Gravitational waves

from the merger of two black holes

Opening of the Academic Year by the Department of Physics and Astronomy (DPA)

VU, Amsterdam, September 21 2016; Jo van den Brand; jo@nikhef.nl

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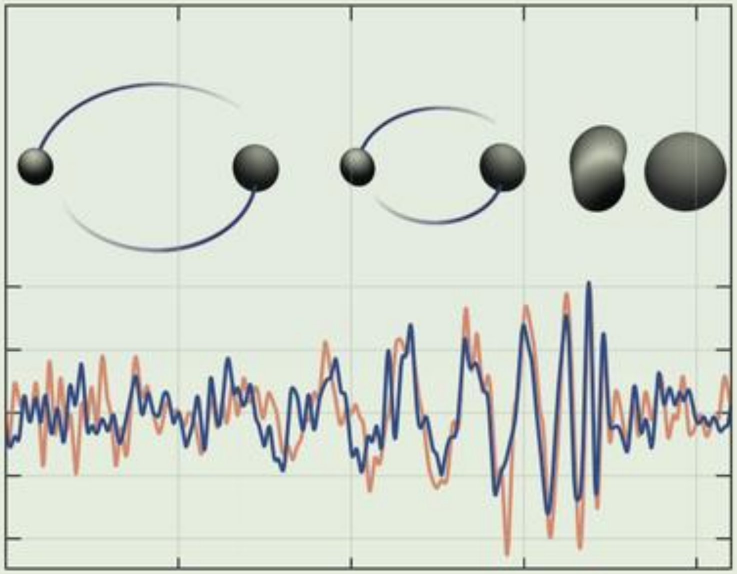

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APS physics

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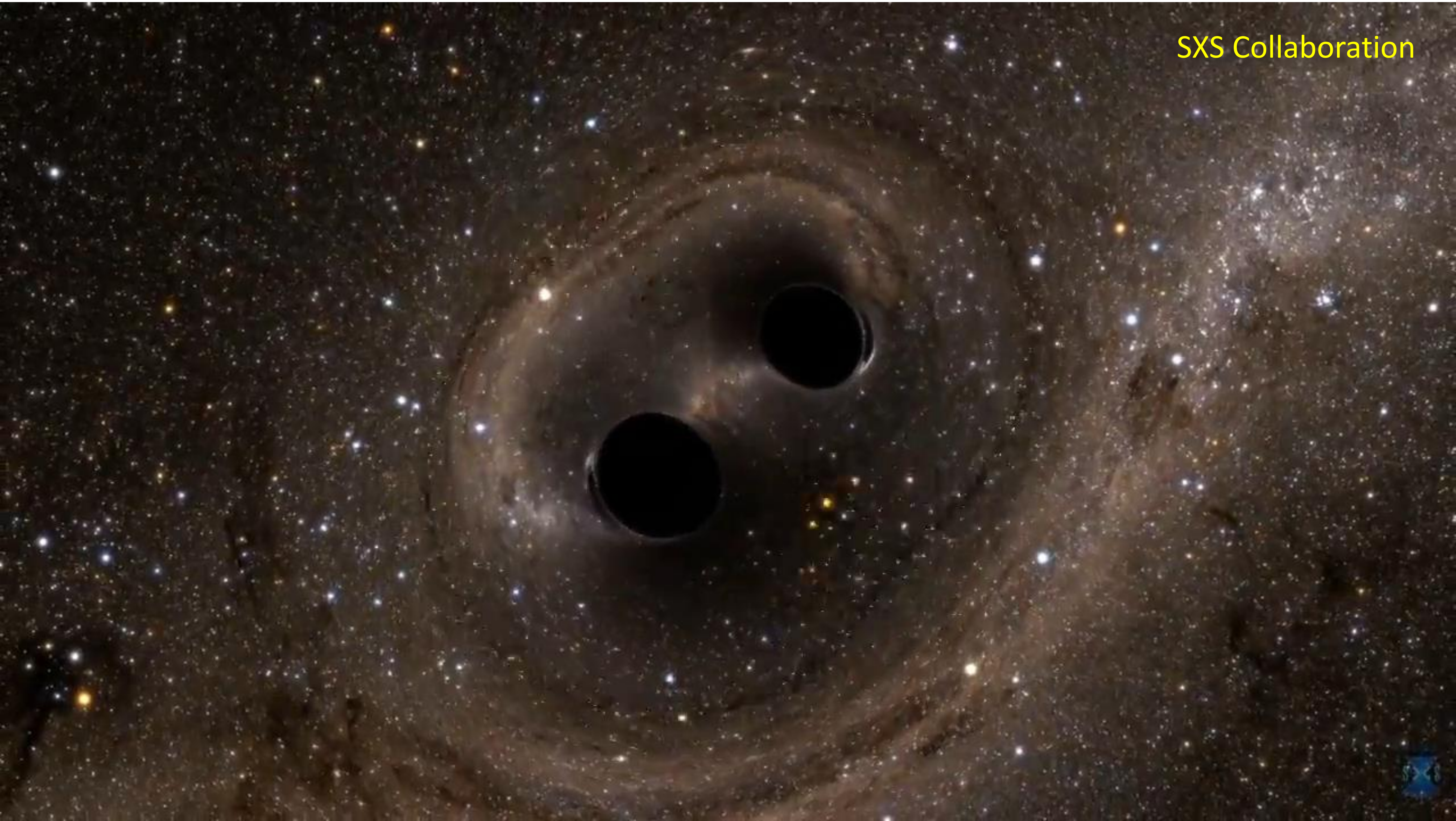
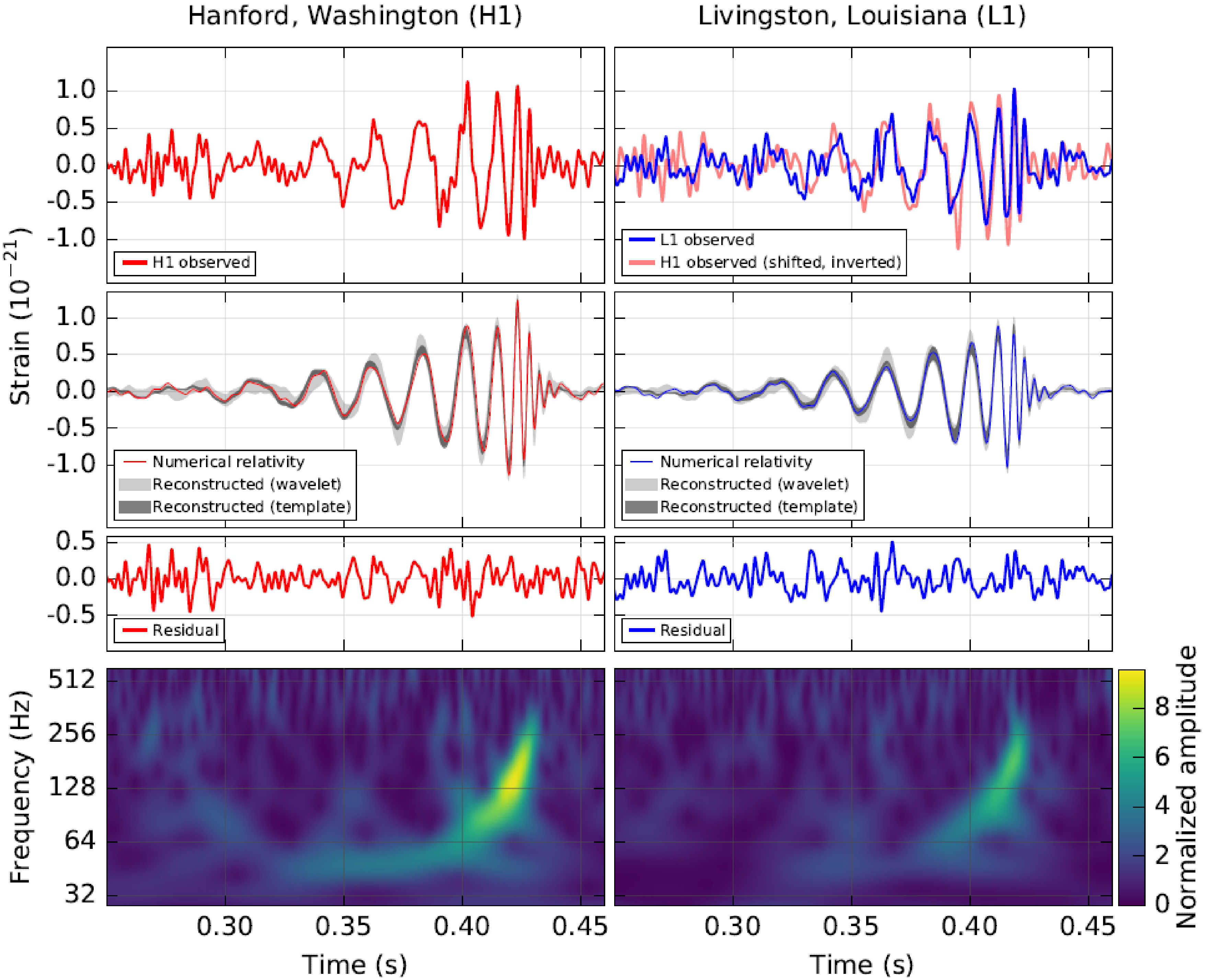
Event GW150914

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



SXS Collaboration


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

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 $M_S^{5/3} = \mu M^{2/3}$

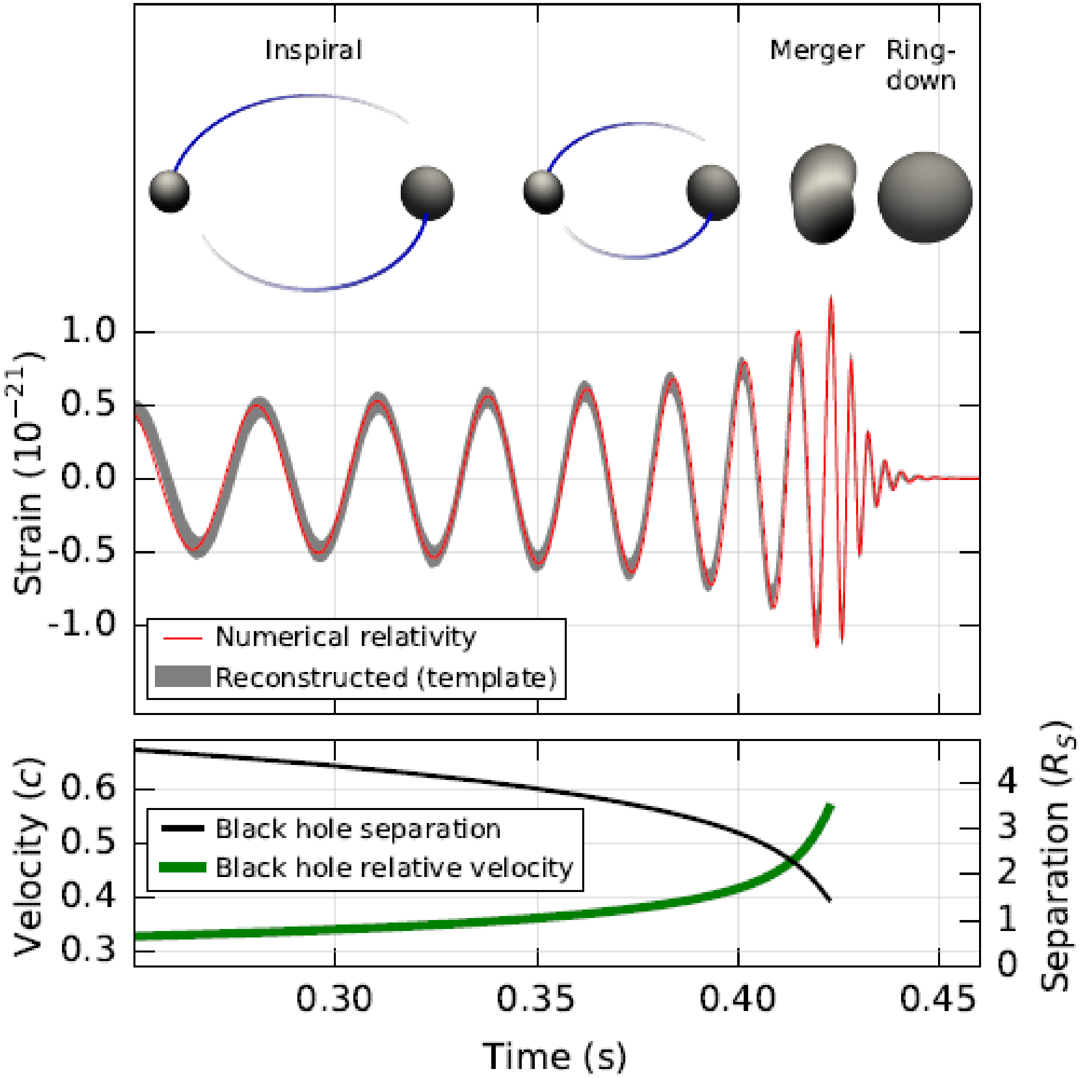
- Chirp $\dot{f} \approx f^{11/3} M_S^{5/3}$
- Maximum frequency $f_{\mathrm{ISCO}} = \frac{1}{6^{3/2}\pi M}$

- 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)

