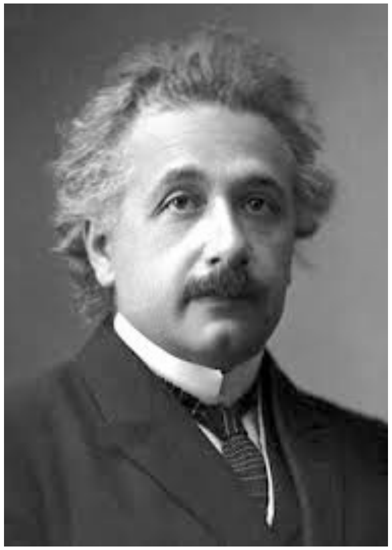
Update on LIGO and gravitational-wave Astrophysics

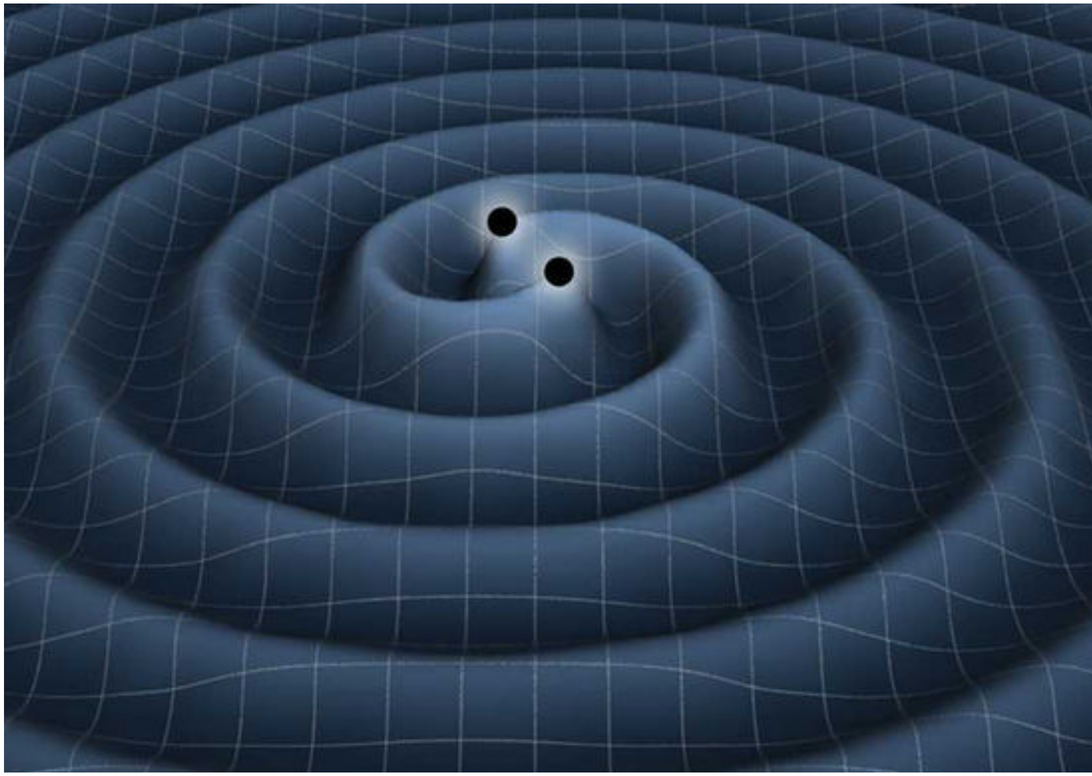
Gravitational Waves (GWs)

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



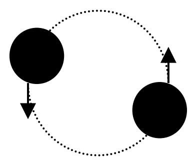
- General Relativity describes gravity in terms of a spacetime which is deformable. [Einstein, 1915]
- GWs are oscillations of that spacetime. [Einstein, 1916]

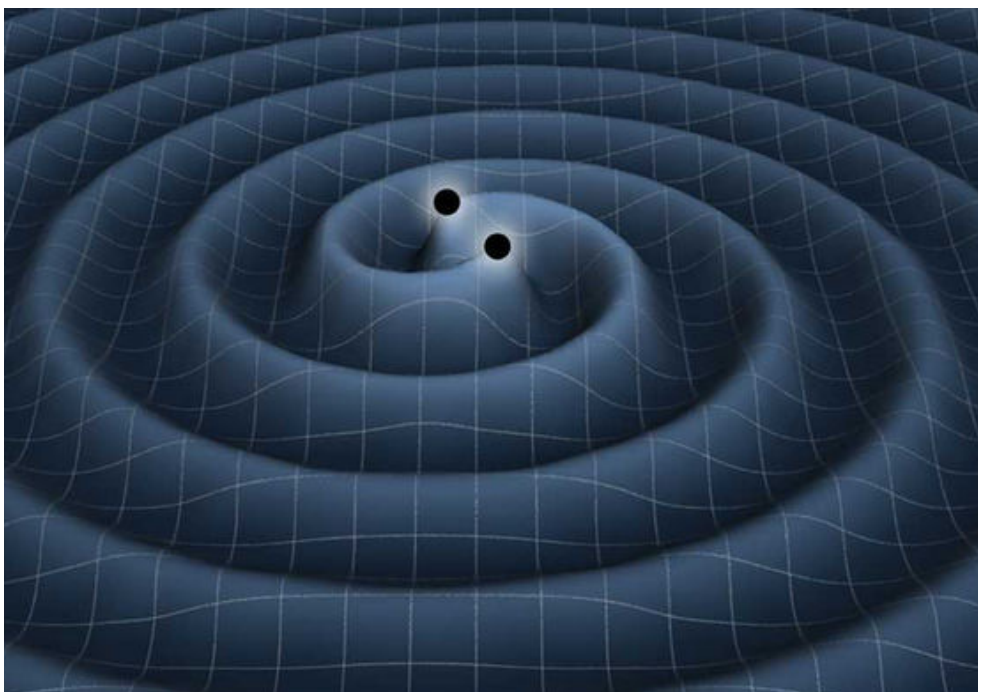
- "ripples in spacetime"



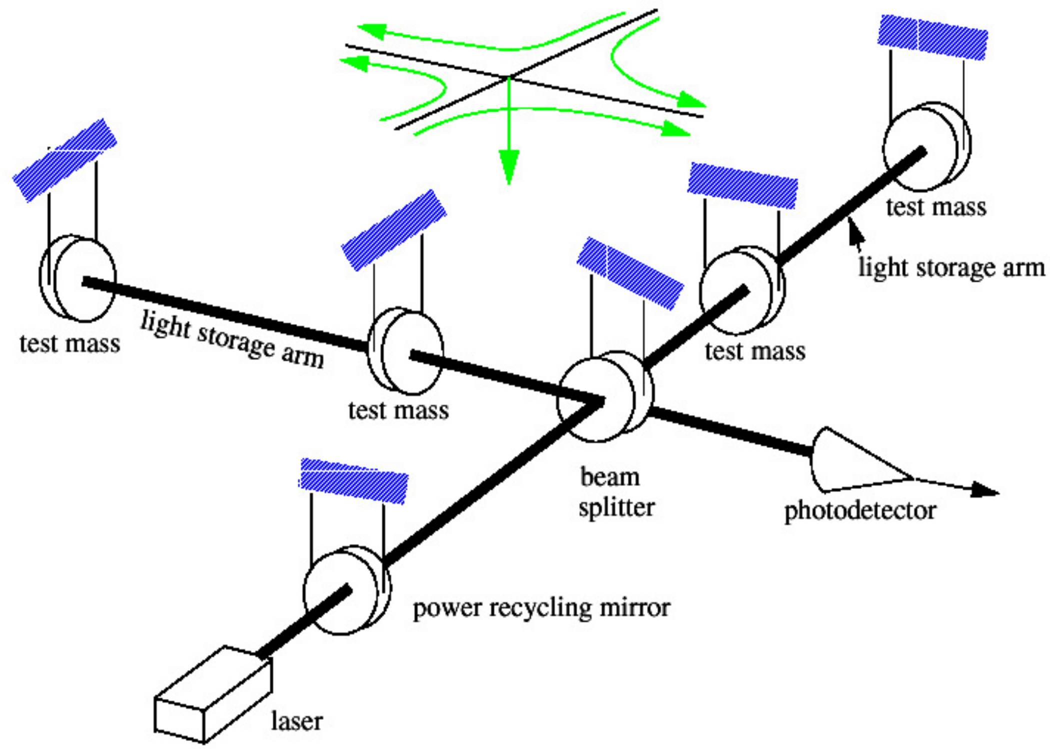
Gravitational waves and LIGO: short version

Binary black hole system





As detected by LIGO:

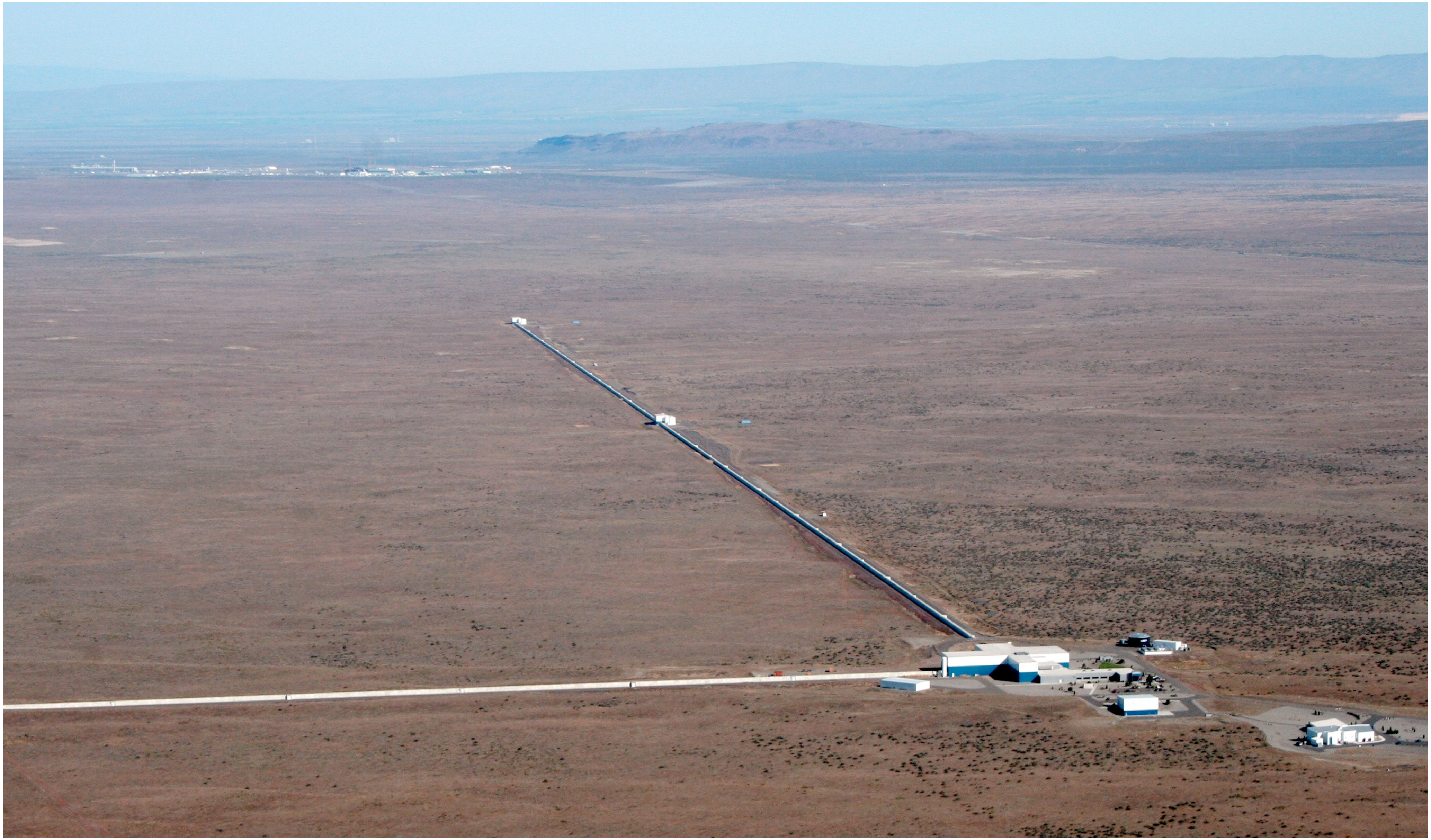


GW ripples manifest as a space strain h, where $h = \Delta L / L$

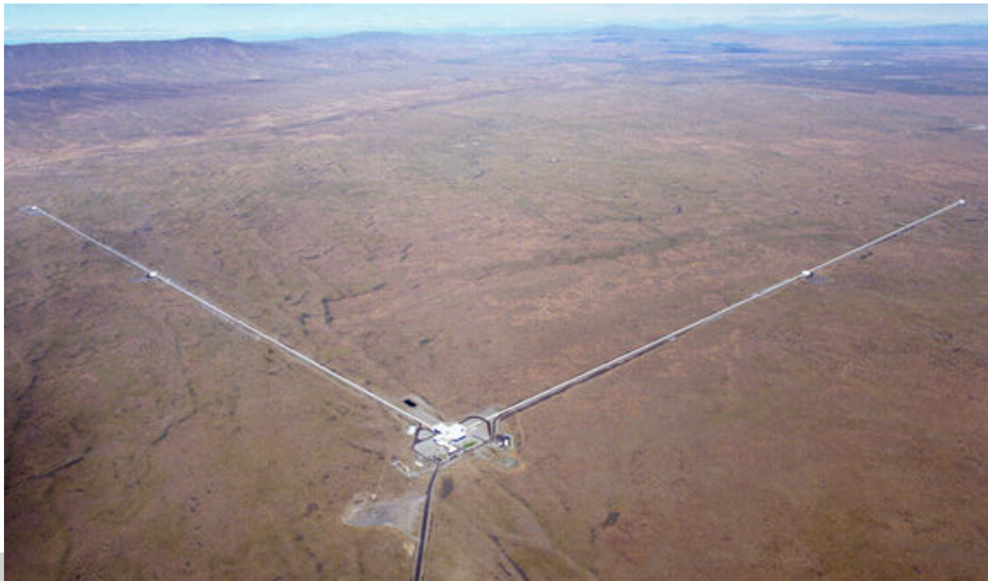
Realistic sources: $h \sim 10^{-23}$

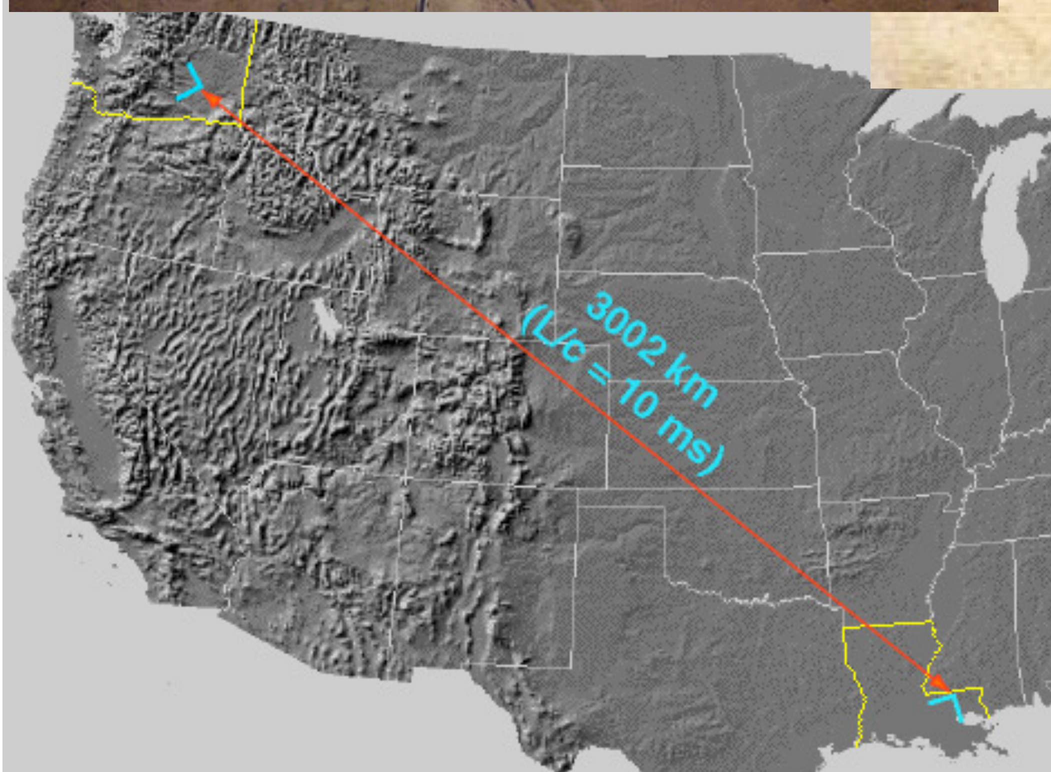
$\Rightarrow \Delta L \sim 10^{-19}$ m (Yikes !)

