# High Energy Messengers from the non-thermal Universe: from Gravitational Waves to the electro magnetic spectrum

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# Outline

# Einstein equations and their linearization

Gravity is responsible for attraction (Newtonian force) and waves (radiation) much like as electromagnetism

- Electromagnetism $A_\mu$, $\mu \in (0..3)$
  1. 1 Coulomb degree of freedom, constrained by sources
  2. 2 radiative d.o.f.
  3. 1 gauge d.o.f.
- Gravity $g_{\mu\nu}$, symmetric 2-tensor, 10 components
  1. 4 constrained degrees of freedom
     (Newtonian potential + General Relativistic generalisations)
  2. 2 radiative d.o.f.
  3. 4 gauge d.o.f.

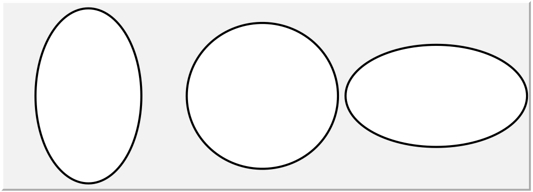
1&3 propagate with "the speed of thought" (Eddington '22)

# GW polarisations

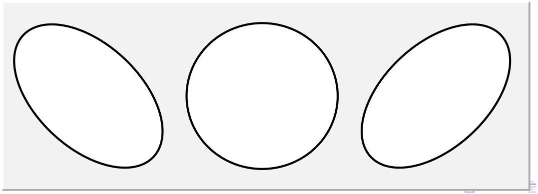
Gauged fixed metric after discarding $h_{0\mu}$ components, which are not radiative: transverse waves

$$h_{ij} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$h_+$



$h_\times$



# Outline

# The LIGO and Virgo observatories

Observation run O1 Sept 12th '15 - Jan 19th '16

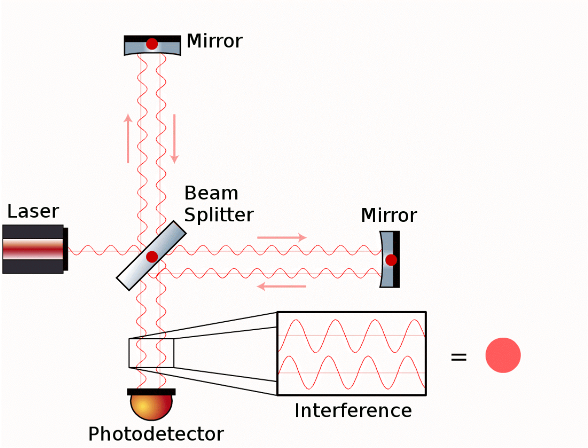
O1 data, $\sim$ 130 days, with 49.6 days of actual data, PRX (2016) 4, 041014, 2 detectors

O2 is currently on-going, Dec. '16 $\sim$ Sept '17 data analysis will be published soon after

O3, 3 detectors, foreseen to start in Aug 2018, last $\sim$ 1yr

In 2020+ Japanese KAGRA and Indian INDIGO will join the collaboration

# A very precise ruler




Light intensity $\propto$ light travel difference in perpendicular arms
Effective optical path increased by factor $N \sim 500$ thanks to Fabry-Perot cavities

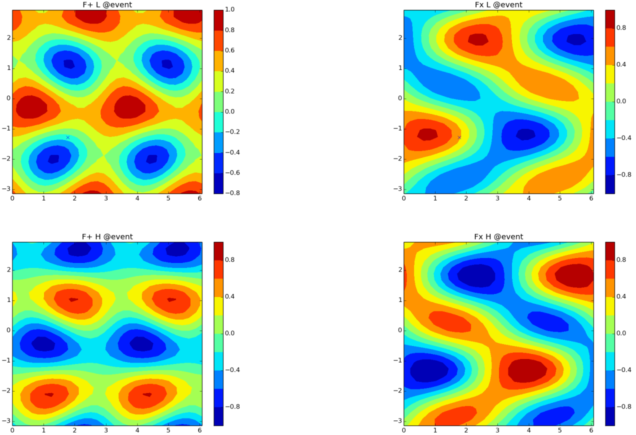
Phase shift $\Delta\phi \sim 10^{-8}$ can be measured $\sim 2\pi N \Delta L/\lambda \rightarrow \Delta L \sim 10^{-15}/N$ m

