Title: Astrophysical Lessons from LIGO-Virgo's Black Holes

Speakers: Maya Fishbach

Series: Colloquium

Date: March 21, 2022 - 2:00 PM

URL: https://pirsa.org/22030107

Abstract: LIGO and Virgo have observed over 80 gravitational-wave sources to date, including mergers between black holes, neutron stars, and mixed neutron star- black holes. The origin of these merging neutron stars and black holes -- the most extreme objects in our Universe -- remains a mystery, with implications for stars, galaxies and cosmology. I will review the latest LIGO-Virgo discoveries and discuss some recent astrophysical lessons, including mass gaps, black hole evolution with cosmic time, and implications for cosmology. While the latest gravitational-wave observations have answered a number of longstanding questions, they have also unlocked new puzzles. I will conclude by discussing what we can expect to learn from future gravitational-wave and multi-messenger discoveries.

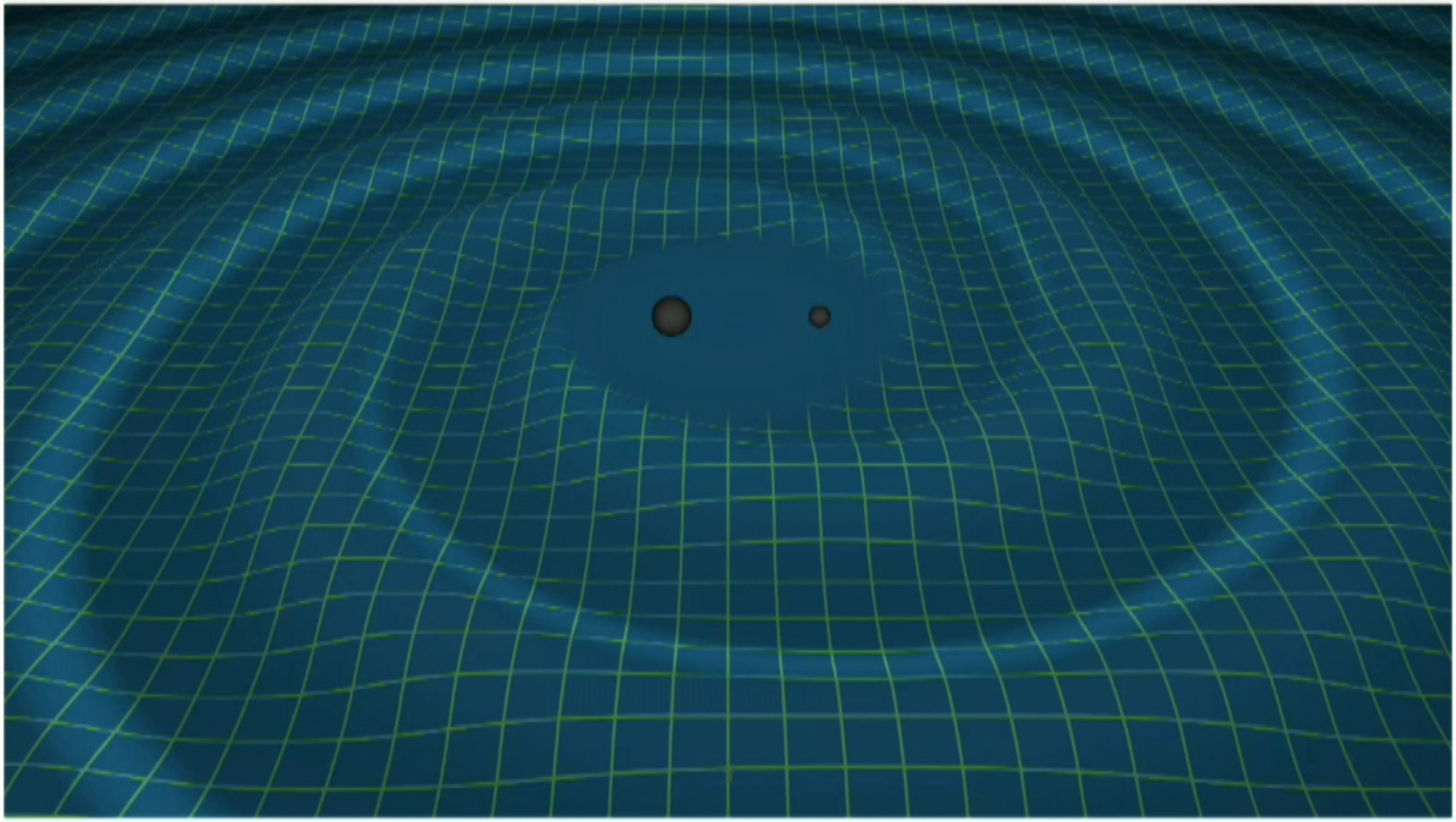
Zoom Link: https://pitp.zoom.us/j/94857758725?pwd=MW1PNXZRNkFGL25xUkpjVWlabmNJZz09


Image Credit: Aurore Simonnet/LIGO-Caltech-MIT-Sonoma State
Astrophysical Lessons from LIGO-Virgo's Black Holes
Maya Fishbach
NASA Einstein Fellow @ CIERA/ Northwestern
Perimeter Institute Colloquium
March 21 2022
CIERA
Center for Interdisciplinary Exploration and Research in Astrophysics
NHFP
NASA Hubble Fellowship Program


