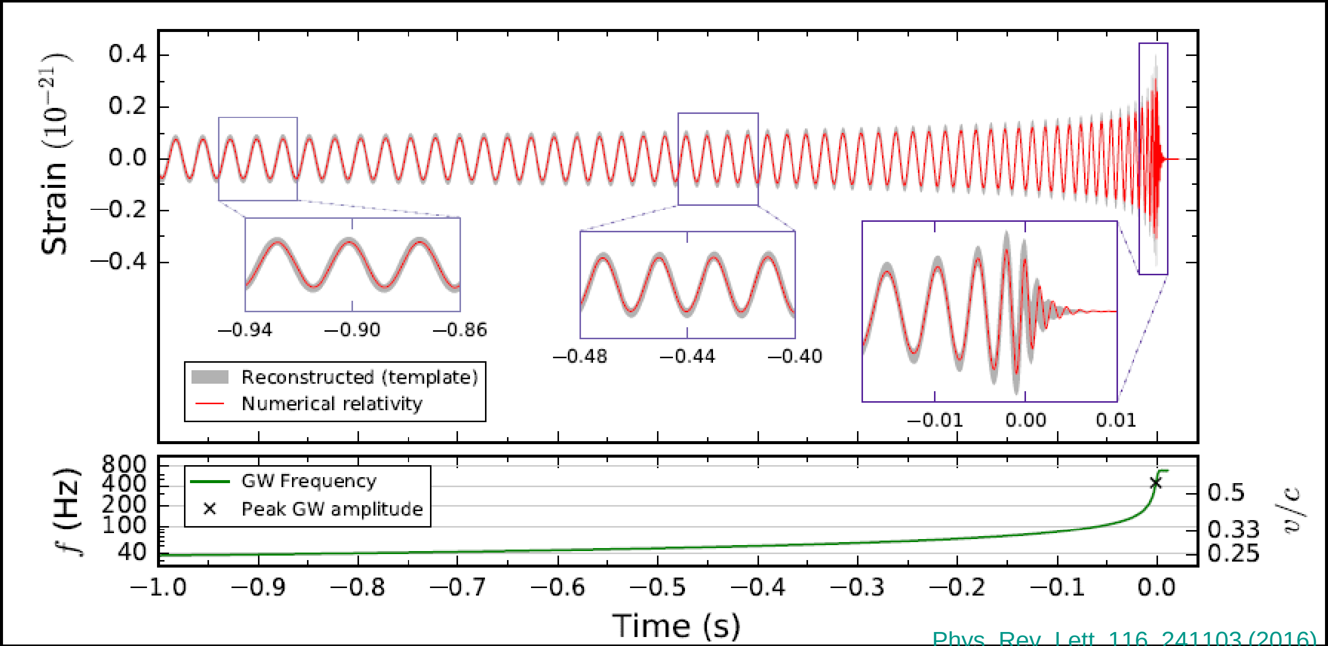


Image credit: LIGO

Second Event, Plus another Candidate

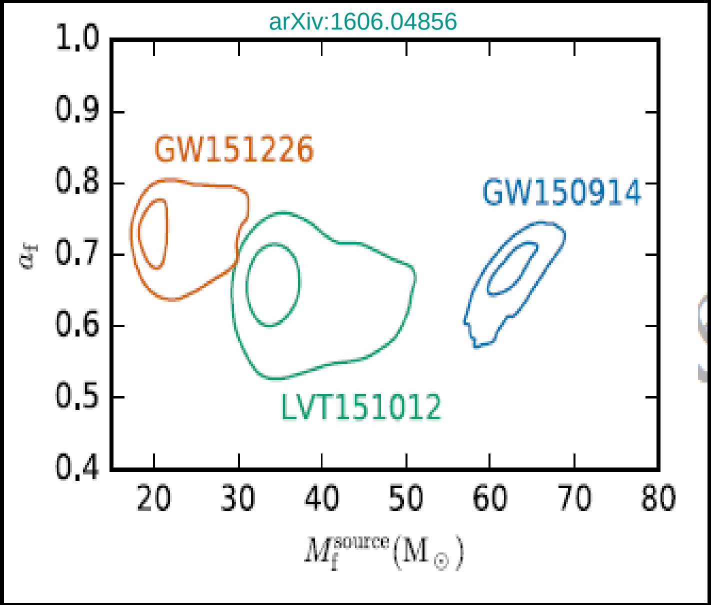


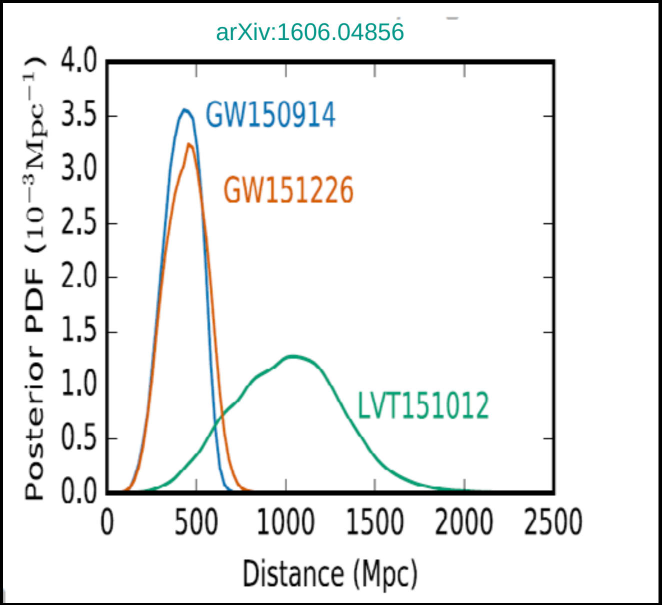
"Second Event" Inspiral and Merger GW151226



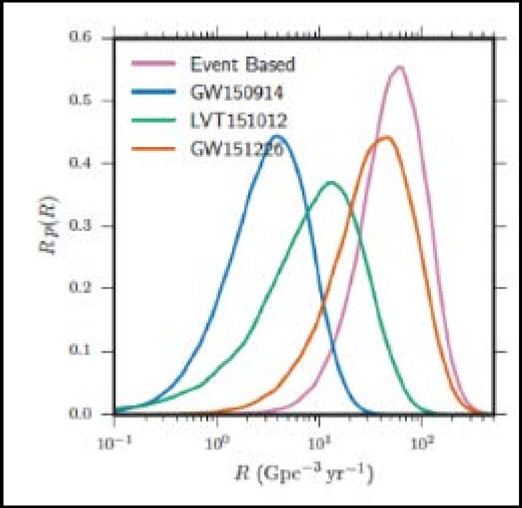
Phys. Rev. Lett. 116, 241103 (2016)

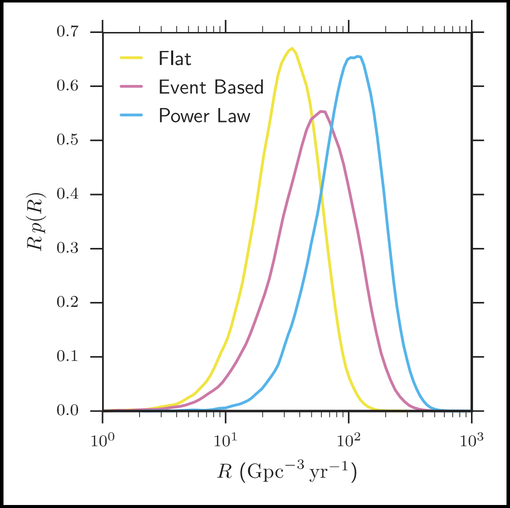
Final Black Hole Masses, Spins and Distance