LIGO Hanford Observatory

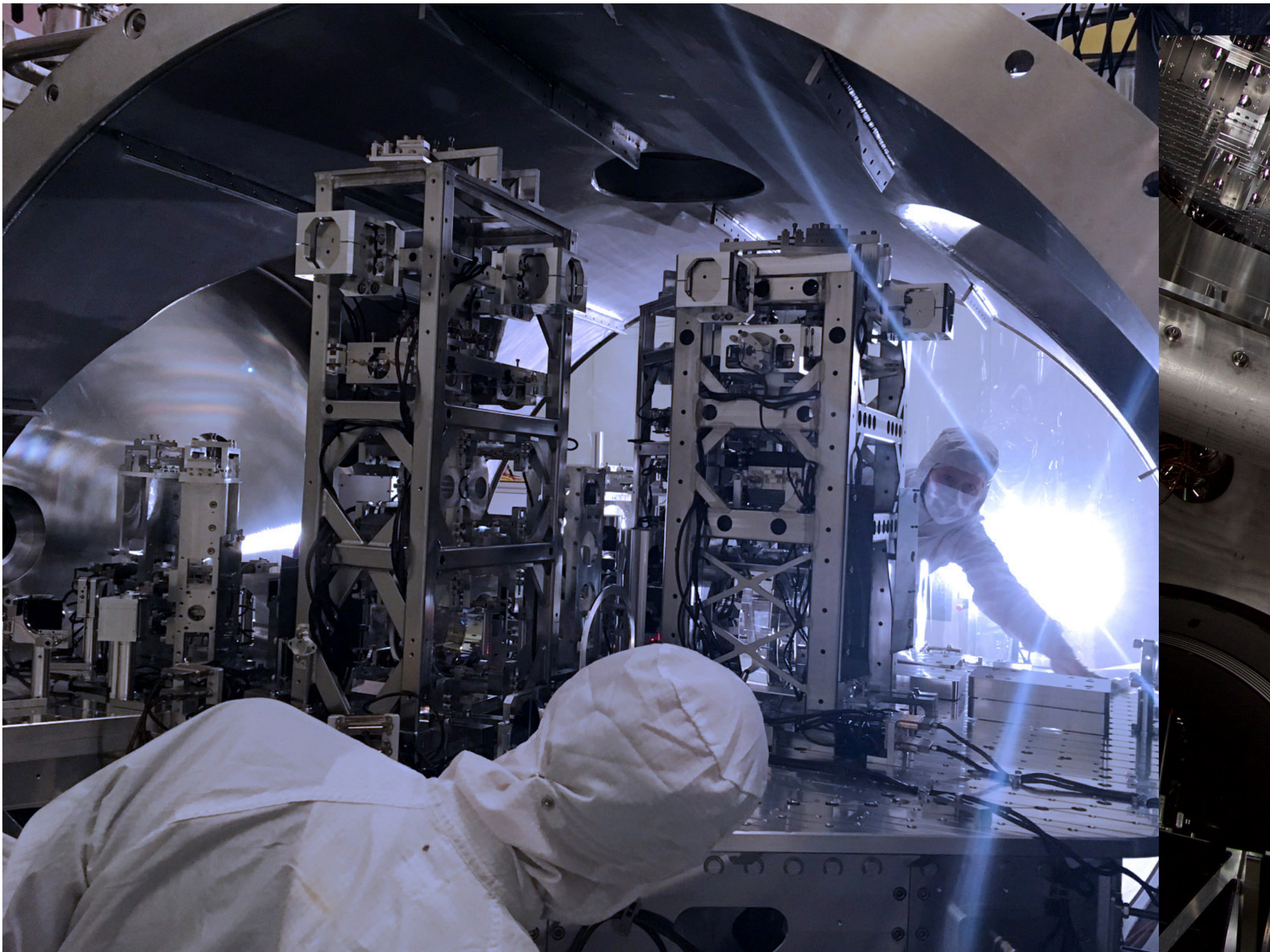


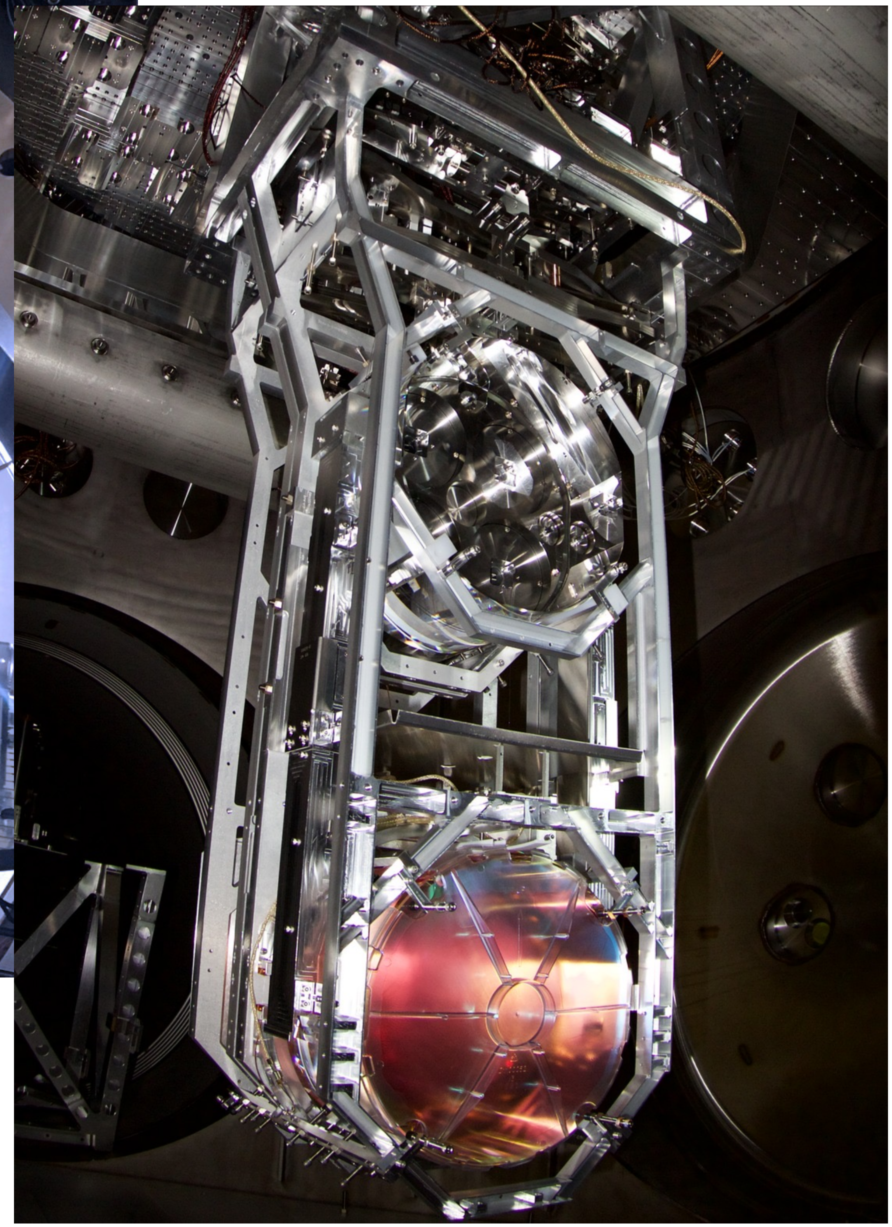
observatories



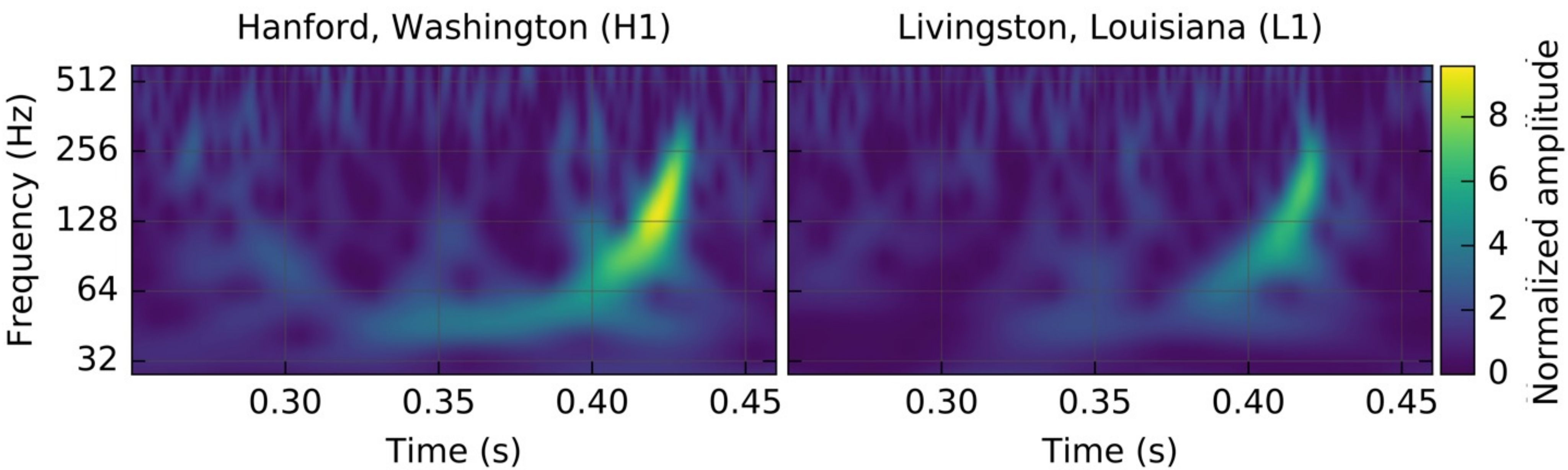


Inside the vacuum chambers





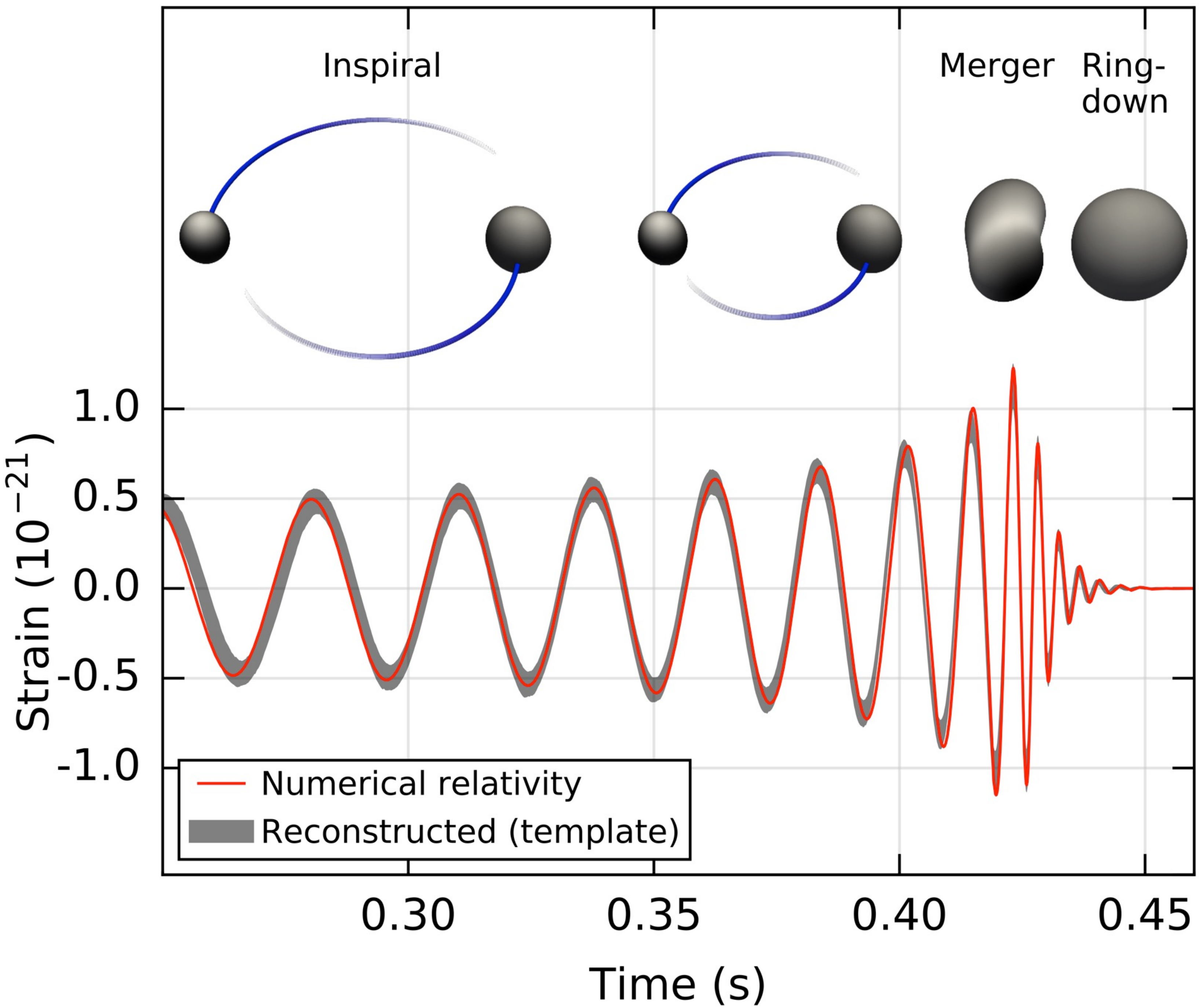
Boom !



GW150914

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

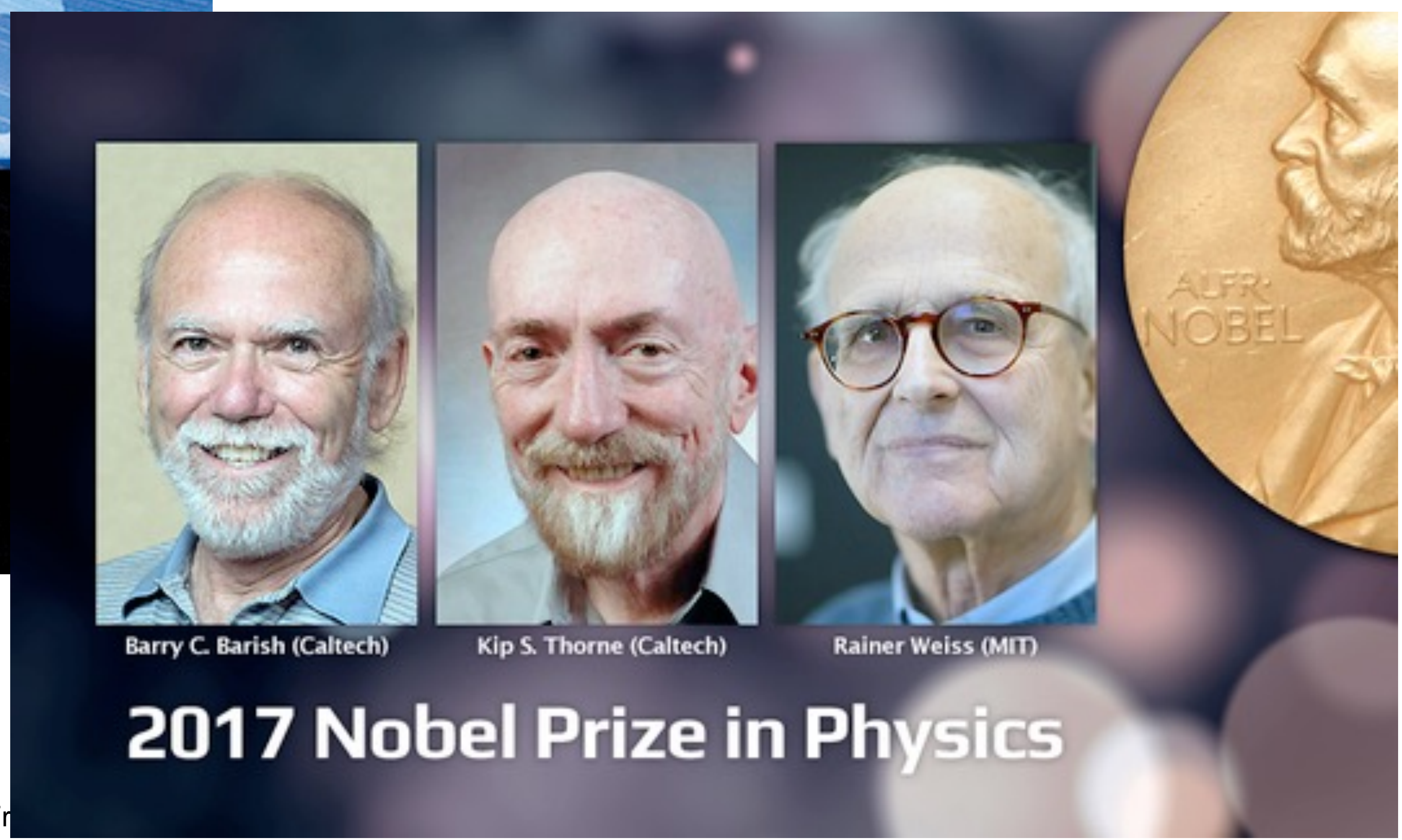
Binary black hole inspiral, merger, ringdown



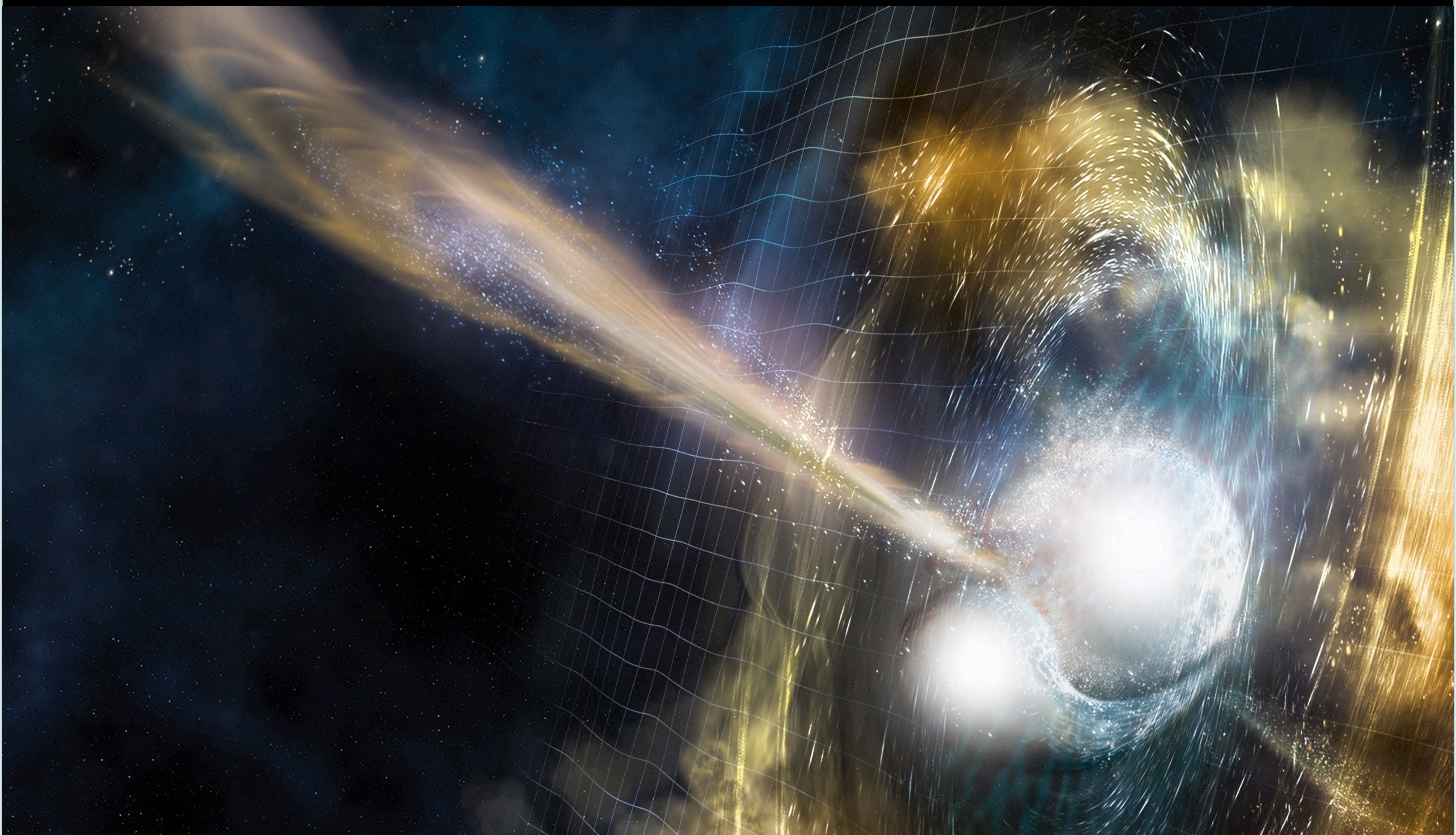
Simulated Nearby View – slowed down 100X

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

GW Discovery Accolades



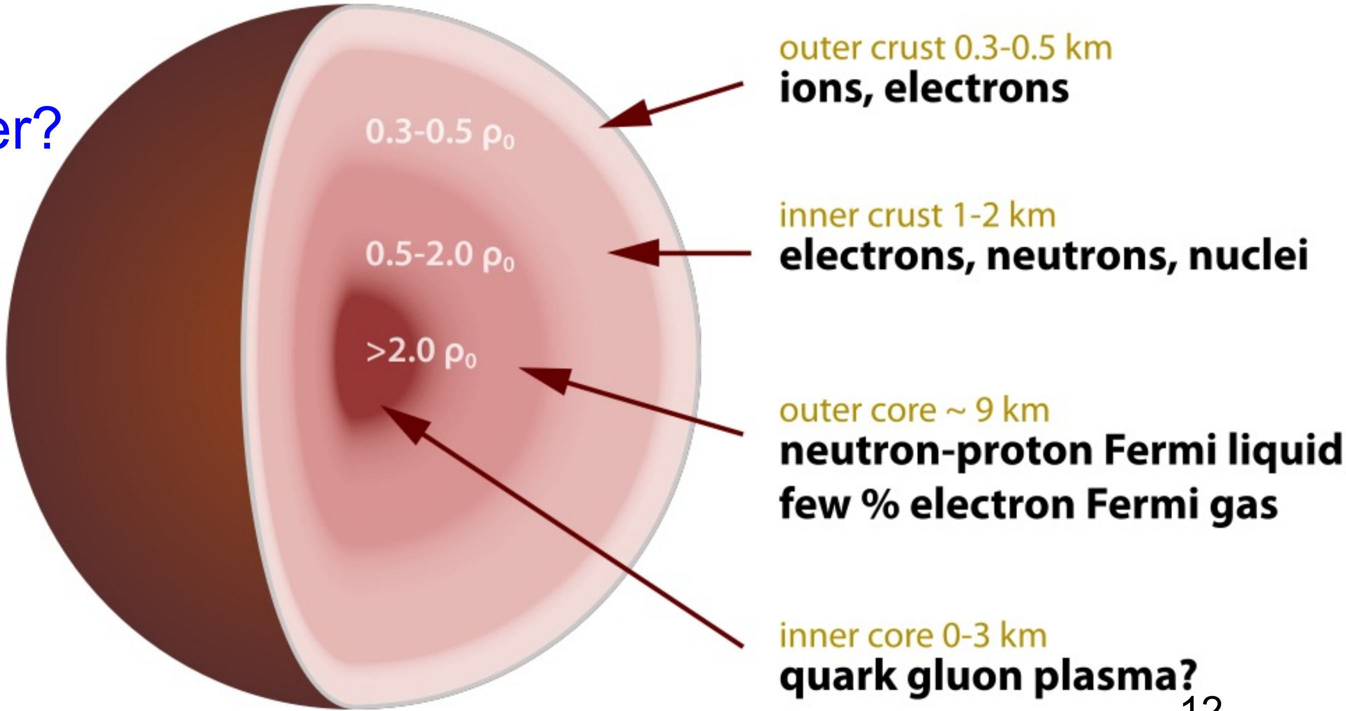
Boom II:
Binary neutron-star merger August 17, 2017



