Gravitational-Wave Observations of Compact Binary Mergers

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Max Planck Institute for Gravitational Physics, Hannover

March 11

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

PhD School Jena

Binary Merger
Observations &
Numerical Relativity

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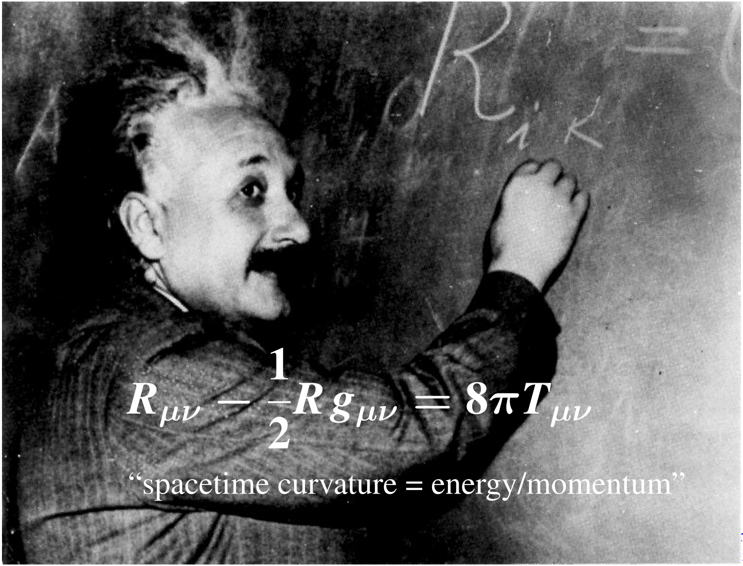
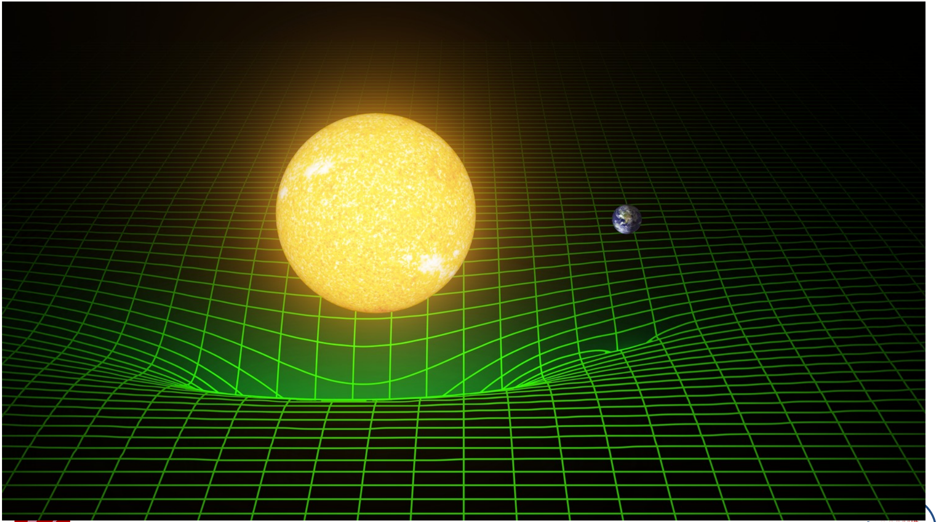
Observations &
Numerical Relativity



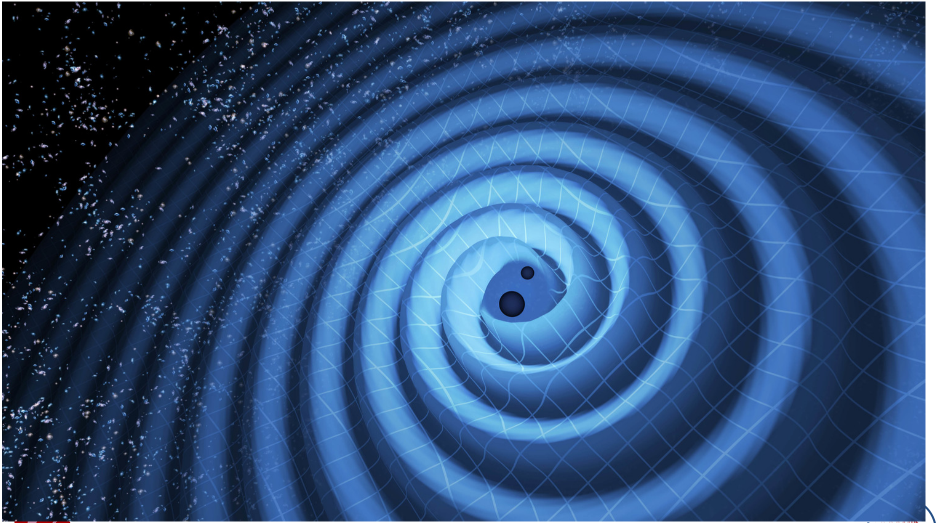
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi T_{\mu\nu}$$

"spacetime curvature = energy/momentum"



Credit: T. Pyle/Caltech/MIT/LIGO Lab

Binary Merger
Observations &
Numerical Relativity



Credit: LIGO/T. Pyle

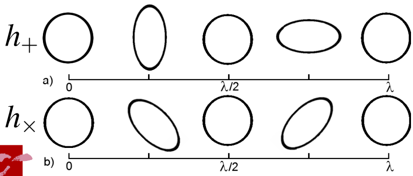
Binary Merger
Observations &
Numerical Relativity

Linearised theory

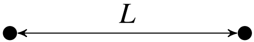
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad |h_{\mu\nu}| \ll 1$$

$$\Rightarrow \text{(Lorentz gauge)} \quad \Box \bar{h}_{\mu\nu} = -16\pi\, T_{\mu\nu}$$

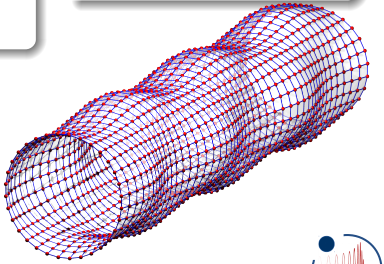
$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \Rightarrow \textit{Gravitational waves}$$



Effect



$$\frac{\delta L}{L} \approx \frac{h_+}{2}$$

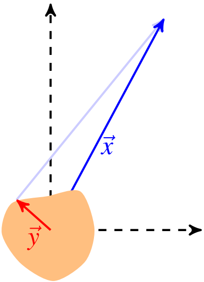


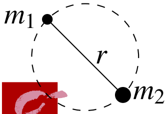
Solution of the wave equation

$$\bar{h}_{ij}(t,\vec{x}) = 4\int \frac{T_{ij}(t-|\vec{x}-\vec{y}|,\vec{y})}{|\vec{x}-\vec{y}|}\,d^3y$$

$$\approx \frac{2}{|\vec{x}|}\frac{d^2}{dt^2}\int y^i\,y^j\,\rho(t-|\vec{x}|,\vec{y})\,d^3y$$

(for $|\vec{x}| \gg |\vec{y}|$, finite-size, non-relativistic sources)





Newtonian binary

Assume the perfect circular motion of two point particles $m_1 = m_2$ with a constant orbital frequency ω.

1. Parameterize the position of both particles $\vec{x}_1(t), \vec{x}_2(t)$.
2. Use $\rho(t,\vec{y}) = m_1\delta(\vec{y}-\vec{x}_1) + m_2\delta(\vec{y}-\vec{x}_2)$ to calculate $\bar{h}_{ij}$.

Solution

Centre-of-mass coordinate system:

$$\vec{x}_1 = \left[\frac{r}{2}\cos(\omega t), \frac{r}{2}\sin(\omega t)\right] = -\vec{x}_2$$

$$\int y^1\, y^1\, \rho(t,\vec{y})\, d^3y = m_1 \frac{r^2}{4}\cos^2(\omega t) + m_2 \frac{r^2}{4}\cos^2(\omega t) = \frac{Mr^2}{4}\cos^2(\omega t)$$

$$\int y^i\, y^j\, \rho(t,\vec{y})\, d^3y = \frac{Mr^2}{4}\begin{pmatrix} \cos^2(\omega t) & \cos(\omega t)\sin(\omega t) \\ \cos(\omega t)\sin(\omega t) & \sin^2(\omega t) \end{pmatrix}$$

$$= \frac{Mr^2}{8}\begin{pmatrix} 1+\cos(2\omega t) & \sin(2\omega t) \\ \sin(2\omega t) & 1-\cos(2\omega t) \end{pmatrix}$$

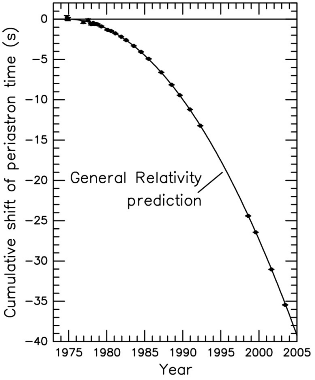
$$\bar{h}_{ij}(t,\vec{x}) = -\frac{Mr^2\omega^2}{|\vec{x}|}\begin{pmatrix} \cos(2\omega t') & \sin(2\omega t') \\ \sin(2\omega t') & -\cos(2\omega t') \end{pmatrix}$$

$$t' = t - |\vec{x}|$$

Binary Merger
Observations &
Numerical Relativity

Observational evidence

Hulse-Taylor pulsar 1978,
Nobel prize 1993



www.nasa.gov

Some numbers

- $m_1 = 1.441 M_\odot$
- $m_2 = 1.387 M_\odot$

$\Rightarrow$ $M = 2.828 M_\odot$

- $D \approx 6.4\,\mathrm{Mpc}$
- $P \approx 7.75\,\mathrm{hr}$

$\Rightarrow$ $\omega_{\mathrm{orb}} \approx 2.25 \times 10^{-4}\,\mathrm{s}^{-1}$

