Astrofisica Nucleare e Subnucleare

Gravitational Waves

Astrofisica Nucleare e Subnucleare

GRB and GW

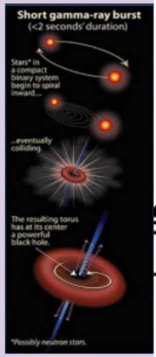
Electromagnetic emission

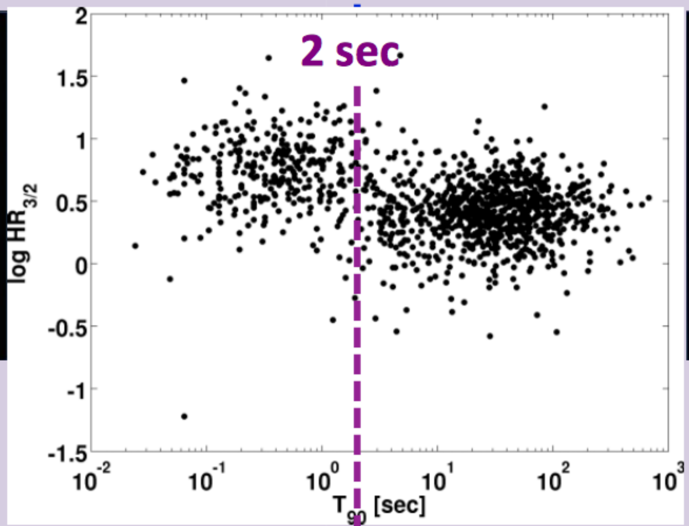
Merger of NS-NS / NS-BH

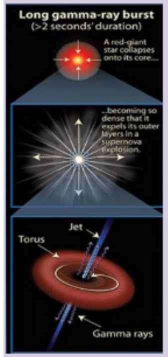
Core collapse of massive star

Gamma-Ray Burst

Short Hard GRB







Long Soft GRB

Kilonovae

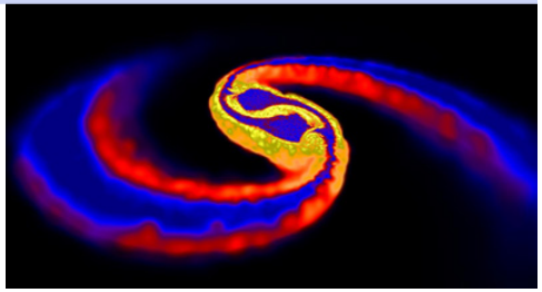
(Optical/IR, radio remnant)

Supernovae

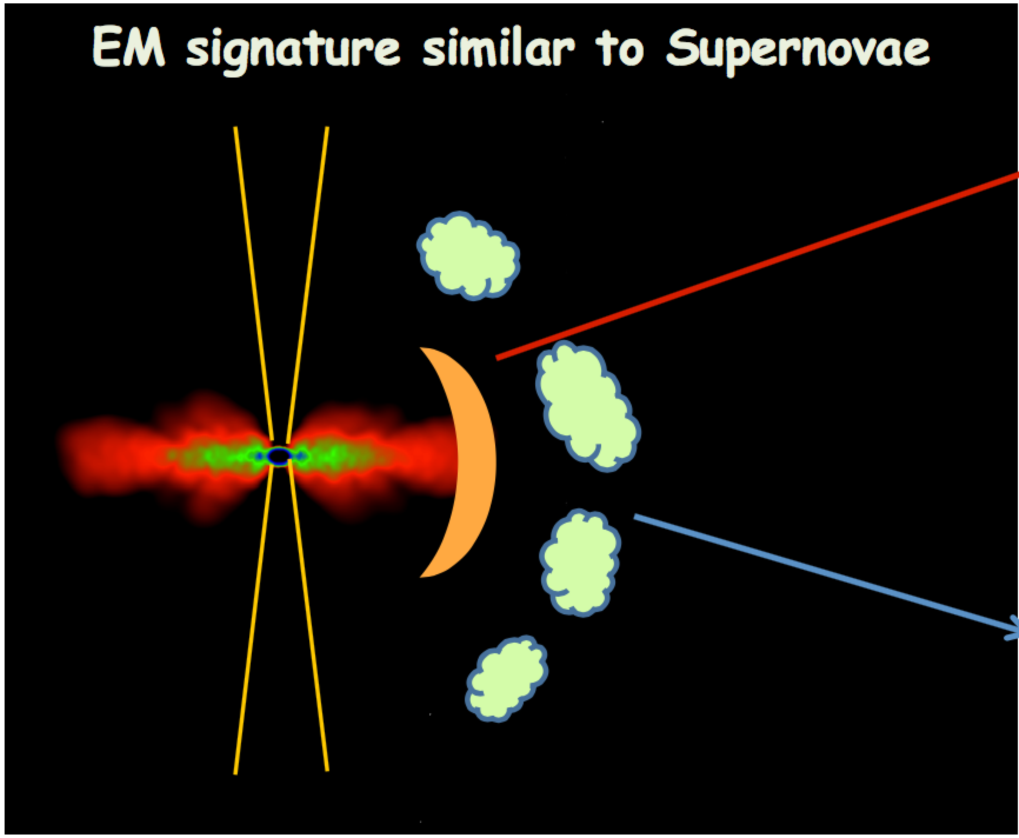
Type II, Ib/c

Kilonovae

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected**
during **NS-NS NS-BH mergers**
at **sub-relativistic velocity (0.1-0.2 c)**



(Piran et al. 2013, MNRAS, 430; Rosswog et al. 2013 , MNRAS, 430)



Macronova – Kilonova

short lived IR-UV signal (days) powered by the radioactive decay of heavy elements synthesized in the ejected outflow

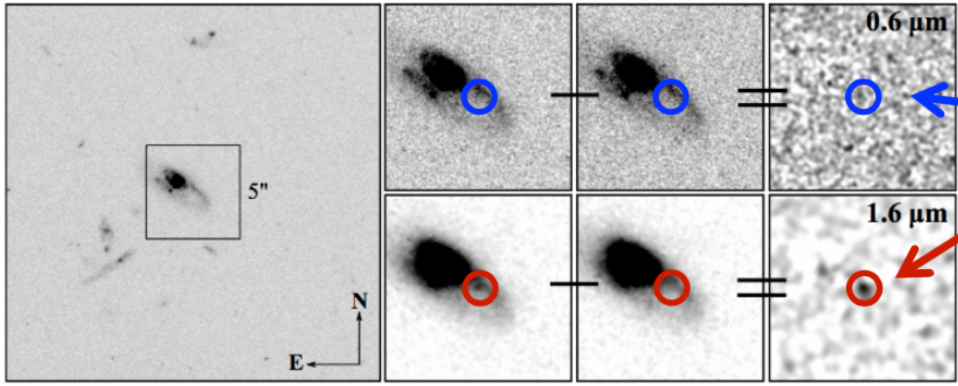
Kulkarni 2005, astro-ph0510256;
Li & Paczynski 1998,ApJL, 507
Metzger et al. 2010, MNRAS, 406;
Piran et al. 2013, MNRAS, 430

RADIO REMNANT

long lasting radio signals (years) produced by interaction of ejected sub-relativistic outflow with surrounding matter **Piran et al. 2013, MNRAS, 430**

Possible HST kilonova detection for short GRB 130603B after 9.4 days

Tanvir et al. 2013, Nature ,500

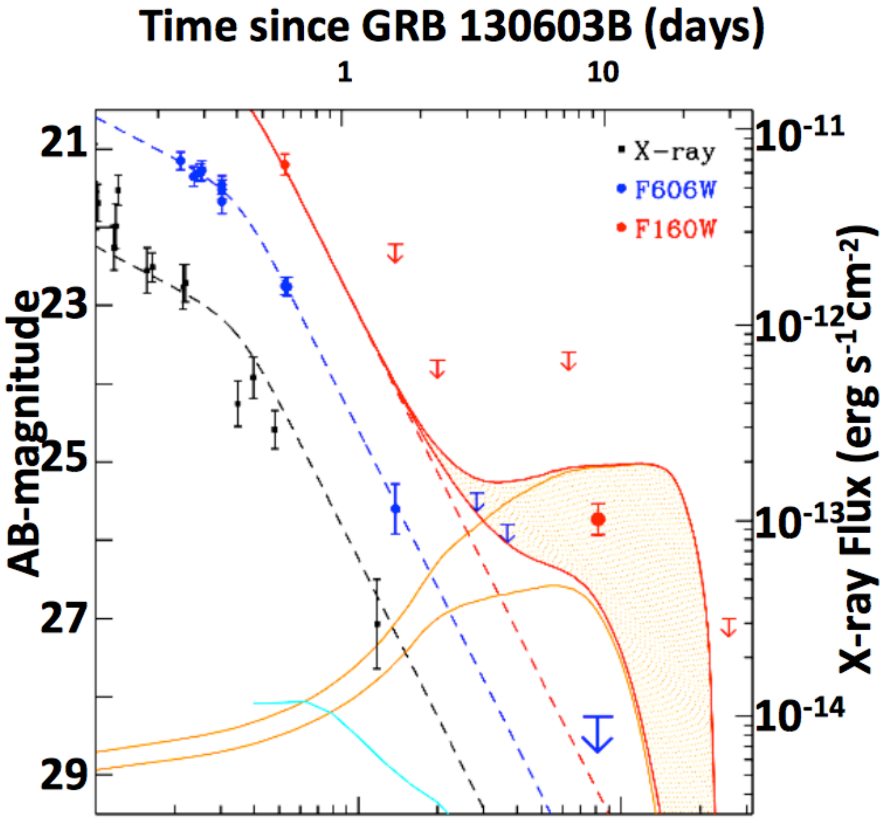


HST two epochs (9d, 30d) observations

F606W/optical

NIR/F160W

Afterglow and host galaxy z=0.356



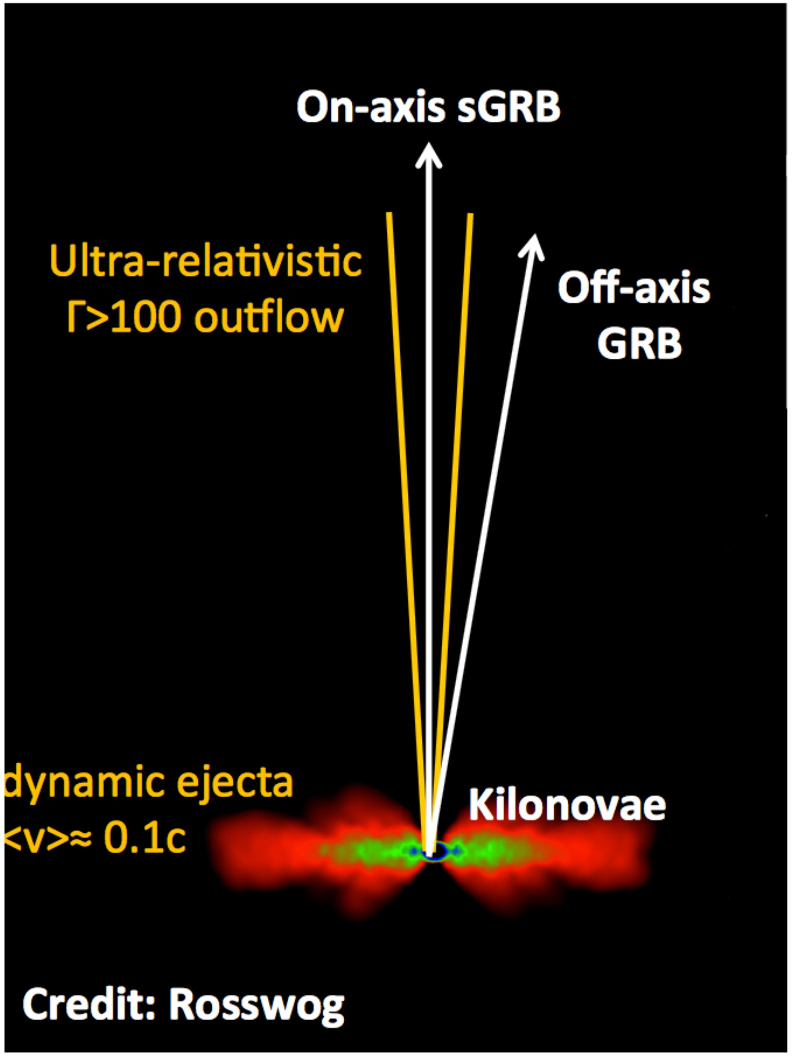
Orange curves → kilonova NIR model

ejected masses of 10^{-2} Mo and 10^{-1}Mo

Solid red curves → afterglow +kilonova

Cyan curve → kilonova optical model

EM signals from NS-NS/NS-BH merger and massive star core-collapse



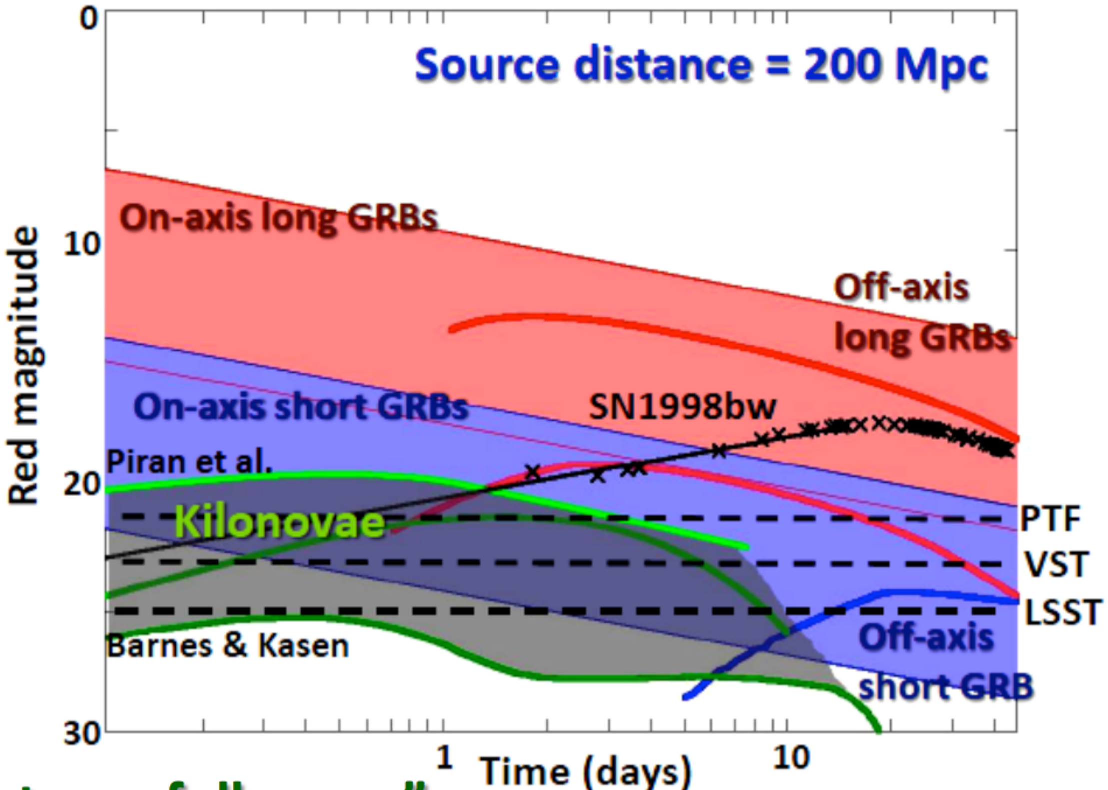
❖ **Prompt ϒ-ray emission (beamed):**

GRB → GW search **"GRB Triggered analysis"**

❖ **GRB afterglow emission, kilonovae:**

GW trigger → EM search

"Low-latency EM follow-up"



❖ **Radio:**

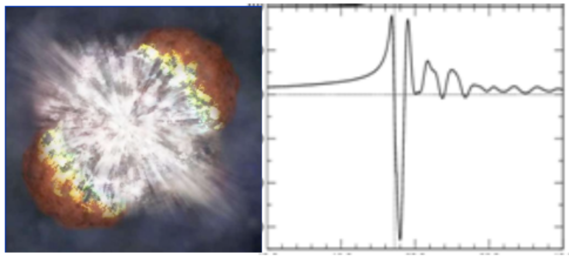
GW trigger → radio search **"High-latency follow-up"**

Blind radio search → GW search **"Triggered off-line analysis"**

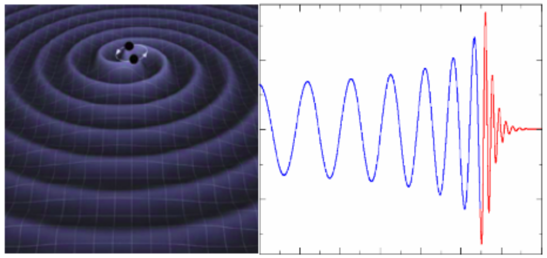
2009-2010 first Electromagnetic follow-up of candidate GW events

Low-latency GW data analysis pipelines

GW transient searches



Unmodeled GW burst
(< 1 sec duration)
Arbitrary waveform
→ Excess power



Compact Binary Coalescence
Known waveform
→ Matched filter

enabled us to:

1) identify GW candidates in "real time"

2) obtain prompt EM observations

Abadie et al. 2012, A&A 539
Abadie et al. 2012, A&A 541

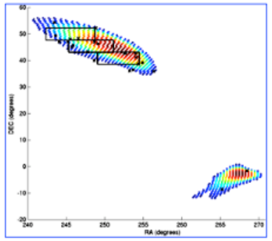
GW triggers

Sky Pointing Position

EM facilities

LIGO-H LIGO-L

Virgo



Event validation

"Search Algorithms"
to identify the GW-triggers

"Software" to identify GW-trigger for the EM follow-up:

- **select statistically significant triggers wrt background**
- **determine telescope pointing**

~ 10 min. → ~ 30 min.

Advanced detector era latency expected to be improved to few minutes!

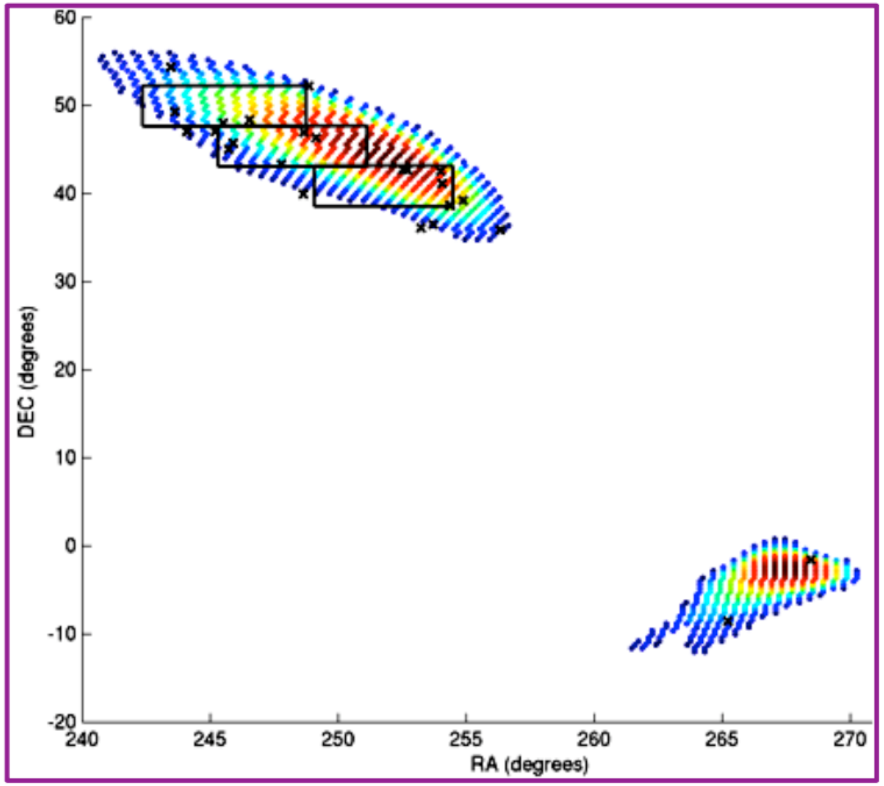
Abadie et al. 2012, A&A 539
Abadie et al. 2012, A&A 541
Evans et al. 2012, ApJS 203
Aasi et al. 2014, ApJS, 211

Additional priors to improve the localization accuracy and increase the chance to observe the EM counterpart

To determine each telescope pointing position:

The probability skymap of each GW trigger was 'weighted'

→ taking into account **luminosity** and **distance of galaxies within the LIGO/Virgo horizon** for binary containing a NS 50 Mpc



Galaxy targeting strategy

Astrofisica Nucleare e Subnucleare

Gravitational Waves Science

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

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

GW Science

Academic Training Lecture Regular Programme

Gravitational Waves: The Present and the Future (1/3)

by Jo van den Brand (NIKHEF, Amsterdam, The Netherlands)

Wednesday 9 Oct 2019, 11:00 → 12:00 Europe/Rome

222/R-001 (CERN)

Description Gravitational waves detection and measurements, the discovery of which was announced to the world in 2016, is a fast moving field. Several events have been detected in LIGO and LIGO+VIRGO, and in spectacular coincidence with gamma ray burst detectors. Clearly we are just at the start of this fast developing discipline. These lectures will discuss the experimental aspects of gravitational wave detection, the information gathered from the present experimental results and the road ahead for these experiments.

CERN_Academic_L... Recording

From the same series 2 3

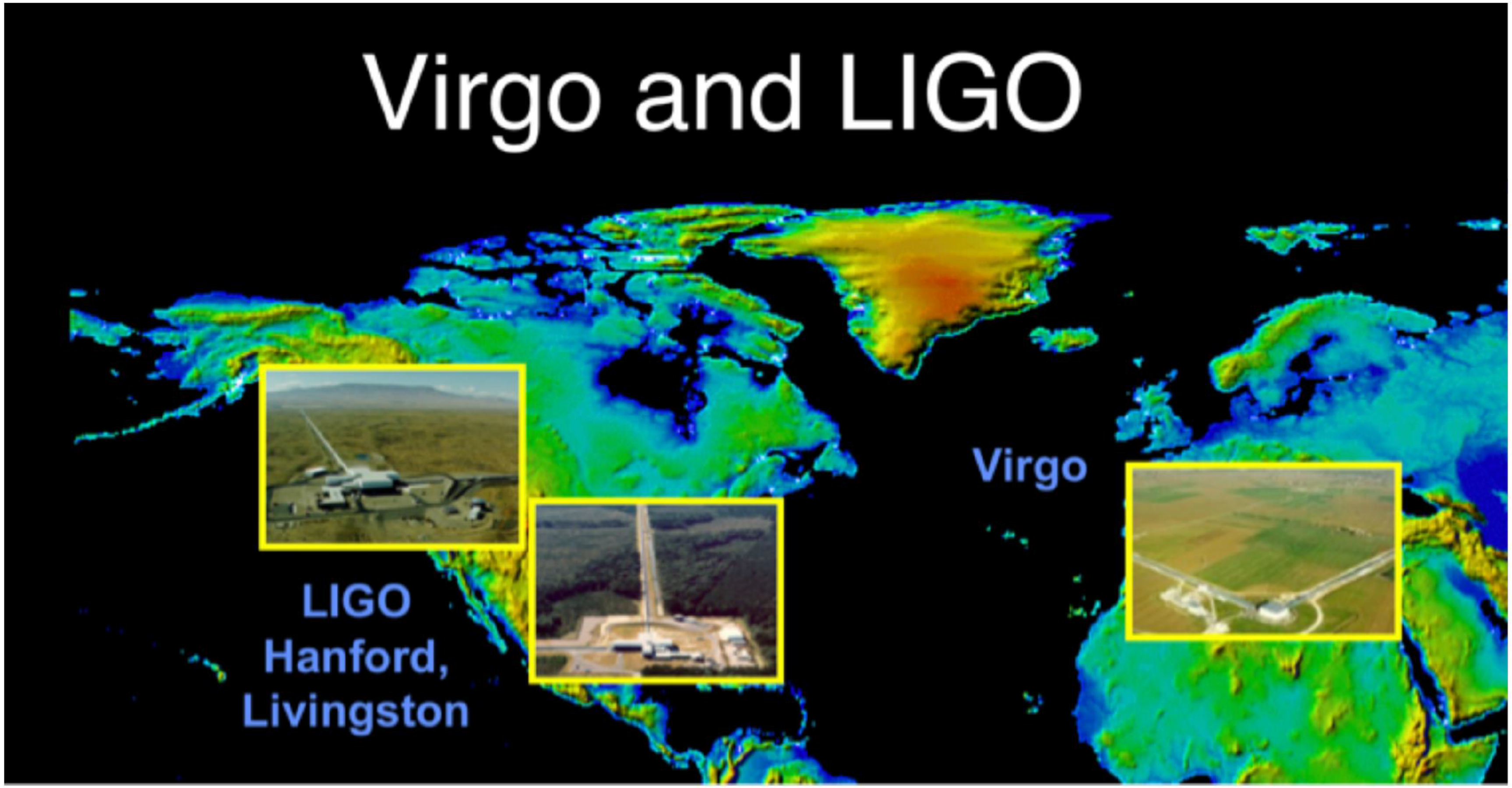
Organized by Jamie Boyd / 90 Participants

https://indico.cern.ch/event/806259/

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



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

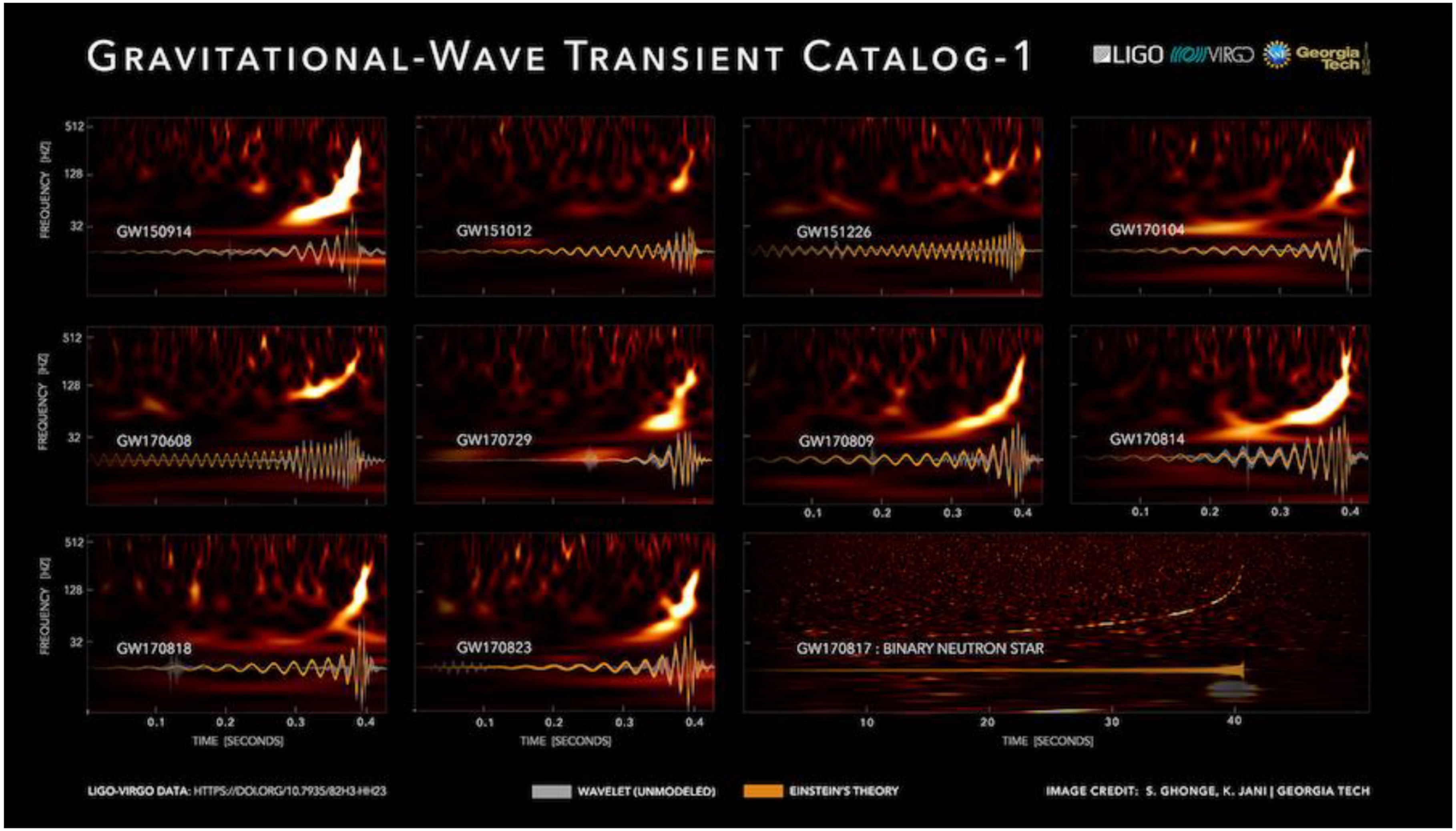


Table of O1 and O2 triggers with source properties

See arXiv:1811.12907

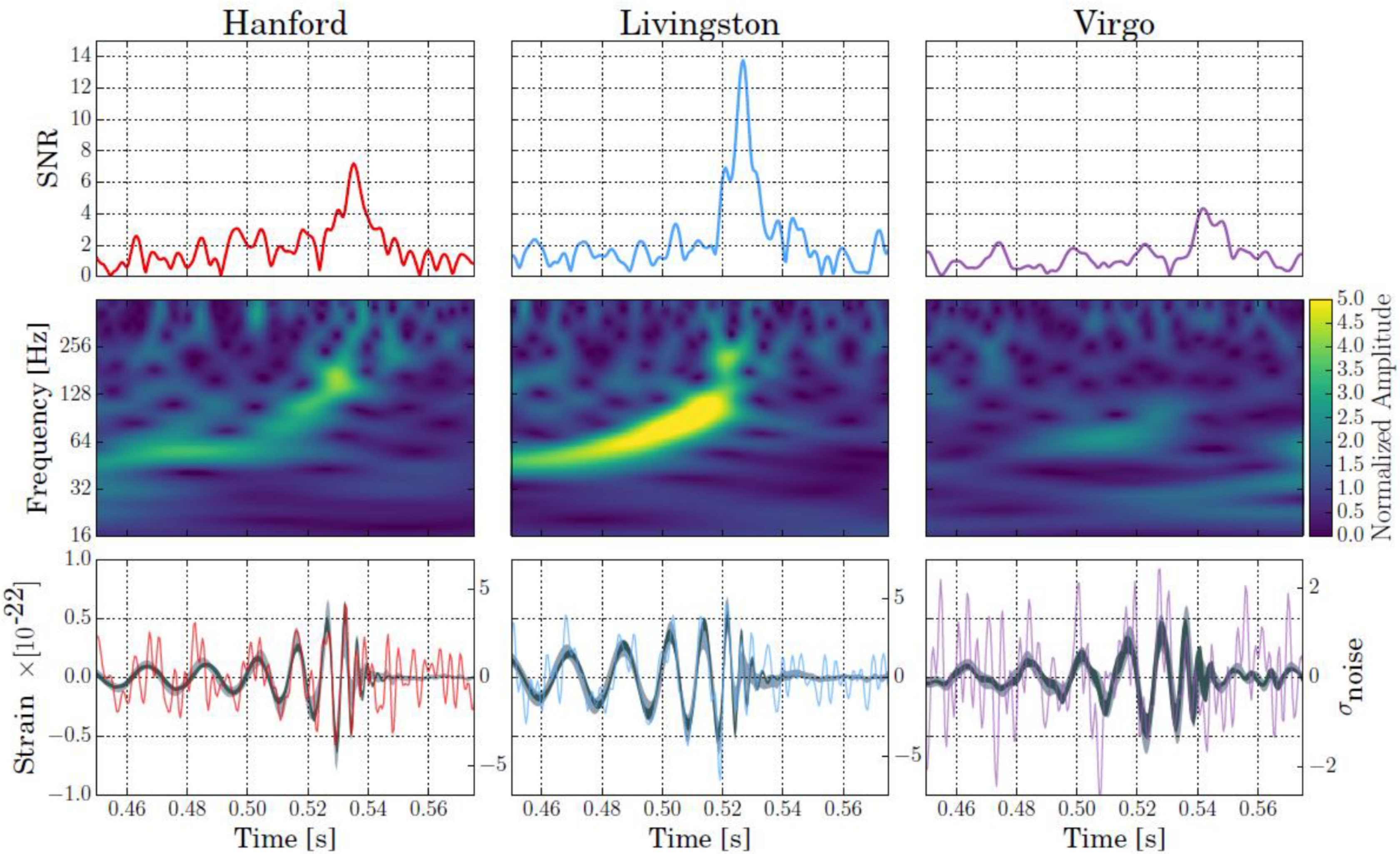
Virgo data contributed to Parameter Estimation of 5 events

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

LIGO EGO European Gravitational Observatory LSC LIGO Scientific Collaboration VIRGO

First triple detection by Virgo and LIGO: GW170814

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 GWs

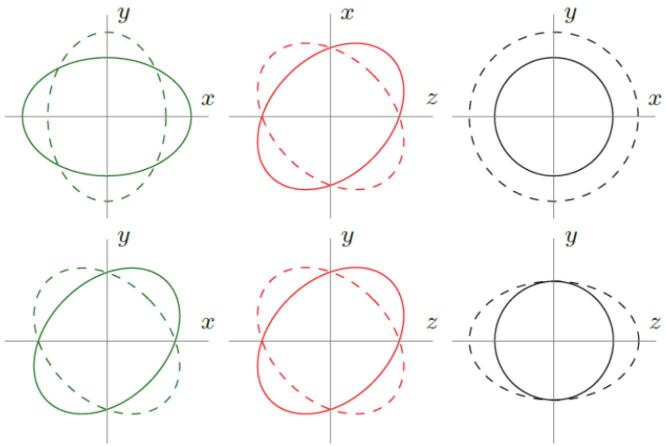


Fundamental physics: polarization of gravitational waves

Polarization is a fundamental property of spacetime. It determined how spacetime can be deformed. General metric theories allow six polarizations. General Relativity allows two (tensor) polarizations

GR only allows (T) polarizations

General metric theories also know
vector (V) and scalar (S) polarizations



Theory	+	x	x	y	b	l
General Relativity	allowed	allowed	forbidden	forbidden	forbidden	forbidden
GR in noncompactified 4/6D Minkowski	allowed	allowed	allowed	allowed	allowed	allowed
Einstein-Æther	allowed	allowed	allowed	allowed	allowed	allowed
5D Kaluza-Klein	allowed	allowed	allowed	allowed	allowed	forbidden
Randall-Sundrum braneworld	allowed	allowed	forbidden	forbidden	forbidden	forbidden
Dvali-Gabadadze-Porrati braneworld	allowed	allowed	depends	depends	depends	depends
Brans-Dicke	allowed	allowed	forbidden	forbidden	allowed	allowed
f(R) gravity	allowed	allowed	forbidden	forbidden	allowed	allowed
Bimetric theory	allowed	allowed	allowed	allowed	allowed	allowed
Four-Vector Gravity	forbidden	forbidden	allowed	allowed	forbidden	forbidden

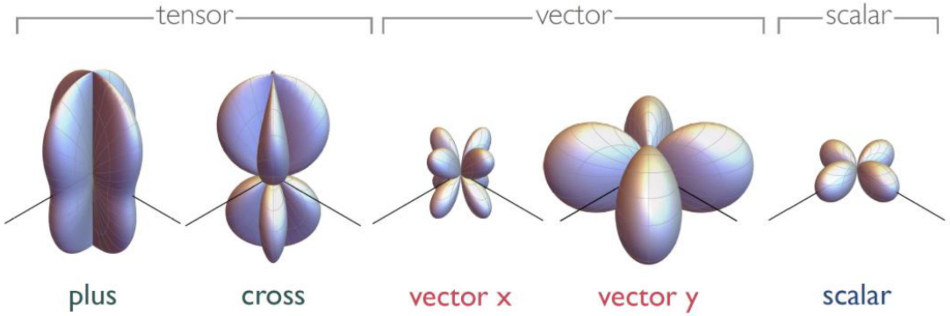
Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther].   allowed / depends / forbidden

GW170814: first test of polarizations of GW

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 allowing for fundamental test of the polarizations of spacetime



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

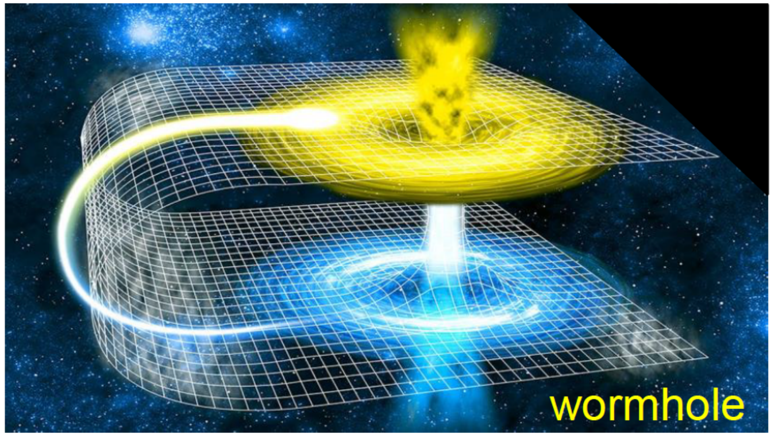
This is a first test, and for BBH we do not know the source position very well

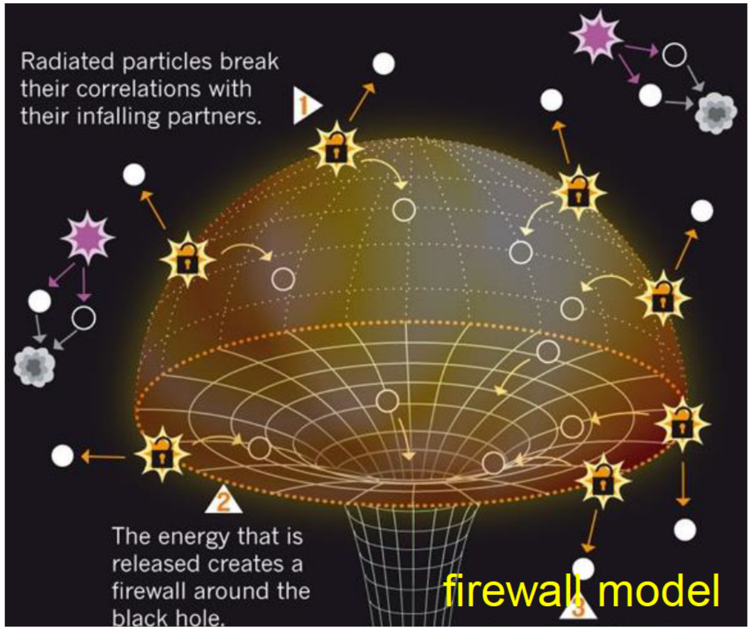
https://arxiv.org/abs/1709.09660

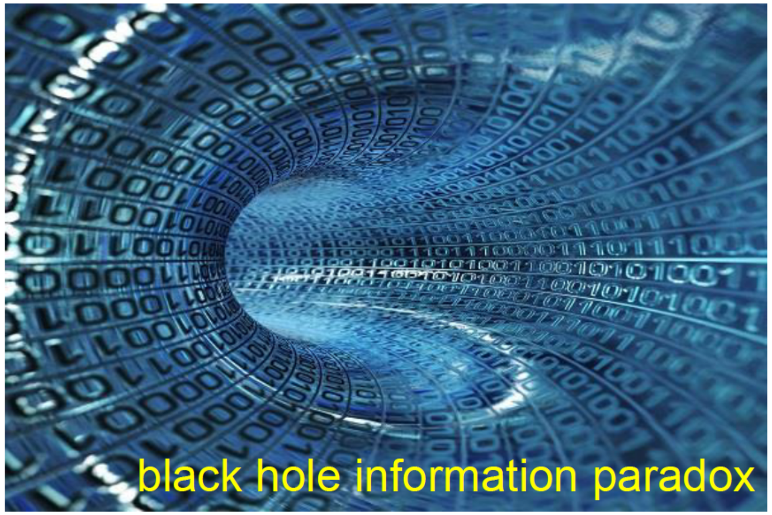
https://arxiv.org/abs/1710.03794

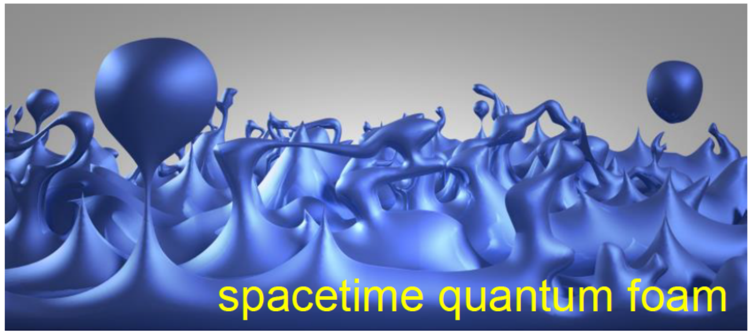
Fundamental physics: did we observe black holes?

