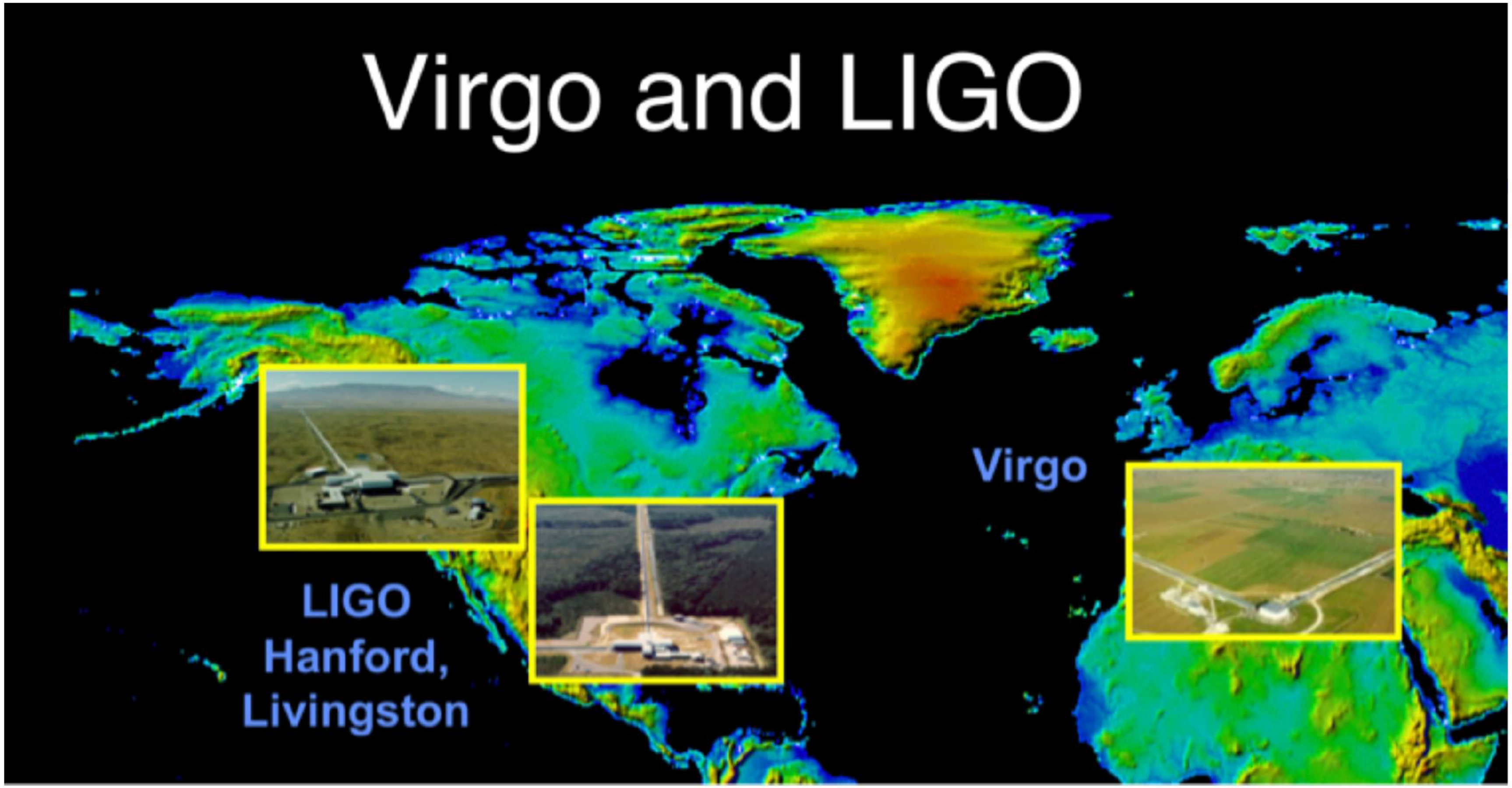
Astrofisica Nucleare e Subnucleare

Gravitational Waves

LIGO and Virgo detector joint data taking in August 2017

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

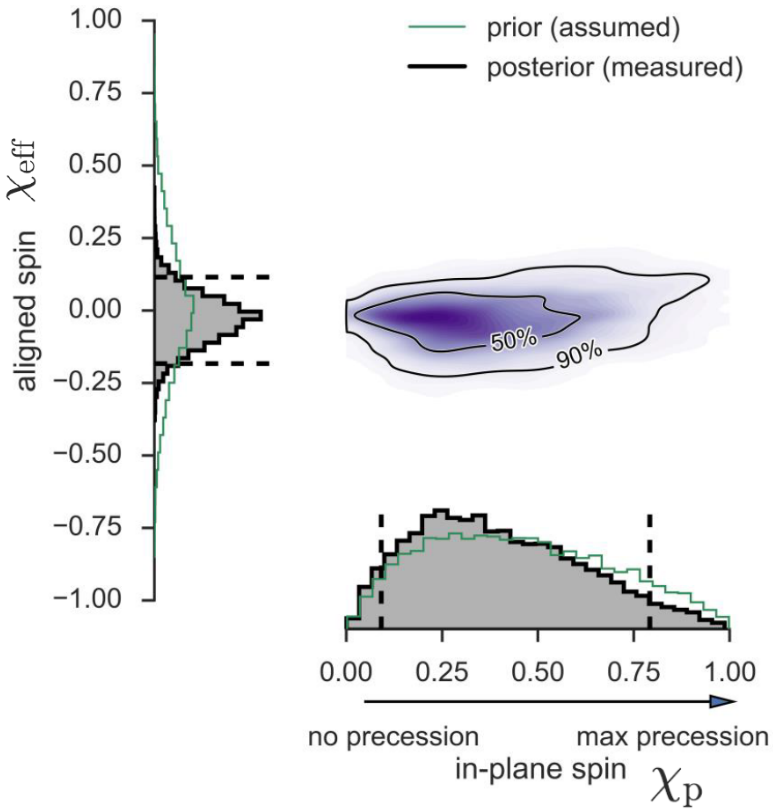
LIGO and Virgo have coordinated data taking and analysis, and release joint publications
LIGO and Virgo work under an MOU already for more than a decade
KAGRA in Japan is expected to join in 2019. LIGO India will join in 2024



Astrofisica Nucleare e Subnucleare
Gravitational Waves Science

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



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

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

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

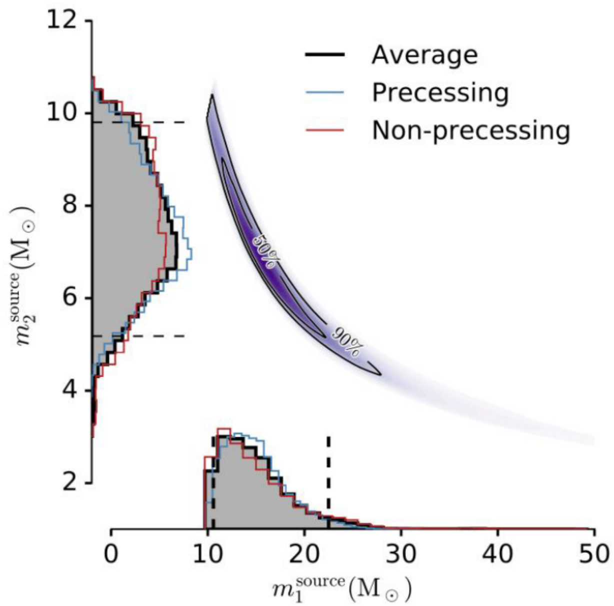
Properties of GW151226

GW151226 has lower mass than GW150914… and non-zero spin!

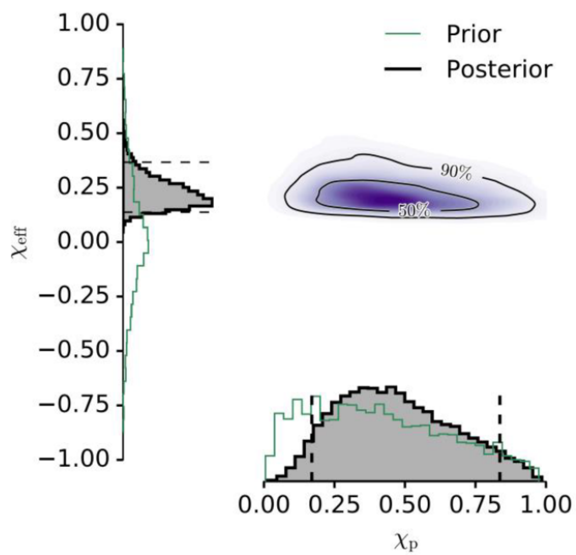
[Abbott et al. 2016, PRL 116, 241103]

Initial masses: $14.2\,^{+8.3}_{-3.7}$ and $7.5 \pm 2.3\ M_\odot$
Final BH mass: $20.8\,^{+6.1}_{-1.7}\ M_\odot$
Energy radiated: $1.0\,^{+0.1}_{-0.2}\ M_\odot c^2$

Luminosity distance: $440\,^{+180}_{-190}$ Mpc



Effective signed spin combination definitely positive
⇒ at least one of the initial BHs has nonzero spin
(we can't tell how the spin is divided up between them due to waveform degeneracy)



Publications of the LIGO Scientific Collaboration and Virgo Collaboration

Note: The LSC and Virgo collaborations have been co-authoring observational result papers since 2010. Beginning in 2021, the KAGRA collaboration too is co-authoring observational results from the full O3 run.

Highlighting: Event discoveries Multi-messenger

Click on any keyword to filter on that keyword | Click to toggle doi information | BibTeX file for these papers

Release Date	Title	Keywords (clear filter)	Science Summary	Journal citation	arXiv Preprint	Public DCC
Mar 21, 2022 *Recent*	**Search for gravitational waves associated with Fast Radio Bursts Detected by CHIME/FRB During the LIGO-Virgo Observing Run O3a** (*by LSC, Virgo and KAGRA*)	O3 FRBs	summary	*Submitted to ApJ*	2203.12038	P2100124
Mar 2, 2022 *Recent*	**First international joint observation of an underground gravitational-wave observatory, KAGRA, with GEO 600** (*by LSC, Virgo and KAGRA*)	O3 CBC Burst	summary	*Submitted to PTEP*	2203.01270	P2100286
Jan 25, 2022	**Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to PRD*	2201.10104	P2100405
Jan 3, 2022	**All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO and Advanced Virgo O3 data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to PRD*	2201.00697	P2100367
Dec 21, 2021	**Narrowband searches for continuous and long-duration transient gravitational waves from known pulsars in the LIGO-Virgo third observing run** (*by LSC, Virgo, KAGRA plus 28 radio astronomers and NICER science team members*)	O3 CW	summary	*Accepted by ApJ*	2112.10990	P2100267
Dec 13, 2021	**Tests of General Relativity with GWTC-3** (*by LSC, Virgo and KAGRA*)	O3 CBC TGR	summary	*Submitted to PRD*	2112.06861	P2100275
Nov 30, 2021	**Search of the Early O3 LIGO Data for Continuous Gravitational Waves from the Cassiopeia A and Vela Jr. Supernova Remnants** (*by LSC and Virgo*)	O3 CW	summary	*Accepted by PRD*	2111.15116	P2100298
Nov 30, 2021	**All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to PRD*	2111.15507	P2100343
Nov 25, 2021	**Searches for Gravitational Waves from Known Pulsars at Two Harmonics in the Second and Third LIGO-Virgo Observing Runs** (*by LSC, Virgo and KAGRA*)	O3 CW	summary	*Submitted to ApJ*	2111.13106	P2100049
Nov 7, 2021	**Constraints on the cosmic expansion history from the third LIGO-Virgo-KAGRA Gravitational-Wave Transient Catalog** (*by LSC, Virgo and KAGRA*)	O3 Cosmology	summary	*Submitted to ApJ*	2111.03604	P2100185
Nov 7, 2021	**GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run** (*by LSC, Virgo and KAGRA*)	O3 CBC GWTC	summary	*Submitted to PRX*	2111.03606	P2000318

https://pnp.ligo.org/ppcomm/Papers.html

LIGO Scientific Collaboration

News | Detections | Our science explained | Multimedia | Educational resources | For researchers | About the LSC | LIGO Lab | Observing Plans

Intro to LIGO & Gravitational Waves | Science Summaries | Popular Articles | Frequently Asked Questions | Magazine | Advanced LIGO

SUMMARIES OF LSC/LVK SCIENTIFIC PUBLICATIONS

For each of our new research articles, we feature a summary of the paper's key points written for the general public. Simply click on any of the titles for an online version, or on the '[flyer]' links for a downloadable file in PDF format. Translations into several languages are also available for some of these summaries. Where not noted separately, translations can be accessed through their language acronyms (e.g. 'es' for Spanish, also see details in the sidebar) or from the top of the English online versions. Most recent papers, and their summaries, are written together by the LIGO Scientific Collaboration (LSC), the Virgo Collaboration and the KAGRA Collaboration, forming the LVK collaboration.

LATEST DETECTIONS

GWTC-3 (Nov 07, 2021)

GWTC-3, a third catalog of gravitational-wave detections [**flyer**]

Also in: Catalan [ca] | Chinese (simplified) [zh-Hans] | Chinese (traditional) [zh-Hant] | French [fr] | German [de] | Italian [it] | Japanese [ja] | Polish [pl] | Spanish [es]

Companion papers: (also available in some other languages):

- Uncovering the population properties of black holes and neutron stars following LIGO and Virgo's third observing run [**flyer**] | [fr] | [ja] | [pl] | [zh-Hant]
- Improving measurements of the cosmic expansion with gravitational waves [**flyer**] | [fr] | [el] | [es] | [ja] | [zh-Hant]
- Searching for quiet gravitational waves produced by gamma-ray bursts in O3b [**flyer**] | [fr] | [it] | [zh-Hant]
- Does Einstein's Theory of Gravity Hold Up to the Latest LIGO/Virgo/KAGRA Observations? (published Dec 13, 2021) [**flyer**] | [fr] | [el] | [it] | [zh-Hans]

GWTC-2.1 (Aug 02, 2021)

GWTC-2.1: Extended catalog of Binary Mergers Observed by LIGO and Virgo During the First Half of the Third Observing Run [**flyer**]

Also in: Italian [it] | Japanese [ja]

GW200105 and GW200115 (Jun 29, 2021)

A new source of gravitational waves: neutron star–black hole binaries [**flyer**]

Also in: Blackfoot [bla] | Catalan [ca] | Chinese (traditional) [zh-Hant] | French [fr] | German [de] | Greek [el] | Italian [it] | Japanese [ja] | Polish [pl] | Portuguese [pt] | Spanish [es]

LOOKING DOWN A DETECTOR ARM

Visitors at LIGO Hanford Observatory gaze down the site's X arm. Half of the 4-kilometer length of the arm is visible in the photo. (Credit: LIGO Laboratory)

TRANSLATIONS: LANGUAGE KEYS

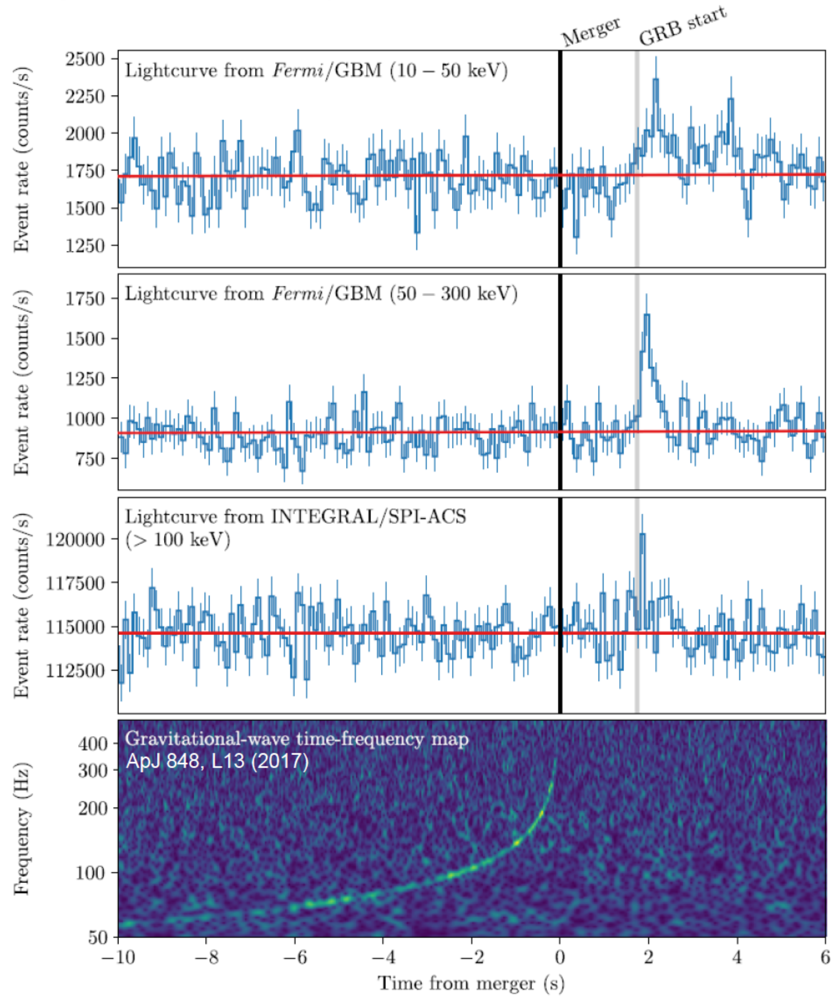
For most summaries, we list the available translations by their ISO 639-1 / ISO 639-2 keys, as listed below. Translations are a volunteer effort and different sets of languages are available for each summary. You can search for the key of your language, in square brackets – for instance [fr] for French – on this page to find all science summaries that have been translated into it.

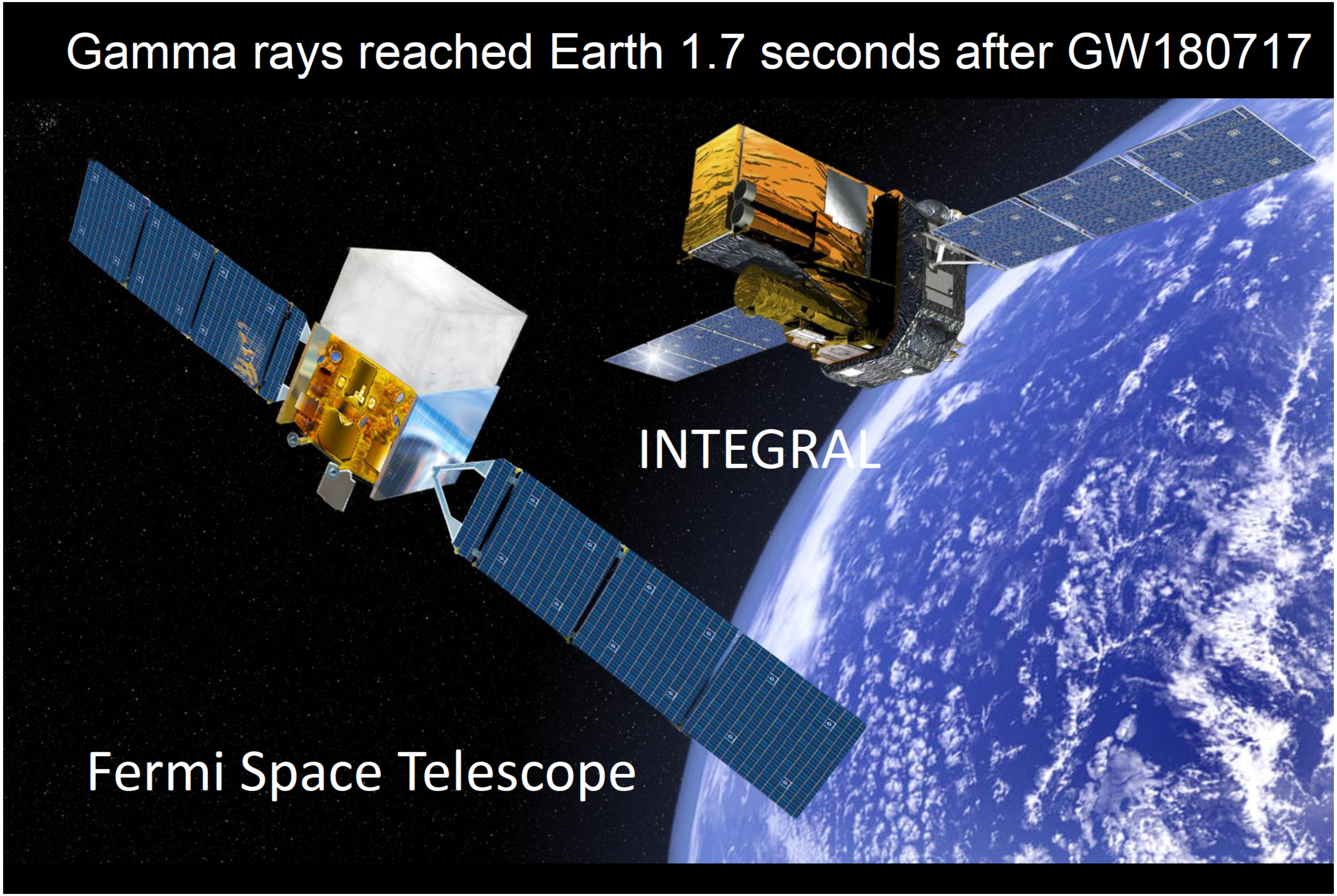
- **[bla]**: Blackfoot
- **[bn]**: Bengali (Bangla / বাংলা)
- **[ca]**: Catalan (Català)
- **[de]**: German (Deutsch)
- **[el]**: Greek (Ellinika / Ελληνικά)
- **[es]**: Spanish (Español / Castellano)
- **[fr]**: French (Français)

https://www.ligo.org/science/outreach.php

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




Gamma rays reached Earth 1.7 seconds after GW180717
INTEGRAL
Fermi Space Telescope

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

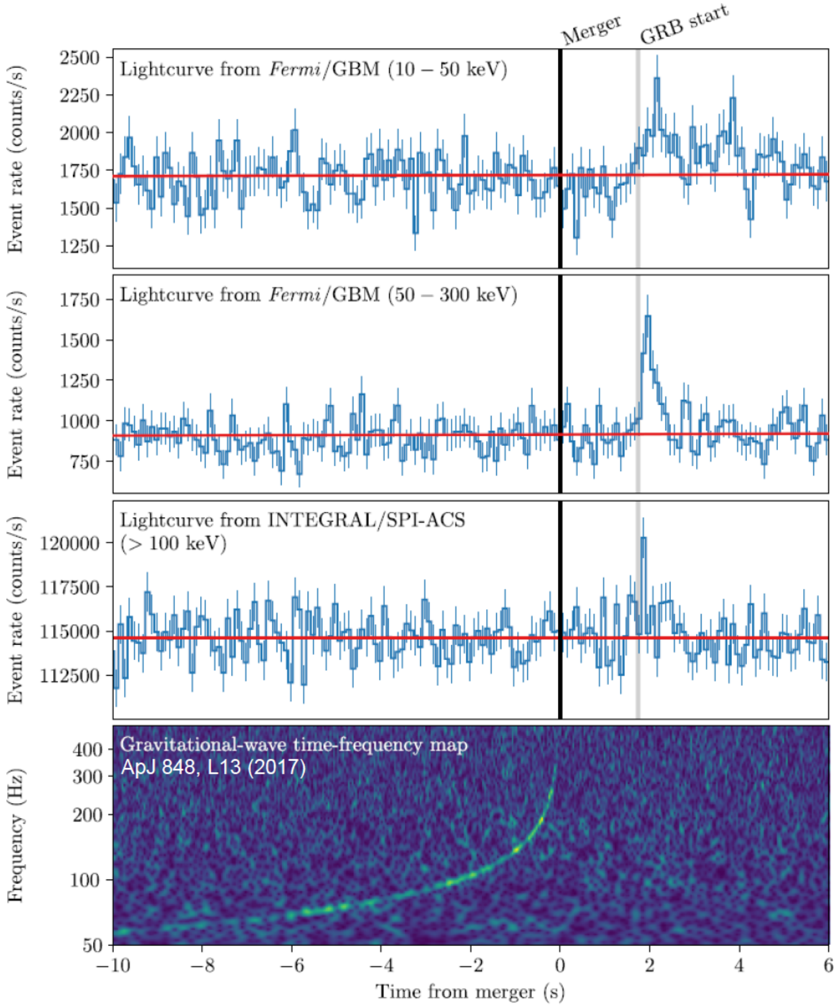
According to General Relativity, GW and EM waves are deflected and delayed by the curvature of spacetime produced by any mass (i.e. background gravitational potential). Shapiro delays affect both waves in the same manner

