Exploring the Warped Universe with Gravitational Waves

The LIGO and Virgo Collaborations

Nergis Mavalvala
MIT

Gravitational waves detected!


LA NACION

Viernes 12 de febrero de 2016 | lanacion.com

Los gremios llevaron al Gobierno sus planteos y salieron conformes

Griesa evalúa si facilita que el país salga del default

El dengue ya es una epidemia en Córdoba

CONFIRMAN LA ÚLTIMA PREDICCIÓN DE EINSTEIN

El Papa inicia su visita al México más crudo

Chicos cada vez más solos

Boca, en crisis, le dio un partido más al DT

Un hallazgo histórico abre una nueva era en la astronomía


Friday 12.02.16
Published in London and Manchester
theguardian.com

theguardian

So it turns out Einstein was right all along ...

Tim Radford

Scientists near Pisa in Italy work on the Virgo gravitational wave detector, part of the scientific consortium that made the breakthrough Photograph: Cyril Fresillon/Getty


Late Edition

The New York Times

NEW YORK, FRIDAY, FEBRUARY 12, 2016

$2.50

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.


Frankfurter Allgemeine

ZEITUNG FÜR DEUTSCHLAND

Ayrault wird Außenminister Frankreichs

Einstein hat wieder mal recht

Einsteins Beben

Zwischen den Fronten


The Washington Post

FRIDAY, FEBRUARY 12, 2016

Deadly prison riot in Mexico

U.S., Russia agree to a halt in Syrian war

Ex-wife's tip led to gunfire at Md. Panera

Fault line spotlighted in Wis. debate

Oregon siege ends as four surrender

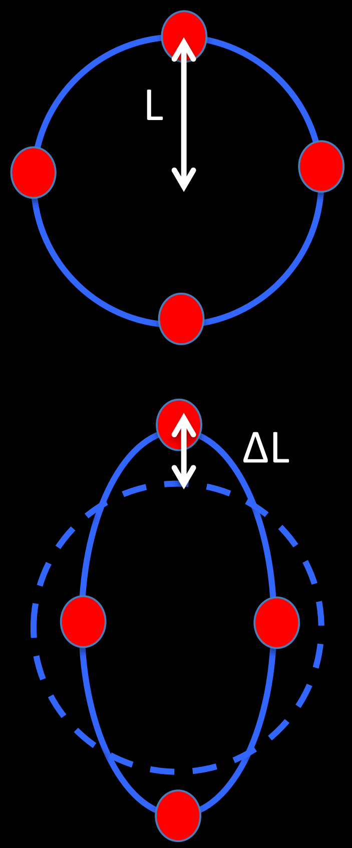
Gravitational waves Einstein foresaw are detected

Gravitational waves enter mainstream culture and society

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

$$\Delta L = h \times L = 10^{-21} \times 1\,\mathrm{m} = 10^{-21}\,\mathrm{m}$$



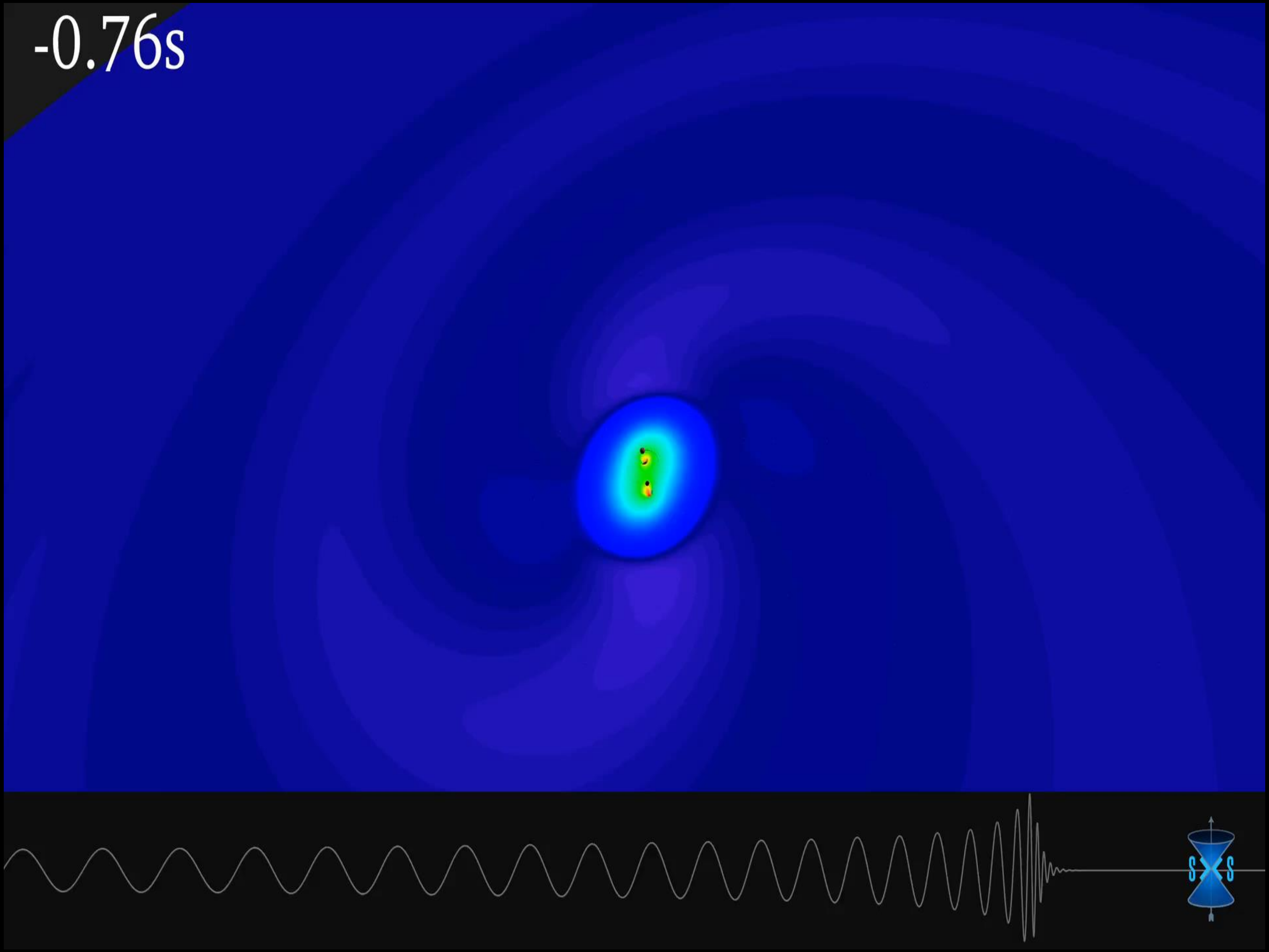
Einstein's ambivalence

- Einstein formulated a complete mathematical framework in which to describe gravity and gravitational waves between 1915 and 1918

Theory of General Relativity

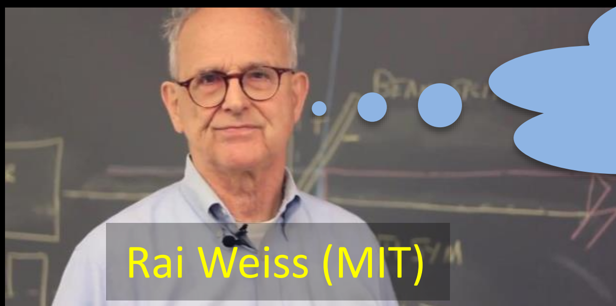
- Einstein remained ambivalent about gravitational waves
- The first observational evidence for neutron stars and black holes did not come in Einstein's life time
- But General Relativity theory made firm predictions about gravity, spacetime and coalescing compact objects

General relativity lets us calculate exactly what gravitational wave signal merging black holes produce



GRAVITATIONAL WAVE DETECTORS

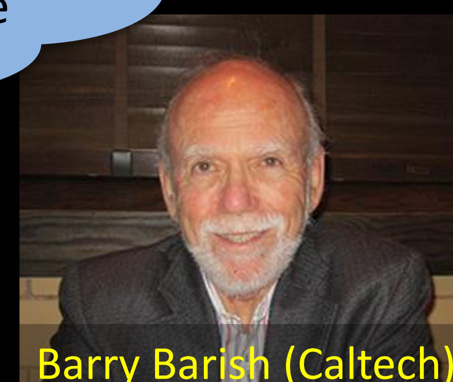
A bold experiment is born



Let's use laser interferometers
Hmm, we have to make them very long

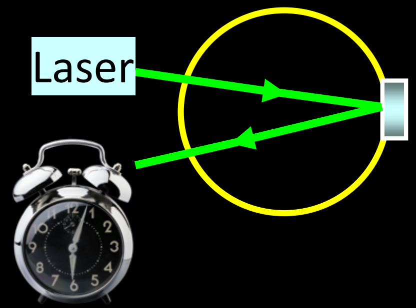
Let's calculate astrophysical waveforms
Hmm, these are some small amplitudes

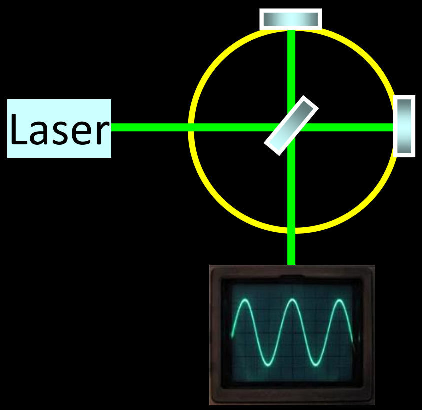
Let's add optical cavities
here there and everywhere



Let's get these damn things working
Hmm, building an observatory is a project

Measurement principle

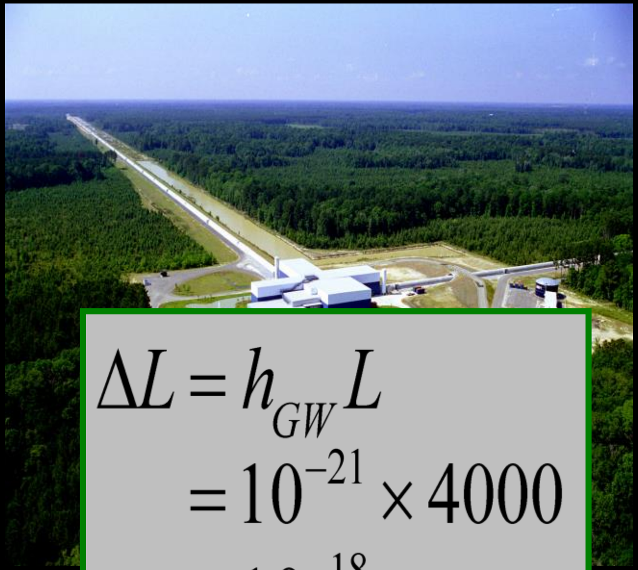




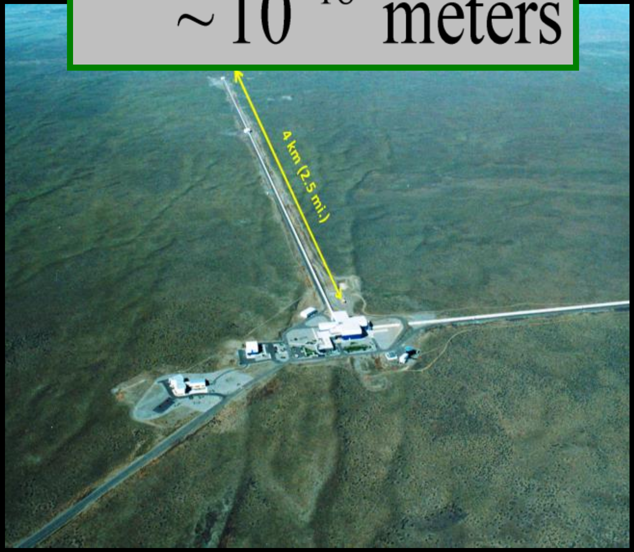
- Make mirrors that are very still
  - Vibration isolation and thermal fluctuation control
- Use laser light to probe the mirror position
  - Quantum-limited precision optical measurement