- $r \sim 10^6\,\mathrm{km}$

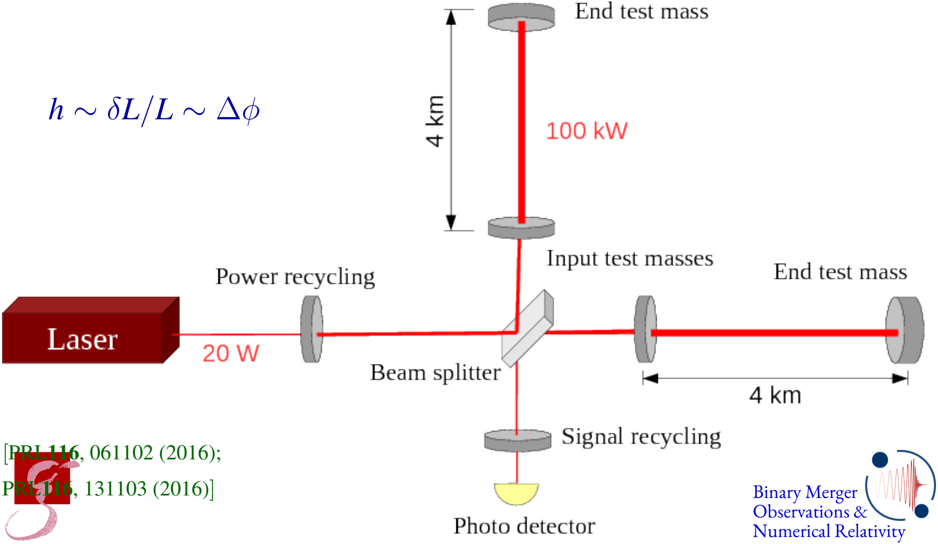
$$\Rightarrow \quad h \sim \mathcal{O}(10^{-26})$$

[for comparison (in metres): Carbon atom radius $\mathcal{O}(10^{-10})$, proton radius $\mathcal{O}(10^{-15})$, earth-moon $\mathcal{O}(10^{8})$, earth-sun $\mathcal{O}(10^{11})$]

Numerical Relativity

Catching Gravitational Waves

$$h \sim \delta L/L \sim \Delta\phi$$



[PRL 116, 061102 (2016);
PRL 116, 131103 (2016)]

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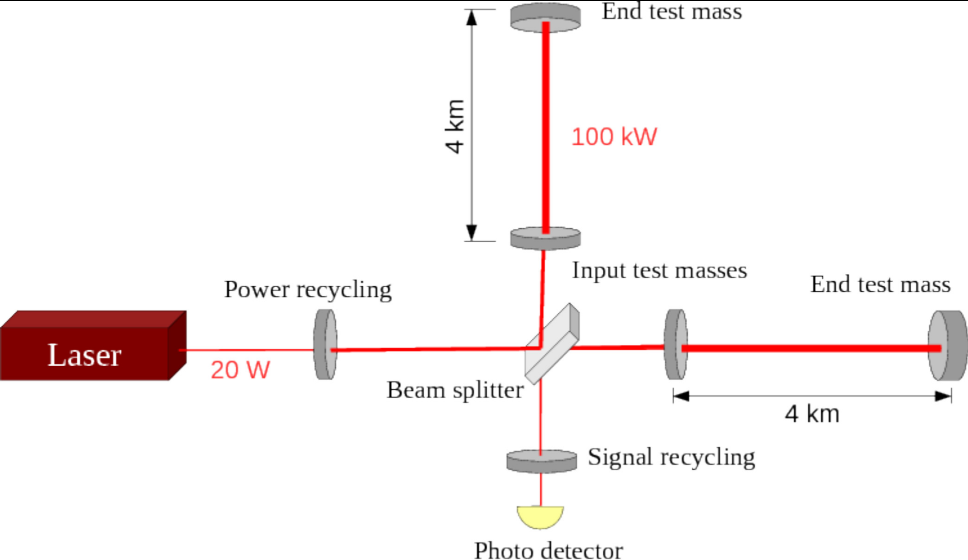
Observations &
Numerical Relativity


End test mass
4 km
100 kW
Input test masses
Power recycling
End test mass
Laser
20 W
Beam splitter
4 km
Signal recycling
Photo detector

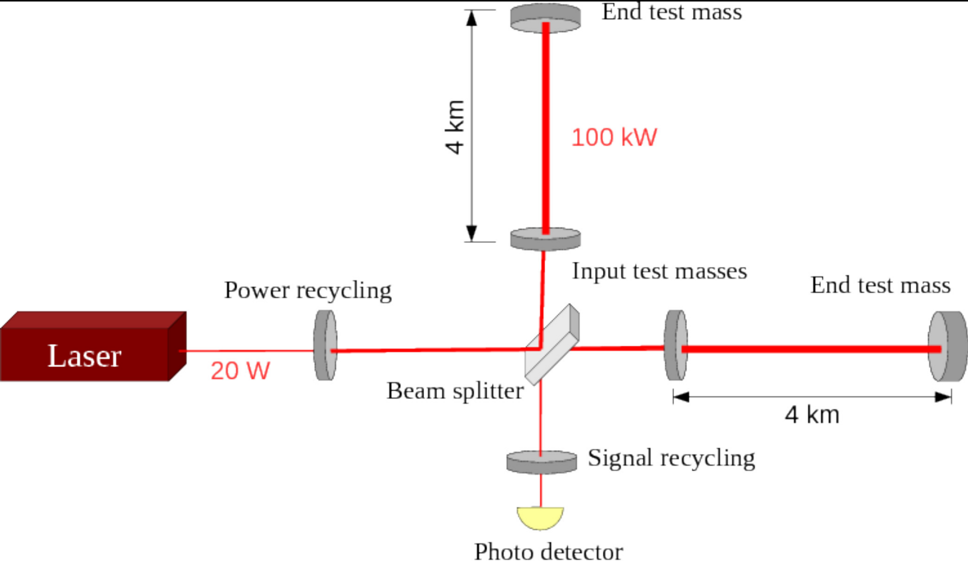

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Photo detector

LIGO Hanford

LIGO Livingston

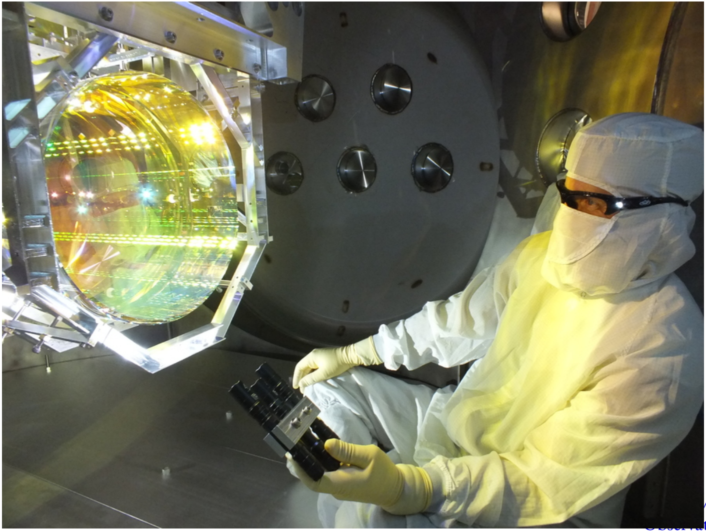
Binary Merger
Observations &
Numerical Relativity