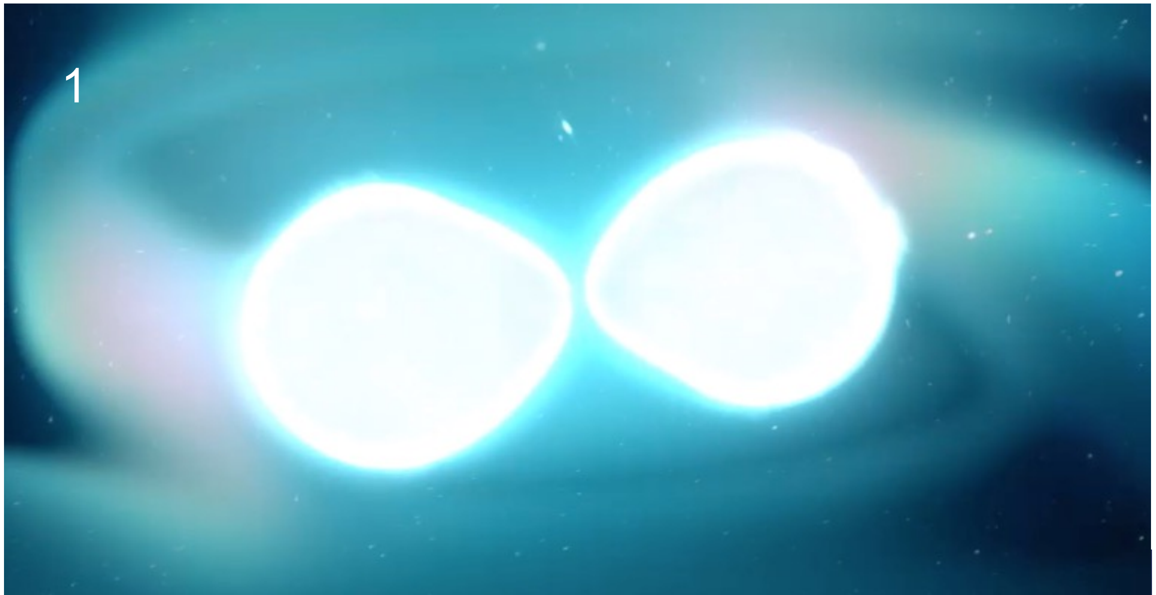
Neutron stars

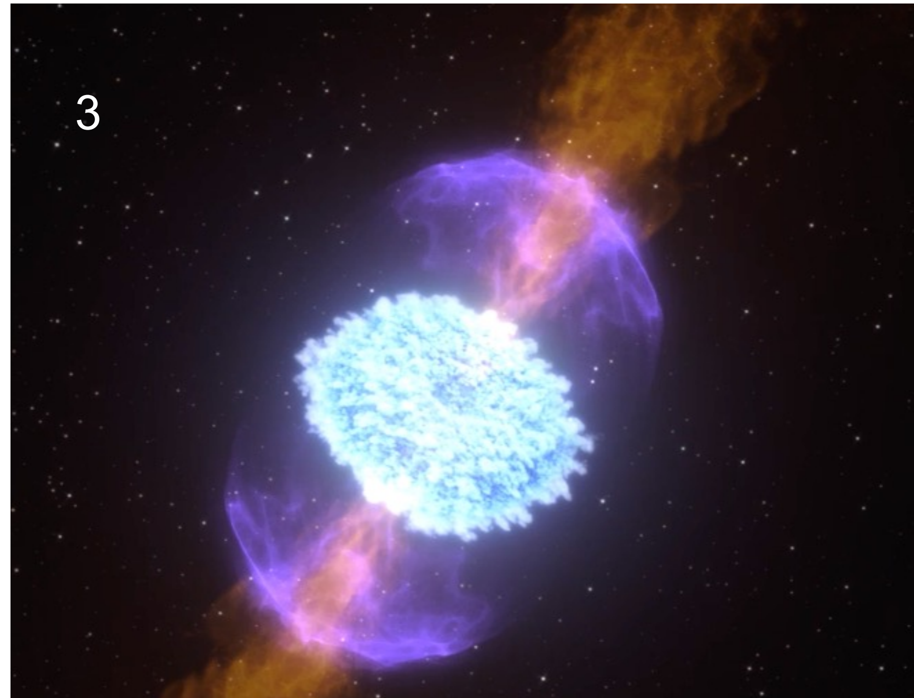
- NS result from normal stellar evolution for massive stars in the range 8 to 40 $M_\odot$
  - Fusion to Iron
  - Supernova (Type II)
- NS mass: 1 to 3 $M_\odot$
  - (heavier remnant → black hole)
- Radius ~ 10 km

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

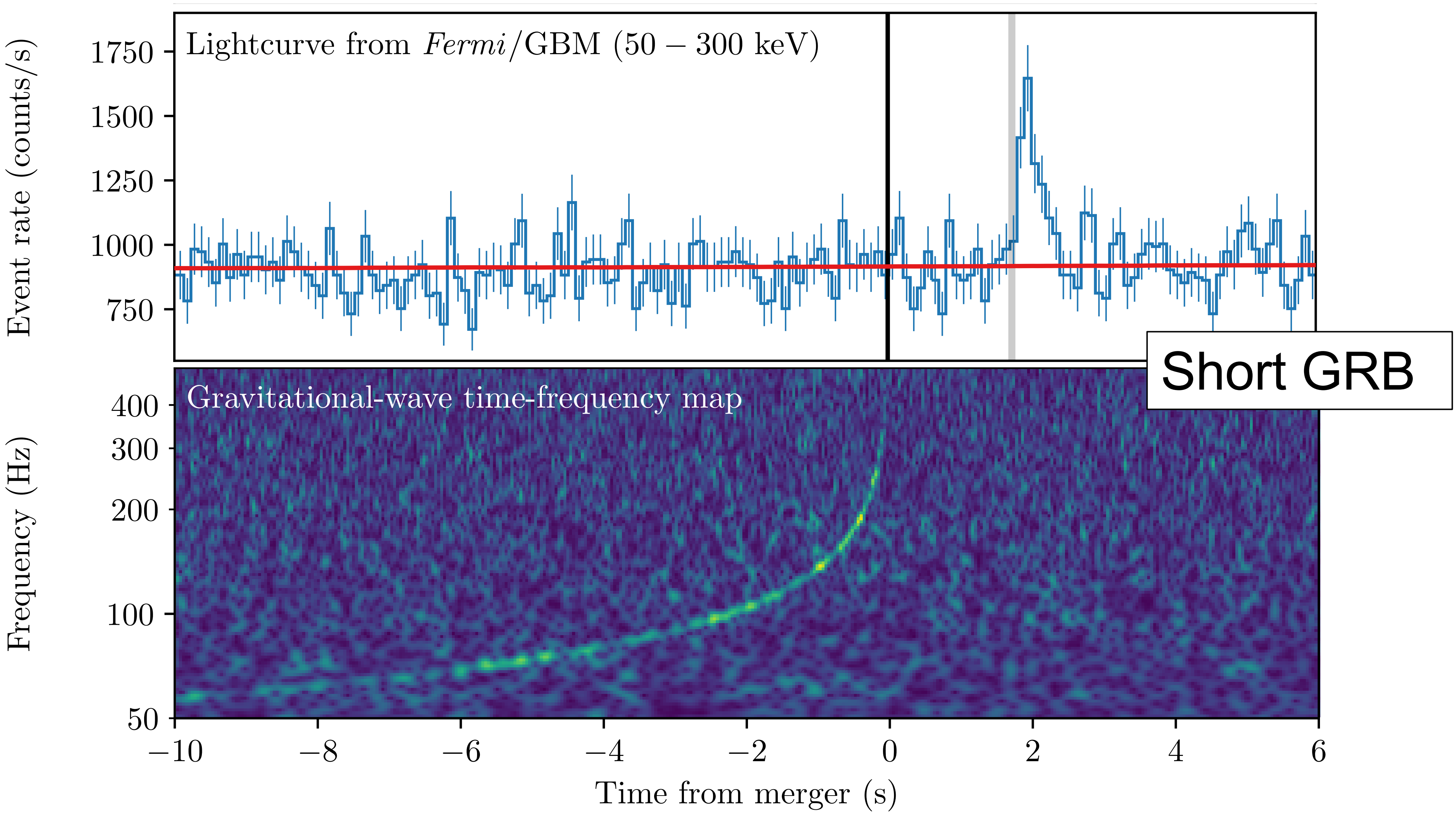


NS Merger, gamma-ray burst, afterglow (“kilonova”)





August 17, 2017: LIGO+Fermi



$\Delta t = 1.74 \pm 0.05$ s

Speed of gravity

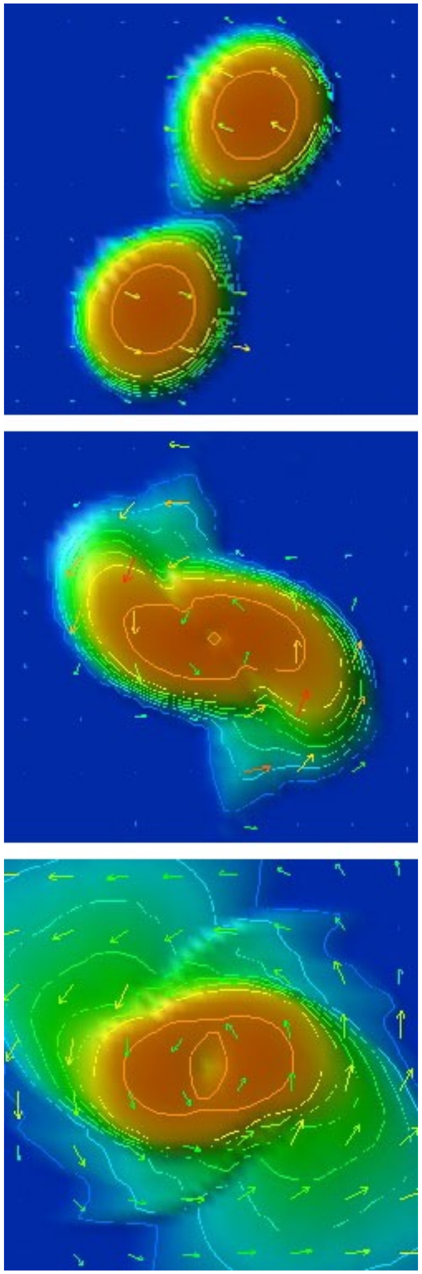
$$\Delta t = 1.74 \pm 0.05\,\mathrm{s} = \Delta t_{\mathrm{astro}} + \frac{D}{c^2}(c_g - c)$$

- 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

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

- Future measurements at different distances can improve this

170817: Astrophysics
The "kilonova"

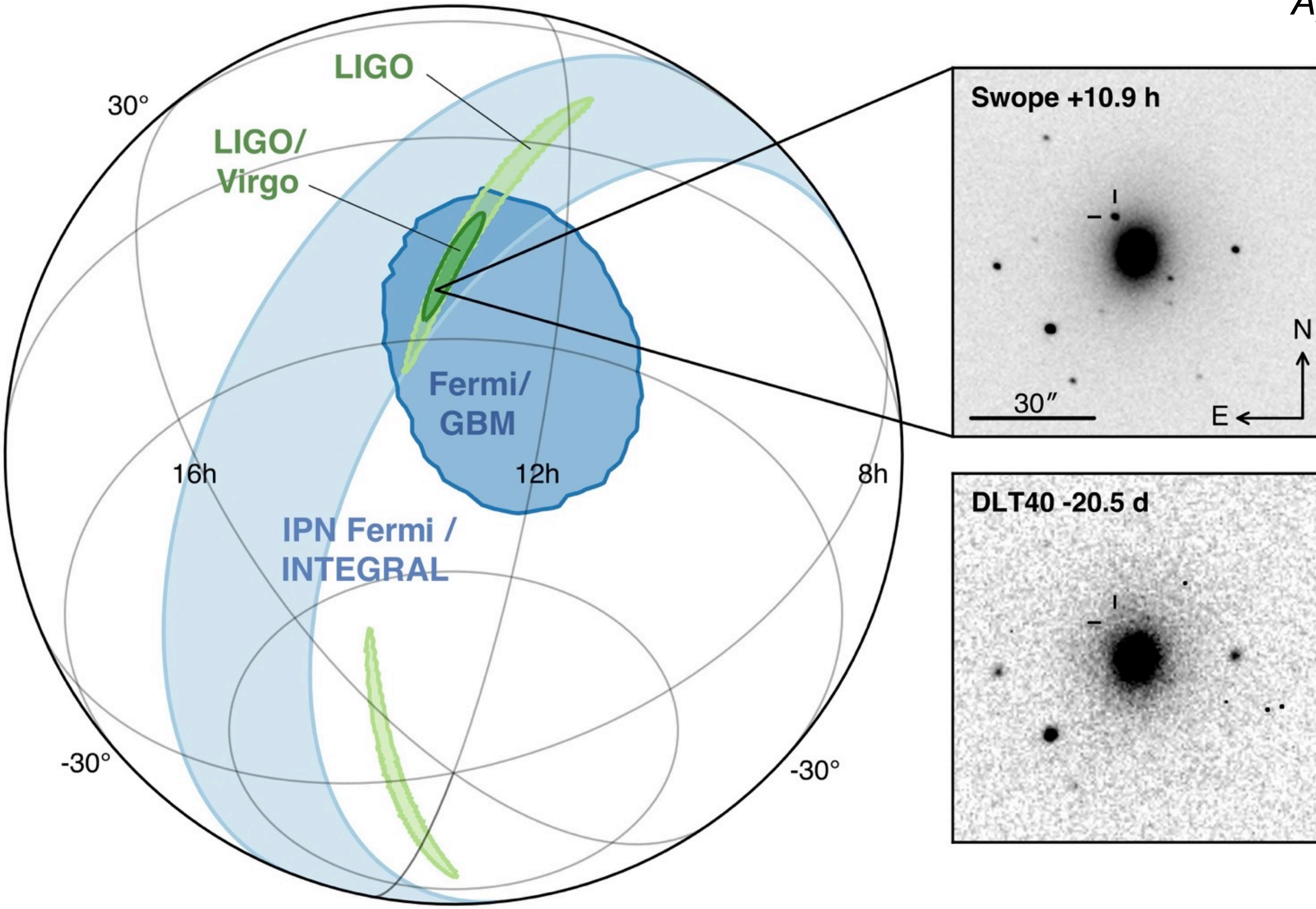


Shibata

- 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

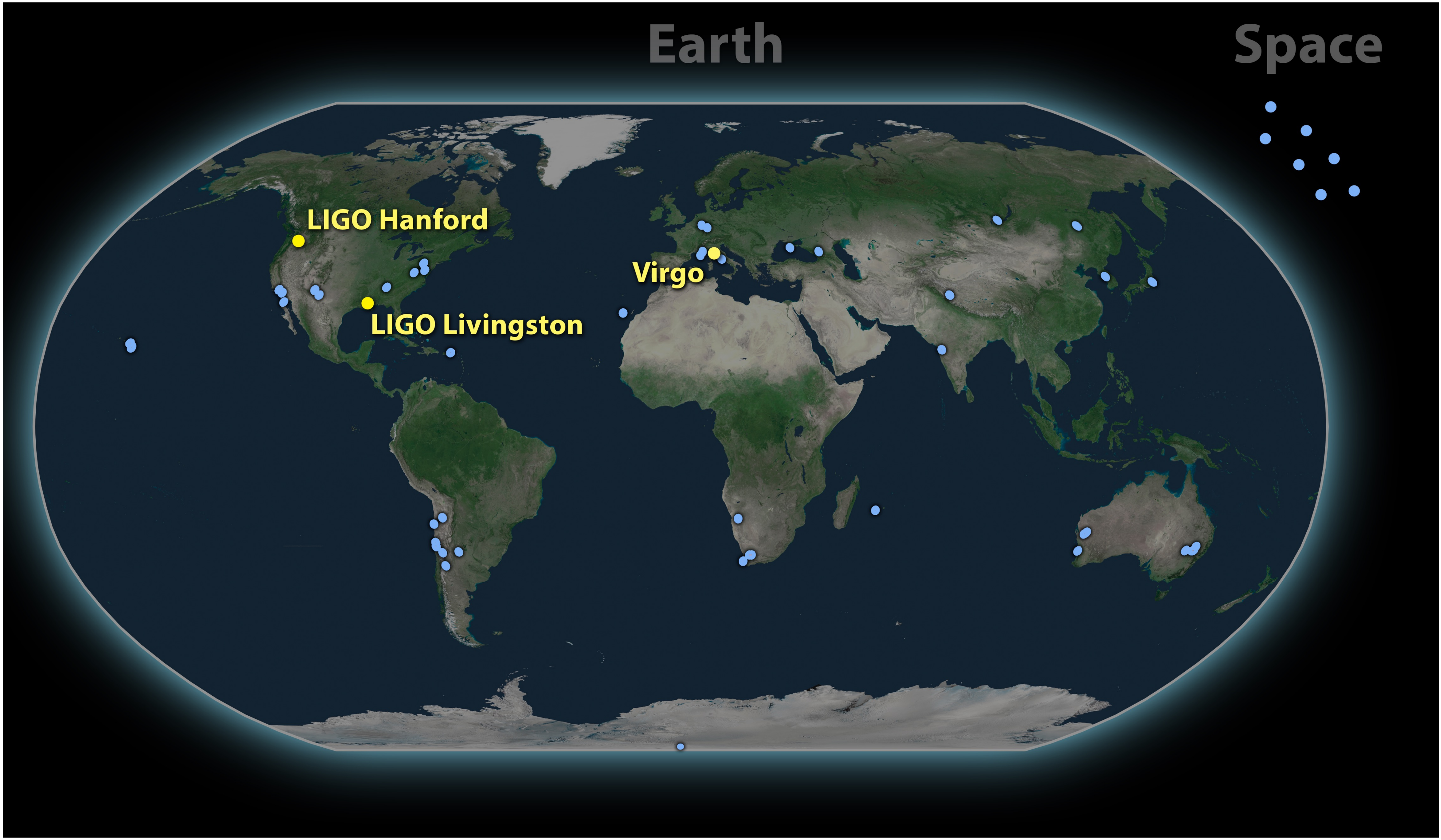


NGC 4993
43 ± 3 Mpc

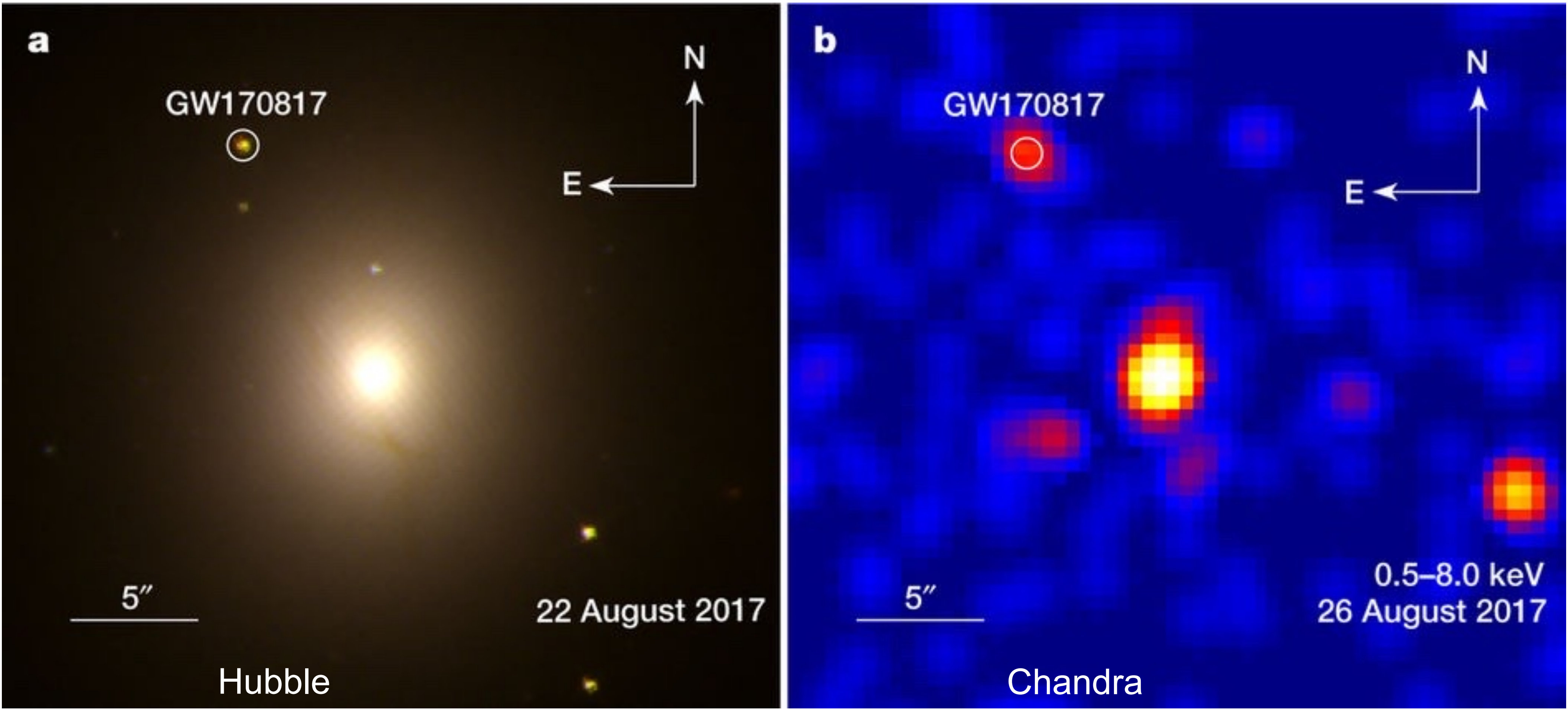
offset of 2 kpc – typical of kicks

"Multimessenger Astronomy"