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



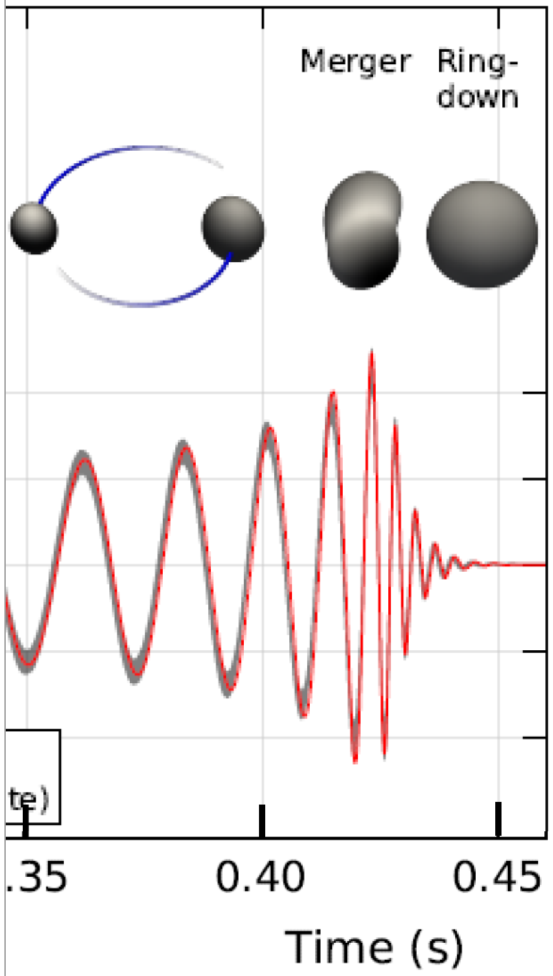


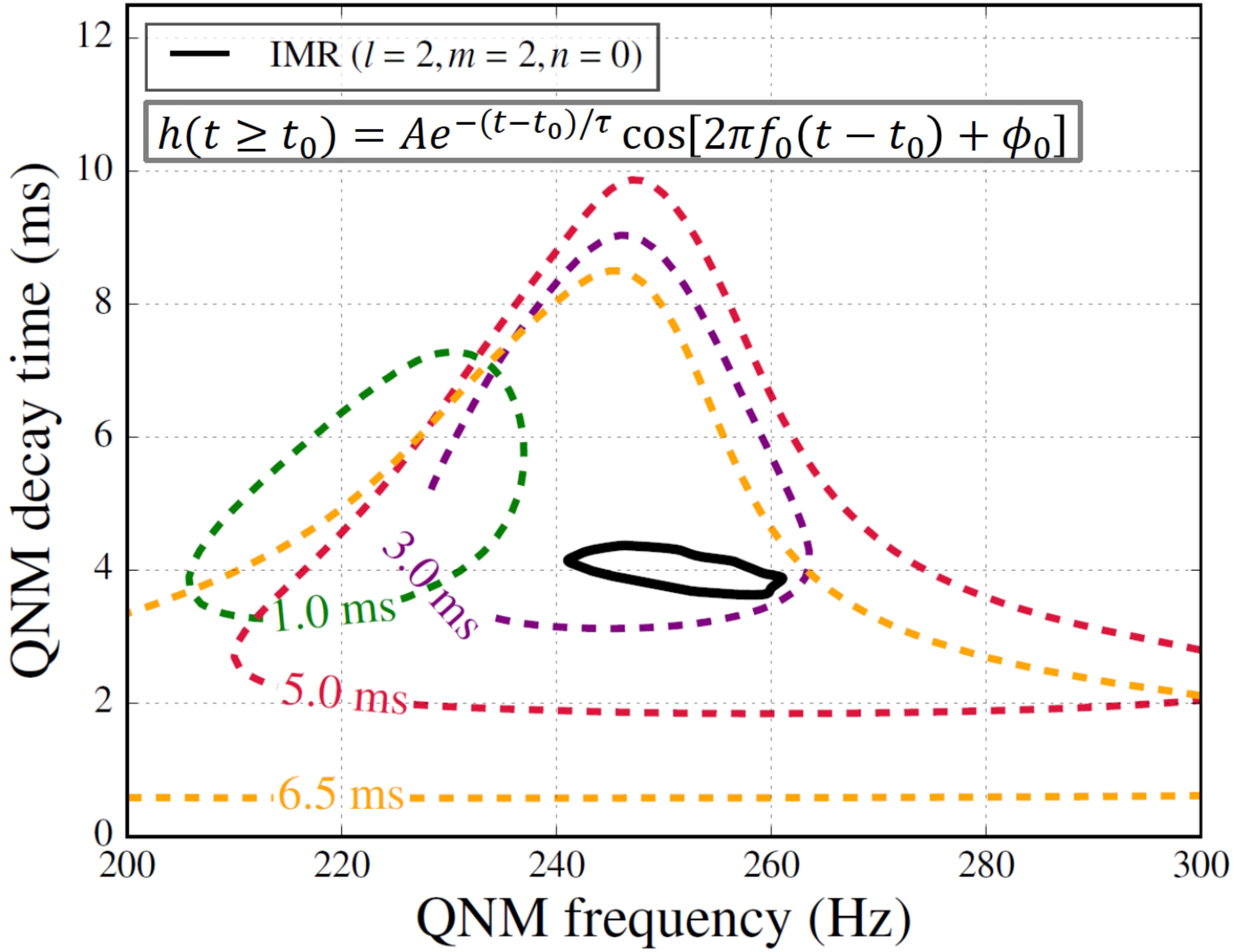




Is a black hole created in the final state?

From the inspiral we can predict that the ringdown frequency of about 250 Hz and 4 ms decay time. This is what we measure (http://arxiv.org/abs/1602.03841). We will pursue this further and perform test of no-hair theorem. This demands good sensitivity at high frequency



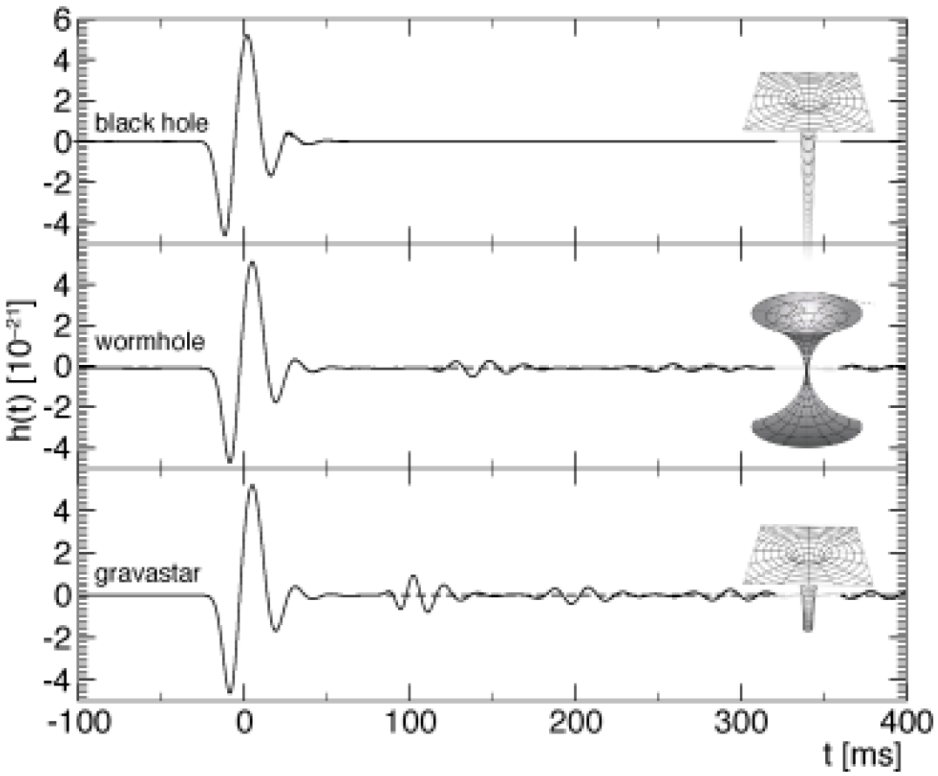


Exotic compact objects

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

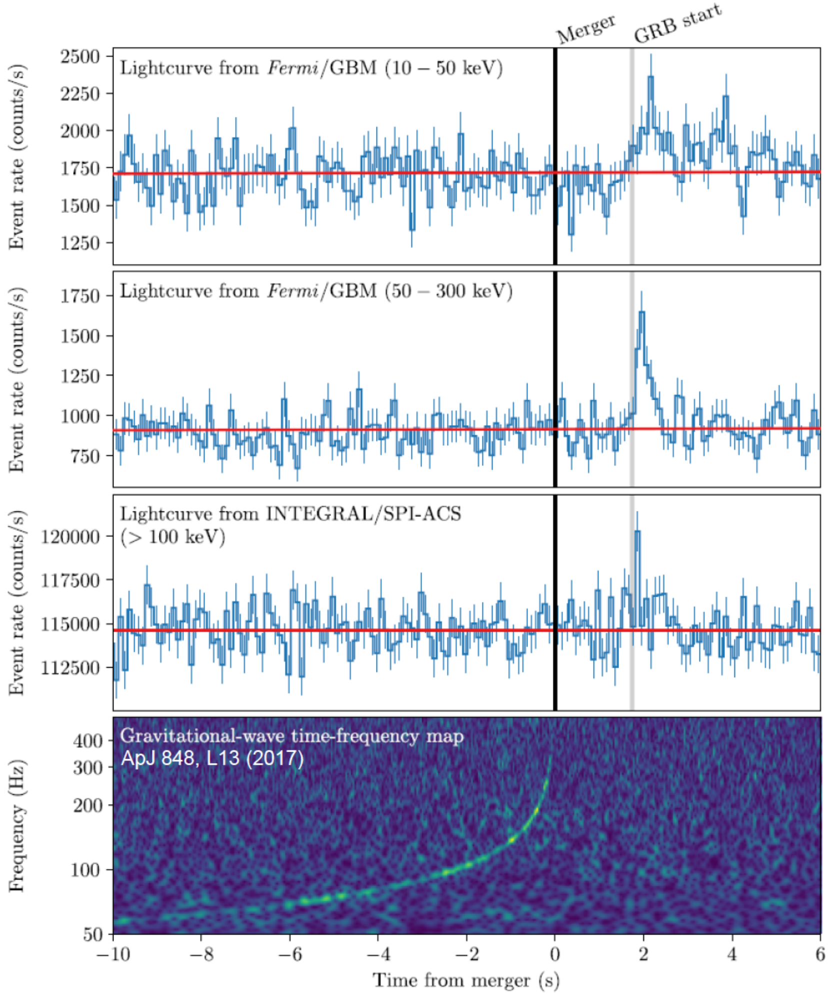
- Objects with de Sitter core where spacetime is self-repulsive
- Held together by a shell of matter
- Relatively low entropy object

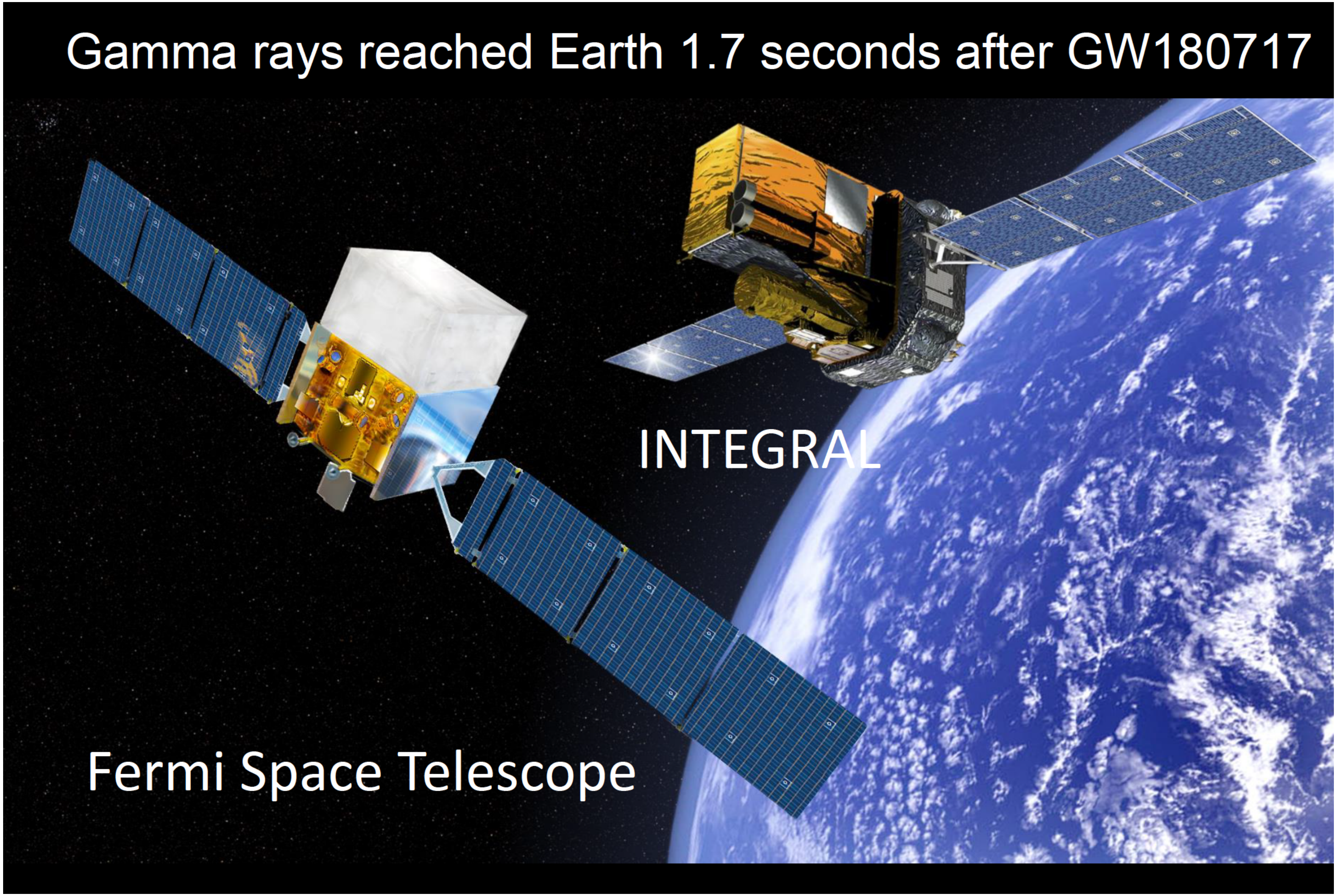
GW observables

- 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

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)

$$-3\times10^{-15} < \frac{\Delta v}{v_{EM}} < +7\times10^{-16}$$

Test of Equivalence Principle

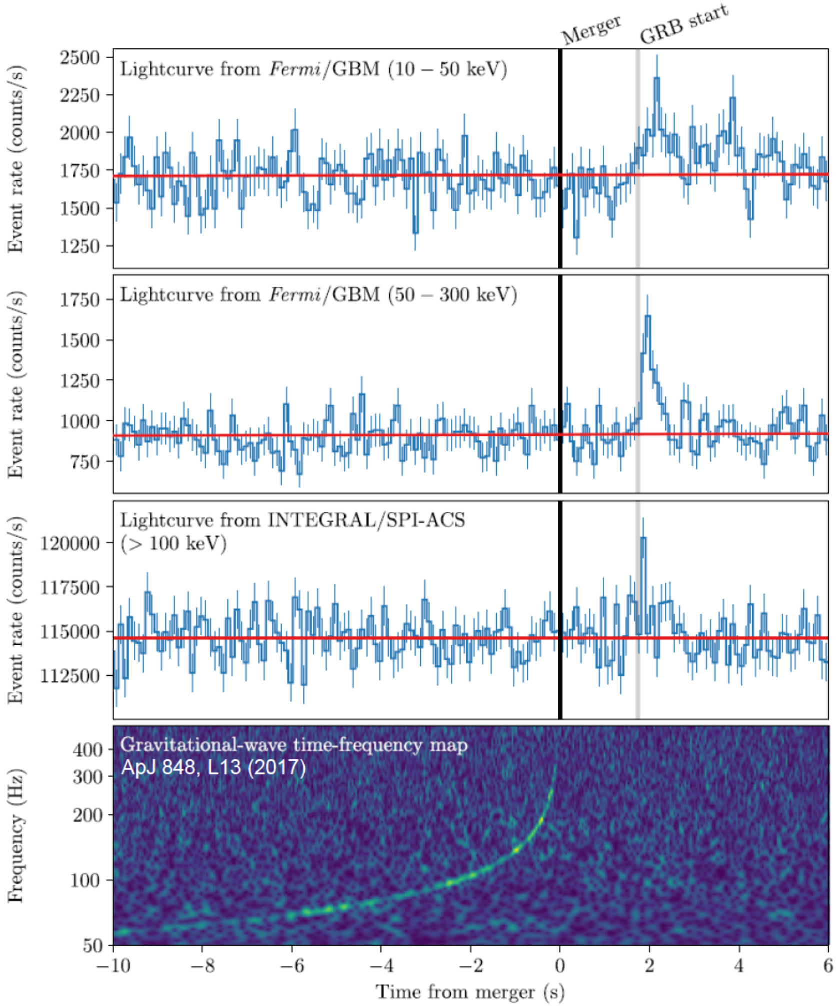
According to General Relativity, GW and EM waves are deflected and delayed by the curvature of spacetime produced by any mass (i.e. background gravitational potential). Shapiro delays affect both waves in the same manner

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

Milky Way potential gives same effect to within
$-2.6\times10^{-7} \le \gamma_{\text{GW}} - \gamma_{\text{EM}} \le 1.2\times10^{-6}$

Including data on peculiar velocities to 50 Mpc we find
$\Delta\gamma \le 4\times10^{-9}$

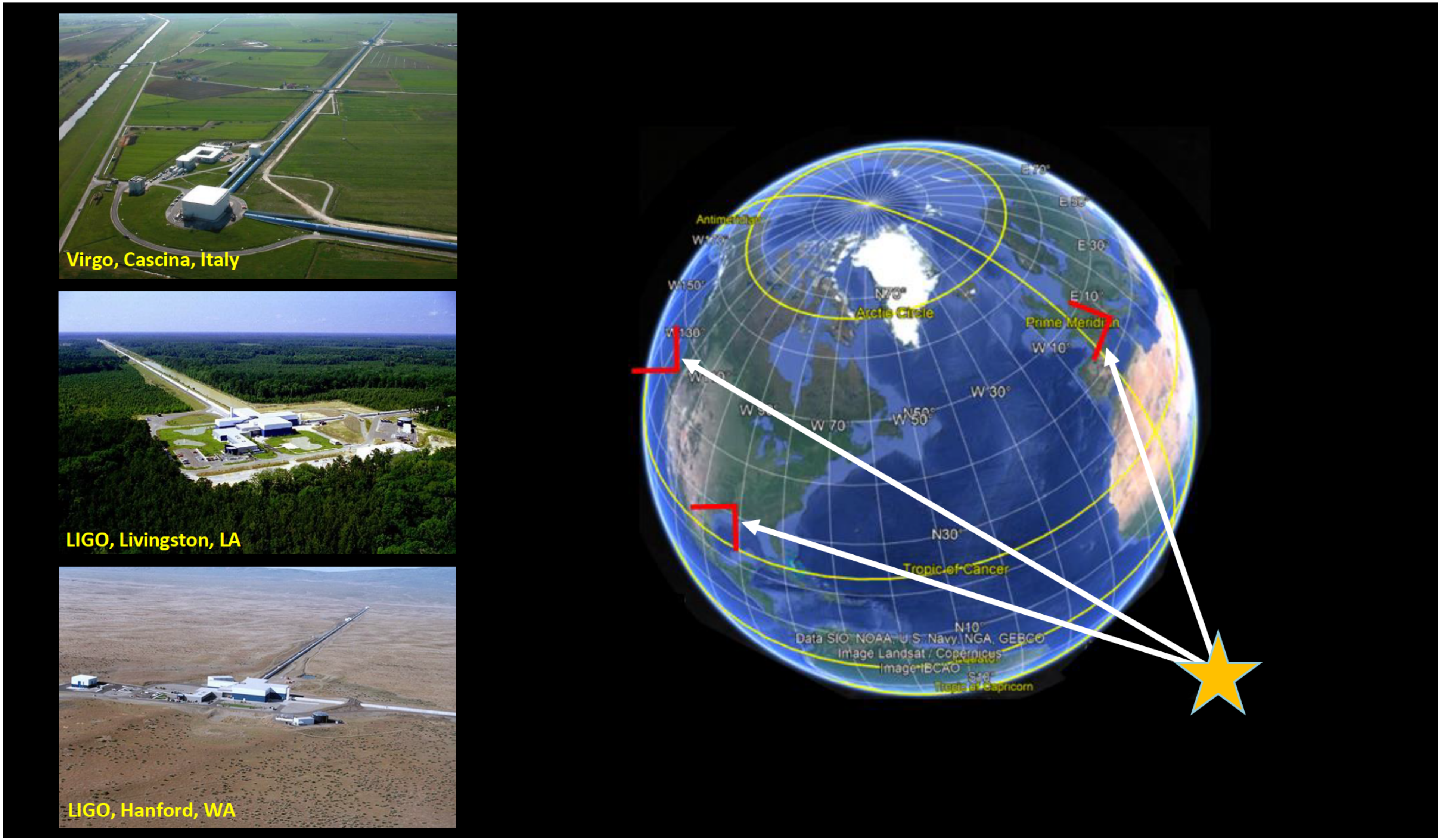
LIGO + Virgo + Fermi + INTEGRAL, ApJ 848, L13 (2017)



Consequences for some DM and DE models

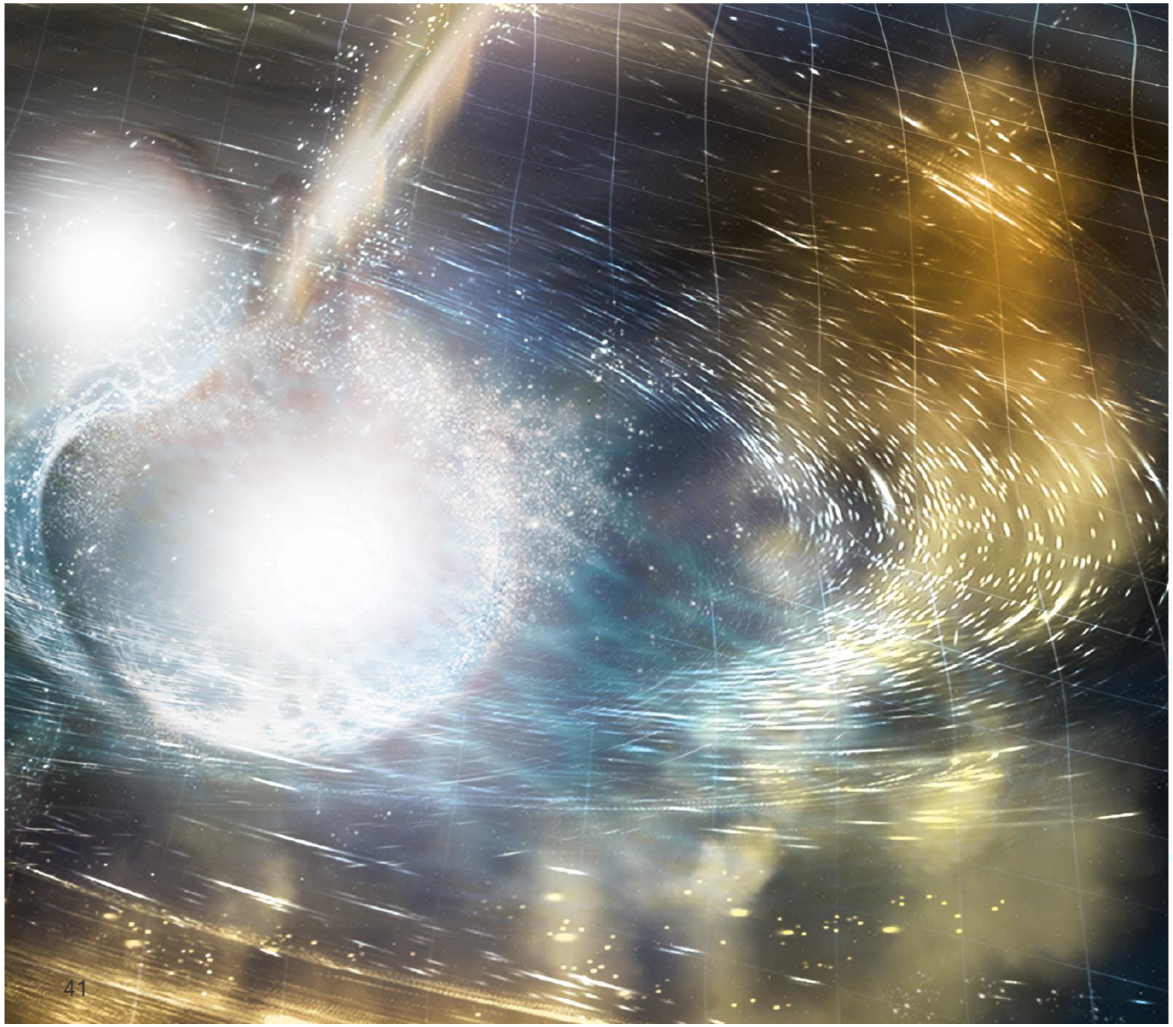
Source location via triangulation

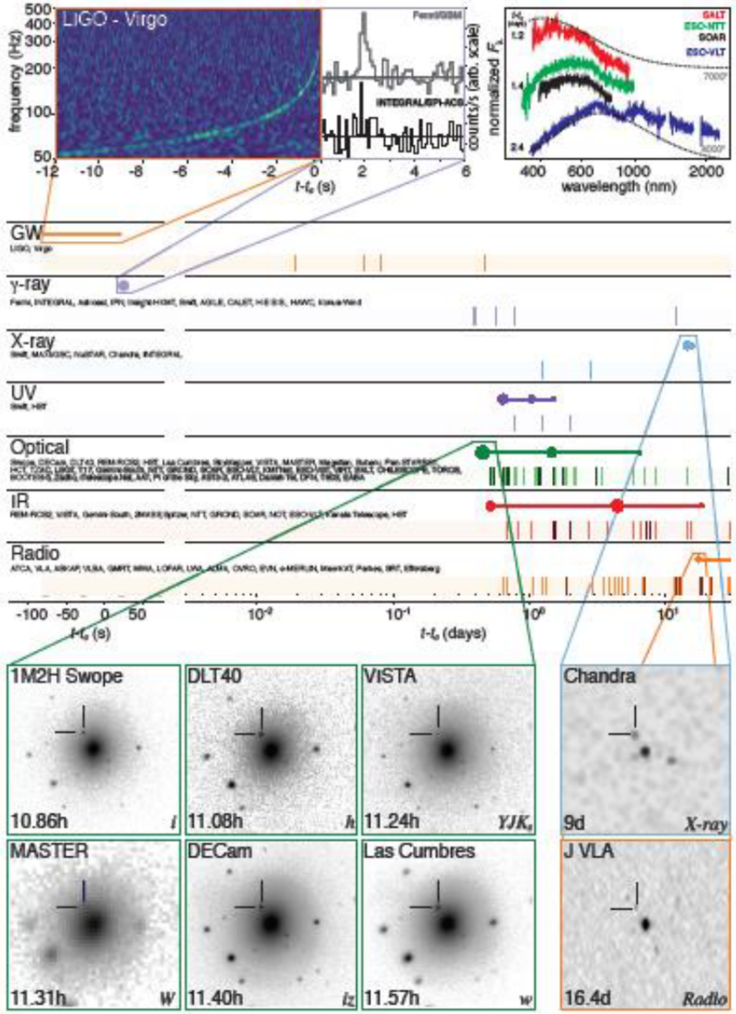
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it



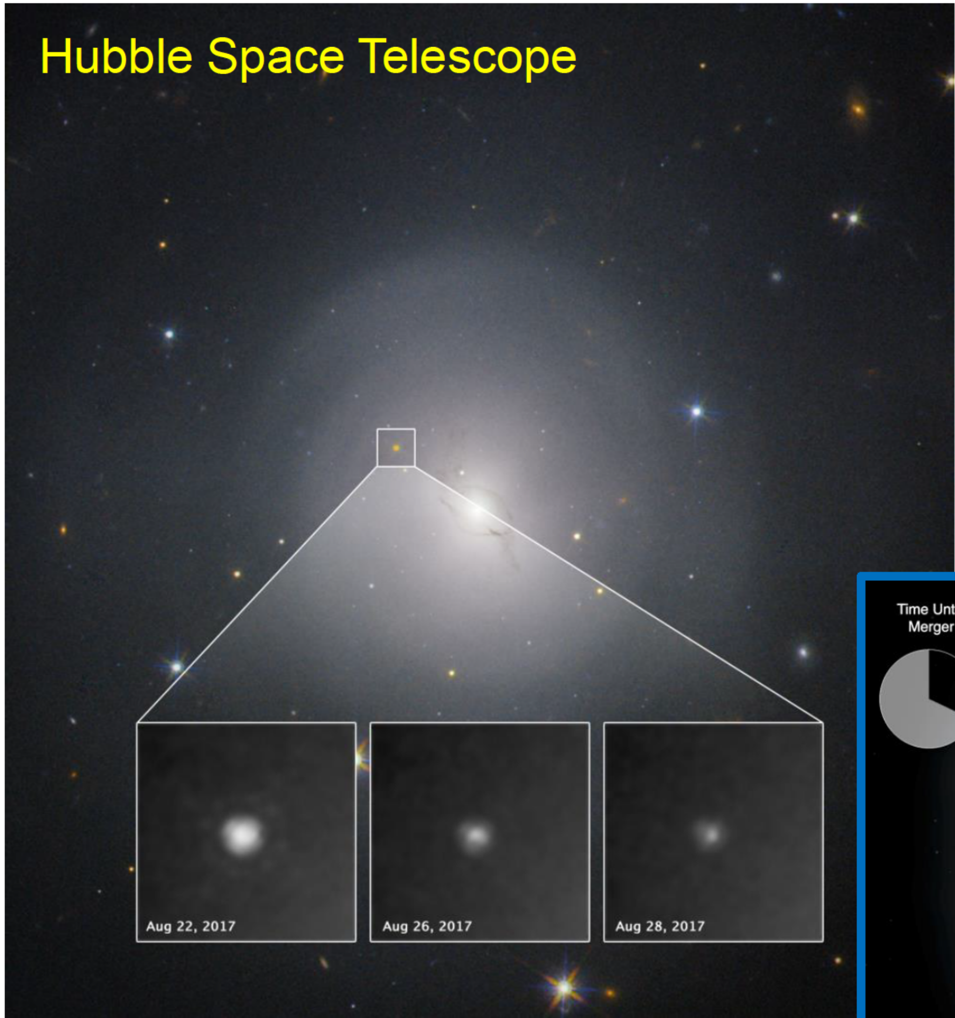
GW170817: start of multi-messenger astronomy with GW

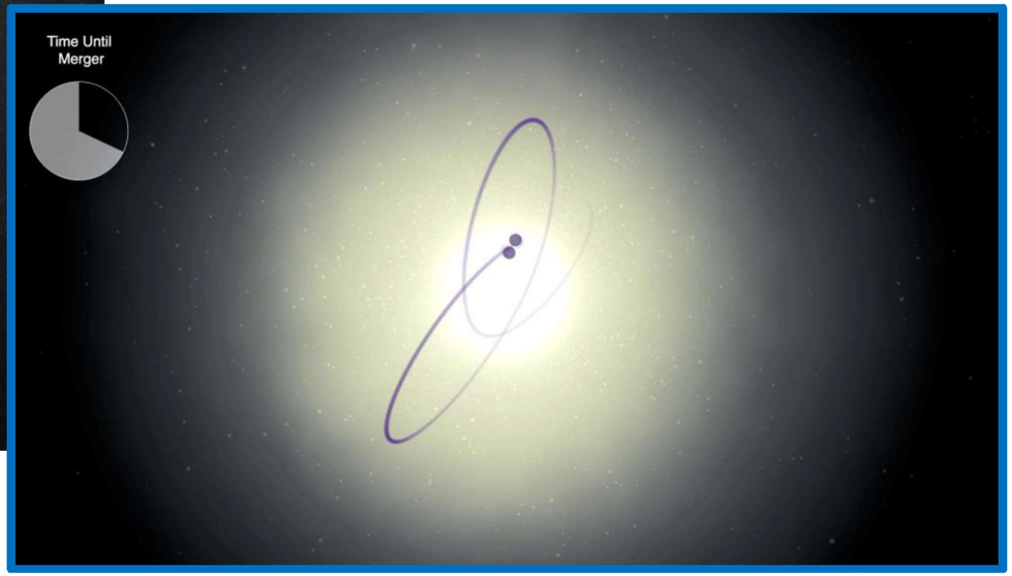
Many compact merger sources emit, besides gravitational waves, also light, gamma- and X-rays, and UV, optical, IR, and radio waves, as well as neutrino’s or other subatomic particles. Our three-detector global network allows identifying these counterparts





NGC 4993 by HST: the galactic home of GW170817

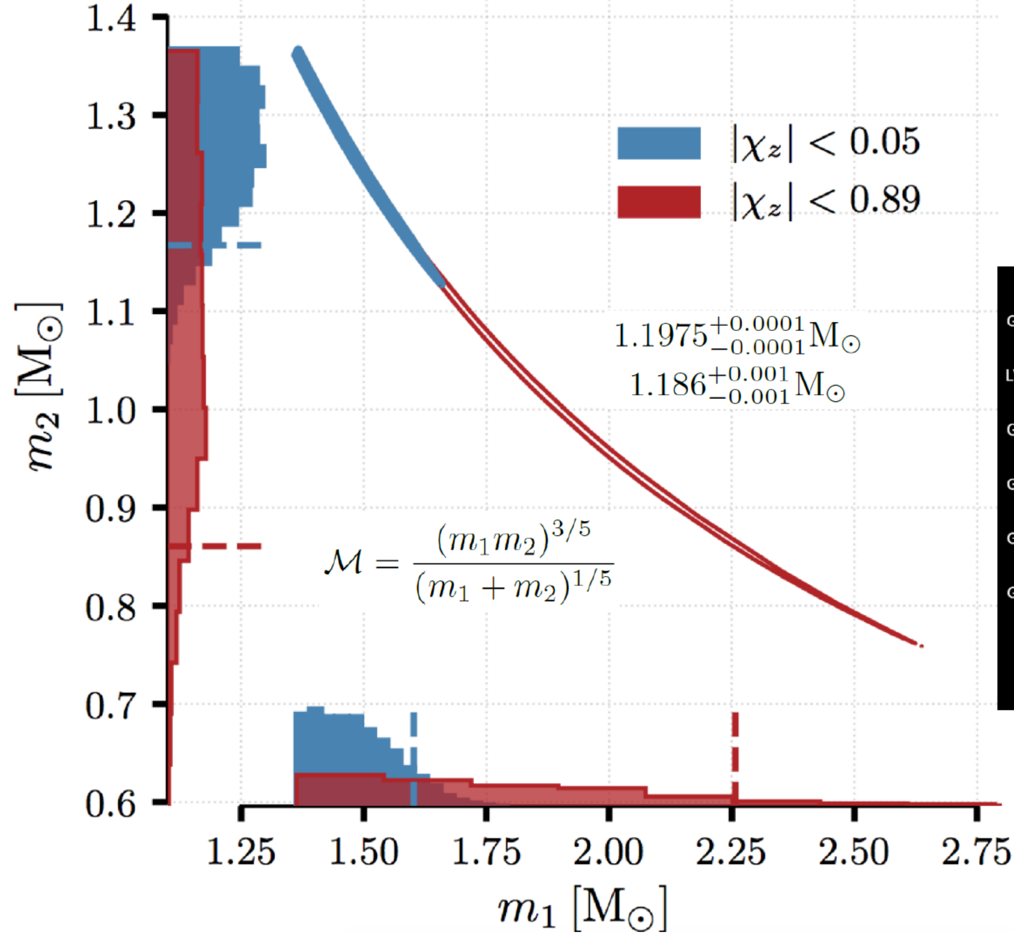




Inferring neutron star properties: masses

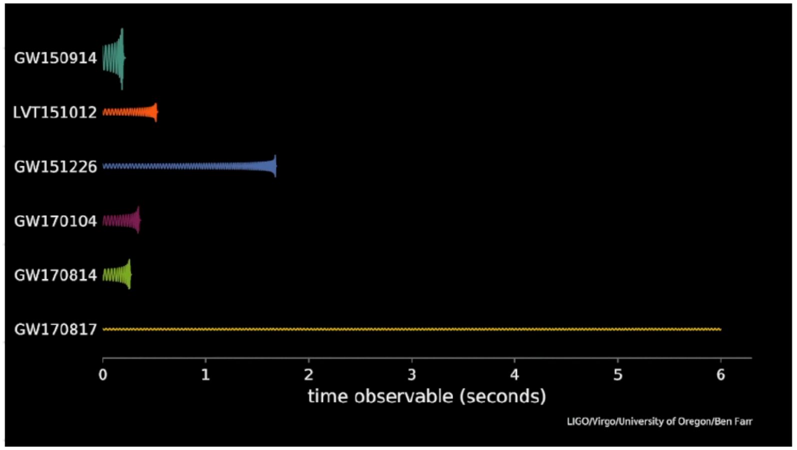
Early estimates now improved using known source location, improved waveform modeling, and re-calibrated Virgo data. Chirp mass can be inferred to high precision. There is a degeneracy between masses and spins

