Gravitational wave studies of dense nuclear matter

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Symposium on QCD and Nuclei, MIT, October 10, 2021

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, 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

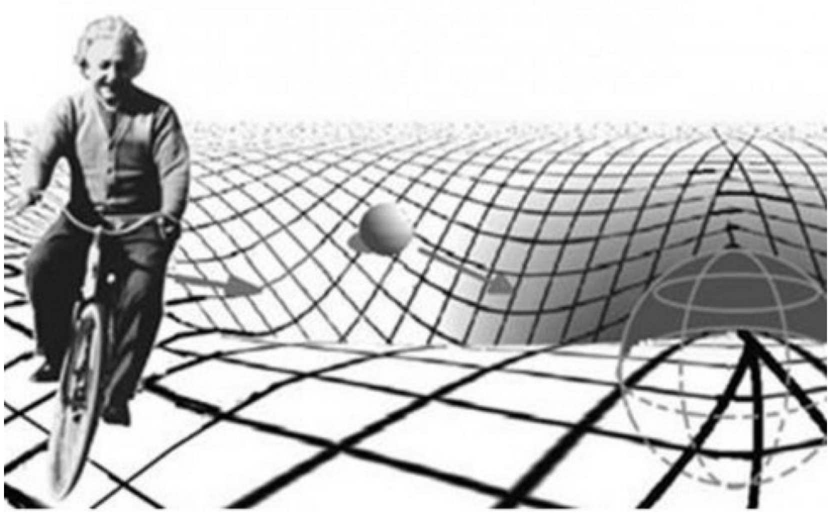
- Astronomy: compact objects, populations, transients, …
- Cosmology: Hubble parameter, Dark Matter, Dark Energy
- Fundamental physics: black holes, spacetime, horizons, matter under extreme conditions

Einstein predicts existence of gravitational waves

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

Einstein's Gravity

- Space and time are physical entities
- 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: curvature perturbations in the spacetime metric

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 $4\pi R^2$:

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

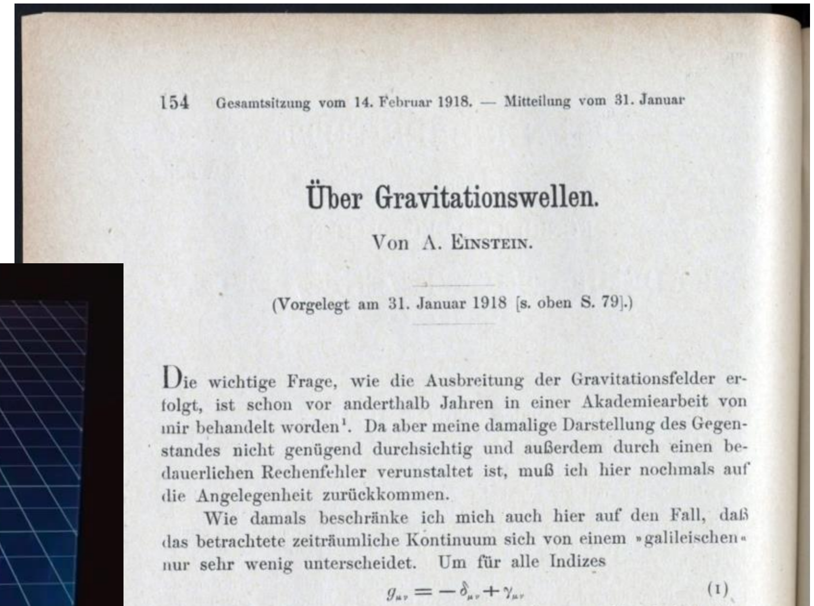
Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

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.

Gravitational waves

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

Curvature perturbations in the spacetime metric that propagate with the speed of light



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

Über Gravitationswellen.

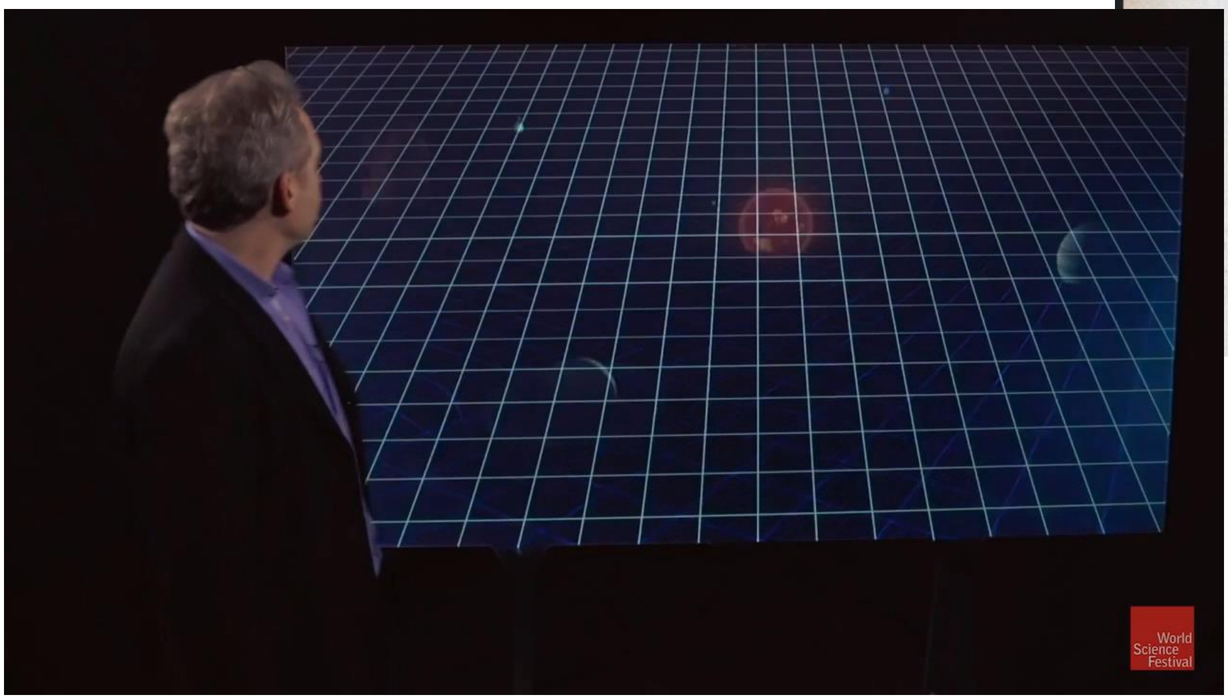
Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

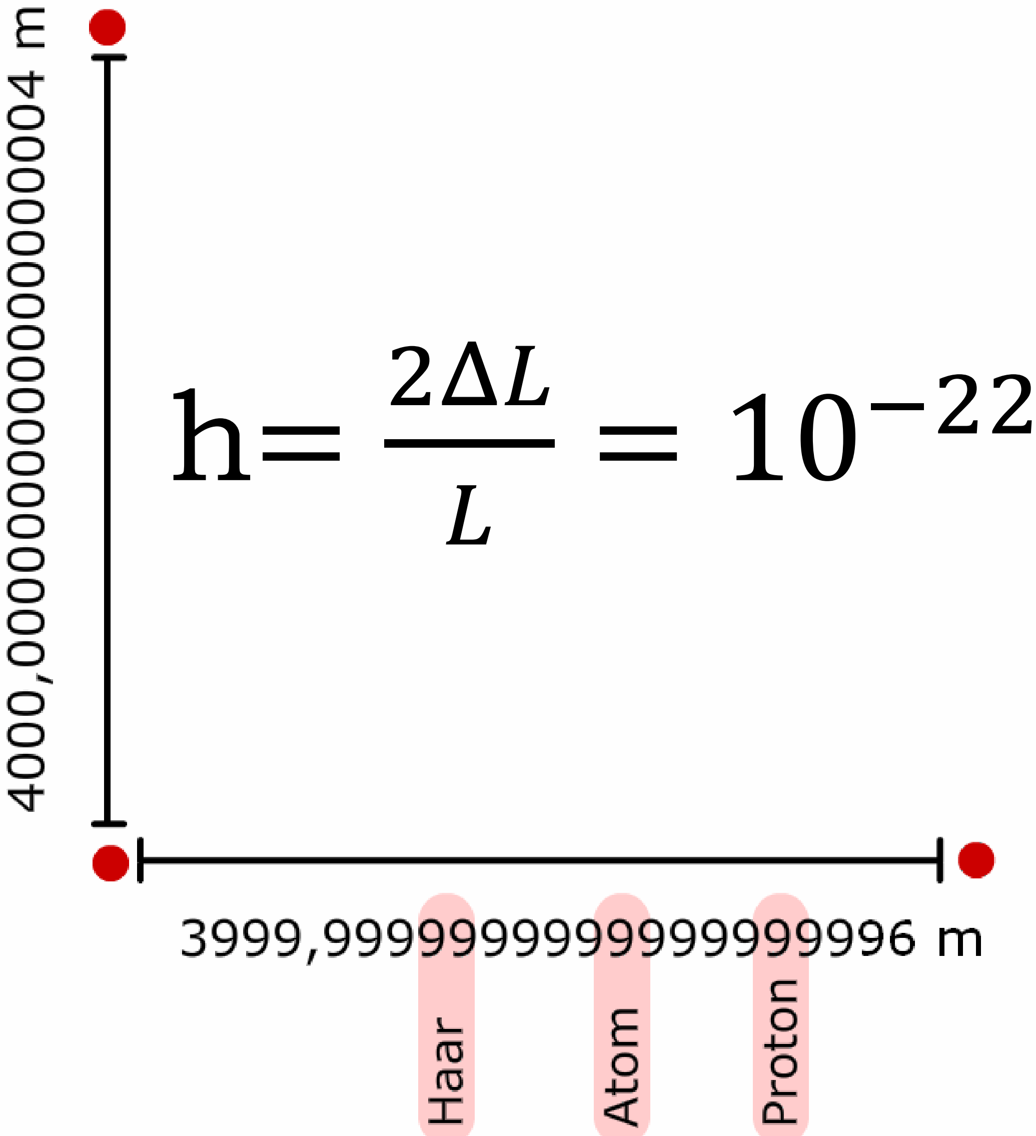
Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

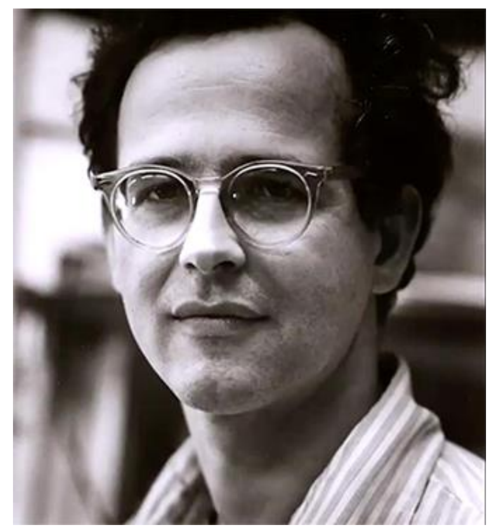


Gravitational waves can be measured with an ITF



$$h = \frac{2\Delta L}{L} = 10^{-22}$$

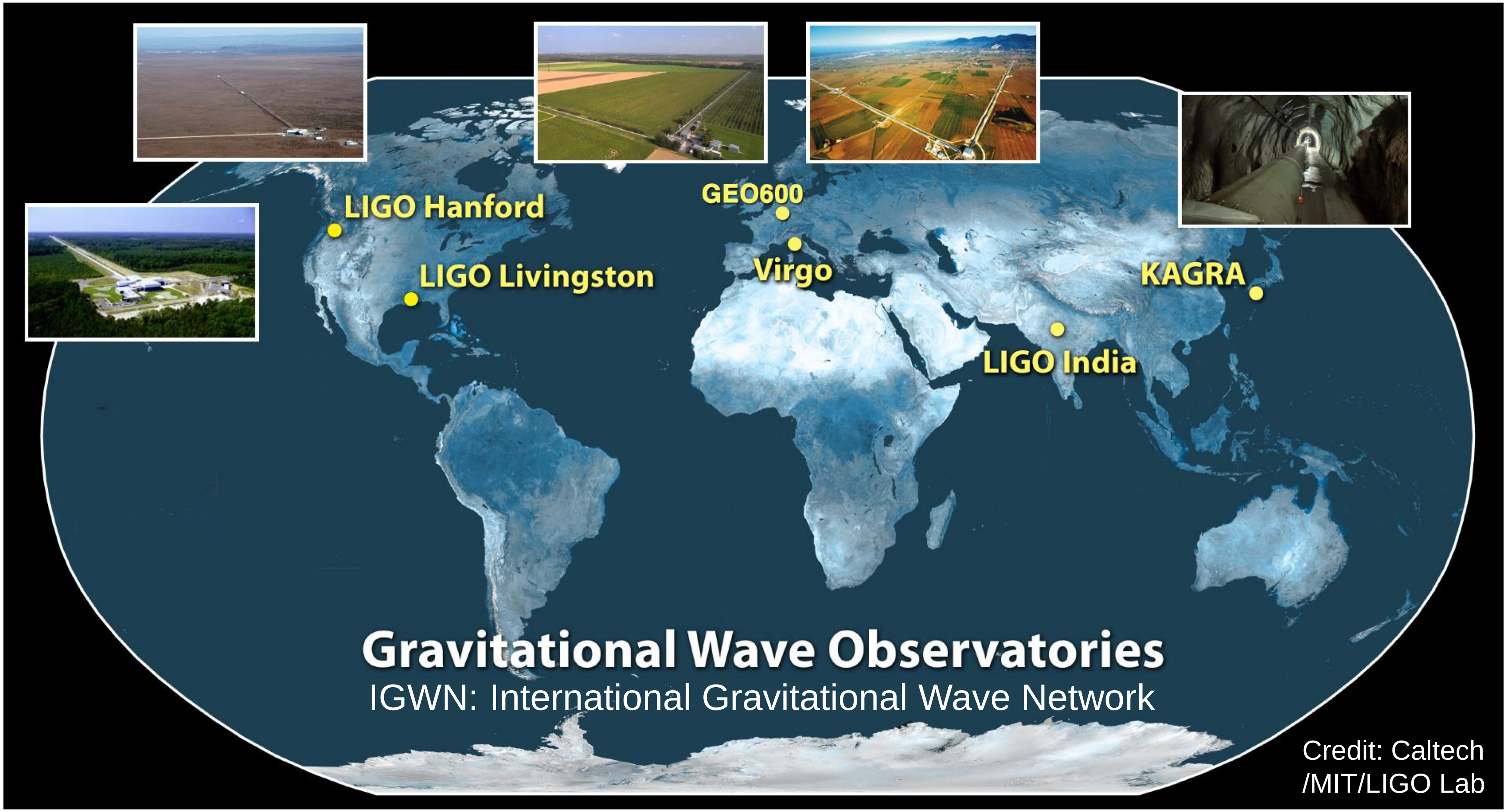
In 1964, Rai Weiss was at MIT as a professor, and asked “What’s really measurable in general relativity?” He found the answer in Pirani’s papers presented at Chapel Hill in 1957



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

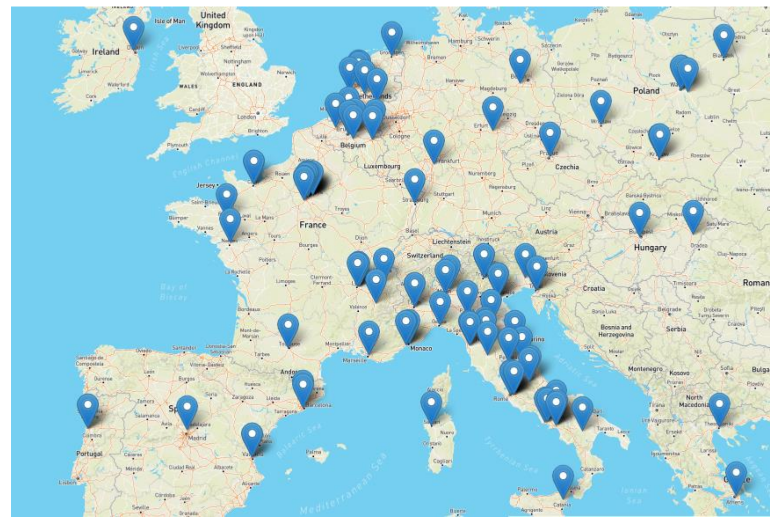
Virgo is a European collaboration with 713 members, 502 authors from 129 institutions in 16 different countries. Virgo has more that doubled its size in the last few years

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, Denmark, 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

