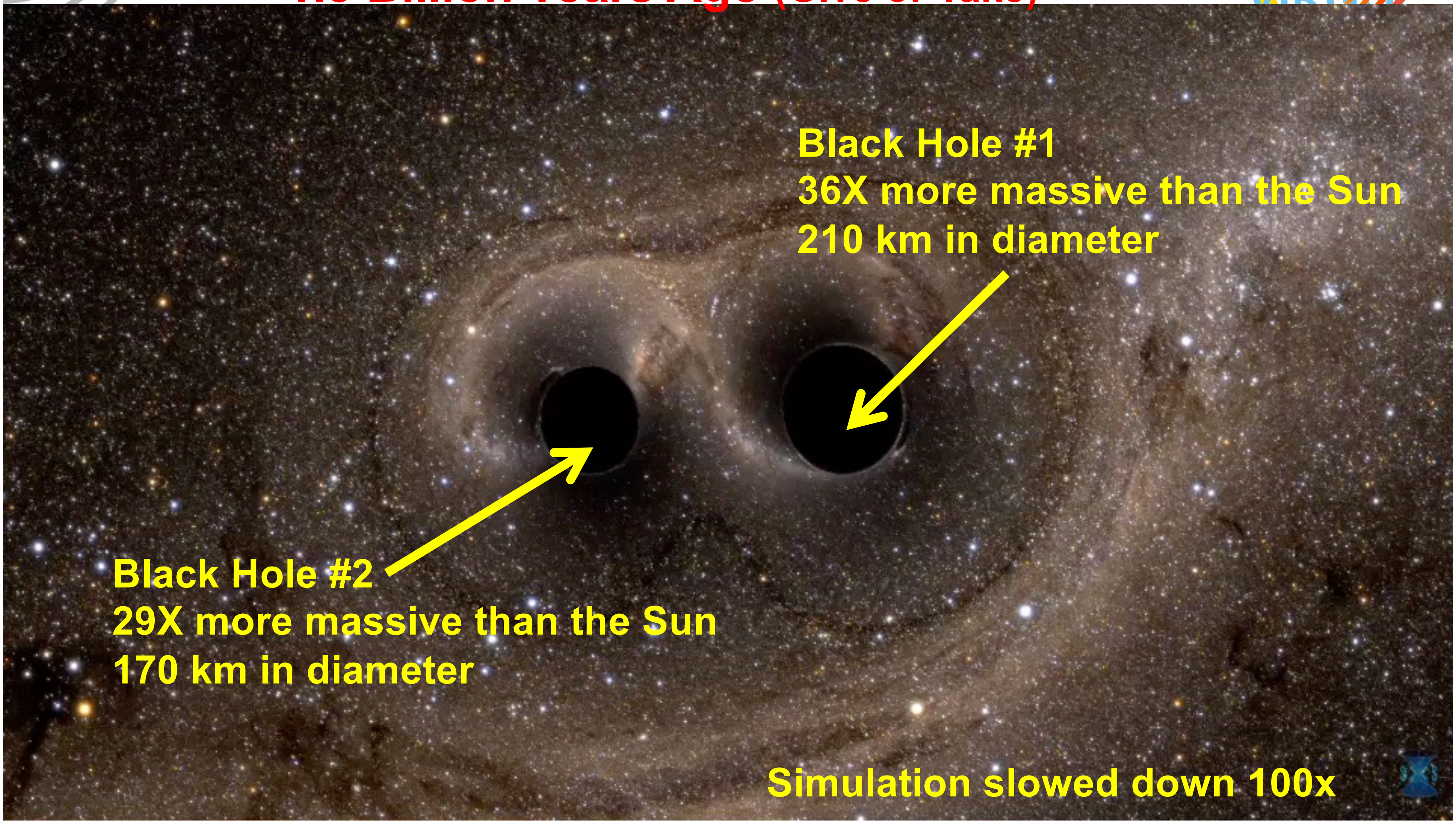
The Ballet of Binary Black Holes 1.3 Billion Years Ago (Give or Take)



Numerical relativity (solution to $G_{\mu\nu} = 0$) simulation

(SXS Collaboration, http://www.black-holes.org/)

Andy Bohn, François Hébert, and William Throwe, SXS

Gravitational Wave physics and astrophysics with LIGO and Virgo

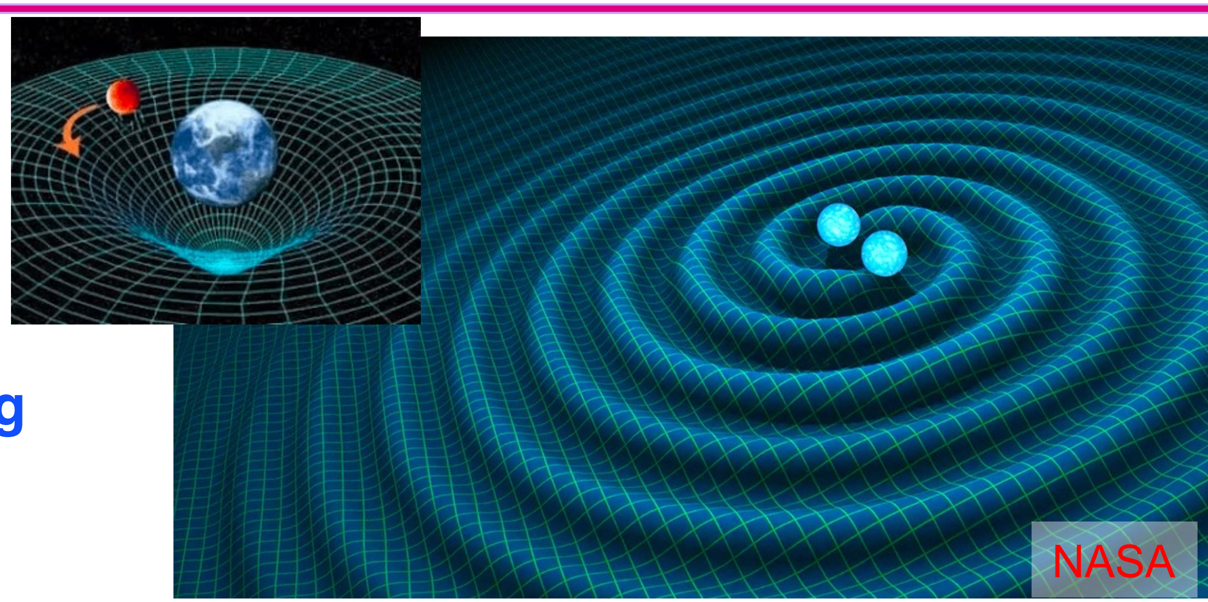
Alan J Weinstein
LIGO Laboratory, Caltech

With Katerina Chatziioannou, Rana Adhikari, Lee McCuller
for the LIGO and Virgo Collaborations

LIGO SURF – June 2023

Gravitational waves

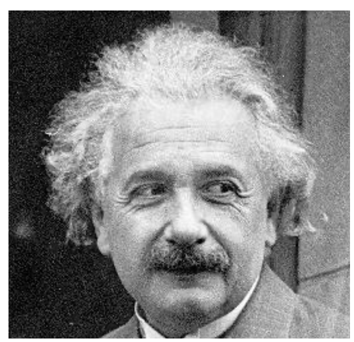
Masses that accelerate (eg, a binary orbit) create ripples of changing gravity (curvature) in space and time.



The “news” of this changing gravity is carried by *gravitational waves*

Predicted by Einstein in 1916 (and discovered 100 years later)

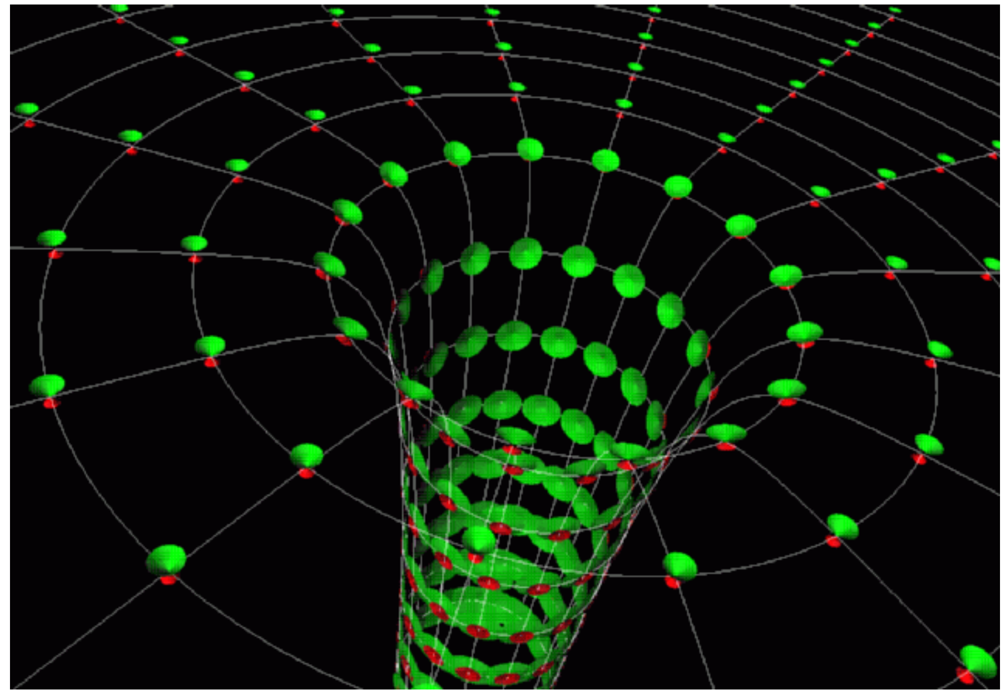
Gravitational waveform can be computed using numerical solutions to *Einstein’s field equations*



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Strong-field

- Most tests of GR focus on small deviations from Newtonian dynamics (post-Newtonian weak-field approximation)
- Space-time curvature is a *tiny* effect everywhere except:
  - The universe in the early moments of the big bang
  - Near/in the horizon of black holes
- This is where GR gets *non-linear* and interesting!
- We aren't very close to any black holes (fortunately!), and can't see them with light or other EM radiation…



But we can search for (*weak-field*) gravitational waves as a signal of their presence and dynamics

Nature of Gravitational Radiation

General Relativity predicts that rapidly changing gravitational fields produce ripples of curvature in fabric of spacetime

- **Stretches and squeezes space between "test masses" – strain $h = \Delta L / L$**
- **propagating at speed of light**
  - ***mass of graviton = 0***
- **space-time distortions are transverse to direction of propagation**
- **GW are tensor fields (EM: vector fields)**

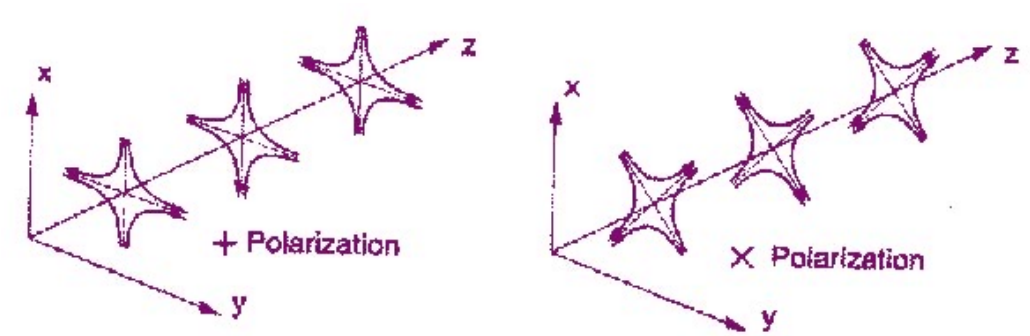
  two polarizations: plus (⊕) and cross (⊗)

  (EM: two polarizations, *x* and *y*)

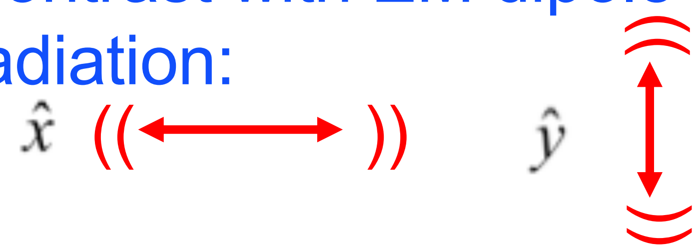
  Spin of graviton = 2

h = ΔL / L

$$h(t,z) = h_{\mu\nu} e^{i(\omega t - kz)} = h_+(t - z/c) + h_\times(t - z/c)$$



Contrast with EM dipole radiation:



Gravitational Waves

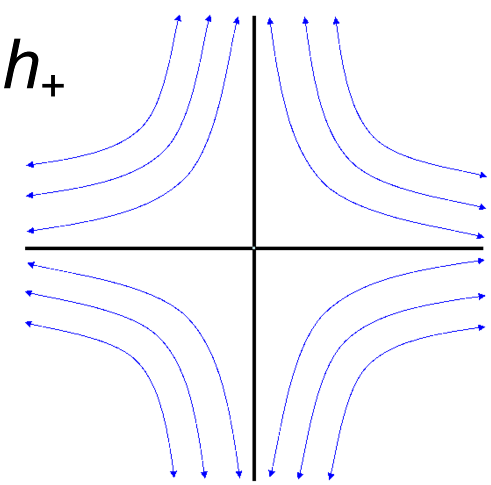
$G_{\mu\nu} = 0 \rightarrow$ **Solution for an outward propagating wave in z-direction:**

$$h(t,z) = h_{\mu\nu} e^{i(\omega t - kz)} = h_+(t - z/c) + h_\times(t - z/c)$$

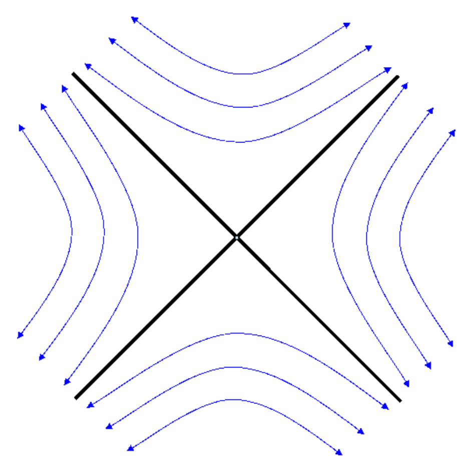
$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Physically, *h* is a *strain*: ΔL/L

h_+



h_x



Gravitational Waves

$G_{\mu\nu} = 0 \rightarrow$ **Solution for an outward propagating wave in z-direction:**

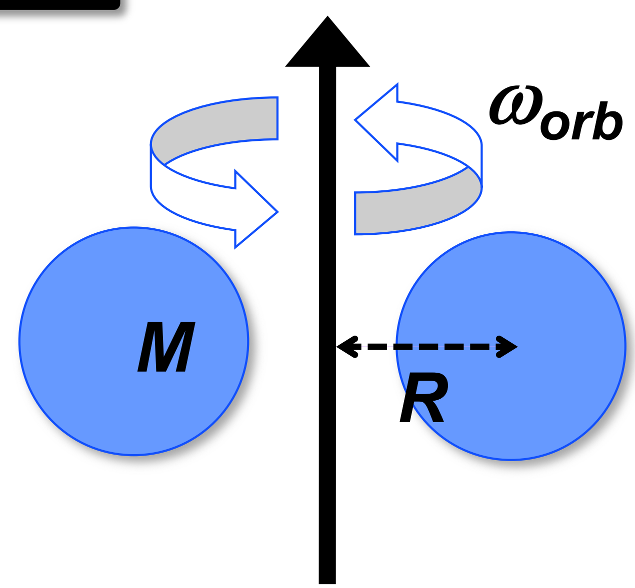
$$h(t,z) = h_{\mu\nu} e^{i(\omega t - kz)} = h_{+}(t - z/c) + h_{\times}(t - z/c)$$

$$h_{\mu\nu} \approx \frac{1}{r} \frac{G}{c^4} \ddot{I}_{\mu\nu}$$

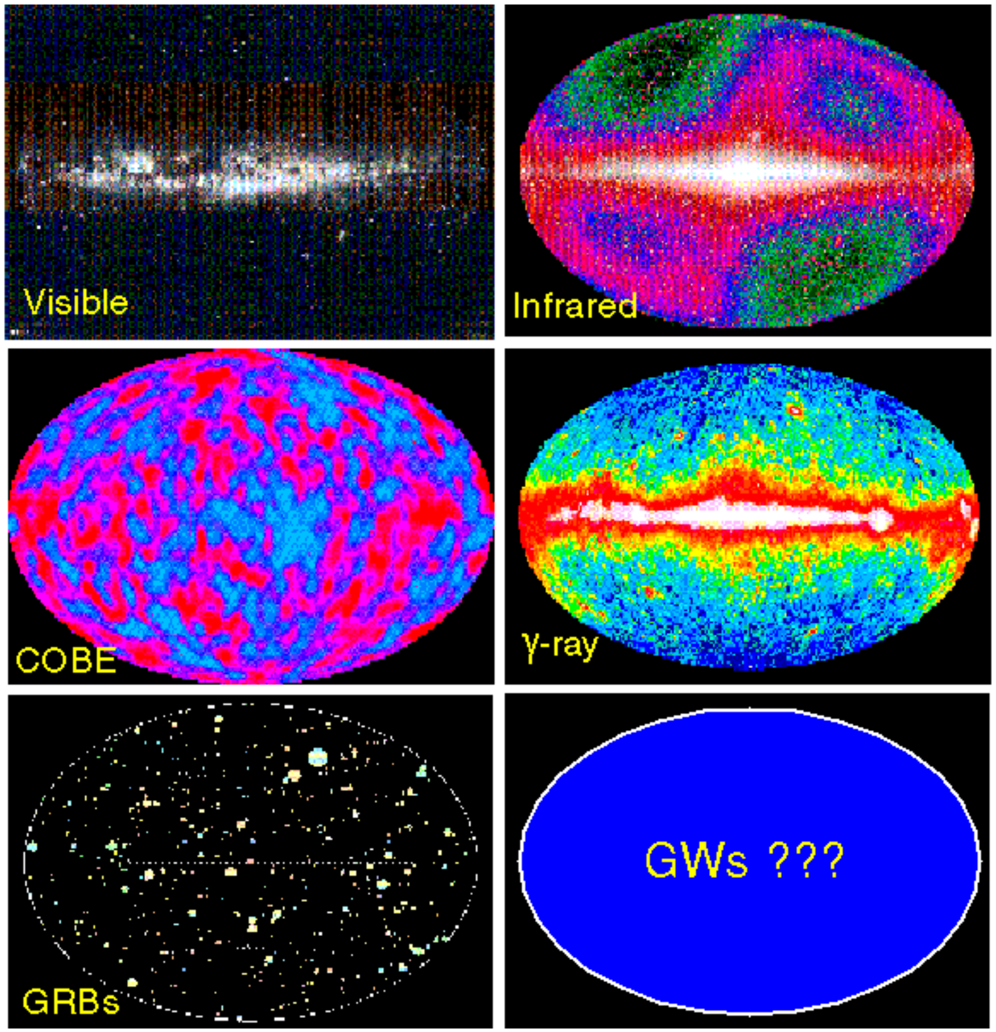
Physically, *h* is a *strain*: ΔL/L

Kepler 3rd: $R^3 \, \omega_{orb}^2 = G \, M_{tot}$

$$h \approx \frac{8 G M R^2 \omega_{orb}^2}{r c^4} \sim 10^{-21}$$



A NEW WINDOW ON THE UNIVERSE



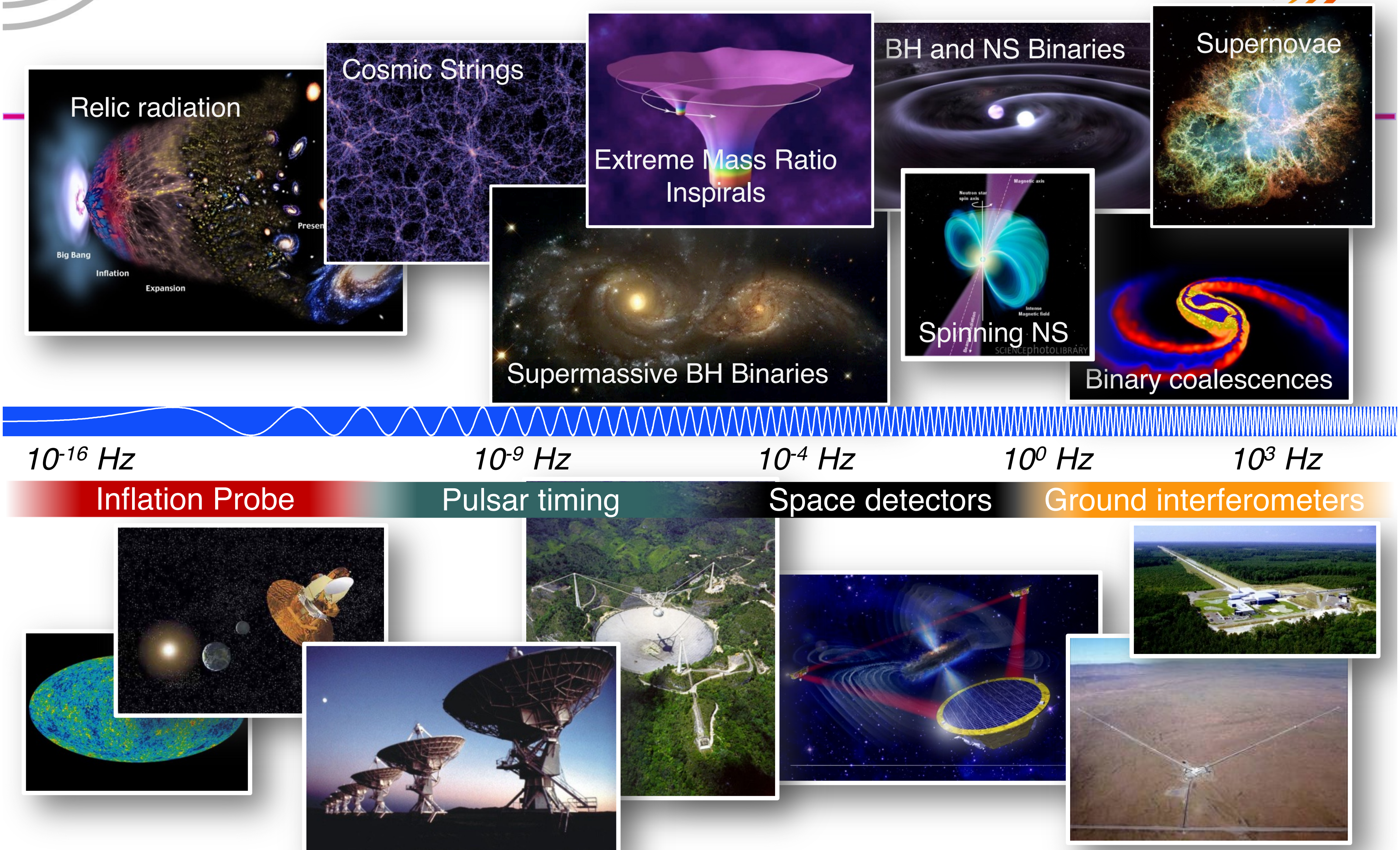
The history of Astronomy:
new bands of the EM spectrum opened → major discoveries!

GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe

The GW Spectrum



GWs at Caltech

- 1980’s – 90’s – Concept, design, construction of Initial LIGO (Caltech / MIT)
- 1998 – Formation of LIGO Scientific Collaboration, LSC
- 1990’s – 2000’s – Concept, original design of LISA (Caltech / JPL)
- 1990’s – 2000’s – Concept, design, search for B-mode polarizations in CMB
- 2000 – 2015 – Design, construction of Advanced LIGO
- 2015 – GW150914 - Discovery of GWs,
- 2017 – Nobel Prize (Barish, Weiss, Thorne)
- 2017 – GW170817 – birth of multi-messenger astronomy (MMA) with GWs
- 2017 – 2022 – GW physics and astronomy with GWs comes of age
- 2022+ – Using GWs and MMA to explore the nature of neutron stars, black holes, massive stars, binary formation mechanisms, probes of cosmology and dark matter – new discoveries!

Active GW faculty / groups at Caltech (in international collaborations):

- GW astrophysics: Weinstein, Chatziioannou (new), Y. Chen, Teukolksy, Scheel
- GWs in numerical relativity: Teukolsky, Scheel, Most (new)
- GW detection, NG detectors, quantum-limited measurement: Adhikari, McCuller (new)
- GWs with LISA, PTA: Vallisneri, Cutler, +
- GWs with CMB polarization: Bock, +

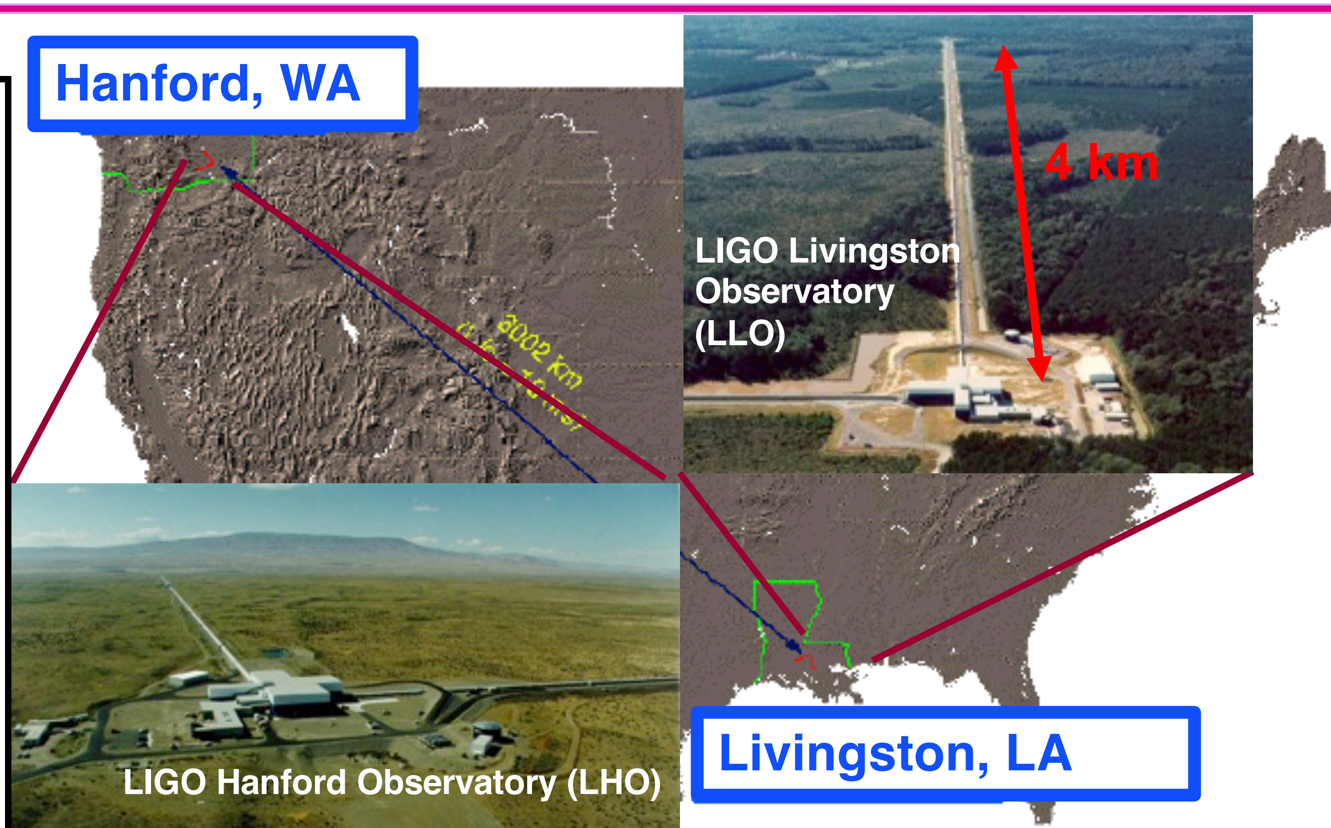
The Laser Interferometer Gravitational Wave Observatory

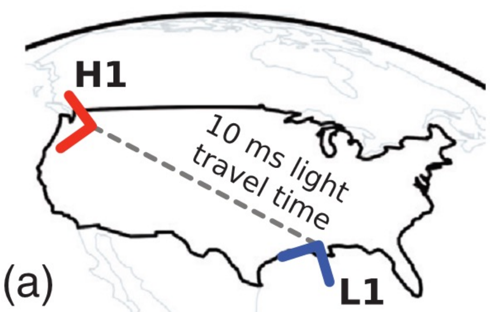
LIGO Laboratory is operated by Caltech and MIT, for the NSF.

