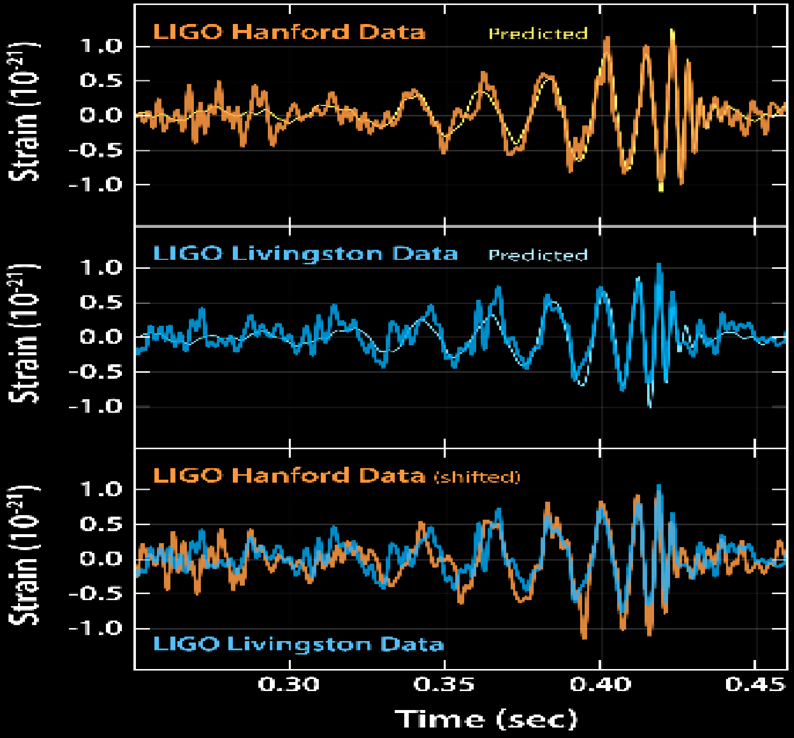
From Einstein to Gravitational Waves and Beyond …



Barry C Barish

Caltech

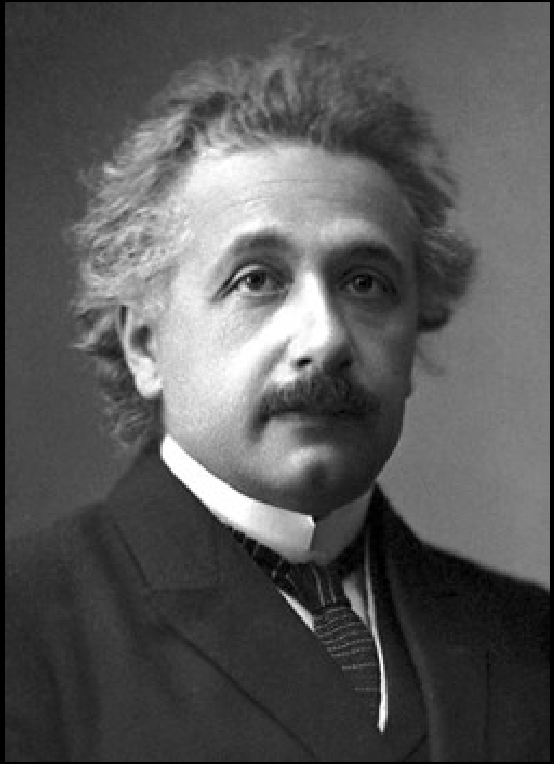
Workshop on Kamioka Underground Physics
Okayama University
23-May-2017

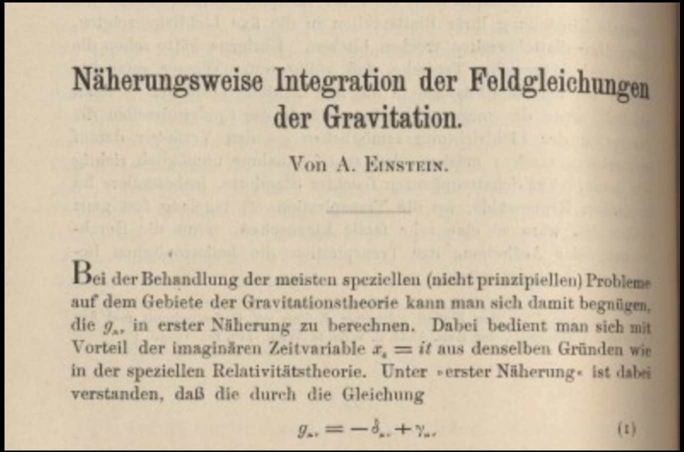
for the
LIGO Scientific Collaboration and Virgo Collaboration

LIGO-G1700695

100 Years Ago -- 1916

Einstein Predicted Gravitational Waves





Näherungsweise Integration der Feldgleichungen der Gravitation.

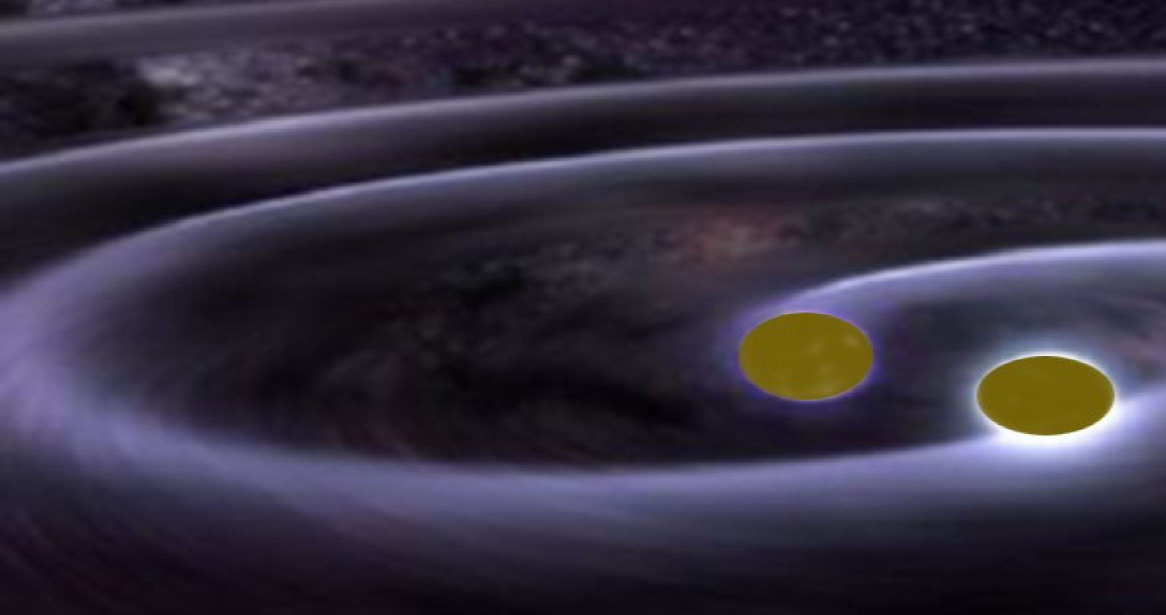
Von A. Einstein.

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

BUT, the effect is incredibly small

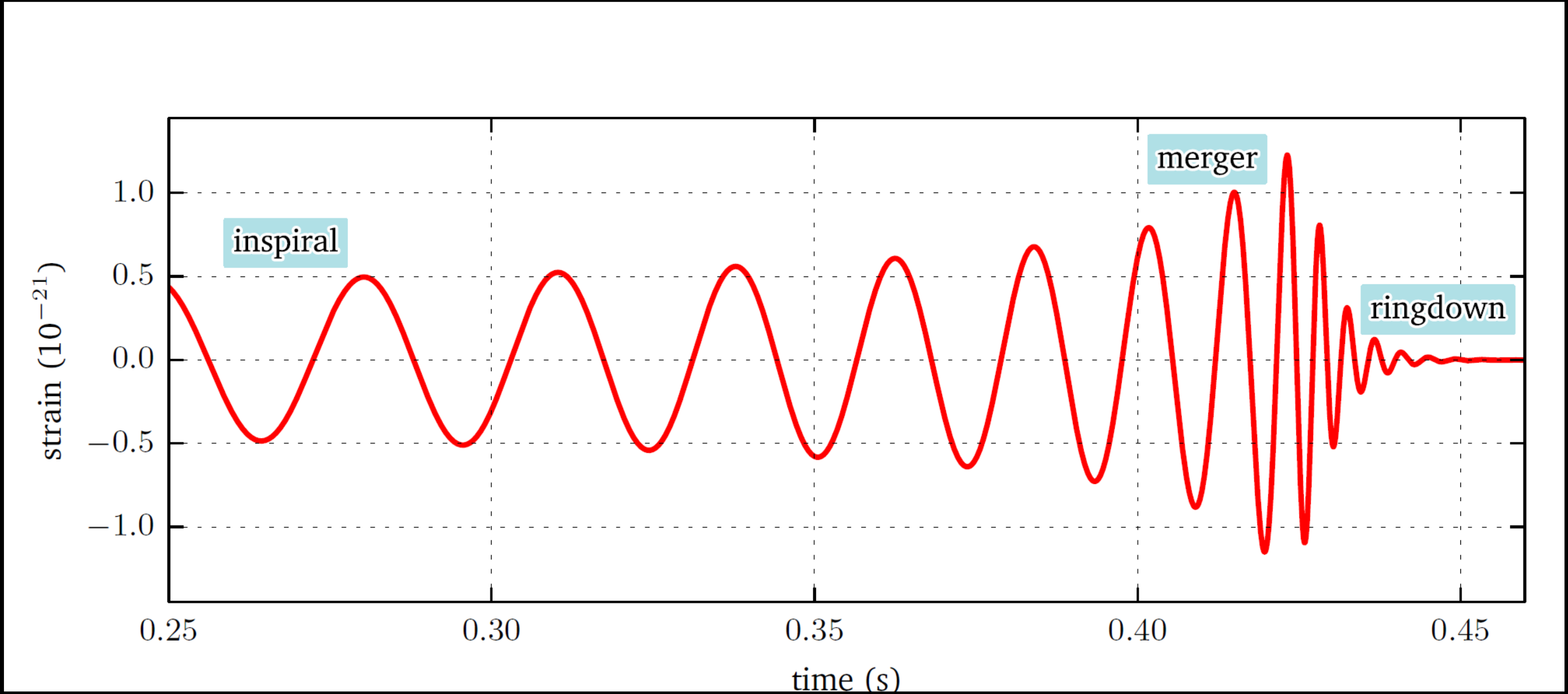


- Consider ~30 solar mass binary Merging Black Holes
  - M = 30 $M_\odot$
    R = 100 km
    f = 100 Hz
    r = 3 10^{24} m (500 Mpc)

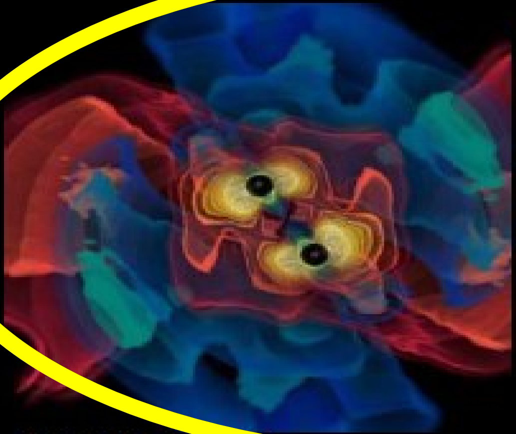
$$h = \Delta L / L \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r} \Rightarrow h \sim 10^{-21}$$

Credit: T. Strohmayer and D. Berr

Emission of Gravitational Waves



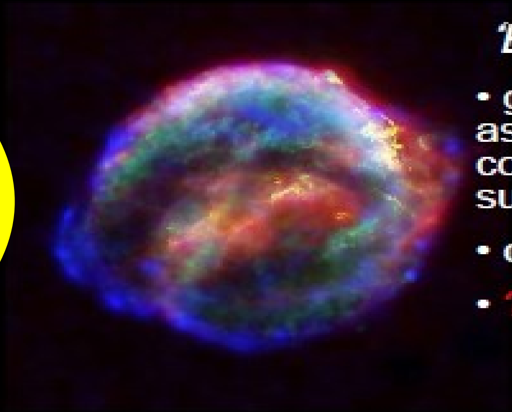
Astrophysical targets for ground-based detectors



Credit: AEI, CCT,

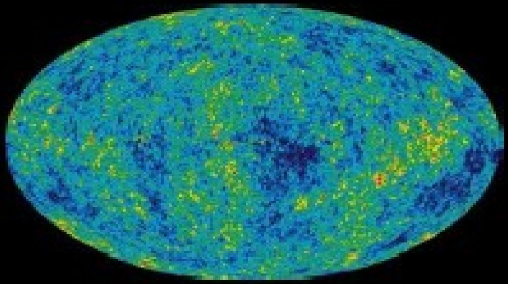
Coalescing Binary Systems

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



'Bursts'

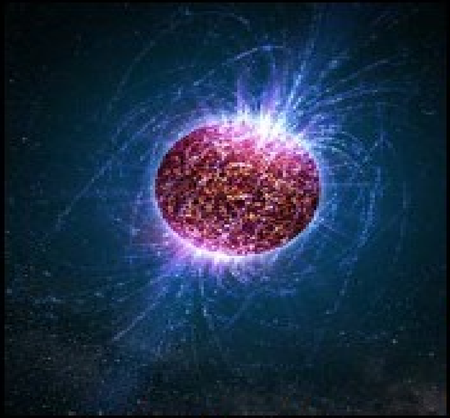
- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



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

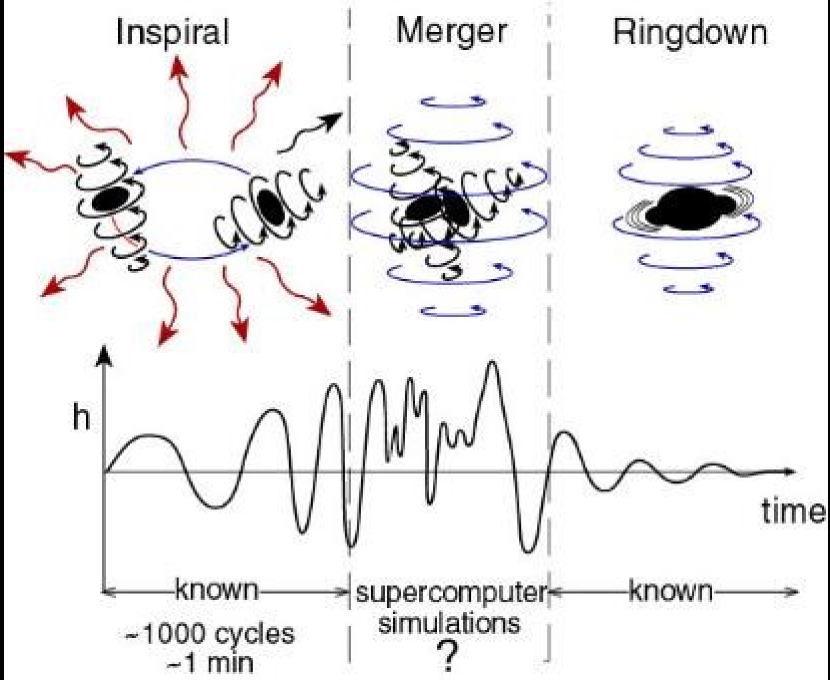


Casey Reed, Penn State

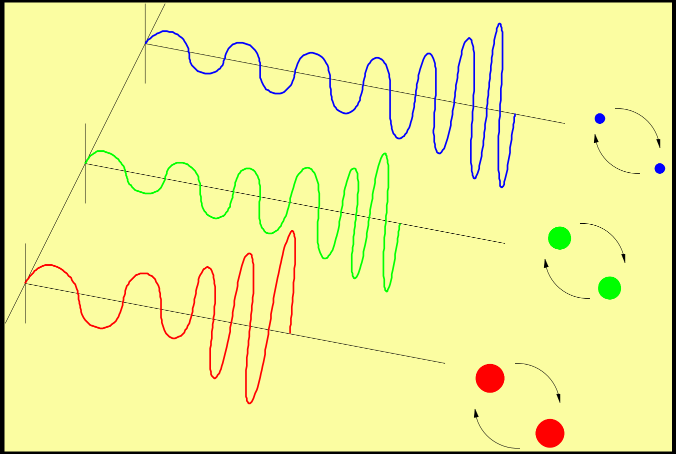
Continuous Sources

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

Compact Binary Collisions

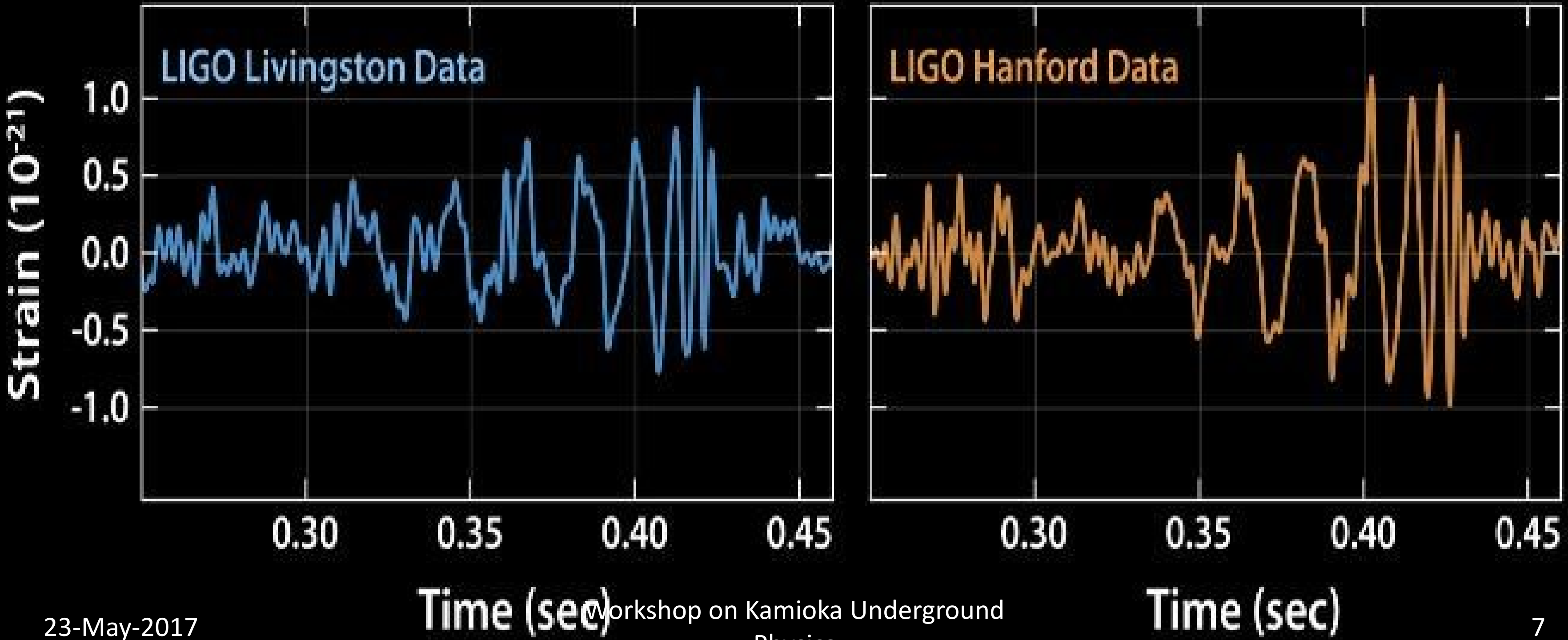


- Neutron Star – Neutron Star
  - **waveforms are well described**
- Black Hole – Black Hole
  - **Numerical Relativity waveforms**
- Search: *matched templates*



"chirps"

Observed Signals – Sept 14, 2015



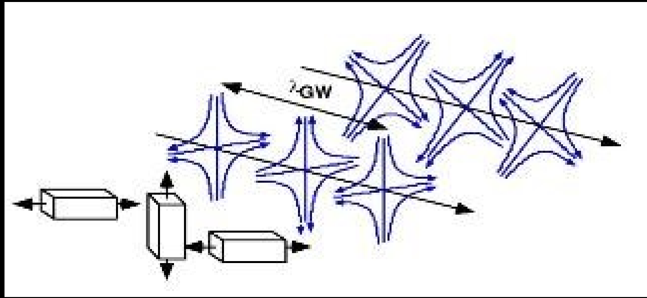
Einstein's Theory of Gravitation

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).