14 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

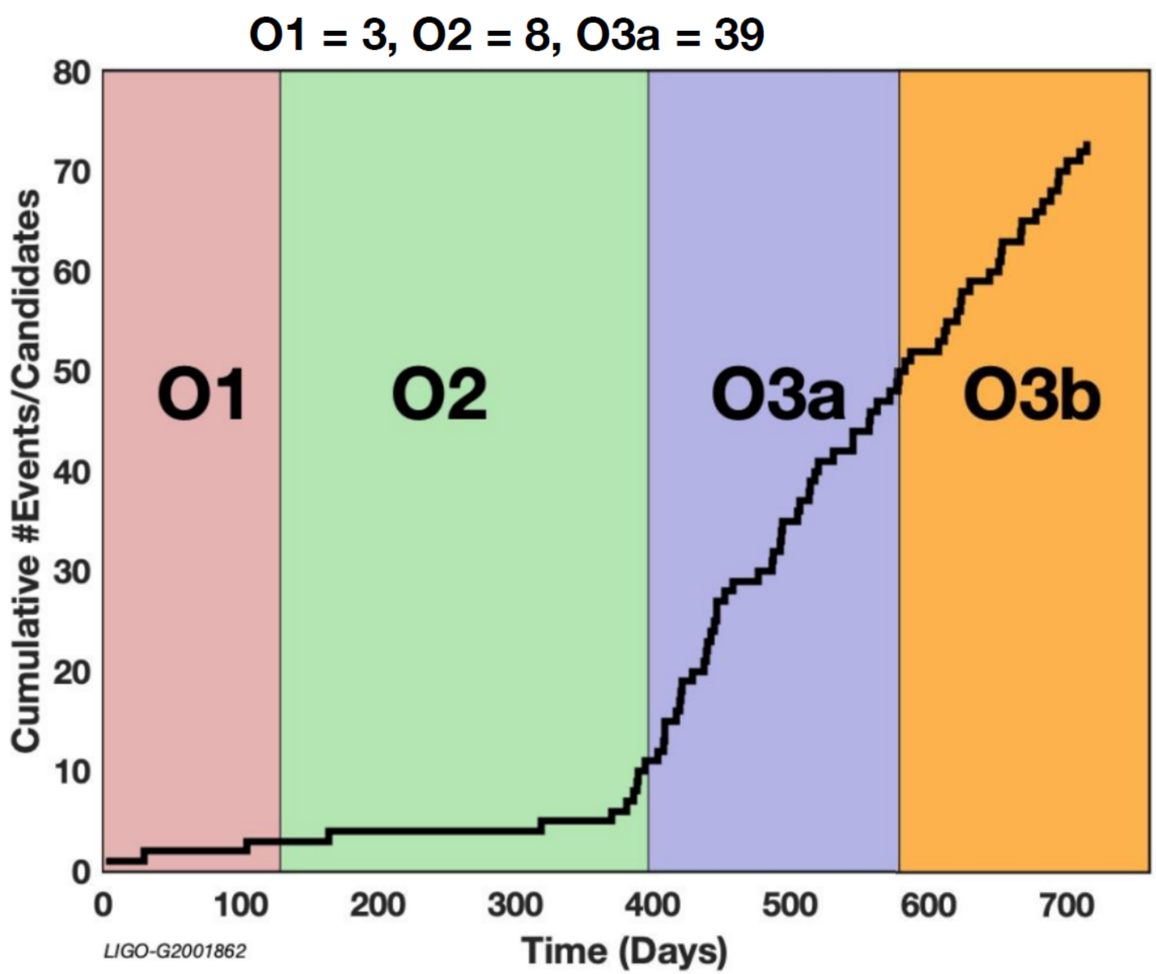
Observing run 2

- 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

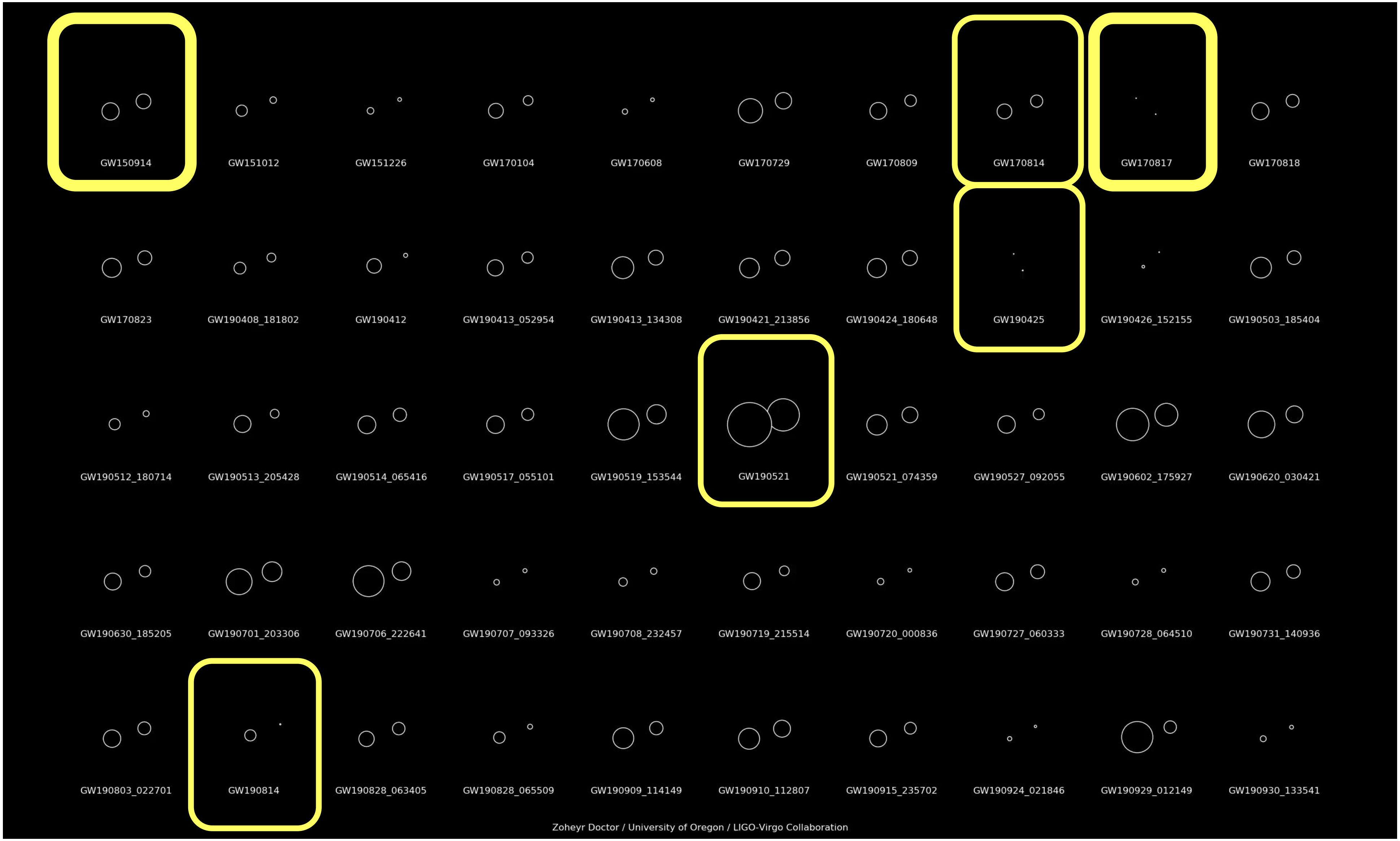


Some scientific highlights from O1, O2 and O3a

Gravitational-Wave Transient Catalog, GWTC2

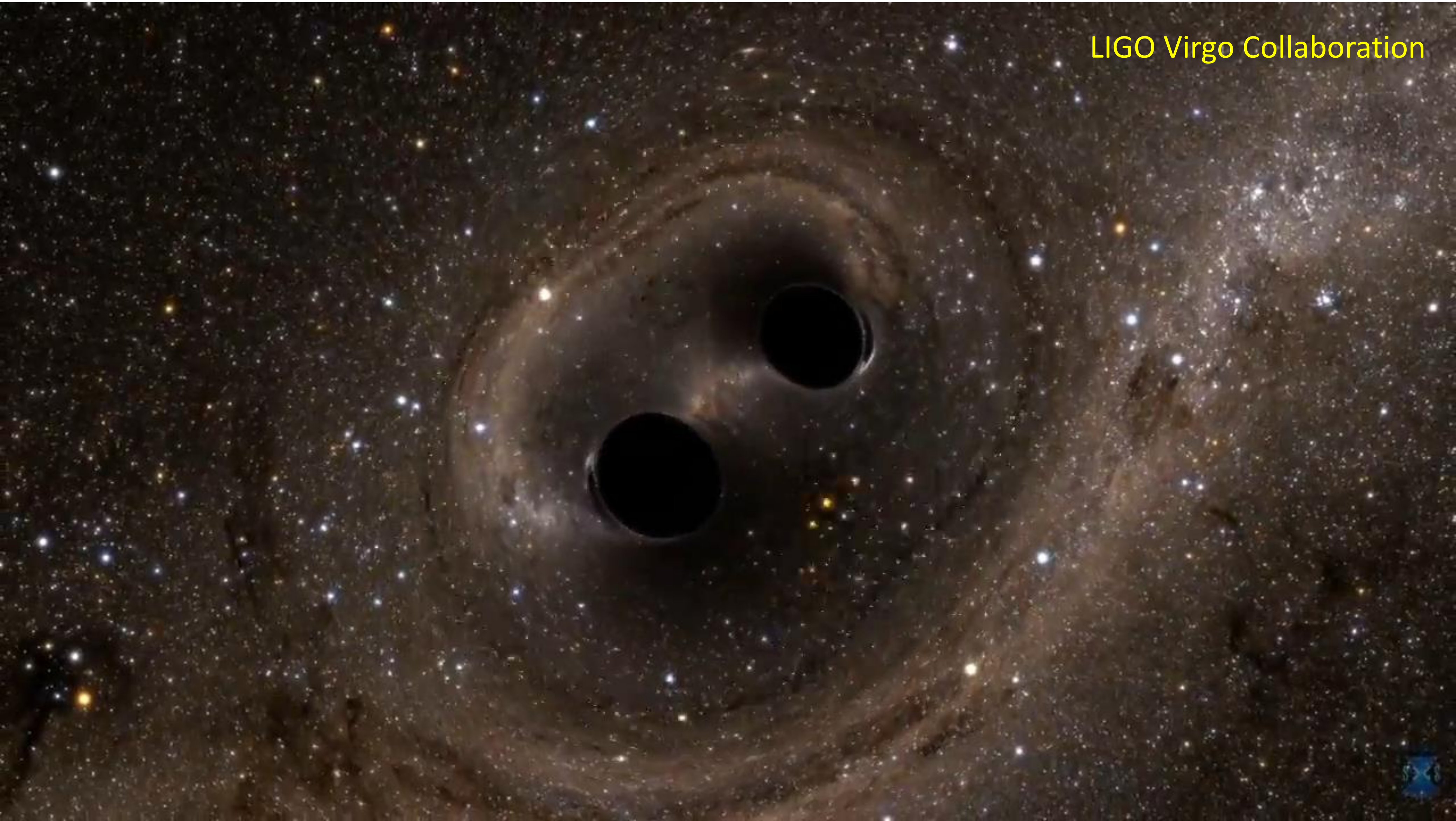
Compact binary coalescences observed by LIGO &Virgo during the first half of the third observing run

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



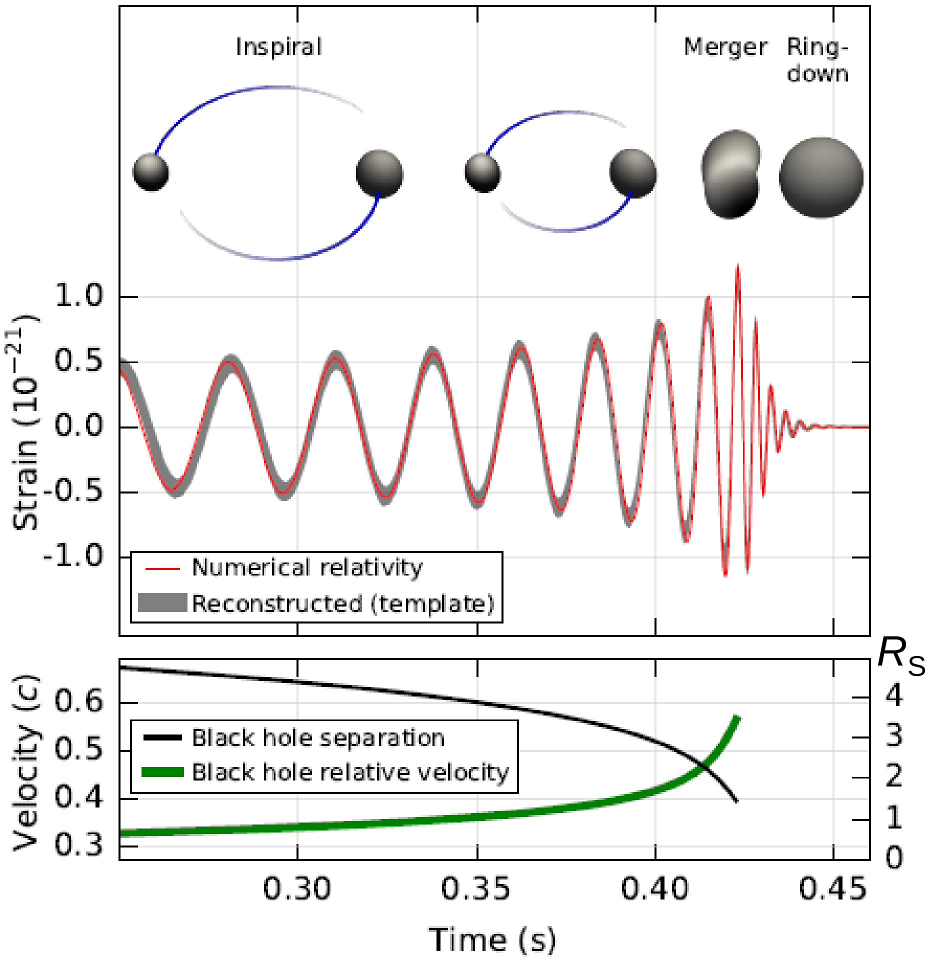
Event GW150914

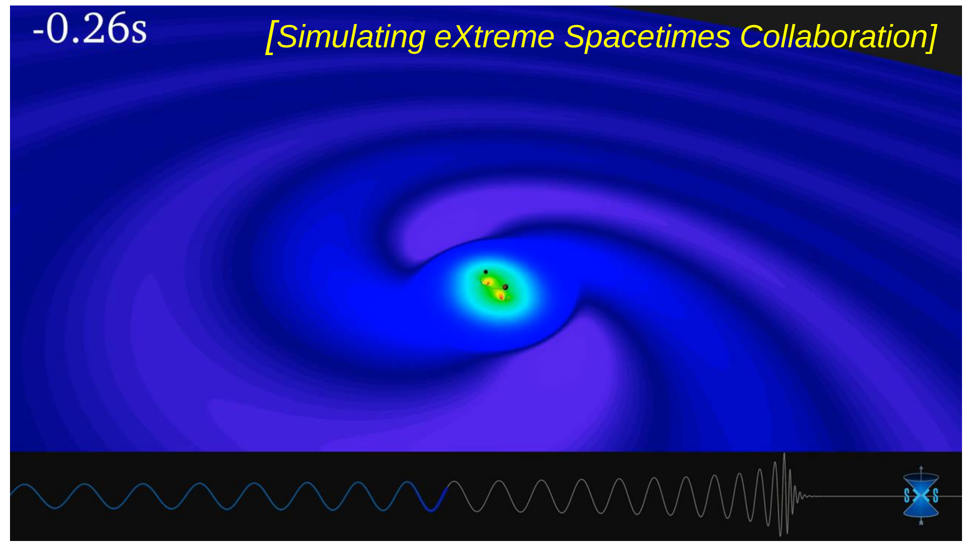
On September 14, 2015 we detected with the LIGO detectors for the first time gravitational waves (vibrations in the fabric of space and time) from the collision of two black holes



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

Parameter inference: component masses and spins

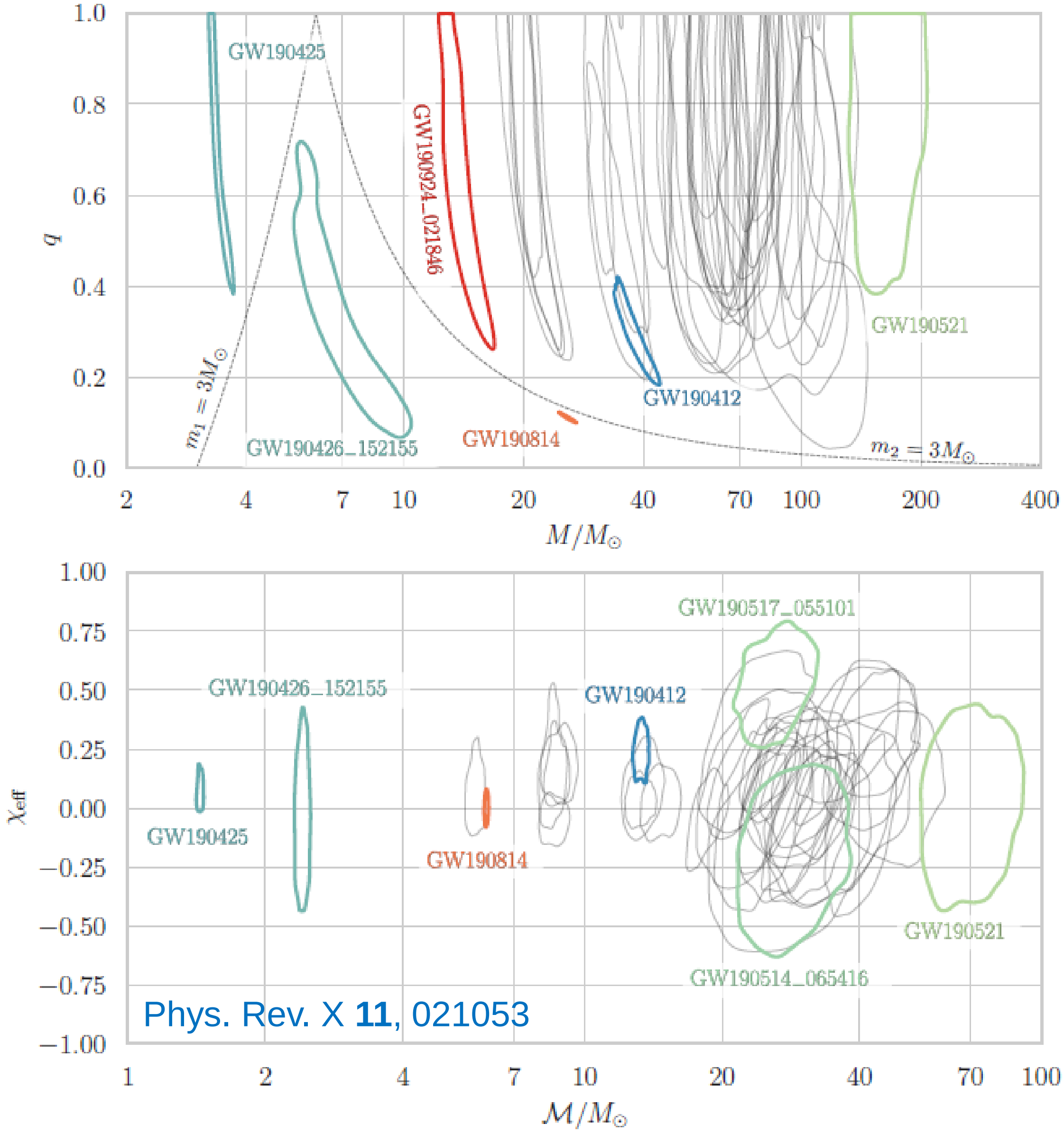
Spin maybe the key to formation channels

