Gravitational Waves:
Detected Events, Implications, and Future Prospects

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for the LIGO Scientific Collaboration and Virgo Collaboration

TAUP2017, Sudbury
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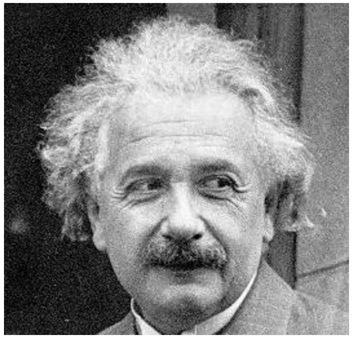
LIGO-G1701303-v1

GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

Gravitational Waves

Predicted to exist by Einstein's general theory of relativity



… which says that gravity is really an effect of "curvature" in the geometry of space-time, caused by the presence of any object with mass

Expressed mathematically by the Einstein field equations

Solutions describe the regular (static) gravitational field,
but also wave solutions which travel at the speed of light

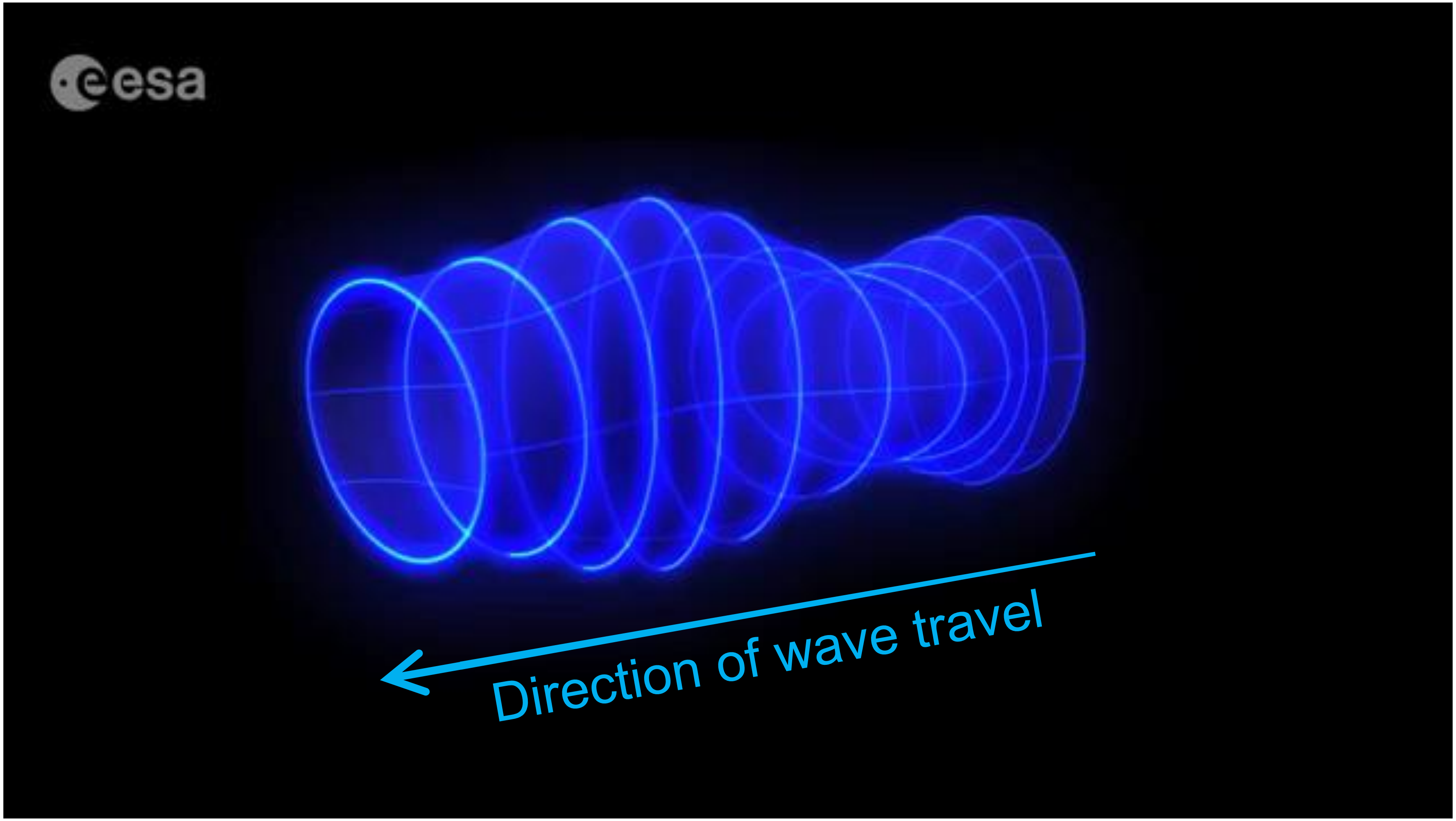
These waves are *perturbations of the spacetime metric* —
the effective distance between points in space and time

$$g_{\mu\nu}$$

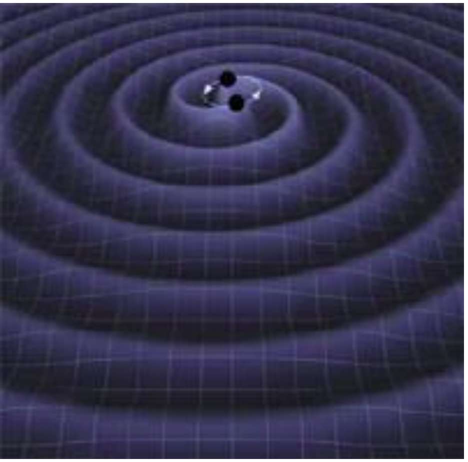
➔**The geometry of space-time is dynamic, not fixed!**

It alternately *stretches* and *shrinks* with a characteristic *strain*, $\frac{\Delta L}{L}$

Gravitational Waves in Motion



The Promise and the Challenge



Gravitational waves can be emitted by astrophysical systems with rapidly changing mass distribution

- Compact binary $\left\{\begin{matrix}\text{neutron stars}\\ \text{black holes}\end{matrix}\right\}$ orbit, inspiral and merger
- Core collapse of a massive star (supernova engine)
- Non-axisymmetric spinning neutron stars
- Cosmic strings, early universe physics, …

GWs come directly from the central engine

Not obscured or scattered by material

➔ Complements photon and neutrino diagnostics of photosphere, outflows, circumburst medium, shocks

Bill Saxton, NRAO/AUI/NSF

But challenging to detect…

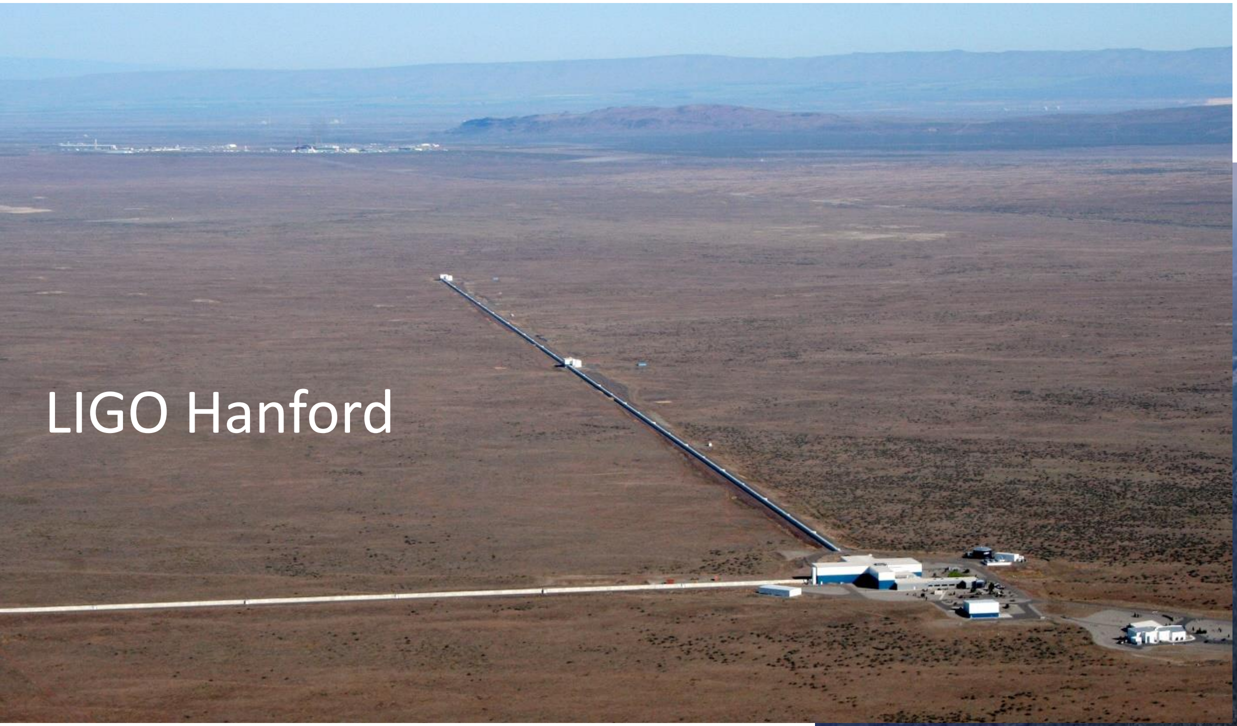
Strain amplitude is inversely proportional to distance from source

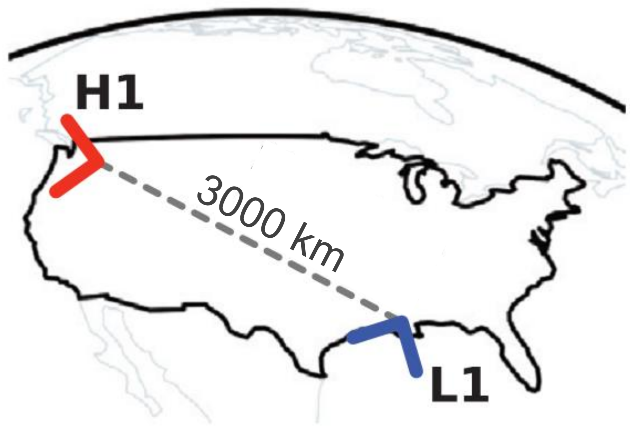
➔ Have to be able to detect weak signals to search a large volume of space

Expected strain at Earth: $\Delta L/L \sim 10^{-21}$ or even smaller !