~180 staff located at Caltech, MIT, LHO, LLO

LIGO Scientific Collaboration:
~ 1200 scientists,
~85 institutions,
15 countries

Vigo Collaboration:
~ 250 scientists, Europe



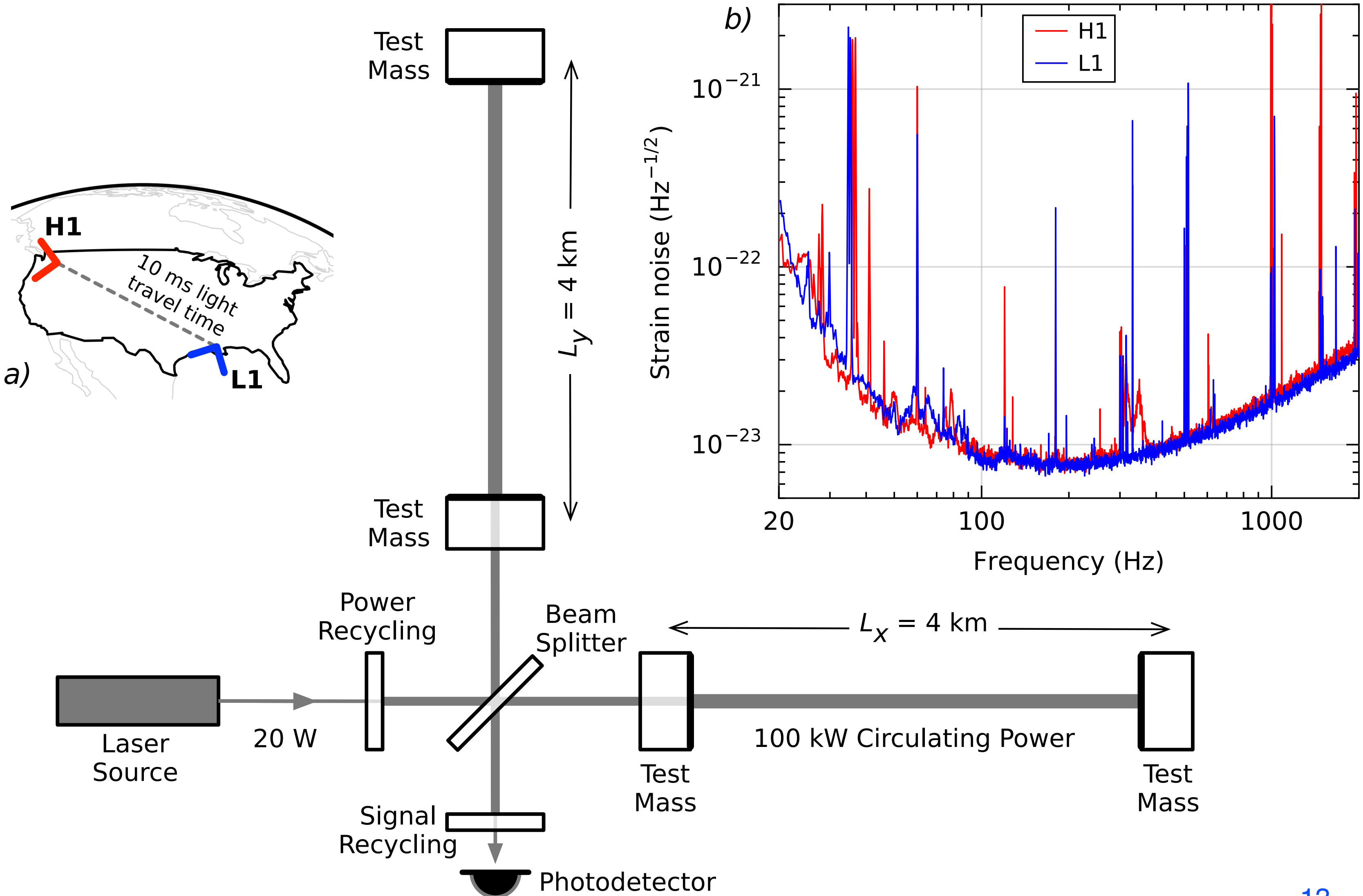


(a)

LIGO Scientific Collaboration

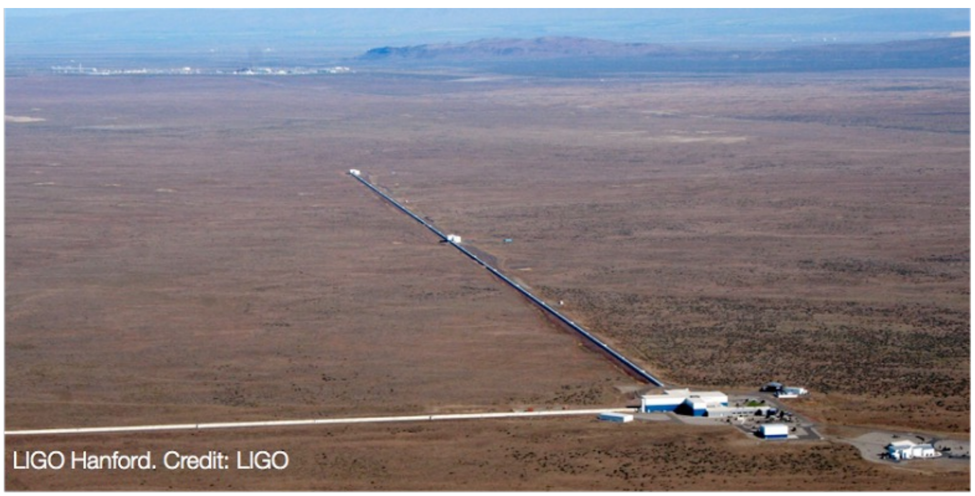
Marshall Space Flight Center

The Advanced LIGO detectors



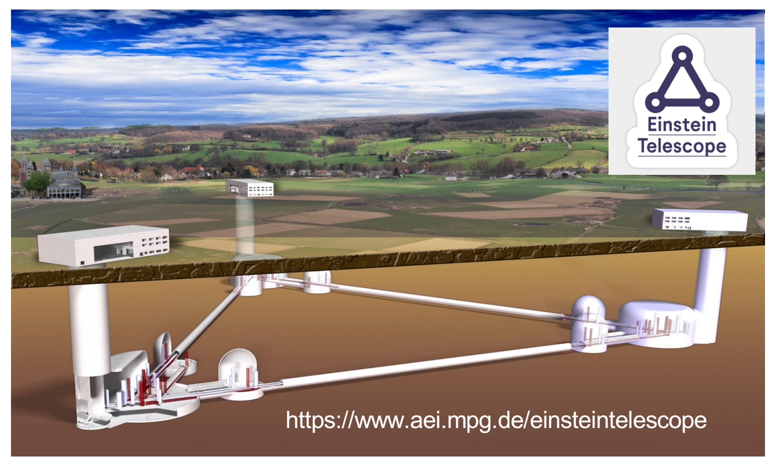
https://dcc.ligo.org/LIGO-P1500237/public/main

LIGO-Virgo-GEO Detector network



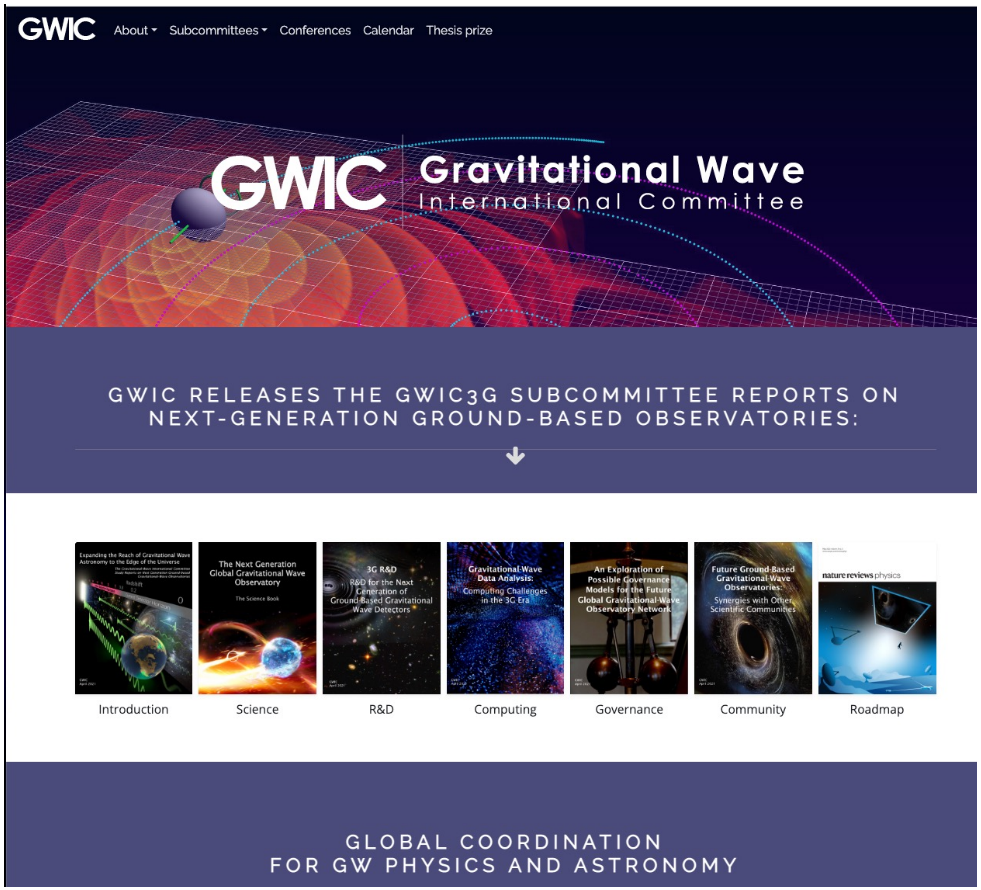
International Gravitational-Wave Network (IGWN)

+



+ iPTA, LISA, …

Gravitational Wave International Committee (GWIC) https://gwic.ligo.org/



GWIC About Subcommittees Conferences Calendar Thesis prize

ABOUT

GWIC's mission is to facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide.

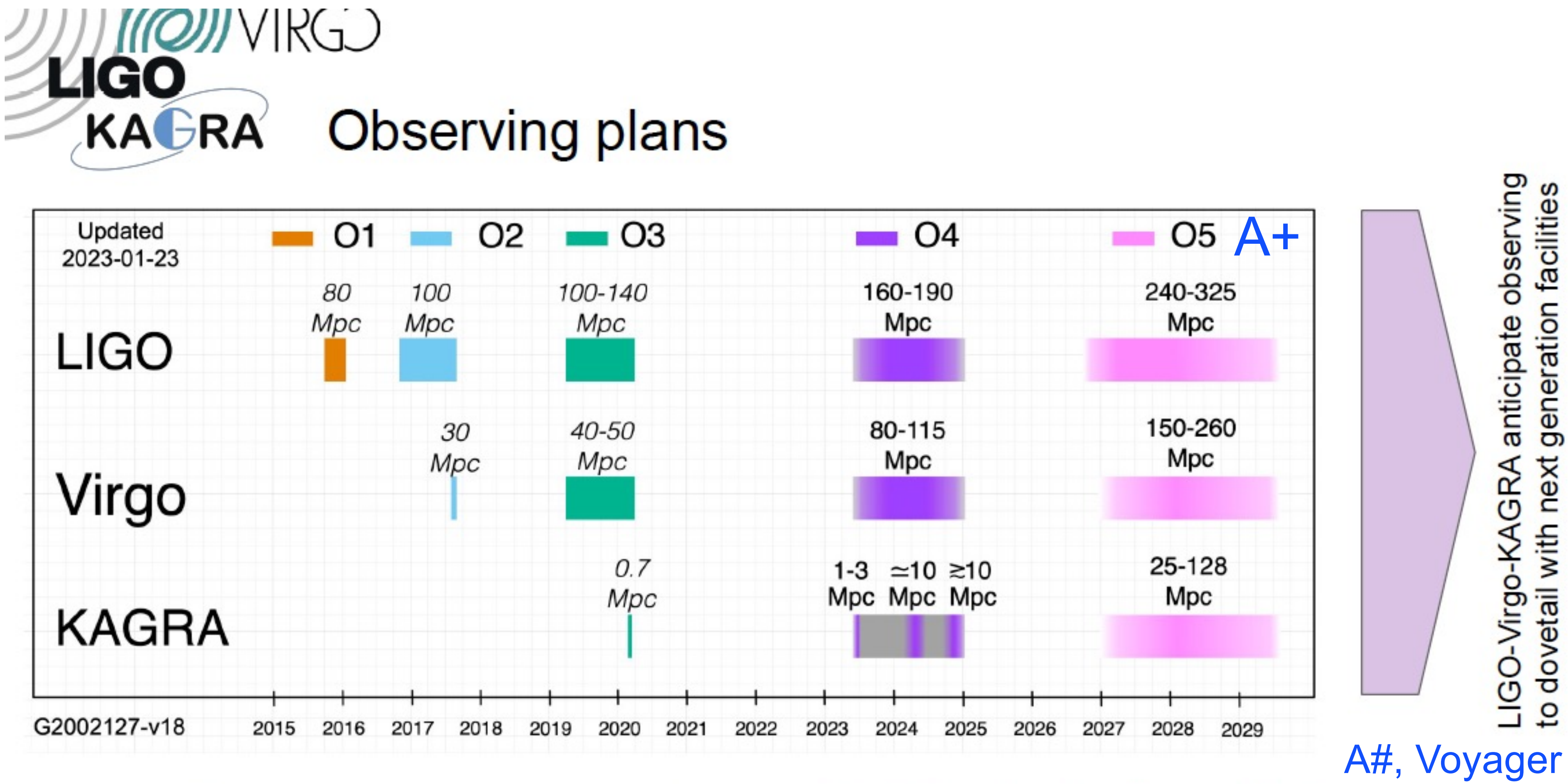
ABOUT GWIC

Gravitational Wave International Committee (GWIC) was formed in 1997 to facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide. It is associated with the International Union of Pure and Applied Physics as its Working Group WG.11. Through this association, GWIC is connected with the International Society on General Relativity and Gravitation (IUPAP's Affiliated Commission AC.2), its Commission C19 (Astrophysics), and another Working Group, the AstroParticle Physics International Committee (APPIC).

GOALS

- Promote international cooperation in all phases of construction and scientific exploitation of gravitational-wave detectors
- Coordinate and support long-range planning for new instrument proposals, or proposals for instrument upgrades
- Promote the development of gravitational-wave detection as an astronomical tool, exploiting especially the potential for multi-messenger astrophysics
- Organize regular, world-inclusive meetings and workshops for the study of problems related to the development and exploitation of new or enhanced gravitational-wave detectors, and foster research and development of new technology
- Represent the gravitational-wave detection community internationally, acting as its advocate
- Provide a forum for project leaders to regularly meet, discuss, and jointly plan the operations and direction of their detectors and experimental gravitational-wave physics generally.

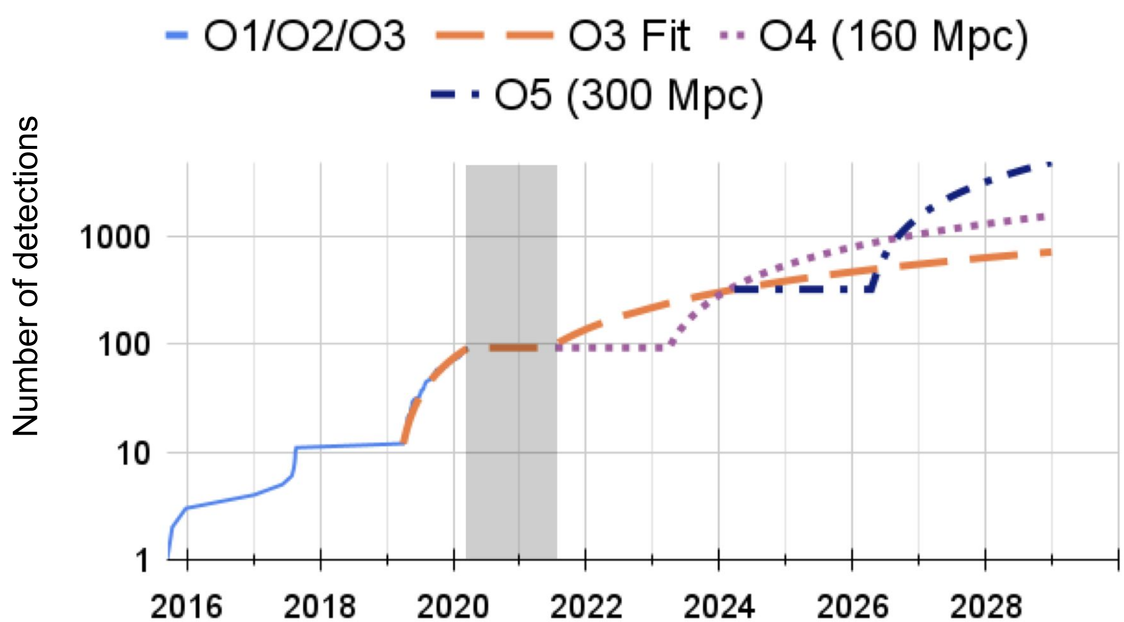
Timeline for LVK Observing runs, 2015 - 2030



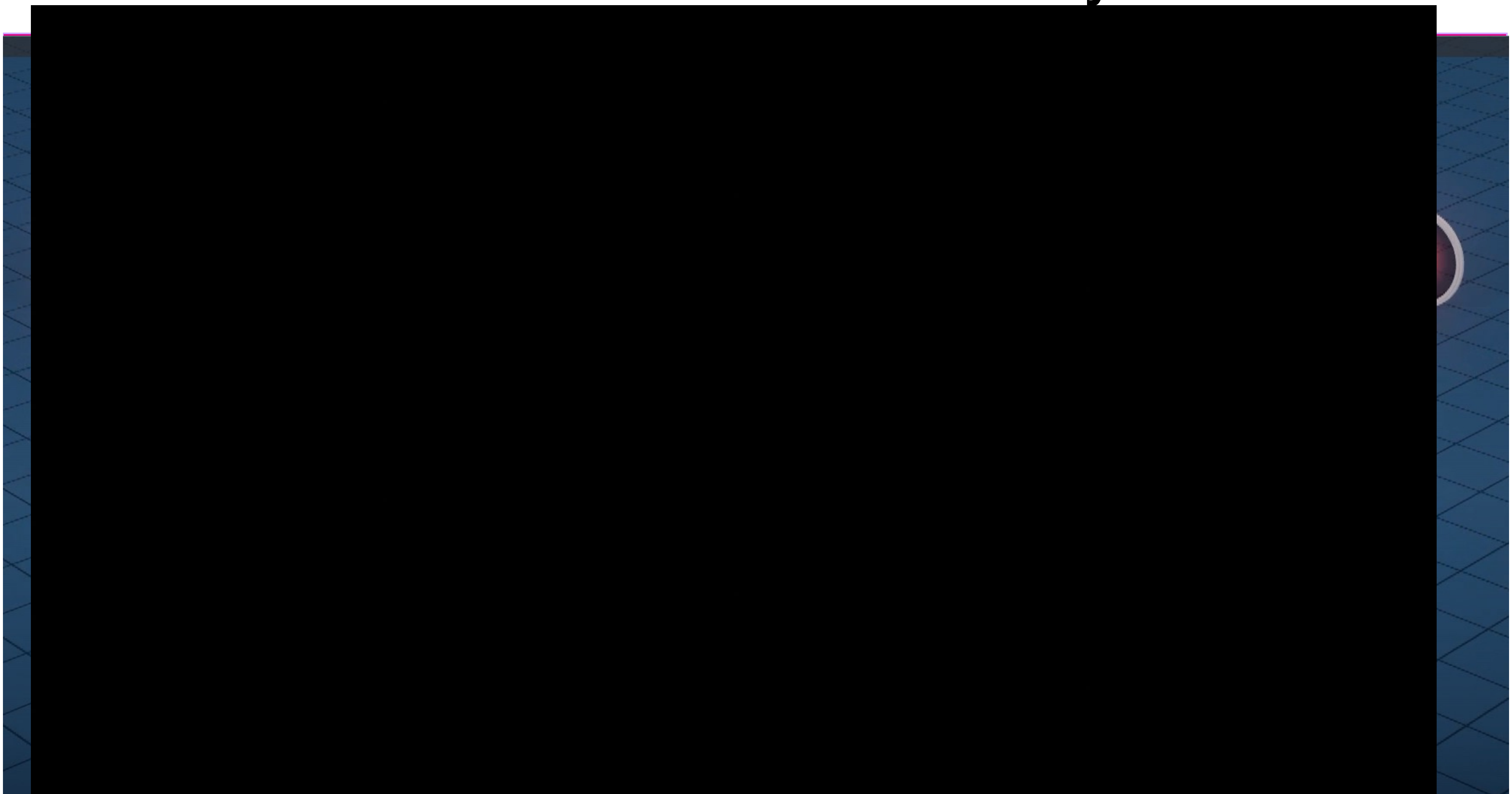
Observing plans are now being maintained at https://observing.docs.ligo.org/plan/

LVK Fourth Observing Run (O4)

- We started the observing run on 24 May 2023
- We plan on 18 calendar months of observing for O4
- Most likely, this will be broken up into there 6-month observing periods, interspersed with commissioning breaks
- This change is motivated by upgrade plans for the O5 observing run, which will likely require more development time
- The additional observing time will increase the scientific output of O4, while O5 upgrades
- Crude extrapolation to O4, O5:

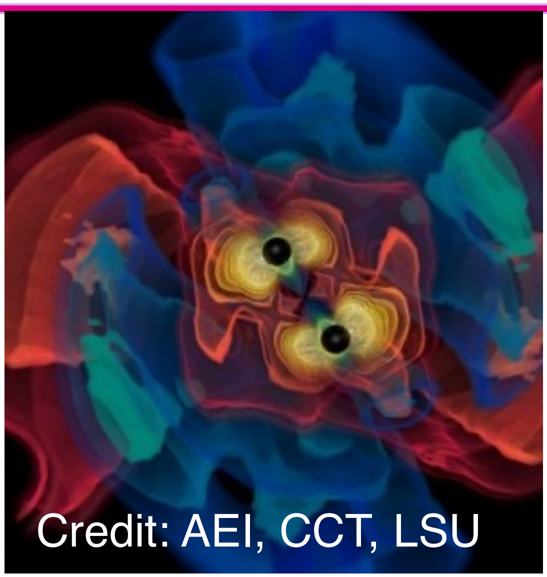


GW detection with laser interferometry



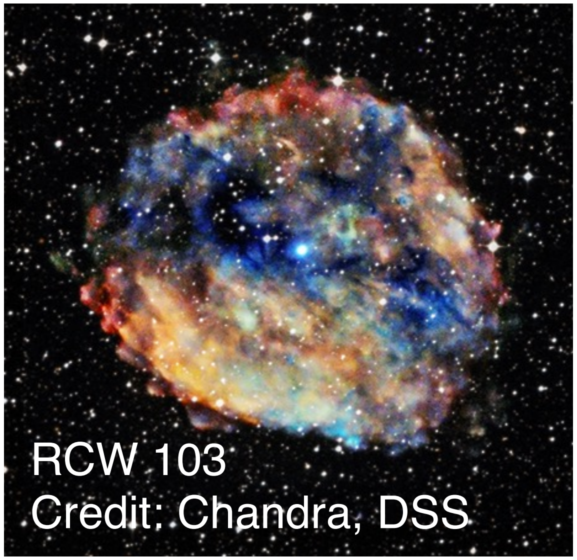
http://mediaassets.caltech.edu/gwave#videos-animations
Journey of a G-wave (3 min video)

GW sources for ground-based detectors: The most energetic processes in the universe



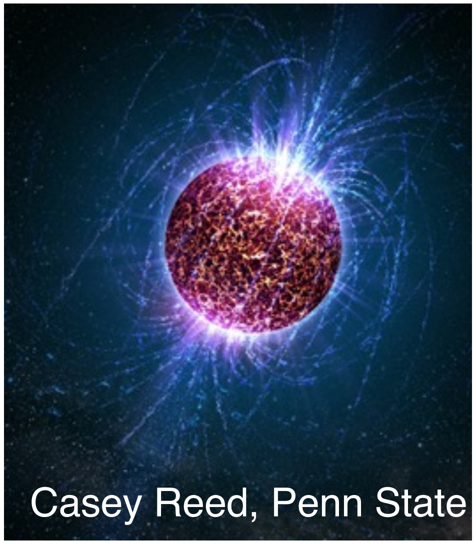
Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,
- (effectively) transient



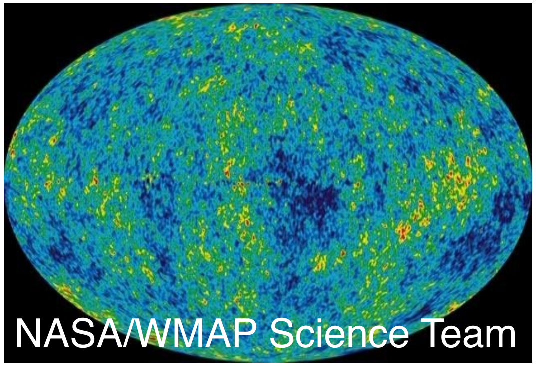
Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class



Spinning neutron stars

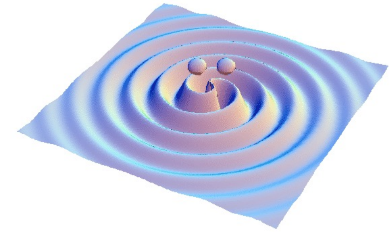
- (effectively) monotonic waveform
- Long duration

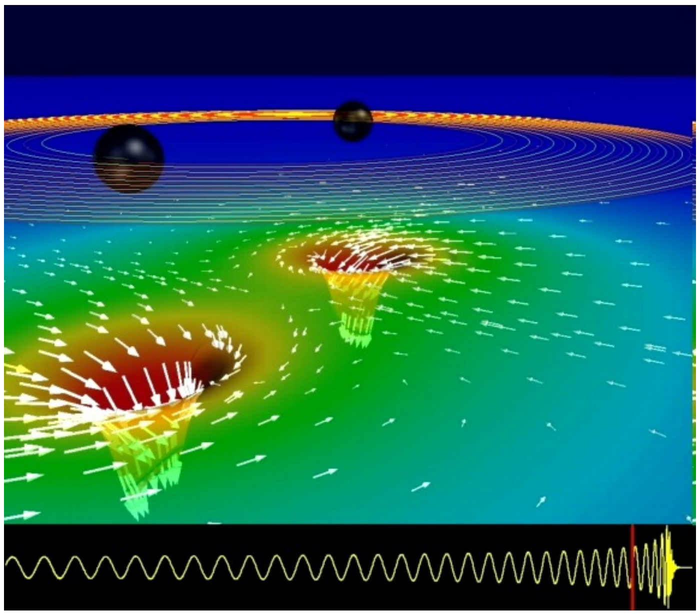


Cosmic Gravitational-wave Background

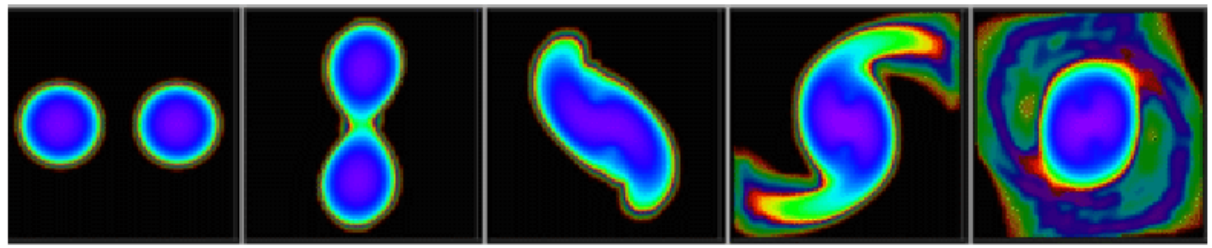
- Residue of the Big Bang, long duration
- Long duration, stochastic background

GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)





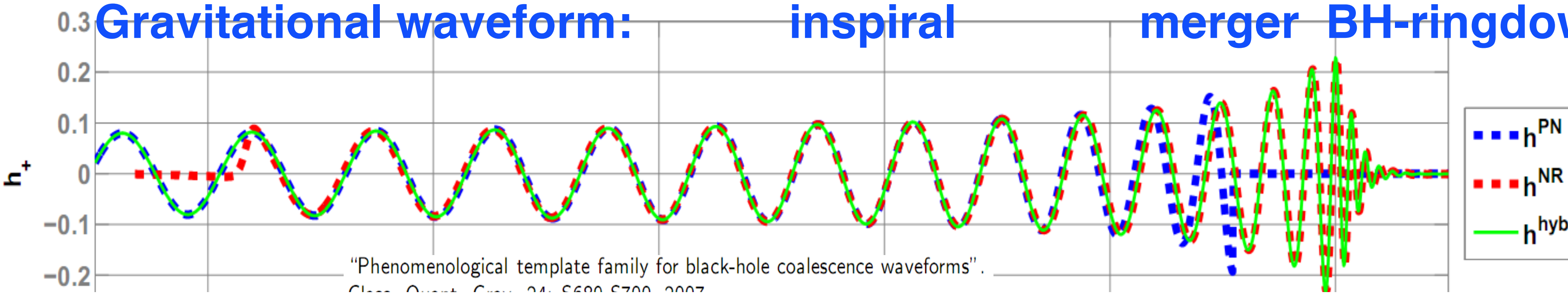
- Neutron star – neutron star (Centrella et al.)