# Almost omnidirectional detectors

$h_{det} =$ $h_+ F_+$ $h_\times F_\times$

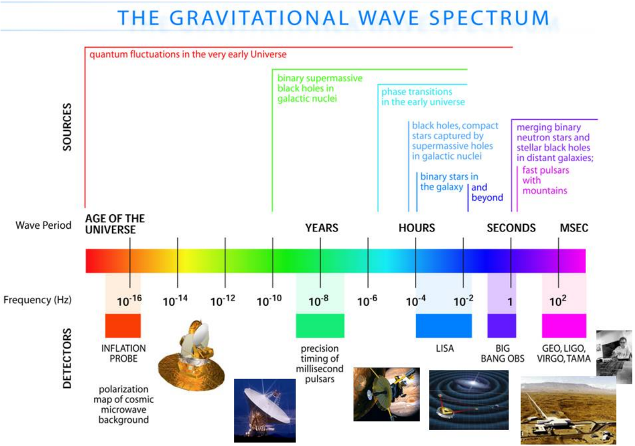
$F_{+,\times}$ L

$F_{+,\times}$ H




$h_{+,\times}$ depend on source, $F_{+,\times}$ on relative orientation source/detector

# GW across the spectrum




A xylophone of GW detectors

http://www.astro.gla.ac.uk/users/martin/powersof60/future.html

# Outline

# Astro sources emitting transient GWs/EM radiation

- Coalescing binary systems of compact objects $M_c \equiv (m_1 m_2)^{3/5} M^{-1/5} \equiv \eta^{3/5} M$

$$\Delta E_{GW} \sim 4 \times 10^{-2} M_\odot \left(\frac{M_c}{1.2 M_\odot}\right)^{5/3} \left(\frac{f_{max}}{1\,\mathrm{kHz}}\right)^{2/3}$$

  A good proxy of the $f_{max}$ is the Innermost Stable Circular Orbit frequency

$$f_{ISCO} = \frac{1}{6\sqrt{6}} \frac{1}{M} \simeq 2\mathrm{kHz} \left(\frac{M}{M_\odot}\right)^{-1}$$

  For NS-BH ejected material supposed to produce short ($< 2$ sec) GRBs
  $E_\gamma \sim$keV-MeV, ejected sub-relativistic material may produce radio signals
  $\nu$: baryon loaded jets may emit $\nu$s: TeV-PeV $\nu$s @ $\gamma$ emission; PeV-EeV $\nu$ @ optical afterglow
- Core-collapse of massive stars, $10^{-8} \lesssim E_{GW}/M_\odot \lesssim 10^{-5} \to$ long GRBs
  $\nu$: low energy $\nu$s ( 10 MeV) emitted, e.g. by SN1987A
- isolated neutron star with sudden energy release
  E.g. star-quakes exciting non-radial modes $10^{-16} \lesssim E_{GW}/M_\odot \lesssim 10^{-6}$
  possibly $\to$ soft $\gamma$ repeaters emitting repetitive flares (0.1 sec, $10^{42}$-$10^{47}$ erg/sec)
  $\nu$: sudden magnetic re-configuration can produce high-energy $\nu$s

M. Branchesi JoP Conf. Ser. (2016)

# Wave generation: localised sources

Einstein formula relates $h_{ij}$ to the source quadrupole moment $Q_{ij}$

$$Q_{ij} = \int d^3x\rho\left(x_ix_j - \frac{1}{3}\delta_{ij}x^2\right) \qquad v^2 \simeq G_N M/r$$
$$h_{ij} = \frac{2G_N}{D}\frac{d^2Q_{ij}}{dt^2} \simeq \frac{2G_N\mu v^2}{D}\cos(2\phi(t))$$

$$f = 2\mathrm{kHz}\left(\frac{r}{30\mathrm{Km}}\right)^{-3/2}\left(\frac{M}{3M_\odot}\right)^{1/2} < f_{Max} \simeq 12kHz\left(\frac{M}{3M_\odot}\right)^{-1}$$
$$v = 0.3\left(\frac{f}{1\mathrm{kHz}}\right)^{1/3}\left(\frac{M}{M_\odot}\right)^{1/3} < \frac{1}{\sqrt{6}}$$