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

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

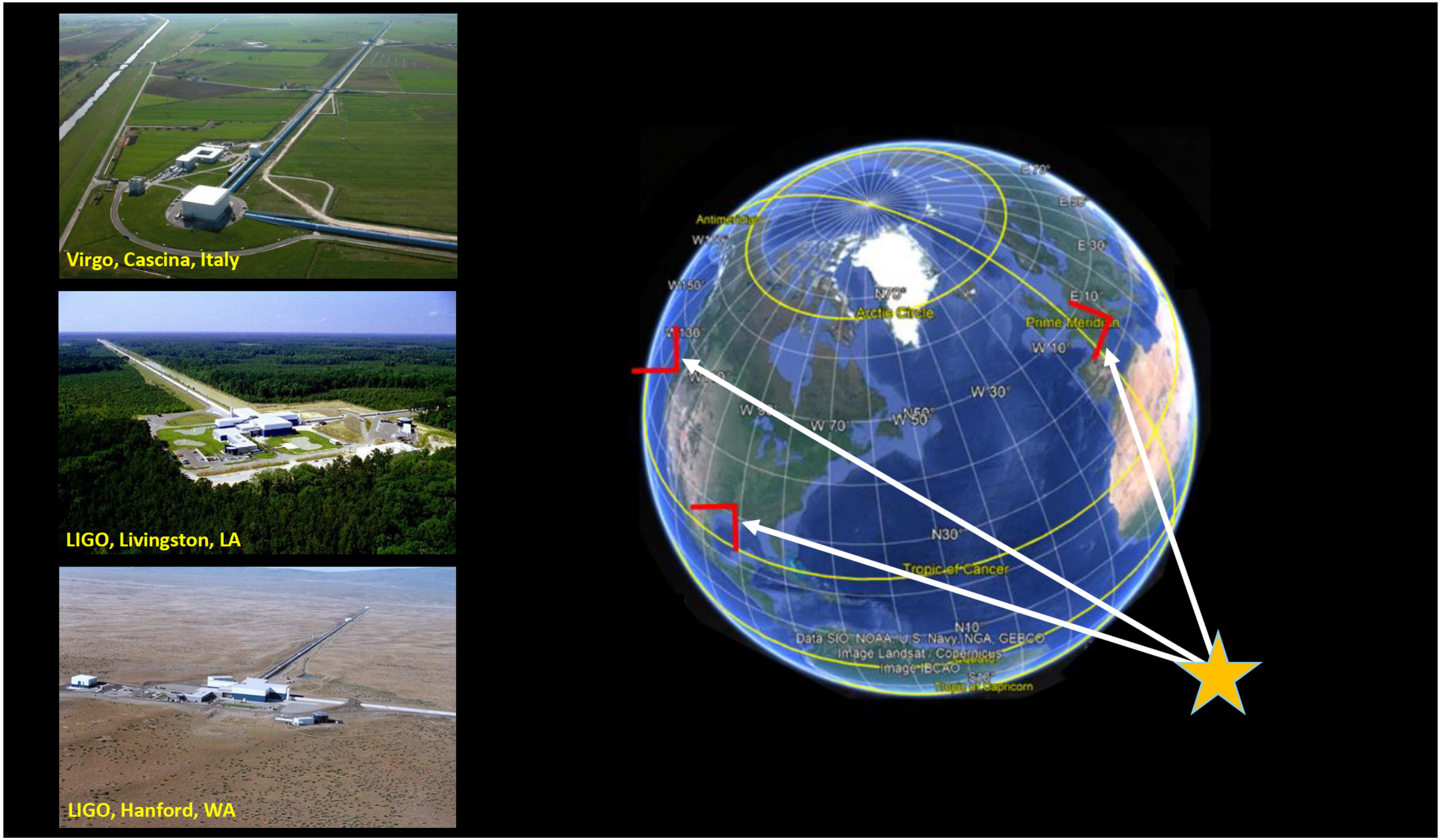
LIGO + Virgo + Fermi + INTEGRAL, ApJ 848, L13 (2017)



Consequences for some DM and DE models

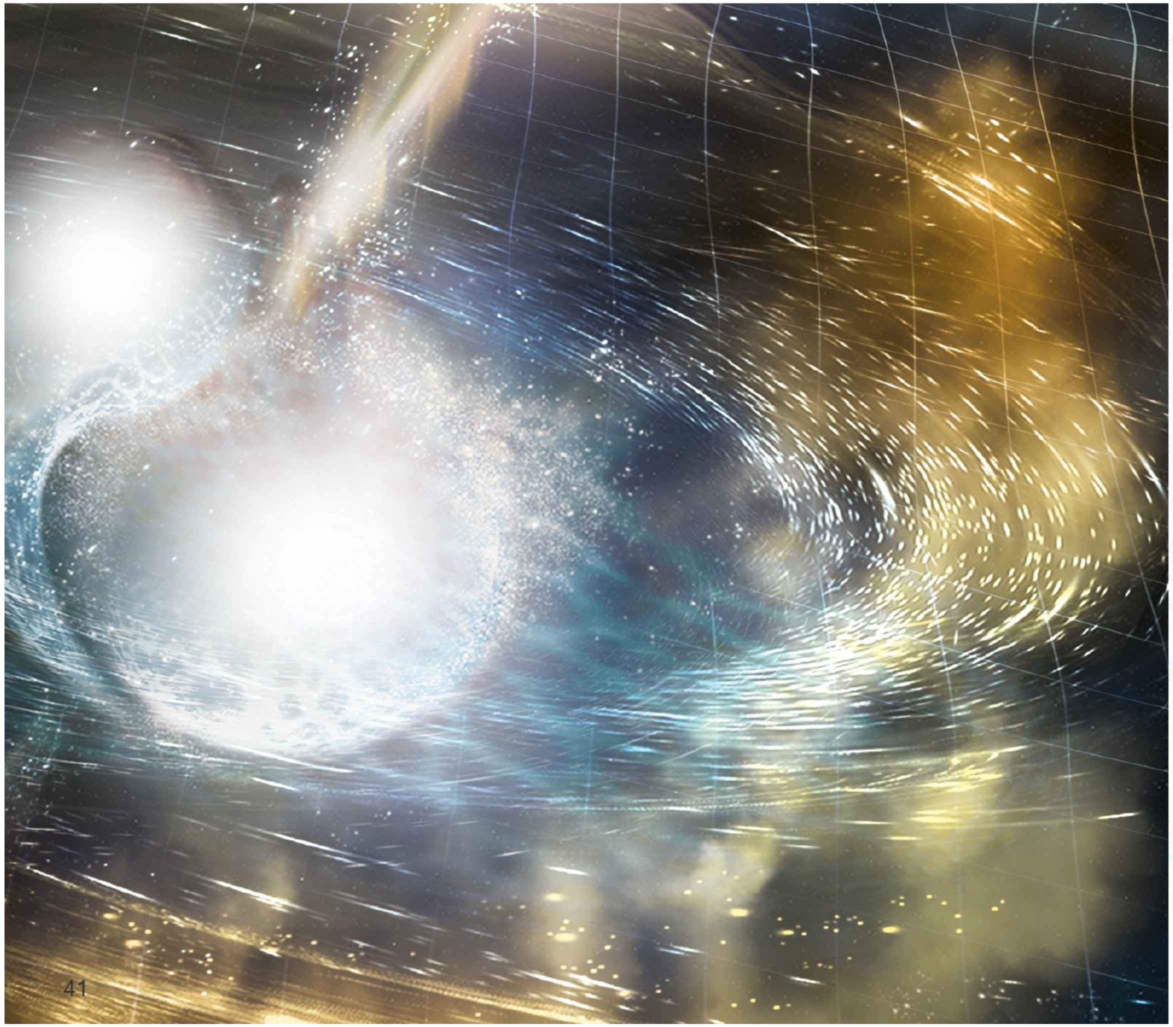
Source location via triangulation

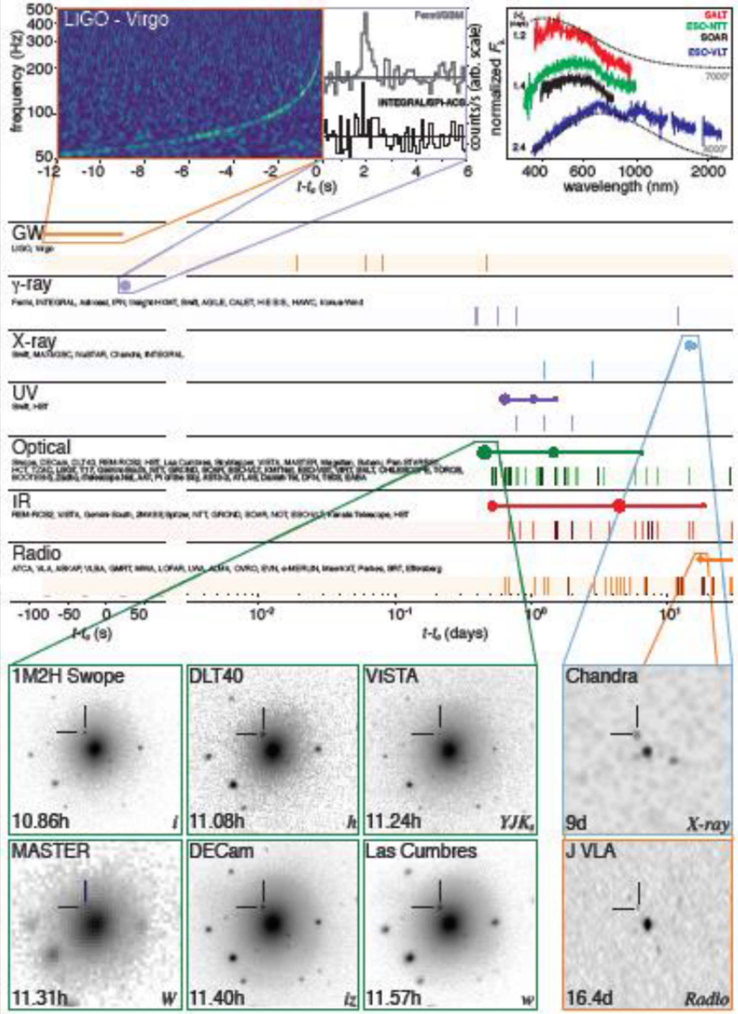
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it



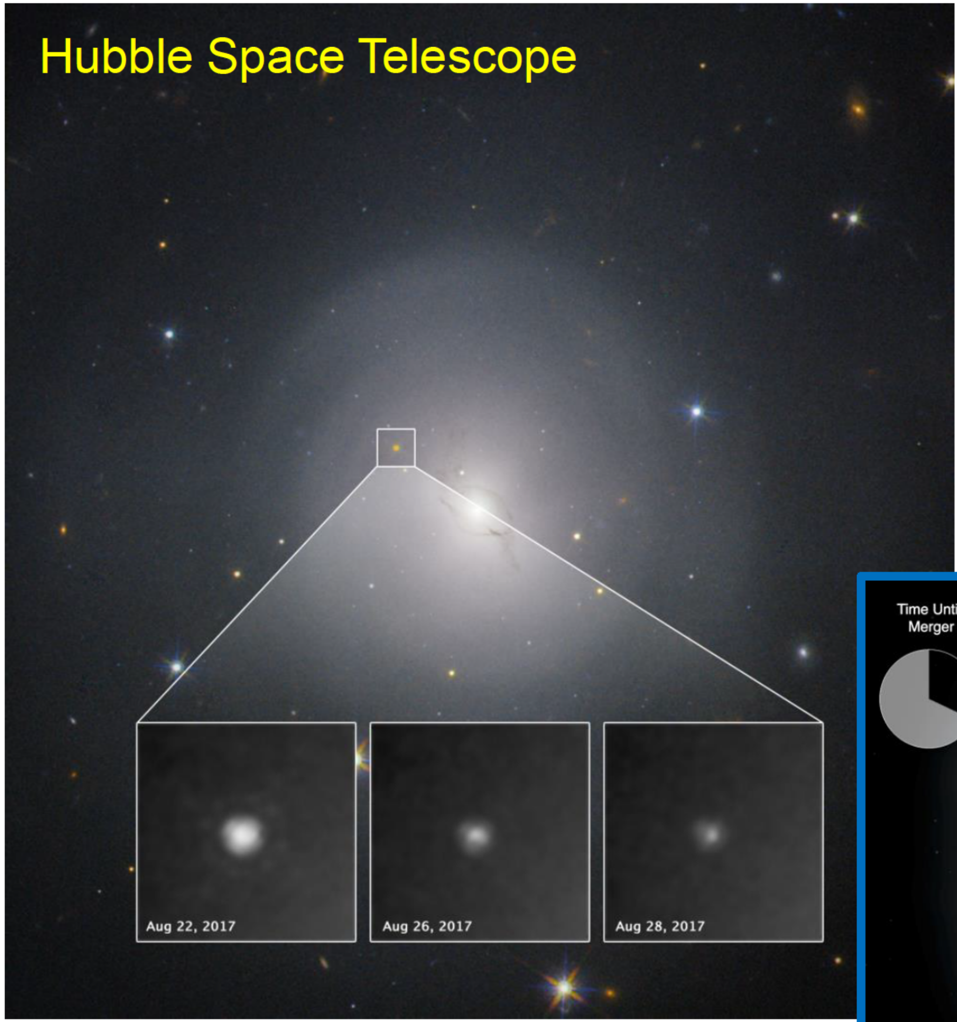
GW170817: start of multi-messenger astronomy with GW

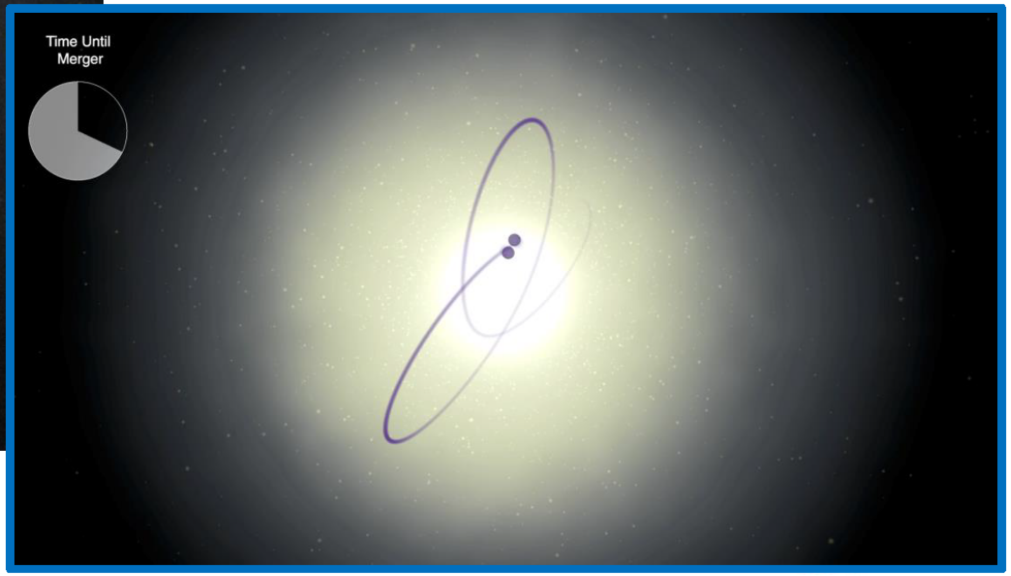
Many compact merger sources emit, besides gravitational waves, also light, gamma- and X-rays, and UV, optical, IR, and radio waves, as well as neutrino's or other subatomic particles. Our three-detector global network allows identifying these counterparts





NGC 4993 by HST: the galactic home of GW170817

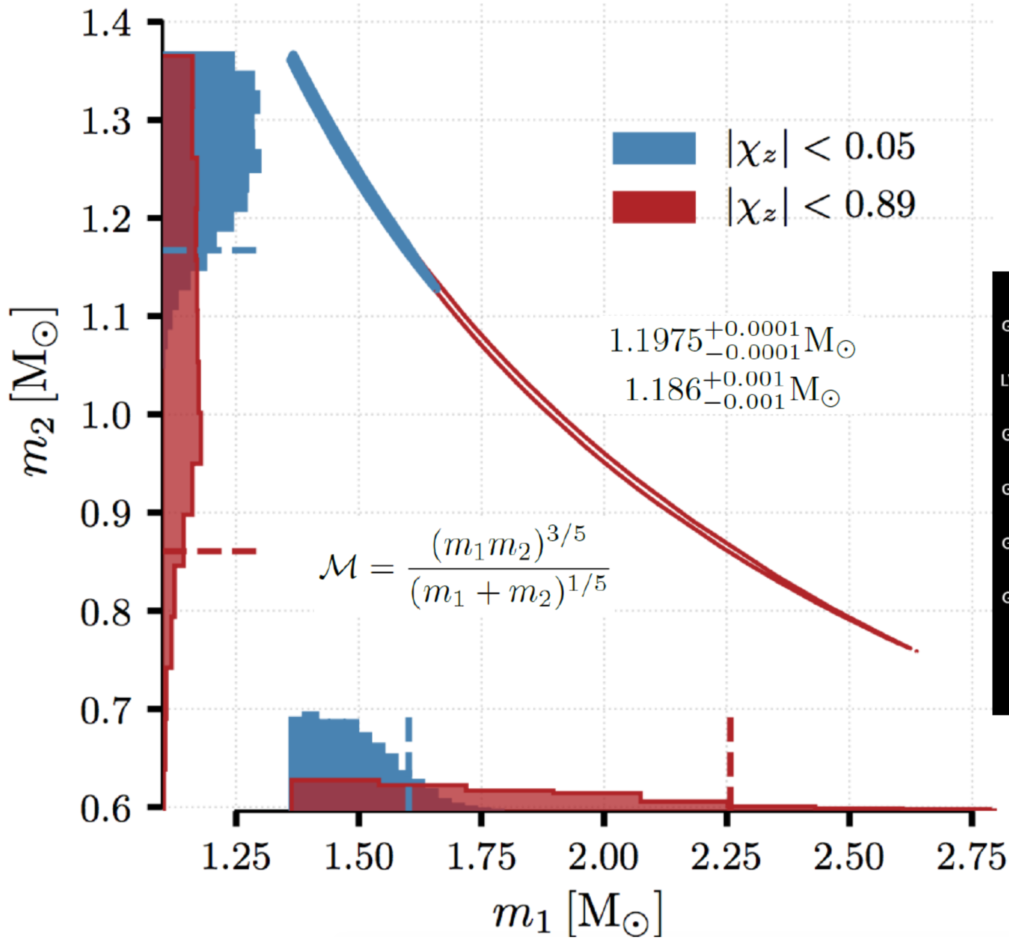




Inferring neutron star properties: masses

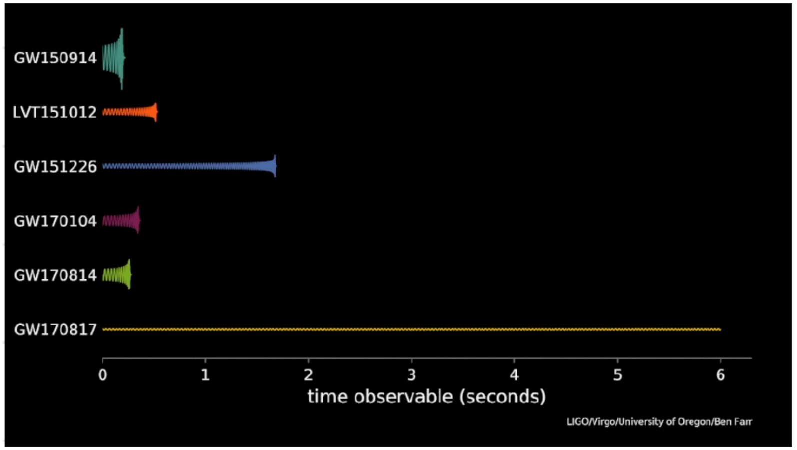
Early estimates now improved using known source location, improved waveform modeling, and re-calibrated Virgo data. Chirp mass can be inferred to high precision. There is a degeneracy between masses and spins

Observation of **binary pulsars** in our galaxy indicates spins are **not larger than ~0.04**



To lowest approximation $\tilde{h}(f) \propto e^{i\Psi(f)}$

with $\Psi(f) = \frac{3}{4}\left(\frac{G\mathcal{M}}{c^3}8\pi f\right)^{-5/3} + \ldots$



Abbott et al. PRL 119 (2017) 161101

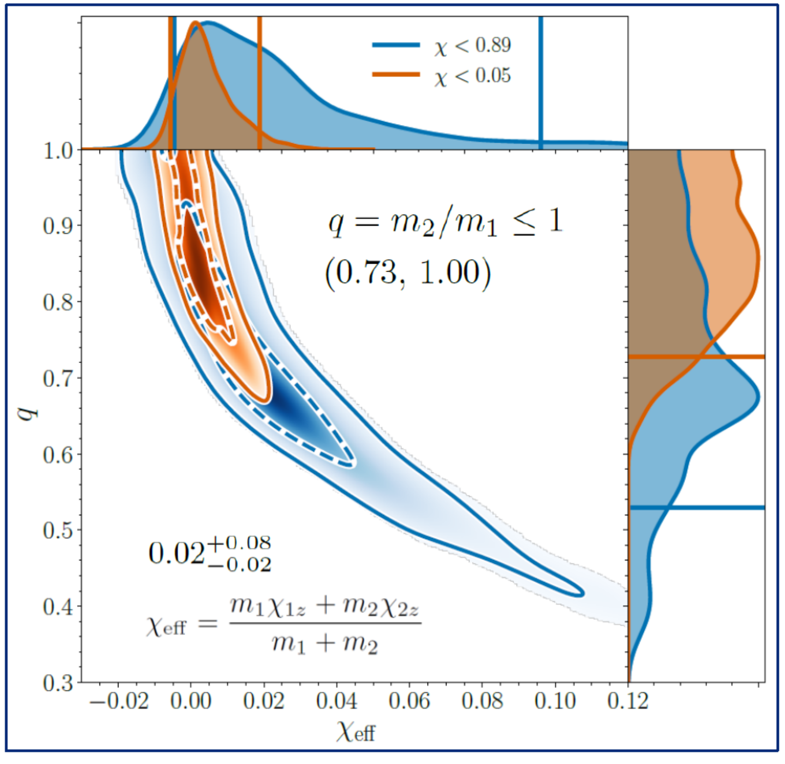
Inferring neutron star properties: spins

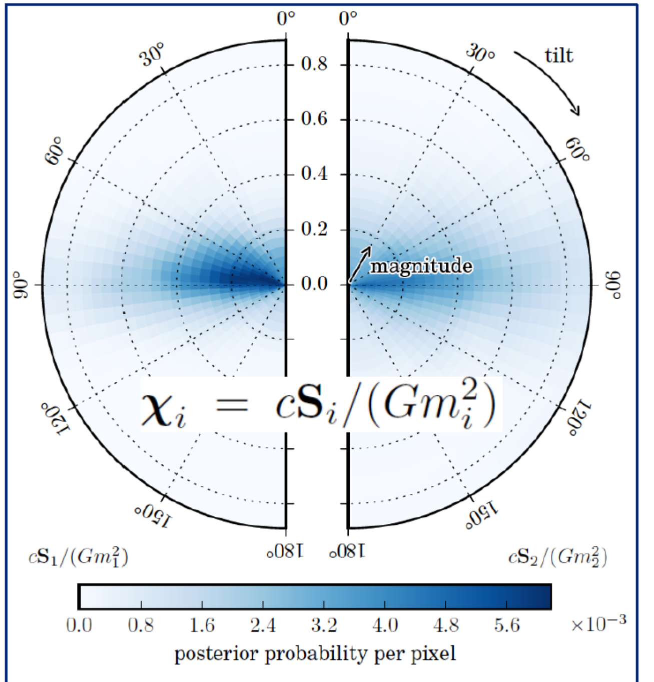
Constrains on mass ratio q, χ_{i} dimensionless spin, χ_{eff} effective spin, and χ_{p} effective spin precession parameter. See https://arxiv.org/abs/1805.11579

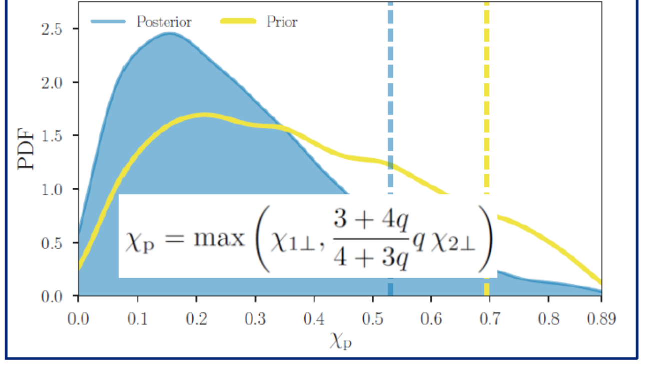
No evidence for NS spin

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

χ_{p} starts contributing at 2 PN





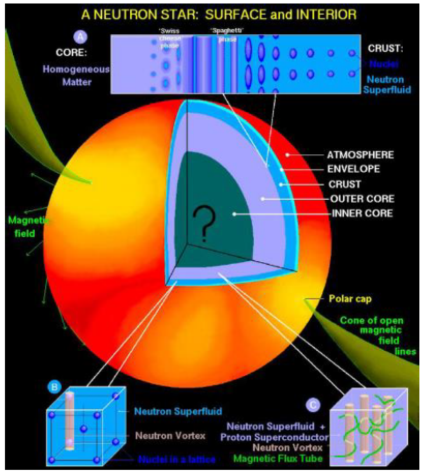


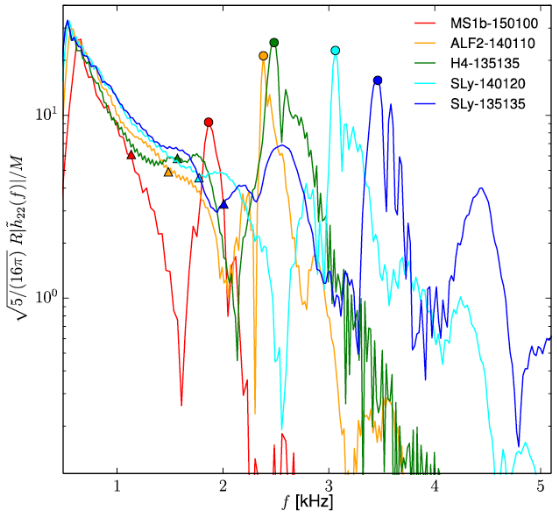
Solving an astrophysical conundrum

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

Structure of neutron stars?

