Probing dynamical spacetimes with gravitational waves

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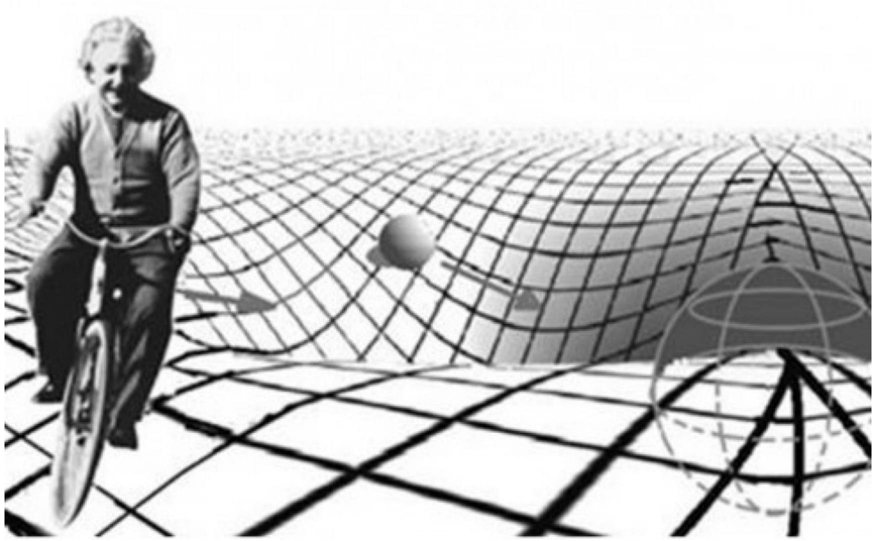
Liège, January 31, 2018

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



Predictions

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

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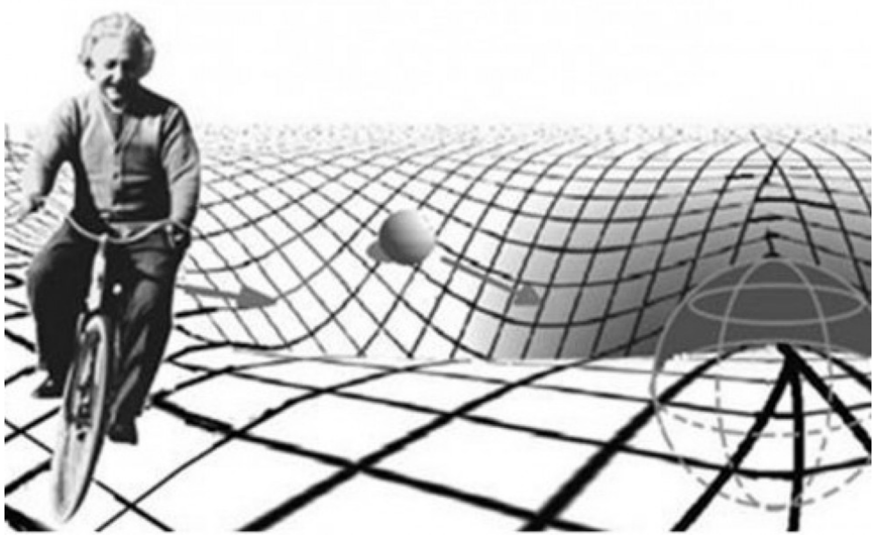

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688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

ein. Man erhält aus ihm also die Ausstrahlung A des Systems pro Zeiteinheit durch Multiplikation mit $4\pi R^2$:

$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3}\right)^2. \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

Gleichwohl müßten die Atome zufolge der inneratomischen Elektronenbewegung nicht nur elektromagnetische, sondern auch Gravitationsenergie ausstrahlen, wenn auch in winzigem Betrage. Da dies in Wahrheit in der Natur nicht zutreffen dürfte, so scheint es, daß die Quantentheorie nicht nur die Maxwellsche Elektrodynamik, sondern auch die neue Gravitationstheorie wird modifizieren müssen.

Binary Neutron Stars (BNS)

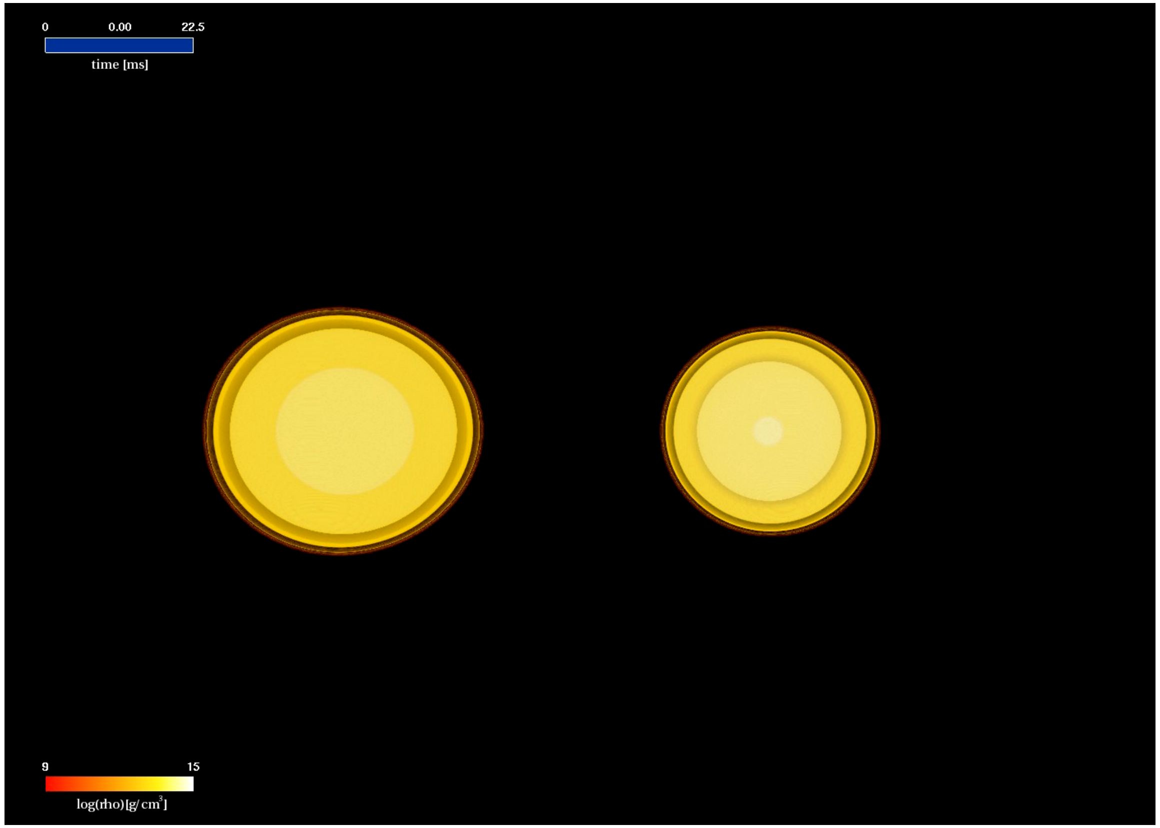
We have observed about 1600 pulsars (NS) in our Milky Way. Thus NS exist and there are probably billions of NS per galaxy

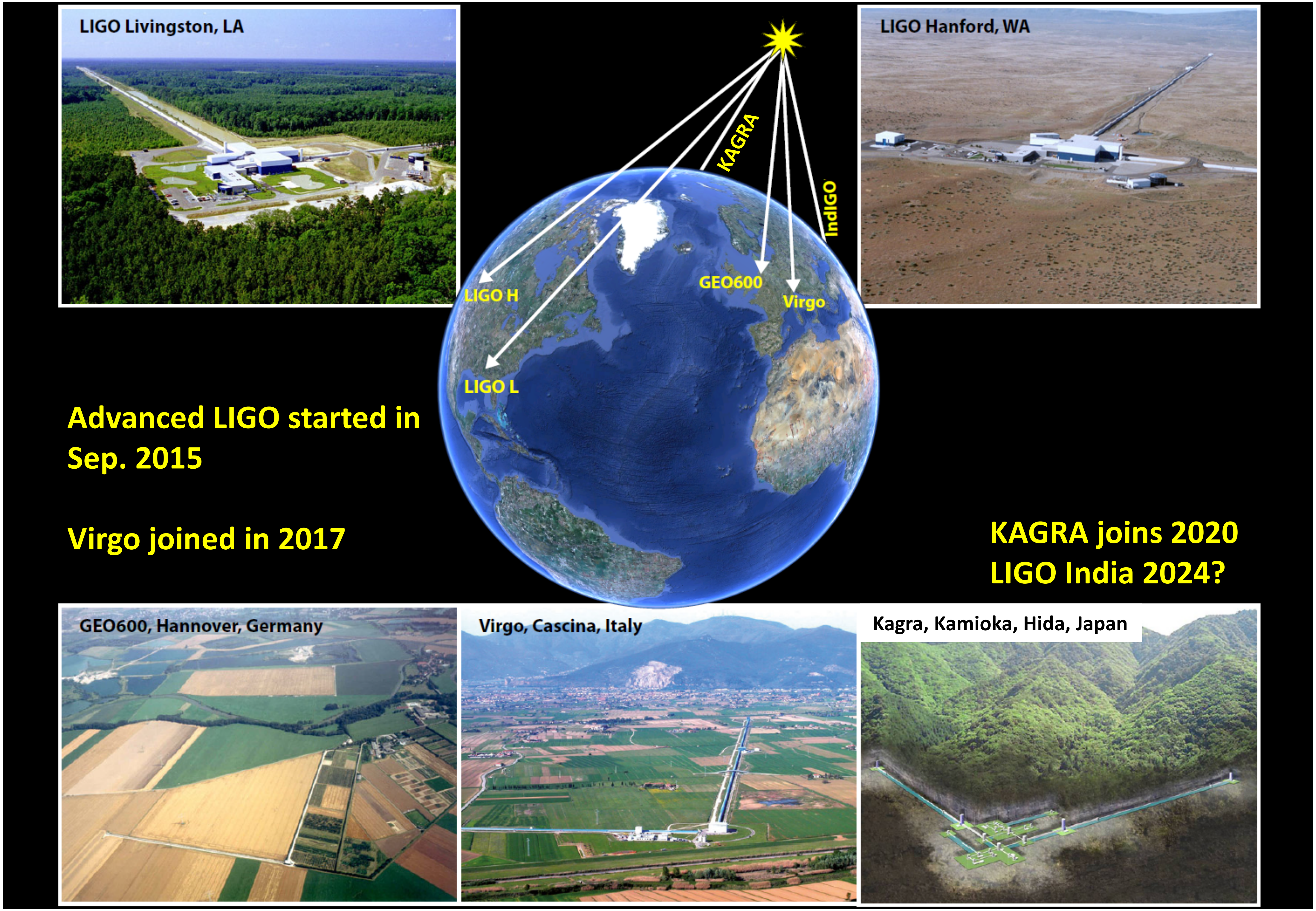
We also discovered 9 binary neutron stars (BNS), *e.g.* Hulse Taylor BNS

These systems undergo strong quadrupole-type acceleration

After a certain time, both NS will collide

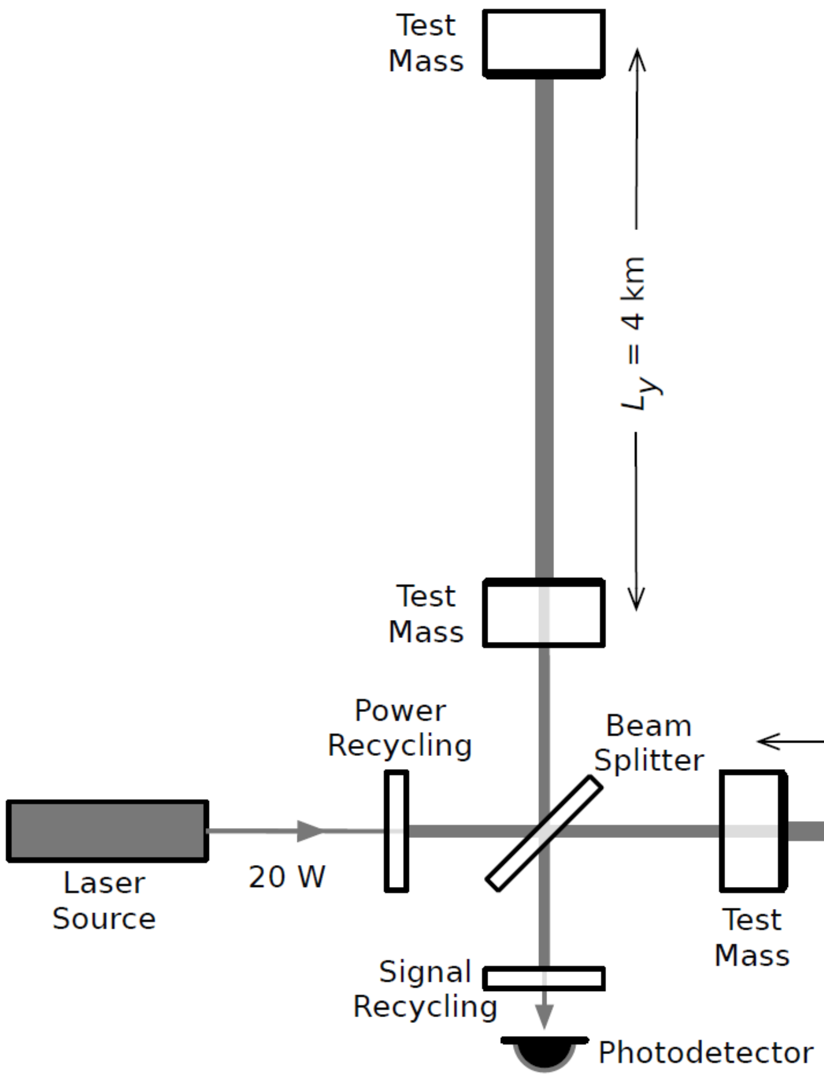
In the process a black hole may be created

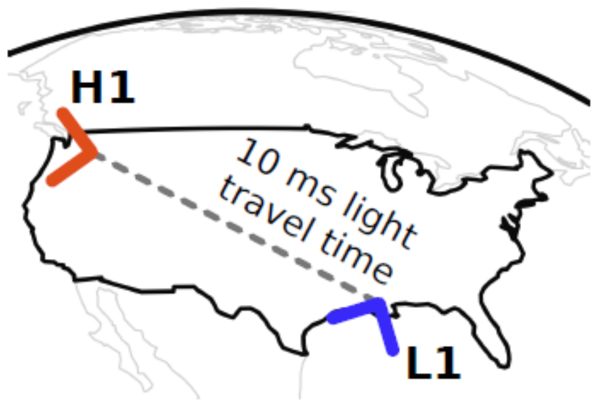



LIGO Livingston, LA
LIGO Hanford, WA
KAGRA
IndIGO
LIGO H
LIGO L
GEO600
Virgo
Advanced LIGO started in Sep. 2015
Virgo joined in 2017
KAGRA joins 2020
LIGO India 2024?
GEO600, Hannover, Germany
Virgo, Cascina, Italy
Kagra, Kamioka, Hida, Japan

The Advanced LIGO detectors

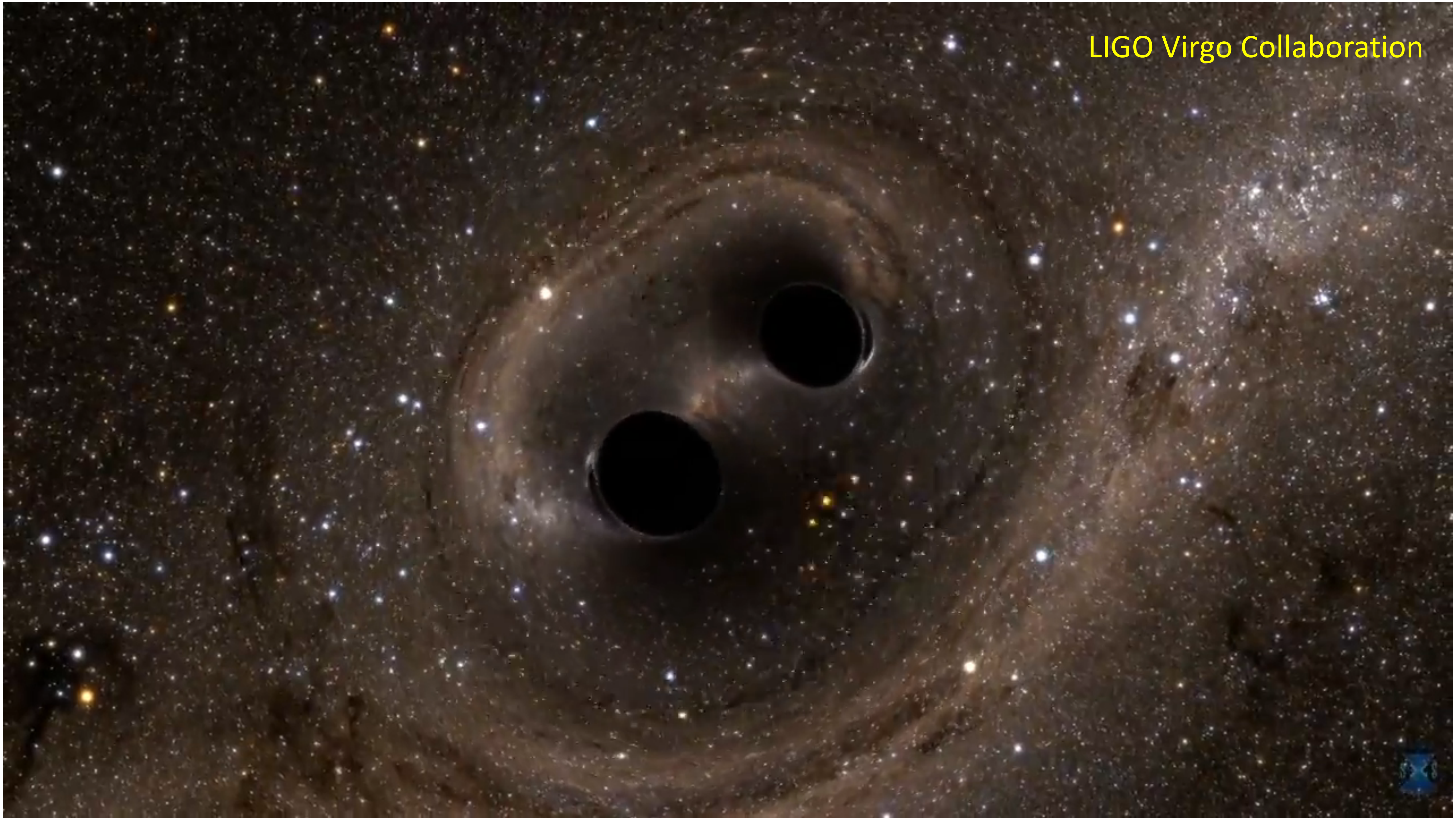
Only the LIGO and GEO detectors of the LIGO Virgo Collaboration were operational in 2015 and 2016. GEO had insufficient sensitivity to detect BBH events, while Virgo join the network in 2017





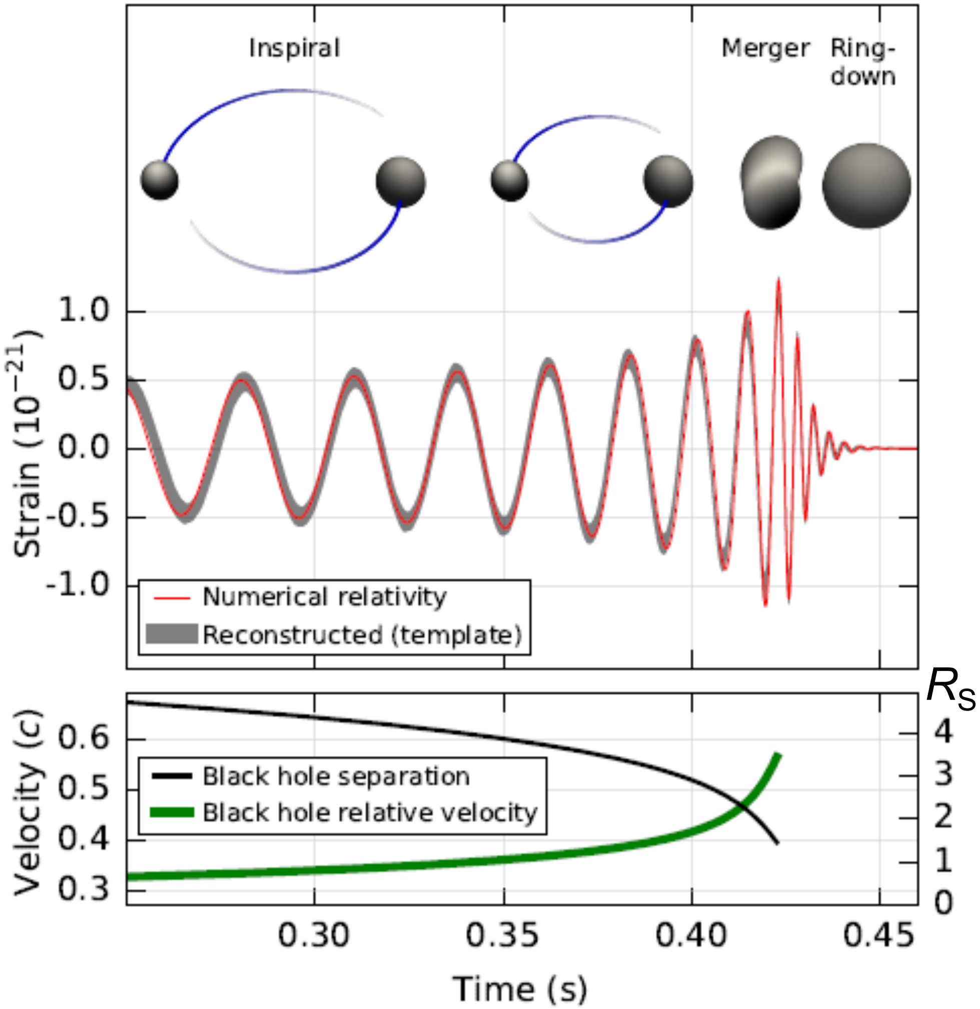
Event GW150914

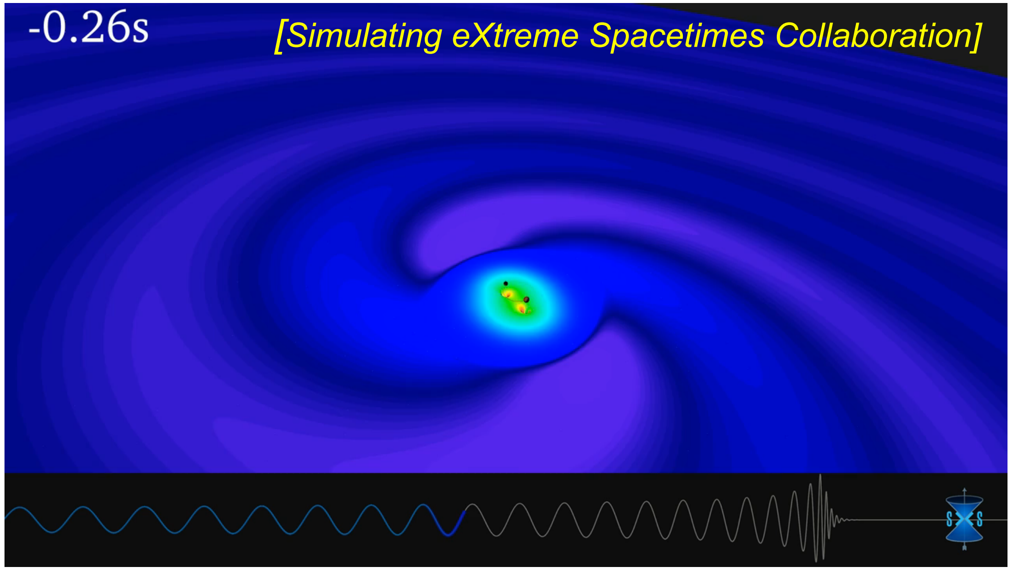
On September 14, 2015 we detected for the first time gravitational waves (vibrations in the fabric of space and time) from the collision of two black holes