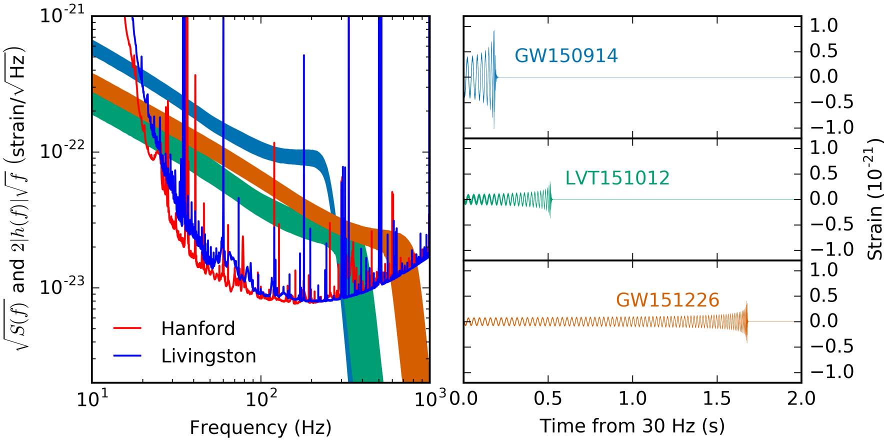
Geometric factor to keep account of transversality projection
(angular momentum L of the binary, observation direction $N$)

$$h_+ \propto (1+\cos^2(\theta_{LN}))/2$$
$$h_\times \propto -\cos(\theta_{LN})$$

No direction for which emission vanishes: quadrupolar motion is bi-dimensional $\rightarrow$
not all motion components can be collinear ($\theta_{LN} \sim \pi/2$) with $N$

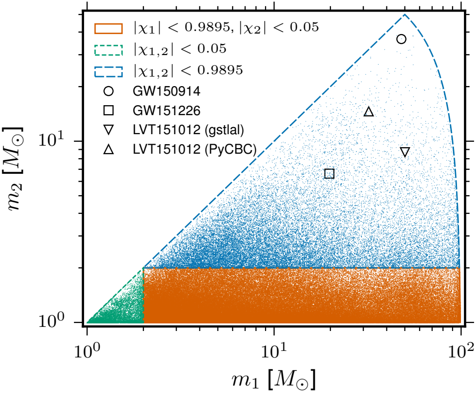
(unlike dipolar motion for the electromagnetic case)

# The 2 confirmed GW events + 1 candidate trigger




LIGO/Virgo PRX (2016) 4, 041014

# Template Bank

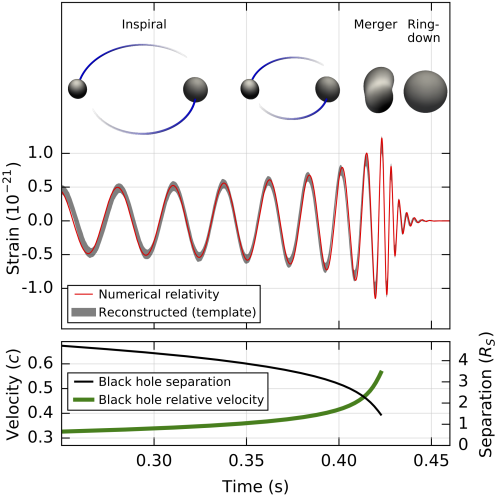



Bank with over 200k templates is prepared, matched-filtering computed against all wfs.
Spin somehow neglected for low masses (anyway non-precessing) because

- astrophysically spin of neutron stars $\chi \equiv |Spin|/m^2 < 0.1$
- impractical as number of templates would explode!

