Virgo: status and future

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EDSU2020, Guadeloupe, March 10, 2020

LIGO Scientific Collaboration

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

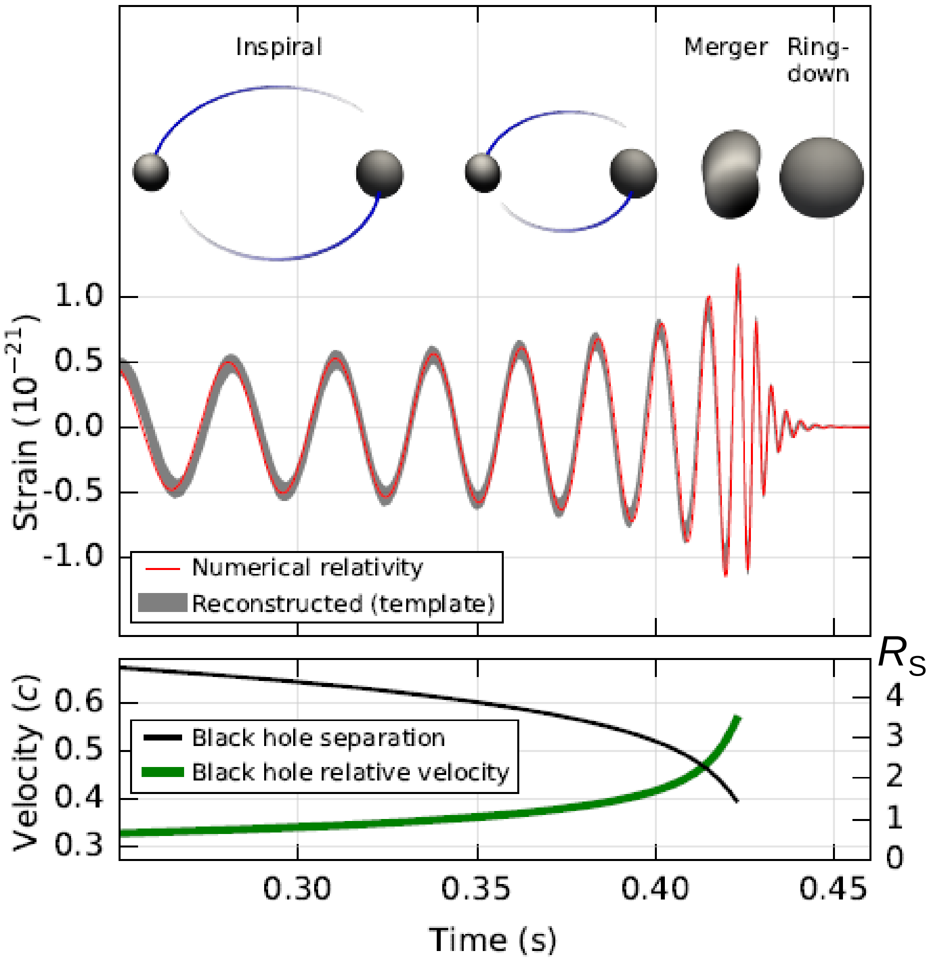
- Dynamical part of gravitation, all space is filled with GW
- Ideal information carrier, almost no scattering or attenuation
- The entire universe has been transparent for GWs, all the way back to the Big Bang

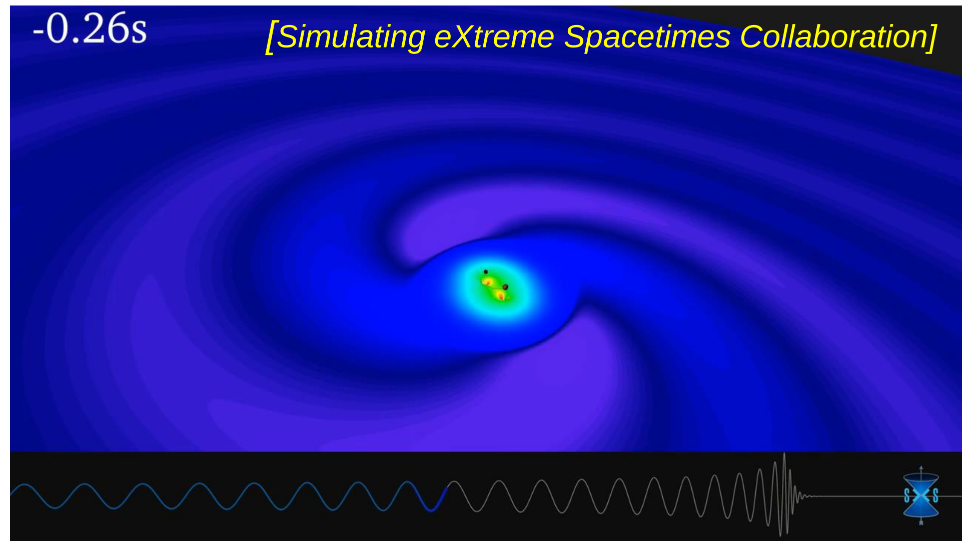
Gravitational wave science can impact

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

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)

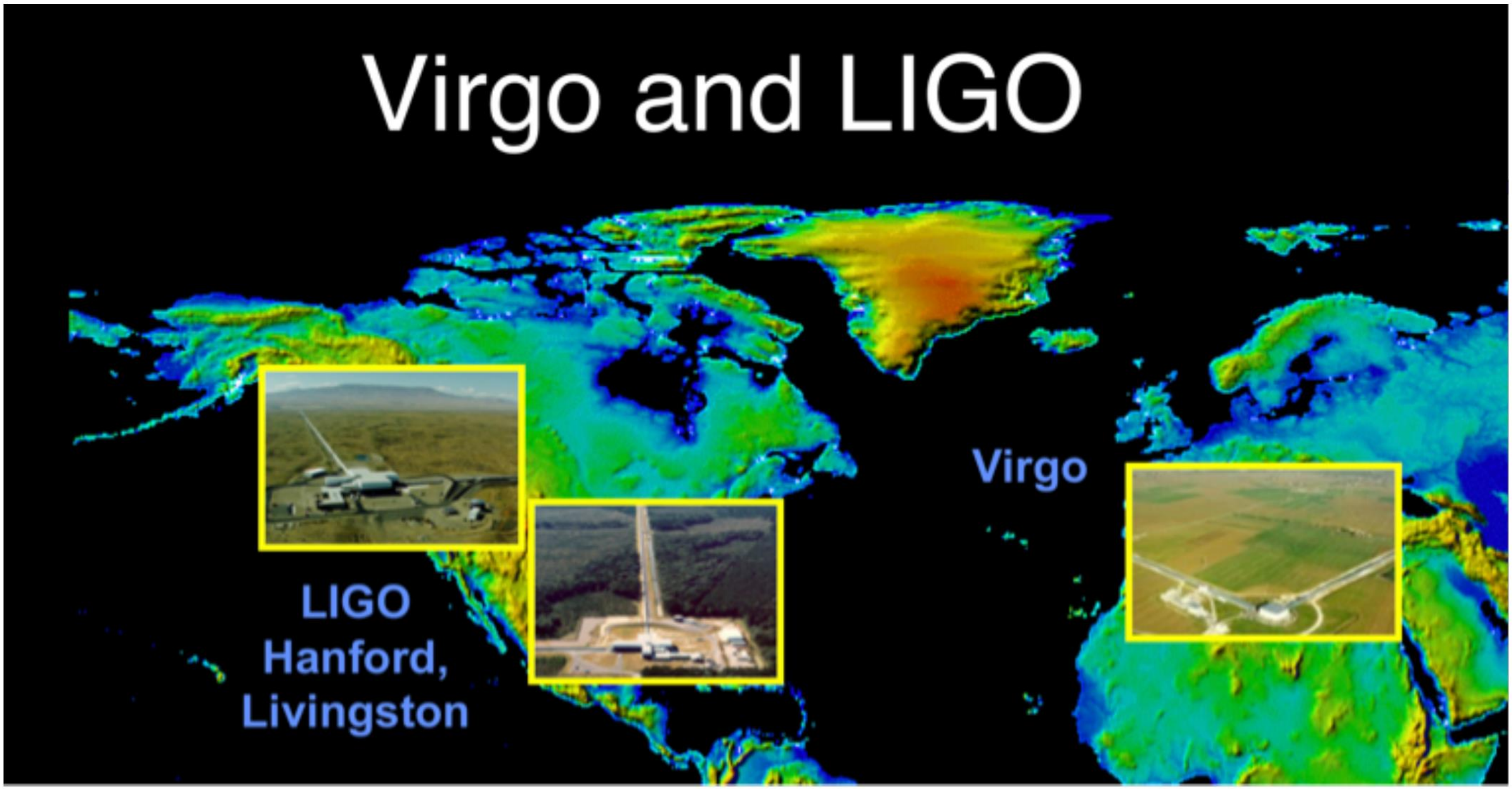
$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$

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

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 already for more than a decade
KAGRA in Japan will join the global network



Virgo Collaboration

Virgo is a European collaboration with 540 members, 352 authors, 104 institutes, 11 countries

Advanced Virgo (AdV) and AdV+: upgrades of the Virgo interferometric detector

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

- Institutes in Virgo Steering Committee
  - APC Paris
  - ARTEMIS Nice
  - IFAE Barcelona
  - ILM and Navier
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - IPHC Strassbourg
  - LAL Orsay ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Maastricht University
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - University Nijmegen
  - RMKI Budapest
  - UCLouvain, ULiege, Uantwerp, KULeuven
  - Univ. of Barcelona
  - University of Sannio
  - Univ. of Valencia
  - University of Jena

Advanced Virgo

Upgrade project of Virgo interferometer

Project has been completed on July 31, 2017

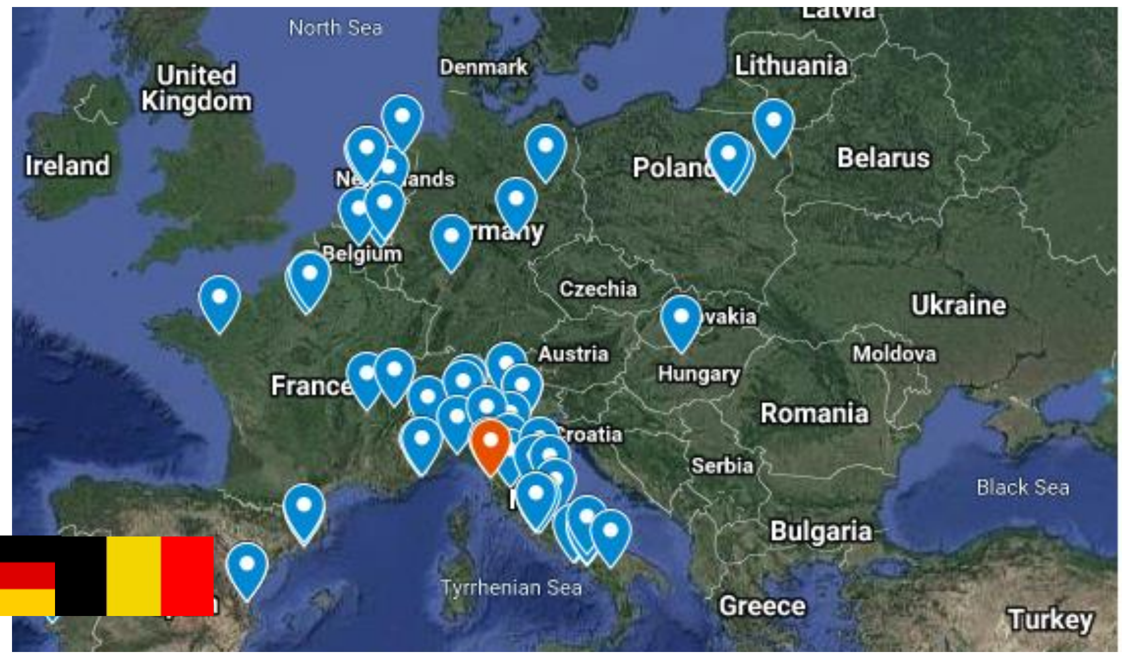
Virgo detector is part of the international network of 2nd generation detectors

Joined the O2 run on August 1, 2017

Now running O3 together with LIGO

Full year data taking ends on April 30, 2020

Collaboration keeps growing



LIGO and Virgo completed observation runs O1 and O2

Gravitational waves were discovered with the LIGO detectors on September 14, 2015. In total 3 events were detected in O1. The Advanced Virgo detector joined at the end of O2