and the astronomy world tuned in

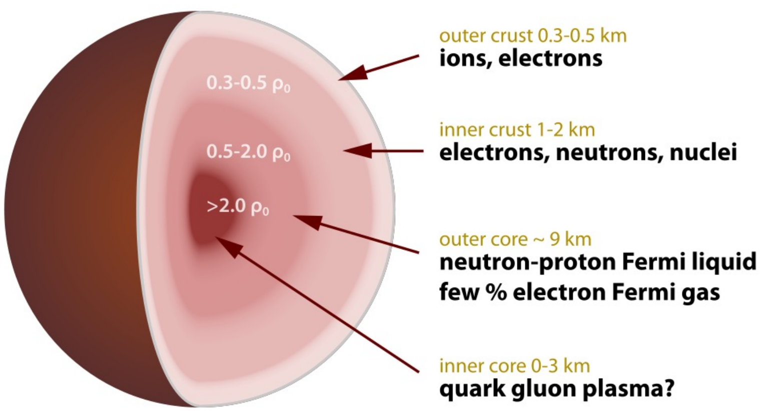


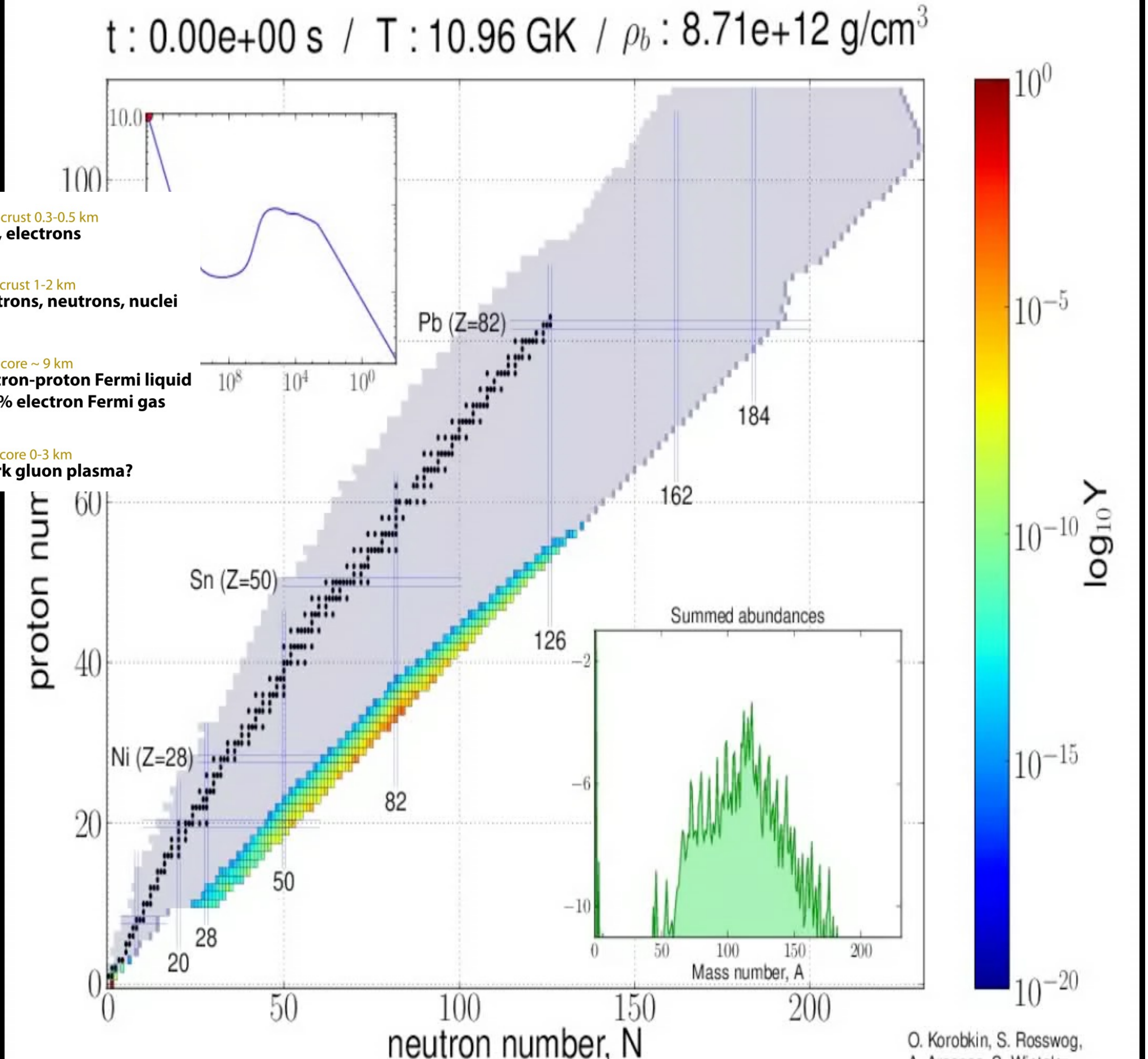
e.g. optical/IR and x-rays



Troja, et al, Nature 2017

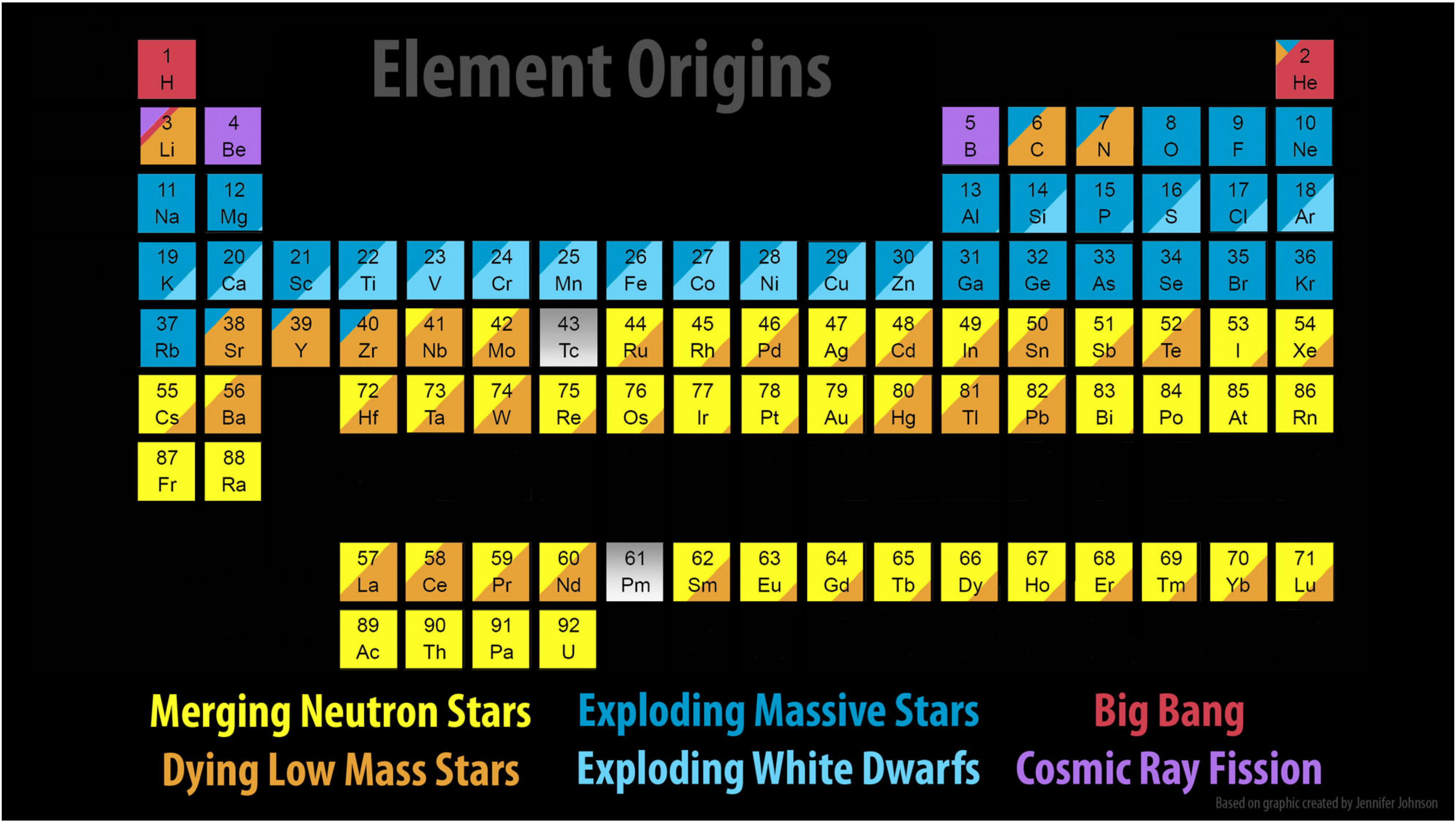
LIGO





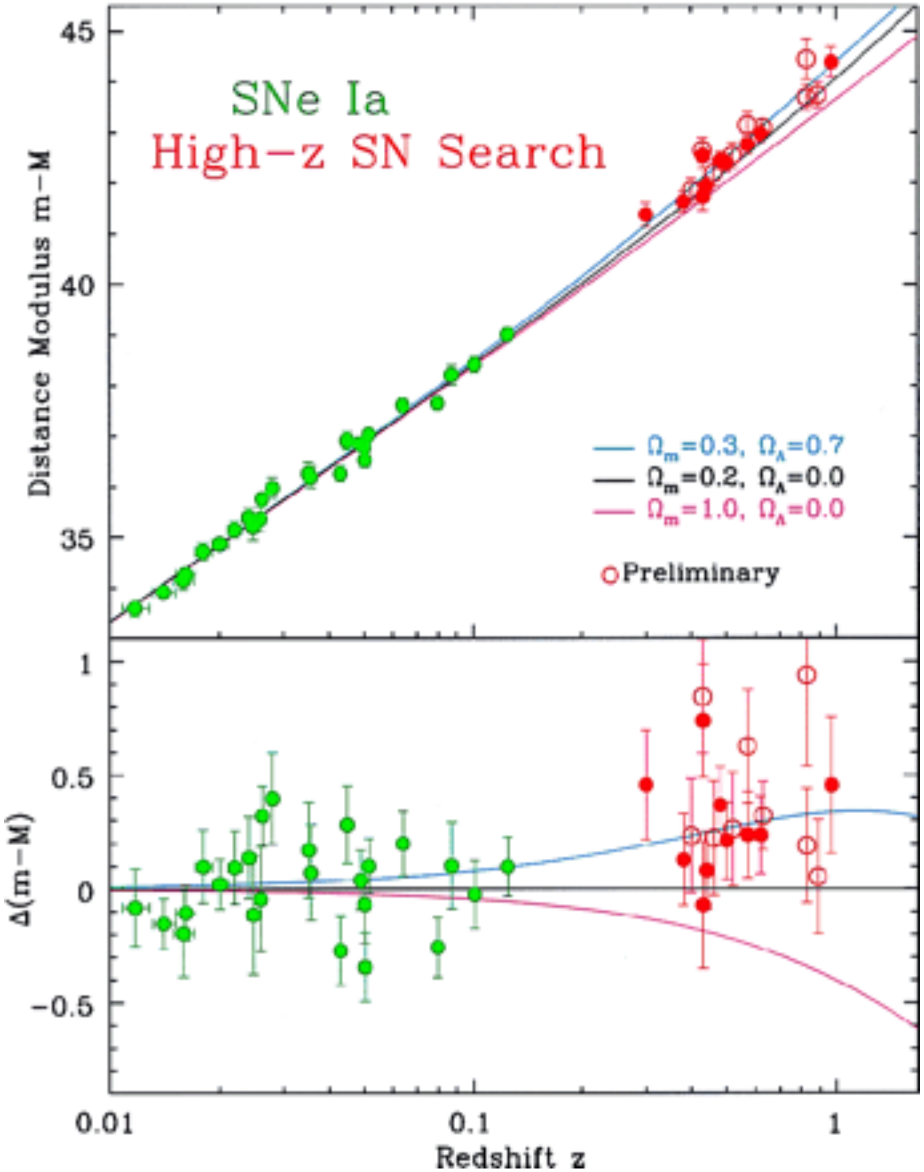
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

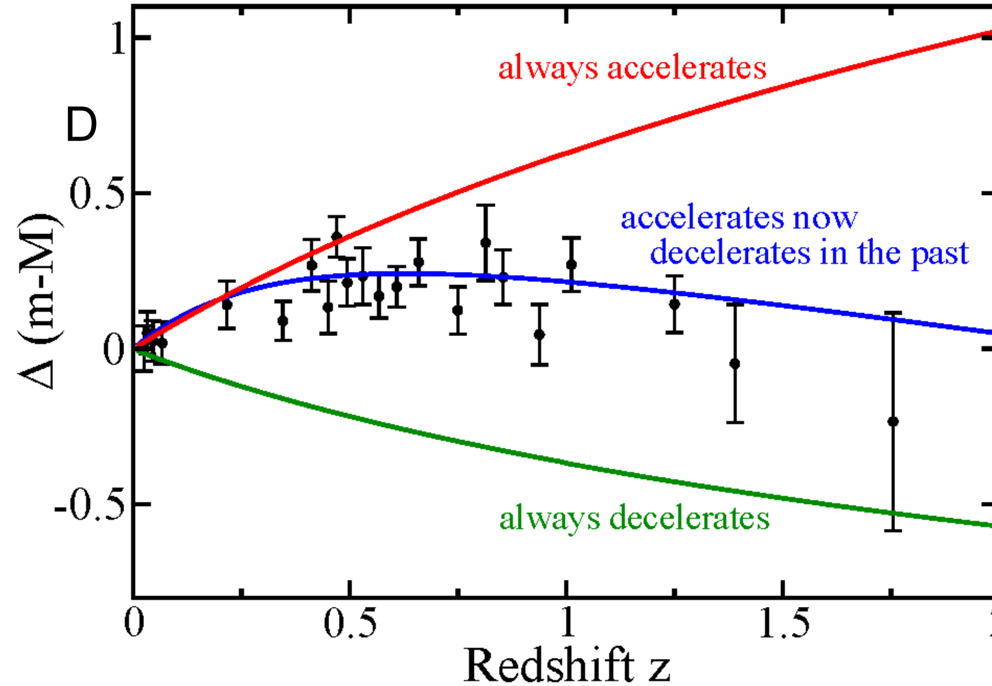
Origins of elements: Major Update due to 170817



170817: Cosmology
GW Measurement of Hubble Flow

$$\dot{R} = H R$$

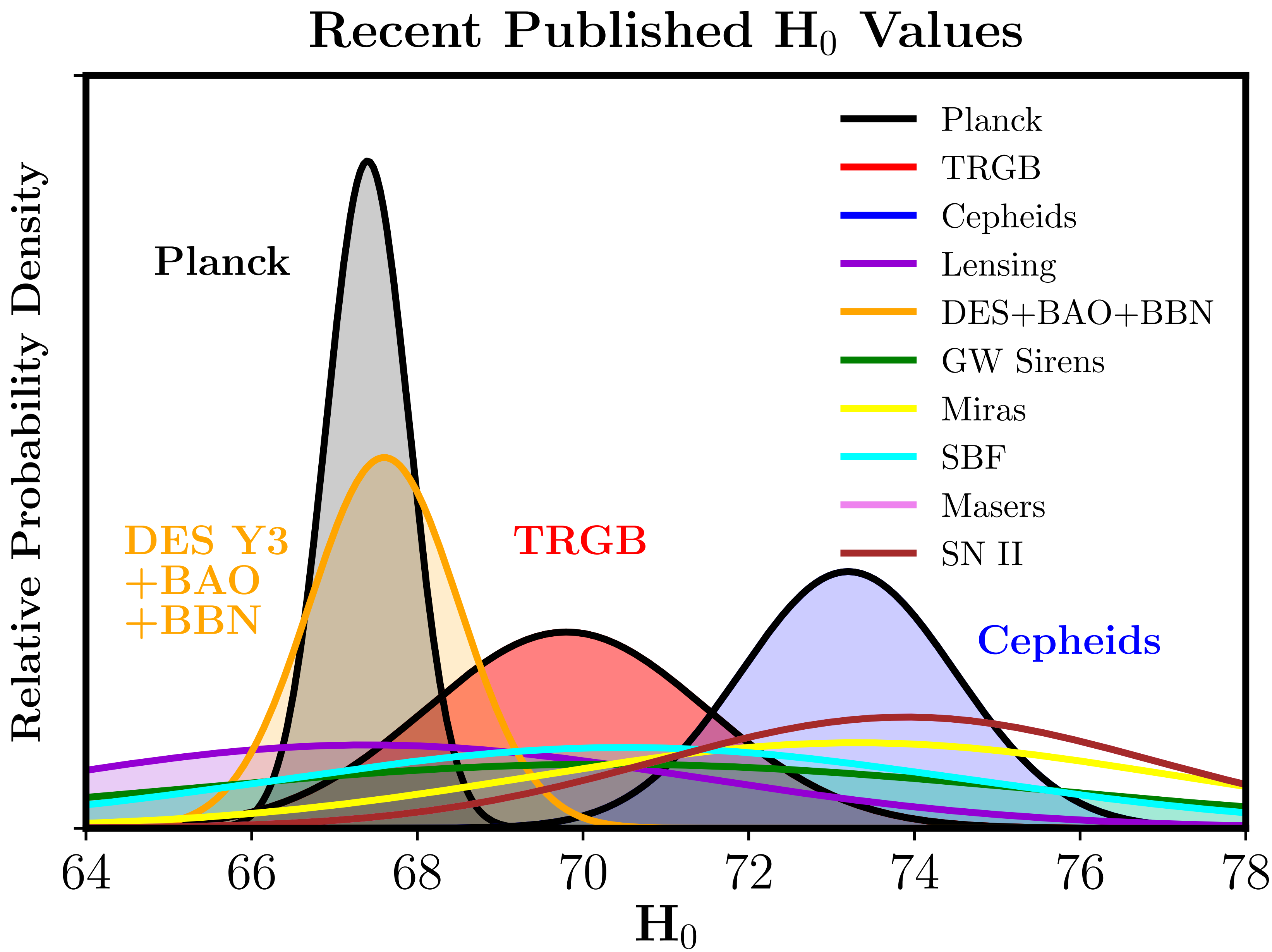




$$D_C(z) = \frac{c}{H_0} \int_0^z dz' \, \frac{H_0}{H(z')} \, .$$

- Need to measure D and z
- H = H(z) describes the expansion history of the Universe
- $H(0) = H_0$ is the Hubble constant

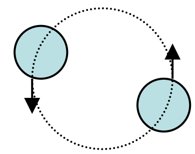
The ‘crisis in cosmology’ - Update ~2021

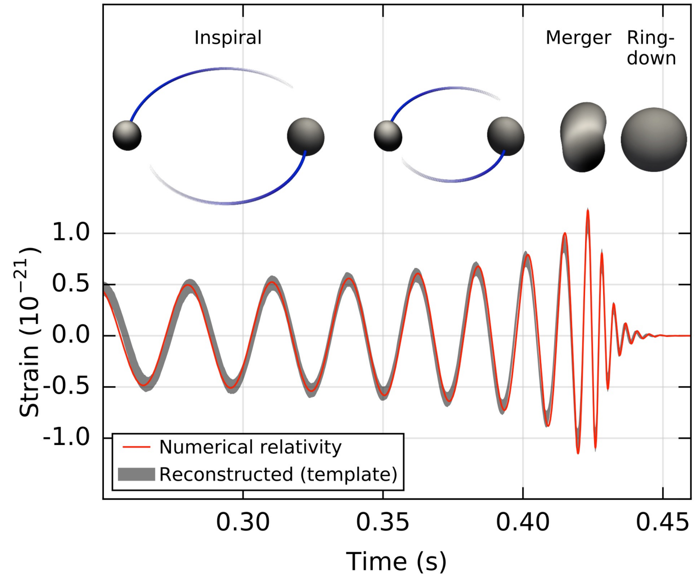


Wendy Freedman
https://arxiv.org/abs/2106.15656

Standard candles → standard GW sirens

Binary inspiral system again:
(lowest PN order)





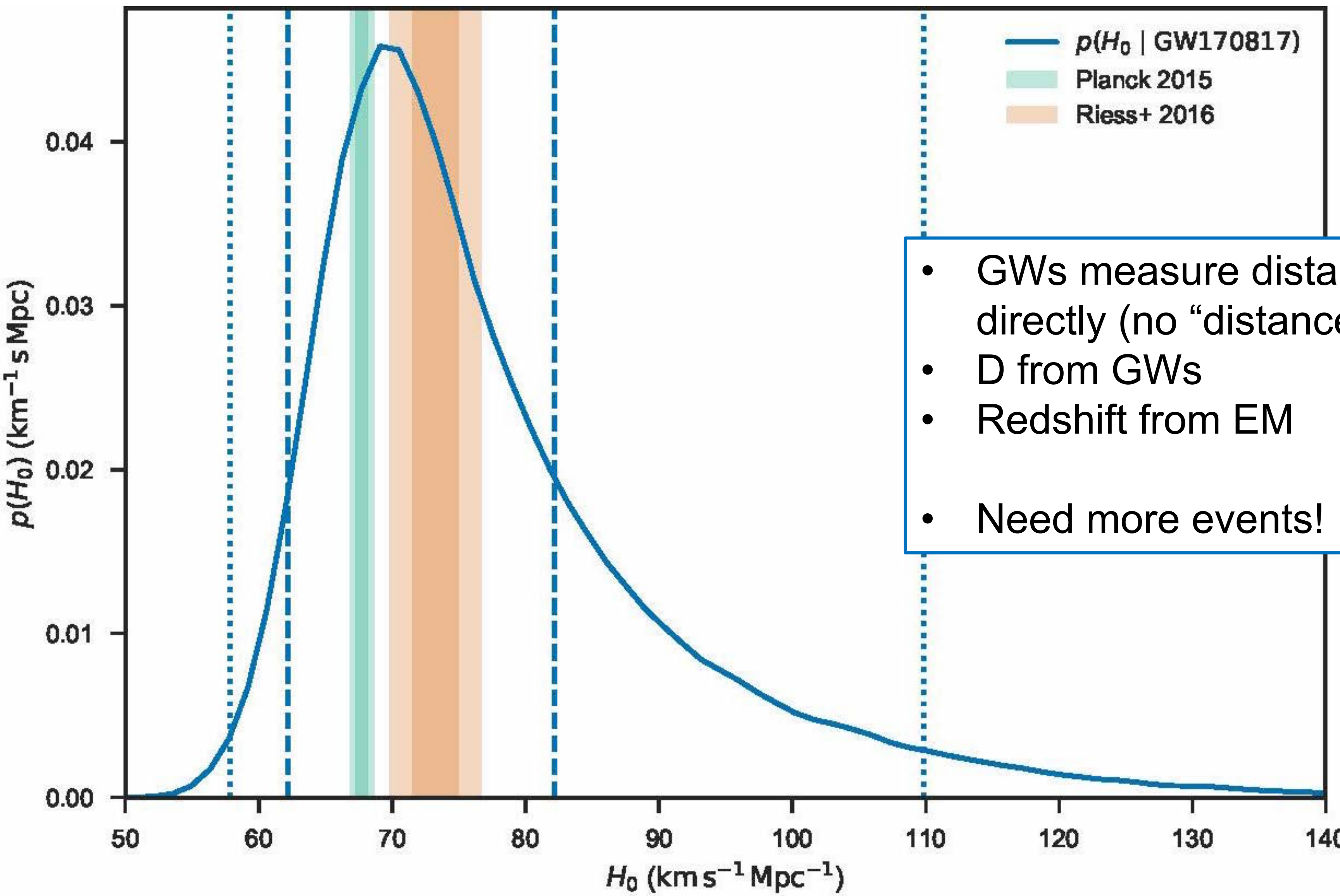
$$h_+ = \frac{2(1+z)\mathcal{M}}{D_L}\left[\pi(1+z)\mathcal{M}f\right]^{2/3}\left(1+\cos^2\iota\right)\times$$
$$\cos 2\Phi_N(t)\ ,$$
$$h_\times = -\frac{4(1+z)\mathcal{M}}{D_L}\left[\pi(1+z)\mathcal{M}f\right]^{2/3}\cos\iota\sin 2\Phi_N(t)\ ,$$
$$\Phi_N(t) = \Phi_c - \left[\frac{t_c - t}{5(1+z)\mathcal{M}}\right]^{5/8}\ , \qquad f \equiv \frac{1}{\pi}\frac{d\Phi_N}{dt}\ . \qquad (1)$$
$$\mathcal{M} = m_1^{3/5} m_2^{3/5}/(m_1+m_2)^{1/5}$$

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

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

170817: H0 with 1 GW event (!)

