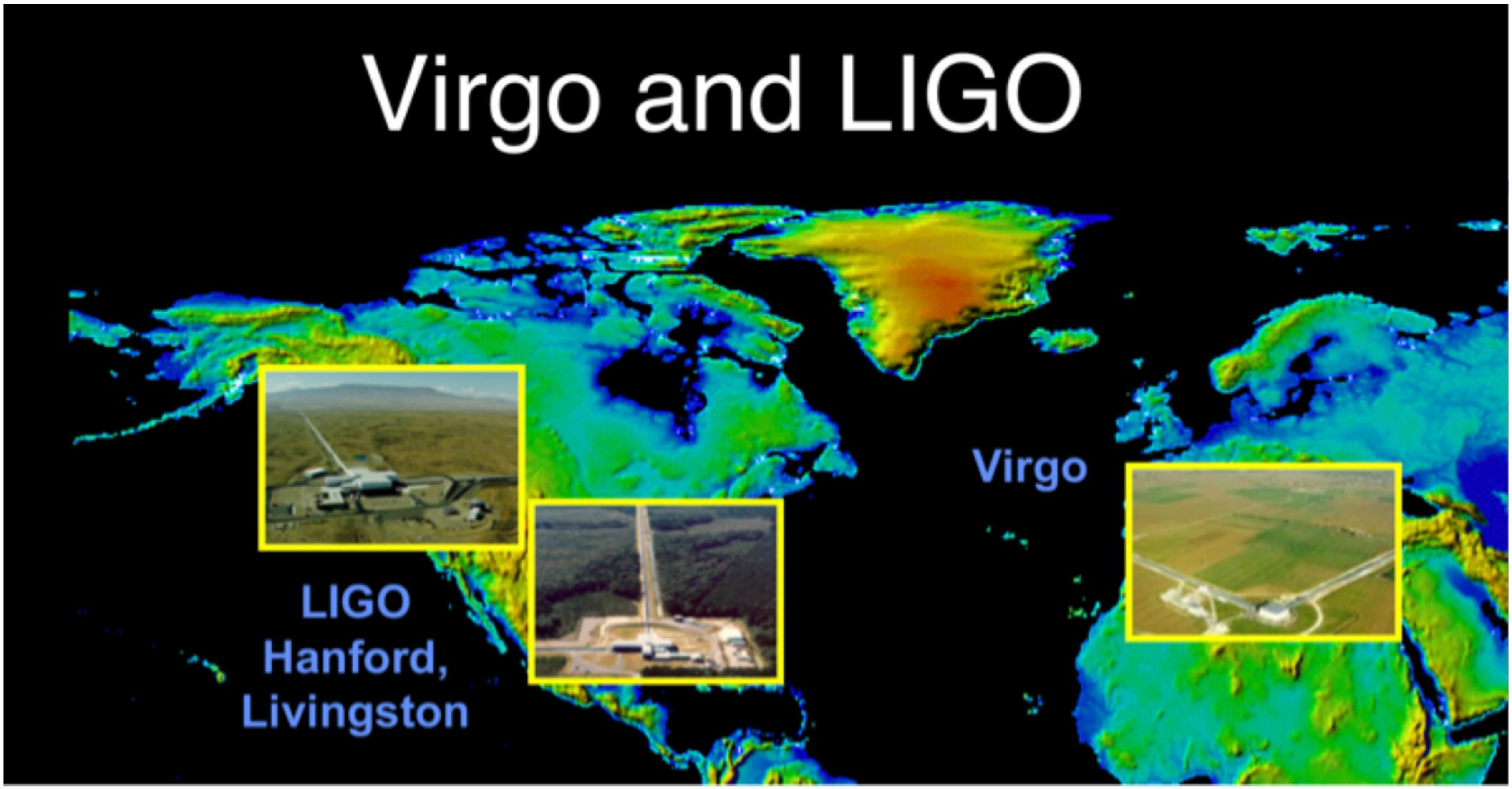
Gravitational wave science and Virgo

Jo van den Brand, Nikhef and VU University Amsterdam, jo@nikhef.nl
Rome, July 4, 2018

LIGO and Virgo

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

Coordinated talks –
» Yesterday: Detection and analysis principles (David Shoemaker, LSC)
» Today: Physics, Astrophysics, and the Future (Jo van den Brand, Virgo)



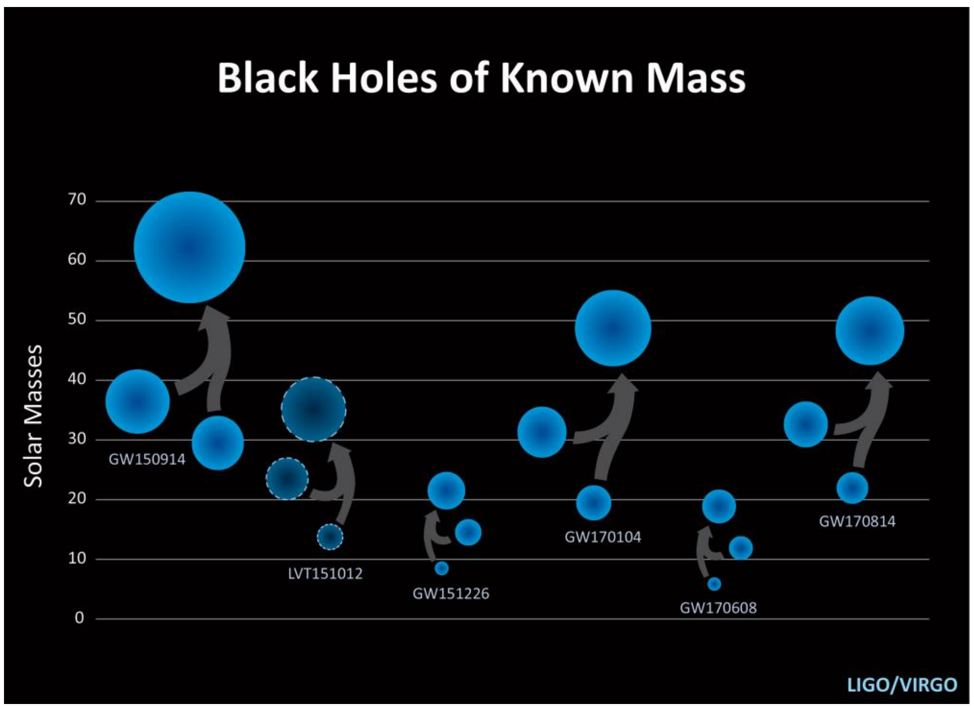
Scientific achievements: properties of black holes

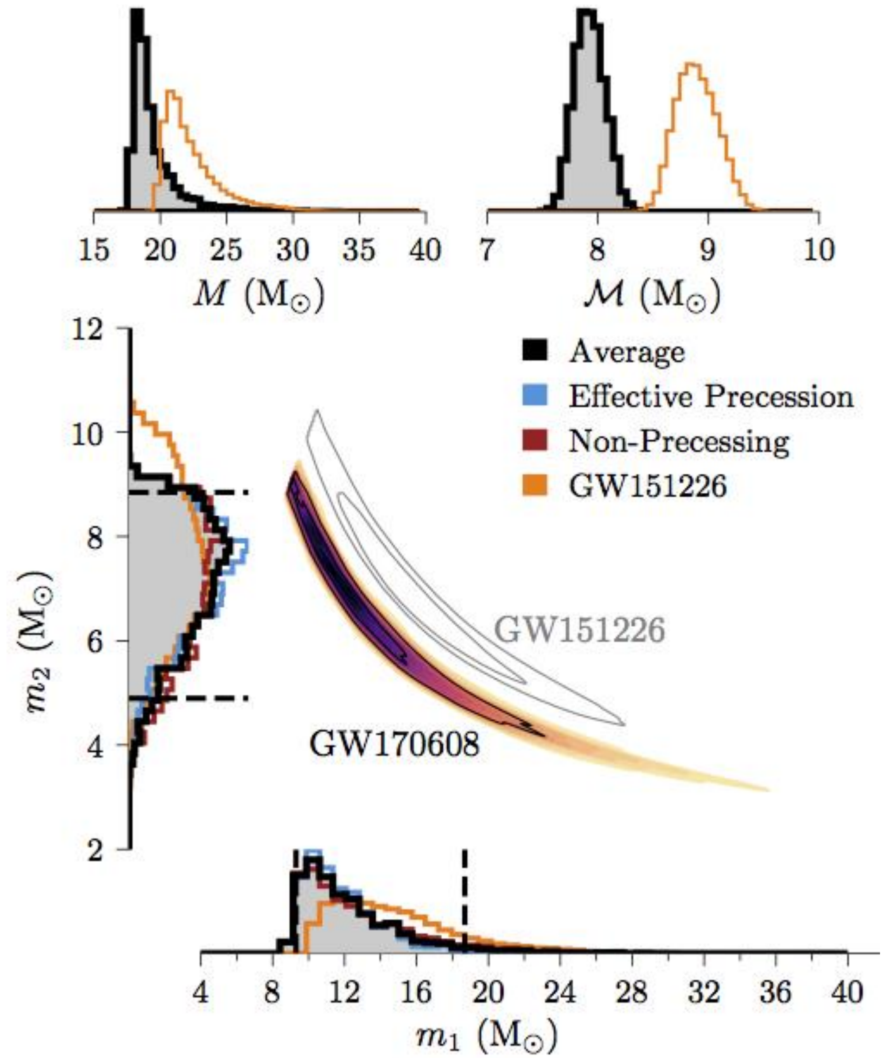
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

LVC reported on 6 BBH mergers

Fundamental physics, astrophysics, astronomy, and cosmology

Testing GR, waveforms (with matter)





Precision tests of GR with BBH mergers

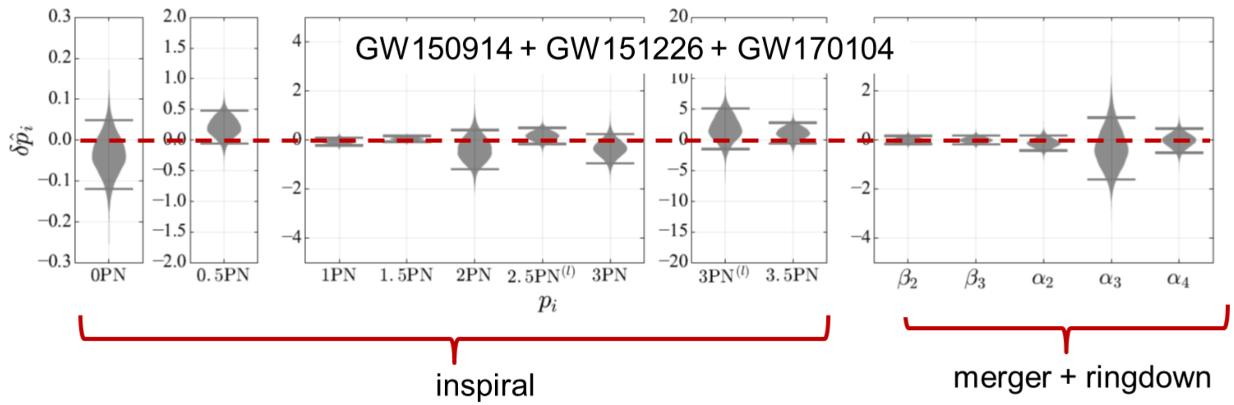
Bayesian analysis increases accuracy on parameters by combining information from multiple events

Inspiral and PN expansion

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

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

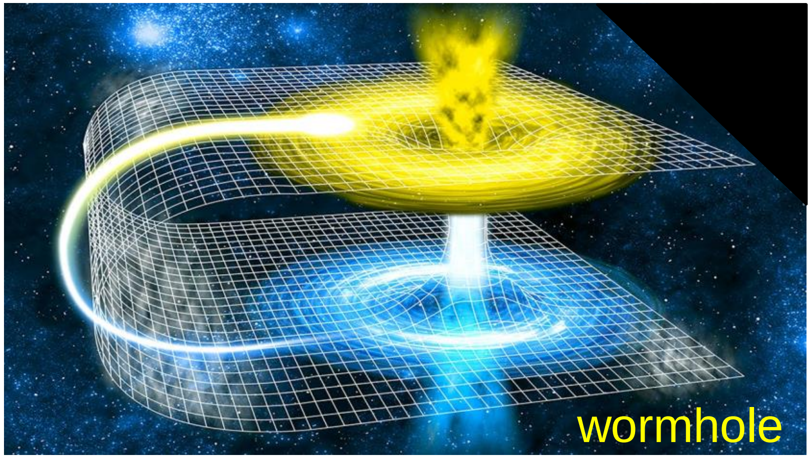
Our collaborations set ambitious goals for the future

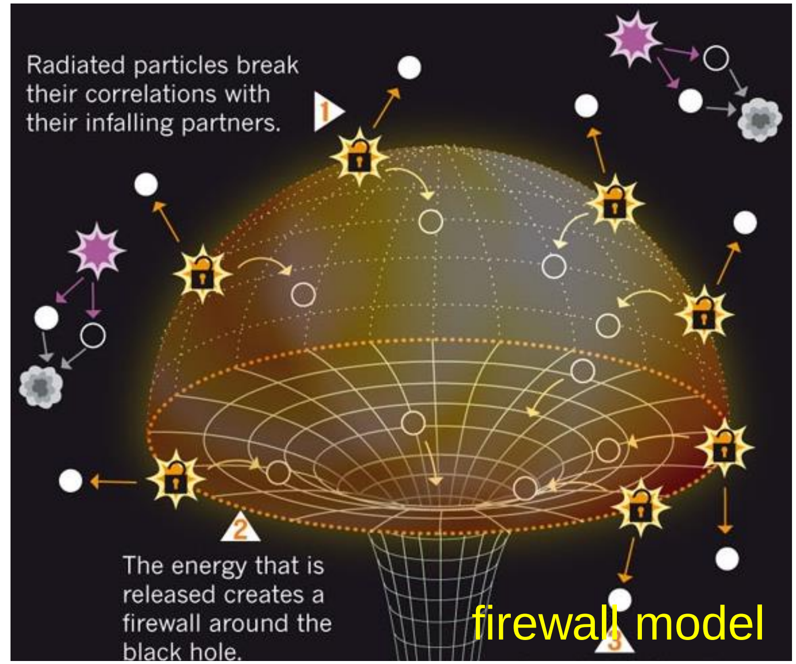
We need to improve:

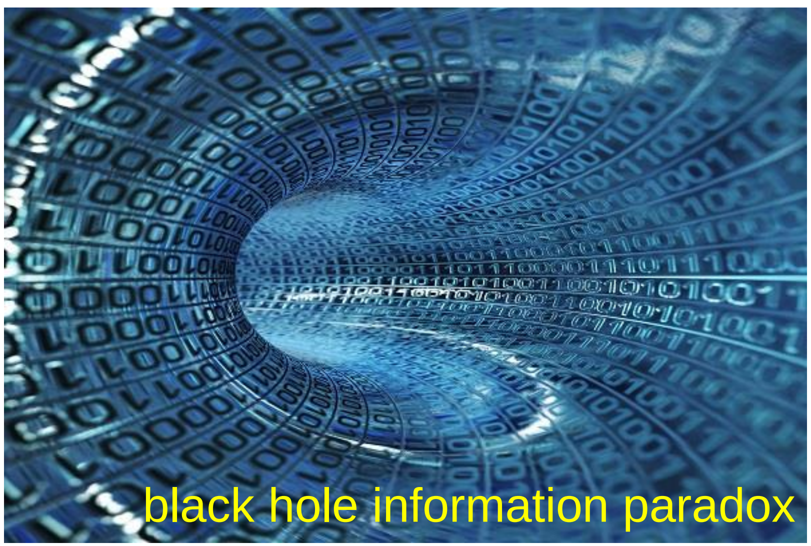
- sensitivity of our instruments over the entire frequency range
- optimize our computing and analysis
- improve our source modeling (NR)

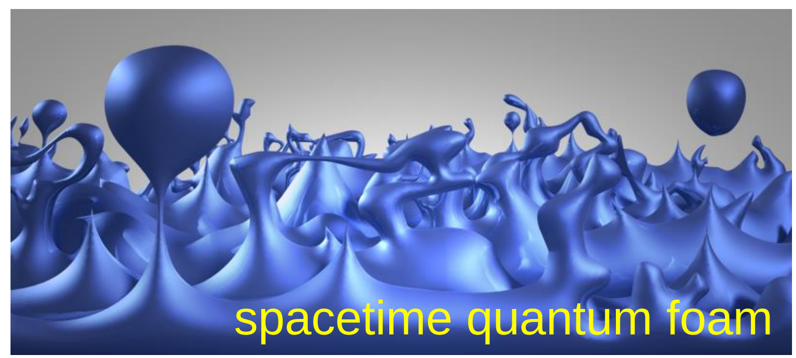
Fundamental physics: did we observe black holes?

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?