Inside LIGO: The tube

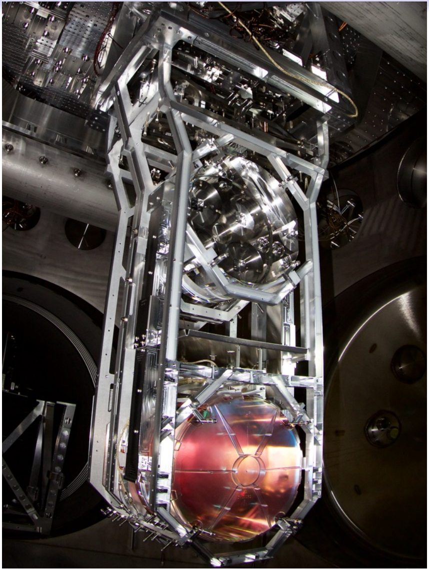
Inside LIGO: Laser and vacuum equipment

ger
Observations &
Numerical Relativity

Inside LIGO: Optics



Inside LIGO: Suspension



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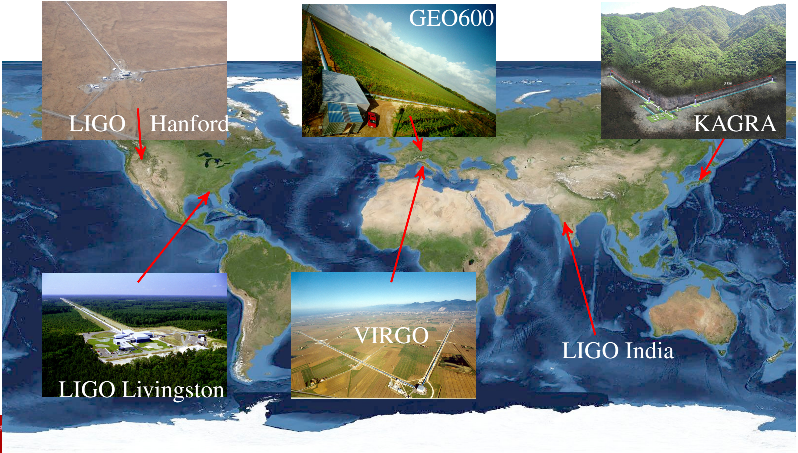
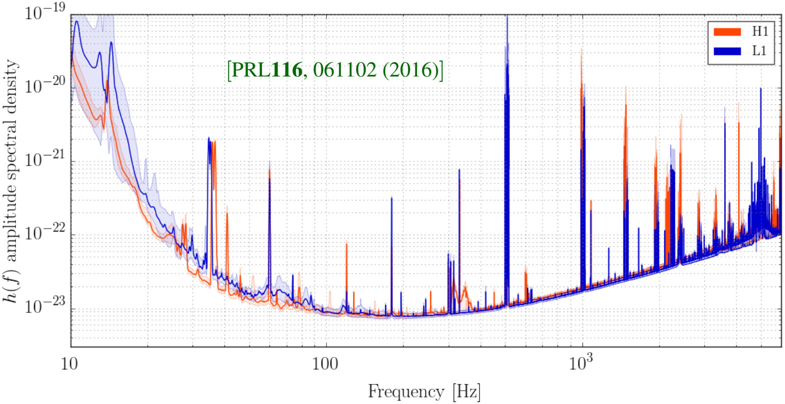
The GW detector network



Observations &
Numerical Relativity

Instrument noise

Seismic	Ground vibrations
Thermal	Finite temperature
Quantum	Light quanta
Gravity gradient	Gravitational field of the environment



[PRL**116**, 061102 (2016)]

Status

aLIGO LHO Logbook

Logbooks LHO LLO Virgo KAGRA

Displaying reports **21-40** of **45917**.Go to page 1 2 3 4 5 6 7 8 9 10 End

Reports until 15:06, Tuesday 05 March 2019

H1 PSL

jason.oberling@LIGO.ORG - posted 15:06, Tuesday 05 March 2019 (47307)

PSL Work Today

P. King, R. Savage, J. Oberling, D. Sigg

https://alog.ligo-wa.caltech.edu/aLOG

FSS RefCav Picomotor Mirror Mounts

At the request of the LHO commissioning team, today we installed 2 picomotor equipped mounts in the FSS RefCav path. We replaced the mount for mirror M2 the FSS EOM, 1st attachment) and for the upper periscope mirror (UPM, 2nd attachment). We used M27 instead of the lower periscope mirror (LPM) because to the RefCav; with this setup, M27 primarily changes beam position while the UPM primarily changes beam angle. The 3rd attachment shows both new picom

The same driver (PICO D) that runs the picomotors for the PMC input mirrors (mirrors M06 and M07) had 2 empty channels, so we used these for the new RefC of now, channels 1 & 2 are for the PMC picomotor mirrors and channels 3 & 4 are for the RefCav; Daniel changed the displayed channel names on the picomot screen to reflect this. To end, we confirmed that all picomotors functioned as expected, which they did. When we left the enclosure the FSS RefCav TPD read was transmitting **~54.5W**. During the next maintenance window where we ***do not*** have an enclosure incursion, I will tweak the alignment into both the PMC and

70W Amplifier Power Monitor PD

We had noticed some odd behavior with the 70W amp power monitor PD (the PD that the 70W amp power watchdog triggers off of). When blocked directly at t PSL Beckhoff software reports ~3W on this PD; when blocked farther away the reading is ~52W. We suspected the cause to be room lights, so we added a tub (808nm pump light filter) screwed onto the end (4th attachment); this second RG850 was added to block more of the room light, as one wasn't quite enough. Th blocked reading to ~3W regardless of how far away the blockage occurred, with no degradation in the amount of power read by the PD when unblocked.

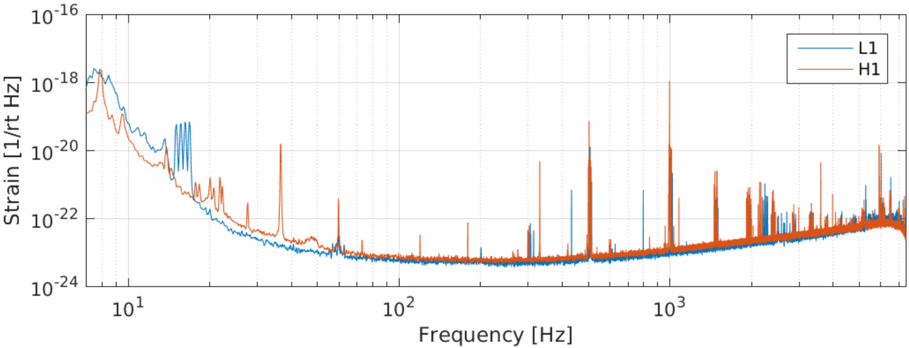
Images attached to this report

H1 CDS (CDS, DCS)

gregory.mendell@LIGO.ORG - posted 13:05, Tuesday 05 March 2019 - last comment - 13:28, Tuesday 05 March 2019(47302)

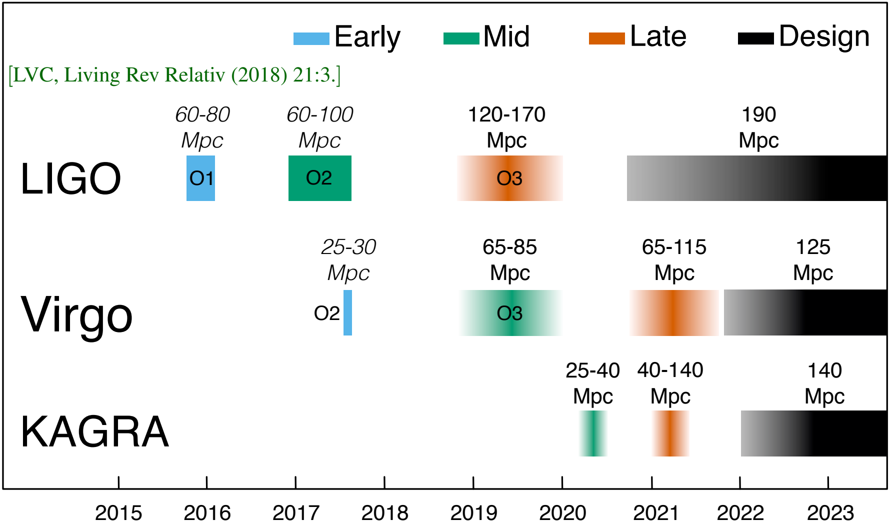
DMT computers have been patched and rebooted, bringing in gds2.18.16-1.el7

The DMT computers have been patched and rebooted, bringing in gds2.18.16-1.el7 and " new features needed to connect idq to the low latency frames " as per



(post by Sheila Dwyer, 01 March 2019)
average binary-neutron-star range $\gtrsim 100\,\mathrm{Mpc}$

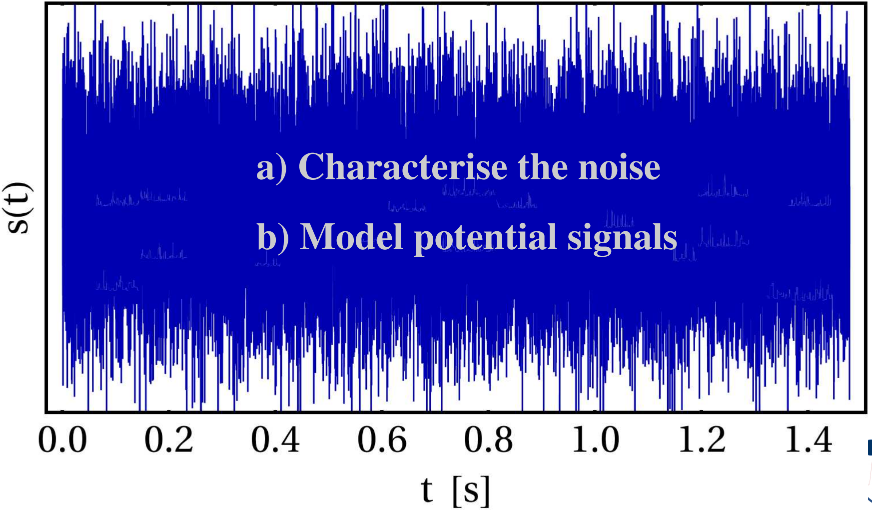
Binary Merger
Observations &
Numerical Relativity



[LVC, Living Rev Relativ (2018) 21:3.]

