Gravitational waves: status of ground-based observatories

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LIGO Scientific Collaboration

KAGRA

Advanced Virgo

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, VRO), particle (LHC), Dark Matter searches (Xenon1T), …

Gravitational waves

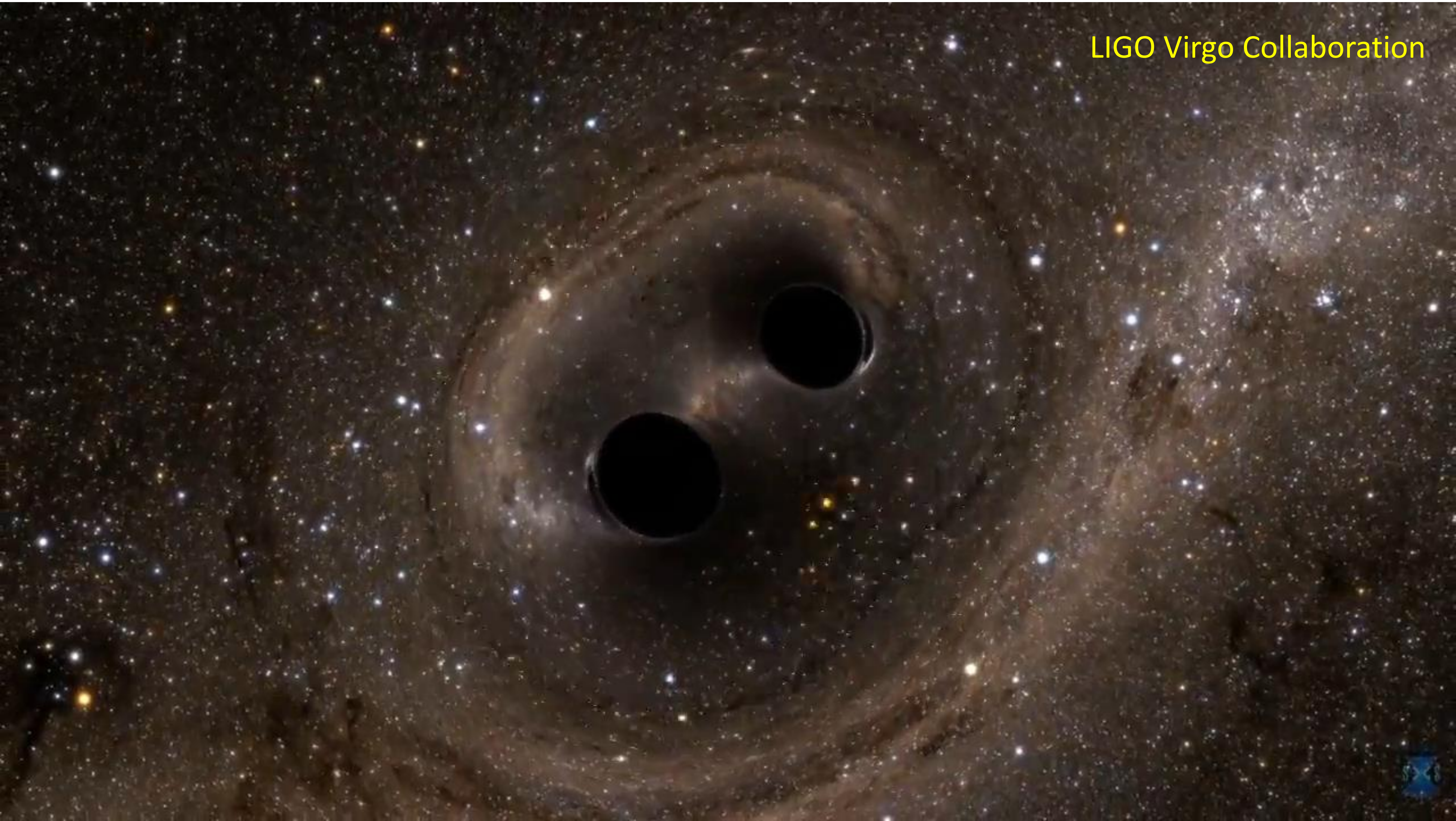
- Dynamical part of gravitation, all space is filled with GW
- Ideal information carrier, almost no scattering or attenuation
- The entire universe has been transparent for GWs, all the way back to the Big Bang

Gravitational wave science can impact

- Fundamental physics: black holes, spacetime, horizons, matter under extreme conditions
- Cosmology: Hubble parameter, Dark Matter, Dark Energy

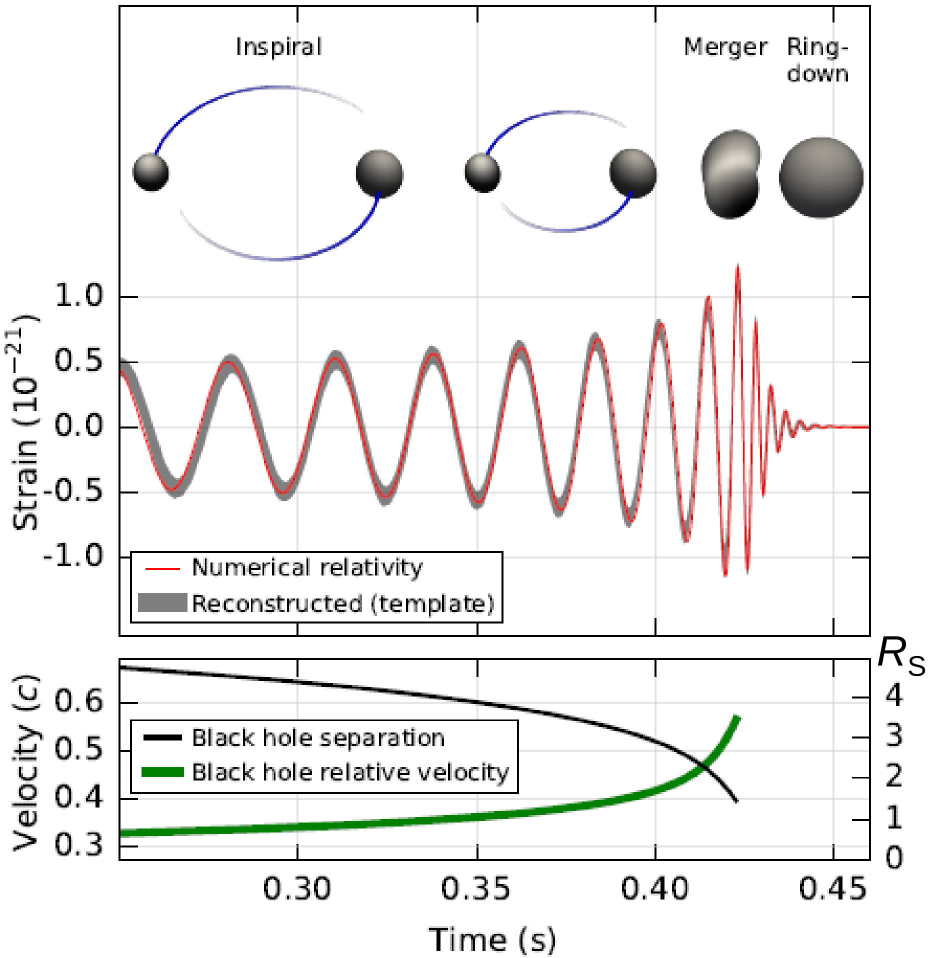
Event GW150914

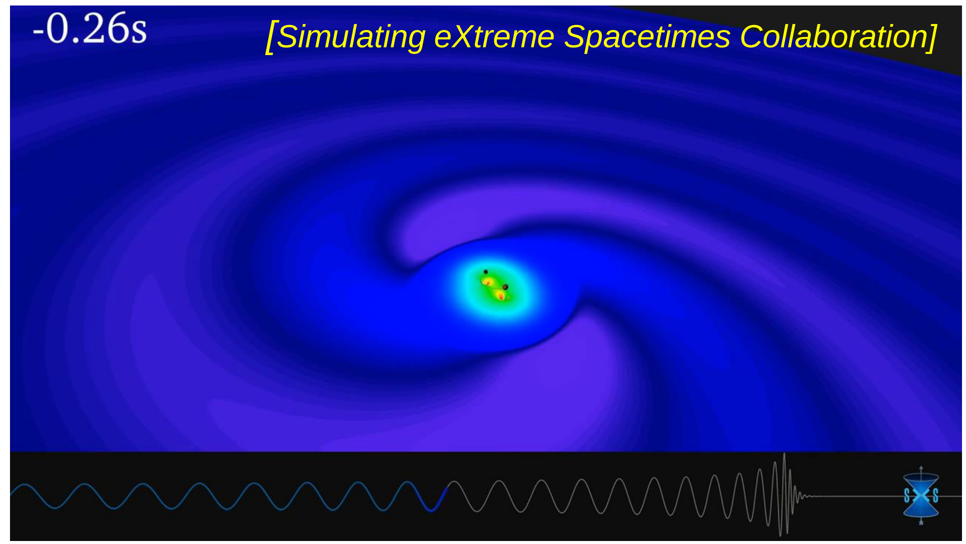
On September 14, 2015 we detected with the LIGO detectors for the first time gravitational waves (vibrations in the fabric of space and time) from the collision of two black holes



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)

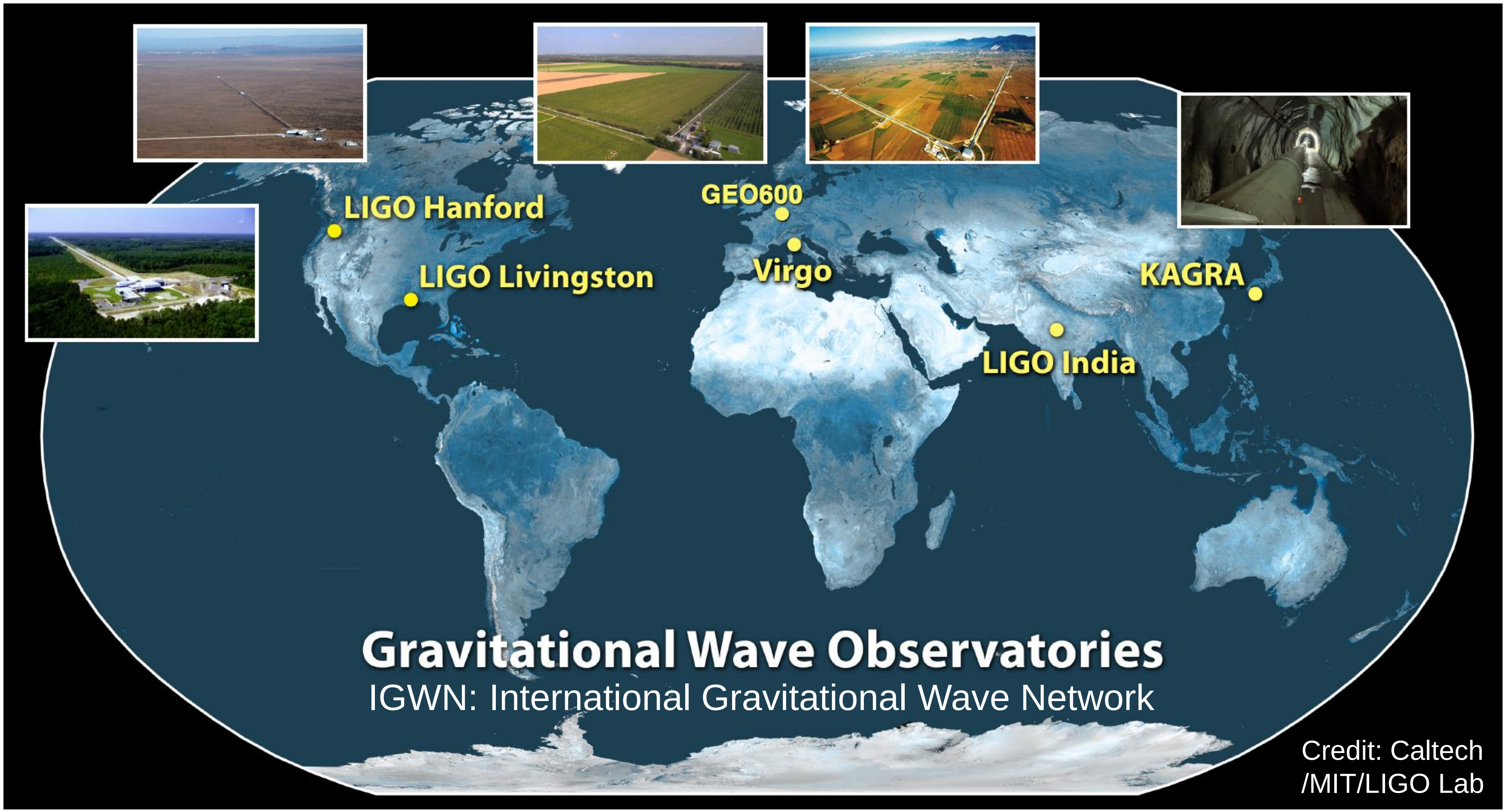
$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$

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

LVK: LIGO Scientific, Virgo and KAGRA Collaborations

Observe together as a network of GW detectors. LVK 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 already for more than a decade
KAGRA in Japan joined in February 2020



Virgo Collaboration

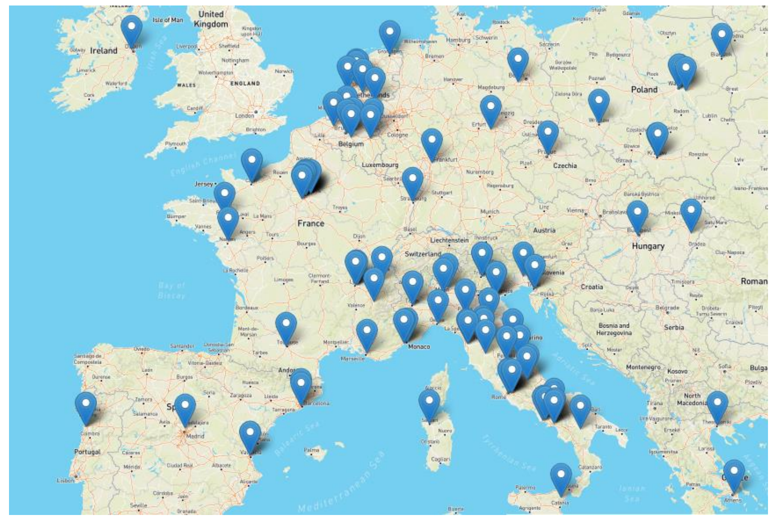
Virgo is a European collaboration with 691 members, 447 authors from 127 institutions in 15 different countries. Virgo has more that doubled its size in the last few years

Virgo is a 2nd generation GW detector in Europe

- EGO Council composed of France, Italy and the Netherlands
- Participation by scientists from Belgium, China, Czechia, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Monaco, Poland, Portugal, Spain, The Netherlands

Gravitational wave science: steep learning curve

- Join gravitational wave science
- Learn about instrumentation and data analysis
- Path to third generation: Einstein Telescope
- Many members traditionally from CERN community



Virgo develops advanced and innovative technology

- Quantum technologies: frequency dependent squeezing
- Large test masses and advanced coatings
- Scattered light mitigation
- Low frequency risk reduction

13 European countries

LIGO – Virgo observation runs

LIGO and Virgo coordinate science data taking. In between the observation runs, the instruments are upgraded and commissioned to achieve better sensitivity

Observing run 1

- September 2015 to January 2016
- LIGO interferometers
- Most notable: first BBH GW150914
- Every few months

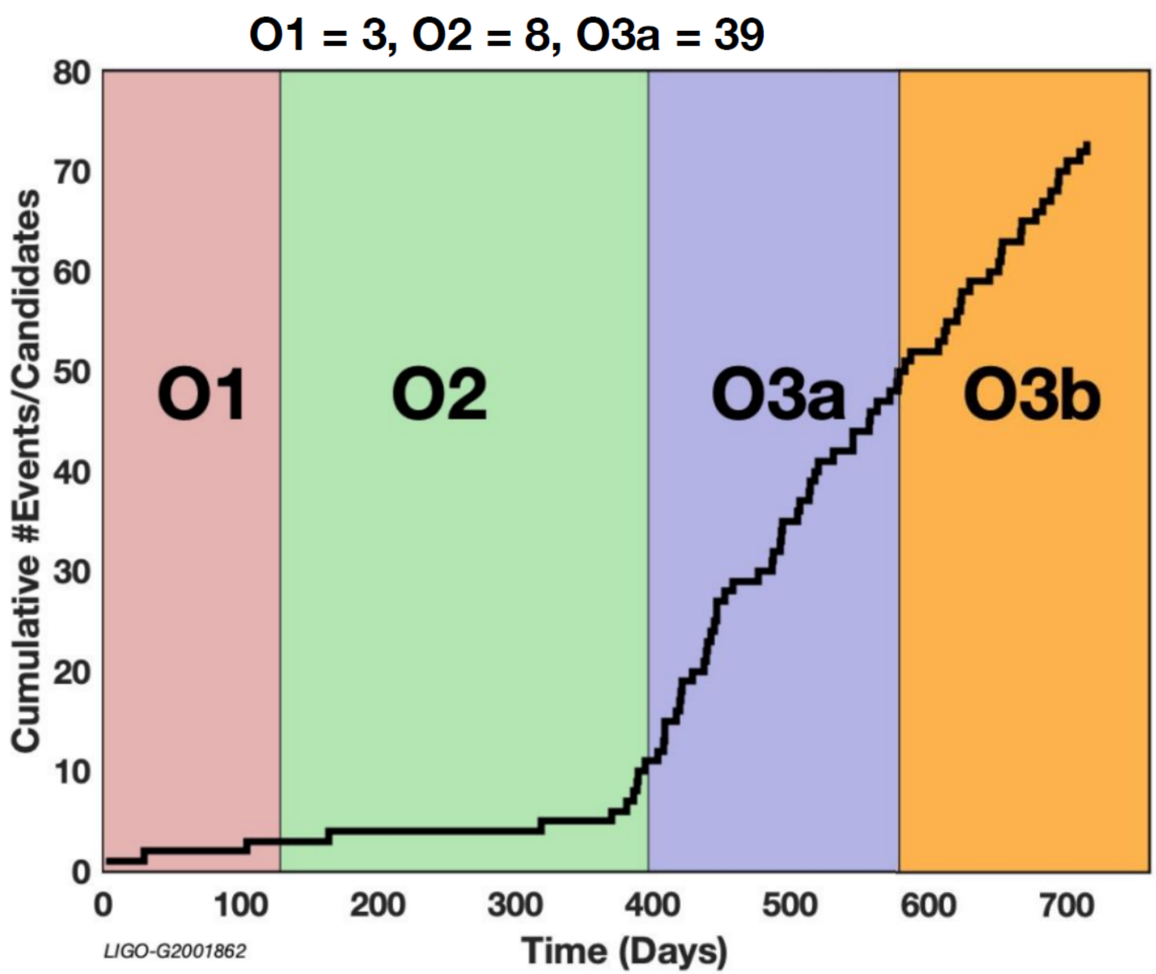
Observing run 2

- November 2016 to August 2017
- LIGO + Virgo (August 2017 only) ITFs
- Most notable: first BNS GW170817