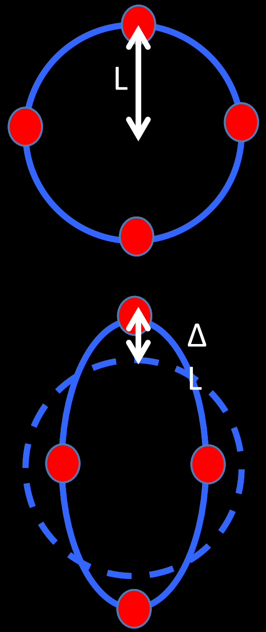


  - Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

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

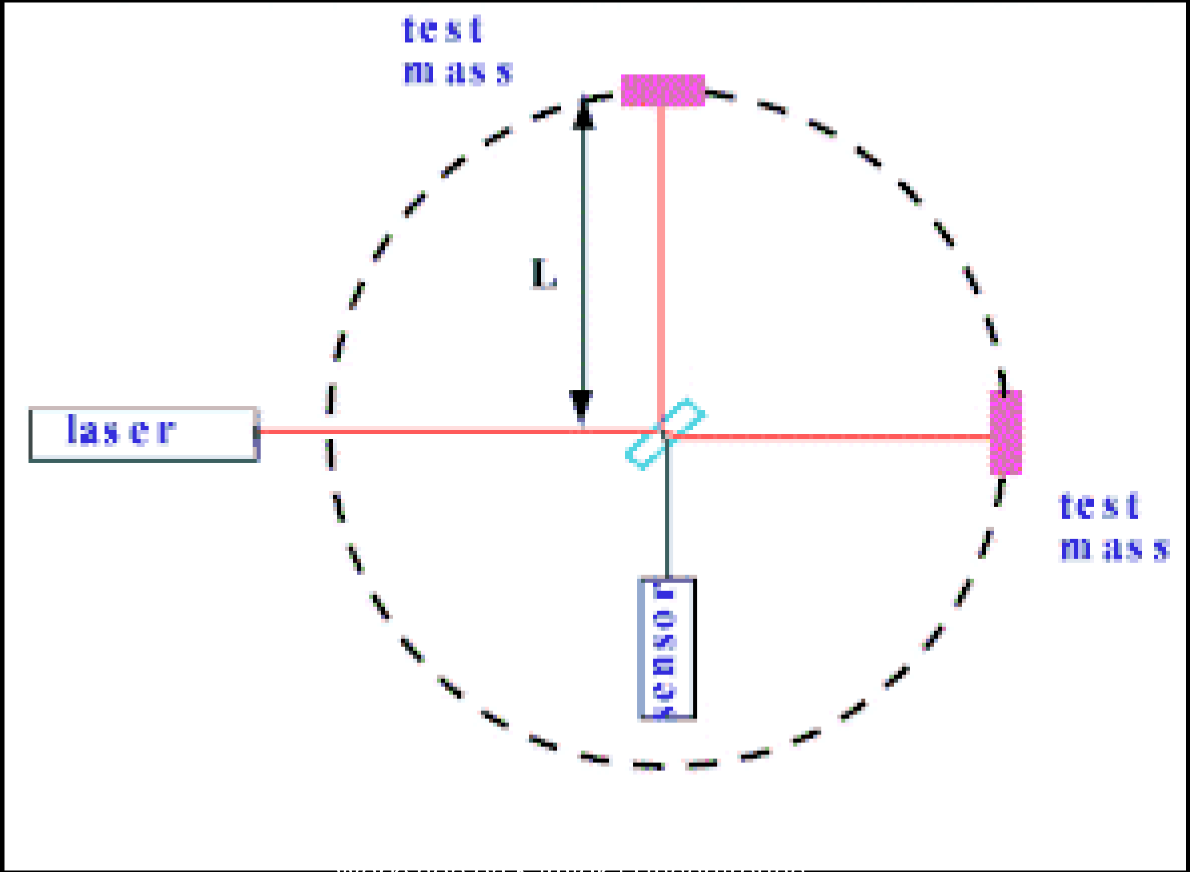
Gravitational waves

- 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



LIGO Sites


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


LIGO Construction Began in 1994

LIGO Interferometers

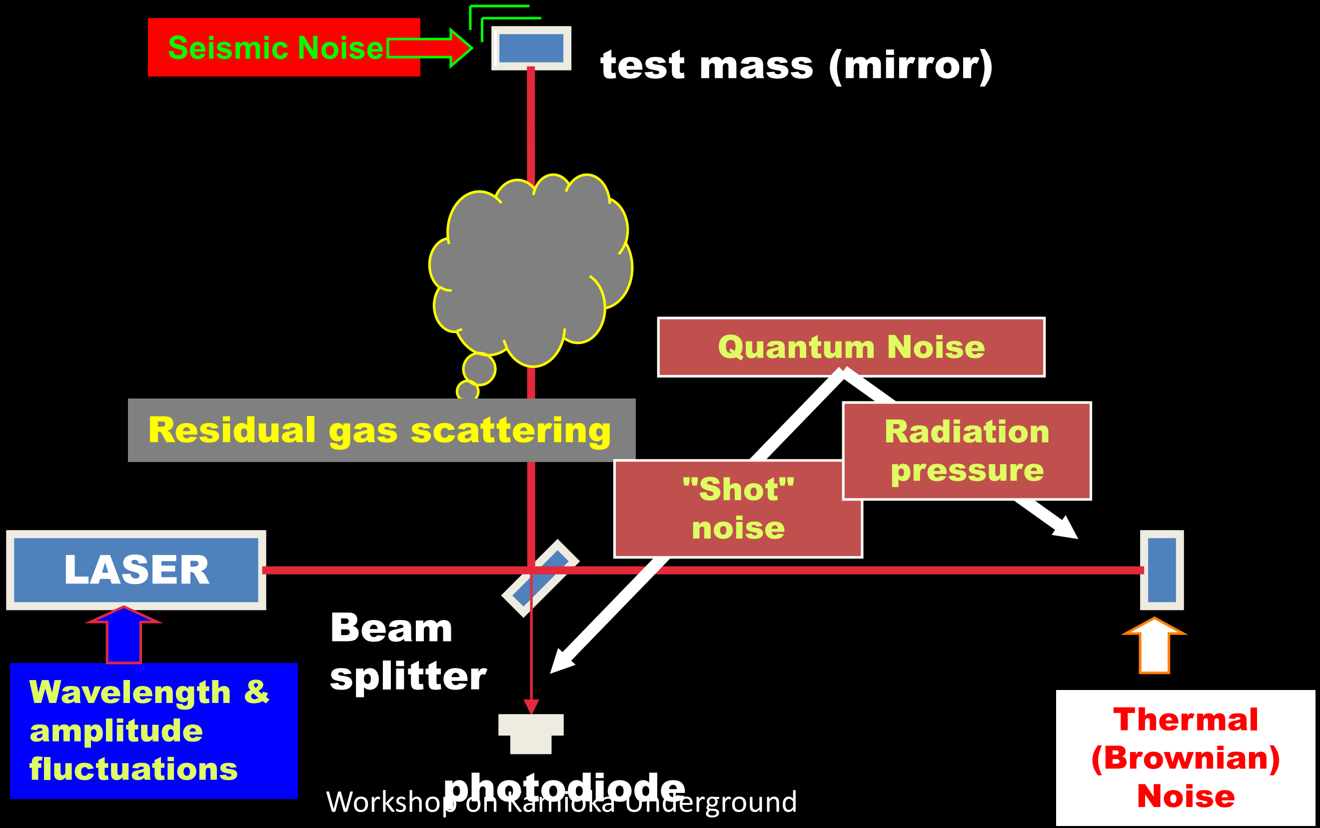
Hanford, WA

Livingston, LA

LIGO Infrastructure beam tube

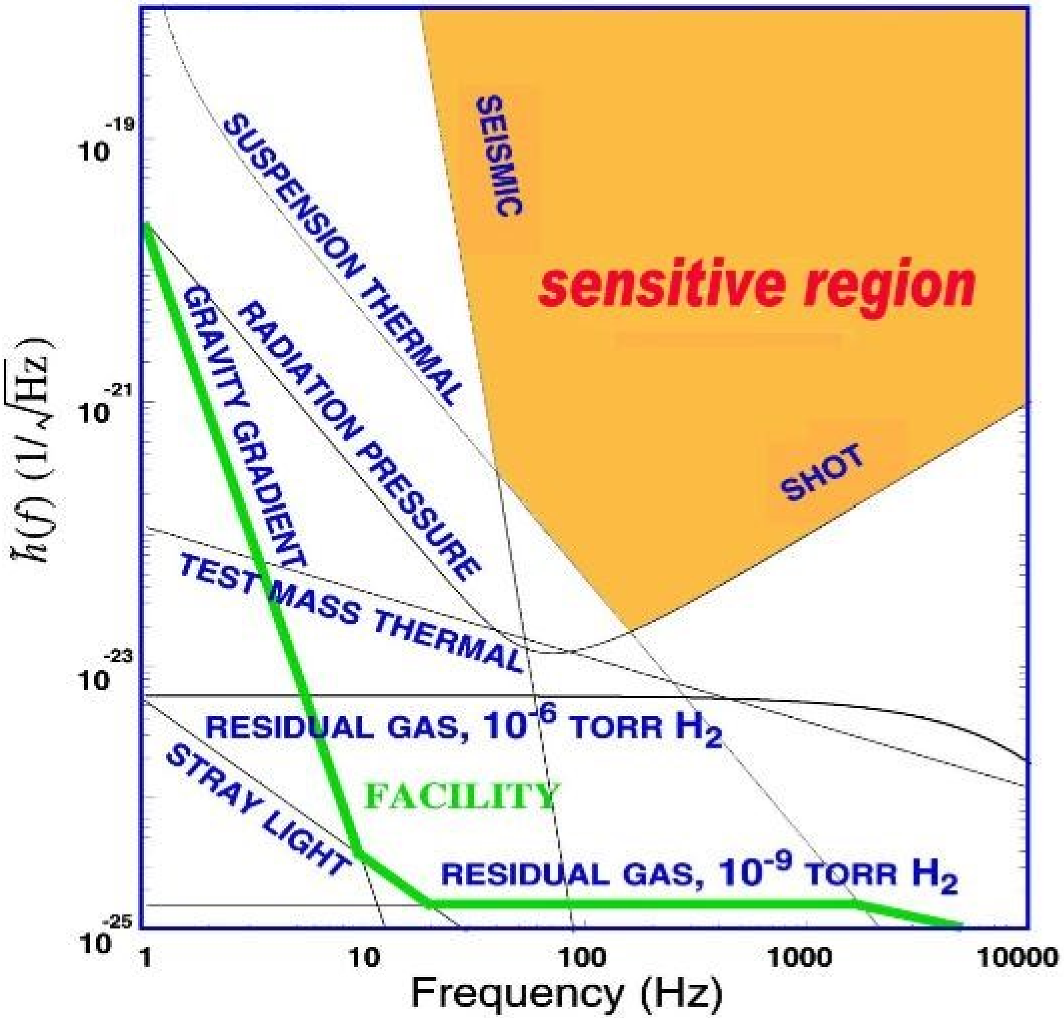
LIGO Interferometer Infrastructure

Interferometer Noise Limits

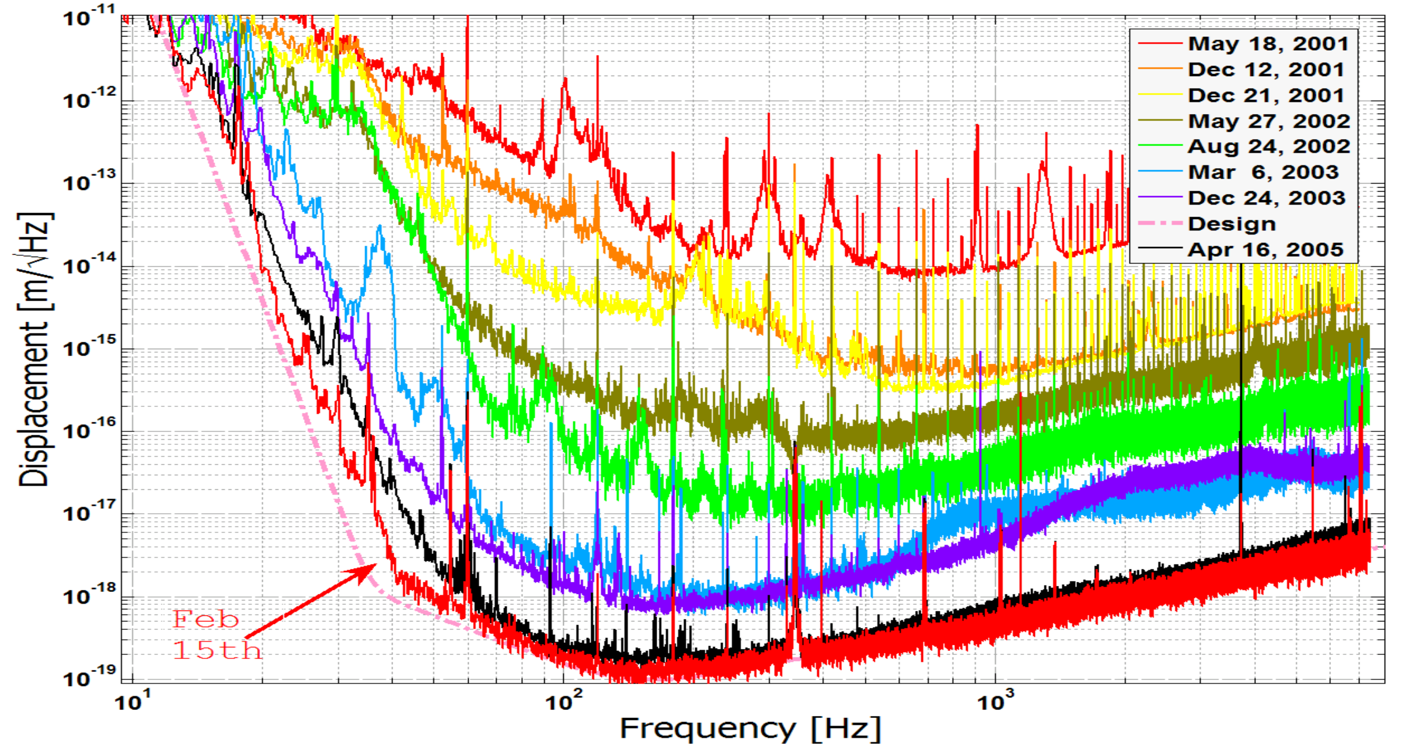


What Limits LIGO Sensitivity?

