The dawn of gravitational-wave astronomy

Graham Woan

SUPA School of Physics & Astronomy
University of Glasgow

LIGO-G1601077-v2

The LIGO detectors

The 'Event'

- Online burst analysis reported a loud simultaneous trigger in both LIGO detectors on 14th September 2015, consistent with a high-mass binary black hole (BBH) merger.

- Instrument configuration frozen until 20th October to collect 16 days-worth of coincident data from the two detectors (to compute a background)

GraceDB Processor — September 14, 2015 5:54 AM
To: klimenko@phys.ufl.edu , reed.essick@ligo.org , Marco Drago — Details
action required for GraceDB event : G184098 (burst_cwb_allsky) — Inbox - UF exchange

```
action required for GraceDB event : https://gracedb.ligo.org//events/view/G184098
(burst_cwb_allsky)
cwb_eventcreation
```

Marco Drago — September 14, 2015 6:54 AM
To: <burst@sympa.ligo.org> and 8 more… — Details
[CBC] Very interesting event on ER8 — Inbox - UF exchange

```
Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098
```

Sergey Klimenko — September 14, 2015 7:15 AM
To: <emfollow@ligo.org> , Peter Shawhan and 2 more… — Details
Fwd: action required for GraceDB event : G184098 (burst_cwb_allsky) — Sent - UF exchange

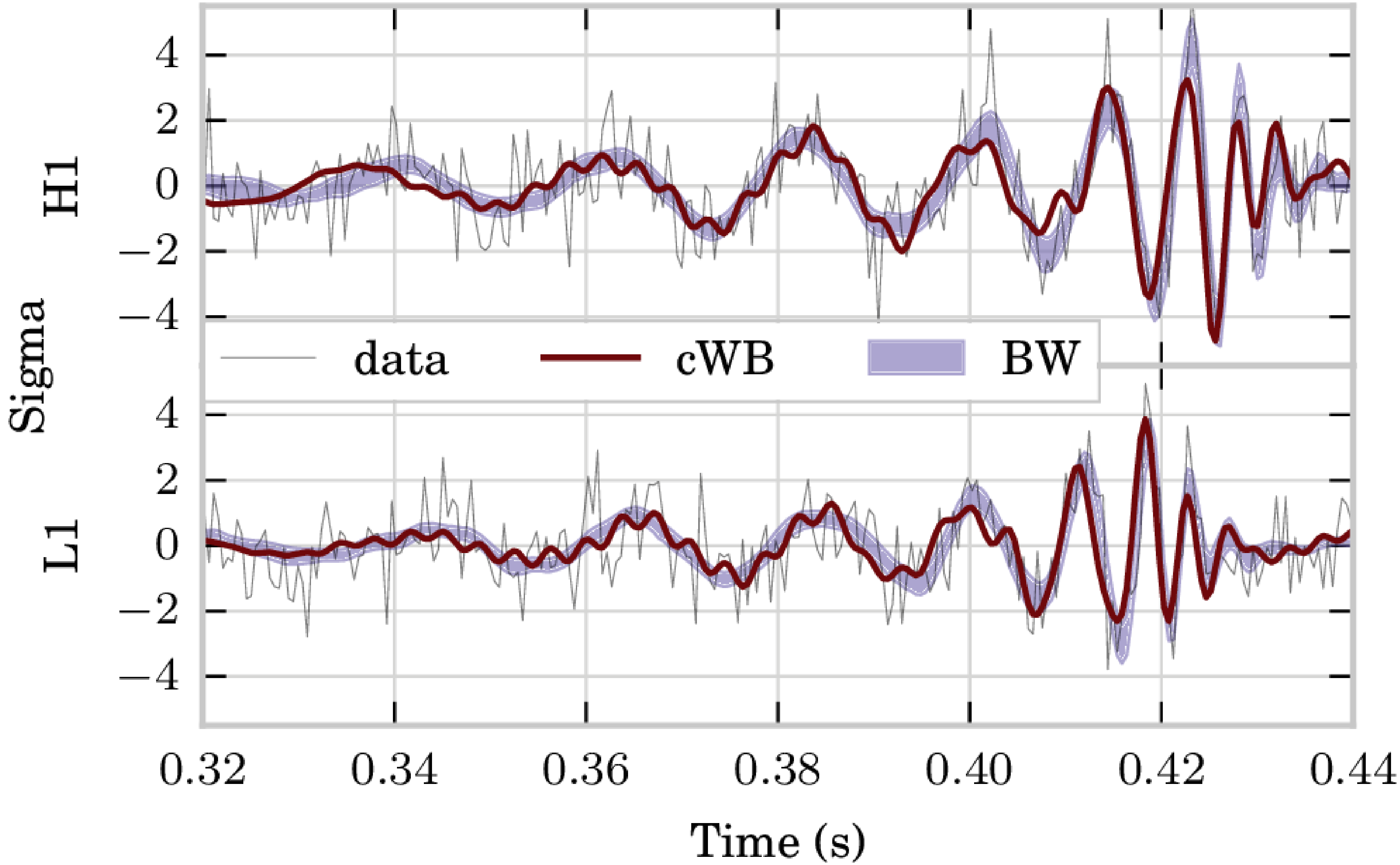
```
Why this event has been rejected by IDQ! -
this is a nice inspiral with Mchirp = 27 Mo.
Sergey.
```

Sergey Klimenko — September 14, 2015 8:06 AM
To: <burst@ligo.org> , Cc: calibration@ligo.org and 7 more… — Details
Re: Re: [burst] [calibration] Very interesting event on ER8 — Sent - UF exchange

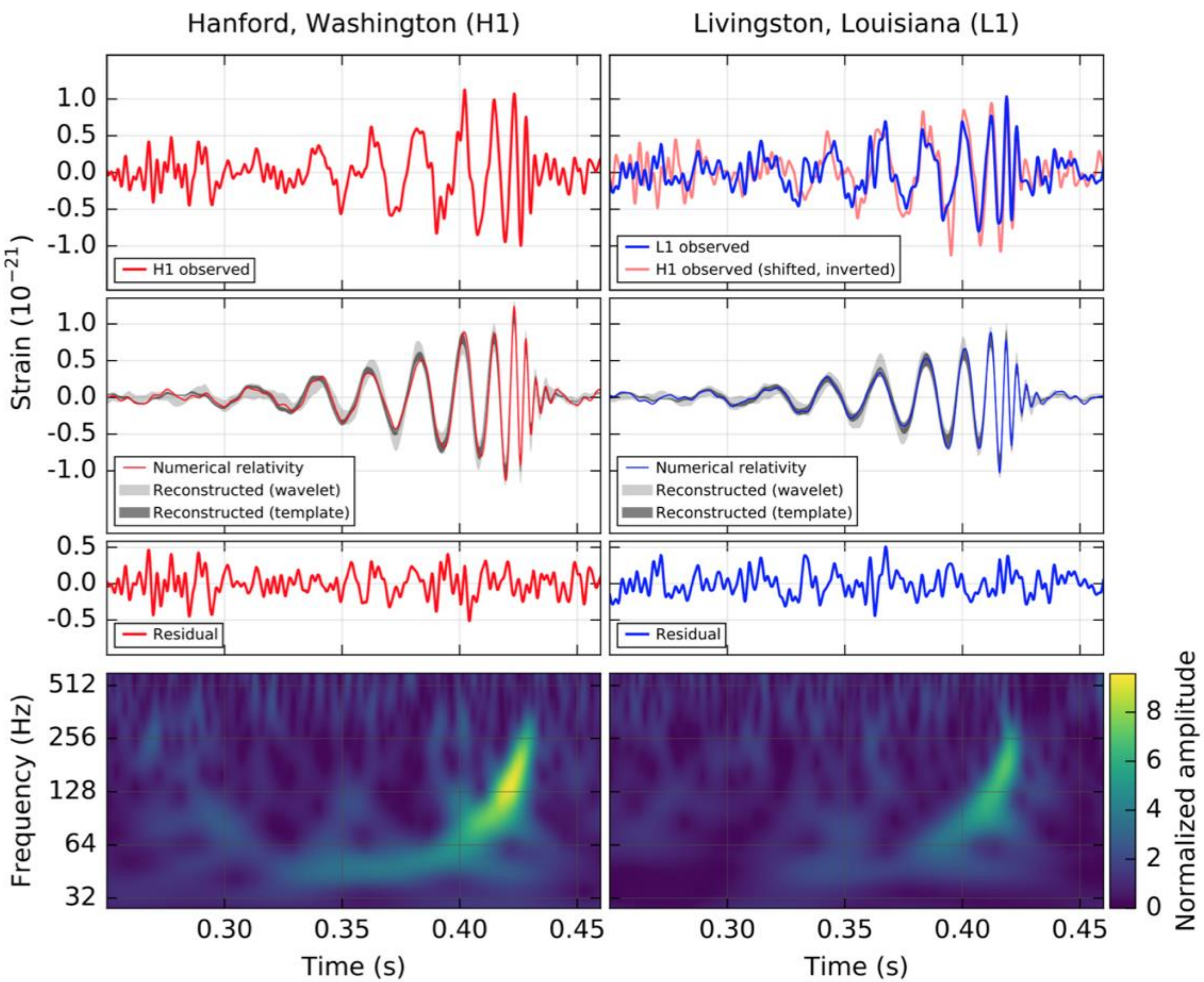
```
This is clean and very significant inspiral with Mchirp = 27 +- 2 Mo.
The polarization is close to circular.
The cWB ER8 offline analysis accumulated ~236 years of background
so far - this event FAR << 1.e-10 Hz. If this is not injection,
I guess, we need to do the detection checklist…
Sergey
```

