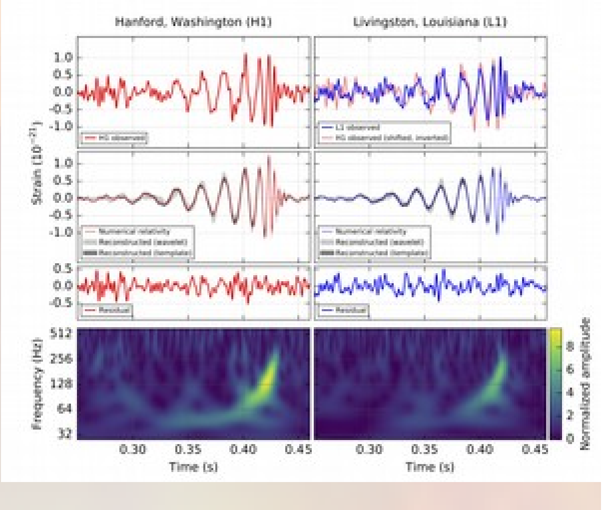
Doing physics with gravitational waves

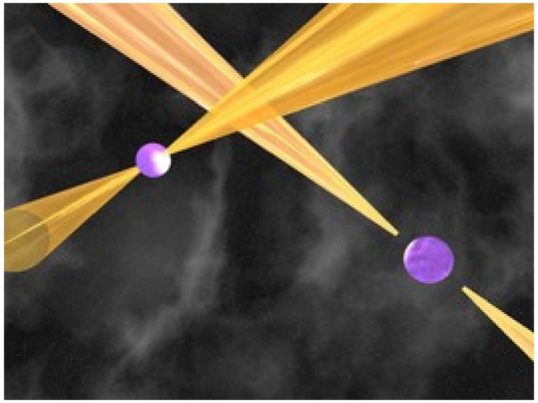
Tests of General Relativity

Gravitational wave astrophysics

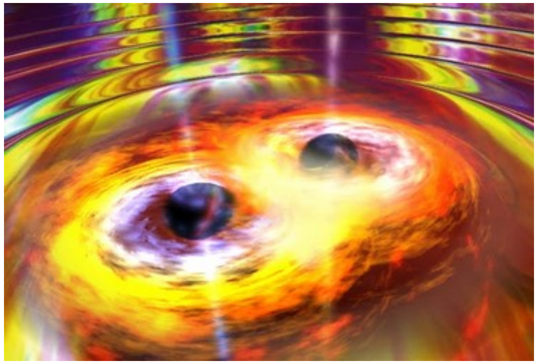


Testing General Relativity (GR)

Two neutron stars
Period 2 hours
Distance ~10^6 km



PSR J0737-3039
most relativistic binary pulsar known today:
orbital velocity **v/c ~ 2 x 10^{-3}**



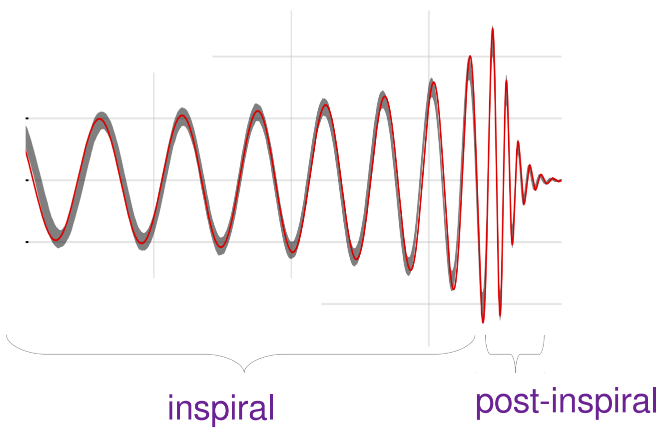
Two black holes
“Period” ~ 0.01 s
“Distance” ~100 km

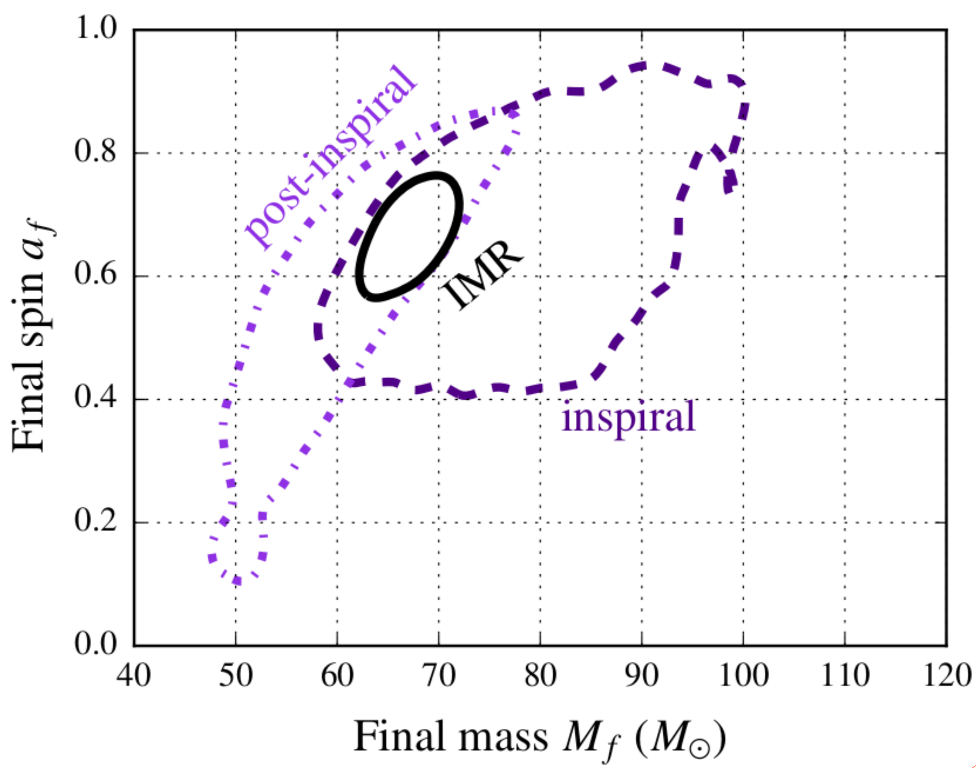
GW150914 and GW151226
large velocity, highly dynamical, strong field regime of gravity
v/c ~ 0.5

