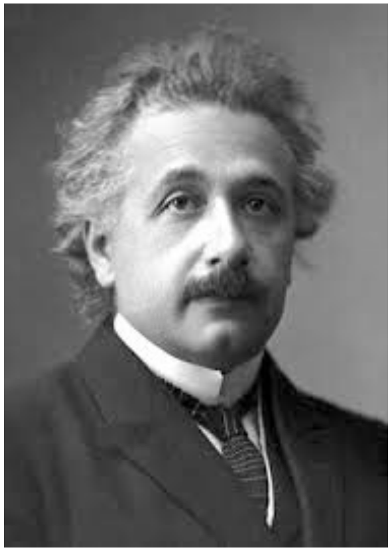
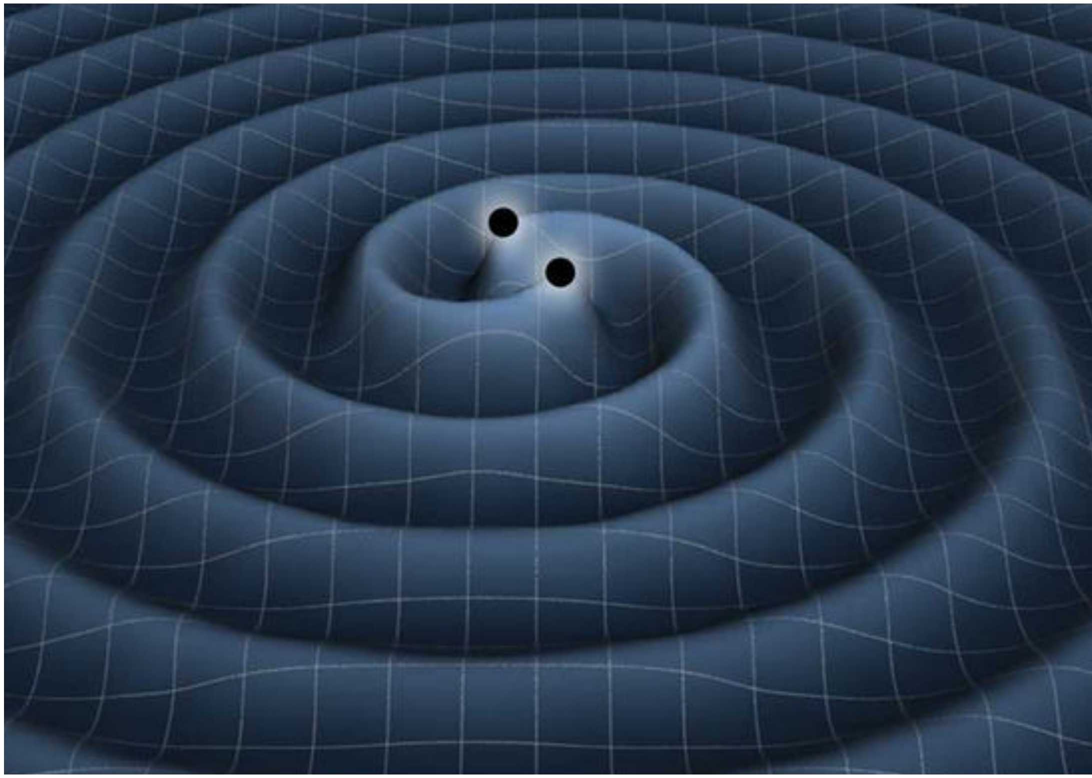
Update on LIGO
and gravitational-wave Astrophysics

Gravitational Waves (GWs)

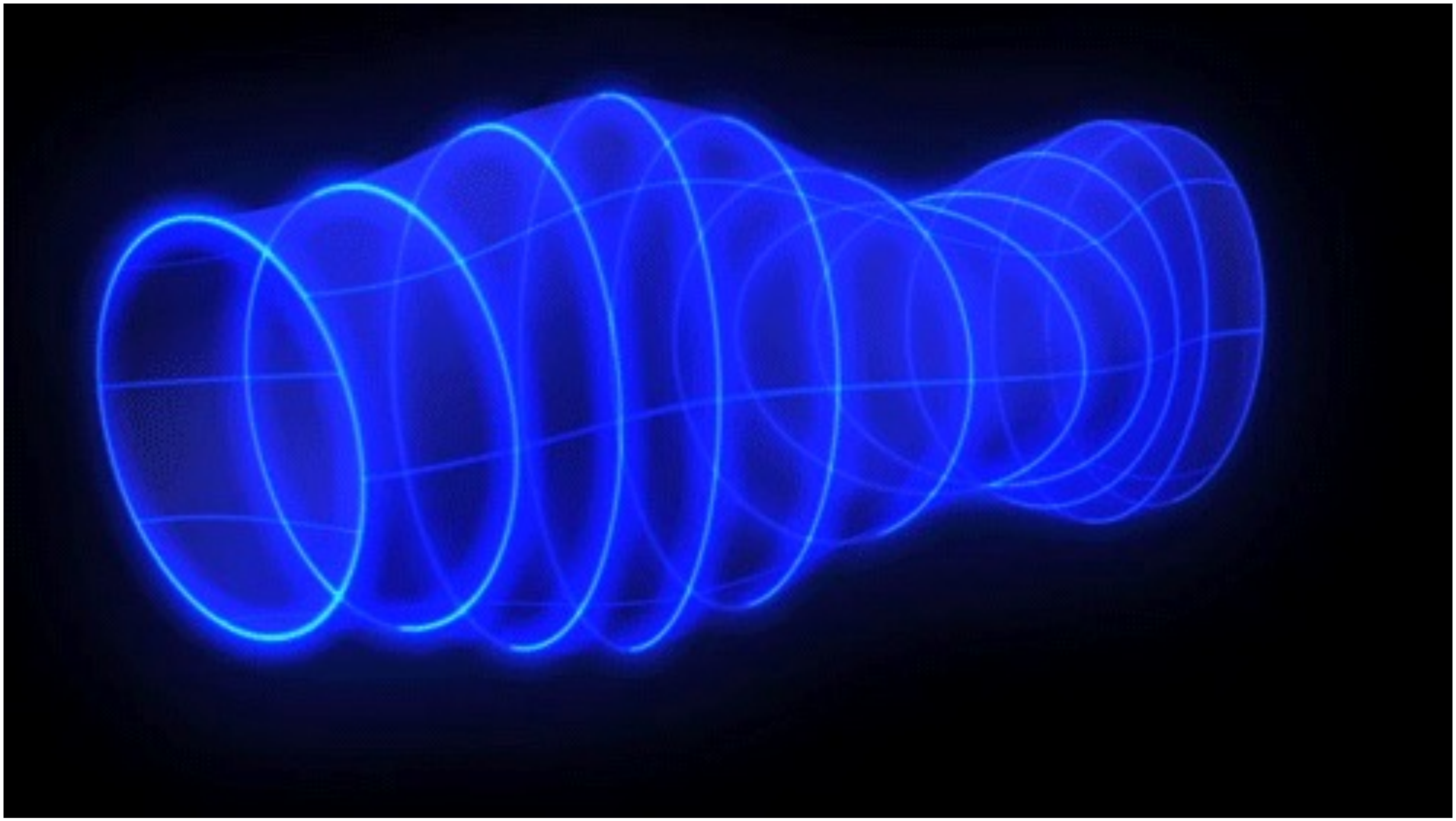
- The waves of the electromagnetic force are realized as (electric and magnetic) fields which propagate through space and time. [Maxwell, 1865]

- General Relativity describes gravity in terms of a spacetime which is deformable. [Einstein, 1915]
- GWs are oscillations of that spacetime. [Einstein, 1916]
- “ripples in spacetime”

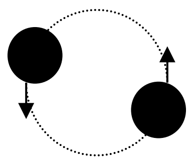


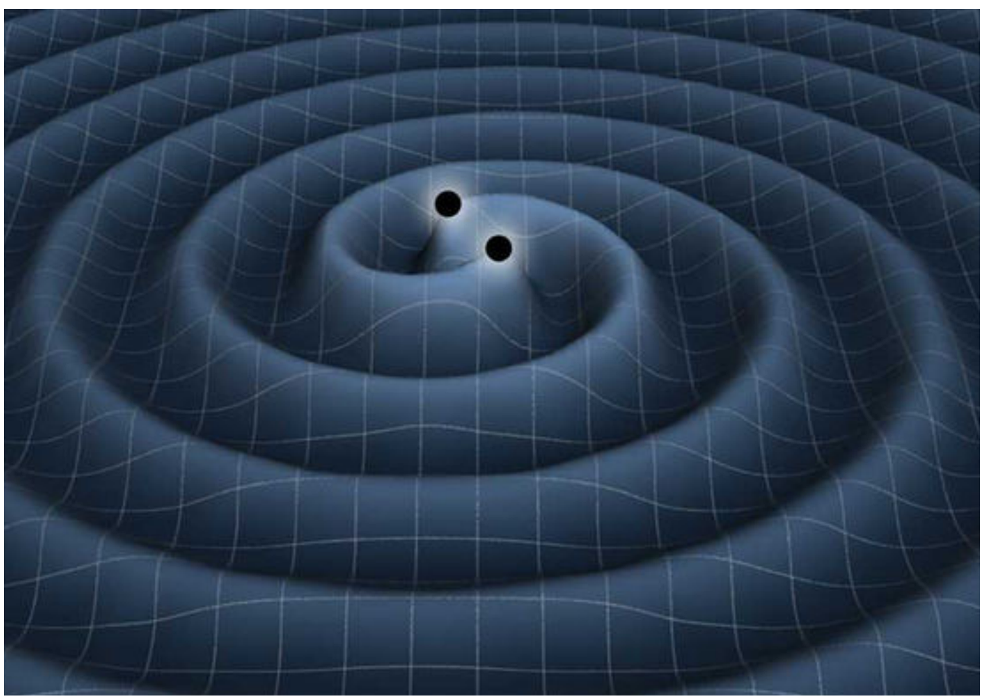
Propagating gravitational wave



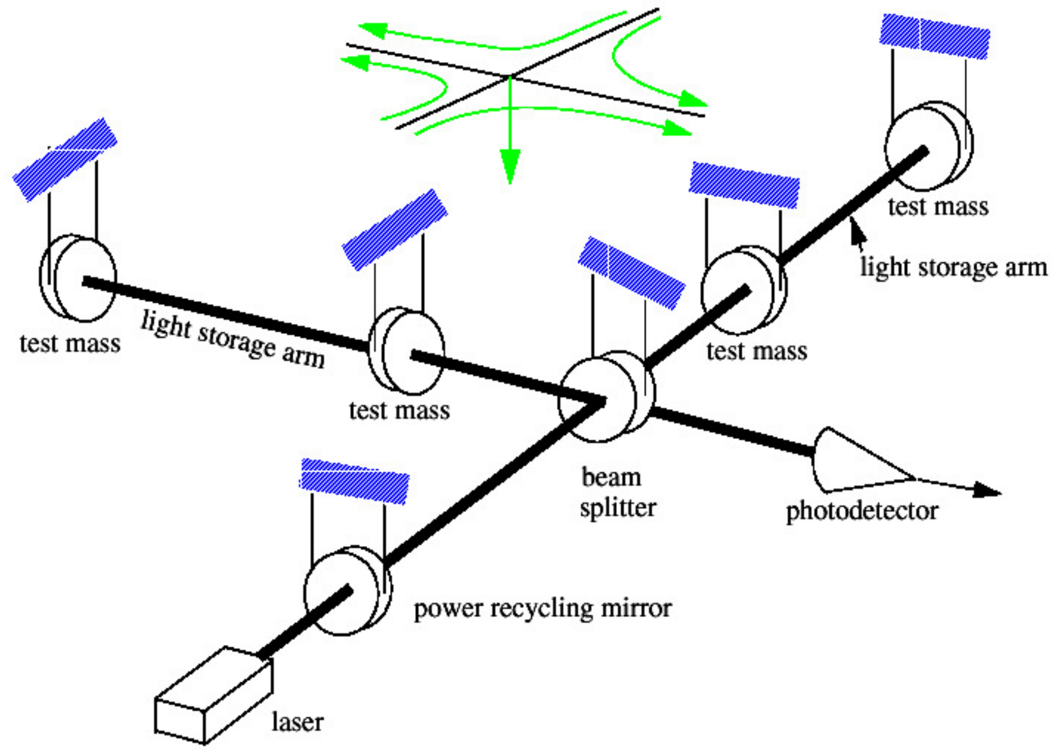
Gravitational waves and LIGO: short version

Binary black hole system





As detected by LIGO:

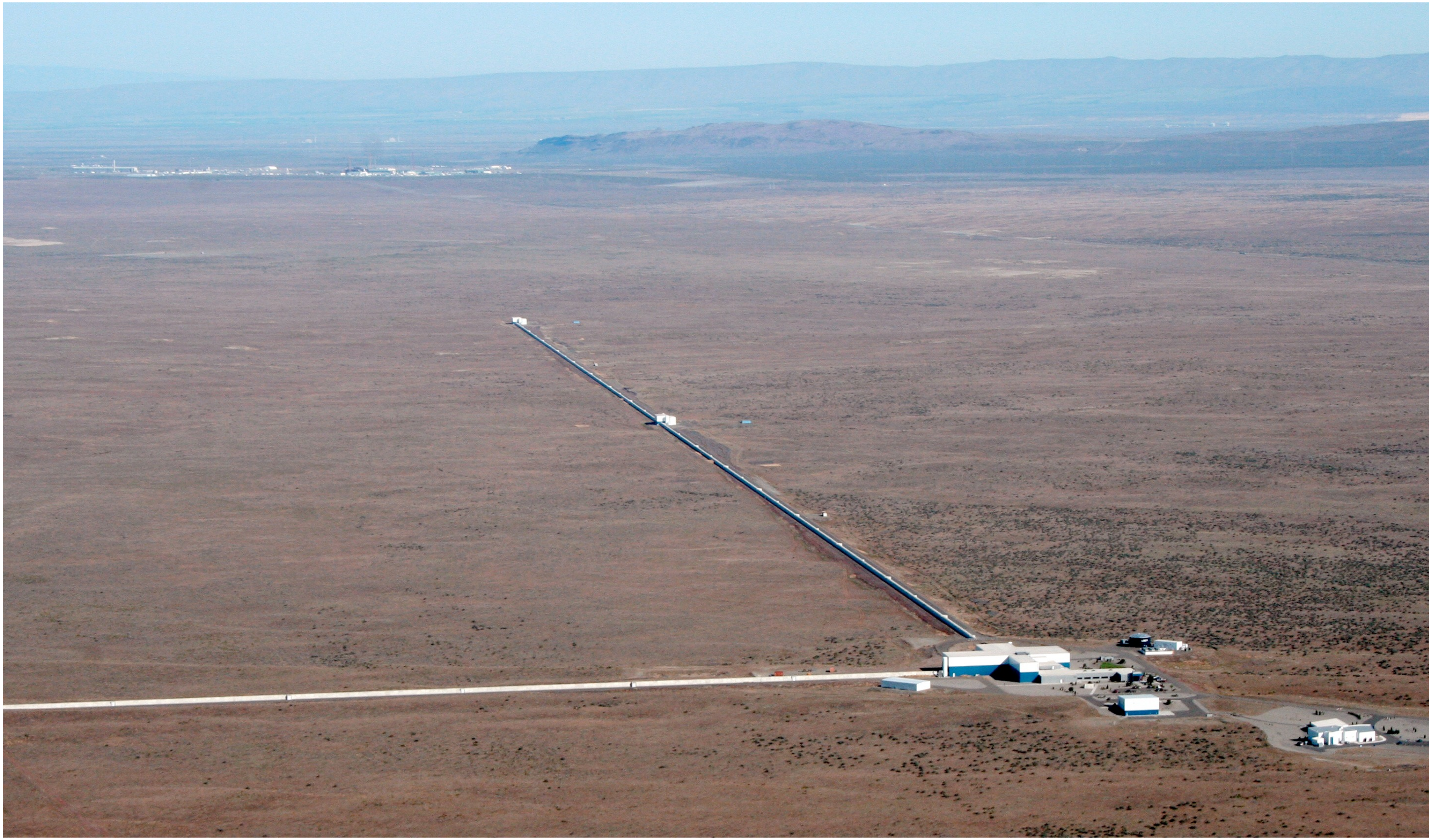


GW ripples manifest as a space strain h, where $h = \Delta L / L$

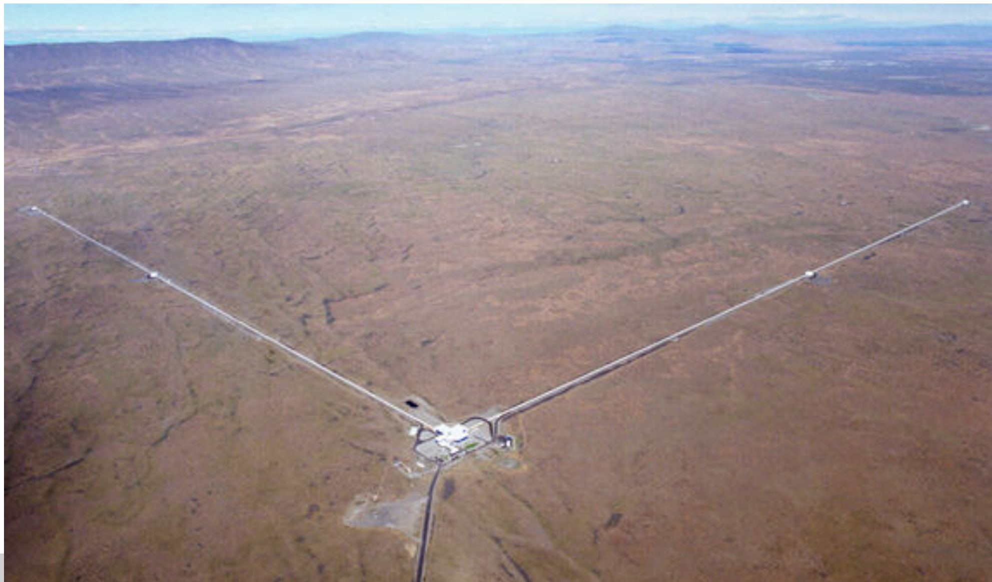
Realistic sources: $h \sim 10^{-23}$

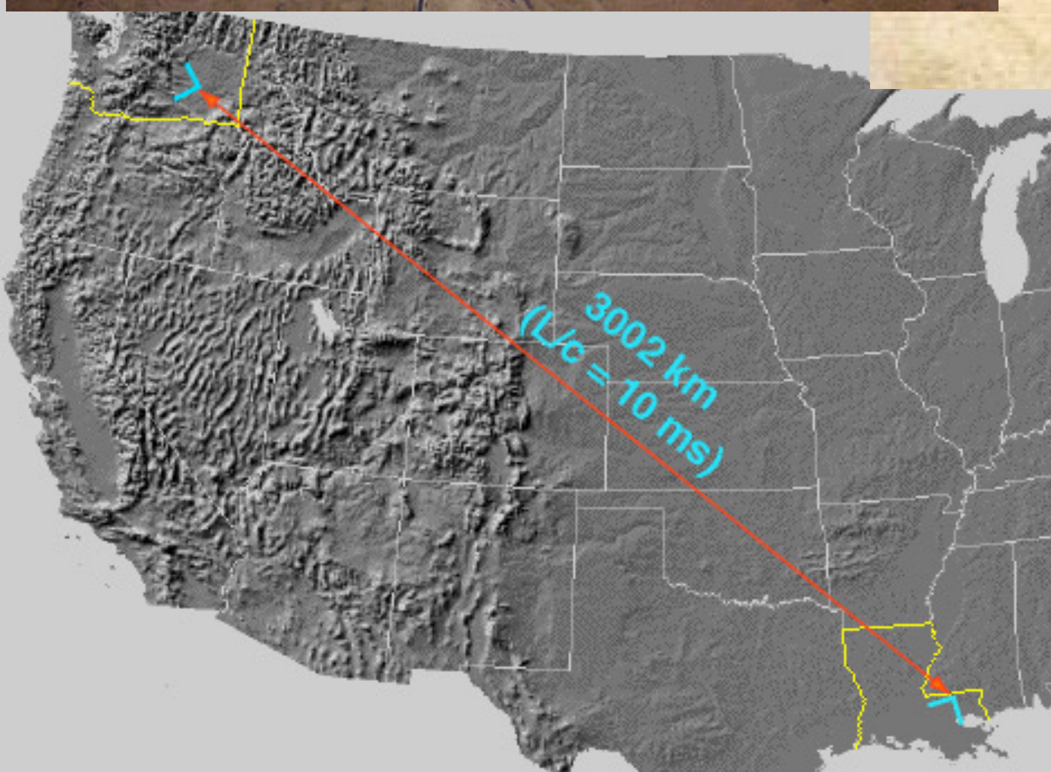
$\Rightarrow \Delta L \sim 10^{-19}$ m (Yikes !)