LIGO

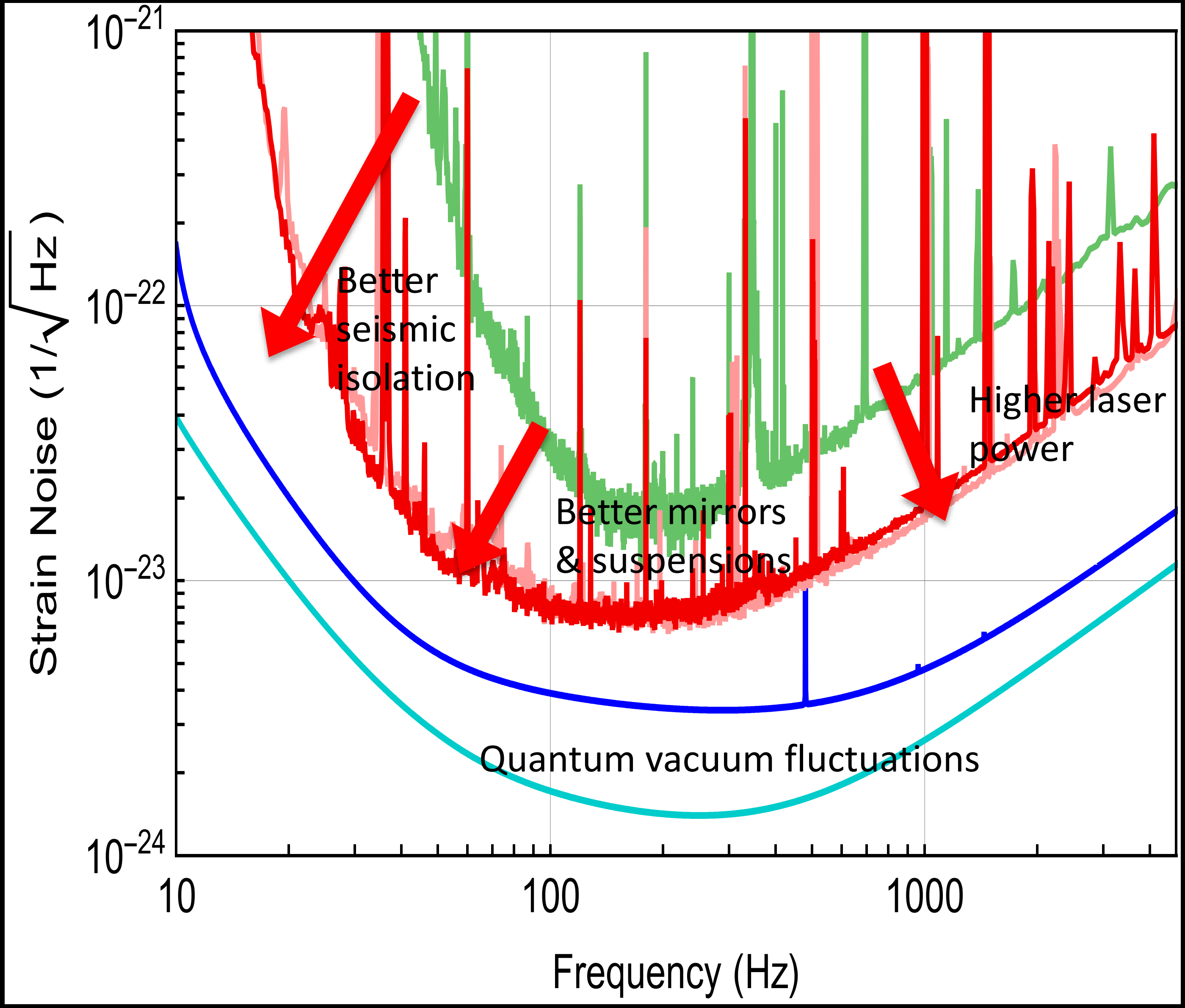
- The Laser Interferometer Gravitational-wave Observatory
- Two sites (in LA and WA) that host two L-shaped detectors
- Laser beams travel along 4km long arms
- Measure changes in mirror separation of $\Delta L = 10^{-18}$ m = 1/1000 the size of a proton over 4km separations



$$\Delta L = h_{GW} L$$
$$= 10^{-21} \times 4000$$
$$\sim 10^{-18} \text{ meters}$$



