GW150914: The first direct detection of gravitational waves

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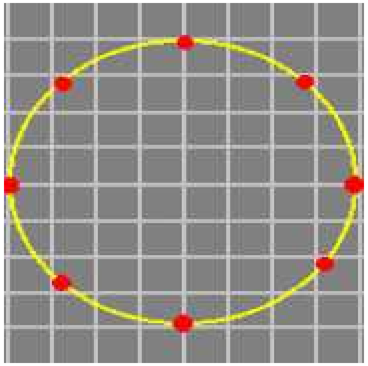
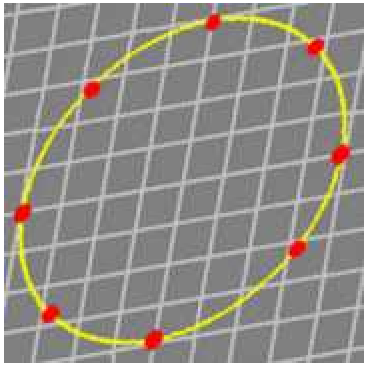
Gravitational waves have been detected!

- The instruments
- The source – and its properties
- Astrophysical significance
- Physical consequences
- Outlook for the future

The principle of detection

Two polarizations – quadrupole transverse wave, interaction with matter:



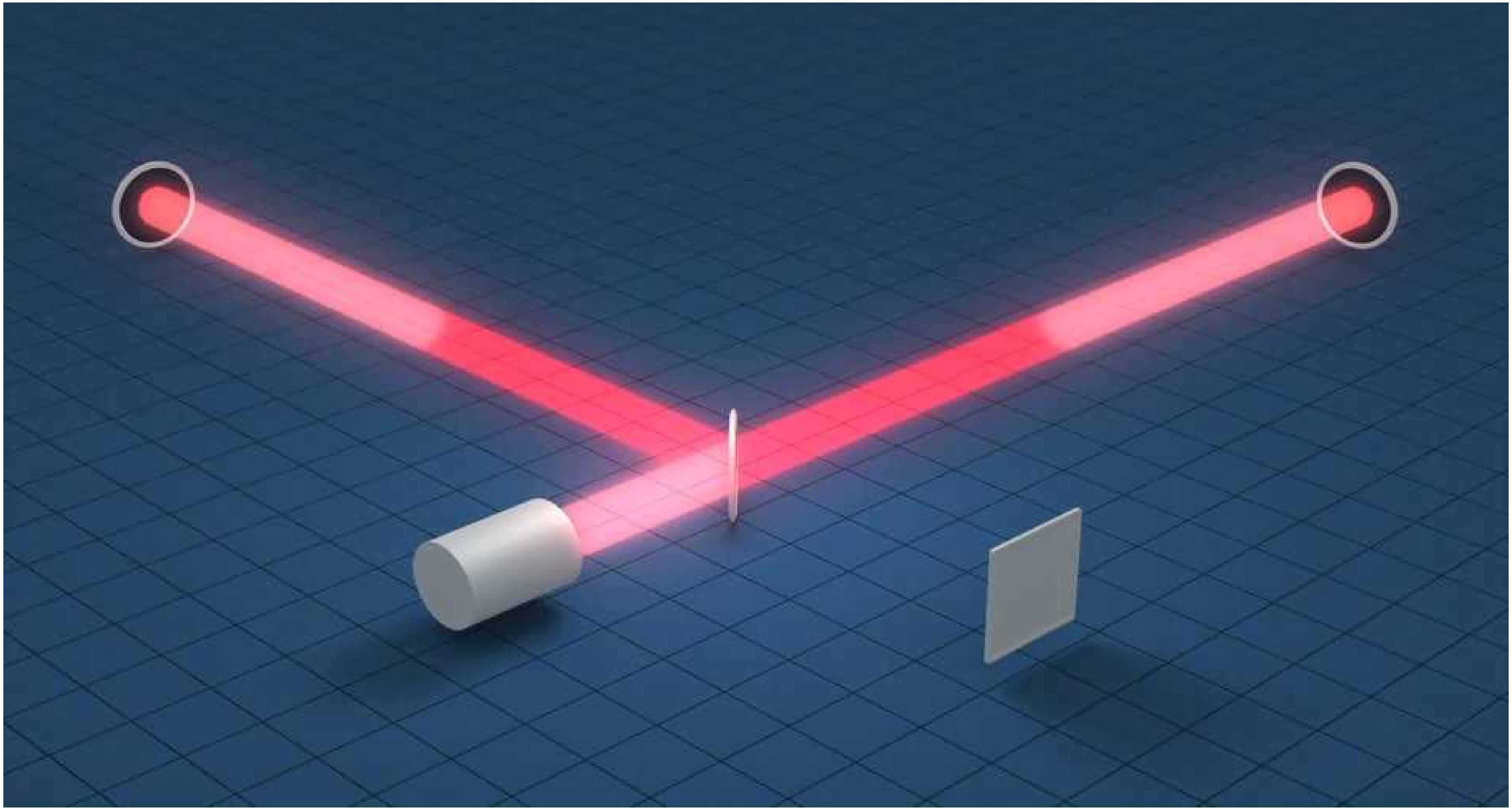


Expected amplitude:

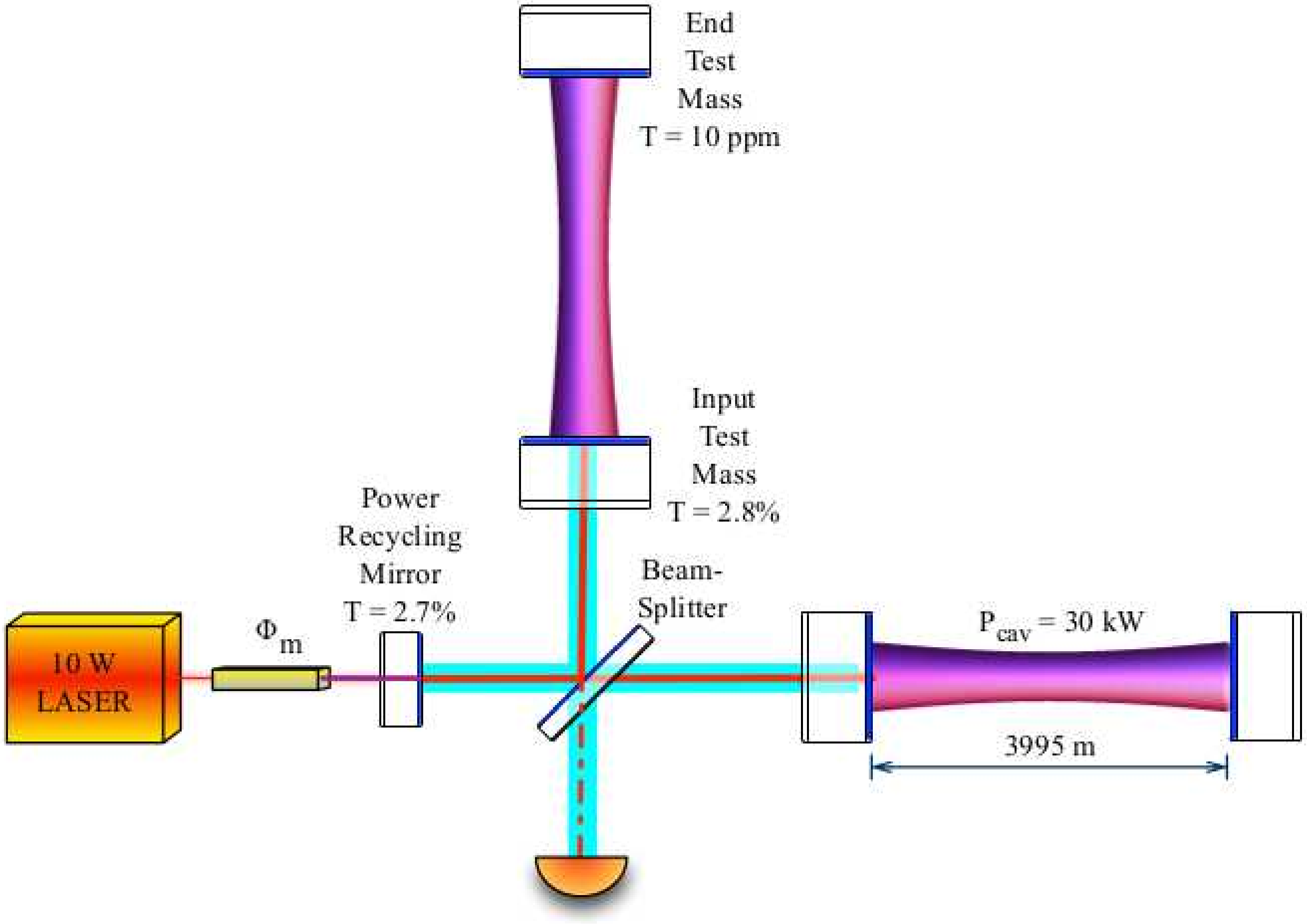
$$h \approx \frac{R_g}{D}\frac{v^2}{c^2} \approx 2 \times 10^{-21}$$

$$M = 60M_\odot \quad D = 400Mpc \; v = 0.2c$$

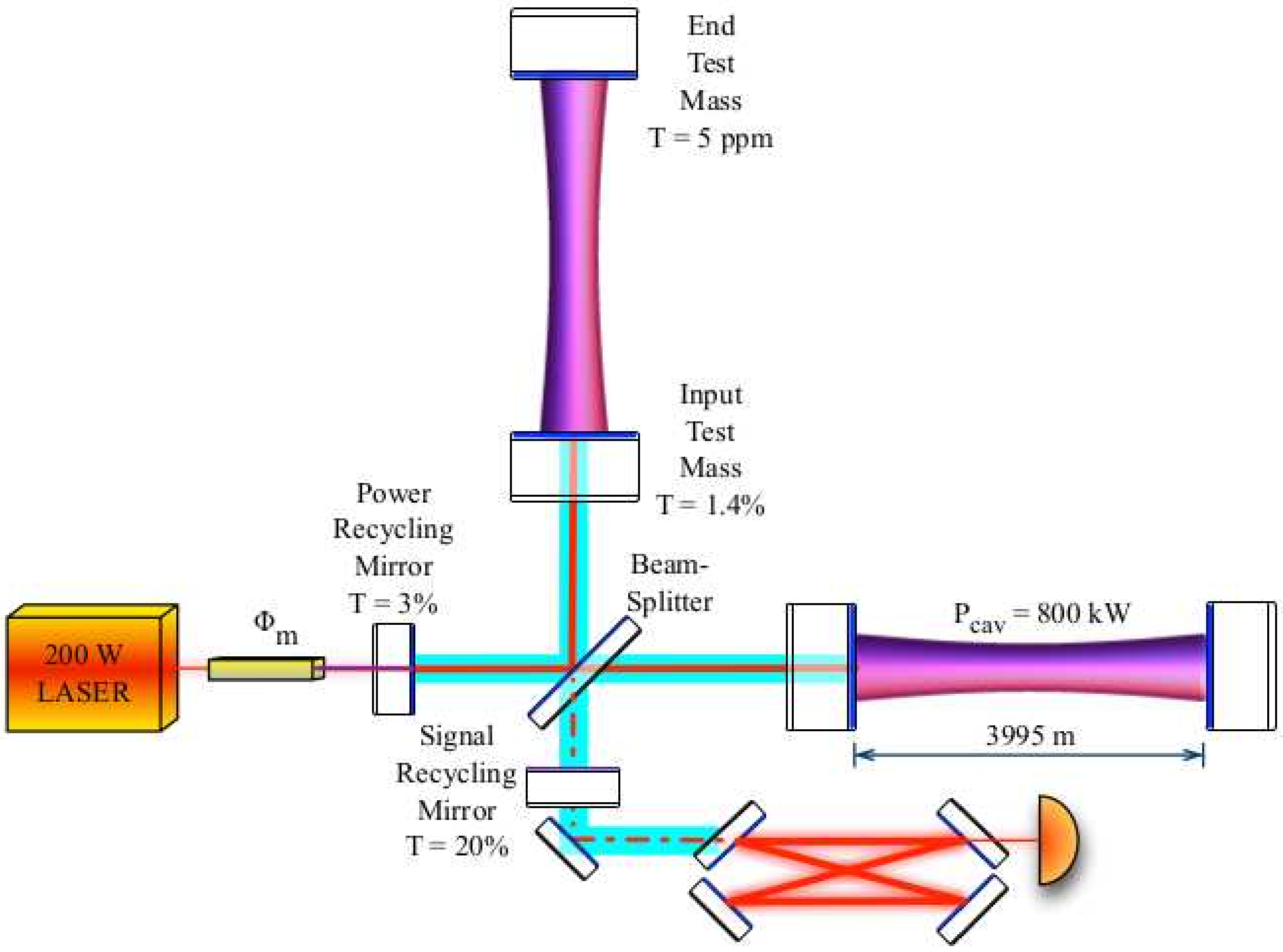
Detection principle



Interferometers: initial



Second generation interferometers



Noise reduction

- Seismic noise quenched by 10 orders of magnitude
- Thermal noise – heavy mass, smart coating
- Quantum shot noise - laser power increase – about 100kW in the cavity
- But – note – fundamental quantum limit.

