Observation of gravitational waves from binary black-hole merger

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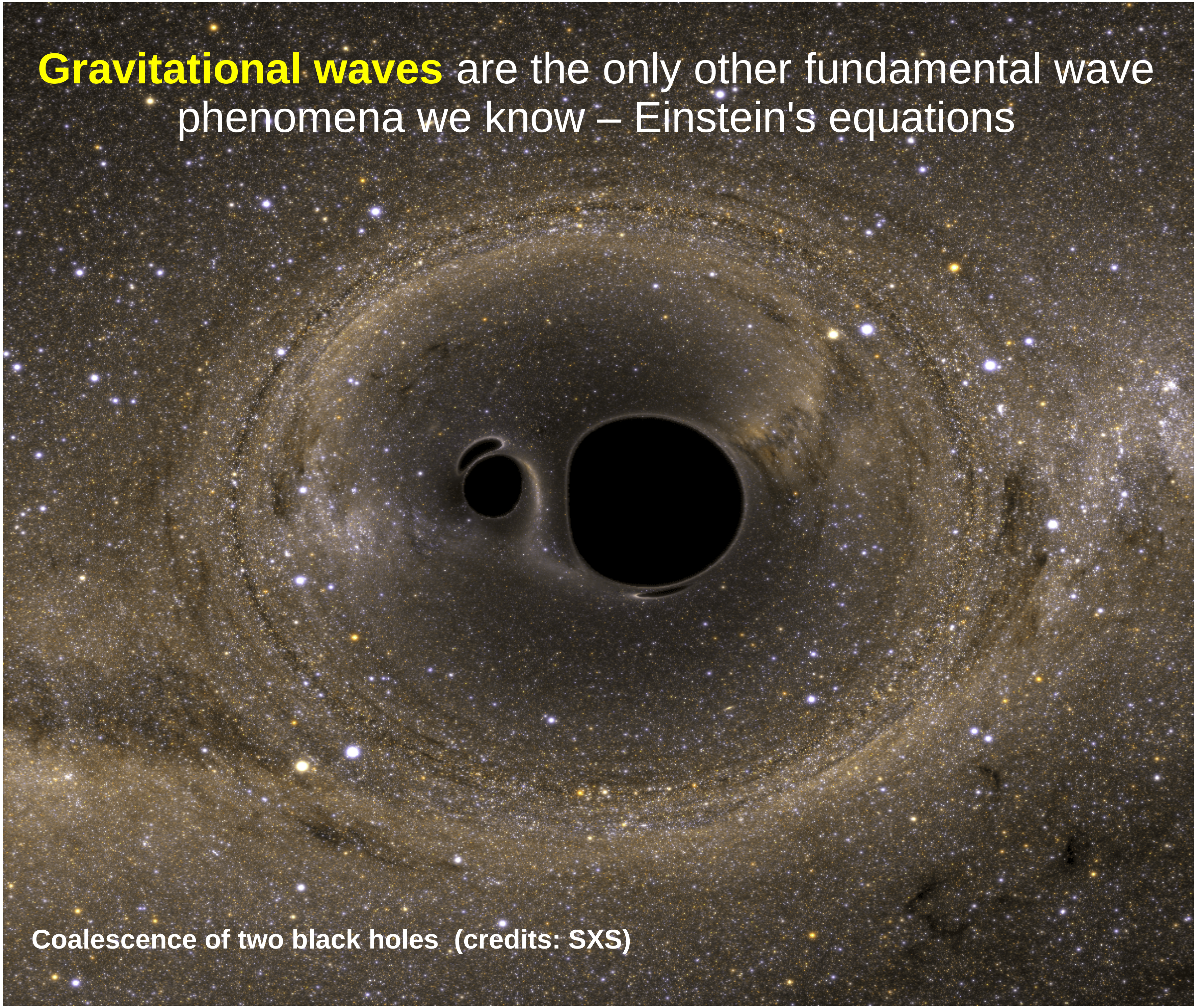
Coalescence of two black holes (credits: SXS)


The only fundamental waves we have observed so far are
electromagnetic waves – Maxwell's equations
(light, radio, microwaves, gamma rays, x-rays)
So far, our **knowledge of the Universe** essentially
comes from electromagnetic waves

Gravitational waves are the only other fundamental wave phenomena we know – Einstein's equations



Coalescence of two black holes (credits: SXS)

Outline

- Primer on gravitational waves

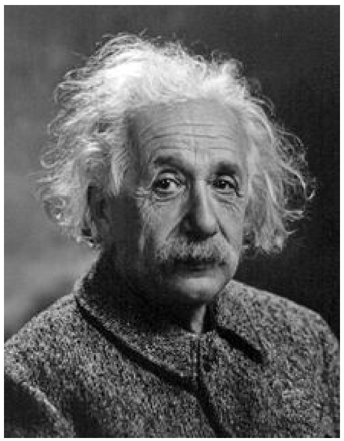
- Path to first detection: historical review

- Interferometric detectors: from principles to sensitivity

- Results from first aLIGO science run
  - Search summary
  - Science beyond detection
  - Multimessenger astronomy

- Outlook

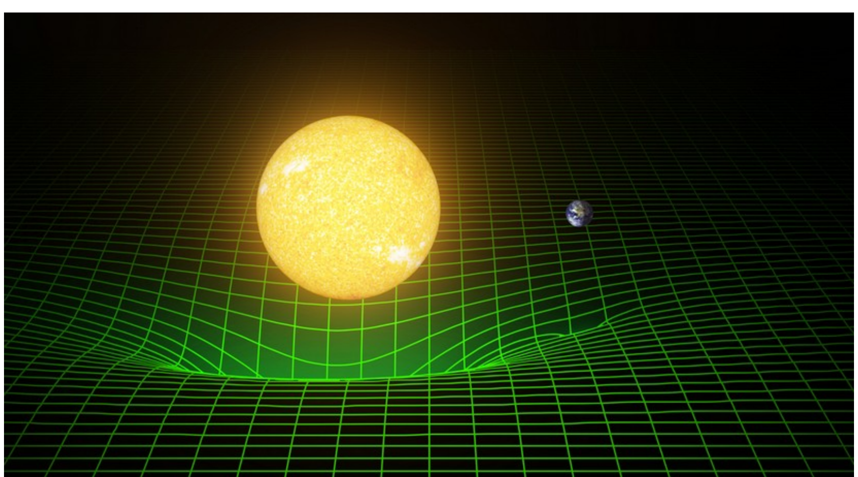
Einstein's General relativity



General relativity – 1915

- Spacetime is a deformable and dynamic object
- Gravity describes as a **geometrical effect coming from spacetime curvature**
- Einstein's fields equations

Space-time geometry
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$
Energy/ Matter



"spacetime tells matter how to move; matter tells spacetime how to curve"

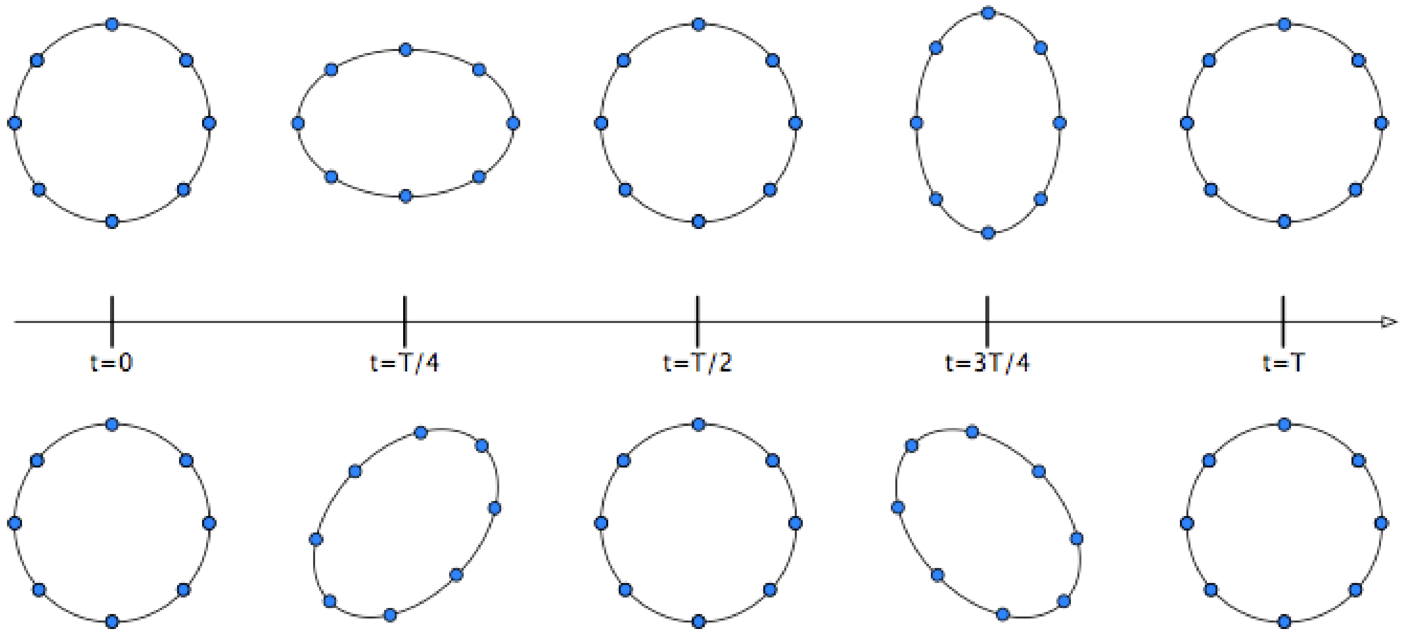
John Archibald Wheeler

Gravitational waves

- Linearization of Einstein equations

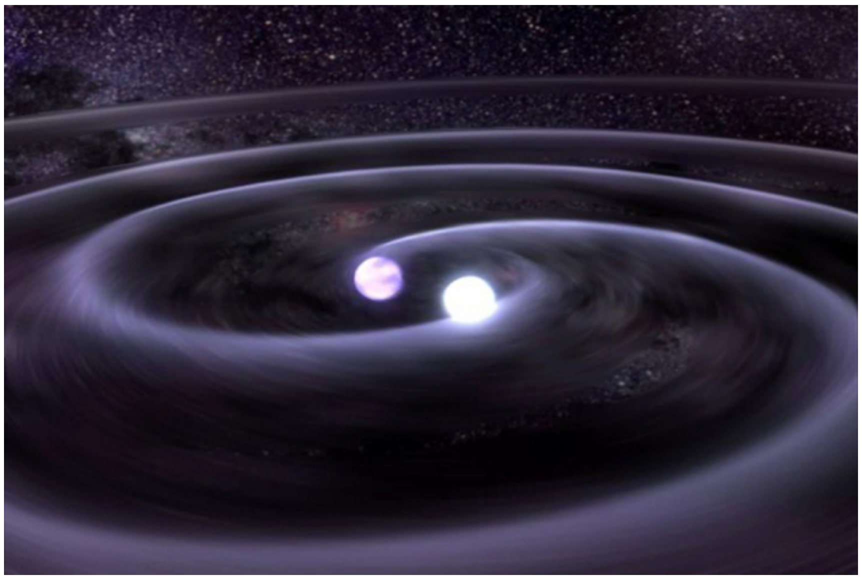
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad |h_{\mu\nu}| \ll 1 \longrightarrow \Box\, \bar{h}_{\mu\nu} = 0$$

- **Propagating perturbations of space-time metric**
  - Travel at the speed of light
  - Tranverse waves
  - Two polarisations x and +
  - Dimensionless strain amplitude *h*



$h \sim 0.5$
in this illustration

Gravitational waves



- Produced by **accelerated mass**
- Rapid changes in shape and orientation of massive systems
- Large masses, relativistic motion

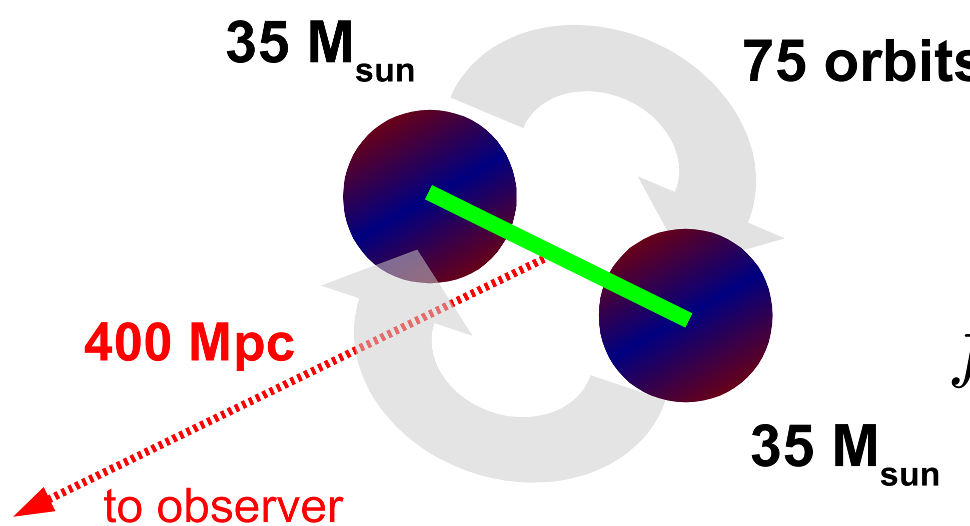
  → **astrophysical sources**
- Variation of the quadrupole

  → Inspiralling binaries of black holes and neutron stars

Quadrupole formula

$$h \sim G/c^4\, \ddot{Q}/d$$

$$c^4/G \sim 10^{44} N$$

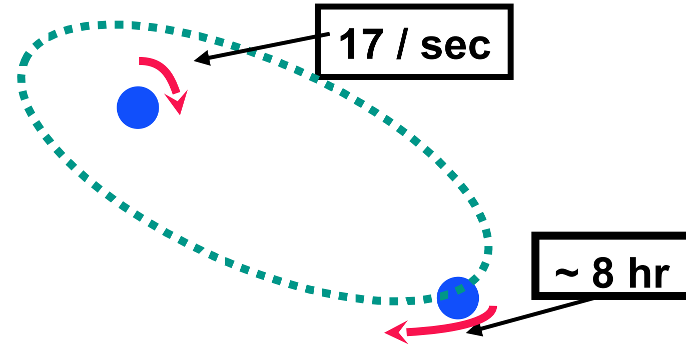


$$h \sim 10^{-21}$$

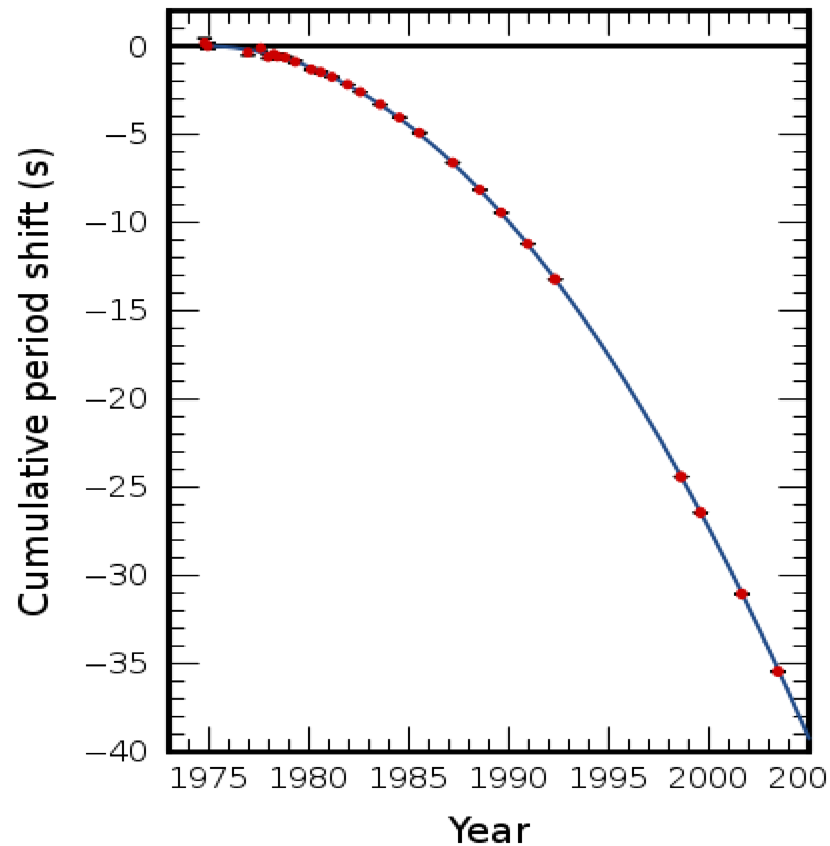
$$f_{GW} \approx 2 f_{\mathrm{orb}}$$

Evidence of existence

- Binary pulsar PSR B1913+16
  - Orbital decay → energy loss due to GW
  - In agreement with GR to ~0.2 %
  - Hulse & Taylor's Nobel prize 1993