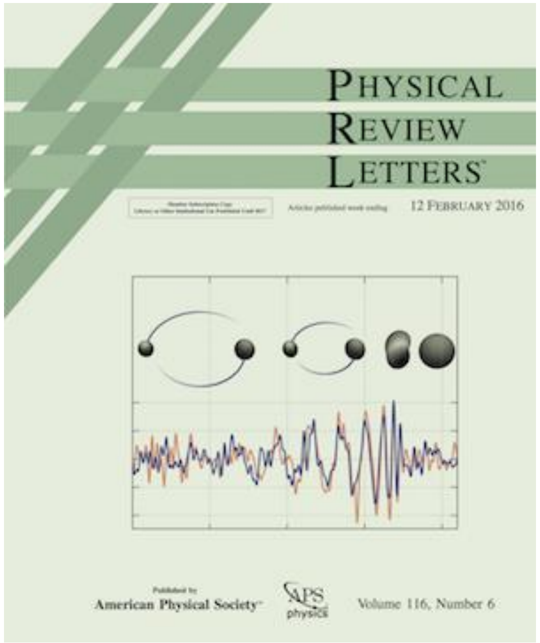
GW150914 – a burst of gravitational waves…

arXiv:1602.03843

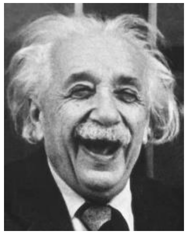


… matching a BBH inspiral and merger waveform from General Relativity





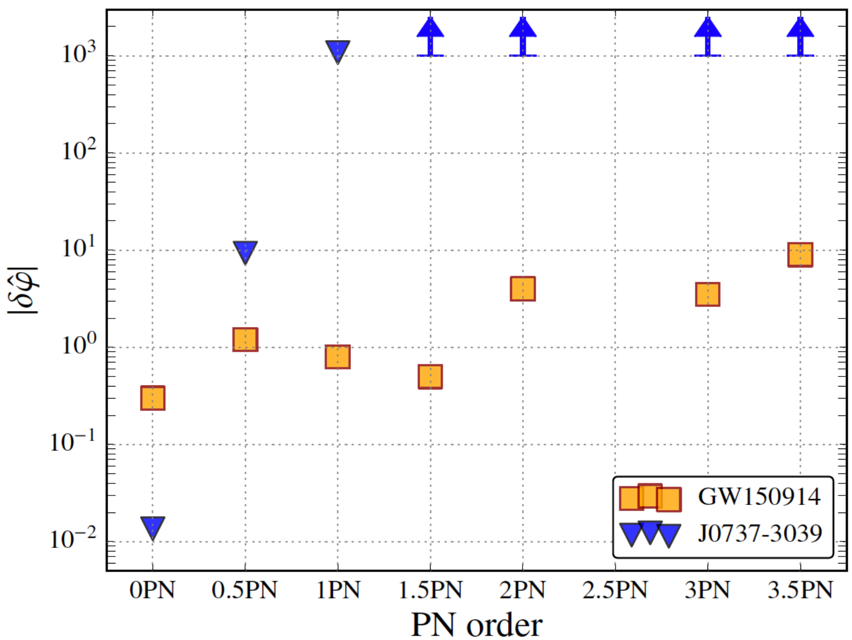
Abbott, et al. ‚LIGO Scientific Collaboration and Virgo Collaboration, 'Observation of Gravitational Waves from a Binary Black Hole Merger'
Phys. Rev. Lett. 116, 061102 (2016)



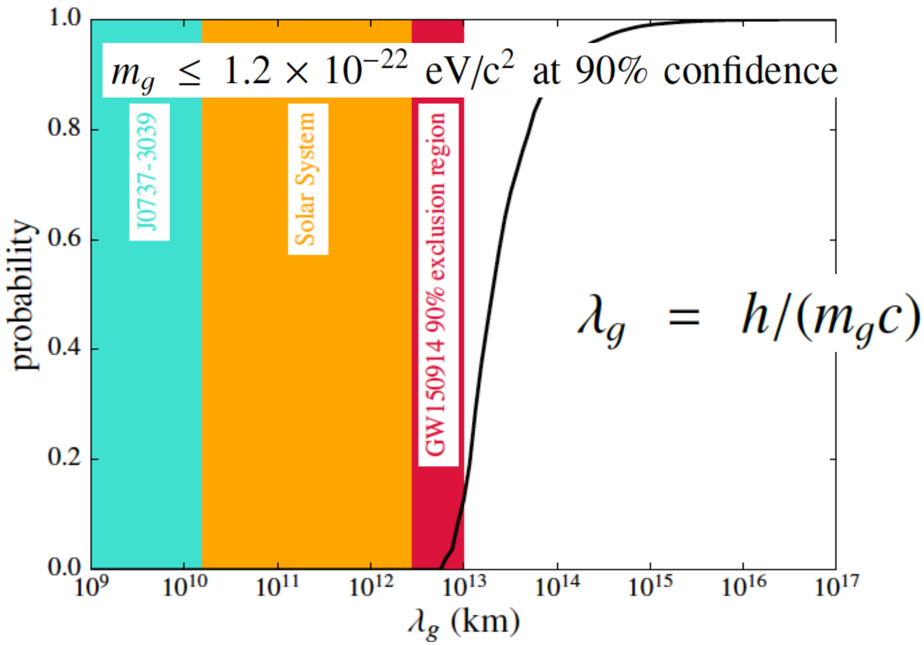
But does General Relativity really fit?

- GW150914 is the first observation of a binary black hole merger
- Our best test of GR in *the strong field, dynamical, nonlinear regime*
- Event better than the binary pulsar system PSR J0737-3039