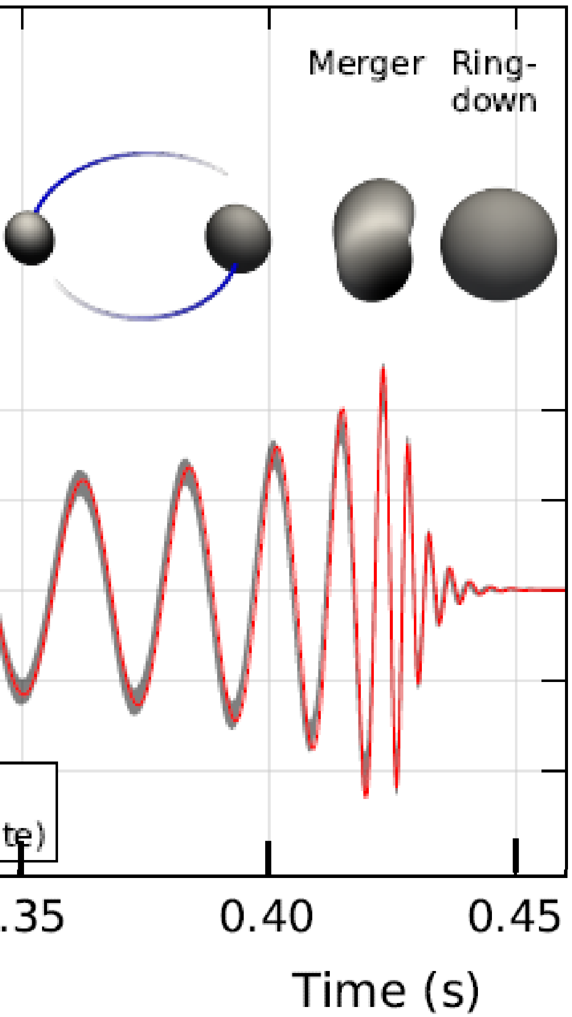


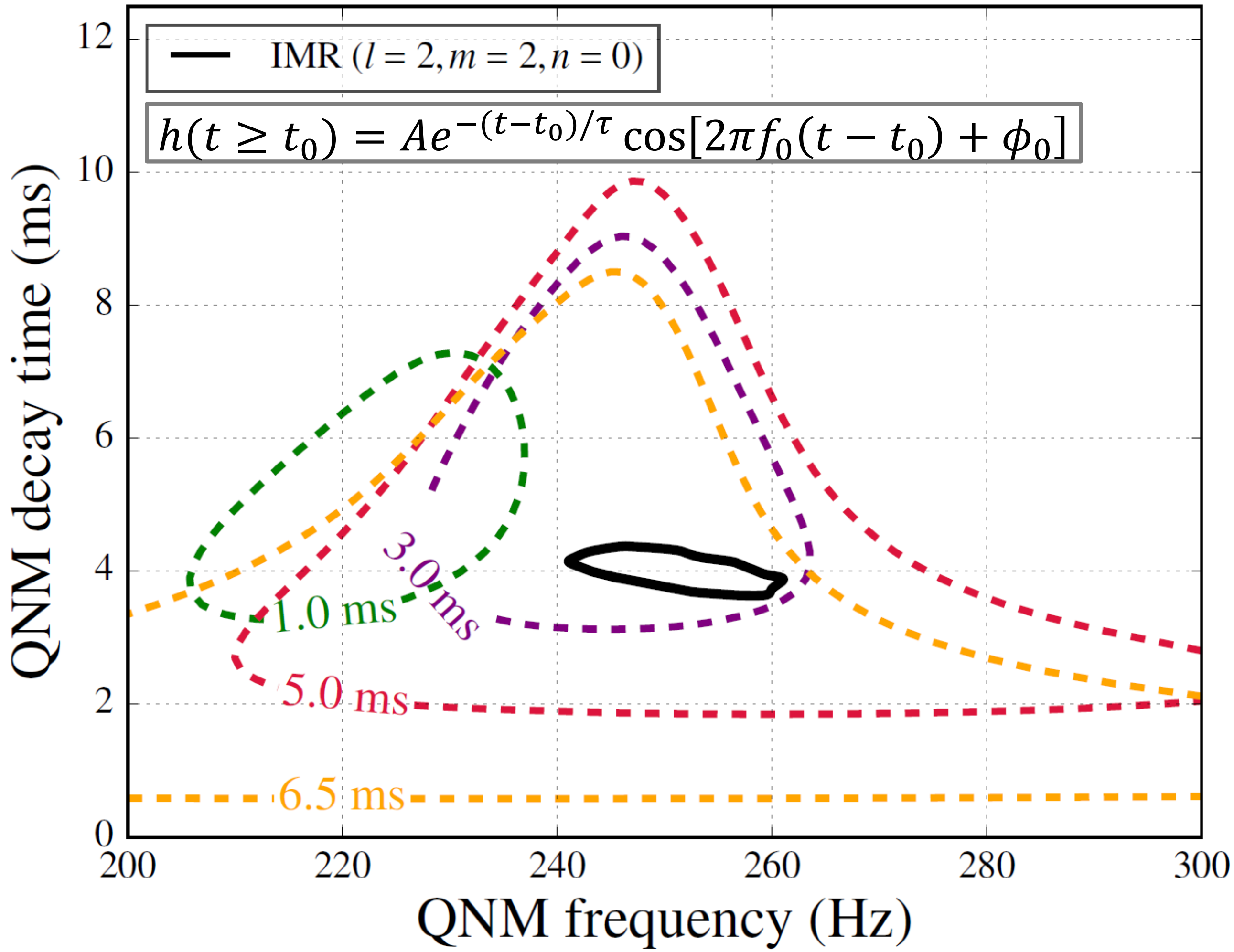




Is a black hole created in the final state?

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

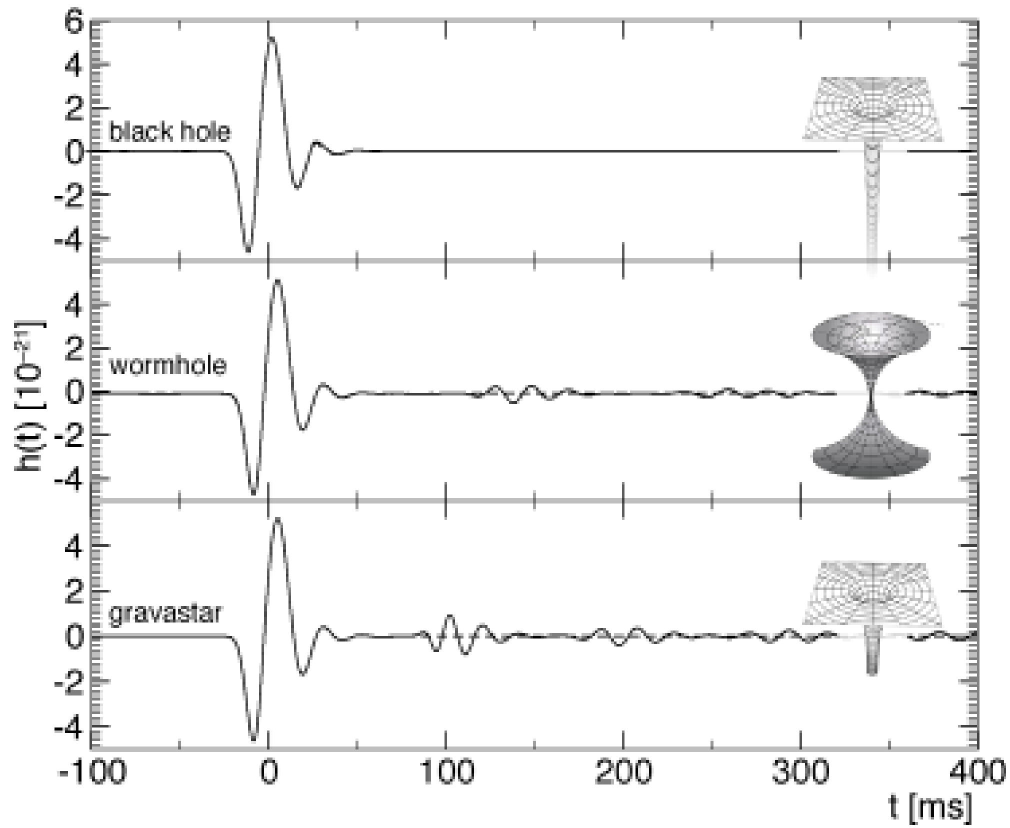
- Dark matter stars

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

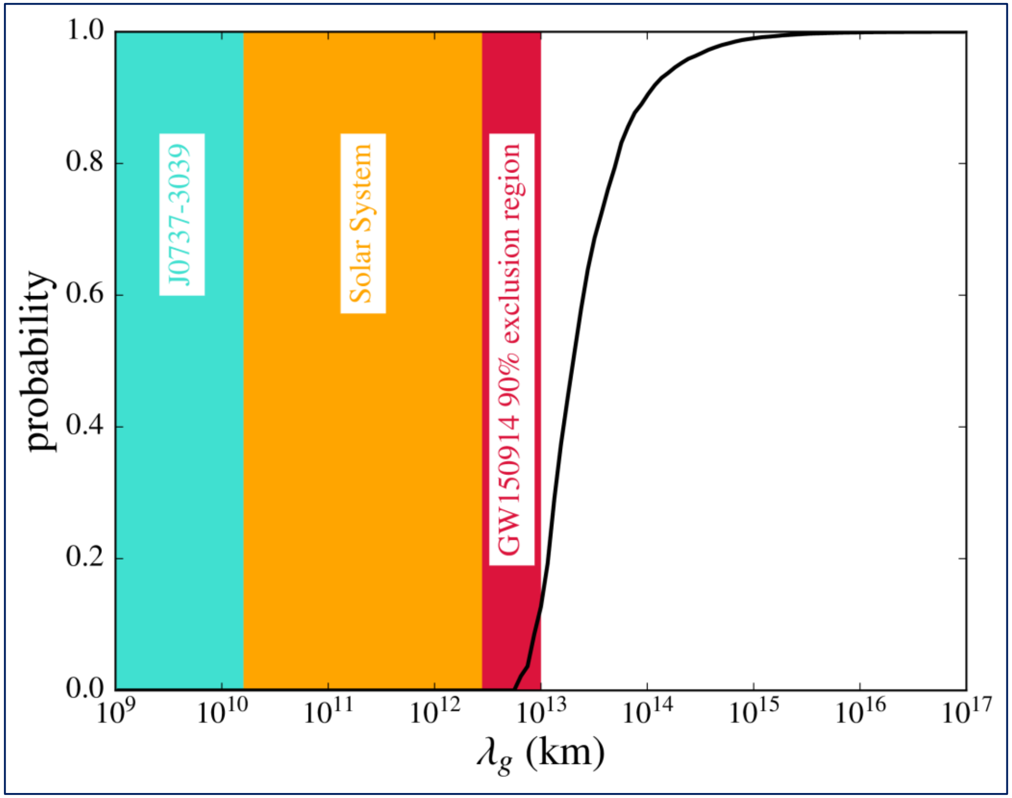


GW observables

- 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

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

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

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

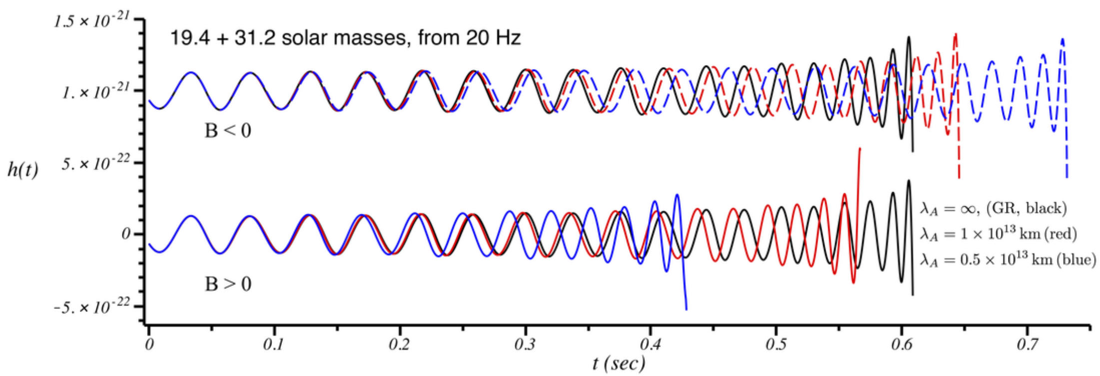
See "*Tests of general relativity with GW150914*"
http://arxiv.org/abs/1602.03841

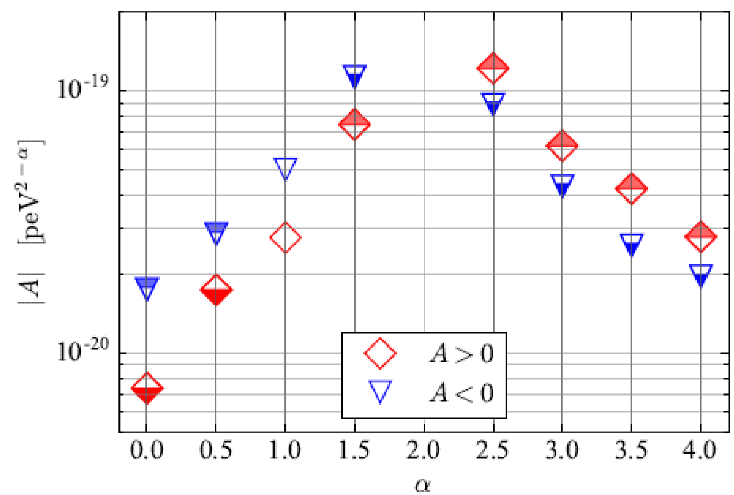
Bounds on violation of Lorentz invariance

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





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, The Netherlands, Poland, Hungary, Spain, Germany

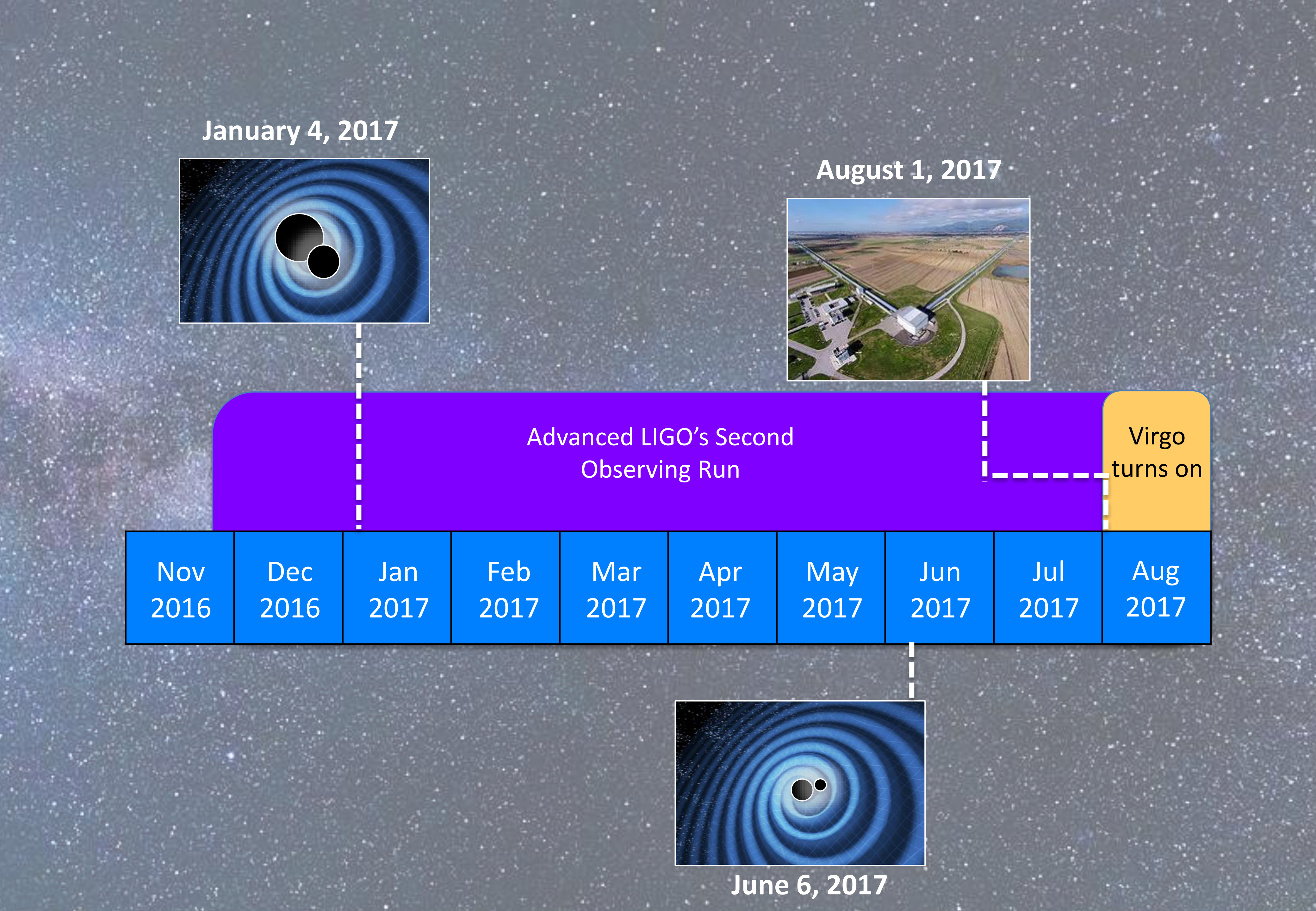
- 20 laboratories, about 280 authors
  - APC Paris
  - ARTEMIS Nice
  - EGO Cascina
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris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