Order of magnitude estimates

$$\Delta L \approx 10^{-18} m$$

500 round trips, expected delay:

$$\Delta L_{eff} = 500 \times 10^{-18}\mathrm{m} \approx 5 \times 10^{-16}\mathrm{m}$$

The laser wavelength is 1064nm. Expected phase amplitude:

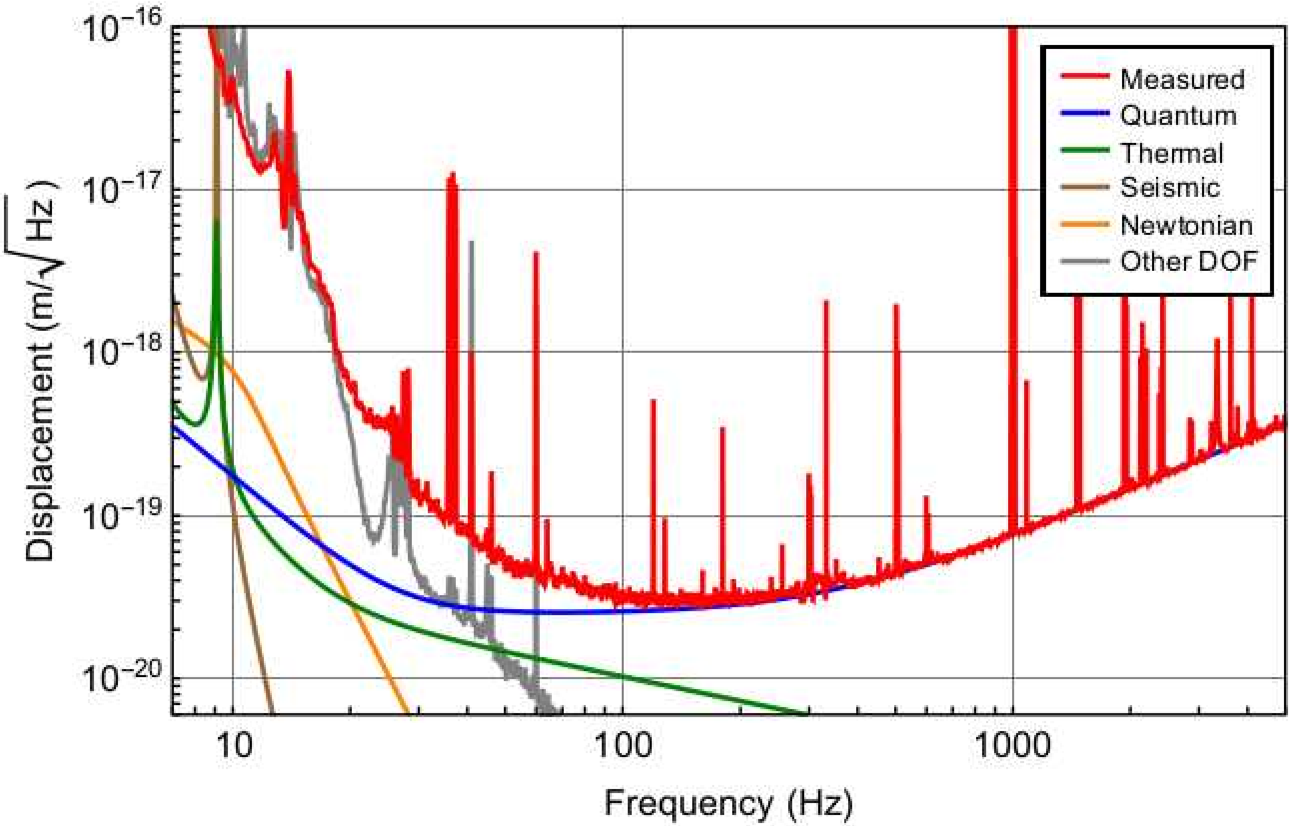
$$\Delta\phi \approx 5 \times 10^{-16}/10^{-6} = 5 \times 10^{-10}$$

With 100kW power the Poisson noise fluctuations are

$$\delta\phi = N^{-1/2} = \sqrt{\frac{hc}{\lambda P \Delta T}} = \sqrt{\frac{10^{-19}\mathrm{J}}{10^{5}\mathrm{W}10^{-2}\mathrm{s}}} \approx 10^{-11}$$

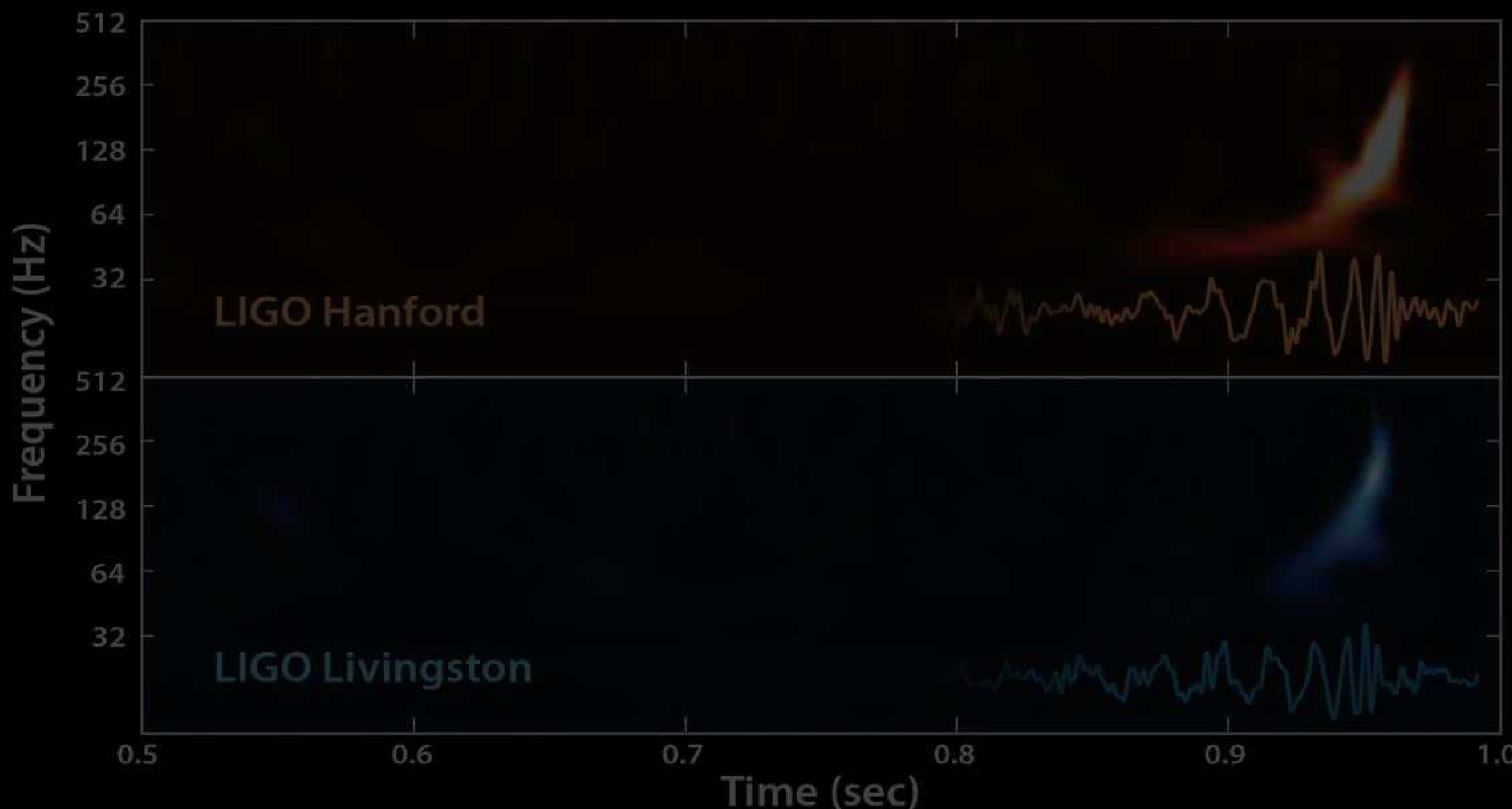
Technical challenges

- Seismic isolation
- Vacuum system
- High power lasers
- Thermal noise
- Quantum fluctuations



Also – newtonian noise, magnetic noise

The detection on Sep 14th, 2015



Burst search

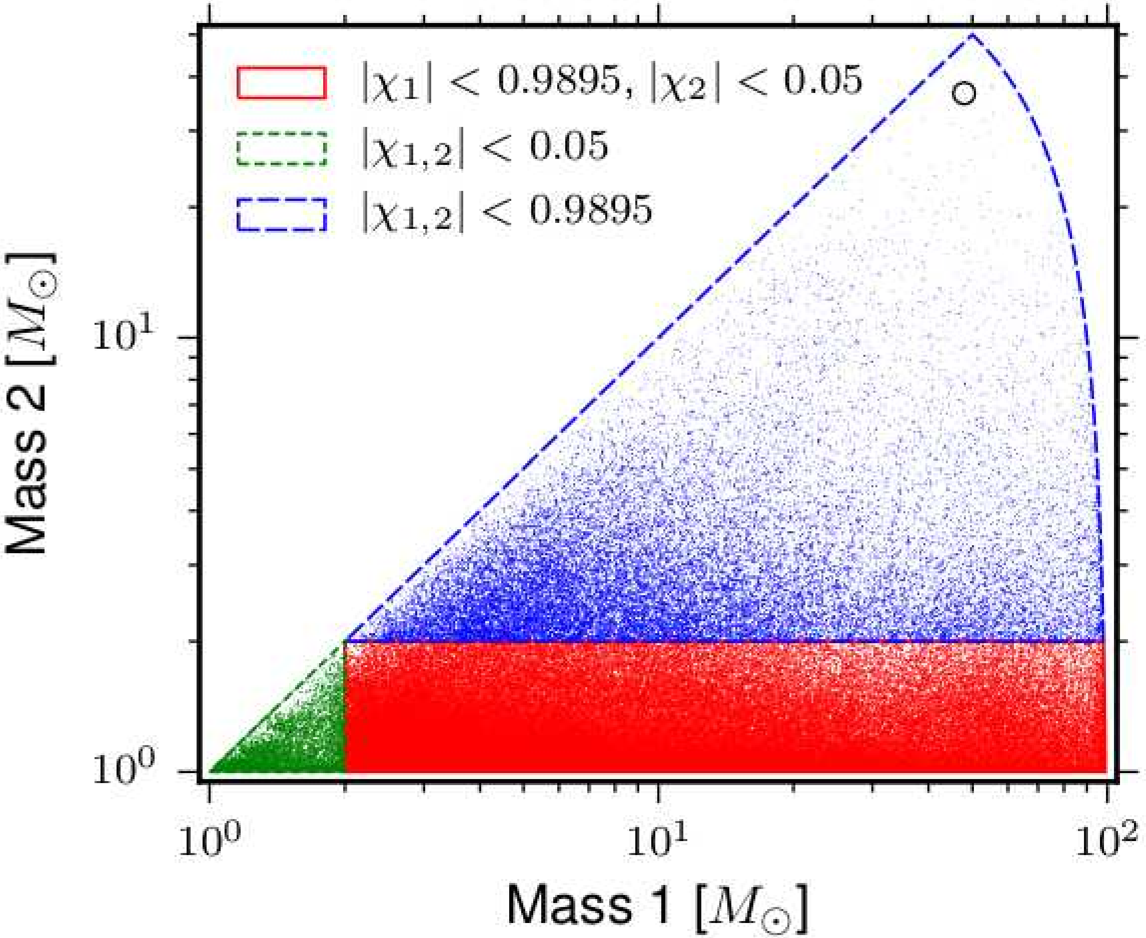
- No prior knowledge of the shape of the signal
- Search for coincident bursts
- Signal reconstruction
- Detection statistics based on similarity of waveforms in two (or more) detectors
- Low latency – less than 3 minutes
- Later off line detailed analysis with background estimates