Post-Newtonian Approximation to GR

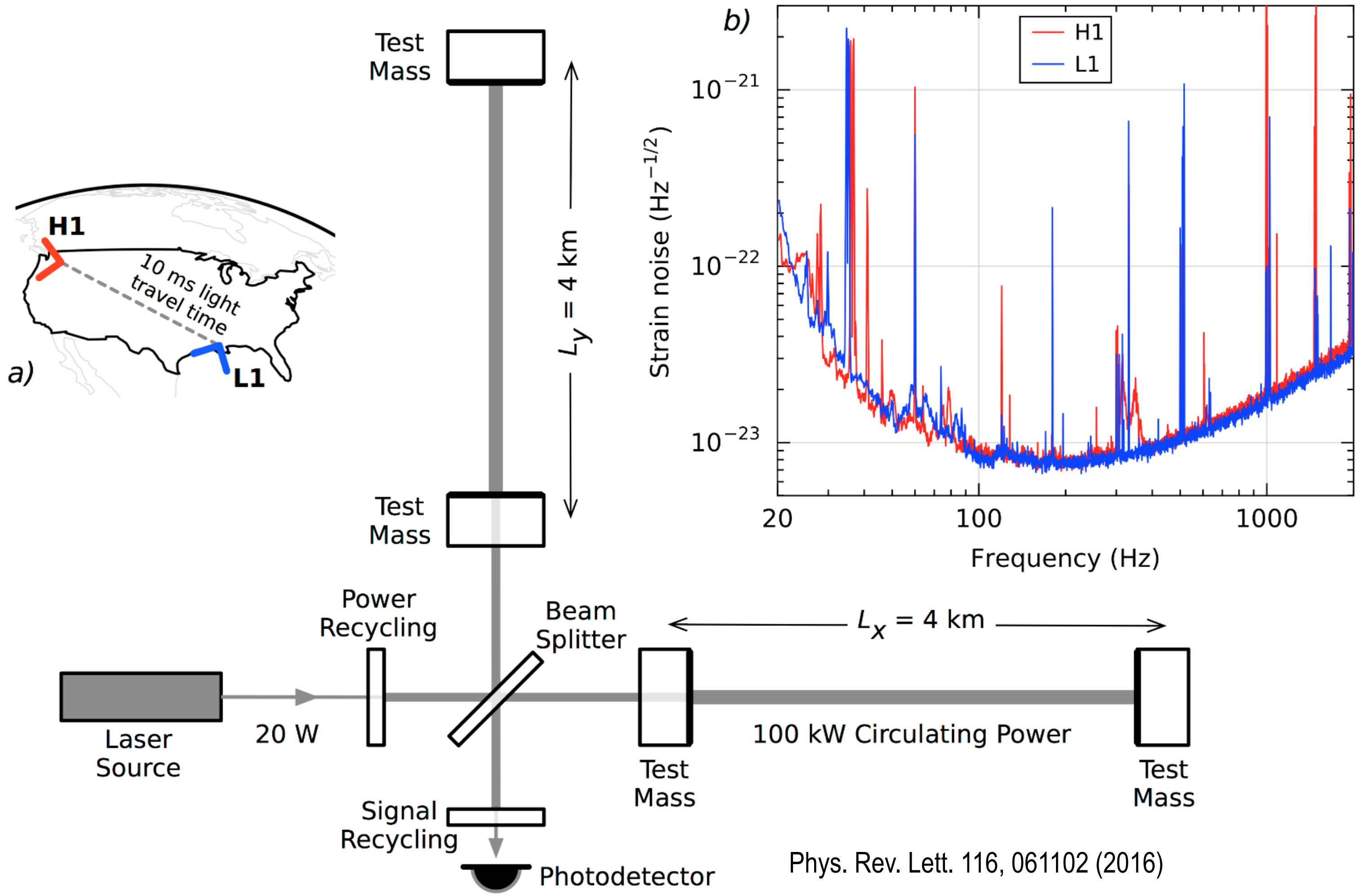


Compton Wavelength of the Graviton



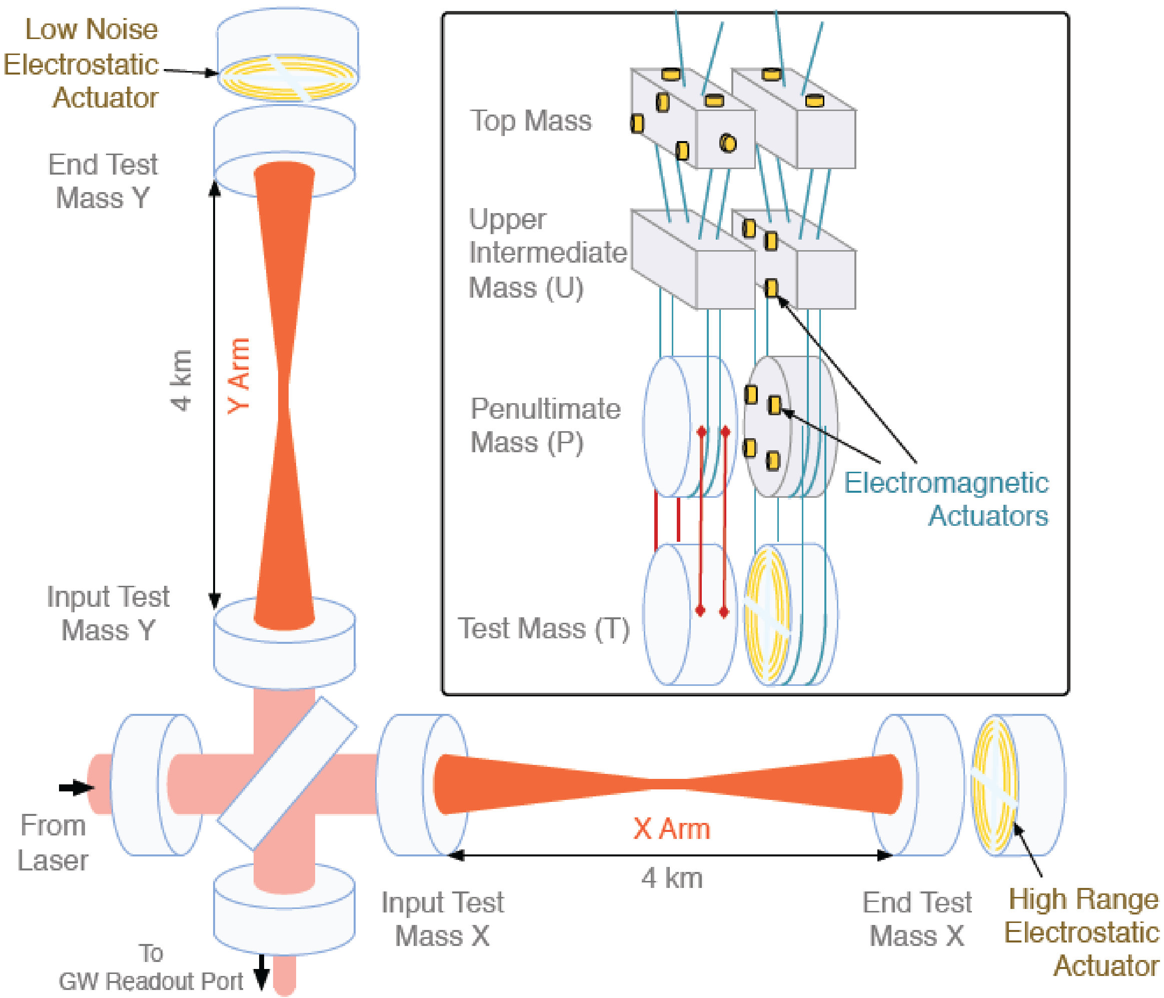
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Tests of general relativity with GW150914”, http://arxiv.org/abs/1602.03841

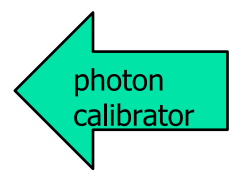
LIGO detectors – first Adv. LIGO run (O1)



Phys. Rev. Lett. 116, 061102 (2016)

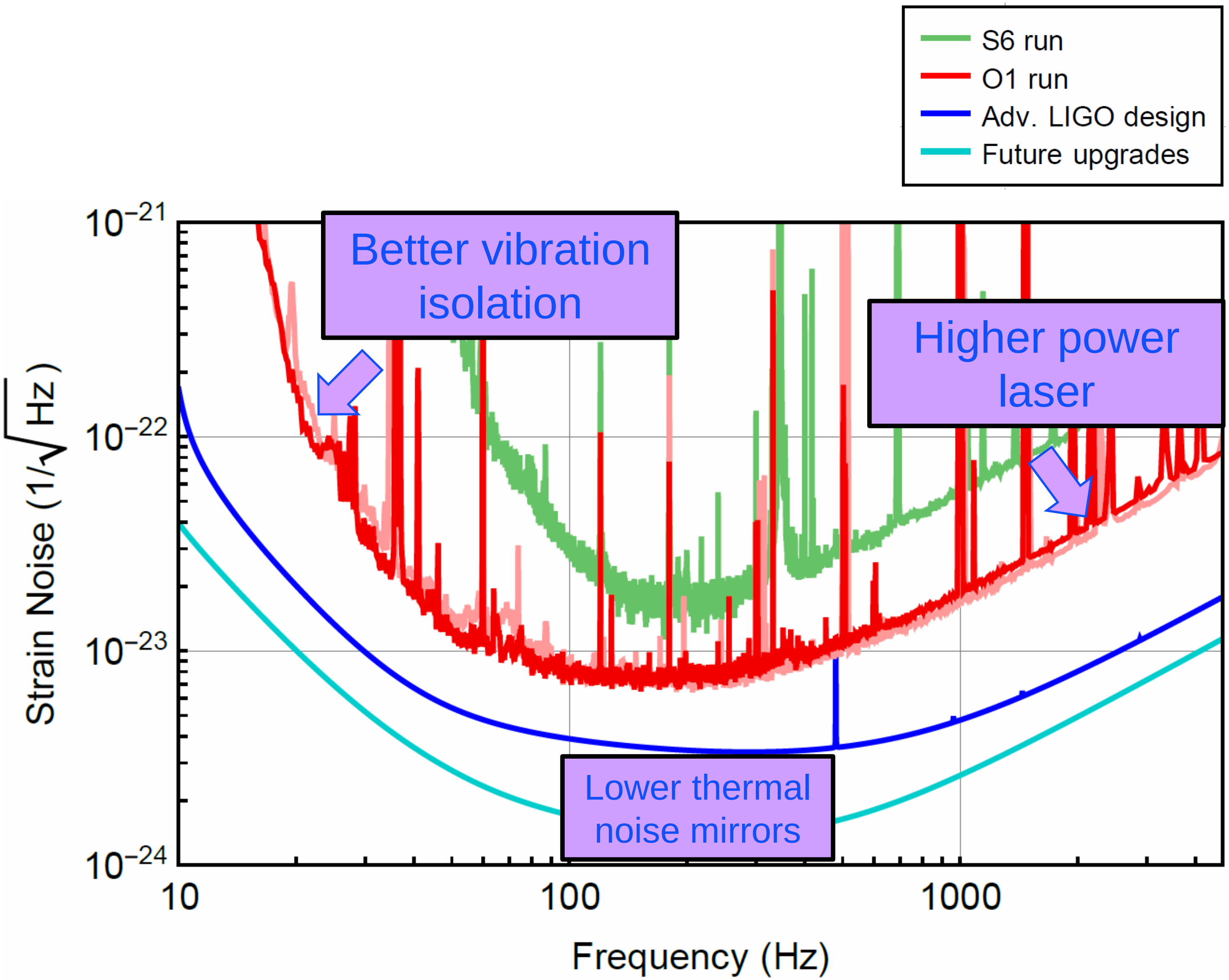
End-mirror quadruple-pendulum suspensions





https://dcc.ligo.org/LIGO-P1500248/public/main

Initial LIGO to Advanced LIGO



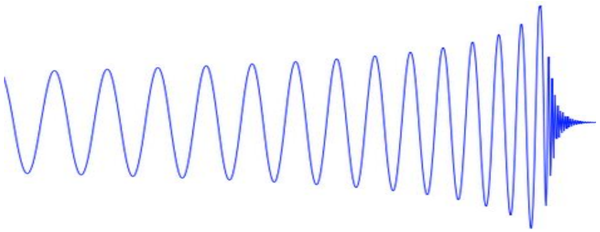
We have a brand-new astrophysical toolbox

- GWs are generated coherently by large accelerated masses, so the amplitudes and phases of these waves are meaningful (i.e., many non-stochastic sources, cf. EM).