The LIGO* Observatories

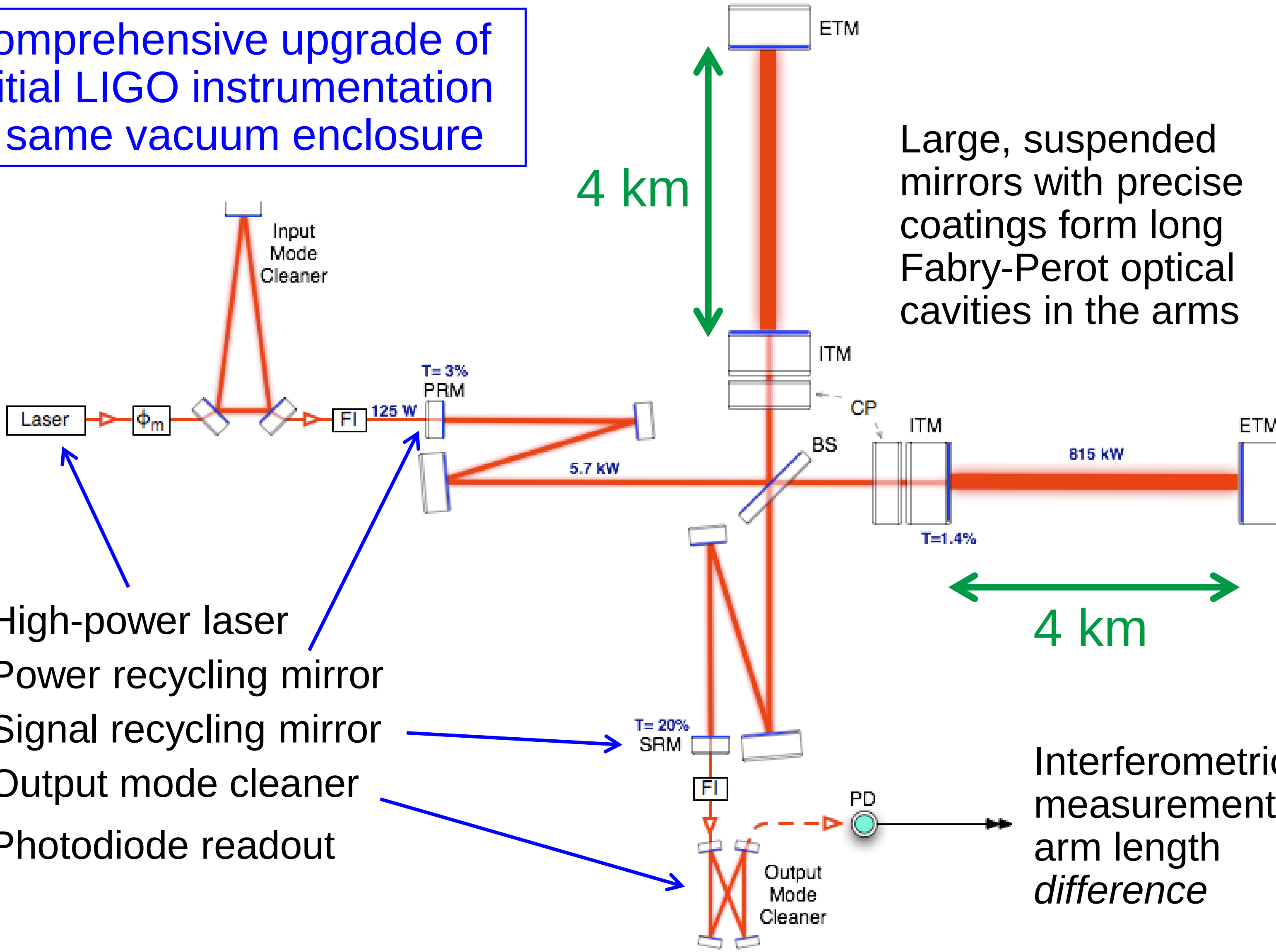
* LIGO = Laser Interferometer Gravitational-wave Observatory



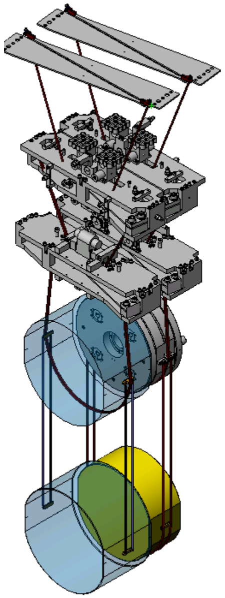


Advanced LIGO Optical Layout

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum enclosure



Large, suspended mirrors with precise coatings form long Fabry-Perot optical cavities in the arms



High-power laser

Power recycling mirror

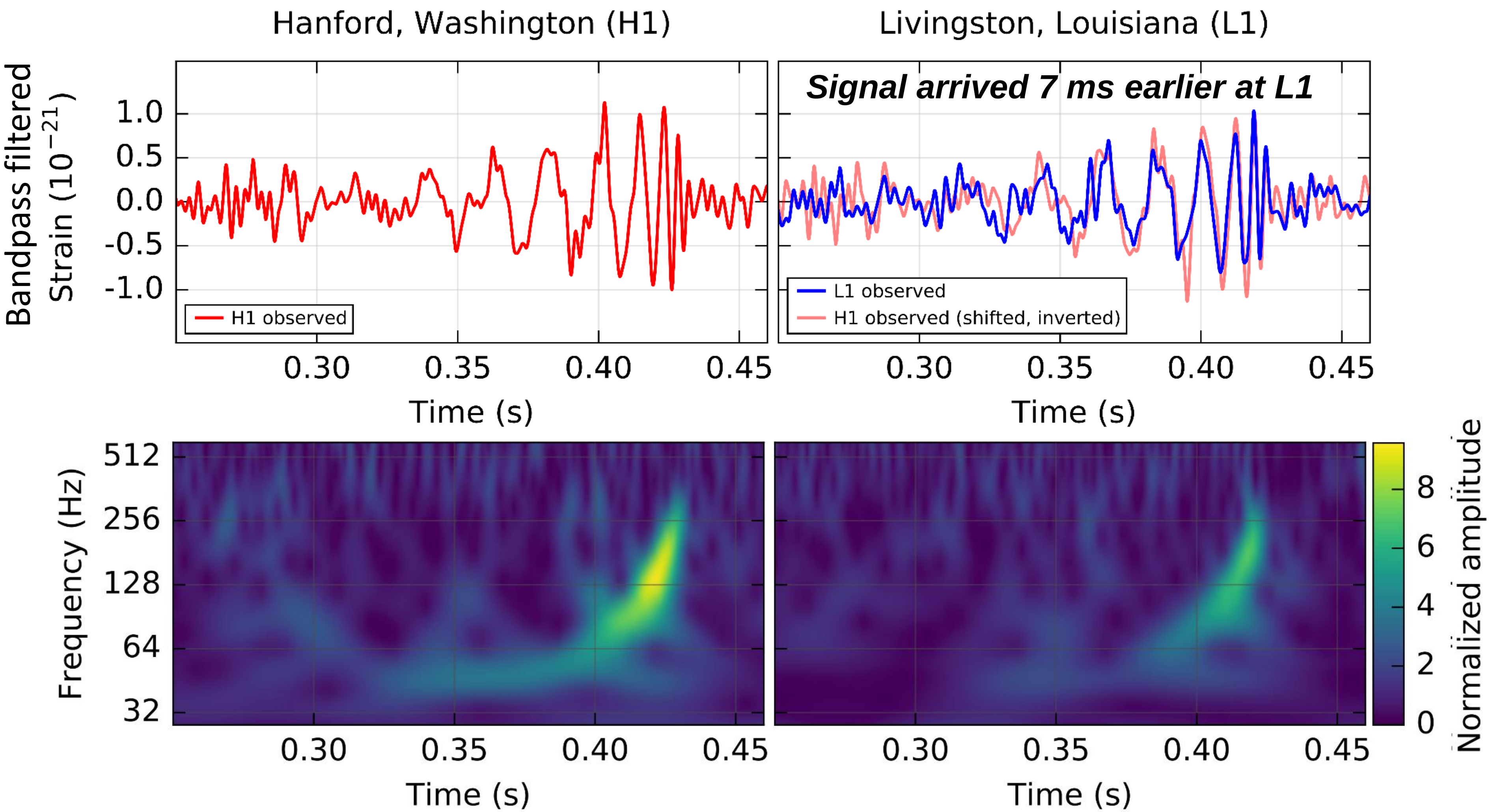
Signal recycling mirror

Output mode cleaner

Photodiode readout

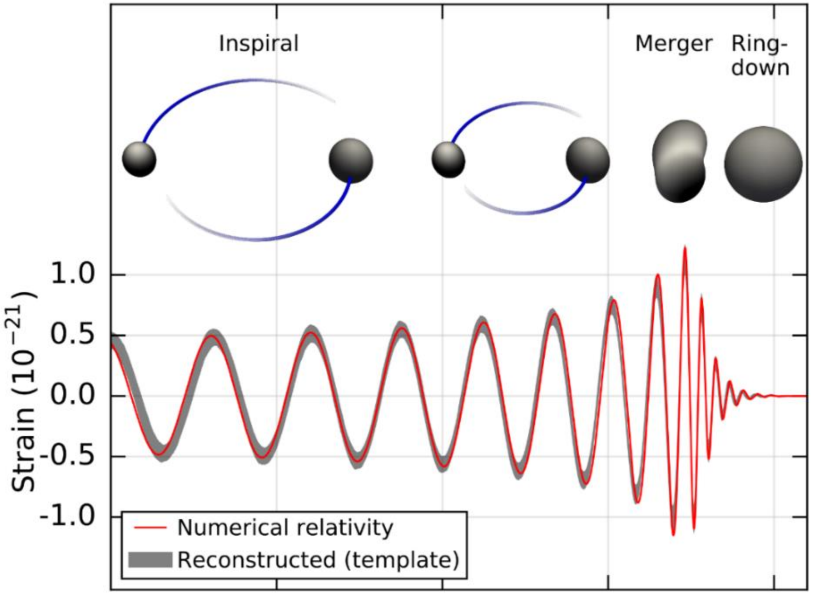
Interferometric measurement of arm length *difference*

Signal Recorded on September 14, 2015

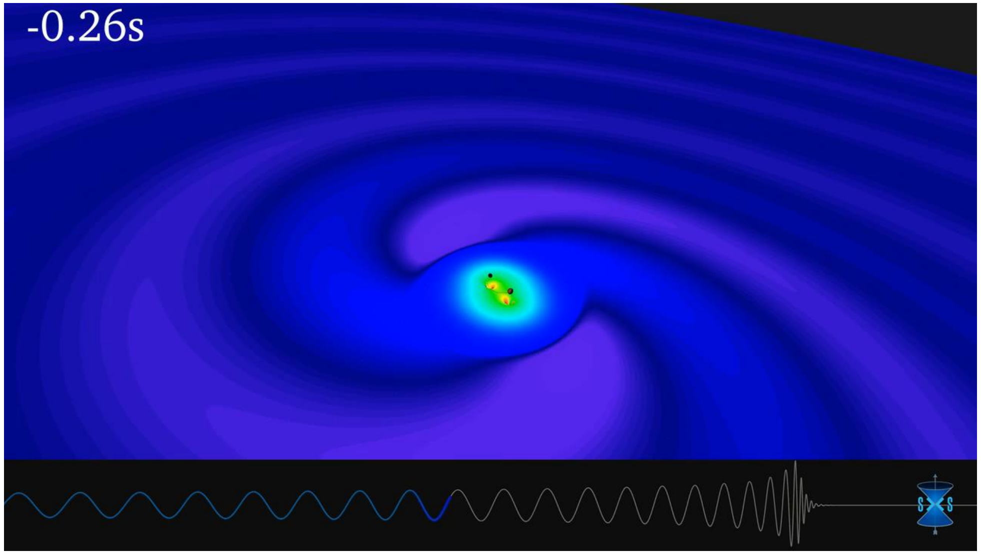


[Abbott et al. 2016, PRL 116, 061102]

Looks just like a binary black hole merger!