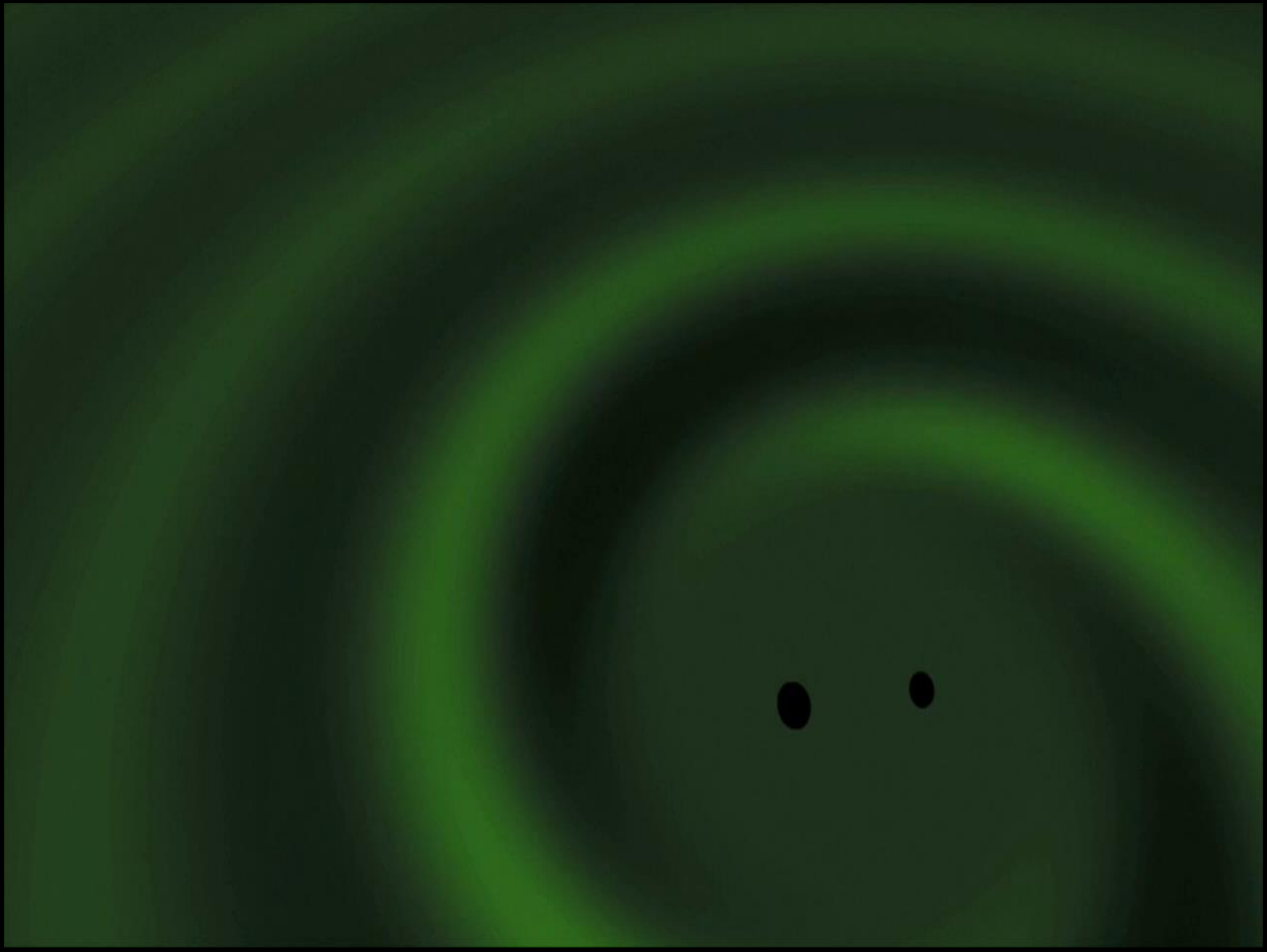
Phases of LIGO



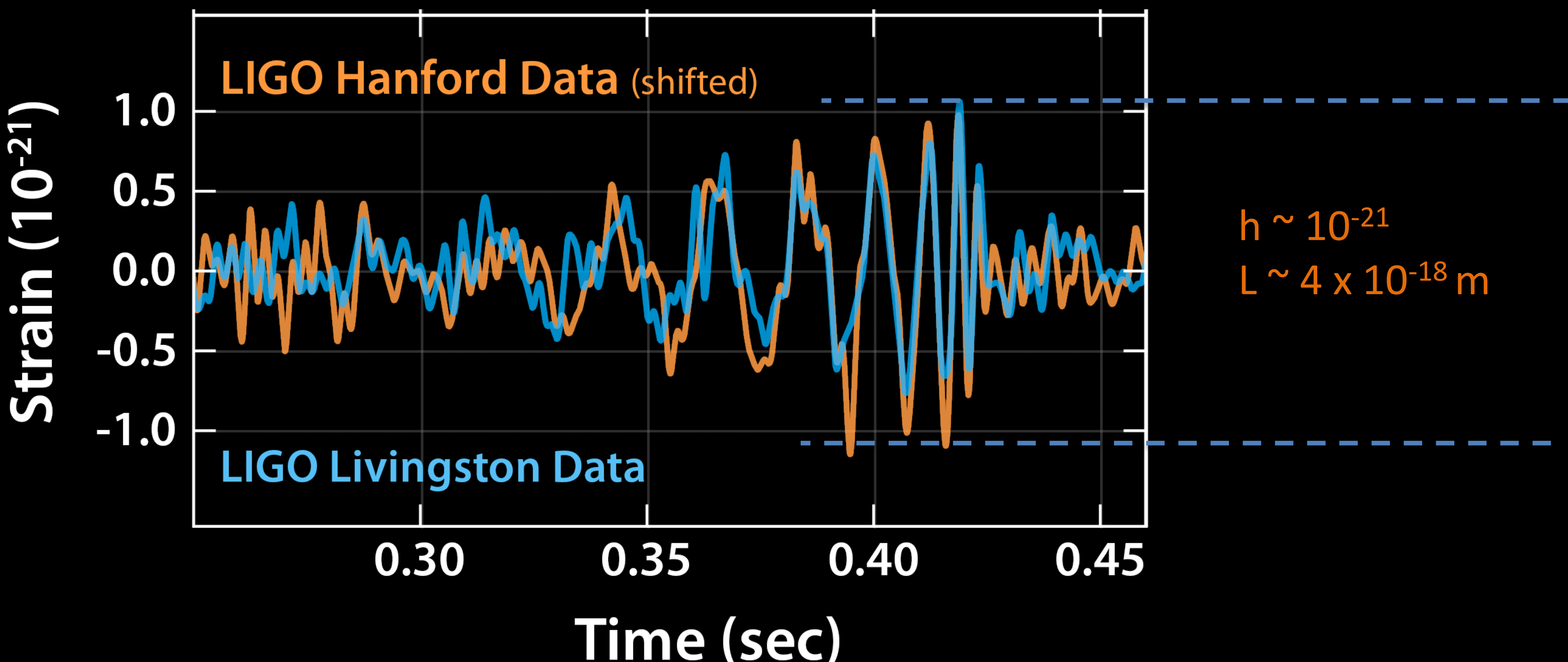
GW150914

A binary black hole merger detected by LIGO on September 14, 2015

Journey across the Universe



GW150914: a binary black hole coalescence detected by LIGO

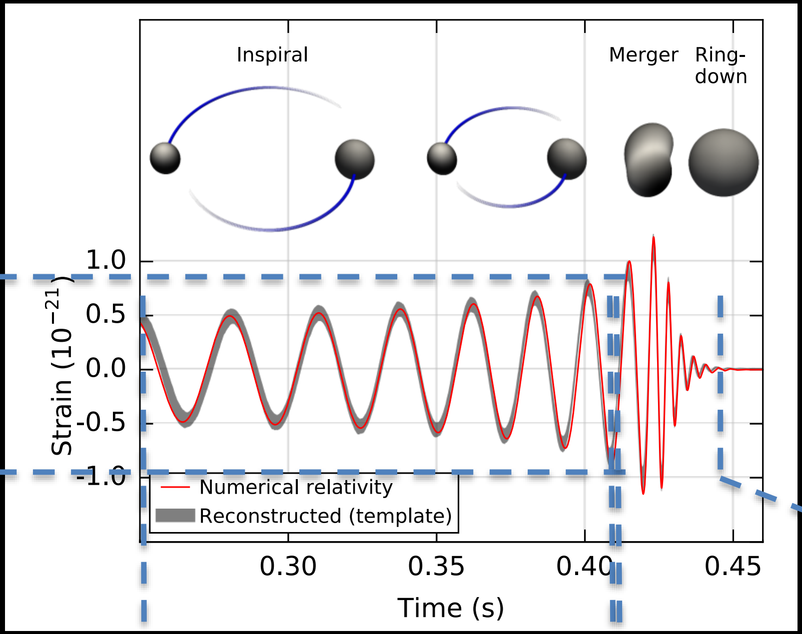


$h \sim 10^{-21}$

$L \sim 4 \times 10^{-18}$ m

Power $\sim 4 \times 10^{49}$ W

What does the signal tell us about the source?



Amplitude
Distance
Inclination angle

Frequency evolution
"Chirp" mass
Mass ratio (weaker)
Initial Spins (weakest)

Frequency and decay time
Final mass
Final spin

The story of two black holes revealed

- Once upon a time, 1.3 billion years ago, there existed two black holes
- They were big black holes, about 30 times more massive than the Sun
- As they danced in orbit about each other, they emitted gravitational waves
- This made them get ever closer to each other and orbit ever faster
- They were moving at 0.5 the speed of light just before they collided
- The black holes merged to form a bigger black hole amid a spectacular storm of gravitational waves as spacetime distorted and contorted
- The newly formed black hole was not as massive as the parents
    - 3 times the mass of our Sun was converted into energy
    - For a brief instant more energy was released than all the shining stars emit
- They did not live happily ever after

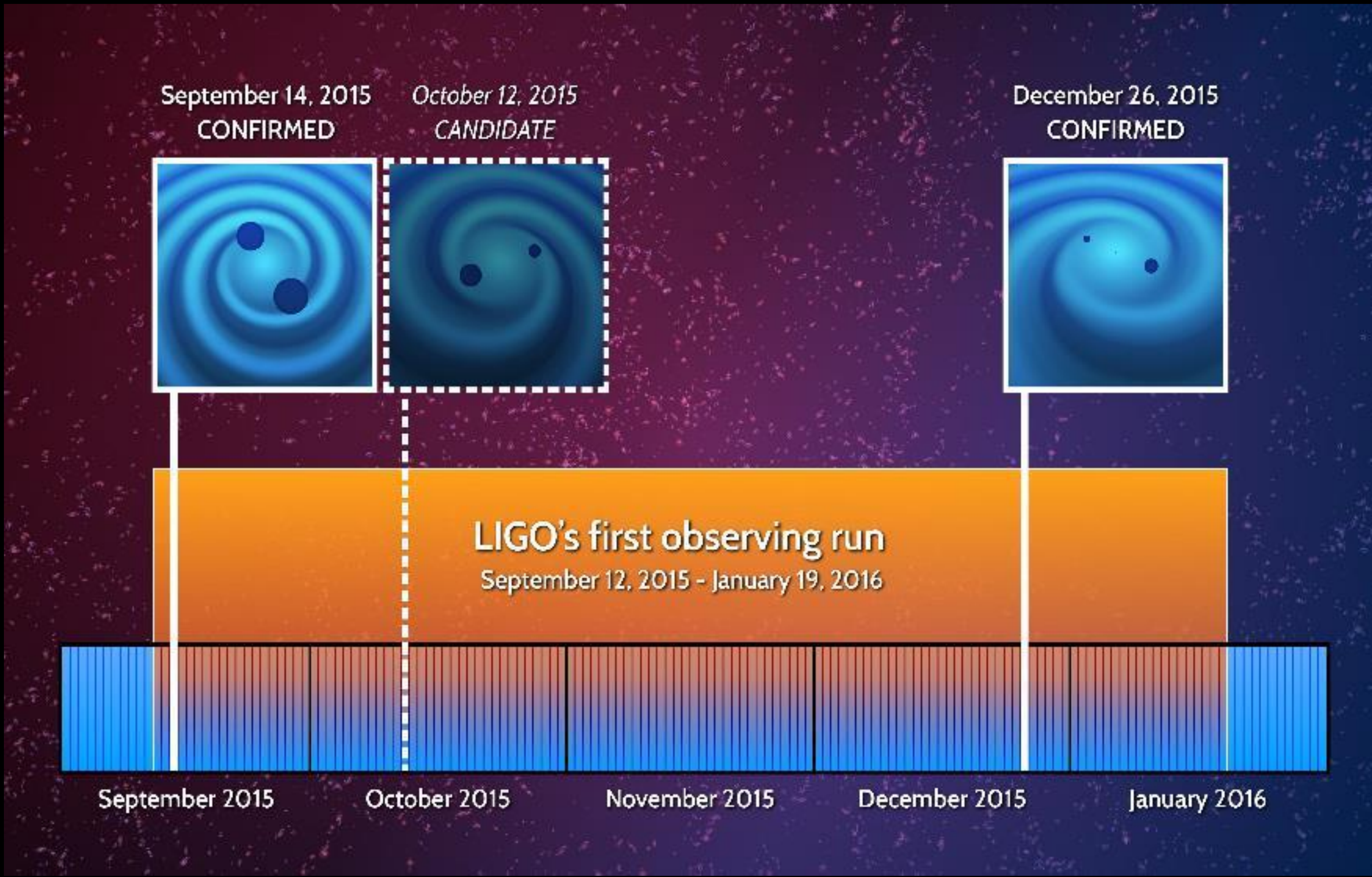
Why all the excitement?

- First direct observation of gravitational waves
- First direct observation of a black holes merging
- First test of Einstein's general relativity theory in strong field limit
- First observation of black holes with 10s of M_{sun}
- The machine works with sub-attometer precision, phew!

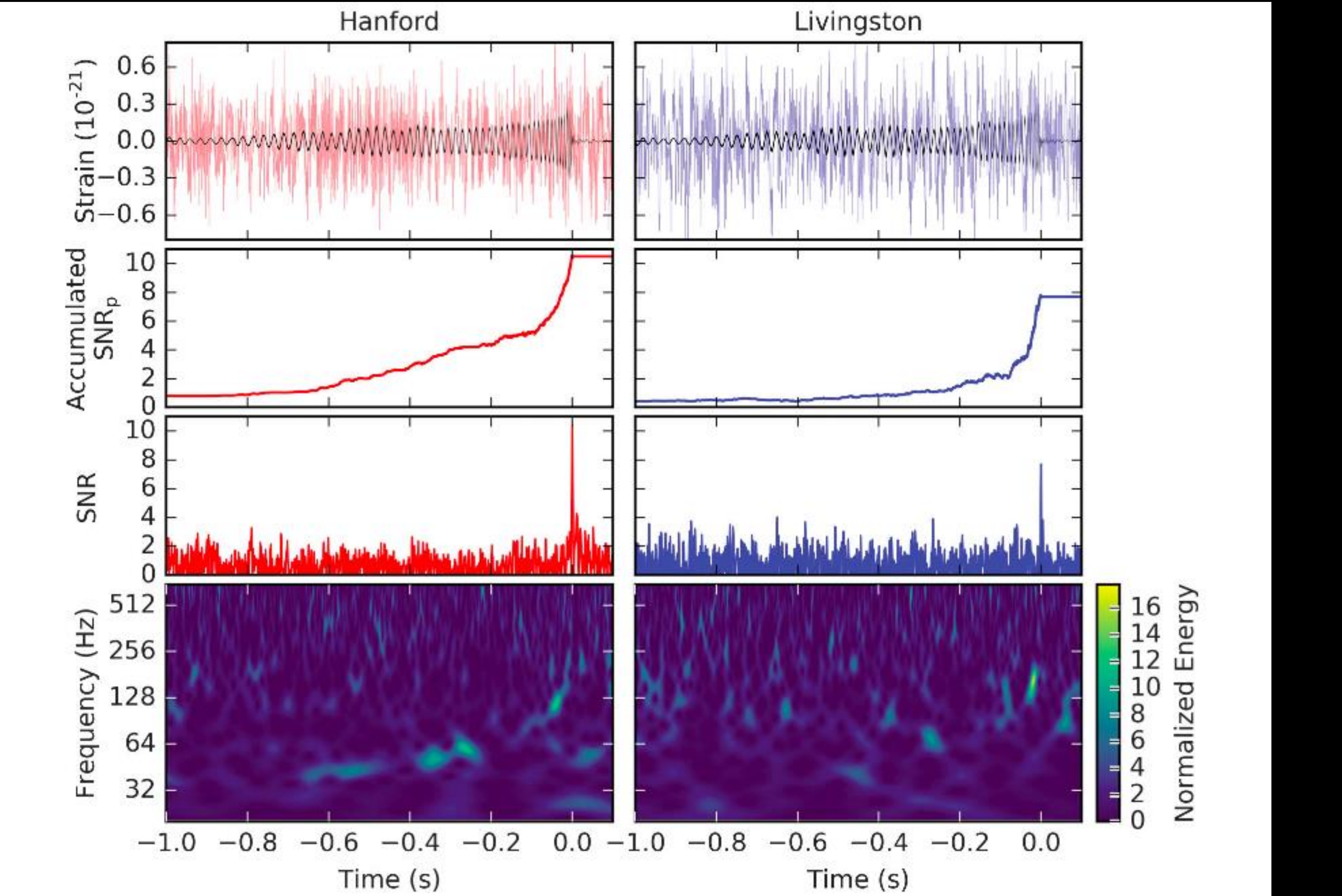
We have turned on a completely new sense with which to study the Universe
The era of gravitational wave astrophysics has begun