CBC search

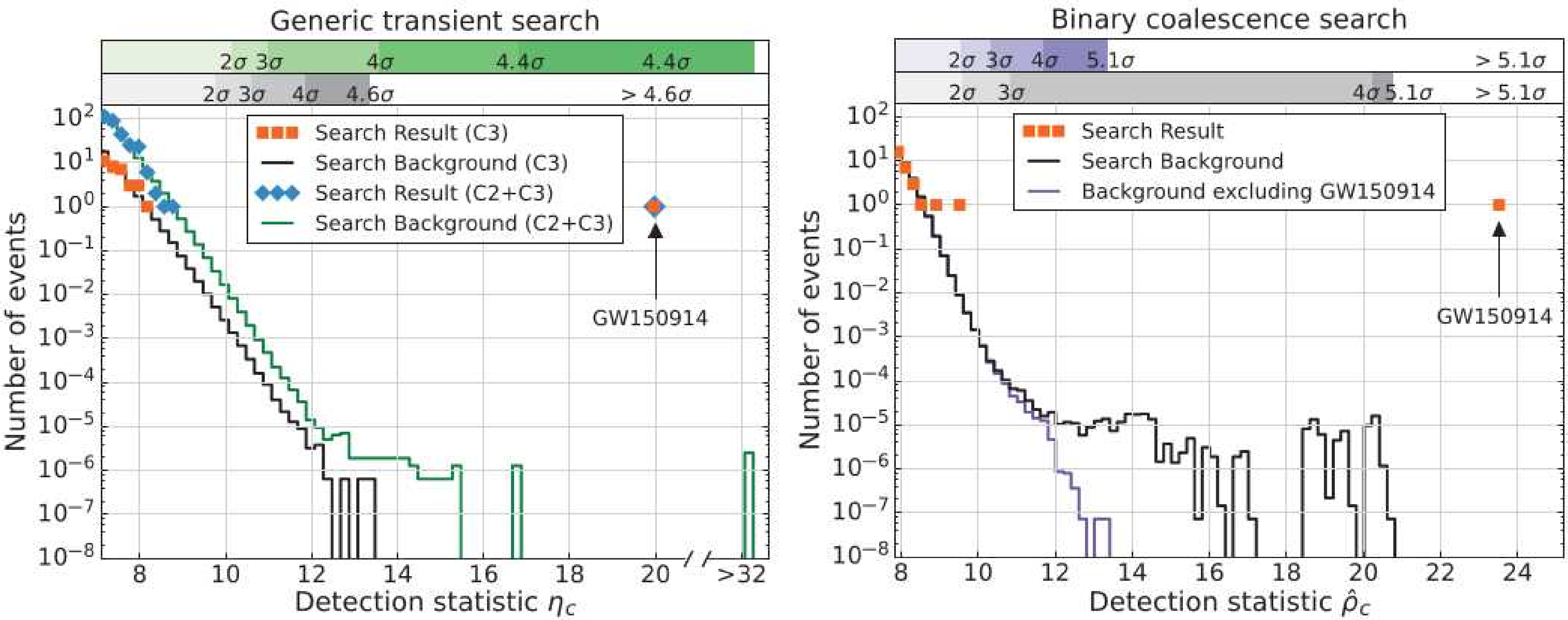
Seacrh targeted at binary coalescence signals: NSNS, BHNS BHBH

Template bank

Background estimate using time shifts



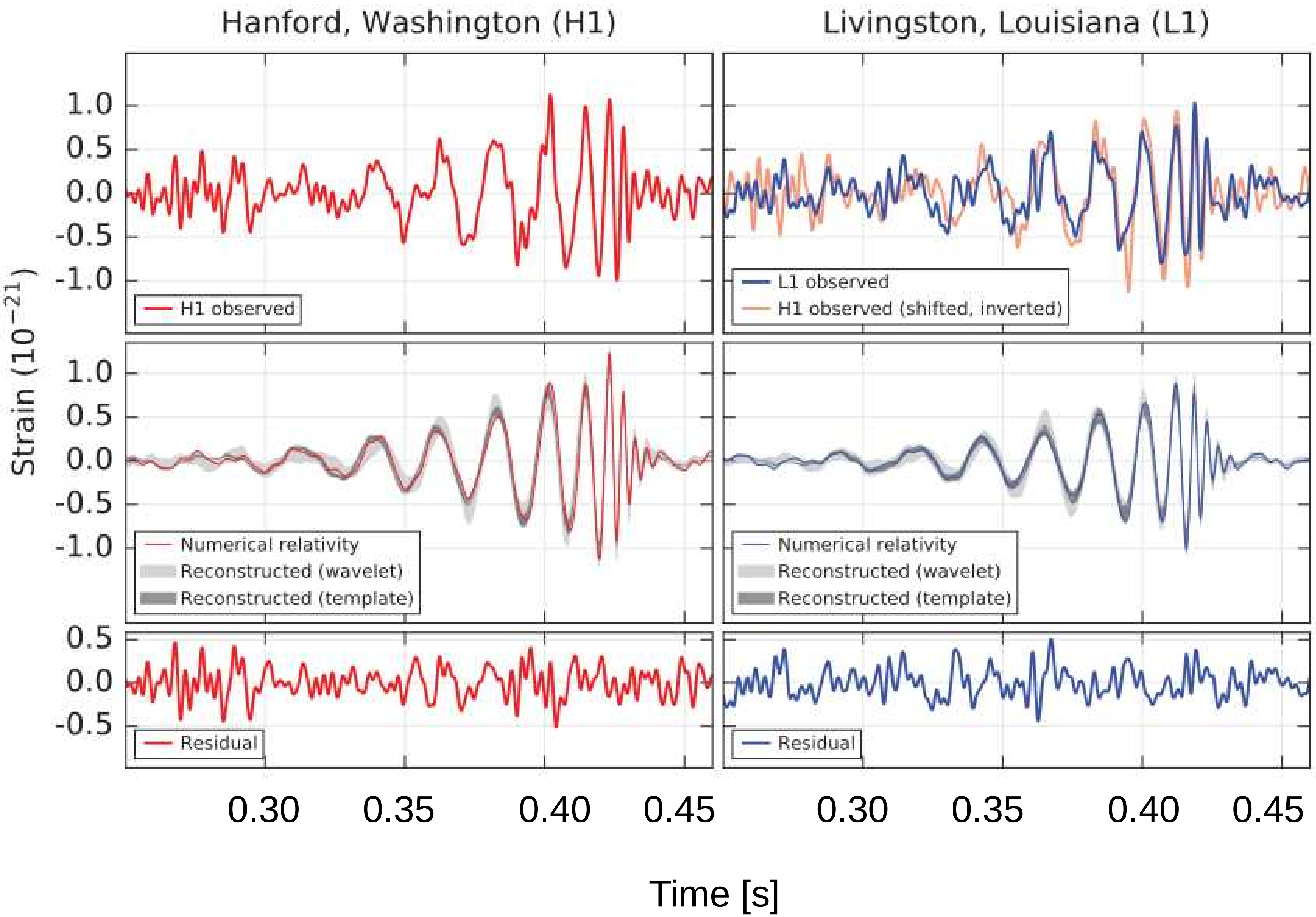
Significance estimation

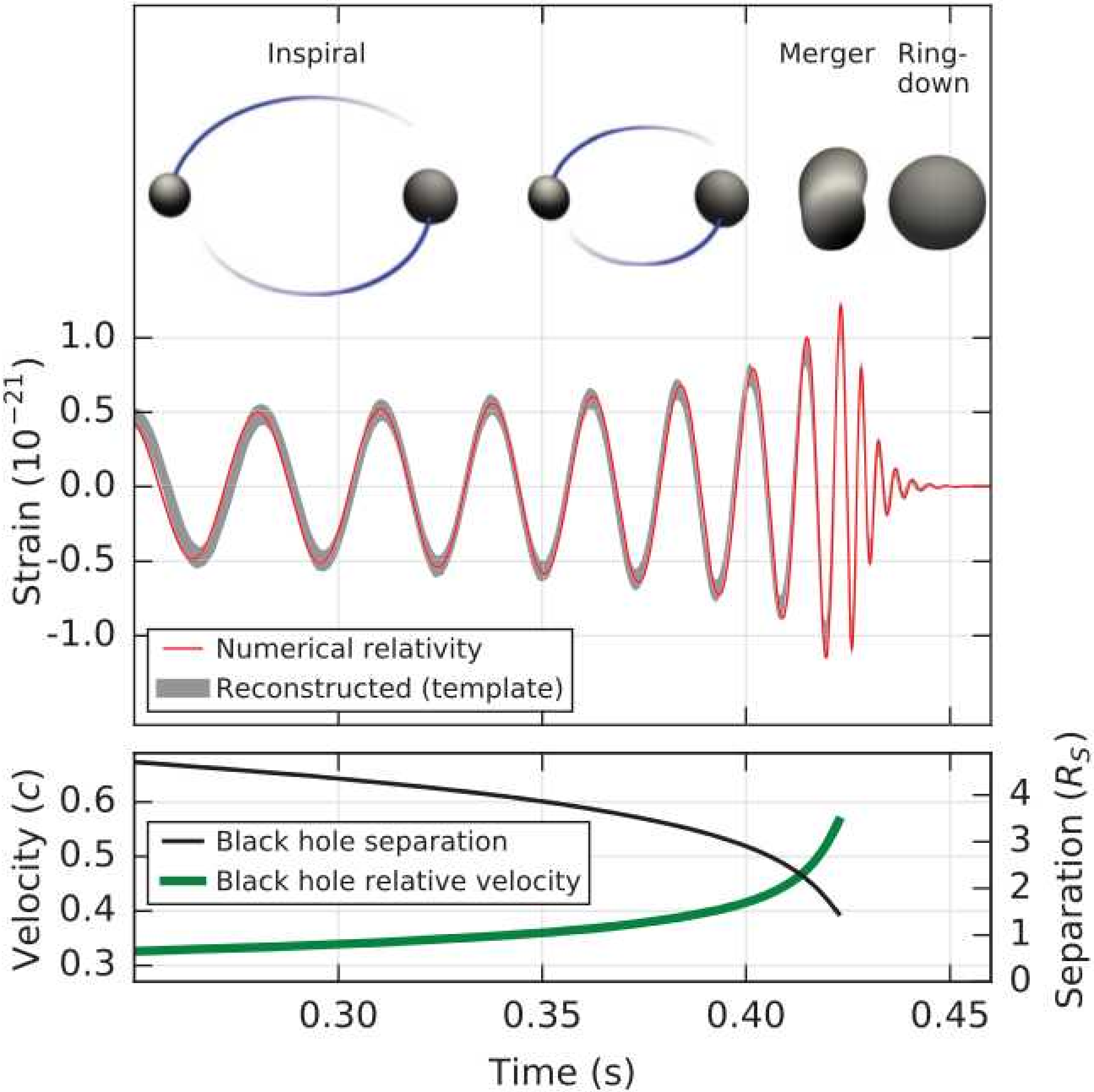


Waited to acquire 16 days background data to estimate properly the significance.