- Precision timing observations possible (cf. pulsars)

- Even at leading post-Newtonian order we can derive simple results, e.g. the ‘chirp mass’:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$



  and the full system parameters (masses, spins, distance…) appear at higher orders.

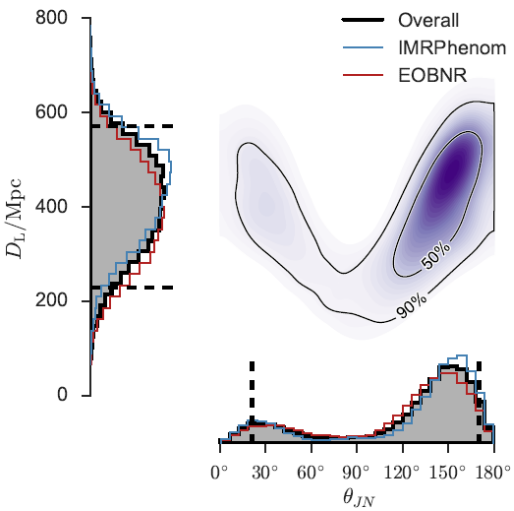
- Chirp shape is sensitive to luminosity distance but not redshift (‘standard sirens’).

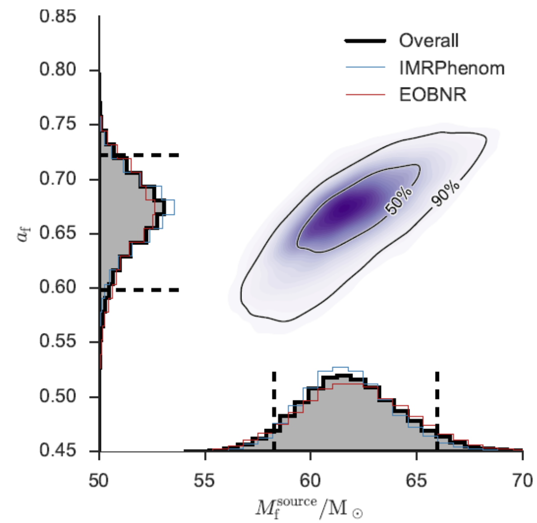
- Fruitful test sites for GR (BH/BH), particle physics (BH/NS, NS/NS, spinning NSs).

- Constraints on extreme equation-of-state, stellar evolution, cosmology …

Parameter posteriors

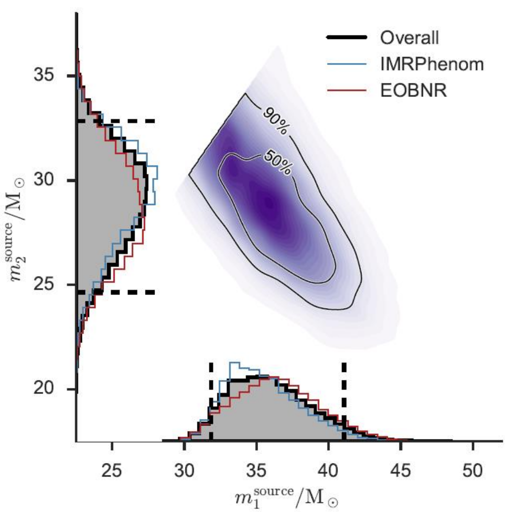
distance vs
orbital inclination

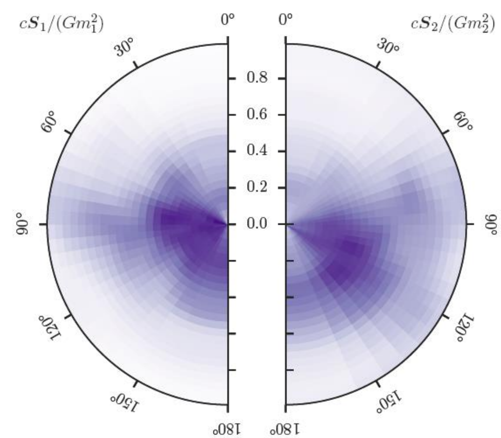




final mass vs
final spin

component mass_1
vs mass_2

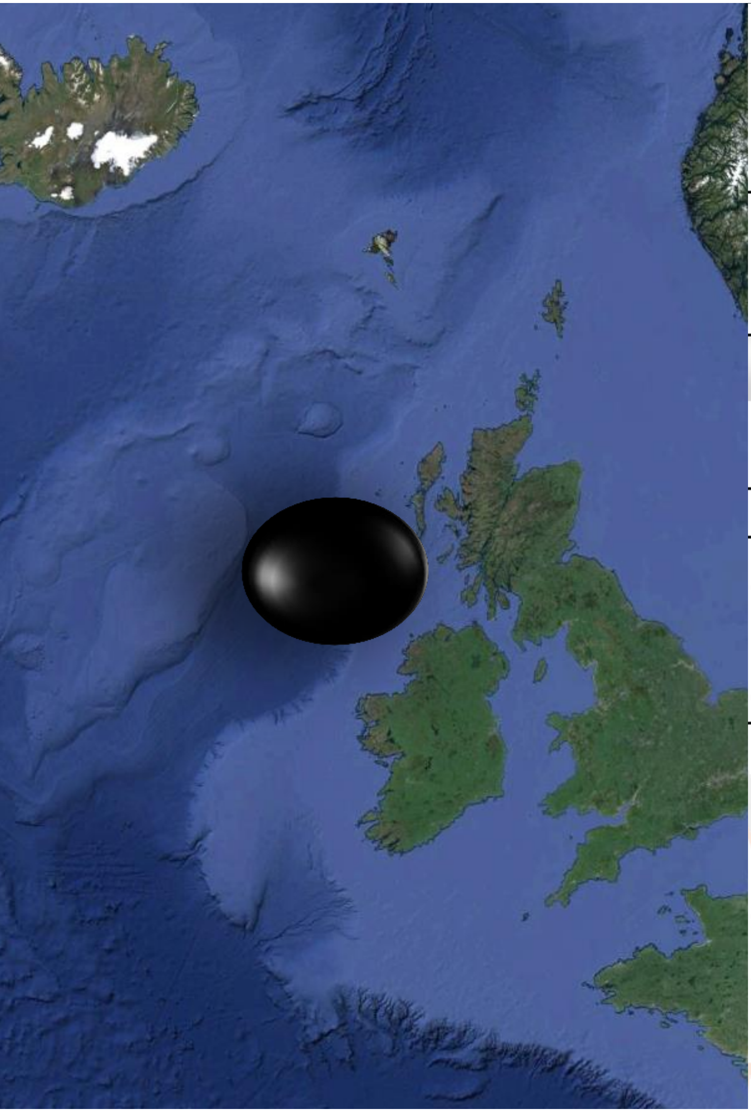




component spins
wrt orbital plane

arXiv:1602.03840

GW150914 results and parameters



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.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
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⊙
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	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	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

