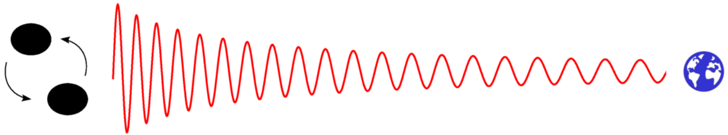
Gravitational waves: from theory to observations

Alexandre Le Tiec

Laboratoire Univers et Théories
Observatoire de Paris / CNRS



Outline

1. General relativity
2. Gravitational waves
3. Gravitational-wave science
4. Gravitational-wave astronomy

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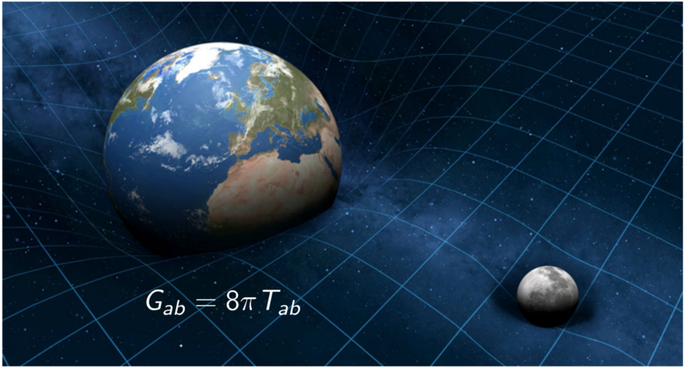
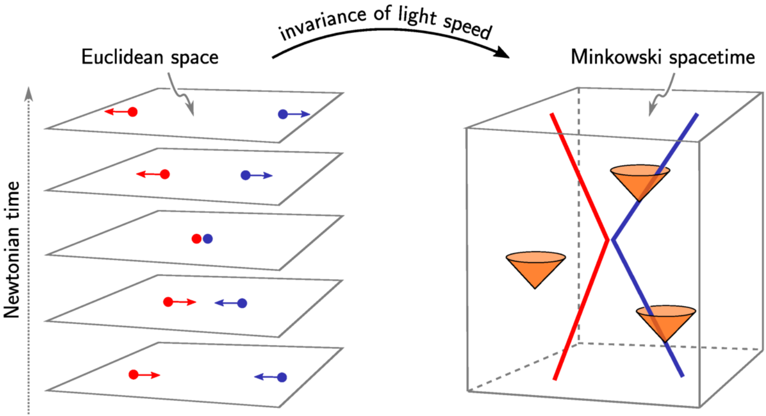
Einstein's theory of General Relativity



General relativity is the theory of **space**, **time** and **gravitation** formulated by Albert Einstein in 1915

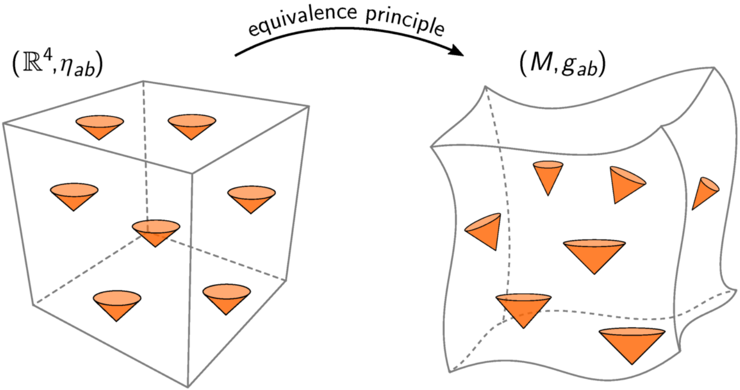
From space and time to spacetime



Prerelativity physics

Special relativity (1905)

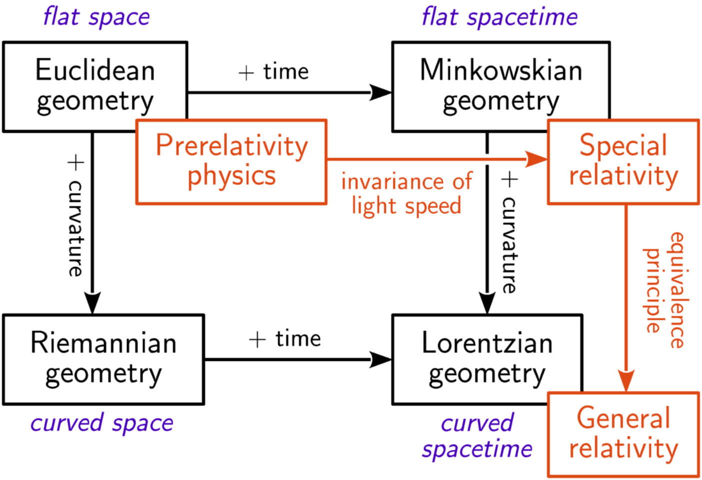
From flat spacetime to curved spacetime



Special relativity (1905)

General relativity (1915)

The road to General Relativity



General Relativity in a nutshell

Einstein field equation

$$G_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

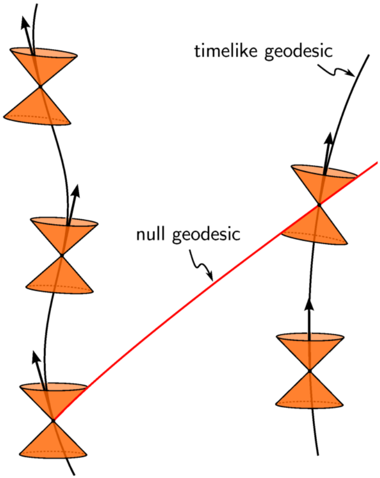
Matter tells spacetime how to curve

$$\Downarrow$$

Local conservation law

$$\nabla^a T_{ab} = 0$$

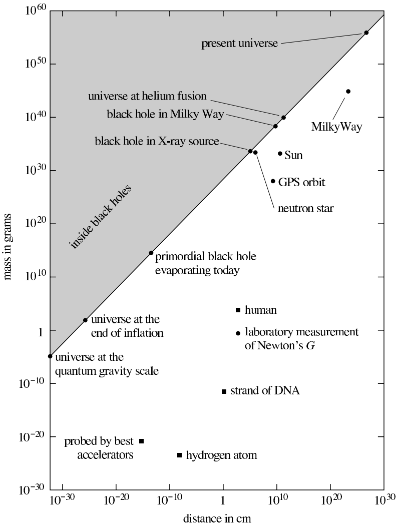
Spacetime tells matter how to move



The realm of General Relativity

$$\text{Compactness} \equiv \frac{G}{c^2}\frac{M}{R}$$

System	Compactness
Proton	$\sim 10^{-39}$
Earth	$\sim 10^{-9}$
Sun	$\sim 10^{-6}$
White dwarf	$\sim 10^{-3}$
Neutron star	~ 0.2
Black hole	~ 0.5
Universe	~ 0.5



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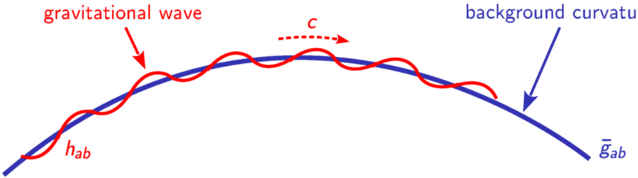
What is a gravitational wave ?