Testing GR: check waveform consistency

Check residuals after subtraction of best-fit waveform
$\rightarrow$ GR-violations in GW150914 < 4%

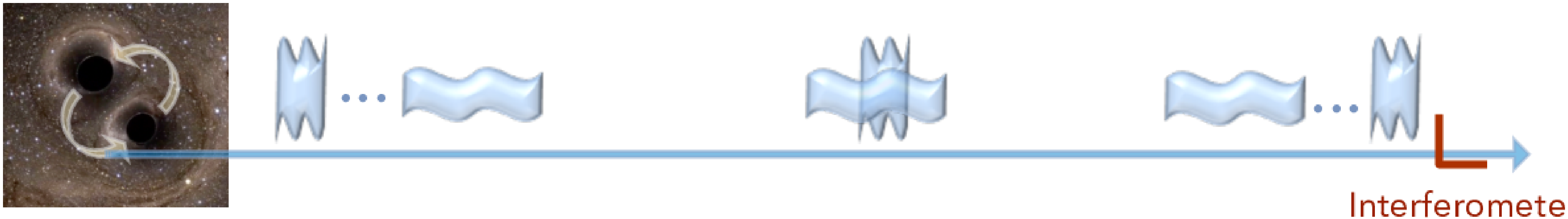
Check of waveform internal consistency



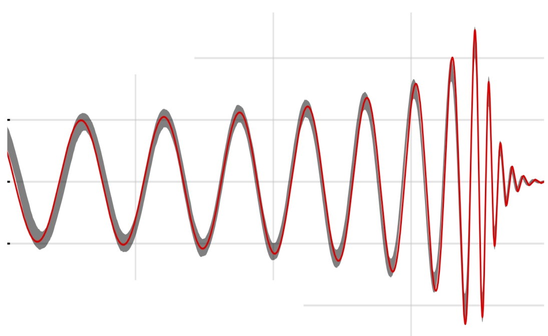


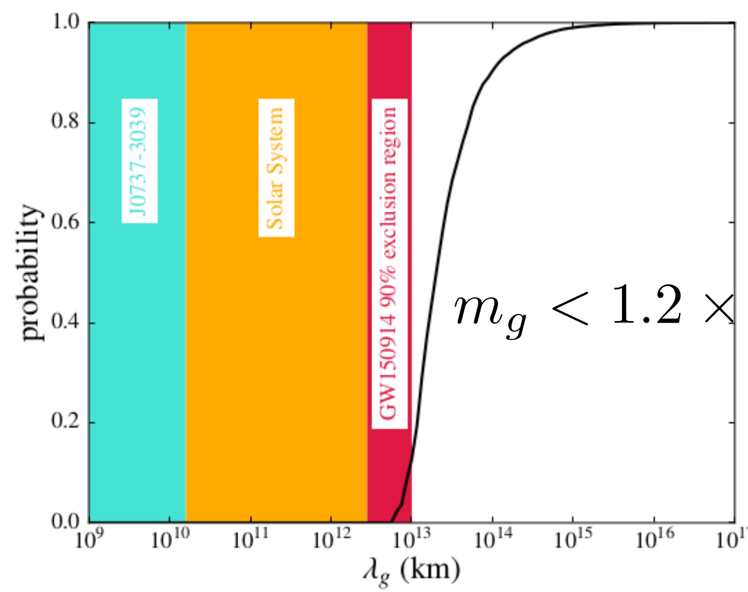
Testing GR: estimate bound on graviton mass

graviton mass ≠ 0 $\rightarrow$ space-time is dispersive for gravitational waves



Shape of the measured waveform $\rightarrow$ bound on graviton mass



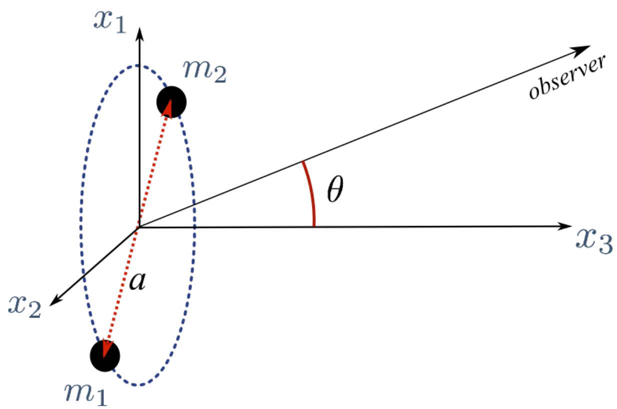


$$m_g < 1.2 \times 10^{-22}\ eV/c^2$$

(90% CL)