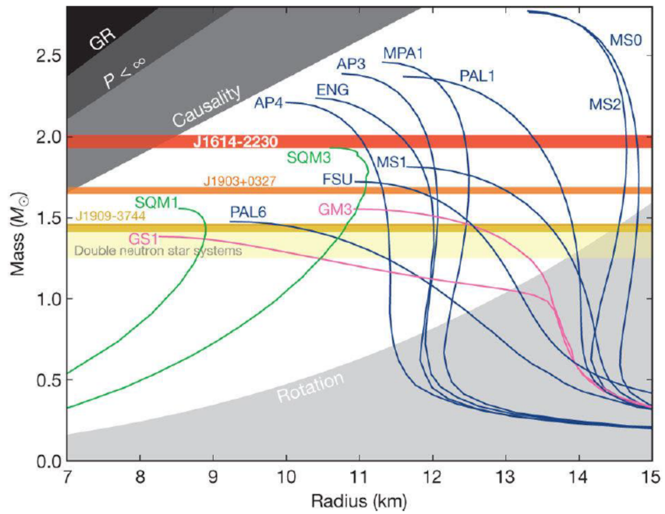
- Structure of the crust?
- Proton superconductivity
- Neutron superfluidity
- “Pinning” of fluid vortices to crust
- Origin of magnetic fields?
- More exotic objects?





Widely differing theoretical predictions for different equations of state

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



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

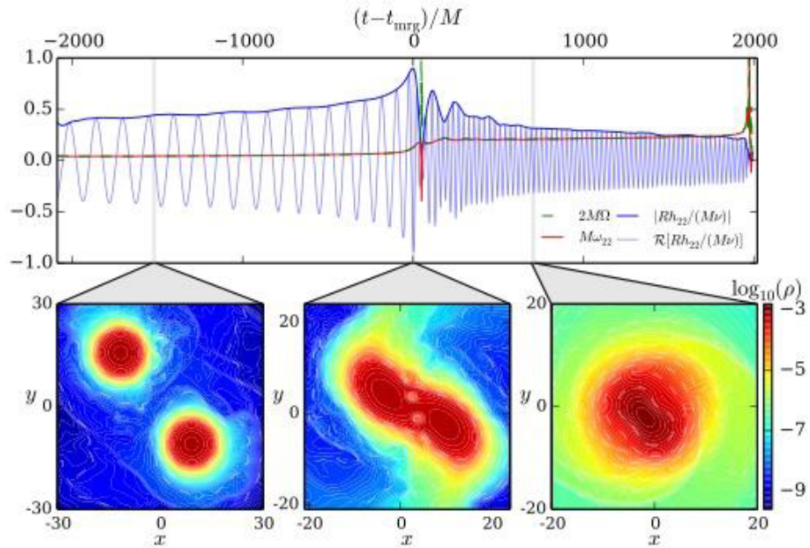
Bernuzzi *et al.*, PRL 115, 091101 (2015)

Probing the structure of neutron stars

Tidal effects leave their imprint on the gravitational wave signal from binary neutron stars. This provides information about their deformability. There is a strong need for more sensitive detectors

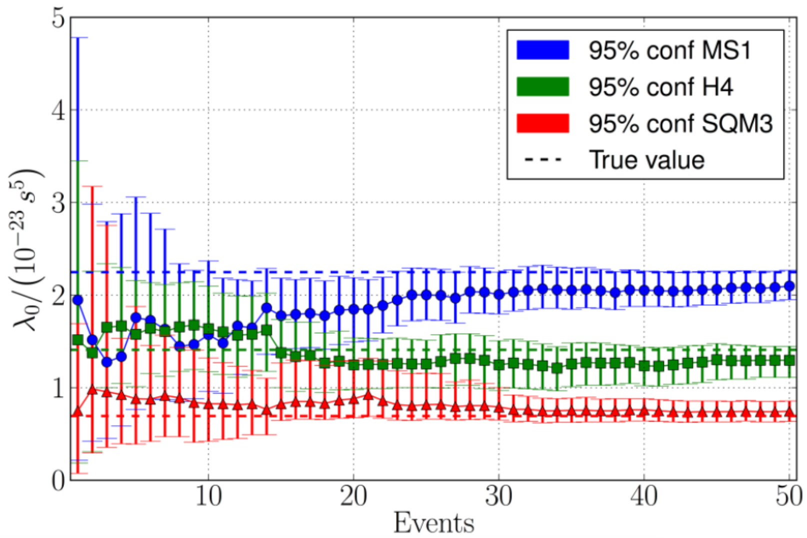
Gravitational waves from inspiraling binary neutron stars

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



Measurement of tidal deformations on GW170817

- More compact neutron stars favored
- “Soft” equation of state

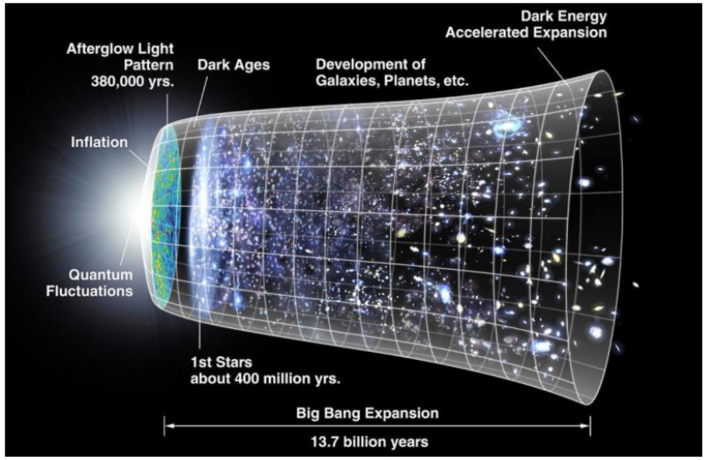


LIGO + Virgo, PRL 119, 161101 (2017)

Bernuzzi, Nagar, Font, …

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

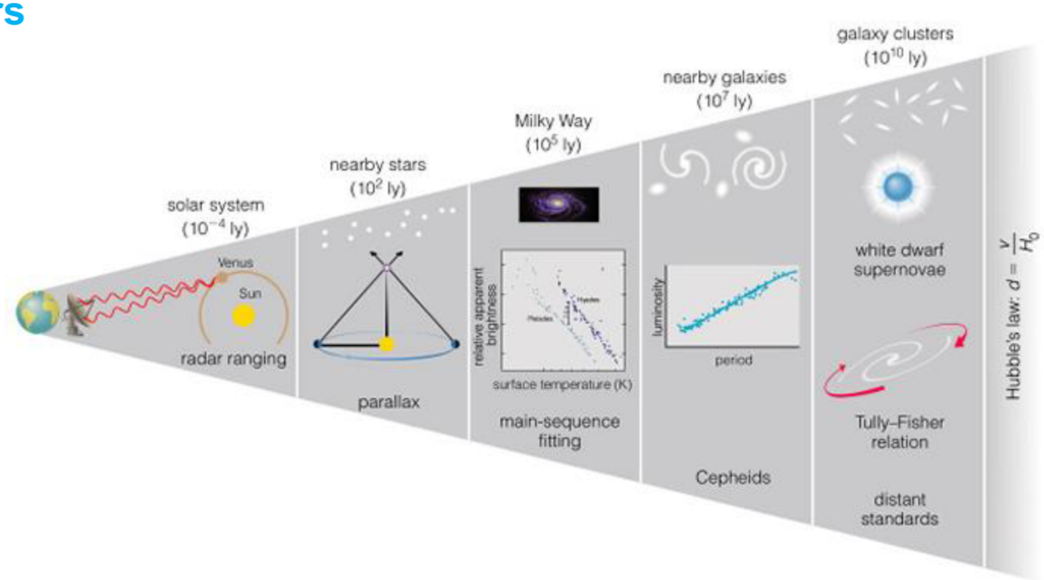


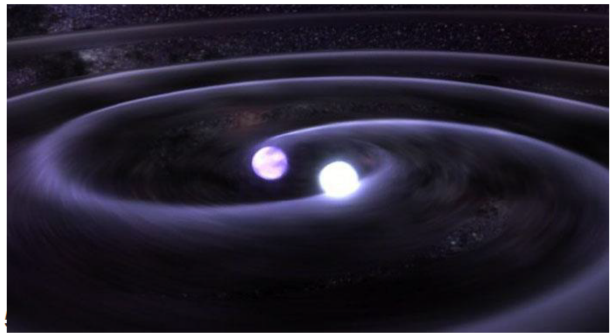
Current measurements depend on cosmic distance ladder

- 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

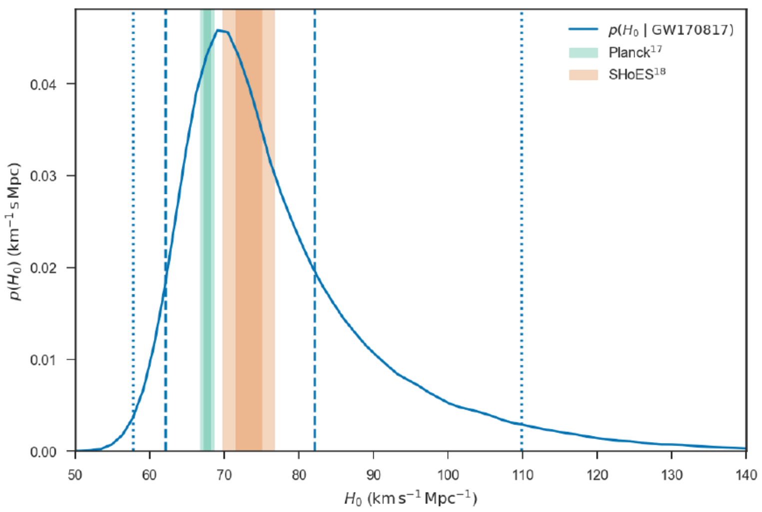
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1-2% accuracy

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)

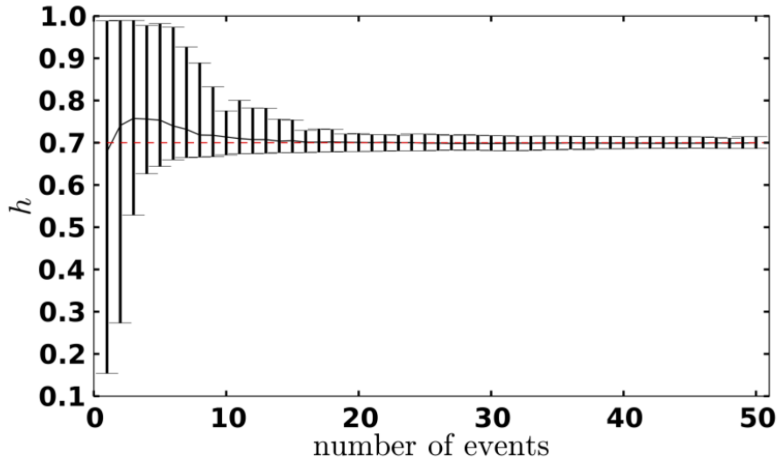


GW170817

- 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

Nobel Prize in Physics 2017

https://www.nobelprize.org/nobel_prizes/physics/laureates/2017/press.html

KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Press Release: The Nobel Prize in Physics 2017

3 October 2017

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2017 with one half to

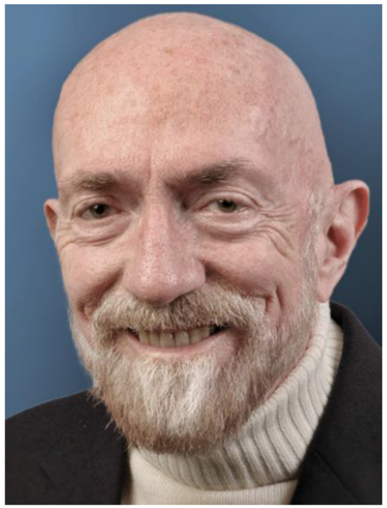
Rainer Weiss
LIGO/VIRGO Collaboration

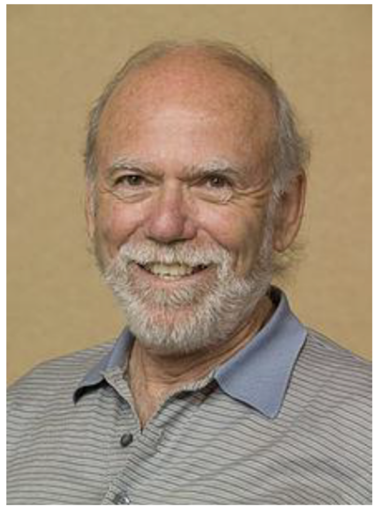
and the other half jointly to

Barry C. Barish
LIGO/VIRGO Collaboration

and

Kip S. Thorne
LIGO/VIRGO Collaboration



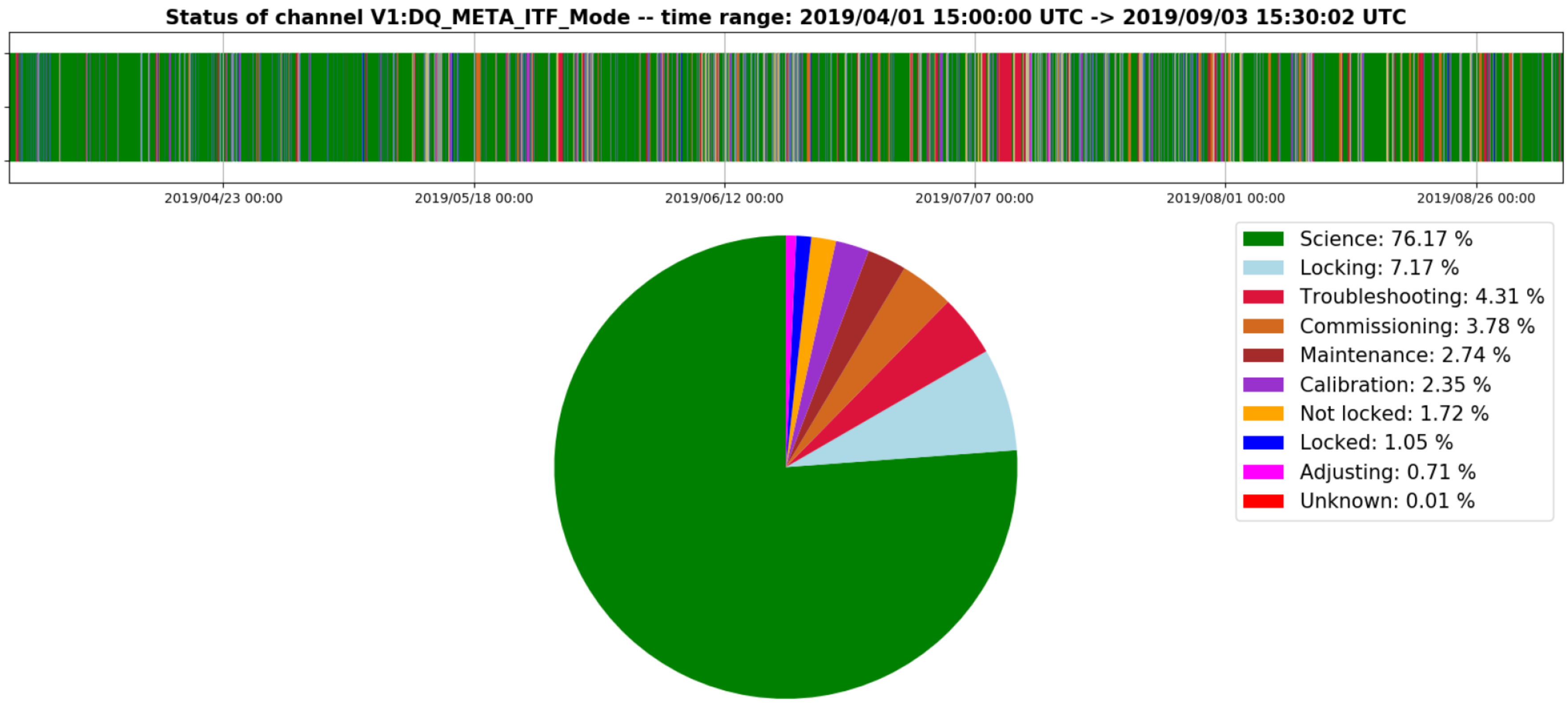


Special thanks to Virgo's founding fathers

Alain Brillet and Adalberto Giazotto

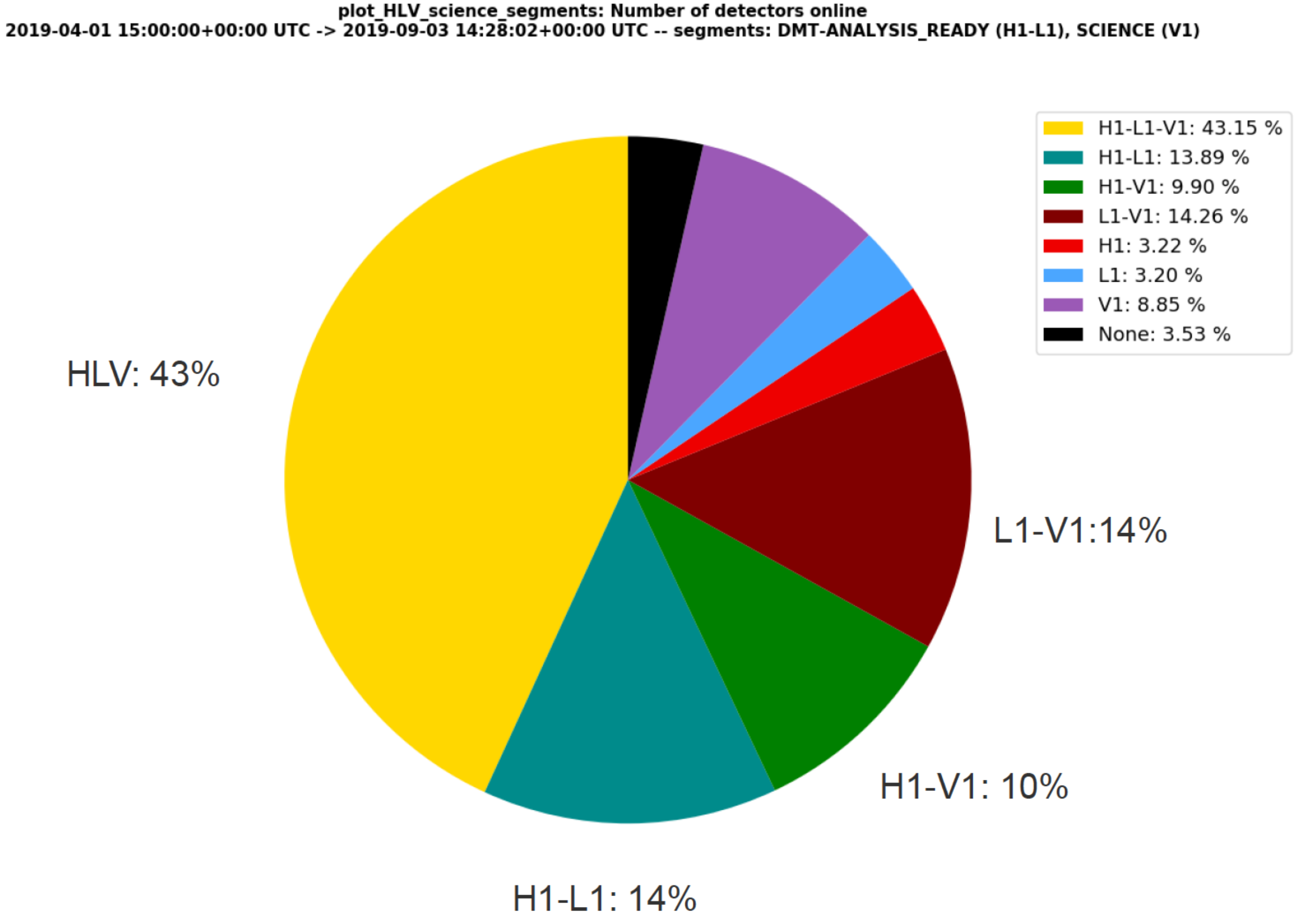
O3 Summary: efficiency

Science mode (green) for 76%. Significant time is now devoted to commissioning (orange). These activities are still ongoing with the focus on stability. Maintenance (brown) and calibration (purple) are other significant activities



O3 Summary: number of detectors online

H1-L1 double efficiency 57%, H1-L1-V1 double+triple efficiency 82%



https://gracedb.ligo.org/latest/

Already 33 (= 41 - 8) public alerts in the 3rd science run: more candidates than O1 and O2 combined

Latest — as of 10 October 2019 17:29:34 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

UTC

UID	Labels	t_start	t_0	t_end	FAR (Hz)	Created
S190930t	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253889264.685342	1253889265.685342	1253889266.685342	1.543e-08	2019-09-30 14:34:30 UTC
S190930s	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253885758.235347	1253885759.246810	1253885760.253734	3.008e-09	2019-09-30 13:36:04 UTC
S190928c	ADVNO EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1253671923.328316	1253671923.364500	1253671923.400684	6.729e-09	2019-09-28 02:14:18 UTC
S190924h	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253326743.785645	1253326744.846654	1253326745.876674	8.928e-19	2019-09-24 02:19:25 UTC
S190923y	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253278576.645077	1253278577.645508	1253278578.654868	4.783e-08	2019-09-23 12:56:22 UTC
S190915ak	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252627039.685111	1252627040.690891	1252627041.730049	9.735e-10	2019-09-15 23:57:25 UTC
S190910h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252139415.544299	1252139416.544448	1252139417.544448	3.584e-08	2019-09-10 08:30:21 UTC
S190910d	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252113996.241211	1252113997.242676	1252113998.264918	3.717e-09	2019-09-10 01:26:35 UTC
S190901ap	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251415878.837767	1251415879.837767	1251415880.838844	7.027e-09	2019-09-01 23:31:24 UTC
S190829u	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251147973.281494	1251147974.283940	1251147975.283940	5.151e-09	2019-08-29 21:06:19 UTC
S190828l	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251010526.884921	1251010527.886557	1251010528.913573	4.629e-11	2019-08-28 06:55:26 UTC
S190828j	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251009262.739486	1251009263.756472	1251009264.796332	8.474e-22	2019-08-28 06:34:21 UTC
S190822c	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1250472616.589125	1250472617.589203	1250472618.589203	6.145e-18	2019-08-22 01:30:23 UTC
S190816i	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249995888.757789	1249995889.757789	1249995890.757789	1.436e-08	2019-08-16 13:05:12 UTC
S190814bv	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249852255.996787	1249852257.012957	1249852258.021731	2.033e-33	2019-08-14 21:11:18 UTC
S190808ae	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249338098.496141	1249338099.496141	1249338100.496141	3.366e-08	2019-08-08 22:21:45 UTC
S190728q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248331527.497344	1248331528.546797	1248331529.706055	2.527e-23	2019-07-28 06:45:27 UTC
S190727h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248242630.976288	1248242631.985887	1248242633.180176	1.378e-10	2019-07-27 06:03:51 UTC
S190720a	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247616533.703127	1247616534.704102	1247616535.860840	3.801e-09	2019-07-20 00:08:53 UTC
S190718y	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247495729.067865	1247495730.067865	1247495731.067865	3.648e-08	2019-07-18 14:35:34 UTC
S190707q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246527223.118398	1246527224.181226	1246527225.284180	5.265e-12	2019-07-07 09:33:44 UTC
S190706ai	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246487218.321541	1246487219.344727	1246487220.585938	1.901e-09	2019-07-06 22:26:57 UTC
S190701ah	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246048403.576563	1246048404.577637	1246048405.814941	1.916e-08	2019-07-01 20:33:24 UTC
S190630ag	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1245955942.175325	1245955943.179550	1245955944.183184	1.435e-13	2019-06-30 18:52:28 UTC
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

https://gracedb.ligo.org/superevents/public/O3/

Already 41 public alerts in the 3rd science run: more candidate events than O1 and O2 combined

