Exploration of the Universe with gravitational waves

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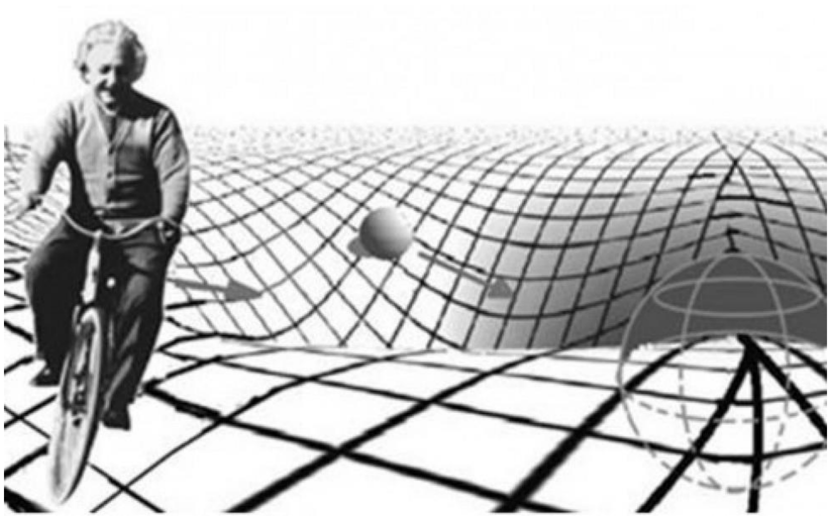
Viva Fysica 2017

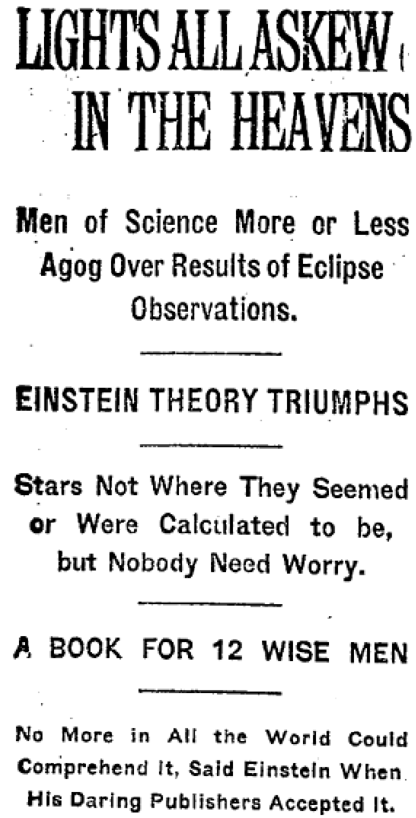
Einstein’s theory of general relativity

Einstein discovers deep connections between space, time, light, and gravity

Einstein’s Gravity

- Space and time are physical objects
- Gravity as a geometry





LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

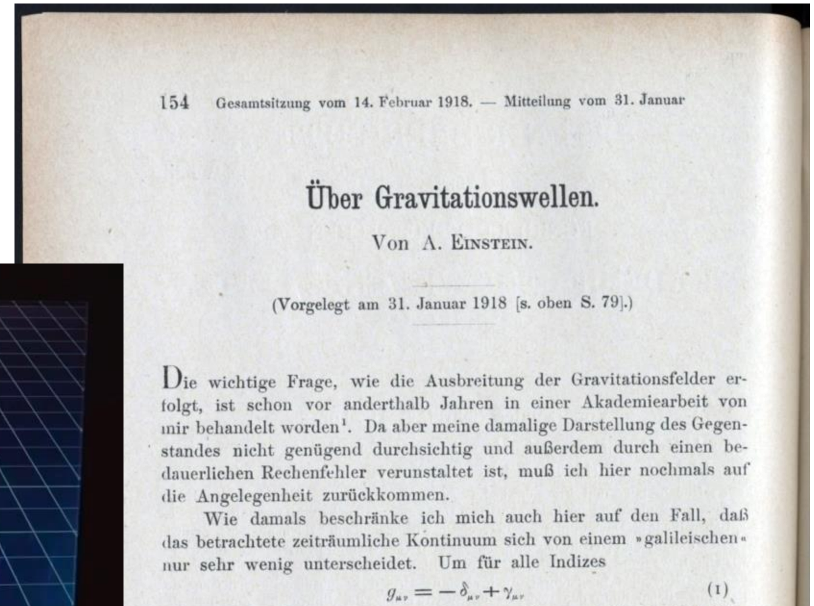
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Predictions

- Gravitation is curvature of spacetime
- Light bends around the Sun
- Expansion of the Universe
- Black holes, wormholes, structure formation, …
- Gravitational waves

Einstein discovers gravitational waves

Einstein publishes his discovery in Sitzungberichte Preussische Akademie der Wissenschaften, 22 June 1916 and on 14 February 1918



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

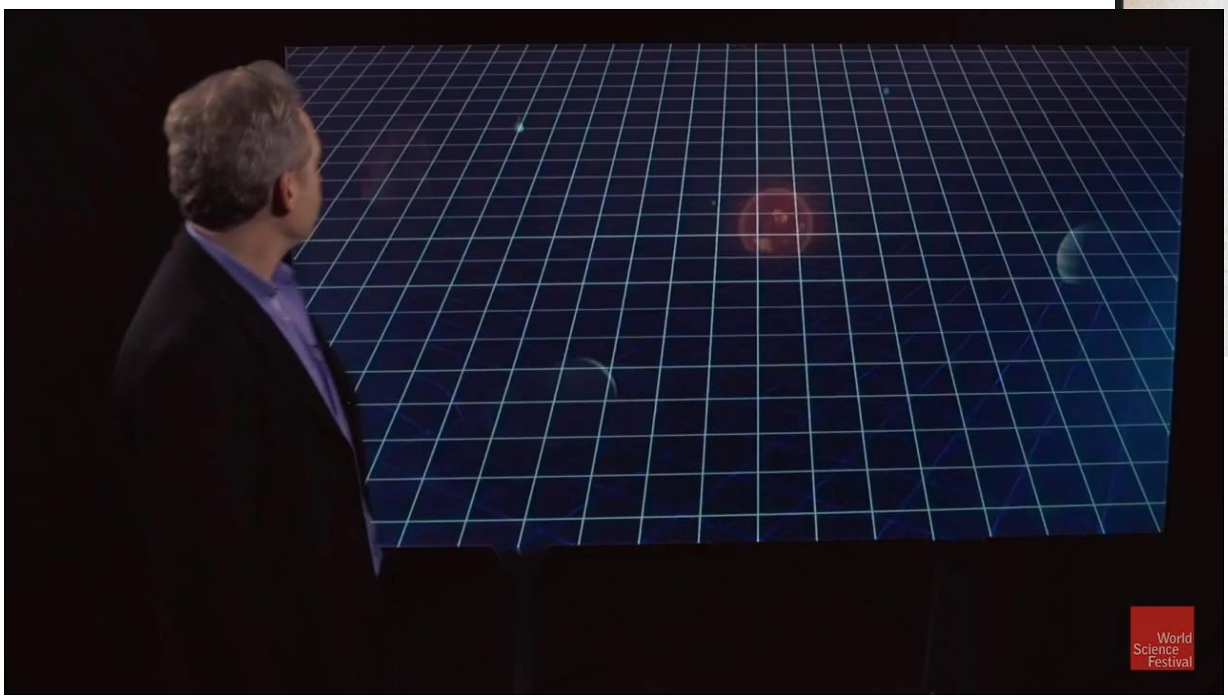
Von A. Einstein.

(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

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$



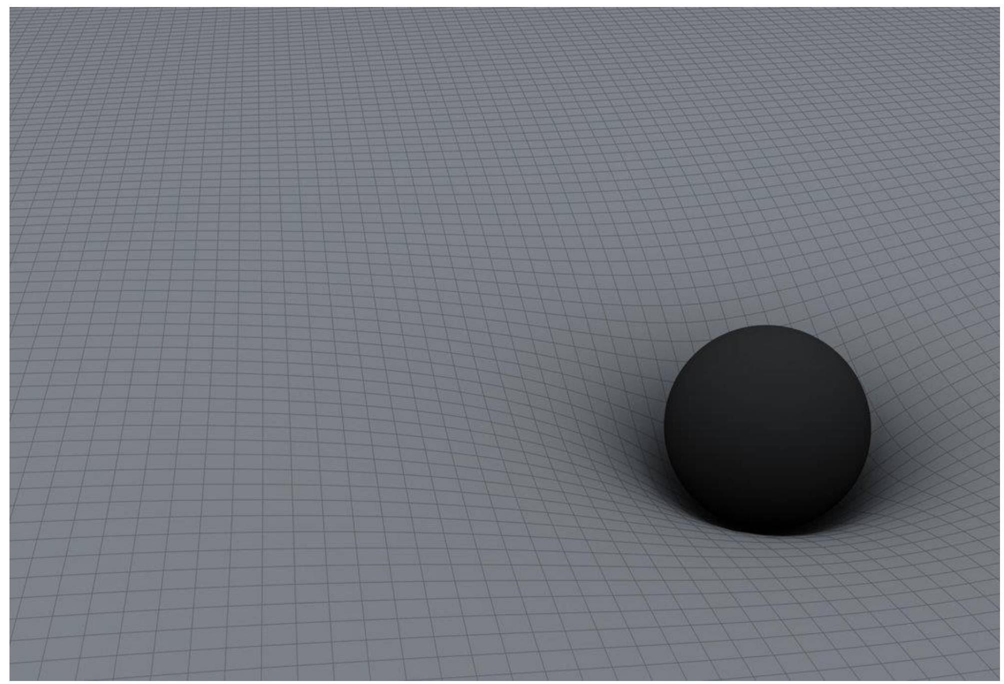
Robert Oppenheimer predicts existence of black holes

Together with Snyder he predicts in 1939 the creation of black holes for neutron stars with masses above approximately $3M_\odot$ (Tolman-Oppenheimer-Volkoff limit)

Black holes are made of spacetime. According to GR all matter has disappeared in a singularity