LIGO Hanford Observatory

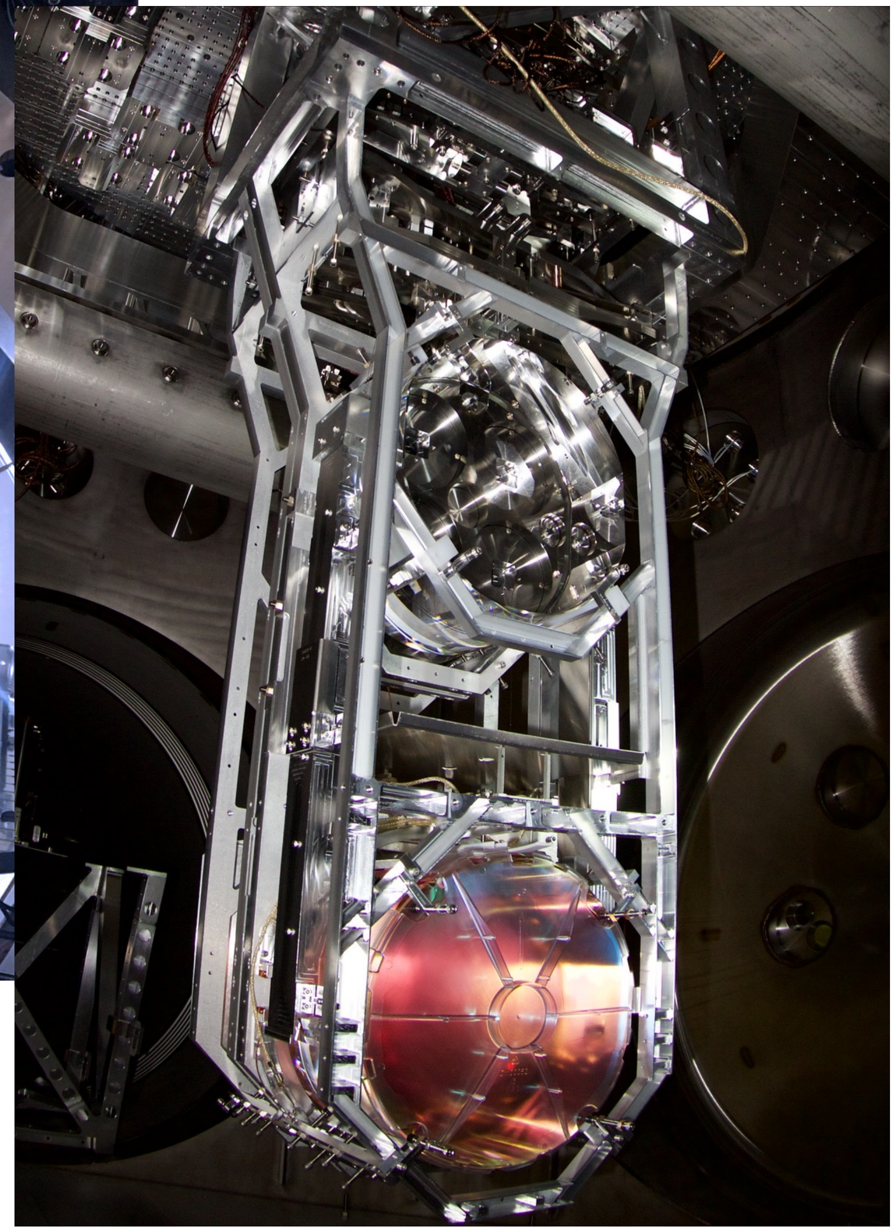


observatories

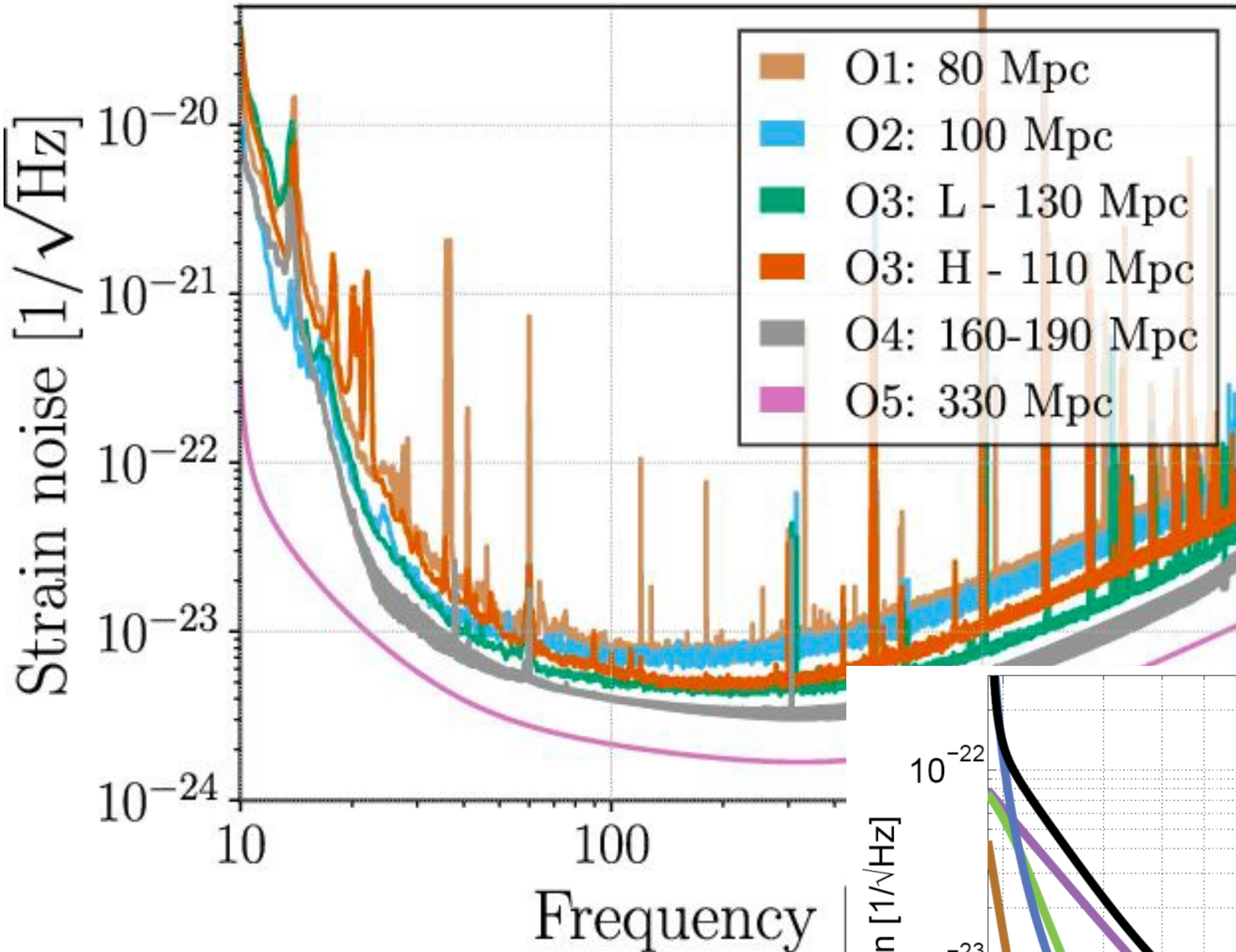


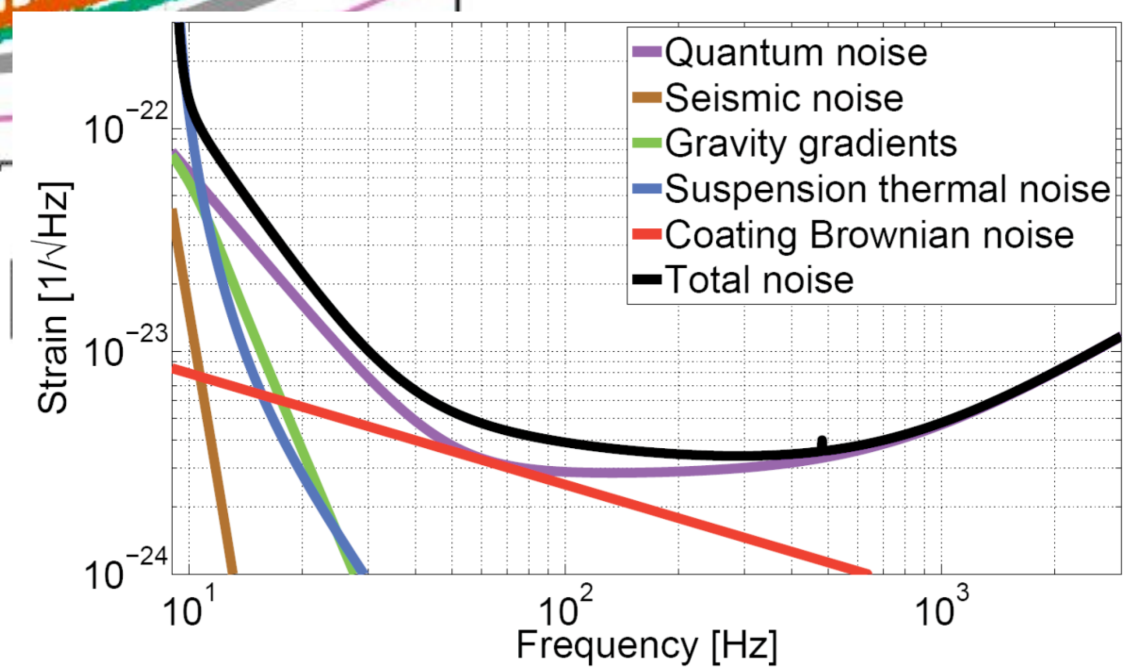


Inside the vacuum chambers

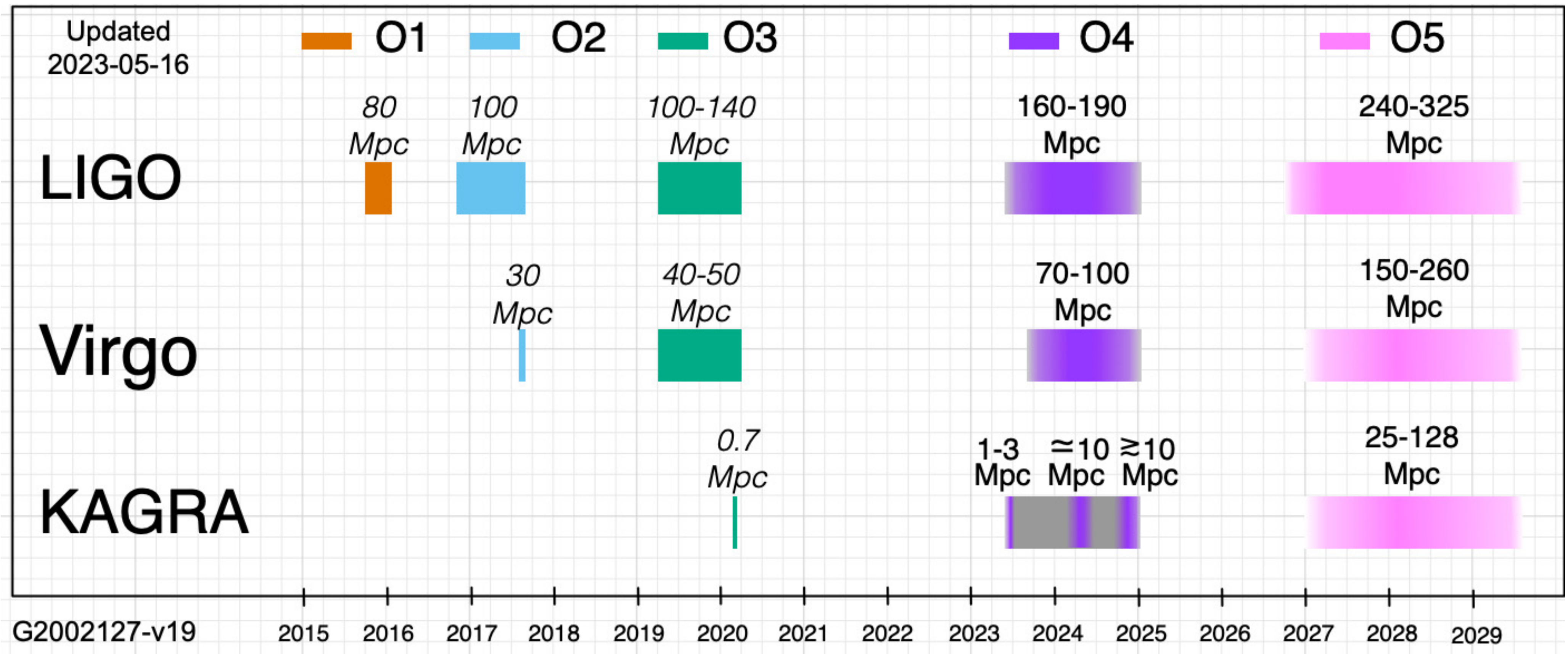


Reducing the noise → increasing sensitivity



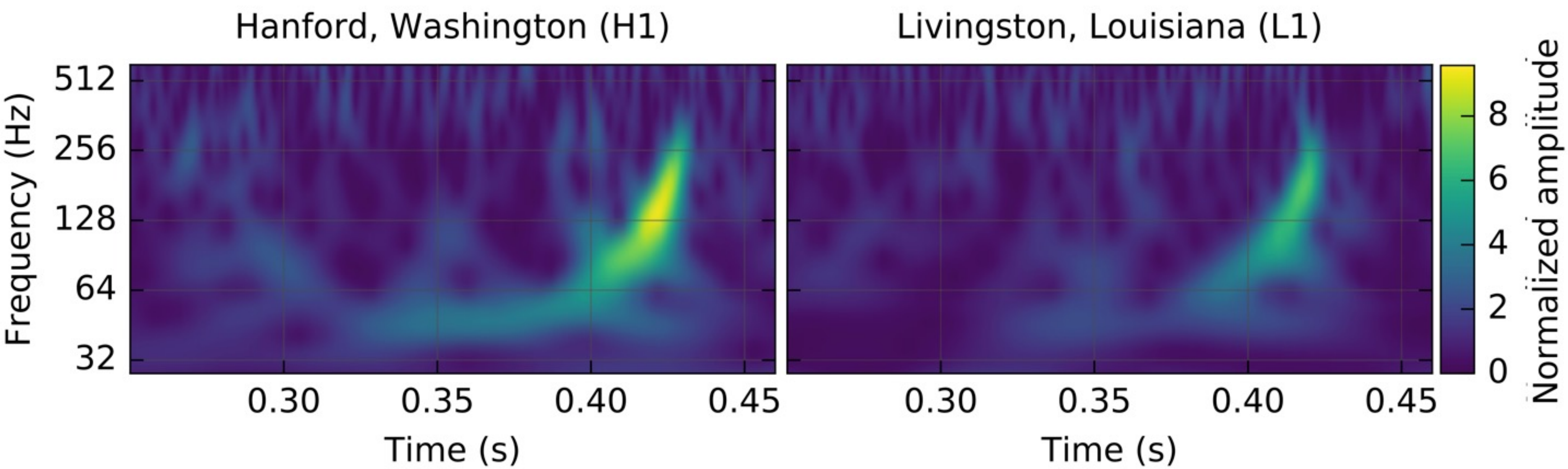


Observing runs



September 14, 2015, 2:51 AM Pacific

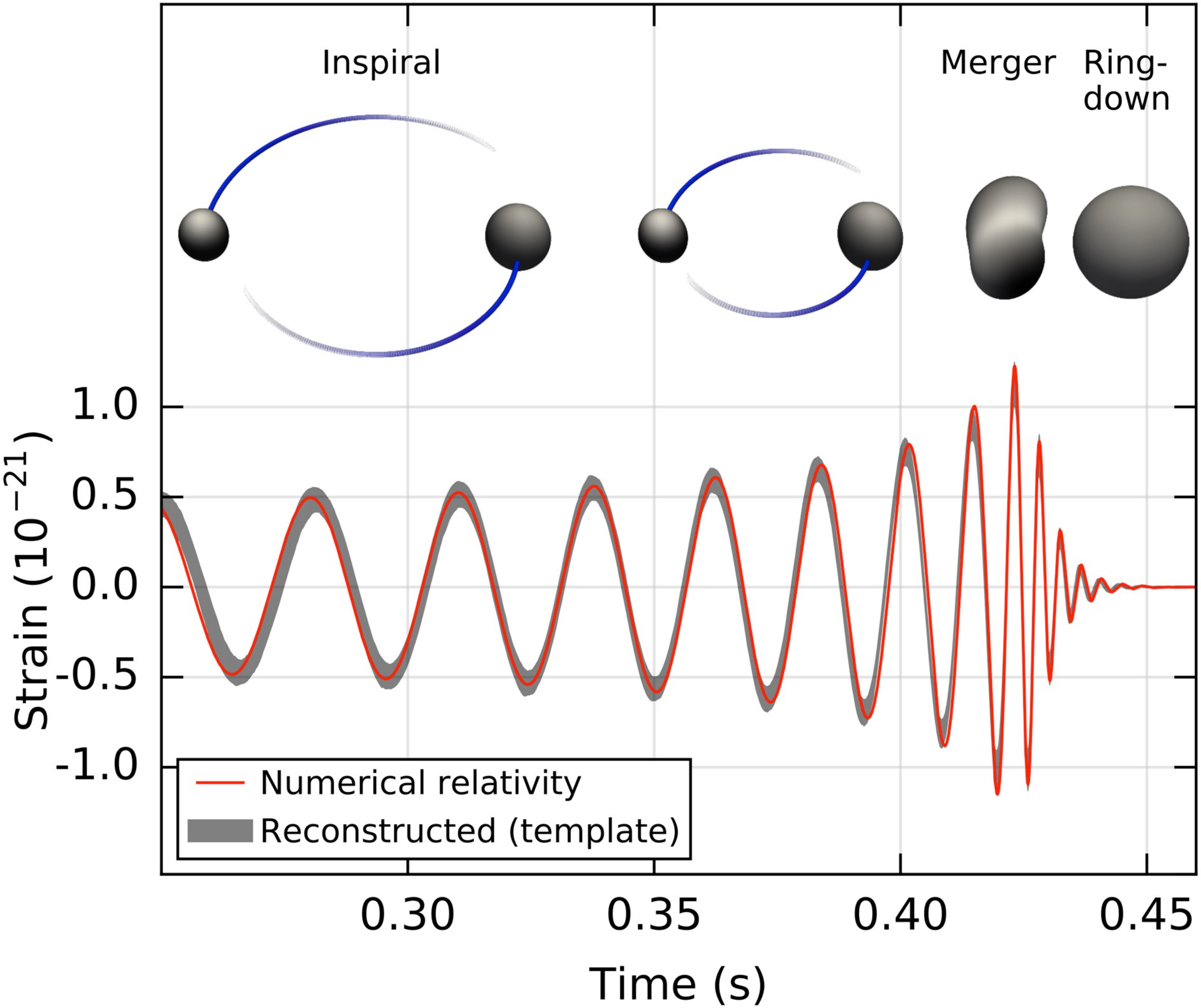
Boom !



