



1

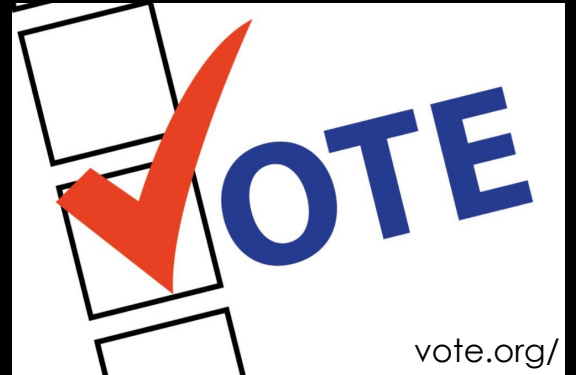
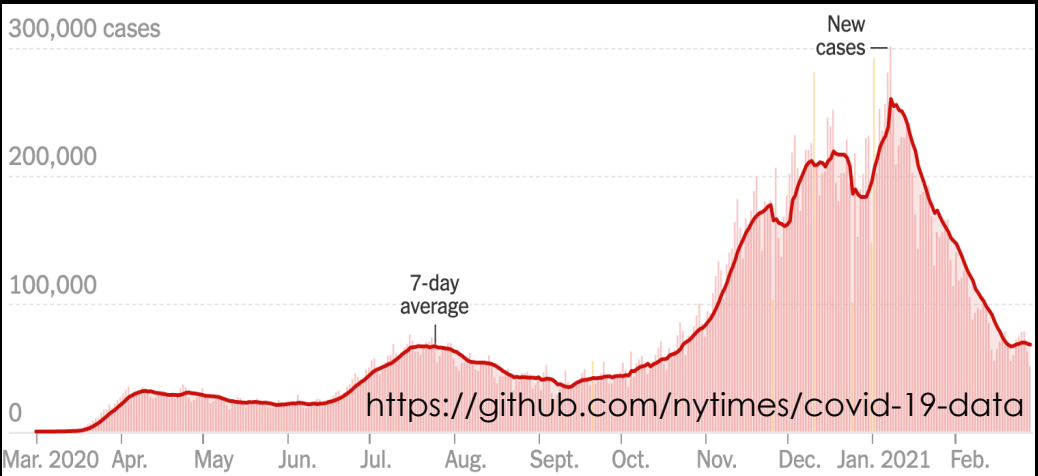
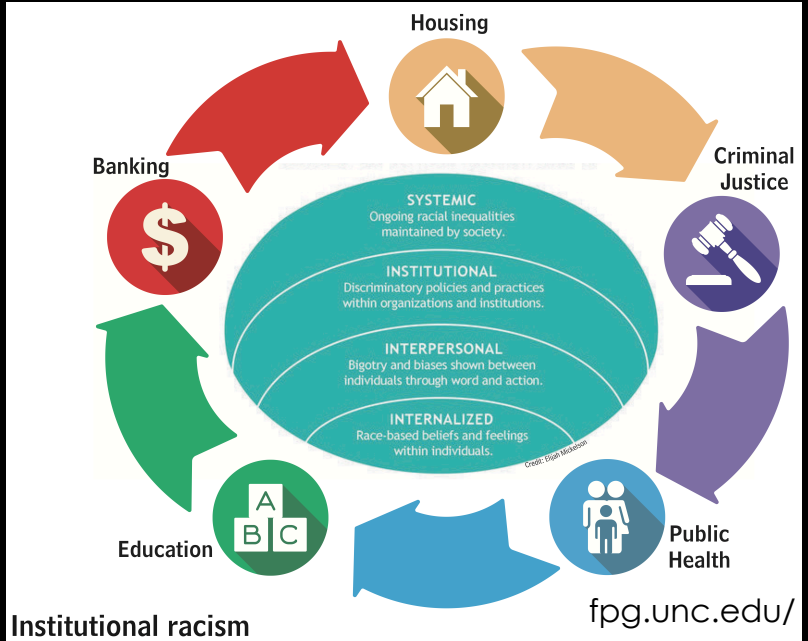
GRAVITATIONAL WAVE ASTRONOMY

HISTORY IN THE MAKING!

J. Kissel, for the LIGO, Virgo, and KAGRA Scientific
Collaborations



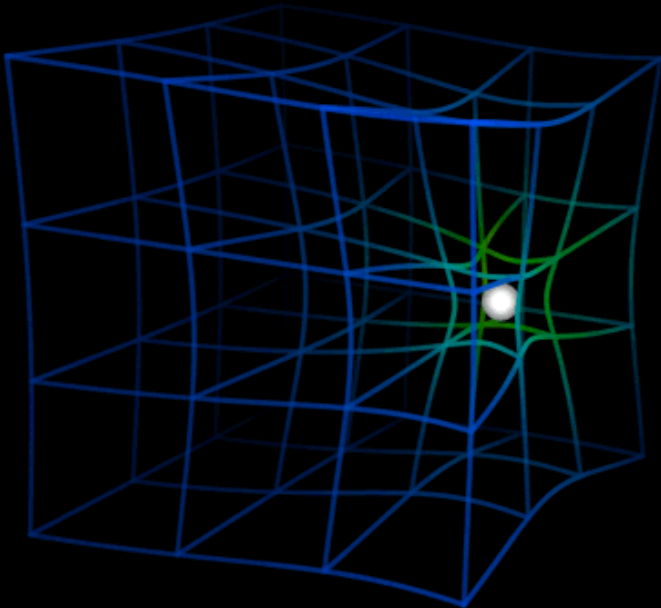
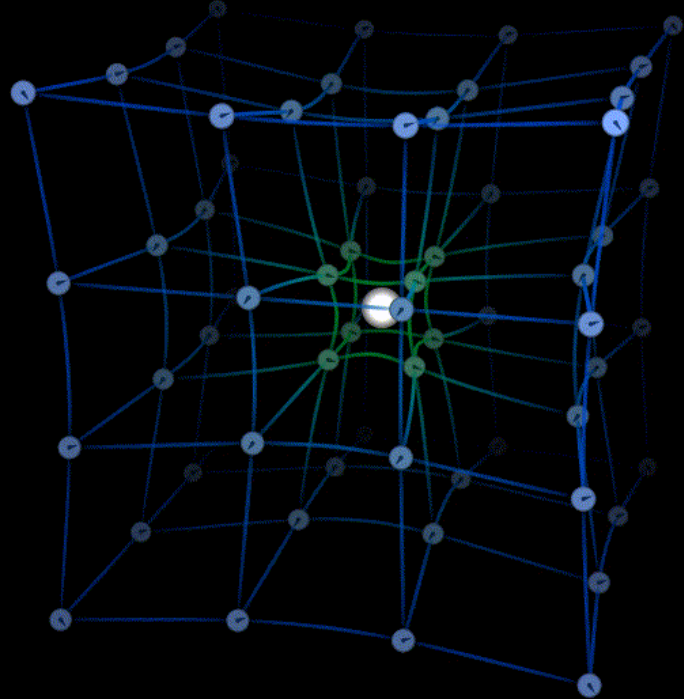
BEFORE WE START





GEOMETRY

Matter tells space-time
how to curve...

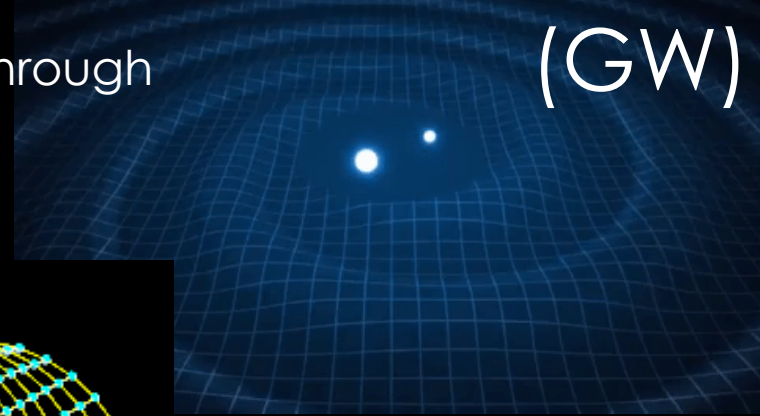


Space-time tells matter
how to move.

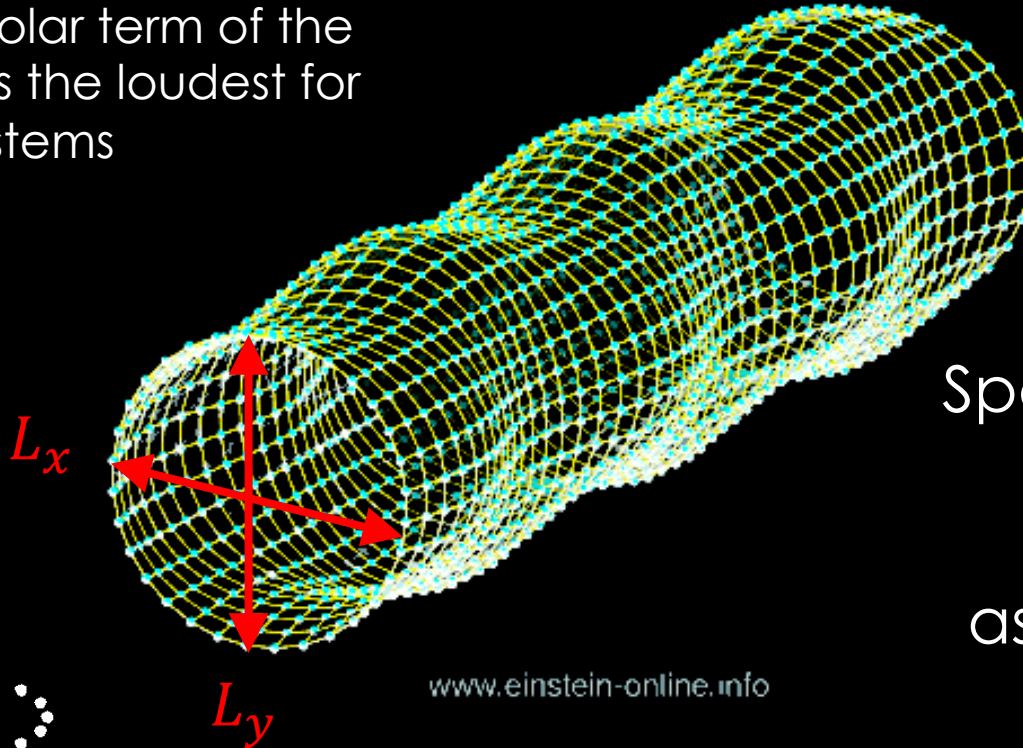


THE GRAVITATIONAL WAVE (GW)