We knew about only 2 events in O2 at the time Virgo turned on

Scientific achievements: properties of binary systems

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

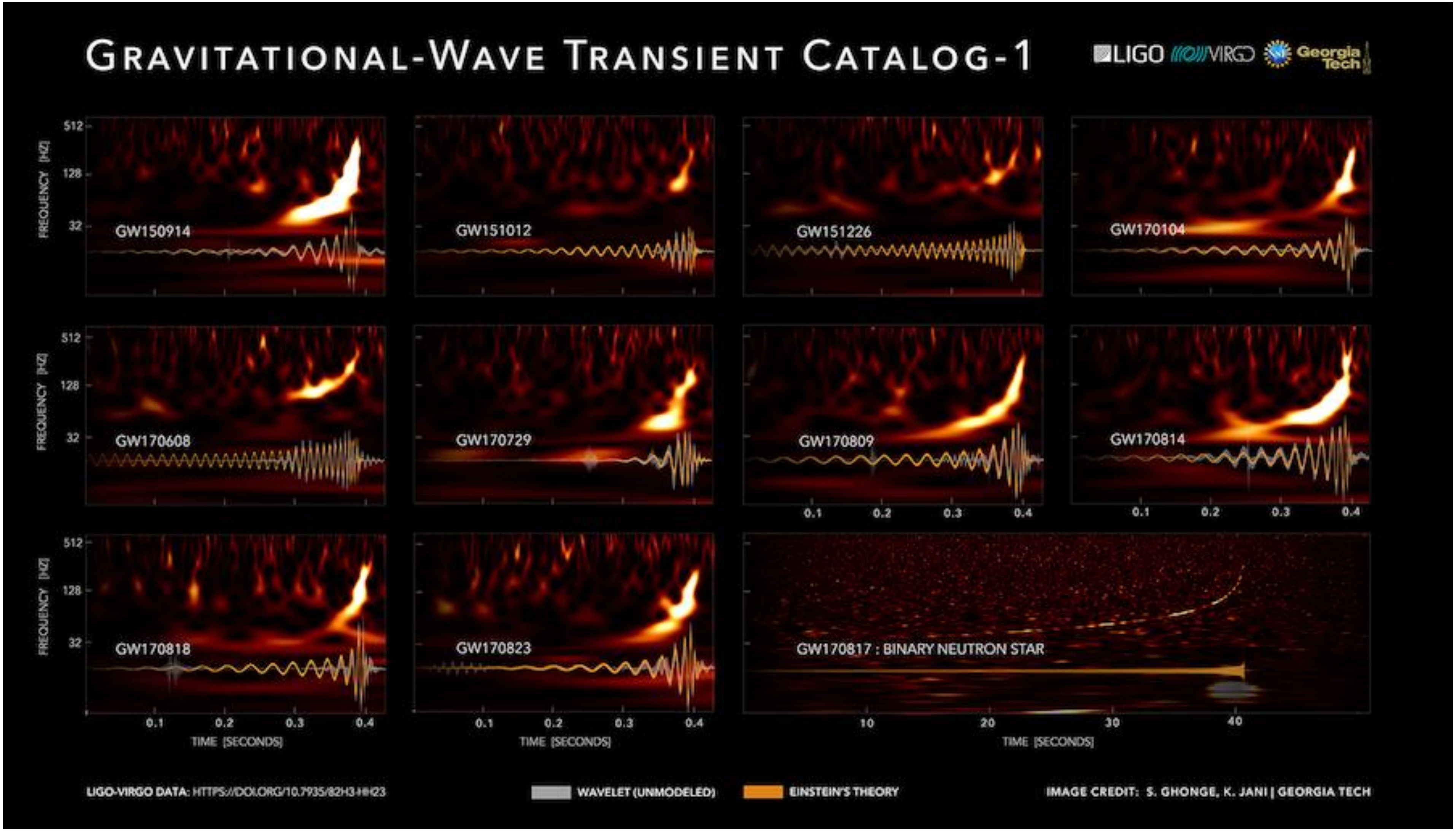


Table of O1 and O2 triggers with source properties

See arXiv:1811.12907

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_{\rm f}/M_\odot$	$a_{\rm f}$	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/(\rm erg\ s^{-1})$	$D_{\rm L}/\rm Mpc$	z	$\Delta\Omega/\rm deg^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	194
GW151012	$23.2^{+14.0}_{-5.4}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.2}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.7}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1491
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1075
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.4^{+5.2}_{-3.9}$	$0.66^{+0.09}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.2^{+0.7}_{-1.0}\times10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	912
GW170608	$11.2^{+5.4}_{-1.9}$	$7.5^{+1.5}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.04^{+0.19}_{-0.06}$	$17.9^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.8^{+0.1}_{-0.1}$	$3.4^{+0.5}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	524
GW170729	$50.7^{+16.3}_{-10.2}$	$34.4^{+8.9}_{-10.2}$	$35.8^{+6.3}_{-4.9}$	$0.37^{+0.21}_{-0.26}$	$80.3^{+14.5}_{-10.3}$	$0.81^{+0.07}_{-0.13}$	$4.9^{+1.6}_{-1.7}$	$4.2^{+0.8}_{-1.5}\times10^{56}$	2760^{+1290}_{-1350}	$0.48^{+0.18}_{-0.21}$	1069
GW170809	$35.2^{+8.3}_{-5.9}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.17}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	310
GW170814	$30.7^{+5.5}_{-2.9}$	$25.6^{+2.8}_{-4.0}$	$24.3^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.6^{+3.2}_{-2.5}$	$0.73^{+0.07}_{-0.05}$	$2.8^{+0.4}_{-0.3}$	$3.7^{+0.5}_{-0.5}\times10^{56}$	560^{+140}_{-210}	$0.12^{+0.03}_{-0.04}$	99
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	22
GW170818	$35.5^{+7.5}_{-4.7}$	$26.9^{+4.4}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.7}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1020^{+430}_{-370}	$0.20^{+0.07}_{-0.07}$	35
GW170823	$39.5^{+10.1}_{-6.6}$	$29.4^{+6.5}_{-7.1}$	$29.3^{+4.2}_{-3.1}$	$0.08^{+0.19}_{-0.22}$	$65.6^{+9.3}_{-6.5}$	$0.71^{+0.08}_{-0.09}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}\times10^{56}$	1860^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1780

Table of O1 and O2 triggers with source properties

See arXiv:1811.12907

Virgo data contributed to Parameter Estimation of 5 events

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_{\mathrm{f}}/M_\odot$	a_{f}	$E_{\mathrm{rad}}/(M_\odot c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$D_{\mathrm{L}}/\mathrm{Mpc}$	z	$\Delta\Omega/\mathrm{deg}^2$
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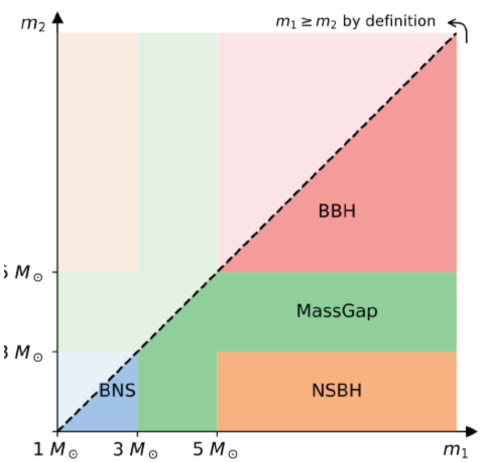
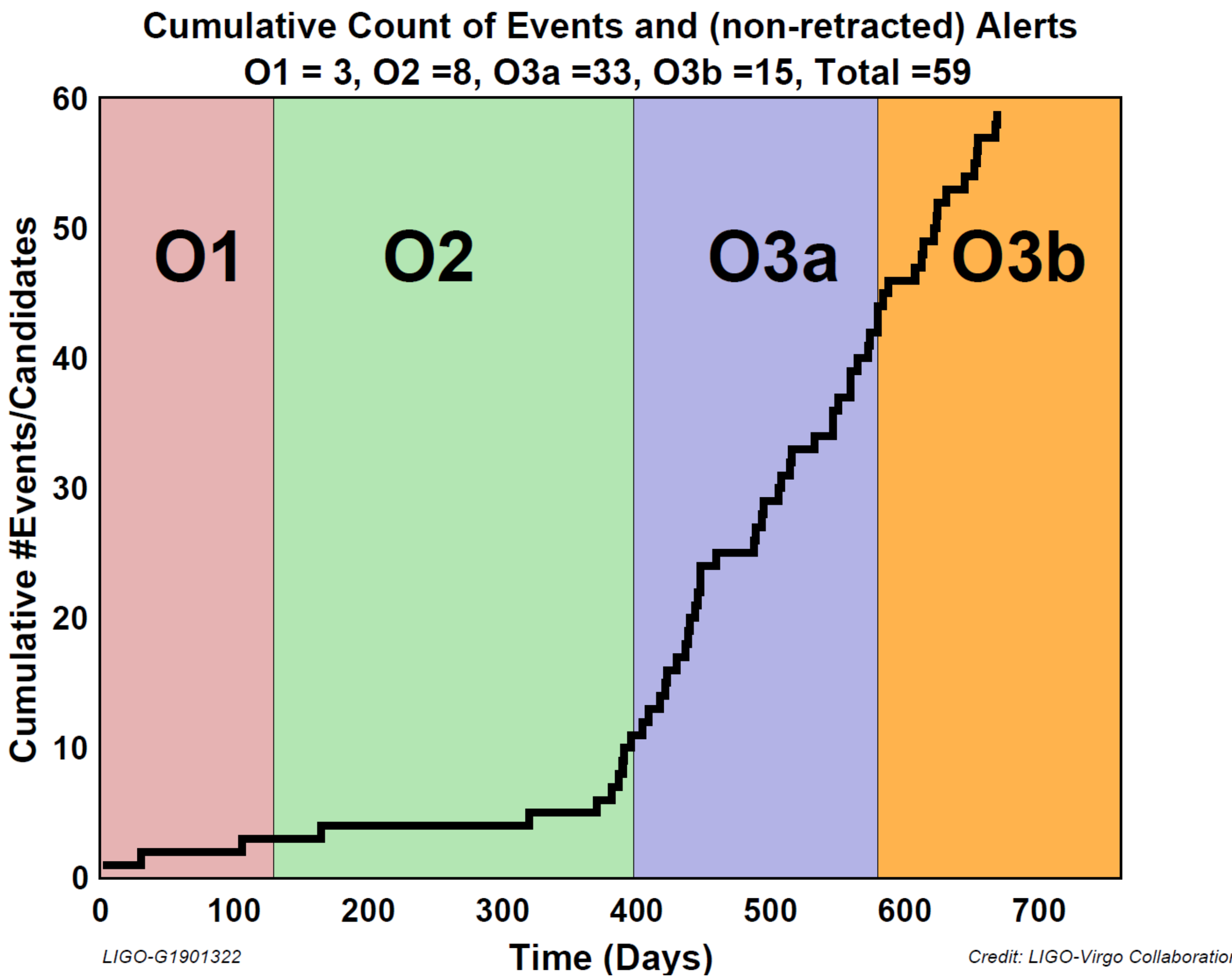
Event rate

LVC is collecting data. We will continue O3 until April 30, 2020

O3 now has

- 32 BBH
- 7 BNS
- 6 NSBH
- 3 MassGap





Release of Open Public Alerts

Procedures defined in MOA between KAGRA, LIGO and Virgo

LIGO and Virgo Collaborations release Open Public Alerts, with low latency, for all interesting signal triggers, and follow-up information sufficient for non-GW observers to find hosts

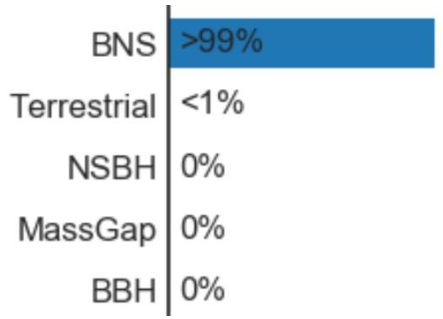
S190425z

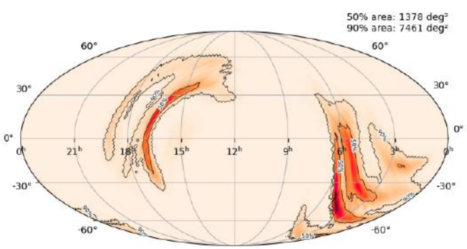
FAR < 1/100 yrs

7461 deg2 in 90% c.r.

Distance 156±41 Mpc

L, V





GCN 24168, 24228

Latest — as of 27 January 2020 14:32:30 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FA
S200116ah	EM_READY PE_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1263211019.170712	1263211020.170712	1263211021.170712	2.02
S200115j	EM_READY PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1263097406.735840	1263097407.752869	1263097408.769043	2.09
S200114f	EM_READY ADVOK EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT		1263002916.239300	1263002916.252885	1.22
S200112r	EM_READY PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1262879936.093931	1262879937.093931	1.28
S200108v	EM_READY PE_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1262512856.558755	1262512857.558755	2.66
S200106av	EM_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK G		1262370881.578613	1262370882.623047	3.12
S200106au	EM_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK G		1262370887.292480	1262370888.456543	3.66
S200105ae	EM_READY PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN		1262276684.057208	1262276685.059117	7.67
S191225aq	EM_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK G		1261346253.870117	1261346254.870117	1.26
S191222n	EM_READY PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1261020955.119478	1261020956.119478	6.45
S191220af	EM_READY PE_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1260879872.690032	1260879873.690394	3.96
S191216ap	EM_READY PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1260567236.472999	1260567237.487849	1.13
S191215w	EM_READY PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1260484270.333152	1260484271.365682	1.00
S191213ai	EM_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK G		1260287963.899585	1260287964.899585	2.00
S191213g	EM_READY PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1260246866.142224	1260246867.145035	3.54
S191212q	EM_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK G		1260174466.641861	1260174467.641861	3.36
S191205ah	EM_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK G		1259617946.568738	1259617947.568738	1.24
S191204r	EM_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK G		1259514944.091822	1259514945.124422	3.06
S191129u	EM_READY PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1259070047.197372	1259070048.244883	2.65
S191124be	ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM		1258624776.099619	1258624777.099619	1.67
S191120at	ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM		1258315735.323325	1258315736.367101	6.10
S191120aj	ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM		1258302232.438461	1258302233.438461	2.86
S191117j	ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM		1258006120.454868	1258006121.454868	1.11
S191110af	ADVNO EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT		1257462422.183200	1257462422.287284	2.49
S191110x	PE_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK G		1257444540.210120	1257444541.210120	2.93
S191109d	EM_READY PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1257296855.220703	1257296856.278186	1.53
S191105e	EM_READY PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READ		1256999739.933105	1256999740.933105	2.28

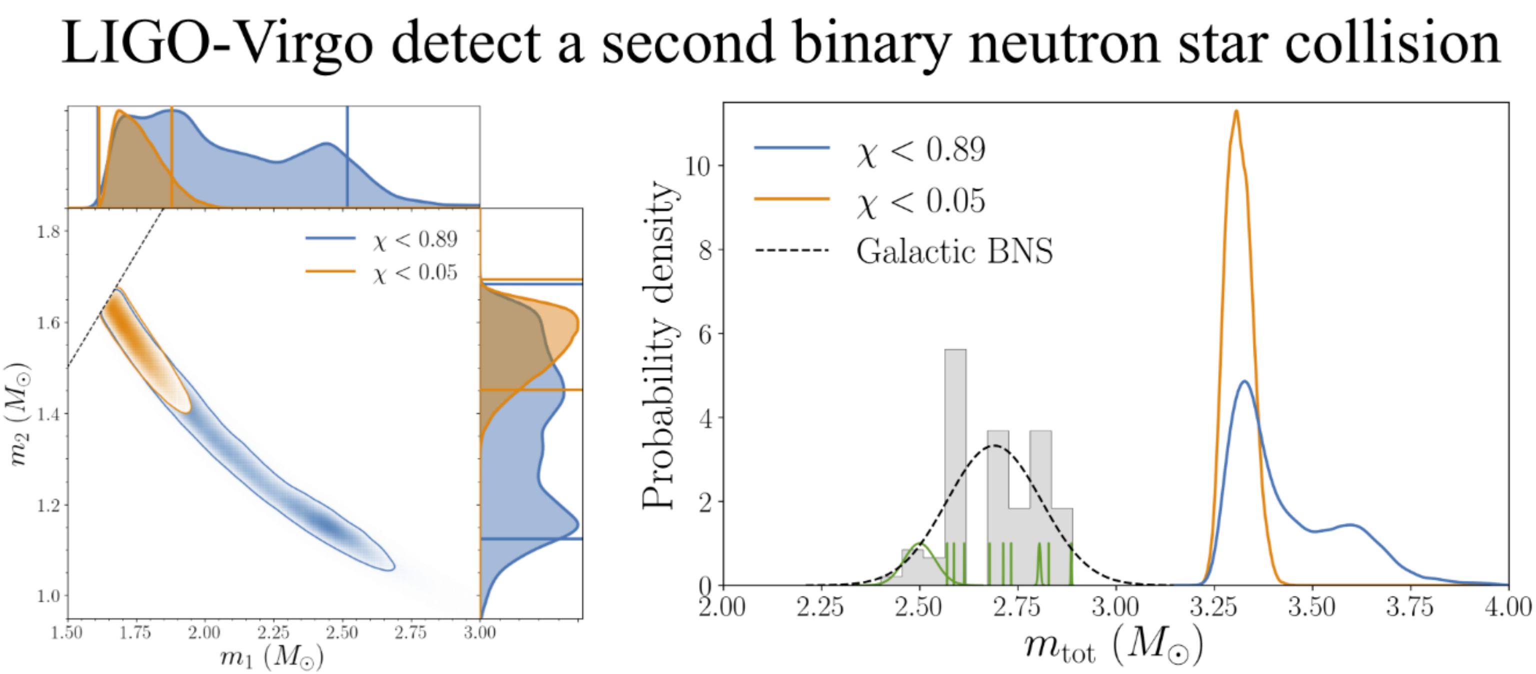
Press Release on January 6, 2020 at IAU meeting in Hawaii

