Gravitational waves, spin and polarization

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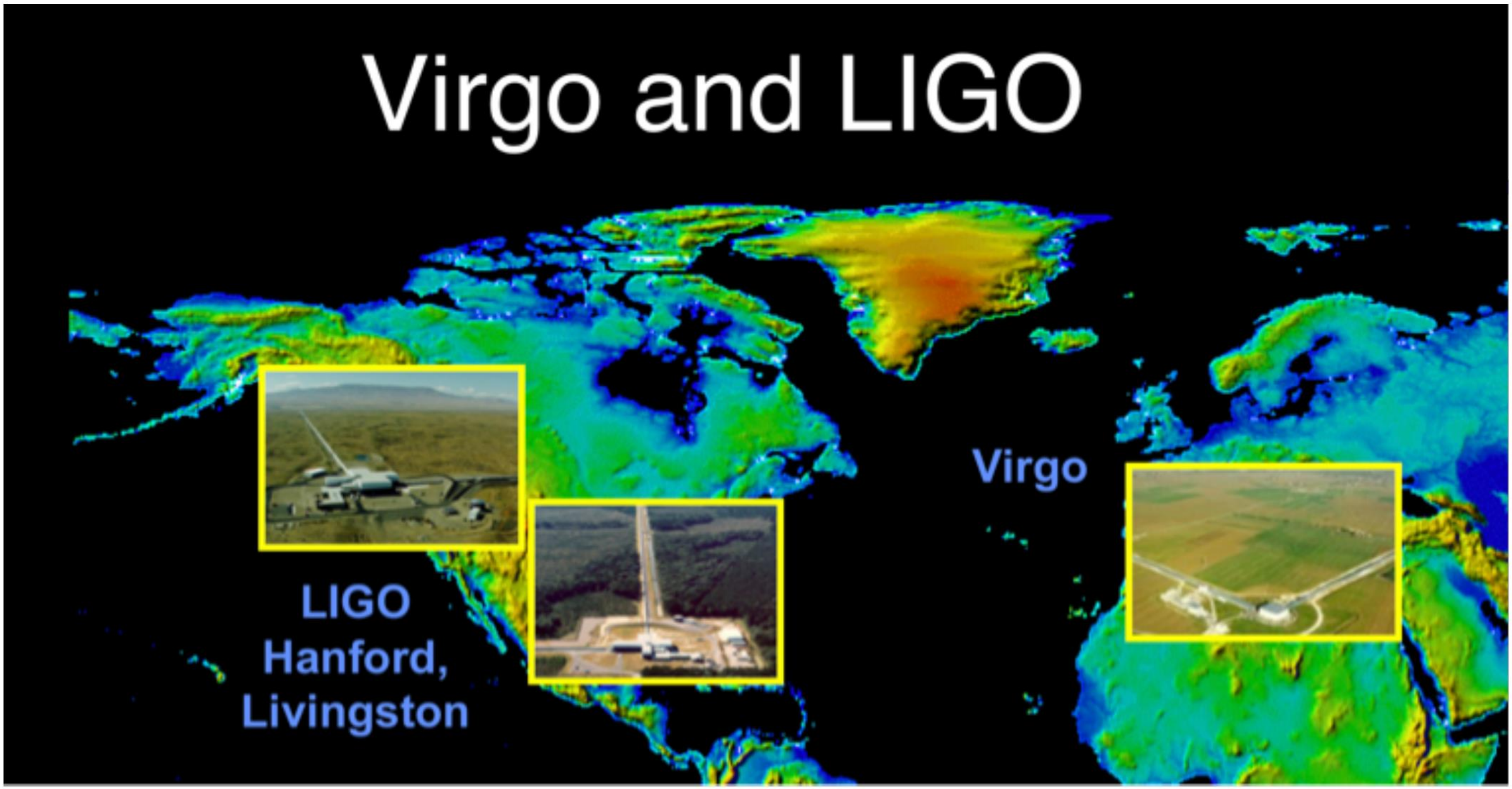
SPIN2018, Ferrara, September 10, 2018

LIGO and Virgo

Observe together as a Network of GW detectors. LVC have integrated their data analysis

LIGO and Virgo have coordinated data taking and analysis, and release joint publications
LIGO and Virgo work under an MOU since about a decade
KAGRA expected to join in 2019



Linearized EFE and gravitational waves

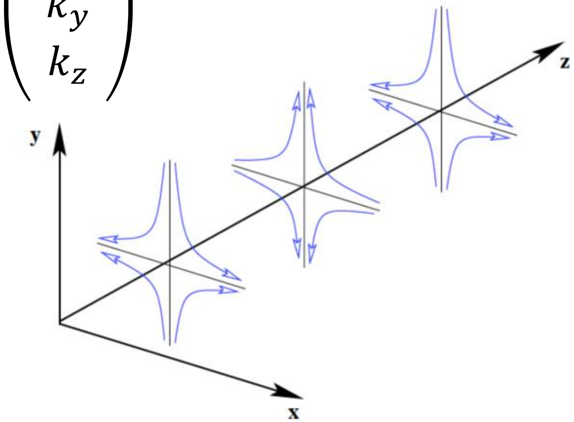
Einstein field equations can be written as a wave equation for metric perturbations

Einstein equations $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$ $\Rightarrow$ $\Box \bar{h}_{\alpha\beta} = \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\bar{h}_{\alpha\beta} = -2\left(\frac{8\pi G}{c^4}\right) T_{\alpha\beta}$

A wave equation for the curvature perturbations where $g_{\alpha\beta} \approx \eta_{\alpha\beta} + h_{\alpha\beta}$. In vacuum $T_{\alpha\beta} = 0$

We consider solutions $\bar{h}_{\alpha\beta} = \mathbb{R}\mathrm{e}\left(\epsilon_{\alpha\beta} e^{-ik_\rho x^\rho}\right)$ with wave vector $k^\rho = \begin{pmatrix} \omega/c \\ k_x \\ k_y \\ k_z \end{pmatrix}$

Using the gauge condition $\partial_\alpha \bar{h}^{\alpha\beta} = 0$ leads to $k_\rho \epsilon^{\rho\sigma} = 0$ and we have 6 remaining independent elements in the polarization tensor

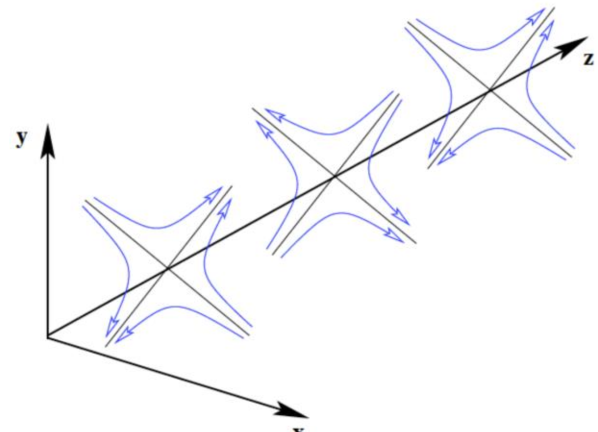


Among the set of coordinate systems, it is possible to choose one for which $\epsilon_{0\sigma} = 0$. In GR this reduces the number of independent elements to 2 denoted “plus” and “cross” polarization

General solution for a wave traveling along the *z*-axis is

$$\epsilon_{\alpha\beta} e^{-ik_\rho x^\rho} = \left(h_+ \epsilon^+_{\alpha\beta} + h_\times \epsilon^\times_{\alpha\beta}\right) e^{-ik_\rho x^\rho}$$

Here is $\epsilon^+_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ and $\epsilon^\times_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ are a basis for the polarization tensor



Scientific achievements: properties of black holes

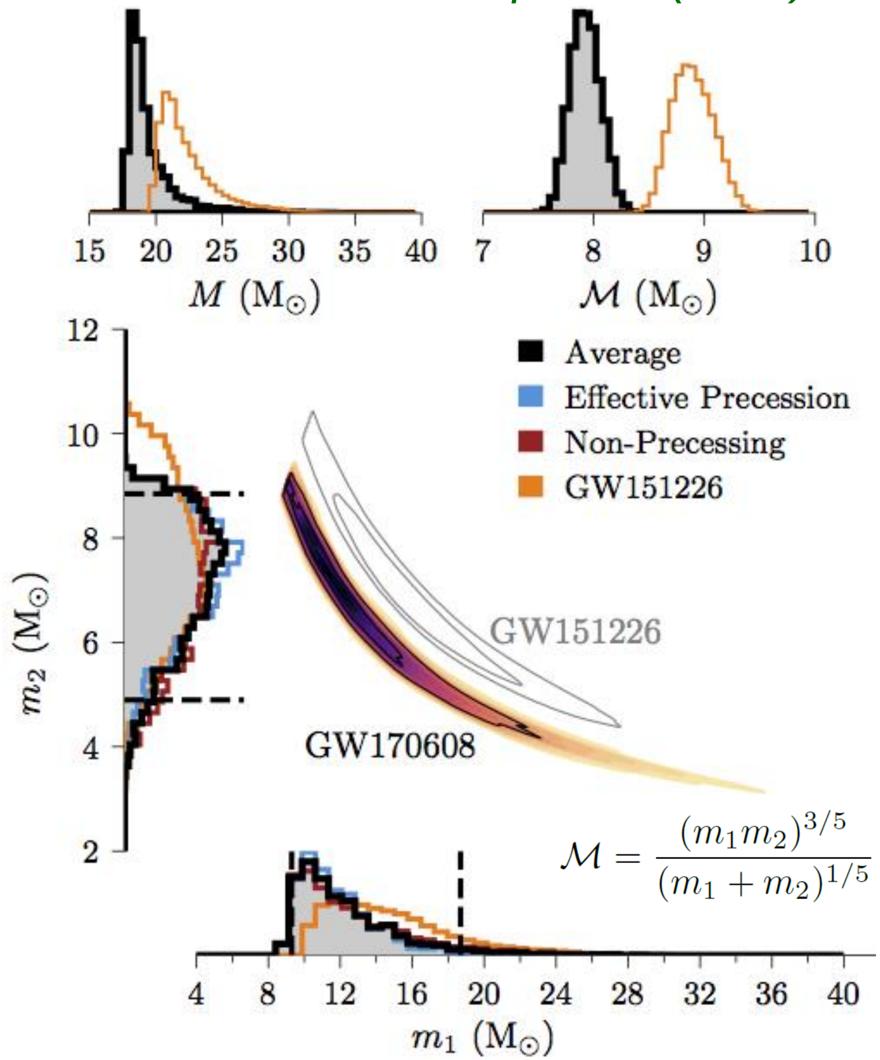
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