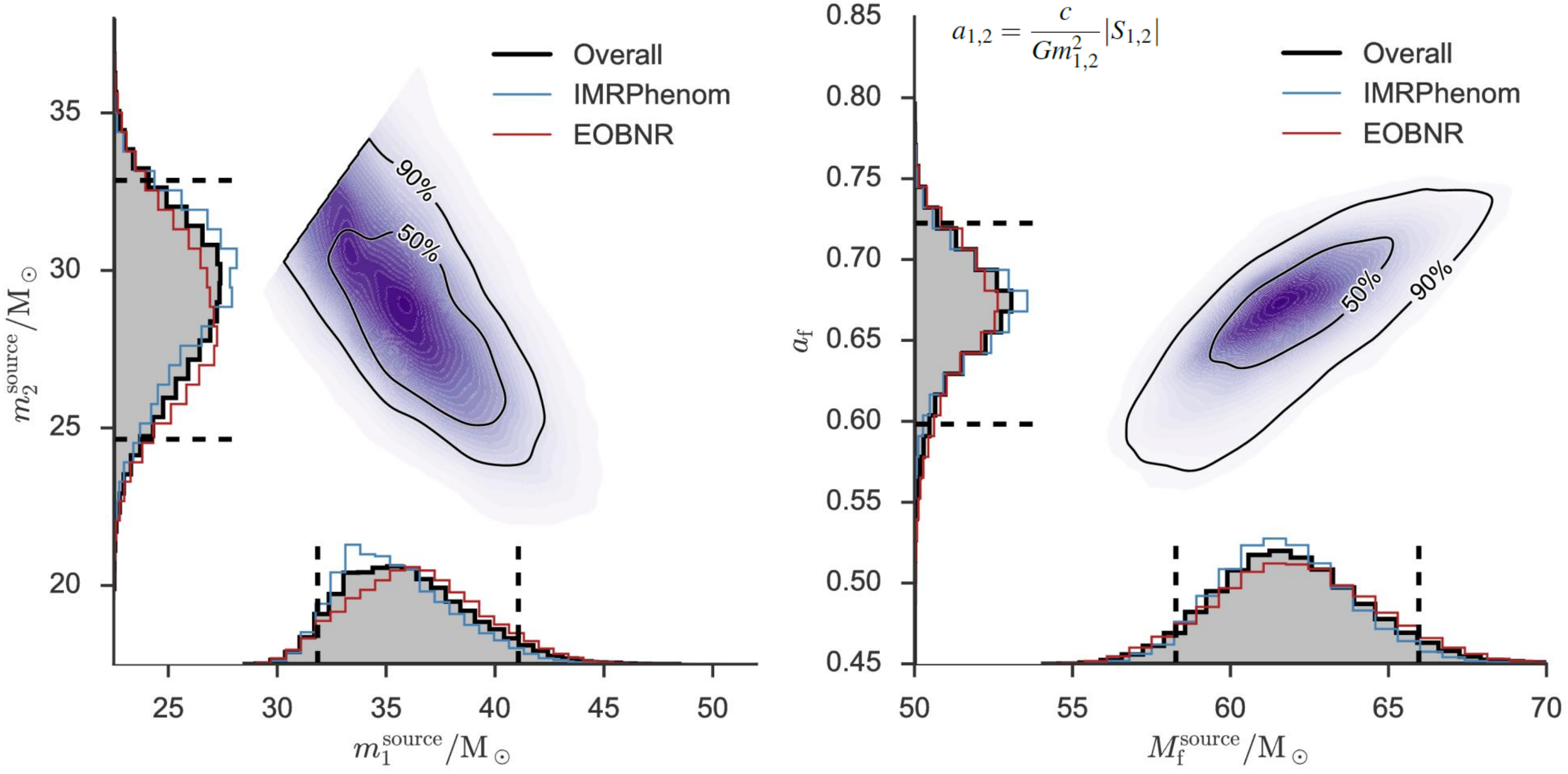
$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^{n}$$

- 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

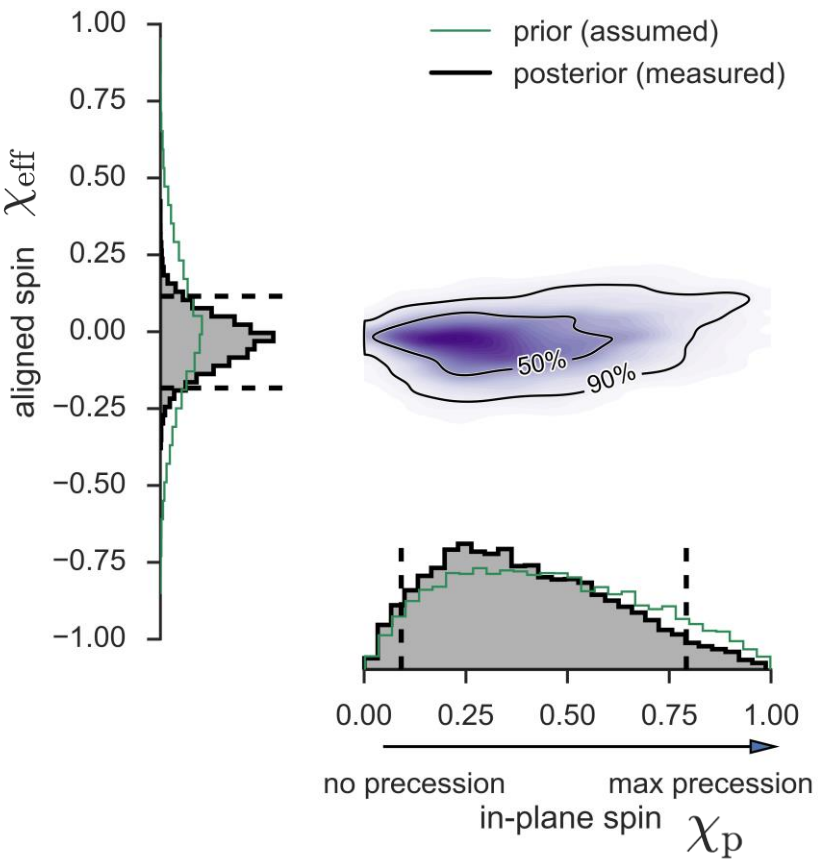


Energy radiated: 3.0 ± 0.5 solar masses. Peak power at merger: 200 solar masses per second

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

Combinations of component spins for GW150914

GW150914 suggests that the individual spins were either small, or they were pointed opposite from one another, cancelling each other's effect



Effective spin parameter

$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\boldsymbol{L}}{|\mathbf{L}|}$$

Precession in BBH

$$\dot{\boldsymbol{L}} = \frac{G}{c^2 r^3}(B_1 \boldsymbol{S}_{1\perp} + B_2 \boldsymbol{S}_{2\perp}) \times \boldsymbol{L}$$

$$\dot{\boldsymbol{S}}_i = \frac{G}{c^2 r^3} B_i \boldsymbol{L} \times \boldsymbol{S}_i,$$

Effective precession spin parameter

$$\chi_p = \frac{c}{B_1 G m_1^2} \max(B_1 S_{1\perp}, B_2 S_{2\perp}) > 0$$

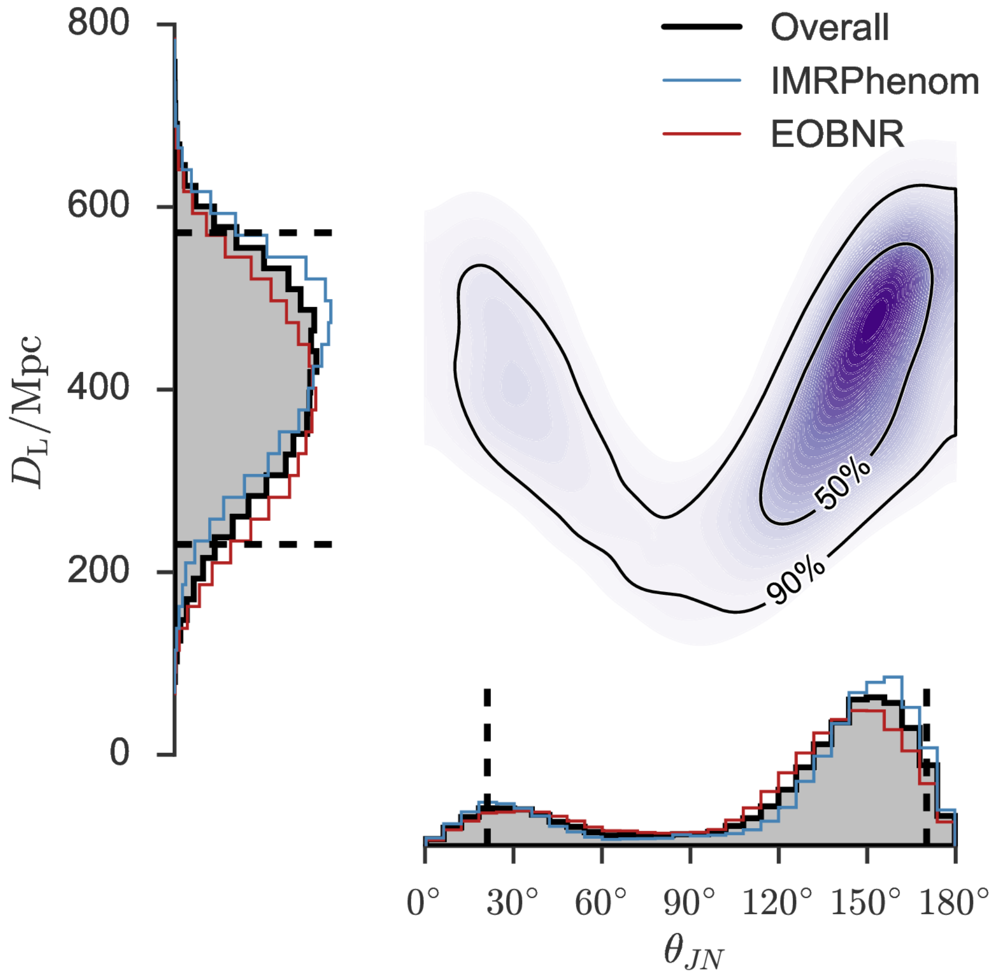
$\chi_p = 0$ aligned-spin (non-precessing) system

$$B_1 = 2 + 3q/2 \ \text{ and } \ B_2 = 2 + 3/(2q), \ \text{ and } \ i = \{1, 2\}$$

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

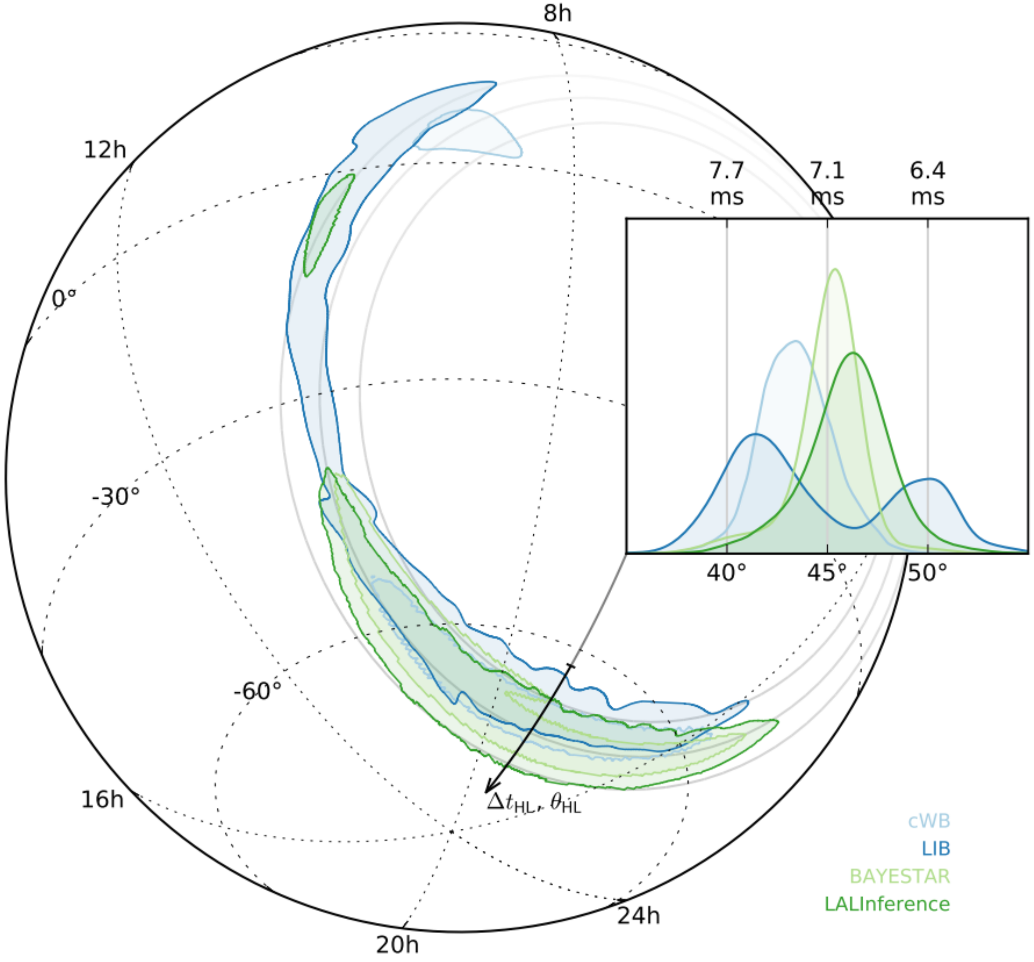
$$h_{+} = \frac{2\nu M}{d}[\pi M f(t)]^{2/3}(1 + \cos^{2}\iota)\cos[2\varphi(t)]$$

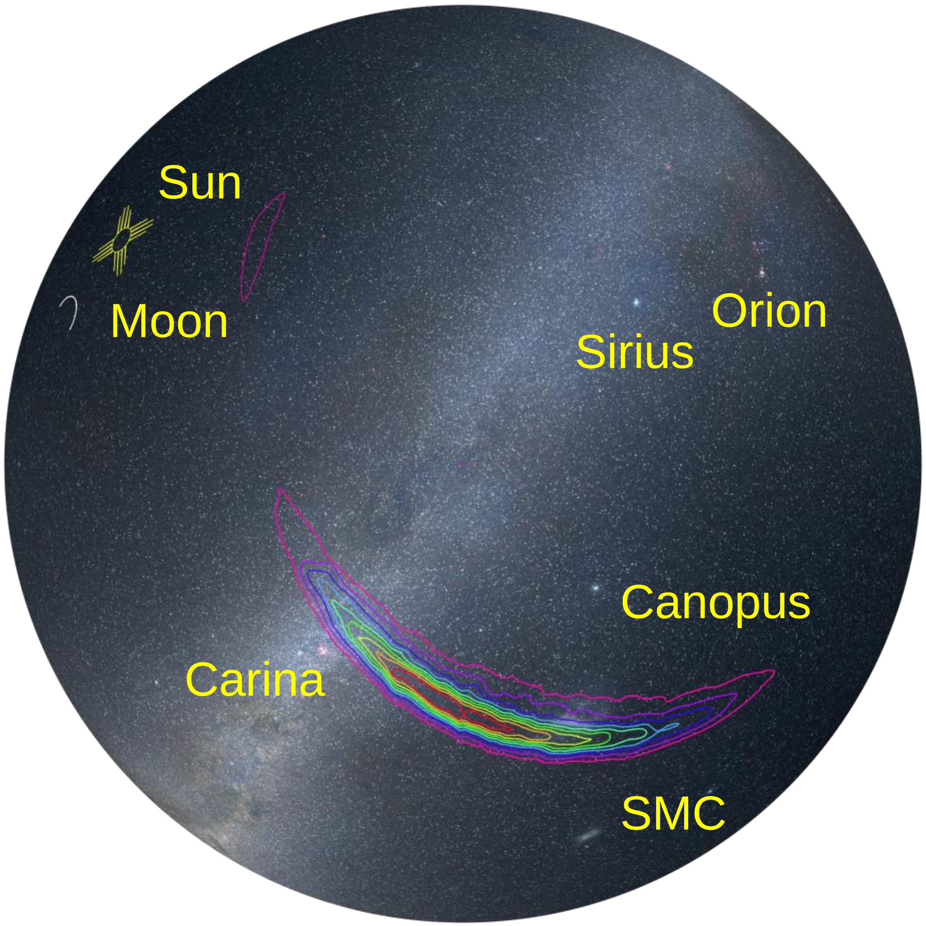
$$h_{\times} = \frac{4\nu M}{d}[\pi M f(t)]^{2/3}\cos\iota\,\sin[2\varphi(t)]$$