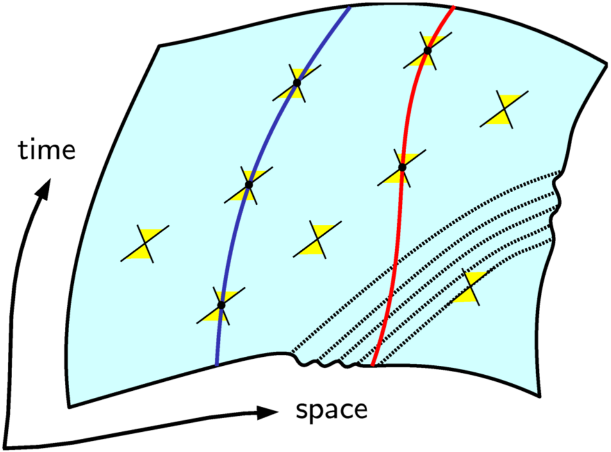
A gravitational wave is a tiny ripple in the curvature of spacetime that propagates at the vacuum speed of light



$$\Box h_{ab} + 2\bar{R}_{acbd}h^{cd} = -16\pi T_{ab}$$

Key prediction of Einstein's general theory of relativity

What is a gravitational wave ?



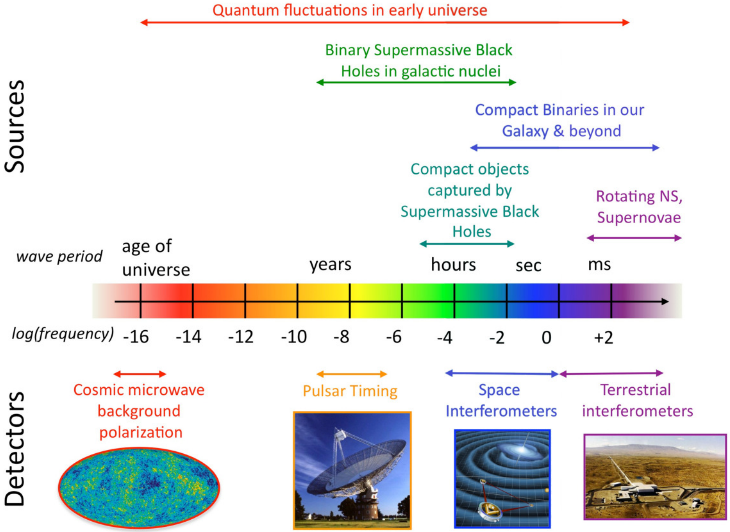
(Credit: E. Gourgoulhon)

Electromagnetic *vs* gravitational waves

	Electromagnetic waves	Gravitational waves
Origin	electromagnetic field	spacetime curvature
Nature	waves in spacetime	waves of spacetime
Sources	accelerated charges	accelerated masses
Wavelength	$\ll$ size of source	$\gtrsim$ size of source
Structure	dipolar	quadrupolar
Coherence	low	high
Interaction	strong	weak
Detection	power	amplitude
Analogy	vision	audition

Complementary sources of information about the Universe

The gravitational-wave spectrum



Gravitational-wave science

Fundamental physics

- Strong-field tests of GR
- Black hole no-hair theorem
- Cosmic censorship conjecture
- Dark energy equation of state
- Alternatives to general relativity

Astrophysics

- Formation and evolution of compact binaries
- Origin and mechanisms of γ-ray bursts
- Internal structure of neutron stars

Cosmology

- Cosmography and measure of Hubble's constant
- Origin and growth of supermassive black holes
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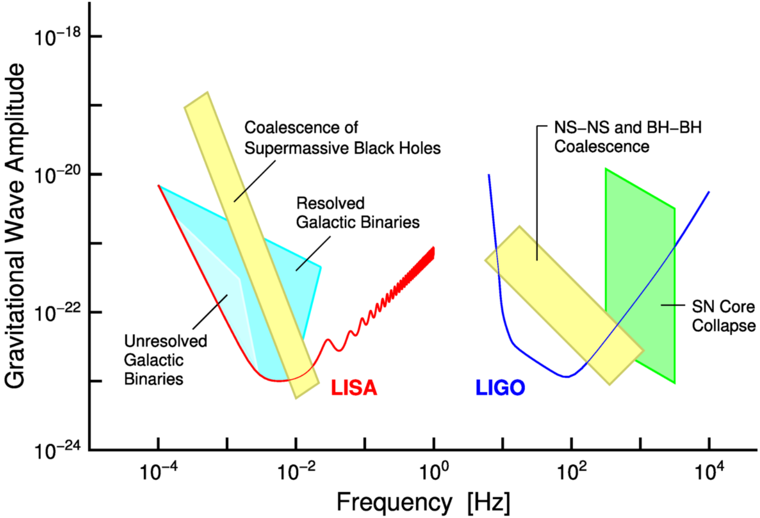
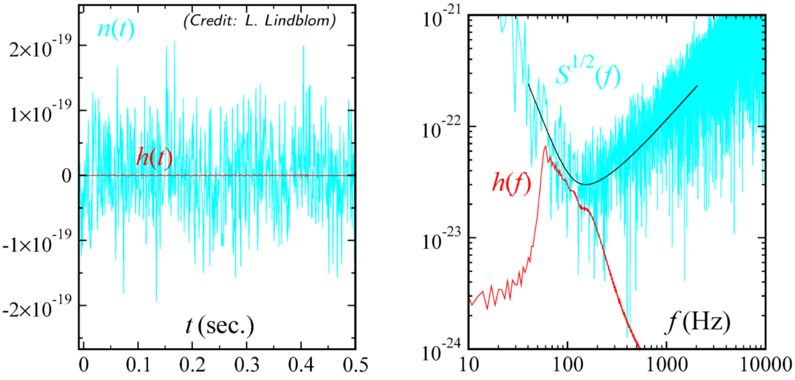
Promising sources of gravitational waves