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190822c	BNS (>99%)	Aug. 22, 2019 01:29:59 UTC	GCN Circulars Notices | VOE		1 per 5.1566e+09 years	RETRACTED
S190816i	NSBH (83%), Terrestrial (17%)	Aug. 16, 2019 13:04:31 UTC	GCN Circulars Notices | VOE		1 per 2.2067 years	RETRACTED
S190814bv	NSBH (>99%)	Aug. 14, 2019 21:10:39 UTC	GCN Circulars Notices | VOE		1 per 1.559e+25 years	
S190808ae	Terrestrial (57%), BNS (43%)	Aug. 8, 2019 22:21:21 UTC	GCN Circulars Notices | VOE		1.0622 per year	RETRACTED
S190728q	BBH (95%), MassGap (5%)	July 28, 2019 06:45:10 UTC	GCN Circulars Notices | VOE		1 per 1.2541e+15 years	
S190727h	BBH (92%), Terrestrial (5%), MassGap (3%)	July 27, 2019 06:03:33 UTC	GCN Circulars Notices | VOE		1 per 229.92 years	
S190720a	BBH (99%), Terrestrial (1%)	July 20, 2019 00:08:36 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190718y	Terrestrial (98%), BNS (2%)	July 18, 2019 14:35:12 UTC	GCN Circulars Notices | VOE		1.1514 per year	
S190707q	BBH (>99%)	July 7, 2019 09:33:26 UTC	GCN Circulars Notices | VOE		1 per 6018.9 years	
S190706ai	BBH (99%), Terrestrial (1%)	July 6, 2019 22:26:41 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190701ah	BBH (93%), Terrestrial (7%)	July 1, 2019 20:33:06 UTC	GCN Circulars Notices | VOE		1 per 1.6543 years	
S190630ag	BBH (94%), MassGap (5%)	June 30, 2019 18:52:05 UTC	GCN Circulars Notices | VOE		1 per 2.2077e+05 years	
S190602aq	BBH (99%)	June 2, 2019 17:59:27 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190524q	Terrestrial (71%), BNS (29%)	May 24, 2019 04:52:06 UTC	GCN Circulars Notices | VOE		1 per 4.5458 years	RETRACTED
S190521r	BBH (>99%)	May 21, 2019 07:43:59 UTC	GCN Circulars Notices | VOE		1 per 100.04 years	
S190521g	BBH (97%), Terrestrial (3%)	May 21, 2019 03:02:29 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190519bj	BBH (96%), Terrestrial (4%)	May 19, 2019 15:35:44 UTC	GCN Circulars Notices | VOE		1 per 5.5578 years	
S190518bb	BNS (75%), Terrestrial (25%)	May 18, 2019 19:19:19 UTC	GCN Circulars Notices | VOE		1 per 3.1557 years	RETRACTED
S190517h	BBH (98%), MassGap (2%)	May 17, 2019 05:51:01 UTC	GCN Circulars Notices | VOE		1 per 13.354 years	
S190513bm	BBH (94%), MassGap (5%)	May 13, 2019 20:54:28 UTC	GCN Circulars Notices | VOE		1 per 84864 years	
S190512at	BBH (99%), Terrestrial (1%)	May 12, 2019 18:07:14 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190510g	Terrestrial (58%), BNS (42%)	May 10, 2019 02:59:39 UTC	GCN Circulars Notices | VOE		1 per 3.5872 years	
S190503bf	BBH (96%), MassGap (3%)	May 3, 2019 18:54:04 UTC	GCN Circulars Notices | VOE		1 per 19.368 years	
S190426c	BNS (49%), MassGap (24%), Terrestrial (14%), NSBH (13%)	April 26, 2019 15:21:55 UTC	GCN Circulars Notices | VOE		1 per 1.6276 years	
S190425z	BNS (>99%)	April 25, 2019 08:18:05 UTC	GCN Circulars Notices | VOE		1 per 69834 years	
S190421ar	BBH (97%), Terrestrial (3%)	April 21, 2019 21:38:56 UTC	GCN Circulars Notices | VOE		1 per 2.1285 years	
S190412m	BBH (>99%)	April 12, 2019 05:30:44 UTC	GCN Circulars Notices | VOE		1 per 1.883e+19 years	
S190408an	BBH (>99%)	April 8, 2019 18:18:02 UTC	GCN Circulars Notices | VOE		1 per 1.1273e+10 years	
S190405ar	Terrestrial (>99%)	April 5, 2019 16:01:30 UTC	GCN Circulars Notices | VOE		6756.4 per year	IMPORTANT: this trigger (S190405ar) is not considered to be astrophysical in o issued but the event ID was truncated to S190405a due to a bug. RETRACTED

https://gracedb.ligo.org/superevents/public/O3/

Black holes are now seen at distances up to 3.9 - 6.7 Gpc (redshift 0.9 - 1.6)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
RETRACTED Terrestial noise						
NSBH (99%)						
RETRACTED						
S190728q	BBH (95%), MassGap (5%)	July 28, 2019 06:45:10 UTC	GCN Circulars Notices | VOE		1 per 1.2541e+15 years	
S190727h	BBH (92%), Terrestrial (5%), MassGap (3%)	July 27, 2019 06:03:33 UTC	GCN Circulars Notices | VOE		1 per 229.92 years	
S190720a	BBH (99%), Terrestrial (1%)	July 20, 2019 00:08:36 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190718y	Terrestrial (98%), BNS (2%)	July 18, 2019 14:35:12 UTC	GCN Circulars Notices | VOE		1.1514 per year	
S190707q	BBH (>99%)	July 7, 2019 09:33:26 UTC	GCN Circulars Notices | VOE		1 per 6018.9 years	
BBH (99%) at 0.9 < z < 1.6						
S190701ah	BBH (93%), Terrestrial (7%)	July 1, 2019 20:33:06 UTC	GCN Circulars Notices | VOE		1 per 1.6543 years	
S190630ag	BBH (94%), MassGap (5%)	June 30, 2019 18:52:05 UTC	GCN Circulars Notices | VOE		1 per 2.2077e+05 years	
S190602aq	BBH (99%)	June 2, 2019 17:59:27 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
RETRACTED						
S190521r	BBH (>99%)	May 21, 2019 07:43:59 UTC	GCN Circulars Notices | VOE		1 per 100.04 years	
S190521g	BBH (97%), Terrestrial (3%)	May 21, 2019 03:02:29 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190519bj	BBH (96%), Terrestrial (4%)	May 19, 2019 15:35:44 UTC	GCN Circulars Notices | VOE		1 per 5.5578 years	
RETRACTED						
S190517h	BBH (98%), MassGap (2%)	May 17, 2019 05:51:01 UTC	GCN Circulars Notices | VOE		1 per 13.354 years	
S190513bm	BBH (94%), MassGap (5%)	May 13, 2019 20:54:28 UTC	GCN Circulars Notices | VOE		1 per 84864 years	
S190512at	BBH (99%), Terrestrial (1%)	May 12, 2019 18:07:14 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
BNS (42%) TERRESTIAL (58%)						
S190503bf	BBH (96%), MassGap (3%)	May 3, 2019 18:54:04 UTC	GCN Circulars Notices | VOE		1 per 19.368 years	
BNS (49%) NSBH (13%) M GAP (24%)						
BNS (99%)						
S190421ar	BBH (97%), Terrestrial (3%)	April 21, 2019 21:38:56 UTC	GCN Circulars Notices | VOE		1 per 2.1285 years	
S190412m	BBH (>99%)	April 12, 2019 05:30:44 UTC	GCN Circulars Notices | VOE		1 per 1.883e+19 years	
S190408an	BBH (>99%)	April 8, 2019 18:18:02 UTC	GCN Circulars Notices | VOE		1 per 1.1273e+10 years	
RETRACTED						(S190405ar) is not considered to be astrophysical in o as truncated to S190405a due to a bug. RETRACTED

GraceDB **Public Alerts** Latest Search Documentation Login

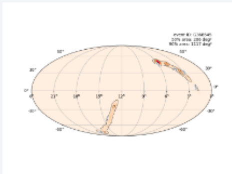
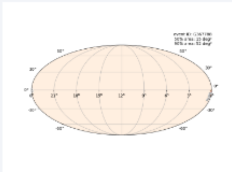
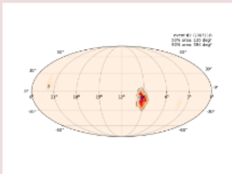
Please log in to view full database contents.

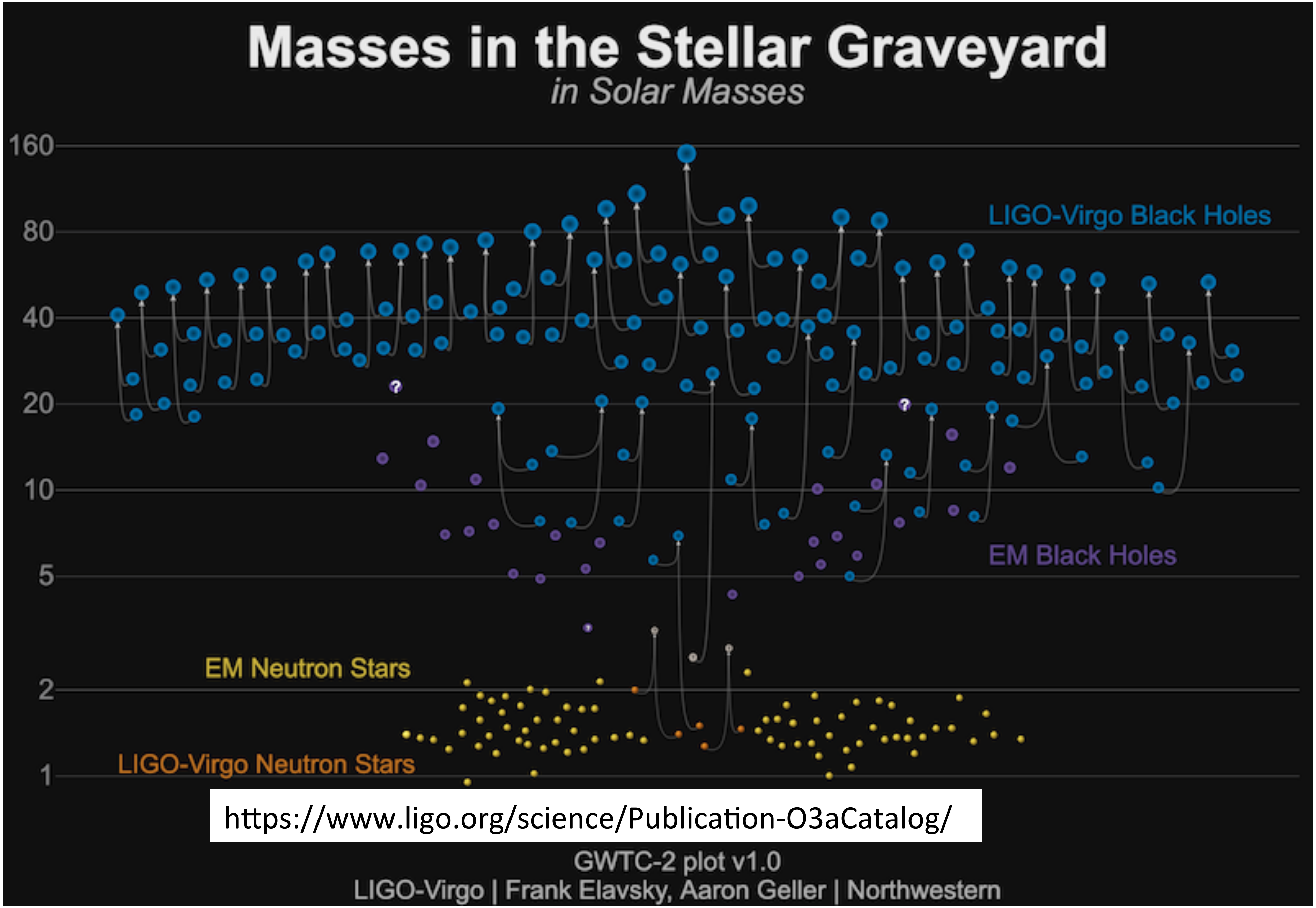
LIGO/Virgo O3 Public Alerts

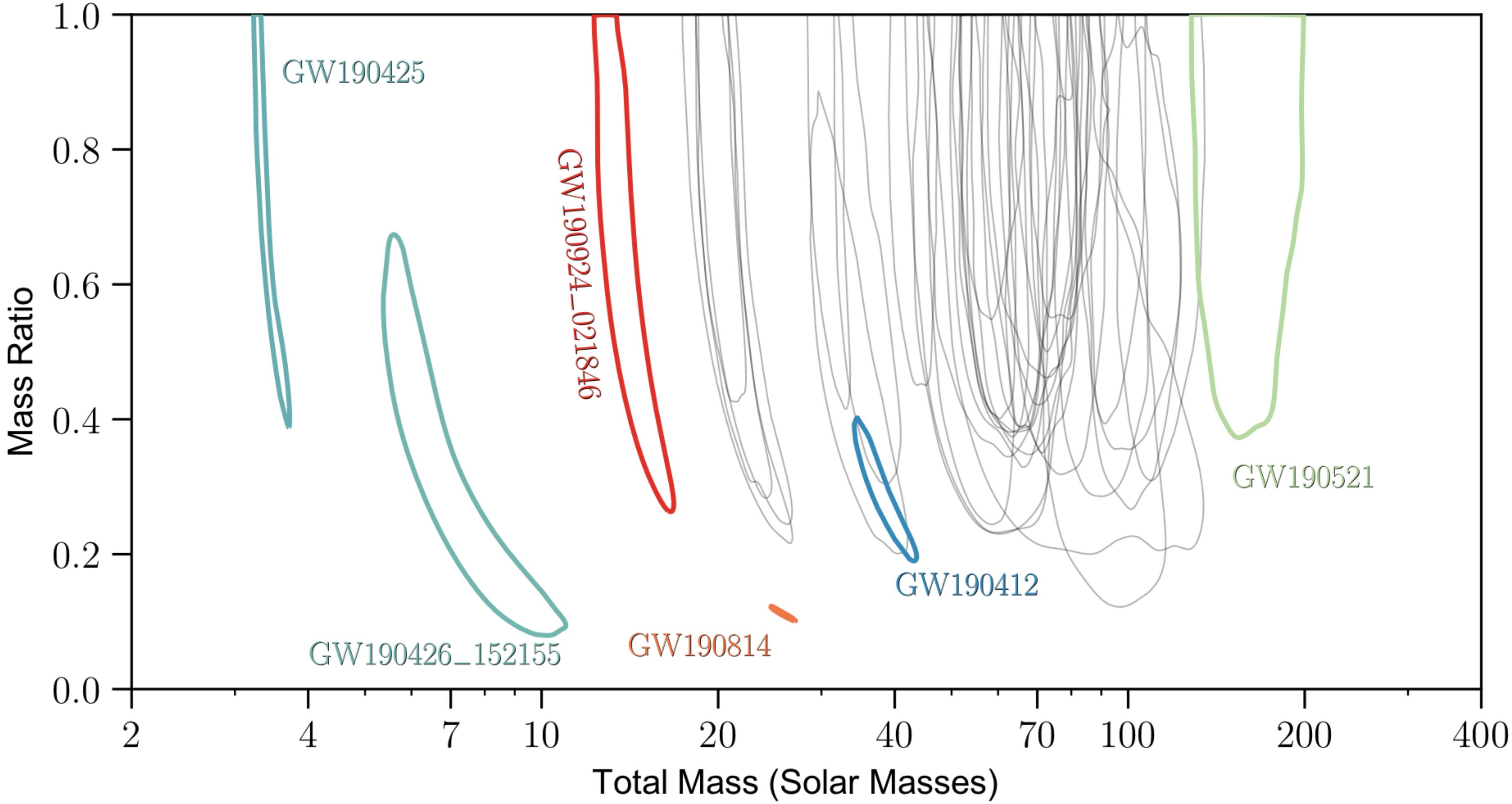
Detection candidates: 56

https://gracedb.ligo.org/superevents/public/O3/

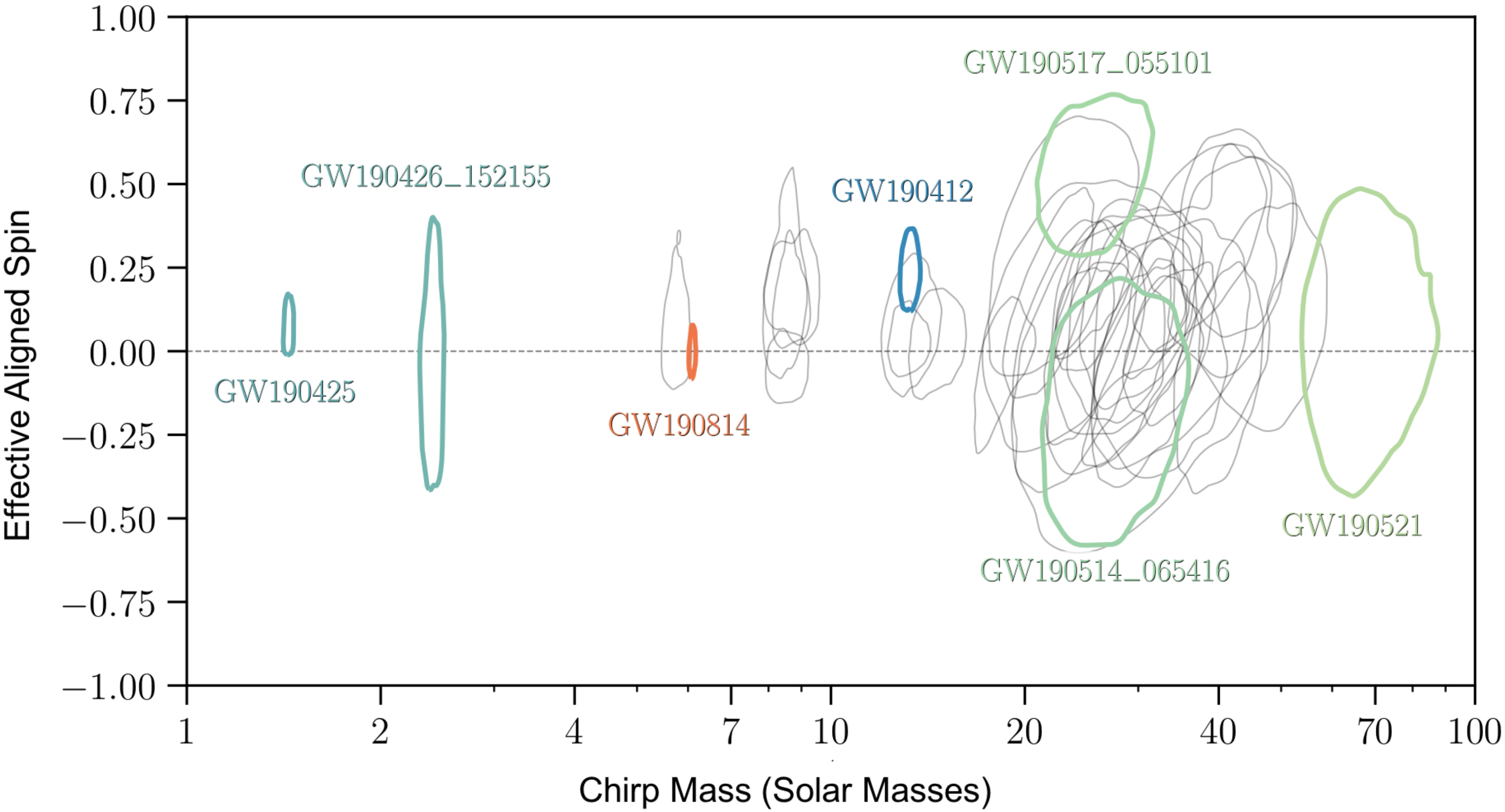
SORT: EVENT ID (A-Z) ▼

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S200316bj	MassGap (>99%)	March 16, 2020 21:57:56 UTC	GCN Circulars Notices | VOE		1 per 446.44 years	
S200311bg	BBH (>99%)	March 11, 2020 11:58:53 UTC	GCN Circulars Notices | VOE		1 per 3.5448e+17 years	
S200308e	NSBH (83%), Terrestrial (17%)	March 8, 2020 01:19:27 UTC	GCN Circulars Notices | VOE		1 per 8.757 years	RETRACTED

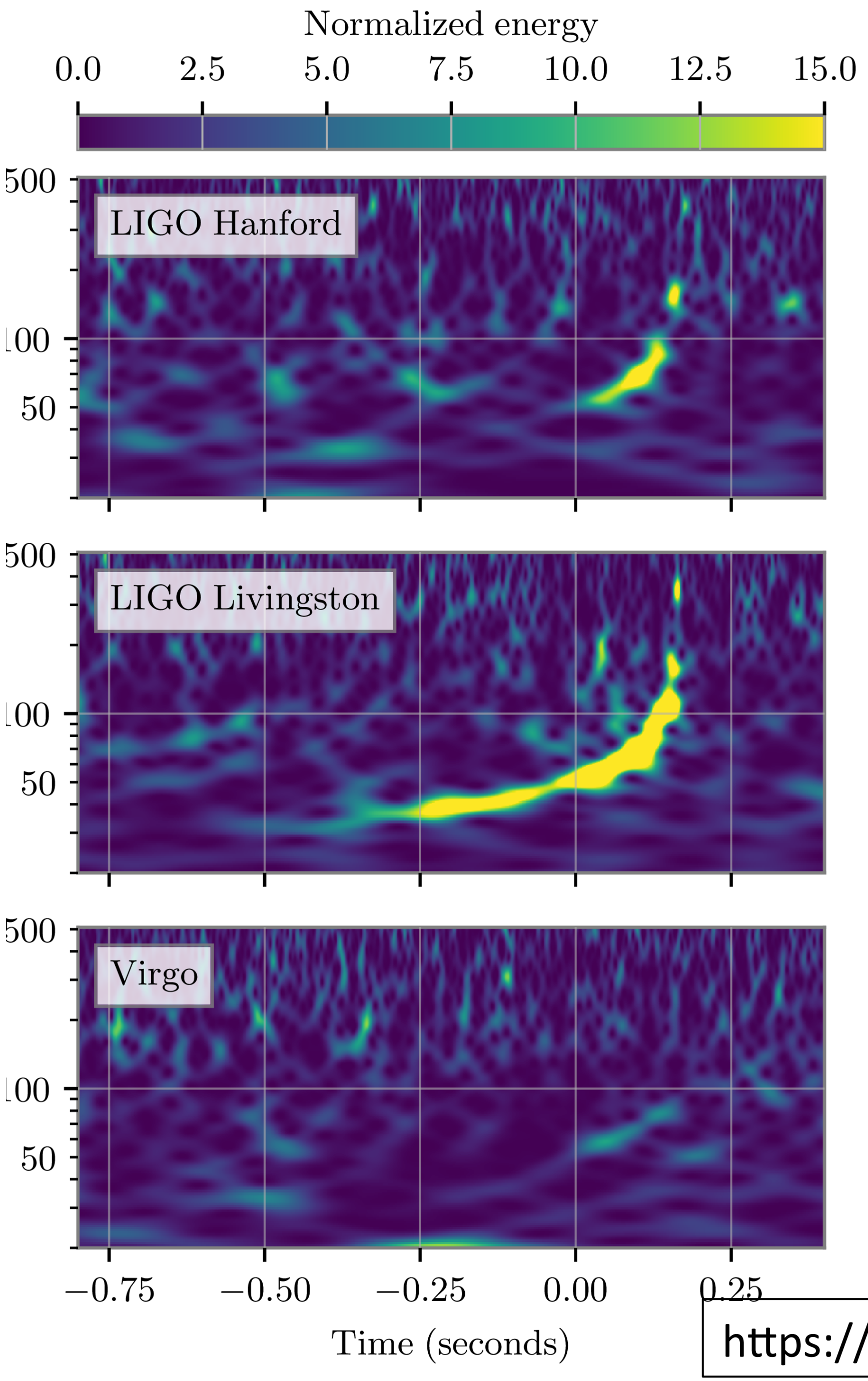

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
https://www.ligo.org/science/Publication-O3aCatalog/
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

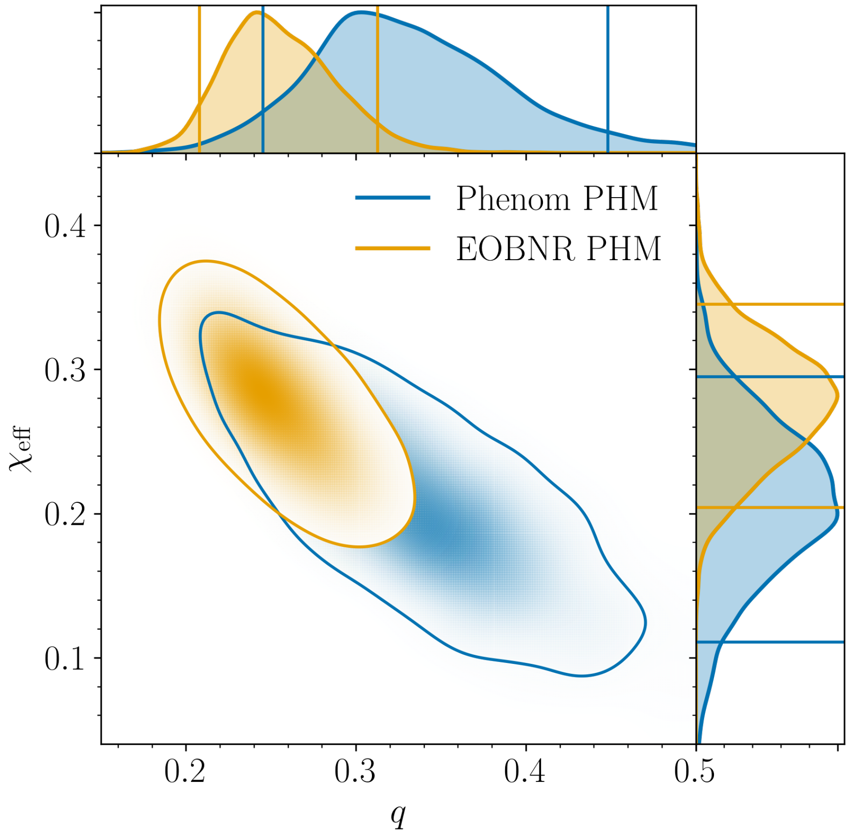


https://www.ligo.org/science/Publication-O3aCatalog/

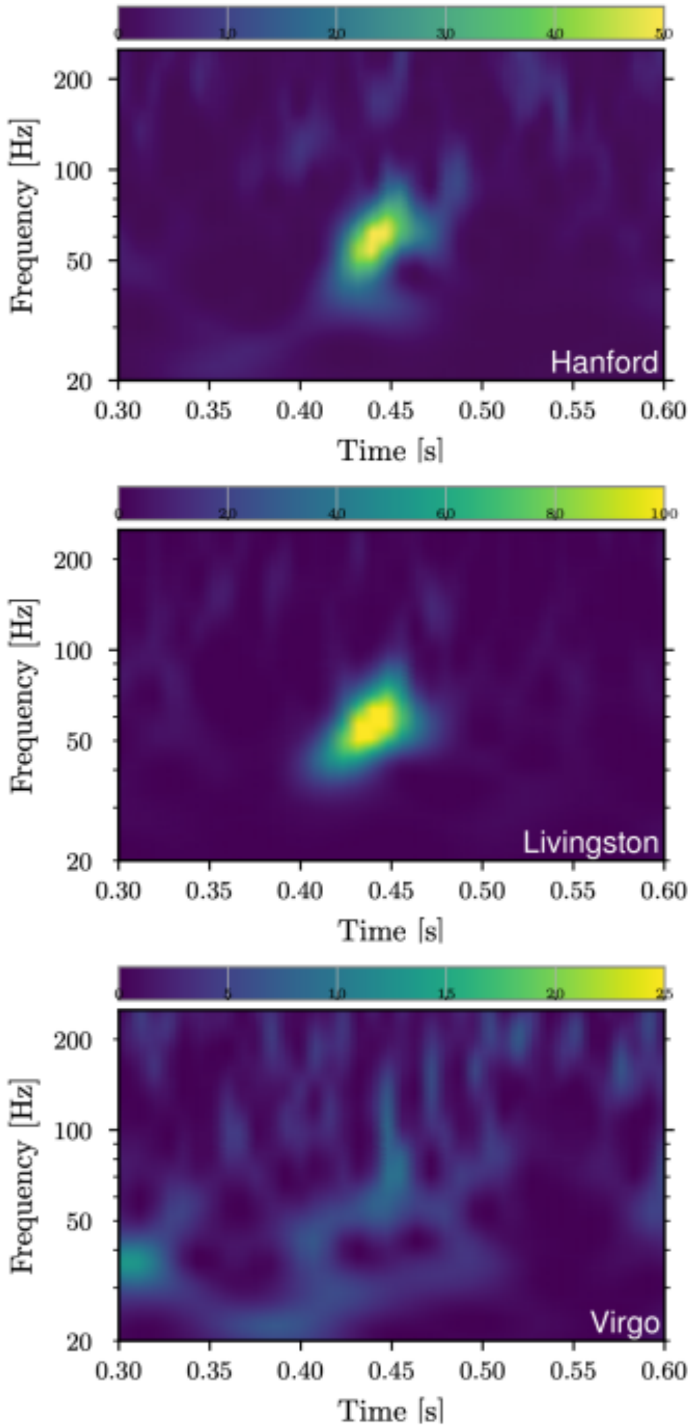


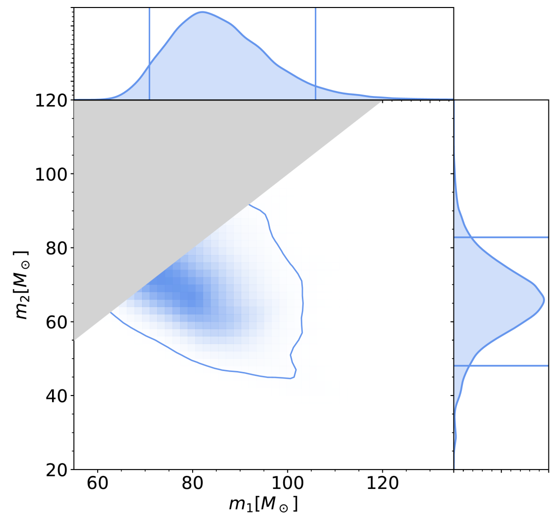
https://www.ligo.org/science/Publication-O3aCatalog/