For this we also need Virgo

Sky localization probability maps

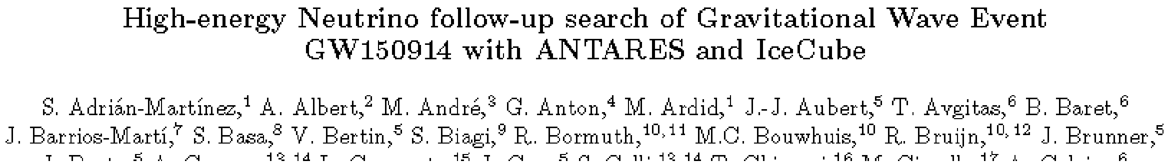
Sky at the time of the event, with 90% credible level contours. View is from the South Atlantic Ocean, North at the top, with the Sun rising and the Milky Way diagonally from NW to SE





Towards multi-messenger astronomy

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

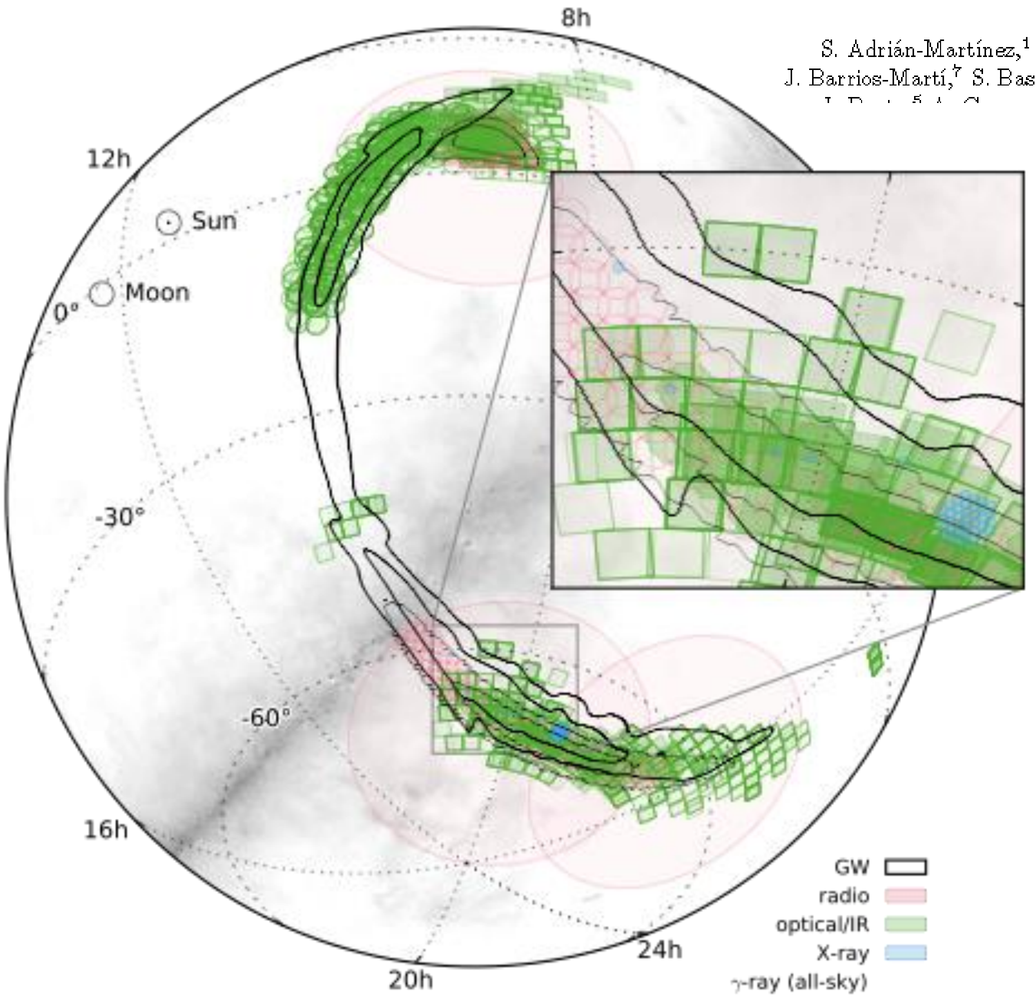


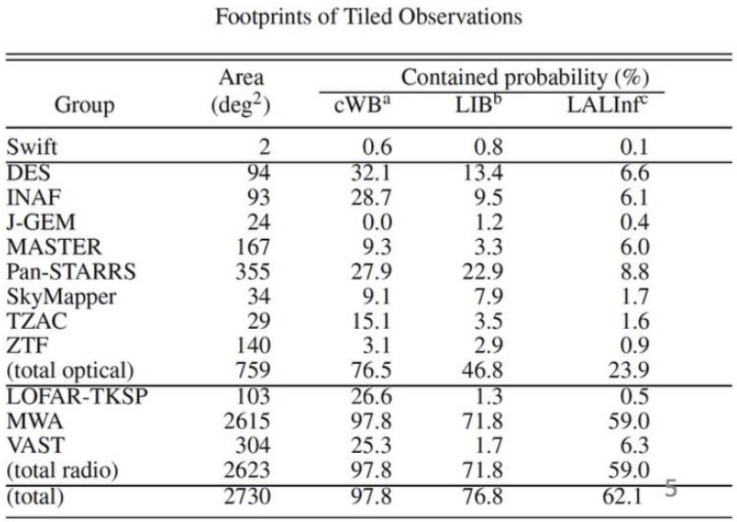
High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube

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/





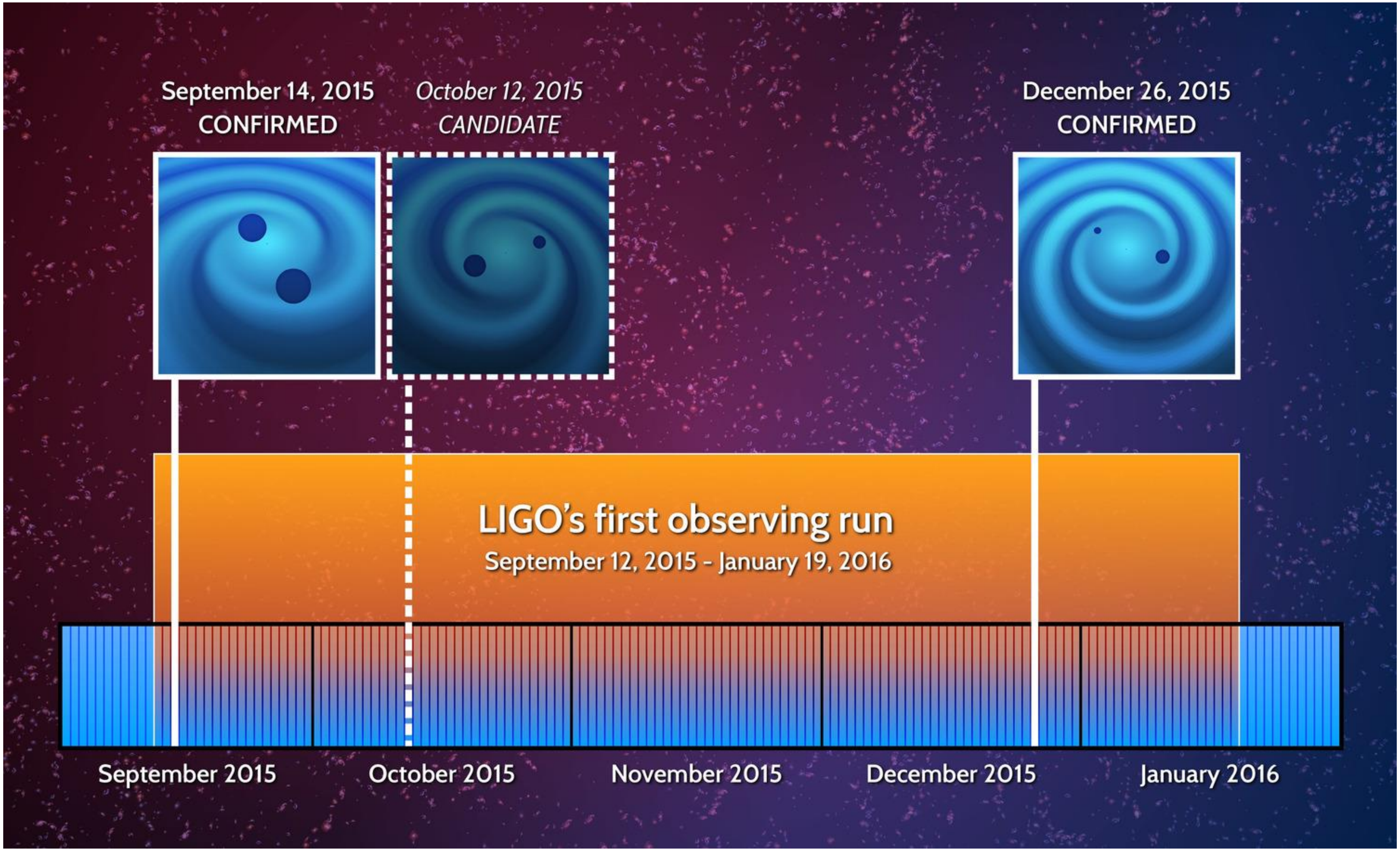
Footprints of Tiled Observations

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

What’s next?

LVC’s first observing run

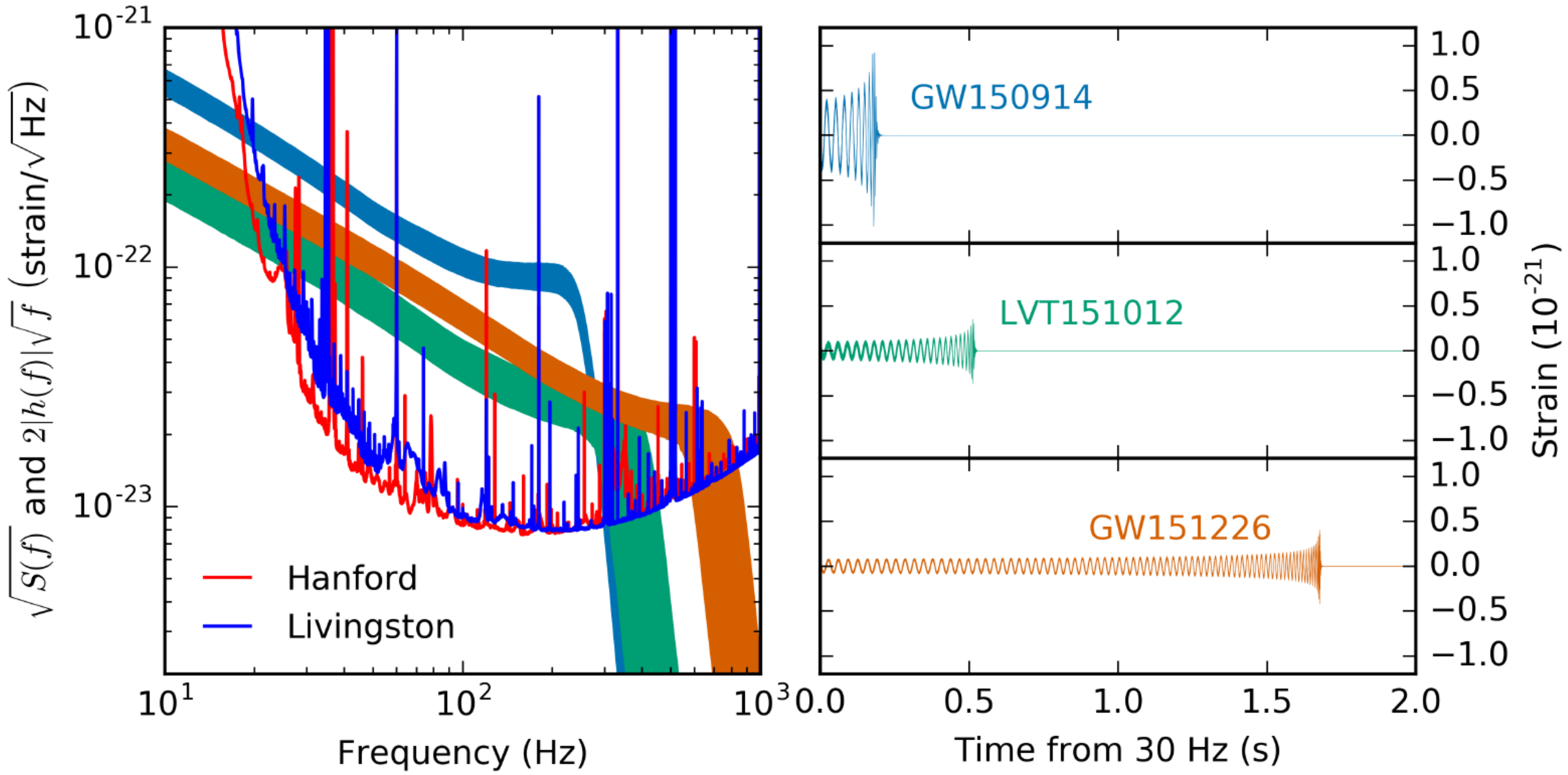
Two confirmed gravitational-wave detections, and one candidate detection. All three events occurred during the first four-month run of Advanced LIGO