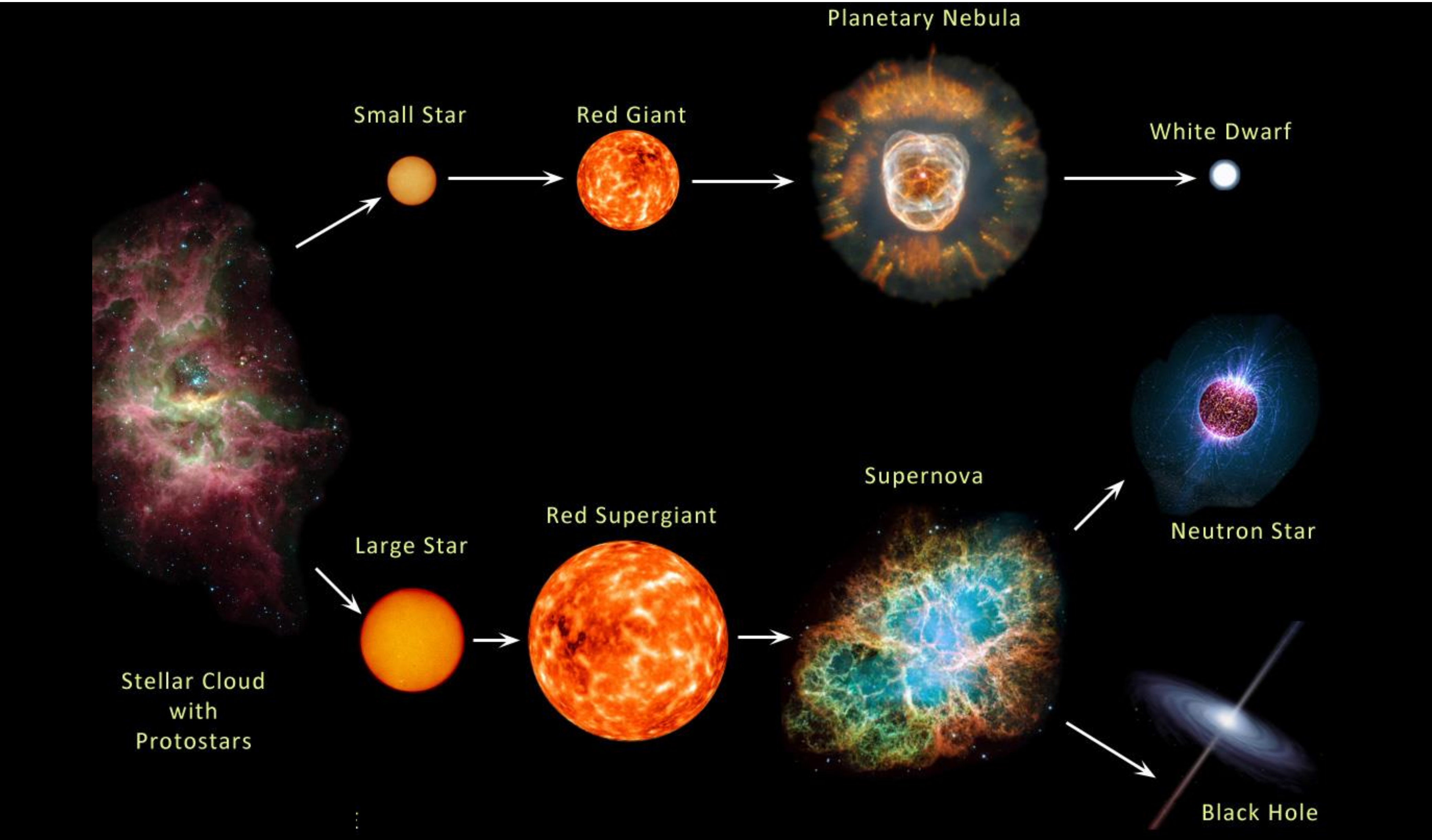
Finkelstein (1958) identified Schwarzschild surface as an event horizon

Discovery of pulsars (1967) and identification as neutron stars (1969)



Evolution of stars

Compact objects are the product of stellar evolution: white dwarfs, neutron stars, and black holes



Binary Neutron Stars (BNS)

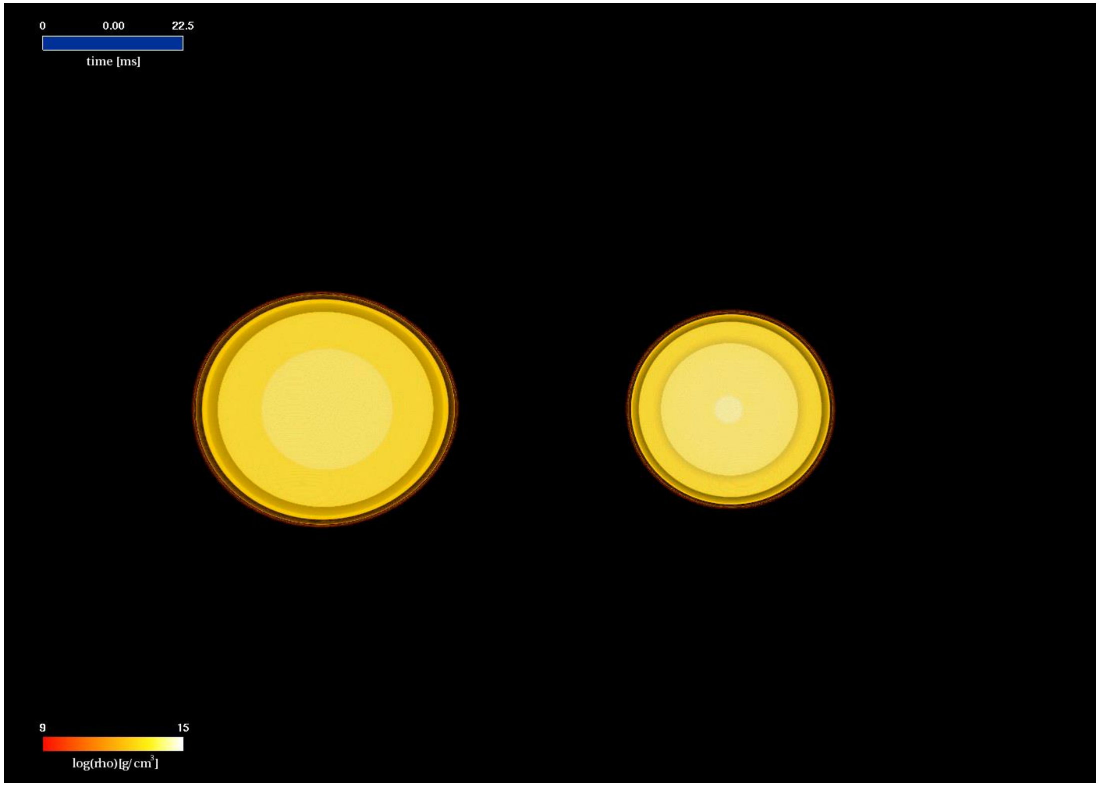
We have observed about 1600 pulsars (NS) in our Milky Way. Thus NS exist and there are probably billions of NS per galaxy

We also discovered 9 binary neutron stars (BNS), *e.g.* Hulse Taylor BNS

These systems undergo strong quadrupole-type acceleration

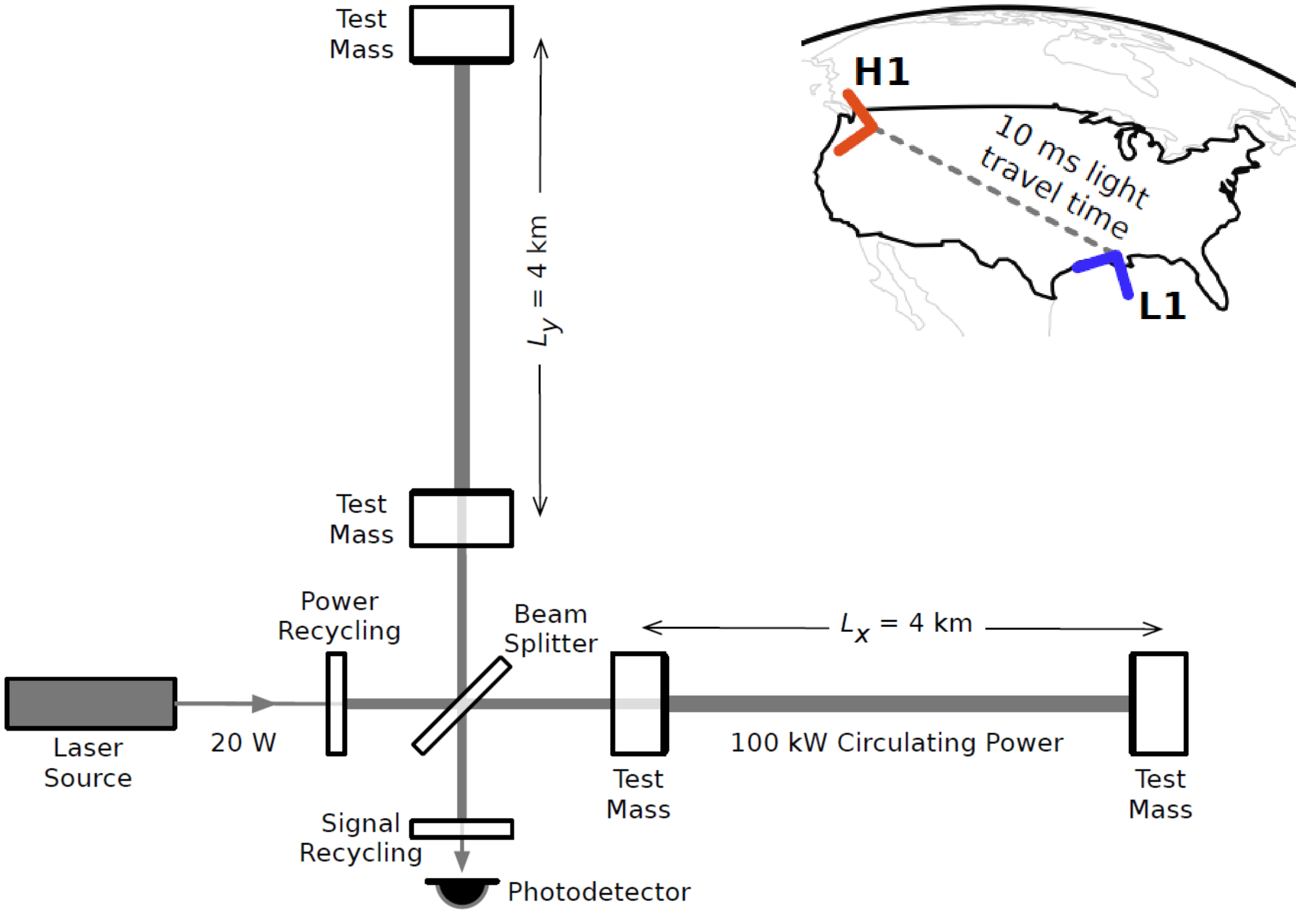
After a certain time, both NS will collide