Binary black hole merger GW150914

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 inspiral and ringdown phase





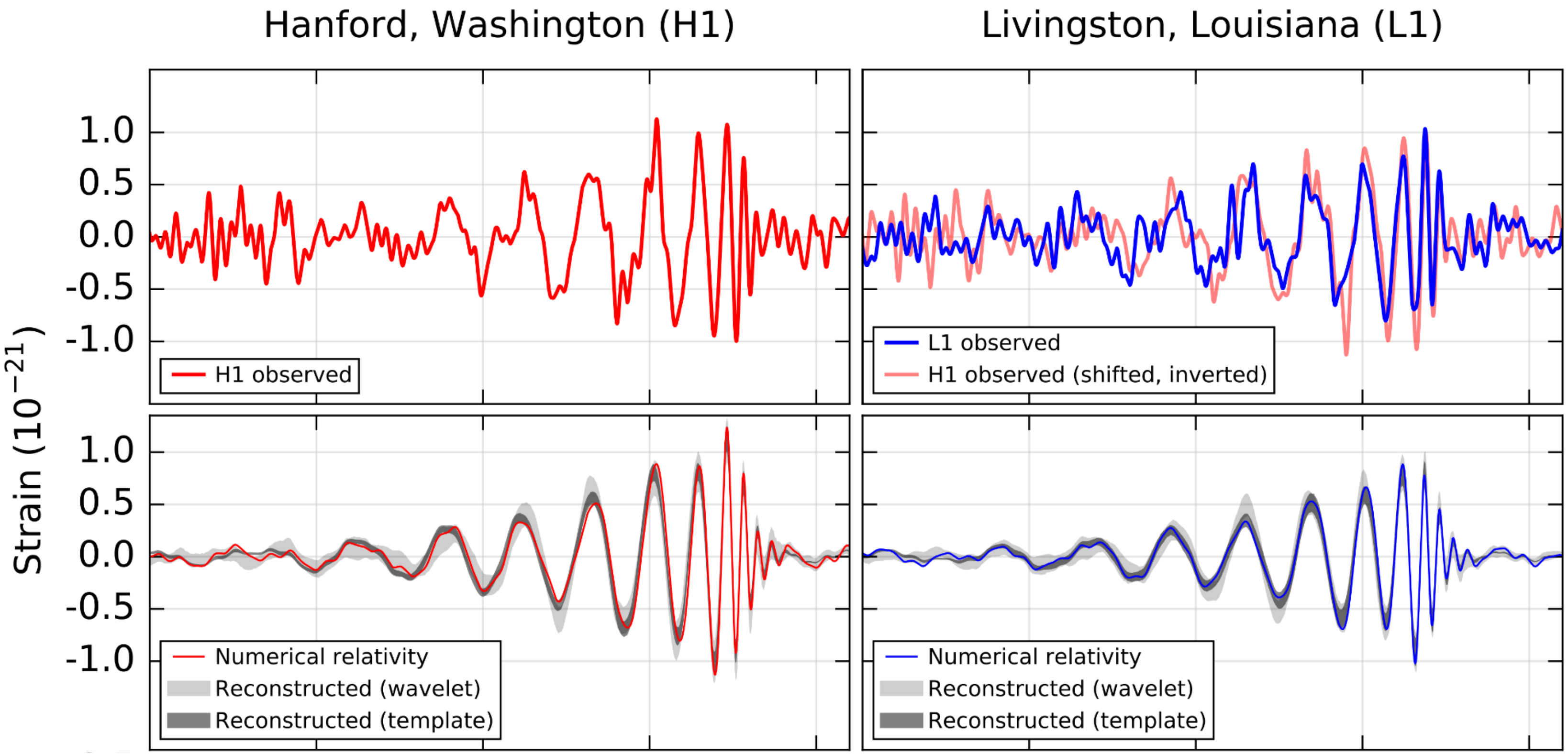
- Chirp $\dot{f} \approx f^{11/3} M_S^{5/3}$
- Maximum frequency $f_{\mathrm{ISCO}} = \frac{1}{6^{3/2}\pi M}$
- Orbital phase (post Newtonian expansion)

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

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

Binary black hole merger GW150914

Matches well to BBH template when filtered the same way

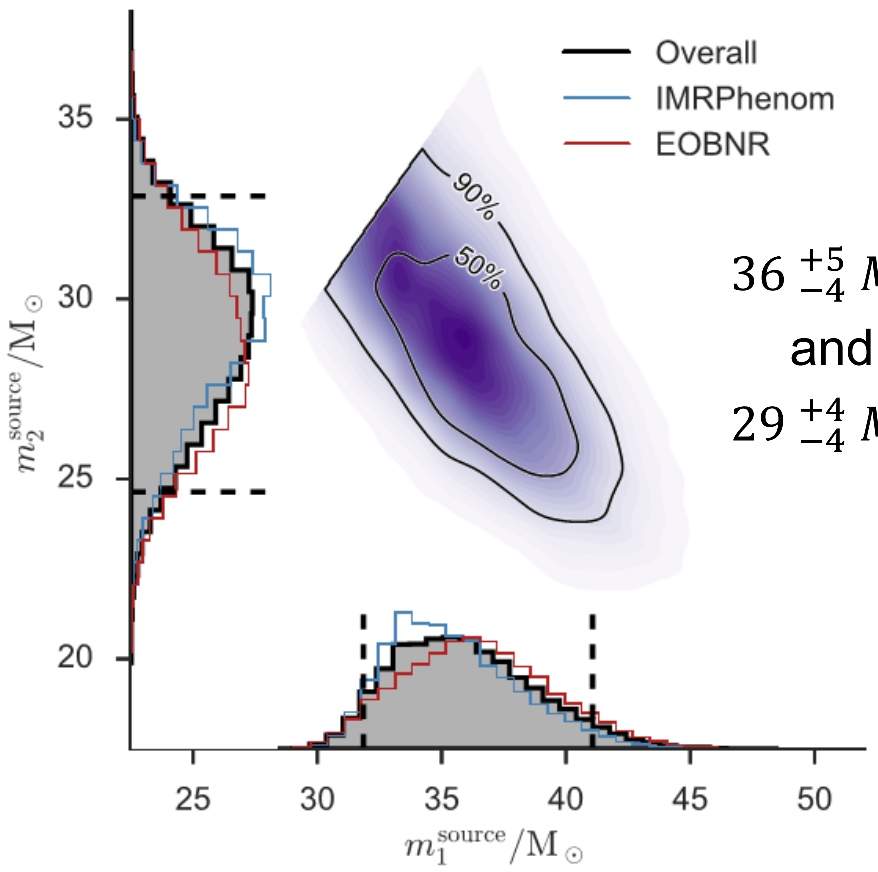


[Abbott et al. 2016, PRL 116, 061102]

Some properties of GW150914

These are surprising heavy for stellar-remnant black holes

Masses



$36^{+5}_{-4}\ M_\odot$

and

$29^{+4}_{-4}\ M_\odot$

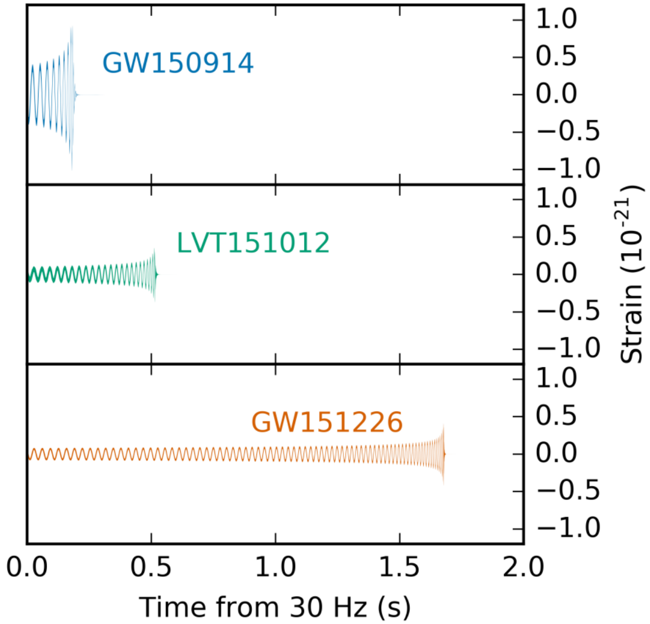
[Abbott et al. 2016, ApJL 833, L1]

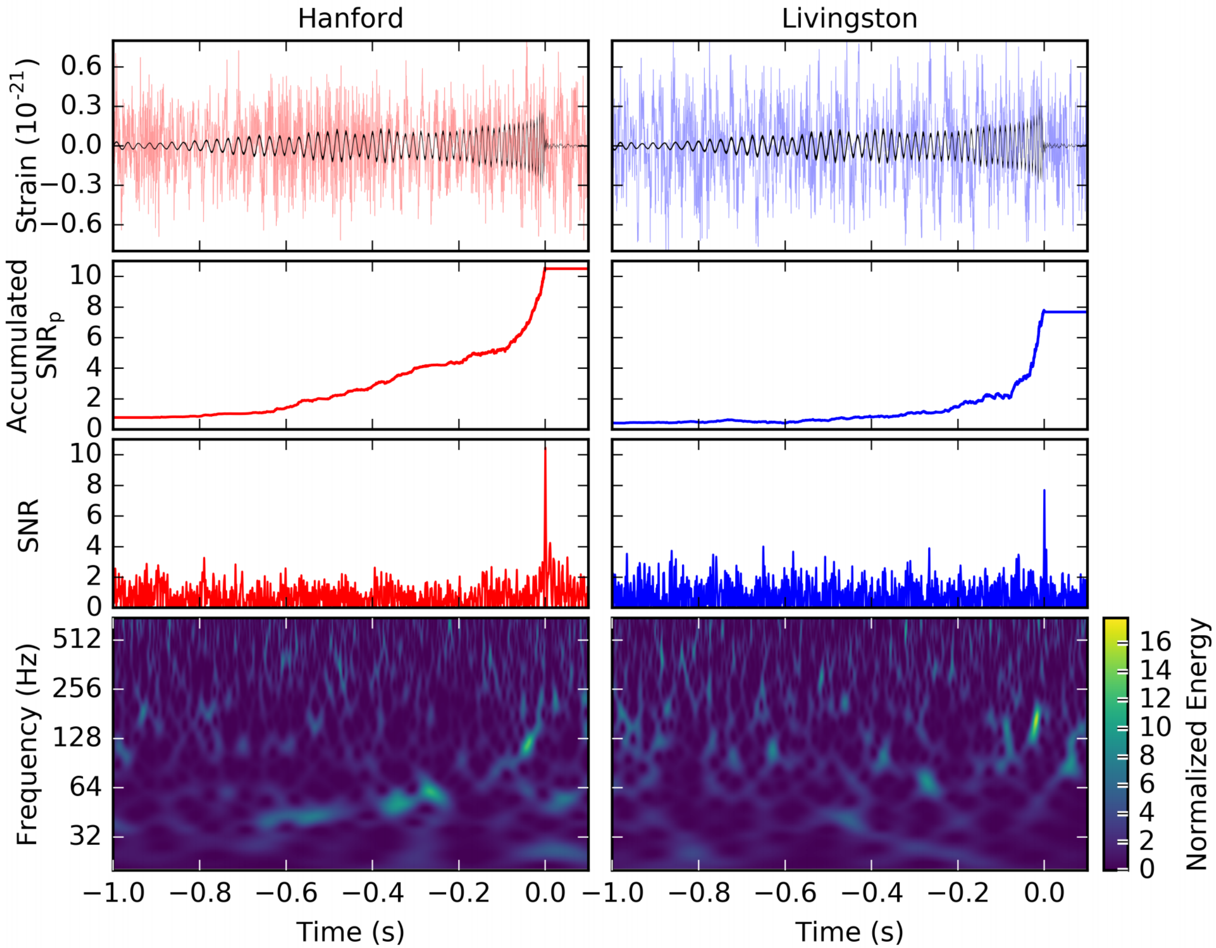
- Final BH mass: $62 \pm 4\ M_\odot$
- Energy radiated: $3.0 \pm 0.5\ M_\odot c^2$
- Peak power ~ $200\ M_\odot c^2/s$!
- Distance: $410\ ^{+160}_{-180}$ Mpc
  $= 1.3 \pm 0.5$ billion light-years
- ➔ Redshift $z \approx 0.09$
- We can't tell if the initial black holes had any "spin" (intrinsic angular momentum), but the spin of the final BH is $0.67\ ^{+0.05}_{-0.07}$ of maximal spin allowed by GR ($\frac{Gm^2}{c}$)

More from the first observing run

Analysis of the complete O1 run data revealed one additional significant binary black hole coalescence signal, GW151226, and a so-called trigger LVT. Matched filtering was essential for detecting GW151226

Another signal consistent with GR but qualitatively different
- Longer duration,
- lower amplitude,
- more “cycles” in band





[Abbott et al. 2016, PRL 116, 241103]

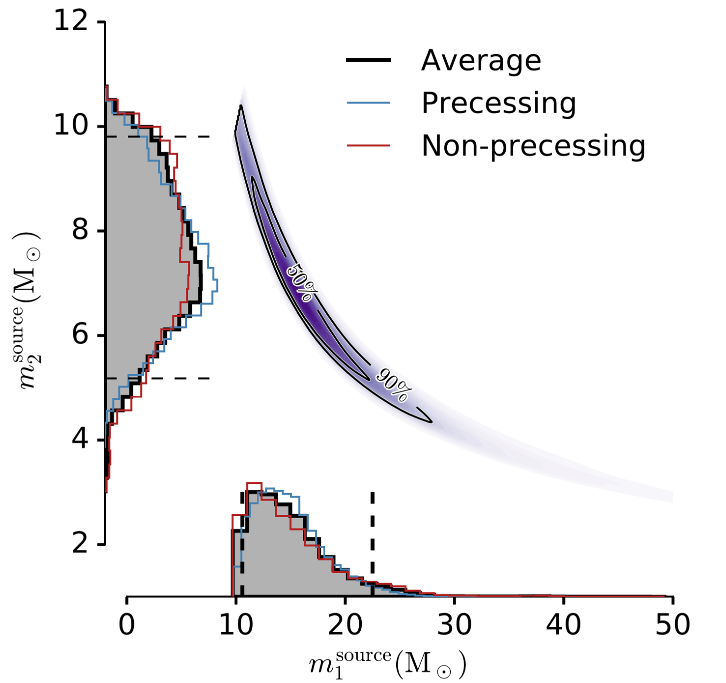
Properties of GW151226

GW151226 has lower mass than GW150914… and nonzero spin!

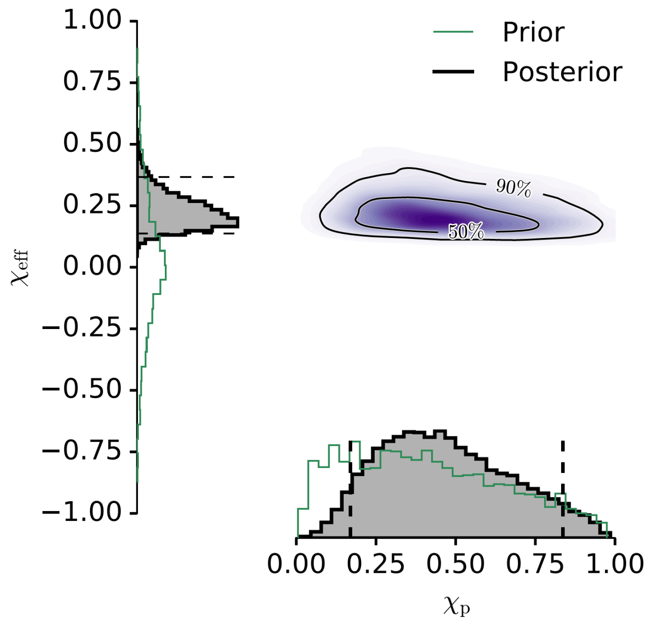
Initial masses: $14.2\,^{+8.3}_{-3.7}$ and $7.5 \pm 2.3\, M_\odot$
Final BH mass: $20.8\,^{+6.1}_{-1.7}\, M_\odot$
Energy radiated: $1.0\,^{+0.1}_{-0.2}\, M_\odot c^2$

Luminosity distance: $440\,^{+180}_{-190}$ Mpc

[Abbott et al. 2016, PRL 116, 241103]



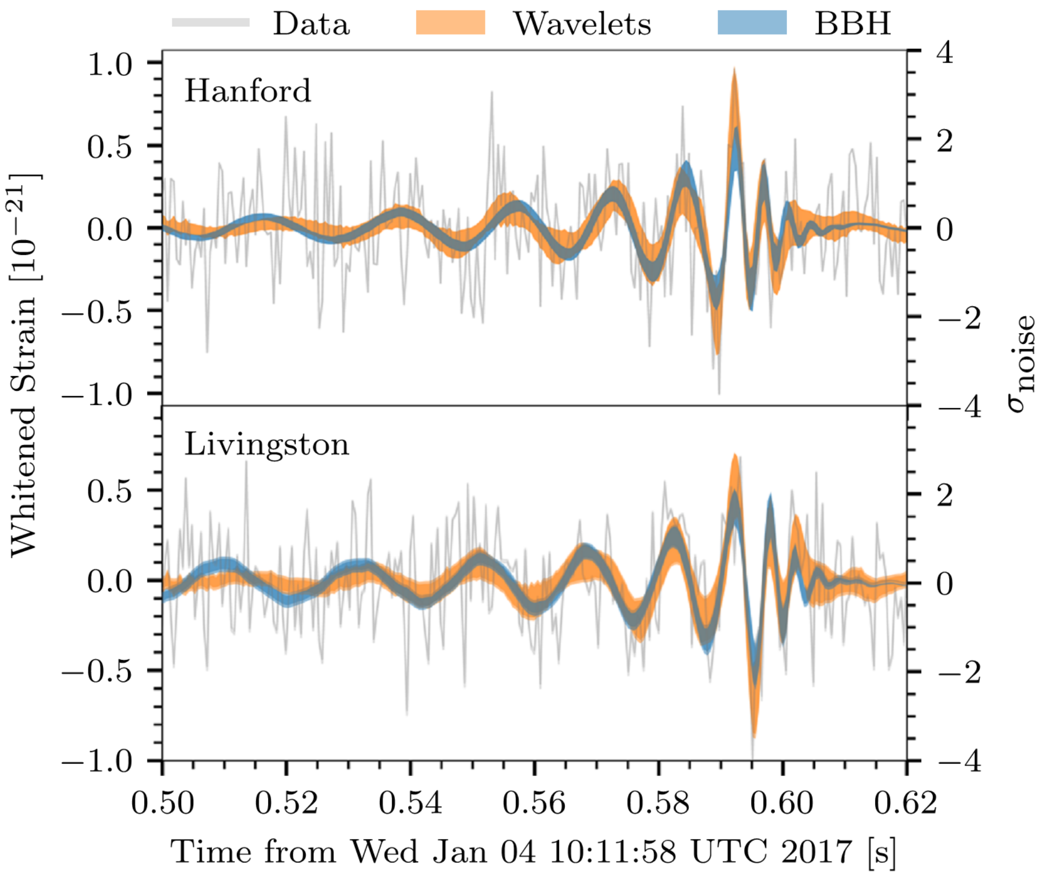
Effective signed spin combination definitely positive
⇒ at least one of the initial BHs has nonzero spin
(we can't tell how the spin is divided up between them due to waveform degeneracy)

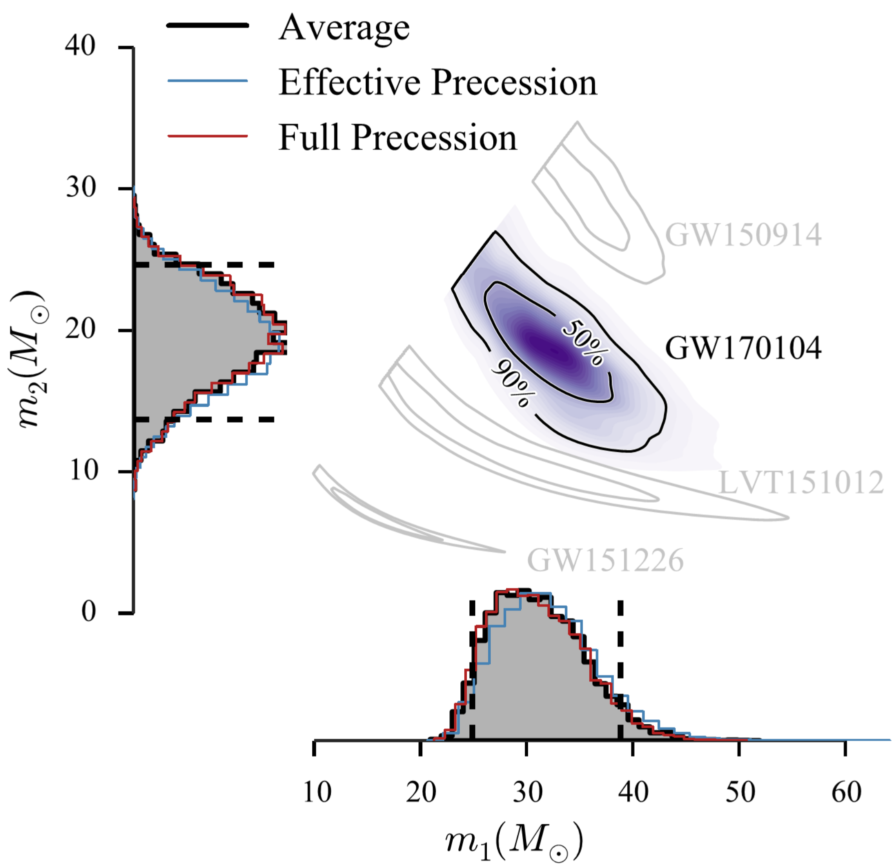


First event from O2 run: GW170104

Another binary black hole merger with masses in between GW150914 and GW151226.
Event is about twice as far away as GW150914 and GW151226