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

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



Phys. Rev. X **11**, 021053

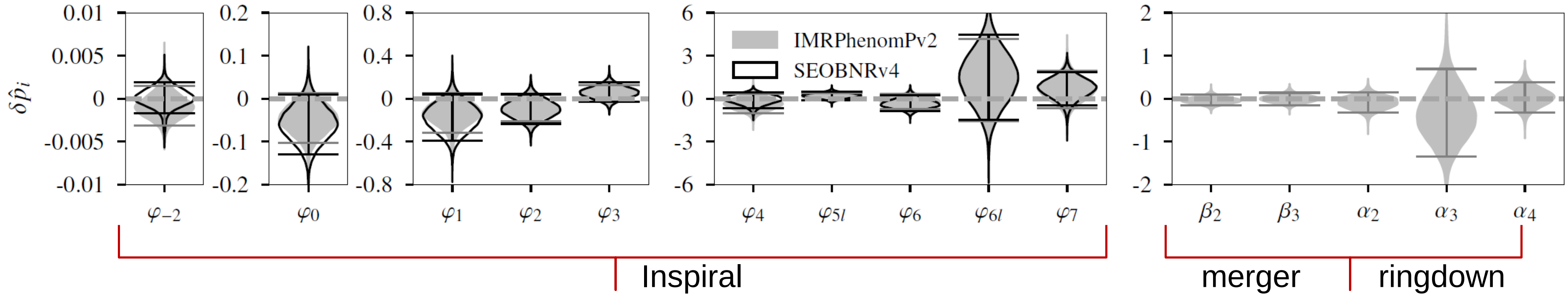
Precision tests of GR with BBH mergers

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): $h^{\alpha\beta}(f) = h^{\alpha\beta} e^{i\Phi(f)}$

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

Towards high precision tests of gravity

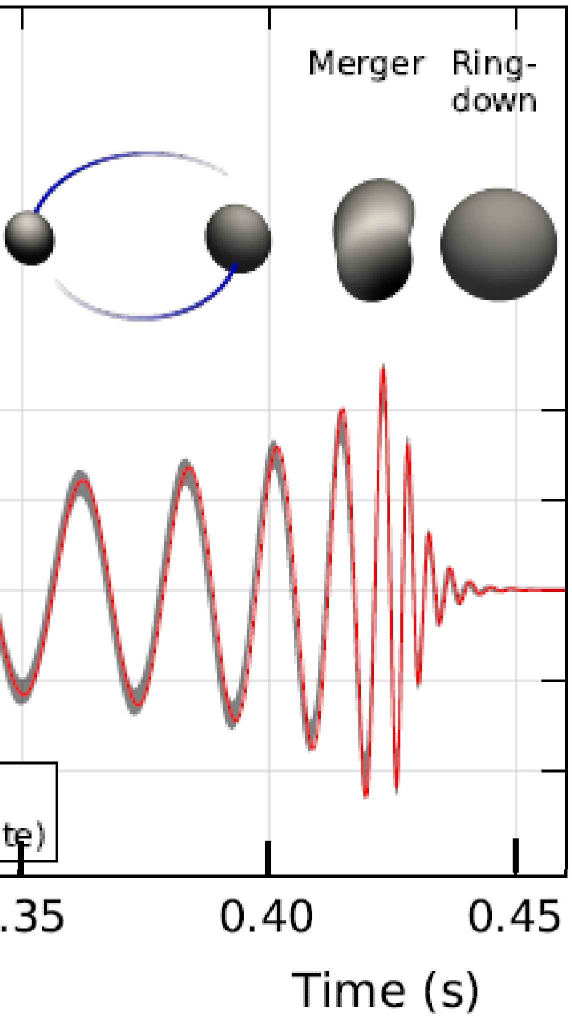
Combining information from multiple events and having high-SNR events will allow unprecedented tests of GR and other theories of gravity

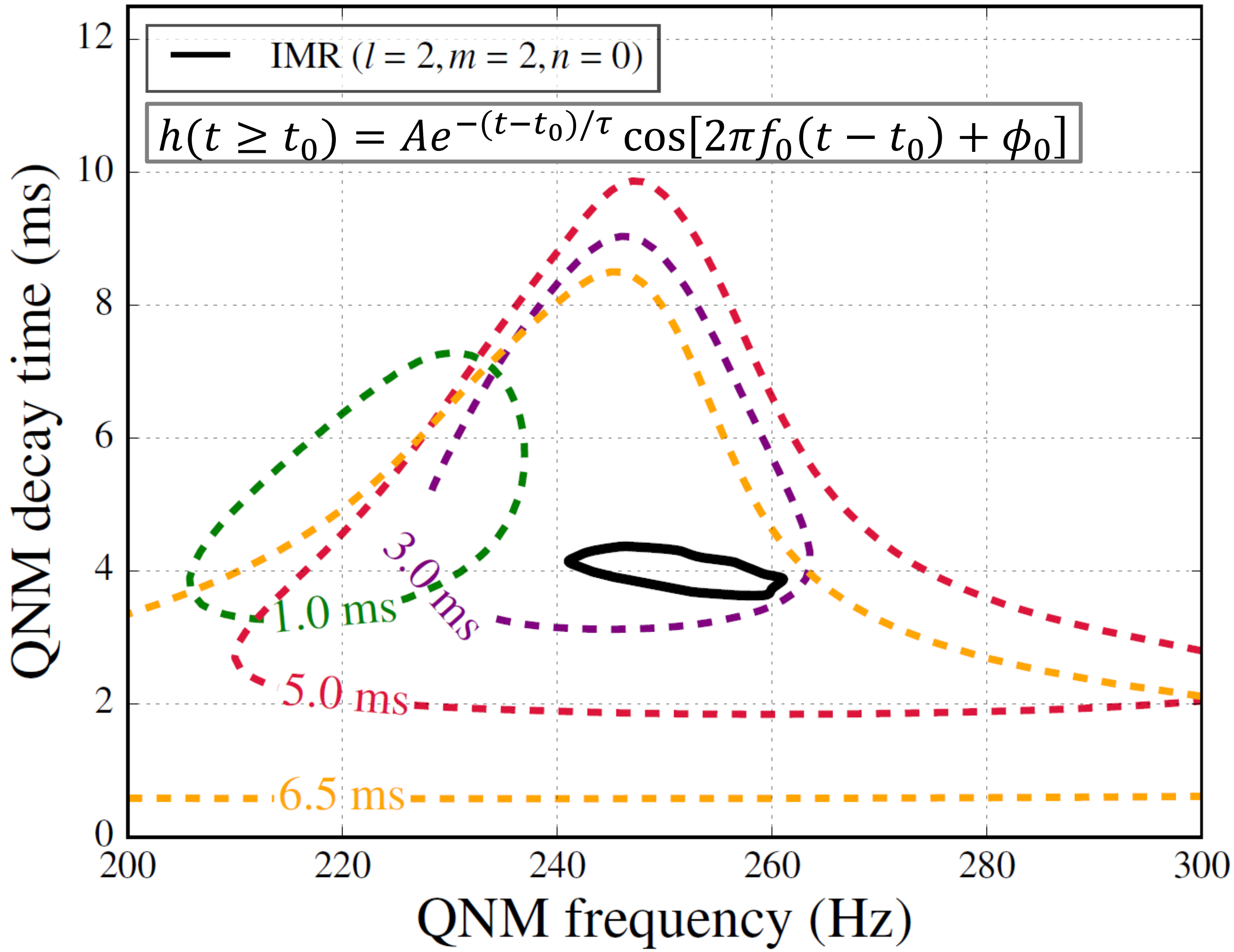
Ringdown terms

Quasi-normal mode analysis; do we see Kerr 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

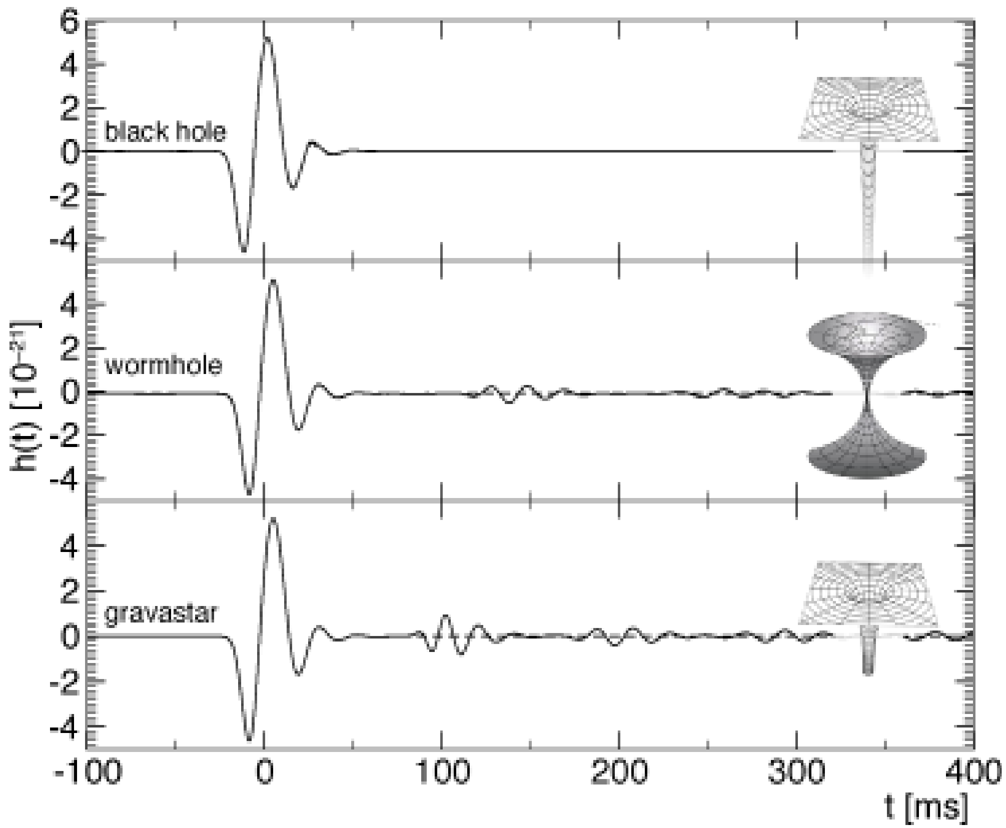
- Dark matter stars

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

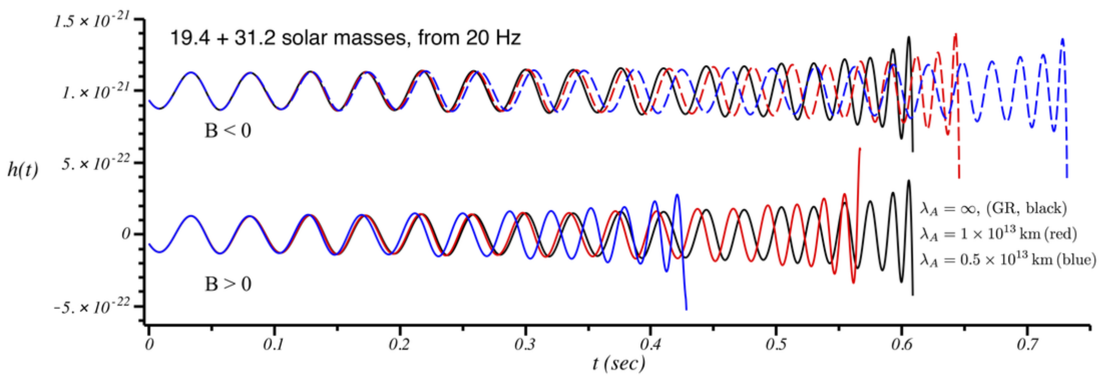
- Inspiral signal: modifications due to tidal deformation effects
- Ringdown process: use QNM to check no-hair theorem
- Echoes: even for Planck-scale corrections $\Delta t \approx -nM \log\frac{l}{M}$
- Studies require good sensitivity at high frequency

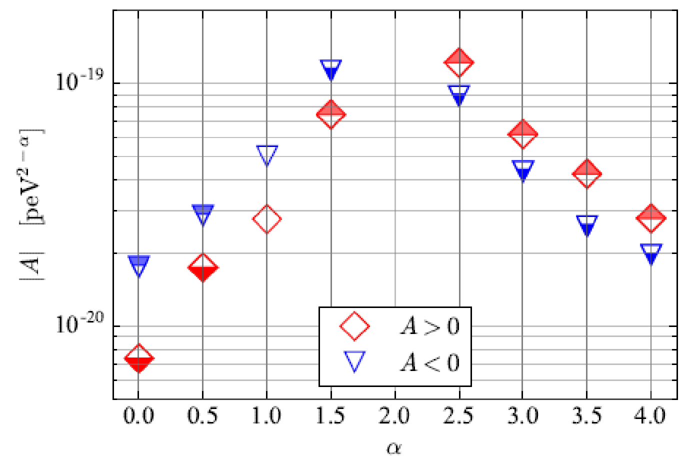
Bounds on violation of Lorentz invariance

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)

Bound on mass of the graviton: $m_g \leq 1.76 \times 10^{-23} \mathrm{eV}/\mathrm{c}^2$

No evidence for deviations from general relativity

Learning about gravity with LIGO and Virgo

See Abbott et al. Phys. Rev D. 103, 122002 (2021)

Observations

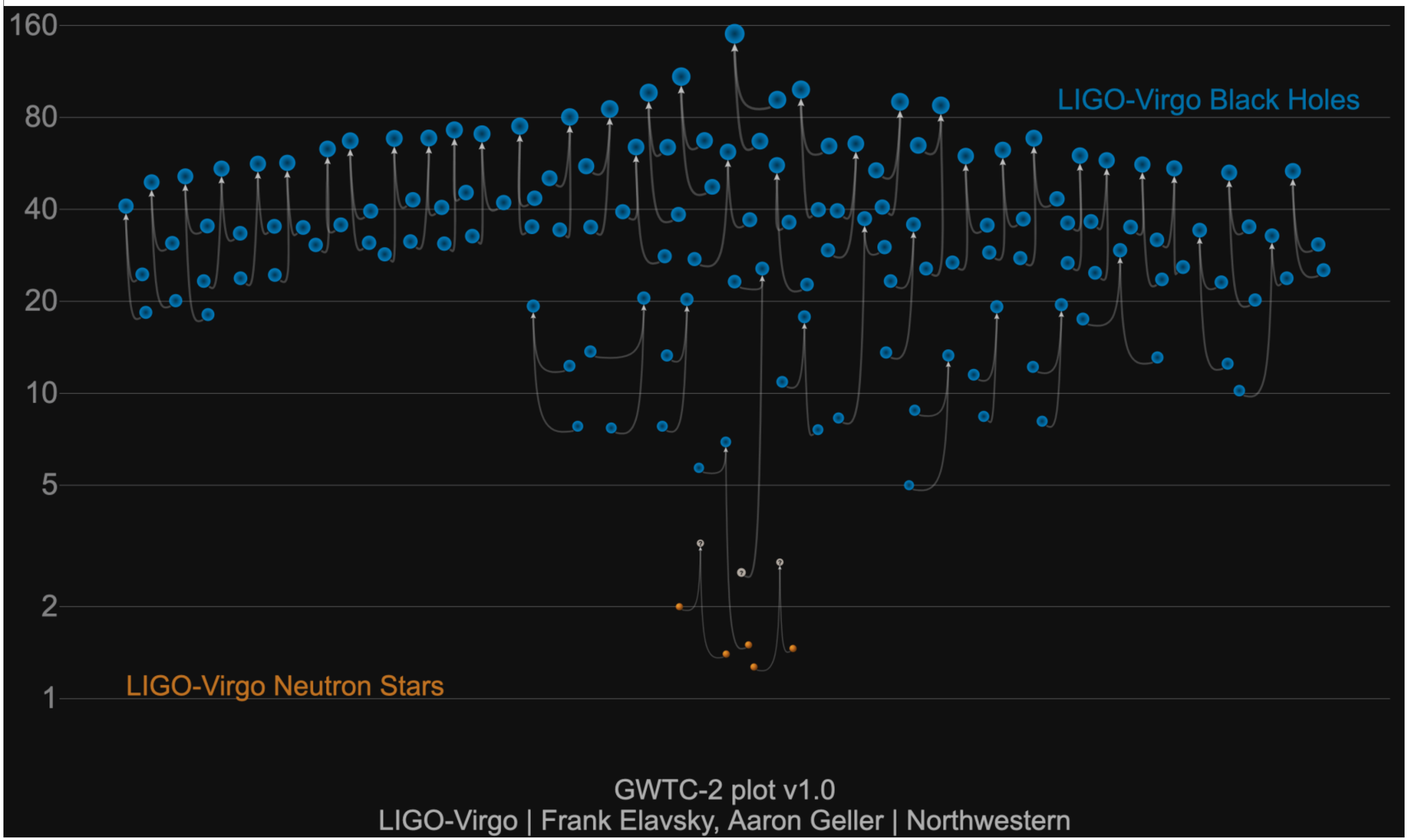
- Residuals from best-fit waveforms consistent with noise ✓
- Consistency of parameters inferred from inspiral and merger-ringdown phases ✓
- No evidence for deviations from the PN coefficients predicted by GR ✓
- Consistency with no dispersion of GWs and massless graviton ✓
- BH spin-induced quadrupole moments are consistent with their Kerr values ✓
- Ringdown frequencies and damping times consistent with GR ✓
- No detection of echoes ✓
- No evidence for pure scalar or pure vector polarizations ✓

- New bound on mass of graviton: $m_g \leq 1.76 \times 10^{-23} \mathrm{eV}/\mathrm{c}^2$

Population inference from GWTC2

Combine many observations to infer underlying properties. More sensitive than single-event inference. See Abbott et al. ApJ Lett. 913, L7 (2021)

Note the presence of compact objects in the 2 – 5 and 60 – 120 $m_\odot$ mass gaps