Numerical Relativity

Typical data stream



a) Characterise the noise

b) Model potential signals

Numerical Relativity

Theory of Stationary Gaussian noise

- **Assume** the following noise properties:
    - Stationarity: invariant under time translation
    - Gaussianity with zero mean
- Fourier spectrum of the noise:

$$\tilde{n}_T(f) = \frac{1}{\sqrt{T}} \int_0^T n(t)\, e^{-i2\pi f\, t}\, dt$$

$$S_n(f) = \left\langle \lim_{T\to\infty} |\tilde{n}_T(f)|^2 \right\rangle$$

- Wiener-Khinchin theorem: S_n is the Fourier transform of the auto-correlation function

$$\Rightarrow \quad \langle \tilde{n}(f)\, \tilde{n}^*(f') \rangle = \frac{1}{2} S_n(f)\, \delta(f - f')$$

Binary Merger Observations & Numerical Relativity

Signal buried in the noise?

- How likely is a particular noise realisation?

$$p(n) \sim e^{-(n|n)/2},$$

with $(a|b) = 4\,\mathrm{Re} \int \frac{\tilde{a}(f)\,\tilde{b}^*(f)}{S_n(f)} df.$

- Is it likely that the observed data stream s contains a signal h, i.e., $s = n + h$?

$$\Lambda = \frac{e^{-(s-h|s-h)/2}}{e^{-(s|s)/2}}$$

$$\ln\Lambda = (s|h) - \frac{(h|h)}{2} \leq \frac{1}{2}\frac{(s|h)}{\sqrt{(h|h)}} = \frac{1}{2}(s|\hat{h})$$

- $(s|\hat{h})$ is commonly referred to as the (recovered) signal-to-noise ratio

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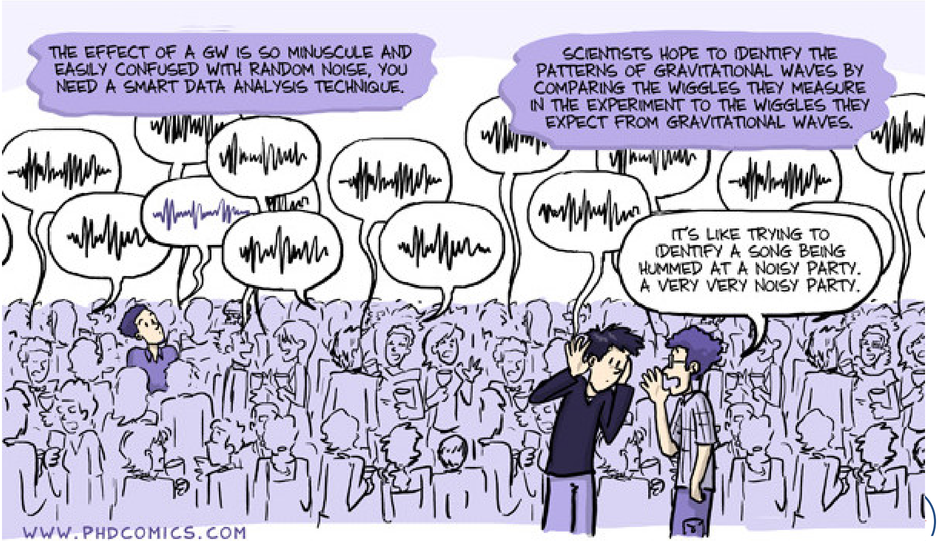
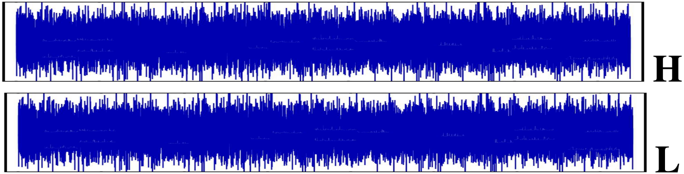


Numerical Relativity

Real-life Searches

1. Need to know the signals we are looking for.
2. Filter data with ~~all~~ some of them.
3. Account for non-stationarity and non-Gaussianity of noise.
4. Quantify false alarm probability.



coherent signal?

Binary Merger Observations & Numerical Relativity

Real-life Searches

1. Need to know the signals we are looking for.
2. Filter data with ~~all~~ some of them.
3. Account for non-stationarity and non-Gaussianity of noise.
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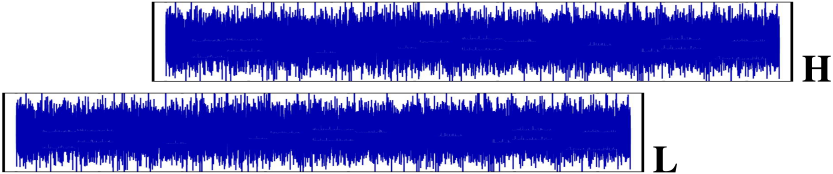
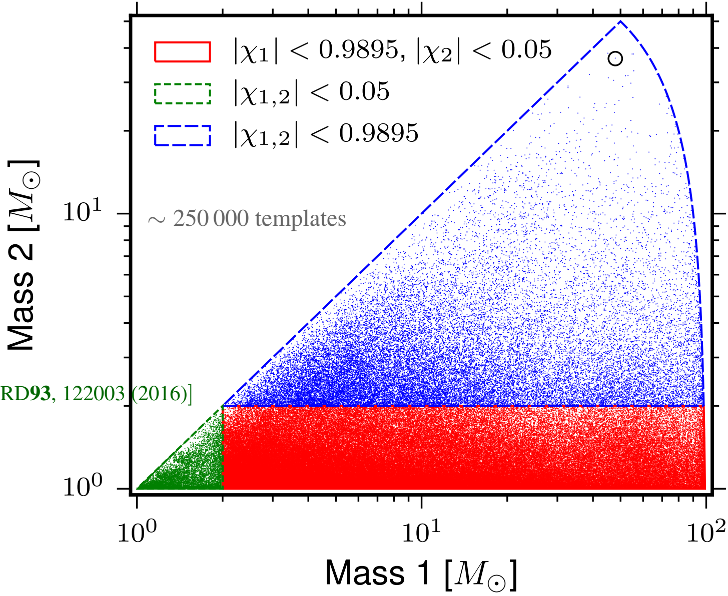
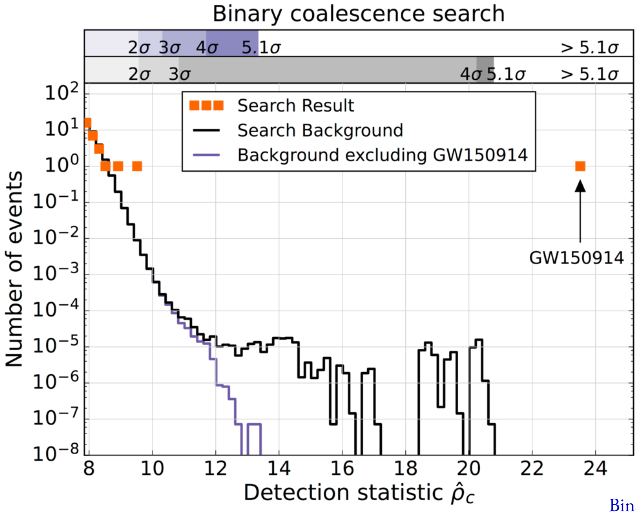


No coherent signal!



[PRD**93**, 122003 (2016)]

Search results – PRL**116**, 061102 (2016) & PRD**93**, 122003 (2016)



Binary Merger Observations & Numerical Relativity

Discovery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Discovery

£1.80 (Ch. Islands £2.20)
Friday 12.02.16
Published in London and Manchester
theguardian.com

theguardian

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

Tim Radford

Physicists have announced the discovery of gravitational waves - ripples in the fabric of space-time that were first anticipated by Albert Einstein a century ago.

The announcement is the climax of a century of speculation, 50 years of trial and error, and 25 years perfecting a set of instruments so sensitive they could identify a distortion in space-time a thousandth of the diameter of an atomic nucleus across a 4km strip of laser beams and mirrors.

"We have detected gravitational waves. We did it," said David Reitze, executive director of the Laser Interferometer Gravitational-Wave Observatory (Ligo), at a press conference in Washington.