Effective spin parameter $\chi_{\mathrm{eff}} = -0.12^{+0.21}_{-0.30}$





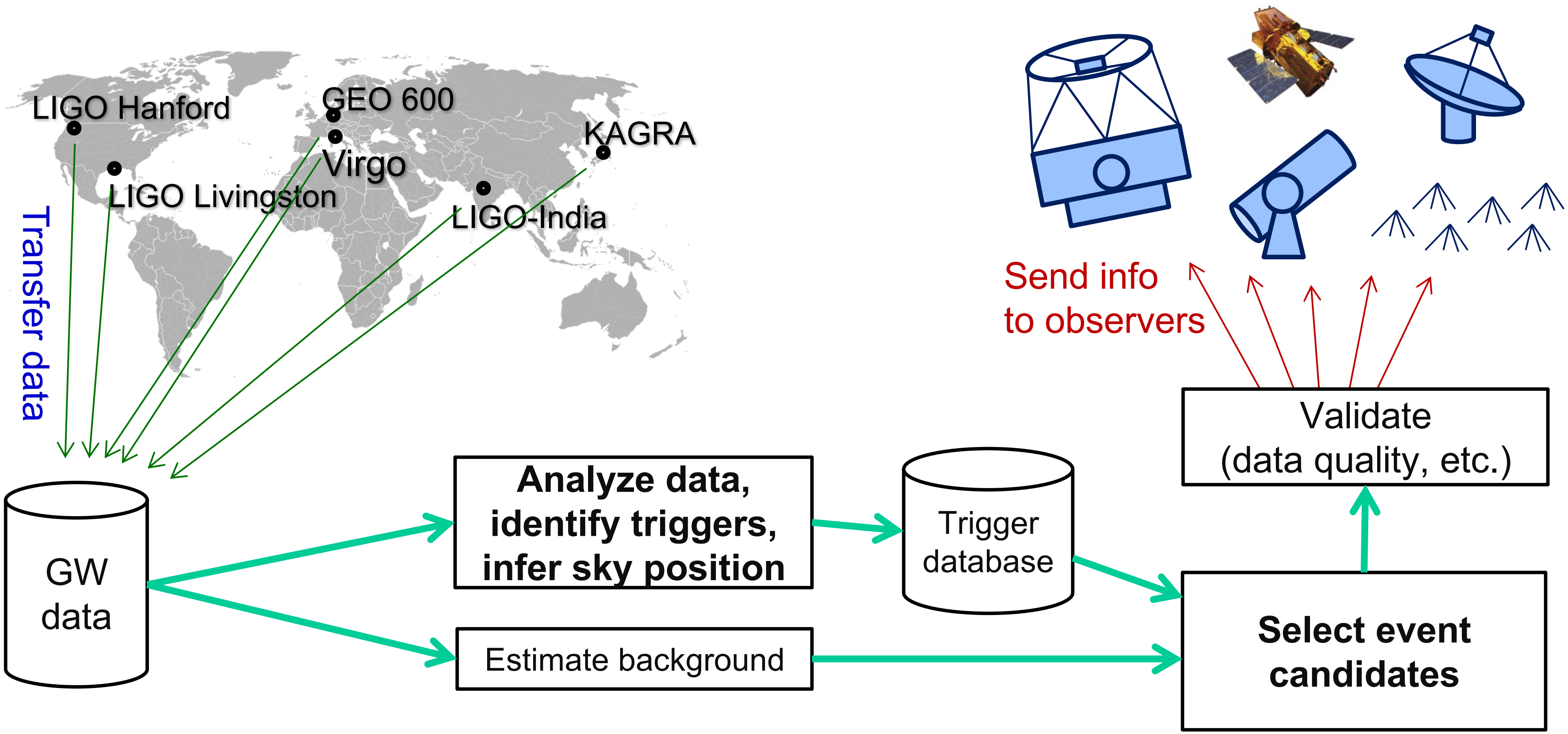
[Abbott et al. 2017, PRL 118, 221101]

We intend to do multi-messenger astronomy

A key feature of GW detectors is their sensitivity at low frequencies which allows to predict a merger

LIGO & Virgo have signed MOUs with 95 groups for burst/EM/neutrino follow-up, in addition to a number of triggered / joint search MOUs

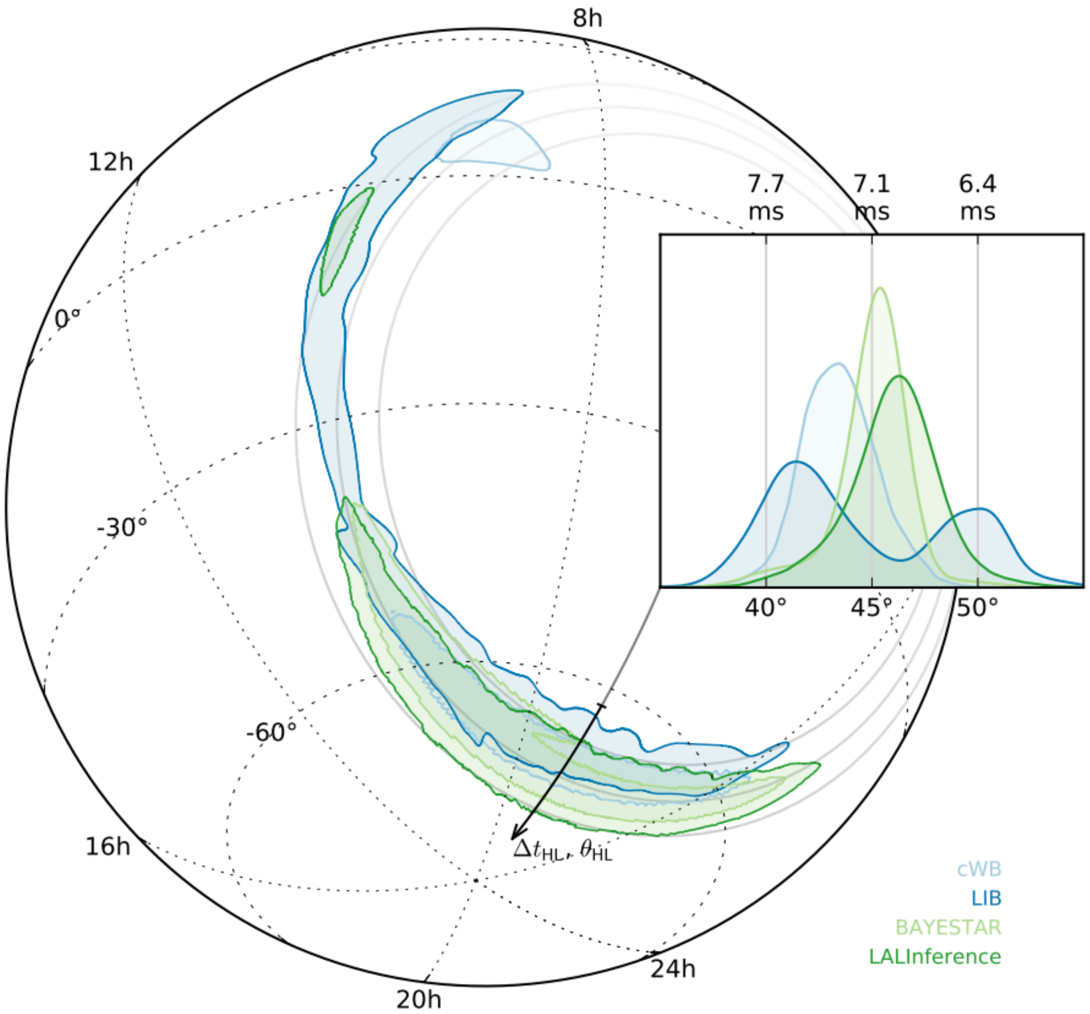
This allows to predict a merger in advance to prepare for EM follow-up

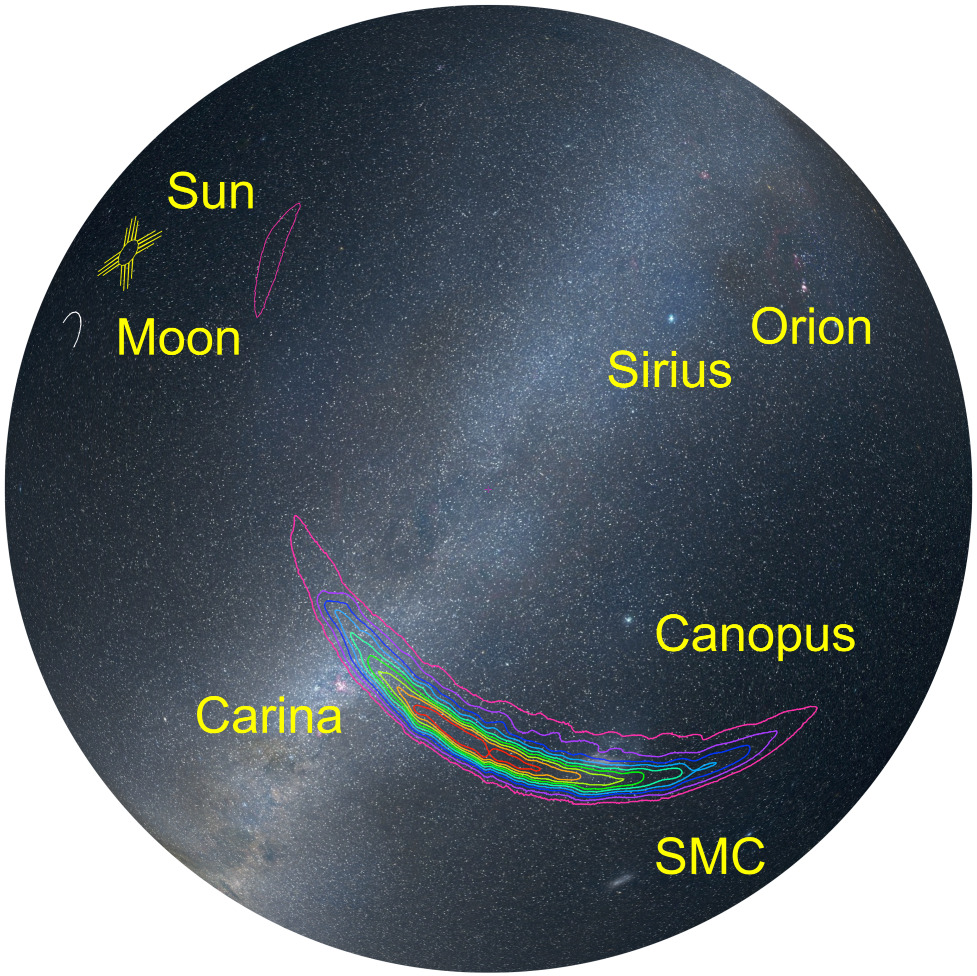


Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

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



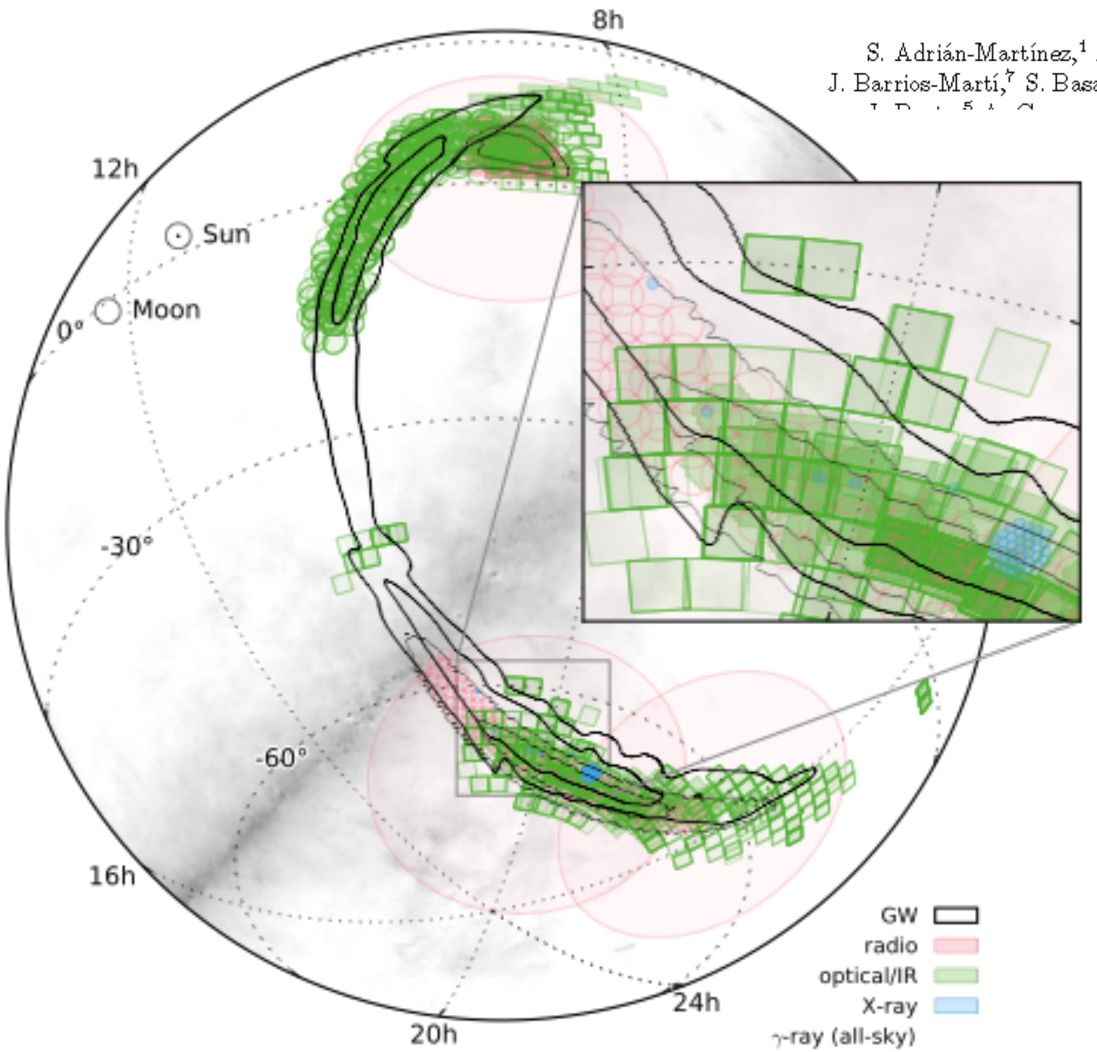


Towards multi-messenger astronomy

Sky map for GW150914 was sent to astronomers (agreements with about 95 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

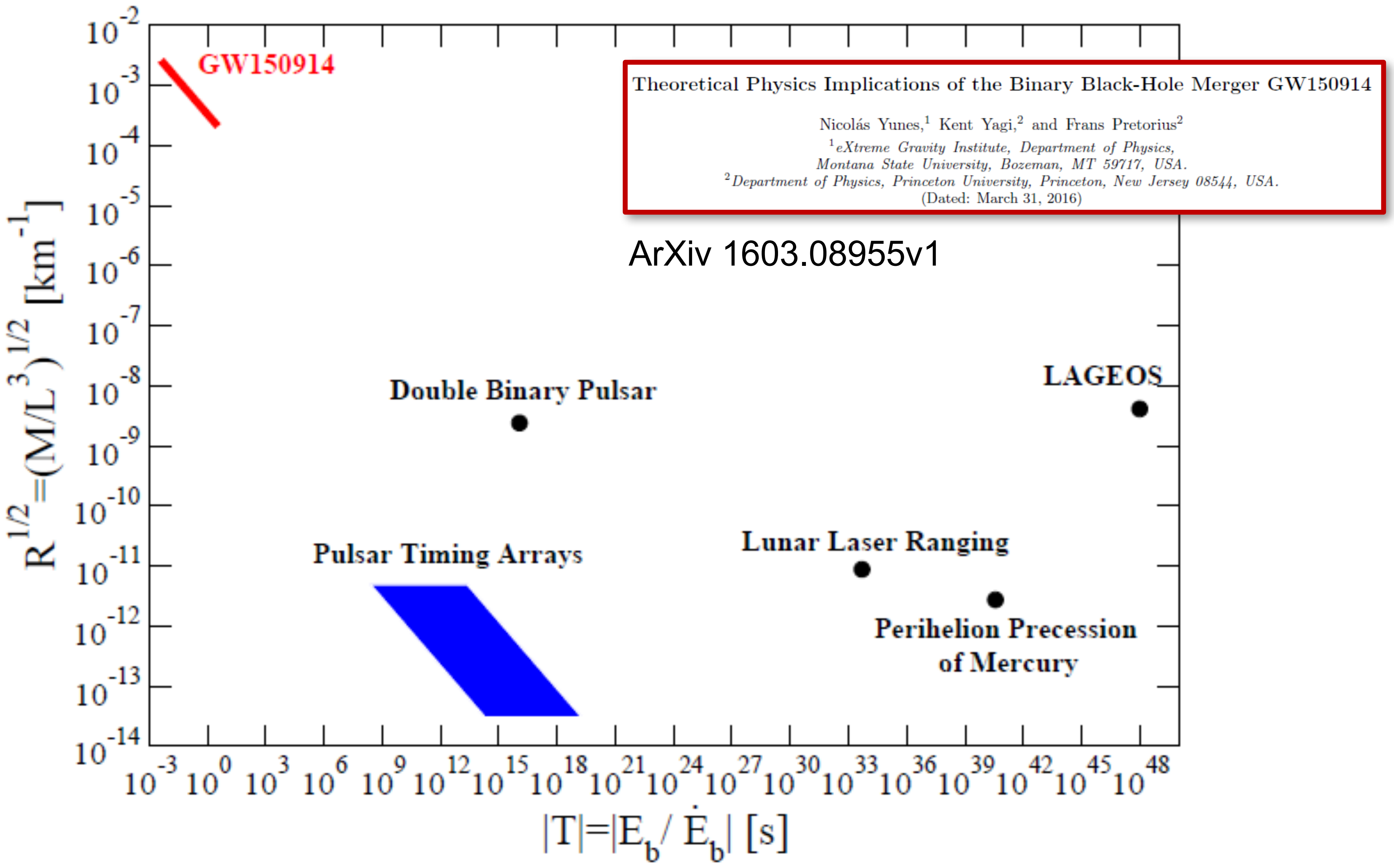
http://astrog80.astro.cf.ac.uk/Gravoscope/

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

Allows to explore GR in the strong-field regime

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



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

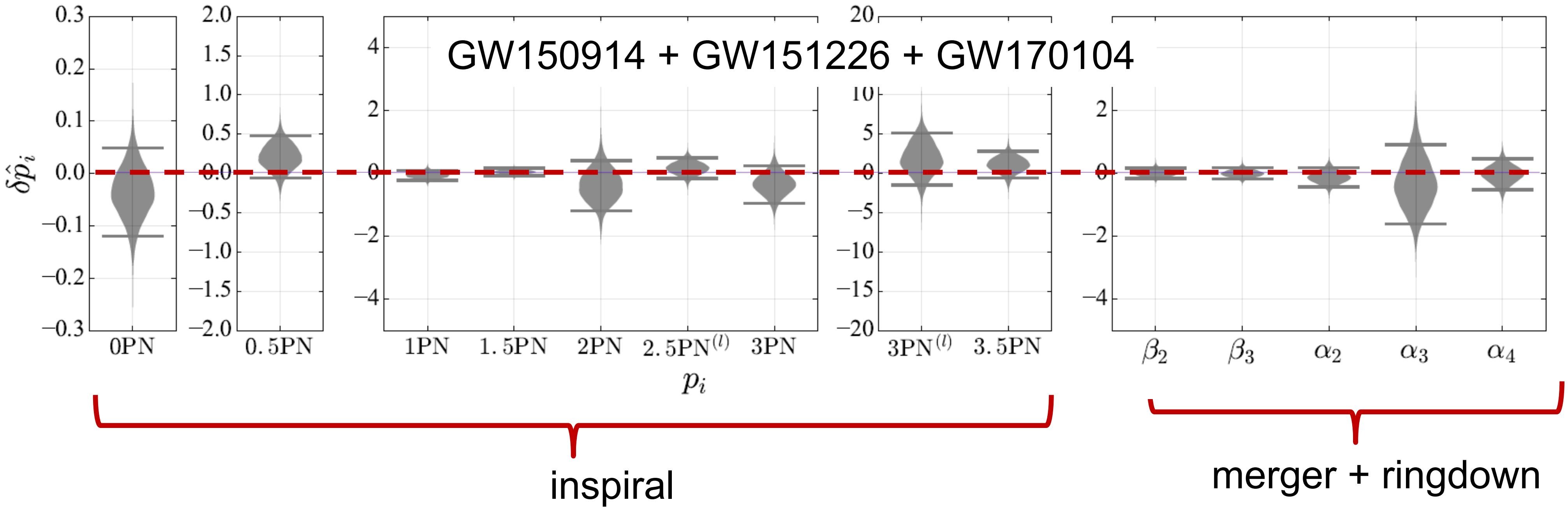
General Relativity passes first precision tests

This can be achieved by combining information from multiple events

Orbital phase (post Newtonian expansion): $h^{\alpha\beta}(f) = h^{\alpha\beta} e^{i\Phi(f)}$

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

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. Coefficients sensitive to GW back-reaction, spin-orbit, spin-spin couplings, …



LVC has seen GWs, black hole binaries, creation of a black holes. We have tested GR and so far it passed all our tests

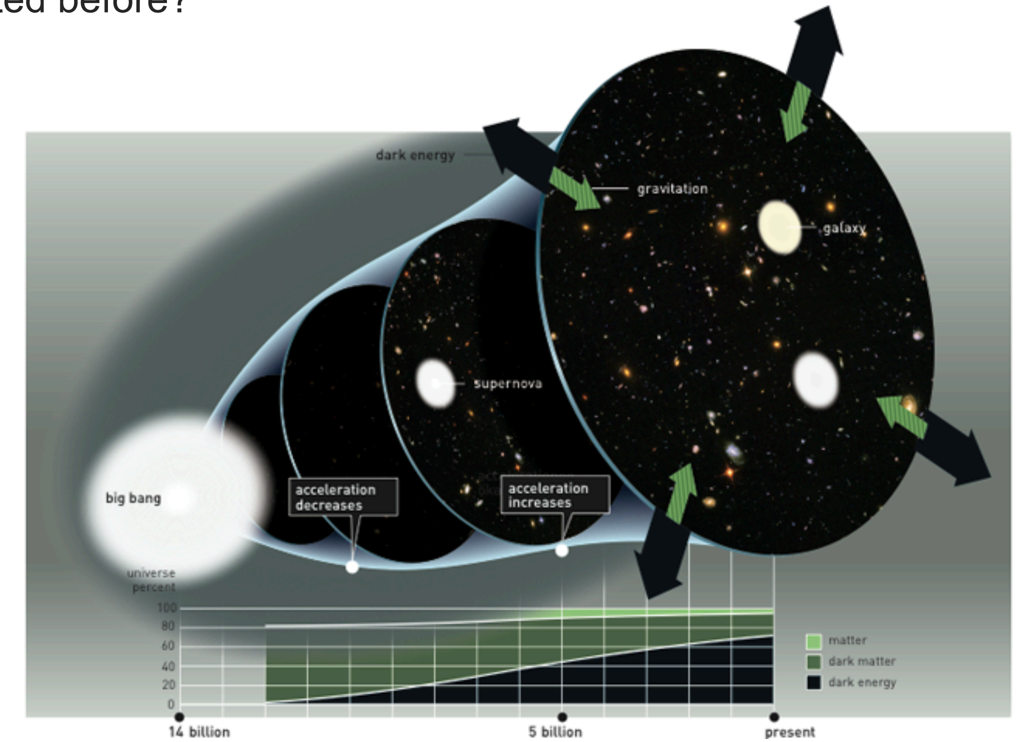
What’s next?