LIGO/Virgo PRX (2016) 4, 041014

# The signal




LIGO/Virgo PRL 116, 061102 (2016)

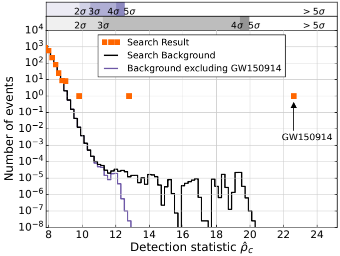
# Could have it happened by chance?

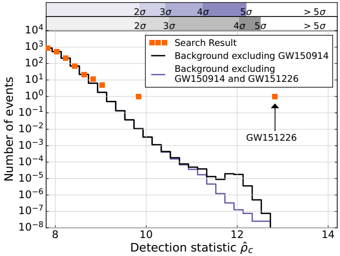
Given the high number of trials ($\sim$ 250$k$ templates) in correlating with data, check needed for random coincidences

False alarm rate estimated by counting coincidences between the two detectors with time-shifted data coincidences at delay $\gtrsim$ 10$msec$ are not GWs

# coincidences at amplitude $\rho_c > 12$ / # shifts $\sim 10^{-8}$

LIGO/Virgo PRX (2016) 4, 041014

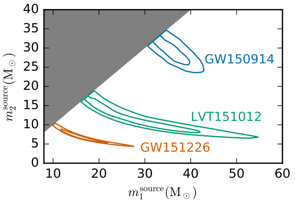


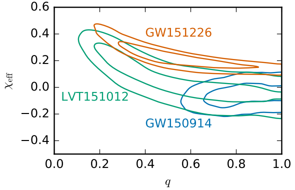



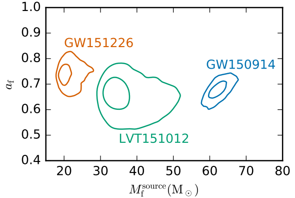

False alarm rate for GW events: $<$ 1/200,000 yrs!

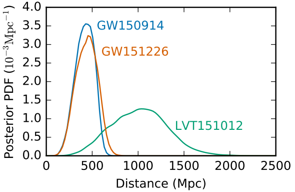
# What constraints on masses/spin/distances magnitudes?

Mass uncertainties $\gtrsim 10\%$ @ 90% C.L.




$$h_+ \propto (1+\cos^2(\theta_{LN}))/2$$

$$h_\times \propto -\cos(\theta_{LN})$$

Spin magnitude $\chi_{eff}||L$

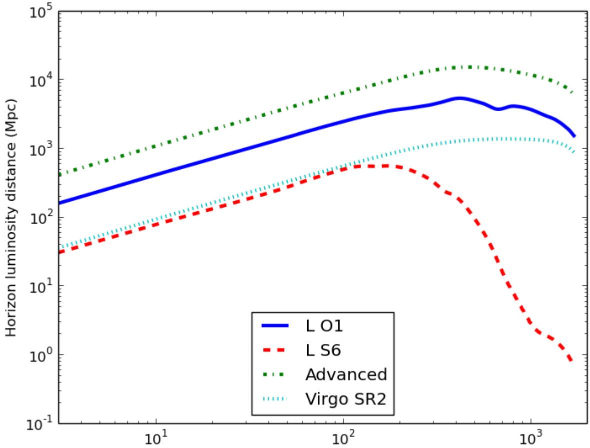
$$\chi_{eff} \equiv \left(\frac{S_1}{m_1}+\frac{S_2}{m_2}\right)\cdot\frac{L}{M}$$