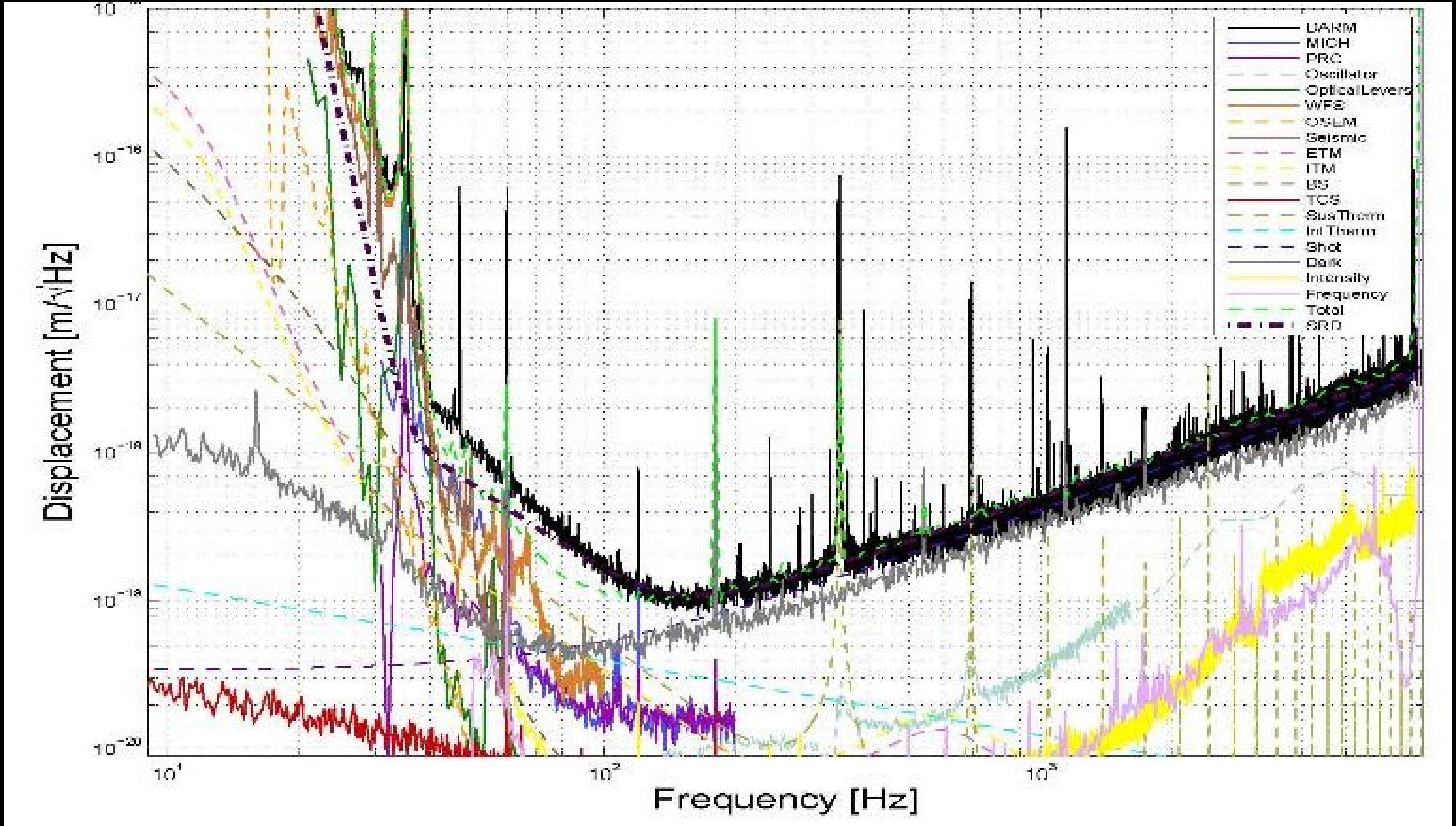
- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals



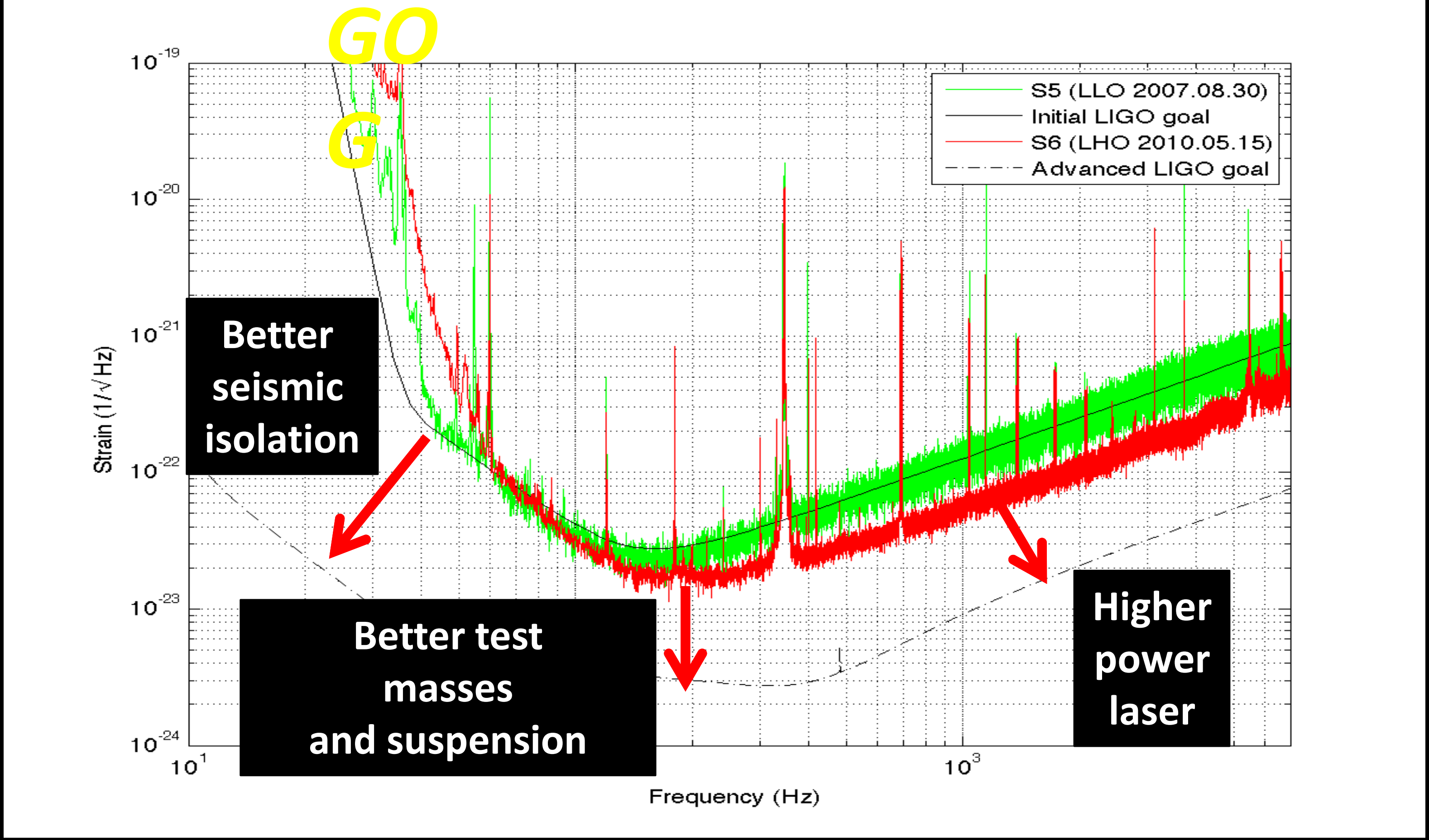
Evolution of LIGO Sensitivity



Initial LIGO Performance (Final)

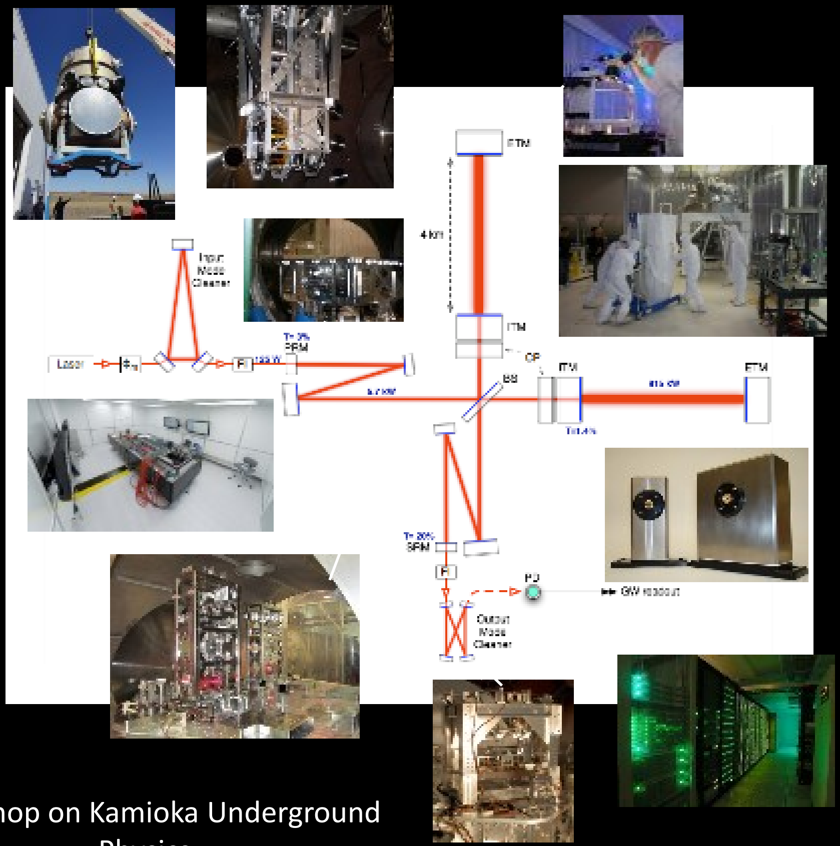


Advanced LIGO GOALS



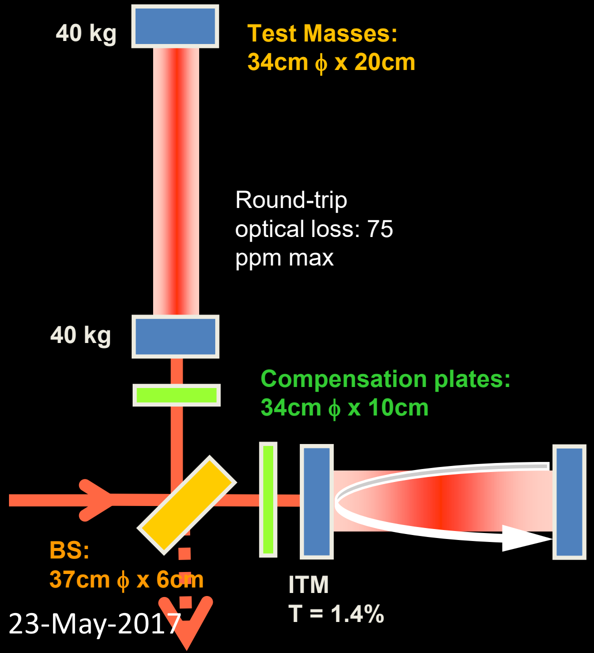
How to obtain a x10 sensitivity improvement?

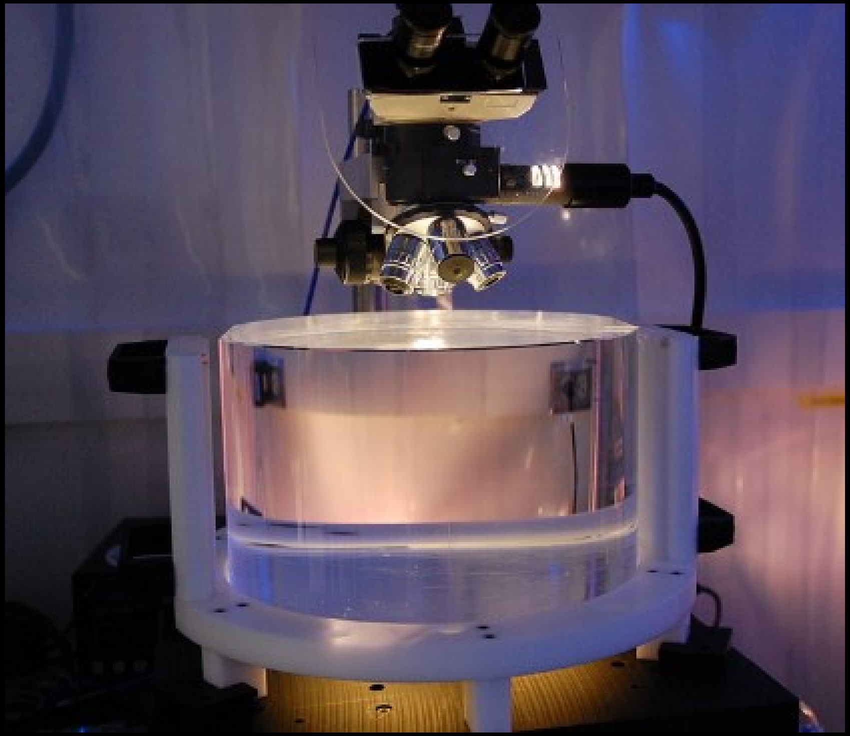
Parameter	*Initial LIGO*	*Advanced LIGO*
Input Laser Power	**10 W (10 kW arm)**	**180 W (>700 kW arm)**
Mirror Mass	**10 kg**	**40 kg**
Interferometer Topology	**Power-recycled Fabry-Perot arm cavity Michelson**	**Dual-recycled Fabry-Perot arm cavity Michelson (stable recycling cavities)**
GW Readout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

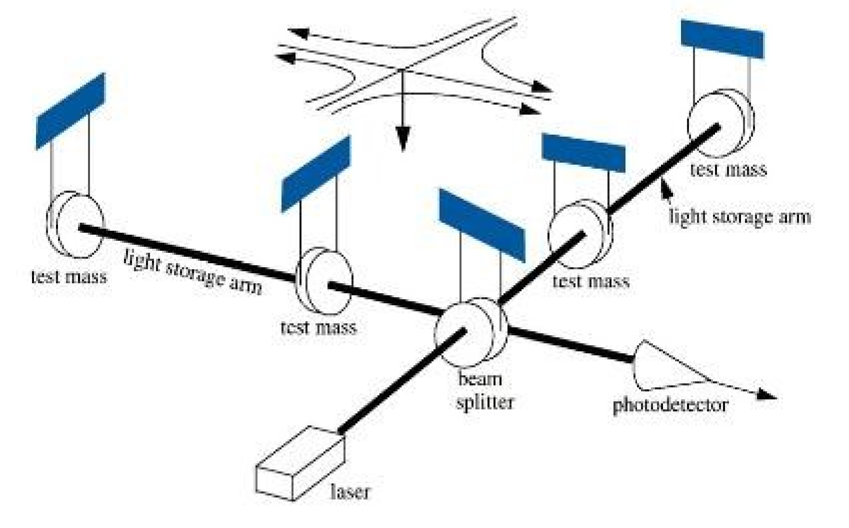


Mirror / Test Masses

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



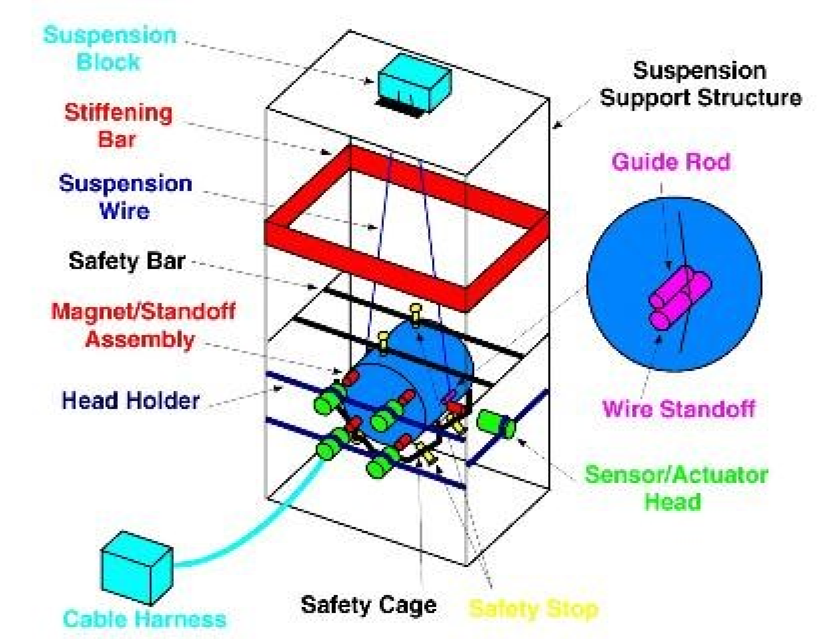




Seismic Isolation

suspension system

suspension assembly for a core optic



- support structure is welded tubular stainless steel
- suspension wire is 0.31 mm diameter steel music wire
- fundamental violin mode frequency of 340 Hz

