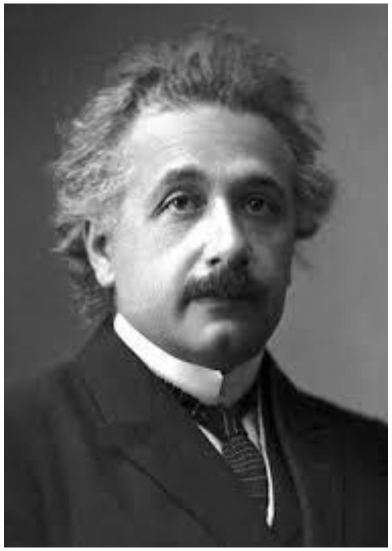
Update on LIGO and gravitational-wave Astrophysics

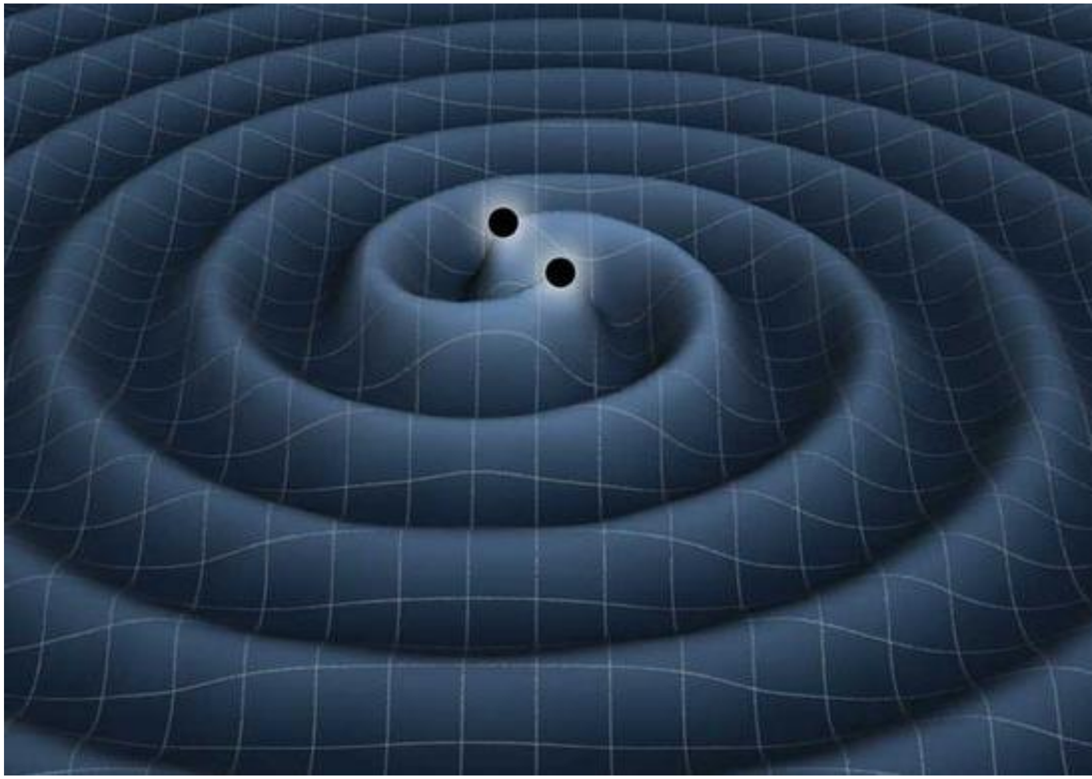
Gravitational Waves (GWs)

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

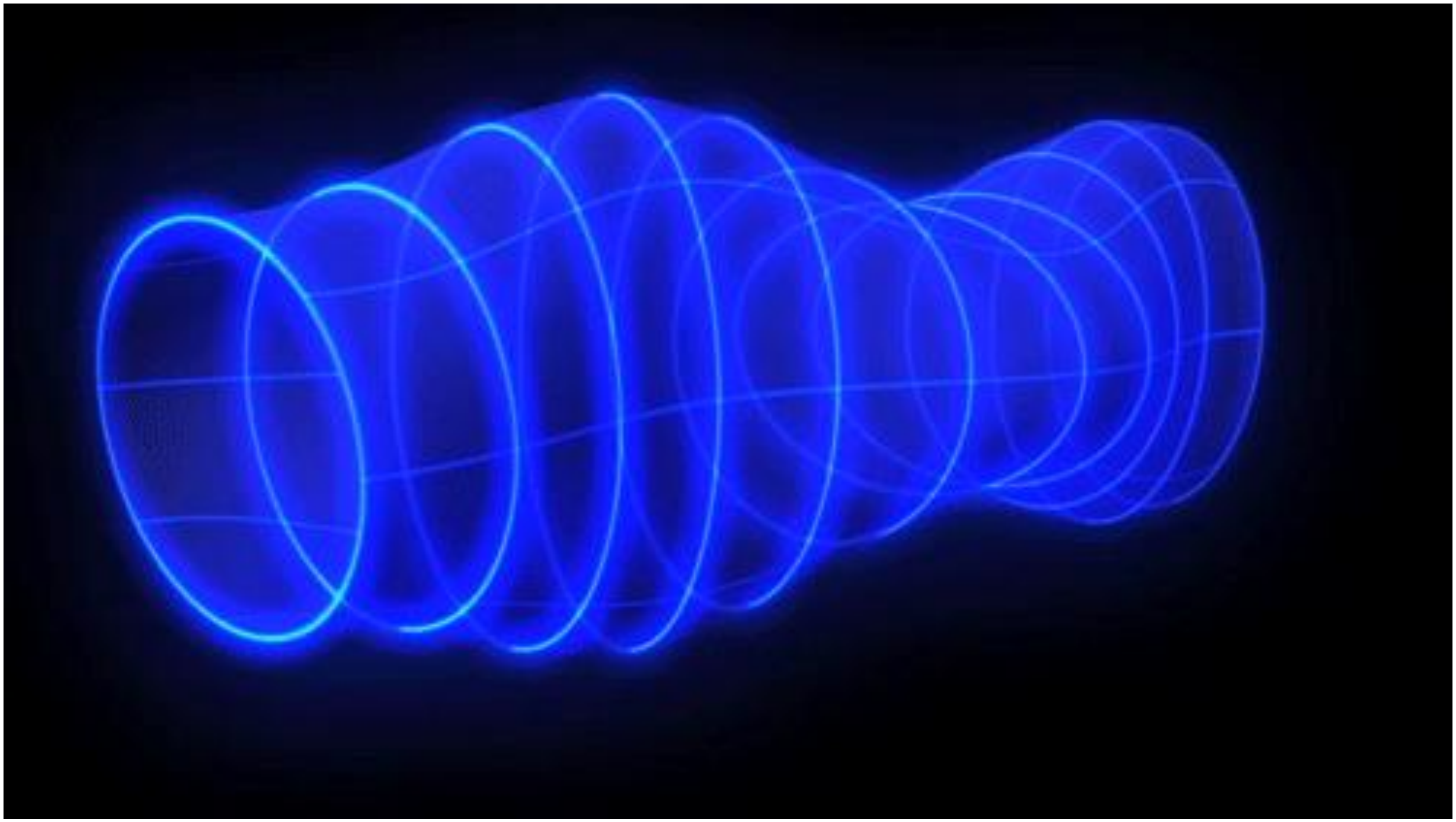
- General Relativity describes gravity in terms of a spacetime which is deformable. [Einstein, 1915]
- GWs are oscillations of that spacetime. [Einstein, 1916]

- "ripples in spacetime"



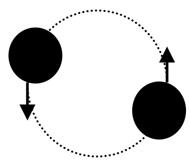


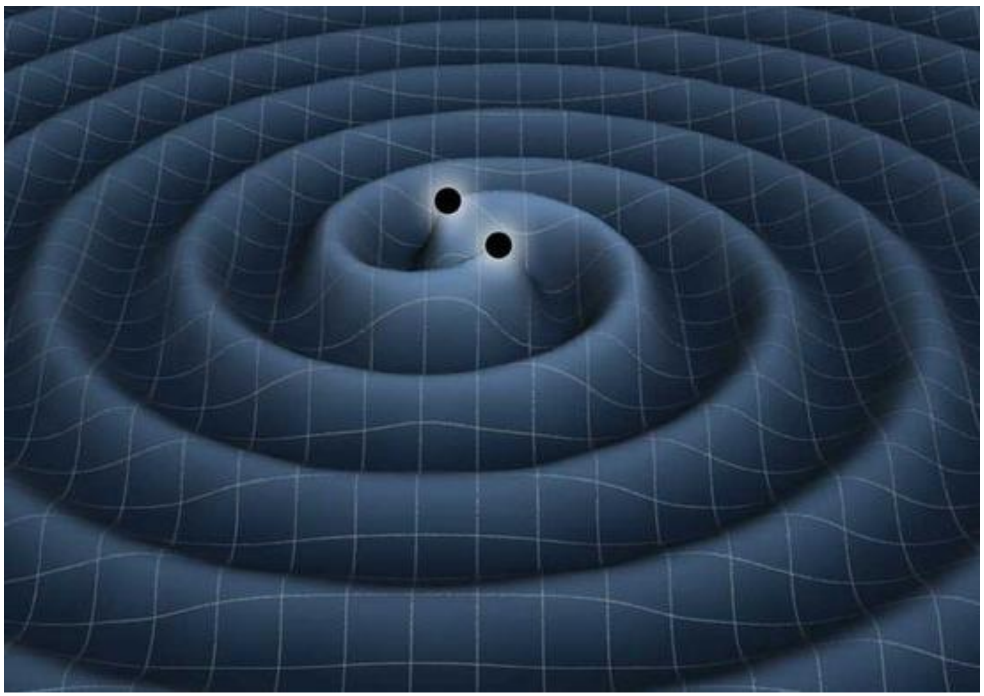
Propagating gravitational wave



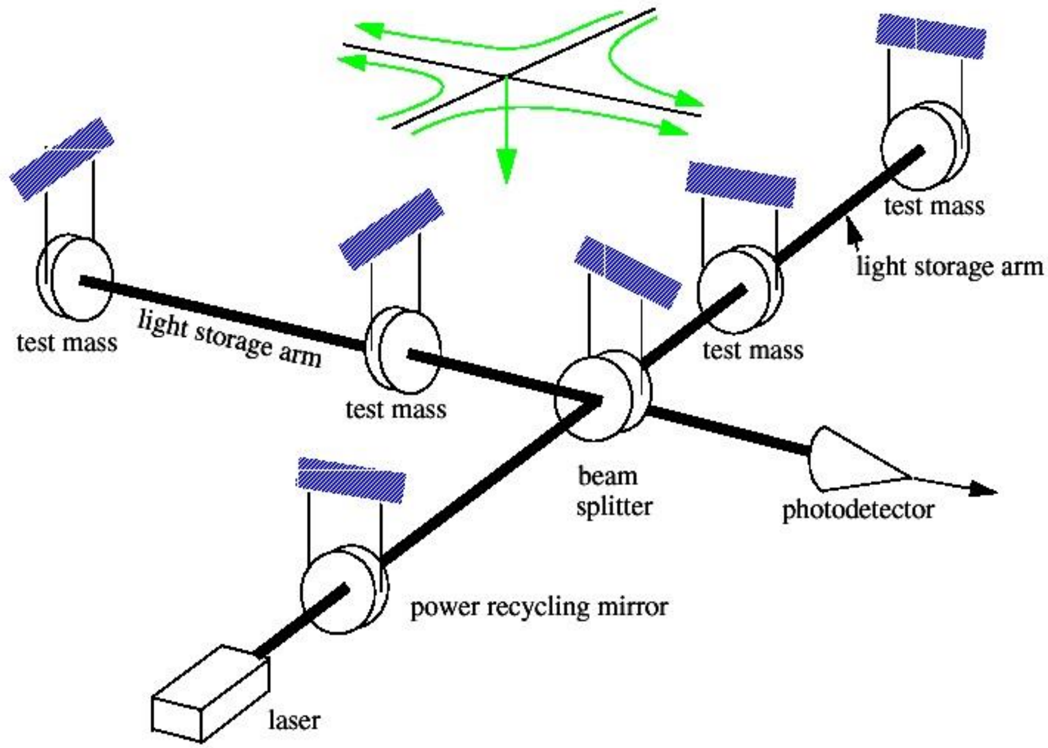
Gravitational waves and LIGO: short version

Binary black hole system





As detected by LIGO:

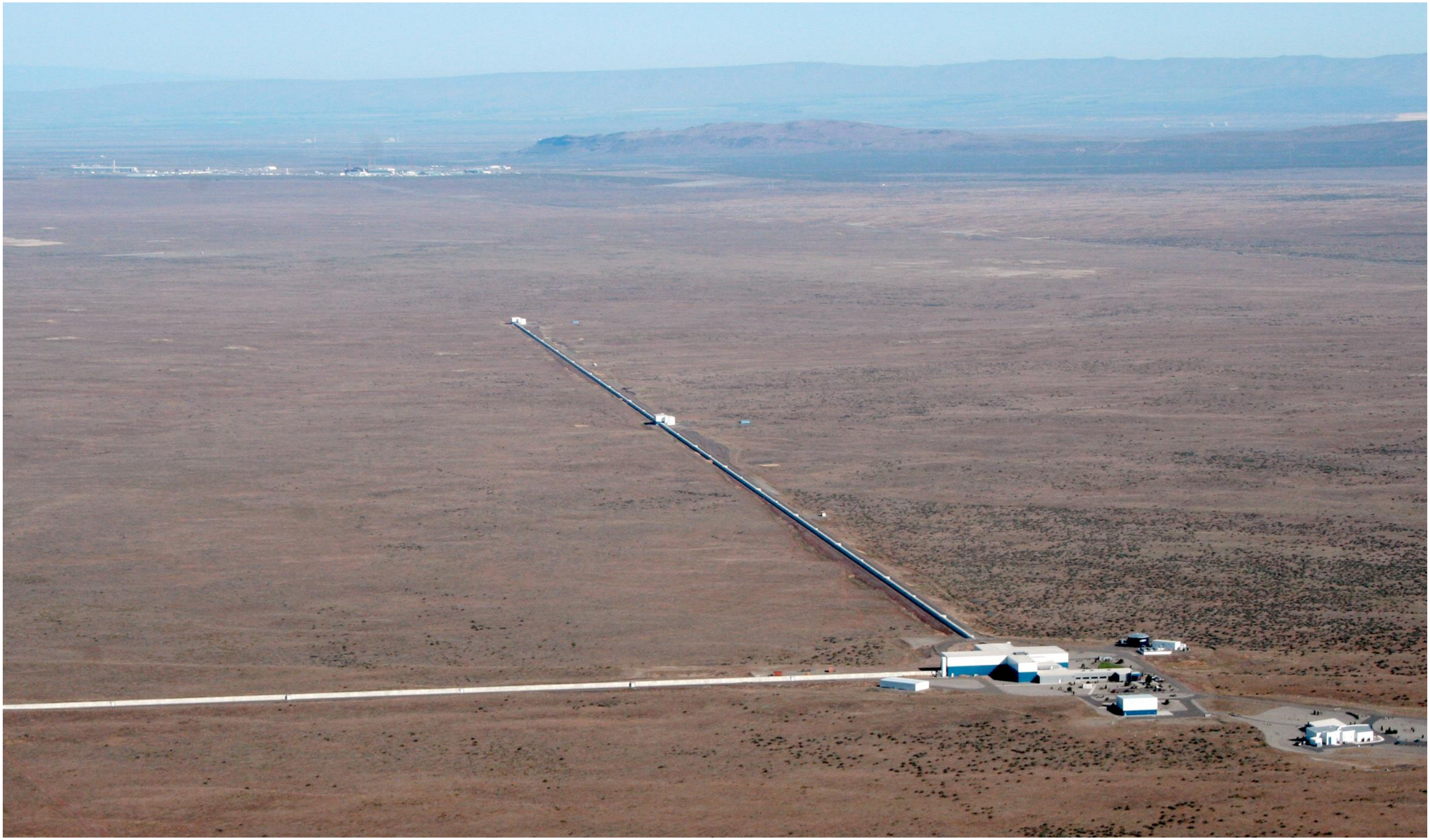


GW ripples manifest as a space strain h, where $h = \Delta L / L$

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

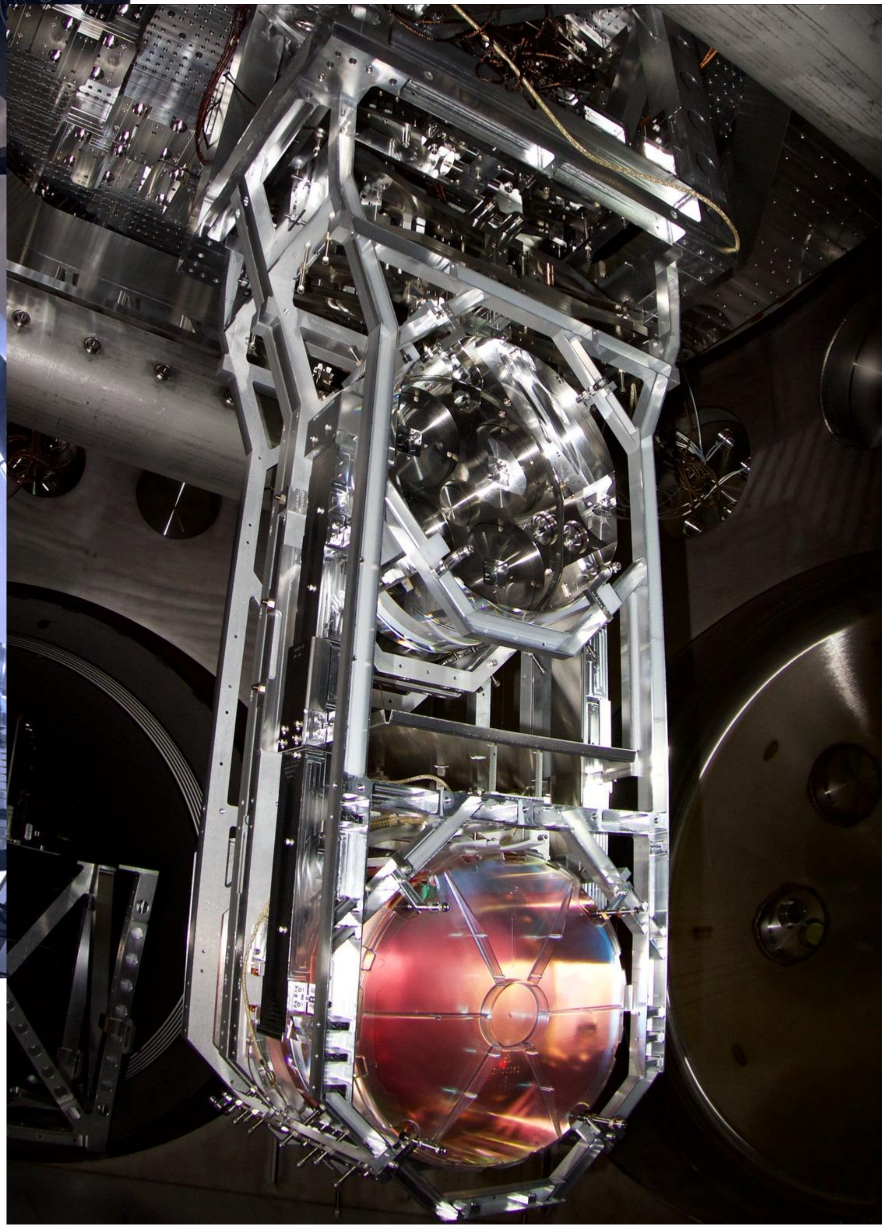
$\Rightarrow \Delta L \sim 10^{-19}$ m (Yikes !)