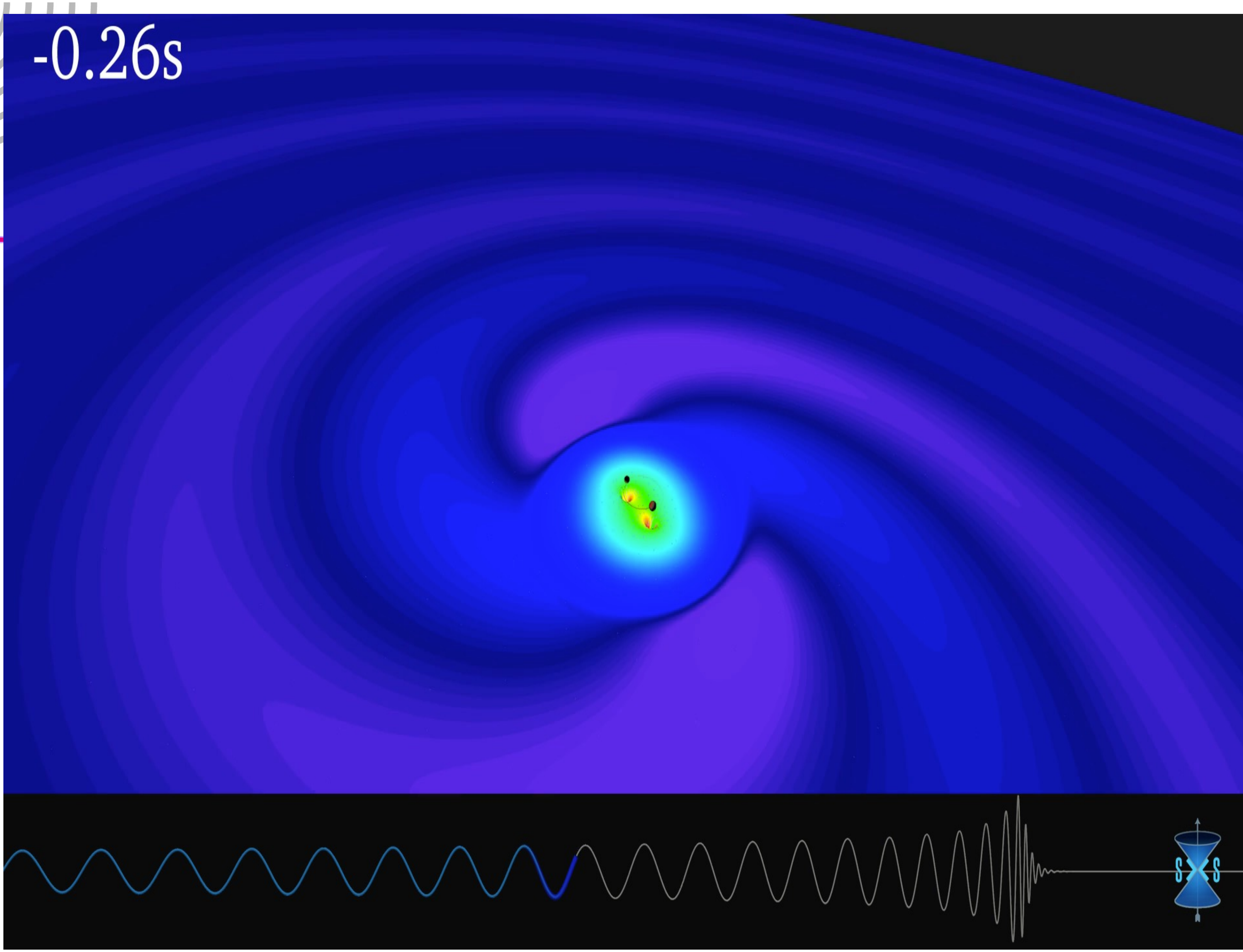
Tidal disruption of neutron star

A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions

Gravitational waveform: inspiral merger BH-ringdown



Waveform carries lots of information about binary masses, orbit, merger

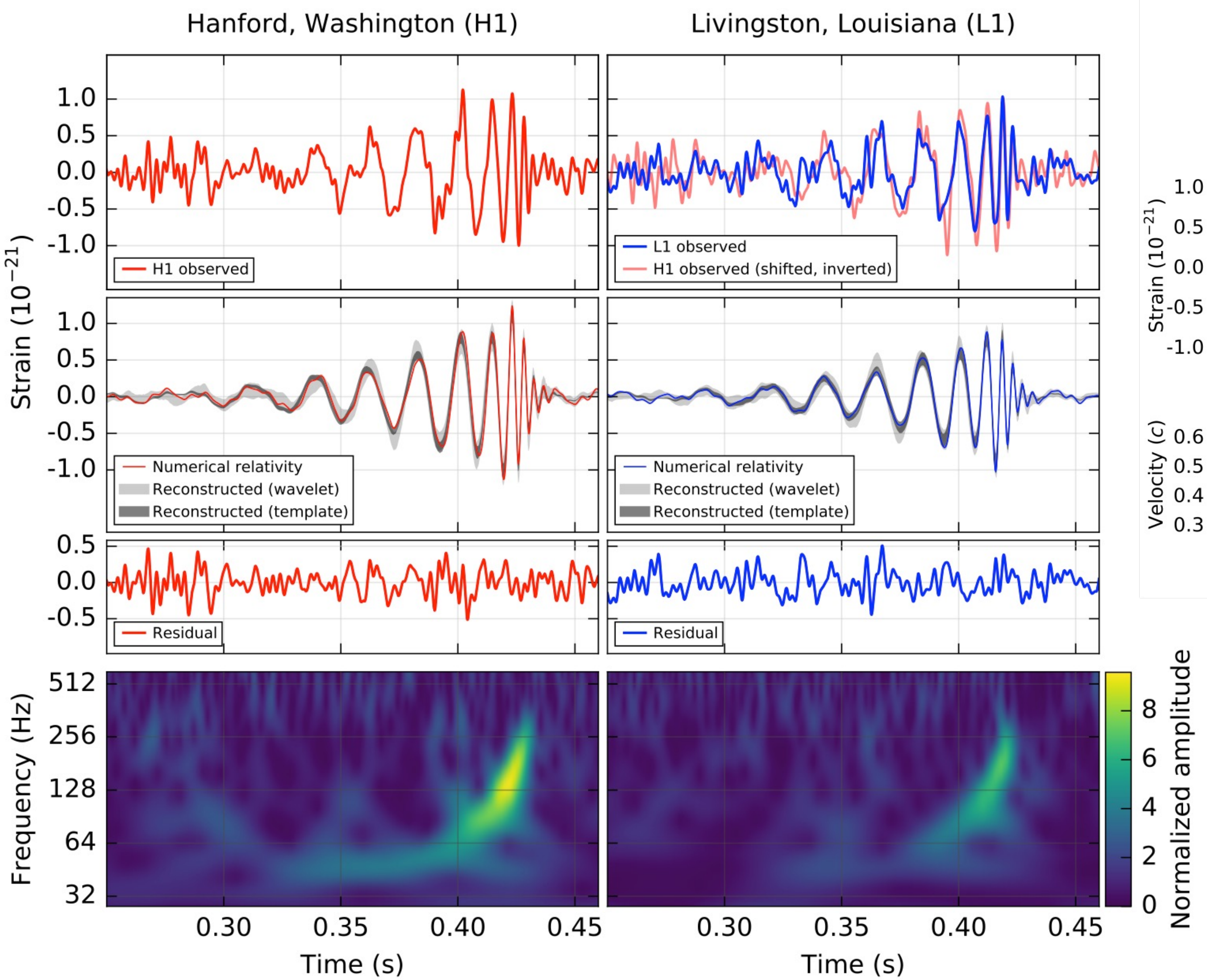


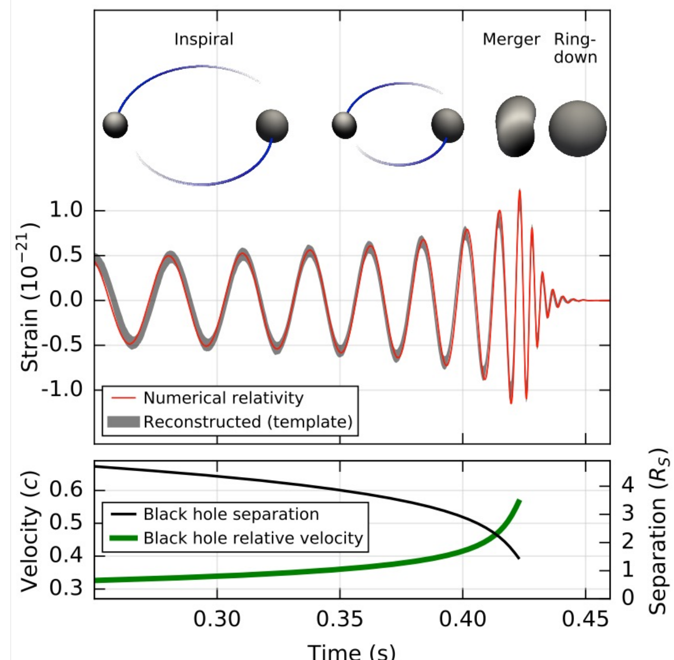
https://www.black-holes.org/explore/movies

GW150914

Phys. Rev. Lett. 116, 061102 – Published 11 February 2016

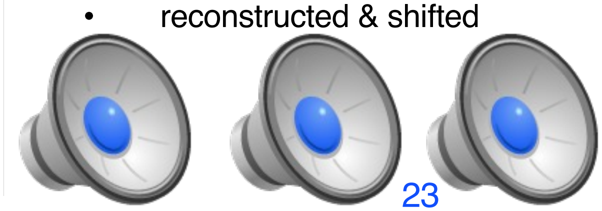
https://dcc.ligo.org/LIGO-P150914/public/main





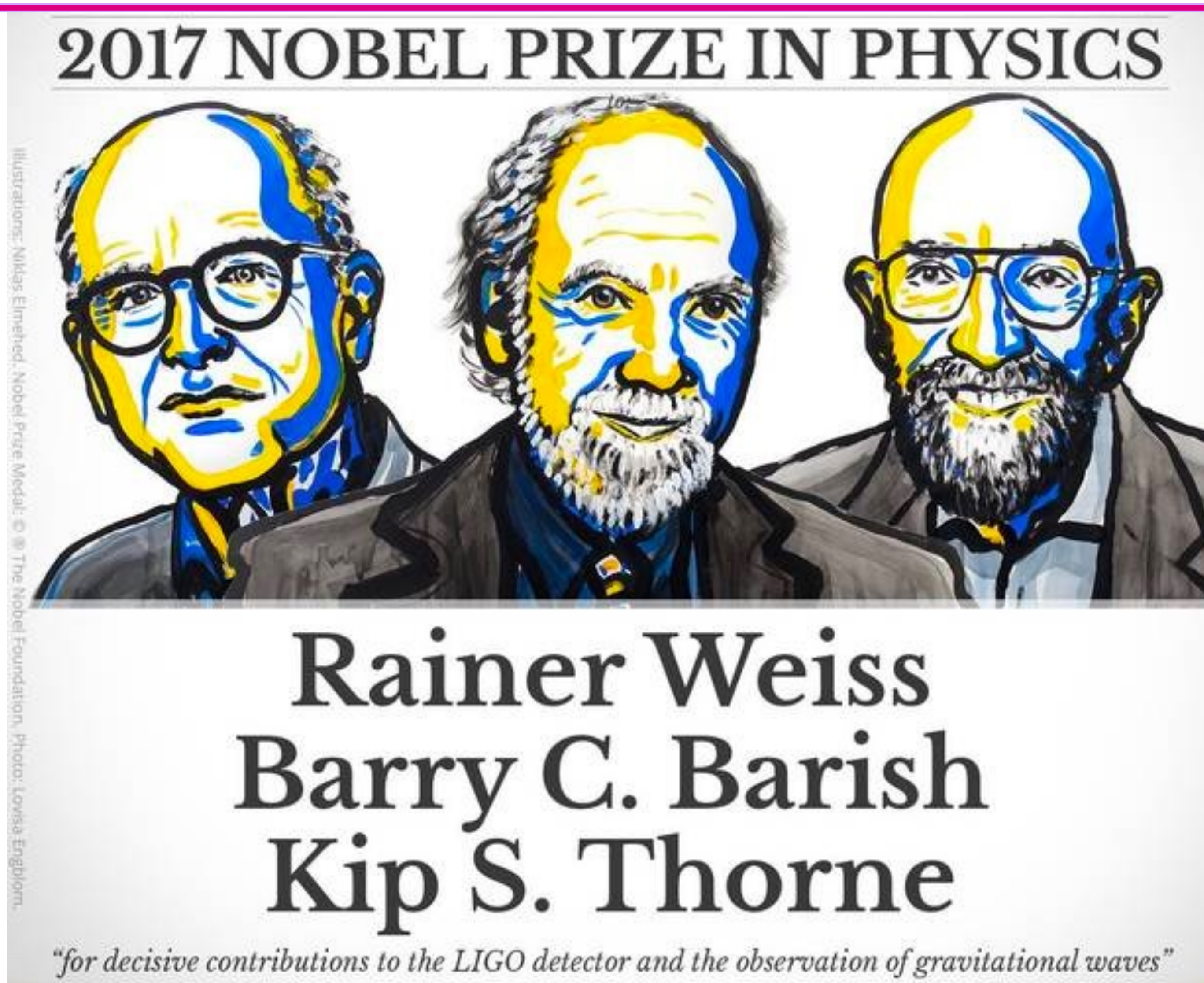
Reconstructed (no whitening)

Audio:
- filtered data
- freq-shifted data
- reconstructed & shifted

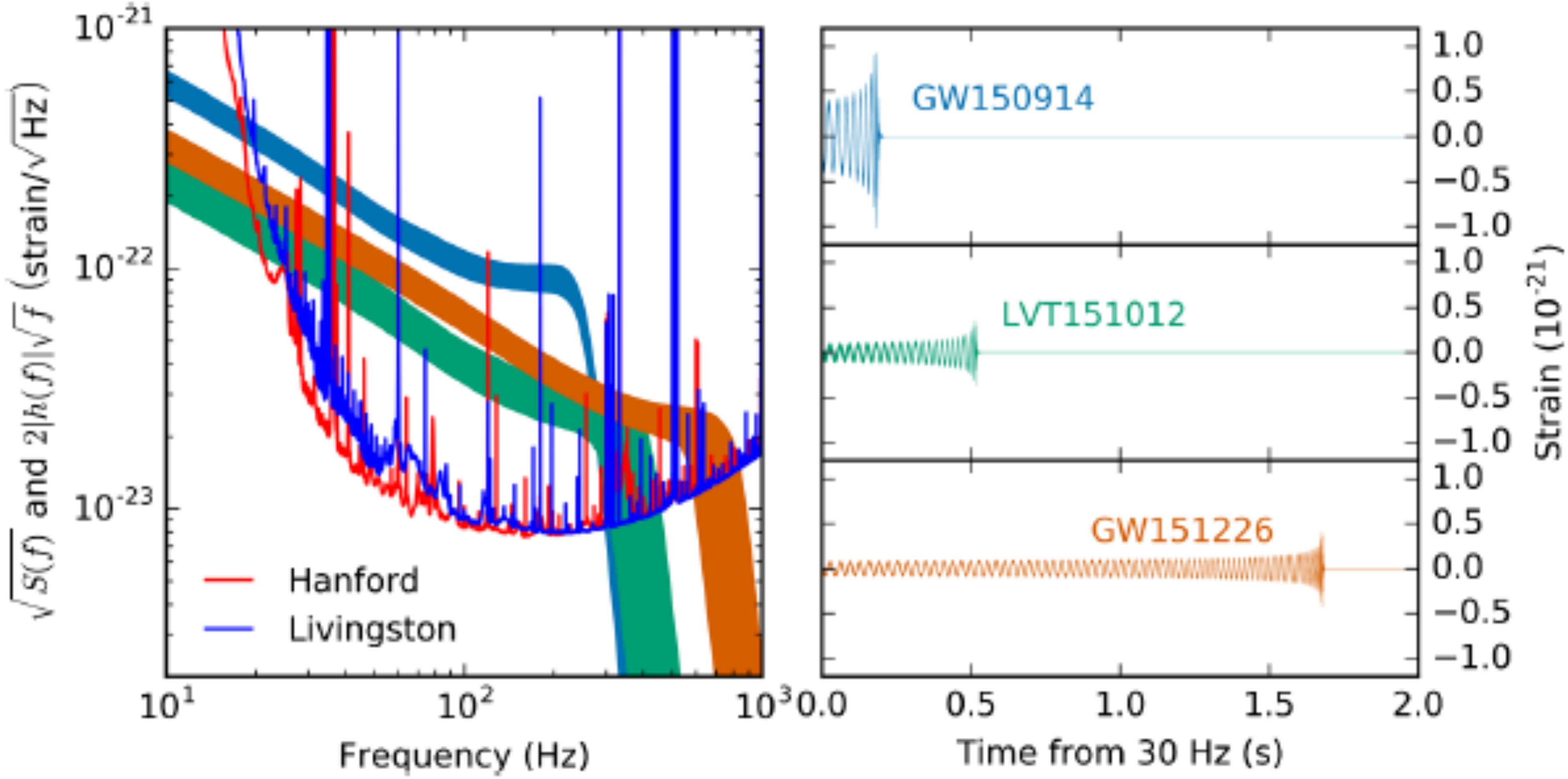


Whitened and band-passed [40-300] Hz

Founders of the LIGO project at Caltech and MIT



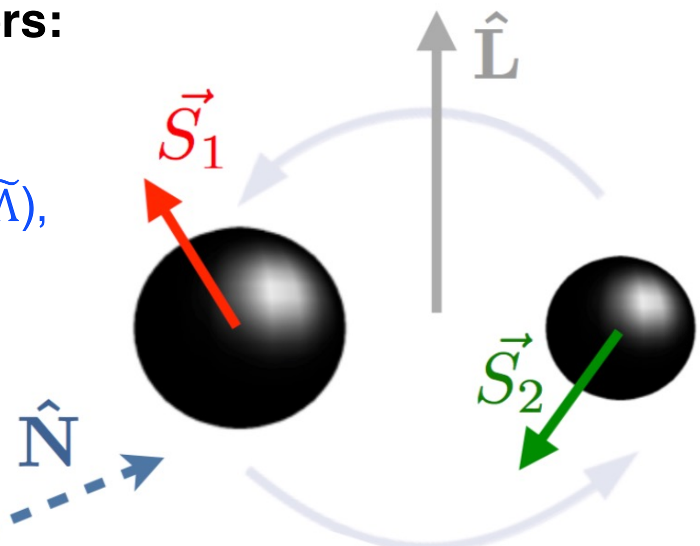
Three BBH events, compared



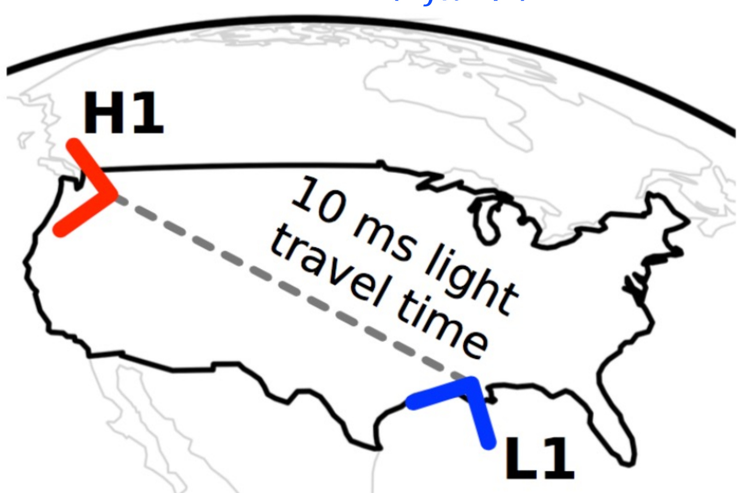
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, https://arxiv.org/abs/1606.04856, Phys. Rev. X 6, 041015 (2016)

Binary merger Model parameters

Intrinsic parameters:
masses (m_1, m_2) ,
spins $(\vec{S}_1, \vec{S}_2)$,
tidal deformability $(\tilde{\Lambda})$,
eccentricity



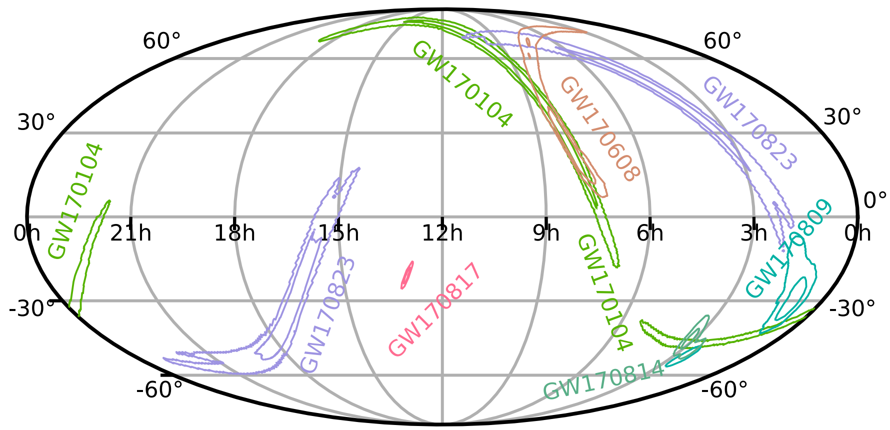
Extrinsic parameters:
time (t_c), reference phase (φ_c),
sky position (α, δ), distance (d_L),
orbital orientation (θ_{Jn}, ψ),

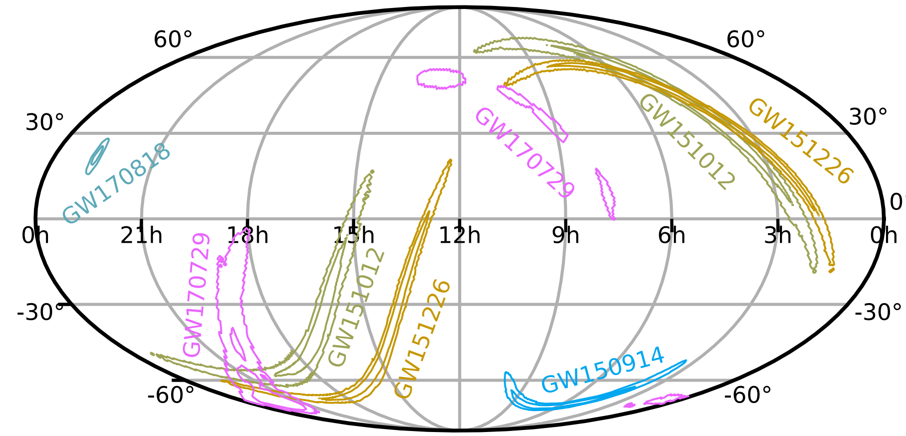


Spin magnitudes and orientations, eccentricity, … tell us something about how these binaries formed

Credit: LIGO/Virgo

Sky localization





O2 GW events for which alerts were sent to EM observers.

O1 events along with O2 events (GW170729, GW170818) not previously released to EM observers.

- Inclusion of Virgo greatly improves sky localization: importance of a *global GW detector network* for accurate localization of GW sources (GW170814, GW170817, GW170818)

- GW170818 (LV) is best localized BBH to date: with a 90% area of 39 deg^2

Radiated energy & luminosity

- GW150914:

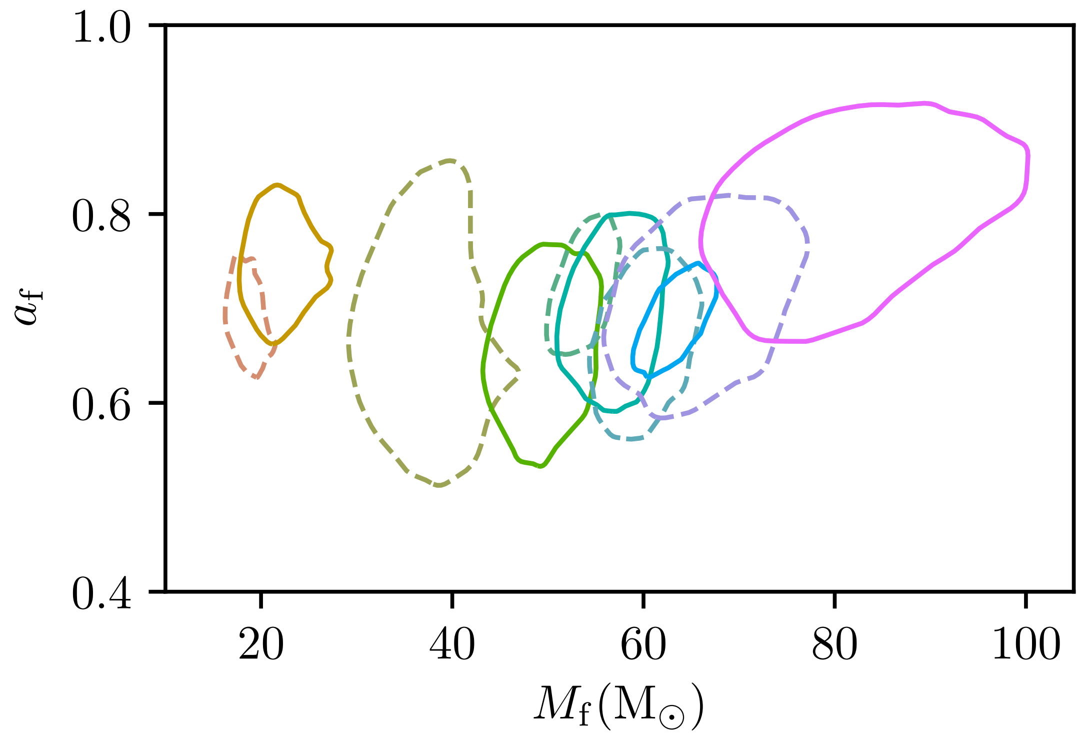
$$E_{\mathrm{rad}} = 3.0^{+0.5}_{-0.4}\,\mathrm{M}_{\odot}c^2$$
$$\ell_{\mathrm{peak}} = 3.6^{+0.5}_{-0.4} \times 10^{56}\mathrm{erg/s}$$

- GW151226:

$$E_{\mathrm{rad}} = 1.0^{+0.1}_{-0.2}\,\mathrm{M}_{\odot}c^2$$
$$\ell_{\mathrm{peak}} = 3.3^{+0.8}_{-1.6} \times 10^{56}\mathrm{erg/s}$$

- LVT151012:

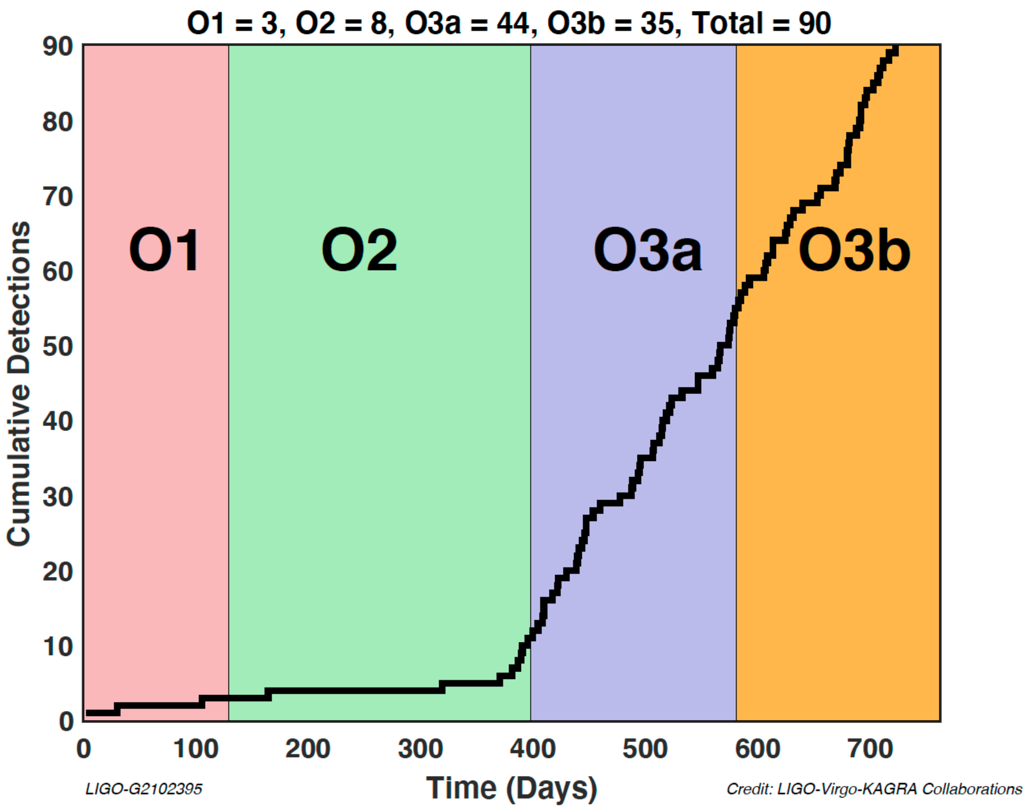
$$E_{\mathrm{rad}} = 1.5^{+0.3}_{-0.4}\,\mathrm{M}_{\odot}c^2$$
$$\ell_{\mathrm{peak}} = 3.1^{+0.8}_{-1.8} \times 10^{56}\mathrm{erg/s}$$

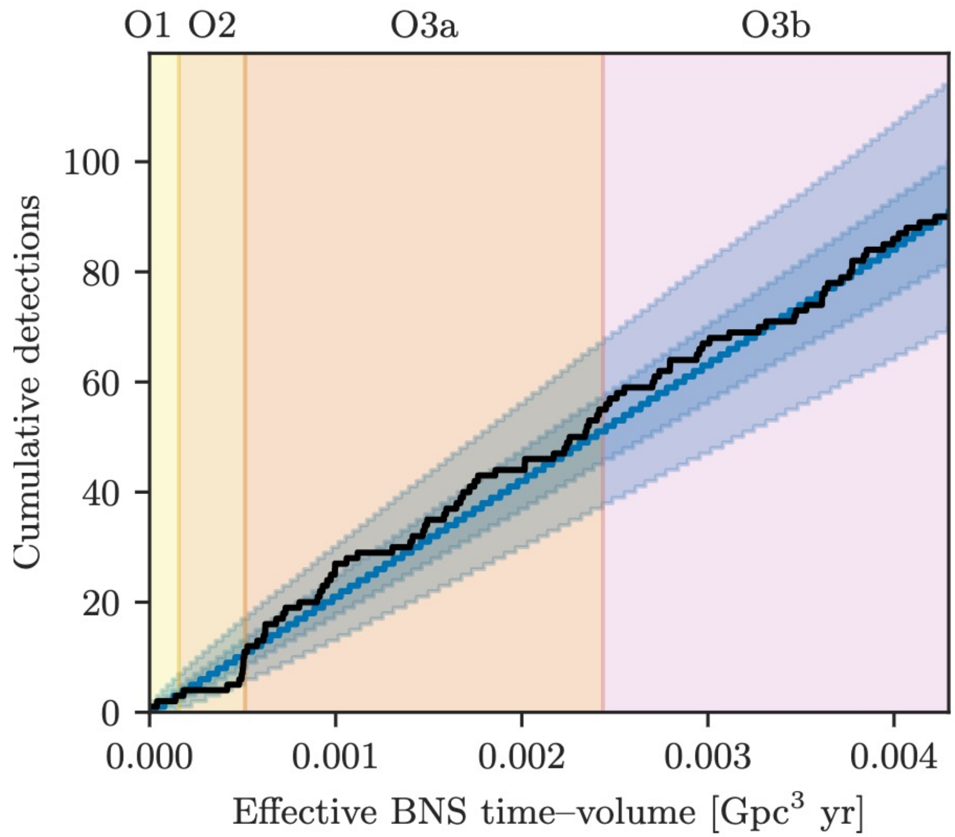


- GW150914: $E_{GW} \approx 3\ M_{\odot}c^2$, or ~4.5% of the total mass-energy of the system.
- Roughly 10^{80} gravitons.
- Peak luminosity $L_{GW} \sim 3.6 \times 10^{54}$ *erg/s*, briefly outshining the EM energy output of all the stars in the observable universe (by a factor ~ 50).