Binary black hole merger rate





90% allowed range: 9 to 240 /Gpc^3/yr

New Astrophysics

- Stellar binary black holes exist
- They form into binary pairs
- They merge within the lifetime of the universe
- The masses ($M > 20\ M_{\odot}$) are much larger than what was known about stellar mass Black Holes.

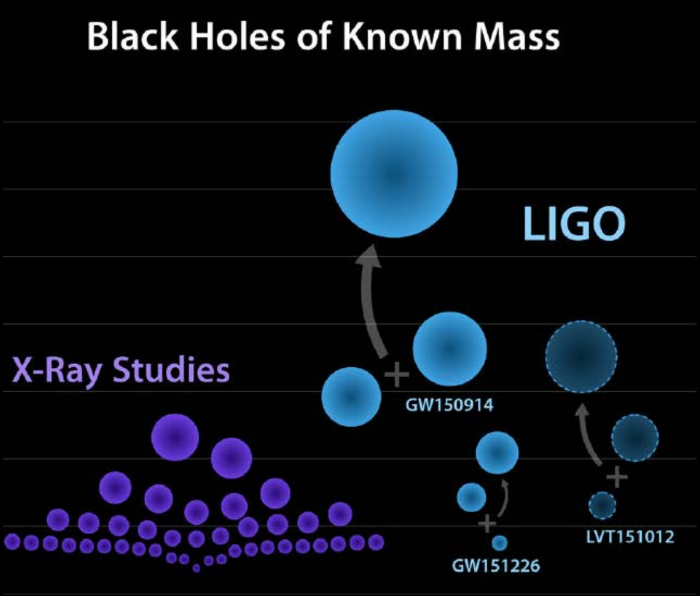
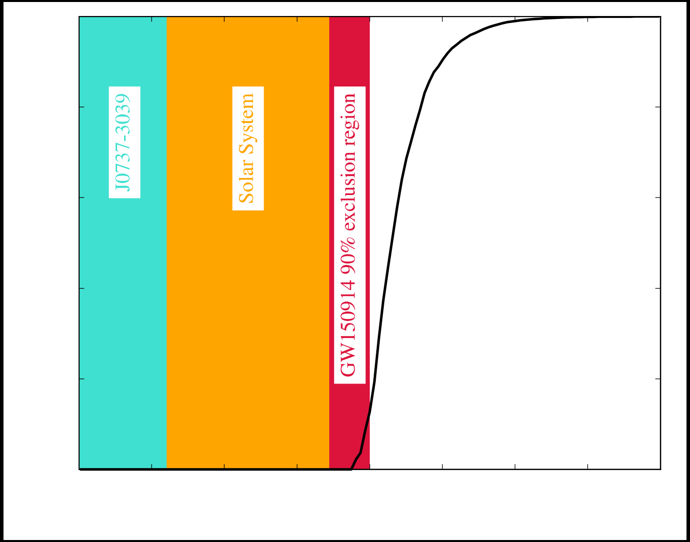