The phenomenon detected was a collision between two black holes. Using the world's most sophisticated detector, the scientists listened for 20 thousandths of a second as the two giant black holes, one 35 times the mass of the sun, the other slightly smaller, revolved around

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

"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLXV . . . No. 57,140 · NEW YORK, FRIDAY, FEBRUARY 12, 2016 · $2.50

Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

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

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

Long in Clinton's Corner, Blacks Notice Sanders

Last Occupier In Rural Oregon

Frankfurter Allgemeine
ZEITUNG FÜR DEUTSCHLAND

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Ayrault wird Außenminister Frankreichs

mic. PARIS, 11. Februar. Der französische Präsident François Hollande hat bei der Regierungsumbildung am Donnerstag die Grünen zurück an den Regierungstisch geholt. Neuer Außenminister wird Hollandes ehemaliger Premierminister Jean-Marc Ayrault. Der 66 Jahre alte Ayrault war Ende März 2014 nach der Wahlniederlage der Sozialisten bei den Kommunalwahlen zurückgetreten. Der ehemalige Deutschlehrer folgt auf Laurent Fabius, der Präsident des Verfassungsrats werden soll. Die Vorsitzende der Partei „Europa Ökologie – Die Grünen" (EELV), Emmanuelle Cosse, wird neue Wohnungsbauministerin. Der grüne Senator Jean-Vincent Placé wird Staatsminister für die Staatsreform, die grüne Abgeordnete Barbara Pompili Staatsministerin für Umwelt, Energie und das Meer. Placé und Pompili hatten die EELV im Streit verlassen. An der grünen Parteibasis ist die Regierungsbeteiligung weiter umstritten. Die bisherige Beraterin für kulturelle Angelegenheiten im Elysée-Palast, Audrey Azoulay, ersetzt die glücklose Fleur Pellerin als Kulturministerin. Umweltministerin Ségolène Royal wird künftig auch verantwortlich für internationale Klimaverhandlungen. „Es ist eine Regierung, die handeln, die reformieren, die vorankommen muss", sagte Hollande am Donnerstagabend im Fernsehen. *(Siehe Seiten 5 und 8.)*

Einstein hat wieder mal recht

Farbenspiele – Das sehen Physiker, wenn sie massereiche schwarze Löcher in ihren Computern miteinander kollidieren lassen. Denn dabei entstehen Gravitationswellen – jene winzigen Verzerrungen von Raum und Zeit, die sich mit Lichtgeschwindigkeit in alle Richtungen ausbreiten.

Einsteins Beben
Von Manfred Lindinger

EDIÇÃO LISBOA SEX 12 FEV 2016

publico.pt

FÍSICA

Simulação de dois buracos negros em colisão, provocando ondas gravitacionais

Gras fressen: Effenberg als Trainer in Paderborn › Die Seite Drei

Süddeutsche Zeitung
NEUESTE NACHRICHTEN AUS POLITIK, KULTUR, WIRTSCHAFT UND SPORT

WWW.SÜDDEUTSCHE.DE · MÜNCHEN, FREITAG, 12. FEBRUAR 2016 · 72. JAHRGANG / 6. WOCHE / NR. 35 / 2,70 EURO

Das Streiflicht

Der Beweis

Vor einhundert Jahren erdachte Albert Einstein die Allgemeine Relativitätstheorie. Seit Donnerstag wissen Physiker, dass er rundum recht hatte. Zwei mehrere Kilometer lange Messgeräte in den USA haben erstmals Gravitationswellen aus dem All empfangen. Solche Erschütterungen der Raumzeit hatte Einstein vorhergesehen. Sie entstehen etwa, wenn massive Himmelskörper, in diesem Fall zwei Schwarze Löcher, kollidieren. Der Nachweis ist für Physiker ein Jahrhundertereignis. › *Thema des Tages*

Heute mit Immobilien: Kauf- und Mietmarkt

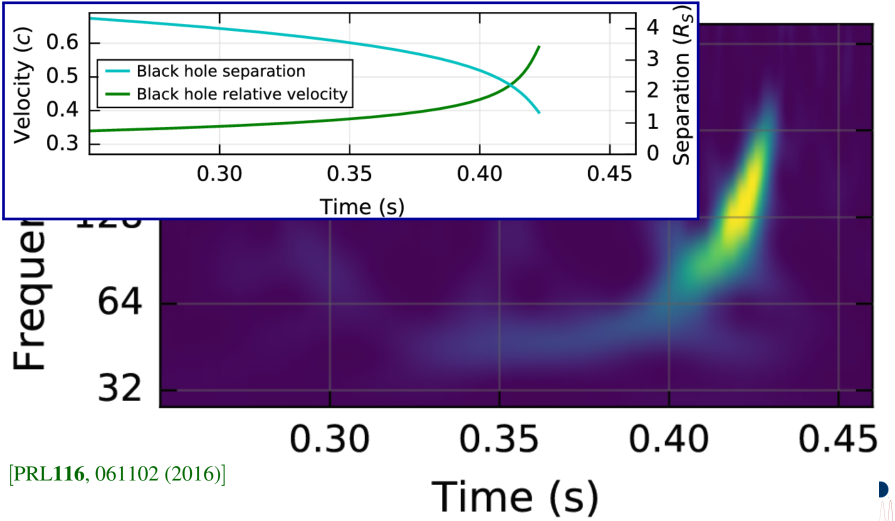
Koalition einigt sich auf Asylpaket

相撞

天文學可能發生革命性變化

時空漣漪 首獲證實

災頭七・雨和淚 A2



[PRL**116**, 061102 (2016)]

Binary Merger Observations & Numerical Relativity

UIB

Universitat
de les Illes Balears

Binary phase evolution

Newtonian binary (arbitrary masses)

$$\begin{aligned} h(t) &= F_+ h_+ + F_\times h_\times \\ &= \mathcal{A}\frac{4M\,\eta\,v(t)^2}{D}\cos(2\phi_{\text{orb}}(t)+\phi_0) \\ E(t) &= -\frac{M\eta}{2}v(t)^2 \\ \mathcal{L}(t) &= \frac{32}{5}\eta^2 v^{10}(t) \end{aligned}$$

$$v(t) = \omega(t)\,r(t)$$

$$\eta = \frac{m_1\,m_2}{M^2}$$

Keppler's law:

$$v^2(t) = \frac{M}{r(t)}$$

Newtonian phase evolution

1. From the energy-balance law, $dE/dt = -\mathcal{L}$, derive a differential equation for the binary's velocity $v(t)$.
2. Calculate $v(t)$ and $\omega(t)$.
3. Integrate $\omega(t)$ to obtain $\phi_{\text{orb}}(t)$.

Solution

$$\frac{dv}{dt}(t) = -\frac{\mathcal{L}(t)}{dE(v)/dv} = \frac{32}{5M}\eta\, v^9(t)$$

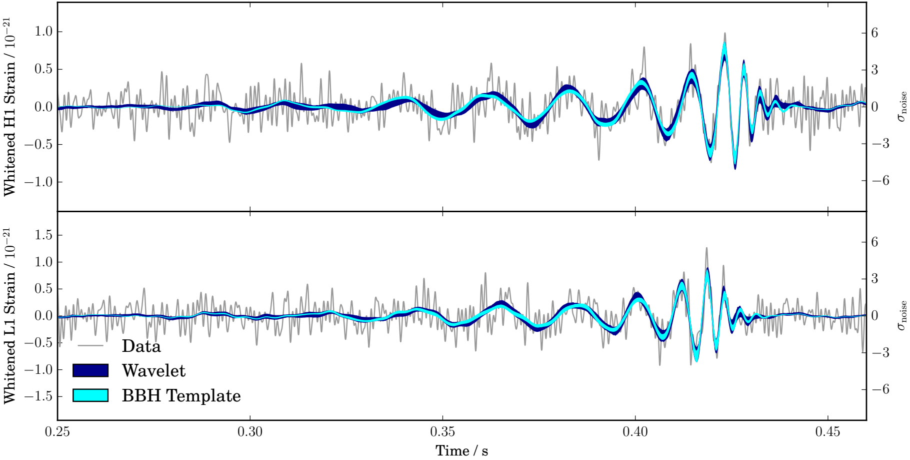
$$v(t) = \frac{1}{2}\sqrt[8]{\frac{5M}{\eta\,(t_c - t)}}$$

$$\omega(t) = \frac{v^3(t)}{M} = \frac{1}{8}\left(\frac{5}{M^{5/3}\eta\,(t_c - t)}\right)^{3/8} = \frac{1}{8M_c^{5/8}}\left(\frac{5}{t_c - t}\right)^{3/8}$$

$$M_c = M\,\eta^{3/5}$$

$$\phi_{\text{orb}}(t) = \int \omega(t)\,dt = \phi_c - \left(\frac{t_c - t}{5M_c}\right)^{5/8}$$

GW150914



[PRL 116, 241102 (2016)]

How much mass is in the system?

see also [LVC 1608.01940]

Binary Merger Observations & Numerical Relativity

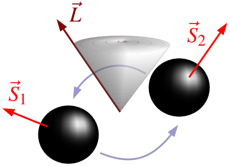
Binary parameters

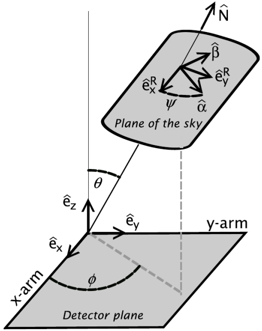
Intrinsic parameters

- 2 masses $(m_1, m_2 \,/\, M_c, q)$
- 6 spin vector parameters
- reference time and phase
- ~~2 eccentricity parameters~~
- tidal parameters (for neutron stars)

Extrinsic parameters

- 2 angles for sky location
- inclination angle (ι)
- polarization angle (ψ)
- distance (D)





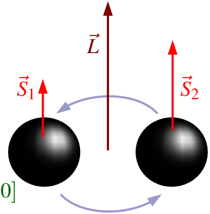
[Sathyaprakash, Schutz, LRR]