In the process a black hole may be created



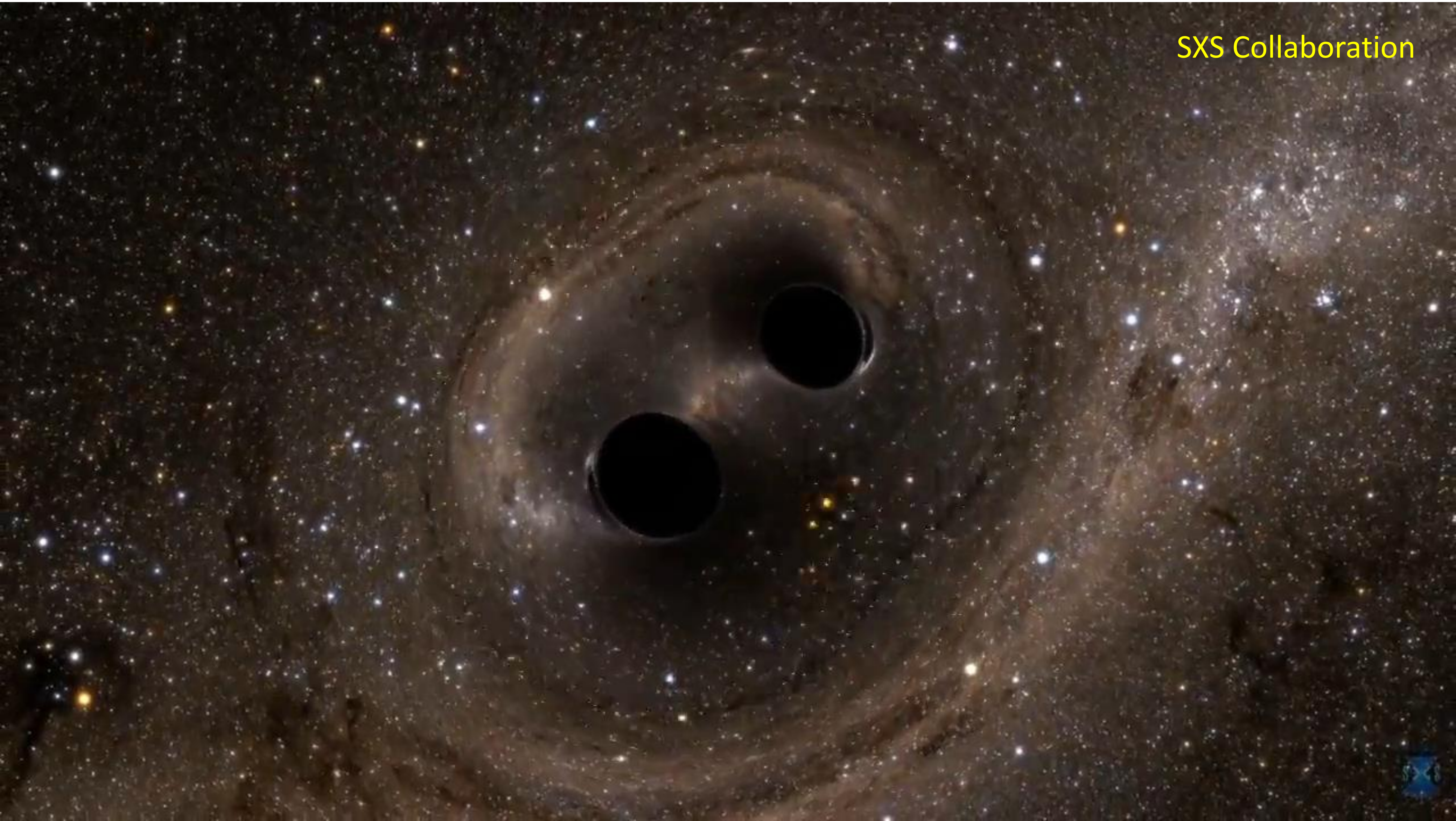
The Advanced LIGO detectors

On the LIGO detectors of the LIGO Virgo Consortium were operational last year. GEO had insufficient sensitivity to detect the event, while Virgo will join the network next year



Event GW150914

Chirp-signal from gravitational waves from two coalescing black holes were observed with the LIGO detectors by the LIGO-Virgo Consortium on September 14, 2015



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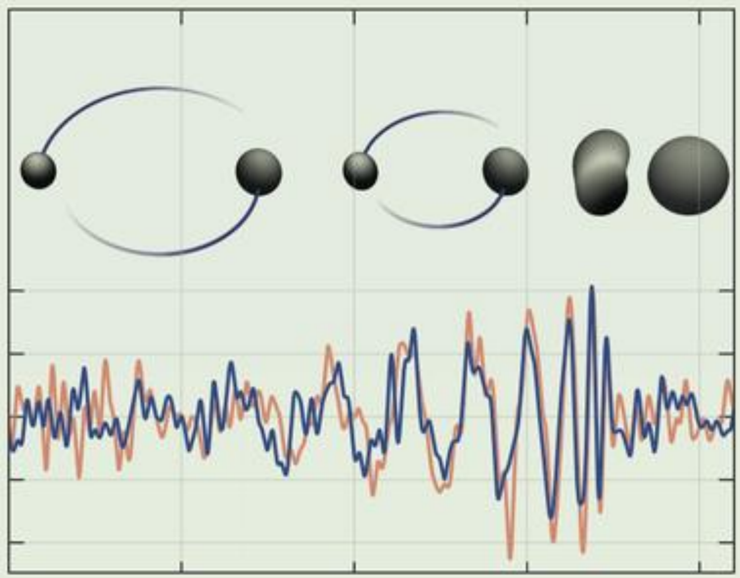

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The basic physics of binary black hole merger GW150914

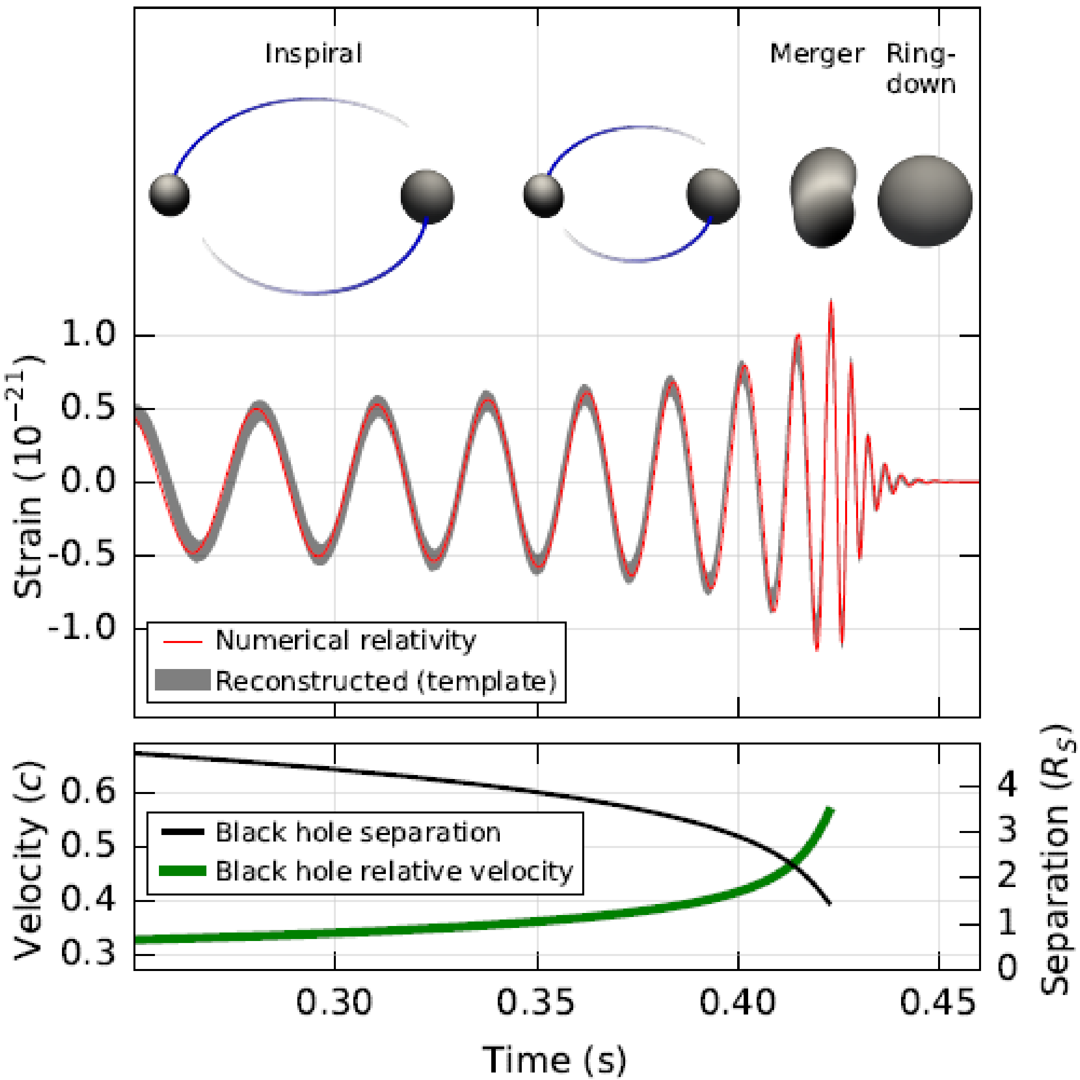
https://arxiv.org/abs/1608.01940

The system will lose energy due to emission of gravitational waves. The black holes get closer and their velocity speeds up. Masses and spins can be determined from this inspiral phase

- Total mass $M = M_1 + M_2$
- Reduced mass $\mu = M_1 M_2 / M$
- Chirp mass $M_S^{5/3} = \mu M^{2/3}$
- Chirp $\dot{f} \approx f^{11/3} M_S^{5/3}$
- Maximum frequency $f_{\text{ISCO}} = \frac{1}{6^{3/2}\pi M}$
- Speed $\frac{v}{c} = \left(\frac{GM\pi f}{c^3}\right)^{1/3}$
- Separation $R_S = \frac{2GM}{c^2}$
- Orbital phase (post Newtonian expansion)