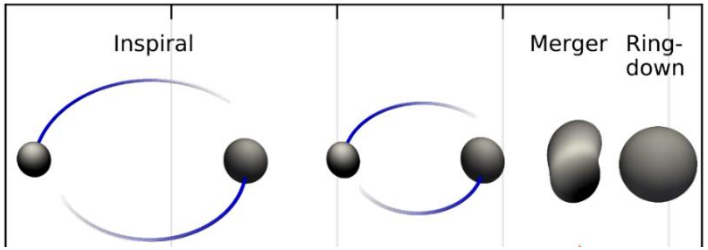


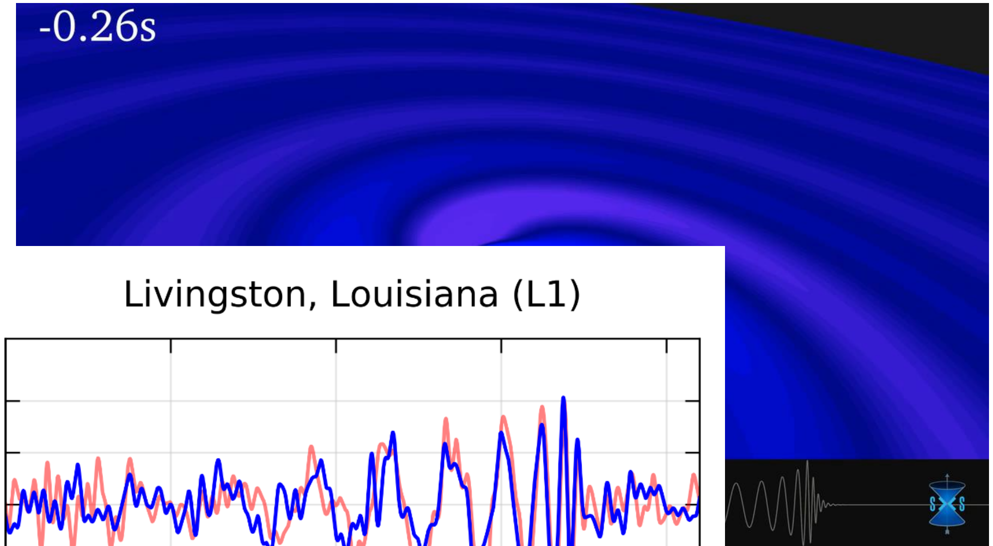
[Abbott et al. 2016, PRL 116, 061102]



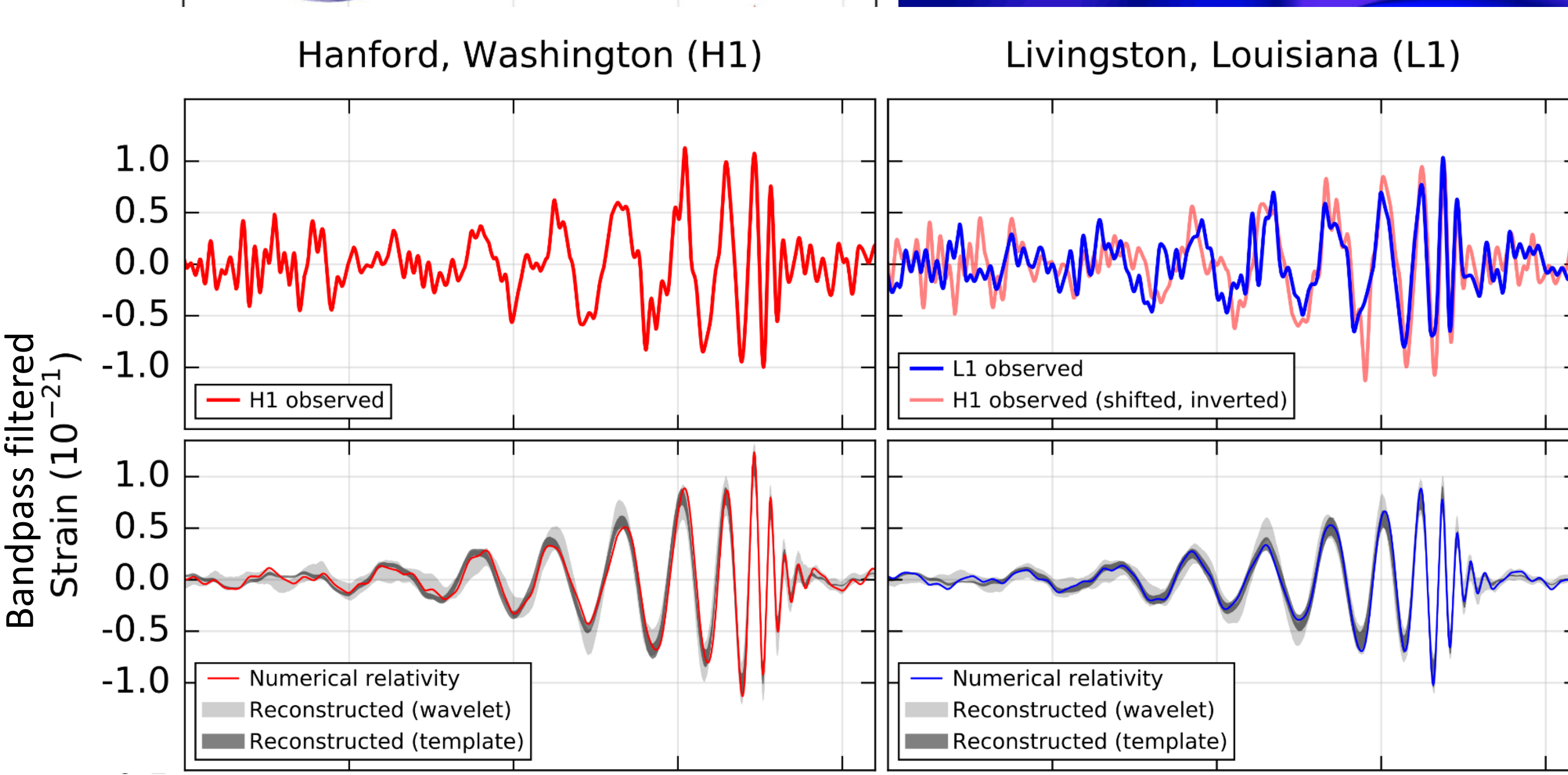
[Simulating eXtreme Spacetimes Collaboration]

Looks just like a binary black hole merger!





s Collaboration]

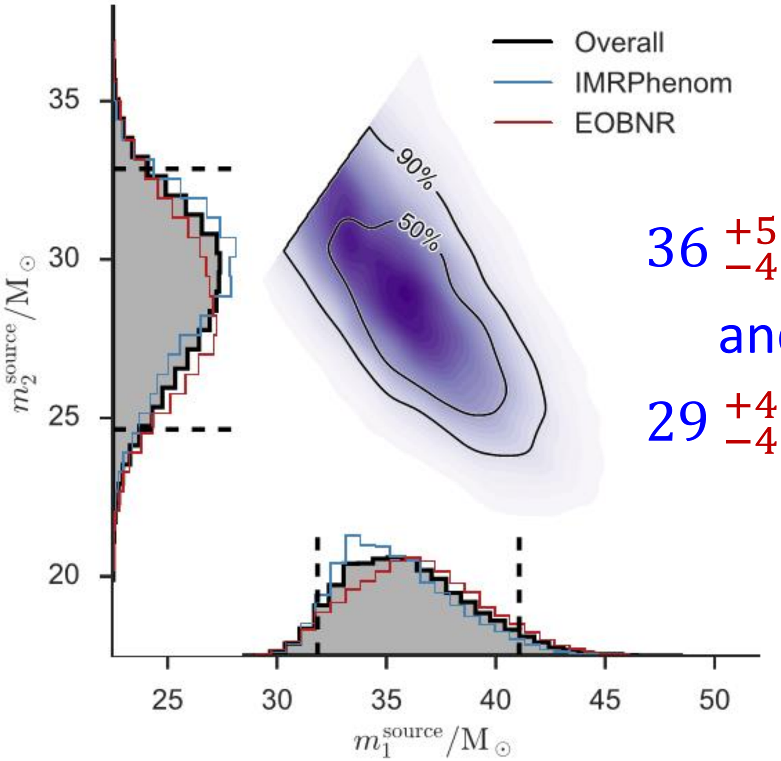


Matches well to BBH template when filtered the same way

[Abbott et al. 2016, PRL 116, 061102]

Some Properties of GW150914

Masses:



$36^{+5}_{-4}\,M_\odot$

and

$29^{+4}_{-4}\,M_\odot$

These are surprisingly *heavy* for stellar-remnant black holes !

Final BH mass: $62 \pm 4\ M_\odot$

Energy radiated: $3.0 \pm 0.5\ M_\odot c^2$

Peak power $\sim 200\ M_\odot c^2/s$!

Distance: 410^{+160}_{-180} Mpc

$= 1.3 \pm 0.5$ billion light-years

➔ Redshift $z \approx 0.09$

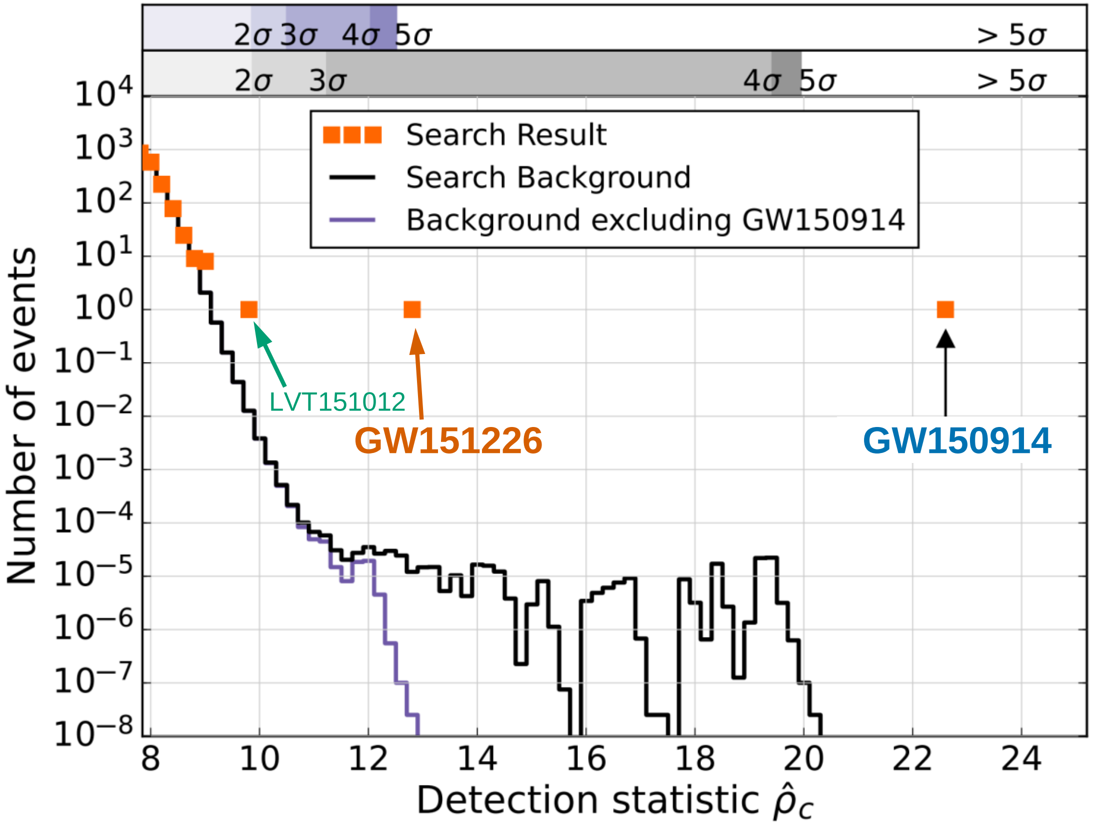
We can't tell if the initial black holes had any "spin" (intrinsic angular momentum), but the spin of the final BH is