GW190425: confirmation of our BNS merger detection in 2017. First released event of O3 run
Marie-Anne Bizouard was present during the press announcement

System is more massive than BNS observed in our galaxy

Remarks:

- Competitive situation among waveform enthusiasts
- Attempts to change draft after VSC approval (e.g. references)
- Virgo not too visible: discussed with LIGO management



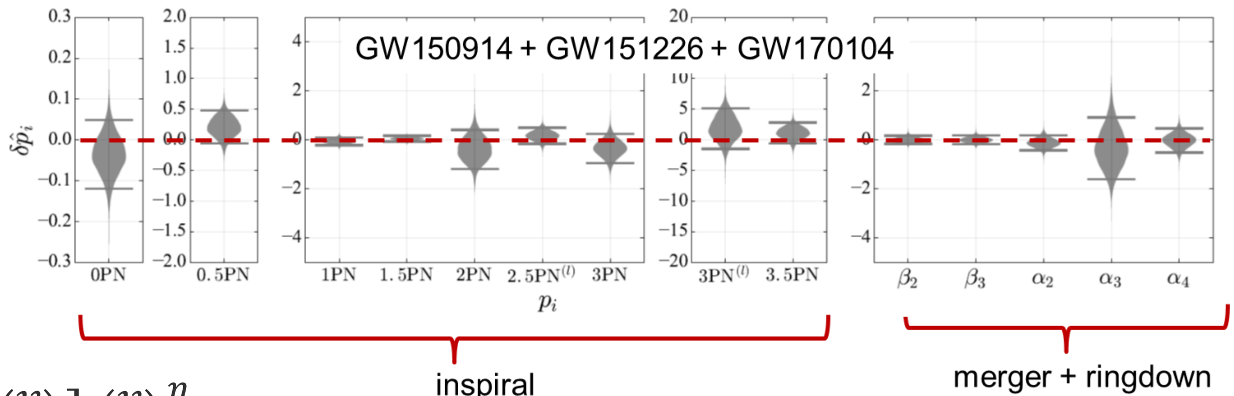
Some scientific highlights: black holes

Precision tests of GR with BBH mergers

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

Inspiral and PN expansion

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



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

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

Merger terms: numerical GR

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

Towards high precision tests of gravity

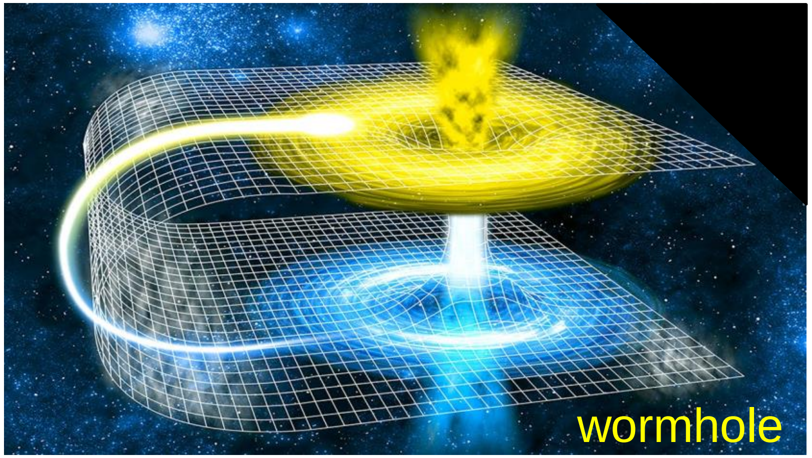
Combining information from multiple events and having high-SNR events will allow unprecedented tests of GR and other theories of gravity

Our collaborations set ambitious goals for the future

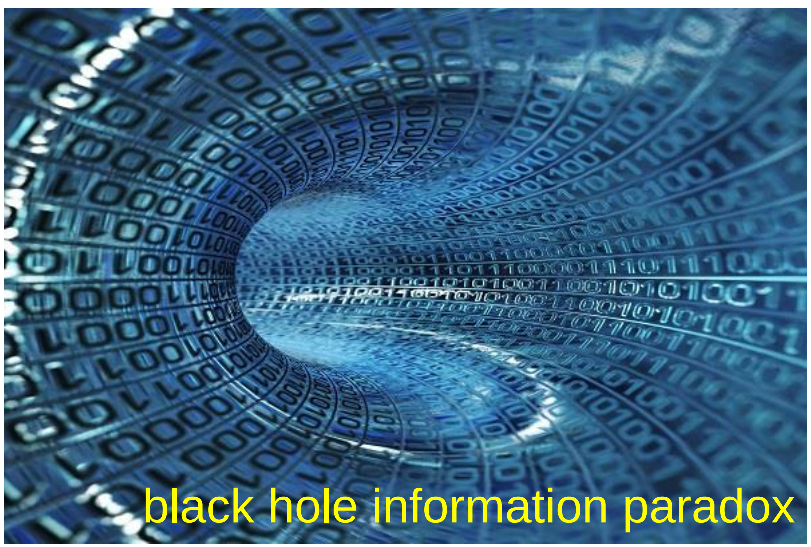
We need to improve:
- sensitivity of our instruments over the entire frequency range
- optimize our computing and analysis
- improve our source modeling (NR)

Fundamental physics: did we observe black holes?

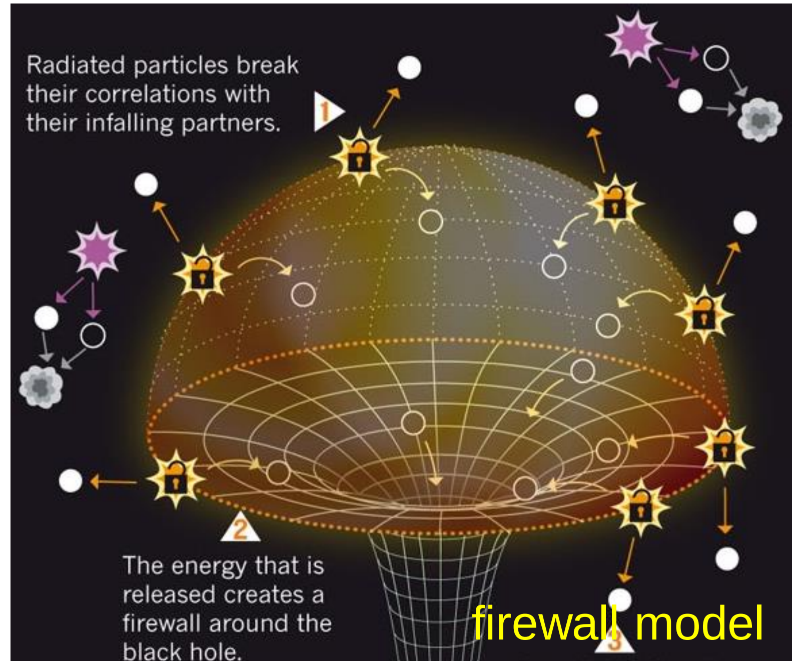
Our theories “predict” the existence of other objects, such as quantum modifications of GR black holes, boson stars, gravastars, firewalls, *etc*. Why do we believe we have seen black holes?



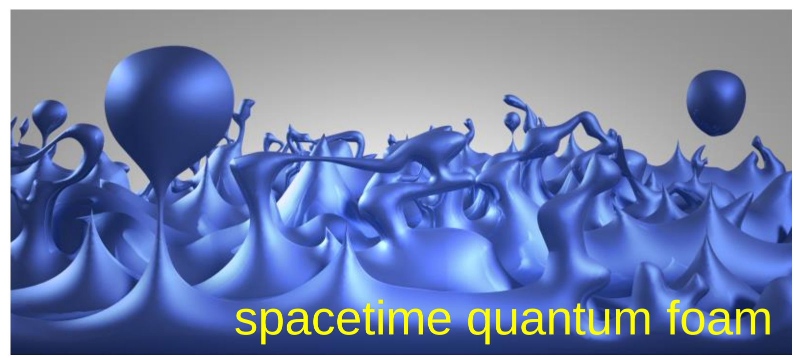
wormhole



black hole information paradox



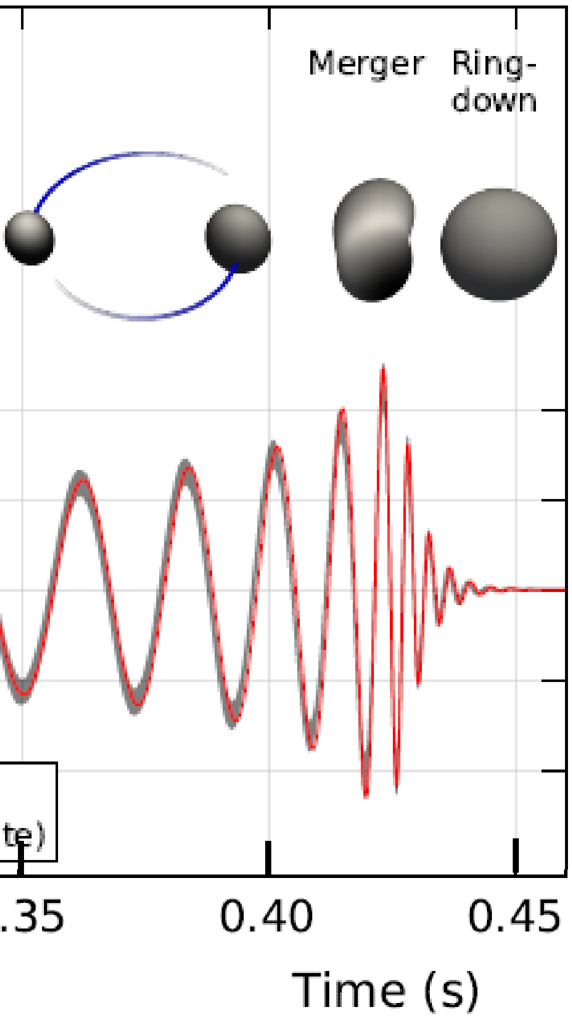
firewall model

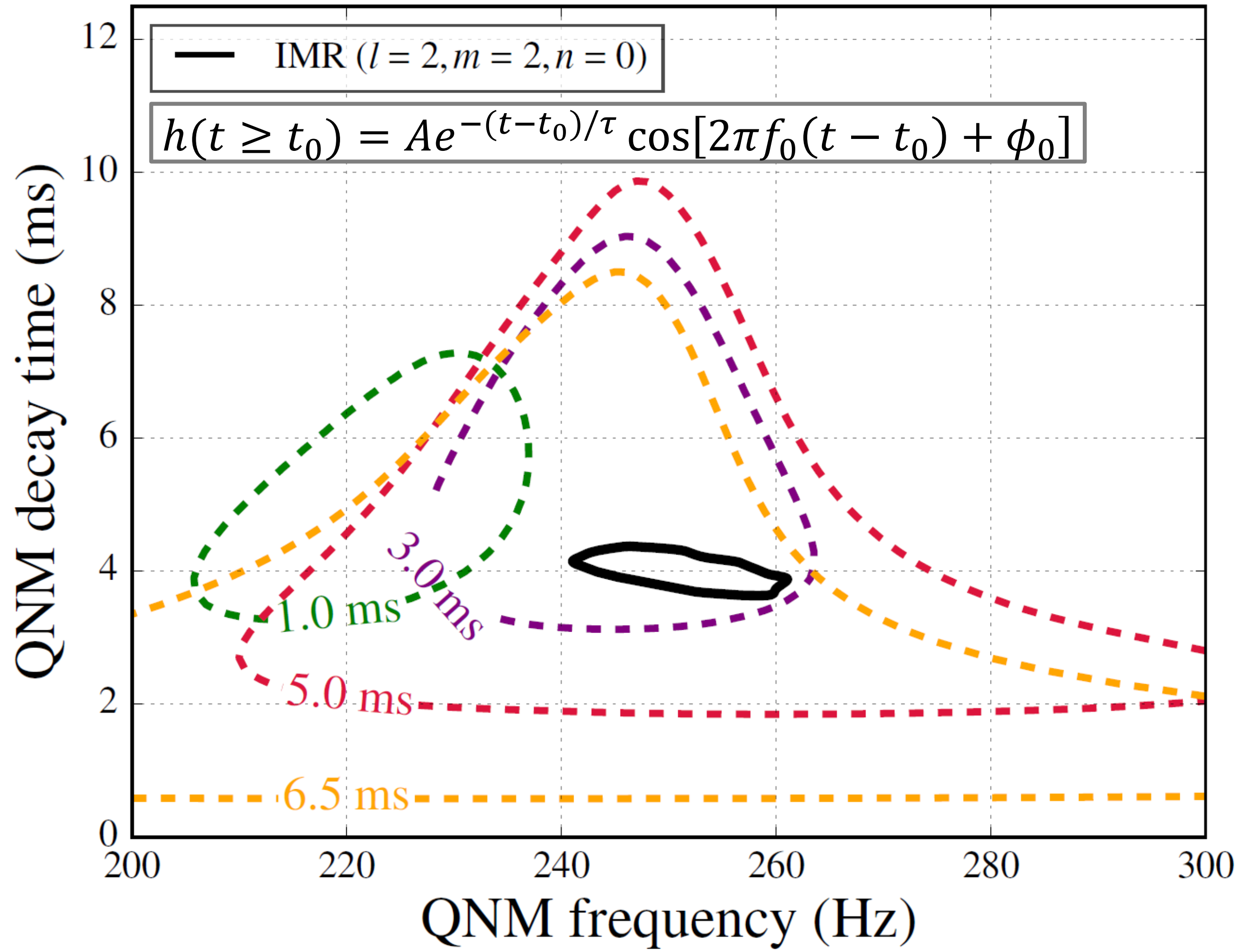


spacetime quantum foam

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. This demands good sensitivity at high frequency