00:10
-00:26


00:20
-00:07

When two black holes coalesce, they source **loud gravitational waves**



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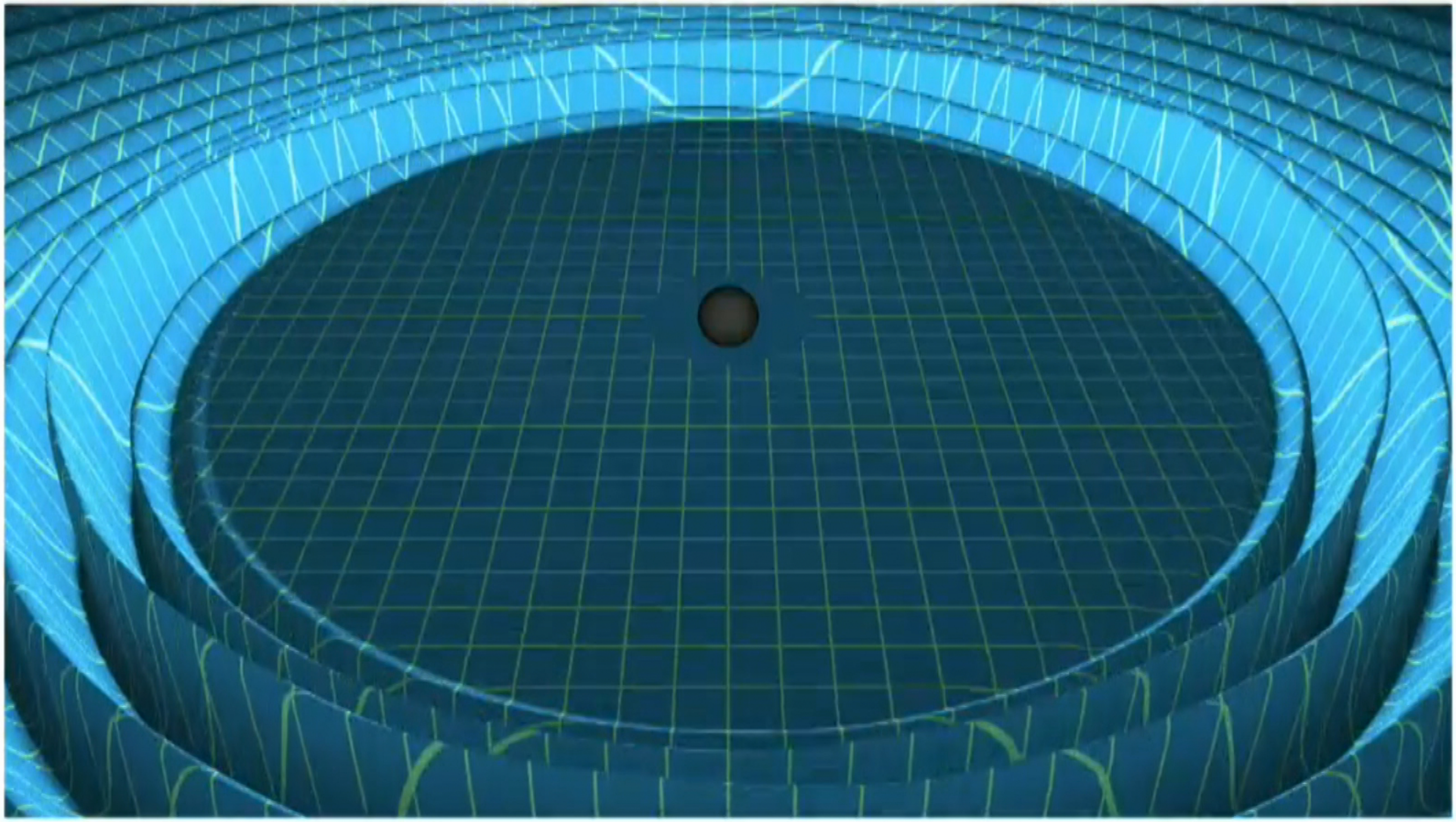
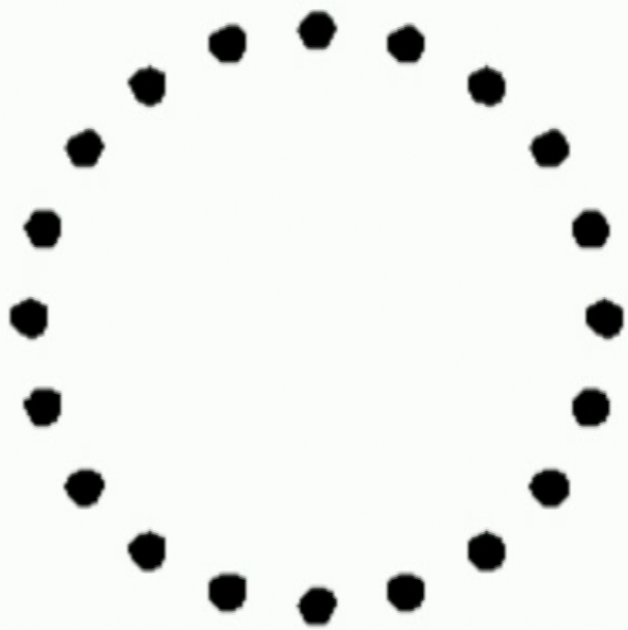


Gravitational waves stretch and squeeze matter



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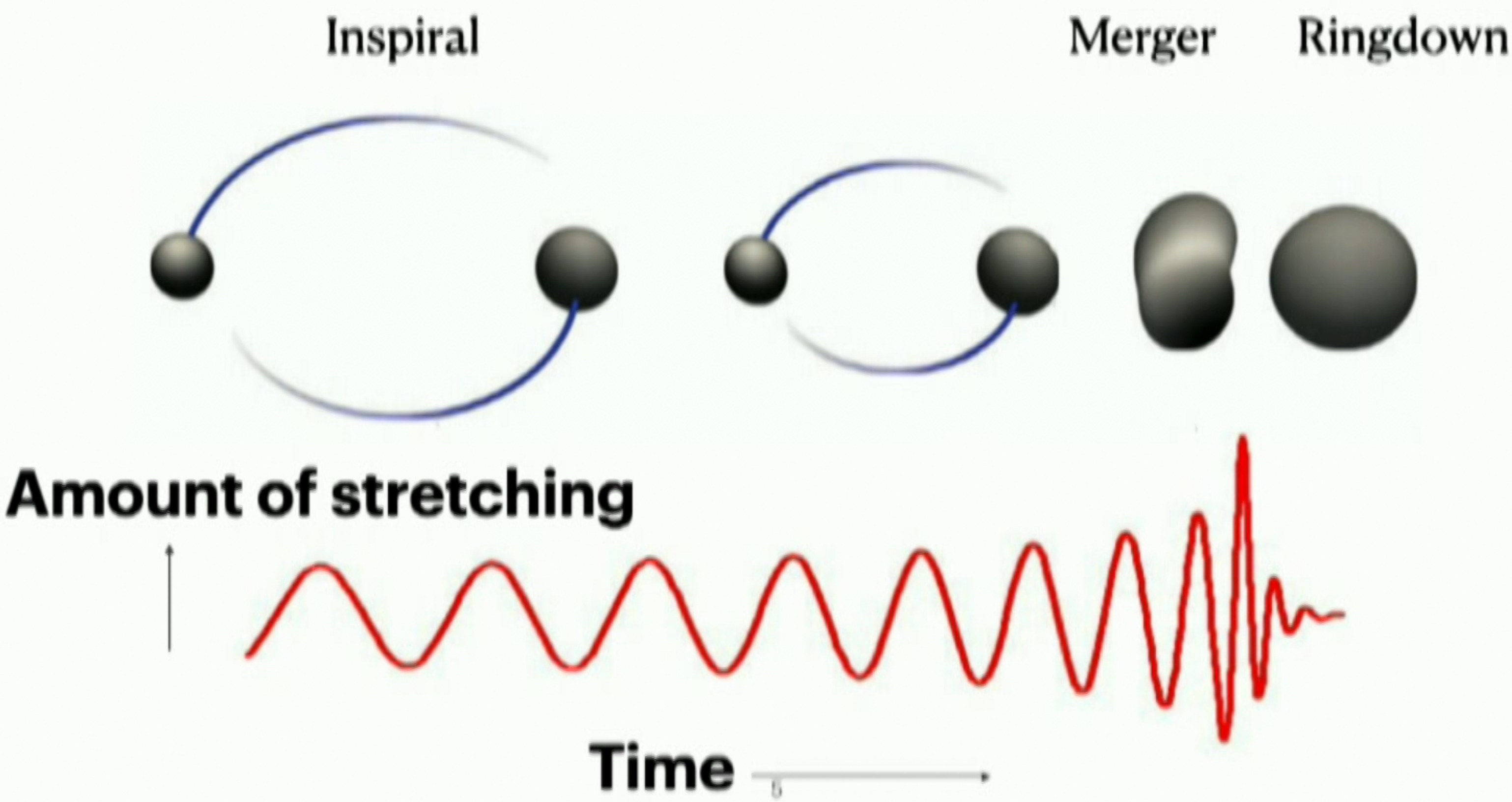
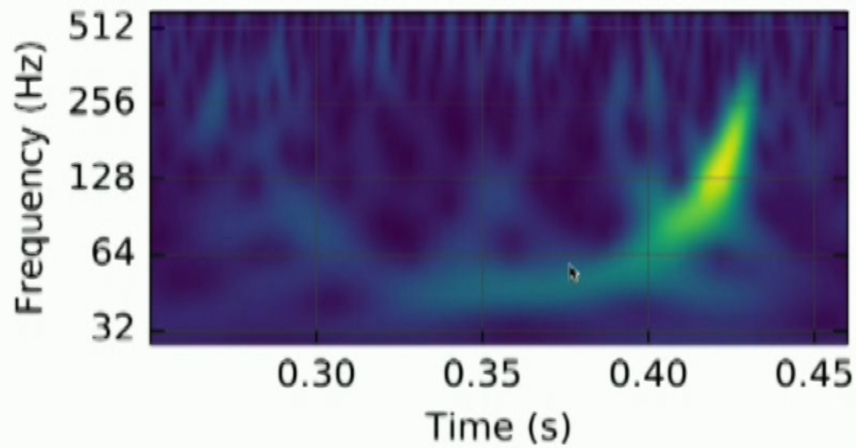
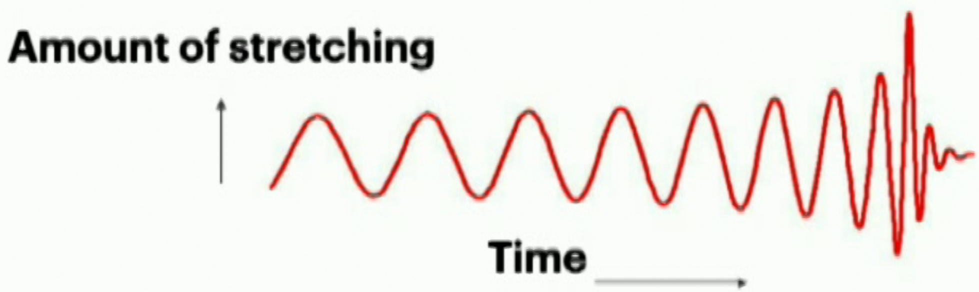
Gravitational Wave Signal from a Coalescence of Two Black Holes