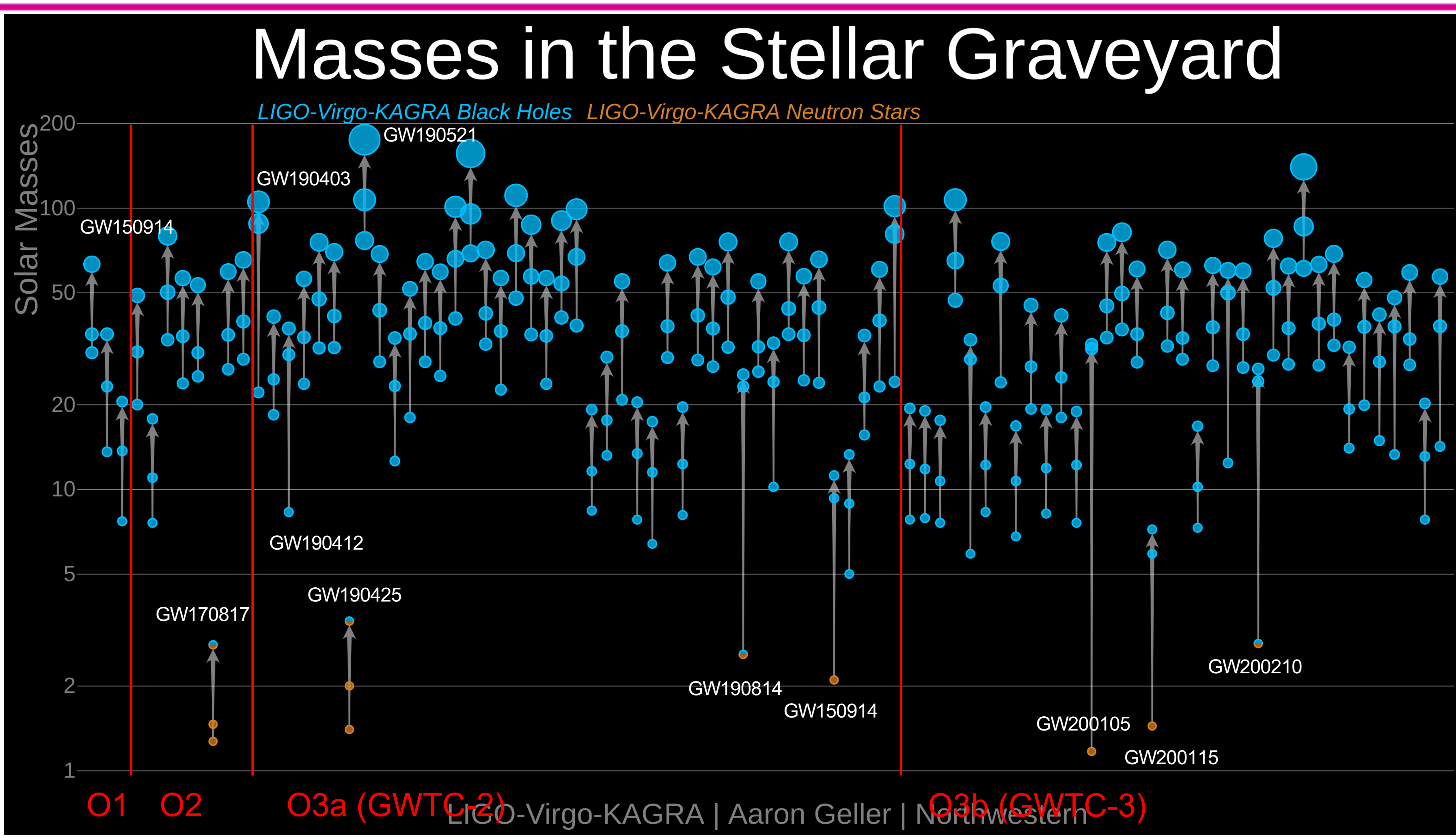
Our third observing run: April 2019 – March 2020

- Average event rate: ~ one GW/month in O2 ⇒
  ~ one GW/week in O3!



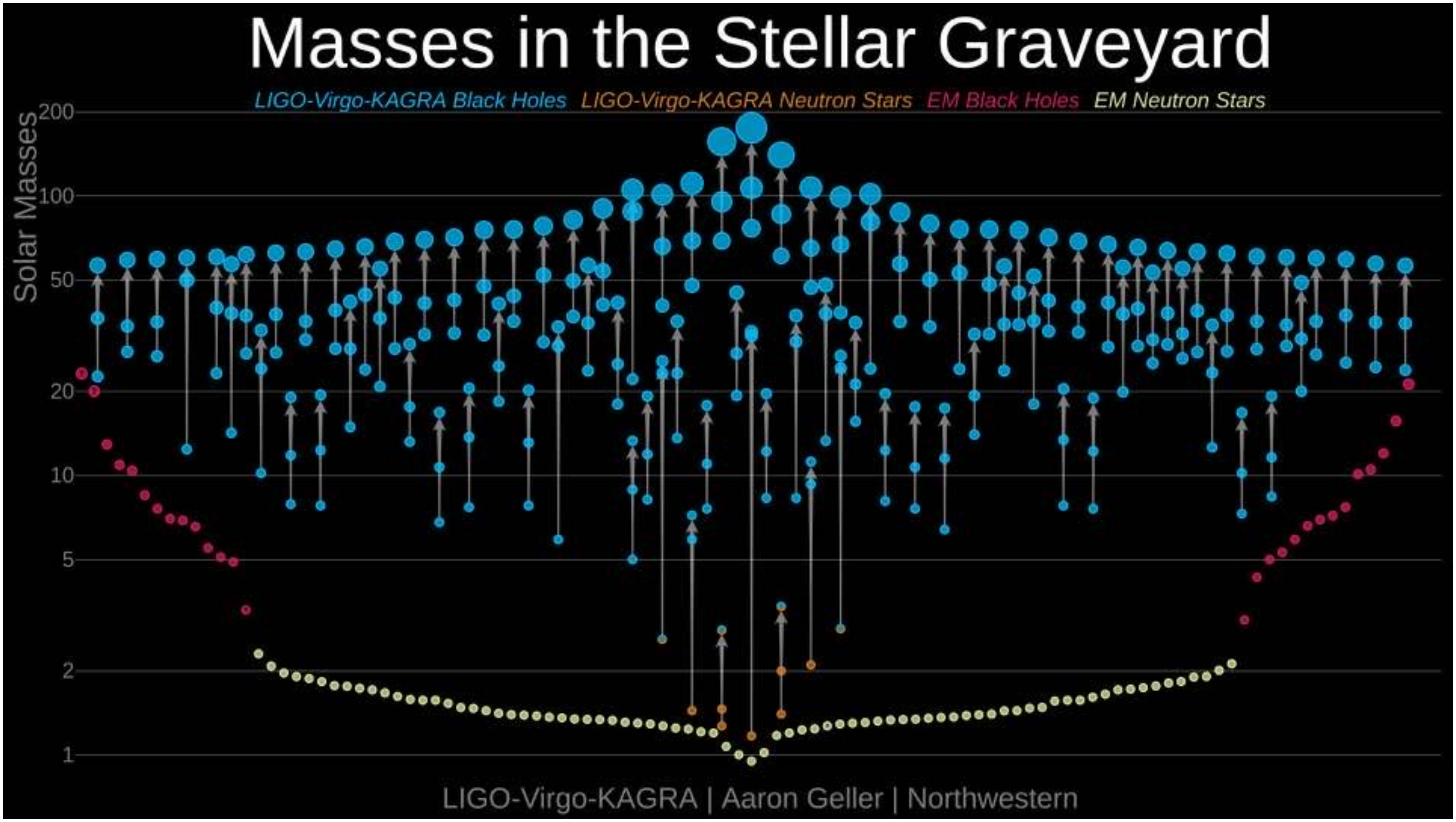


GW Transient Catalog (GWTC) up to 93 events! (BNS, NSBH, BBH)



GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run
LVK - https://arxiv.org/abs/2111.03606

GW Transient Catalog
up to ~ 90 events! (BNS, NSBH, BBH)



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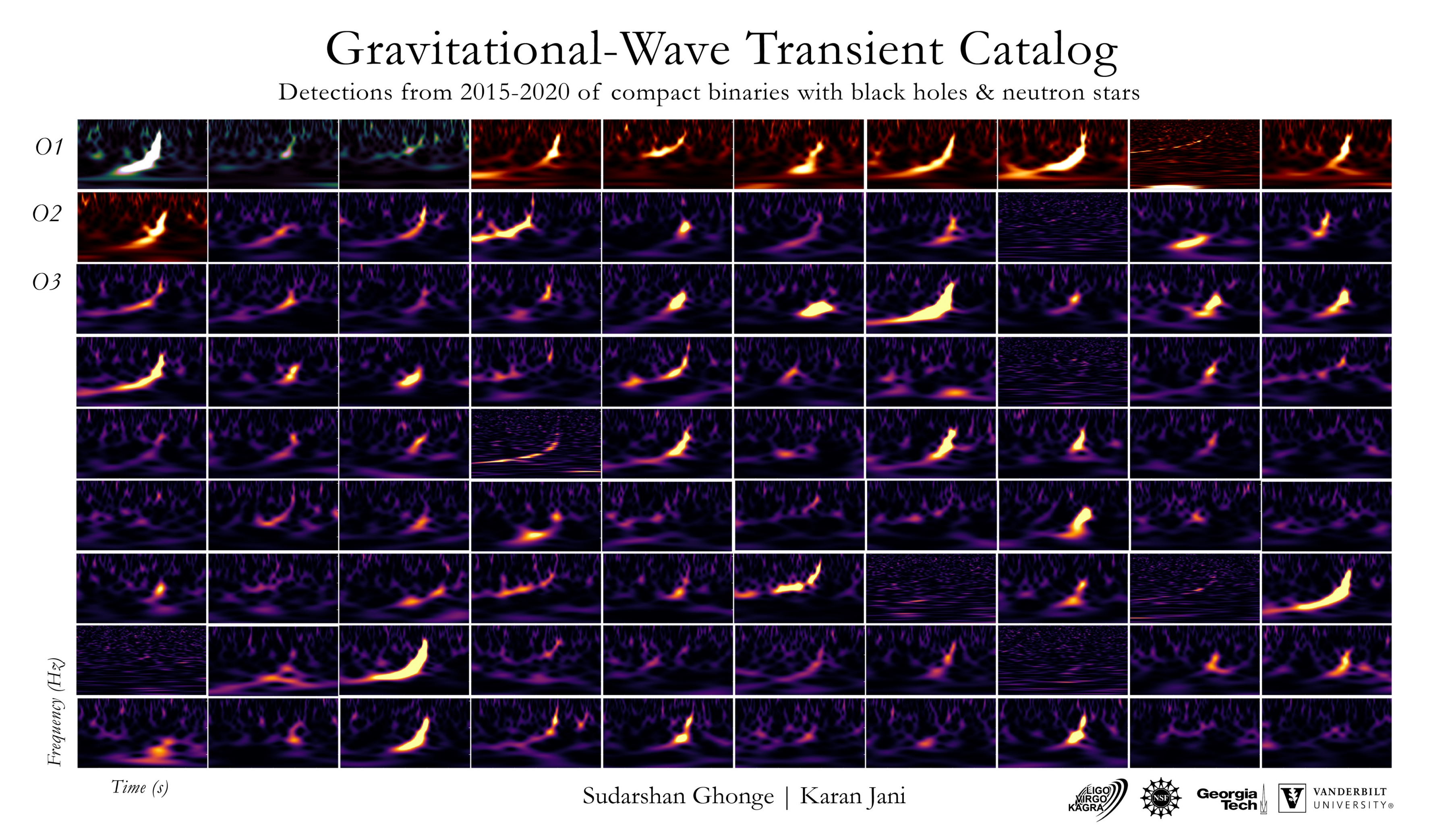
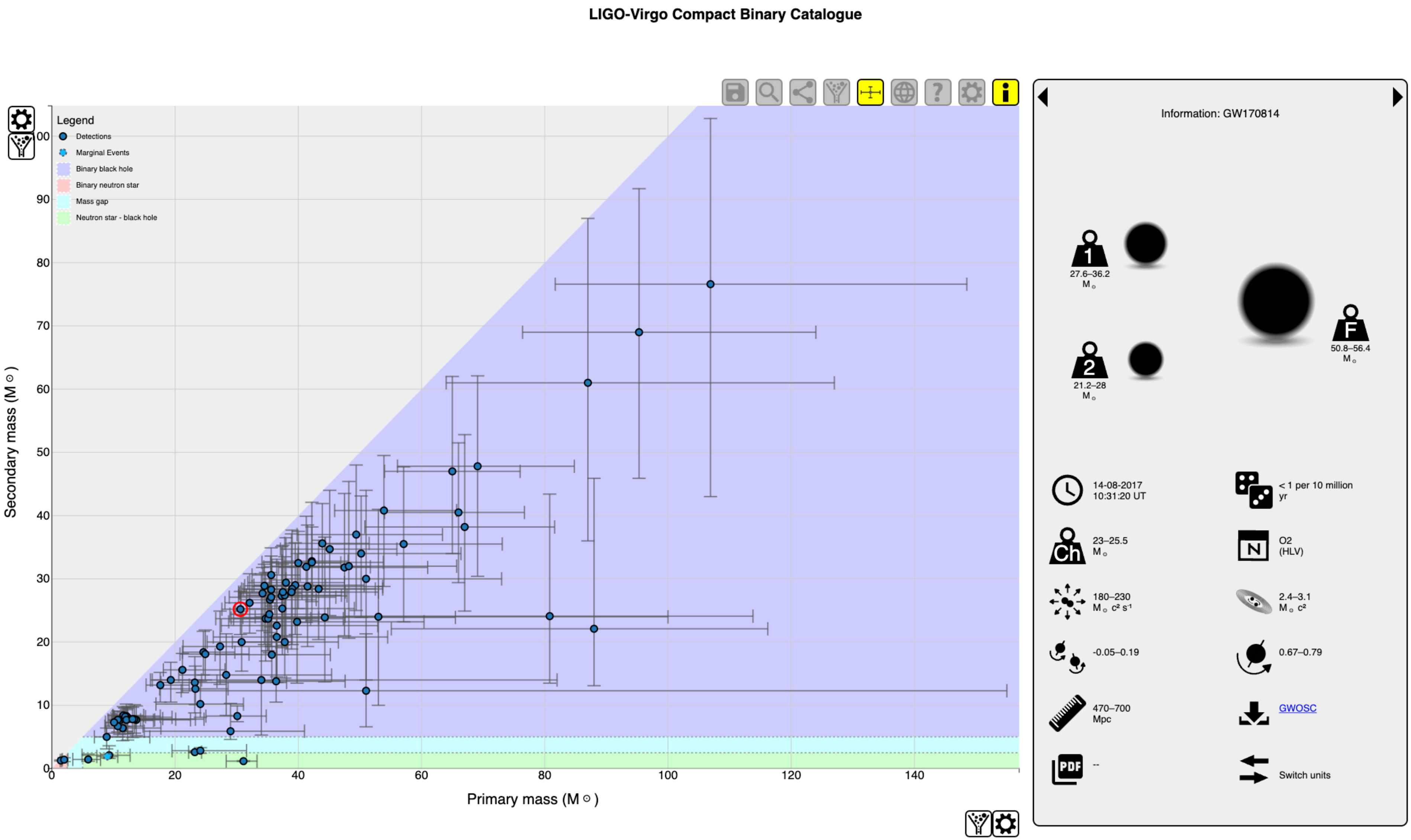
GWTC-3



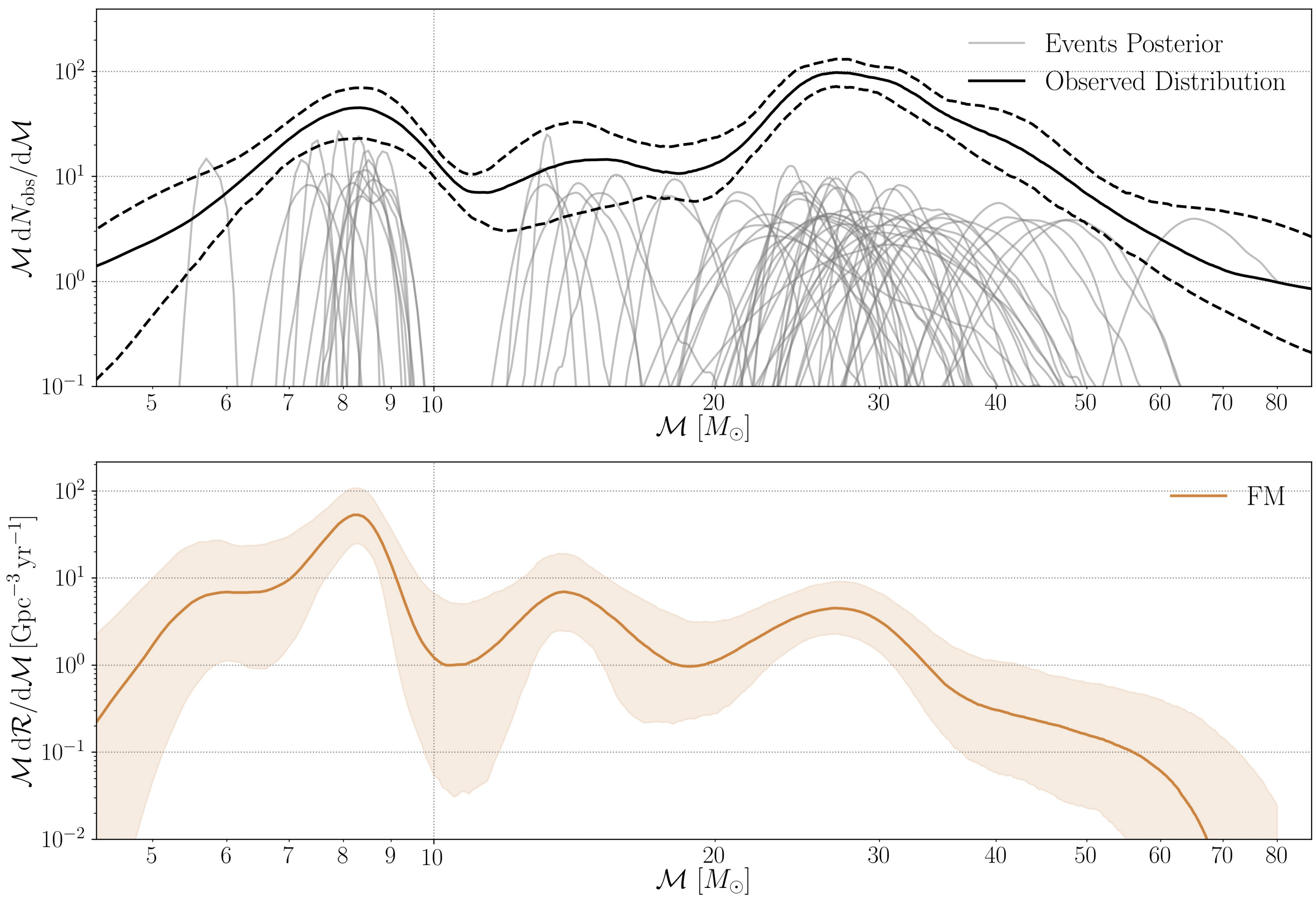
Gravitational-Wave Transient Catalog
Detections from 2015-2020 of compact binaries with black holes & neutron stars
O1
O2
O3
Frequency (Hz)
Time (s)
Sudarshan Ghonge | Karan Jani
LIGO VIRGO KAGRA
Georgia Tech
VANDERBILT UNIVERSITY

GW Transient Catalog interactive plotter

http://catalog.cardiffgravity.org/

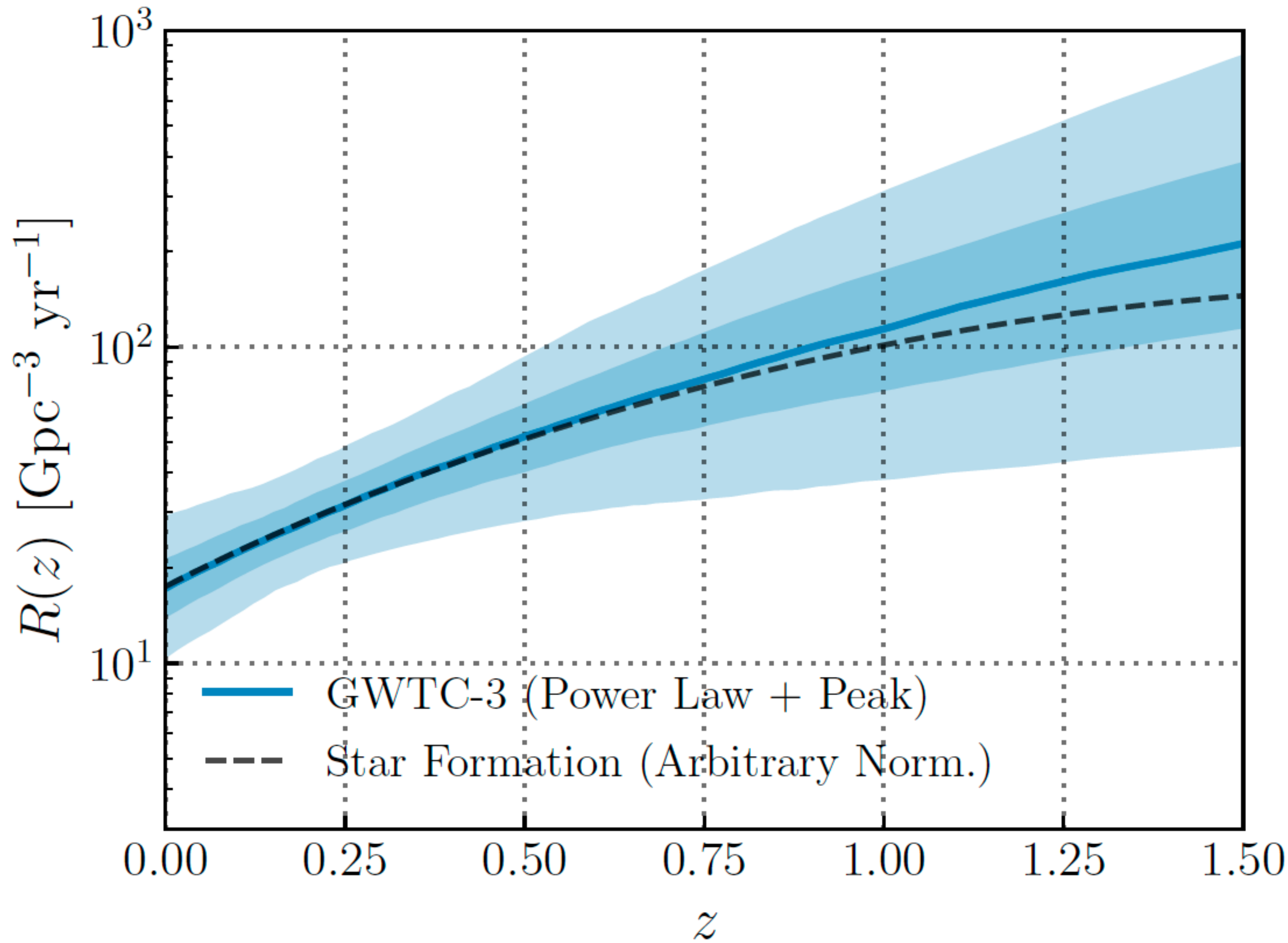


BH Mass distribution in BBH merger rate



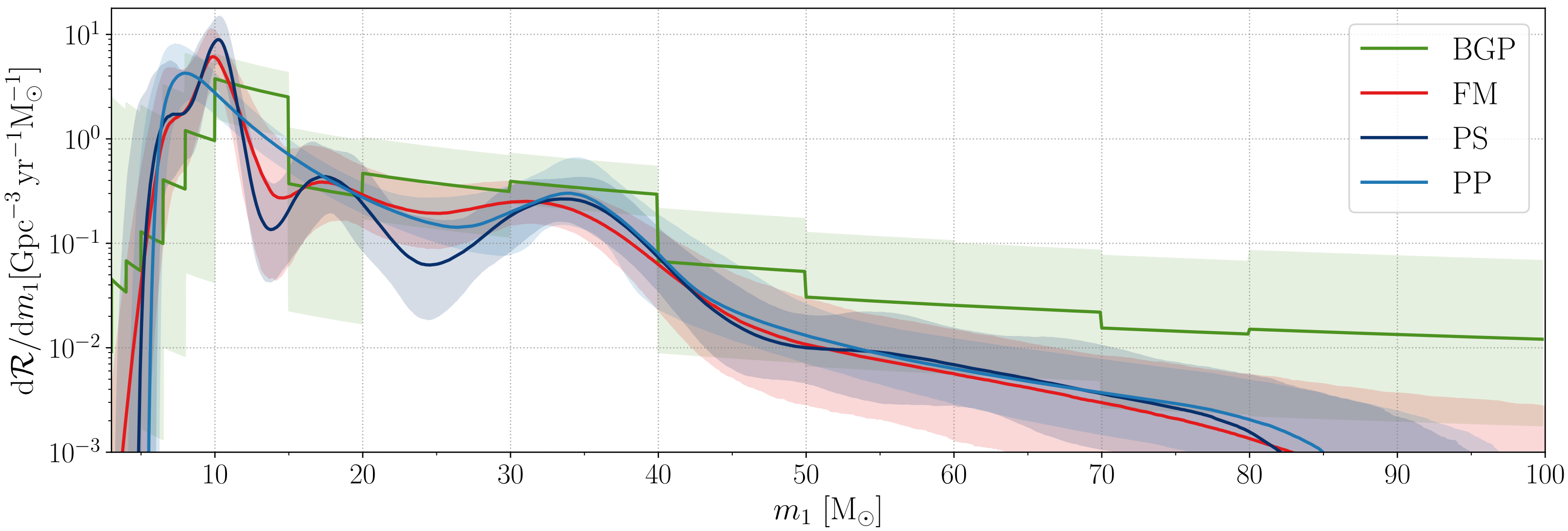
The population of merging compact binaries inferred using gravitational waves through GWTC-3
LVK - https://arxiv.org/abs/2111.03634

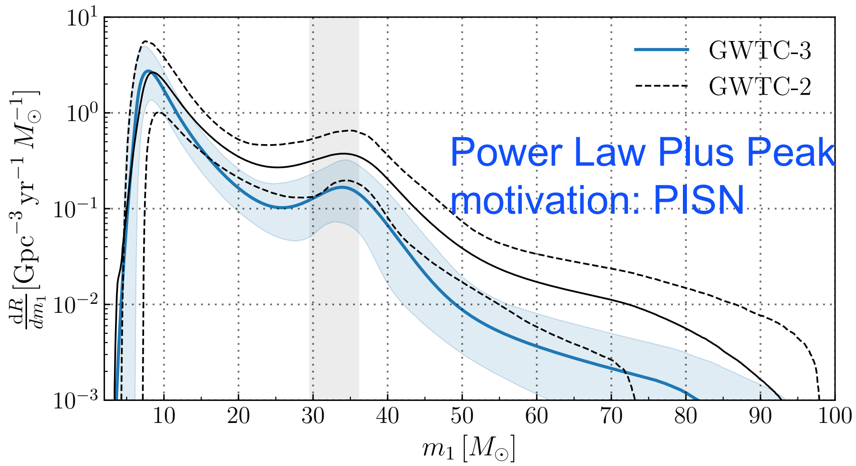
The merger rate evolves with redshift, roughly following star formation rate

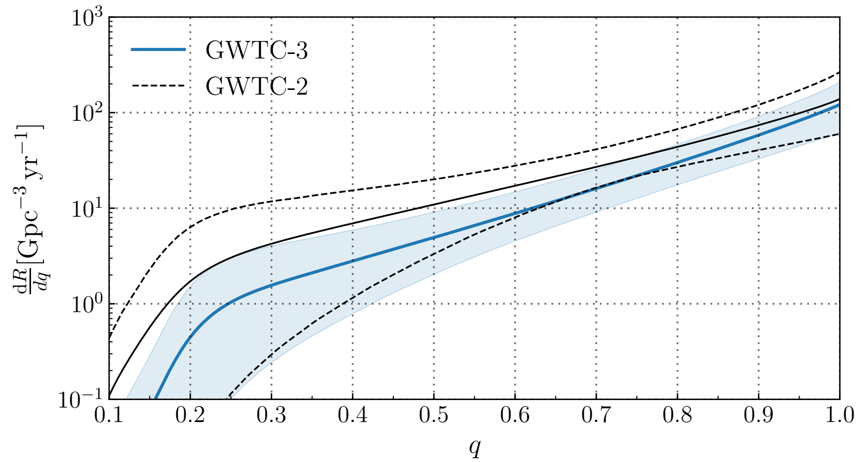


The population of merging compact binaries inferred using gravitational waves through GWTC-3
LVK - https://arxiv.org/abs/2111.03634

BH Mass distribution in BBH merger rate (correcting for Malmquist bias)





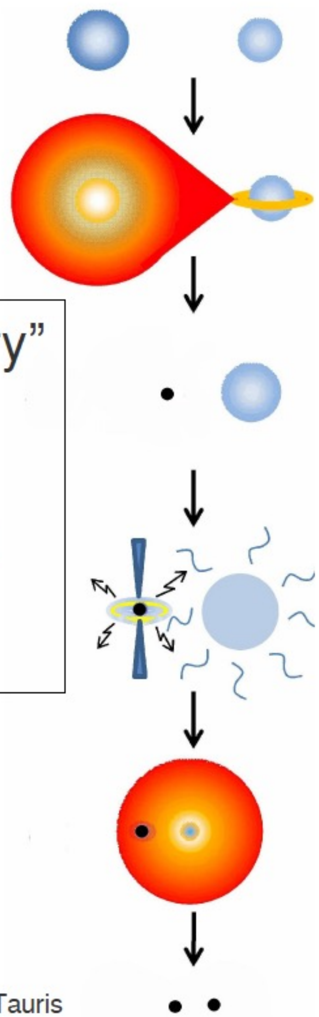


The population of merging compact binaries inferred using gravitational waves through GWTC-3
LVK - https://arxiv.org/abs/2111.03634