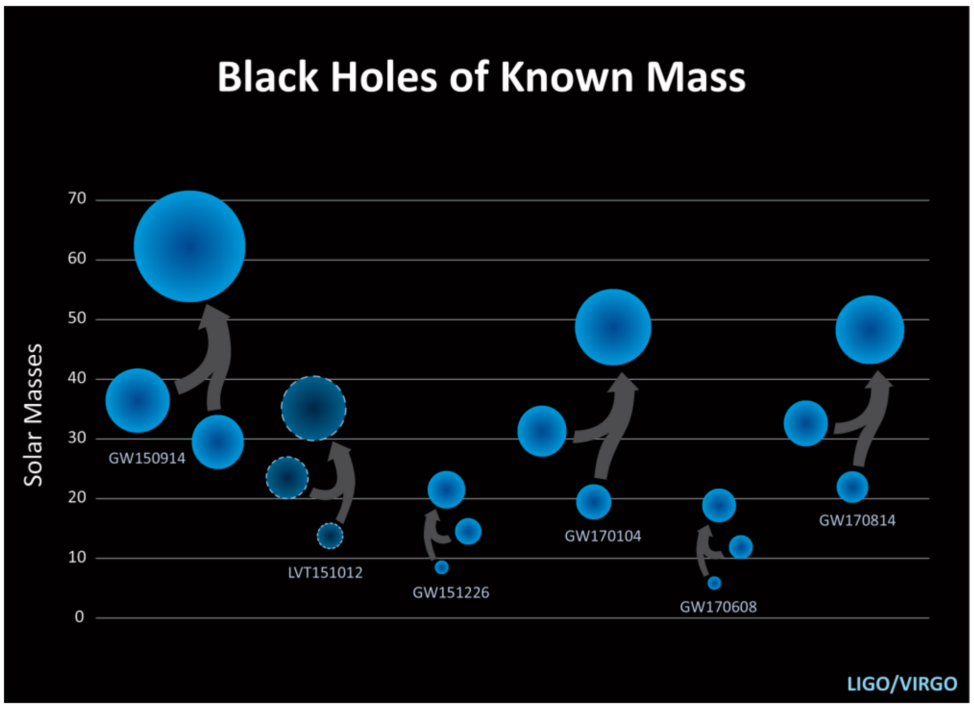
LVC reported on 6 BBH mergers

Chirp mass is well inferred

Merger dynamics more sensitive to total mass

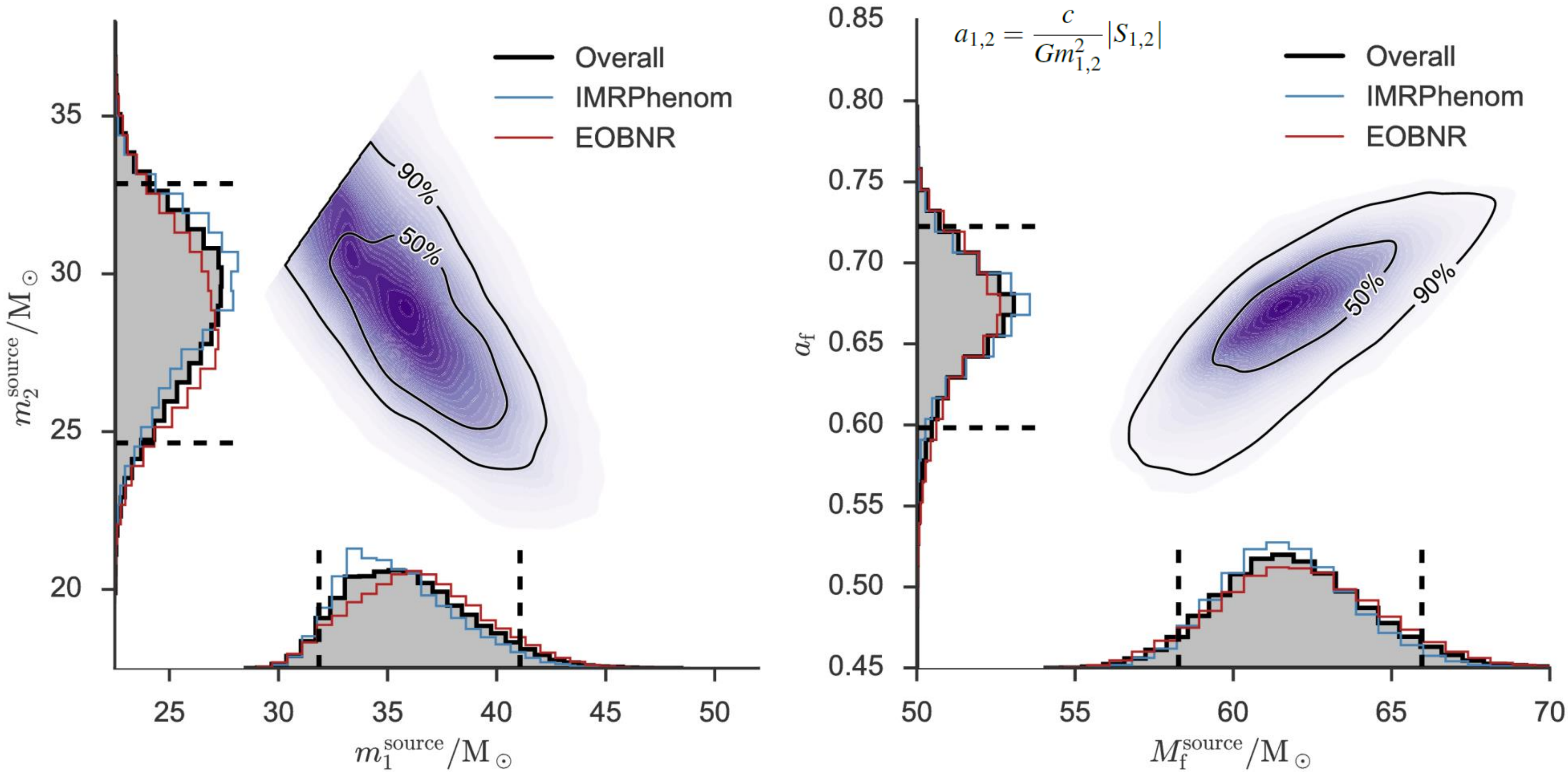
Abbott et al. ApJ 851 (2017) L35





Source parameters for GW150914

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

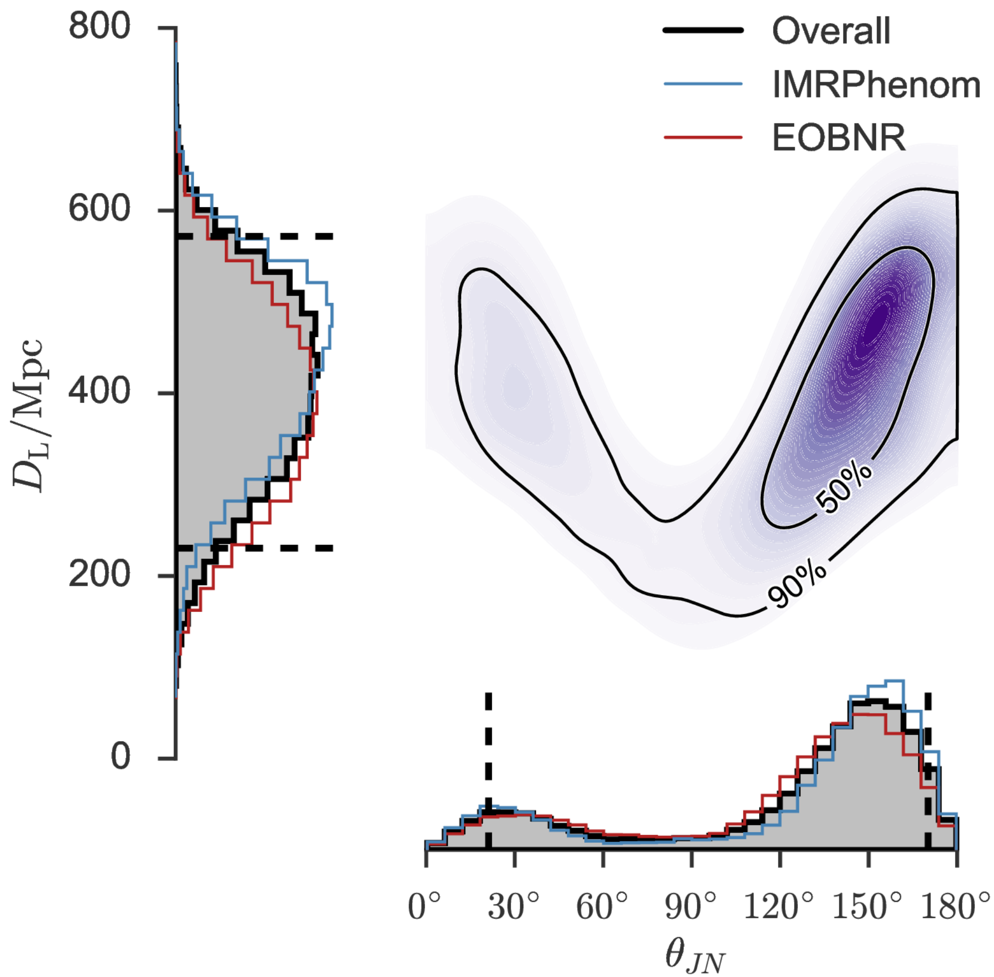


Energy radiated: 3.0 ± 0.5 solar masses. Peak power at merger: 200 solar masses per second

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

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

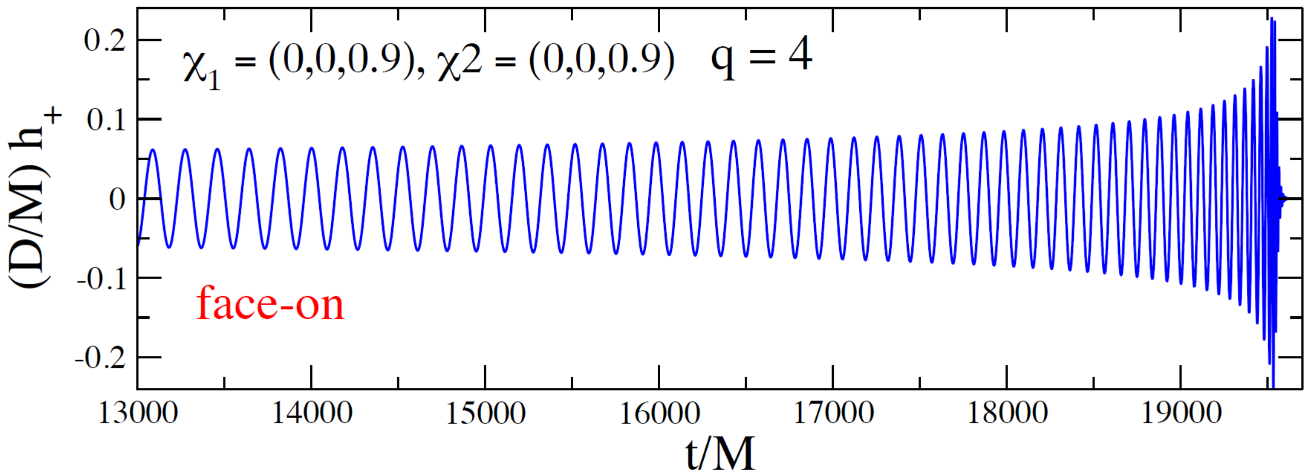
$$h_\times = \frac{4\nu M}{d}[\pi M f(t)]^{2/3}\cos\iota\,\sin[2\varphi(t)]$$

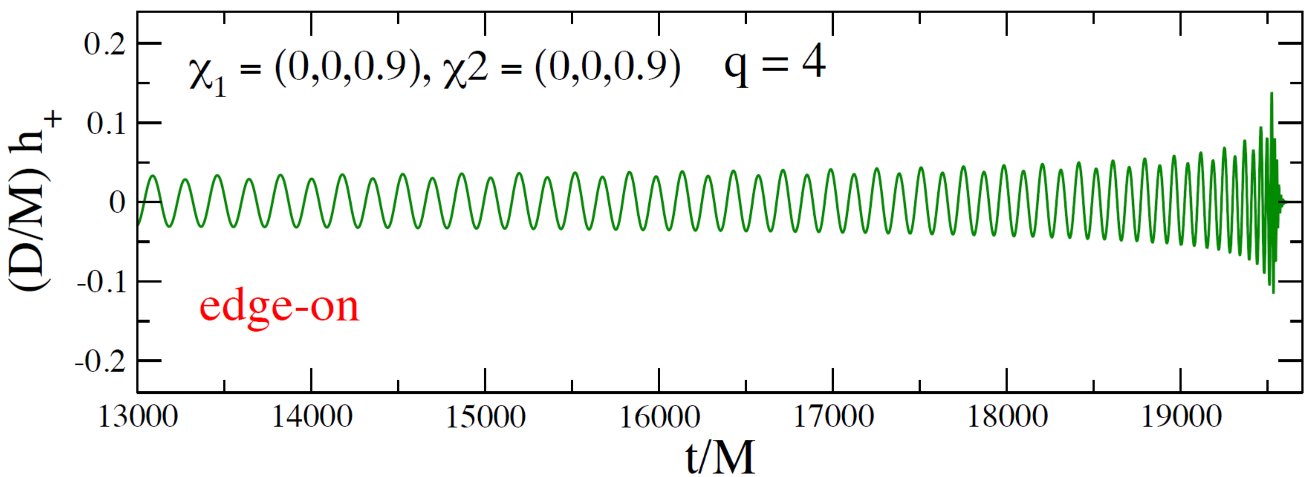
For this we need a third detector: Virgo

Effect of orientation of binary's orbital plane

Polarization of gravitational waves depends on the orientation of the orbital plan of the binary system. Face-on we observe a mixture, while edge-on we observe pure h+

Spinning, but non-precessing binary

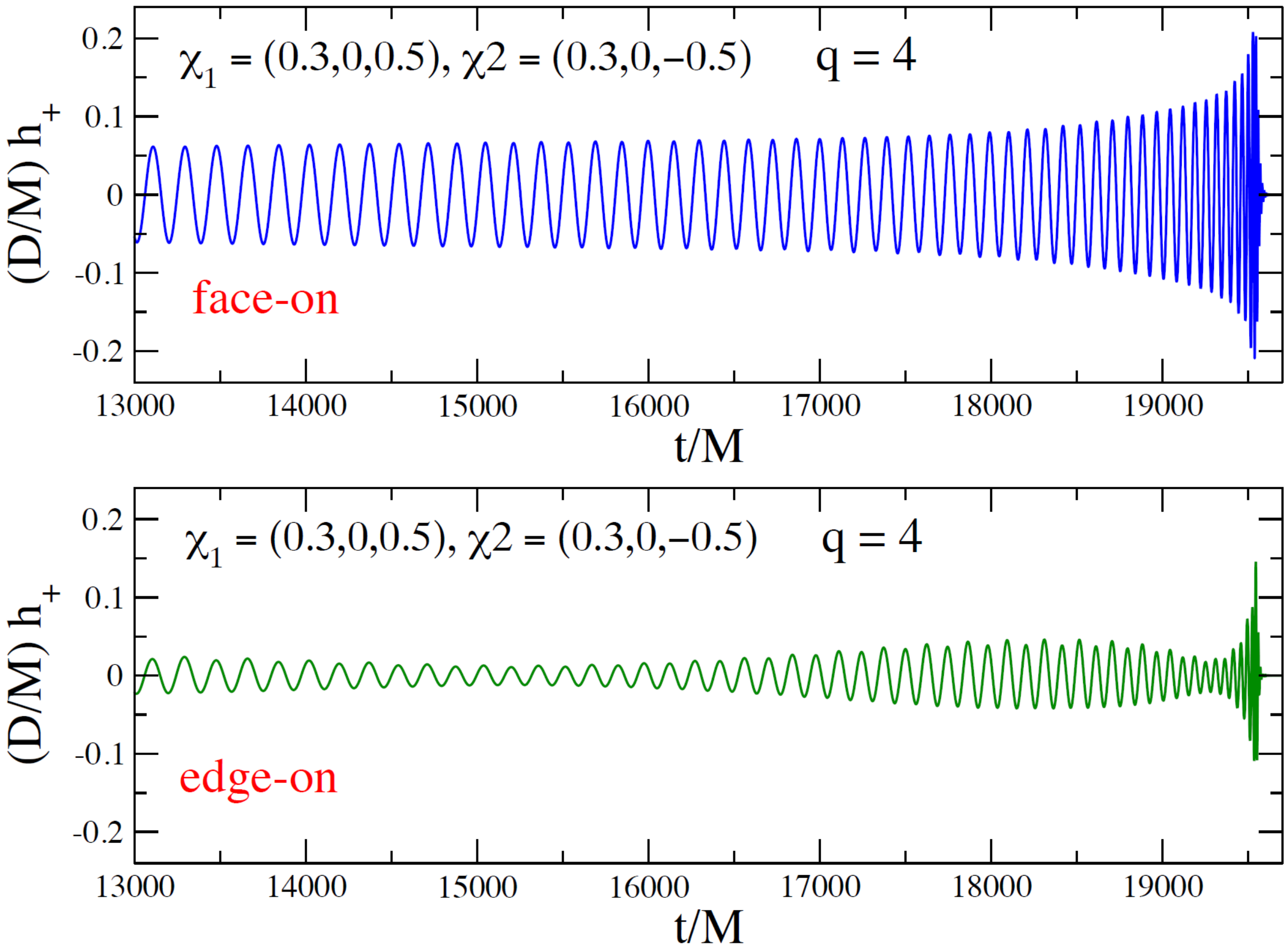




Effect of orientation of binary's orbital plane

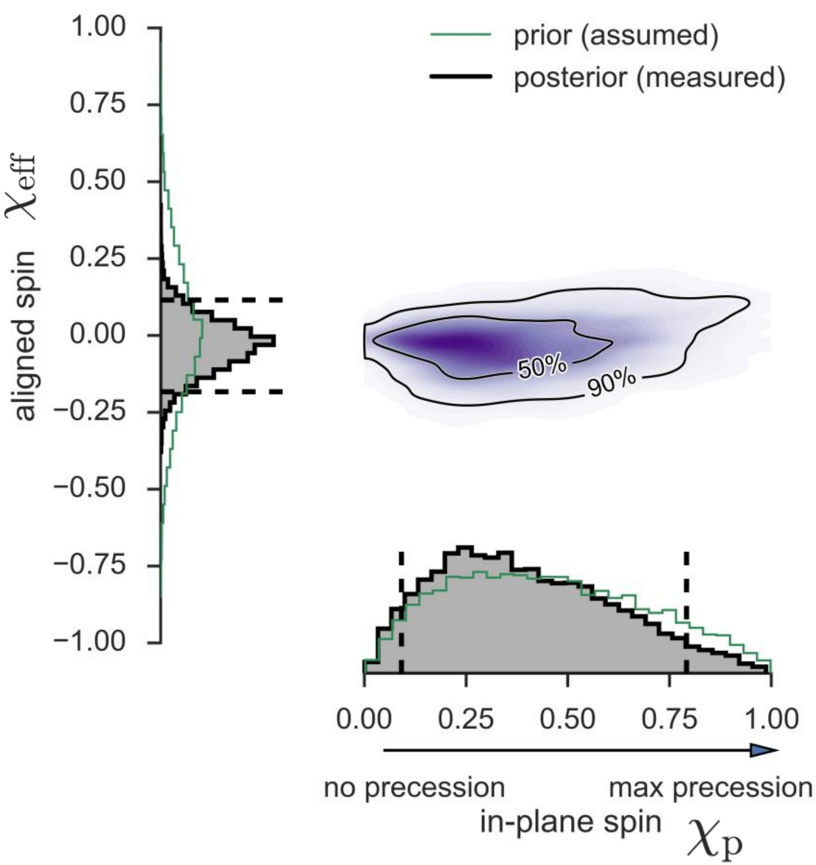
Spin precession leads to amplitude and frequency modulation

Spin-precessing binary



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

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

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

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

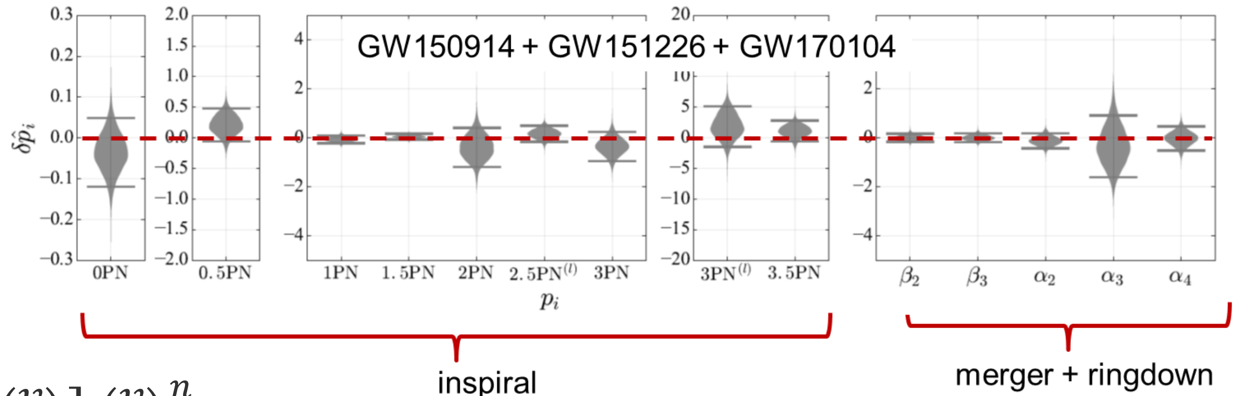
$\chi_p = 0$ aligned-spin (non-precessing) system

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

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

Precision tests of GR with BBH mergers

Bayesian analysis increases accuracy on parameters by combining information from multiple events



Inspiral and PN expansion

Inspiral PN and logarithmic terms:
Sensitive to GW back-reaction, spin-orbit, spin-spin couplings, …

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

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

Merger terms: numerical GR

Ringdown terms: quasi-normal modes; do we see Kerr black holes?