Pair instability mass gap

Lower mass gap

GW190425: LIGO-Virgo detect a second binary neutron star merger

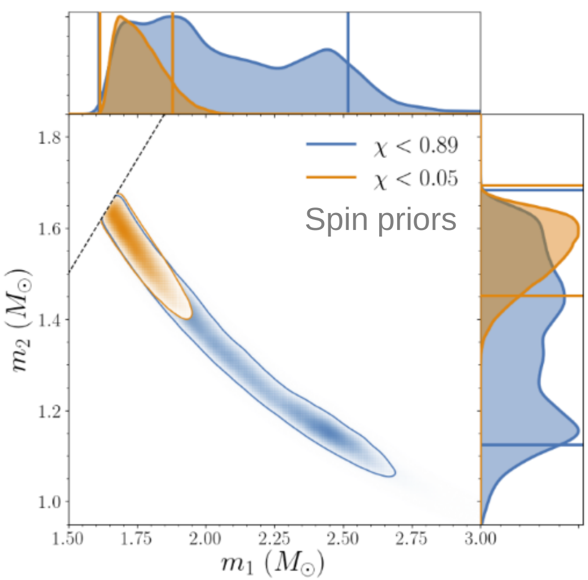
Confirmation of our BNS merger detection in 2017 (most likely). Cannot rule out BBH or NSBH

First released event of O3 run: Press Release on January 6, 2020 at IAU meeting in Hawaii

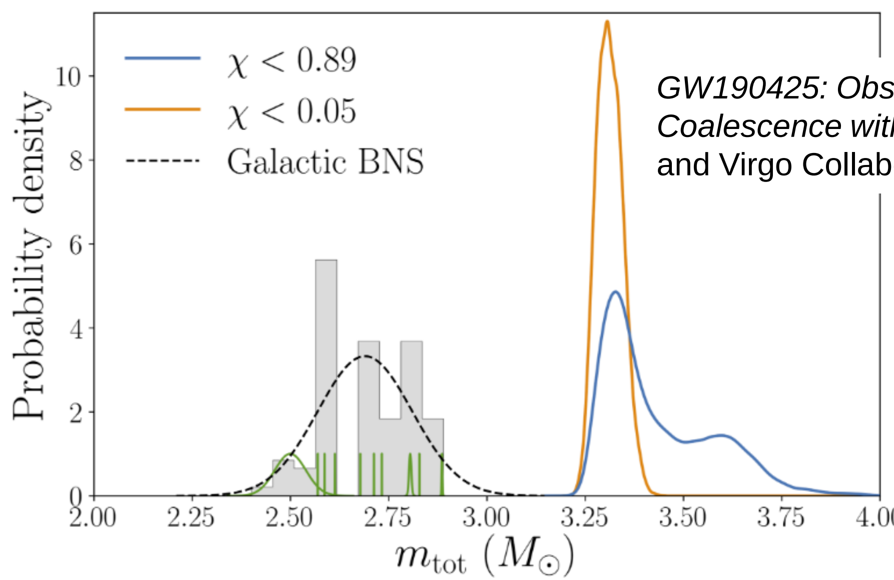
Remarks:

- 2-interferometer observation with SNR = 12.9 (FAR > 1 in 69,000 yr): LIGO-Livingston (L1) and Virgo
- Total mass of about 3.4 $M_\odot$ is larger than in any known system
- Component masses 1.12 to 2.52 M⊙ (1.45 to 1.88 M⊙ if we restrict component spin magnitudes)
- Initial sky map had a 90% credible region of 10,200 deg^2 at luminosity distance of 159^{+69}_{-72} Mpc

Posteriors of component masses



Total system masses under different spin priors



GW190425: Observation of a Compact Binary Coalescence with Total Mass ~ 3.4 M, LIGO and Virgo Collaborations, ApJL, 892:L3, 2020

GW190814: a 23 $M_\odot$ BH merges with a 2.6 $M_\odot$ compact object

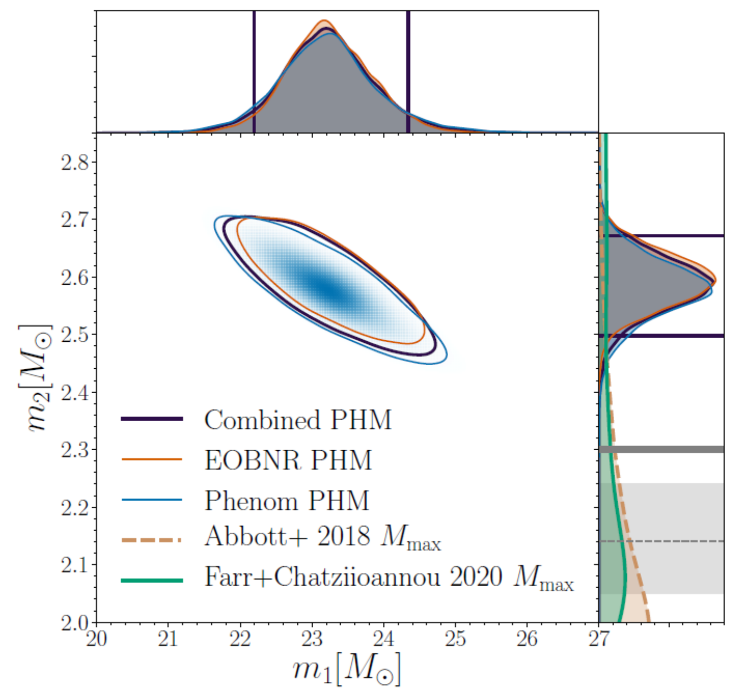
Either the heaviest neutron star or lightest black hole ever observed (ever = not only via GW)
Can we distinguish neutron stars and black holes based on mass?

Press Release on June 24, 2020

Remarks:

- Signal first identified by LIGO-Livingston (L1) and Virgo; classified as mass gap and later NSBH
- Subsequent 3-interferometer analysis yields SNR = 25
- Most unequal mass ratio yet observed of 9:1
- Strongest evidence for multipole emission observed so far, and in agreement with General Relativity
- Spin of primary black hole well constrained to ≤ 0.07
- Clear evidence for inclination
- Challenge for formation models
- Sky map had a 90% credible region of 18.5 deg^2
- Luminosity distance of 241^{+41}_{-45} Mpc

Posteriors of component masses



GW190521: discovery of an intermediate mass black hole

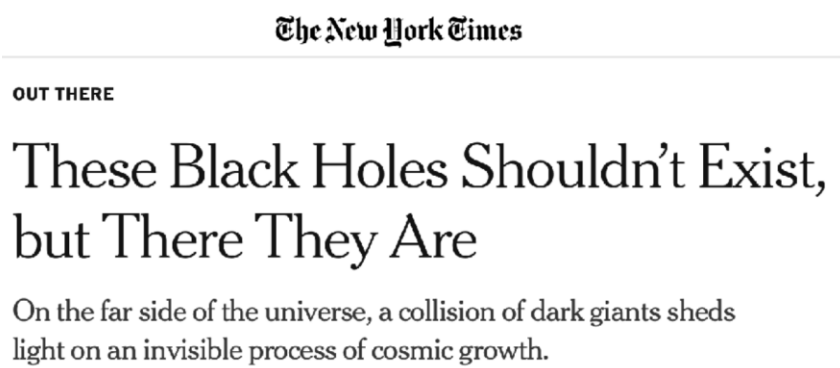
Binary black hole merger at 5.3 Gpc
See Abbott et al. Phys. Rev. Lett. 125, 101102 (2020) and Abbott et al. ApJ Lett. 900, L13 (2020)

A massive binary black hole merger encroaching on the pair-instability mass gap

m_1	m_2	$m_{\rm tot}$
$\sim 85\,\mathrm{M}_\odot$	$\sim 66\,\mathrm{M}_\odot$	$\sim 150\,\mathrm{M}_\odot$

Remarks:

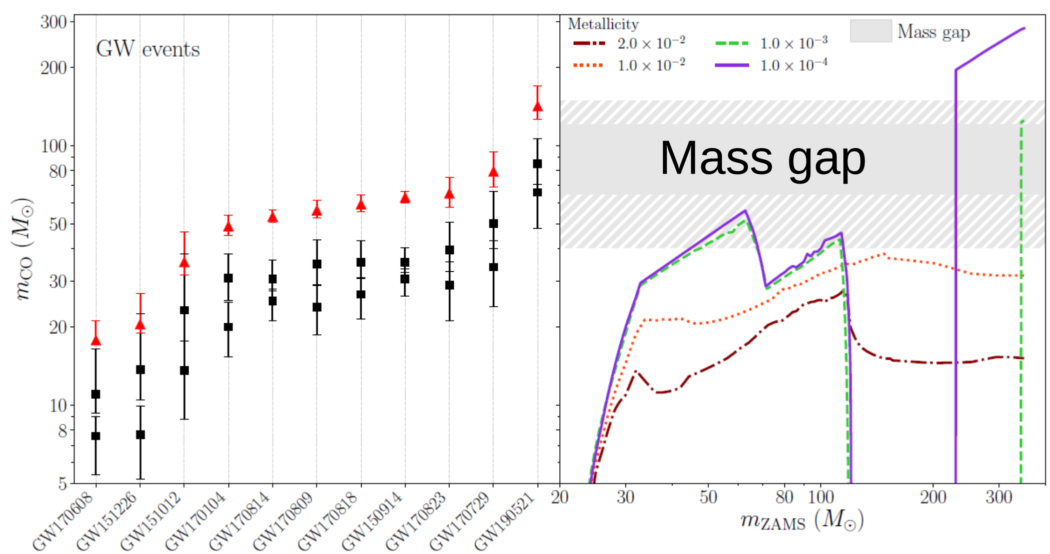
- GW190521: Triple LIGO-Virgo open public alert of a BBH candidate at 3931±953 Mpc and 765 $\deg^2$
- Most massive GW binary observed to-date
- First clear detection of “intermediate mass” black hole
- Primary sits squarely in expected mass gap between 50 and 120 solar mass
- Also challenging for standard formation scenarios!


The New York Times

OUT THERE

These Black Holes Shouldn’t Exist, but There They Are

On the far side of the universe, a collision of dark giants sheds light on an invisible process of cosmic growth.

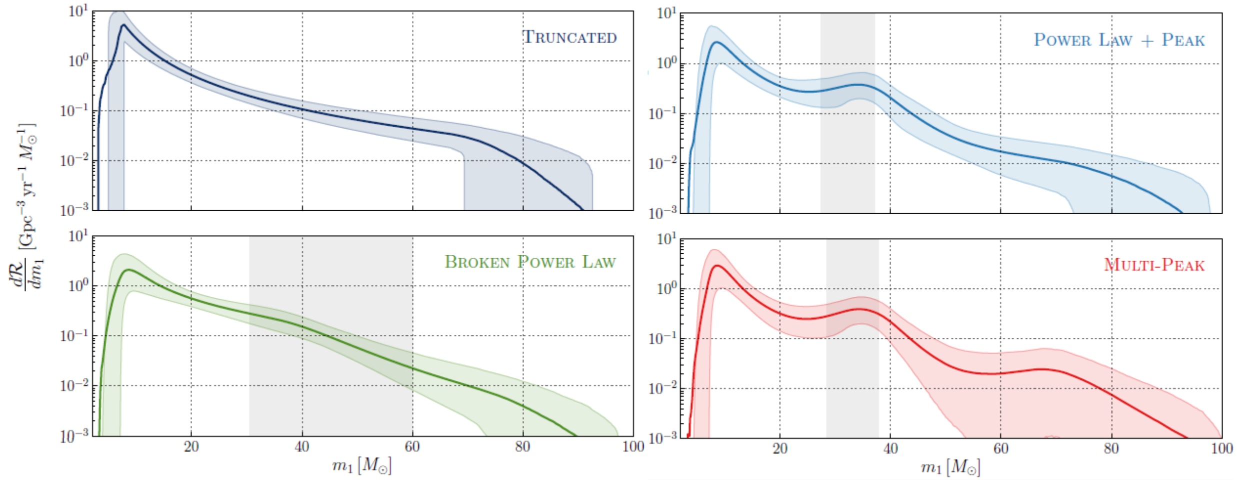


Binary black hole population inference from GWTC-2

Combine many observations to infer underlying properties. More sensitive than single-event inference. See Abbott et al. ApJ Lett. 913, L7 (2021)

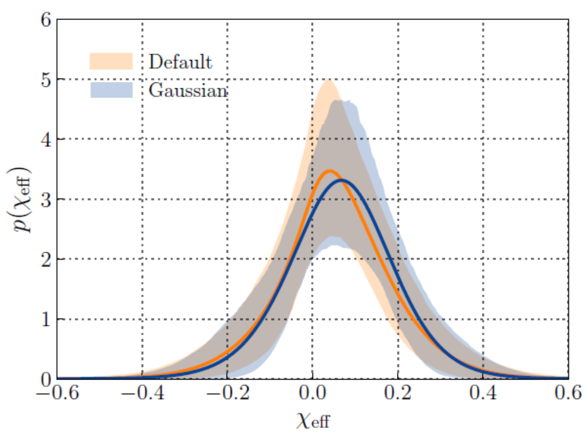
Mass distribution

- Used 47 BBH events
- FAR < 1 per yr
- Truncated model is not a good fit to the data
- Evidence of a feature around 35 - 40 M⊙



Spin distribution

- Mostly small components spin magnitudes
- Some BBH systems have spins misaligned with orbital angular momentum



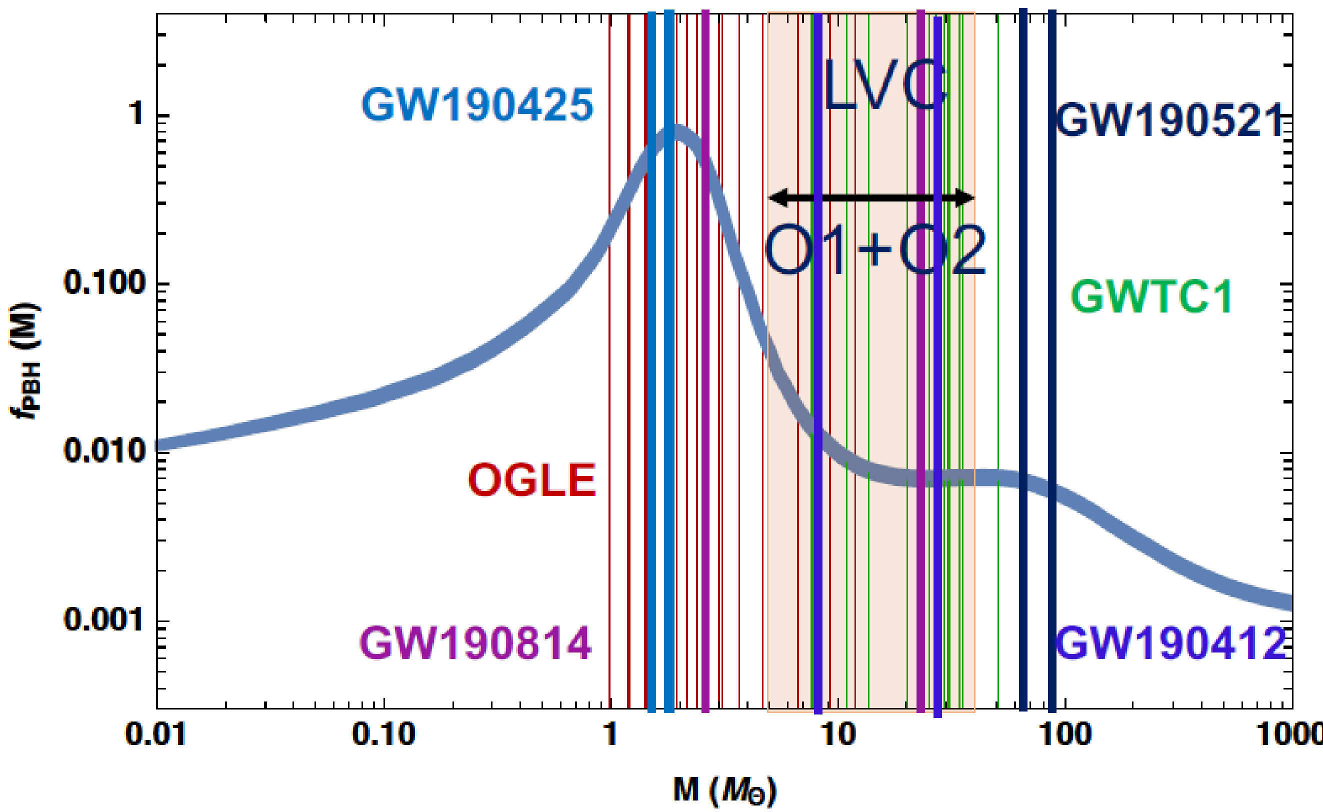
Candidate mergers and PBH from QCD epoch

PBH formation is boosted at the time of the QCD transition due to collapse of large primordial density fluctuations in the early Universe. Predict a proton-peak at 2 – 3 $m_{\odot}$ and a pion bump at 30 – 50 $m_{\odot}$

GW190425 and GW190814 in lower mass gap, while GW190521 is in pair-instability mass gap

PBH merger rates do not exceed LIGO/Virgo limits. PBH may explain low component spins

PBH can explain (even totality) of Dark Matter, but must be clustered to obey astrophysical limits



Blue: PBH mass distribution from almost scale-invariant power spectrum of curvature fluctuations with $n_s = 0.97$

