Gravitational waves and fundamental physics

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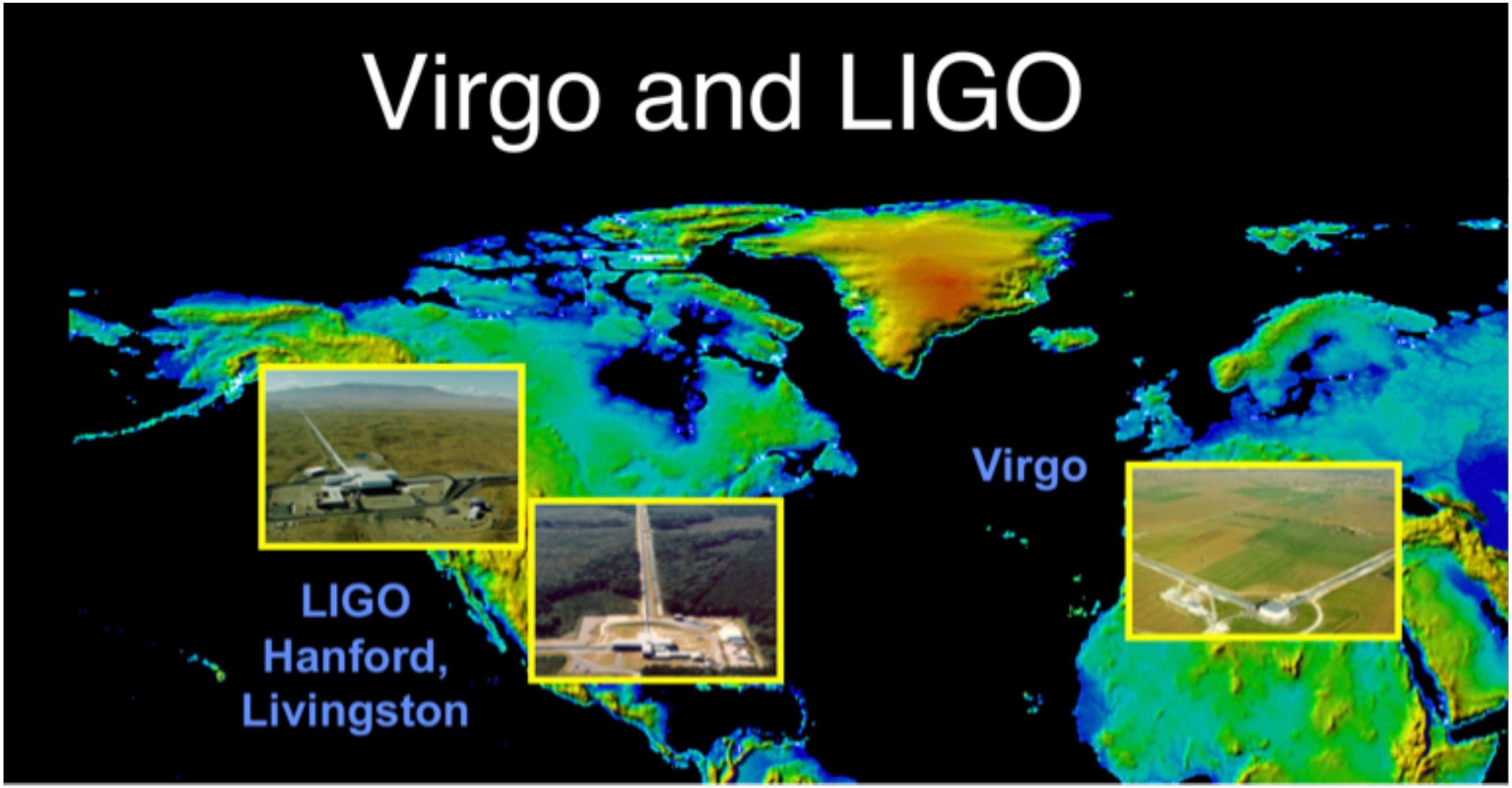
Florence, October 3, 2018

LIGO
Scientific
Collaboration

LIGO and Virgo

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

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



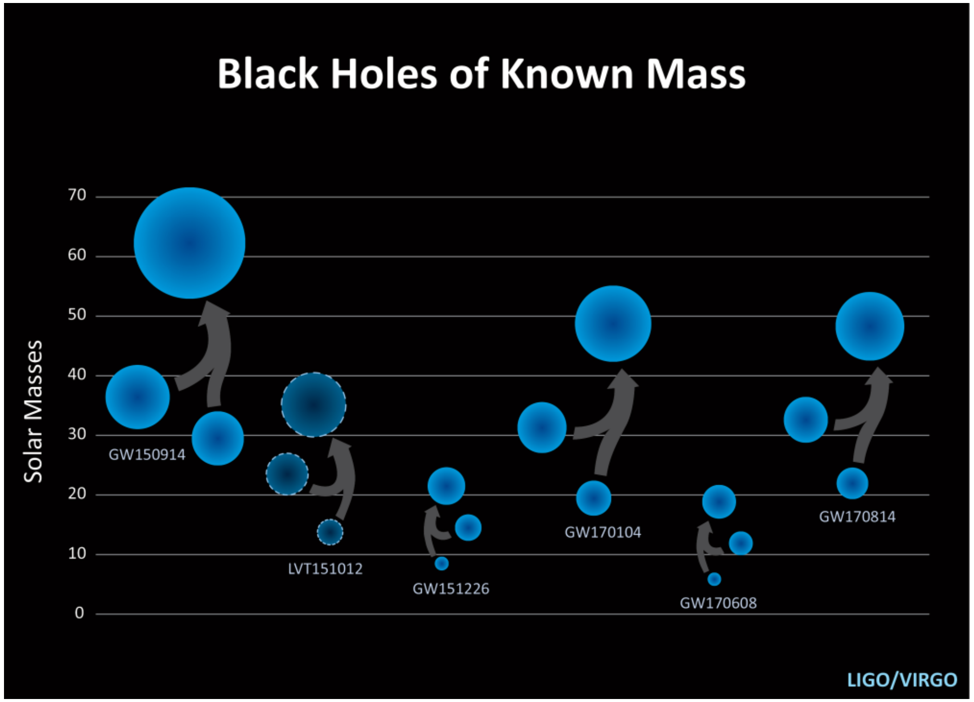
Scientific achievements: properties of black holes

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

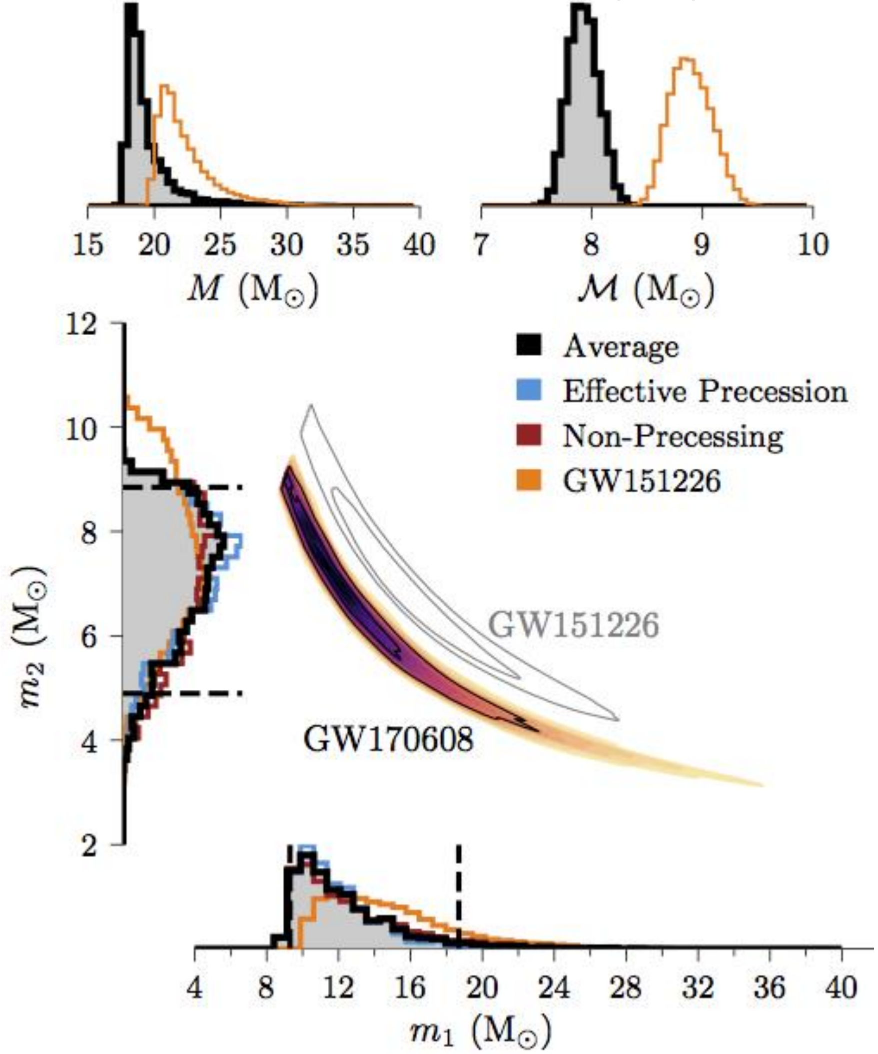
LVC reported on 6 BBH mergers

Fundamental physics, astrophysics, astronomy, and cosmology

Testing GR, waveforms (with matter)



Abbott et al. APJL 851:L35 (2017)



Precision tests of GR with BBH mergers

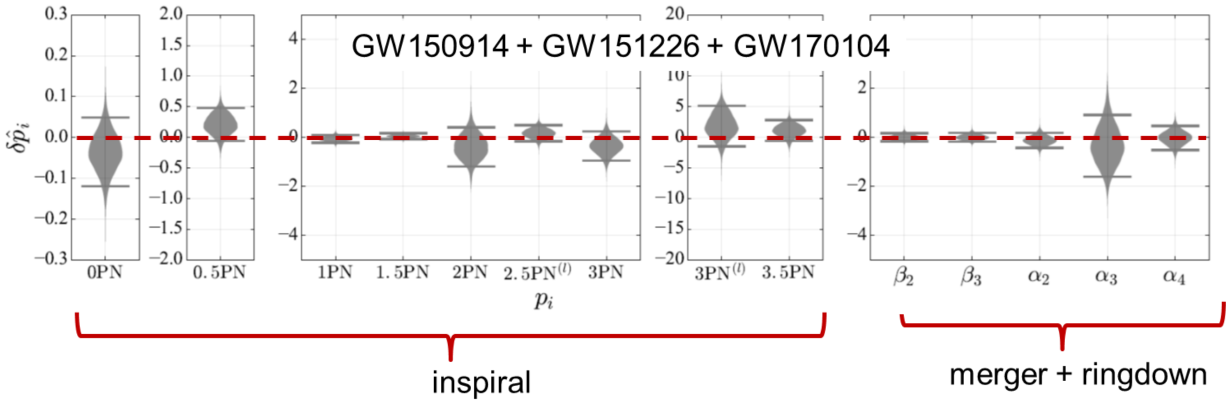
Bayesian analysis increases accuracy on parameters by combining information from multiple events

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?



arXiv:1706.01812

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

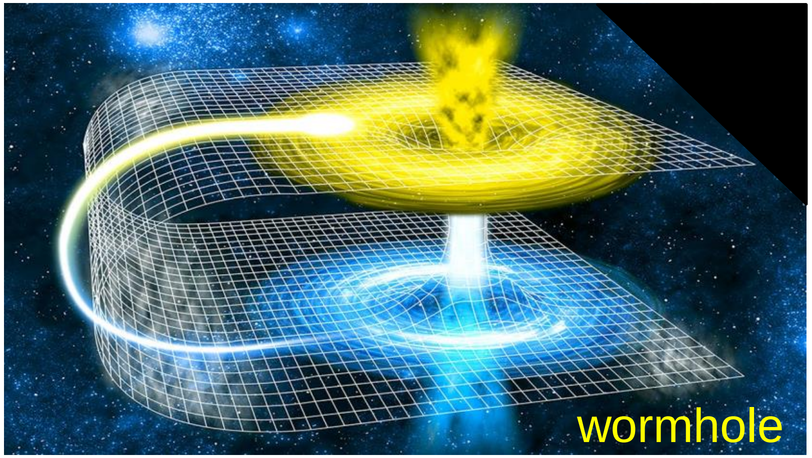
Our collaborations set ambitious goals for the future

We need to improve:

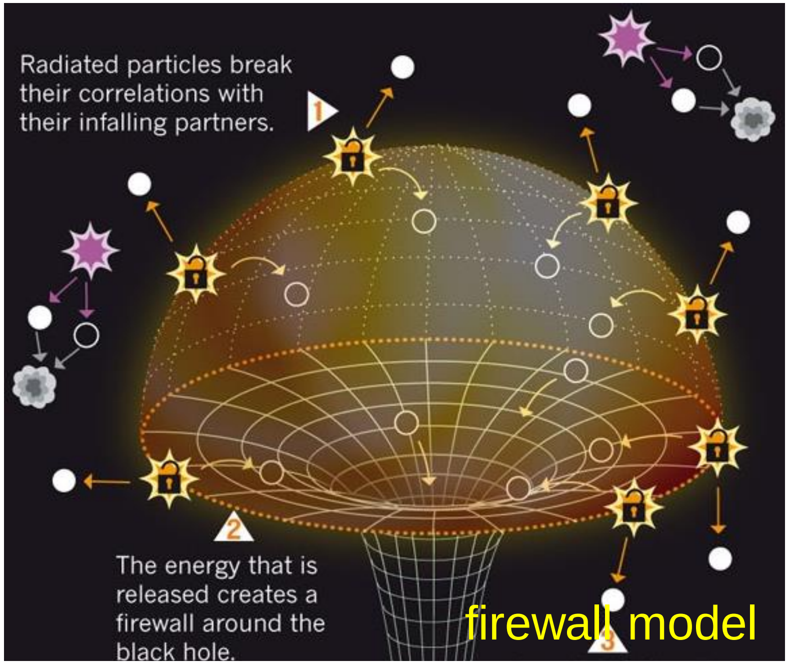
- sensitivity of our instruments over the entire frequency range
- optimize our computing and analysis
- improve our source modeling (NR)

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?



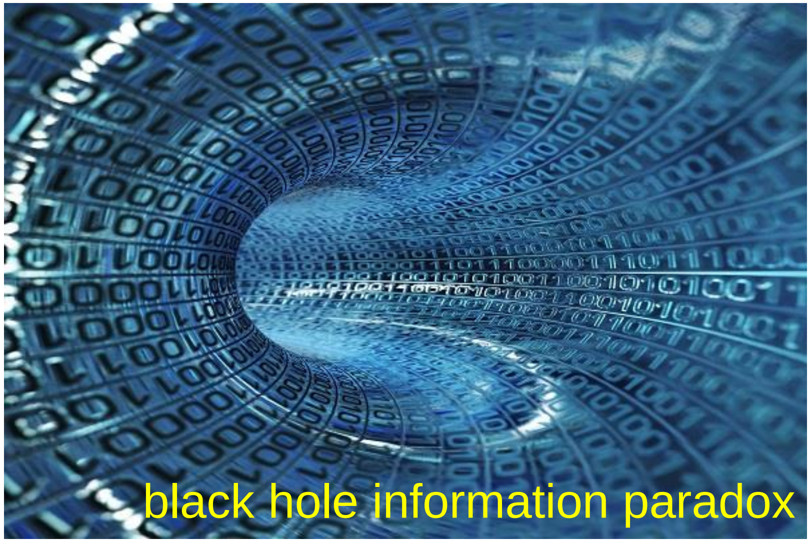
wormhole



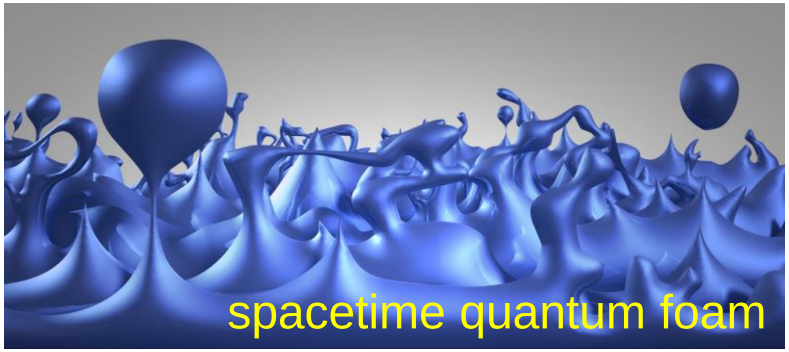
Radiated particles break their correlations with their infalling partners.

