The detection of Gravitational waves and the AdV status

Helios Vocca – University of Perugia and INFN of Perugia

Newtonian physics:
Space is a rigid grid described by Cartesian Coordinates

General Relativity goes beyond this view
Space becomes a dynamic and deformable medium,
combined with time in a 4D space-time
All dimensions are lengths (time is a light distance)
c=cost.

- Gravity is related to the geometric features of space-time

> "Spacetime *tells matter* how to move; *matter tells* spacetime how to curve."

Minkowski metric

$$ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2 = \underline{\eta_{\mu\nu}dx^\mu dx^\nu}$$

interval

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Describes a <u>flat</u> space-time

GR Metric

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

metrica

$$\boxed{g_{\mu\nu} = g_{\mu\nu}(x^\alpha)}$$

$$g_{\mu\nu} = \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}$$

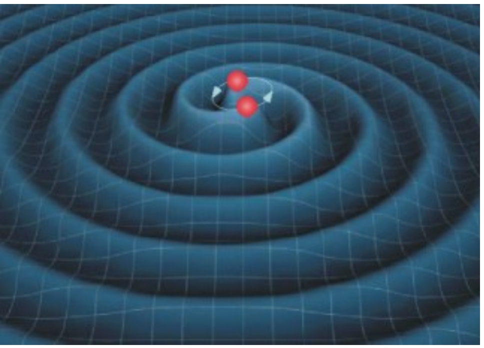
In general space-time is curved

Einstein Equations

"*geometry*"

$$\mathbf{G} = k\,\mathbf{T}$$

"*matter-energy*"



$$k = \frac{8\pi G}{c^4} = 2.08 \cdot 10^{-43}\ \mathrm{N}^{-1}$$

!

'Similar' to the equation: $\varepsilon = E^{-1}\sigma$

E=Young's modulus

strain

stress

- space-time is an elastic medium
- space-time has an extremely high rigidity

(We passed from an *infinitely* rigid space-time to an *extremely* rigid one)

Gravitational Waves

Nearly-flat space-time

Absence of matter

Gauge Transverse-Traceless

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Minkowski

perturbation

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

Einstein equations take the form of <u>WAVE EQUATIONS</u>

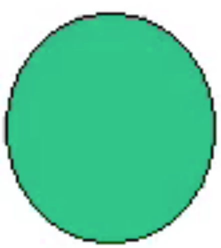
Polarization

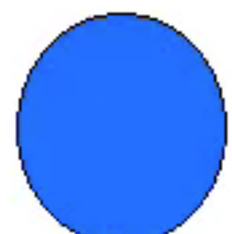
$$\hat{h}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & a & b & 0 \\ 0 & b & -a & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$h = a\,\hat{h}_{+} + b\,\hat{h}_{\times}$$

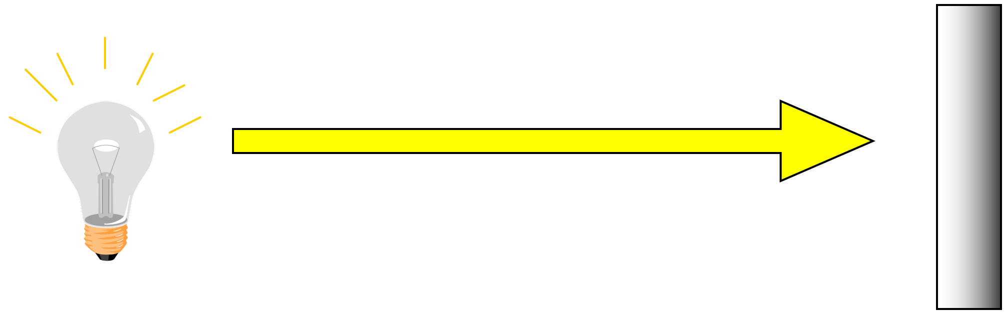
$$\hat{h}_{+} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\hat{h}_{\times} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$





Gravitational Waves (2)



$$ds^2 = 0 = g_{\mu\nu}\, dx^{\mu}\, dx^{\nu}$$

$$= (\eta_{\mu\nu} + h_{\mu\nu})\, dx^{\mu}\, dx^{\nu}$$

$$= -c^2 dt^2 + (1 + h_{11})\, dx^2 \qquad dx \rightarrow dx \cdot \left(1 + \frac{1}{2} h_{11}\right)$$

The distance between *free masses* varies like: $\boxed{\dfrac{\Delta l}{l} = \dfrac{h}{2}}$

Gravitational Radiation

- Accelerated masses emit energy in form of *gravitational waves*.
- Emitted radiation can be expressed in terms of *retarded potential*.
- It is possible to use the *multipolar expansion* of the gravitational field.

Gravitational Radiation (2)

- Monopole
- Dipole
- Quadrupole

$$\int dV\ \rho(\vec{r}) = \text{cost}$$

$$d_g \equiv \int dV\ \rho(\vec{r})\vec{r} \Rightarrow \dot{d}_g = \text{cost}$$

$$\mu_g \equiv \int dV\ \rho(\vec{r})\vec{r} \times \vec{v}(r) = \text{cost}$$

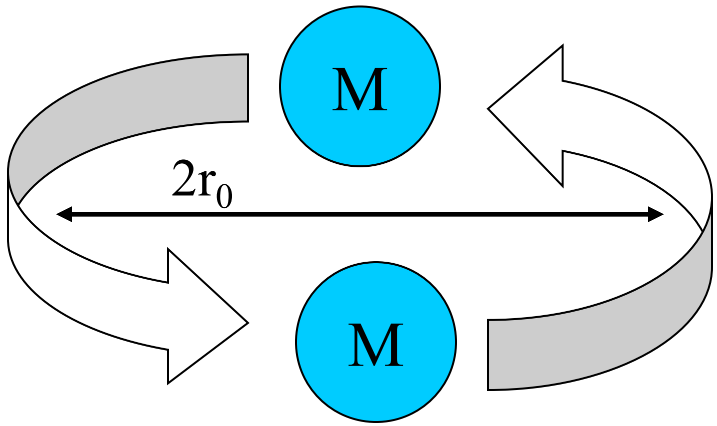
Energy impulse conservation laws

$$I_{\mu\nu} = \int dV \left(x_\mu x_\nu - \frac{1}{3}\delta_{\mu\nu} r^2 \right) \rho(\vec{r}) \Longrightarrow h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu}$$

I is the mass quadrupole moment of the source.

<u>Coherent relativistic motion of large masses can be directly observed.</u>

Gravitational Radiation (3)



$$M = 3\cdot 10^{30}\ \mathrm{kg} = 1.4\mathrm{M}_S$$
$$r_0 = 20\ \mathrm{km}$$
$$f_{\mathrm{orb}} = 400\ \mathrm{Hz}$$
$$R = 15\,\mathrm{Mpc} \approx 4.5\times 10^{23}\, m$$

VIRGO Cluster

$$\begin{cases} h_{xx} = -h_{yy} = \dfrac{32\pi^2 G}{Rc^4} M r_0^2 f_{\mathrm{orb}} \cos 2(2\pi\ f_{\mathrm{orb}})t \\[2ex] h_{xy} = h_{yx} = -\dfrac{32\pi^2 G}{Rc^4} M r_0^2 f_{\mathrm{orb}} \sin 2(2\pi\ f_{\mathrm{orb}})t \end{cases}$$

$$h \equiv \left| h_{\mu\nu} \right| \approx \frac{r_{s1} r_{s2}}{r_0 R} \approx \underline{10^{-21}}$$

What is interesting about gravitational waves?

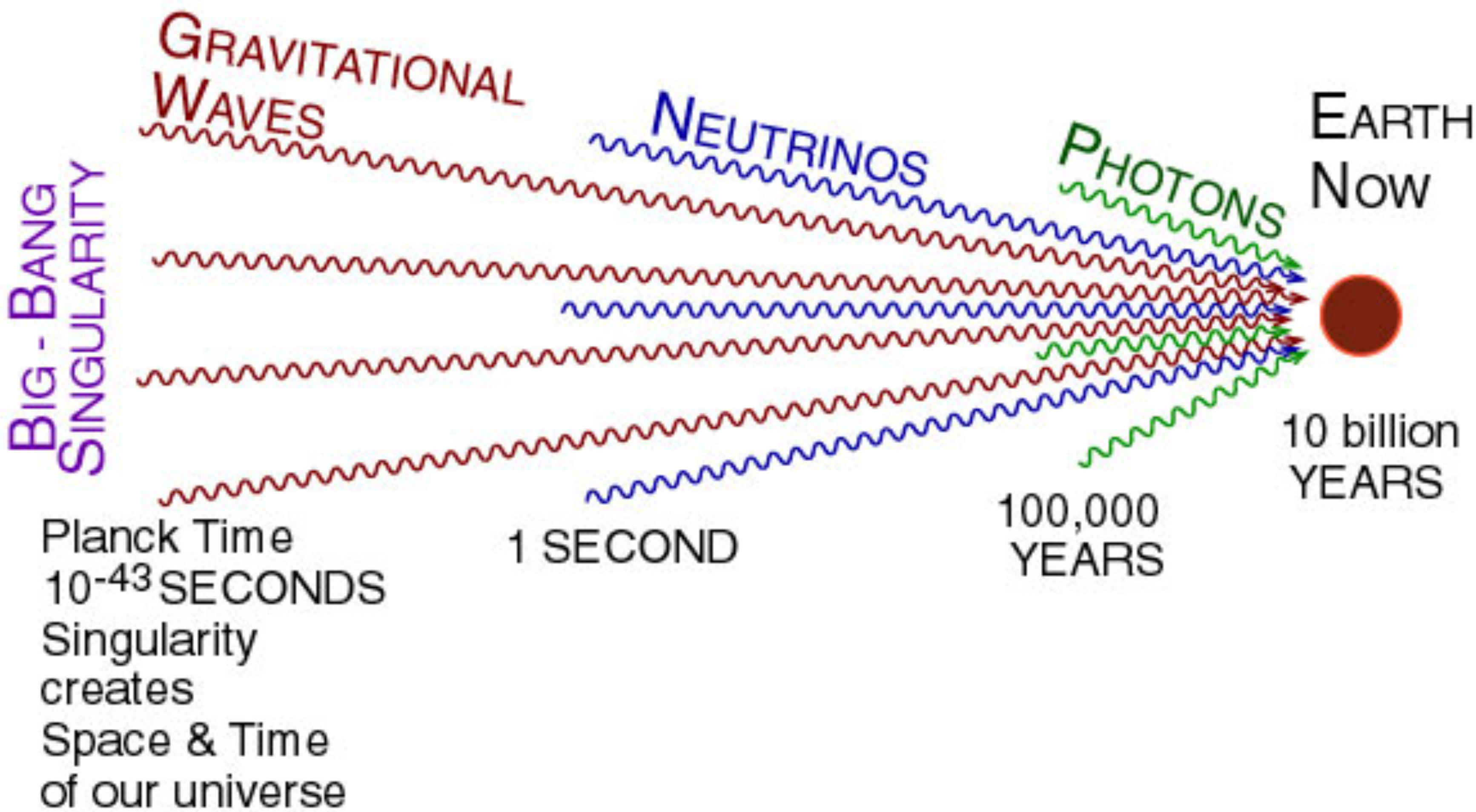
- Embody gravity's obedience to the principle "no signal faster than light"
- Travel through otherwise opaque matter
- Can be generated by pure spacetime
  - Black holes
  - Early universe fluctuations

Thus, gravitational waves can reveal, like nothing else can, the dynamics of strongly-curved spacetime.

What kinds of things might we see? Might we learn?

- Binaries of neutron stars and black holes
  - Study black hole spacetime
  - Learn neutron star equation of state
  - What is the engine of gamma ray bursts?
- Stellar core collapse
  - Dynamics that lead to supernova
- Rotating neutron stars
  - What mechanisms can make neutron stars lumpy?
- Early universe dynamics

The First One Second of Universe's Life

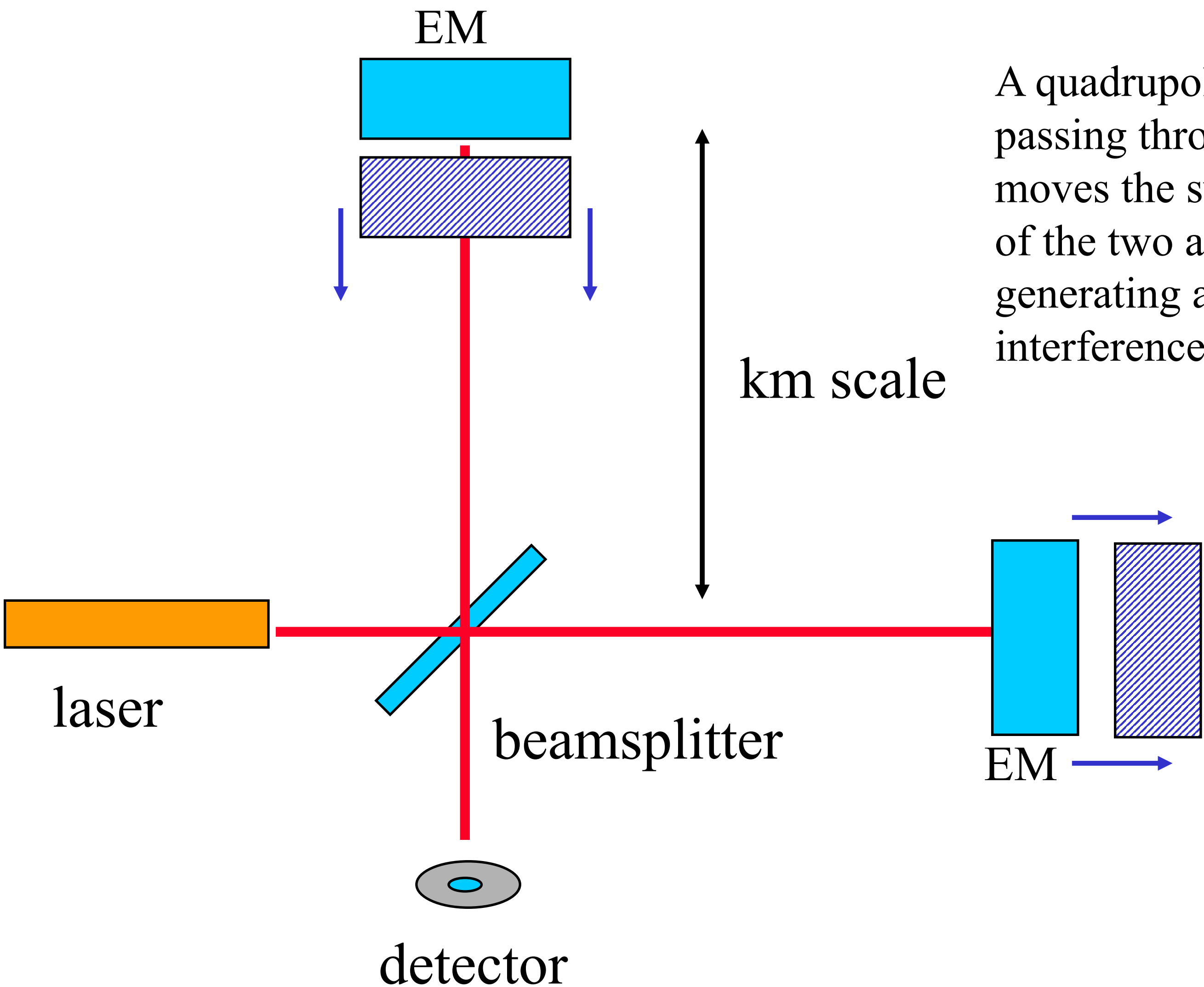


Experimental challange

- How to implement the measurement?
- How to make it sensitive enough?
  N.B.: Relative motions of test masses turned out to be at the level of $\Delta L/L \sim 10^{-21}$!