GW150914

- First observation of GWs
- First direct observation of black holes

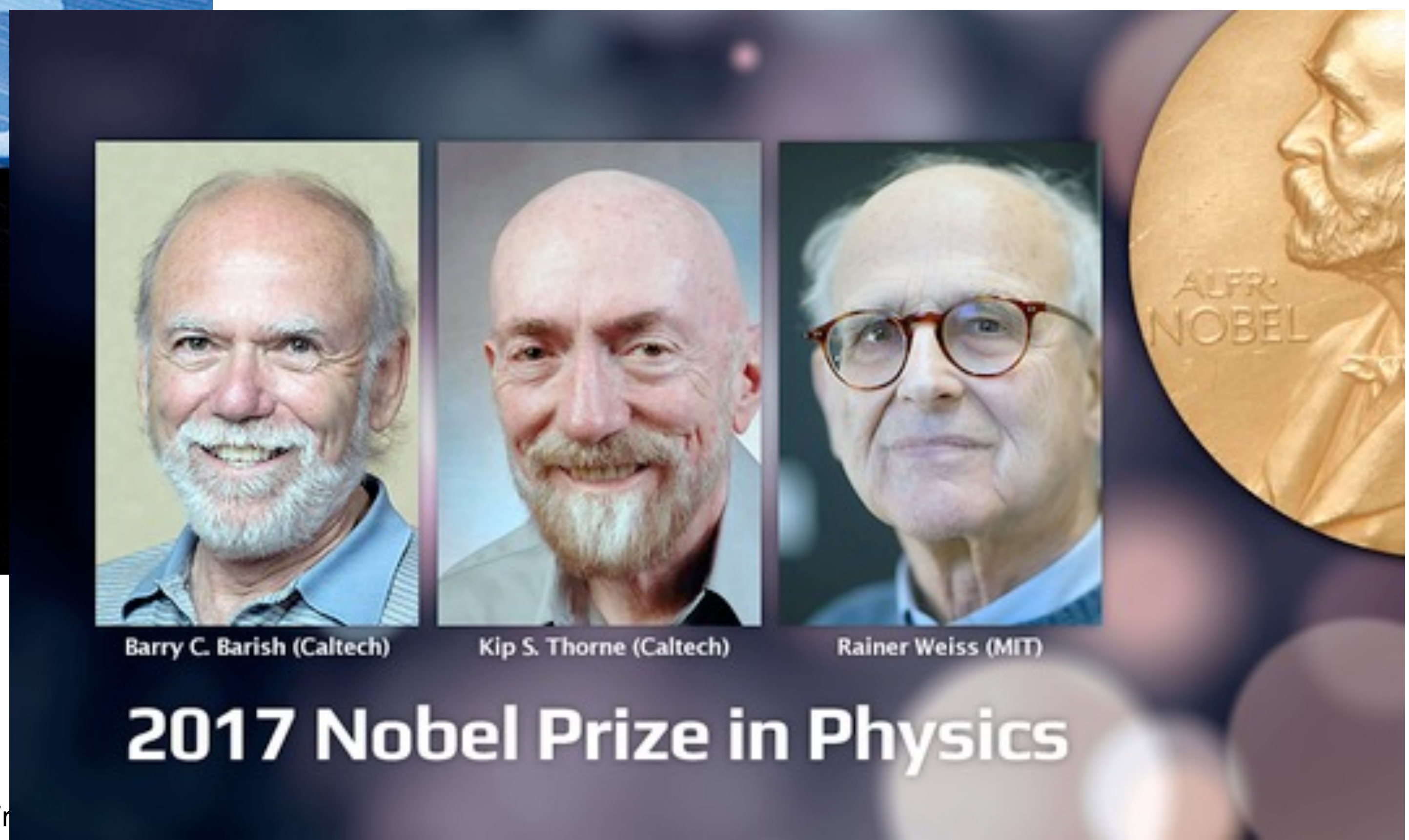
Binary black hole inspiral, merger, ringdown



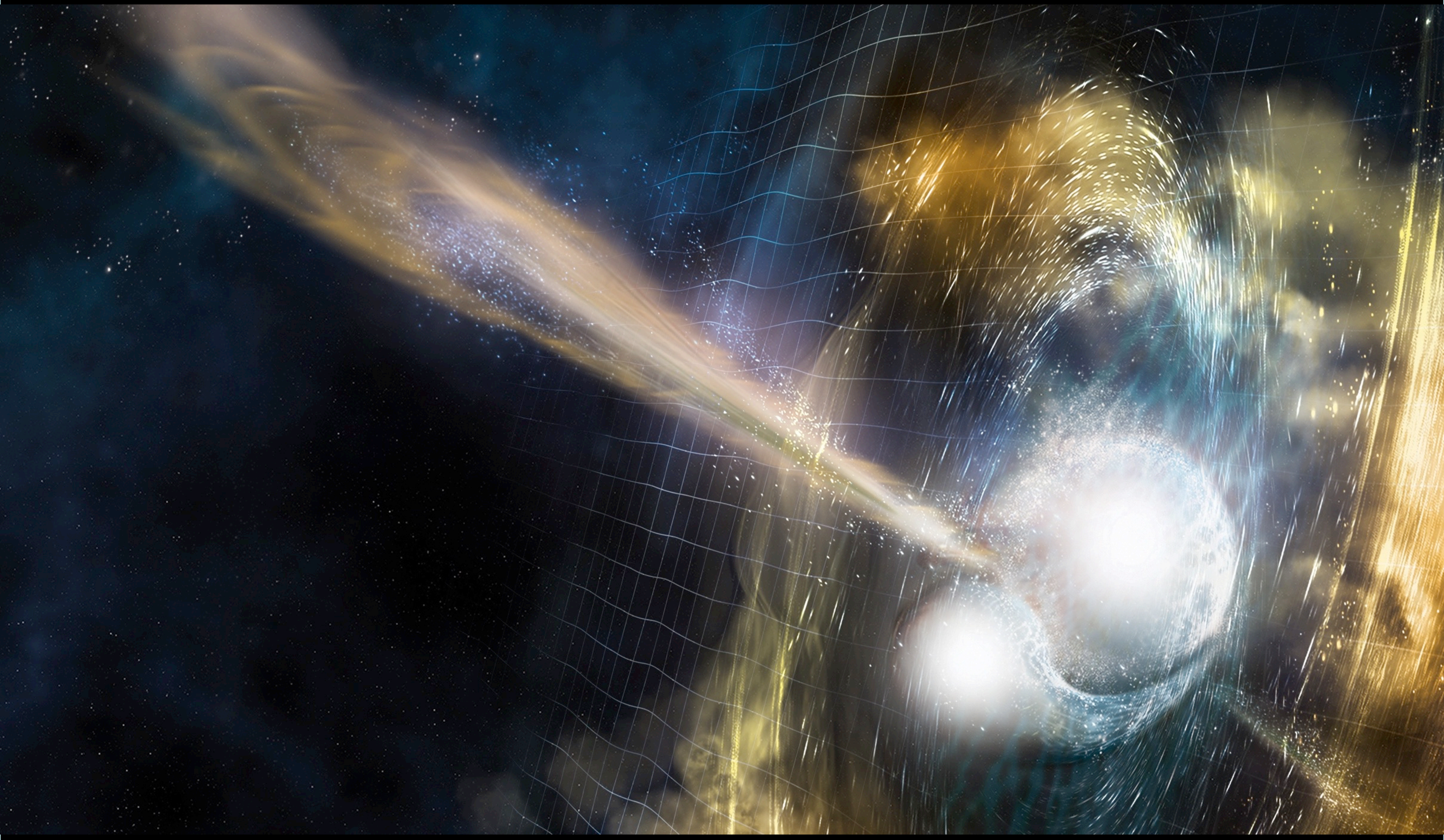
Simulated Nearby View – slowed down 100X

Video link: https://youtu.be/I_88S8DWbcU

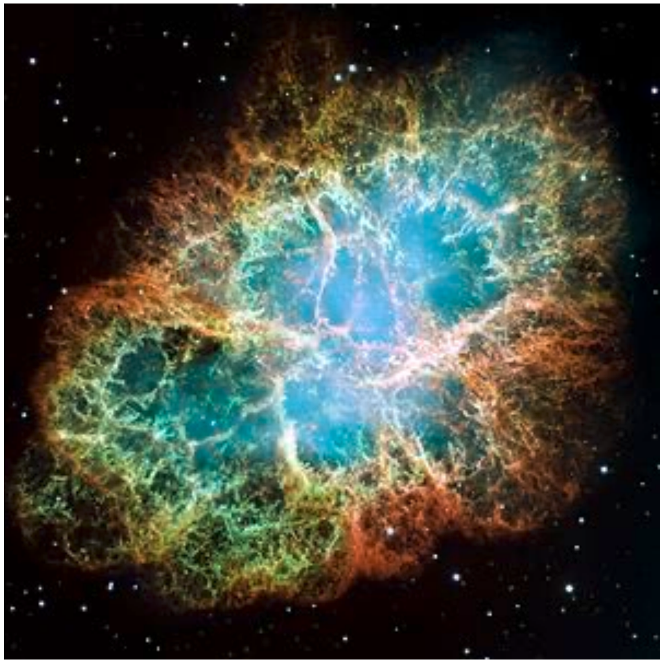
GW Discovery Accolades



Boom II:
Binary neutron-star merger August 17, 2017 (O2)

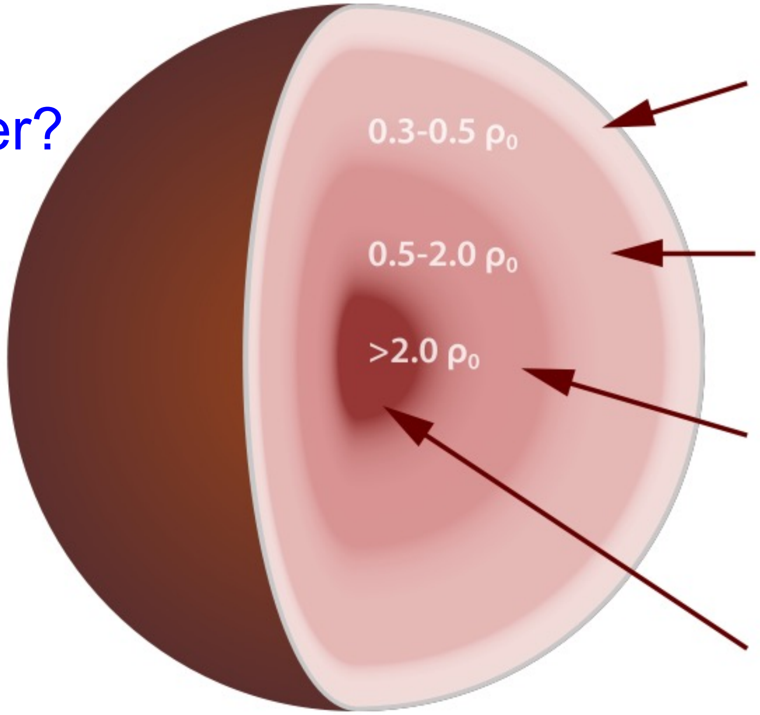


Neutron stars

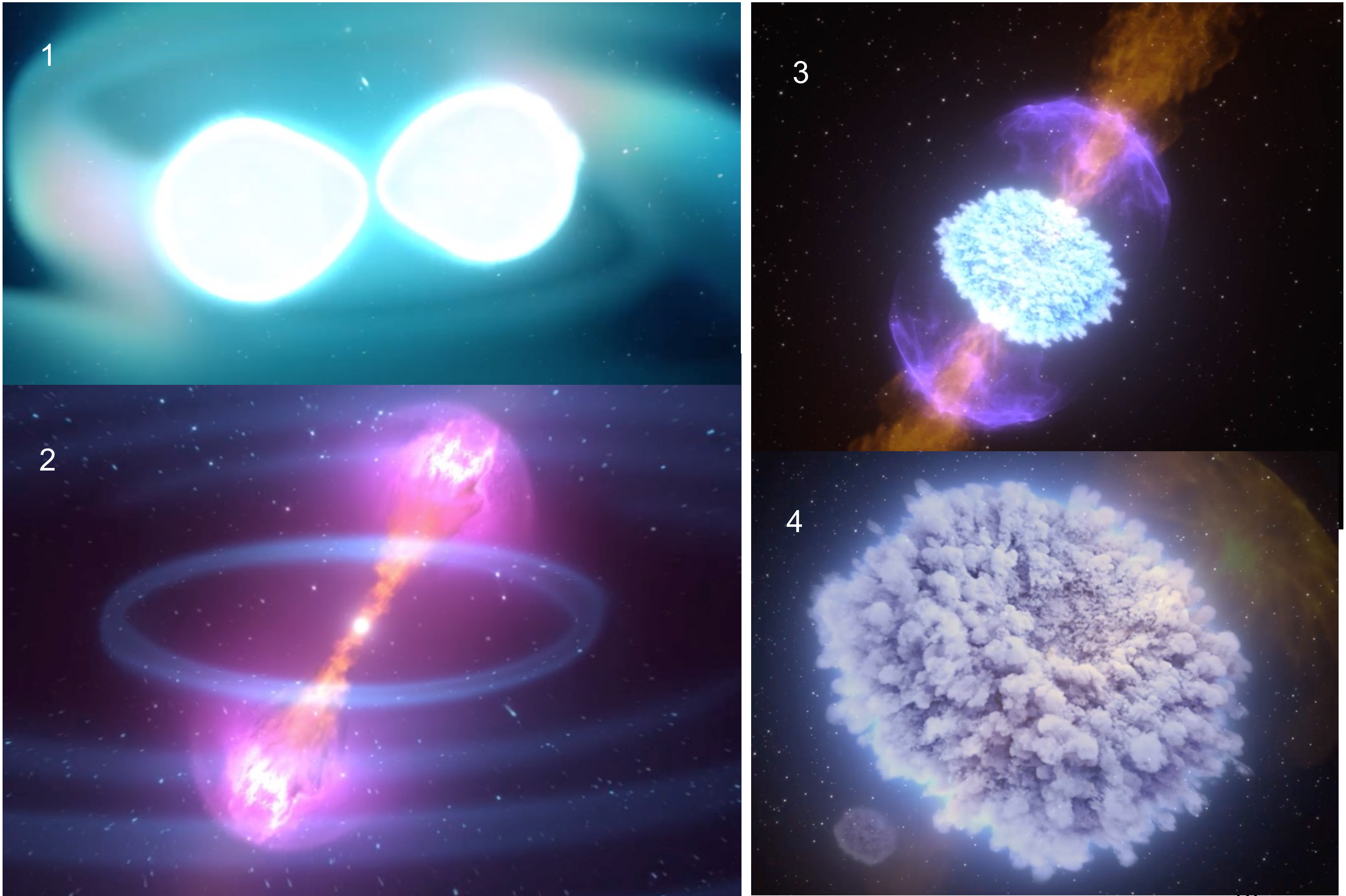


- NS result from normal stellar evolution for massive stars in the range 8 to 40 $M_\odot$
  - Fusion to Iron
  - Supernova (Type II)
- NS mass: 1 to 3 $M_\odot$
  - (heavier remnant → black hole)
- Radius ~ 10 km

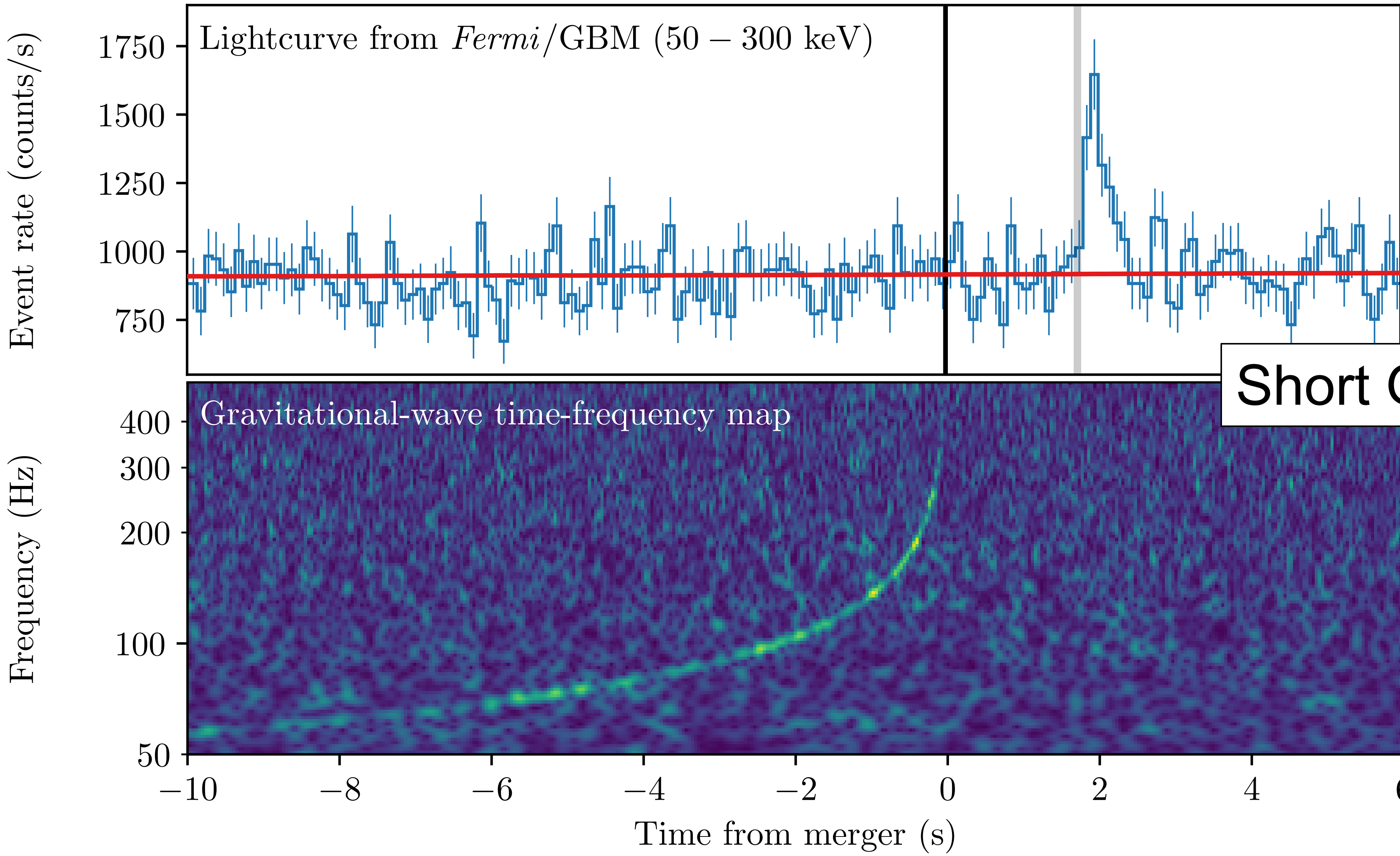
  ~ nuclear density! At surface: g=$2\times10^{12}\, m/s^2$
- Mysterious composition
  - new phases of matter?