Gravitational energy transmitted through strain, h , of space-time



Quadrupolar term of the strain, h , is the loudest for binary systems



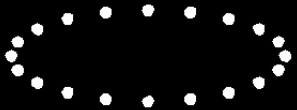
Space-time is very stiff

Strain from astrophysical sources on earth is

$$h \approx 10^{-21}$$

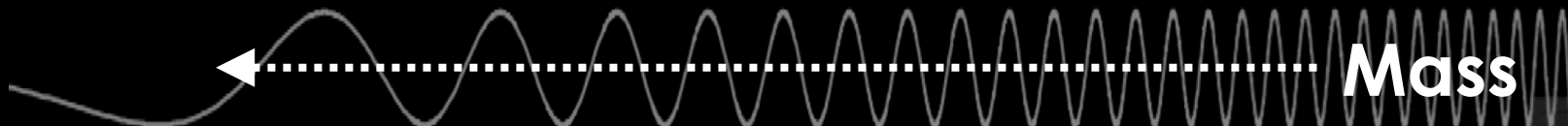
www.einstein-online.info

$$h = (L_x - L_y) / \bar{L}$$

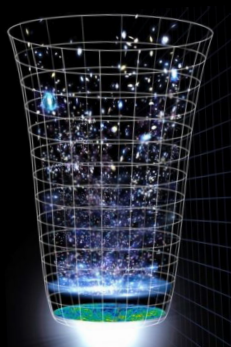




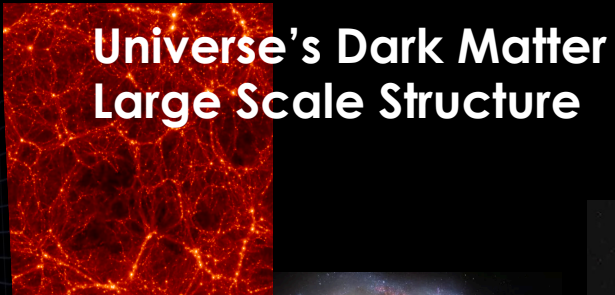
MASS DEFINES A GW SPECTRUM



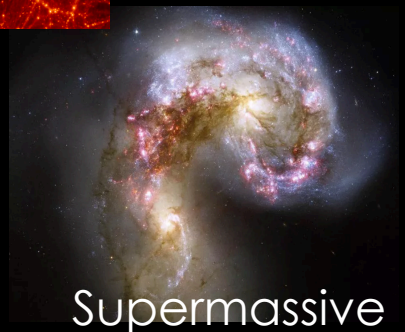
Period:	Billions of Years	Decades	Years	Days	Minutes	Seconds	Fractions of seconds	
Wavelength scale:	Universe	Galaxies	Star Systems		Planets	Countries	Kilometers	
Frequency:	10^{-18} Hz	10^{-9} Hz	10^{-3} Hz	1 Hz	10 Hz	100 Hz	1000 Hz	



The Big Bang and the Entire Universe



Universe's Dark Matter Large Scale Structure



Supermassive



Intermediate mass



Stellar Mass



Supernovae

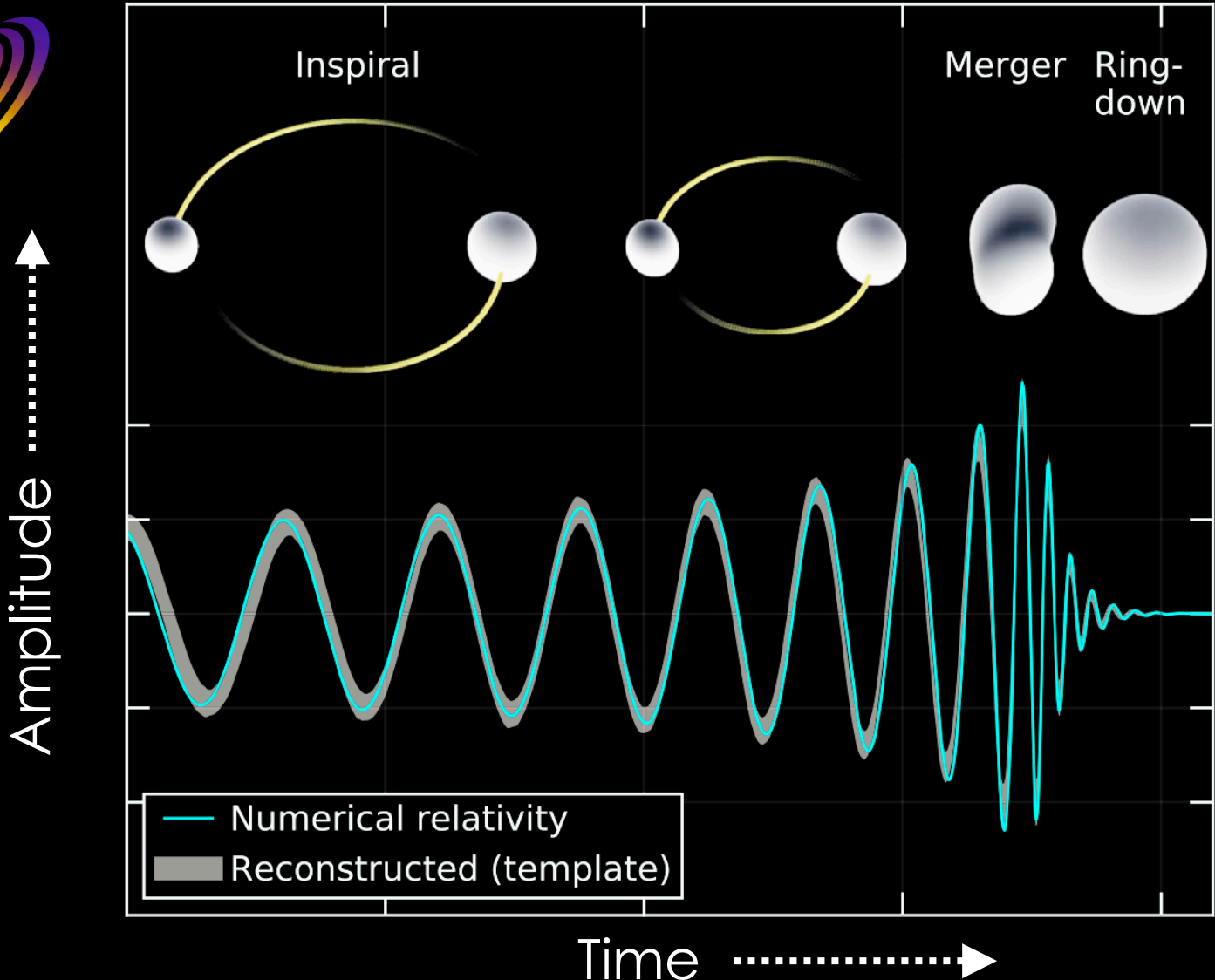


Neutron Star Collisions

←..... **Black Hole Collisions**→

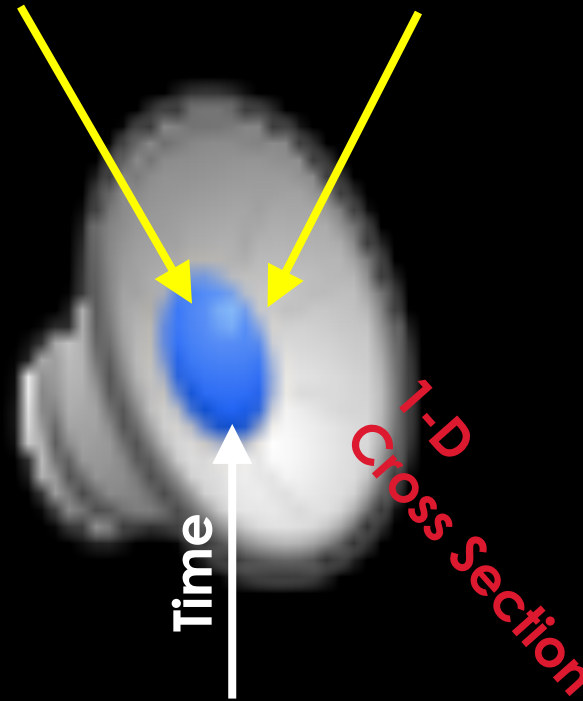


THE FLAGSHIP G-WAVE





BLACK HOLES COLLIDE



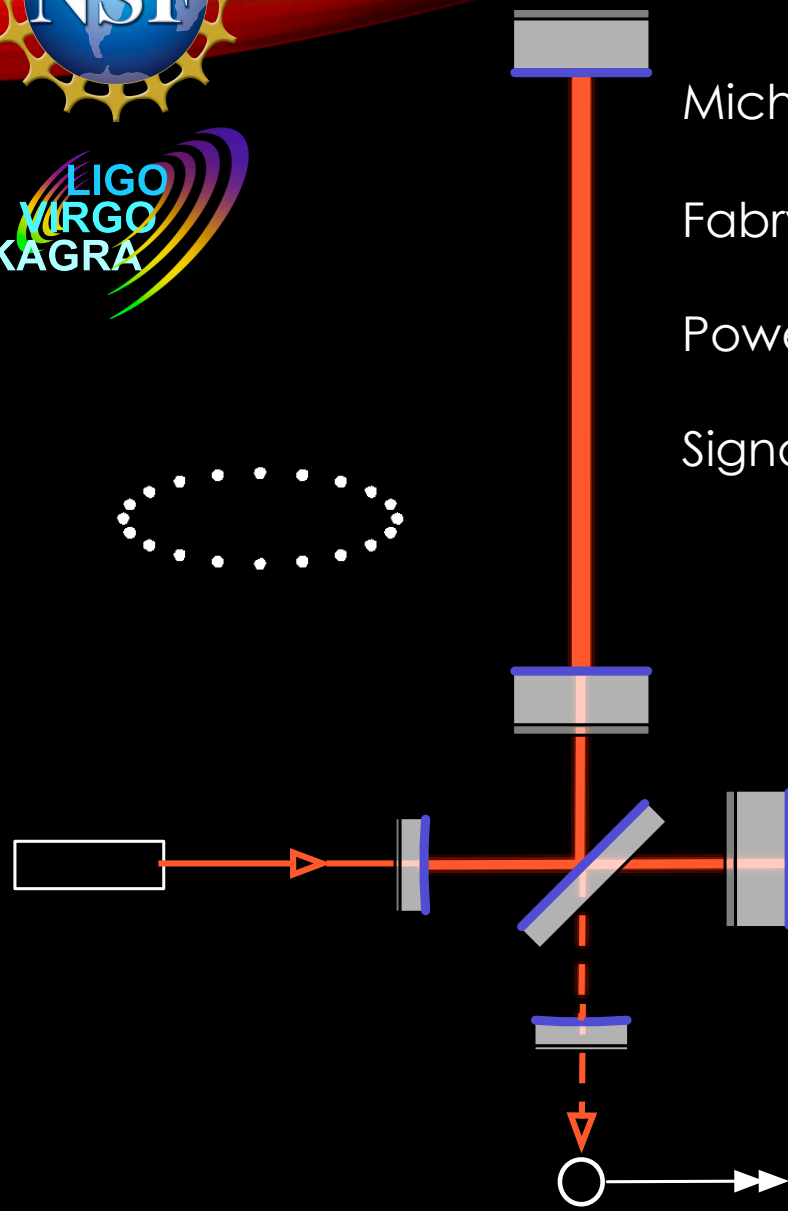
1-D Amplitude



Predicted Gravitational Waveform



THE MODERN INTERFEROMETERS



Michelson

Fabry Perot Arm Cavities

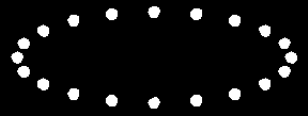
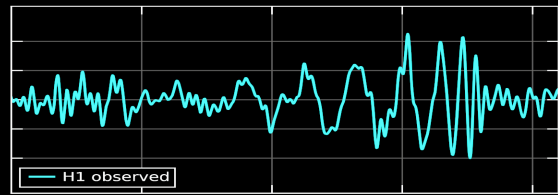
Power Recycling Cavity

Signal Extraction Cavity

Interference of fields from two perpendicular arm cavities, with optics that are "free of forces."