False alarm probability – better than 1 event in 203000 years.

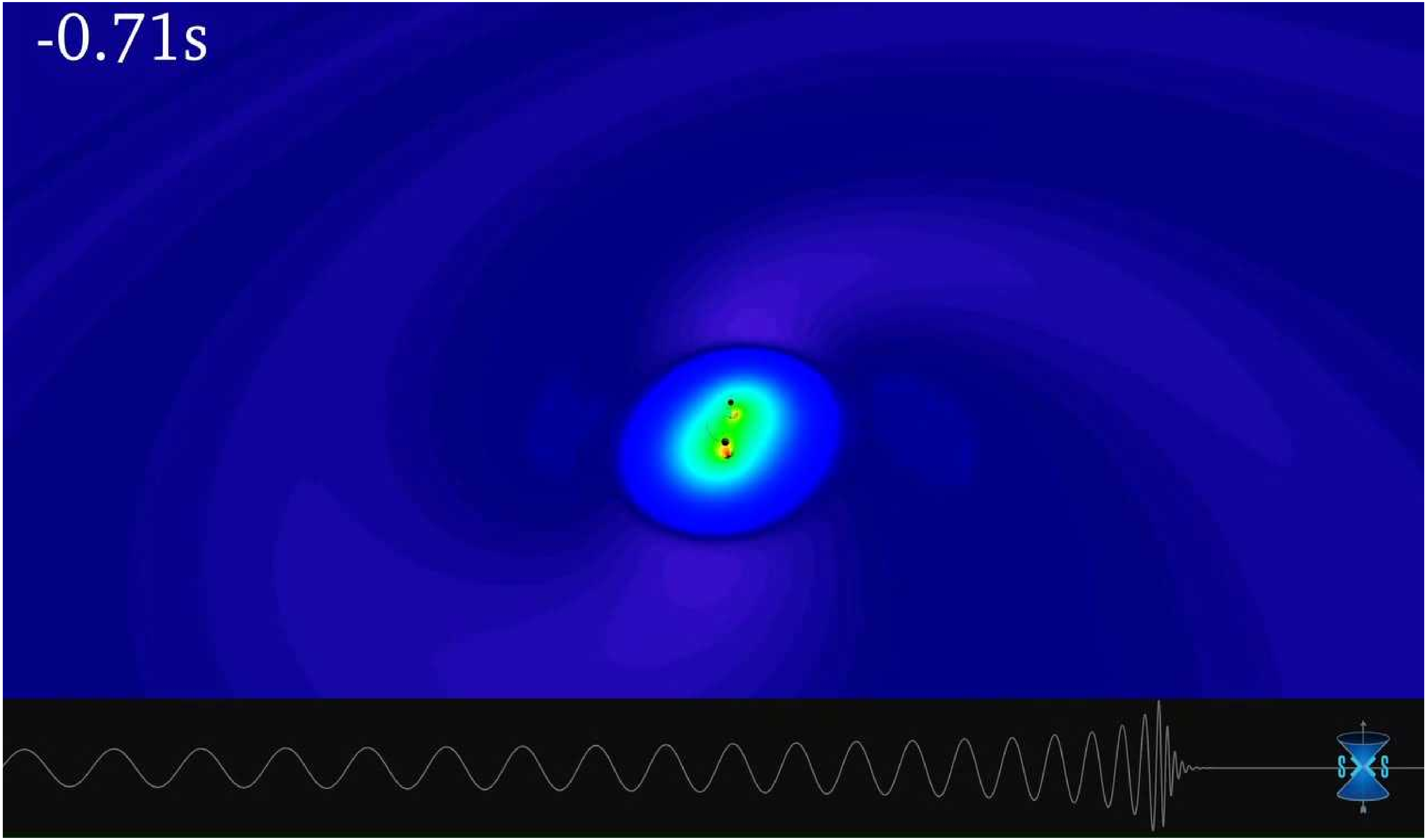
Reconstructed waveform





Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

How does the merger look?



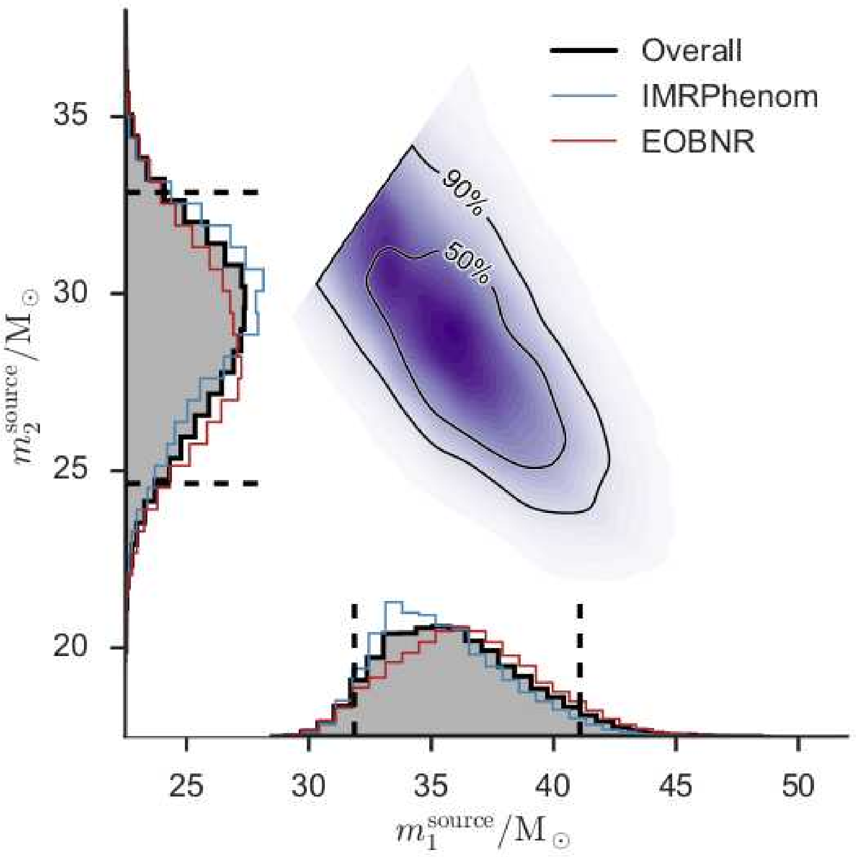
What is it?

- A binary black hole!

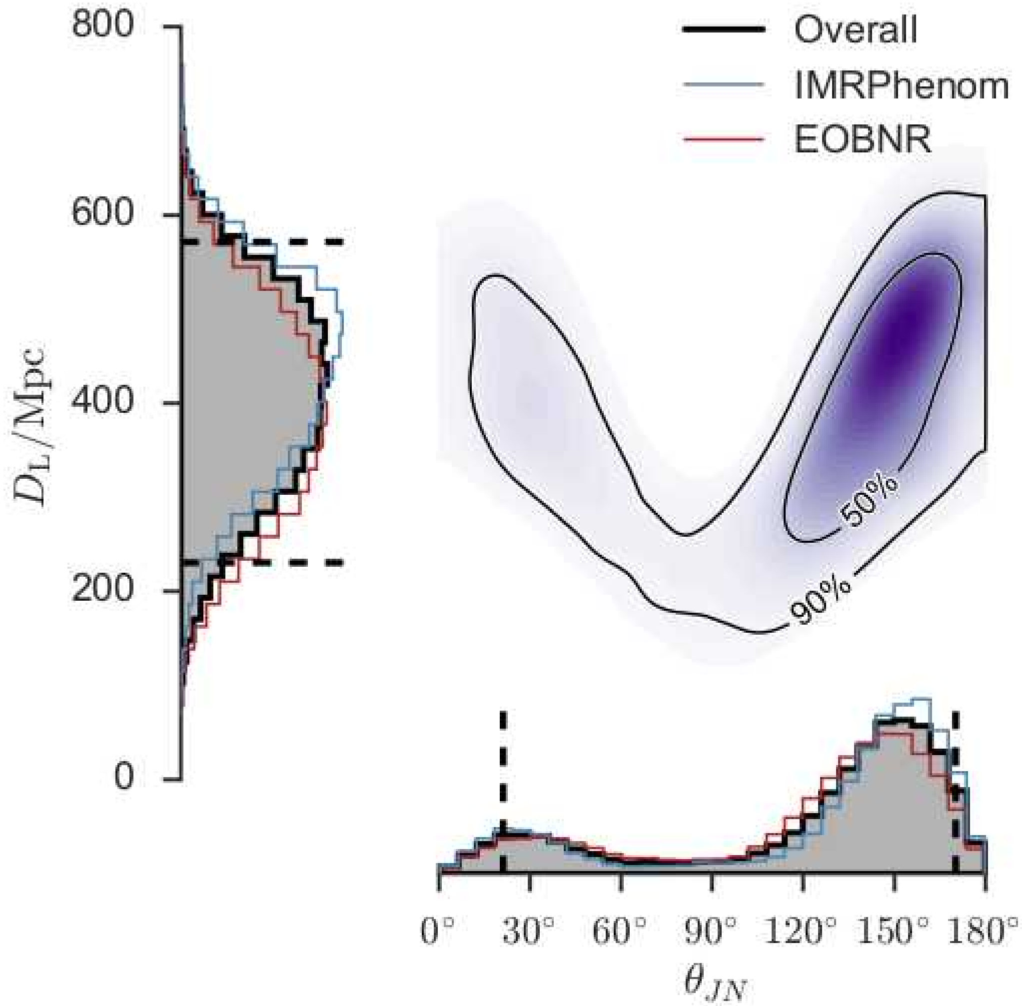
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

How do we know it?