Gravitational Wave Signal from a Merger of Two Black Holes:
Time-frequency ***Chirp***





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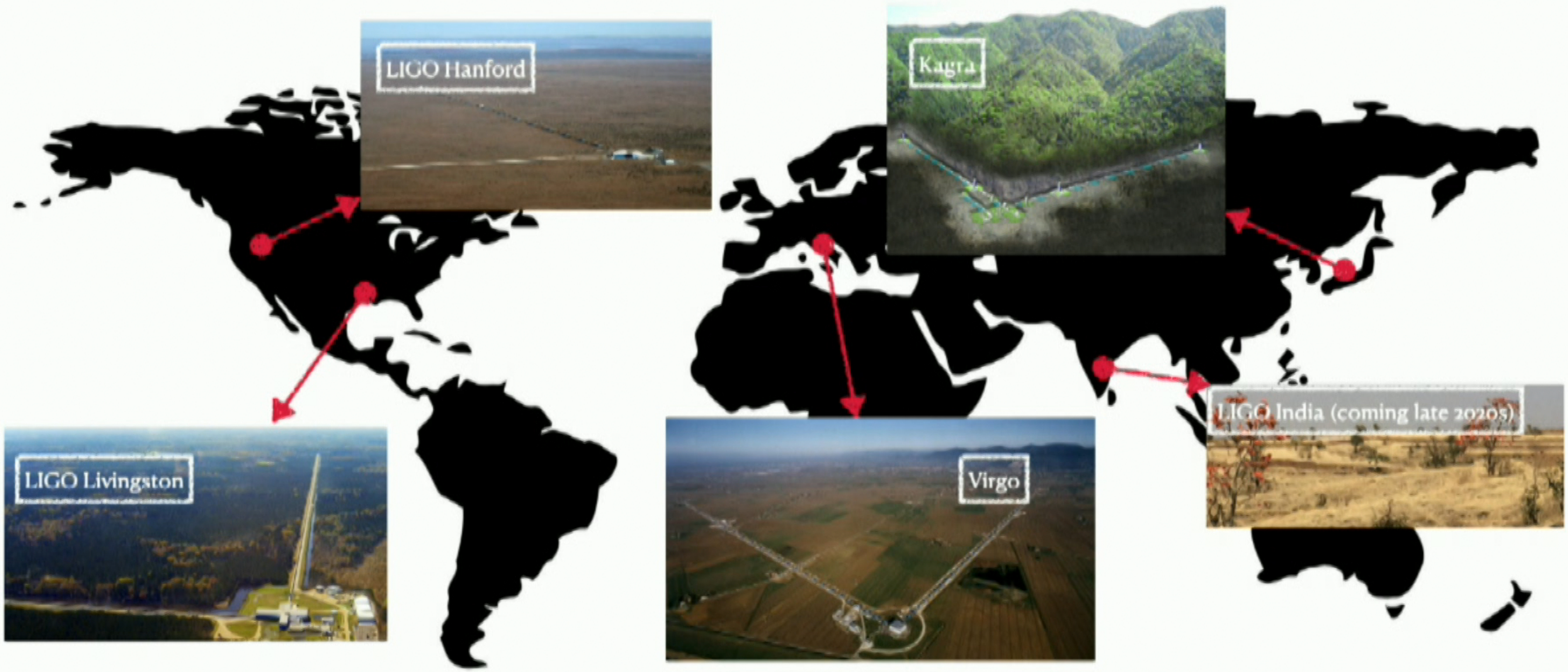
Gravitational-wave observatories



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 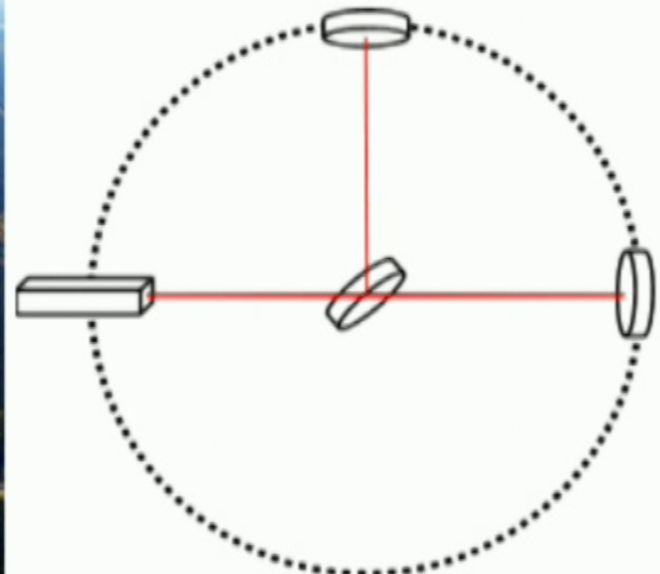

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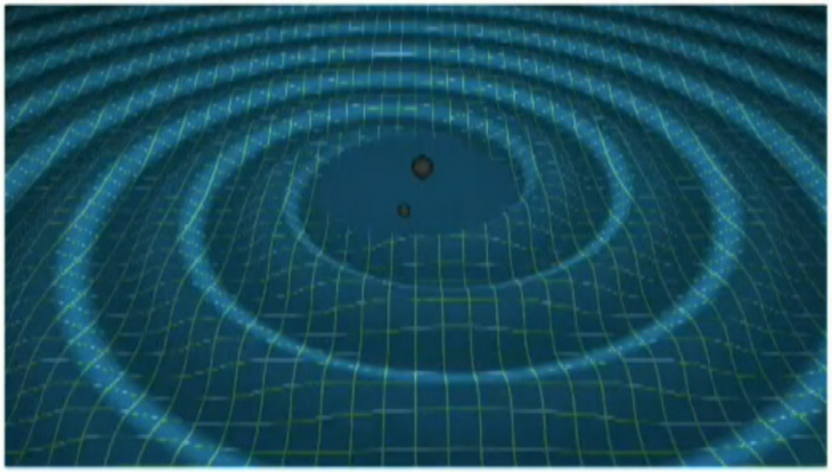
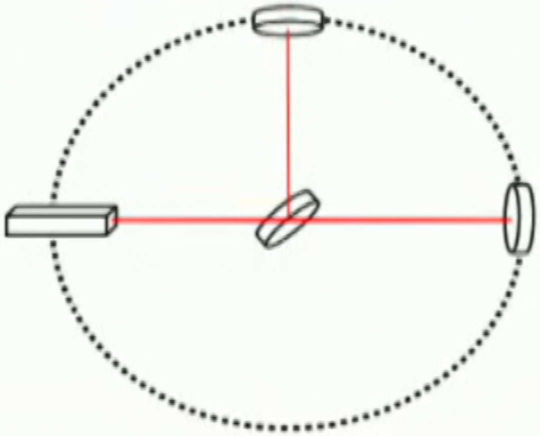
A *compact binary coalescence* emits loud gravitational waves