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

Part of the international network of 2nd generation detectors

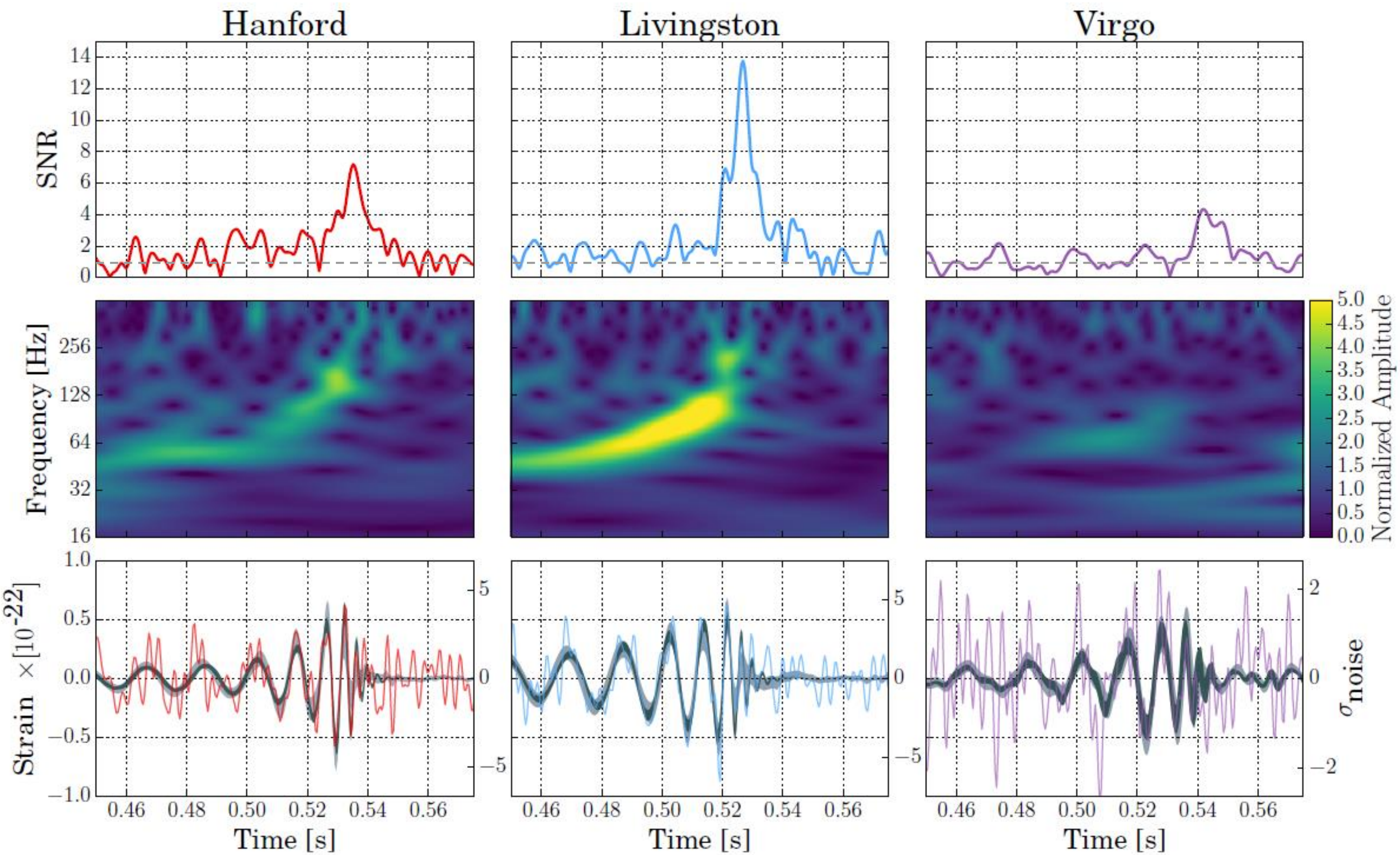
Joined the O2 run on August 1, 2017

7 European countries


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



Special thanks to Virgo’s founding fathers

Alain Brillet and Adalberto Giazotto

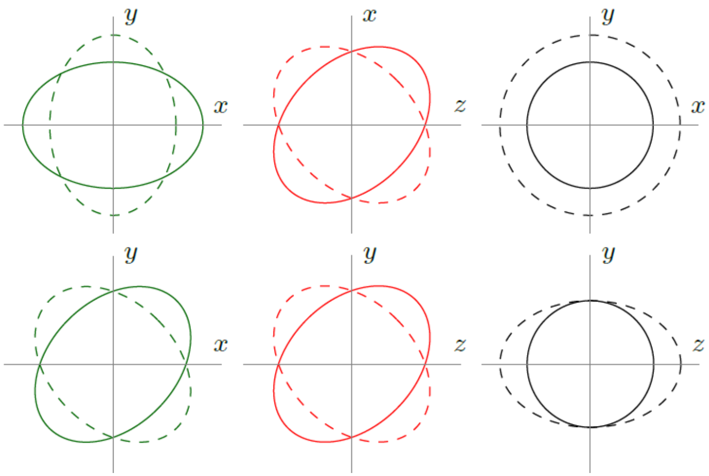
Advanced Virgo

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].

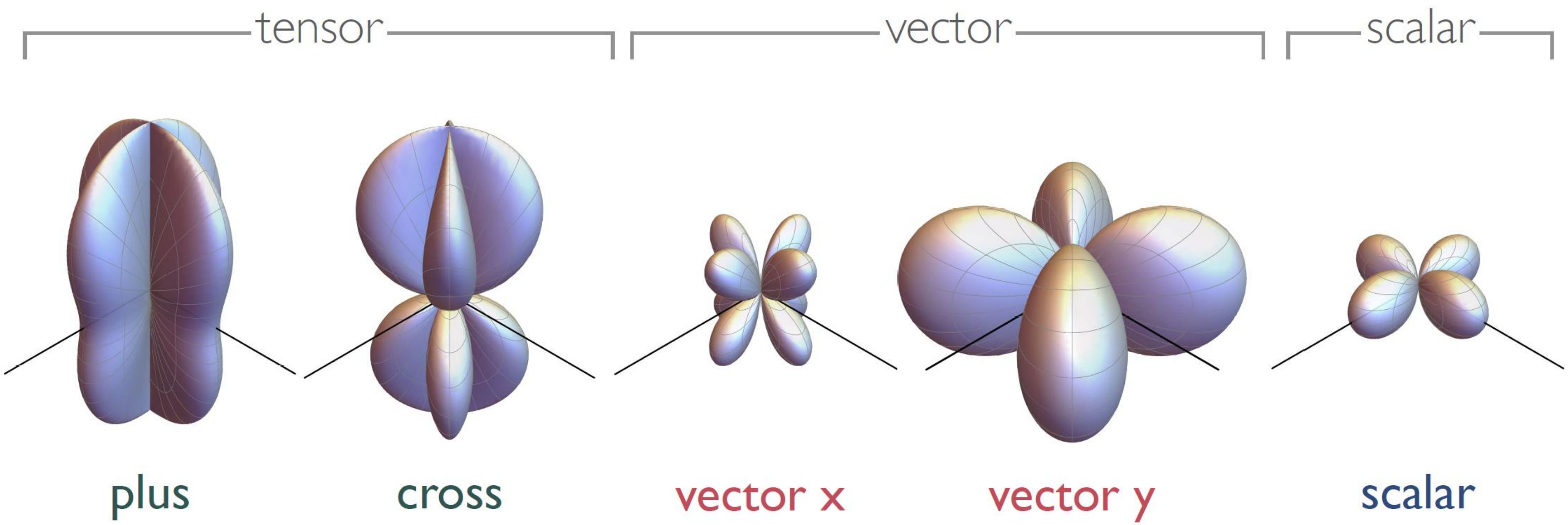
allowed / depends / forbidden

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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tensor vector scalar

Our analysis favors tensor polarizations in support of General Relativity

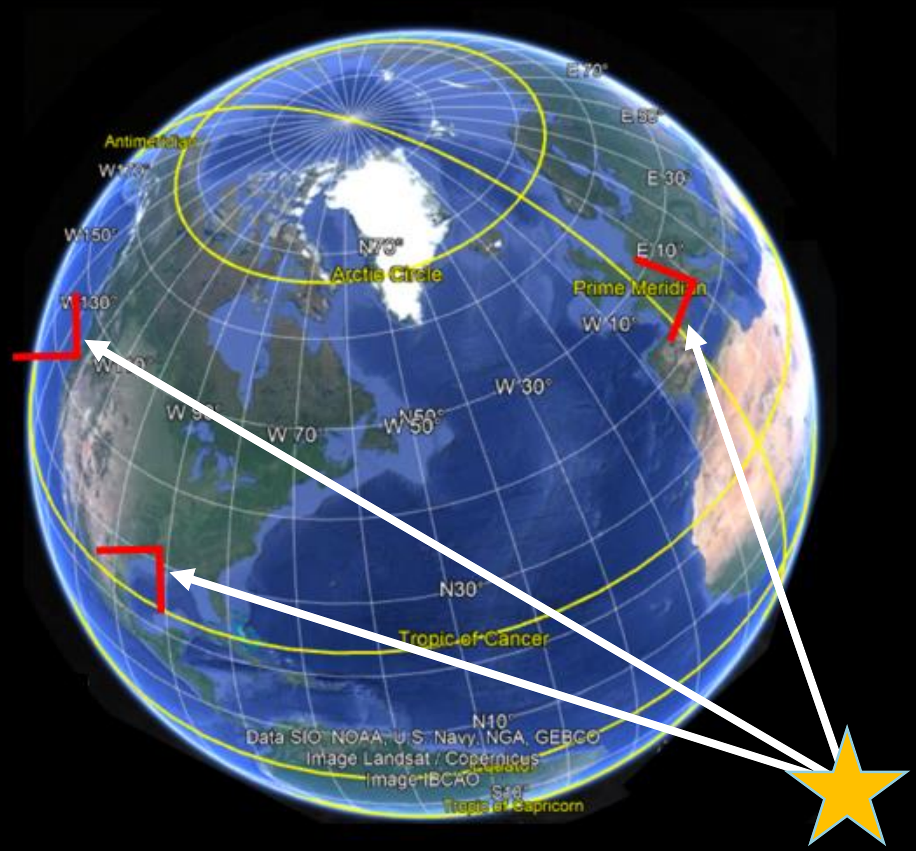
Our data favor tensor structure over vector by about a (Bayes) factor 200

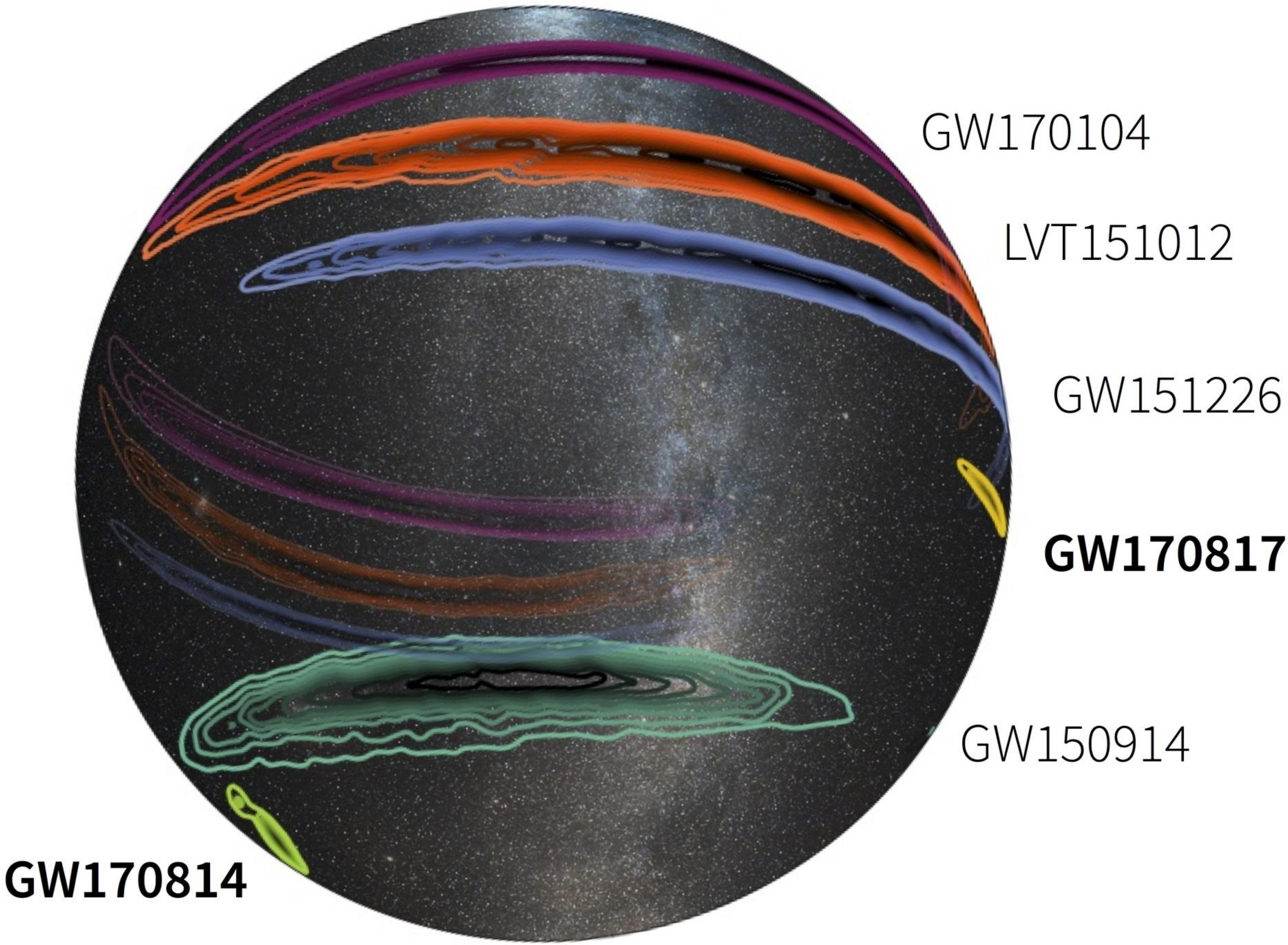
And tensor over scalar by about a factor 1000

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

Virgo allowed source location via triangulation

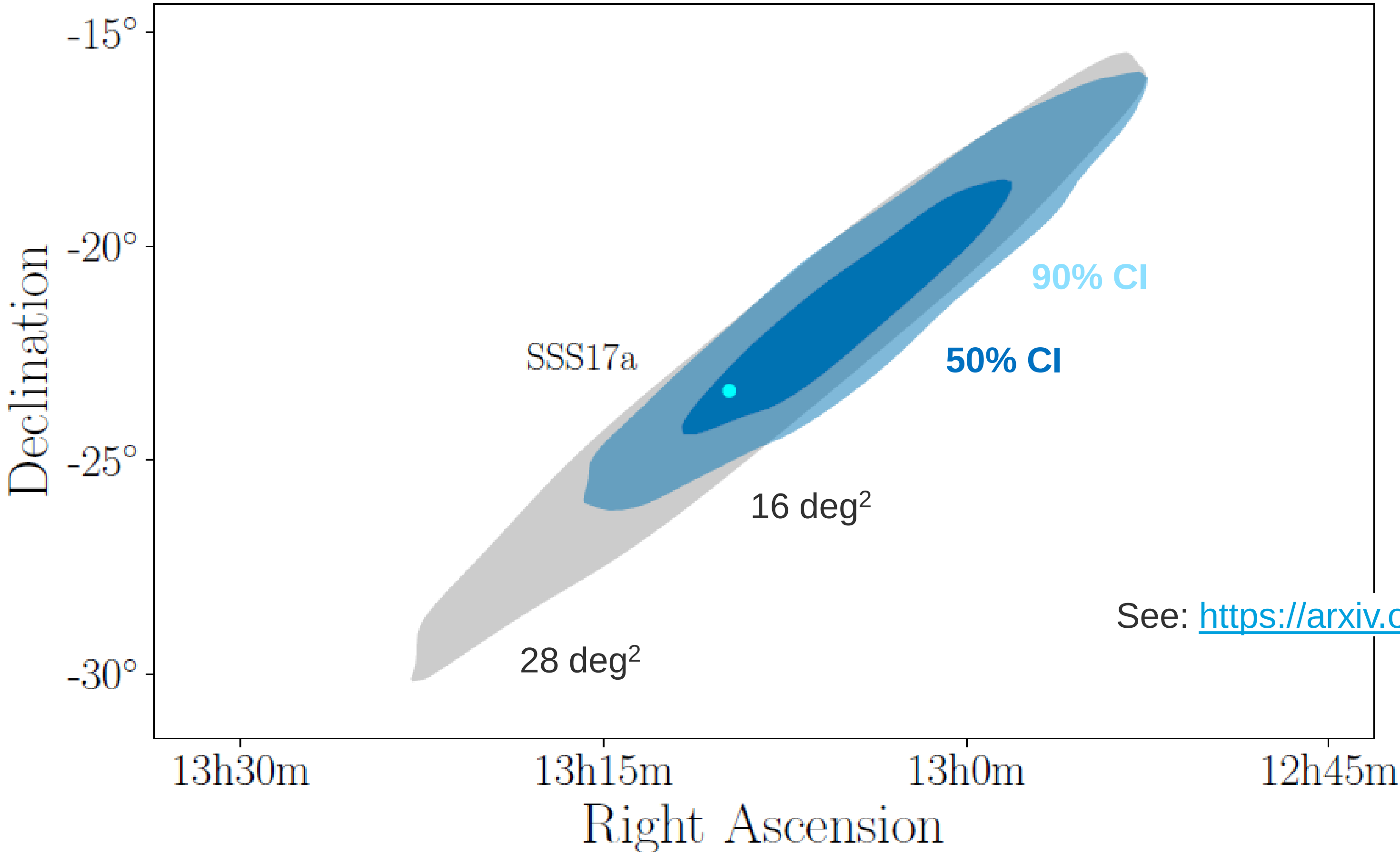
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it




GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814

Localization by Virgo and LIGO

Improved localization of GW170817, with the location of the associated counterpart SSS17a/AT 2017gfo has been obtained. The darker and lighter blue shaded regions correspond to 50% and 90% credible regions respectively, and the gray shaded region shows the previously derived 90% credible region presented in B. Abbott et al., PRL **119**, 161101 (2017)



See: https://arxiv.org/abs/1805.11579

GW170817 properties: inclination, masses, spins

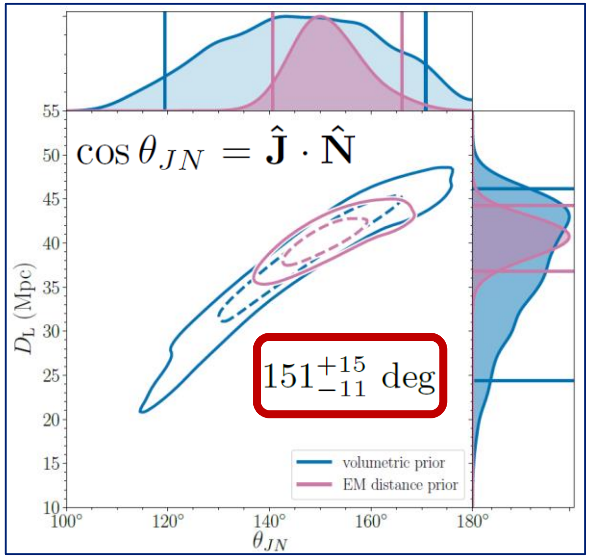
Constrains on inclination angle, chirp mass, mass ratio q, χ_{i} dimensionless spin, χ_{eff} effective spin, χ_{p} effective spin precession parameter. Include EM-information. See https://arxiv.org/abs/1805.11579

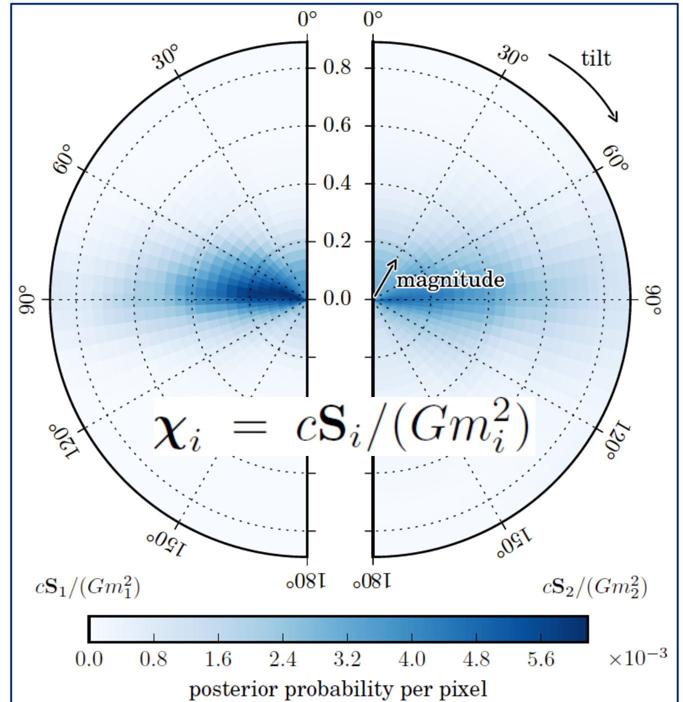
EM localization and Virgo recalibration improved θ_{JN}