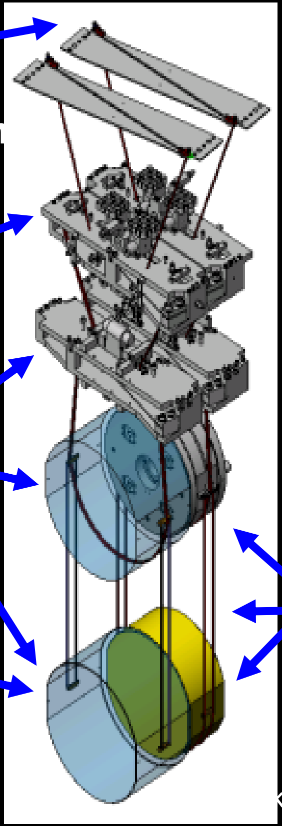
Test Mass
Quadruple Pendulum Suspension

Optics Table Interface
(Seismic Isolation Systen

Damping Controls

Hierarchical Global
Controls

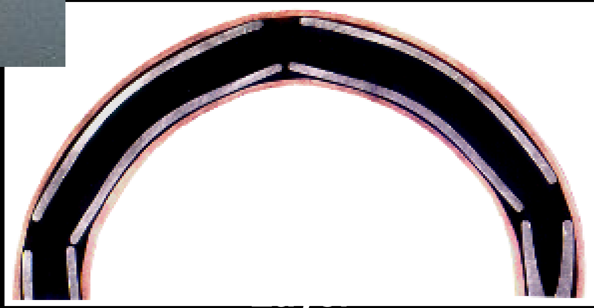
Electrostatic
Actuation



Final elements
All Fused silica

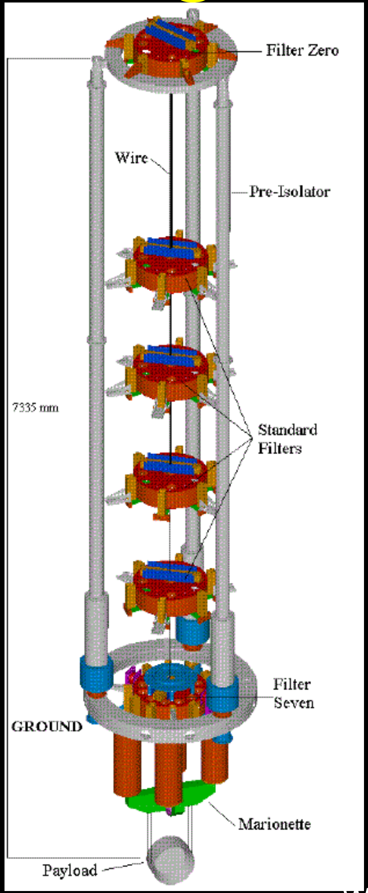
Passive Seismic Isolation

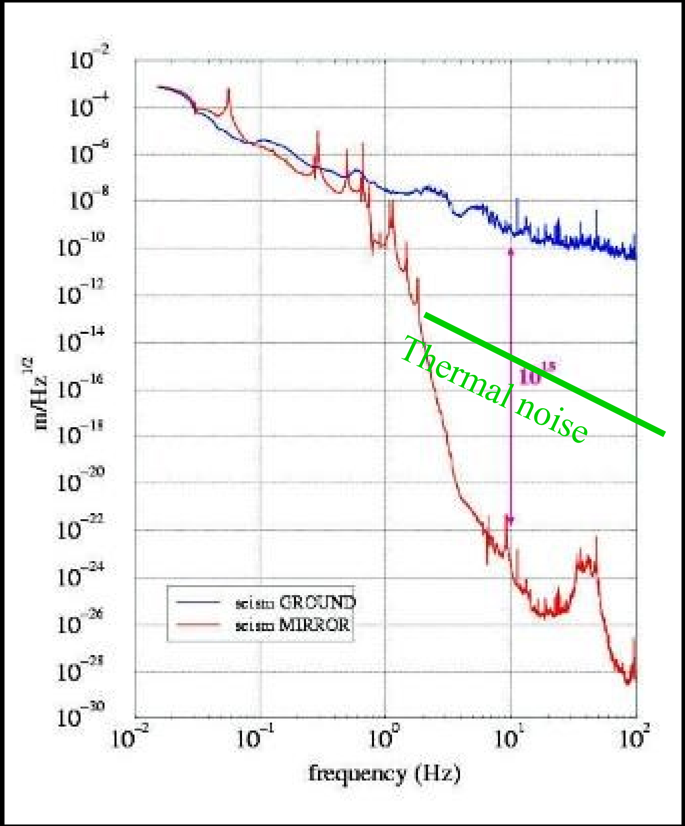
Initial ILIGO



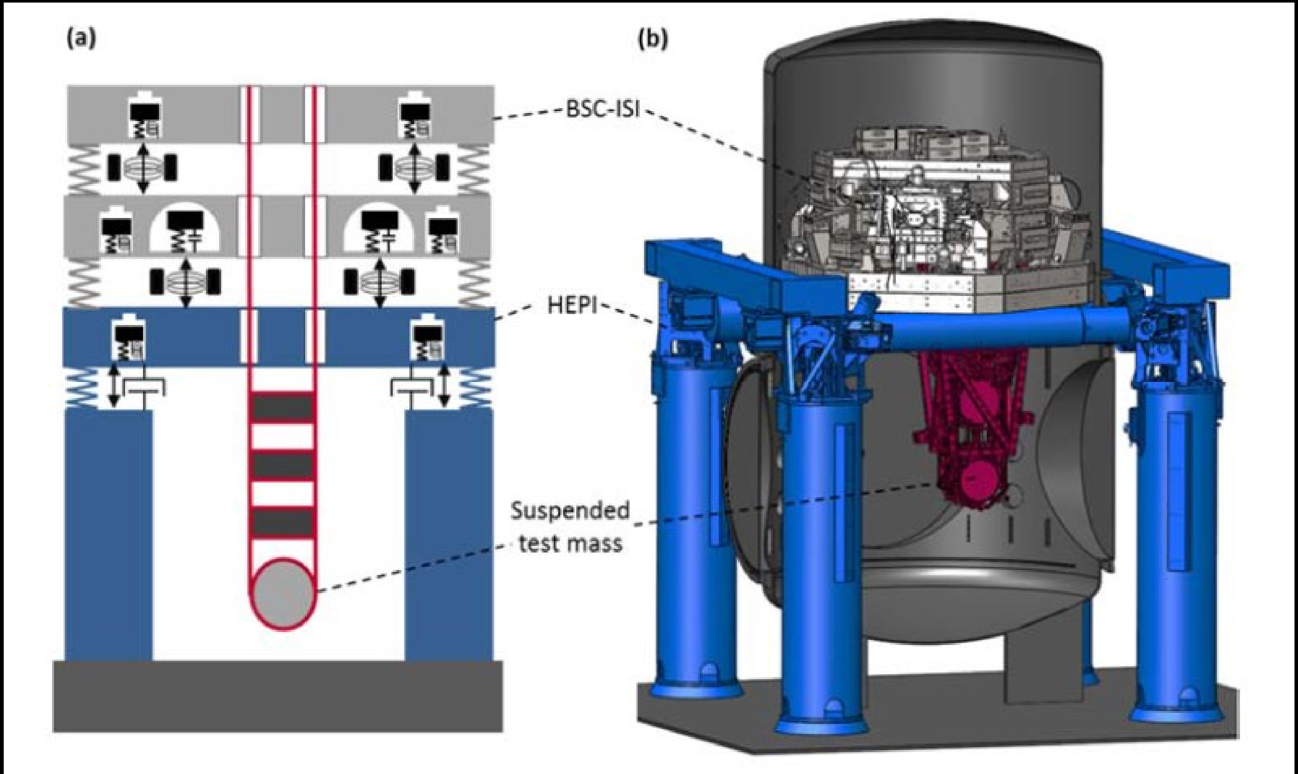
damped spring

Virgo Seismic Performance



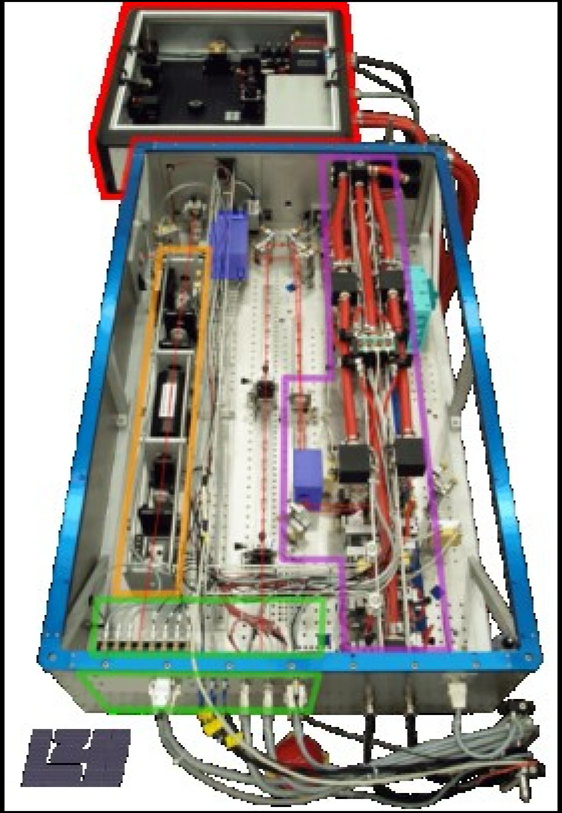


Seismic Isolation
Passive / Active Multi-Stage



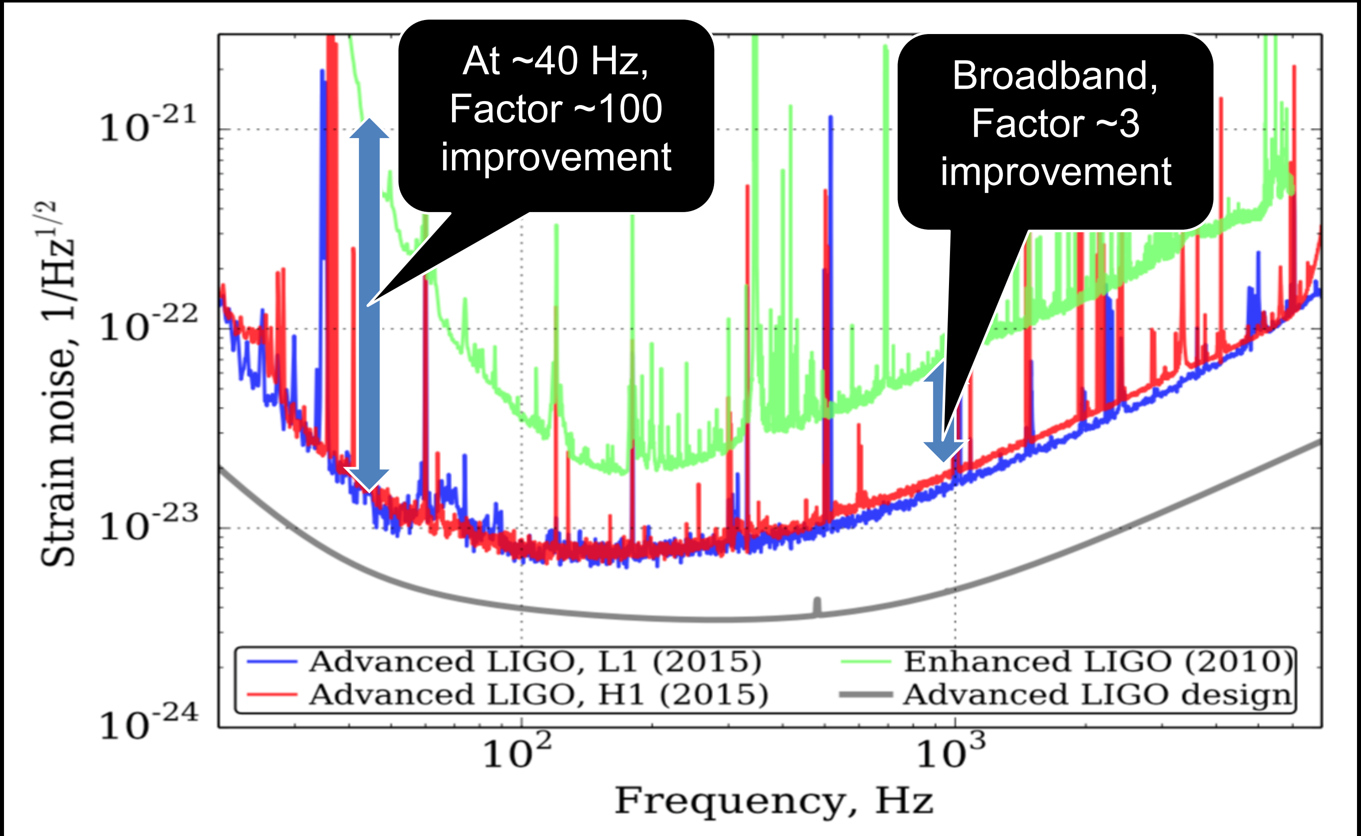
200W Nd:YAG laser

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**

Sensitivity for first Observing run



Initial LIGO

O1 aLIGO

Design aLIGO

Phys. Rev. D 93, 112004 (2016

Gravitational Wave Event

GW150914

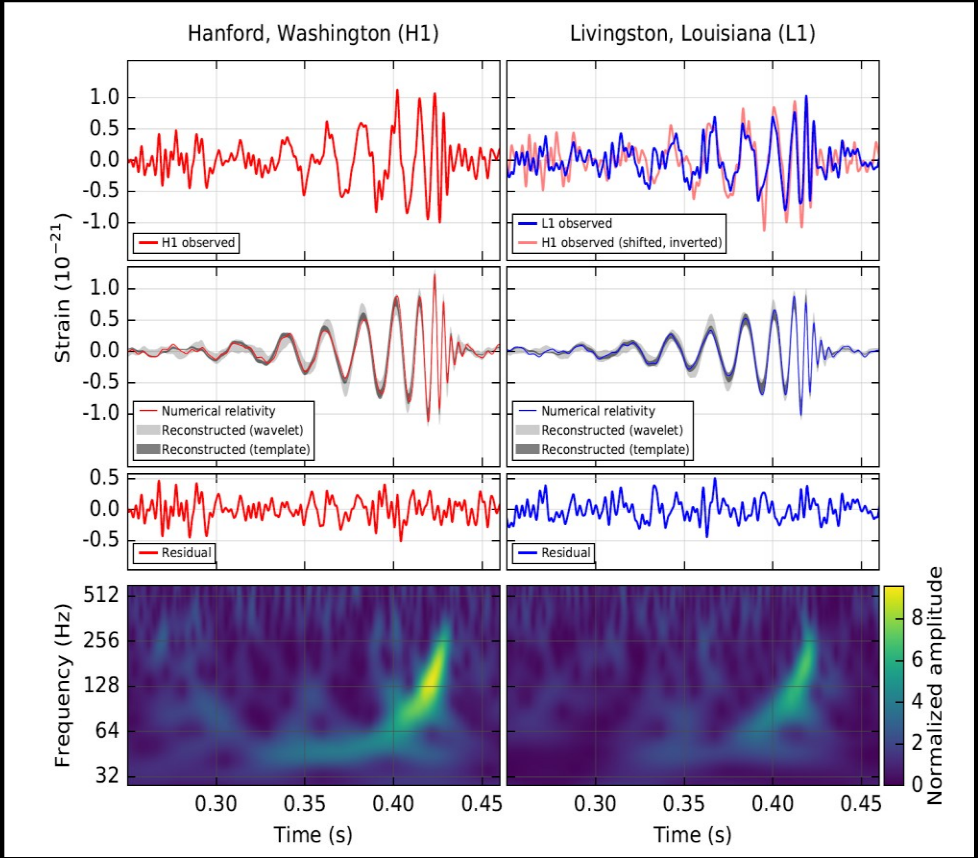
Data bandpass filtered between 35 Hz and 350 Hz

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)

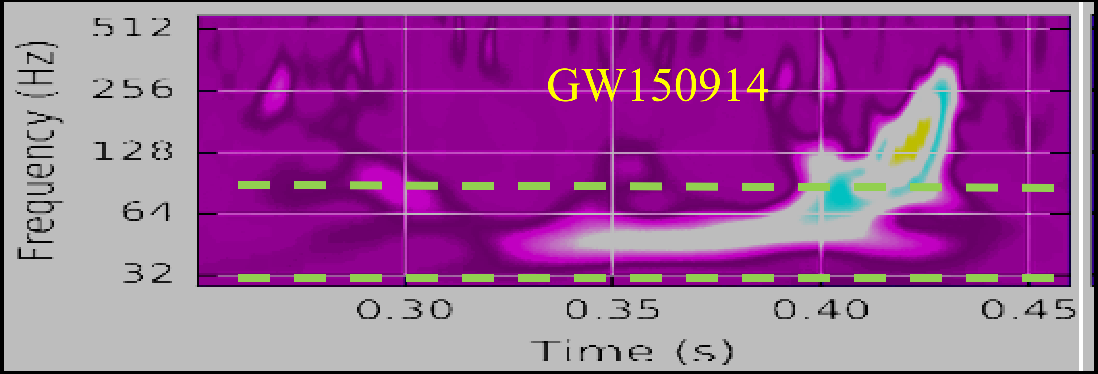
Third Row –residuals

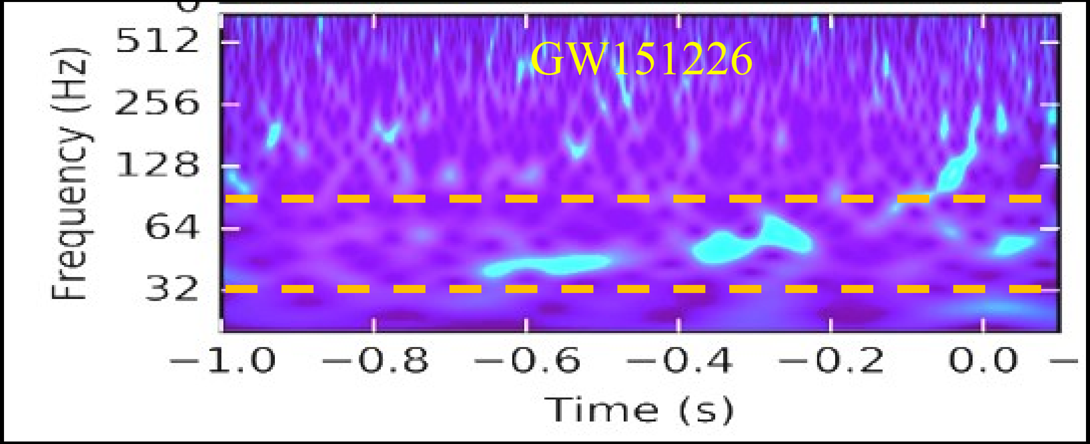
bottom row – time frequency plot showing frequency increases with time (chirp)