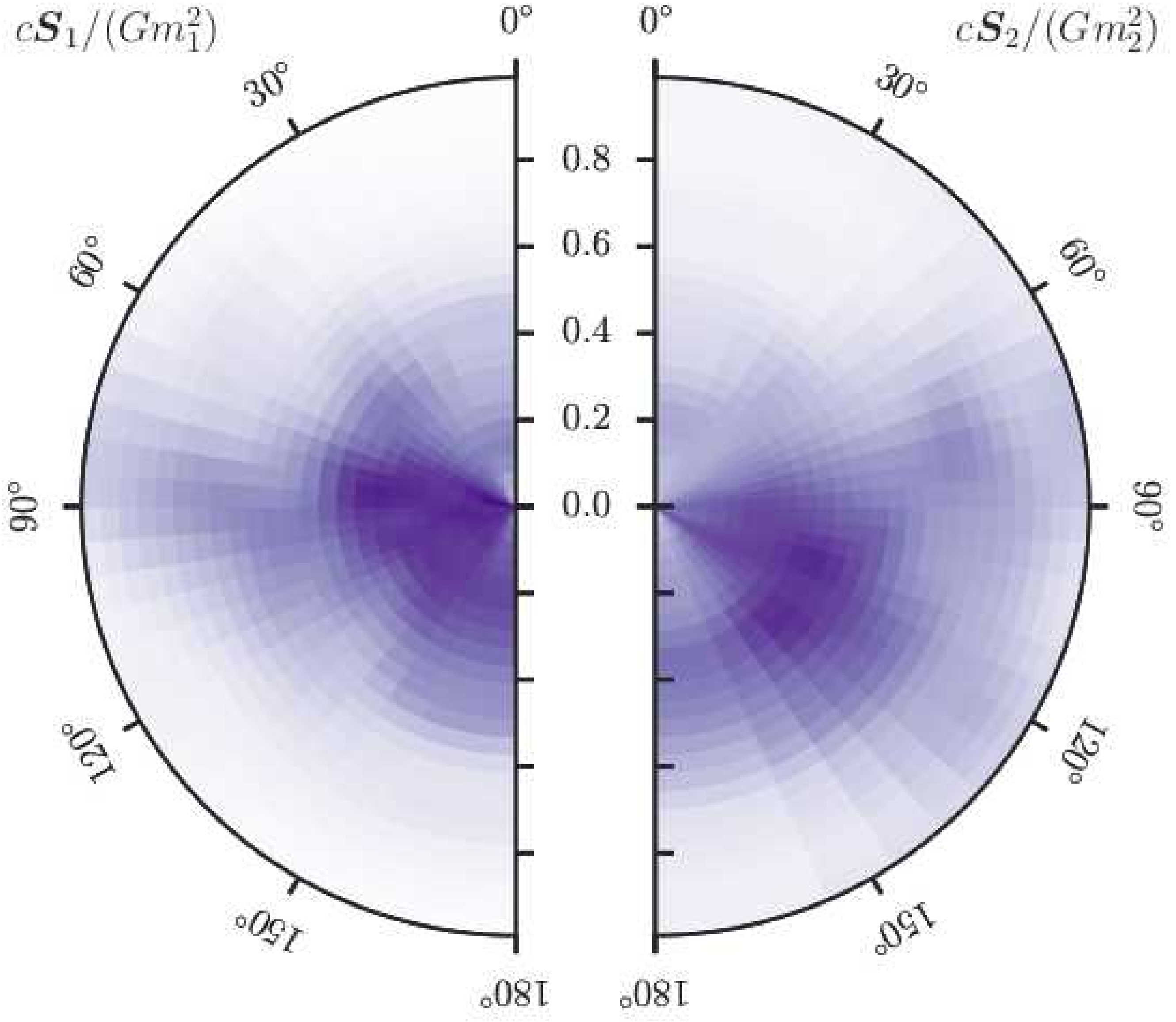
Masses


Overall
IMRPhenom
EOBNR
90%
50%
35
30
25
20
$m_2^{\mathrm{source}}/\mathrm{M}_\odot$
25
30
35
40
45
50
$m_1^{\mathrm{source}}/\mathrm{M}_\odot$

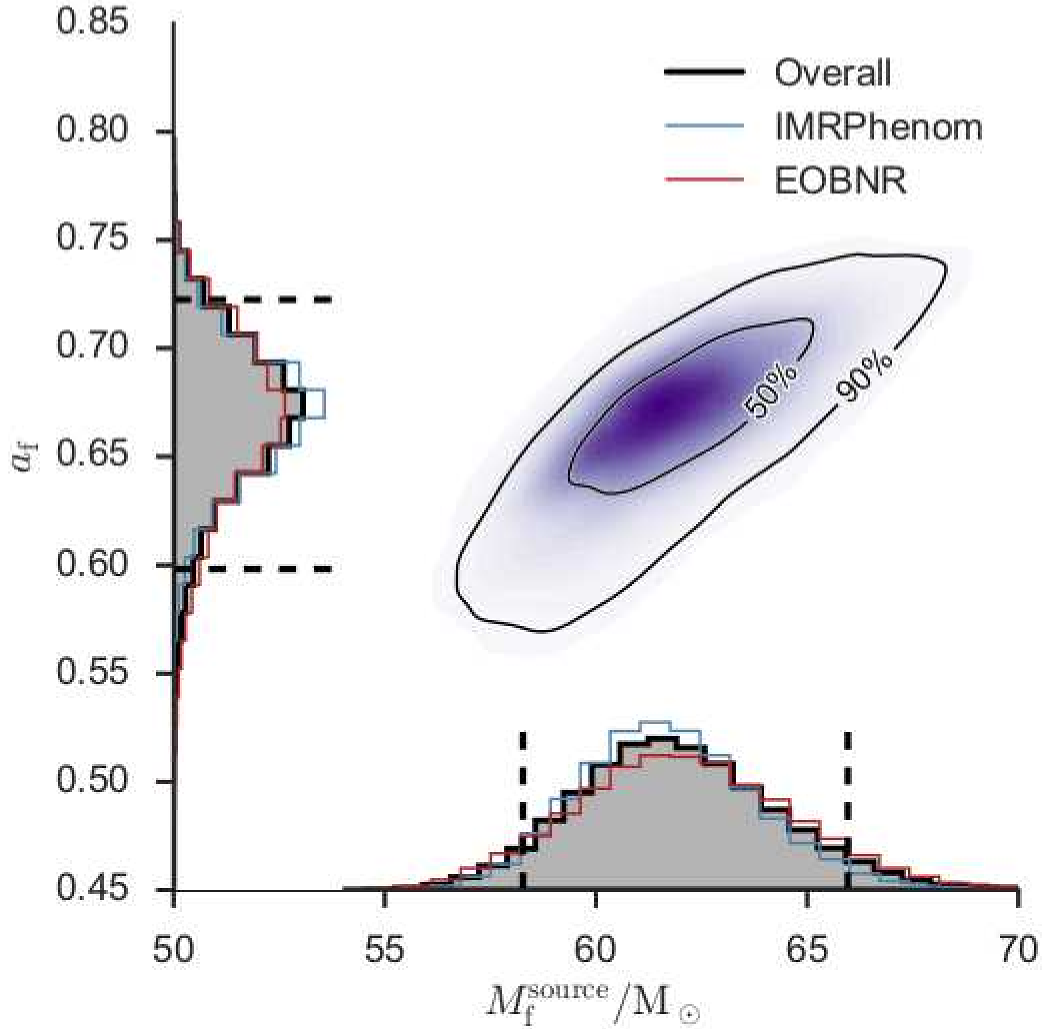
Distance and inclination



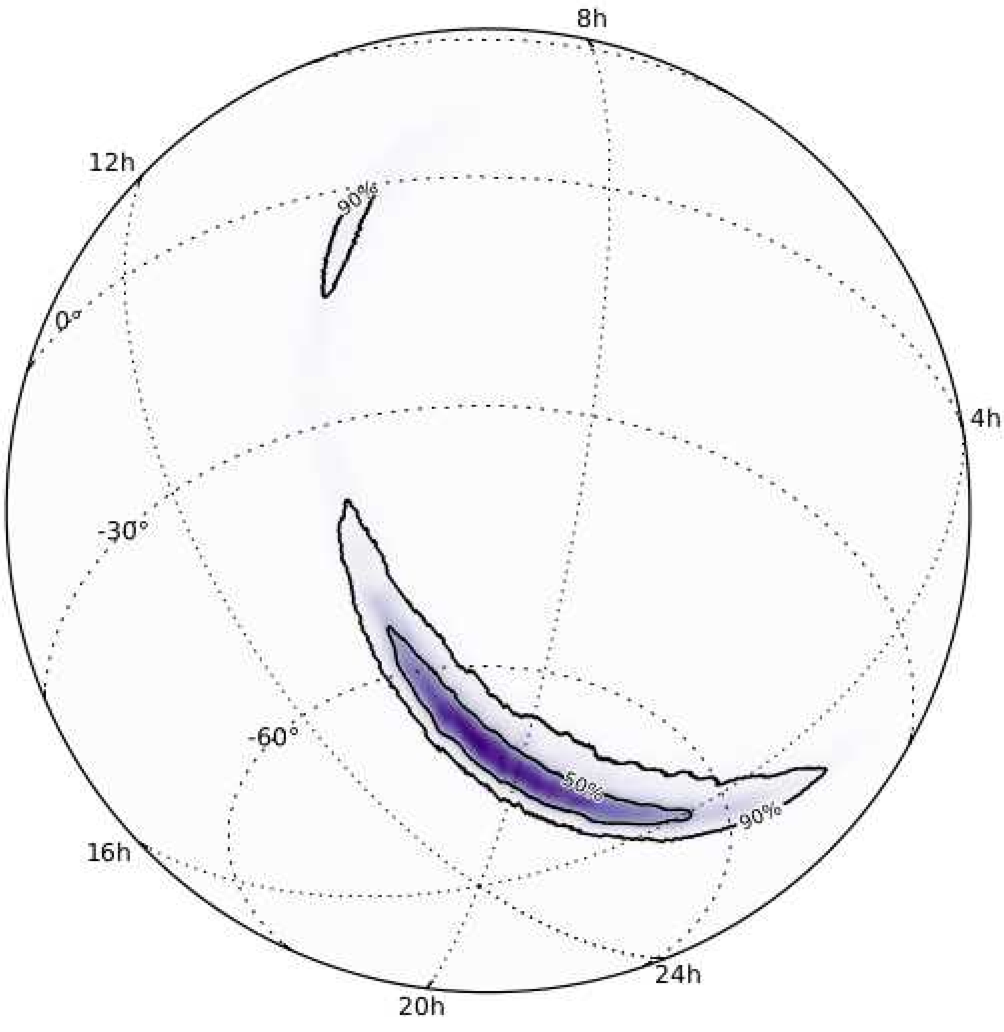
Spins



Final black hole



Localization



140 deg^2
50% confidence

590 deg^2
90% confidence

Our firsts:

- Detection of gravitational waves
- Detection of a black hole
- Detection of black hole binary
- Evidence for BHs with masses of 30 and and up to 60 solar masses
- The brightest source ever seen in the sky:

$$L_{GW} = 200^{+30}_{-20} \mathrm{M}_{\odot} s^{-1} = 3.6^{+0.5}_{-0.4} \times 10^{56} \mathrm{erg\ s}^{-1}$$

Astrophysical rate density

- Can one estimate the rate with a single measurement?
- The detection and the second highest ranked event (Chance probability=0.02)