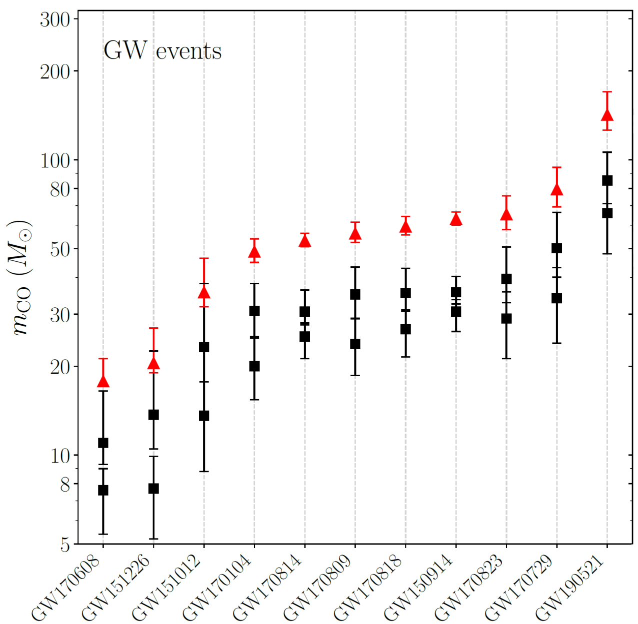




https://www.ligo.org/science/Publication-GW190412/

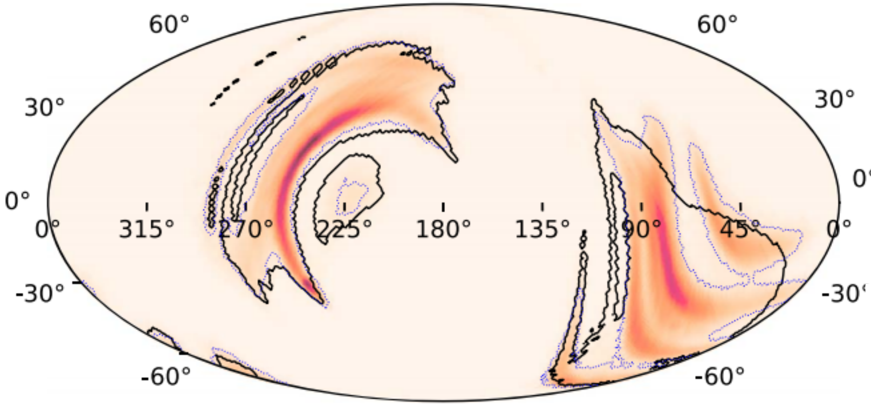


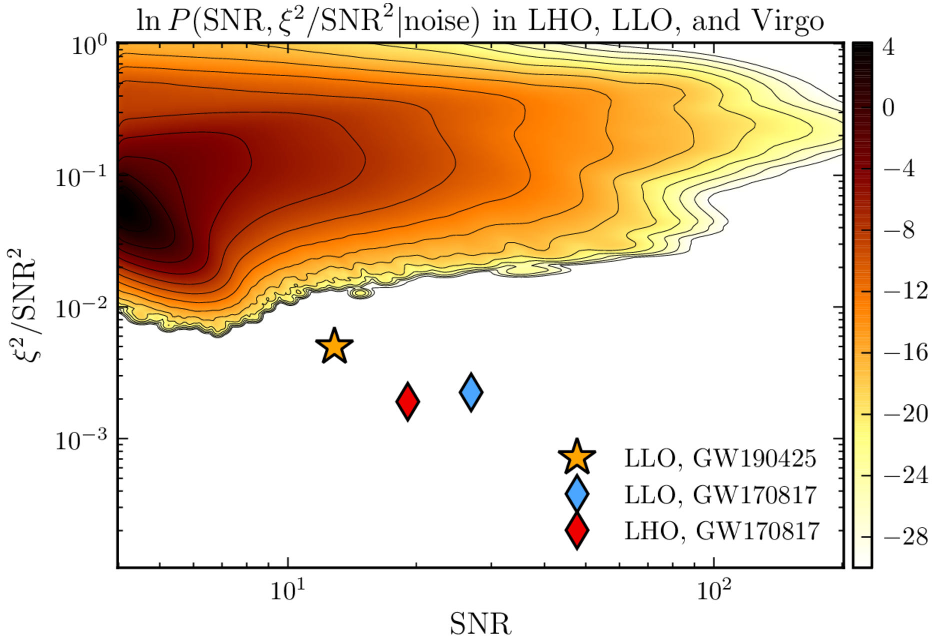


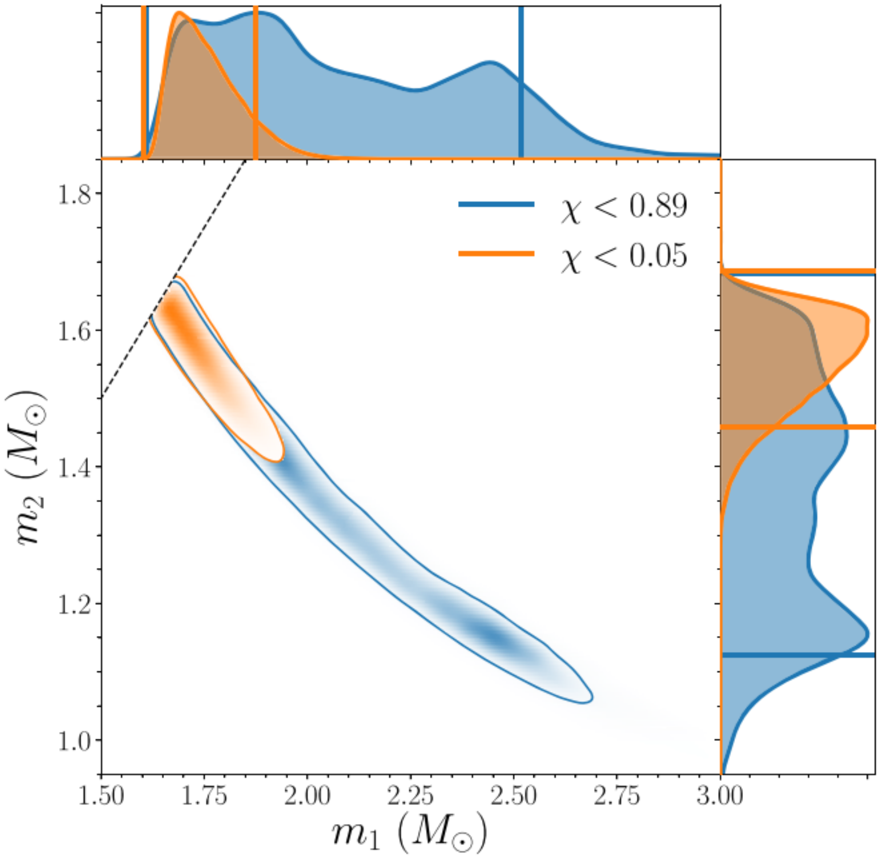


https://www.ligo.org/science/Publication-GW190521/

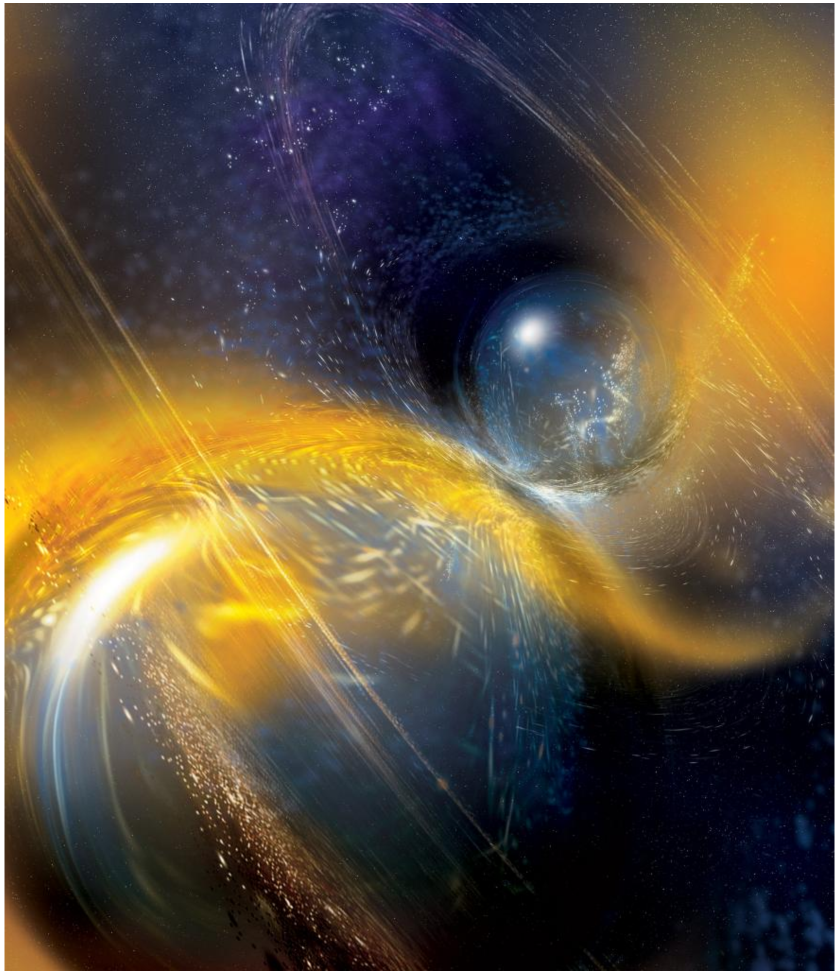
https://www.ligo.org/science/Publication-GW190425/

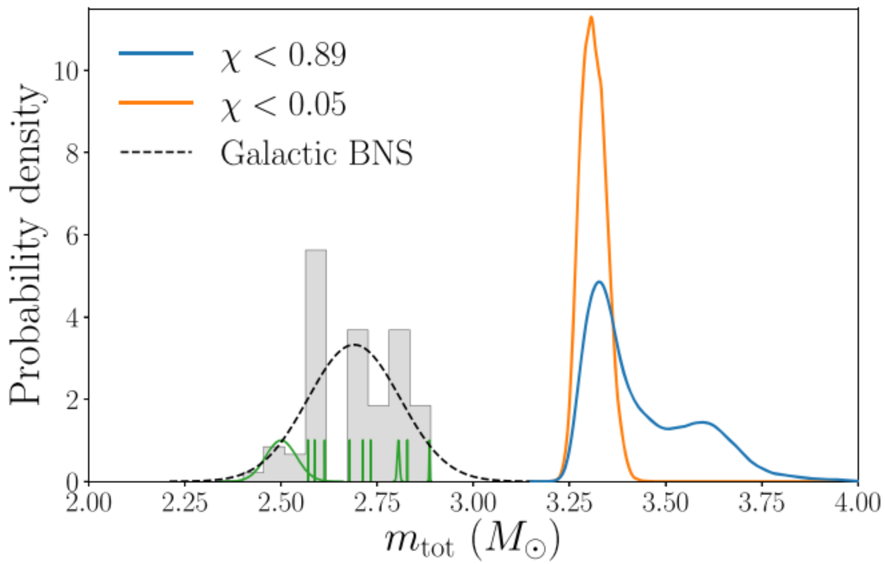


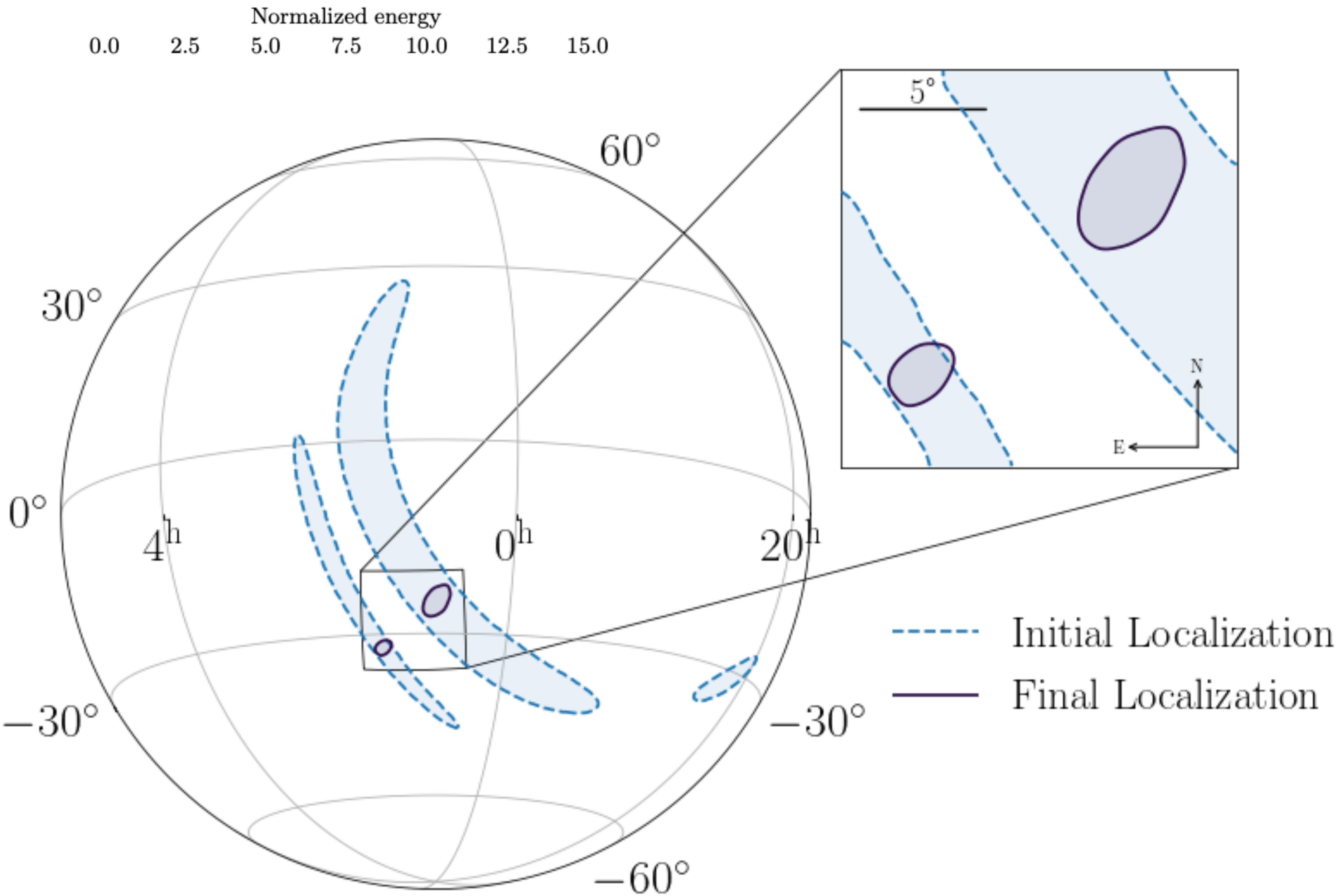




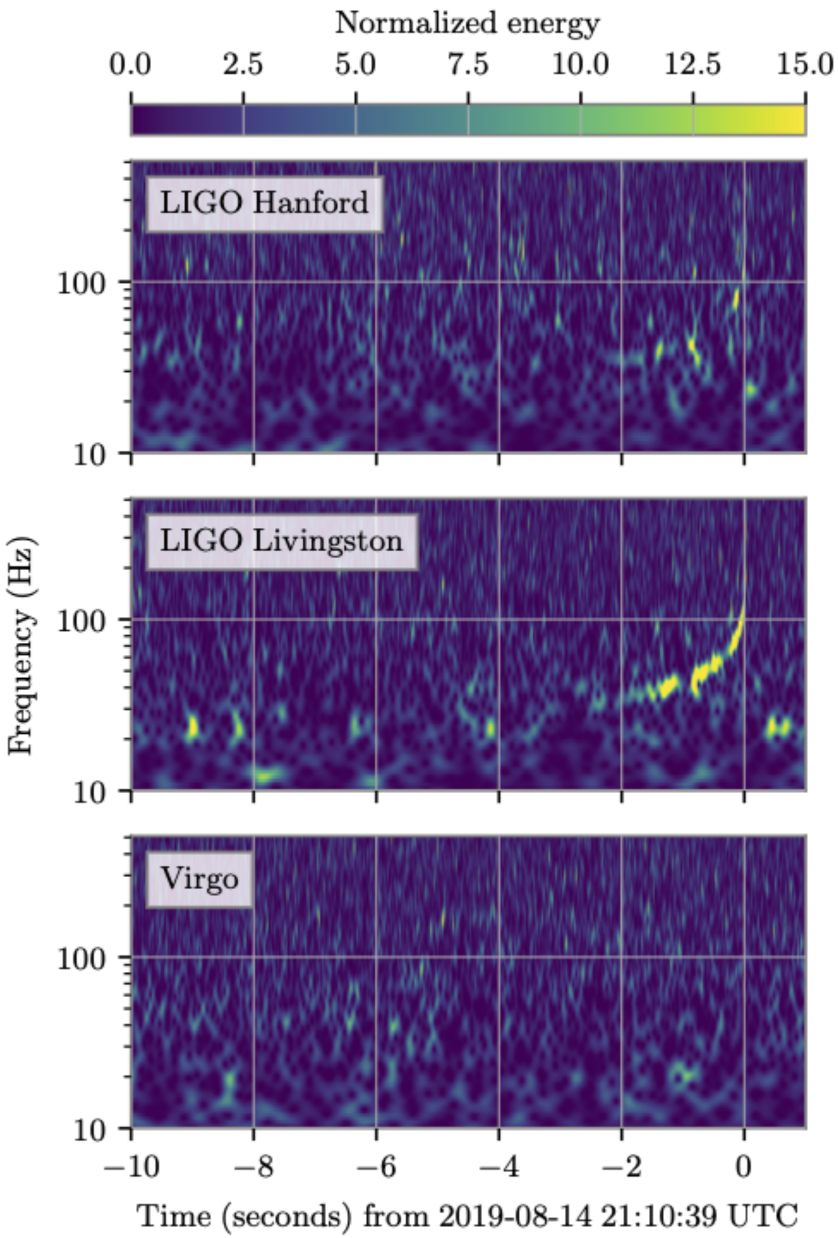
https://www.ligo.org/science/Publication-GW190425/

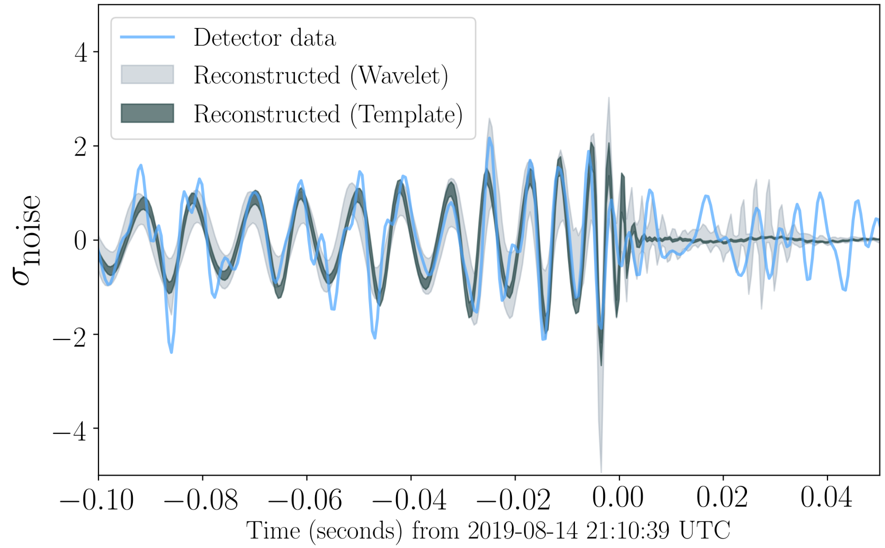


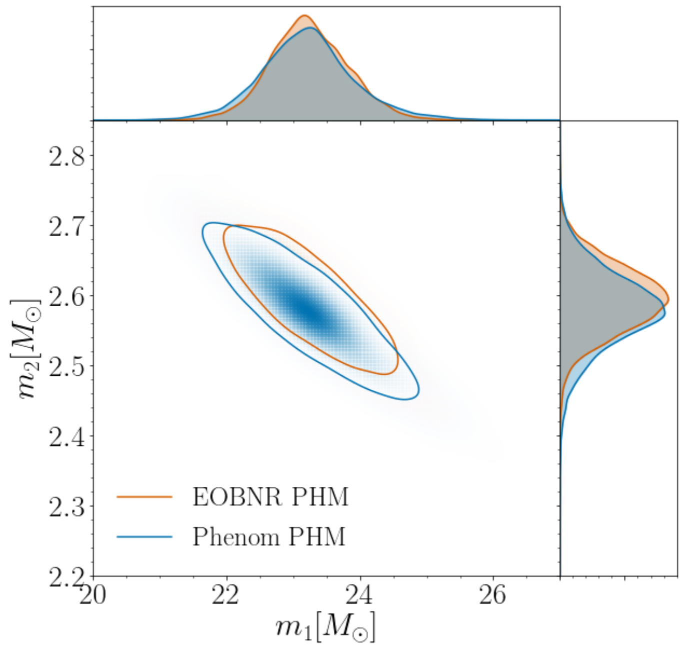




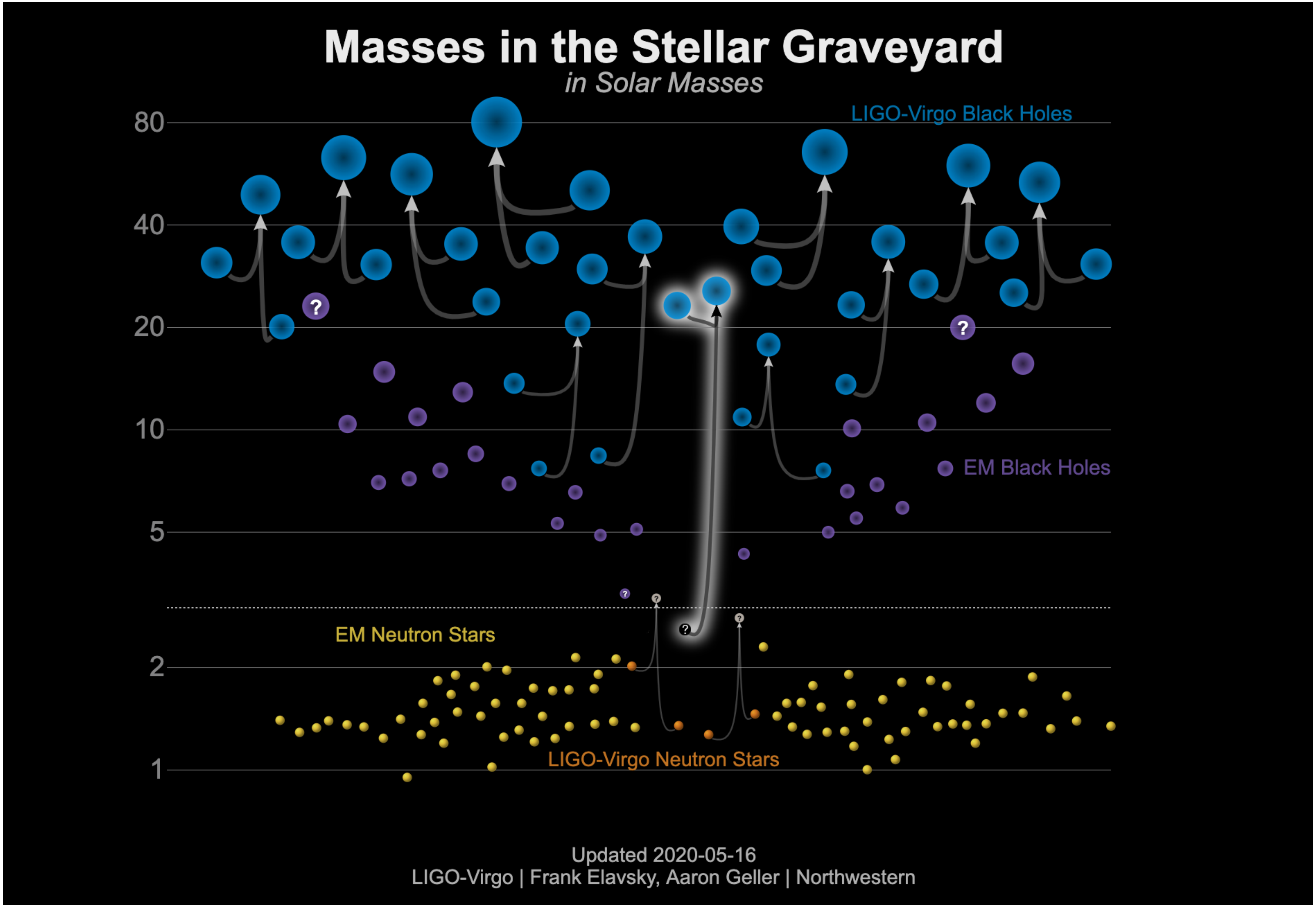
https://www.ligo.org/science/Publication-GW190814/