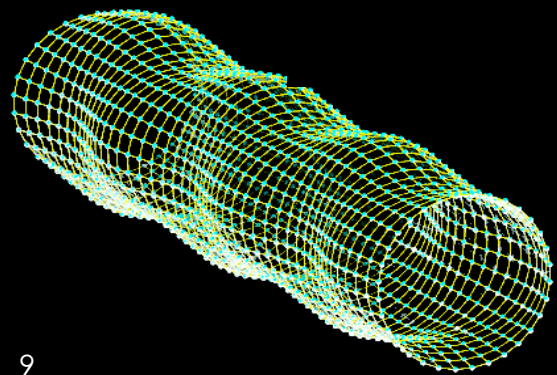
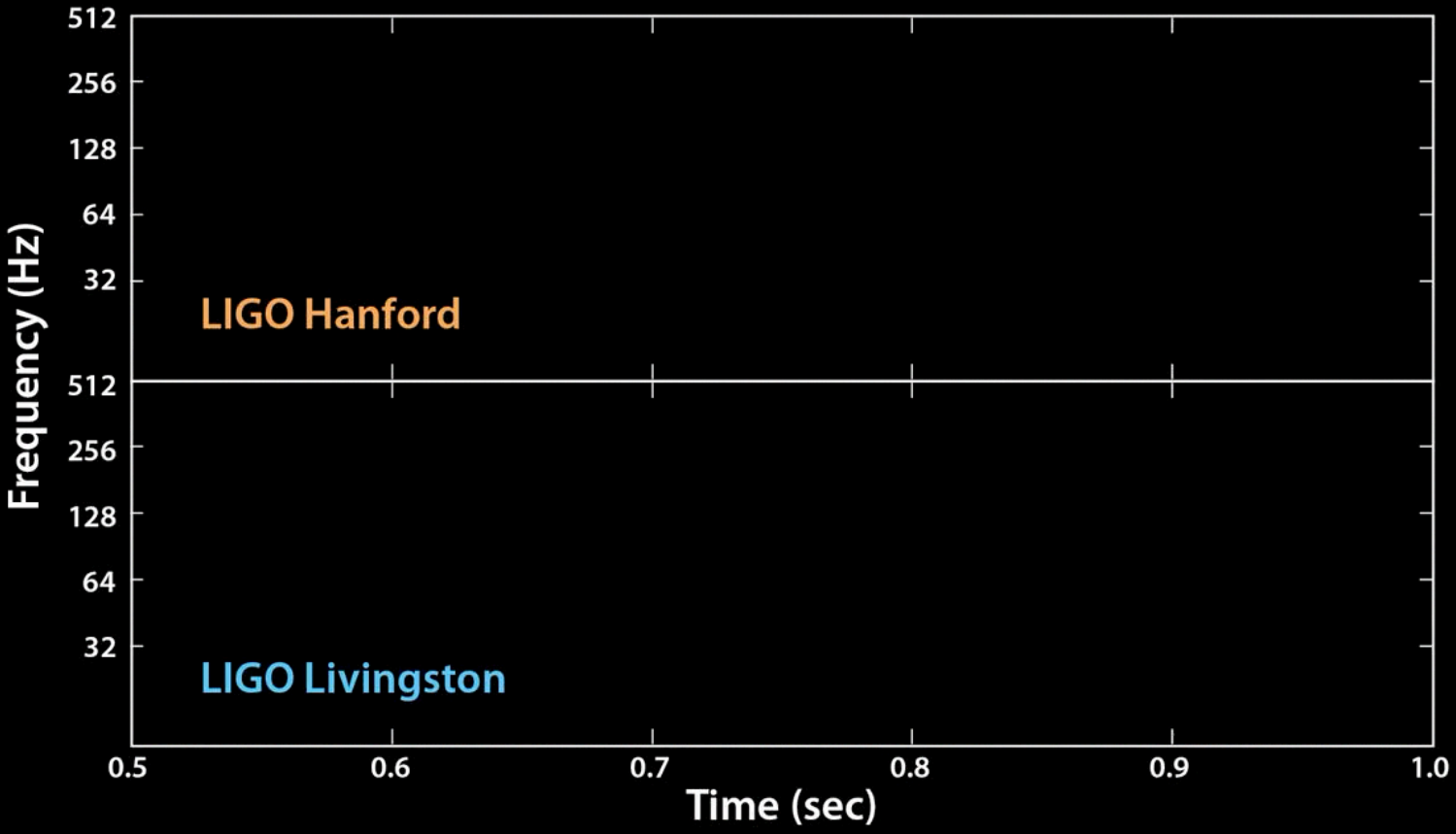
GW space-time distortion causes change in light travel time along the arms which changes interference pattern.

Interference pattern measured with photodiodes at the "dark" port of the beam splitter, converted to electrical signal with amplitude and phase.





DETECTION



In this sense, we're now LISTENING to the SOUNDS of the universe!