...that stretch and squeeze matter

...and can be detected as a relative change in distance (*strain*) by interferometers





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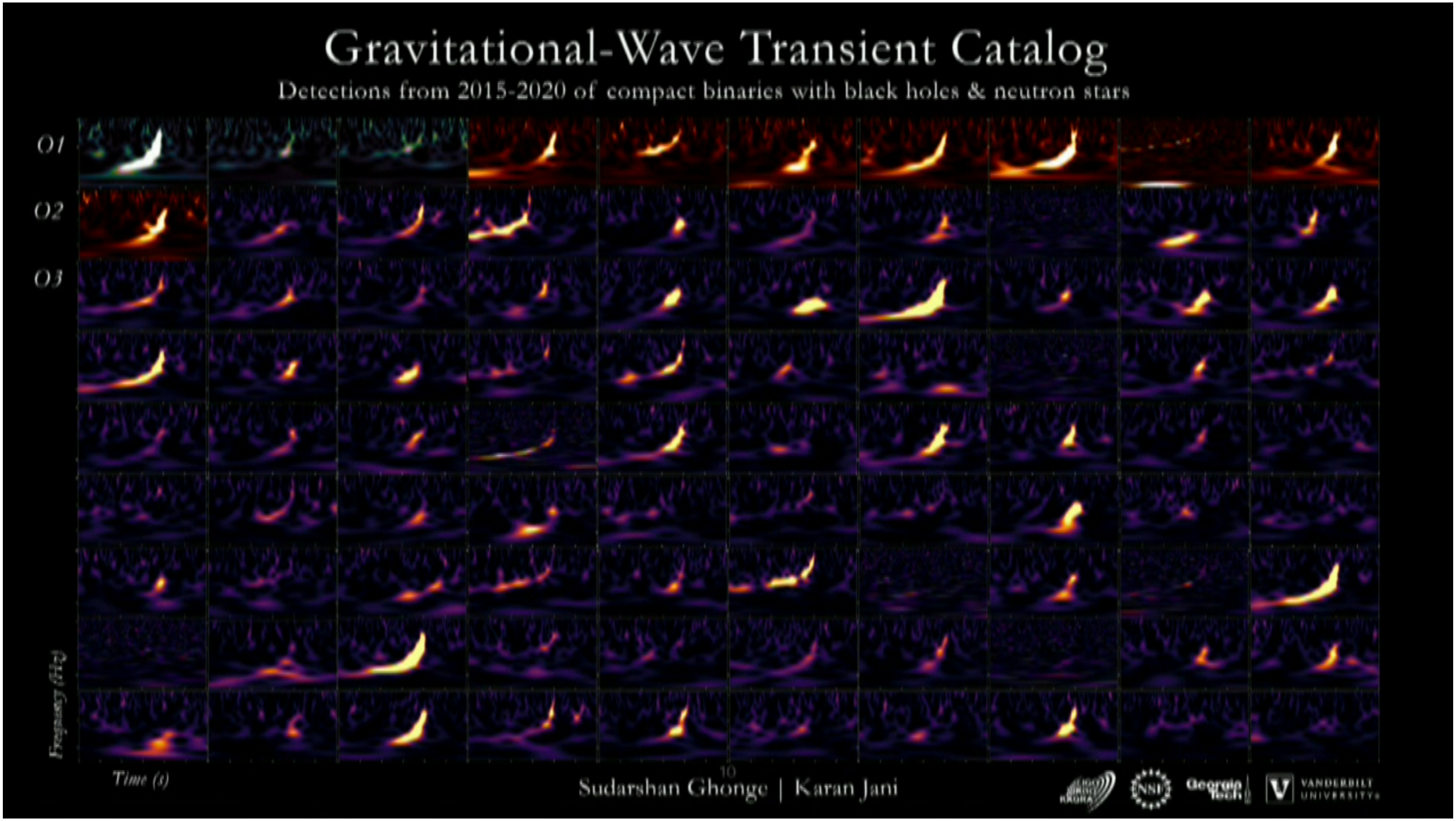
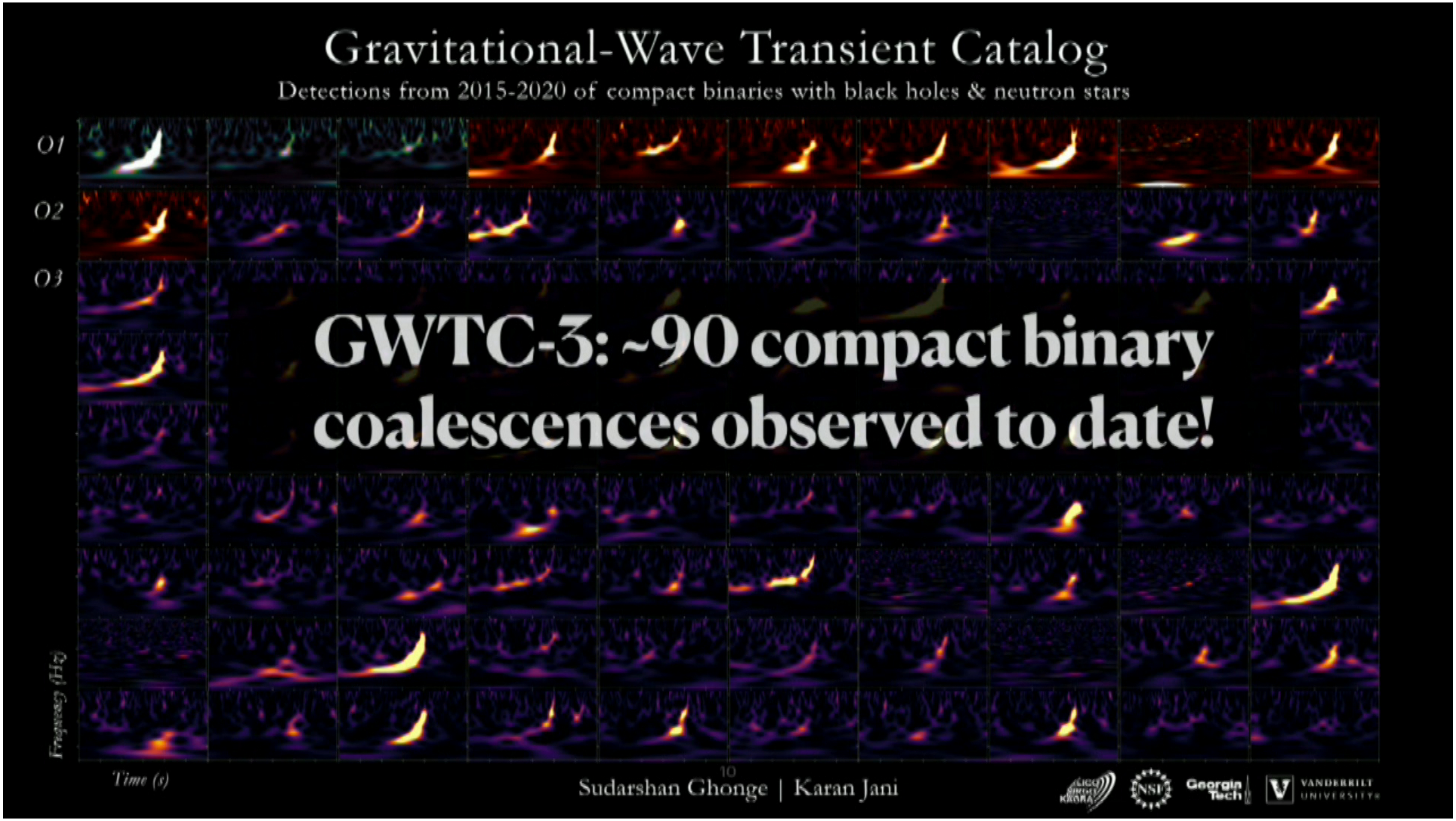
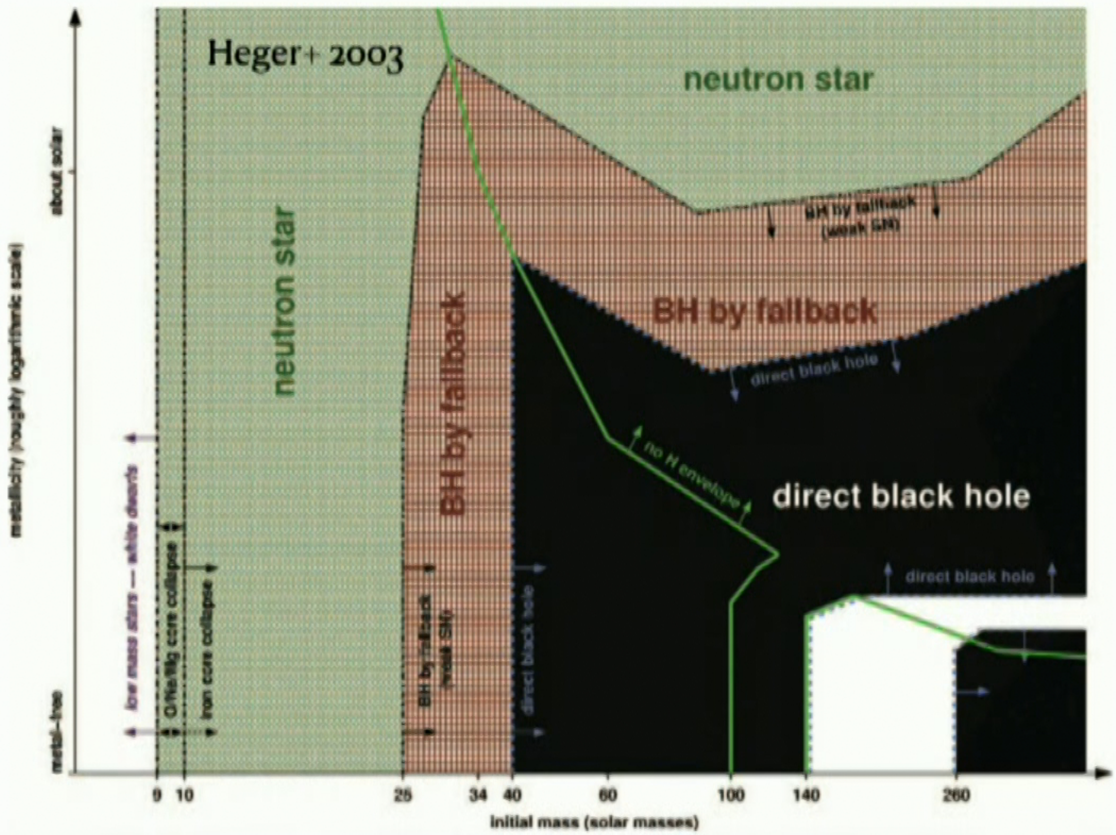