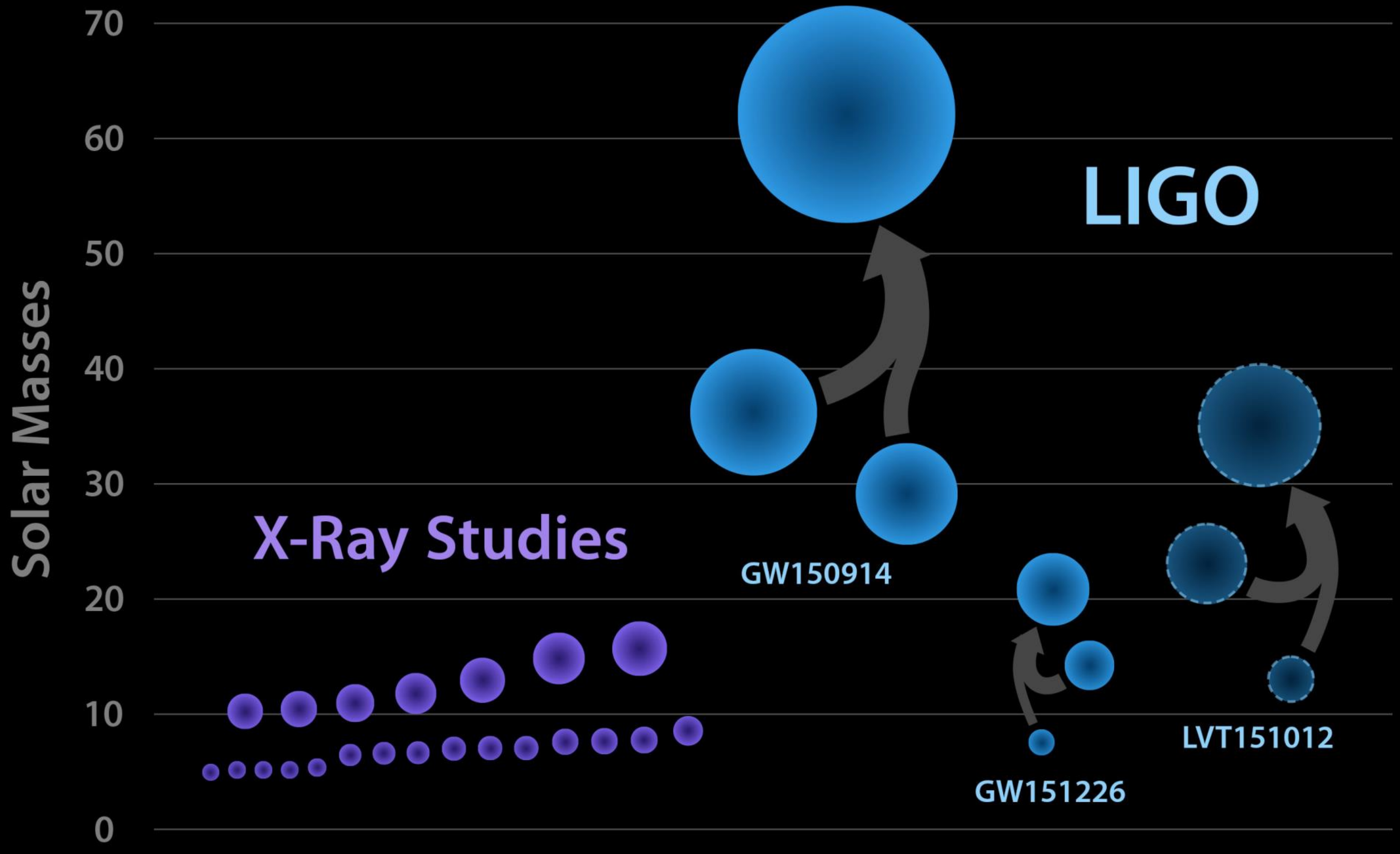
Discovery of gravitational waves

https://dcc.ligo.org/public/0124/P1600088/017/bbh-o1.pdf

Binary Black Hole Mergers in the first Advanced LIGO Observing Run



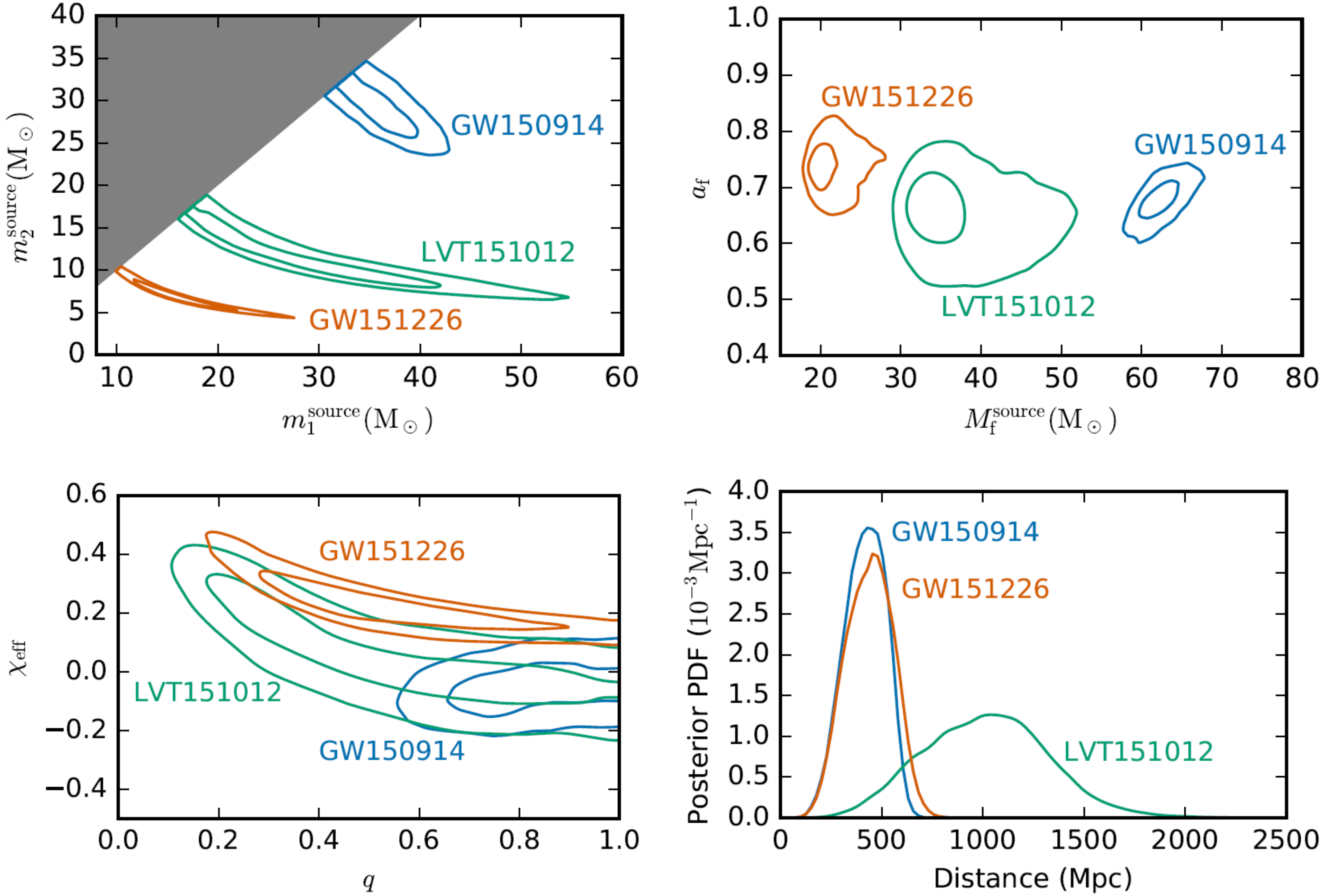
Black Holes of Known Mass



Source properties

https://dcc.ligo.org/public/0124/P1600088/017/bbh-o1.pdf

Binary Black Hole Mergers in the first Advanced LIGO Observing Run



General Relativity passes first precision tests

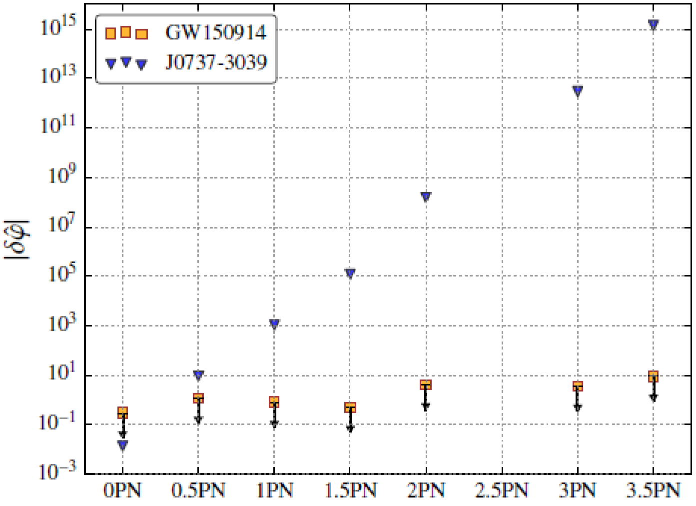
Our Bayesian analysis allows combination of different events in order to improve hypothesis testing

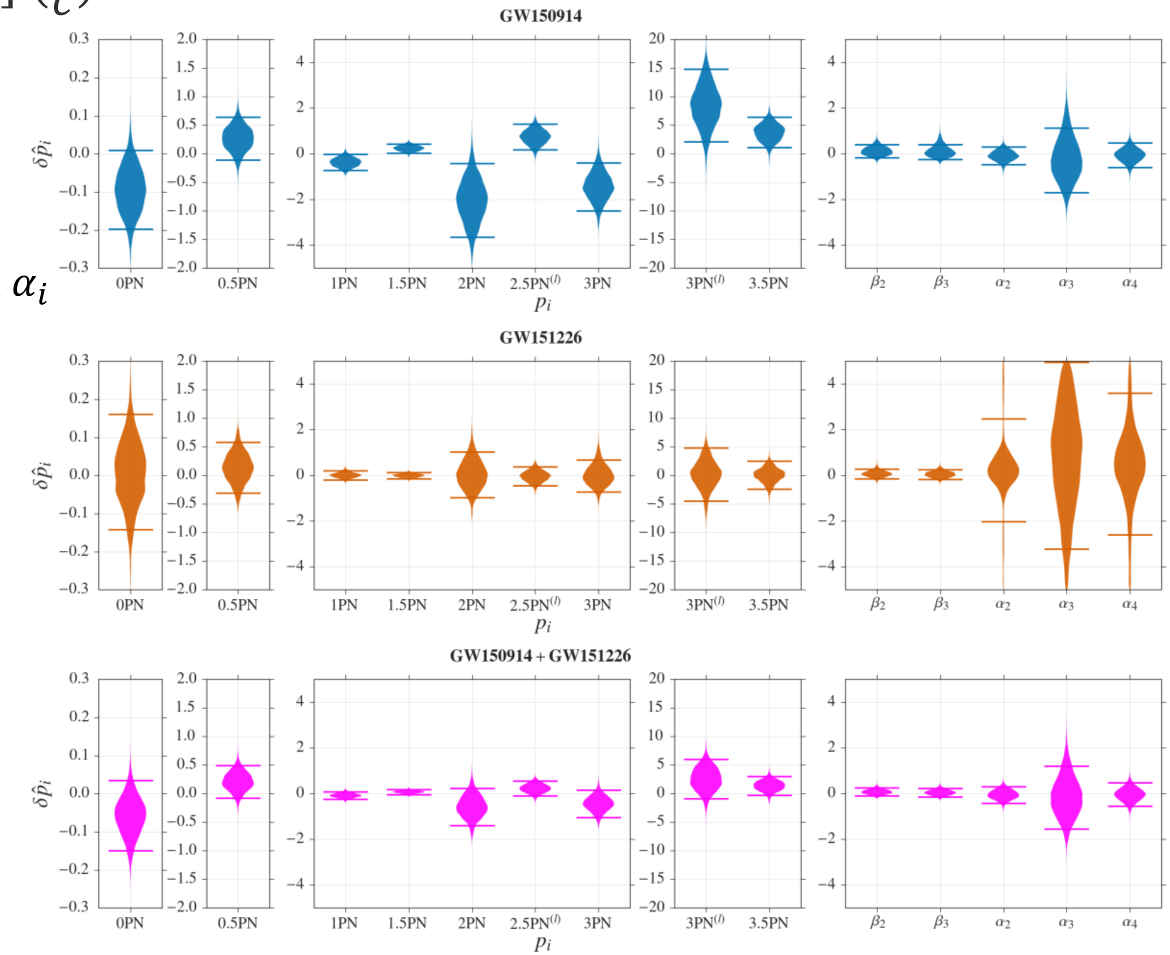
Orbital phase (post Newtonian expansion)

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

Inspiral PN terms $\varphi_j, j = 0,..,7$ and logarithmic terms $\varphi_{jl},\ j = 5,6$