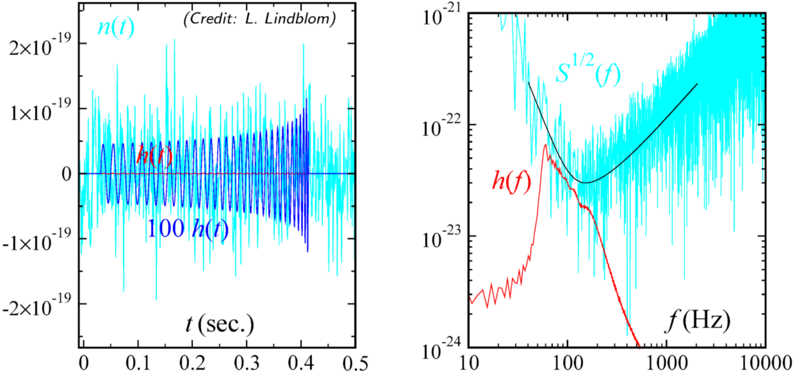


Need for accurate template waveforms



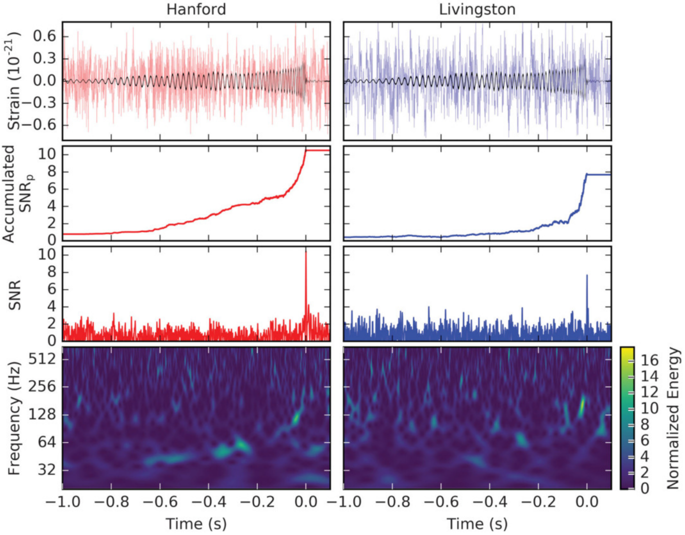
If the expected signal is *known in advance* then $n(t)$ can be filtered and $h(t)$ recovered by matched filtering $\longrightarrow$ **template waveforms**

Need for accurate template waveforms



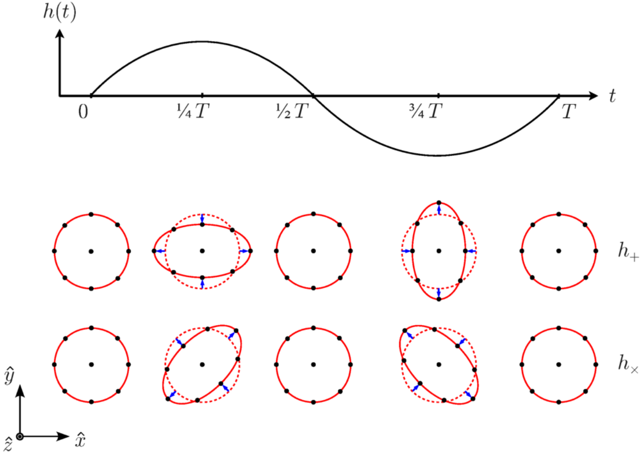
If the expected signal is *known in advance* then $n(t)$ can be filtered and $h(t)$ recovered by matched filtering $\longrightarrow$ **template waveforms**

An example: the event GW151226



[PRL **116** (2016) 241103]

Effect of a traveling gravitational wave

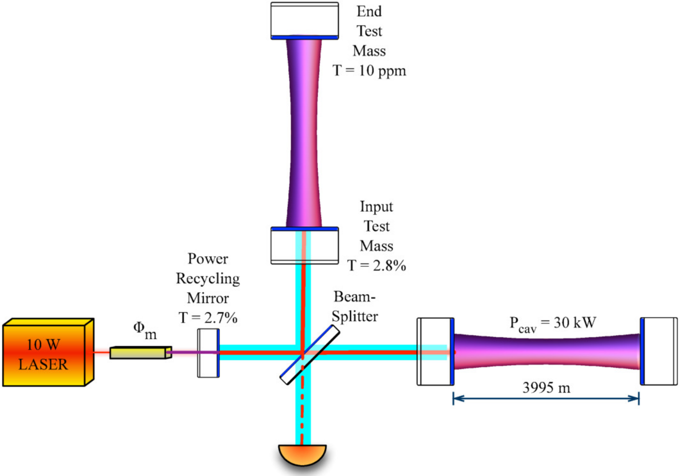


A traveling GW induces a variation in length $\delta L \sim \frac{1}{2} h\, L$

Ground-based interferometric detectors

Optical design of the LIGO interferometers

[Rev. Mod. Phys. **6** (2014) 121]



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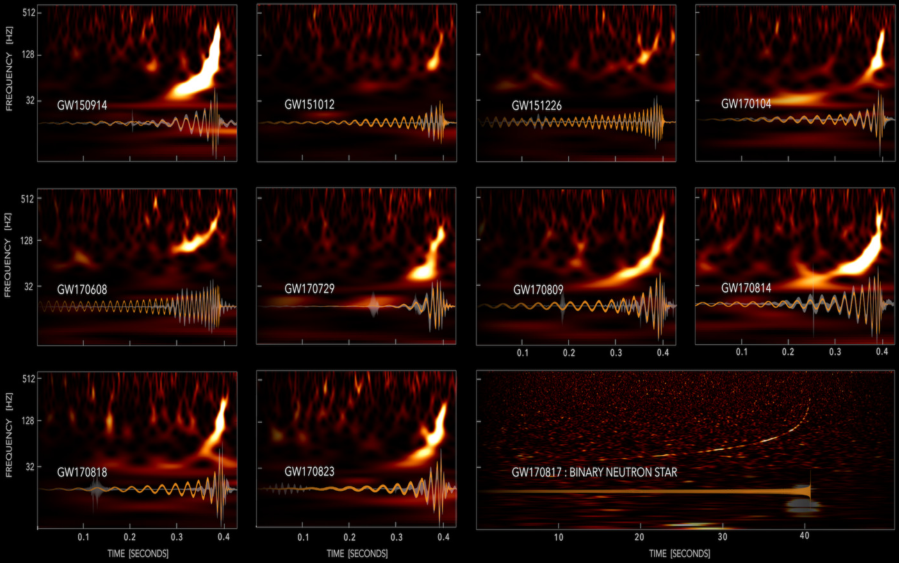
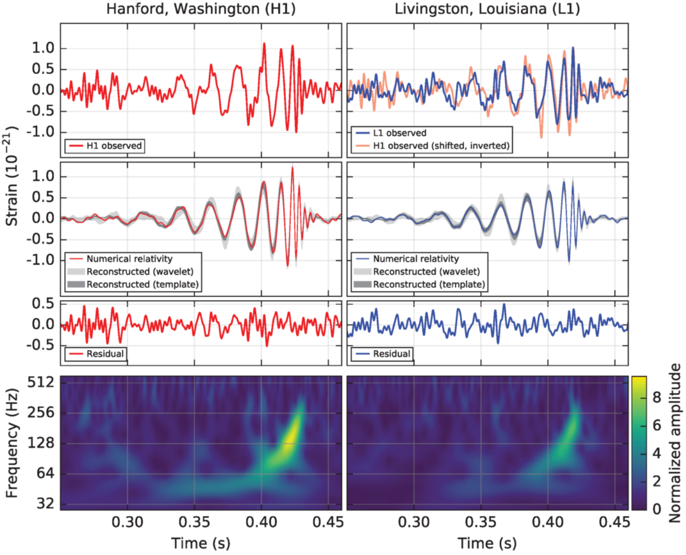
Gravitational-Wave Transient Catalog-1



LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23 WAVELET (UNMODELED) EINSTEIN'S THEORY S. GHONGE, K. JANI | GEORGIA TECH

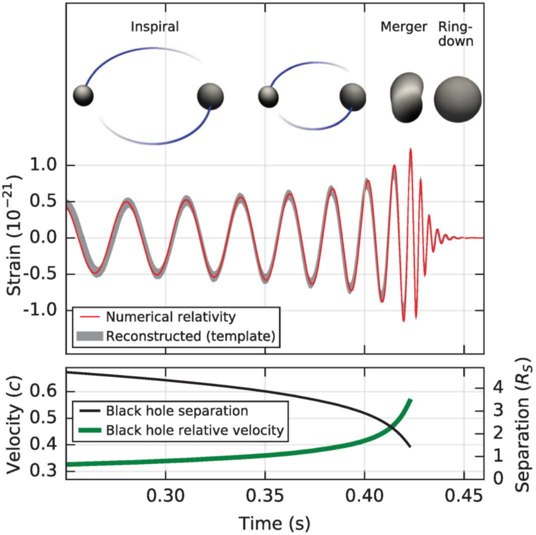
[PRL **116** (2016) 061102]

The event GW150914



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

Two black holes merged



Why is it such a big deal?

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

- First direct detection of GW from the cosmos
- Most robust proof of the existence of black holes
- Discovery of the first binary black hole system
- First test of GR in the strong-field regime

Gravitational-wave science

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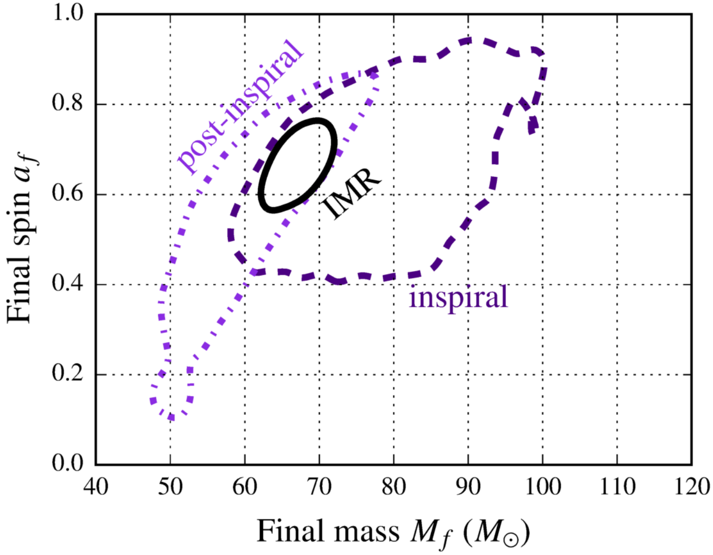
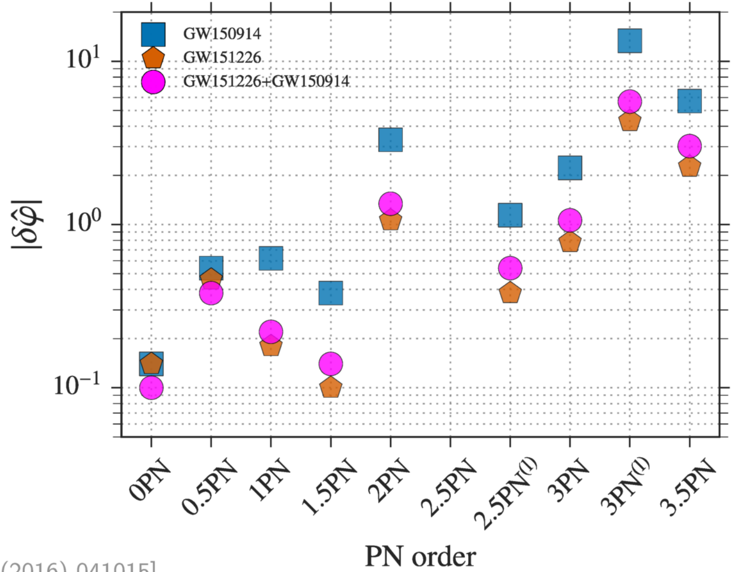
Consistency test for final mass and spin



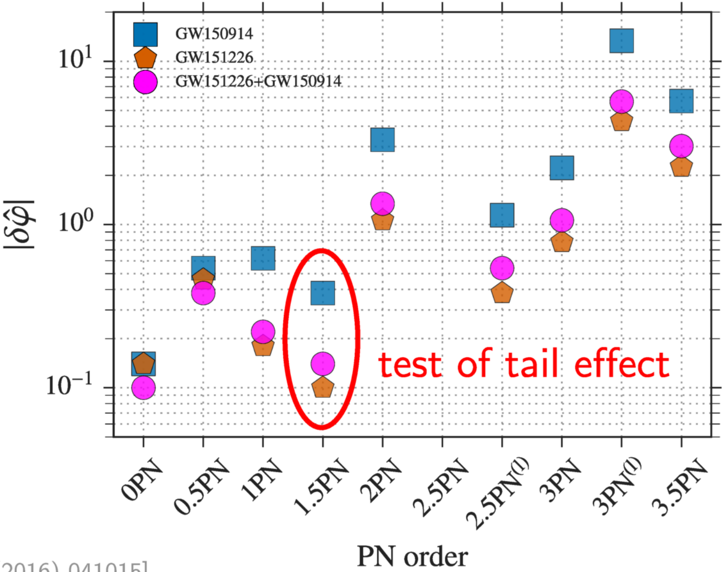
[PRL **116** (2016) 221101]

Constraining post-Newtonian parameters



[PRX **6** (2016) 041015]

Constraining post-Newtonian parameters



[PRX **6** (2016) 041015]