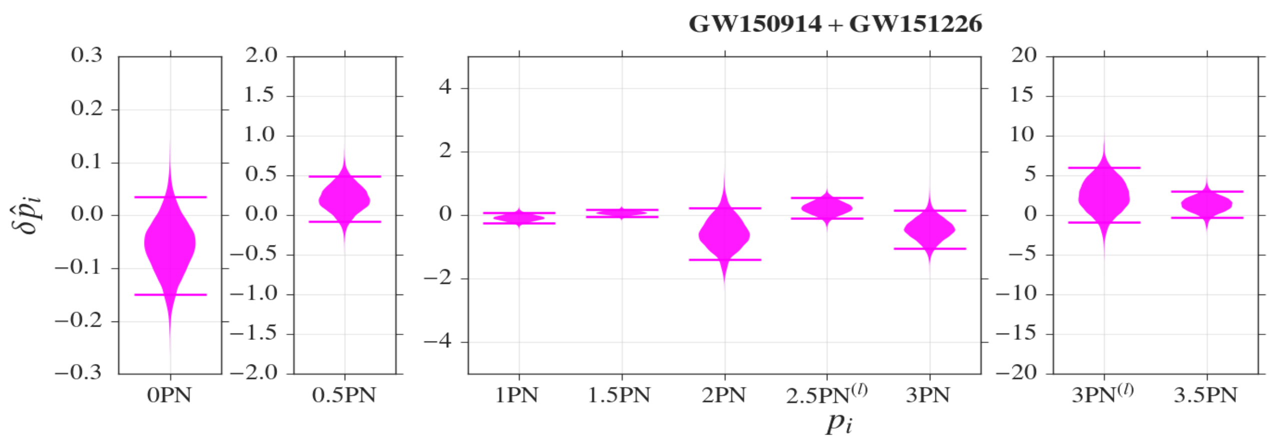
Testing GR: search for GR deviations

Binary system $\rightarrow$ Newton case + post-newtonian corrections



k	N	2	3	4	5
$\mathcal{F}_k$	$\frac{32\eta^2 v^{10}}{5}$	$-\frac{1247}{336} - \frac{35\eta}{12}$	4π	$-\frac{44711}{9072} + \frac{9271\eta}{504} + \frac{65\eta^2}{18}$	$-\left(\frac{8191}{672} + \frac{535\eta}{24}\right)\pi$
t_k^v	$-\frac{5m}{256\eta v^8}$	$\frac{743}{252} + \frac{11\eta}{3}$	$-\frac{32\pi}{5}$	$\frac{3058673}{508032} + \frac{5429\eta}{504} + \frac{617\eta^2}{72}$	$-\left(\frac{7729}{252} + \eta\right)\pi$
ϕ_k^v	$-\frac{1}{16\eta v^5}$	$\frac{3715}{1008} + \frac{55\eta}{12}$	-10π	$\frac{15293365}{1016064} + \frac{27145\eta}{1008} + \frac{3085\eta^2}{144}$	$\left(\frac{38645}{672} + \frac{15\eta}{8}\right)\pi \ln\left(\frac{v}{v_{\rm lso}}\right)$
ϕ_k^t	$-\frac{2}{\eta\theta^5}$	$\frac{3715}{8064} + \frac{55\eta}{96}$	$-\frac{3\pi}{4}$	$\frac{9275495}{14450688} + \frac{284875\eta}{258048} + \frac{1855\eta^2}{2048}$	$\left(\frac{38645}{21504} + \frac{15\eta}{256}\right)\pi \ln\left(\frac{\theta}{\theta_{\rm lso}}\right)$
F_k^t	$\frac{\theta^3}{8\pi m}$	$\frac{743}{2688} + \frac{11\eta}{32}$	$-\frac{3\pi}{10}$	$\frac{1855099}{14450688} + \frac{56975\eta}{258048} + \frac{371\eta^2}{2048}$	$-\left(\frac{7729}{21504} + \frac{3}{256}\eta\right)\pi$
τ_k	$\frac{3}{128\eta}$	$\frac{5}{9}\left(\frac{743}{84} + 11\eta\right)$	-16π	$2\phi_4^v$	$\frac{1}{3}\left(8\phi_5^v - 5t_5^v\right)$