LIGO Hanford Observatory

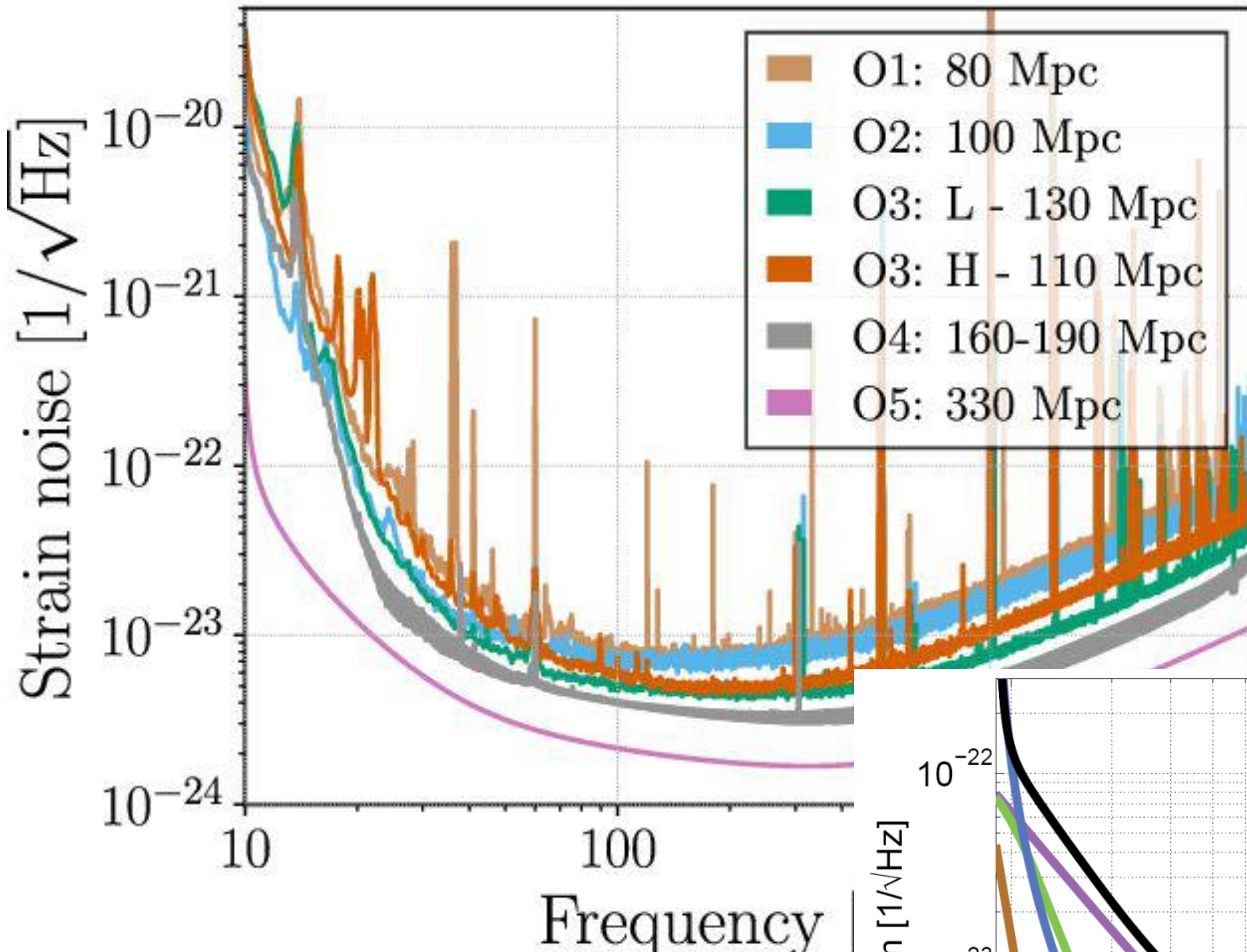


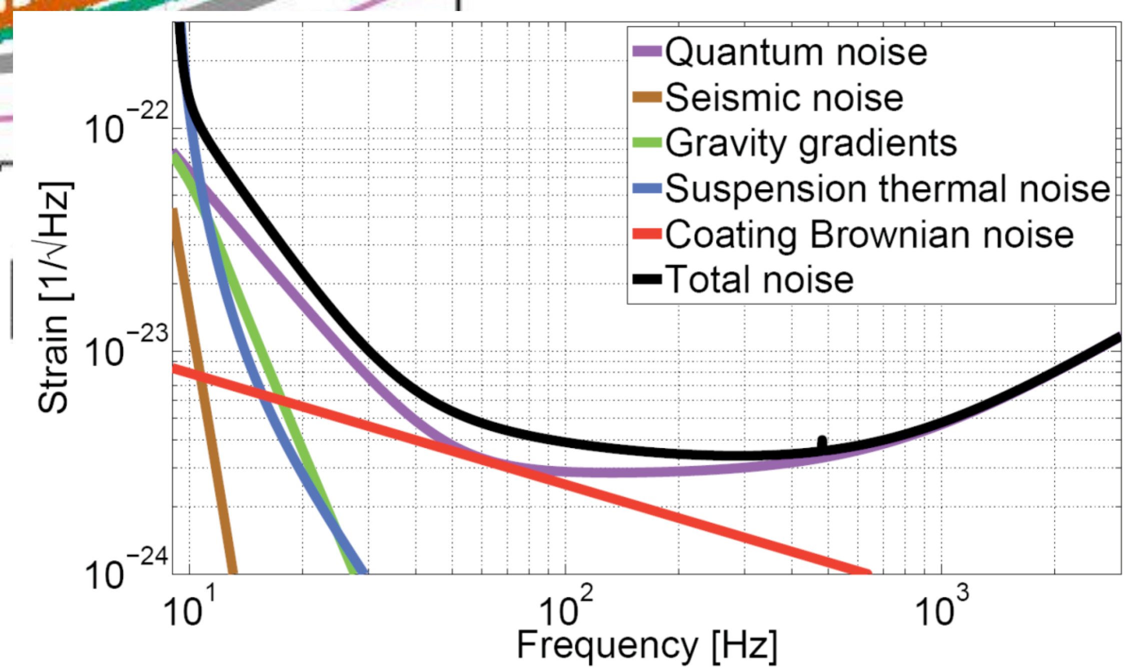
observatories

Inside the vacuum chambers

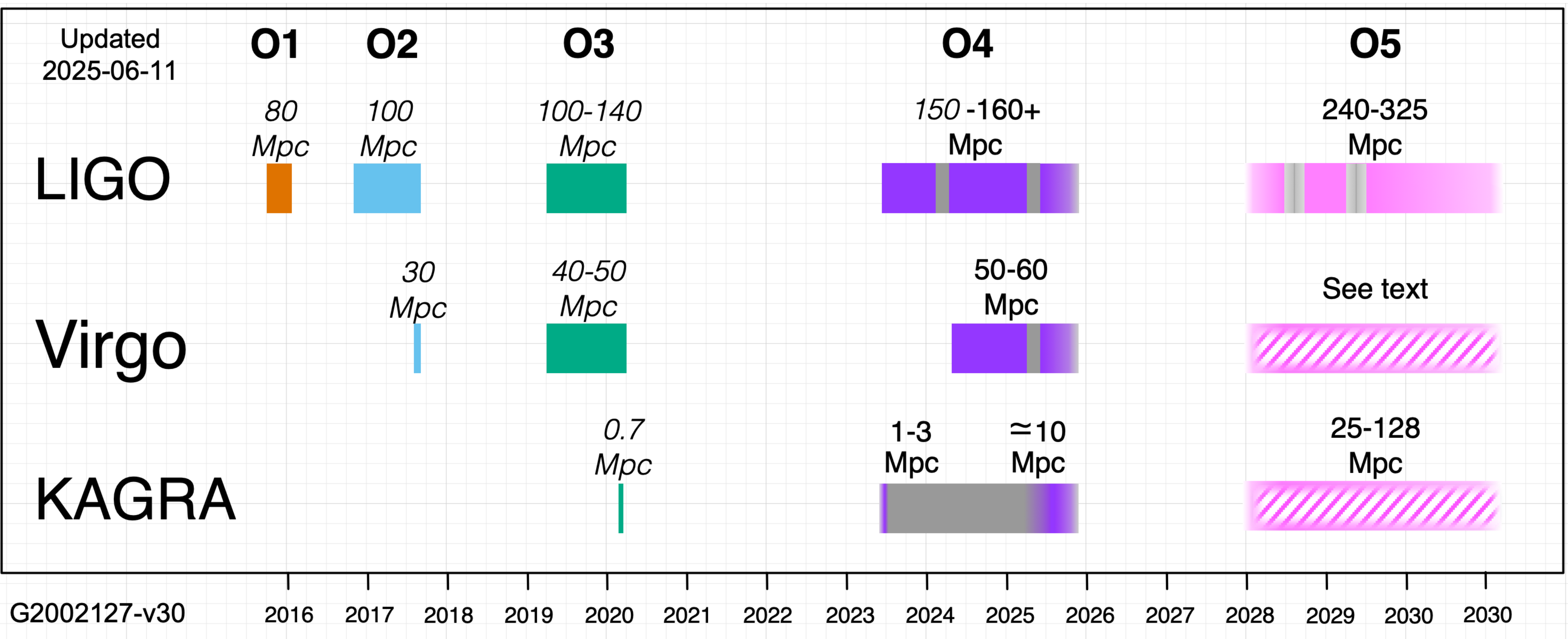


Reducing the noise ➔ increasing sensitivity





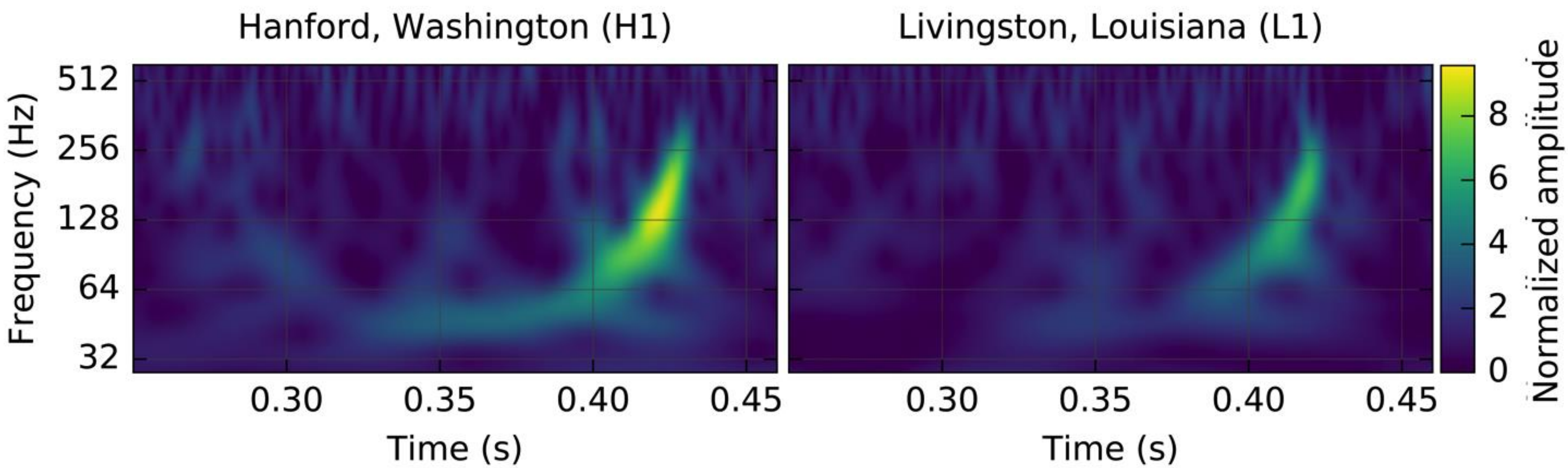
Observing runs



The numbers represent the GW sensitivity of the detectors.
Specifically, they are the distance (in Mpc) that a binary neutron star (BNS) merger can be clearly observed (SNR=8) by a single detector when average over all sky positions. The maximum distance ('horizon') is about 2.3 further.
Because of their larger masses, BH mergers can be observed **much** further: several Gpc in O4.

September 14, 2015, 2:51 AM Pacific

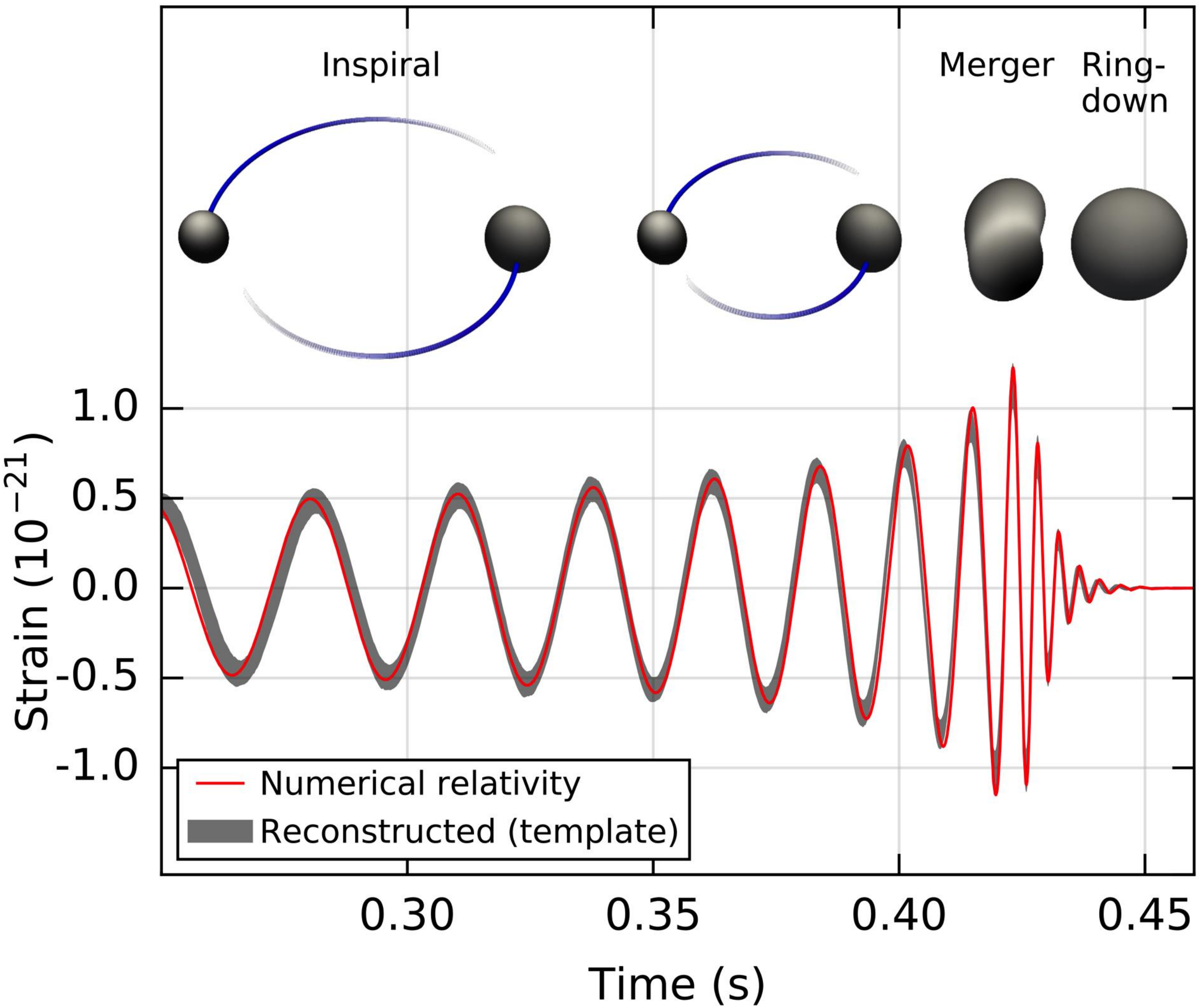
Boom !