The energy that is released creates a firewall around the black hole.

firewall model



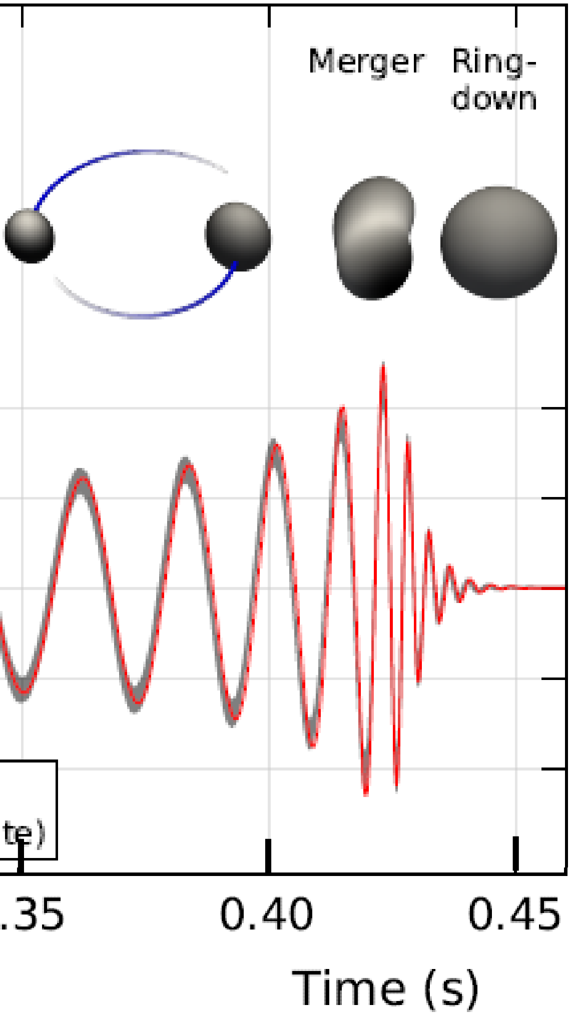
black hole information paradox

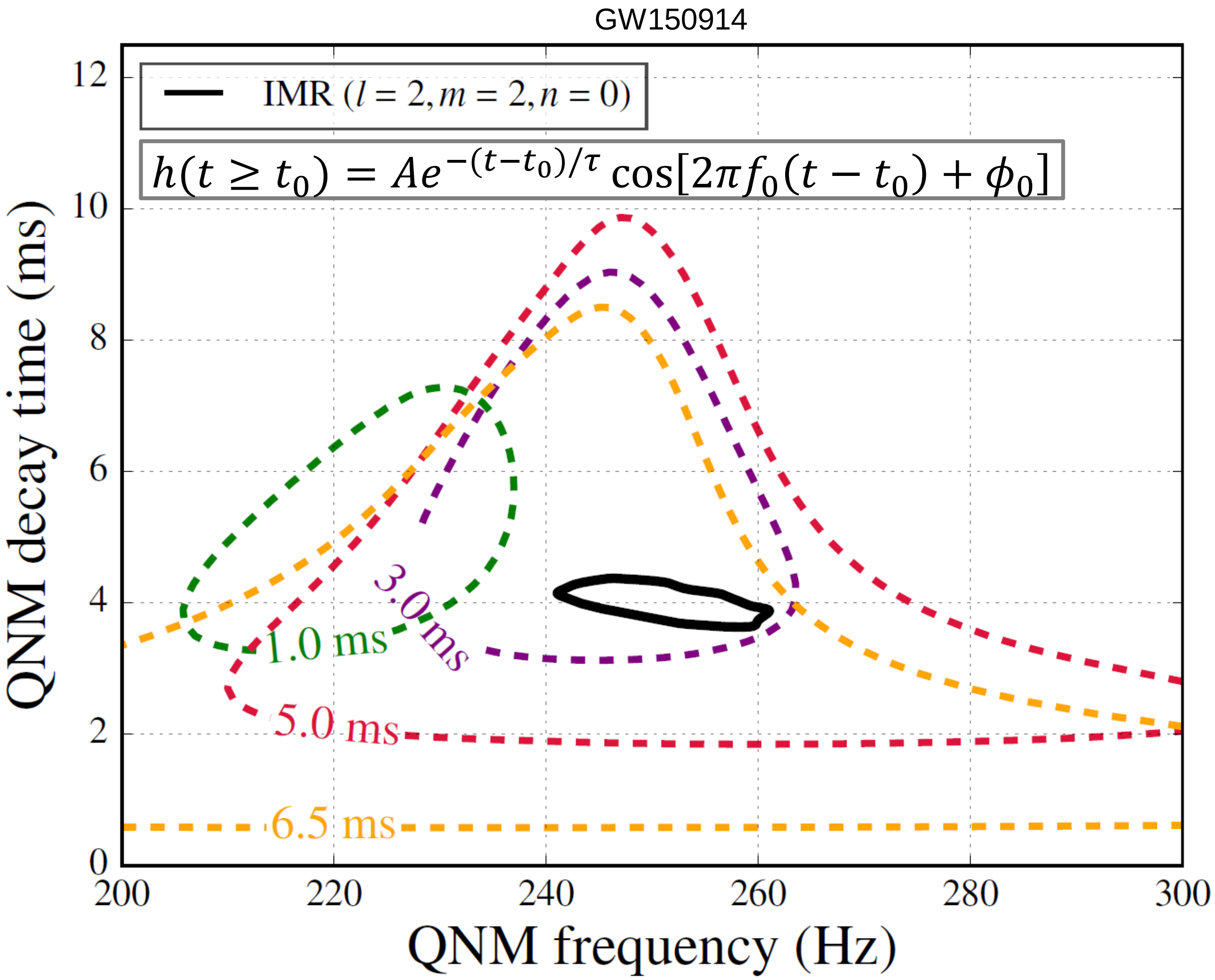


spacetime quantum foam

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

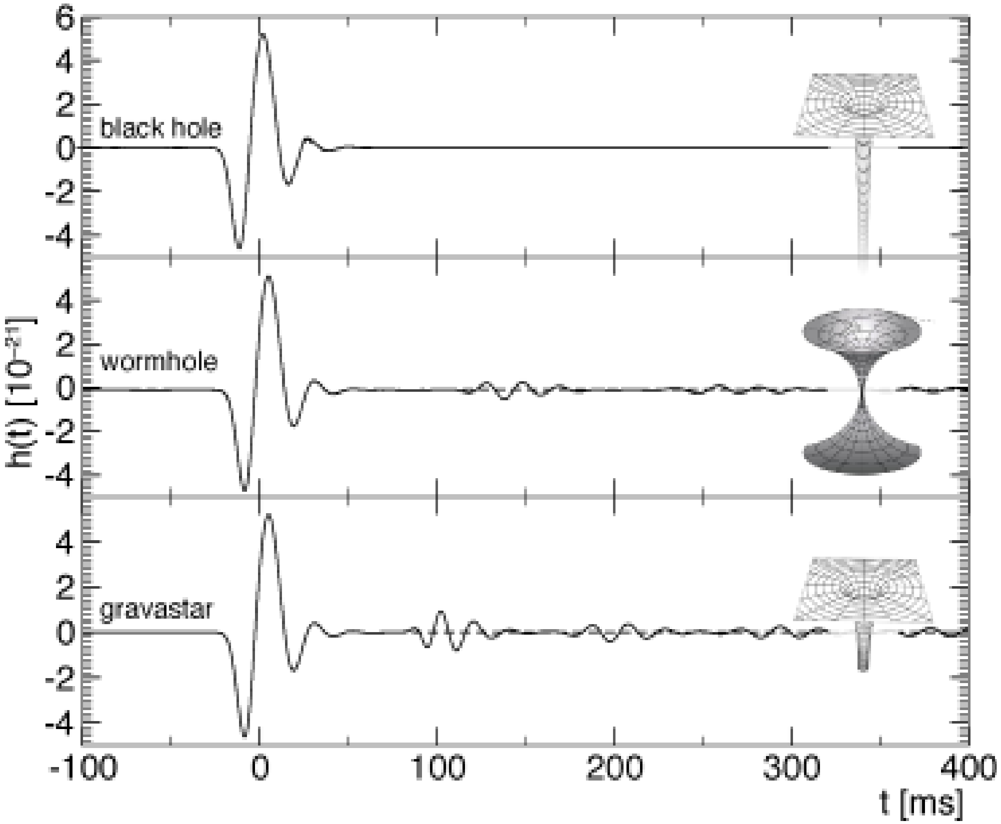
- Dark matter stars

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



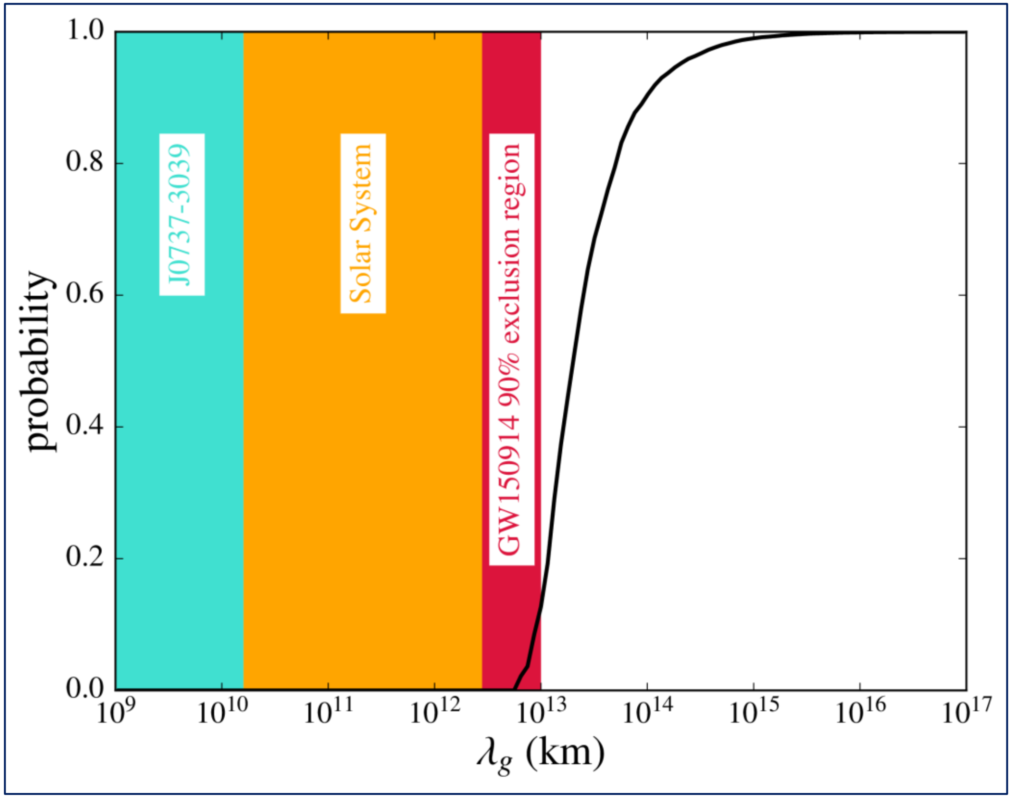
Cardoso et al. PRD 94, 084031 (2016)

GW observables

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

Limit on the mass of the graviton

Bounds on the Compton wavelength $\lambda_g = {}^{h}/_{m_g c}$ of the graviton compared to Solar System or double pulsar tests. Some cosmological tests are stronger (but make assumptions about dark matter)



$$\delta\Phi(f) = -\frac{\pi D c}{\lambda_g^2(1+z)} f^{-1}$$

Will, Phys. Rev. D **57**, 2061 (1998)

Massive-graviton theory dispersion relation $E^2 = p^2c^2 + m_g^2c^4$

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

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

$\lambda_g > 10^{13}\mathrm{km}$
$m_g \leq 10^{-22}\mathrm{eV/c^2}$

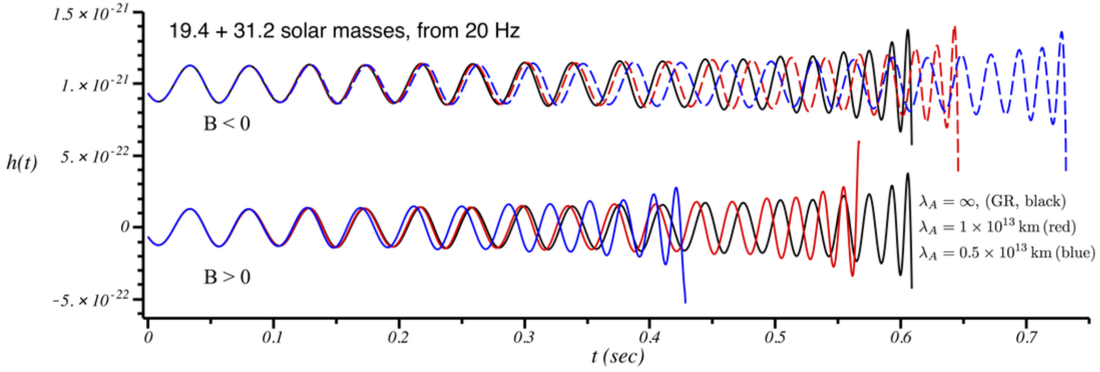
See “*Tests of general relativity with GW150914*” http://arxiv.org/abs/1602.03841

Bounds on violation of Lorentz invariance

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

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

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



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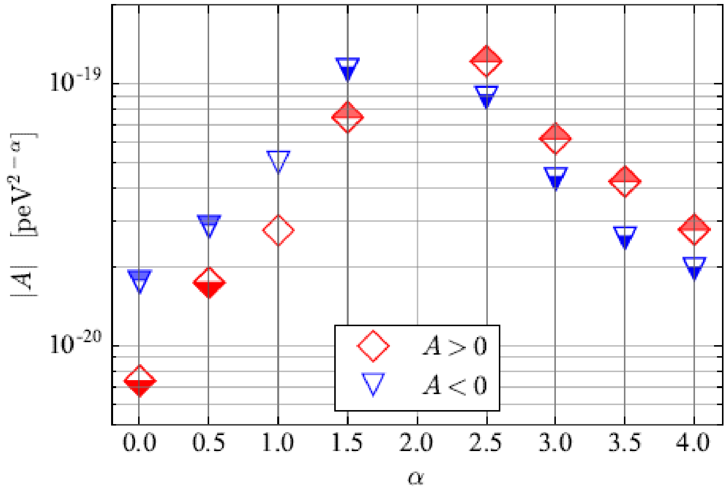


Abbott et al. PRL 118, 221101 (2017)

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

Virgo joins LIGO in August 2017

Advanced Virgo

Virgo is a European collaboration with about 280 members

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

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

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

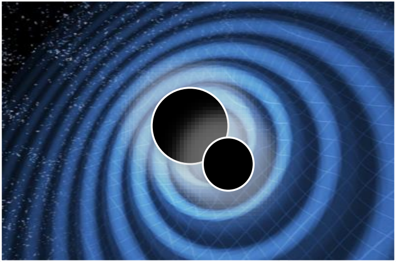
Advanced Virgo project has been formally completed on July 31, 2017