Formation channels

https://dcc.ligo.org/LIGO-P1500262/public/main

Isolated binary



“ordinary”
or
rapid
rotation
or
PopIII

5

Fig. after Tauris

Dynamical formation

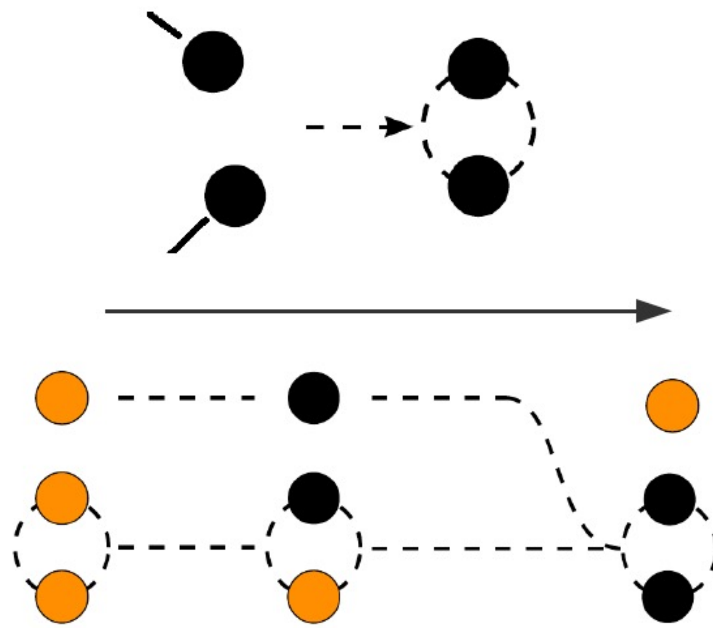
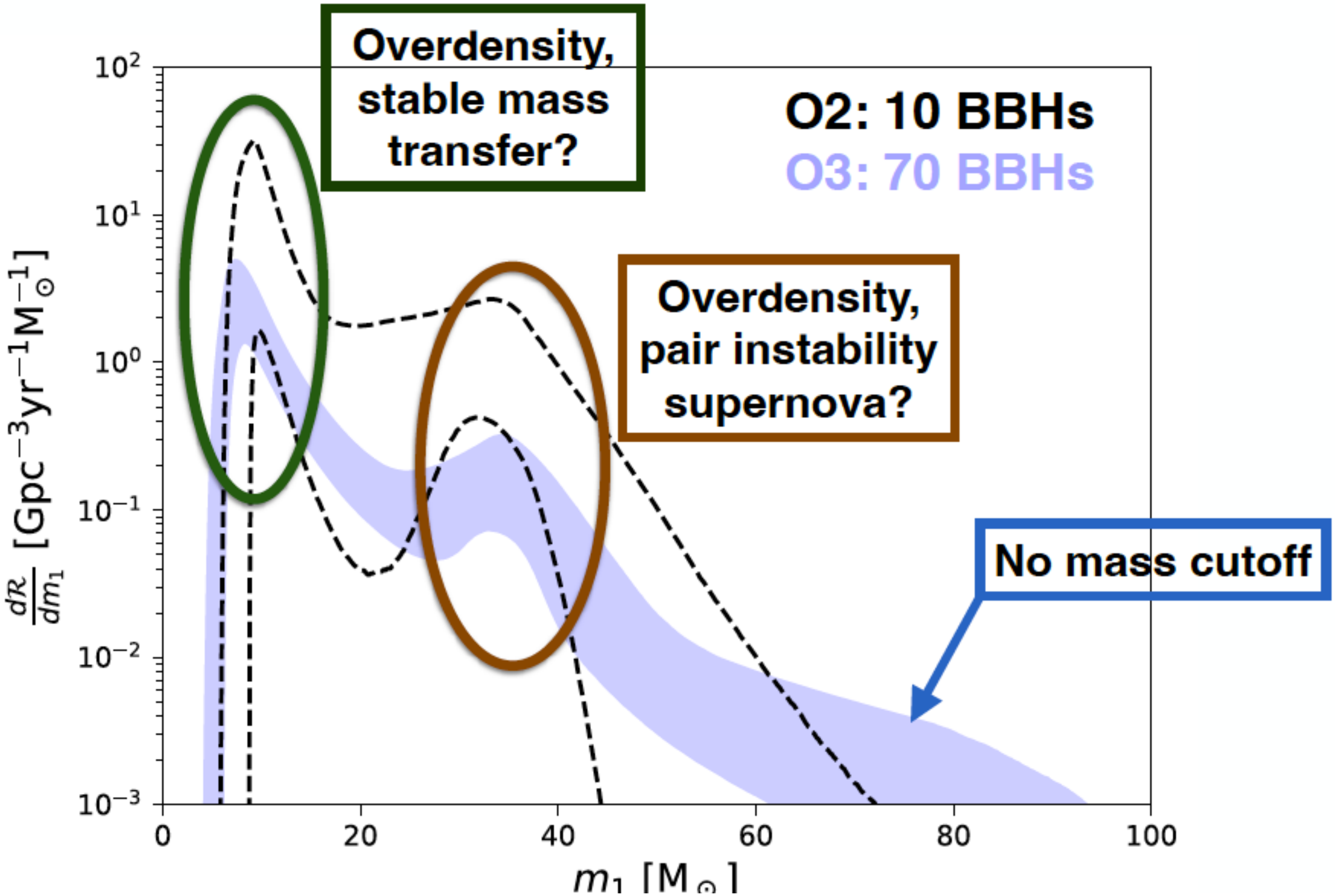


Fig. after Ziosi

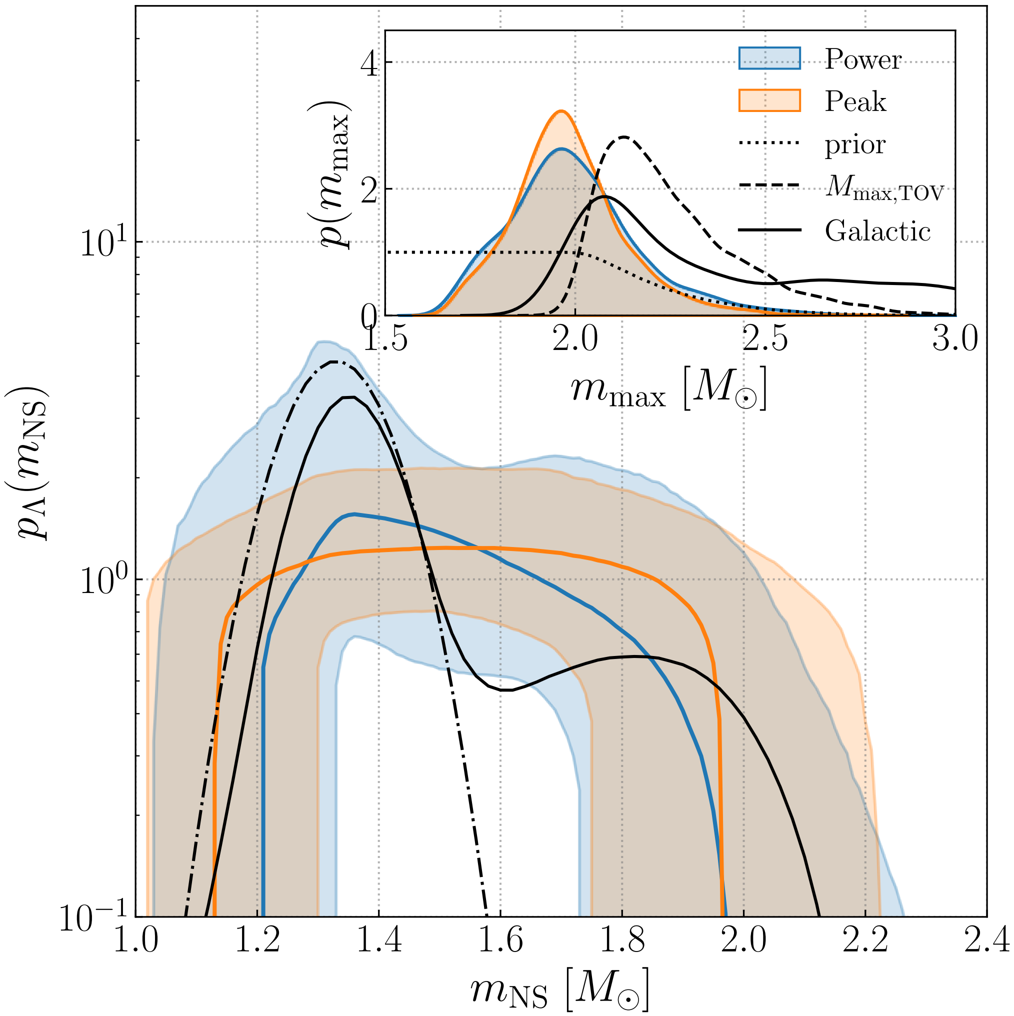
Globular/young clusters/gal. nuclei

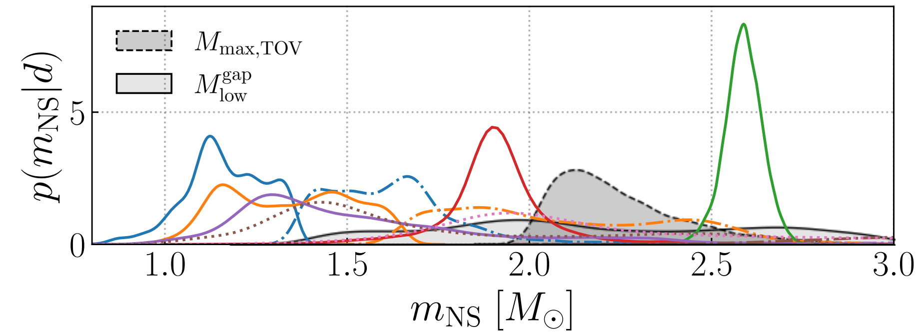
Radboud Universiteit Nijmegen

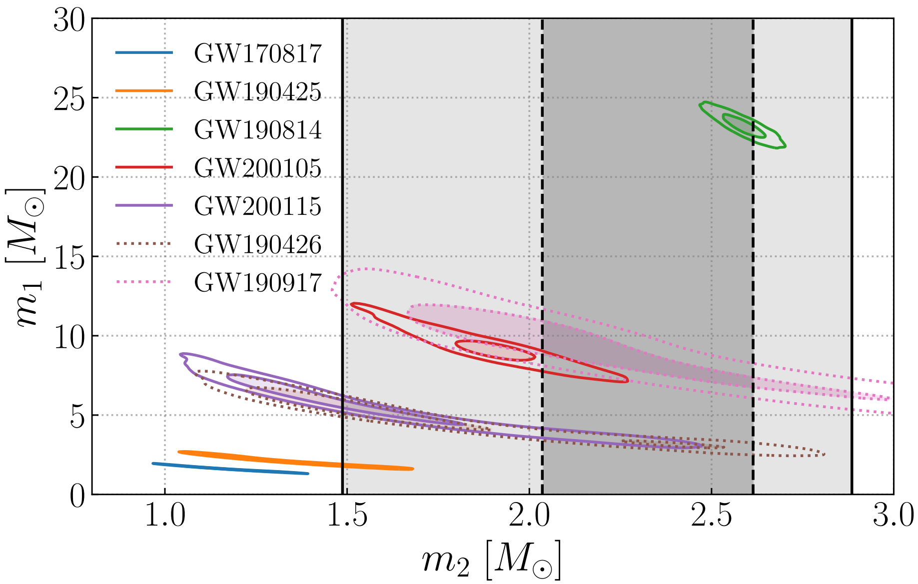
BH Mass distribution in BBH merger rate



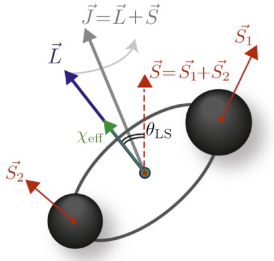
NS mass distribution inferred from BNS and NSBH events in GWTC, compared with galactic NSs, theory







The population of merging compact binaries inferred using gravitational waves through GWTC-3
LVK - https://arxiv.org/abs/2111.03634



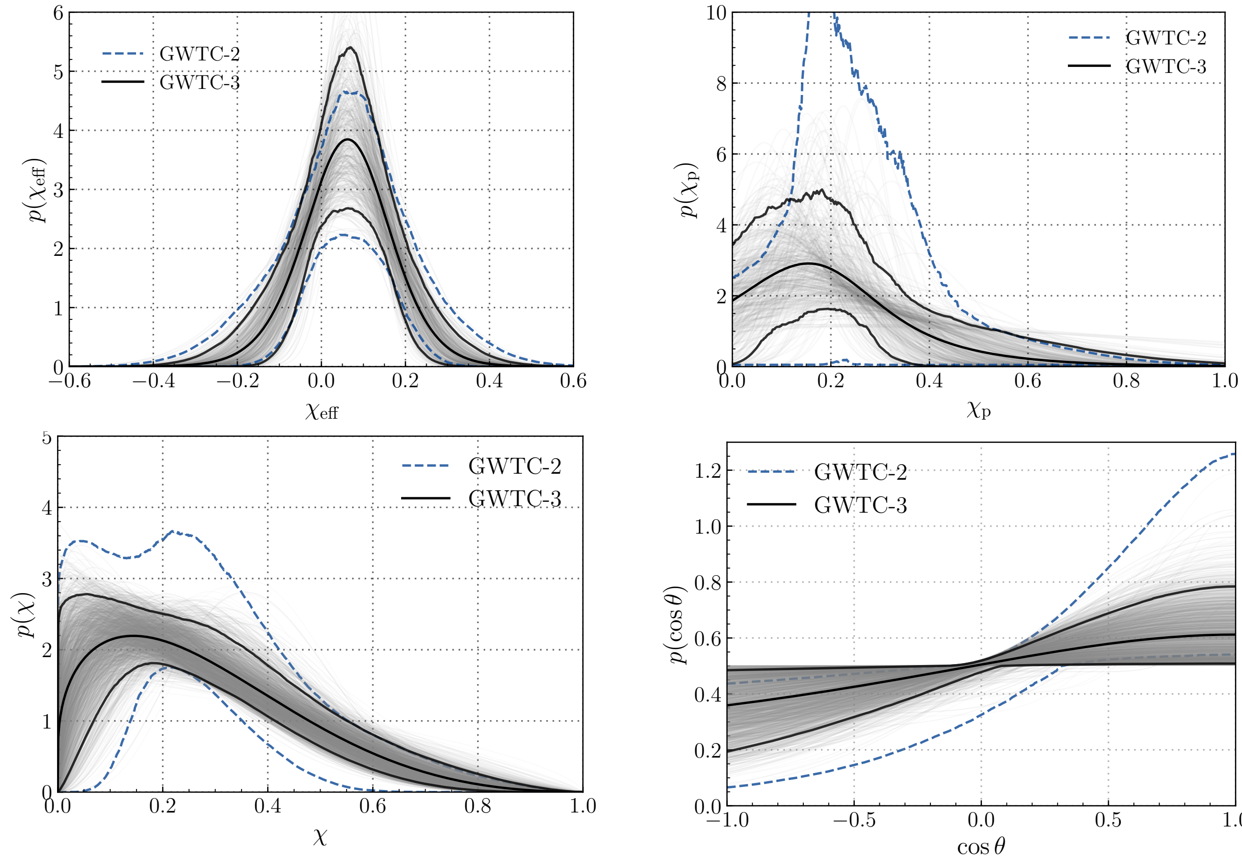
Component black hole spin distributions

Effective aligned spin

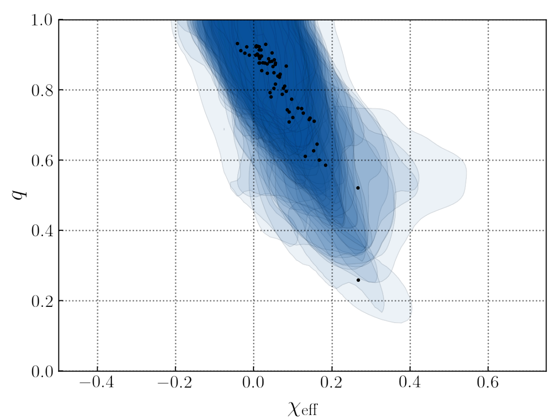
$$\chi_{\rm eff} = \frac{(m_1\boldsymbol{\chi_1} + m_2\boldsymbol{\chi_2})\cdot\hat{\boldsymbol{L}}}{m_1+m_2}$$

Precessing (in-plane) spin

$$\chi_{\rm p} = \max\left[\chi_1 \sin\theta_1,\ \left(\frac{3+4q}{4+3q}\right) q\chi_2 \sin\theta_2\right]$$

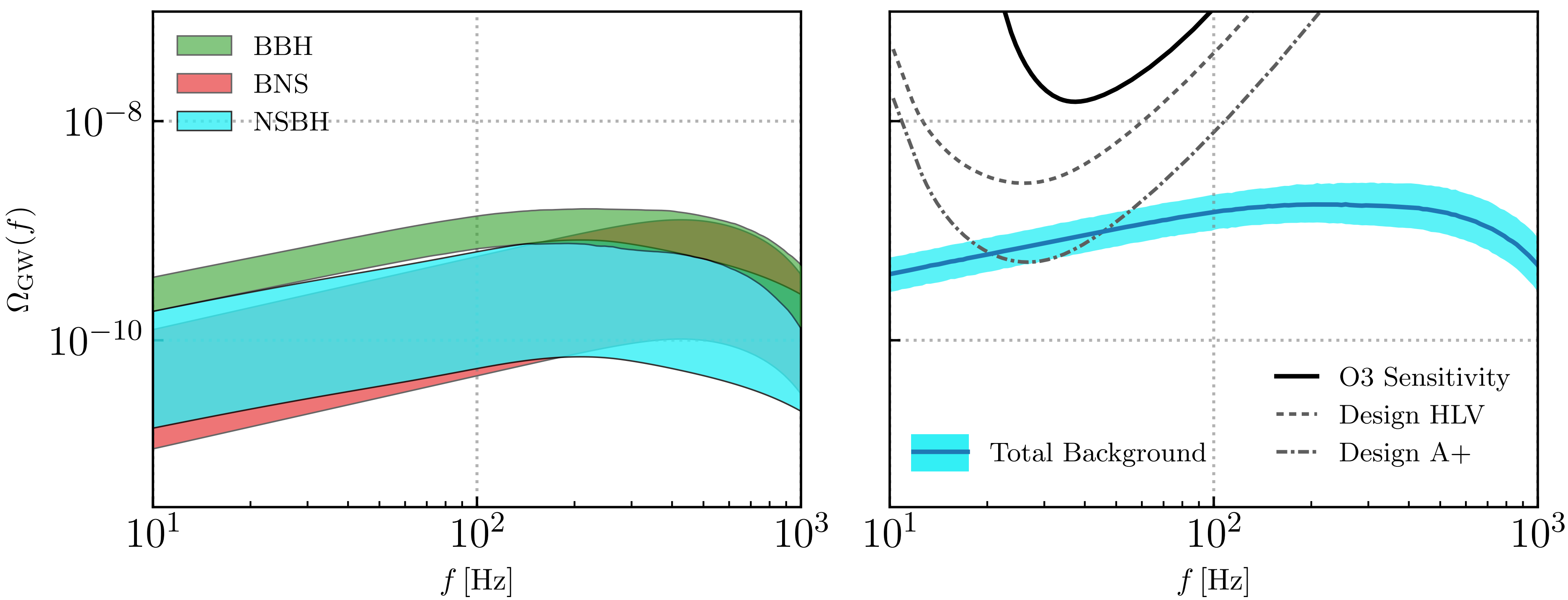


Spin magnitudes and tilt angles



High spin seems to correlate with asymmetric mass binaries

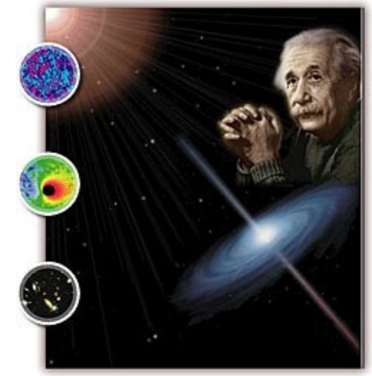
Forecast of astrophysical stochastic GW background due to binary mergers in GWTC



- We will be detecting a SGWB before I'm dead!

The population of merging compact binaries inferred using gravitational waves through GWTC-3
LVK - https://arxiv.org/abs/2111.03634

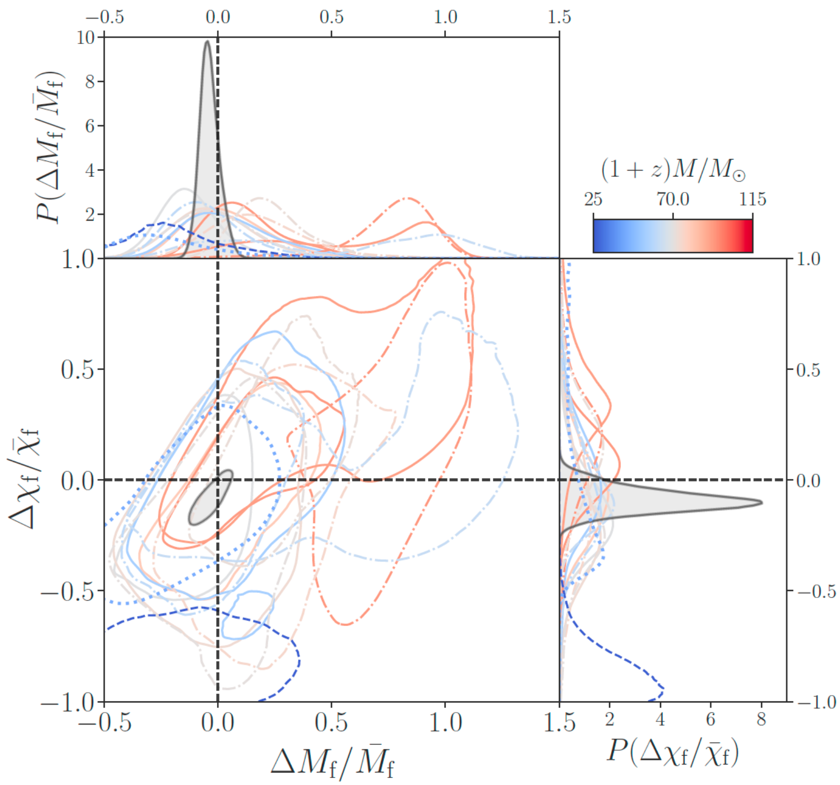
Tests of General Relativity in the strong-field, highly dynamical regime



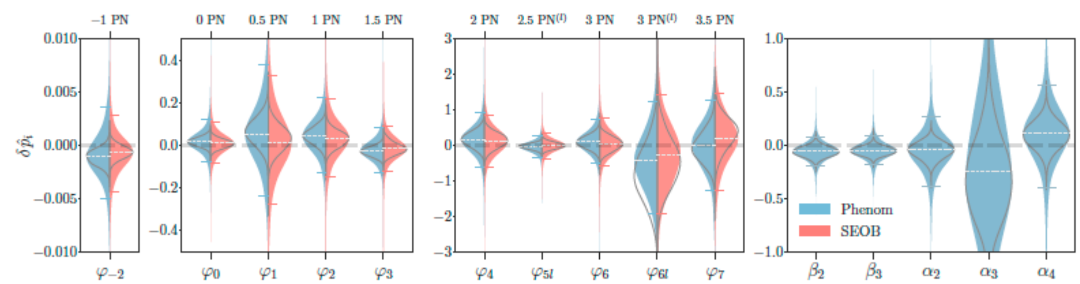
- There are many ways to extend or modify GR, but they are all more complicated, and we do not have precise waveform model / predictions from them to compare with data.
- For now, we look for *consistency* between our data and the waveforms from numerical GR.
- Tests of General Relativity with Binary Black Holes from the second LIGO–Virgo Gravitational-Wave Transient Catalog Phys. Rev. D 103, 122002 (2021)
  - Subtract best-fit signal; are residuals consistent with Gaussian detector noise?
  - Compare Inspiral, Merger, Ringdown – are they consistent?
  - Ringdown modes: consistent with BH no-hair theorem?
  - Any evidence for quantum gravity; eg, firewalls producing echoes?
  - Tests of post-Newtonian expansion in inspiral; post-Einstein parameterized merger, ringdowns
  - Tests of propagation: speed of GWs, graviton mass, anisotropy, Lorentz violation
- TGR from GWTC-3 – 10+ different kinds of tests – GR seems ok for now…

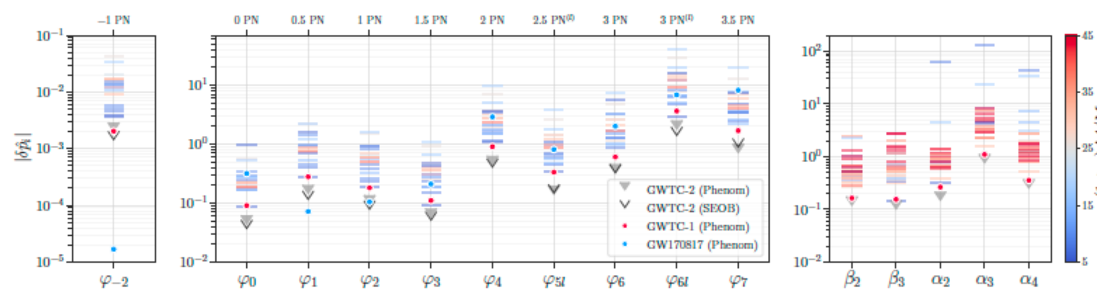
Tests of General Relativity in the strong-field, highly dynamical regime

IMR Consistency – M_f, χ_f



GR-violating parameters





Inspiral → *Merger* → *Ringdown*

Data release - https://www.gw-openscience.org/eventapi/html/GWTC/

GWTC-3 strain data, parameter estimation samples, skymaps, …

Full strain data

Tutorial, software
Detector status
Event alerts
Lots more!

Gravitational Wave Open Science Center

Data▾ Software▾ Online Tools▾ About GWOSC▾

New Search Help

Event List

GWTC
The GWTC (Gravitational Wave Transient Catalog) is a cumulative set of gravitational wave transients maintained by the LIGO/Virgo/KAGRA collaboration. The online GWTC contains confidently-detected events from multiple data releases. For further information, see documentation for individual releases: GWTC-1, GWTC-2, GWTC-2.1, and GWTC-3.

Note, this catalog is only updated periodically, and may not contain recently published events. For the most recent events, you can browse all available events.

Previous versions of this catalog are archived in zenodo.

- Toggle columns on/off with widget at right.
- Click an event name for more information.
- Values in the table below are from the **Default SEARCH** and **Default PE** cases found in the individual event's page.
- See Event Portal Usage Notes for more details.