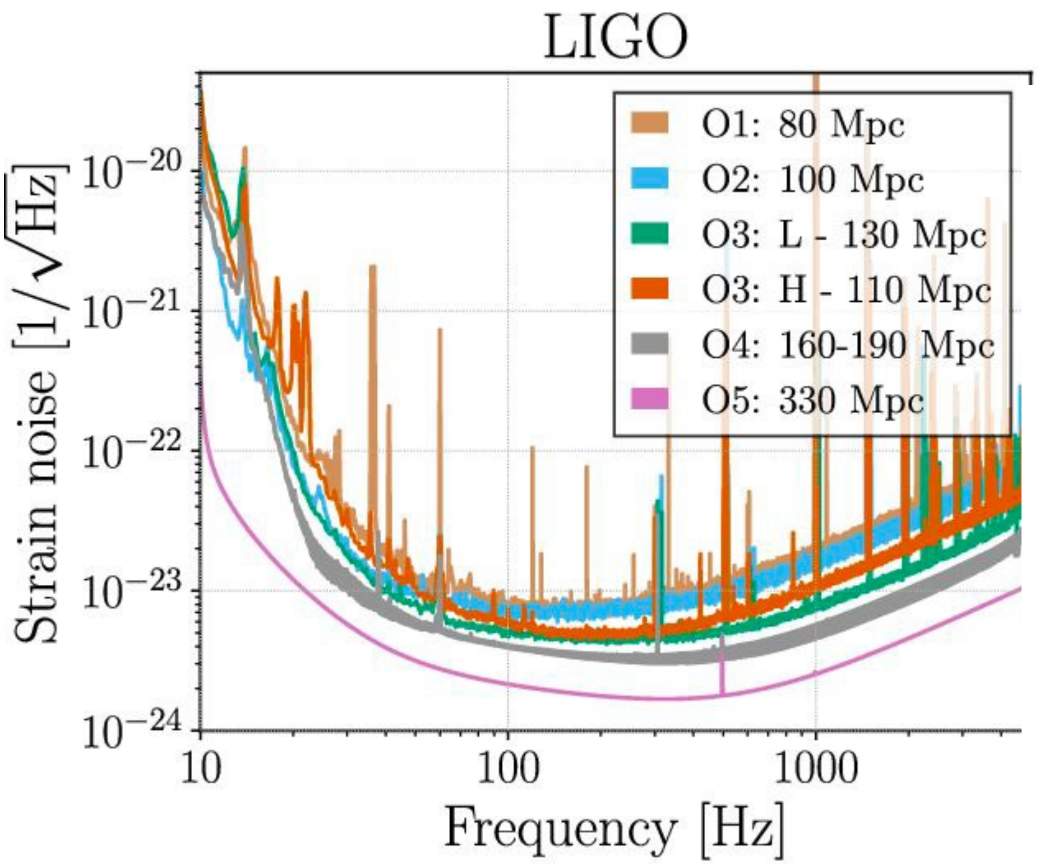
LIGO-Virgo: Nature 551, 85–88

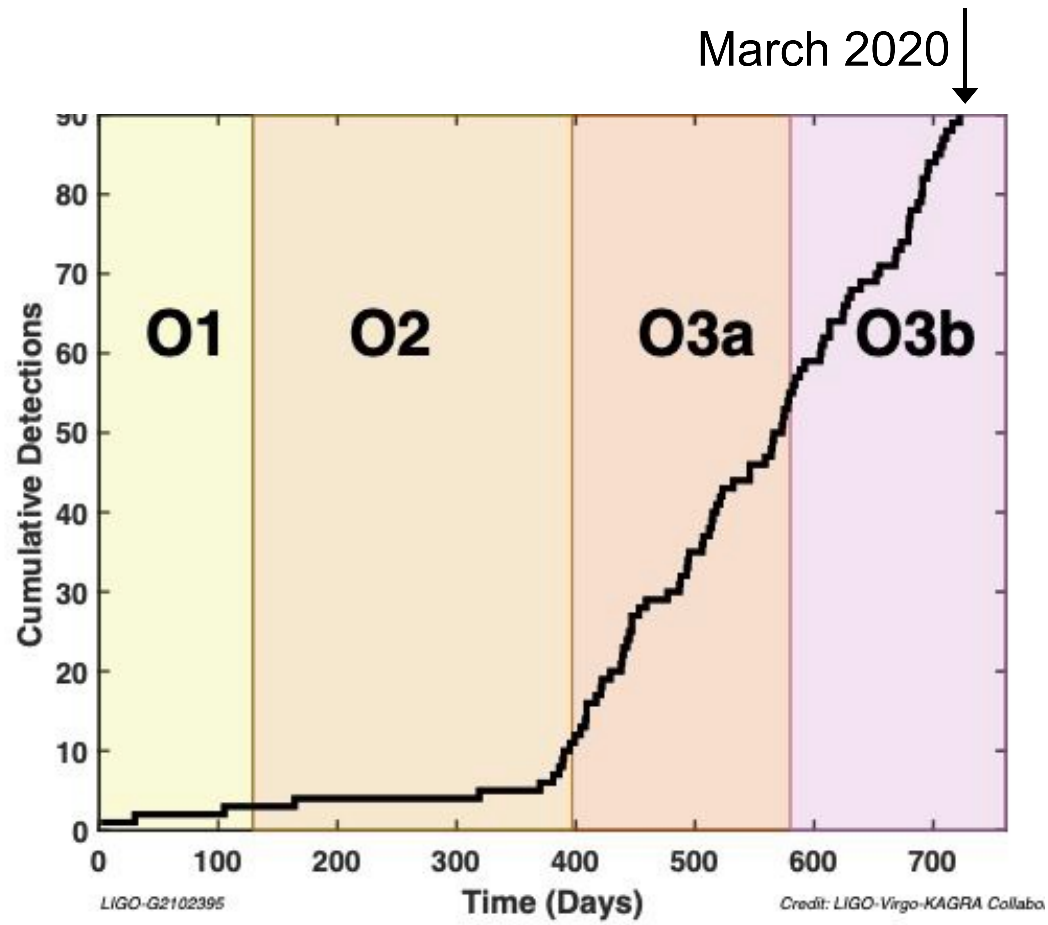


- GWs measure distance directly (no "distance ladder")
- D from GWs
- Redshift from EM

- Need more events!

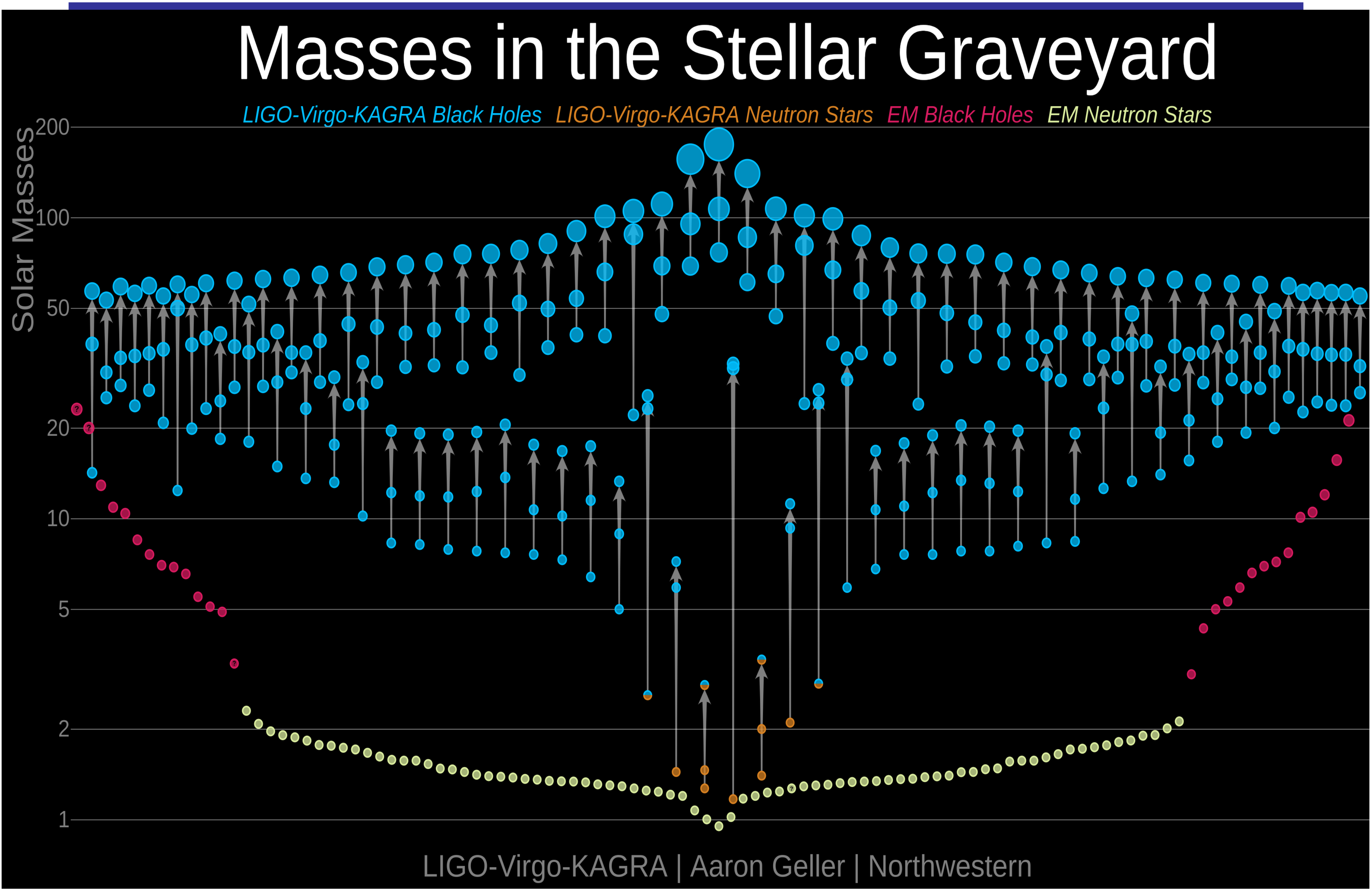
Those were the highlights for O1 and O2. What about O3 ?





- 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)

Events to date



What do we do with these events?

Black Holes

- What is the origin of these systems?
  - Normal stellar evolution of massive stars?
  - Pop III ?
  - Clusters?
  - Primordial??
- Spins
- Mass gap?

Neutron Stars

- Our sole probe of matter at super-nuclear densities
- Understanding the synthesis of heavy elements from merger remnants
- Using them as tracers to understand the evolution of the universe (H0)
  - Resolving H0 discrepancy: ‘Crisis in Cosmology’
  - Is dark energy real?

- How about a NS-BH merger!?

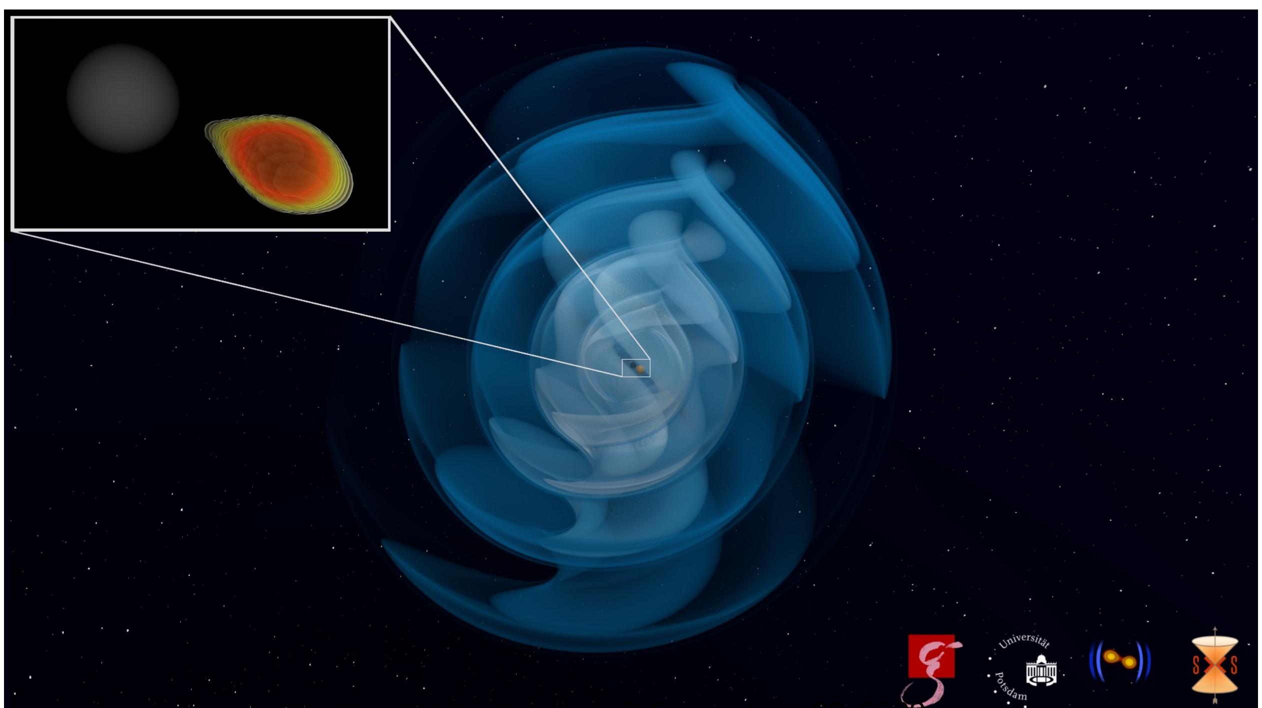
‘What about a BH-NS merger?”

June 29, 2021 The New York Times

How about 2?!

A Black Hole Feasted on a Neutron Star. 10 Days Later, It Happened Again.

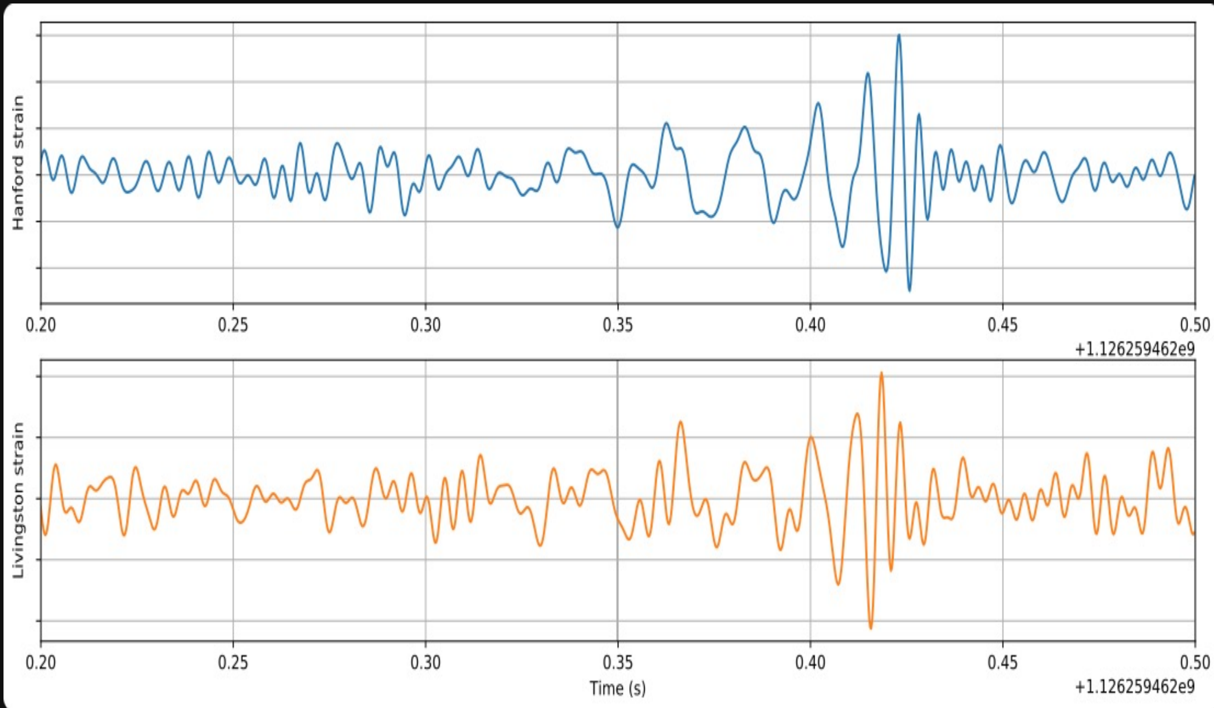
Astronomers had long suspected that collisions between black holes and dead stars occurred, but they had no evidence until a pair of recent detections.

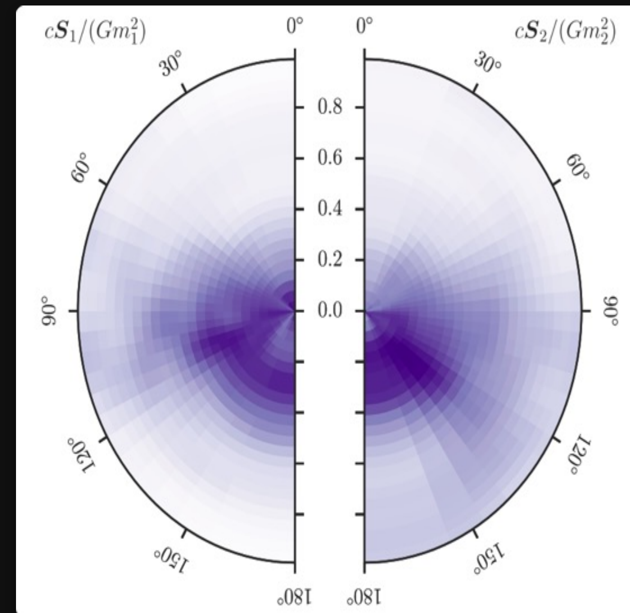


How to distinguish between a BH-BH merger and a NS-BH merger?