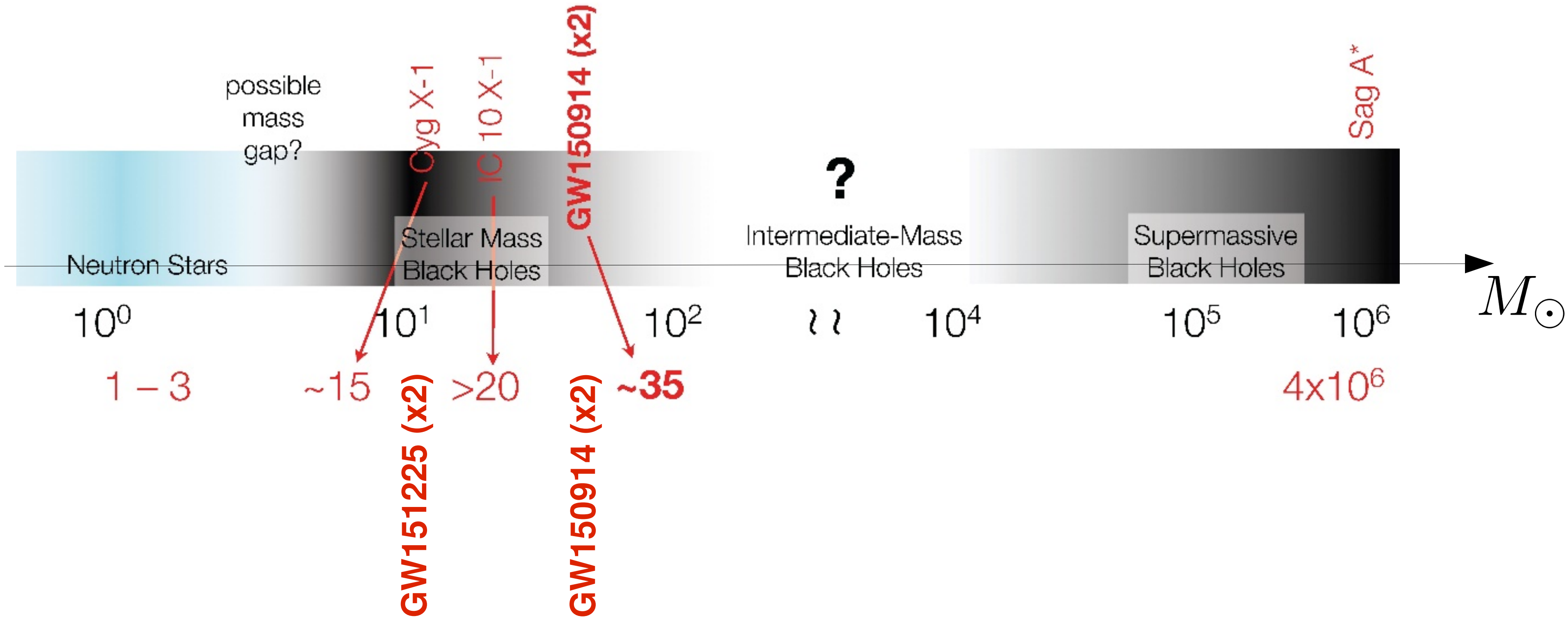
Fit waveform letting free the post-newtonian correction factors



$\rightarrow$ No evidence for deviation from General Relativity in waveform

Astrophysical implications: intermediate mass black holes

Relatively **heavy stellar-mass black holes exist** (>25 $M_\odot$)

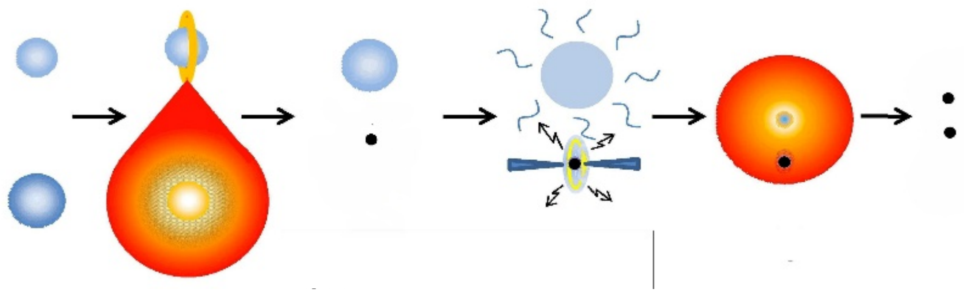


Formation of such black holes needs

- Weak massive-star winds
- Low metallicity environment

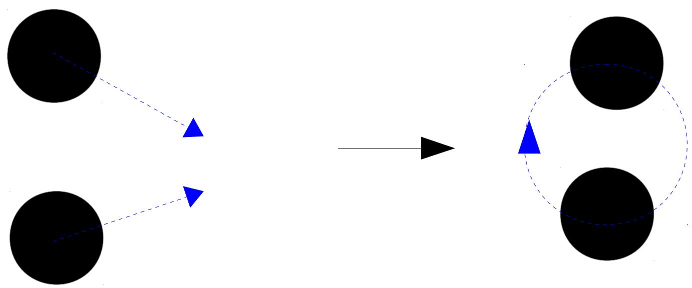
Astrophysical implications: formation of binary black holes

Isolated star binaries?



Probably
aligned-spins

Dynamical capture in dense star clusters?



Probably
not aligned-spins

GW discoveries → Binary black holes form in nature
not enough spin information to choose between both formation scenario yet

Astrophysical implications: rate of binary black hole mergers

BBH merge within the age of the Universe at detectable rate

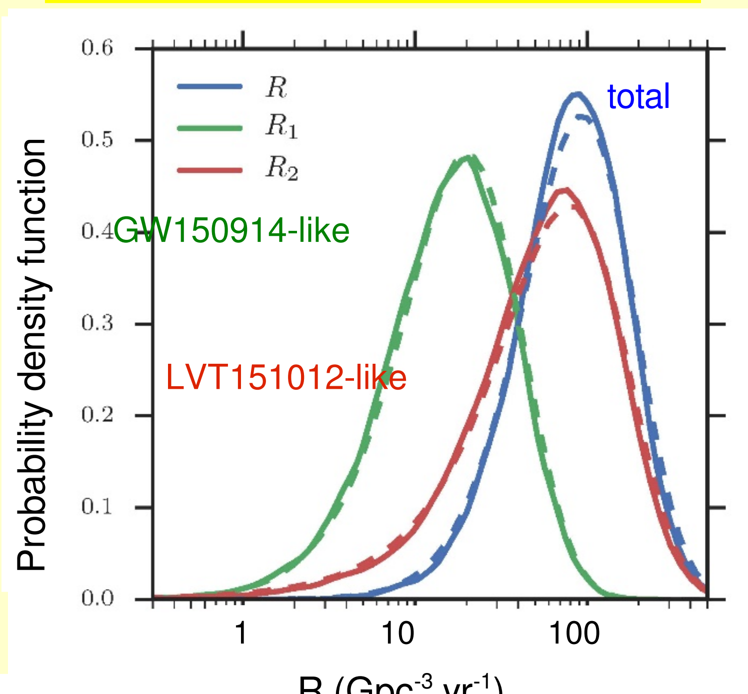
Electromagnetic observations
+ population modelling:
R ~ 0.1 to 300 Gpc^{-3}.yr^{-1}