Towards high precision tests of gravity

Combining information from multiple events and having high-SNR events will allow unprecedented tests of GR and other theories of gravity

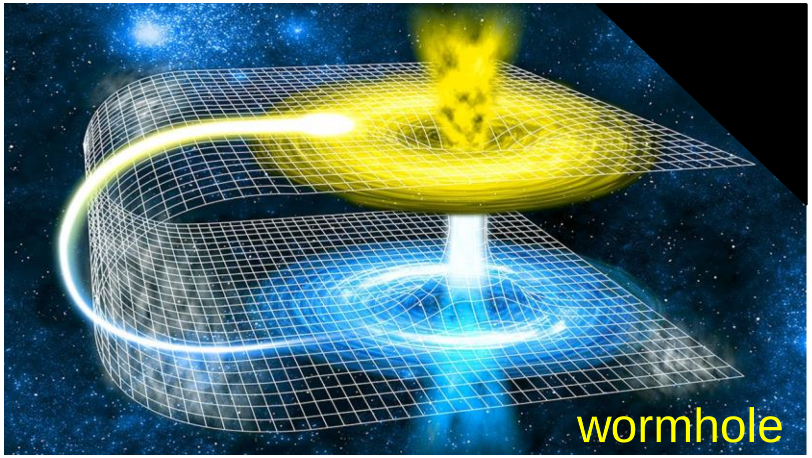
Our collaborations set ambitious goals for the future

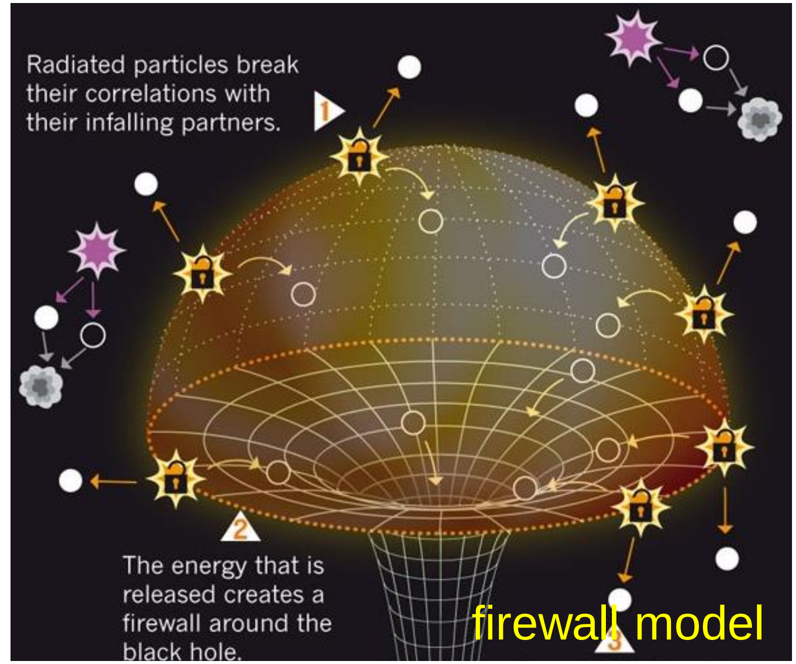
We need to improve:

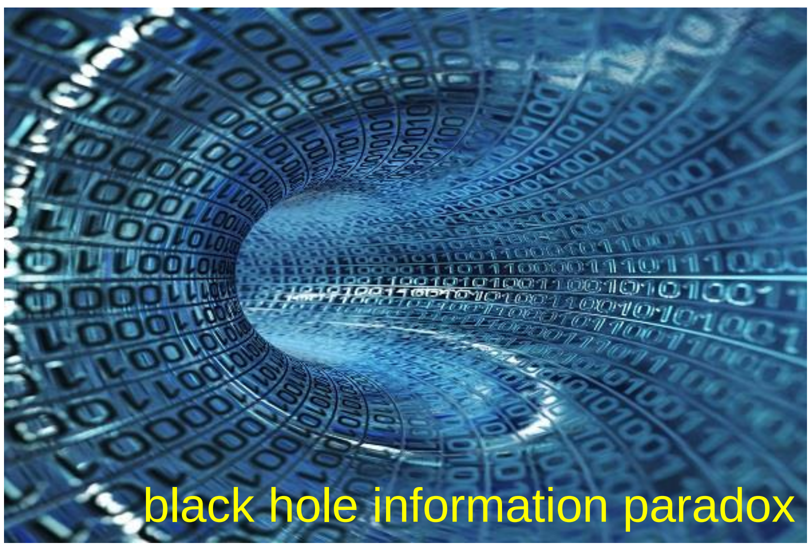
- sensitivity of our instruments over the entire frequency range
- optimize our computing and analysis
- improve our source modeling (NR)

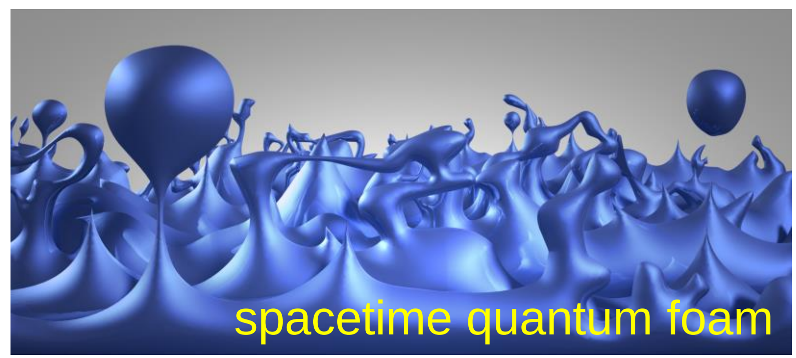
Fundamental physics: did we observe black holes?

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?



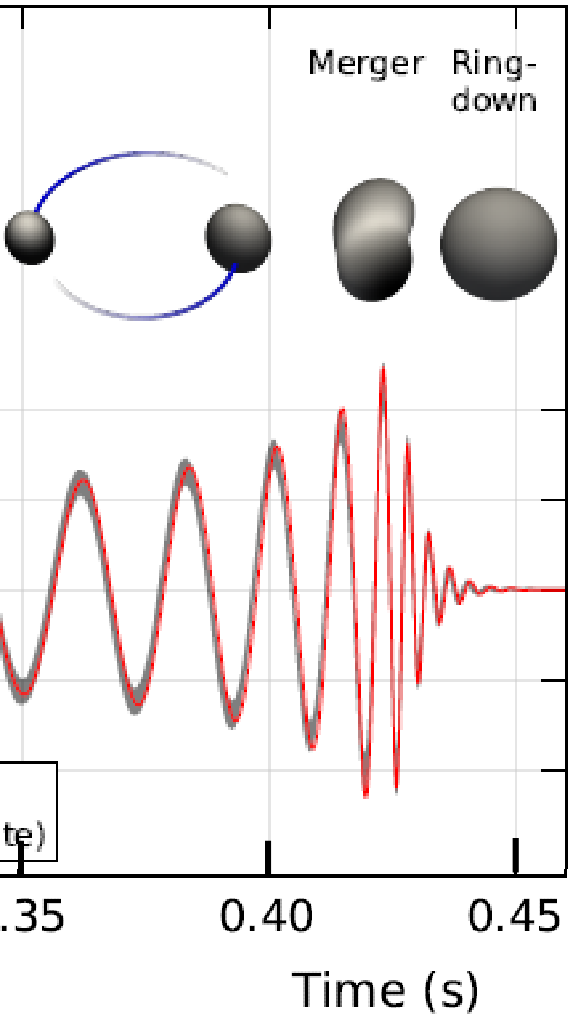


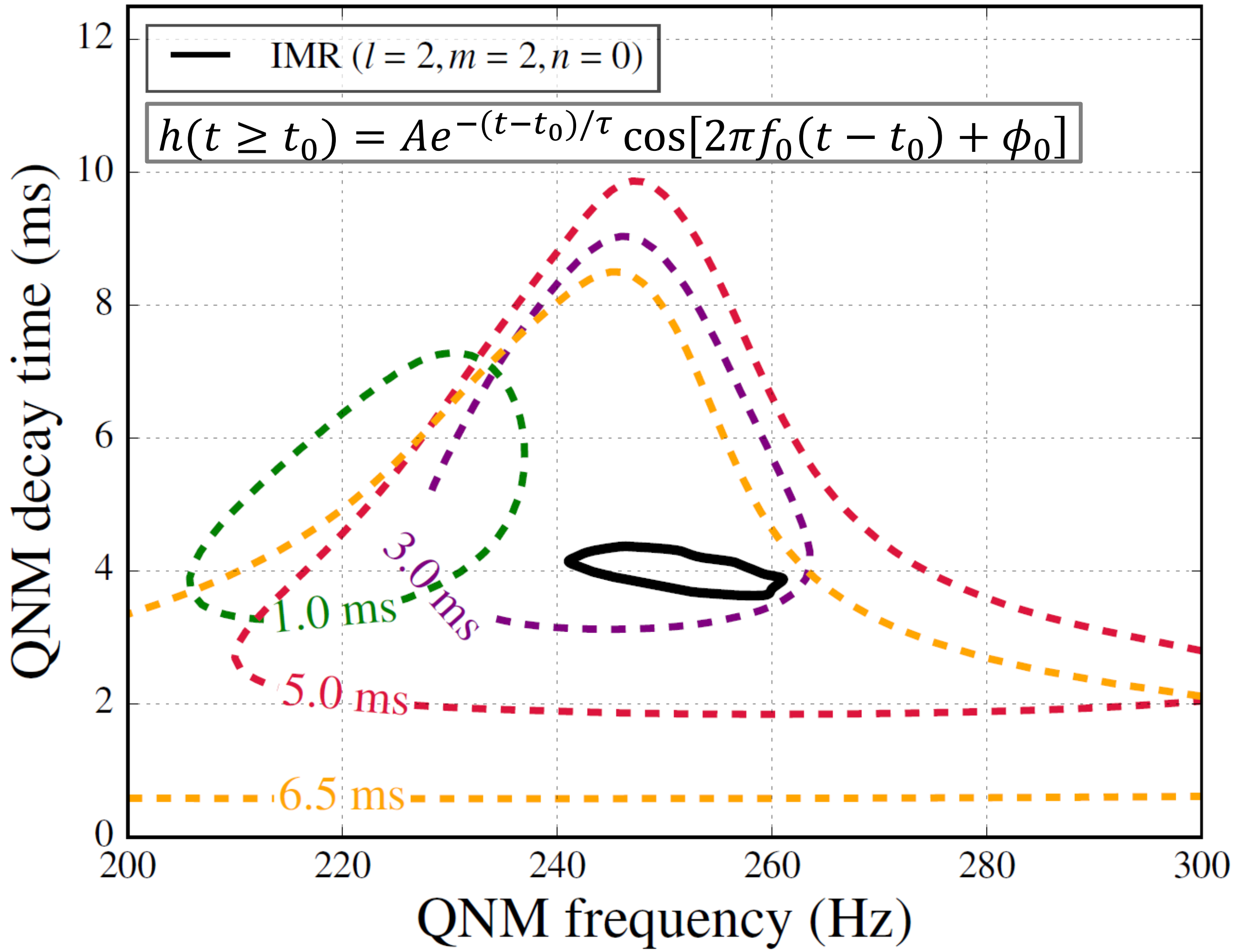




Is a black hole created in the final state?

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 and perform test of no-hair theorem





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

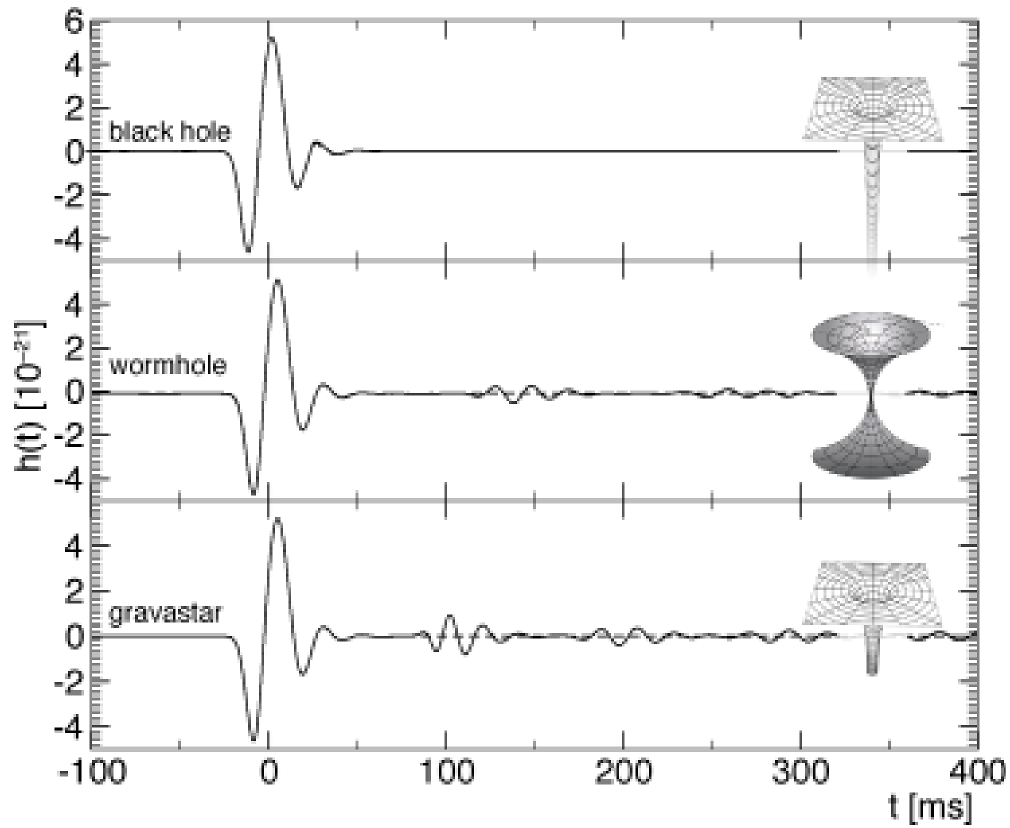
- Dark matter stars

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

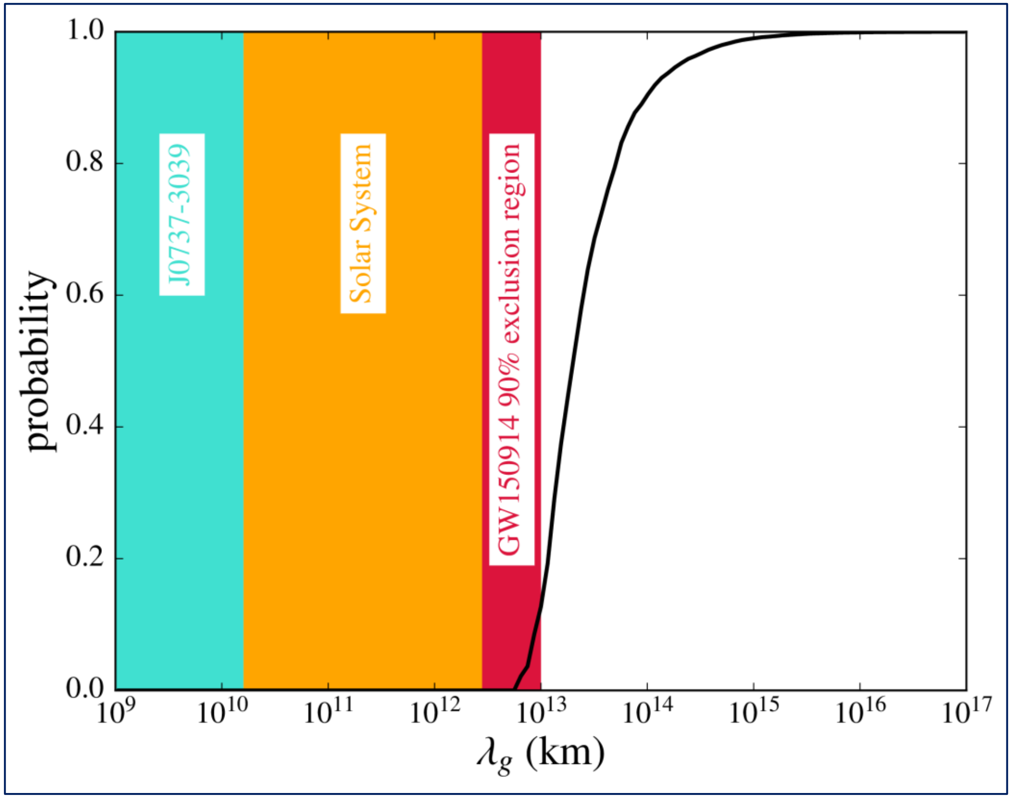


GW observables

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

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

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

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

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

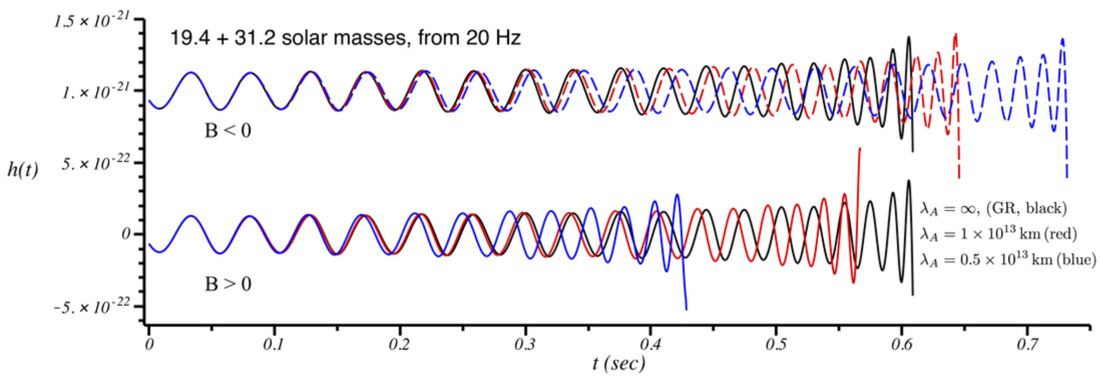
See "*Tests of general relativity with GW150914*"
http://arxiv.org/abs/1602.03841