Part of the international network of 2nd generation detectors

Joined the O2 run on August 1, 2017

8 European countries

January 4, 2017

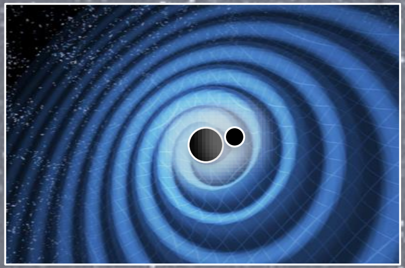


August 1, 2017

Advanced LIGO's Second Observing Run

Virgo turns on

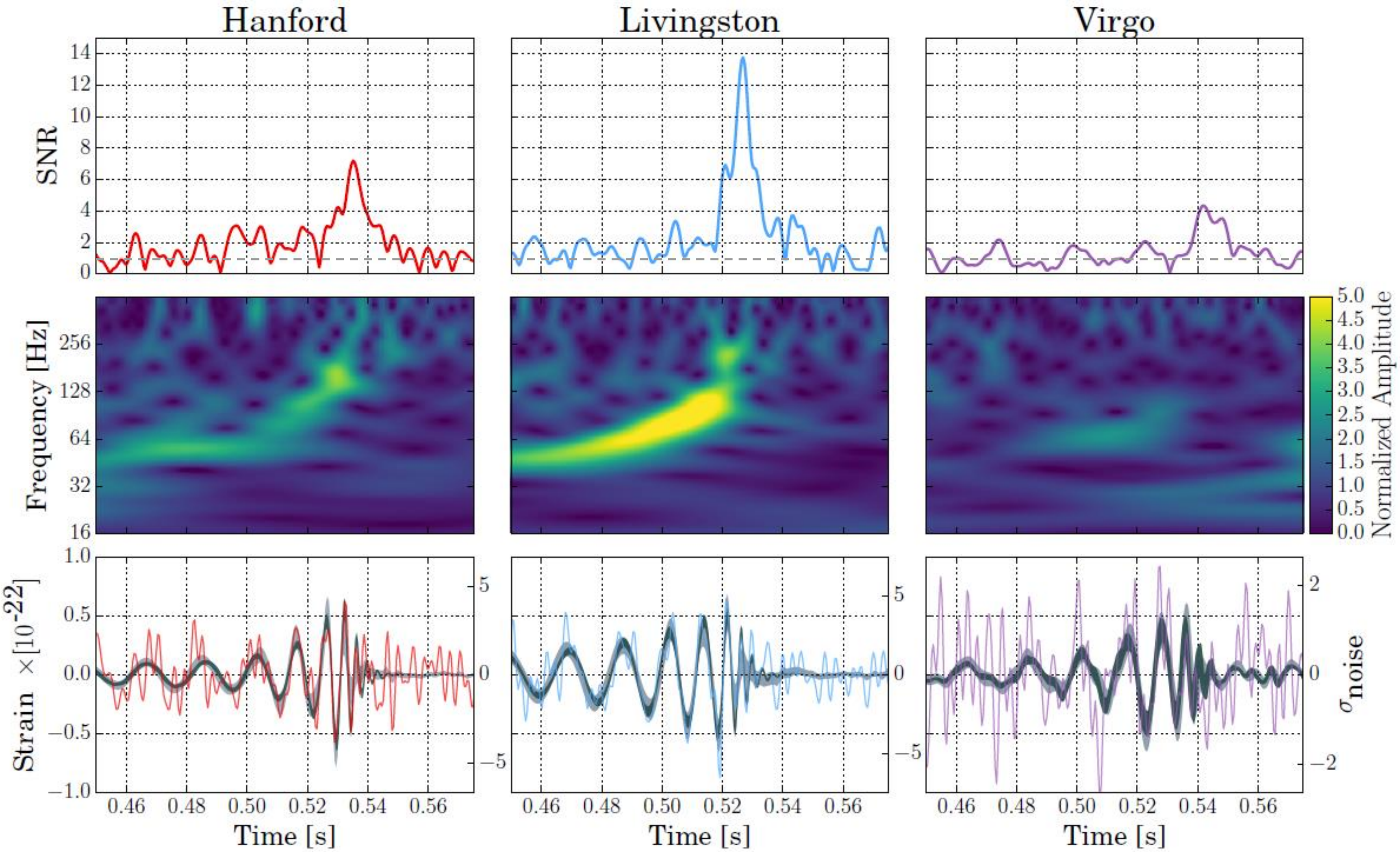
Nov 2016	Dec 2016	Jan 2017	Feb 2017	Mar 2017	Apr 2017	May 2017	Jun 2017	Jul 2017	Aug 2017



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



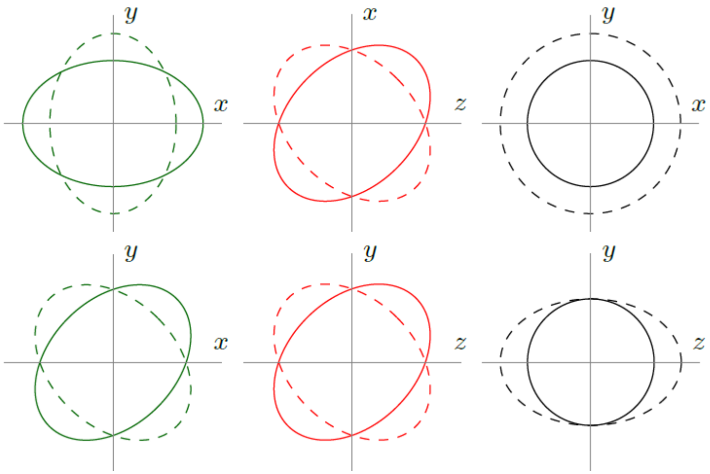
Abbott et al. PRL 119, 141101 (2017)

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	y	b	l
General Relativity	🟩	🟩	🟥	🟥	🟥	🟥
GR in noncompactified 4/6D Minkowski	🟩	🟩	🟩	🟩	🟩	🟩
Einstein-Æther	🟩	🟩	🟩	🟩	🟩	🟩
5D Kaluza-Klein	🟩	🟩	🟩	🟩	🟩	🟥
Randall-Sundrum braneworld	🟩	🟩	🟥	🟥	🟥	🟥
Dvali-Gabadadze-Porrati braneworld	🟩	🟩	🟨	🟨	🟨	🟨
Brans-Dicke	🟩	🟩	🟥	🟥	🟩	🟩
f(*R*) gravity	🟩	🟩	🟥	🟥	🟩	🟩
Bimetric theory	🟩	🟩	🟩	🟩	🟩	🟩
Four-Vector Gravity	🟥	🟥	🟩	🟩	🟥	🟥

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

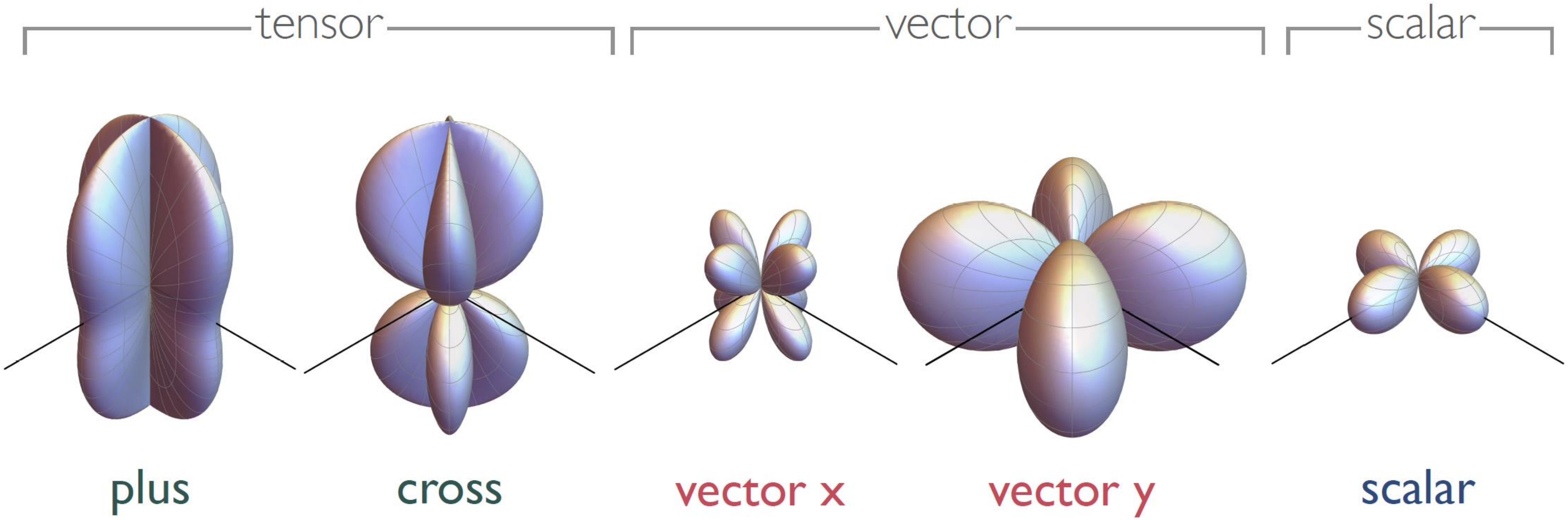
🟩 allowed / 🟨 depends / 🟥 forbidden

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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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

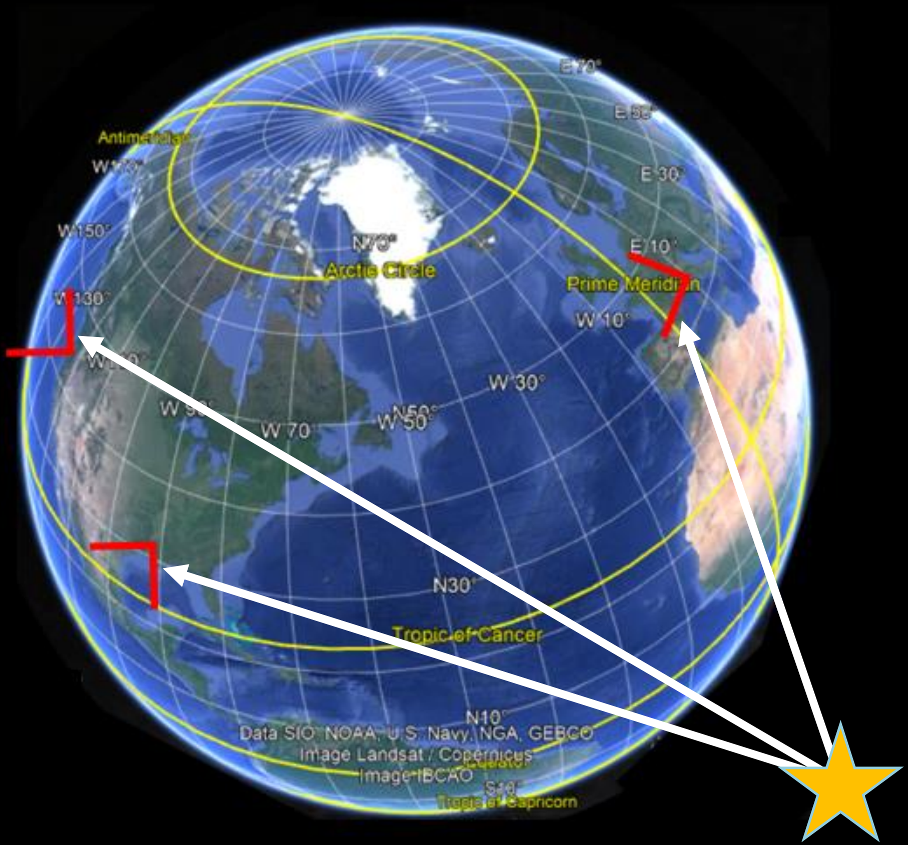
Virgo allowed source location via triangulation

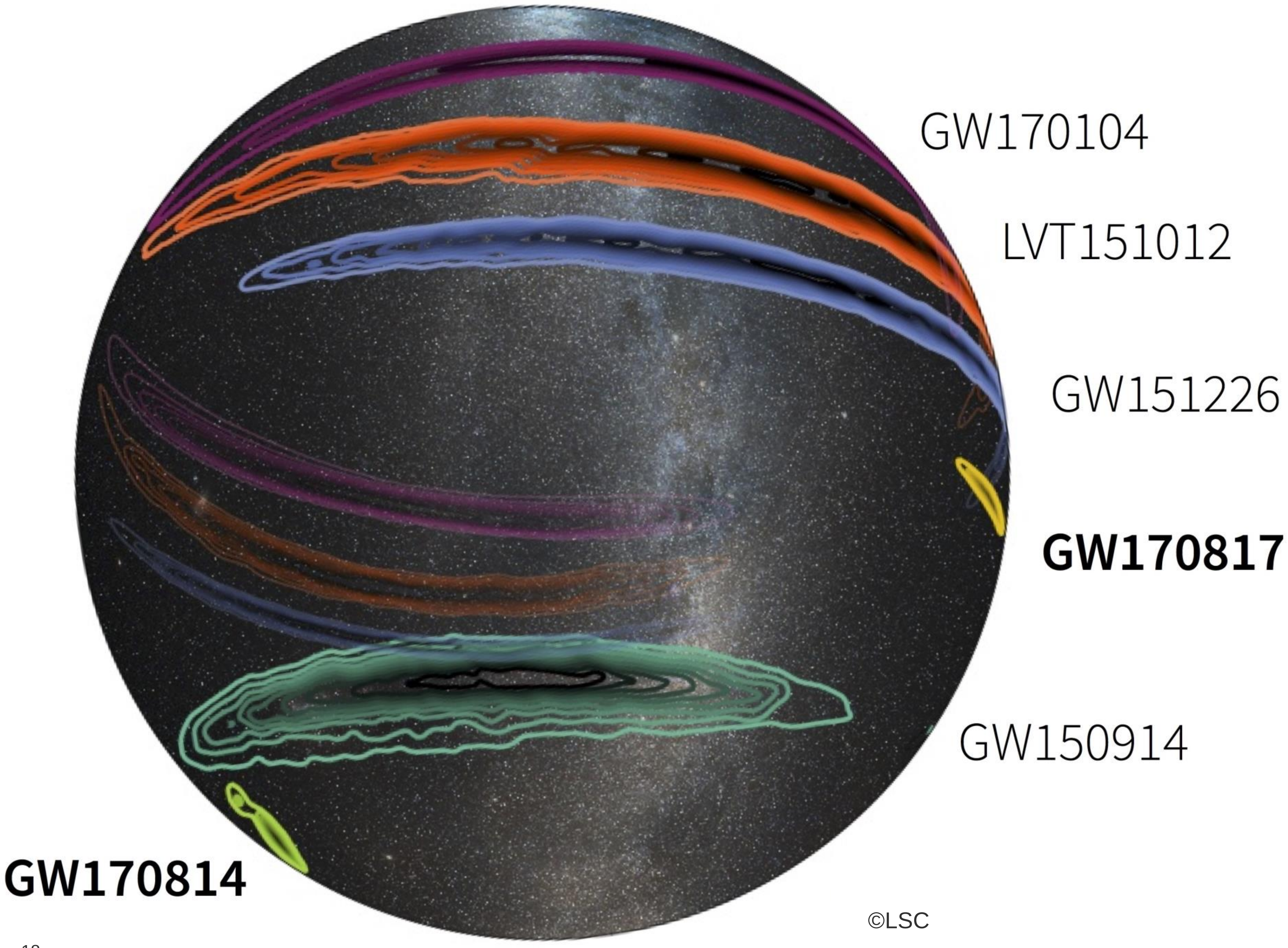
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it