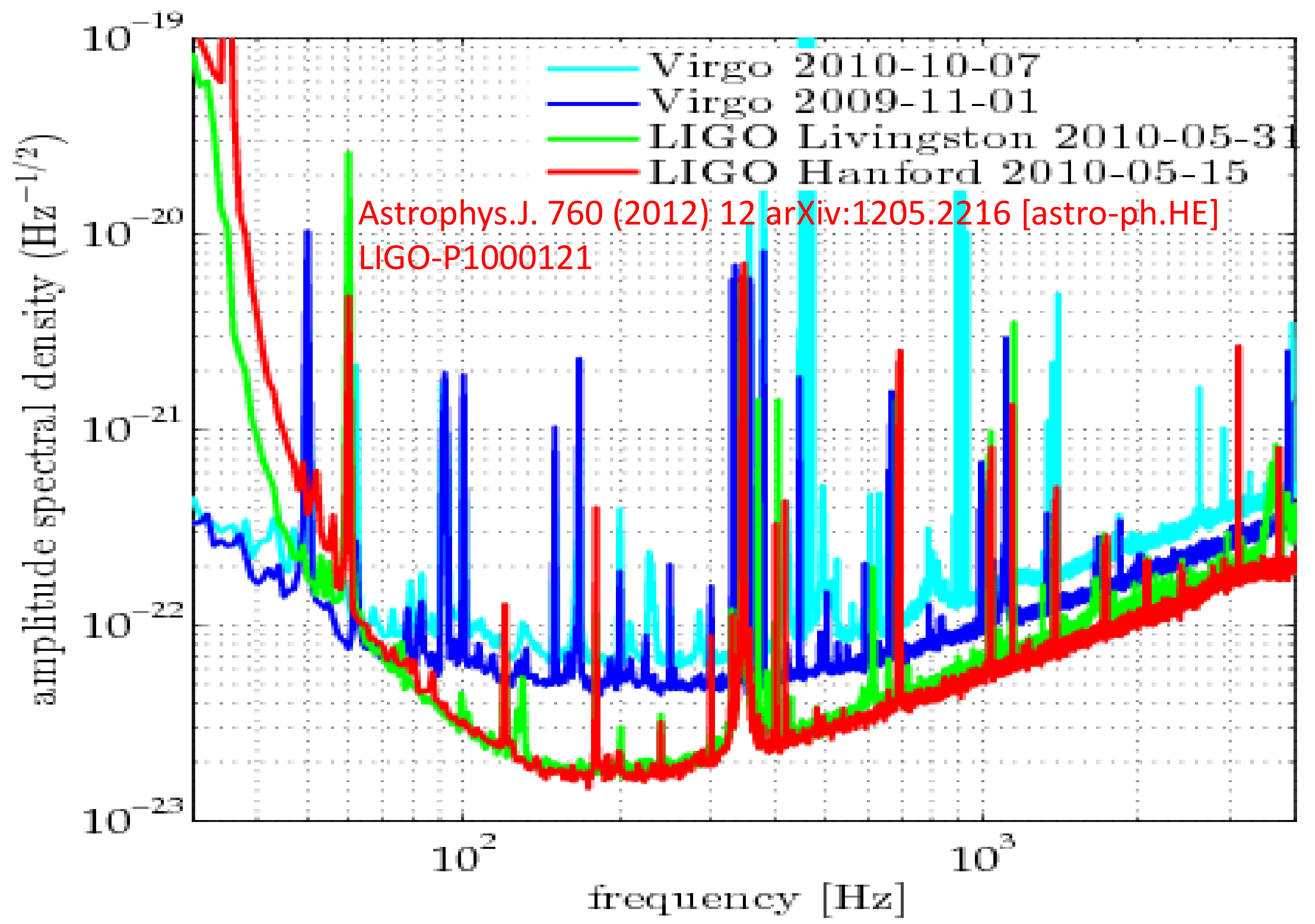
Phys. Rev. Lett. 116, 061102 (2016)

Black Hole Merger Events and Low Frequency Sensitivity

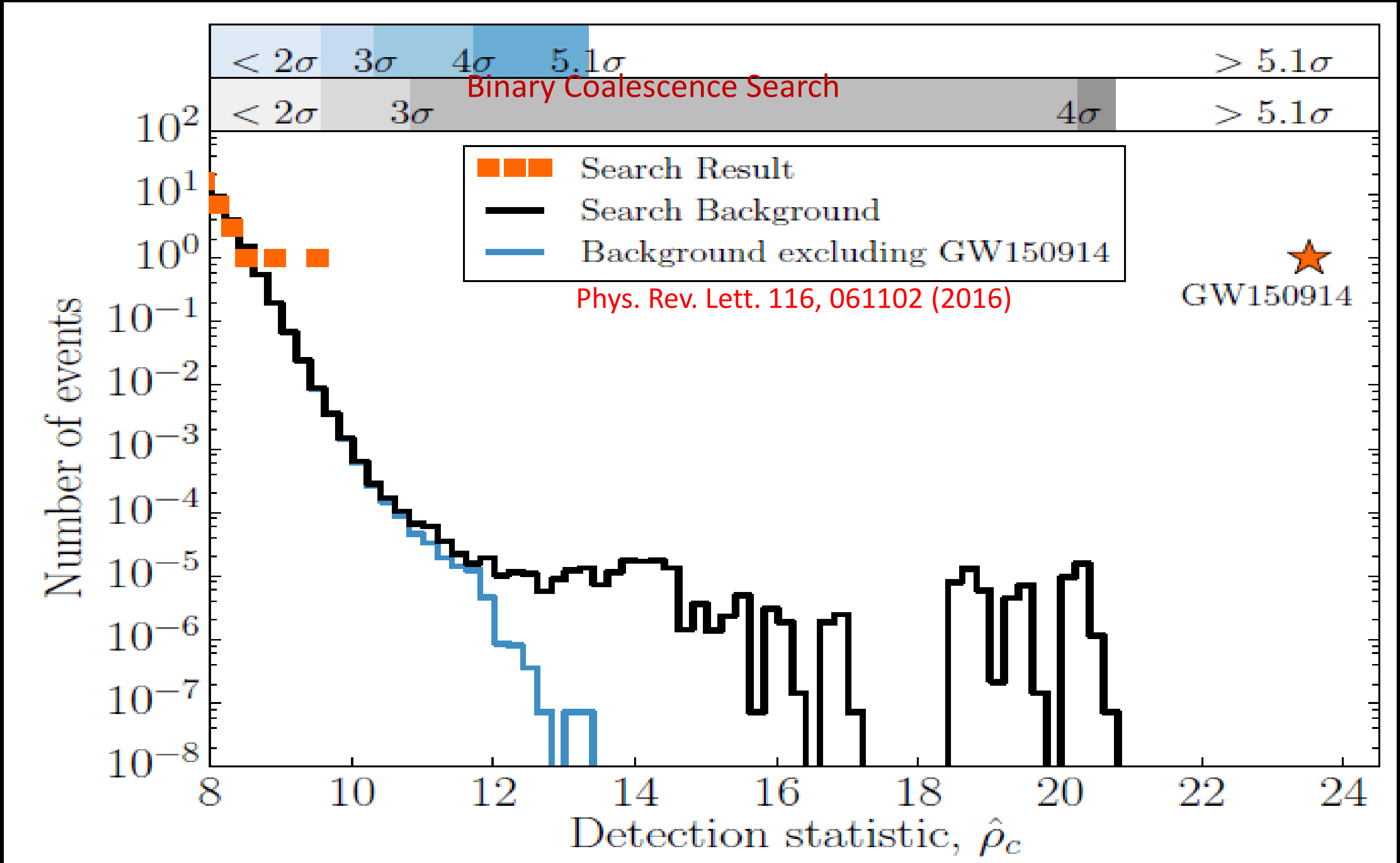




Sensitivity of Initial LIGO-Virgo



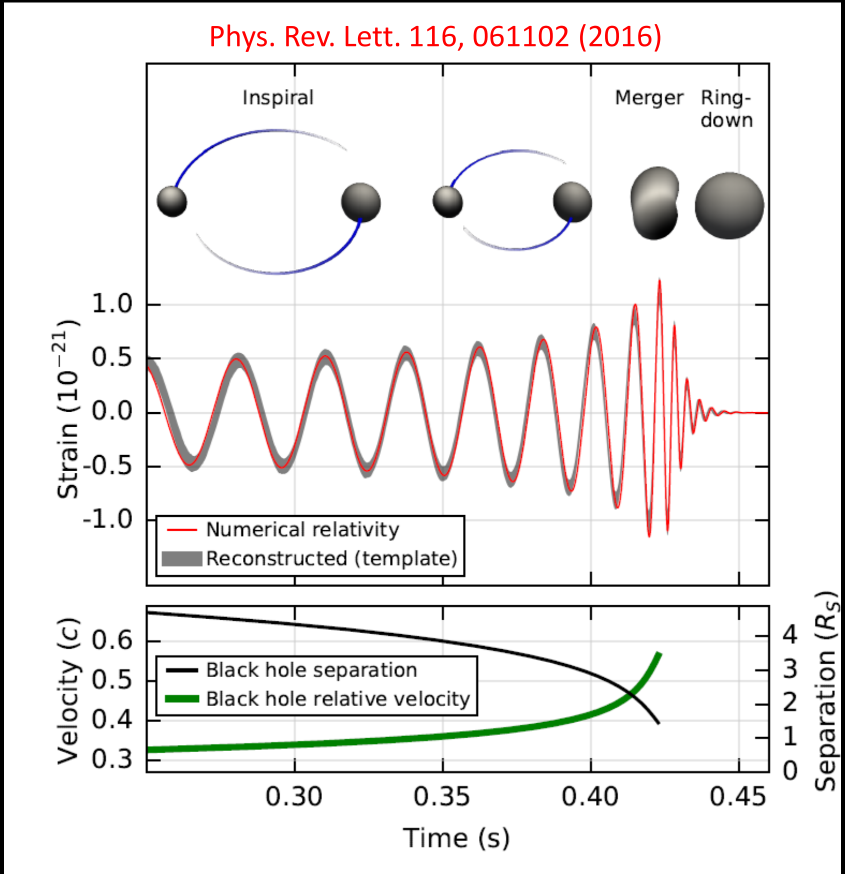
Statistical Significance of GW150914



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



Measuring the parameters

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

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

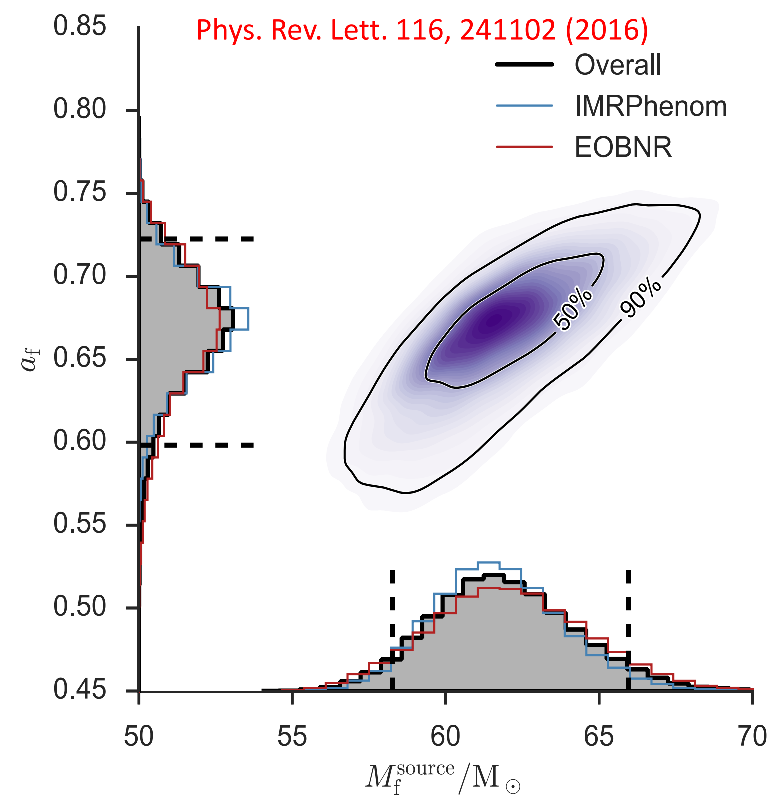
  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.
- Sky location,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

Black Hole Merger Parameters for GW150914

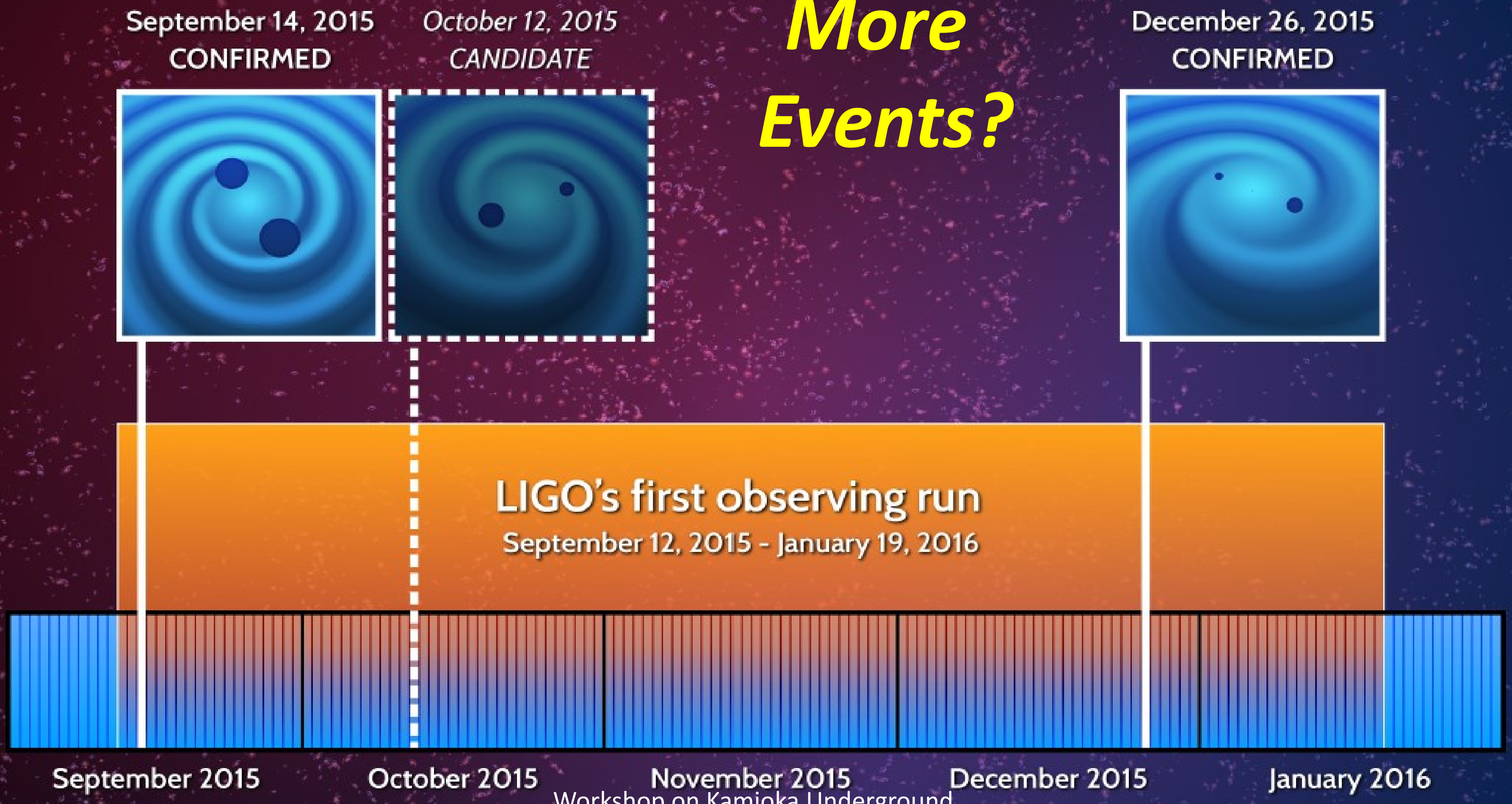
- Use numerical simulations fits of black hole merger to determine parameters; determine total energy radiated in gravitational waves is 3.0±0.5 $M_o c^2$. The system reached a peak ~3.6 x10^{56} ergs, and the spin of the final black hole < 0.7 (not maximal spin)

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)

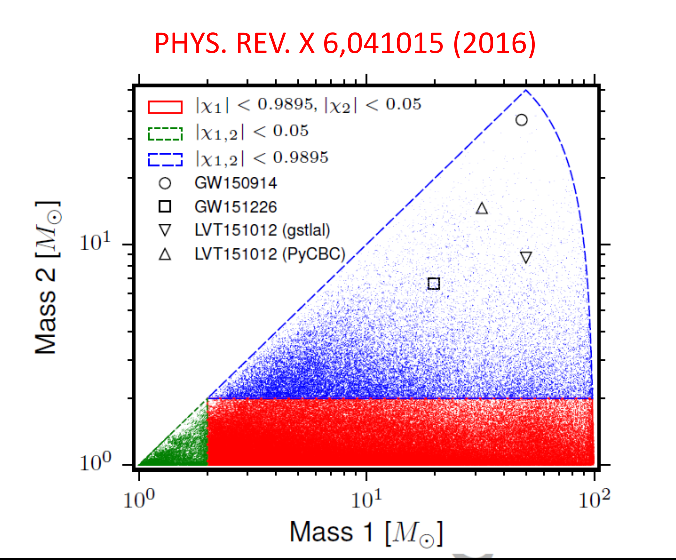


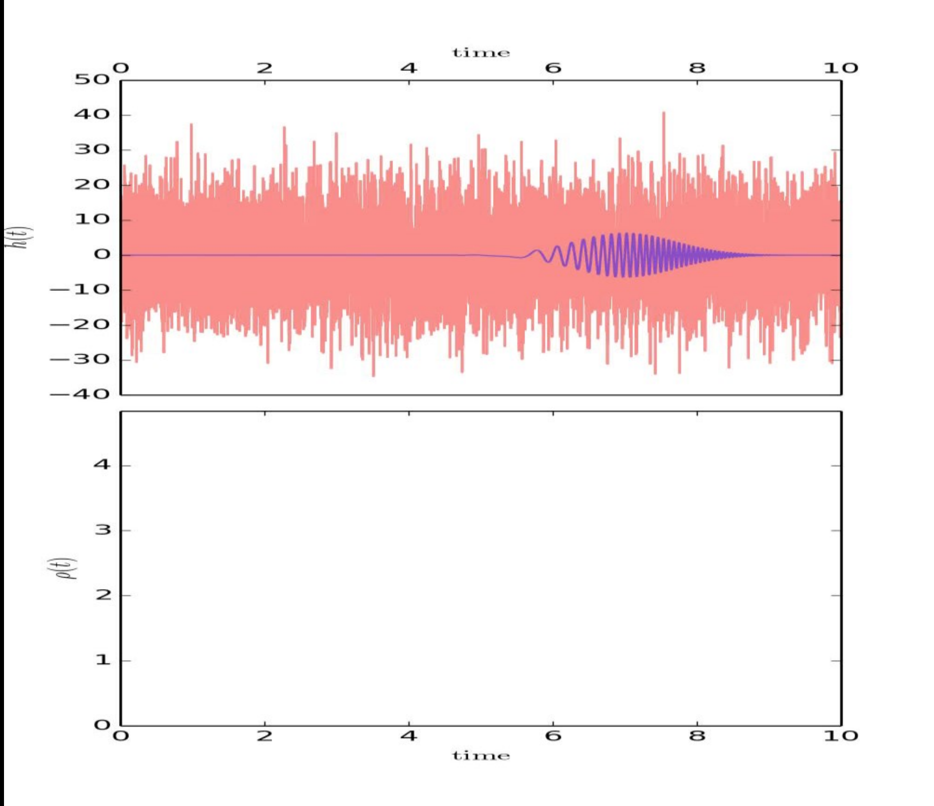
More Events?