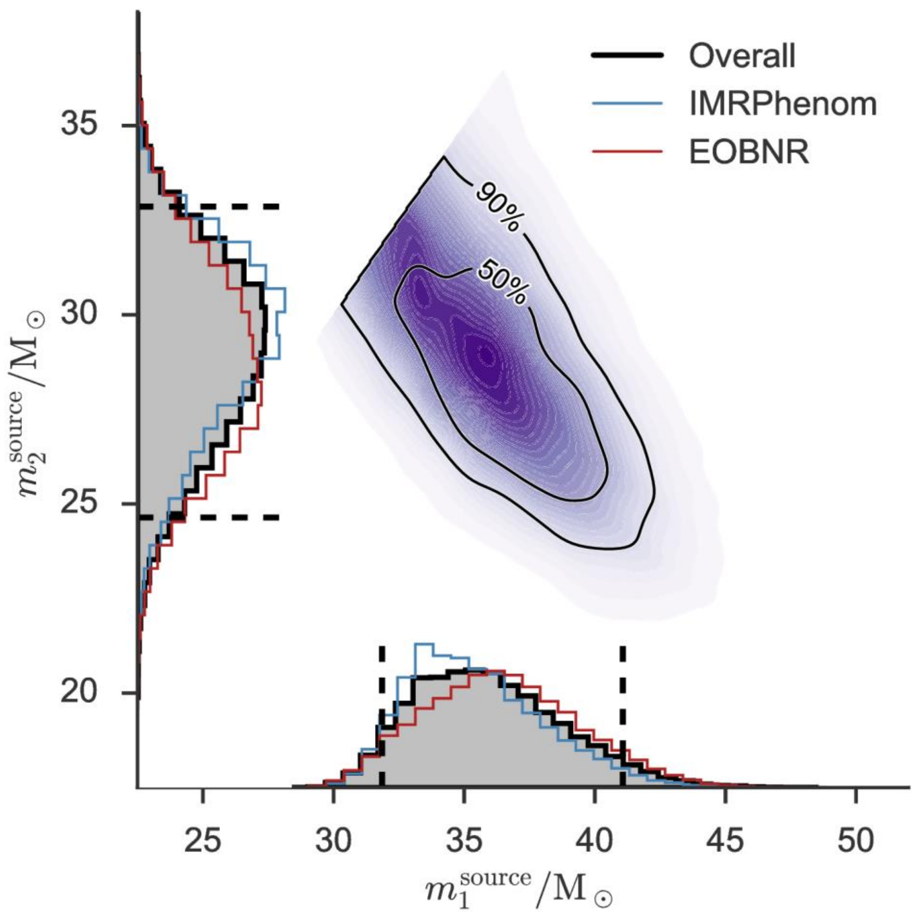
$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$

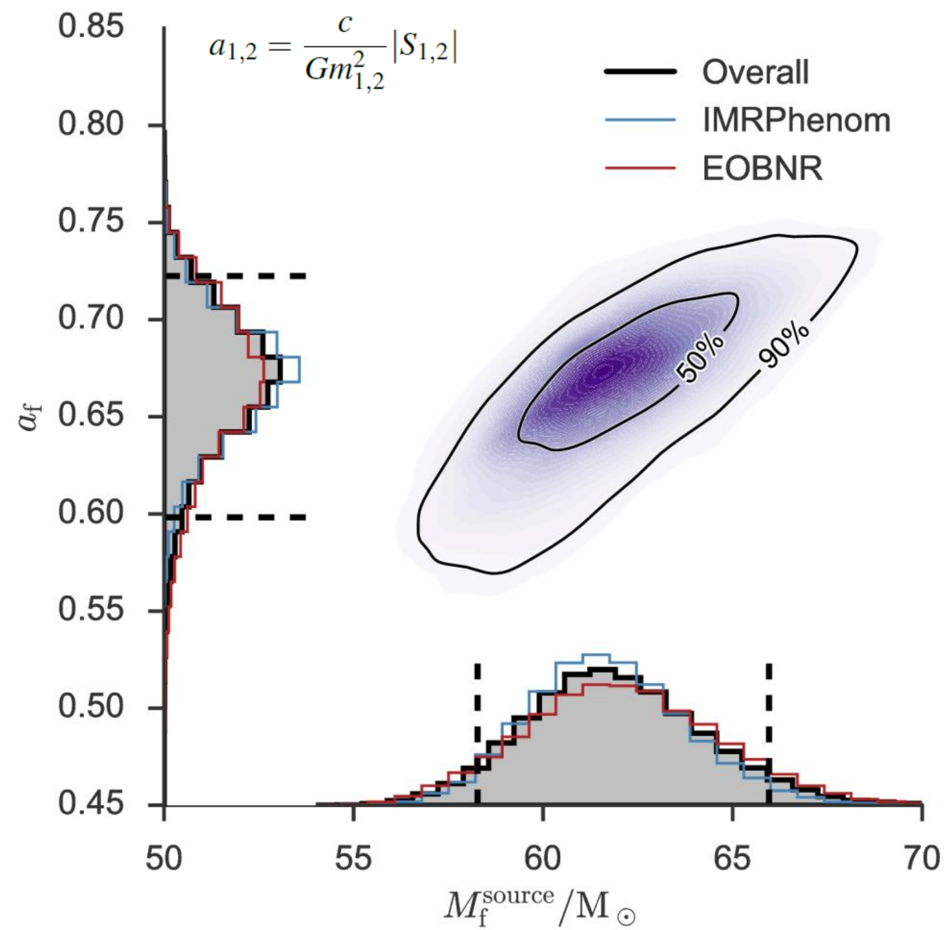
- Strain $h \approx \frac{M_S^{5/3} f^{2/3}}{r} = \frac{\dot{f}}{r f^3}$



Source parameters for GW150914

Estimated masses (90% probability intervals) for the two black holes in the binary (m_1^{source} is the mass of the heavier black hole). Different curves show different models. Mass and spin of the final black hole



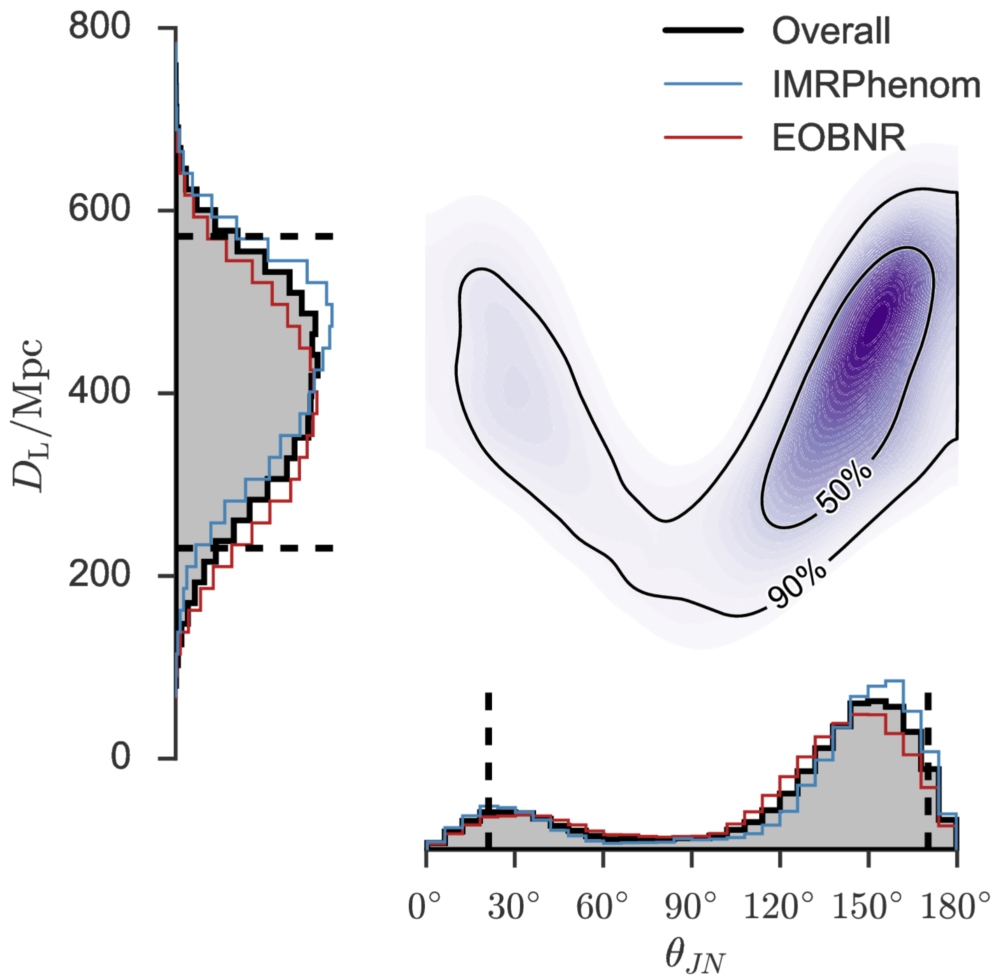


Energy radiated: 3.0 ± 0.5 solar masses. Peak power at merger: 200 solar masses per second

See “*Properties of the Binary Black Hole Merger GW150914*” http://arxiv.org/abs/1602.03840

Luminosity distance to the source

Estimated luminosity distance and binary inclination angle. An inclination of $\theta_{JN} = 90^{\circ}$ means we are looking at the binary (approximately) edge-on. Again 90% credible level contours



Polarization can be used to break the degeneracy between distance and inclination