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

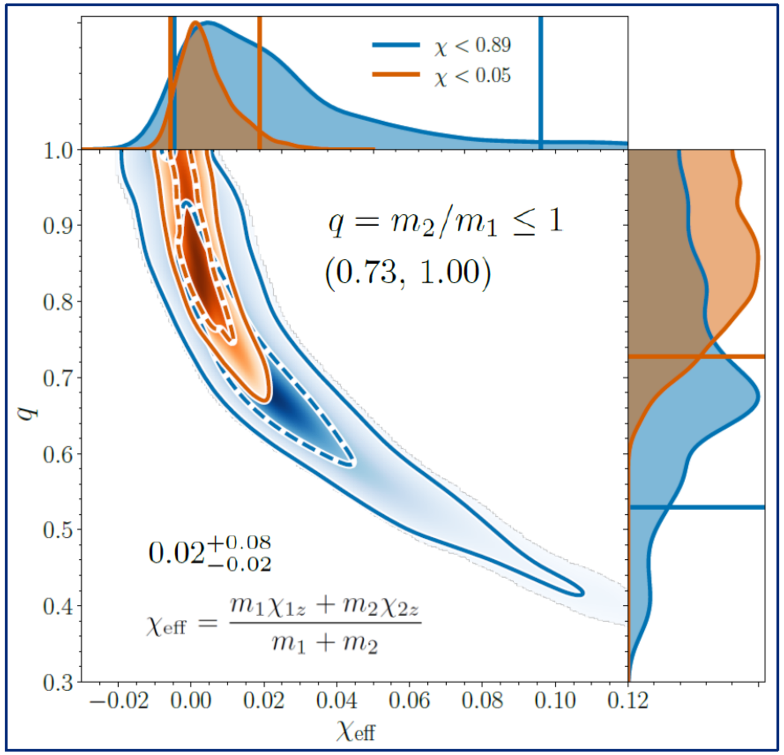
Inferring neutron star properties: spins

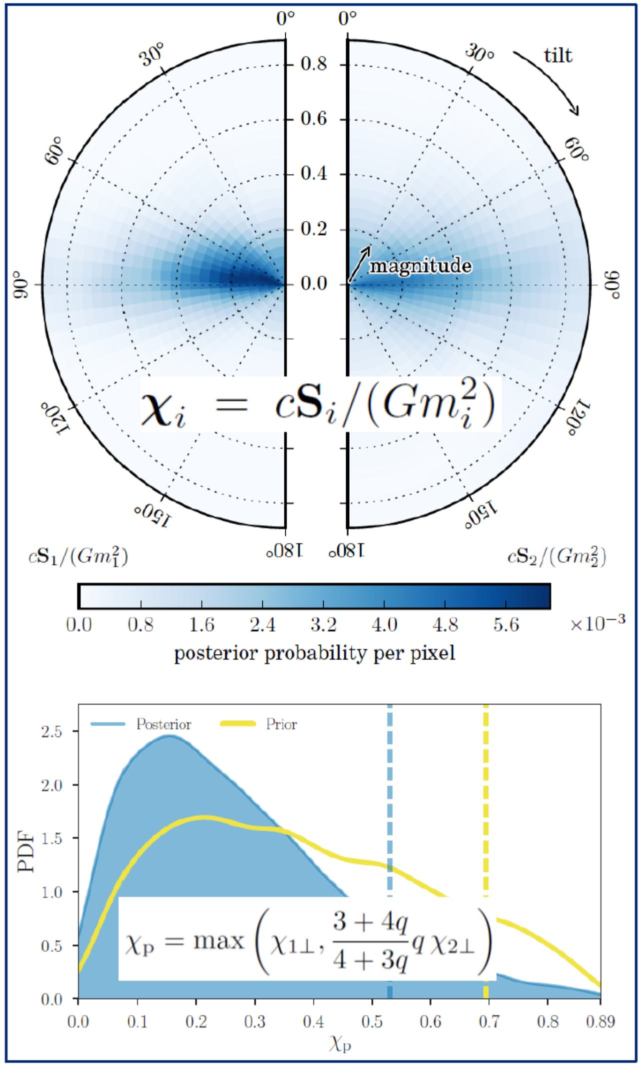
Constrains on mass ratio q, χ_i dimensionless spin, χ_eff effective spin, and χ_p effective spin precession parameter. See https://arxiv.org/abs/1805.11579

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



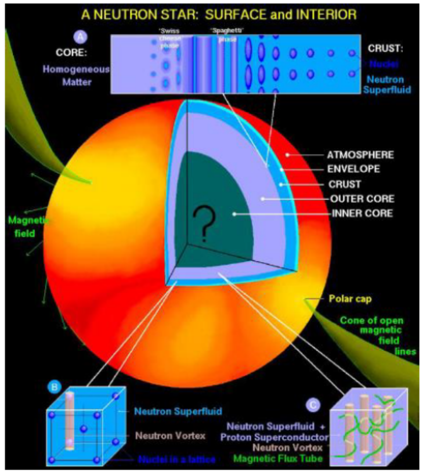


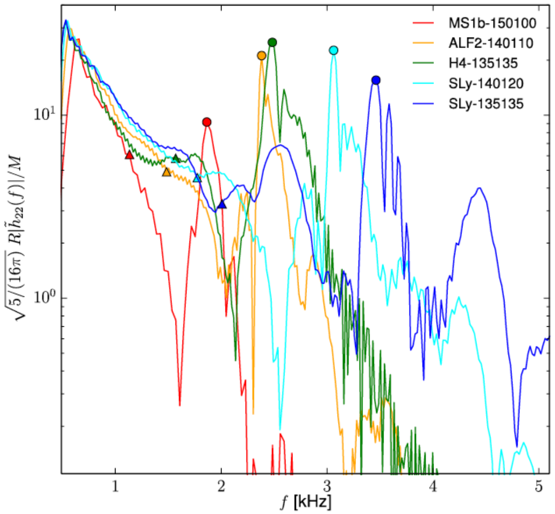
Solving an astrophysical conundrum

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?

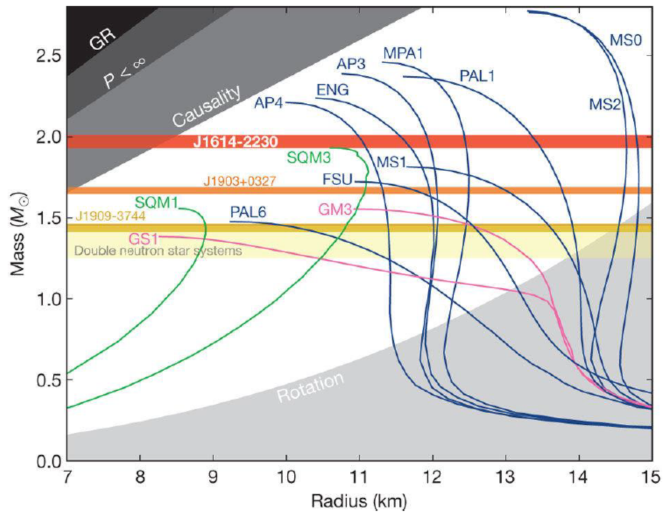
- Structure of the crust?
- Proton superconductivity
- Neutron superfluidity
- "Pinning" of fluid vortices to crust
- Origin of magnetic fields?
- More exotic objects?





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)

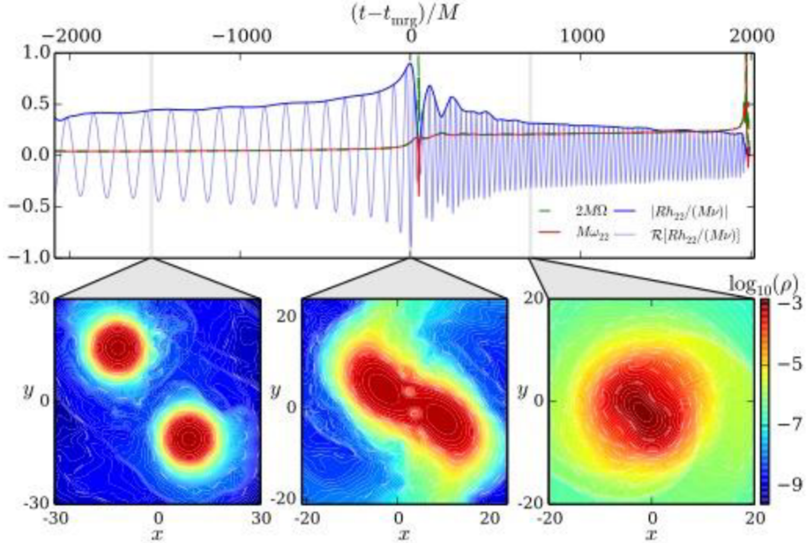
Bernuzzi *et al.*, PRL 115, 091101 (2015)

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

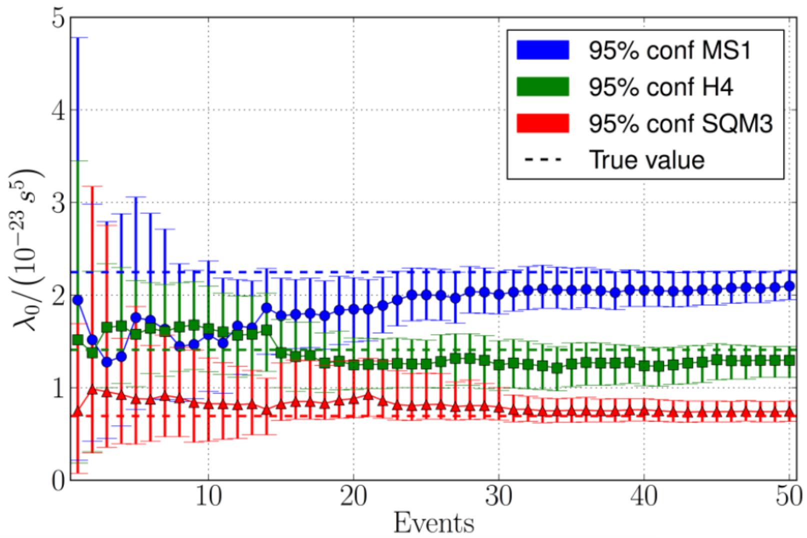
Gravitational waves from inspiraling binary neutron stars

- 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)

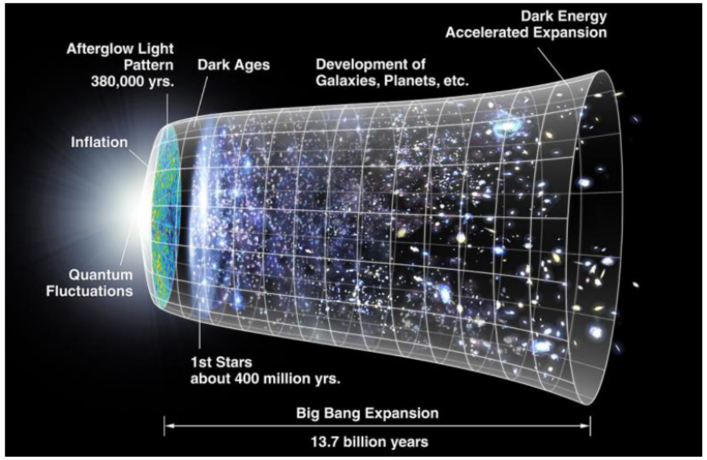
Bernuzzi, Nagar, Font, …

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

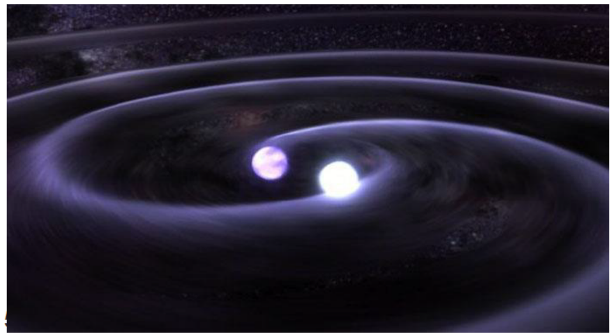
Current measurements depend on cosmic distance ladder

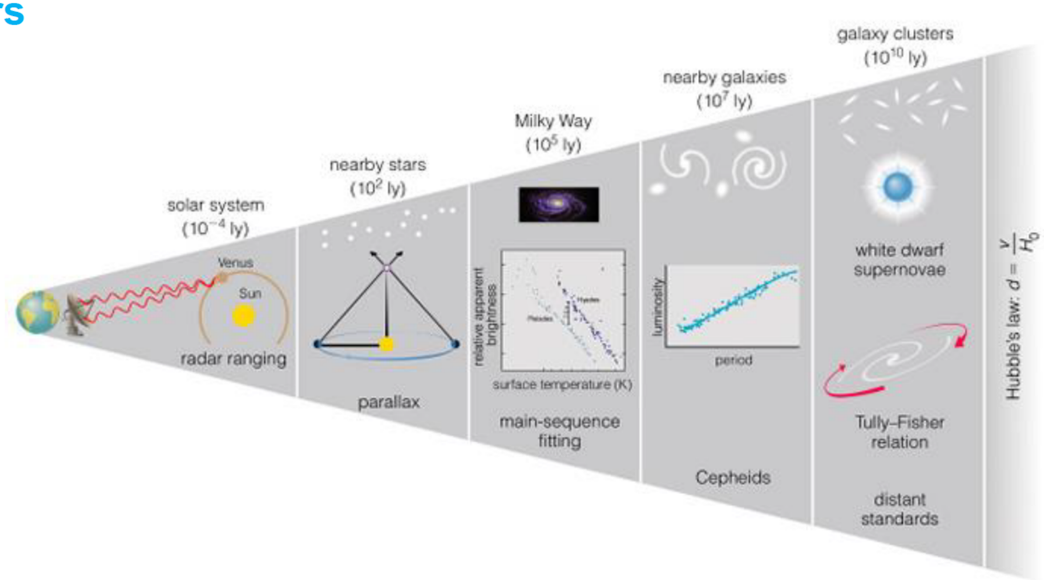
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder



Gravitational waves from binary mergers

Distance can be measured directly from the gravitational wave signal!





A new cosmic distance marker

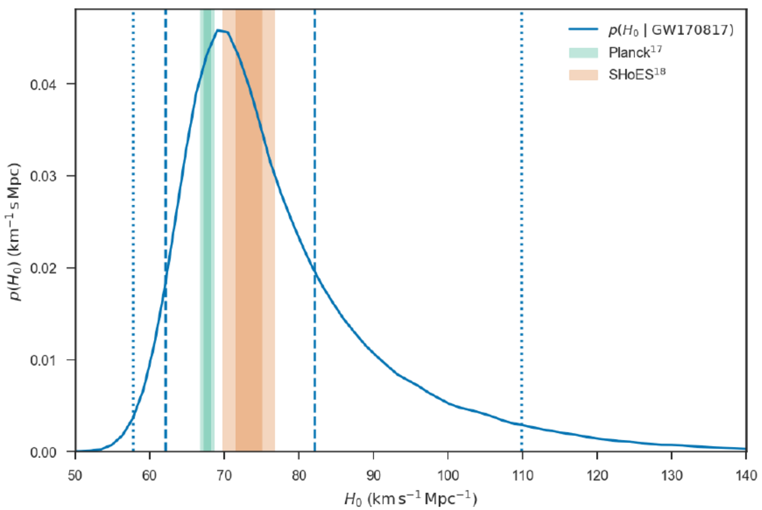
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1-2% accuracy

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)

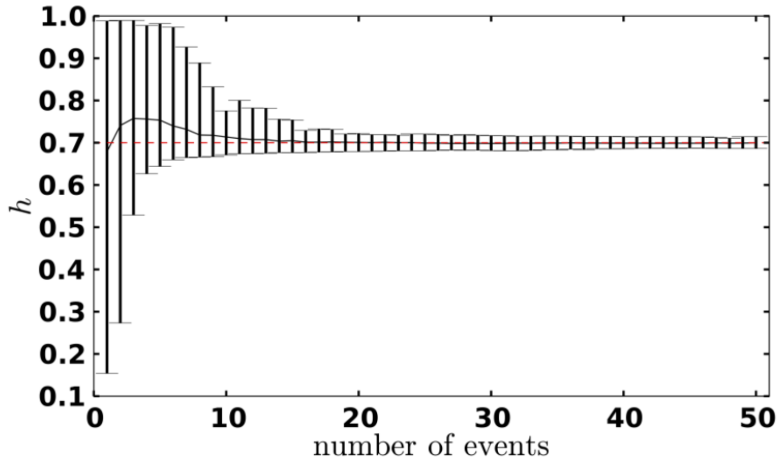


GW170817

- 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

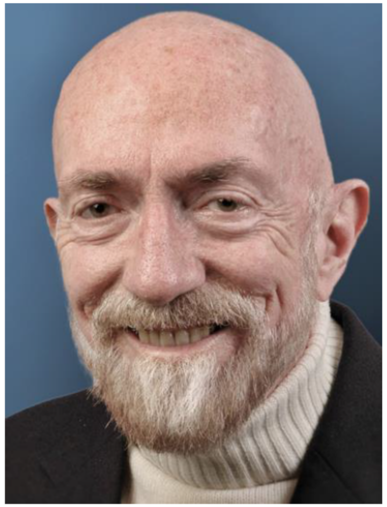
Rainer Weiss
LIGO/VIRGO Collaboration

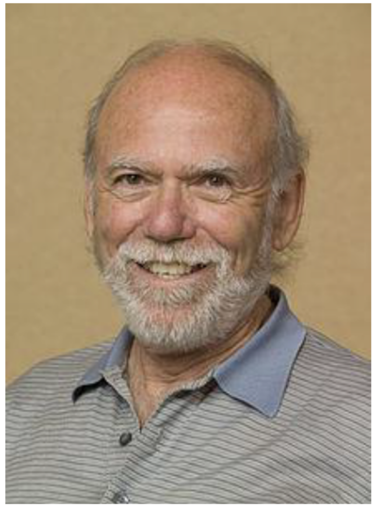
and the other half jointly to

Barry C. Barish
LIGO/VIRGO Collaboration

and

Kip S. Thorne
LIGO/VIRGO Collaboration



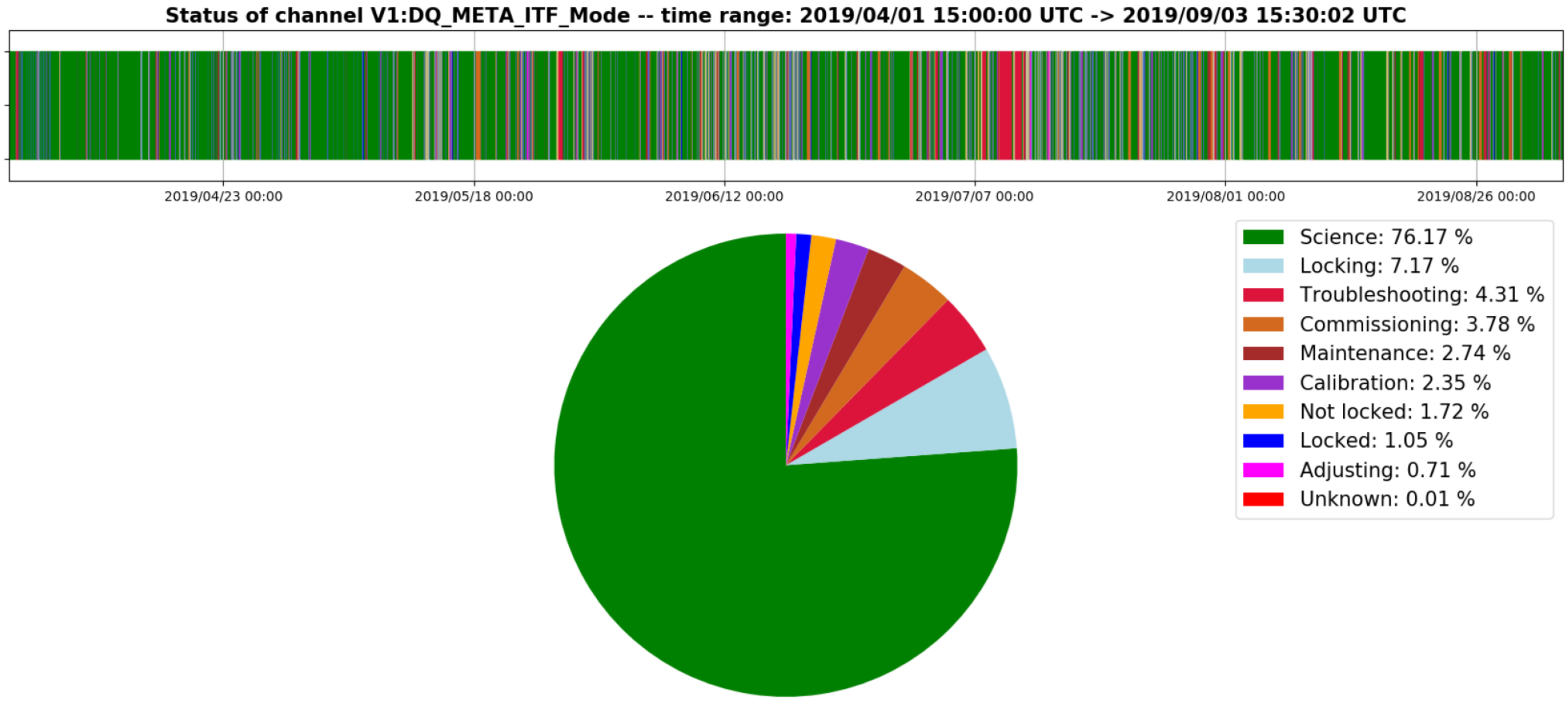


Special thanks to Virgo’s founding fathers

Alain Brillet and Adalberto Giazotto

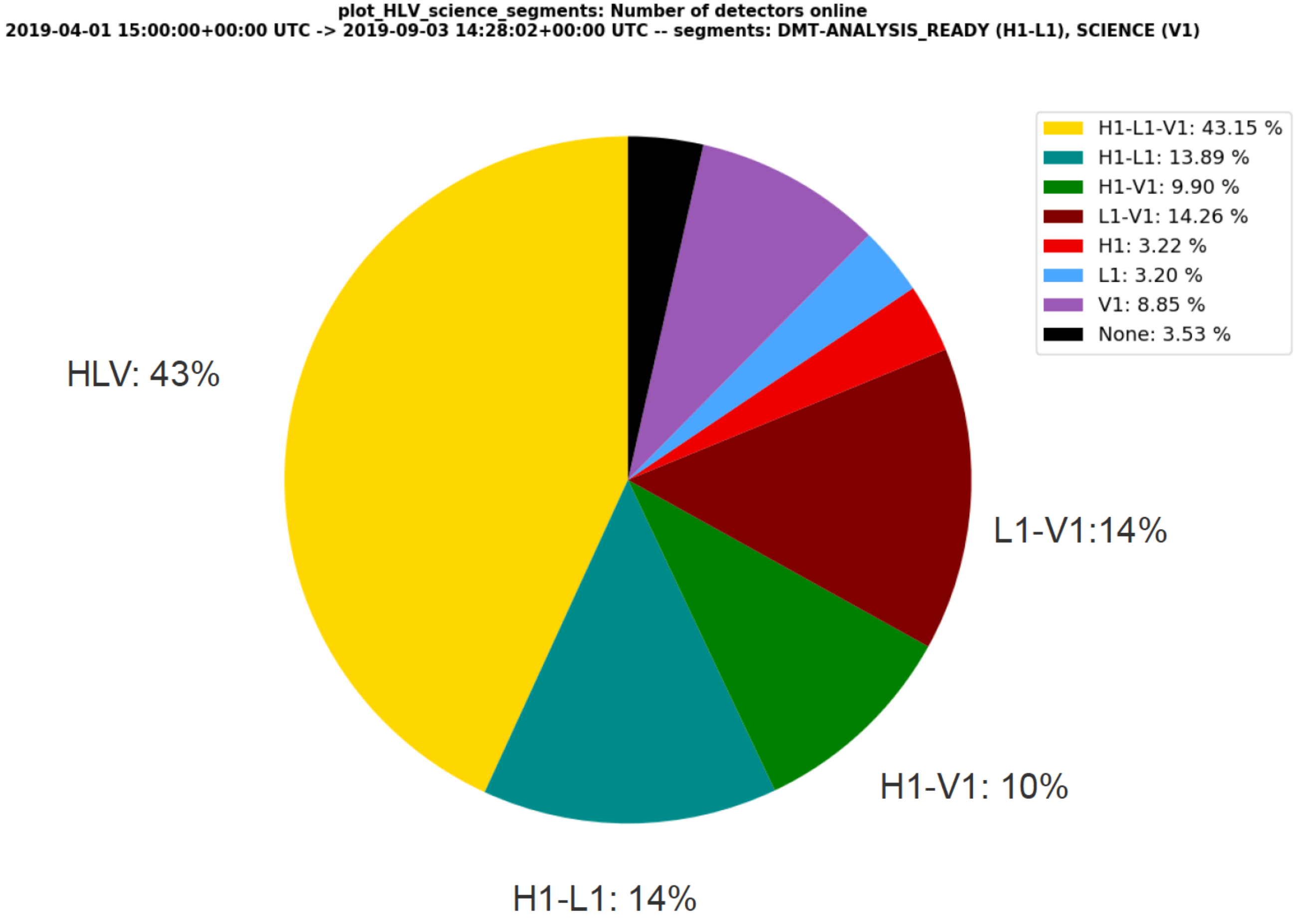
O3 Summary: efficiency

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
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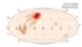
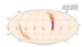
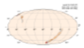
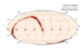
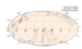
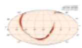
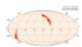
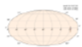
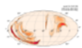
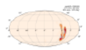
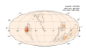
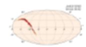
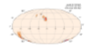
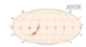
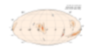
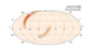
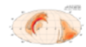
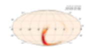
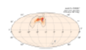
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	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

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
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

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
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

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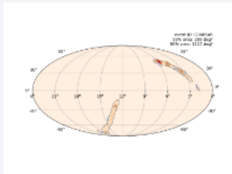
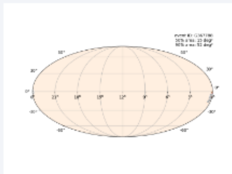
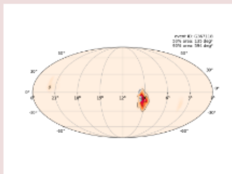
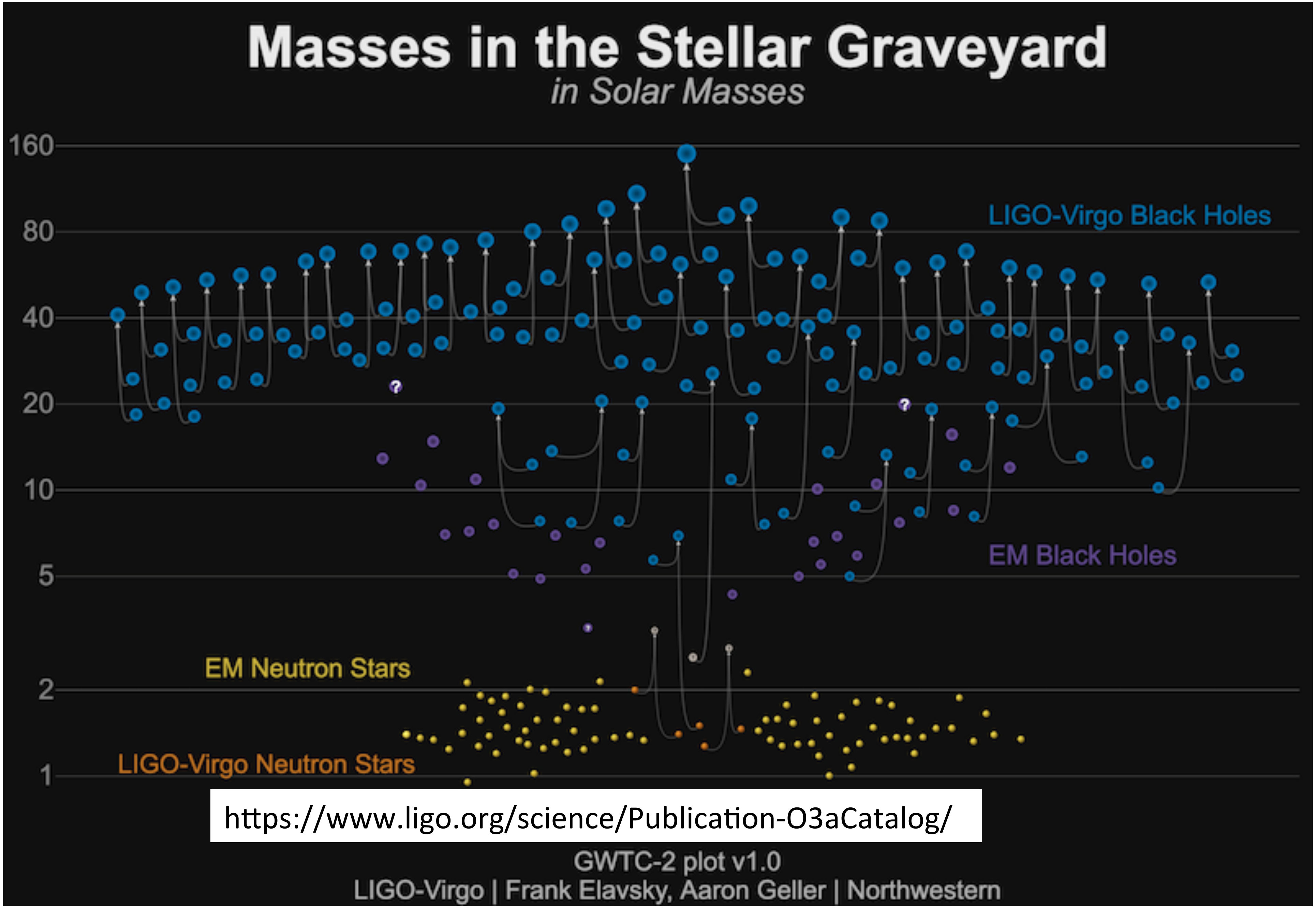
LIGO/Virgo O3 Public Alerts

Detection candidates: 56

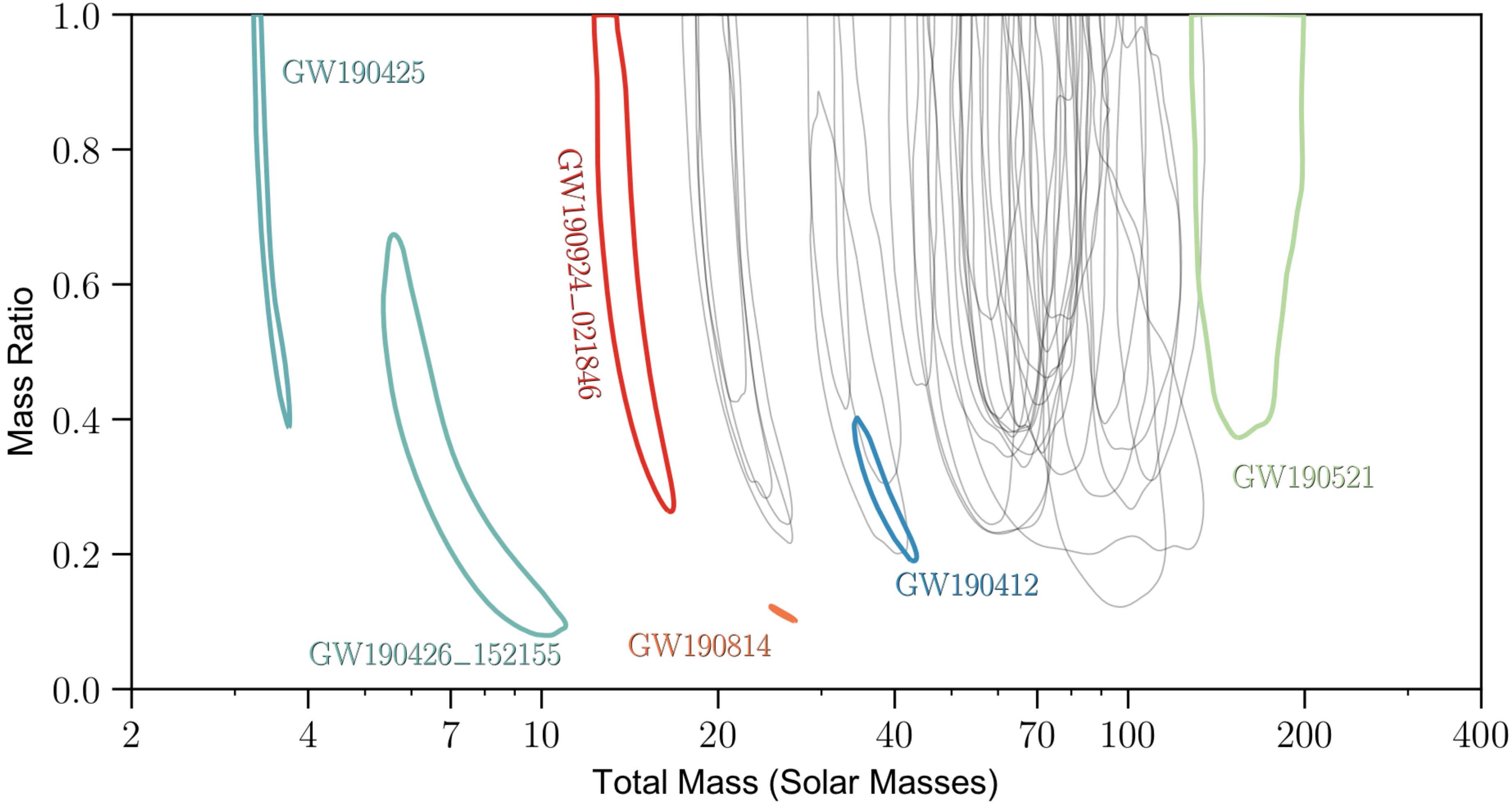
https://gracedb.ligo.org/superevents/public/O3/

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



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



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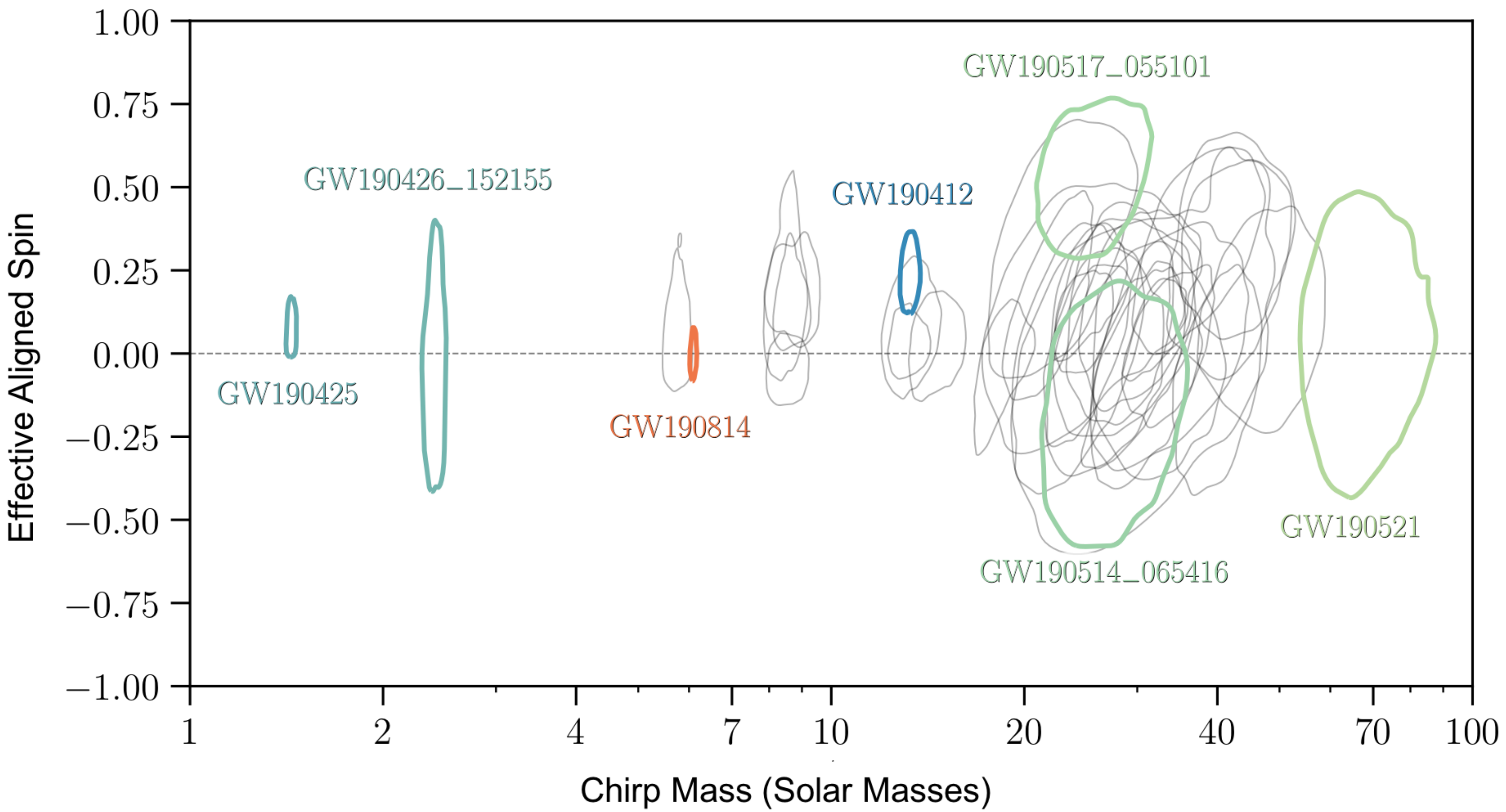