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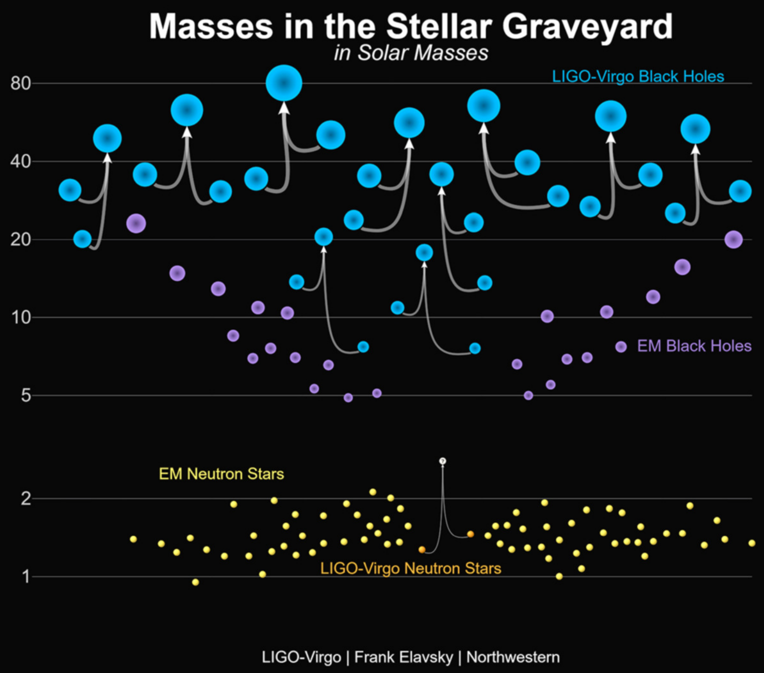
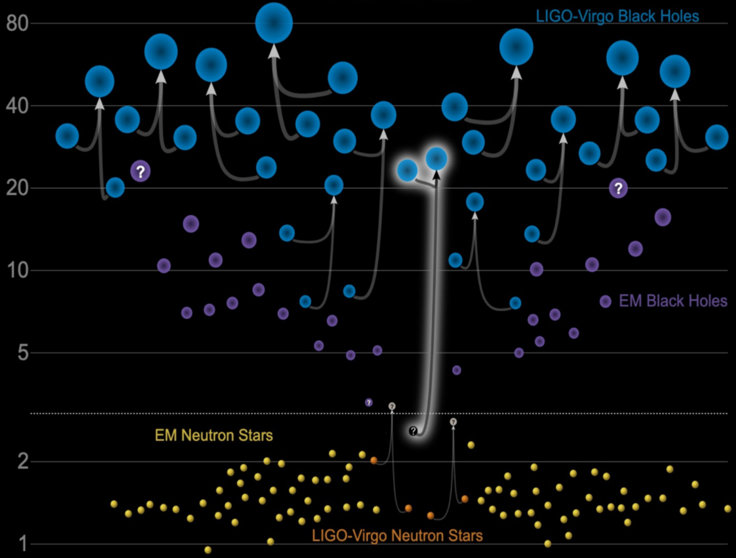


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
LIGO-Virgo | Frank Elavsky | Northwestern

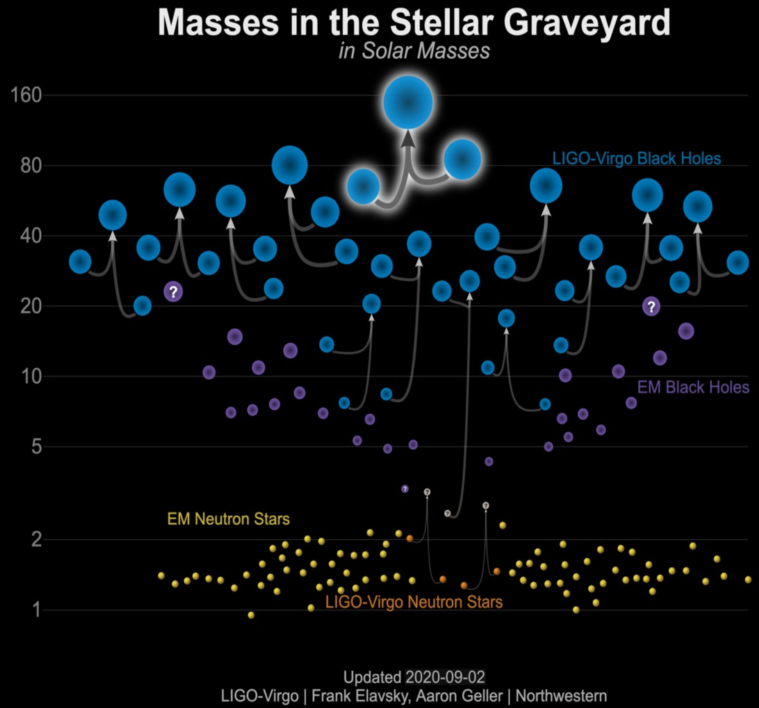
Masses in the Stellar Graveyard

in Solar Masses



Updated 2020-05-16

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

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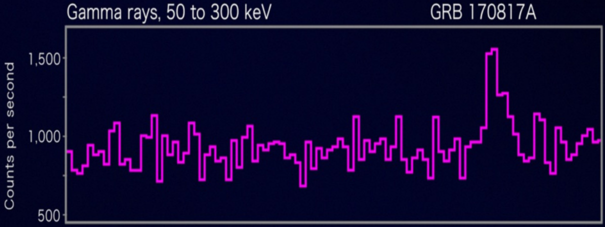
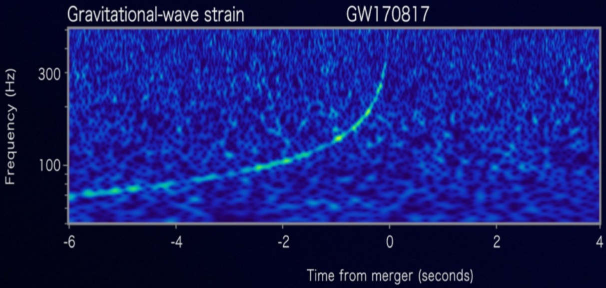
Fermi