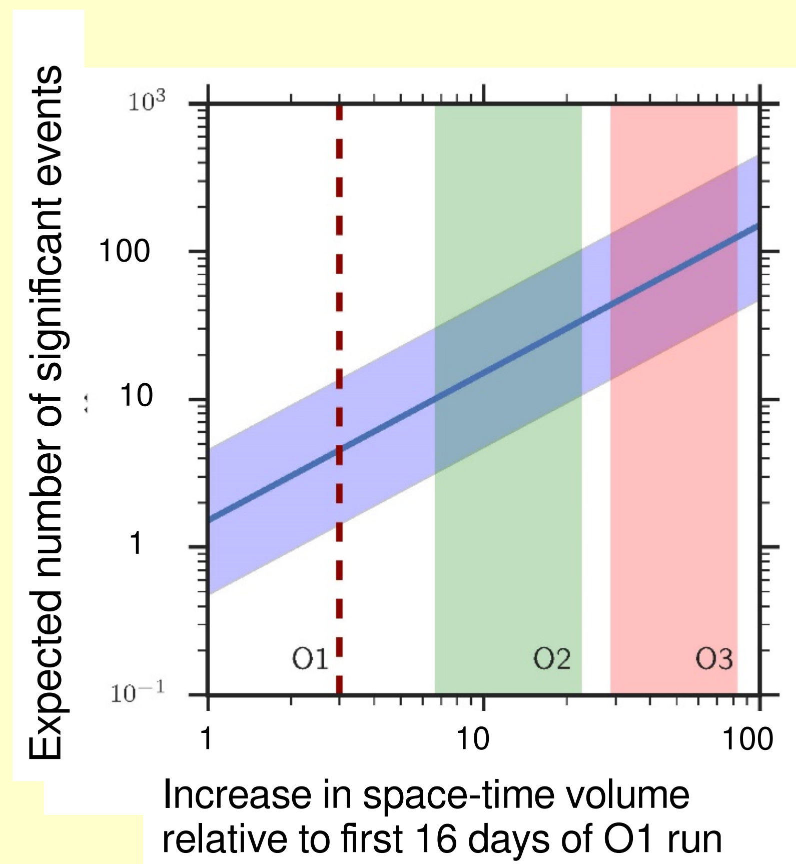
LIGO-Virgo rate upper limits in 2011
R < 140 Gpc^{-3}.yr^{-1} for GW150914 parameters

Counting signals in experiments
→ very low statistics

Estimating sensitivity to population of sources
→ depends on hardly known mass distribution

→ R ~ 2 to 400 Gpc^{-3}.yr^{-1}





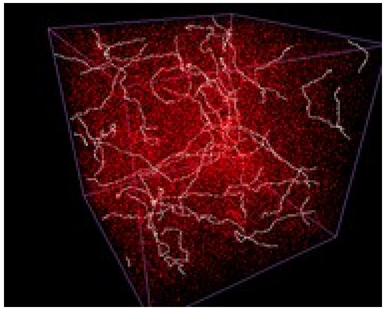
Other searches, and more data to come

4 months of O1 data under analysis
A lot of different searches on-going...
Second observation run to start next Fall

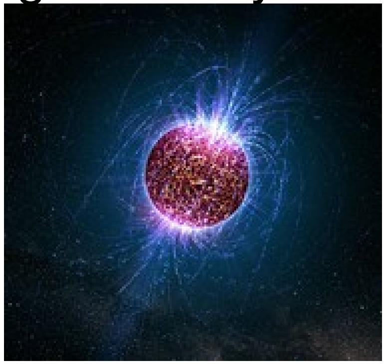
Binary neutron stars
Neutron star-black hole binaries
Intermediate mass black holes

GW's from GRBs...