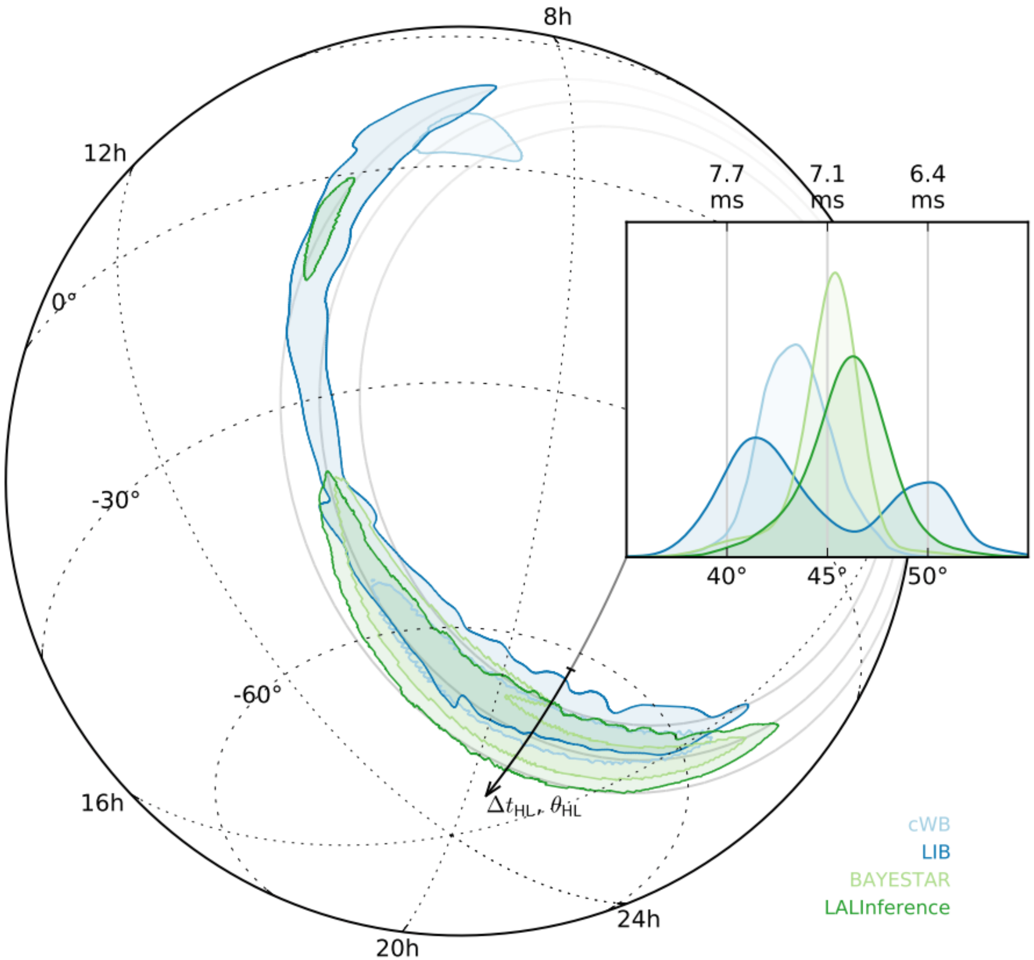
$$h_+ = \frac{2\nu M}{d}[\pi M f(t)]^{2/3}(1 + \cos^2\iota)\cos[2\varphi(t)]$$

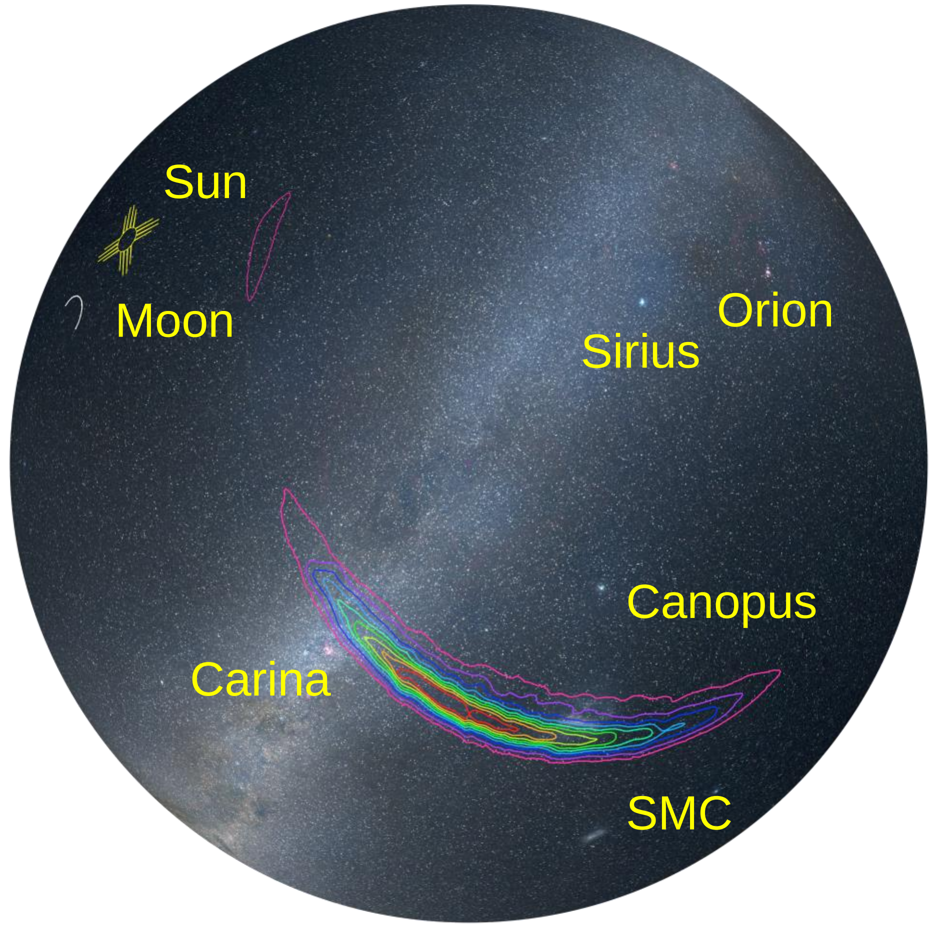
$$h_\times = \frac{4\nu M}{d}[\pi M f(t)]^{2/3}\cos\iota\,\sin[2\varphi(t)]$$

For this we also need Virgo

Sky localization probability maps

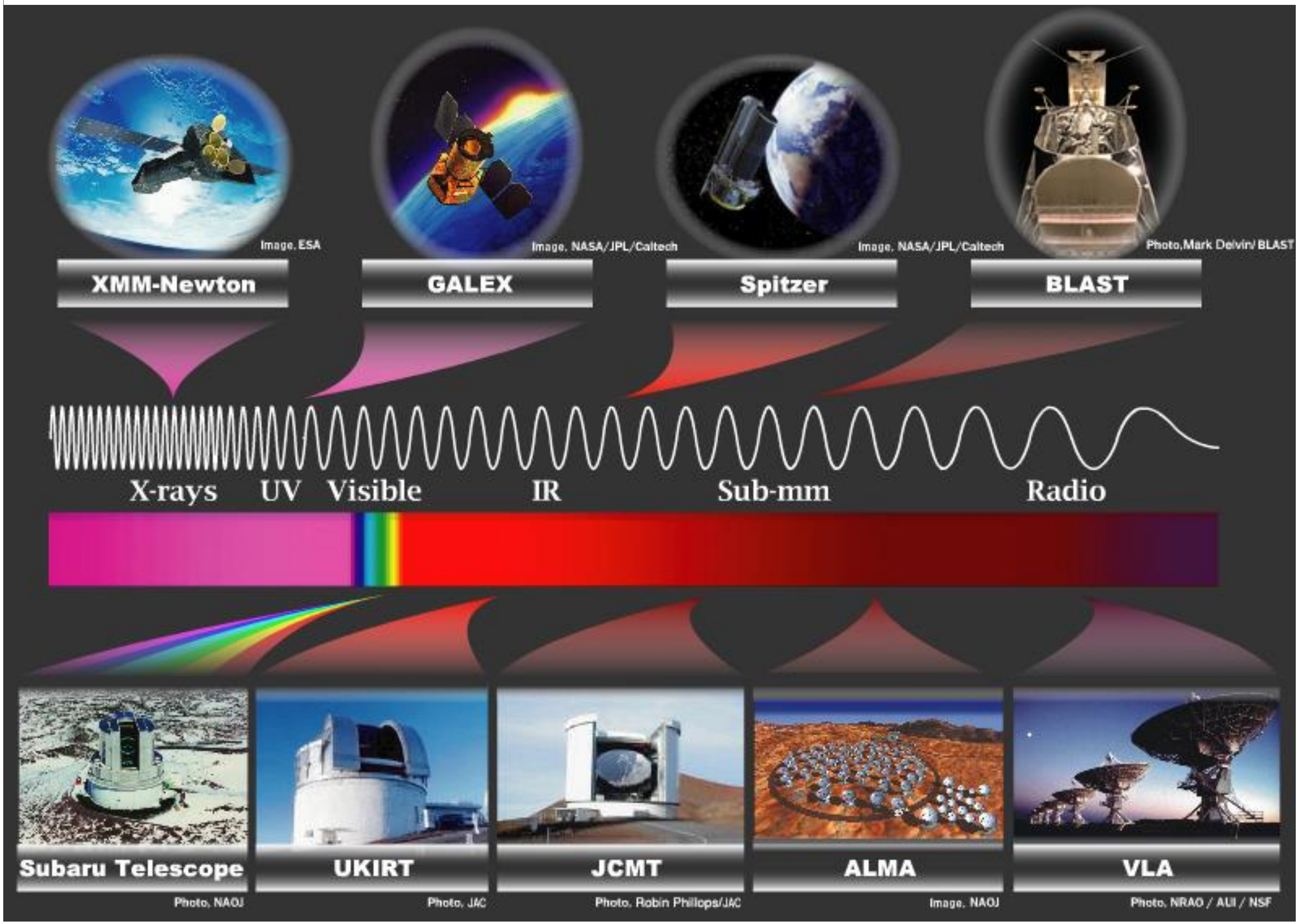
Sky at the time of the event, with 90% credible level contours. View is from the South Atlantic Ocean, North at the top, with the Sun rising and the Milky Way diagonally from NW to SE





The instruments of astronomers

Sky map for GW150914 was sent to astronomers (agreements with 74 groups), and they looked.
However, we do not expect any EM emission from binary black holes