- Normalized to $f_{\text{PBH}} = 1$
- PBH / Hubble mass ratio 0.8

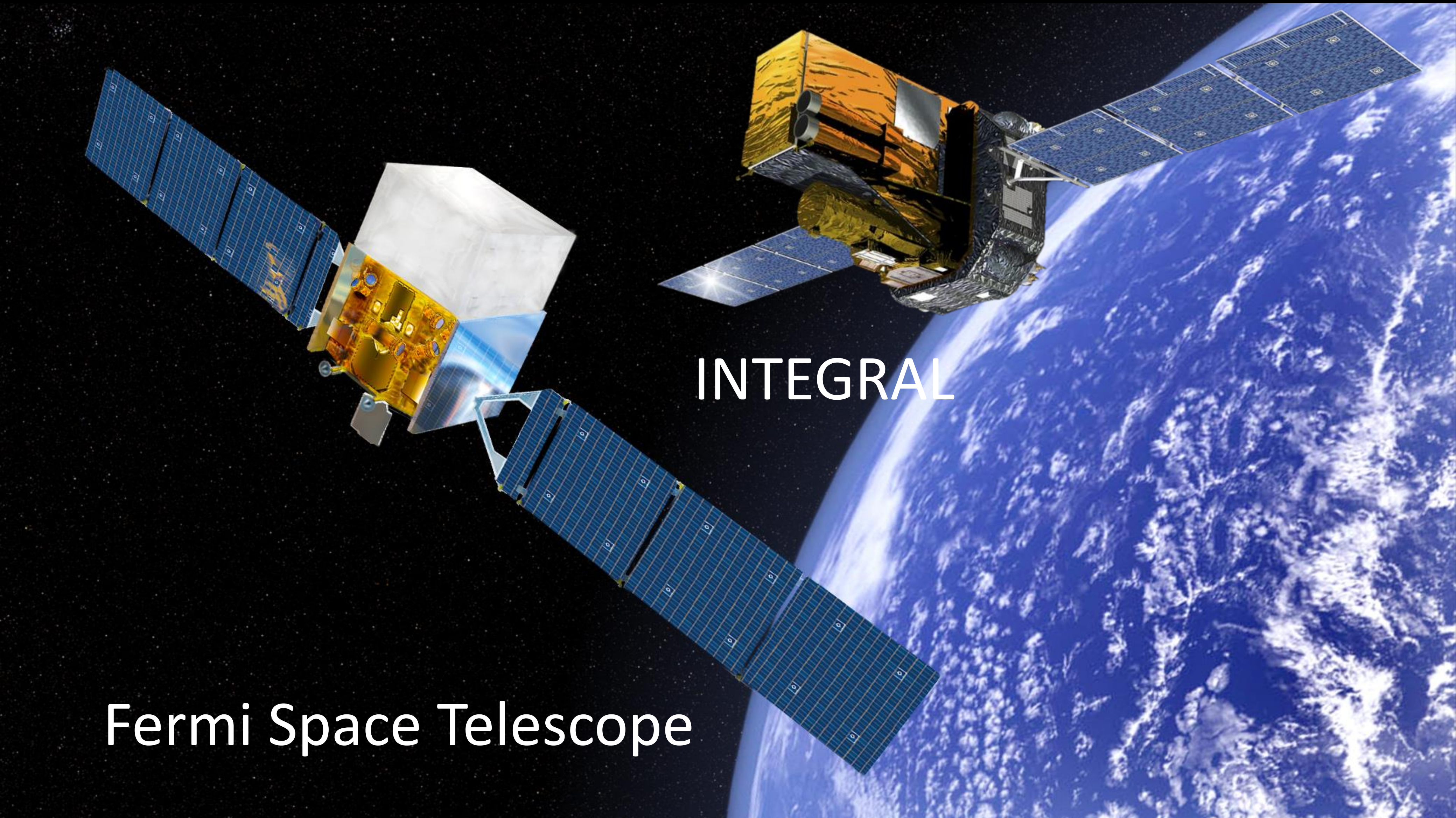
Green: events from GWTC1

Red: microlensing OLGE/GAIA

arXiv: 2007.06481v3

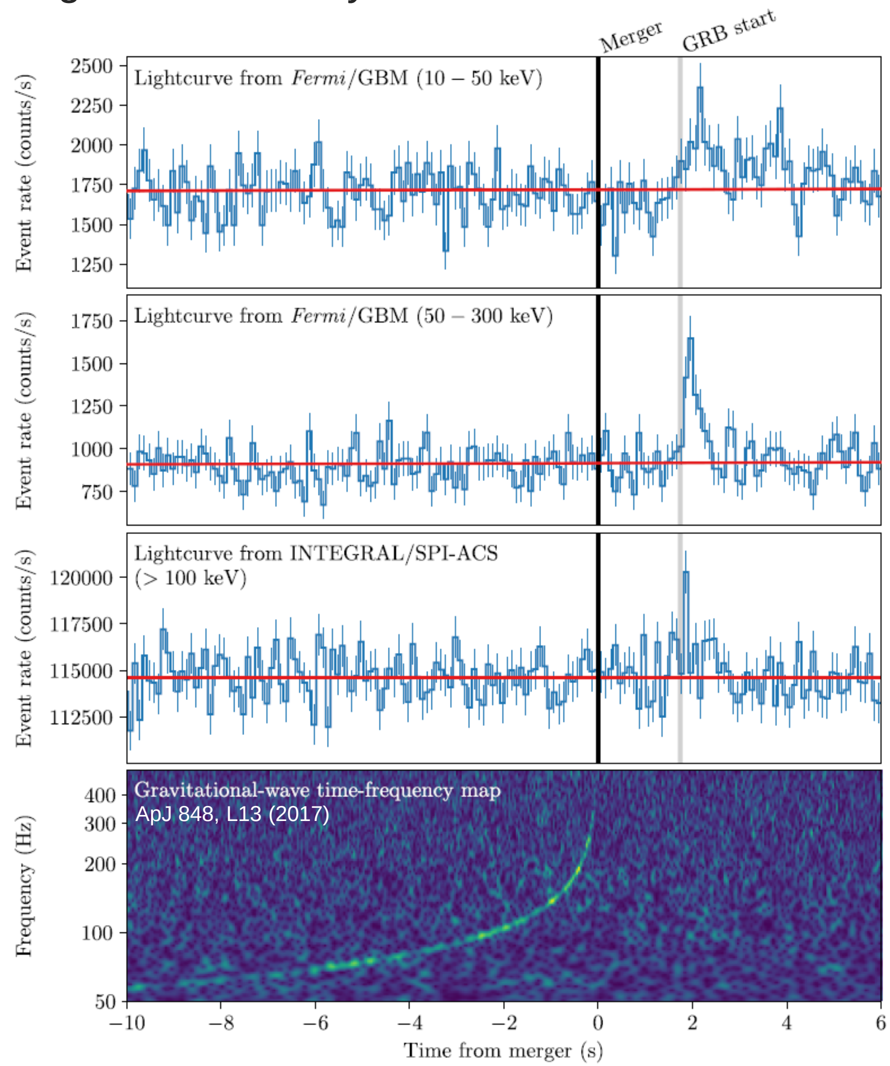
Some scientific highlights: neutron stars

GW180717: gamma rays emitted 1.7 seconds after merger



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 time nuclear density

Temperature: up to 10^{12} K

Magnetic field: up to 10^{11} T

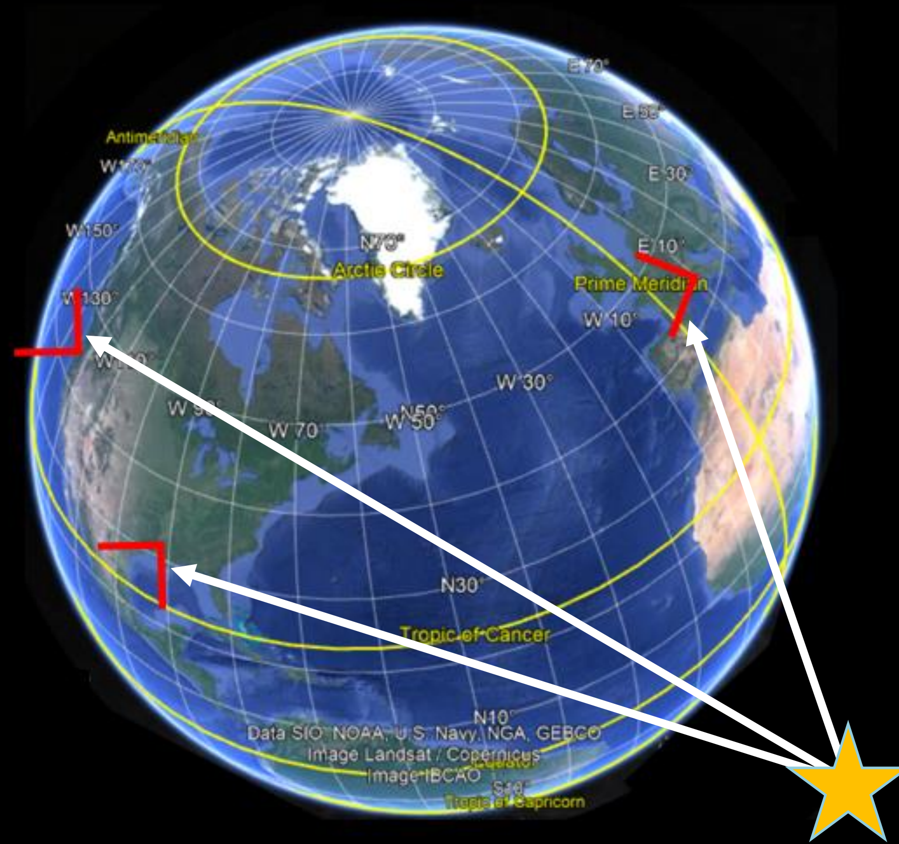
Held together by gravity and supported by degeneracy pressure and NN repulsion

Extrapolate behavior of QCD, superconductivity, and superfluidity

Equation Of State: many models

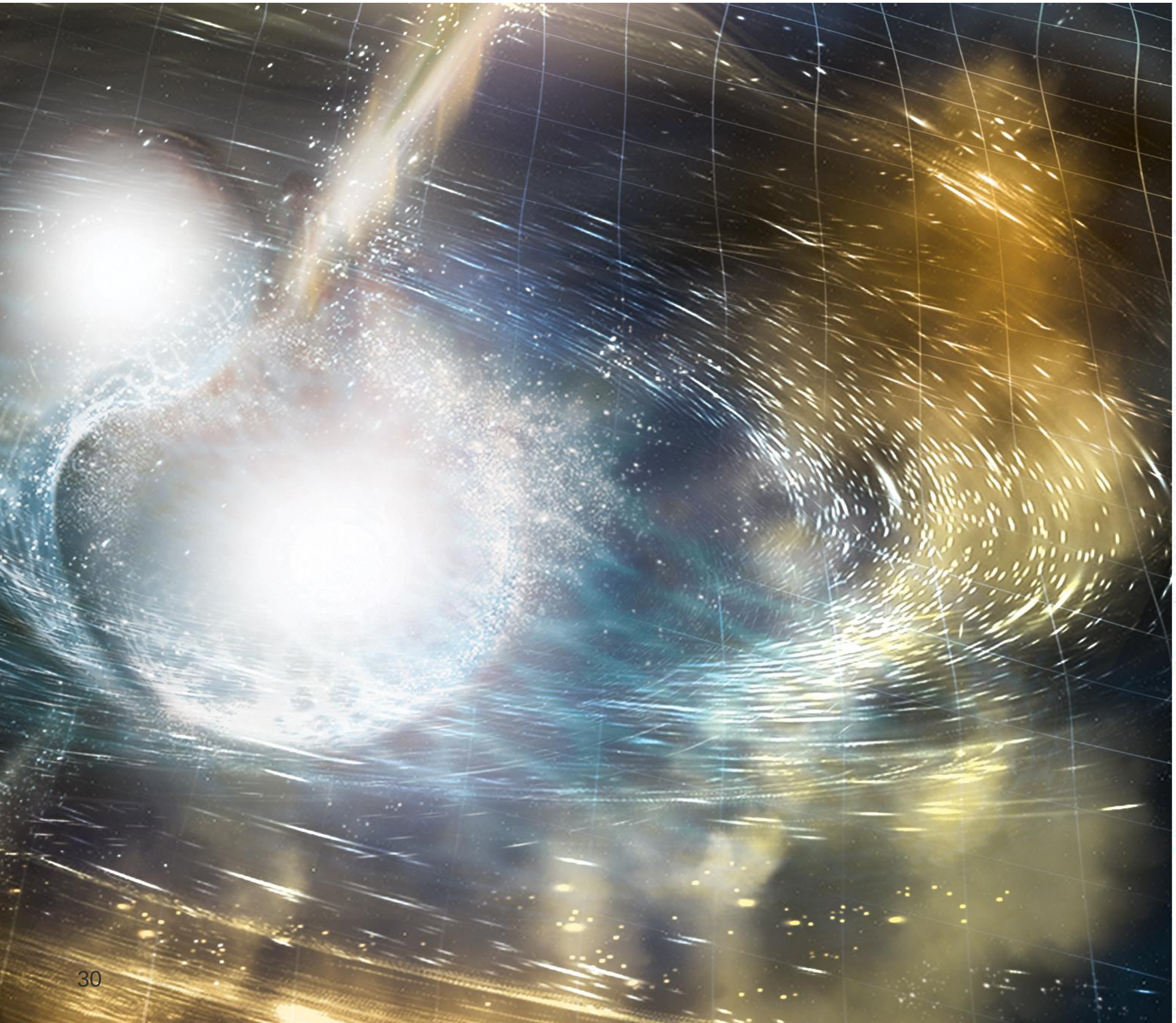
Source location via triangulation

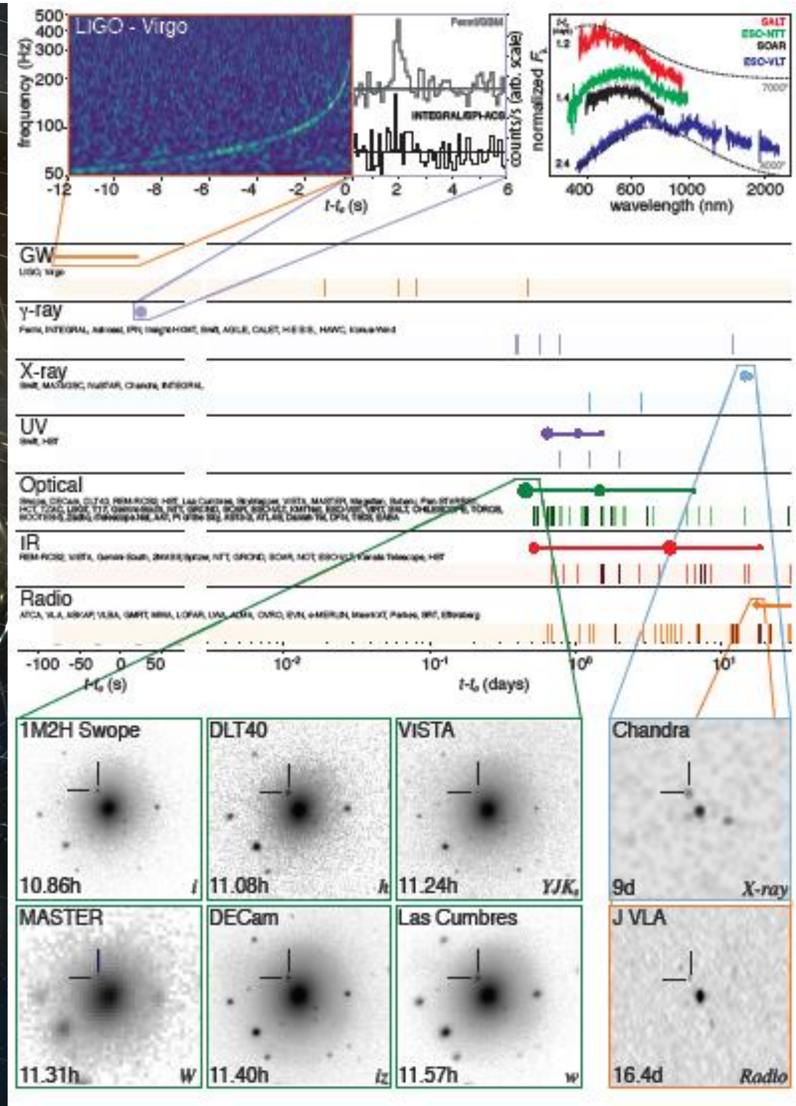
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it

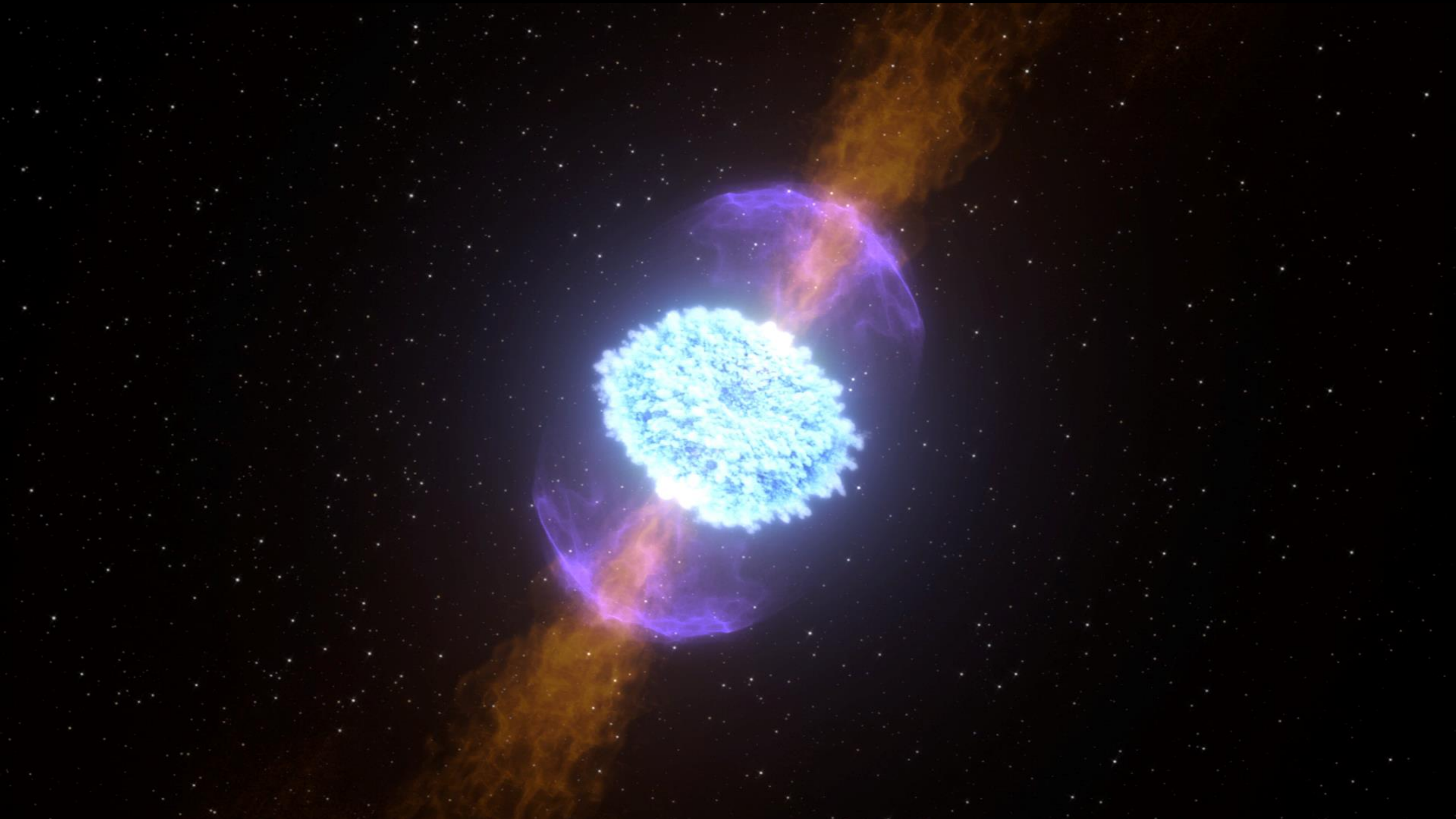


GW170817: start of multi-messenger astronomy with GW

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)