September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

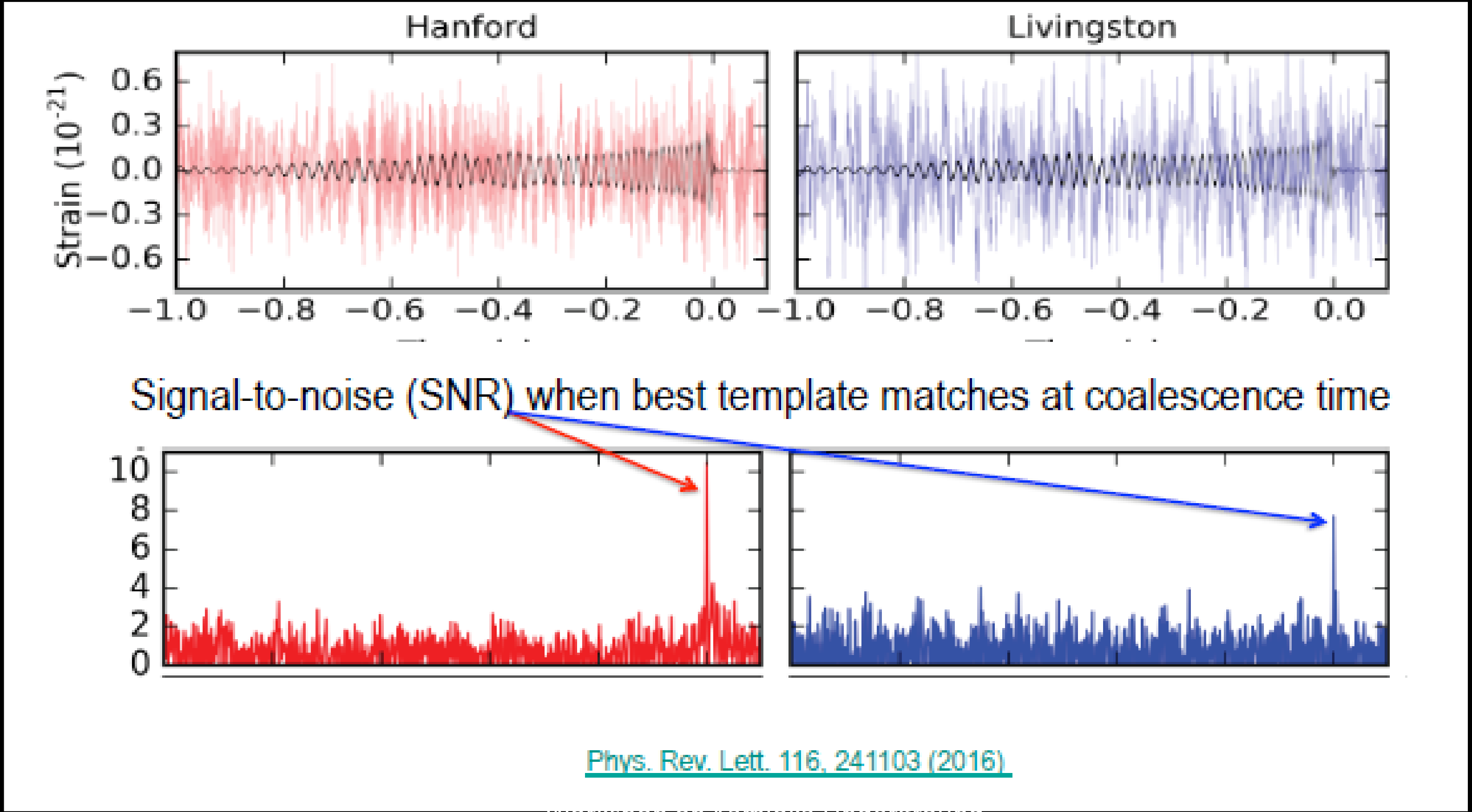
Finding a weak signal in noise

- "Matched filtering" lets us find a weak signal submerged in noise.
- For calculated signal waveforms, multiply the waveform by the data
- Find signal from cumulative signal/noise

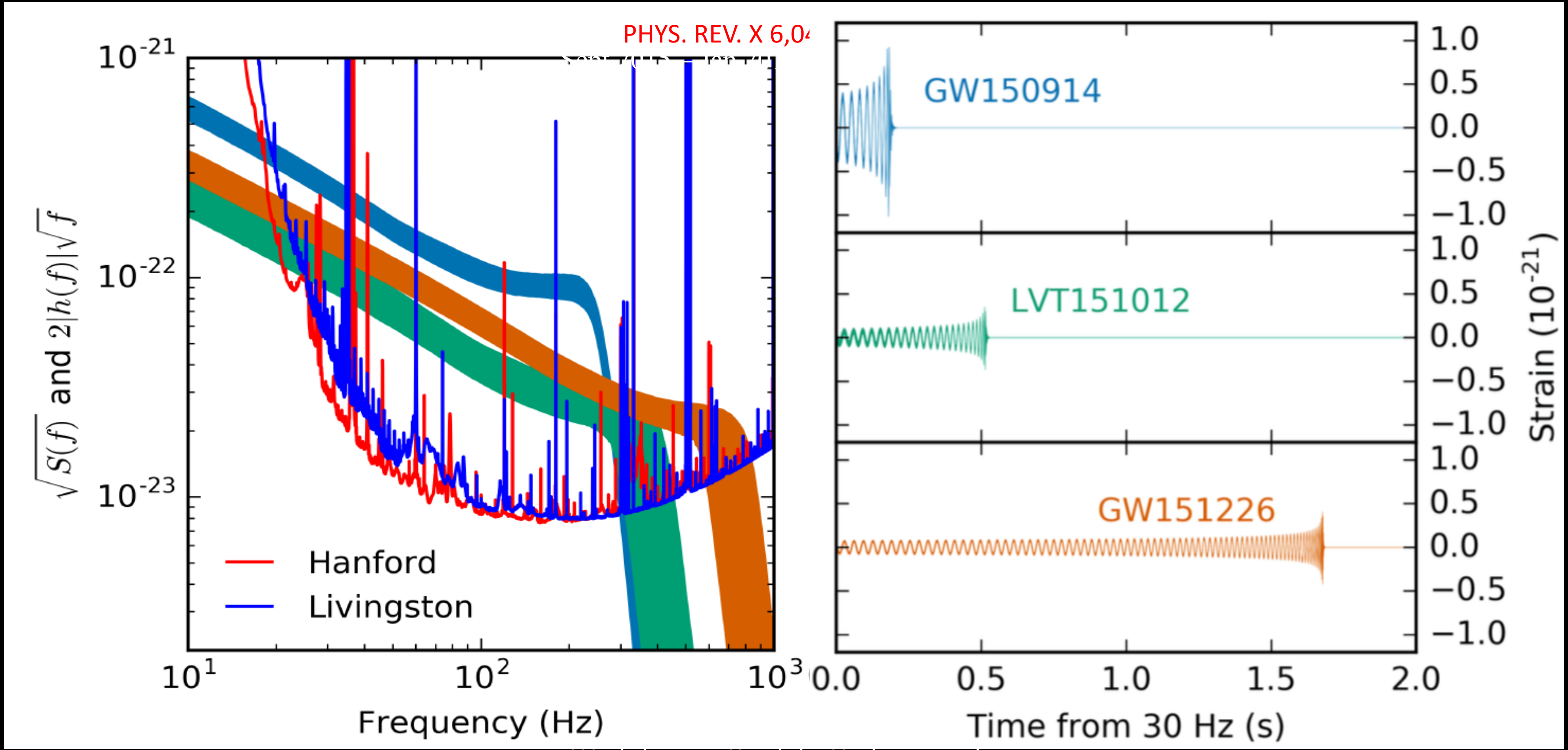




GW151226 – Matched Filter



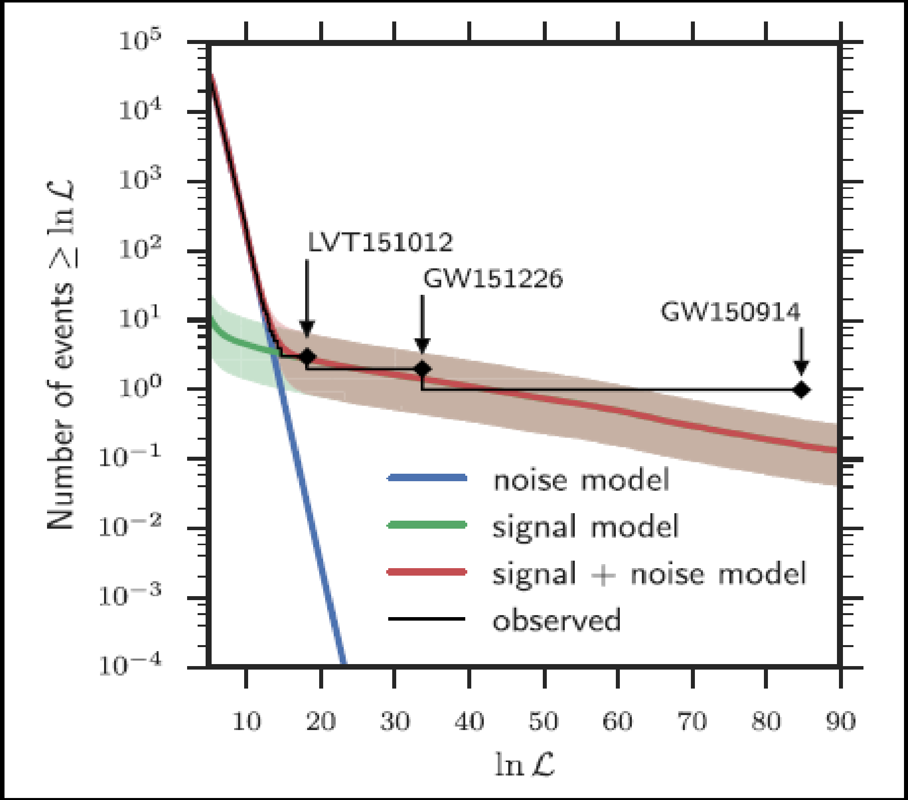
Second Event, Plus another Candidate



Sensitivity

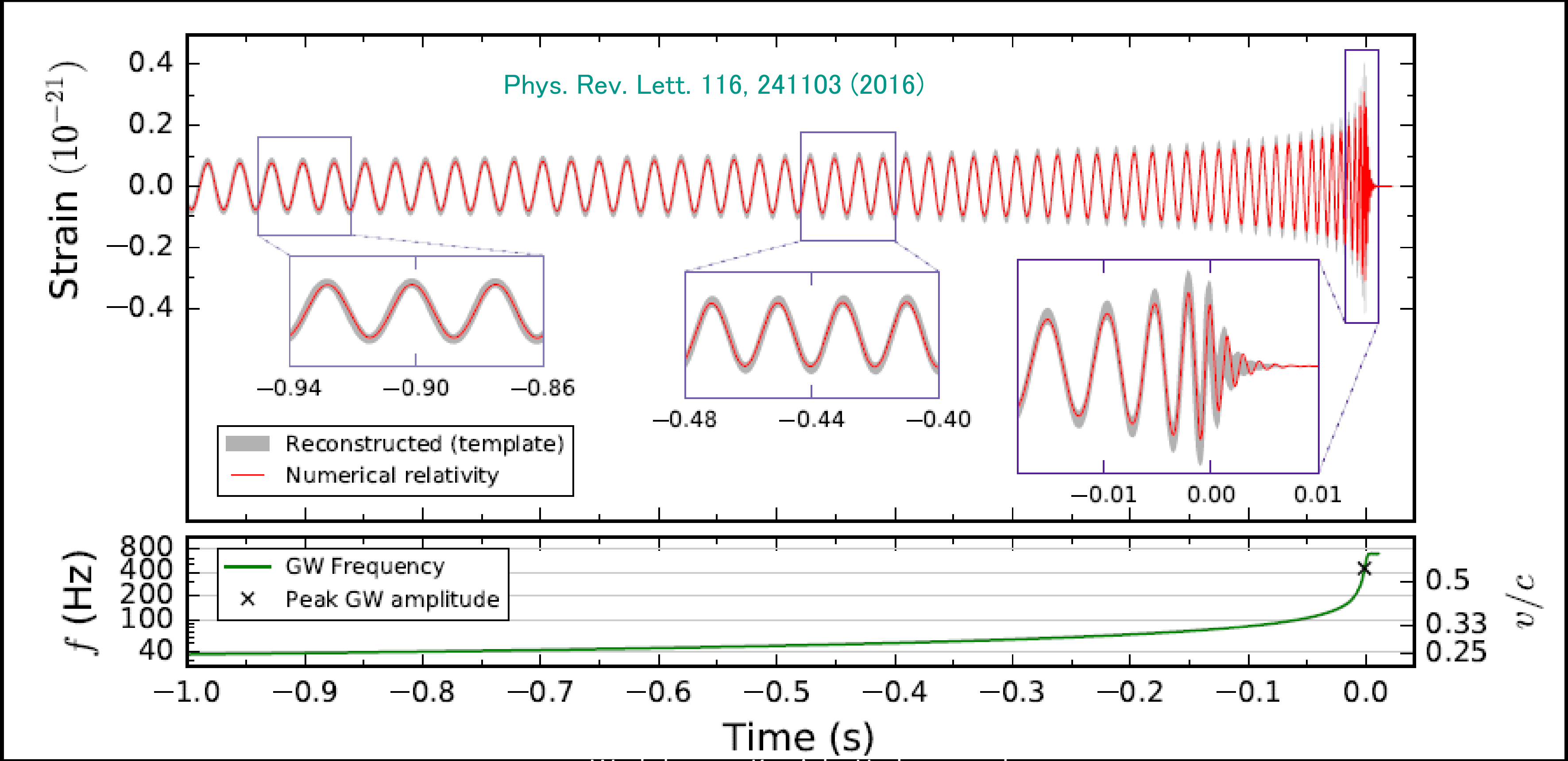
Lessons from LIGO O1

- Steep drop in false alarm rate versus size means edge of observable space is very sharp
  - » Very far out on tail of noise due to need to overcome trials factor

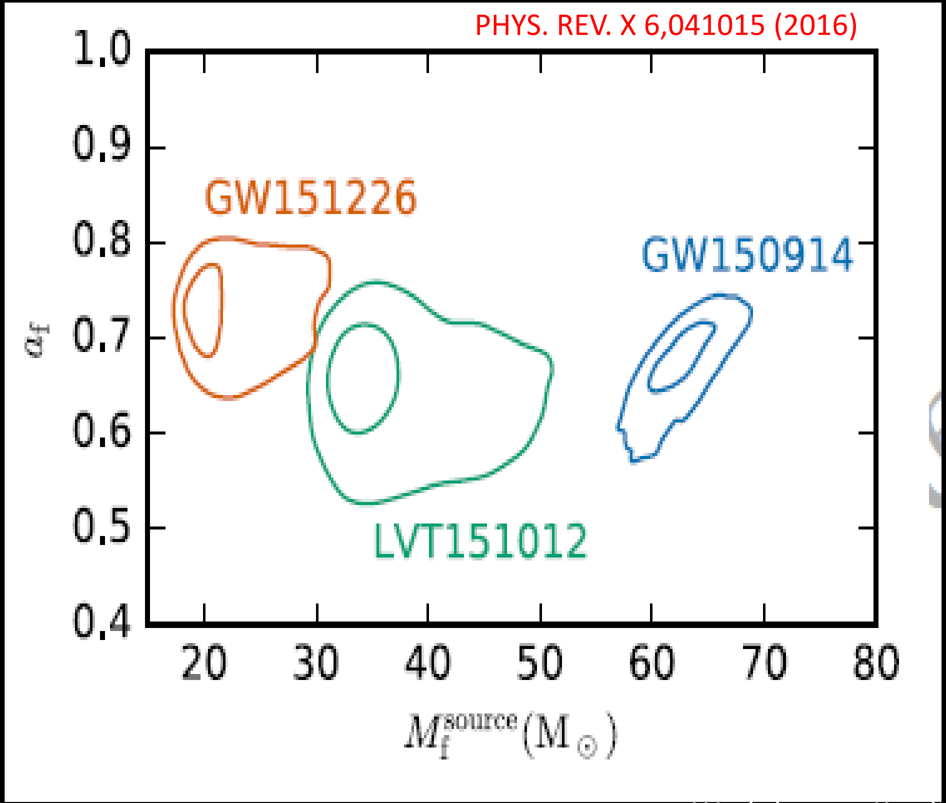


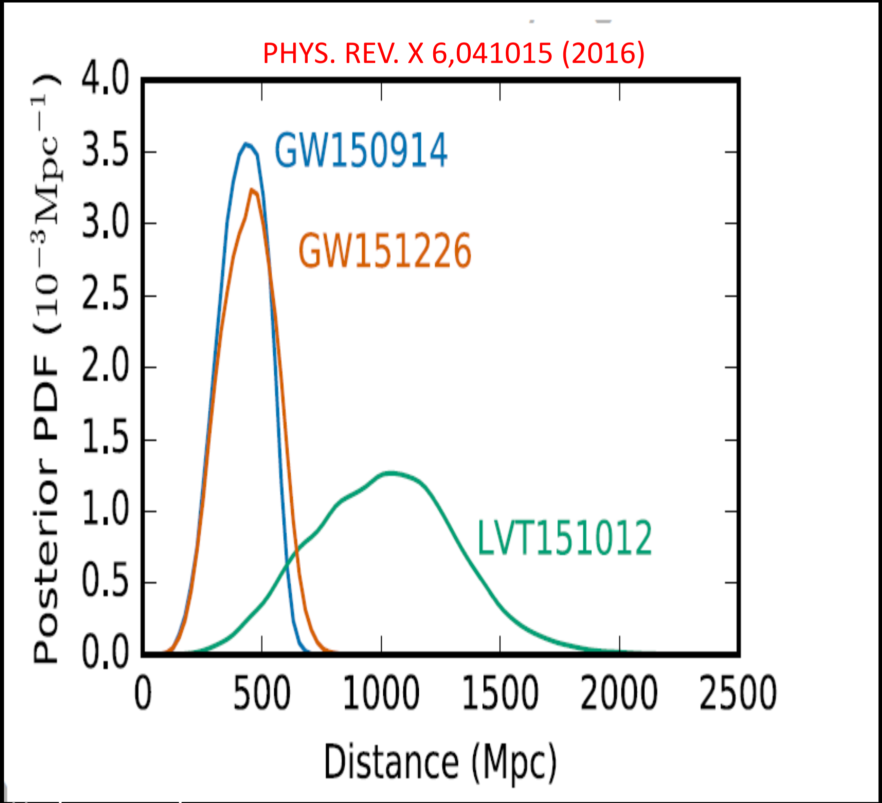
O1 BBH Search

"Second Event" Inspiral and Merger GW151226



Final Black Hole Masses, Spins and Distance





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.