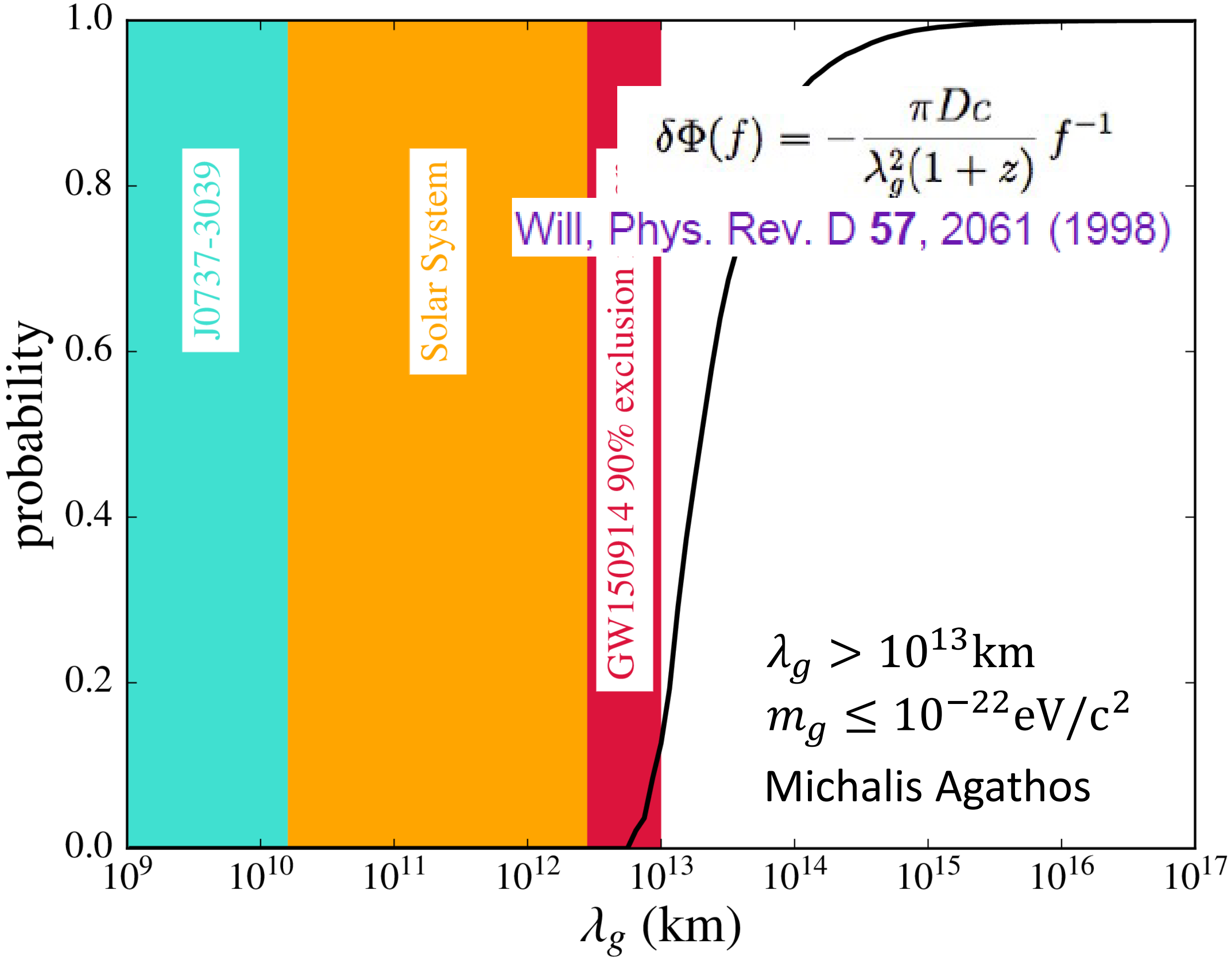
Intermediate and merger-ringdown β_i and α_i





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)

$\lambda_g > 10^{13}$km

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

Michalis Agathos

The mass of the graviton is less than 1.2×10^{-22}eV c^{-2}

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

Yukawa-type potential

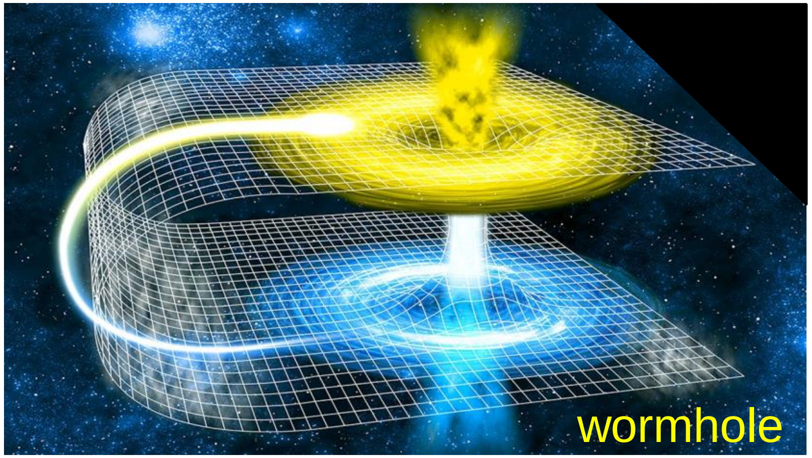
$$\varphi(r) = (\frac{GM}{r})[1 - \exp(-r/\lambda_g)]$$

used for static Solar System bounds

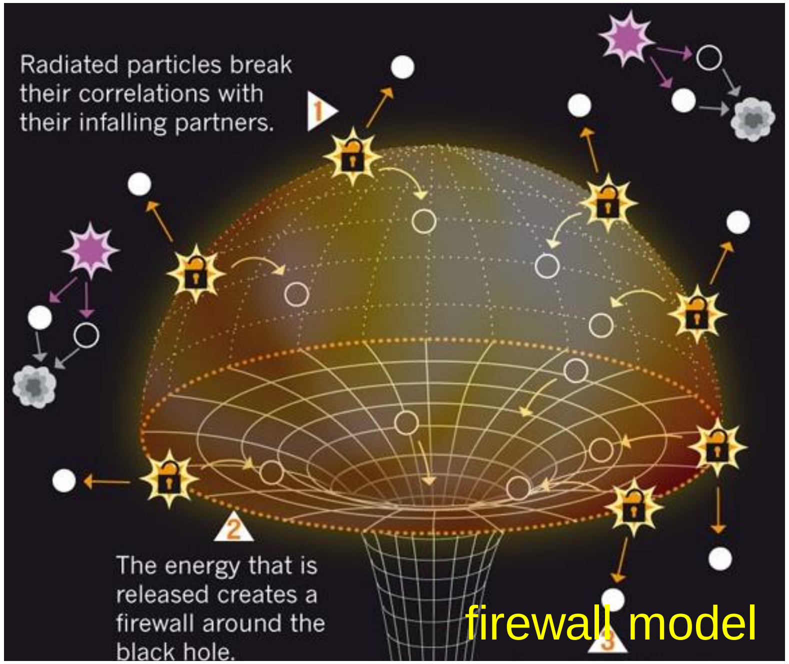
See “*Tests of general relativity with GW150914*” http://arxiv.org/abs/1602.03841

Did we observe black holes?

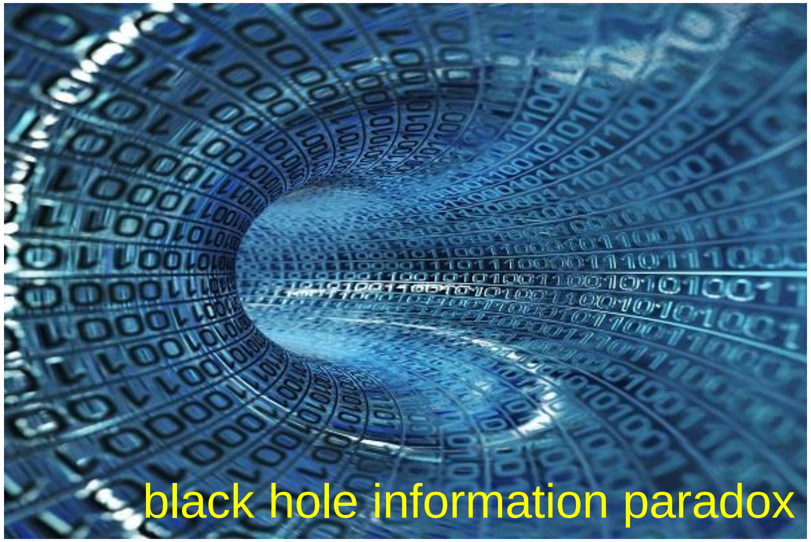
Our theories “predict” the existence of other objects, such as worm holes, boson stars, quark stars, gravastars, firewalls, *etc*. Why do we believe we have seen black holes?



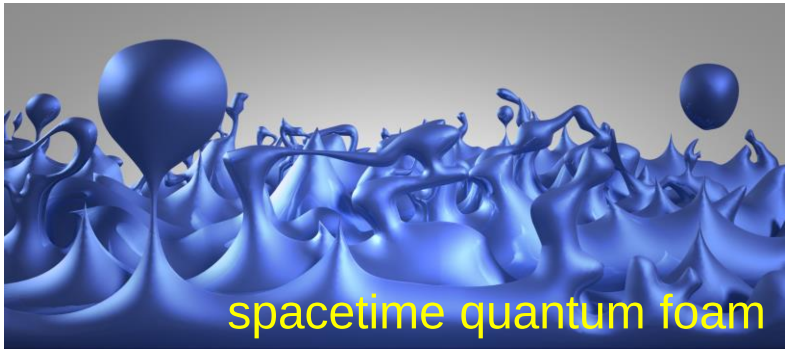
wormhole



firewall model



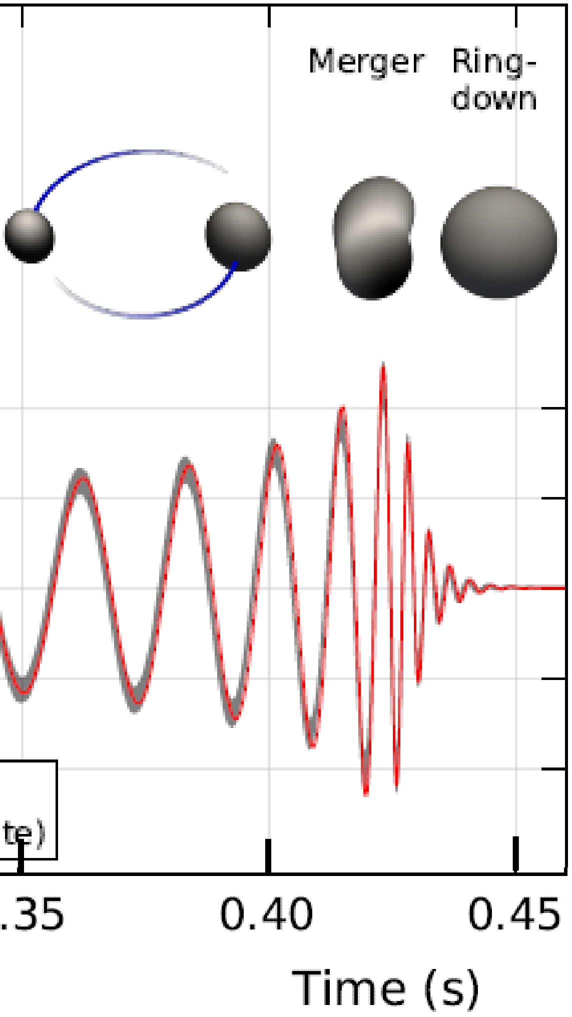
black hole information paradox

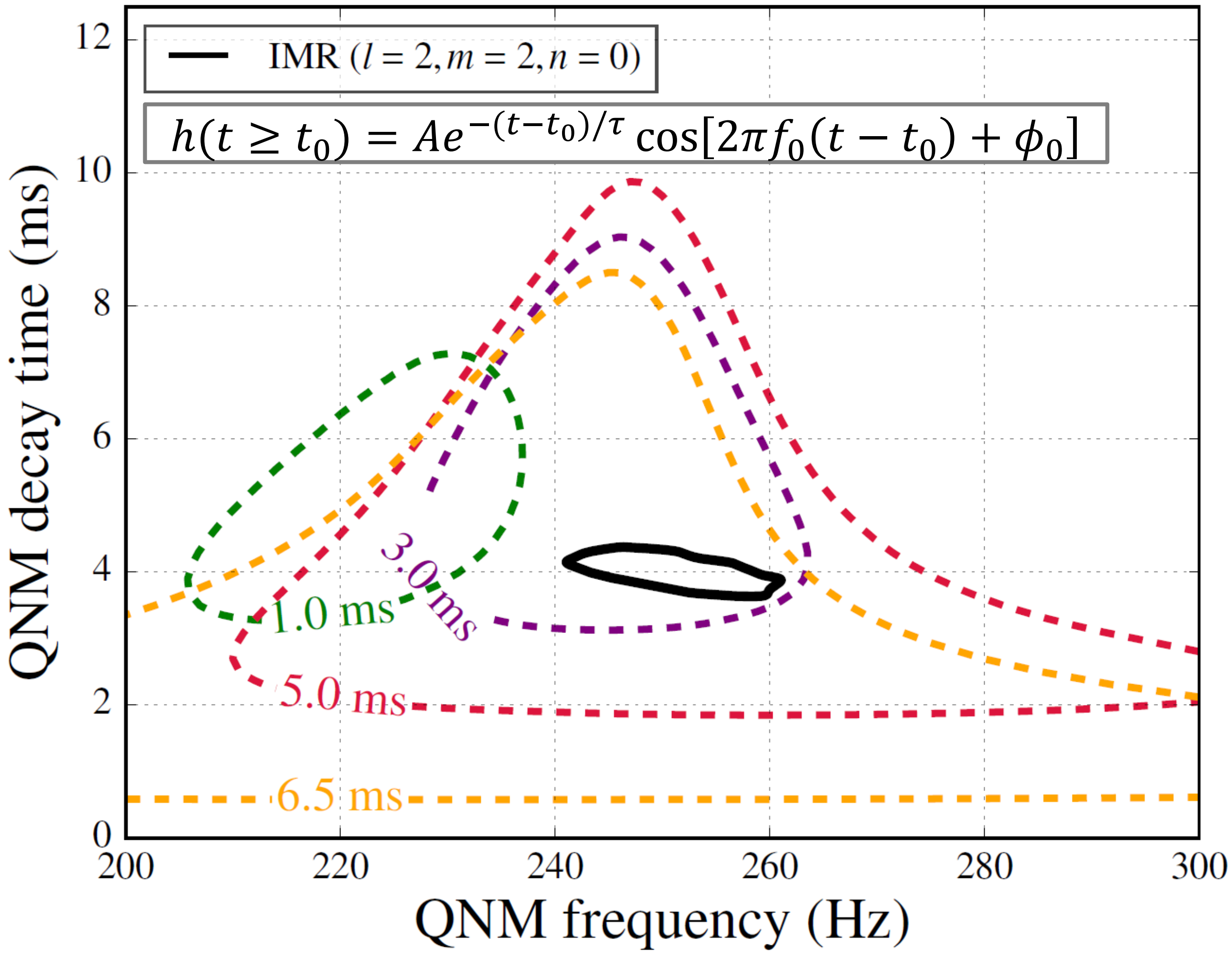


spacetime quantum foam

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)