- The masses, as measured using GWs
- A gamma ray burst (GRB), although it is beamed and may be missed
- An afterglow or kilonova, although they cannot be observed if too distant

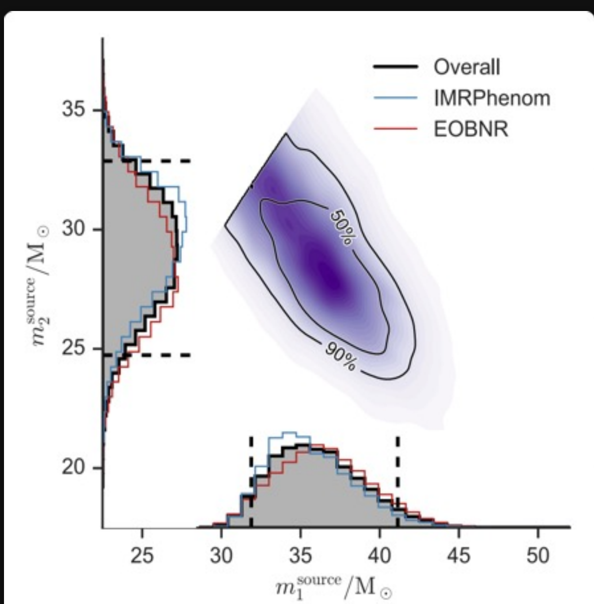
Parameter Estimation



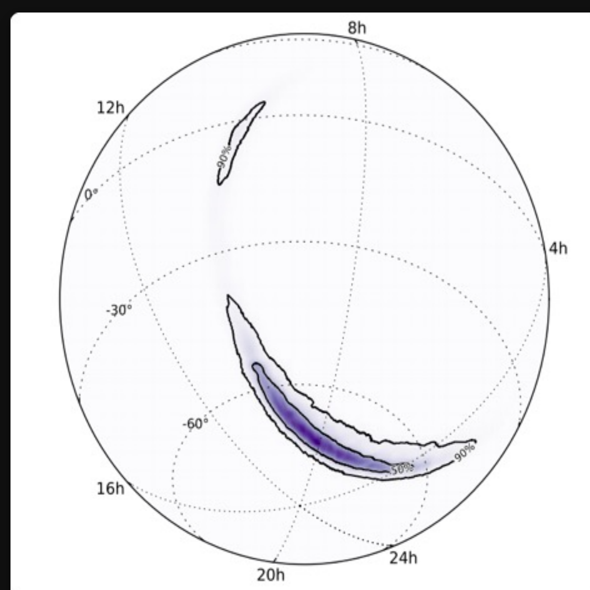


Spins

Masses



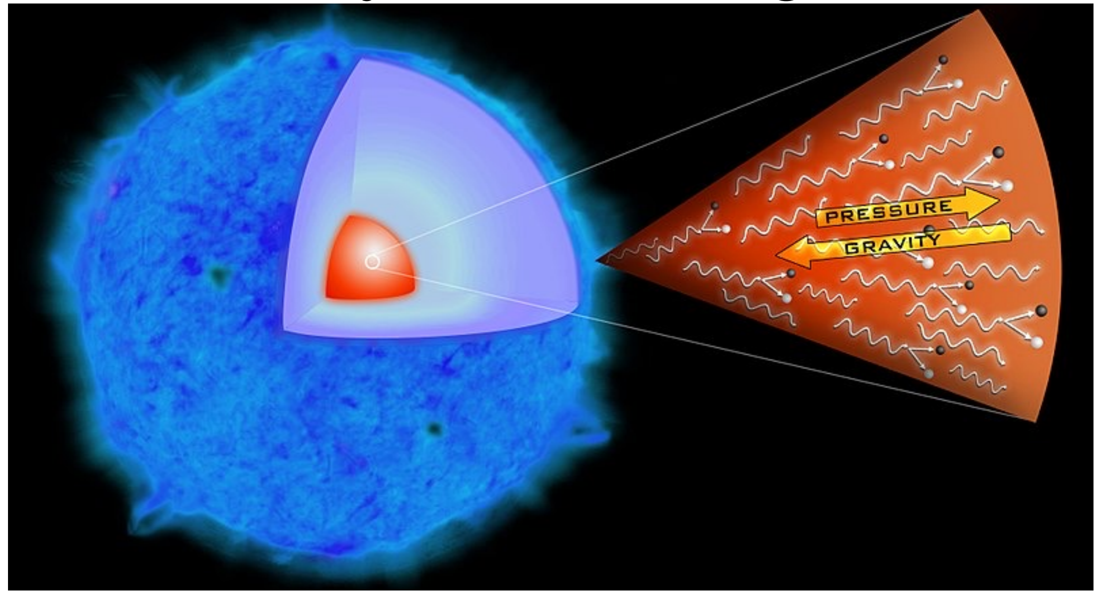
Location



(e.g., GW150914)

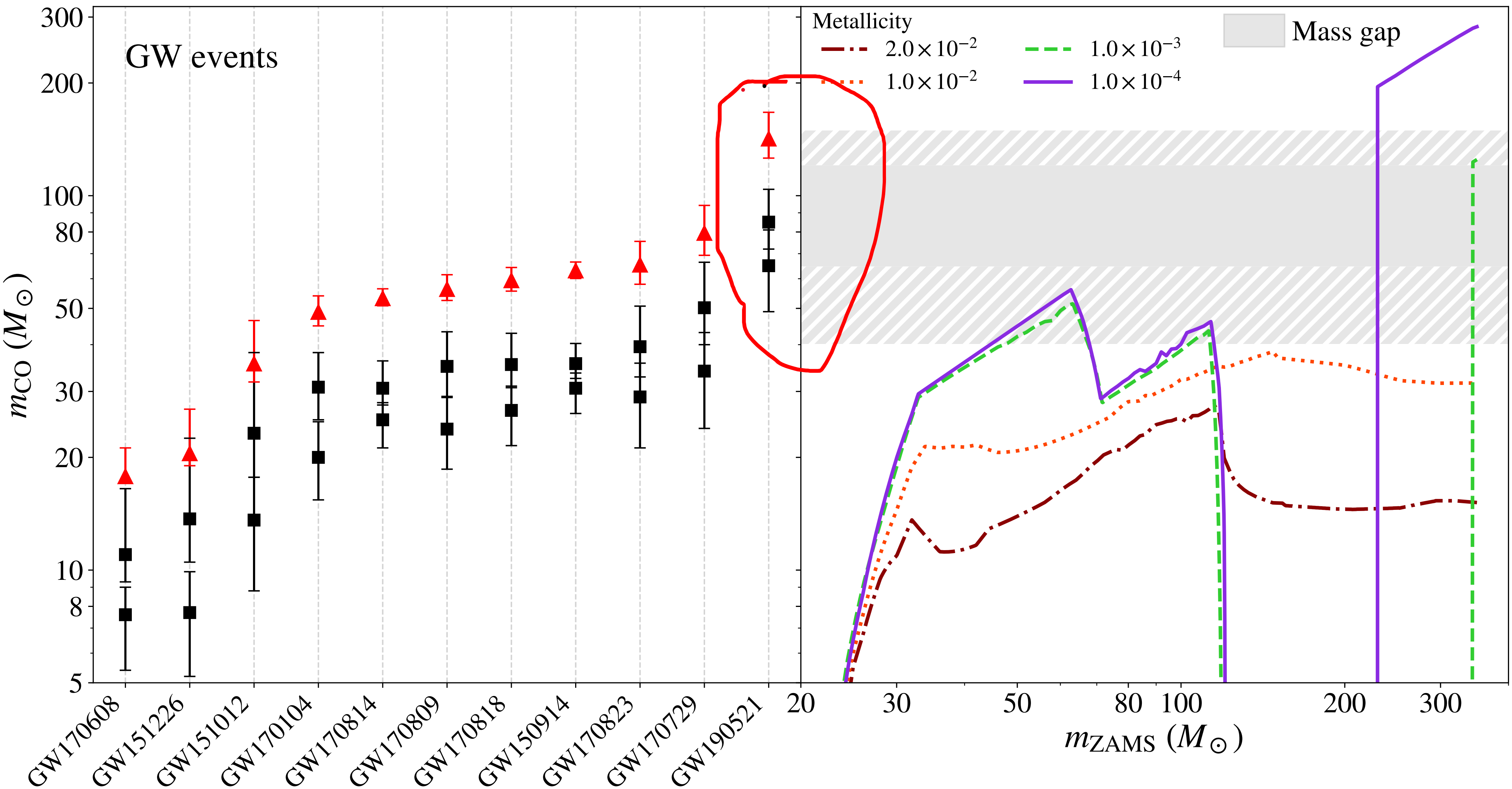
Black hole masses

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



- 'Stellar mass'
  - Presumed to be 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

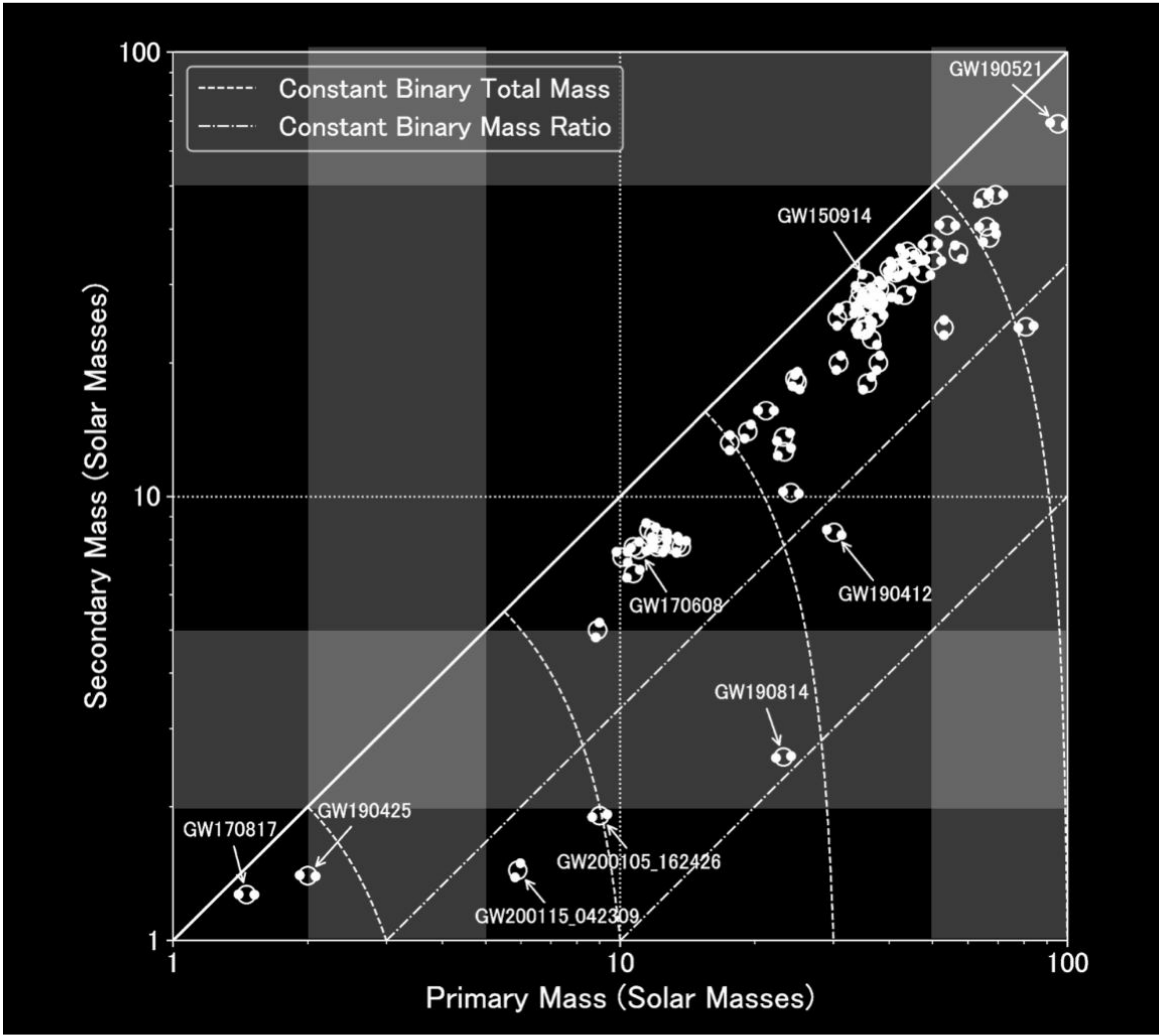
The 'mass gap' undone ? Sequential mergers?



New in O3

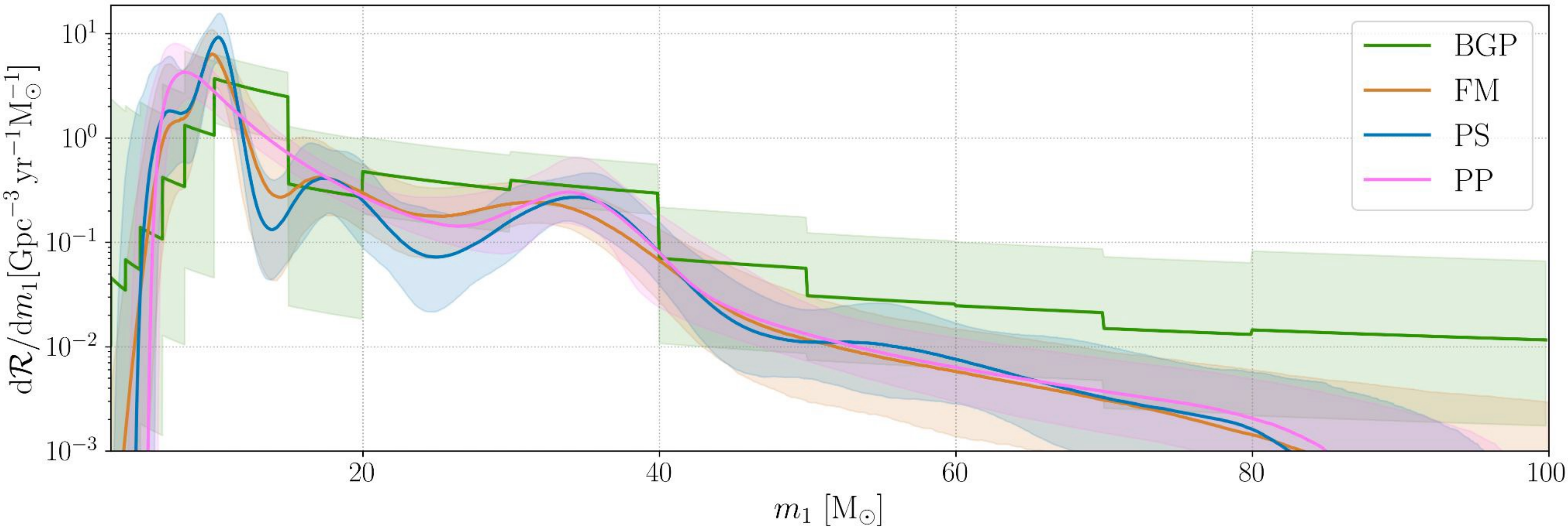
Black holes in pair-instability mass gap

Compact object (BH or NS??) in range 2-5 $M_\odot$



Merger rate as function of (primary) BH mass

- Work by Bruce Edelman, UO, for the collaboration ‘astrophysical distributions’ paper



- No evidence of a ‘mass gap’ above 60 $M_\odot$
- Neutral on mass gap in 2-5 $M_\odot$ range
- Peaks appearing most likely to be real

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

Black hole origins

Too early to make definitive statements about the origin of black holes (and, thus, massive stars), but…

- Probably most BBHs originate from binaries of massive stars, which then each evolve to black holes
- At least some of the observed BHs result from some dynamical formation* channel and sequential mergers
  - No PISN mass gap above ~60 $M_\odot$
  - Evidence for misaligned spins and some anti-aligned spins
  - More spin misalignment for unequal mass binaries

* Multi-body interactions in a dense environment, e.g. globular clusters or the accretion disks around Active Galactic Nuclei

- Starting to observe the rate of BBH mergers as a function of distance (i.e. redshift, or lookback time)
  - It is increasing with redshift
  - Is it consistent with the observations for ‘living’ stars?

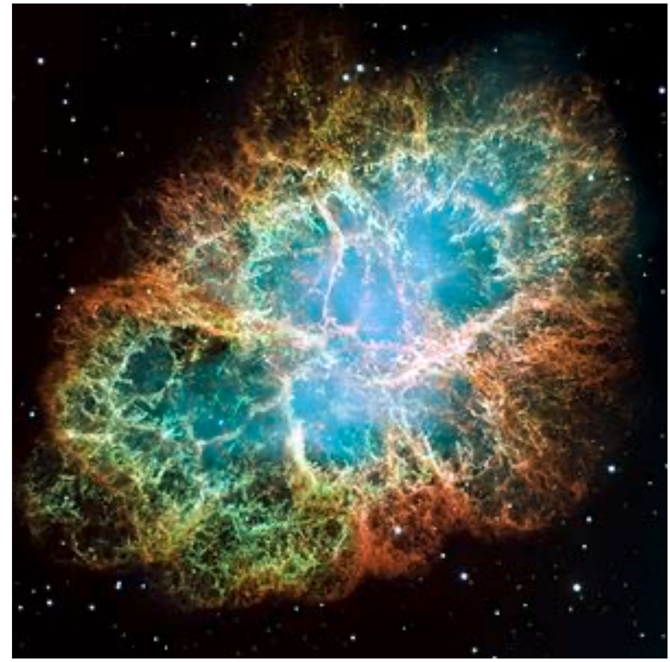
Beyond binary mergers…

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



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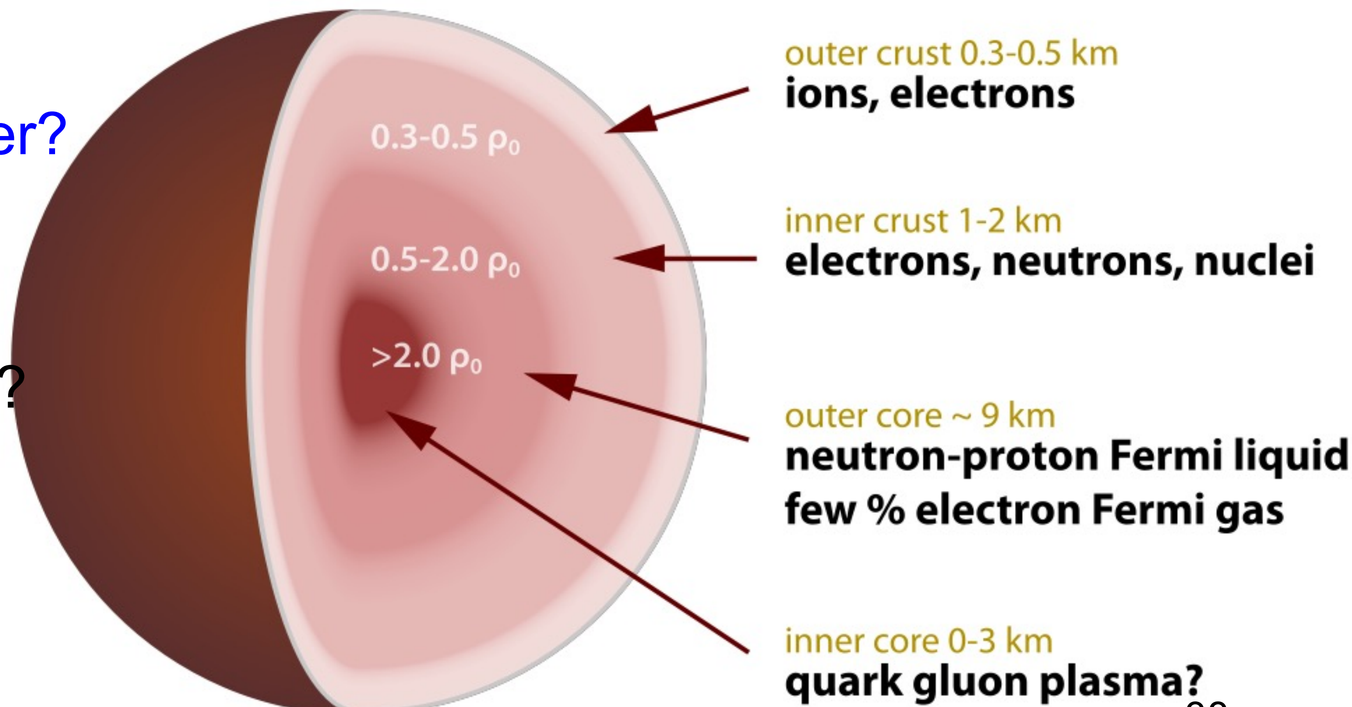
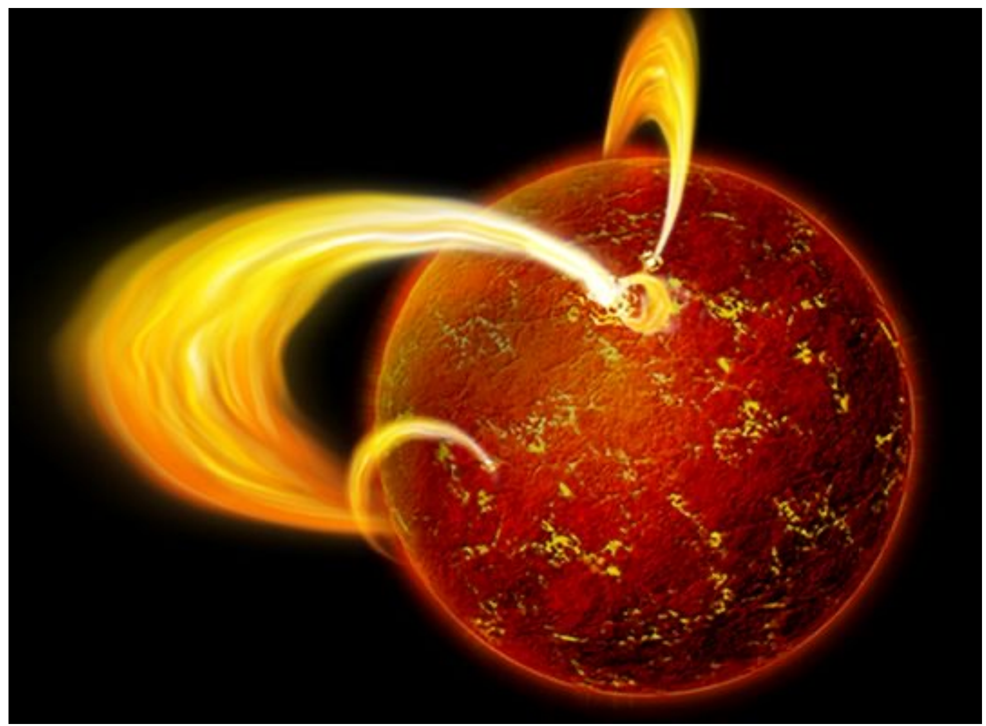
- Radius ~ 10 km

  ~ 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?