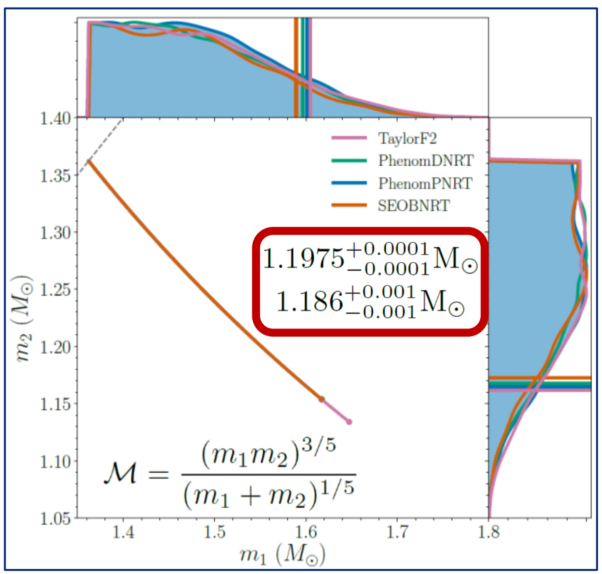
No evidence for NS spin

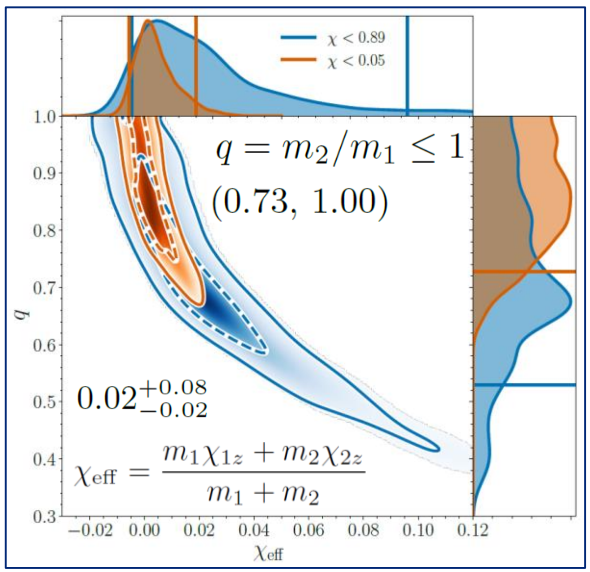
χ_{eff} contributes to GW phase at 1.5 PN, and is degenerate with q

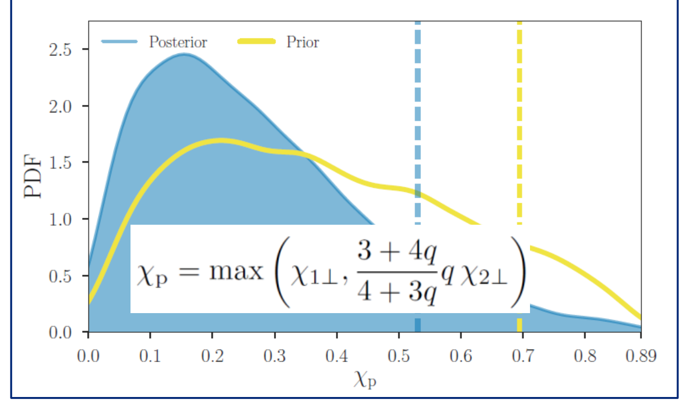
χ_{p} starts contributing at 2 PN









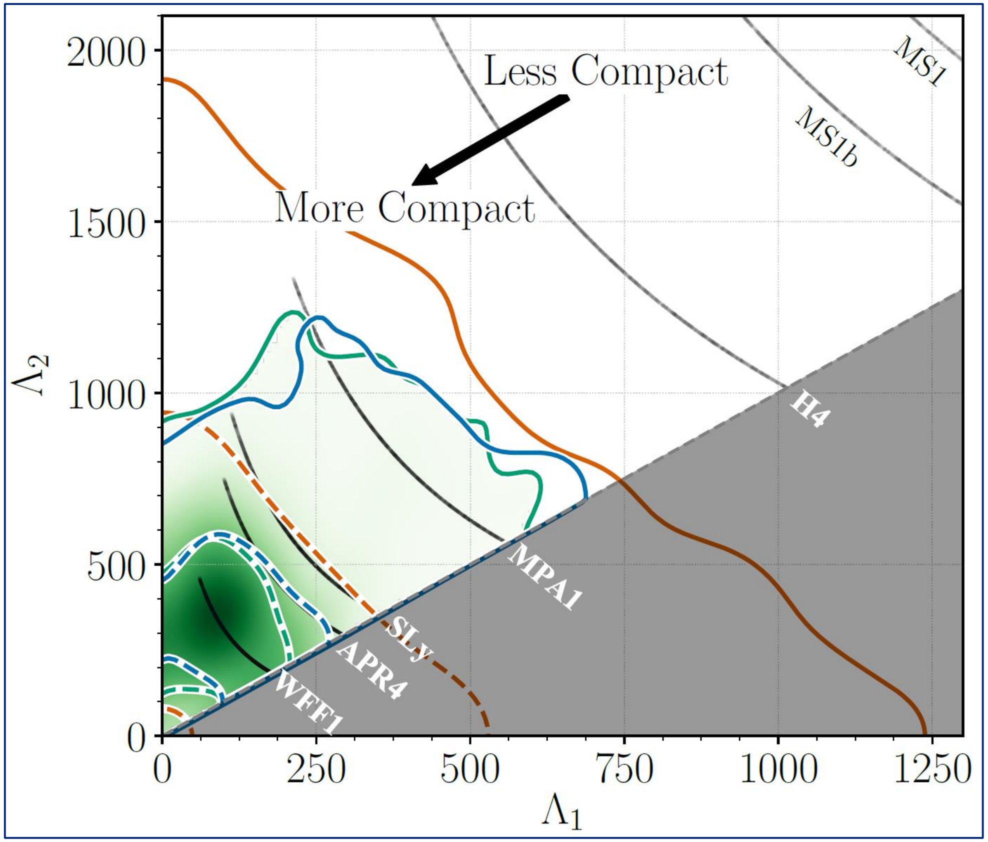


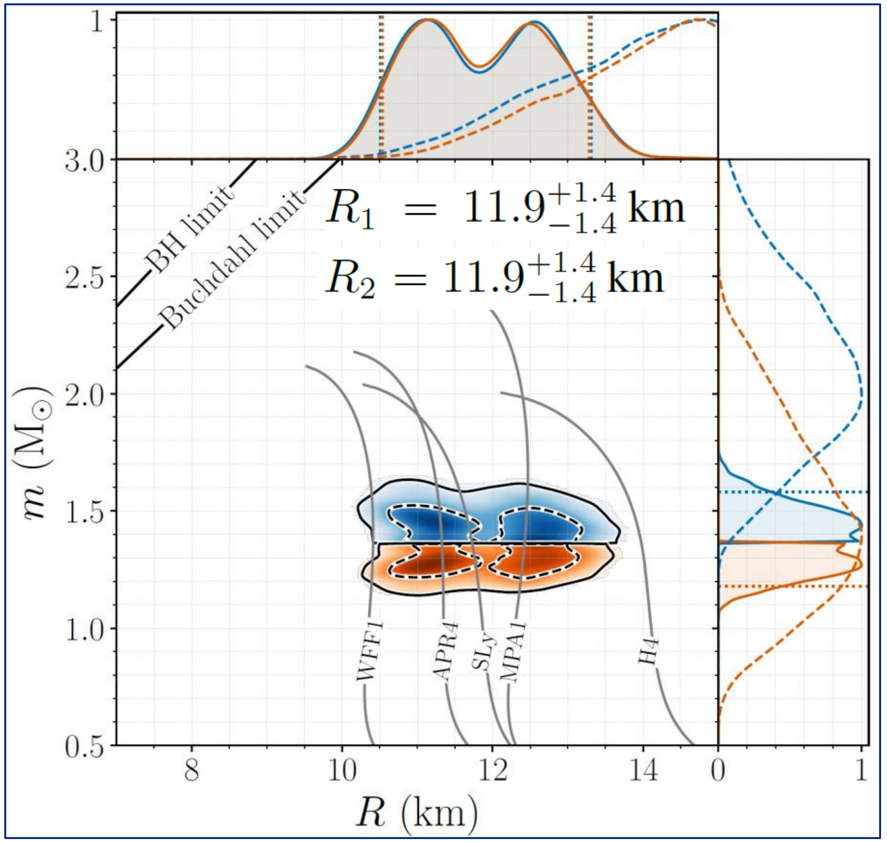
GW170817 properties: tidal deformability, EOS, radii

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: $\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1 + (m_2+12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$

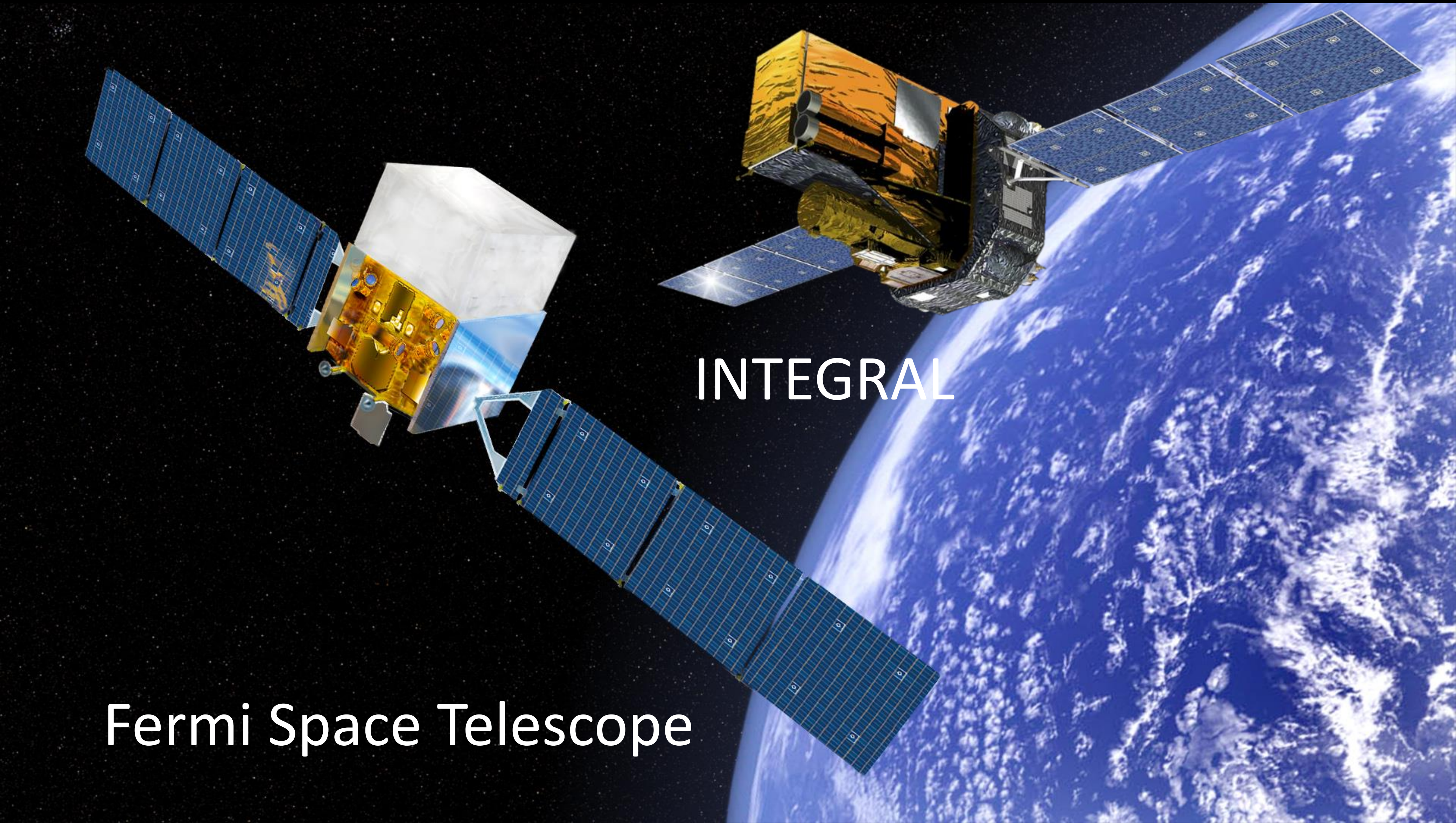
Employ common EOS for both NS (green shading), EOS insensitive relations (green), parametrized EOS (blue), independent EOSs (orange). See: LVC, https://arxiv.org/abs/1805.11581





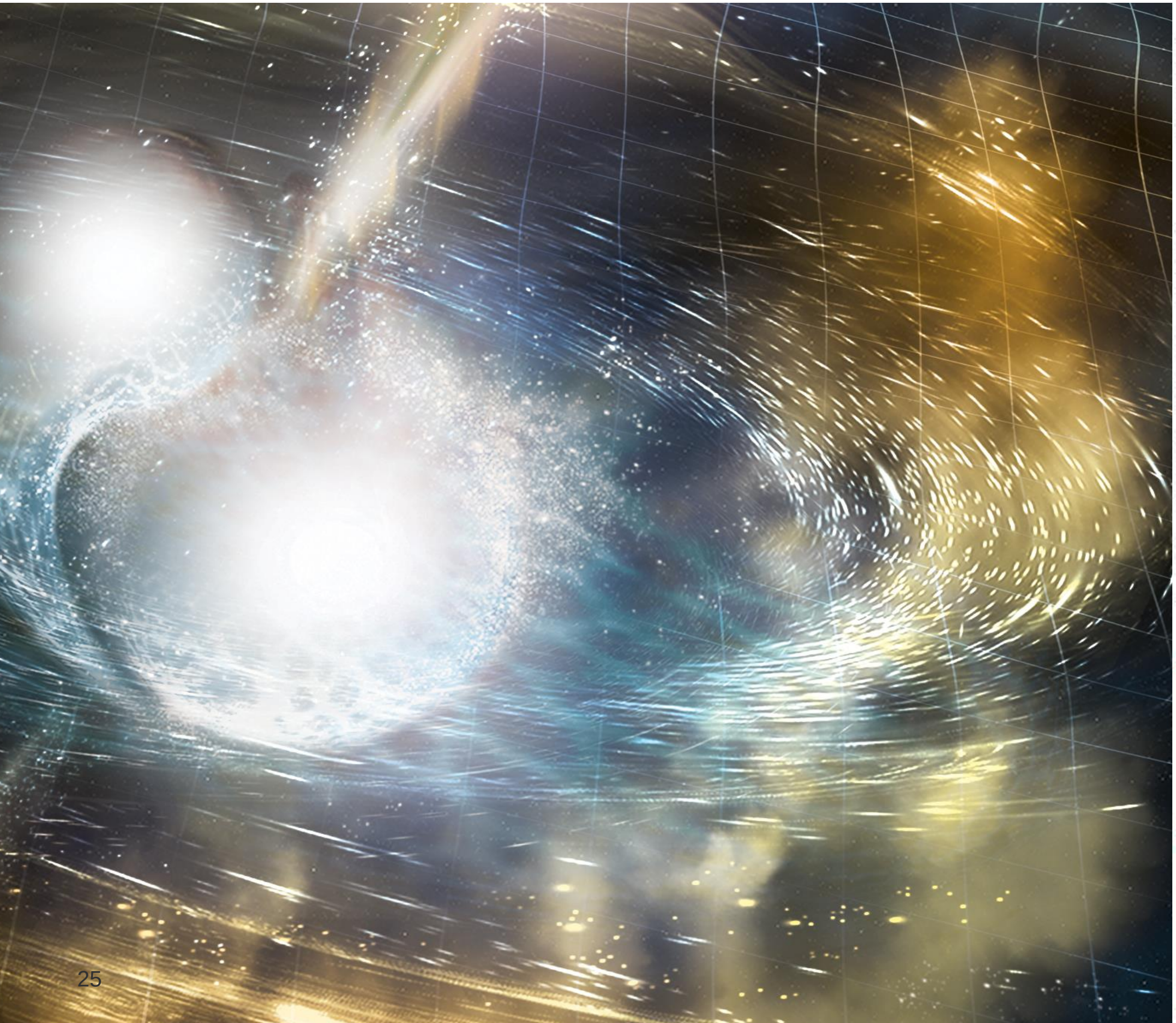
Multi-messenger astronomy

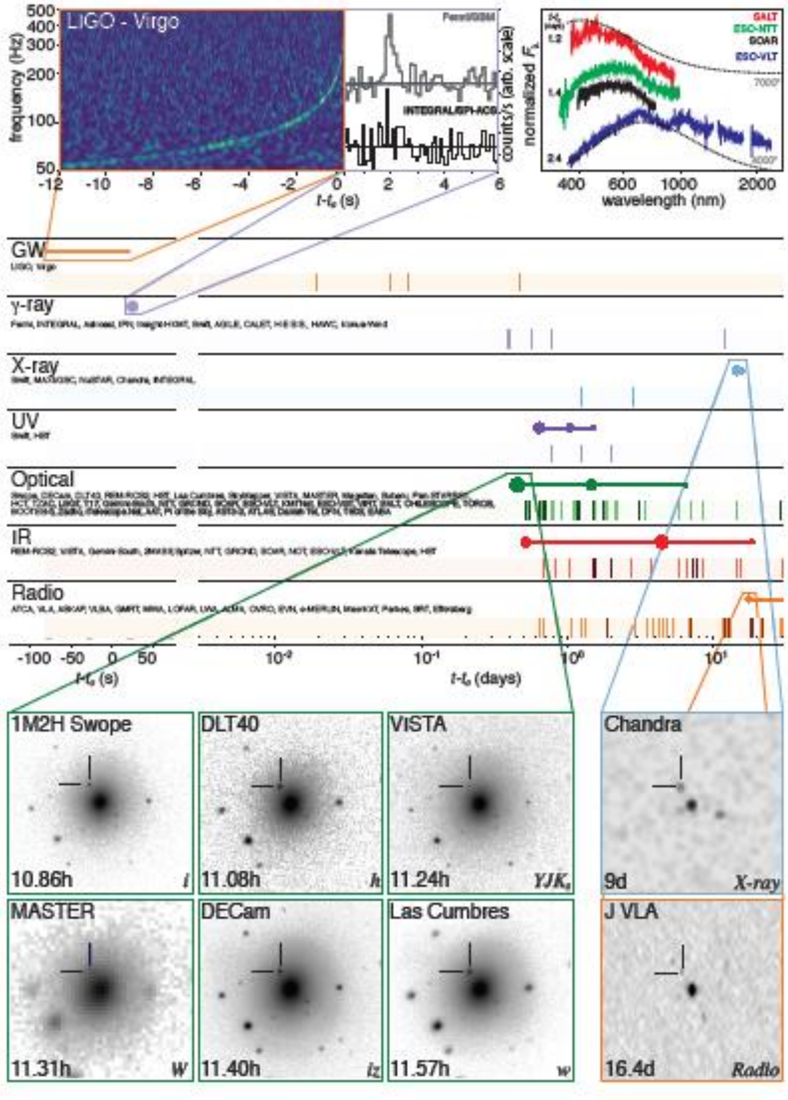
Gamma rays reached Earth 1.7 seconds after GW event