GW150914

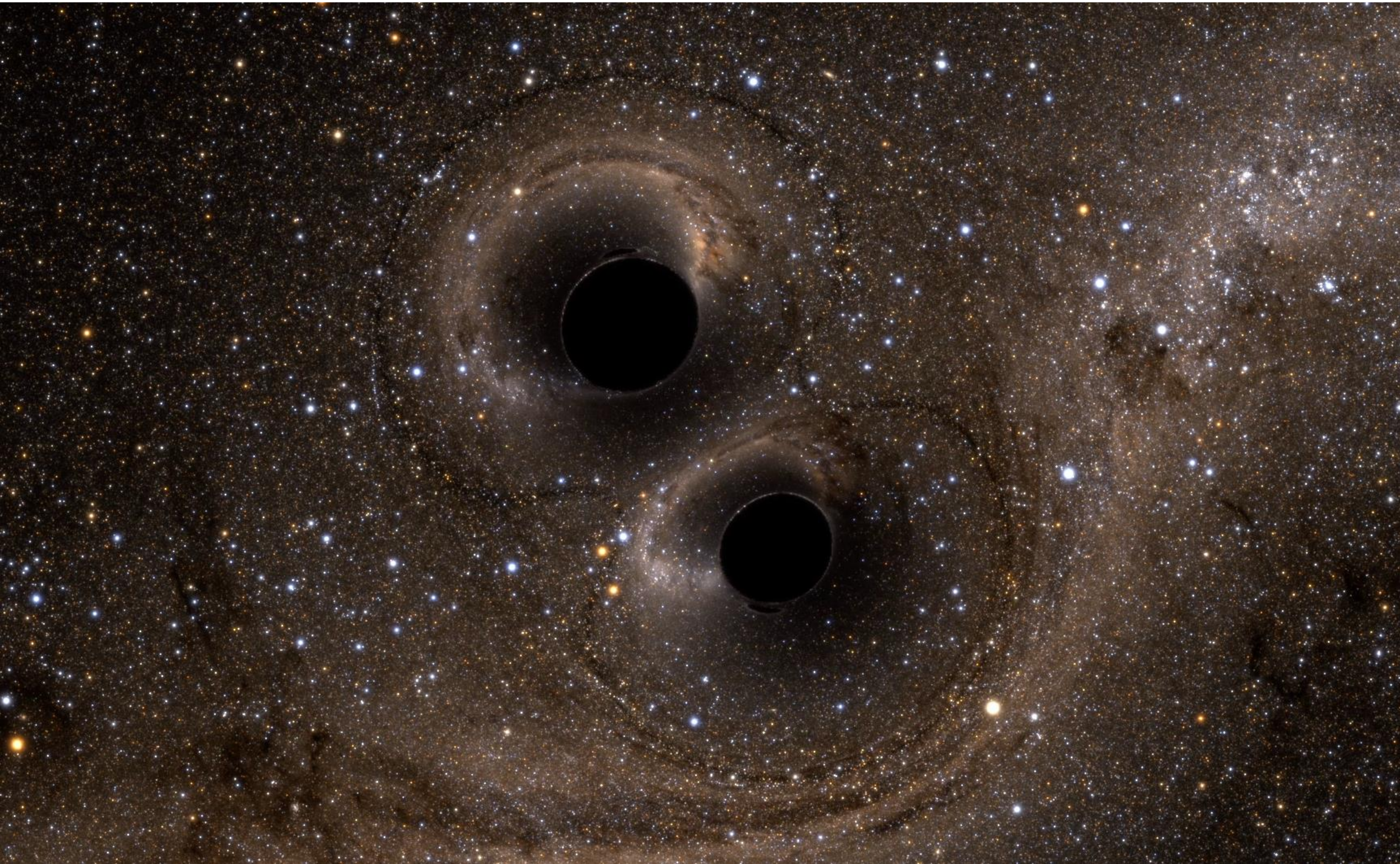
- First observation of GWs
- First direct observation of black holes

Binary black hole inspiral, merger, ringdown

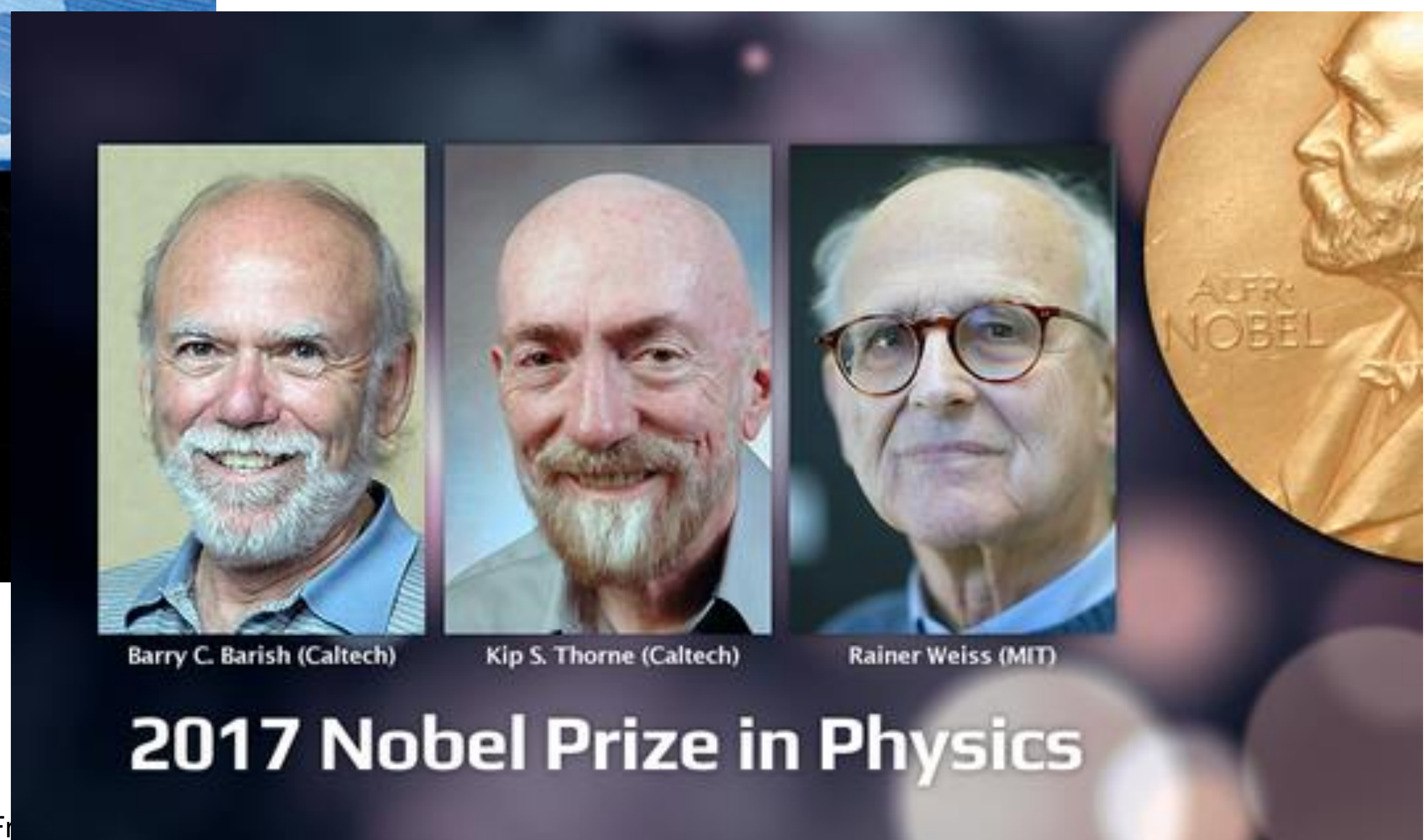


Simulated Nearby View – slowed down 100X

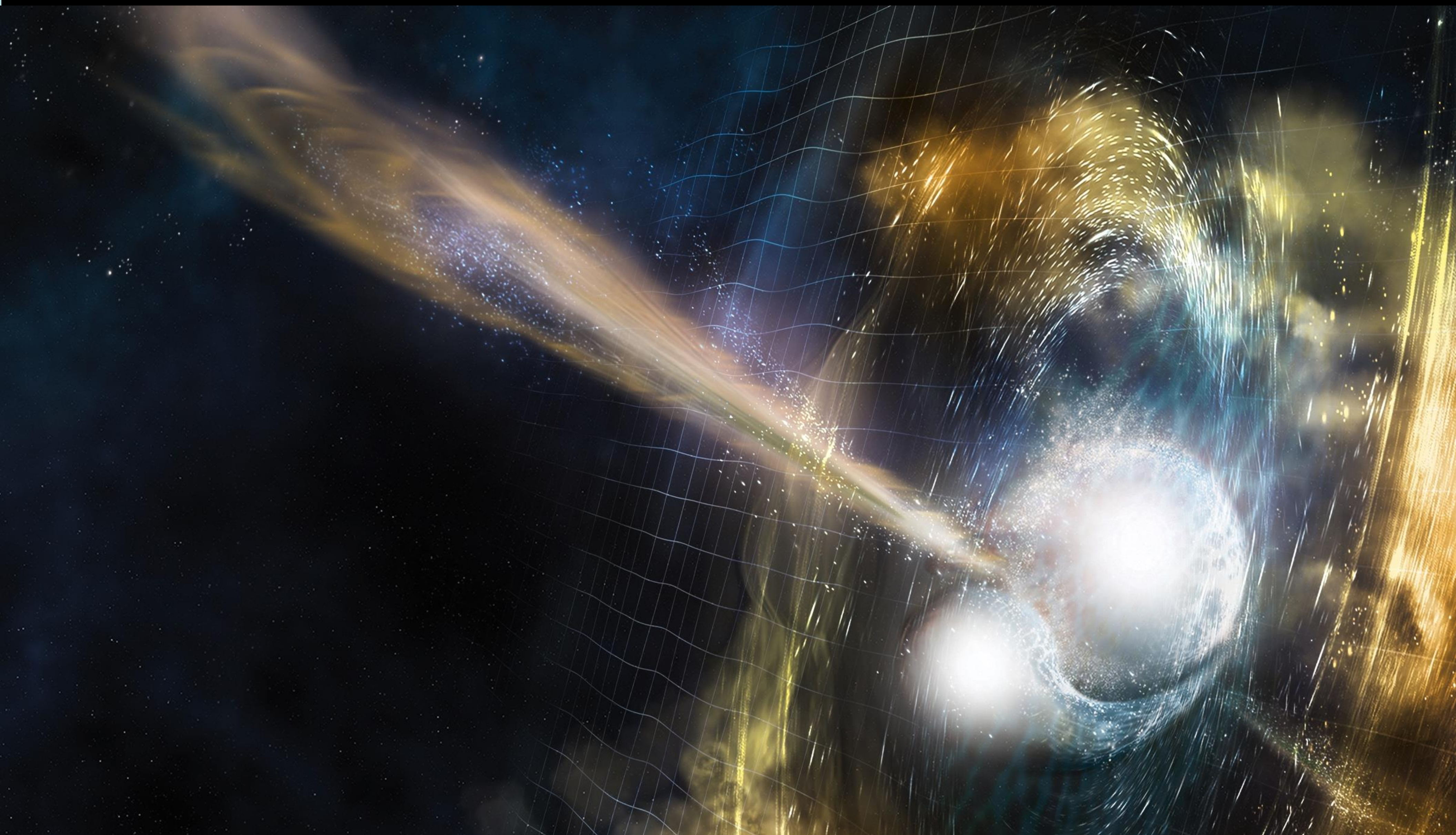
Video link: https://youtu.be/I_88S8DWbcU



GW Discovery Accolades



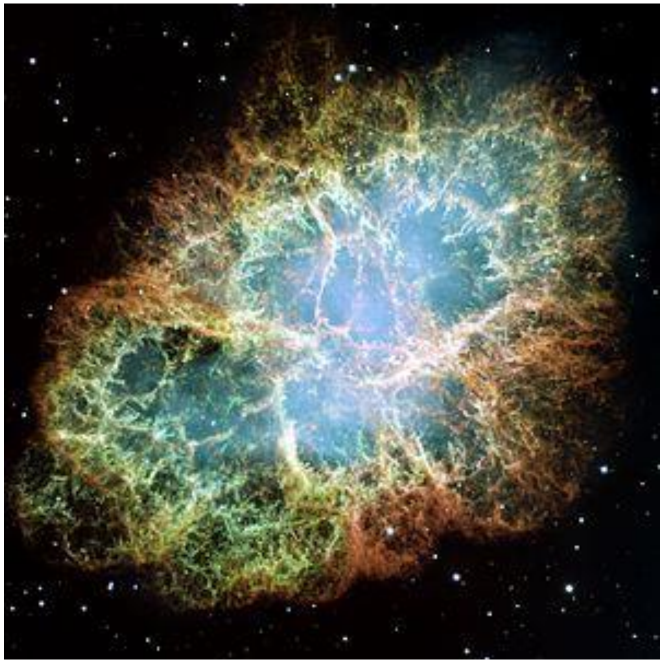
Boom II:
Binary neutron-star merger August 17, 2017 (O2)

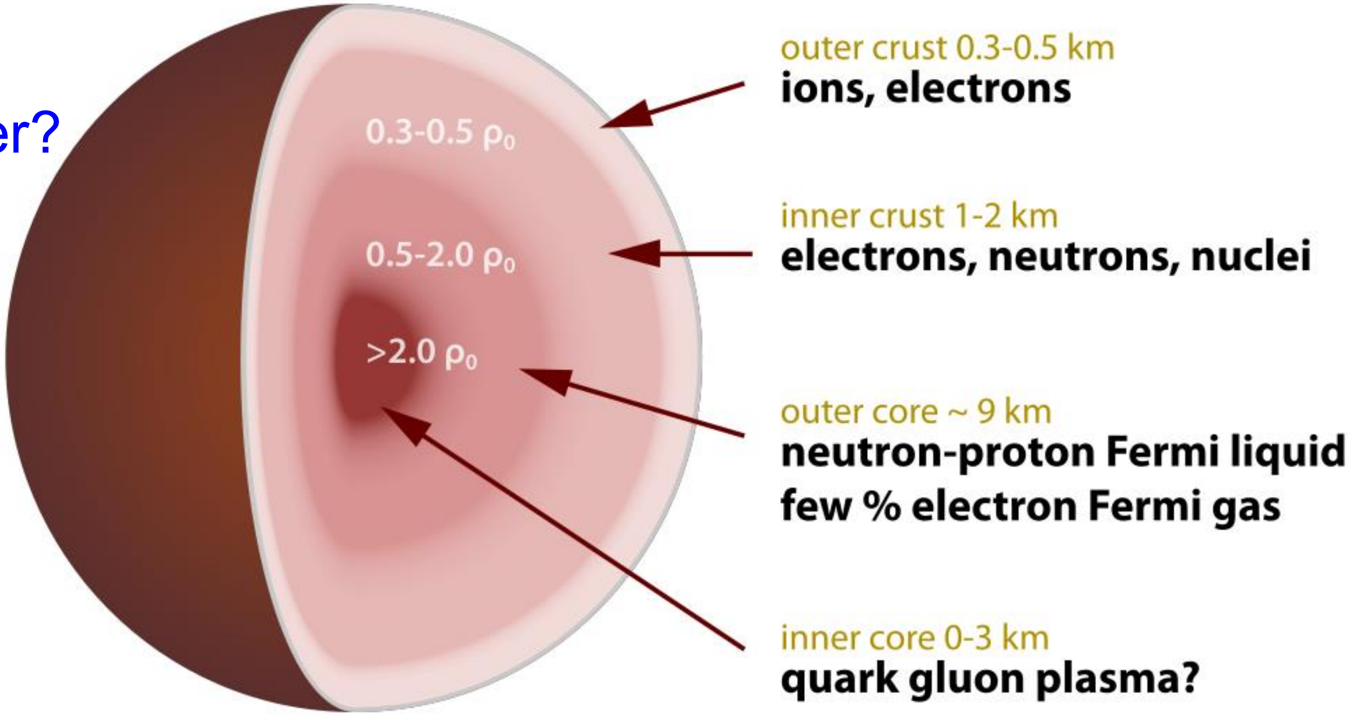


Neutron stars

- 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× $10^{12}\, m/s^2$
- Mysterious composition
  - new phases of matter?
  - quark matter?
  - dark matter?