Virgo, Cascina, Italy

LIGO, Livingston, LA

LIGO, Hanford, WA





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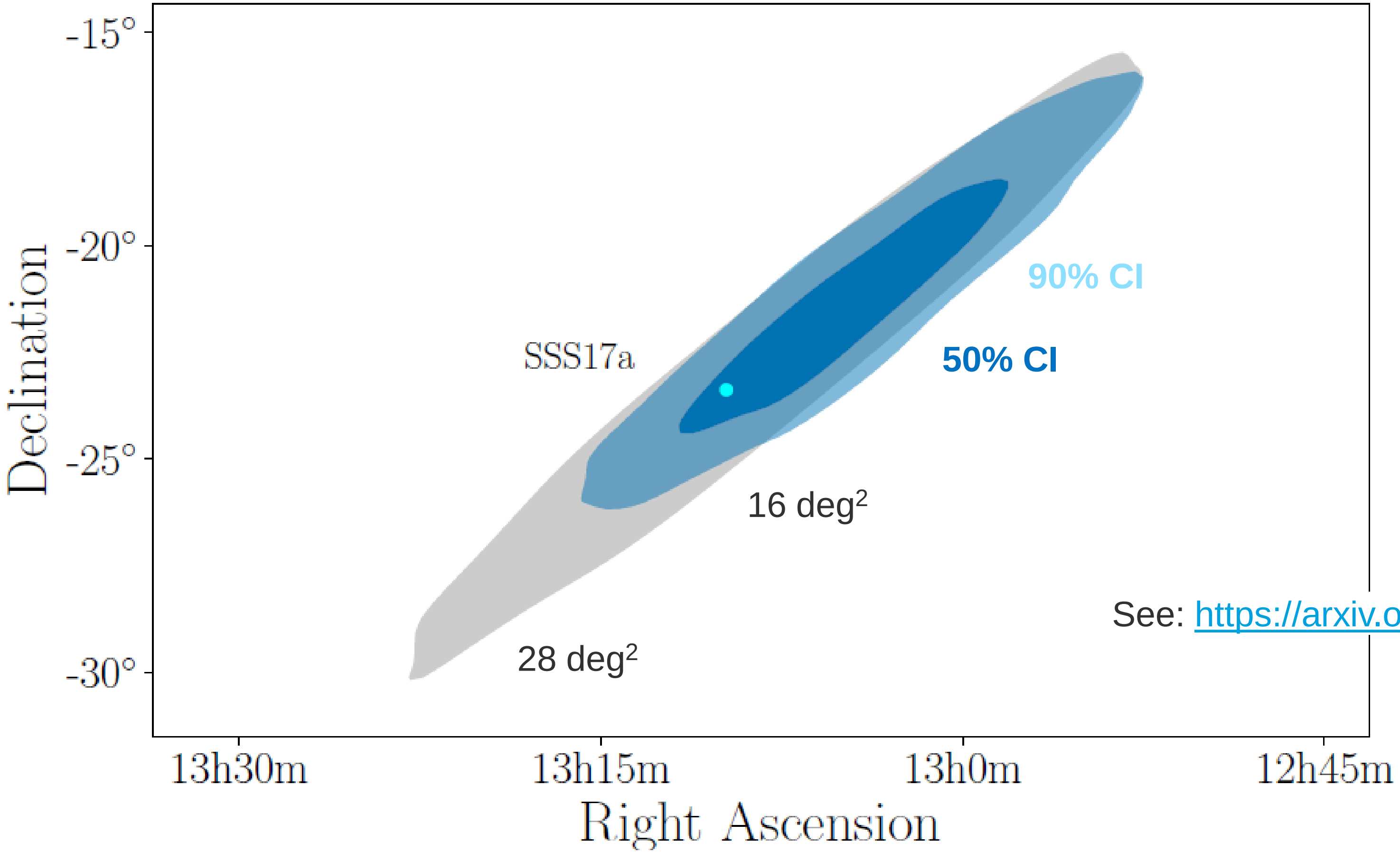
Localization by Virgo and LIGO

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

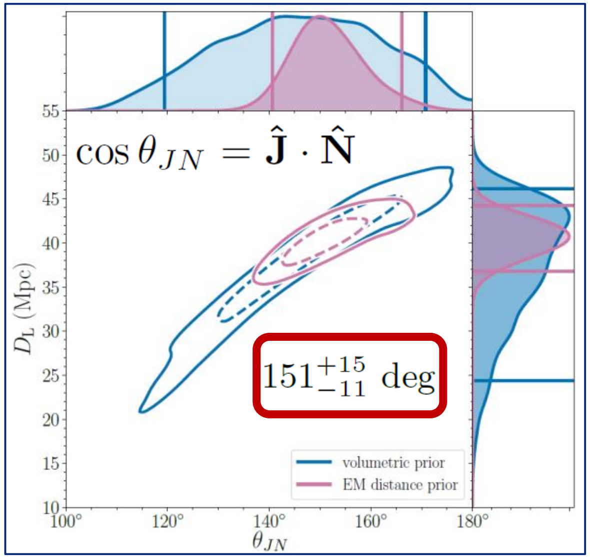
Constrains on inclination angle, chirp mass, mass ratio q, χ_i dimensionless spin, χ_eff effective spin, χ_p effective spin precession parameter. Include EM-information. See https://arxiv.org/abs/1805.11579

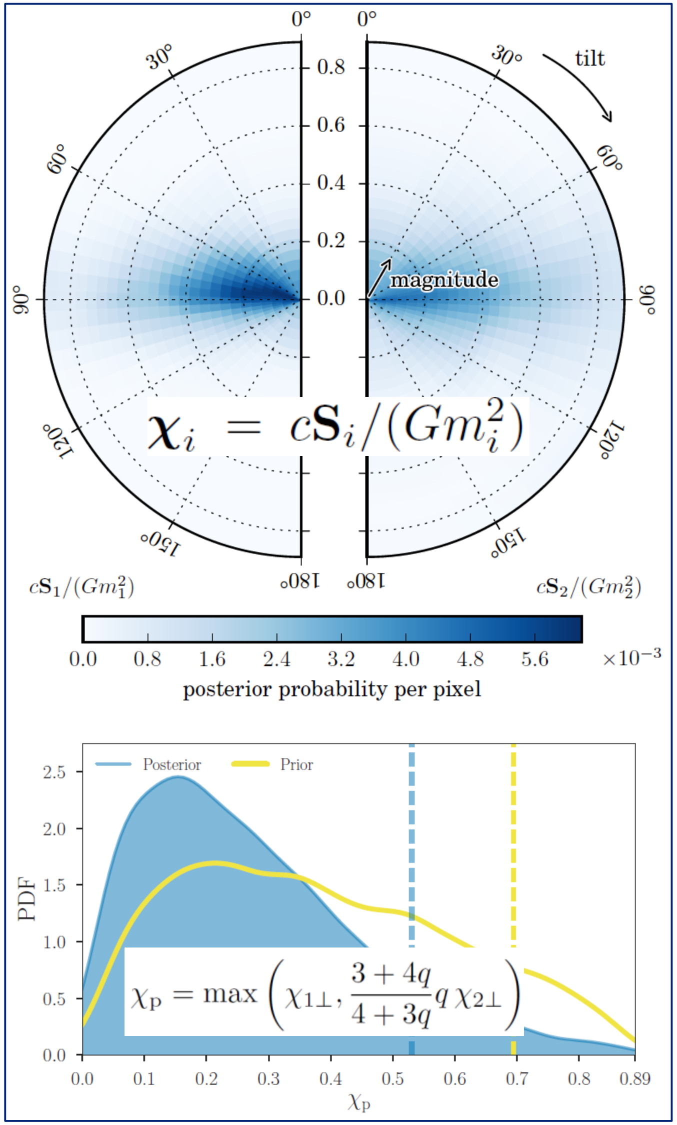
EM localization and Virgo recalibration improved θ_{JN}

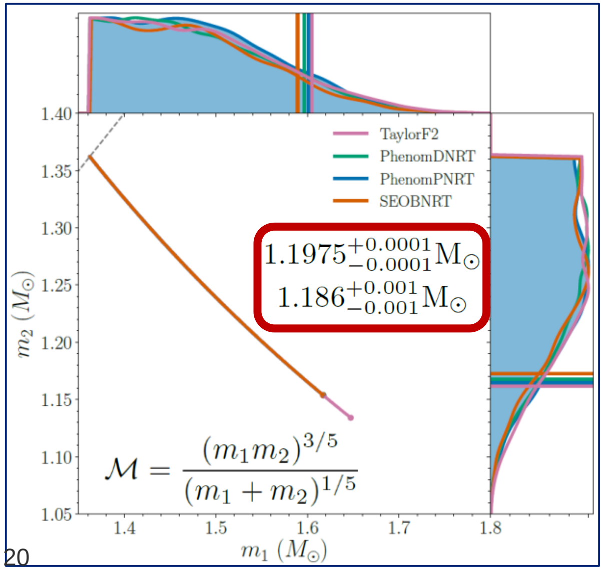
No evidence for NS spin

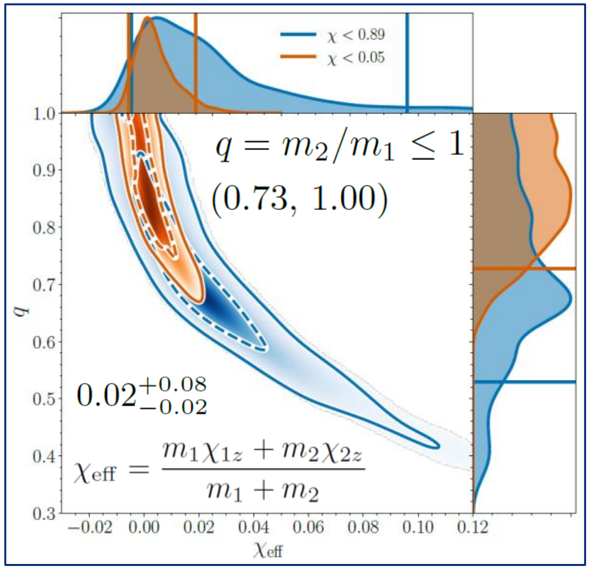
χ_eff contributes to GW phase at 1.5 PN, and is degenerate with q

χ_p starts contributing at 2 PN









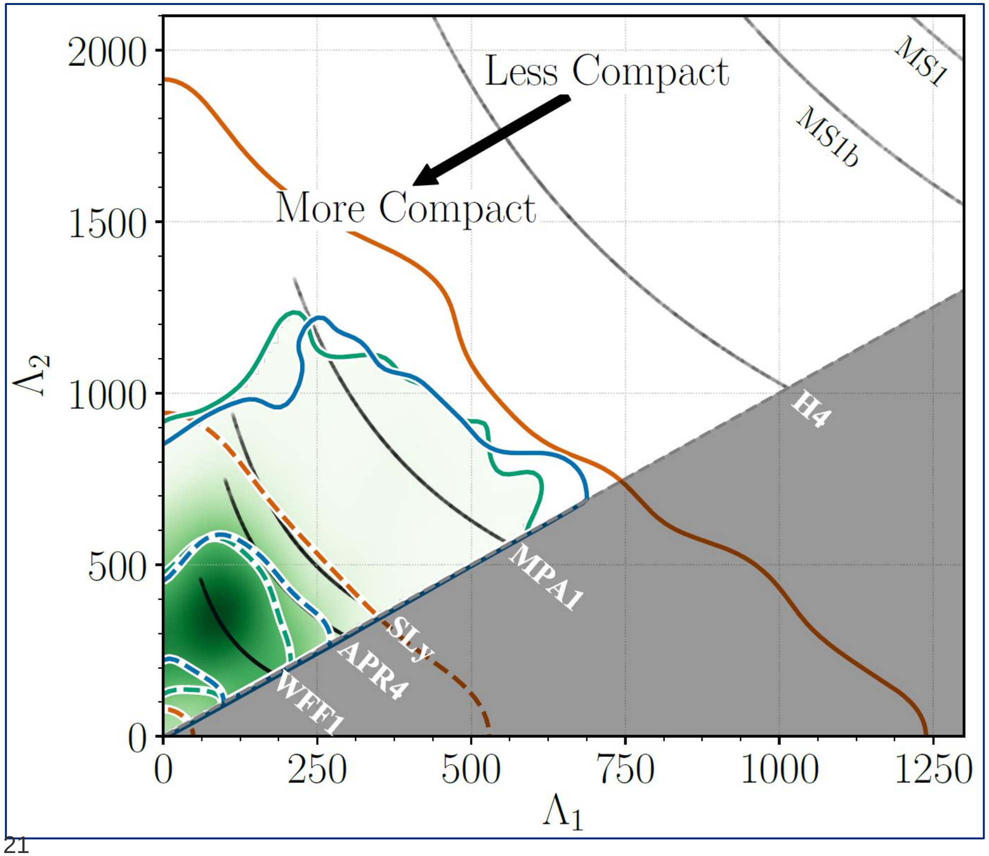
GW170817 properties: tidal deformability, EOS, radii

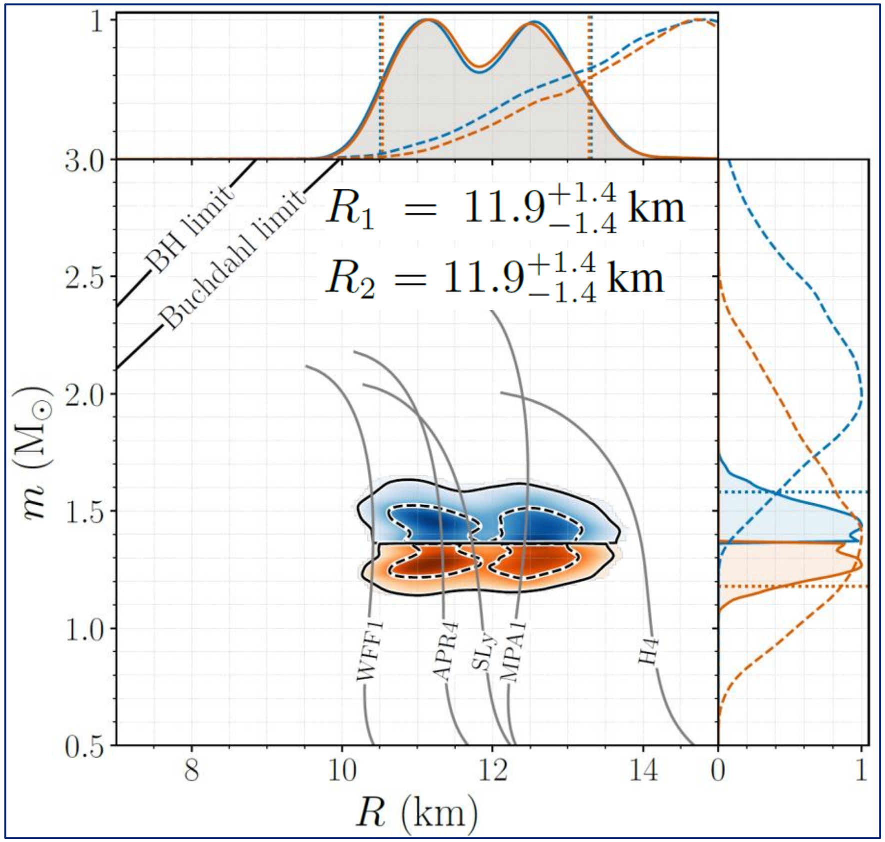
Tidal deformability gives support for “soft” EOS, leading to more compact NS. Various models can now be excluded. We can place the additional constraint that the EOS must support a NS $1.97\,\mathrm{M}_\odot$