ADVANCED LIGO OBSERVING RUN 1

Advanced LIGO Observing Run 1
Sept. 18, 2016 to Jan. 12, 2017



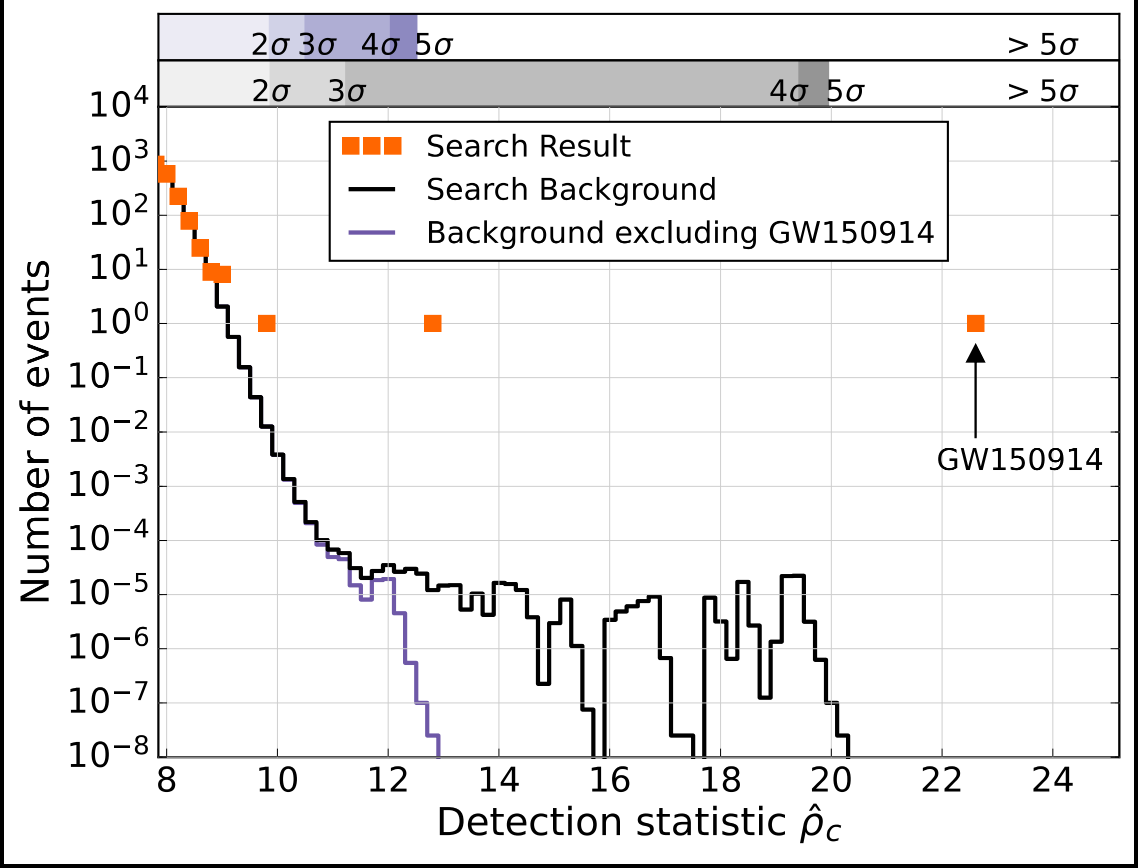
GW151226



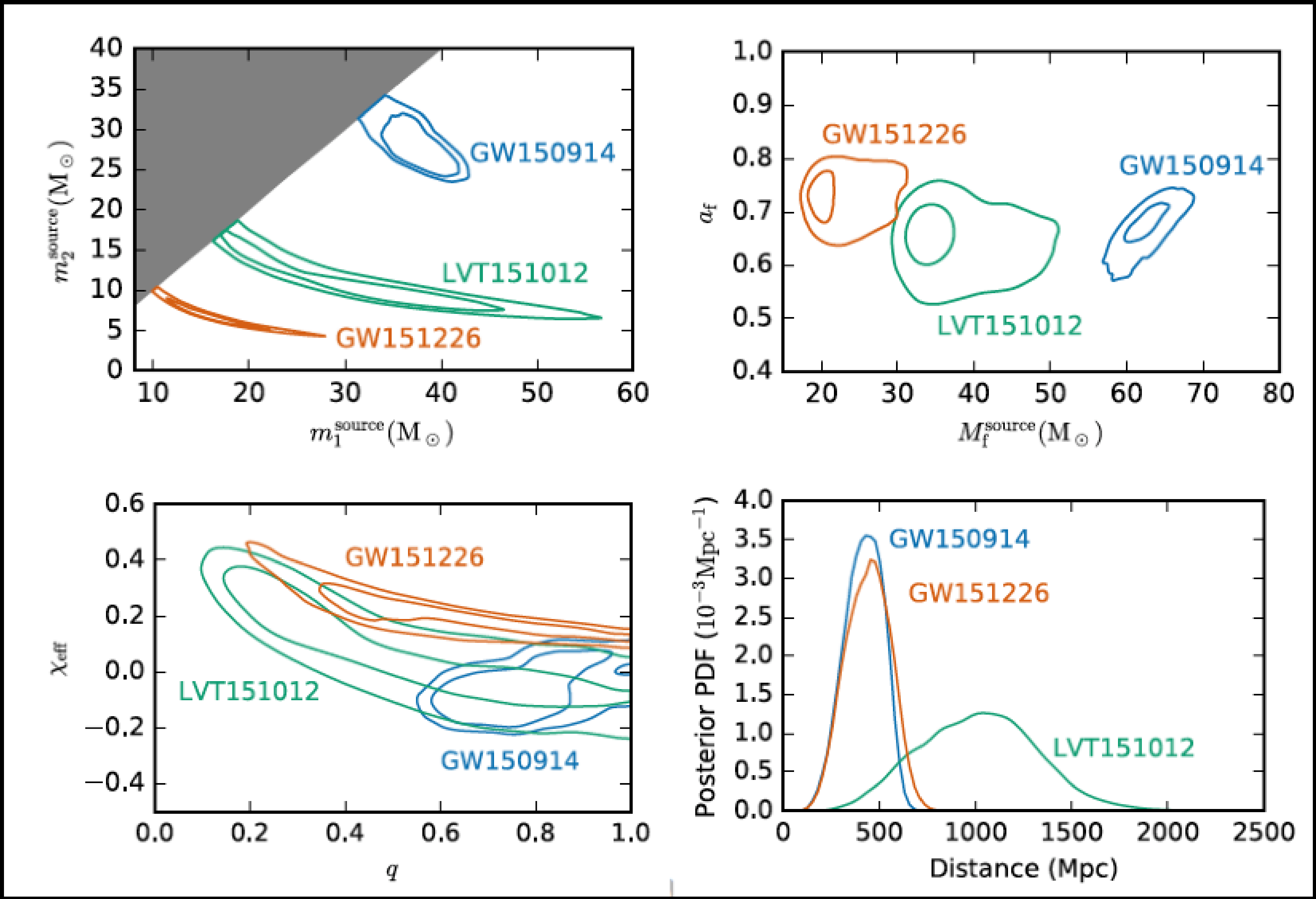
Hanford
Livingston
Strain (10^{-21})
0.6
0.3
0.0
−0.3
−0.6
Accumulated SNR_p
10
8
6
4
2
0
SNR
Frequency (Hz)
512
256
128
64
32
Normalized Energy
16
14
12
10
8
6
4
2
0
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Time (s)

Binary black hole searches in O1

- 48 days of coincident data
- Search for total mass $2 < M_{tot}/M_{\odot} < 100$