Observing run 3

- April 2019 to March 2020
- LIGO + Virgo interferometers
- O1 - O3a: 50 significant detections

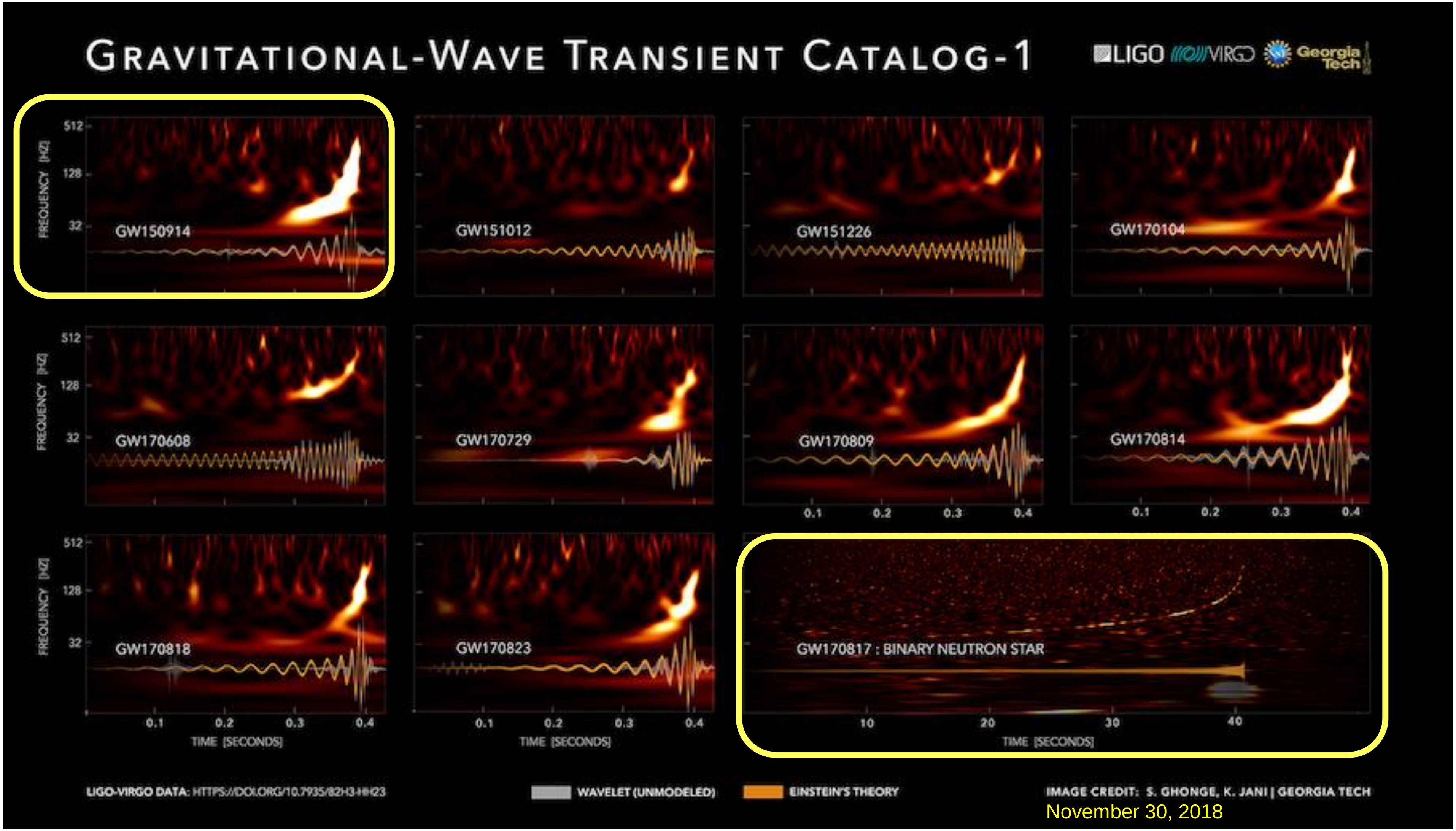
  Abbott et al. Phys. Rev. X 11, 021053 (2021)
- Weekly detections



Some scientific highlights from O1 and O2

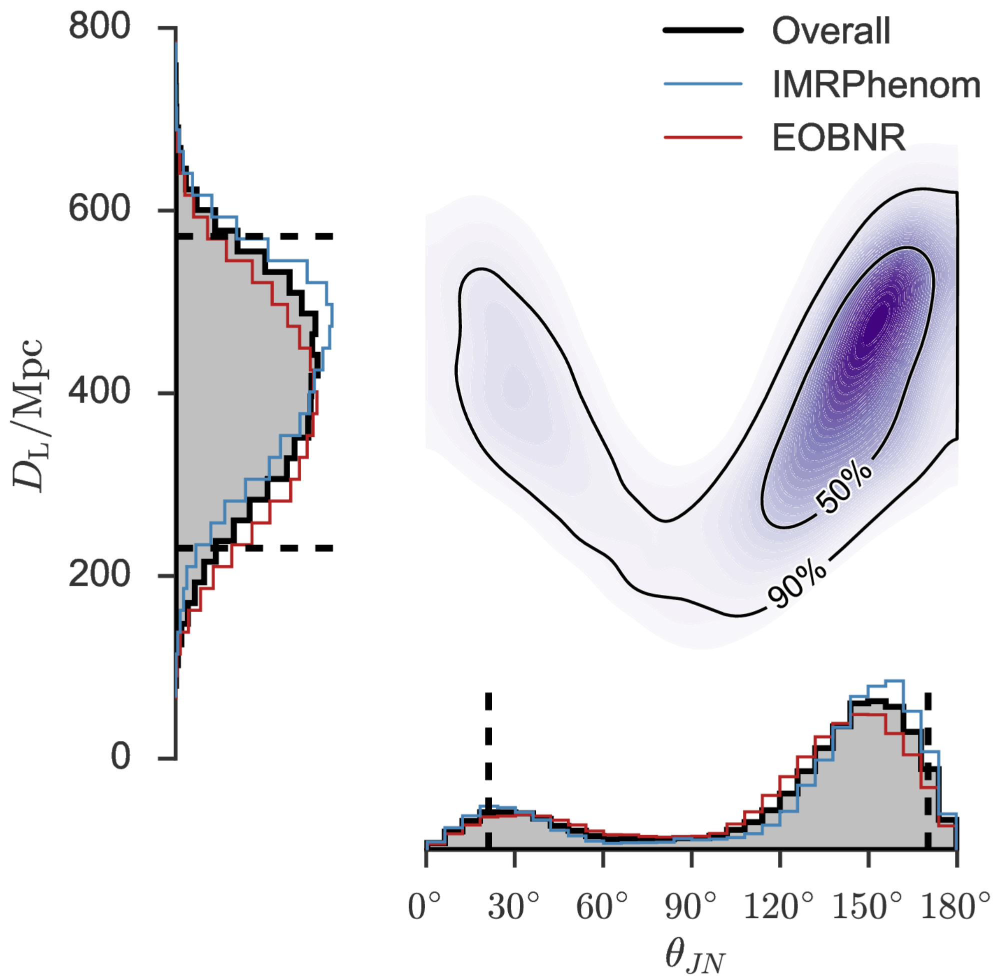
Scientific achievements: properties of binary systems

"GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs", LIGO Virgo Collaboration, [arXiv:1811.12907](https://arxiv.org/abs/1811.12907)



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

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

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

To measure the polarization components, we need a third detector, i.e. Virgo, oriented at about 45 degrees with respect to LIGO

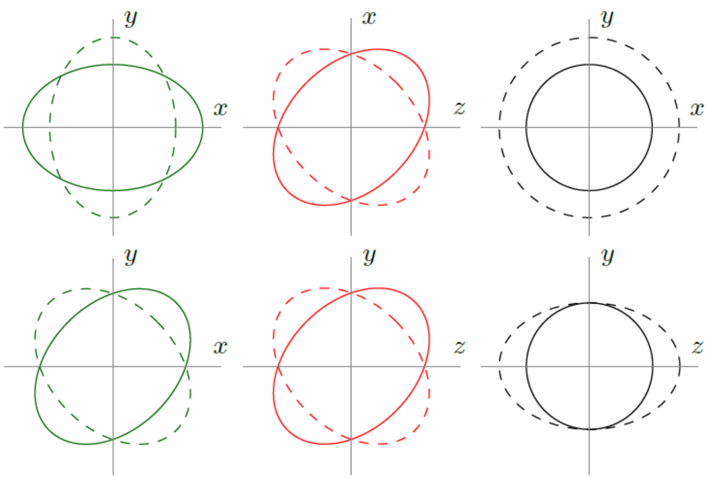
See "*Properties of the Binary Black Hole Merger GW150914*" http://arxiv.org/abs/1602.03840

Fundamental physics: 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

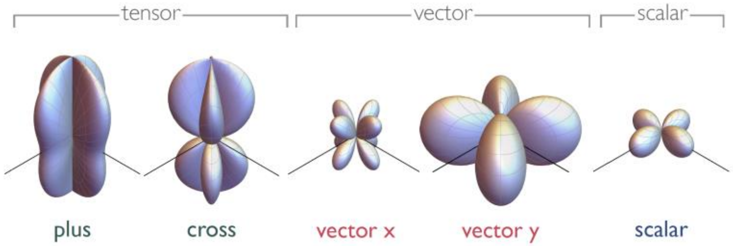
Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther].   allowed / depends / forbidden

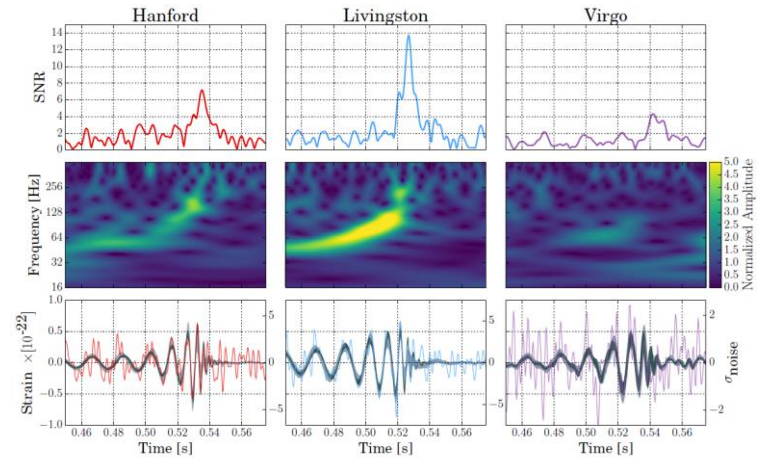
GW170814: first test of polarizations of GW

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 fundamental test 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

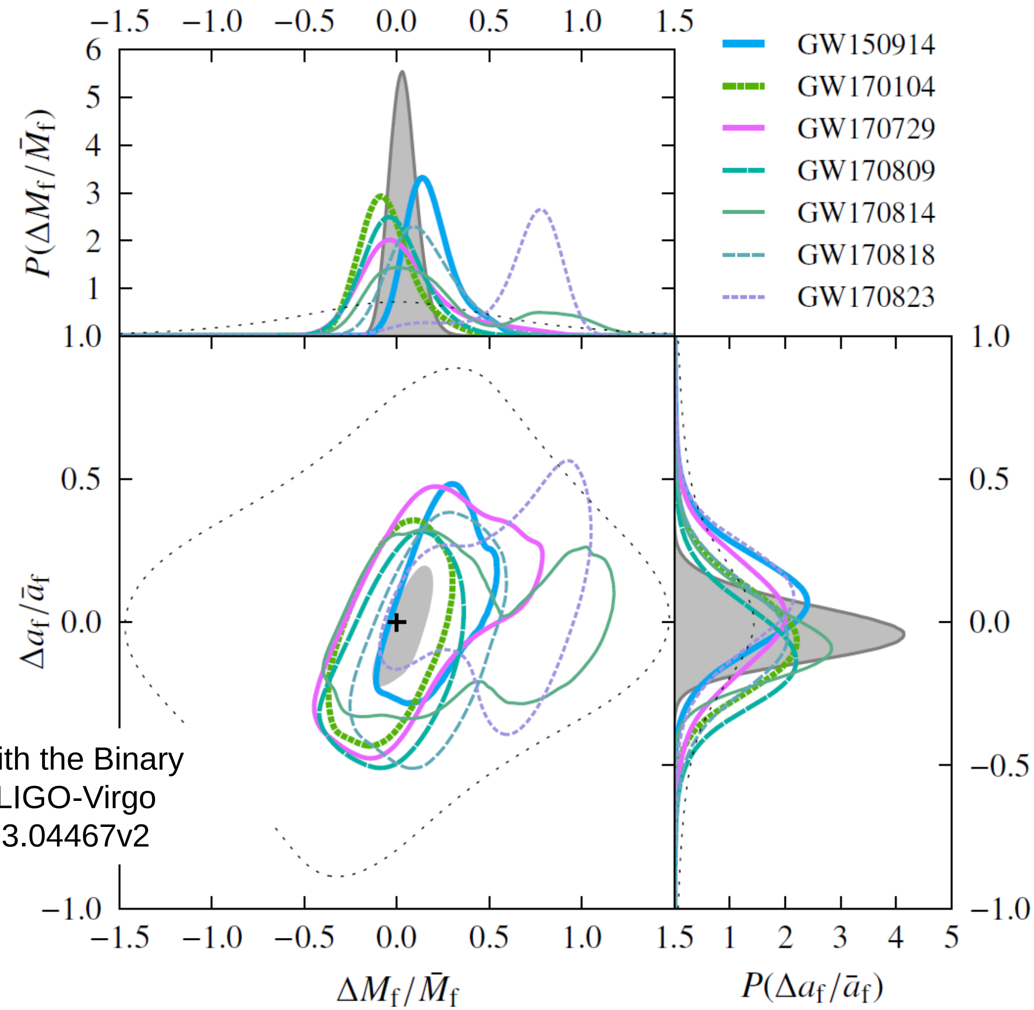
Inspiral-merger-ringdown consistency test for BBH

The 90% credible regions of the posterior distributions of $(M_f/\bar{M}_f, \Delta a_f/\bar{a}_f)$ are in agreement with the expected value for GR (marked with a cross)

Side panels show the marginalized posteriors for $\Delta M_f/\bar{M}_f$ and $\Delta a_f/\bar{a}_f$

Thin black dashed curve represents the prior distribution

Grey shaded areas correspond to the combined posteriors from the five most significant events



Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1, arXiv: 1903.04467v2

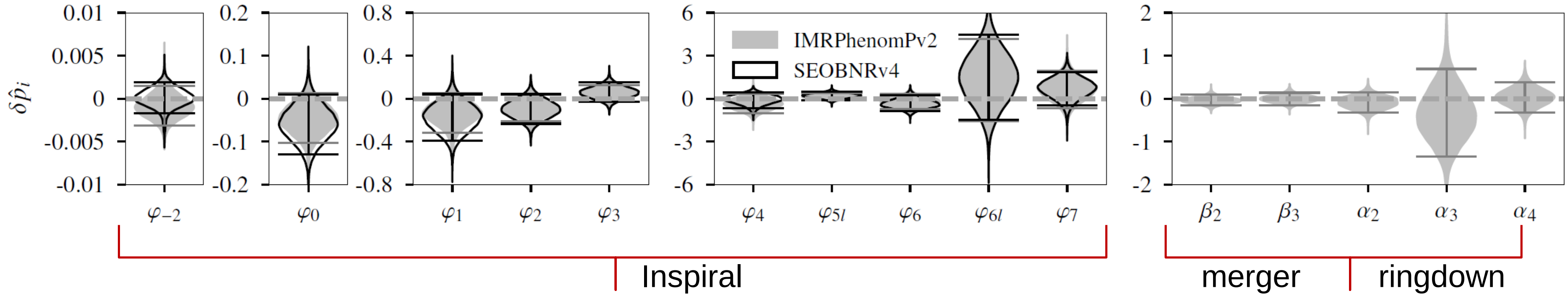
Precision tests of GR with BBH mergers

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, …

LIGO Virgo Collaboration
arXiv:1903.04467v2



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

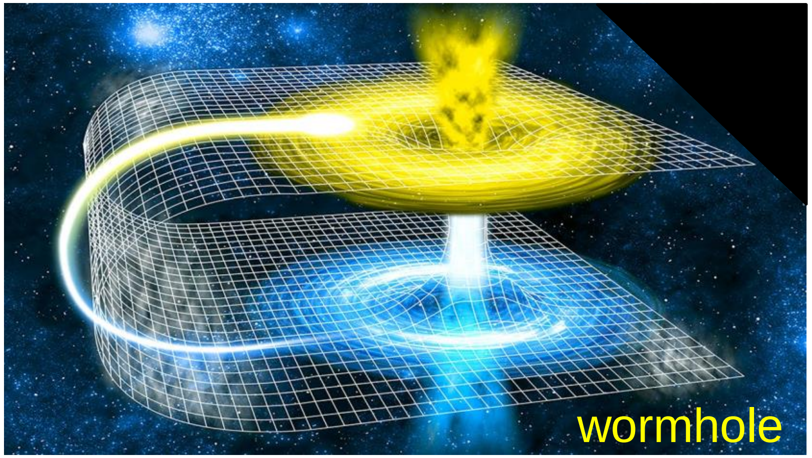
Ringdown terms: quasi-normal modes; do we see Kerr black holes?