Gravitational-Wave Transient Catalog
Detections from 2015-2020 of compact binaries with black holes & neutron stars
O1
O2
O3
Frequency (Hz)
Time (s)
Sudarshan Ghonge | Karan Jani


Gravitational-Wave Transient Catalog
Detections from 2015-2020 of compact binaries with black holes & neutron stars
O1
O2
O3
GWTC-3: ~90 compact binary coalescences observed to date!
Frequency (Hz)
Time (s)
10
Sudarshan Ghonge | Karan Jani

How are black holes made?

Compact object remnants of massive stars

Initial metallicity
(abundance of elements
heavier than helium)



Initial mass of star

Note: this diagram is for evolution of *single* stars

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How are *binary* black holes made?

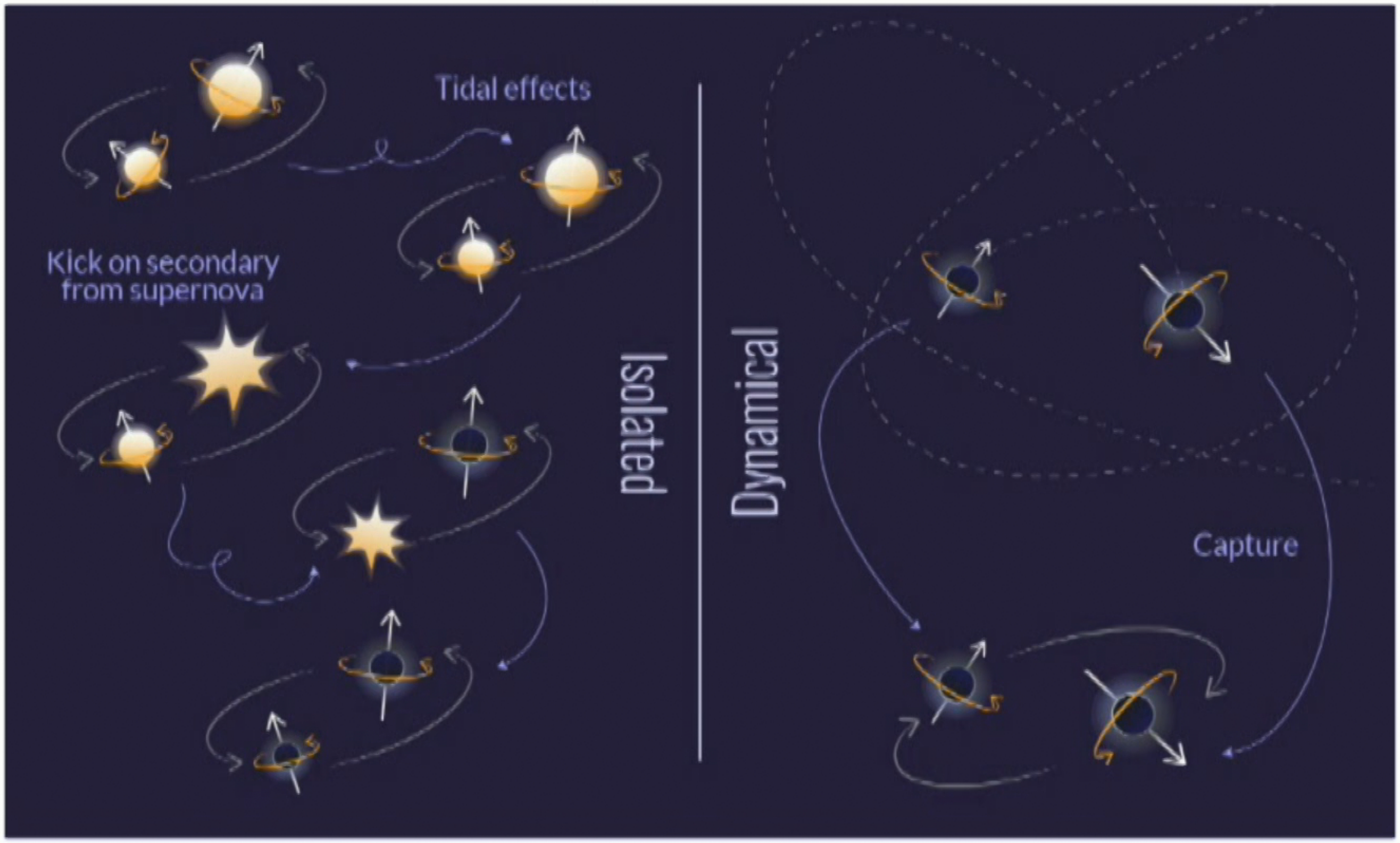

Figure credit: Shanika Galaudage

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How are *binary* black holes made?