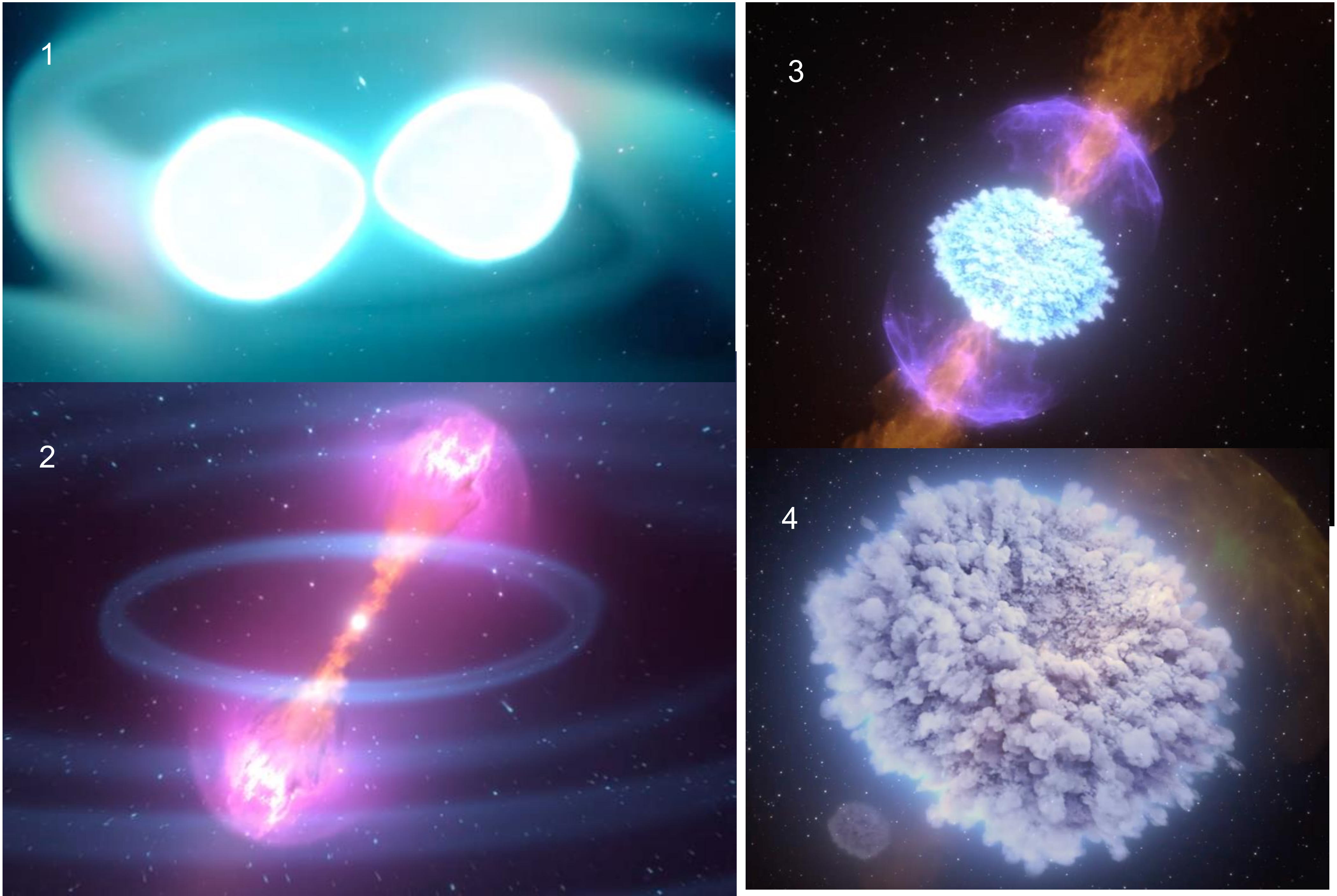




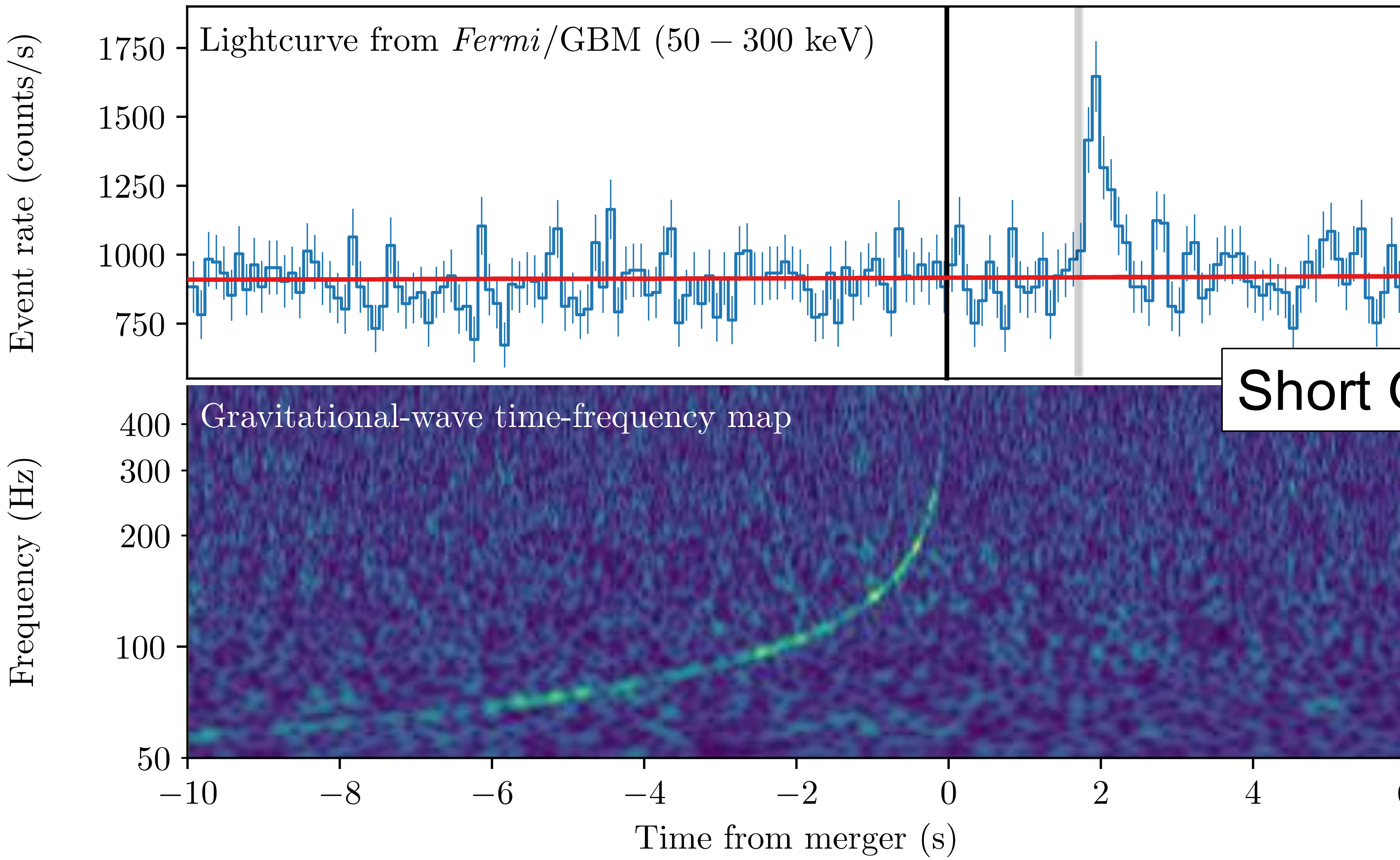
R Frey

LIGO

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

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

- 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 ✓

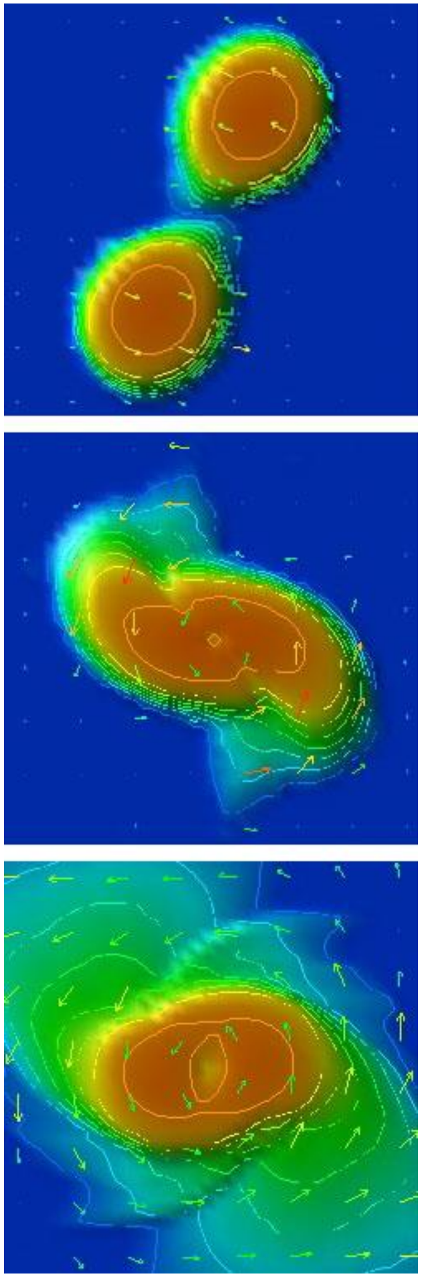
- Limits: (1) Let Δt_astro = 0; (2) Let Δt_astro = 10 s:

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

- Future measurements at different distances can improve this

170817: Astrophysics
The "kilonova"

LIGO

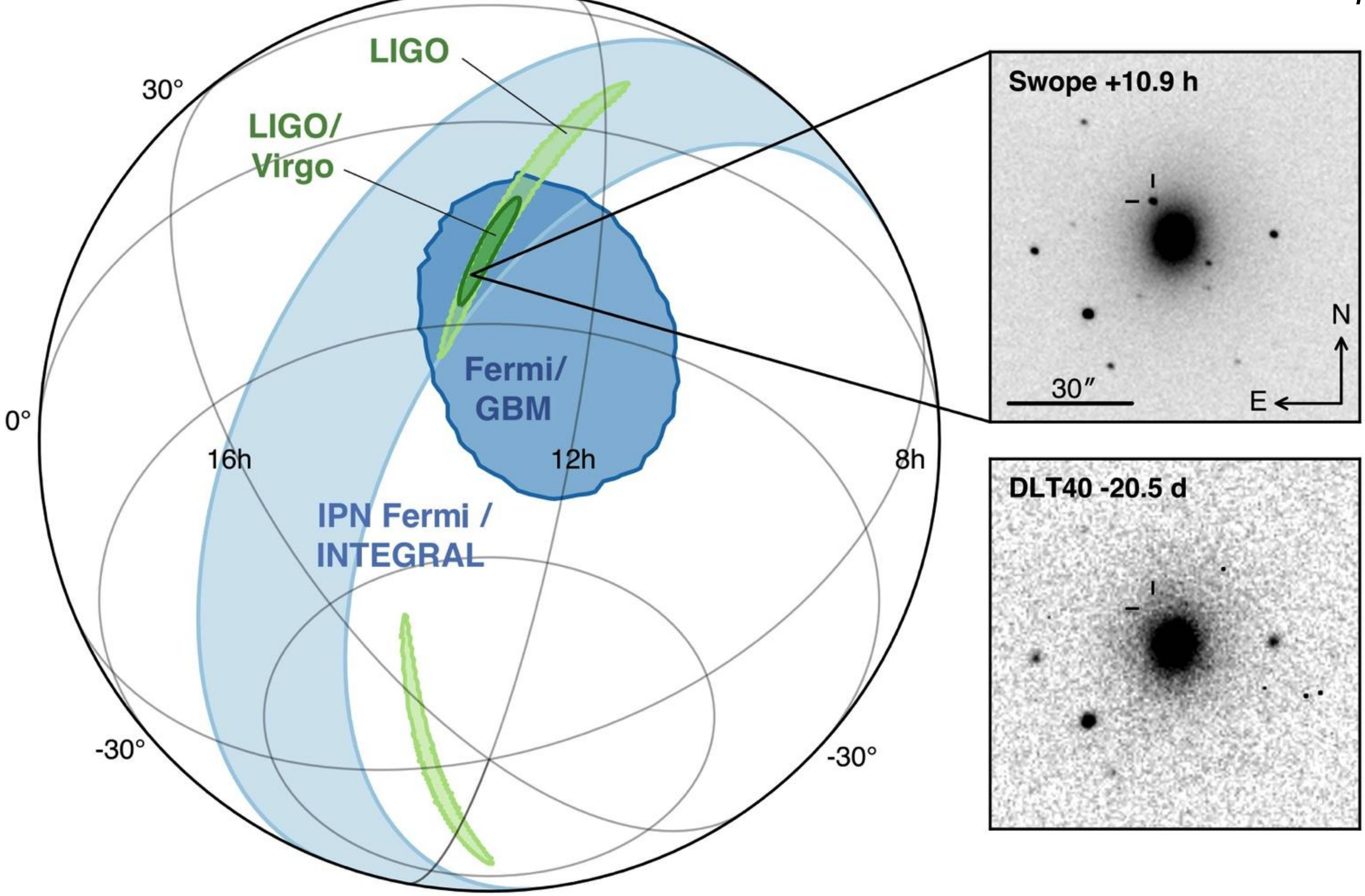


Shibata

- 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

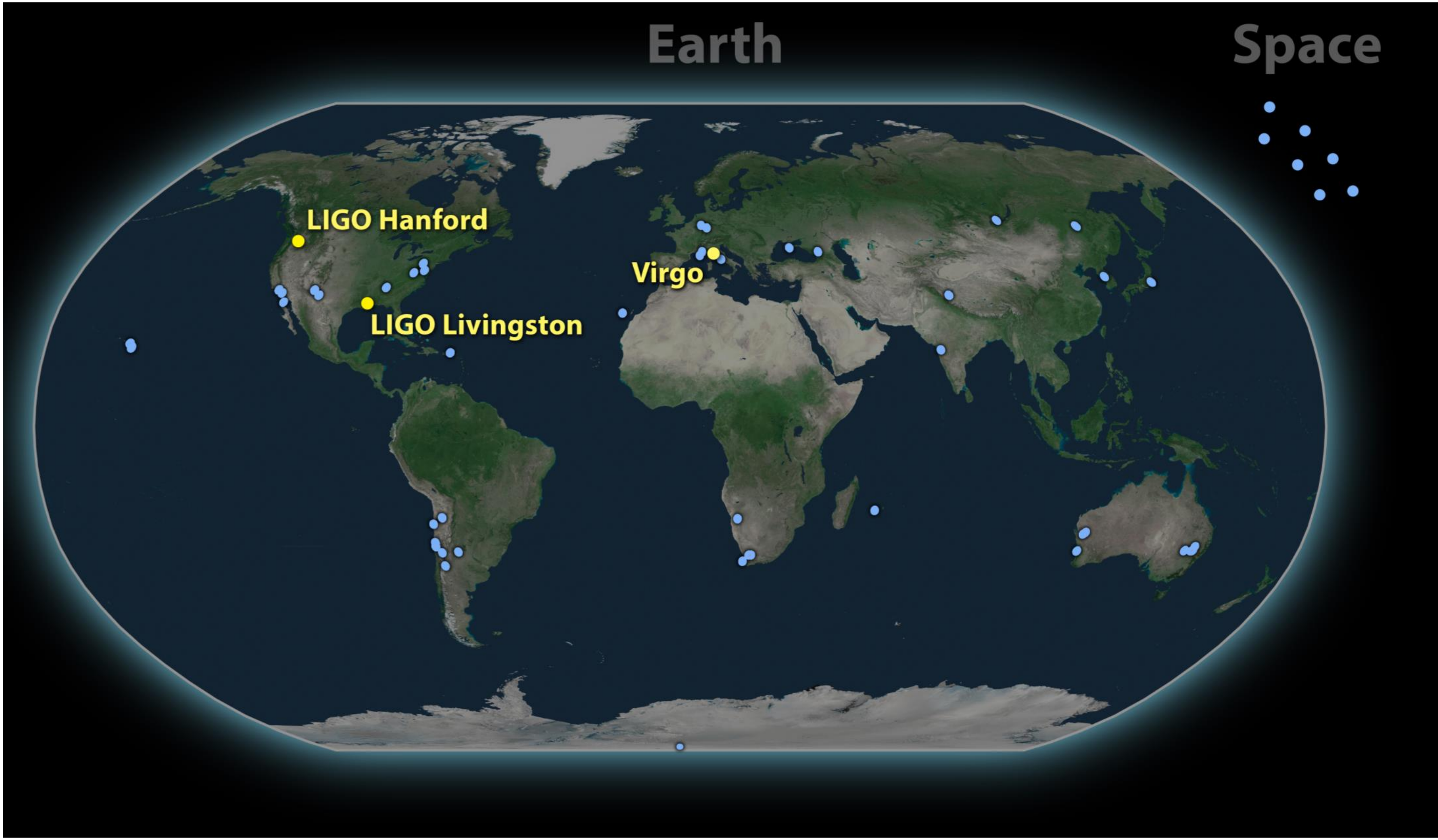


NGC 4993
43 ± 3 Mpc

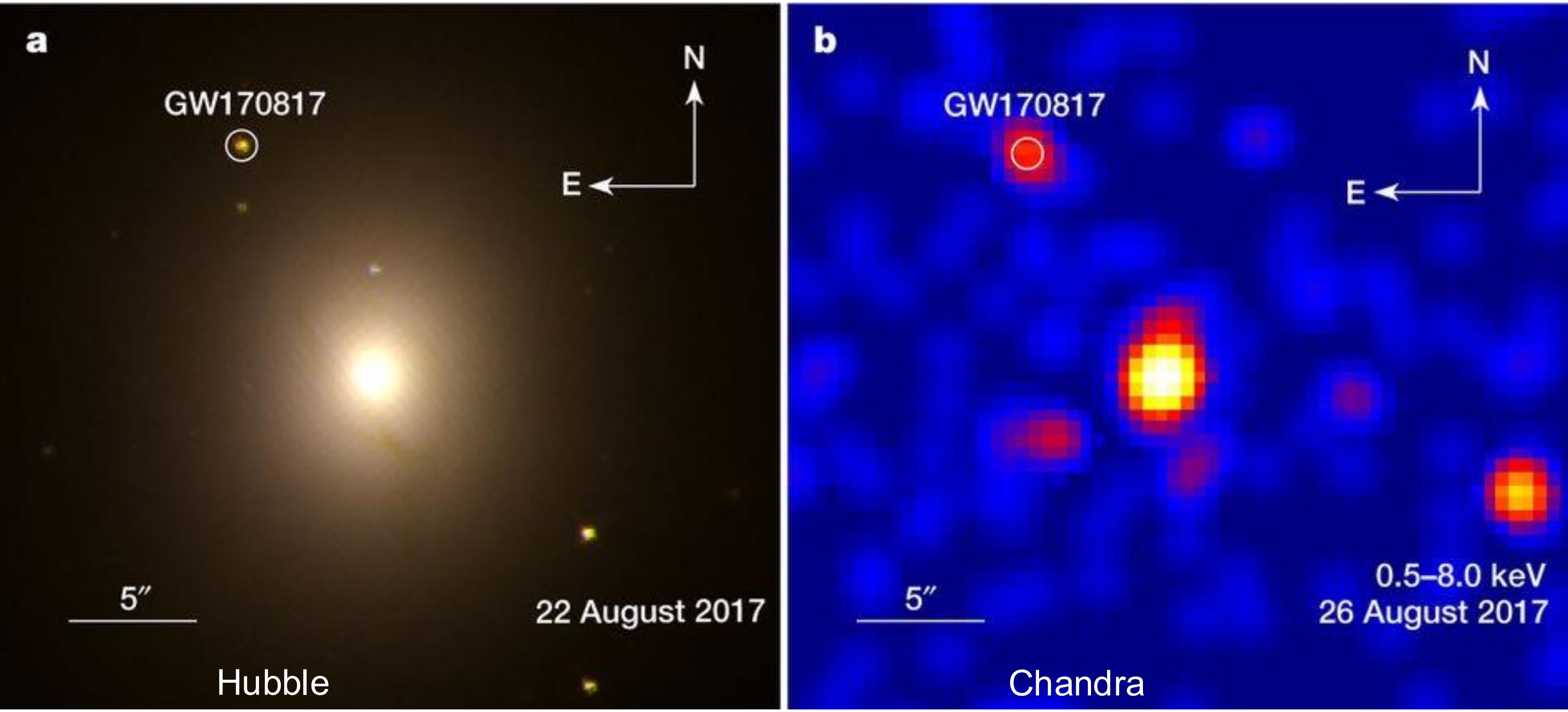
offset of 2 kpc – typical of kicks

“Multimessenger Astronomy”