https://losc.ligo.org/events/GW150914/

Implications for progenitor stars

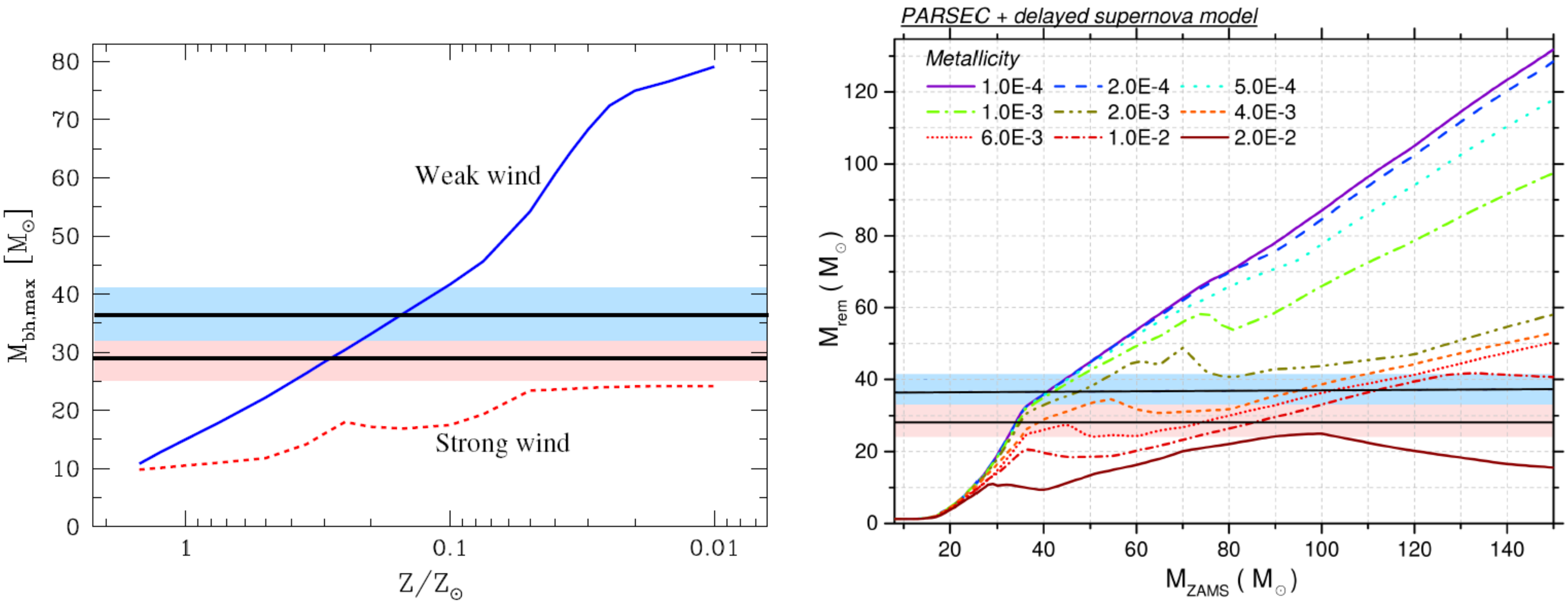
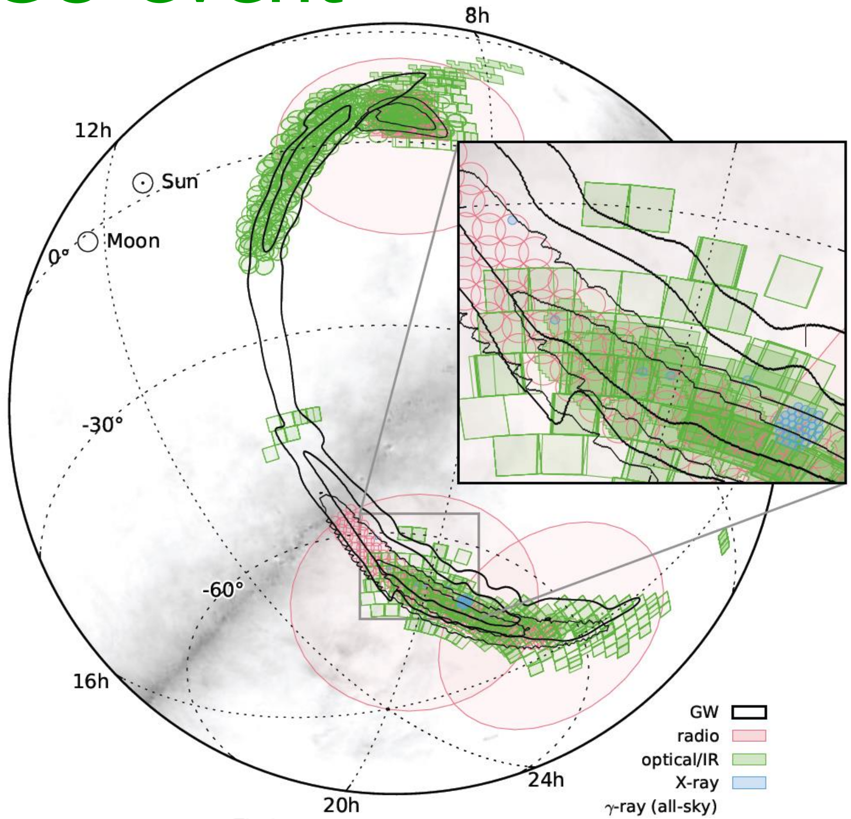


Figure 1. Left: dependence of maximum BH mass on metallicity Z, with $Z_\odot = 0.02$ for the old (strong) and new (weak) massive star winds (Figure 3 from Belczynski et al. 2010a). Right: compact-remnant mass as a function of zero-age main-sequence (ZAMS; i.e., initial) progenitor mass for a set of different (absolute) metallicity values (Figure 6 from Spera et al. 2015). The masses of GW150914 are indicated by the horizontal bands.

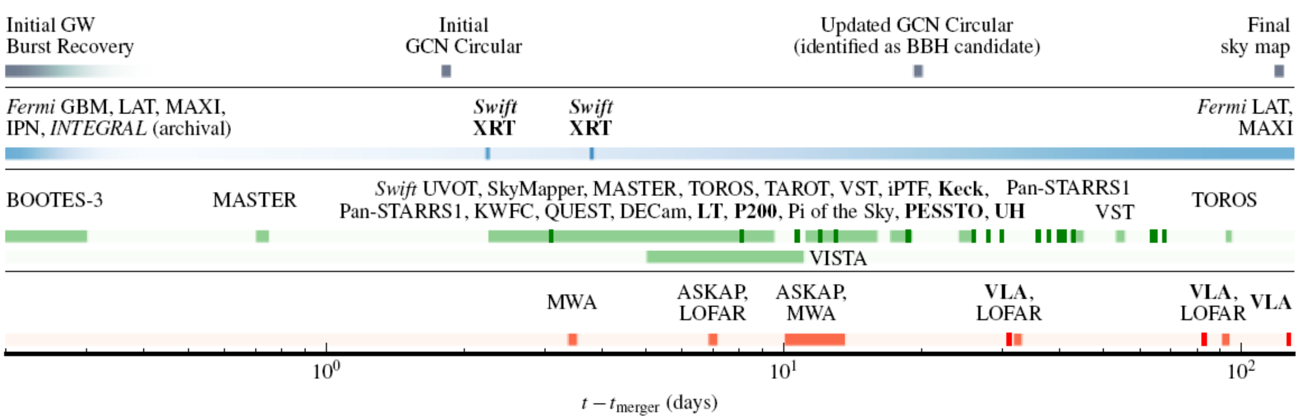
Astrophysical Implications of the Binary Black-Hole Merger GW150914
ApJL, 818, L22, 2016

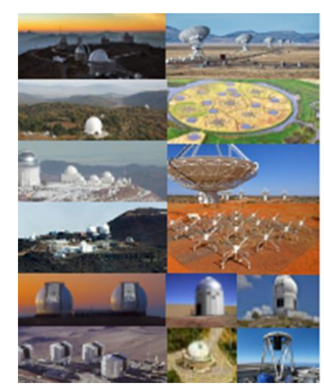
Electromagnetic follow-up of the first LIGO event

- Consortium agreement between LIGO and 63 teams using ground- and space-based telescopes (gamma-ray, X-ray, optical, IR and radio) to follow-up the alert.