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)

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

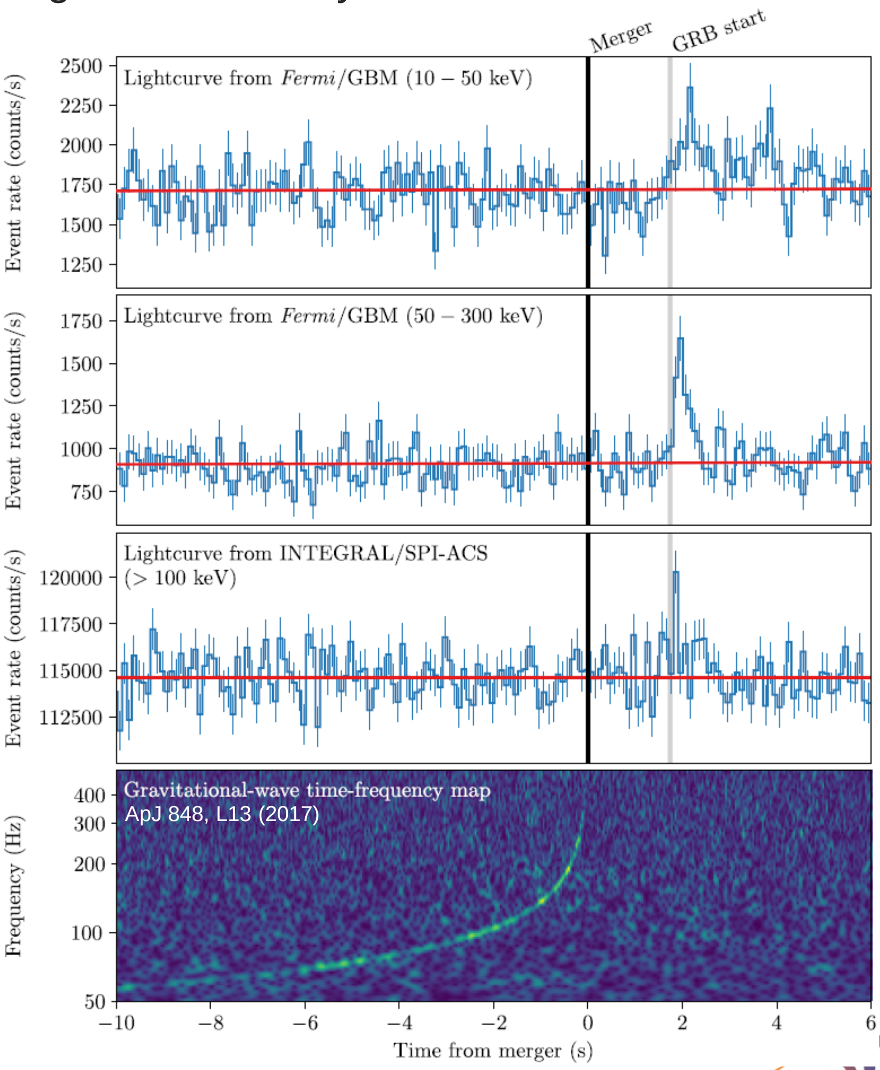
Test of Equivalence Principle

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

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

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
$\Delta\gamma \leq 4 \times 10^{-9}$



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 or MoG/Scalar-Tensor-Vector ideas have the property that GW propagate on different geodesics (normal matter) from those followed by photons and neutrinos (effective mass to emulate dark matter)

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

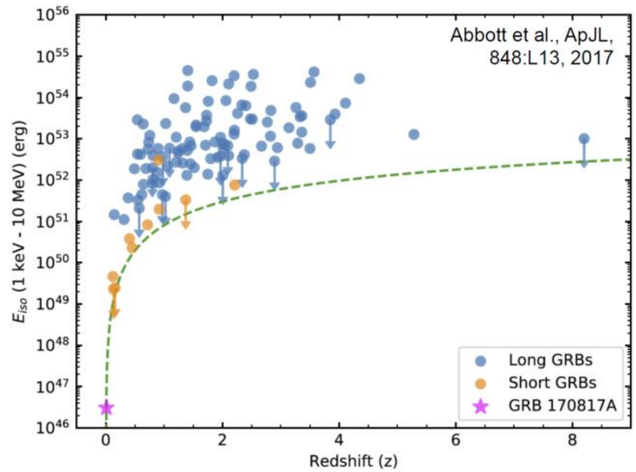
Looking into the heart of a dim nearby sGRB

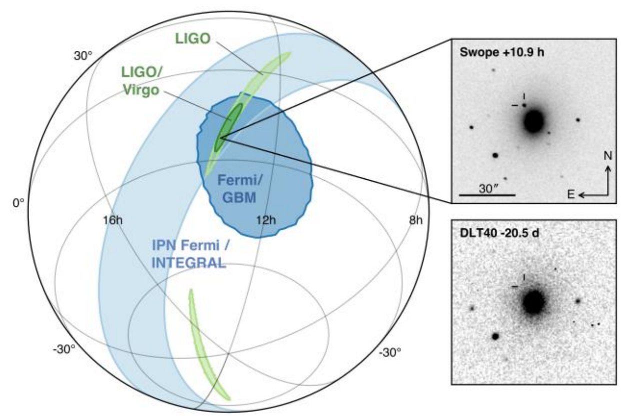
Gravitational waves identified the progenitor of the sGRB and provided both space localization and distance of the source. This triggered the EM follow-up by astronomers for the kilonova

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

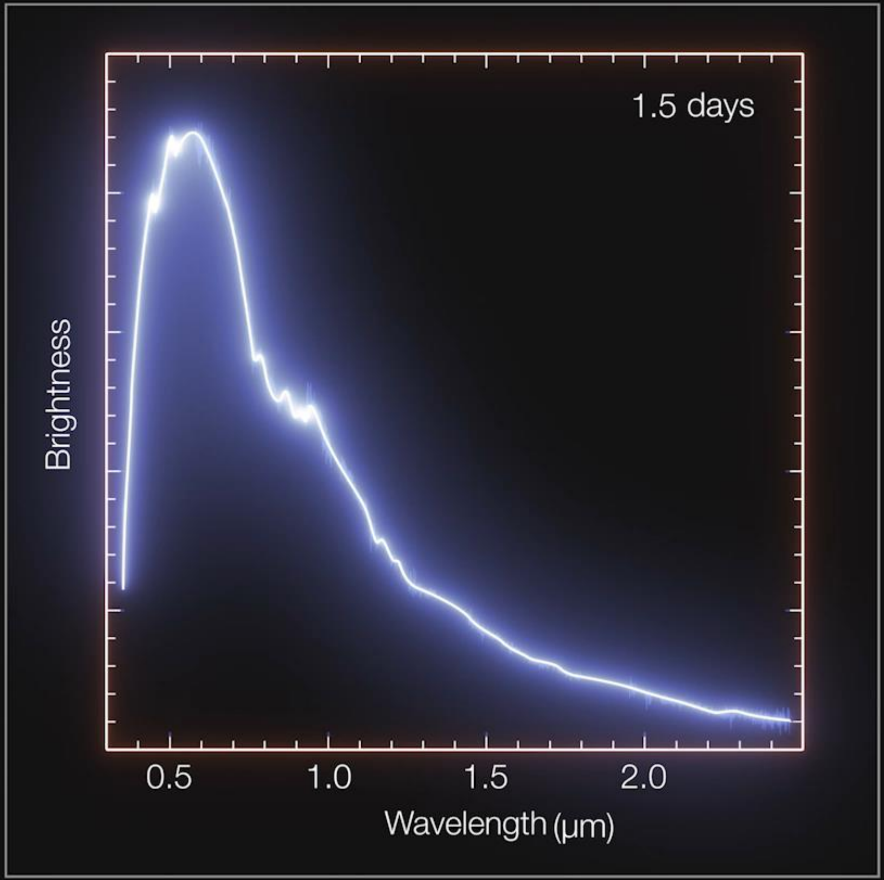




European Southern Observatory

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

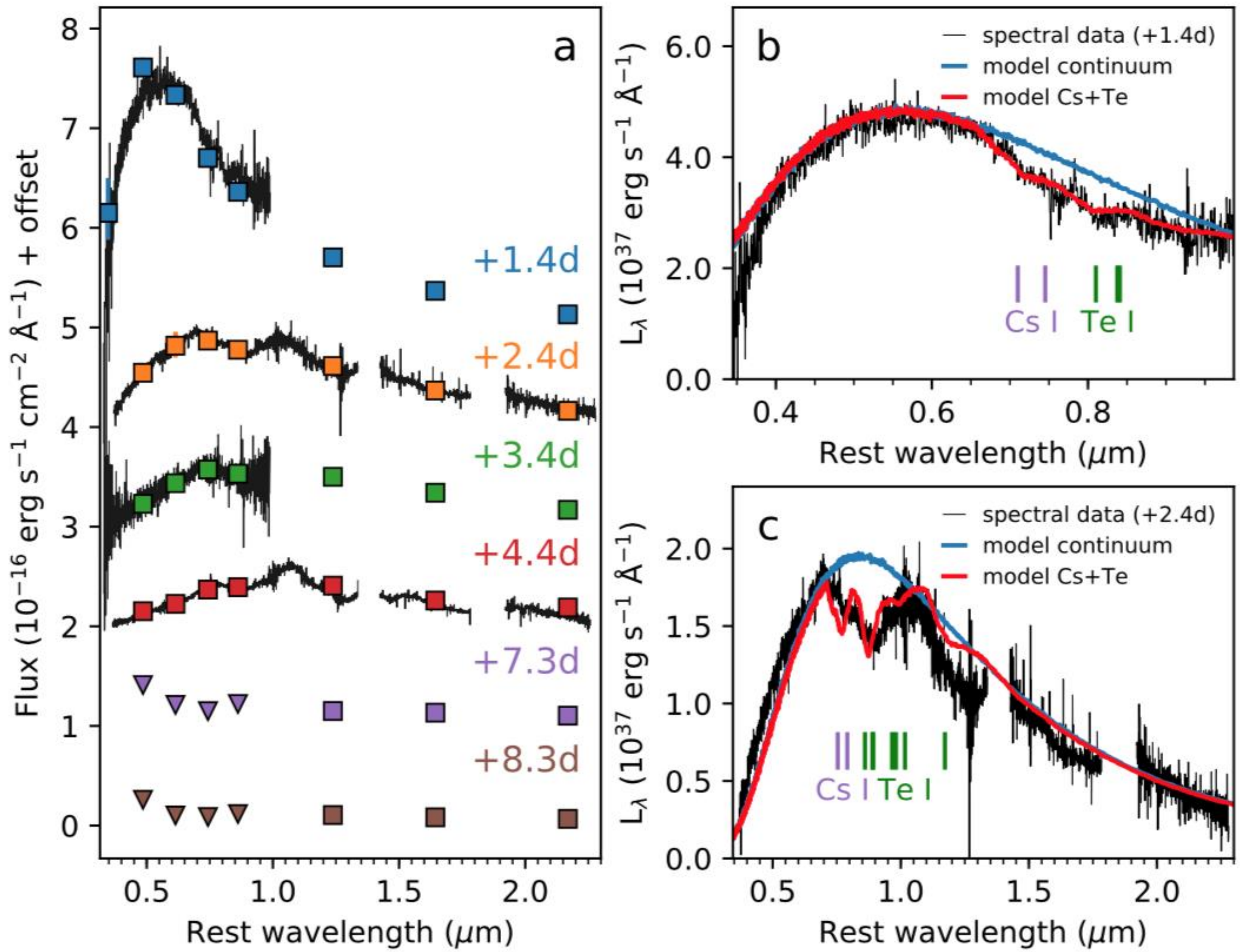
The kilonova essentially has a black-body spectrum (6000 K; blue curve in panel C)

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)

See talk by Stephan Rosswog

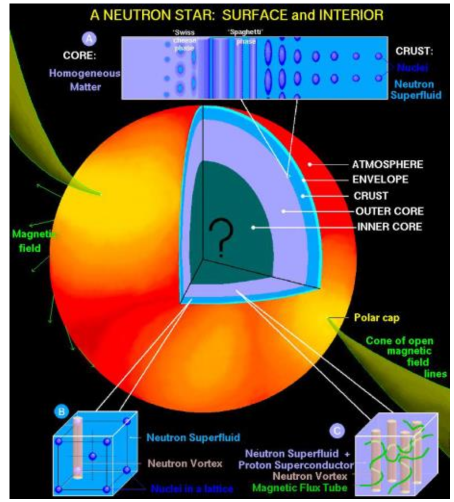


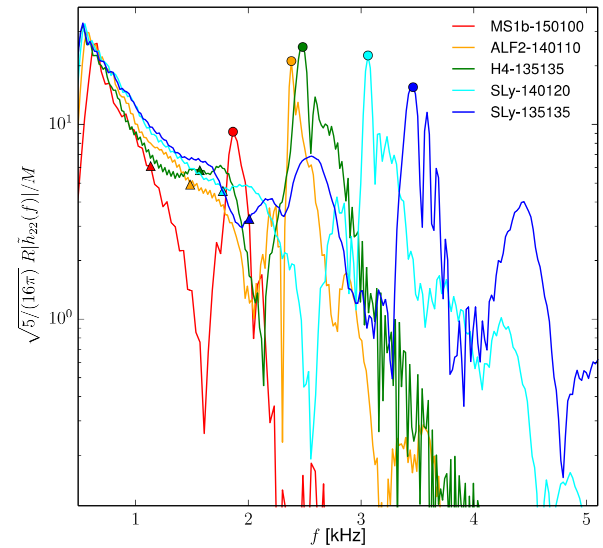
Solving an astrophysical conundrum

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?

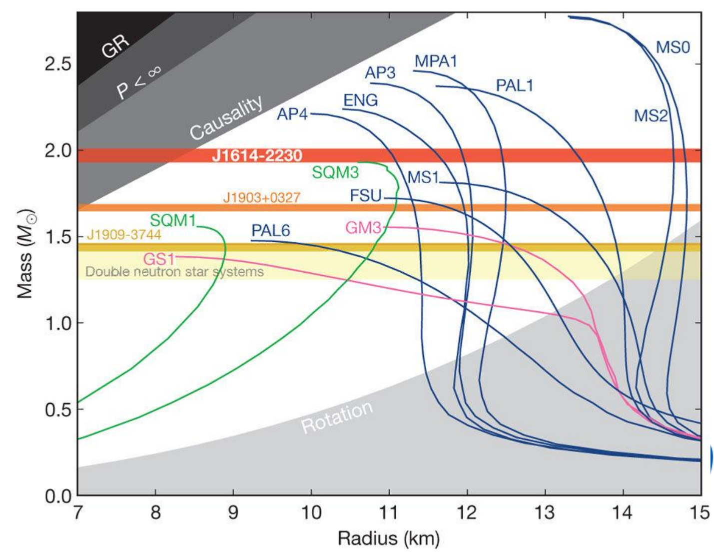
- Structure of the crust?
- Proton superconductivity
- Neutron superfluidity
- “Pinning” of fluid vortices to crust
- Origin of magnetic fields?
- More exotic objects?