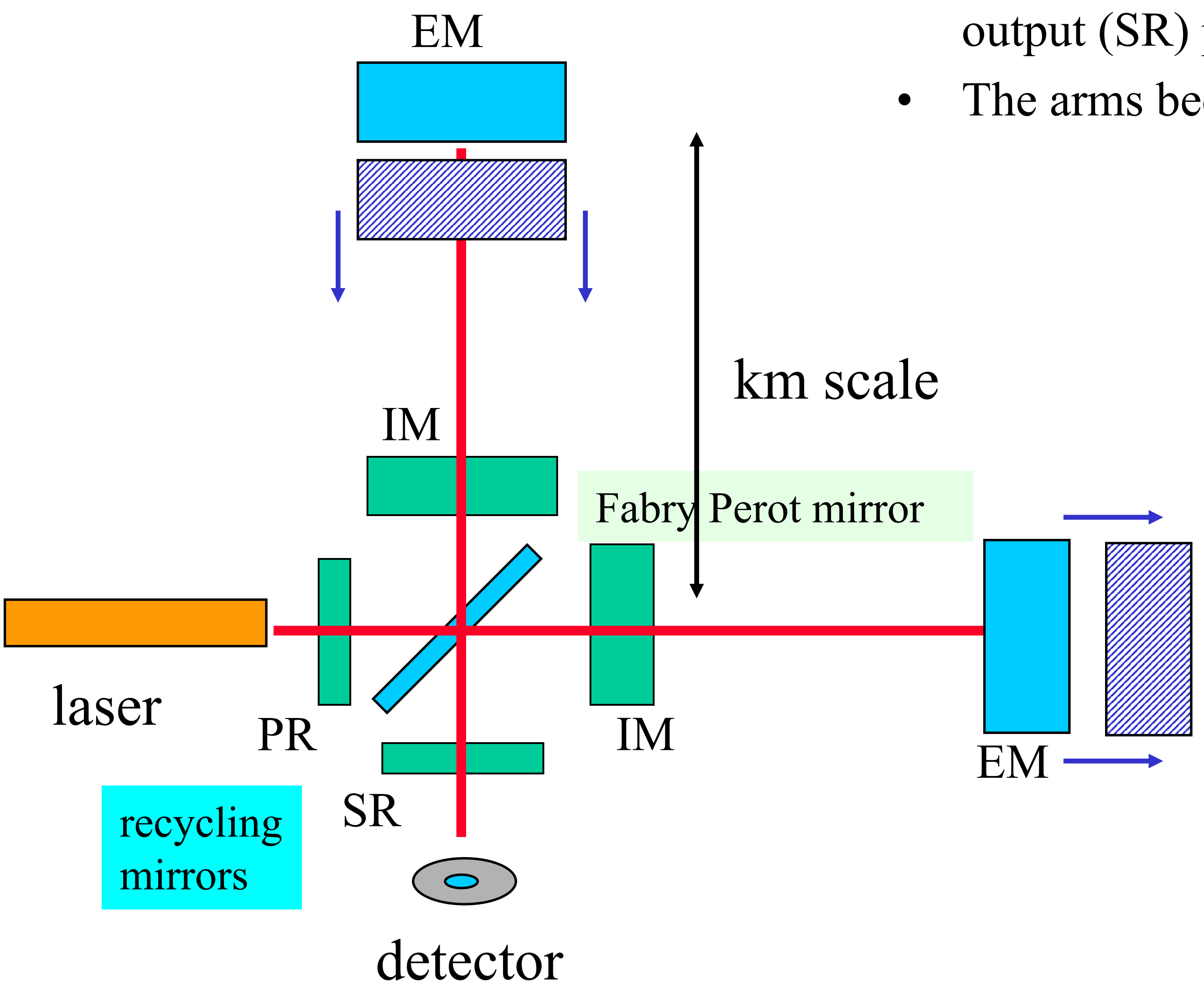
Interferometer

Working principle



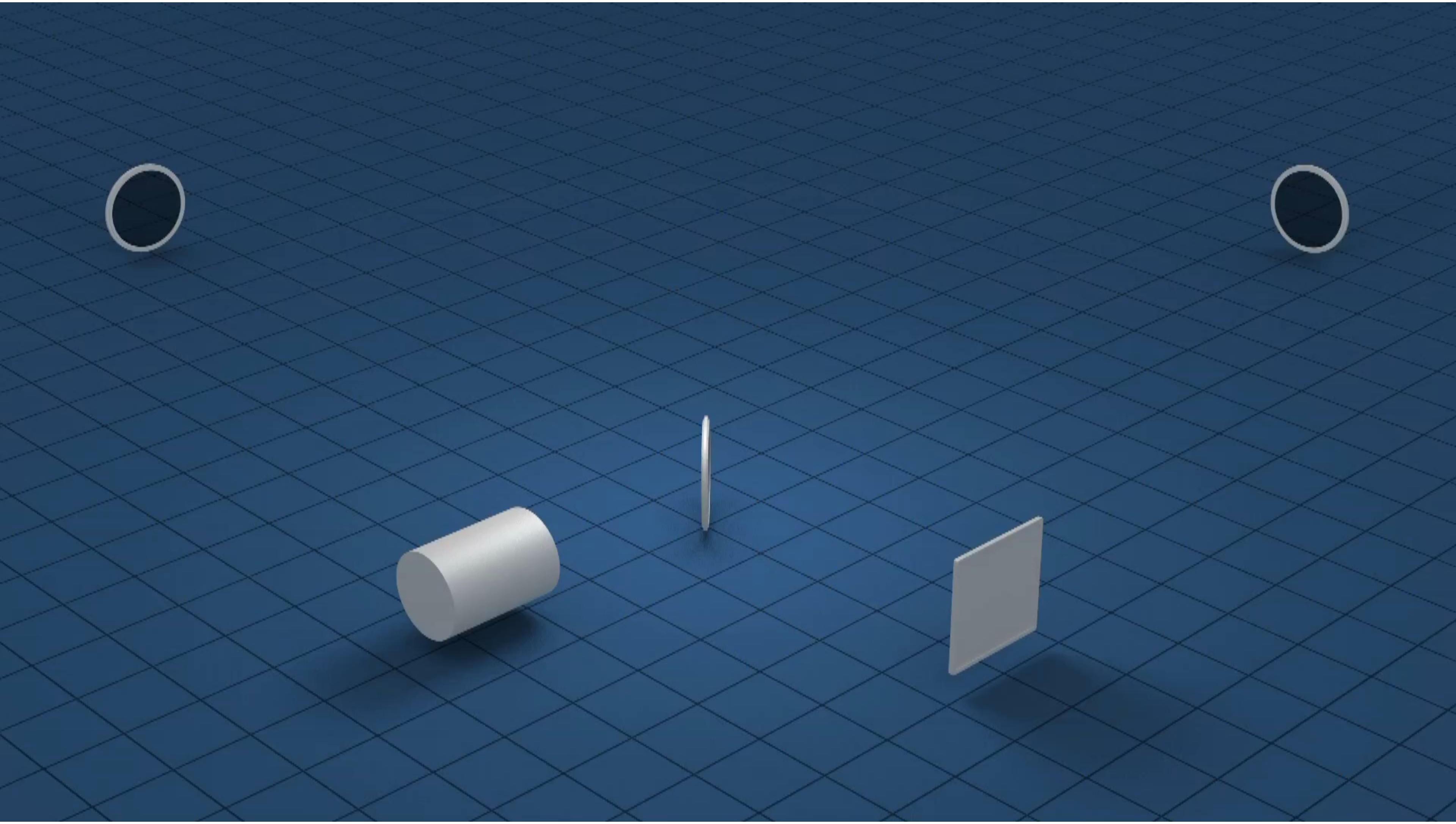
A quadrupolar gravitational wave passing through the instrument moves the suspended mirrors (EM) of the two arms in counter-phase generating a change in the interference fringes.

Fabry-Perot Interferometer for GW



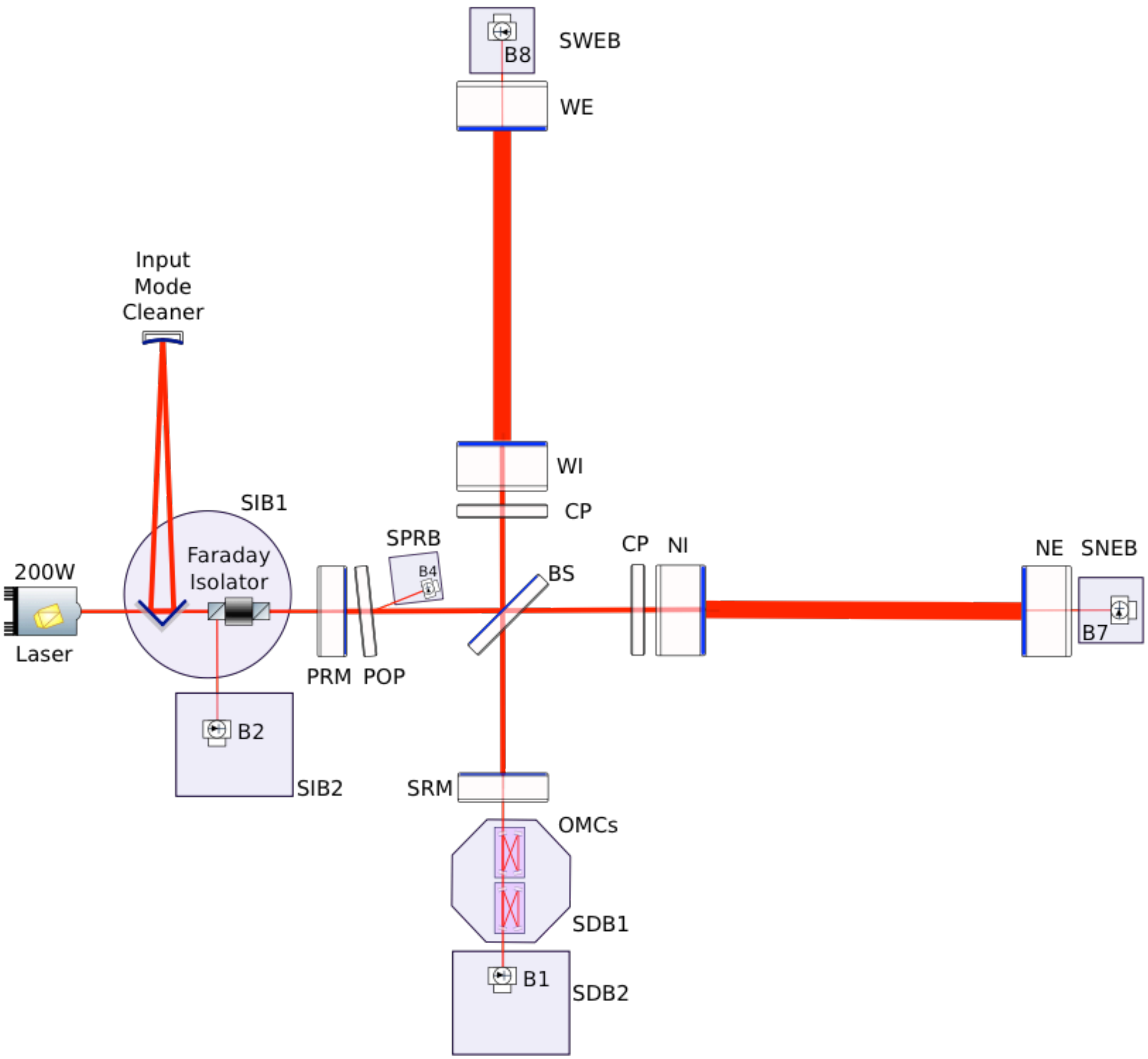
- Added mirrors at the input (PR) and output (SR) ports
- The arms become resonant cavities

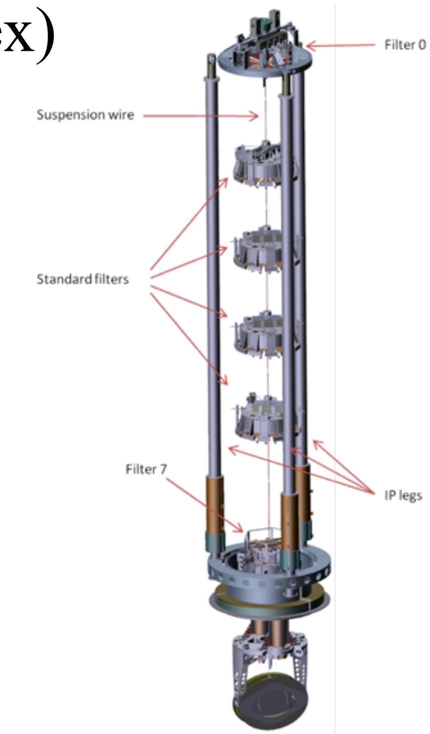
- More complex optics (not shown) is added to filter and 'clean' the laser.

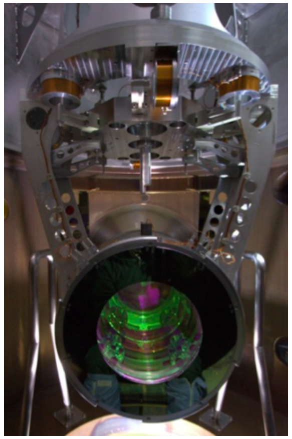


Fabry-Perot Interferometer for GW

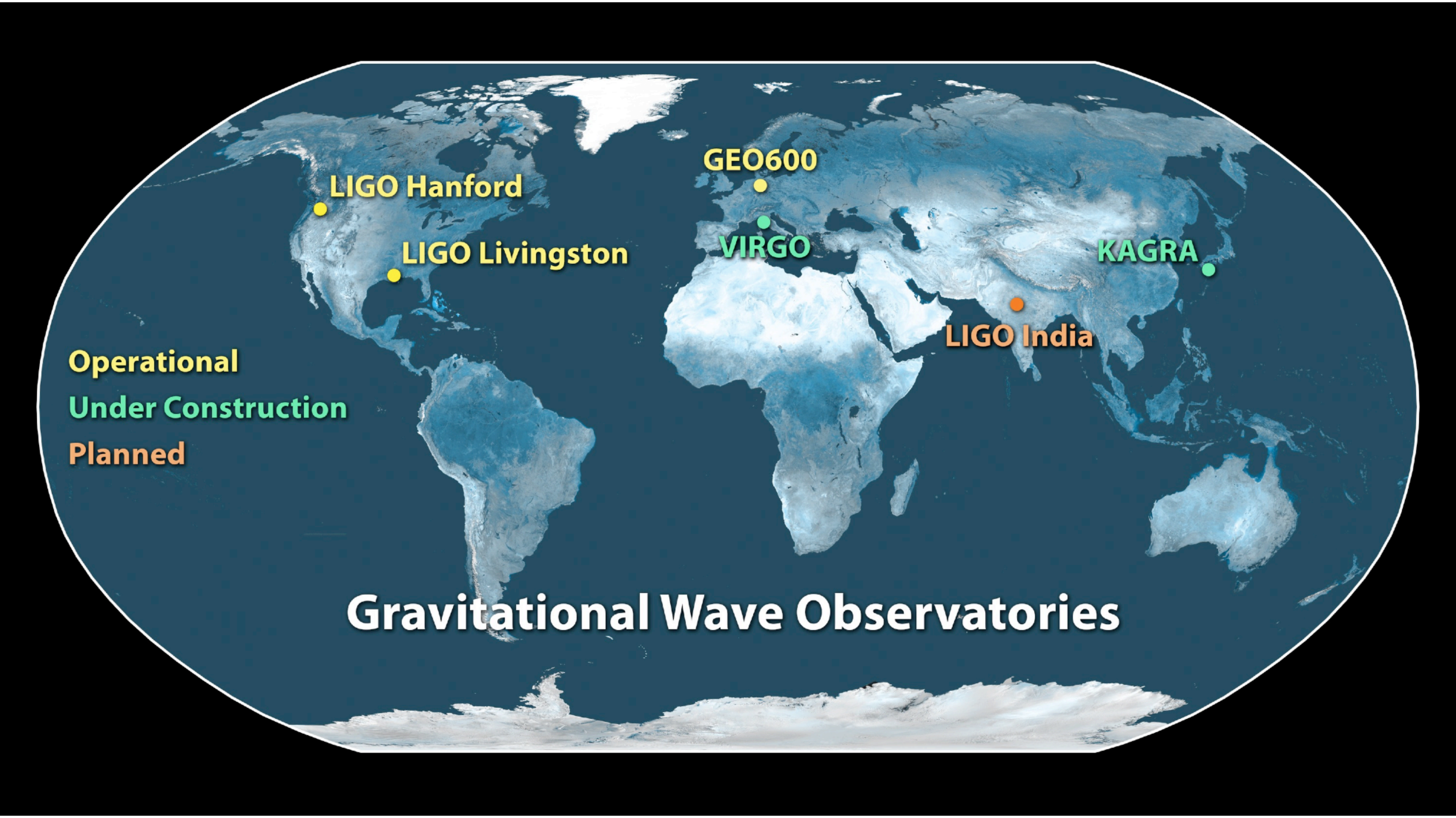
(The real design is much more complex)







Detector Network



Detectors in Operation (O1&O2)

LSC

Ligo Scientific Collaboration

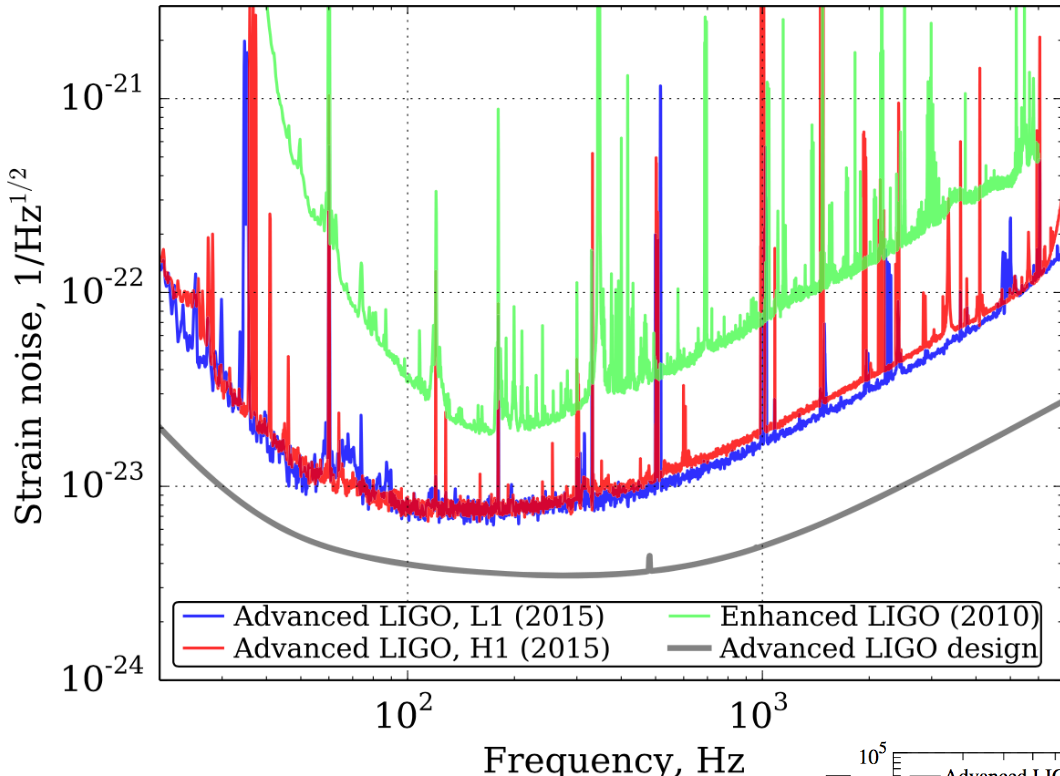
Virgo

(since 2007 there is a formal collaboration between LSC and Virgo to exchange scientific competences and for common data Analysis)