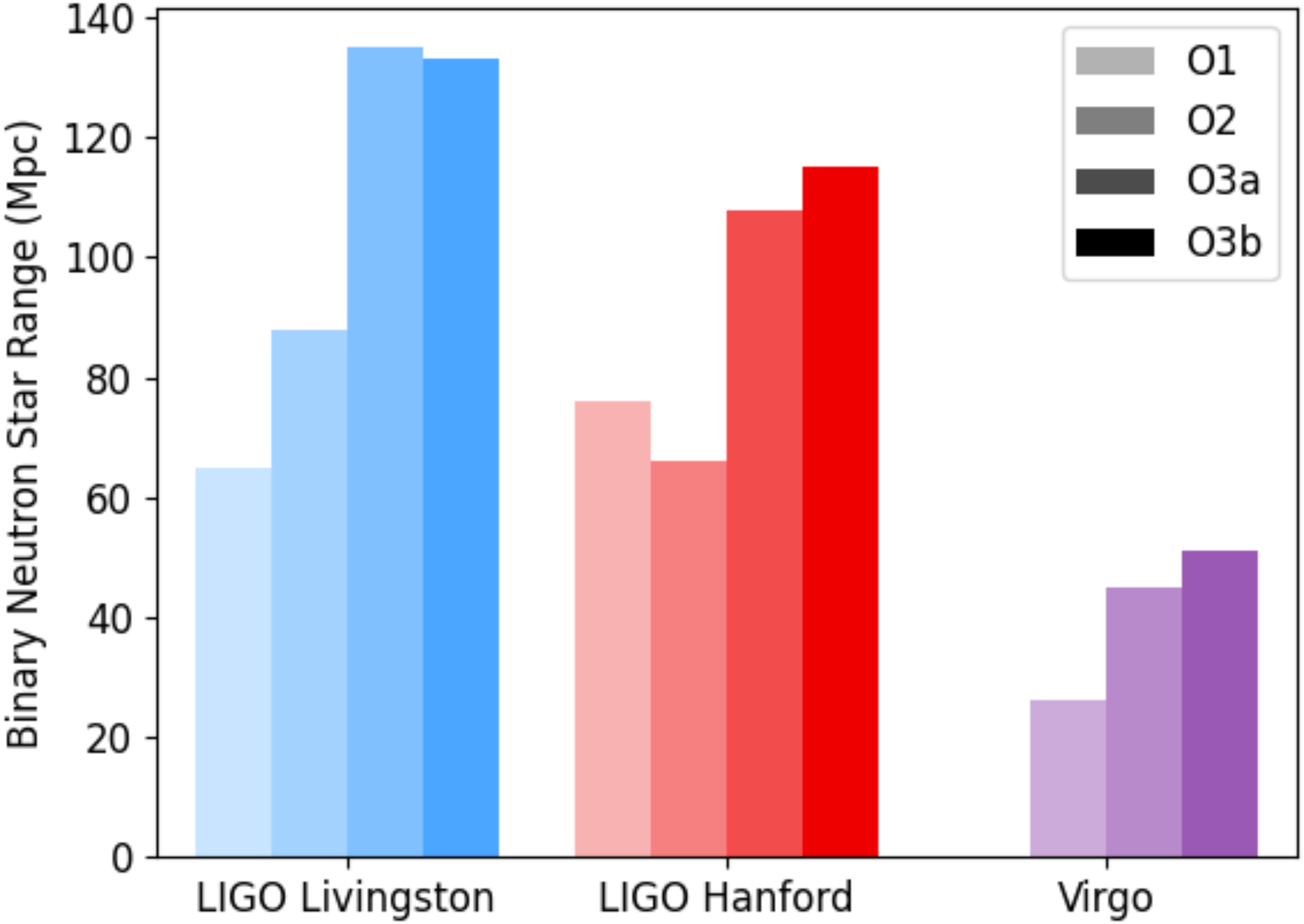




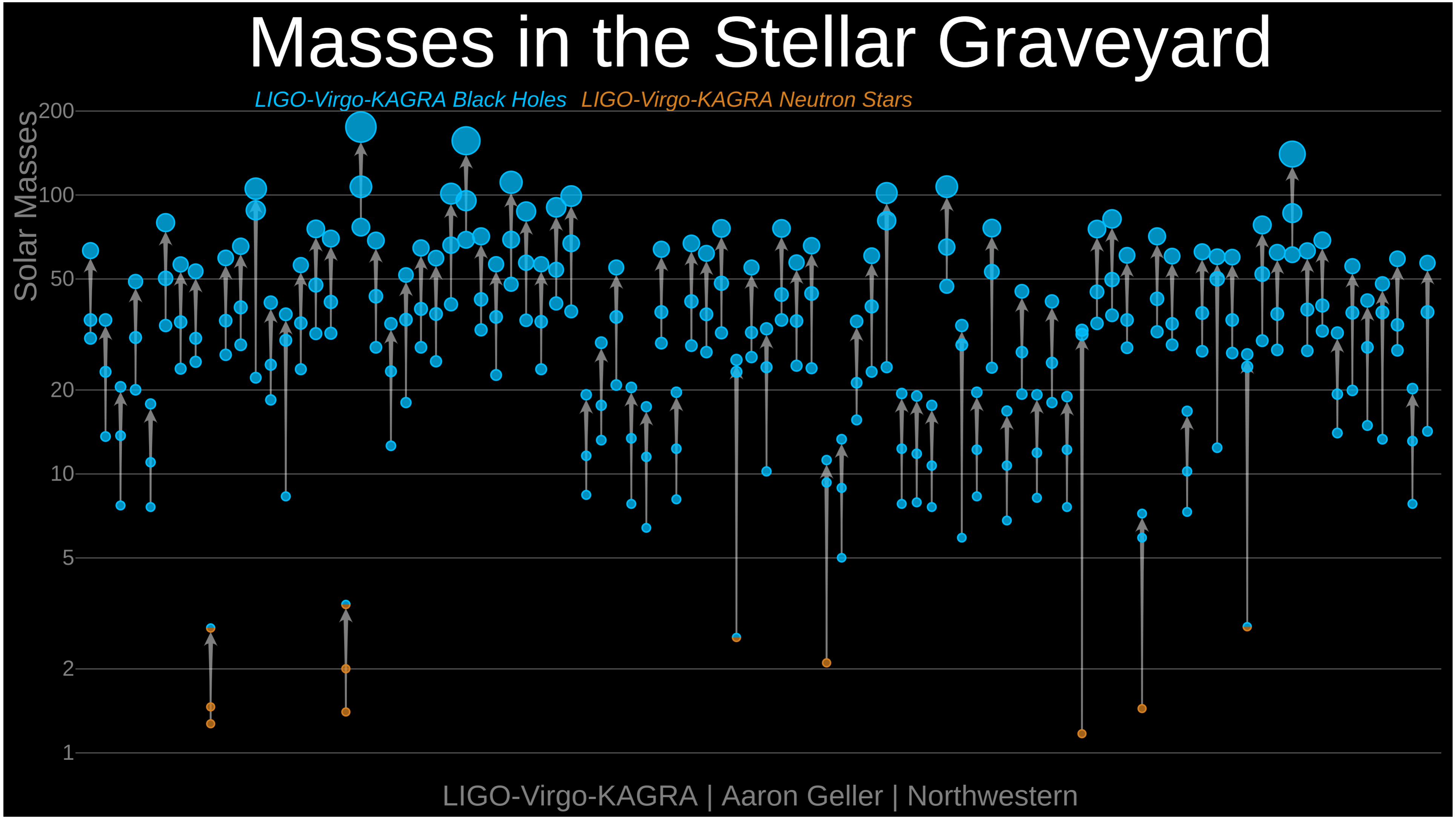


https://www.ligo.org/science/Publication-GW190814/

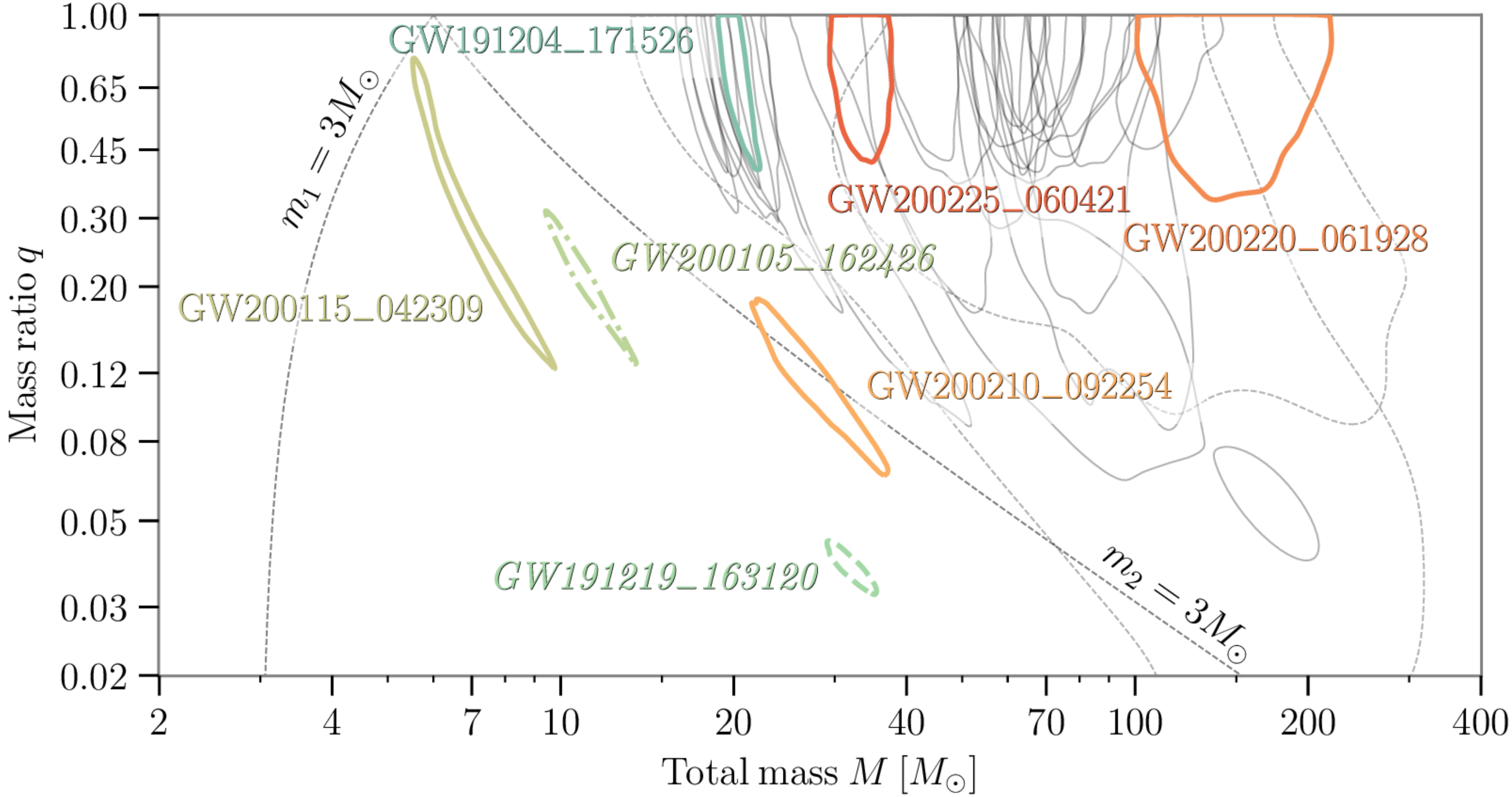

Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-05-16
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



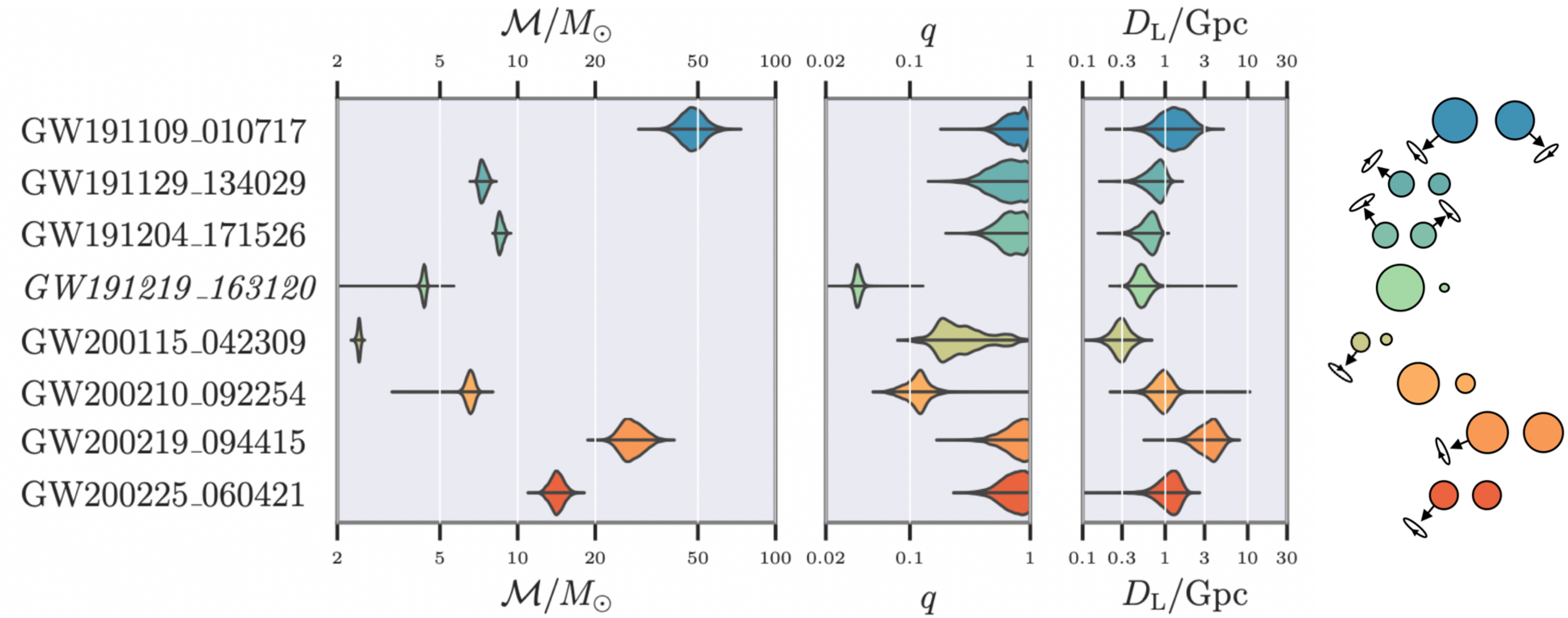
https://www.ligo.org/science/Publication-O3bCatalog/



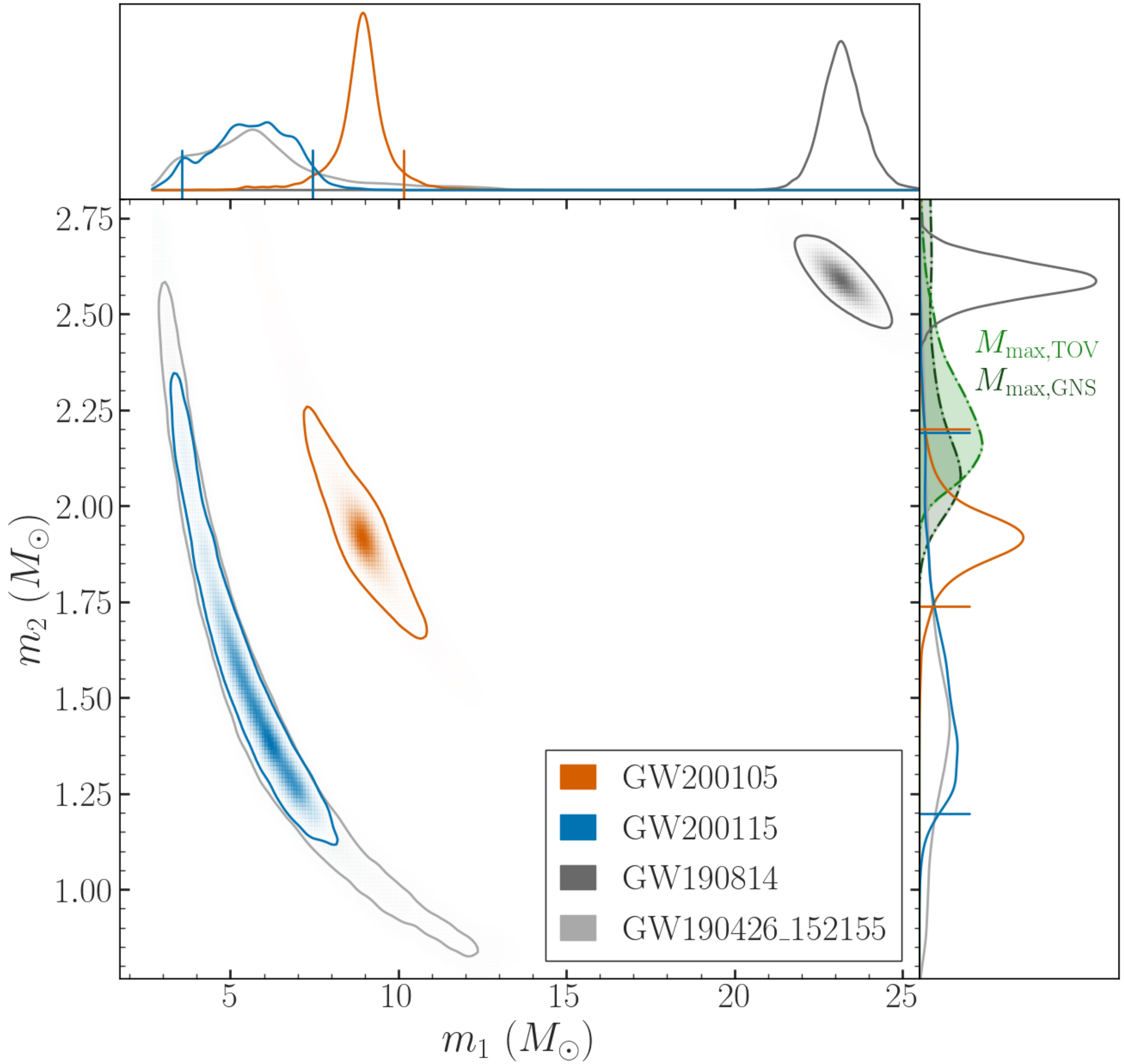
https://www.ligo.org/science/Publication-O3bCatalog/



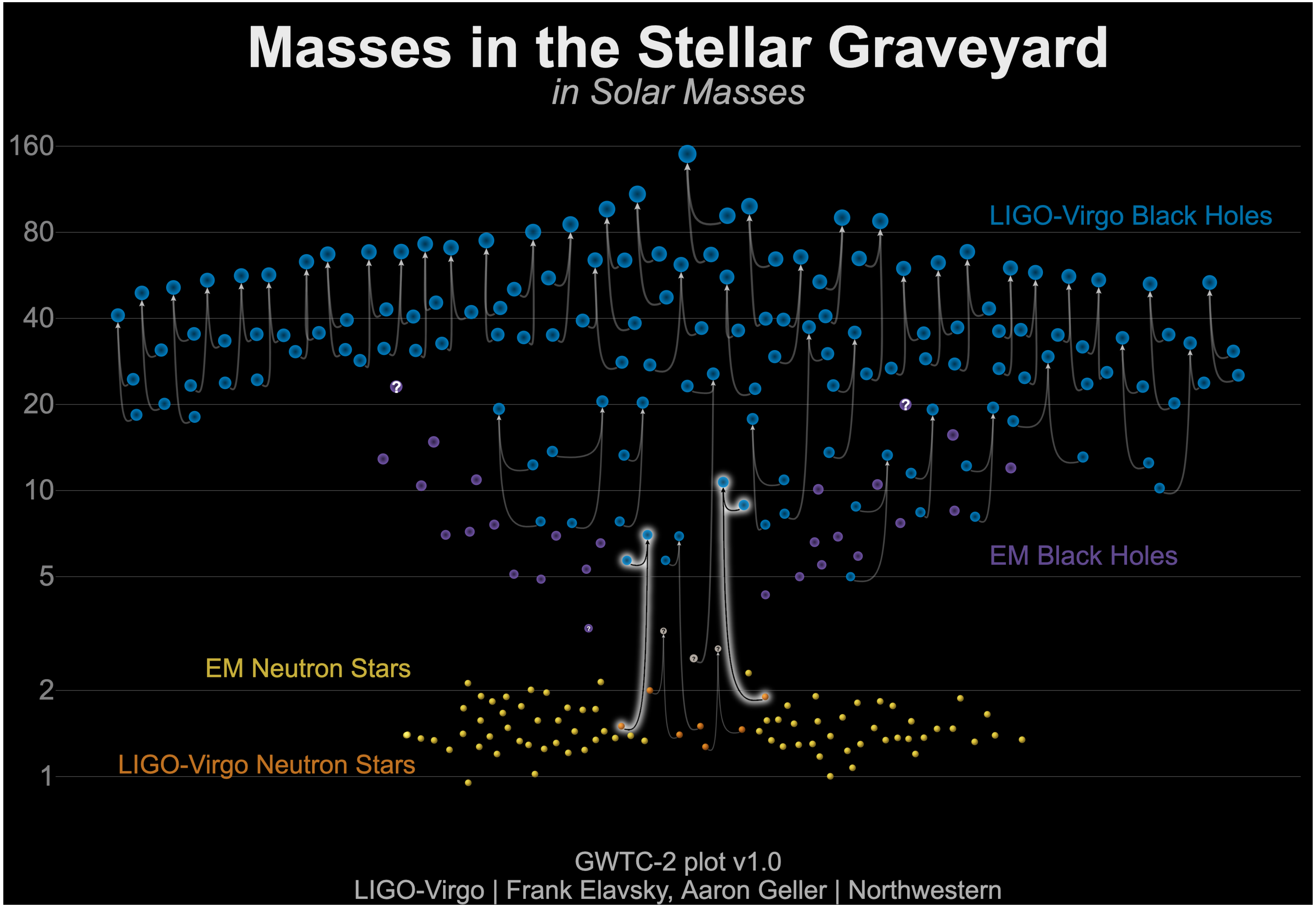
https://www.ligo.org/science/Publication-O3bCatalog/



https://www.ligo.org/science/Publication-O3bCatalog/



https://www.ligo.org/science/Publication-NSBHDiscovery/

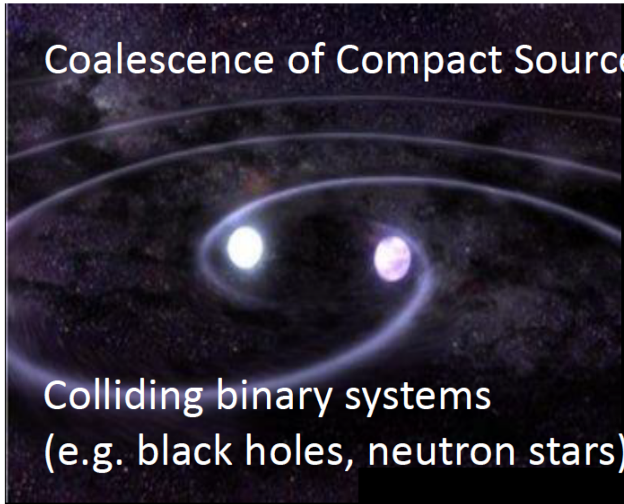


https://www.ligo.org/science/Publication-NSBHDiscovery/

LIGO-Virgo analyses for sources of gravitational waves

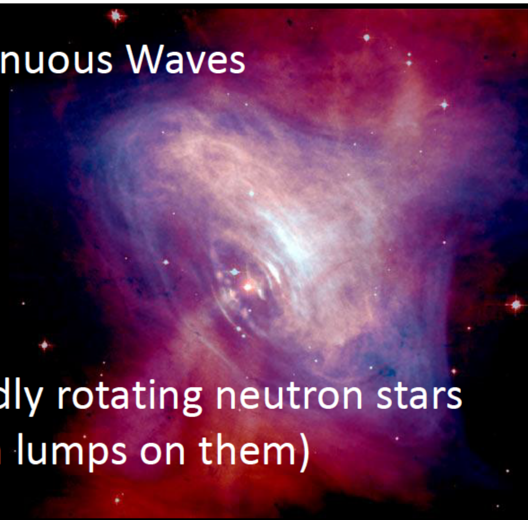
Sources can be transient or of continuous nature, and can be modeled or unmodeled