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

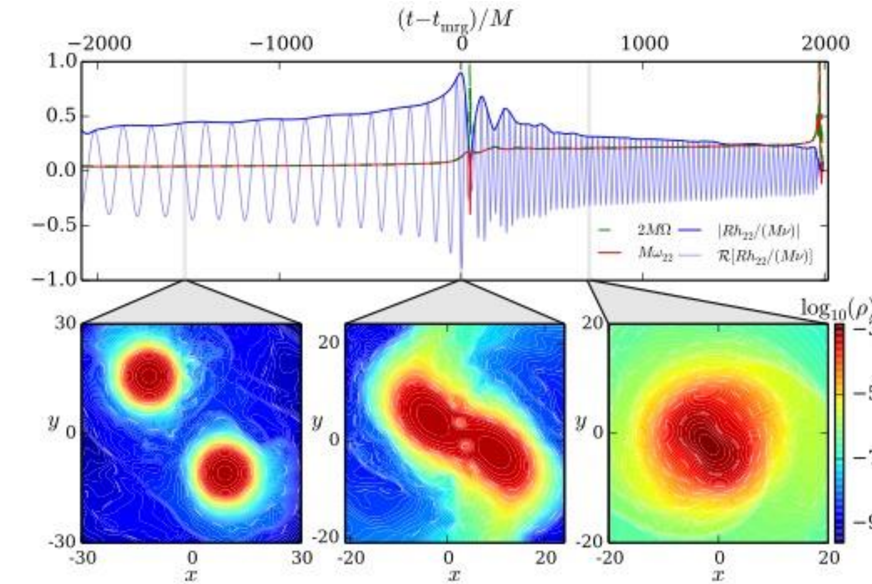


Probing the structure of neutron stars

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

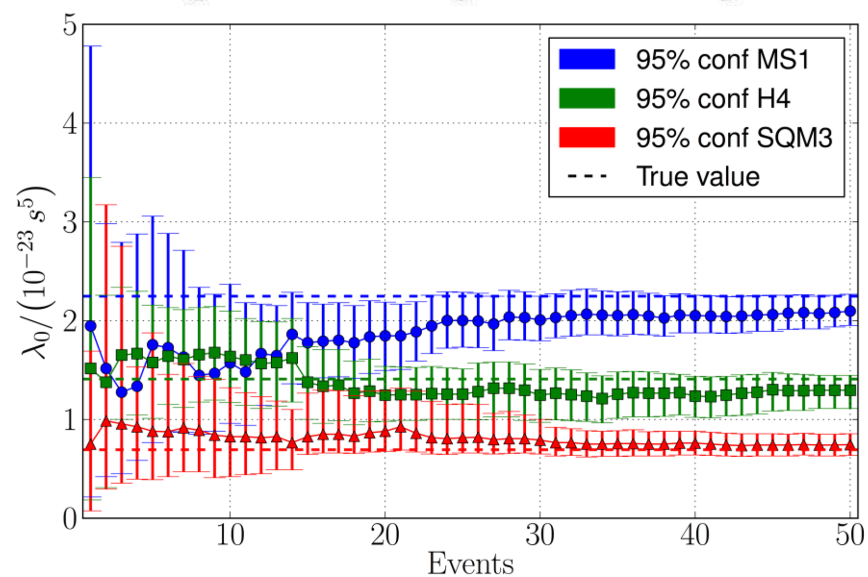
Gravitational waves from inspiraling binary neutron stars

- 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



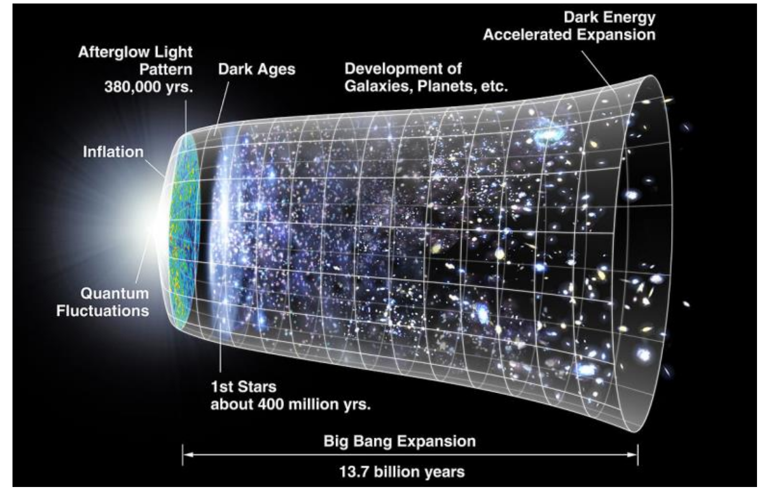
Measurement of tidal deformations on GW170817

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



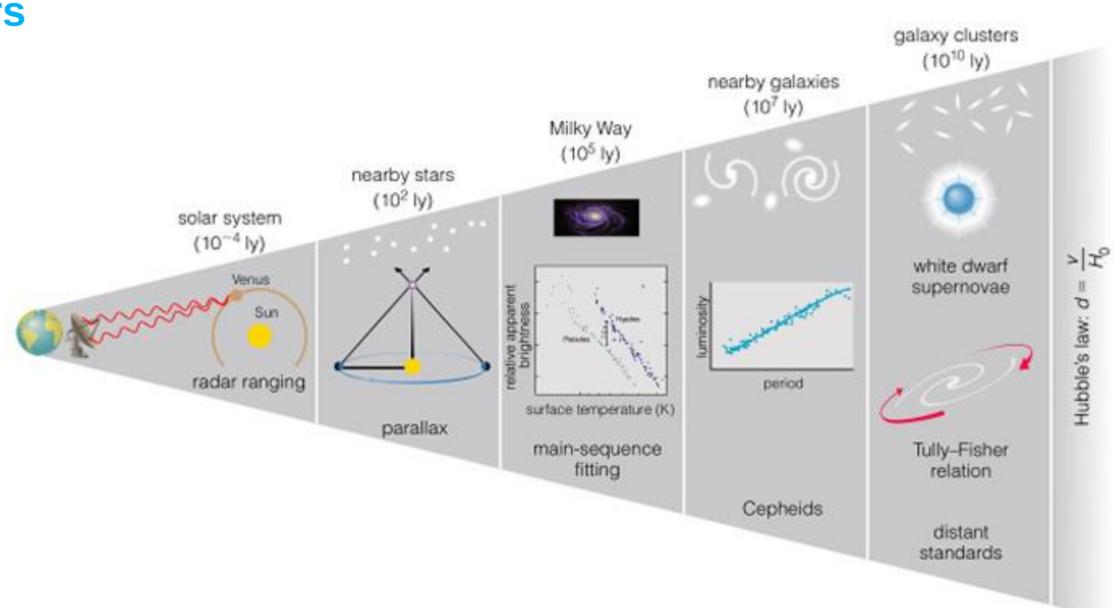
A new cosmic distance marker

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



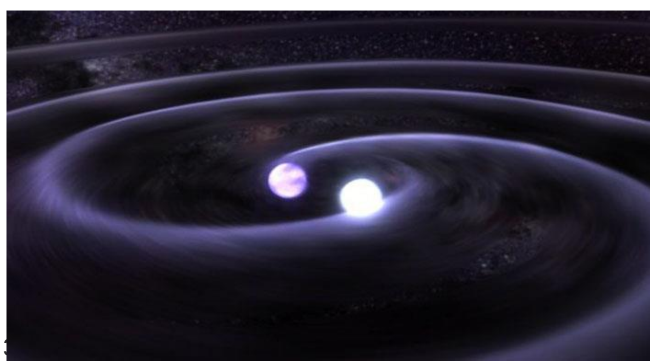
Current measurements depend on cosmic distance ladder

- 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

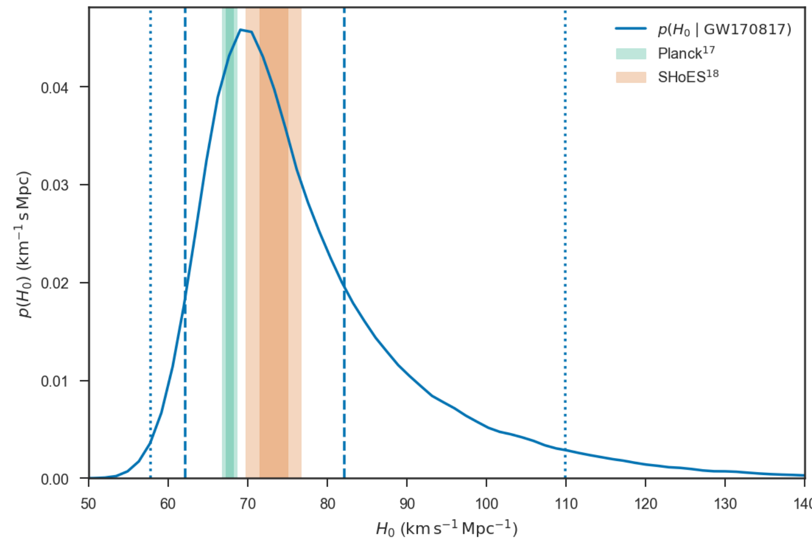
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1-2% accuracy

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)

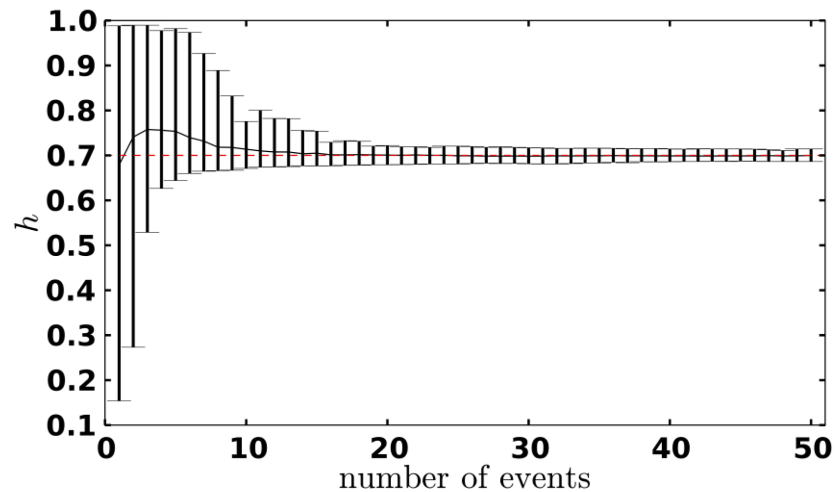


GW170817

- 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

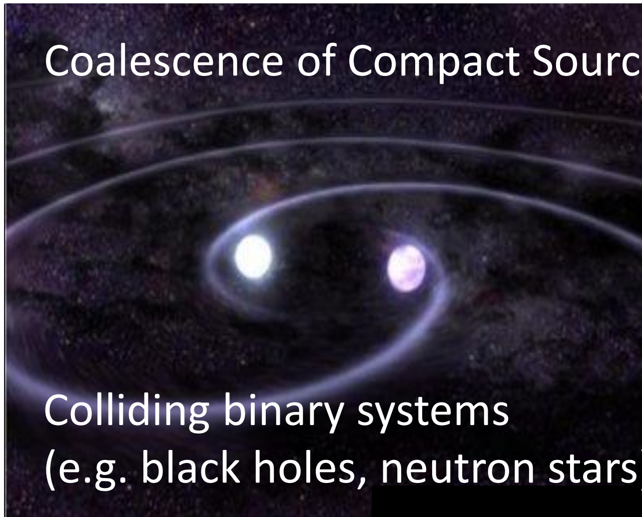
Tidal interactions between neutron stars get imprinted on gravitational waves
Access to equation of state

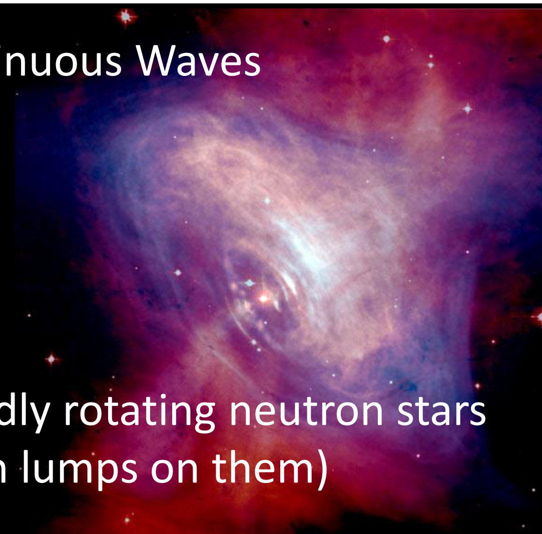
LVC will be back with improved instruments to start the next observation run (O3)

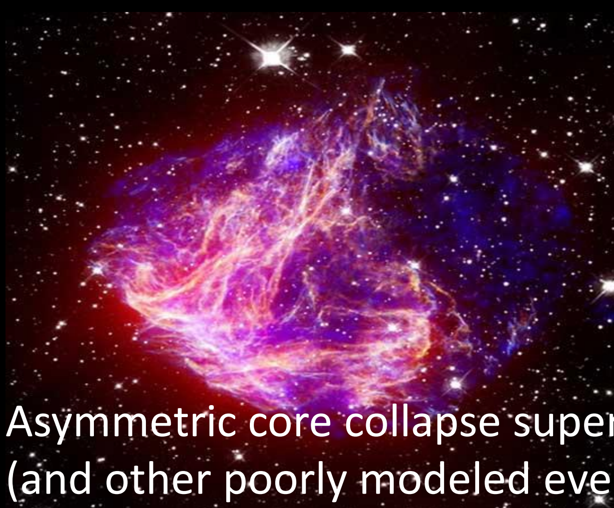
Other searches

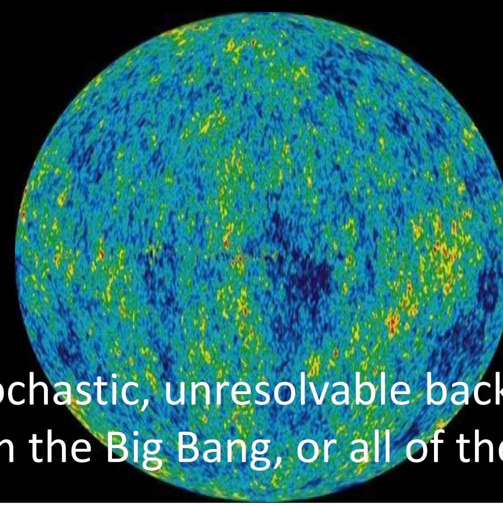
LIGO-Virgo analyses for sources of gravitational waves

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









Continuous Waves

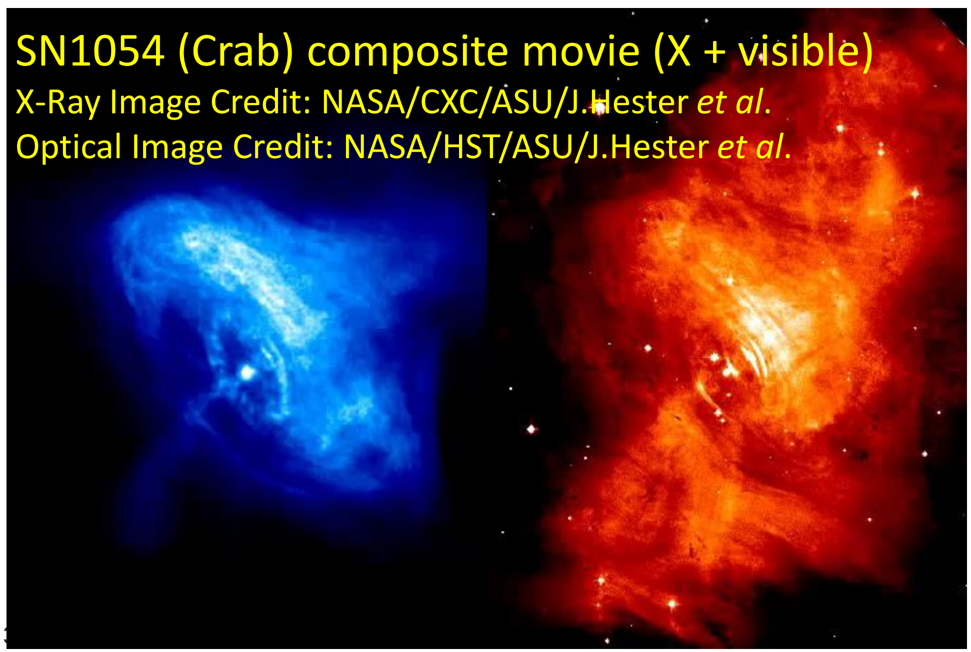
Astrophysics

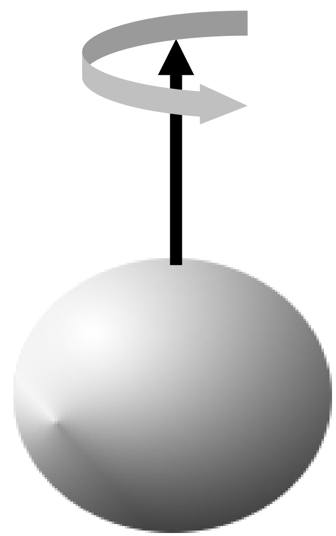
More than 2500 observed NSs (mostly pulsars) and O(10^8 –10^9) expected to exist in our galaxy
Sources must have some degree of non-axisymmetry originating from

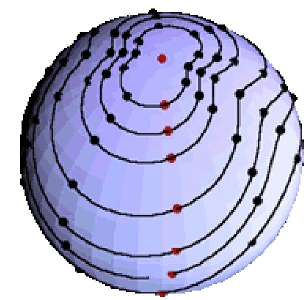
- deformation due to elastic stresses or magnetic field not aligned to the rotation axis ($f_{GW} = 2f_r$)
- free precession around rotation axis ($f_{GW} \sim f_{rot} + f_{prec}$; $f_{GW} \sim 2f_{rot} + 2f_{prec}$)
- excitation of long-lasting oscillations (e.g. *r*-modes; $f_{GW} \sim 4f_r/3$)
- deformation due to matter accretion (e.g. LMXB; $f_{GW} \sim 2f_r$)

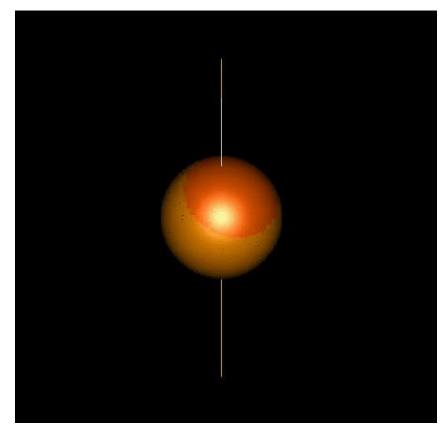
Source characteristics

Emission of quasi-monochromatic waves with a slowly decreasing intrinsic frequency
Constant amplitude, but weak, and persistent over years of data taking









Continuous Waves analysis (talk by Paola Leaci)

Types of Continuous Waves searches

- Targeted searches: observed NSs with known source parameters as sky location, frequency & frequency derivatives (e.g. the Crab and Vela pulsars)
- Narrowband searches: observed NSs with uncertainties in rotational parameters. A small mismatch between the GW frequency (spindown) and the rotational star frequency (spindown) inferred from EM observations needs to be taken into account
- Directed searches: sky location is known while frequency and frequency derivatives are unknown (e.g. Cassiopeia A, SN1987A, Scorpius X-1, galactic center, globular clusters)
- All-sky searches: unknown pulsars => computing challenge (Einstein@Home – Cloud – Grid)

Papers

- First search for gravitational waves from known pulsars (LVC, ApJ 839, 12, 2017)
  - Analyzed 200 known pulsars (119 out of 200 are in binary systems)
  - Spindown limit beaten for 8 pulsars, including both Crab & Vela: For the Crab and Vela pulsars less than 2x10-3 and 10-2 of the spindown luminosity is being lost via GWs, respectively
- Narrowband search: LVC, PRD 96, 122006 (2017)
- Directed searches from Scorpius-X1 (LVC 2017: PRD 95, 122003; ApJ 847, 47, PRL 118, 121102)
- All-sky searches up to high frequencies (LVC, PRD 97, 102003, 2018)
- All-sky searches at low frequencies LVC, PRD 96, 122004, 2018)
- Search for non-tensorial polarizations (LVC, PRL 120, 031104, 2018)