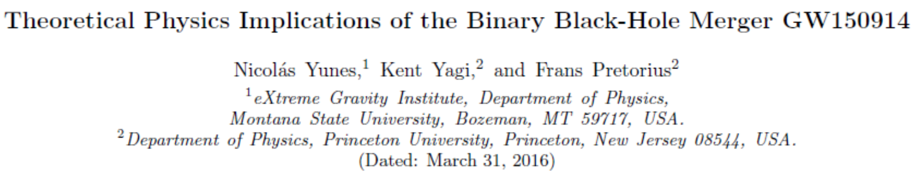


GW150914 theoretical physics implications

Curvature-radiation reaction time-scale phase space sampled by relevant experiments. E_b is the characteristic gravitational binding energy and $\dot{E}_b$ is the rate of change of this energy

Search for additional ringdown modes
(nice to have SNR > 100)

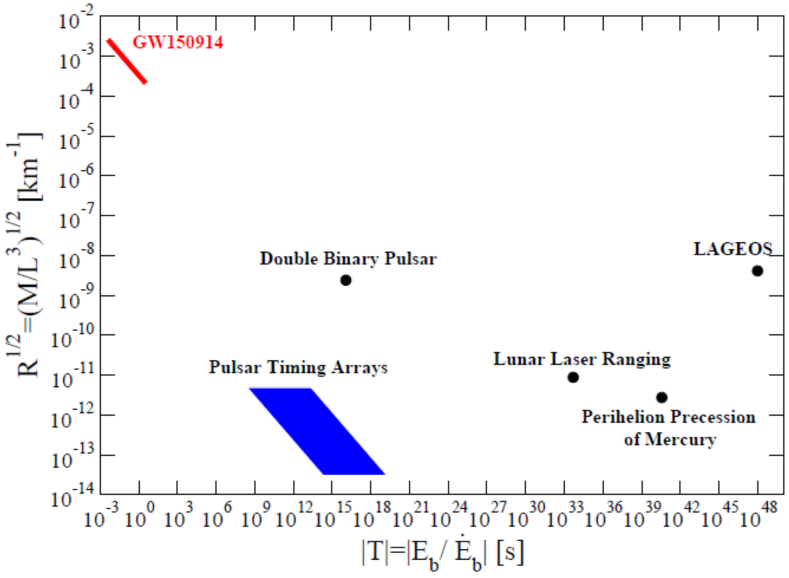
Address topics as
- Is a horizon formed?
- BBH or gravastars, wormholes, firewalls
- Test no-hair theorem
- Cosmic censorship hypotheses
- Naked singularities
- …



Theoretical Physics Implications of the Binary Black-Hole Merger GW150914

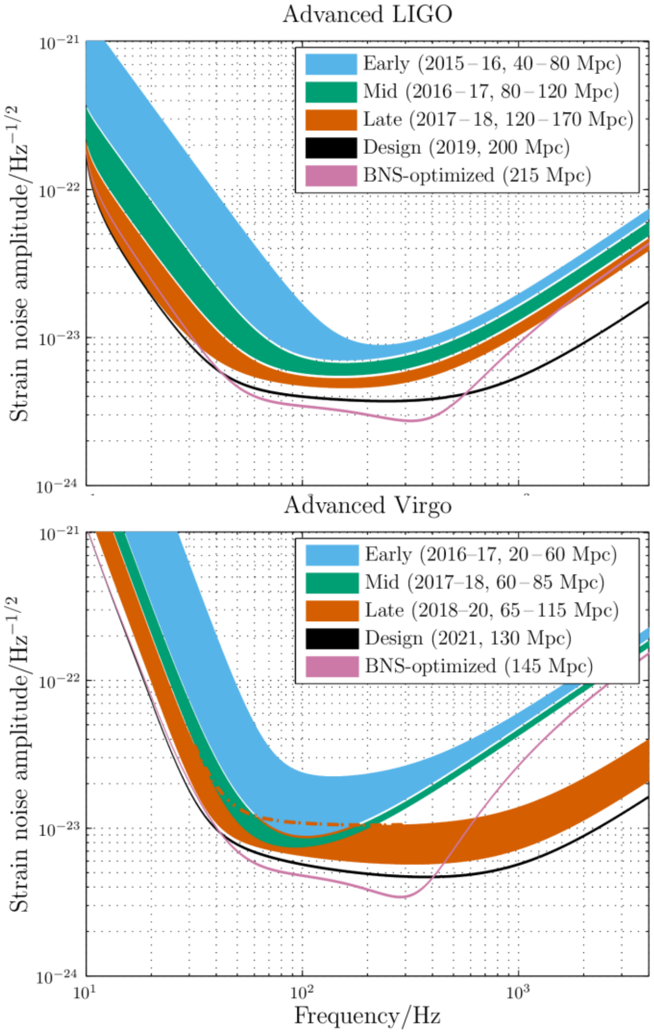
Nicolás Yunes,[1] Kent Yagi,[2] and Frans Pretorius[2]
[1] *eXtreme Gravity Institute, Department of Physics,*
Montana State University, Bozeman, MT 59717, USA.
[2] *Department of Physics, Princeton University, Princeton, New Jersey 08544, USA.*
(Dated: March 31, 2016)

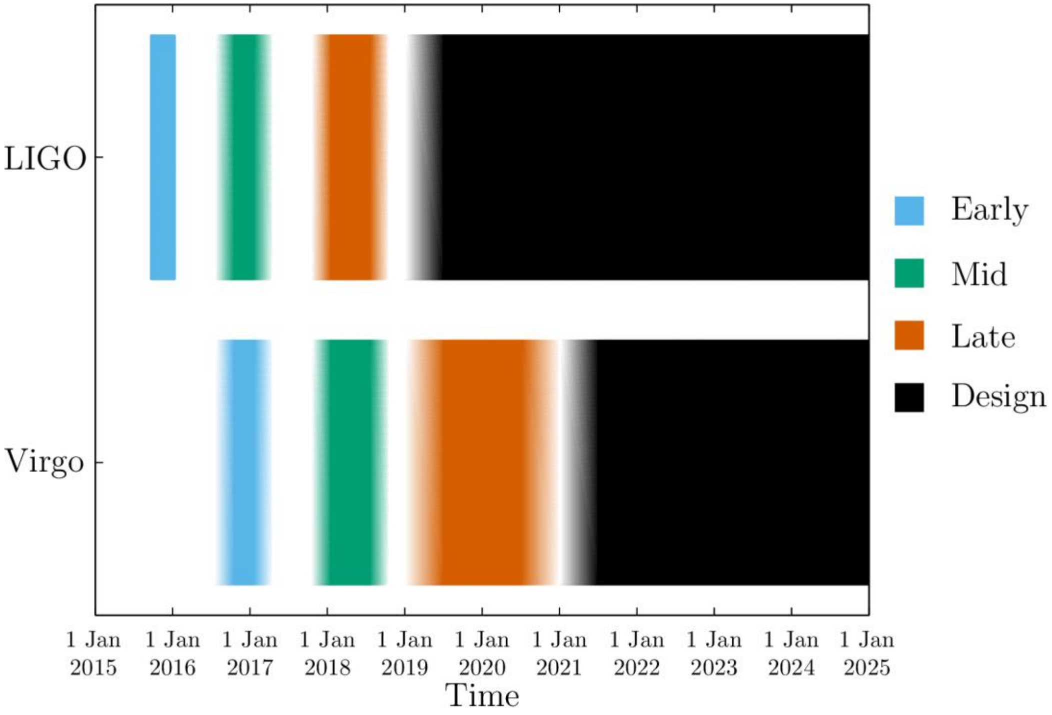
ArXiv 1603.08955v1



Spacetime volume probed by LVC

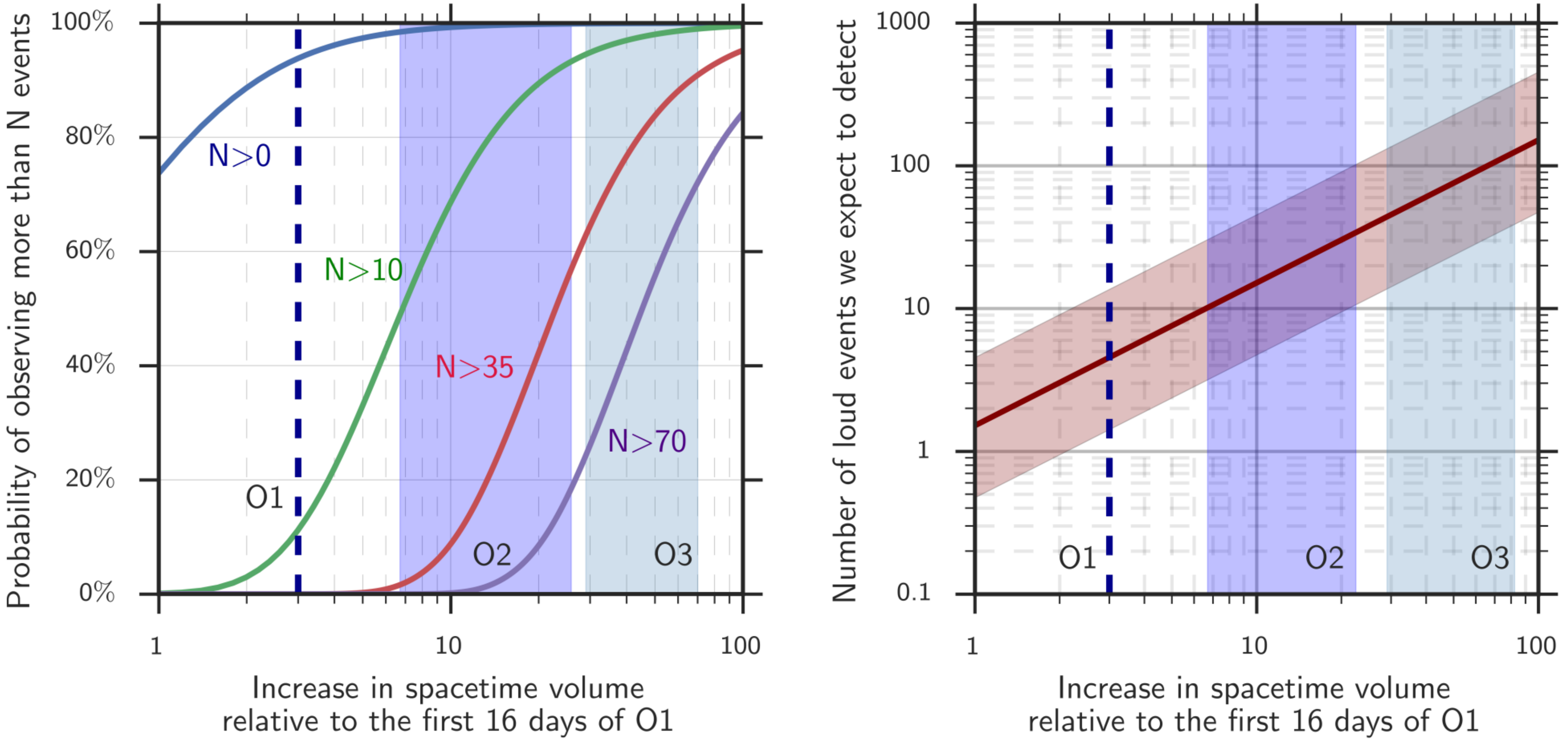
Plausible time-line for how LIGO and Virgo detectors will operate over the coming decade. The colored bars correspond to observing runs, with the colors matching those in the sensitivity plots above. Between observing runs, we work on tuning our detectors to improve their sensitivity, and have engineering runs where we test the instruments





Spacetime volume probed by LVC

The percentage chance of making 0, 10, 35 and 70 more detections of binary black holes as time goes on and detector sensitivity improves (based upon our data so far)



Binary Neutron Stars (BNS)

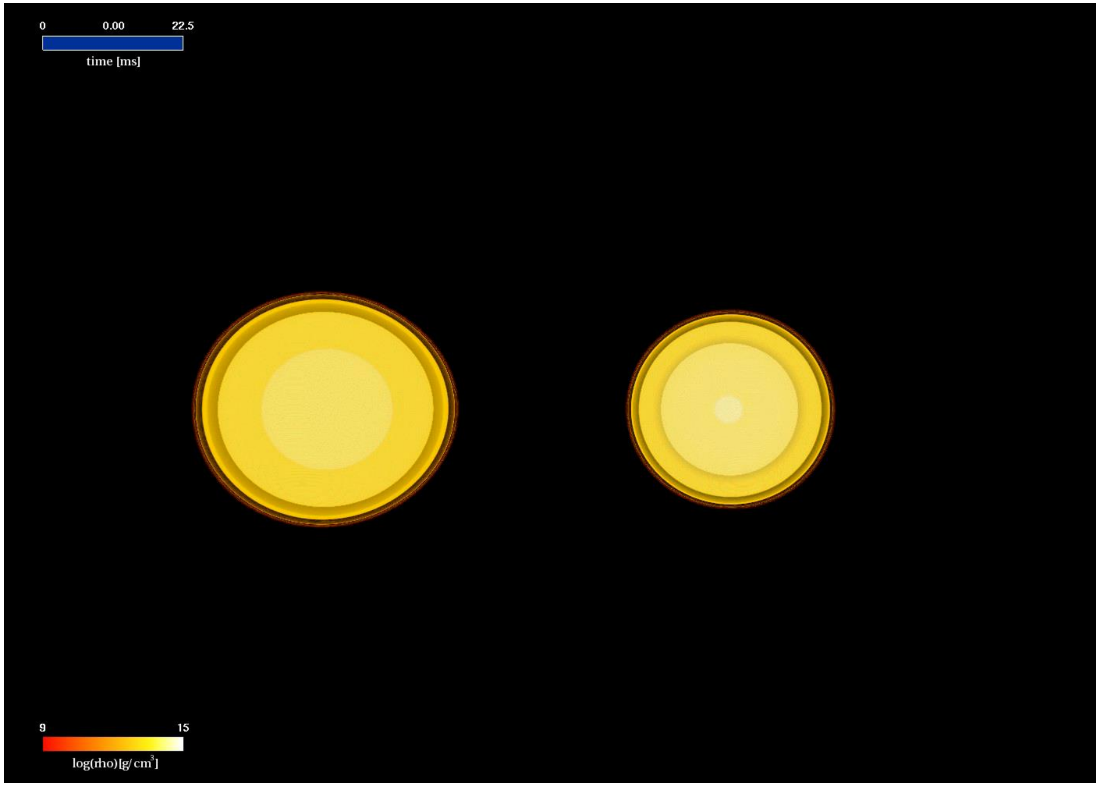
We have observed about 1600 pulsars (NS) in our Milky Way. Thus NS exist and there are probably billions of NS per galaxy