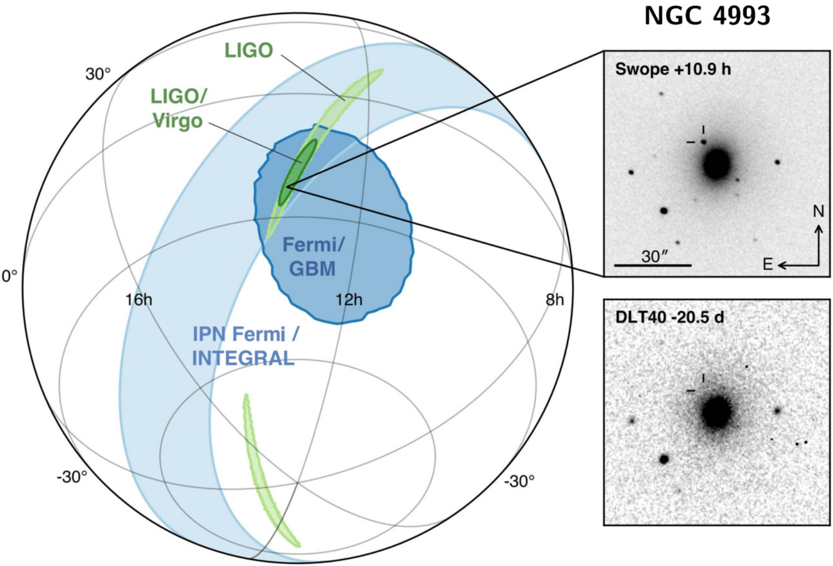

Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500

LIGO


Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

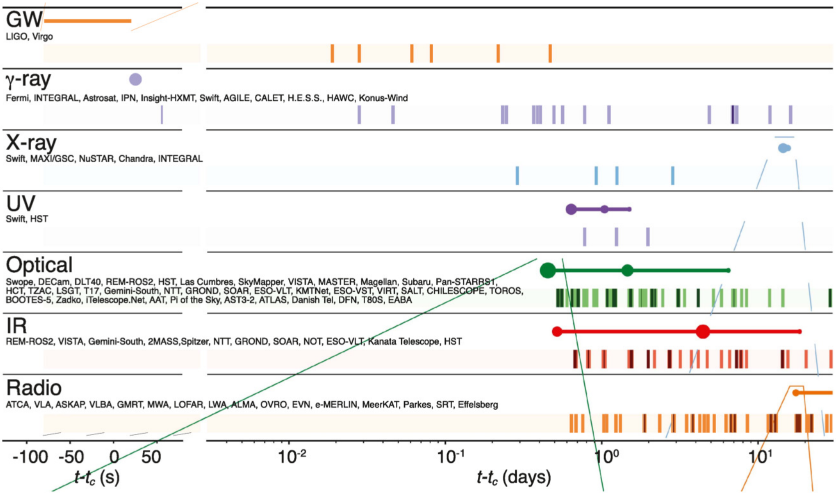
[ApJ **848** (2017) L12]

A binary neutron star merger



[ApJ **848** (2017) L12]

Multi-messenger astronomy



Why is it such a big deal?

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

- First observation of a binary neutron star merger
- Supports the theory of *r*-process nucleosynthesis
- Neutron star mergers $\leftrightarrow$ short γ-ray bursts
- Measure of Hubble constant $H_0 = 70 \pm 10$ km/s/Mpc
- Constraint on nuclear matter equation of state
- Strong bound on $|c_g/c - 1|$

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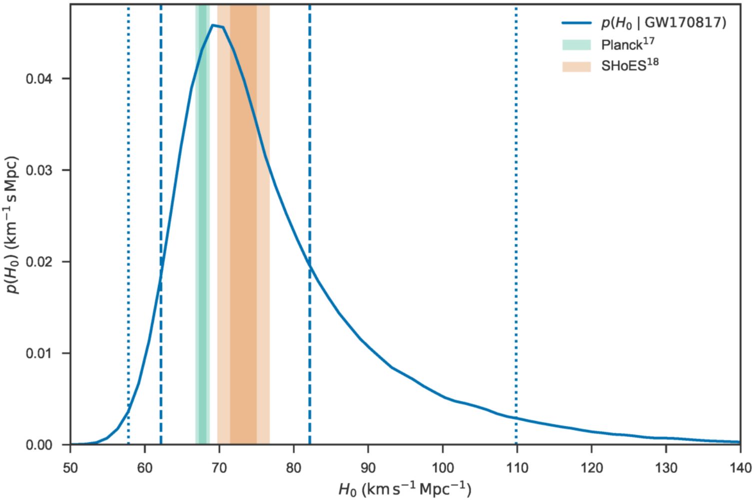
Independent measure of Hubble's constant



[Nature **551** (2017) 85]

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Falsifying many scalar-tensor theories

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity	quartic/quintic Galileons [13, 14]
	quintessence/k-essence [42]	Fab Four [15, 16]
	Brans-Dicke/$f(R)$ [43, 44]	de Sitter Horndeski [45]
	Kinetic Gravity Braiding [46]	$G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18]	quartic/quintic GLPV [19]
	Disformal Tuning (22)	DHOST [20, 48] with $A_1 \neq 0$
	DHOST with $A_1 = 0$	
	Viable after GW170817	Non-viable after GW170817

$$|c_g/c - 1| < 10^{-15}$$

[PRL **119** (2017) 251304]

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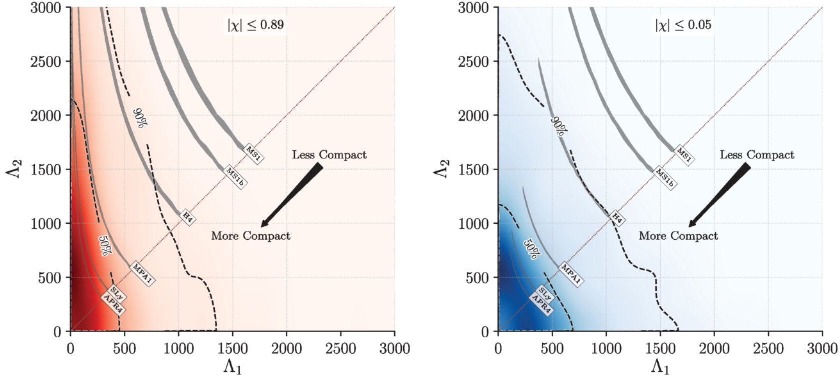
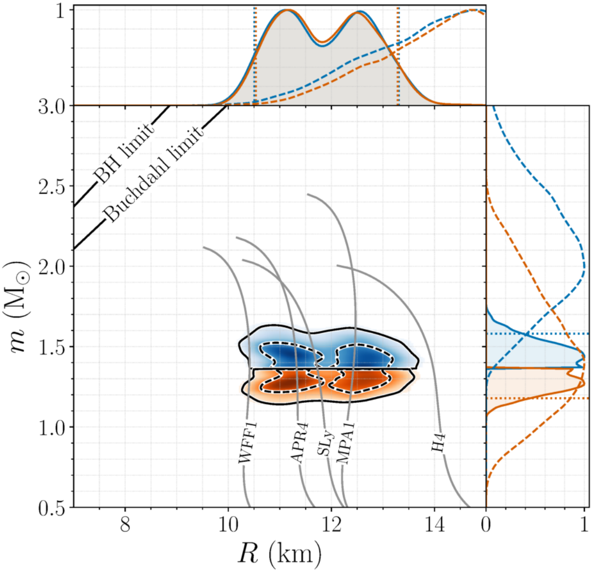
Tidal deformability of neutron stars



$$\Lambda \propto \left(\frac{c^2 R}{Gm}\right)^5$$

[PRL **119** (2017) 161101]

Mass, radius and equation of state



[LIGO-P1800115 (2018)]