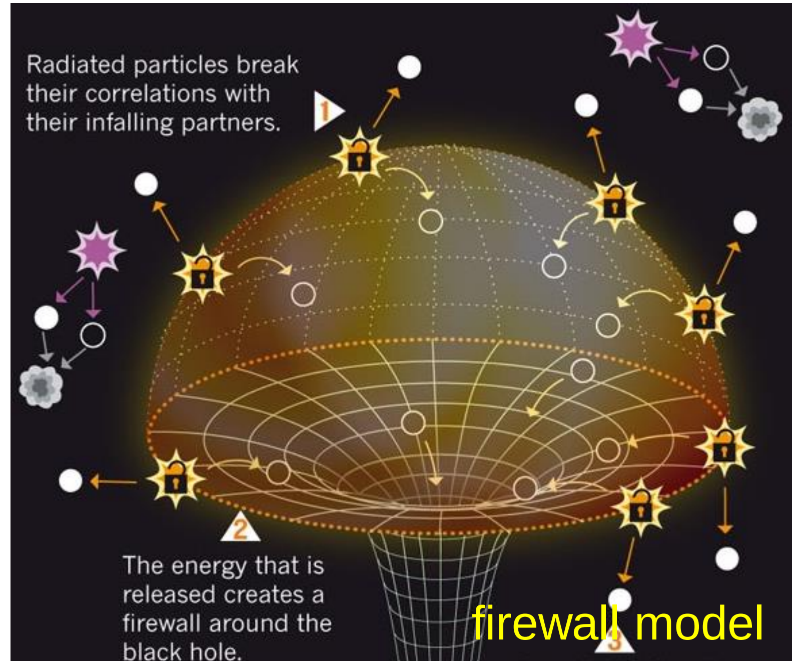
Towards high precision tests of gravity

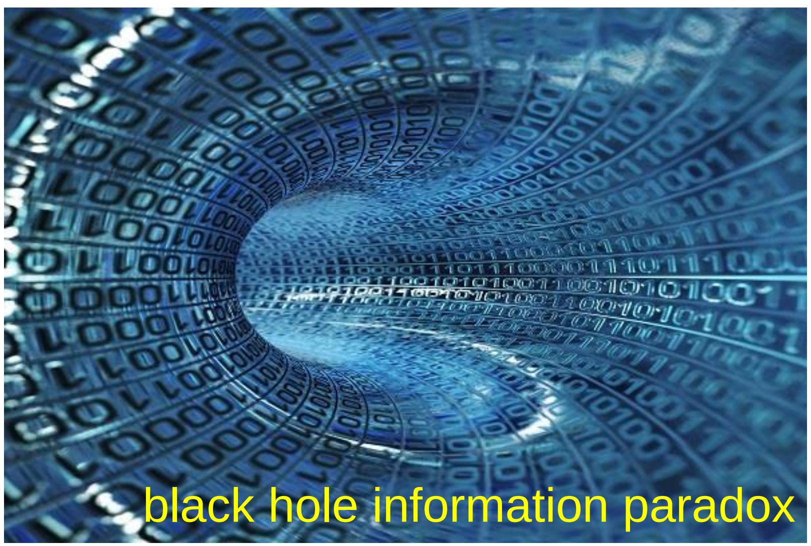
Combining information from multiple events and having high-SNR events will allow unprecedented tests of GR and other theories of gravity

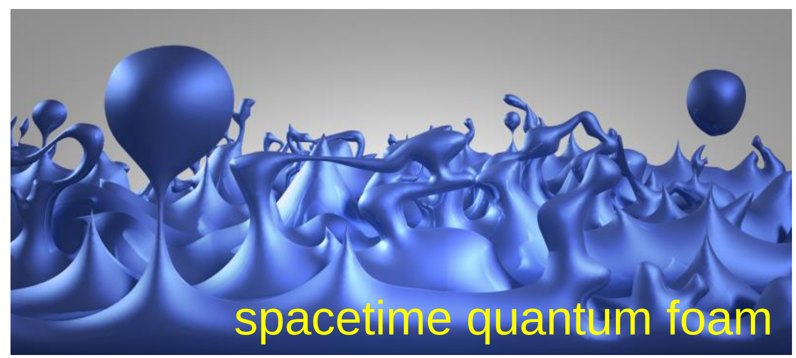
Fundamental physics: did we observe black holes?

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?



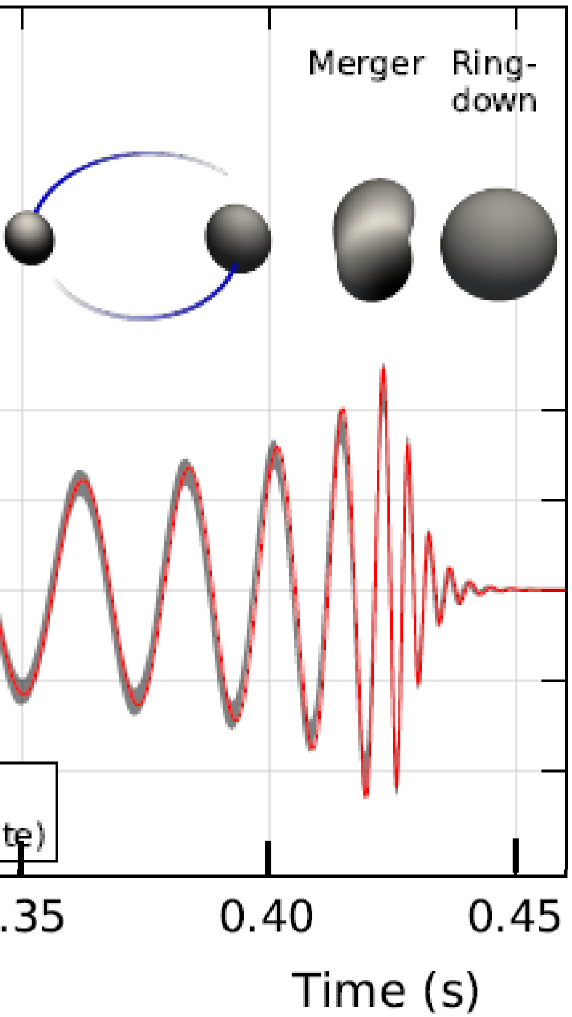


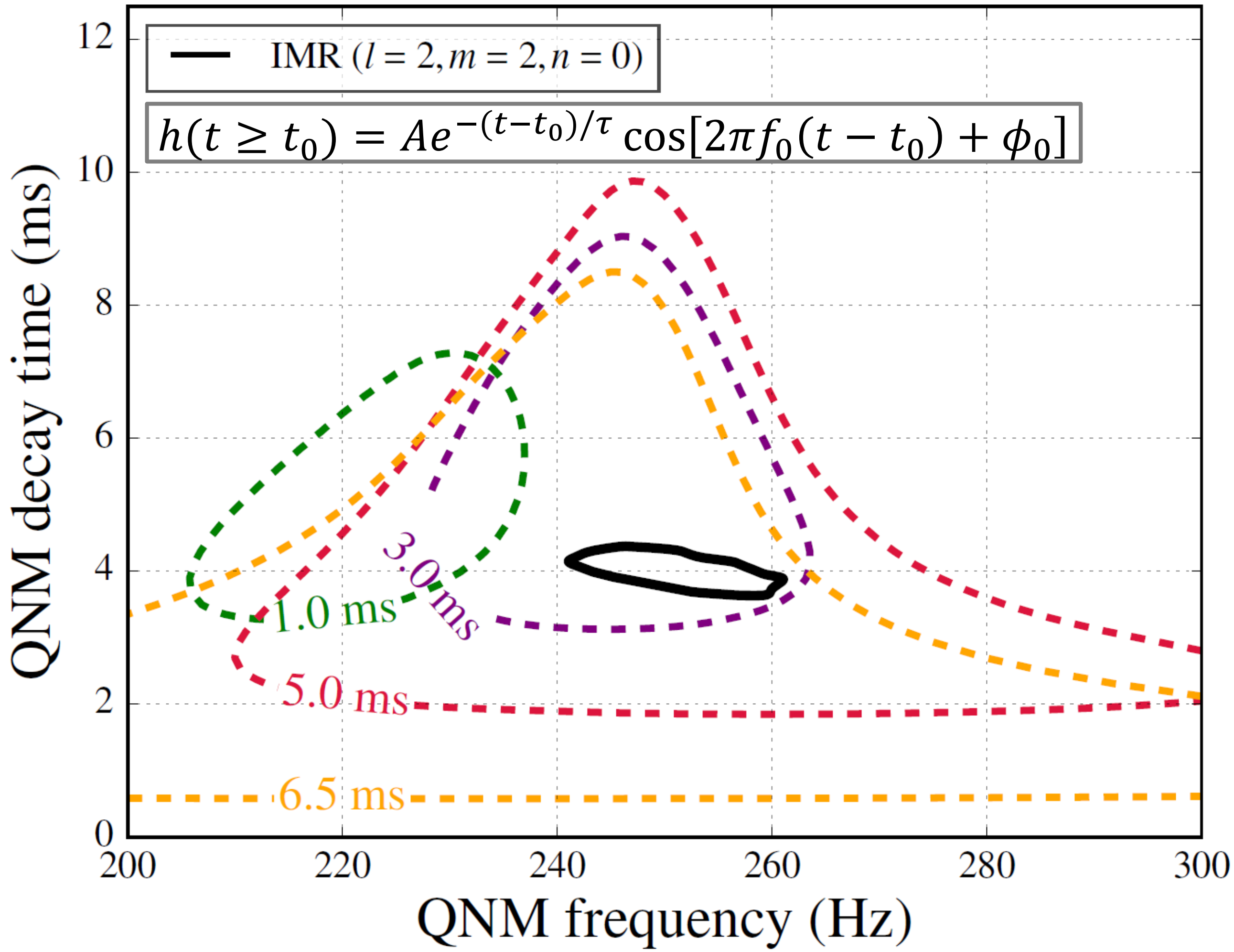




Is a black hole created in the final state?

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. This demands good sensitivity at high frequency





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

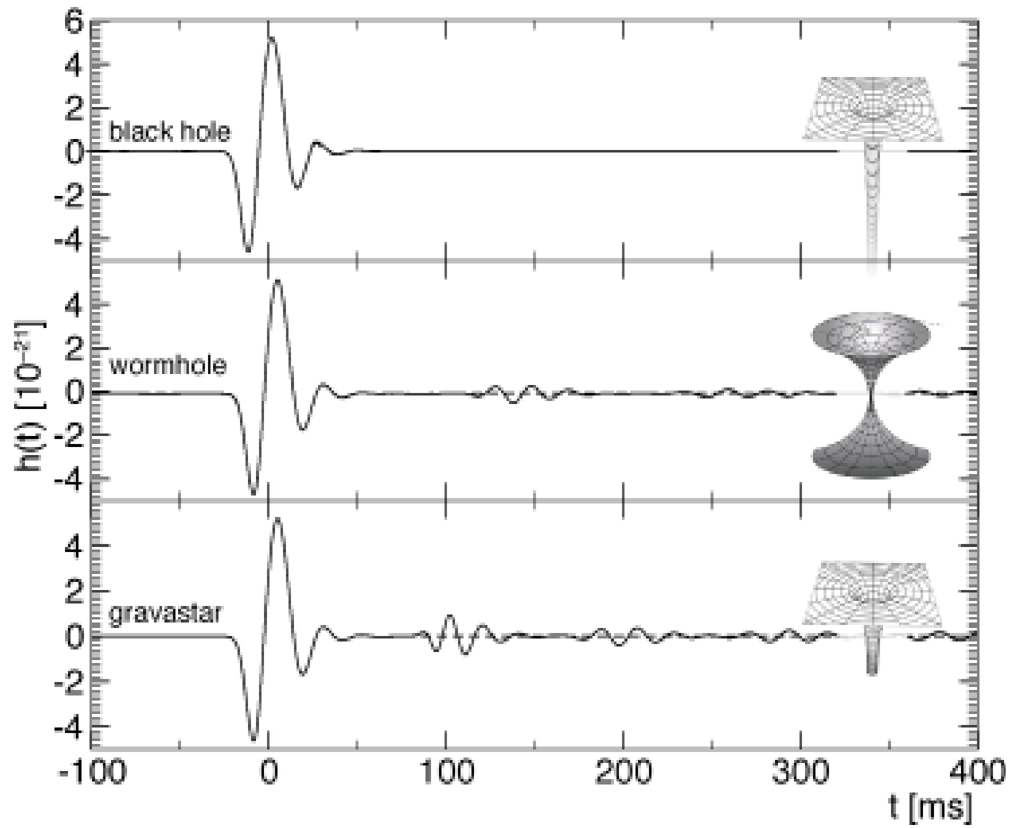
- Dark matter stars

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

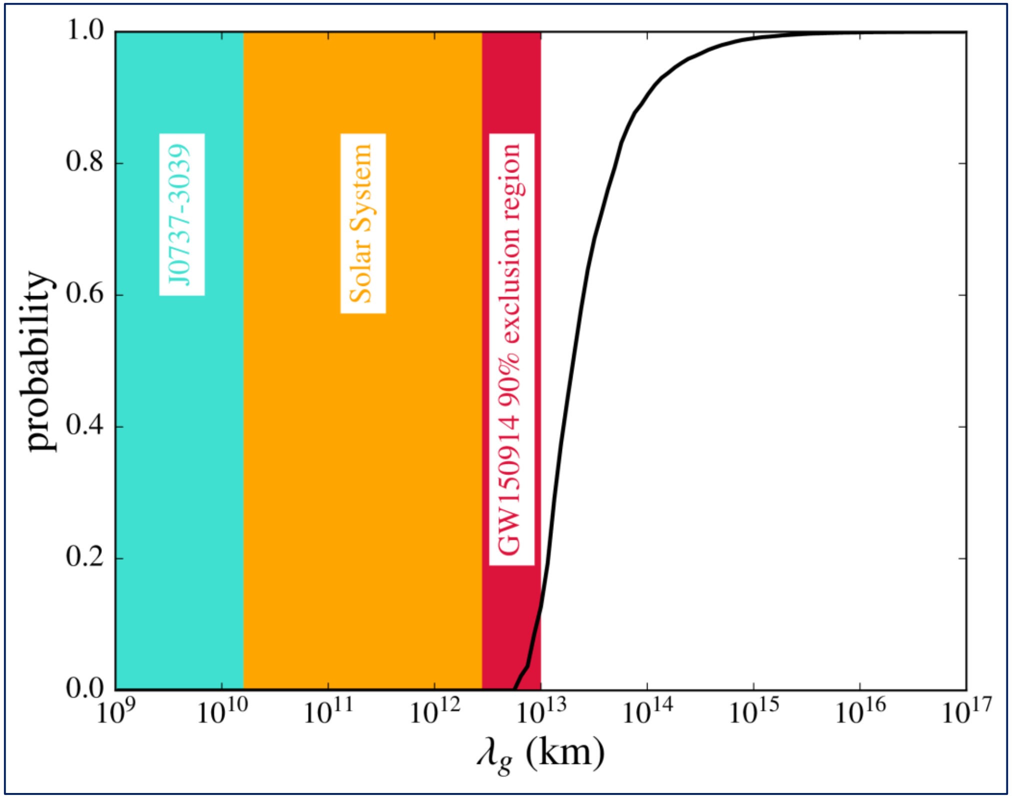


GW observables

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

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 $E^2 = p^2c^2 + m_g^2 c^4$

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

Thus frequency dependent speed

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

$\lambda_g > 10^{13}$ km

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

See "*Tests of general relativity with GW150914*"

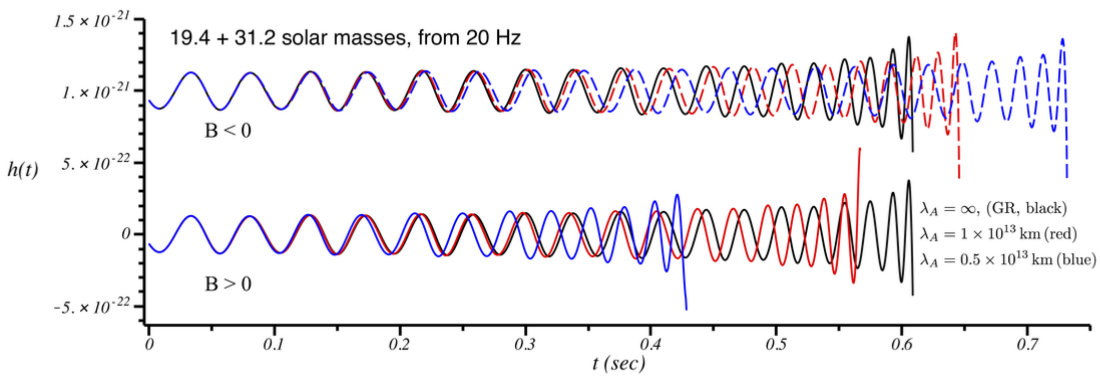
http://arxiv.org/abs/1602.03841

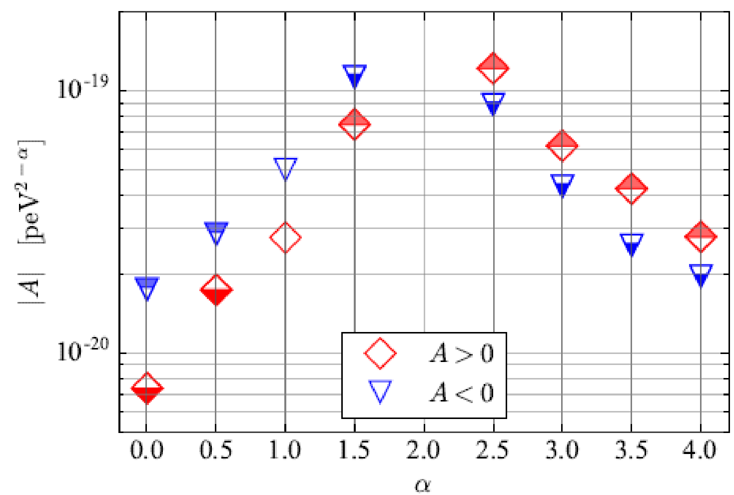
Bounds on violation of Lorentz invariance