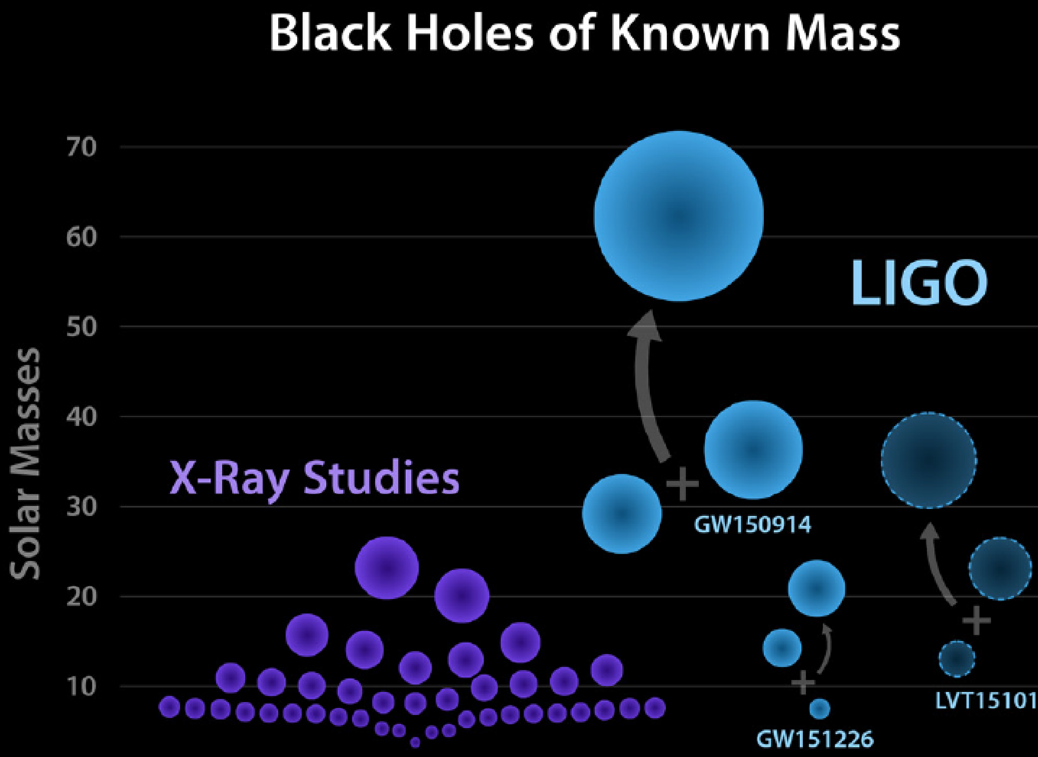
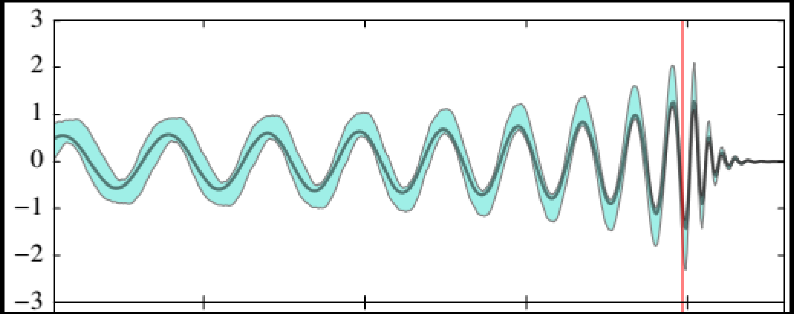
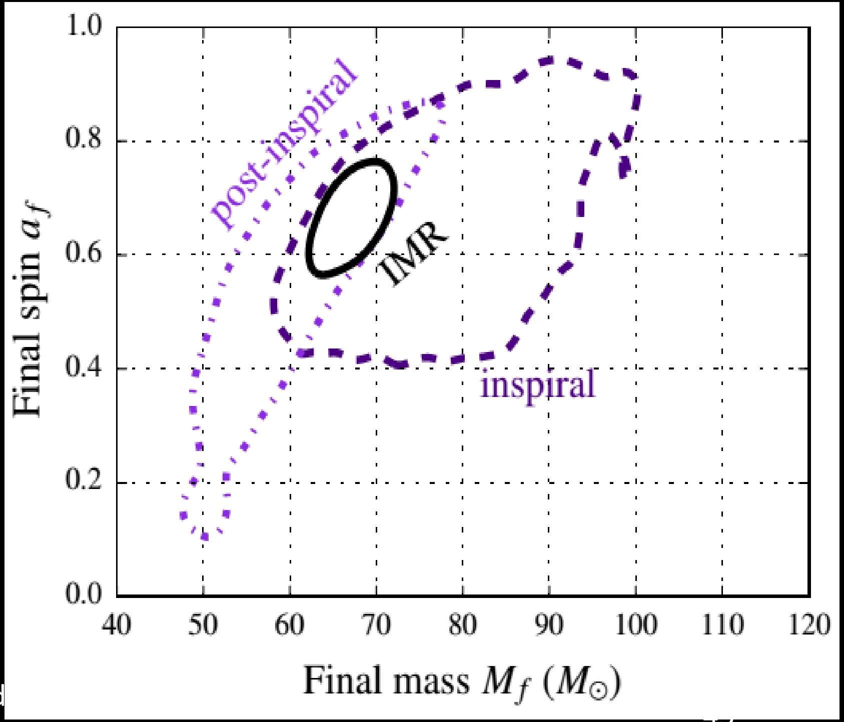


Image credit: LIGO

Testing General Relativity

- We examined the detailed waveform of GW150914 in several ways to see whether there is any deviation from the GR predictions
  - Known through post-Newtonian (analytical expansion) and numerical relativity
- Inspiral / merger / ringdown consistency test
  - Compare estimates of mass and spin from before vs. after merger

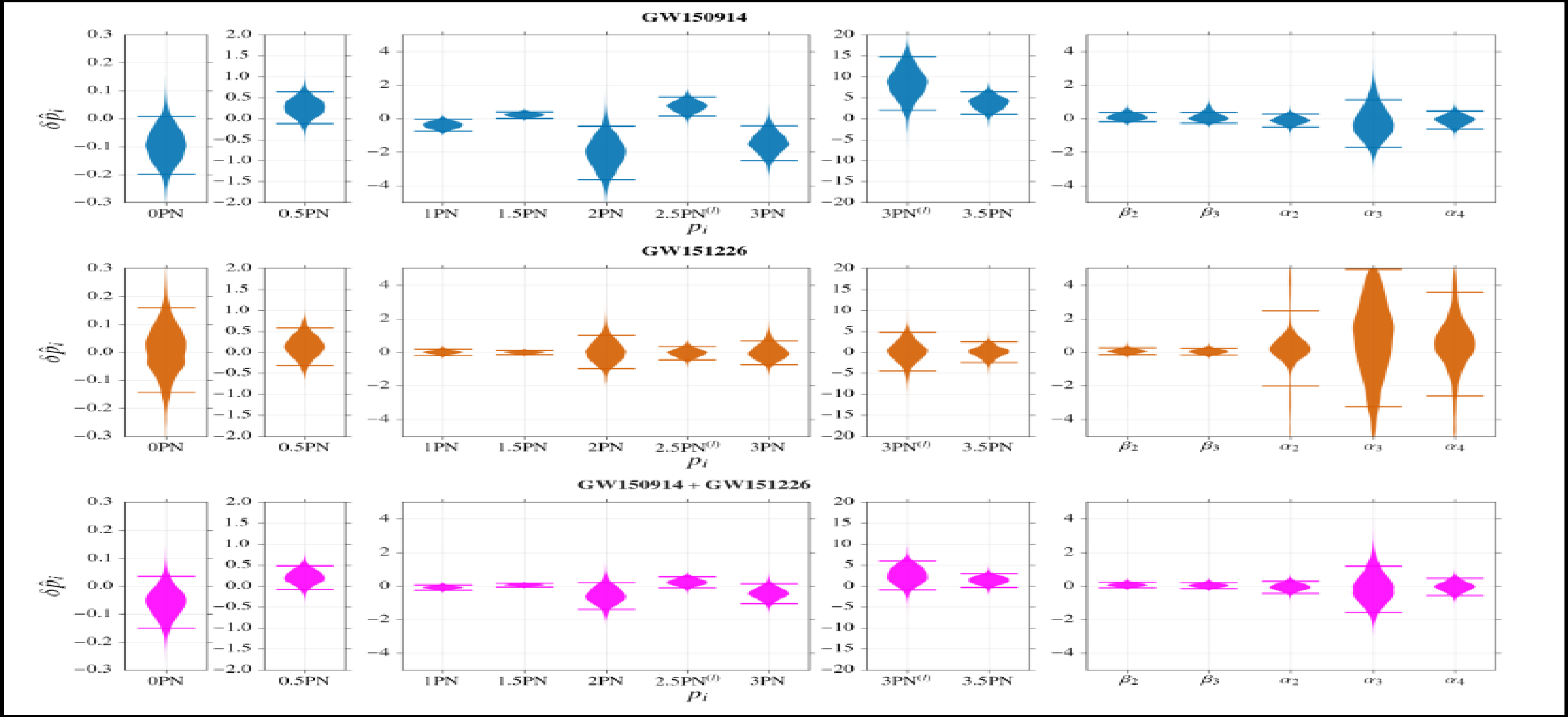




- Pure ringdown of final BH?
  - Not clear in data, but consistent

PRL 116, 221101 (2016)

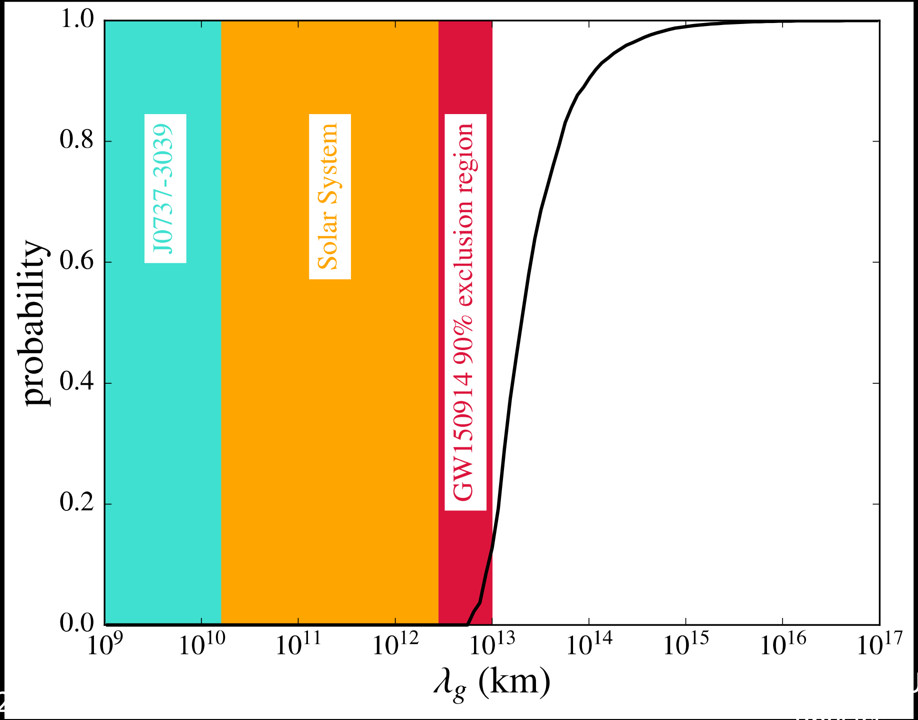
Testing General Relativity – Both Events



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



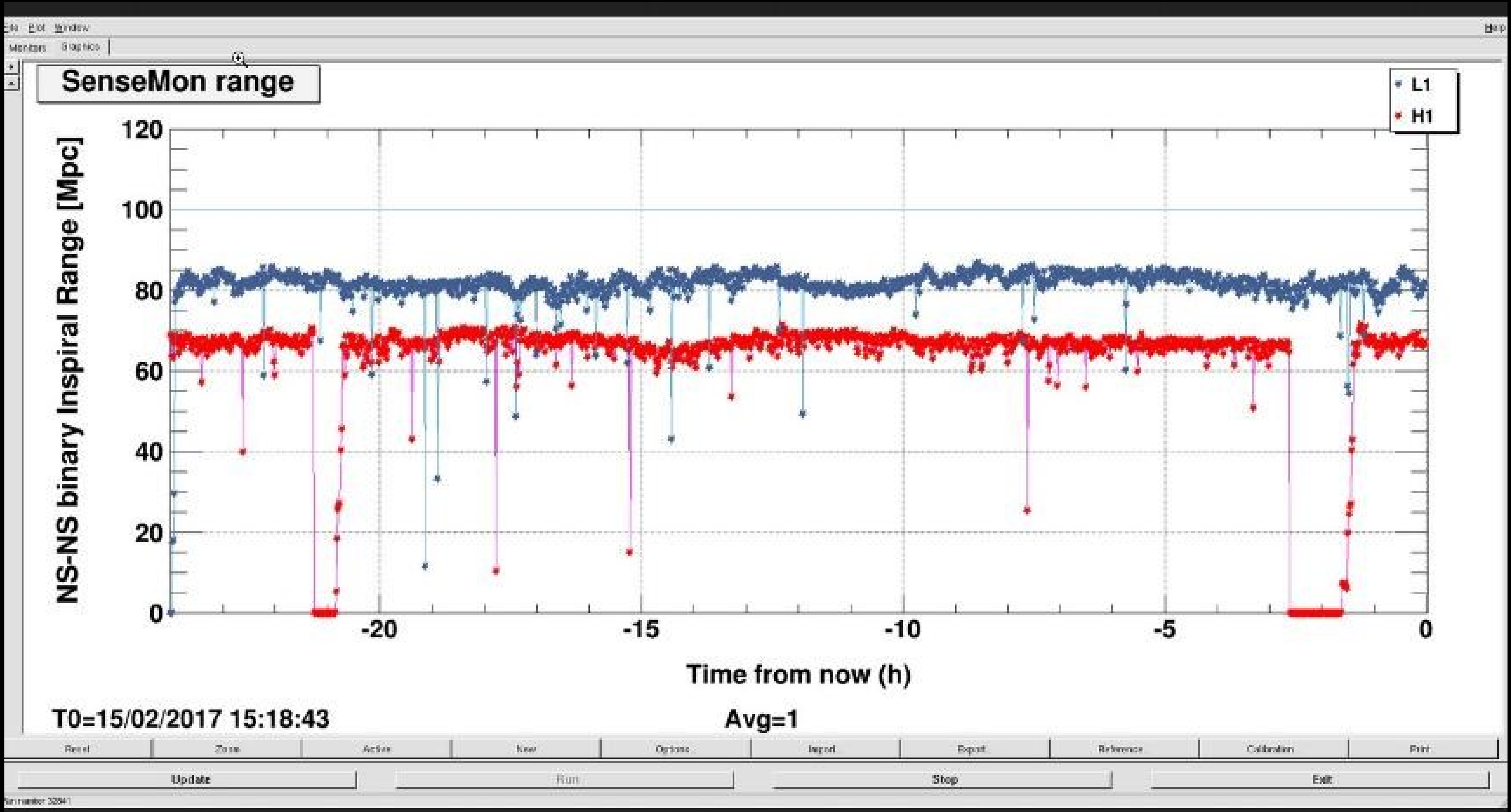
$$\lambda_g > 10^{13}\ \mathrm{km}$$

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

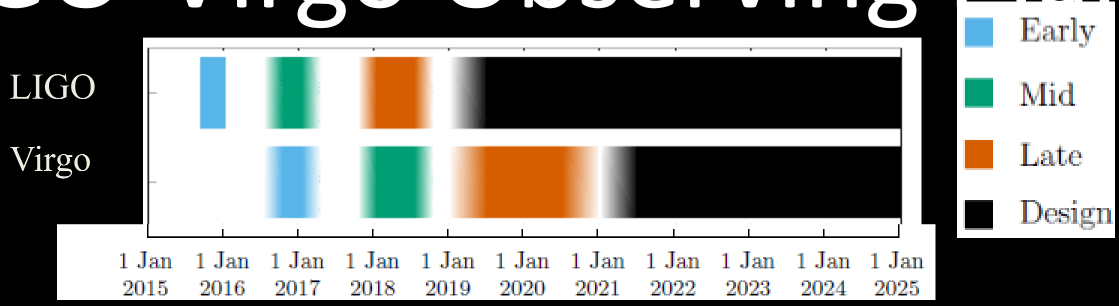
LIMIT 90% Confidence

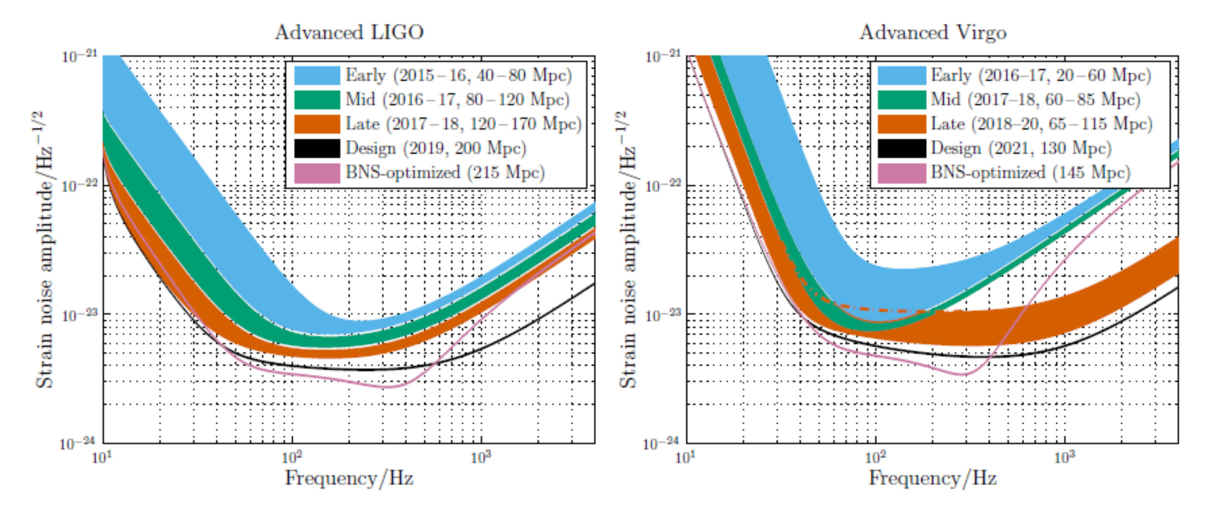
Phys. Rev. Lett. 116, 221102 (2016)