« for the discovery of a new type of pulsar, a discovery that has opened up new possibilites for the study of gravitation »



Binary orbit will continue to decay
over 300 millions years until coalescence

R Hulse J Taylor J Weisberg T Damour

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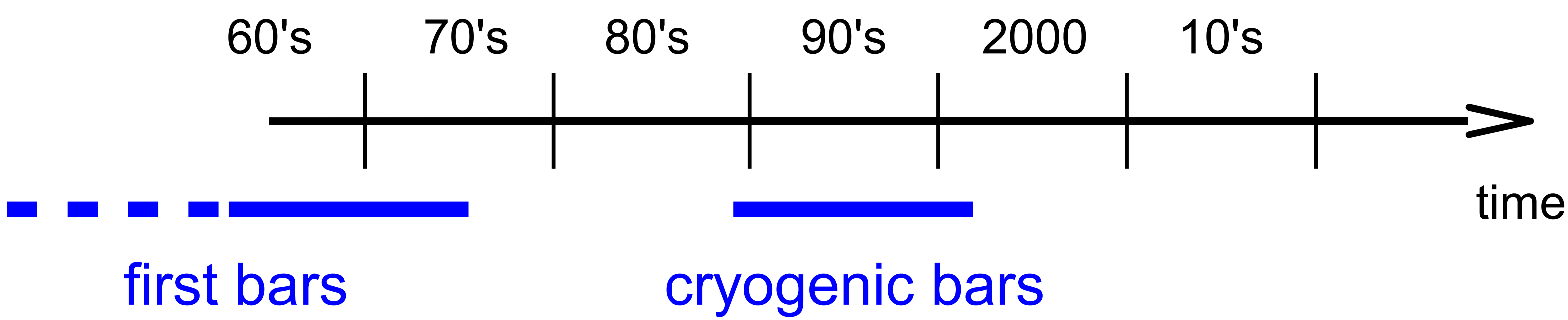
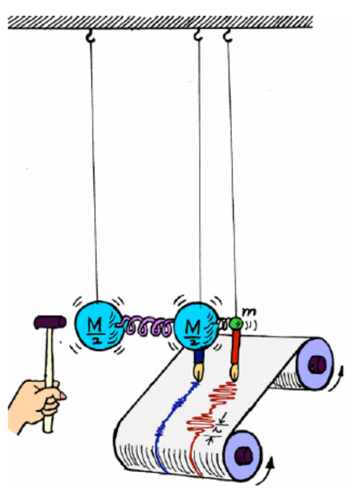
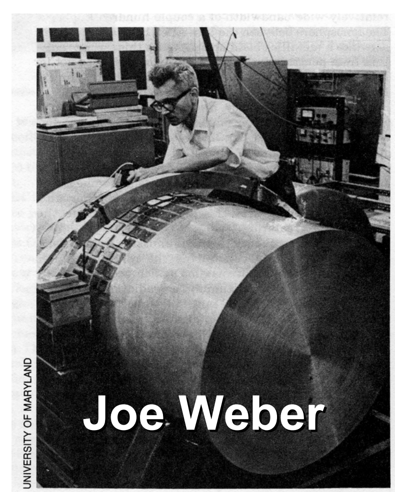
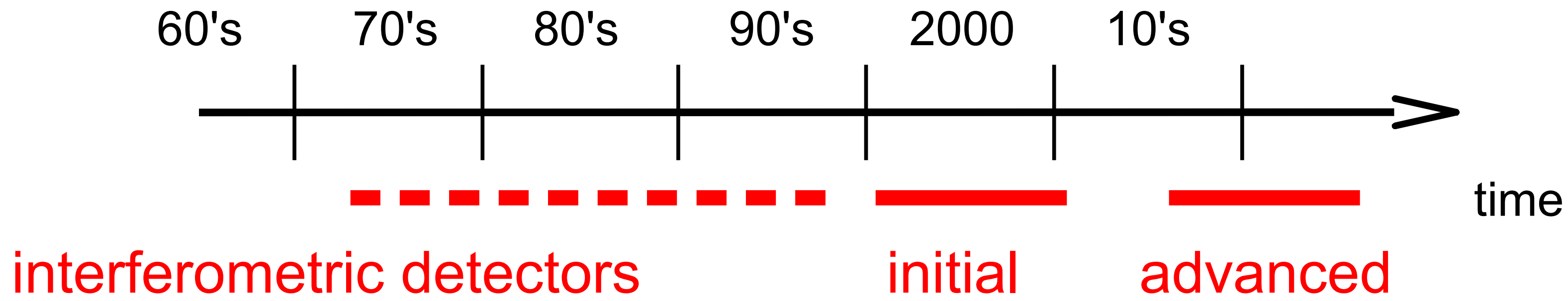
History of direct detection (1)

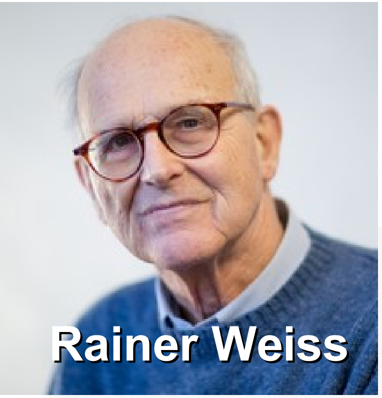


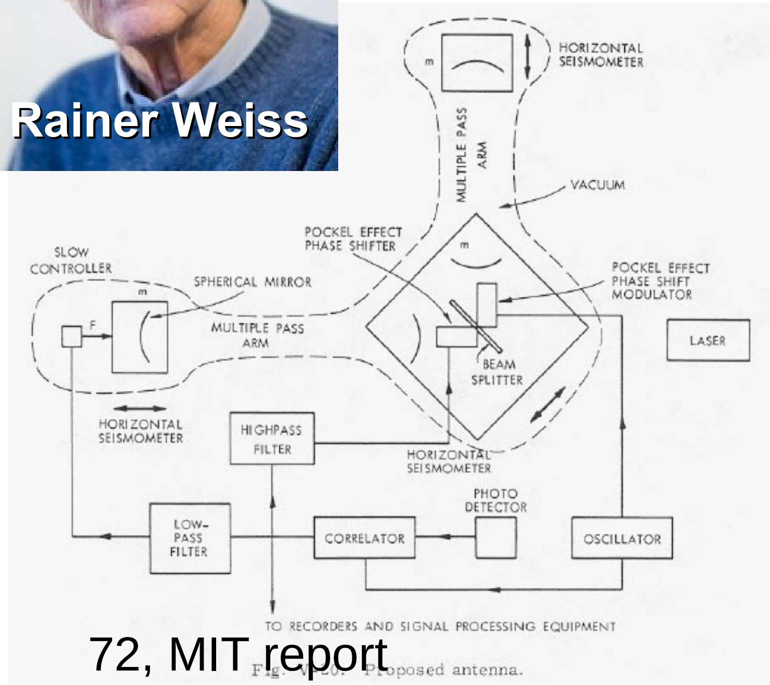




History of direct detection (2)







72, MIT report

Adalberto Giazotto
Alain Brillet

Since 2007 LIGO and Virgo operates as a network
Data are shared and analyzed jointly

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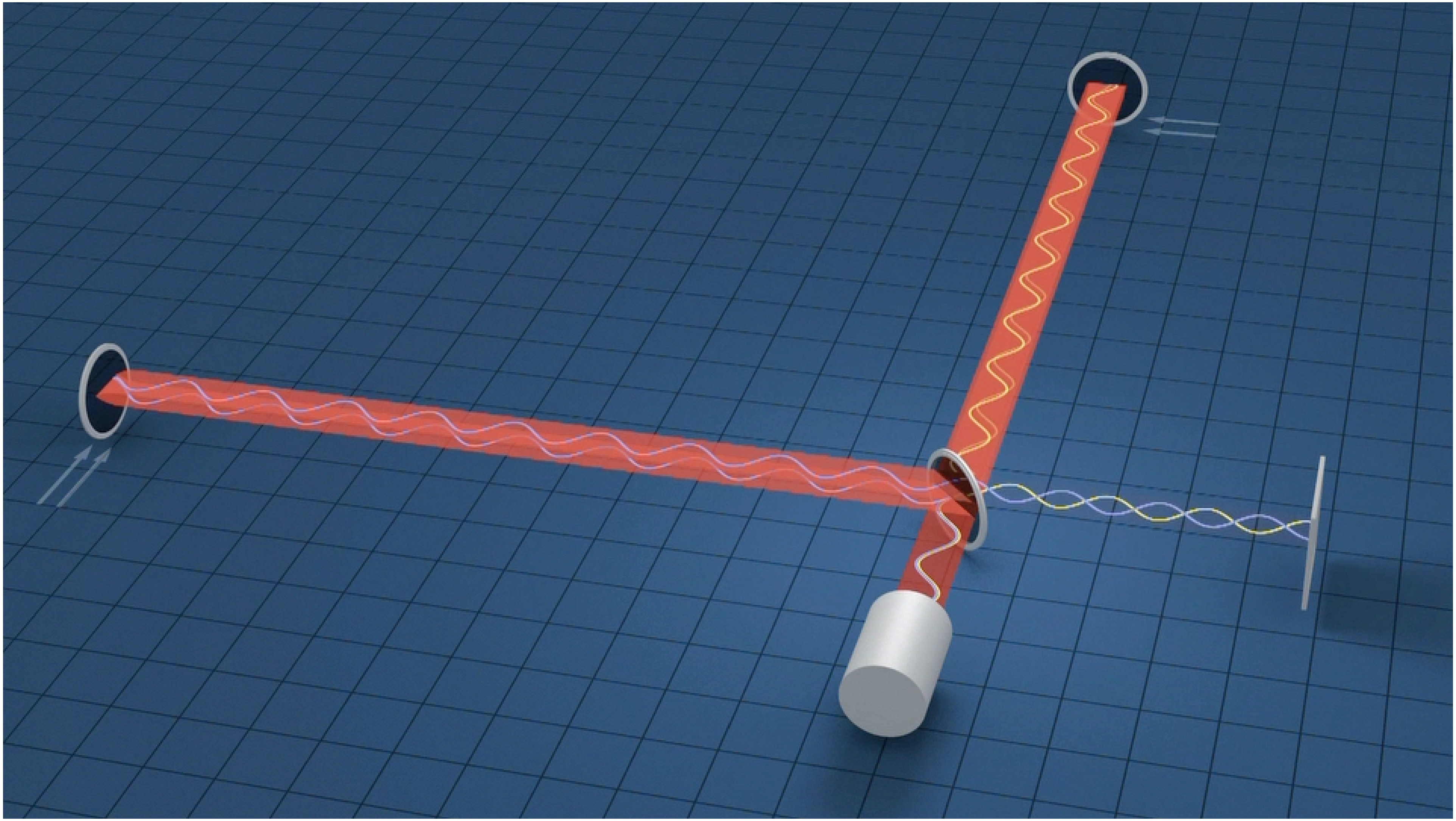
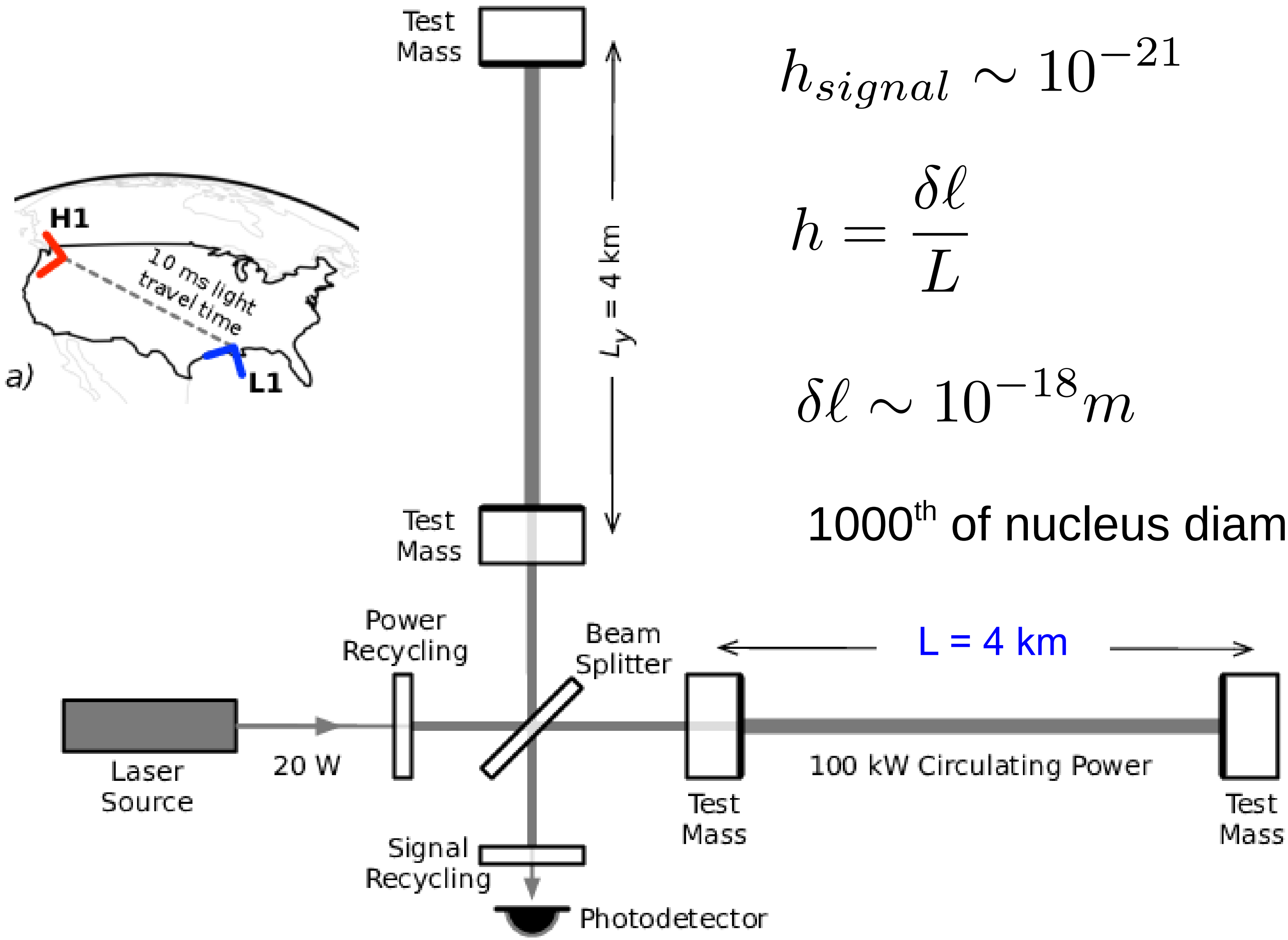
Michelson interferometer