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





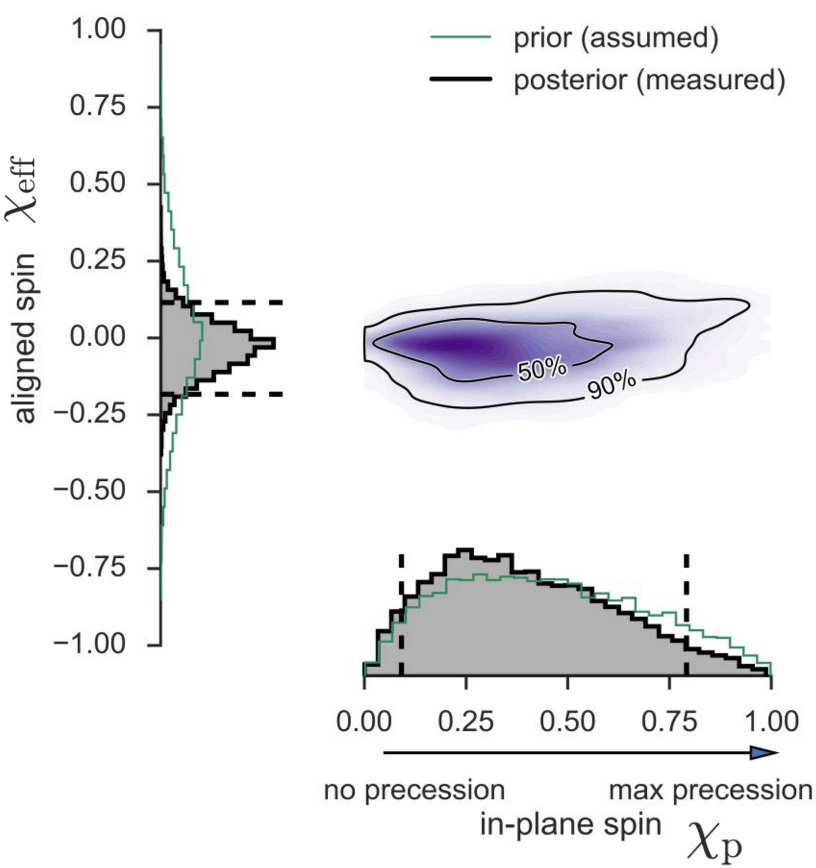
Several modified theories of gravity predict specific values of α:

- 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)

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. Spin maybe the key to formation channels

Precession is an important clue into how the black holes formed. If there is not any precession it is more likely that the black holes formed together. If there is a lot of precession it is more likely that the black holes formed separately and before coming together



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

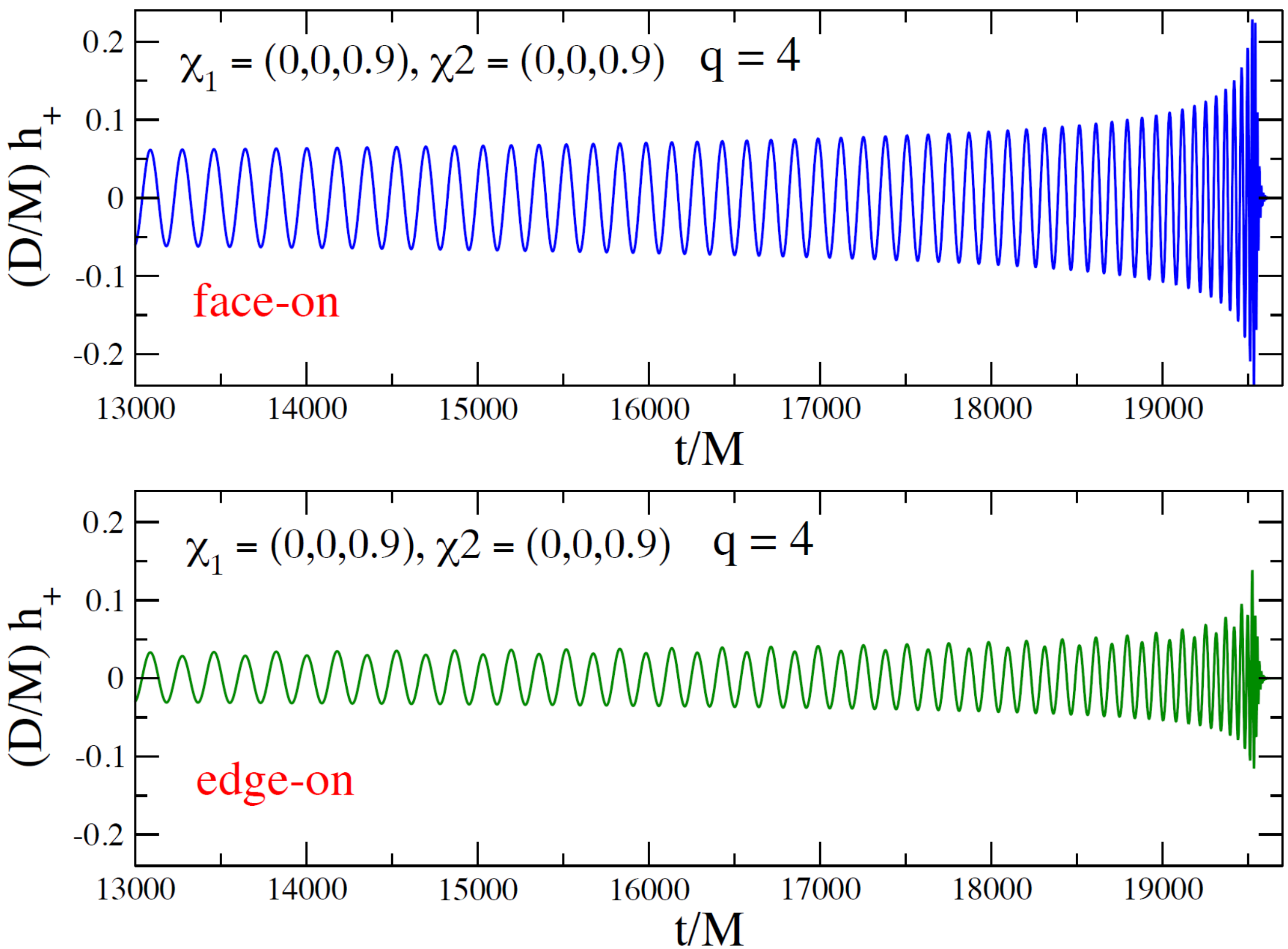
$$B_1 = 2 + 3q/2 \text{ and } B_2 = 2 + 3/(2q), \text{ and } i = \{1, 2\}$$

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

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+

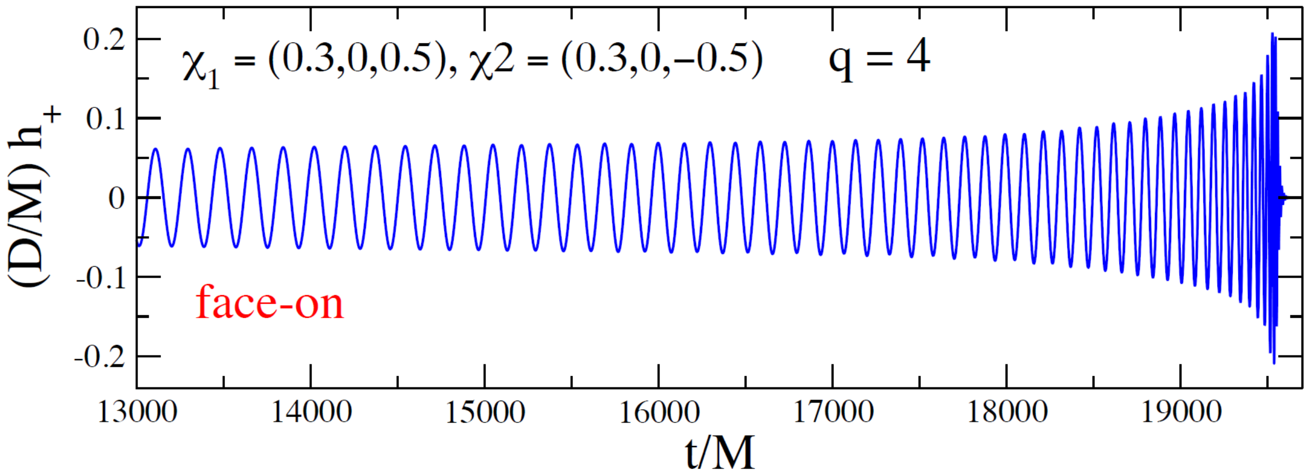
Spinning, but non-precessing binary

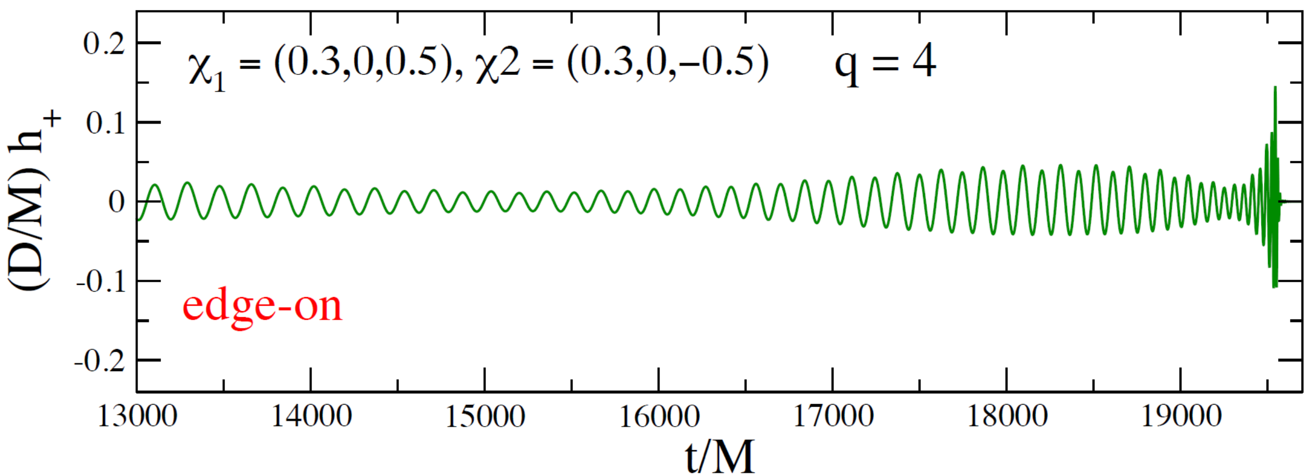


Effect of orientation of binary's orbital plane

Spin precession leads to amplitude and frequency modulation
Having good low frequency sensitivity will enable observing precession effects

Spin-precessing binary

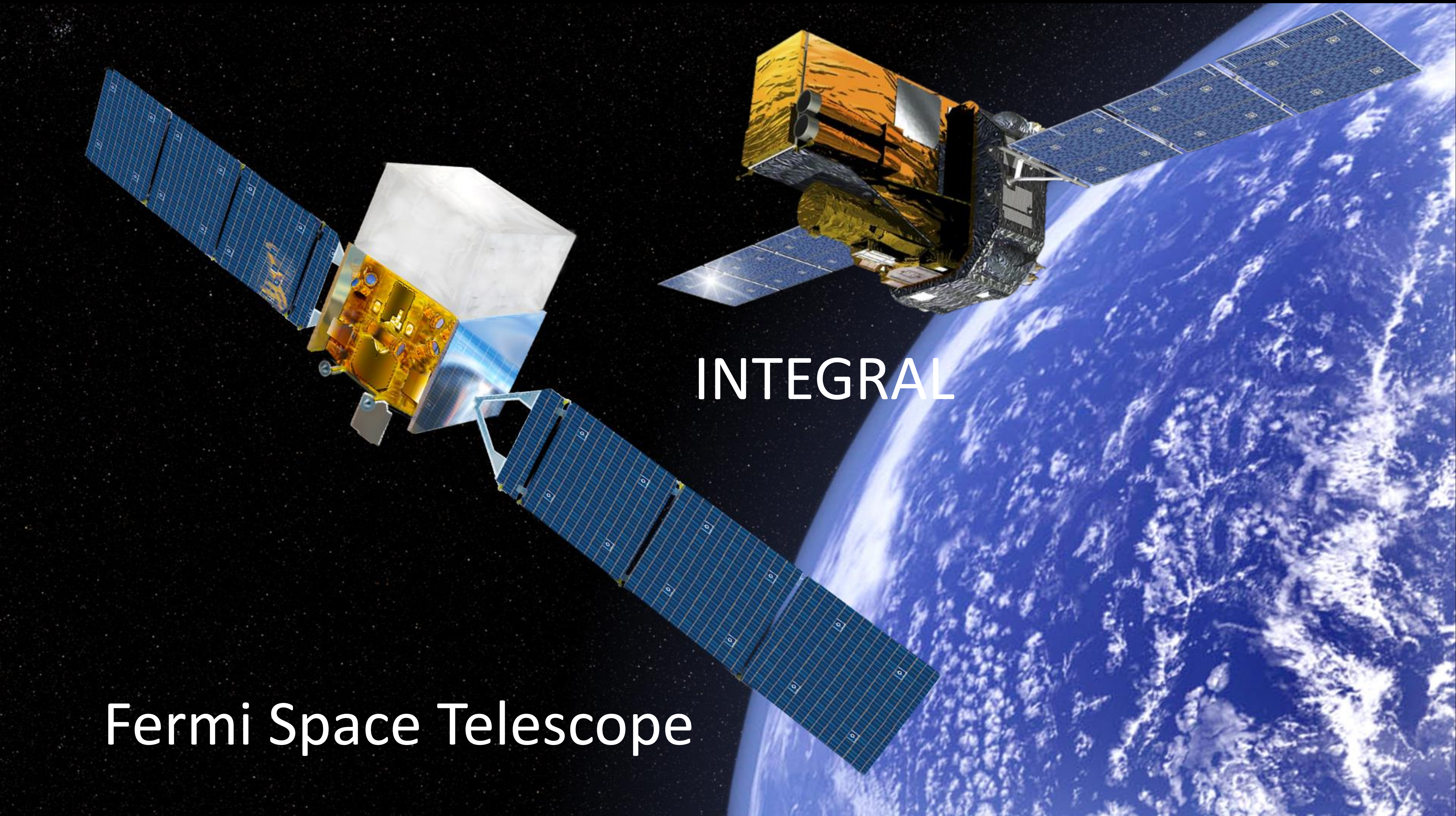




In-band time T is related to the low-frequency cut off frequency $T \approx \left(\frac{1}{f_0}\right)^{8/3}$

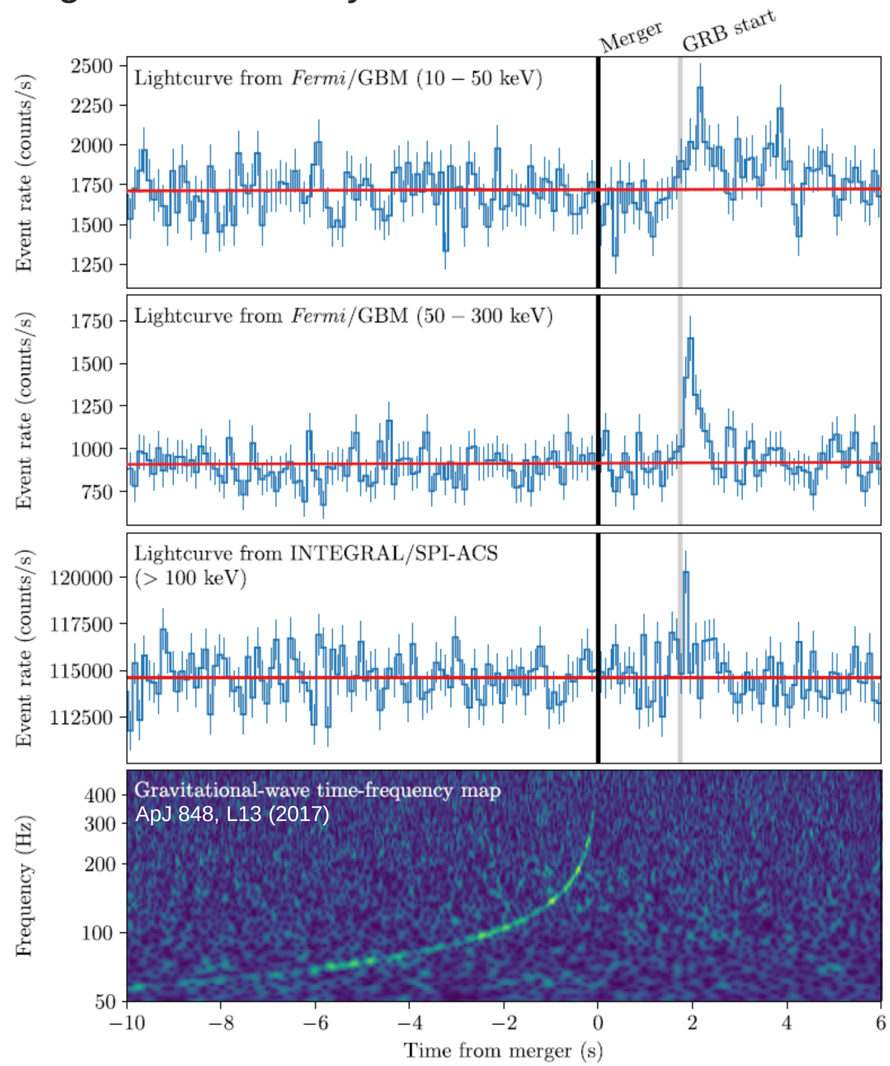
Some scientific highlights: neutron stars