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

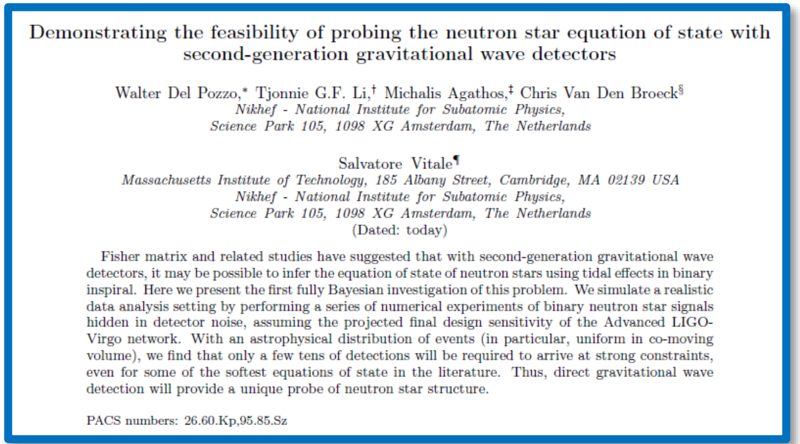
In the process a black hole may be created



Astrophysics: probing the interior structure of neutron stars

Data on BNS mergers can be used to probe the neutron star equation of state. The EOS of neutron stars is currently unknown: theoretical prediction of $P(\rho)$ differ by an order of magnitude

Neutron star represents a rich system



Demonstrating the feasibility of probing the neutron star equation of state with second-generation gravitational wave detectors

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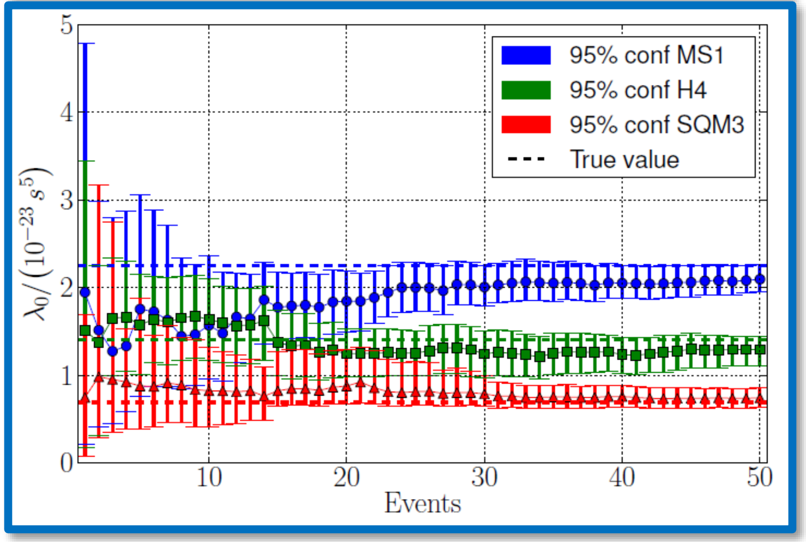
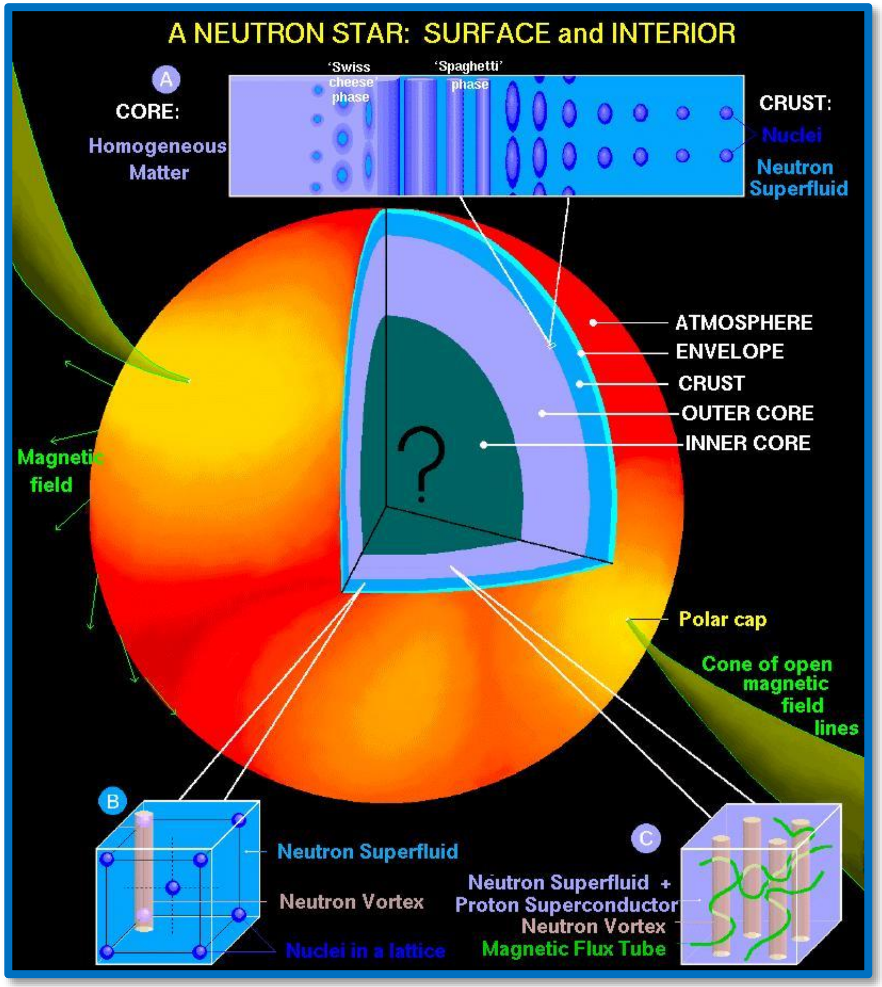
Science Park 105, 1098 XG Amsterdam, The Netherlands

(Dated: today)

Fisher matrix and related studies have suggested that with second-generation gravitational wave detectors, it may be possible to infer the equation of state of neutron stars using tidal effects in binary inspiral. Here we present the first fully Bayesian investigation of this problem. We simulate a realistic data analysis setting by performing a series of numerical experiments of binary neutron star signals hidden in detector noise, assuming the projected final design sensitivity of the Advanced LIGO-Virgo network. With an astrophysical distribution of events (in particular, uniform in co-moving volume), we find that only a few tens of detections will be required to arrive at strong constraints, even for some of the softest equations of state in the literature. Thus, direct gravitational wave detection will provide a unique probe of neutron star structure.

PACS numbers: 26.60.Kp,95.85.Sz





Sebastiano Bernuzzi

Nikhef will start an activity on numerical relativity (Vidi, ERC-STG, postdoc and PhD)

Full Einstein equations + hydrodynamics

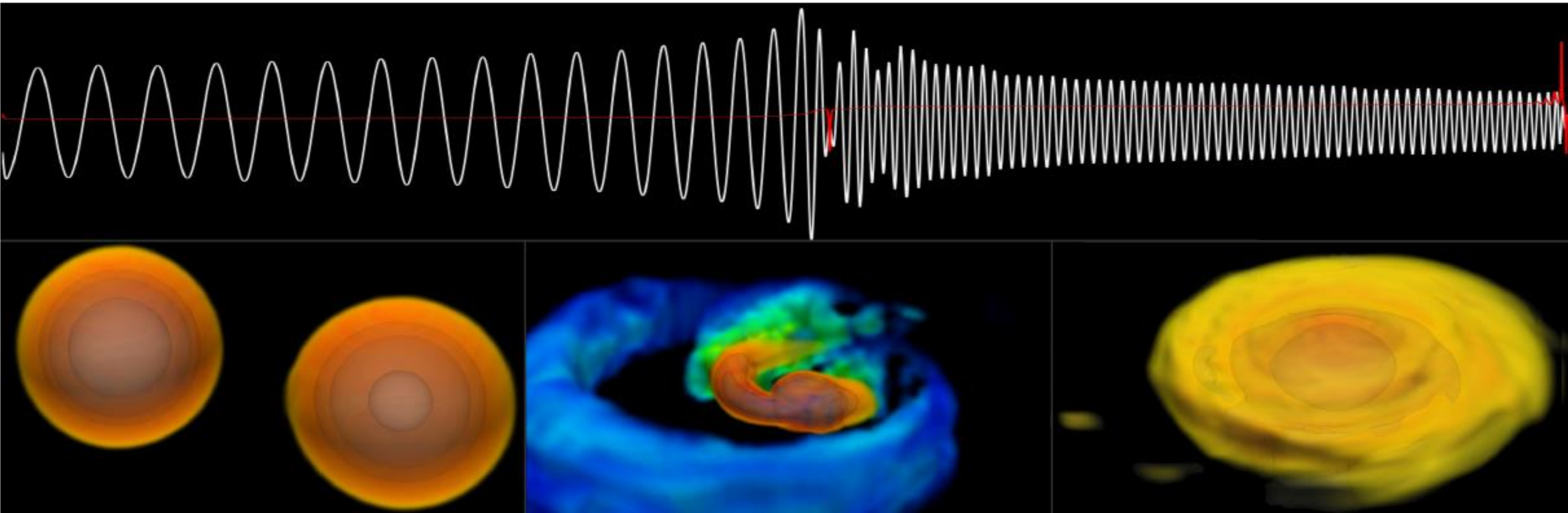
No symmetries

Multi-scales

Spin and tidal interactions

High-performance computing

First numerical relativity group in the Netherlands

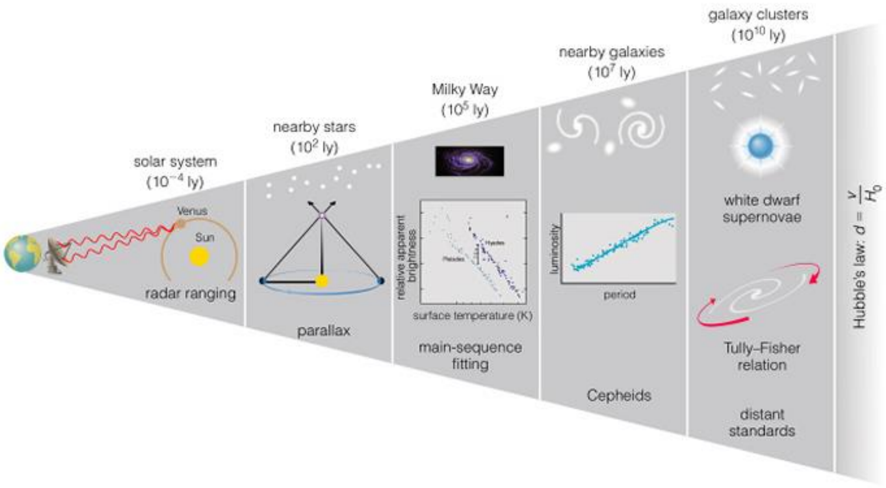


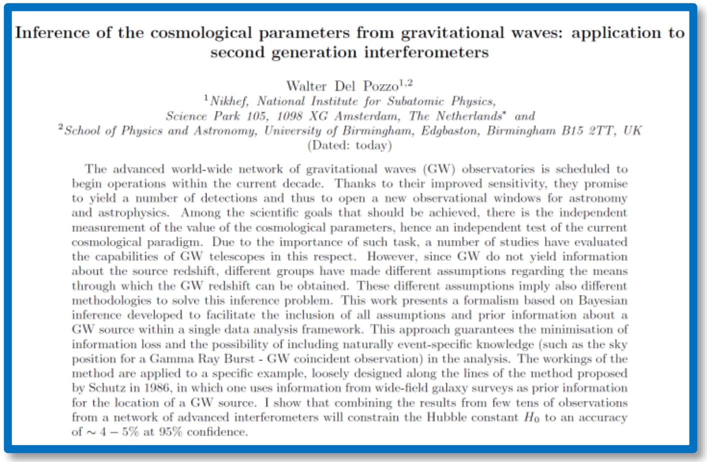
Cosmology with BNS

Employ BNS as self-calibrating “standard sirens”: no need for a cosmic distance ladder. Bayesian analysis allows combining events to increase accuracy

Topics

- Hubble parameter with Advanced LIGO and Virgo
- Cosmological parameters with Einstein Telescope:
  e.g. time evolution of EOS parameter for dark energy





Inference of the cosmological parameters from gravitational waves: application to second generation interferometers

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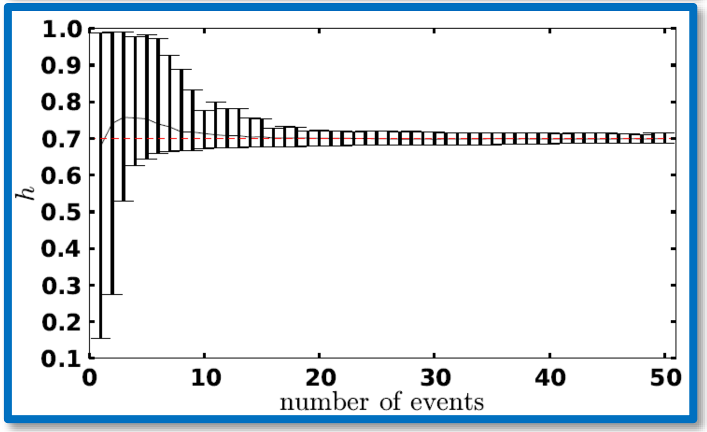
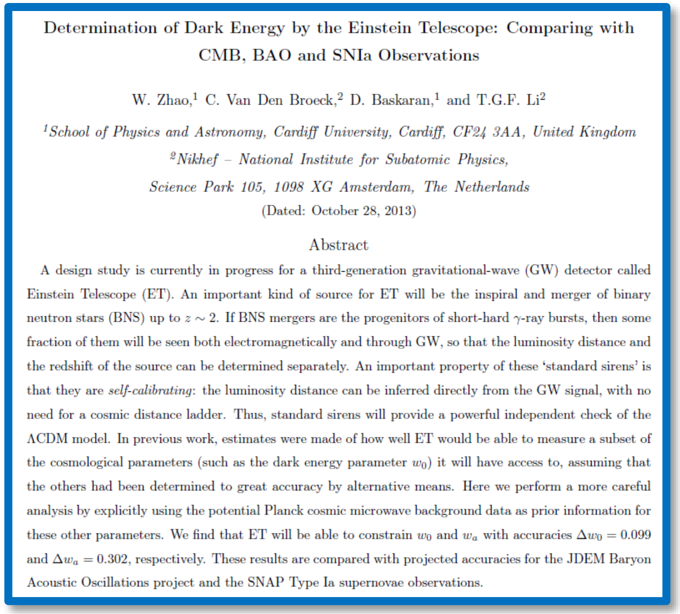
(Dated: today)