Advanced LIGO (1)

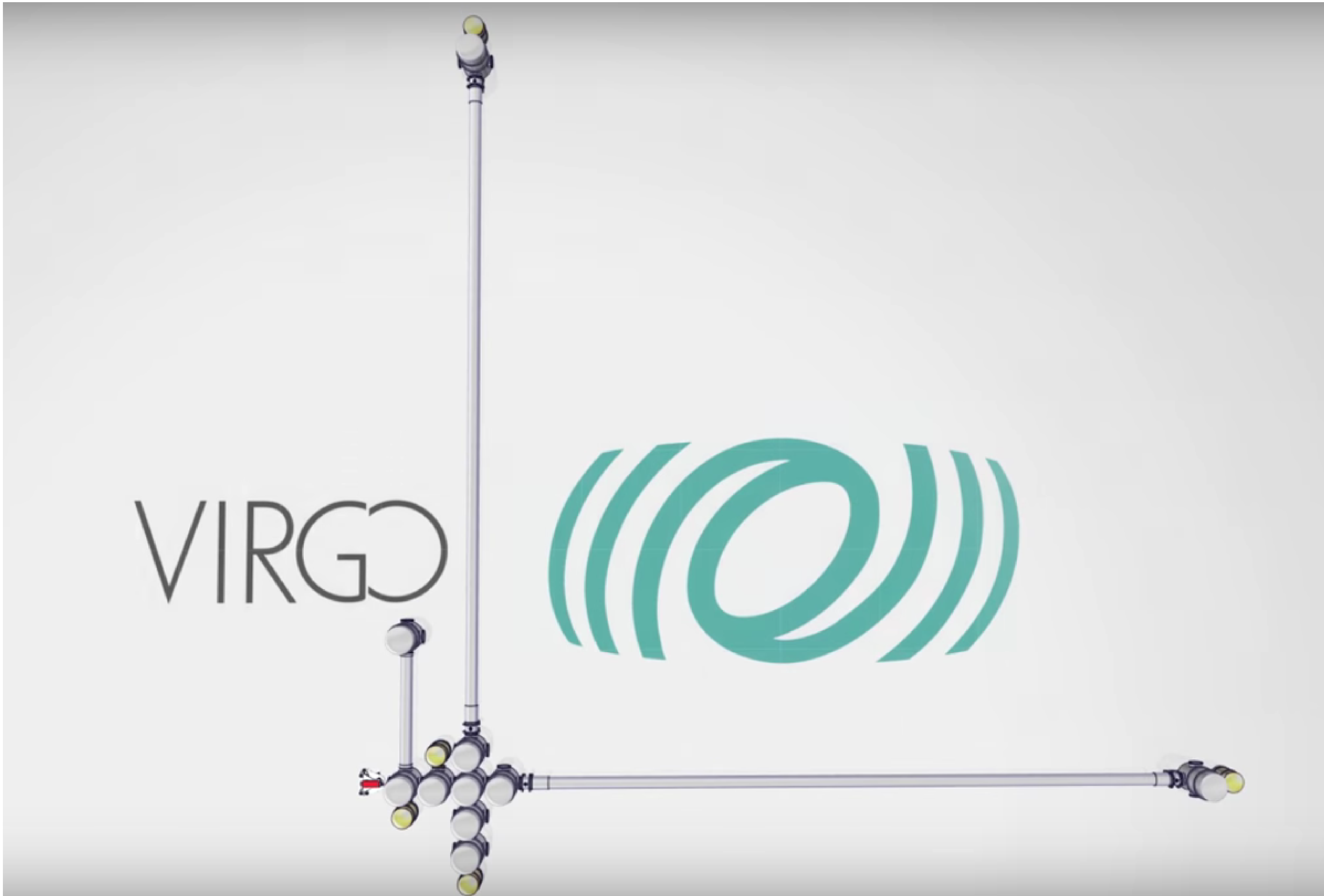


$$h_{signal} \sim 10^{-21}$$

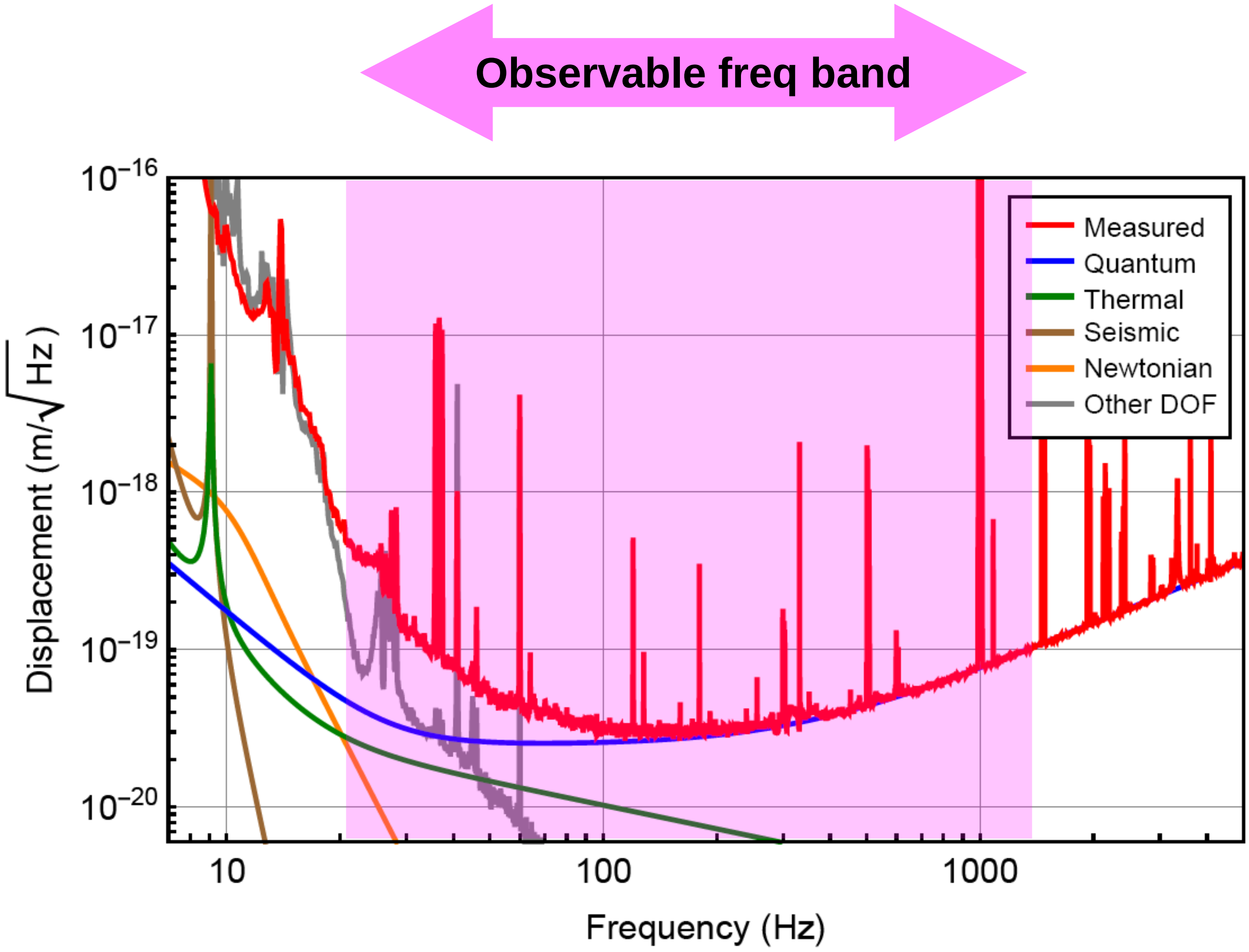
$$h = \frac{\delta\ell}{L}$$

$$\delta\ell \sim 10^{-18} m$$

1000th of nucleus diameter!


VIRGO

O1 science run
sep 2015 – 4 months



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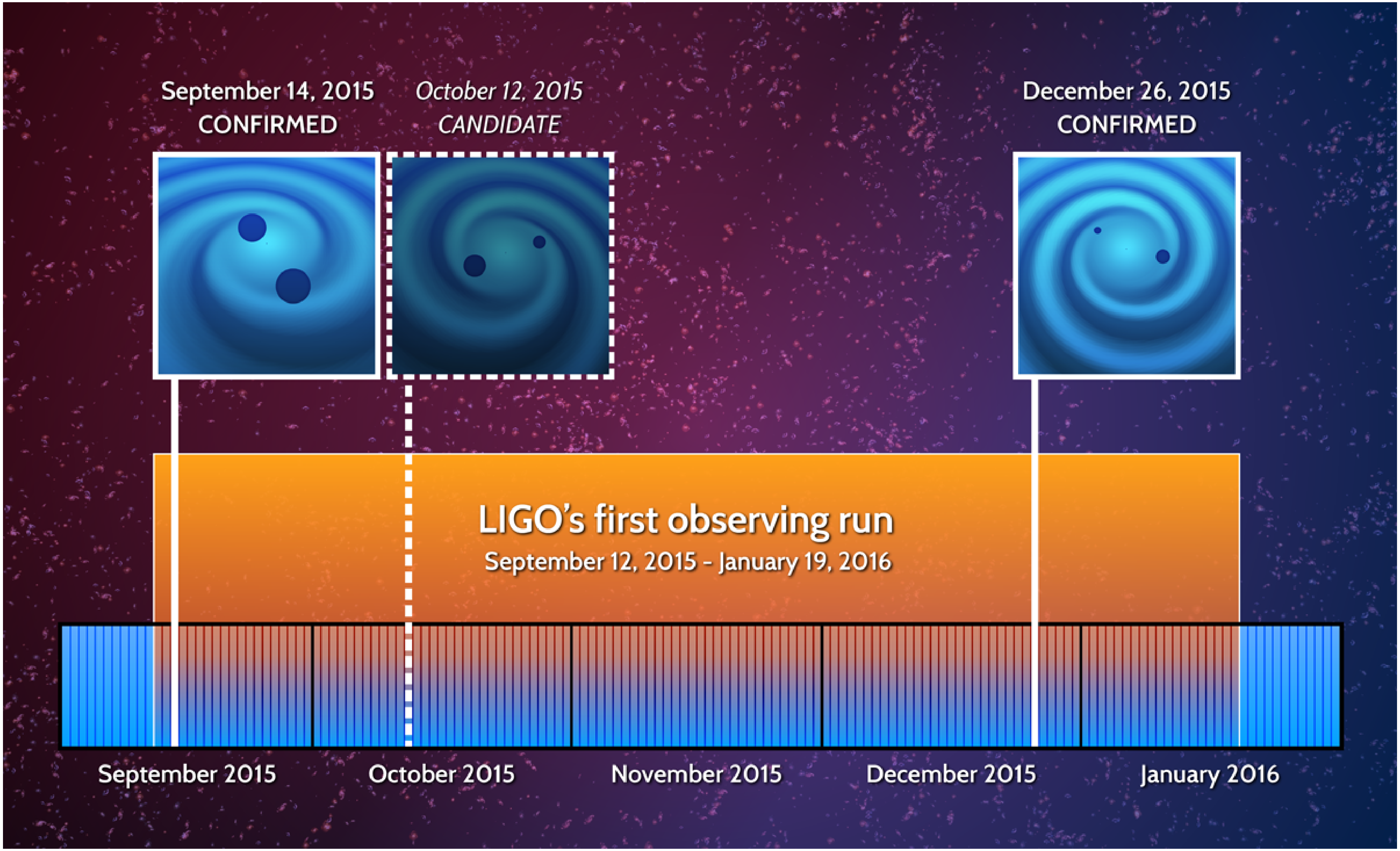
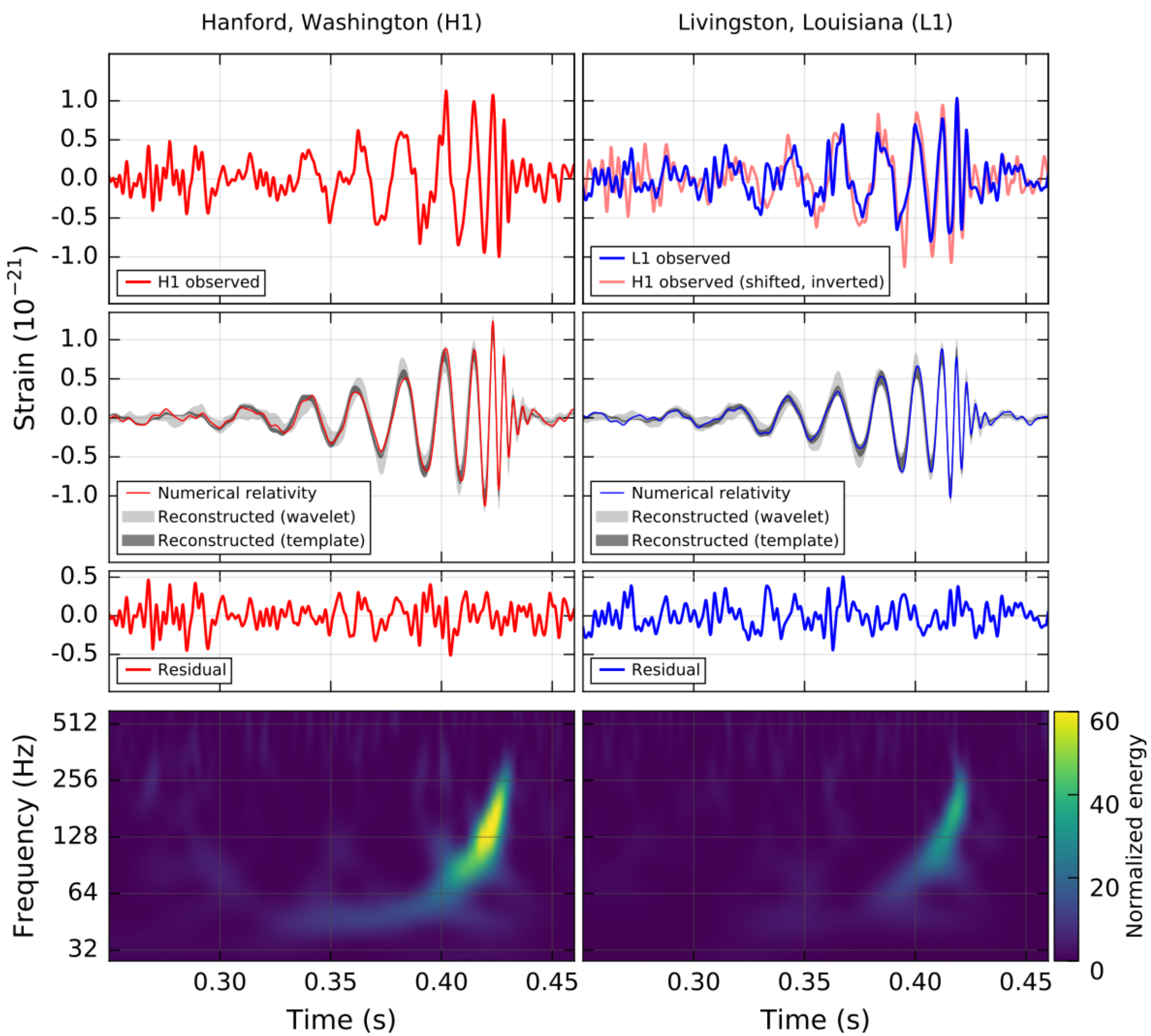