$0.67^{+0.05}_{-0.07}$ of maximal spin allowed by GR $\left(\frac{Gm^2}{c}\right)$

[Abbott et al. 2016, ApJL 833, L1]

More from Advanced LIGO's First Observing Run (O1)

Analysis of the complete O1 run data revealed one additional significant binary black hole coalescence signal, GW151226



O1 run:
Sept 12, 2015 – Jan 9, 2016

[Abbott et al. 2016, PRX 6, 041015]

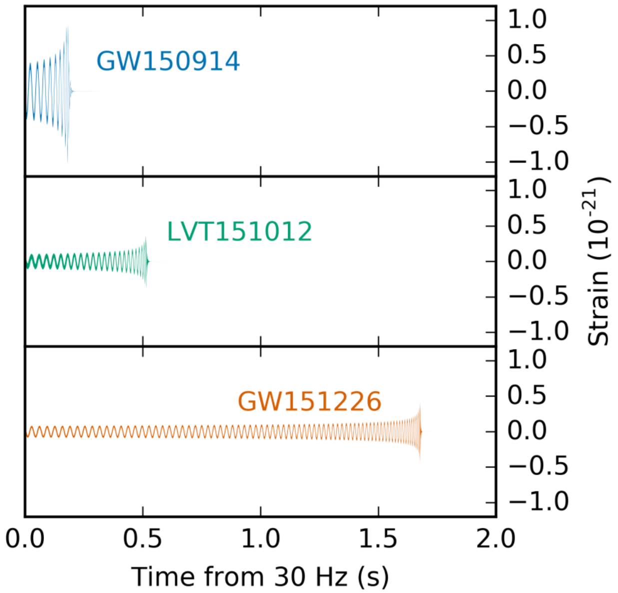
Weaker than GW150914, but still detected with $> 5\sigma$ significance

Also a marginal candidate LVT151012 – we estimate 87% prob of being real

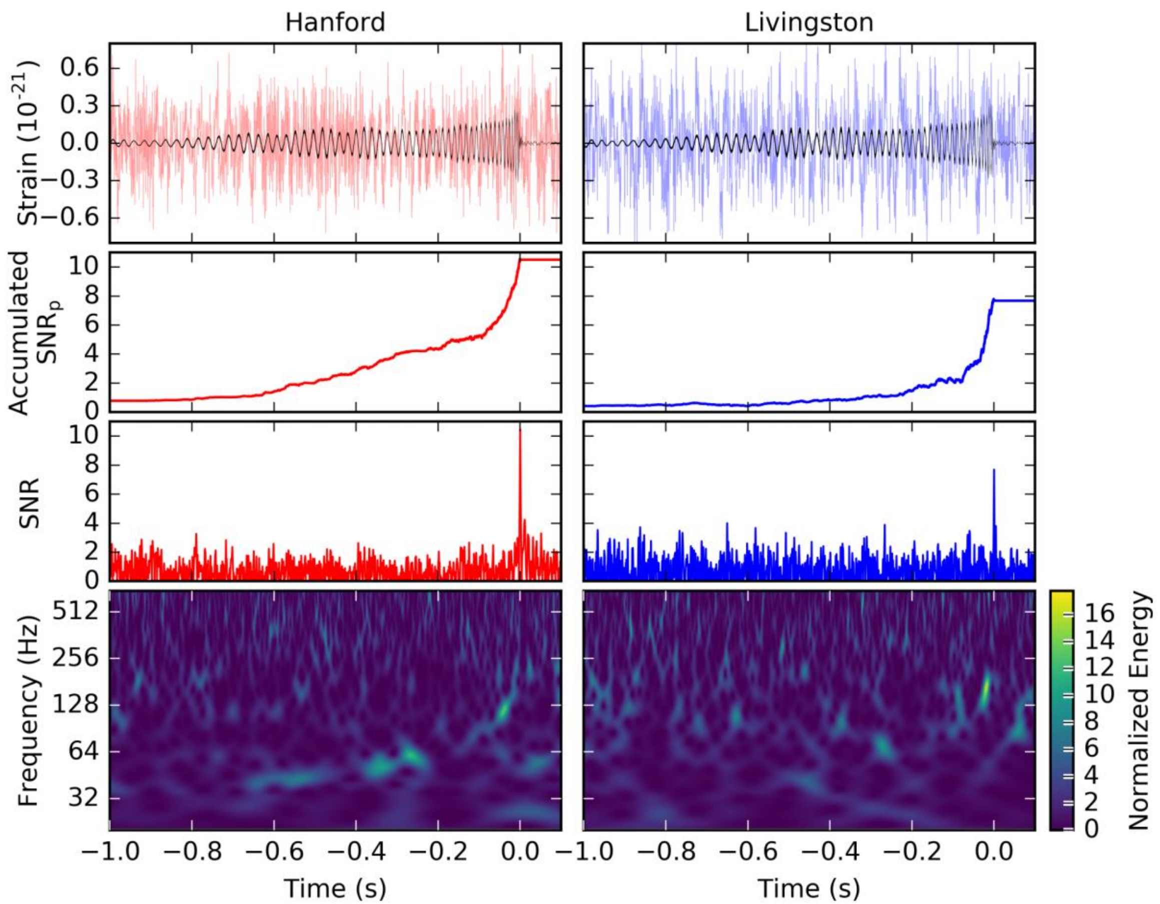
Not so visible in the data…

Another signal consistent with GR, but qualitatively different

Longer duration,
lower amplitude,
more "cycles" in band



➔ *Matched filtering* was essential for detecting GW151226

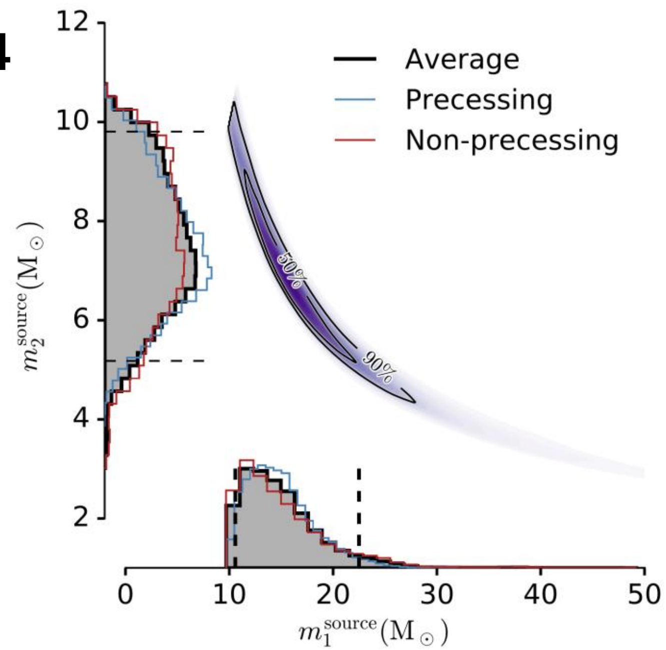


[Abbott et al. 2016, PRL 116, 241103]

GW151226 has lower mass than GW150914

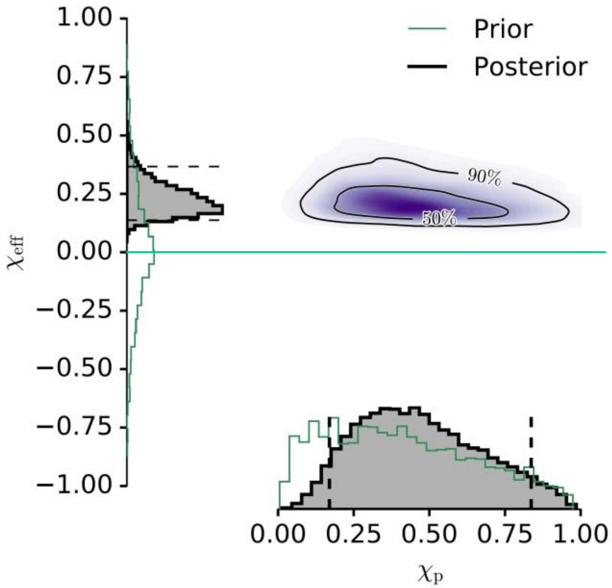
Initial masses: $14.2^{+8.3}_{-3.7}$ and $7.5 \pm 2.3\ M_\odot$
Final BH mass: $20.8^{+6.1}_{-1.7}\ M_\odot$
Energy radiated: $1.0^{+0.1}_{-0.2}\ M_\odot c^2$

Luminosity distance: 440^{+180}_{-190} Mpc



[Abbott et al. 2016, PRL 116, 241103]

… and nonzero spin !



Effective signed spin combination definitely positive
⇒ at least one of the initial BHs has nonzero spin
(we can't tell how the spin is divided up between them due to waveform degeneracy)