Kagra

First Observation Run (O1)

(12th September 2015 – 19th January 2016)

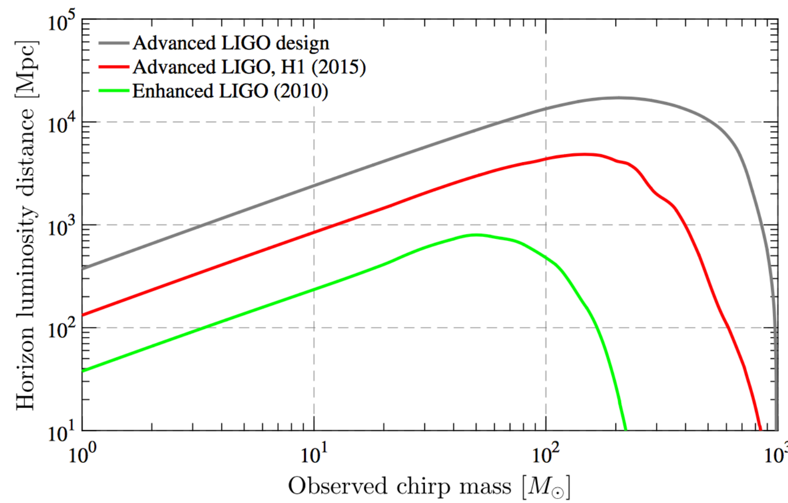


iLIGO best (2010)

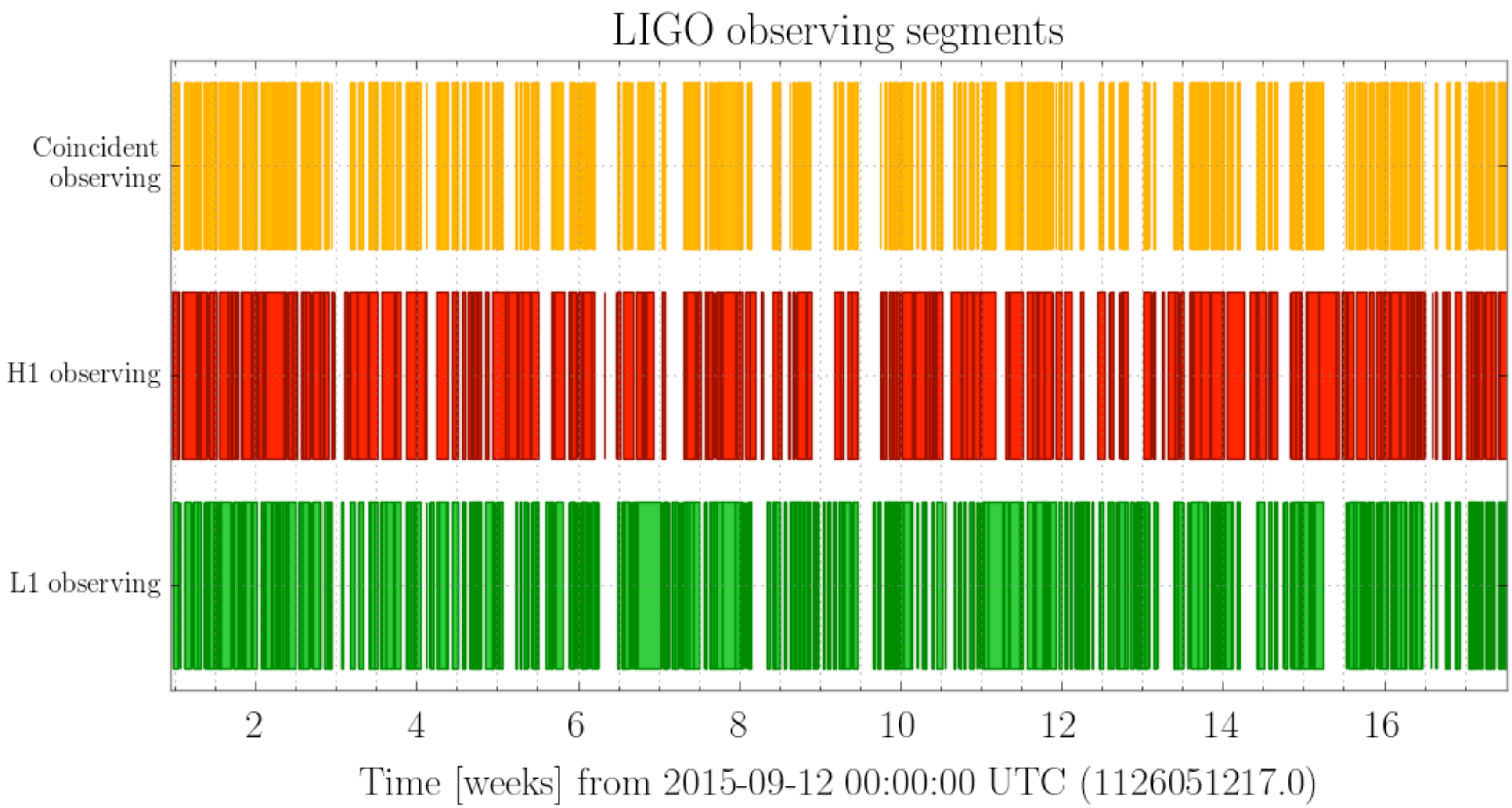
aLIGO O1 (2015)

aLIGO design

D Martynov et al, PRD 93 (2016), 112004

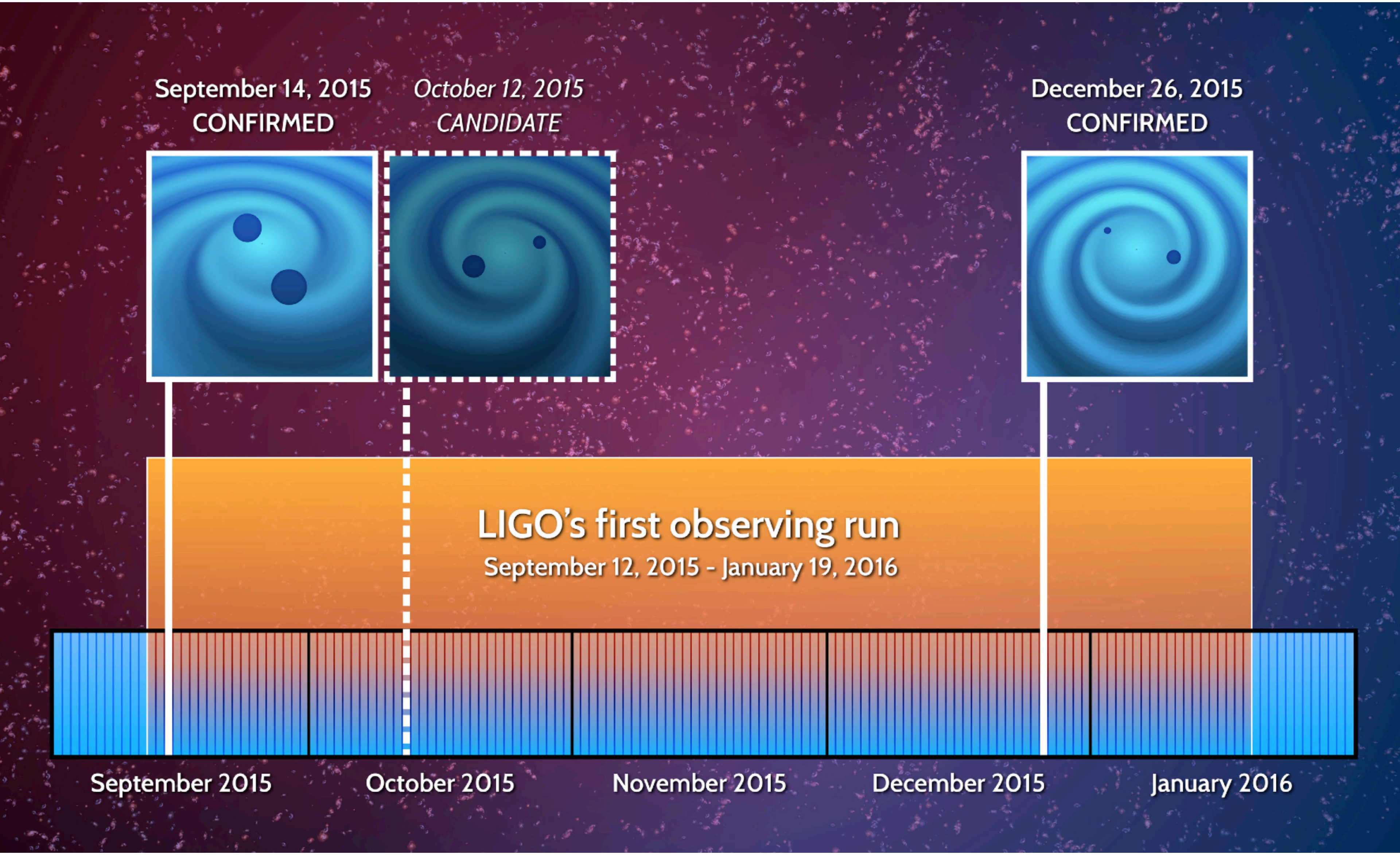


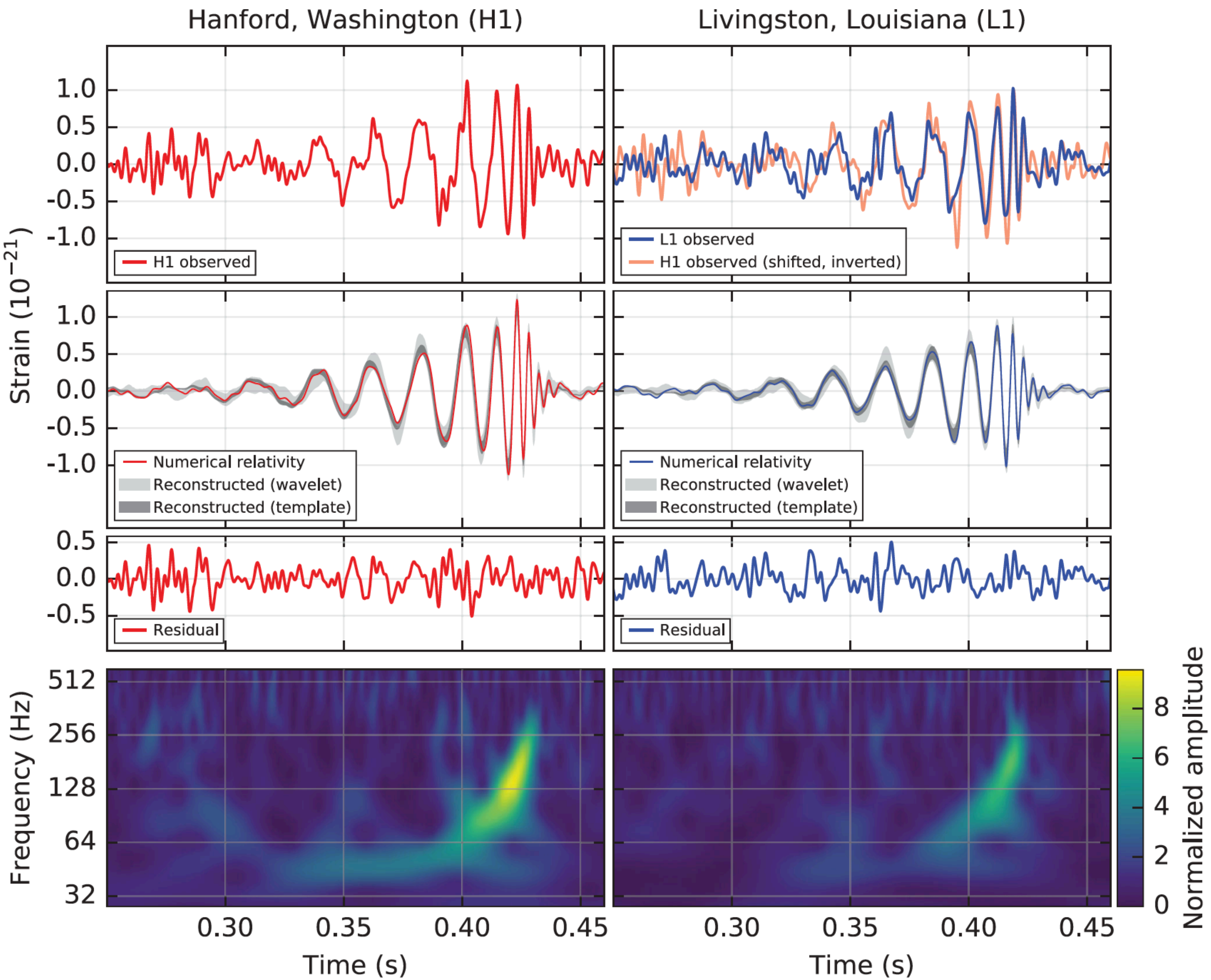
Detection Timeline



- 51,5 days of coincident analysis time
- Approximately 3 days of contaminated data
- 48.6 days of analysed coincident time