Gamma rays reached Earth 1.7 seconds after GW170817



Binary neutron star merger on August 17, 2017

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



Neutron stars are laboratories for extreme physics

Mass: from about 1.1 to about 2.2 solar mass

Density: up to several times nuclear density

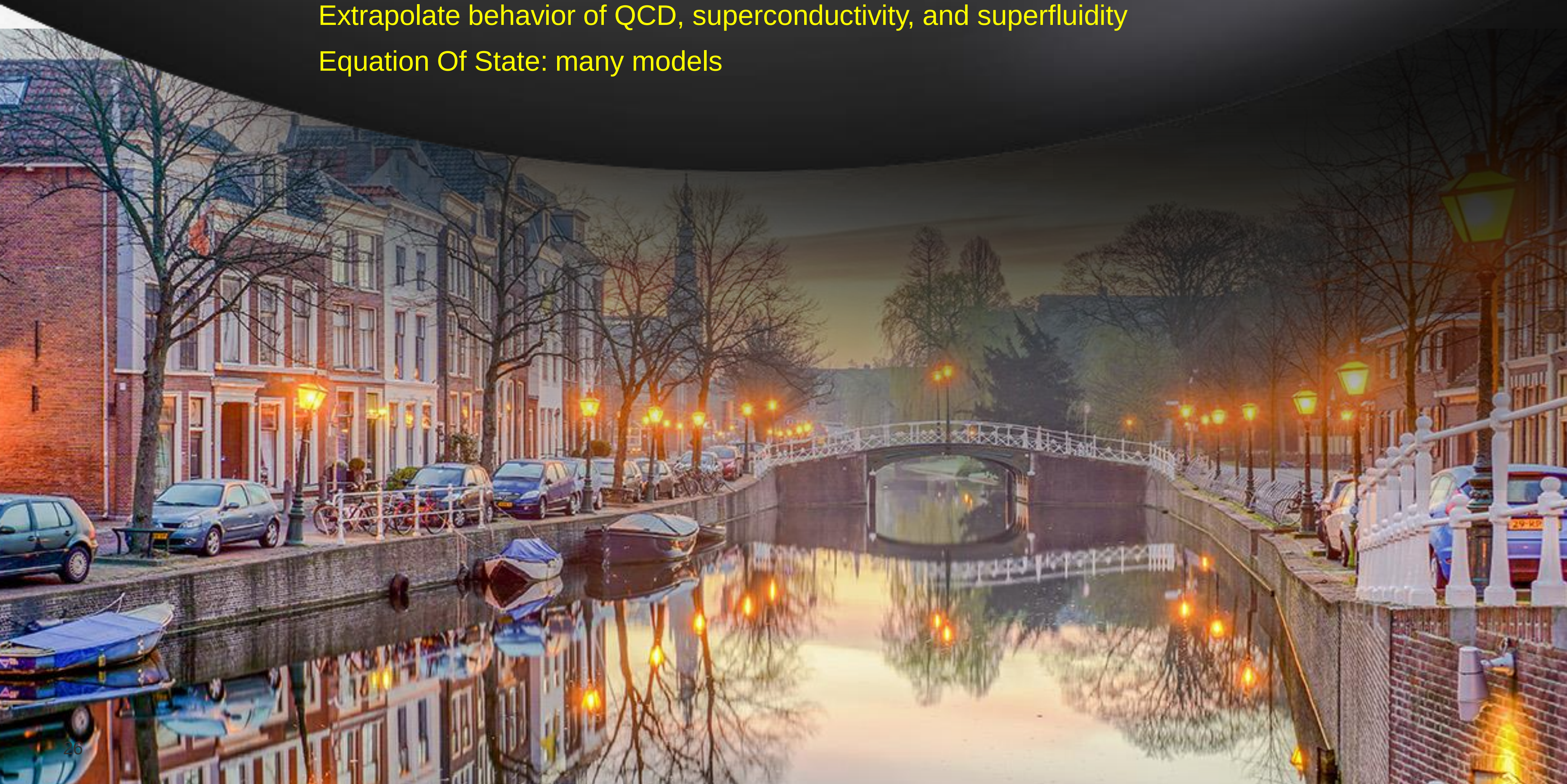
Temperature: up to 10^{12} K

Magnetic field: up to 10^{11} T

Held together by gravity and supported by degeneracy pressure and NN repulsion

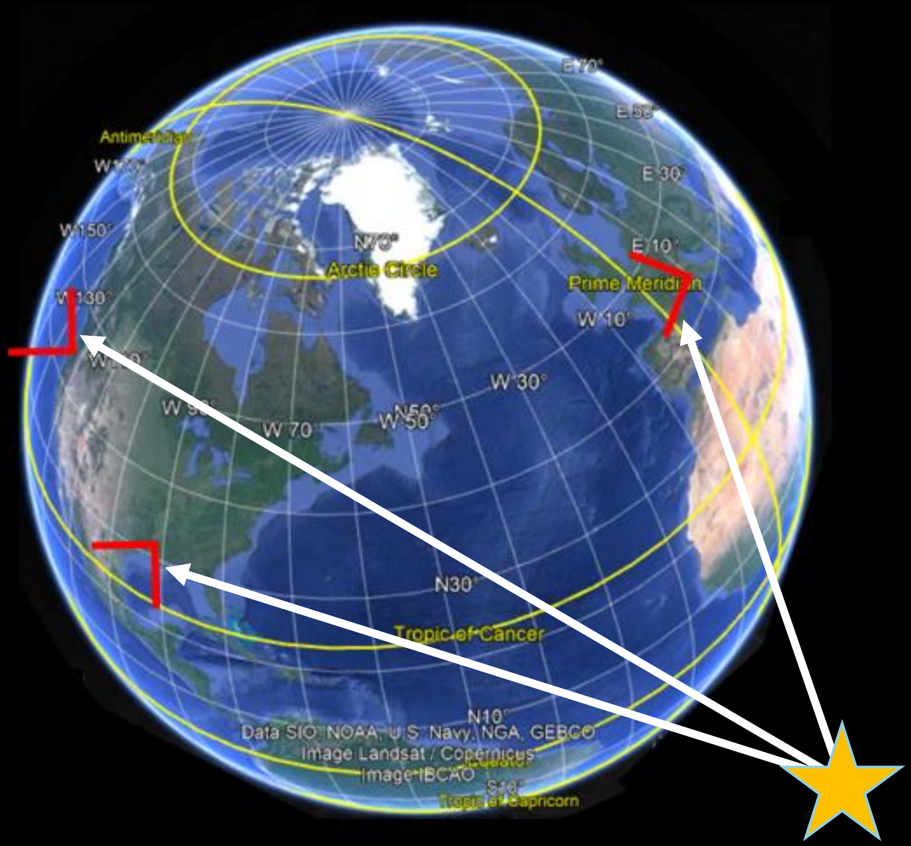
Extrapolate behavior of QCD, superconductivity, and superfluidity

Equation Of State: many models



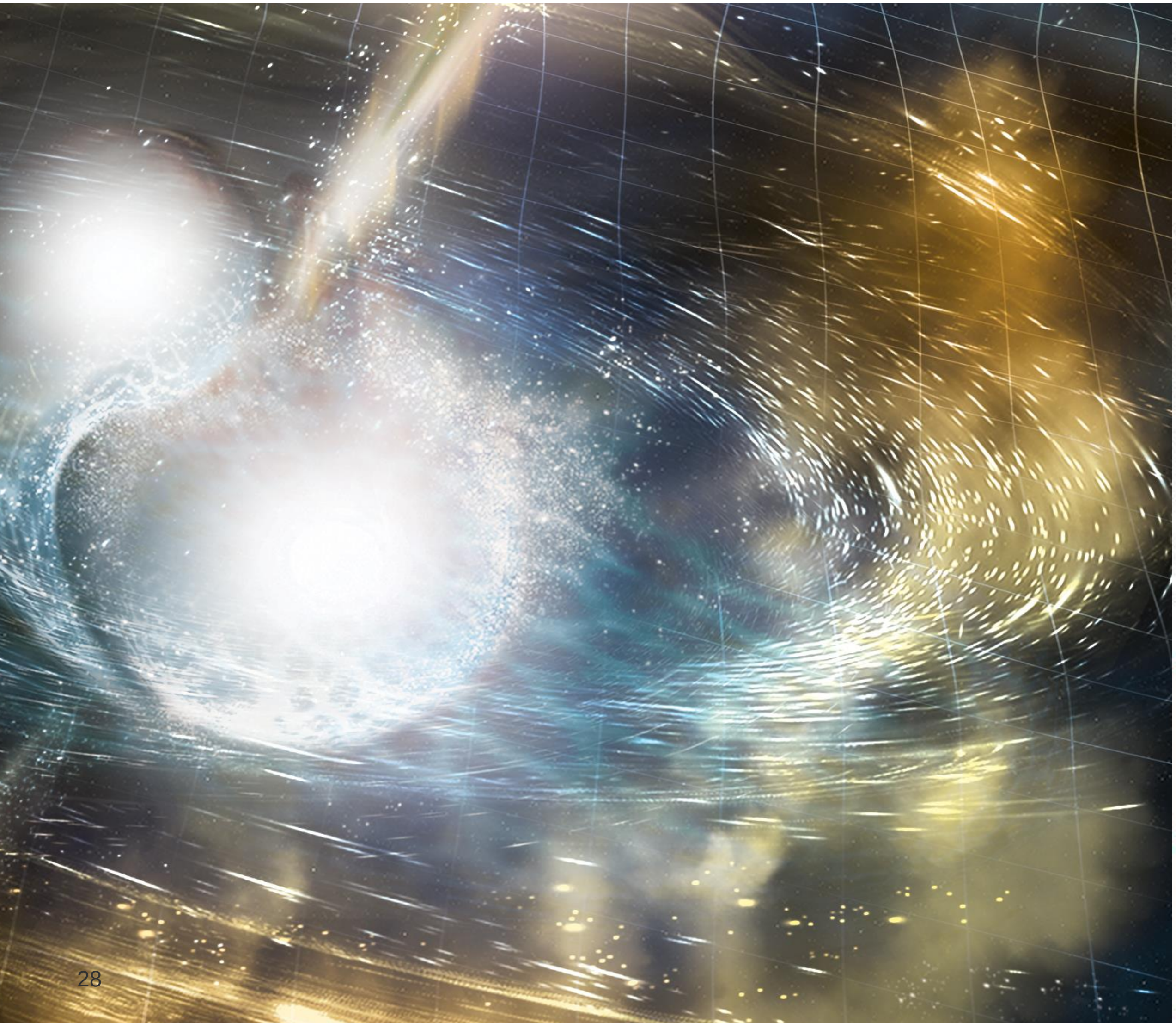
Source location via triangulation

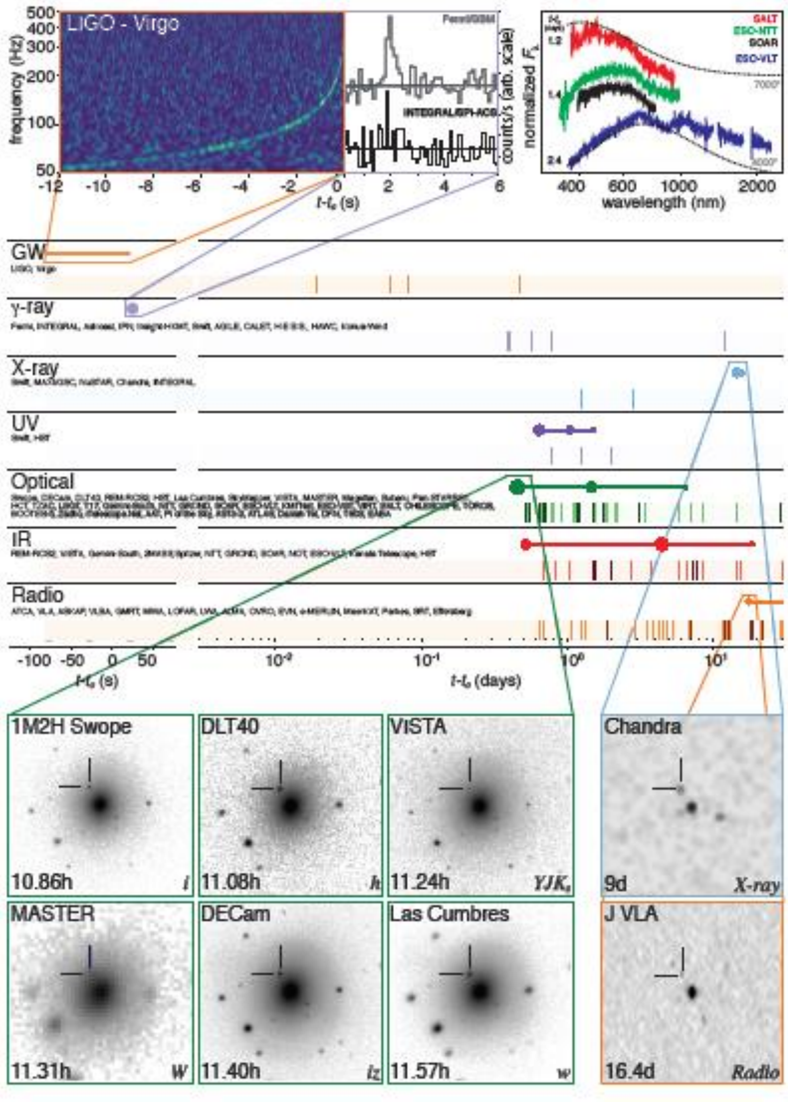
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it

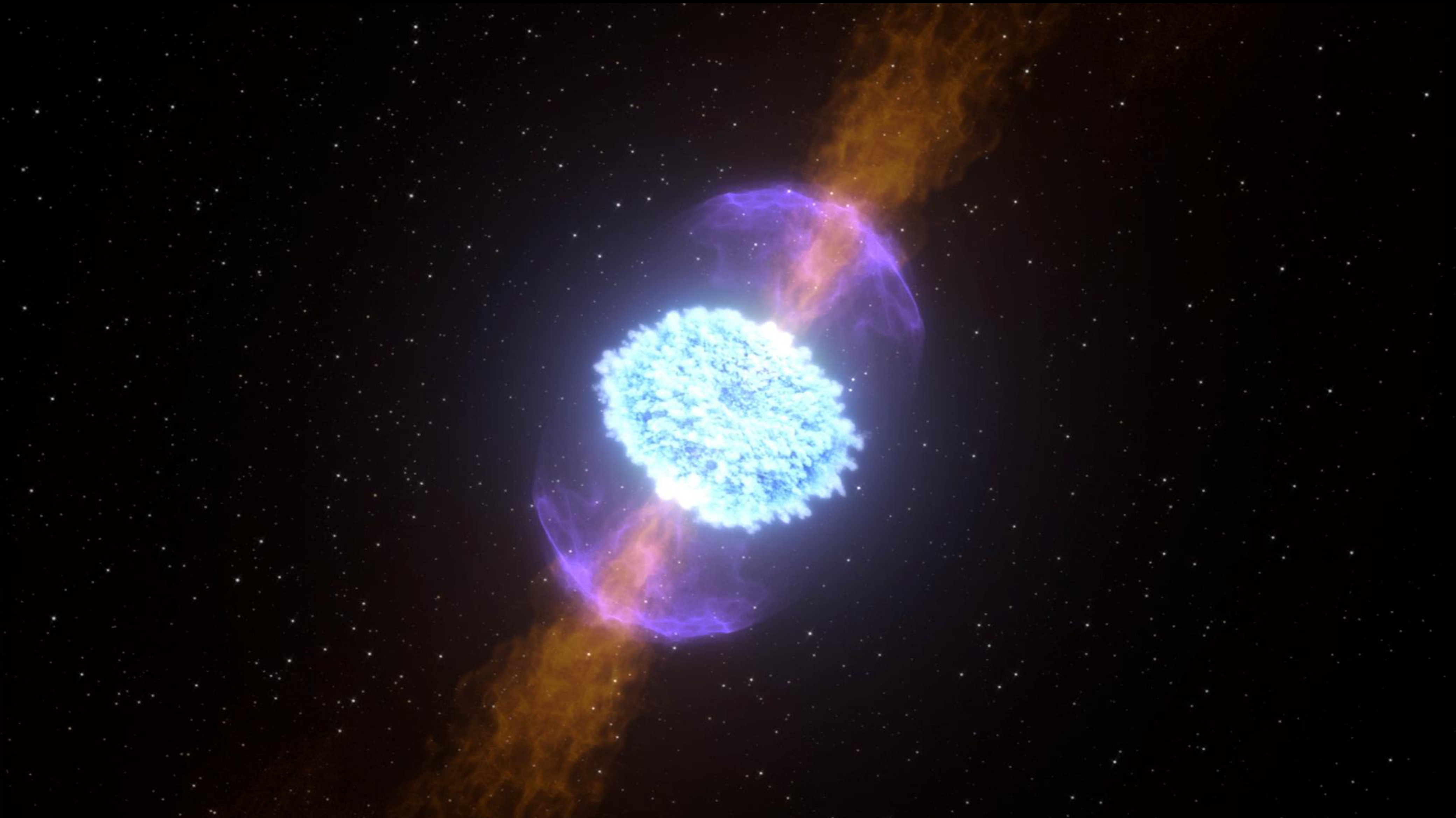


GW170817: start of multi-messenger astronomy with GW

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)