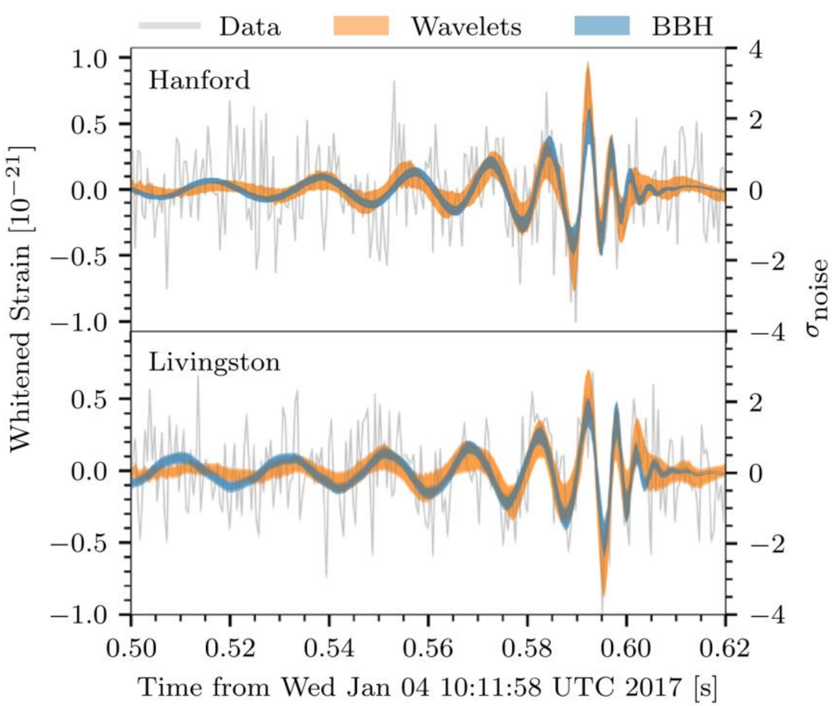
First Event from the O2 Run: GW170104

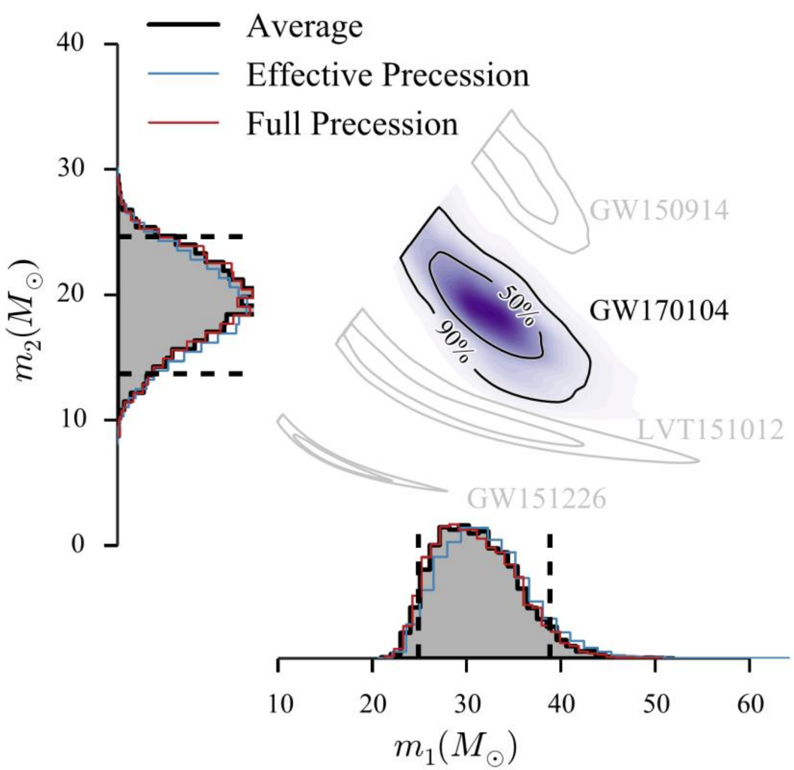
Another binary black hole merger

Masses in between GW150914 and GW151226

About twice as far away as GW150914 and GW151226

Spin parameter: $\chi_{\text{eff}} = -0.12^{+0.21}_{-0.30}$





[Abbott et al. 2017, PRL 118, 221101]

Astrophysical Implications

There are black hole binaries out there, orbiting closely enough to merge, and *heavy !*

For comparison, reliable BH masses in X-ray binaries are typically $\sim 10\ M_\odot$

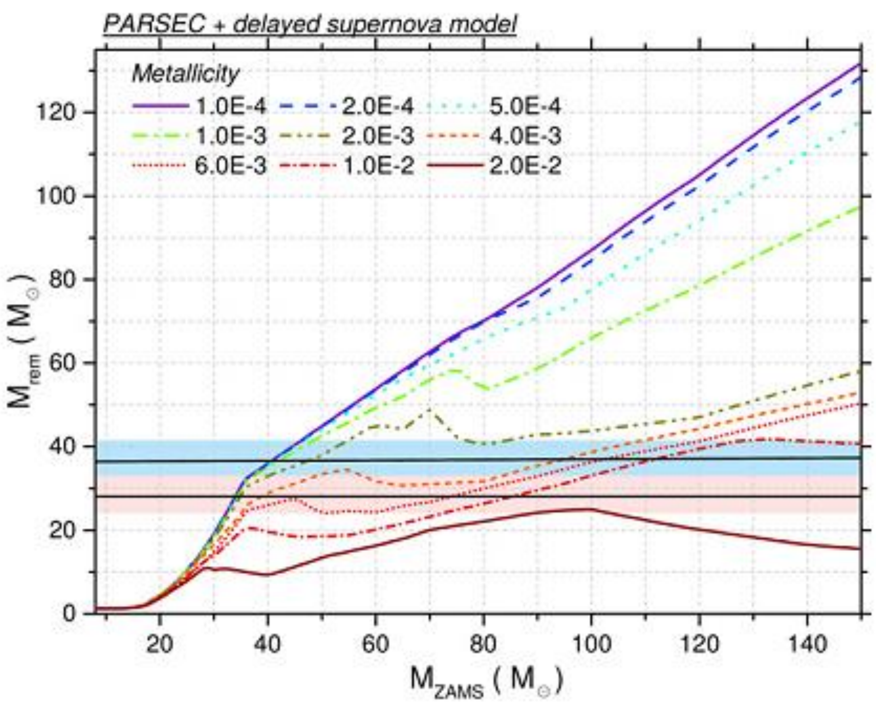
We presume that each of our BHs formed directly from a star

➔Low metallicity is required to get such large masses

Otherwise, strong stellar winds limit the final BH mass

We can't tell when the binaries formed

Inspiral may have taken many billion years



Spera et al., MNRAS 451, 4086

[Abbott et al. 2016, ApJL 818, L22]

Astrophysical Implications

Different formation pathways are possible:

- A massive binary star system with sequential core-collapses
- Chemically homogeneous evolution of a pair of massive stars in close orbit
- Dynamical formation of binary from two BHs in a dense star cluster
- Binaries formed from a population of primordial black holes

Key piece of evidence: spins of the initial black holes

Orbit-aligned components: $\chi_{\mathrm{eff}} = 0.21^{+0.21}_{-0.10}$ for GW151226,
but consistent with zero for the other events

In-plane components (which would cause precession during inspiral):
little information from the events detected so far

All we can really say now is that these binary systems did not have large black-hole spins positively aligned with the orbital axis

→ Disfavors chemically homogeneous evolution model

[Abbott et al. 2017, PRL 118, 221101]

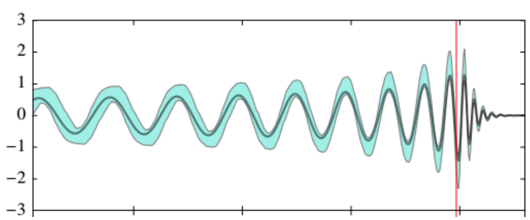
Tests of GR

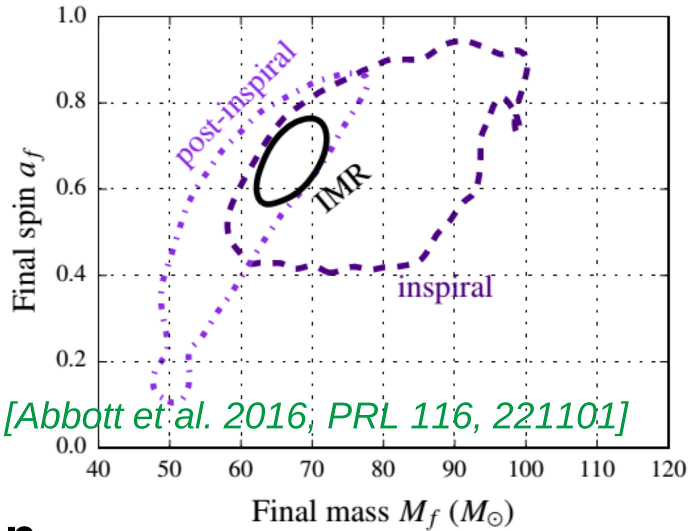
We examine the waveforms of the detected events in several ways to see whether there is any deviation from the GR predictions

Known through post-Newtonian (analytical expansion) and numerical relativity

Inspiral / merger / ringdown consistency

Compare estimates of mass and spin from before vs. after merger





[Abbott et al. 2016, PRL 116, 221101]

Consider possibility of a massive graviton

Would distort waveform due to dispersion

From lack of distortion, we place a limit on graviton Compton wavelength: $\lambda_g > 1.5 \times 10^{13}$ km

➔ $m_g < 7.7 \times 10^{-23}\ \mathrm{eV}/c^2$

[Abbott et al. 2017, PRL 118, 221101]

Multi-Messenger Searches with GWs

LIGO/Virgo have done many *externally triggered* GW searches

(deep analysis of GW data around the time and/or sky position of reported EM event)

and have collaborated on *joint* searches

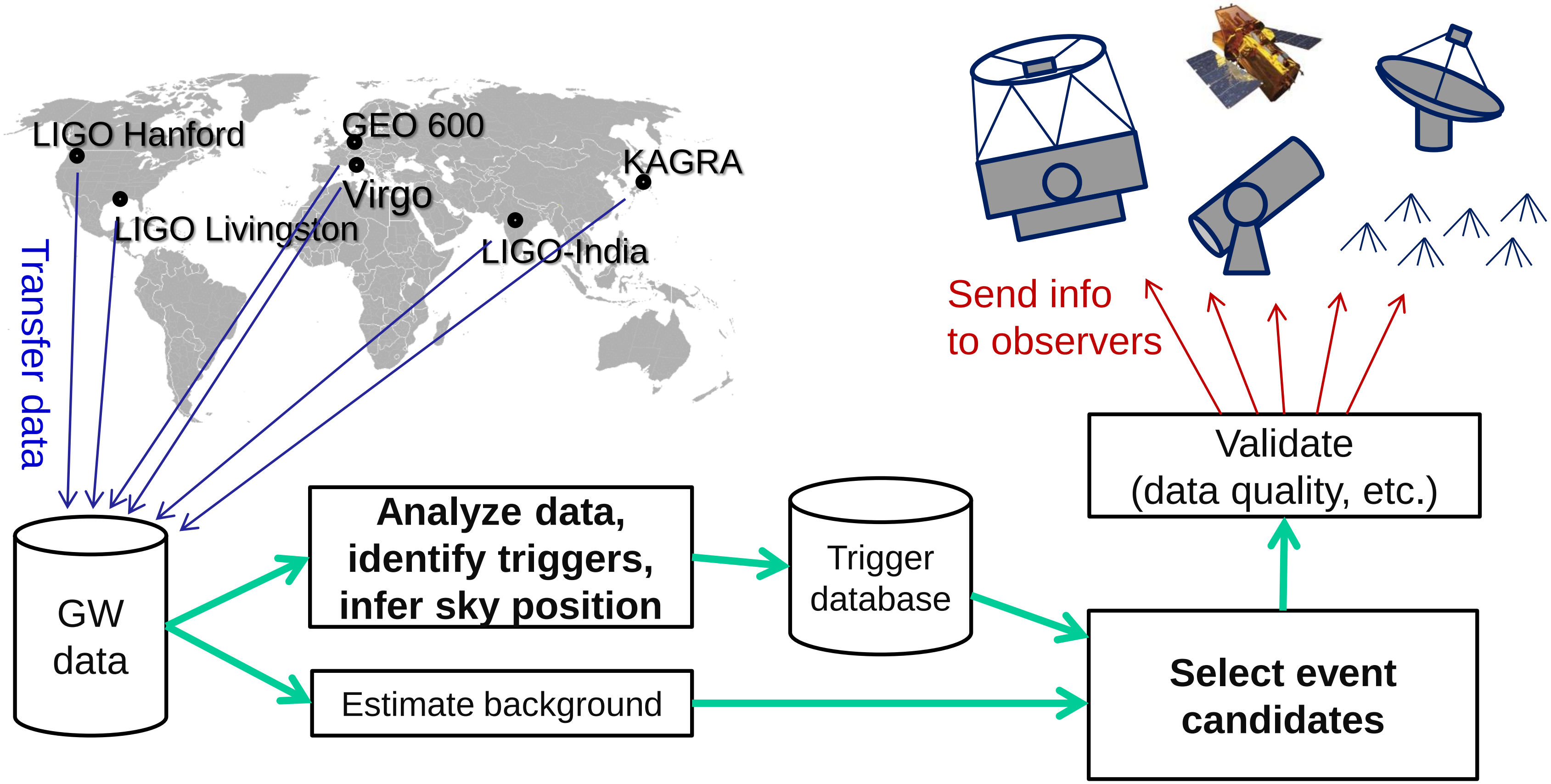
(compare sets of candidate events)