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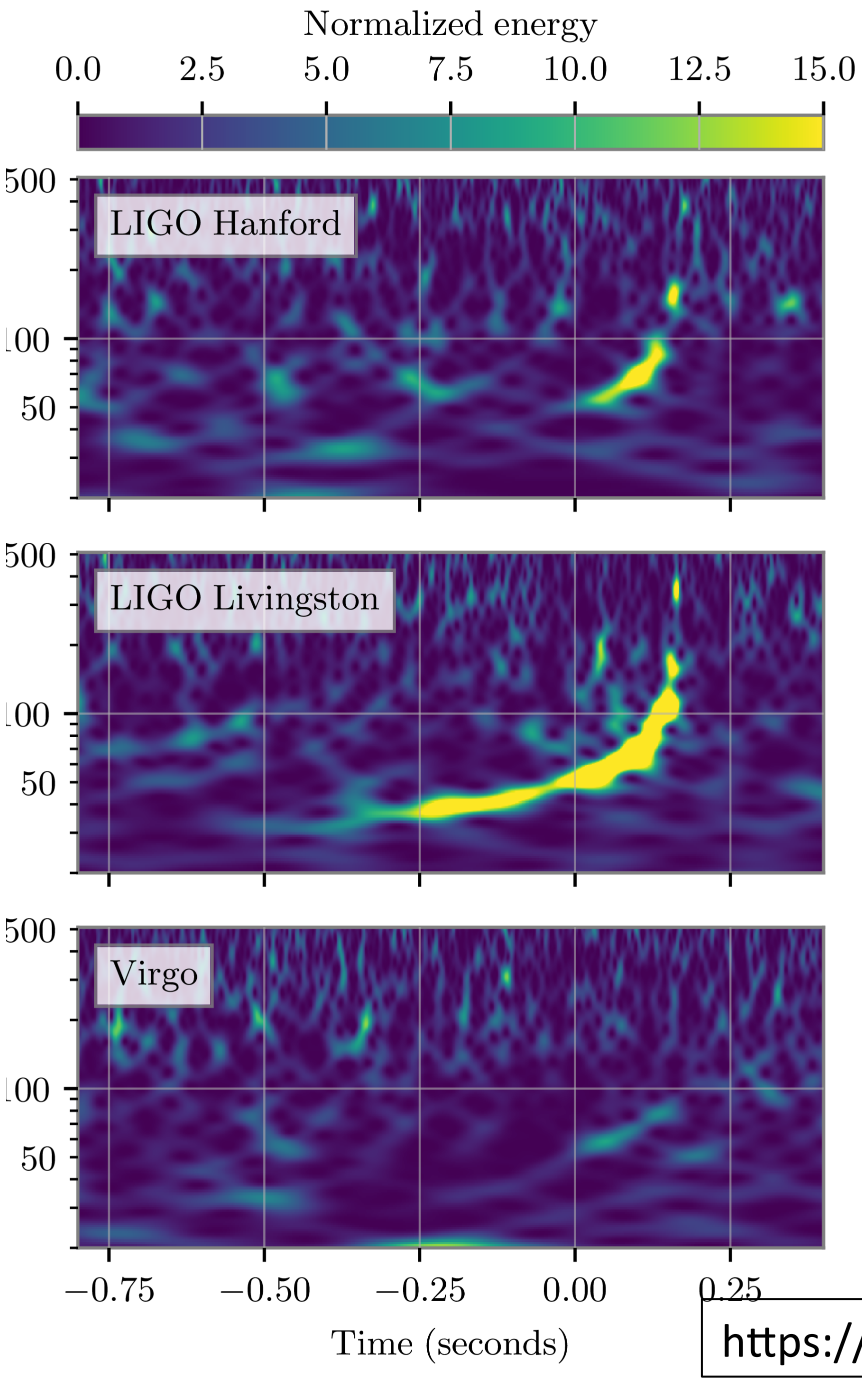
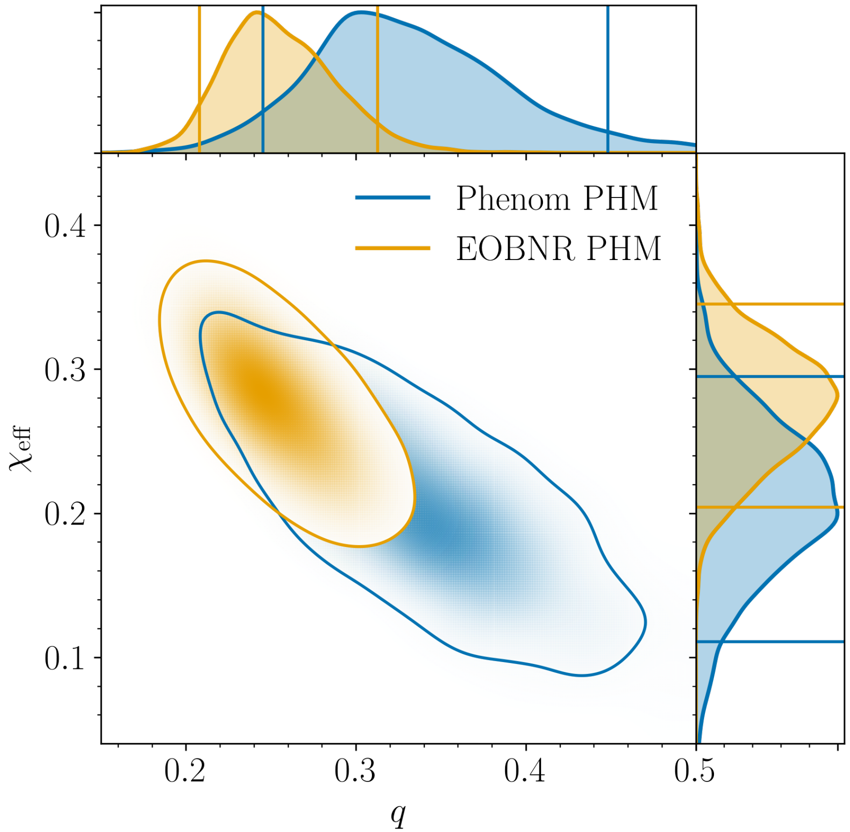
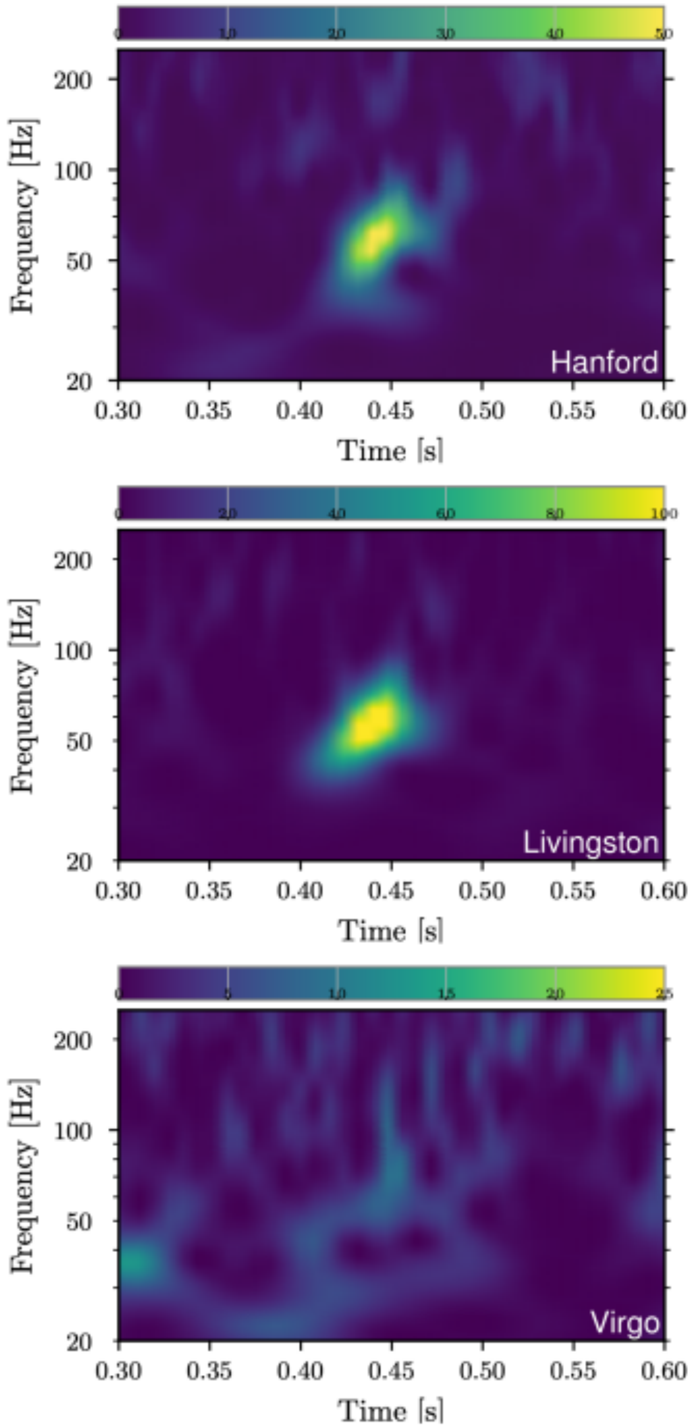
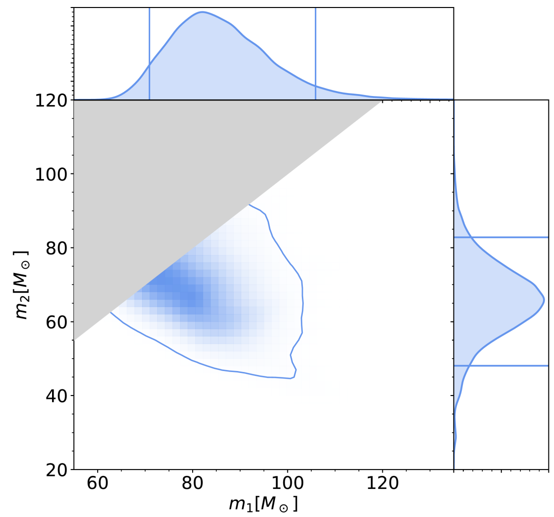
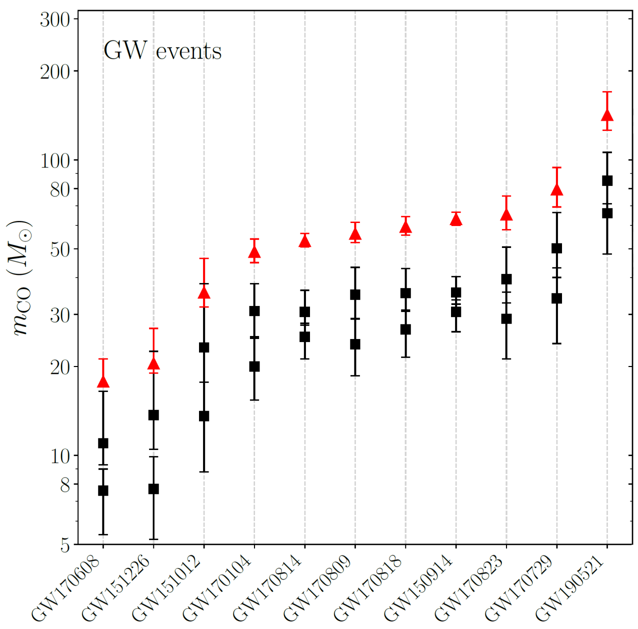




https://www.ligo.org/science/Publication-GW190412/

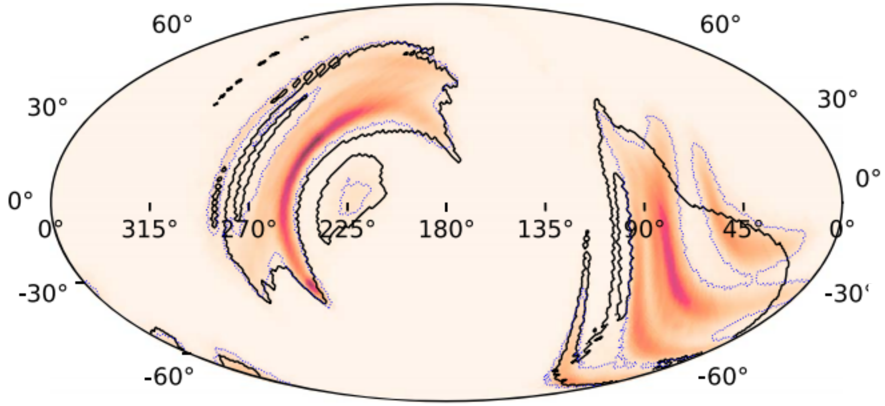


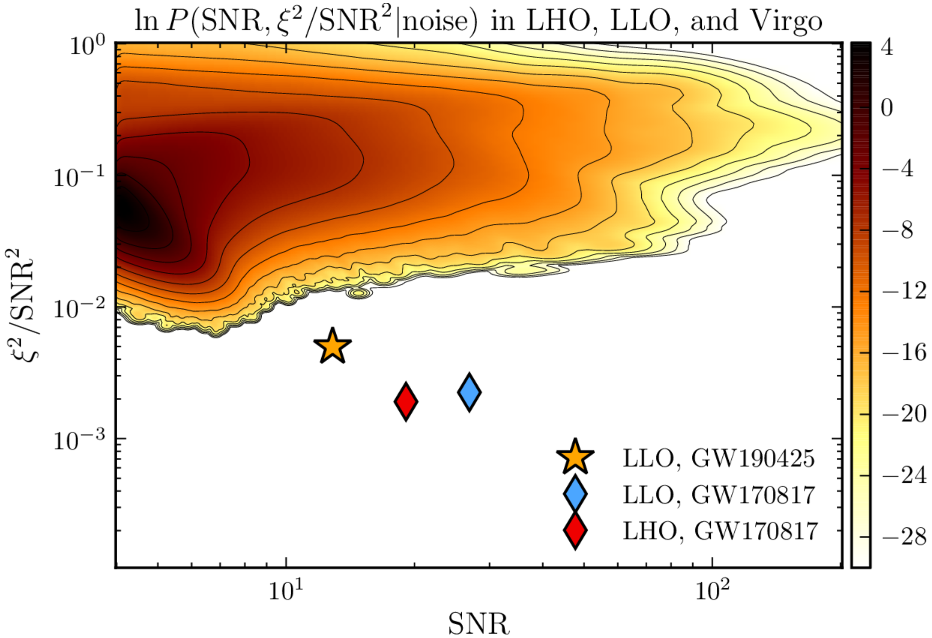


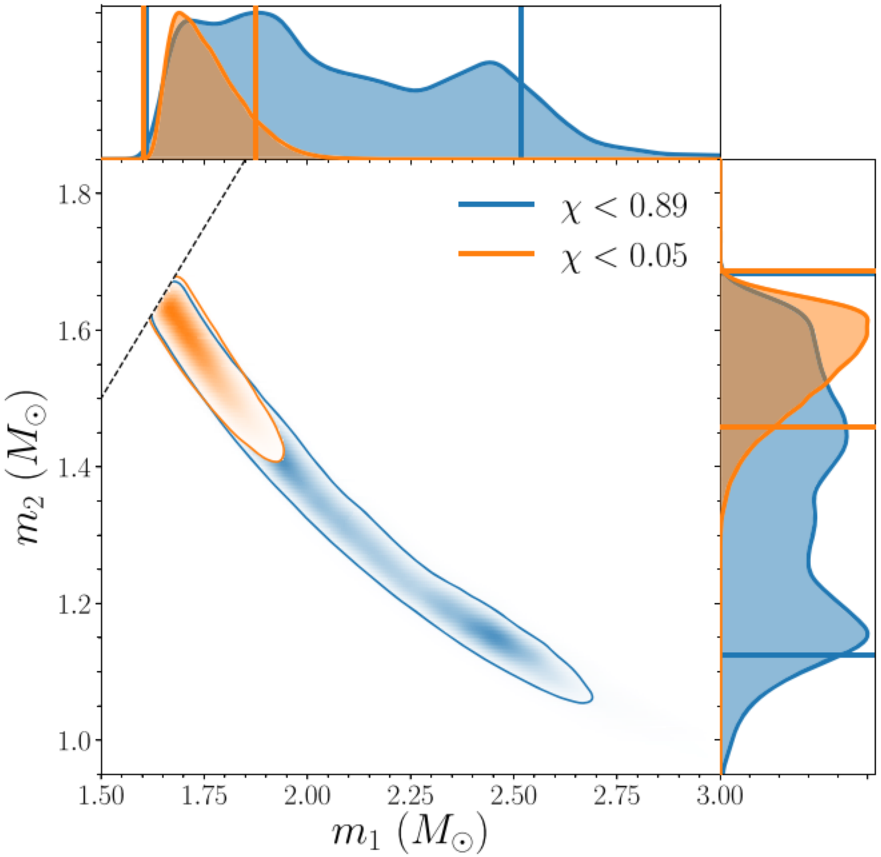


https://www.ligo.org/science/Publication-GW190521/

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







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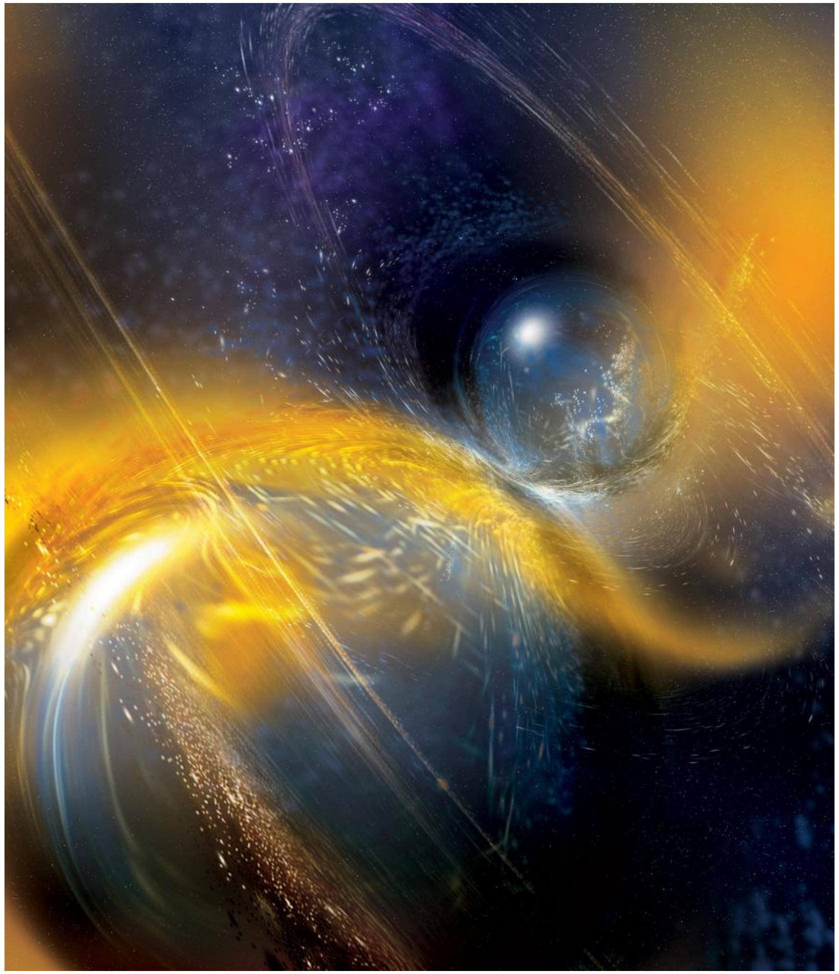
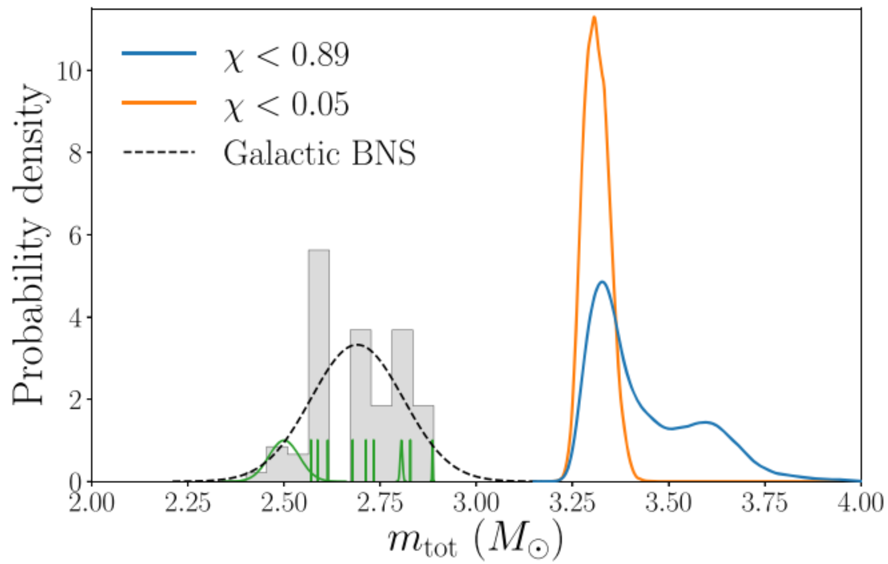
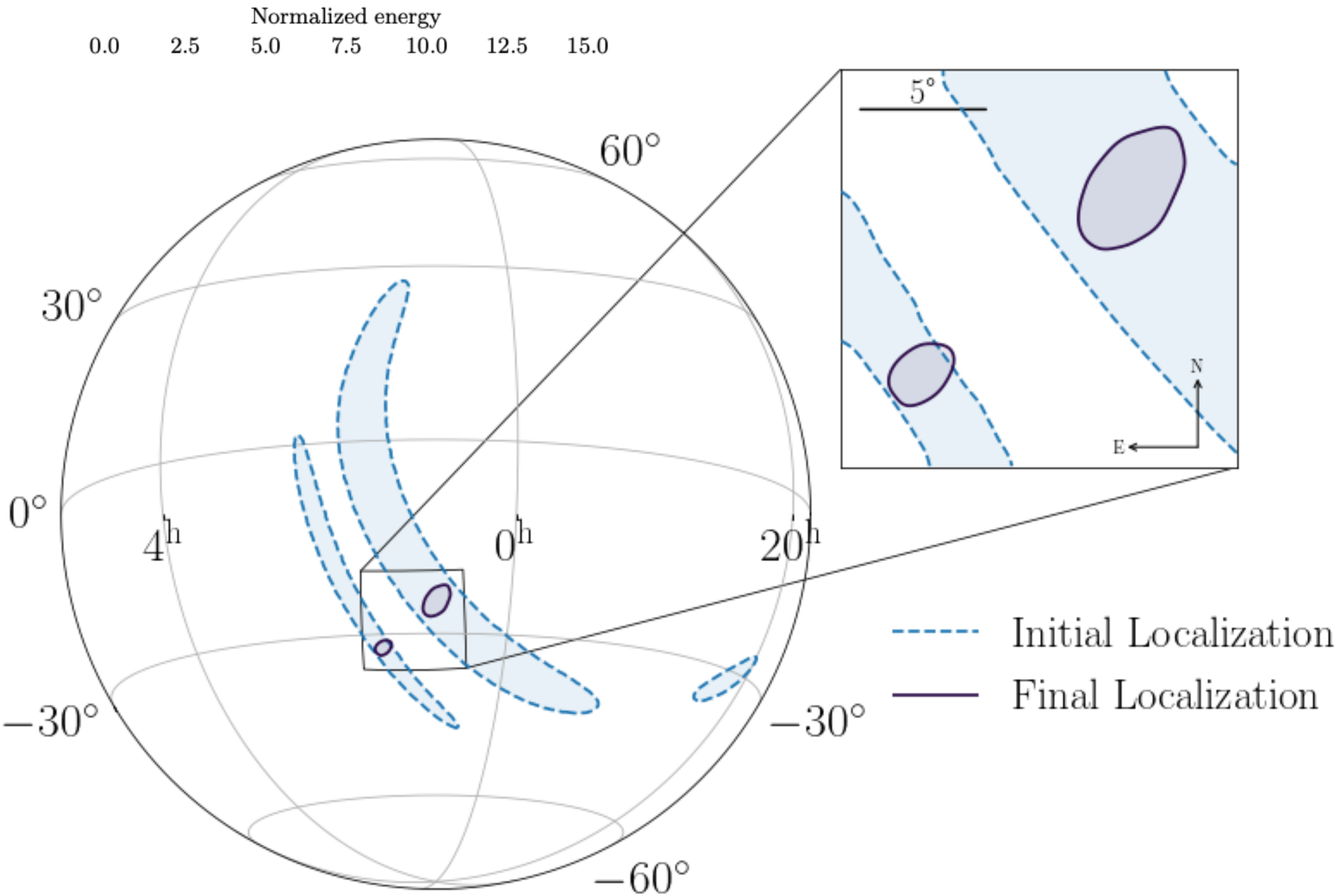
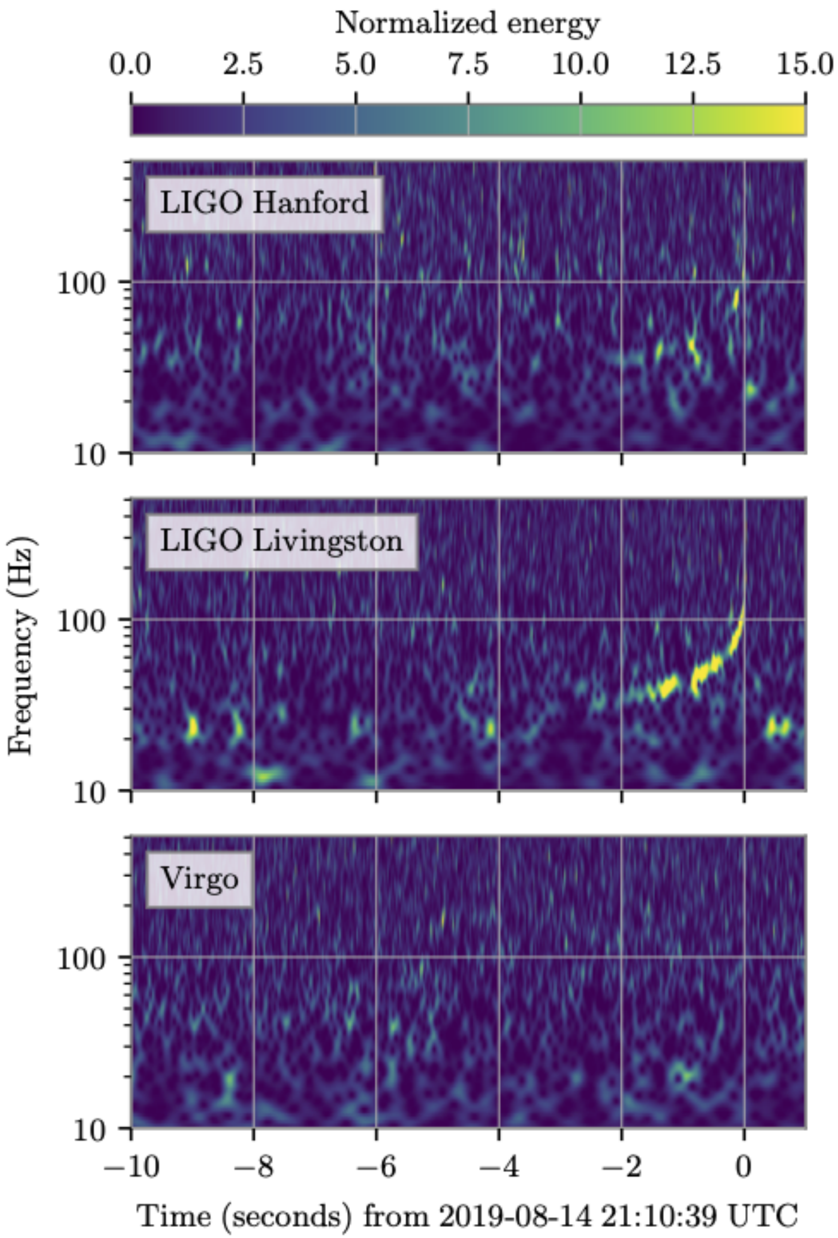
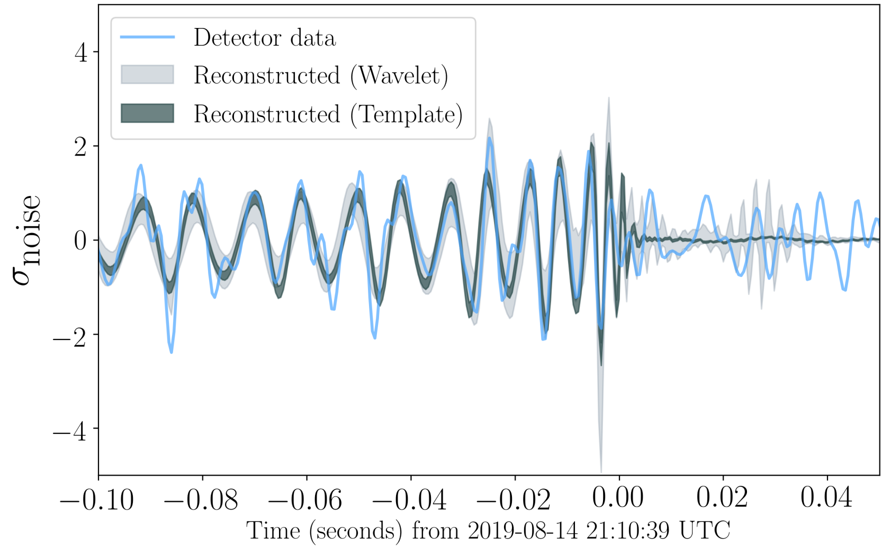


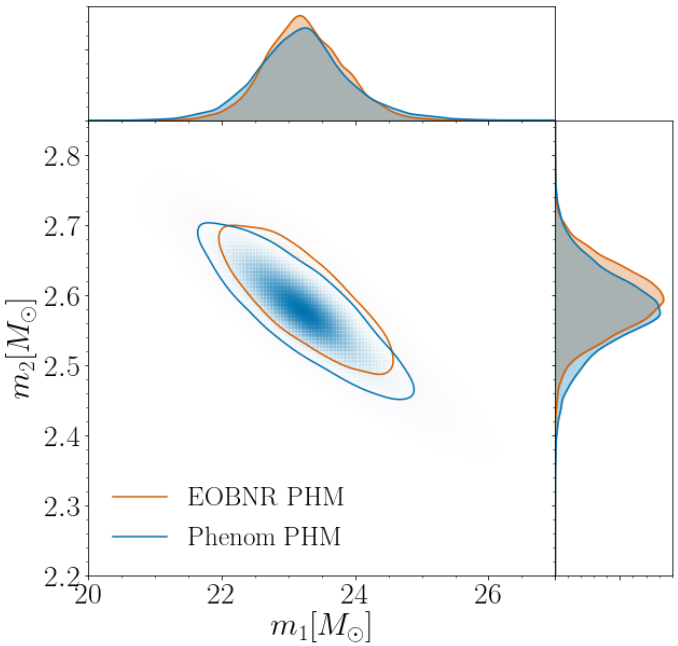




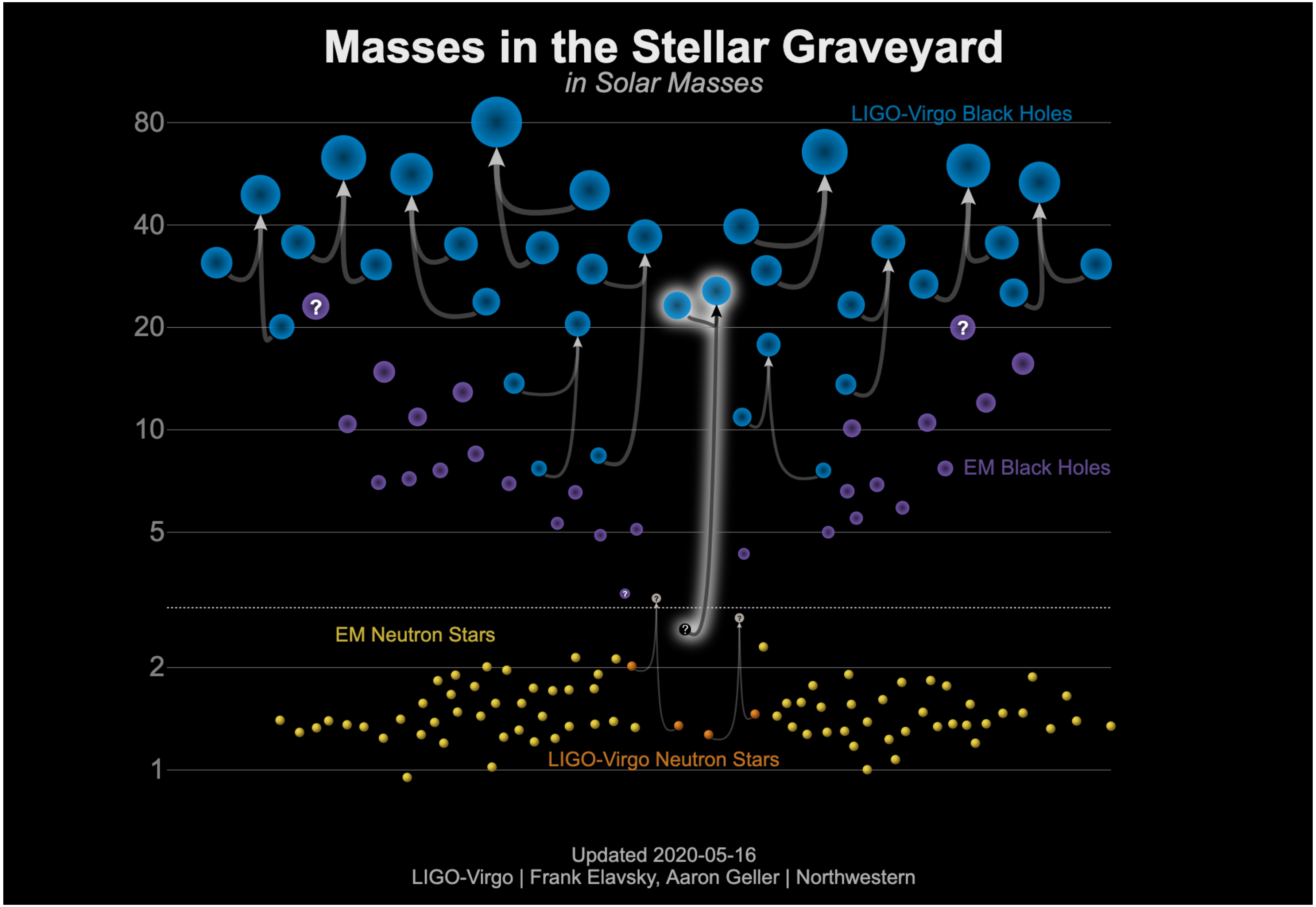
https://www.ligo.org/science/Publication-GW190814/



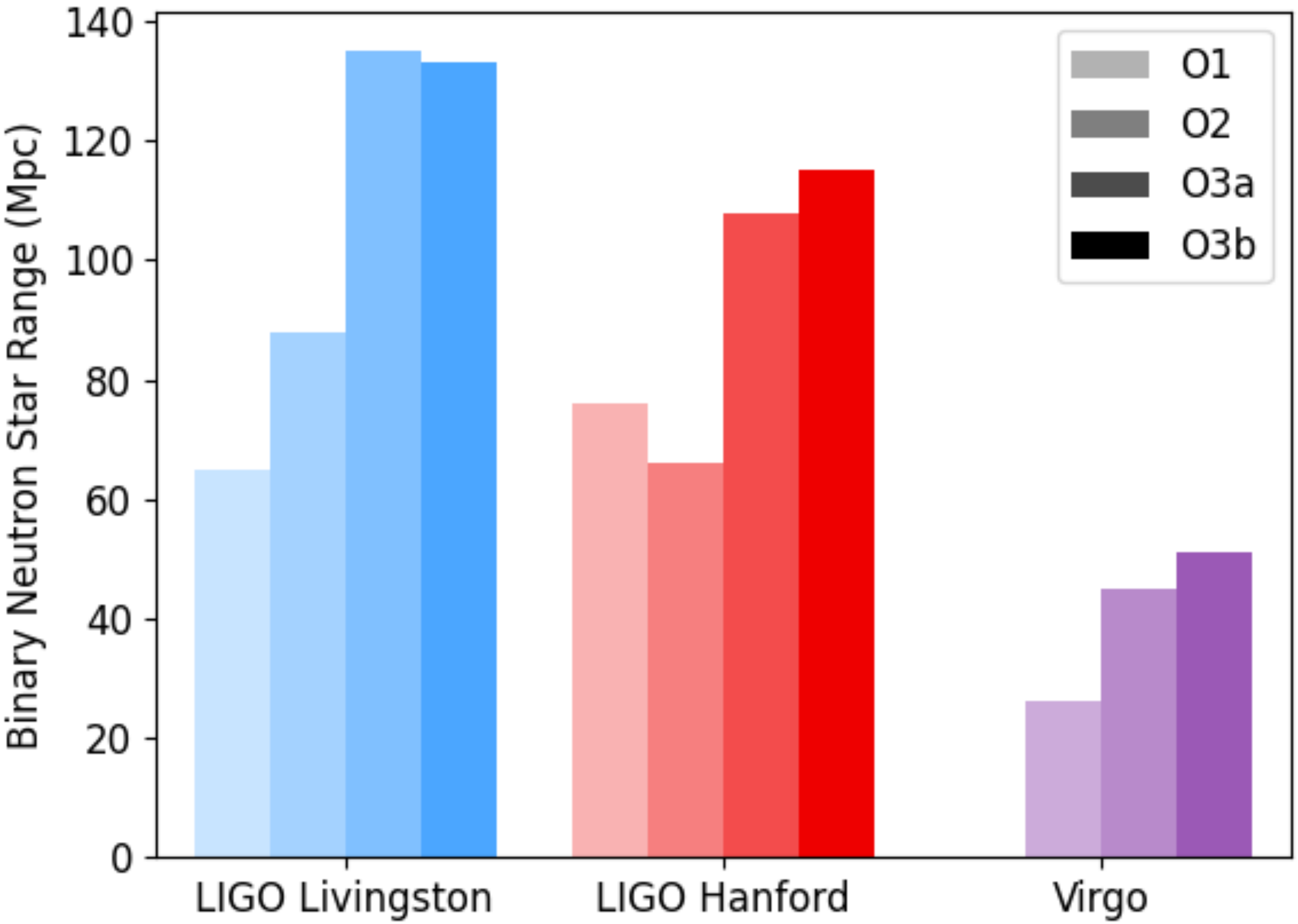




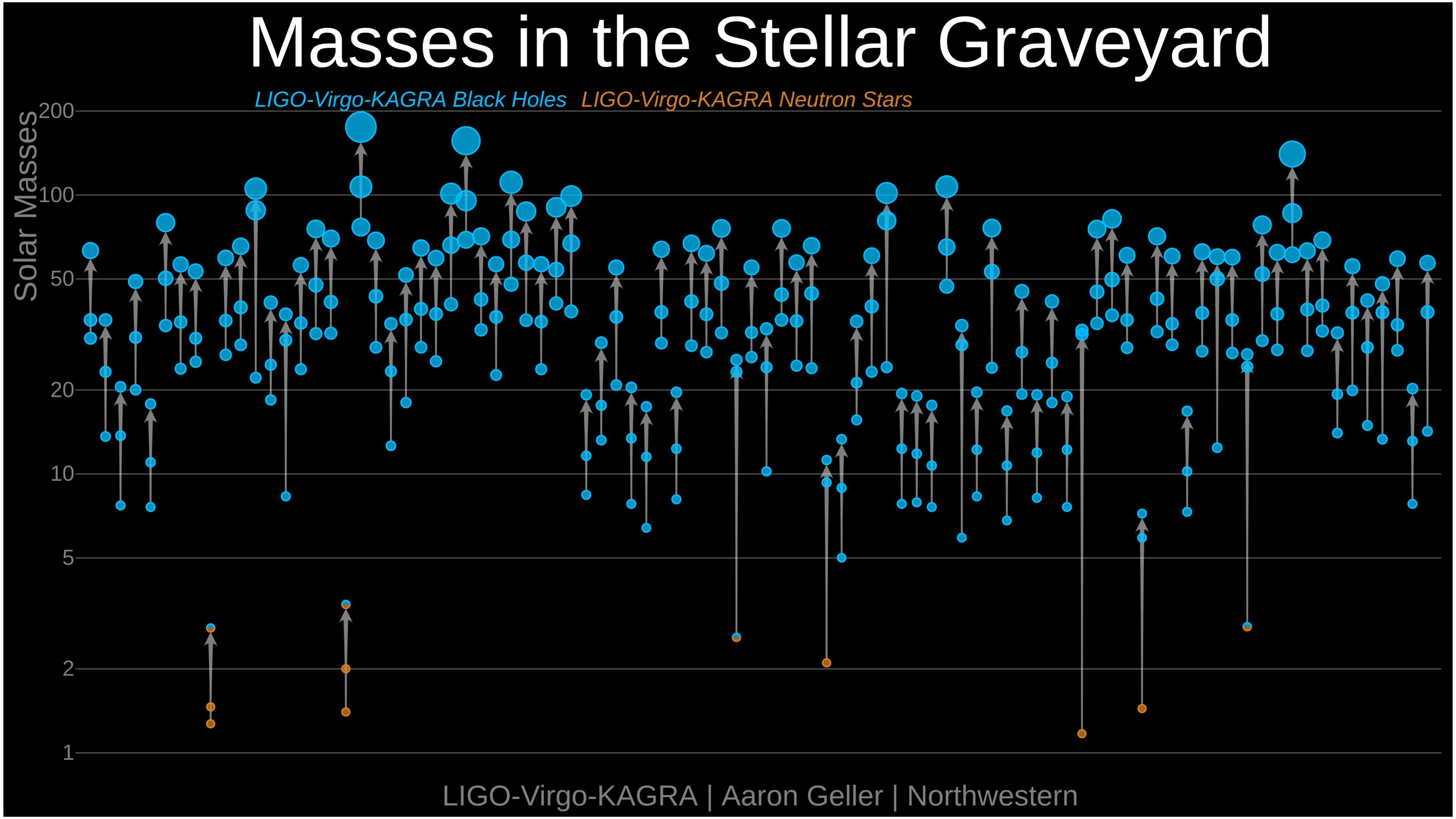
https://www.ligo.org/science/Publication-GW190814/