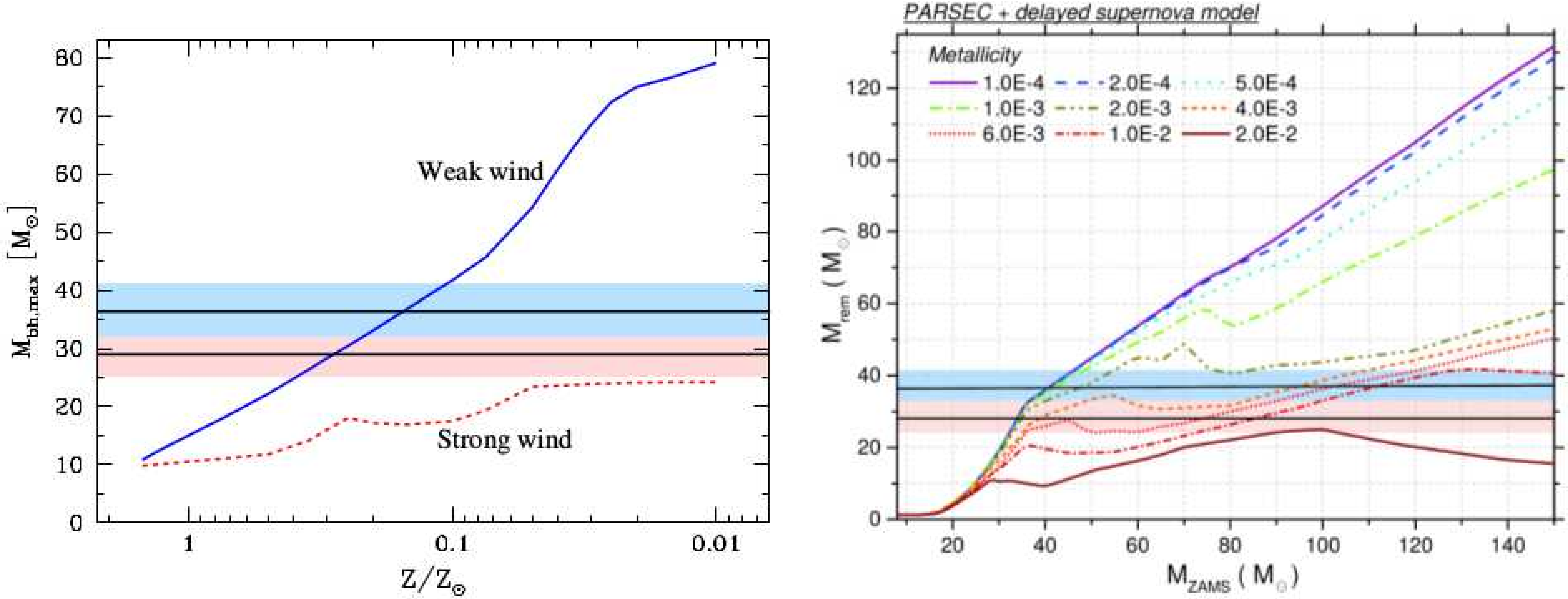
$$\mathcal{R} = 2 - 400\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

- Will be updated with the full analysis of O1

Astrophysical origin

- How can such massive BHs form?
- How do they form binaries?
- Early Universe, or recent formation?
- What else do we expect to see?

Masses of compact objects

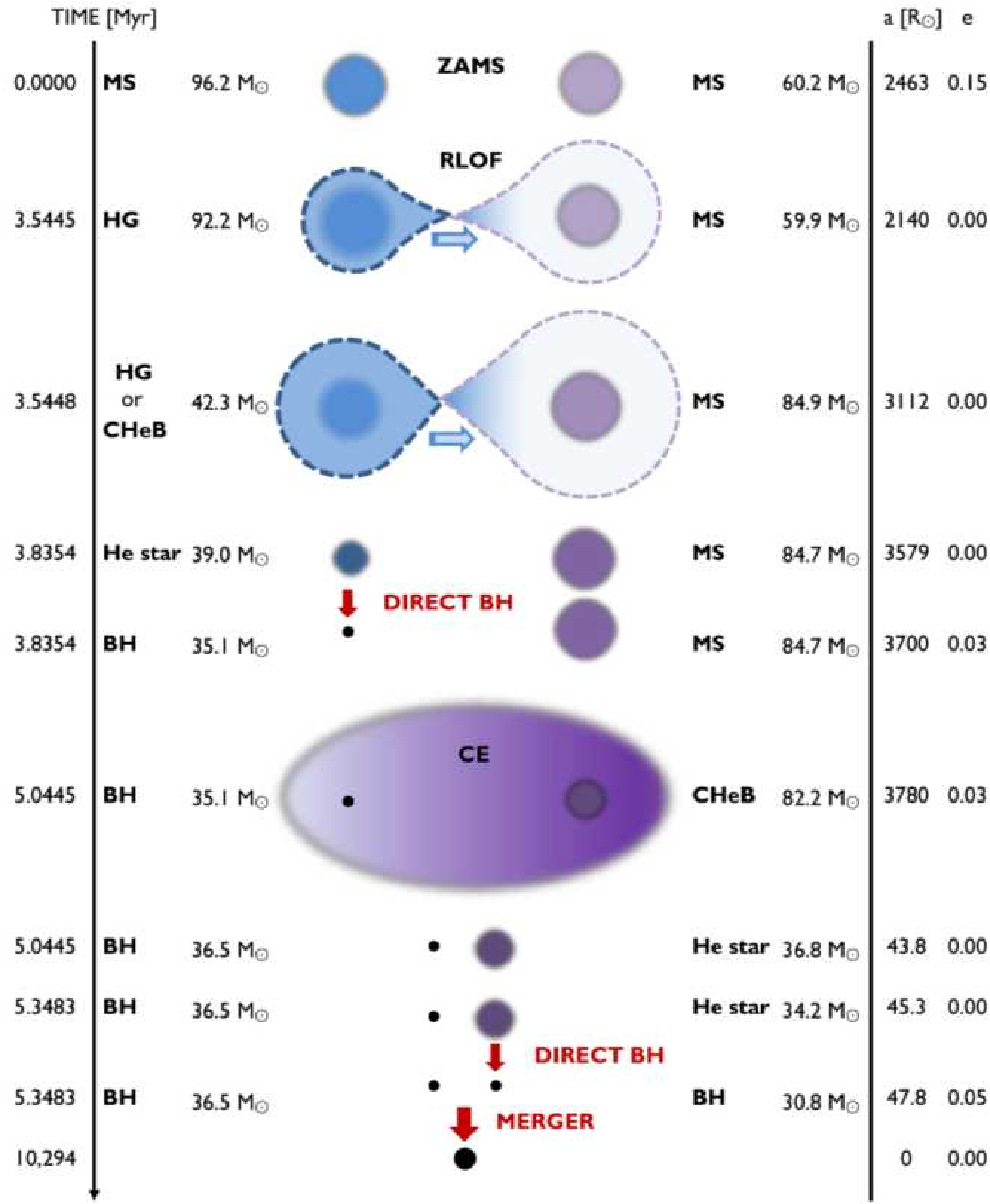


Black holes with the masses above 20 solar masses can form in low metallicity environments.

Modelling underlying field population

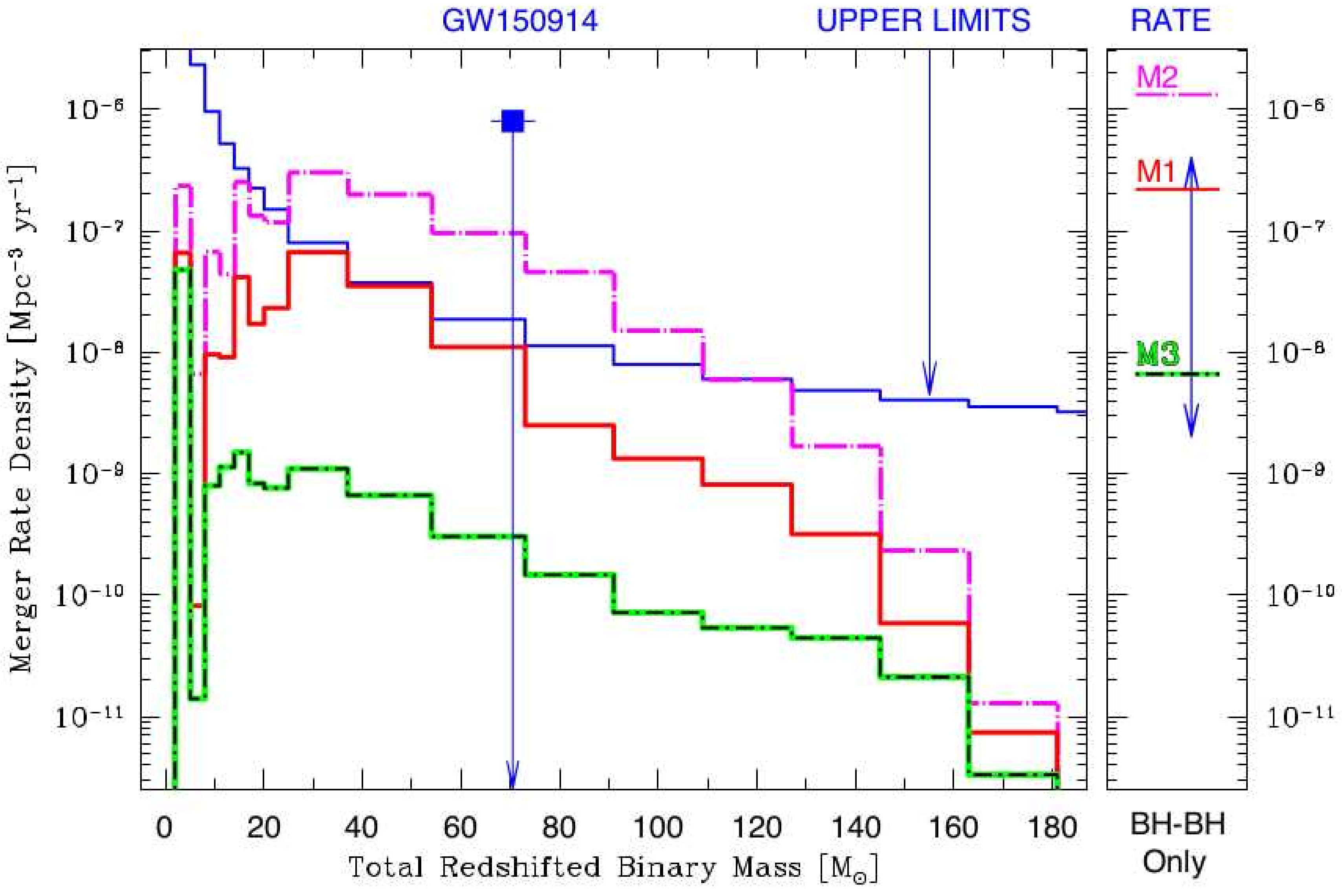
- Star formation rate
- Binary evolution
- Coalescence times
- Mass distribution
- Detection simulation using realistic waveforms and proper detector noise