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

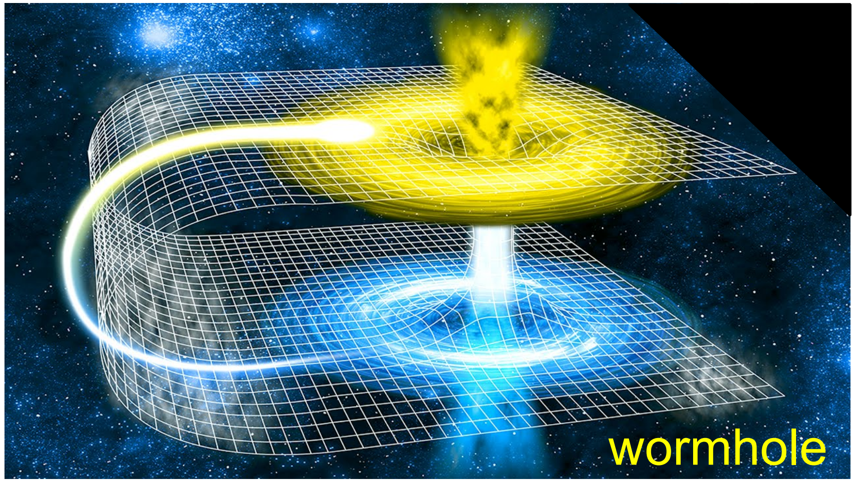
- Dynamical part of gravitation, all space is filled with GW
- Ideal information carrier, almost no scattering or attenuation
- The entire universe has been transparent for GWs, all the way back to the Big Bang

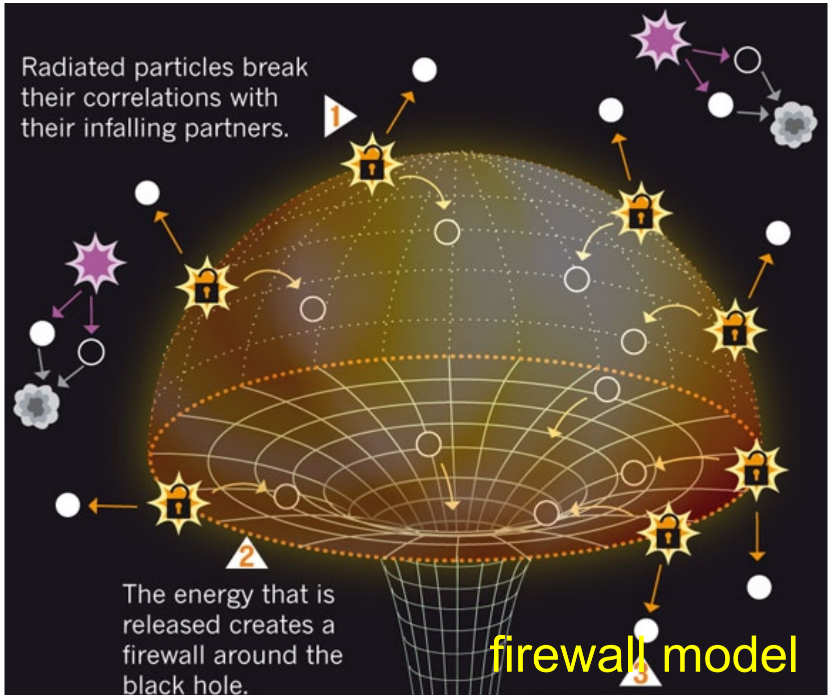
Gravitational wave science can impact

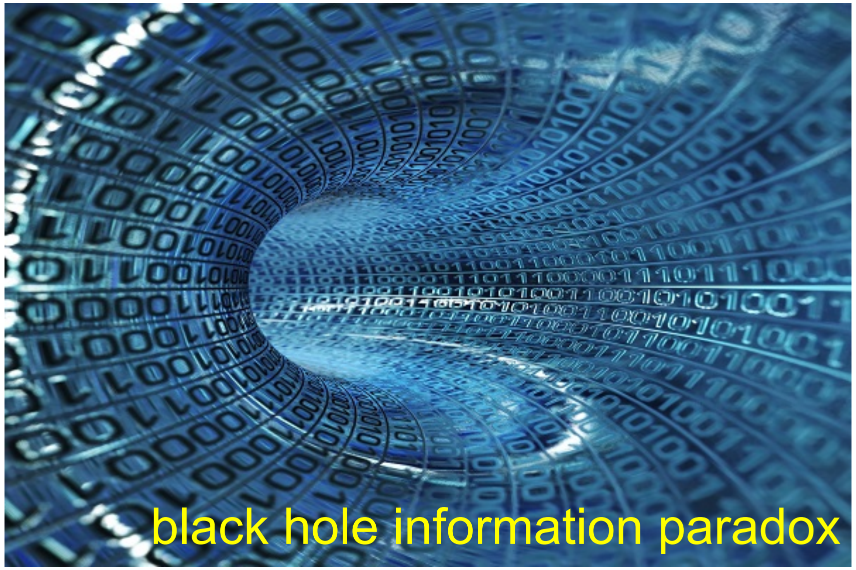
- Fundamental physics: black holes, spacetime, horizons
- Cosmology: Hubble parameter, dark matter, dark energy

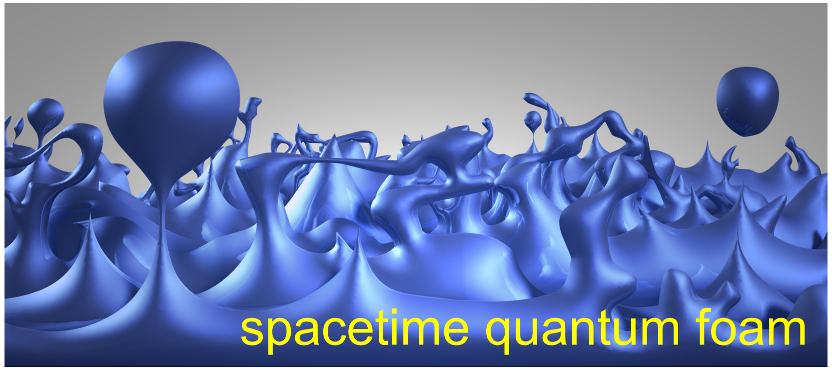
Fundamental physics: did we observe black holes?

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



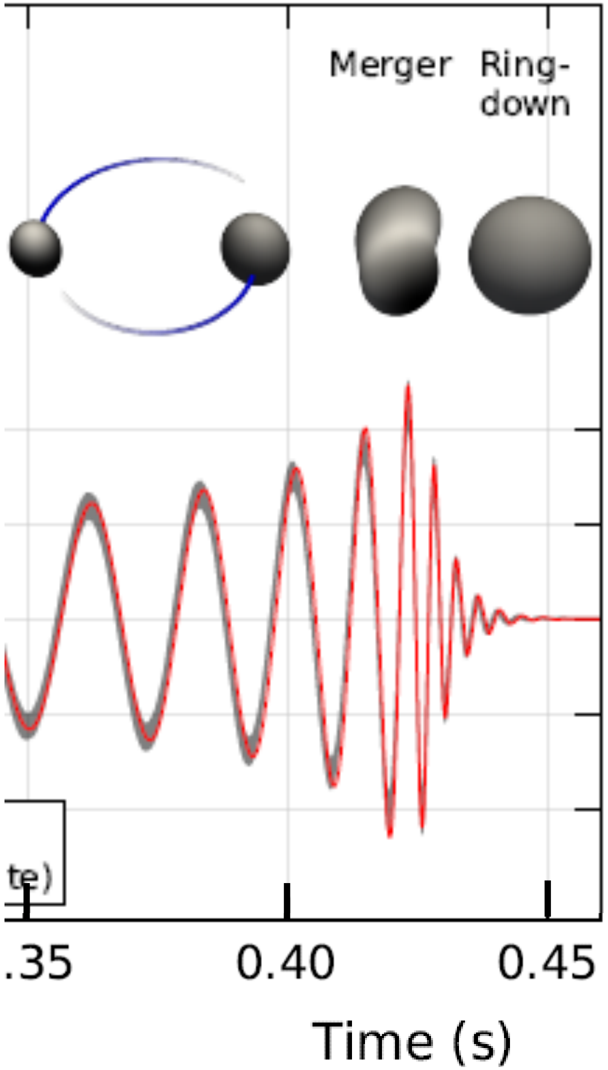


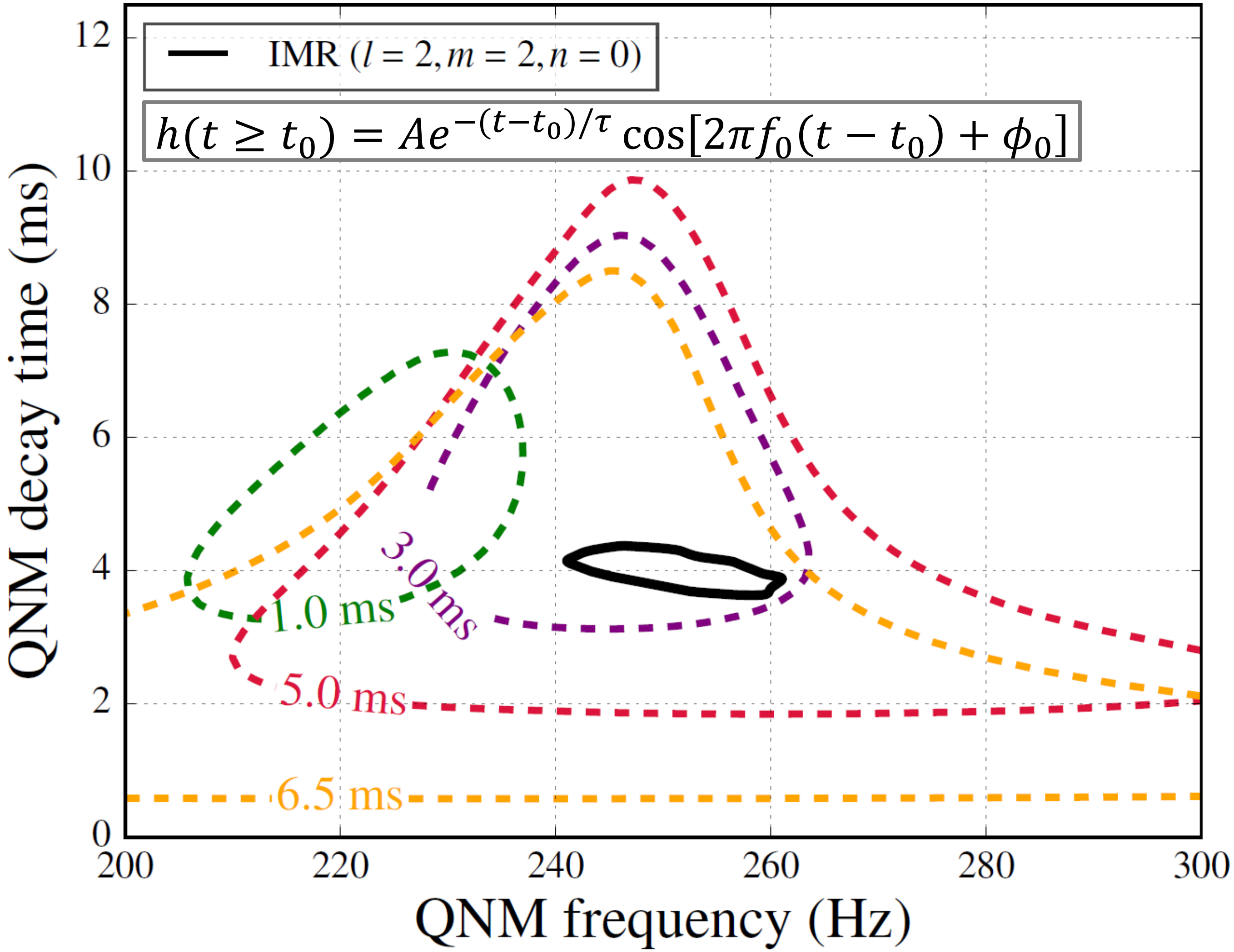




Is a black hole created in the final state?

From the inspiral we can predict that the ringdown frequency of about 250 Hz and 4 ms decay time.
This is what we measure (http://arxiv.org/abs/1602.03841). We will pursue this further





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

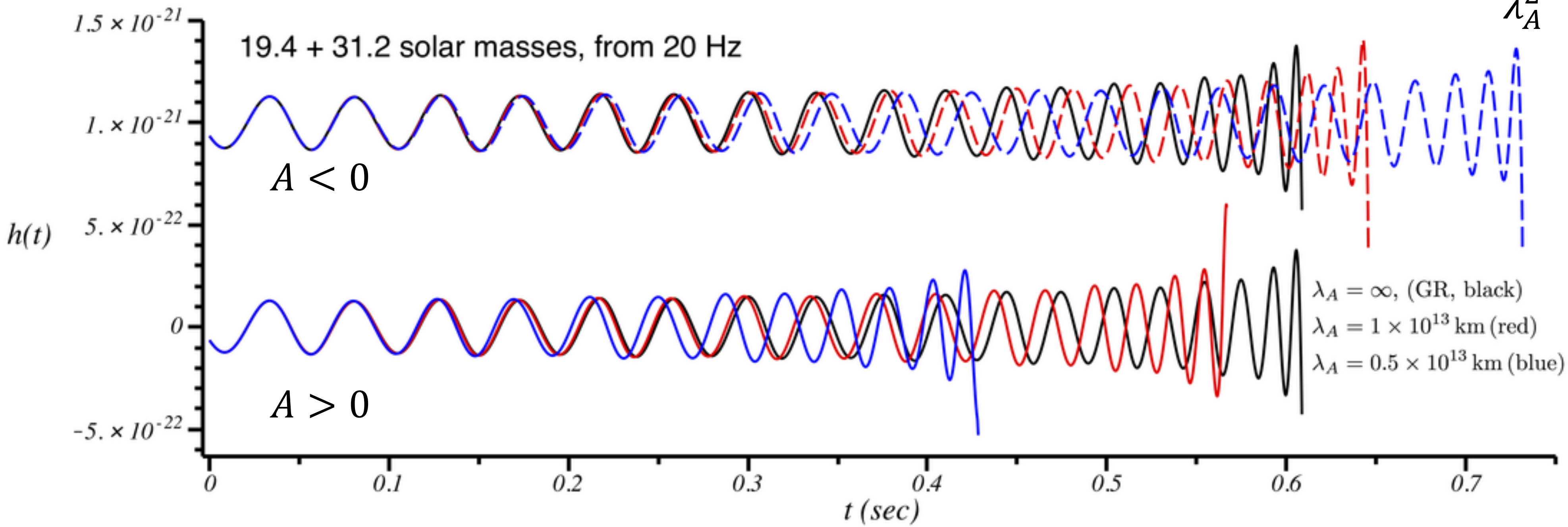
Bounds on violation of Lorentz invariance

First bounds derived from gravitational-wave observations, and the first tests of superluminal propagation in the gravitational sector

Generic dispersion relation $E^2 = p^2c^2 + Ap^\alpha c^\alpha, \alpha \geq 0 \Rightarrow \frac{v_g}{c} \cong 1 + (\alpha - 1)AE^{\alpha-2}/2$

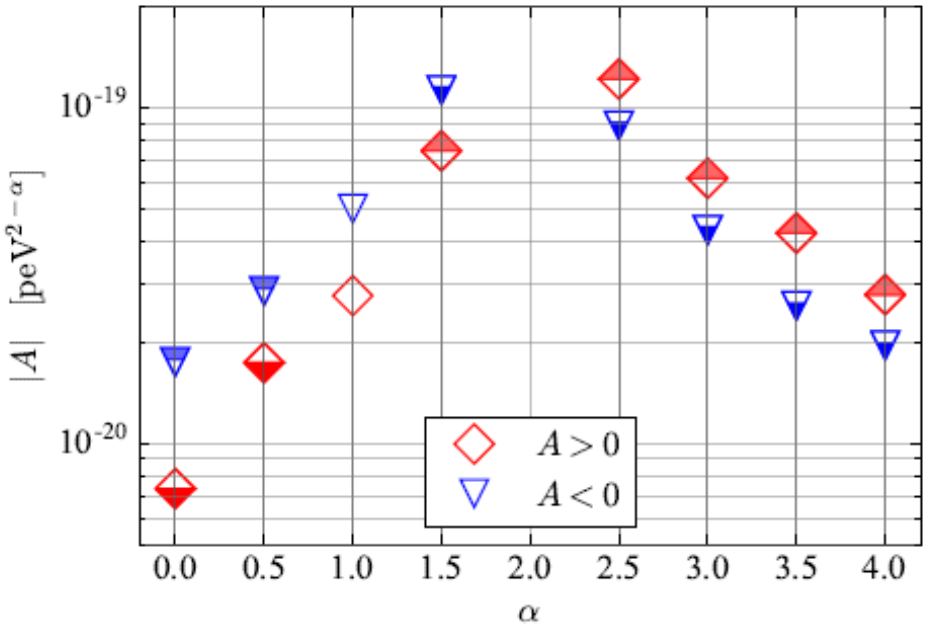
Gravitational wave phase term
$$\delta\Psi = \begin{cases} \frac{\pi}{\alpha-1}\frac{AD_\alpha}{(hc)^{2-\alpha}}\left[\frac{(1+z)f}{c}\right]^{\alpha-1} & \alpha \neq 1 \\ \frac{\pi AD_\alpha}{hc}\ln\left(\frac{\pi G\mathcal{M}^{det}f}{c^3}\right) & \alpha = 1 \end{cases}$$

$$A \cong \pm\frac{MD_\alpha}{\lambda_A^2}$$



Bounds on violation of Lorentz invariance

First bounds derived from gravitational-wave observations, and the first tests of superluminal propagation in the gravitational sector



Note: $1\ \mathrm{peV} \simeq h \times 250\ \mathrm{Hz}$
Top filled: superluminal speed

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \alpha \geq 0$$

$$\Rightarrow \frac{v_g}{c} \cong 1 + (\alpha - 1)AE^{\alpha-2}/2$$

Several modified theories of gravity predict specific values of α:
massive-graviton theories (α = 0, A > 0), multifractal spacetime (α = 2.5),
doubly special relativity (α = 3), and Horava-Lifshitz and extradimensional theories (α = 4)

See “*GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2*”
http://arxiv.org/abs/1706.01812

Exotic compact objects

Gravitational waves from coalescence of two compact objects is the Rosetta Stone of the strong-field regime. It may hold the key and provide an in-depth probe of the nature of spacetime

Quantum modifications of GR black holes

- Motivated by Hawking's information paradox
- Firewalls, fuzzballs, EP = EPR, …

Fermionic dark matter

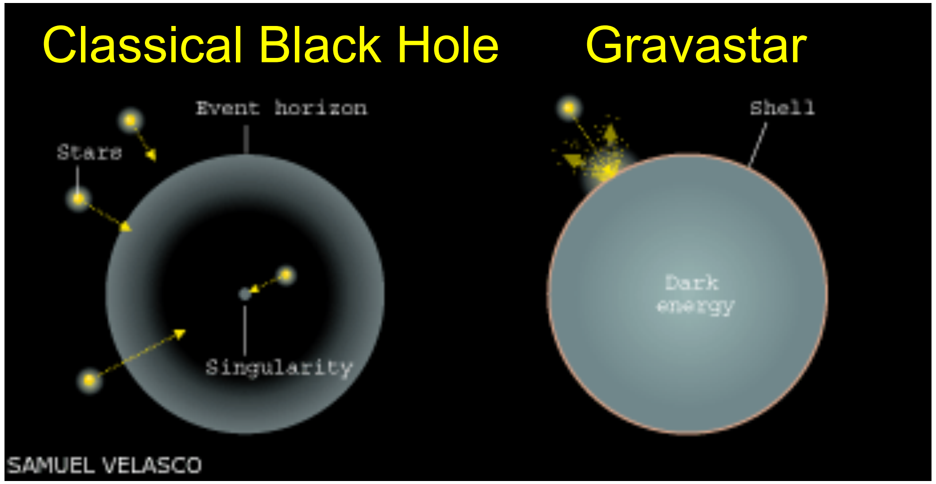
- Dark matter stars

Boson stars

- Macroscopic objects made up of scalar fields

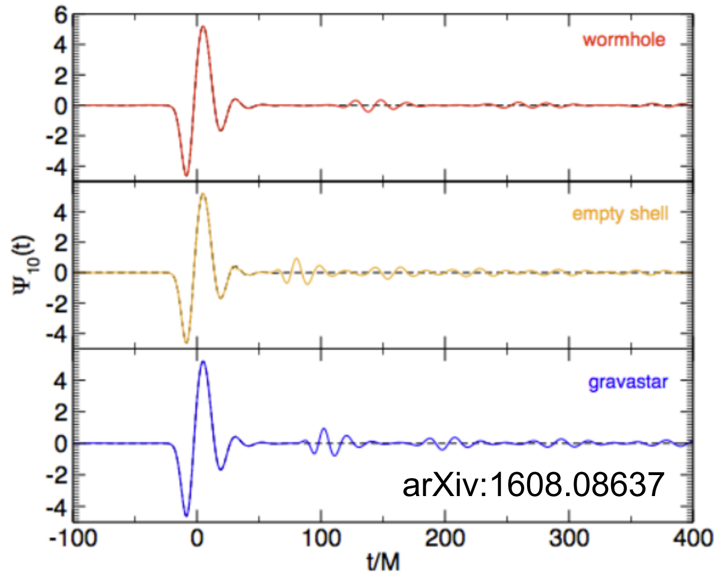
Gravastars

- Objects with de Sitter core where spacetime is self-repulsive
- Held together by a shell of matter
- Relatively low entropy object



GW observables

- Inspiral signal: modifications due to tidal deformation effects
- Ringdown process: use QNM to check no-hair theorem
- Echoes: even for Planck-scale corrections $\Delta t \approx -nM \log \frac{l}{M}$



Advanced Virgo

Advanced Virgo

Virgo is a European collaboration with about 280 members

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participation by scientists from France, Italy, The Netherlands, Poland, Hungary, Spain

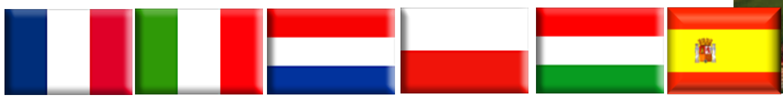
- 20 laboratories, about 280 authors
  - APC Paris
  - ARTEMIS Nice
  - EGO Cascina
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - RADBOUD Uni. Nijmegen
  - RMKI Budapest
  - Univ. of Valencia