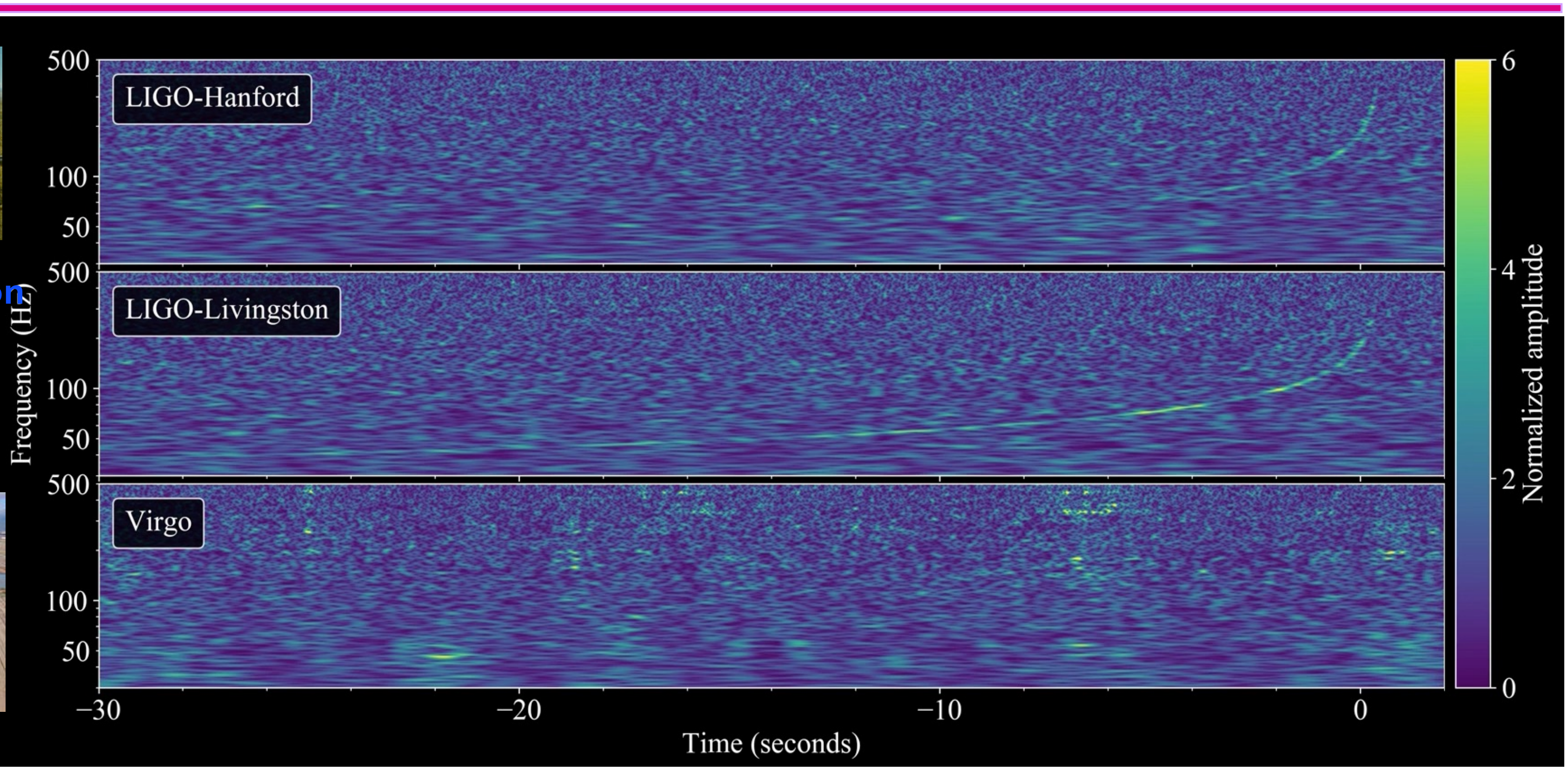
SORT: GPS ↓

Name	Version	Release	GPS ↓	Mass 1 ($M_\odot$)	Mass 2 ($M_\odot$)	Network SNR	Distance (Mpc)	χ_{eff}	Total Mass ($M_\odot$)	Redshift	False Alarm Rate (yr^{-1})	Final Mass ($M_\odot$)
GW200322_091133	v1	GWTC-3-confident	1268903511.3	34^{+48}_{-18}	$14.0^{+16.8}_{-8.7}$	$6.0^{+1.7}_{-1.2}$	3600^{+7000}_{-2000}	$0.24^{+0.45}_{-0.51}$	55^{+37}_{-27}	$0.60^{+0.84}_{-0.30}$	140	53^{+38}_{-26}
GW200316_215756	v1	GWTC-3-confident	1268431094.1	$13.1^{+10.2}_{-2.9}$	$7.8^{+1.9}_{-2.9}$	$10.3^{+0.4}_{-0.7}$	1120^{+470}_{-440}	$0.13^{+0.27}_{-0.10}$	$21.2^{+7.2}_{-2.0}$	$0.22^{+0.08}_{-0.08}$	≤ 1.0e-05	$20.2^{+7.4}_{-1.9}$
GW200311_115853	v1	GWTC-3-confident	1267963151.3	$34.2^{+6.4}_{-3.8}$	$27.7^{+4.1}_{-5.9}$	$17.8^{+0.2}_{-0.2}$	1170^{+280}_{-400}	$-0.02^{+0.16}_{-0.20}$	$61.9^{+5.3}_{-4.2}$	$0.23^{+0.05}_{-0.07}$	≤ 1.0e-05	$59.0^{+4.8}_{-3.9}$
GW200308_173609	v1	GWTC-3-confident	1267724187.7	$36.4^{+11.2}_{-9.6}$	$13.8^{+7.2}_{-3.3}$	$7.1^{+0.5}_{-0.5}$	5400^{+2700}_{-2600}	$0.65^{+0.17}_{-0.21}$	$50.6^{+10.9}_{-8.5}$	$0.83^{+0.32}_{-0.35}$	2.4	$47.4^{+11.1}_{-7.7}$
GW200306_093714	v1	GWTC-3-confident	1267522652.1	$28.3^{+17.1}_{-7.7}$	$14.8^{+6.5}_{-6.4}$	$7.8^{+0.4}_{-0.6}$	2100^{+1700}_{-1100}	$0.32^{+0.28}_{-0.46}$	$43.9^{+11.8}_{-7.5}$	$0.38^{+0.24}_{-0.18}$	24	$41.7^{+12.3}_{-6.9}$
GW200302_015811	v1	GWTC-3-confident	1267149509.5	$37.8^{+8.7}_{-8.5}$	$20.0^{+8.1}_{-5.7}$	$10.8^{+0.3}_{-0.4}$	1480^{+1020}_{-700}	$0.01^{+0.25}_{-0.26}$	$57.8^{+9.6}_{-6.9}$	$0.28^{+0.16}_{-0.12}$	0.11	$55.5^{+8.9}_{-6.6}$
GW200225_060421	v1	GWTC-3-confident	1266645879.3	$19.3^{+5.0}_{-3.0}$	$14.0^{+2.8}_{-3.5}$	$12.5^{+0.3}_{-0.4}$	1150^{+510}_{-530}	$-0.12^{+0.17}_{-0.28}$	$33.5^{+3.6}_{-3.0}$	$0.22^{+0.09}_{-0.10}$	≤ 1.1e-05	$32.1^{+3.5}_{-2.8}$
GW200224_222234	v1	GWTC-3-confident	1266618172.4	$40.0^{+6.9}_{-4.5}$	$32.5^{+5.0}_{-7.2}$	$20.0^{+0.2}_{-0.2}$	1710^{+490}_{-640}	$0.10^{+0.15}_{-0.15}$	$72.2^{+7.2}_{-5.1}$	$0.32^{+0.08}_{-0.11}$	≤ 1.0e-05	$68.6^{+6.6}_{-4.7}$
GW200220_124850	v1	GWTC-3-confident	1266238148.1	$38.9^{+14.1}_{-8.6}$	$27.9^{+9.2}_{-9.0}$	$8.5^{+0.3}_{-0.5}$	4000^{+2800}_{-2200}	$-0.07^{+0.27}_{-0.33}$	67^{+17}_{-12}	$0.66^{+0.36}_{-0.31}$	30	64^{+16}_{-11}
GW200220_061928	v1	GWTC-3-confident	1266214786.7	87^{+40}_{-23}	61^{+26}_{-25}	$7.2^{+0.4}_{-0.7}$	6000^{+4800}_{-3100}	$0.06^{+0.40}_{-0.38}$	148^{+55}_{-33}	$0.90^{+0.55}_{-0.40}$	6.8	141^{+51}_{-31}
GW200219_094415	v1	GWTC-3-confident	1266140673.1	$37.5^{+10.1}_{-6.9}$	$27.9^{+7.4}_{-8.4}$	$10.7^{+0.3}_{-0.5}$	3400^{+1700}_{-1500}	$-0.08^{+0.23}_{-0.29}$	$65.0^{+12.6}_{-8.2}$	$0.57^{+0.22}_{-0.22}$	0.00099	$62.2^{+11.7}_{-7.8}$
GW200216_220804	v1	GWTC-3-confident	1265926102.8	51^{+22}_{-13}	30^{+14}_{-16}	$8.1^{+0.4}_{-0.5}$	3800^{+3000}_{-2000}	$0.10^{+0.34}_{-0.36}$	81^{+20}_{-14}	$0.63^{+0.37}_{-0.29}$	0.35	78^{+19}_{-13}
GW200210_092254	v1	GWTC-3-confident	1265361792.9	$24.1^{+7.5}_{-4.6}$	$2.83^{+0.47}_{-0.42}$	$8.4^{+0.5}_{-0.7}$	940^{+430}_{-340}	$0.02^{+0.22}_{-0.21}$	$27.0^{+7.1}_{-4.3}$	$0.19^{+0.08}_{-0.06}$	1.2	$26.7^{+7.2}_{-4.3}$
GW200209_085452	v1	GWTC-3-confident	1265273710.1	$35.6^{+10.5}_{-6.8}$	$27.1^{+7.8}_{-7.8}$	$9.6^{+0.4}_{-0.5}$	3400^{+1900}_{-1800}	$-0.12^{+0.24}_{-0.30}$	$62.6^{+13.9}_{-9.4}$	$0.57^{+0.25}_{-0.26}$	0.046	$59.9^{+13.1}_{-8.9}$
GW200208_222617	v1	GWTC-3-confident	1265235995.9	51^{+104}_{-30}	$12.3^{+9.0}_{-5.7}$	$7.4^{+1.4}_{-1.2}$	4100^{+4400}_{-1900}	$0.45^{+0.43}_{-0.44}$	63^{+100}_{-25}	$0.66^{+0.54}_{-0.28}$	4.8	61^{+100}_{-25}
GW200208_130117	v1	GWTC-3-confident	1265202095.9	$37.8^{+9.2}_{-6.2}$	$27.4^{+6.1}_{-7.4}$	$10.8^{+0.3}_{-0.4}$	2230^{+1000}_{-850}	$-0.07^{+0.22}_{-0.27}$	$65.4^{+7.8}_{-6.8}$	$0.40^{+0.15}_{-0.14}$	0.00031	$62.5^{+7.3}_{-6.4}$
GW200202_154313	v1	GWTC-3-confident	1264693411.5	$10.1^{+3.5}_{-1.4}$	$7.3^{+1.1}_{-1.7}$	$10.8^{+0.2}_{-0.4}$	410^{+150}_{-160}	$0.04^{+0.13}_{-0.06}$	$17.58^{+1.78}_{-0.67}$	$0.09^{+0.03}_{-0.03}$	≤ 1.0e-05	$16.76^{+1.87}_{-0.66}$
GW200129_065458	v1	GWTC-3-confident	1264316116.4	$34.5^{+9.9}_{-3.2}$	$28.9^{+3.4}_{-9.3}$	$26.8^{+0.2}_{-0.2}$	900^{+290}_{-380}	$0.11^{+0.11}_{-0.16}$	$63.4^{+4.3}_{-3.6}$	$0.18^{+0.05}_{-0.07}$	≤ 1.0e-05	$60.3^{+4.0}_{-3.3}$
GW200128_022011	v1	GWTC-3-confident	1264213229.9	$42.2^{+11.6}_{-8.1}$	$32.6^{+9.5}_{-9.2}$	$10.6^{+0.3}_{-0.4}$	3400^{+2100}_{-1800}	$0.12^{+0.24}_{-0.25}$	75^{+17}_{-12}	$0.56^{+0.28}_{-0.28}$	0.0043	71^{+16}_{-11}
GW200115_042309	v2	GWTC-3-confident	1263097407.7	$5.9^{+2.0}_{-2.5}$	$1.44^{+0.85}_{-0.29}$	$11.3^{+0.3}_{-0.5}$	290^{+150}_{-100}	$-0.15^{+0.24}_{-0.42}$	$7.4^{+1.8}_{-1.7}$	$0.06^{+0.03}_{-0.02}$	≤ 1.0e-05	$7.2^{+1.8}_{-1.7}$
GW200112_155838	v1	GWTC-3-confident	1262879936.0	$35.6^{+6.7}_{-4.5}$	$28.3^{+4.4}_{-5.9}$	$19.8^{+0.1}_{-0.2}$	1250^{+430}_{-460}	$0.06^{+0.15}_{-0.15}$	$63.9^{+5.7}_{-4.6}$	$0.24^{+0.07}_{-0.08}$	≤ 1.0e-05	$60.8^{+5.3}_{-4.3}$
GW191230_180458	v1	GWTC-3-confident	1261764316.4	$49.4^{+14.0}_{-9.6}$	37^{+11}_{-12}	$10.4^{+0.3}_{-0.4}$	4300^{+2100}_{-1900}	$-0.05^{+0.26}_{-0.31}$	86^{+19}_{-12}	$0.69^{+0.26}_{-0.27}$	0.050	82^{+17}_{-11}
GW191222_033537	v1	GWTC-3-confident	1261020955.1	$45.1^{+10.9}_{-8.0}$	$34.7^{+9.3}_{-10.5}$	$12.5^{+0.2}_{-0.3}$	3000^{+1700}_{-1700}	$-0.04^{+0.20}_{-0.25}$	79^{+16}_{-11}	$0.51^{+0.23}_{-0.26}$	≤ 1.0e-05	$75.5^{+15.3}_{-9.9}$

This was something completely different…
130 million years ago, in a galaxy far, far away …

https://www.youtube.com/watch?v=e7LcmWicIOs

This is what I woke up to on August 17, 2017, just before 6am PT…

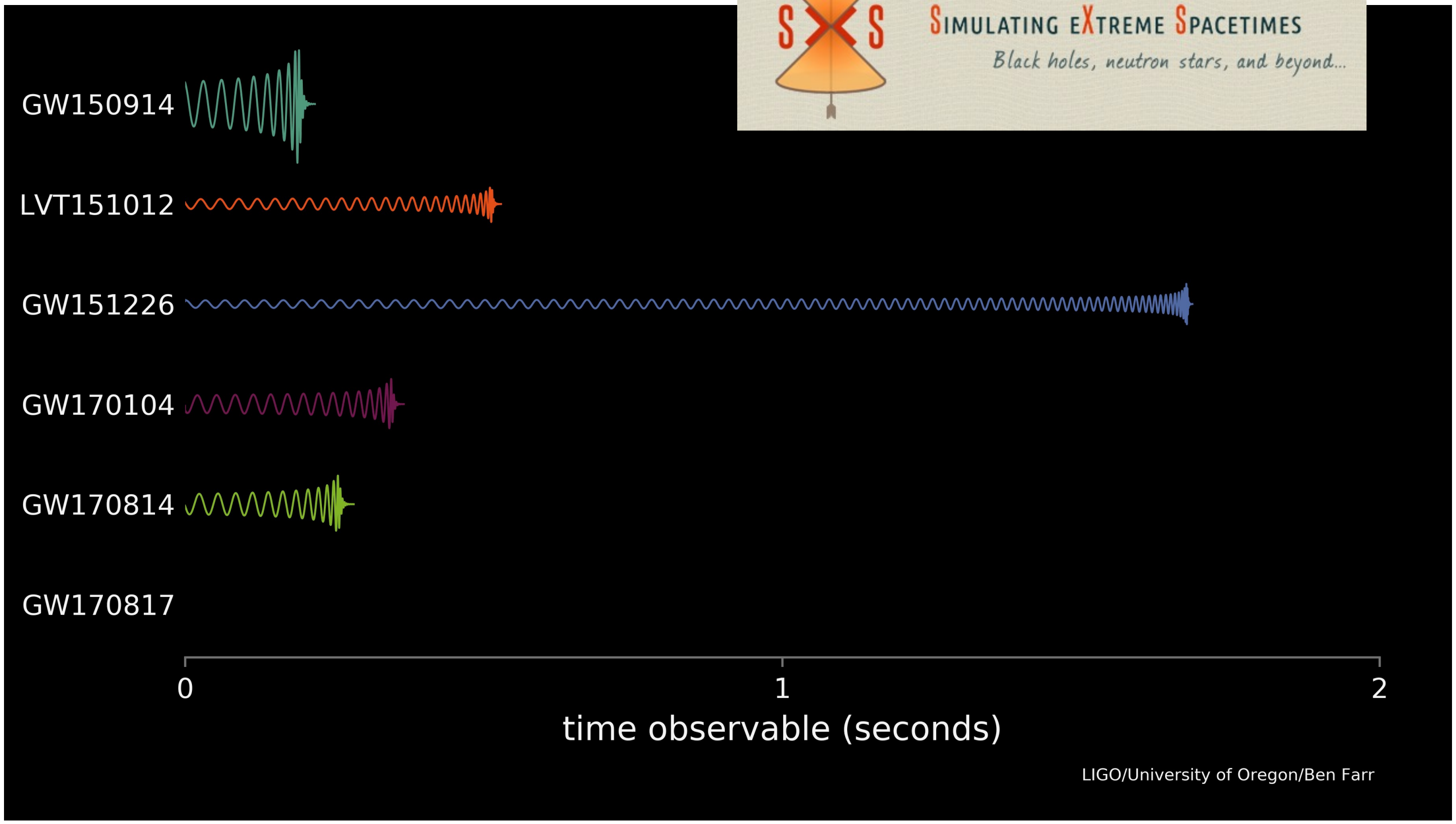


GW170817
A Binary Neutron Star Merger! (!!!!!!)

http://ligo.org/detections/GW170817.php

Our automated software ("pipeline") matched the GW signal to a predicted waveform for a binary neutron star merger

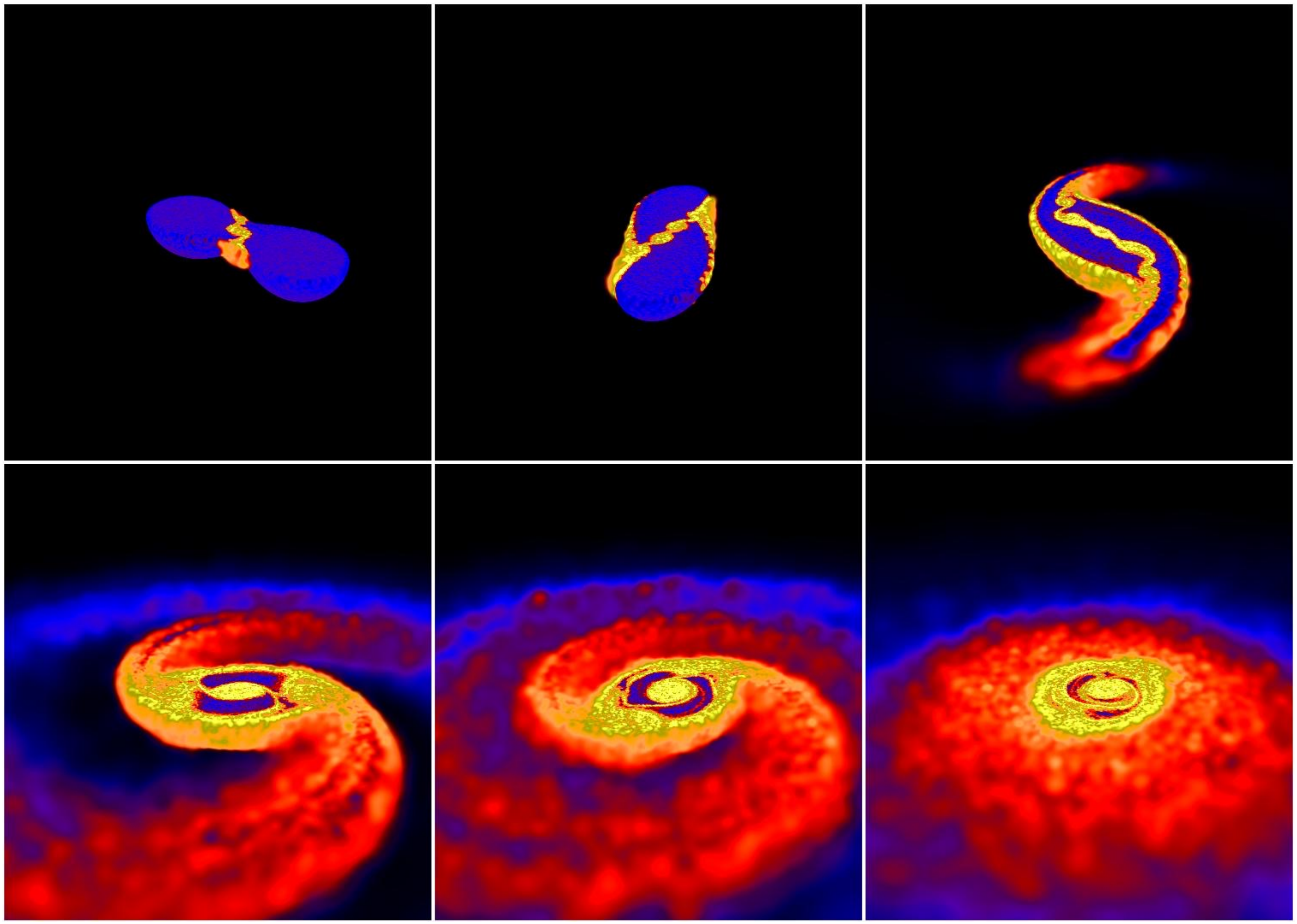
SIMULATING EXTREME SPACETIMES
Black holes, neutron stars, and beyond...



The longest (~ 60 s), loudest (SNR ~ 32), closest (40 Mpc) signal LIGO has ever observed!

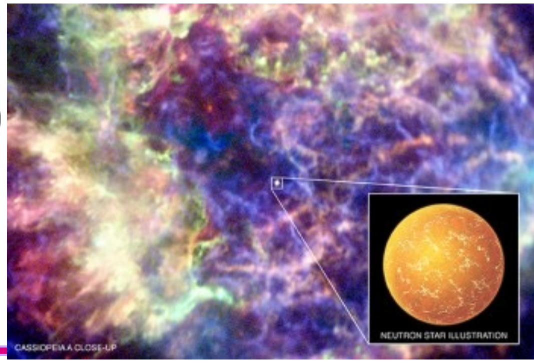
https://www.youtube.com/watch?v=WoDCPTLgxh4

BNS mergers, tidal distortion and disruption

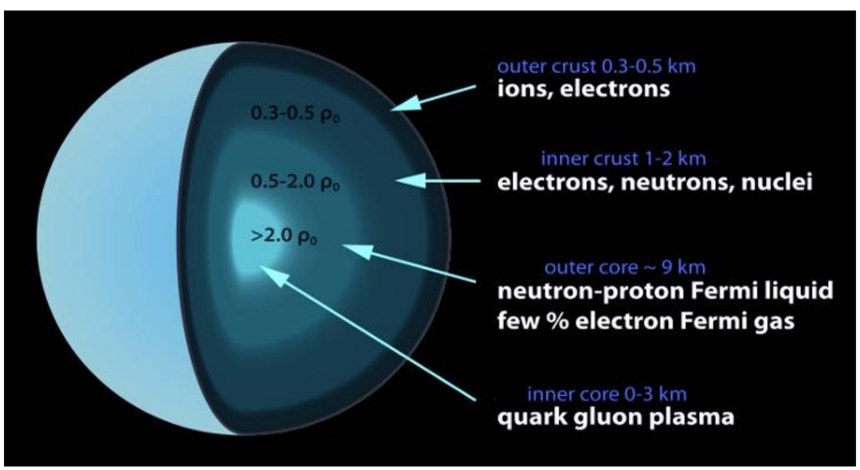


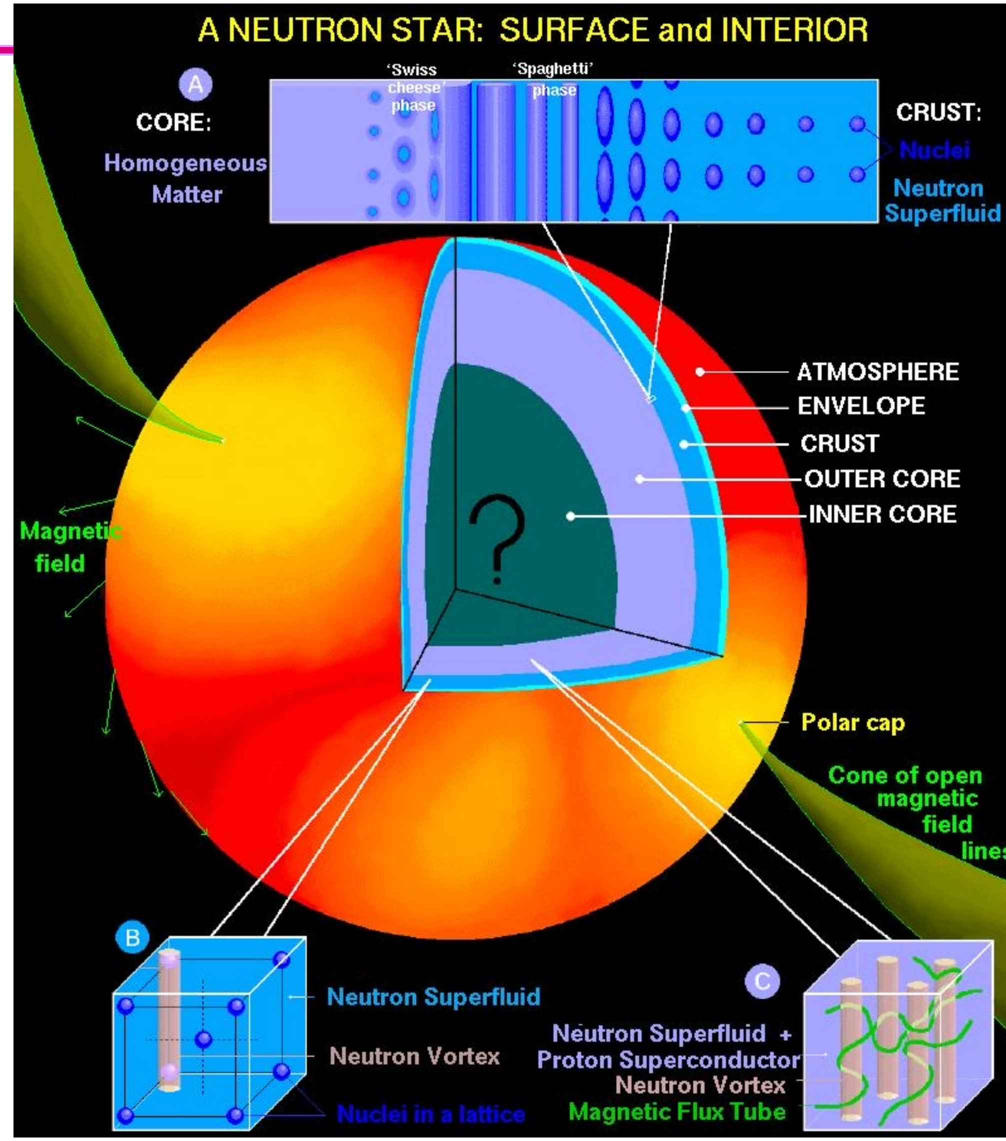
Credit: Daniel Price and Stephan Rosswog

Neutron stars



- Dead remnants of massive star core collapse supernovae
- A unique laboratory for fundamental physics
- All four forces of nature, Strong, Weak, EM, gravity – all under *the most extreme beyond-laboratory conditions*
- Structure can be revealed through binary mergers

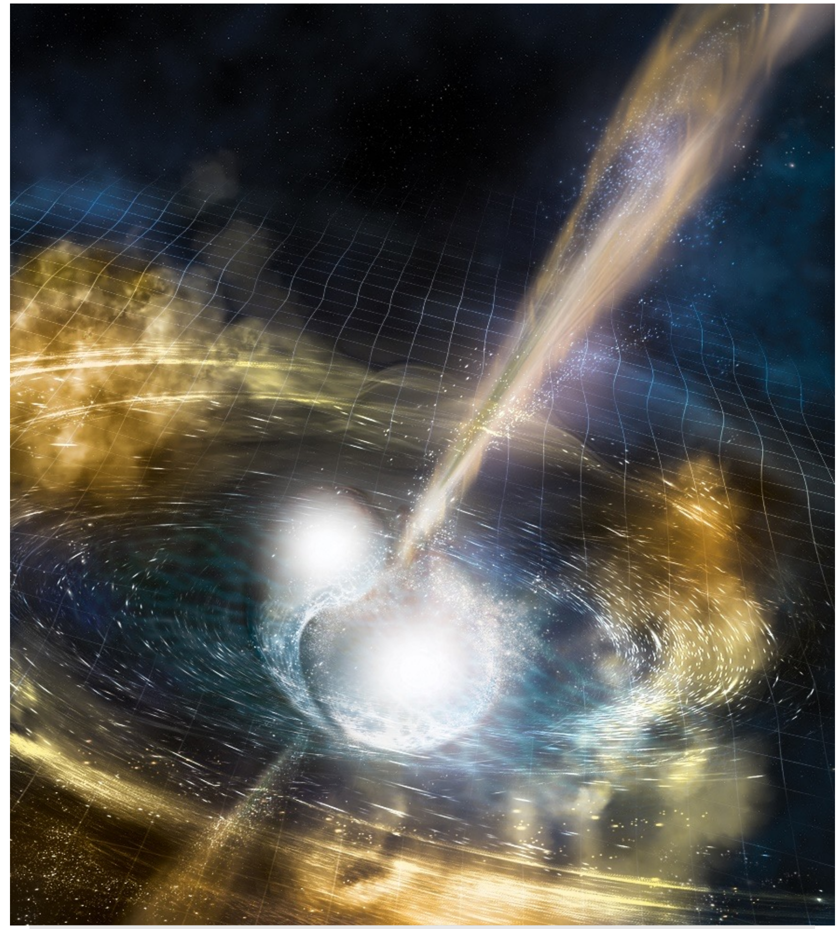




http://www.astro.umd.edu/~miller/nstar.html

As the stars spiral together, they get torn apart by each other's gravity: Tidal distortion → Disruption!

The disruption of the stars results in a huge outflow of neutron-rich "dynamical ejecta" that powers a GRB and broad-band afterglow

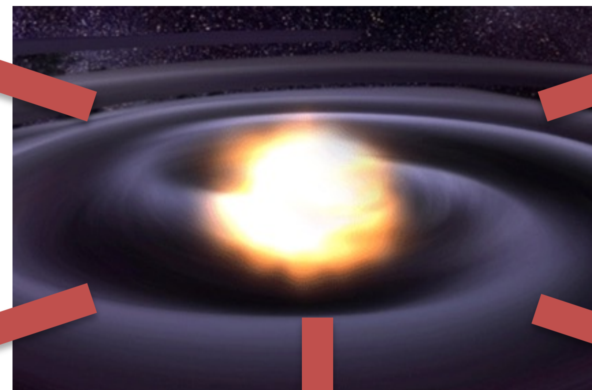


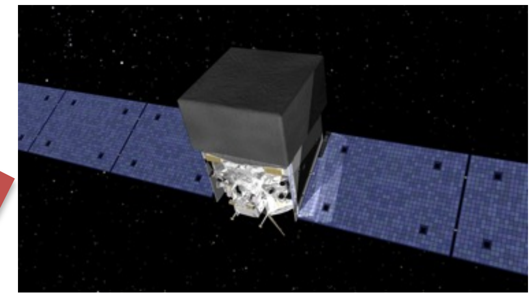
NSF/LIGO/Sonoma State University/A. Simonnet

Multi-messenger Astronomy with Gravitational Waves

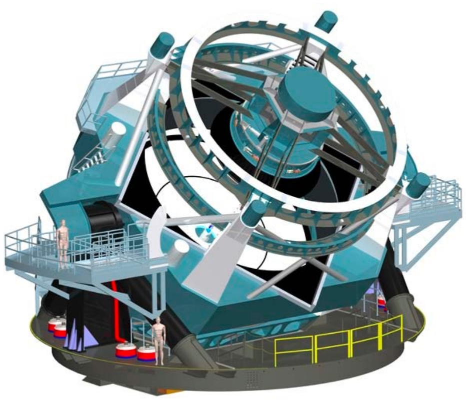
GWs

astrophysical fireball





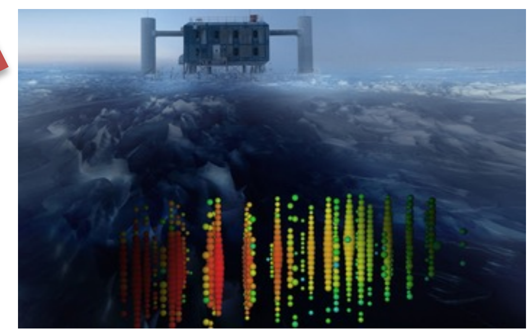
X-rays, γ rays



UV,optical,IR

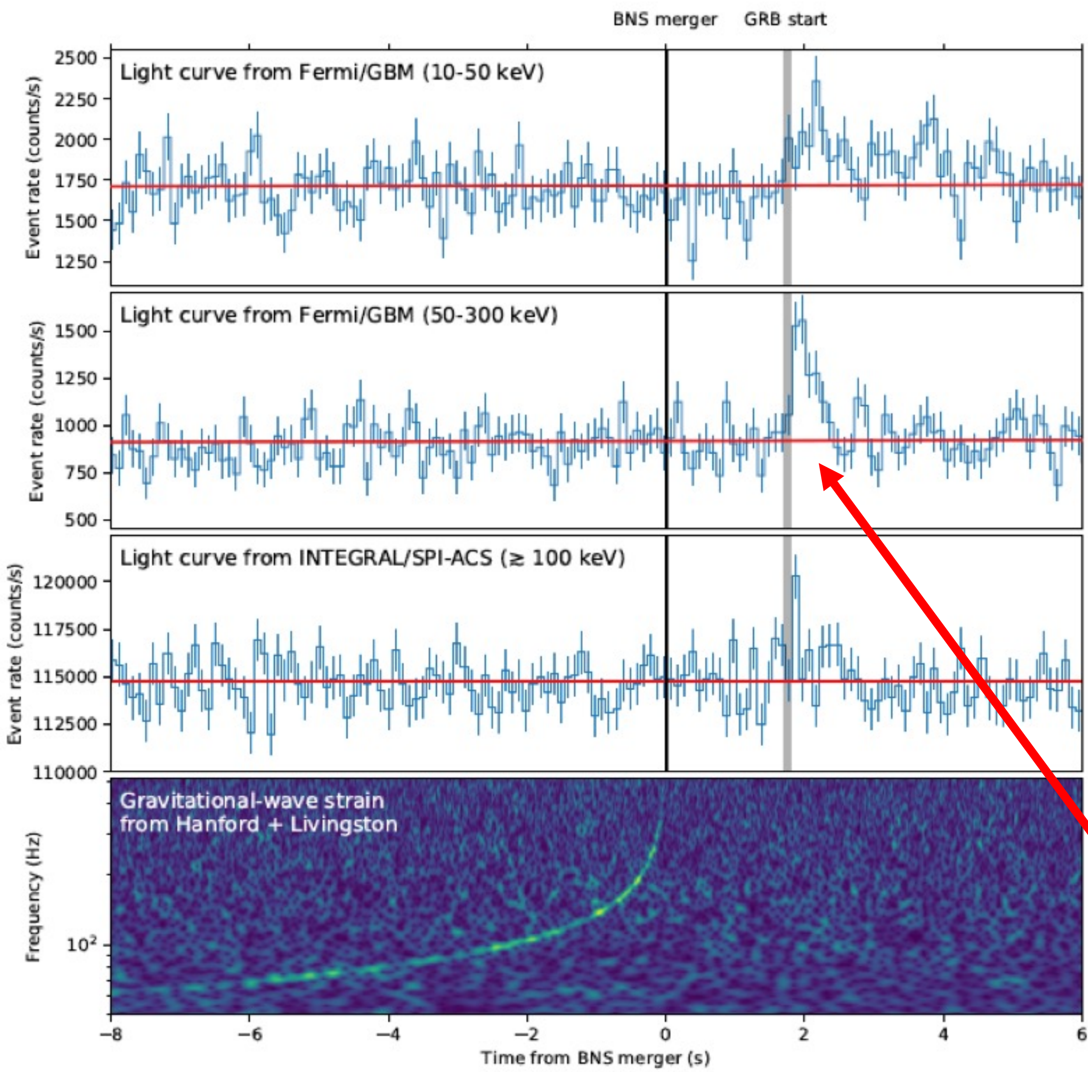
Vera C. Rubin
Observatory (LSST)

radio



neutrinos

To add to the excitement: a gamma-ray burst (GRB)!