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/



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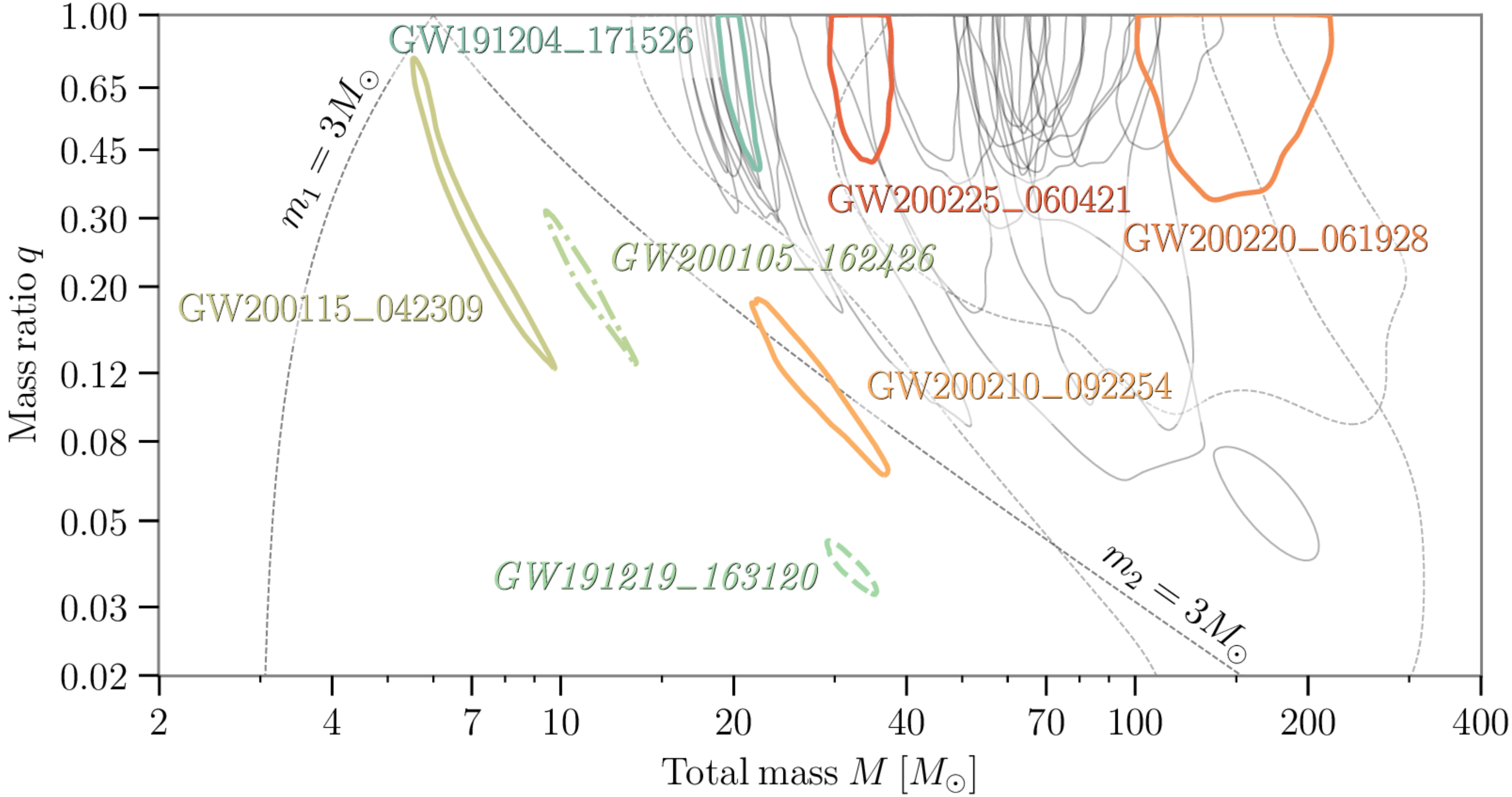

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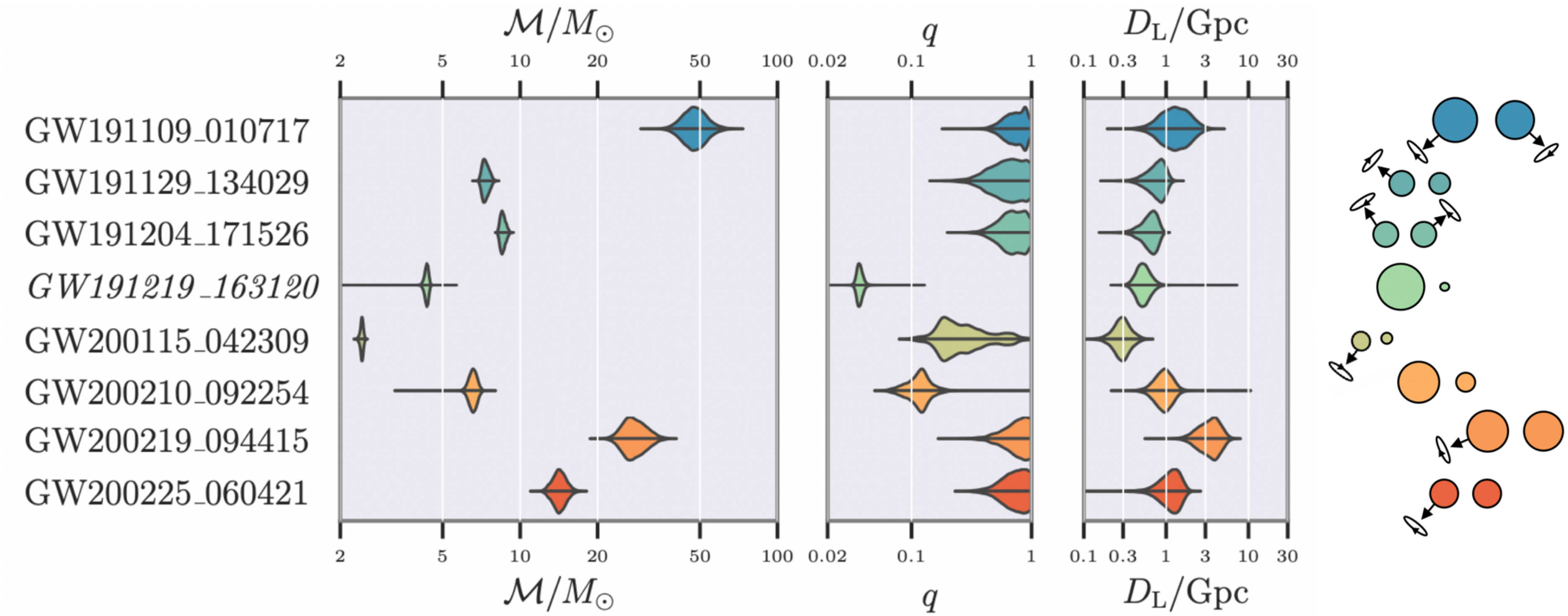

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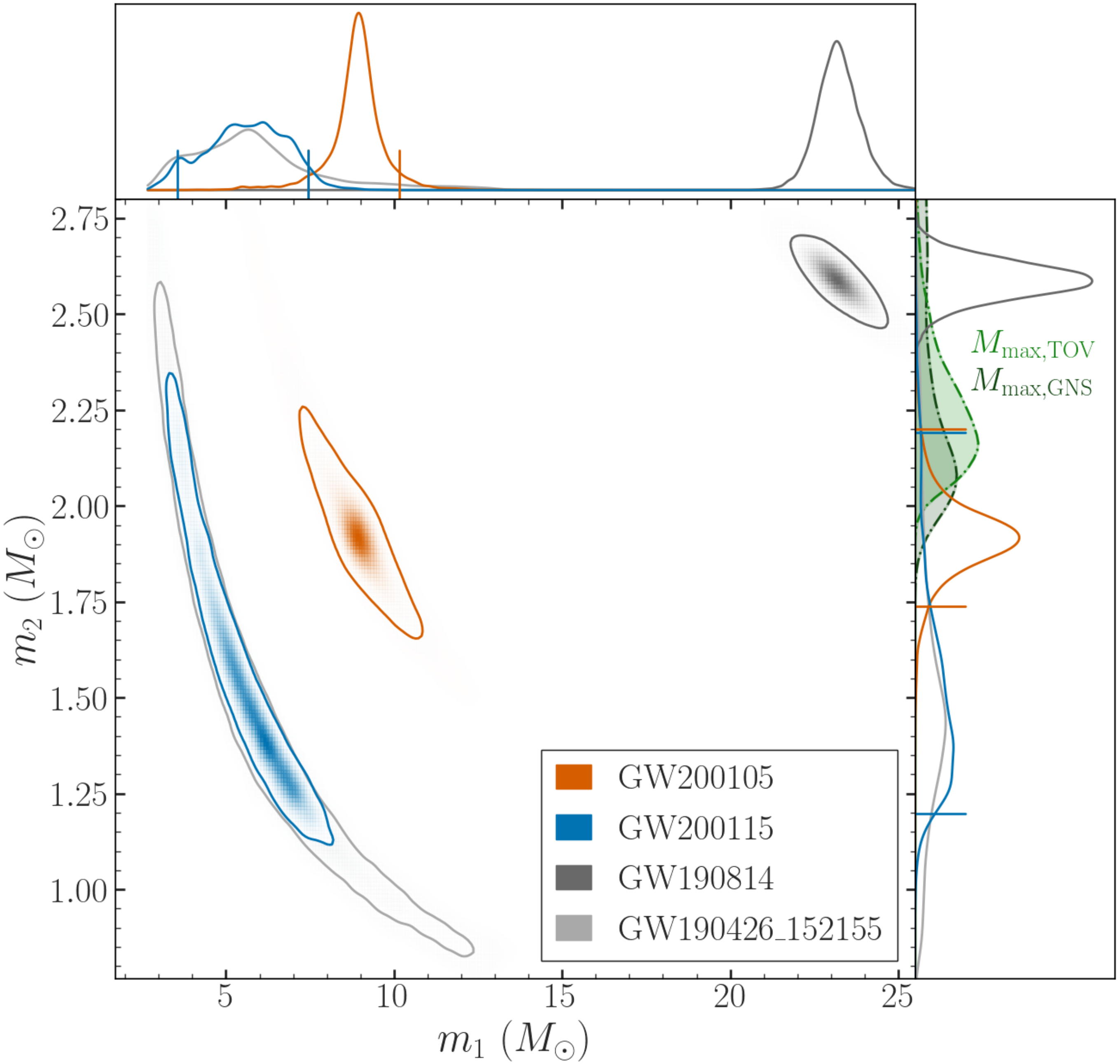
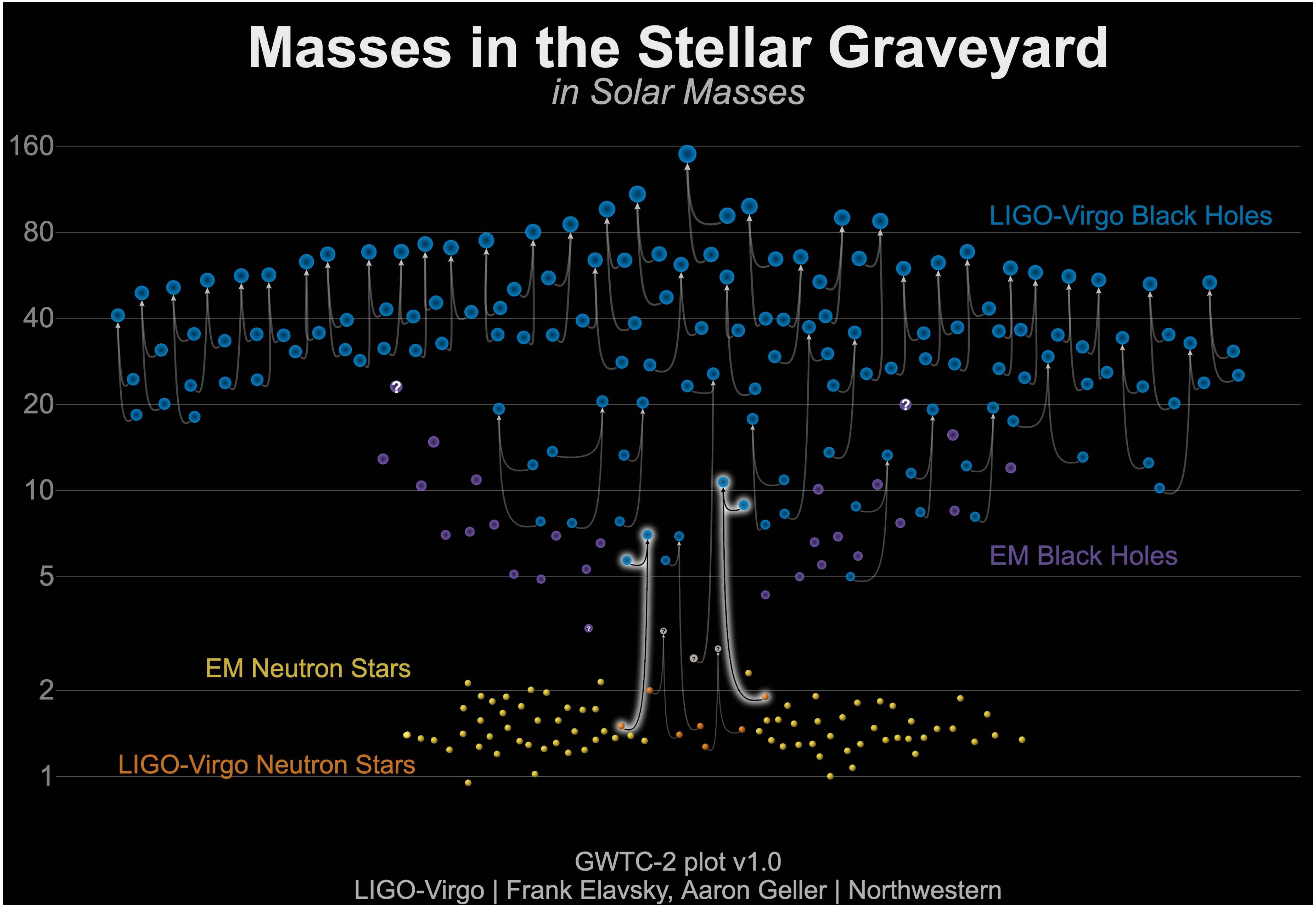


https://www.ligo.org/science/Publication-NSBHDiscovery/

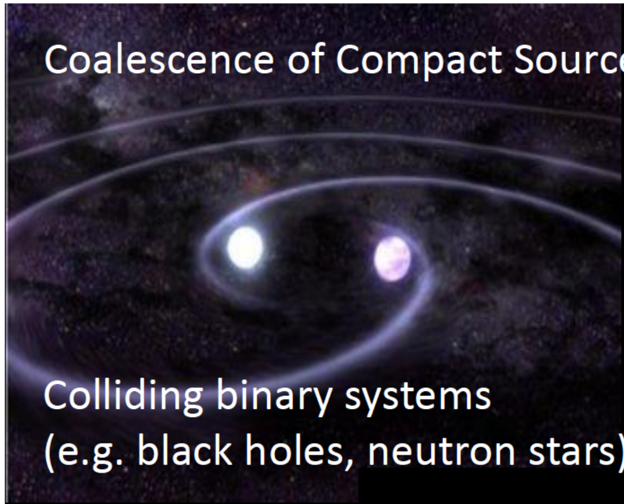


https://www.ligo.org/science/Publication-NSBHDiscovery/

LIGO-Virgo analyses for sources of gravitational waves

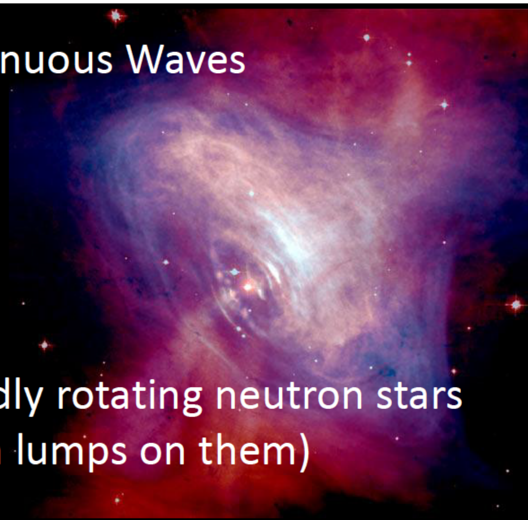
Sources can be transient or of continuous nature, and can be modeled or unmodeled

Coalescence of Compact Sources



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

Continuous Waves

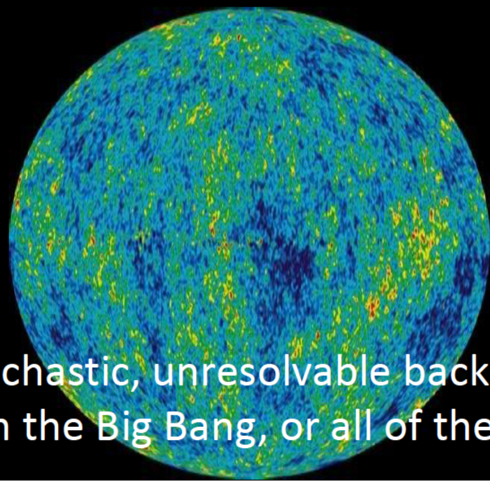


Rapidly rotating neutron stars
(with lumps on them)

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

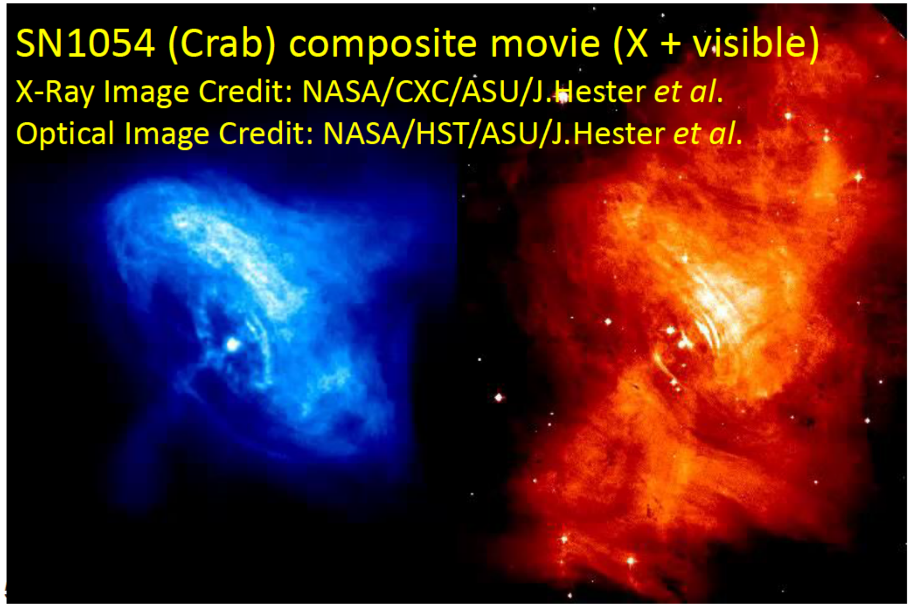
Sources must have some degree of non-axisymmetry originating from

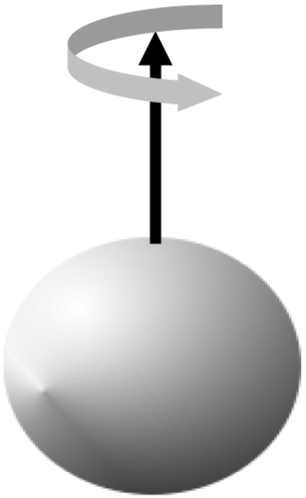
- deformation due to elastic stresses or magnetic field not aligned to the rotation axis ($f_{GW} = 2f_r$)
- free precession around rotation axis ($f_{GW} \sim f_{rot} + f_{prec}$; $f_{GW} \sim 2f_{rot} + 2f_{prec}$)
- excitation of long-lasting oscillations (e.g. *r*-modes; $f_{GW} \sim 4f_r/3$)
- deformation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

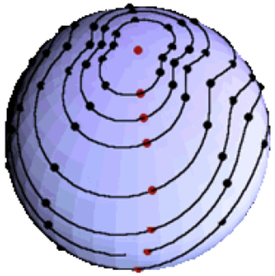
Source characteristics

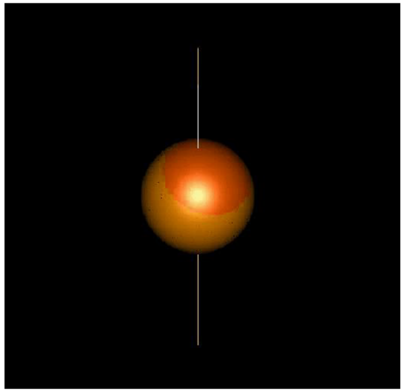
Emission of quasi-monochromatic waves with a slowly decreasing intrinsic frequency

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

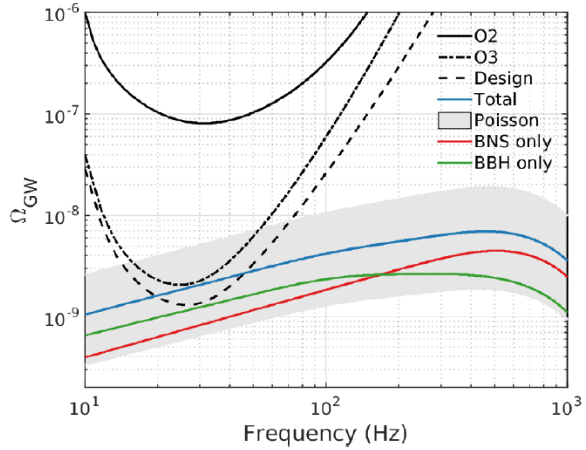
- First search for gravitational waves from known pulsars (LVC, ApJ 839, 12, 2017)
  - Analyzed 200 known pulsars (119 out of 200 are in binary systems)
  - Spindown limit beaten for 8 pulsars, including both Crab & Vela: For the Crab and Vela pulsars less than 2x10-3 and 10-2 of the spindown luminosity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

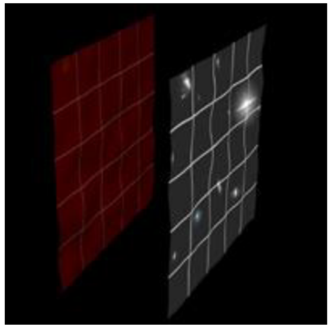
Many individual sources at larger distances that contribute to SGWB

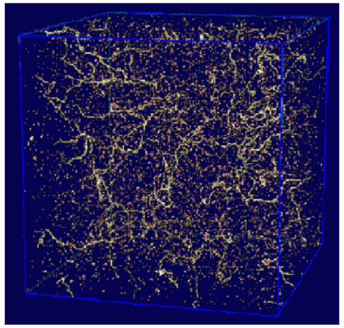
This could be the next milestone for LIGO/Virgo

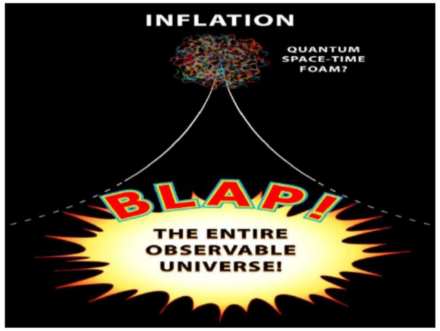
Cosmological SGWB

Signatures of the early Universe

Inflation, cosmic strings, no phase transition in LIGO/Virgo

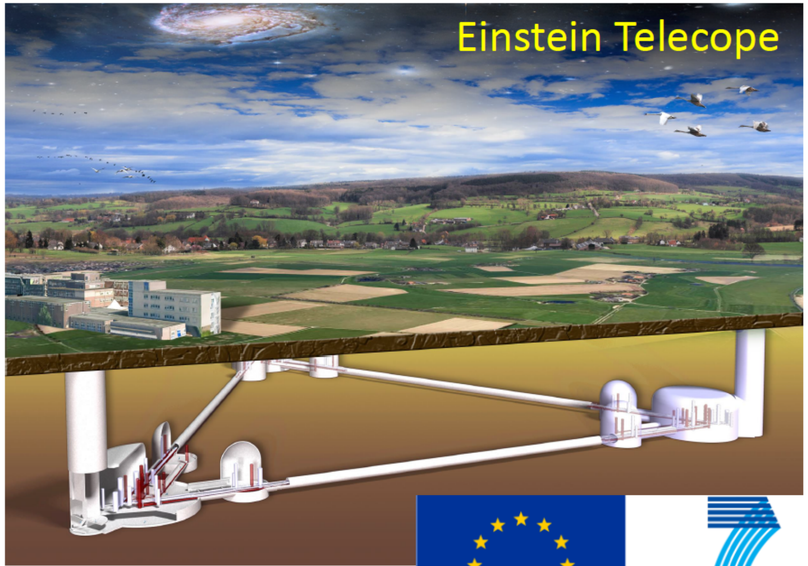




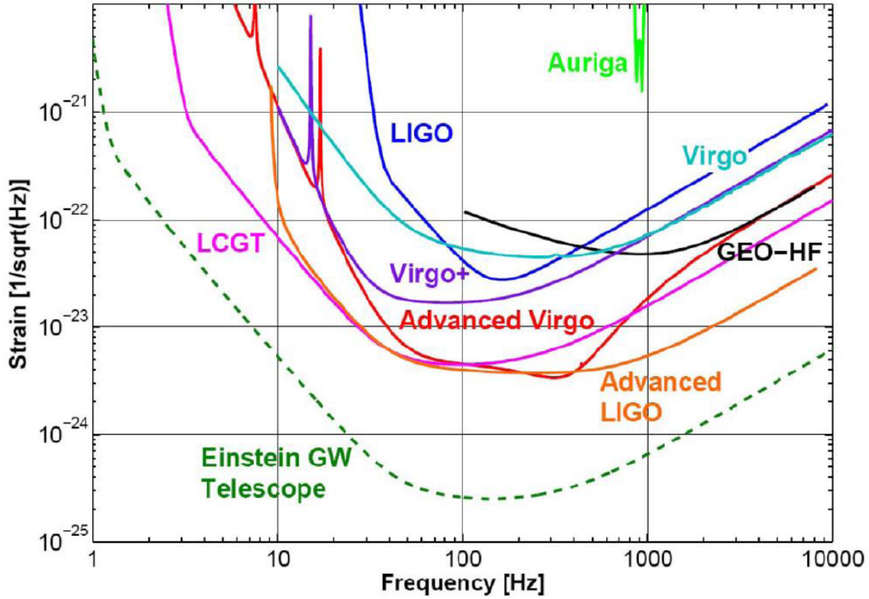


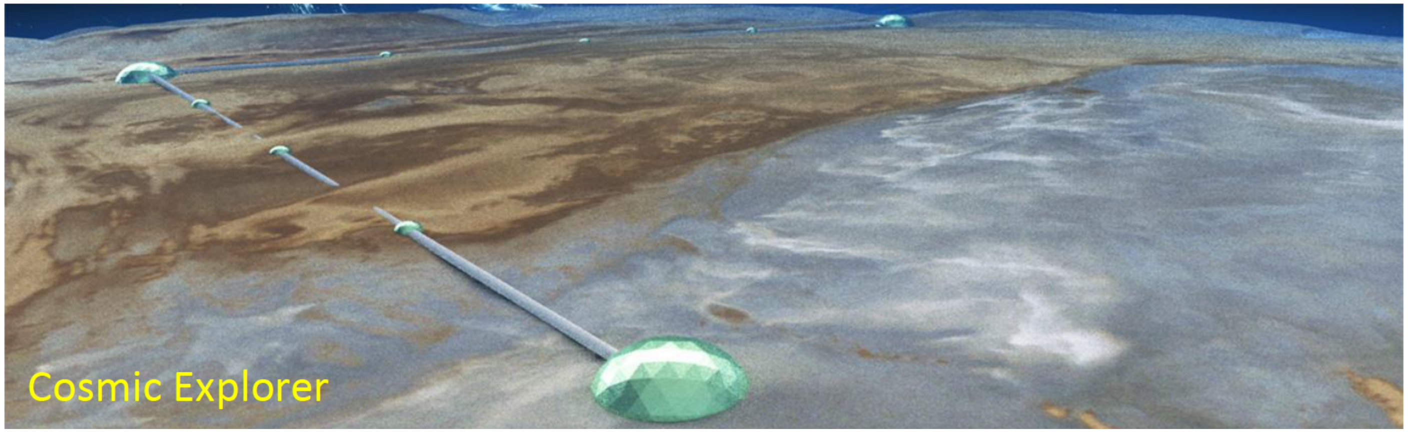
Einstein Telescope and Cosmic Explorer

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



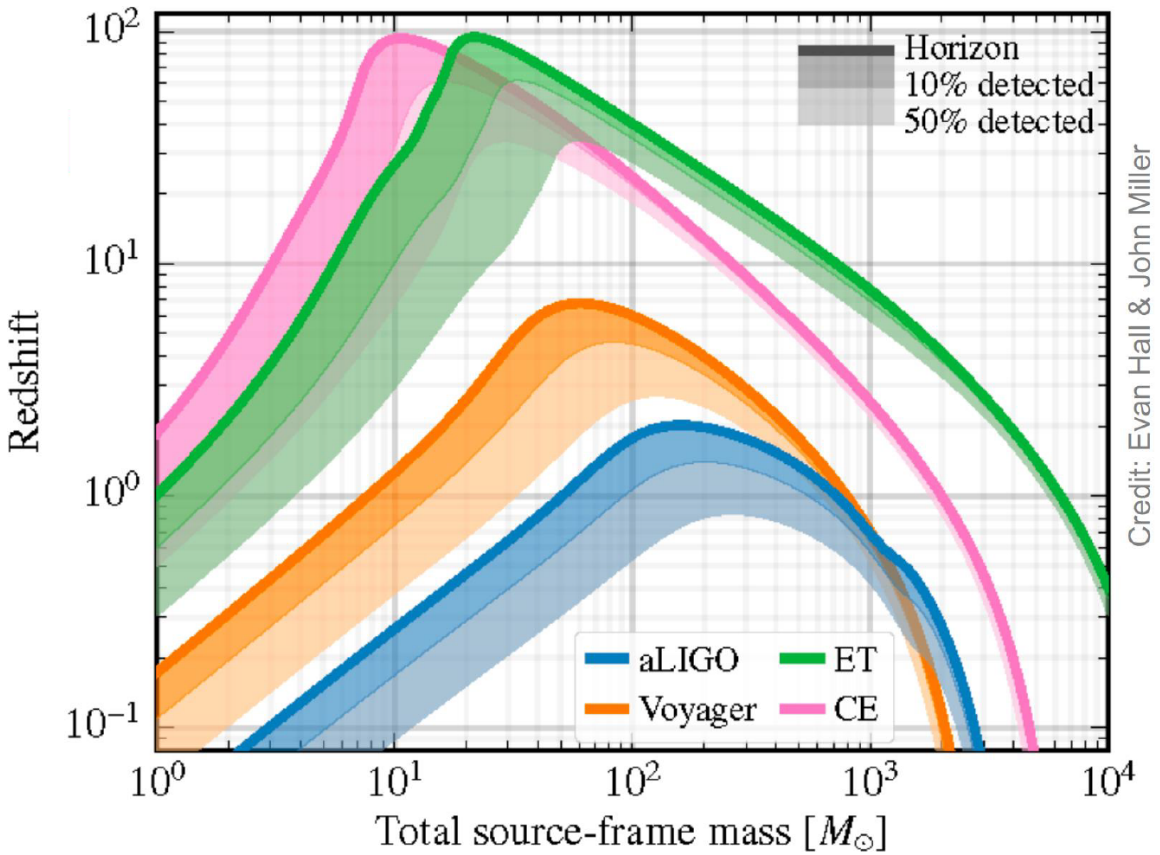
SEVENTH FRAMEWORK PROGRAMME





Einstein Telescope and Cosmic Explorer

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

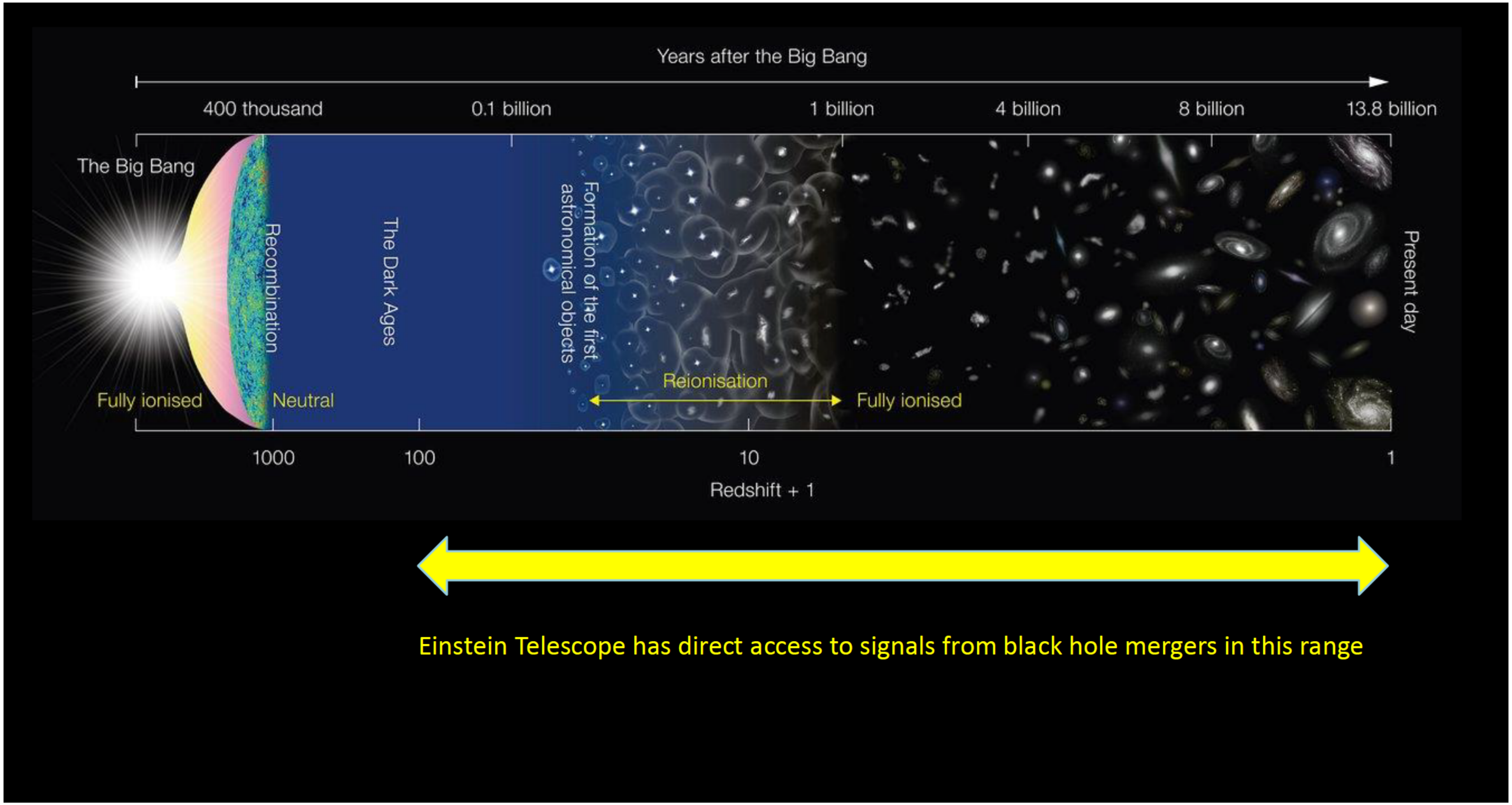


For science case, see https://www.dropbox.com/s/gihpzcue4qd92dt/science-case.pdf?dl=0