Advanced Virgo project has been formally completed on July 31, 2017

Part of the international network of 2nd generation detectors

Joined the O2 run on August 1, 2017

6 European countries

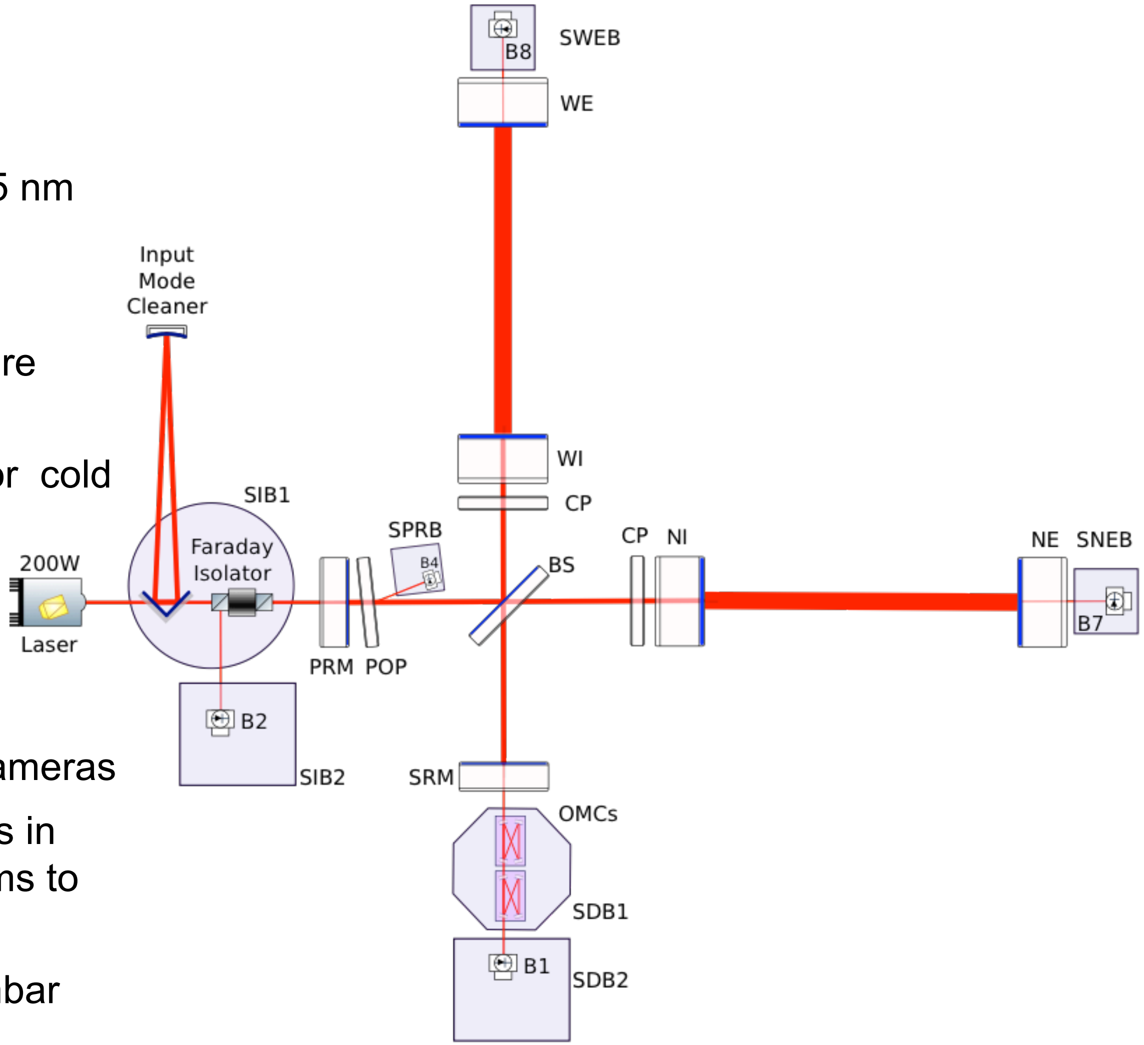


Advanced Virgo design

Advanced Virgo started operation on August 1, 2017. It features many improvements with respect to Virgo and Virgo+

For 2017

- Larger beam: 2.5x larger at ITMs
- Heavier mirrors: 2x heavier
- Higher quality optics: residual roughness < 0.5 nm
- Improved coatings for lower losses:
  absorption < 0.5 ppm, scattering < 10 ppm
- Reducing shot noise: arm finesse of cavities are
  3 x larger than in Virgo+
- Thermal control of aberrations: compensate for cold and hot defects on the core optics:
  - ring heaters
  - double axicon CO2 actuators
  - CO2 central heating
  - diagnostics: Hartmann sensors & phase cameras
- Stray light control: suspended optical benches in vacuum, and new set of baffles and diaphragms to catch diffuse light
- Improved vacuum: 10^{-9} mbar instead of 10^{-7} mbar

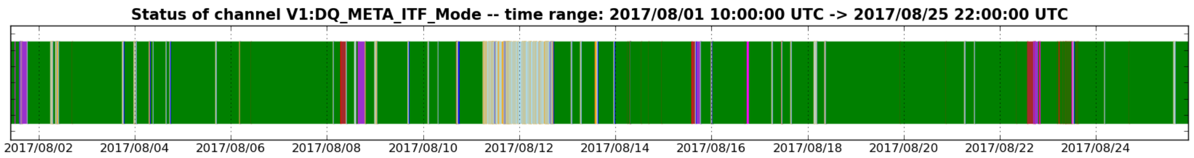


End of science run O2

Virgo just finished together with LIGO a run with three interferometers. Virgo's highest BNS range is 28.2 Mpc and longest stable lock stretch was 69 hours. Virgo science duty cycle was about 85%

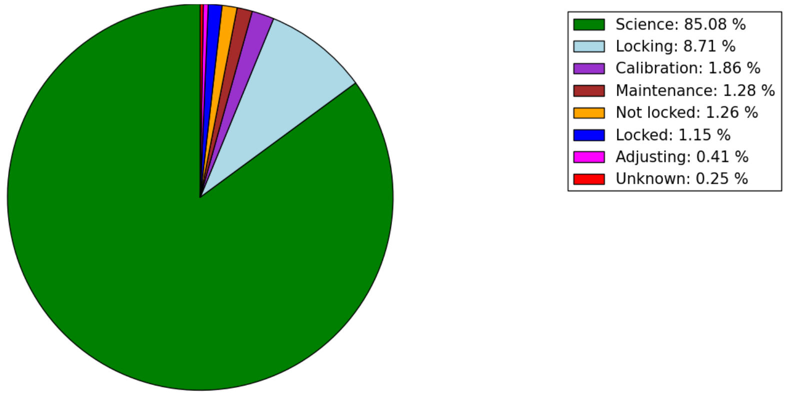
Highlights of O2 run

- Longest stable lock stretch (# 39064) was 69 hours
- BNS range up to 28.2 Mpc
- Virgo science duty cycle was about 85%



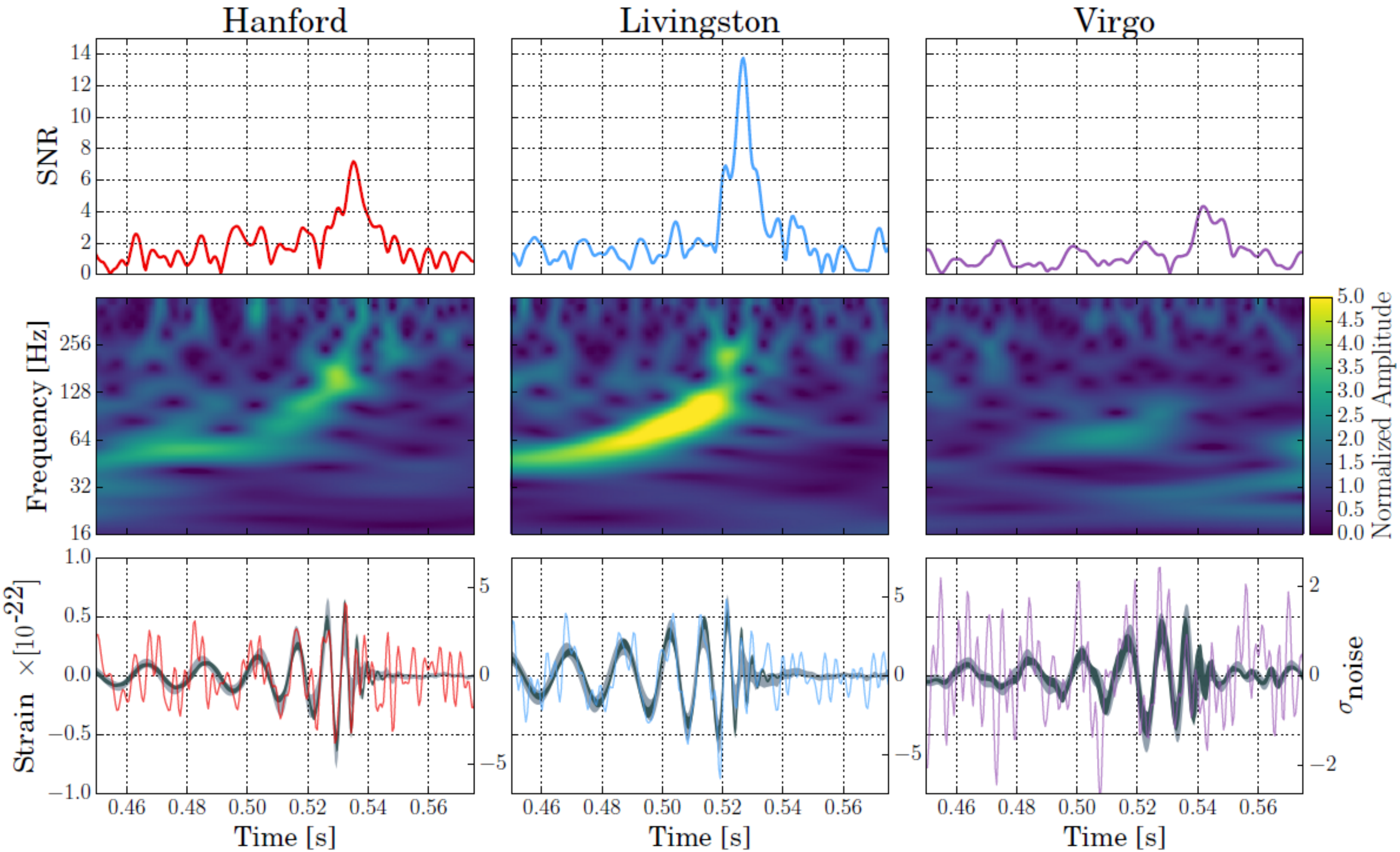
Added scientific value of Virgo in the network

- Increased data set LH → LH **+ LV + HV + LHV**
- Increase of sky coverage
- Improvement of sky location of sources
- Measurement of GW polarization
- Improvement in distance measurement
- Three-fold coincidence measurement for increased robustness
- Improvement in parameter estimation



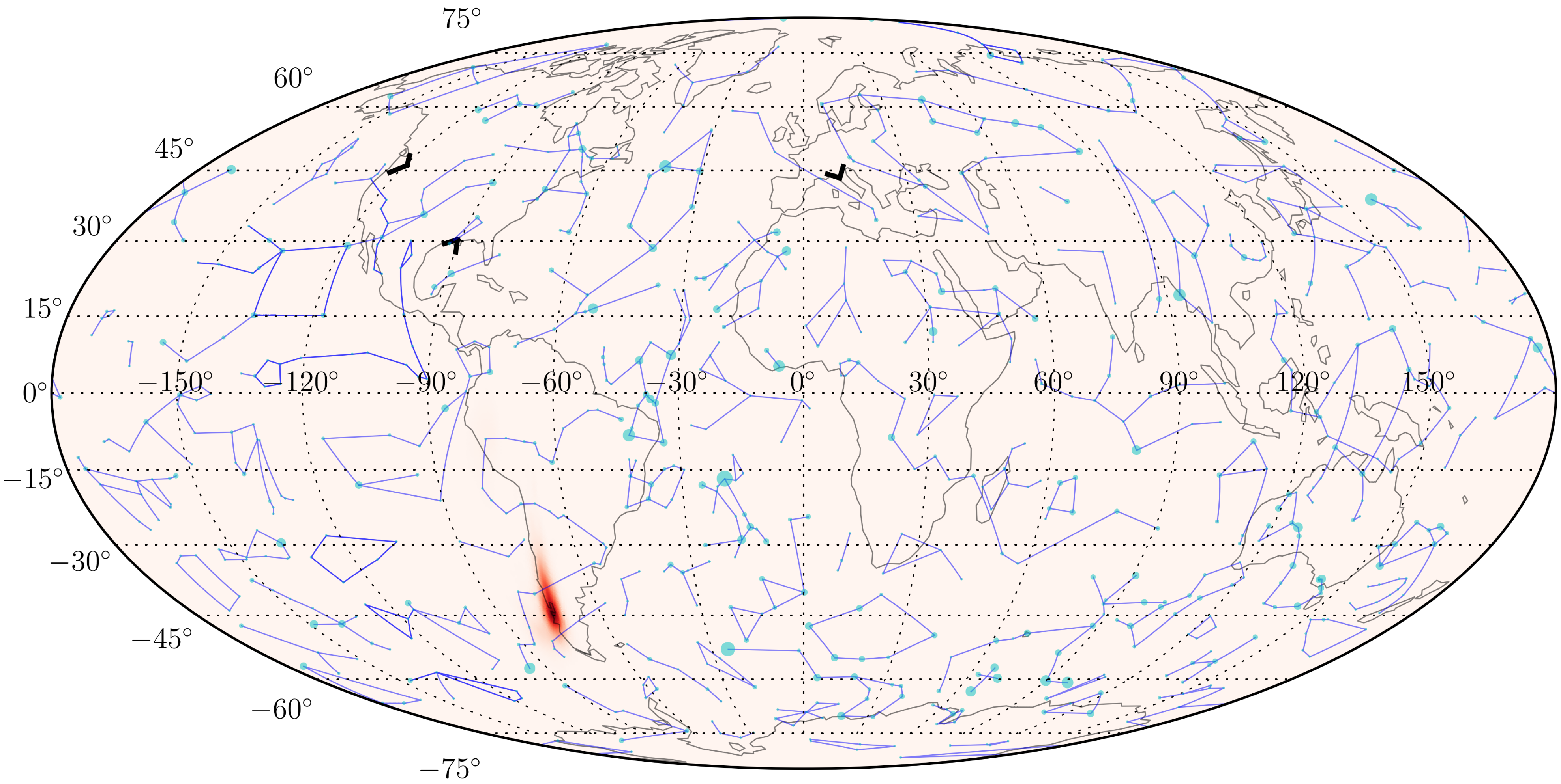
First triple detection by Virgo and LIGO

August 14, 2017 three detectors observed BBH. Initial black holes were 31 and 25 solar mass, while the final black hole featured 53 solar masses. About 3 solar mass radiated as pure GWs



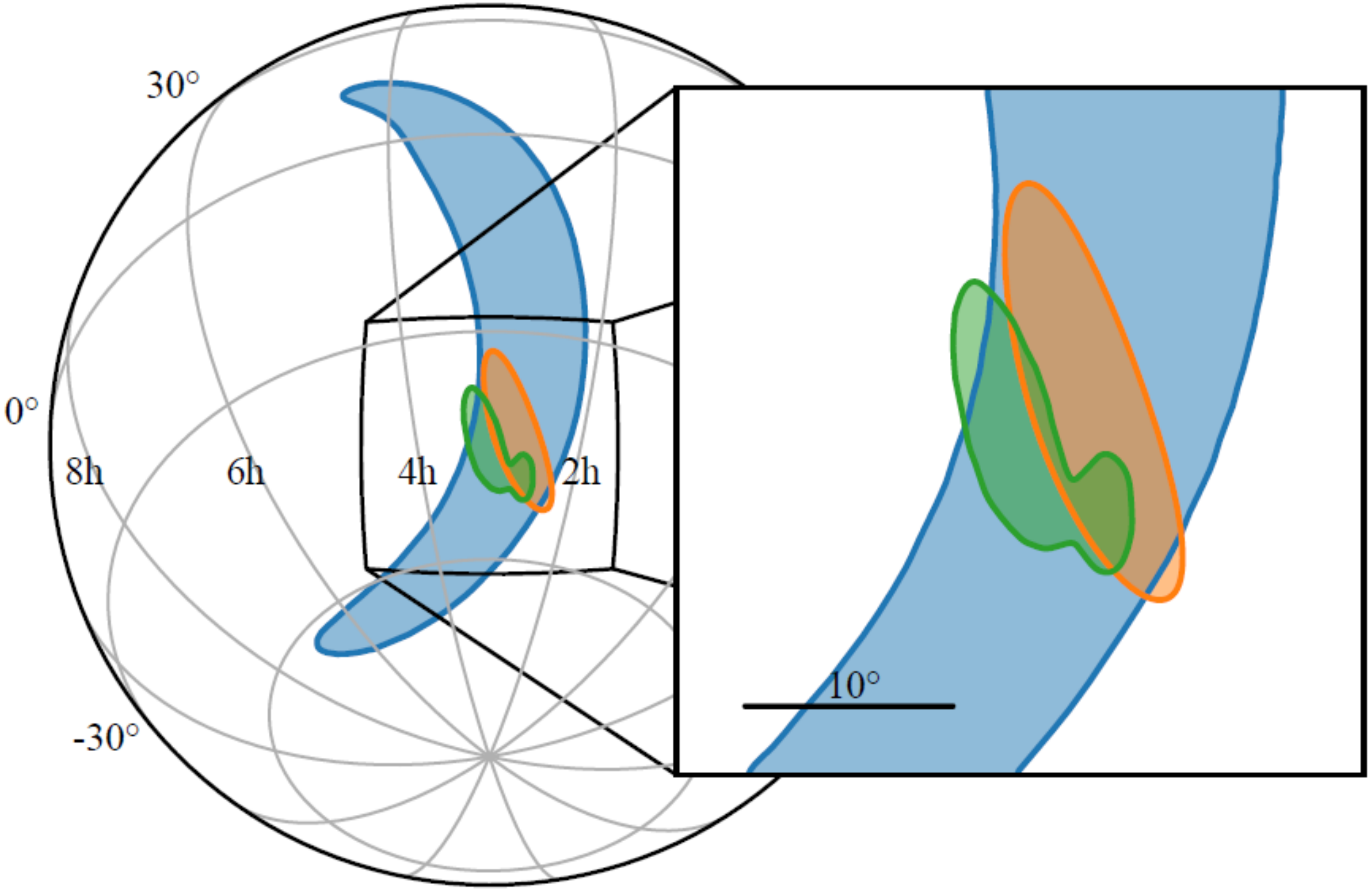
First triple detection by Virgo and LIGO

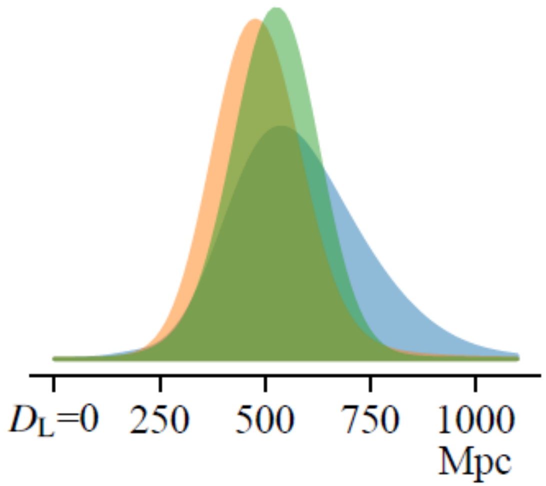
Gravitational wave traveled for almost 2 billion years through the Universe and hit Earth first at lat. 44.95 degr S, long 72,97 degr W, Puerto Aysen, Chili. The source was in the constellation Eridanus

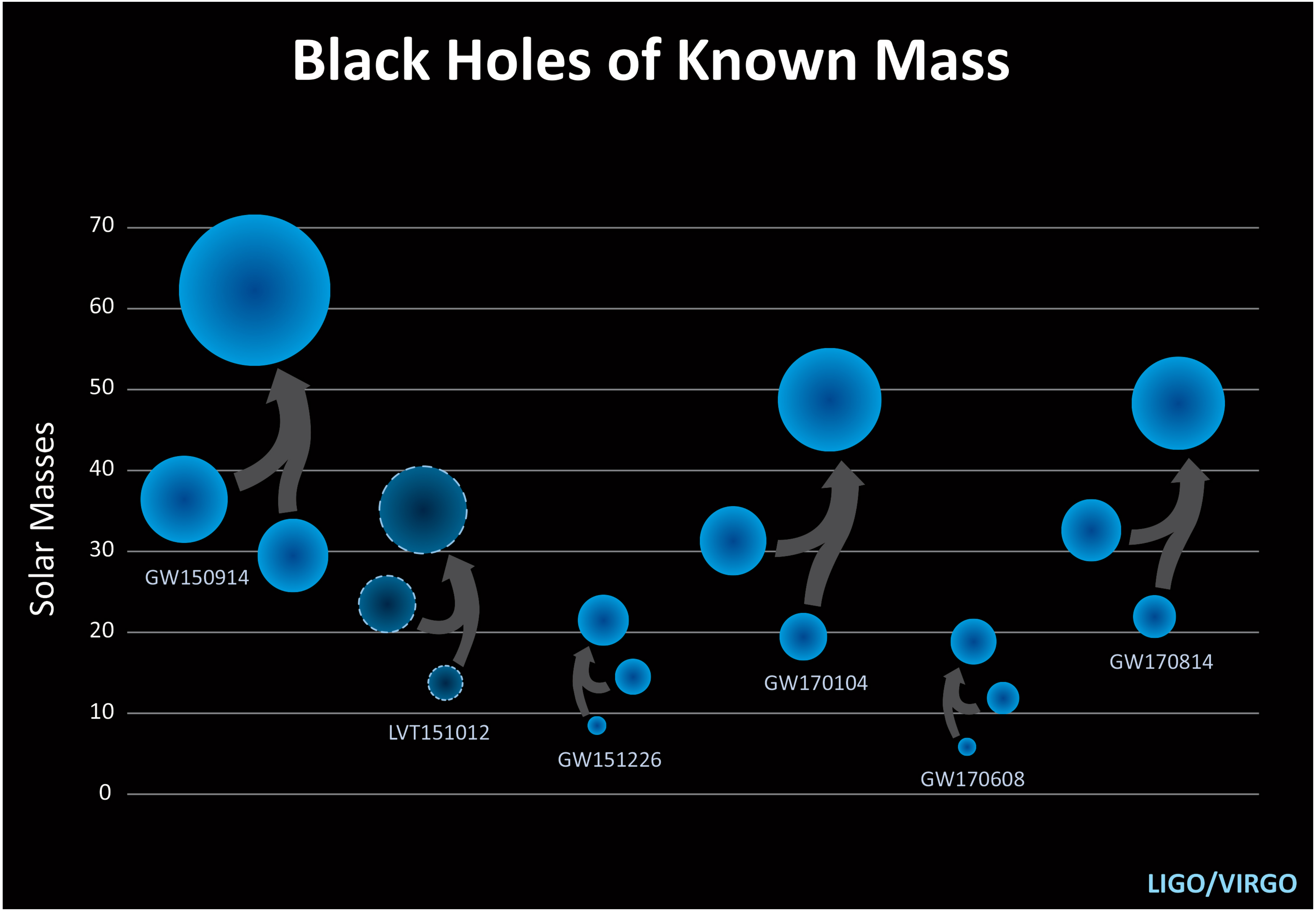


First triple detection by Virgo and LIGO

Three detectors observed BBH: first LLO, 8 ms later LHO, and again 6 ms later Virgo. This allow triangulation and for GW170814 the source volume improved with more than a factor 20






Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
LIGO/VIRGO

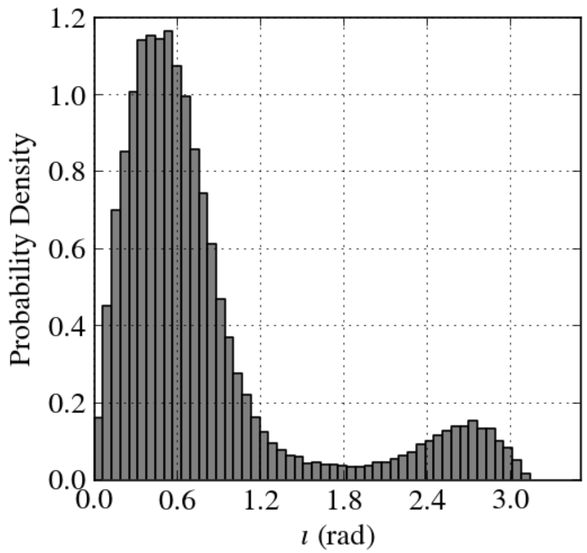
Gravitational waves from a coalescing binary