Still to come: O2 results from targeted, narrowband, directed and all-sky searches

- See https://galaxy.ligo.caltech.edu/svn/cw/public/index.html

Stochastic GW Background (talk by Tania Regimbau)

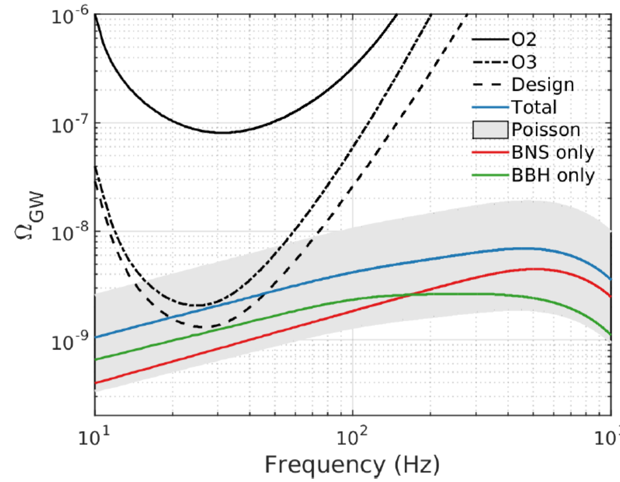
A stochastic background of gravitational waves has resulted from the superposition of a large number of independent unresolved sources from different stages in the evolution of the Universe

Astrophysical SGWB

All the sources since the beginning of stellar activity
Dominated by compact binary coalescences: BBHs, BNSs, BH-NSs

LIGO and Virgo have already observed 5 (+1?) BBHs and 1 BNS
Events are individual sources at z~0.07-0.2 for BBHs, 0.01 for BNS

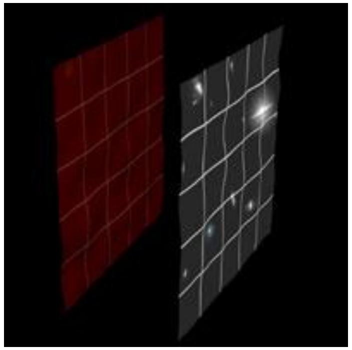
Many individual sources at larger distances that contribute to SGWB
This could be the next milestone for LIGO/Virgo

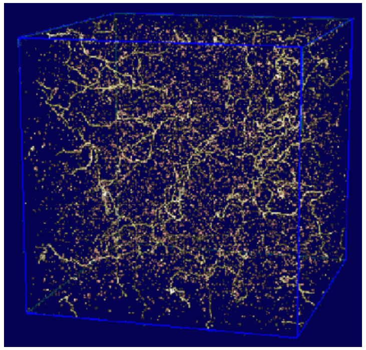


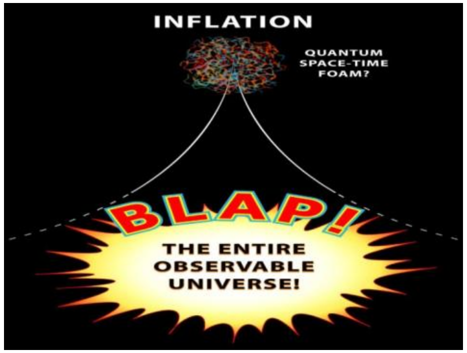
Abbott et al. PRL120.091101, 2017

Cosmological SGWB

Signatures of the early Universe
Inflation, cosmic strings, no phase transition in LIGO/Virgo







Next steps

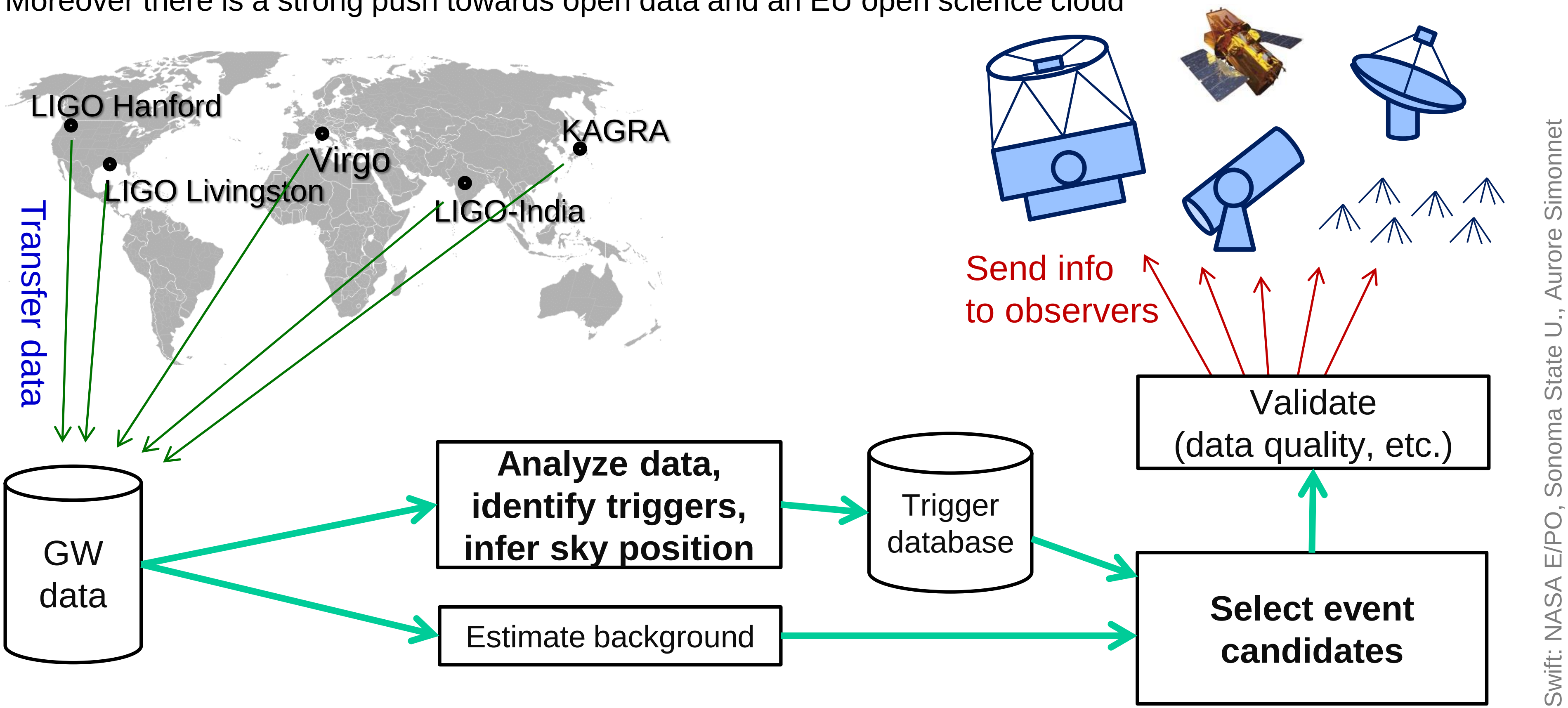
Observation run 3 (O3) expected to start early 2019

The LIGO-Virgo Collaboration is upgrading their instruments with the intention to achieve a doubling of the sensitivity and start multi-messenger astronomy (MMA). MMA requires rapid follow-up of interesting triggers and fast distribution of science data between partners distributed over the globe

Computing will become increasingly important as experiments mature

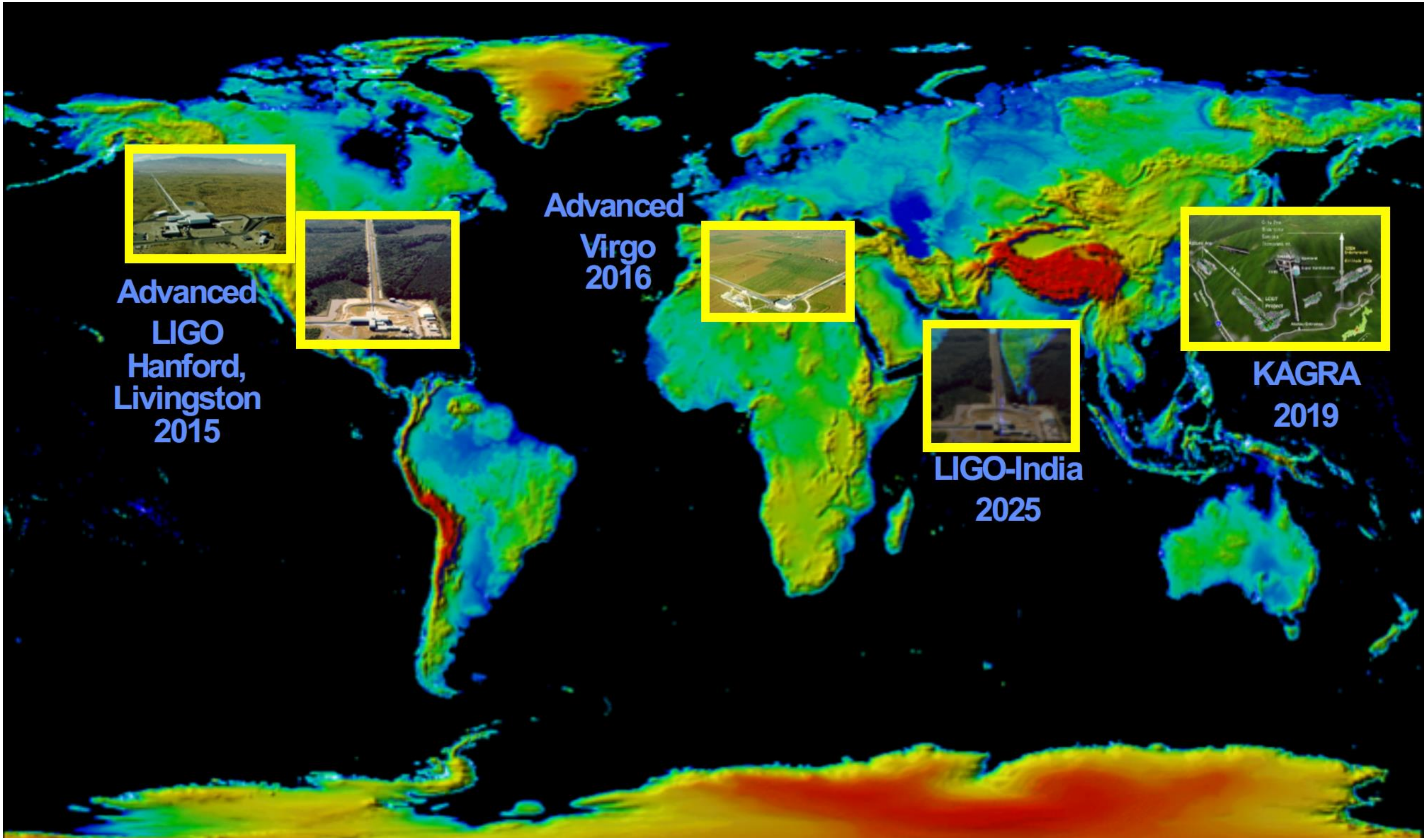
- GW event rate rapidly increases as sensitivity improves (note that GW-amplitude is measured; Rate $\sim S_{GW}^3$)
- Also computing needs grow as templates get longer

Moreover there is a strong push towards open data and an EU open science cloud



KAGRA

Expected to join LIGO and Virgo in Observation run 3



AdV+ and A+ as the next steps forward in sensitivity

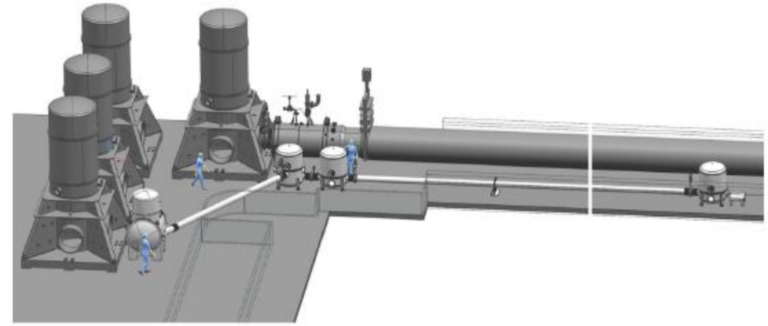
AdV+ is the European plan to maximize Virgo's sensitivity within the constrains of the EGO site. It will be carried out in parallel with the LIGO A+ upgrade

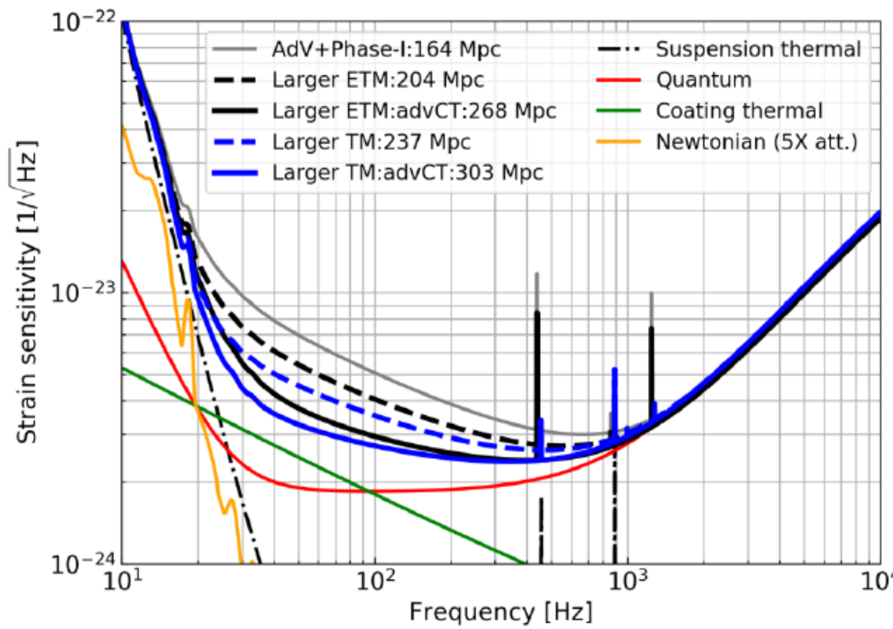
AdV+ features

- Maximize science
- Secure Virgo's scientific relevance
- Safeguard investments by scientists and funding agencies
- Implement new innovative technologies
- De-risk technologies needed for third generation observatories
- Attract new groups wanting to enter the field

Upgrade activities

- Tuned signal recycling and HPL: 120 Mpc
- Frequency dependent squeezing: 150 Mpc
- Newtonian noise cancellation: 160 Mpc
- Larger mirrors (105 kg): 200-230 Mpc
- Improved coatings: 260-300 Mpc





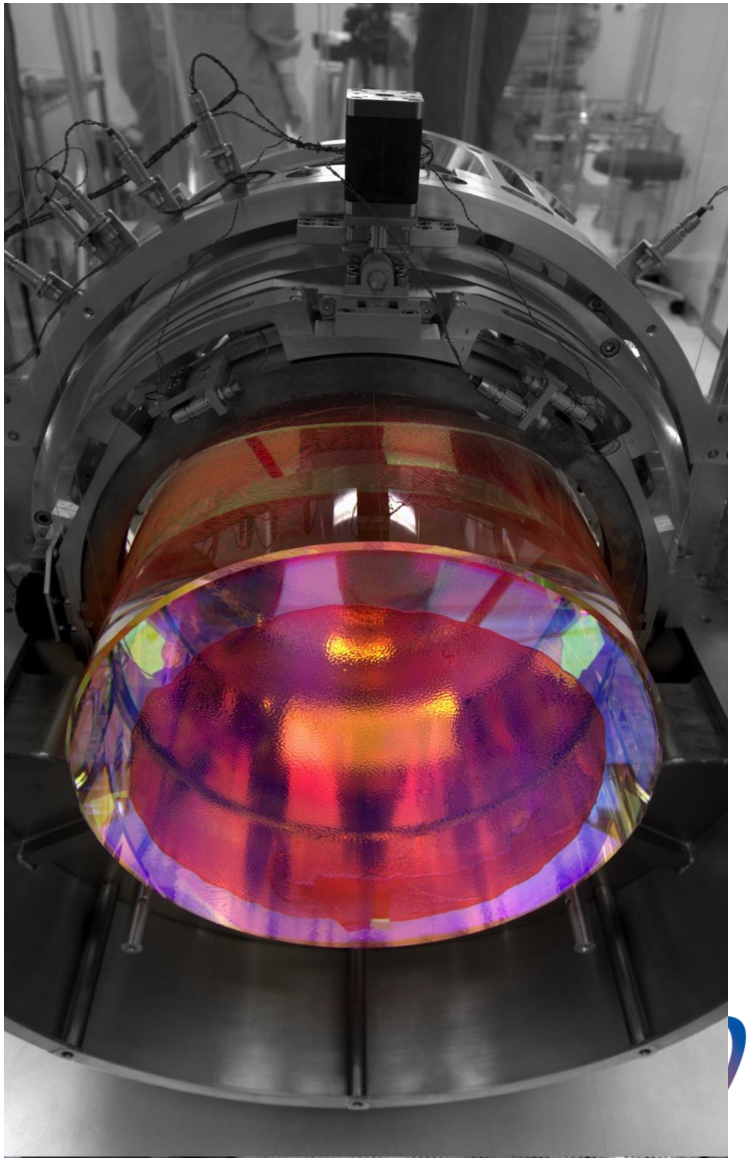
Injection of squeezed light states

Employ frequency dependent squeezing to overcome quantum noise at low and high frequencies

Virgo squeezer from AEI, Hanover

AdV+ upgrade and extreme mirror technology

Laboratoire des Matériaux Avancés LMA at Lyon produced the coatings used on the main mirrors of the two working gravitational wave detectors: Advanced LIGO and Virgo. These coatings feature low losses, low absorption, and low scattering properties