Towards multi-messenger astronomy

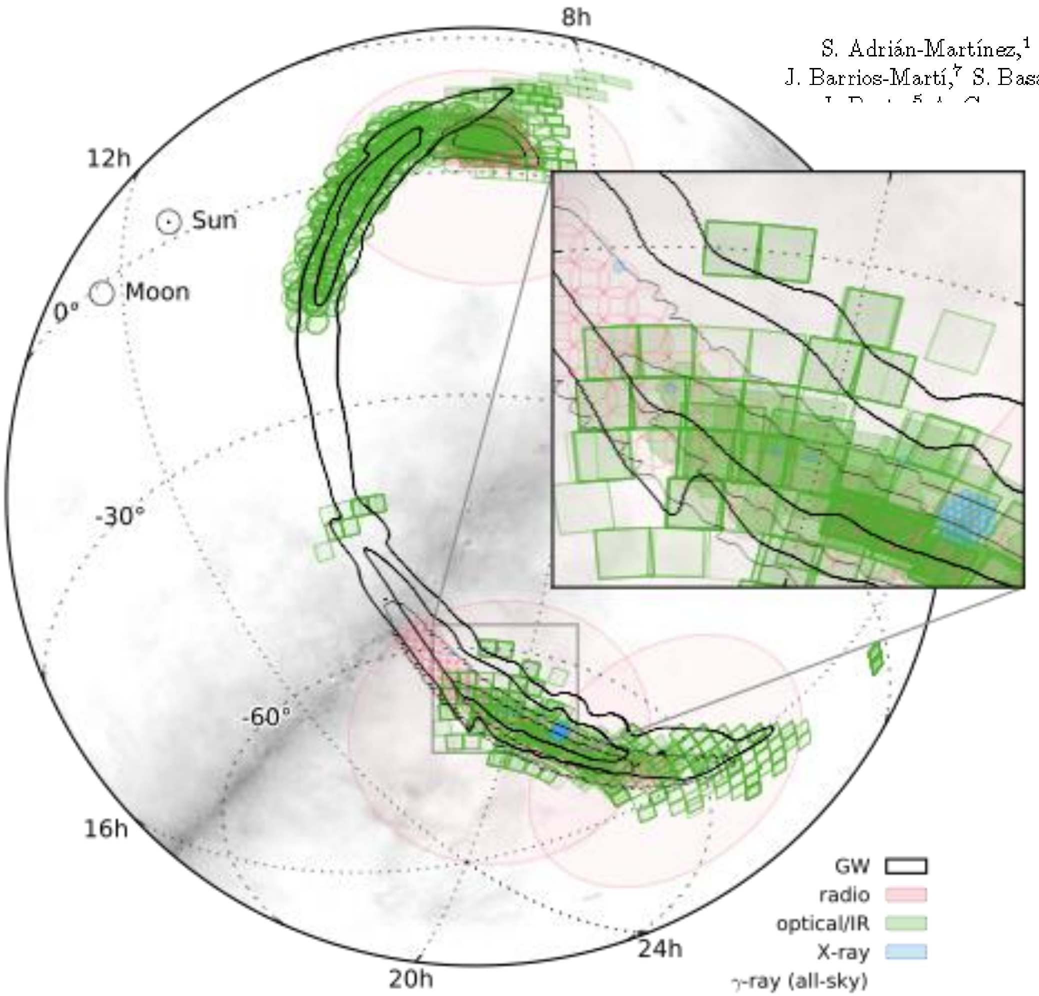
Sky map for GW150914 was sent to astronomers (agreements with more than 80 groups), and they looked. However, in GR we do not expect any EM emission from binary black holes

High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube

S. Adrián-Martínez,[1] A. Albert,[2] M. André,[3] G. Anton,[4] M. Ardid,[1] J.-J. Aubert,[5] T. Avgitas,[6] B. Baret,[6] J. Barrios-Martí,[7] S. Basa,[8] V. Bertin,[5] S. Biagi,[9] R. Bormuth,[10,11] M.C. Bouwhuis,[10] R. Bruijn,[10,12] J. Brunner,[5]