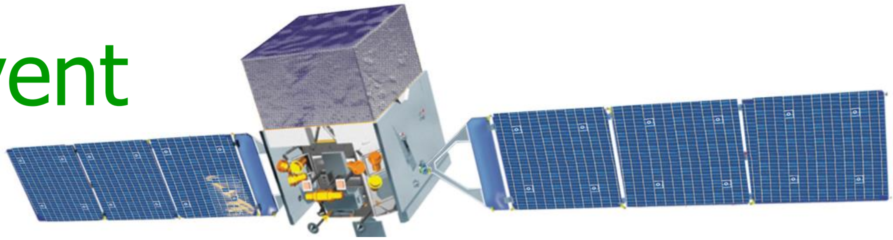


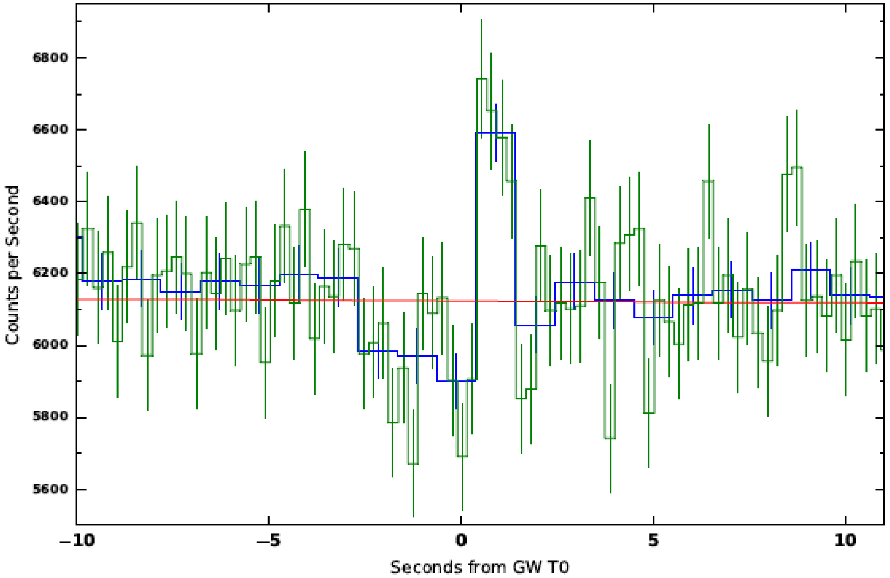
http://arxiv.org/abs/1602.08492

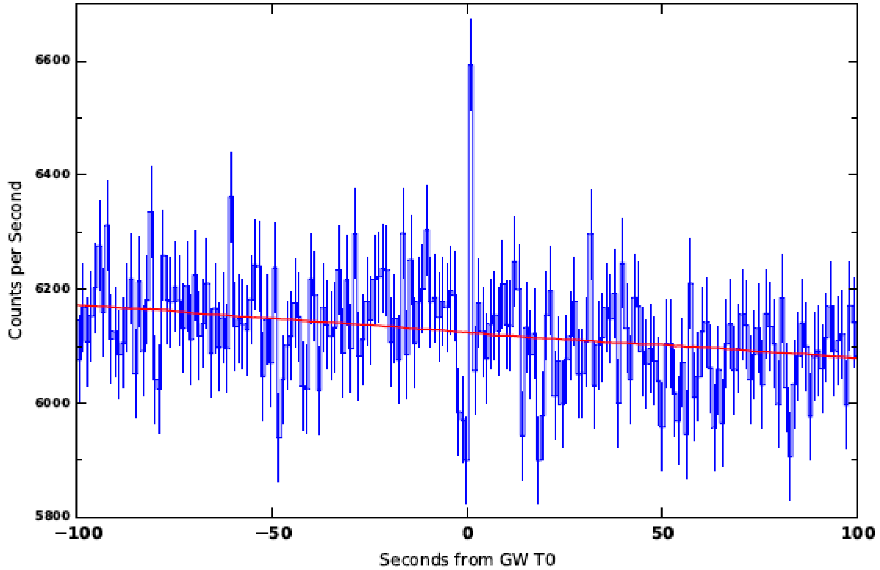




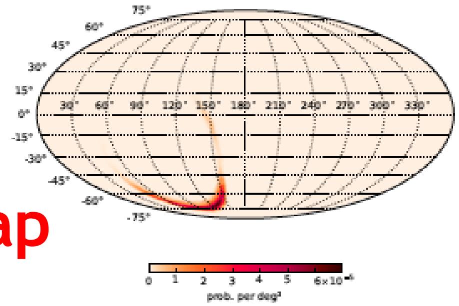
Fermi GBM around the time of the event

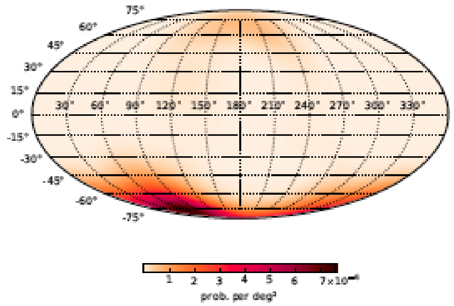






LIGO map





GBM map

http://arxiv.org/abs/1602.03920

https://losc.ligo.org/events/GW150914/

LIGO

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

- Getting Started
- Tutorials
- Data
  - Events
  - Bulk Data
- Timelines
- My Sources
- Software
- GPS ↔ UTC
- About LIGO
- Data Analysis Projects
- Acknowledgement

Data release for event GW150914

This page has been prepared by the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration to inform the broader community about a confirmed astrophysical event observed by the gravitational-wave detectors, and to make the data around that time available for others to analyze. There is also a **technical details** page about the data linked below, and feel free to **contact us**. This dataset has the Digital Object Identifier (doi) http://dx.doi.org/10.7935/K5MW2F23

Summary of Observation

The event occurred at GPS time 1126259462.39 == September 14 2015, 09:50:45.39 UTC. The false alarm rate is estimated to be less than 1 event per **203,000 years**, equivalent to a significance of **5.1 sigma**. The event was detected in data from the LIGO Hanford and LIGO Livingston observatories.

- There are Science Summaries, covering the information below in ordinary language.
- There is a one page factsheet about GW150914, summarizing the event.

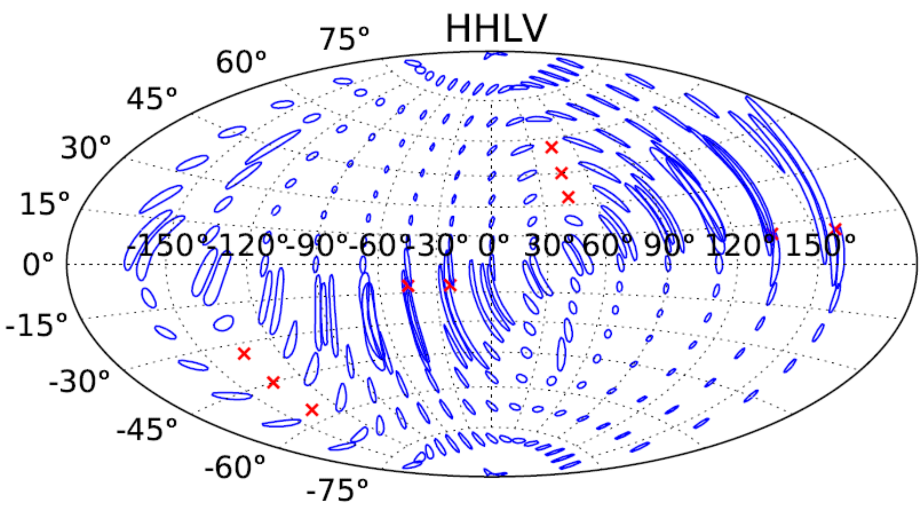
How to Use this Page

- **Click on the section headings below to show available data files.**
  - (click to Open/Close all sections)
- There are lots of data files available in the sections below, look for the word **DATA**.
- Click on each thumbnail image for larger image.
- See the papers linked below for full information, references, and meaning.
- Many of the data files linked below have heterogeneous formatting; if you have any questions, please contact us.

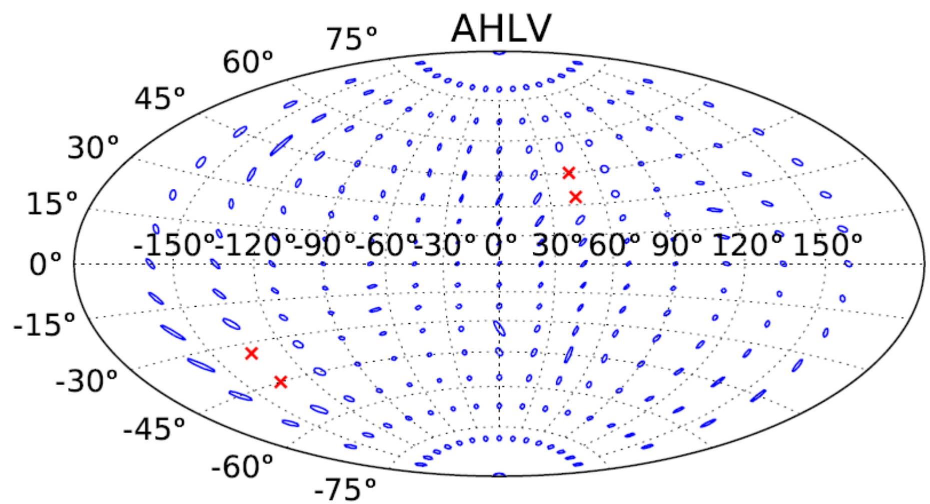
Detector array beam pattern

- The sky localisation depends on
  - the individual detector beam patterns
  - time delay between signal arrival at spatially separated sites

- *vastly* improved with more detectors:



LIGO and Virgo only

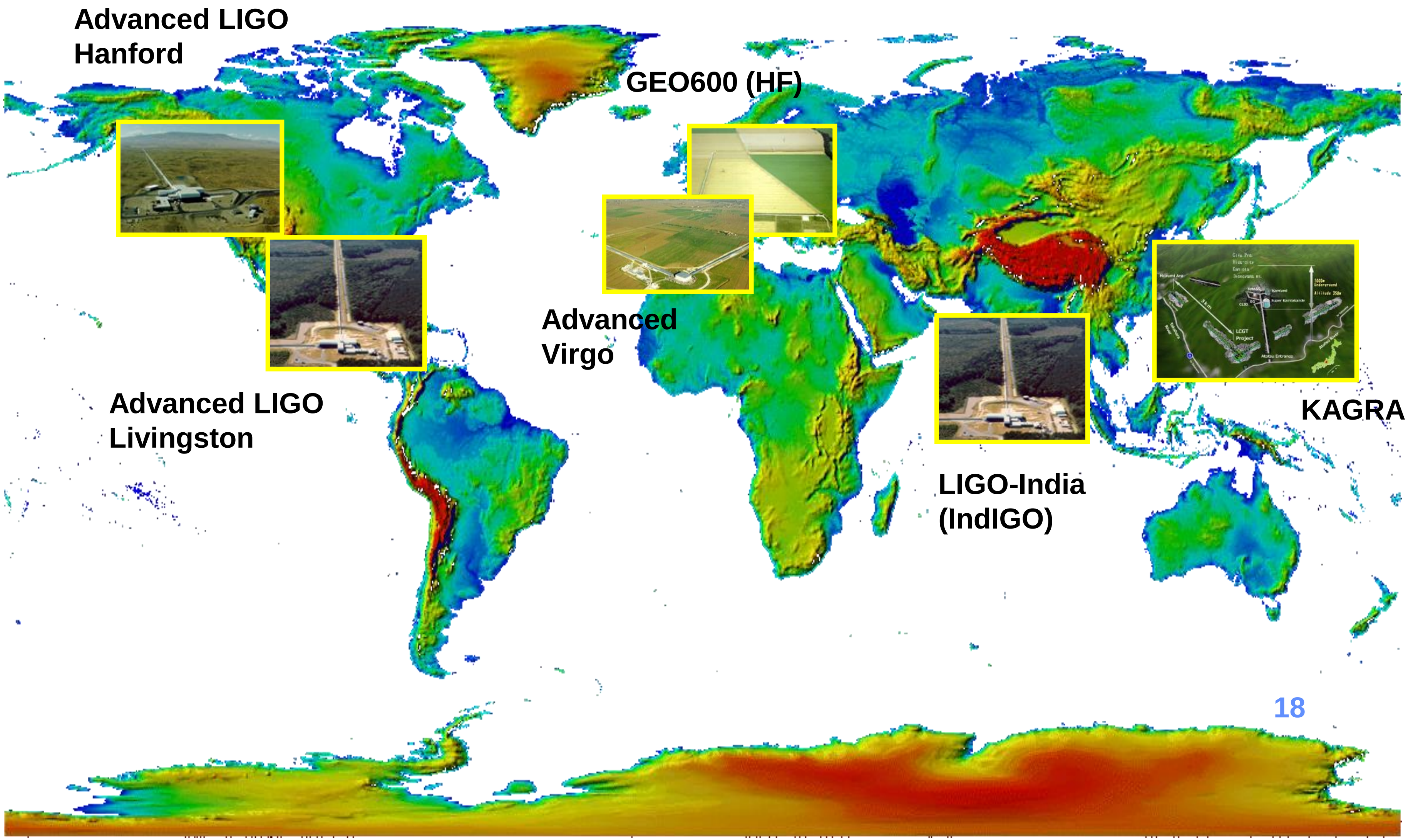


Adding LIGO India

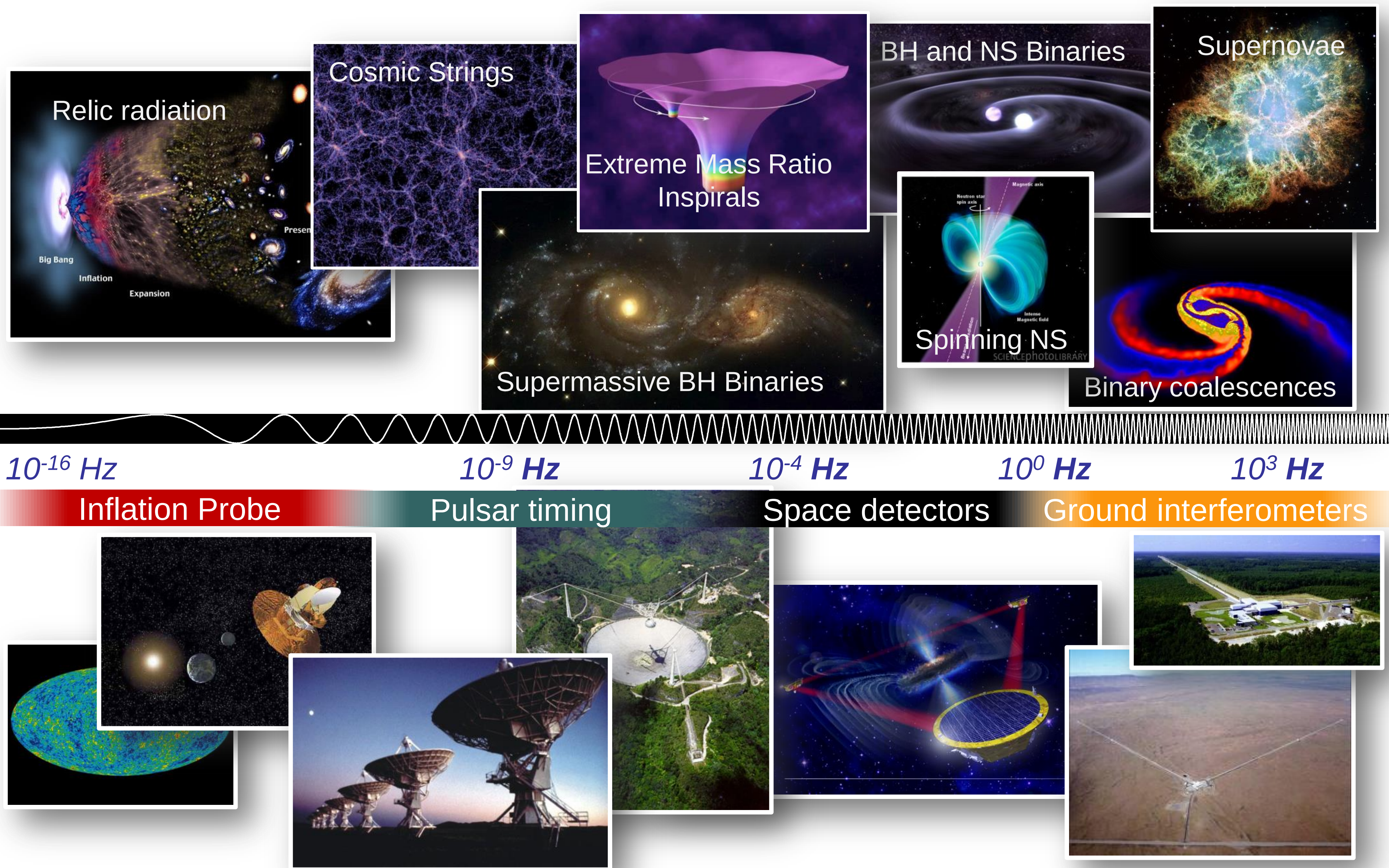
(In-principle approval and MOU)

Class.Quant.Grav.28:105021,2011

The advanced GW detector network

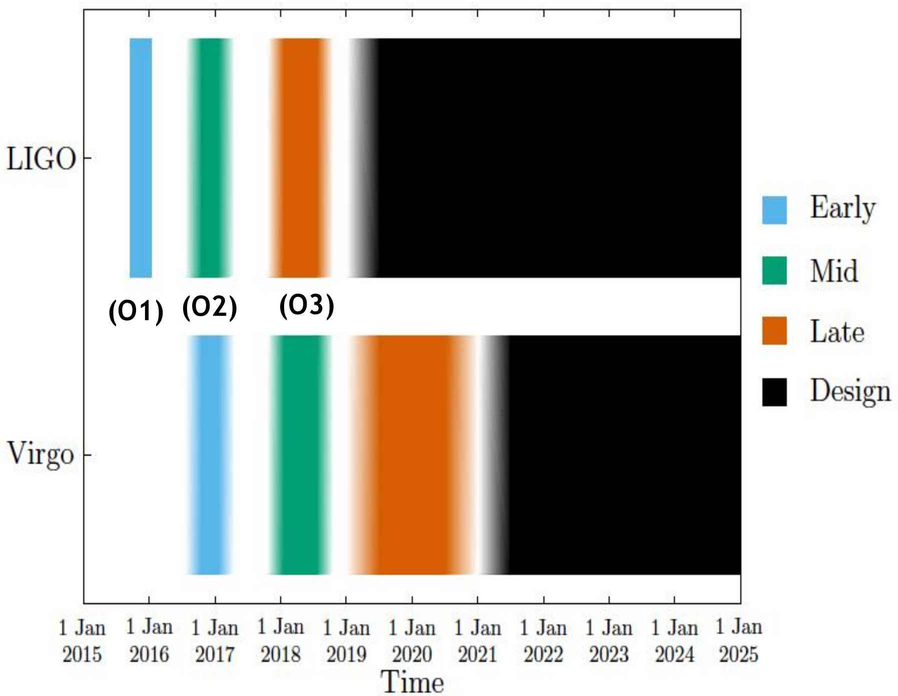


Gravitational astronomy

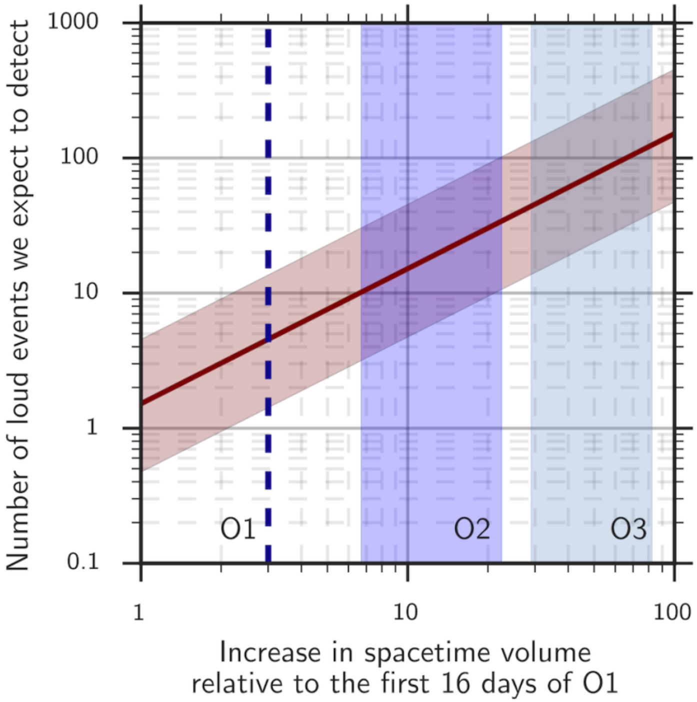


Summary

- LIGO has made the first measurement of a gravitational waveform
- Heavy stellar-mass black holes exist, singly and in binaries
- LIGO has seen black holes up-close, and a merging binary black hole, both for the first time



http://relativity.livingreviews.org/Articles/lrr-2016-1/



arXiv:1602.03842

- LIGO will restart in the Autumn, and Virgo will join in
- The first steps in gravitational-wave astronomy!