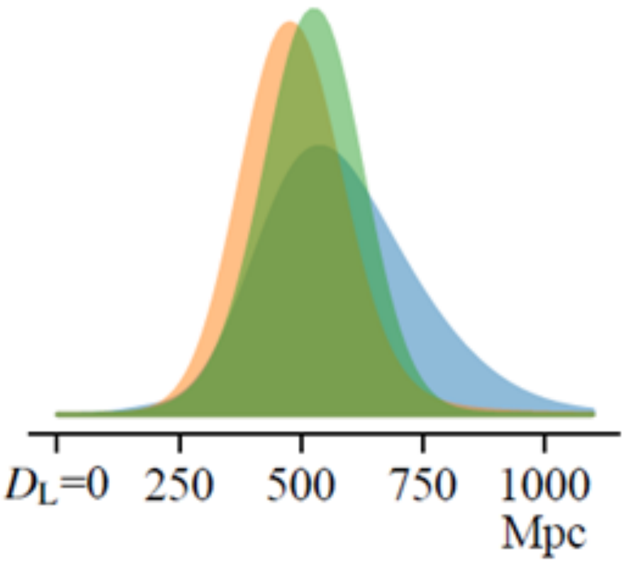
According to general relativity there should only be 2 polarizations (a tensor)

Two strains perpendicular to direction of motion

$$h_+ = \frac{4}{r}\frac{G\mu R^2\omega^2}{c^4}\frac{1+\cos^2(\iota)}{2}\cos(2\omega t_{\rm ret}+2\phi)$$
$$h_\times = \frac{4}{r}\frac{G\mu R^2\omega^2}{c^4}\cos(\iota)\,\sin(2\omega t_{\rm ret}+2\phi)$$

Angle iota is the inclination angle of the binary
Polarization can be used to break the degeneracy between distance and inclination





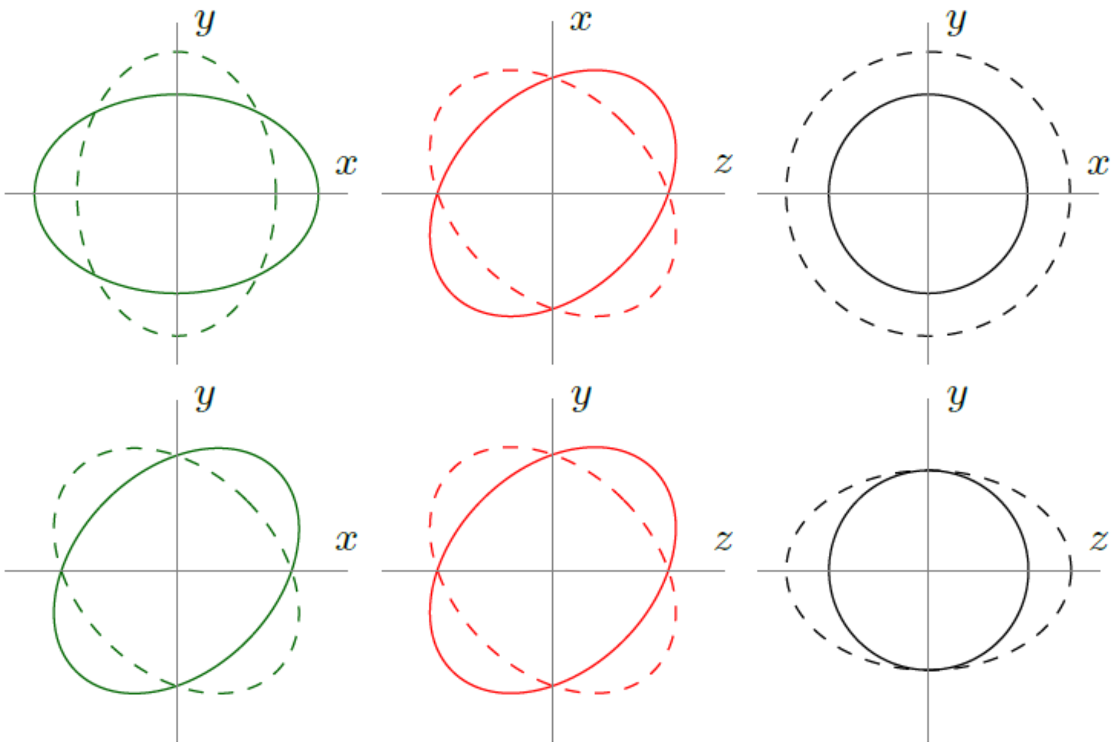
First test of polarizations of gravitational waves

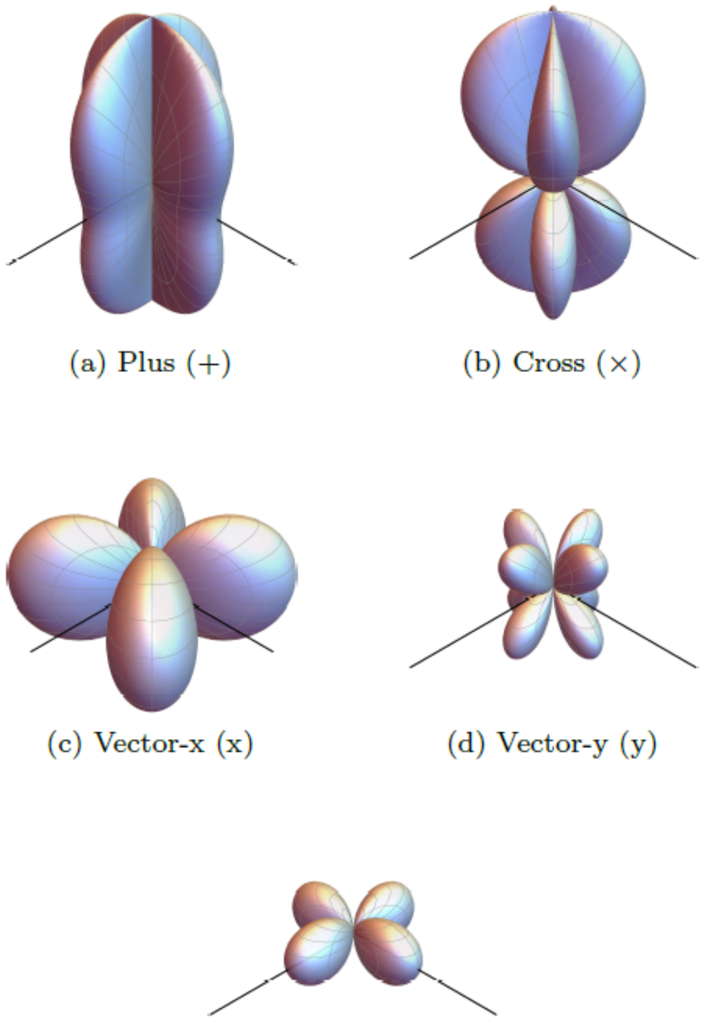
According to Einstein's general relativity there should only be 2 polarizations. General metric theories of gravity allow up to 6 polarizations. GW180814 confirms Einstein's prediction

GR allows only tensor (T) polarizations

General metric theories also vector (V) and scalar (S)

Angular response (antenna patterns) differ for T, V, S





(a) Plus (+)

(b) Cross (×)

(c) Vector-x (x)

(d) Vector-y (y)

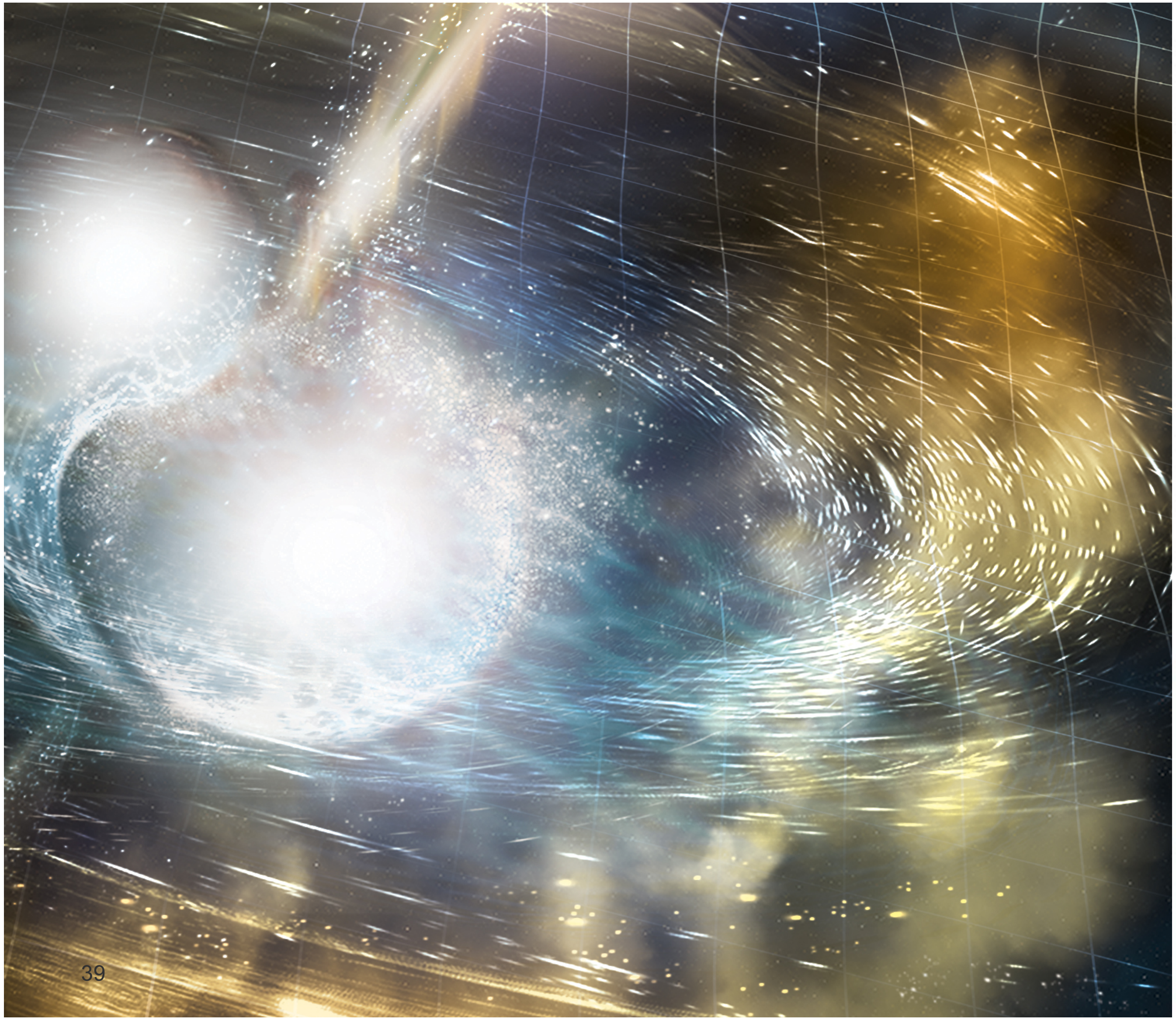
(e) Scalar (s)

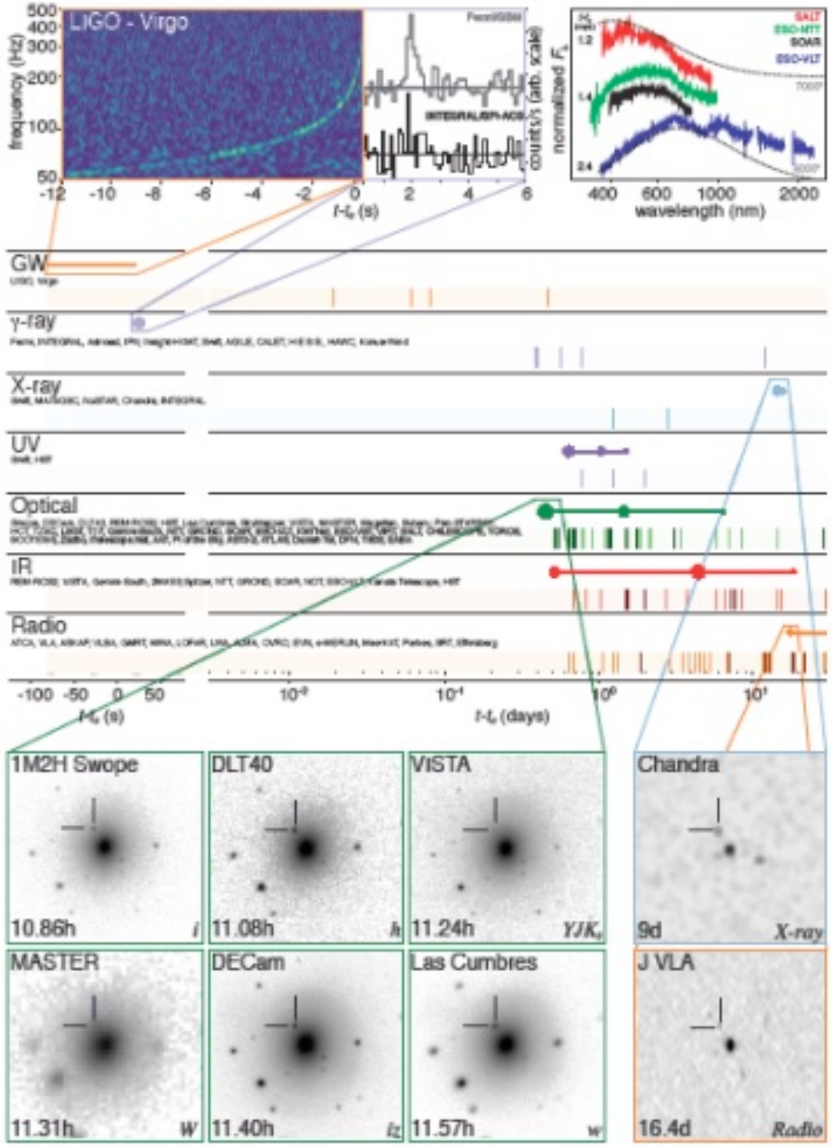
September 27, 2017: announcement at G7 Science

Virgo and LIGO announced the first joint detection of a binary black hole merger

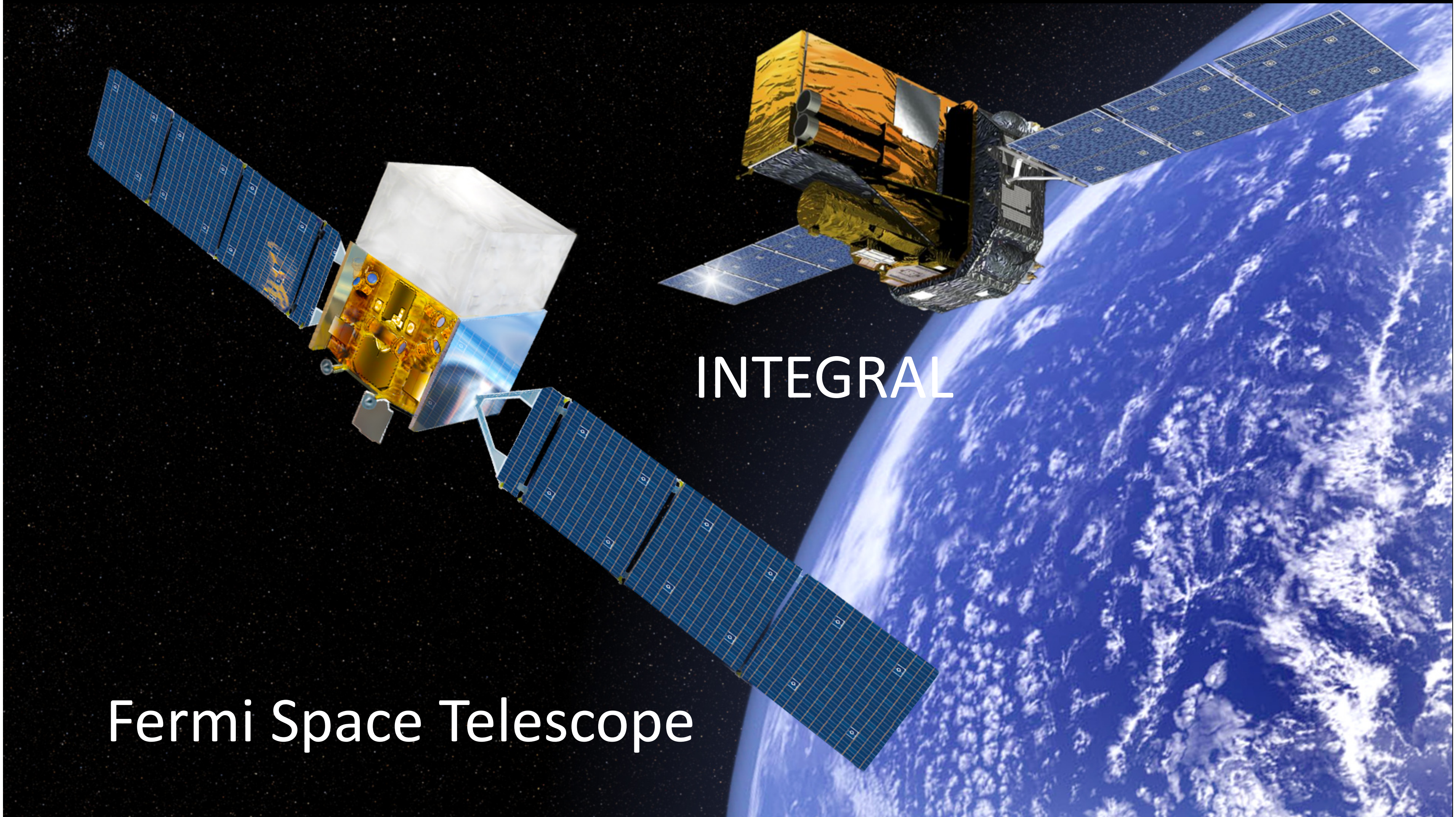
GW170817: start of multi-messenger astronomy with GW

Many compact merger sources emit, besides gravitational waves, also light, gamma- and X-rays, and UV, optical, IR, and radio waves, as well as neutrino's or other subatomic particles. Our three-detector global network allows identifying these counterparts





Gamma rays reached Earth 1.7 seconds after GW event



Implications for fundamental physics

Gamma rays reached Earth 1.7 s after the end of the gravitational wave inspiral signal. The data are consistent with standard EM theory minimally coupled to general relativity

GWs and light propagation speeds

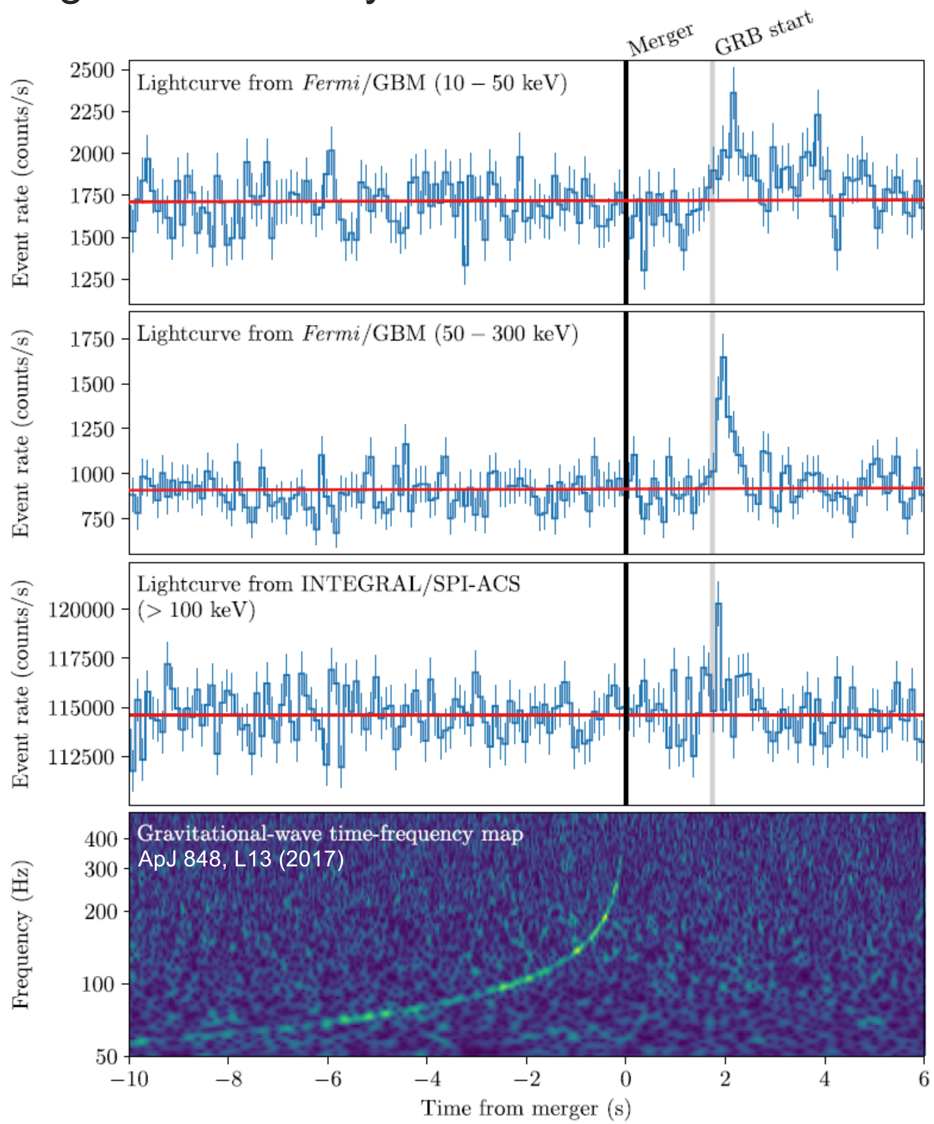
Identical speeds to about 1 part in 10^{15}

Test of Equivalence Principle

According to General Relativity, GW and EM waves are deflected and delayed by the curvature of spacetime produced by any mass (i.e. background gravitational potential). Shapiro delays affect both waves in the same manner

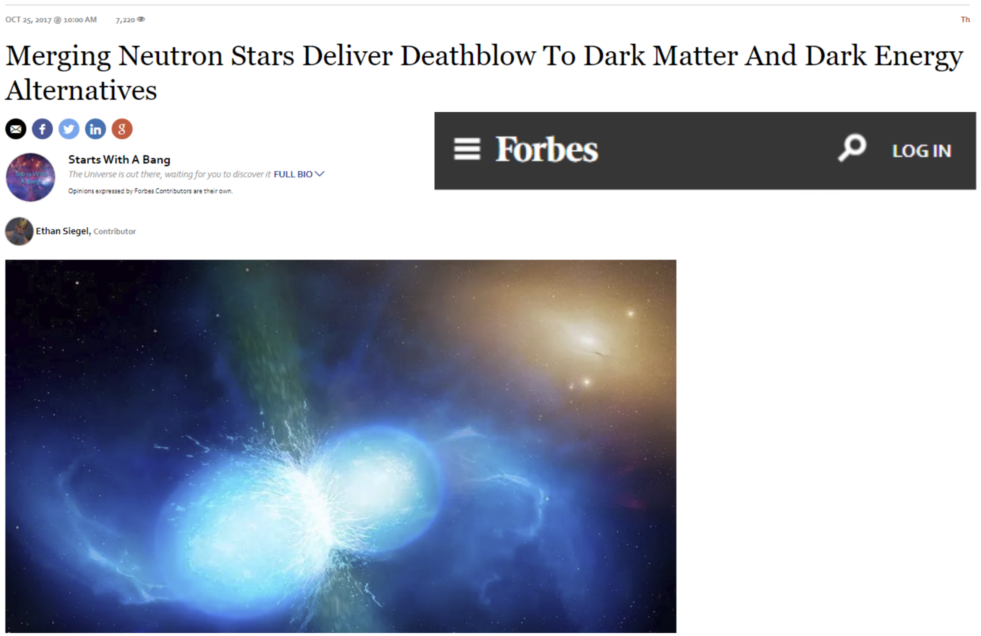
Milky Way potential gives same effect to within about 1 part in a million