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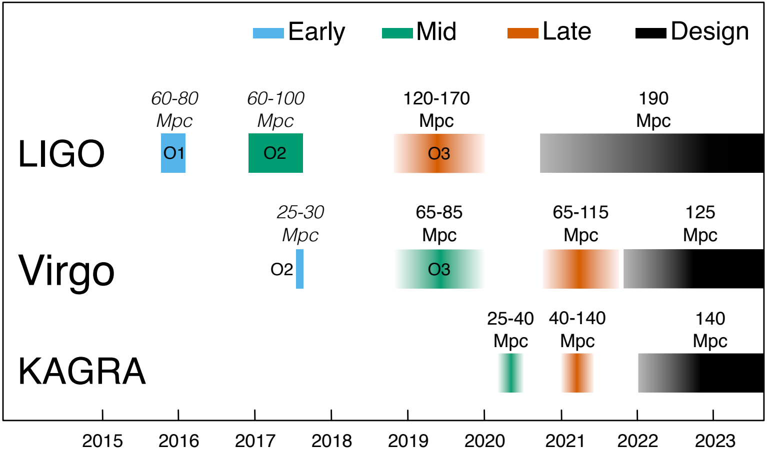
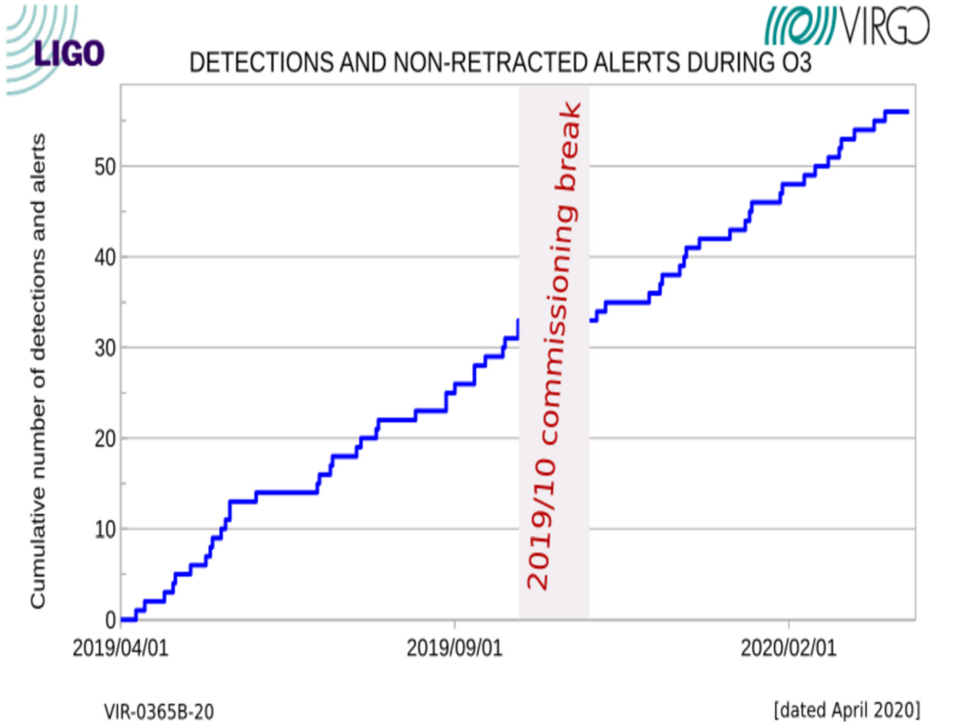
An upcoming network of GW observatories

- Upgrade to Advanced LIGO/Virgo + KAGRA in Japan
- Second generation: sensitivity $\times 10 \Longrightarrow$ event rate $\times 10^3$

Roadmap for advanced GW detectors

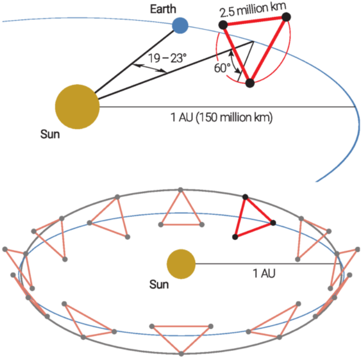
[Living Rev. Relativity **19** (2016)]

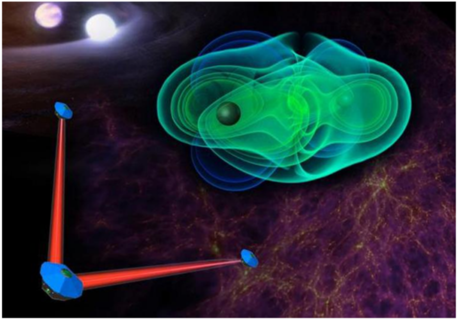




LIGO
VIRGO
DETECTIONS AND NON-RETRACTED ALERTS DURING O3
Cumulative number of detections and alerts
0
10
20
30
40
50
2019/04/01
2019/09/01
2020/02/01
2019/10 commissioning break
VIR-0365B-20
[dated April 2020]

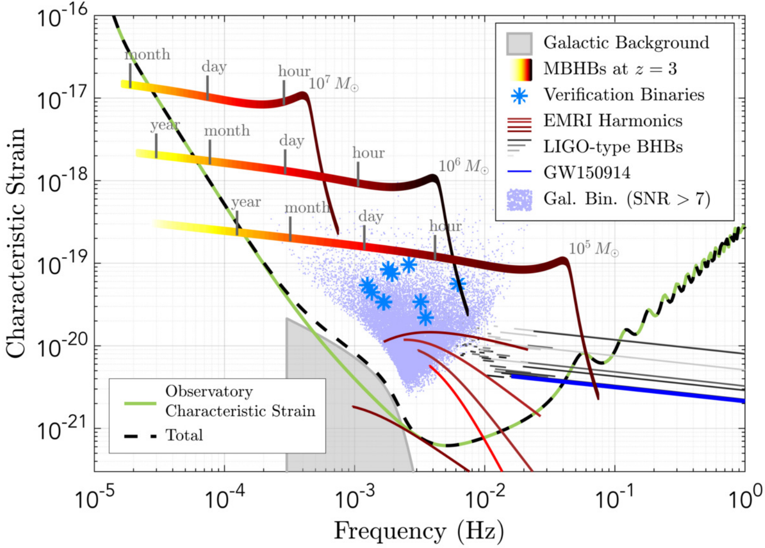
LISA: a gravitational antenna in space



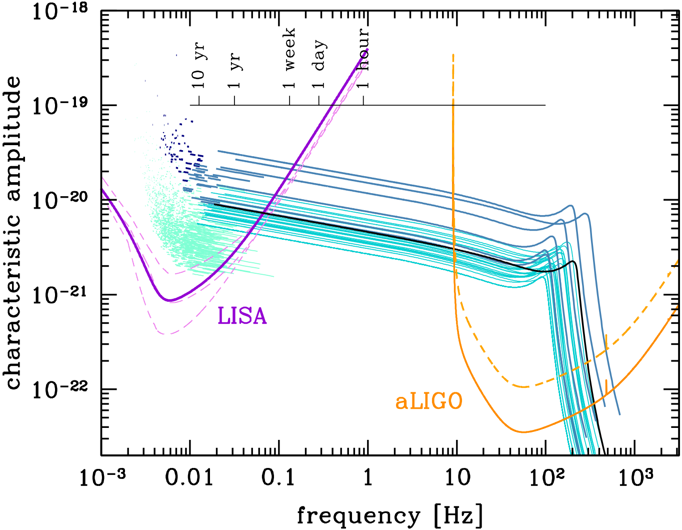


The *LISA mission* proposal was selected by ESA in 2017 for L3 slot, with a launch planned for 2034 [http://www.lisamission.org]