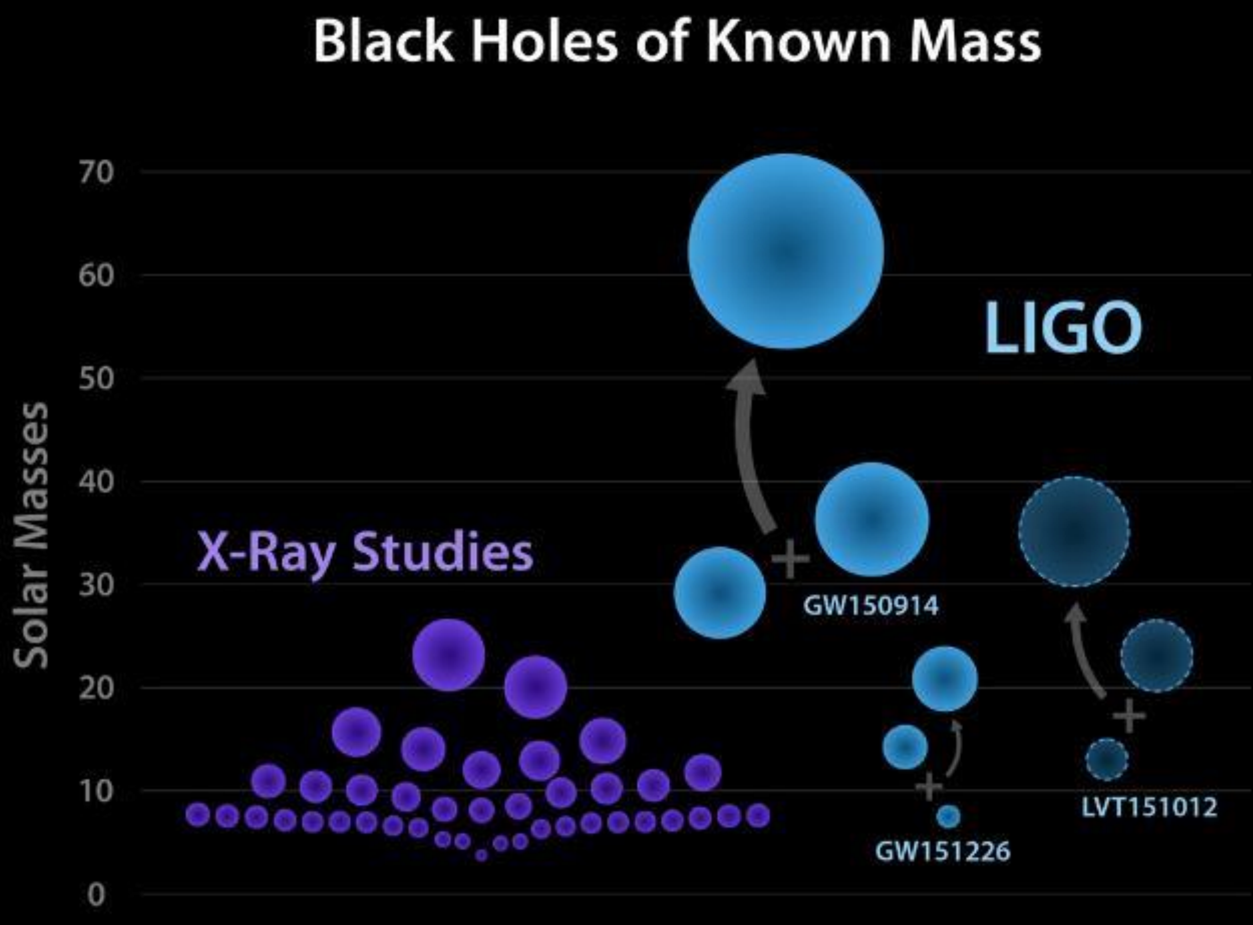


Parameters of the binary systems

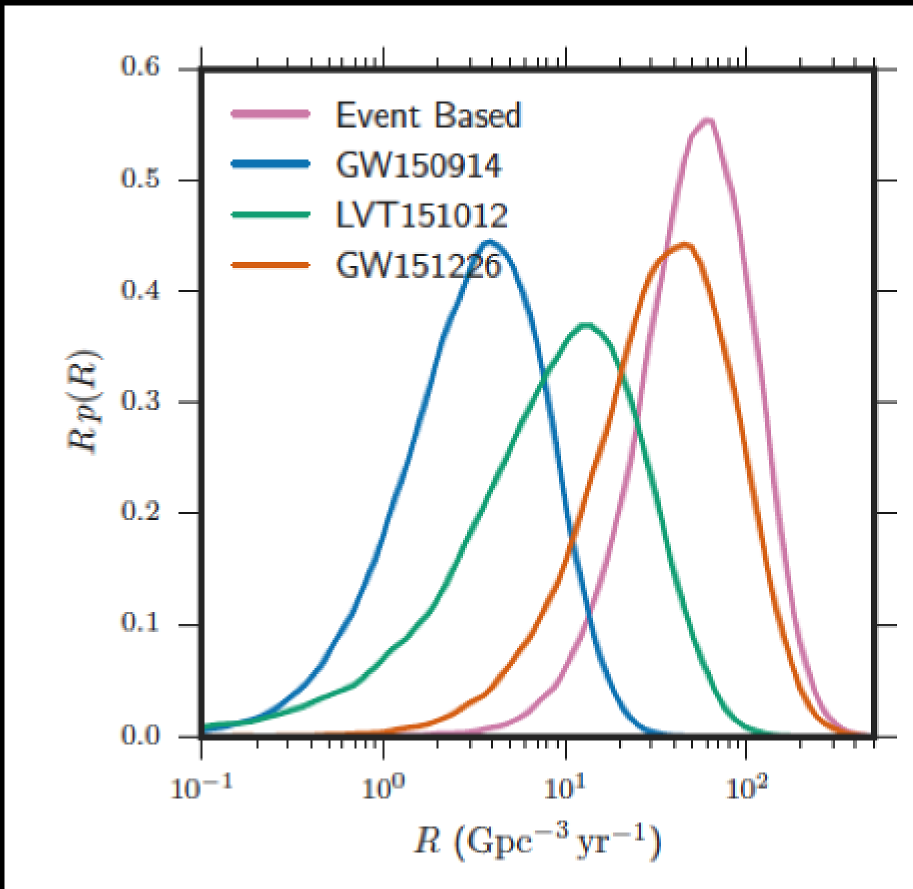


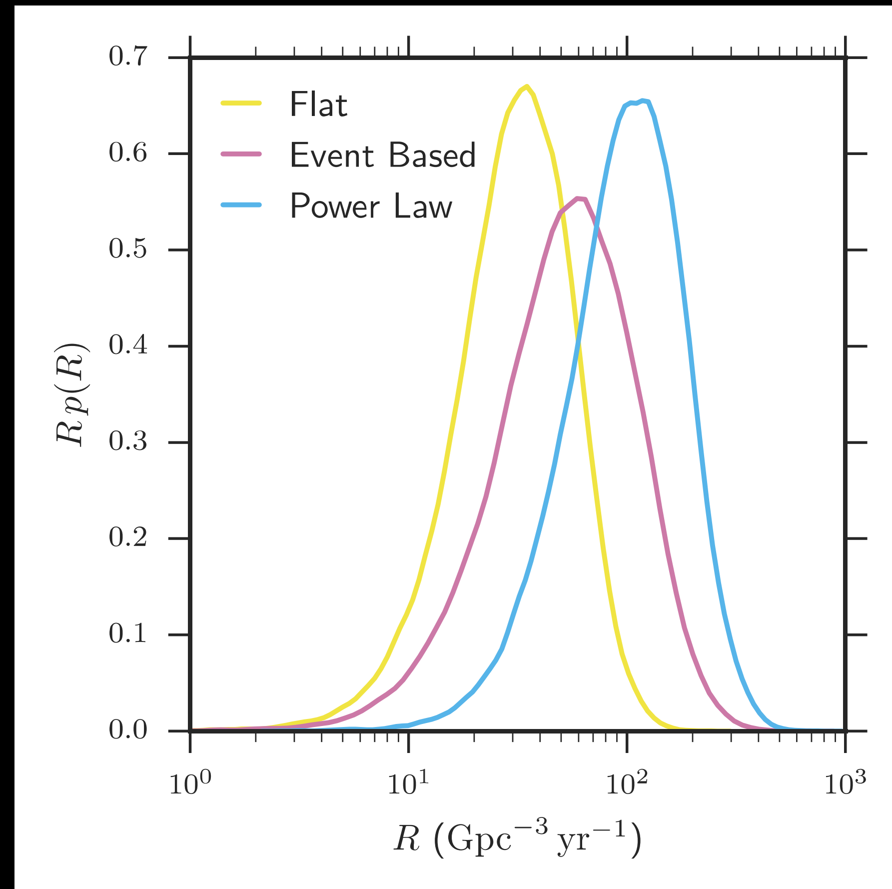
50% and 90% credible regions

Learning about black hole populations



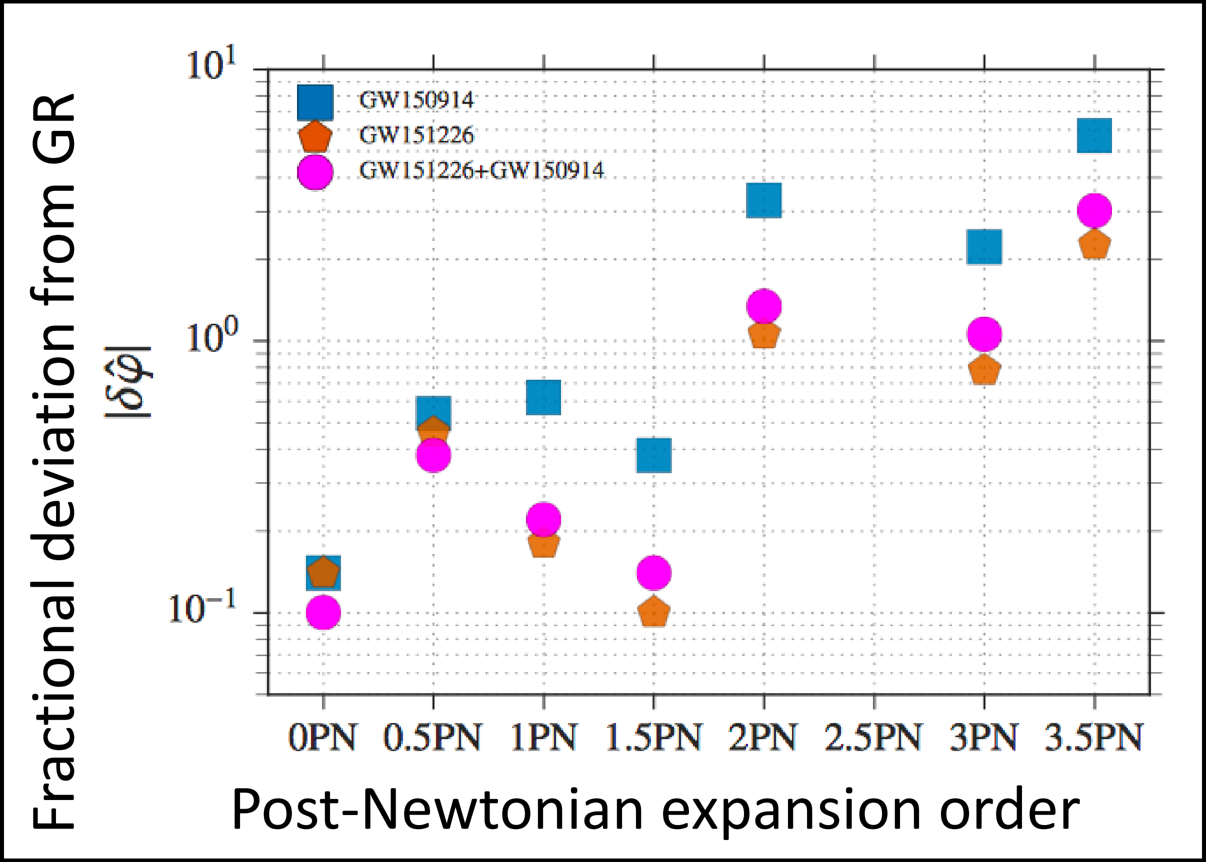
Binary black hole merger rate





90% allowed range: 9 to 240 /Gpc^3/yr

Testing General Relativity



Double pulsar J0737-3039

Masses ~ M_{sun}

Speeds ~ 1e-3 c

Derivative orbital period ~ 1e-12

Double black hole GW150914

Masses ~ 30 M_{sun}

Speeds ~ 0.5 c

Derivative orbital period ~ 1

Localization on the sky

Actual estimates with H1 and L1

Simulated estimates with Virgo

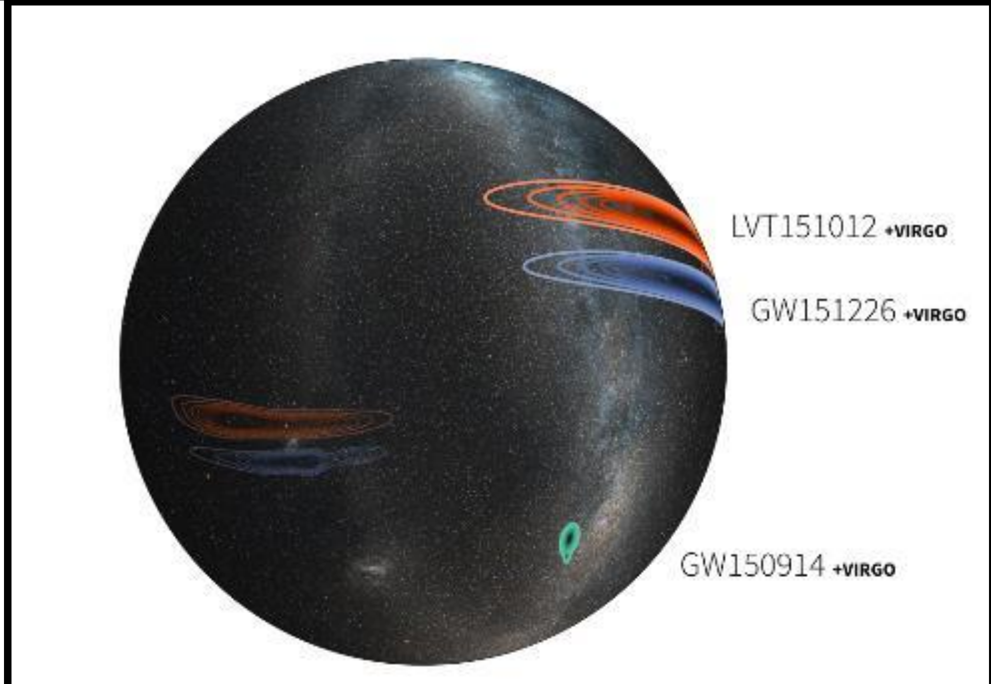
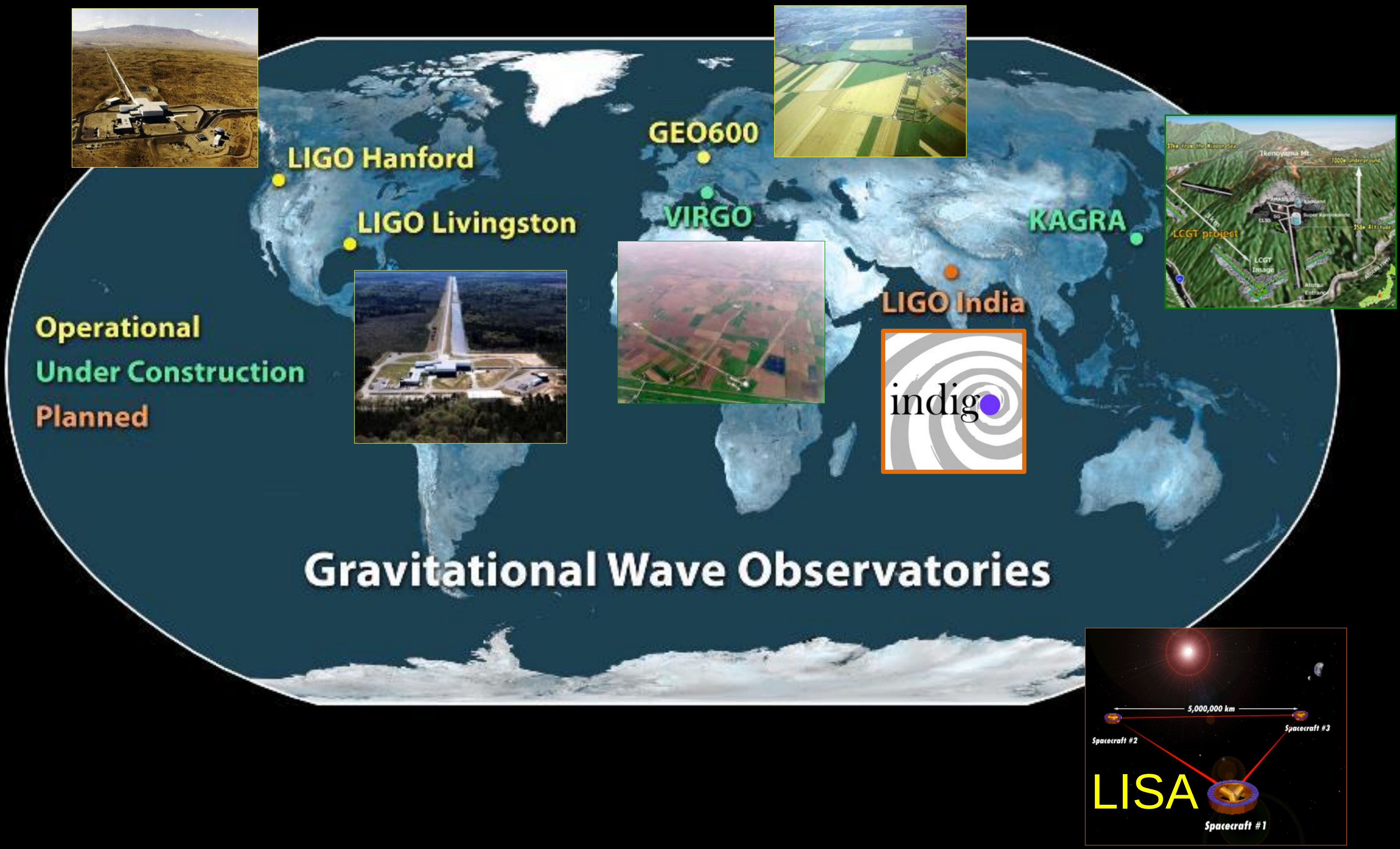