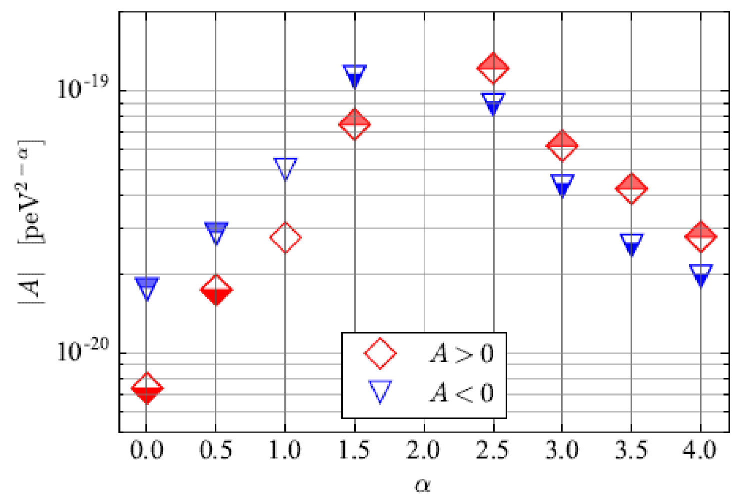
Bounds on violation of Lorentz invariance

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
$$\delta\Psi = \begin{cases} \frac{\pi}{\alpha-1}\frac{AD_\alpha}{(hc)^{2-\alpha}}\left[\frac{(1+z)f}{c}\right]^{\alpha-1} & \alpha \neq 1 \\ \frac{\pi AD_\alpha}{hc}\ln\left(\frac{\pi G\mathcal{M}^{det}f}{c^3}\right) & \alpha = 1 \end{cases} \qquad A \cong \pm\frac{MD_\alpha}{\lambda_A^2}$$





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)

Virgo joins LIGO in August 2017

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, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

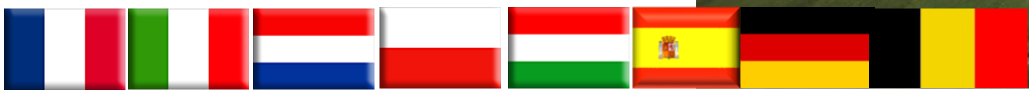
- 22 laboratories, about 280 authors
  - APC Paris
  - ARTEMIS Nice
  - EGO Cascina
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris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

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

8 European countries

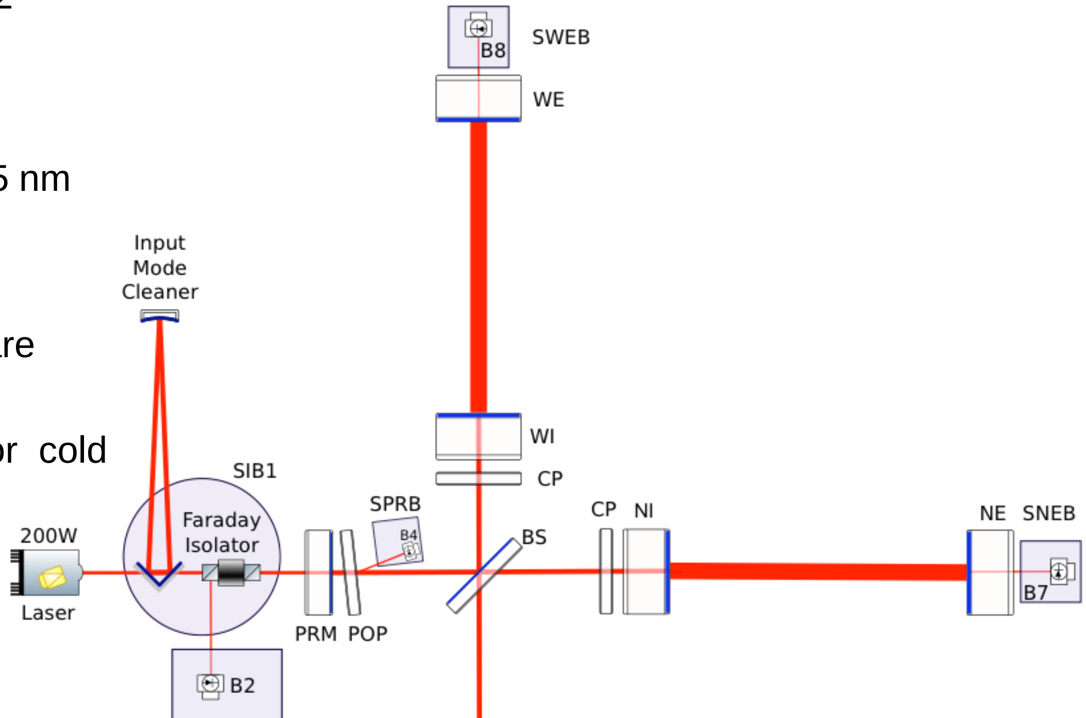


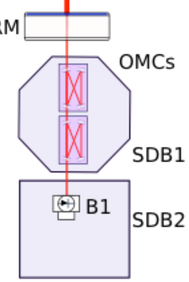
Advanced Virgo

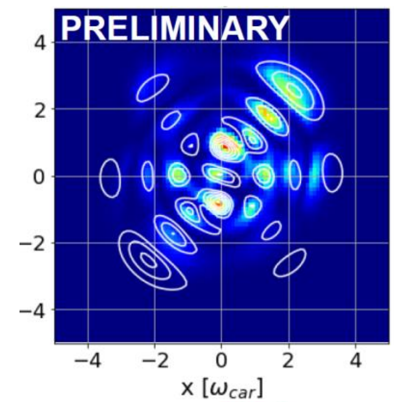
Advanced Virgo started operation on August 1, 2017. It features many improvements with respect to Virgo and Virgo+

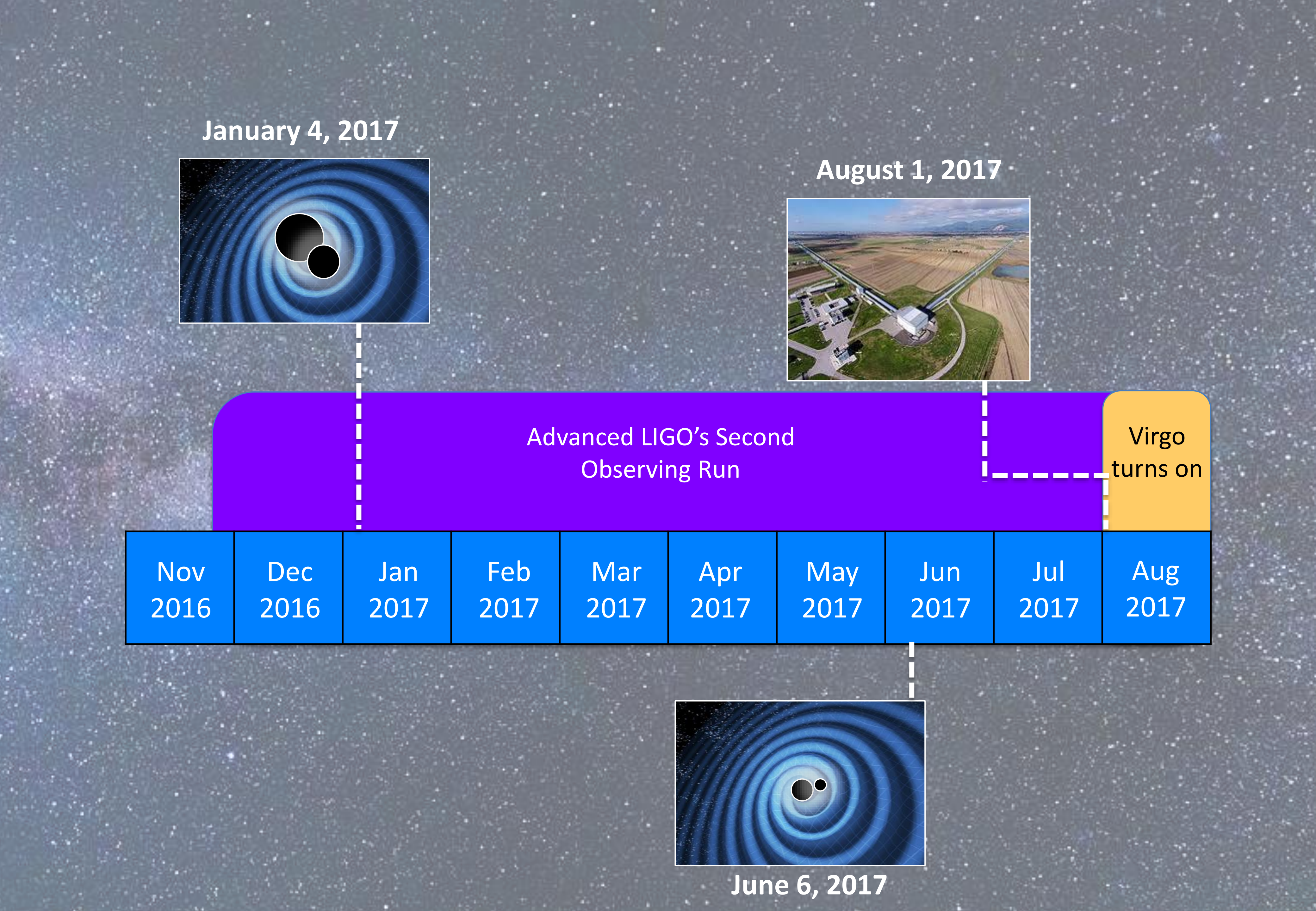
Instrumentation improvements for Observing run 2

- 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 CO_2 actuators
  - CO_2 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





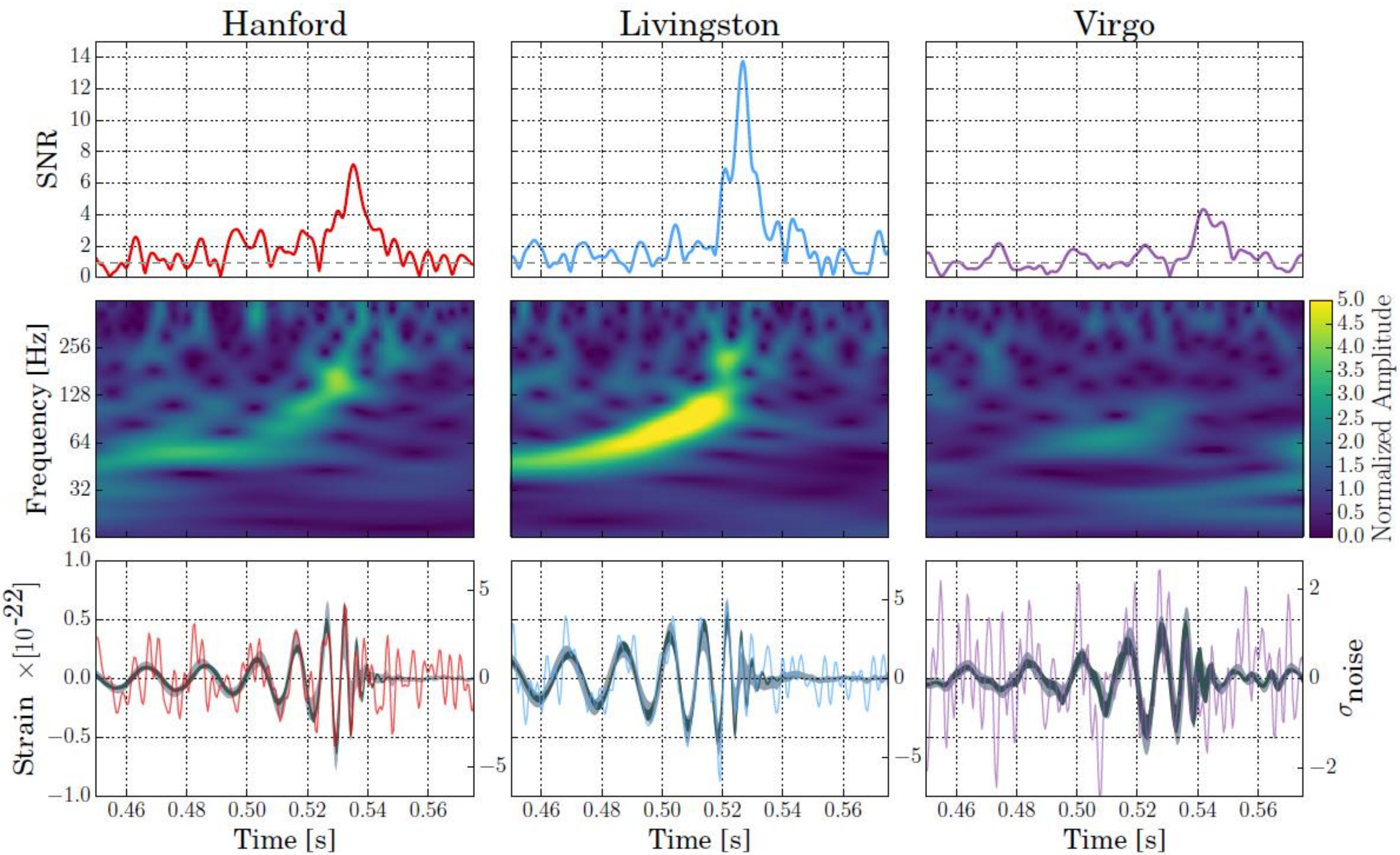




January 4, 2017
August 1, 2017
Advanced LIGO's Second Observing Run
Virgo turns on
Nov 2016
Dec 2016
Jan 2017
Feb 2017
Mar 2017
Apr 2017
May 2017
Jun 2017
Jul 2017
Aug 2017
June 6, 2017

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

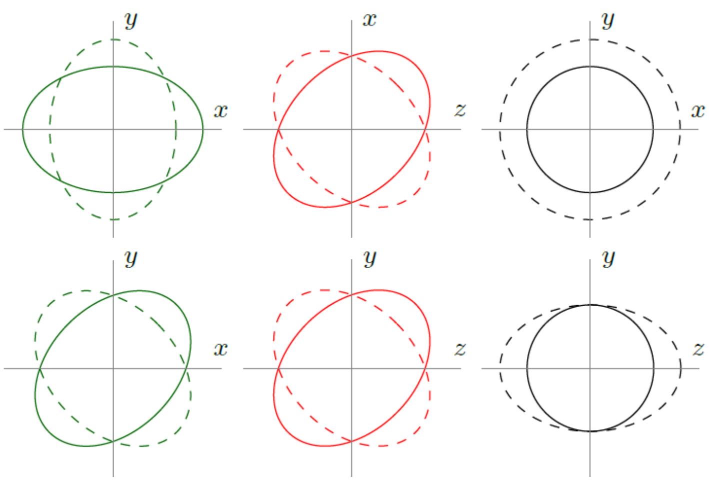


Polarization of gravitational waves

Polarization is a fundamental property of spacetime. It determined how spacetime can be deformed. General metric theories allow six polarizations. General Relativity allows two (tensor) polarizations

GR only allows (T) polarizations

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



Theory	+	x	x	y	b	l
General Relativity	allowed	allowed	forbidden	forbidden	forbidden	forbidden
GR in noncompactified 4/6D Minkowski	allowed	allowed	allowed	allowed	allowed	allowed
Einstein-Æther	allowed	allowed	allowed	allowed	allowed	allowed
5D Kaluza-Klein	allowed	allowed	allowed	allowed	allowed	forbidden
Randall-Sundrum braneworld	allowed	allowed	forbidden	forbidden	forbidden	forbidden
Dvali-Gabadadze-Porrati braneworld	allowed	allowed	depends	depends	depends	depends
Brans-Dicke	allowed	allowed	forbidden	forbidden	allowed	allowed
f(R) gravity	allowed	allowed	forbidden	forbidden	allowed	allowed
Bimetric theory	allowed	allowed	allowed	allowed	allowed	allowed
Four-Vector Gravity	forbidden	forbidden	allowed	allowed	forbidden	forbidden

Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther].