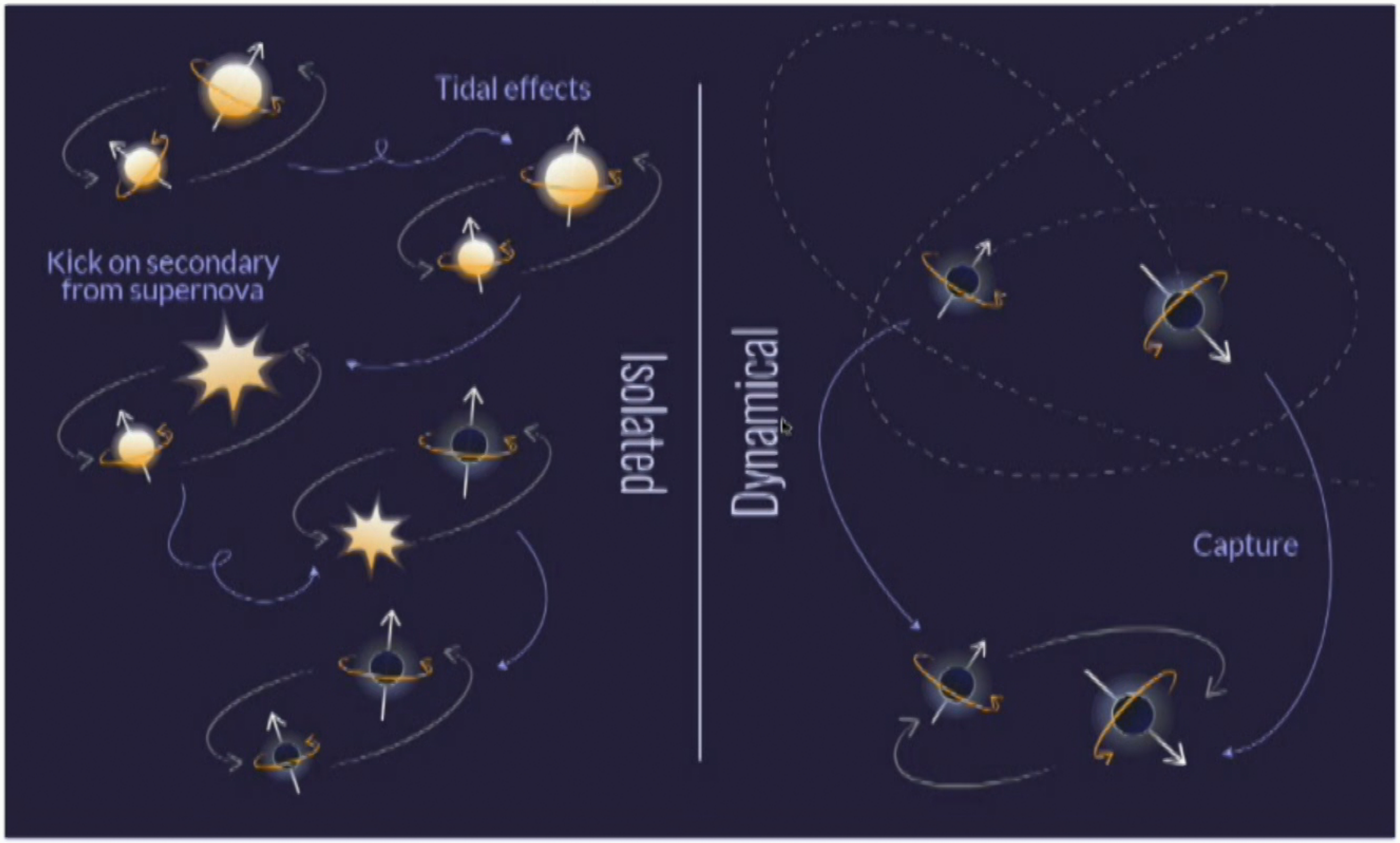

Figure credit: Shanika Galaudage

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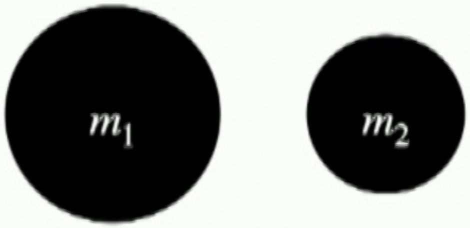
The origins of LIGO-Virgo's black holes

- What were their progenitors? *(For this talk, I am assuming massive stars)*
- When and where did these massive stars live?
- How did these stars die?
- How did these stellar remnants pair up into merger partners?
- How did the resulting mergers affect their environments?

All of these pieces affect the observable properties of gravitational-wave events

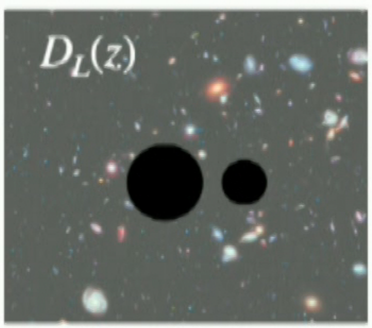
Observing Binary Black Holes

How *big* is each black hole?



How fast are they *spinning*? Where are the spin axes pointing?

Where and *when* did they merge?



How are black holes made?