Image credit: LIGO/Mellinger

10% to 90% confidence regions

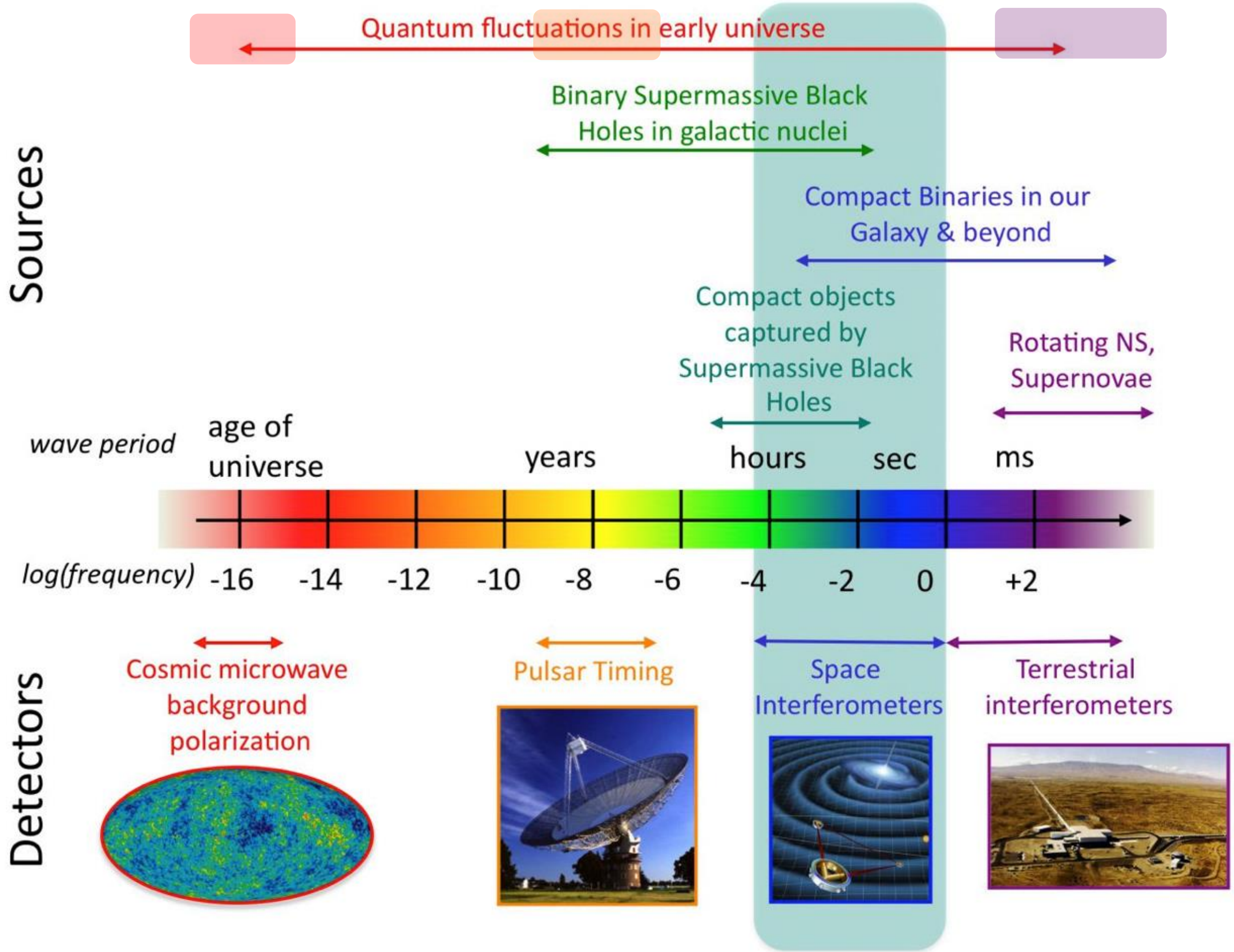
More detectors with large spatially separations and non-degenerate orientations needed