Image credit: LIGO

Testing General Relativity

graviton mass

If $v_{GW} < c$, gravitational waves then have a modified dispersion relation. There is no evidence of a modified inspiral



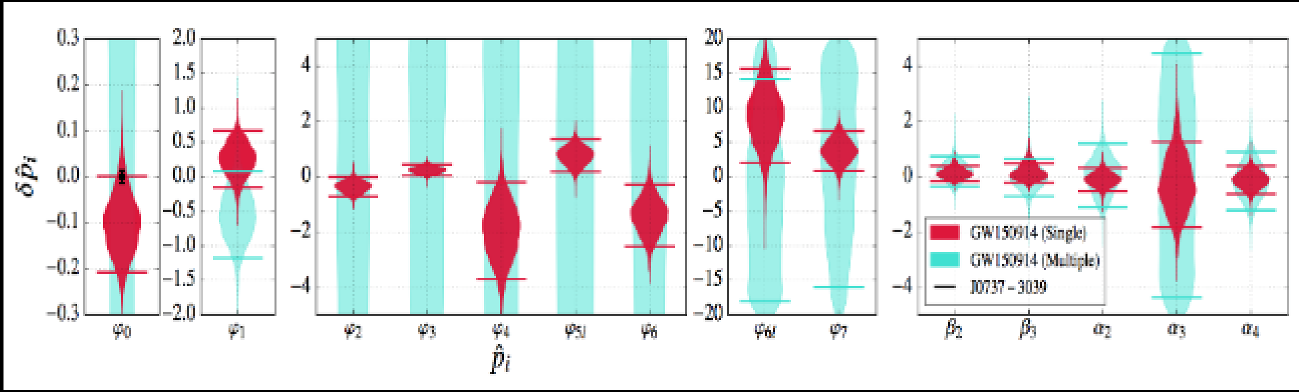
$$\lambda_g > 10^{13} \text{ km}$$

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

LIMIT 90% Confidence

Phys. Rev. Lett. 116, 061102 (2016)