Detection Timeline

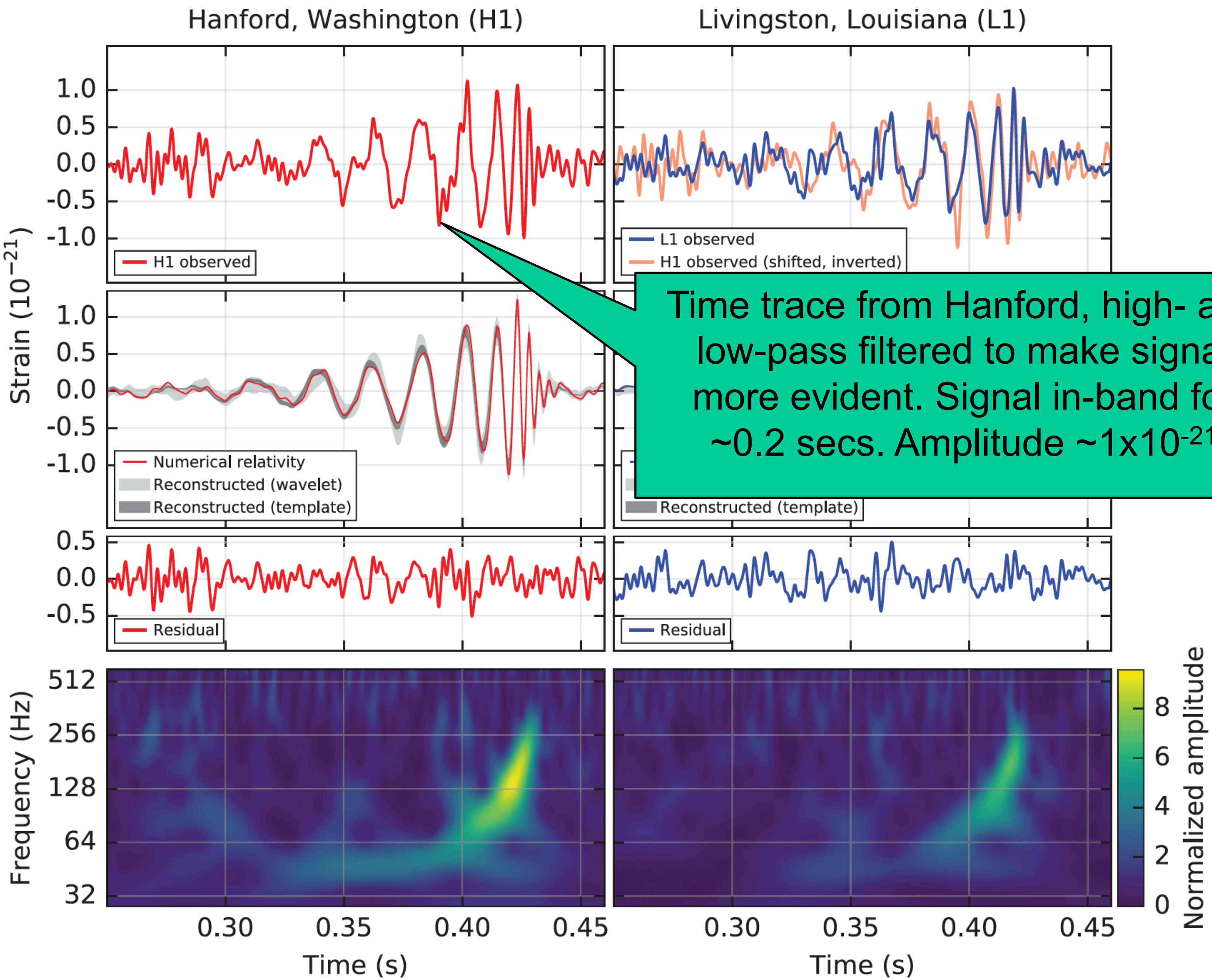




B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

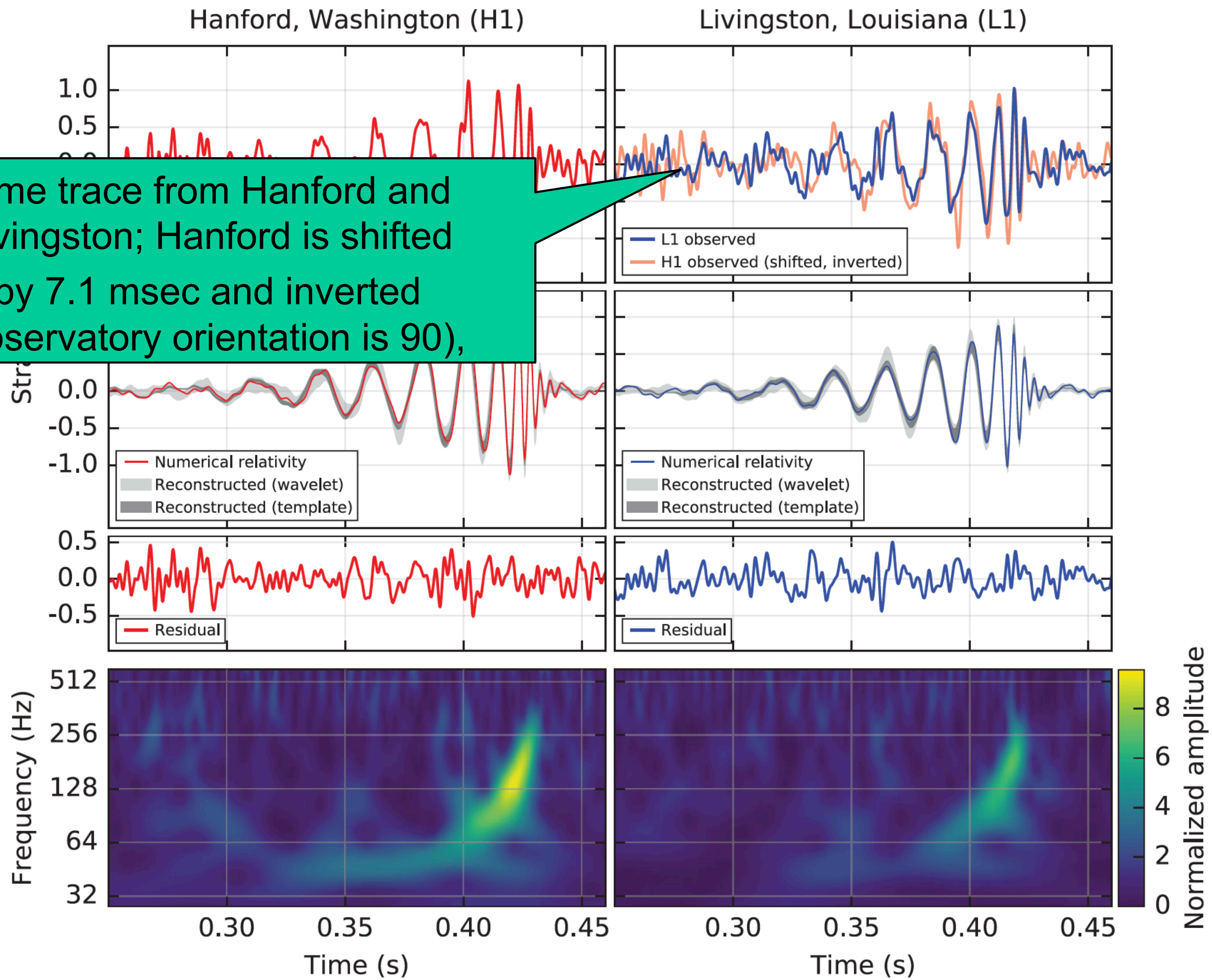
What was momentous about the discovery of GW150914?

- First reception (“direct detection”) of gravitational waves.
- First observation of the existence of binary black holes.
- Demonstration that predicted waveform matches what nature produces.



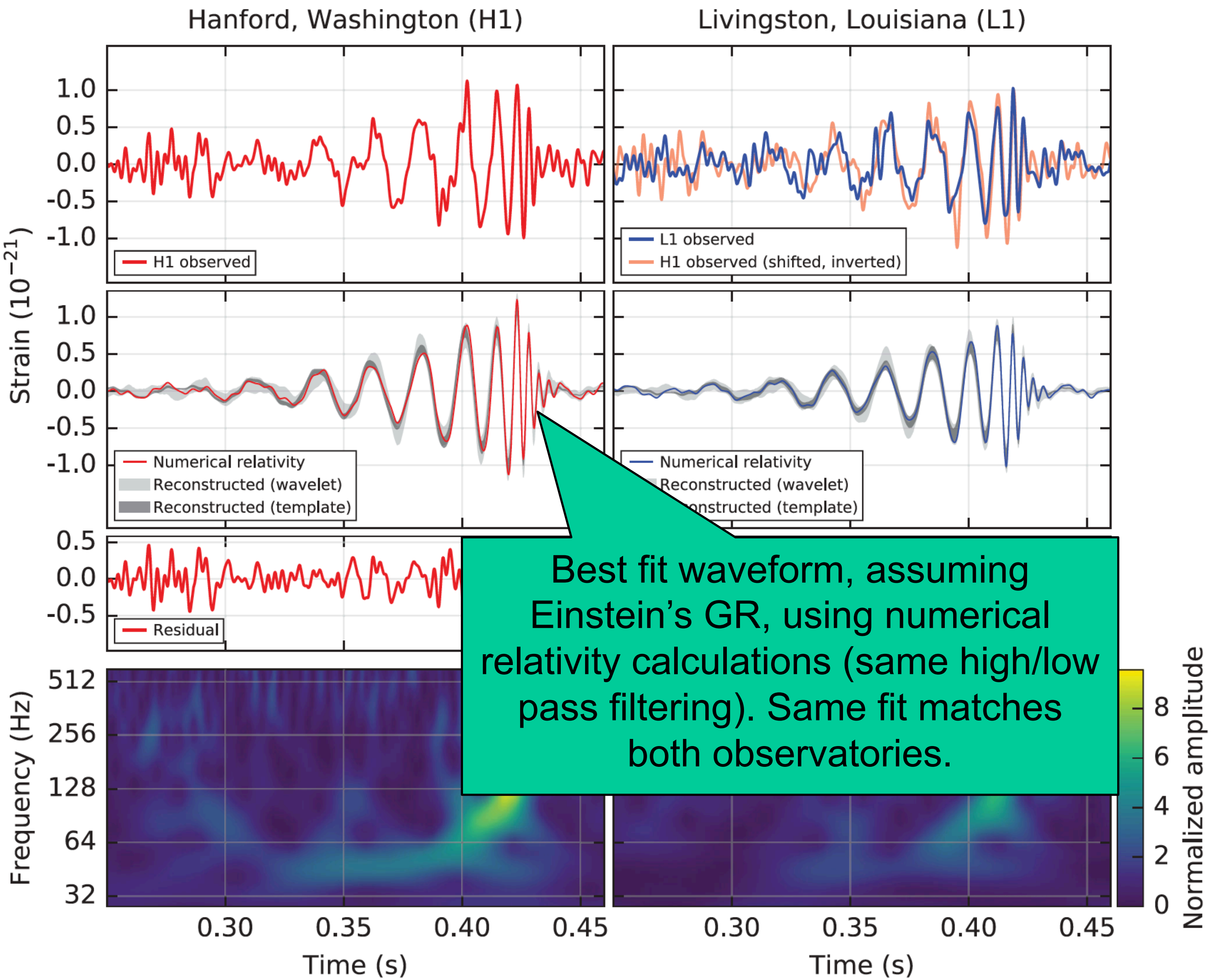
Time trace from Hanford, high- and low-pass filtered to make signal more evident. Signal in-band for ~0.2 secs. Amplitude ~1x10^{-21}

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)



Time trace from Hanford and Livingston; Hanford is shifted by 7.1 msec and inverted (observatory orientation is 90),

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)



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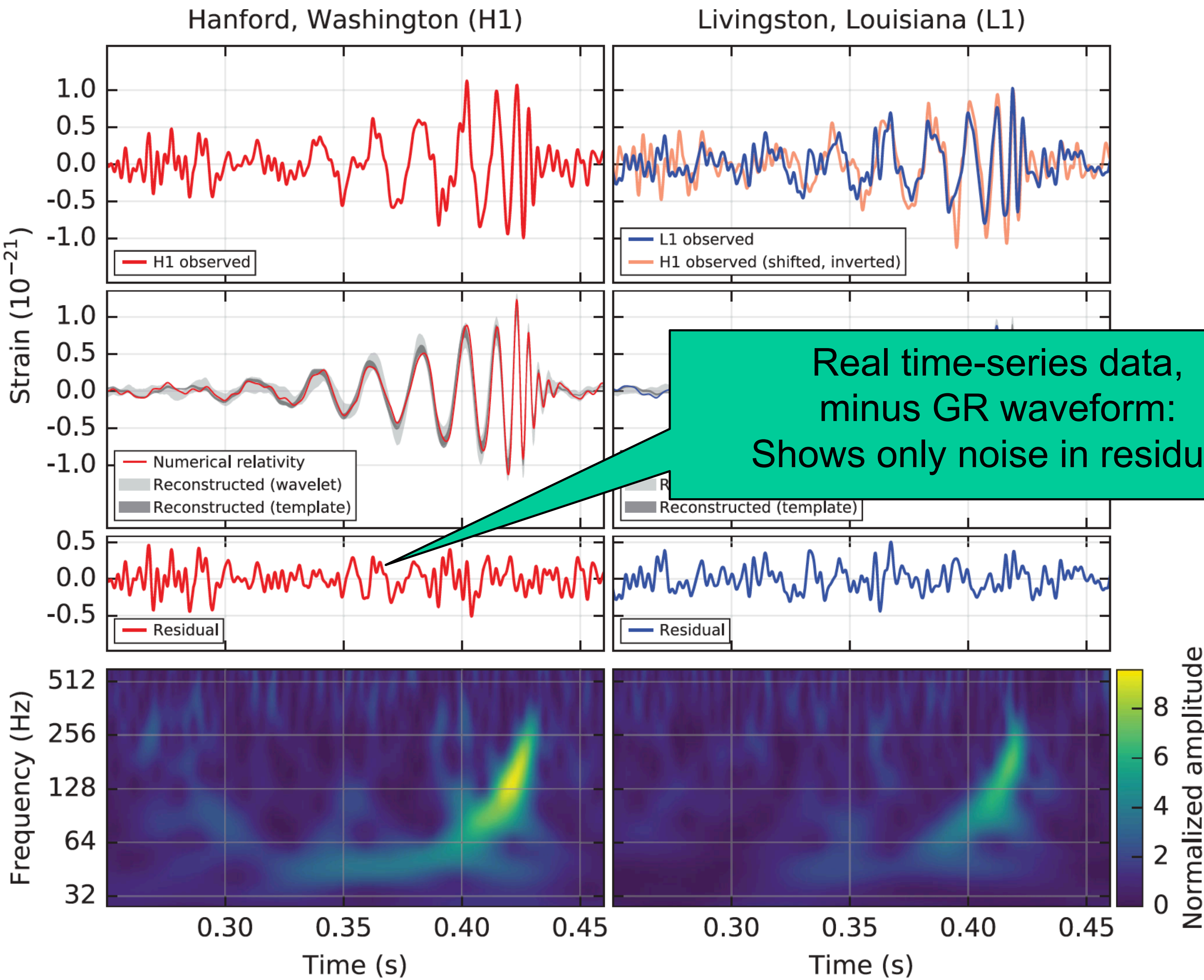
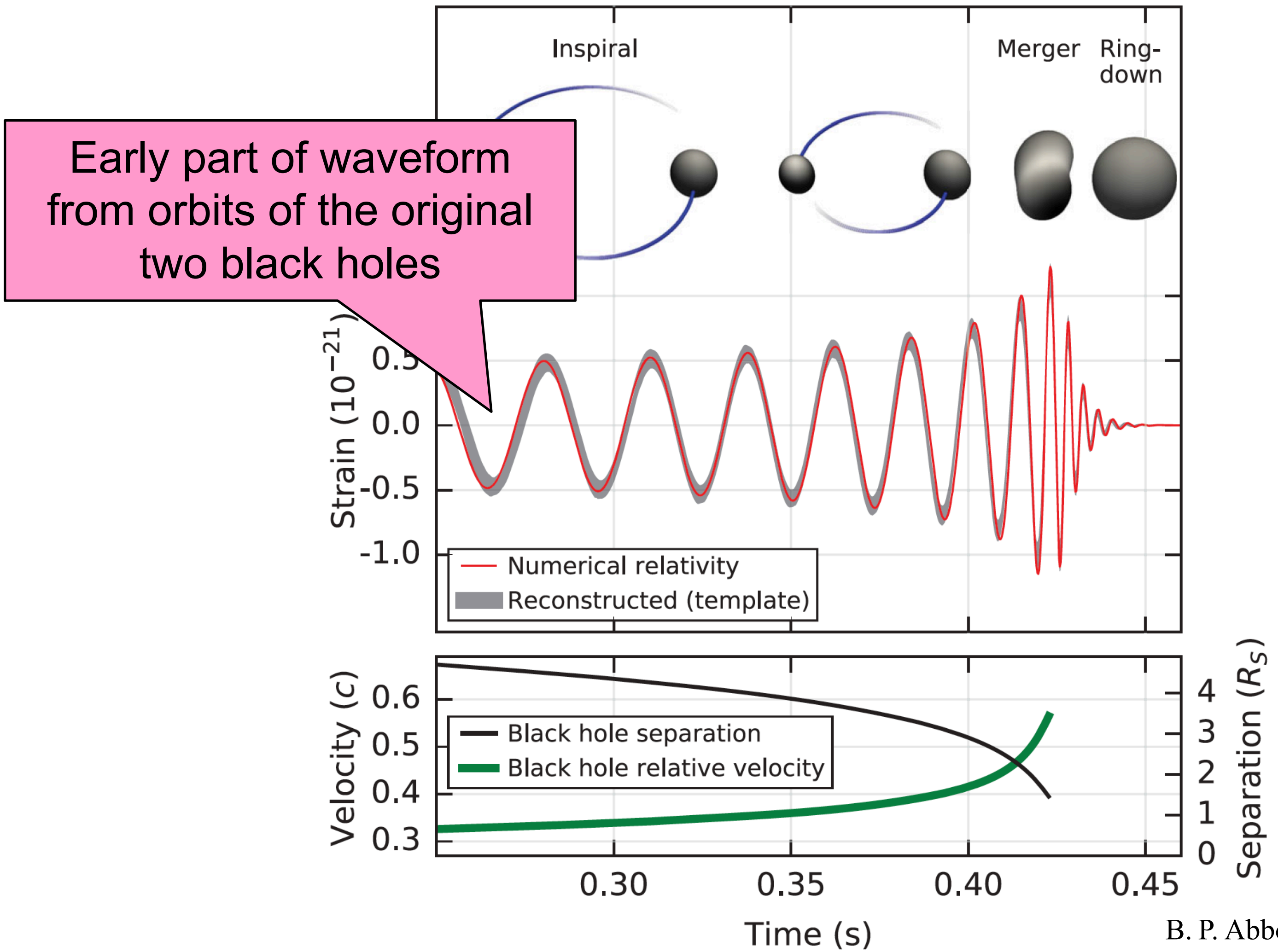


Real time-series data,
minus GR waveform:
Shows only noise in residual.

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

How do we learn from h(t)?