Evolutionary scenario



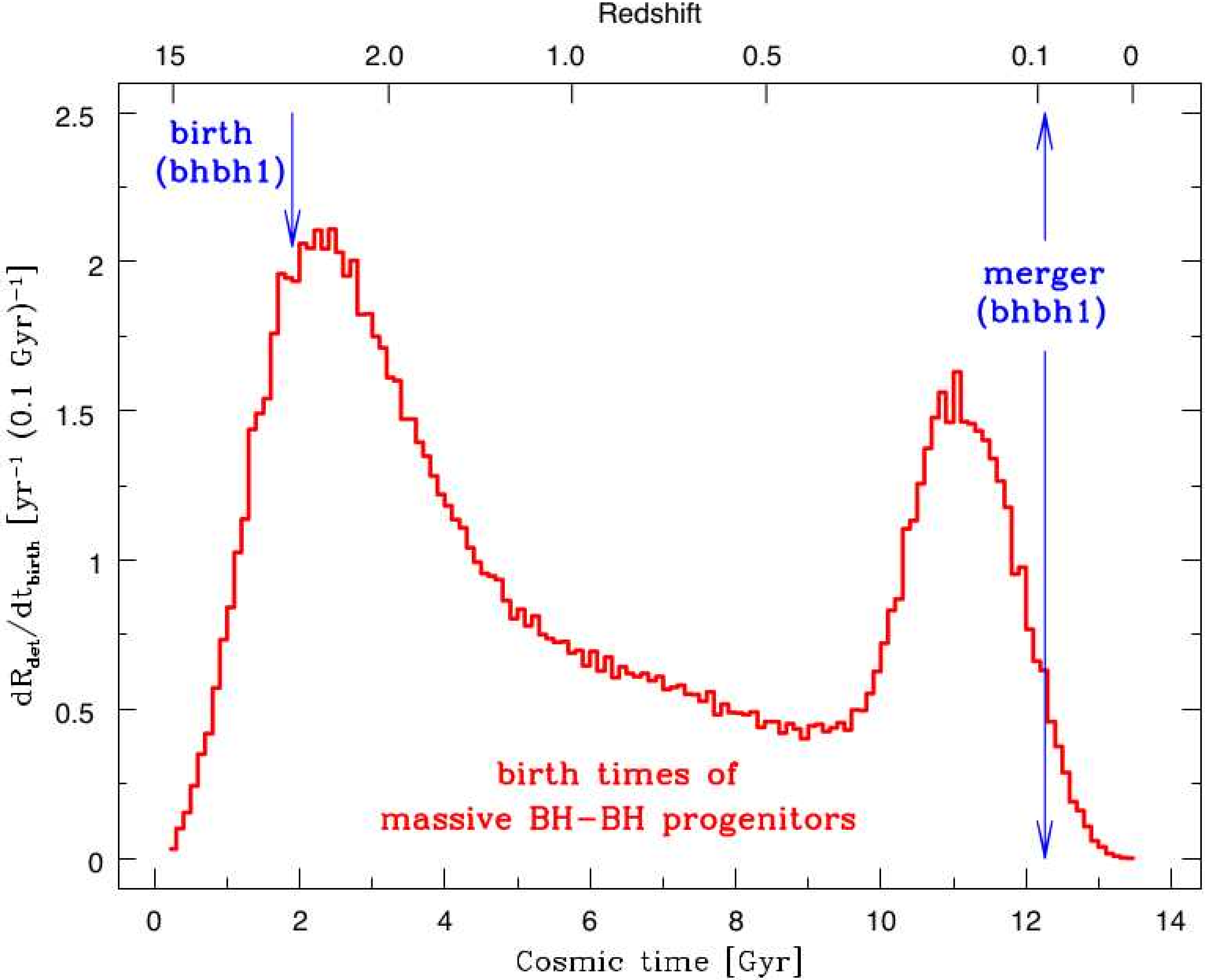
Credit: Wojtek Gładysz

Total mass distribution



Belczynski, Bulik, Holz, O'Shaughnessy 2016

Formation time

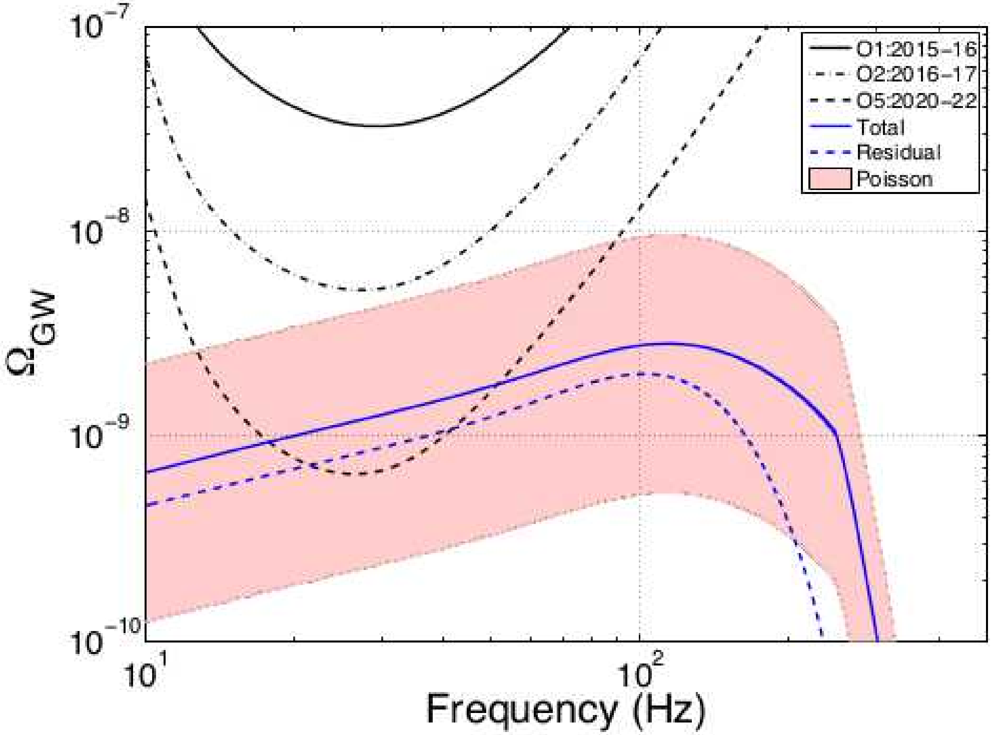


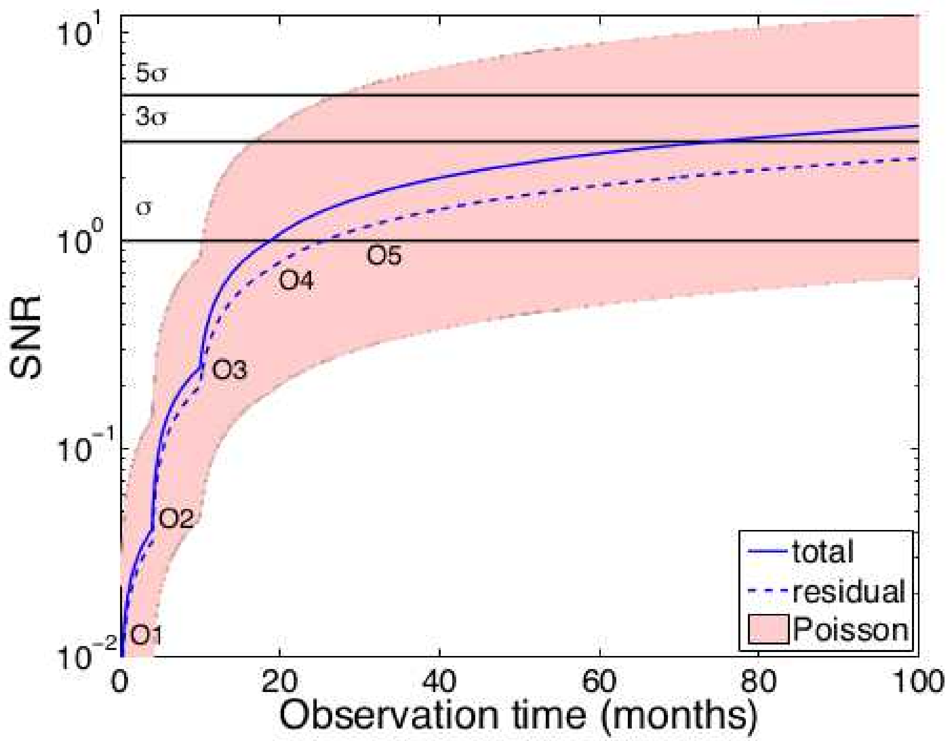
Belczynski, Bulik, Holz, O'Shaughnessy 2016

Possible dynamical formation

- Formation of BBH in dense stellar clusters
- Possible ejection of BHs from cluster – hierarchical formation difficult
- Possibly distinguishable by spin direction measurement
- But this needs more work to verify if true...

Stochastic background





Detection possible with the Advanced detectors!

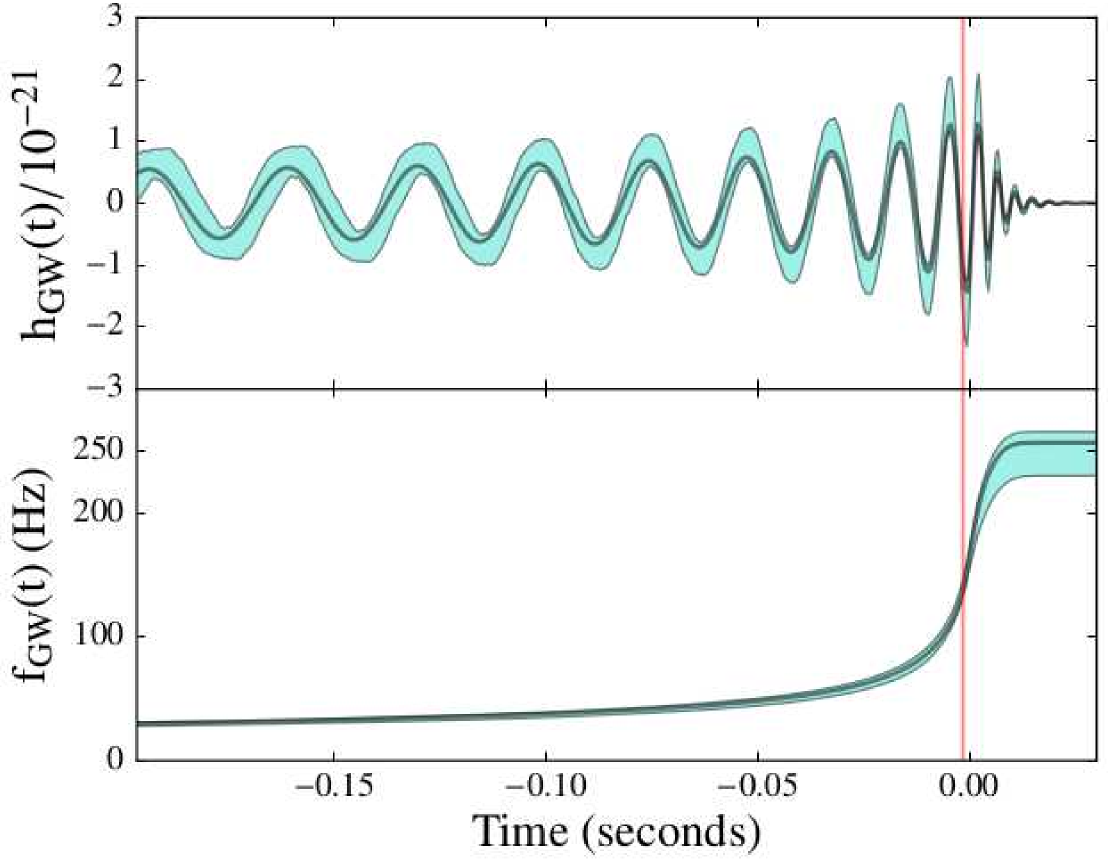
Physics

The reconstructed waveform allows to place lmits on fundamental physics:

Graviton mass

General relativity

Probe no hair theorem – not yet but soon!