September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

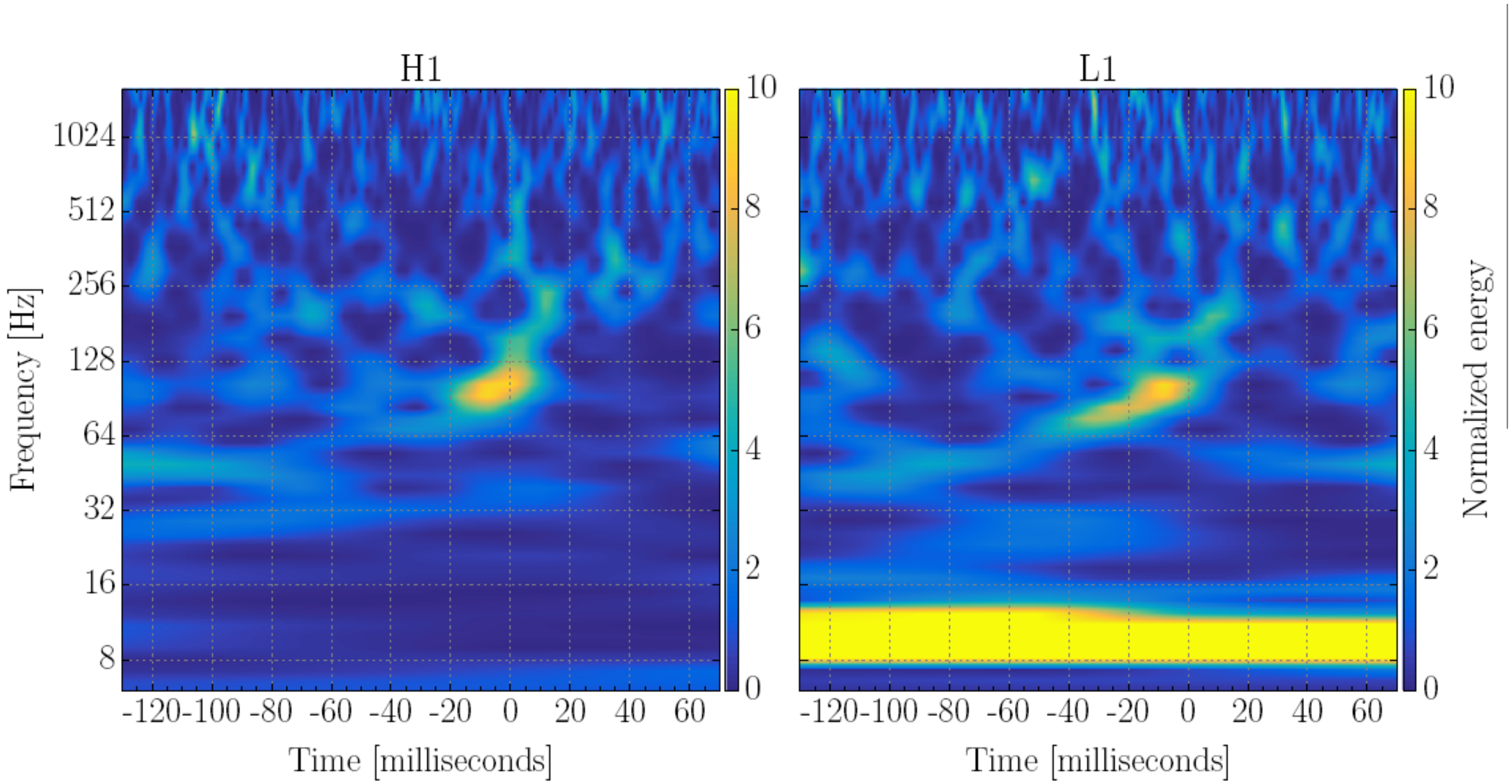
Sep 14, 2015 09:50:45 UTC



Merger of $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$ black holes at 410^{+160}_{-180} Mpc

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

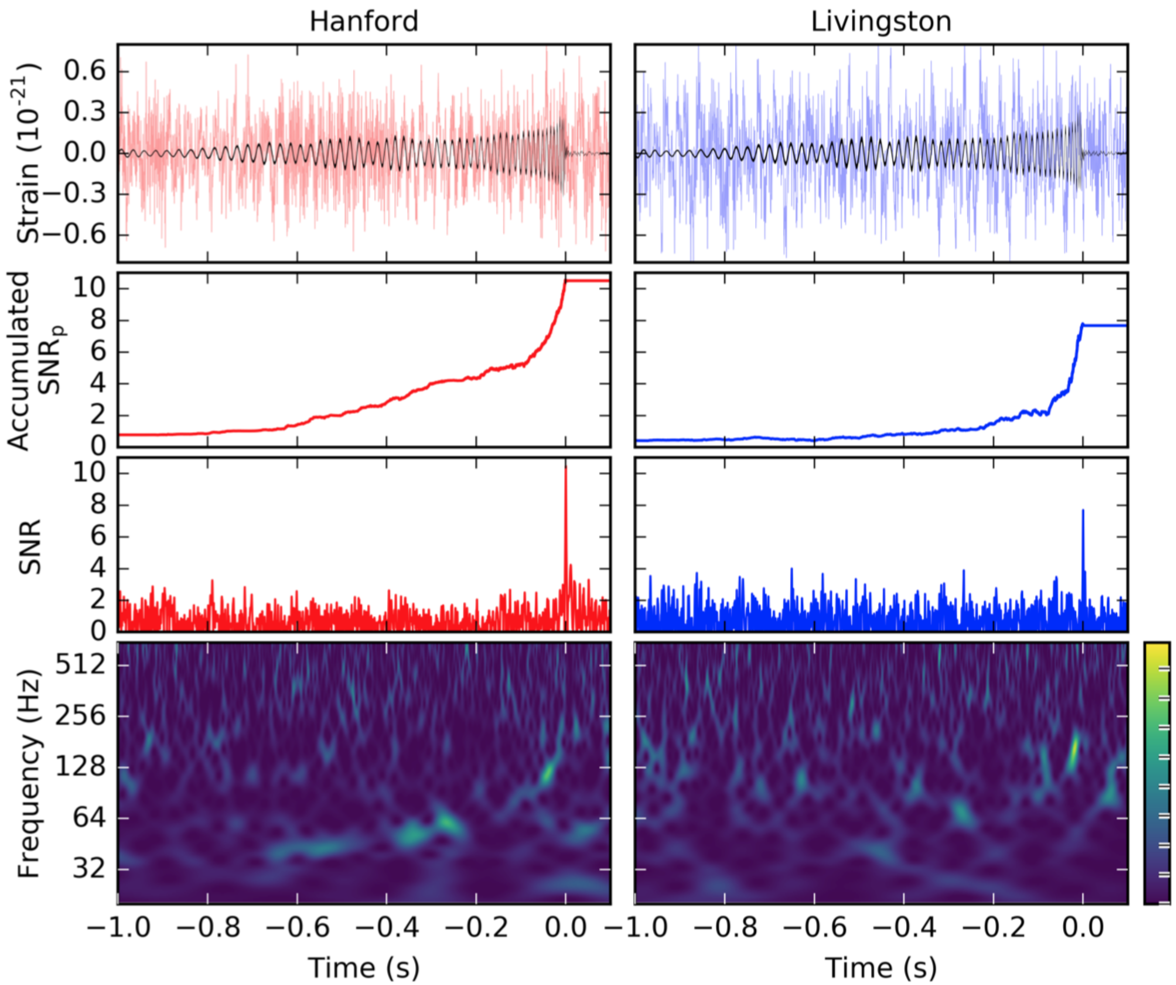
Oct 12 2015 09:54:43 UTC



Likely merger of $23^{+18}_{-5}\ M_\odot$ and $13^{+4}_{-5}\ M_\odot$ black holes at 1100^{+500}_{-500} Mpc

arXiv:1606.04856

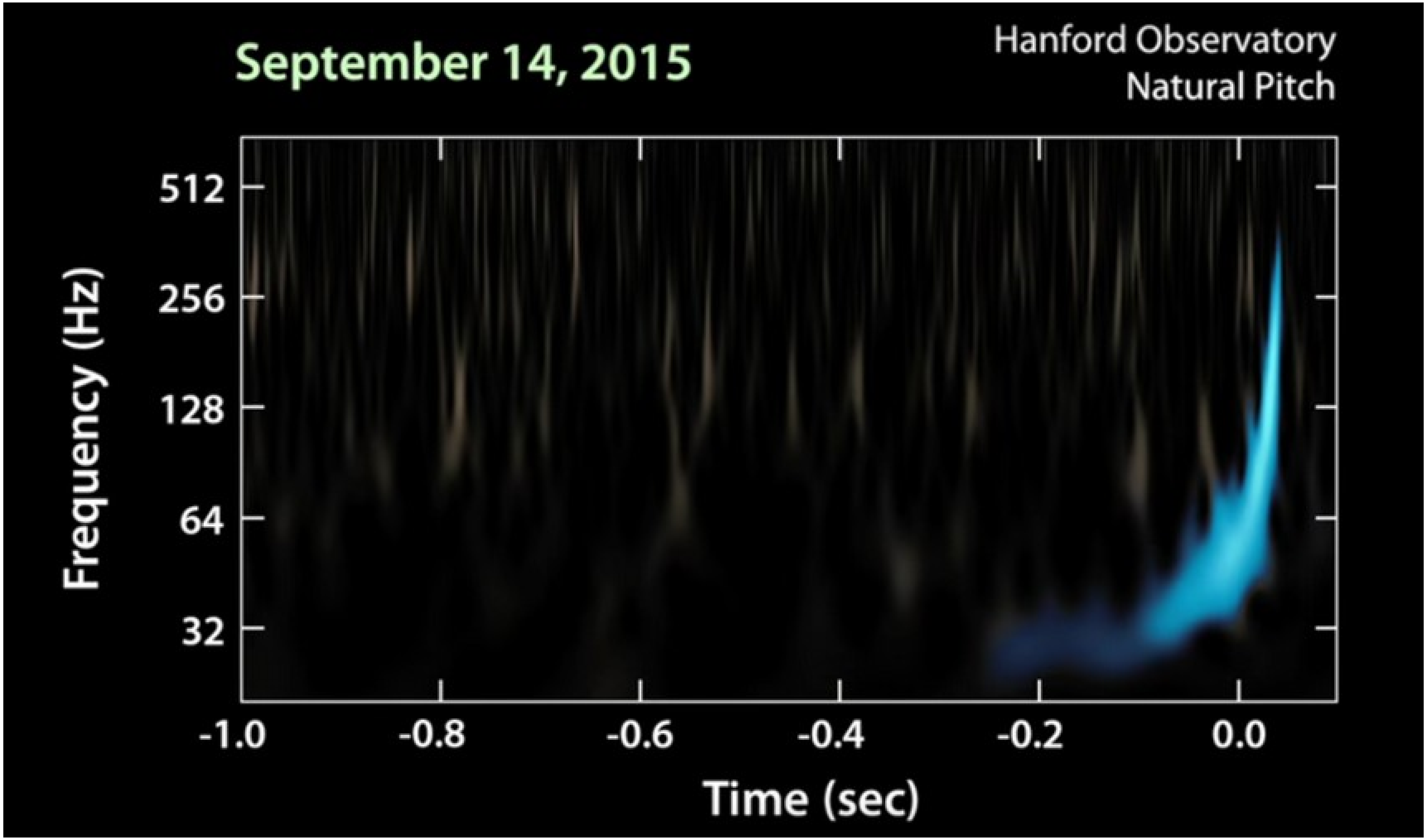
Dec 26 2015 03:38:53 UTC



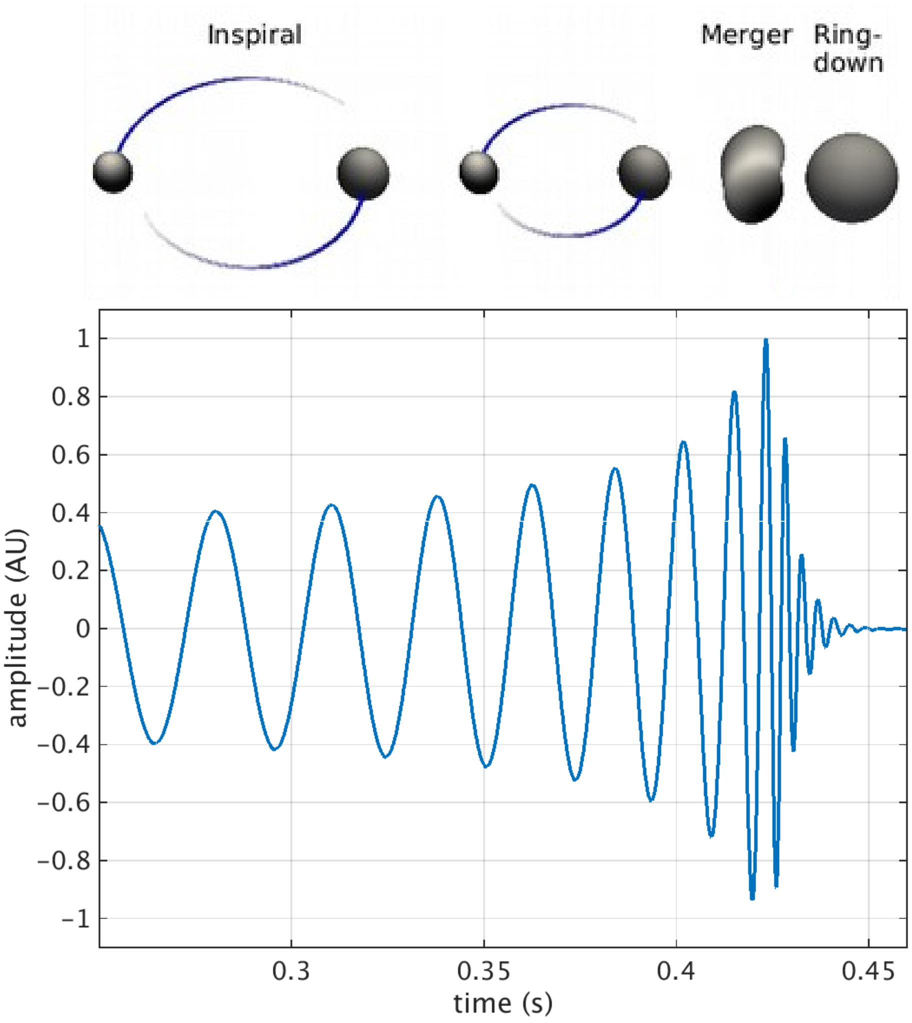
Merger of $14.2^{+8.3}_{-3.7} M_\odot$ and $7.5^{+2.3}_{-2.3} M_\odot$ black holes at 440^{+180}_{-190} Mpc

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

Chirps!


September 14, 2015
Hanford Observatory
Natural Pitch
512
256
128
64
32
Frequency (Hz)
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
Time (sec)

What did we search for?