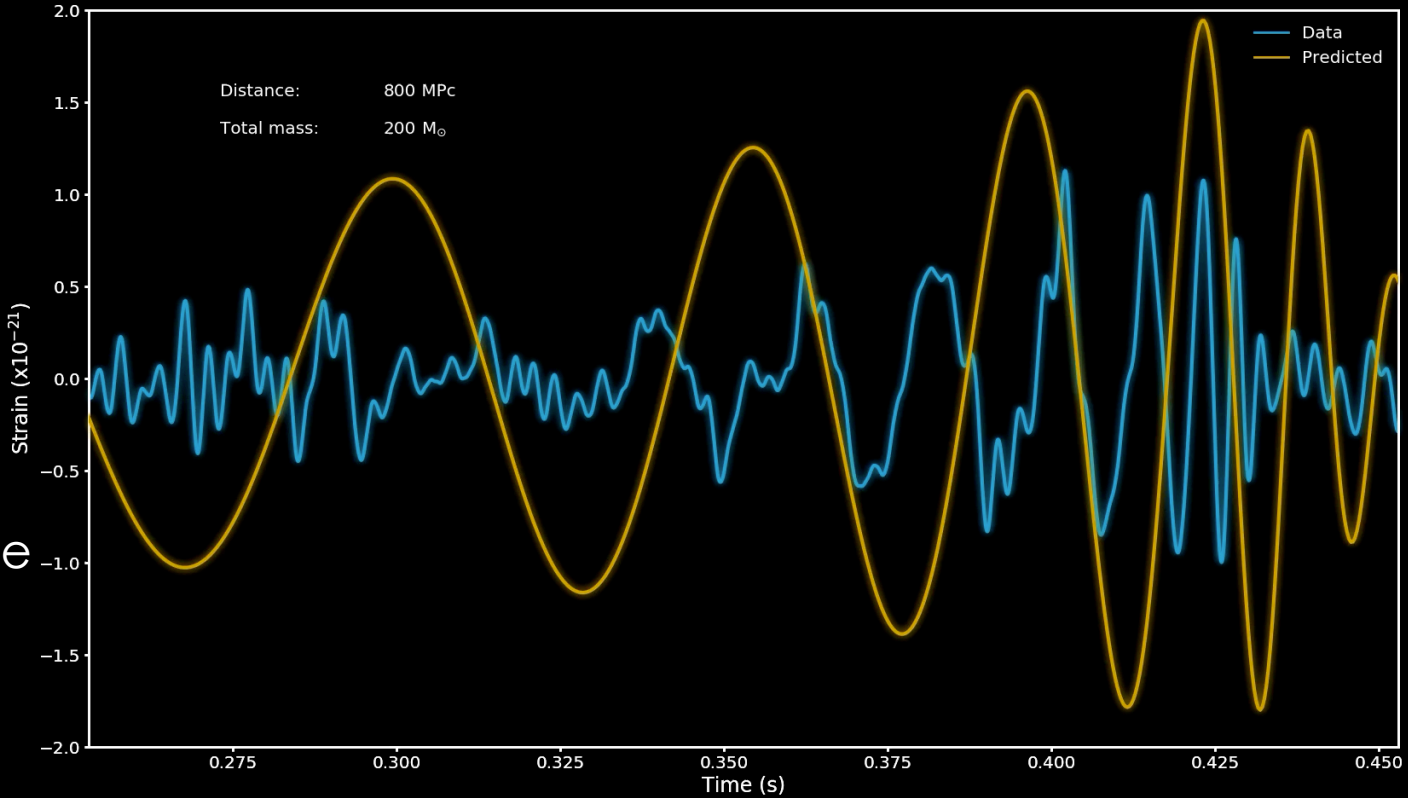


GW ENCODES SOURCE PARAMETERS



Total Mass of the binary system

Distance to the binary system

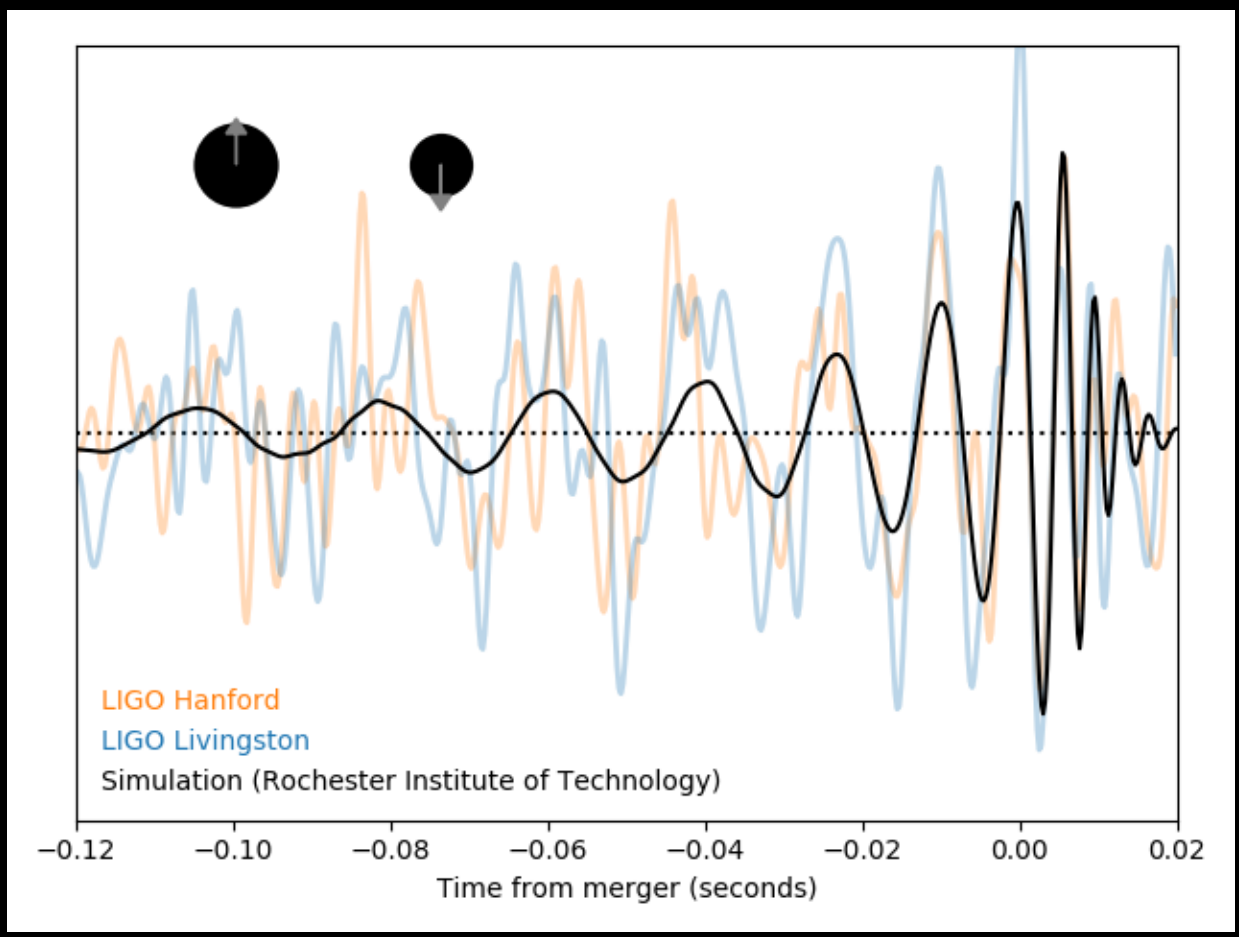


But measurement near the limit of **“Noisy” Detectors**

Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)



GW ENCODES SOURCE PARAMETERS



Mass Ratio of the binary system

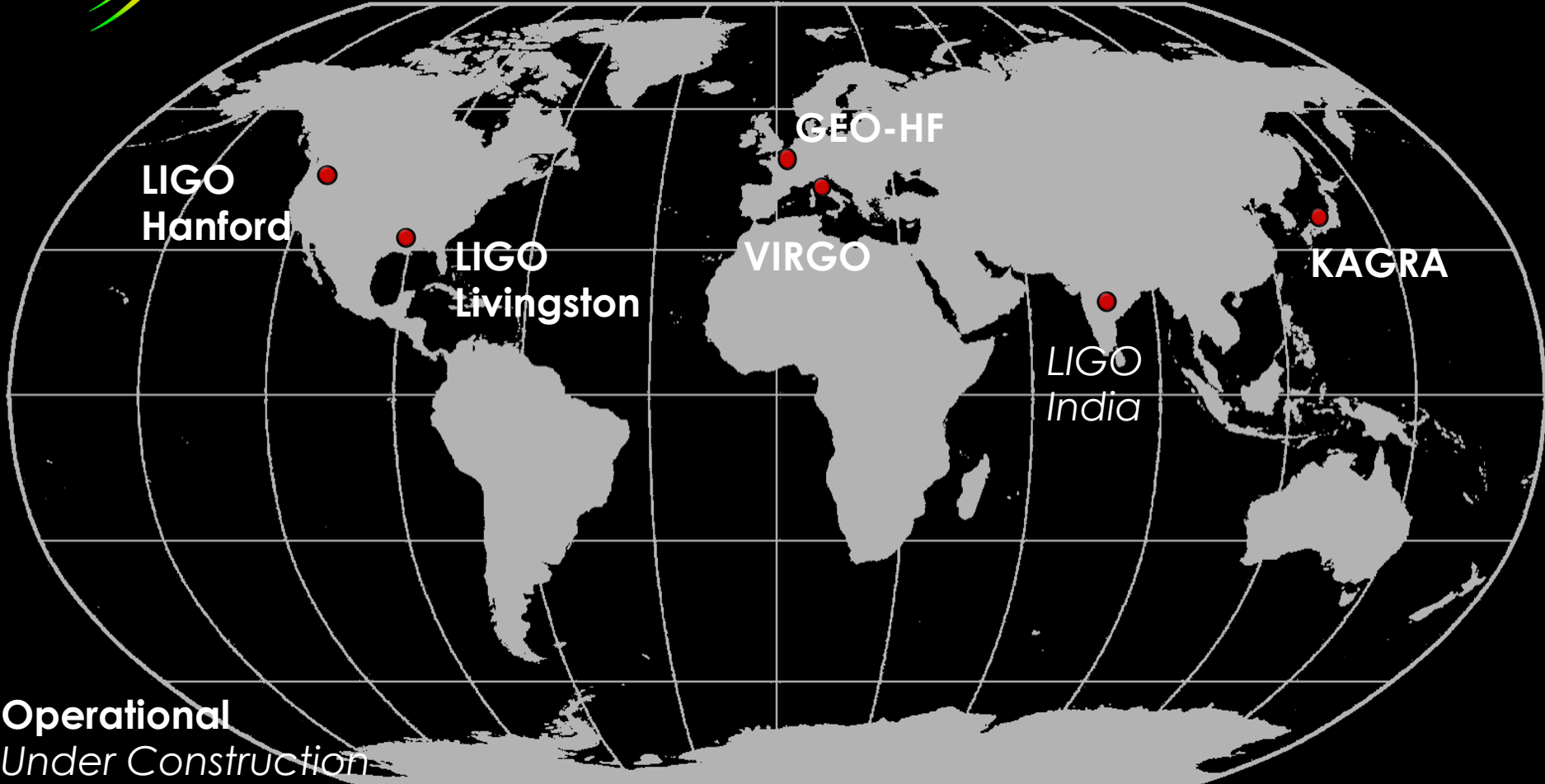
Spin of components of the binary system



THE GW DETECTOR NETWORK



With a **network** of detectors and depending on their sensitivity, one can begin to determine **sky location, orbital inclination, polarization, tidal deformation...**



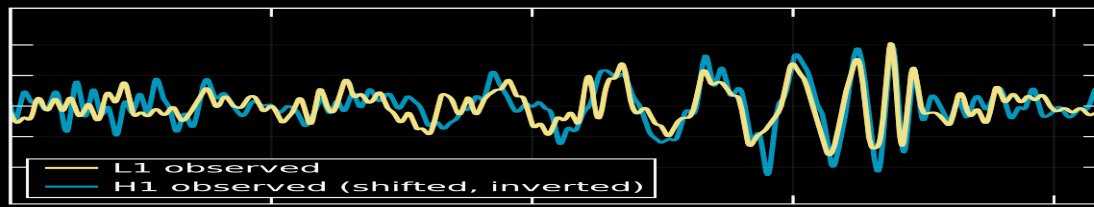
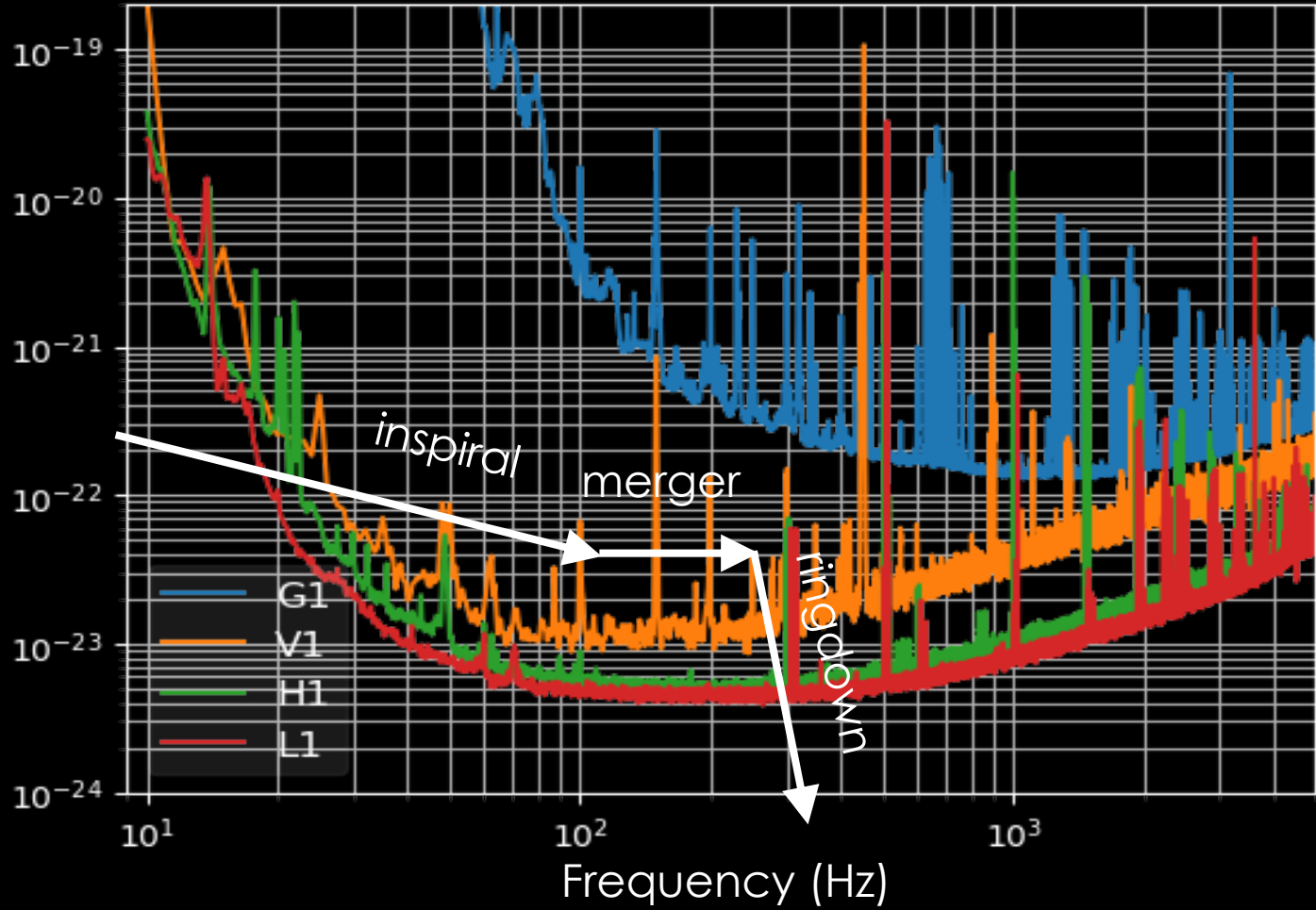
Operational
Under Construction