Features

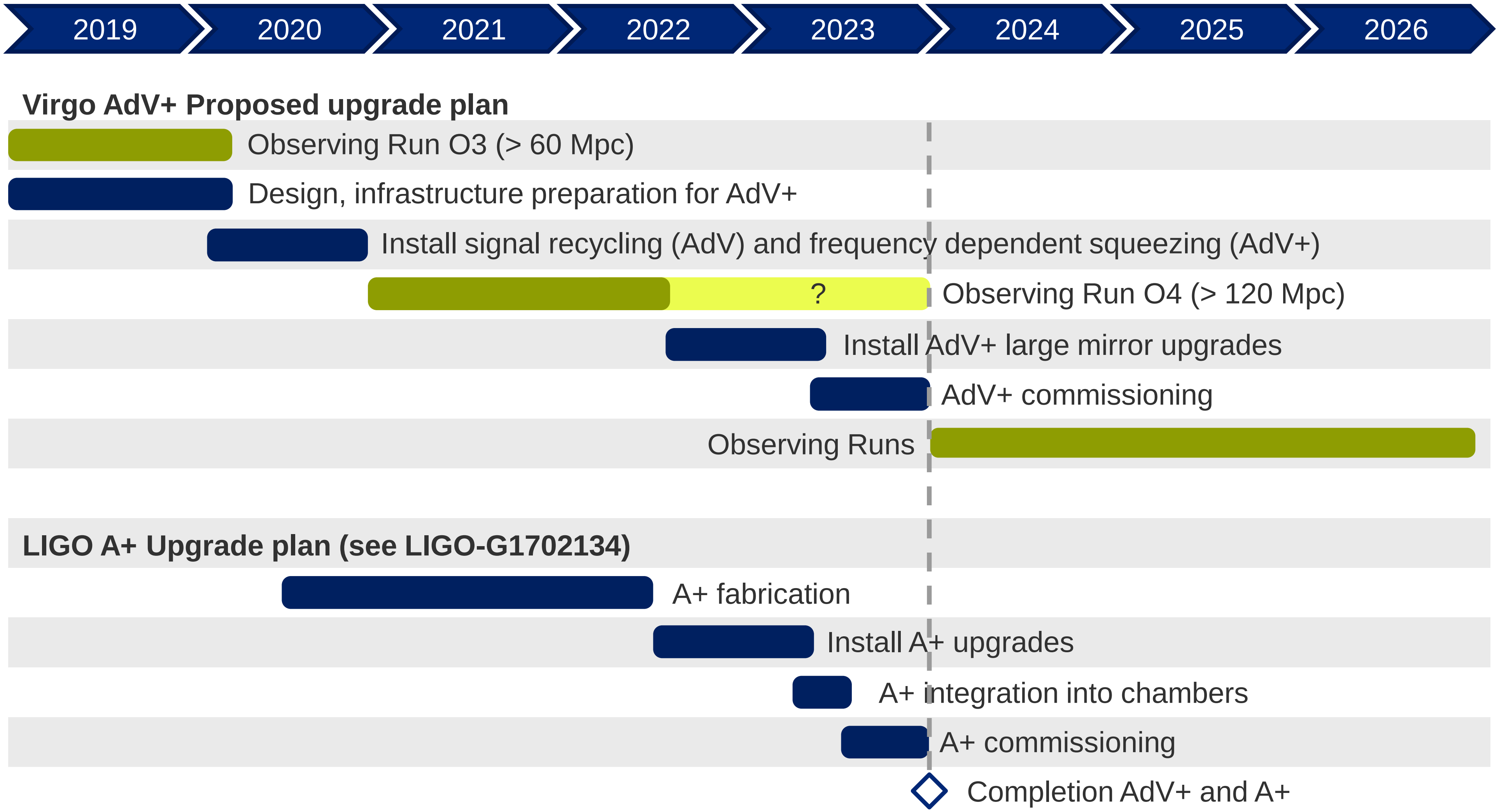
- Flatness < 0.5 nm rms over central 160 mm of mirrors by using ion beam polishing (robotic silica deposition was investigated)
- $Ti{:}Ta_2O_5$ and SiO_2 stacks with optical absorption about 0.3 ppm

Expand LMA capabilities for next generation

LMA is the only coating group known to be capable of scaling up

AdV+ to be carried out in parallel with LIGO's A+ upgrade

Five year plan for observational runs, commissioning and upgrades



Note: duration of O4 has not been decided at this moment

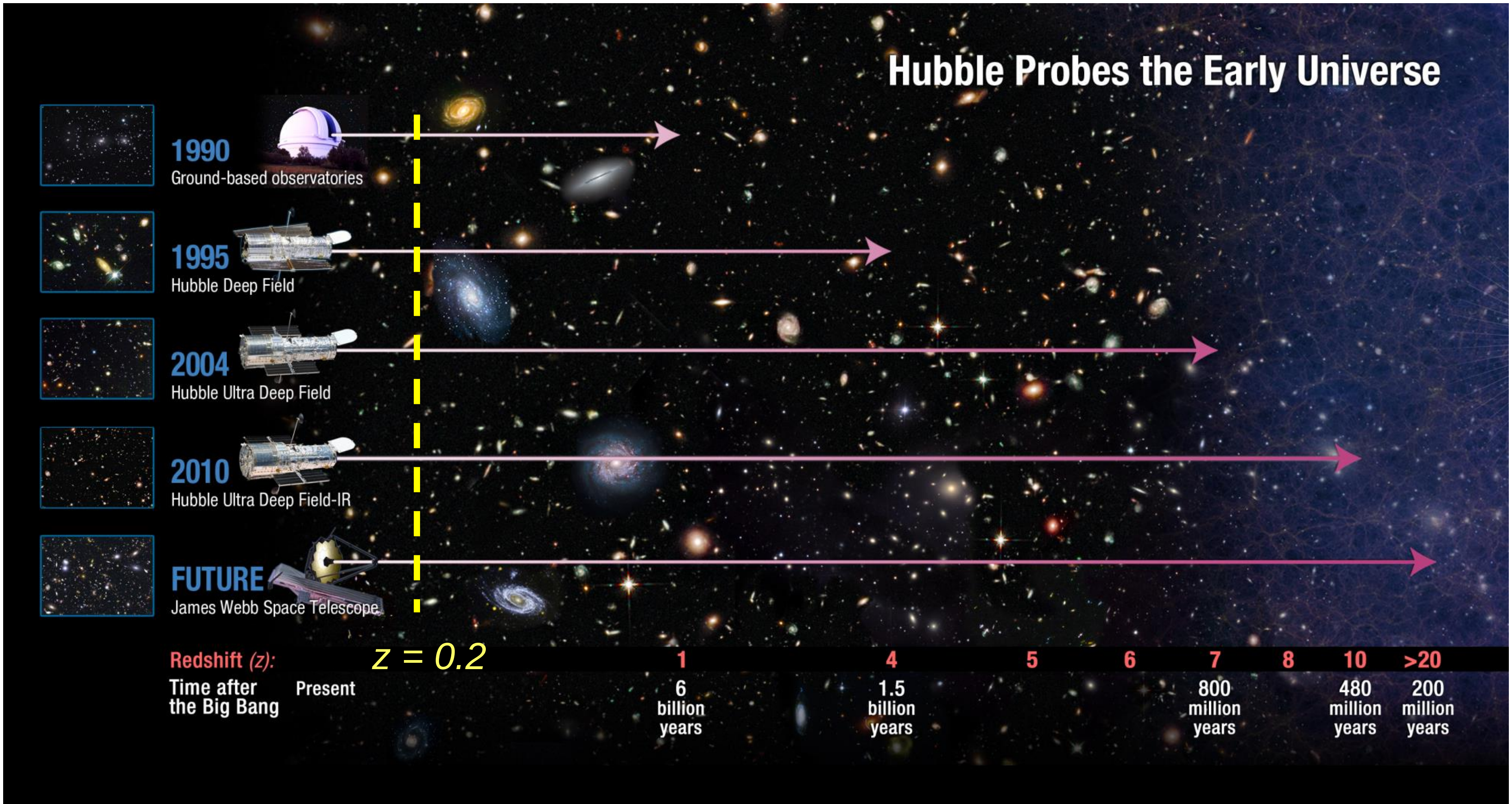
AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope

Einstein Telescope: observing all BBH mergers in Universe

This cannot be achieved with existing facilities and requires a new generation of GW observatories

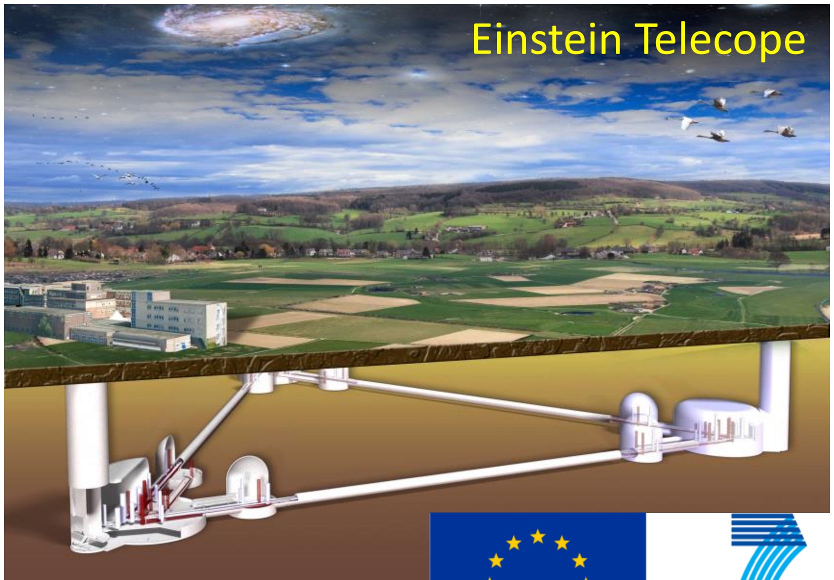
We want to collect high statistics (*e.g.* millions of BBH events), high SNR, distributed over a large z-range ($z < 20$)

This allows sorting data versus redshift, mass distributions, *etc*. Early warning, IMBH, early Universe, CW, …

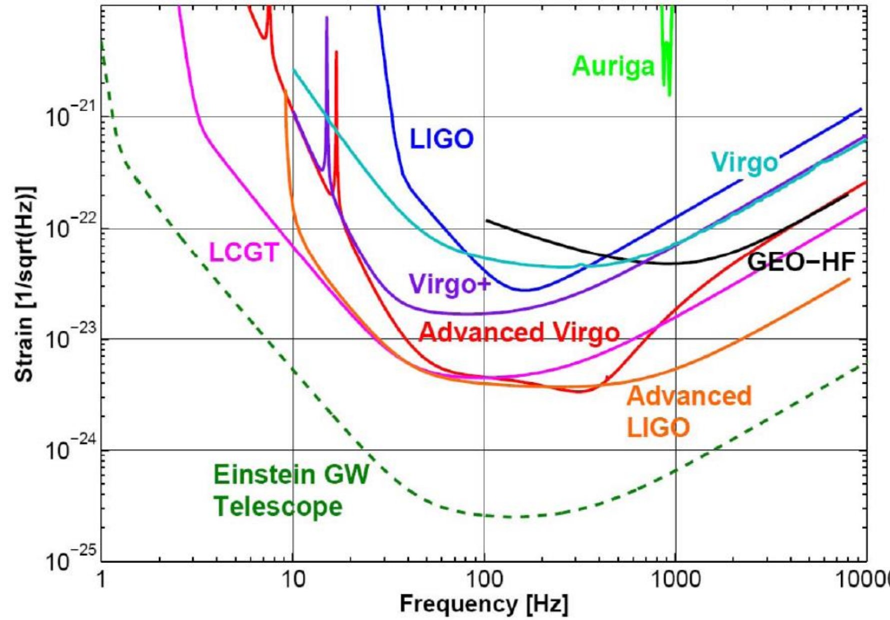


ET and CE (talk by Giovanni Losurdo)

Realizing the next gravitational wave observatories is a coordinated effort with US to create a worldwide 3G network

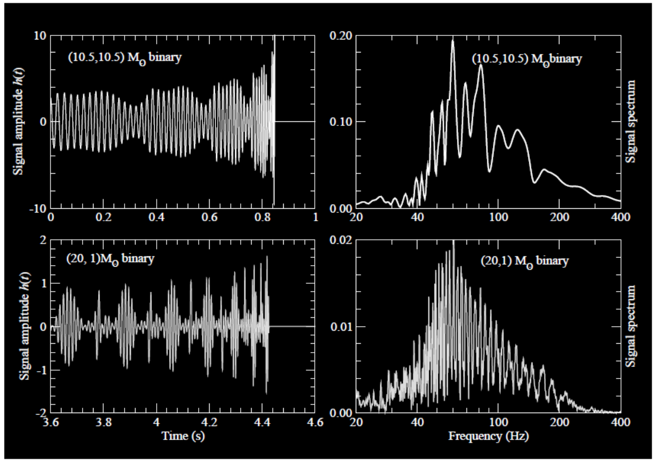


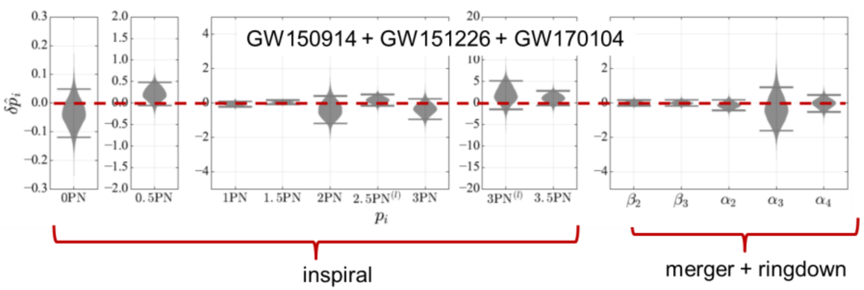
SEVENTH FRAMEWORK PROGRAMME

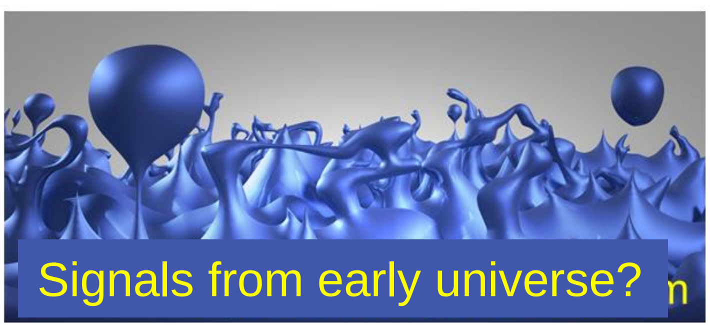


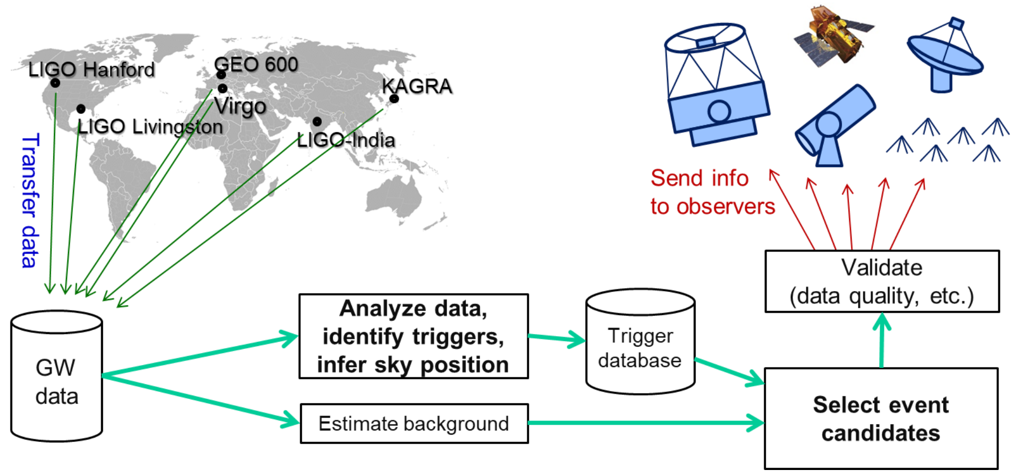
3G science

Detailed studies of gravity, near black holes. Early warning to EM follow-up community. Precision tests of detailed aspects of CBC. Cross correlation of the largest data sets. Access to early Universe







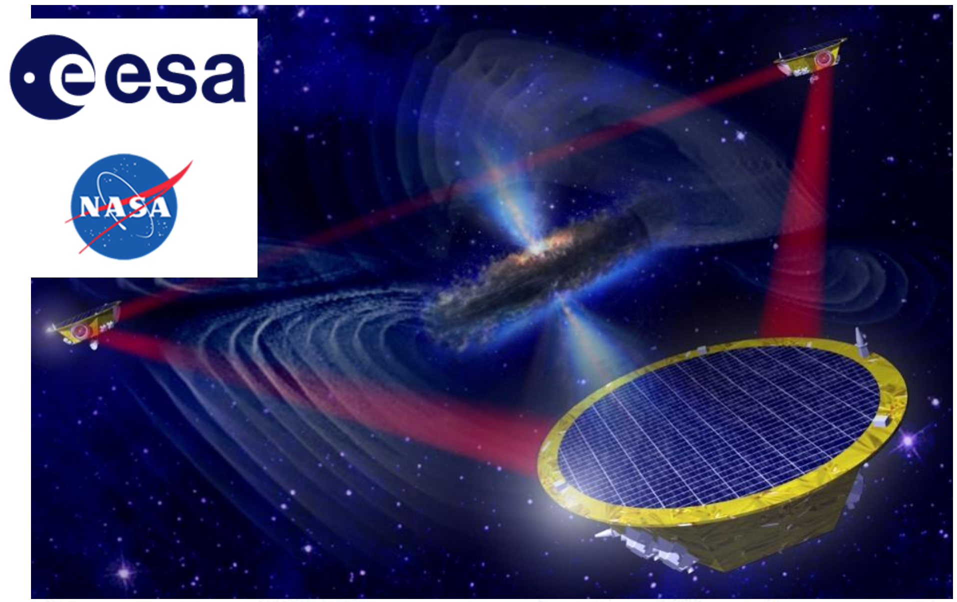


Bright future for gravitational wave research

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

Gravitational wave research

- LIGO and Virgo operational
- KAGRA to join next year
- LIGO-India under construction (2025)
- ESA selects LISA, NASA rejoins
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation



Einstein Telescope

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

Next steps for 3G

- Organize the community and prepare a credible plan for EU funding agencies
- ESFRI Roadmap (2019)
- Support ET: http://www.et-gw.eu/index.php/letter-of-intent