and the astronomy world tuned in

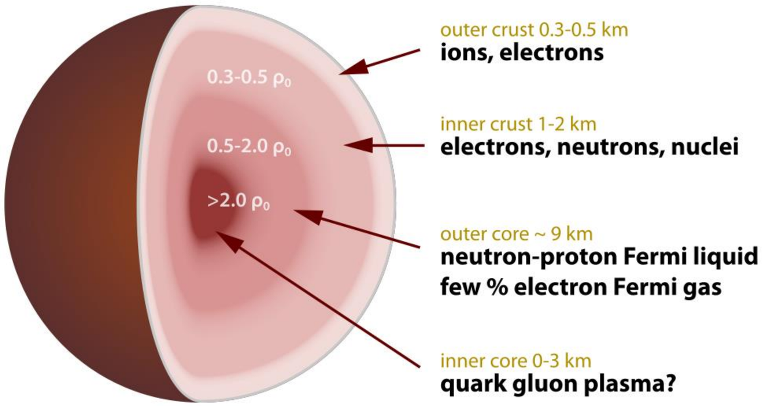


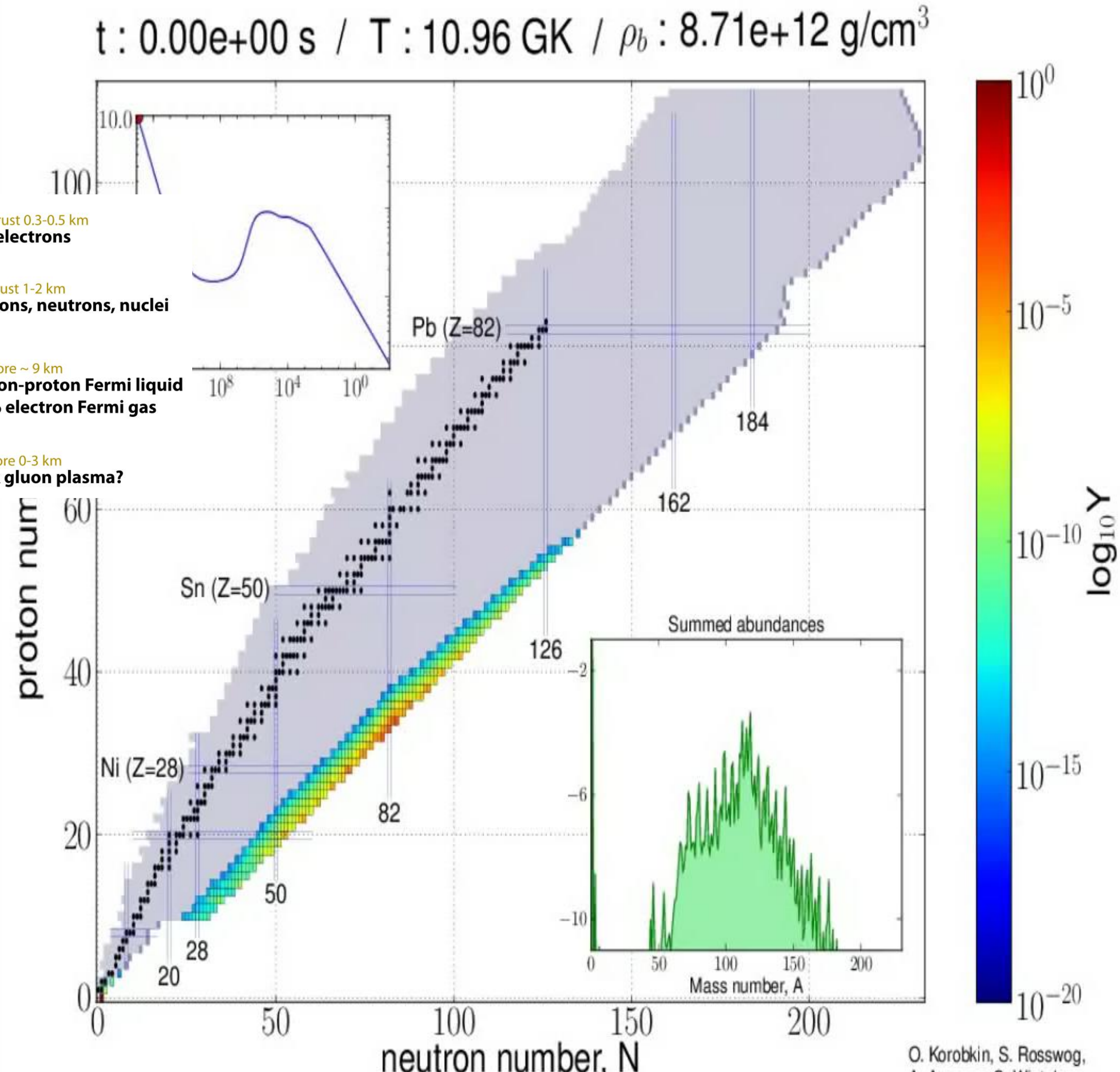
e.g. optical/IR and x-rays



Troja, et al, Nature 2017

LIGO

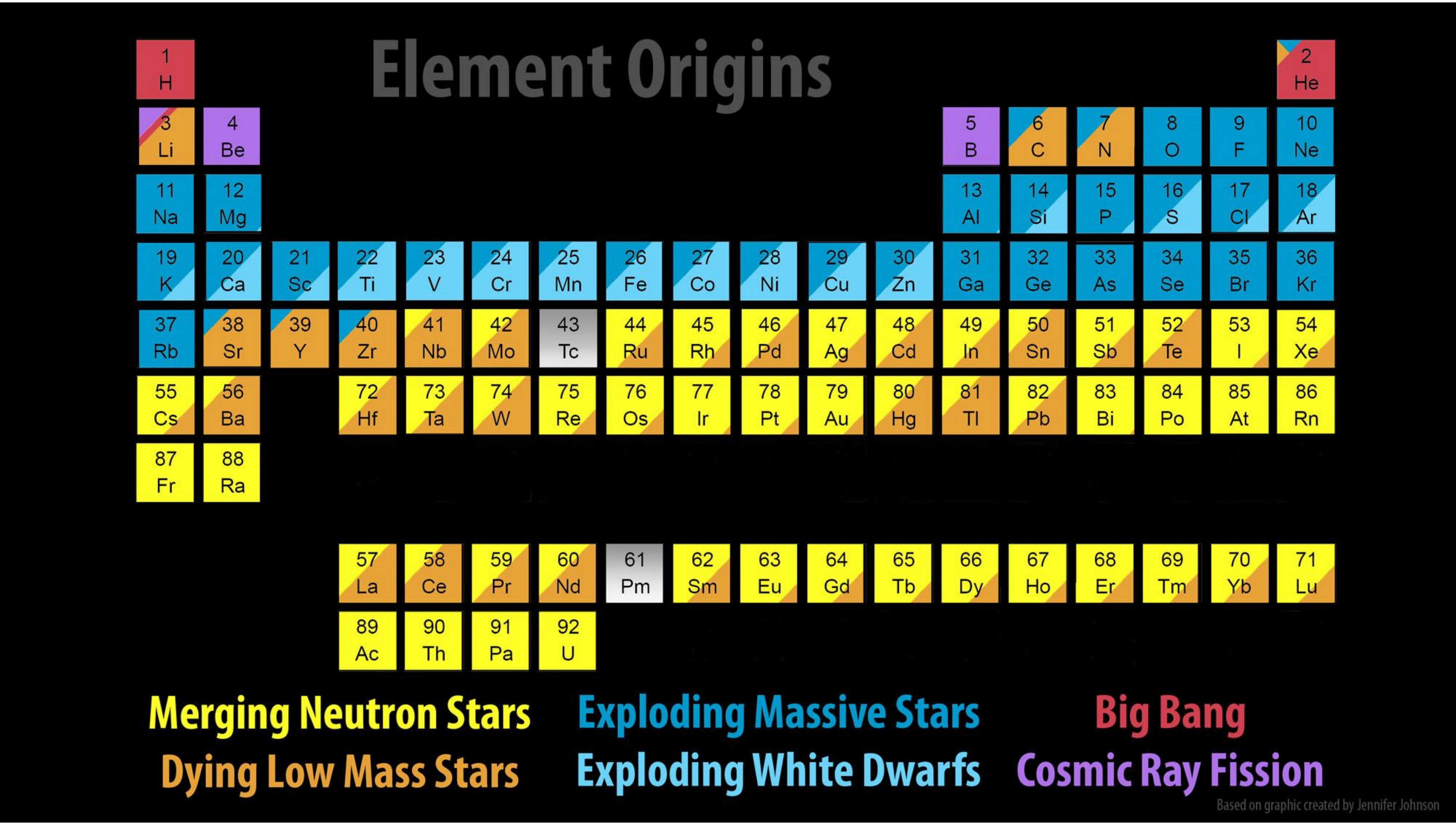




O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

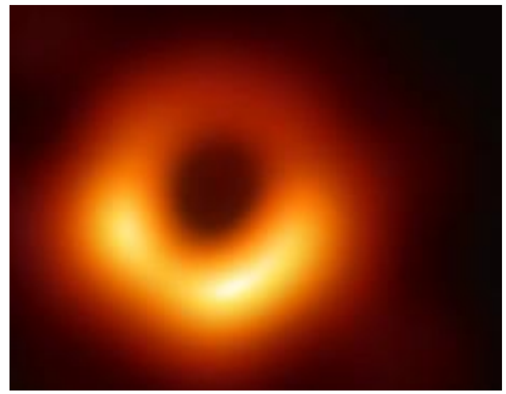
LIGO

Origins of elements: Major Update due to 170817

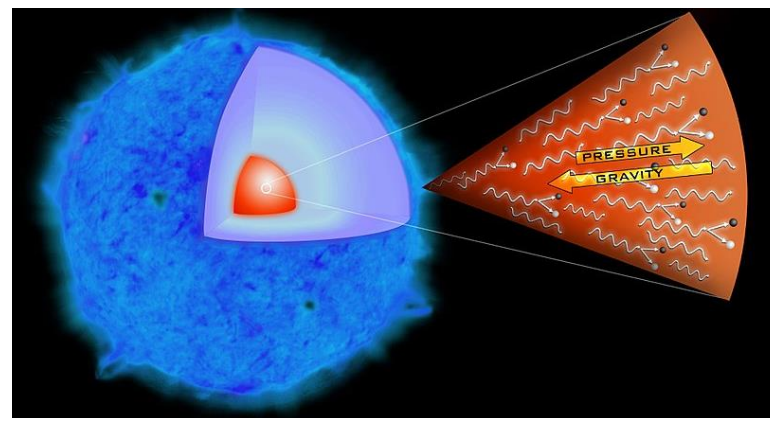


Black hole masses

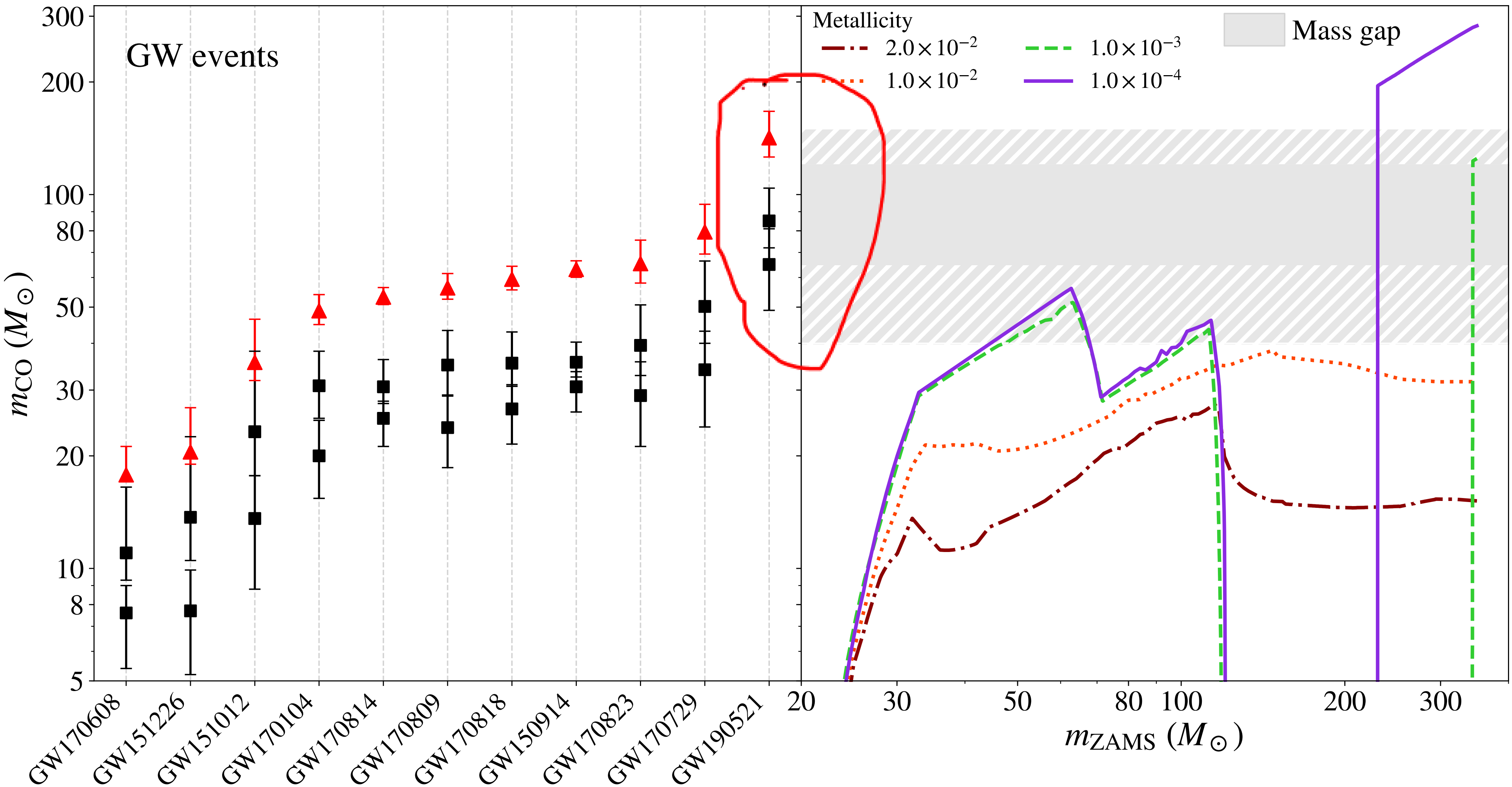
- Supermassive – rapid accretion in early star forming era
  - not observable by LIGO
  - Galactic centers
  - Milky Way: $4 \times 10^6\ M_\odot$
  - M87: $6 \times 10^9\ M_\odot$



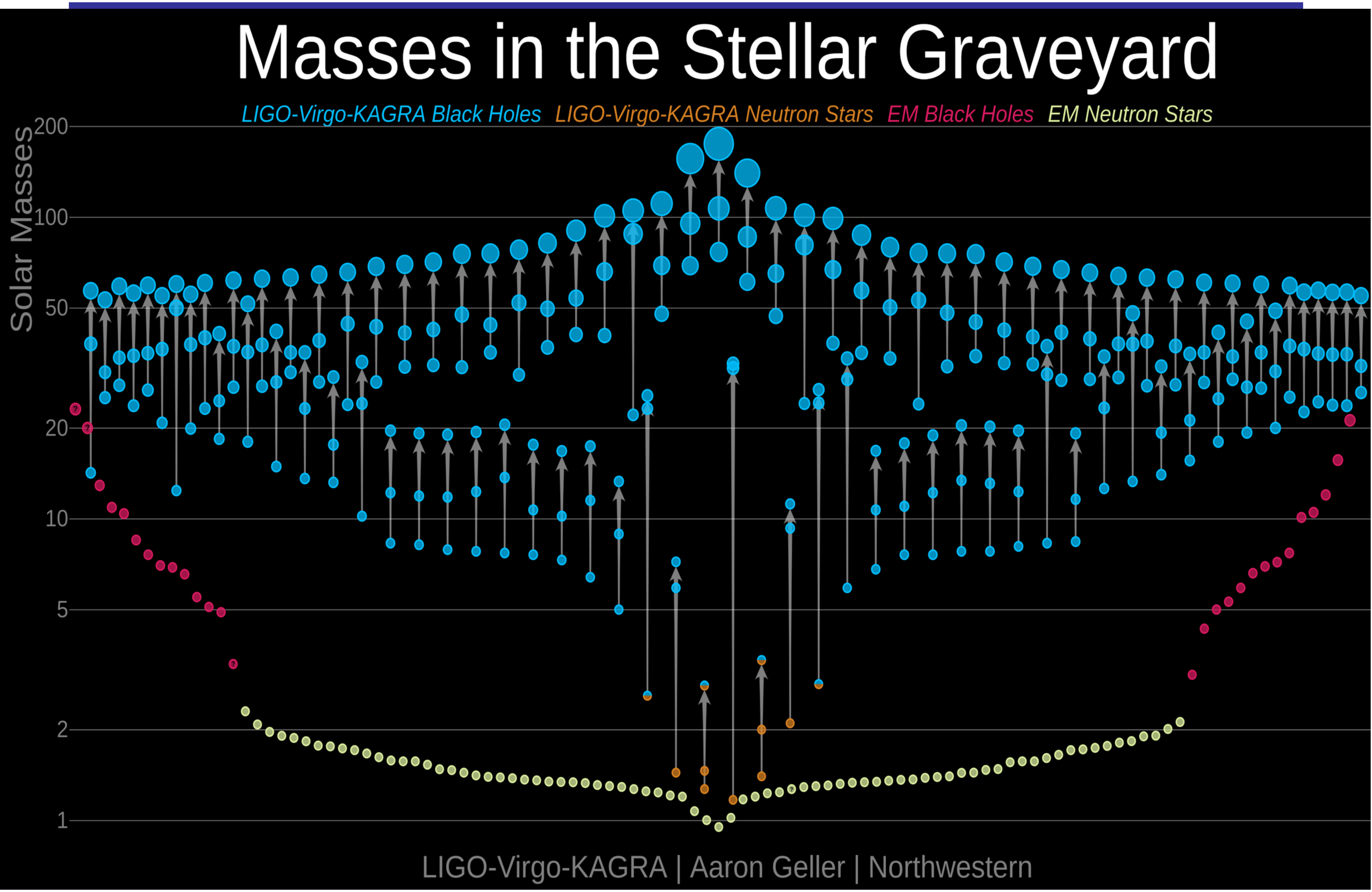
- 'Stellar mass'
  - Presumed products of stellar evolution
  - $M > 3\ M_\odot$ (TOV)
  - If $M < M_\odot$ then primordial (!)
  - $40 < M < 60\ M_\odot$ 'difficult' but observed (low metallicity)
  - $60 < M < 130\ M_\odot$ not supposed to exist (pair instability)
  - $M > 130\ M_\odot$ possible; not yet observed



The ‘mass gap’ undone ? Sequential mergers?