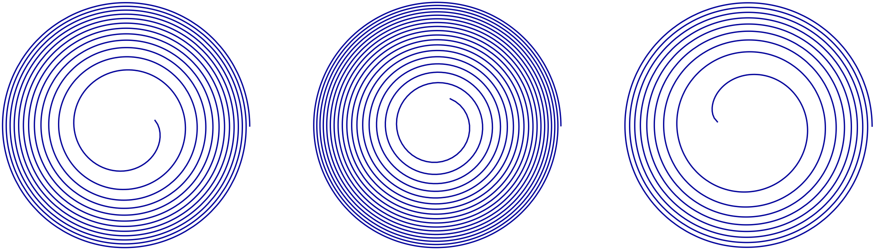
Non-precessing systems

Aligned spins

- Parameters: $M,\ \eta,\ \chi_i = \dfrac{\vec{S}_i \cdot \hat{L}}{m_i^2}$
- Reduced spin: $\chi_\text{eff} = \dfrac{m_1\chi_1 + m_2\chi_2}{M}$

[Poisson, Will, 9502040; Ajith, 1107.1267, Pürrer *et al.*, 1306.2320]



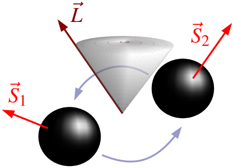


$q = 1,\ \ \chi_1 = \chi_2 = 0$ $q = 1,\ \ \chi_1 = \chi_2 = 0.99$ $q = 1,\ \ \chi_1 = \chi_2 = -0.99$

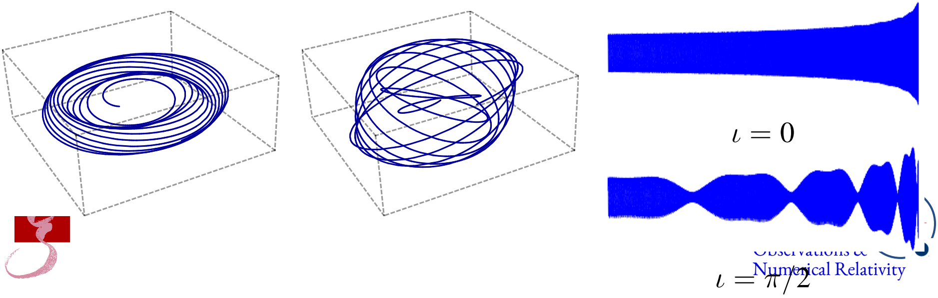
Generic spins: precession

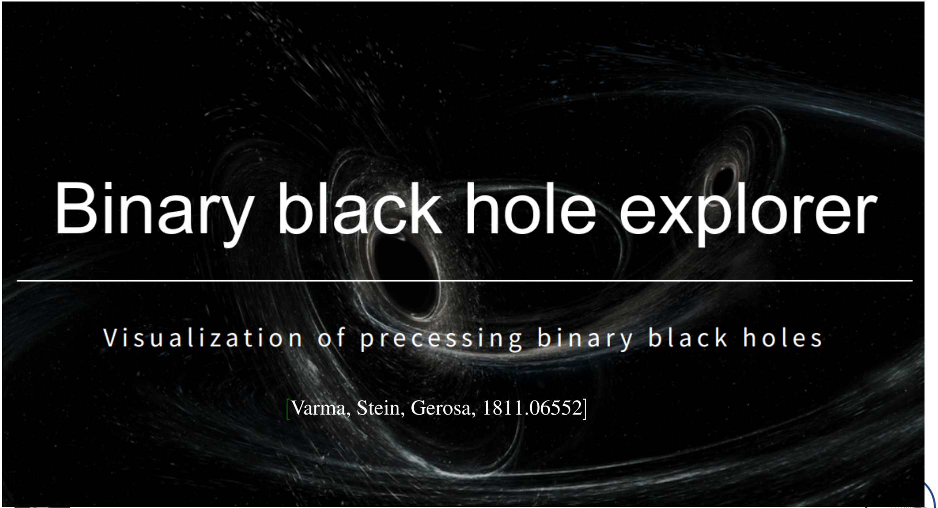
Parameters

- $\eta, \vec{S}_1^\perp, \vec{S}_2^\perp \mapsto \eta, \chi_p$ [Schmidt, FO, Hannam 1408.1810]
- Waveform depends non-trivially on orientation, in particular inclination ι



[Hannam, 1312.3641]





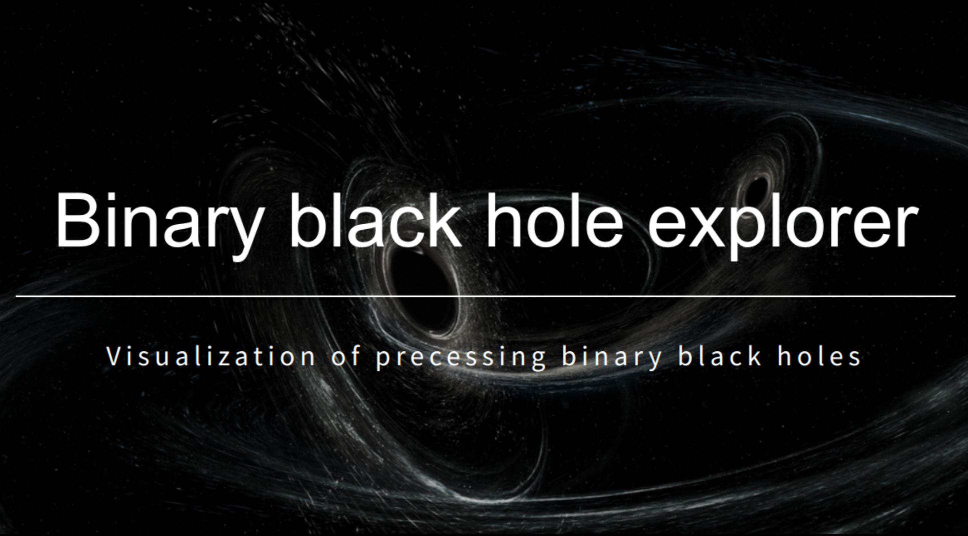
Binary black hole explorer

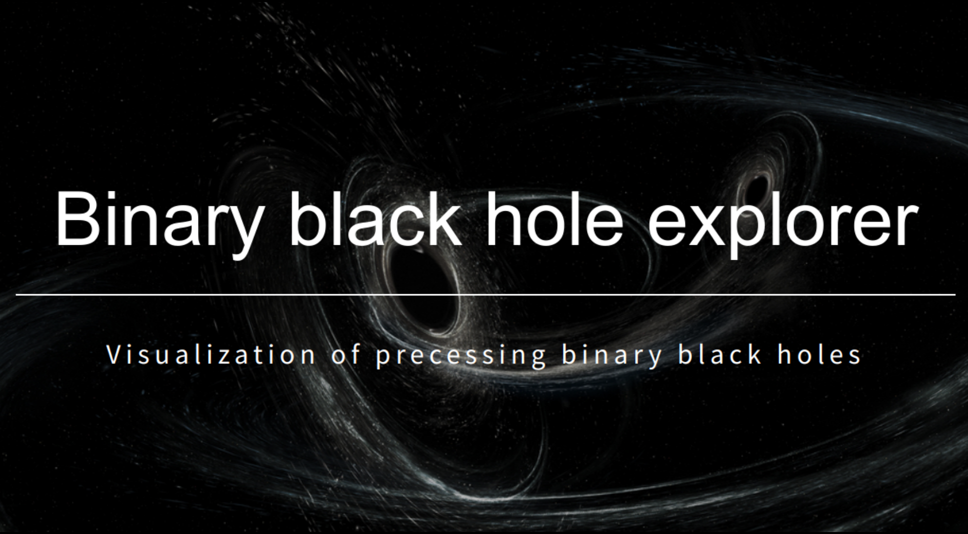
Visualization of precessing binary black holes

[Varma, Stein, Gerosa, 1811.06552]

Binary black hole explorer

Visualization of precessing binary black holes



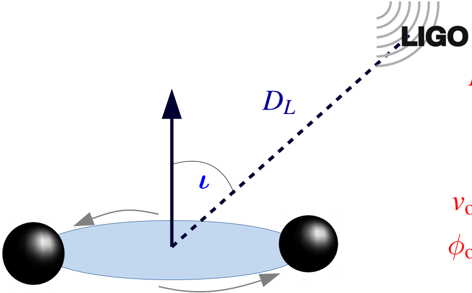


Binary black hole explorer

Visualization of precessing binary black holes

Distance and inclination

$$h_+ \approx 2\left(1 + \cos^2 \iota\right) \frac{M\eta v_{\mathrm{orb}}(t)^2}{D_L} \cos\left[2\phi_{\mathrm{orb}}(t)\right]$$