Over two dozen papers…

CBC, Burst	GRBs	– using public (GCN) and	private info
CW	Known pulsars	public	private
Burst	SGR/magnetar flares	public	private
Burst	Pulsar glitch (Vela)		private
Burst	High-energy neutrinos		private
Burst	Radio transients		private
Burst	Supernovae	public (CBET, etc.)	
CBC	Offline follow-up with satellite	public γ/X-ray data	

Also initiated an *EM follow-up program*, distributing GW event candidates to observers to enable them to search for counterparts

Generating and Distributing Prompt Alerts



LIGO & Virgo have signed MOUs with >90 groups for EM/neutrino follow-up, in addition to a number of triggered / joint search MOUs

Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

Follow-up Observations During O1

About half of those with observing capability responded to at least one of the 3 alerts during the run

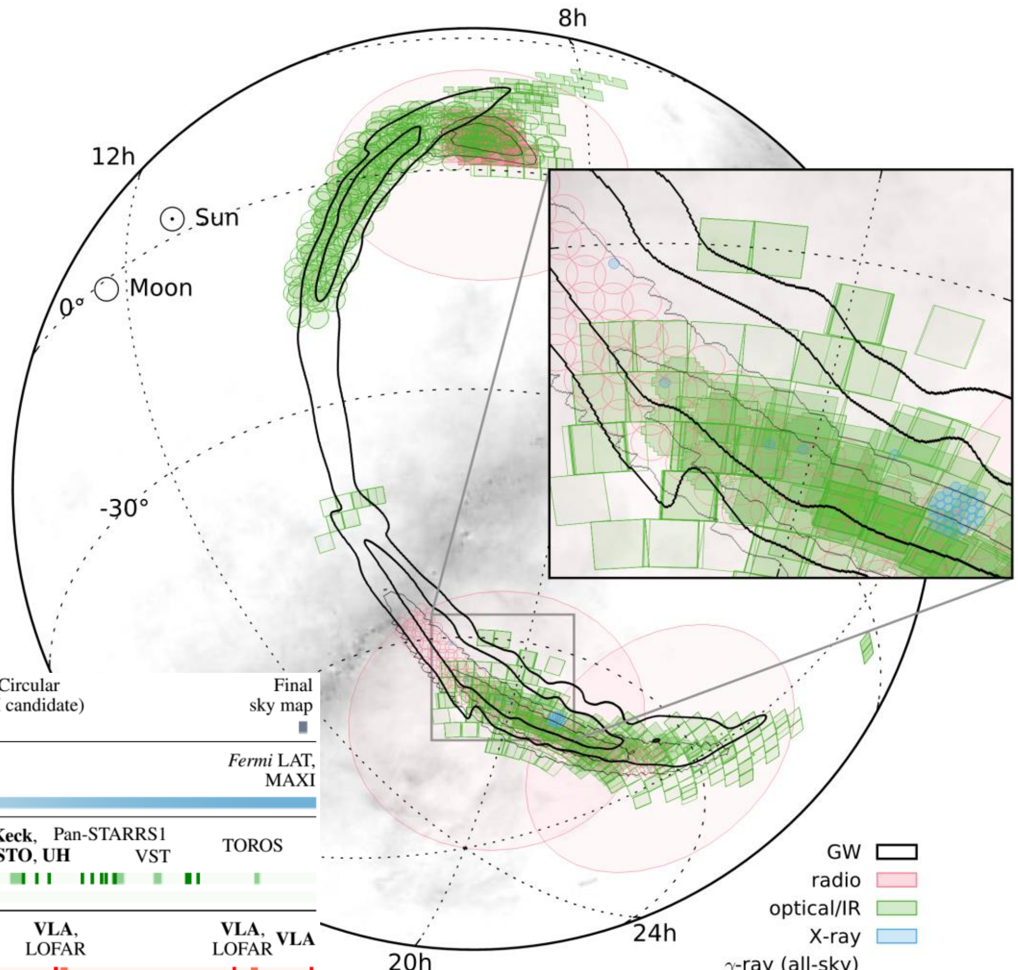
For GW150914:

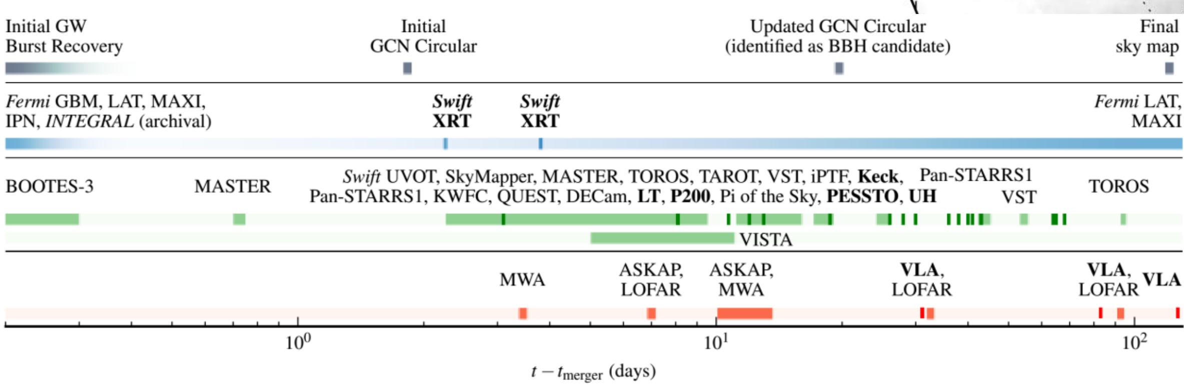
Covered most of skymap area at a wide range of wavelengths starting within a few hours

~50 GCN Circulars, ~12 papers

Also strong response for GW151226, GW170104, and other candidates

[Abbott et al. 2016, ApJL 826, L13]

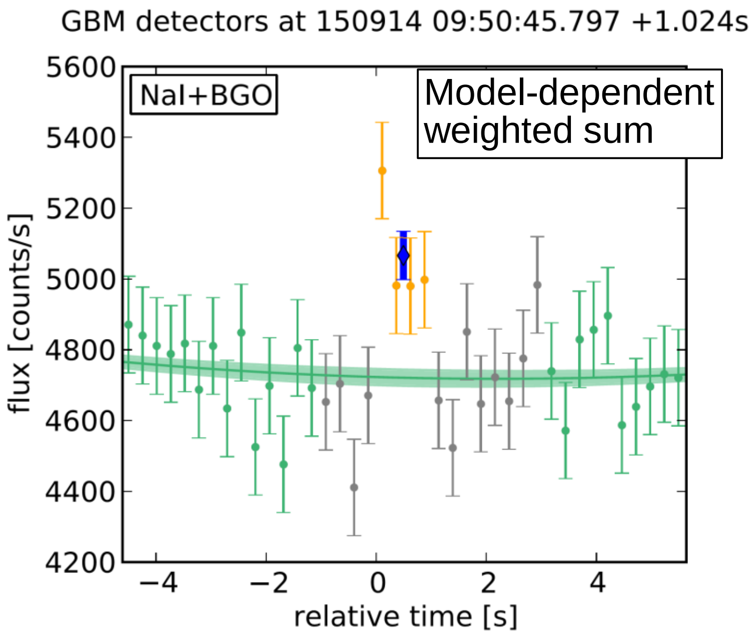




A weak signal was detected by the Fermi Gamma-ray Burst Monitor (GBM) ~0.4 second after the time of GW150914

Intriguing but inconclusive! ($< 3\sigma$)

[Connaughton et al. 2016, ApJL 826, 13]

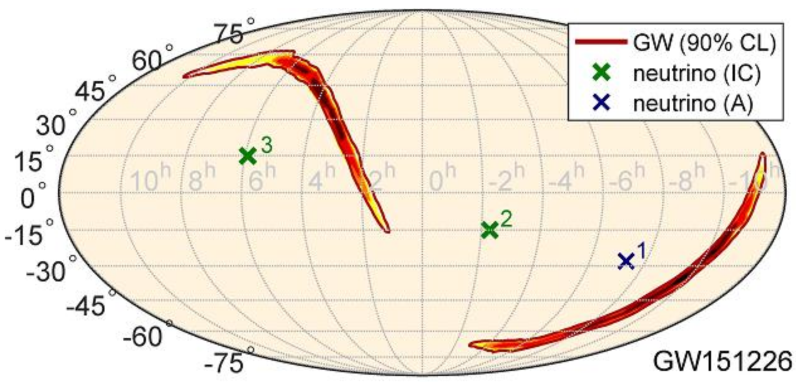


Many other searches for optical, radio, or X-ray counterparts have found nothing related so far

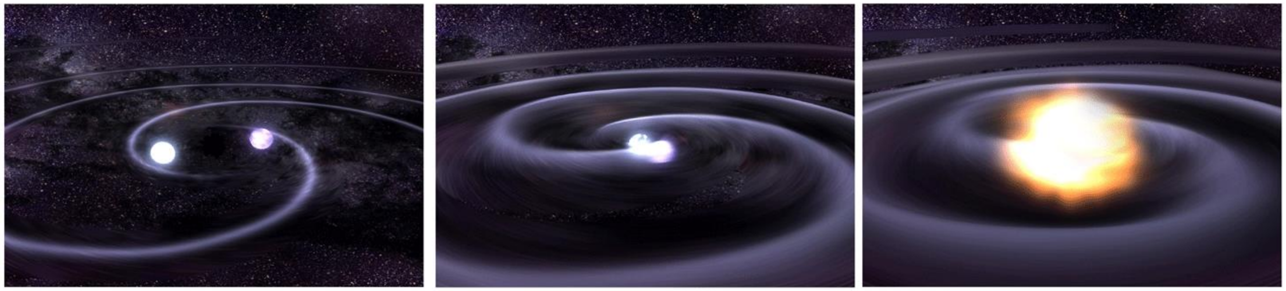
Searches for high-energy neutrinos carried out with IceCube & ANTARES

[Adrián-Martínez et al. 2016, PRD 93, 122010]

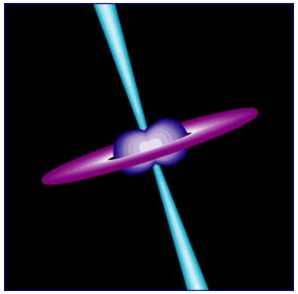
[Albert et al. 2017, PRD 96, 022005]



Short Gamma-ray Bursts = Mergers?