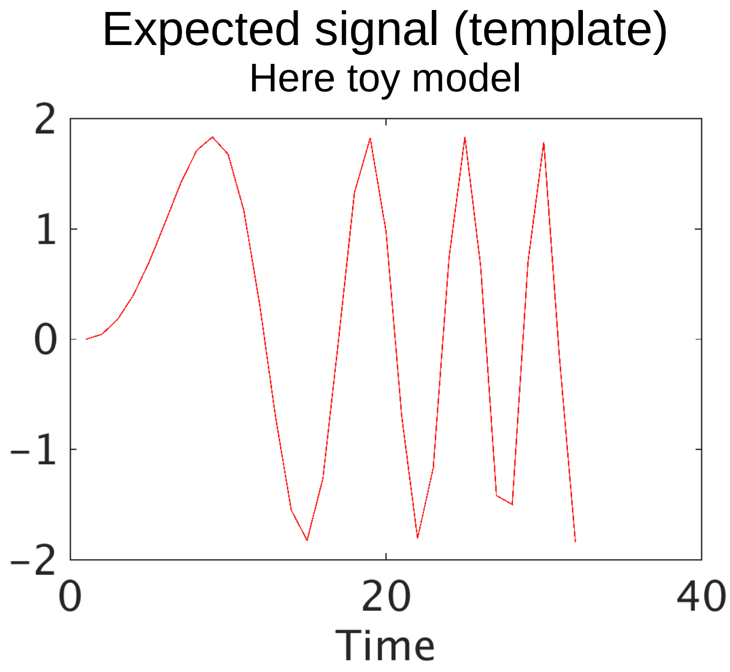


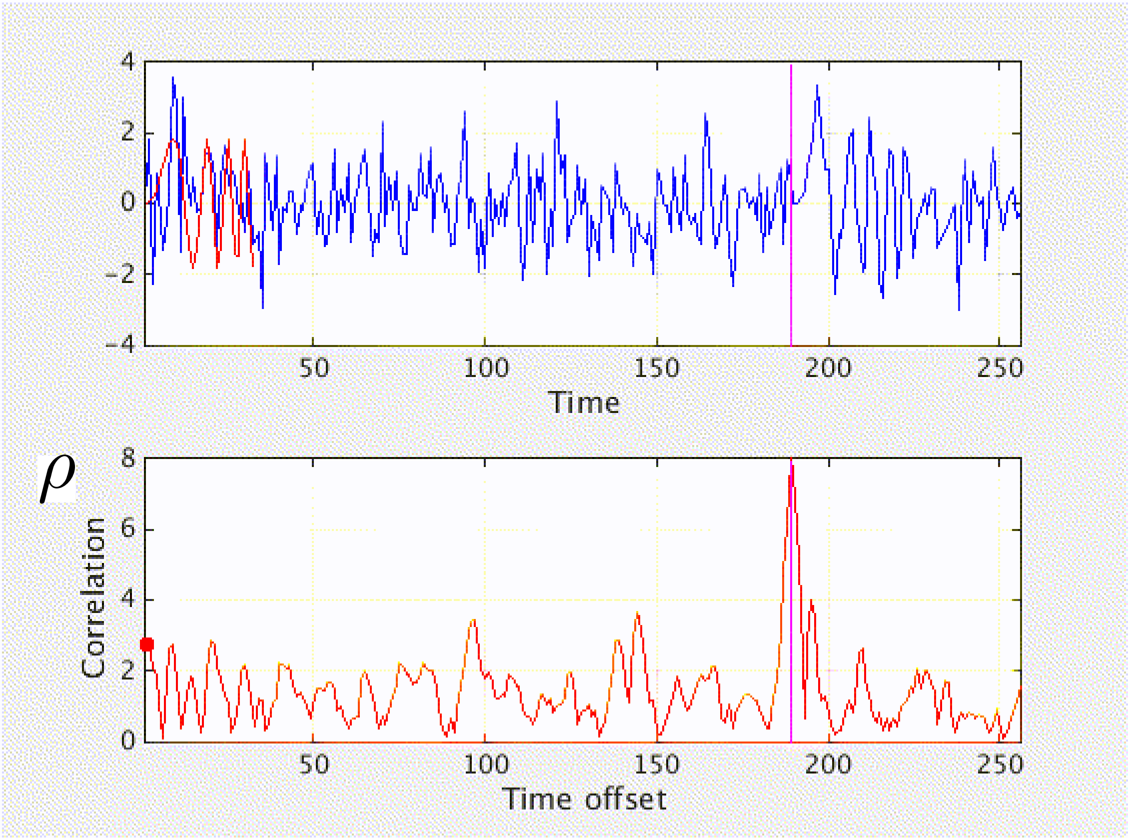
Template from astrophysical model

- Characteristic chirp waveform
- Encodes system dynamics
  - Inspiral
    - Leading order: *chirp mass*
    - Next to leading order: mass ratio, spin (assumed aligned with orbital angular momentum)
  - Merger and ringdown
    - Governed by final black-hole mass and spin
- 11 parameters total
  - 4 mass and (aligned) spins, and geometrical params (no excentricity)

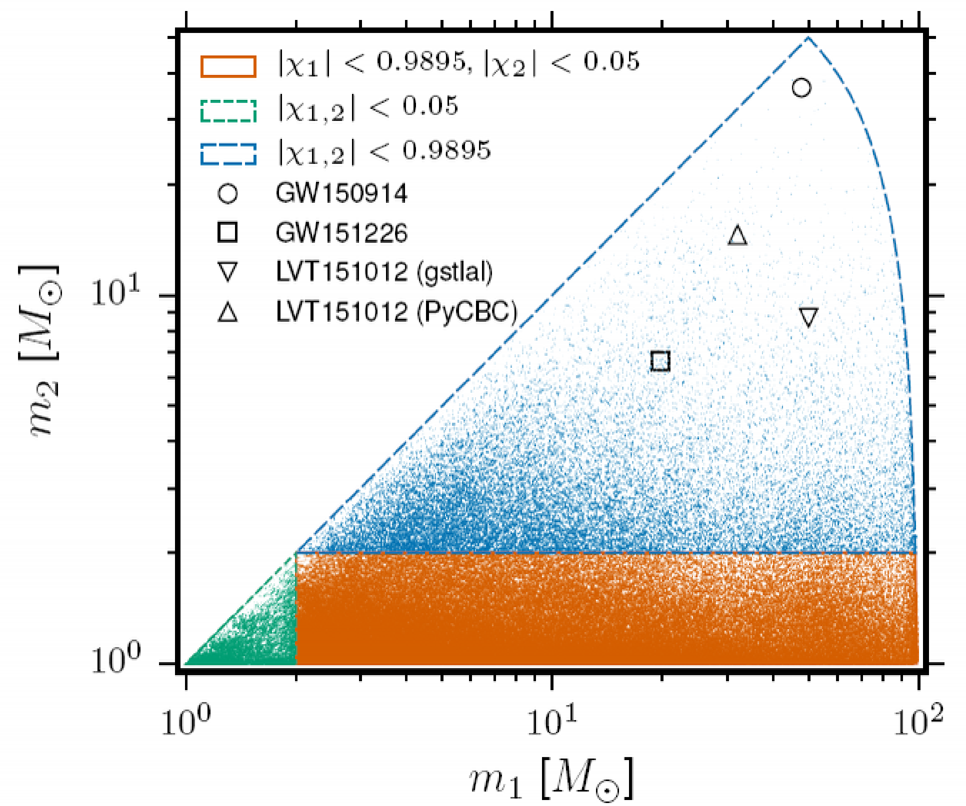
How did we search? Matched filtering

Correlate data with expected signal





Matched filtering: basic ideas (2)



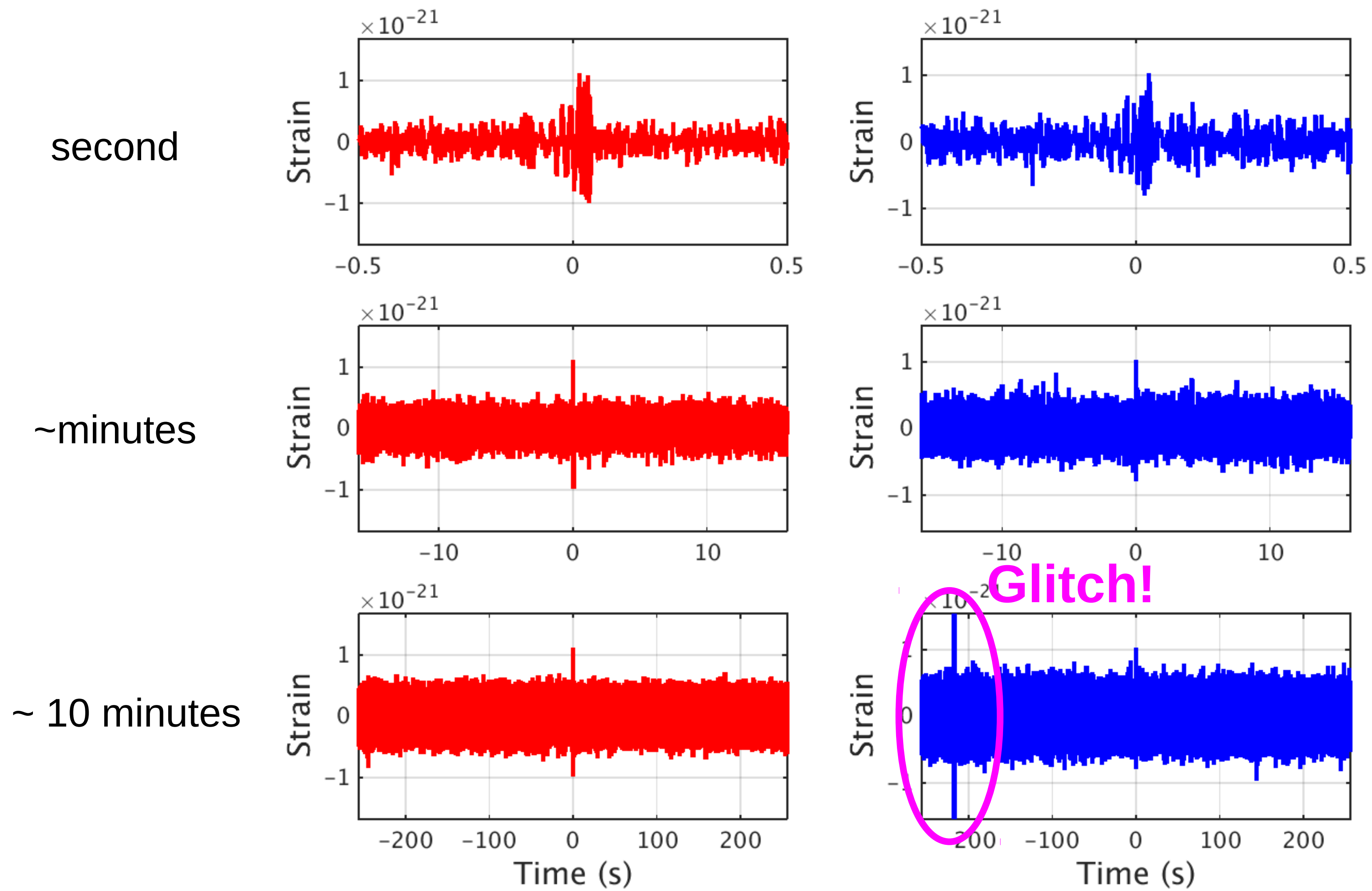
250 000 templates

covers BNS, NS-BH, BBH

Bank of chirp templates

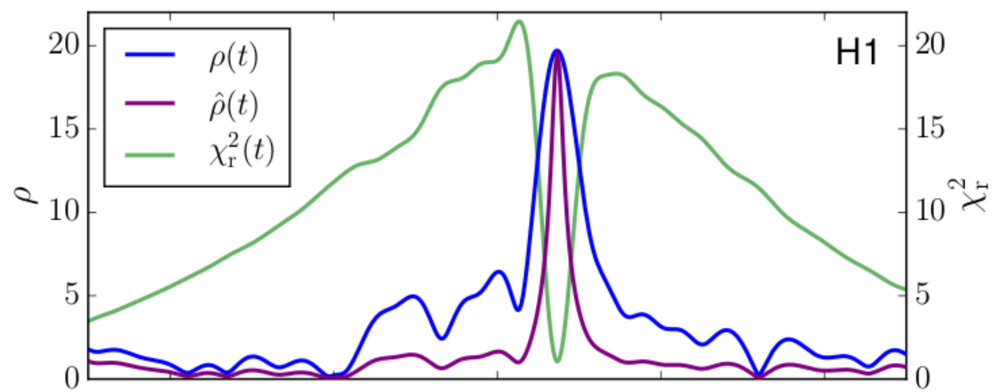
- Detect **any signal** in a **space of possible signals** all with different phase evolution
- Do it with a **finite set of templates**!
- Make sure there is a “close” template for every part of the signal space
- Natural metric: correlation between neighboring templates → regular or random lattices of templates

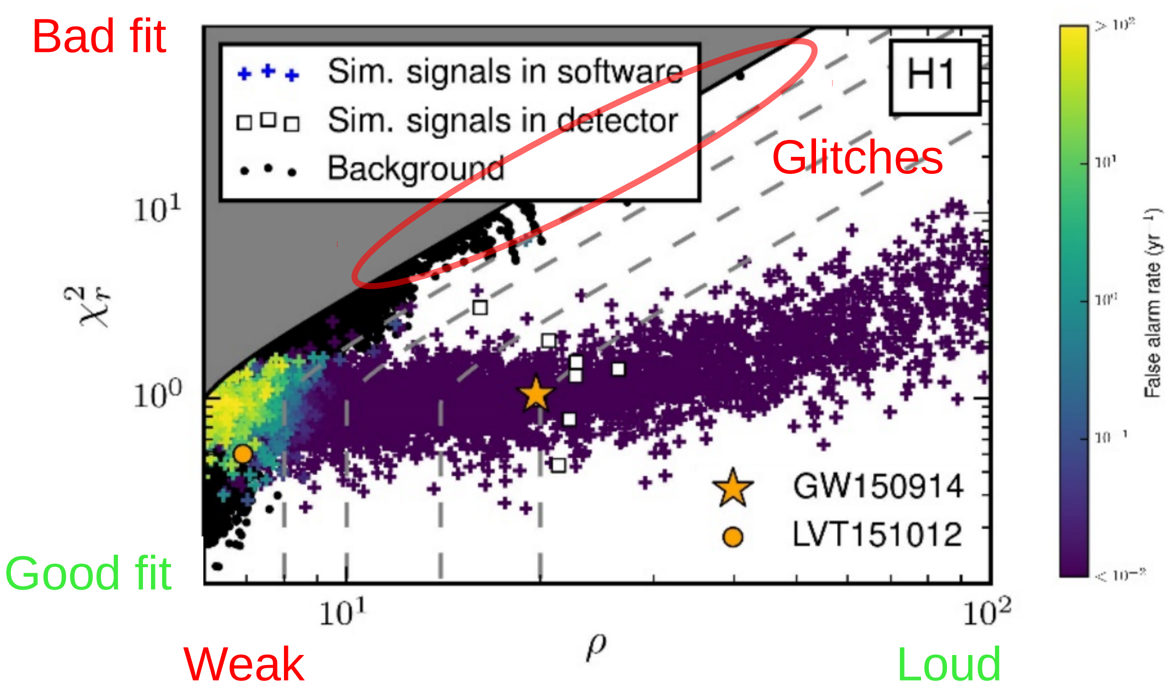
Non-Gaussian noise – Glitches



Glitch rate ~ 1 per few seconds to 1 per 20 min

Signal consistency





Non-Gaussian artefacts (glitches)

Waveform consistency

- χ^2_r test that checks consistency of spectral power distribution
- Detection statistic

$$\hat{\rho} = \rho \left\{ [1 + (\chi^2_r)^3]/2] \right\}^{-1/6}$$

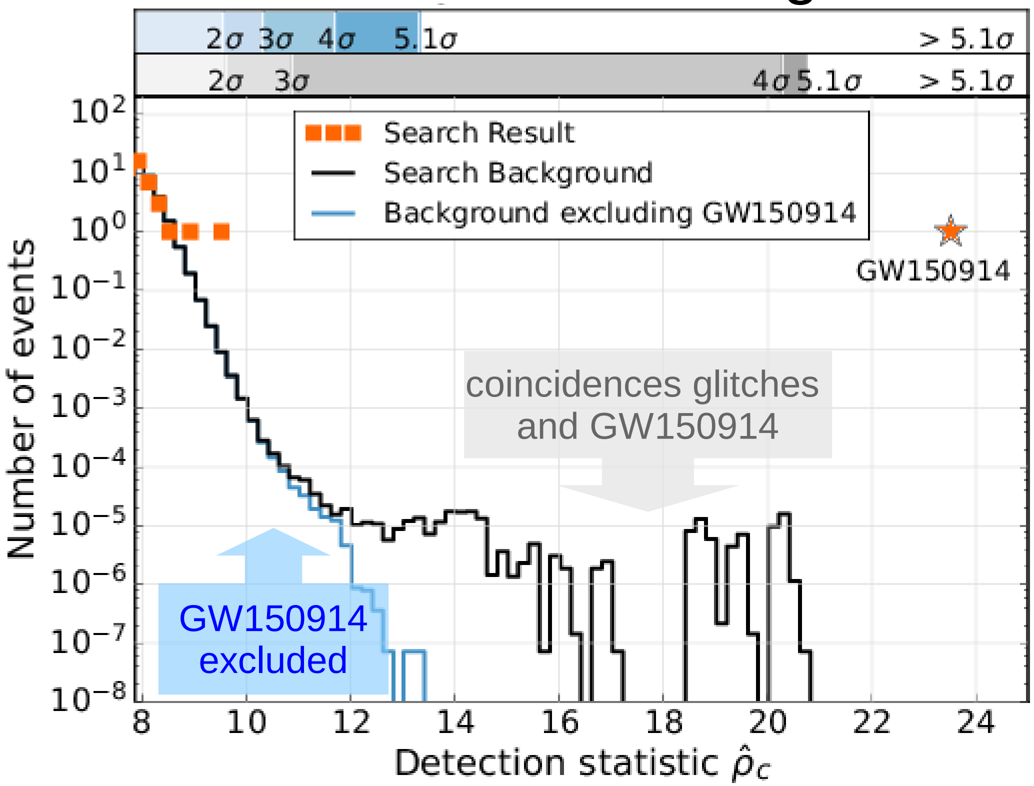
Coincident triggers in both detectors (time and mass/spins)