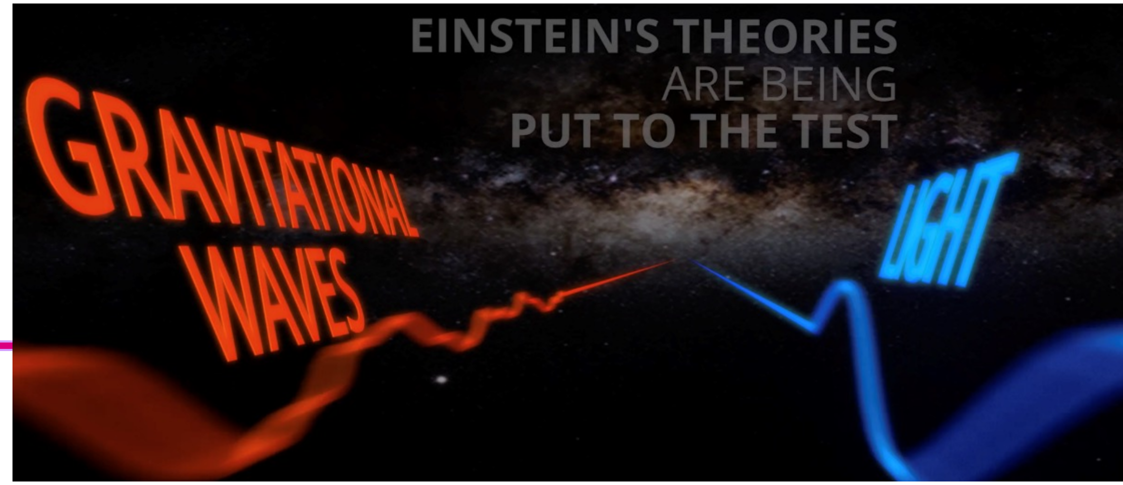
1.7 seconds later, duration < 2 seconds

It has long been theorized that sGRBs come from binary neutron star mergers, and a ~2 s delay fits typical models…

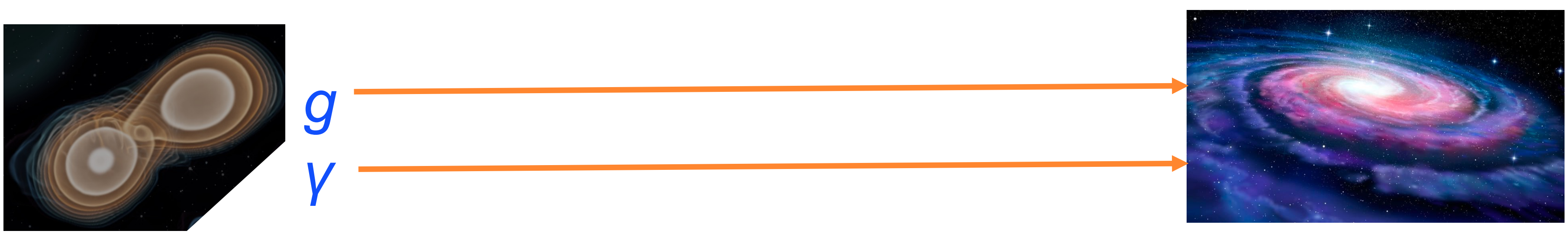
kinda wimpy, though…

B. Abbott et al, LIGO-Virgo, Astroph.J.Lett. 848, 2, L13 (2017)

For the physicists: Fundamental properties of GWs and NSs



- The GW signal is ***fully consistent with General Relativity, over thousands of cycles***.
- ***GW polarization is consistent with "tensorial"*** – (+ and ×), not (pure) vector or scalar.
- Tidal disruption is weak: nuclear EOS is not stiff, NS radius < 14 km
- GWs, and γ-rays travelled for 130 million years (4×10^{15} s), arrived within 2 seconds of each other:
- The ***"speed of gravity"*** : $V_{GW} = V_{light}$ to one part in 10^{15} !
- ***No dispersion: mass of the graviton*** $m_g <$ (few) $\times 10^{-23}$ eV/c^2 , ***consistent with 0***.
- Improved Lorentz invariance violation limits; constrained to one part in 10^{13}.
- Both the gravitons and the photons "fell" into the Milky Way Galaxy over the same time: ***the Equivalence Principle holds between*** gravitons and photons ***.***

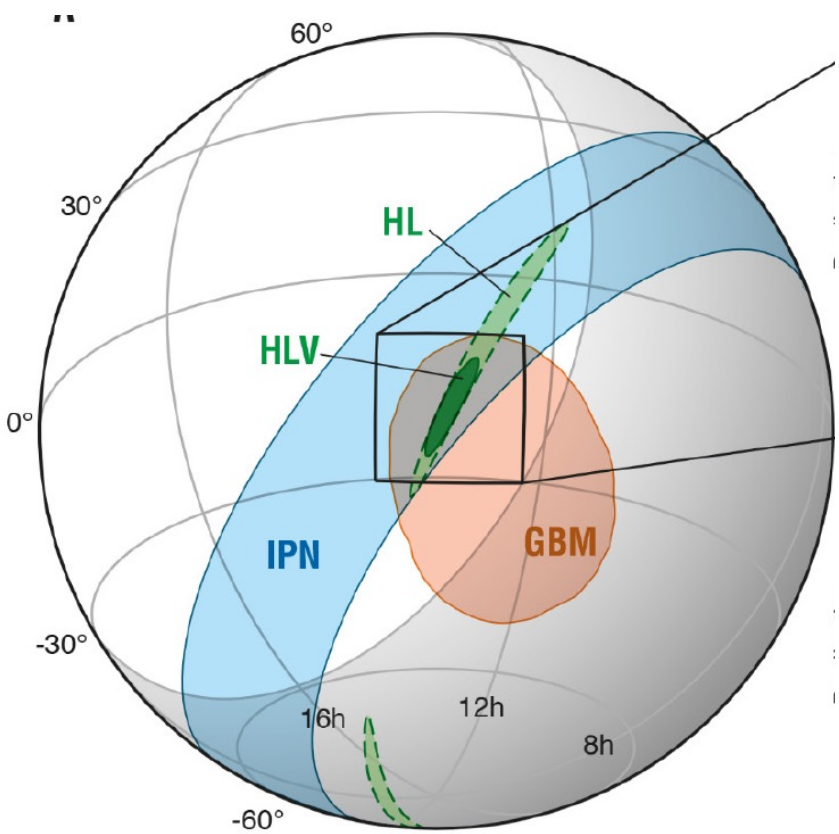


For the astronomers: within minutes, locate the source on the sky, tell telescopes where to point.

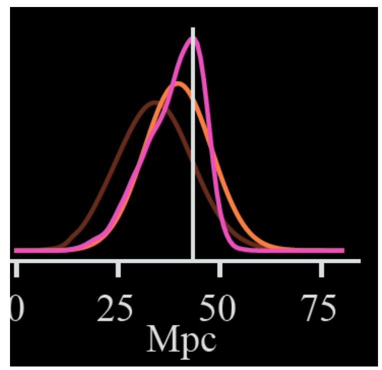
Source located to 28 sq deg, and ~ 40 Mpc.

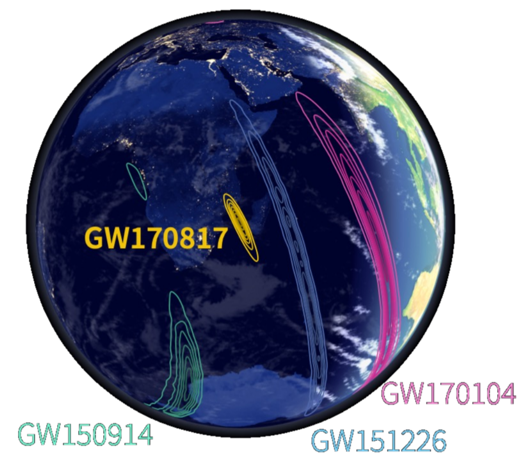
Time is of the essence!

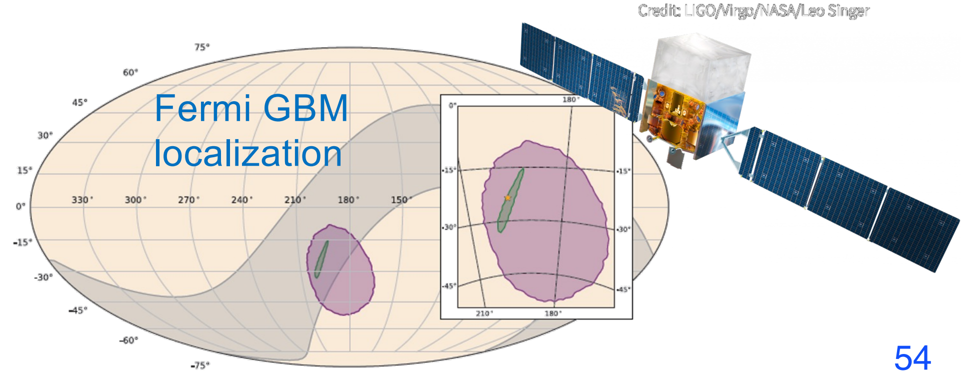
(Initial alert sent out *27 minutes* after the GWs passed through LIGO)



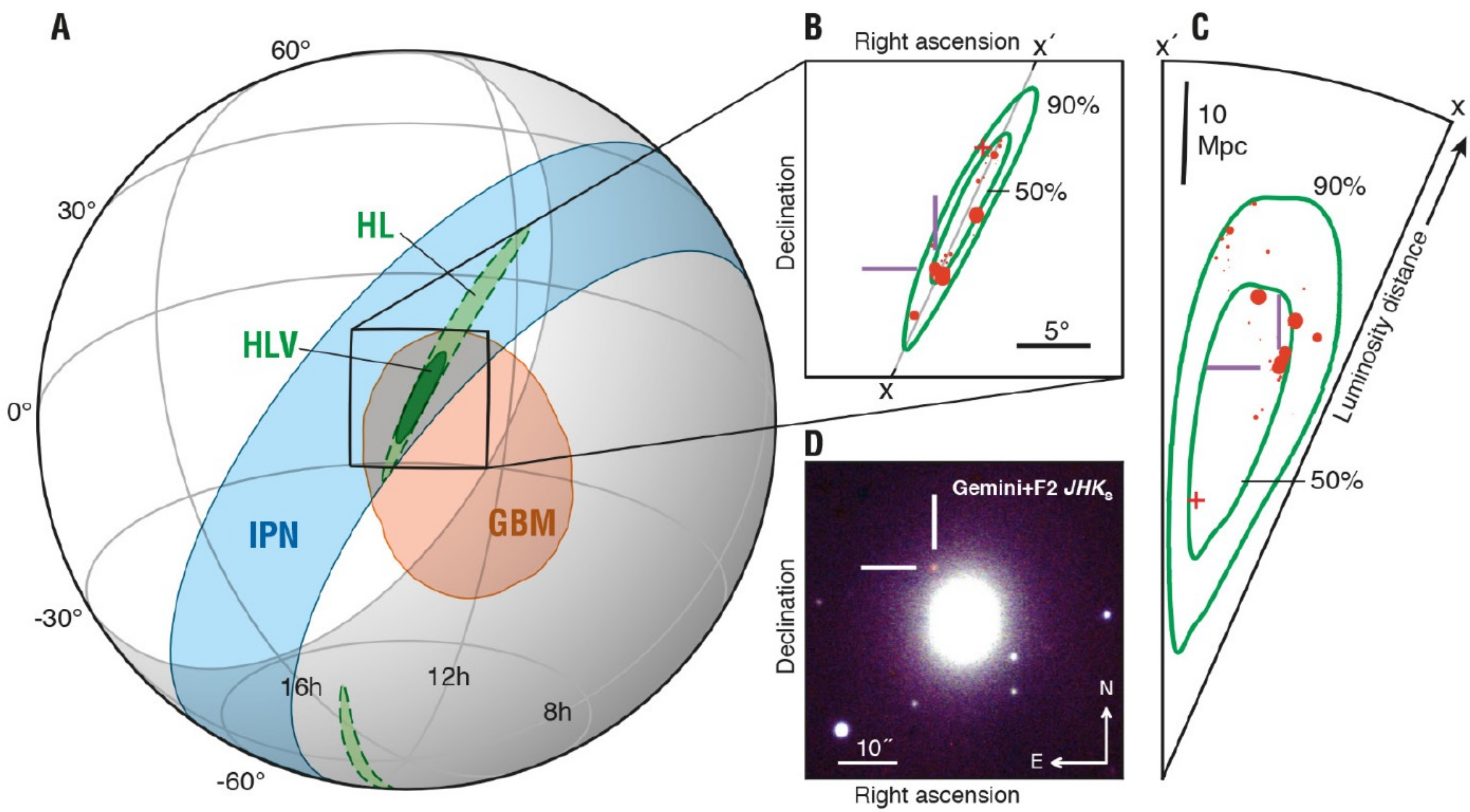
We can locate the source in 3D – GWs are "standard sirens"





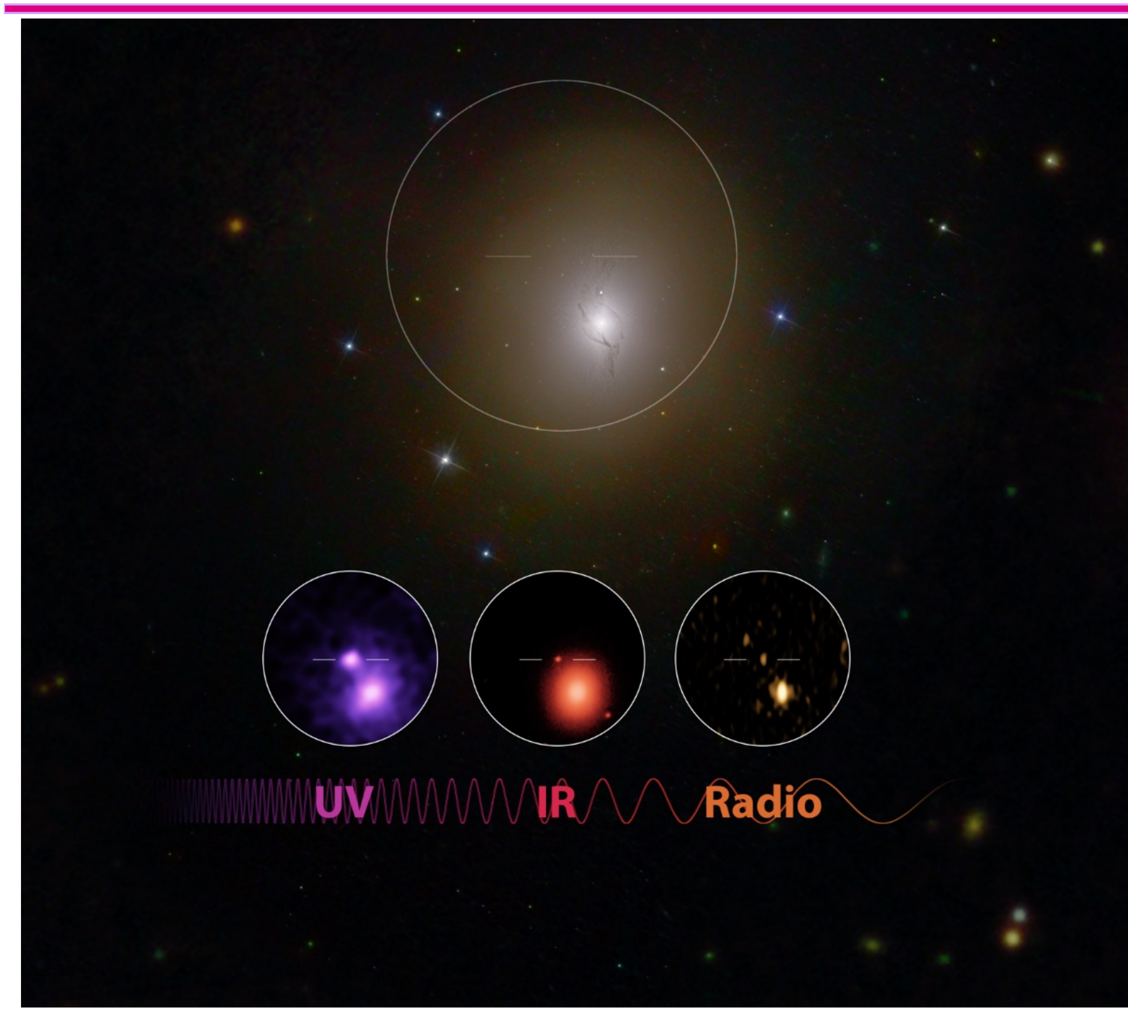


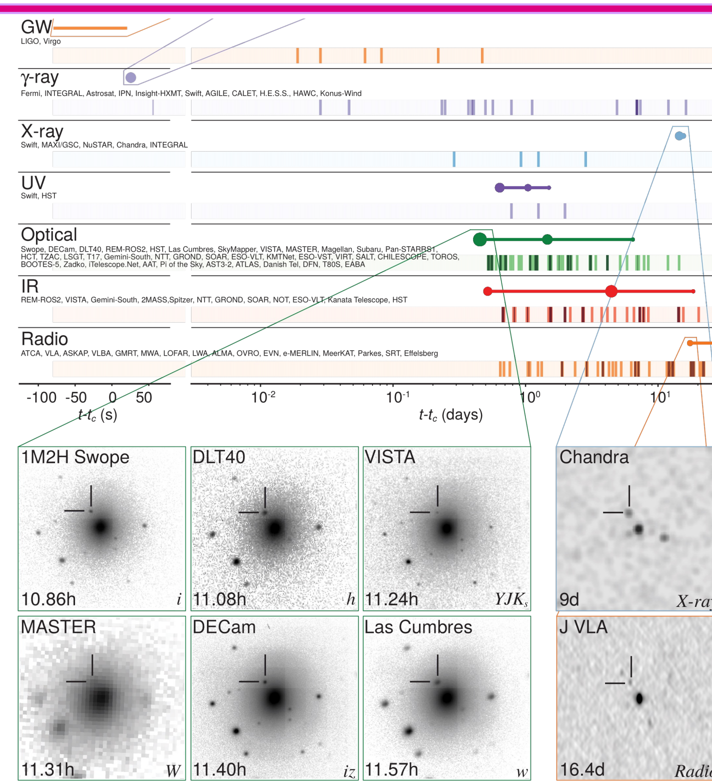
The next evening: they got it!

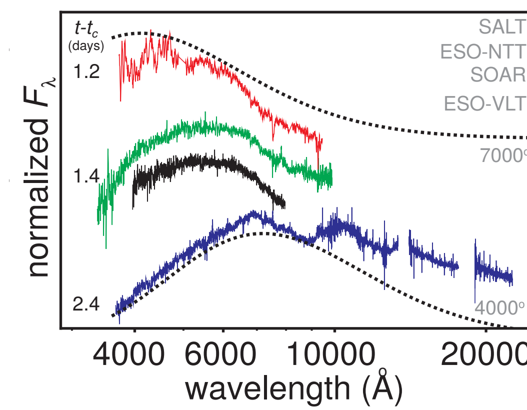


M. M. Kasliwal *et al*., *Science* 10.1126/science.aap9455 (2017).

Light at Every Wavelength

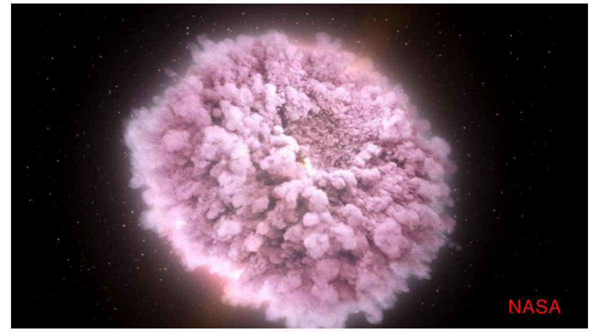


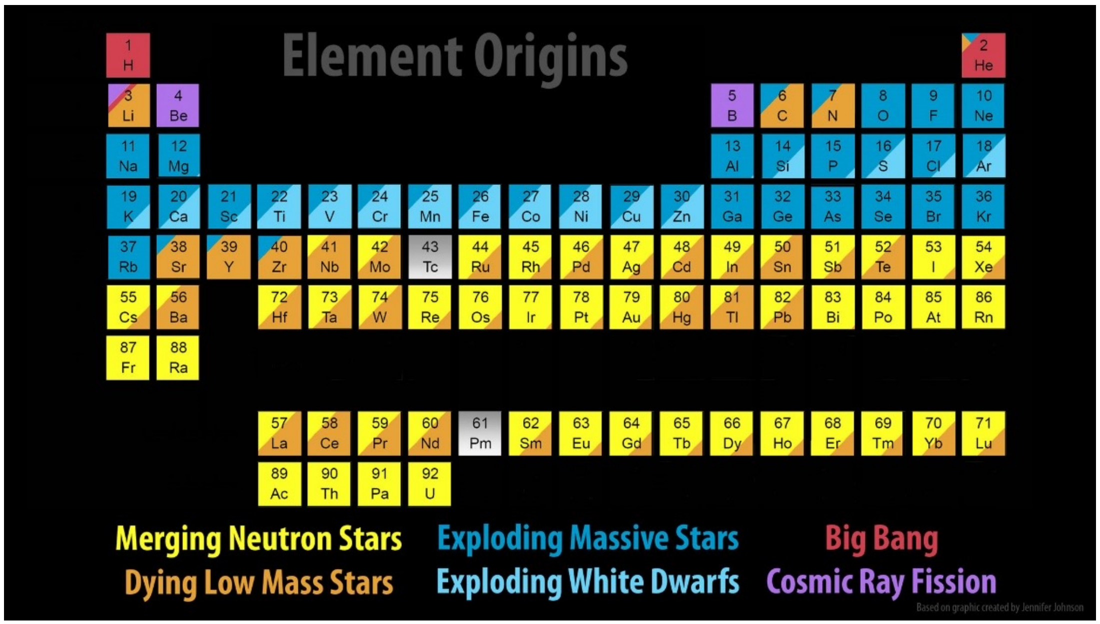


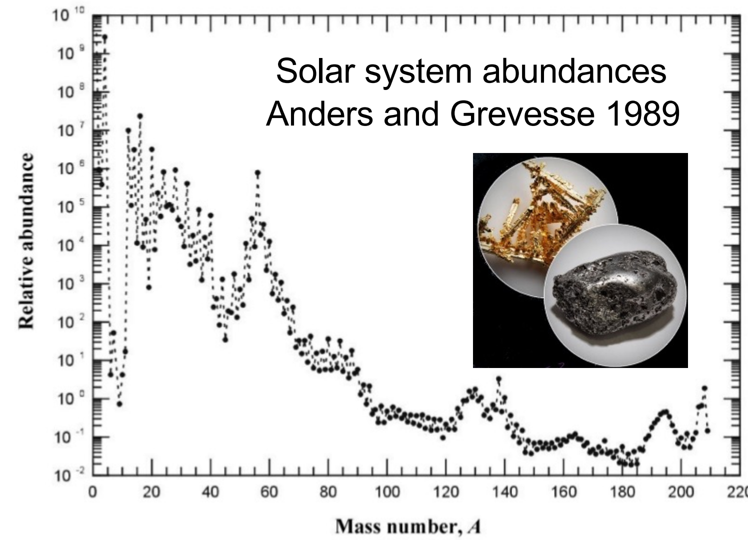


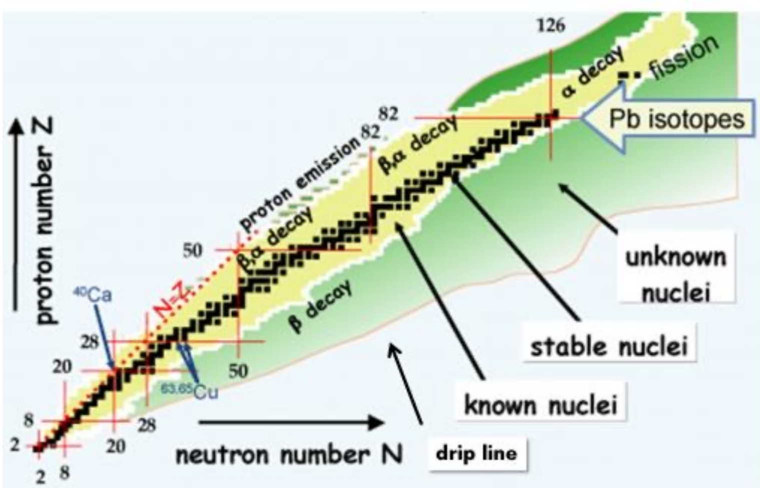
Host galaxy: NGC 4993; redshift: ~ 0.01

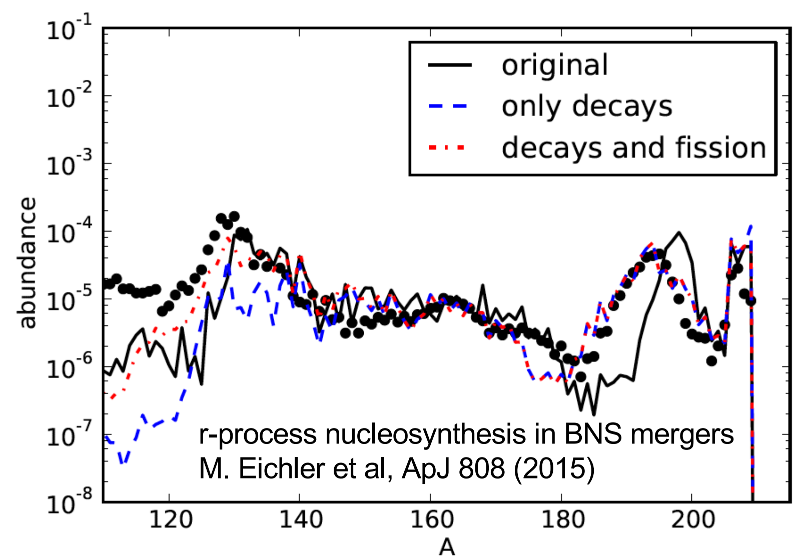
The origin of the (heavy) elements









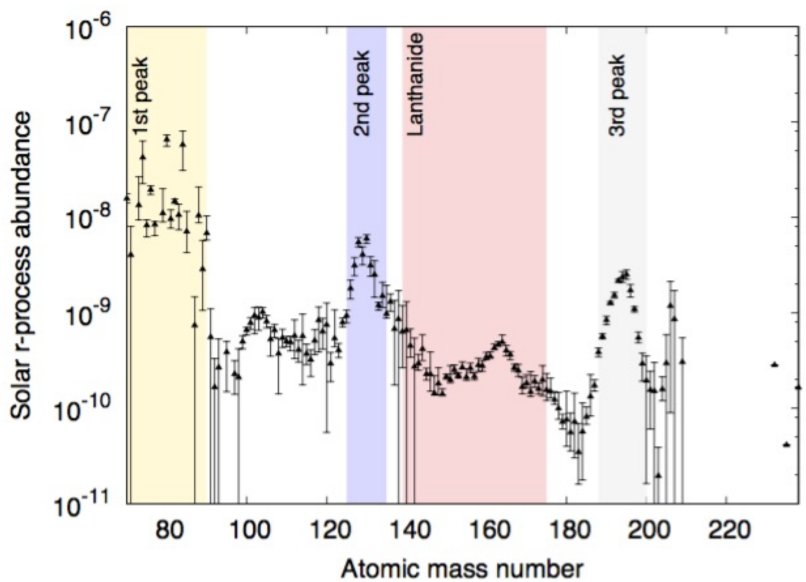


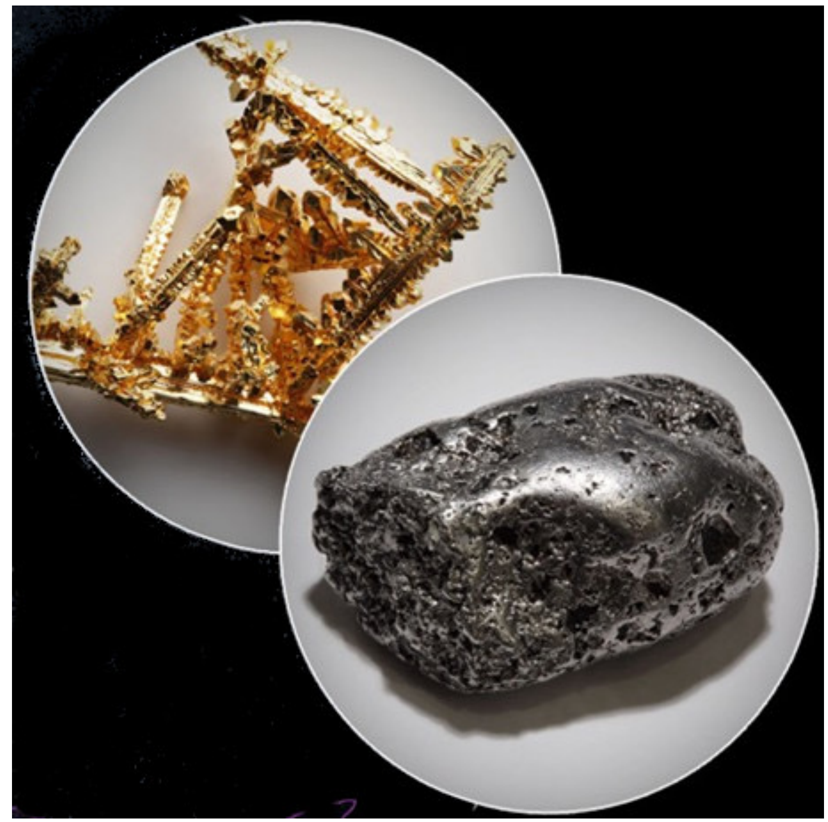
Not just a site, but *the* site of heavy element production?