Advanced Virgo

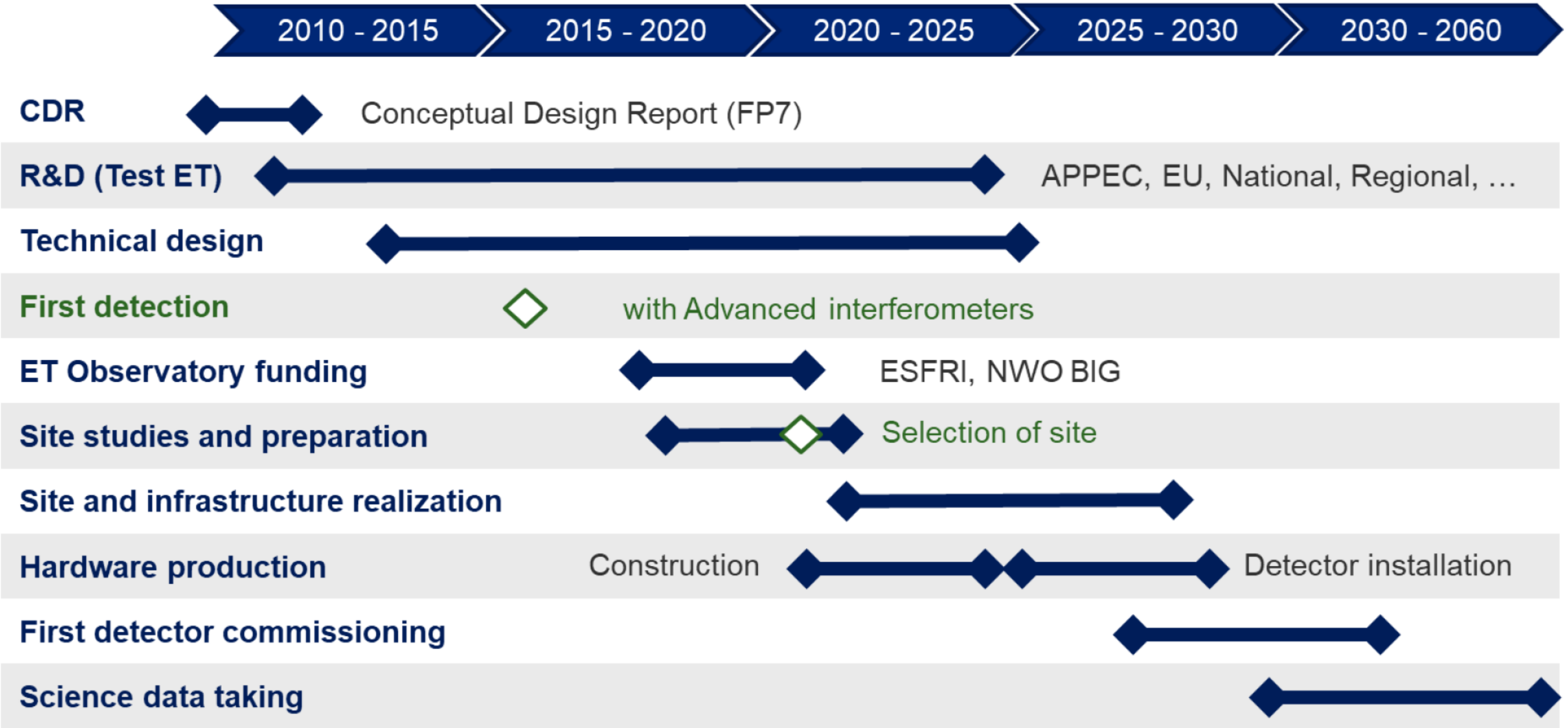
Einstein Telescope

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

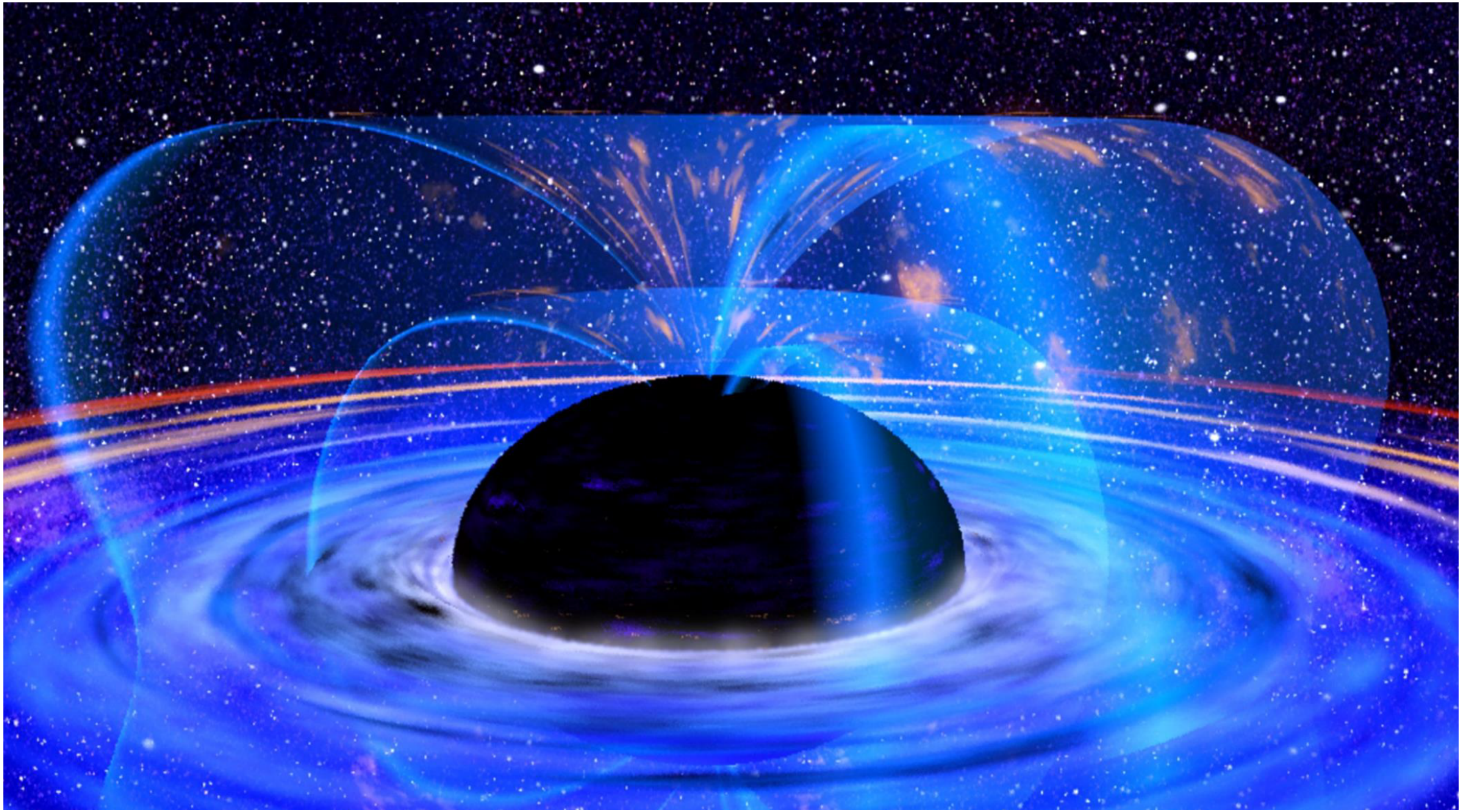


Einstein Telescope: cosmography

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

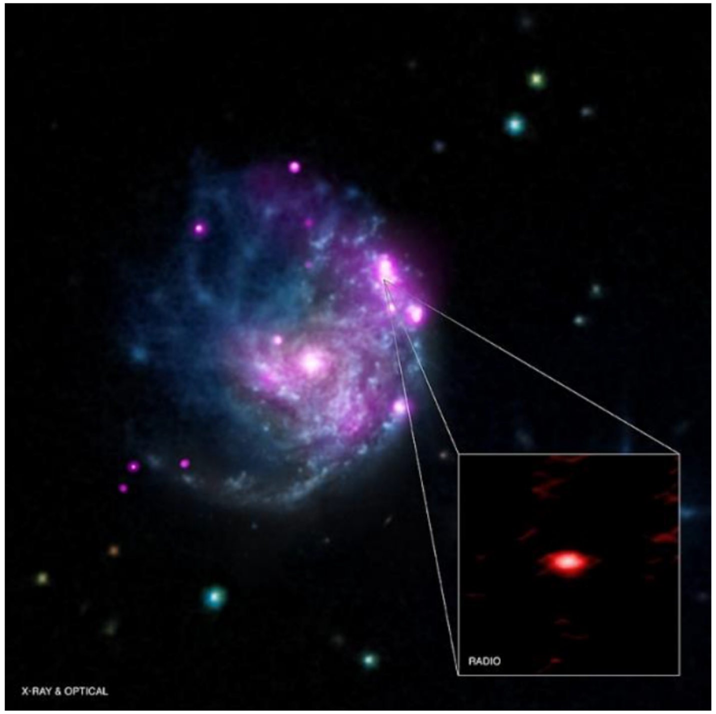
Globular clusters may host intermediate-mass black holes (IMBHs) with masses in the range 100 to 1000 solar masses

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

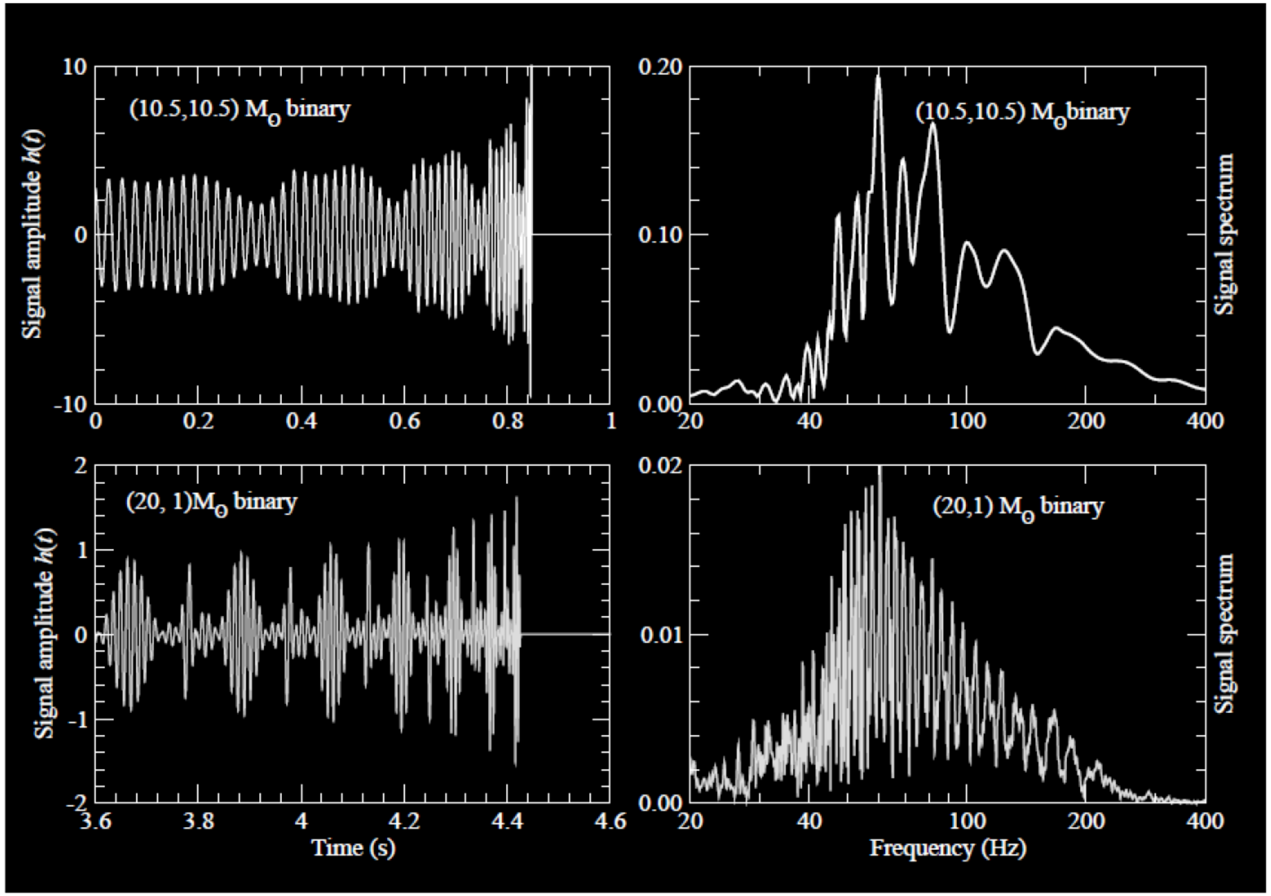


NGC 2276-3c: NASA's Chandra Finds Intriguing Member of Black Hole Family Tree
http://chandra.harvard.edu/photo/2015/ngc2276/

Provide early warning alerts hours in advance

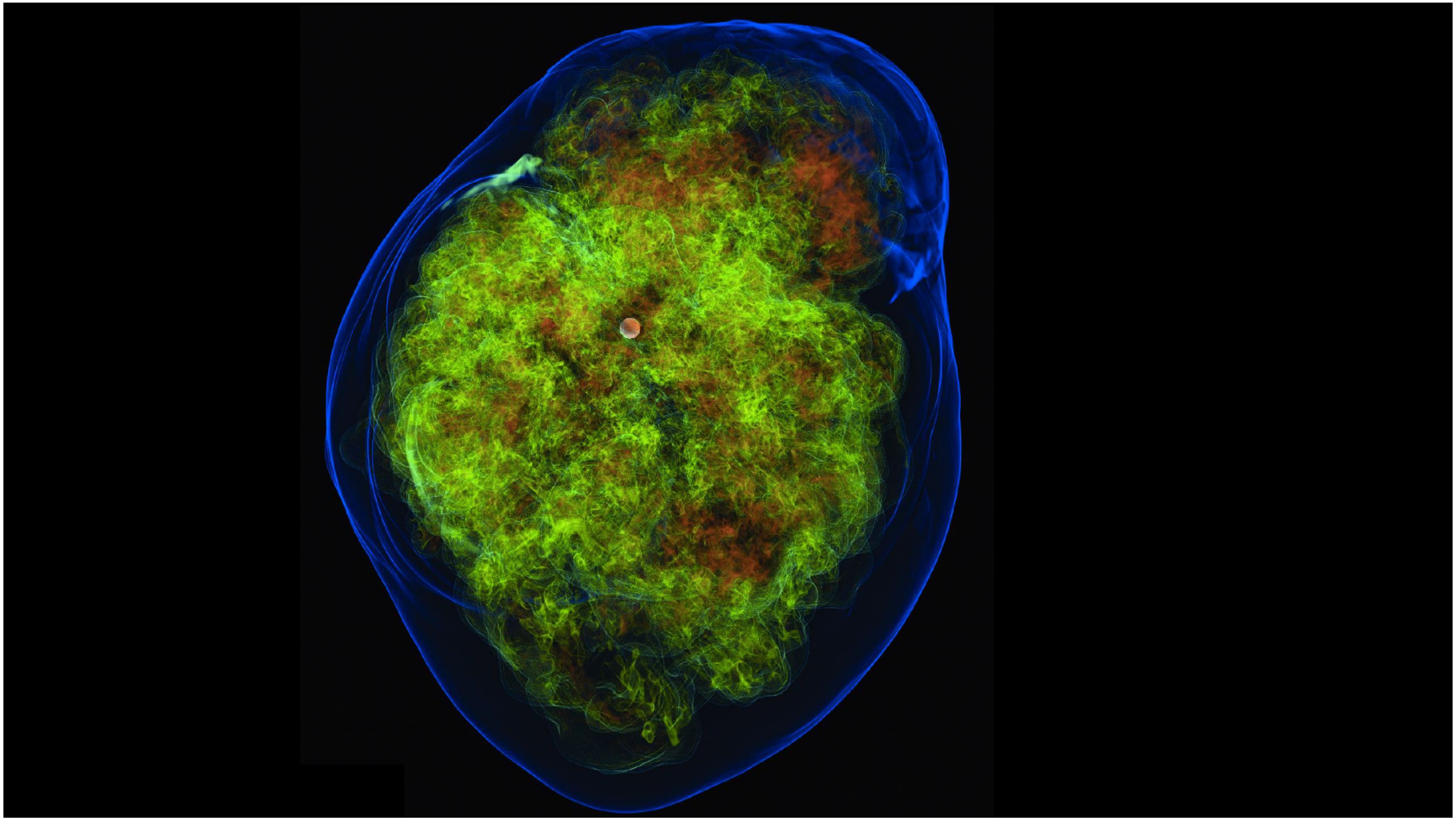
A BNS system will stay in ET's sensitivity band for nearly 20 hours starting from 2 Hz, and a little less than 2 hours starting from 5 Hz. For the same lower frequency limits the duration of a BBH signal from a pair of 10 M BHs is 45 minutes and 4 minutes

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



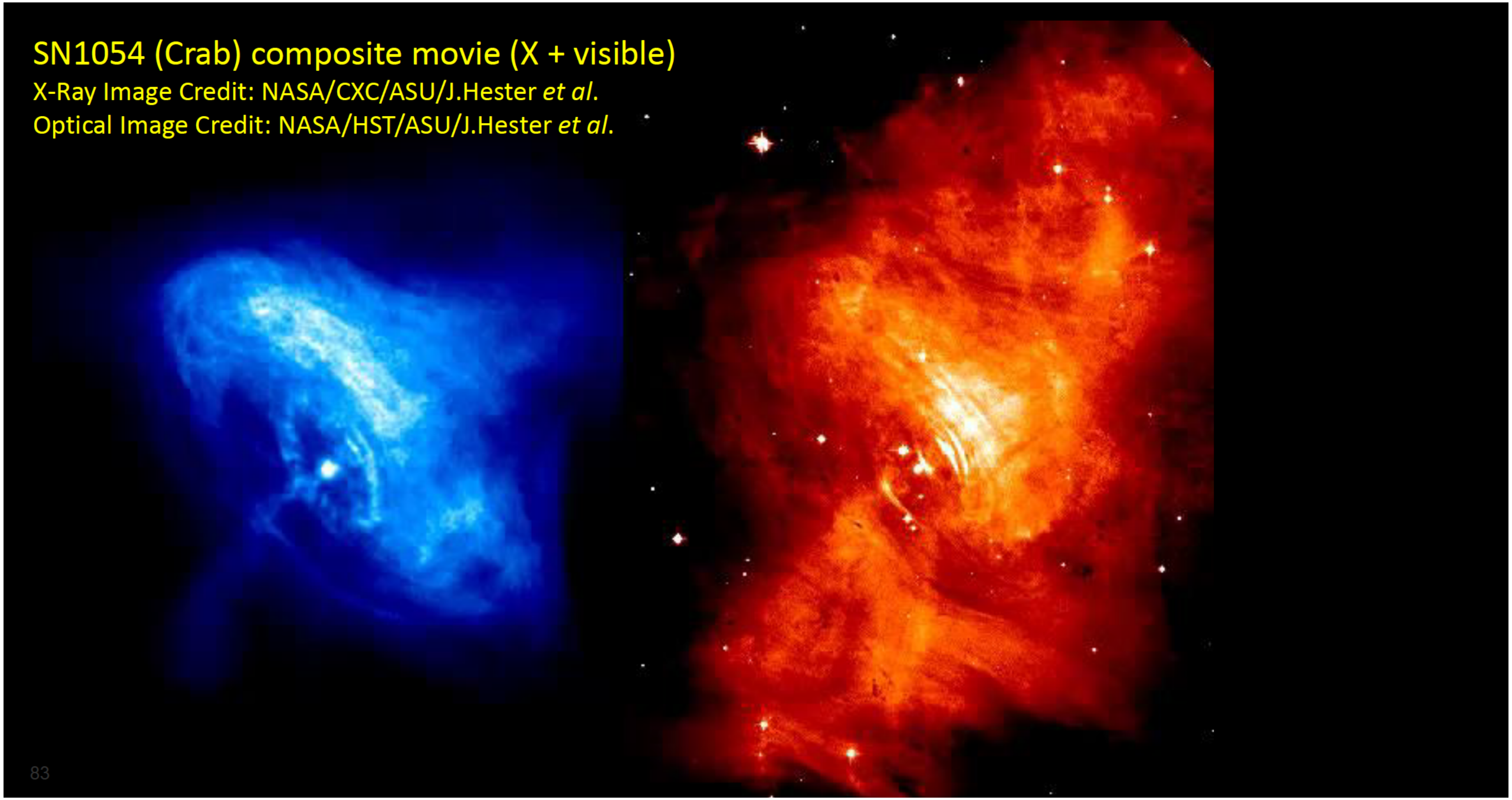
Physics of supernovae

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



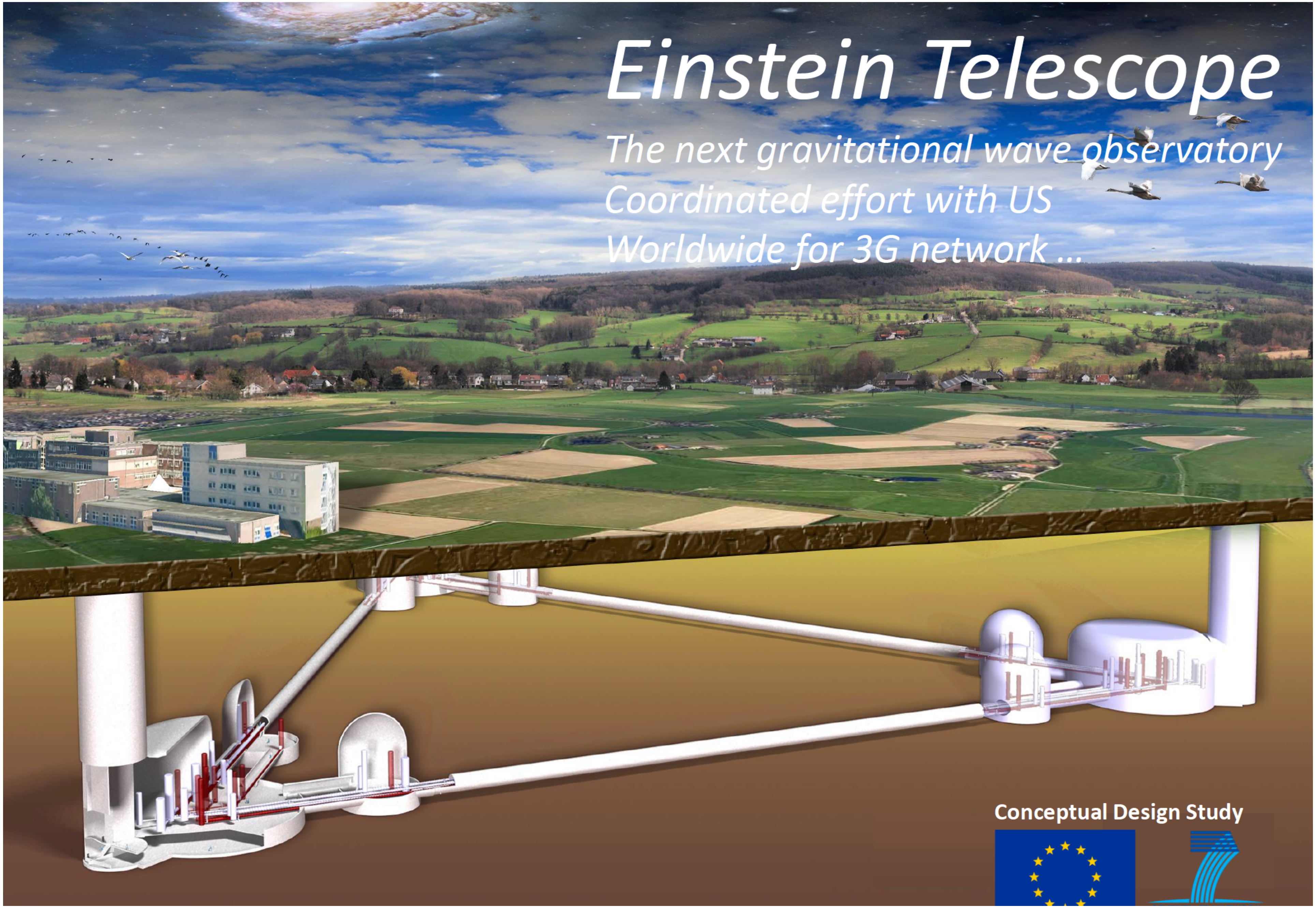
Physics of neutron stars

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

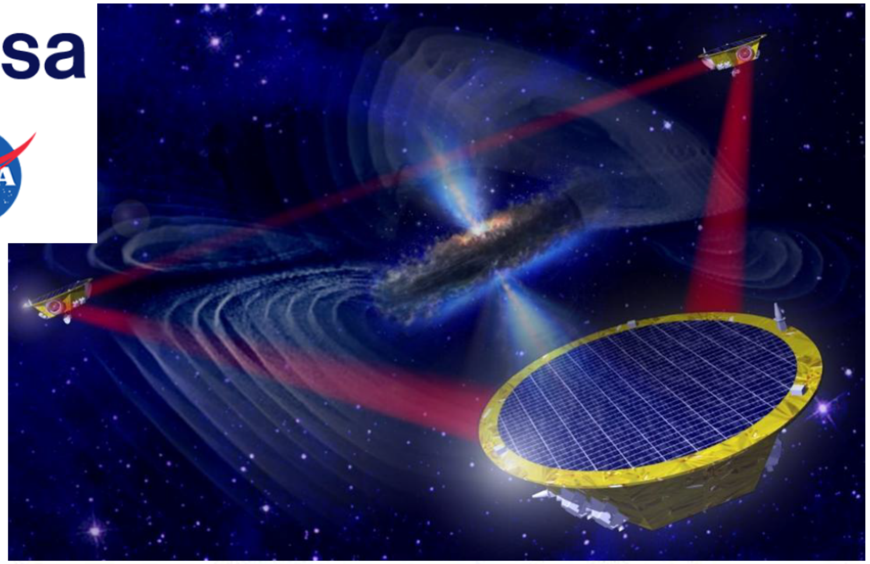

Einstein Telescope
The next gravitational wave observatory
Coordinated effort with US
Worldwide for 3G network …
Conceptual Design Study

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

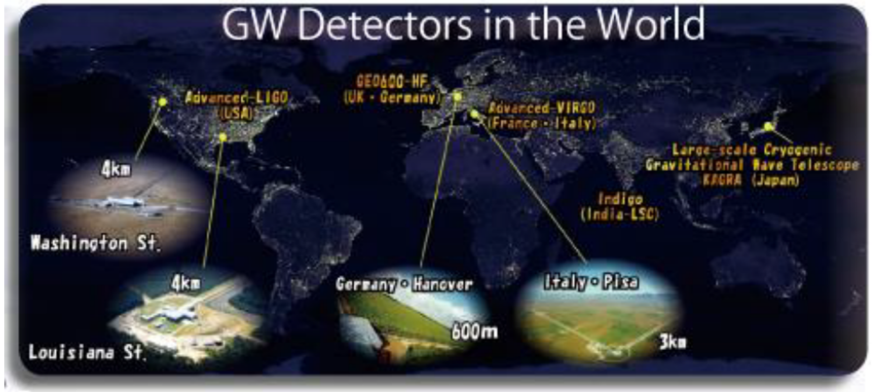
Gravitational wave research

- 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

Astrofisica Nucleare e Subnucleare

Nuclear Astrophysics – II

Kilonova: An electromagnetic signal of heavy element nucleosynthesis

Gabriel Martínez-Pinedo

IPN Seminar, Orsay, April 11, 2018

Heavy element nucleosynthesis: the r process

Gabriel Martínez Pinedo

GSI

TECHNISCHE UNIVERSITÄT DARMSTADT

55th Karpacz Winter School of Theoretical Physics
ChETEC COST Action CA16117 training school
Artus Hotel, Karpacz, February 24 - March 2, 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

SFB 1245

DFG

R-process nucleosynthesis in neutron star mergers

Gabriel Martínez-Pinedo

EMMI Workshop: New avenues for low energy NuSTAR program at GSI-FAIR

GSI, September 16-17, 2021

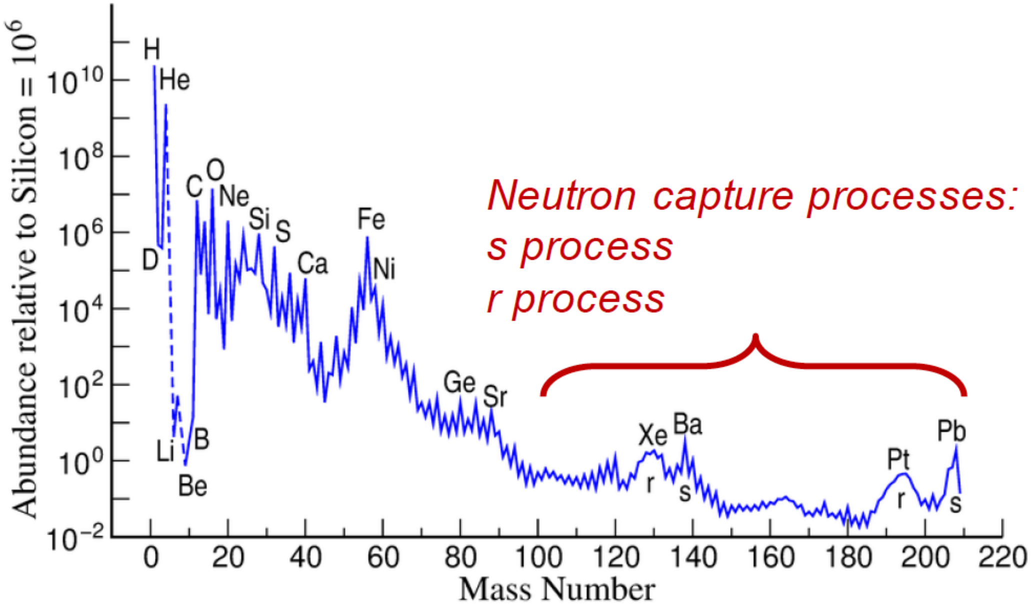
Helmholtz Forschungsakademie Hessen für FAIR

European Research Council

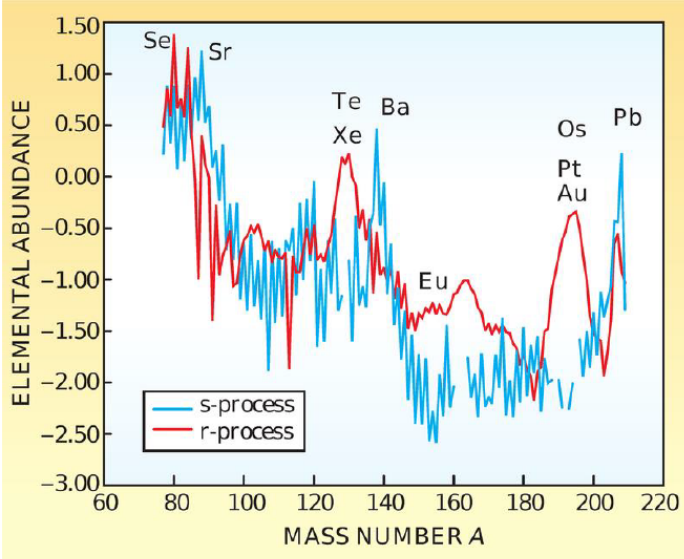
Established by the European Commission

HELMHOLTZ

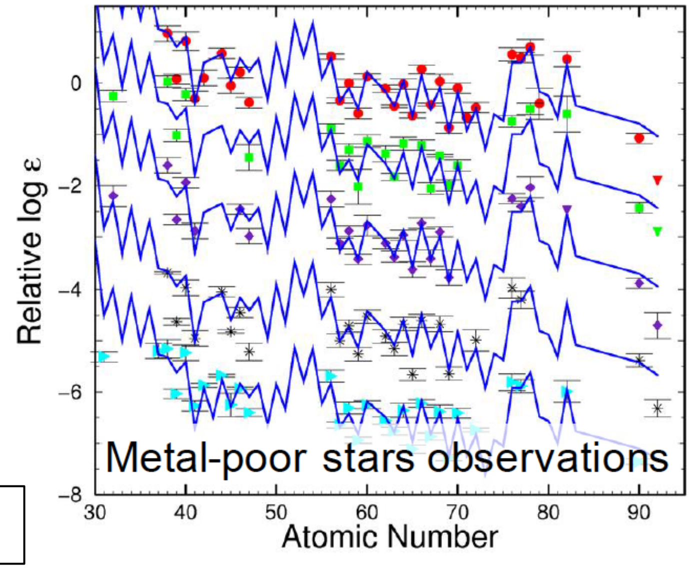
Signatures of nucleosynthesis



Neutron capture processes:
s process
r process



- Heavy elements produced in neutron capture processes
- r process operates at early Galactic history



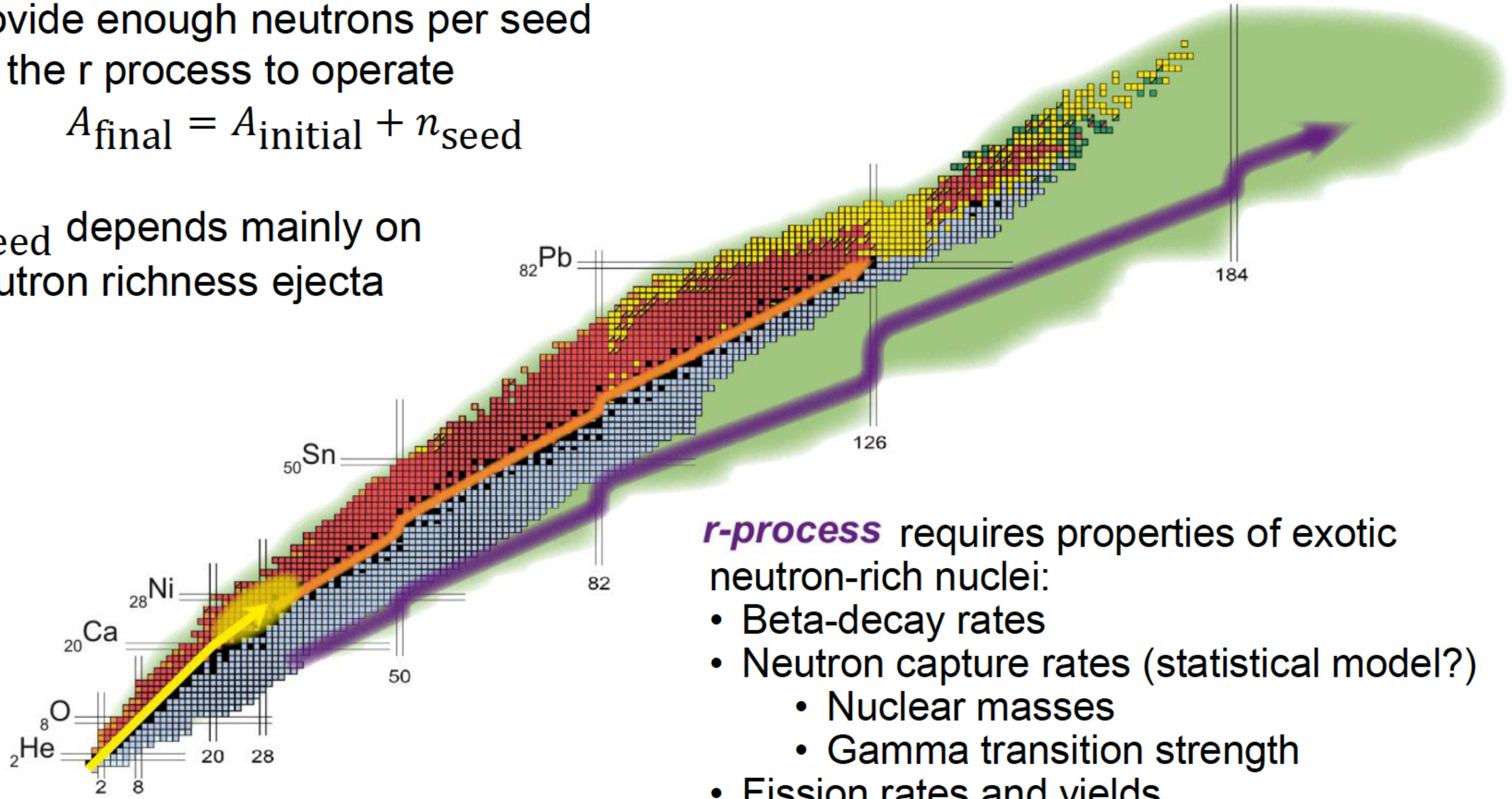
https://space.mit.edu/home/afrebel/review_frebel.pdf

R process nuclear needs

Astrophysical environment should provide enough neutrons per seed for the r process to operate

$$A_{\text{final}} = A_{\text{initial}} + n_{\text{seed}}$$

n_{seed} depends mainly on neutron richness ejecta



r-process requires properties of exotic neutron-rich nuclei:

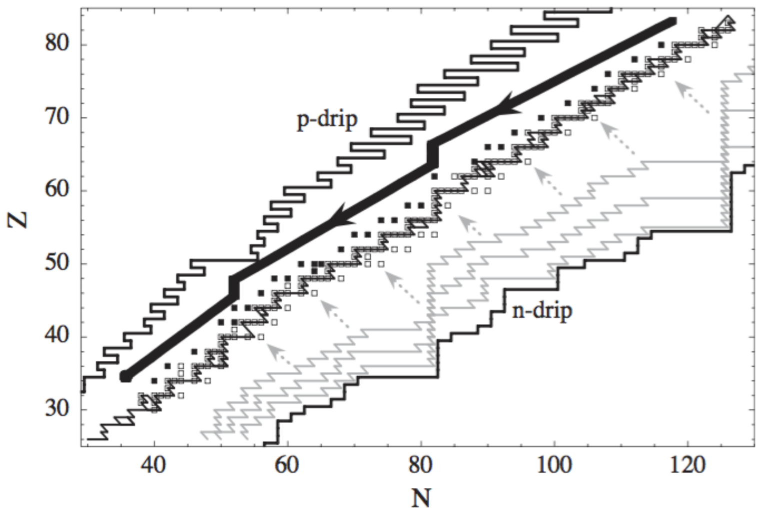
- Beta-decay rates
- Neutron capture rates (statistical model?)
    - Nuclear masses
    - Gamma transition strength
- Fission rates and yields
    - Fission barriers

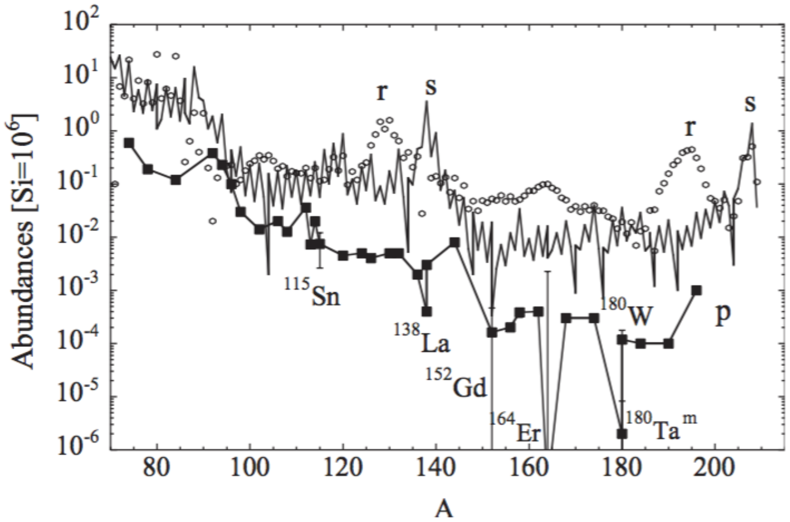
Benchmark against observations:

- Solar and stellar abundances (indirect)
- Electromagnetic emission, kilonova (direct), sensitive Atomic and Nuclear Physics

Nucleosynthesis beyond iron

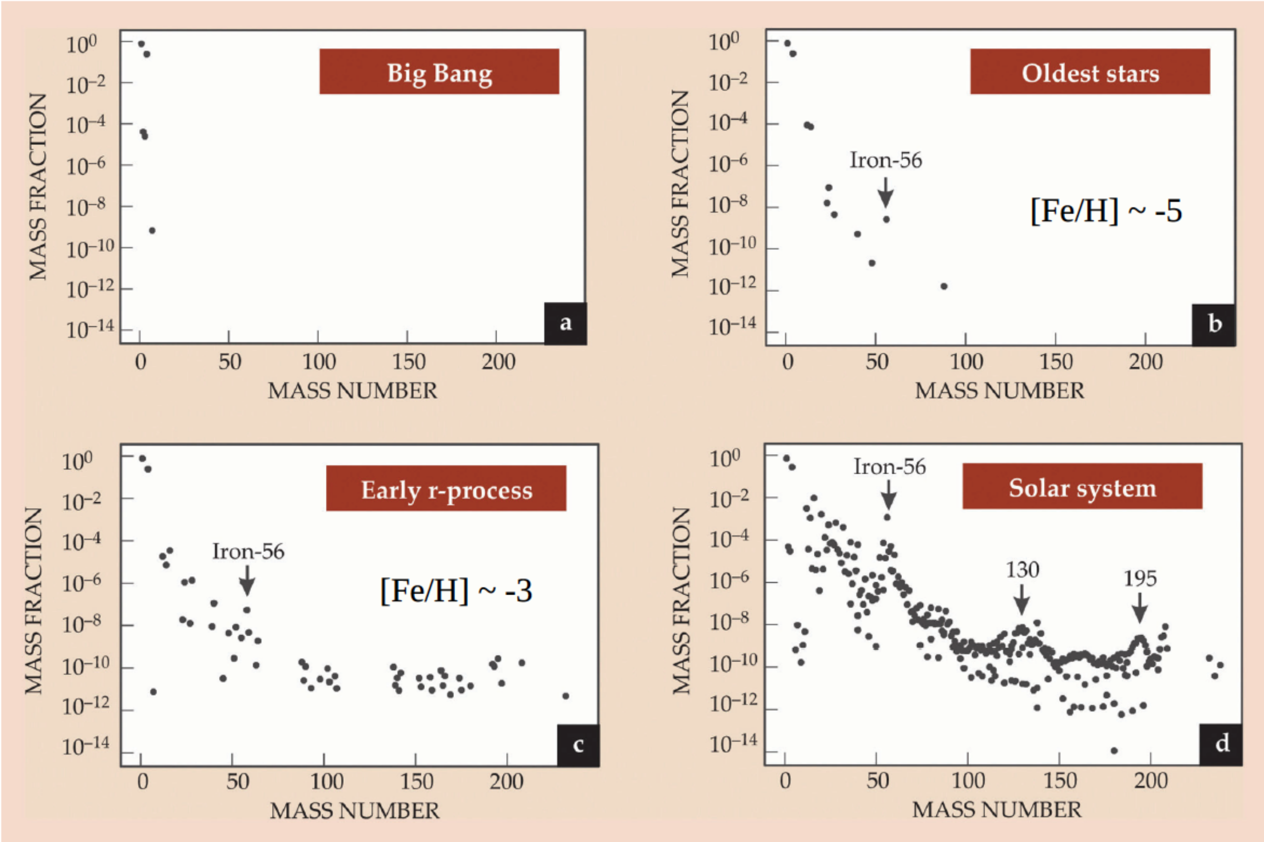
Three processes contribute to the nucleosynthesis beyond iron: s-process, r-process and p-process (γ-process).