NS Merger, gamma-ray burst, afterglow (“kilonova”)



August 17, 2017: LIGO+Fermi



Short GRB

$\Delta t = 1.74 \pm 0.05$ s

Speed of gravity

$$\Delta t = 1.74 \pm 0.05\,\text{s} = \Delta t_{\text{astro}} + \frac{D}{c^2}(c_g - c)$$

- Δt_astro ~2 s is very reasonable
  - Our prior based on astrophysics of SGRBs was Δt = [0,4] s
  - jet with γ ~ 50 is delayed by ~2 s (relative to v=c) at a photospheric radius of ~30 AU ✓

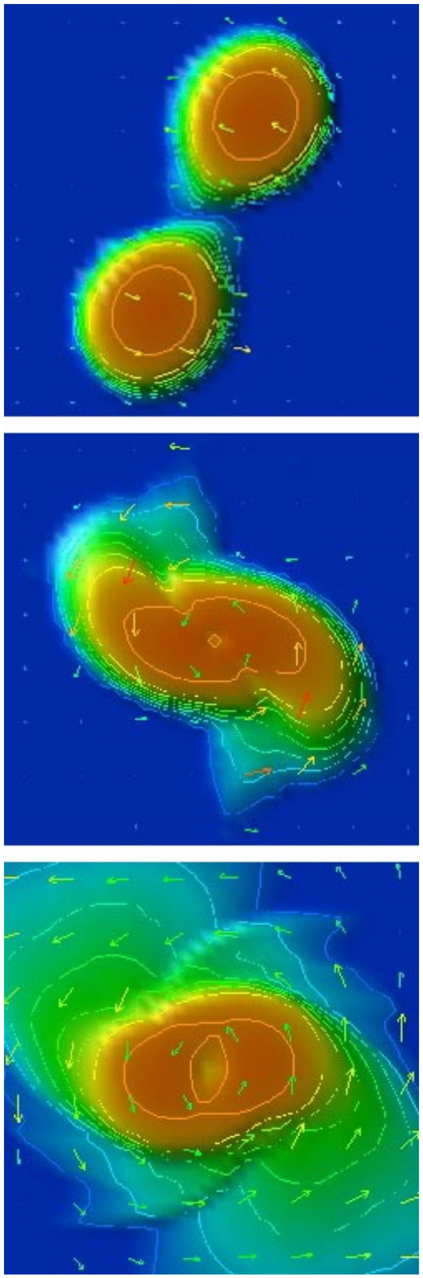
- Limits: (1) Let Δt_astro = 0; (2) Let Δt_astro = 10 s:

$$-3 \times 10^{-15} < \frac{c_g - c}{c} < 7 \times 10^{-16}$$

- Future measurements at different distances can improve this

170817: Astrophysics
The "kilonova"

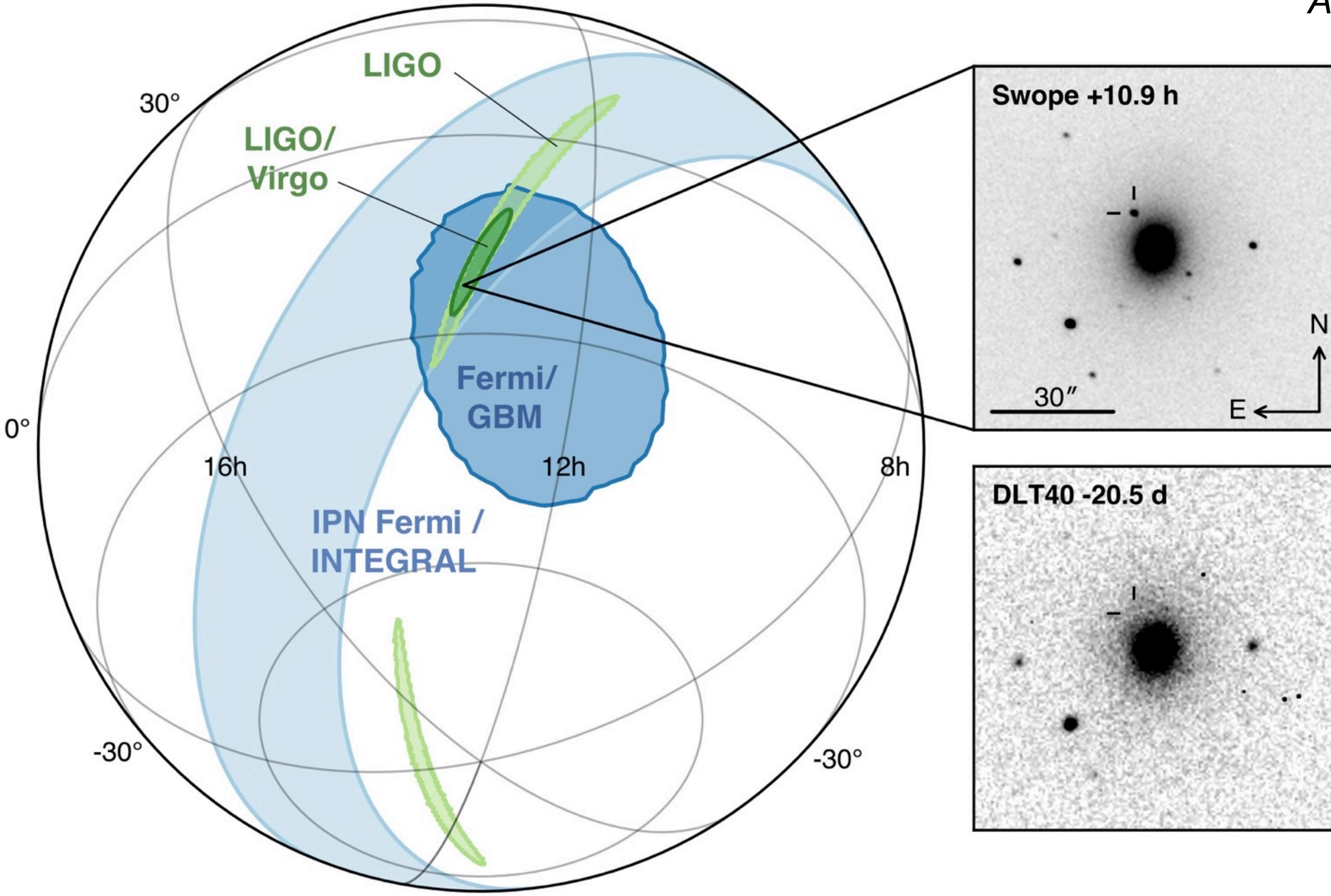
Shibata



- Tidal disruption of the merging neutron stars
  - Disruption depends on NS "stiffness" (EOS)
    - Subtle effects in GW waveforms
- Hypothesis pre-170817:
  - Nuclear ejecta bombarded by neutrons
    - v ~ 0.1-0.3 c
  - Creation of heavy nuclei (r-process)
  - Unstable isotopes → decay → glowing object "kilonova"
  - Similar to Supernova afterglow

GW localization allows ID of afterglow (kilonova)

ApJL **848** L12

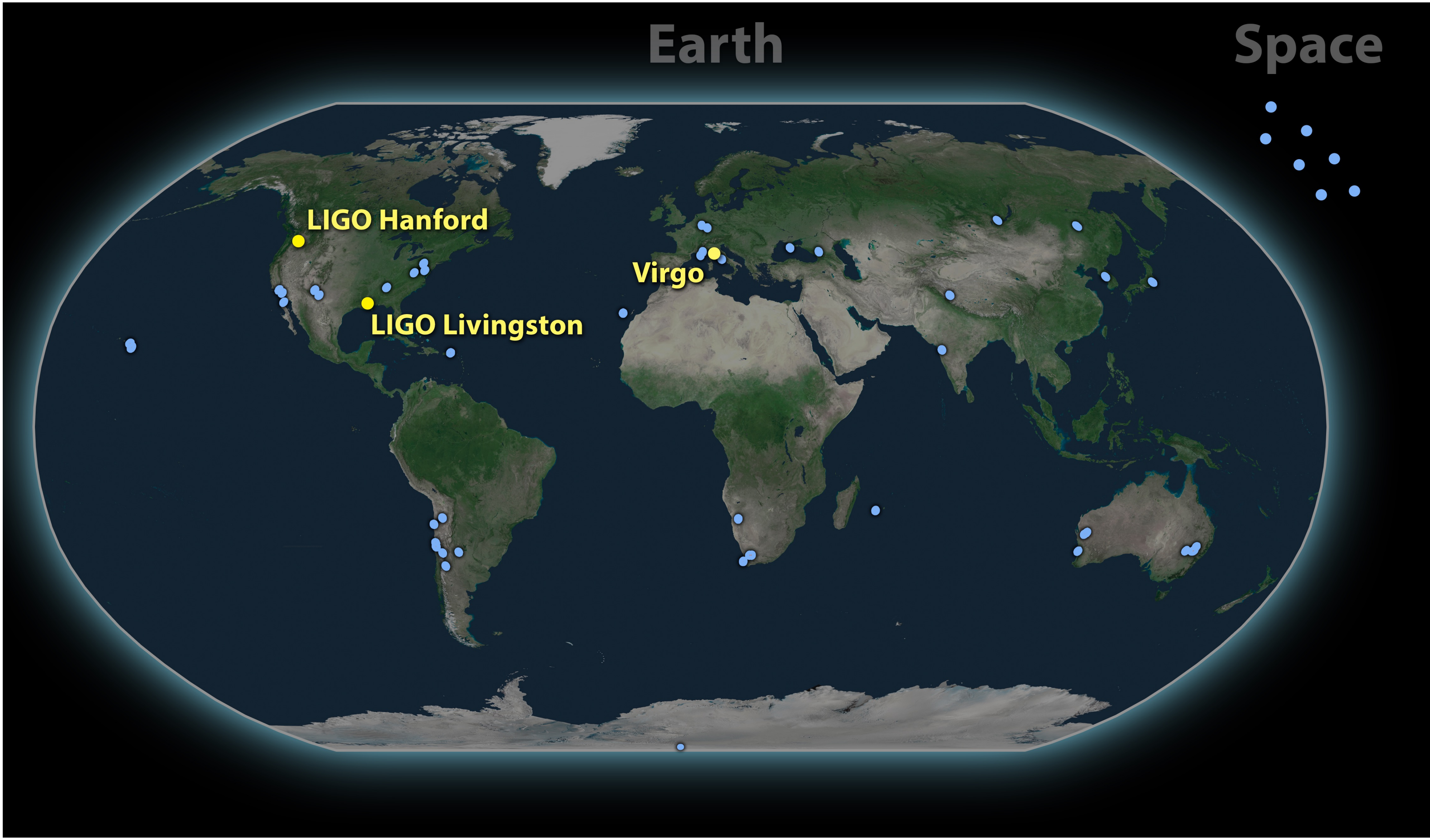


NGC 4993
43 ± 3 Mpc

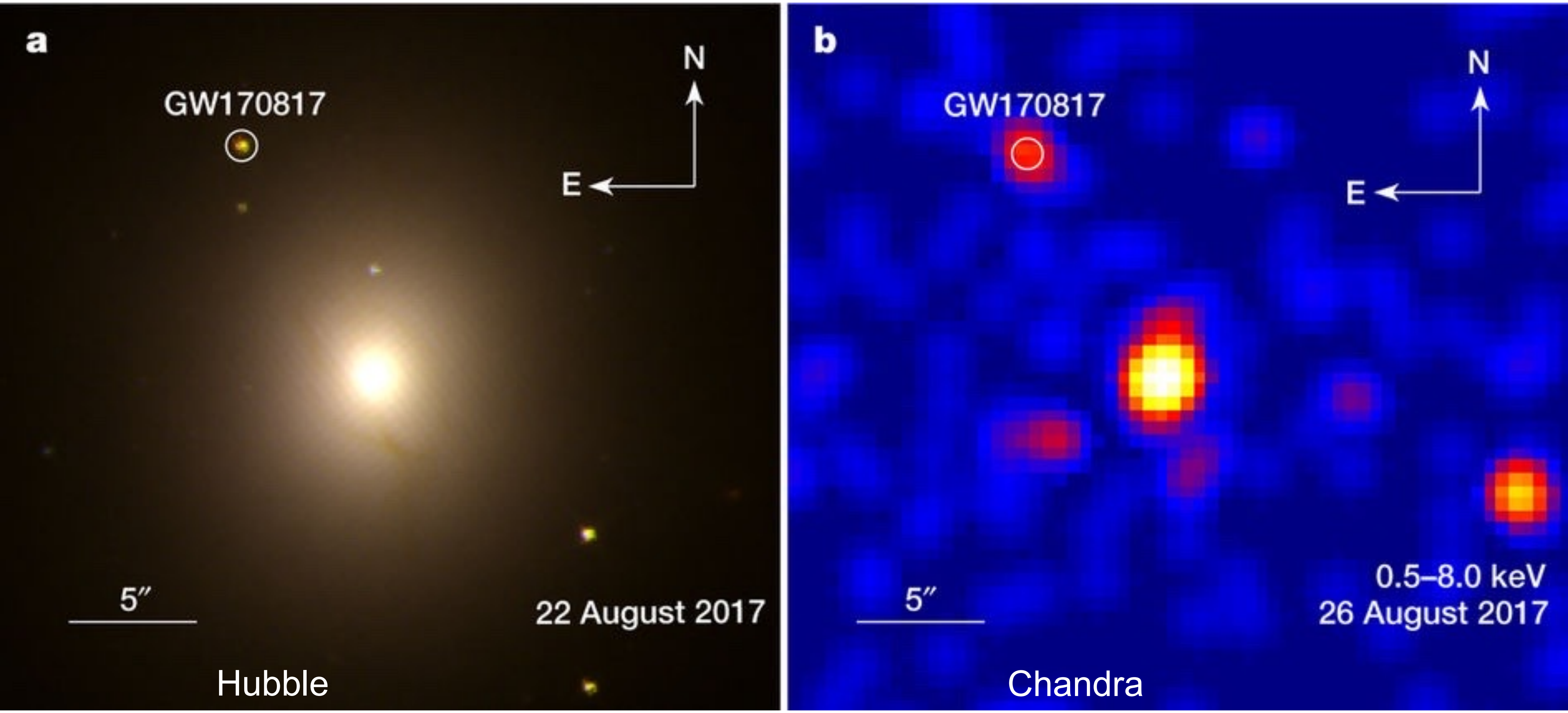
offset of 2 kpc – typical of kicks

"Multimessenger Astronomy"

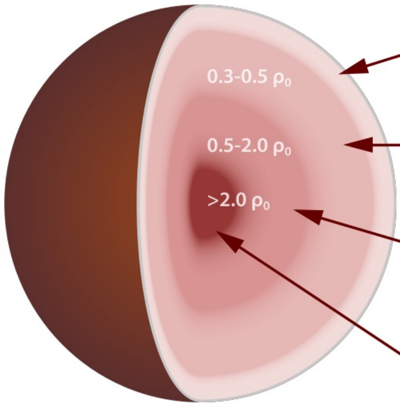
and the astronomy world tuned in

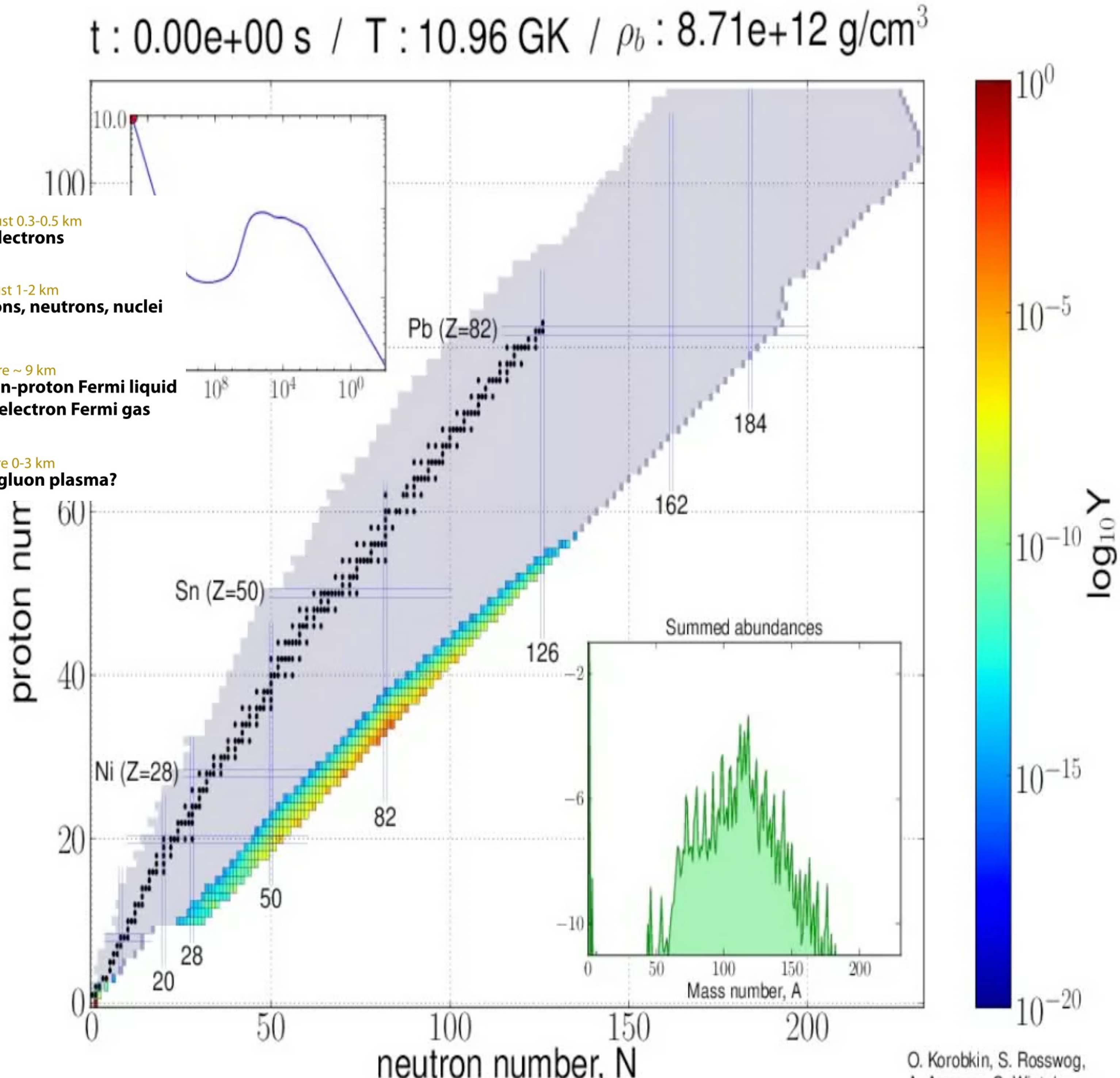


e.g. optical/IR and x-rays



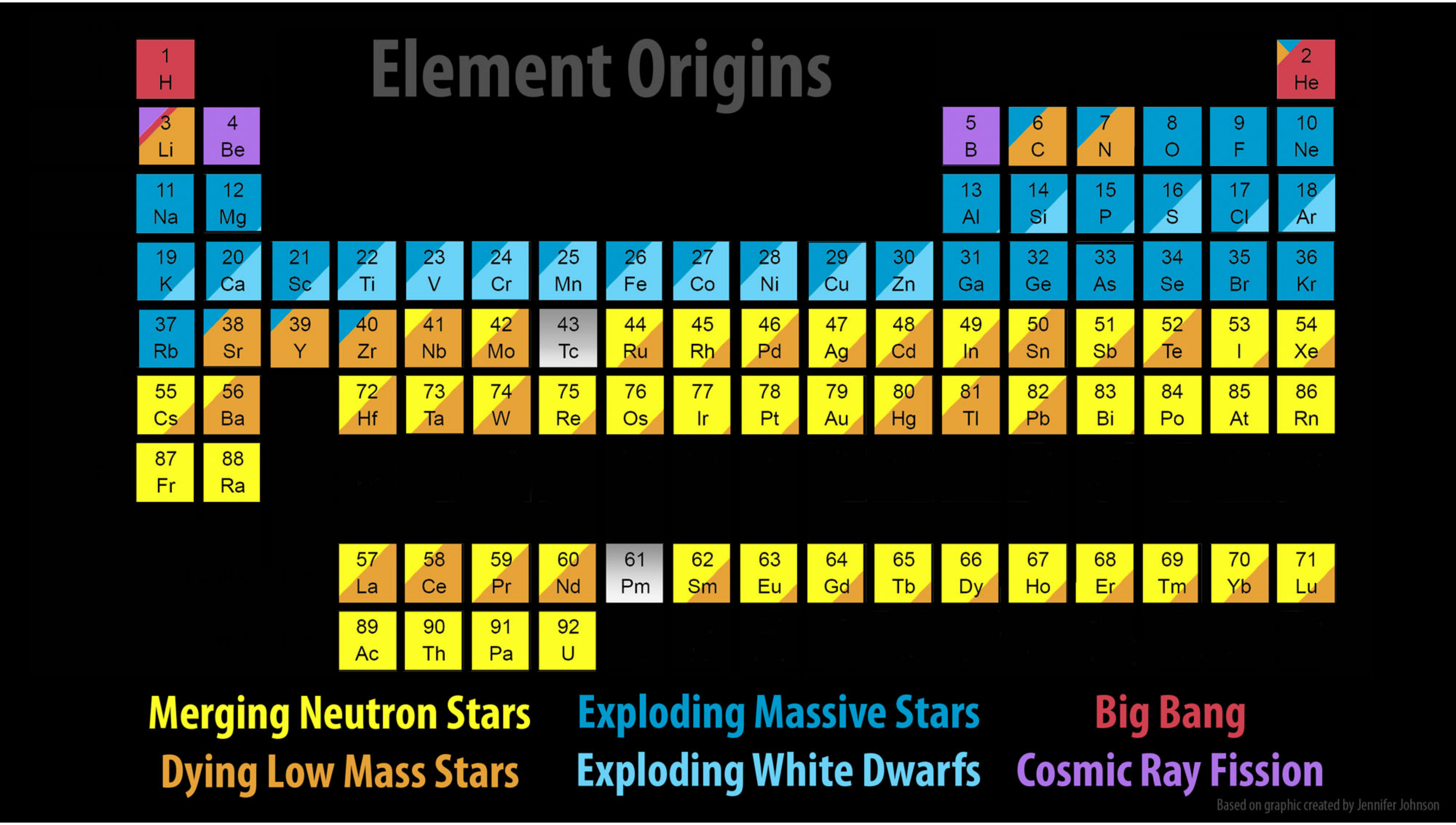
Troja, et al, Nature 2017





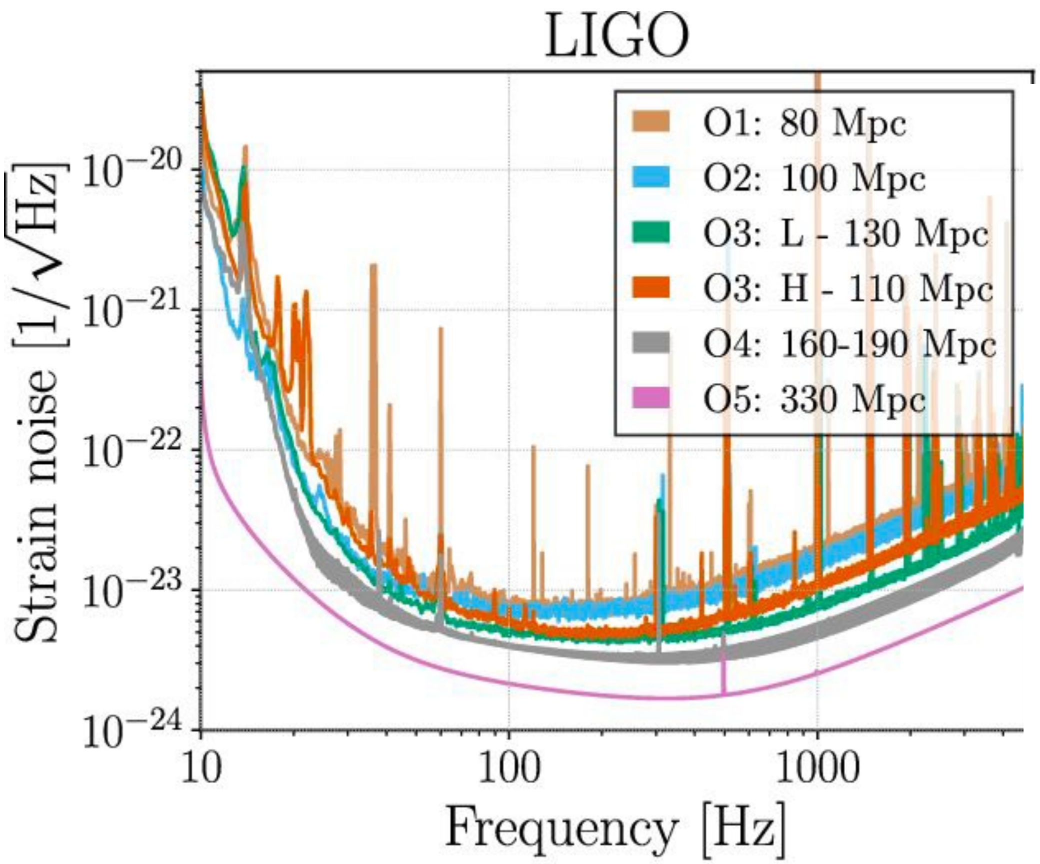
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