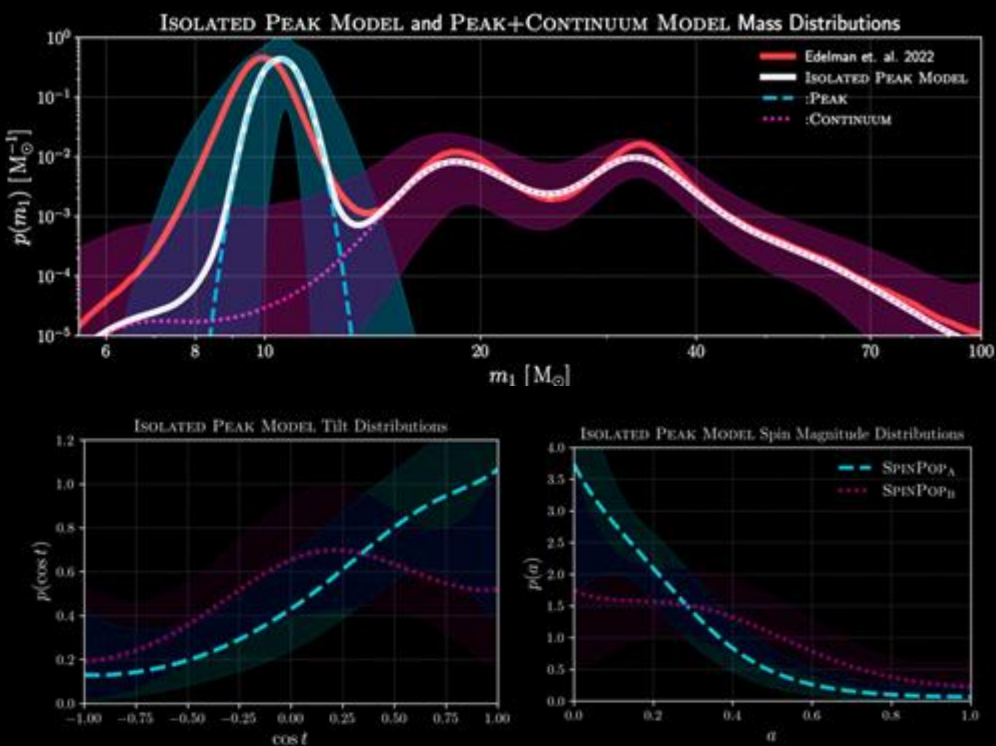
NS/BH mergers detected as of May 2023



BBH Subpopulation Models

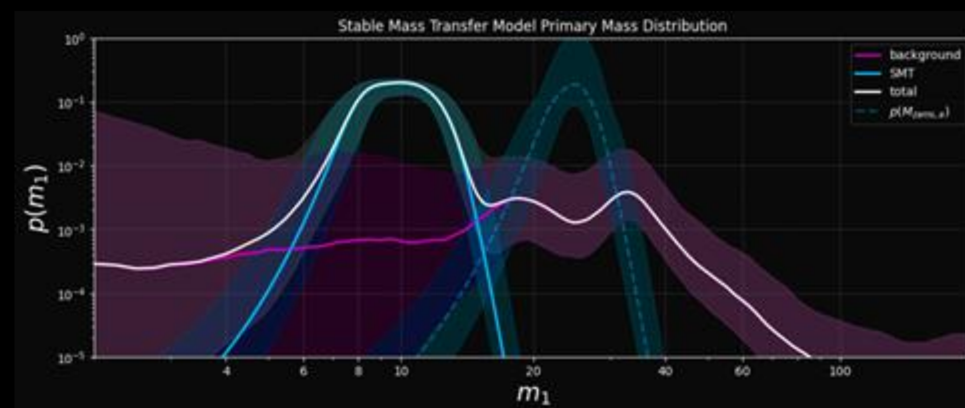
Jaxen Godfrey

Cosmic Cousins: 10 Msun Subpopulation (update)



arXiv:2304.01288

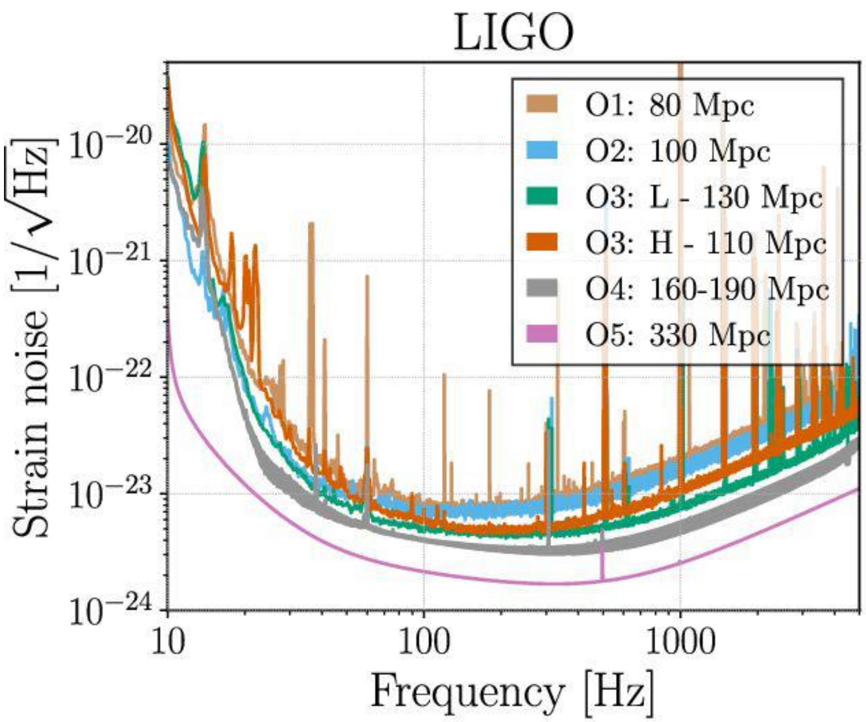
New Project: Building a Model for Stable Mass Transfer BHs

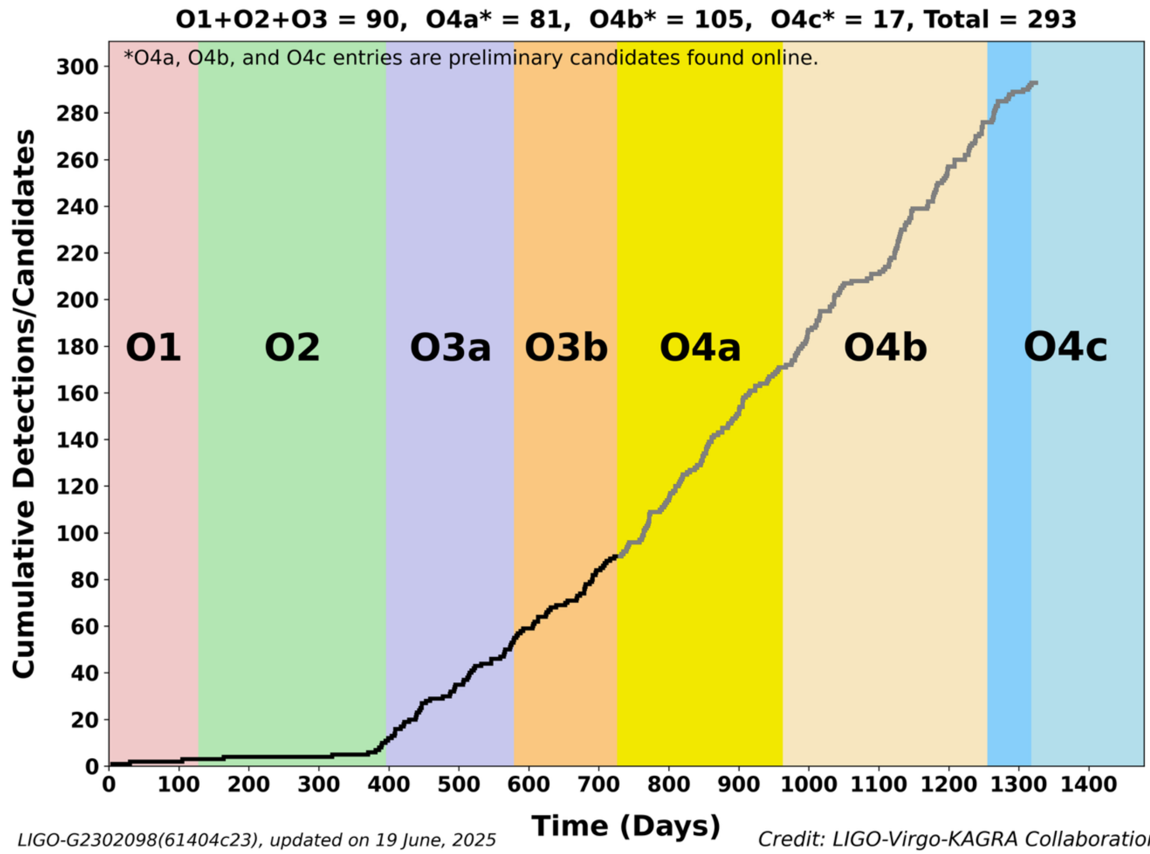


-> Directly model mass distributions of BBH progenitor stars (dashed curve) that undergo stable mass transfer prior to BBH formation

-> prelim results: 10 Msun peak consistent with SMT channel

Those were the highlights for O1, O2 O3. What about O4 ?





- The GW horizon is limited by our ability to reduce the noise of the interferometer
- Rate of detected events ~ horizon^3
- O4: May 2023 – Nov 2025

Beyond binary mergers…

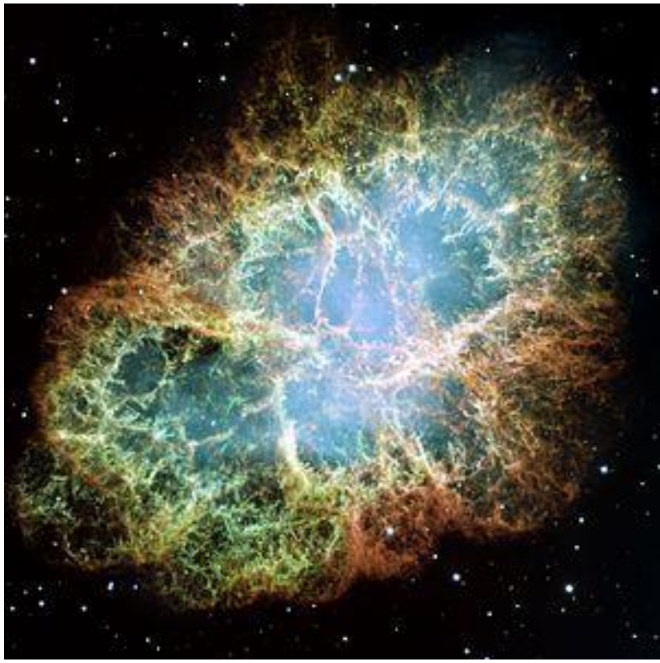
The ever-increasing sensitivity of LIGO will…

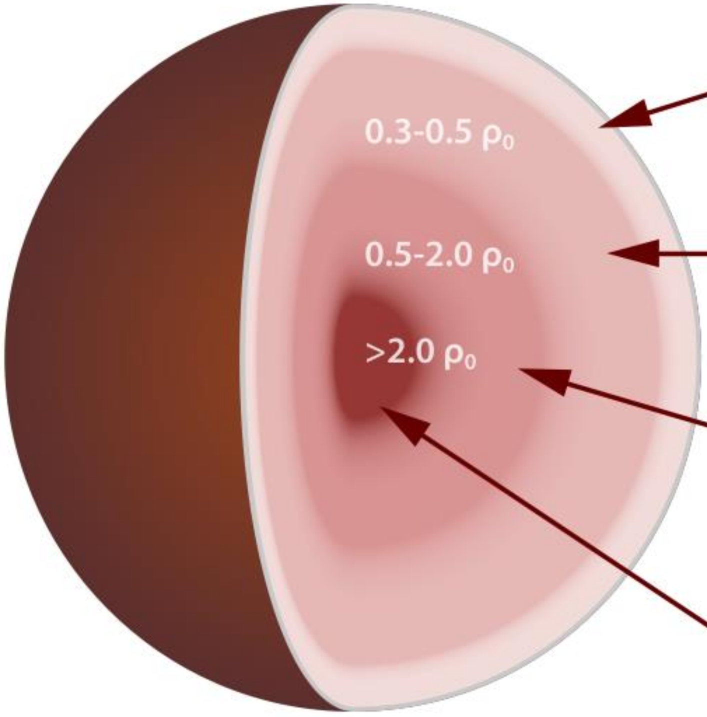
- Allow more observations of mergers of BHs and NSs
  - More
  - Further: In O4 observing BBH mergers to ~6 Gly
    - More short gamma-ray bursts
  - Wider mass range (sub-solar mass?), $M>100\ M_\odot$
  - Greater fidelity (SNR) → details of the GW waveforms

- Allow opportunity for observing new types of GW sources
  - Supernovae
  - Magnetars
  - Long gamma-ray bursts
  - Cosmic strings
  - Cosmic 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)
- Mysterious composition
  - new phases of matter?
- GW observations can tease out the NS composition – equation of state