Including data on peculiar velocities to 50 Mpc: gives the same effect to within 4 parts in a billion



Dark Energy and Dark Matter after GW170817

GW170817 had consequences for our understanding of Dark Energy and Dark Matter



GW170817 falsifies Dark Matter Emulators

No-dark-matter modified gravity theories like TeVeS or MoG/Scalar-Tensor-Vector ideas have the property that GW propagate on different geodesics (normal matter) from those followed by photons and neutrinos (effective mass to emulate dark matter)

This would give a difference in arrival times between photons and gravitational waves by approximately 800 days, instead of the 1.7 seconds observed (arXiv:1710.06168v1)

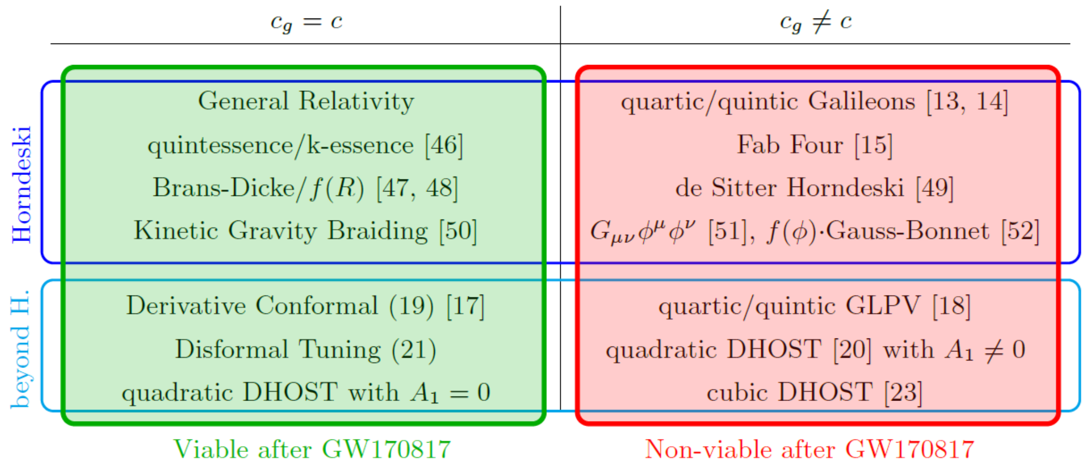
Dark Energy after GW170817

Adding a scalar field to a tensor theory of gravity, yields two generic effects:

1. There's generally a *tensor speed excess* term, which modifies (increases) the propagation speed of GW
2. The scale of the effective Planck mass changes over cosmic times, which alters the damping of the gravitational wave signal as the Universe expands

Simultaneous detection of GW and EM signals rules out a class of modified gravity theories (arXiv:1710.05901v2)

A large class of scalar-tensor theories and DE models are highly disfavored, e.g. covariant Galileon, but also other gravity theories predicting varying cg such as Einstein-Aether, Horava gravity, Generalized Proca, TeVeS and other MOND-like gravities



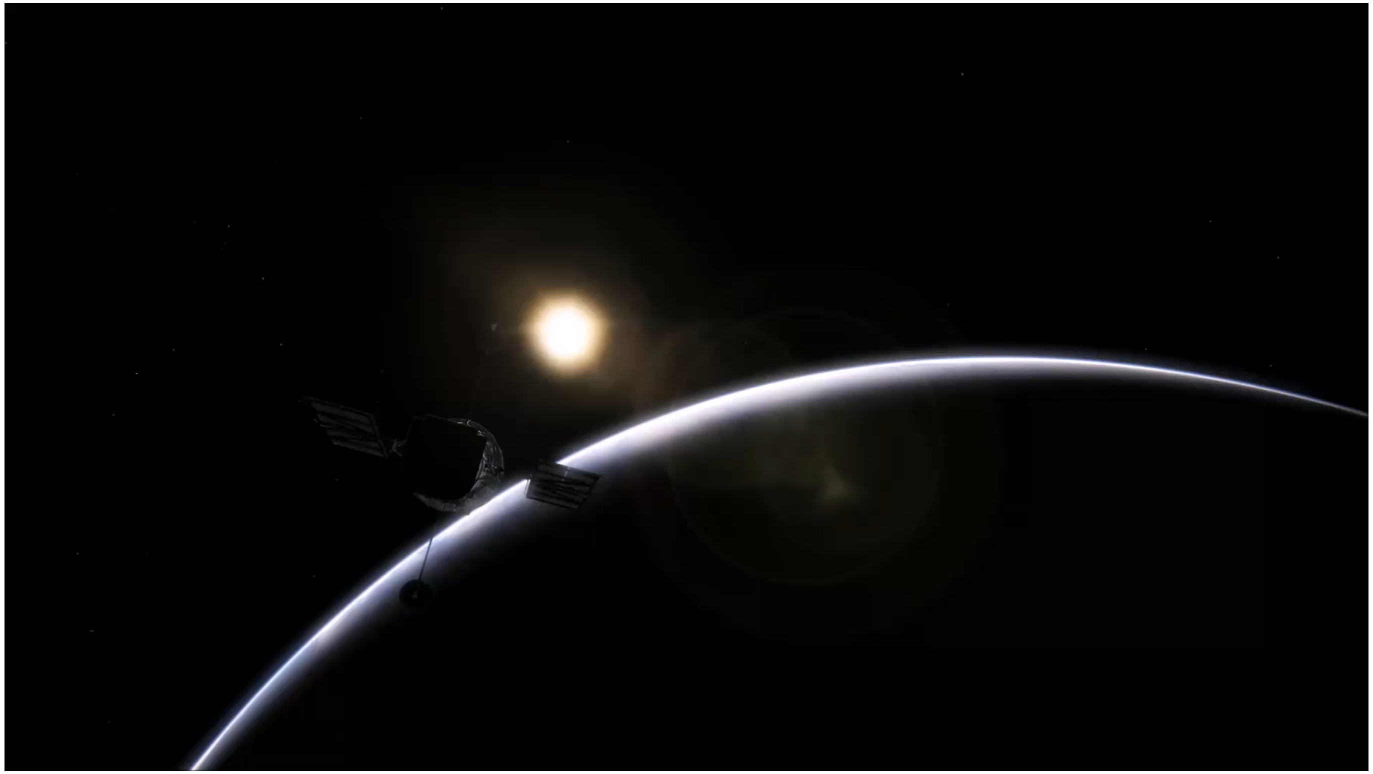
Looking into the heart of a dim nearby sGRB

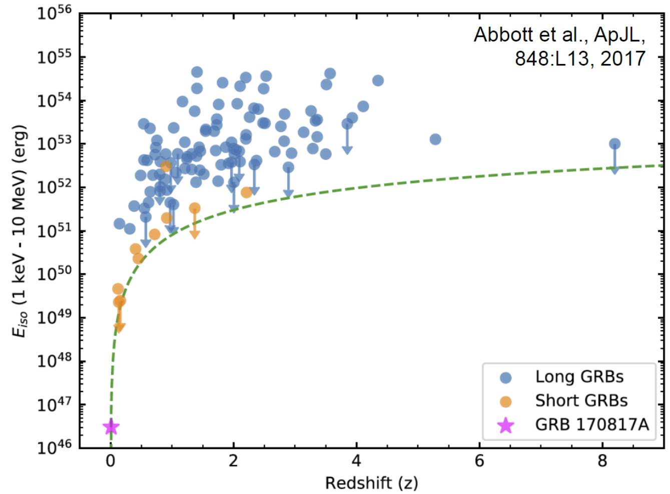
Gravitational waves identified the progenitor of the sGRB and provided both space localization and distance of the source. This triggered the EM follow-up by astronomers for the kilonova

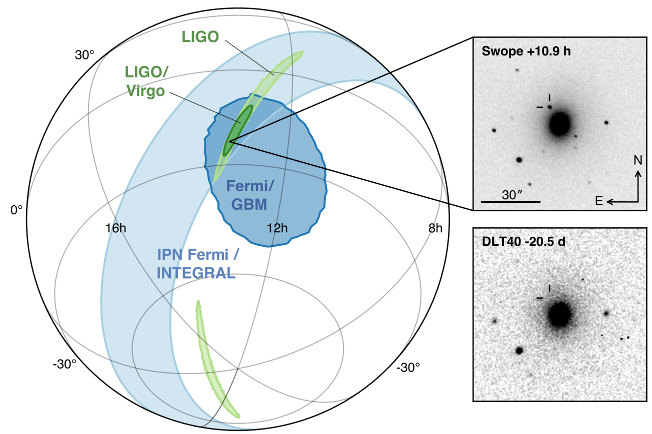
Closest by and weakest sGRB, highest SNR GW event

LIGO/Virgo network allowed source localization of 28 (degr)^2 and distance measurement of 40 Mpc

This allowed astronomers to study for the first time a kilonova, the r-process production of elements, a rapidly fading source





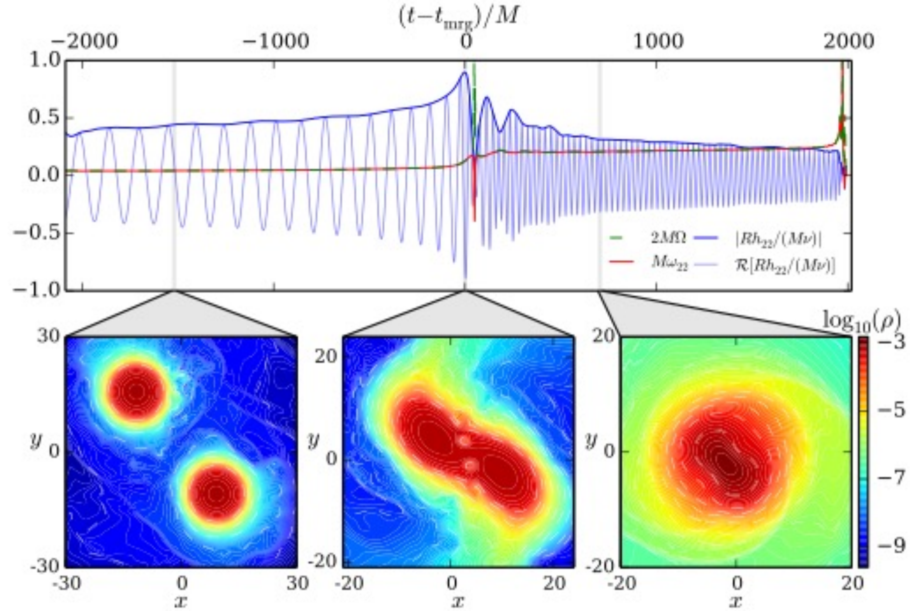


Probing the structure of neutron stars

Tidal effects leave their imprint on the gravitational wave signal from binary neutron stars. This provides information about their deformability. There is a strong need for more sensitive detectors

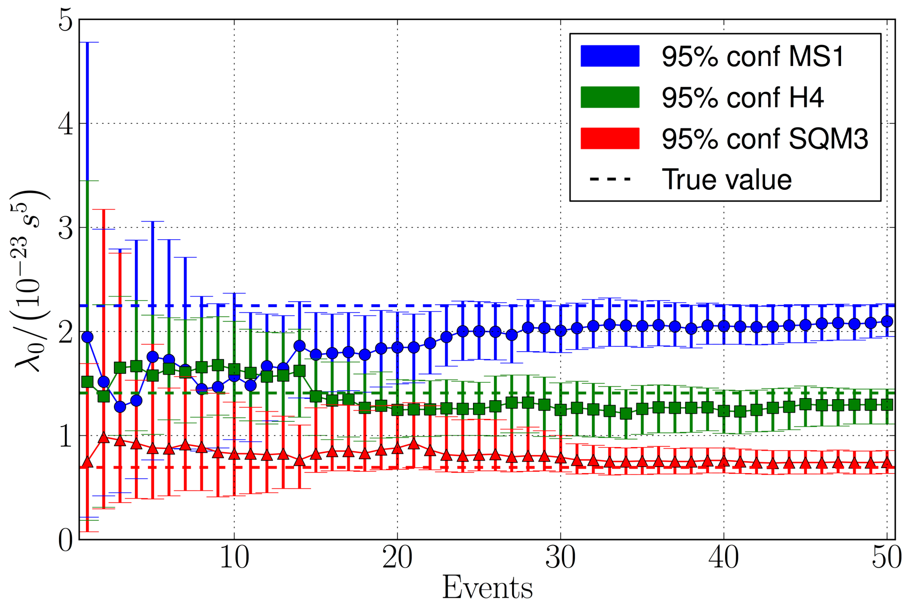
Gravitational waves from inspiraling binary neutron stars

- When close, the stars induce tidal deformations in each other
- These affect orbital motion
- Tidal effects imprinted upon gravitational wave signal
- Tidal deformability maps directly to neutron star equation of state



Measurement of tidal deformations on GW170817

- More compact neutron stars favored
- “Soft” equation of state



LIGO + Virgo, PRL 119, 161101 (2017)

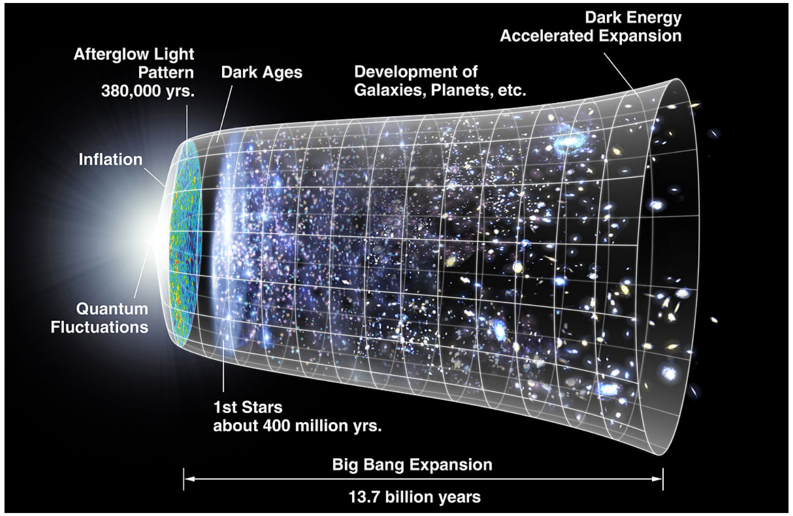
Bernuzzi, Nagar, Font, …

A new cosmic distance marker

Binary neutron stars allow a new way of mapping out the large-scale structure and evolution of spacetime by comparing distance and redshift

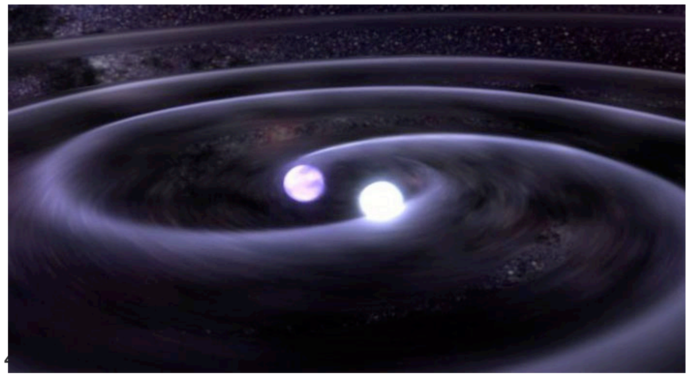
Current measurements depend on cosmic distance ladder

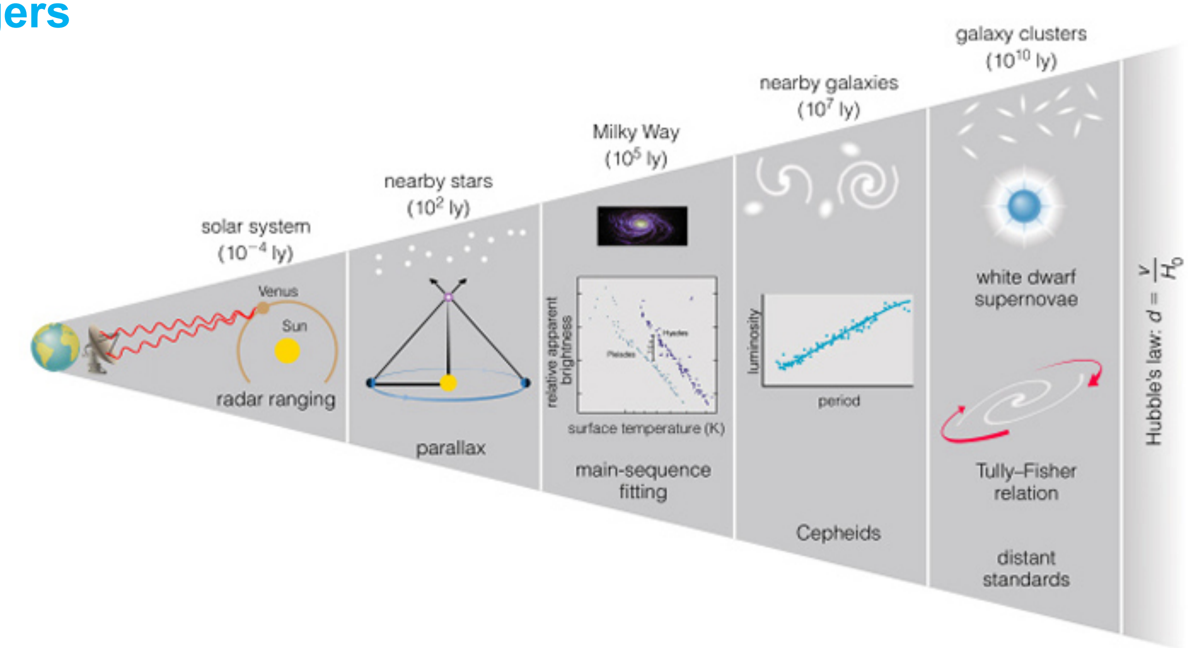
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder



Gravitational waves from binary mergers

Distance can be measured directly from the gravitational wave signal!





A new cosmic distance marker

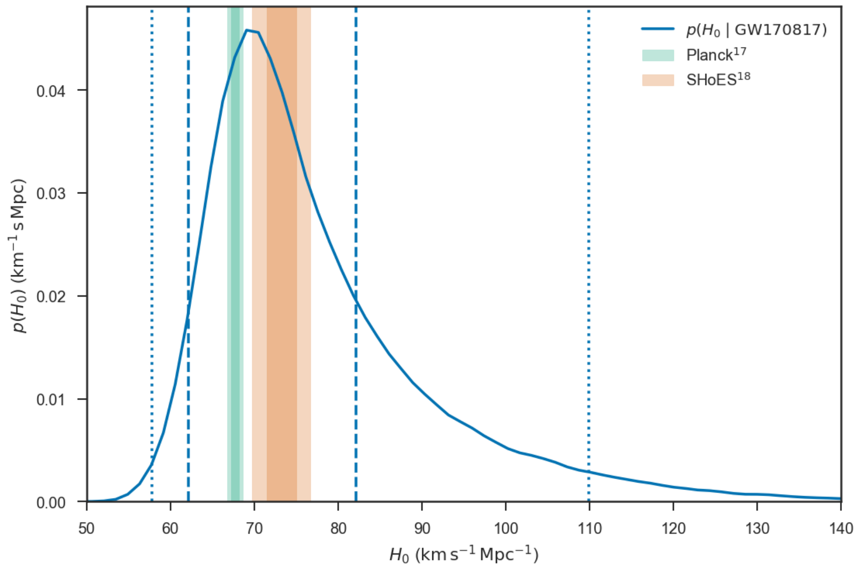
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1% accuracy

Measurement of the local expansion of the Universe

The Hubble constant

- Distance from GW signal
- Redshift from EM counterpart (galaxy NGC 4993)

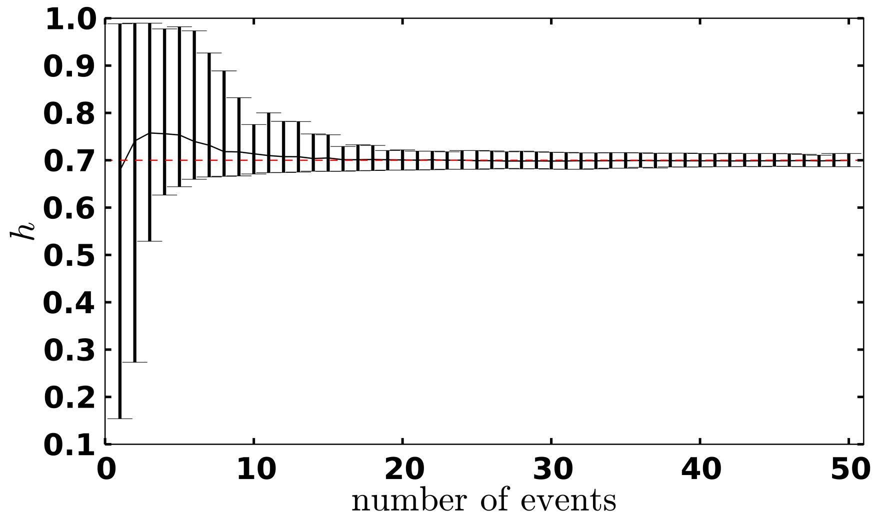
LIGO+Virgo *et al.*, Nature 551, 85 (2017)



GW170817

- One detection: limited accuracy
- Few tens of detections with LIGO/Virgo will be needed to obtain O(1%) accuracy

Del Pozzo, PRD 86, 043011 (2012)



Third generation observatories allow studies of the Dark Energy equation of state parameter

Scientific impact of gravitational wave science

Multi-messenger astronomy started: a broad community is relying of detection of gravitational waves

Fundamental physics

Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes, echo's
Lorentz-invariance, equivalence principle, polarization, parity violation, axions