The advanced world-wide network of gravitational waves (GW) observatories is scheduled to begin operations within the current decade. Thanks to their improved sensitivity, they promise to yield a number of detections and thus to open a new observational windows for astronomy and astrophysics. Among the scientific goals that should be achieved, there is the independent measurement of the value of the cosmological parameters, hence an independent test of the current cosmological paradigm. Due to the importance of such task, a number of studies have evaluated the capabilities of GW telescopes in this respect. However, since GW do not yield information about the source redshift, different groups have made different assumptions regarding the means through which the GW redshift can be obtained. These different assumptions imply also different methodologies to solve this inference problem. This work presents a formalism based on Bayesian inference developed to facilitate the inclusion of all assumptions and prior information about a GW source within a single data analysis framework. This approach guarantees the minimisation of information loss and the possibility of including naturally event-specific knowledge (such as the sky position for a Gamma Ray Burst - GW coincident observation) in the analysis. The workings of the method are applied to a specific example, loosely designed along the lines of the method proposed by Schutz in 1986, in which one uses information from wide-field galaxy surveys as prior information for the location of a GW source. I show that combining the results from few tens of observations from a network of advanced interferometers will constrain the Hubble constant H_0 to an accuracy of $\sim 4 - 5\%$ at 95% confidence.





Determination of Dark Energy by the Einstein Telescope: Comparing with CMB, BAO and SNIa Observations

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(Dated: October 28, 2013)

Abstract

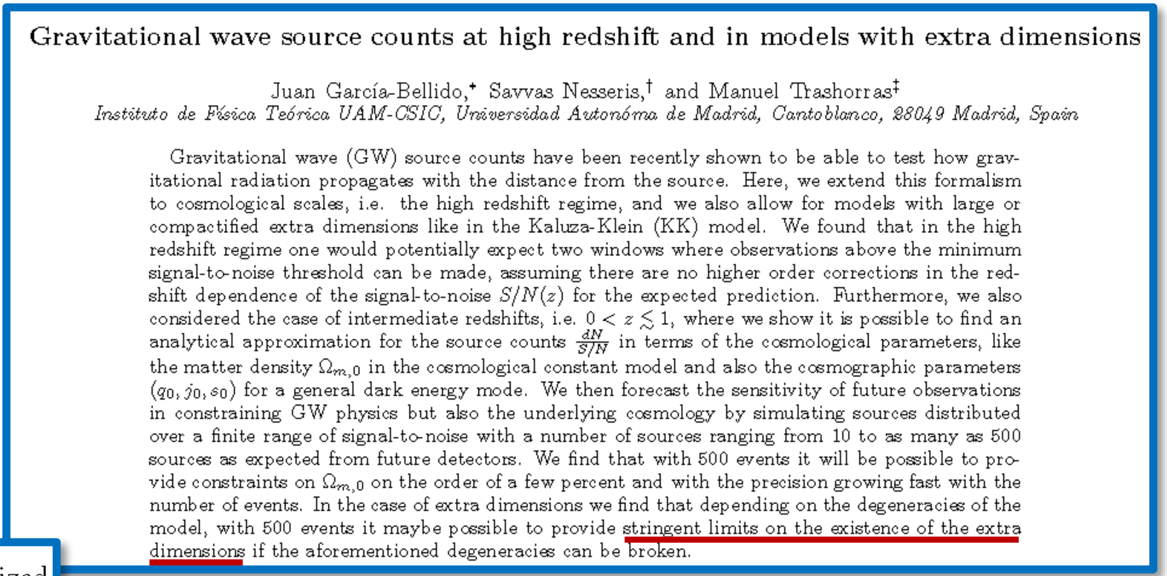
A design study is currently in progress for a third-generation gravitational-wave (GW) detector called Einstein Telescope (ET). An important kind of source for ET will be the inspiral and merger of binary neutron stars (BNS) up to $z \sim 2$. If BNS mergers are the progenitors of short-hard γ-ray bursts, then some fraction of them will be seen both electromagnetically and through GW, so that the luminosity distance and the redshift of the source can be determined separately. An important property of these ‘standard sirens’ is that they are *self-calibrating*: the luminosity distance can be inferred directly from the GW signal, with no need for a cosmic distance ladder. Thus, standard sirens will provide a powerful independent check of the ΛCDM model. In previous work, estimates were made of how well ET would be able to measure a subset of the cosmological parameters (such as the dark energy parameter w_0) it will have access to, assuming that the others had been determined to great accuracy by alternative means. Here we perform a more careful analysis by explicitly using the potential Planck cosmic microwave background data as prior information for these other parameters. We find that ET will be able to constrain w_0 and w_a with accuracies $\Delta w_0 = 0.099$ and $\Delta w_a = 0.302$, respectively. These results are compared with projected accuracies for the JDEM Baryon Acoustic Oscillations project and the SNAP Type Ia supernovae observations.

Rich physics

Many more questions can be addressed

Topics

- Astrophysics, astronomy
- Dark matter, dark energy, Hubble constant
- Scalar-Tensor-Vector Gravity (MOG)
  - Alternative theory without DM
- Mass of the graviton



Gravitational wave source counts at high redshift and in models with extra dimensions

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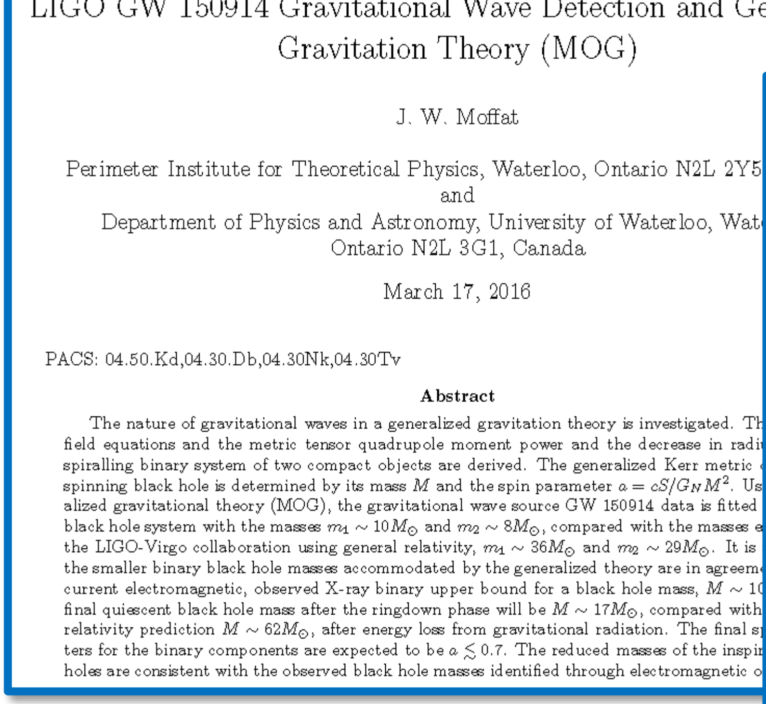
Gravitational wave (GW) source counts have been recently shown to be able to test how gravitational radiation propagates with the distance from the source. Here, we extend this formalism to cosmological scales, i.e. the high redshift regime, and we also allow for models with large or compactified extra dimensions like in the Kaluza-Klein (KK) model. We found that in the high redshift regime one would potentially expect two windows where observations above the minimum signal-to-noise threshold can be made, assuming there are no higher order corrections in the redshift dependence of the signal-to-noise $S/N(z)$ for the expected prediction. Furthermore, we also considered the case of intermediate redshifts, i.e. $0 < z \lesssim 1$, where we show it is possible to find an analytical approximation for the source counts $\frac{dN}{S/N}$ in terms of the cosmological parameters, like the matter density $\Omega_{m,0}$ in the cosmological constant model and also the cosmographic parameters (q_0, j_0, s_0) for a general dark energy mode. We then forecast the sensitivity of future observations in constraining GW physics but also the underlying cosmology by simulating sources distributed over a finite range of signal-to-noise with a number of sources ranging from 10 to as many as 500 sources as expected from future detectors. We find that with 500 events it will be possible to provide constraints on $\Omega_{m,0}$ on the order of a few percent and with the precision growing fast with the number of events. In the case of extra dimensions we find that depending on the degeneracies of the model, with 500 events it maybe possible to provide stringent limits on the existence of the extra dimensions if the aforementioned degeneracies can be broken.



LIGO GW 150914 Gravitational Wave Detection and Generalized Gravitation Theory (MOG)

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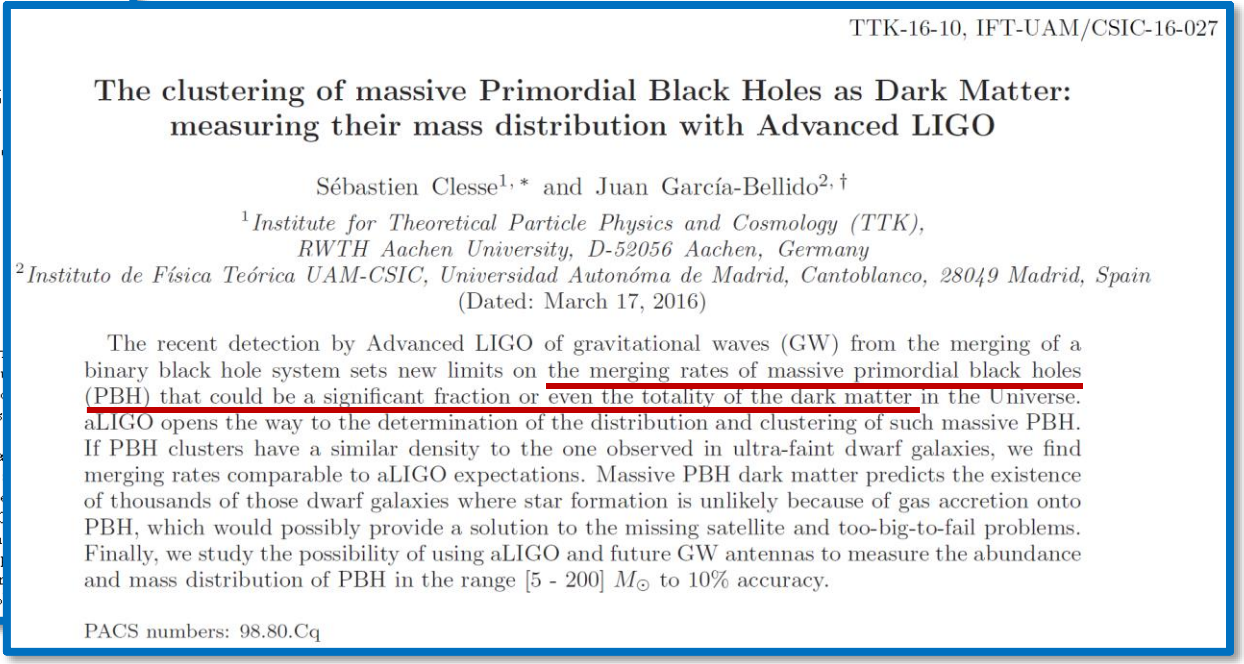
PACS: 04.50.Kd,04.30.Db,04.30Nk,04.30Tv

Abstract

The nature of gravitational waves in a generalized gravitation theory is investigated. Th
field equations and the metric tensor quadrupole moment power and the decrease in radi
spiralling binary system of two compact objects are derived. The generalized Kerr metric
spinning black hole is determined by its mass M and the spin parameter $a = cS/G_N M^2$. Us
alized gravitational theory (MOG), the gravitational wave source GW 150914 data is fitted
black hole system with the masses $m_1 \sim 10 M_\odot$ and $m_2 \sim 8 M_\odot$, compared with the masses e
the LIGO-Virgo collaboration using general relativity, $m_1 \sim 36 M_\odot$ and $m_2 \sim 29 M_\odot$. It is
the smaller binary black hole masses accommodated by the generalized theory are in agreeme
current electromagnetic, observed X-ray binary upper bound for a black hole mass, $M \sim 1$
final quiescent black hole mass after the ringdown phase will be $M \sim 17 M_\odot$, compared with
relativity prediction $M \sim 62 M_\odot$, after energy loss from gravitational radiation. The final s
ters for the binary components are expected to be $a \lesssim 0.7$. The reduced masses of the inspi
holes are consistent with the observed black hole masses identified through electromagnetic o



TTK-16-10, IFT-UAM/CSIC-16-027

The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO

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(Dated: March 17, 2016)

The recent detection by Advanced LIGO of gravitational waves (GW) from the merging of a binary black hole system sets new limits on the merging rates of massive primordial black holes (PBH) that could be a significant fraction or even the totality of the dark matter in the Universe. aLIGO opens the way to the determination of the distribution and clustering of such massive PBH. If PBH clusters have a similar density to the one observed in ultra-faint dwarf galaxies, we find merging rates comparable to aLIGO expectations. Massive PBH dark matter predicts the existence of thousands of those dwarf galaxies where star formation is unlikely because of gas accretion onto PBH, which would possibly provide a solution to the missing satellite and too-big-to-fail problems. Finally, we study the possibility of using aLIGO and future GW antennas to measure the abundance and mass distribution of PBH in the range [5 - 200] $M_\odot$ to 10% accuracy.

PACS numbers: 98.80.Cq

To be continued …

Volgende week