GW NETWORK SENSITIVITY

$$h = (L_x - L_y) / \bar{L}$$

Dimensionless Strain [(m/m) / Hz^{1/2}]

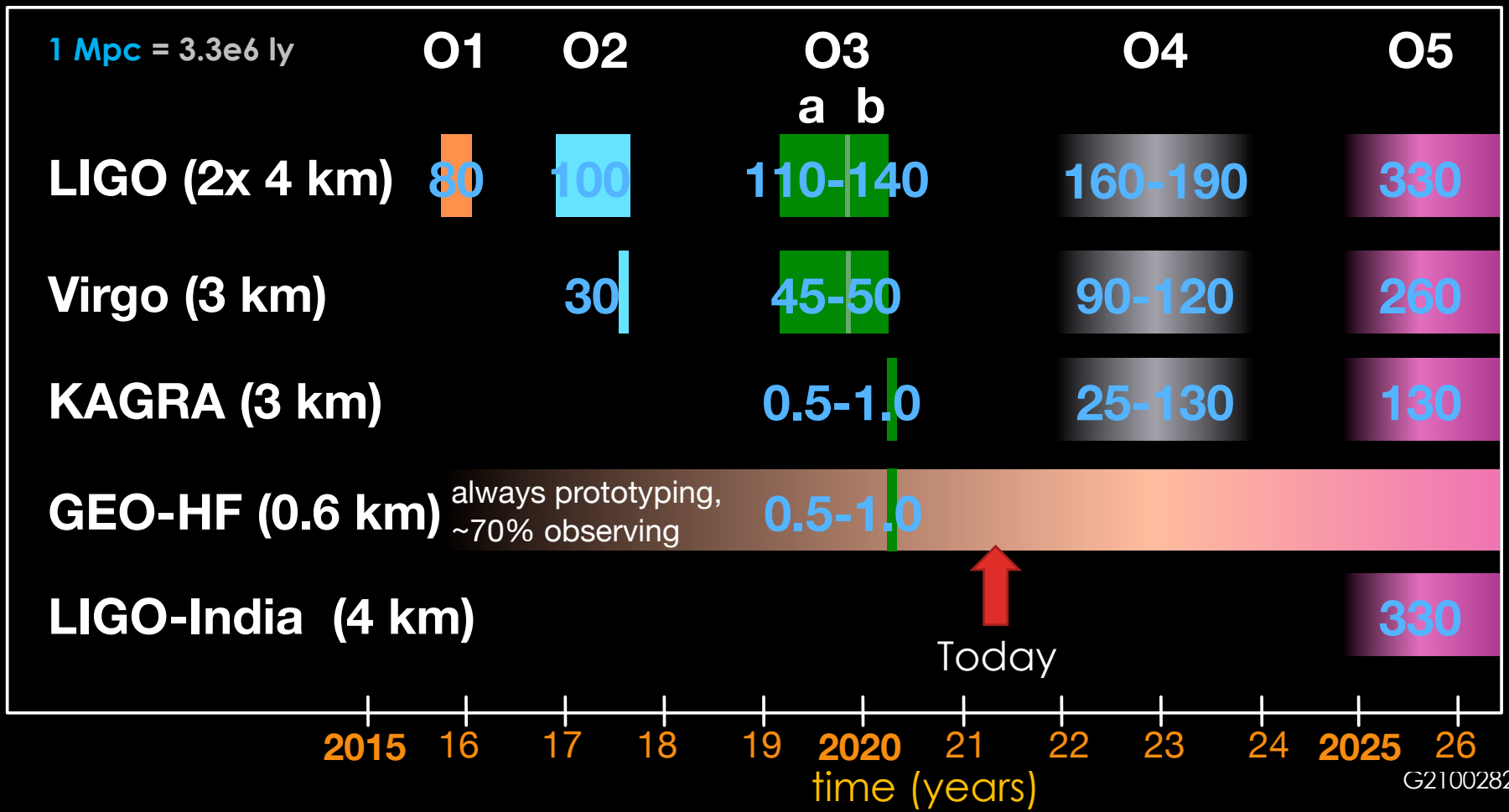




GW NETWORK TIMELINE



The **number of detections** is proportional to the **time** spent observing **and** the **volume (defined by spherical radius)** observed





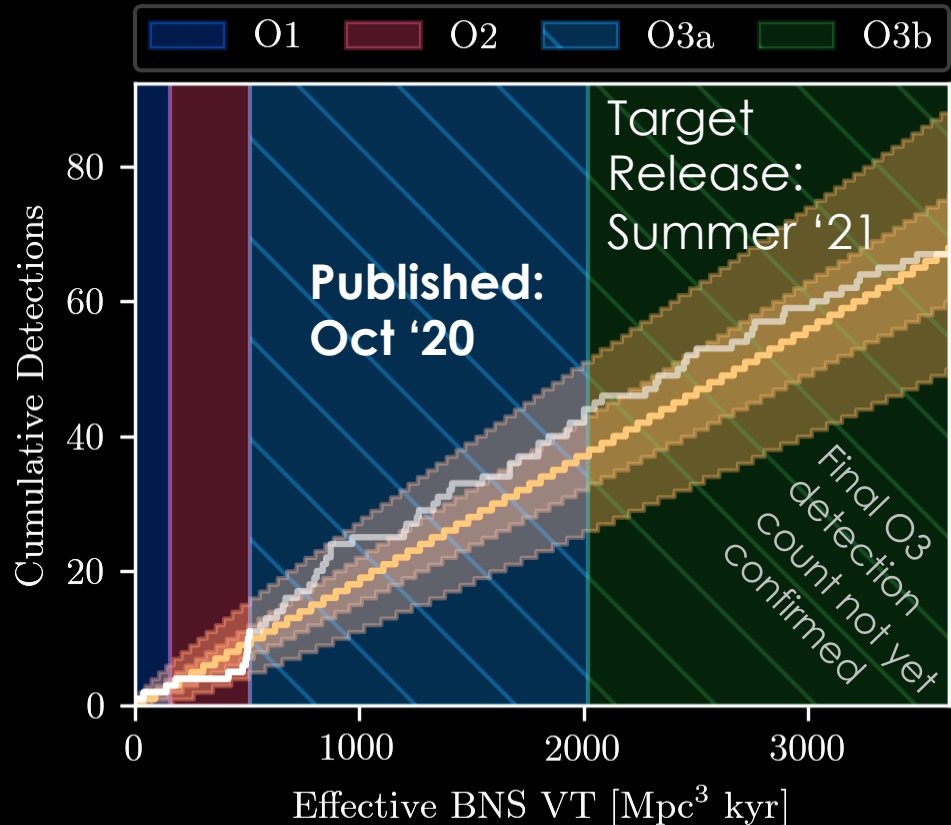
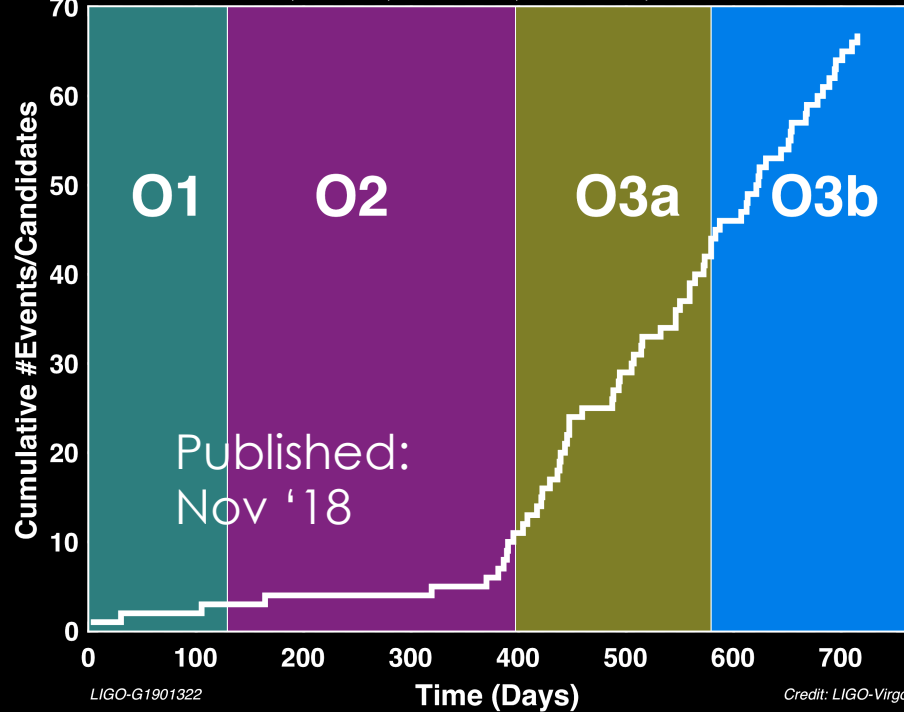
GW NETWORK DETECTIONS

Now hard to discuss all individual event detections in one talk.
Even too many “exceptional” events for one talk.

We begin to talk about **populations** of event properties.