LIGO O2 Observational Run Underway



LIGO-Virgo Observing Plans





Living Rev. Relativity 19 (2016), 1

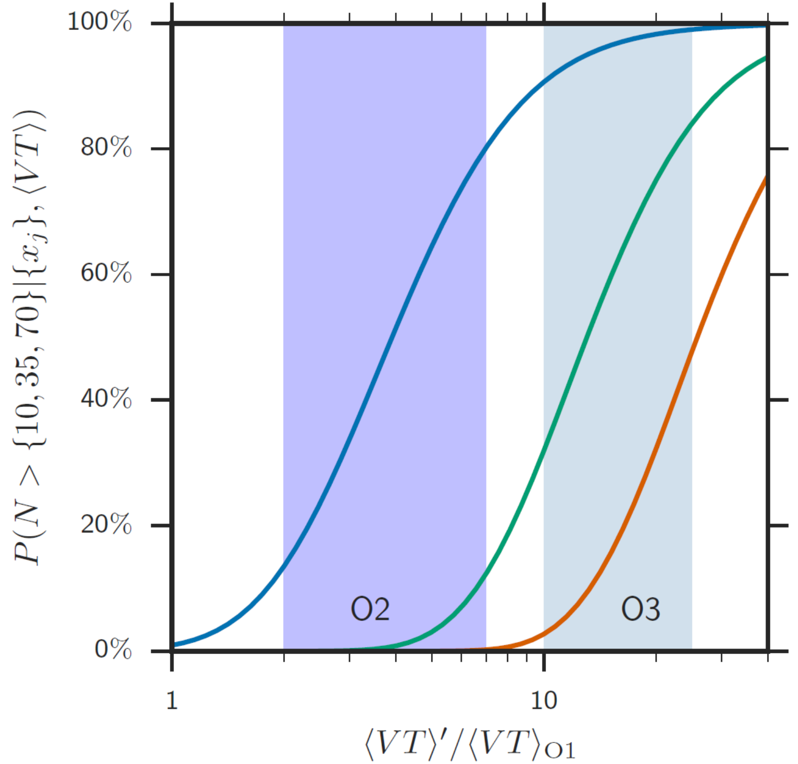
Black Hole Binary Rate expectations

future running

Black Hole Binaries

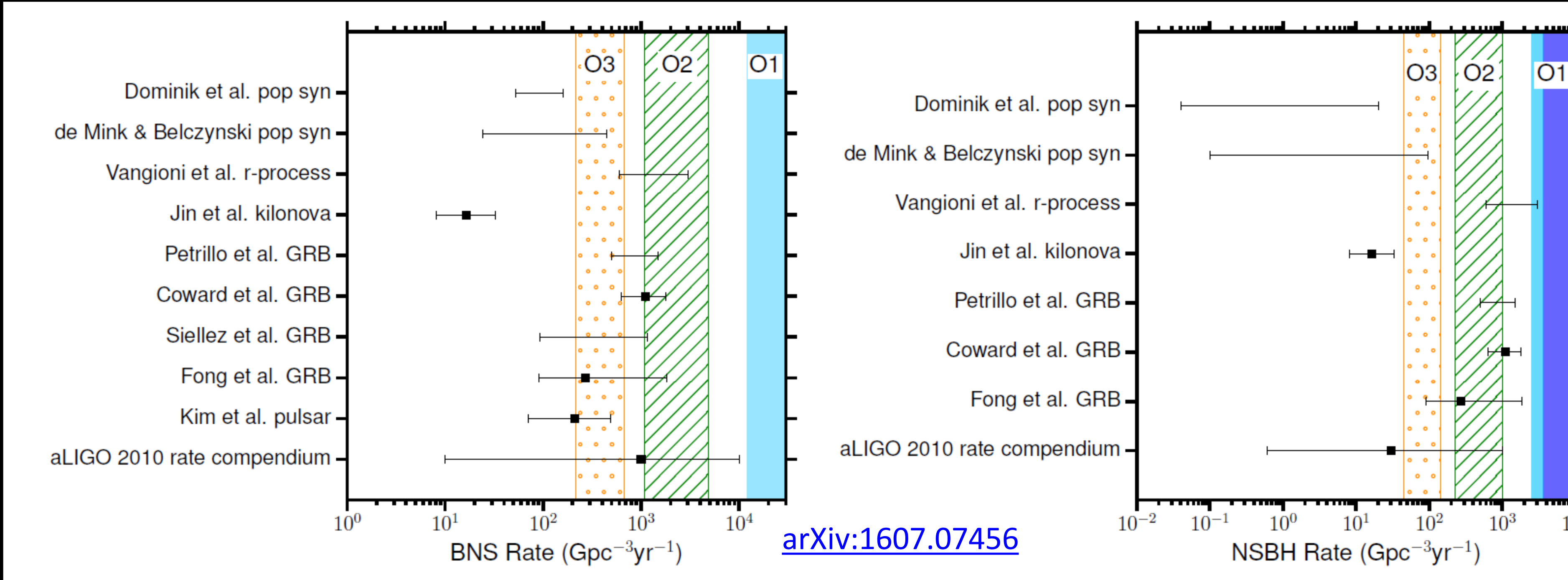
Probability of observing

- N > 10
- N > 35
- N > 70 events
- highly significant events, as a function of surveyed time-volume.



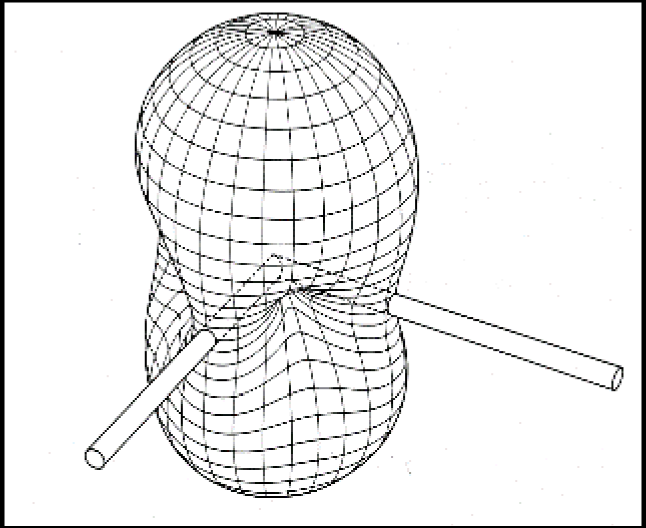
Phys. Rev. X 6, 041015 (2016)

Predicted Rates BNS and NSBH merger



- Left – Comparison of BNS merger rates and O1 low spin exclusion region (blue)
- Right – Comparison of NSBH merger rates and O1 exclusion regions for 10-1.4 Solar masses (blues)

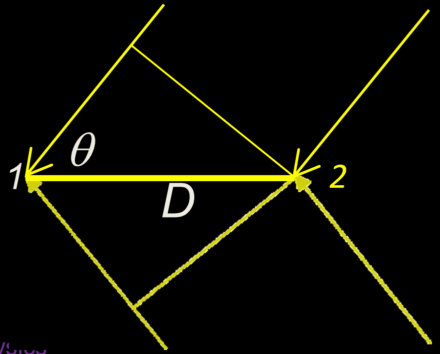
Source Localization Using Time-of-flight



- LIGO detectors are nearly omni-directional
  - Individually they provide almost no directional information
- Array working together can determine source location
  - Analogous to "aperture synthesis" in radio astronomy

- Accuracy tied to diffraction limit

$$\Delta t = (D\cos\theta)/c$$



Comparing time of arrival and amplitude

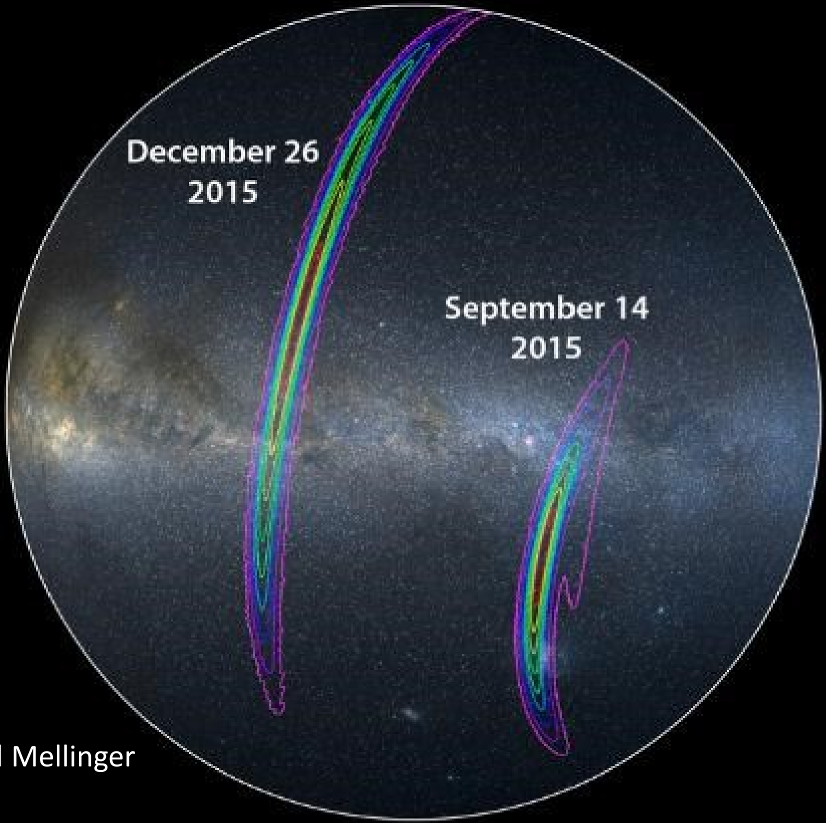
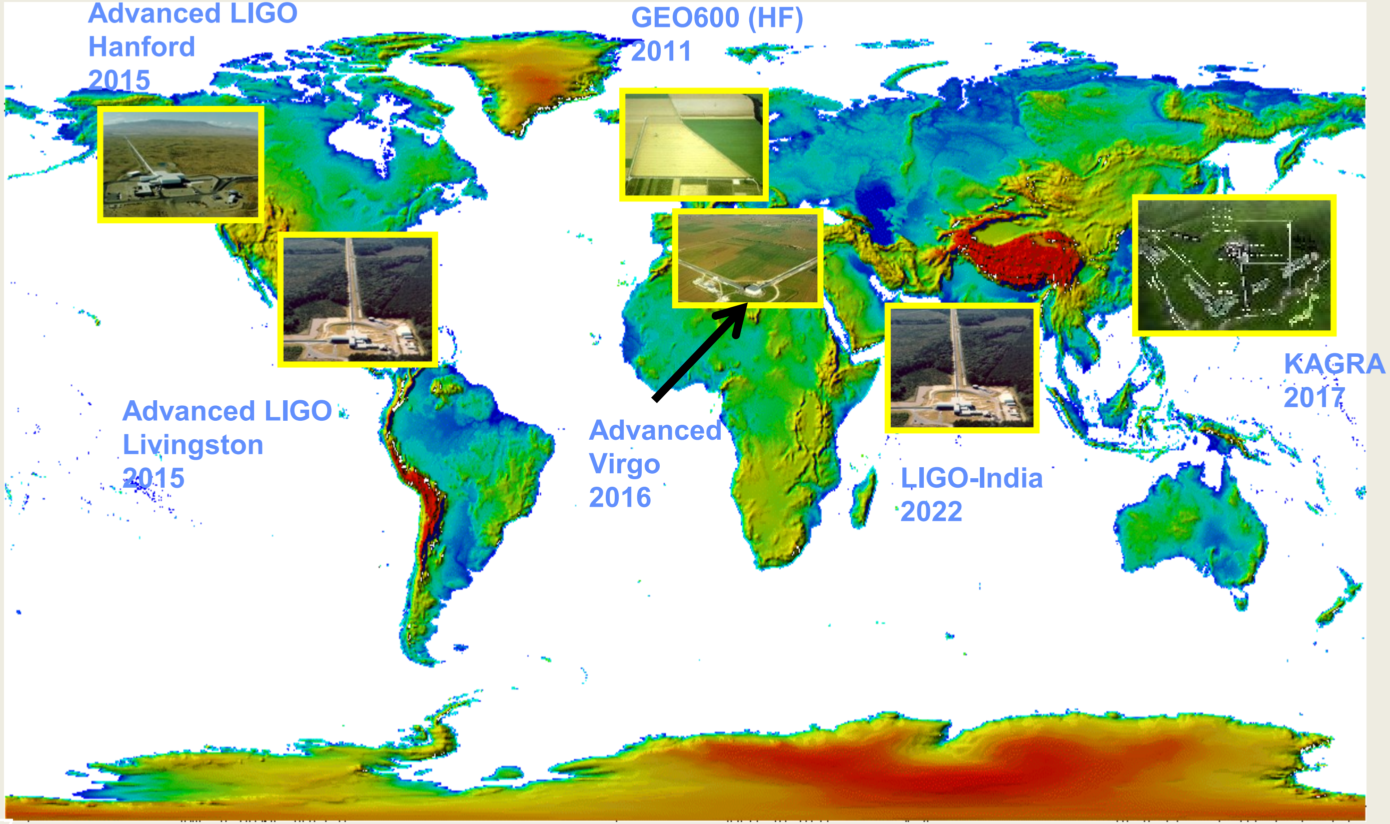


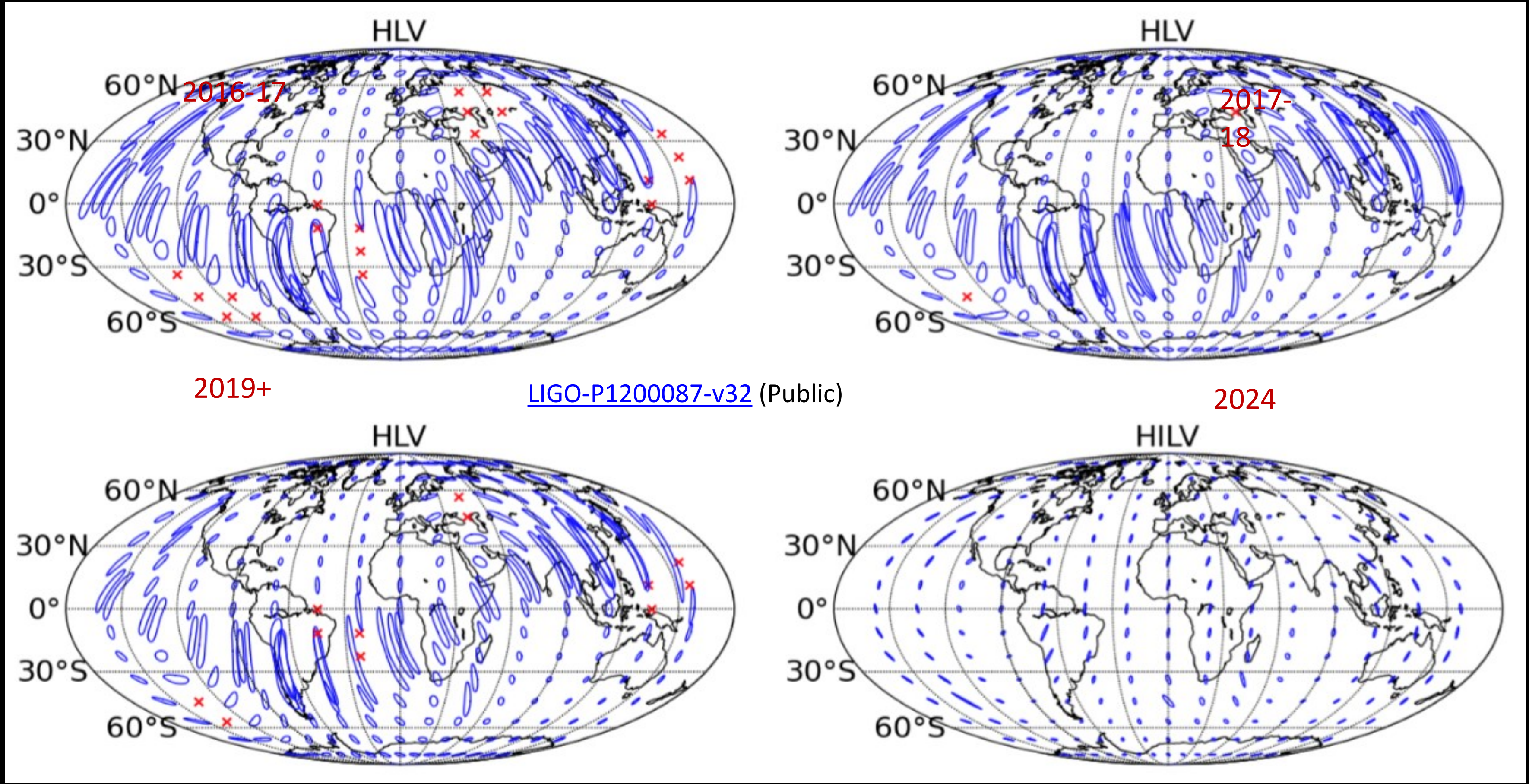
Image credit: LIGO/Axel Mellinger

GW150914: Signal arrived 6.9 milliseconds earlier in LIGO Livingston, LA than LIGO Hanford, WA

GW detector network: 2015-2025



Improving Localization



LIGO-P1200087-v32 (Public)

Thanks!