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





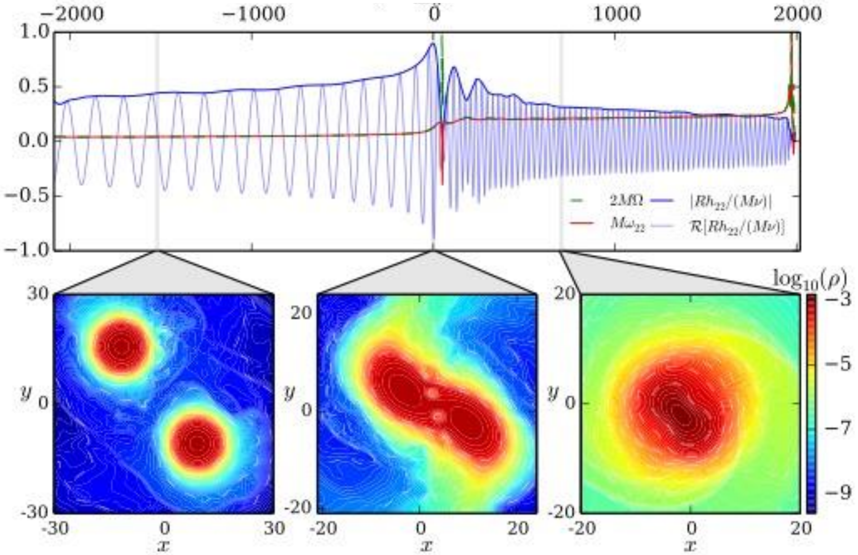
Probing the structure of neutron stars

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

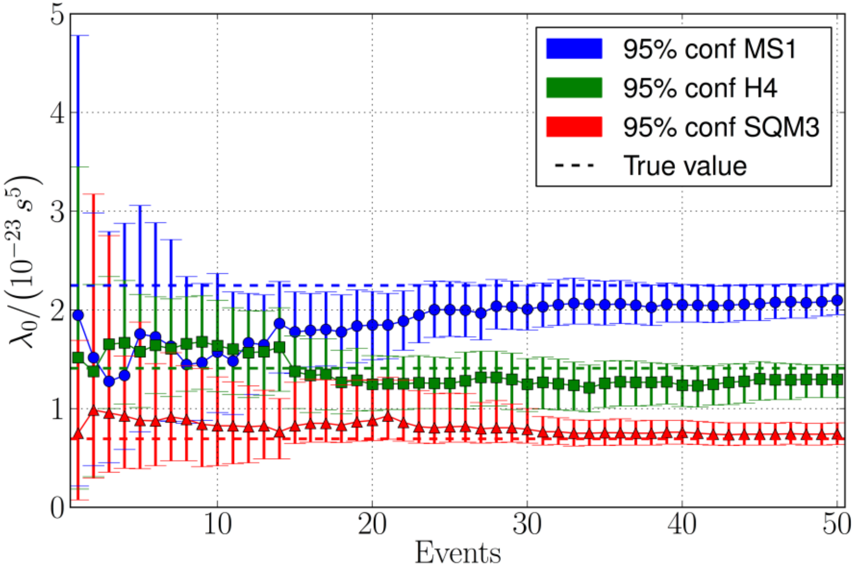
- When close, the stars induce tidal deformations in each other
- These affect orbital motion
- Tidal effects imprinted upon gravitational wave signal
- Tidal deformability maps directly to neutron star equation of state

Bernuzzi et al. PRL 115, 091101 (2015)



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)



Agathos et al. PRD 92, 023012 (2015)

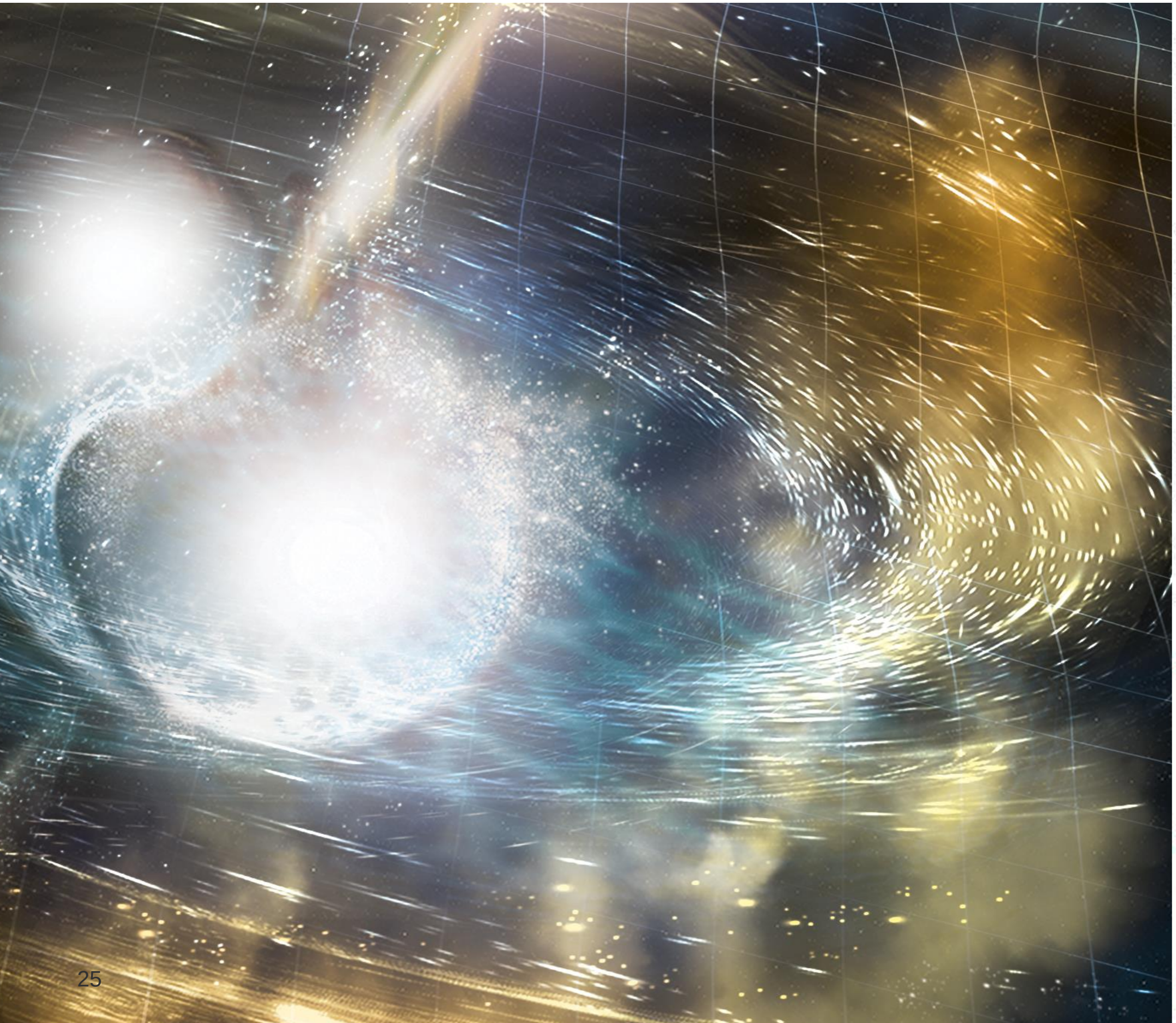
Multi-messenger astronomy

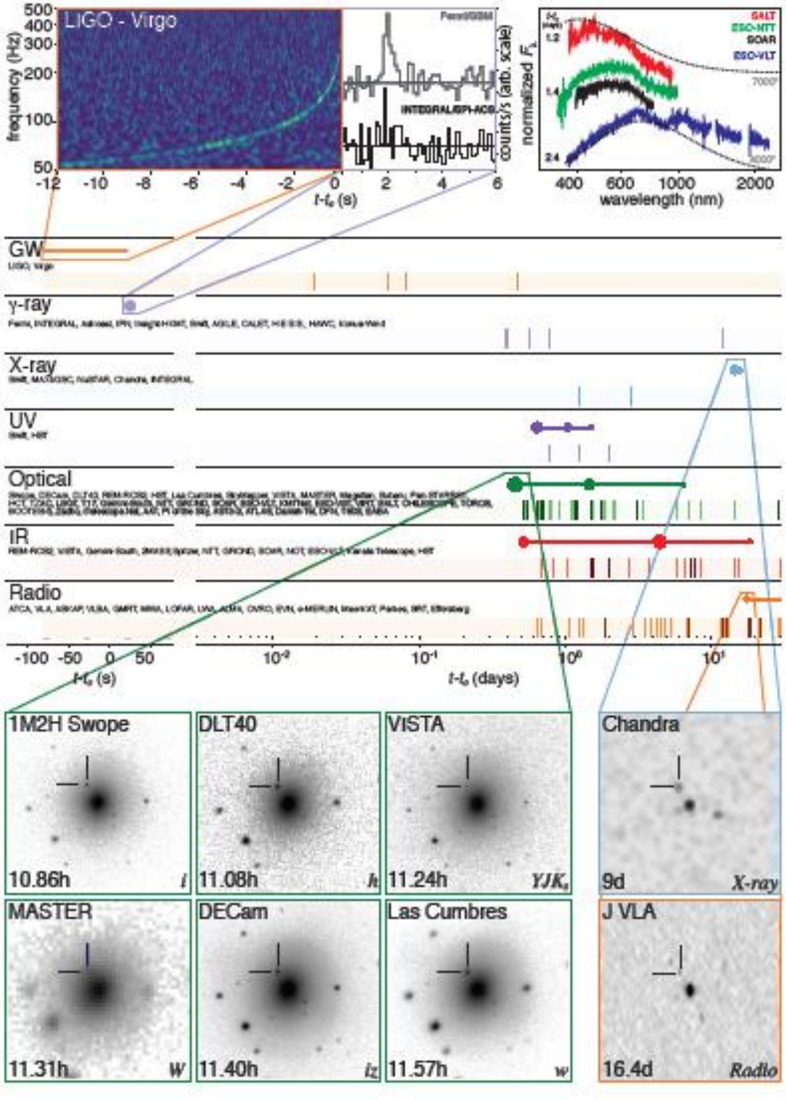
Gamma rays reached Earth 1.7 seconds after GW event

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

Abbott et al. APJL, 848:L12 (2017)

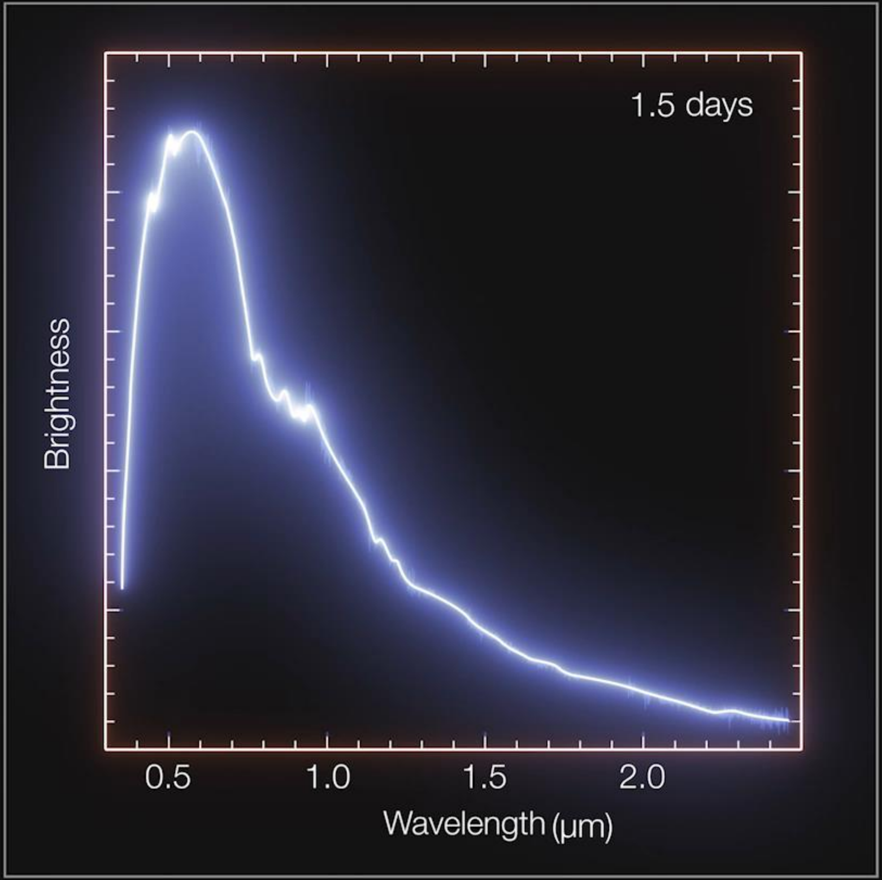




European Southern Observatory

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 provided 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

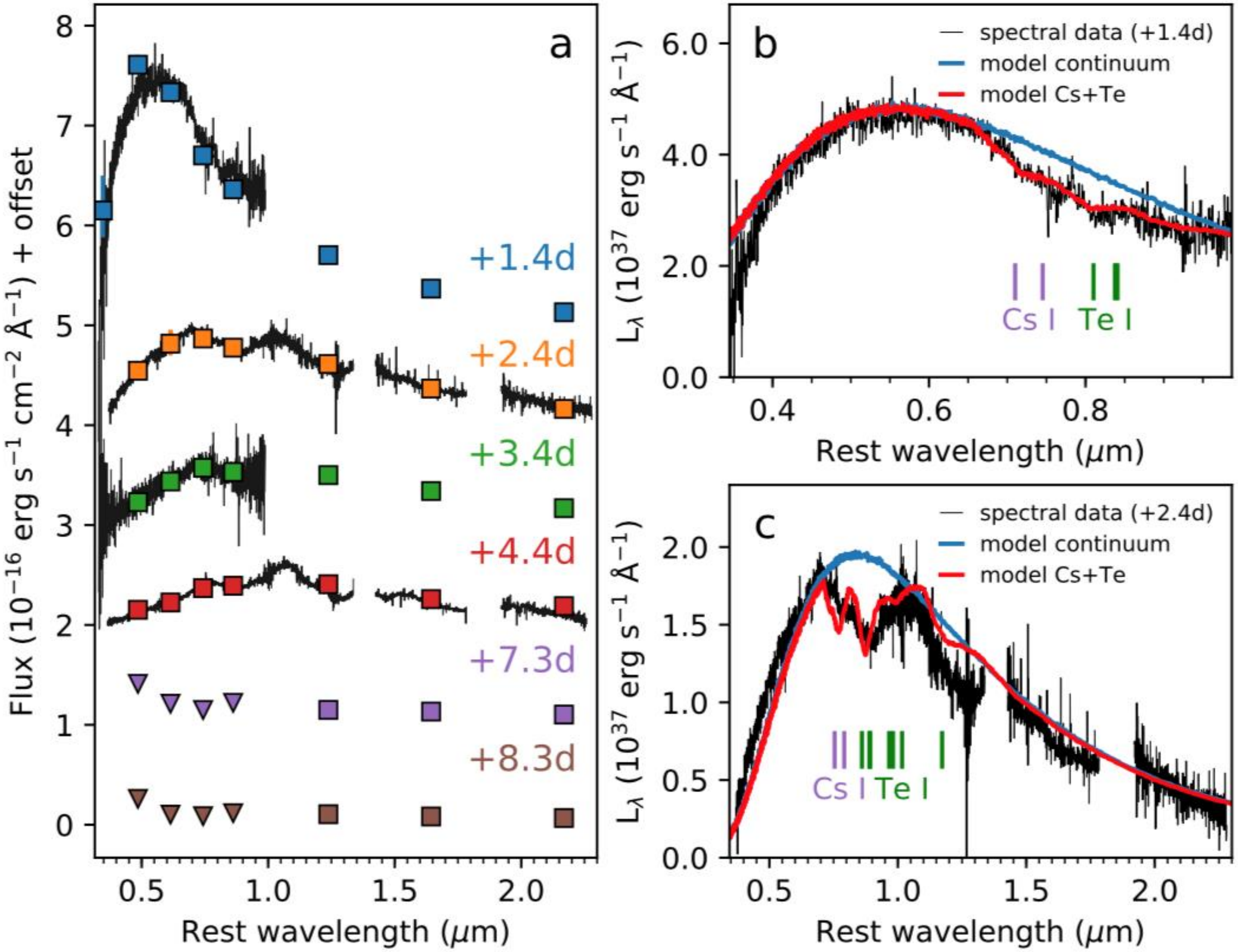
ePESSTO and VLT xshooter spectra with TARDIS radiative transfer models
See Smartt S.J. *et al.*, Nature, 551, 75-79, 2017 for more details