Testing General Relativity



<u>Double pulsar J0737-3039</u>

Masses ~ M_{sun}

Speeds ~ 1e-3 c

Derivative orbital period ~ 1e-12

<u>Double black hole GW150914</u>

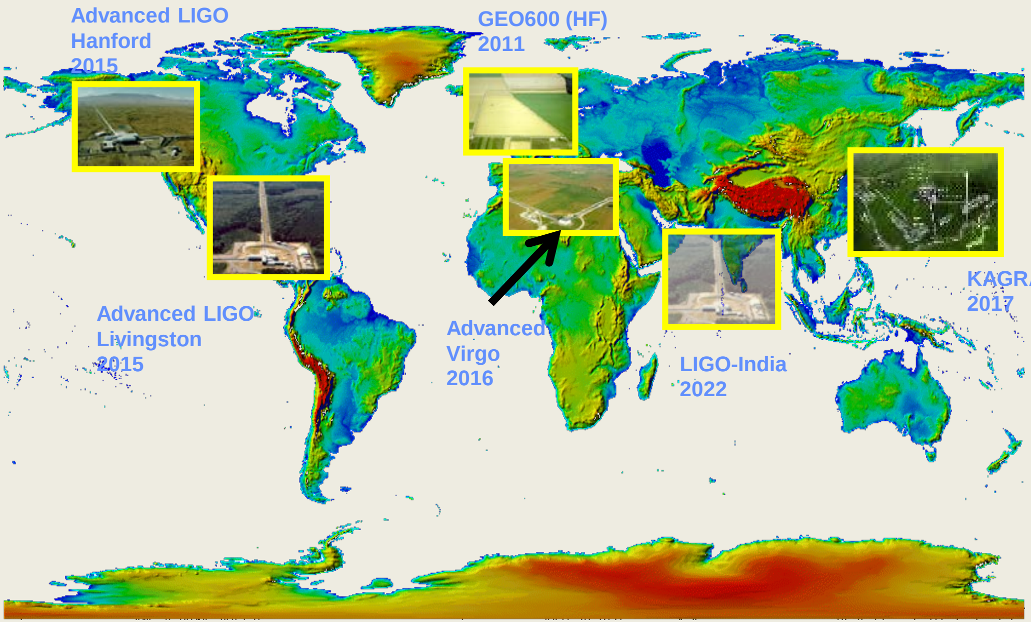
Masses ~ 30 M_{sun}

Speeds ~ 0.5 c

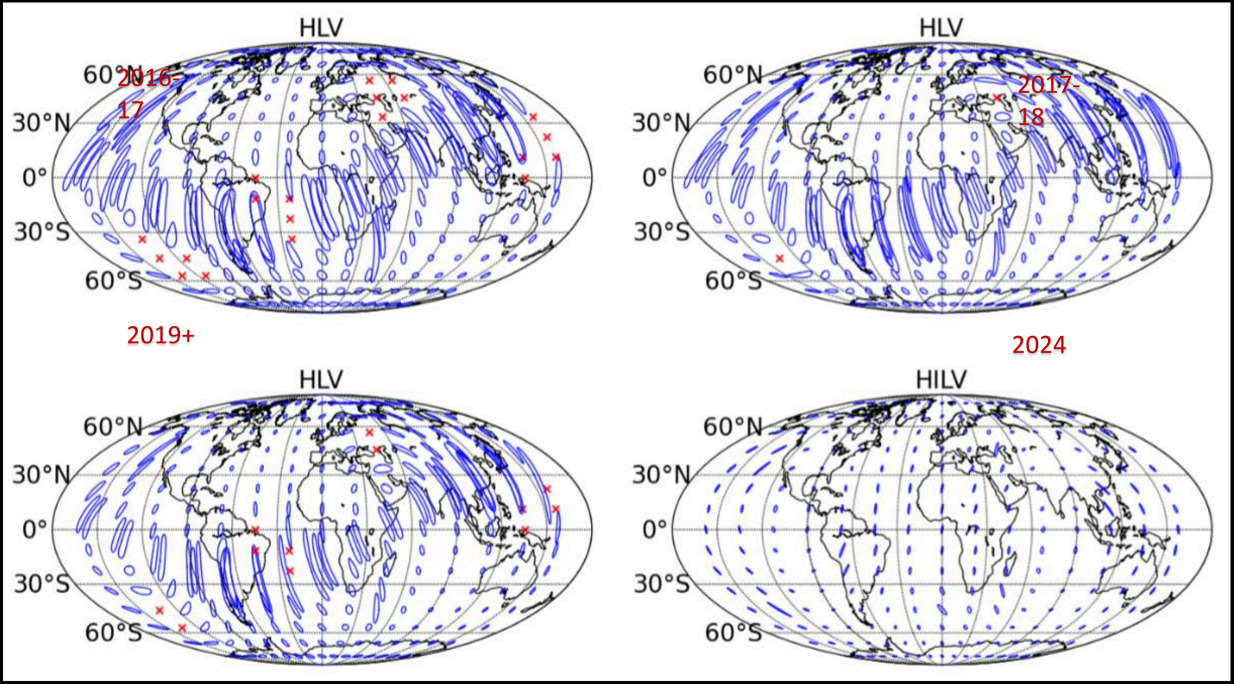
Derivative orbital period ~ 1

The most stringent test of strong field gravity

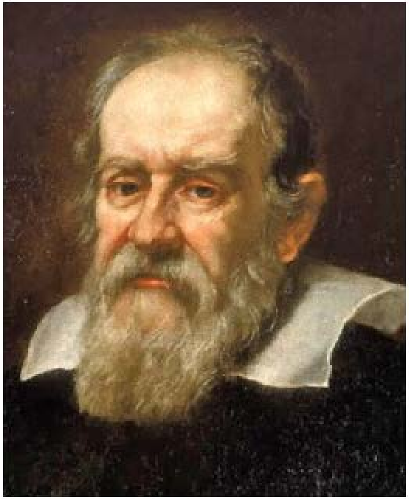
GW detector network: 2015-2025



Improving Localization



The Birth of a New Astronomy



Thanks!