Statistical significance (1)

- What is the chance that this event is noise? (i.e., the event **statistical significance**)
  - Probability that glitches occur in coincidence at both detectors
  - Challenging to **measure the experimental background**
    - Non-Gaussian noise (glitches) is **impossible to model**
    - **Can't shield the detector** from gravitational wave!
    - Estimate background to **high-significance (*p-value* $< 10^{-6}$)**
      For comparison: glitch occurrence ~1–10% of observation time
- **Empirical estimate from the data – resampling**
  - Data time-stamps are artificially shifted by an offset much larger than the inter-site propagation time
  - Repeat this operation million times with different offsets

Statistical significance (2)

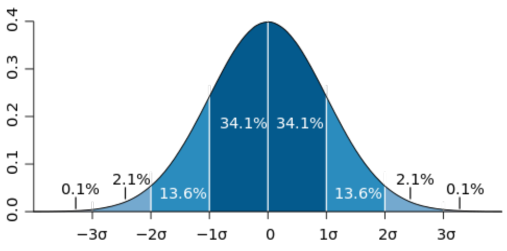
Binary coalescence search
Matched filtering



> 5.1 σ

Probability that this event is due to background alone is ~ 1/5 000 000

16 days of observation → less than 1 noise event per 203 000 years

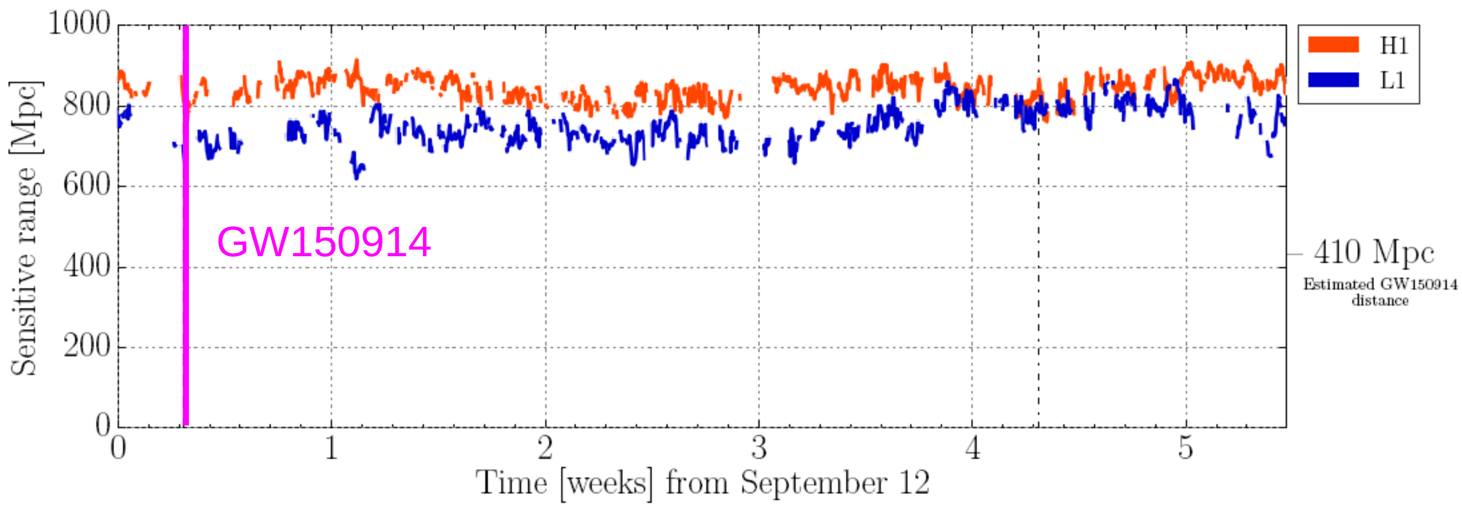


5σ

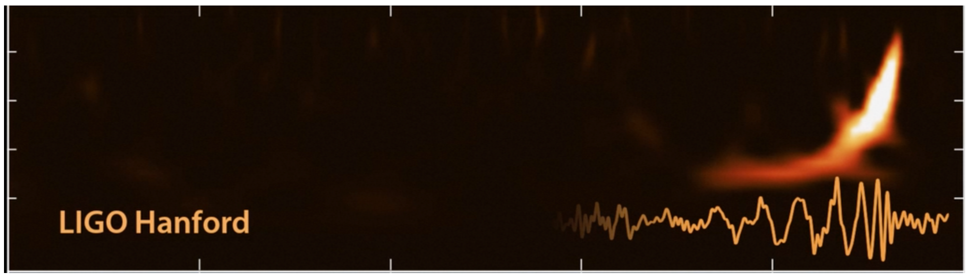
↓

Why are we confident in the detection?

- Event occurred in a **normal/stable operation period**
- **Monitor instrument and environment constantly**
  - 200 000 auxiliary channels
  - Seismometers, microphones, magnetometers, …
  - Coupling measured between the instrument environment and *h(t)*
- Environmental origin for GW150914 **ruled out**
  - Excess power in any auxiliary channel too small by factor > 17 to account for GW150914
  - Would not match signal morphology anyway



How do we know this is a black hole binary?



Over 200 ms, **frequency and amplitude increase** from 35 to 150 Hz (~8 cycles)

- GW-driven of two orbiting masses
- Inspiral evolution characterized by **chirp mass**

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

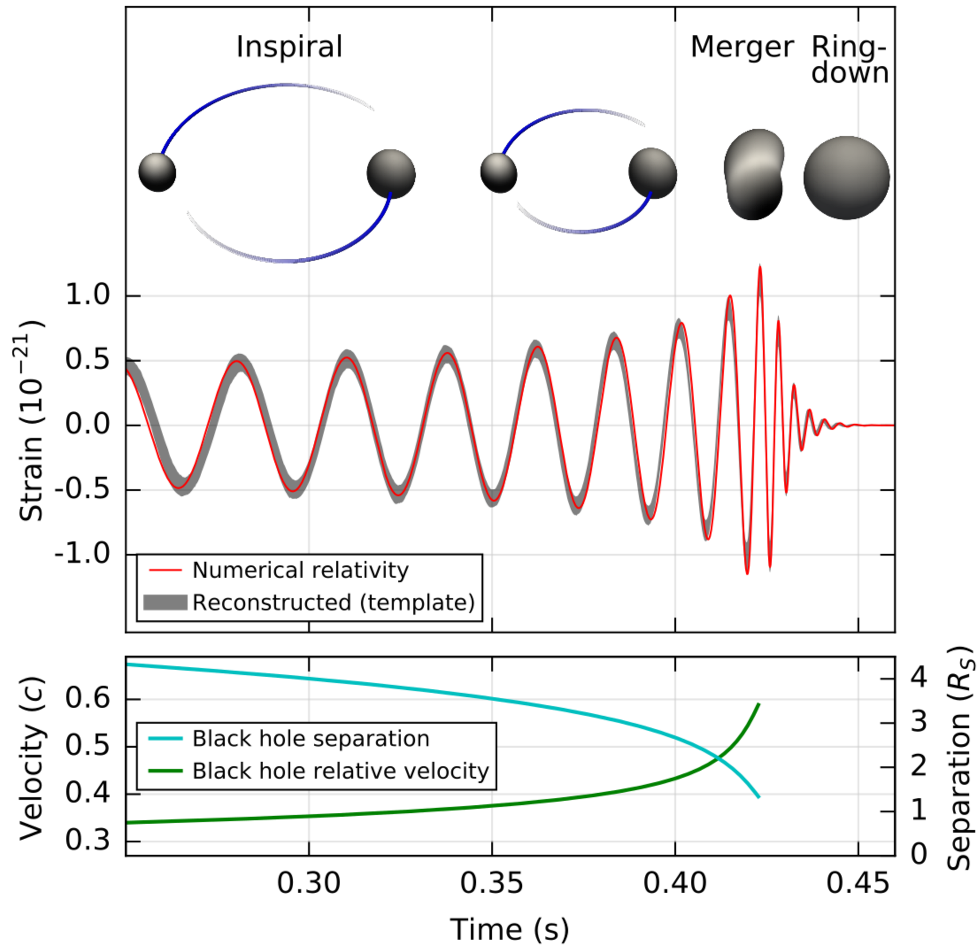
$$\mathcal{M} \approx 30 M_\odot \qquad M > 70 M_\odot$$

Keplerian separation gets close to Schwarzschild radius

- BNS too light, NSBH would merge at lower frequencies

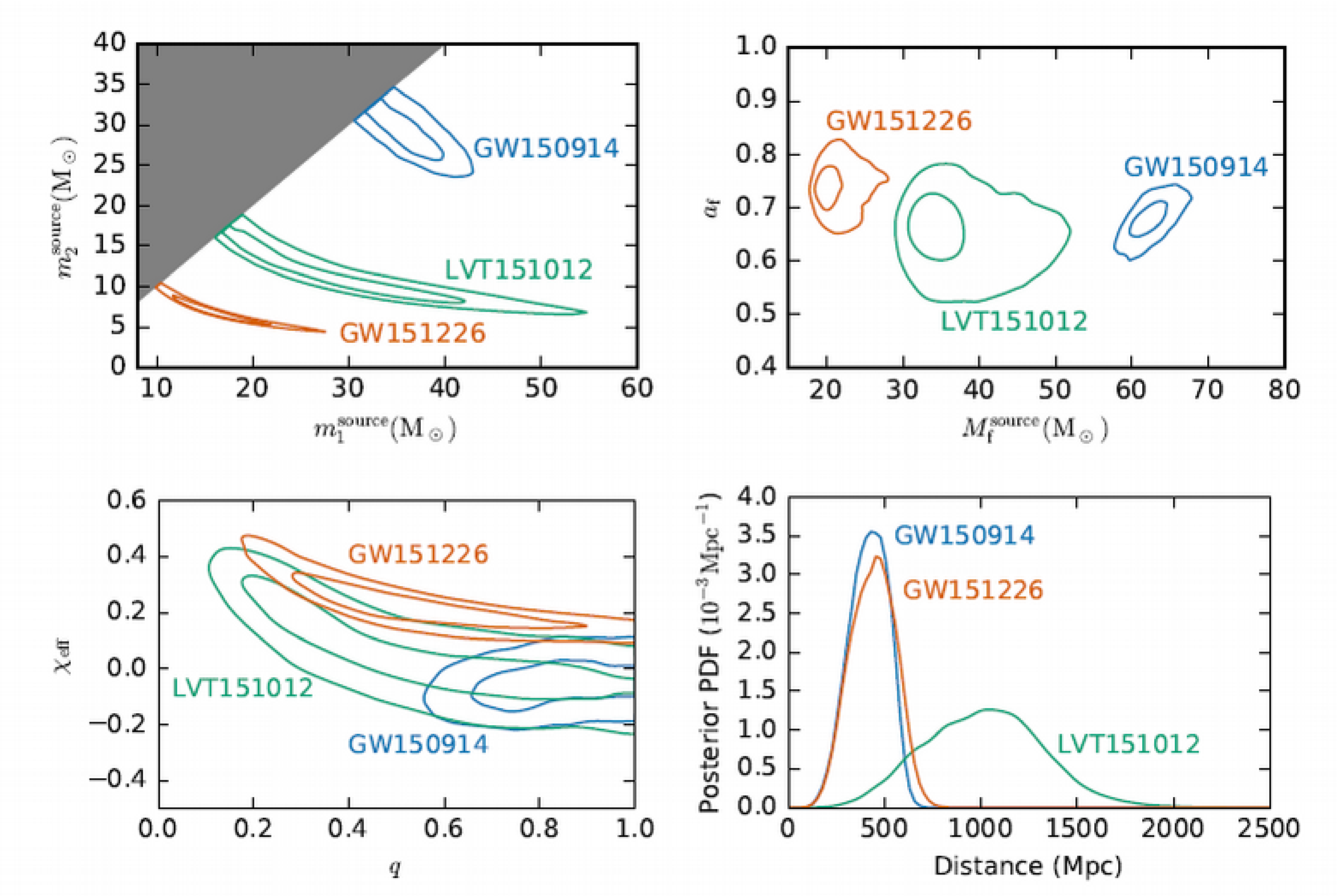
Decay of waveform after peak

- Consistent with damped oscillations of BH relaxing to final stationary Kerr configuration
- But SNR too low to claim observation of normal modes



$$R_S = 2GM/c^2 \geq 210\,\mathrm{km}$$

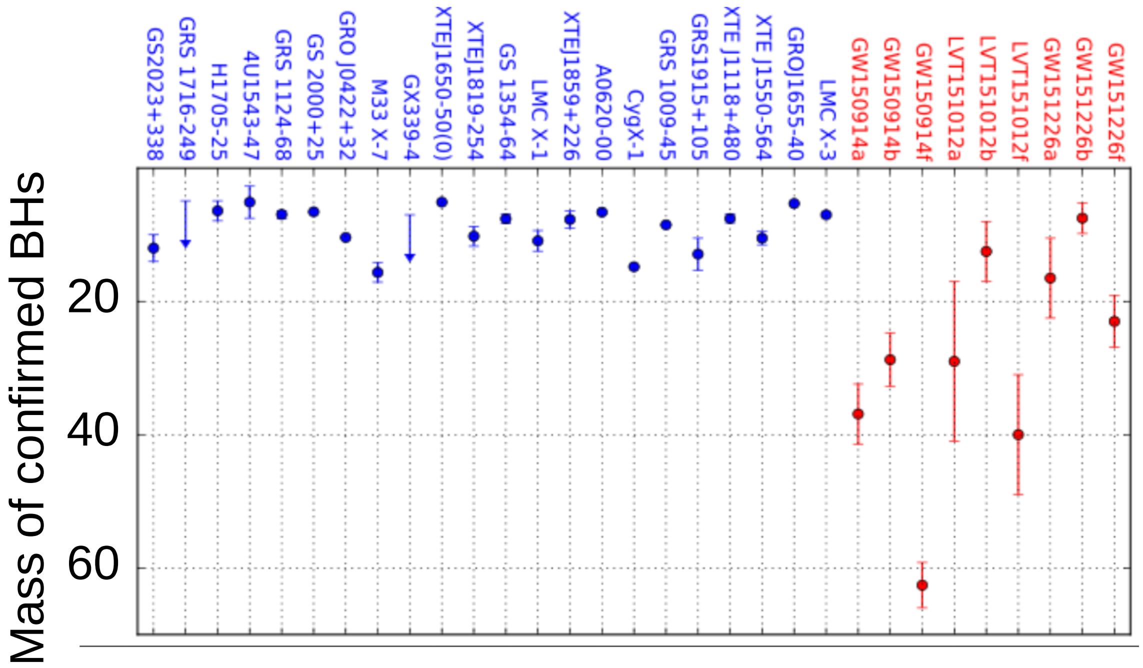
Beyond detection: Parameter estimation



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR/yr^{-1}}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_f^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

~50 x more luminous than all the stars in the Universe!