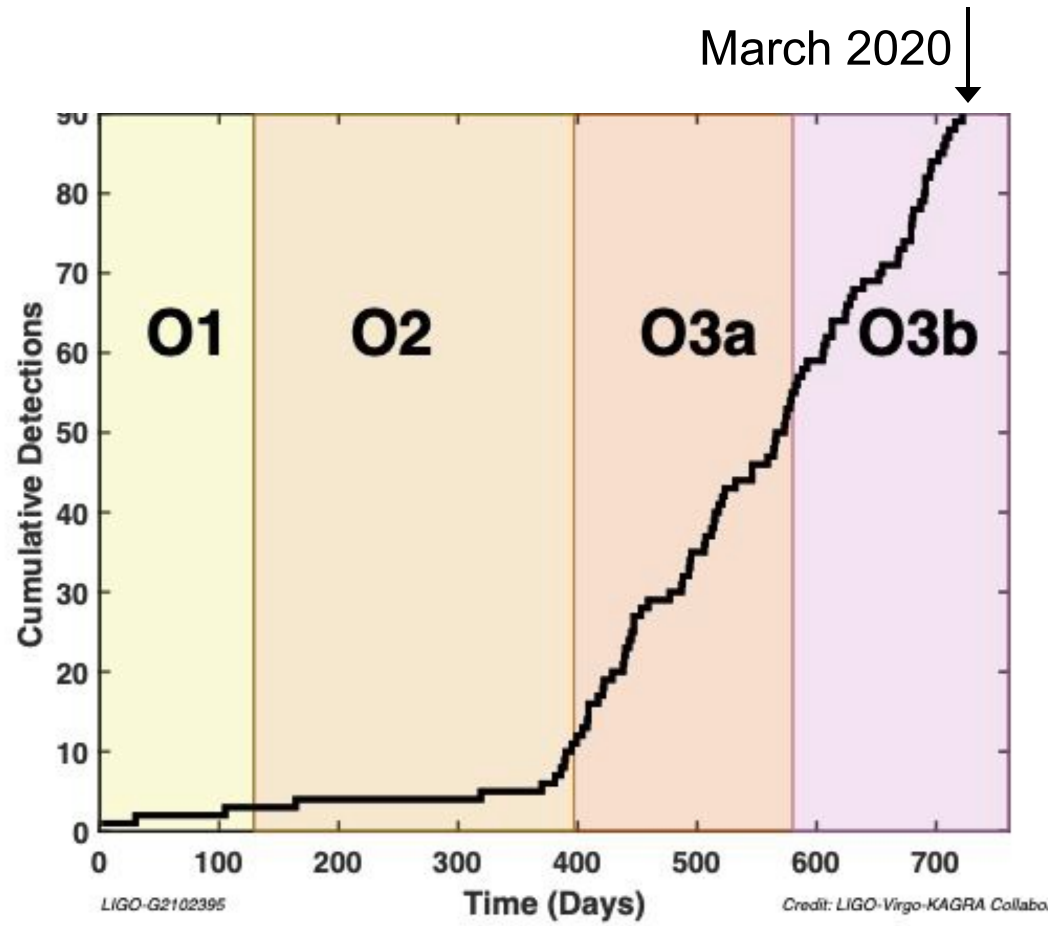
Origins of elements: Major Update due to 170817



LIGO

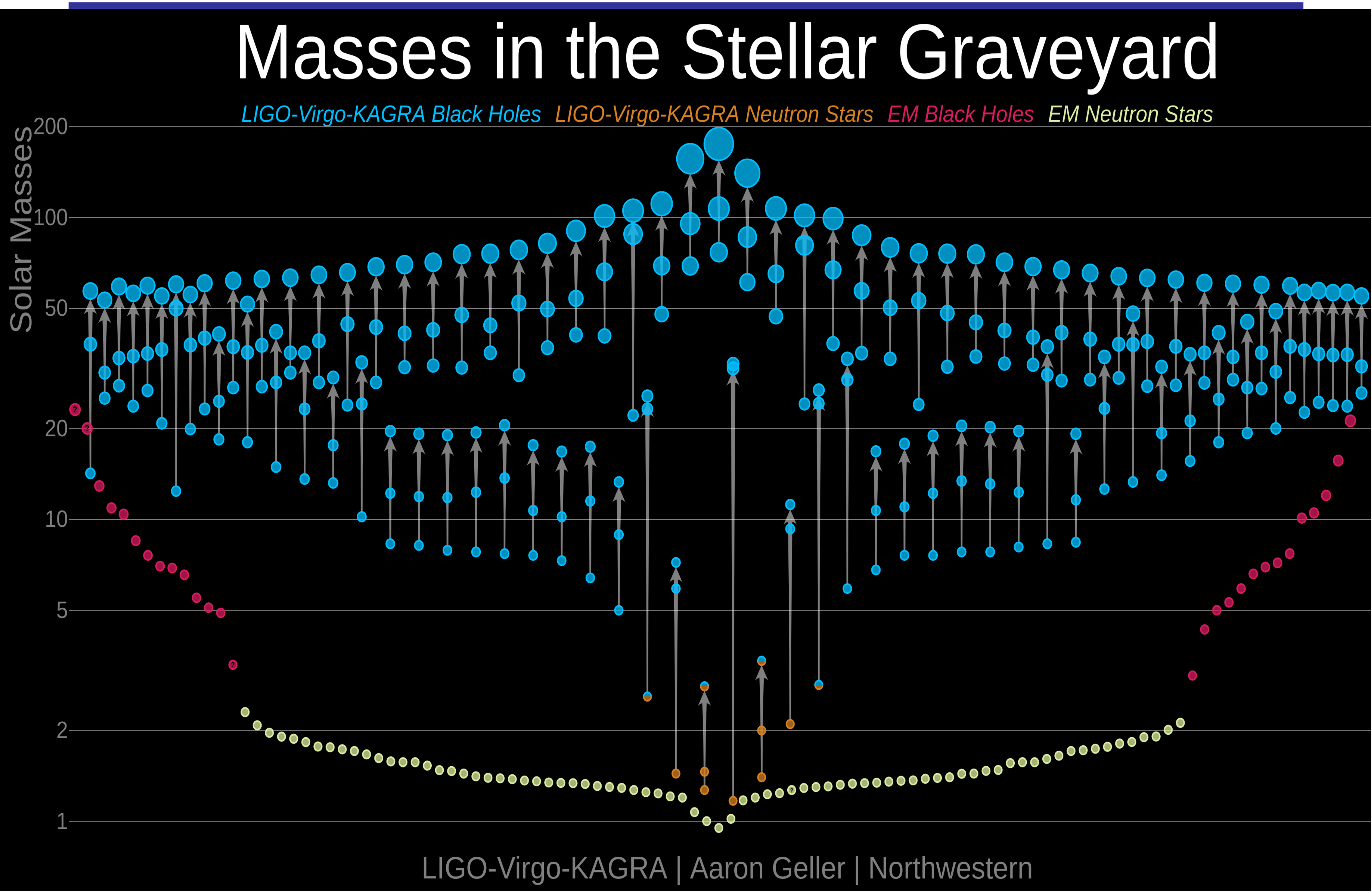
Those were the highlights for O1 and O2. What about O3 ?



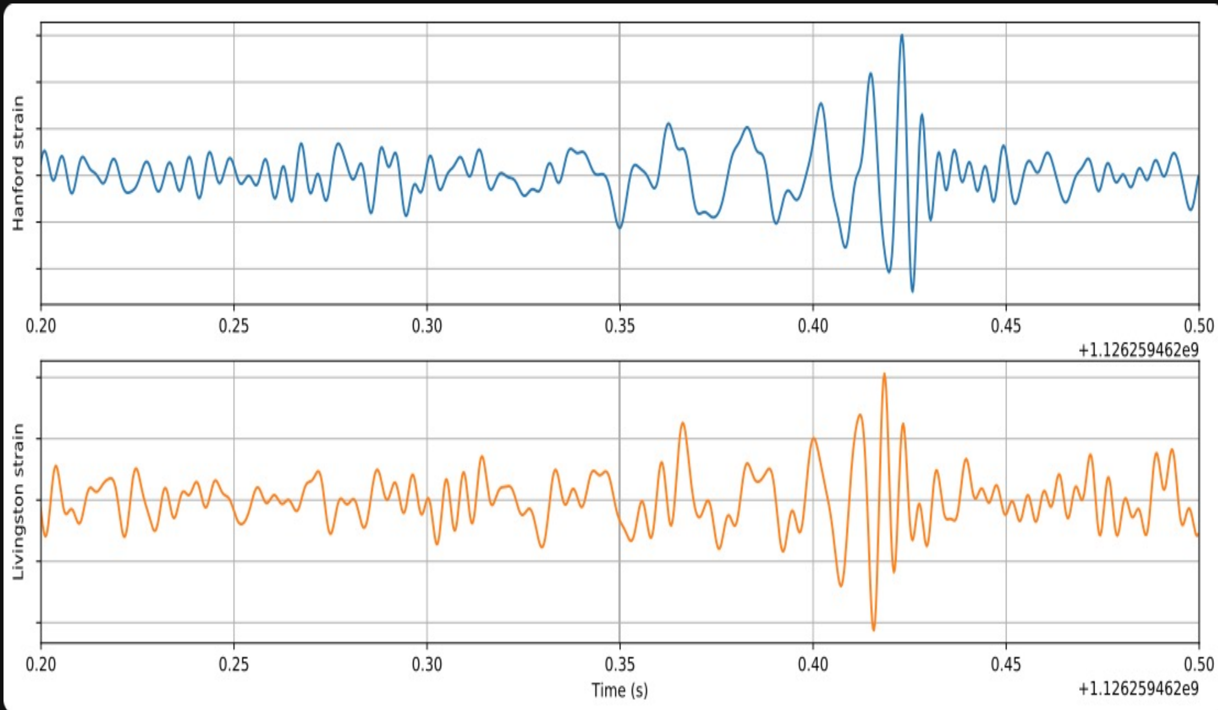


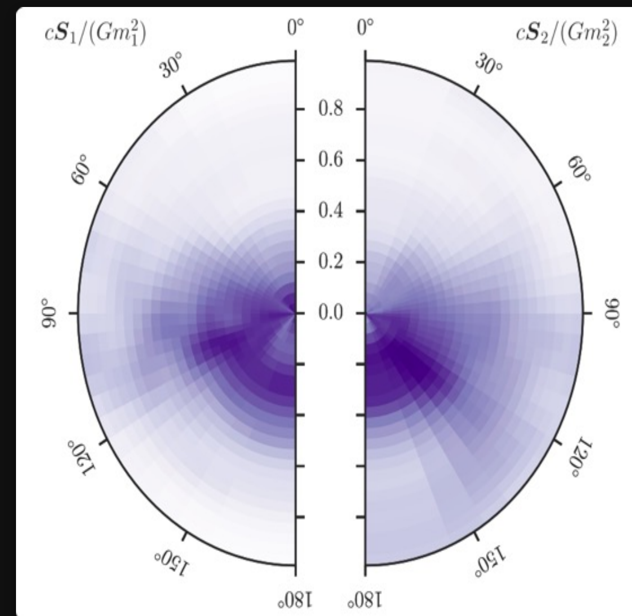
- The GW horizon is limited by our ability to reduce the noise of the interferometer
- Rate of detected events ~ horizon^3
- Next is O4 (early 2023)

NS/BH detections as of May 2023

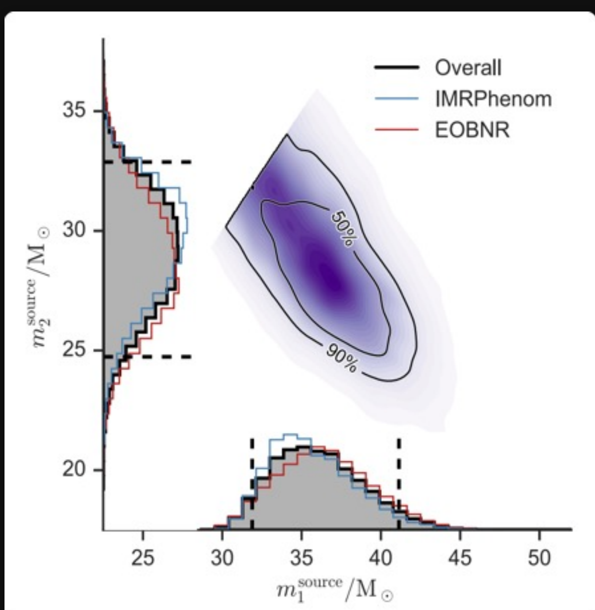


Parameter Estimation

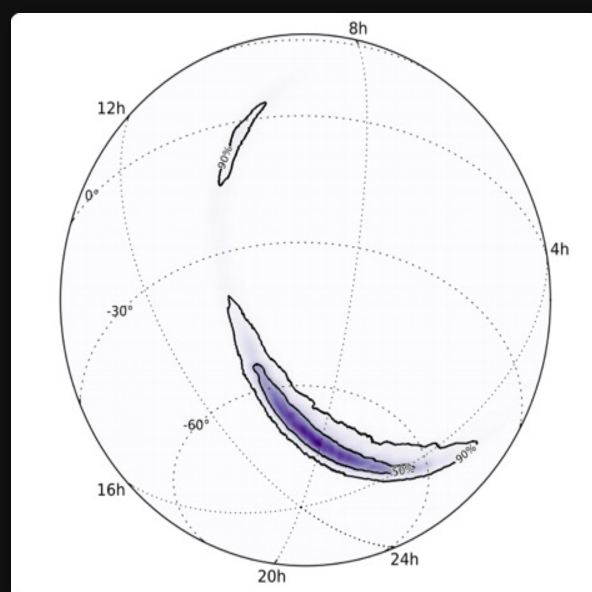




Masses



Location



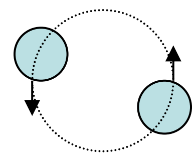
Spins

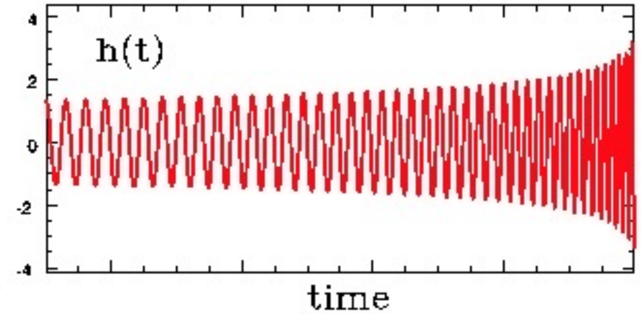
(e.g., GW150914)

LIGO

Measuring masses, distance, sky location

Binary inspiral system (lowest PN order):





$$h_+ = \frac{2(1+z)\mathcal{M}}{D_L}\left[\pi(1+z)\mathcal{M}f\right]^{2/3}\left(1+\cos^2\iota\right) \times$$
$$\cos 2\Phi_N(t) \ ,$$

$$h_\times = -\frac{4(1+z)\mathcal{M}}{D_L}\left[\pi(1+z)\mathcal{M}f\right]^{2/3}\cos\iota\sin 2\Phi_N(t) \ ,$$

$$\Phi_N(t) = \Phi_c - \left[\frac{t_c - t}{5(1+z)\mathcal{M}}\right]^{5/8} \ , \qquad f \equiv \frac{1}{\pi}\frac{d\Phi_N}{dt} \ . \qquad (1)$$

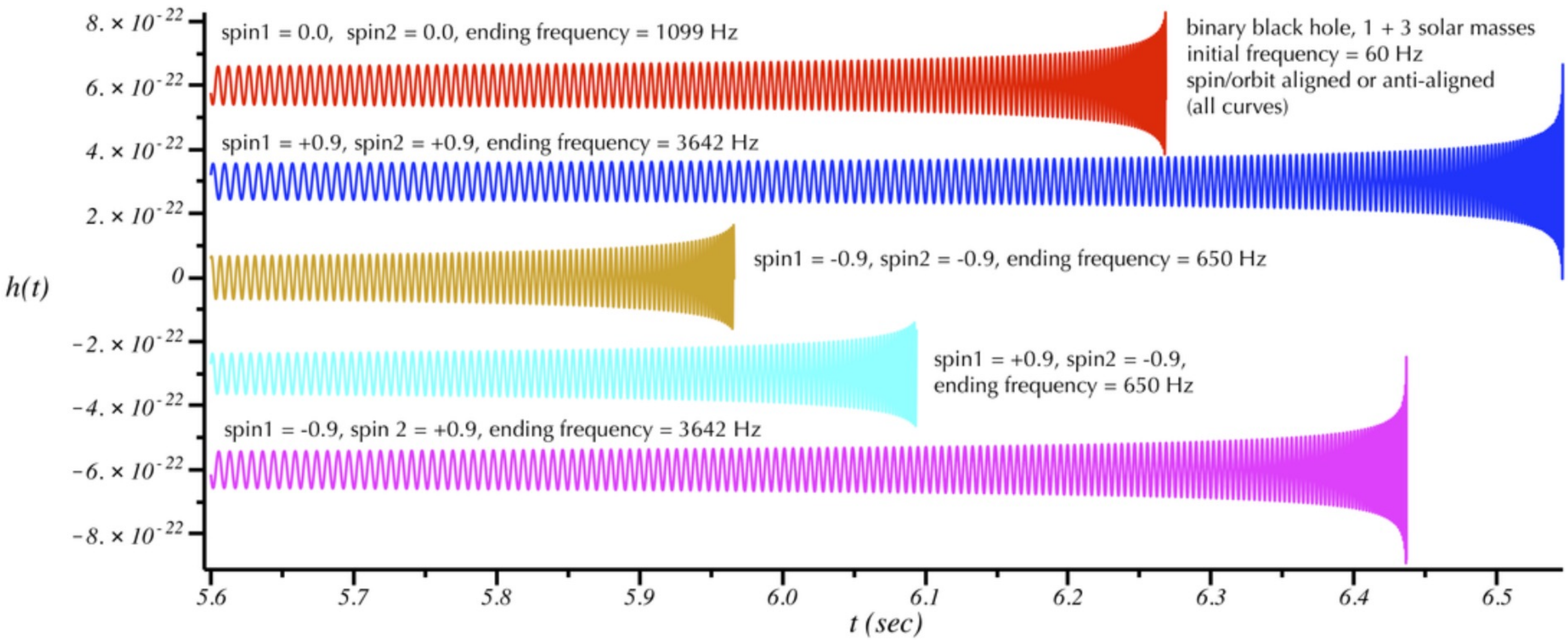
$$\mathcal{M} = m_1^{3/5} m_2^{3/5} / (m_1 + m_2)^{1/5}$$