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

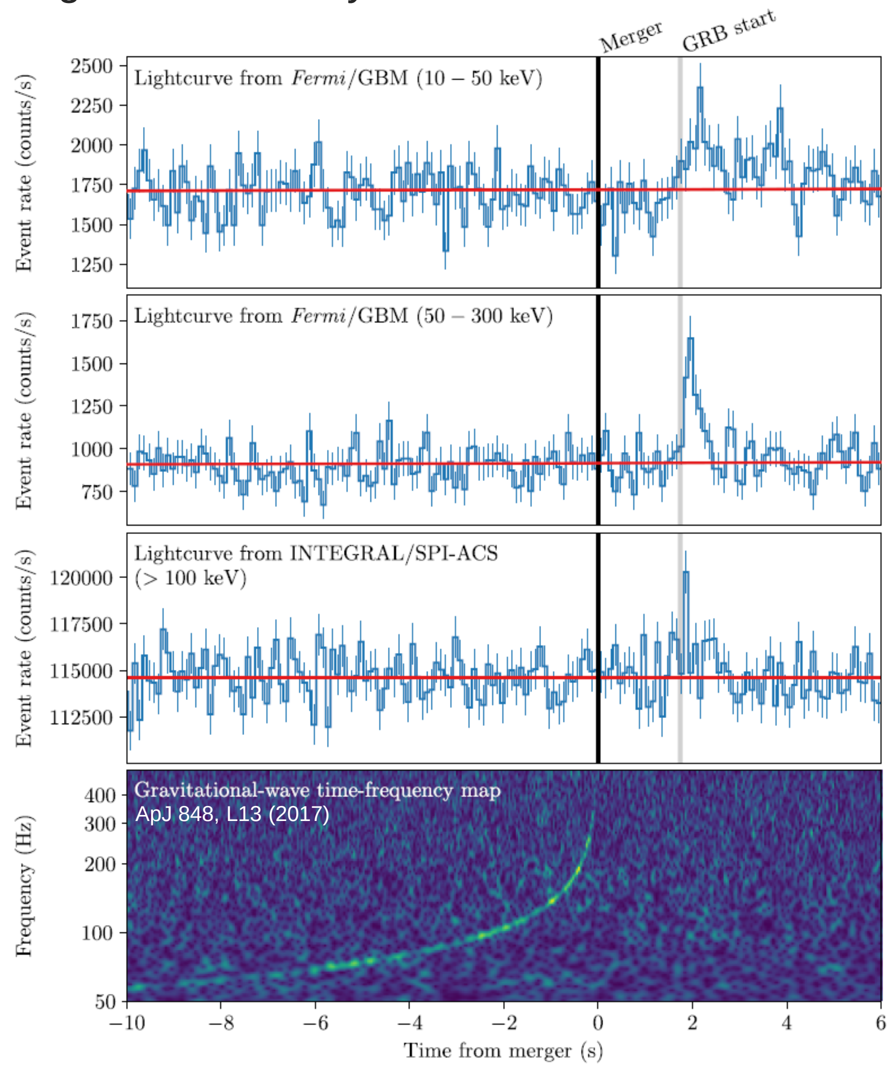
Test of Equivalence Principle

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

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

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

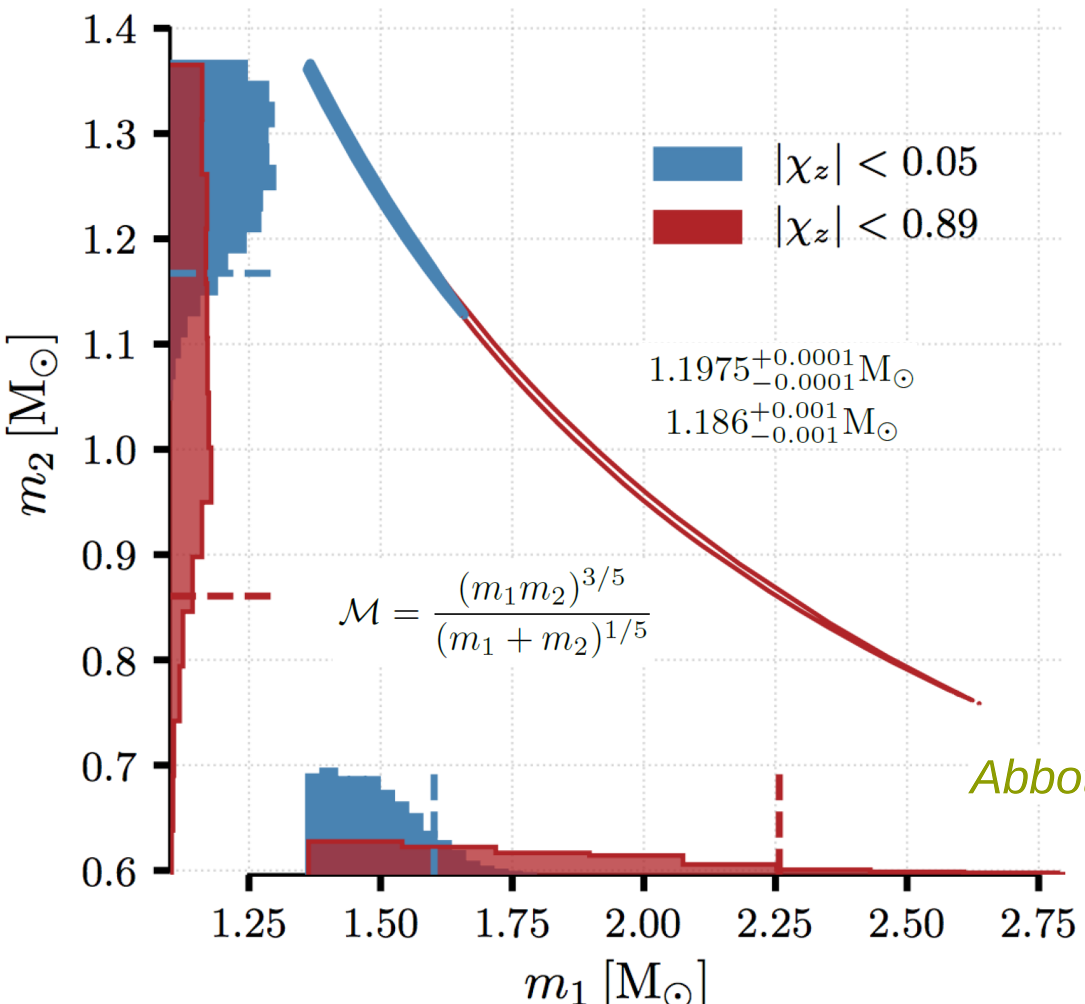
Including data on peculiar velocities to 50 Mpc we find
$\Delta\gamma \leq 4 \times 10^{-9}$



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

Advanced Virgo

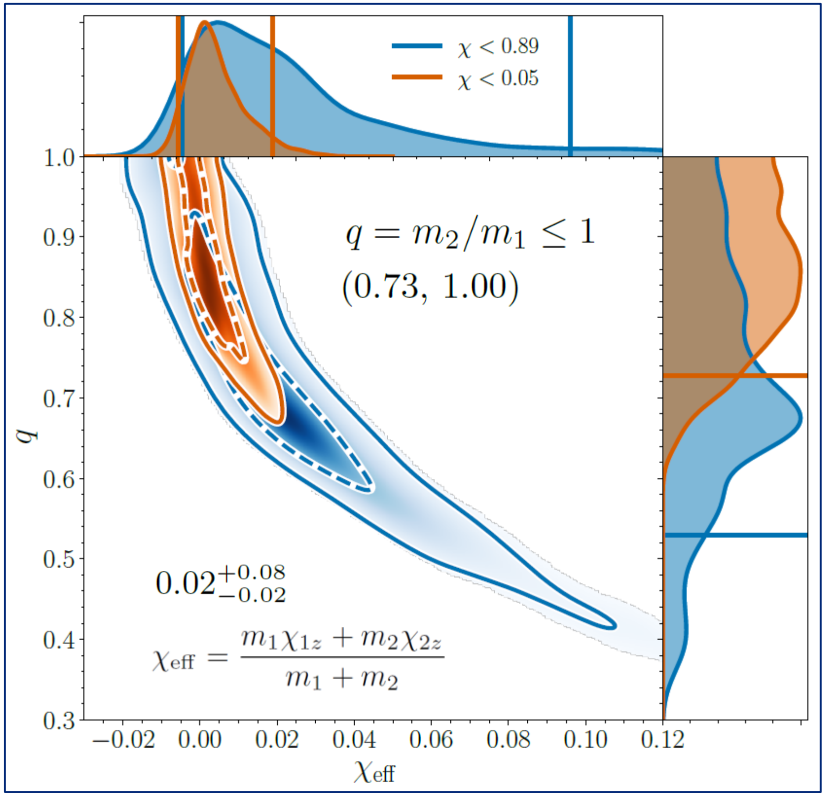
Inferring neutron star properties: spins

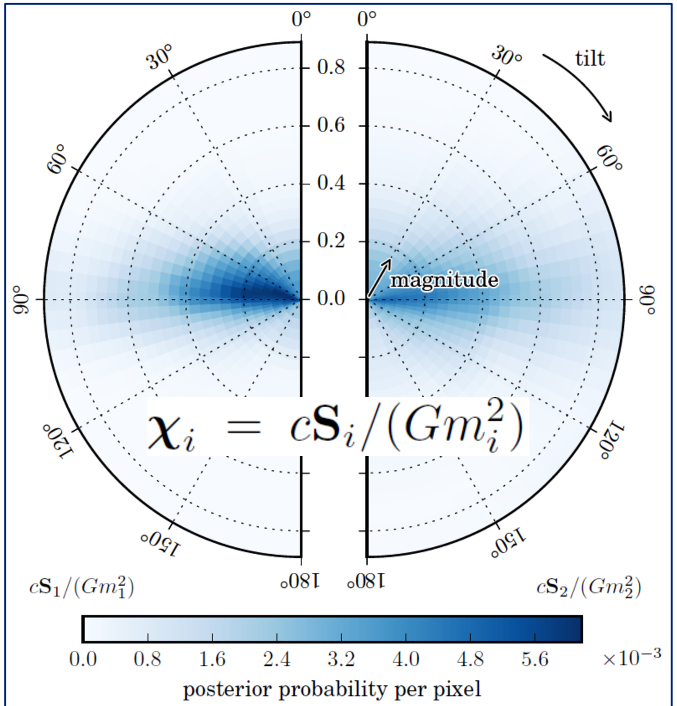
Constrains on mass ratio q, χ_i dimensionless spin, χ_eff effective spin, and χ_p effective spin precession parameter. See https://arxiv.org/abs/1805.11579

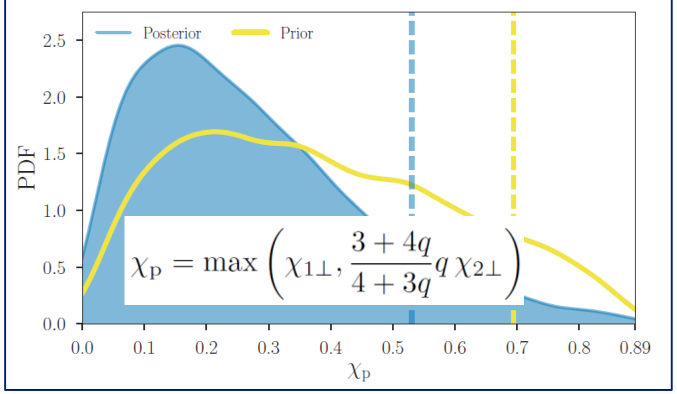
No evidence for NS spin

χ_eff contributes to GW phase at 1.5 PN, and degenerate with q

χ_p starts contributing at 2 PN





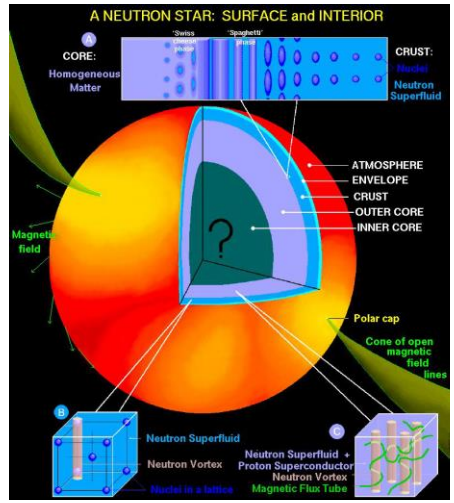


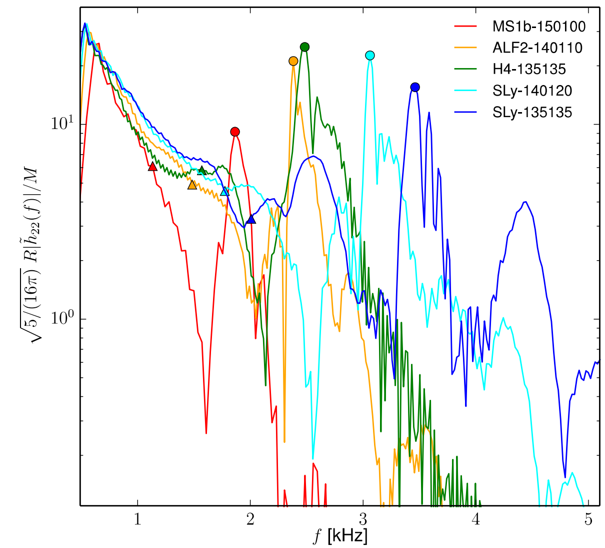
Solving an astrophysical conundrum

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?

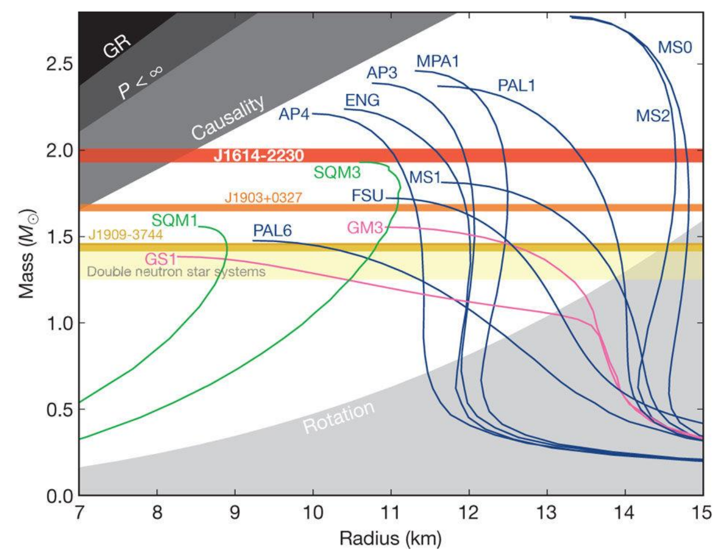
- Structure of the crust?
- Proton superconductivity
- Neutron superfluidity
- “Pinning” of fluid vortices to crust
- Origin of magnetic fields?
- More exotic objects?