LISA sources of gravitational waves



Multi-band gravitational wave astronomy



[PRL **116** (2016) 231102]

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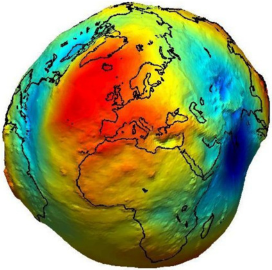
- Origin and mechanisms of γ-ray bursts
- Internal structure of neutron stars

Cosmology

- Cosmography and measure of Hubble's constant
- Origin and growth of supermassive black holes
- Phase transitions during primordial Universe

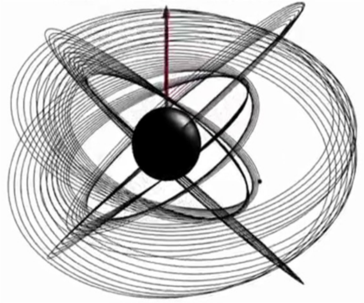
Do black holes have hair?

Geodesy



M_ℓ arbitrary

Botriomeladesy



$M_\ell + iS_\ell = M(ia)^\ell$

Gravitational-wave science

Fundamental physics

- Strong-field tests of GR
- Black hole no-hair theorem
- Cosmic censorship conjecture
- Dark energy equation of state
- Alternatives to general relativity

Astrophysics

- Formation and evolution of compact binaries
- Origin and mechanisms of γ-ray bursts
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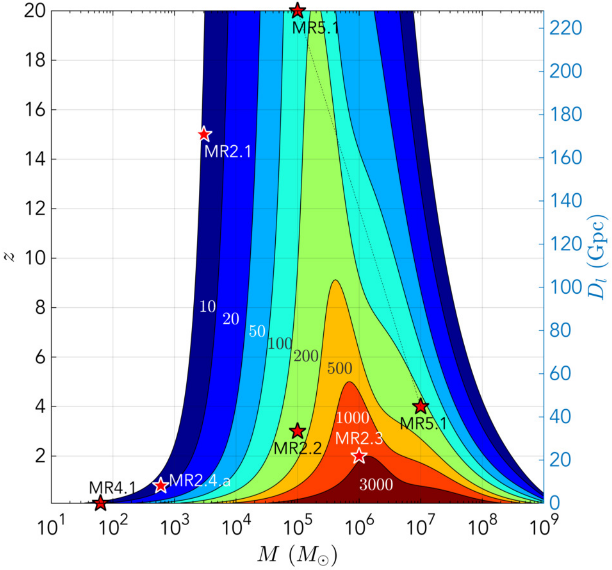
Cosmology

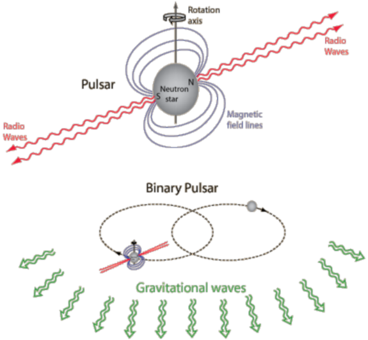
- Cosmography and measure of Hubble's constant
- **Origin and growth of supermassive black holes**
- Phase transitions during primordial Universe

How do massive black holes form?

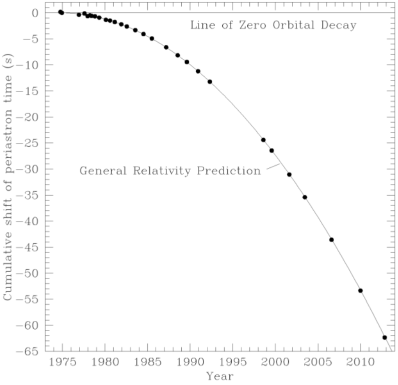


Additional Material

Indirect evidence for the existence of GW



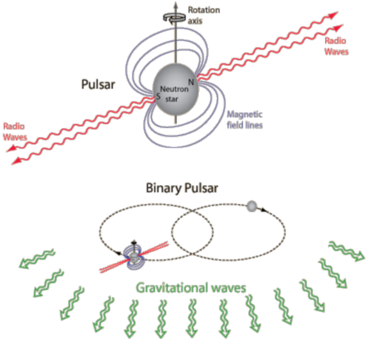
Binary pulsar PSR B1913+16
[Hulse & Taylor, ApJ 1975]



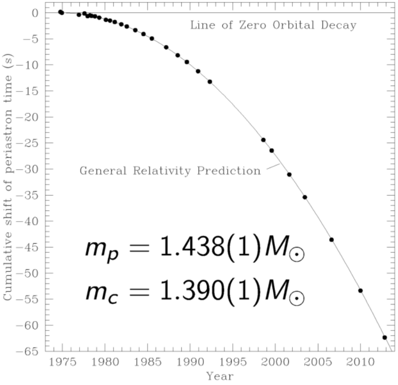
[Weisberg & Huang, ApJ 2016]

Orbital decay due to GW emission confirmed at the **0.16%** level

Indirect evidence for the existence of GW



Binary pulsar PSR B1913+16
[Hulse & Taylor, ApJ 1975]

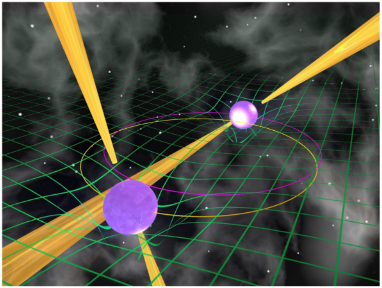


$$m_p = 1.438(1) M_\odot$$
$$m_c = 1.390(1) M_\odot$$

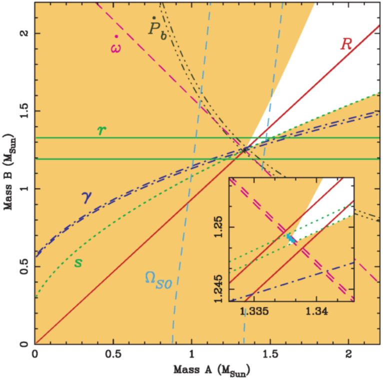
[Weisberg & Huang, ApJ 2016]

Orbital decay due to GW emission confirmed at the **0.16%** level

Indirect evidence for the existence of GW



Double pulsar PSR J0737-3039
[Burgay *et al.*, Nature 2003]



[Kramer & Wex, CQG 2009]

Orbital decay due to GW emission confirmed at the **0.1%** level