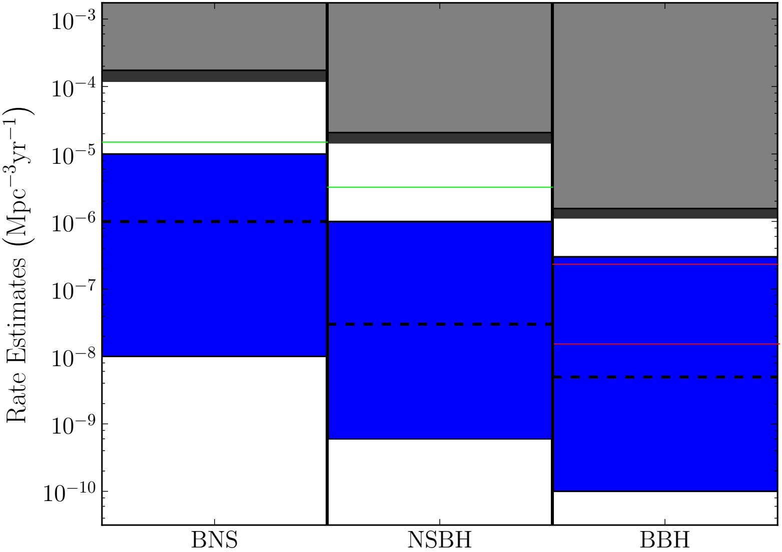
LIGO/Virgo PRX (2016) 4, 041014

# Horizon distances vs. rate estimation

$9 < \text{Rate}_{BH-BH} \ /(Gpc^3 yr) < 240$ Galaxy density $\sim 2 \times 10^7 / Gpc^3$

LIGO/Virgo PRL 116 (2016)






Astro predictions, upper bounds from science run5/6/O1 and measure from O1.

LIGO/Virgo CQG (2010) 27 173001, PRX (2016) 4 041014, APJ (2016) 832

# Outline

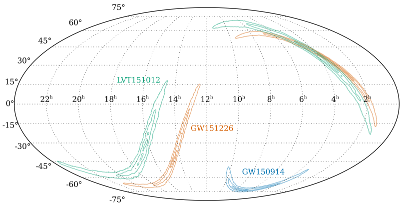
# EM counterparts of binary coalescences

Binary coalescences involving a neutron star can give rise to energetic outflows at different timescale/wavelength

- Relativistic jet $\rightarrow$ prompt short $\gamma$-ray burst (GRB) duration $\lesssim 1$ sec followed by $X$, optical, radio afterglows (hrs $-$ days)
- Rapid neutron capture in the sub-relativistic ejecta can produce a kilonova or macronova, with optical and near-infrared signal (hours - weeks)
- Eventually radio blast from sub-relativistic outflow (months to years) Several seconds prior to or tens of minutes after merger, coherent radio burst lasting milliseconds may be emitted

LIGO/Virgo + EM partners ApJ Let. 2016

# Where do they come from?




LIGO/Virgo PRX (2016) 4, 041014

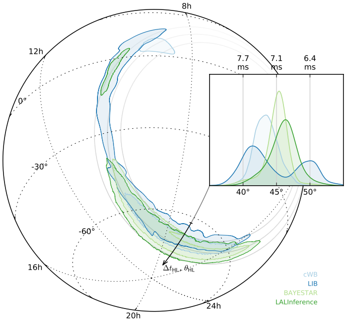
Arrival direction estimated from time delays (and amplitude modulation)
Triangulation will allow a better sky localisation
(down to $\sim$ few$^{o2}$ with $>$ 3 detectors)
GW vs. EM $\leftrightarrow$ time vs. space localisation

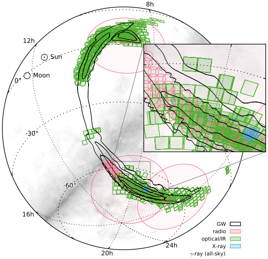
# EM analysis of GW150914, ApJ. L. 2016

74 groups with space/ground facilities for a joint EM-LIGO/Virgo program: 63 in O1

Detailed GW sky map (masses) not promptly available: accurate analysis requires time!