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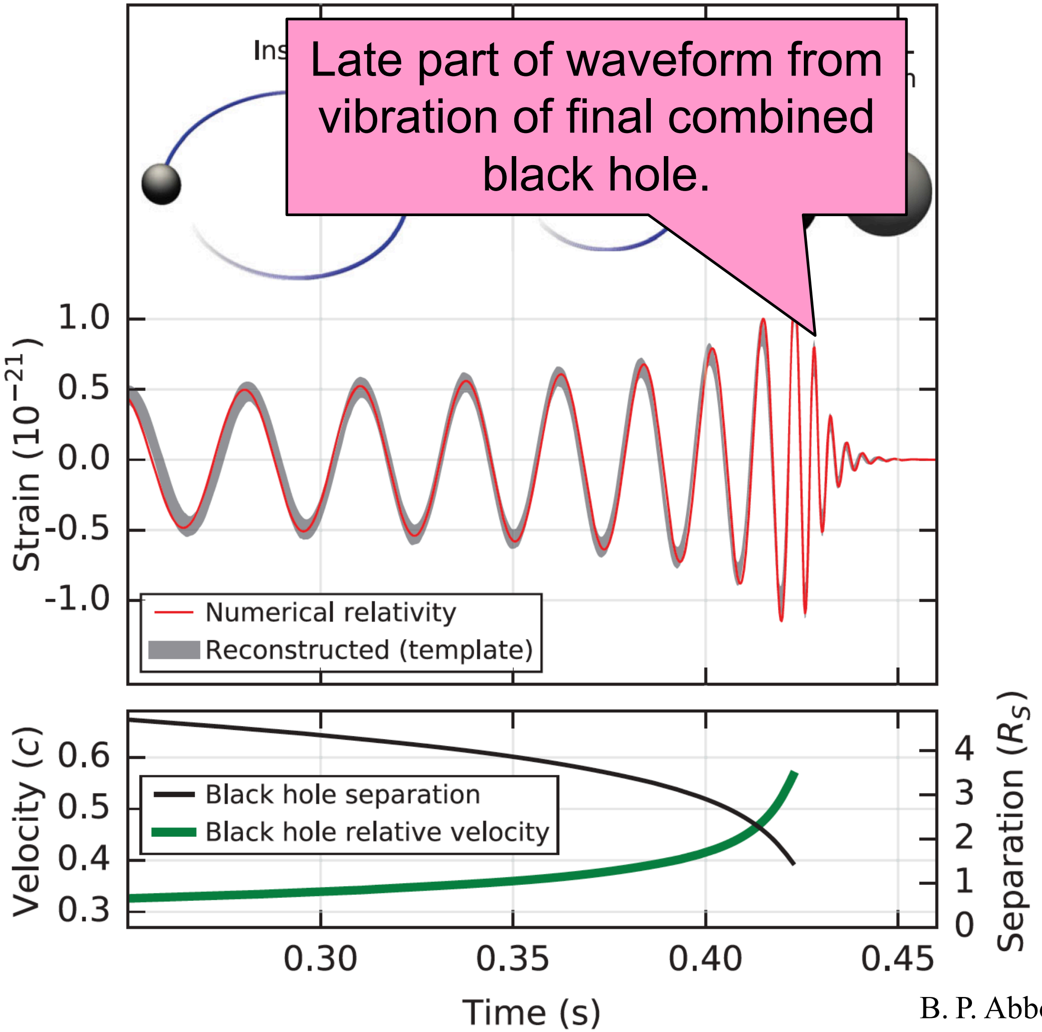

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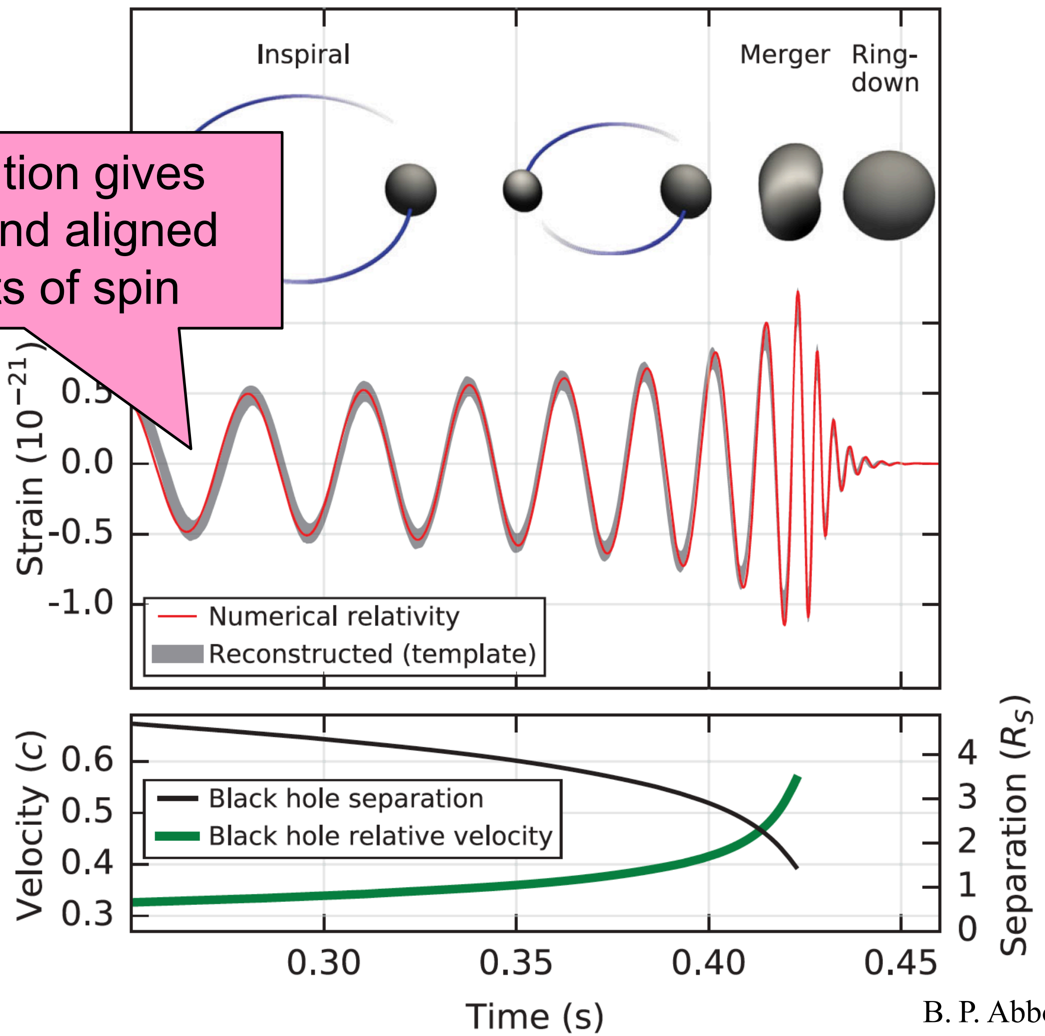
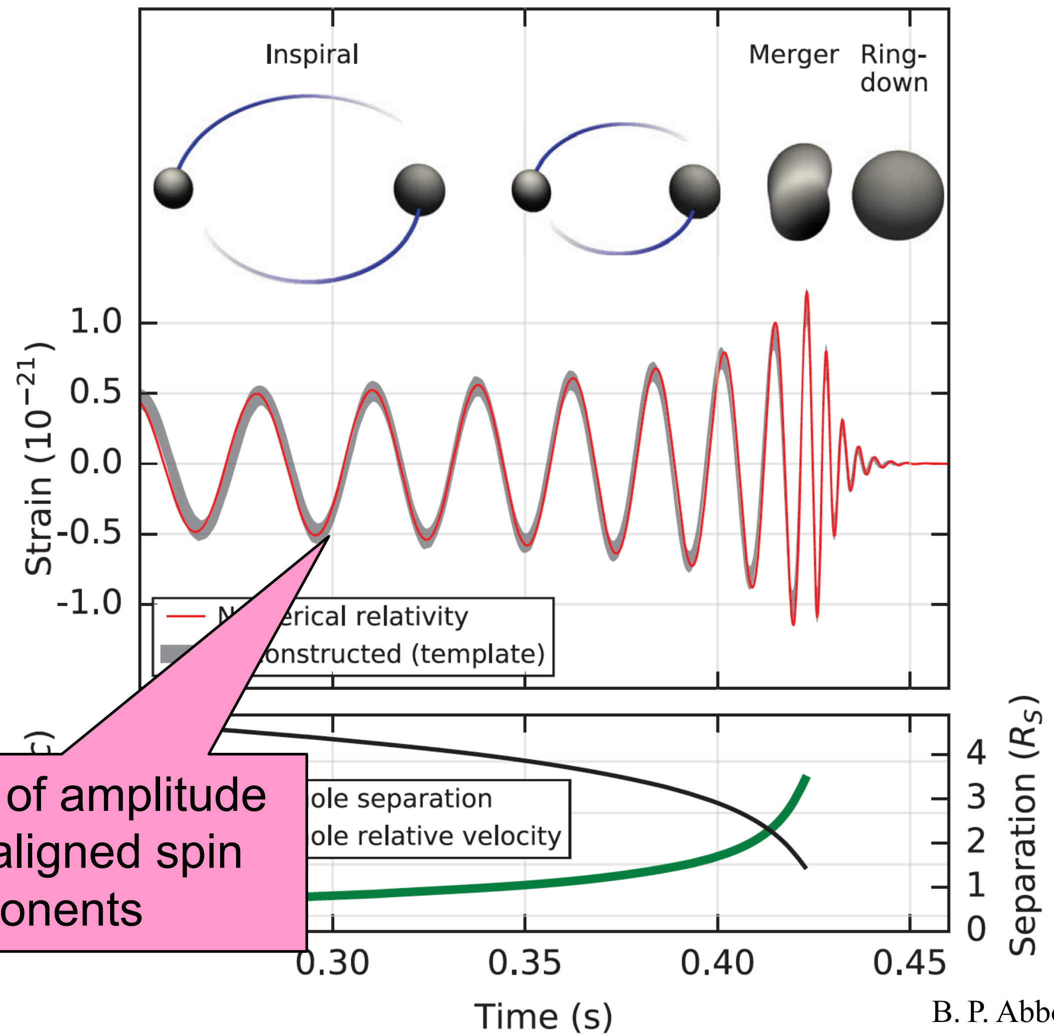


Phase evolution gives chirp mass and aligned components of spin

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

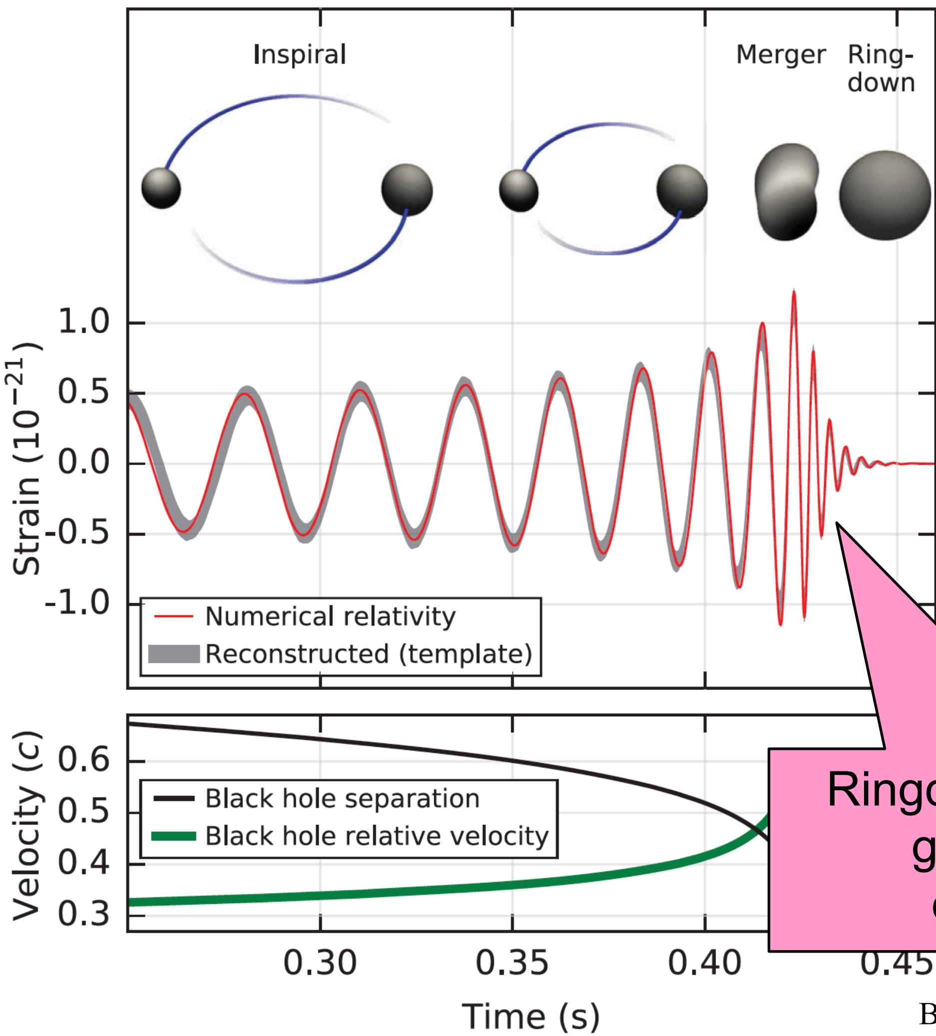
How do we learn from h(t)?



Modulation of amplitude gives nonaligned spin components

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

How do we learn from h(t)?



Ringdown frequency and Q
give mass and spin
of final black hole

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

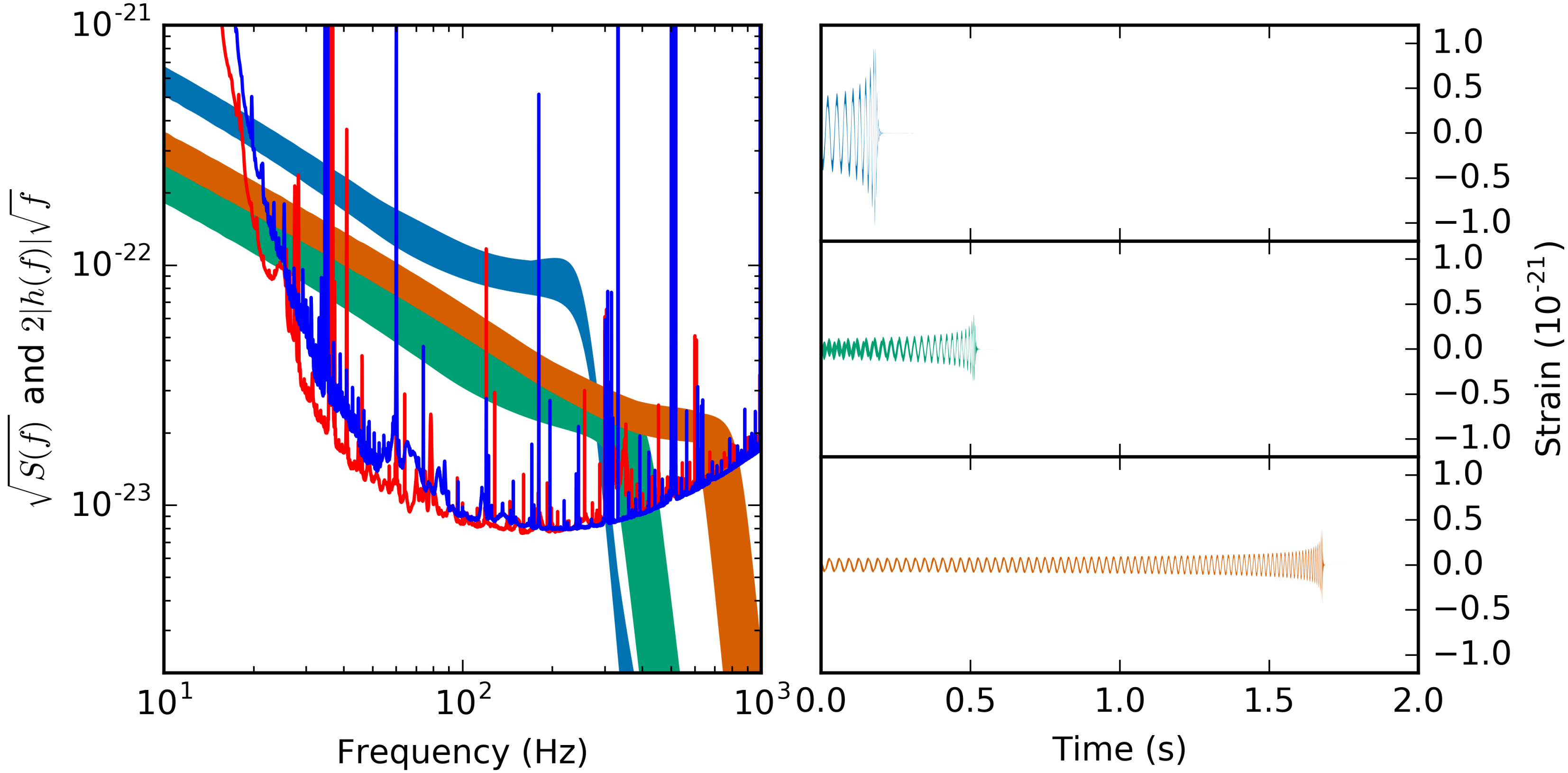
General relativity works!

It took analytical relativity and numerical relativity to predict the waveform from a coalescing binary.

The best fit waveforms leave no significant residual – they work!

Future observations will provide more stringent comparisons, tighter tests of GR.