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)



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)

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

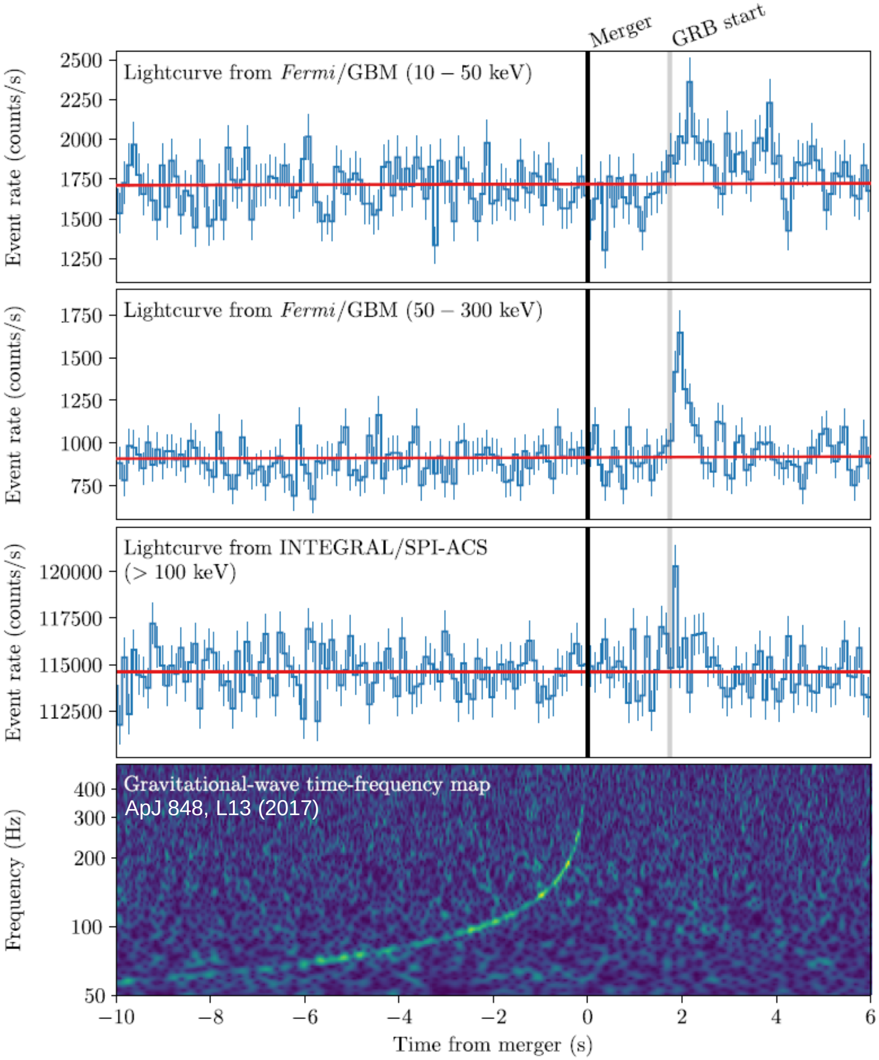
Test of Equivalence Principle

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



ApJ 848, L13 (2017)

Dark Energy and Dark Matter after GW170817

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

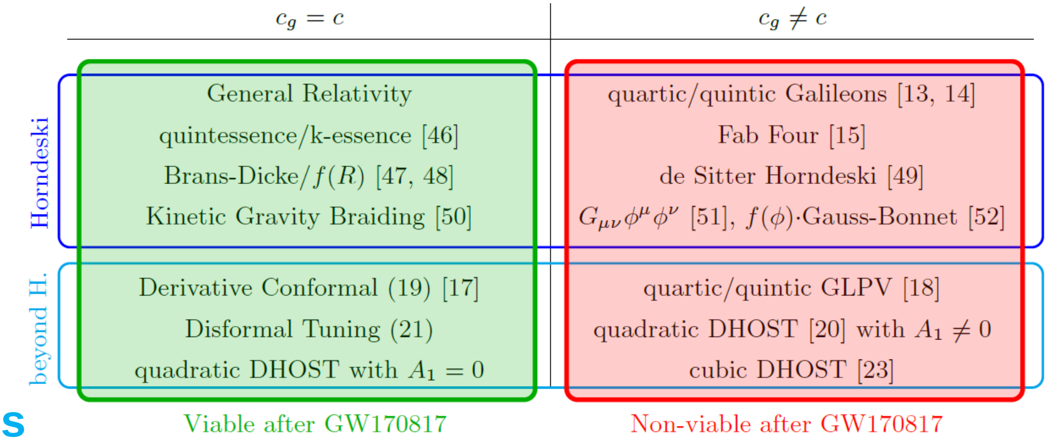
Dark Energy after GW170817

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], $f(\phi)$·Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

GW170817 falsifies Dark Matter Emulators

No-dark-matter modified gravity theories like TeVeS and relativistic bi-metric extensions of Milgrom's MOND ideas have the property that GW propagate on different geodesics (normal matter) from those followed by photons and neutrinos (effective mass to emulate dark matter) (arXiv:1710.11177v1)

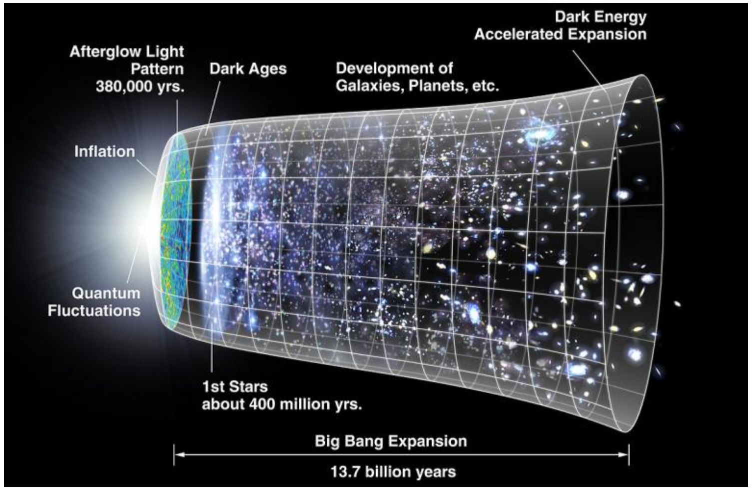
This would give a difference in arrival times between photons and gravitational waves by approximately 800 days, instead of the 1.7 seconds observed (arXiv:1710.06168v1)

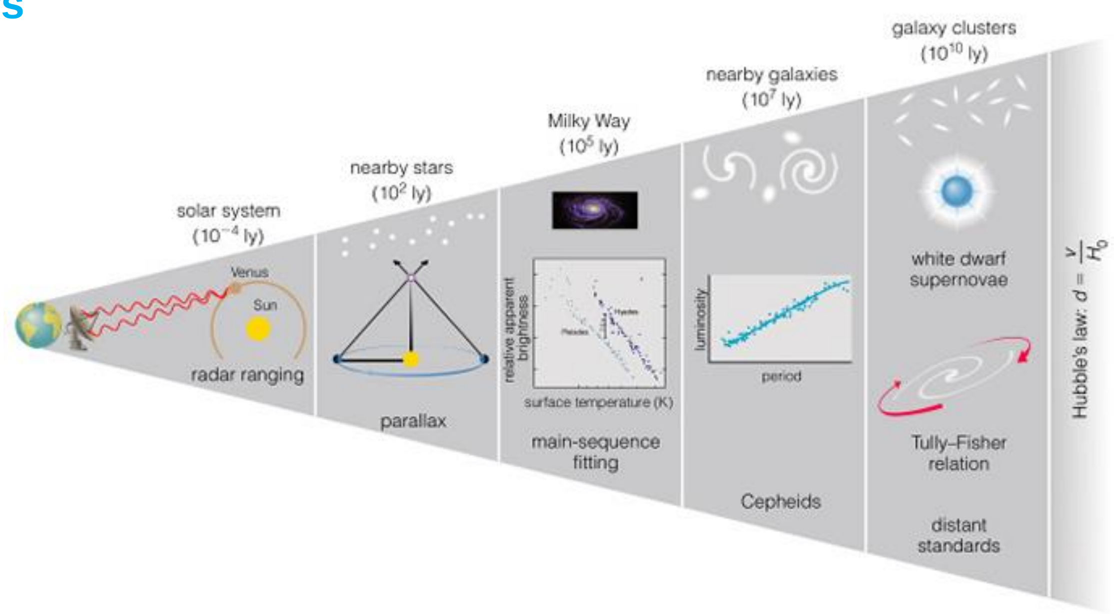
A new cosmic distance marker

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

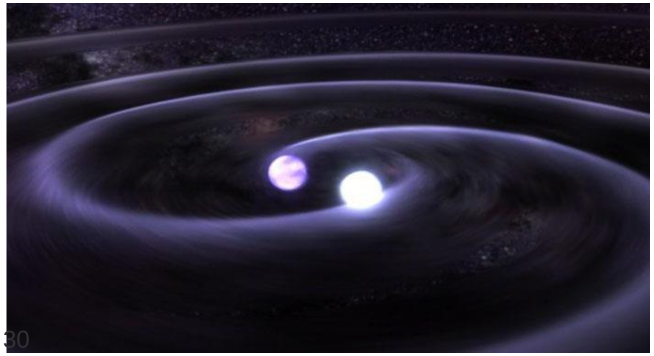
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder





Gravitational waves from binary mergers

Distance can be measured directly from the gravitational wave signal!



A new cosmic distance marker

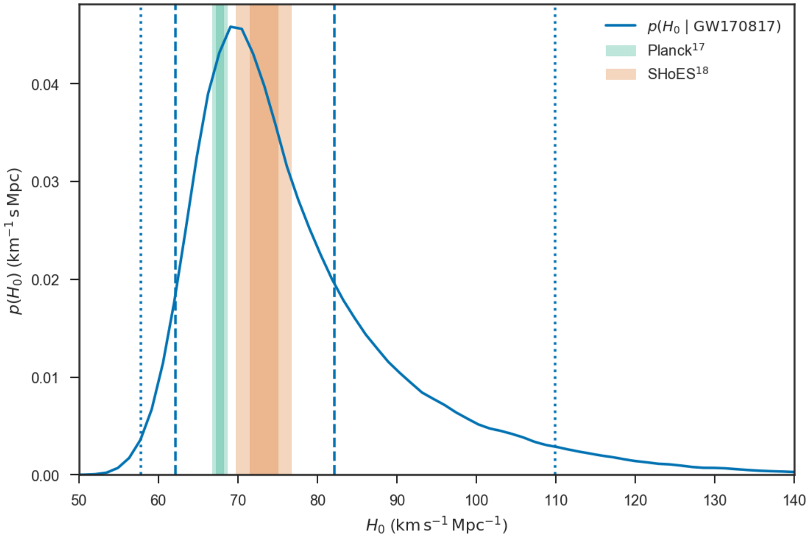
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1-2% accuracy

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)

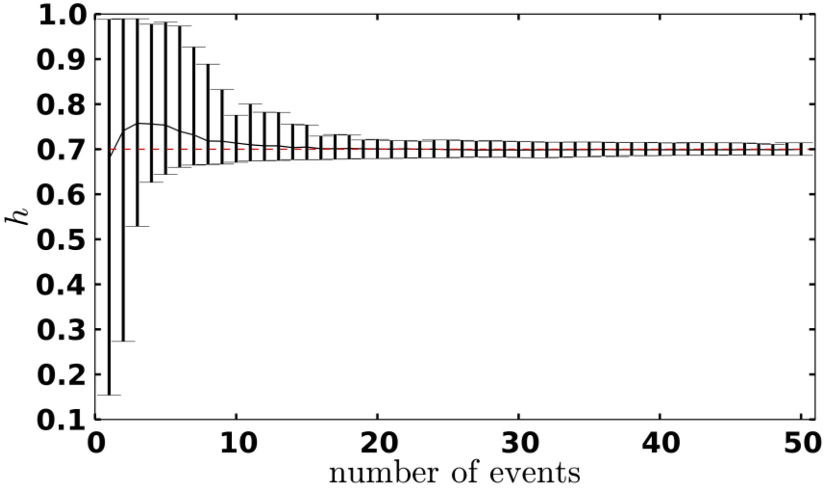


GW170817

- 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, dilatons/moduli

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

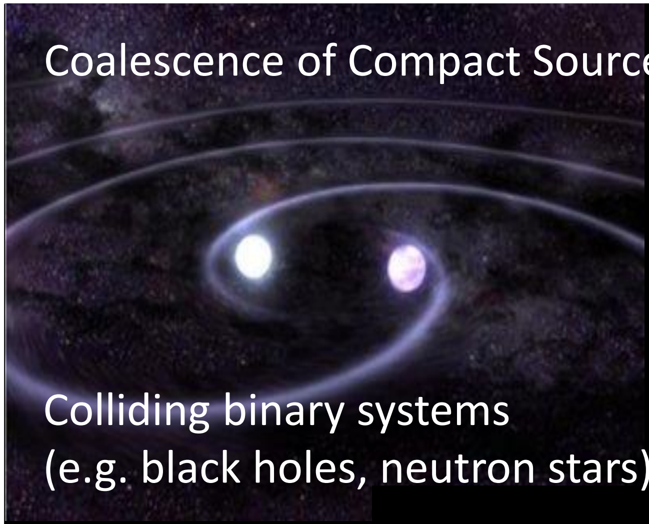
LVC will be back with improved instruments to start the next observation run (O3)

Other searches

LIGO-Virgo analyses for sources of gravitational waves

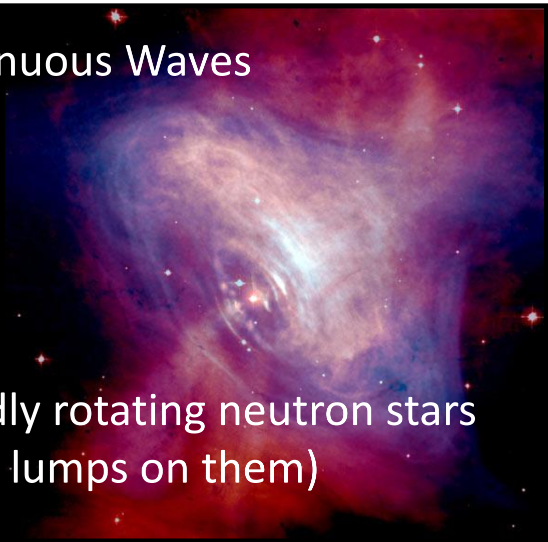
Sources can be transient or of continuous nature, and can be modeled or unmodeled

Coalescence of Compact Sources



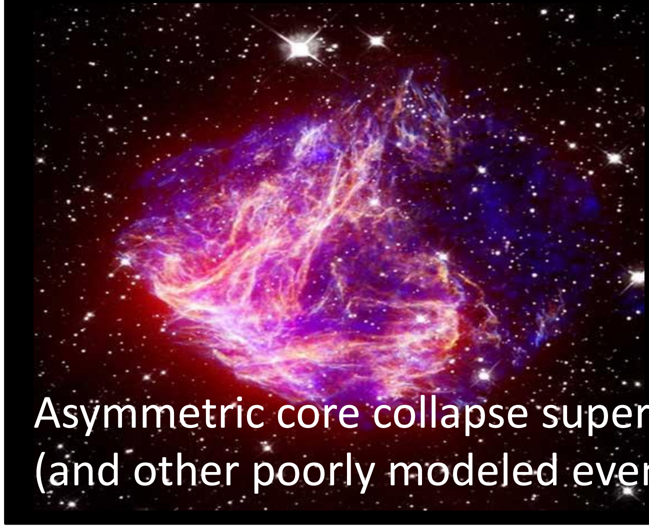
Colliding binary systems
(e.g. black holes, neutron stars)