Exotic compact objects

Gravitational waves from coalescence of two compact objects is the Rosetta Stone of the strong-field regime. It may hold the key and provide an in-depth probe of the nature of spacetime

Quantum modifications of GR black holes

- Motivated by Hawking's information paradox
- Firewalls, fuzzballs, EP = EPR, …

Fermionic dark matter

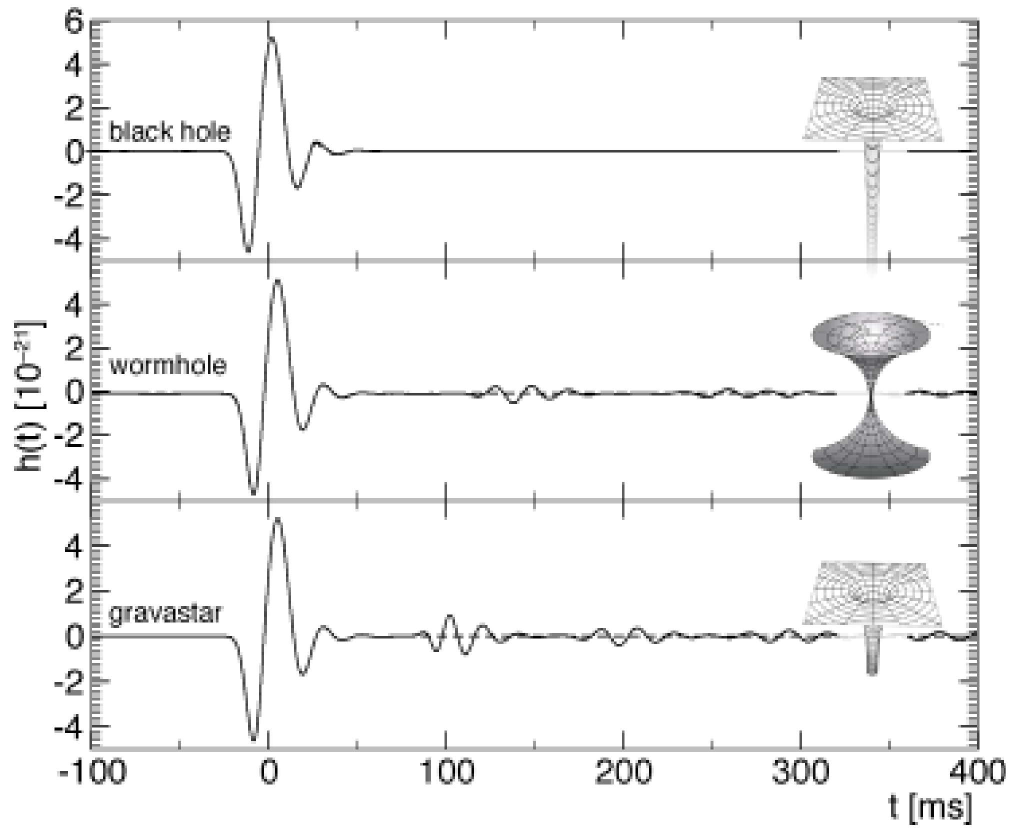
- Dark matter stars

Boson stars

- Macroscopic objects made up of scalar fields

Gravastars

- Objects with de Sitter core where spacetime is self-repulsive
- Held together by a shell of matter
- Relatively low entropy object

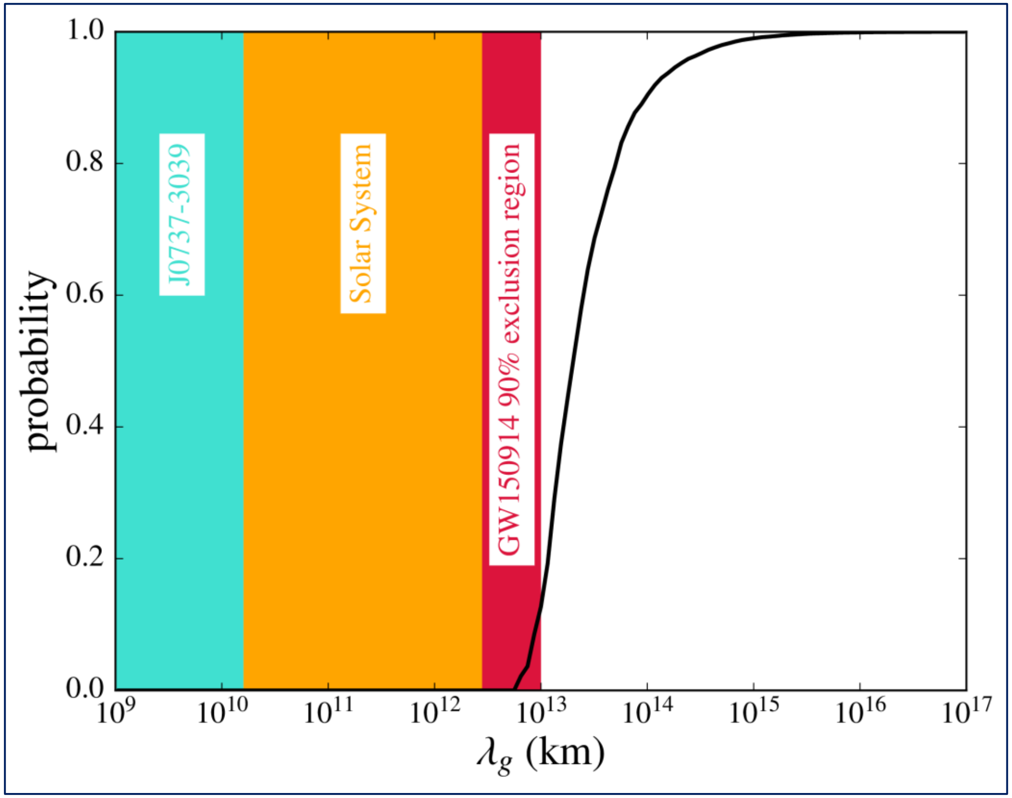


GW observables

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

Limit on the mass of the graviton

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



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

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

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

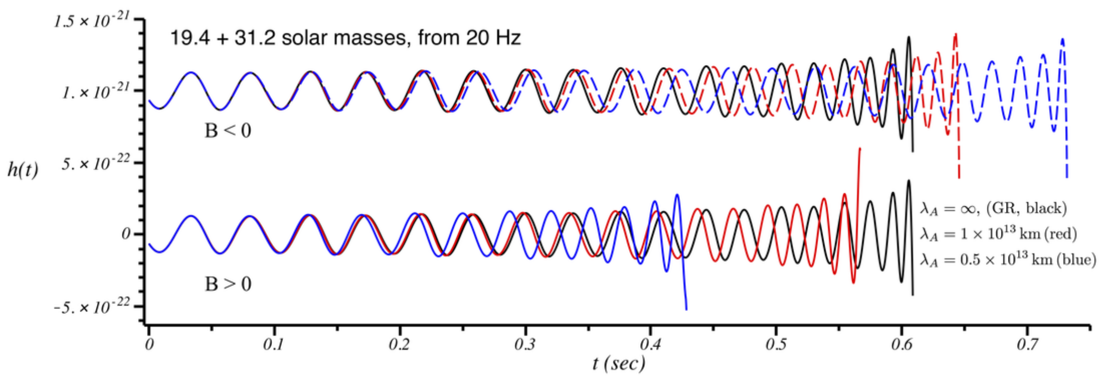
$\lambda_g > 10^{13}$ km
$m_g \leq 10^{-22} \mathrm{eV}/\mathrm{c}^2$

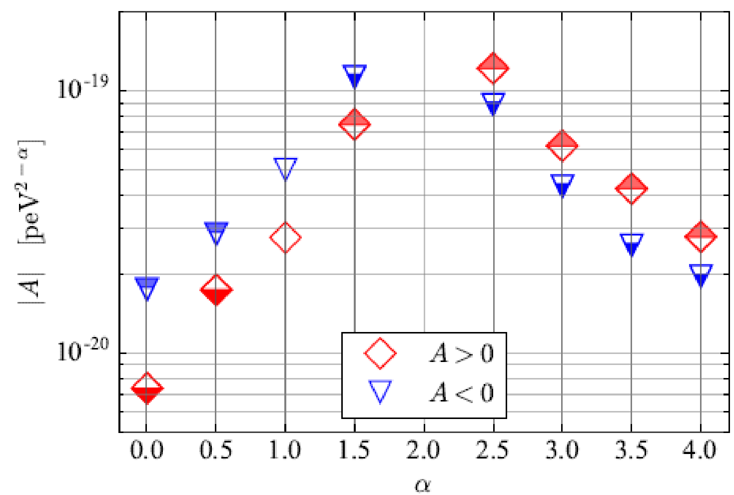
Bounds on violation of Lorentz invariance

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

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

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





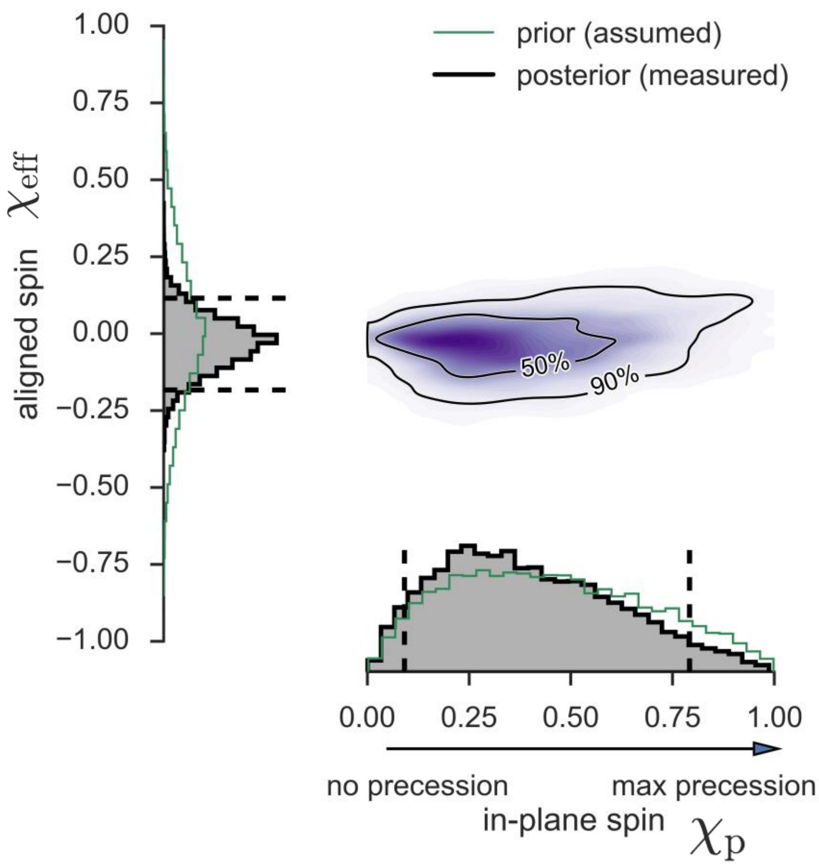
Several modified theories of gravity predict specific values of α:

- massive-graviton theories (α = 0, A > 0), multifractal spacetime (α = 2.5),
- doubly special relativity (α = 3), and Horava-Lifshitz and extradimensional theories (α = 4)

Combinations of component spins for GW150914

GW150914 suggests that the individual spins were either small, or they were pointed opposite from one another, cancelling each other's effect. Spin maybe the key to formation channels

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



Effective spin parameter

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

Precession in BBH

$$\dot{\boldsymbol{L}} = \frac{G}{c^2 r^3}(B_1 \boldsymbol{S}_{1\perp} + B_2 \boldsymbol{S}_{2\perp}) \times \boldsymbol{L}$$

$$\dot{\boldsymbol{S}}_i = \frac{G}{c^2 r^3} B_i \boldsymbol{L} \times \boldsymbol{S}_i,$$

Effective precession spin parameter

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

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

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

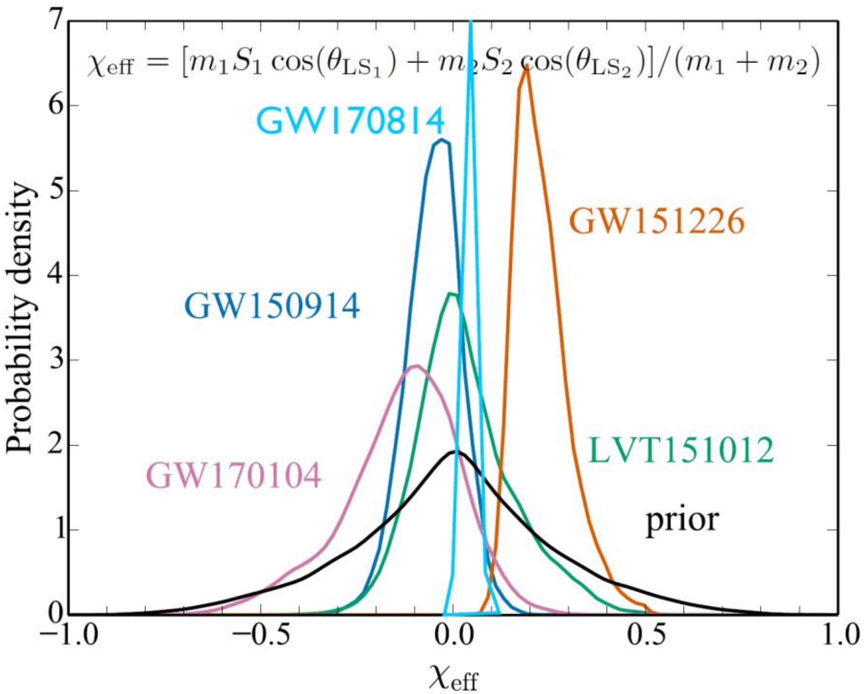
See "*Properties of the Binary Black Hole Merger GW150914*" http://arxiv.org/abs/1602.03840