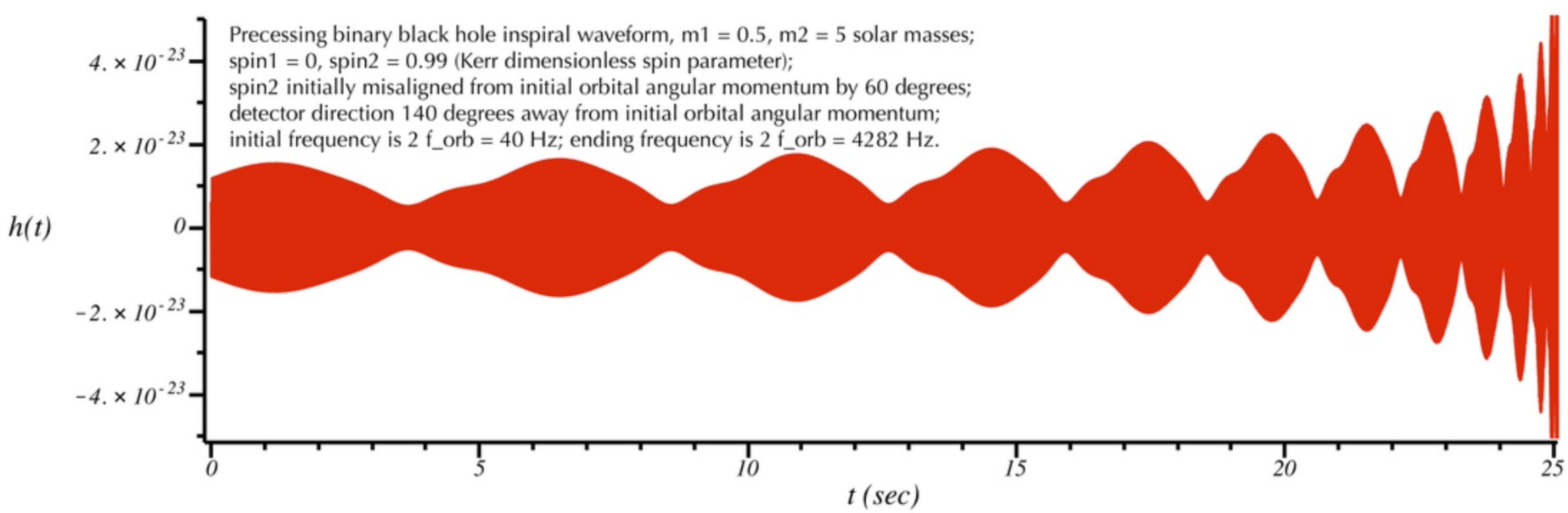
measured: $h(t) = F_+(\theta,\phi,\psi)\, h_+ + F_-(\theta,\phi,\psi)\, h_-$

Units: $M \rightarrow (G/c^2)M$, e.g. $M_\odot = 1.47$ km
$M \rightarrow (G/c^3)M$, e.g. $M_\odot = 4.92\ \mu$s

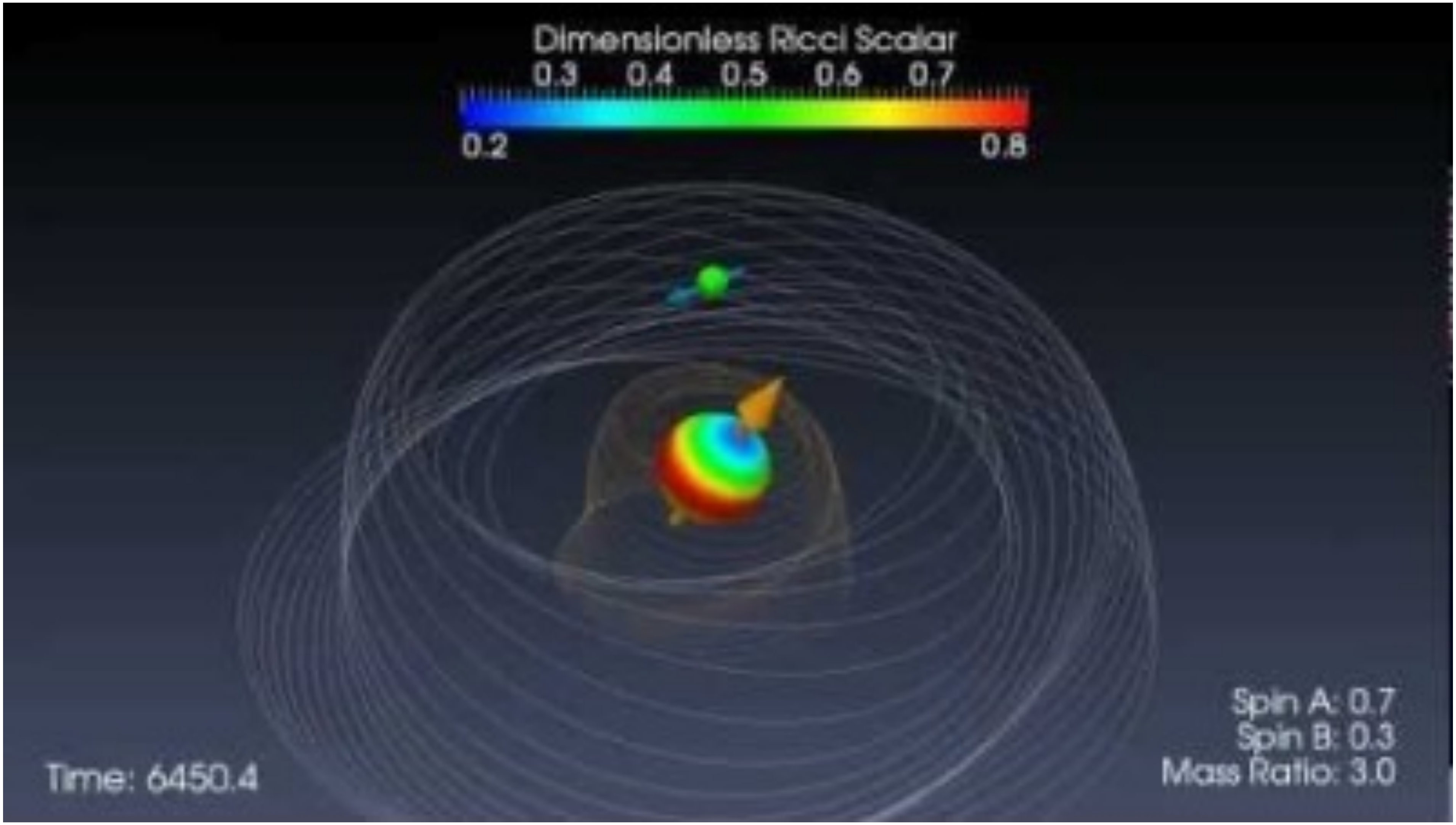
Parameters:
$(1+z)\mathcal{M}, D_L, \iota, \theta, \phi, \psi$

Effect of spins on waveforms



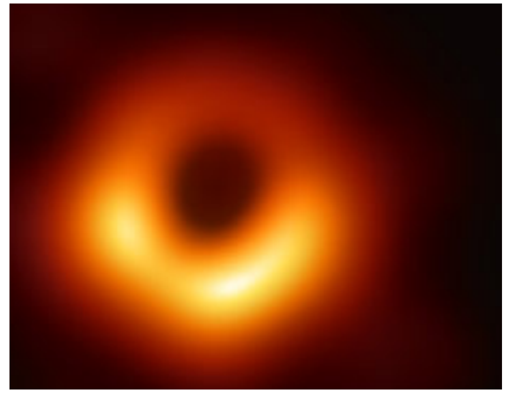


Unaligned spinning black holes

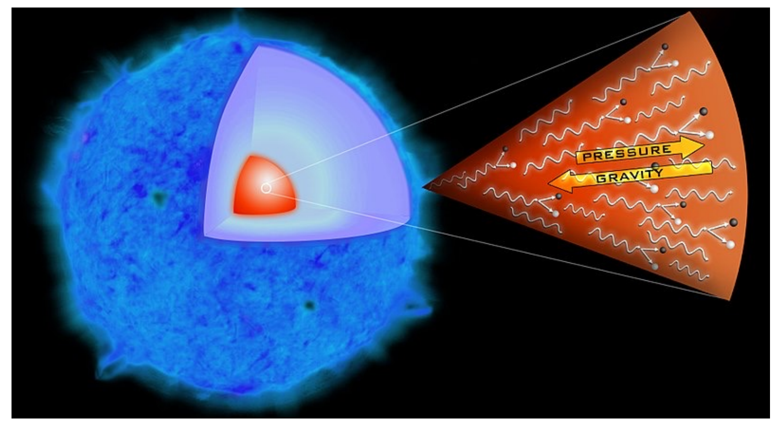


Black hole masses

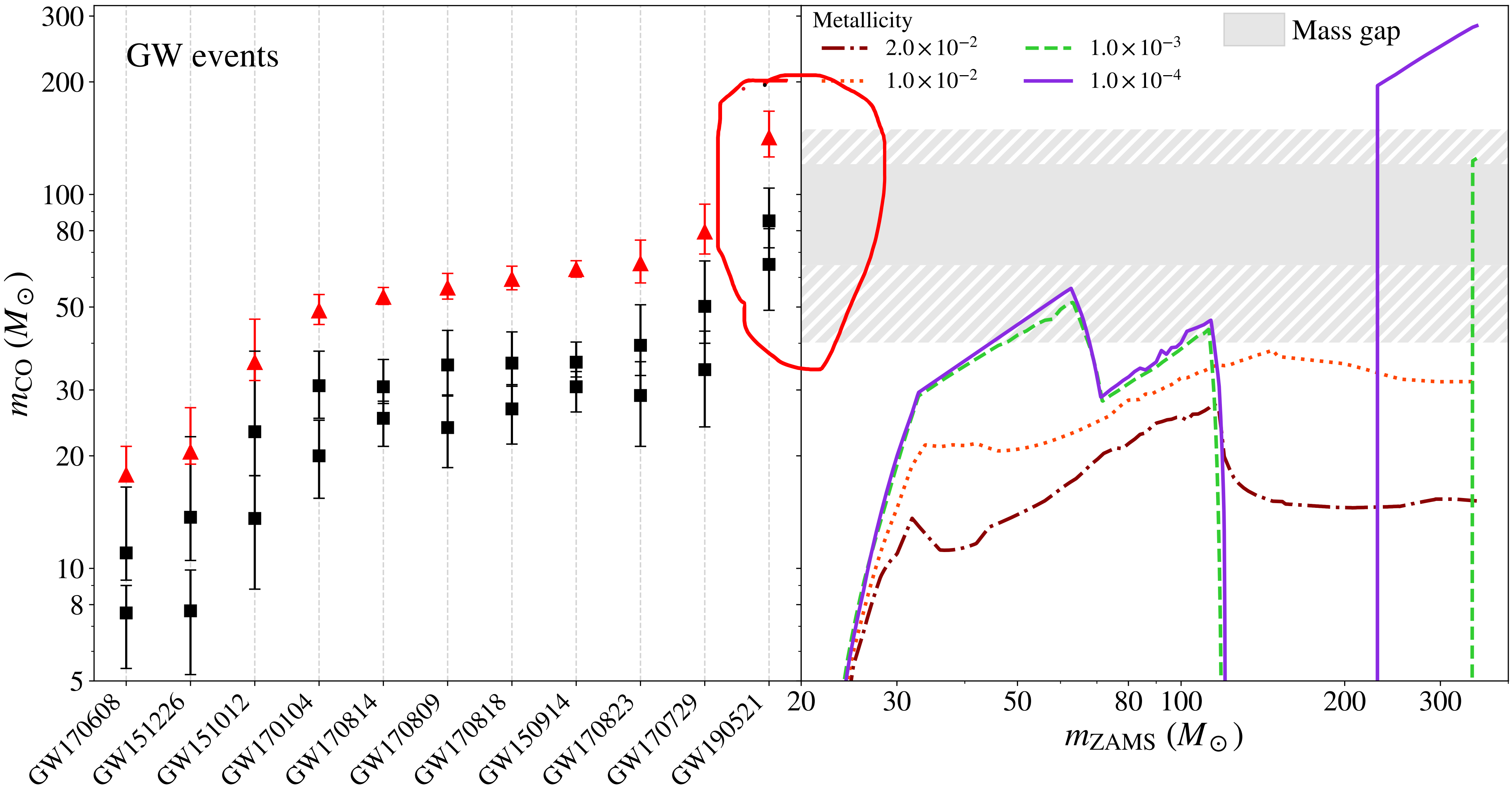
- Supermassive – rapid accretion in early star forming era
  - not observable by LIGO
  - Galactic centers
  - Milky Way: $4 \times 10^{6}\ M_{\odot}$
  - M87: $6 \times 10^{9}\ M_{\odot}$



- ‘Stellar mass’
  - Presumed products of stellar evolution
  - $M > 1.4\ M_{\odot}$
  - If $M < M_{\odot}$ then primordial (!)
  - $40 < M < 60\ M_{\odot}$ ‘difficult’ but observed (low metallicity)
  - $60 < M < 130\ M_{\odot}$ not supposed to exist (pair instability)
  - $M > 130\ M_{\odot}$ possible; not yet observed



The ‘mass gap’ undone ? Sequential mergers?



Black hole spins

- Spin magnitude
  - In GR, BH spin must be $0 \leq J \leq \frac{GM^2}{c} = J_{max}$
  - Define spin parameter $a = J/J_{max}$ between 0 and 1.
  - Typically, BHs from stellar evolution have spin $a < 0.5$
  - Binary merger: remnant BH has spin $a \approx 0.7$
- Spin direction
  - Evolution of binary stars → BHs : spins align with orbital angular momentum
- BBHs from normal stellar evolution – aligned spins, a<0.7
- BBHs from dynamical formation – unaligned spins
- ‘Impossible’ BH masses from *sequential* mergers would have unaligned (randomly oriented) spins and larger initial spins, a~0.7

Beyond binary mergers…

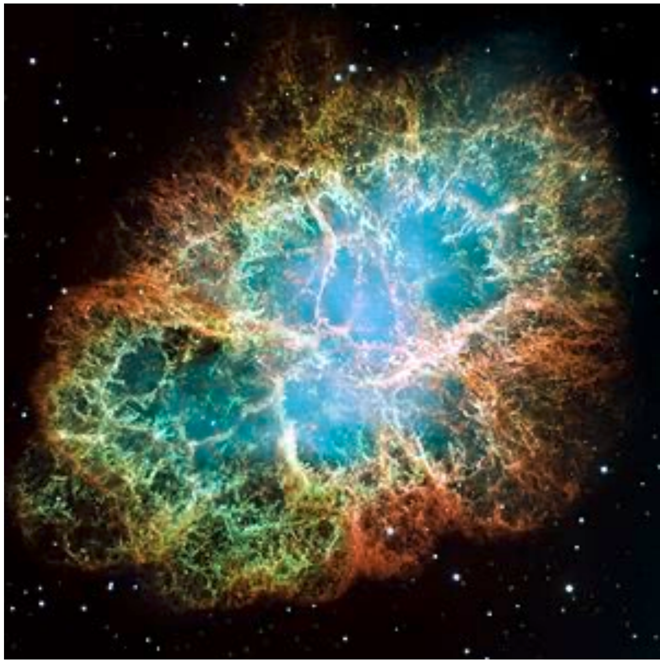
The ever-increasing sensitivity of LIGO will…

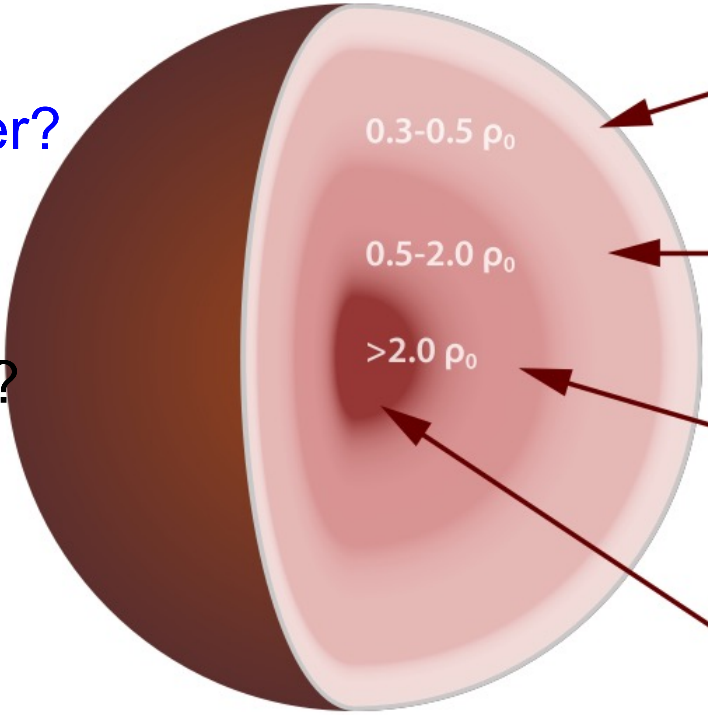
- Allow more observations of mergers of BHs and NSs
  - More
  - Further
    - More short gamma-ray bursts
  - Wider mass range (sub-solar mass?)
  - Greater fidelity (SNR) → details of the GW waveforms

- Allow opportunity for observing new types of GW sources
  - Supernovae
  - Magnetars
  - Long gamma-ray bursts
  - Cosmic strings
  - Inflation

Neutron stars

- NS result from normal stellar evolution for massive stars in the range 8 to 40 $M_\odot$
  - Fusion to Iron
  - Supernova (Type II)
- NS mass: 1 to 2-ish $M_\odot$
  - (heavier remnant → black hole)
- Radius ~ 10 km
  - ~ nuclear density! At surface: g=$2\times10^{12}\ m/s^2$
- Mysterious composition
  - new phases of matter?
- GWs from NS mergers
  - GW170817
- Other GW observations?