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

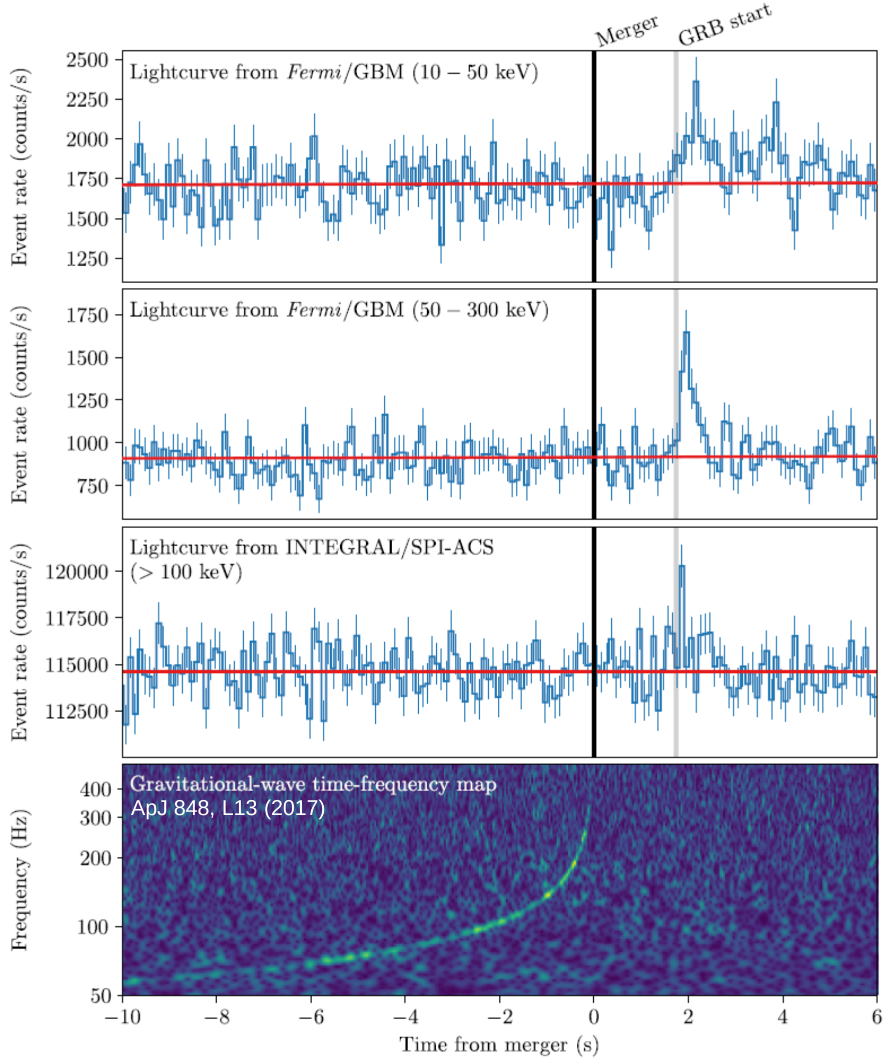
Test of Equivalence Principle

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

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

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

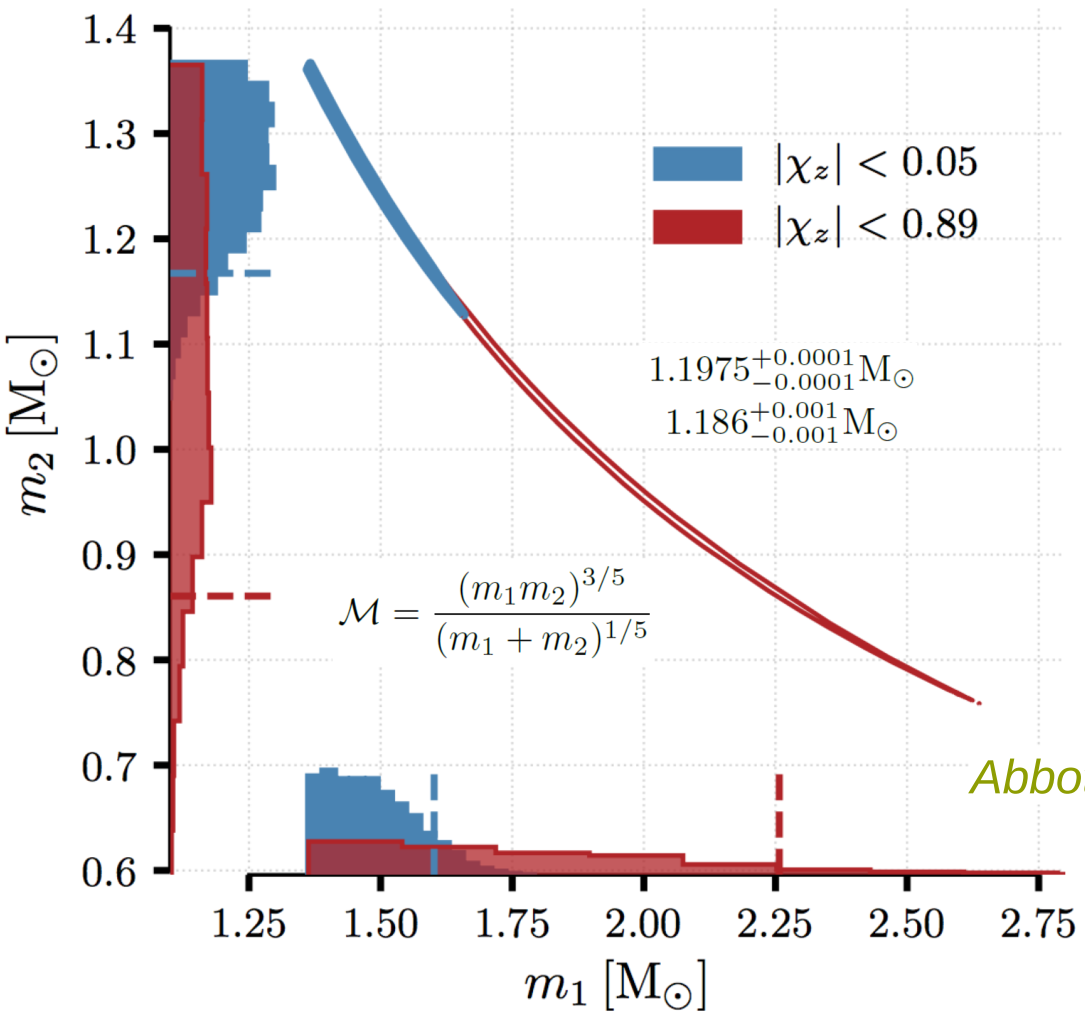
Including data on peculiar velocities to 50 Mpc we find
$\Delta\gamma \leq 4 \times 10^{-9}$



Inferring neutron star properties: masses

Early estimates now improved using known source location, improved waveform modeling, and re-calibrated Virgo data. 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

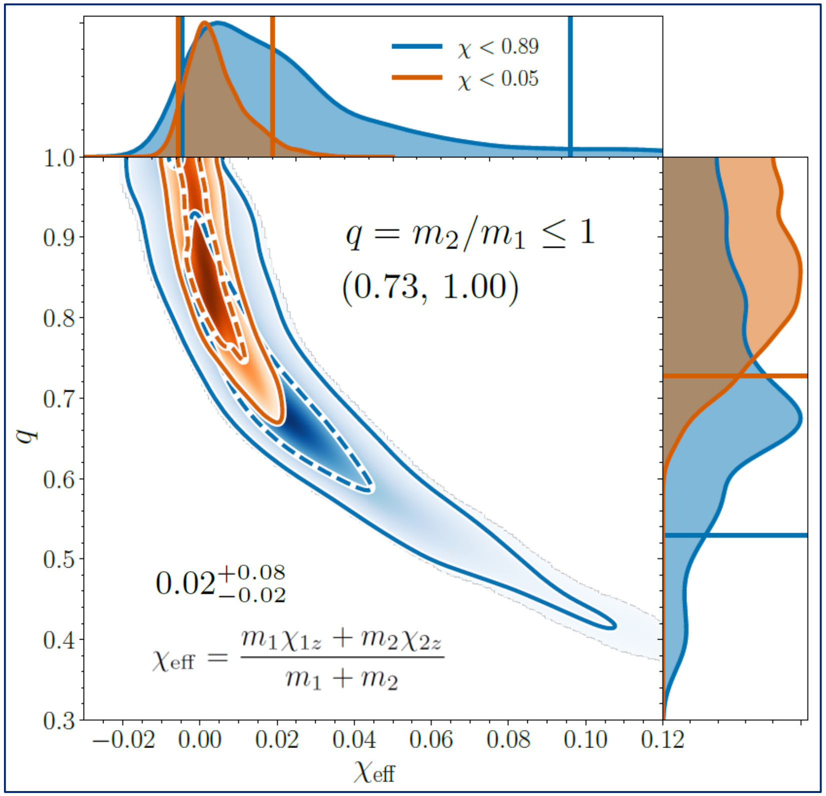
Inferring neutron star properties: spins

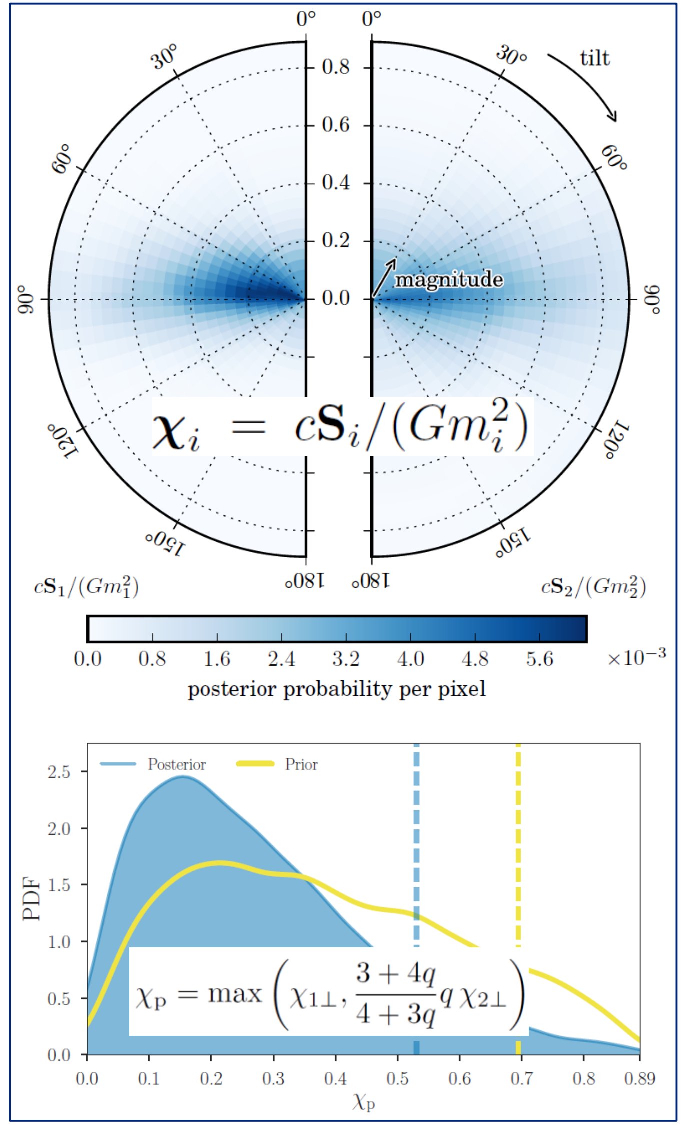
Constrains on mass ratio q, χ_i dimensionless spin, χ_eff effective spin, and χ_p effective spin precession parameter. See https://arxiv.org/abs/1805.11579

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



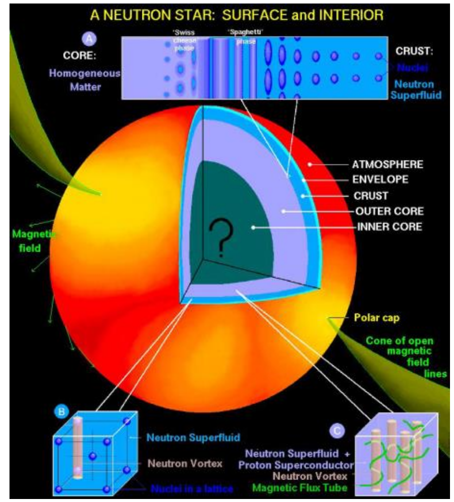


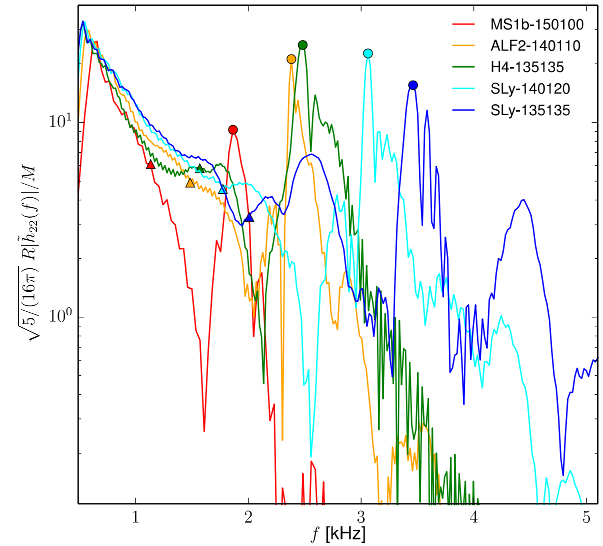
Solving an astrophysical conundrum

Neutron stars are rich laboratories with extreme matter physics in a strong gravitational environment. Stability is obtained due to quantum physics

Structure of neutron stars?

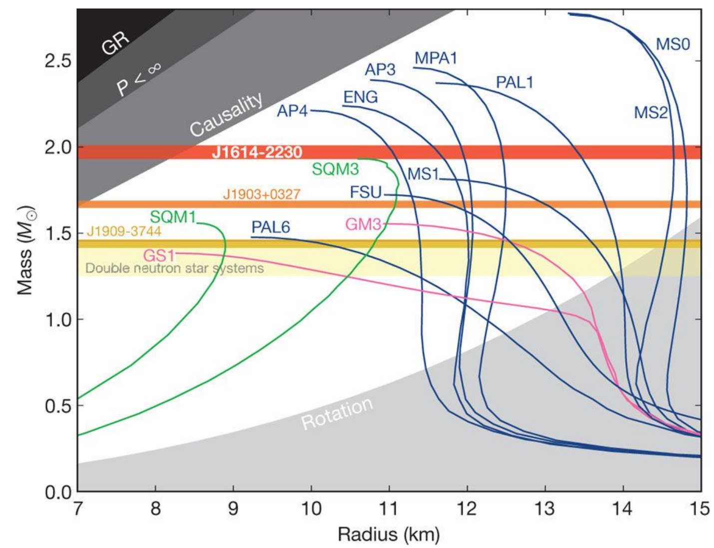
- Structure of the crust?
- Proton superconductivity
- Neutron superfluidity
- “Pinning” of fluid vortices to crust
- Origin of magnetic fields?
- More exotic objects?





Widely differing theoretical predictions for different equations of state

- Pressure as a function of density
- Mass as a function of radius
- Tidal deformability as a function of mass
- Post-merger signal depends on EOS
  - “Soft”: prompt collapse to black hole
  - “Hard”: hypermassive neutron star



Demorest *et al*., Nature 467, 1081 (2010)

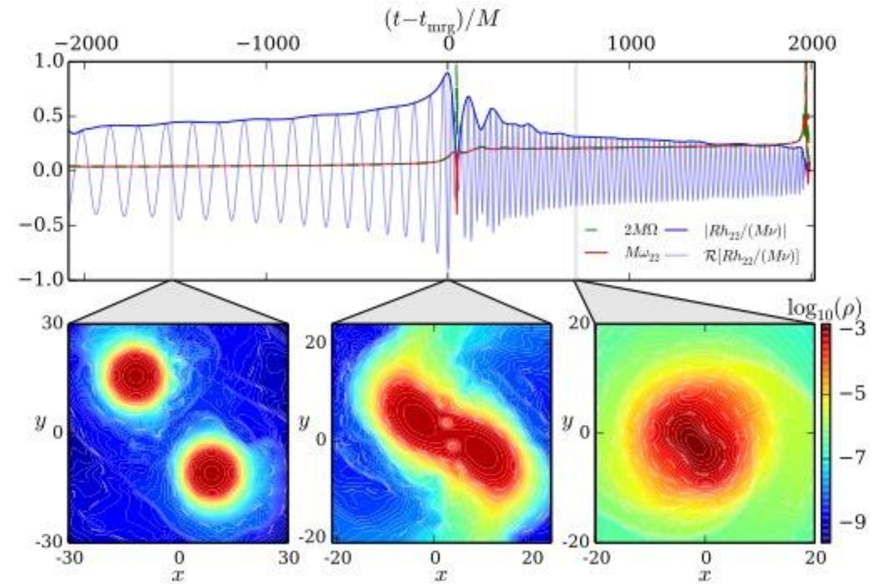
Bernuzzi *et al*., PRL 115, 091101 (2015)

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

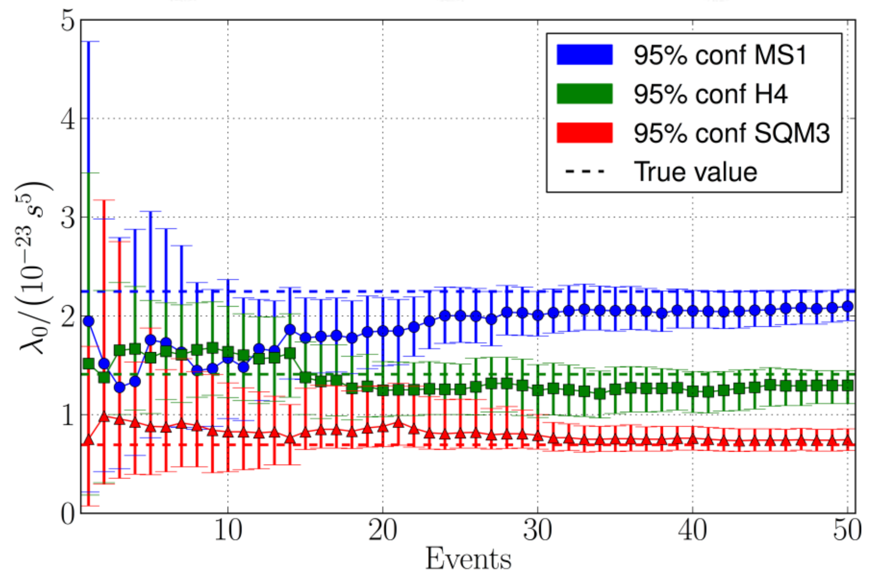
Gravitational waves from inspiraling binary neutron stars

- 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)