Observed Solar Abundance

= Quantity per merger x Rate of Mergers

>~0.05 solar-mass x >~300/Gpc^3/yr



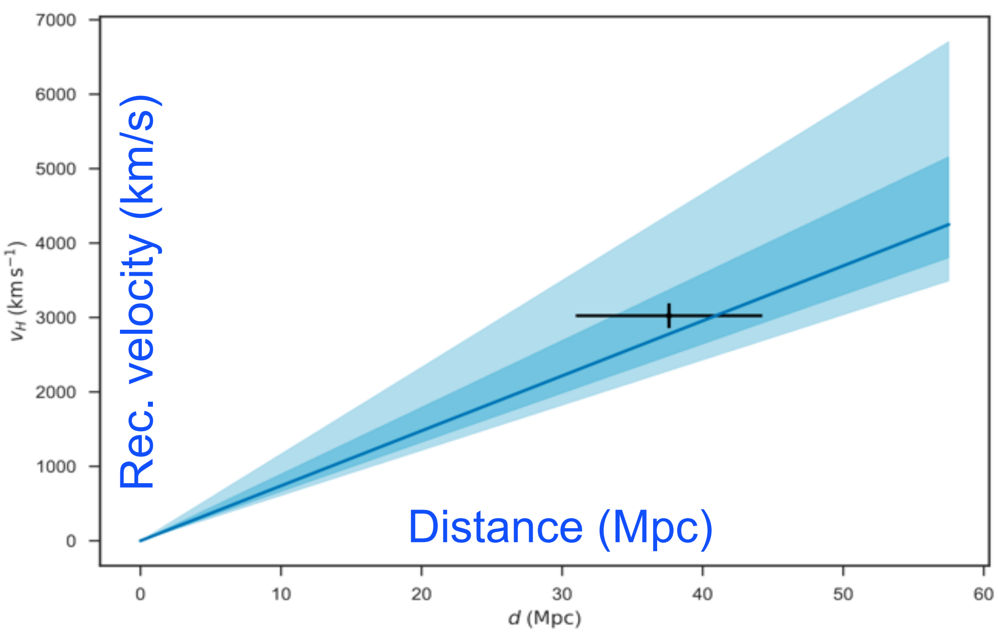


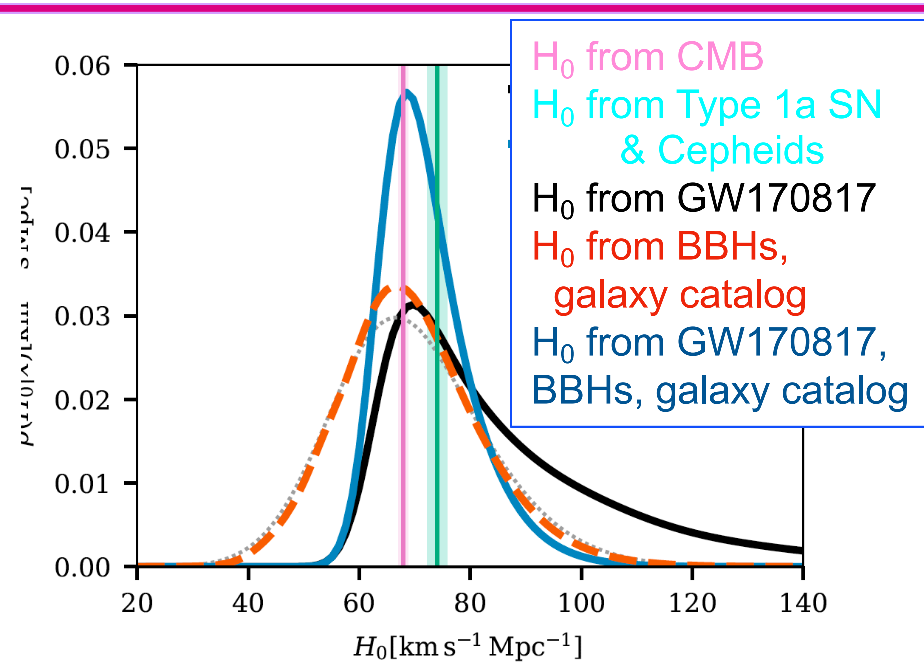
Ejecta mass estimate: ~0.05 solar mass

Merger rate estimate: $R = 1540^{+3200}_{-1220}\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Consistent!

Measuring the expansion rate of the universe in an entirely new way!

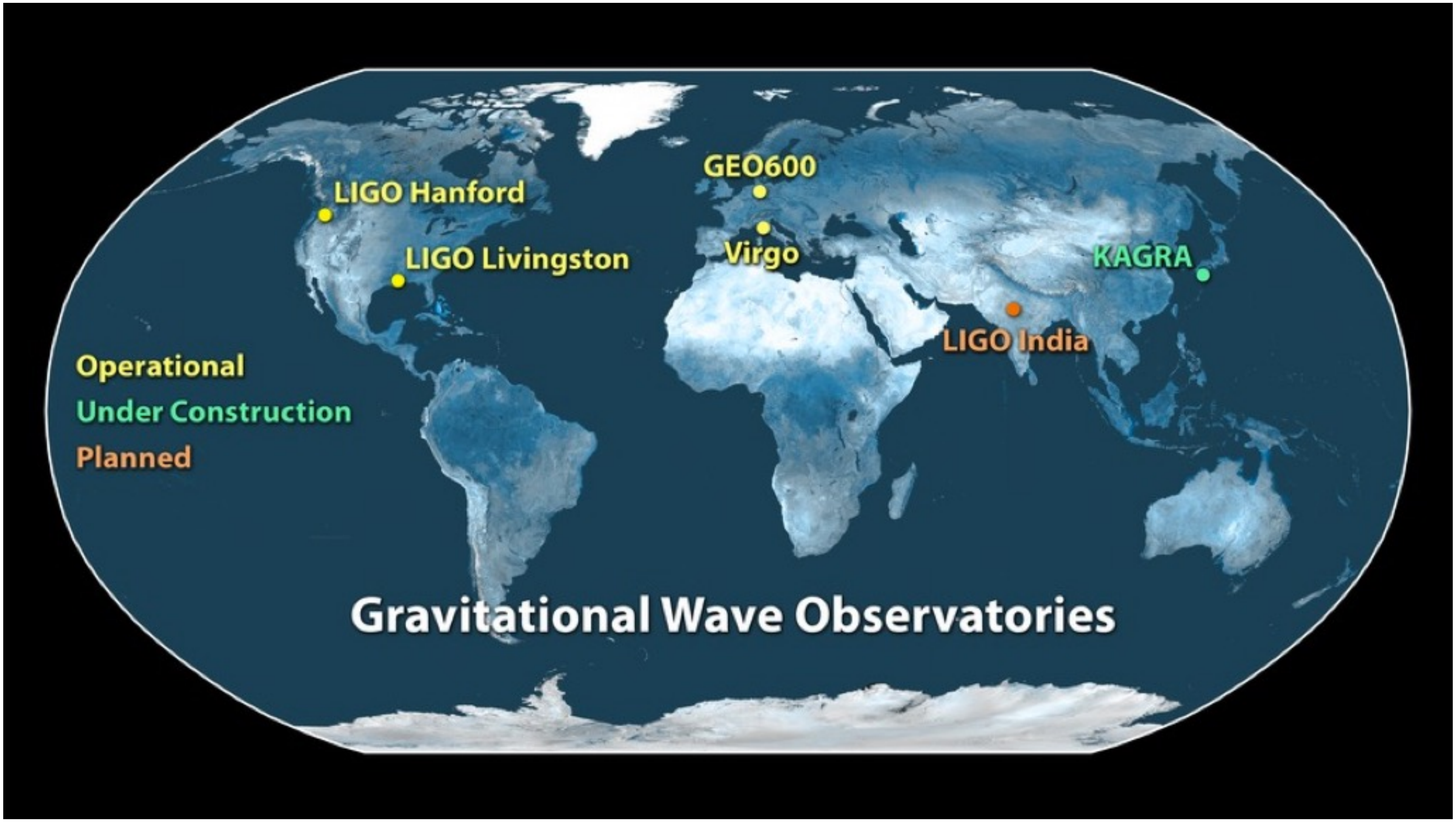




LVK arXiv:2111.03604 (2021)

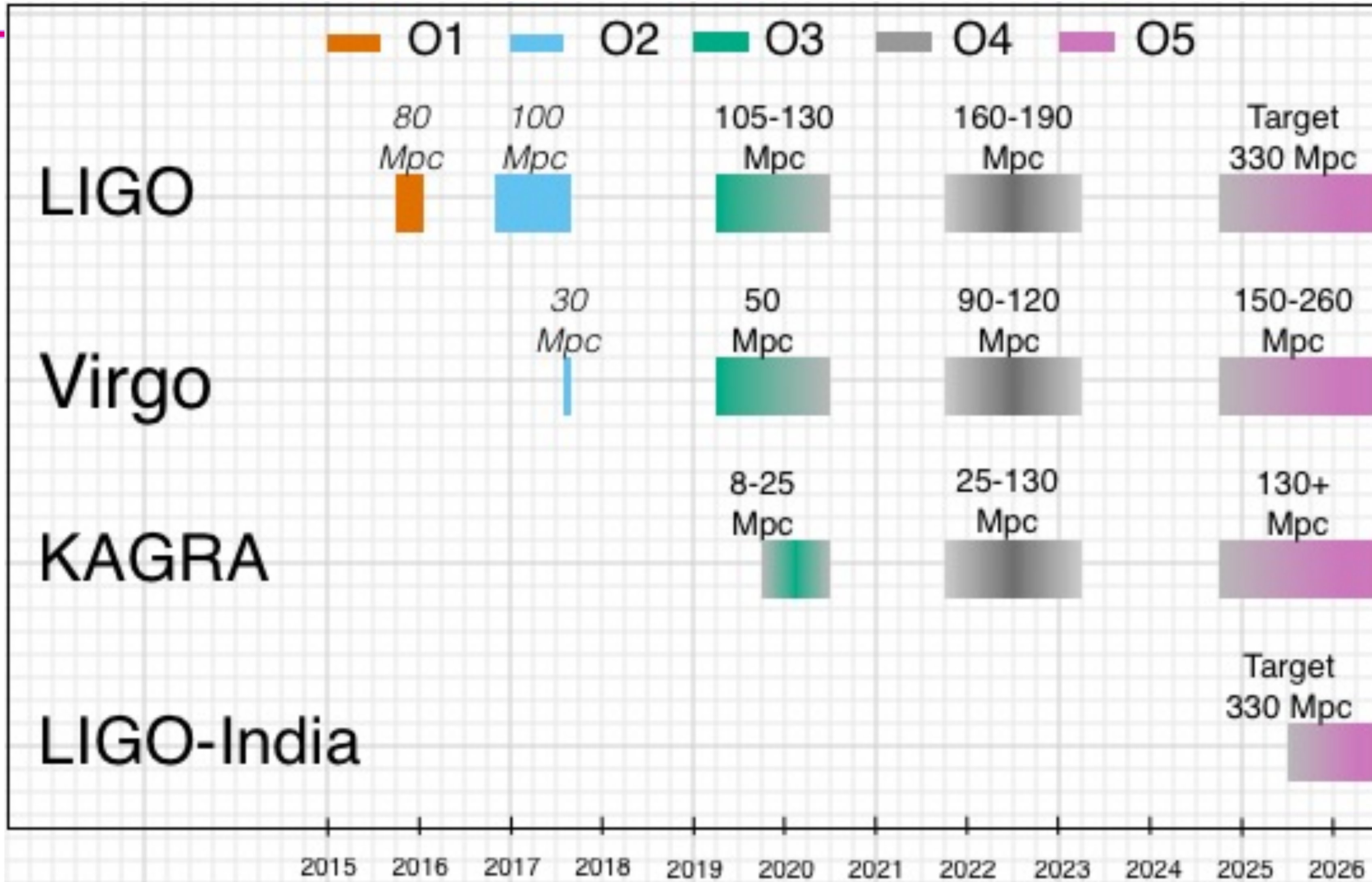
- **From the GWs, we can measure the distance to the source fairly accurately: 40 Mpc or 130 Mly**
- **From the optical afterglow of GW170817 we can measure the redshift (recessional velocity) of the source galaxy NGC4993.**
- **Combining them gives the Hubble expansion rate H_0.**
- **Not terribly accurate yet, but in good agreement with measurements made in entirely different ways (which don't agree with each other!)**

Coming years: more, and more sensitive detectors



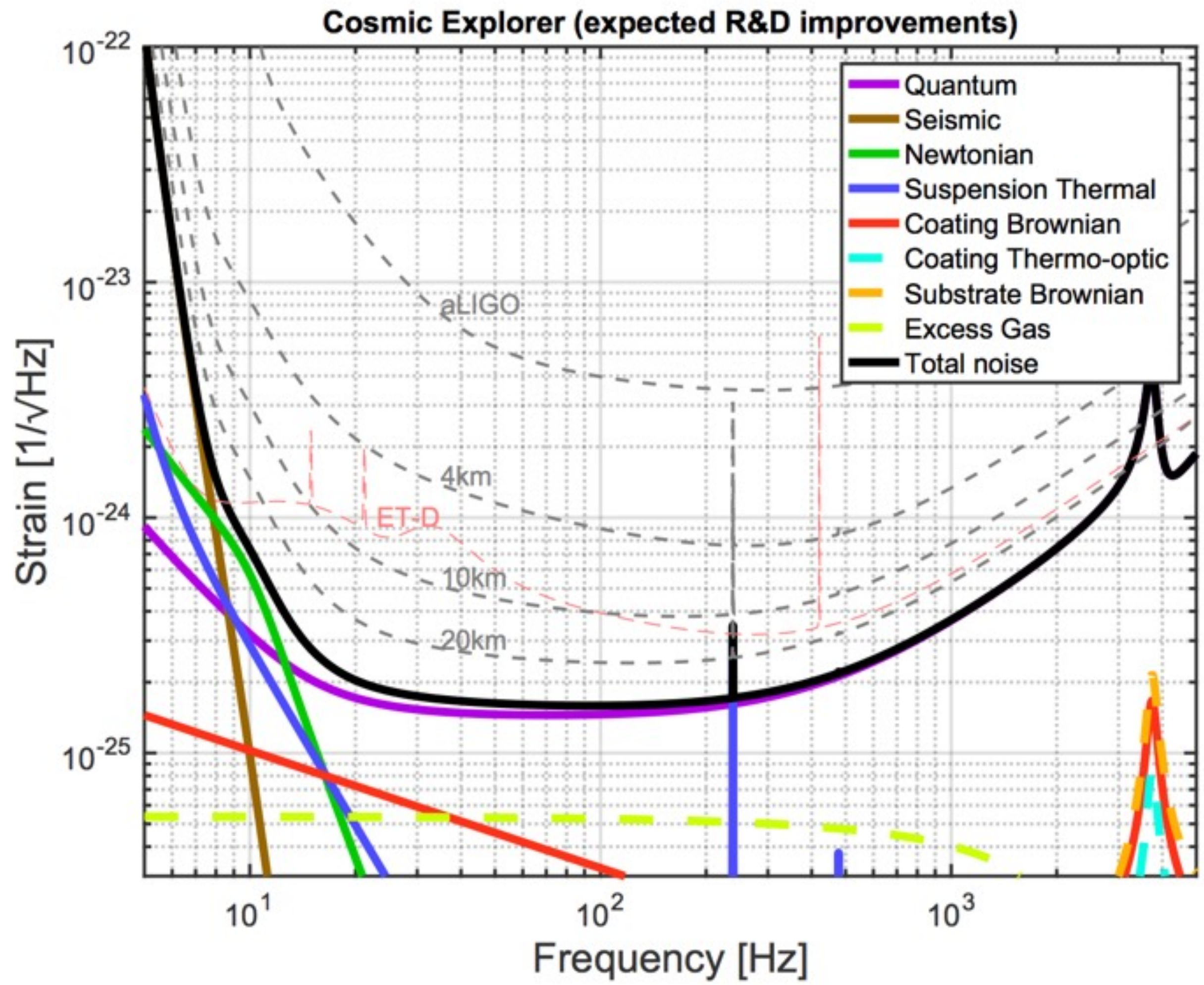
http://ligo.org/detections/GW170817.php

Coming years: more, and more sensitive detectors



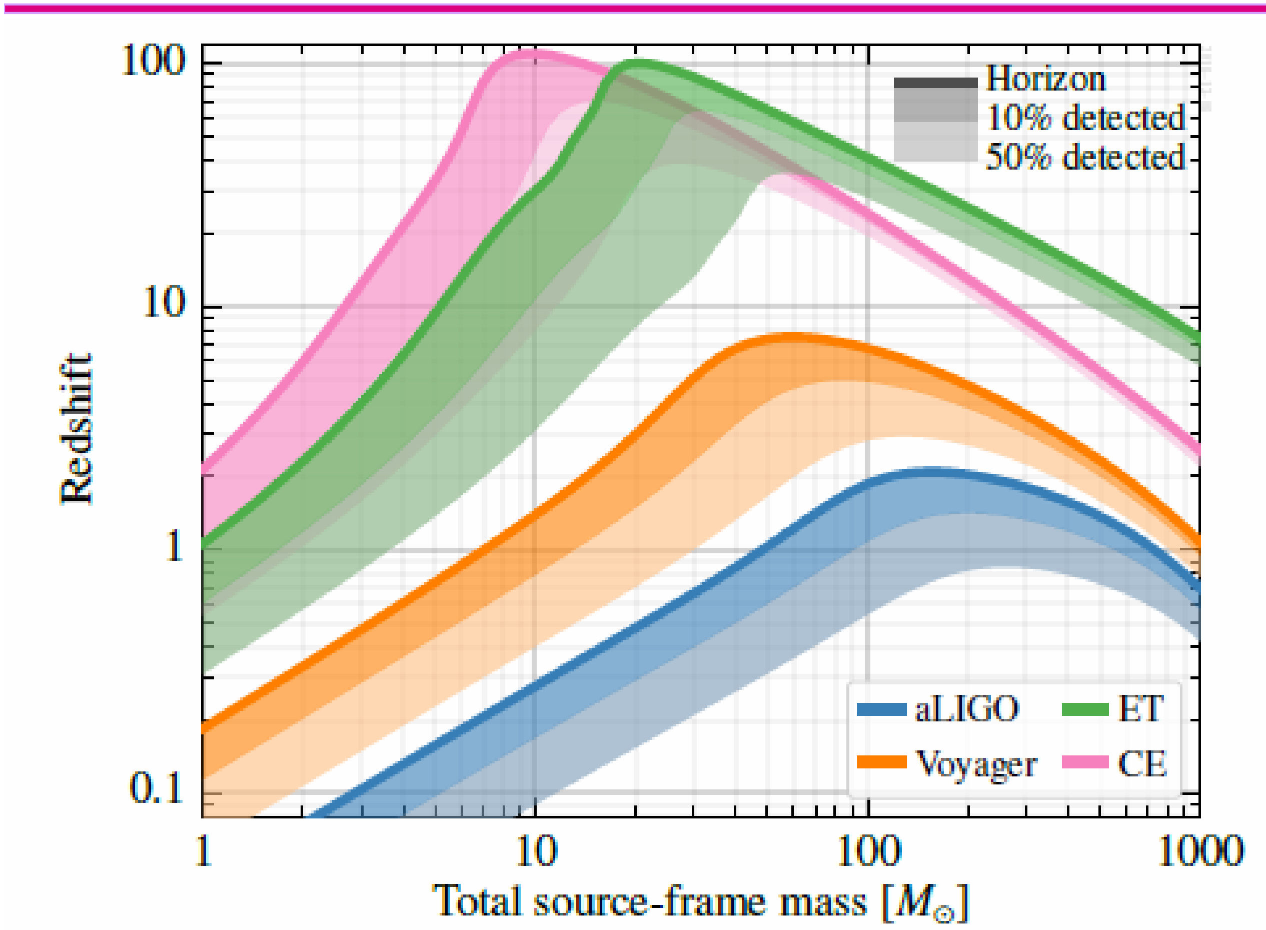
https://dcc.ligo.org/LIGO-P1200087/public - Living Rev Relativ 23, 3 (2020)

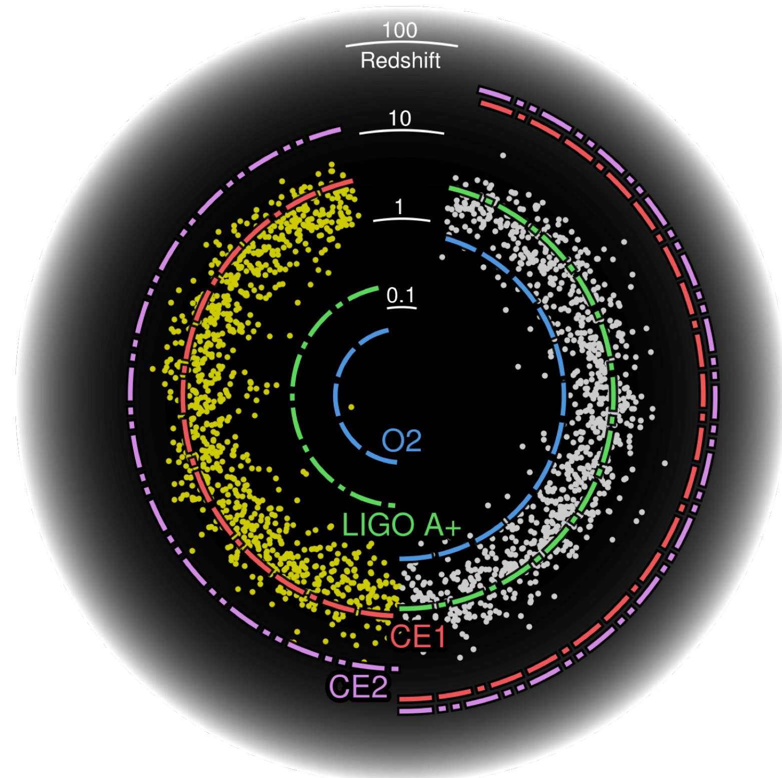
Future prospects for terrestrial gravitational wave astronomy



B. P. Abbott et al. CQG 34 (2017)
http://iopscience.iop.org/article/10.1088/1361-6382/aa51f4

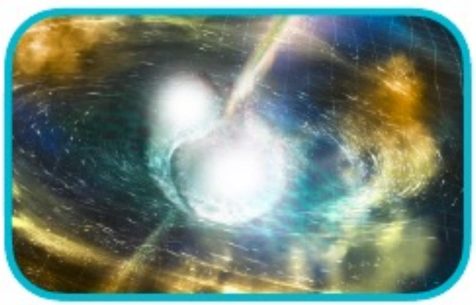
Seeing to the edge of the (astrophysical) universe

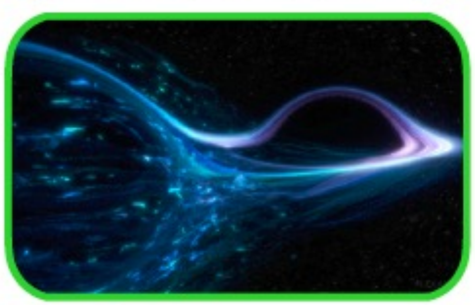


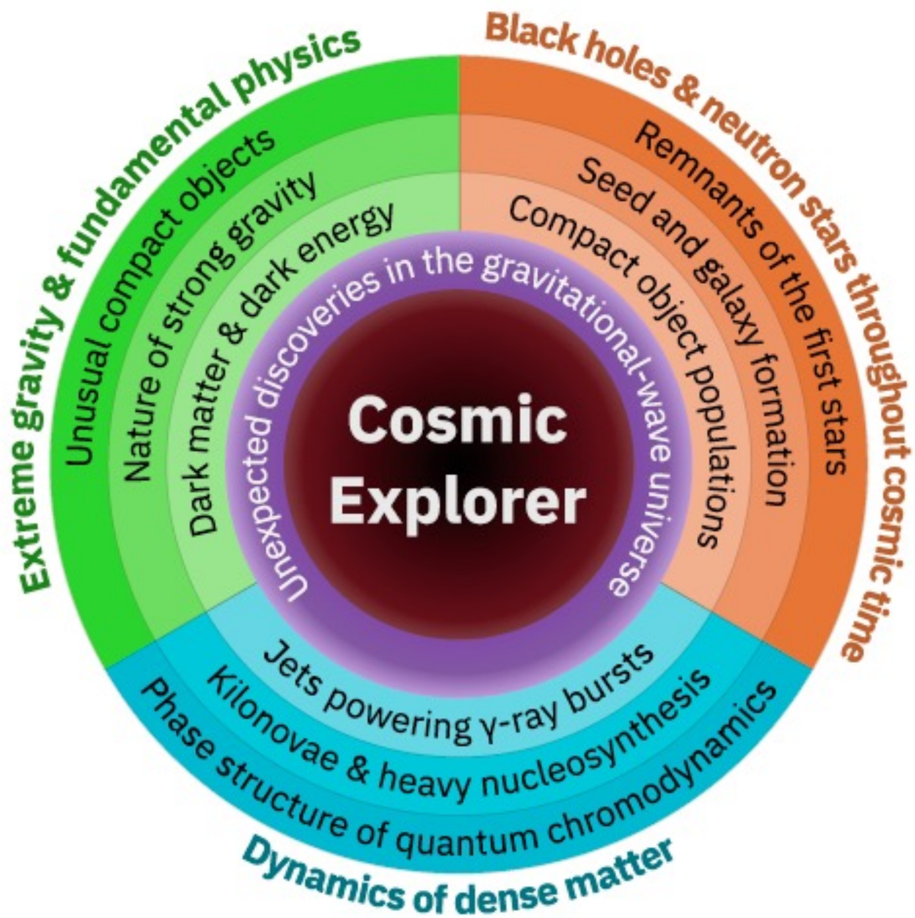


Cosmic Explorer Horizon Study
https://cosmicexplorer.org

Seeing to the edge of the (astrophysical) universe



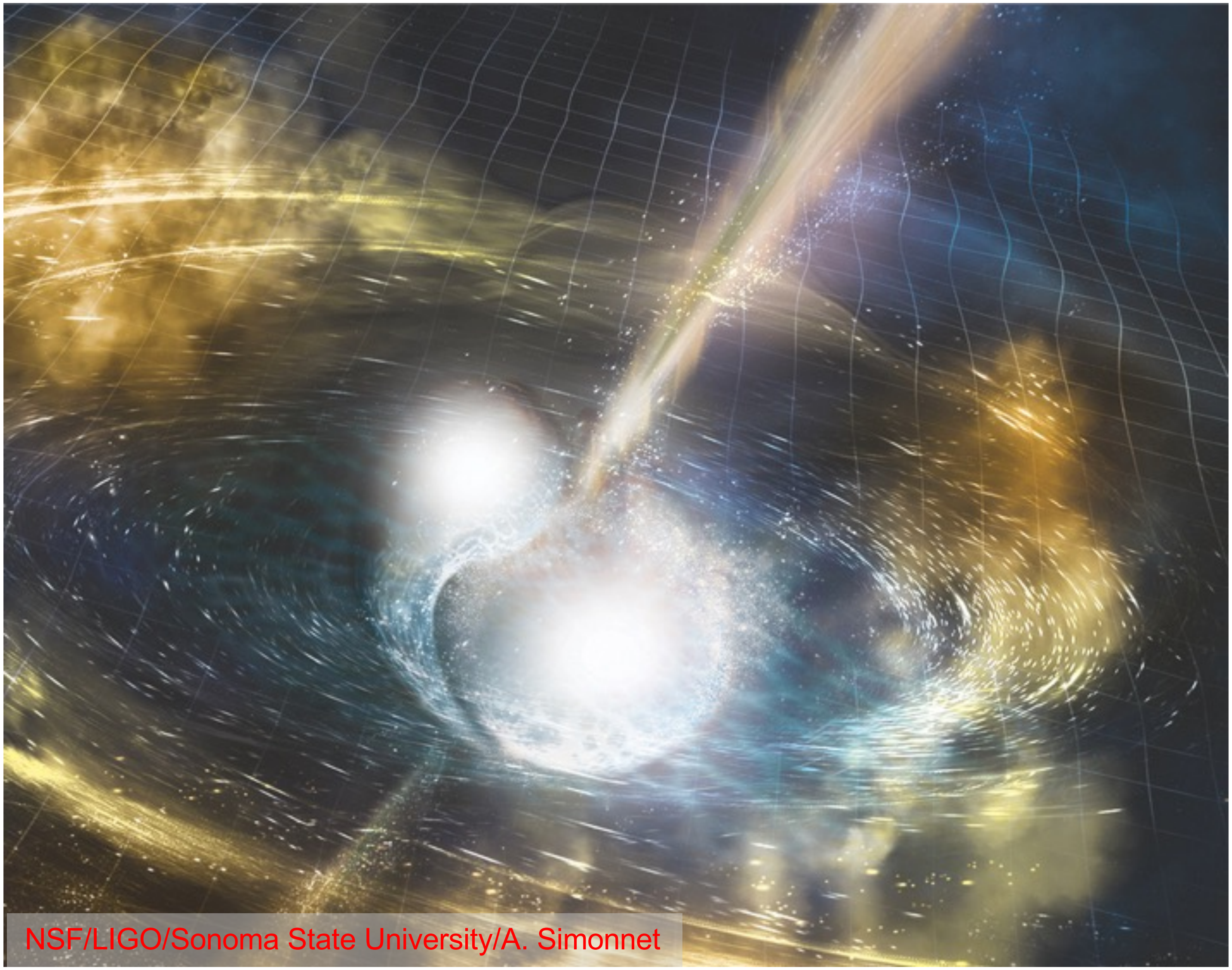




Cosmic Explorer Horizon Study
https://cosmicexplorer.org

Obligatory ending cliché:

The future of gravitational wave astrophysics is … golden!


NSF/LIGO/Sonoma State University/A. Simonnet

THANKS to my LIGO & Virgo collaborators, and to the 100's of EM astronomers who found GRB170817A and EM170817!

Thanks to the NSF!

And…
thank you for your attention!