Mass range → distance → galaxy localisation




"Tiling" by EM observatories

Accurate mass (sky reconstruction) sent out 20 (120) days after event:

No candidate found: stellar BBH $\not\to$ EM/$\nu$

(density and magnetic fields typical of interstellar medium)

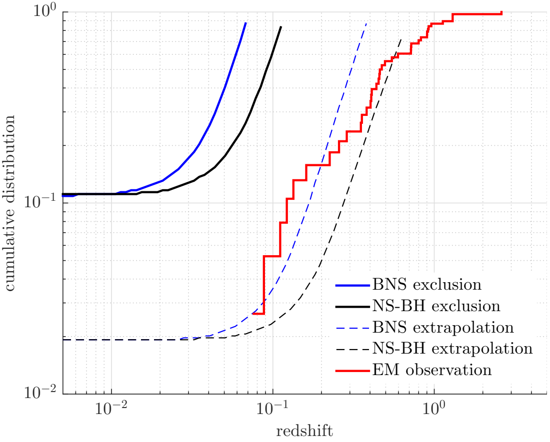
# EM partners analysis

25 teams spanning 19 order of magnitude in wave-length with a variety of coverage of the 600 deg$^2$ of the sky map:

- $\gamma, X$ observatories: complete coverage down to $10^{-9}$erg/(cm$^2$s) minimal flux $10^{-13} - 10^{-11}$ by SWIFT XRT ($\sim$keV, 5 deg$^2$)
- optical tiled jointly 900 deg$^2$.
  GW Range for a NS-BH $\sim$ 70 Mpc: GRB would have been detectable at that distance and similar depths in optical and IR bands (app. magnitude 17-24)
- near infrared, radio: wide fields down to mJy flux densities, narrow-field VLA could identify localised radio transient down to $\mu$Jy ($f \gtrsim$ GHz)

LIGO/Virgo + EM partners ApJL 2016

# Verify association with 20 short GRB during O1

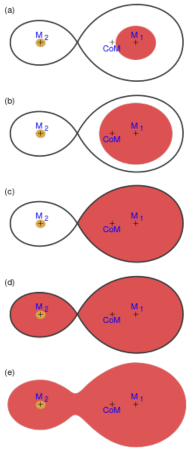



GW searched in a [-5,+1) sec window with GRB

GW constraints far from EM exclusion distance, but extrapolation to design Advanced LIGO sensitivity (2 years of data) will lead to detection/non-trivial constraints

LIGO/Virgo arXiv:1611.07947, APJ in press

# How GW150914/GW151226 progenitors formed? I




Izzard et al. Proc. IAU 2012

Isolated binary in galactic field
A binary system of massive stars ($M_{binary} \sim 100 M_{odot}$) can go through a common envelope phase that shrinks considerably the orbit and align the spins $\rightarrow$ collapse to black holes
Lower metallicity $\rightarrow$ lower star mass loss

Belczynski et al. Nature 2016

vs.

# How GW150914/GW151226 progenitors formed? II

Globular Cluster: medium with high density of black holes/stars, when 3 black holes meet one is ejected and the binary shrinks

T. Hartwig et al. arXiv:1603.05655

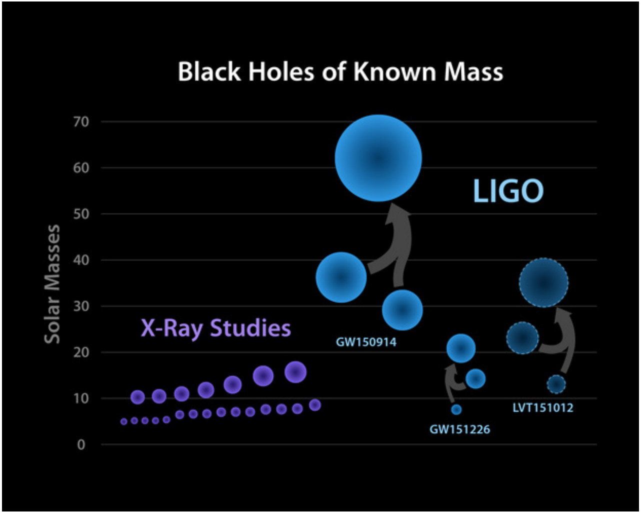
Remnants of the first stars, produced at $z \sim 6$ can give only a small contribution to the total rate

Primordial black-holes? viable if $10^{-2} \lesssim M_{BH}/M_{\odot} \lesssim 1$ (constraints from evaporation, microlensing and CMB) but could grow later to 20-100 $M_{\odot}$ by merger

If present in globular cluster may also explain their cosmological abundance as dark matter

Sasaki M. et al. PRL 2016, Bird S. et al. PRL 2016, Clesse S. and García-Bellido Phys. Dark Univ. 2017

# Black holes of known mass




New astronomical era ahead of us!