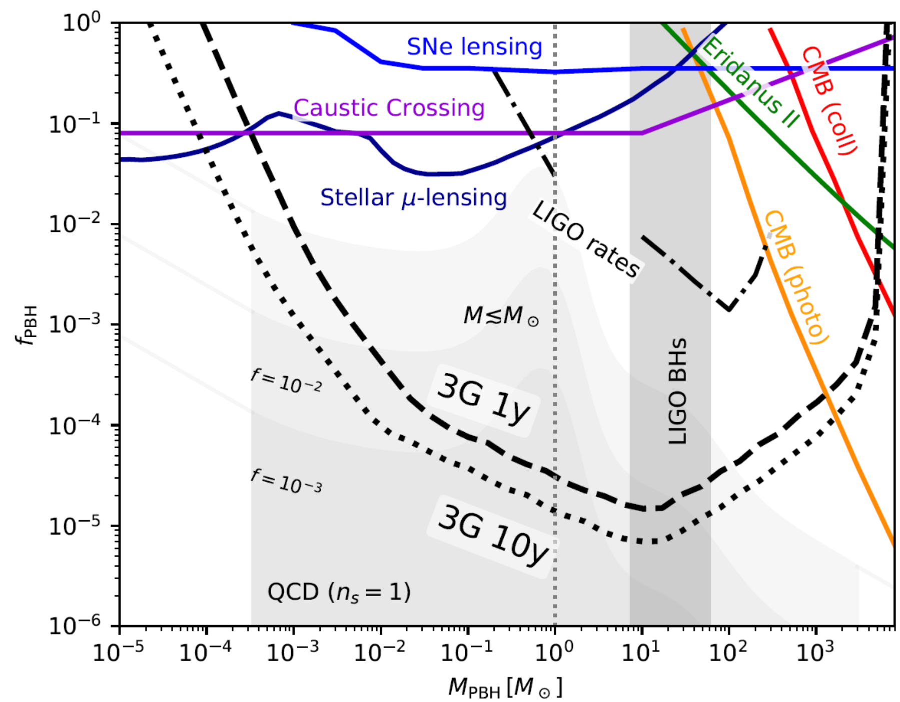
Primordial black holes as dark matter candidates

BBH events suggest that the individual spins were either small, or they pointed opposite from one another, cancelling each other. Precession is an important clue into how the black holes formed

PBHs might have been produced from the collapse of large primordial density fluctuations in the early Universe (perhaps at the QCD phase transition)

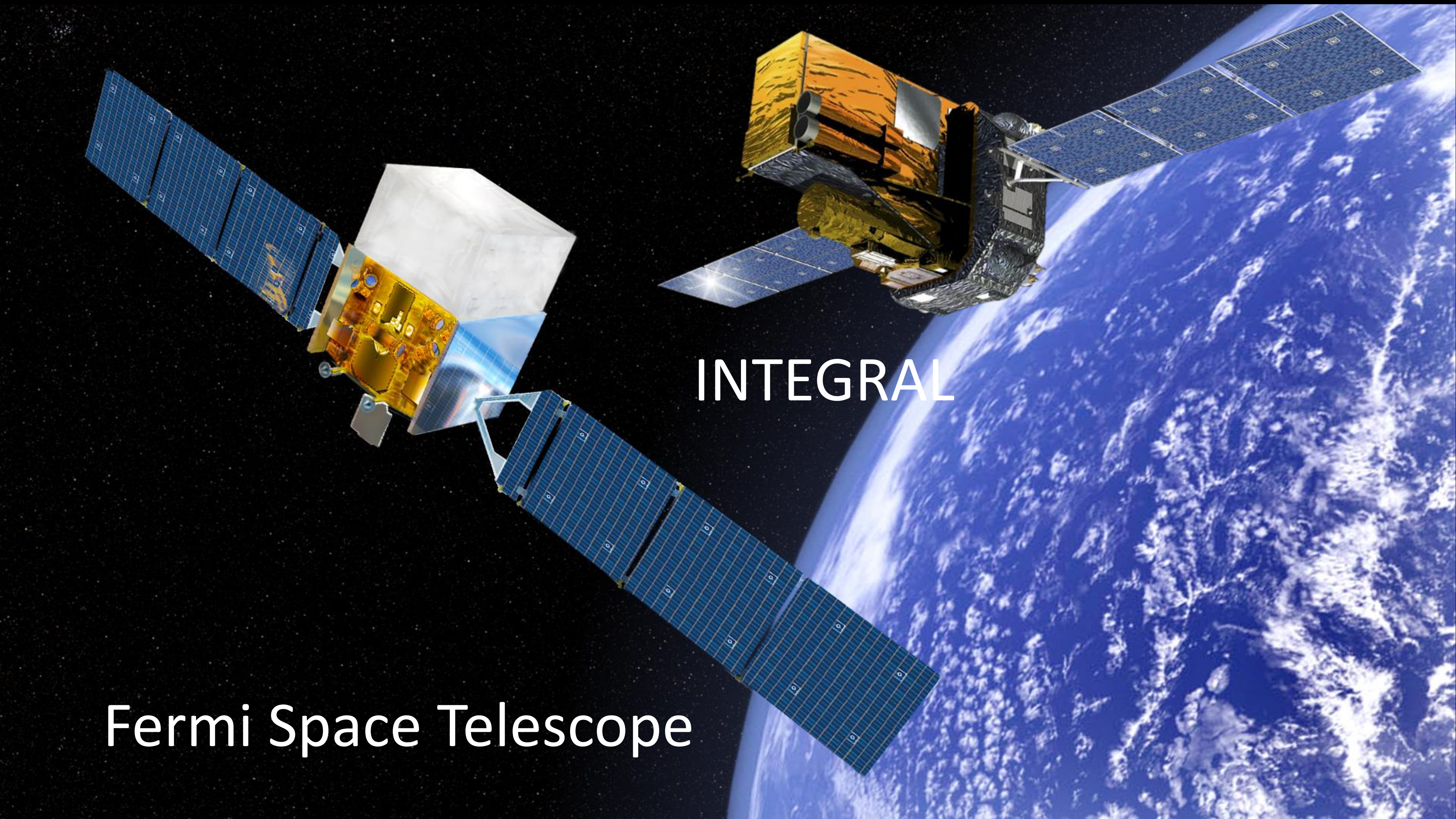
The shaded regions (right figure) correspond to the mass function imprinted by the QCD phase transition, for different primordial BH abundances and a primordial scale invariant spectrum





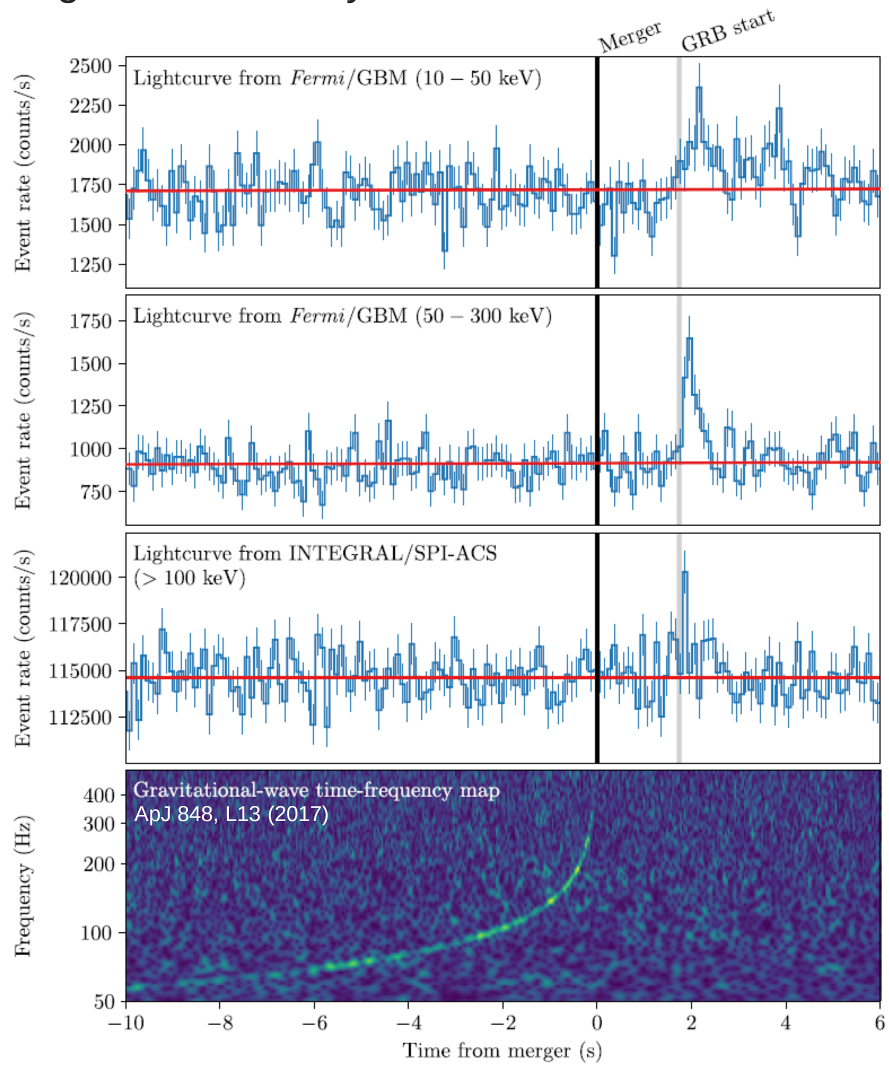
Some scientific highlights: neutron stars

Gamma rays reached Earth 1.7 seconds after GW180717



Binary neutron star merger on August 17, 2017

Gamma rays reached Earth 1.7 s after the end of the gravitational wave inspiral signal. The data are consistent with standard EM theory minimally coupled to general relativity



Neutron stars are laboratories for extreme physics

Mass: from about 1.1 to about 2.2 solar mass

Density: up to several times nuclear density

Temperature: up to 10^{12} K

Magnetic field: up to 10^{11} T

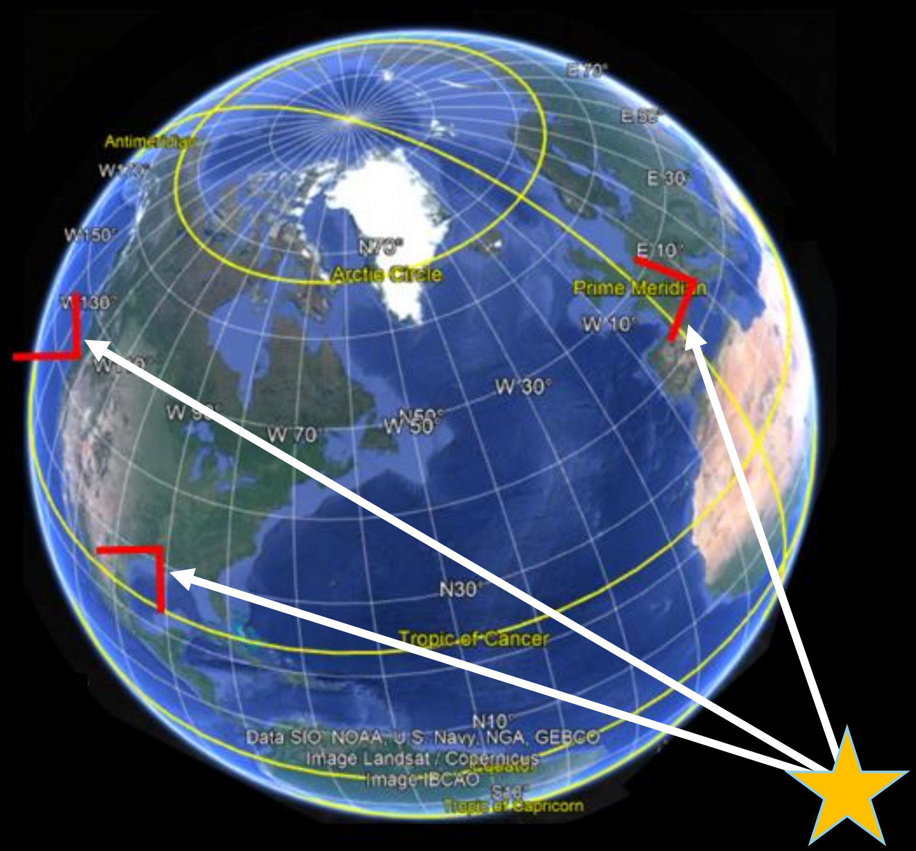
Held together by gravity and supported by degeneracy pressure and NN repulsion