Global network of detectors



A BRILLIANTLY WARPED (AND DARK) FUTURE

Gravitational wave universe



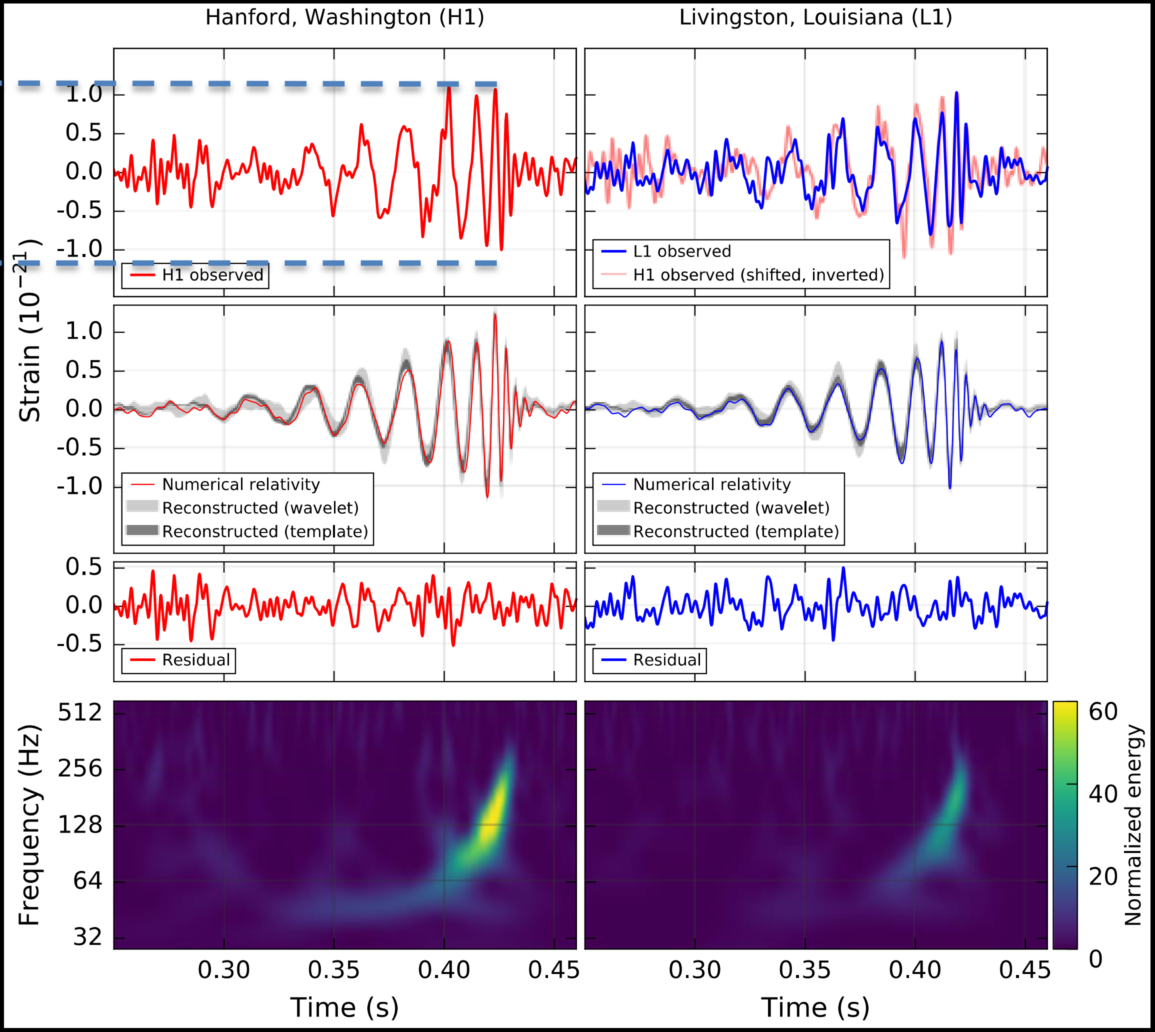
ADDITIONAL MATERIAL

GW150914: a binary black hole coalescence detected by LIGO

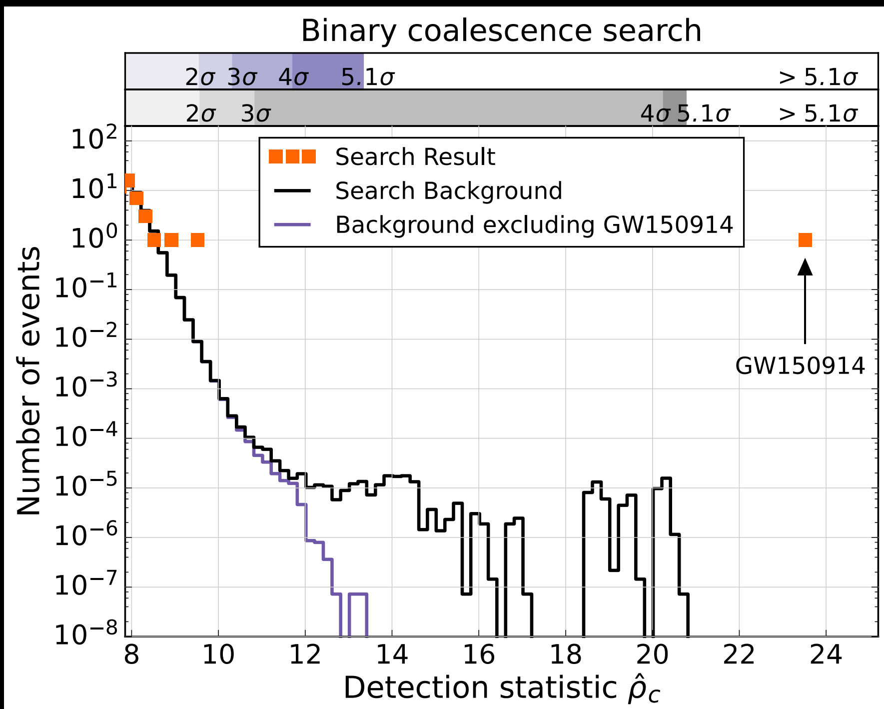
Strain ~ 10^{-21}

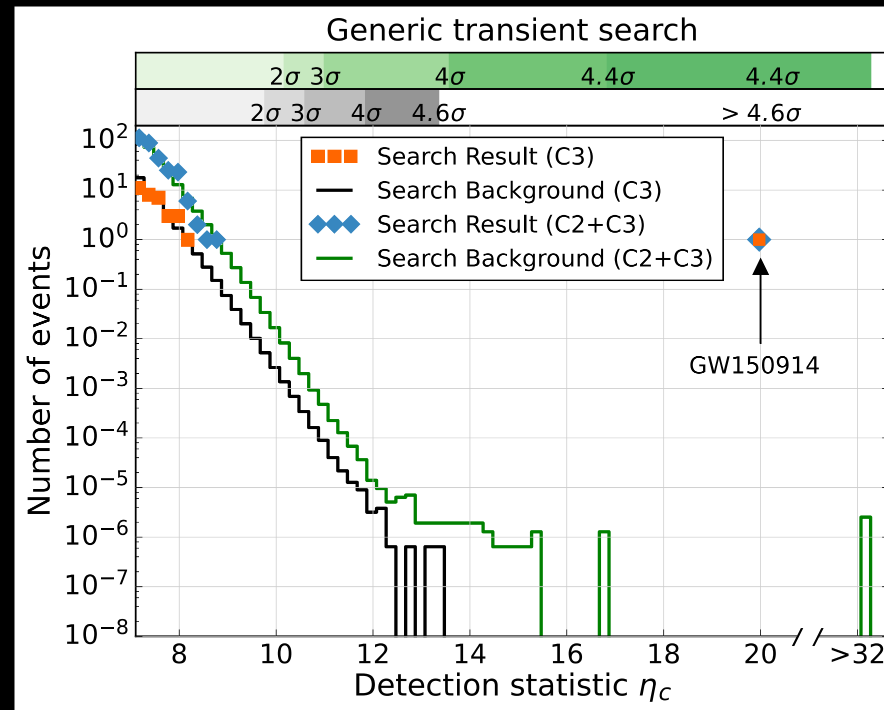
Displacement ~ 4 x 10^{-18} m

Power ~ 4 x 10^{49} W



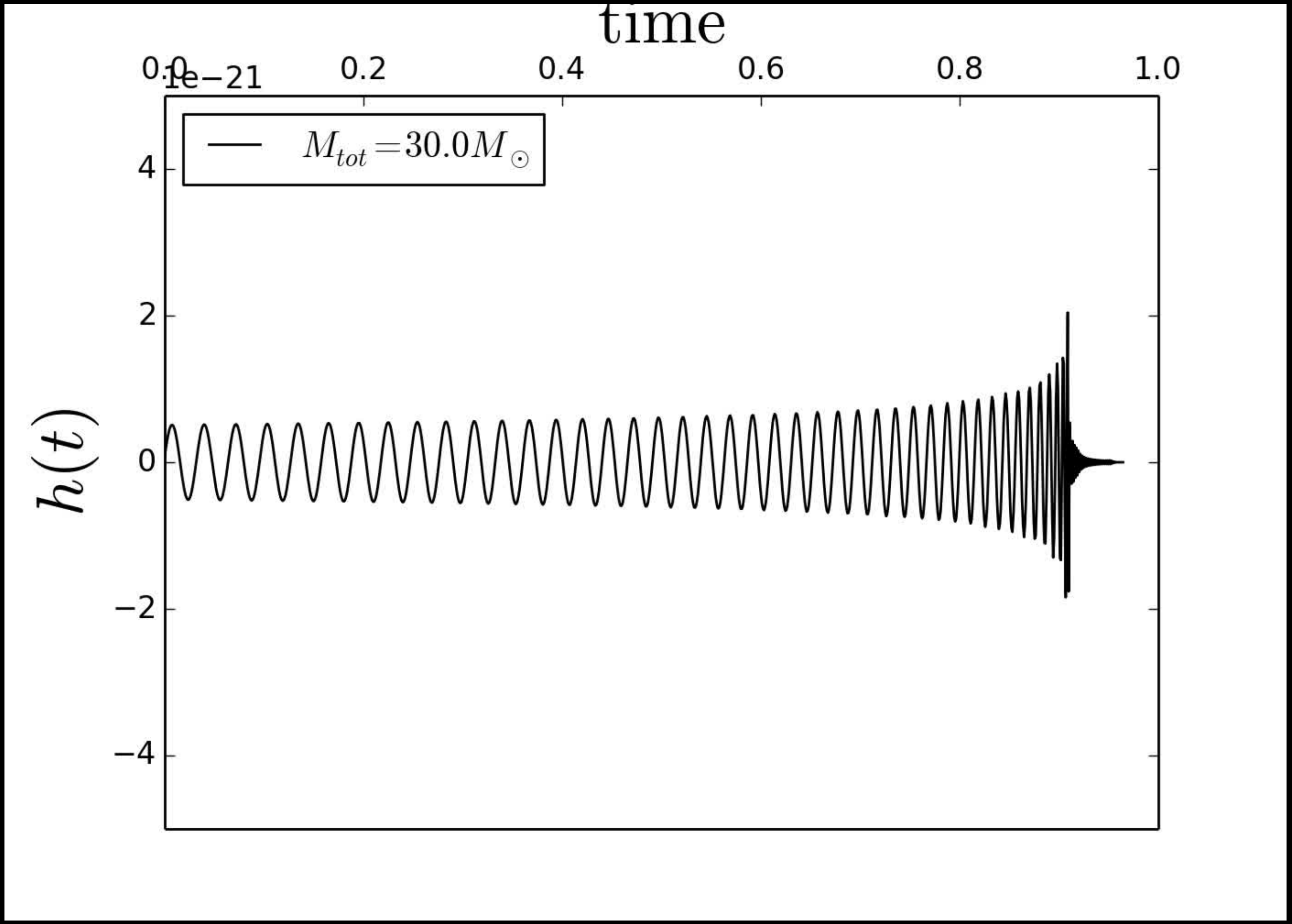
Multiple search techniques





- Confidence >5.1σ
- False alarm rate < 1 per 200,000 years
- False alarm probability < 2 x 10^{-7}

Different source parameters lead to different waveforms



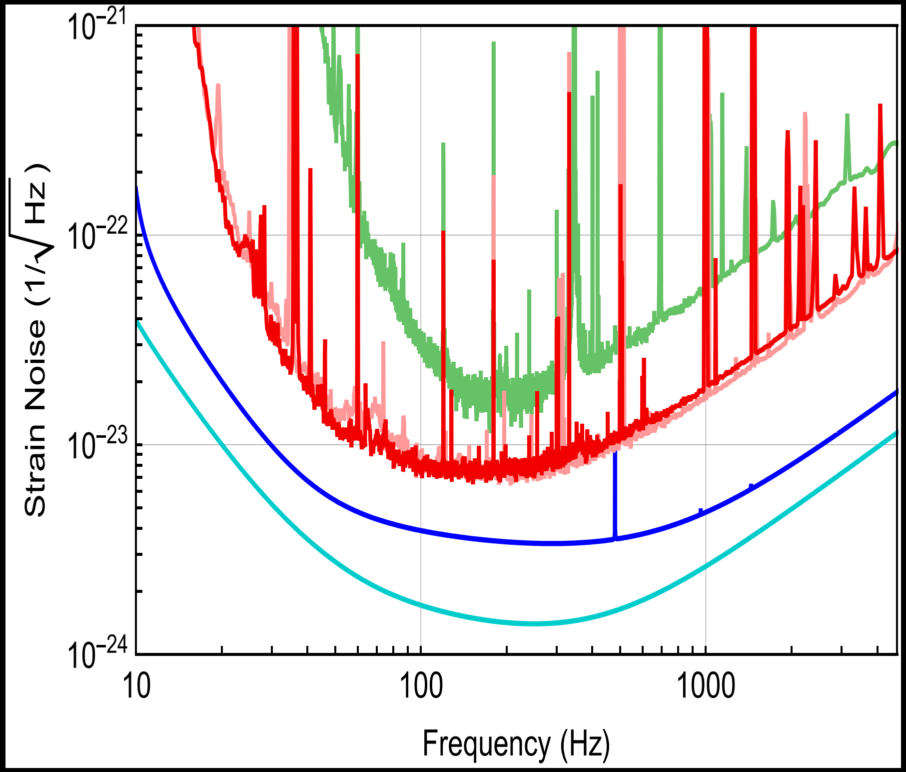
Main parameters of the source

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

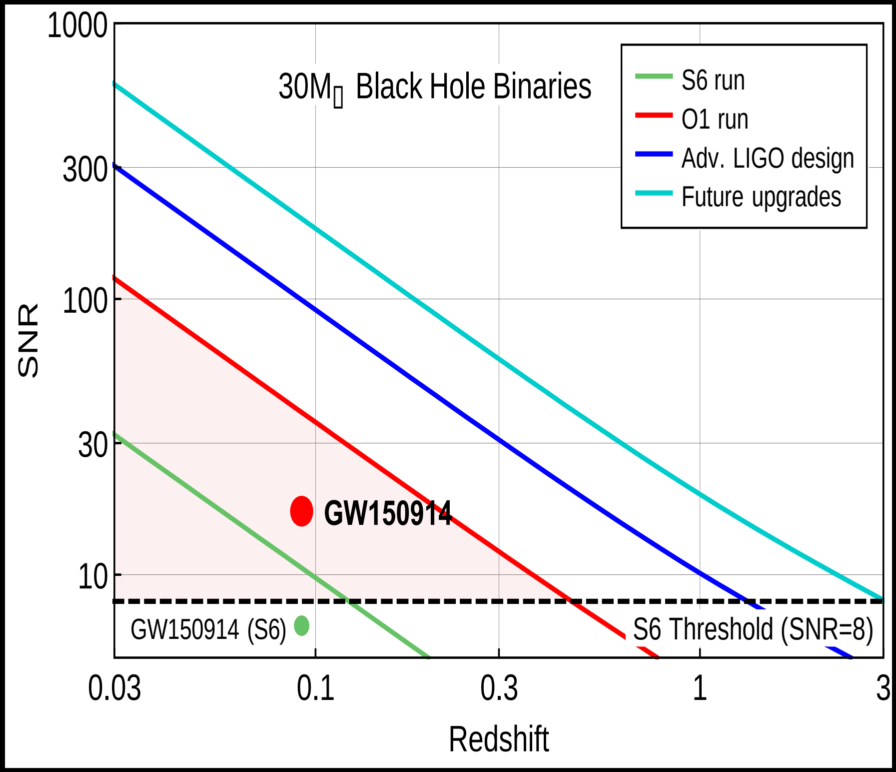
GW150914 companion papers

- Detector description
- Detector characterization
- Calibration
- Searches for transient (burst) sources
- Searches for coalescing compact binary (chirp) sources
- Electro-magnetic follow-up
- Estimating the parameters of the source
- Testing General Relativity
- Astrophysical implications
- Rates of occurrence
- Stochastic background of many sources
- GWs and high energy neutrinos

Why now, in O1?