Continuous Waves



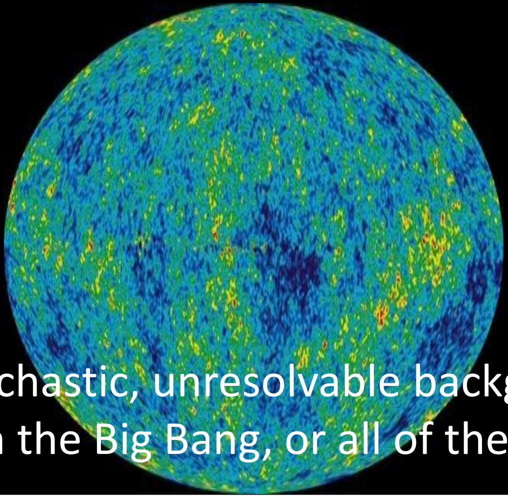
Rapidly rotating neutron stars
(with lumps on them)

Burst



Asymmetric core collapse supernovae
(and other poorly modeled events)

Stochastic



A stochastic, unresolvable background
(from the Big Bang, or all of the above)

Next steps

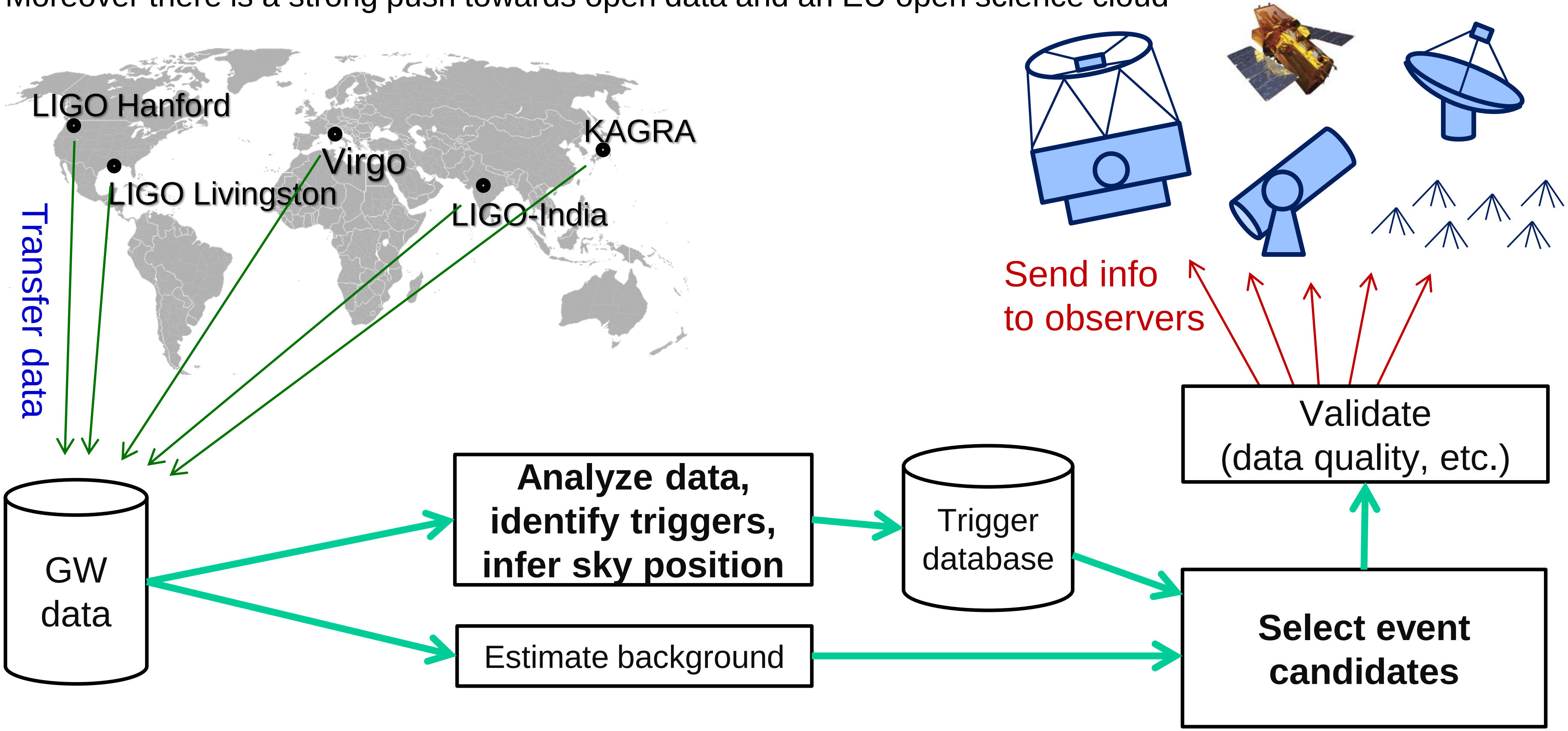
Observation run 3 (O3) expected to start early 2019

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; $\text{Rate} \sim S_{GW}^{3}$)
- Also computing needs grow as templates get longer

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



LIGO Hanford

LIGO Livingston

Virgo

KAGRA

LIGO-India

Transfer data

GW data

Analyze data, identify triggers, infer sky position

Estimate background

Trigger database

Select event candidates

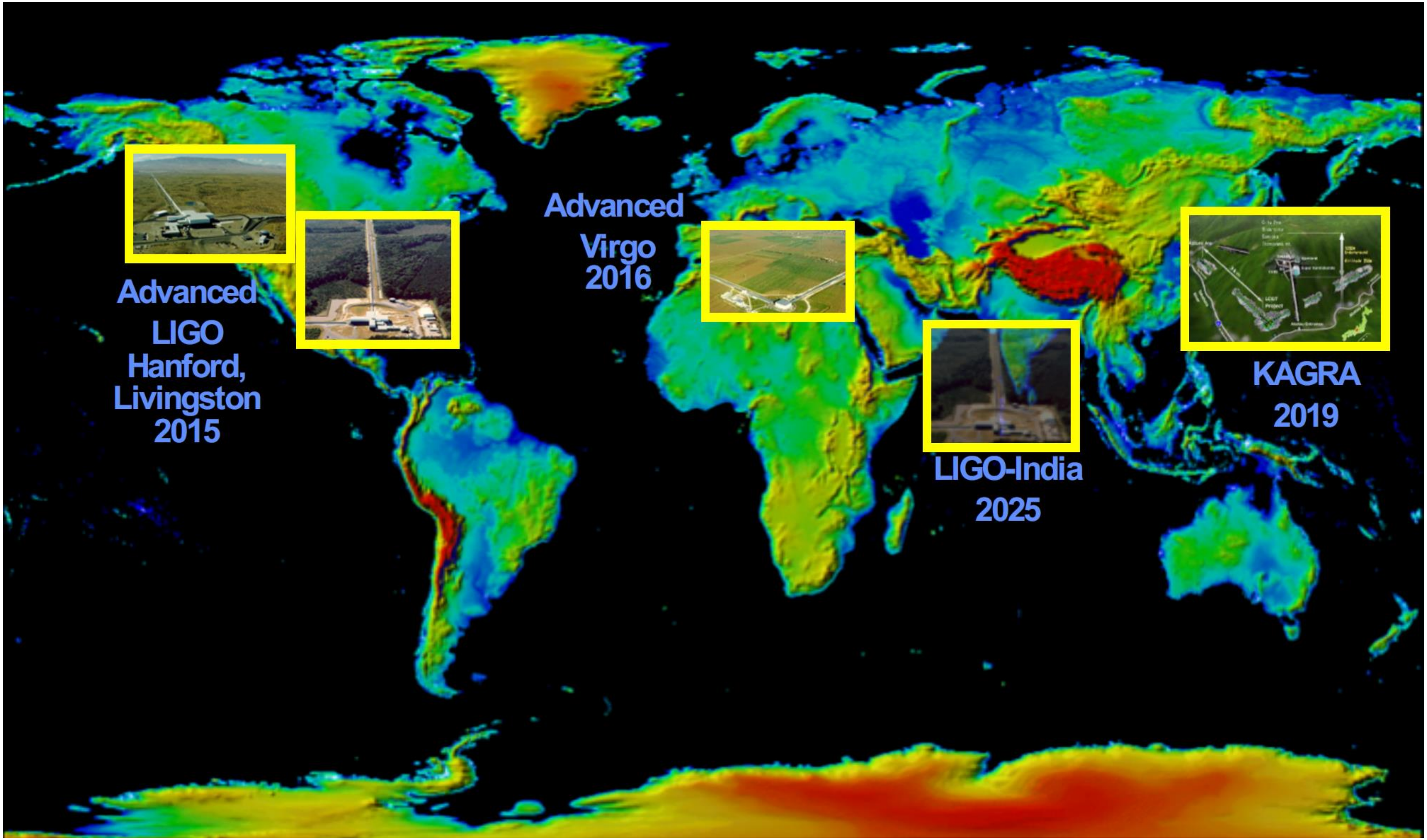
Validate (data quality, etc.)

Send info to observers

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

KAGRA

Expected to join LIGO and Virgo in Observation run 3



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

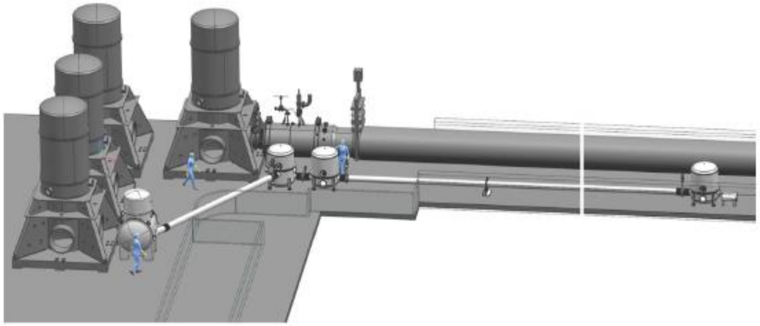
AdV+ is the European plan to maximize Virgo’s sensitivity within the constrains of the EGO site. It will be carried out in parallel with the LIGO A+ upgrade