SUPA members of the LIGO roster (70)

Alan Cumming, Alastair Grant, Andrew Spencer, Angus Bell, Borja Sorazu, Bryan Barr, Brynley Pearlstone, Chris Messenger, Christian Graef, Daniel Williams, Daniela Pascucci, David Vine, Des Gibson, Ewan Houston, Gareth Davies, Gavin Newton, Giles Hammond, Graham Woan, Hafizah Isa, Harry Ward, Husni Almoubayyed, Ian MacLaren, Ian Martin, Ignacio Santiago-Prieto, Siong Heng, Jade Powell, James Hough, Jamie Scott, Jan Devenson, Jan-Simon Hennig, Jennifer Wright, Jessica Steinlechner, Jonathan Gair, Joshua Logue, Karen Haughian, Karl Toland, Ken Strain, Kirill Tokmakov, Kyung-ha Lee, Liam Cunningham, ManLeong Chan, Margot Phelps, Mariela Masso-Reid, Marielle van Veggel, Mark Fletcher, Martin Hart, Martin Hendry, Martin Sinclair, Matthew Pitkin, Michael Perreur-Lloyd, Nick Lockerbie, Norna Robertson, Peter Murray, Raymond Robie, Rebecca Douglas, Ross Birney, Russell Jones, Sabina Huttner, Sean Leavey, Sean Macfoy, Sebastian Steinlechner, Sharat Jawahar, Sheena Barclay, Sheila Rowan, Stefan Danilishin, Stefan Hild, Stuart Reid, Teng Zhang, Valentina Mangano, Zeno Tornasi end

697

SITZUNGSBERICHTE 1916.

XXXIII.

DER

KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN.

688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

"Approximate integration of the field equations of gravitation"

Von A. Einstein.

First paper is "is disfigured by a regrettable calculation error", leading Einstein to think, by 1918, that no energy is carried by GWs…

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

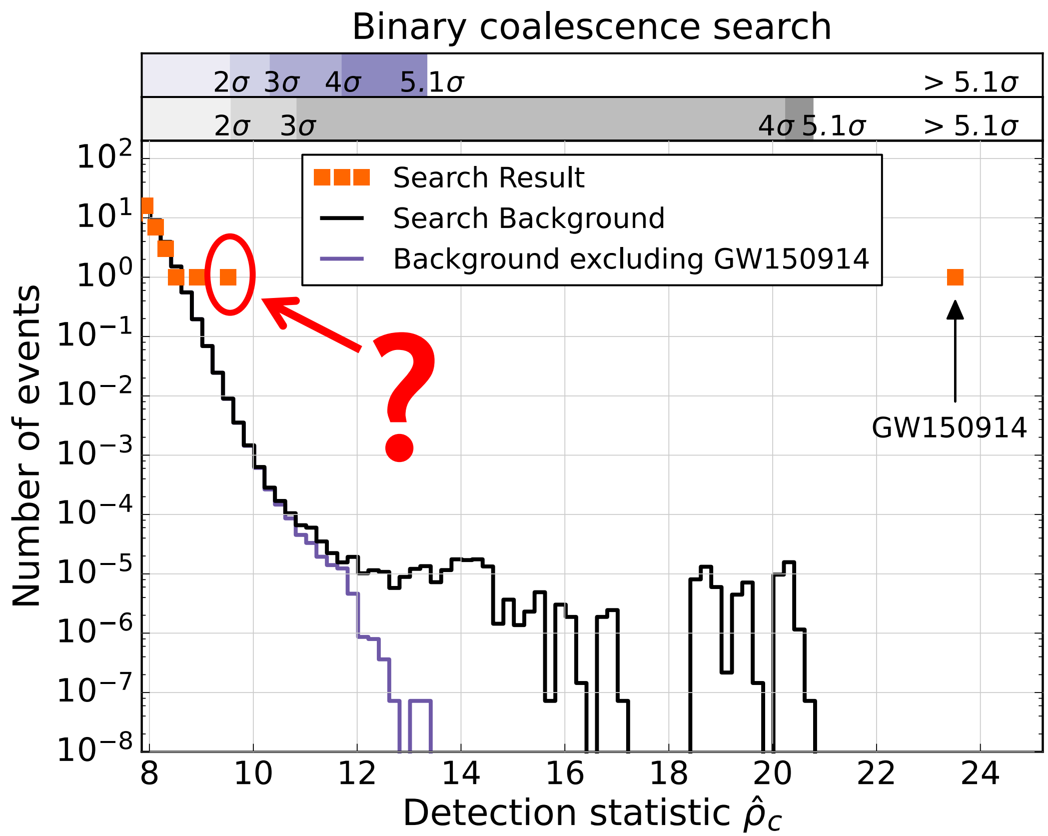
Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

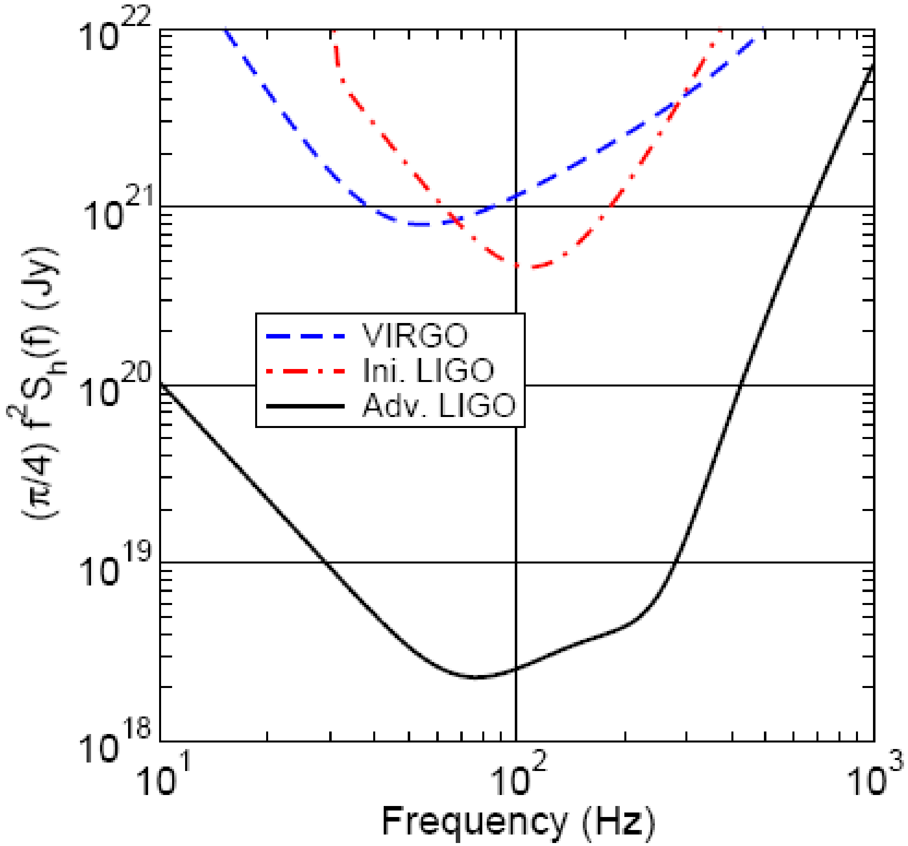
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

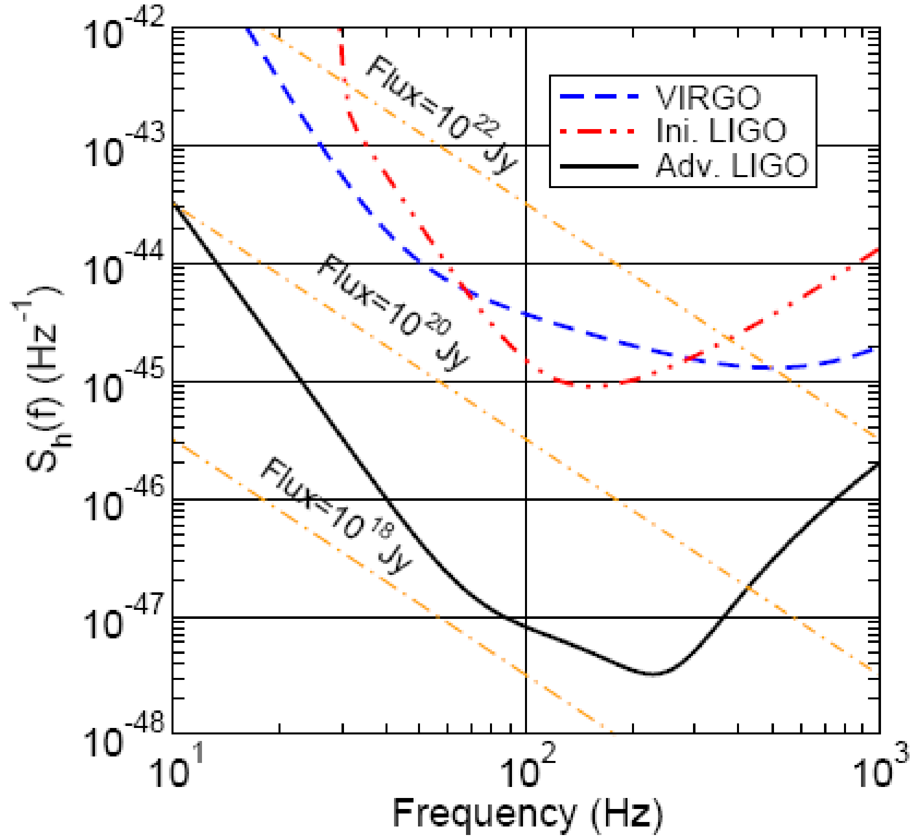
The second loudest event

Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 ($2.1\,\sigma$)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}



Flux (in)sensitivity





Sathyaprakash and Schutz 2009

… but looked at another way, GW sources are VERY bright!