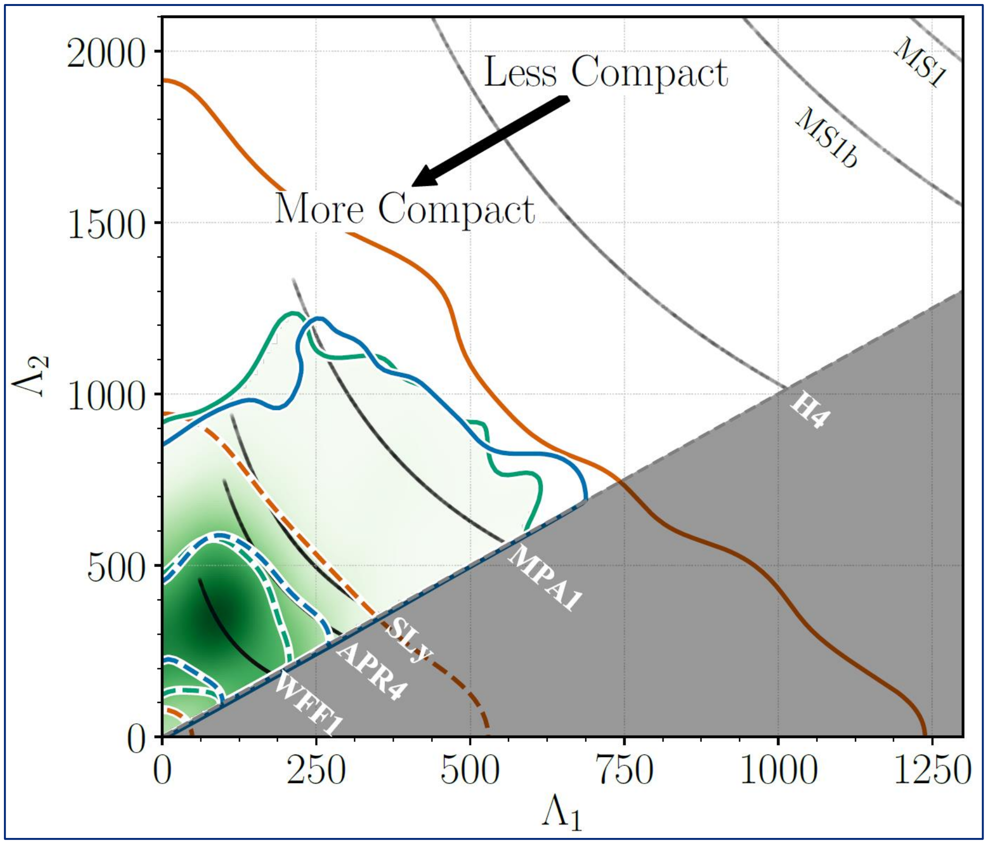
Bernuzzi, Nagar, Font, …

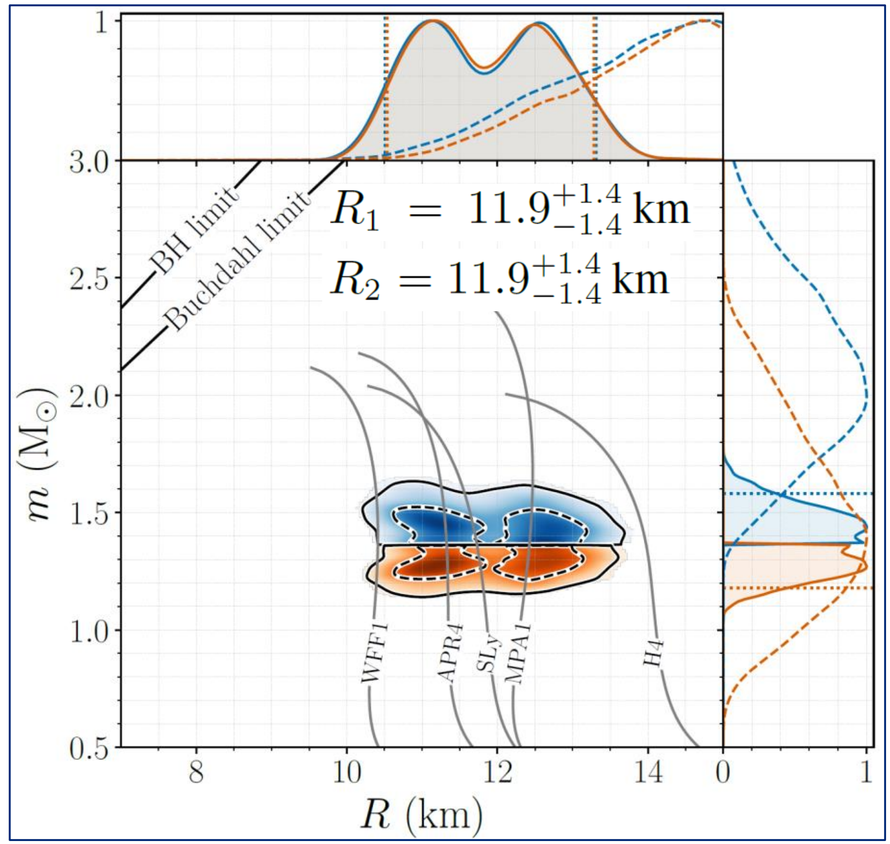
Event GW170817: tidal deformability, EOS, radii

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

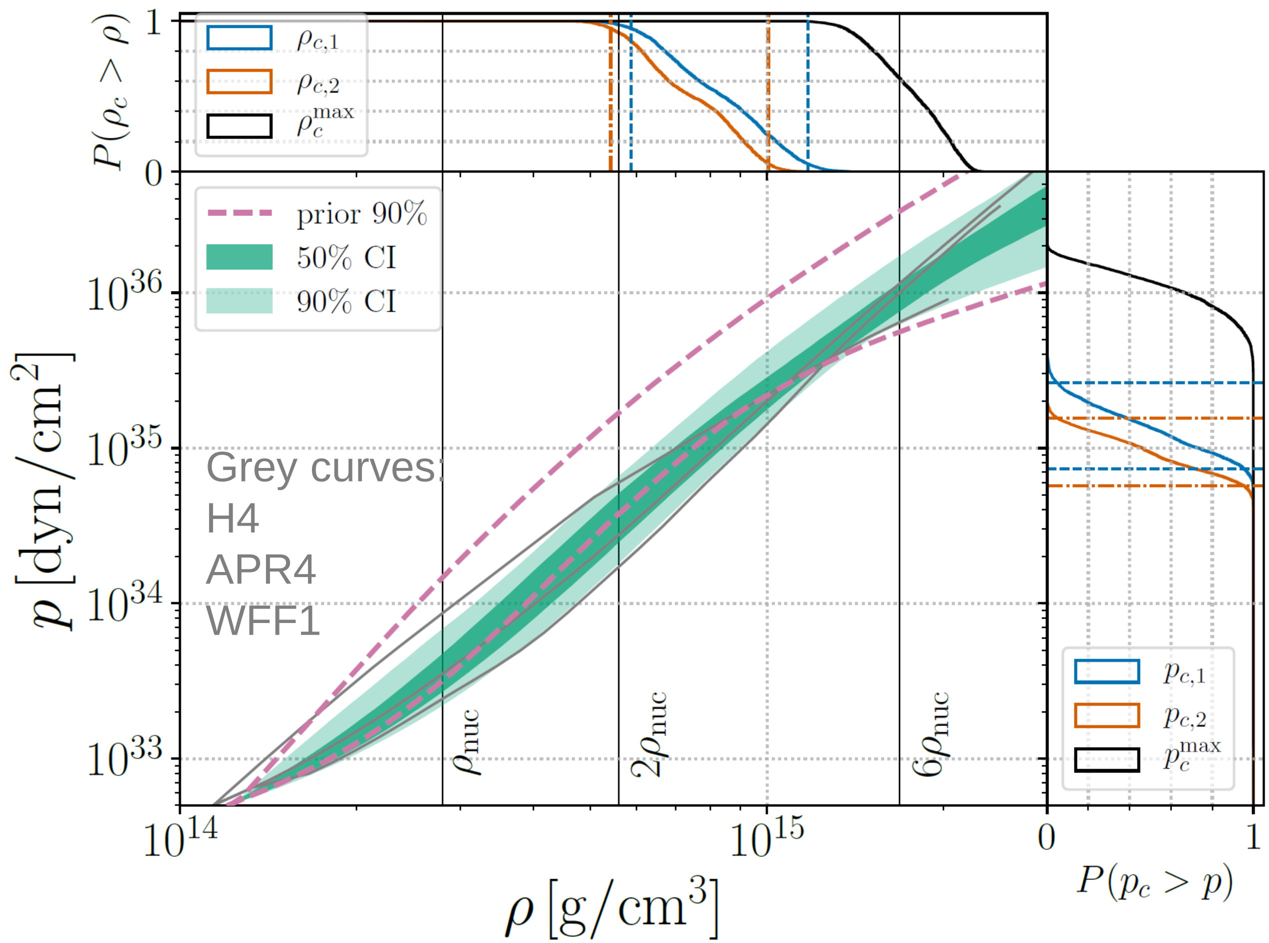




Pressure versus rest-mass density of NS interior

Spectral EOS parametrization and imposing a lower limit on the maximum NS mass supported by the EOS of 1.97 M_solar

The pressure posterior is shifted from the 90% credible prior region (marked by the purple dashed lines) and towards the soft floor of the parametrized family of EOS



No experimental support for new degrees of freedom or phase transition around five times nuclear density

See: LVC, https://arxiv.org/abs/1805.11581

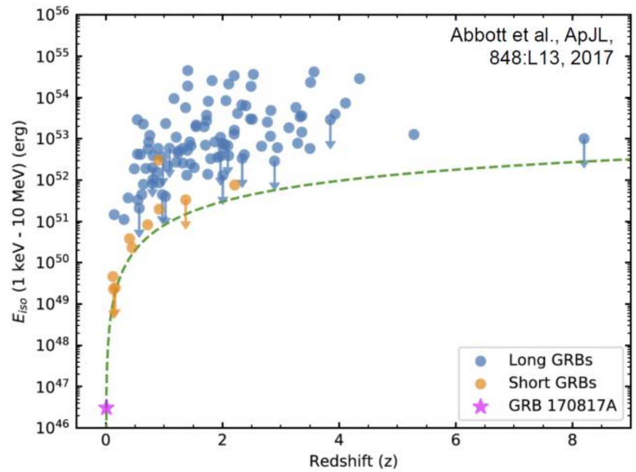
Looking into the heart of a dim nearby sGRB

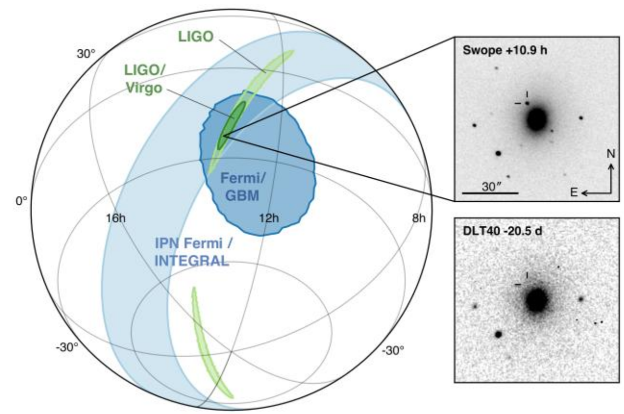
Gravitational waves identified the progenitor of the sGRB and provided both space localization and distance of the source. This triggered the EM follow-up by astronomers for the kilonova

Closest by and weakest sGRB, highest SNR GW event

LIGO/Virgo network allowed initial source localization of 28 $(\mathrm{degr})^2$ 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

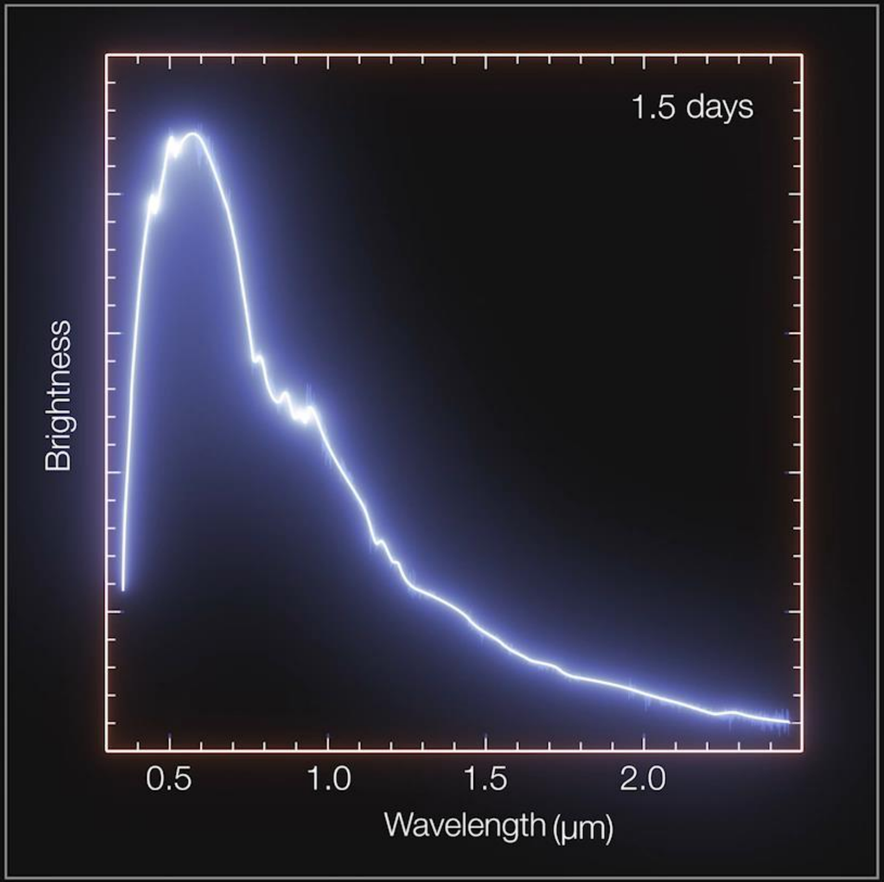


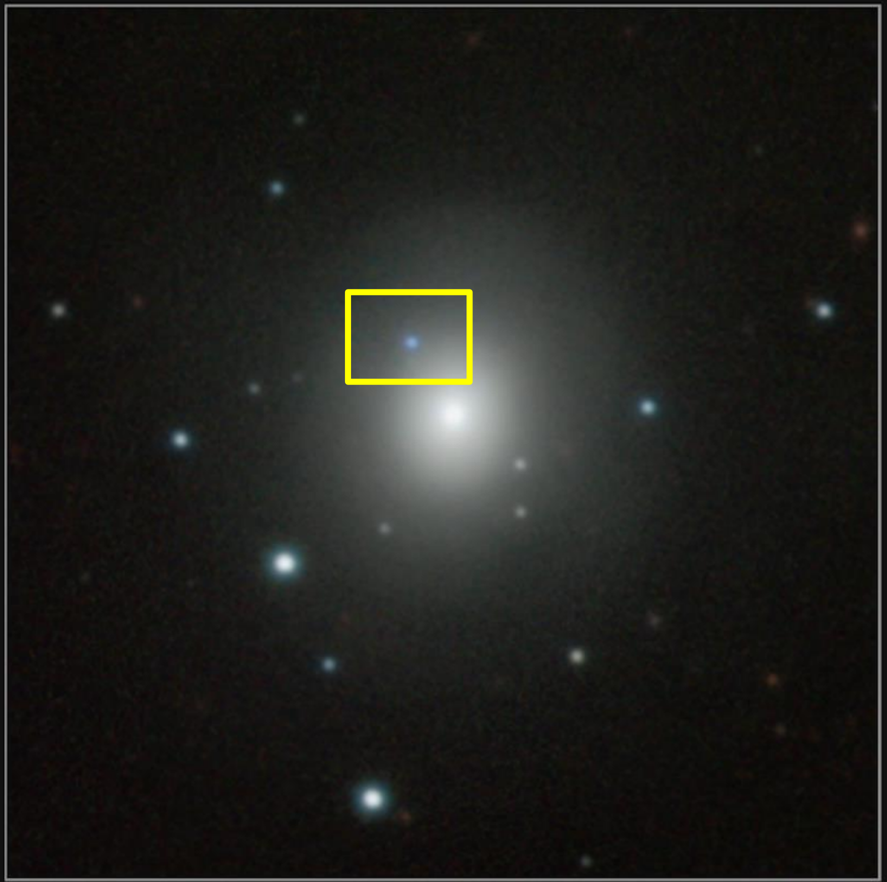


European Southern Observatory

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

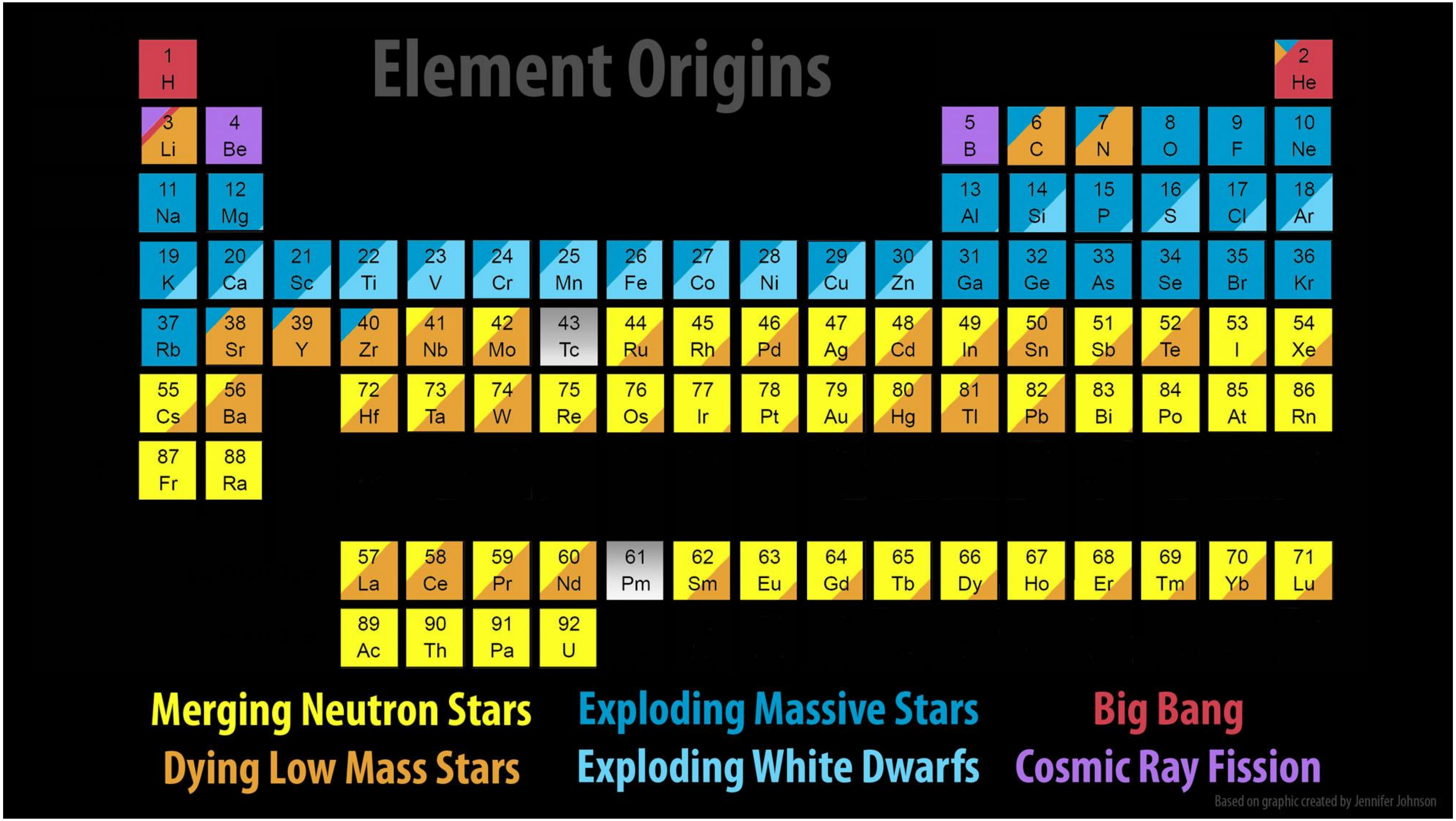
Since LIGO/Virgo provide the distance and BNS source type, it was recognized that we are dealing with a weak (non-standard) GRB. This led to the optical counterpart to be found in this region