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)

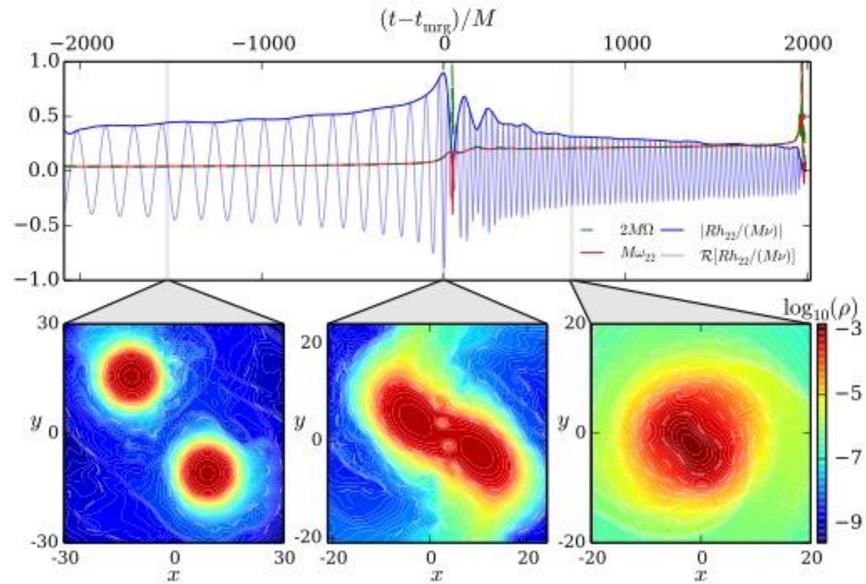
Bernuzzi *et al*., PRL 115, 091101 (2015)

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

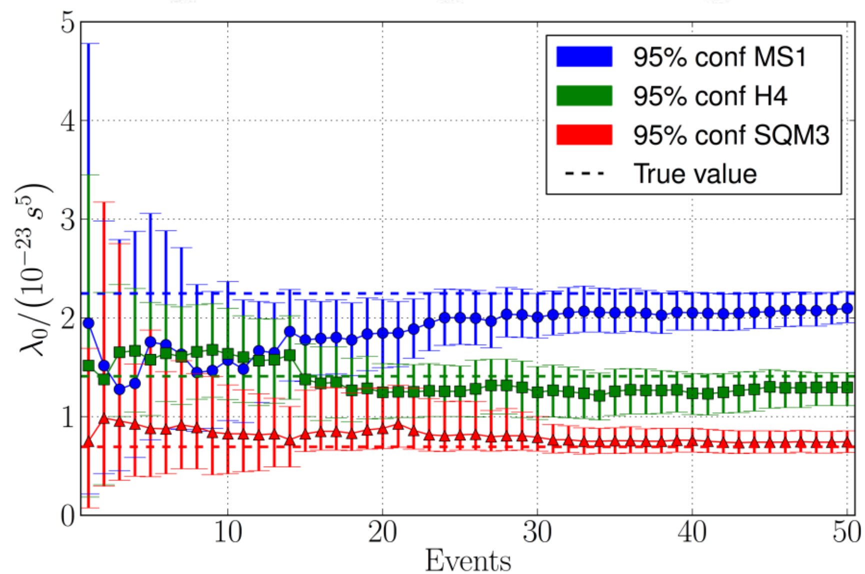
Gravitational waves from inspiraling binary neutron stars

- 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)

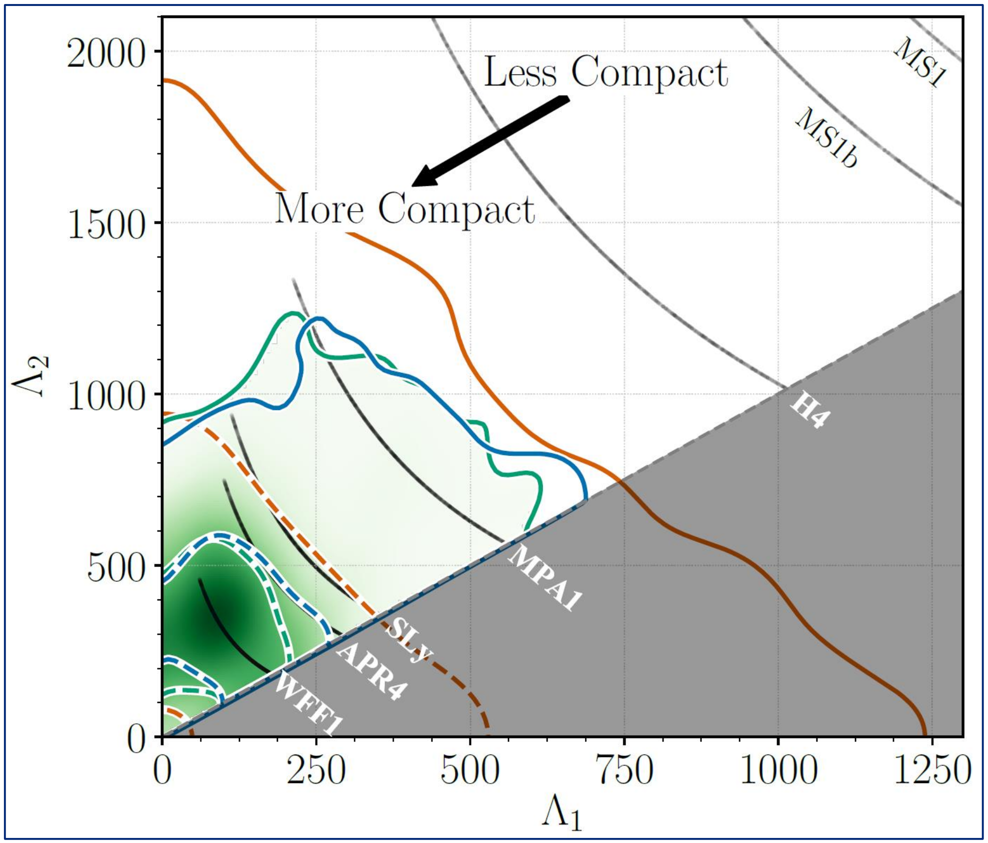
Bernuzzi, Nagar, Font, …

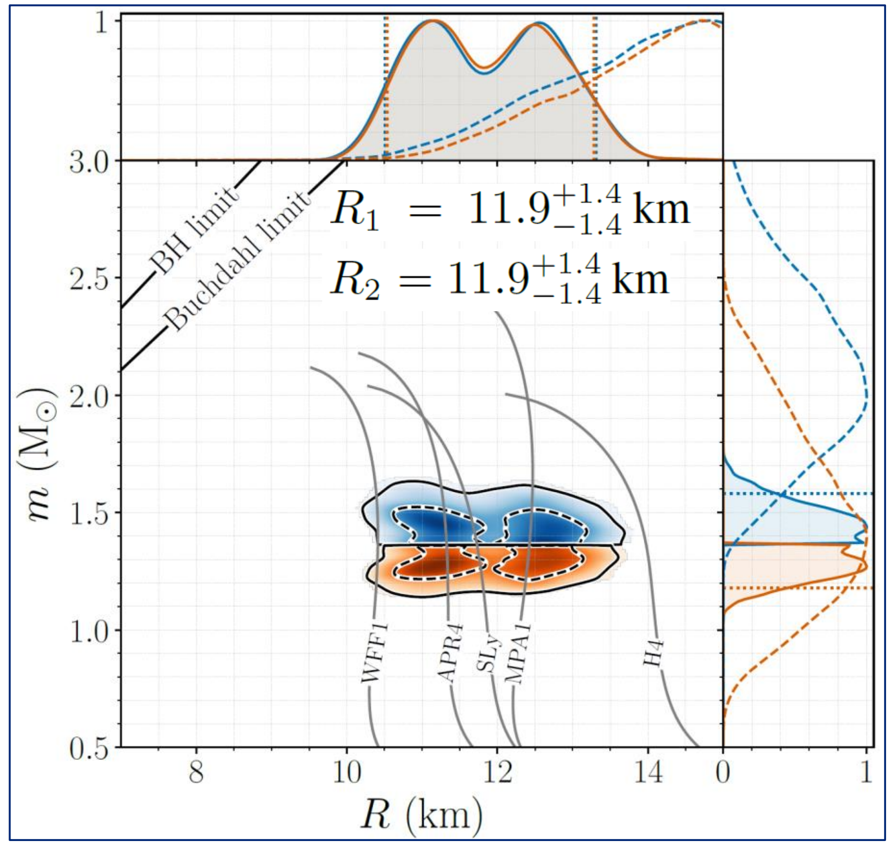
Event GW170817: tidal deformability, EOS, radii

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



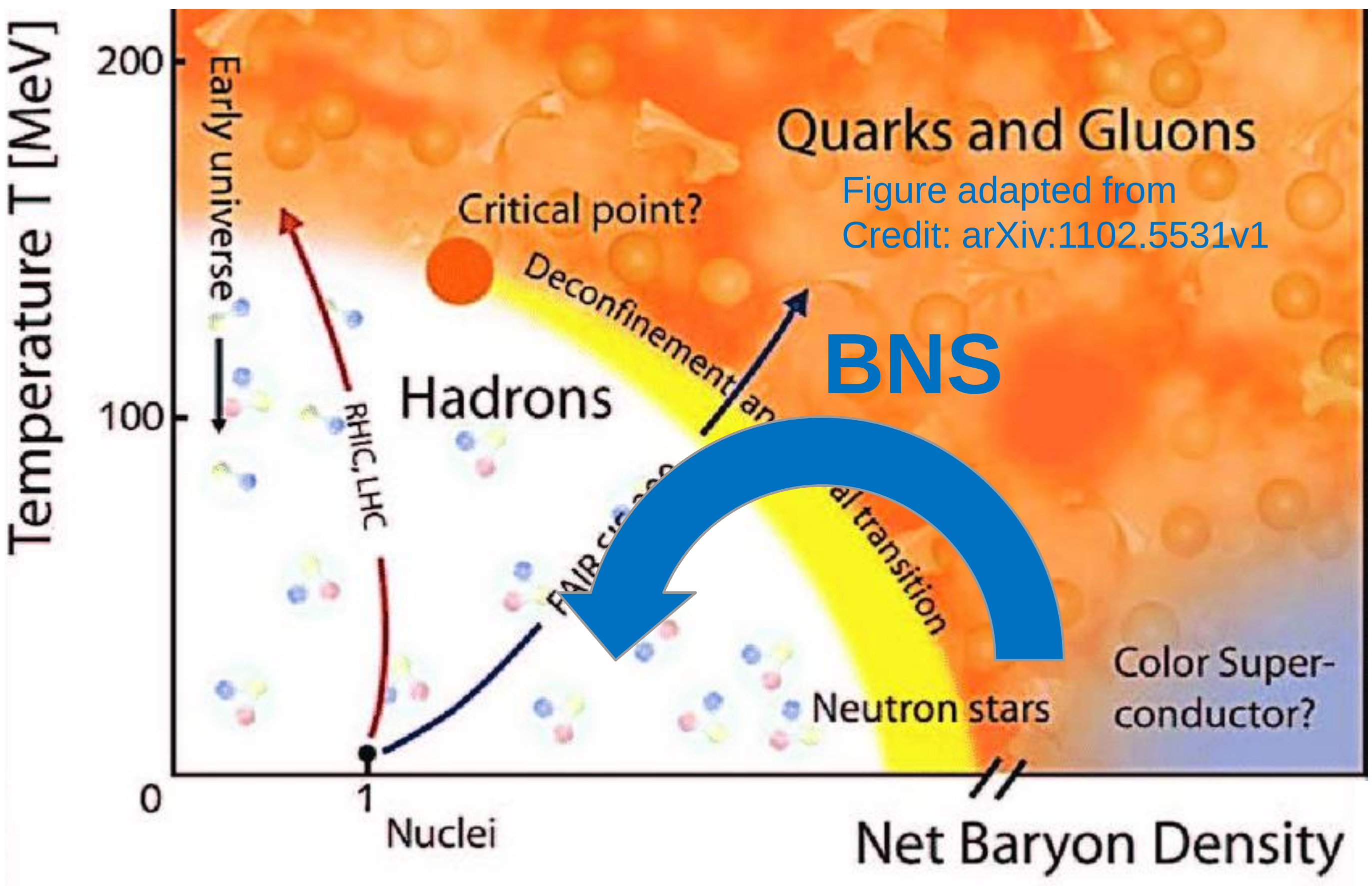


Schematic QCD phase diagram

Cores of neutron stars hold supranuclear-density matter in a cold neutron-rich equilibrium

Physics of binary neutron star mergers is relevant for high baryon density (up to $10n_0$) and temperatures from keV to 50 – 100 MeV

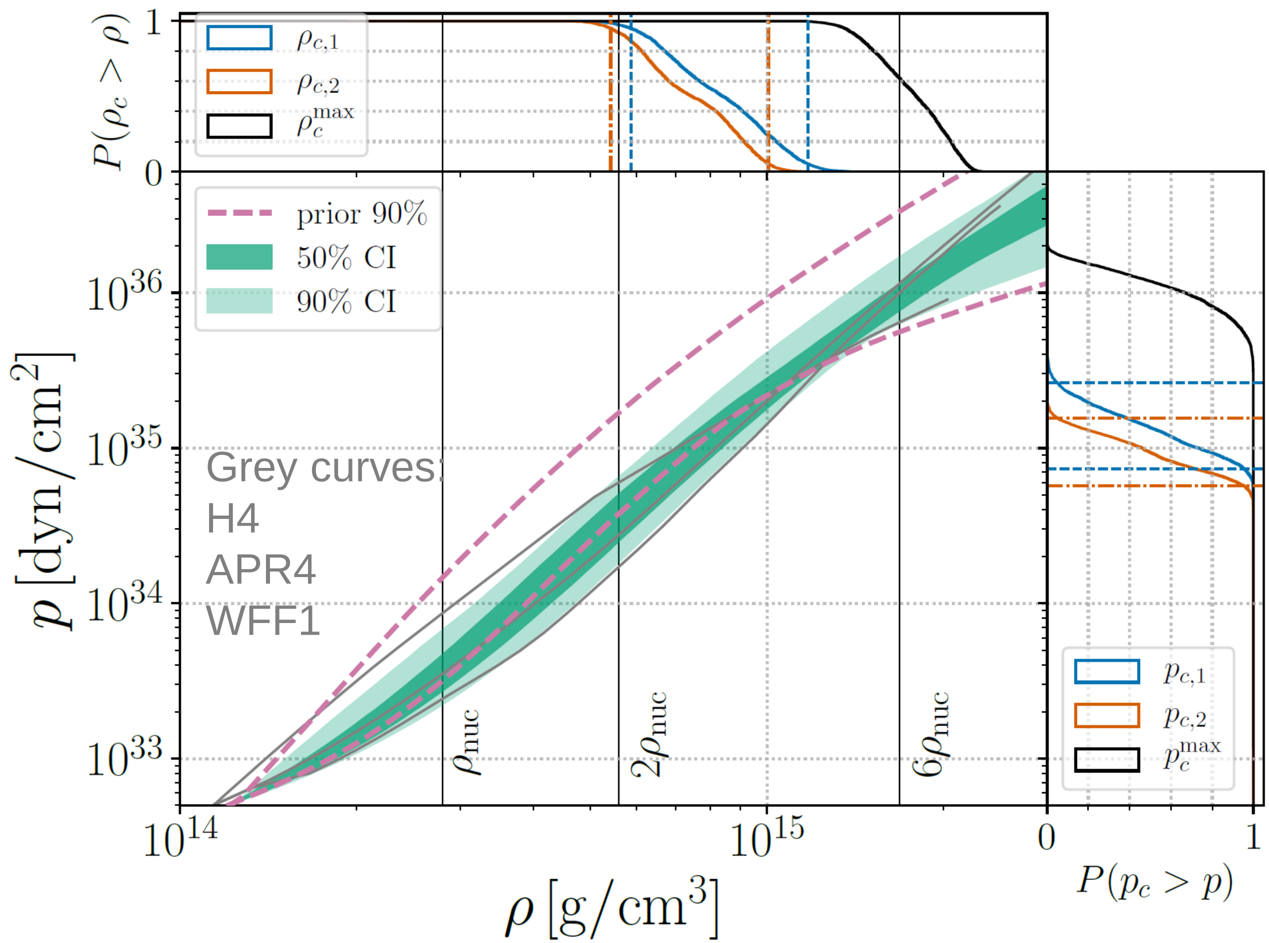
Study effective degrees of freedom and their interactions



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

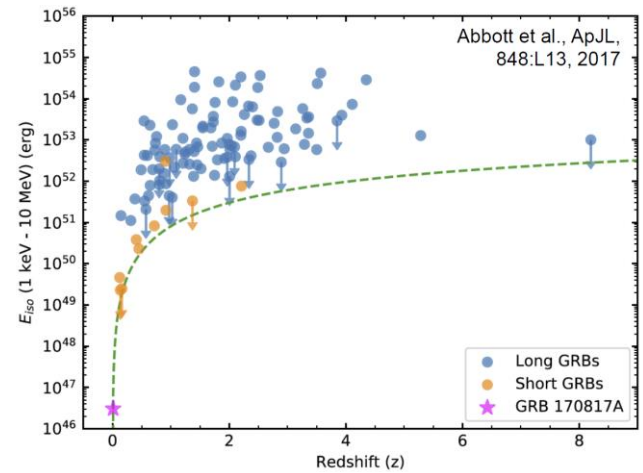
Looking into the heart of a dim nearby sGRB

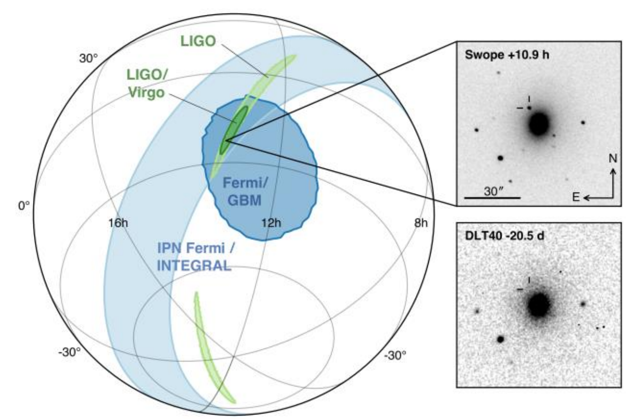
Gravitational waves identified the progenitor of the sGRB and provided both space localization and distance of the source. This triggered the EM follow-up by astronomers for the kilonova