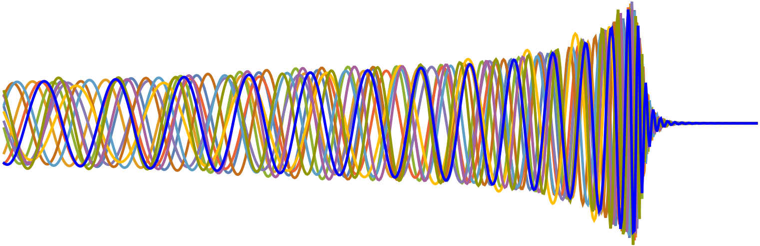
M: total mass, $M = m_1 + m_2$

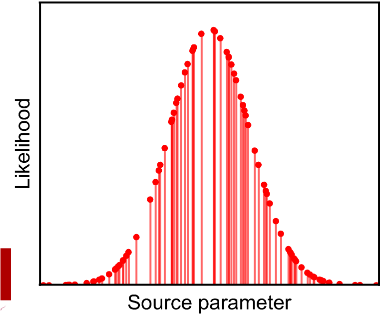
η: symmetric mass ratio, $\eta = m_1 m_2 / M^2$

v_{orb}: orbital velocity

ϕ_{orb}: orbital phase

Binary Merger Observations & Numerical Relativity

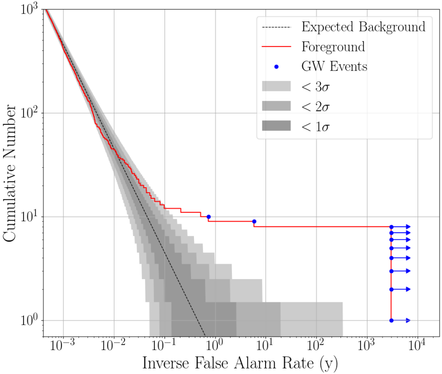




- $\boldsymbol{\vartheta}$: Source parameters
- $\Lambda(s|\boldsymbol{\vartheta}) \sim \exp(-\frac{1}{2}\|s - h(\boldsymbol{\vartheta})\|^2)$
- **Posterior probability**$(\boldsymbol{\vartheta}|s)$ $\sim \Lambda(s|\boldsymbol{\vartheta}) \times \mathit{prior}(\boldsymbol{\vartheta})$

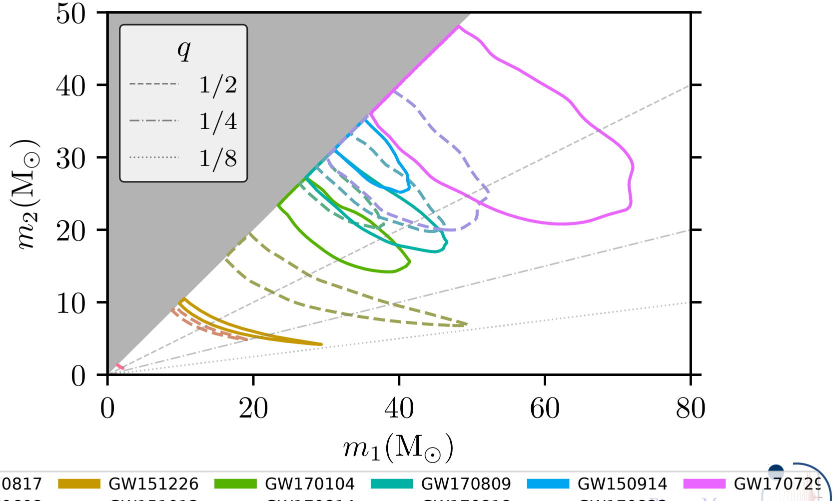
Binary Merger
Observations &
Numerical Relativity

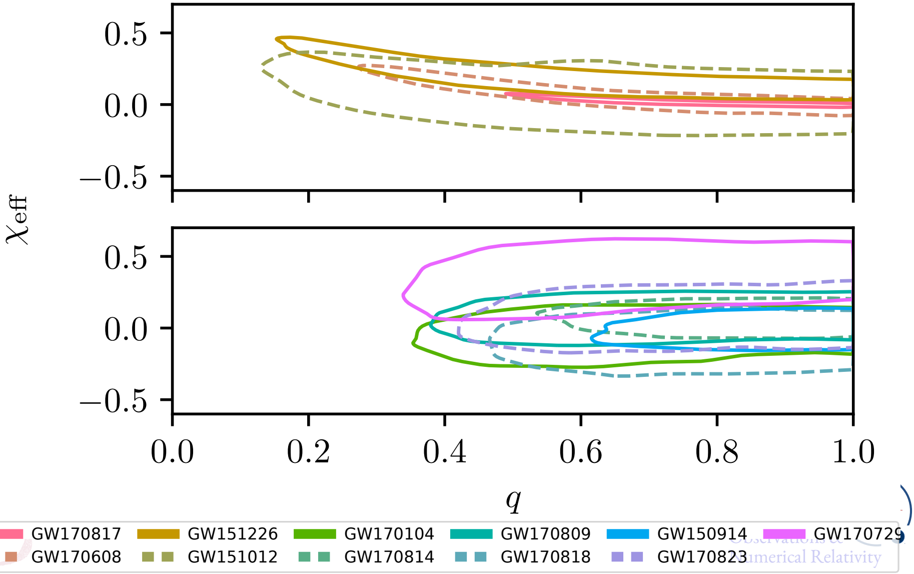
Gravitational-Wave Transient Catalog



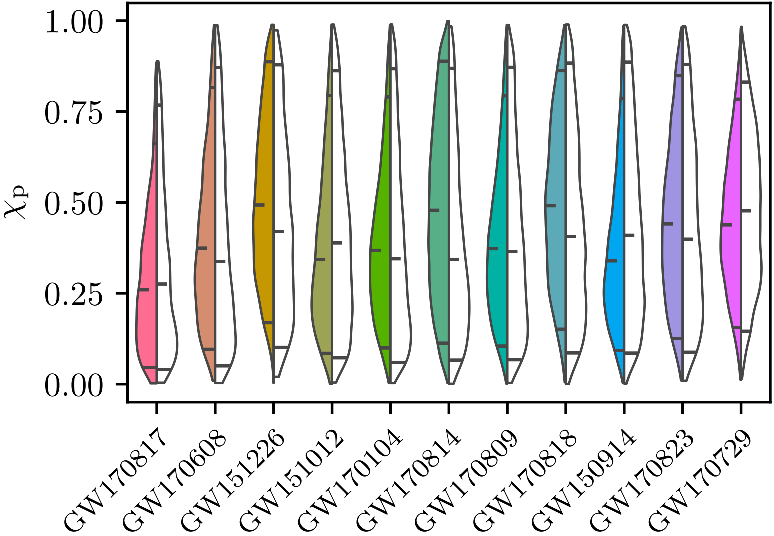
- Advanced LIGO's first and second observing runs, 2015-2017
- 10 binary black holes
- 1 binary neutron star

[LIGO+Virgo 1811.12907]


q
1/2
1/4
1/8
$m_2(\mathrm{M}_\odot)$
0
10
20
30
40
50
0
20
40
60
80
$m_1(\mathrm{M}_\odot)$
GW170817
GW151226
GW170104
GW170809
GW150914
GW17072
GW170608
GW151012
GW170814
GW170818
GW170823

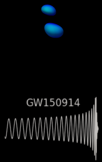

0.5
0.0
−0.5
$\chi_{\rm eff}$
0.5
0.0
−0.5
0.0
0.2
0.4
0.6
0.8
1.0
q
GW170817
GW151226
GW170104
GW170809
GW150914
GW170729
GW170608
GW151012
GW170814
GW170818
GW170823

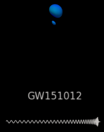
GWTC-1



χ_p
1.00
0.75
0.50
0.25
0.00
GW170817
GW170608
GW151226
GW151012
GW170104
GW170814
GW170809
GW170818
GW150914
GW170823
GW170729