arXiv 1602.05411

http://astrog80.astro.cf.ac.uk/Gravoscope/

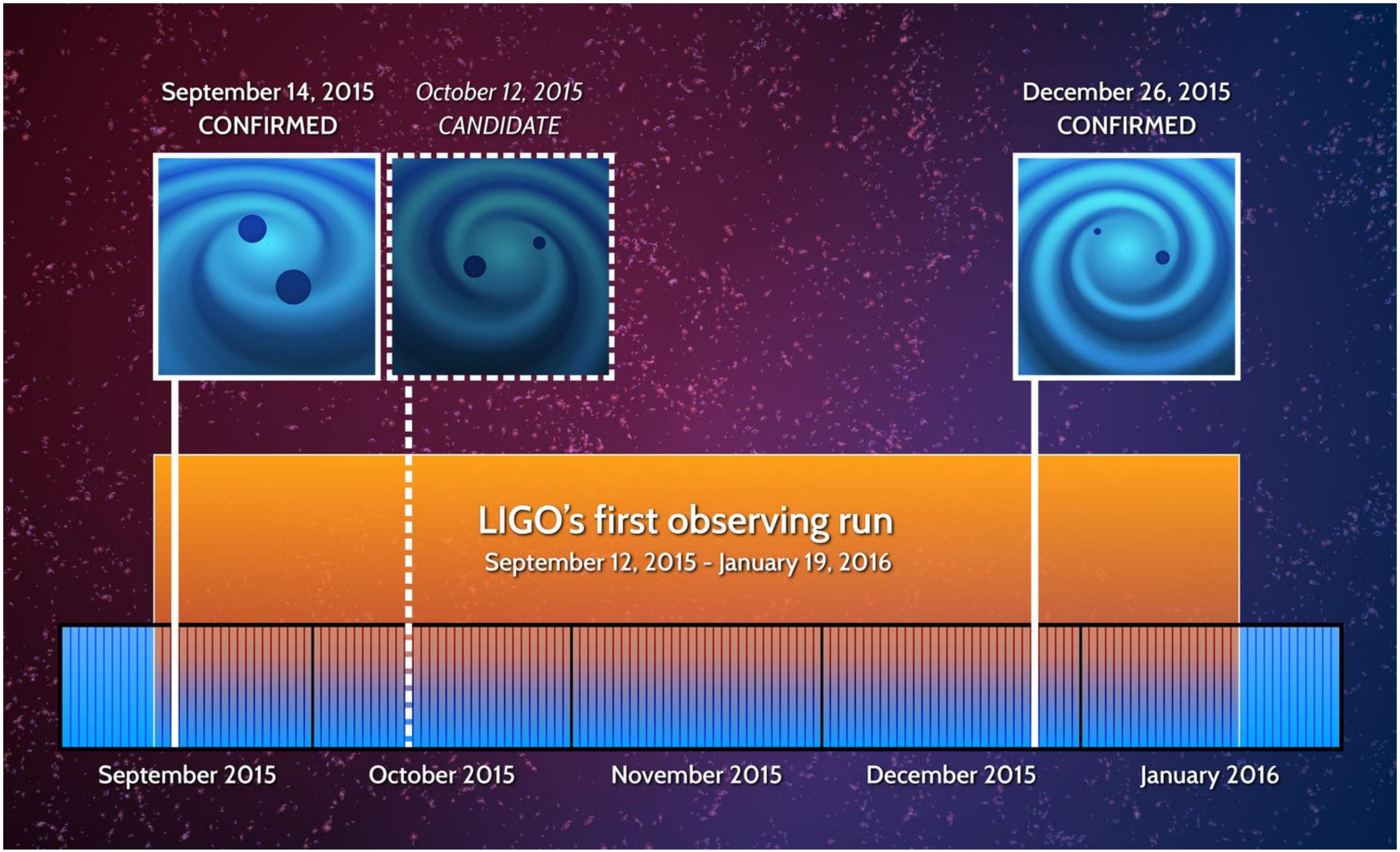


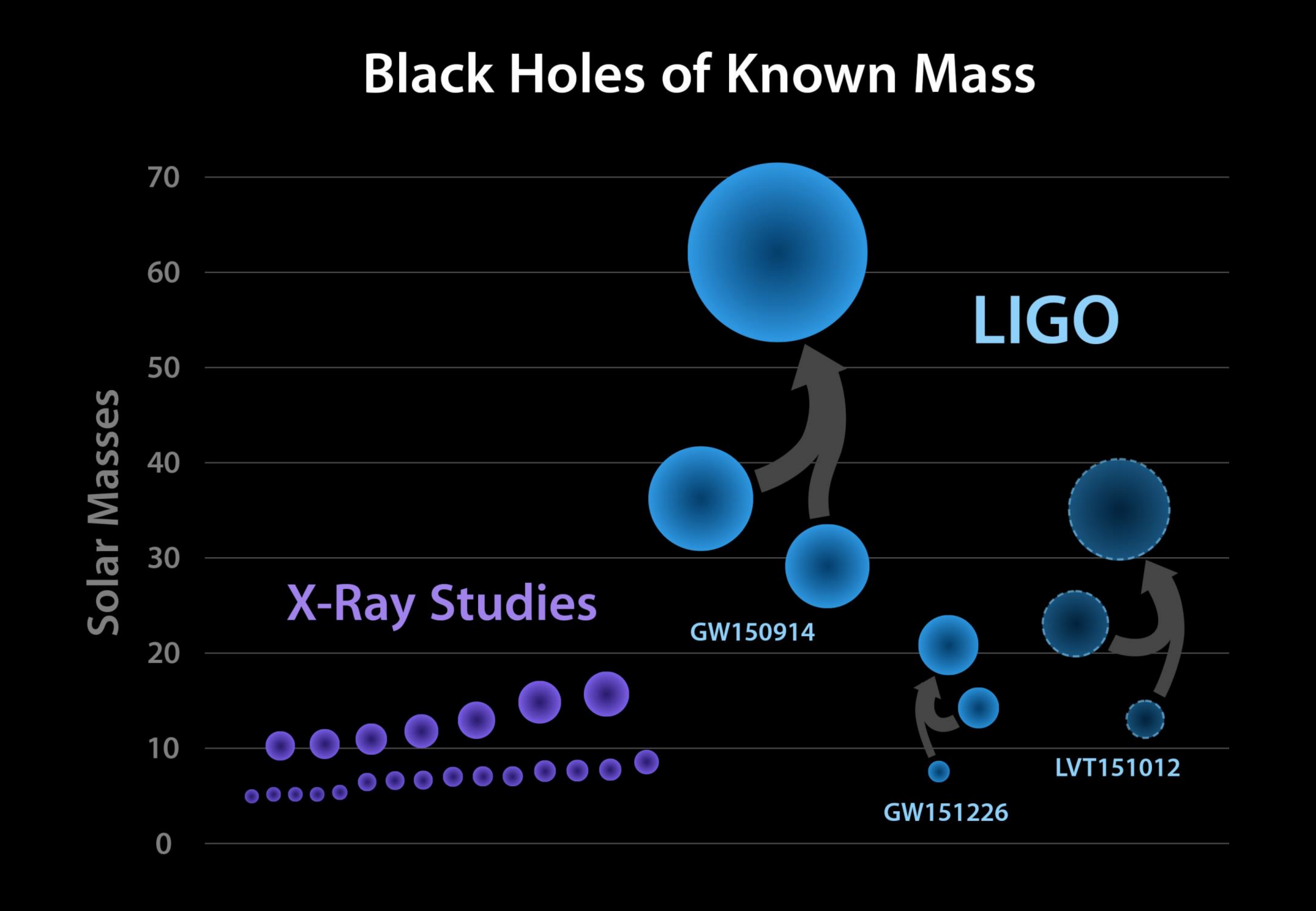
Footprints of Tiled Observations

Group	Area (deg^2)	Contained probability (%) cWB[a]	LIB[b]	LALInf[c]
Swift	2	0.6	0.8	0.1
DES	94	32.1	13.4	6.6
INAF	93	28.7	9.5	6.1
J-GEM	24	0.0	1.2	0.4
MASTER	167	9.3	3.3	6.0
Pan-STARRS	355	27.9	22.9	8.8
SkyMapper	34	9.1	7.9	1.7
TZAC	29	15.1	3.5	1.6
ZTF	140	3.1	2.9	0.9
(total optical)	759	76.5	46.8	23.9
LOFAR-TKSP	103	26.6	1.3	0.5
MWA	2615	97.8	71.8	59.0
VAST	304	25.3	1.7	6.3
(total radio)	2623	97.8	71.8	59.0
(total)	2730	97.8	76.8	62.1

LVC's first observing run

Two confirmed gravitational-wave detections, and one candidate detection. All three events occurred during the first four-month run of Advanced LIGO





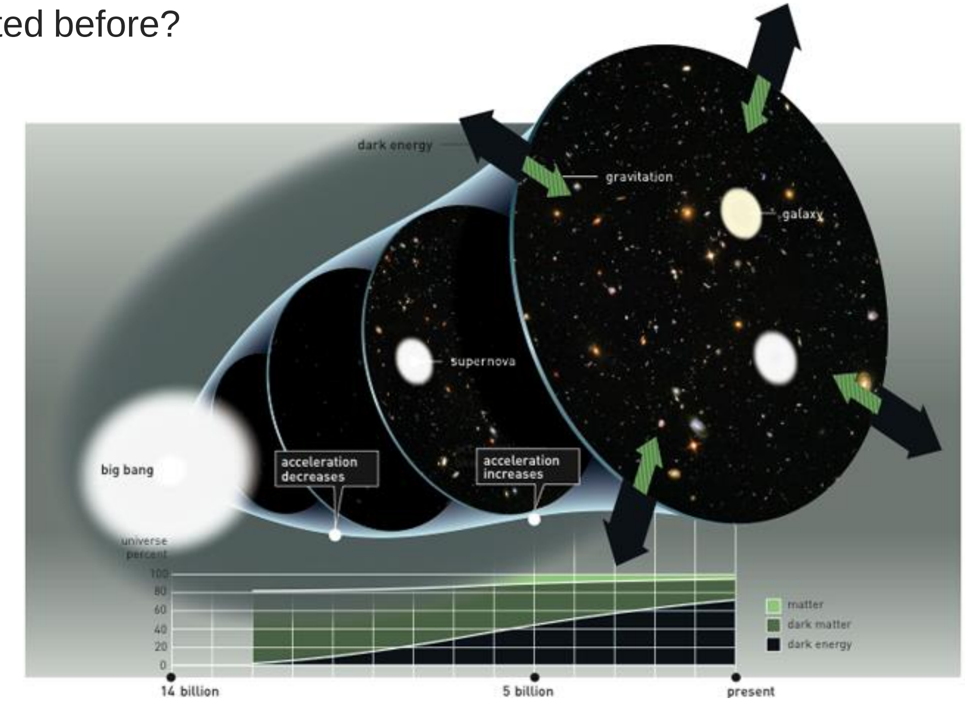
Black Holes of Known Mass
70
60
50
40
30
20
10
0
Solar Masses
LIGO
X-Ray Studies
GW150914
GW151226
LVT151012

What does it all mean? What's next?

Gravity

Gravity is the least understood fundamental interaction with many open questions. Should we not now investigate general relativity experimentally, in ways it was never tested before?

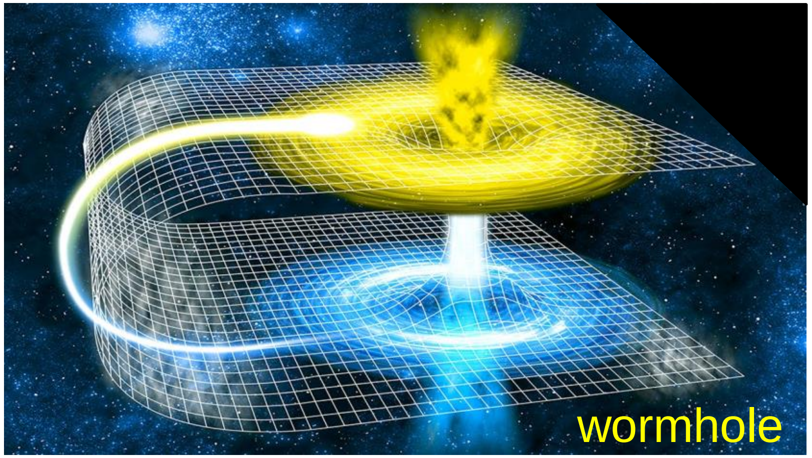
- Gravity
  - Main organizing principle in the Universe
    - Structure formation
  - Most important open problems in contemporary science
    - Acceleration of the Universe is attributed to dark energy
    - Standard Model of Cosmology features dark matter
    - Or does this signal a breakdown of general relativity?
- Large world-wide intellectual activity
  - Theoretical: combining GR + QFT, cosmology, …
  - Experimental: astronomy (CMB, Euclid, LSST), particle physics (LHC), dark matter searches (Xenon1T), …

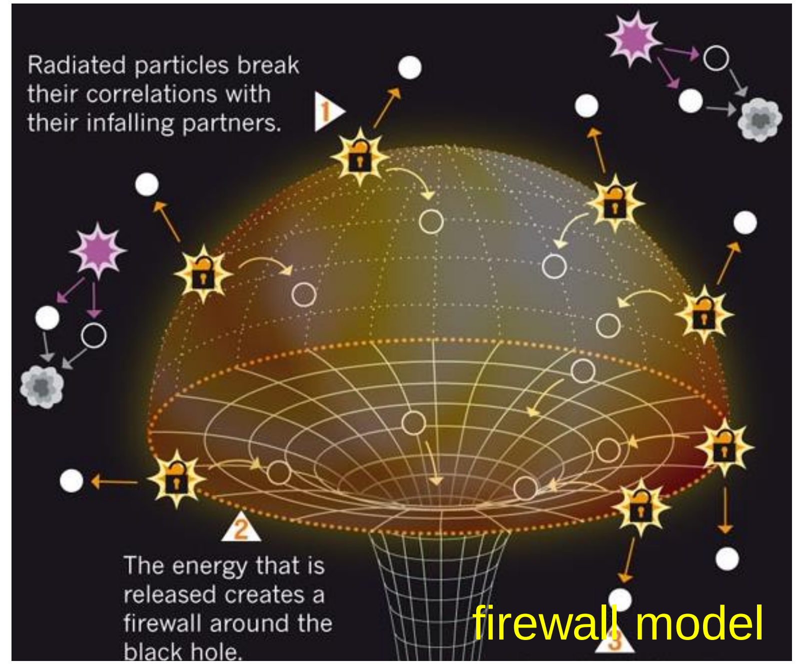


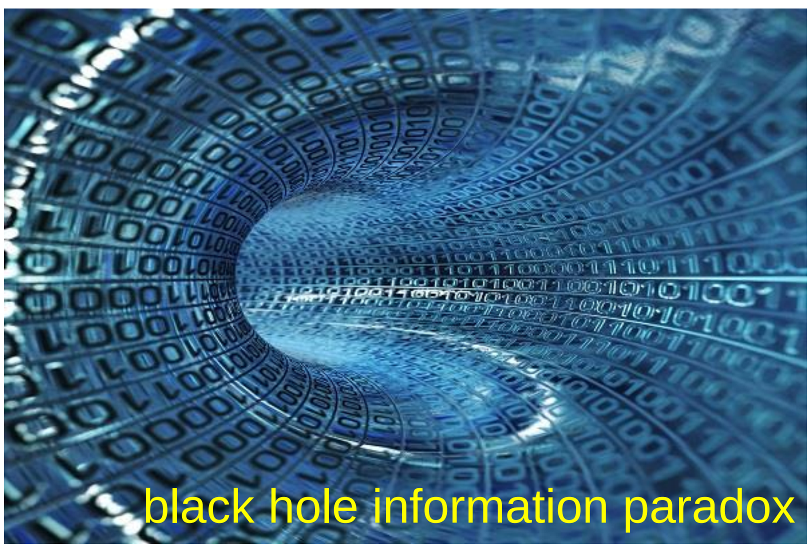
- Gravitational waves
  - Dynamical part of gravitation, all space is filled with GW
  - Ideal information carrier, almost no scattering or attenuation
  - The entire universe has been transparent for GWs, all the way back to the Big Bang
- Two examples of gravitational wave science
  - Fundamental physics
  - Cosmology

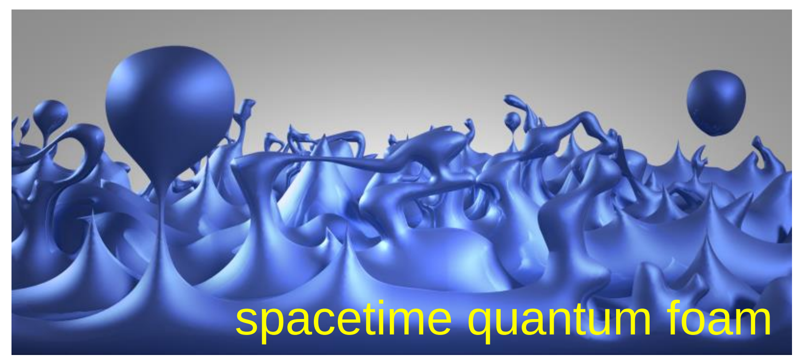
Fundamental physics: did we observe black holes?