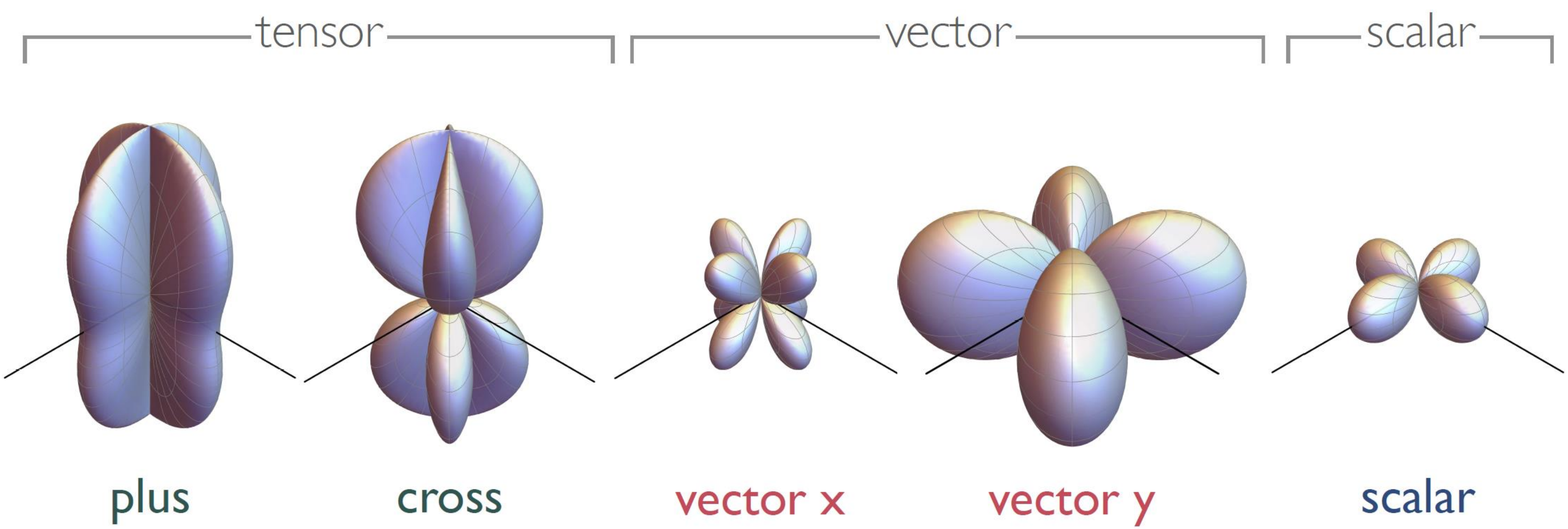
allowed / depends / forbidden

First test of polarizations of gravitational waves

According to Einstein's General Relativity there exist only two polarizations. General metric theories of gravity allow six polarizations. GW170814 confirms Einstein's prediction

Angular dependence (antenna-pattern) differs for T, V, S

LIGO and Virgo have different antenna-patterns
This allows for a fundamental of the polarizations of spacetime



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Angular dependence (antenna-pattern) differs for T, V, S

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This allows for a fundamental of the polarizations of spacetime

Our analysis favors tensor polarizations in support of General Relativity

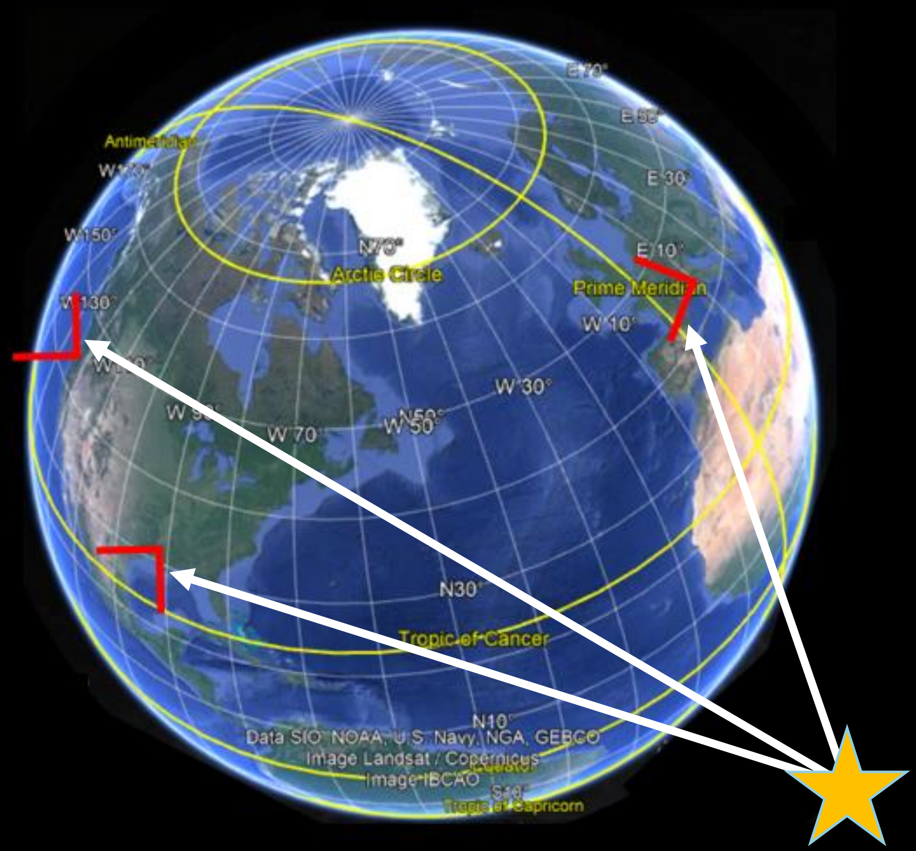
Our data favor tensor structure over vector by about a (Bayes) factor 200

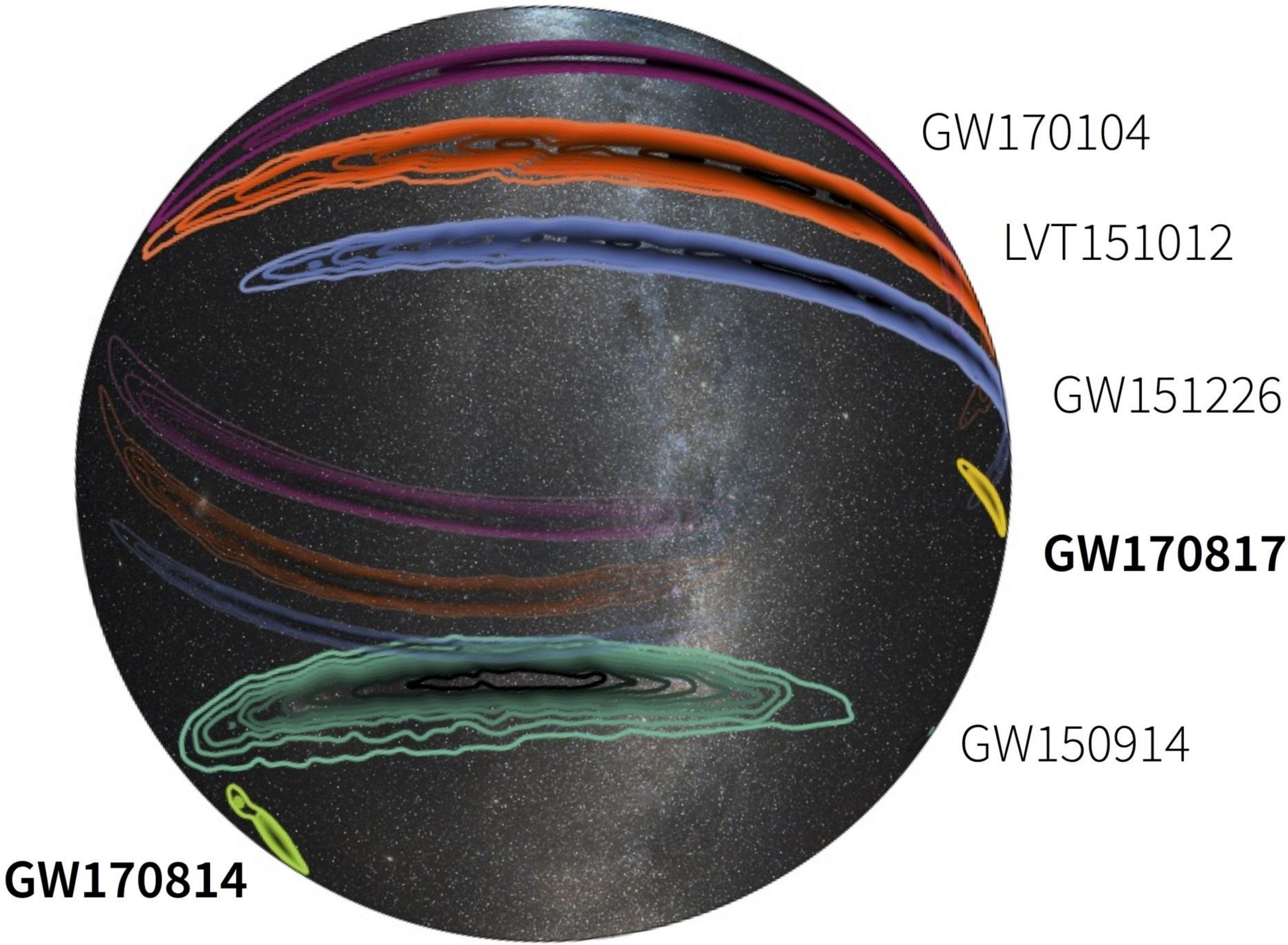
And tensor over scalar by about a factor 1000

This is a first test, and for BBH we do not know the source position very well

Virgo allowed source location via triangulation

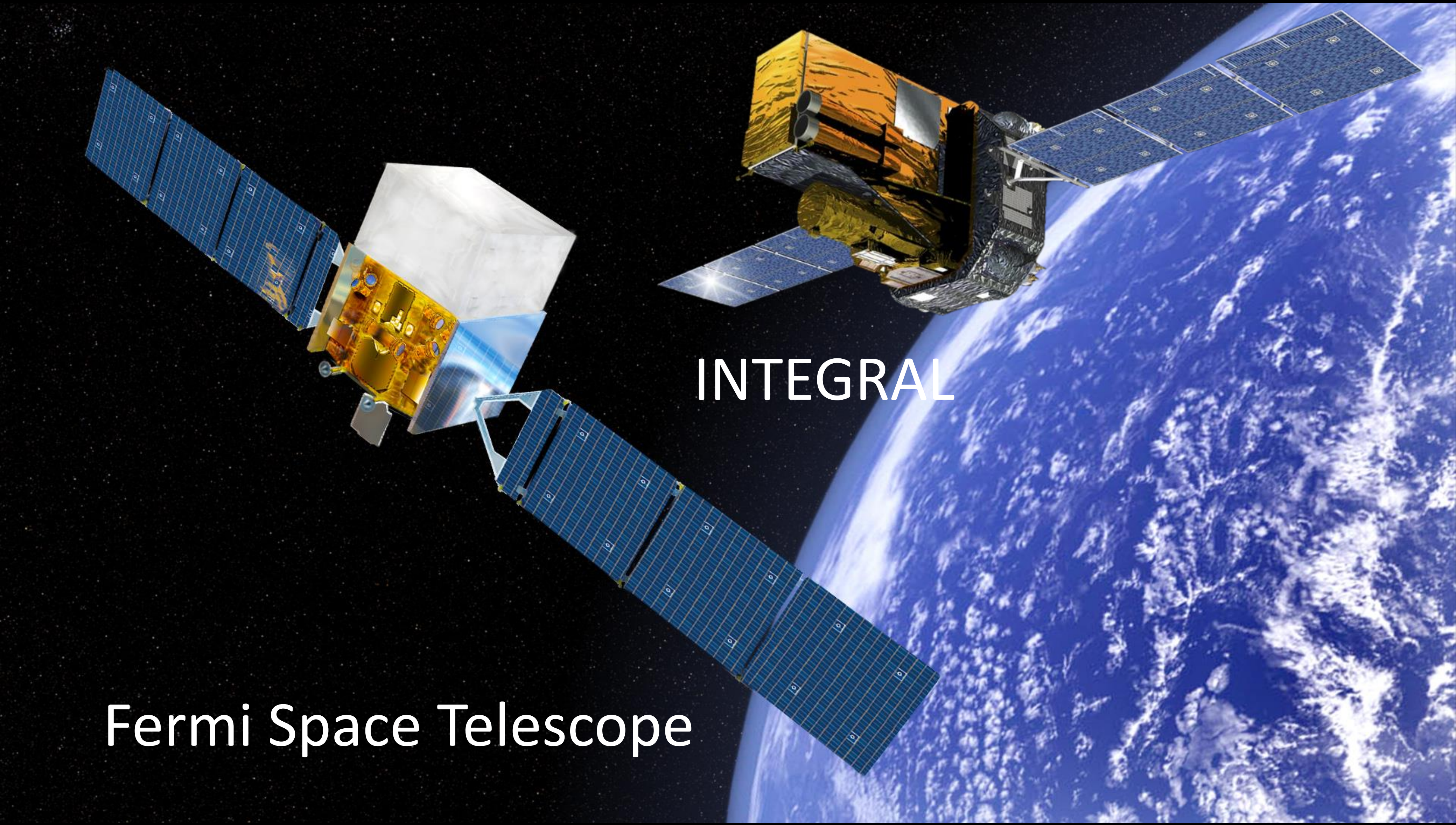
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it




GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814

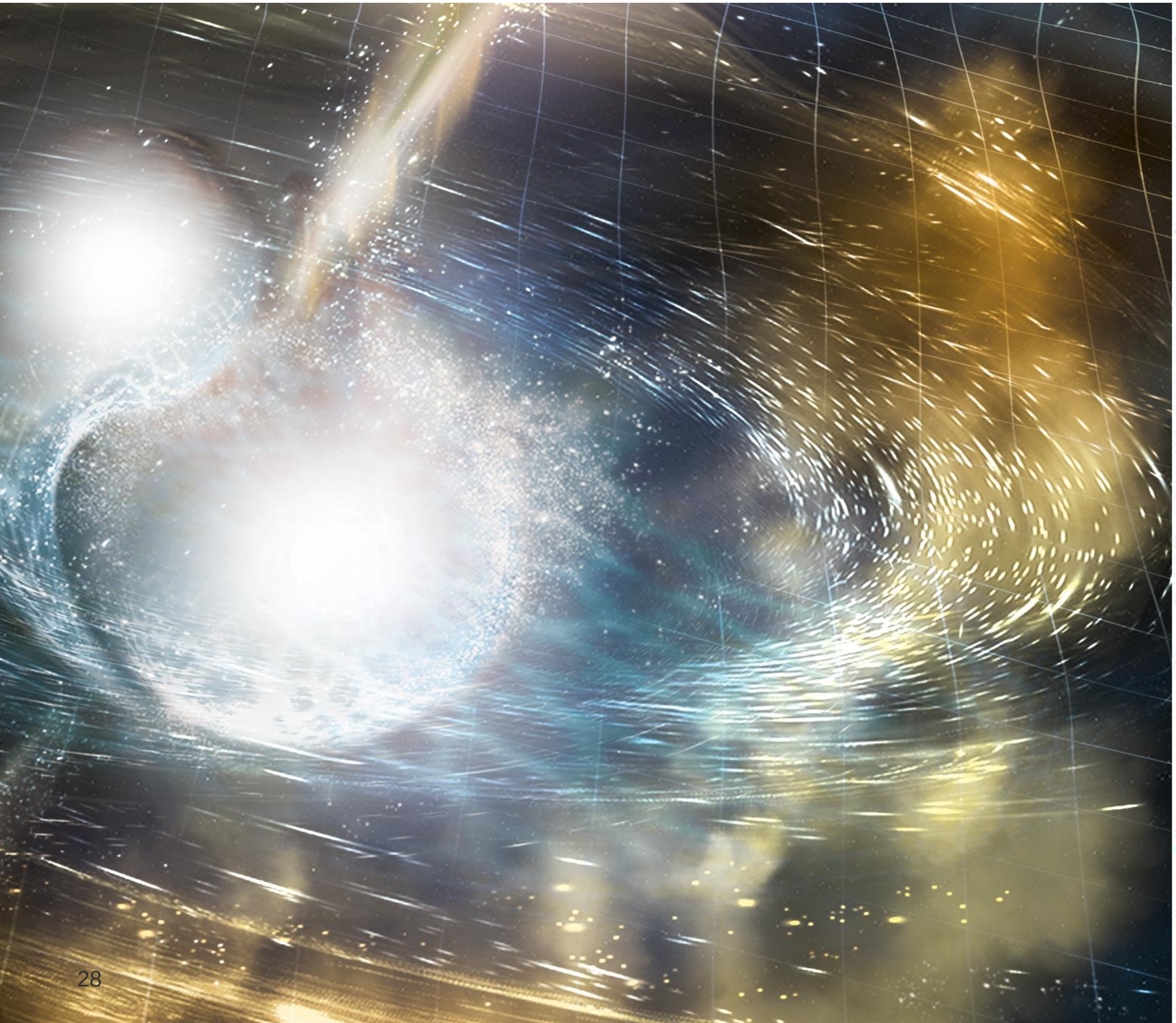
Multi-messenger astronomy

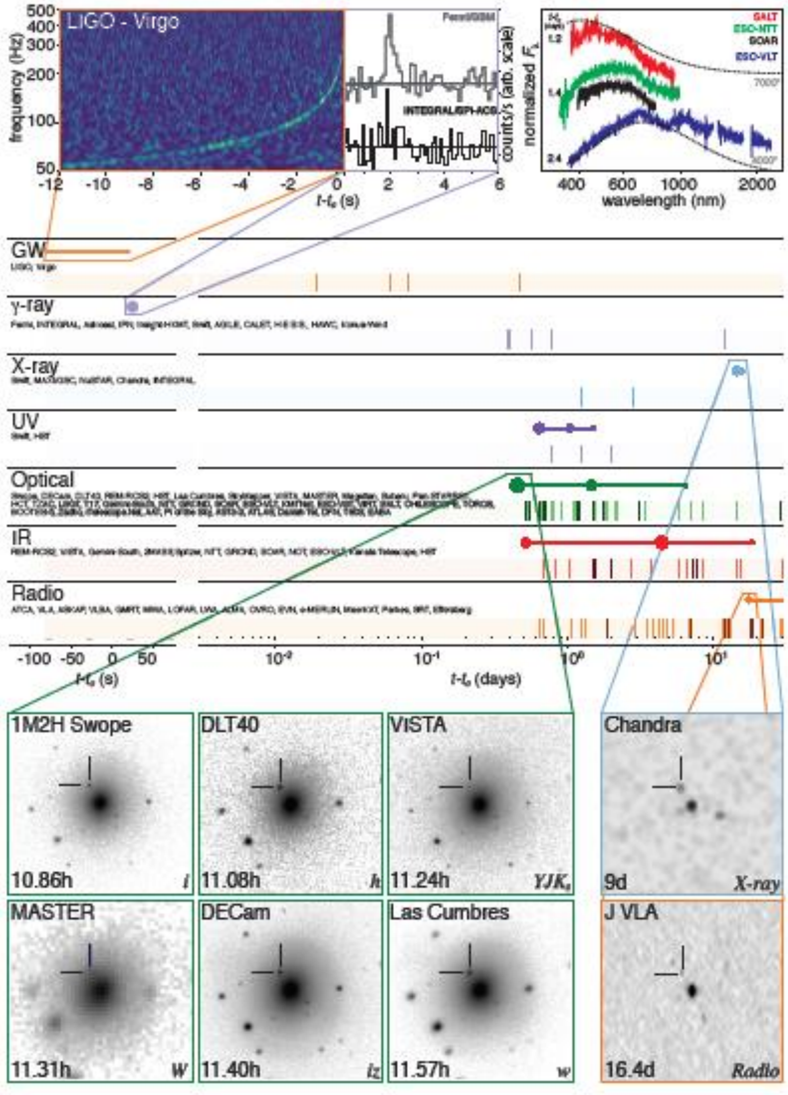
Gamma rays reached Earth 1.7 seconds after GW event



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





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 (assuming conservative lower bound on distance from GW signal of 26 Mpc)

$$-3\times 10^{-15} < \frac{\Delta v}{v_{EM}} < +7\times 10^{-16}$$

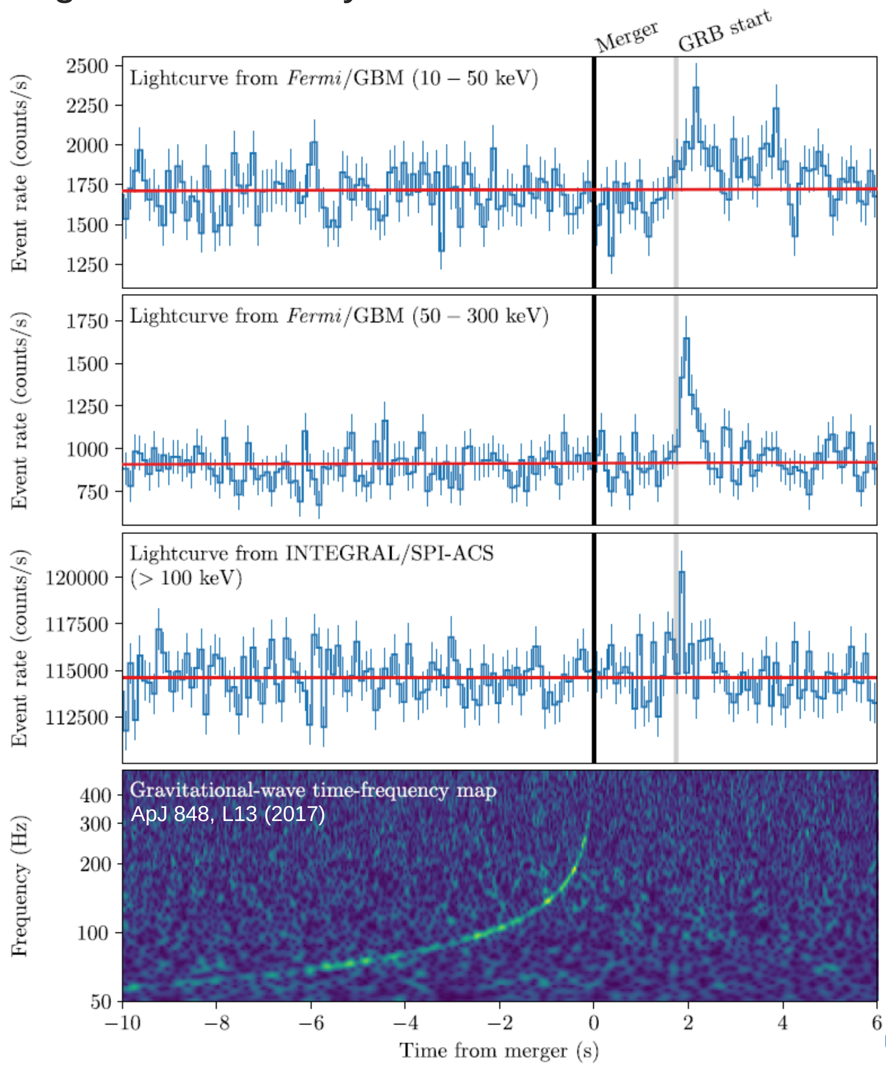
Test of Equivalence Principle

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

$$\Delta t_{\text{gravity}} = -\frac{\Delta\gamma}{c^3}\int_{r_0}^{r_e} U(r(t);t)\,dr$$

Milky Way potential gives same effect to within
$-2.6\times 10^{-7} \le \gamma_{\text{GW}} - \gamma_{\text{EM}} \le 1.2\times 10^{-6}$

Including data on peculiar velocities to 50 Mpc we find
$\Delta\gamma \le 4\times 10^{-9}$



Dark Energy and Dark Matter after GW170817

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

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

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^\mu\phi^\nu$ [51], $f(\phi)\cdot$Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

GW170817 falsifies Dark Matter Emulators

No-dark-matter modified gravity theories like TeVeS and relativistic bi-metric extensions of Milgrom's MOND 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)

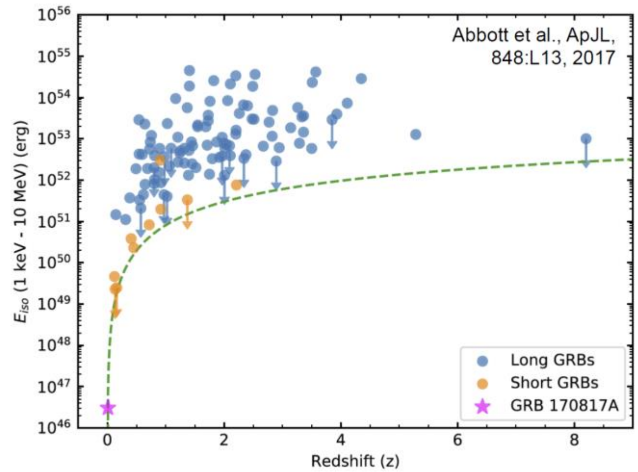
Looking into the heart of a dim nearby sGRB

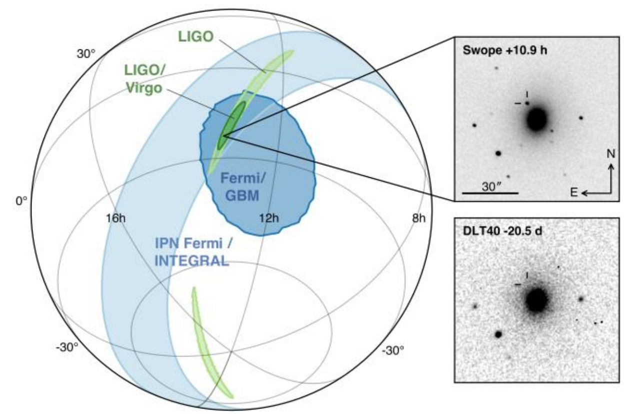
Gravitational waves identified the progenitor of the sGRB and provided both space localization and distance of the source. This triggered the EM follow-up by astronomers for the kilonova

Closest by and weakest sGRB, highest SNR GW event

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

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

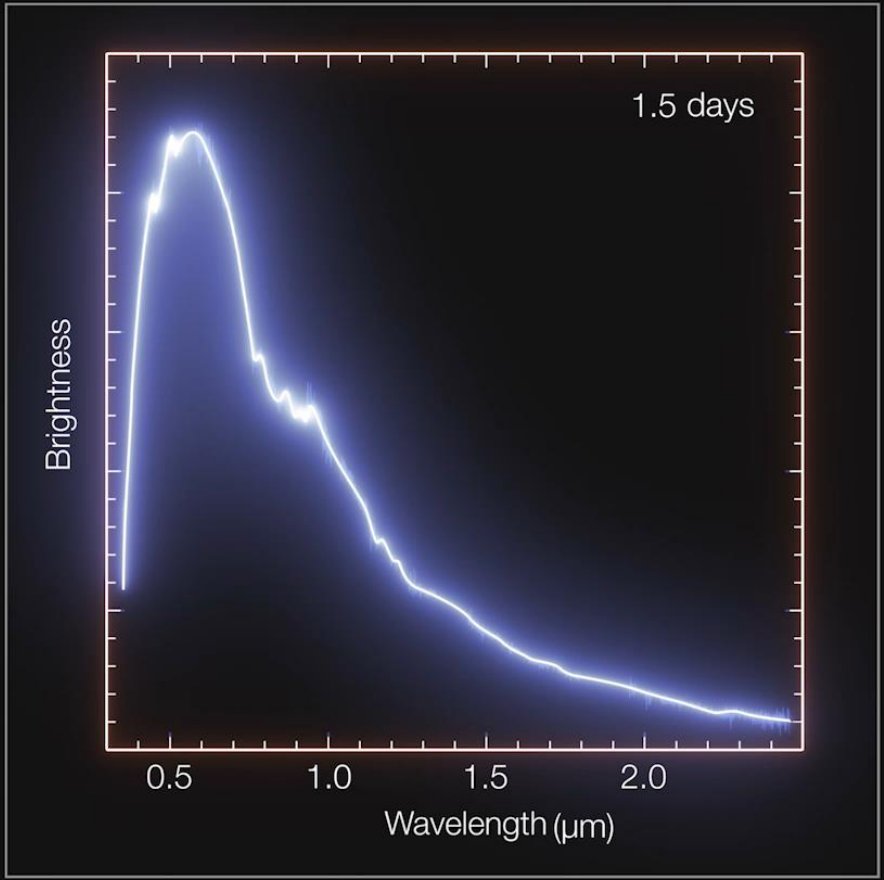




European Southern Observatory

About 70 observatories worldwide observed the event by using space telescope (e.g. Hubble and Chandra) and ground-based telescopes (e.g. ESO) in all frequency bands (UVOIR). We witness the creation of heavy elements by studying their spectral evolution

Since LIGO/Virgo provide the distance and BNS source type, it was recognized that we are dealing with a weak (non-standard) GRB. This led to the optical counterpart to be found in this region