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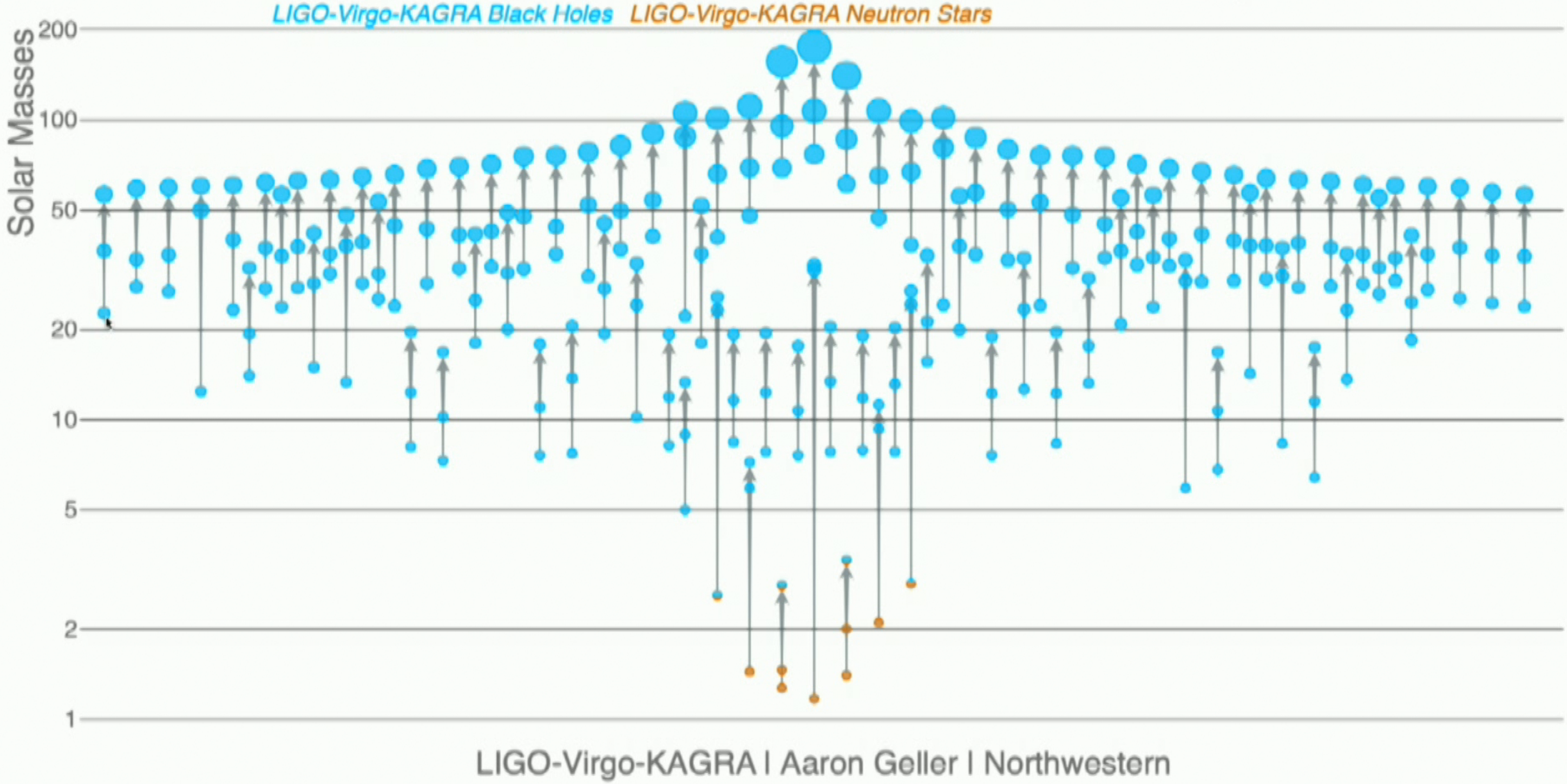
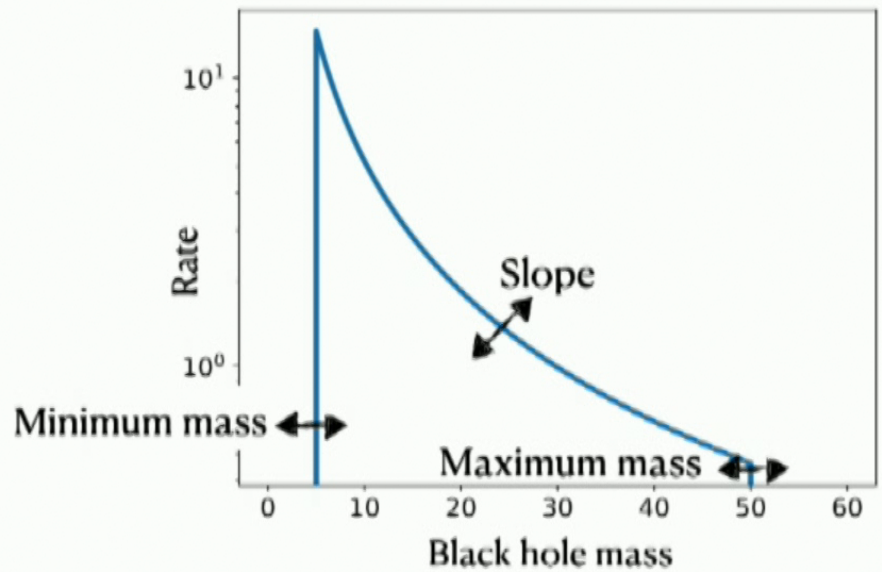
Masses in the Stellar Graveyard



From Single Events to a Population

- Introduce a population model that describes the **distributions** of masses, spins, redshifts across **multiple events.**
- Example: Fit **a power law to black hole masses**.
    - Population parameters: power-law slope, minimum black hole mass, maximum black hole mass.
- Take into account measurement uncertainty and **selection effects.**



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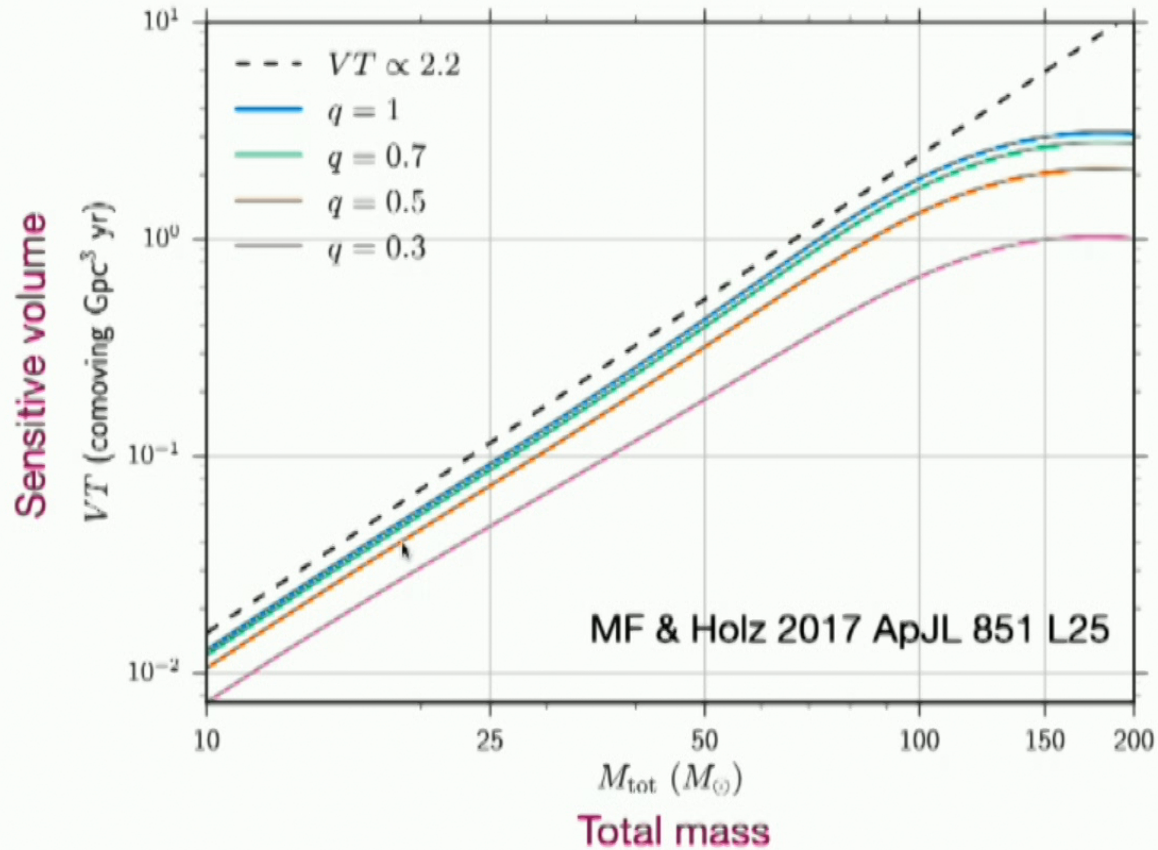
Example of selection effects:

Big black holes are louder than small black holes



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Astrophysical lessons in this talk