Many heavy elements were produced in such collisions

GW170817 does not allow identification of spectra of these individual elements



Identification of strontium in event GW170817

Identification of Strontium, an element that could only have been synthesised so quickly under an extreme neutron flux, provides the first direct spectroscopic evidence that neutron stars comprise neutron-rich matter

Watson et al., arXiv:1910.10510v1

The kilonova essentially has a blackbody (blue dotted lines) with a temperature of 3,700 K

Assume solar r-process abundance ratios

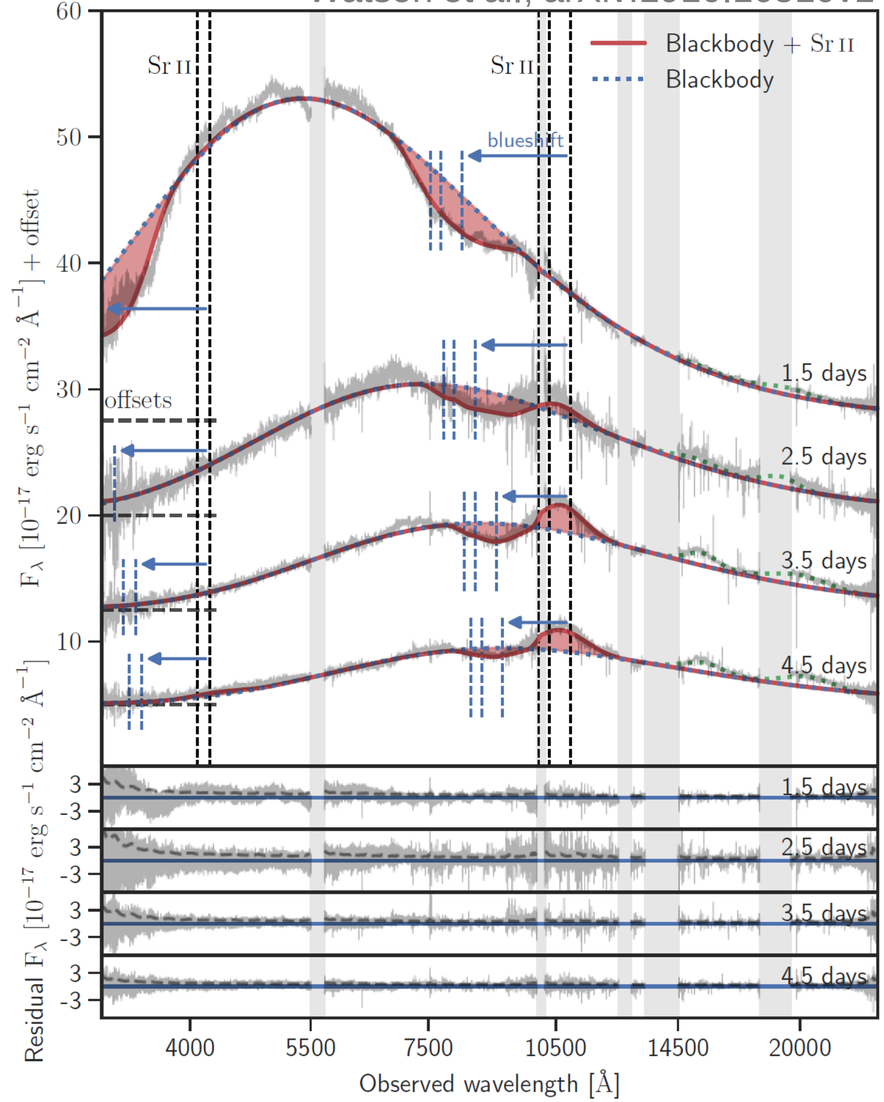
Sr accounts for at least a few percent by mass of all r-process elements

P Cygni profiles (red transparent fill) increasingly develop in time for the Sr lines

Lines are Doppler broadened by 0.2 c due to the high speed of the ejected material and blue-shifted by 0.23 c

Extreme-density stars composed of neutrons were proposed shortly after the discovery of the neutron, and identified with pulsars three decades later

GW170817 provides first spectroscopic evidence of neutron-rich matter in neutron stars



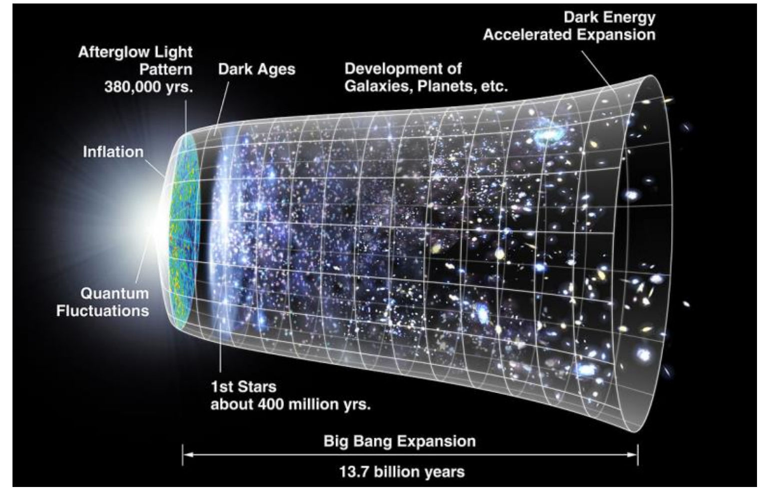
Cosmology

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

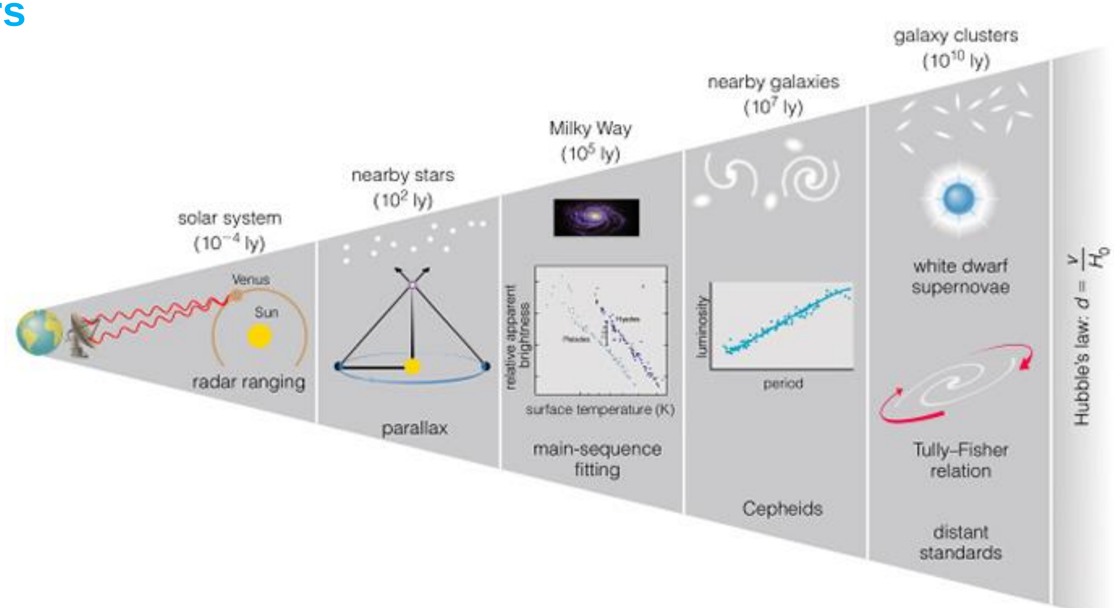
Current measurements depend on cosmic distance ladder

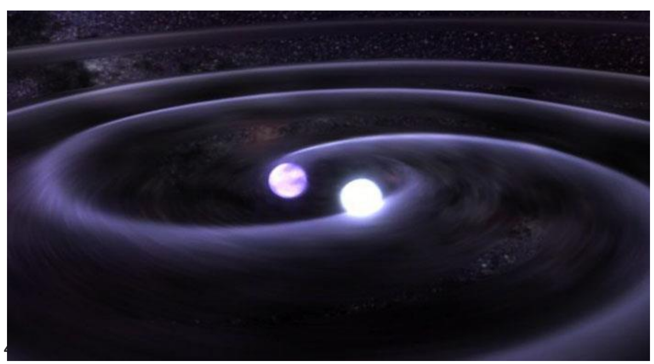
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder



Gravitational waves from binary mergers

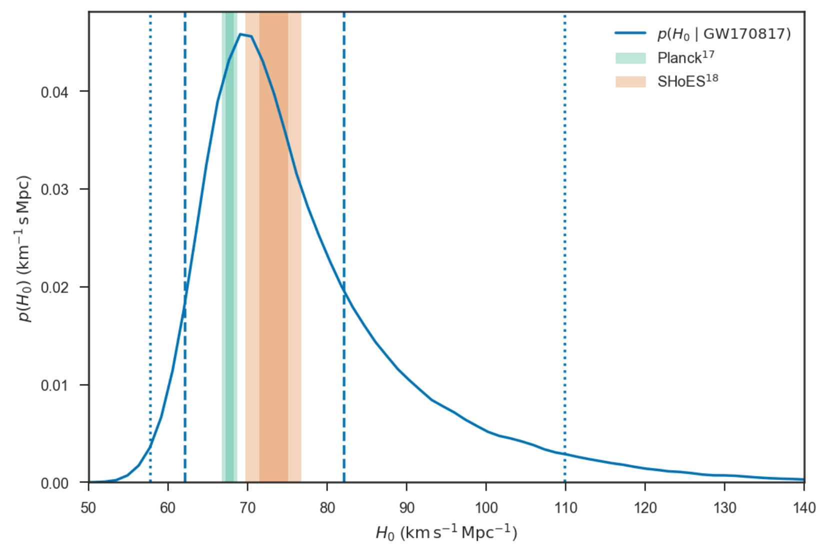
Distance can be measured directly from the gravitational wave signal!





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

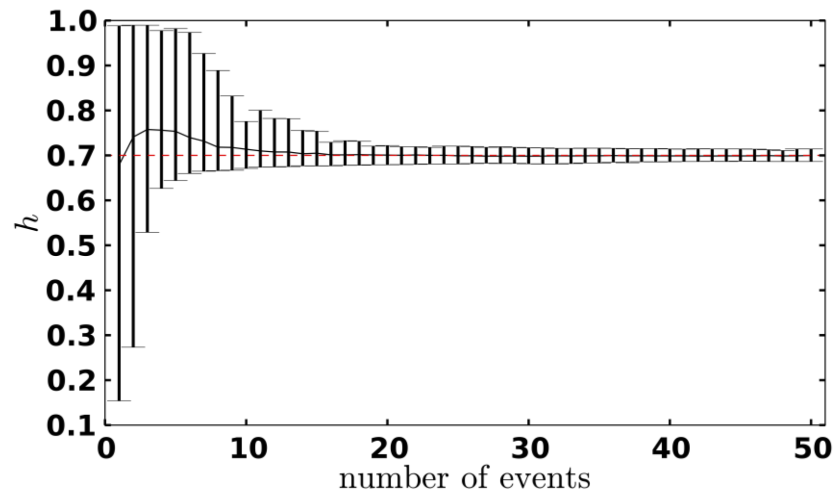


Measurement of the local expansion of the Universe

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

April 1, 2019: LIGO and Virgo started observation run O3

Joining O3 is another important step for Virgo

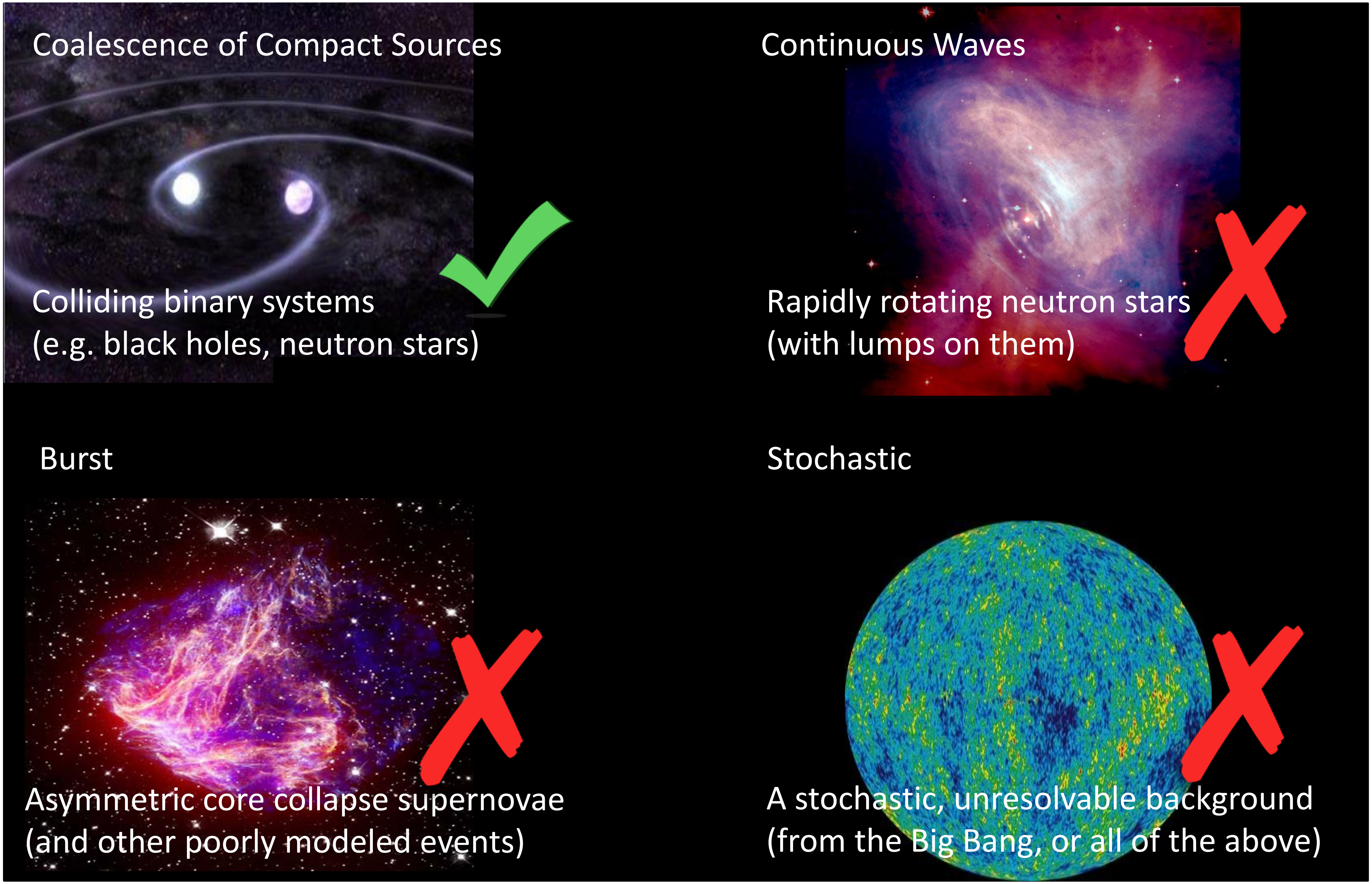
Gravitational-Wave Transient Catalog, GWTC - 2

Compact binary coalescences observed by LIGO &Virgo during the first half of the third observing run

See Abbott et al. Phys. Rev. X 11, 021053 (2021)

Status of gravitational-wave detections

Sources can be transient or of continuous nature, and can be modeled or unmodeled



Scientific impact of gravitational wave science

Multi-messenger astronomy started: a broad community is relying of detection of gravitational waves
Scientific program is limited by the sensitivity of LVC instruments over the entire frequency range

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