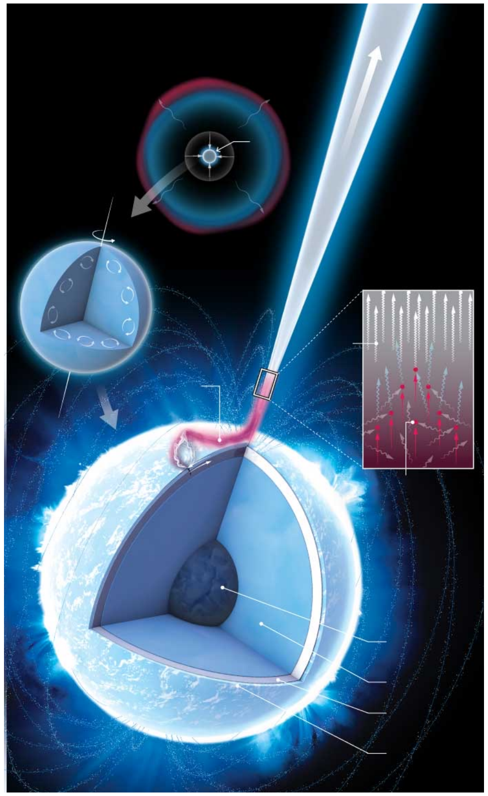


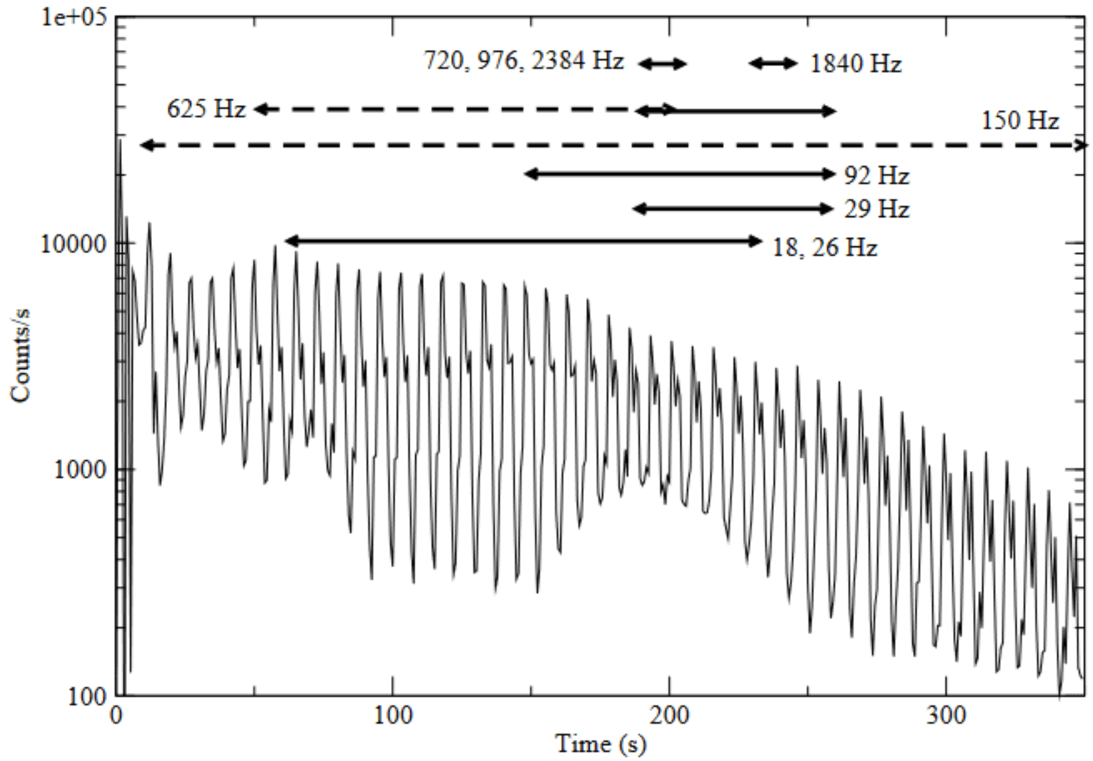


Magnetars

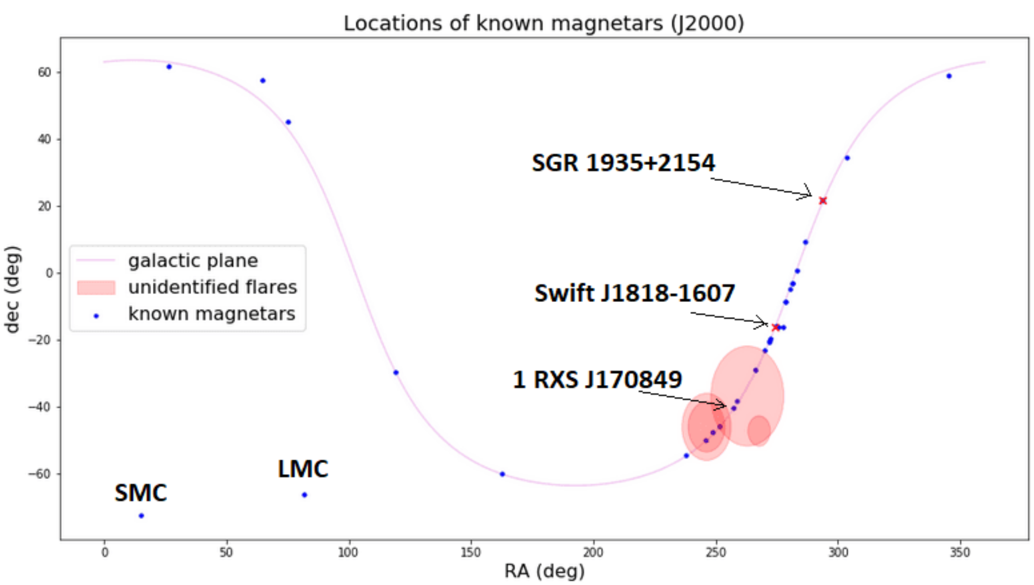
- Magnetars are young neutron stars with magnetic fields about 1000x that of ‘normal’ neutron stars
  - $B \sim 10^{13} - 10^{15}$ G
  - Earth: 0.5 G
- Slowly rotating: few Hz or less (magnetic braking)
- About 90%/10% of core-collapse supernovae result in normal neutron stars/magnetars
- Earth (and satellites!) receive a giant x-ray flare every 5-10 years
- Frequent smaller x-ray flares

Magnetars and GWs ?





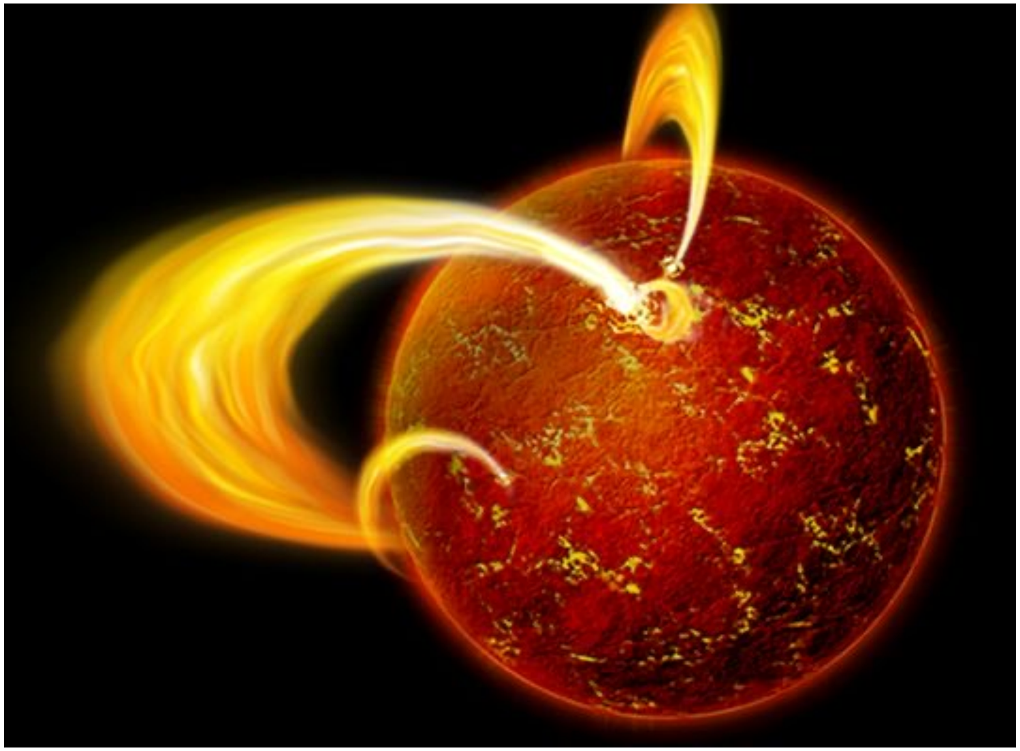
X-rays from 2004 giant flare SGR 1806-20

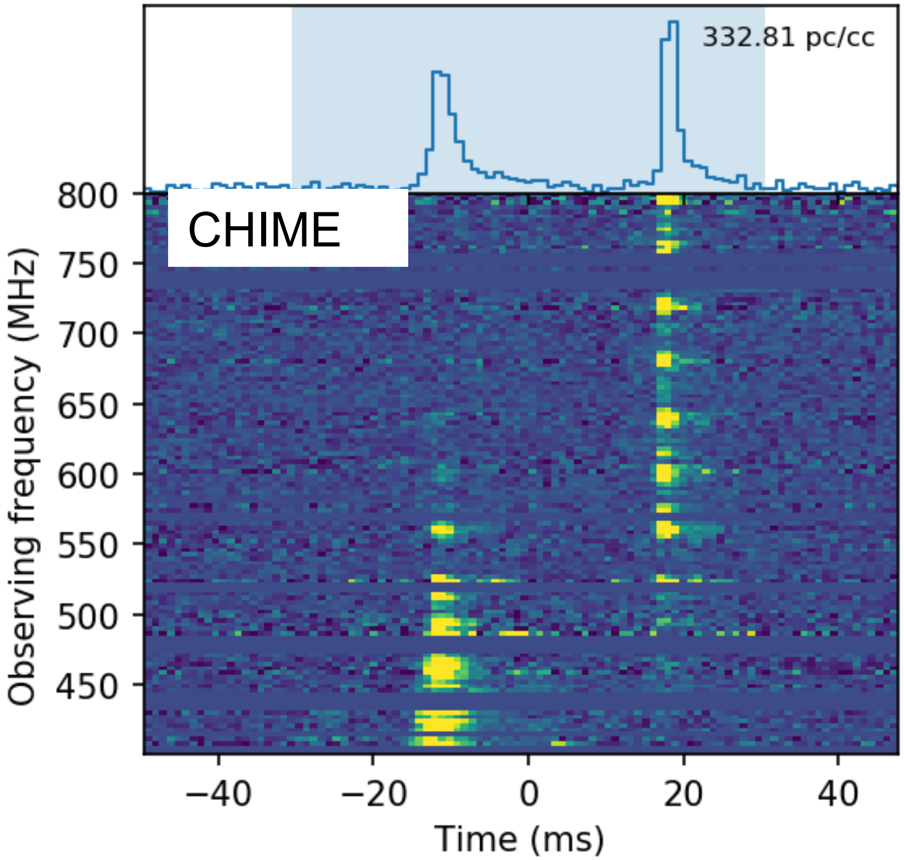


- Starquakes produce (giant) x-ray flares
- They also ring-up mechanical modes in the magnetar, some (e.g. f-modes) can produce GWs
- ← No giant flares during O3 run, but many ordinary x-ray flares
- UO student Kara Merfeld leading the O3 collaboration analysis/paper

Magnetars and FRBs

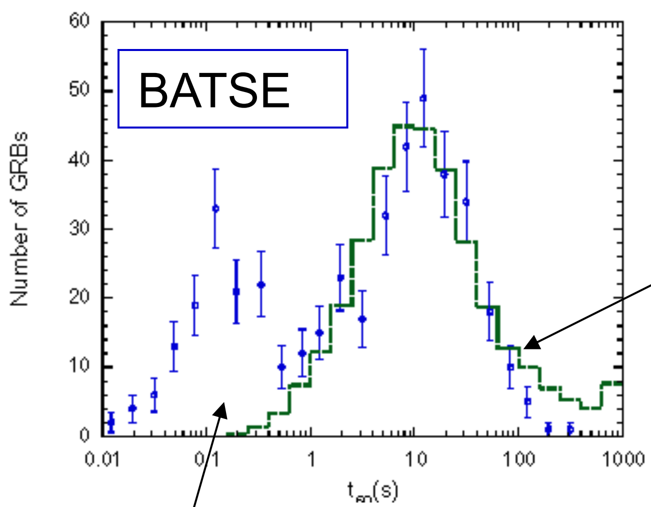
- Fast Radio Bursts are a cosmic mystery
- New FRB detector CHIME has revolutionized the field
- April 28, 2020: galactic FRB (first!) associated with known magnetar SGR1935+2154
- UO students Kara Merfeld and Matthew Ball on it





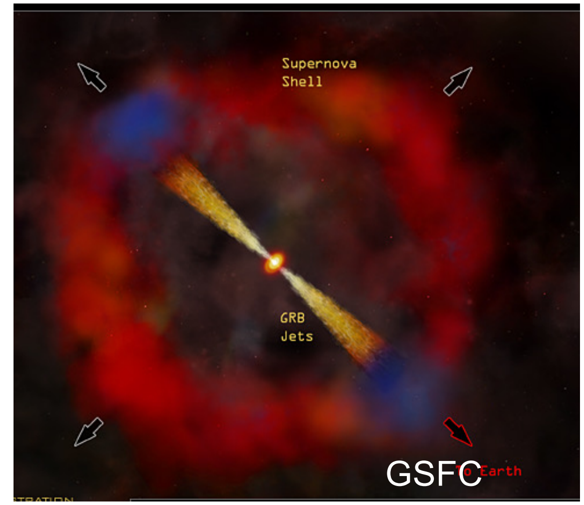
LIGO

Gamma-ray Bursts



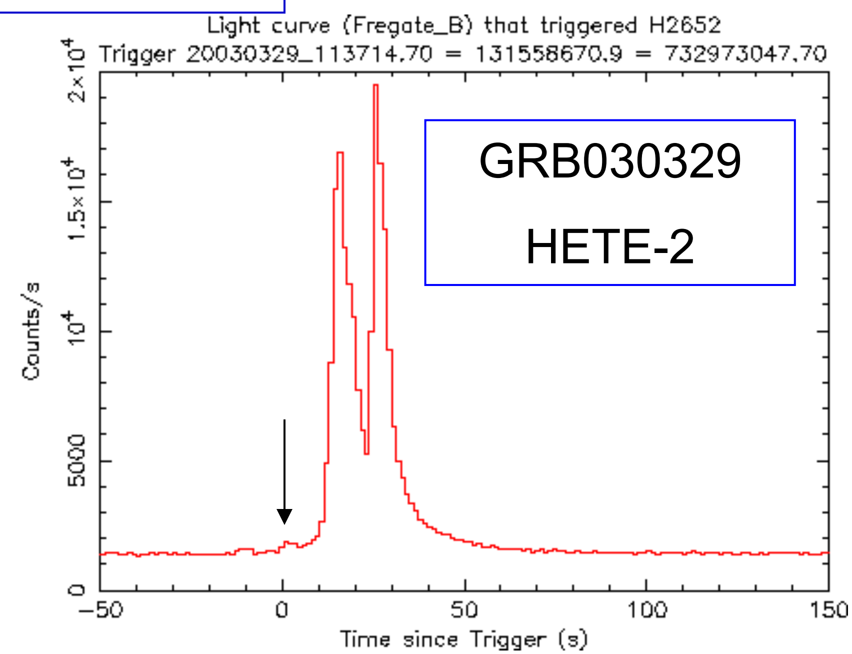
Long-duration GRBs

- SNe-like progenitors “hypernovae”, “collapsars”
- mean z ≈ 2.3
- not expected to be efficient GW radiators

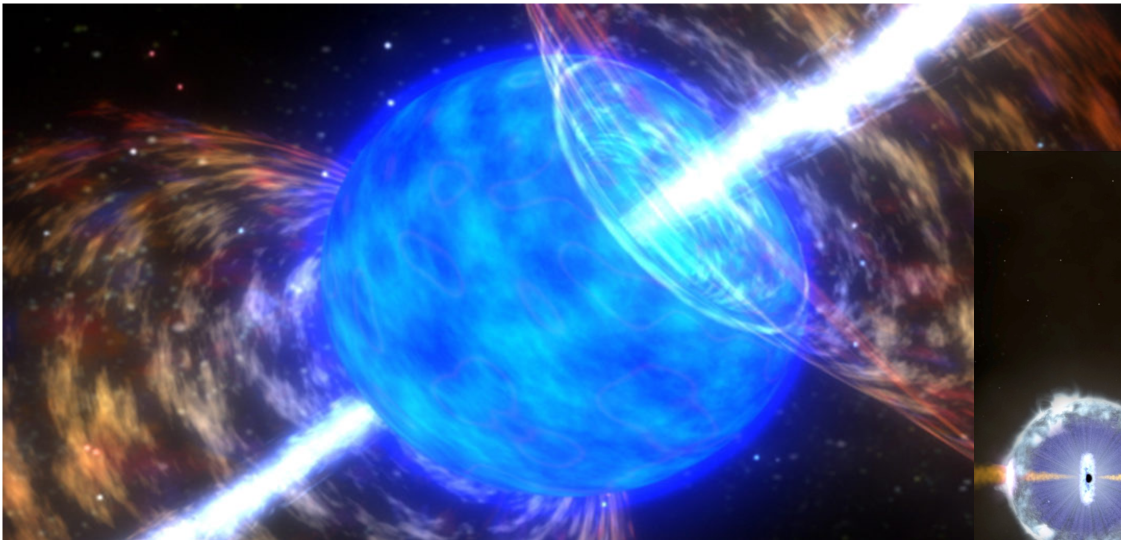


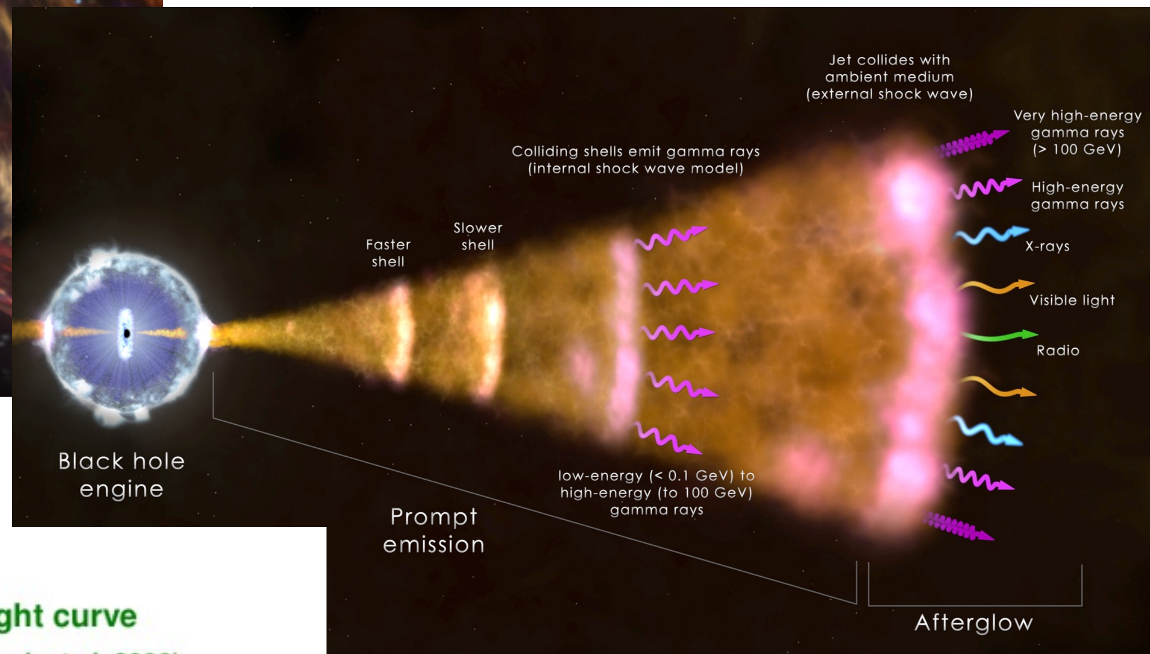
Short-duration GRBs

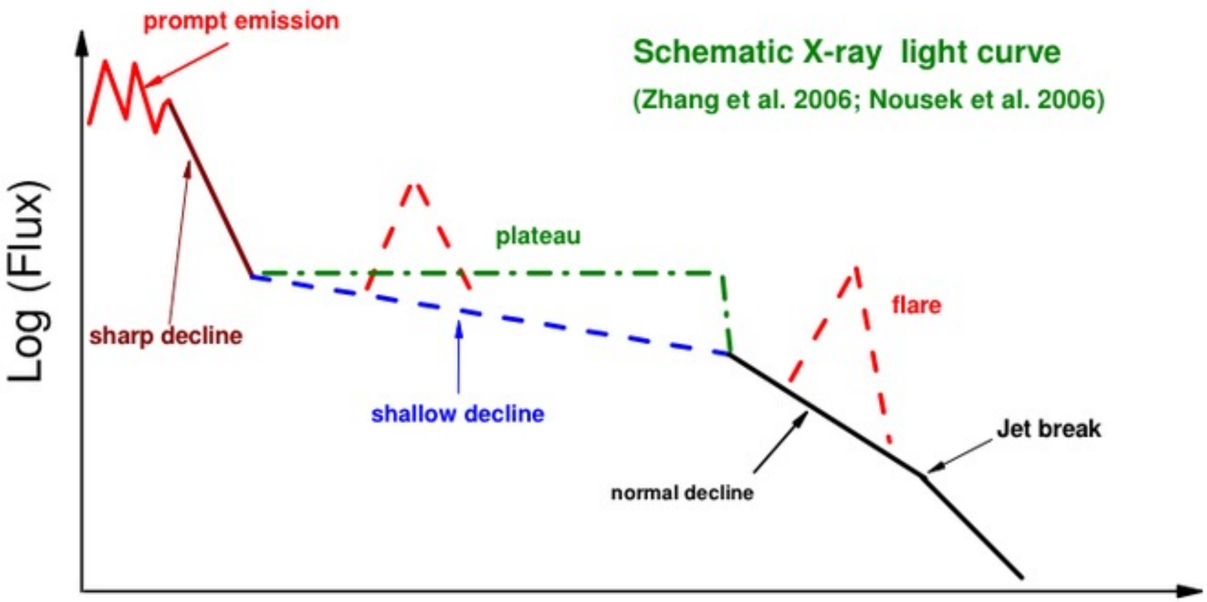
- NS-NS or NS-BH mergers
- mergers are efficient GW radiators
- mean z ~ 1
- GRB 170817: only GRB with GW counterpart so far



GWs from Collapsars ('long' GRBs)







- GW mechanisms
  - Initial collapse
  - Hypermassive NS
  - Accretion disk instabilities (flares!)