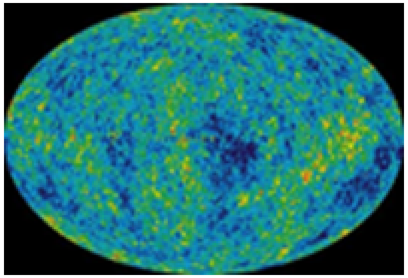
Generic transients
Cosmic strings



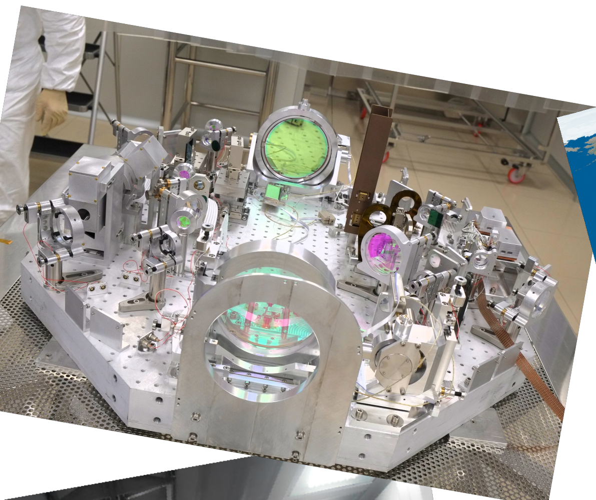
Rotating non axisymmetric neutron stars

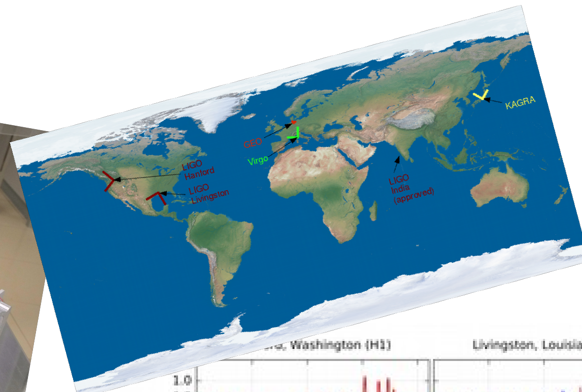


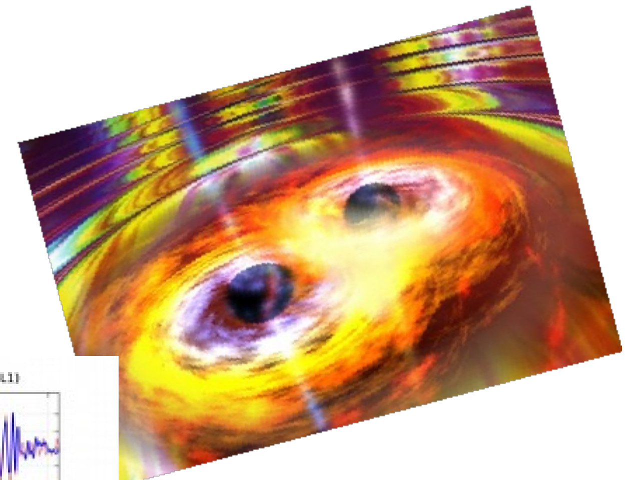
Stochastic GW background

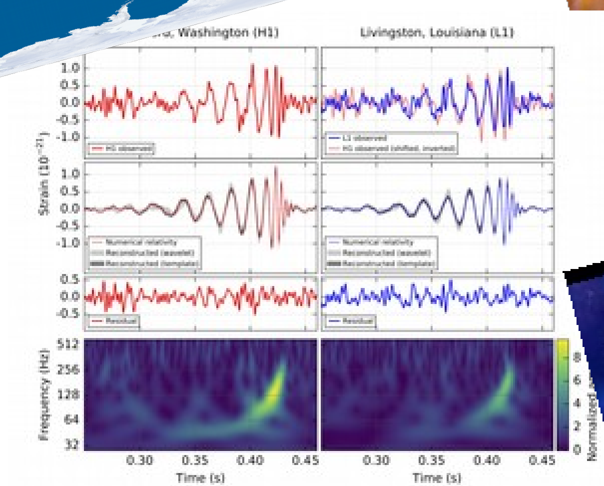


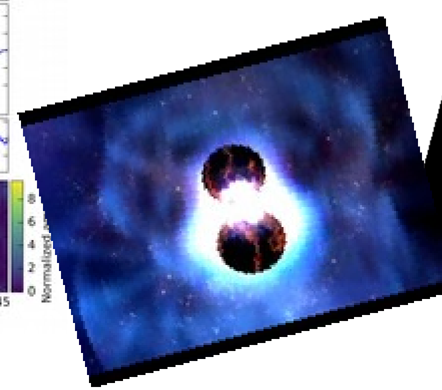
A lot of gravitational fun in front of us!