Our theories "predict" the existence of other objects, such as wormholes, boson stars, dark matter stars, gravastars, firewalls, *etc*. Why do we believe we have seen black holes?



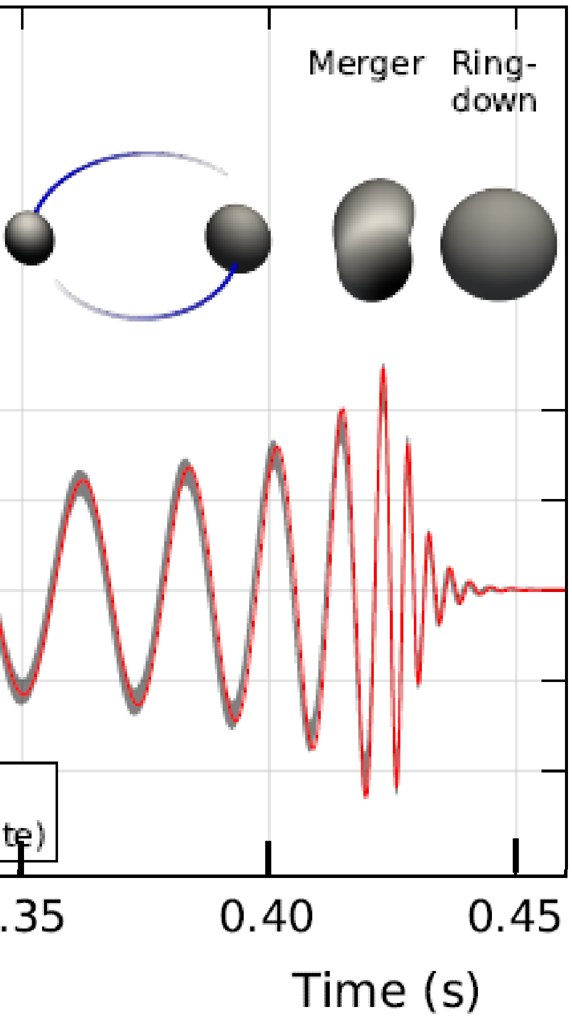


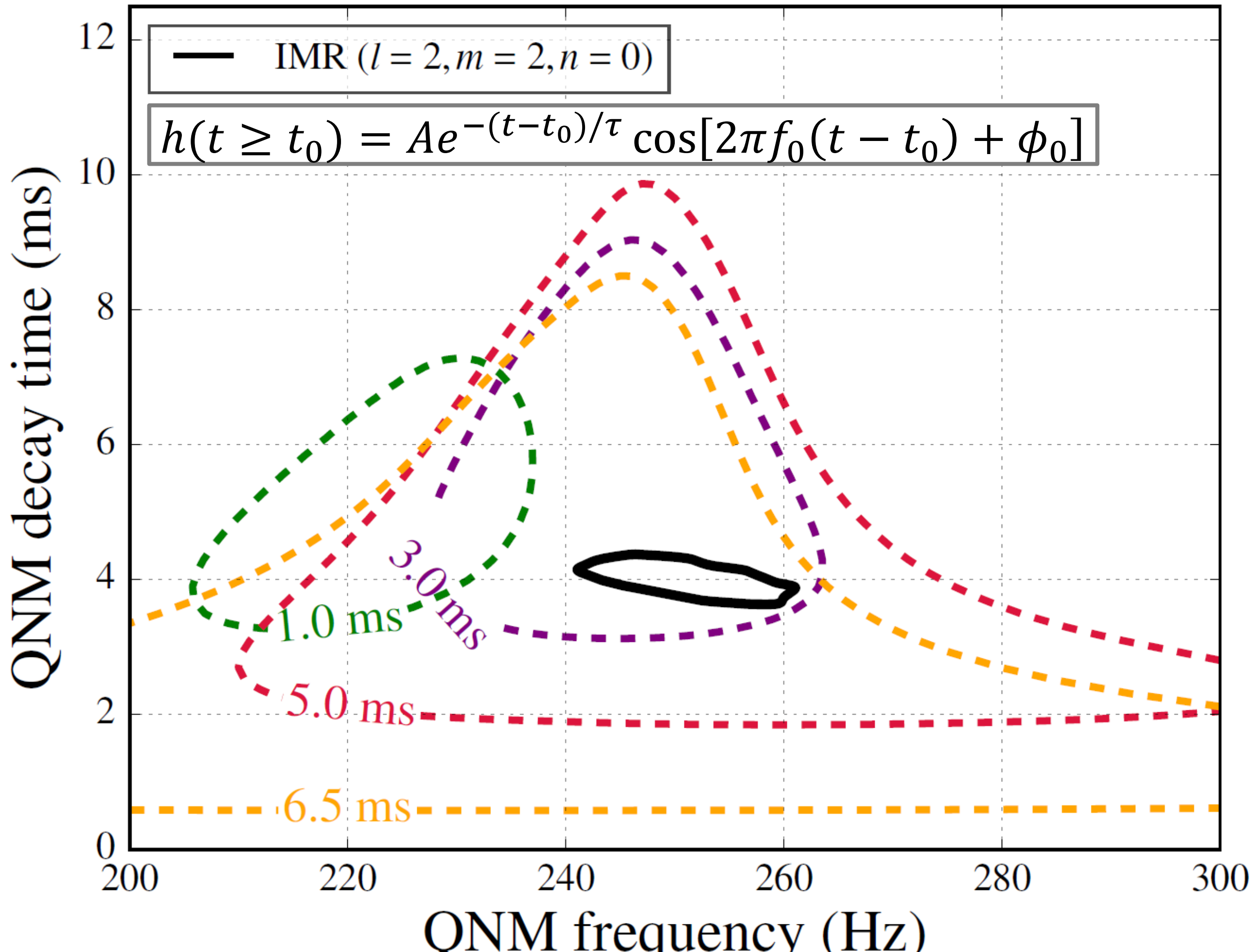




Is a black hole created in the final state?

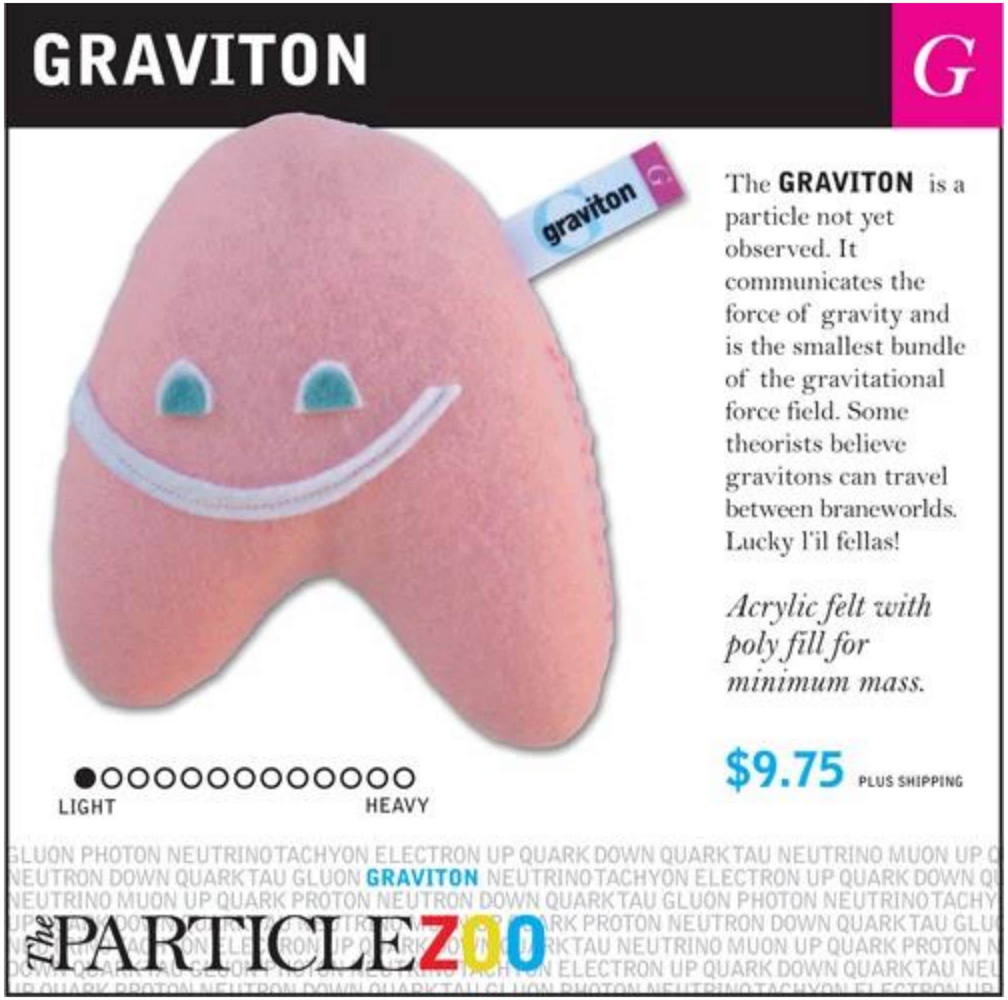
From the inspiral we can predict that the ringdown frequency should be about 250 Hz.
This is what we measure! (http://arxiv.org/abs/1602.03841)





Limit on the mass of the graviton

Bounds on the Compton wavelength $\lambda_g = {}^{h}/_{m_g c}$ of the graviton compared to Solar System or double pulsar tests. Some cosmological tests are stronger (but make assumptions about dark matter)



$$\delta\Phi(f) = -\frac{\pi D c}{\lambda_g^2(1+z)} f^{-1}$$

Will, Phys. Rev. D **57**, 2061 (1998)

Massive-graviton theory dispersion relation $E^2 = p^2c^2 + m_g^2c^4$

We have $\lambda_g = h/(m_g c)$

Thus frequency dependent speed $\frac{v_g^2}{c^2} \equiv \frac{c^2p^2}{E^2} \cong 1 - h^2c^2/(\lambda_g^2 E^2)$

$\lambda_g > 10^{13}\mathrm{km}$

$m_g \leq 10^{-22}\mathrm{eV/c^2}$

Michalis Agathos (Nikhef 2016)

See "*Tests of general relativity with GW150914*" http://arxiv.org/abs/1602.03841

Thank you! Questions?