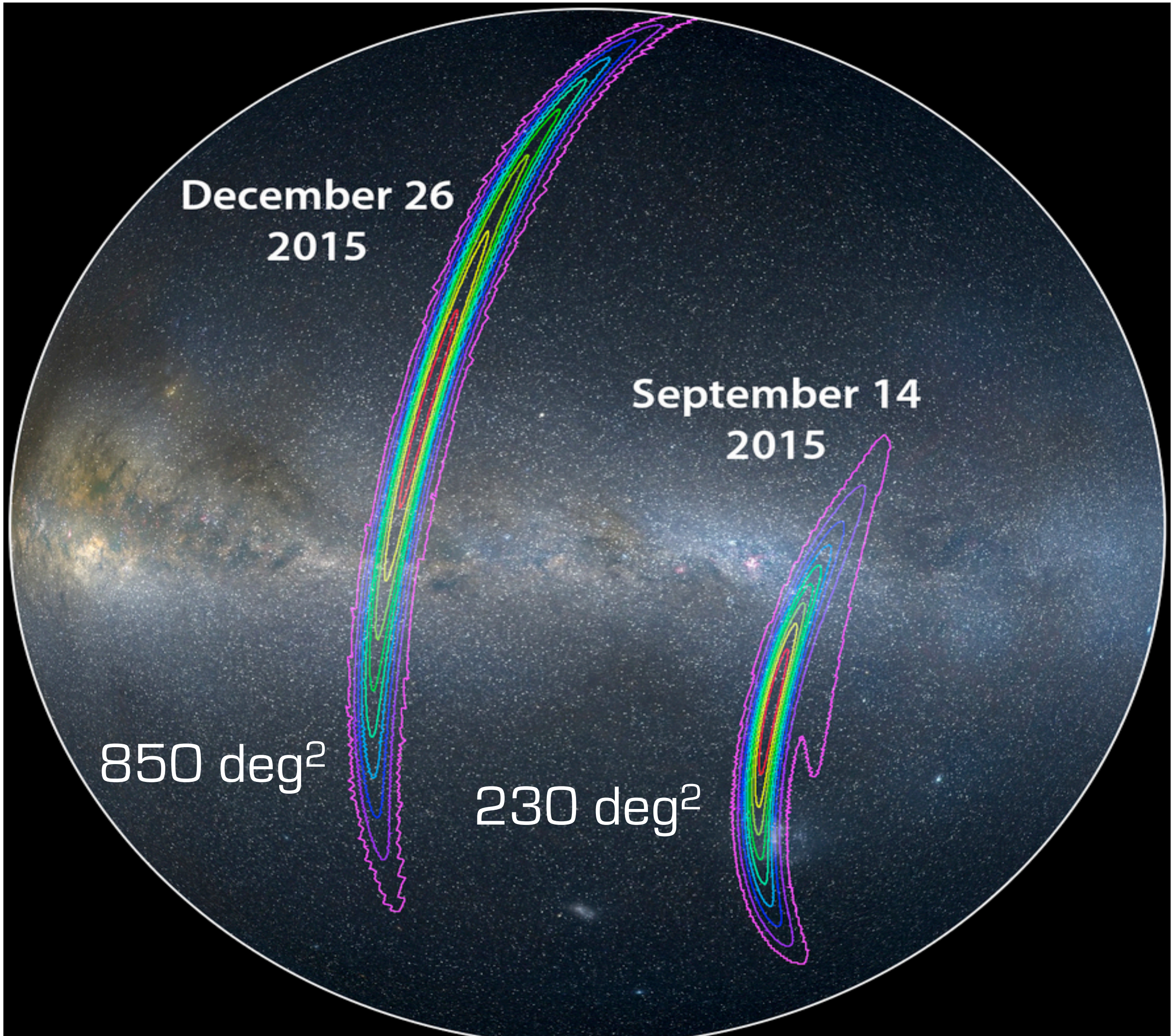
O1 BBH Detections



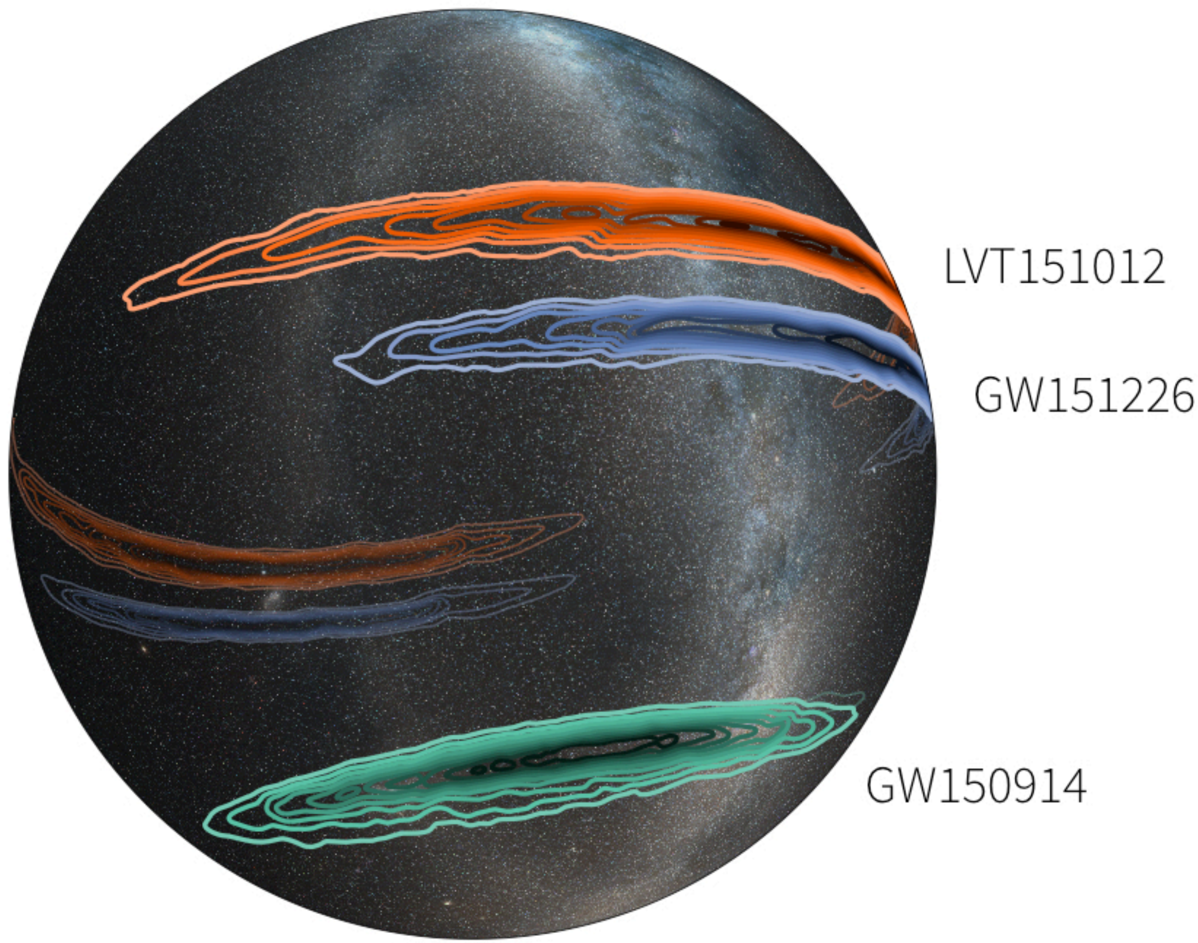
O1 BBH Detections

Event	GW150914	GW151226	LVT151012
SNR	23.6	13	9.7
FAR (yr^{-1})	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.44
p-value	7.5×10^{-8}	7.5×10^{-8}	0.05
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass ($\mathrm{M}_\odot$)	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass ($\mathrm{M}_\odot$)	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass ($\mathrm{M}_\odot$)	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	15^{+1}_{-1}
Total mass ($\mathrm{M}_\odot$)	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effiective inspiral spin	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin	$0.67^{+0.05}_{-0.06}$	$0.72^{+0.05}_{-0.05}$	$0.65^{+0.08}_{-0.10}$
Radiated energy ($\mathrm{M}_\odot c^2$)	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity ($\mathrm{erg\,s^{-1}}$)	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance (Mpc)	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization (deg^2)	230	850	1600

Sky Location



Sky Location



Why does data taking stop?

$\#\ \mathrm{EVENTS}\ d^3\ T$

1 day of data at a range of 80 Mpc is equivalent to 64 days at 20 Mpc

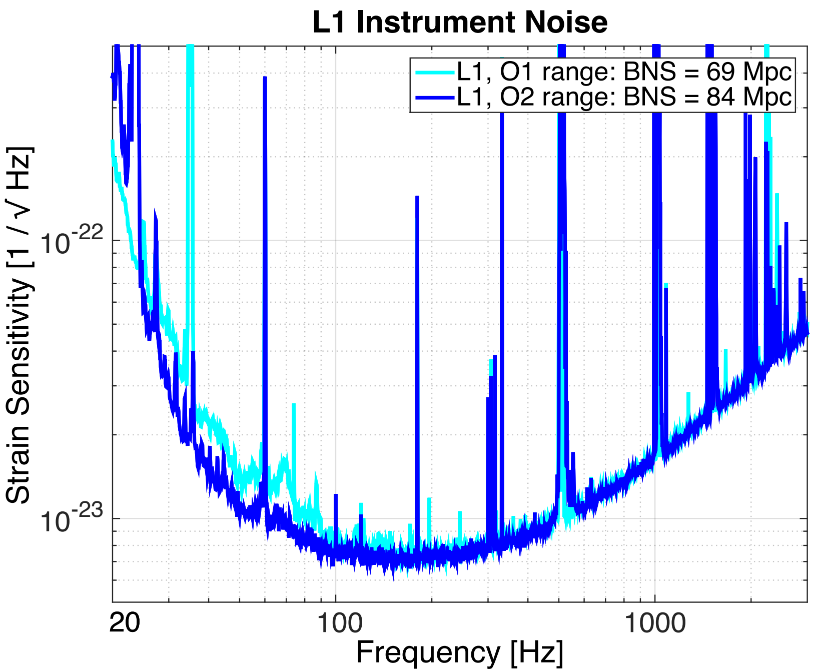
1 day of data at a range of 100 Mpc is equivalent to 2 days at 80 Mpc

it’s good to observe for a long time,
it’s even better to improve the sensitivity further

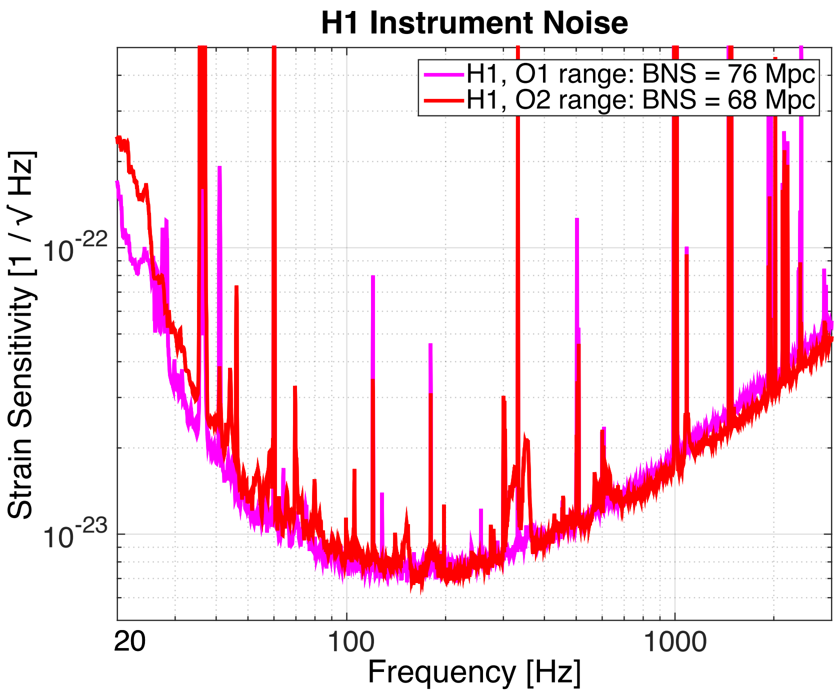
for this reason science runs are stopped and time is dedicated to commissioning in order to further increase the volume of observable universe (d^3) and improve the machine stability (T)

Second Observation Run (O2)

(November 2017 – end August 2017)



LIGO G-1602060

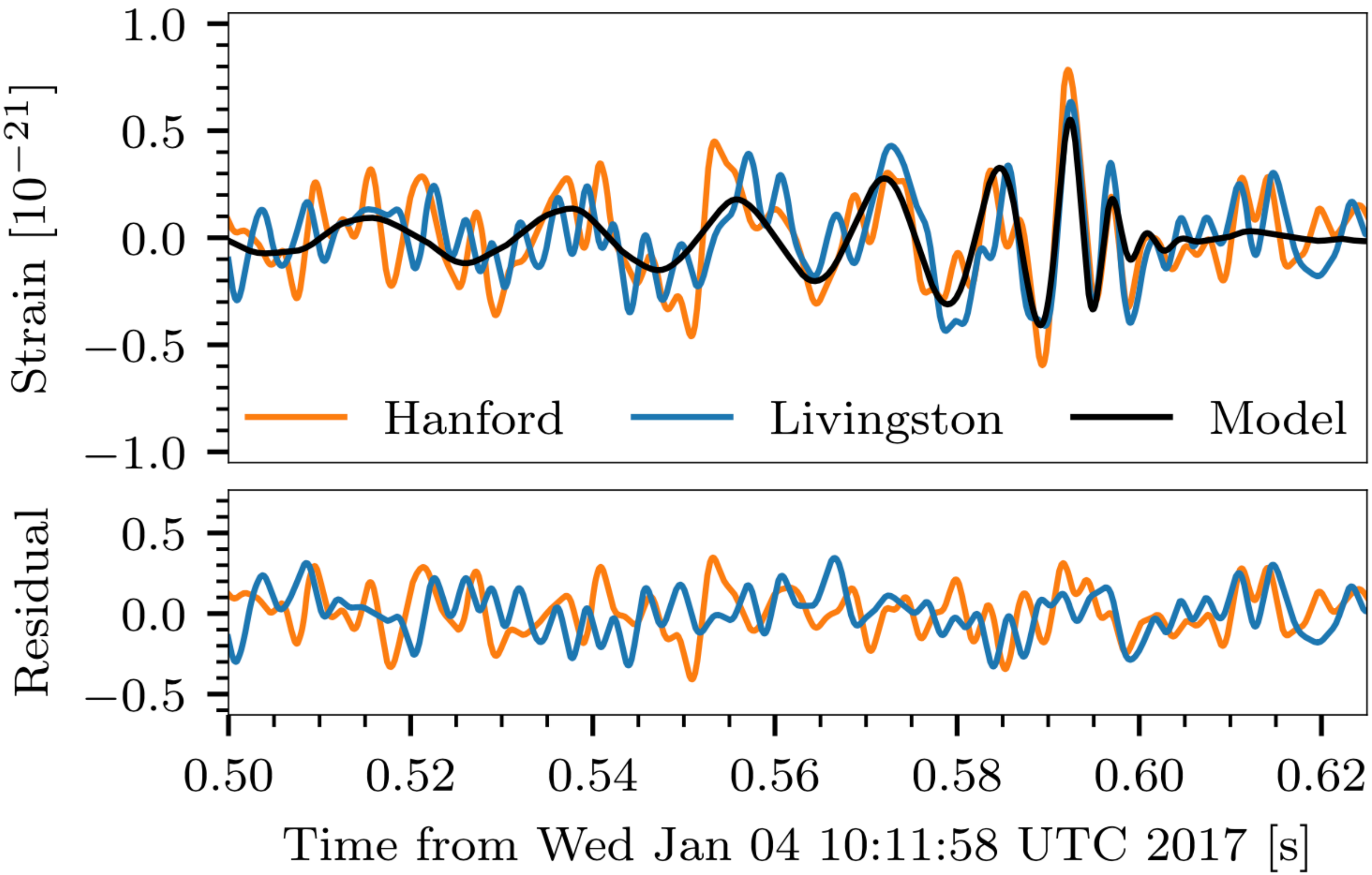


LIGO G-1602060

Advanced Virgo will join later O2

GW170104

BP Abbott et al (LVC), PRL 118 (2017), 221101



GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

B. P. Abbott *et al.*[*]

(LIGO Scientific and Virgo Collaboration)

(Received 9 May 2017; published 1 June 2017)

We describe the observation of GW170104, a gravitational-wave signal produced by the coalescence of a pair of stellar-mass black holes. The signal was measured on January 4, 2017 at 10:11:58.6 UTC by the twin advanced detectors of the Laser Interferometer Gravitational-Wave Observatory during their second observing run, with a network signal-to-noise ratio of 13 and a false alarm rate less than 1 in 70 000 years. The inferred component black hole masses are $31.2^{+8.4}_{-6.0} M_\odot$ and $19.4^{+5.3}_{-5.9} M_\odot$ (at the 90% credible level). The black hole spins are best constrained through measurement of the effective inspiral spin parameter, a mass-weighted combination of the spin components perpendicular to the orbital plane, $\chi_{\mathrm{eff}} = -0.12^{+0.21}_{-0.30}$. This result implies that spin configurations with both component spins positively aligned with the orbital angular momentum are disfavored. The source luminosity distance is 880^{+450}_{-390} Mpc corresponding to a redshift of $z = 0.18^{+0.08}_{-0.07}$. We constrain the magnitude of modifications to the gravitational-wave dispersion relation and perform null tests of general relativity. Assuming that gravitons are dispersed in vacuum like massive particles, we bound the graviton mass to $m_g \leq 7.7 \times 10^{-23}$ eV$/c^2$. In all cases, we find that GW170104 is consistent with general relativity.