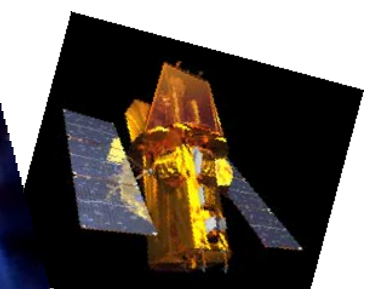




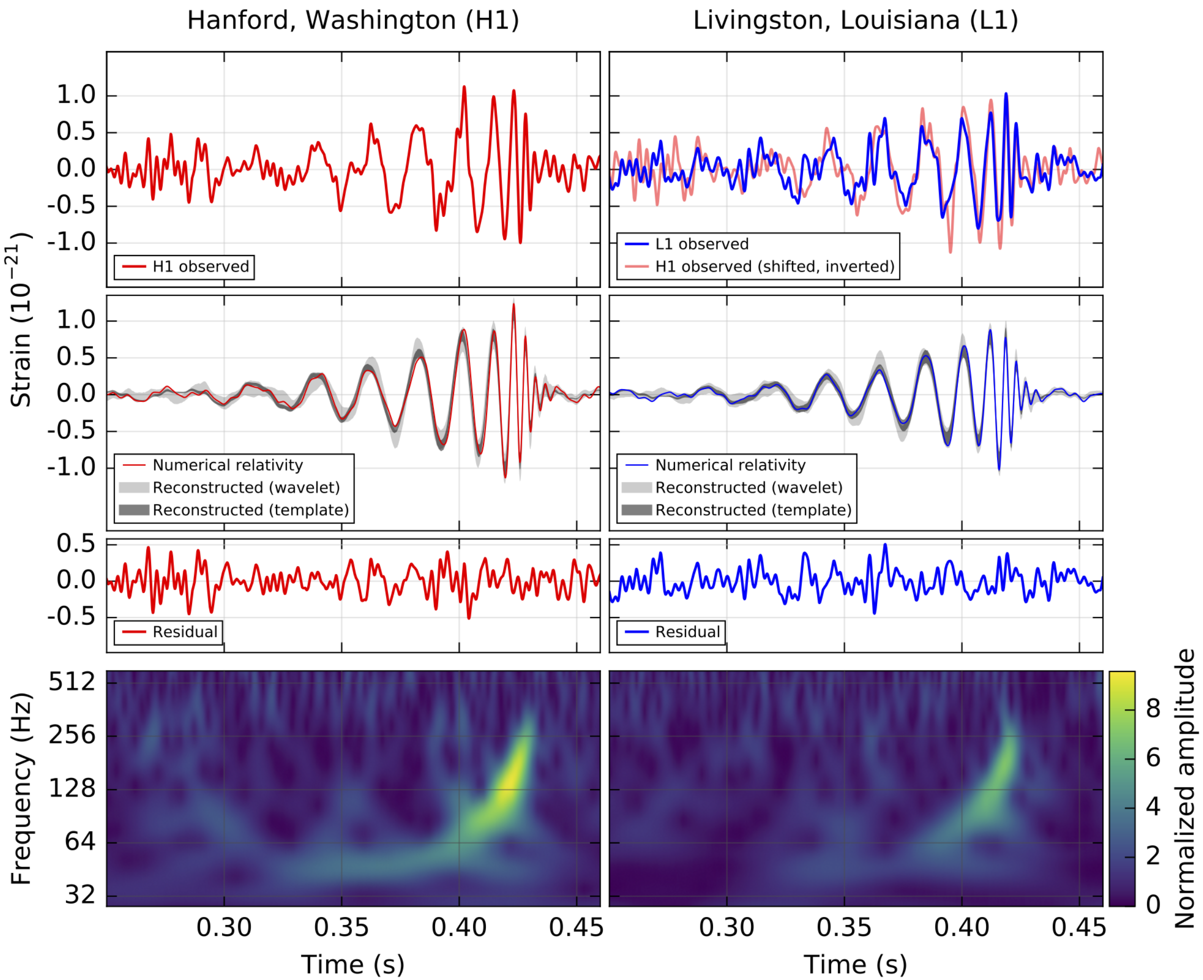








The first direct detection of gravitational waves (GW)



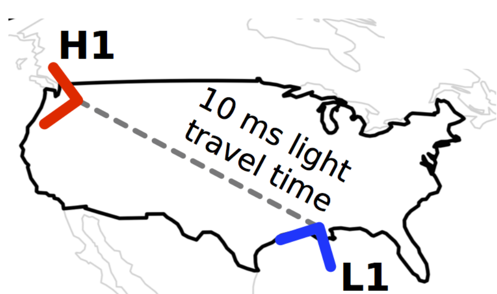
14 Sept 2015, 9h50m45s UTC

Seen in 2 LIGO detectors
with arrival time delay of 7 ms

Signal seen from 30 Hz:
duration **~200 ms**
number of cycles ~10

Peak GW strain: **$1x10^{-21}$**
frequency 150 Hz (λ ~ 2000 km)

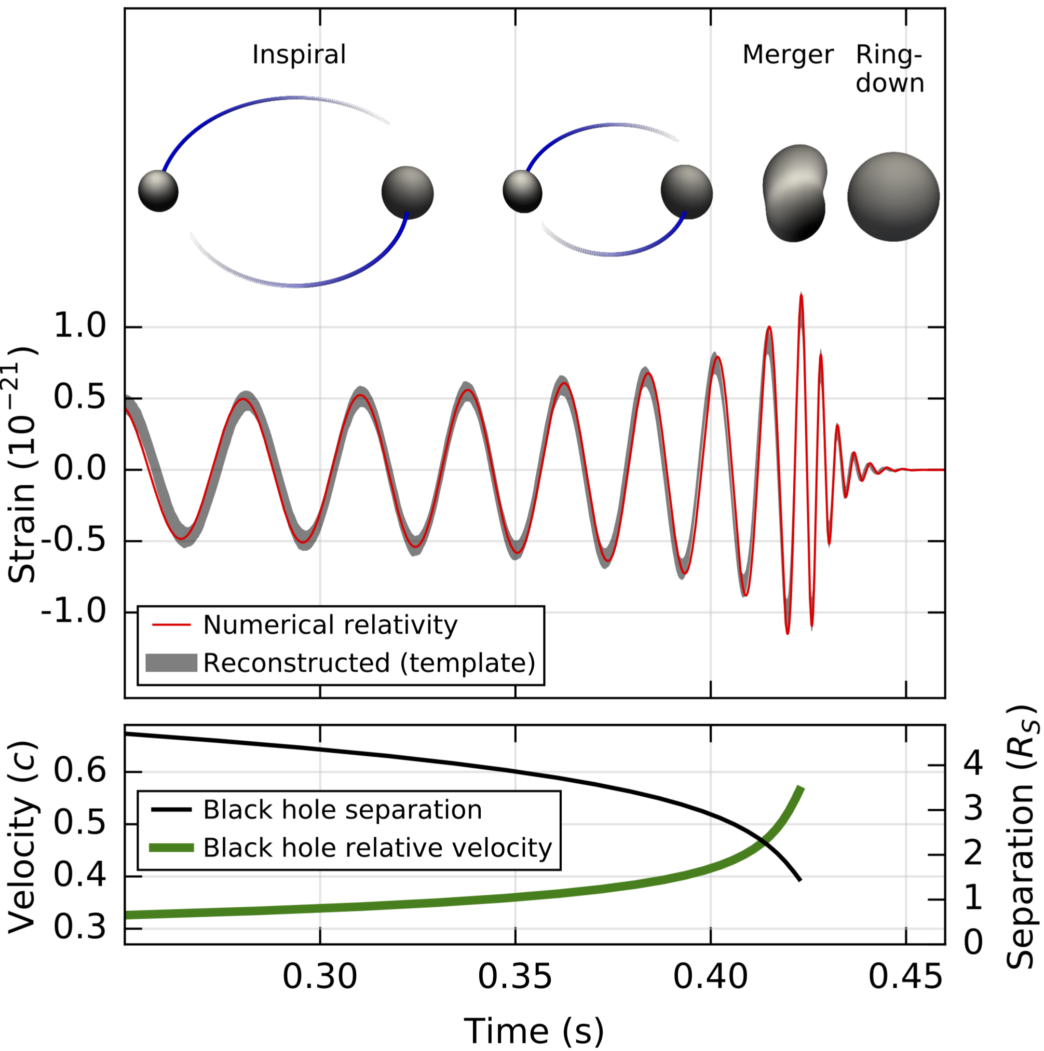
Signal-to-noise ratio: 24
False alarm rate: <1 in 200,000 years