NASA



P.J.T. Leonard (NASA/GSFC)

Compact binary mergers containing at least one neutron star are thought to cause most short GRBs

Strong evidence from host galaxy types and typical offsets
[Fong & Berger, ApJ 776, 18]

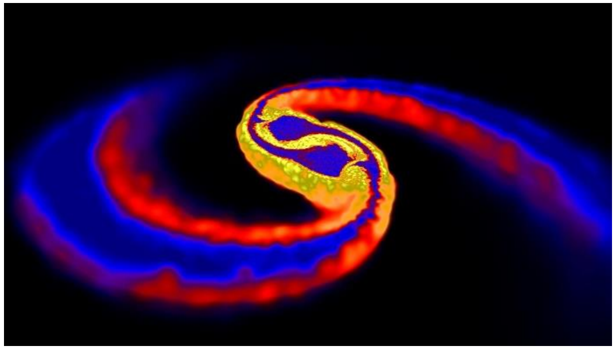
Could be NS-NS or NS-BH, with post-merger accretion producing a jet

Beamed gamma-ray emission → many more mergers than GRBs

Some opening angles measured, e.g. $16 \pm 10°$ *[Fong+ 2016, ApJ 815, 102]*

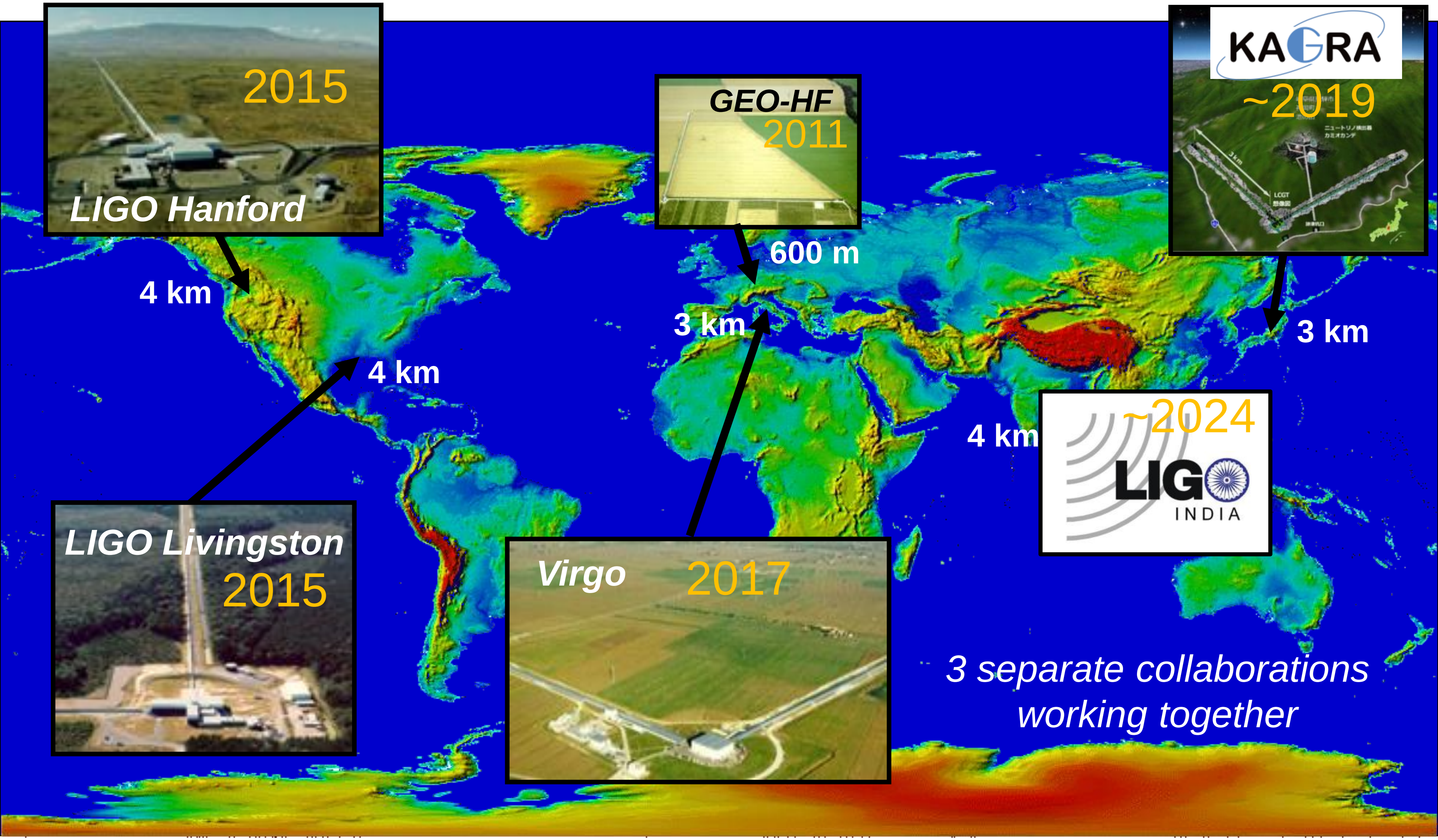
Also may be able to detect "kilonova" optical signature from ejecta

Peaks on day-to-week time scale
[Metzger, Liv. Rev. Rel., arXiv:1610.09381]



Price/Rosswog/Press

Advanced GW Detector Network: Under Construction → Operating



Virgo: Joining Very Soon!

Will join the O2 run a week or so from now!

As its sensitivity gets closer to LIGO's, having three detectors will improve sky localization and parameter estimation

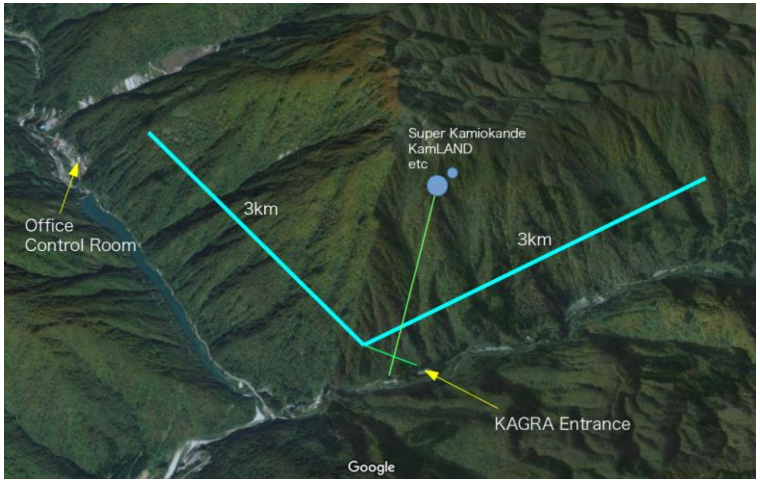
For details, see talk by Antonino Chiummo on Wednesday afternoon

Under Construction: KAGRA

The new neighbor in the Kamioka mine

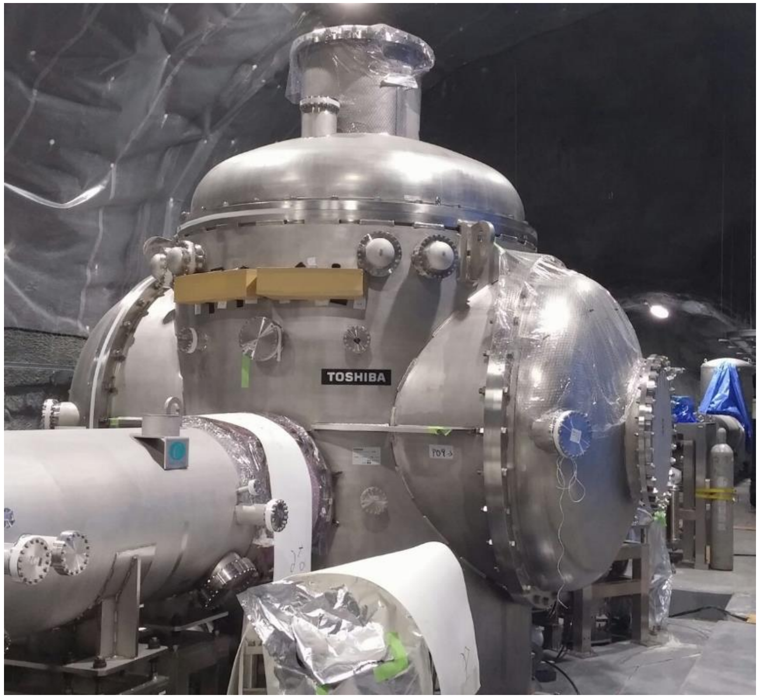
Underground ➔ less ground motion

Tunnels are complete,
vacuum system installed,
operated simple Michelson in 2016



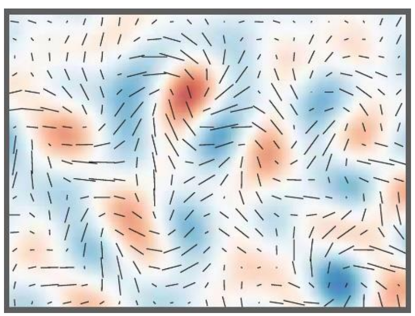
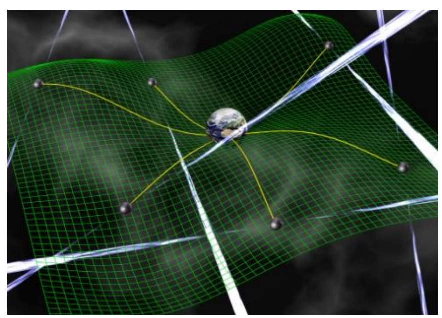
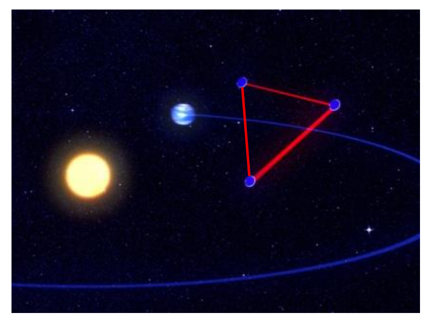
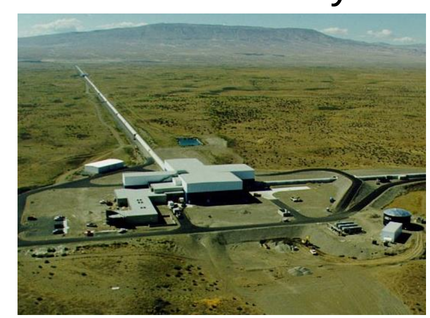
Now preparing to install cryogenic mirror payloads for lower thermal noise

Ultimately will have sensitivity similar to LIGO and Virgo



For details, see Wednesday afternoon talk by Yuta Michimura

The Wide Spectrum of Gravitational Waves

	$\sim 10^{-17}$ Hz	$\sim 10^{-8}$ Hz	$\sim 10^{-2}$ Hz	~ 100 Hz
Likely sources	**Primordial GWs from inflation era**	***Gravitational radiation driven Binary Inspiral + Merger*** Supermassive BHs	Massive BHs, extreme mass ratios	Neutron stars, stellar-mass BHs
		Cosmic strings?	**Ultra-compact Galactic binaries**	**Spinning NSs** **Stellar core collapse** Cosmic strings?
Detection method	B-mode polarization patterns in cosmic microwave background	Pulsar Timing Array (PTA) campaigns	Interferometry between spacecraft	Ground-based interferometry
	 BICEP2	 David Champion	 AEI/MM/exozet	 LIGO Laboratory
Projects	BICEP2/Keck, ACT, EBEX, POLARBEAR, SPTpol, SPIDER, …	NANOGrav, European PTA, Parkes PTA	LISA, DECIGO	LIGO, GEO 600, Virgo, KAGRA

Detecting GWs with Pulsar Timing

Millisecond pulsars are precise clocks!