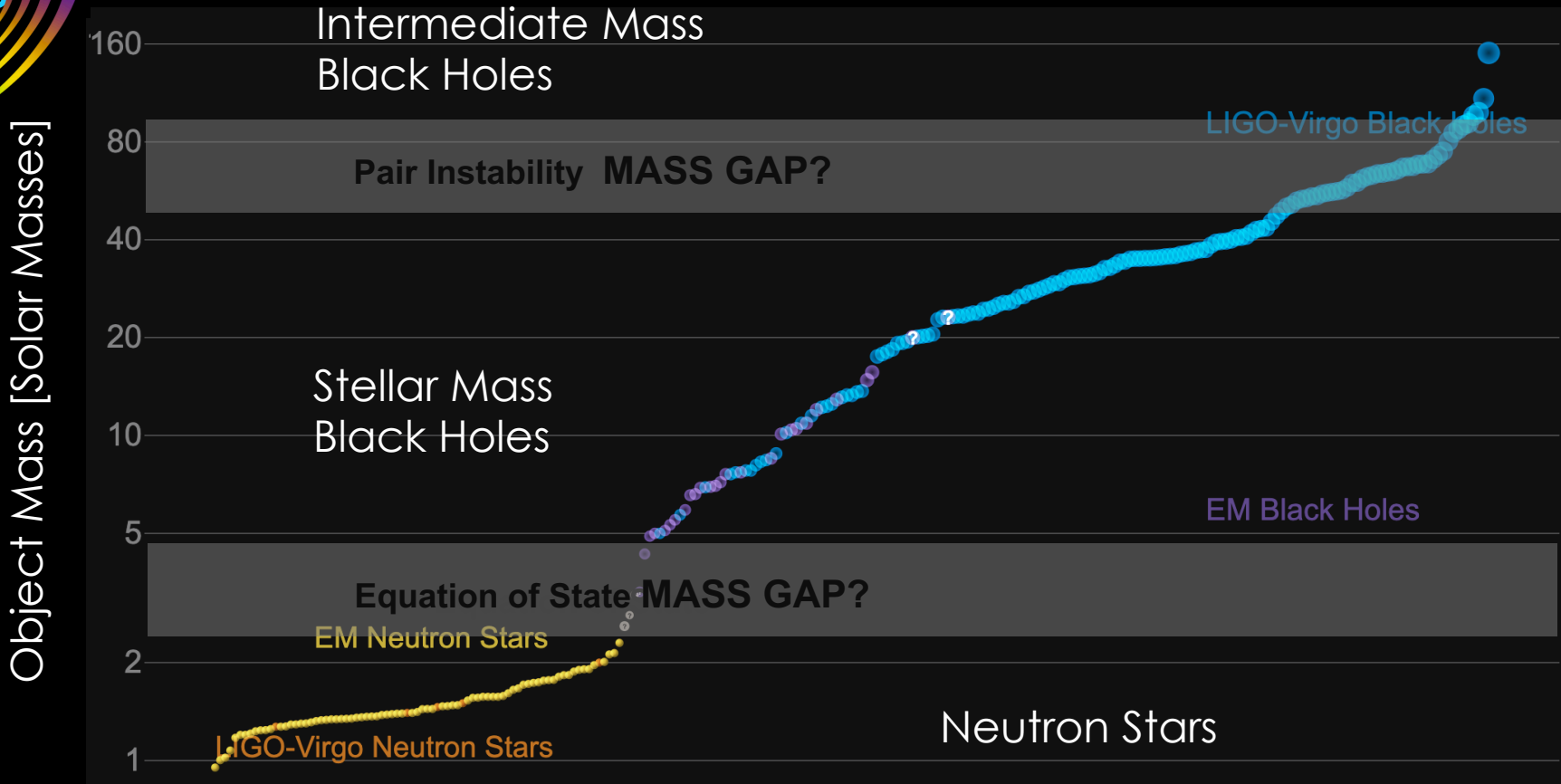
We are astronomers.

Cumulative Count of Events and (non-retracted) Alerts
O1 = 3, O2 = 8, O3a = 33, O3b = 23, Total = 67





FILLING IN THE "EM" GAPS



GWTC-1 = O1 & O2

[PRX 9.3 \(2019\): 031040](#)

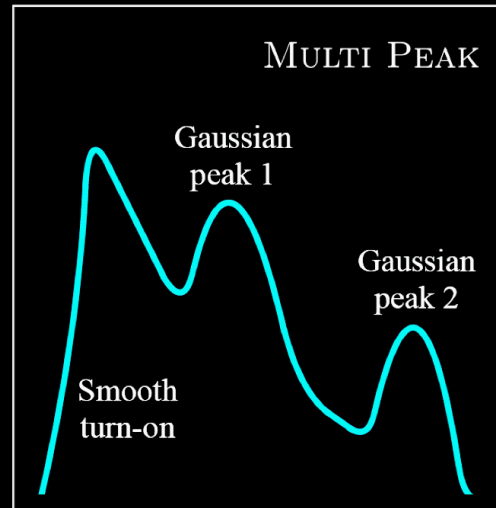
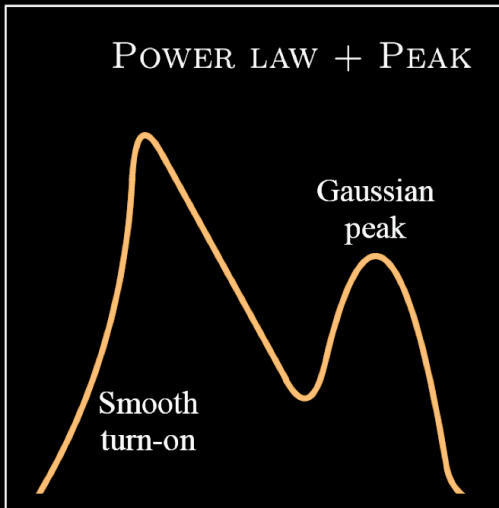
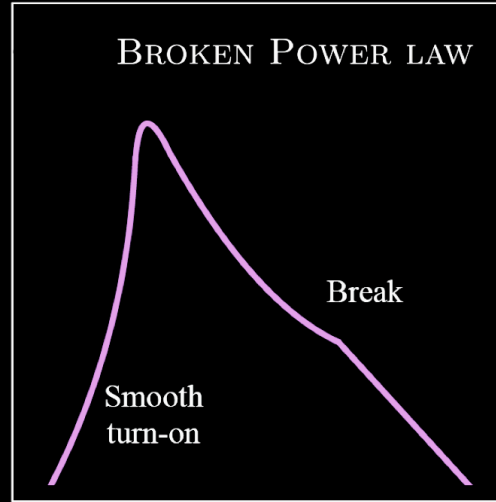
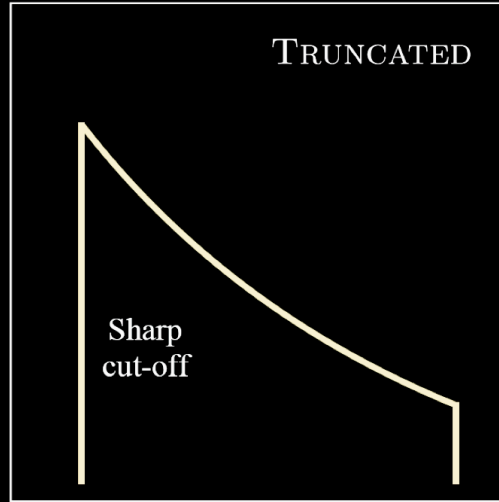
GWTC-2 = O3a

[arXiv:2010.14527 \(2020\)](#)



BLACK HOLE MASS FUNCTIONS

Rate or Probability
of Occurrence



Black Hole Mass

Remember:
Models based on observations may have bias proportional to

the **time** spent observing,

the **volume** observed, and

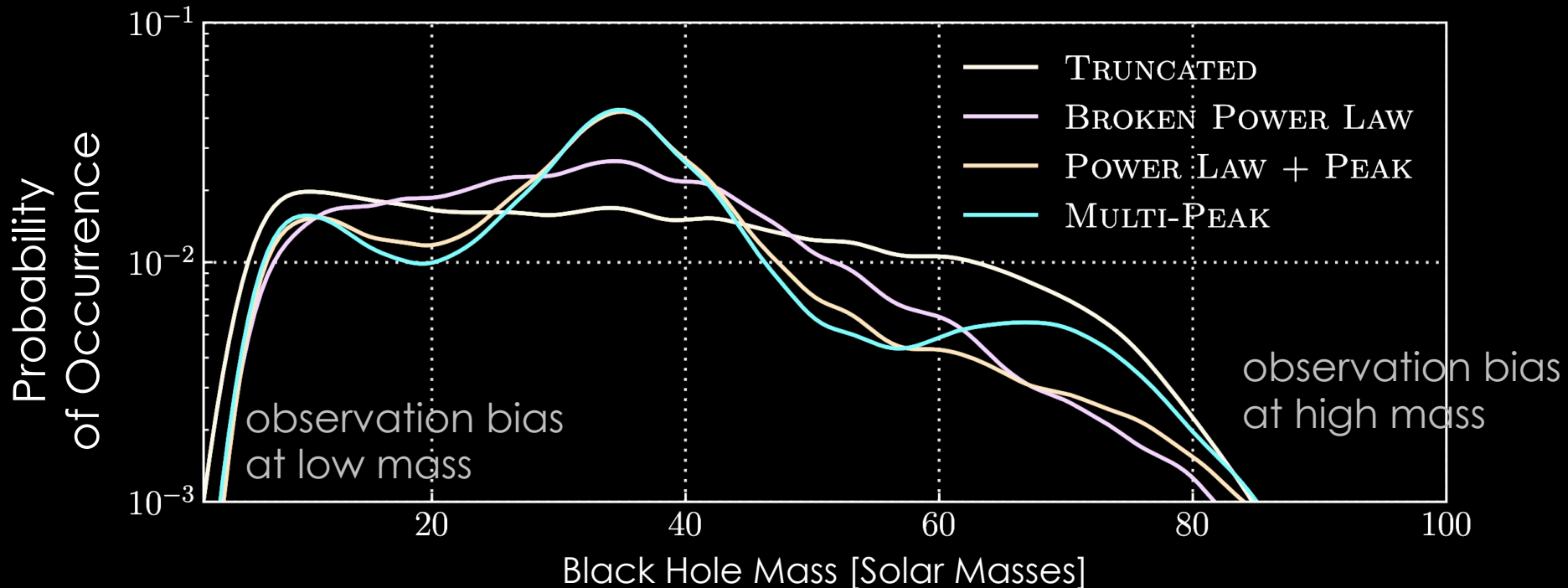
the **mass** involved in the merger.



OBSERVED MASS FUNCTION



Using all GW detections through O3a, we can concoct a probability distribution of **observed mass function** assuming different model types...