DOI: 10.1103/PhysRevLett.118.221101

JAN 4$^{\mathrm{TH}}$, 2017: FIRST O2 DETECTION. PUBLISHED ON PRL, JUN 2$^{\mathrm{ND}}$

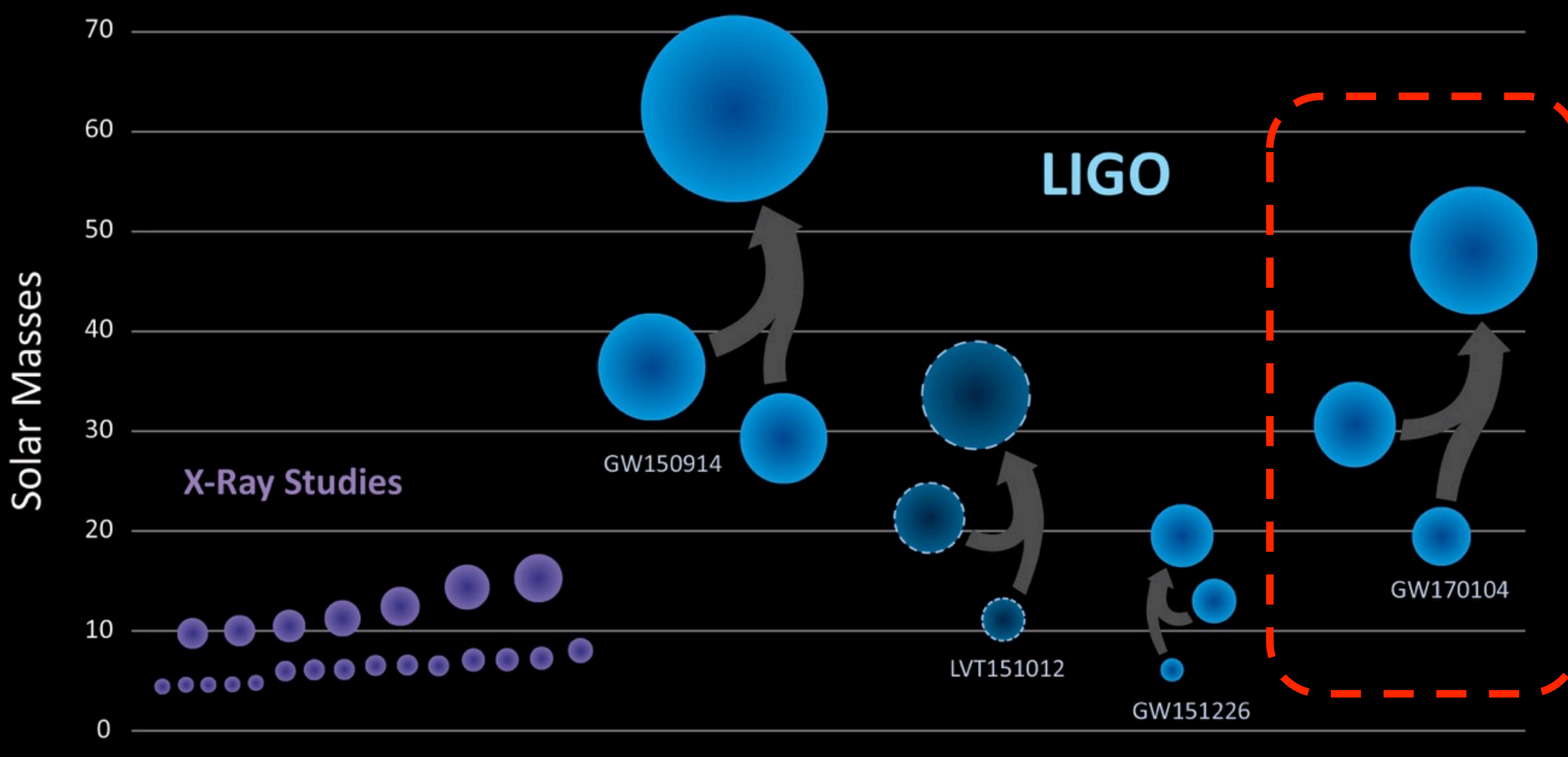
GW100104: PARAMETERS

Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy $E_{\rm rad}$	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\ s^{-1}}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

BP Abbott et al (LVC), PRL 118 (2017), 221101

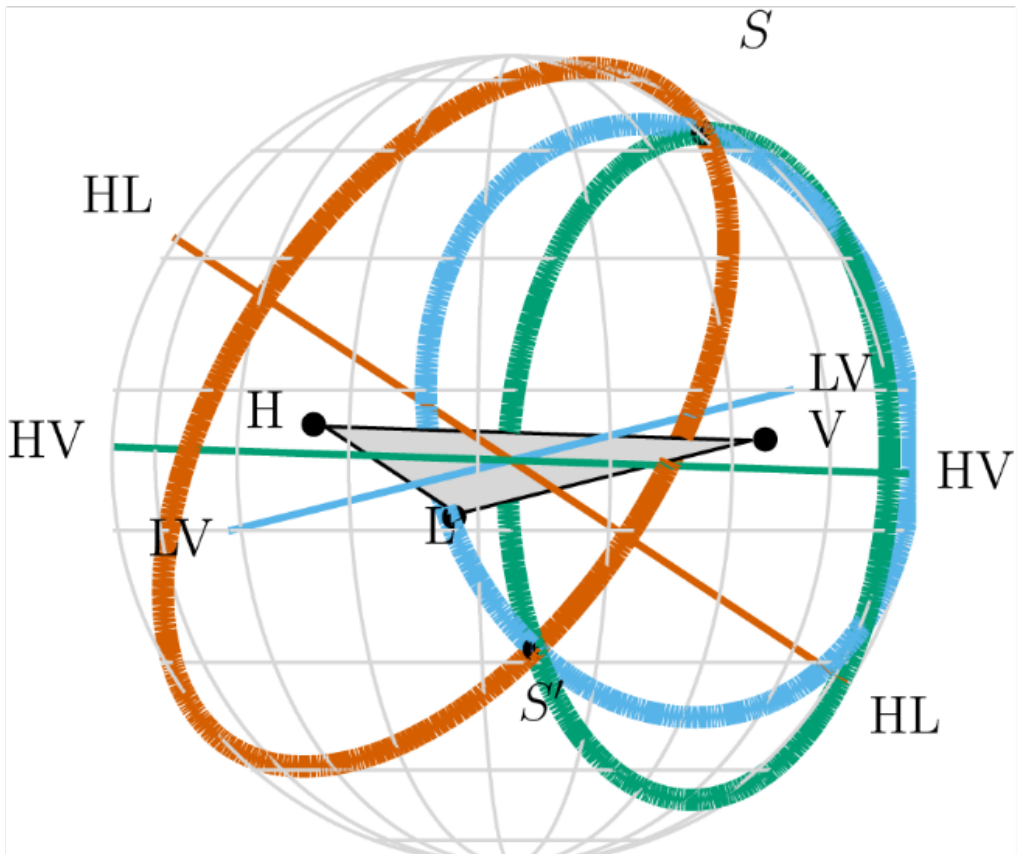
Black Holes of Known Mass

Image credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)



To find the direction to a source, triangulate with a global network

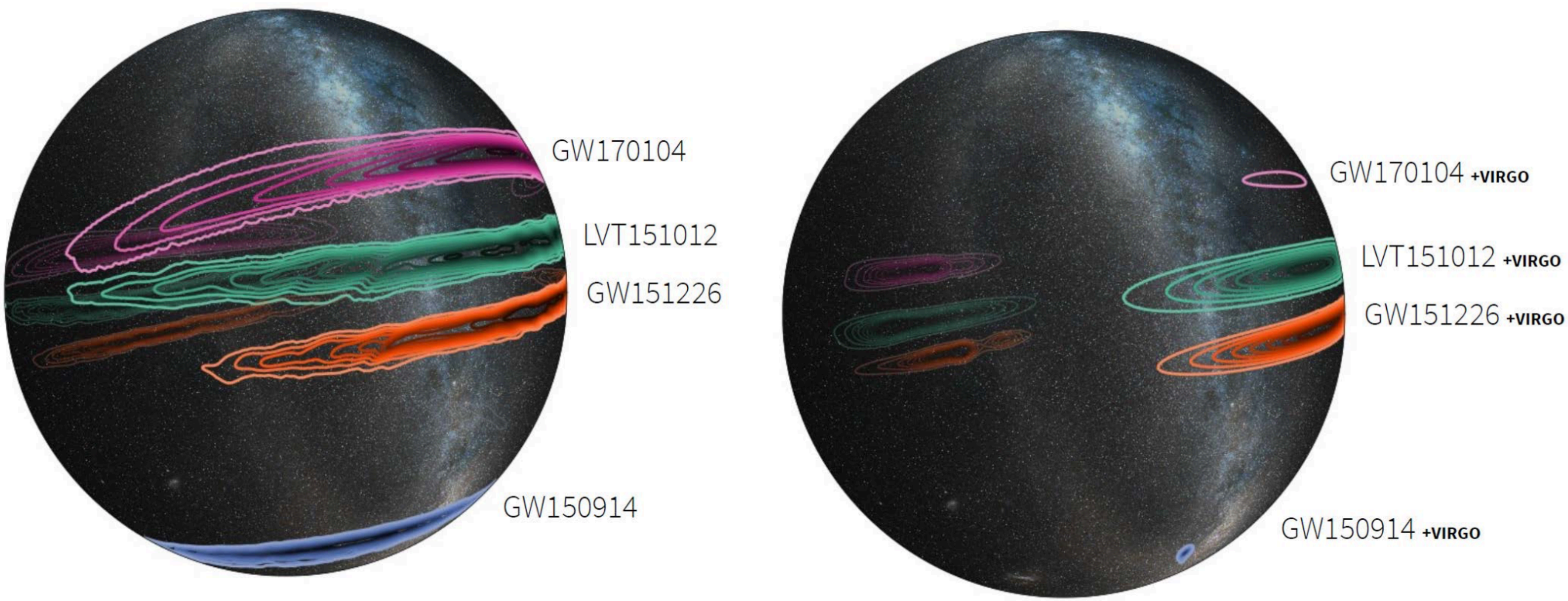
… here, illustrated with LIGO and Virgo.



Abbott, et al., Living Rev. Relativity, 19, (2016), 1

Towards the network

- Localization is a key ingredient to find electromagnetic counterparts and open the era of multimessenger astronomy
- Virgo will soon contribute to improve the localization (adding a 3rd detector to the triangulating network)

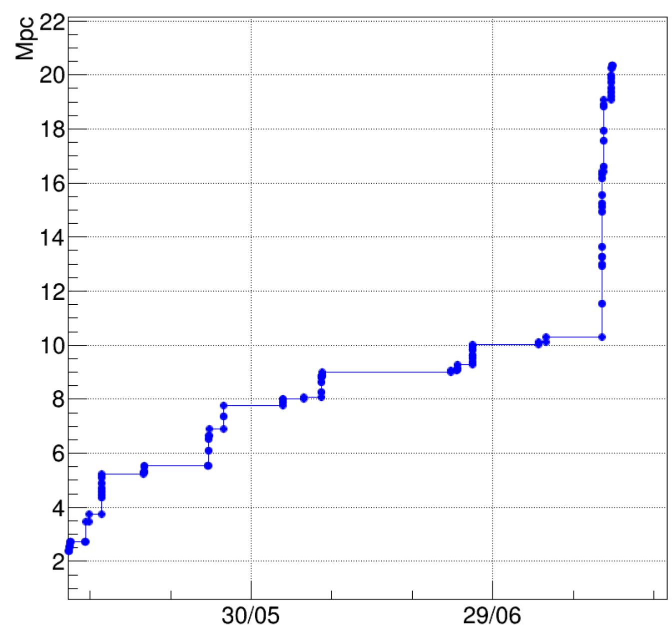


Advanced Virgo Status

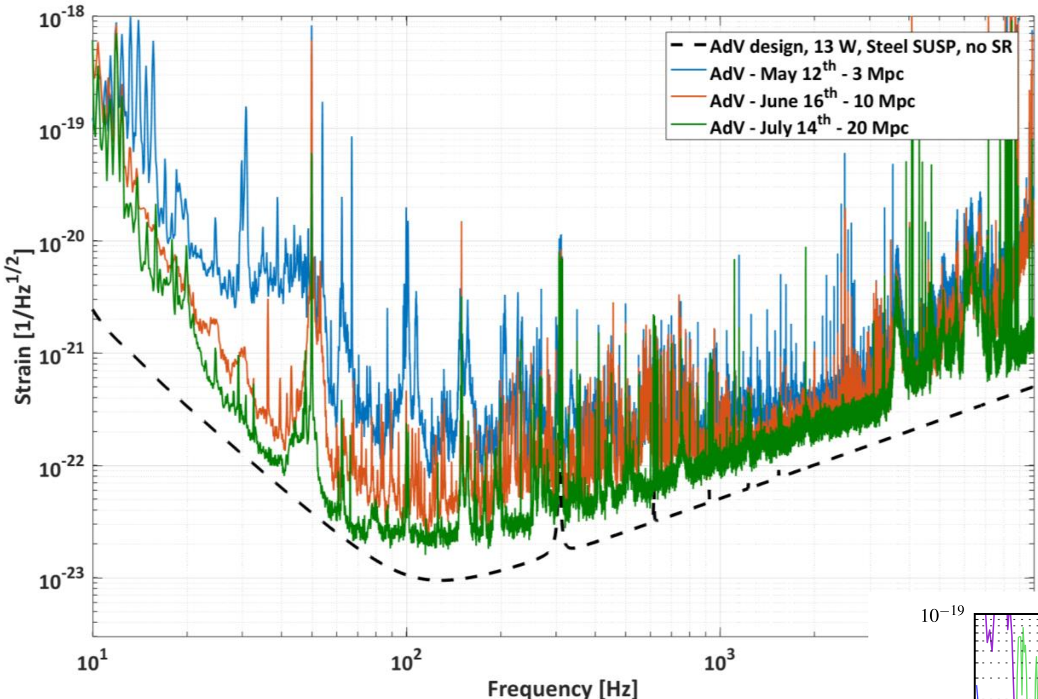
- First AdV Commissioning Run (C8) performed in May (5th to 8th);
- ER11 in June in coincidence with LIGO:
  - First fraction from 16th to 19th: BNS range fluctuating between 5 to 9 Mpc, duty cycle around 70%;
  - Second half from 23rd to 26th: reduced BNS range fluctuations (8-9 Mpc), duty cycle close to 80%;
- Since then, activities focused on noise hunting and sensitivity improvement:
  - Investigation on scattered light from B4 ghost beam;
  - Magnetic and acoustic noise injections;
  - Switch off tests;
  - SDB1 scattered light.
  - Non linear growth of the BNS range:

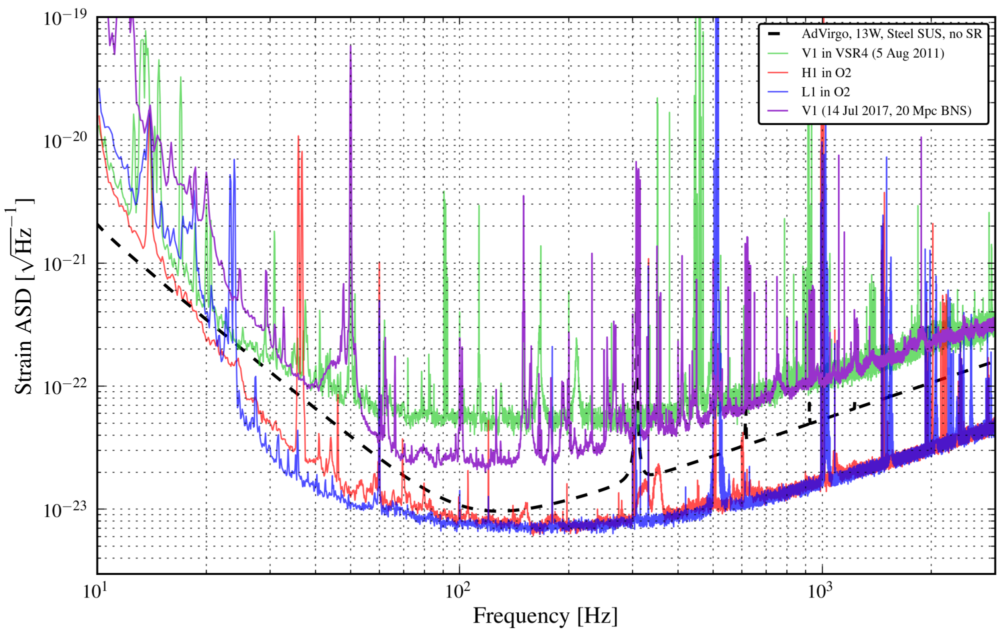
Milestone "20 Mpc" reached on July 14th.

AdV best BNS range (from May 7 to July 14)



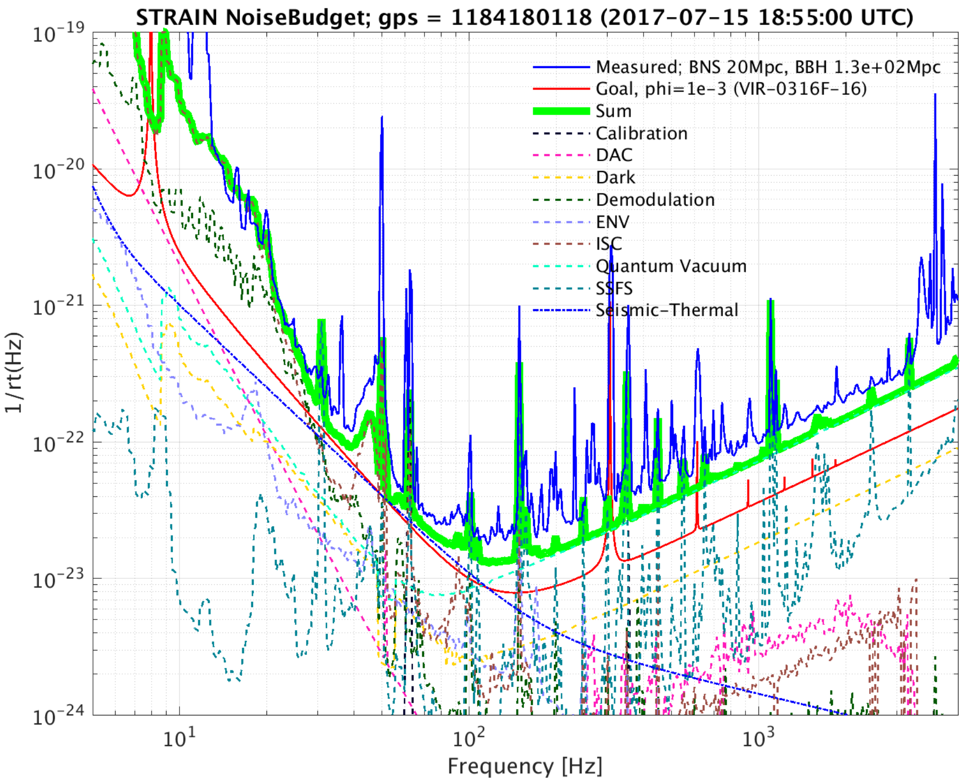
Sensitivity evolution





Where do we stand

- Between 20 Hz - 30 Hz, control noise or timing noise?
- From 30 Hz to 70 Hz nearly thermal noise limited (except 50 Hz bump);
- In the bucket, from 70 Hz to 150 Hz, non stationary noise;
- Above 150 Hz:
  - Violin modes;
  - Some structures and peaks most likely associated to SDB1;
  - Mystery noise floor above shot noise.