Astrophysical implications



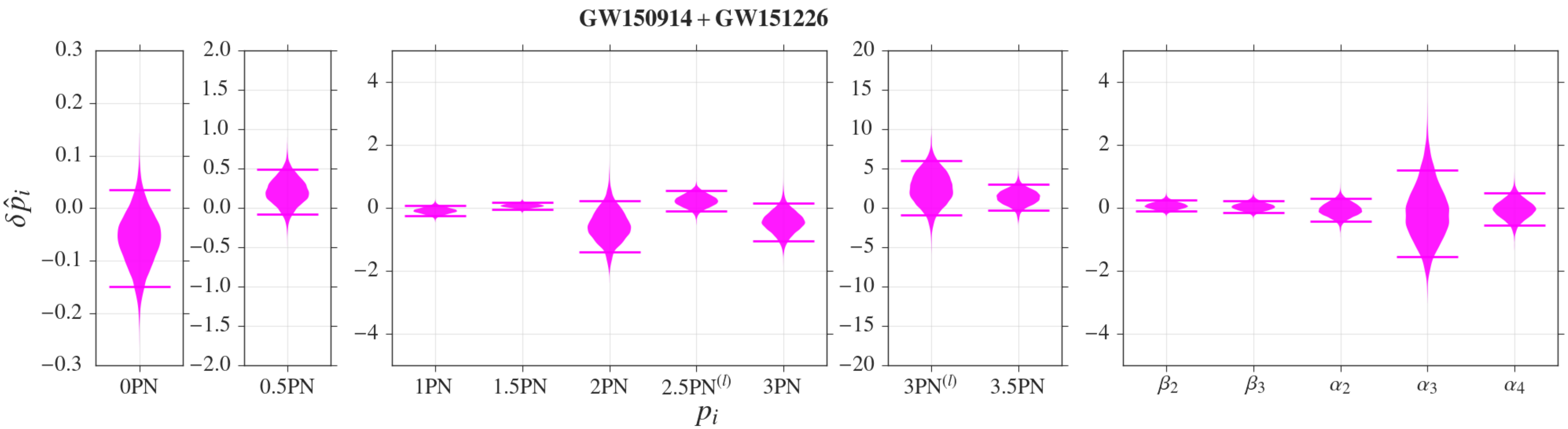
Courtesy: Salvatore Vitale (MIT)

Reveals a yet unobserved population of heavy stellar-mass black holes (> 15 M_{sun})

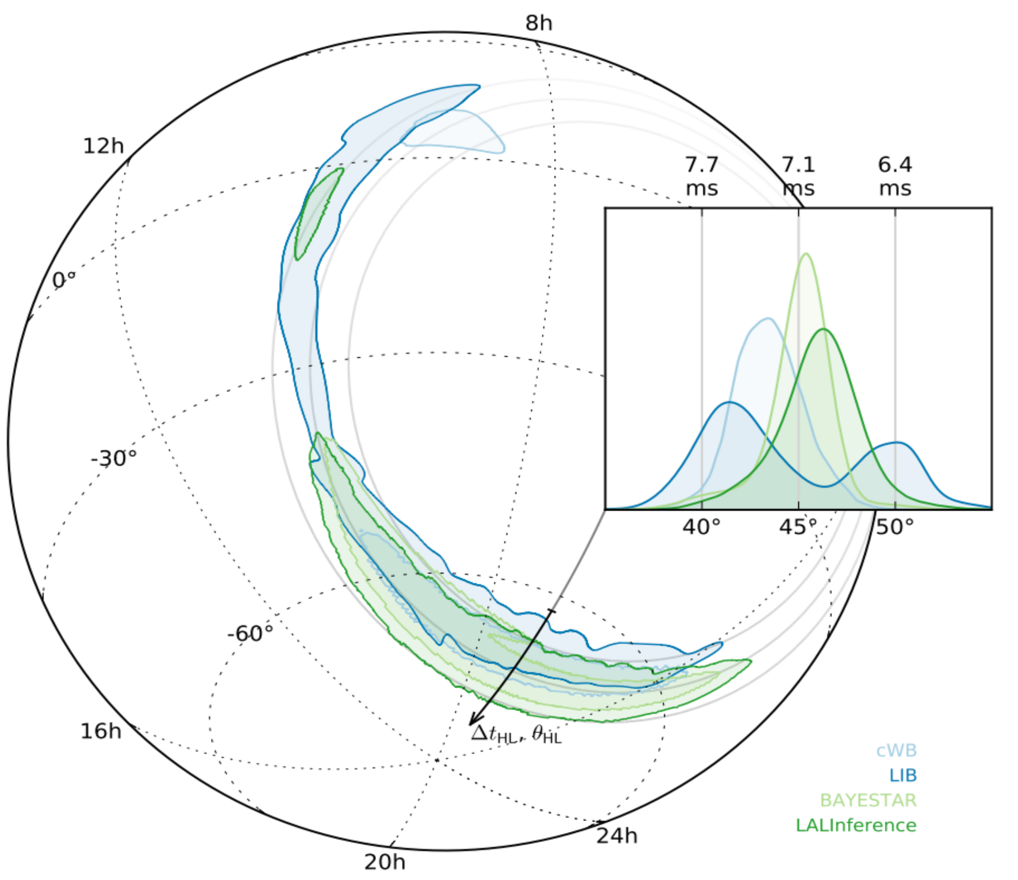
Formation channel?

Tests of General Relativity

- **Most relativistic binary pulsar** known today
  - J0737-3039, orbital velocity: v/c ~ 2 x 10^{-3}
- GW150914 and GW151226
  - **Strong field**, non linear, high velocity regime: **v/c ~ 0.5**
- **No evidence for deviation** from general relativity



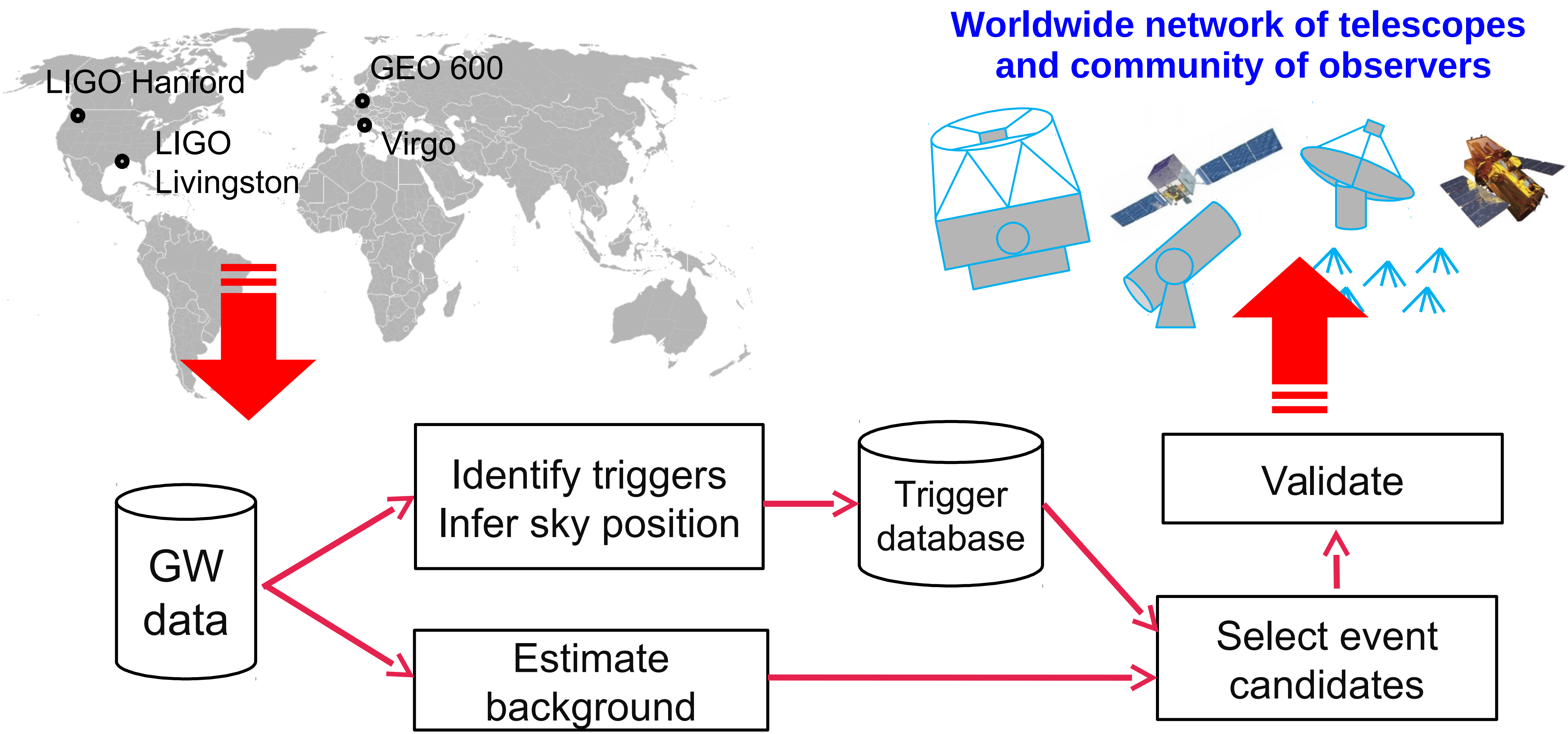
Electromagnetic follow-up (1)



From time-delay, amplitude and phase

~600 square degrees – 3000 full moons!

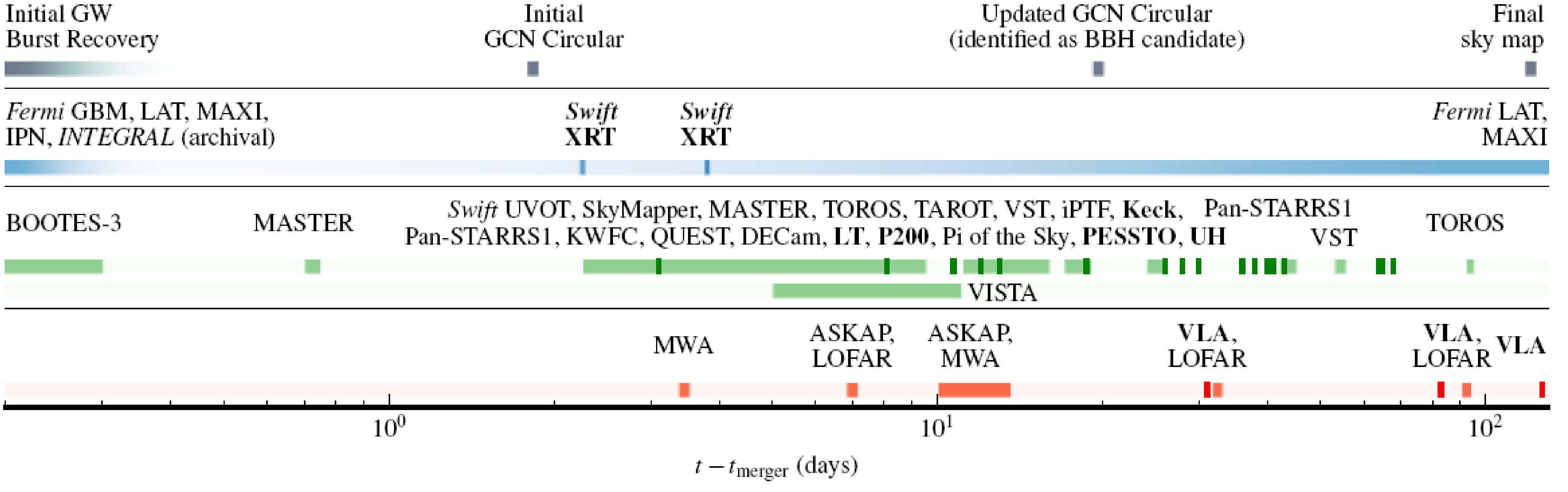
Electromagnetic follow-up (2)



Electromagnetic follow-up (3)

25 teams of observers responded to the GW alert

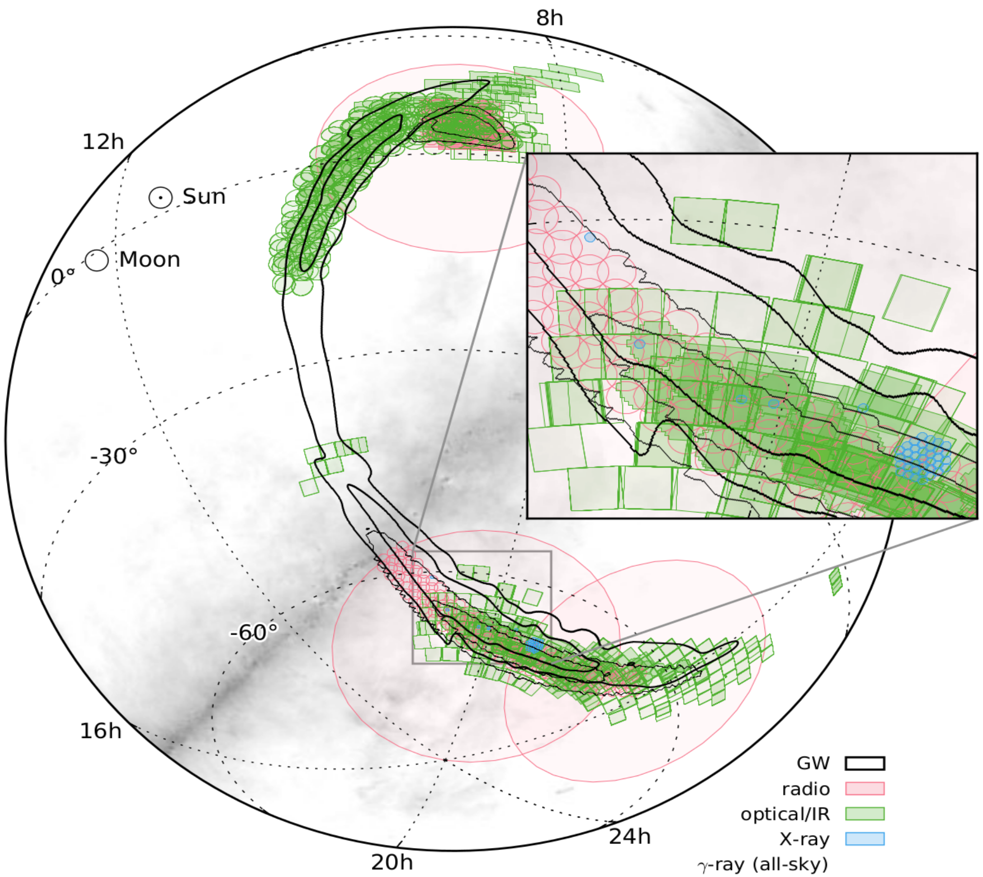
Multiwavelength: from radio to gamma-rays



T0+2 days

B. P. Abbott et al, Localization and broadband follow-up of the gravitational-wave transient GW150914. ApJL in press.

Electromagnetic follow-up (4)



Follow-up by conventional astronomical observatories

~25 observatories
from radio waves (100 MHz) ...
to gamma-rays (300 GeV)