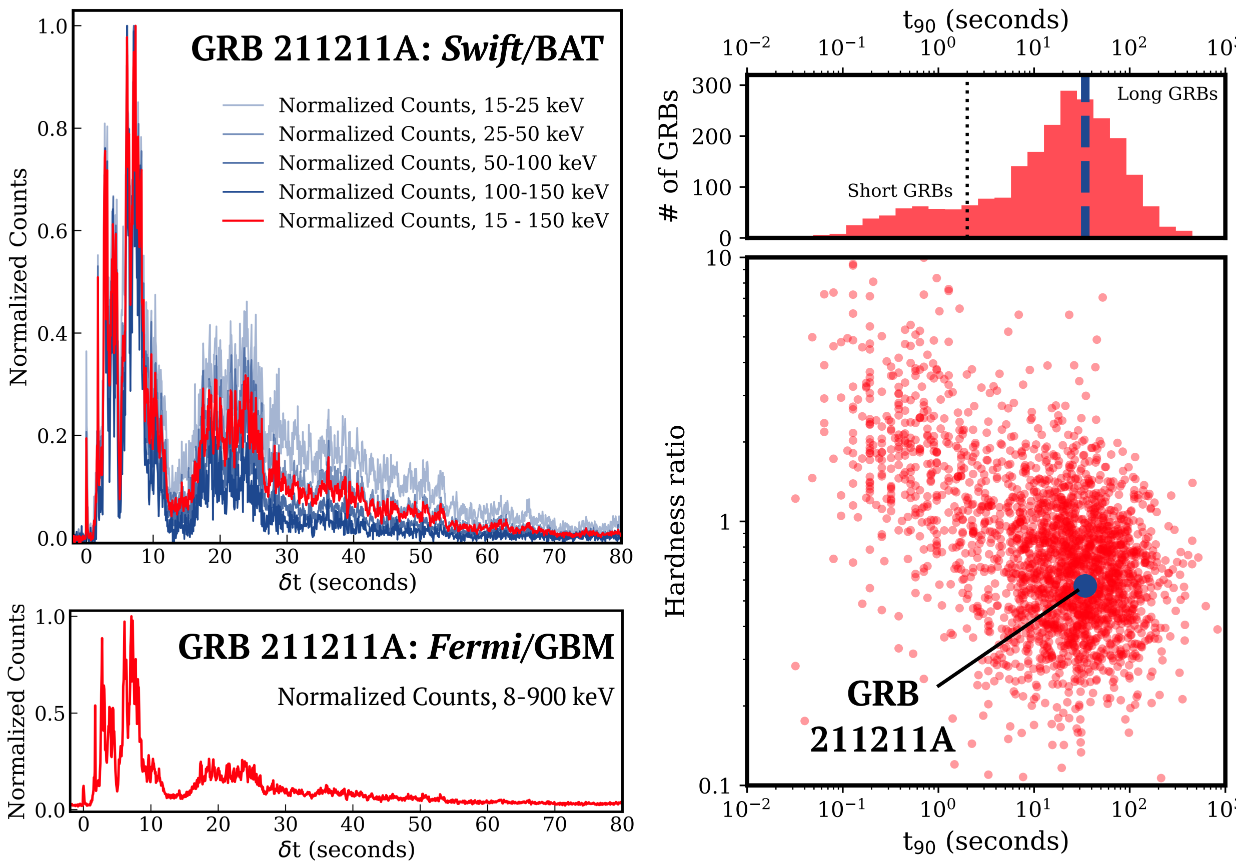
Long and short GRBs: Not so fast!

HE] 22 Apr 2022

A Kilonova Following a Long-Duration Gamma-Ray Burst at 350 Mpc

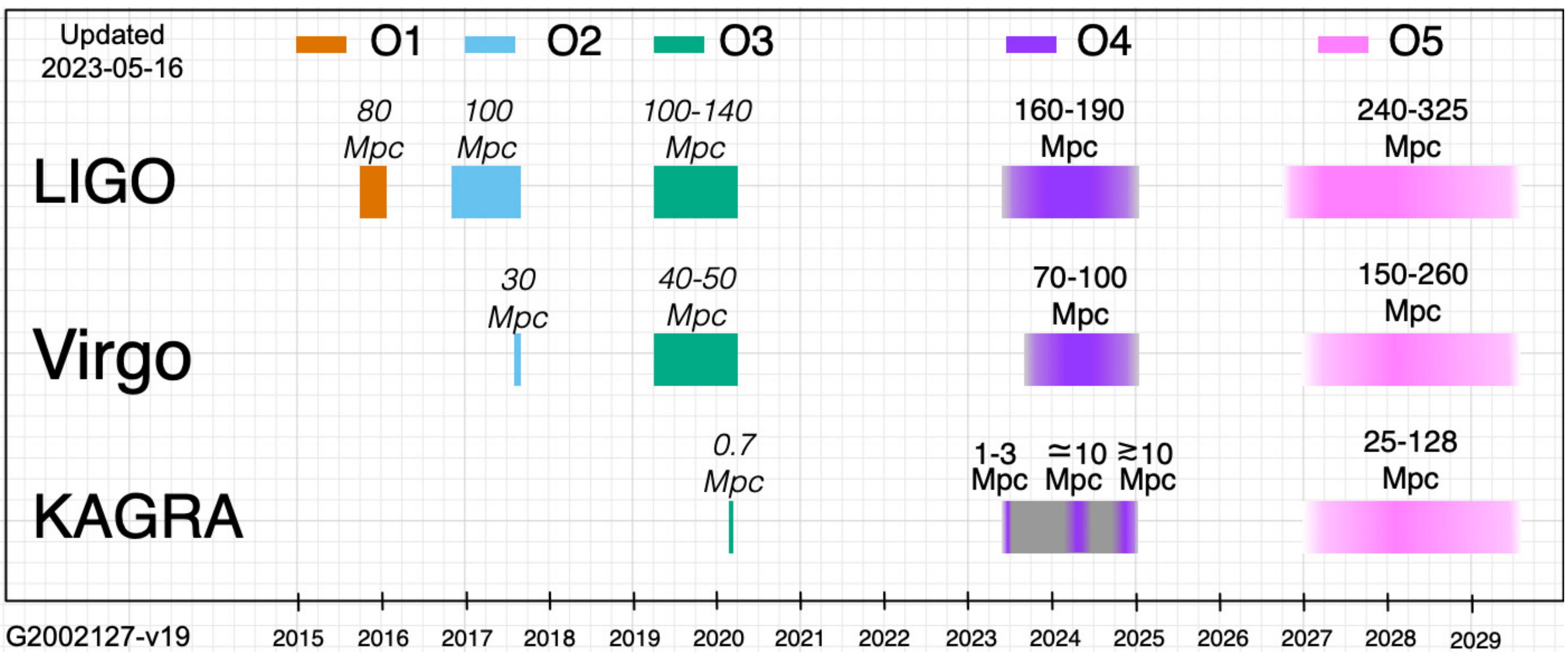
Jillian Rastinejad[1*], Benjamin P. Gompertz[2], Andrew J. Levan[3], Wen-fai Fong[1], Matt Nicholl[2], Gavin P.

A long GRB from a NS-NS merger!

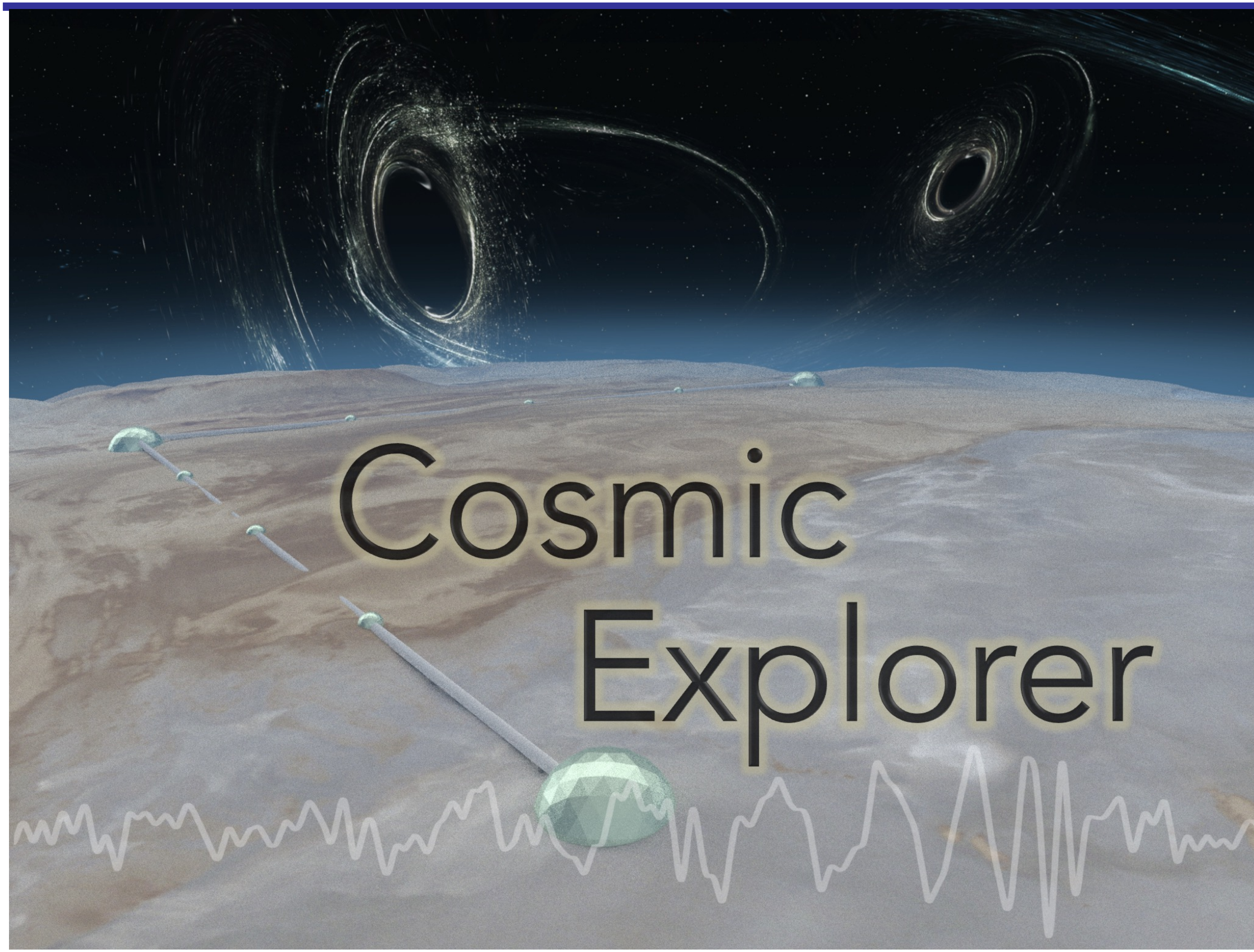


The near future

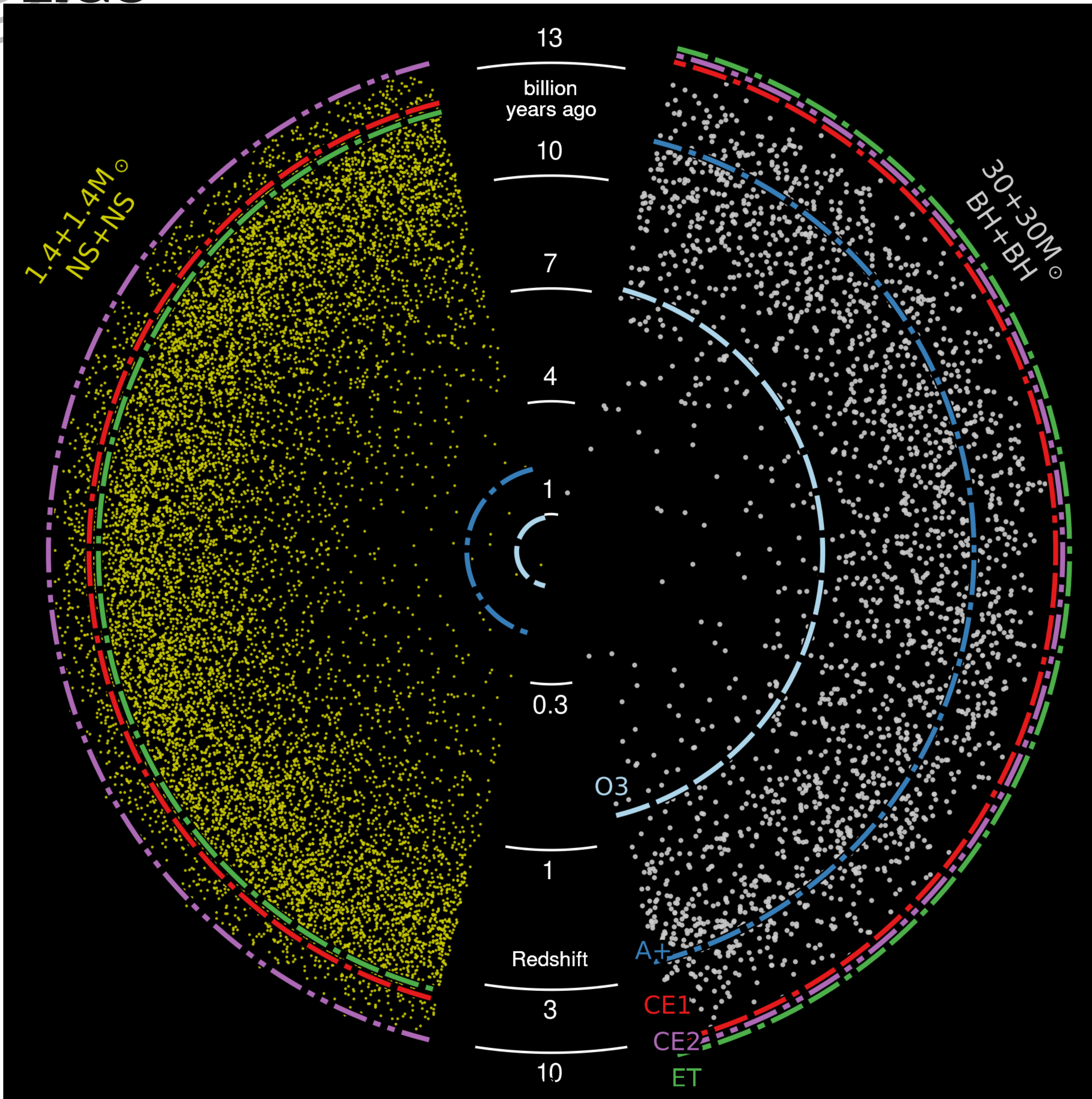
- In O1-O2: about 1 GW event per month
  - GW discovery
  - Binary neutron star merger
- In O3: about 1 GW event per 5-days
  - Routine quantum squeezing
  - ‘impossible’ high mass black holes
- O4 (started May 24, 2023): expect about 1 event per day
  - Frequency-dependent squeezing
  - What new discovery awaits??



The farther future (2030s)



Why CE ?



Also:
10% of BBH will have SNR>1000

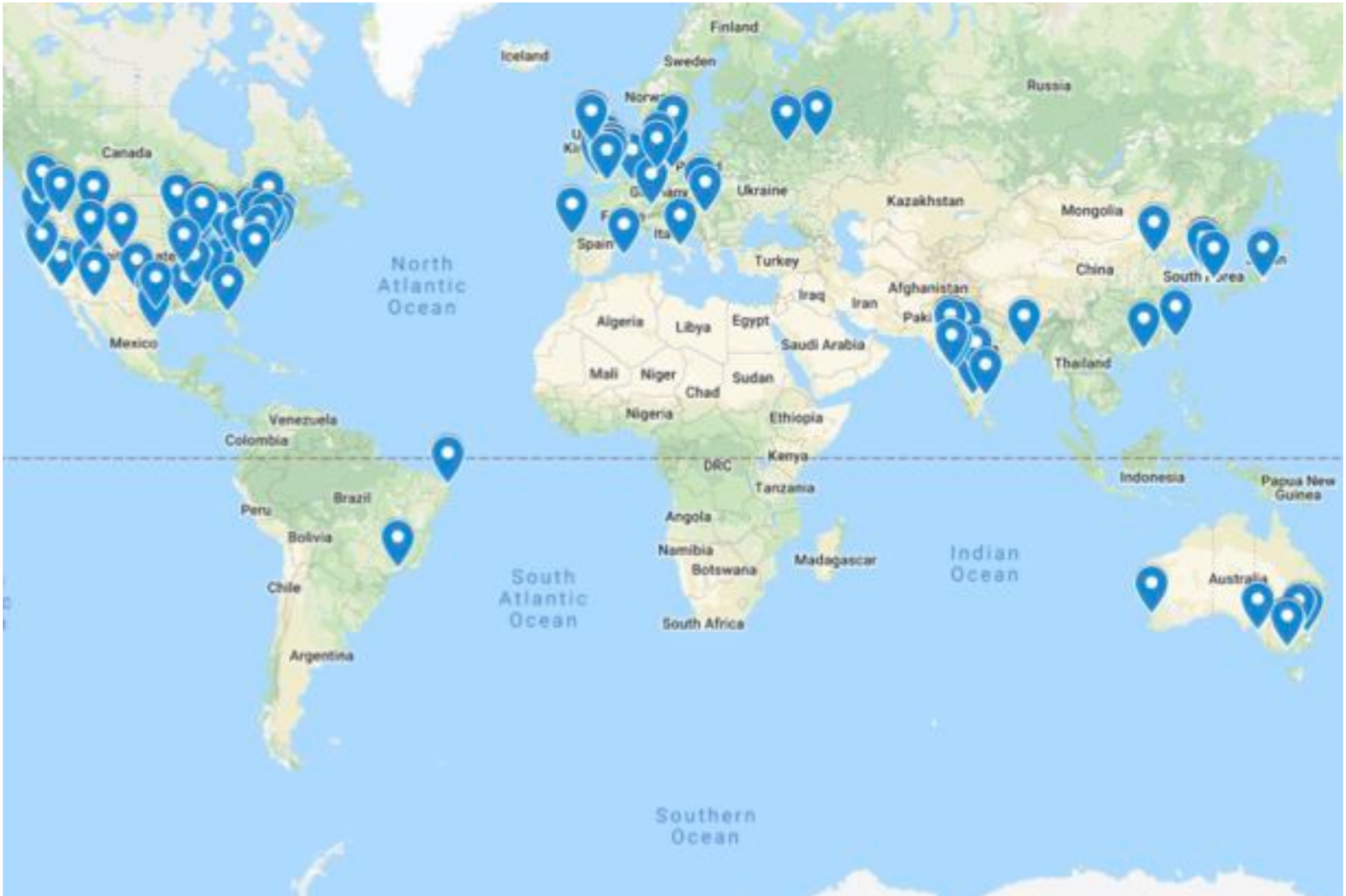
1% SNR~10,000

UO-LIGO 2023

- Ray Frey, Professor
- Ben Farr, Assistant Professor → Associate Professor
- Robert Schofield, Research Professor
- Philippe Nguyen, (Data Quality, GRB physics) → PhD 2022
- Kara Merfeld, 5th year (DQ, magnetars, FRBs) → PhD June 2023
- Bruce Edelman, 5th year (BBH populations) → PhD June 2023
- JD Merritt, 4th year (DQ, BBH populations)
- Adrian Helmling-Cornell, 4th year (DQ, cosmic strings)
- Matthew Ball, 4th year (DQ, magnetars)
- Gino Carillo, 4th year (GRB afterglows)
- Sangeet Paul – 4th year (BBH populations)
- Jaxen Godfrey – 3rd year
- Ben Mannix – 3rd year

LIGO

LSC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Canada
Ukraine
Kazakhstan
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Iraq
Iran
Afghanistan
Spain
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Mexico
Algeria
Libya
Egypt
Saudi Arabia
Mali
Niger
Chad
Sudan
Thailand
Nigeria
Ethiopia
Venezuela
Colombia
Kenya
DRC
Tanzania
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Papua New Guinea
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Botswana
Madagascar
Indian Ocean
South Atlantic Ocean
Chile
South Africa
Australia
Argentina
Southern Ocean

UO-LIGO June 28, 2021