Coalescence of Compact Sources



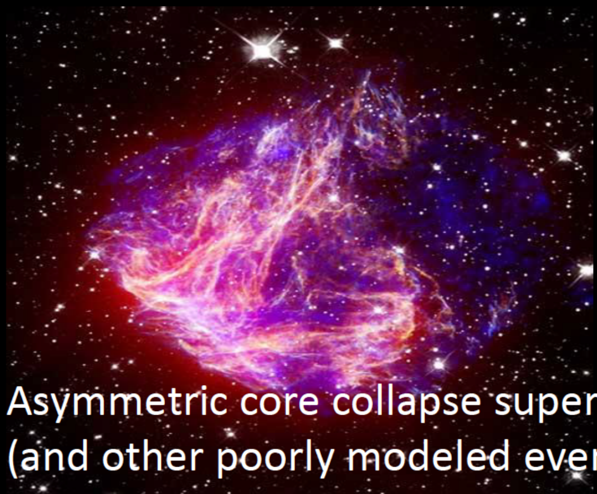
Colliding binary systems
(e.g. black holes, neutron stars)

Continuous Waves



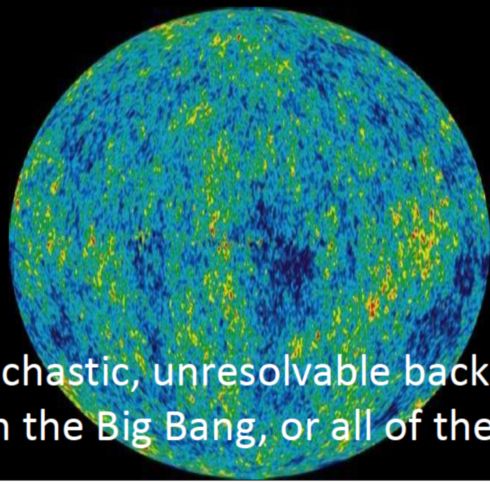
Rapidly rotating neutron stars
(with lumps on them)

Burst



Asymmetric core collapse supernovae
(and other poorly modeled events)

Stochastic



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

Continuous Waves

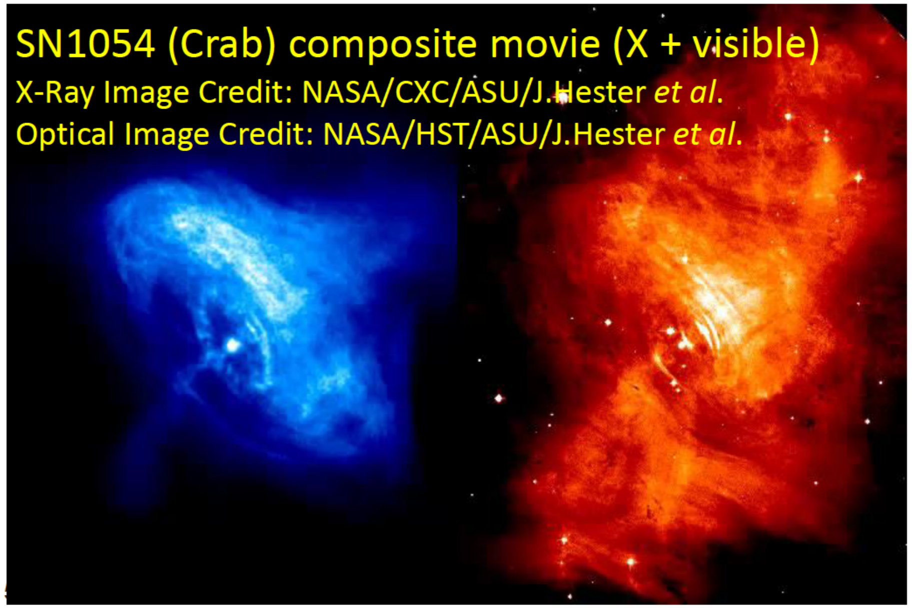
Astrophysics

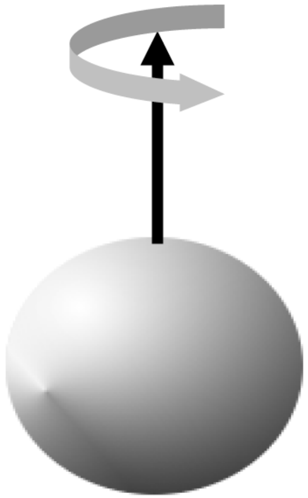
More than 2500 observed NSs (mostly pulsars) and O(10^8 –10^9) expected to exist in our galaxy
Sources must have some degree of non-axisymmetry originating from

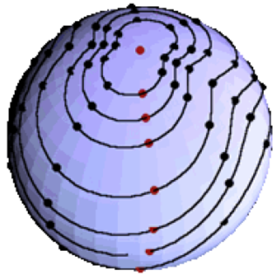
- deformation due to elastic stresses or magnetic field not aligned to the rotation axis ($f_{GW} = 2f_r$)
- free precession around rotation axis ($f_{GW} \sim f_{rot} + f_{prec}$; $f_{GW} \sim 2f_{rot} + 2f_{prec}$)
- excitation of long-lasting oscillations (e.g. *r*-modes; $f_{GW} \sim 4f_r/3$)
- deformation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

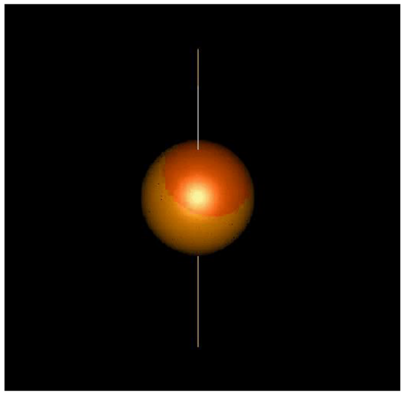
Source characteristics

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

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

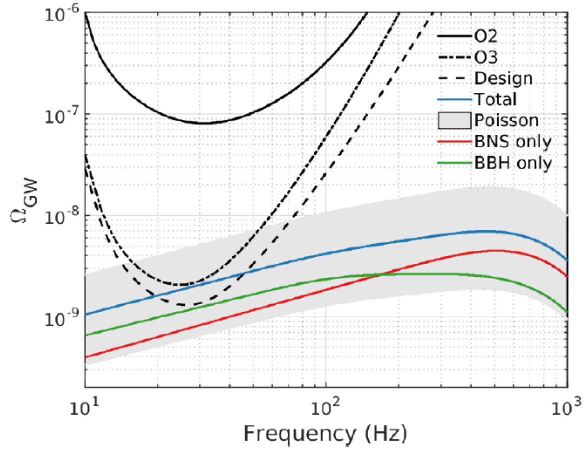
- First search for gravitational waves from known pulsars (LVC, ApJ 839, 12, 2017)
  - Analyzed 200 known pulsars (119 out of 200 are in binary systems)
  - Spindown limit beaten for 8 pulsars, including both Crab & Vela: For the Crab and Vela pulsars less than 2x10-3 and 10-2 of the spindown luminosity 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

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



Abbott et al. PRL120.091101, 2017

Astrophysical SGWB

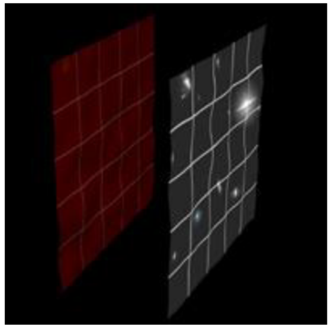
All the sources since the beginning of stellar activity
Dominated by compact binary coalescences: BBHs, BNSs, BH-NSs

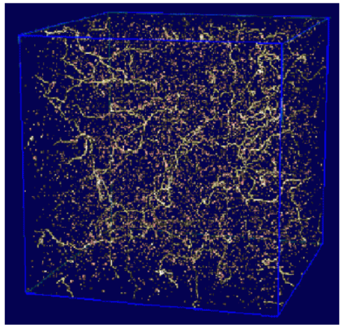
LIGO and Virgo have already published 10 BBHs and 1 BNS
Events are individual sources at z~0.07-0.2 for BBHs, 0.01 for BNS

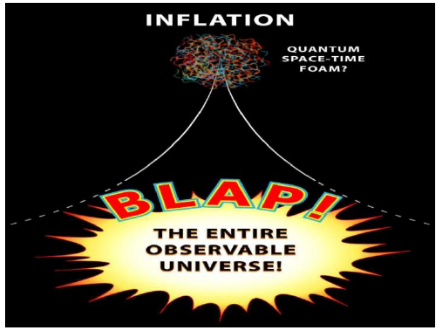
Many individual sources at larger distances that contribute to SGWB
This could be the next milestone for LIGO/Virgo

Cosmological SGWB

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

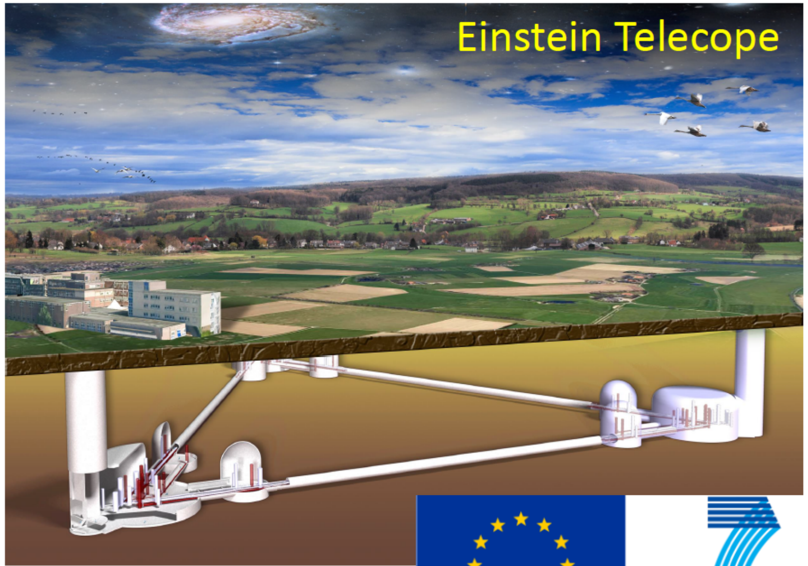




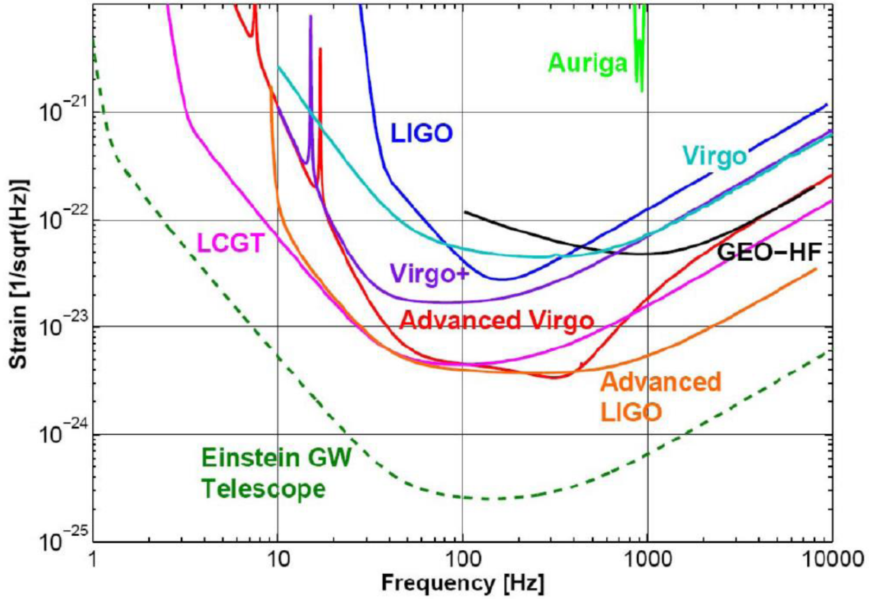


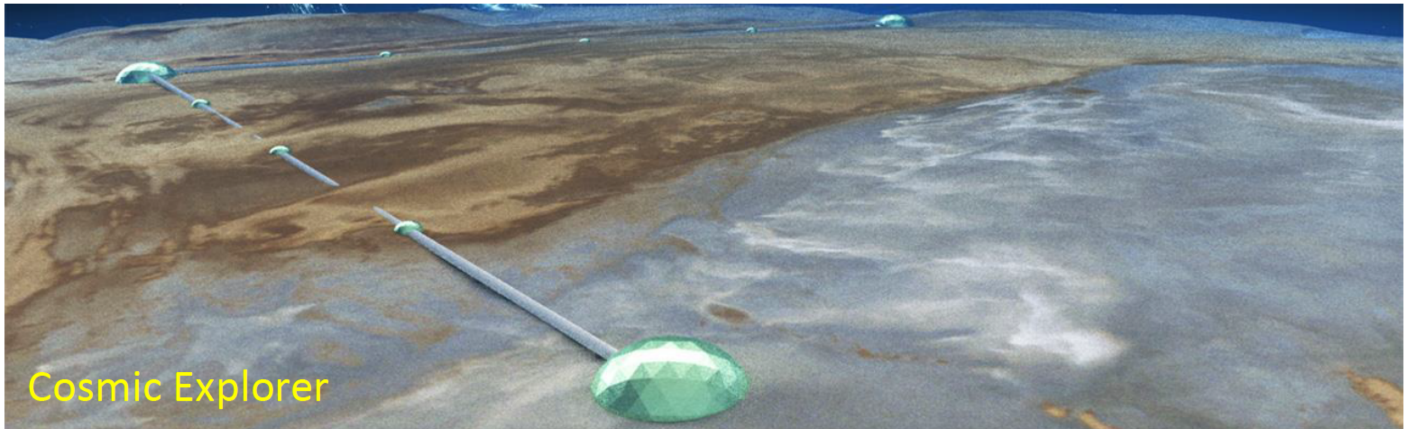
Einstein Telescope and Cosmic Explorer

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



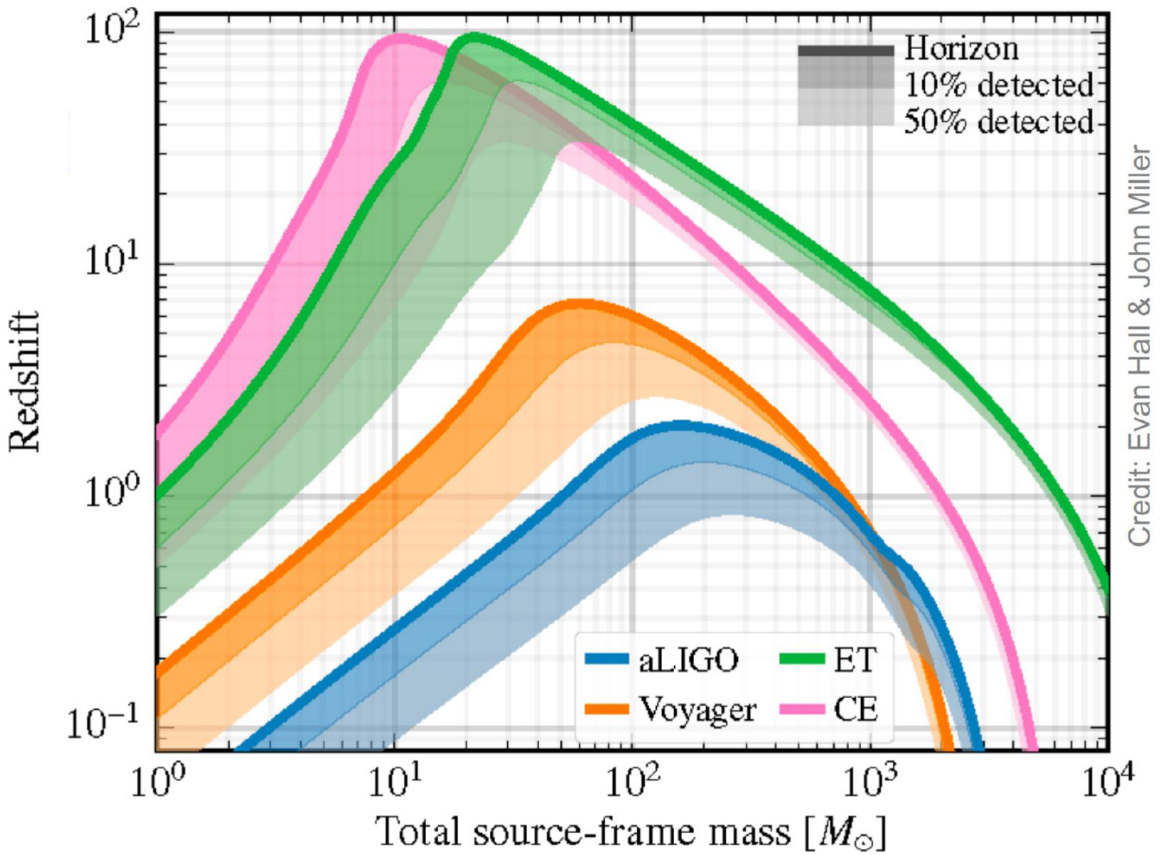
SEVENTH FRAMEWORK PROGRAMME





Einstein Telescope and Cosmic Explorer

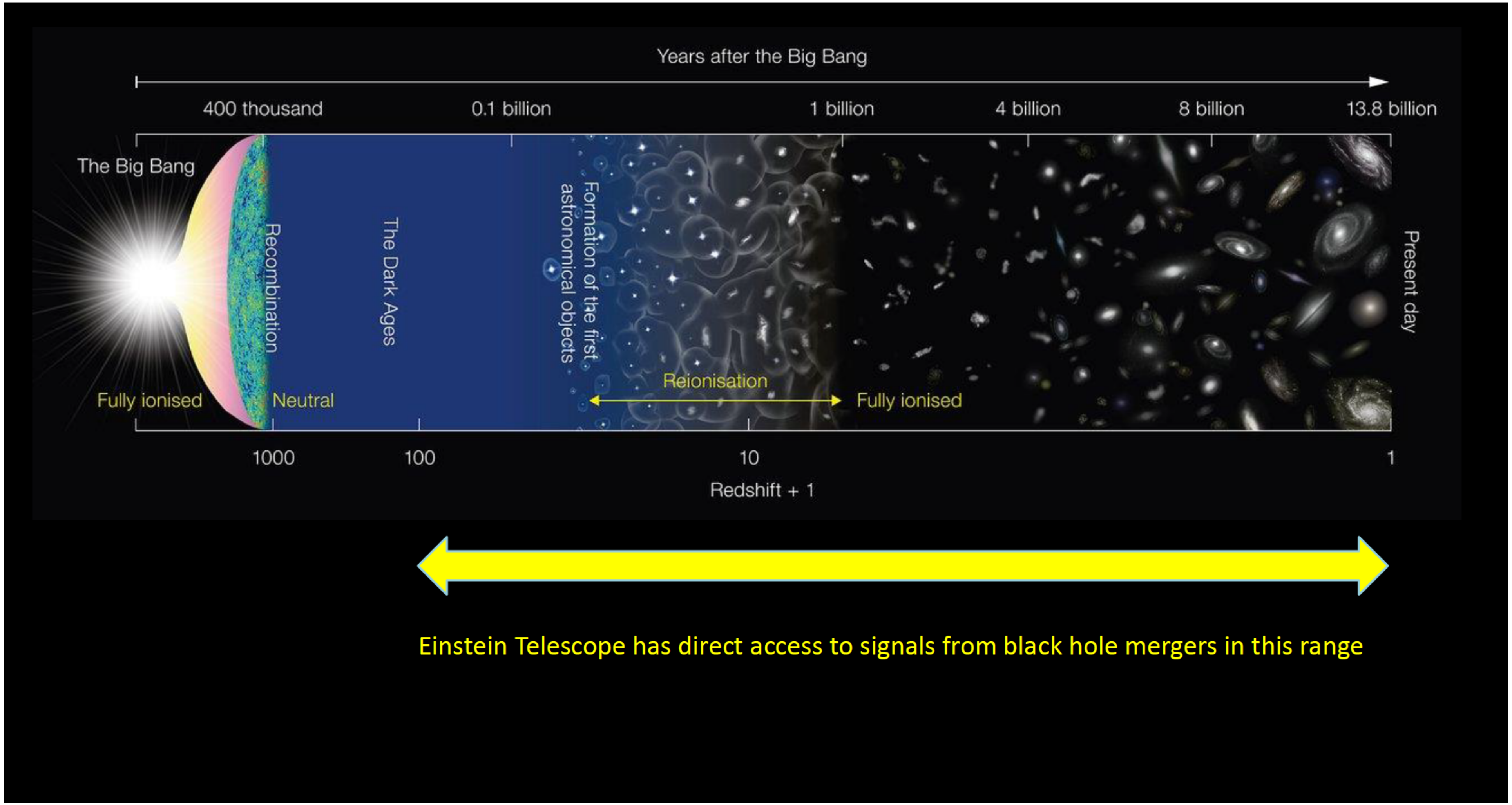
Einstein Telescope will feature excellent low-frequency sensitivity and have great discovery potential



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

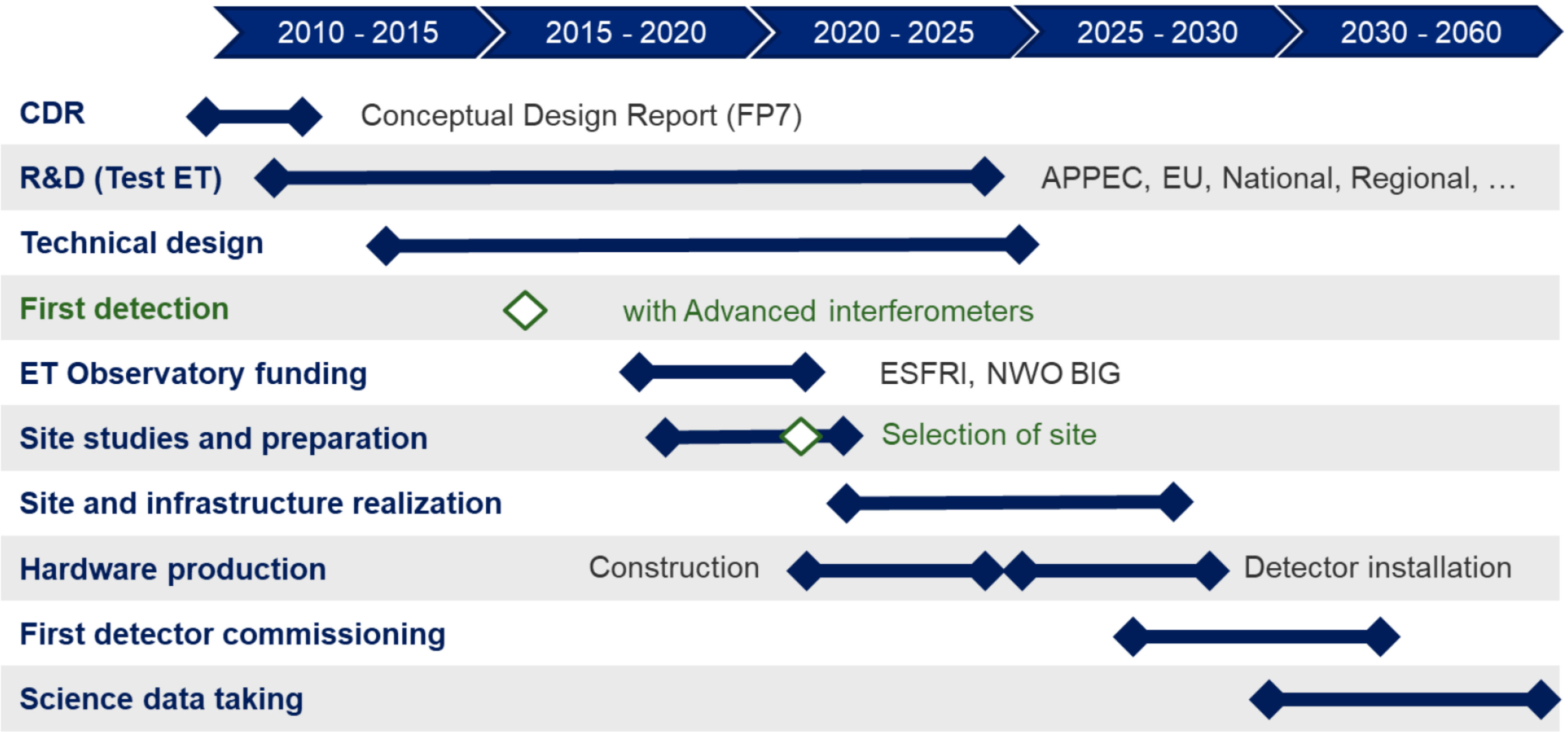
Einstein Telescope

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: an infrastructure for 50 to 100 years