Extrapolate behavior of QCD, superconductivity, and superfluidity

Equation Of State: many models

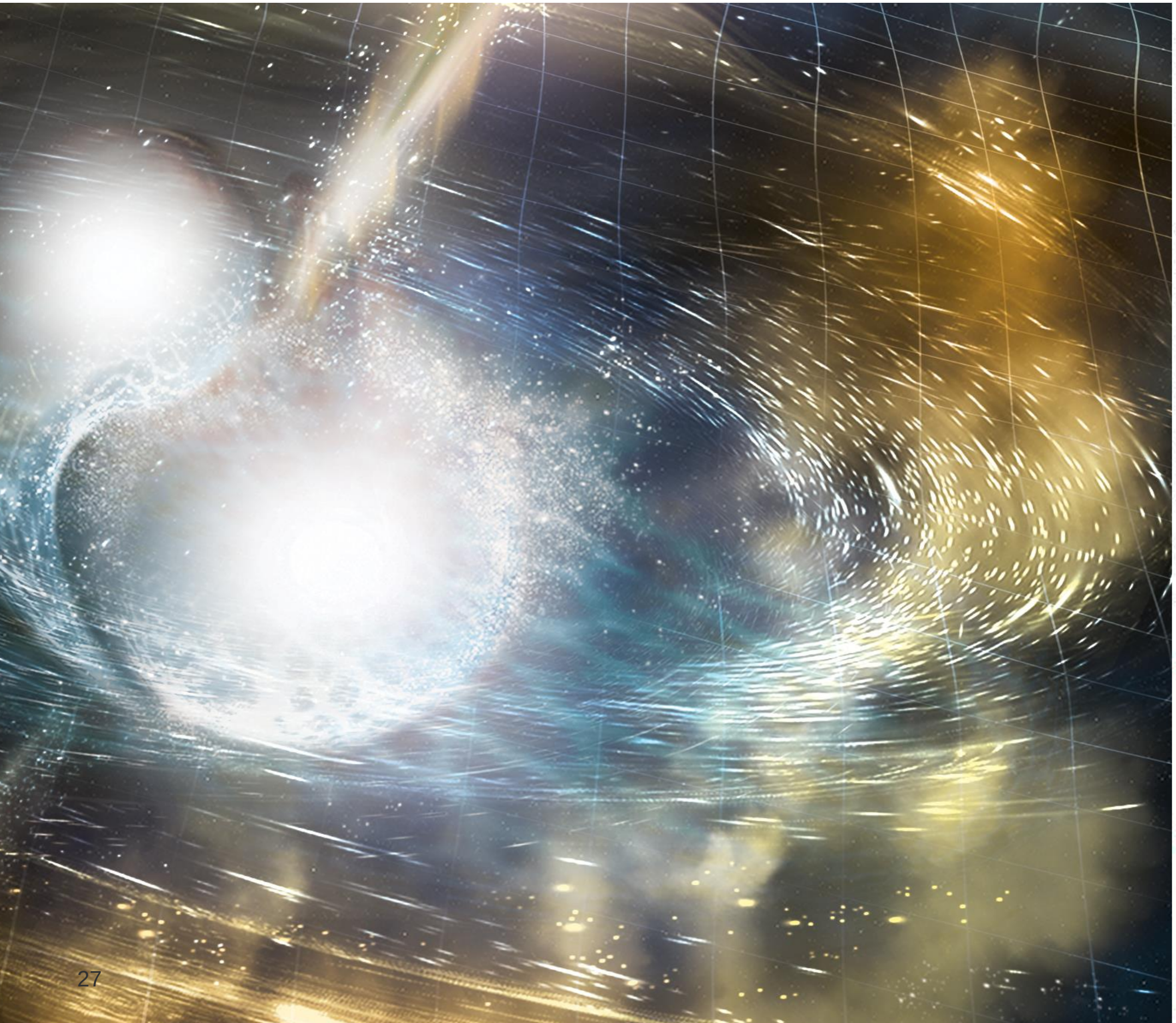
Source location via triangulation

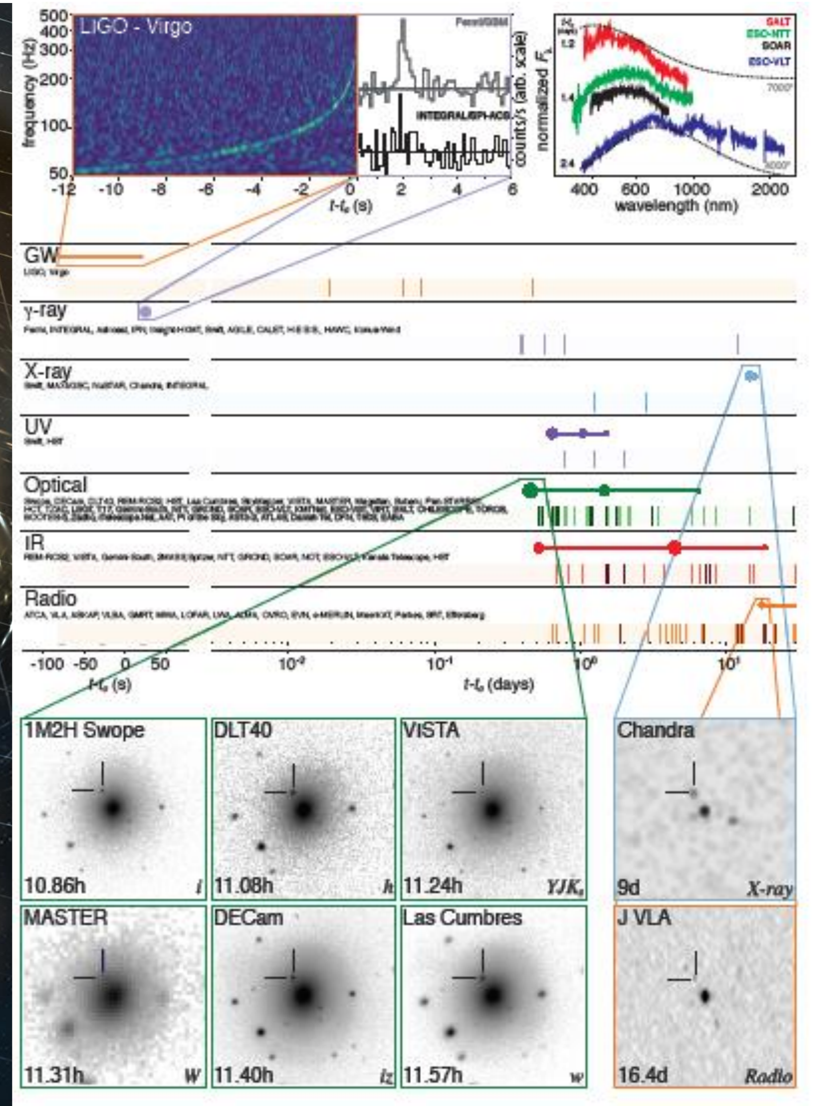
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it

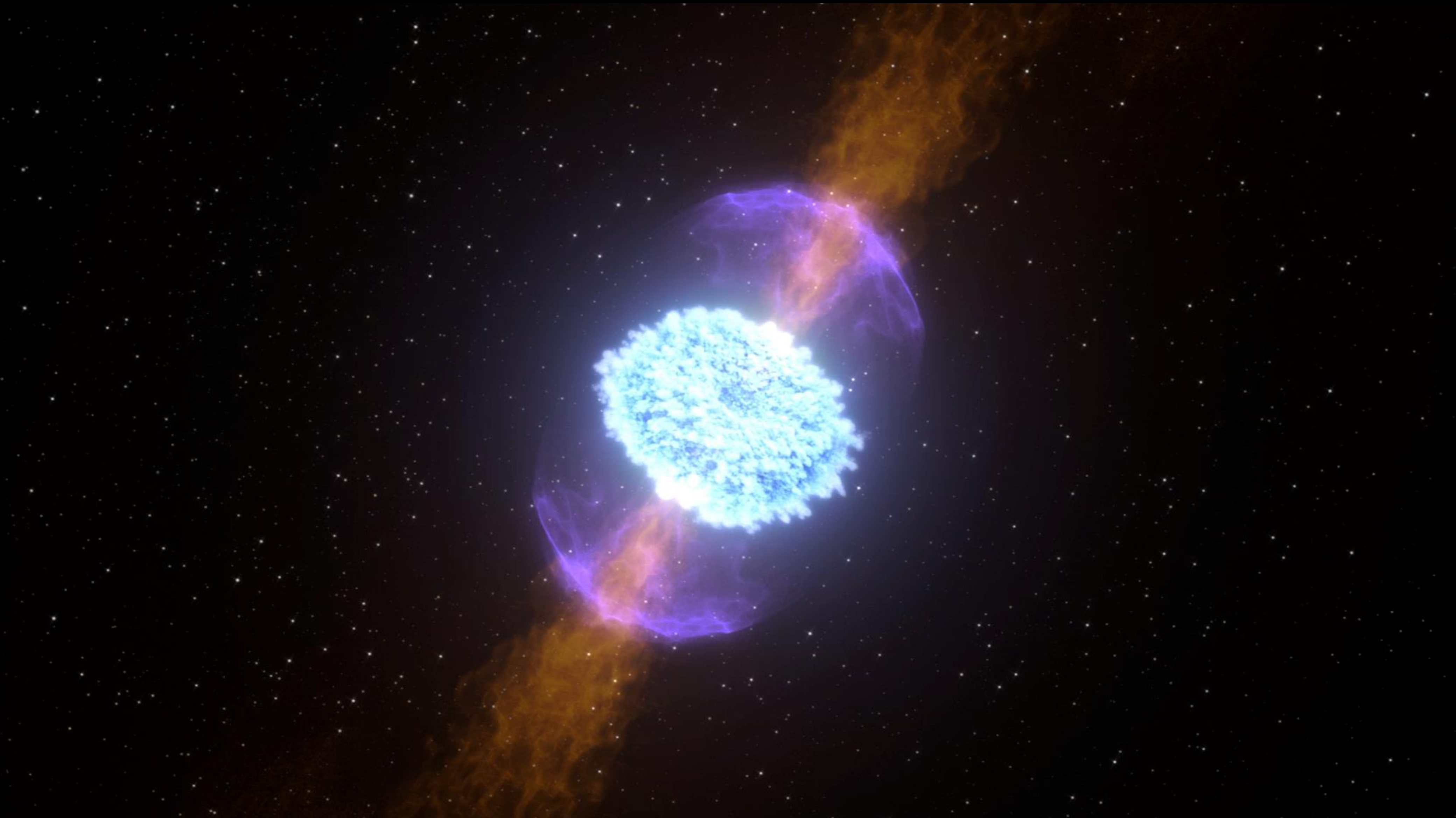


GW170817: start of multi-messenger astronomy with GW

Many compact merger sources emit, besides gravitational waves, also light, gamma- and X-rays, and UV, optical, IR, and radio waves, as well as neutrino’s or other subatomic particles. Our three-detector global network allows identifying these counterparts







Implications for fundamental physics

Gamma rays reached Earth 1.7 s after the end of the gravitational wave inspiral signal. The data are consistent with standard EM theory minimally coupled to general relativity

GWs and light propagation speeds

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

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

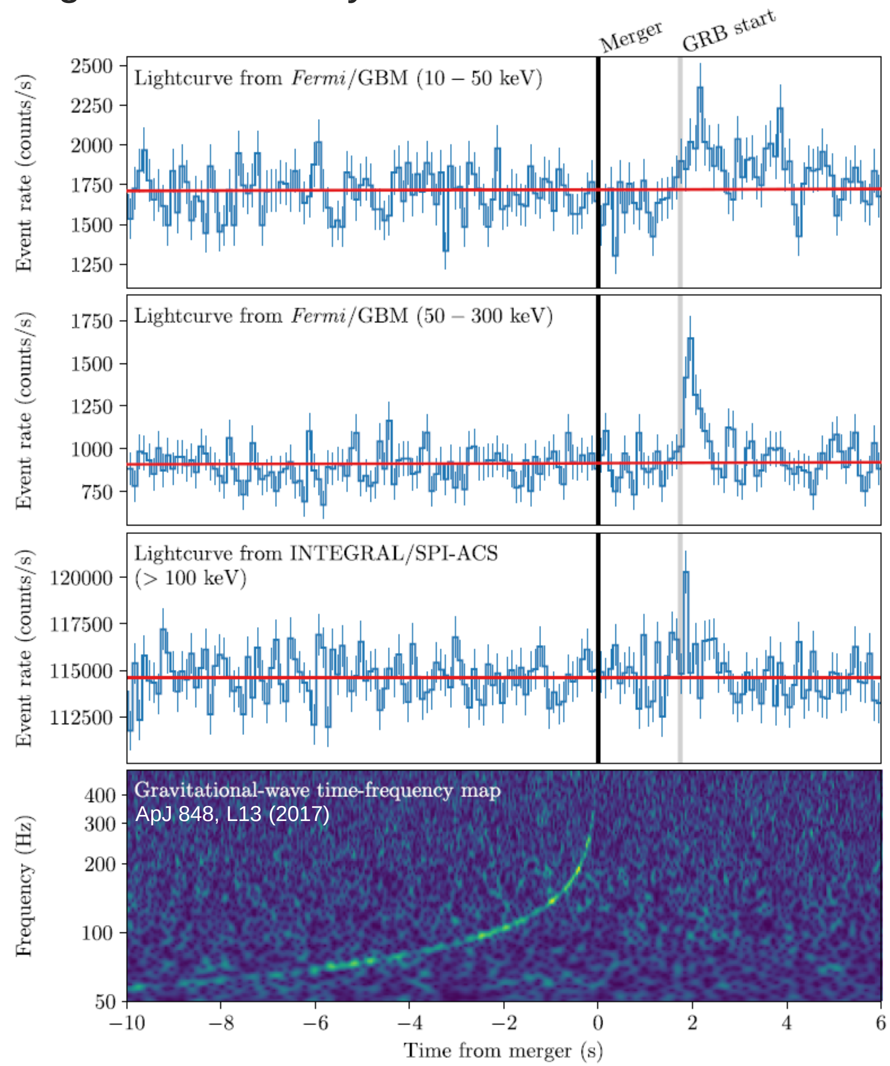
Test of Equivalence Principle

According to General Relativity, GW and EM waves are deflected and delayed by the curvature of spacetime produced by any mass (i.e. background gravitational potential). Shapiro delays affect both waves in the same manner

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

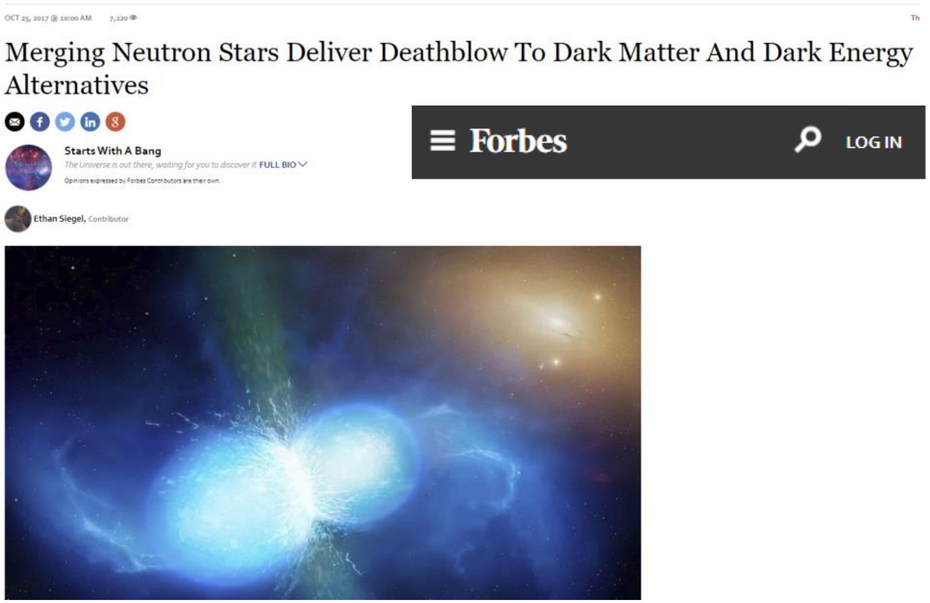
Milky Way potential gives same effect to within
$-2.6 \times 10^{-7} \leq \gamma_{\text{GW}} - \gamma_{\text{EM}} \leq 1.2 \times 10^{-6}$

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



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)