- s-process: relatively low neutron densities, $n_n = 10^{10-12}$ cm^{-3}, $\tau_n > \tau_\beta$
- r-process: large neutron densities, $n_n > 10^{20}$ cm^{-3}, $\tau_n < \tau_\beta$.
- p-process: photodissociation of s-process material.

Time evolution: metalicity



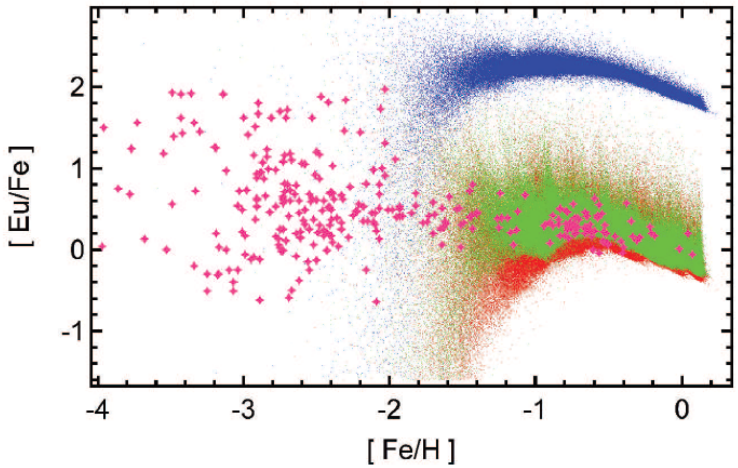
Astronomers use the metalicity:

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{*} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\odot}$$

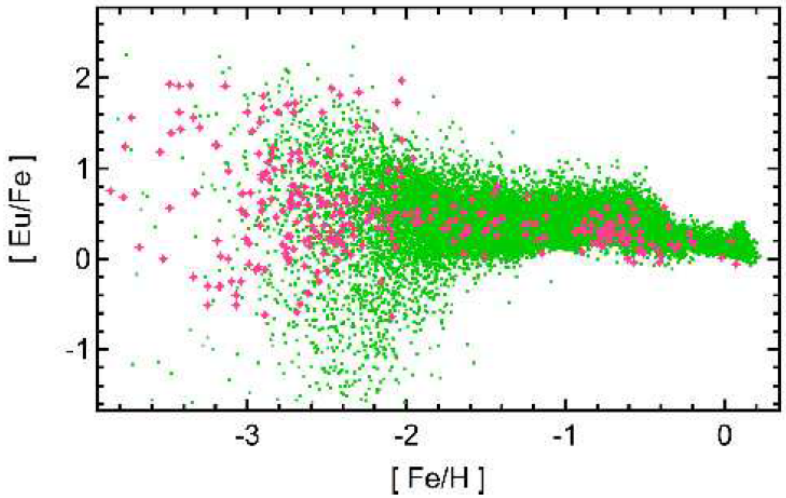
as a proxy for age.

Introduction: Summary

- The r process is a primary process operating in a site that produces both neutrons and seeds. Large neutron densities imply a site with extreme conditions of temperature and/or density.
- There is strong evidence that the bulk of r-process content in the Galaxy originates from a high yield/low frequency events.
- Neutron star mergers may account for most of the r-process material in the galaxy. However, due to the coalescent delay time they may not contribute efficiently at low metalicities. Magneto-rotational supernova may contribute at low metalicities.



- Red dots: 10^8 yr coalescence time
- Green dots: 10^6 yr coalescence time
- Blue dots: larger merger probability.

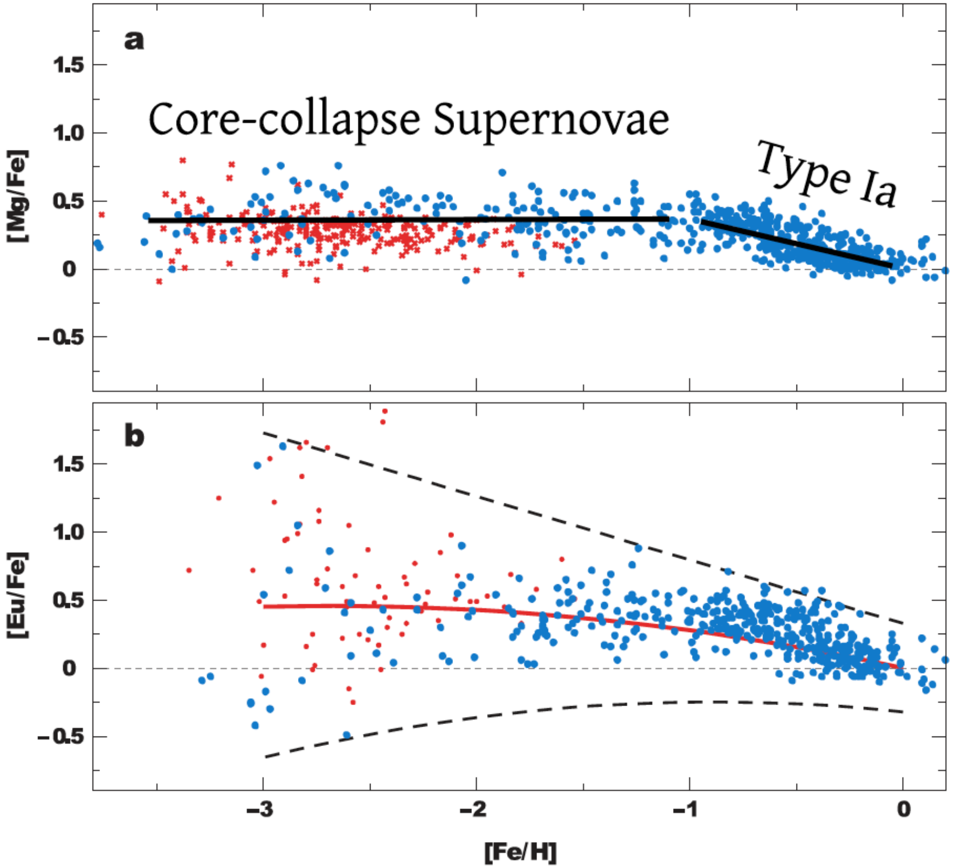


- Including MHD-jet supernovae

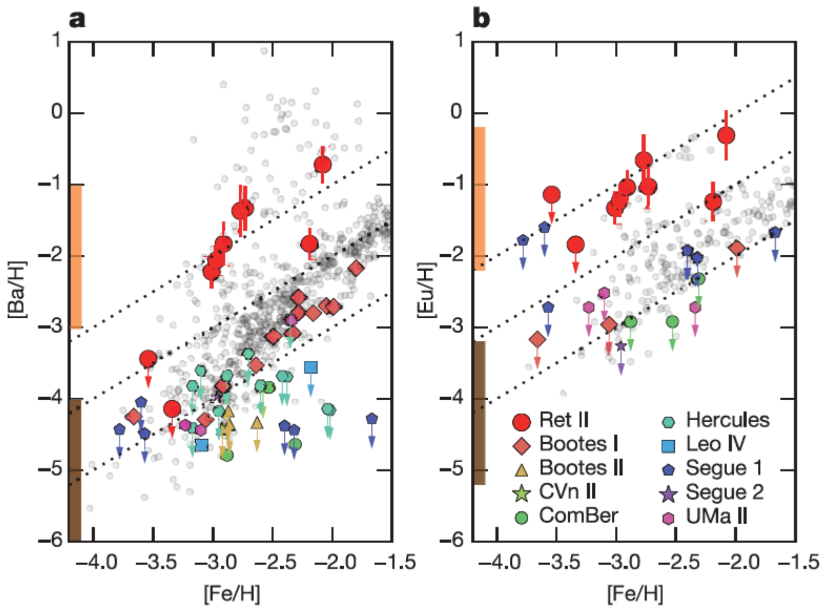
Wehmeyer, B., M. Pignatari, and F.-K. Thielemann , Mon. Not. Roy. Astron. Soc. 452, 1970 (2015)

Implications from observations

Individual stars, Milky Way Halo
Sneden, Cowan & Gallino, 2008



Ji et al 2016 found that only 1 of 10 ultrafaint dwarf galaxies is enriched in r-process elements



R process related to rare high yield events not correlated with Iron enrichment

Similar results obtained by ^{60}Fe and ^{244}Pu observations in deep sea sediments (Wallner et al, 2015; Hotokezaka et al, 2015)

Types of reactions

In order to dissentangle changes in the density (hydrodynamics) from changes in the composition (nuclear dynamics), the abundance is introduced:

$$Y_a = \frac{n_a}{n}, \quad n \approx \frac{\rho}{m_u} = \text{Number density of nucleons (constant)}$$

- $\sum_i Y_i Z_i = Y_e$ (charge neutrality)

R-process sites

- Any r-process site should be able to produce both the "seed" nuclei where neutrons are captured and the neutrons that drive the r-process. The main parameter describing the feasibility of a site to produce r-process nuclei is the neutron-to-seed ratio: n_n/n_{seed}.
- If the seed nuclei have mass number A_{seed} and we have n_n/n_{seed} neutrons per seed, the final mass number of the nuclei produced will be $A = A_{\text{seed}} + n_n/n_{\text{seed}}$.
- For example, taking $A_{\text{seed}} = 90$ we need $n_n/n_{\text{seed}} = 100$ if we want to produce the 3rd r-process peak ($A \sim 195$) and $n_n/n_{\text{seed}} = 150$ to produce U and Th.

r-process nucleosynthesis relevant parameters

Independently of the astrophysical site the nucleosynthesis is sensitive to a few parameters that determine the neutron-to-seed ratio and the heavier elements that can be produced:

$$A_f = A_i + n_s, \quad n_s = n_n/n_{\text{seed}} \sim s^3/(Y_e^3 \tau_{\text{dyn}})$$

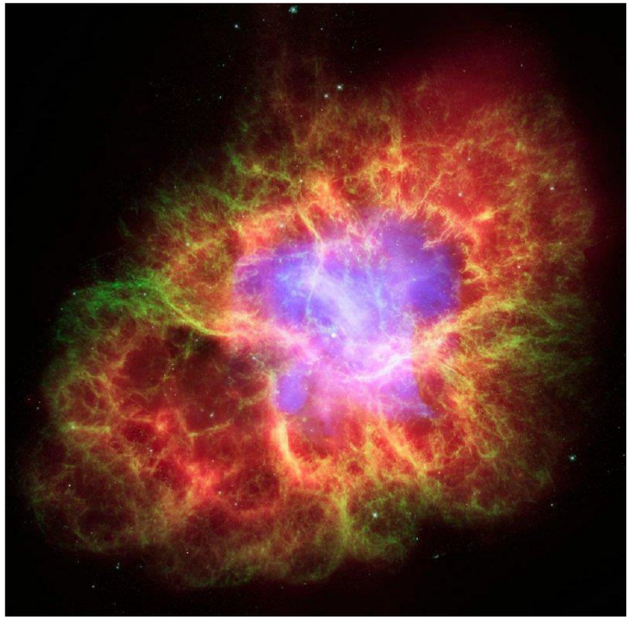
Y_e The lower the value of Y_e more neutrons are available and the larger n_s

entropy Large entropy $s \sim T^3/\rho$, means low density and high temperature (large amount of photons). Both are detrimental to the build up of seeds by 3-body reactions.

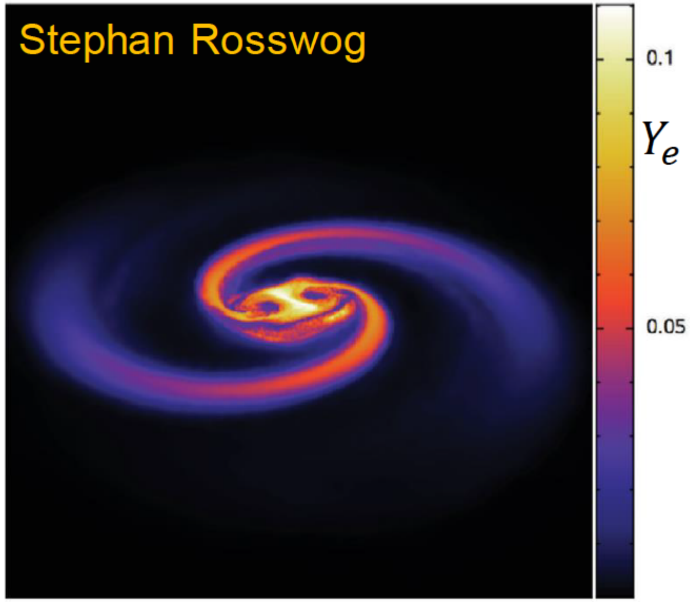
expansiton time scale The faster the matter expands, smaller τ_{dyn}, the less time one has to build up seeds

Astrophysical sites

Core-collapse supernova



Compact binary mergers

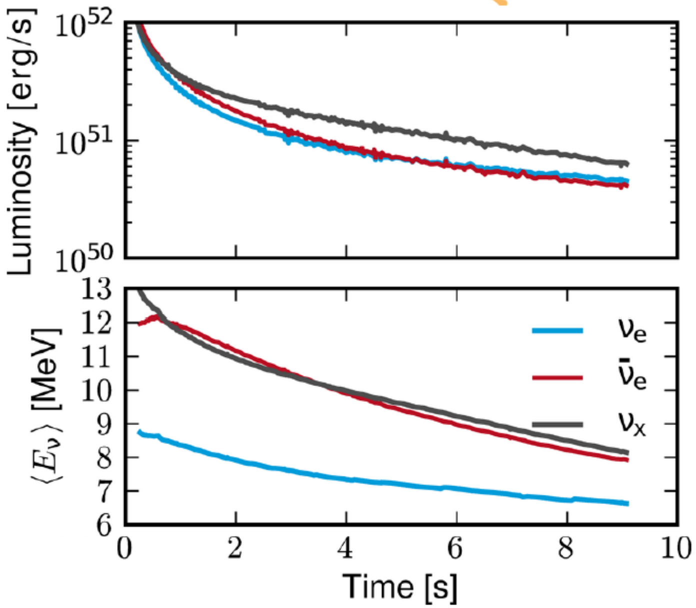


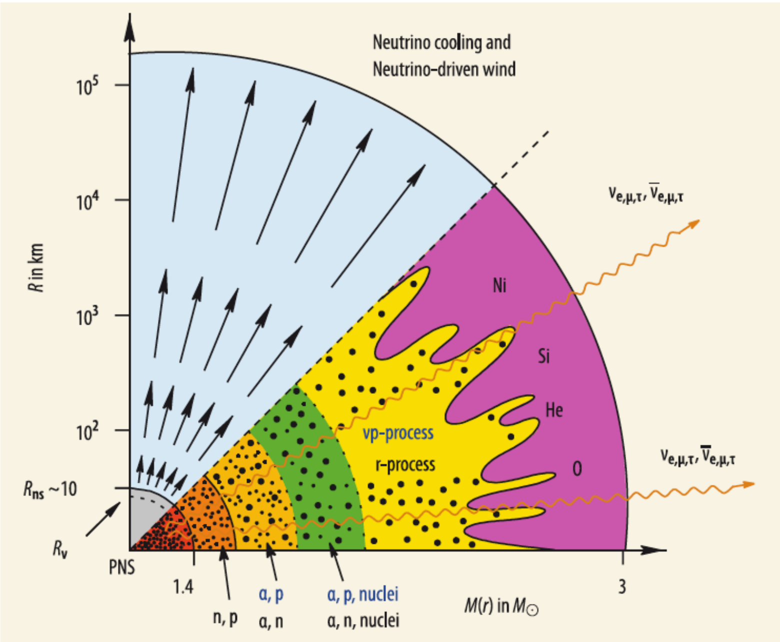
	Supernova	Mergers
Optimal conditions	☹	☺
Yield / Frequency	😐	☺
Direct signature	☹	☺

Supernova nucleosynthesis

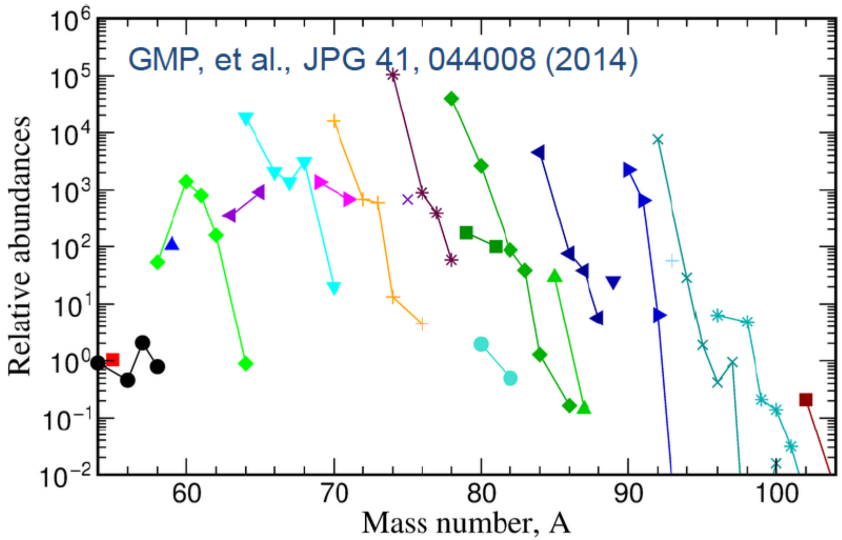
Heavy elements produced in neutrino winds from protoneutron star cooling. Neutrino interactions determine proton-to-nucleon ratio, Y_e

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$





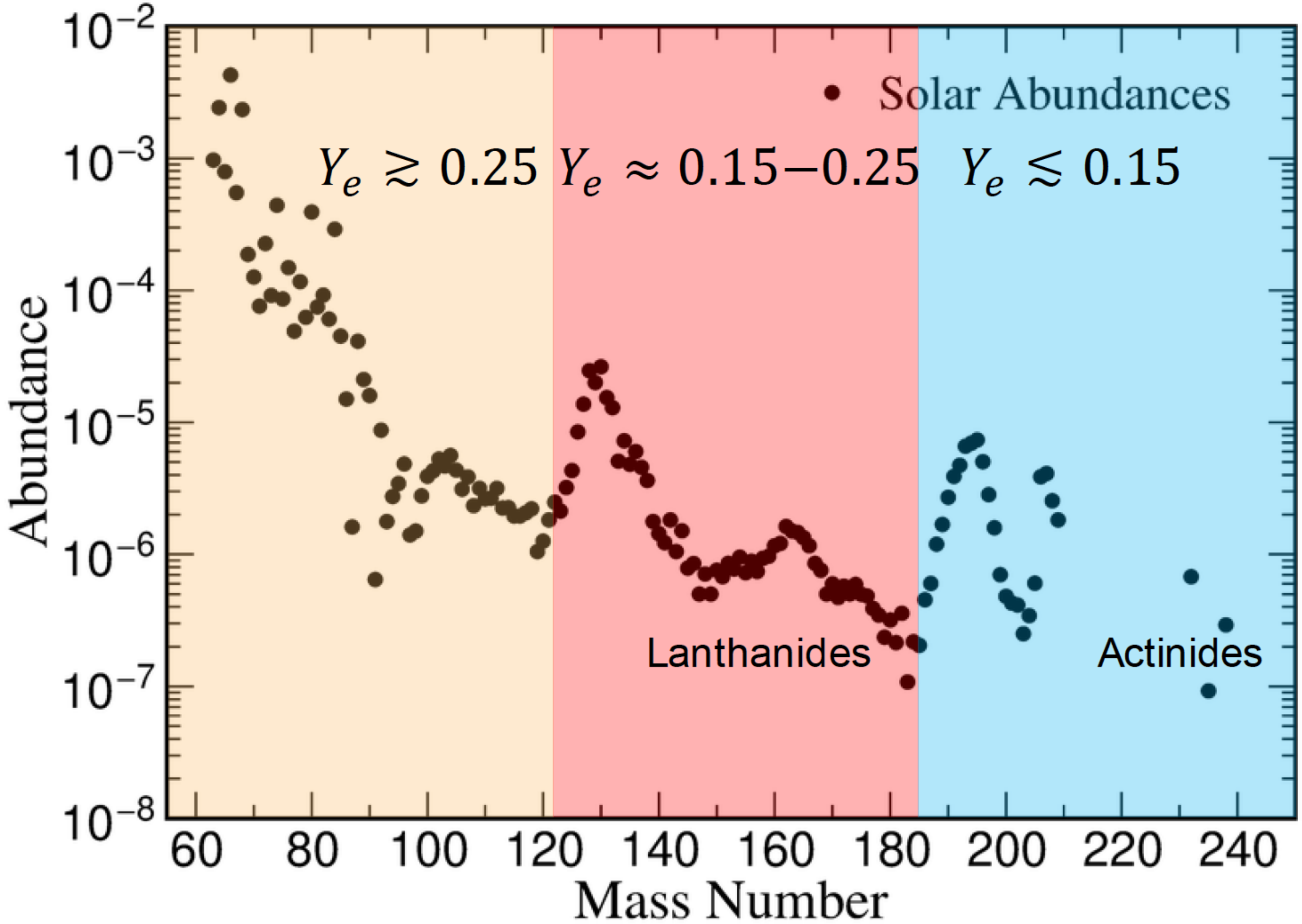
Supernova produce only medium mass nuclei



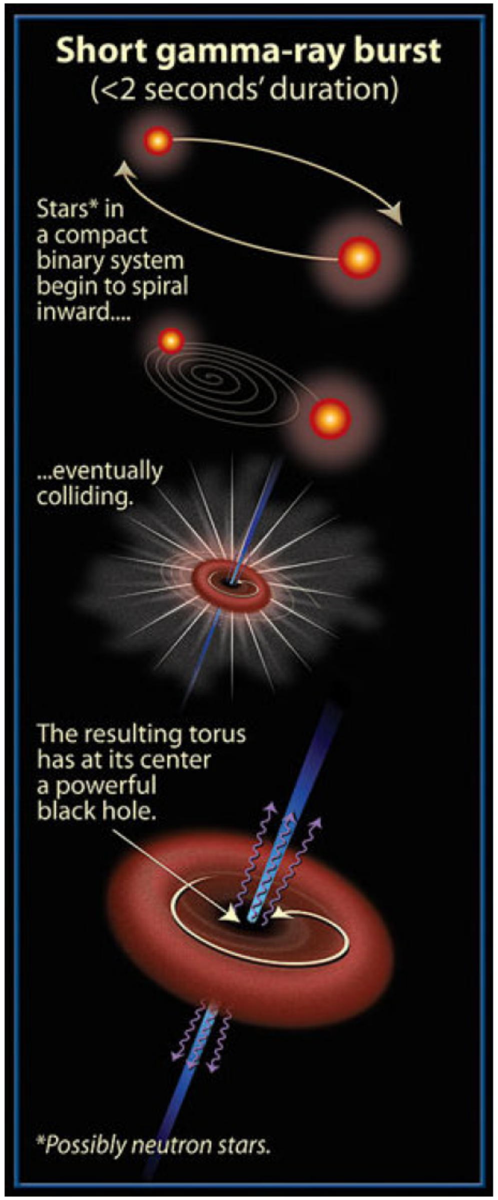
Nucleosynthesis dependence on Y_e

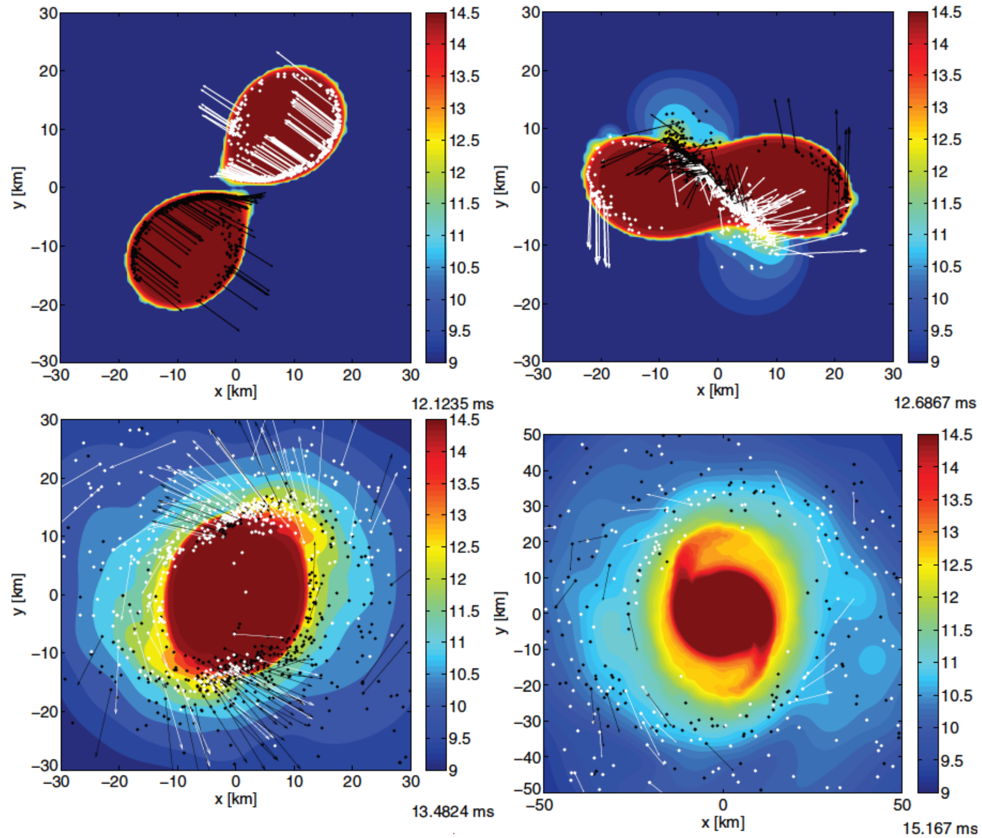
Nucleosynthesis mainly sensitive to proton-to-nucleon ratio, Y_e

$\nu_e + n \rightleftarrows p + e^-$ vs $\bar{\nu}_e + p \rightleftarrows n + e^+$



Neutron star mergers: Short gamma-ray bursts and r-process



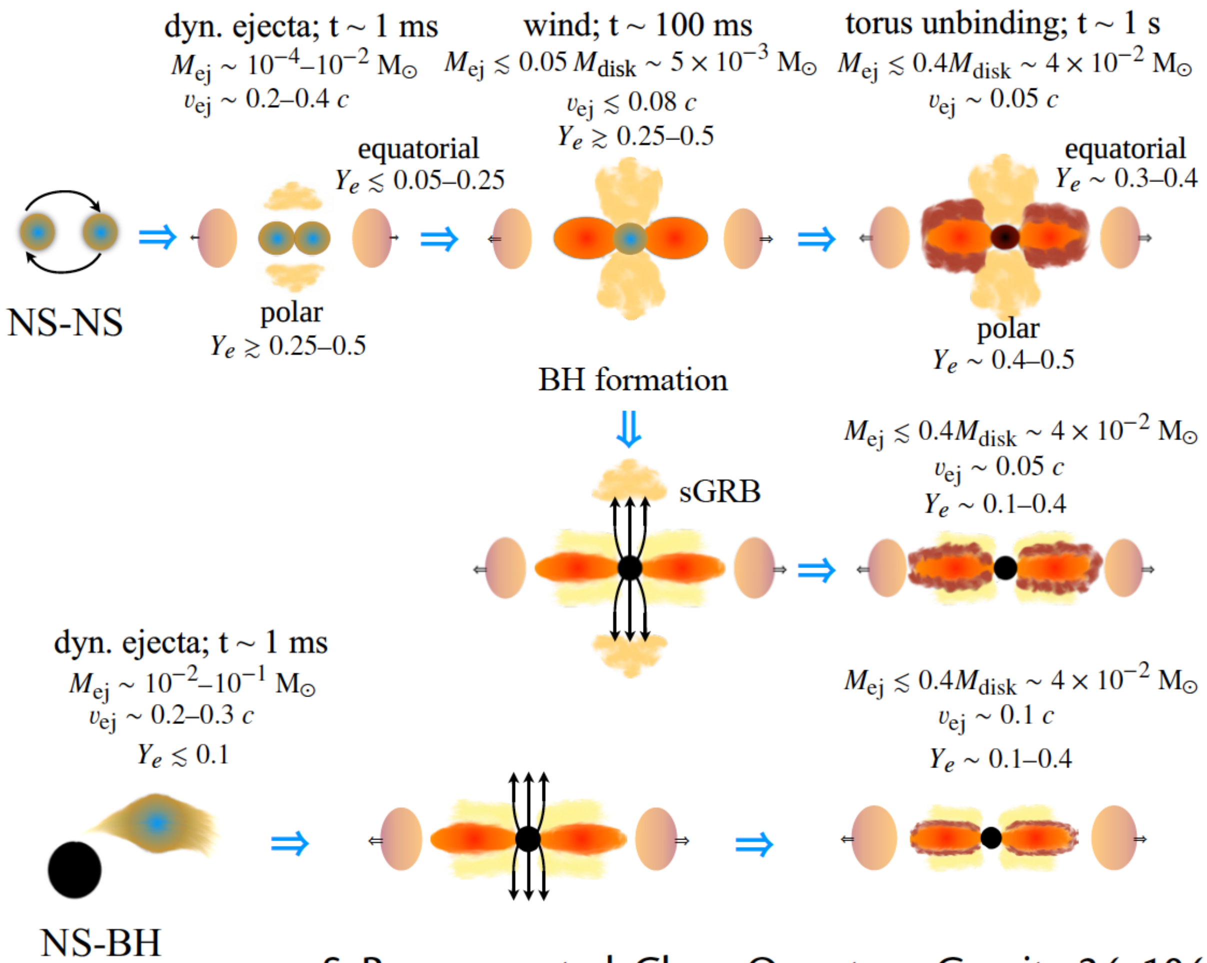


Basuswein, Goriely, Janka, ApJ 773, 78 (2013)

- Mergers are associated with short-gamma ray bursts.
- They are also promising sources of gravitational waves.
- Observational signatures of the r-process?

Merger channels and ejection mechanism

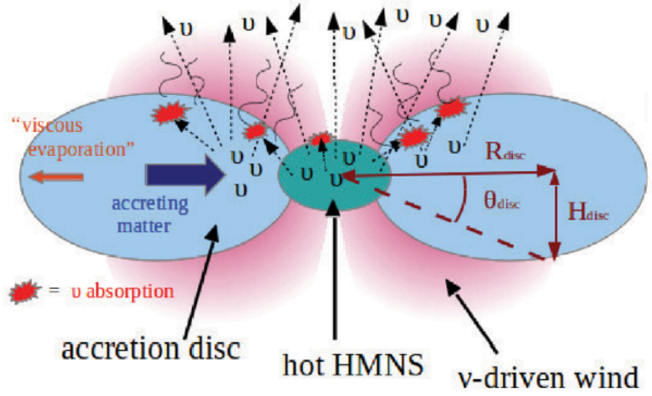
In mergers we deal with a variety of initial configurations (netron-star neutron-star vs neutron-star black-hole) with additional variations in the mass-ratio. The evolution after the merger also allows for further variations.



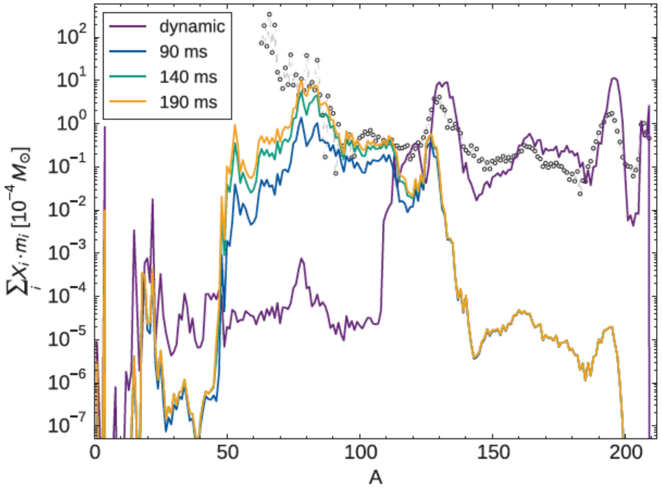
S. Rosswog, et al, Class. Quantum Gravity 34, 104001 (2017).

Post-merger Nucleosynthesis (NS remnant)

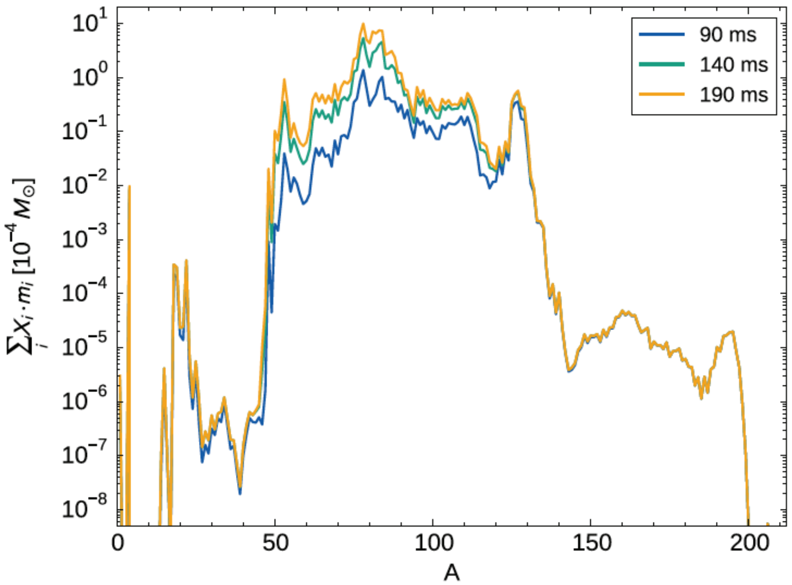
An Hypermassive neutron star produces large neutrino fluxes that drive the composition to moderate neutron rich ejecta.



Perego, *et al*, MNRAS 443, 3134 (2014)



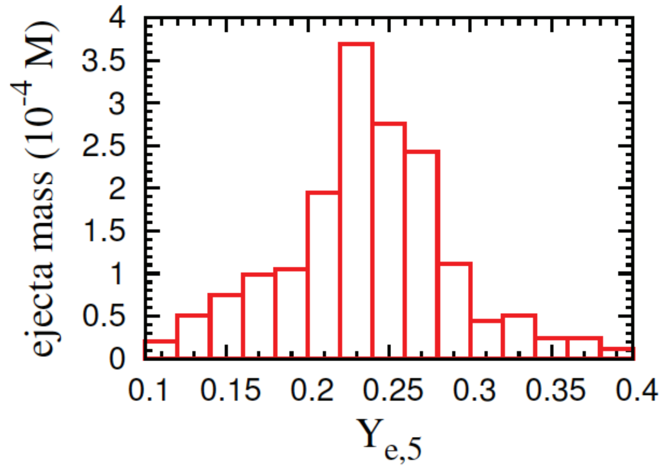
Martin, *et al*, ApJ 813, 2 (2015)



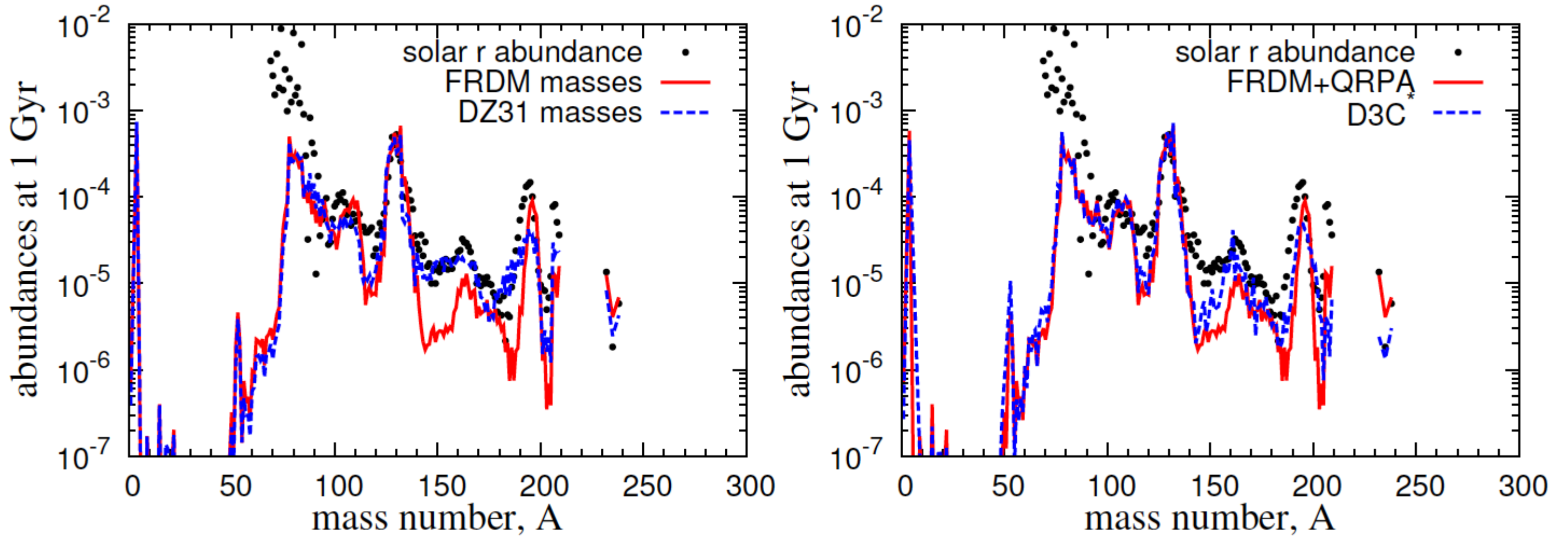
Only nuclei with $A < 120$ are produced (no lanthanides, blue kilonova).