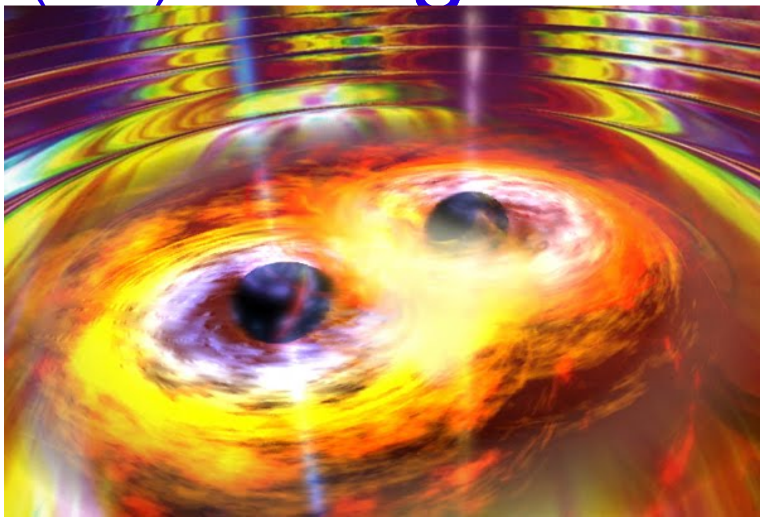


2 detectors in the United-States

GW150914

First observation of a binary black hole (BH) merger





Distance ~1.3×10^9 light-years (z~0.1)

Initial black holes (total mass ~65 $M_\odot$)

~36 $M_\odot$ and 29 $M_\odot$

peak speed of BH's: ~0.6 c

Remnant black hole

mass ~62 $M_\odot$

spin ~70% of maximum

horizon ~ 180 km

Energy radiated into GW (in 200 ms): 3 $M_\odot$

GW150914

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	less than 1 in 5 million
false alarm rate	1 in 200,000 yr
Source Masses	$M_\odot$
total mass	65
chirpmass	28
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	62
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.7
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 $M_\odot$
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	< 1.2×10^{-22} eV
coalescence rate	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameters with a range (e.g. distance) are 90% credible bounds; fractional error on parameters without a range is less than 10%. **Acronyms:** L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46 x 10^{12} km; Mpc=mega parsec=3.2 million

GW151225

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	26 Dec 2015
time	03:38:53 UTC
distance	250 to 620 Mpc
redshift	0.05 to 0.13
signal-to-noise ratio	13
false alarm prob.	~ 1 in 10 million
Source Masses	M⊙
total mass	20 to 28
primary BH	11 to 23
secondary BH	5 to 10
remnant BH	19 to 27
mass ratio	> 0.28
spin of one of the black holes	> 0.2
remnant BH spin	0.7 to 0.8
resolved to	~850 sq. deg.

duration from 35 Hz	~1 s
# cycles from 35 Hz	~55
signal arrival time delay	arrived in H1 1 ms after L1
peak GW strain	~ 3.4 x 10^{-22}
peak displacement of interferometers arms	~ ±0.7 am
frequency/wavelength at peak GW strain	420 Hz, 710 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	2 to 4 x 10^{56} erg s^{-1}
radiated GW energy	0.8-1.1 M⊙
remnant ringdown freq.	~ 750 Hz
remnant damping time	~ 1.3 ms
remnant size, area	60 km, 3.5 x 10^4 km^2
online trigger latency	~ 67 s
# offline analysis pipelines	2

Parameter ranges correspond to 90% credible bounds. **Acronyms:** L1/H1=LIGO Livingston/Hanford; Mpc=mega parsec=3.2 million lightyear, am=attometer=10^{-18} m, M⊙=1 solar mass=2 x 10^{30} kg