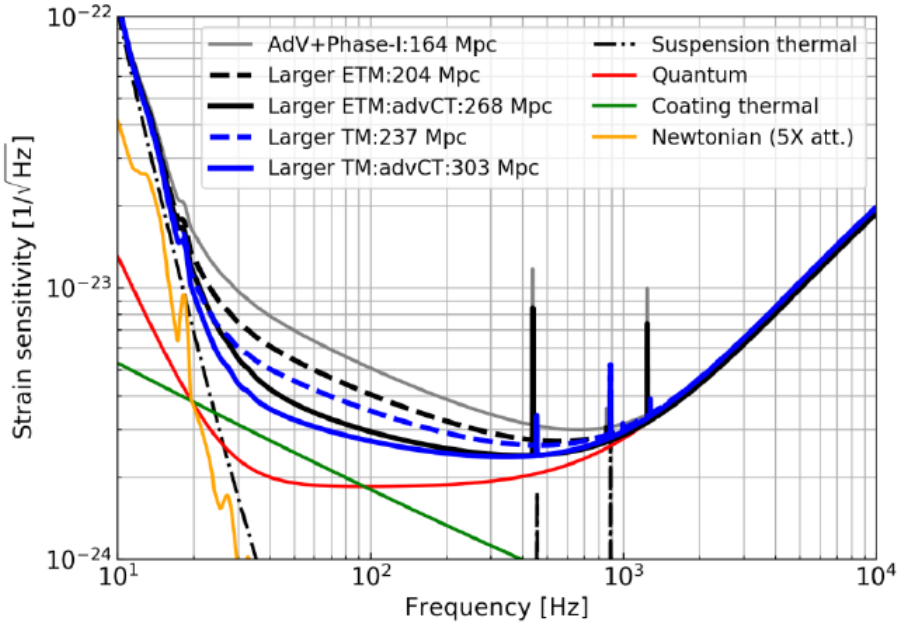
AdV+ features

- 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





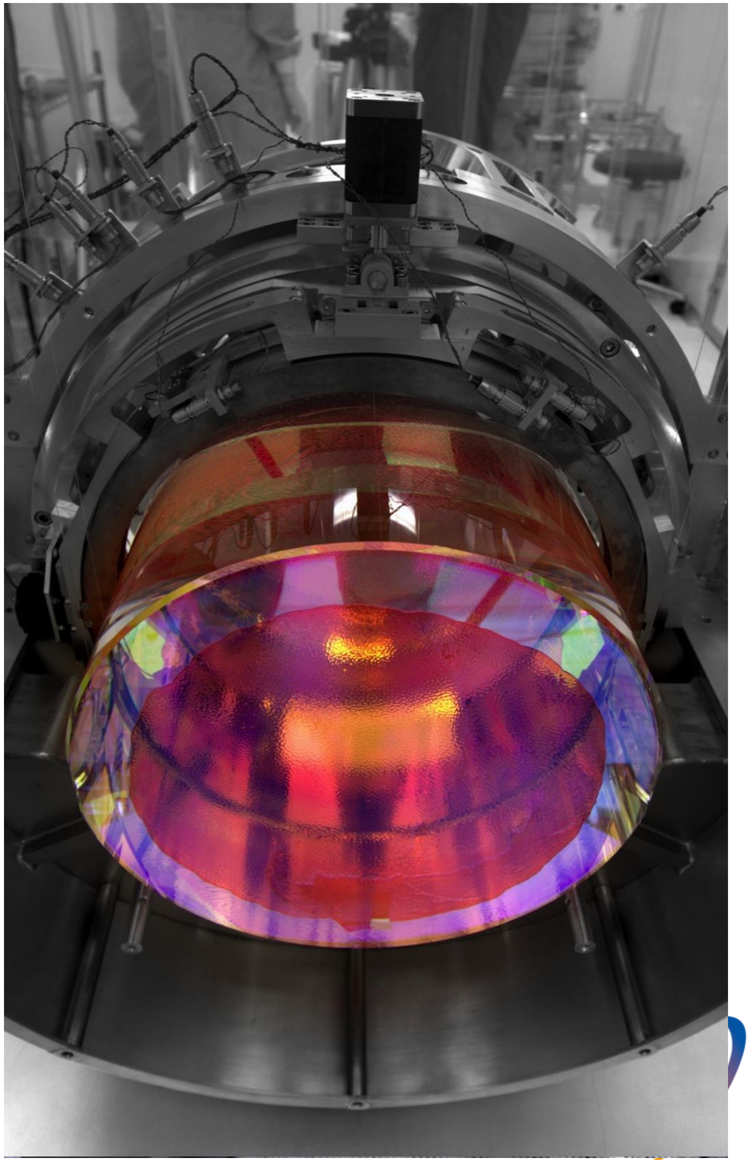
Injection of squeezed light states

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

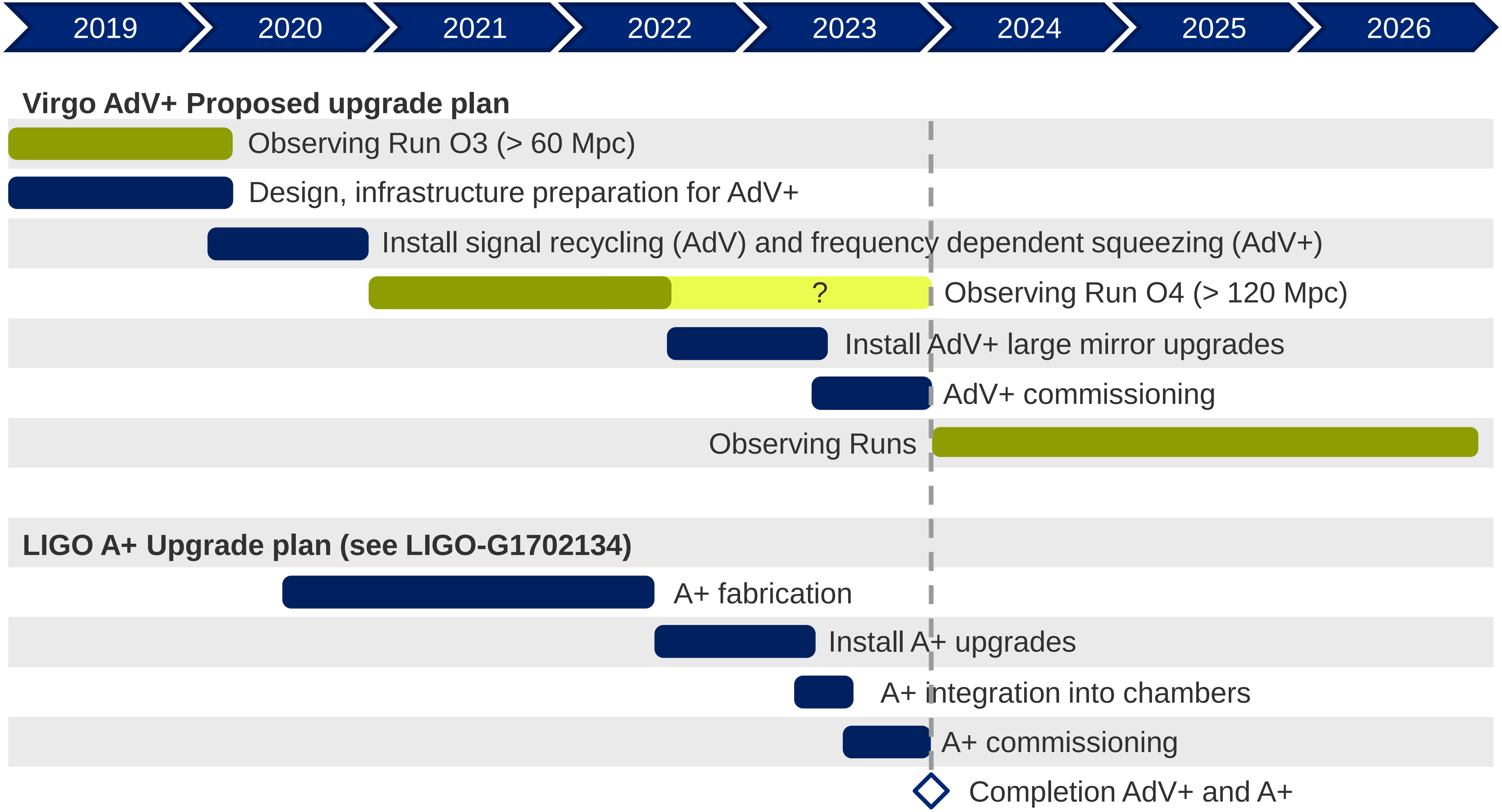
- Flatness < 0.5 nm rms over central 160 mm of mirrors by using ion beam polishing (robotic silica deposition was investigated)
- Ti:Ta_2O_5 and SiO_2 stacks with optical absorption about 0.3 ppm

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



2019 2020 2021 2022 2023 2024 2025 2026

Virgo AdV+ Proposed upgrade plan

Observing Run O3 (> 60 Mpc)

Design, infrastructure preparation for AdV+

Install signal recycling (AdV) and frequency dependent squeezing (AdV+)

? Observing Run O4 (> 120 Mpc)

Install AdV+ large mirror upgrades

AdV+ commissioning

Observing Runs

LIGO A+ Upgrade plan (see LIGO-G1702134)

A+ fabrication

Install A+ upgrades

A+ integration into chambers

A+ commissioning

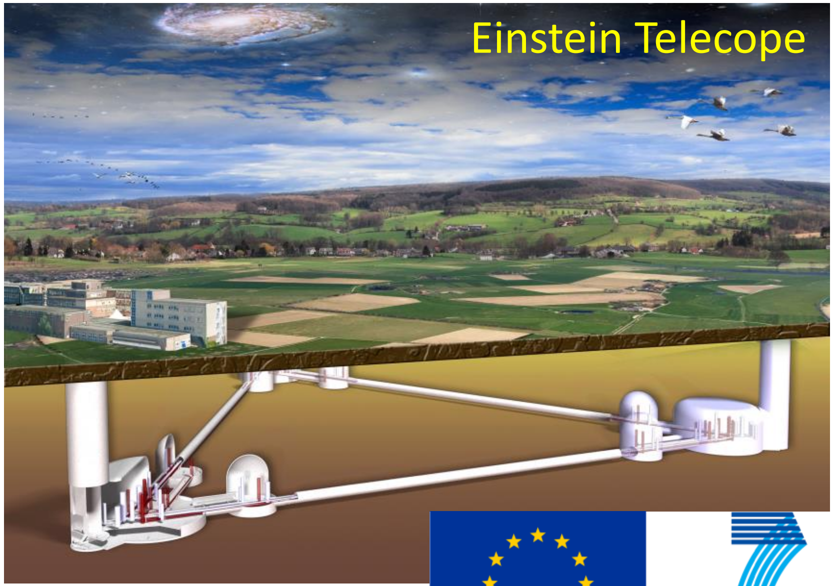
Completion AdV+ and A+

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

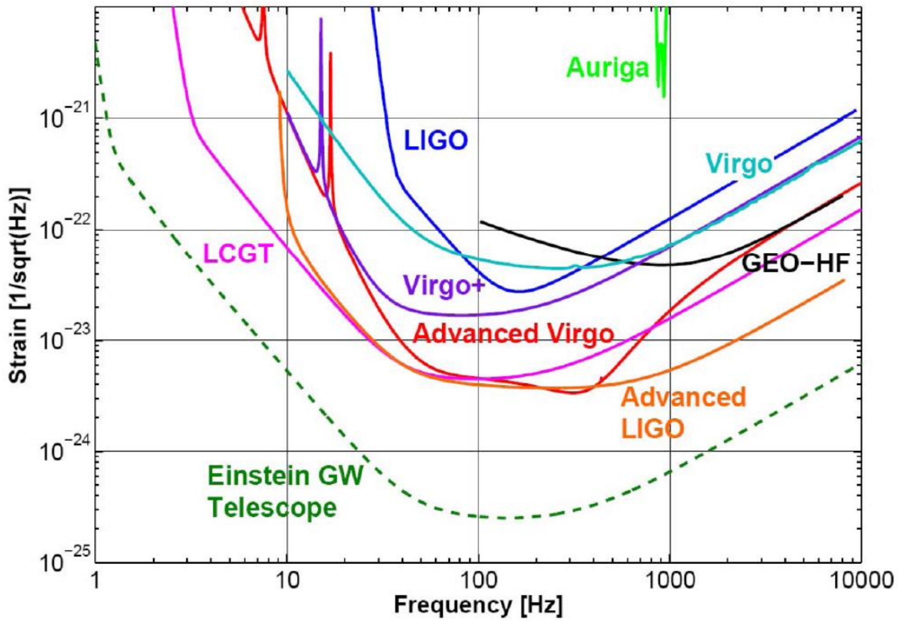
AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope

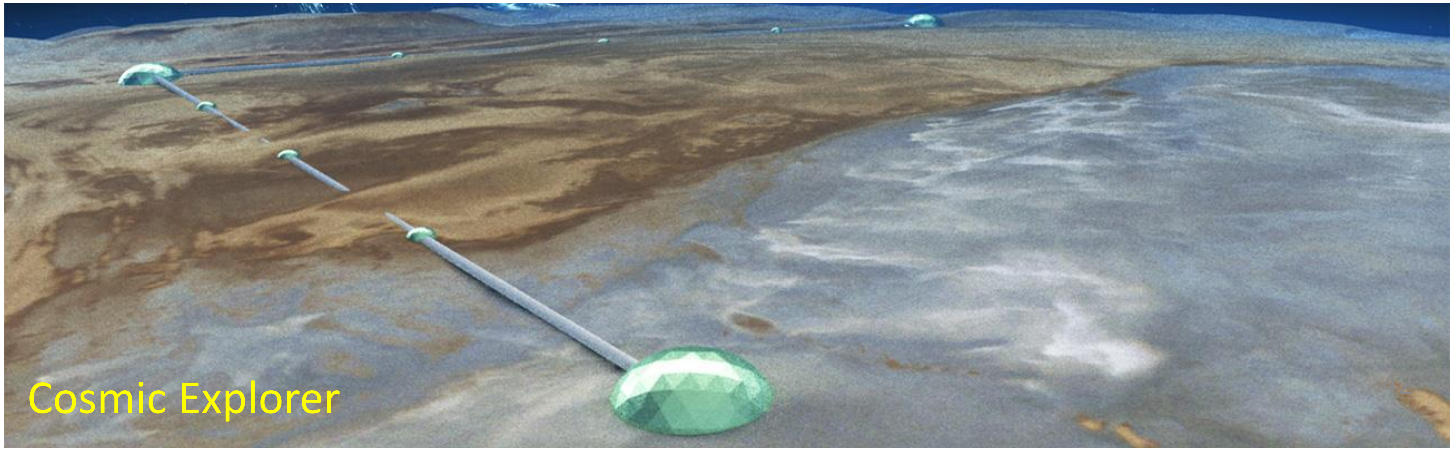
ET and CE

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



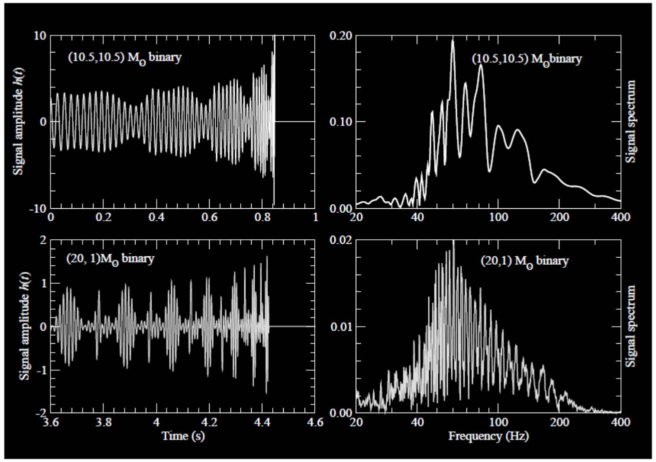
SEVENTH FRAMEWORK PROGRAMME

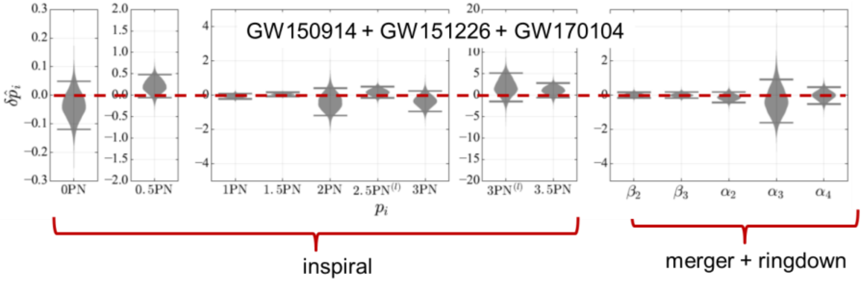


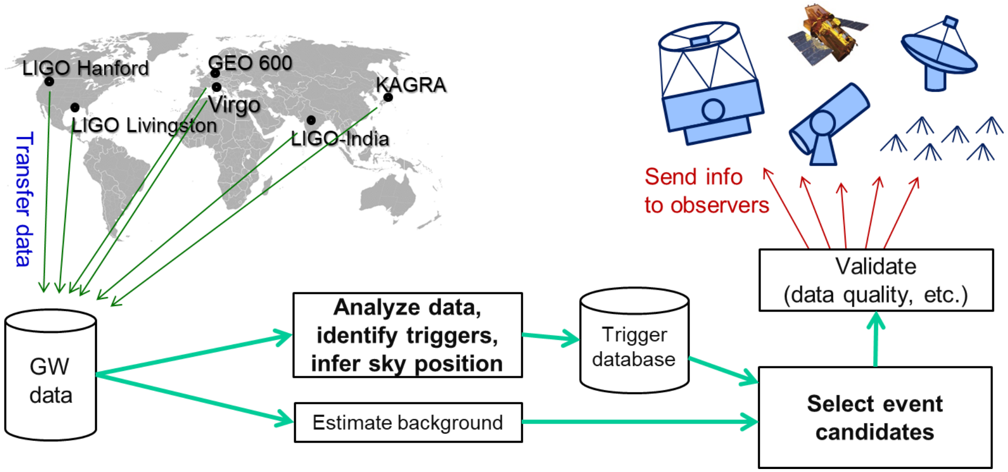


3G science

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







GW data

Analyze data, identify triggers, infer sky position

Trigger database

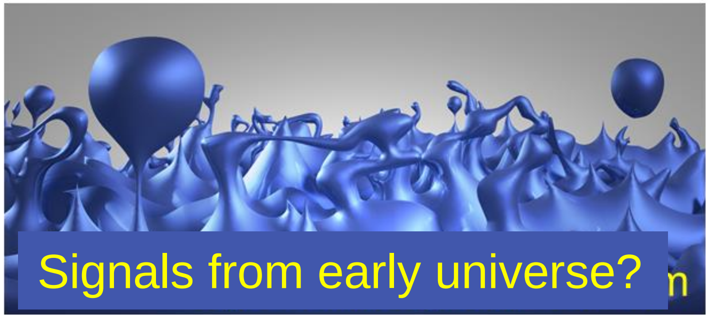
Validate (data quality, etc.)

Select event candidates

Estimate background


PREPARING FOR BIG DATA

Developing methods to mine, analyze, and understand LSST data

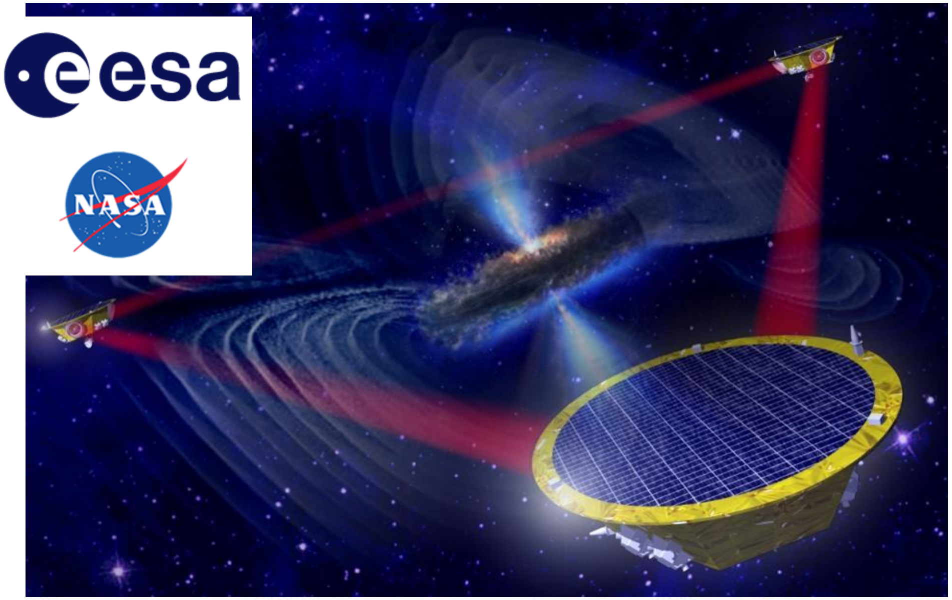

Signals from early universe?

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