Kilonova description for GW170817

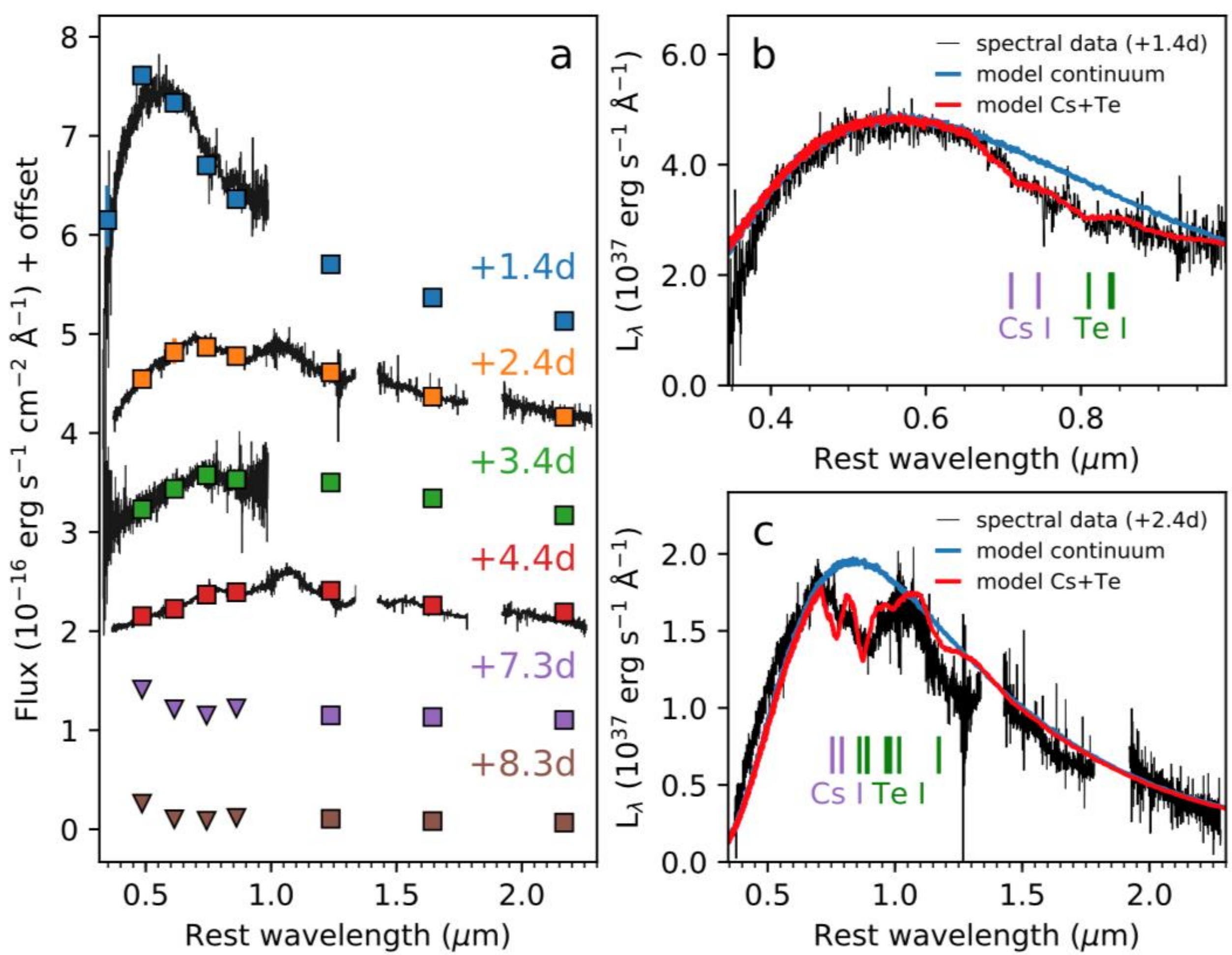
ePESSTO and VLT xshooter spectra with TARDIS radiative transfer models
See Smartt S.J. *et al.*, Nature, 551, 75-79, 2017 for more details

The kilonova essentially has a black-body spectrum (6000 K; blue curve in panel C)

Data shows evidence for absorption lines (see model with tellurium and cesium with atomic numbers 52 and 55)

Formation of Cs and Te is difficult to explain in supernova explosions

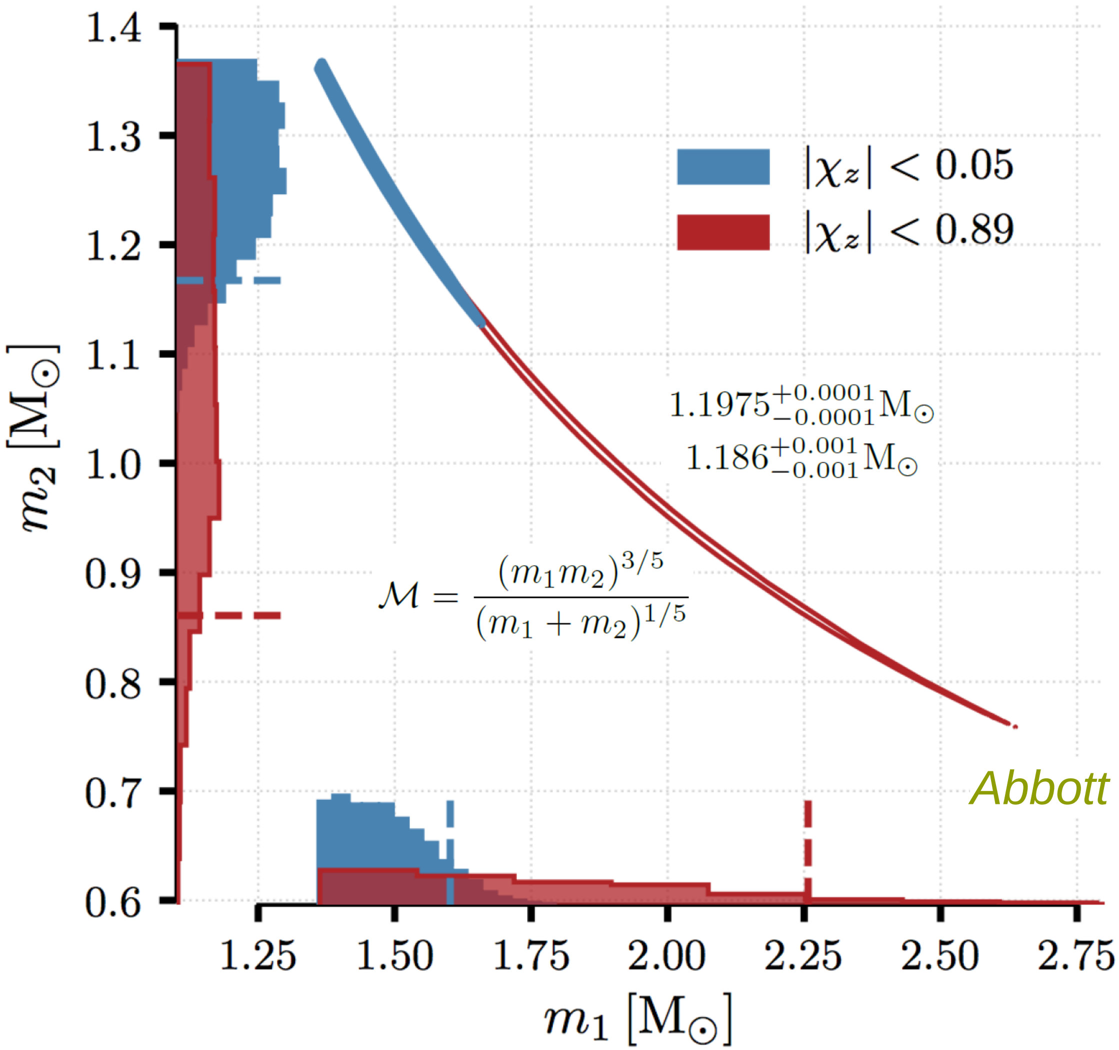
The lines are Doppler broadened due to the high speed of the ejected material (about 60,000 km/s)



GW170817 source properties: BNS chirp mass

Chirp mass can be inferred to high precision. There is a degeneracy between masses and spins

Observation of **binary pulsars** in our galaxy indicates spins are **not larger than ~0.04**



To lowest approximation $\tilde{h}(f) \propto e^{i\Psi(f)}$

with $\Psi(f) = \frac{3}{4}\left(\frac{G\mathcal{M}}{c^3}8\pi f\right)^{-5/3} + \ldots$

Abbott et al. PRL 119 (2017) 161101

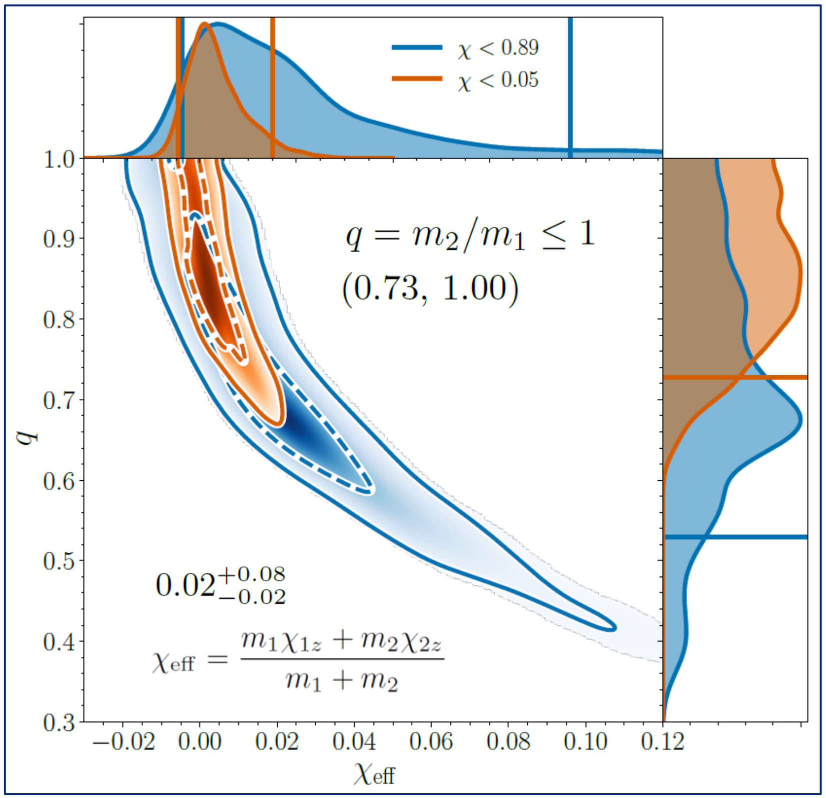
GW170817 inferred properties: spins

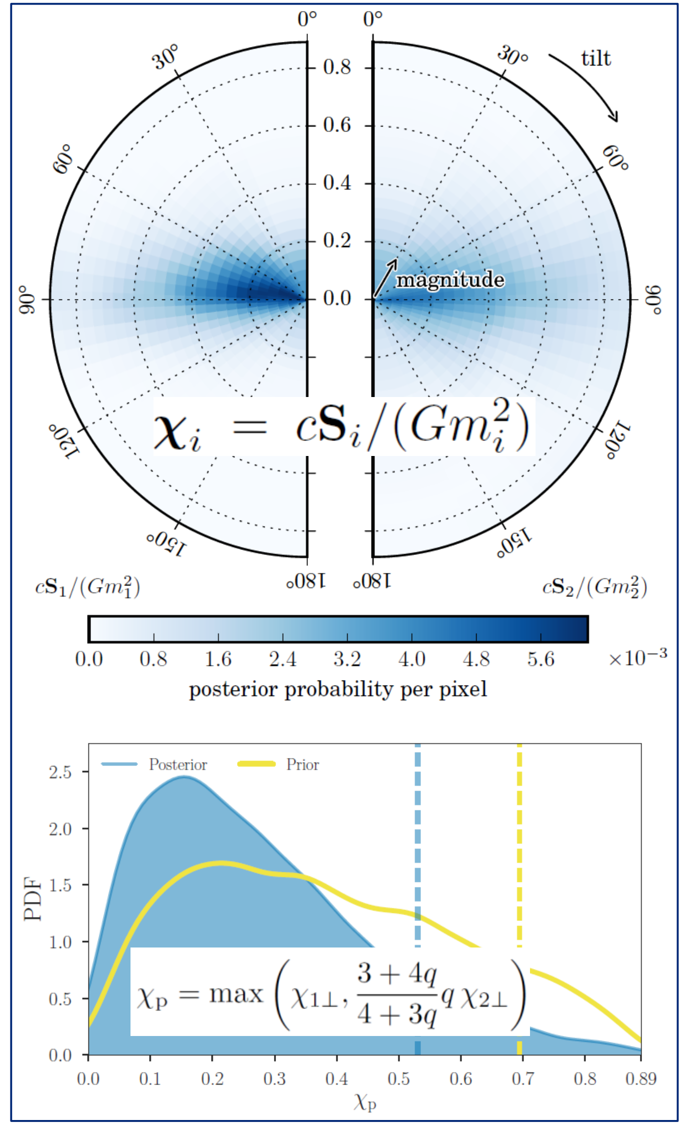
Constrains on mass ratio q, χ_{i} dimensionless spin, χ_{eff} effective spin, and χ_{p} effective spin precession parameter. See https://arxiv.org/abs/1805.11579

No evidence for NS spin

χ_{eff} contributes to GW phase at 1.5 PN, and degenerate with q

χ_{p} starts contributing at 2 PN





GW170817 properties: inclination angle

Including EM-information allows to constrain the inclination angle of the binary system

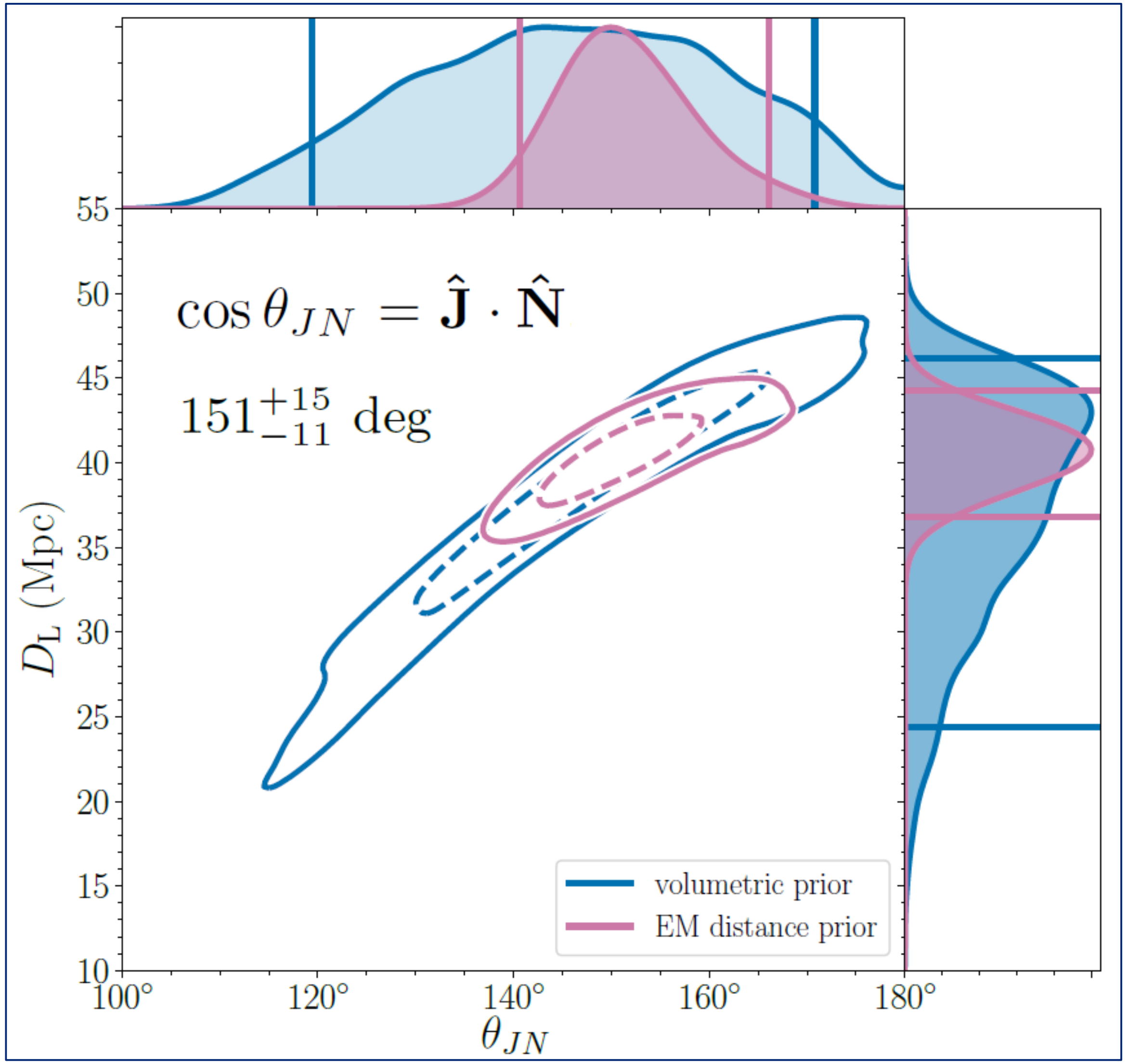
GW amplitude and polarization are dependent on binary inclination angle