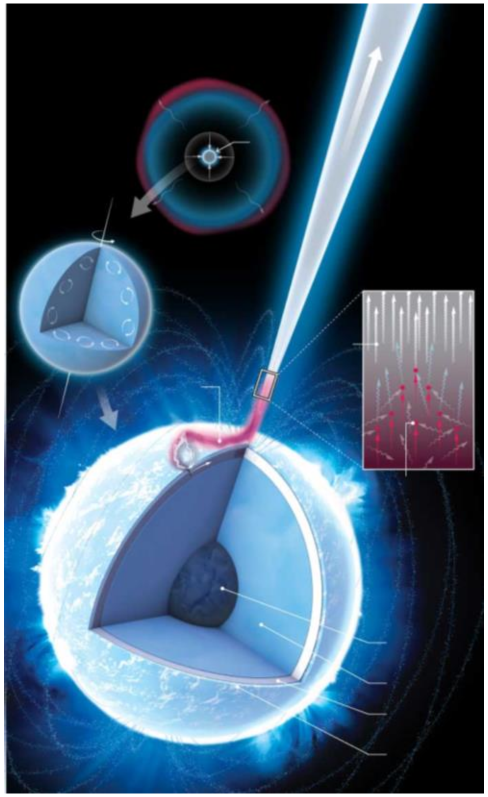
R Frey

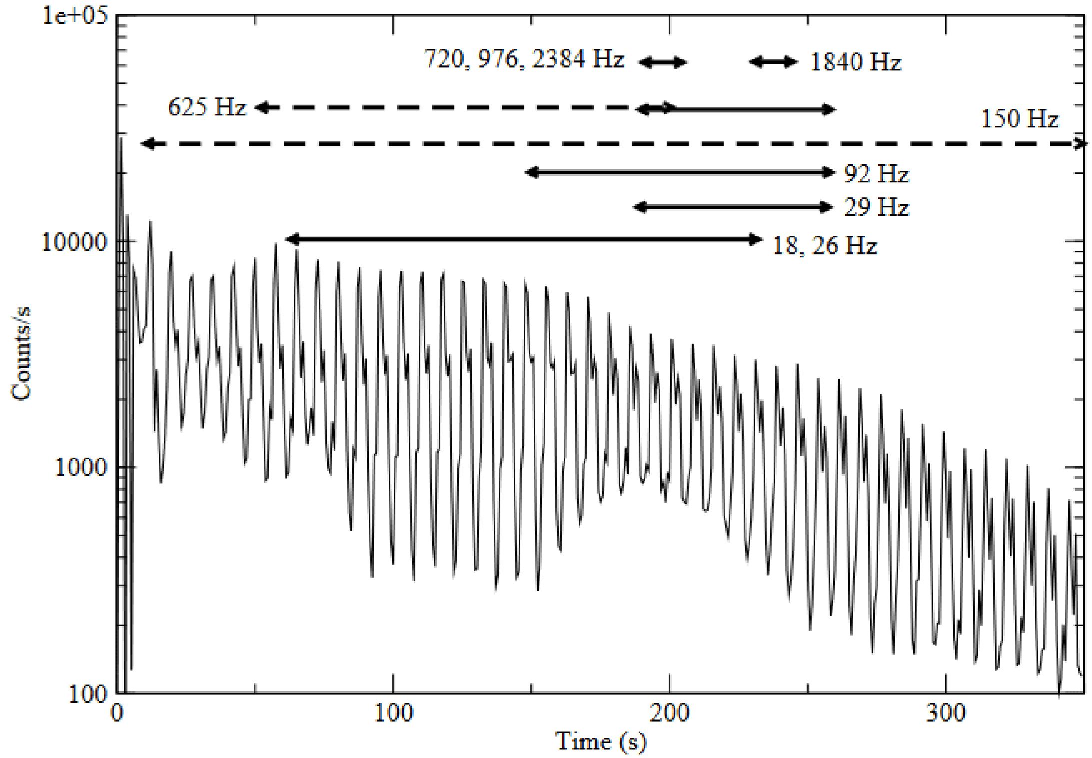
LIGO

Magnetars

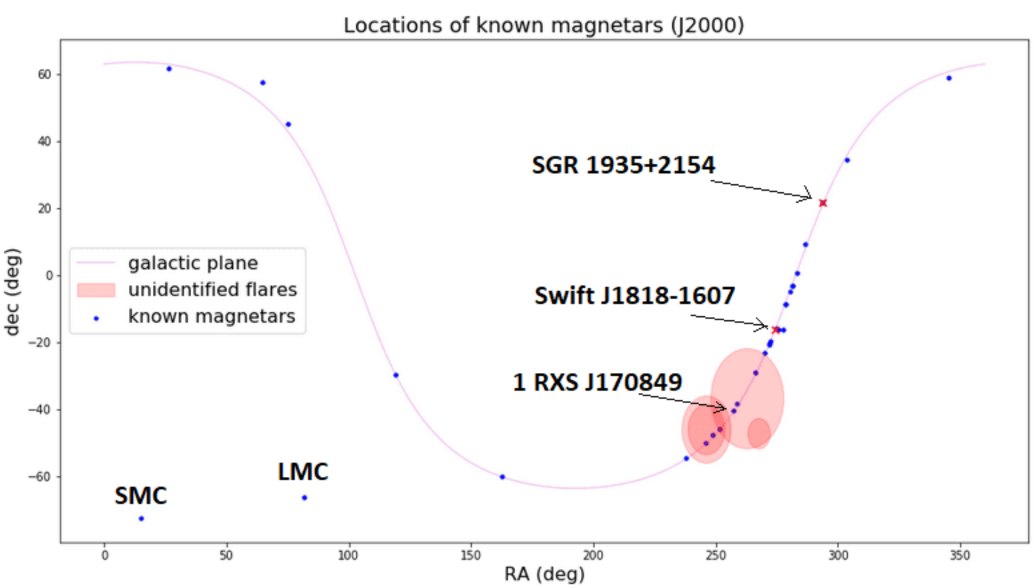
- Magnetars are young neutron stars with magnetic fields about 1000x that of ‘normal’ neutron stars
  - $B \sim 10^{13} - 10^{15}$ G
  - Earth: 0.5 G
- Slowly rotating: few Hz or less (magnetic braking)
- About 90%/10% of core-collapse supernovae result in normal neutron stars/magnetars
- Earth (and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

Magnetars and GWs ?





X-rays from 2004 giant flare SGR 1806-20

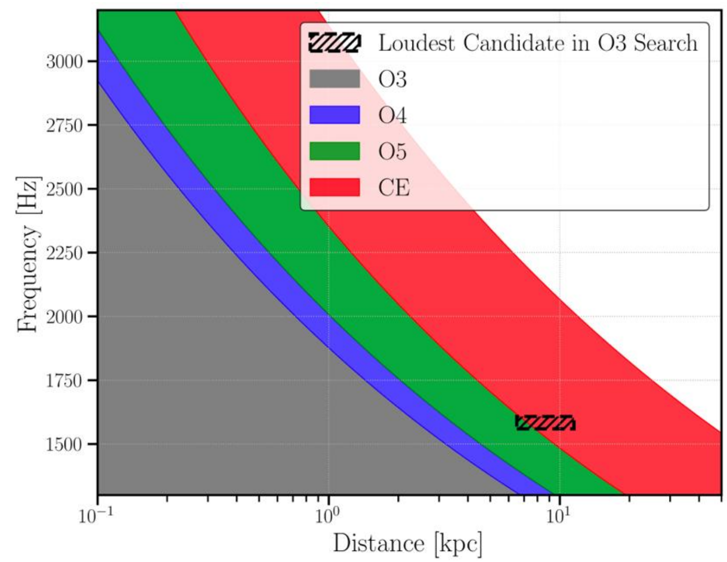


- Starquakes produce (giant) x-ray flares
- They also ring-up mechanical modes in the magnetar, some (e.g. f-modes) can produce GWs
- ← No giant flares during O3 run, but many ordinary x-ray flares
- UO student Kara Merfeld led the O3 collaboration analysis/paper

Astrophysical inference from NS f-modes

- X-ray flares from magnetars accompany a major perturbation, such as crust cracking or B-field rearrangement
- These probably ring up mechanical modes: f-modes → GWs
- Can use a detection or non-detection to infer NS properties

Matthew Ball, Frey, Merfeld
arXiv:2310.15315

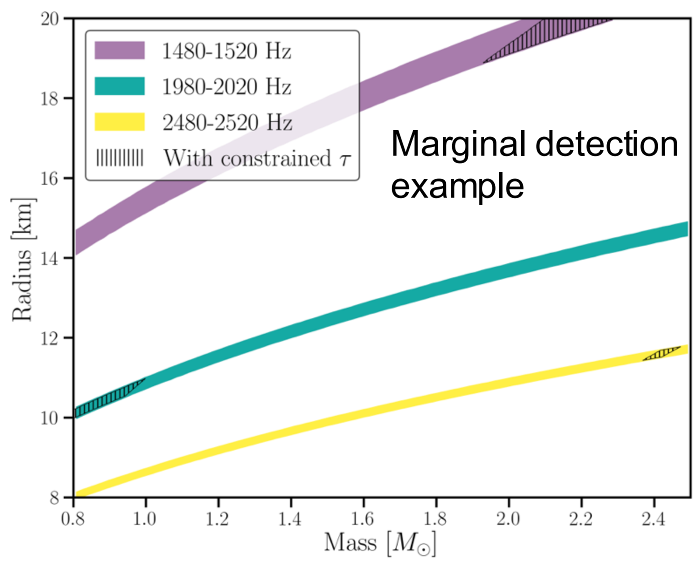


Distance/frequency space where 10% of candidates could be detected with SNR>3 for current/future detectors

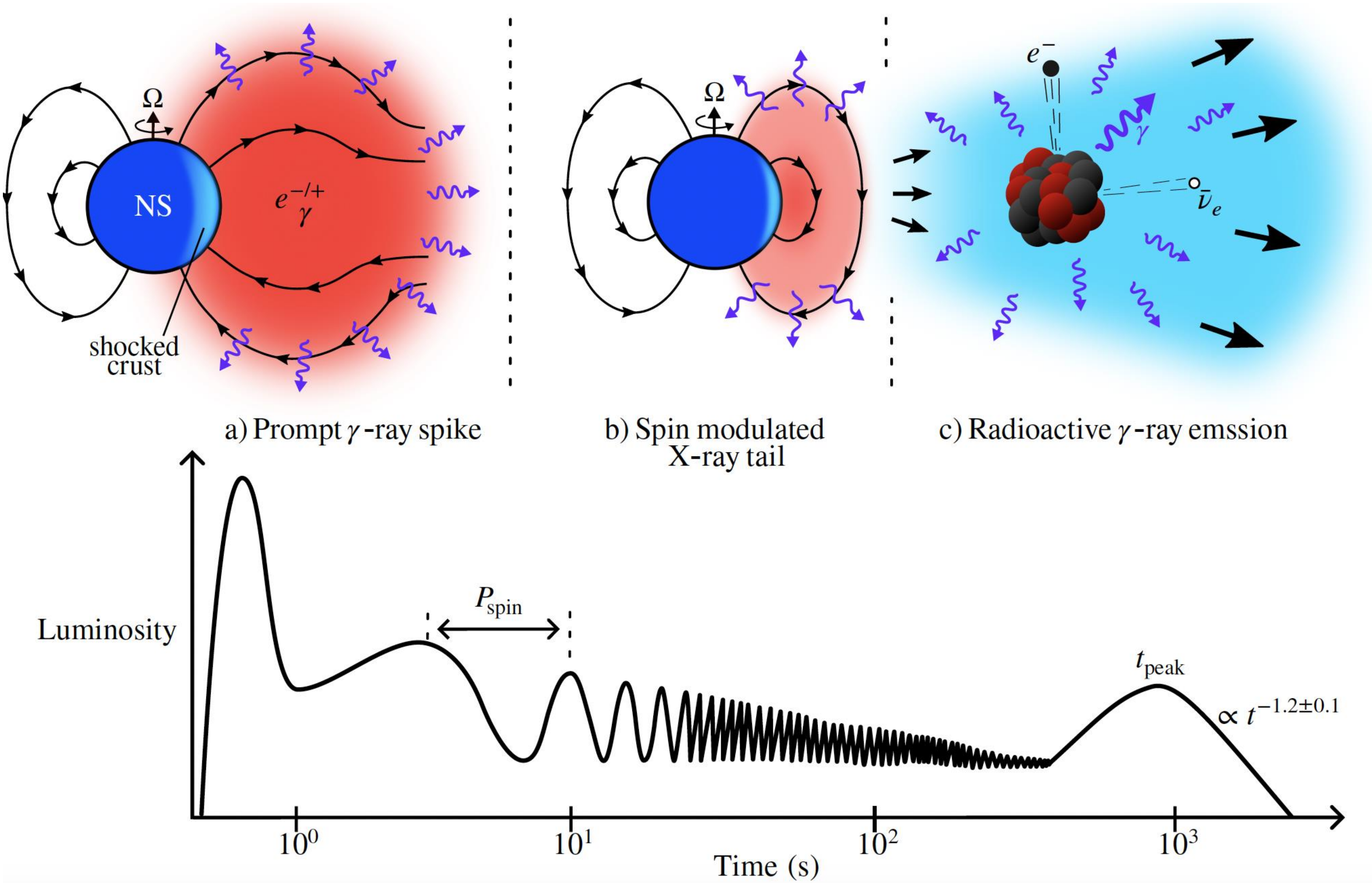
f-modes as damped sinusoids (Andersson & Kokkotas

$$\nu_{GW}(kHz) \approx 0.78 + 1.635 \left(\frac{\overline{M}}{\overline{R}^3}\right)^{1/2}$$

$$\frac{1}{\tau_{GW}(s)} \approx \frac{\overline{M}^3}{\overline{R}^4}\left[22.85 - 14.65\left(\frac{\overline{M}}{\overline{R}}\right)\right]$$



And now: r-process nucleosynthesis from magentars!



Metzger, et al (2025)

Vela Glitch of April 29, 2024

Radio observations:

- Rotational frequency changed: $\frac{\Delta f}{f} \sim 2.4 \times 10^{-6}$
- Time of glitch known to ~ +/- 4 s

An impulse which can ring up f-modes ?

➔ analysis ~ magnetar flare

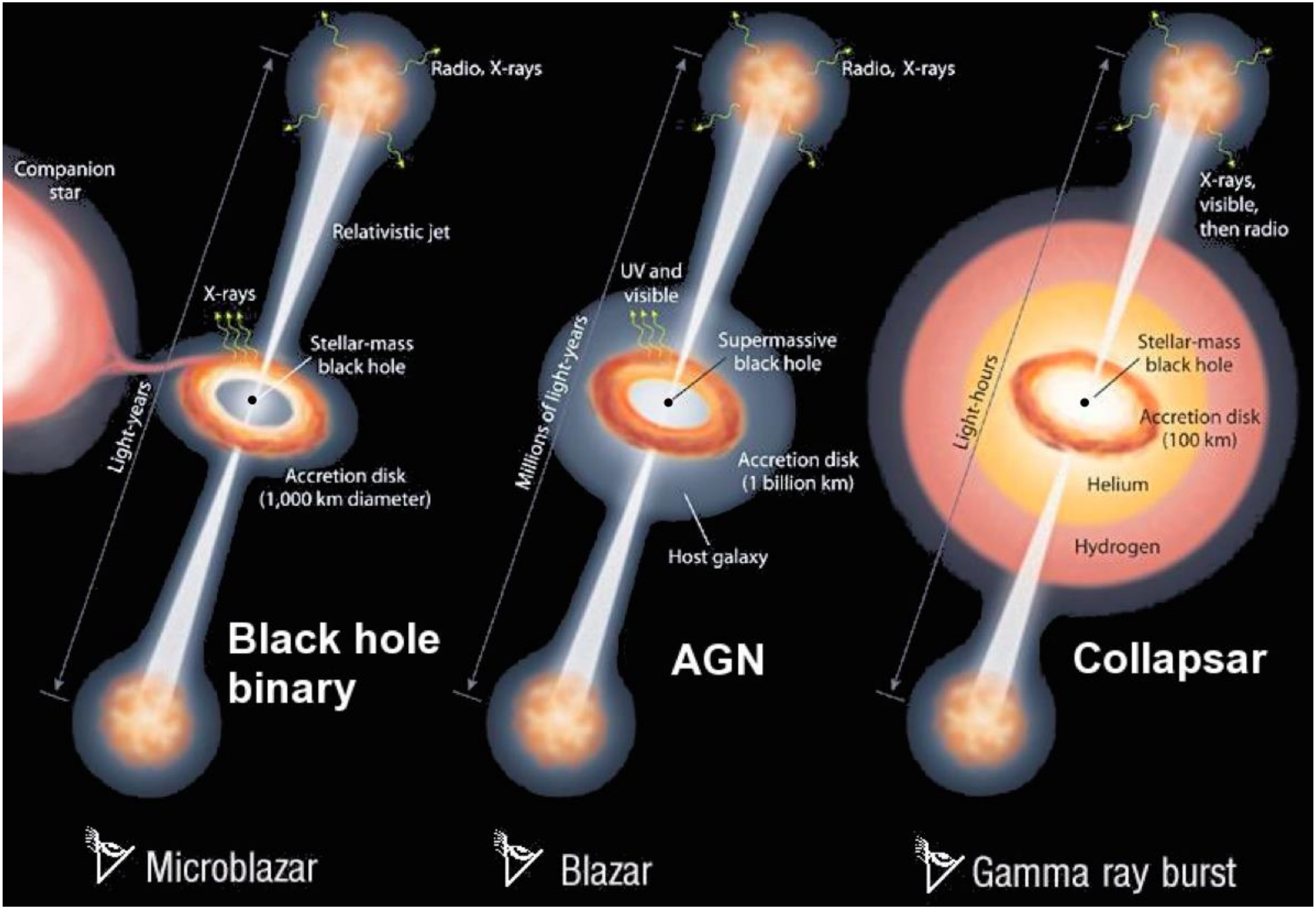
Vela distance: 267 pc

Matthew Ball, Frey, et al

Assume all glitch energy goes into f-modes:

Analysis complete and paper almost ready to send to a journal.