ET will study events from the entire Universe. Gravitational waves will become a common tool just like conventional astronomy has been for the last four centuries



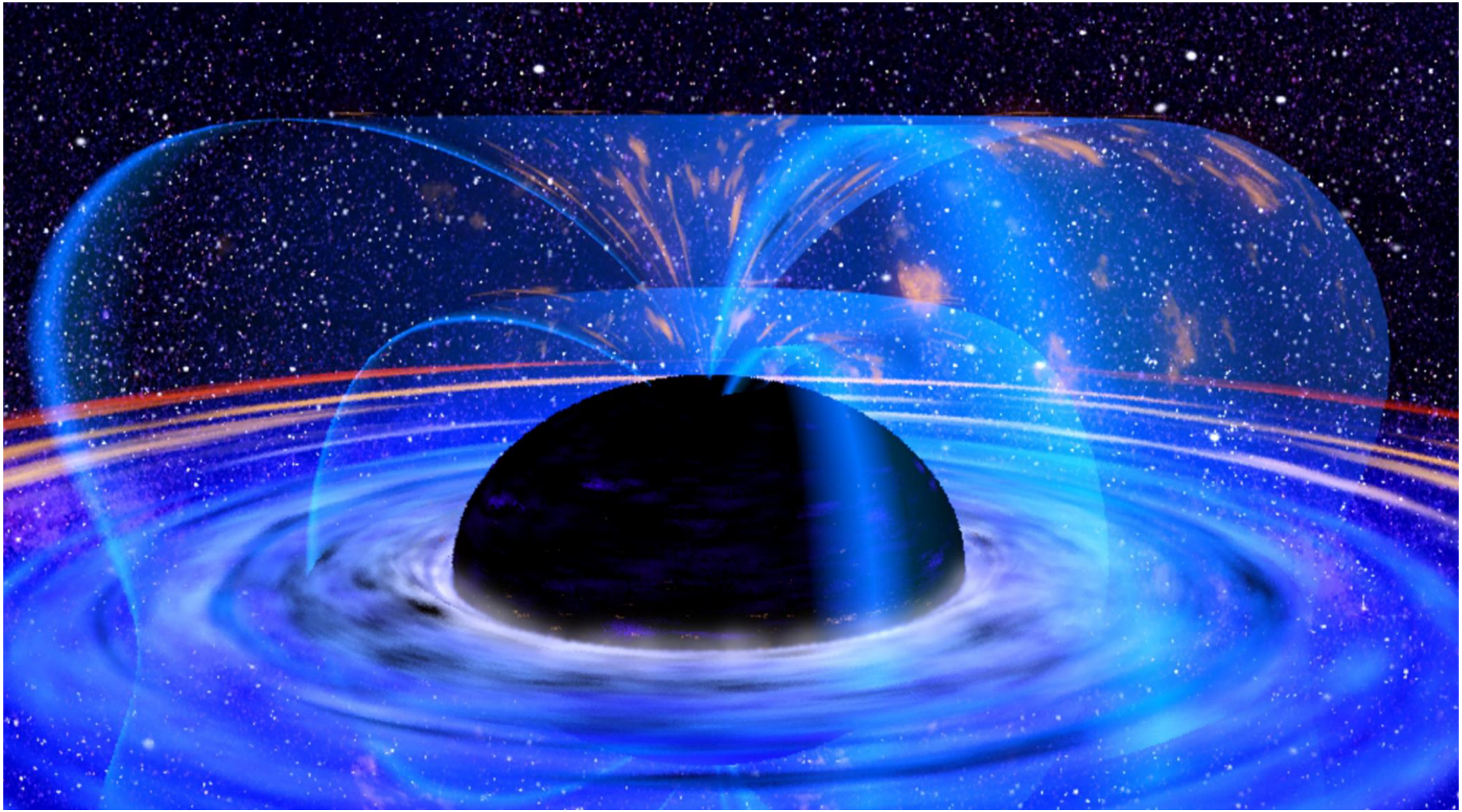
Einstein Telescope: cosmography

What is this mysterious dark energy that is tearing the Universe apart?
Use BNS and BBH as standard “candles” (so-called “sirens”)

Einstein Telescope: fundamental physics

What happened at the edge of a black hole?

Is Einstein's theory correct in conditions of extreme gravitation? Of does new physics await?



Observe intermediate-mass black holes

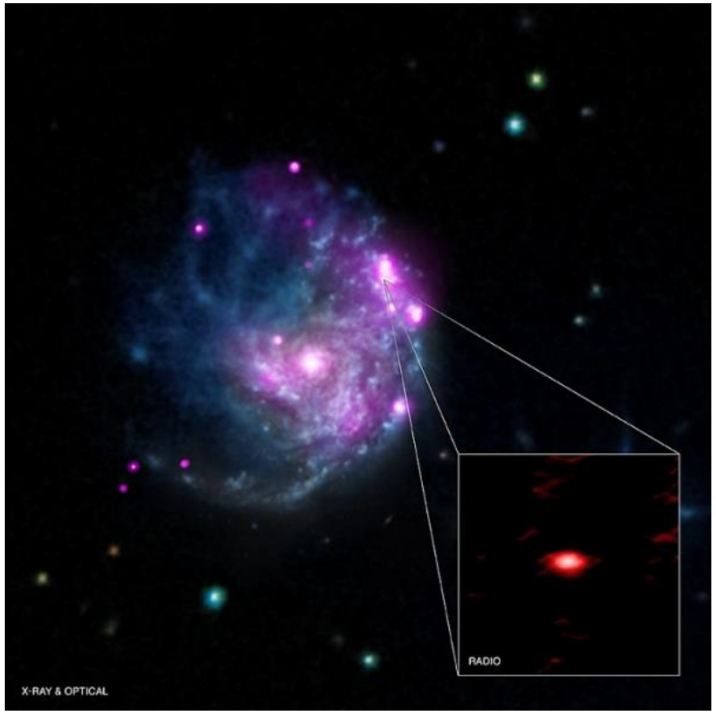
Globular clusters may host intermediate-mass black holes (IMBHs) with masses in the range 100 to 1000 solar masses

IMBH will be the most massive object in the cluster and will readily sink to the center

Binary with a compact-object companion will form. The binary will then harden through three-body interactions

Binary will eventually merge via an intermediate-mass-ratio inspiral (IMRI)

The number of detectable mergers depends on the unknown distribution of IMBH masses and their typical companions. Detect 300 events per year out to z = 1:5 for 100M (redshifted) primaries and 10M secondaries

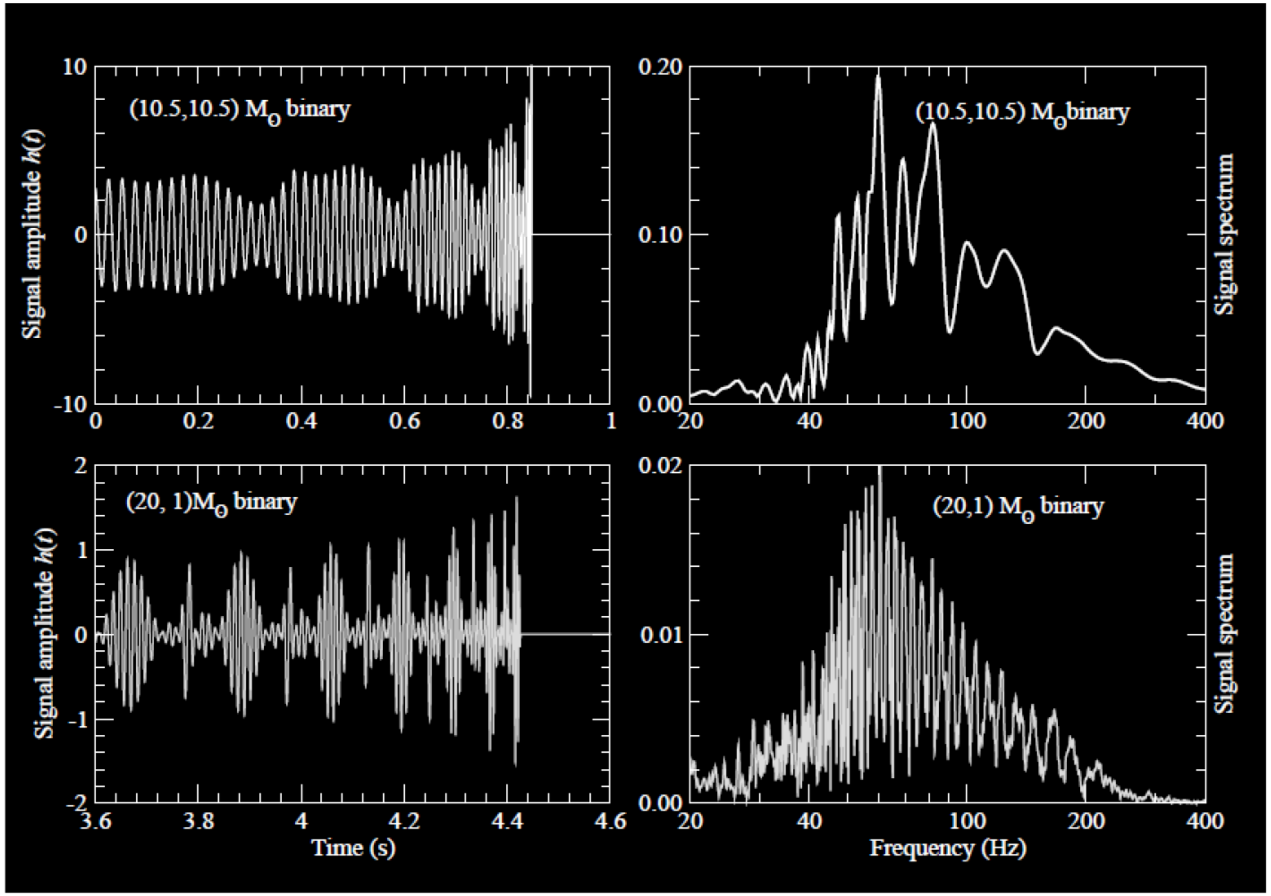


NGC 2276-3c: NASA's Chandra Finds Intriguing Member of Black Hole Family Tree
http://chandra.harvard.edu/photo/2015/ngc2276/

Provide early warning alerts hours in advance

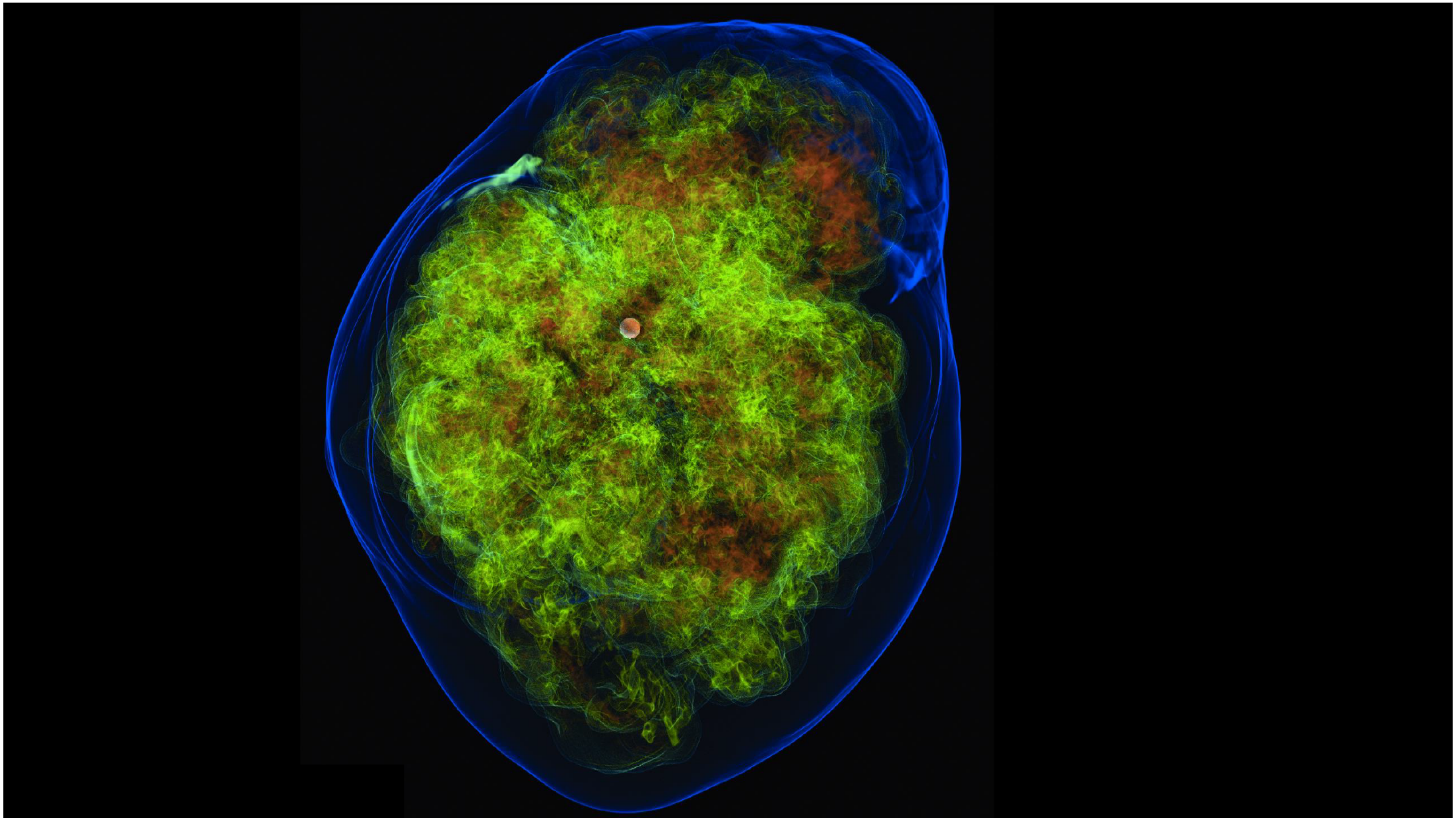
A BNS system will stay in ET's sensitivity band for nearly 20 hours starting from 2 Hz, and a little less than 2 hours starting from 5 Hz. For the same lower frequency limits the duration of a BBH signal from a pair of 10 M BHs is 45 minutes and 4 minutes

It is of great importance to study spin-precession effects. Modulations encode the parameters of sources such as their masses, spins, and inclination of the orbit



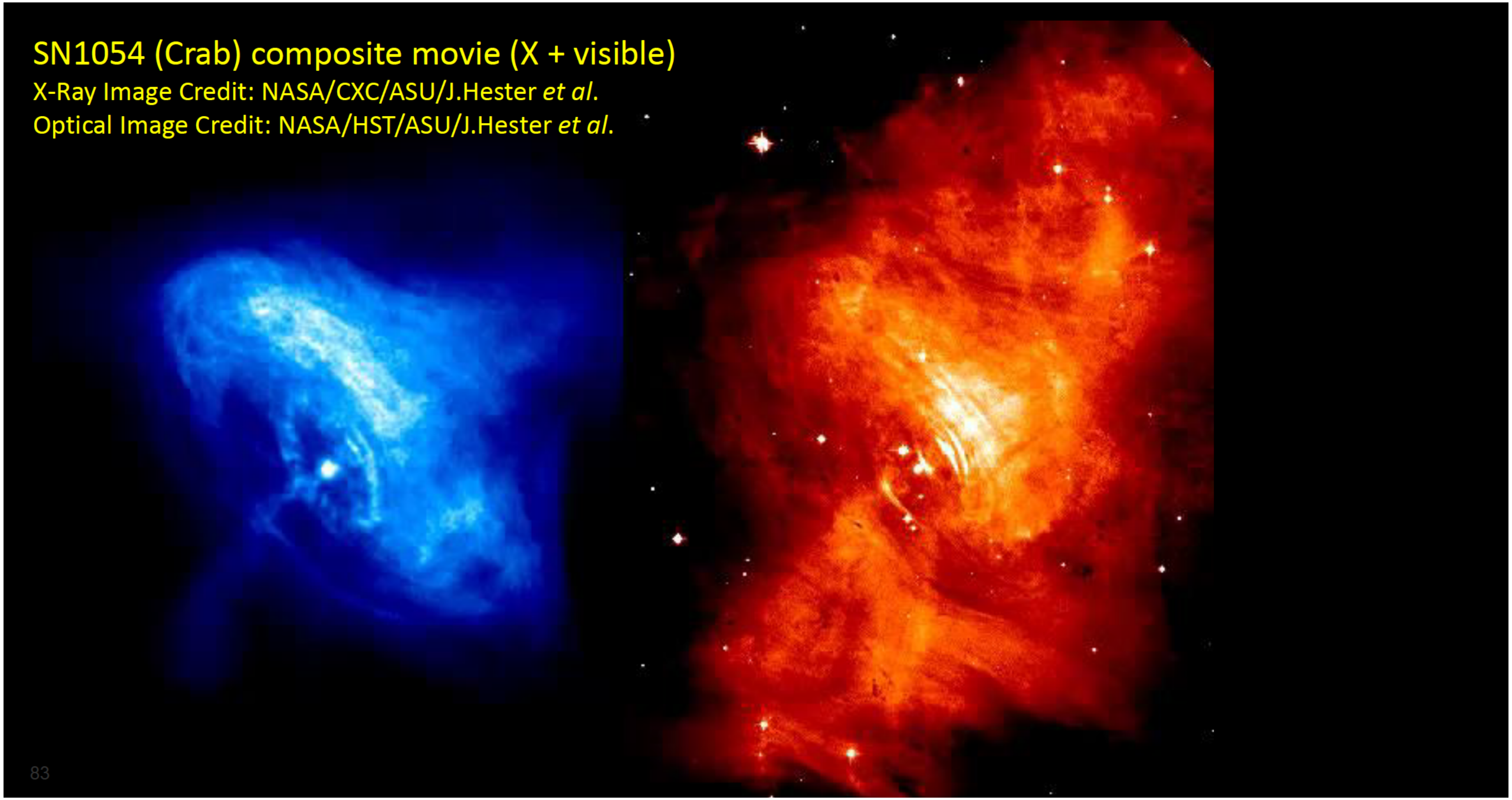
Physics of supernovae

Study progenitor mass, proto neutron star (NS) core oscillations, core rotation rate, mass accretion rate from shock, geometry of core collapse, effects of NS Equation of State, fate of collapse: NS or BH



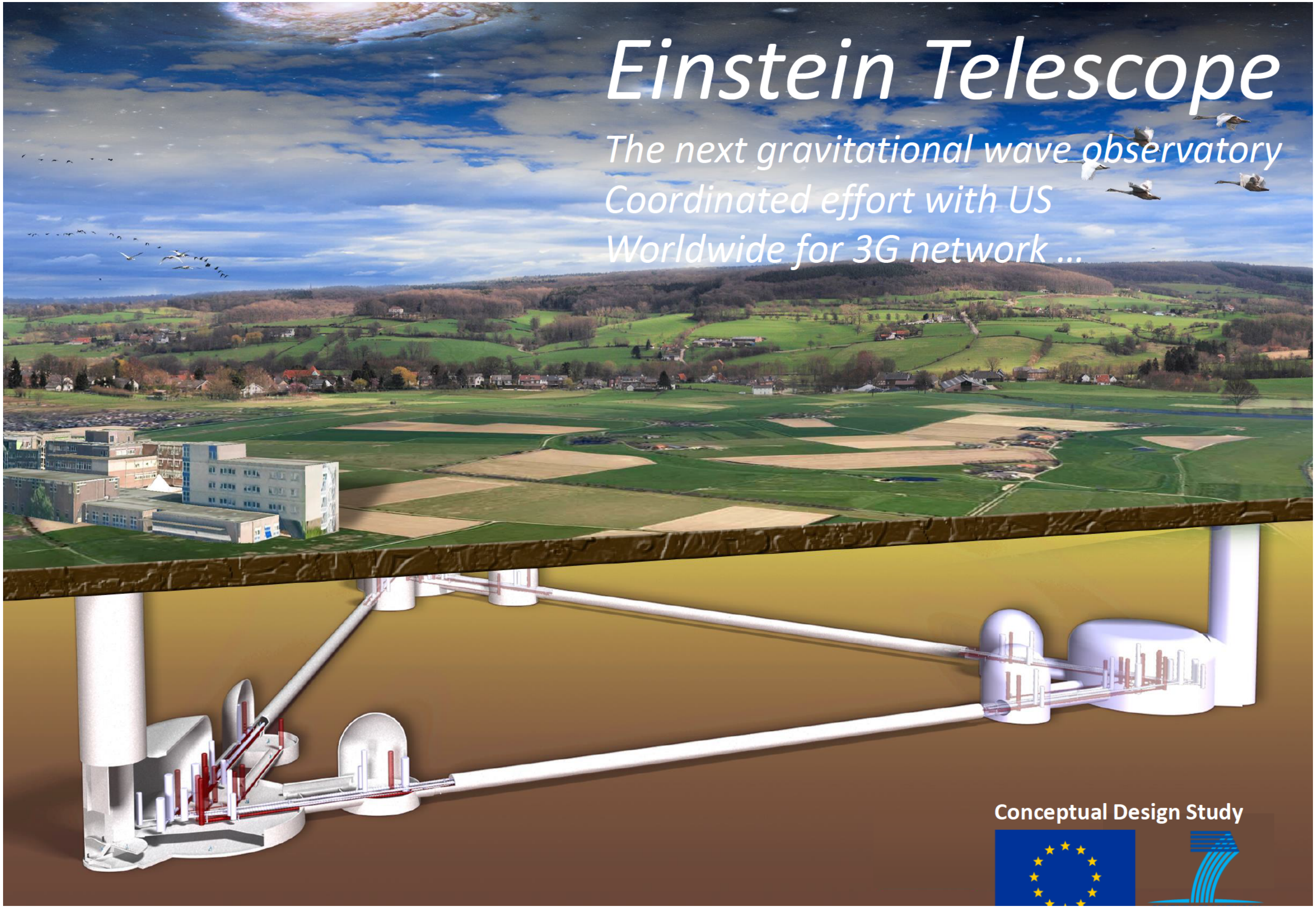
Physics of neutron stars

Deformation due to elastic stresses or magnetic field not aligned to the rotation axis, free precession around rotation axis, excitation of long-lasting oscillations (e.g. *r*-modes), deformation due to matter accretion (e.g. LMXB)



Physics from the early Universe

A stochastic background of gravitational waves may be observed from the earliest stages of the Universe

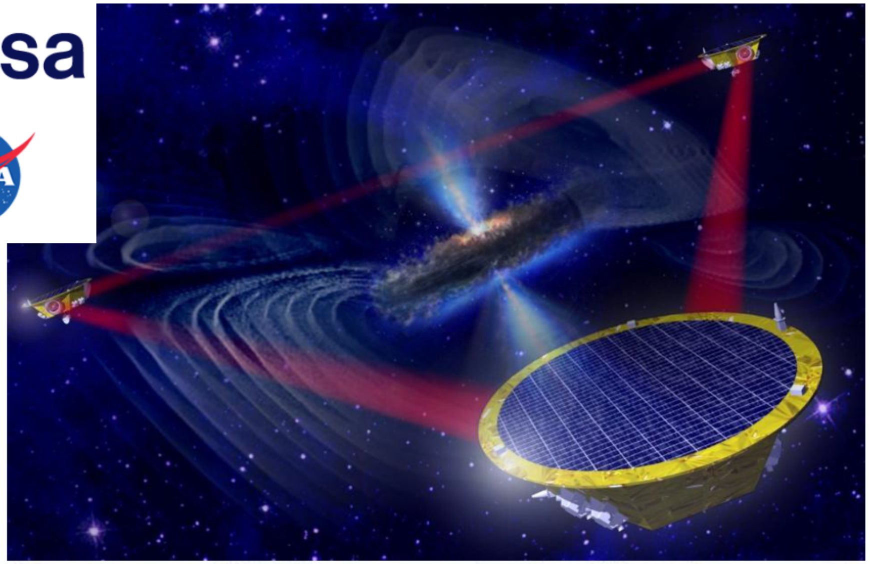

Einstein Telescope
The next gravitational wave observatory
Coordinated effort with US
Worldwide for 3G network …
Conceptual Design Study

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

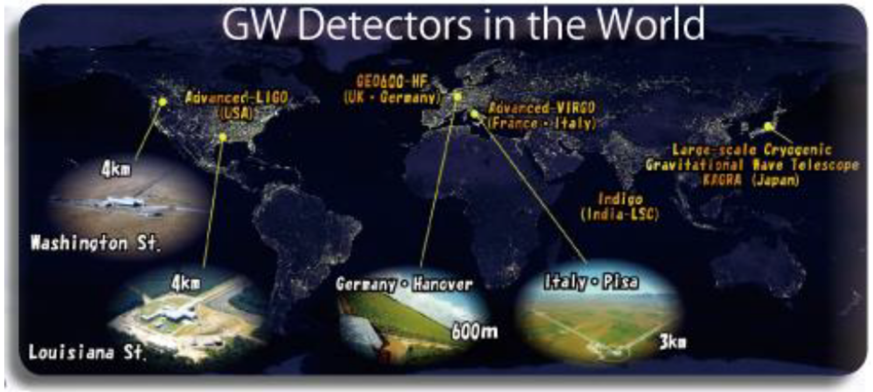
Gravitational wave research

- 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