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

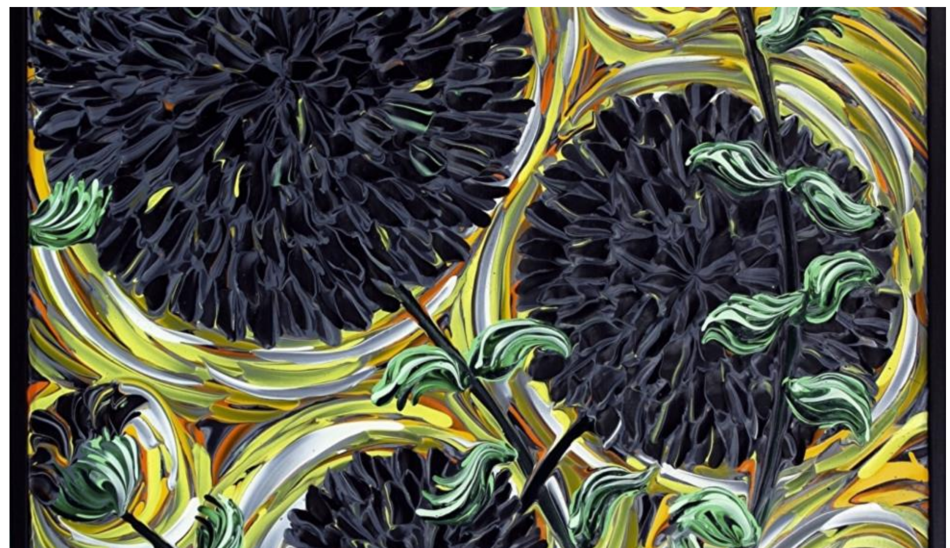
Simultaneous detection of GW and EM signals rules out a class of modified gravity theories (arXiv:1710.05901v2)

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

Gregory Horndeski

See https://horndeskicontemporary.com/



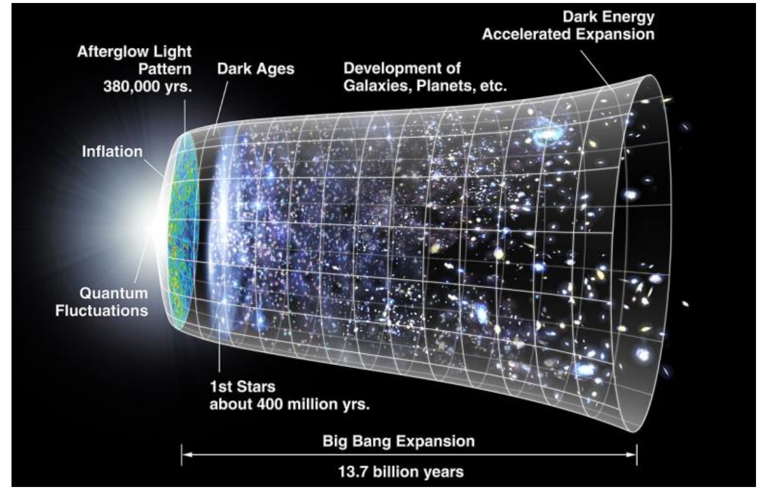
Cosmology

A new cosmic distance marker

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

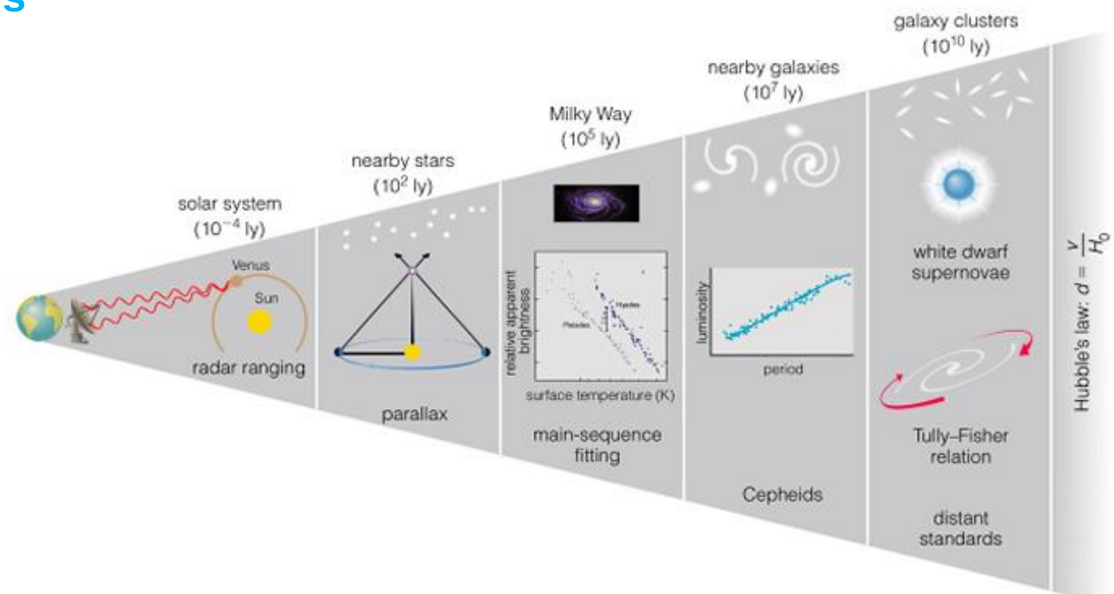
Current measurements depend on cosmic distance ladder

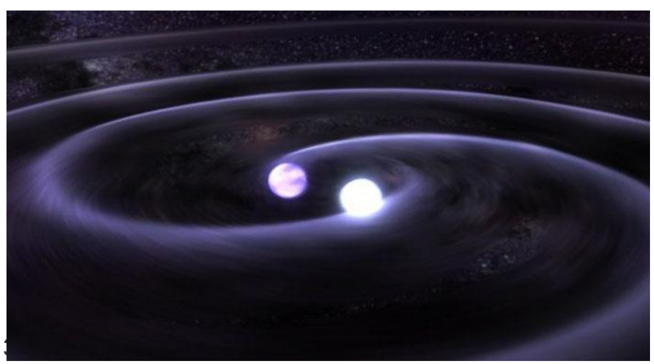
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder



Gravitational waves from binary mergers

Distance can be measured directly from the gravitational wave signal!





A new cosmic distance marker

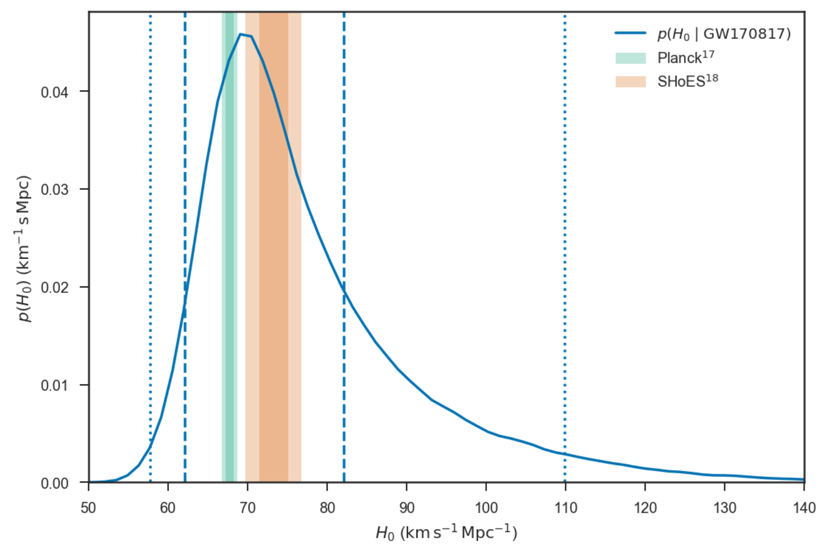
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1-2% accuracy

Measurement of the local expansion of the Universe

The Hubble constant

- Distance from GW signal
- Redshift from EM counterpart (galaxy NGC 4993)

LIGO+Virgo *et al*., Nature 551, 85 (2017)

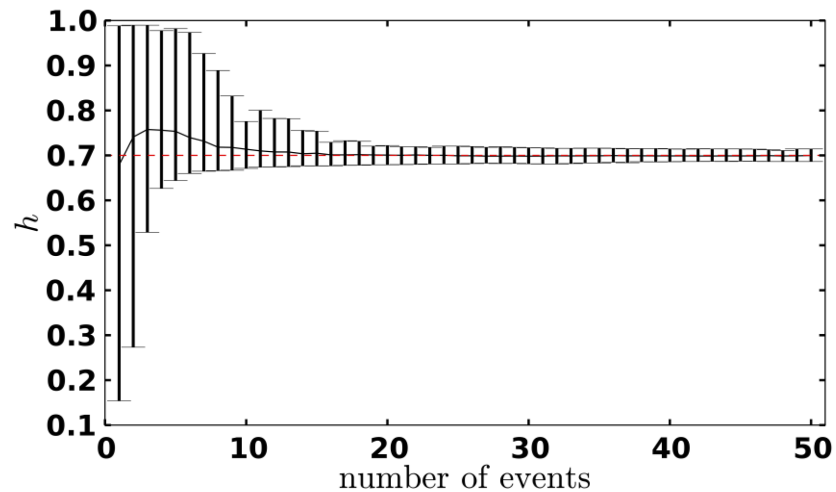


GW170817

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

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

Walter Del Pozzo, PRD 86, 043011 (2012)



Third generation observatories allow studies of the Dark Energy equation of state parameter

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

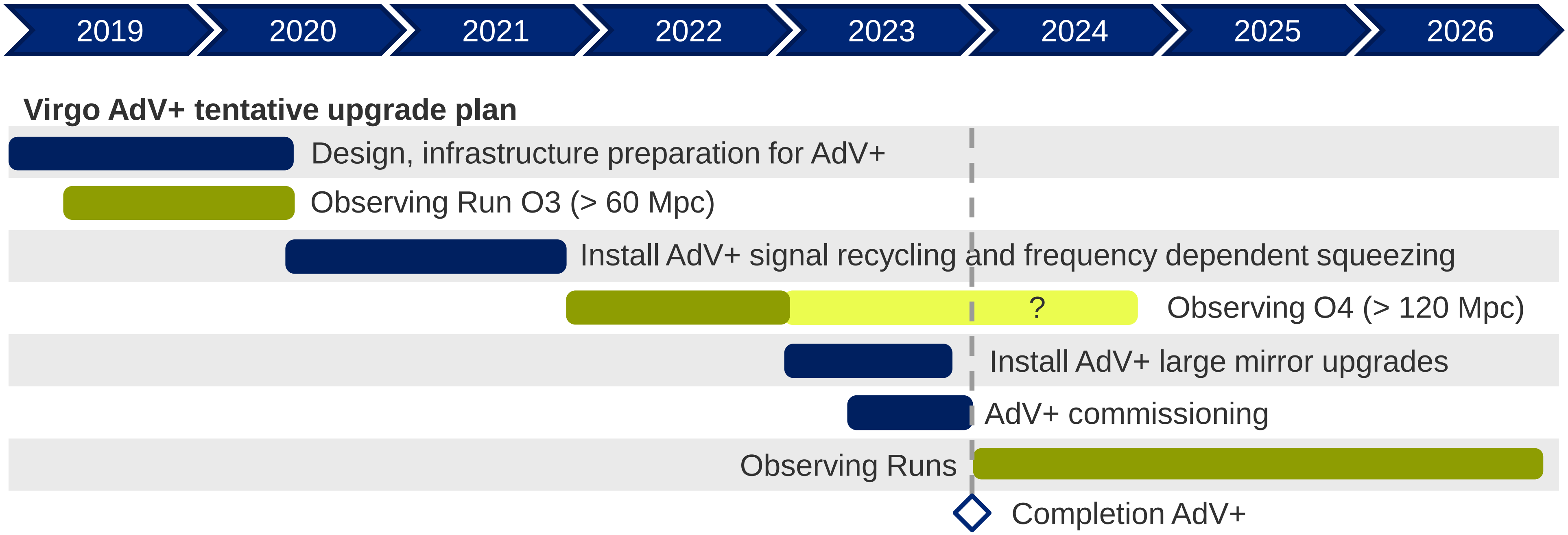
Astronomy
Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies

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

Scheduling of science runs, AdV+ installation and commissioning

Five year plan for observational runs, commissioning and upgrades



Commissioning break in October 2019

Duration of O3: until the end of April 2020 (duration of O4 has not been decided)

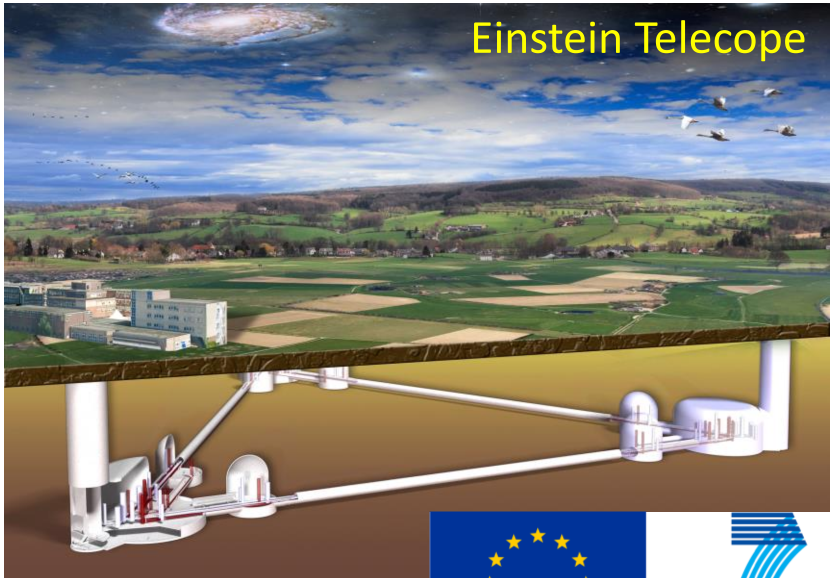
Break between O3 and O4 probably around 18 months (allow installation and commissioning)

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

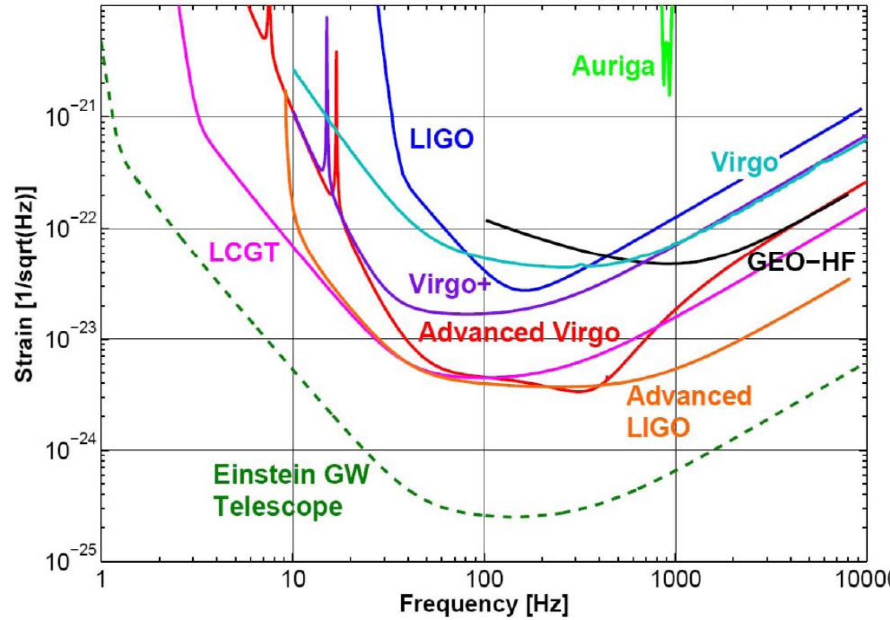
AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope

Einstein Telescope and Cosmic Explorer

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

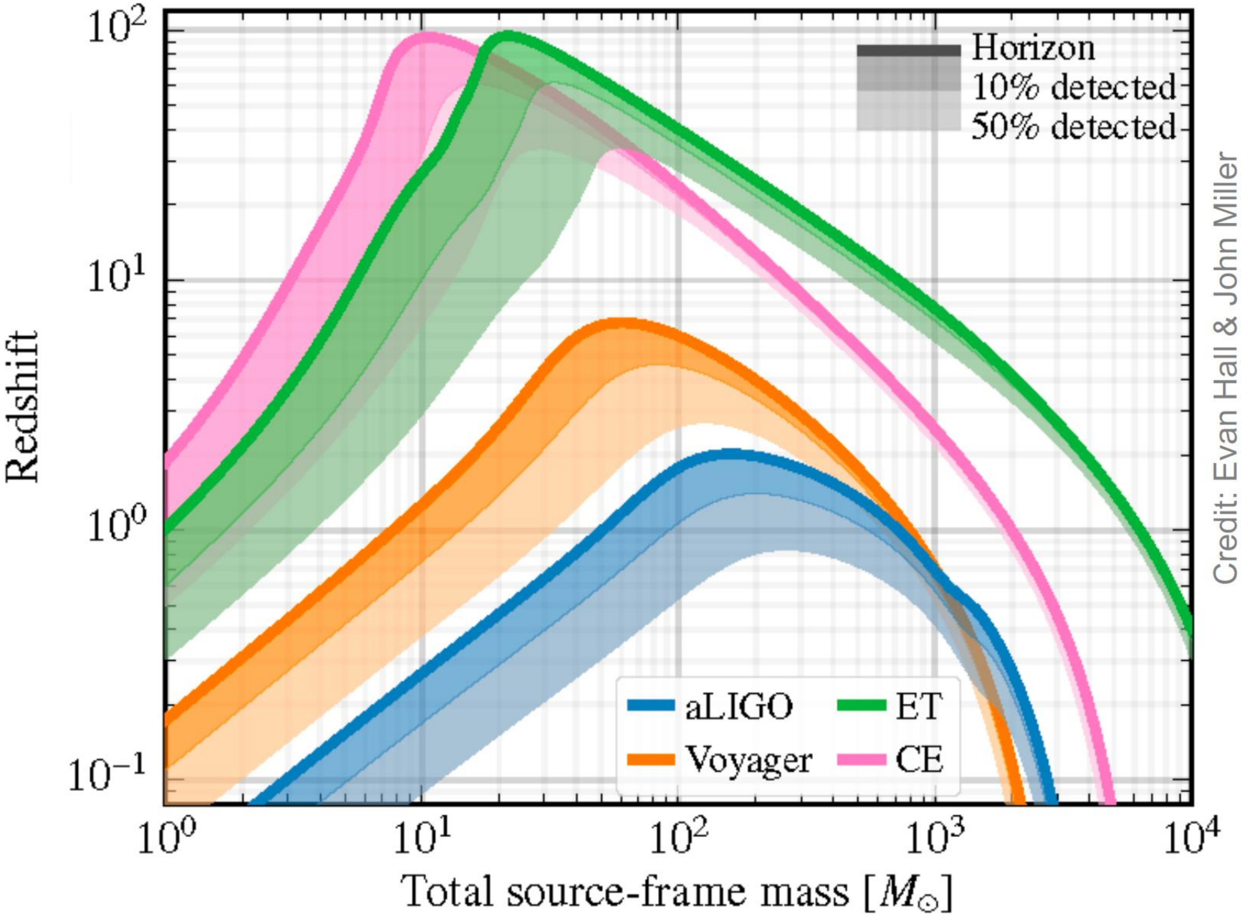


SEVENTH FRAMEWORK PROGRAMME



Einstein Telescope and Cosmic Explorer

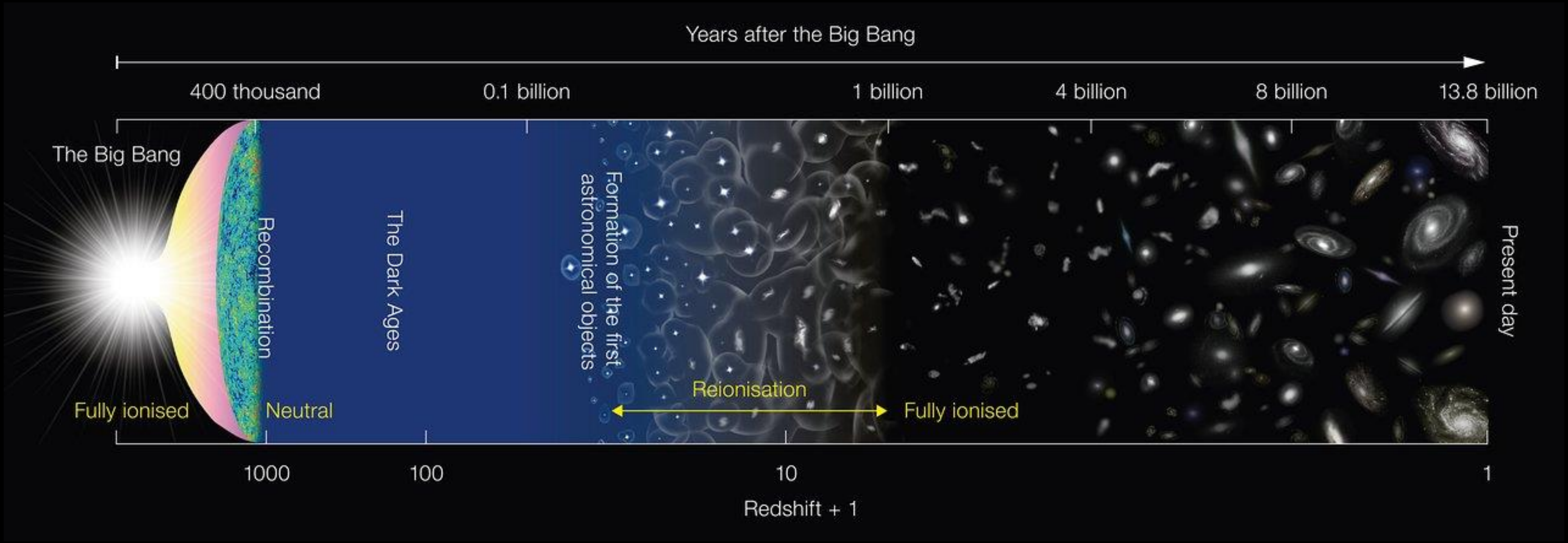
Einstein Telescope will feature excellent low-frequency sensitivity and have great discovery potential

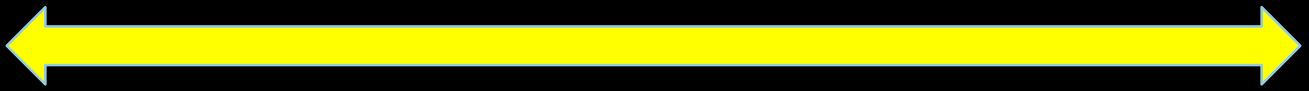


For science case, see https://www.dropbox.com/s/gihpzcue4qd92dt/science-case.pdf?dl=0

Einstein Telescope

Einstein Telescope can observe BBH mergers to red shifts of about 100. This allows a new approach to cosmography. Study primordial black holes, BH from population III stars (first metal producers), *etc*.





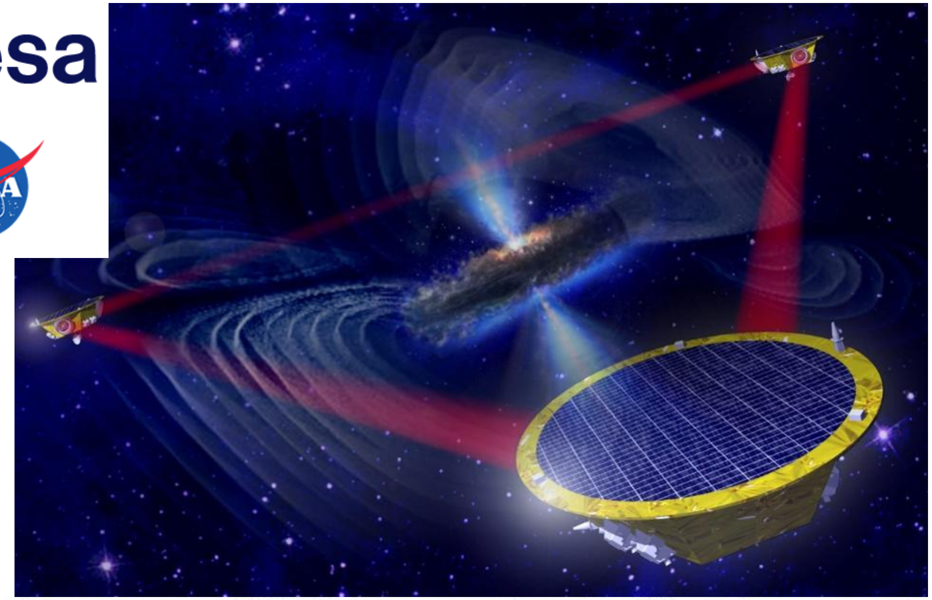
Einstein Telescope has direct access to signals from black hole mergers in this range

Bright future for gravitational wave research

LIGO and Virgo are operational. KAGRA in Japan joins this year, LIGO-India under construction. ESA launches LISA in 2034. Einstein Telescope and CE CDRs financed. Strong support by APPEC

Gravitational wave research

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



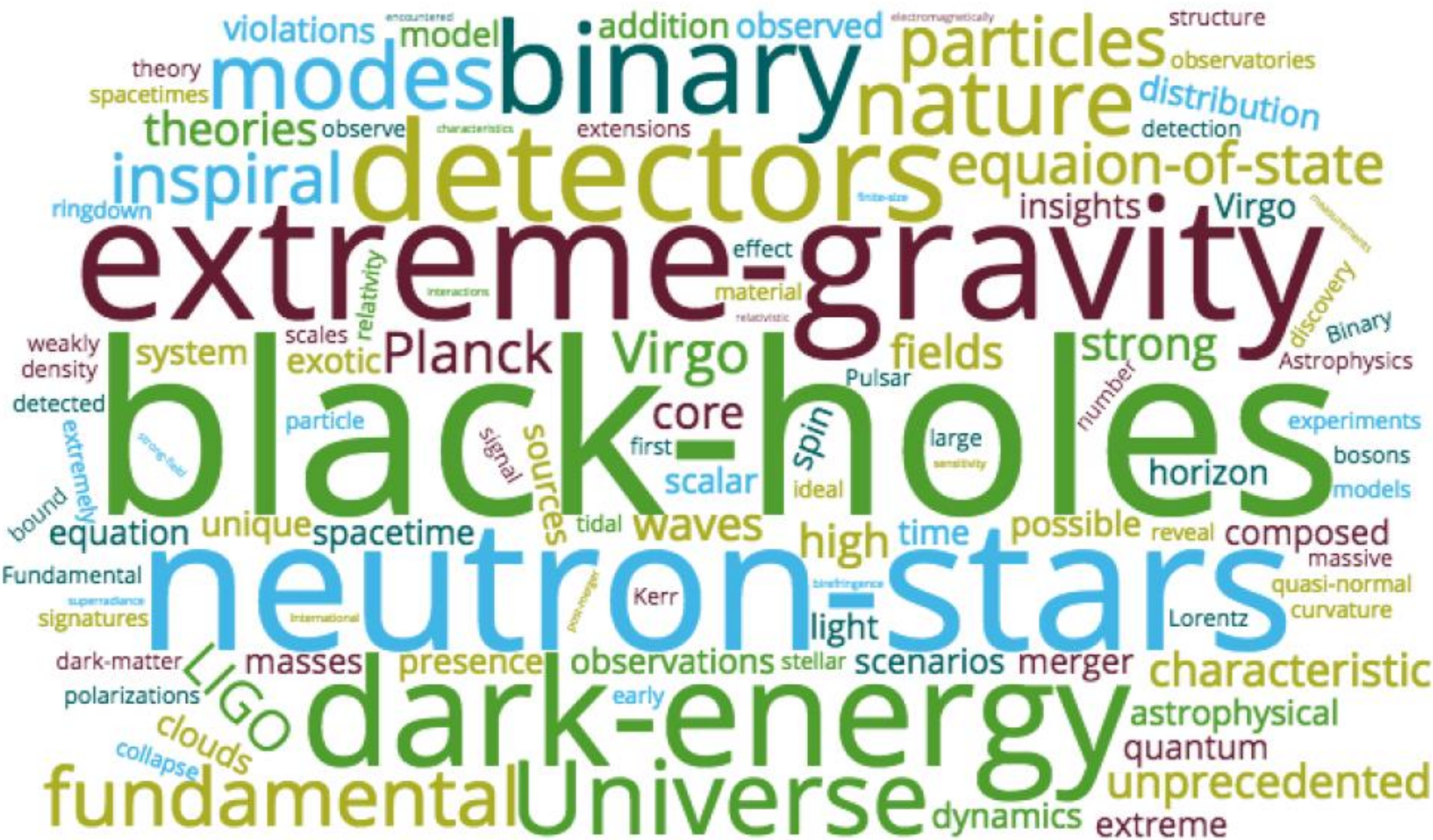
Einstein Telescope and Cosmic Explorer

- CDR ET financed by EU in FP7, CE by NSF
- 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 (2020)
- Support 3G: http://www.et-gw.eu/index.php/letter-of-intent

Questions?



extreme-gravity
black-holes
neutron-stars
dark-energy
detectors
binary
modes
particles
nature
Universe
fundamental
equaion-of-state
inspiral
theories
violations
model
addition
observed
structure
observatories
distribution
detection
theory
spacetimes
observe
extensions
ringdown
insights
Virgo
effect
material
relativity
weakly
density
system
scales
exotic
Planck
Virgo
fields
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Pulsar
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time
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curvature
signatures
Kerr
light
Lorentz
dark-matter
LIGO
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presence
observations
stellar
scenarios
merger
characteristic
polarizations
early
astrophysical
clouds
collapse
quantum
unprecedented
dynamics
extreme