Use distance prior from EM follow-up observations

Use volumetric prior from GW measurements

Line of sight vector $\hat{\boldsymbol{N}}$

Binary angular momentum vector $\hat{\boldsymbol{J}}$

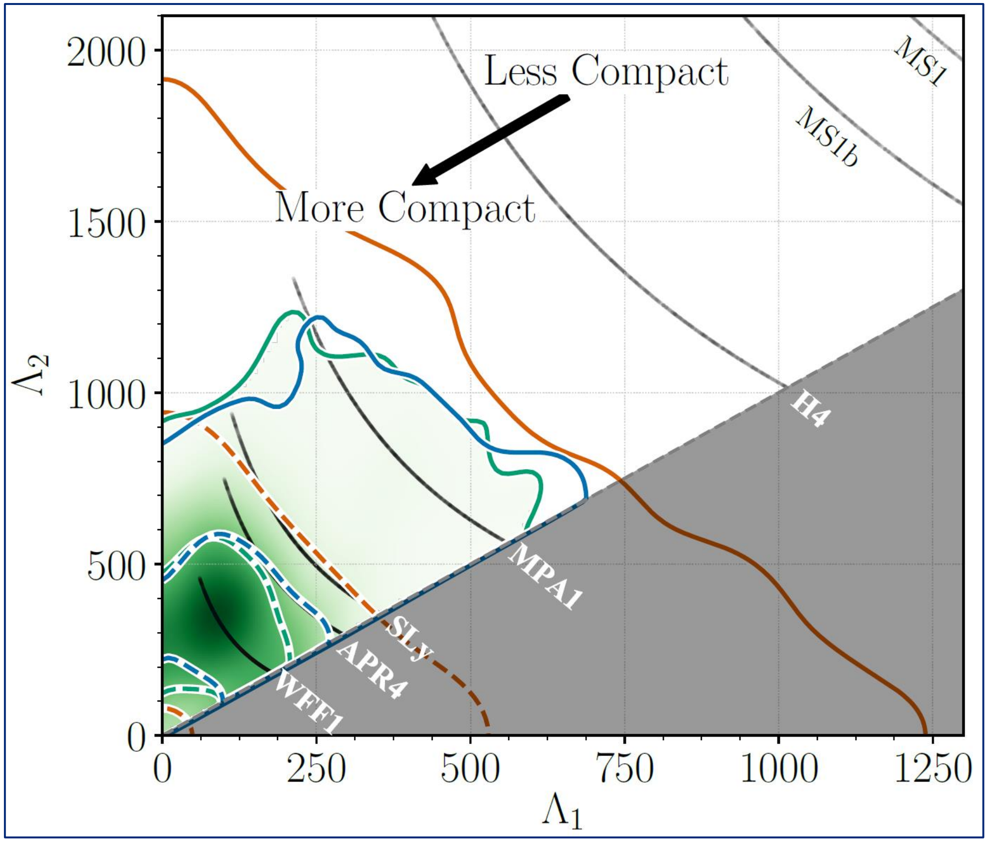


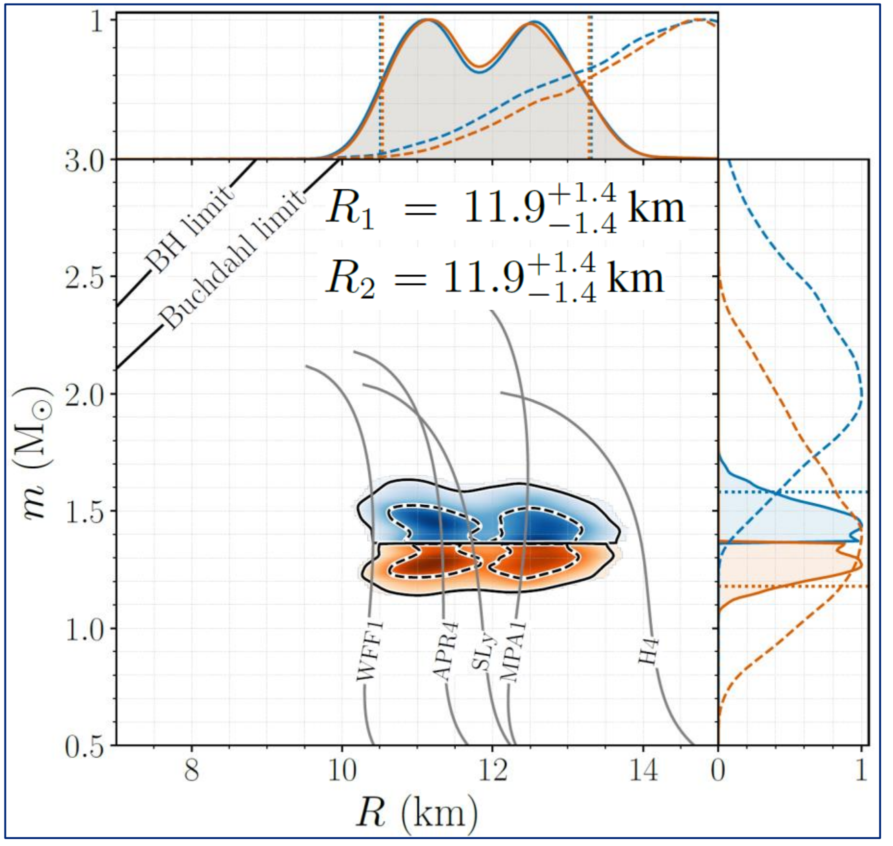
GW170817 properties: tidal deformability, EOS, radii

Tidal deformability gives support for “soft” EOS, leading to more compact NS. Various models can now be excluded. We can place the additional constraint that the EOS must support a NS $1.97\,\mathrm{M}_\odot$

Leading tidal contribution to GW phase appears at 5 PN: $\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1 + (m_2+12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$

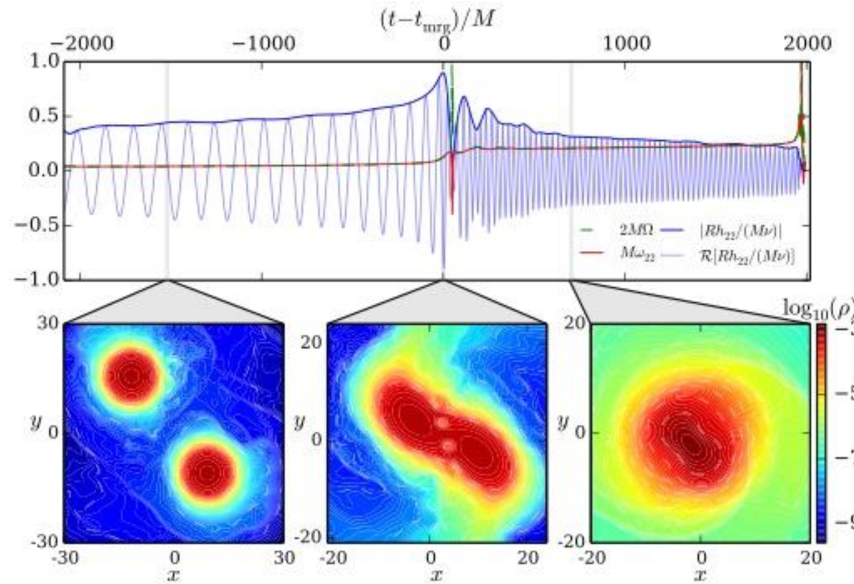
Employ common EOS for both NS (green shading), EOS insensitive relations (green), parametrized EOS (blue), independent EOSs (orange). See: LVC, https://arxiv.org/abs/1805.11581





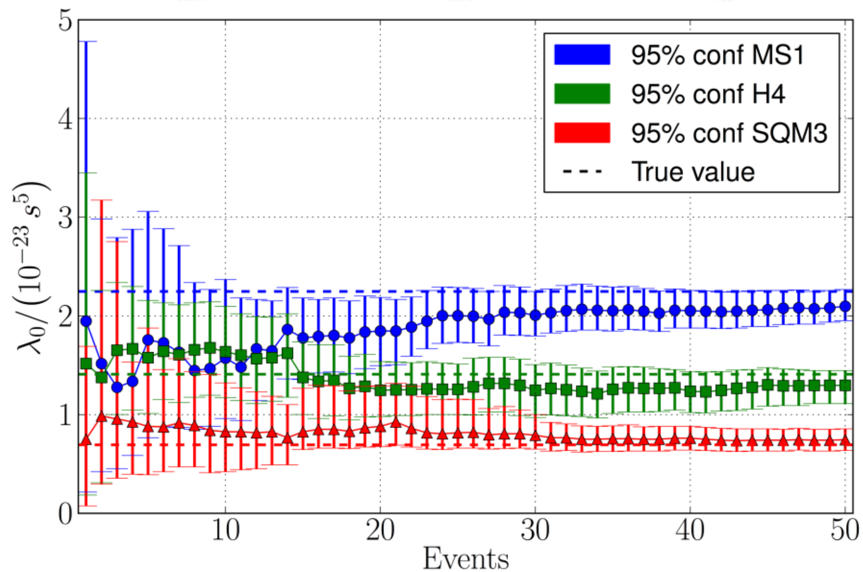
Probing the structure of neutron stars

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

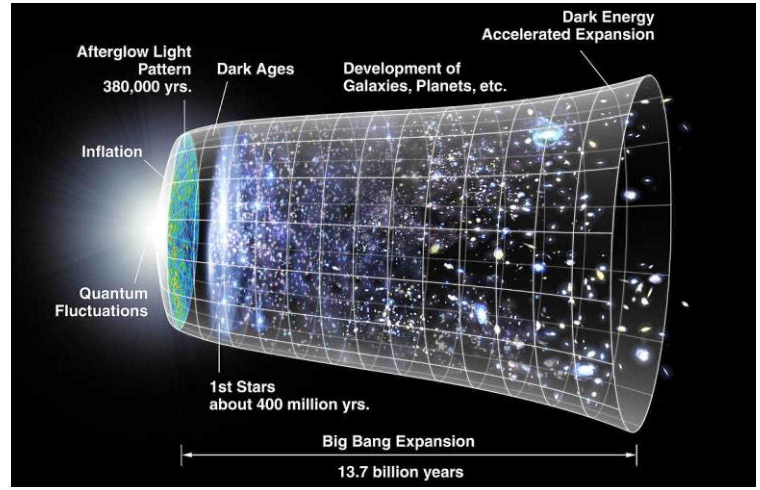
- More compact neutron stars favored
- “Soft” equation of state
- See LVC, https://arxiv.org/abs/1805.11581
- LVC, PRL 119, 161101 (2017)

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

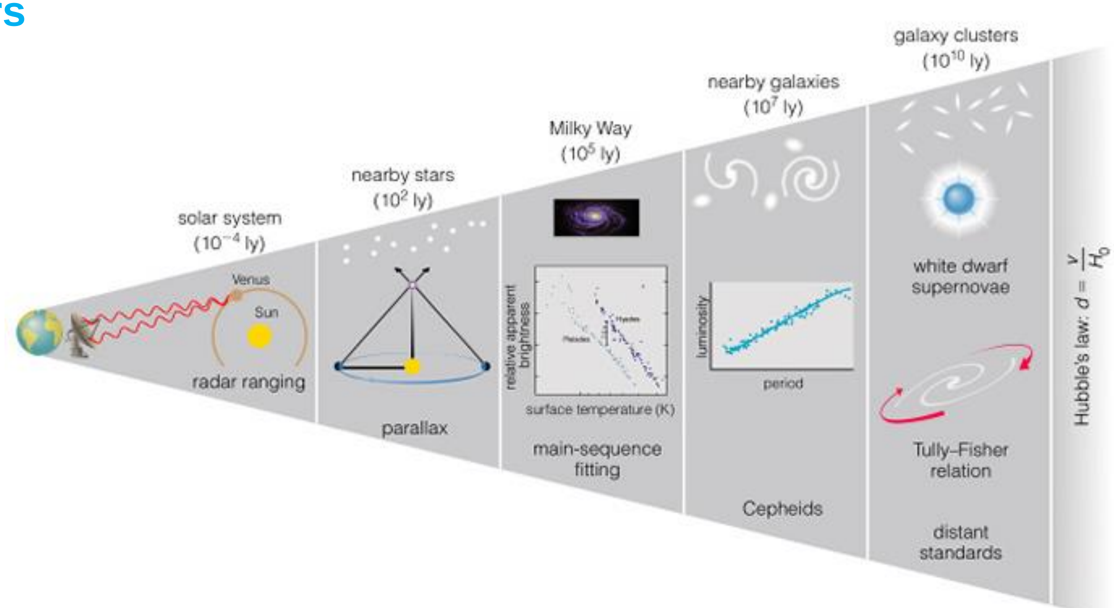
Current measurements depend on cosmic distance ladder

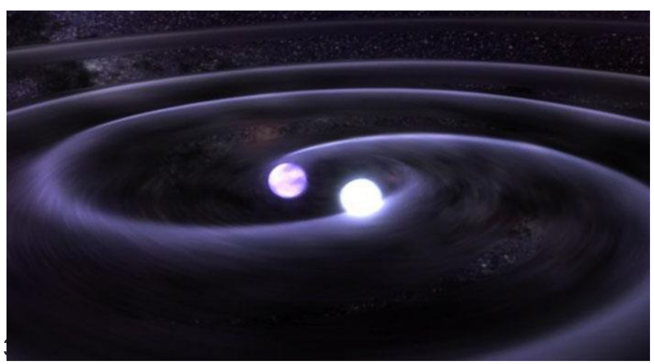
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder



Gravitational waves from binary mergers

Distance can be measured directly from the gravitational wave signal!





A new cosmic distance marker

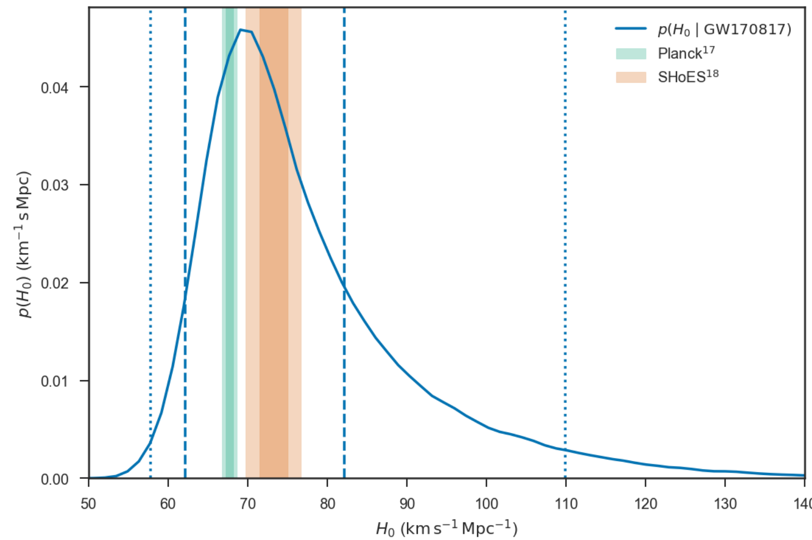
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1-2% accuracy

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)

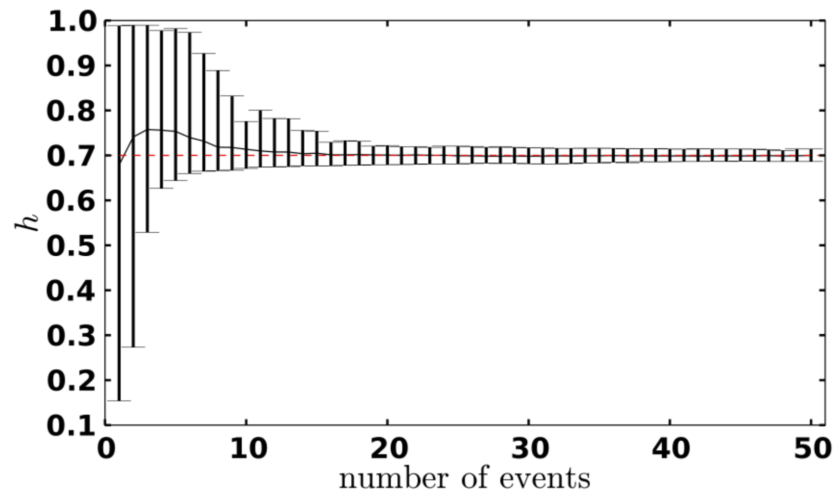


GW170817

- One detection: limited accuracy
- Few tens of detections with LIGO/Virgo will be needed to obtain O(1-2%) accuracy

Bernard Schutz, Nature 323, 310–311 (1986)

Walter 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)