Closest by and weakest sGRB, highest SNR GW event

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

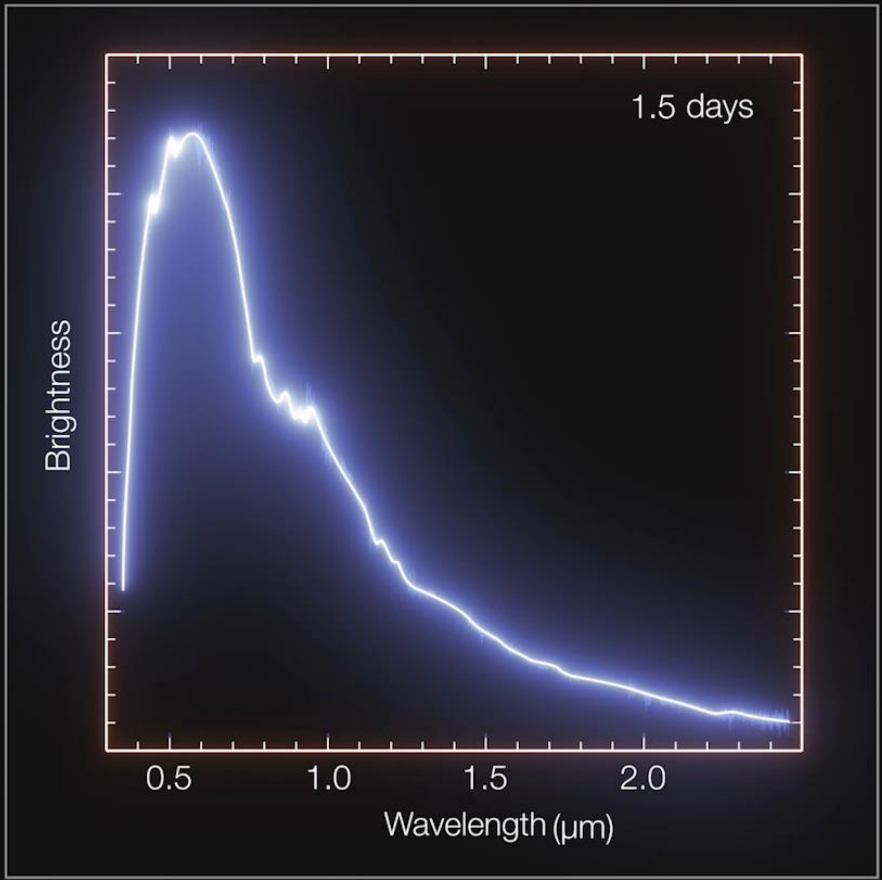


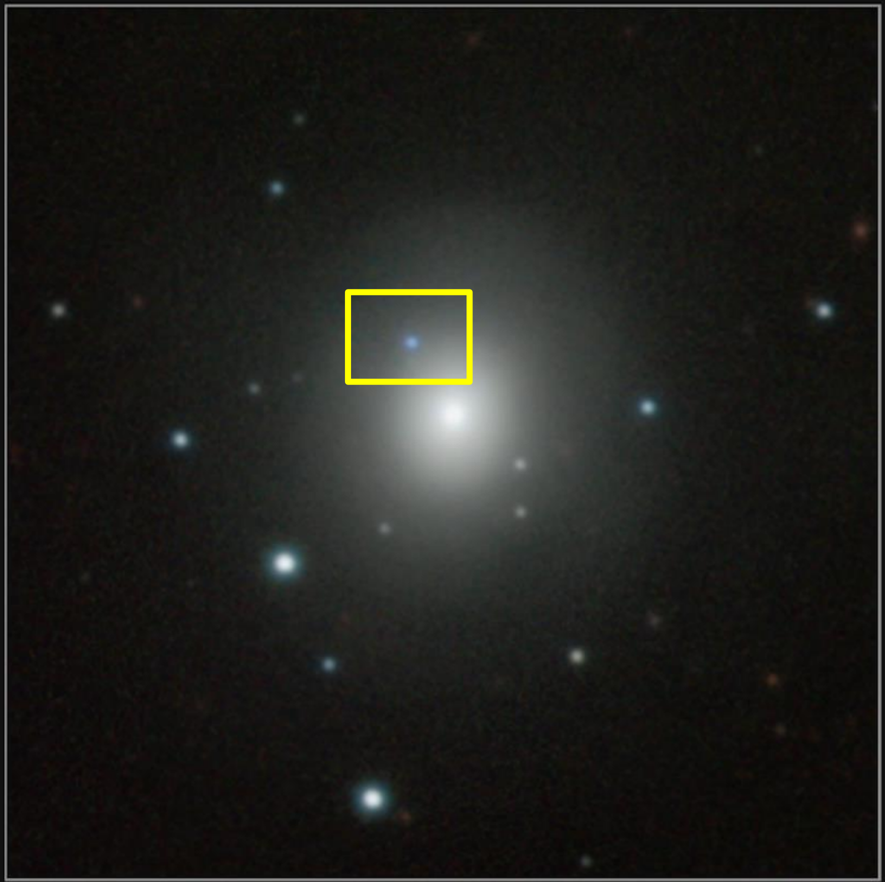


European Southern Observatory

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

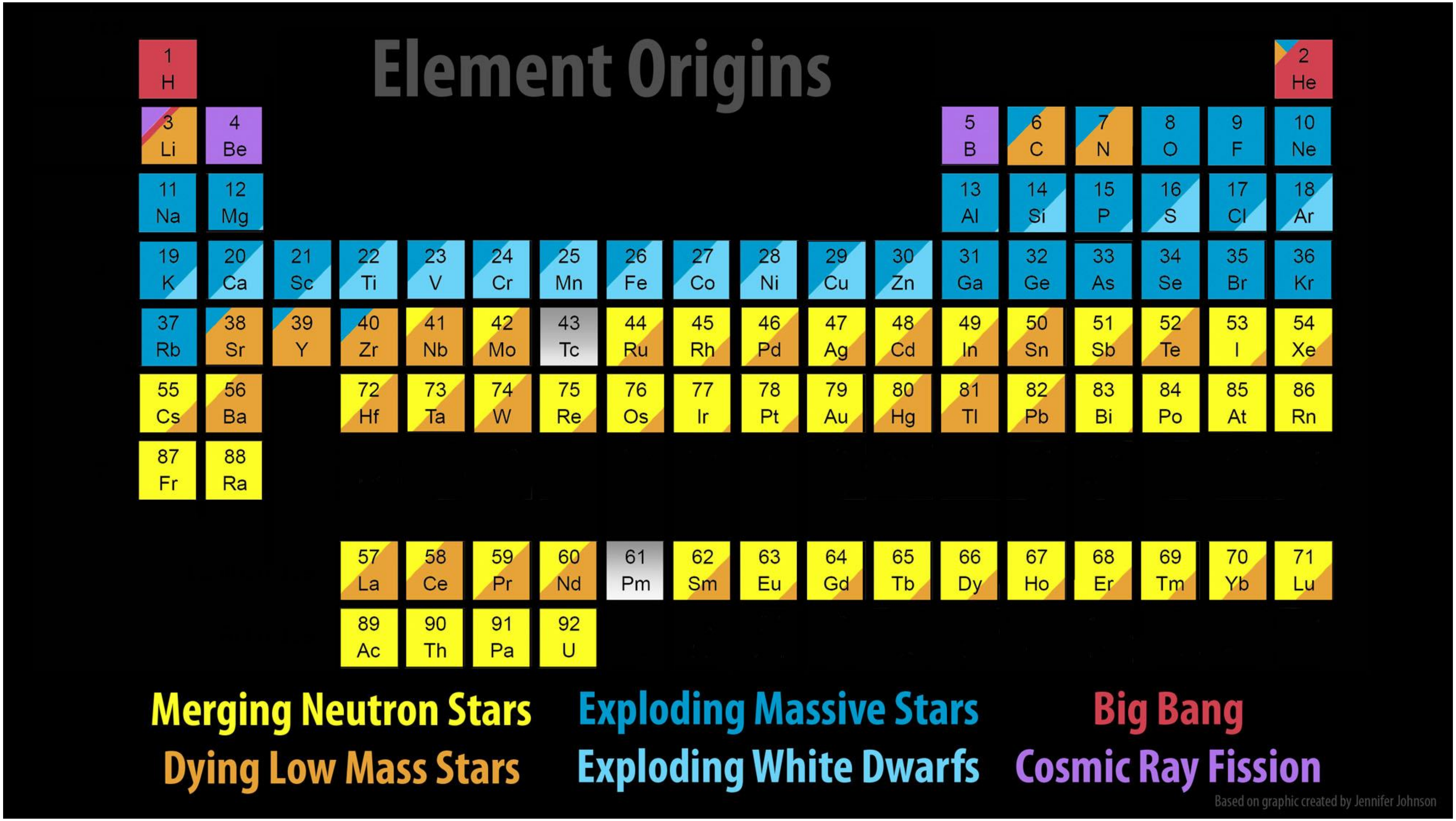
Since LIGO/Virgo provide the distance and BNS source type, it was recognized that we are dealing with a weak (non-standard) GRB. This led to the optical counterpart to be found in this region





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

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

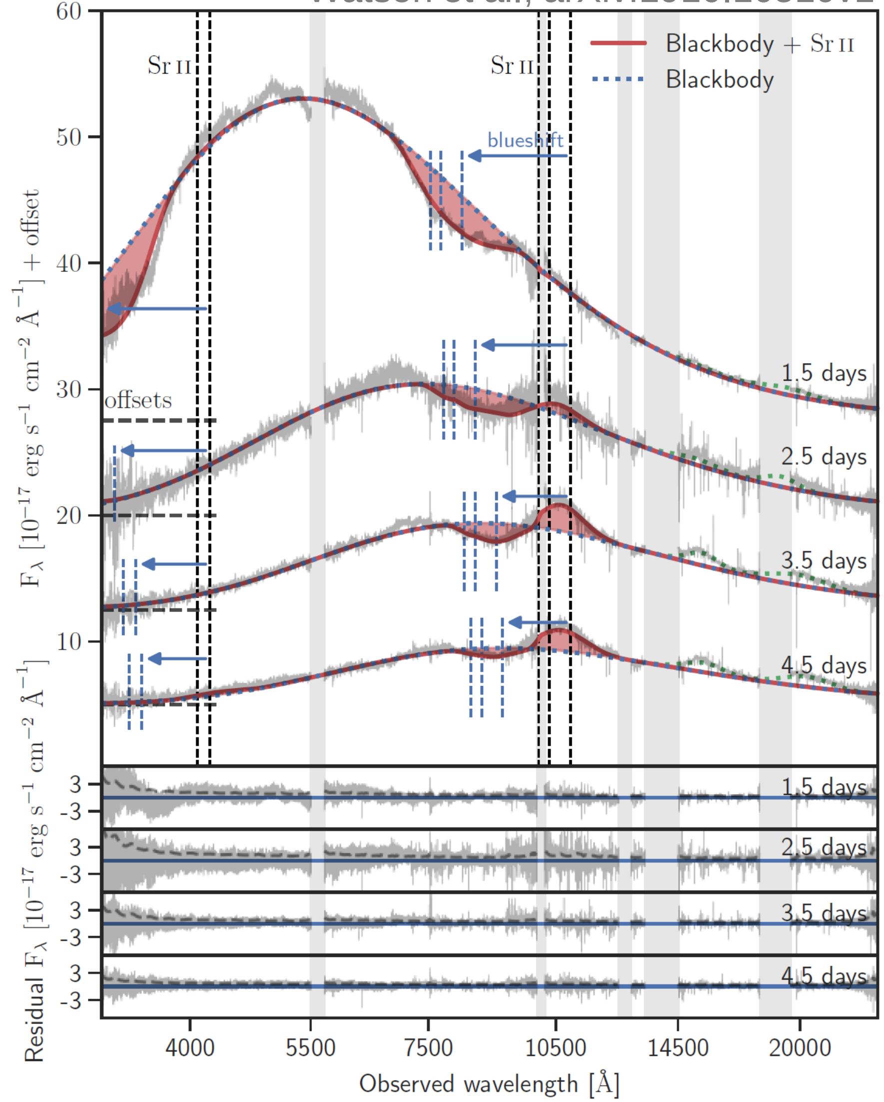
P Cygni profiles (red transparent fill) increasingly develop in time for the Sr lines

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

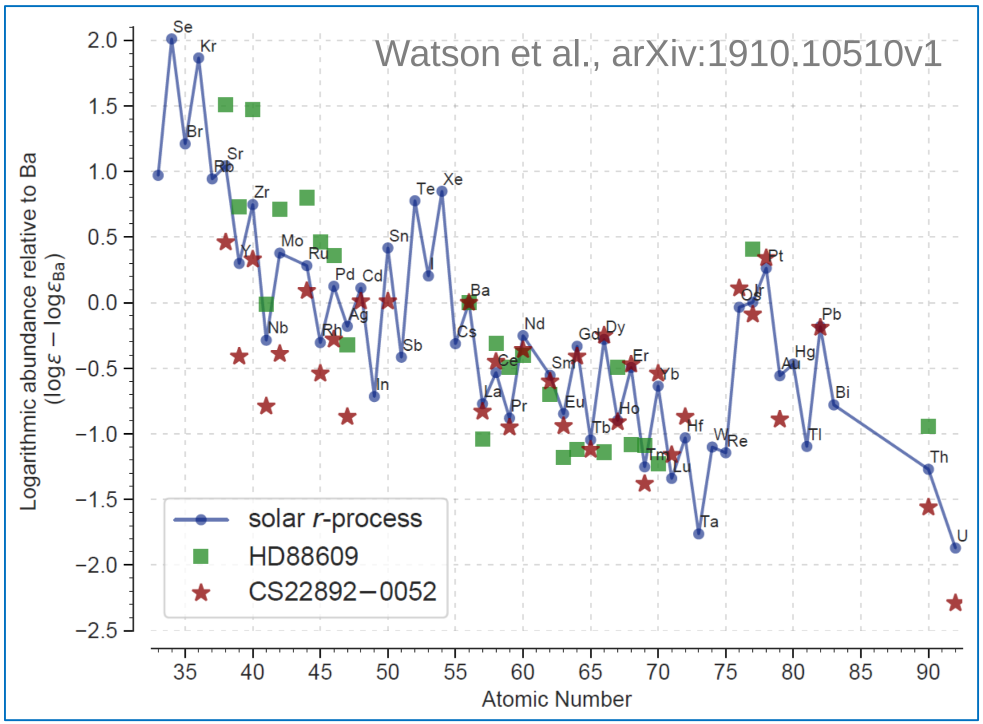
Watson et al., arXiv:1910.10510v1



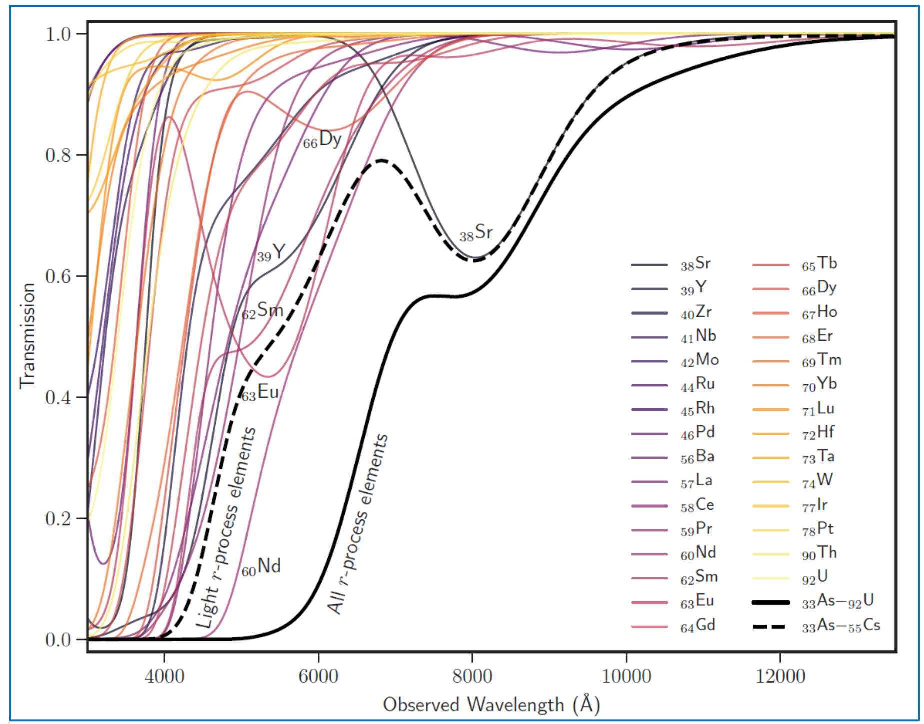
Identification of strontium in event GW170817

Identification of Strontium through spectral modeling with a LTE spectral synthesis code, the LTE line analysis and spectrum synthesis code MOOG, and with the moving plasma radiative transfer code, TARDIS. TARDIS code's atomic database was extended to include elements up to 92U with the latest Kurucz line lists with its 2.31 million lines

Relative r-process abundances normalized to the Ba abundance are shown for the sun and two metal-poor stars, CS 22892-05239 and HD88609



Synthetic r-process transmission spectra. The spectra are generated with MOOG. The elements contributing most at the reddest wavelengths are noted in the plot



Neutron skins and neutron stars in the MMA era

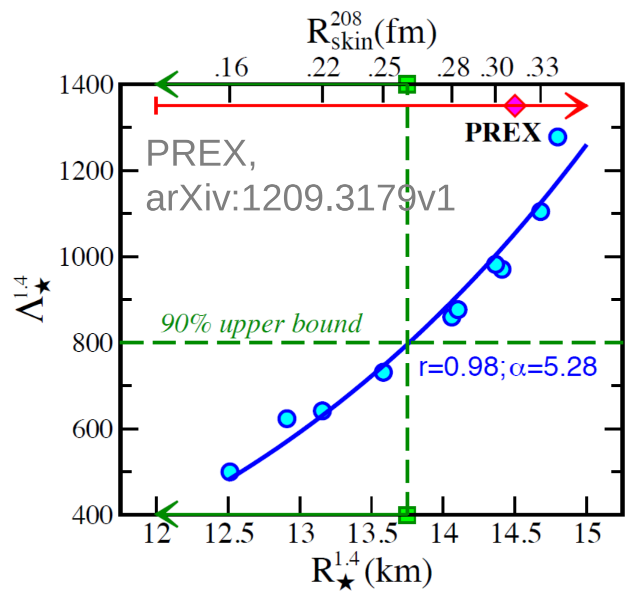
Tidal deformability derived for GW170817 rules out models that predict large stellar radii.
Fattoyev et al. (see arXiv:1711.06615v2) infer a corresponding upper limit of about $R^{208}_{\text{skin}} \leq 0.25$ fm

Tidal deformability $\Lambda = \frac{2}{3} k_2 \left(\frac{c^2 R}{GM} \right)^5 = \frac{64}{3} k_2 \left(\frac{R}{R_s} \right)^5$ of GW170817 rules out stiff symmetry energy

A neutron star having a large radius is much easier to polarize than the corresponding compact star with the same mass but a smaller radius

Nuclear symmetry energy: a quantity that represents the increase in the energy of the system as it departs from the symmetric limit of equal number of neutrons and protons

Despite a difference in length scales of 19 orders of magnitude, the size of a neutron star and the thickness of the neutron skin share a common origin: the pressure of neutron-rich matter. That is, whether pushing against surface tension in an atomic nucleus or against gravity in a neutron star, both the neutron skin and the stellar radius are sensitive to the same EOS



Neutron-skin thickness of ^{208}Pb is sensitive to the symmetry energy (albeit at a lower density)

If the **upcoming PREX-II experiment** measures a significantly thicker skin, this may be evidence of a softening of the symmetry energy at high densities likely indicative of a phase transition in the interior of neutron stars

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