Black holes with accretion

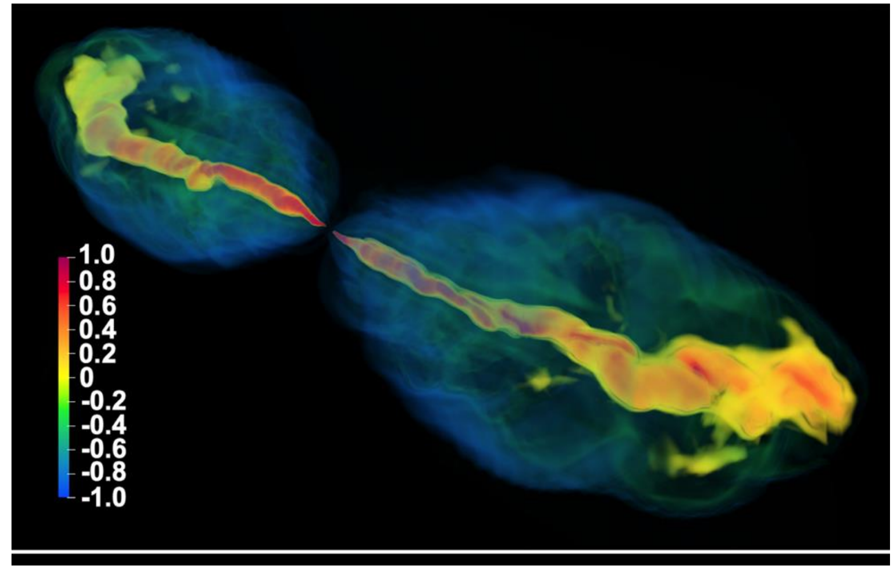


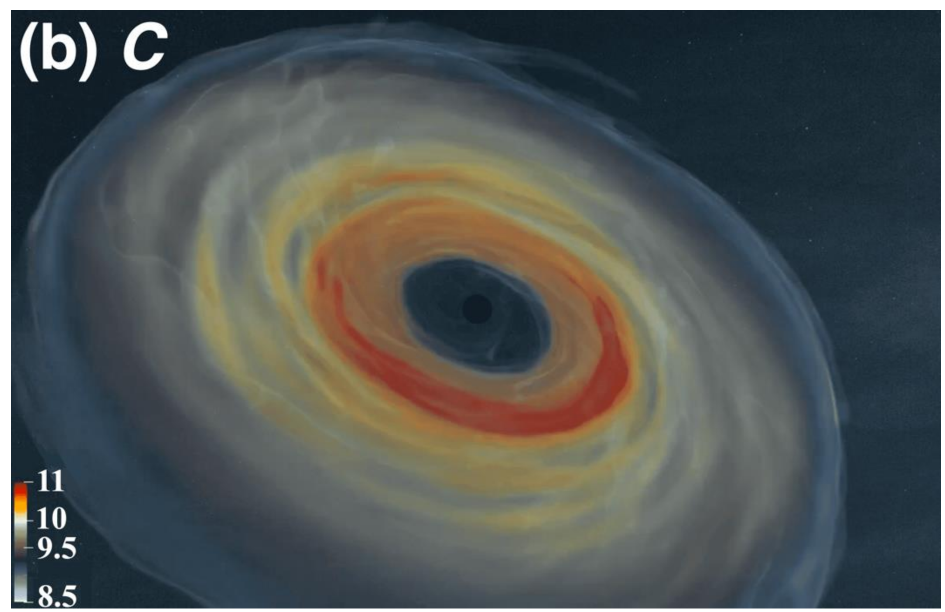
GWs from collapsars

- Collapsars: The collapse of massive, highly rotating evolved stars
- Progenitors of long GRBs (gamma-ray light curves longer than ~2s)
- LGRB distance follows star formation
  - Most distant z~8
  - Nearest 40 Mpc (pre-LIGO)
  - Redshifts largely unmeasured (few %)
- Collapsar accretion disks are potential GW sources – non-homogeneities
- First full GR + magnetohydrodynamic simulations give new insights:

- Wobbling GRB jets (top)
- Generically get robust GW emission from non-uniformities in the accretion disk -- Rossby vortices (bottom)

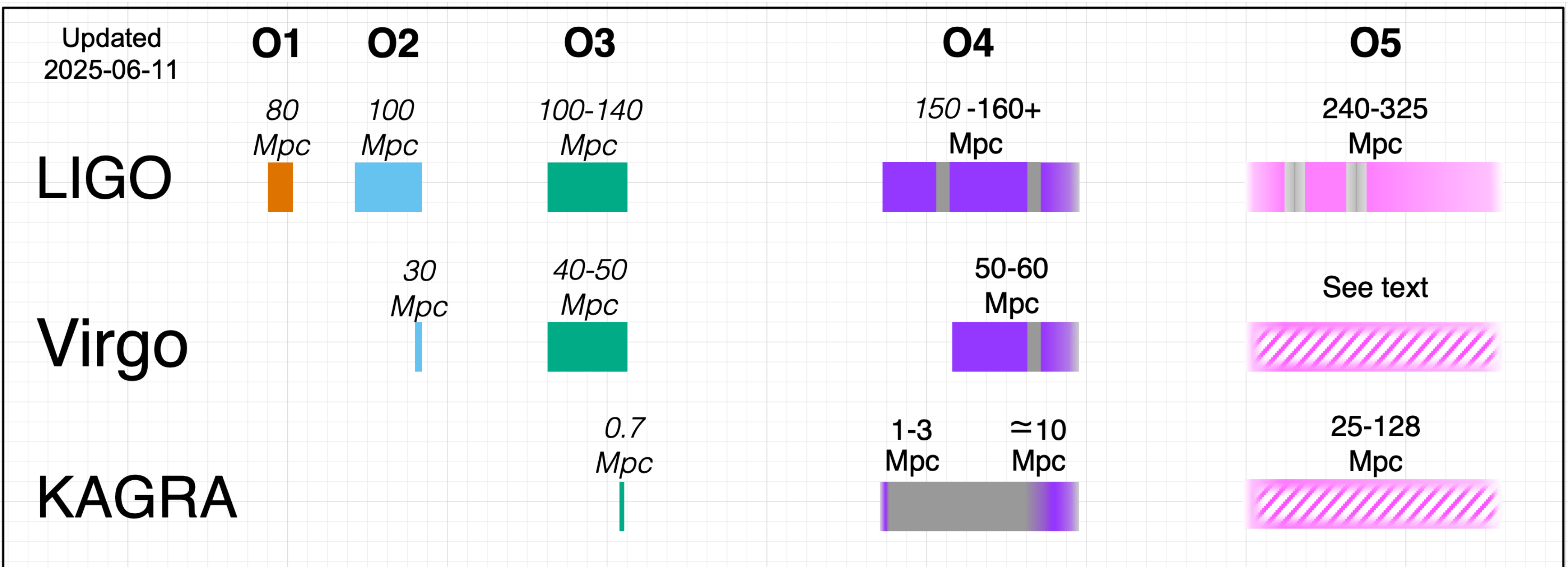
Gottlieb, et al



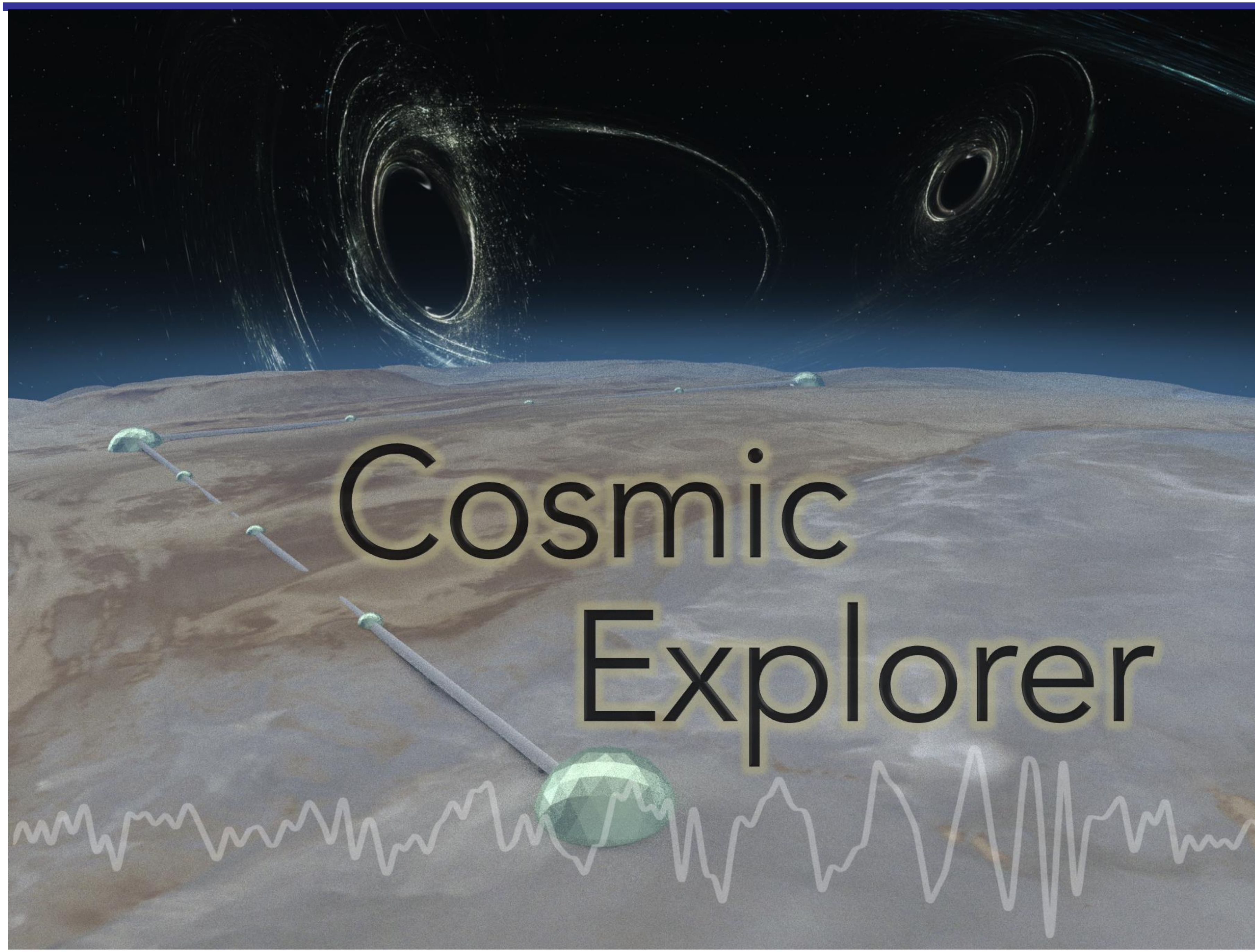


The near future

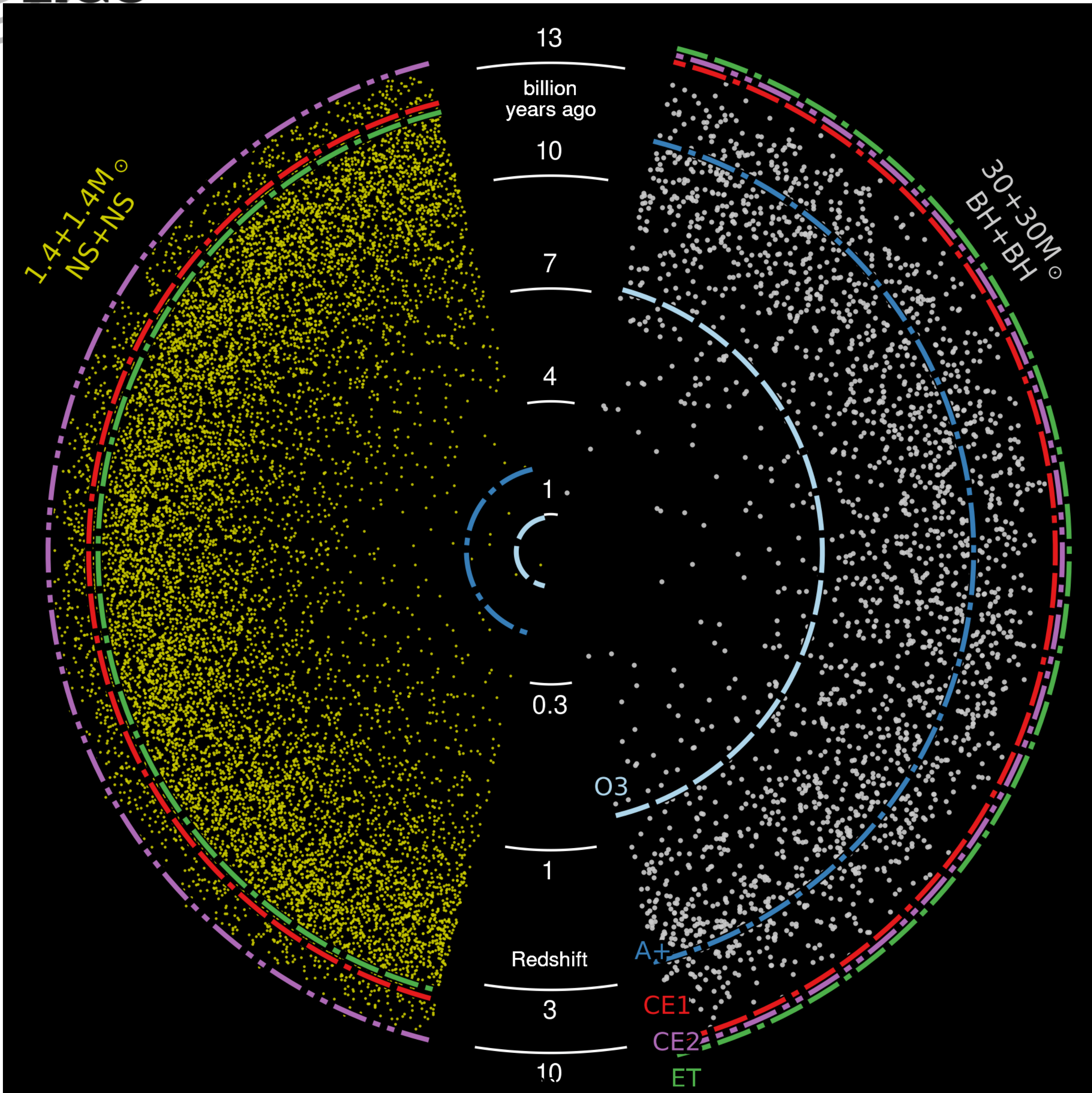
- In O1-O2: about 1 GW event per month
  - GW discovery
  - Binary neutron star merger
- In O3: about 1 GW event per 5-days
  - Routine quantum squeezing
  - ‘impossible’ high mass black holes
- O4: more than 2 events per week
  - Frequency-dependent squeezing
  - What new discoveries await??



The farther future (2030s)



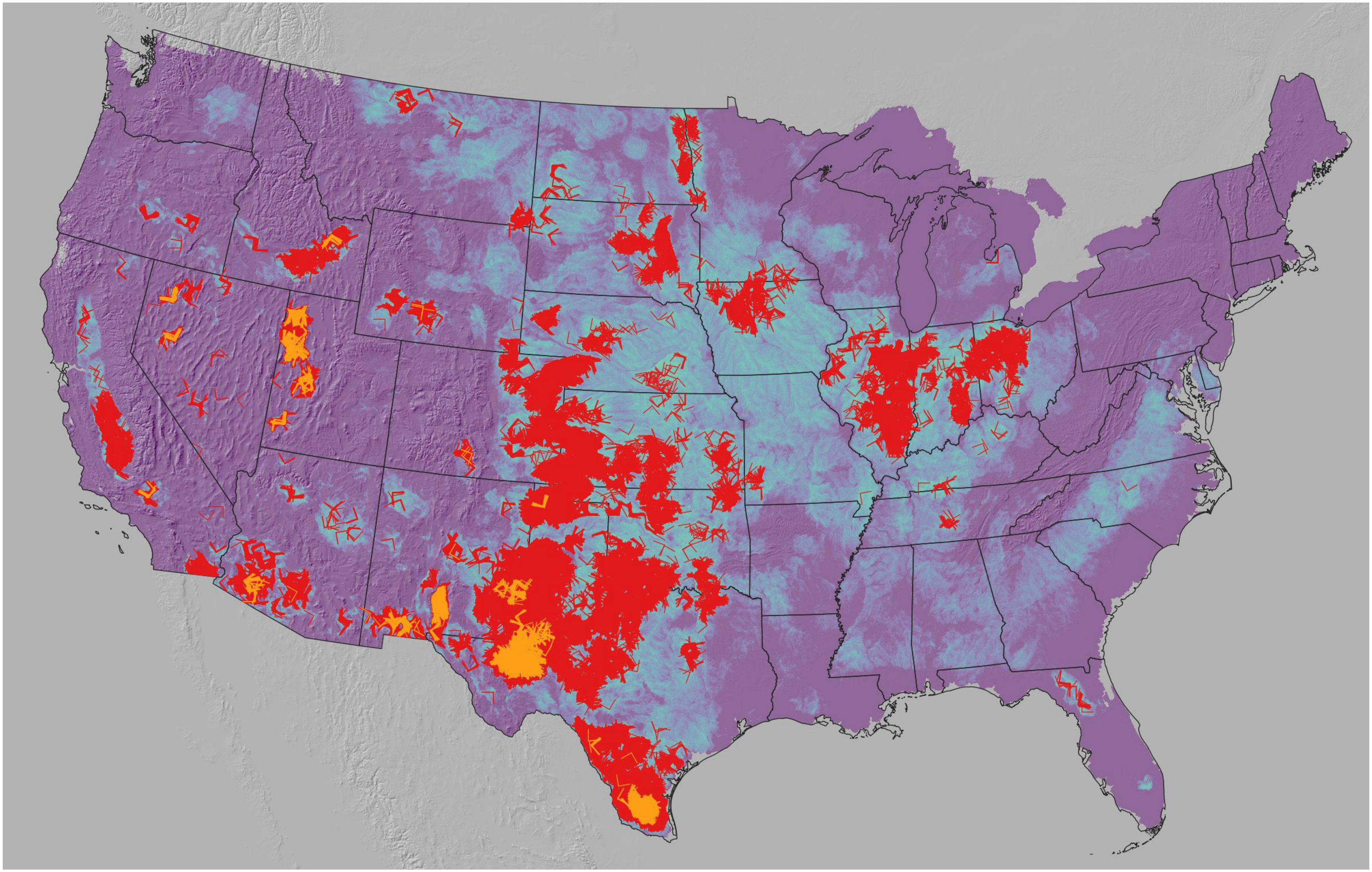
Why CE ?



Also:
10% of BBH will have SNR>1000

1% SNR~10,000

Site Study



Connection to the native people of the site

Yvette Cendes- Radio Astronomer here!

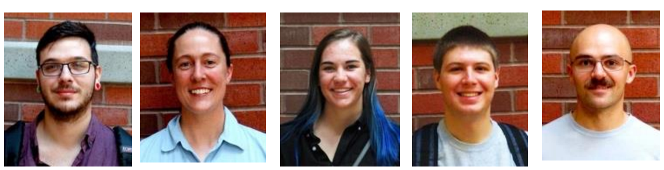
- New faculty member - astronomer !
- Specializing in transient radio astronomy- signals that change over time- using telescopes like the Very Large Array (VLA) in New Mexico
- Research covers a range of astronomical objects, ranging from black holes that shred stars (Tidal Disruption Events, or TDEs), exoplanets, supernovae, gamma-ray bursts…
- Also involved in outreach, in traditional and social media (from editor for the *Guinness Book of World Records* to Reddit)
- Article in latest issue of Scientific American

LIGO

UO LIGO Group

Graduate Students
Lance Blagg
Samantha Callos*
Genevieve Connolly
Adrian Helmling-Cornell
Benjamin Mannix
Sangeet Paul
Samatha Callos
Ivan Juarez-Reyes
Aislinn McCann
Miranda Claypool
Claire Nelle

Recent PhDs:
Bruce Edelman
Kara Merfeld
Matthew Ball
Jaxen Godfrey
JD Merritt



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