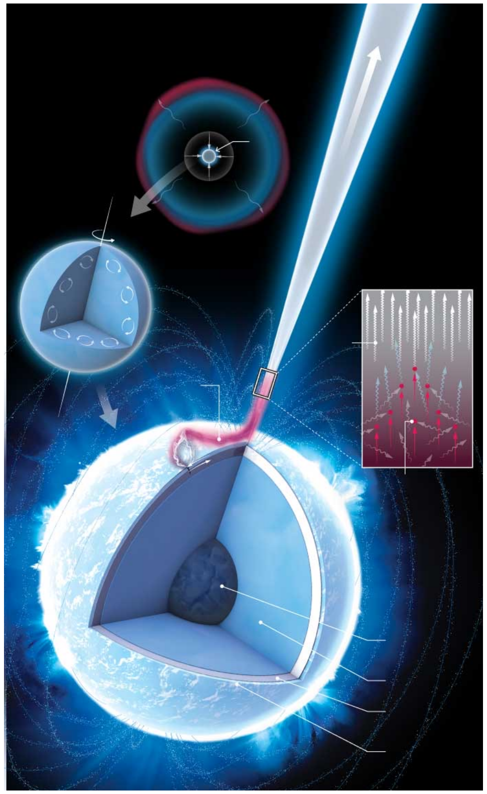


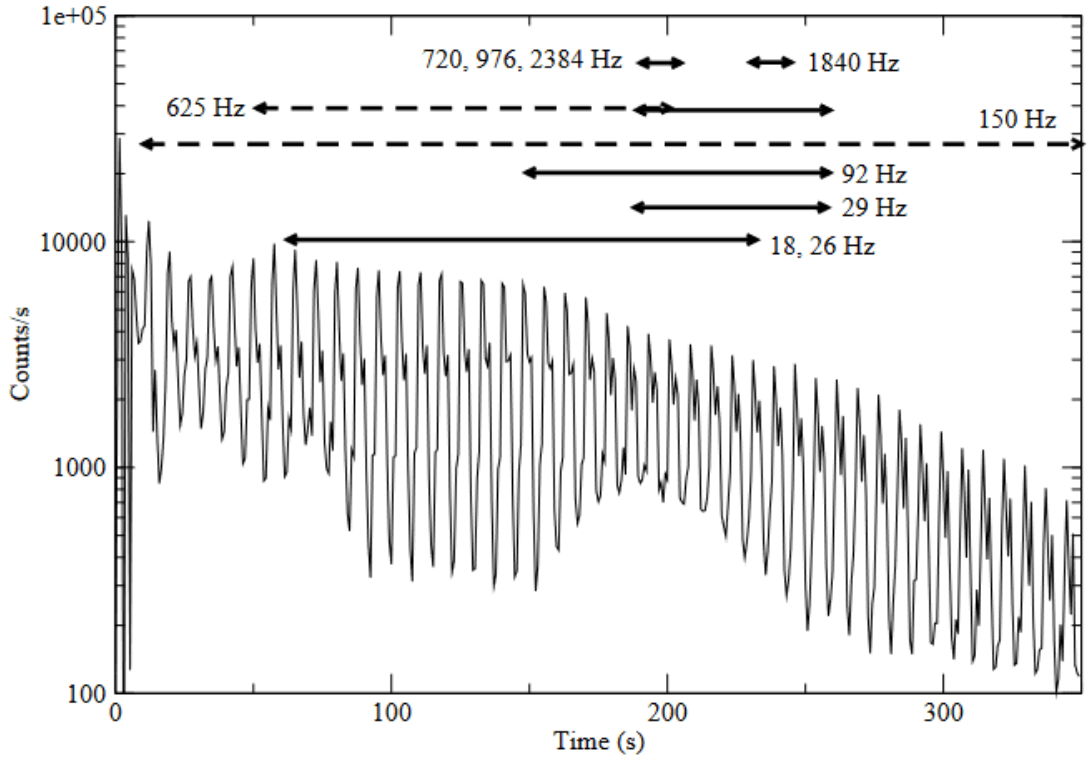
Magnetars

- 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

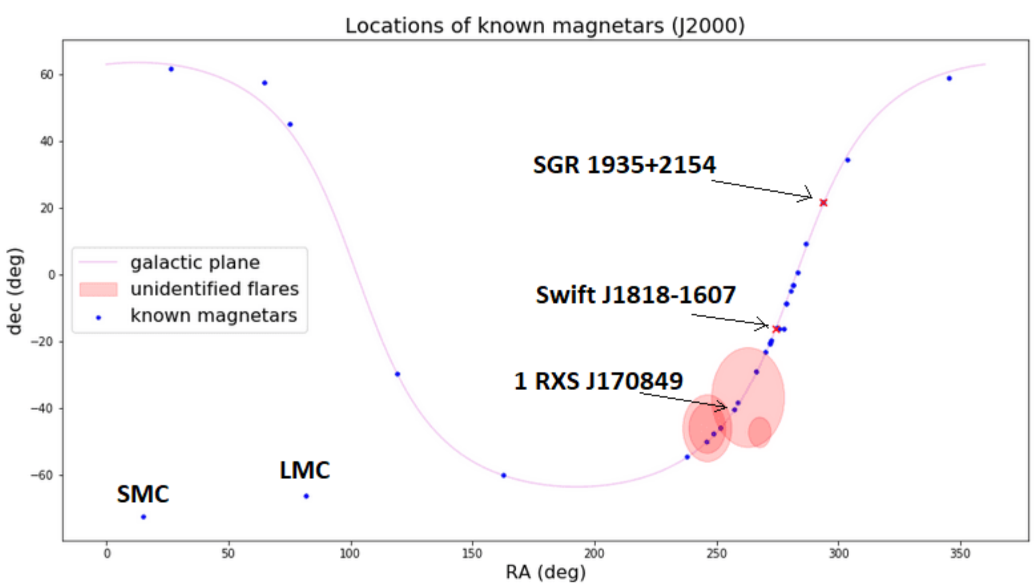


Magnetars and GWs ?





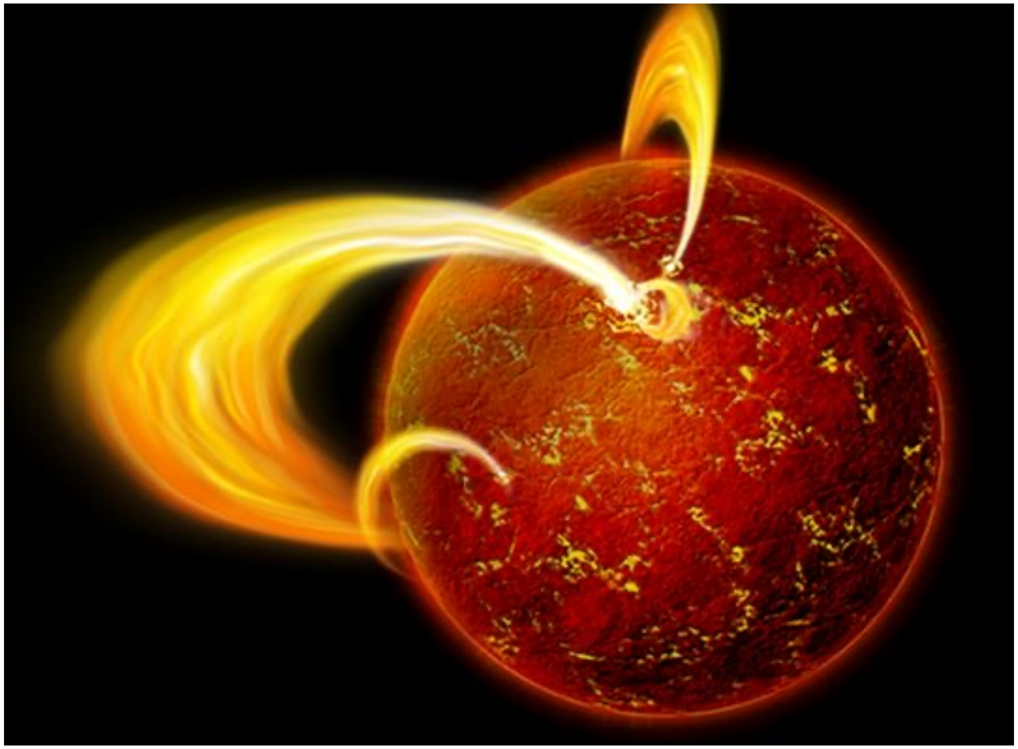
X-rays from 2004 giant flare SGR 1806-20

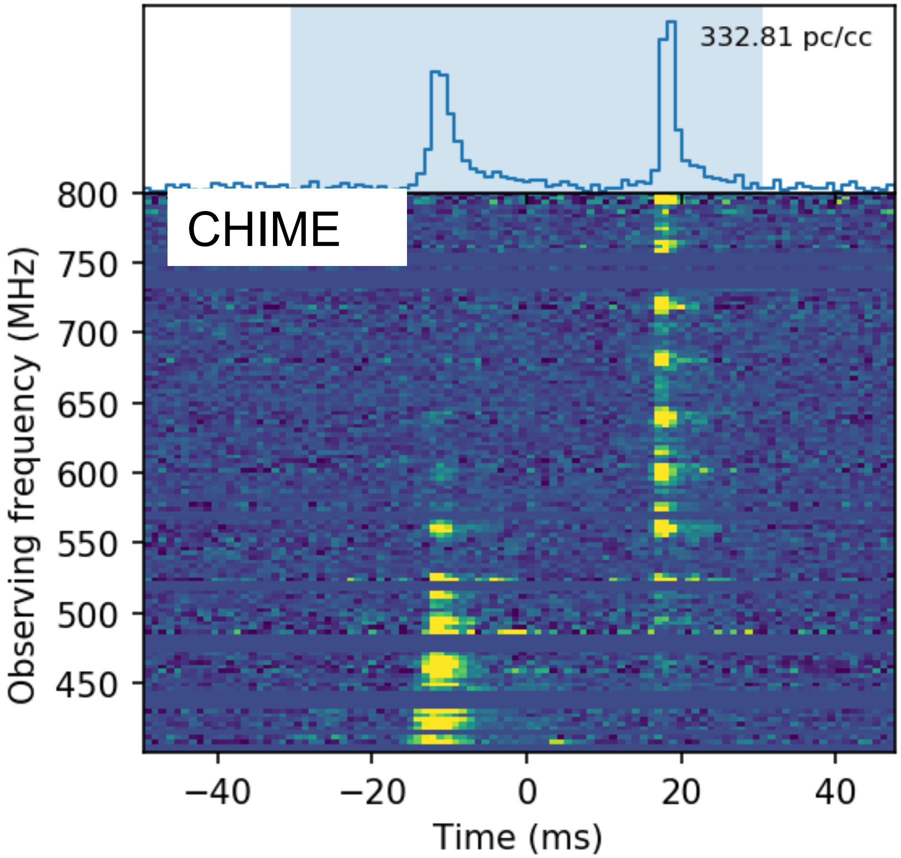


- Starquakes produce (giant) x-ray flares
- They also ring-up mechanical modes in the magnetar, some (e.g. f-modes) can produce GWs
- ← No giant flares during O3 run, but many ordinary x-ray flares
- UO student Kara Merfeld leading the O3 collaboration analysis/paper

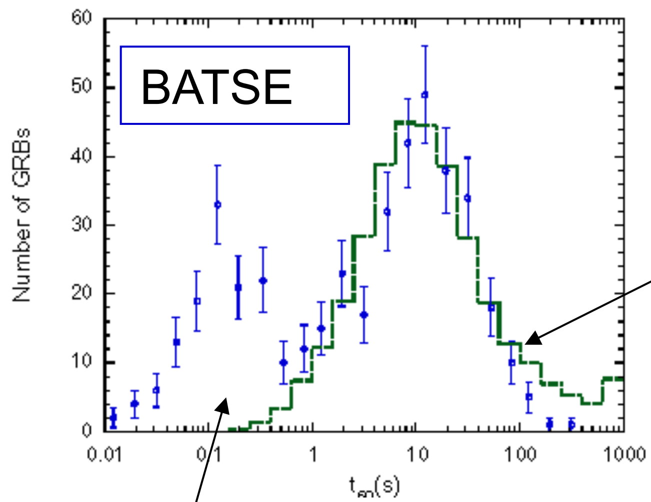
Magnetars and FRBs

- 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





Gamma-ray Bursts

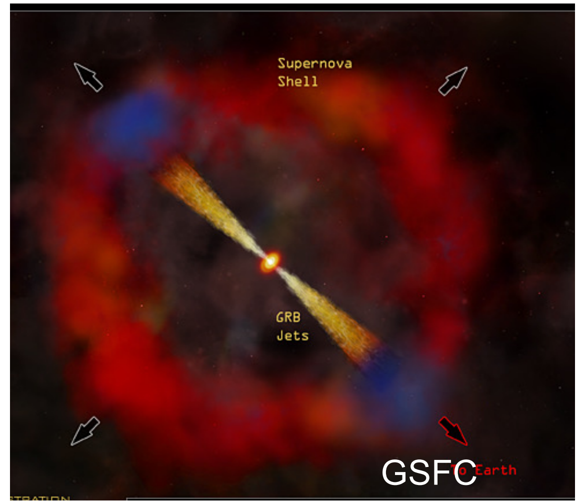


Long-duration GRBs

• SNe-like progenitors "hypernovae", "collapsars"

• mean z ≈ 2.3

• not expected to be efficient GW radiators



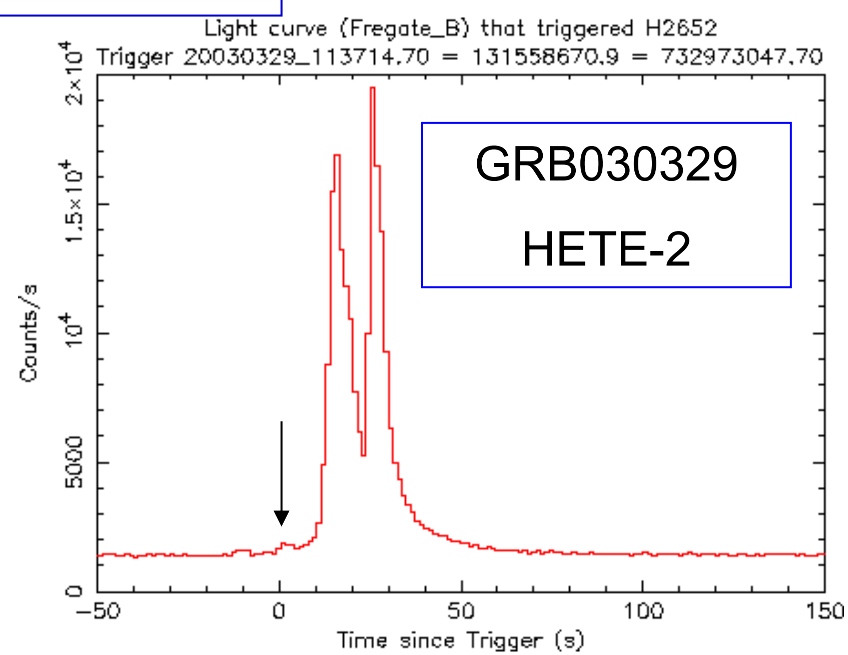
Short-duration GRBs

• NS-NS or NS-BH mergers

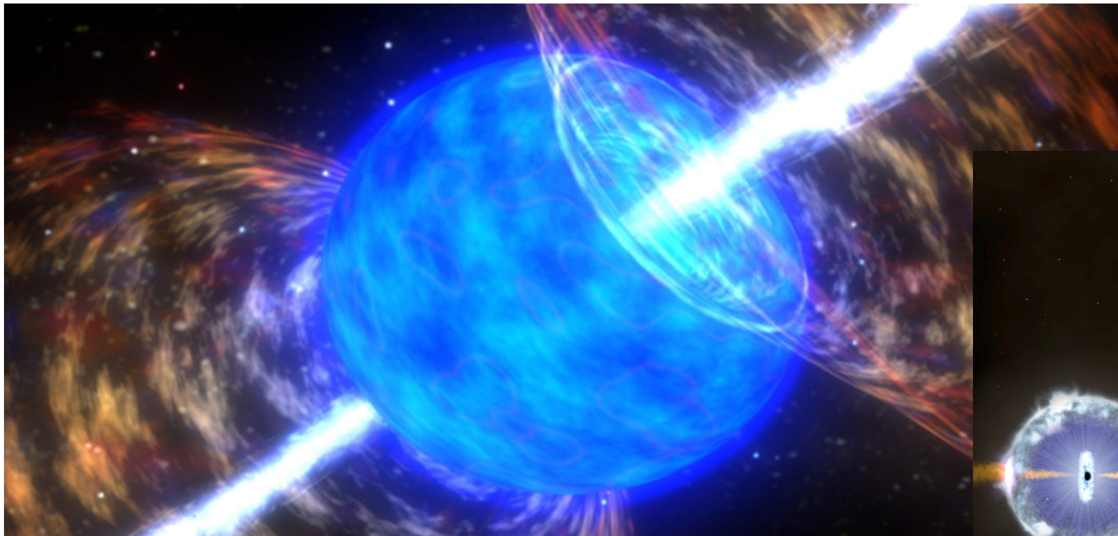
• mergers are efficient GW radiators

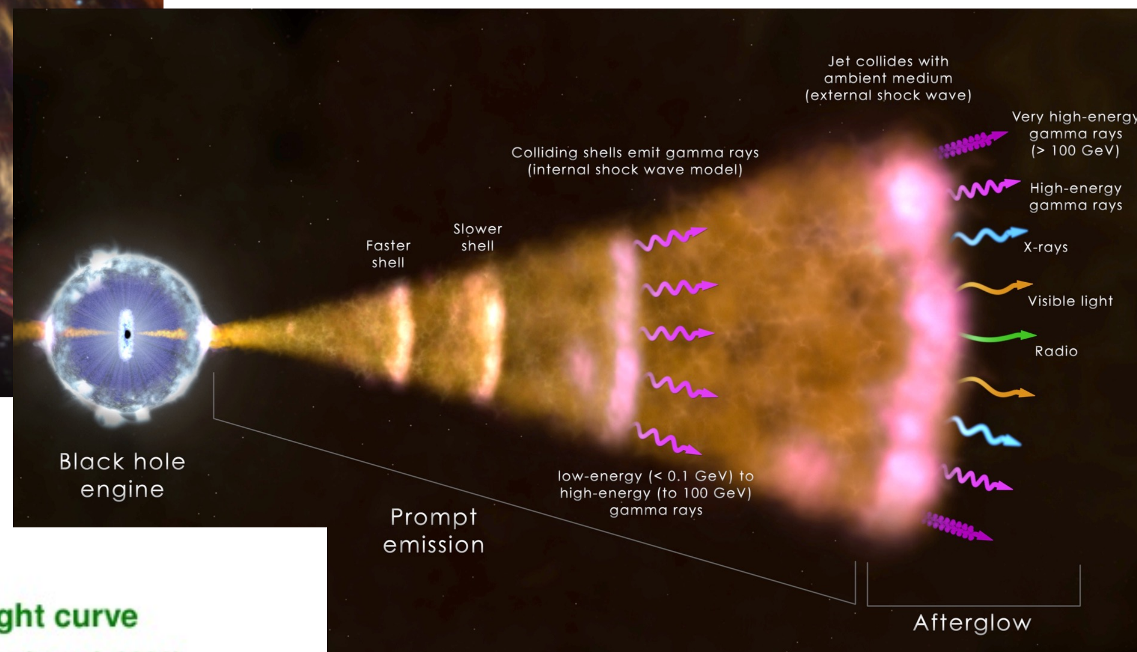
• mean z ~ 1

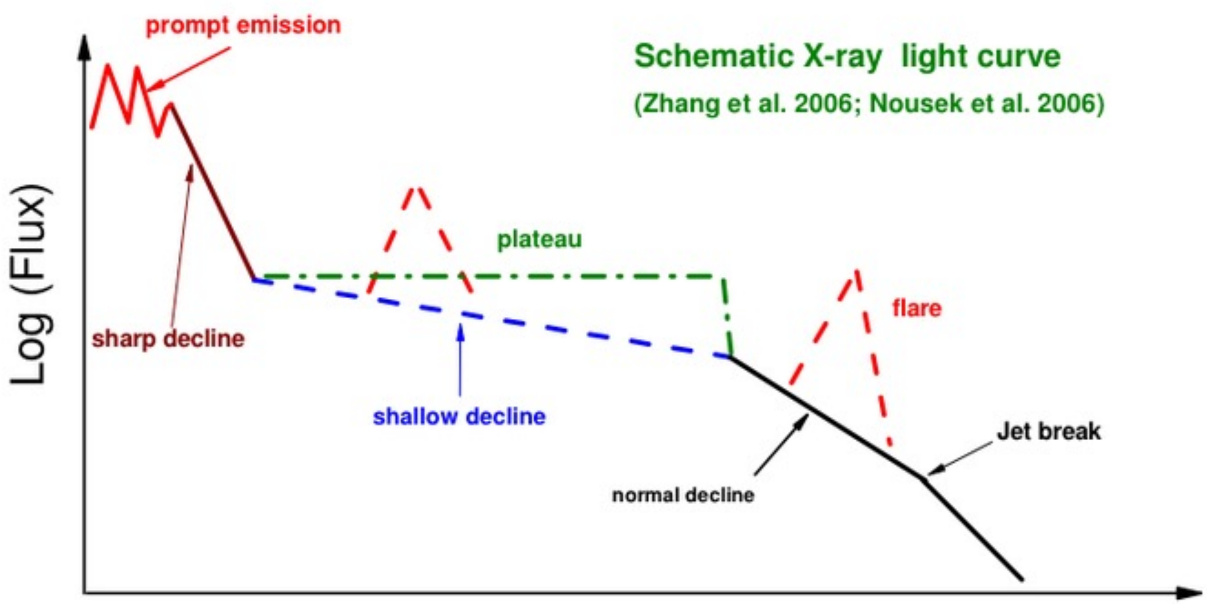
• GRB 170817: only GRB with GW counterpart so far