Astrophysics

First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

Astronomy

Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies

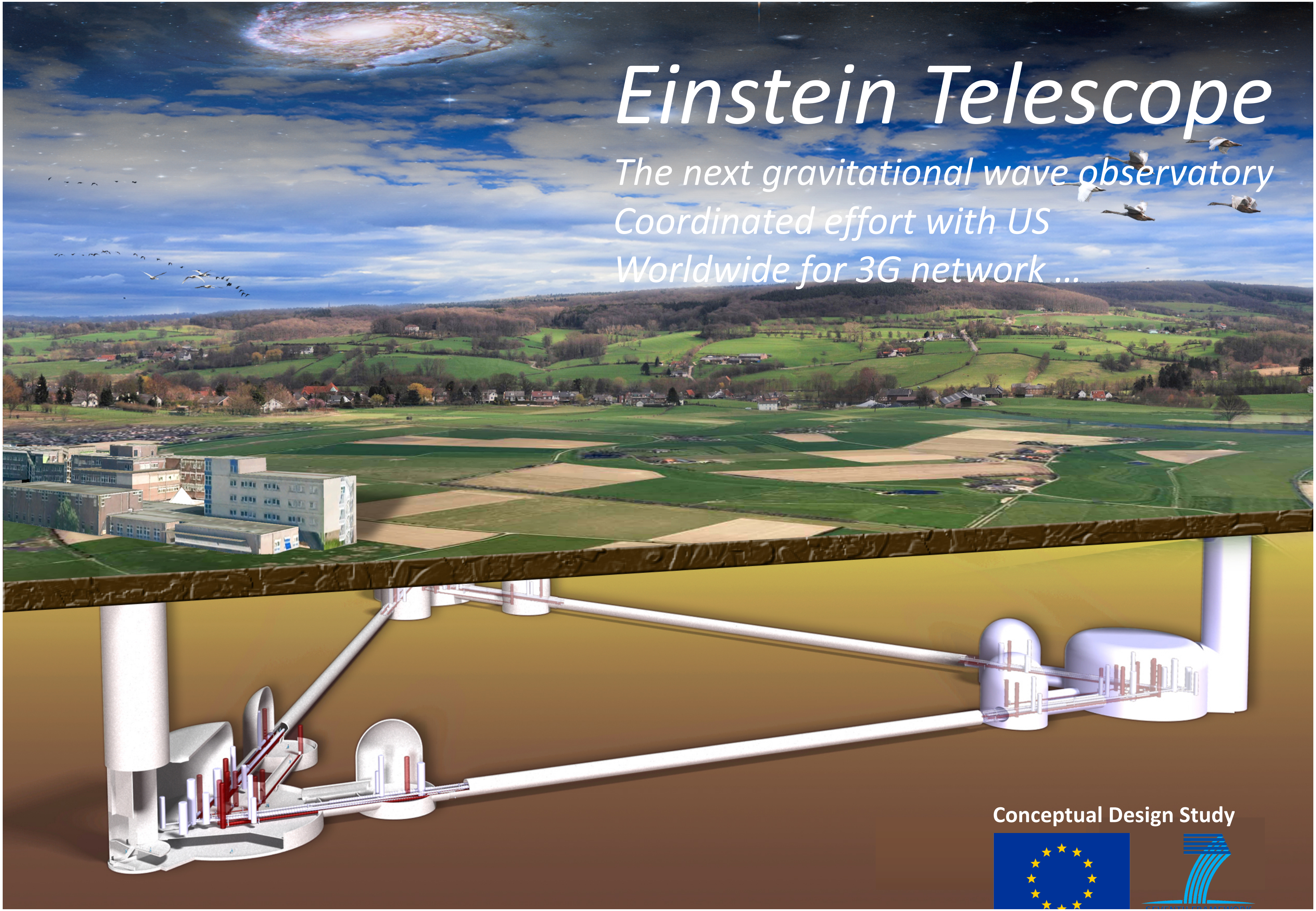
Cosmology

Binary neutron stars can be used as standard "sirens"
Dark Matter and Dark Energy

Nuclear physics

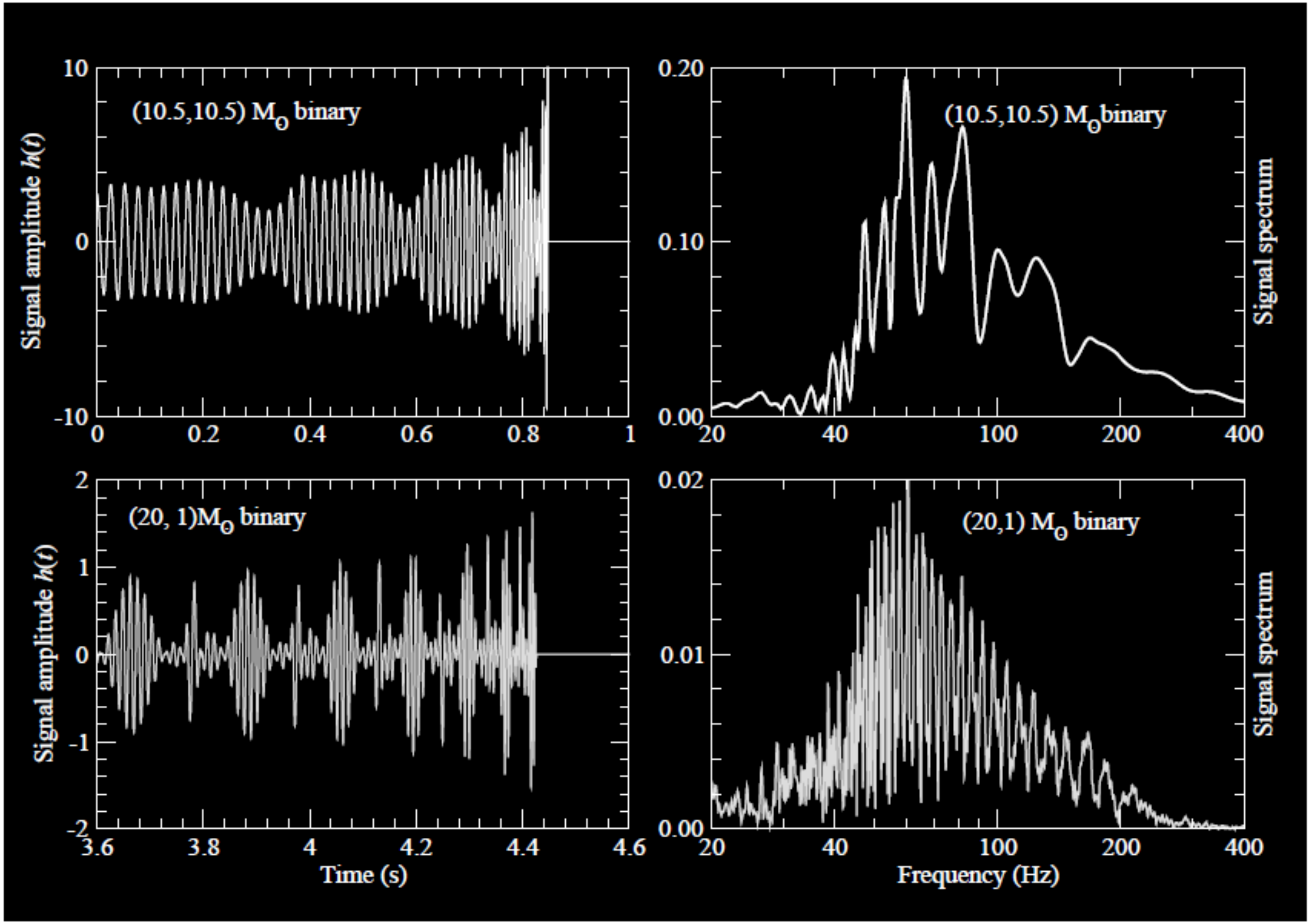
Tidal interactions between neutron stars get imprinted on gravitational waves
Access to equation of state

LVC will be back with improved instruments to start the next observation run (O3) in H2 this year


Einstein Telescope
The next gravitational wave observatory
Coordinated effort with US
Worldwide for 3G network ...
Conceptual Design Study

We want to observe our signals over a long time

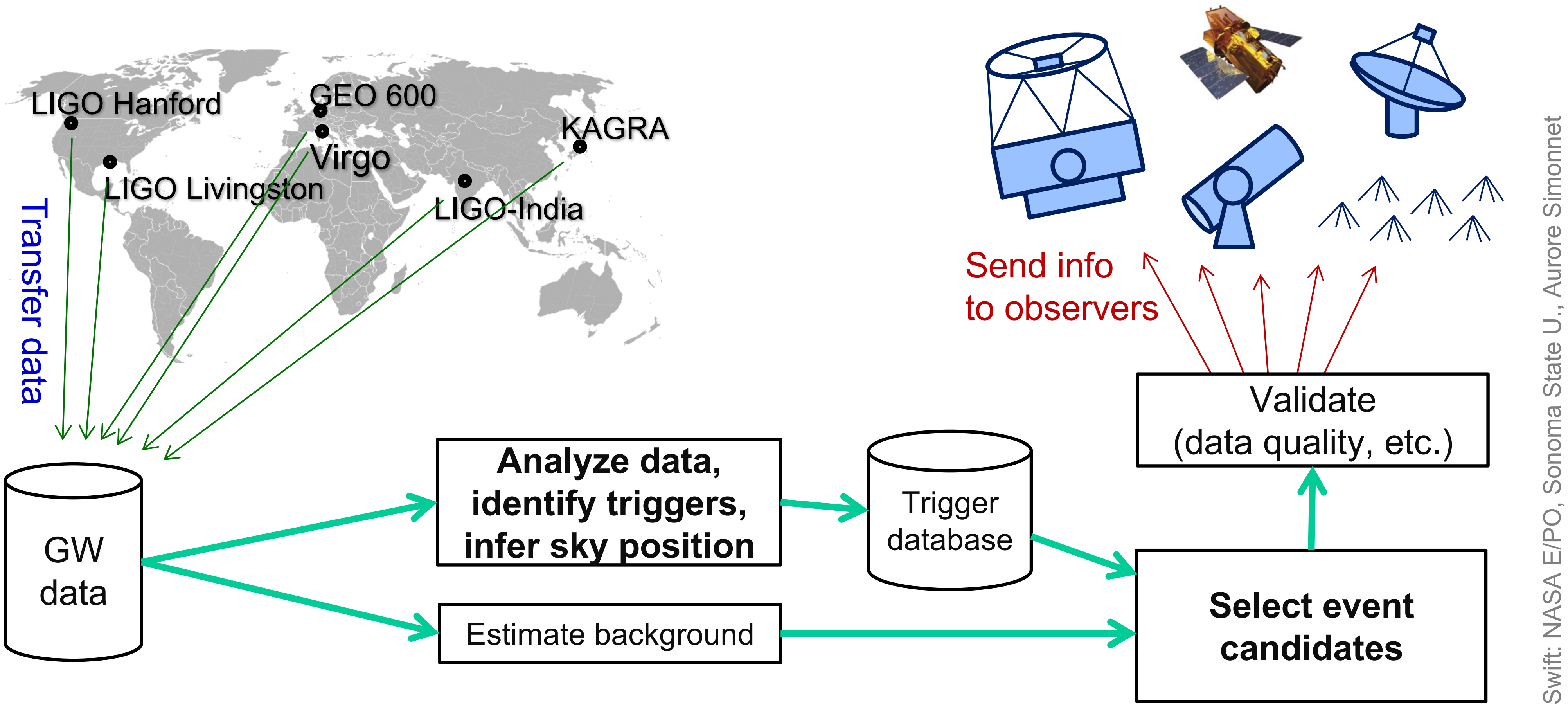
It is of great importance to study spin-precession effects. Modulations encode the parameters of sources (their masses, spins, inclination of the orbit, etc.



We will do multi-messenger astronomy

A BNS system will stay in ET's sensitivity band for nearly a week starting from 1 Hz, 20 hours starting from 2 Hz, and a little less than 2 hours starting from 5 Hz. For the same lower frequency limits the duration of a BBH signal from a pair of 10 M BHs is 2 days, 45 minutes and 4 minutes

LIGO & Virgo have signed MOUs with 95 groups for burst/EM/neutrino follow-up, in addition to a number of triggered / joint search MOUs



We want to do precision science requiring many events

This can be achieved by combining information from multiple events. What length for ET and CE?

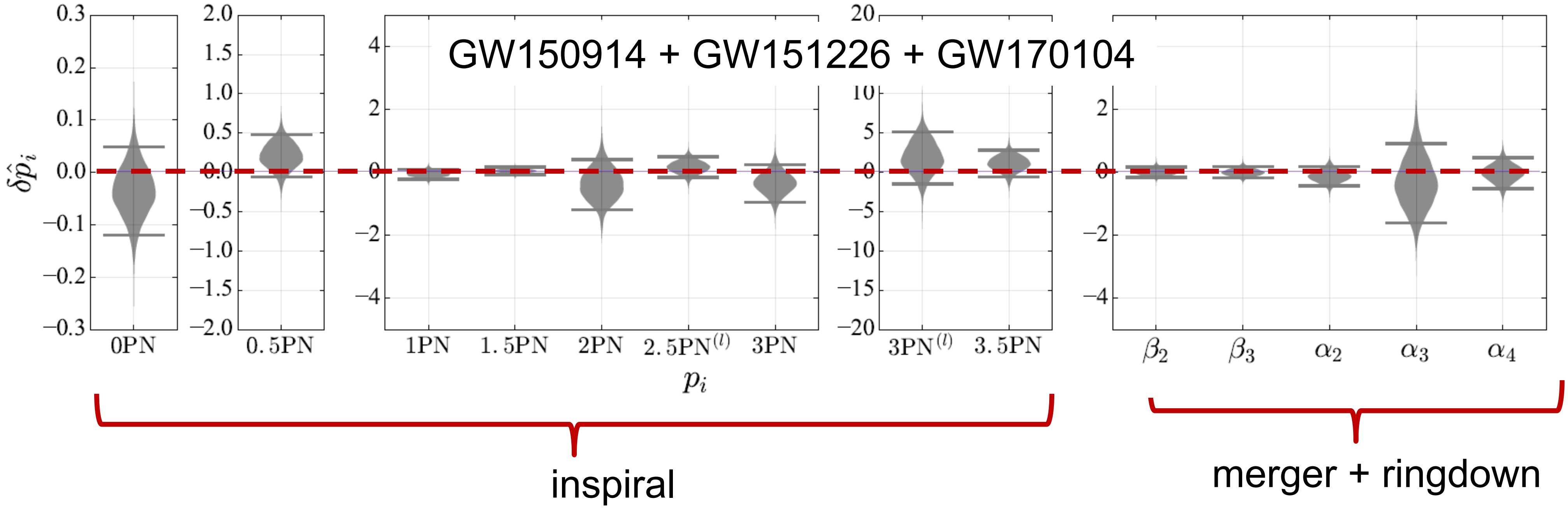
Are our waveform models robust for stacking, e.g. to sub-per-mille precision on PN terms?

- Can we face-up to the computing challenge?
- Do we prefer events a few high-SNR events (thus long arms), or can we combine lower SNR events?

Orbital phase (post Newtonian expansion): $h^{\alpha\beta}(f) = h^{\alpha\beta} e^{i\Phi(f)}$

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

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. Coefficients sensitive to GW back-reaction, spin-orbit, spin-spin couplings, …



Observe the entire sky with high pointing precision

We want to constantly observe the entire sky and this requires multiple 3G observatories

We require a network of 3G detectors spread over the globe

- Correlate high statistics GW data with other (e.g. EM) observations (SKA-II, LSST, Theseus, …)
- One L-shaped sensitive instrument, or one triangular detector? Or do we need a 3G network?

We want to observe intermediate-mass black holes

Globular clusters may host intermediate-mass black holes (IMBHs) with masses in the range 100 to 1000 solar masses

IMBH will be the most massive object in the cluster and will readily sink to the center

Binary with a compact-object companion will form. The binary will then harden through three-body interactions

Binary will eventually merge via an intermediate-mass-ratio inspiral (IMRI)

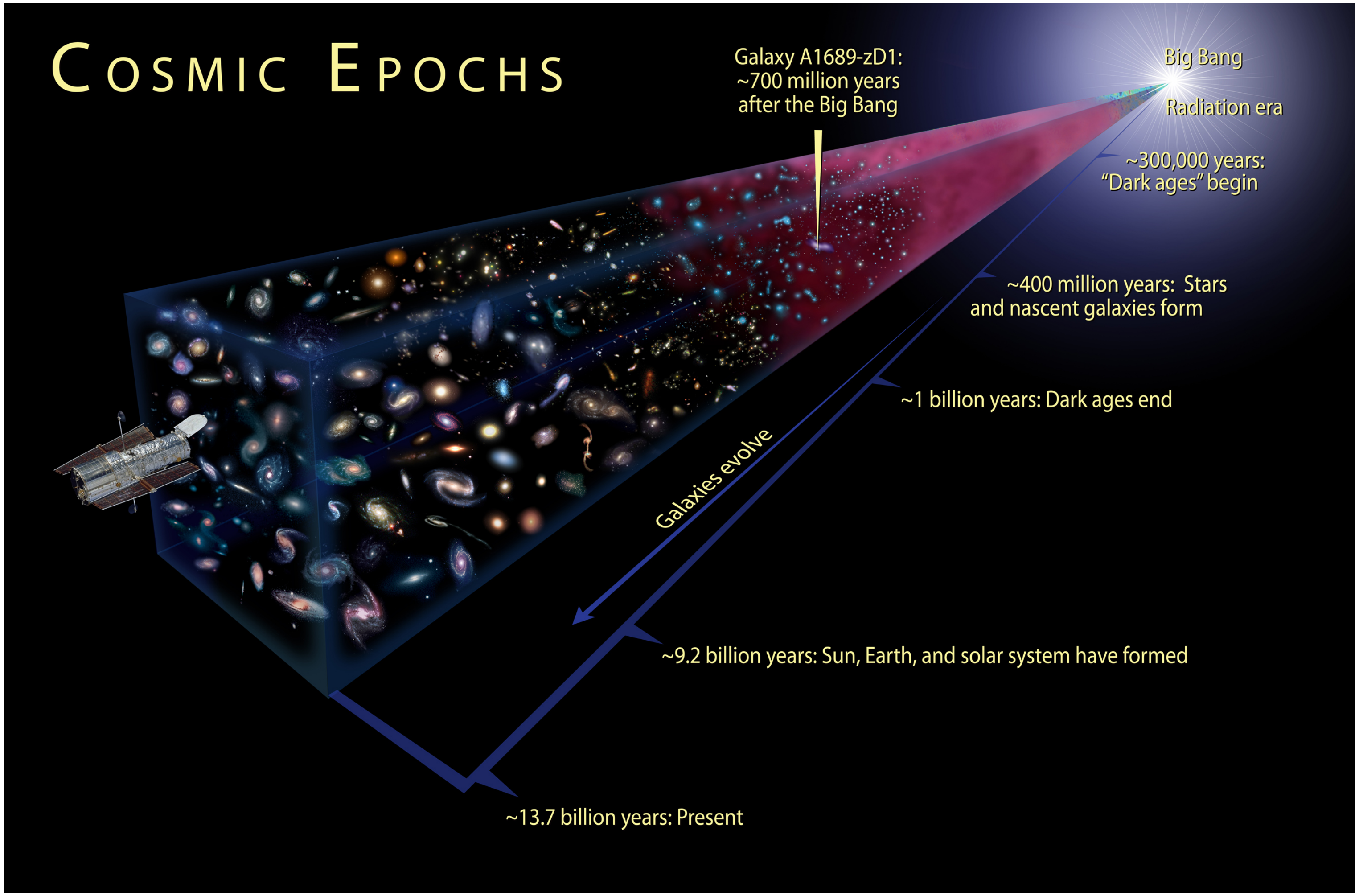
The number of detectable mergers depends on the unknown distribution of IMBH masses and their typical companions. Detect 300 events per year out to z = 1:5 for 100M (redshifted) primaries and 10M secondaries

NGC 2276-3c: NASA's Chandra Finds Intriguing Member of Black Hole Family Tree
http://chandra.harvard.edu/photo/2015/ngc2276/

Study events from dark ages with large redshifts

We want sensitivity for high-z events. Einstein Telescope can measure up to $z \approx 20$ and gravitational waves will be redshifted

ET also needs sensitivity at low-frequency. For this we need to go underground to suppress seismic noise



Bright future for gravitational wave research

LIGO and Virgo are operational. LIGO-India and KAGRA in Japan under construction. ESA launches LISA in 2034. Einstein Telescope CDR financed by EU, strong support by APPEC

Gravitational wave research

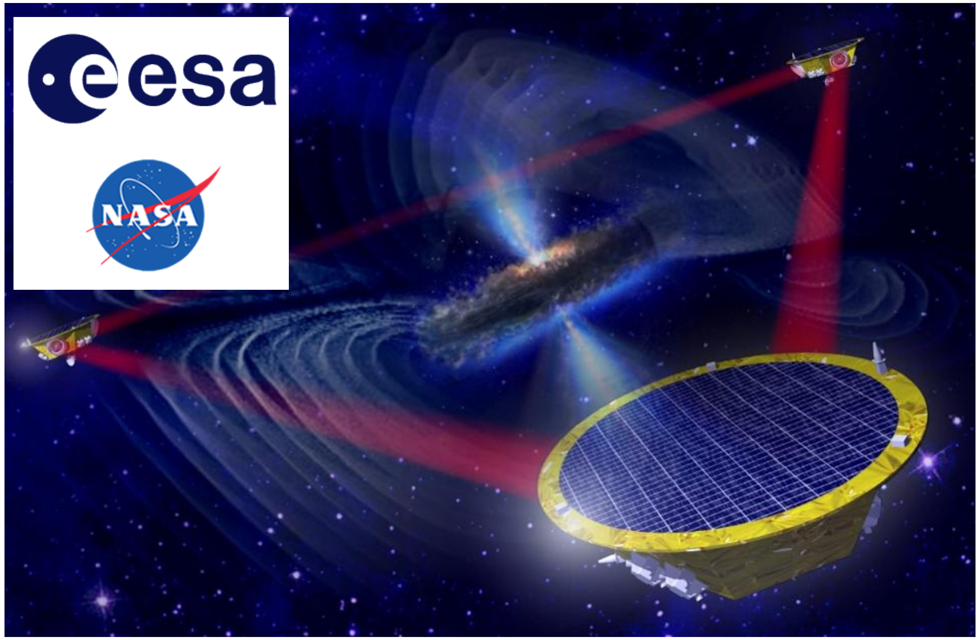
- LIGO and Virgo operational
- LIGO-India and KAGRA under construction
- ESA and NASA select LISA
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation

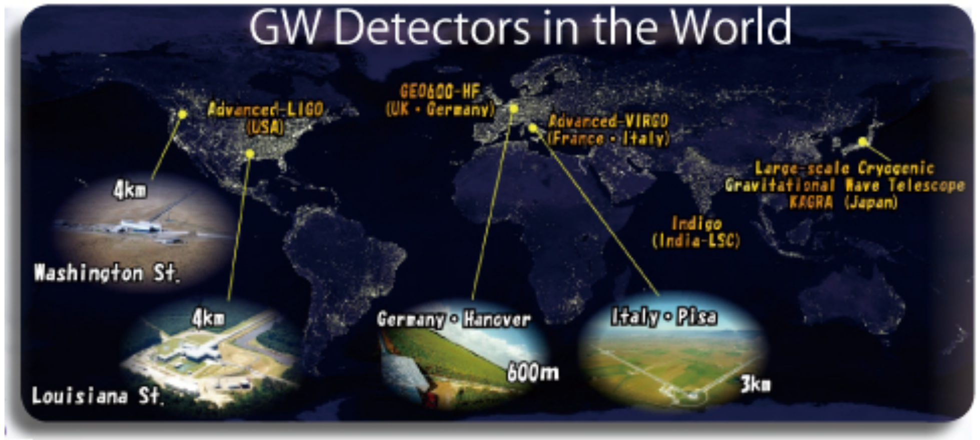
Einstein Telescope

- Design financed by EU in FP7
- APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET

Next steps

- Organize the community and prepare a credible plan for EU funding agencies
- ESFRI Roadmap (2019)





Thank you for your attention!