LIGO VIRGO


GW150914

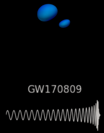

GW151012

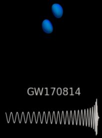

GW151226

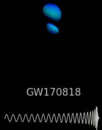

GW170104

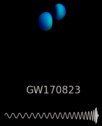

GW170608

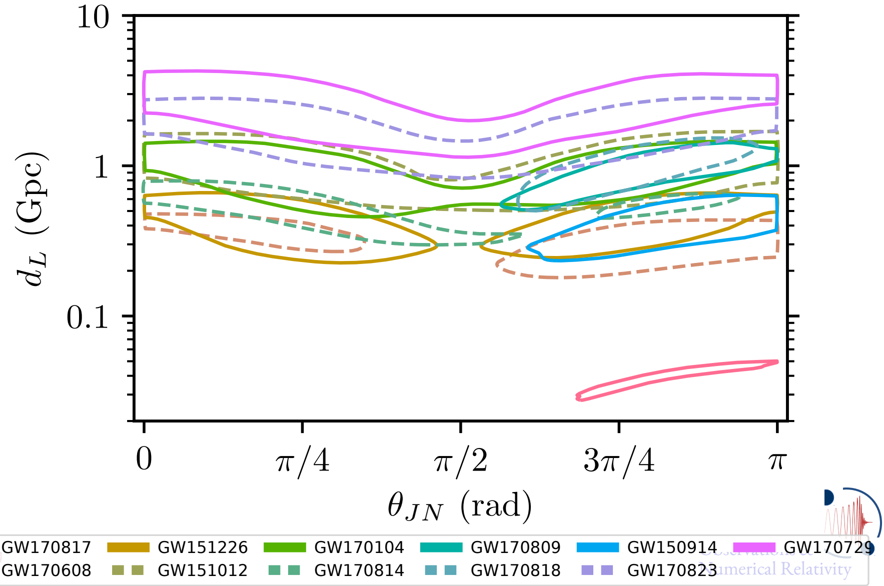

GW170729

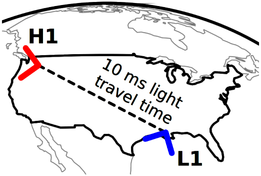

GW170809


GW170814

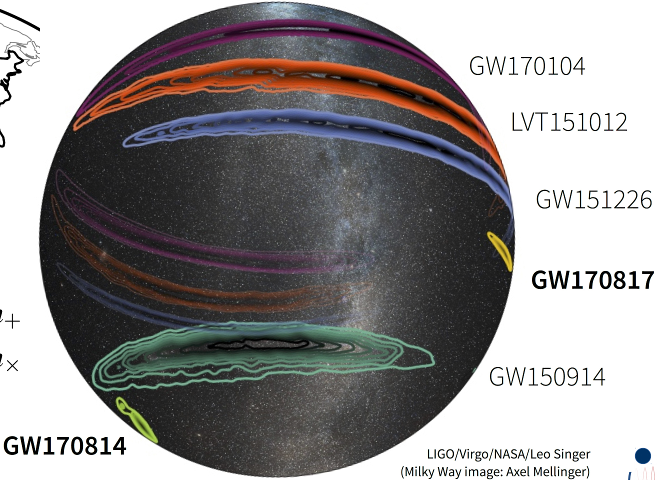

GW170818


GW170823


10
1
0.1
d_L (Gpc)
0
$\pi/4$
$\pi/2$
$3\pi/4$
π
θ_{JN} (rad)
GW170817
GW151226
GW170104
GW170809
GW150914
GW170729
GW170608
GW151012
GW170814
GW170818
GW170823



$$h = F_+(\alpha, \delta, \psi)\ h_+ + F_\times(\alpha, \delta, \psi)\ h_\times$$

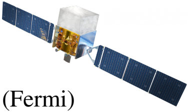


LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

August 17, 2017 – first binary neutron star detection

[ApJL 848:L12 (2017)]

+14s

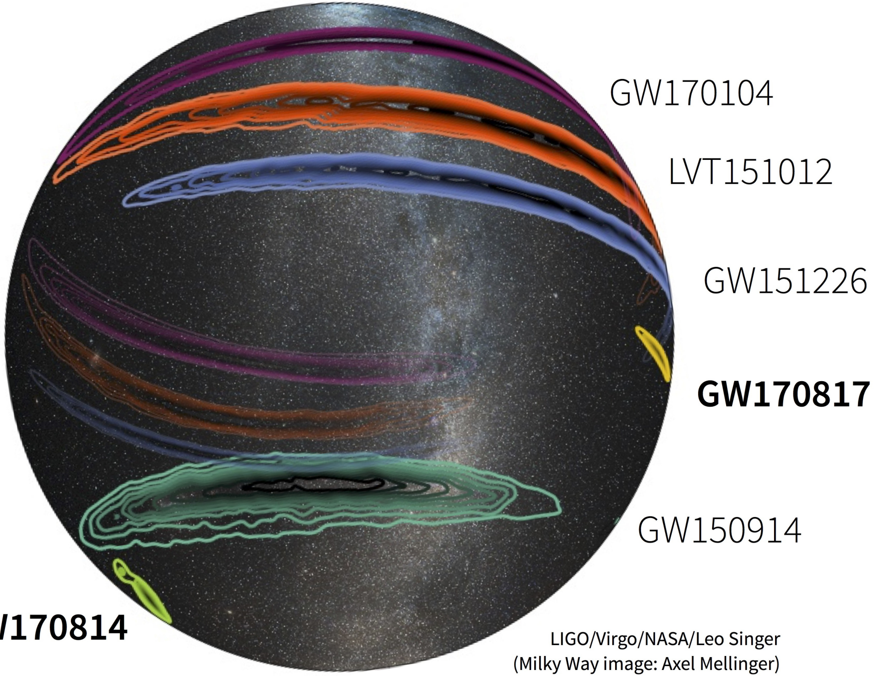


(Fermi)

12:41:06 UTC: I've seen a γ-ray burst.

Wait...

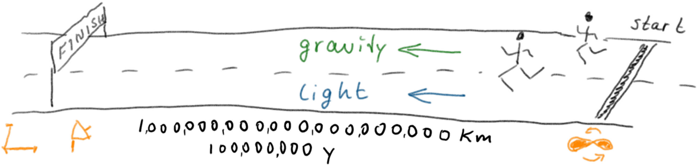
+27min



LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Highlight results

- Binary neutron-star mergers occur and are measurable through gravitational waves. [LIGO/Virgo, PRL**119** no.16 161101 (2017)]
- Binary neutron-star mergers are progenitors of short gamma-ray bursts and kilonovae. [LIGO/Virgo/Fermi, ApjL 848, L13 (2017)]
- A significant fraction of heavy elements (gold, platinum, etc…) is created in neutron-star mergers.
- Matter at extreme densities is not very stiff.
- The speed of light and speed of gravity are similar to at least $\Delta v/c \lesssim 10^{-15}$.



Getting involved

Gravitational Wave Open Science Center

Getting Started
Data
Catalogs
Bulk Data
Tutorials
Software
Detector Status
Timelines
My Sources
GPS ↔ UTC
About the detectors
Projects
Acknowledge GWOSC

www.gw-openscience.org

LIGO Hanford Observatory, Washington
(Credits: C. Gray)

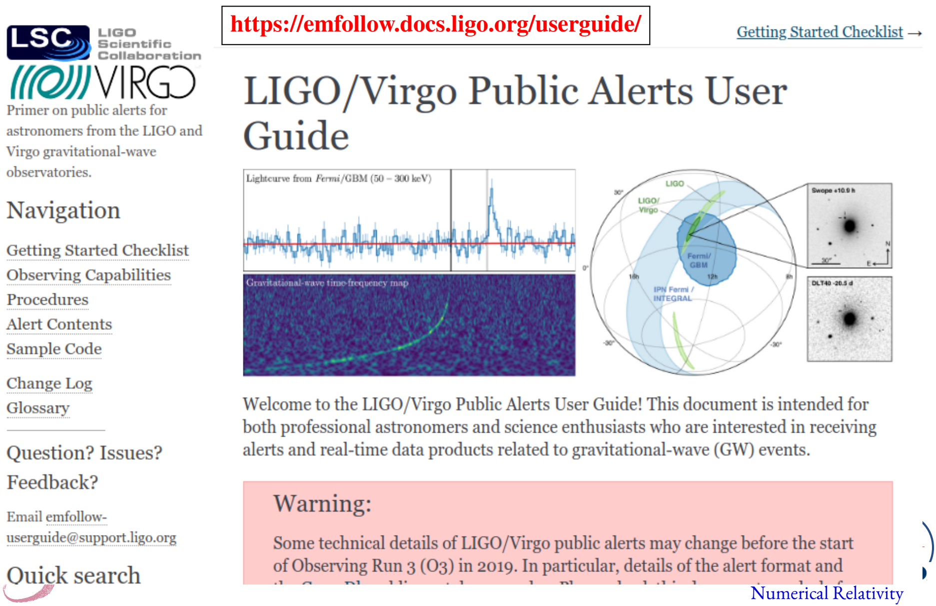
LIGO Livingston Observatory, Louisiana
(Credits: J. Giaime)

The Gravitational Wave Open Science Center provides data from gravitational-wave

- **O2 Bulk Data Release!**
- **Get started!**
- **Download data**
- **GWTC-1: Catalog of Compact Binary Mergers**
- **Join the email list**
- **Attend an open data workshop**

Getting involved

https://emfollow.docs.ligo.org/userguide/



LSC LIGO Scientific Collaboration

VIRGO

Primer on public alerts for astronomers from the LIGO and Virgo gravitational-wave observatories.

Navigation

- Getting Started Checklist
- Observing Capabilities
- Procedures
- Alert Contents
- Sample Code

- Change Log
- Glossary

Question? Issues? Feedback?

Email emfollow-userguide@support.ligo.org

Quick search

Getting Started Checklist →

LIGO/Virgo Public Alerts User Guide

Welcome to the LIGO/Virgo Public Alerts User Guide! This document is intended for both professional astronomers and science enthusiasts who are interested in receiving alerts and real-time data products related to gravitational-wave (GW) events.

Warning:

Some technical details of LIGO/Virgo public alerts may change before the start of Observing Run 3 (O3) in 2019. In particular, details of the alert format and

Numerical Relativity

What I intended you learn

- Basics of gravitational-wave emission
    - Source: second time derivative of mass quadrupole moment
- Gravitational-wave interferometers
    - GW → differential length change → laser light phase difference → signal
    - Complex instruments, variety of noise sources
- Gravitational-wave analysis
    - If model available: extract information by comparing data and model
- Binary dynamics and measurement
    - Masses & spins ↔ phase/frequency evolution
    - Distance & inclination ↔ amplitude
    - Location ↔ time difference
- Gravitational-wave astronomy in action

Binary Merger
Observations &
Numerical Relativity