GWs from Collapsars ('long' GRBs)







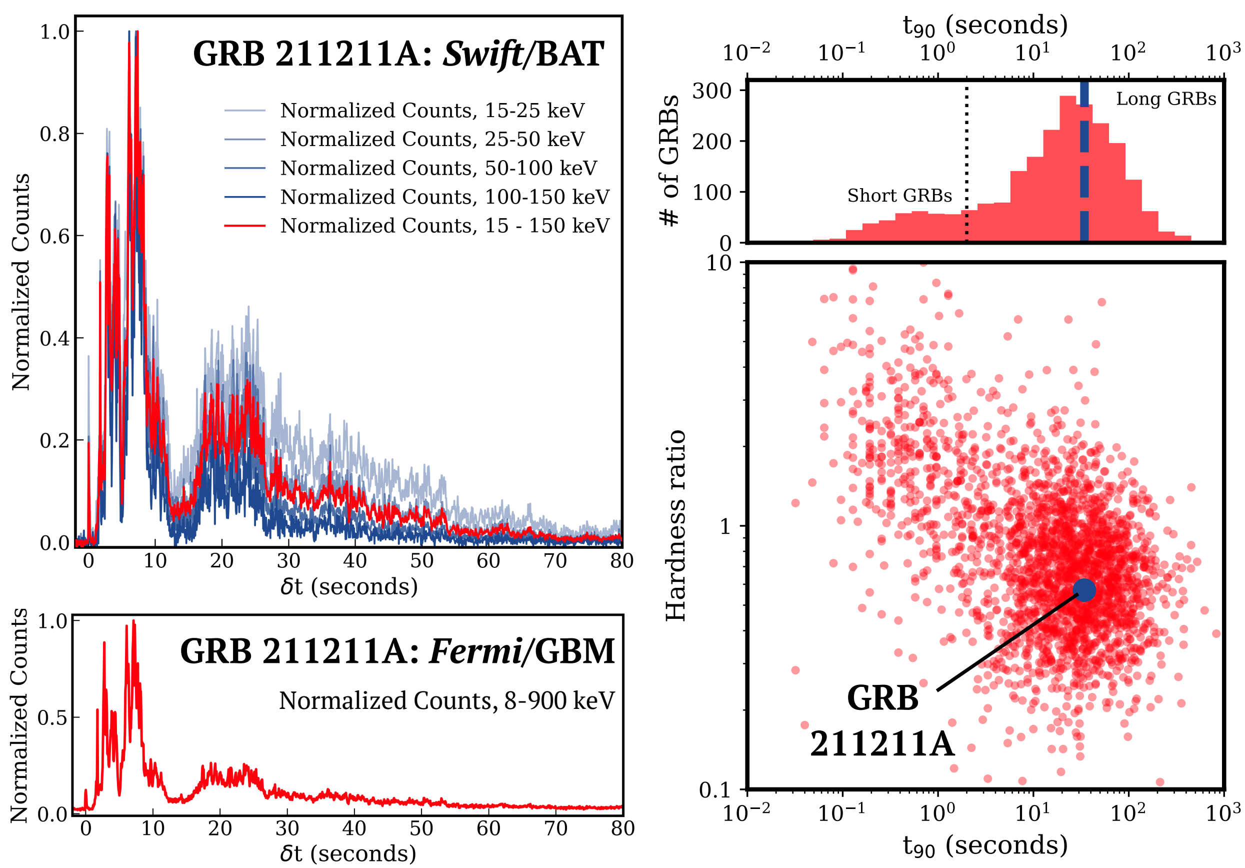
- GW mechanisms
  - Initial collapse
  - Hypermassive NS
  - Accretion disk instabilities (flares!)

Long and short GRBs: Not so fast!

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

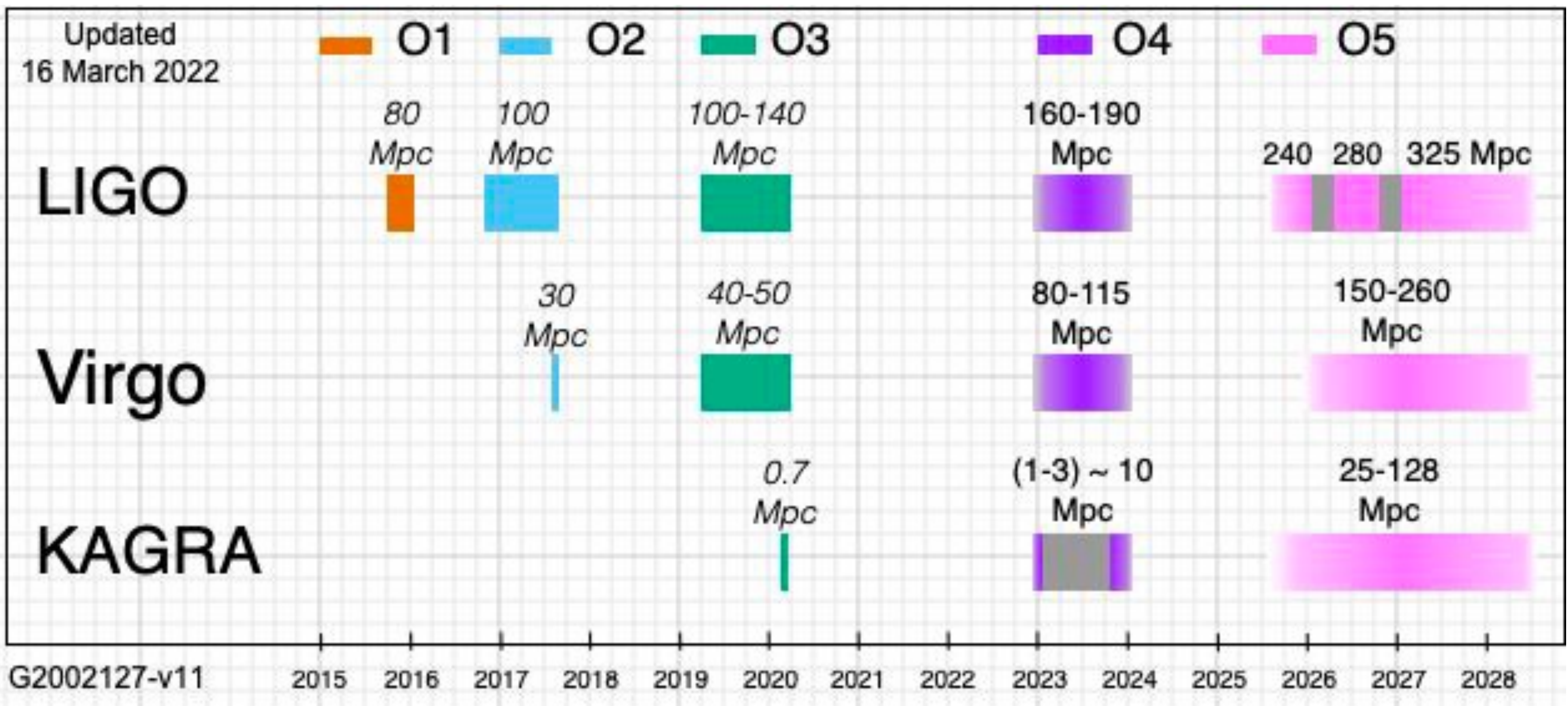
Jillian Rastinejad[1*], Benjamin P. Gompertz[2], Andrew J. Levan[3], Wen-fai Fong[1], Matt Nicholl[2], Gavin P.

A long GRB from a NS-NS merger!

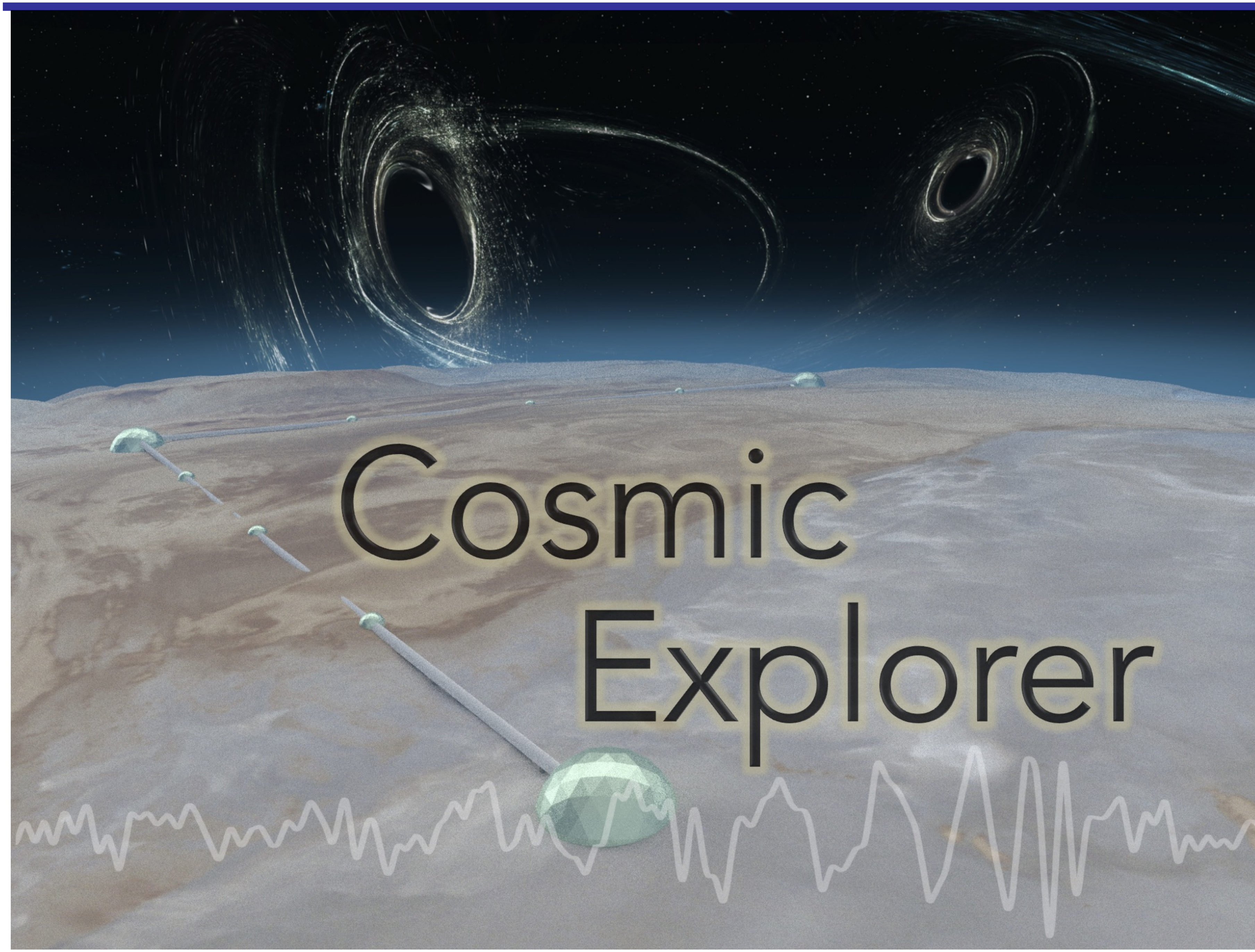


The near future

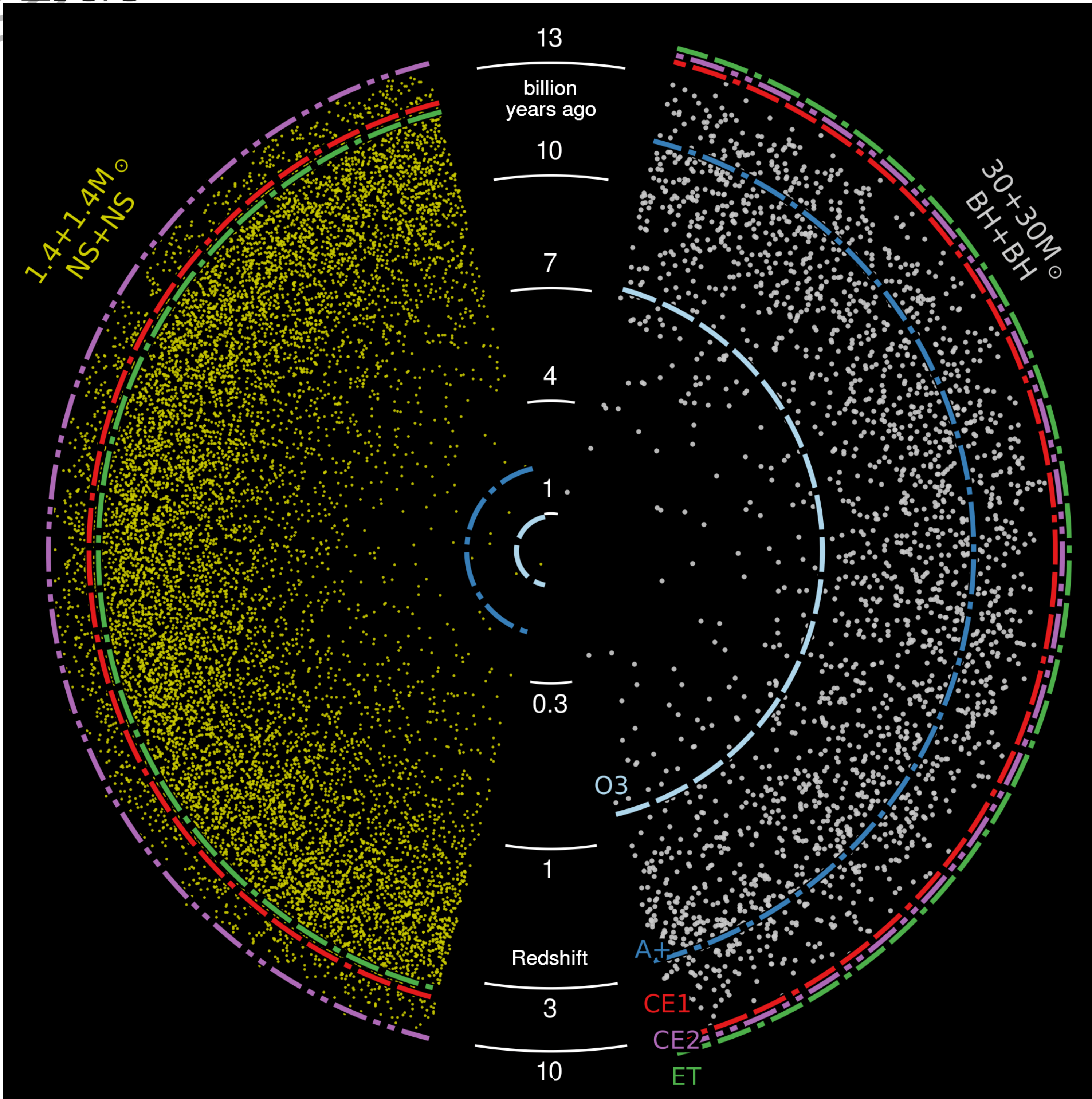
- In O1-O2: about 1 GW event per month
- In O3: about 1 GW event per 5-days
  - Routine quantum squeezing
- O4 (starting March 2023): about 1 event per day
  - Frequency-dependent squeezing



The farther future (2030s)



Why CE ?



Also:
10% of BBH will have SNR>1000

1% SNR~10,000

UO-LIGO 2022

- Ray Frey, Professor
- Ben Farr, Assistant Professor
- Robert Schofield, Research Professor
- Philippe Nguyen, 5th year (Data Quality, GRB physics)
- Kara Merfeld, 4th year (DQ, magnetars, FRBs)
- Bruce Edelman, 4th year (BBH populations)
- JD Merritt, 3rd year (DQ, BBH populations)
- Adrian Helmling-Cornell, 4th year (DQ, cosmic strings)
- Matthew Ball, 4th year (DQ, magnetars)
- Gino Carillo, 3rd year (GRB afterglows)
- Sangeet Paul – 3rd year (BBH populations)
- Ben Mannix – 2nd year
- Jaxsen Godfrey – 2nd year

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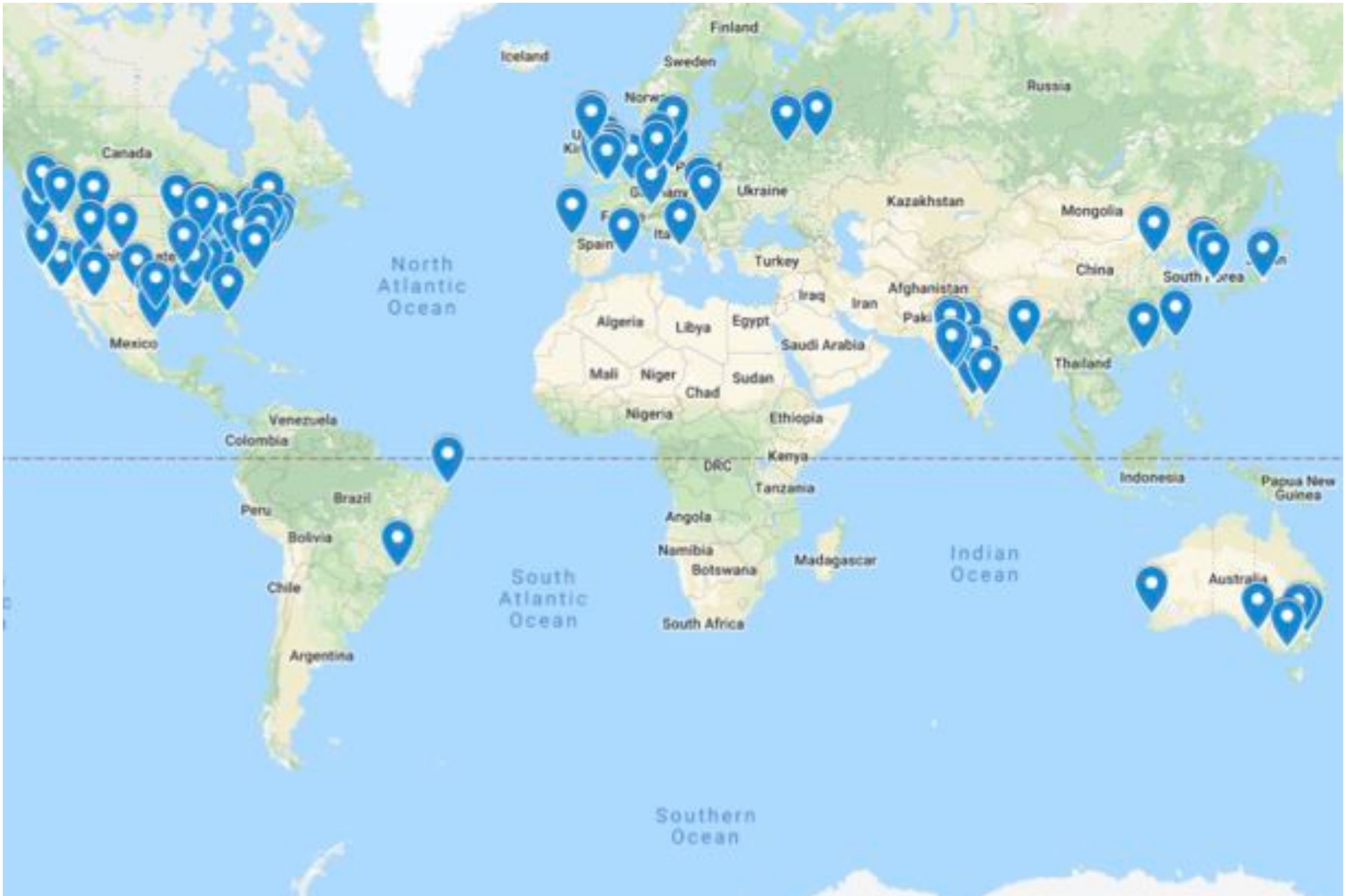
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Egypt
Mexico
Saudi Arabia
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Venezuela
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DRC
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Southern Ocean

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UO-LIGO June 28, 2021