No convincing counterpart has been found so far

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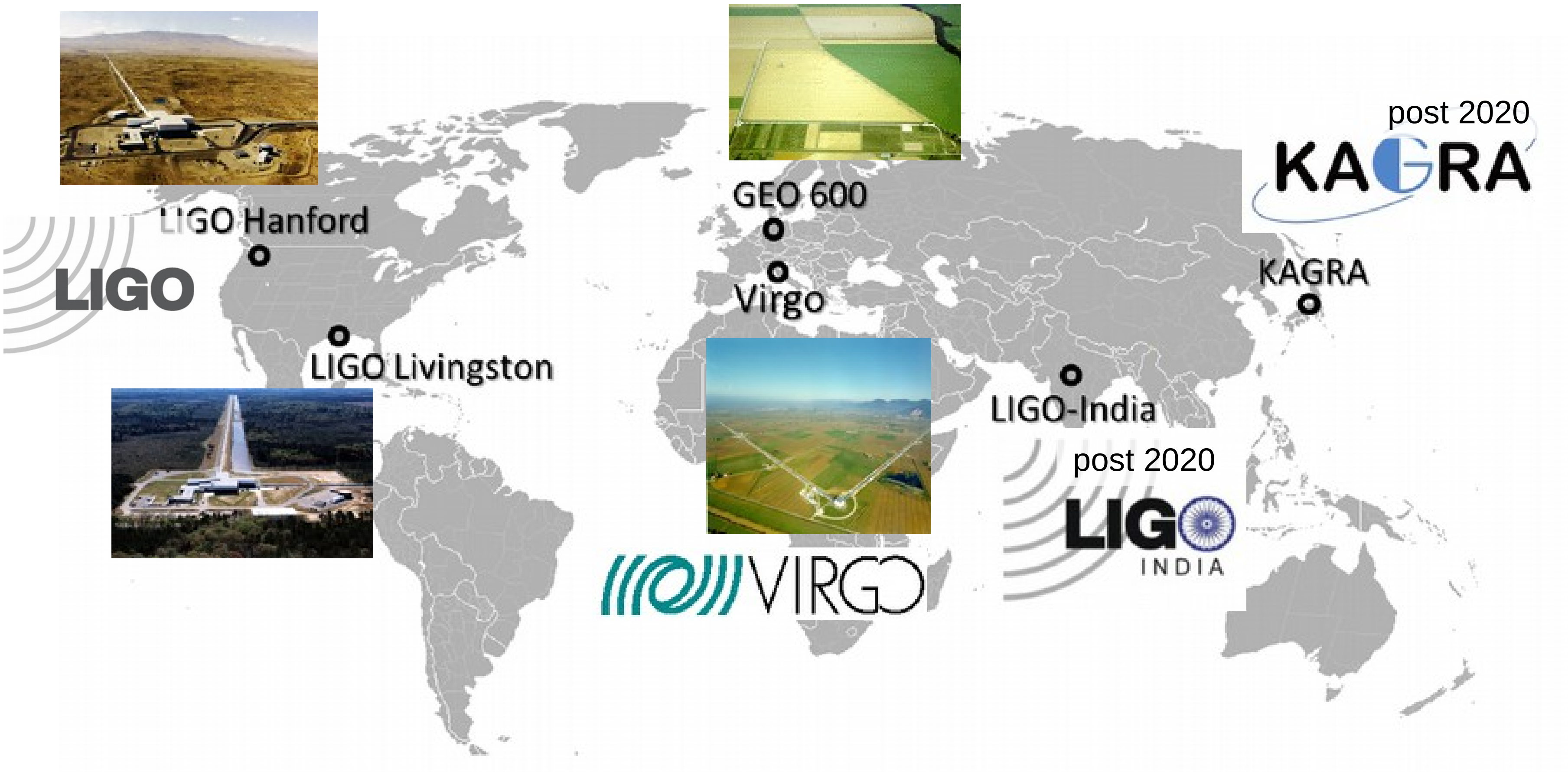
What next?


LIGO Hanford
LIGO
LIGO Livingston
GEO 600
Virgo
VIRGO
LIGO-India
post 2020
LIGO
INDIA
post 2020
KAGRA
KAGRA

What next?

- **Immediate future**
  - O2 (starting in September for 6 months)
    Sensitivity x ~3 – 10 BBH?
  - Virgo joining – Better sky resolution
- **1 year**
  - O3 (2017-2018) – another x 2-3 – 10-100 BBH? BNS? NS-BH?
- **5 years**
  - Kagra – LIGO India joining – (sub-)degree sky resolution!
- **10 years A+**
  - Upgrade to advanced detector
- **15-20 years**
  - 3rd generation – target: x 10 sensitivity
  - Observe the whole Universe in gravitational waves

ArXiv:1606.04856

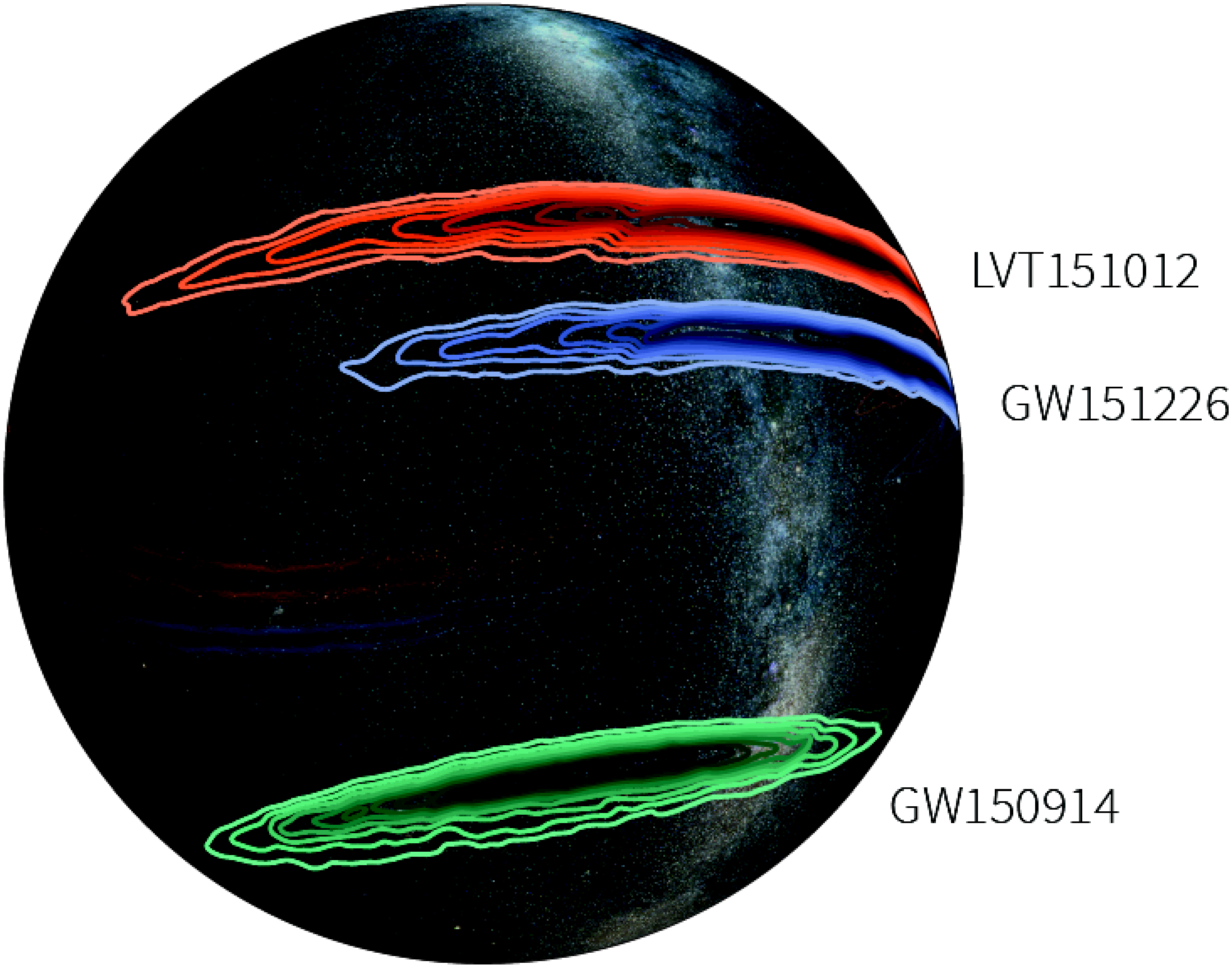


image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

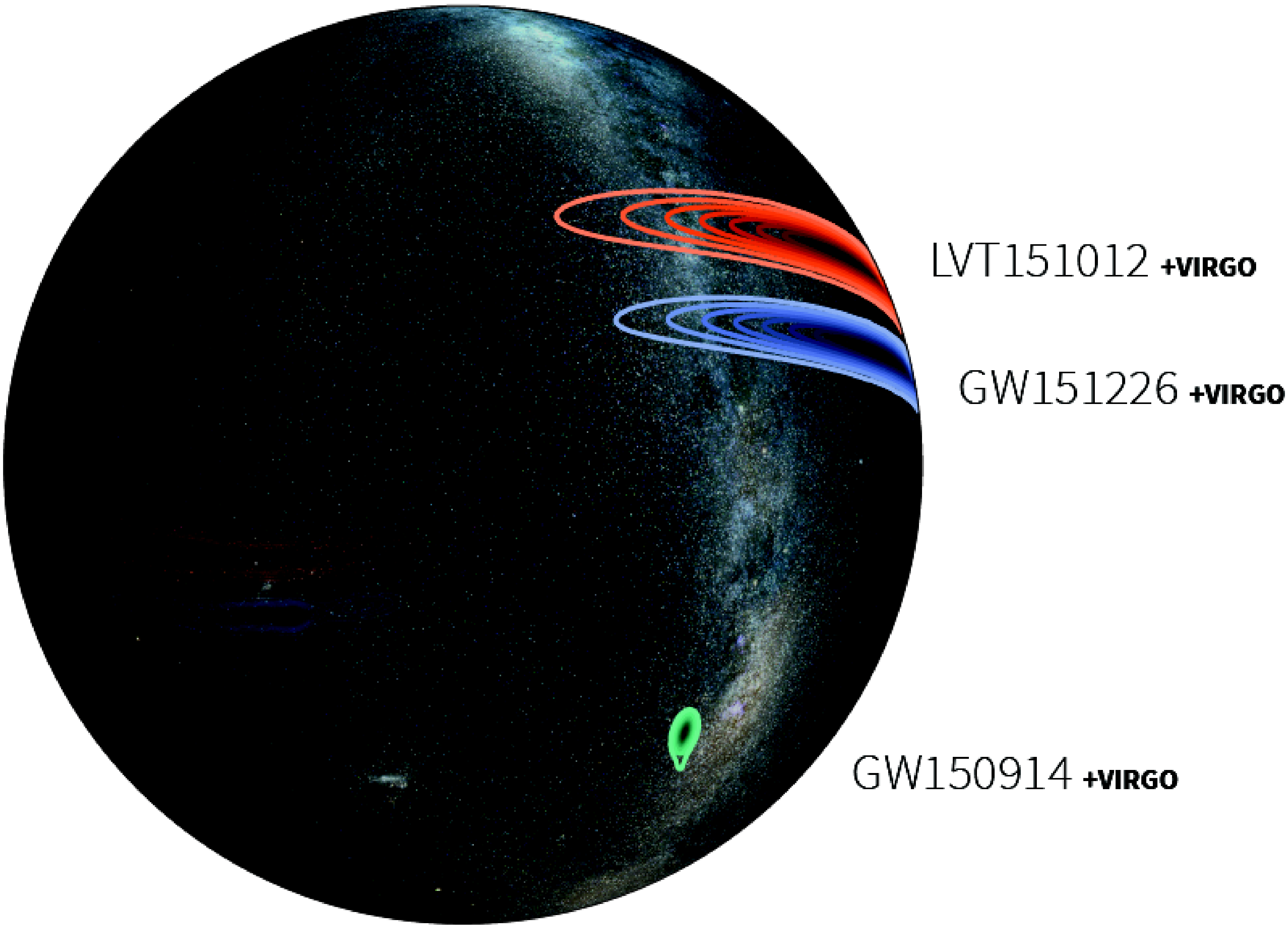
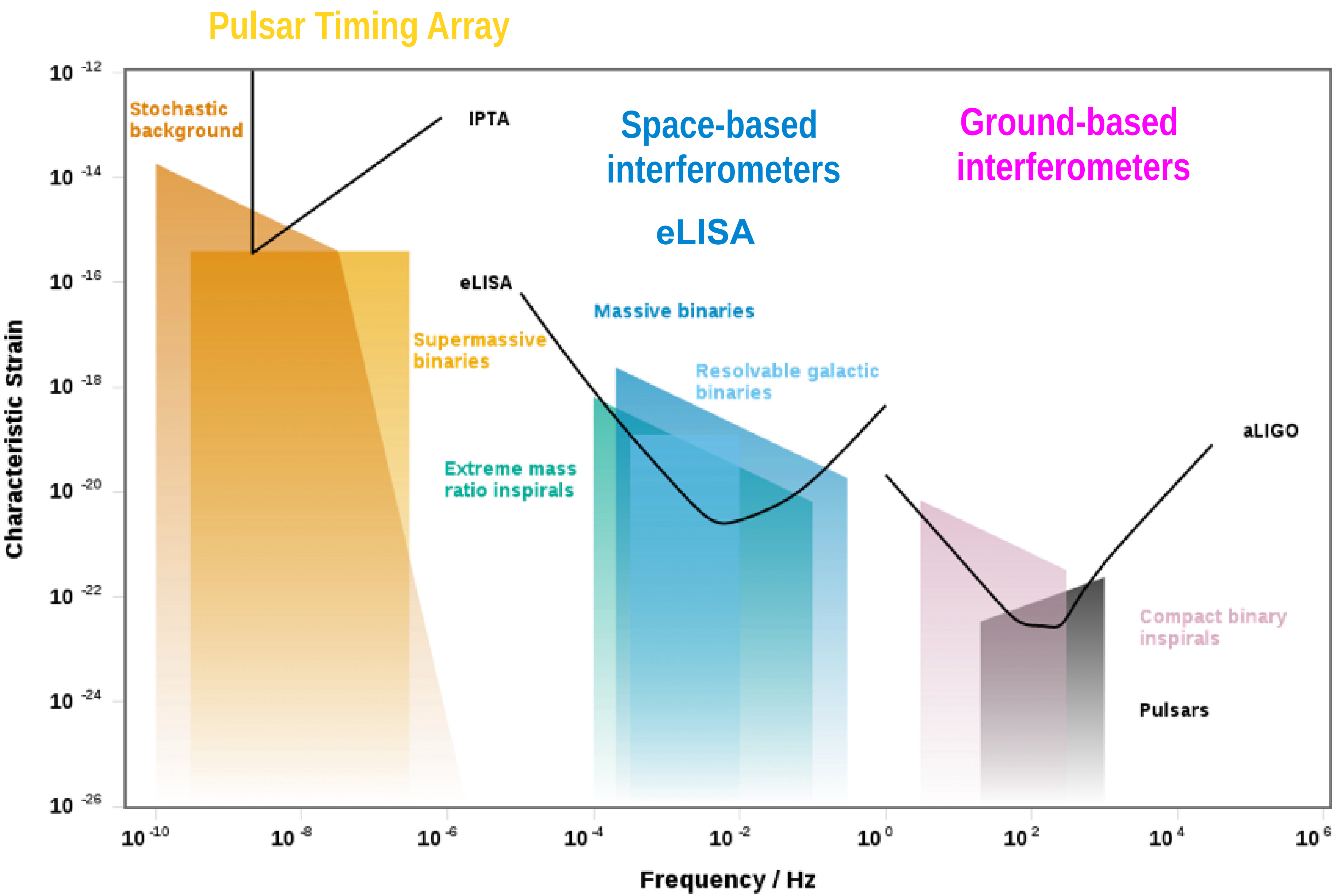


image credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

Gravitational wave astronomy



This is just the beginning!