See also Lippuner et al, MNRAS **472**, 904 (2017)

Post-merger nucleosynthesis (BH remnant)



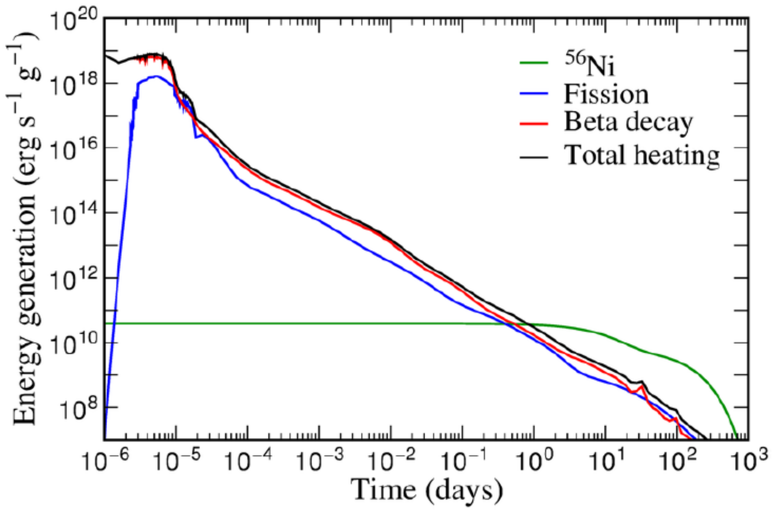
- Accretion disk around BH ejects relatively neutron-rich matter [Fernández, Metzger, MNRAS 435, 502 (2013)]
- Produces all r-process nuclides (Lanthanide/Actinide rich ejecta) [Wu *et al*, MNRAS 463, 2323 (2016)]

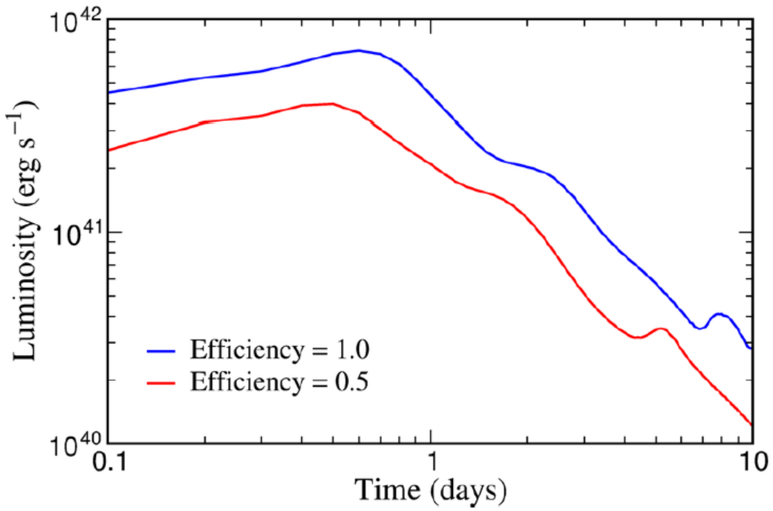


See also Just et al, MNRAS 448, 541 (2015), Siegel and Metzger PRL 119, 231102 (2017)

Kilonova: Electromagnetic signature of the r process

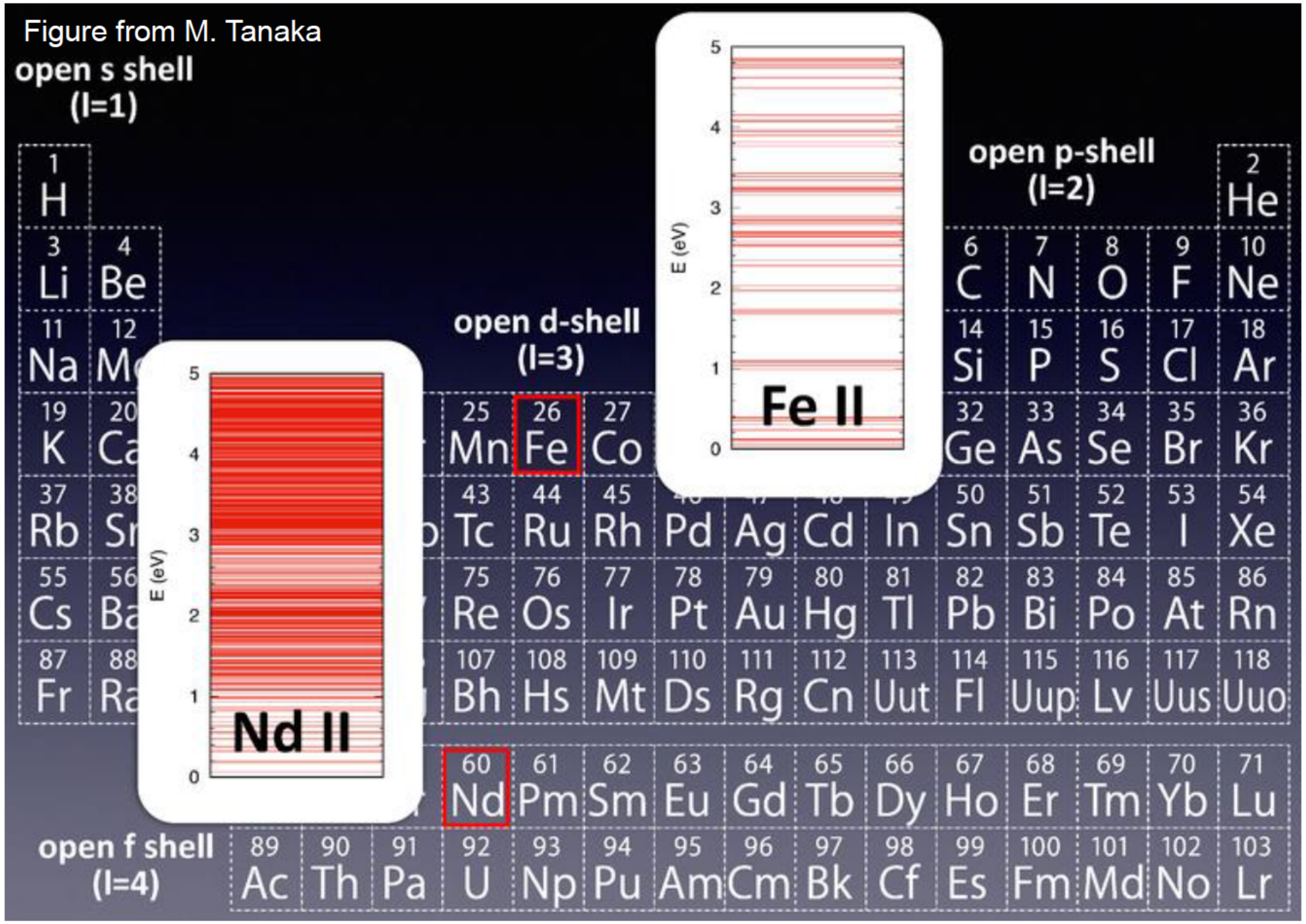
- Ejecta produces electromagnetic signatures [Li & Paczyński 1998]
- Transient due to radioactive decay of r-process nuclei [Metzger et al, 2010]
  Heating: $\dot{\varepsilon} \sim t^{-1.3}$
  Luminosity like 1000 novas: Kilonova
  Peak on timescales days in optical/blue
- Presence of Lanthanides reduces luminosity and delays peak to ~ week in red/infrared [Barnes & Kasen, 2013]
- Similar effect due to Actinides [Mendoza-Temis et al, 2015]
- Accurate treatment of thermalization of radioactive products [Barnes, et al, 2016]





Metzger, GMP, Darbha, Quataert, Arcones et al, MNRAS 406, 2650 (2010)

Impact Lanthanides



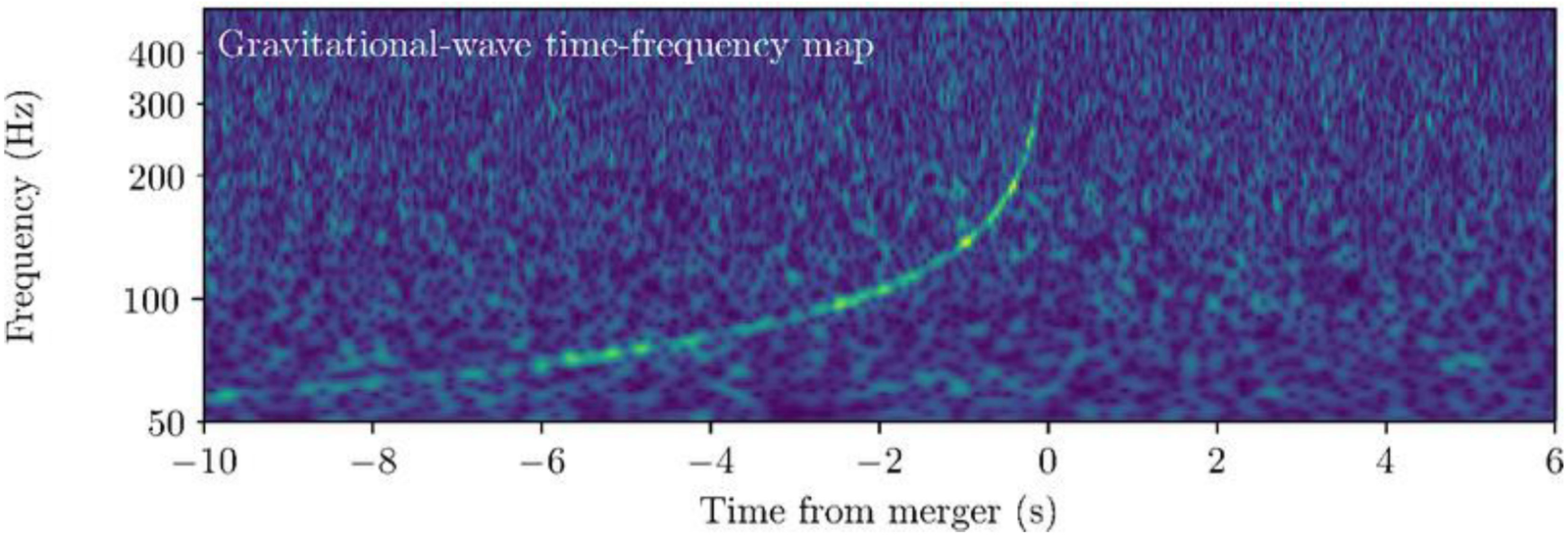
Large number of states of Lanthanides/Actinides leads to a high opacity

Barnes & D. Kasen, Astrophys. J. 775, 18 (2013);Tanaka & Hotokezaka, Astrophys. J. 775, 113 (2013).

GW170817: First detection gravitational waves from NS merger

On August 17, 12:41:04 UTC advanced LIGO and Virgo detect the first GW signal from a binary neutron star inspiral

Abbott, et al, PRL 119, 161101 (2017).

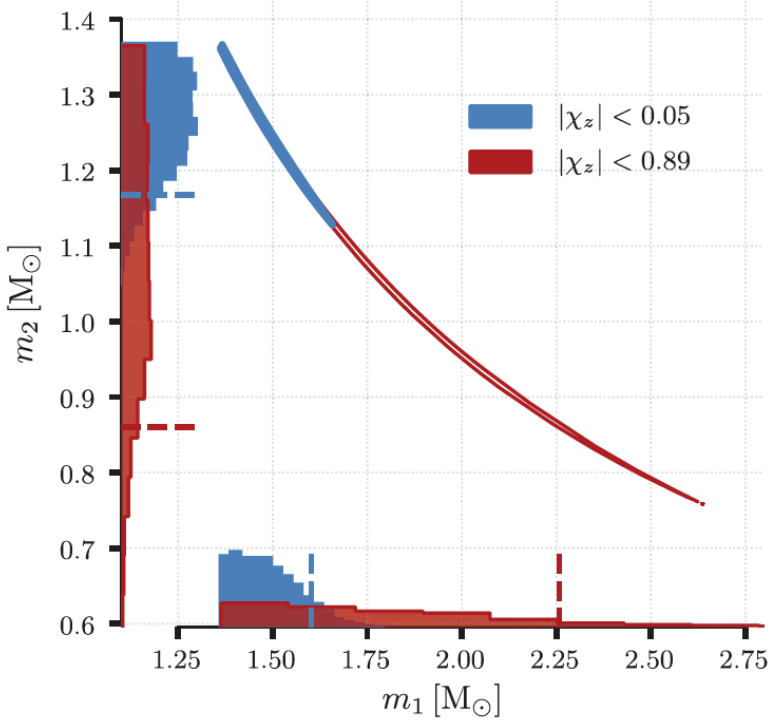


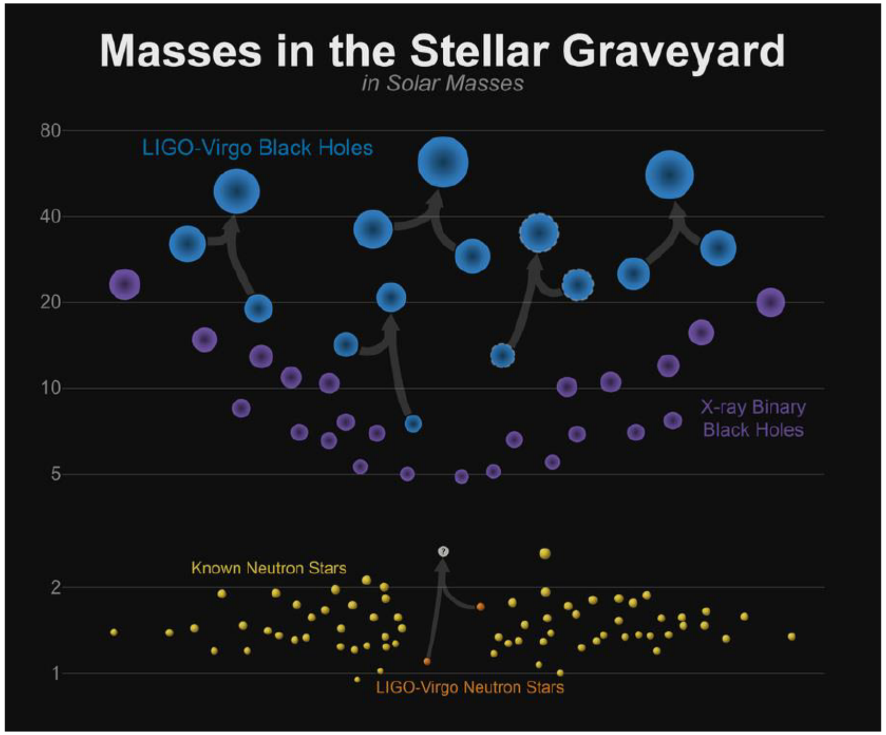
Frequency growth determined by chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = 1.188^{+0.004}_{-0.002}\ \mathrm{M}_\odot$

$$\frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} t + \frac{3}{8} f^{-8/3} + C = 0$$

GW170817: Individual masses

Individual masses depend on assumed spin parameter $\chi = c\,J\,/\,(GM^2)$





For the low spin case masses are very well constrained

Total mass: $M = 2.74^{+0.04}_{-0.01}\ \mathrm{M_\odot}$, $q = m_2/m_1 = 0.7 - 1.0$

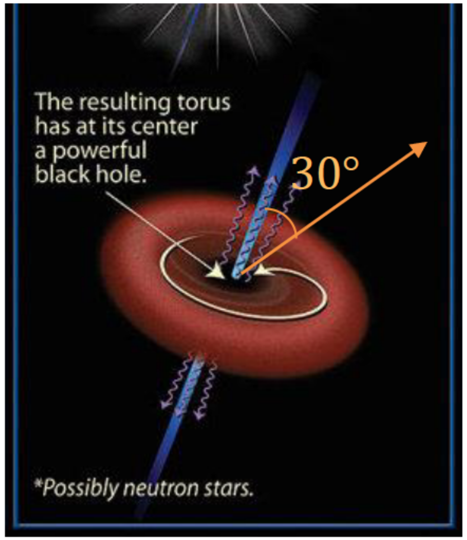
Primary mass: $m_1 \in (1.36\text{–}1.60)\ \mathrm{M_\odot}$

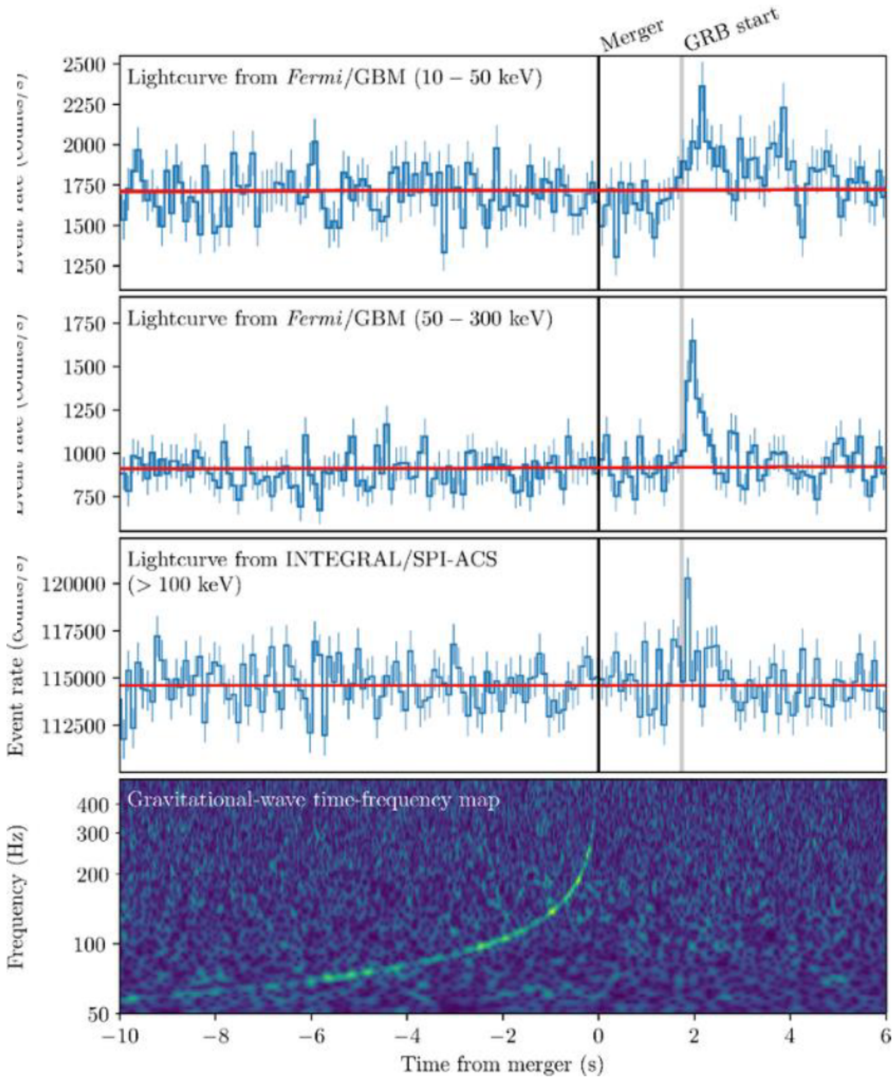
Secondary mass: $m_2 \in (1.17\text{–}1.36)\ \mathrm{M_\odot}$

Distance: 40^{+8}_{-14} Mpc

GW170817: A big reveal from the cosmos

- 1.7 s later Fermi and INTEGRAL detected the short GRB 170817 A
- Despite being the closest SGRB is 2-6 order of magnitude weaker than typical SGRBs.
- Explained assuming jet forms ~ $30°$ with line of view.
- Combined analysis favors formation BH on timescales $\lesssim 100$ ms.

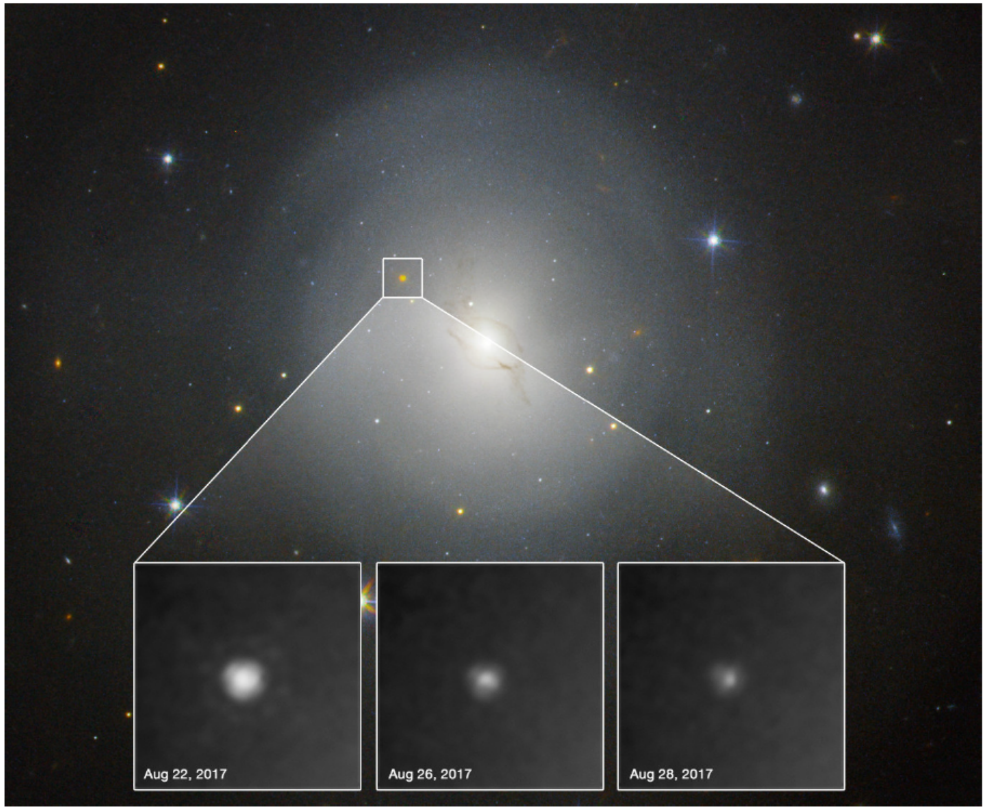




B. P. Abbott, et al, Astrophys. J. 848, L13 (2017).

AT 2017 gfo: electromagnetic signature from r process

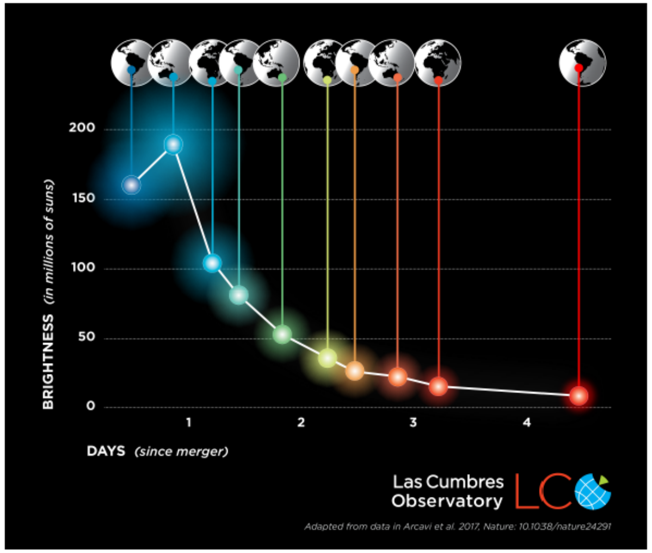
In-situ signature of r process nucleosynthesis

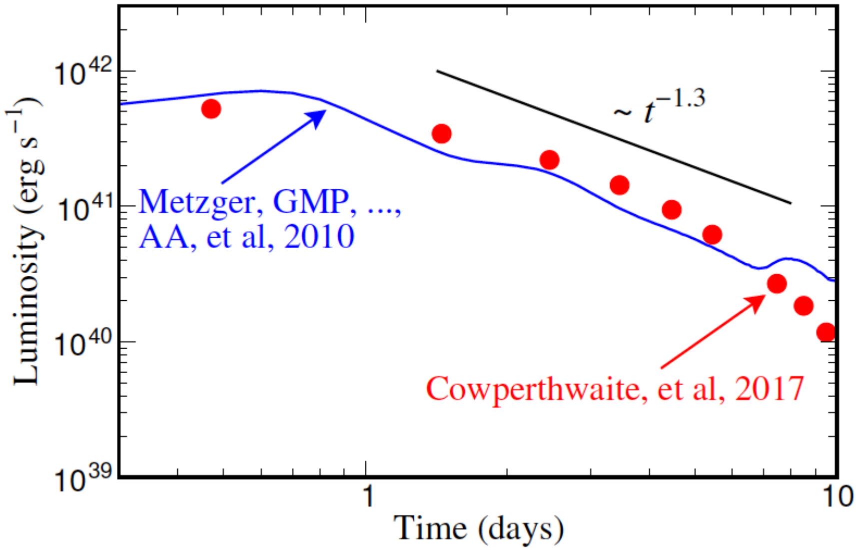


NASA and ESA. N. Tanvir (U. Leicester), A. Levan (U. Warwick), and A. Fruchter and O. Fox (STScI)

- Novel fastly evolving transitent
- Signature of statistical decay of fresly synthesized r process nuclei

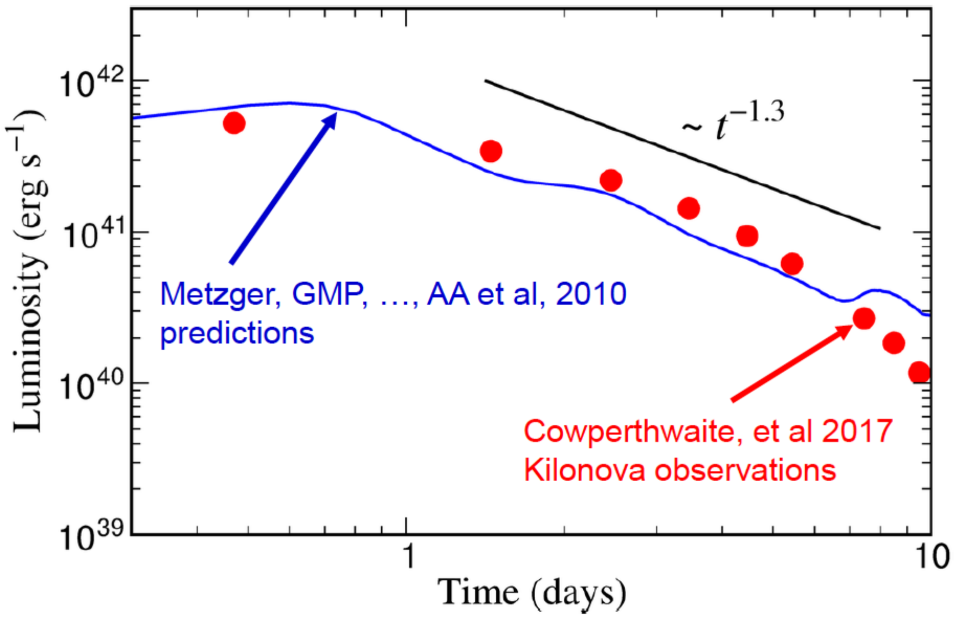
AT 2017 gfo: interpretation



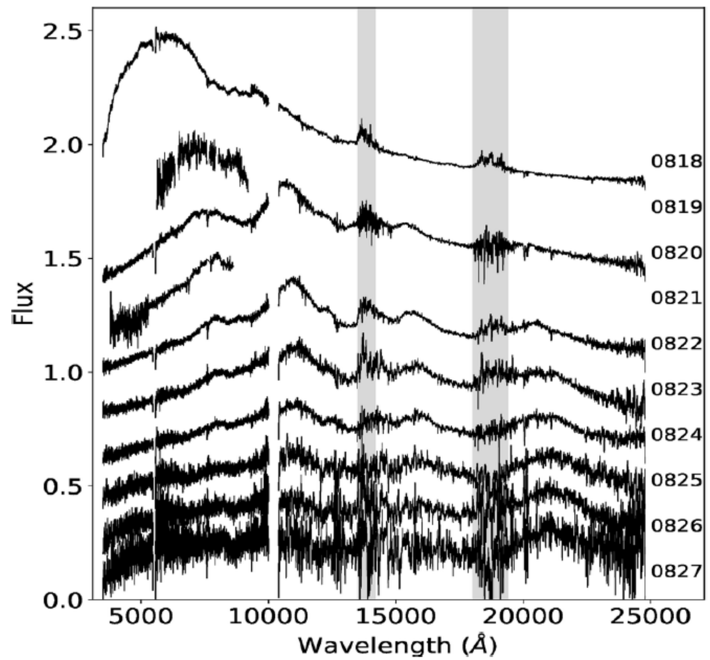


- Time evolution determined by the radioactive decay of r-process nuclei
- Two components:
  - blue dominated by light elements ($Z < 50$)
  - Red due to presence of Lanthanides ($Z = 57$–71) and/or Actinides ($Z = 89$–103)
- Likely source of heavy elements including Gold, Platinum and Uranium

Kilonova: Electromagnetic transient powered by decay of r-process nuclei



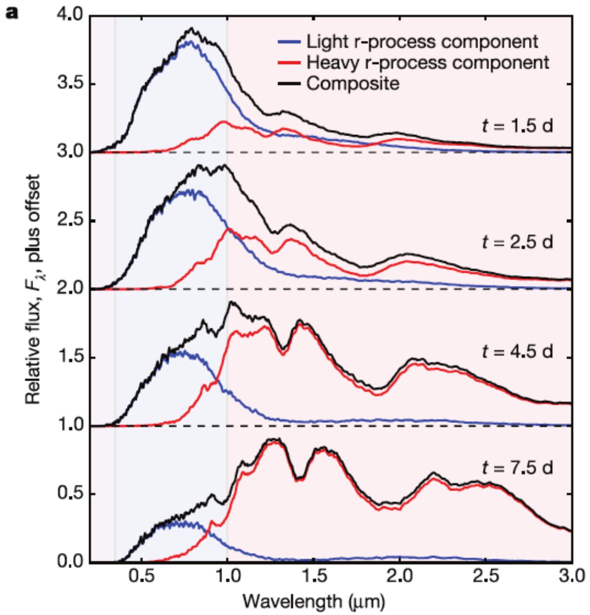
Pian et al., Nature 551, 67 (2017)



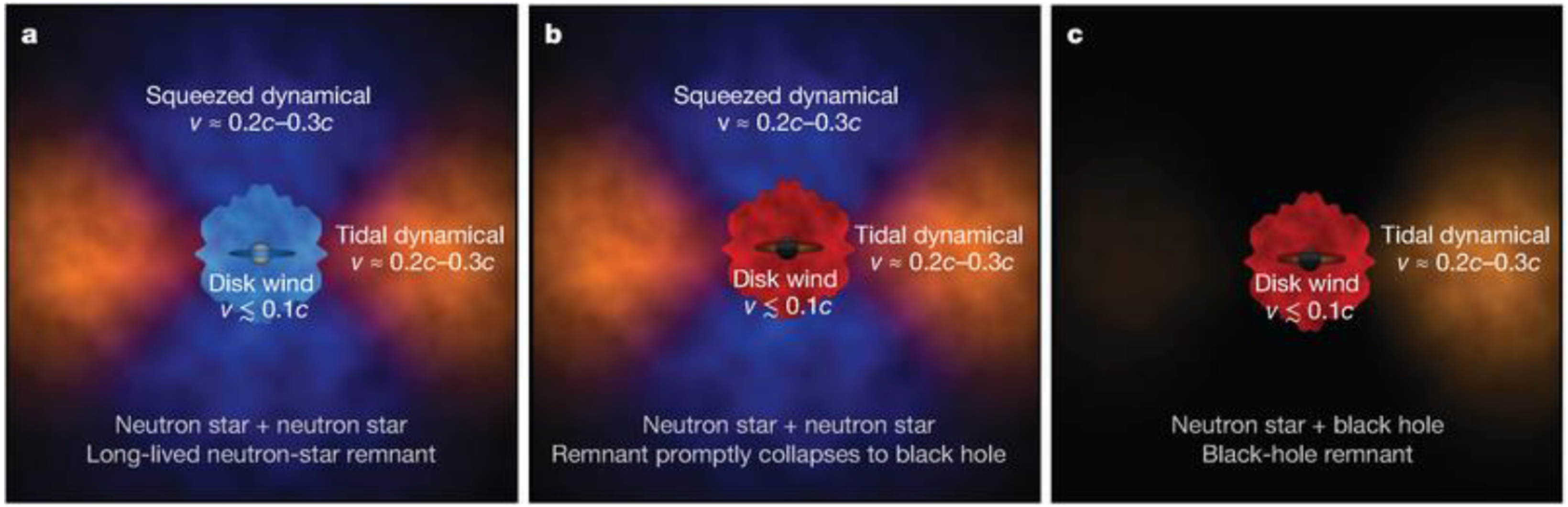
- Time evolution determined by the radioactive decay of r-process nuclei
- Two components, Kasen et al, Nature 551, 80 (2017)
  - Blue dominated by light elements (Z < 50) ($M = 0.025\ M_\odot, v = 0.3c, X_{\rm lan} = 10^{-4}$, dynamical ejecta?, signature neutrino interactions)
  - Red due to presence of Lanthanides ($M = 0.04\ M_\odot, v = 0.15c, X_{\rm lan} = 10^{-1.5}$, ejecta accretion disk?, points to the formation of a black hole)
- Spectroscopic identification of r-process element Sr (Watson et al, 2019)

Two components model

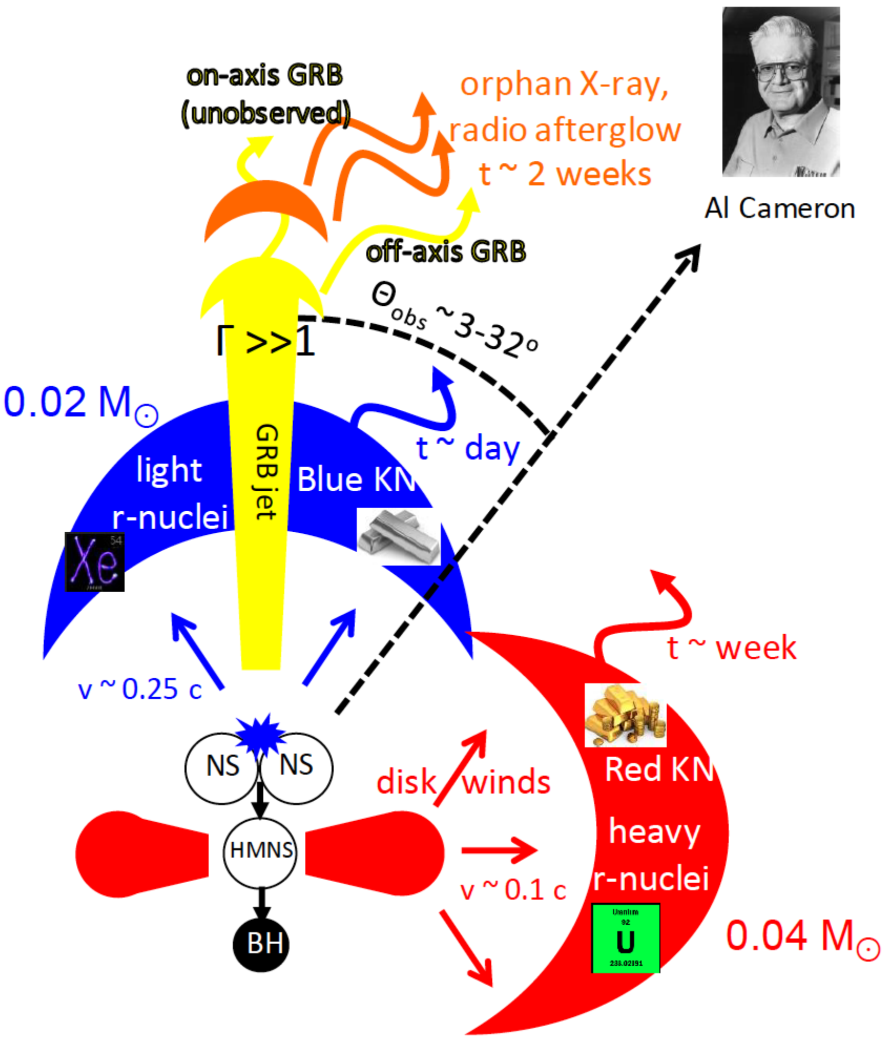
Kasen et al, Nature 551, 80 (2017)



- Blue component from polar ejecta subject to strong neutrino fluxes (light r process)
  $M = 0.025\, M_\odot, v = 0.3c, X_{\text{lan}} = 10^{-4}$
- Red component disk ejecta after NS collapse to a black hole (includes both light and heavy r process)
  $M = 0.04\, M_\odot, v = 0.15c, X_{\text{lan}} = 10^{-1.5}$



Unified scenario EM counterparts



Sketch from B. Metzger

Summary

- Heavy elements are observed at very early times in Galactic history. Produced by a primary process that creates both neutrons and seeds.
- Neutron star mergers are likely the site where the "main r process" takes place.
- Radioactive decay of r-process ejecta produces an electromagnetic transient observed for the first time after GW170817.
- Observations of Blue and Red kilonova components show that both light ($A \lesssim 120$) and heavy ($A \gtrsim 120$) elements are produced. No direct evidence of individual elements.
  - How can we determine composition?
  - What were the heavier elements produced in the merger?
  - How does the nucleosynthesis depends on merging system?
  - What is the contribution of mergers to light r process elements?

Bibliography:

Cowan, *et al.*, *Making the Heaviest Elements in the Universe: A Review of the Rapid Neutron Capture Process*, arXiv:1901.01410 [astro-ph.HE]