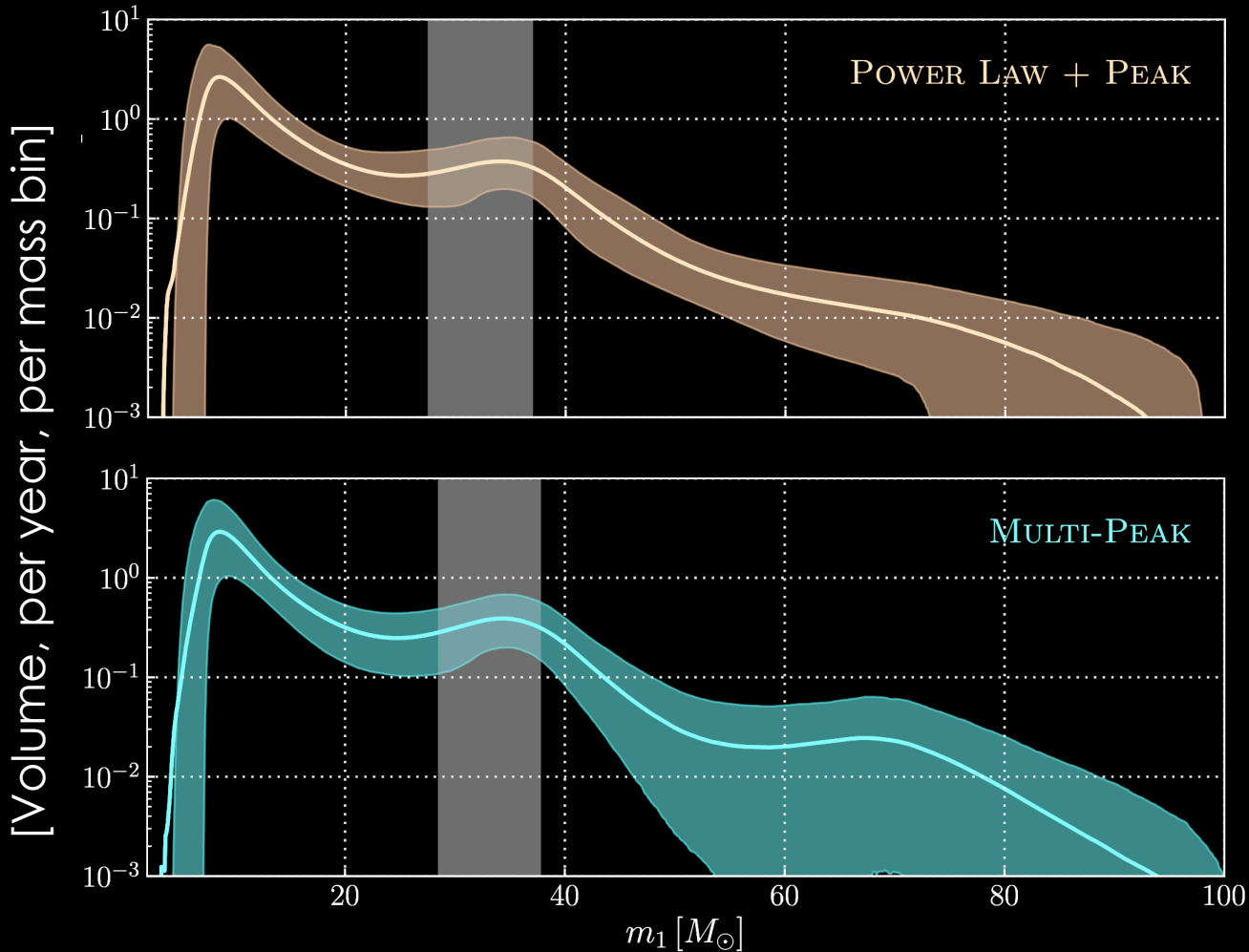
New data from O3a (high mass detections) demands function models that favor a more sophisticated mass function model that “just” truncated power law used for O1&O2!



PREDICTED MASS FUNCTIONS

$$\frac{dR}{dm_1} [\text{Gpc}^{-3} \text{yr}^{-1} M_\odot^{-1}]$$

Astrophysical Occurrence Rate



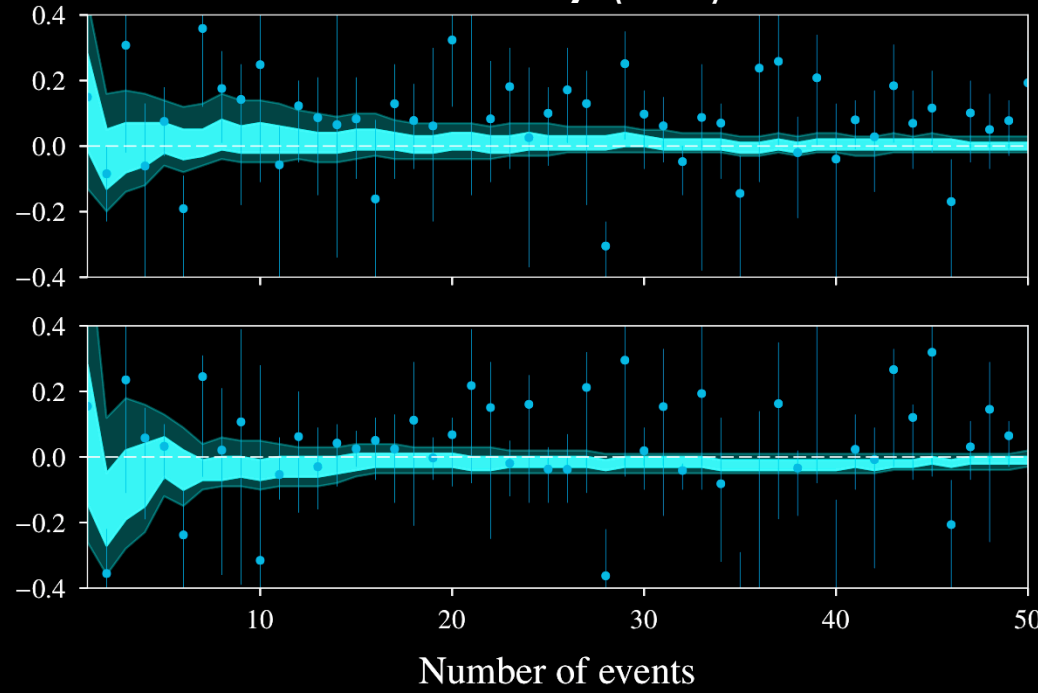
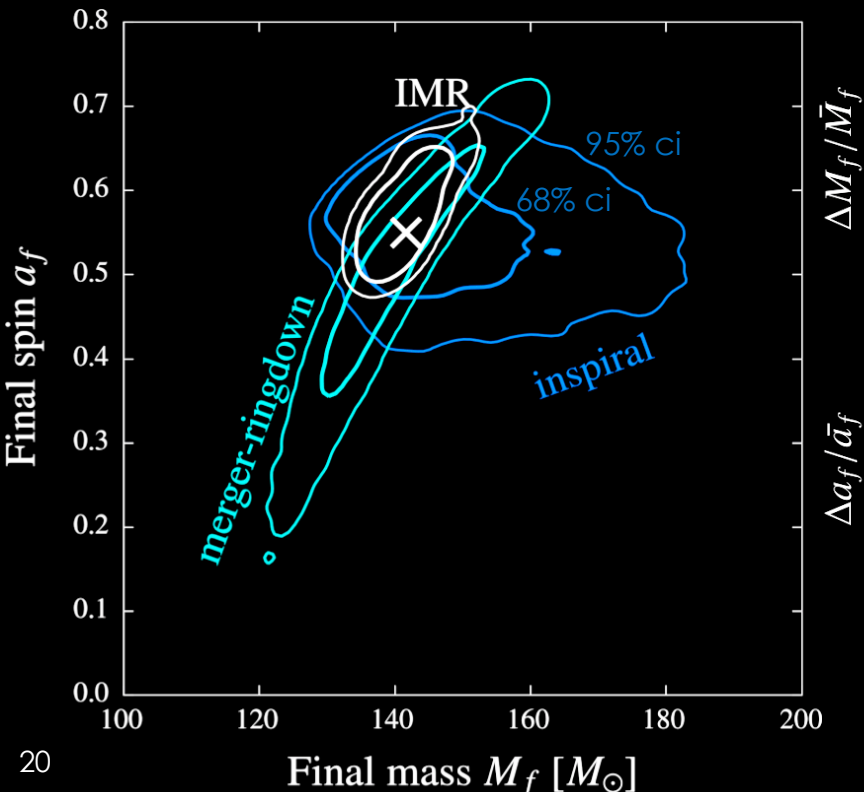
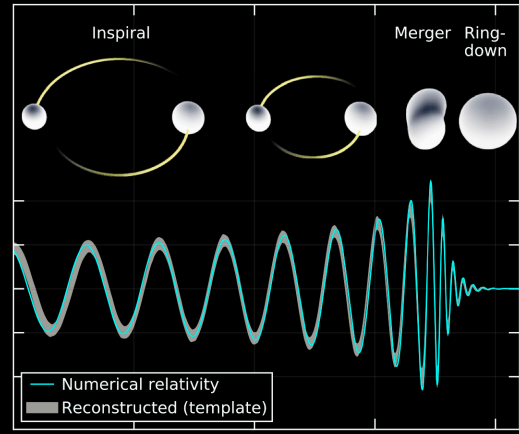
Can/should no longer “just” tell you the rate “of all binary black hole collisions!”



GENERAL RELATIVITY

Compare mass and spin of final black hole predicted by

- **inspiral** wave prior to merger (Newtonian Expansion)
- **ring-down** after merger (Perturbation Theory)
- **numerical relativity (IMR)**