# Outline

# Measuring $H_0$

Coalescing binary systems are standard sirens:

$$h(t) = \frac{G_N \eta M^{5/3} f_s^{2/3}}{D} \cos\left[\phi(t_s)\right]$$

In cosmological settings source and observer clocks tick differently:

$$dt_o = (1+z) dt_s \qquad f_o(1+z) = f_s$$

$$h(t_o) = \frac{G_N \eta f_o^{2/3} M^{5/3} (1+z)^{2/3}}{a(t_o) D} \qquad \cos\left[\phi(t_s(t_o))\right]$$

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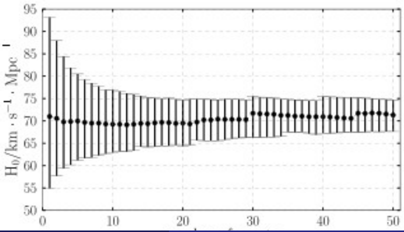
$$\phi(t_s/M) = \phi(t_o/M(1+z)) \implies$$
$$\phi\left(t_o/\mathcal{M}\right) = \phi\left(t_s/M\right) \qquad \mathcal{M} \equiv M(1+z)$$

Hubble law: $z = H_0 d_L$

$D_L$ can be measured, $z$ degenerate with $M$, however if

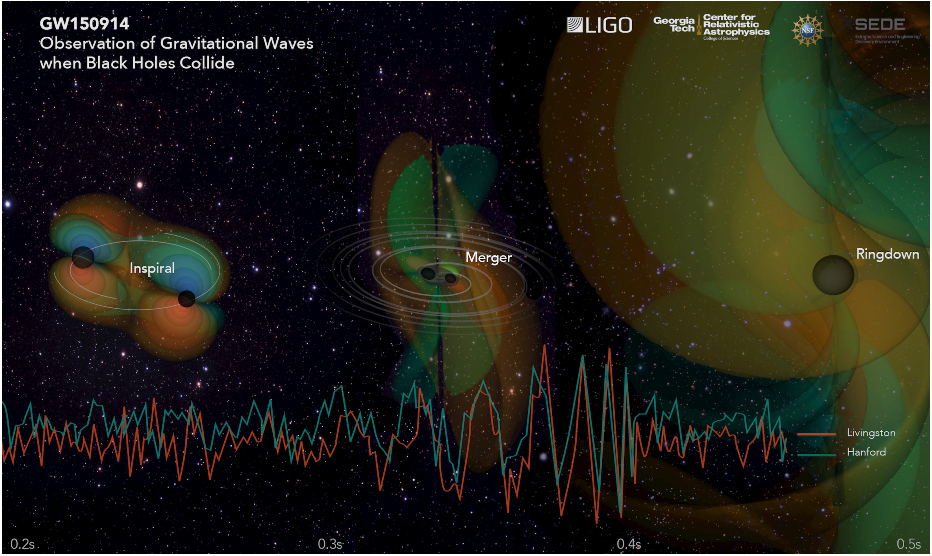
- the source in the sky has been localised $(\alpha, \delta)$
- GW sources are in the galaxy catalogue with known red-shift

$$P(z, D_L|c_i) = \int d\mathcal{M}\, d\vec{\theta}\, d\alpha\, d\delta\, P(D_L\mathcal{M}, \vec{\theta}, \alpha, \delta|c_i)\pi(z, |\alpha, \delta)$$




Schutz, Nature (1986) 323 310

W. Del Pozzo, Phys.Rev.D86 (2012) 043011


GW150914
Observation of Gravitational Waves
when Black Holes Collide
LIGO
Georgia Tech
Center for Relativistic Astrophysics
NSF
SEDE
Inspiral
Merger
Ringdown
Livingston
Hanford
0.2s
0.3s
0.4s
0.5s

# Extra slides