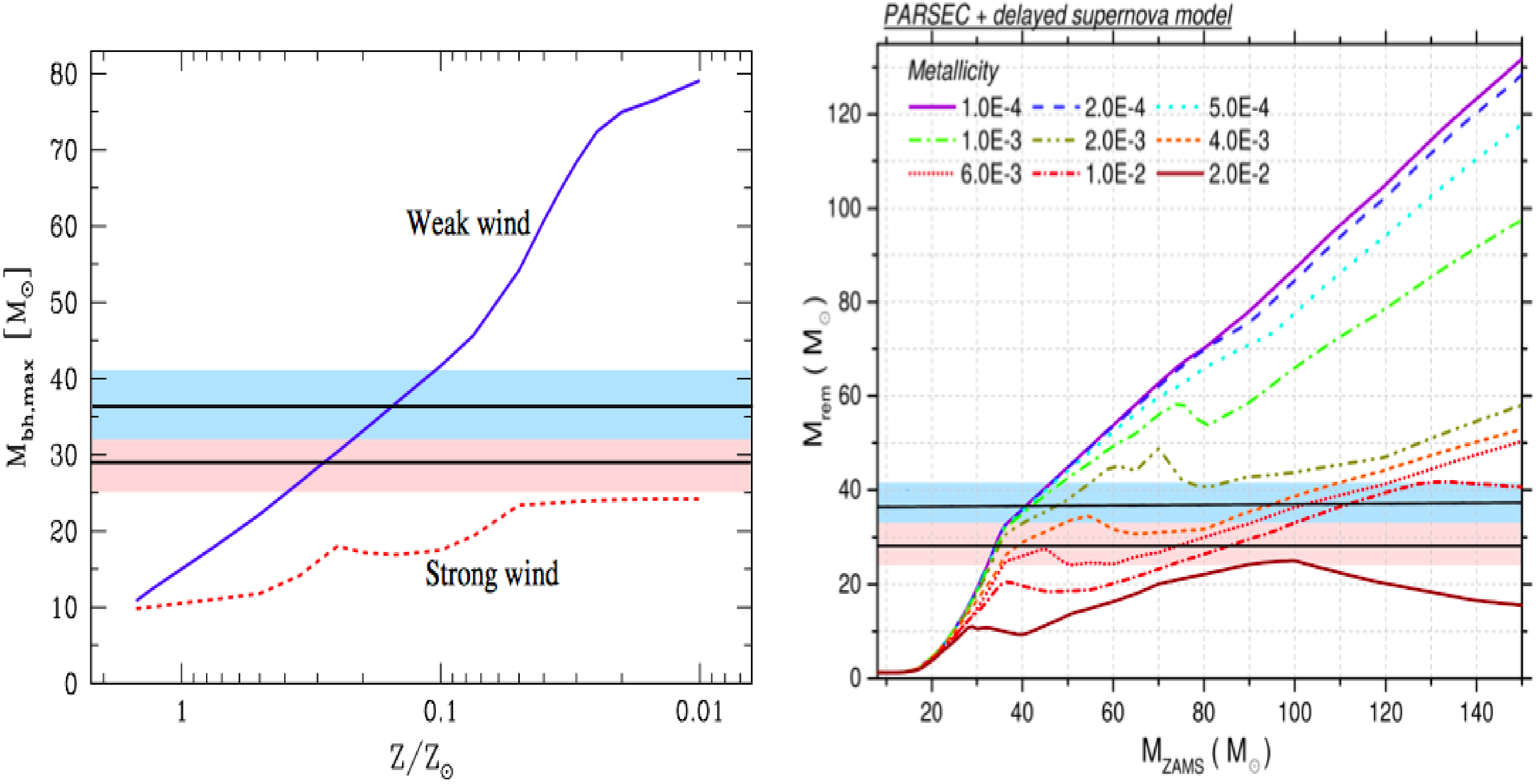


Strain Noise (1/√Hz)
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
10
100
1000
Frequency (Hz)



30M Black Hole Binaries
S6 run
O1 run
Adv. LIGO design
Future upgrades
SNR
1000
300
100
30
10
GW150914
GW150914 (S6)
S6 Threshold (SNR=8)
0.03
0.1
0.3
1
3
Redshift

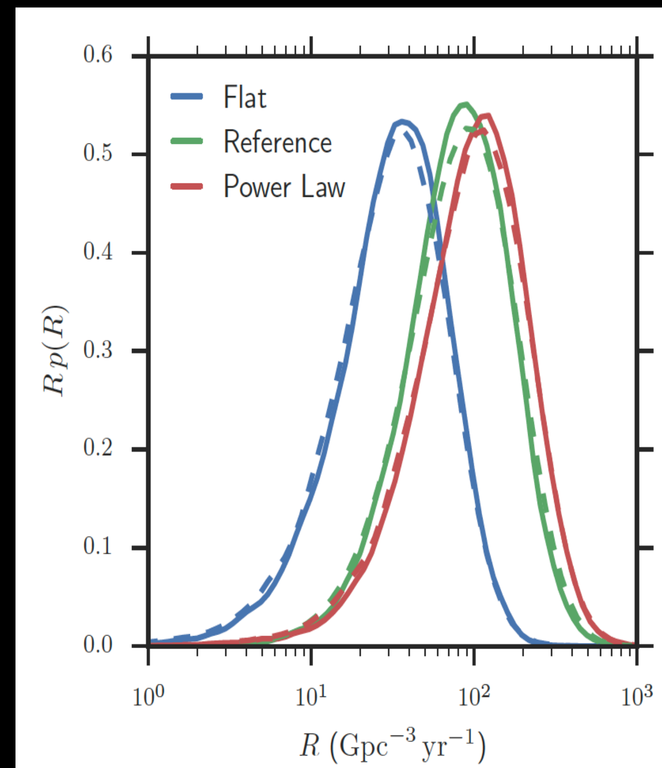
How do such heavy black holes form?



From massive parent stars in weak-wind, low-metallicity environments

Astrophysical rates of binary black holes

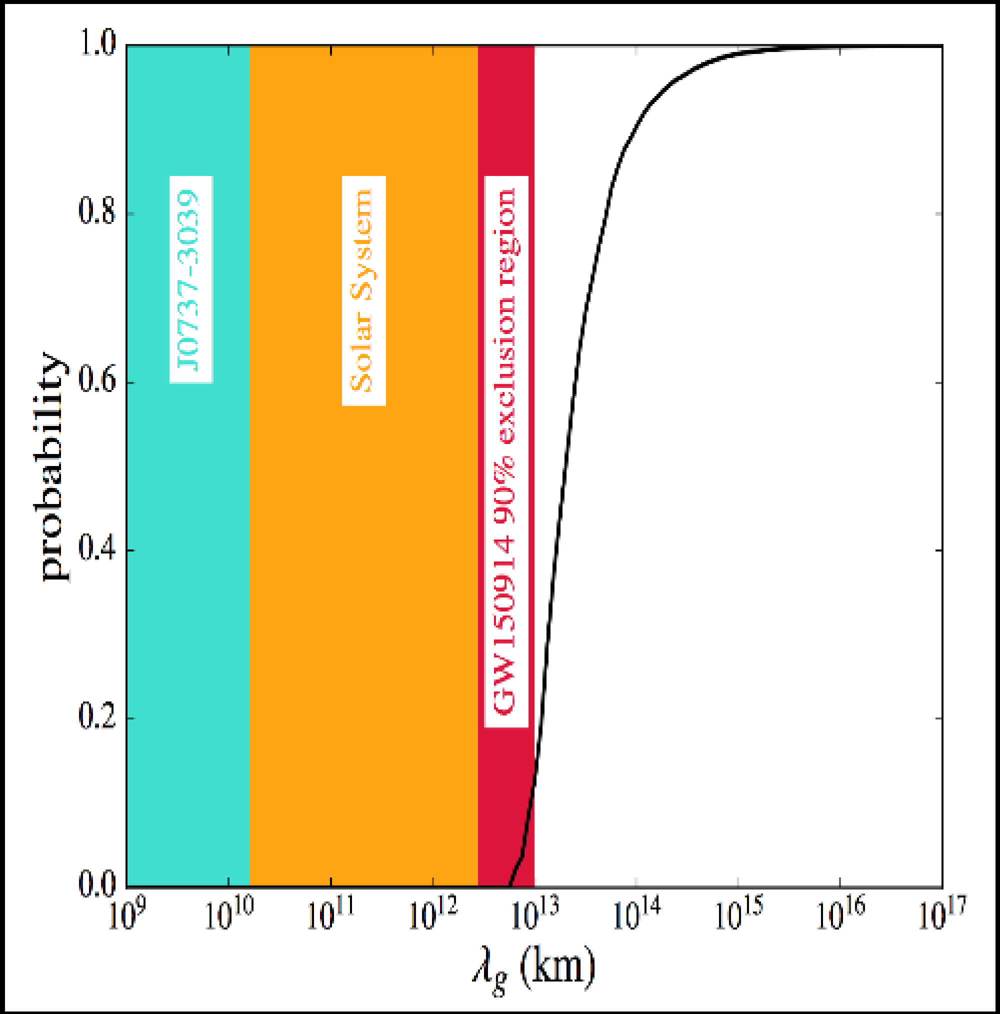
Mass Distribution	$R/\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ Combined
GW150914	17^{+39}_{-13}
G197392	62^{+165}_{-54}
Both	83^{+168}_{-63}
	Astrophysical
Flat	33^{+62}_{-26}
Power Law	100^{+201}_{-79}



We can expect 5 or more events in the next observing run

(2 to 400 $\mathrm{Gpc}^3\ \mathrm{yr}^{-1}$)

Compton wavelength and mass of the graviton



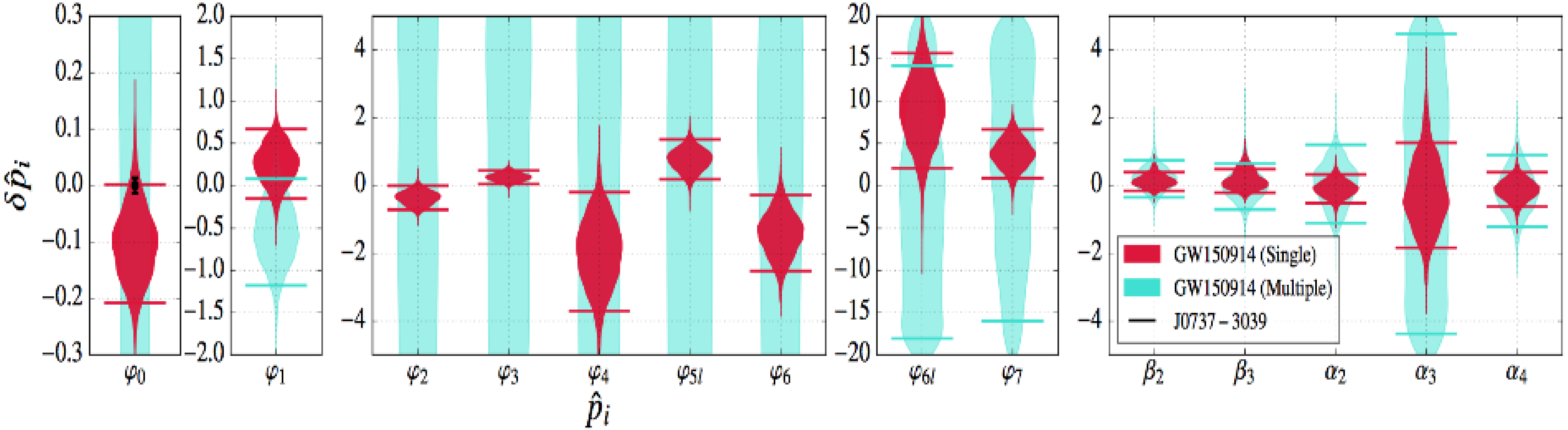
Massive graviton modifies the dispersion relation

↓

The Compton wavelength $\lambda_g > 10^{13}$ km (90% CL)

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

Does General Relativity describe GW150914?



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Masses ~ M_{sun}

Speeds ~ 1e-3 c

Derivative orbital period ~ 1e-12

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Masses ~ 30 M_{sun}

Speeds ~ 0.5 c

Derivative orbital period ~ 1

The most stringent test of strong field gravity

Template matching