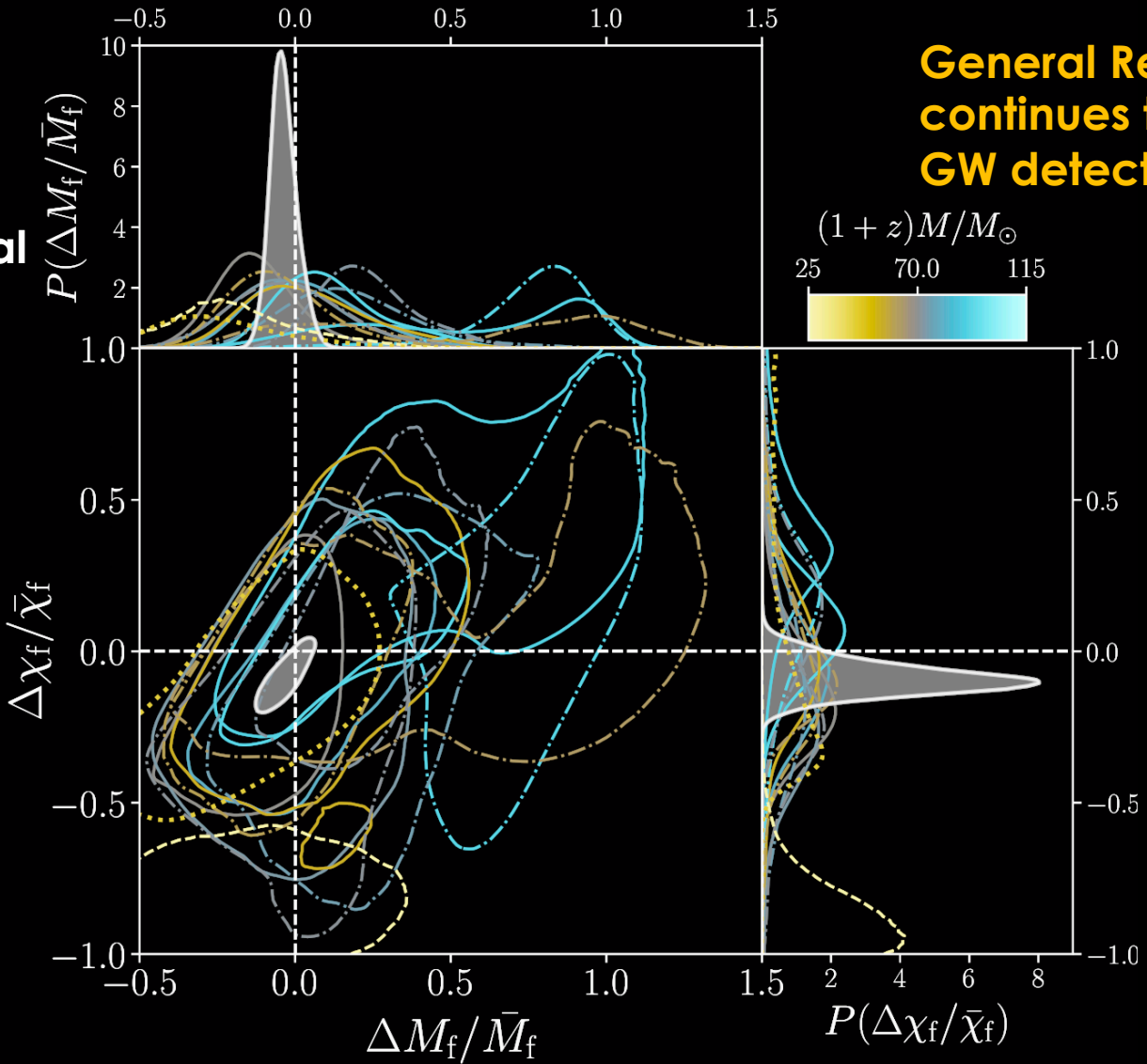


GENERAL RELATIVITY

90% ci's for final mass and spin of

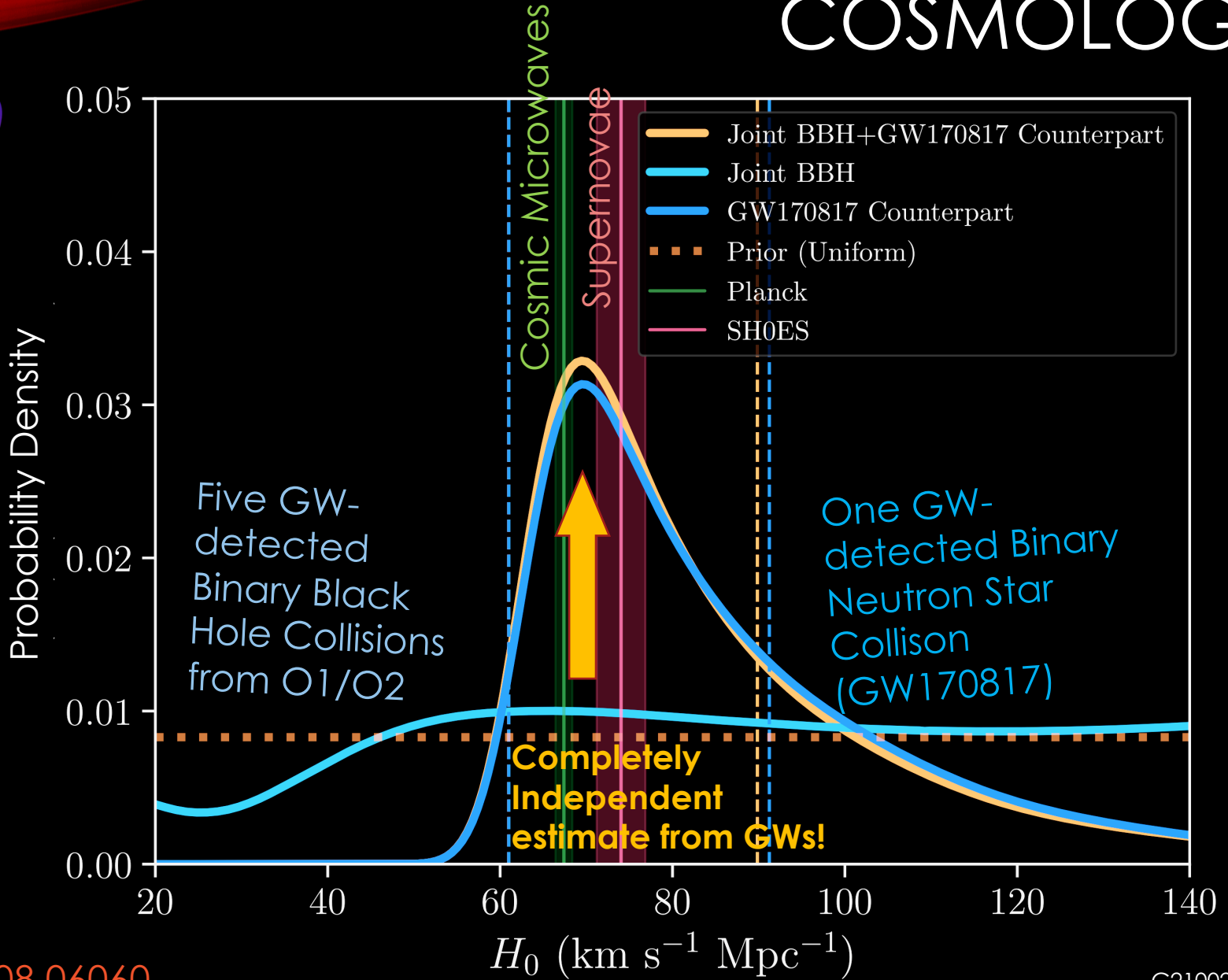
- High mass systems
- Low mass systems
- Product

- Solid = GWTC-2 events
- Dash-dot = GWTC-1 events





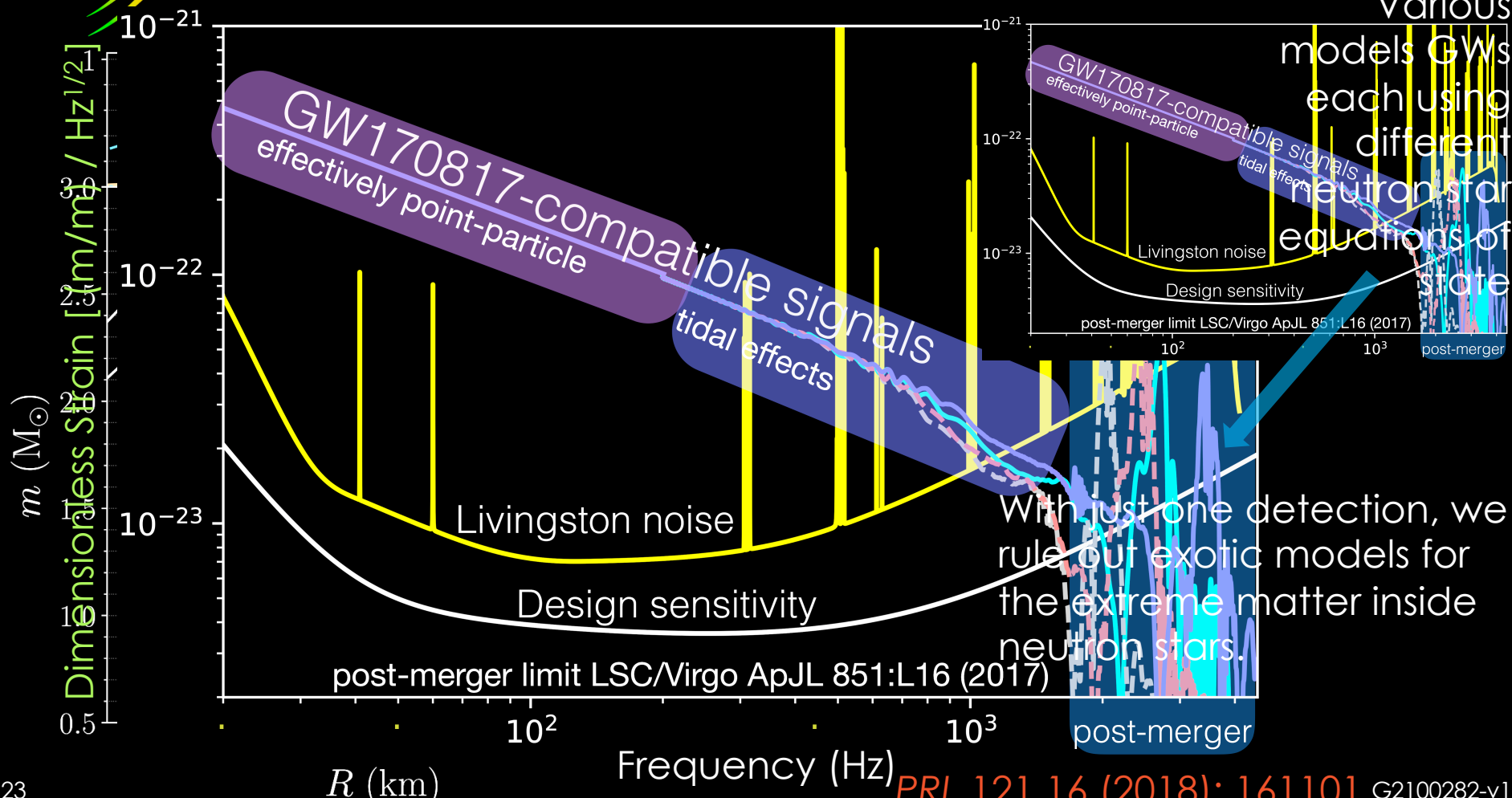
COSMOLOGY





NS EQUATION OF STATE

GW170817 – a nearby binary neutron star collision with MANY electromagnetic counterparts -- was amazing for so many reasons. Here's another one.





THE FUTURE IS LOUD!



- Gravitational waves have “broken the sound barrier:” we can now “listen” to the universe
- Individual results are ground-breaking in so many different ways
- Study of event populations are becoming competitive
- Cracking all sorts of mysteries in all corners of astrophysics
- Stay tuned: many more exciting results to come this year!

Thank you!