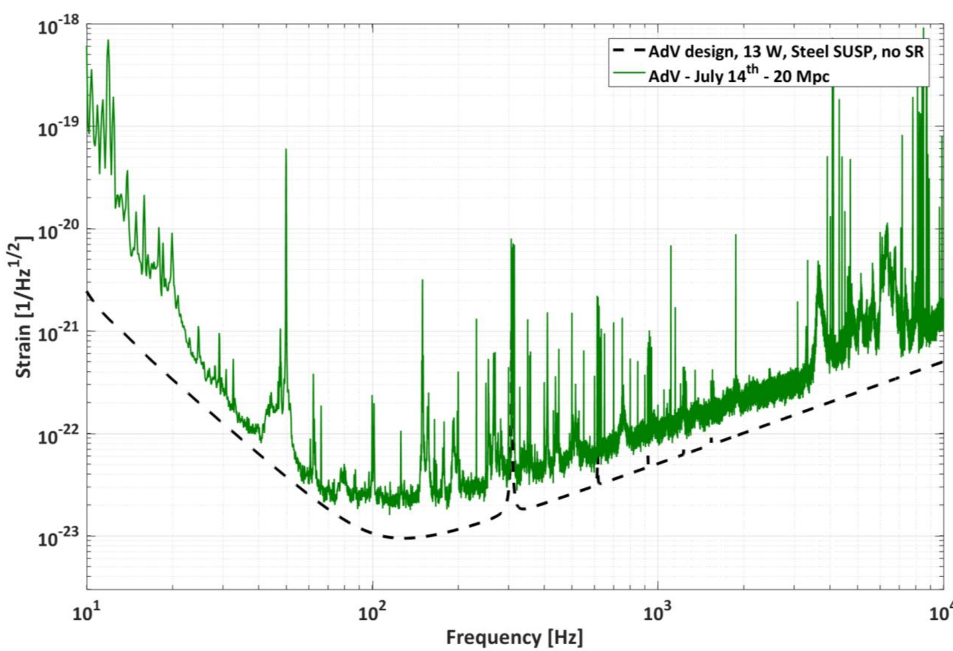


Sum of projected noises at 32 Mpc

Gap between measured noise and explained noise is shrinking

Where do we need to push?

- Currently: BNS range 20 Mpc and 30 Msol BBH range about 107 Mpc;
- Improving the sensitivity at low frequencies:
  - BNS range increase by a few Mpc;
  - 30 Msol BBH range increase 20-25%;
- Between 70 Hz and 200 Hz:
  - About 15Mpc increase for BNS;
  - Marginal gain for 30Msol BBHs;
- Above 200 Hz:
  - About 2.5 Mpc for BNS;
  - No gain for 30Msol BBHs.



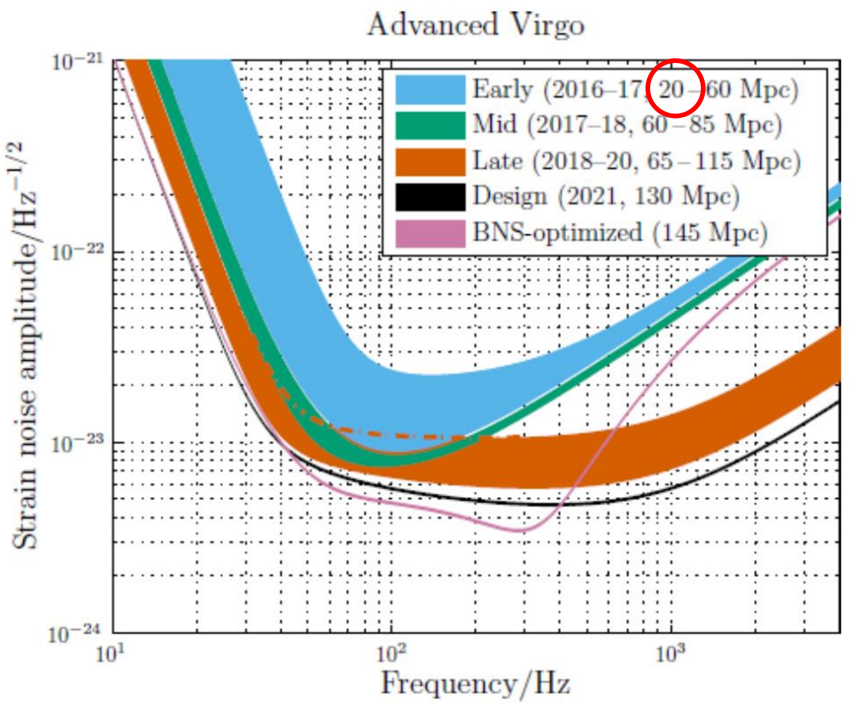
On the way to join O2

We have now reached the minimum sensitivity goal for the "Early" configuration;

This matches the milestone to join O2;

There is still room for improvement:

- Design sensitivity accounts for about 45 Mpc for BNS;
- Not all noise sources identified;
- More noise hunting and loops fine tuning ongoing;
- Not easy to predict how fast improvements could come.



Abbott BP et al. (LSC-Virgo), arXiv:1304:0670

Pushing forward to O3

Roughly 1 year gap between O2 and O3

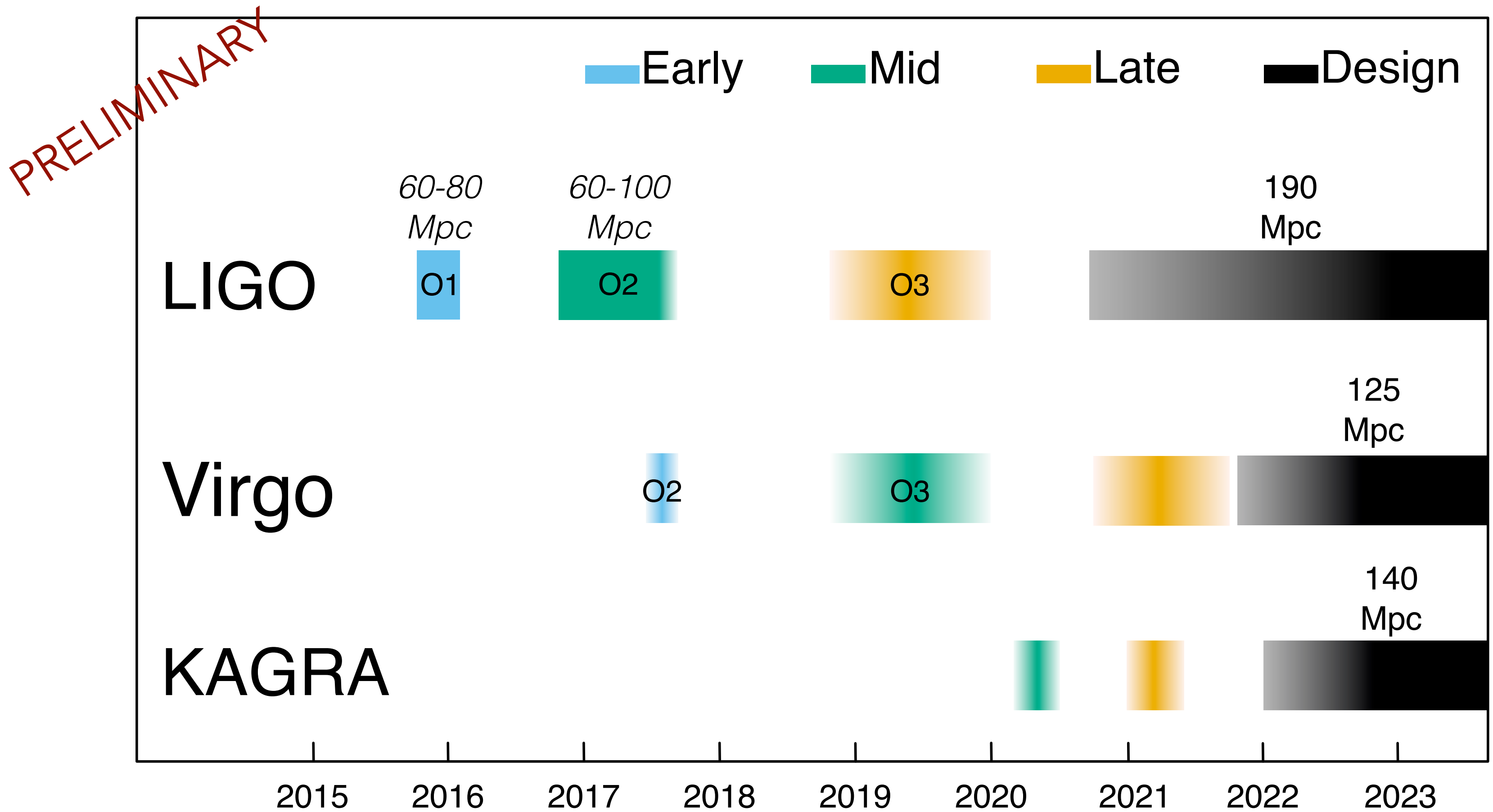
Both LIGO and Virgo will undergo significant upgrades

Virgo:

- monolithic suspensions
- high power laser

LIGO:

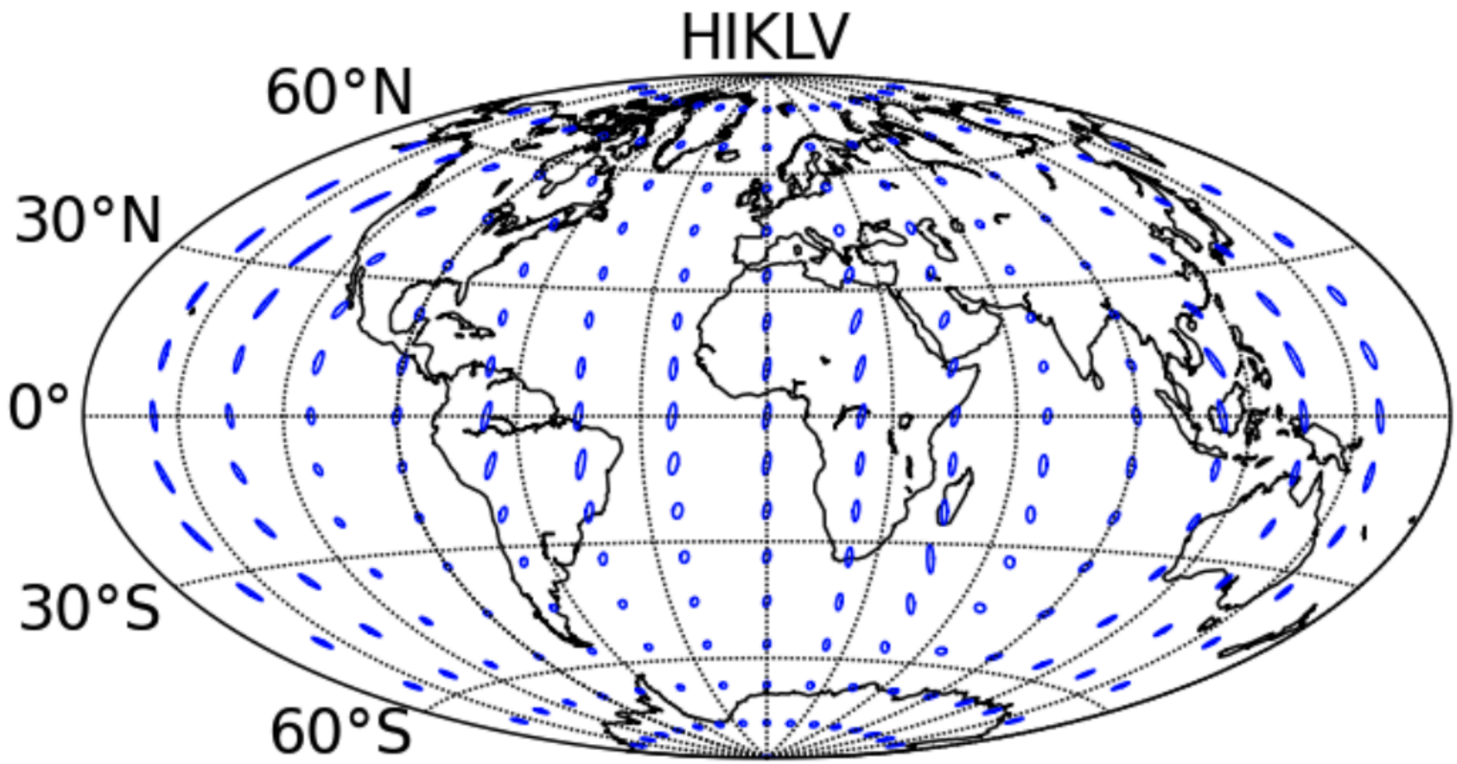
- high power laser
- squeezed light injection



…and LIGO India plans to come on line with Advanced LIGO sensitivity – with any upgrades incorporated – in 2024

B.P. Abbott et al. "Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA" (in preparation)

The mid-term goal



S Fairhurst, CQG 28, 2001

Localization capabilities of the 2G network at mid 2020s:
>60% of the sources localized within 10 deg^2

Vision beyond Advanced Virgo

The path from Advanced Virgo to Einstein Telescope
See VIR-0136A-16

Sensitivity of Advanced Virgo will be improved further within current infrastructure limits

- Additional hardware implementations are planned: MS, FDS, HPL, SR
  - Main limits: mirror thermal noise and quantum noise
- New ideas are under study
  - Larger beam and larger mirrors, and better coatings
  - Newtonian noise subtraction, and improved suspensions

Phased approach

- Phase I: achieve design sensitivity (2017 – 2021)
- Phase II: achieve maximum sensitivity (1.5 x AdV design) within infrastructure limits (2021 – 2025)
- Phase III: optimize AdV in view of a new available infrastructure (> 2025)

From Advanced Virgo to Einstein Telescope

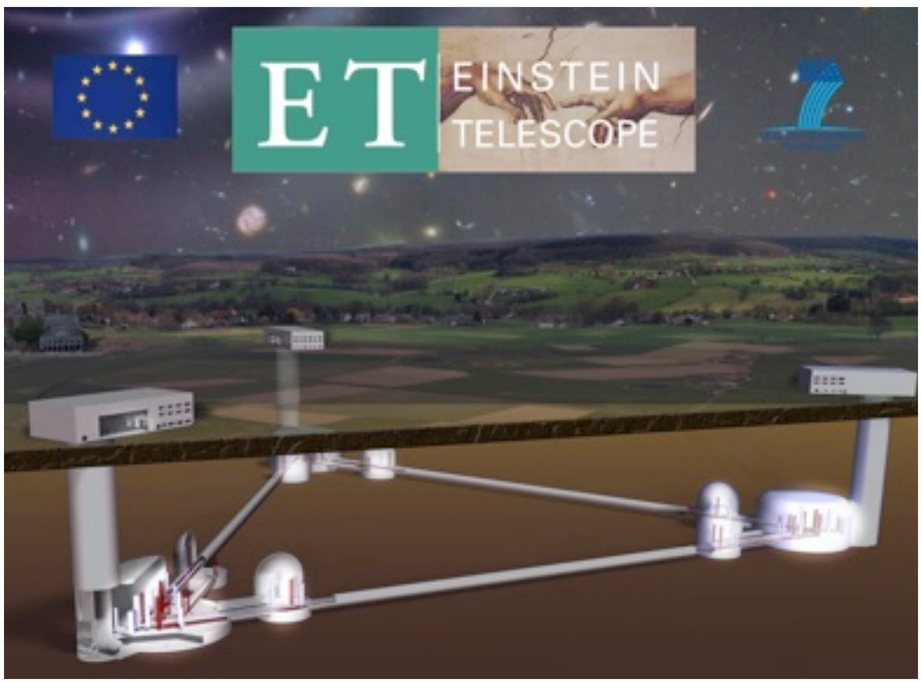
- Scientific excellence with the network of advanced detectors: LIGO, Virgo, KAGRA
- Vigorous and international R&D program focused on third generation with spin-off to advanced detectors
- Position Virgo as an attractive international gateway to GW science

Strategic decision of EU agencies on their commitment for ground-based GW science is required

- Important roles for ApPEC and GWIC

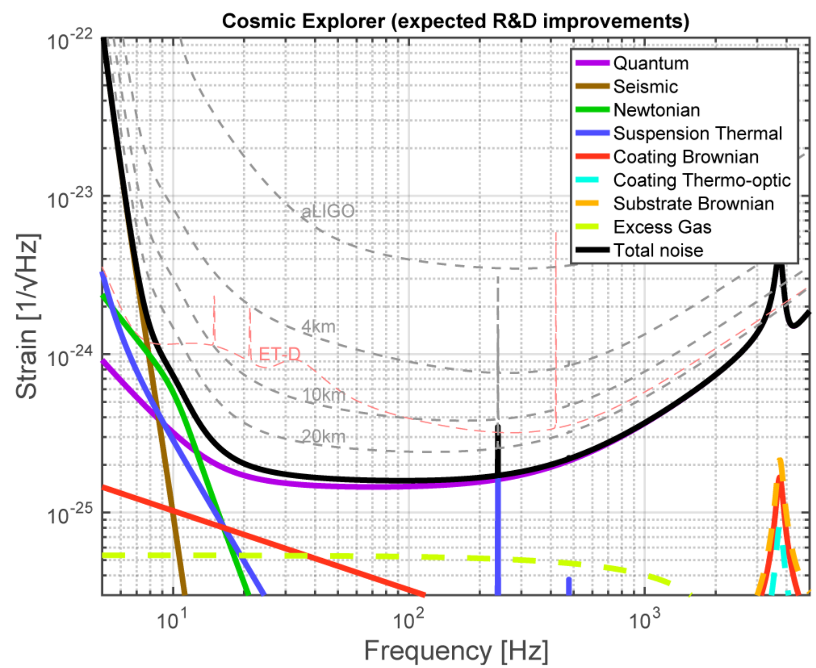
Visions of 3rd generation detectors

Schematic of the Einstein Telescope, a proposed 10-km underground detector.



Source: https://www.aei.mpg.de/18498/03_Einstein_Telescope

Noise spectrum of Cosmic Explorer, a proposed 40-km above-ground detector.



Abbott et al., Class. Quantum Grav. **34** (2017) 044001