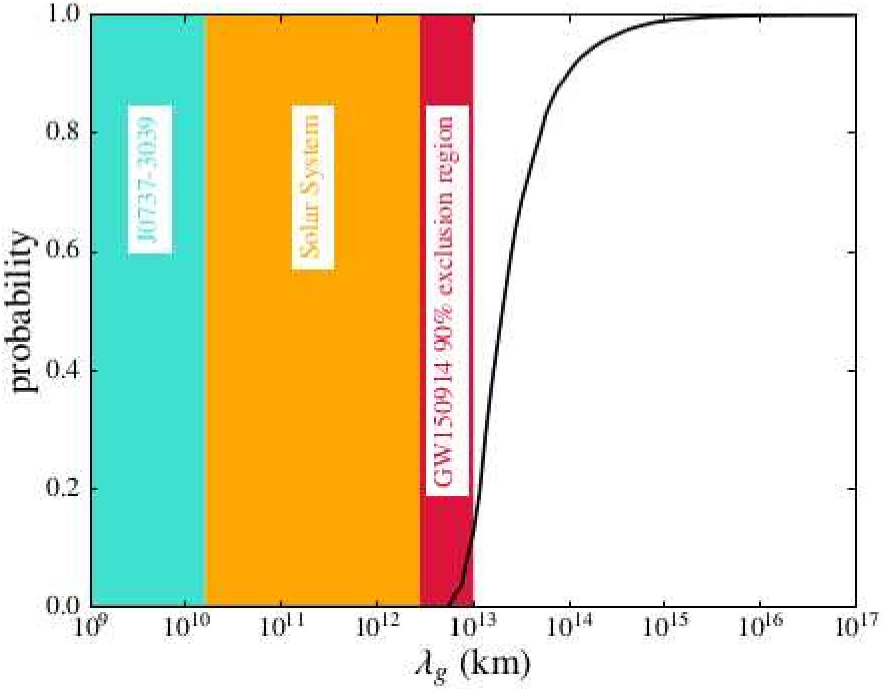
Graviton

- Graviton mass limits

$$\frac{v_g}{c} = \sqrt{1 - \frac{h^2 c^2}{\lambda_g^2 E^2}}$$

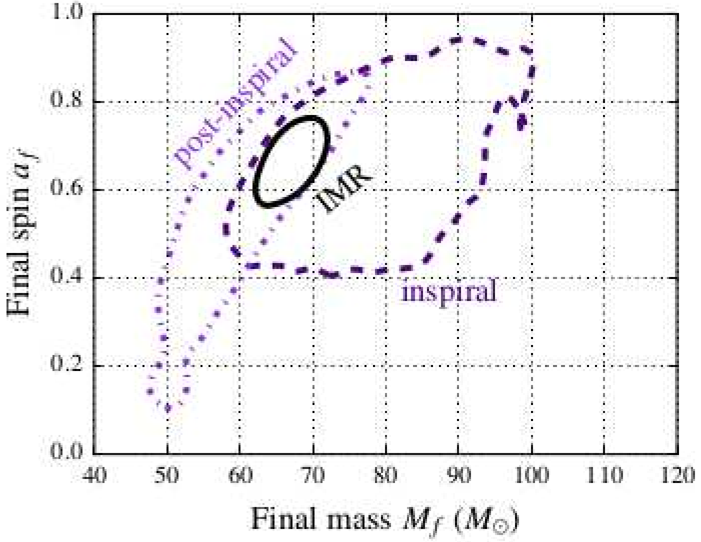
$$\lambda_g > 10^{13}\mathrm{km}$$

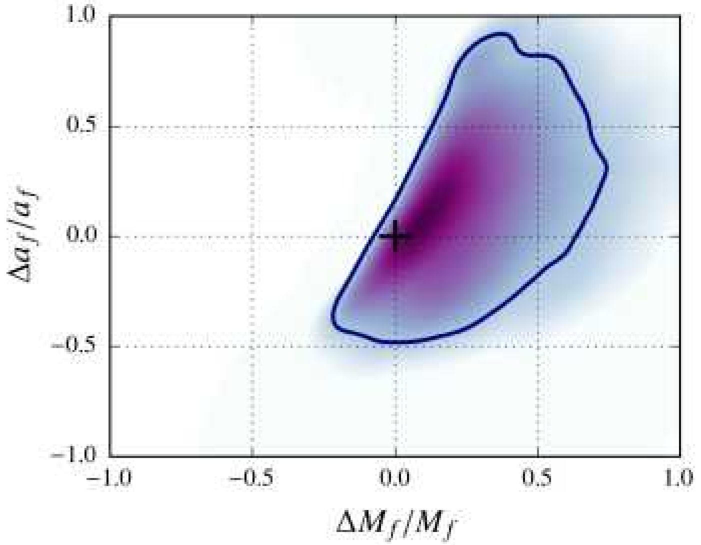
$$m_g < 10^{-22}\mathrm{eV/c^2}$$



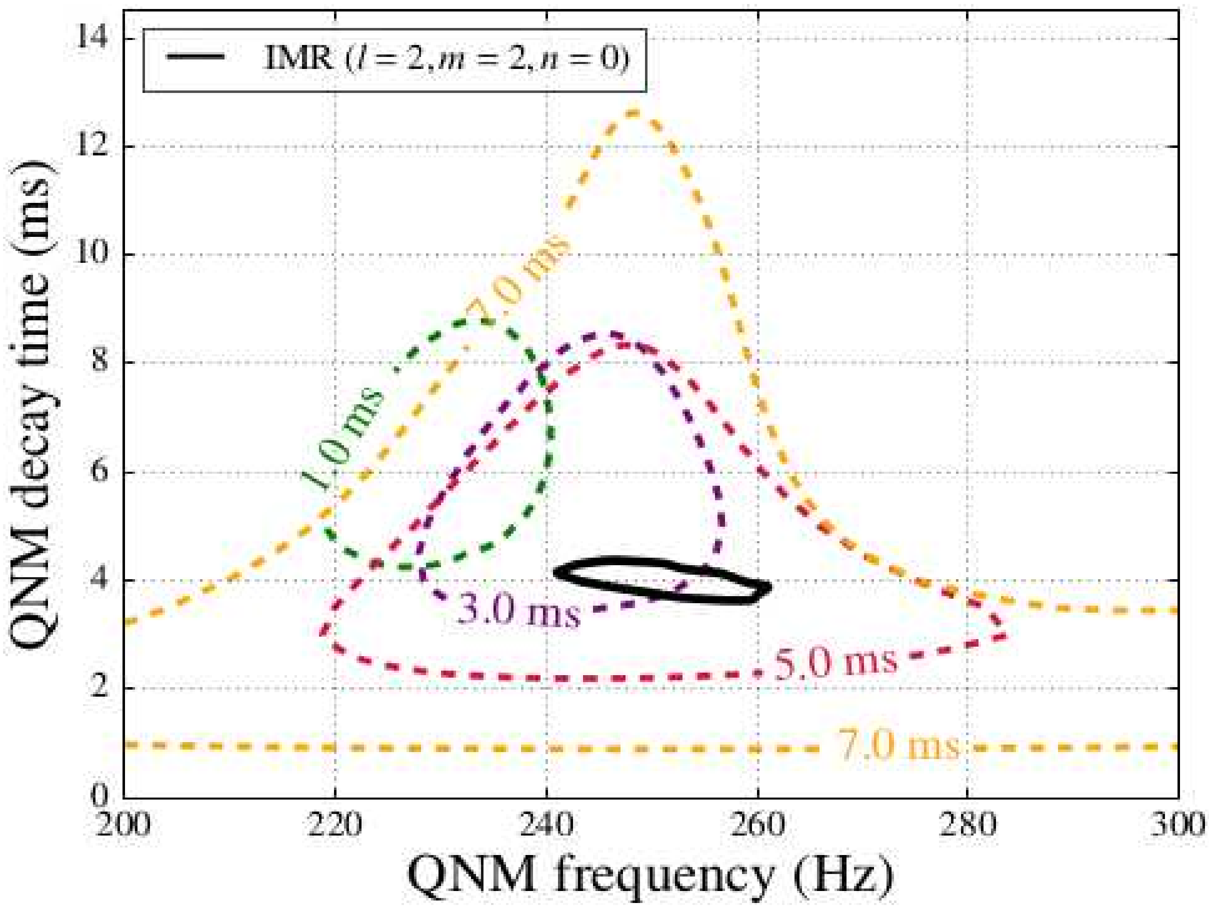
Tests of General Relativity

- The final mass and spin is implied by the the initial ones.
- Measure the mass in the inspiral phase
- Measure the final mass and spin with quasi normal modes
- Check consistency





Ringdown of the new BH

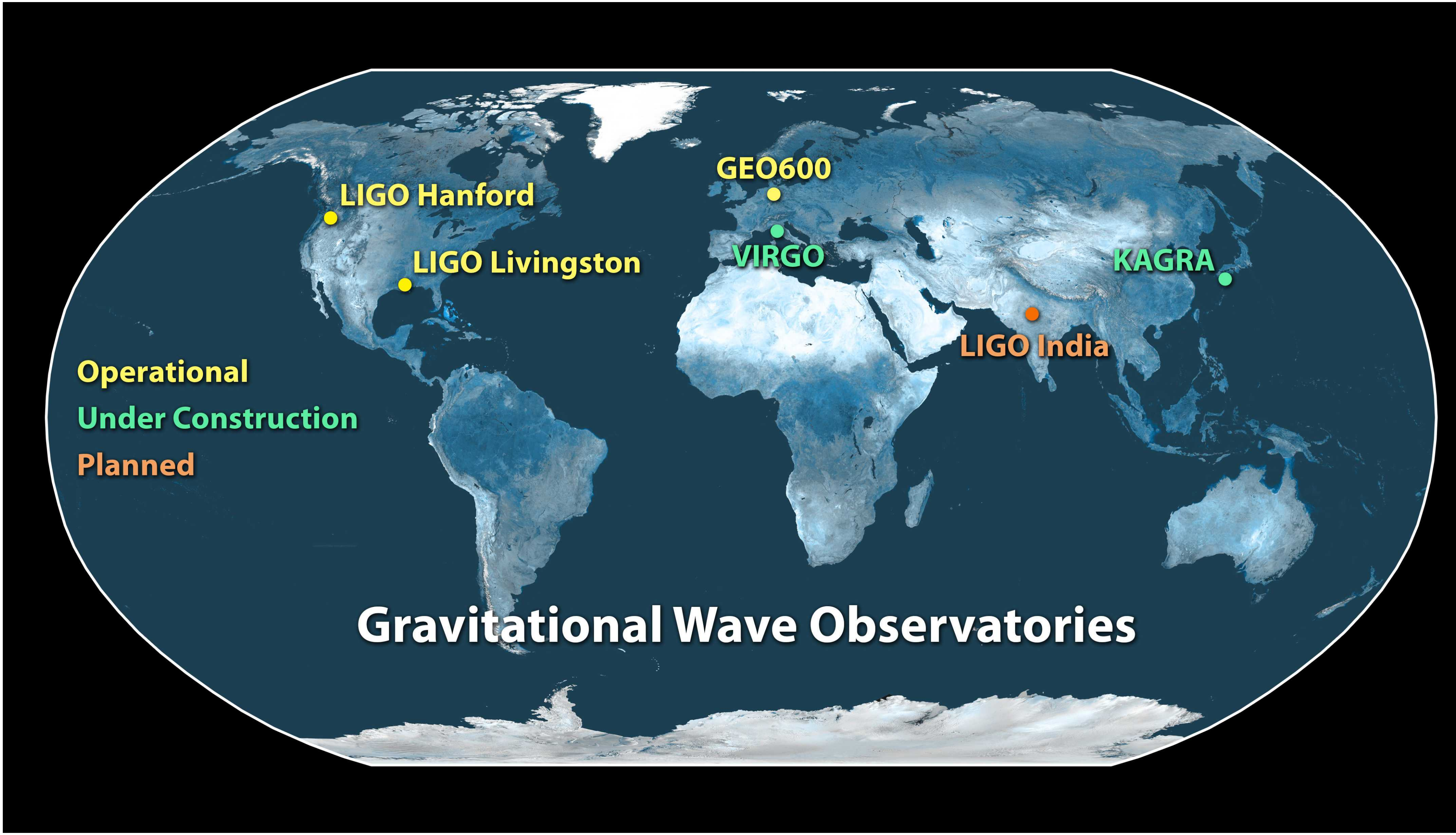


Model and measurements – assuming diffferent time of formation of the single BH

Next steps

- Addition of VIRGO
- Expected sensitivity in the O2 run
- Expected O2 range.
- Further improvements planned
- KAGRA to join in 2 years
- LIGO India has just been approved

GW Astronomy outlook



Gw astronomy – far future

- Cosmic Explorer - US
- Einstein Telecope – Europe

- Longer arms, cryogenic mirrors, squeezed light injection, underground location, etc...

Summary

- The new era has begun!
- Gravitational wave astronomy is now a science with at least one source!
- Many more discoveries to come...