Look for correlated variations in the times of pulses arriving at Earth

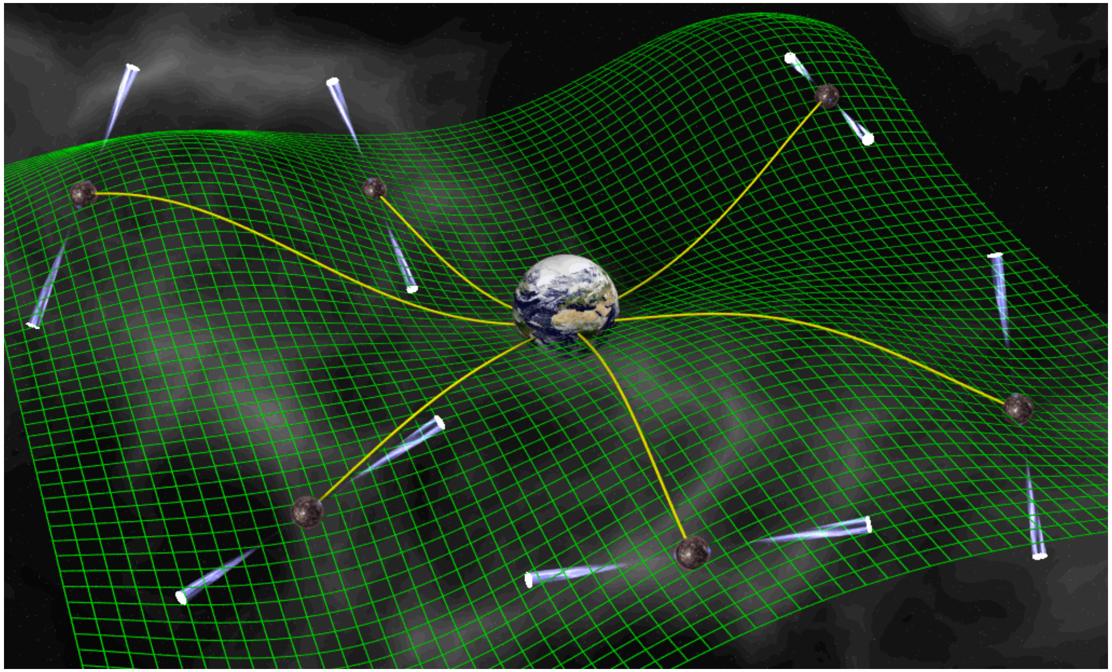


Image: David Champion

Timing campaigns are being carried out by three collaborations with access to different radio telescopes:

- NANOGrav (Arecibo, Green Bank)
- European Pulsar Timing Array
- Parkes Pulsar Timing Array

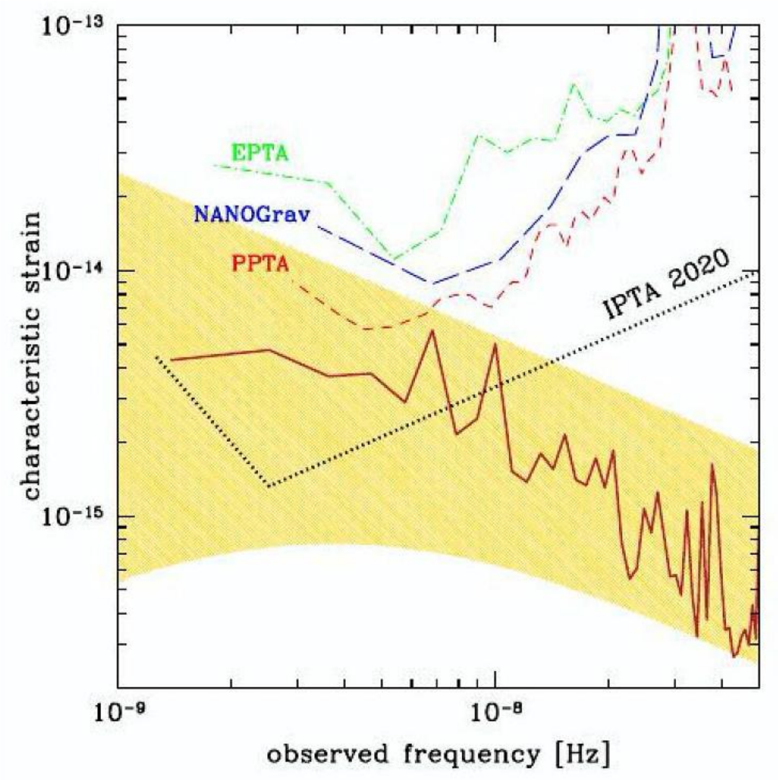
Also collaborating as the *International Pulsar Timing Array*

Pulsar Timing Results and Prospects

Sensitivity improves with observation time span, number of pulsars monitored, and pulse timing precision

New pulsars are added as they are discovered

Pulsar timing is getting close to the expected stochastic signal from supermassive black hole binaries in the universe



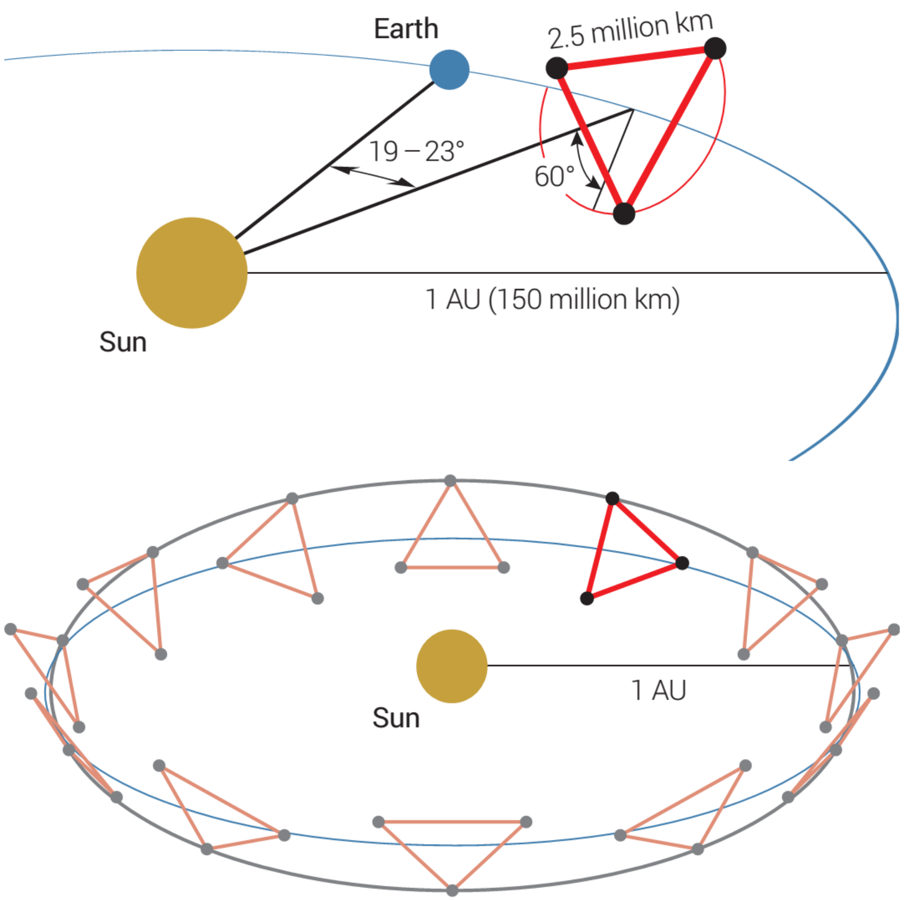
[Figure by A. Sesana, in Hobbs+Dai, arXiv:1707.01615]

Also search for individual black hole binaries, cosmic strings, and arbitrary transient signals

Note: some of these radio telescopes are at risk of being shut down!
See article in July 2017 issue of *Physics Today*

GW Detection with Spacecraft: LISA

Use laser interferometry to measure changes in the distances among a trio of spacecraft in orbit around the Sun



- Forms two independent Michelson interferometers plus a Sagnac null channel

~milliHertz sources:

- Supermassive black hole binaries
- Intermediate mass BH binaries
- Extreme mass ratio inspirals (maps spacetime near BH)
- Galactic compact binaries
- Stochastic GW background?

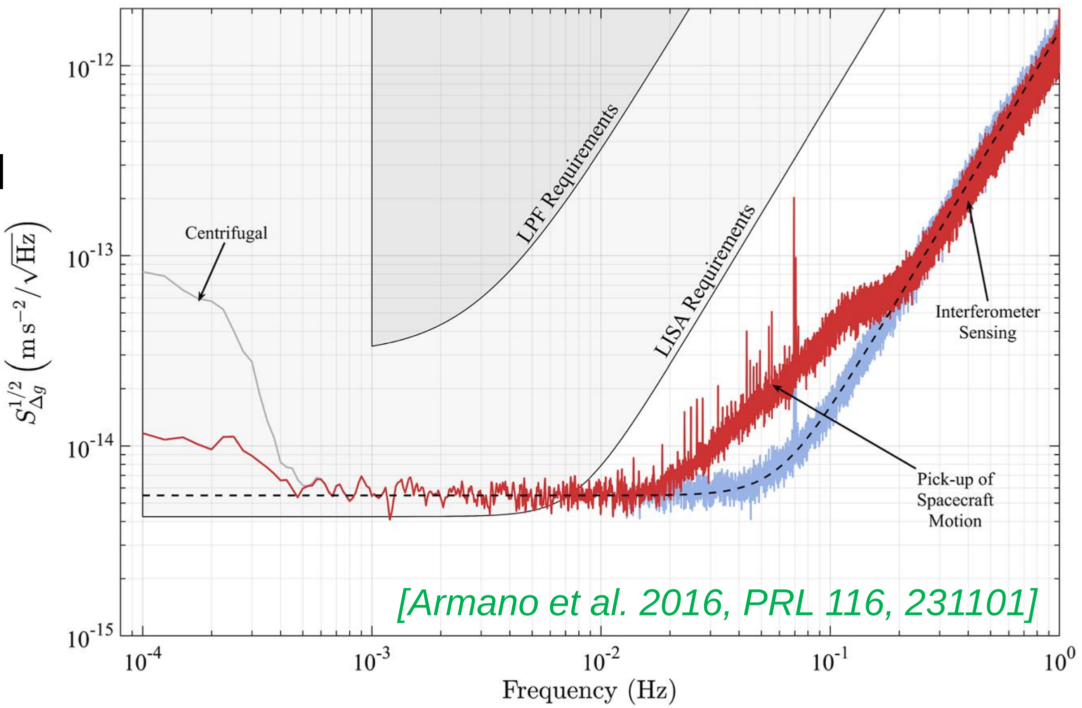
[Danzmann et al. 2017, LISA Proposal to ESA]

Progress Toward Realizing LISA

LISA Pathfinder mission was a great success!

Demonstrated the free-fall gravitational reference (test mass) technology needed for LISA

Mission ended July 18



The LISA mission was formally selected last month as the concept to be developed as ESA's third large-scale science mission

Projected launch date: 2034

NASA planning to make a significant contribution

Summary and Outlook

With 3.87 events detected so far, we are starting to get a picture of the population of merging binary black hole systems

- Enabling tests of GR and constraints on astrophysical models
- When will we detect neutron star binary mergers? Other sources?

LIGO is running pretty well, but not yet at design sensitivity; Virgo, after its upgrade, is about to begin observing

- Next will be KAGRA, then LIGO-India
- Third-generation ground-based GW detector designs are being developed

Pulsar timing campaigns are pushing down limits

LISA has a launch date