1. Gaps in the mass distribution
2. Evolution with cosmic time
3. Applications to cosmology

Astrophysical lessons in this talk

1. Gaps in the mass distribution
   A. Upper Black Hole Mass Gap
   B. Lower Neutron Star Mass Gap
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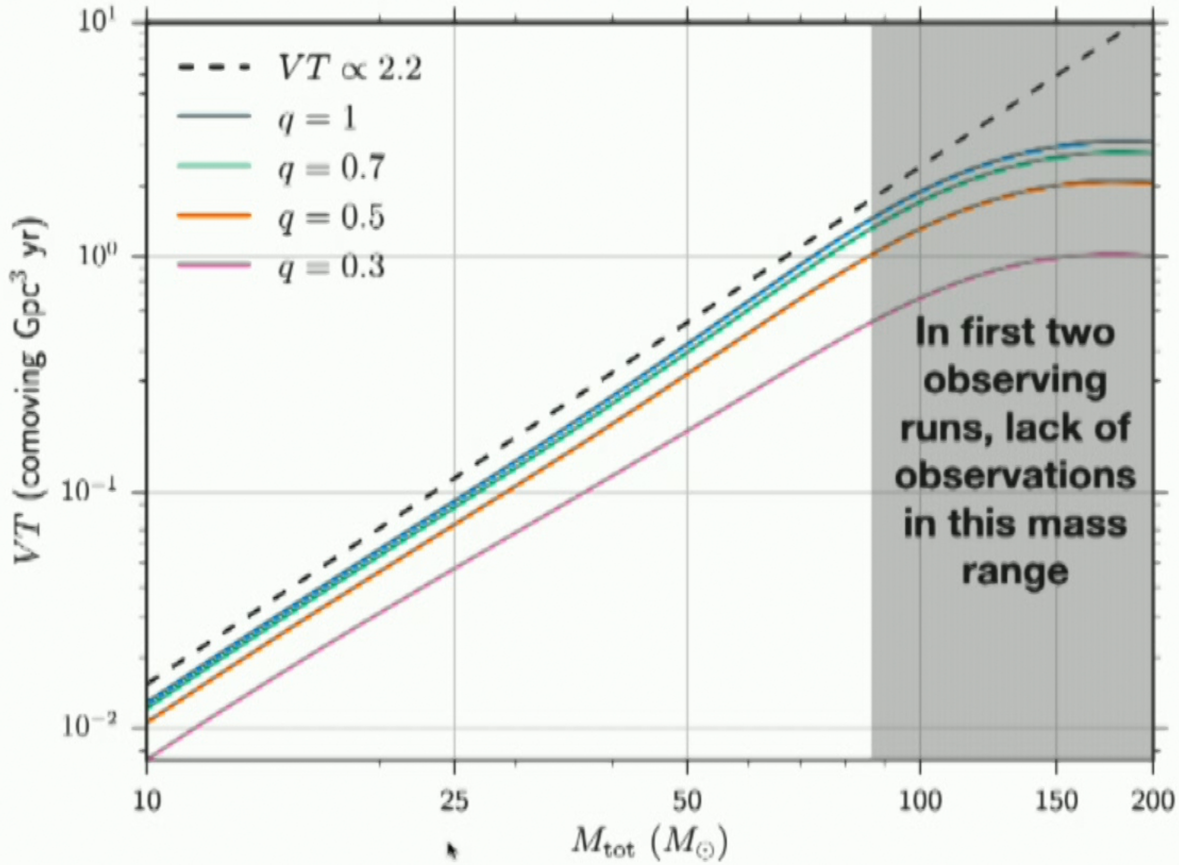
Where are LIGO's Big Black Holes?

Big black holes are very loud, and yet among the first 10, we did not see any binary black holes with component masses above ~40 solar masses (total masses above ~80 solar masses)

→ *These systems must be rare in the underlying population.*



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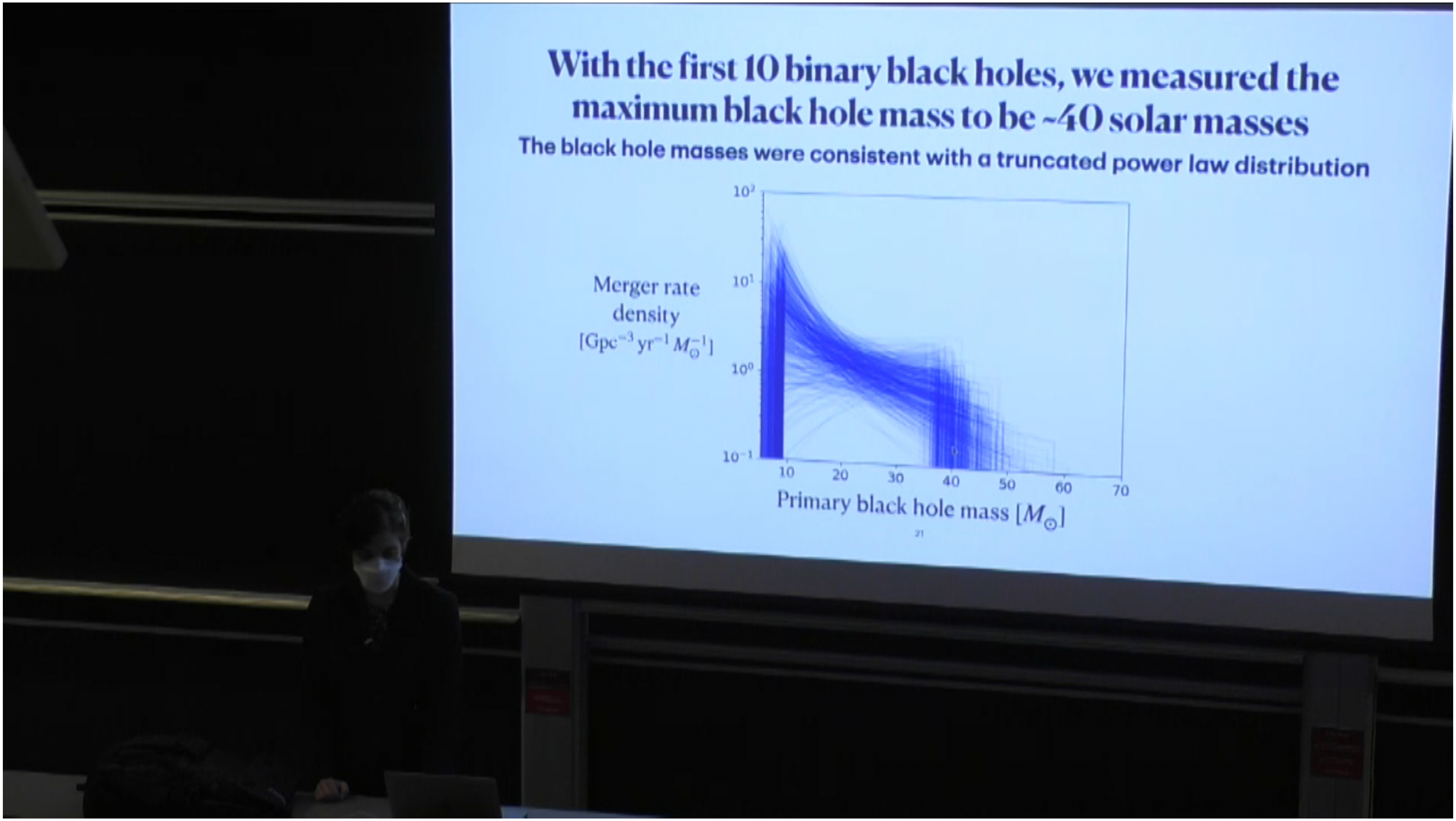
MF & Holz 2017 ApJL 851 L25


With the first 10 binary black holes, we measured the maximum black hole mass to be ~40 solar masses
The black hole masses were consistent with a truncated power law distribution
Merger rate density [Gpc^{-3} yr^{-1} $M_\odot^{-1}$]
10^2
10^1
10^0
10^{-1}
10 20 30 40 50 60 70
Primary black hole mass [$M_\odot$]
21

Is 40 solar masses the lower edge of the pair-instability gap?

- (Pulsational) pair-instability supernovae predict an absence of black holes in the range $\sim 40 - 120\, M_\odot$
- Applies to black holes formed from stellar collapse
- Uncertainties in theorized gap location due to: nuclear reaction rates, stellar structure, possible beyond-standard model physics
- Black holes formed via other channels — for example, **from smaller black holes** — may populate the gap

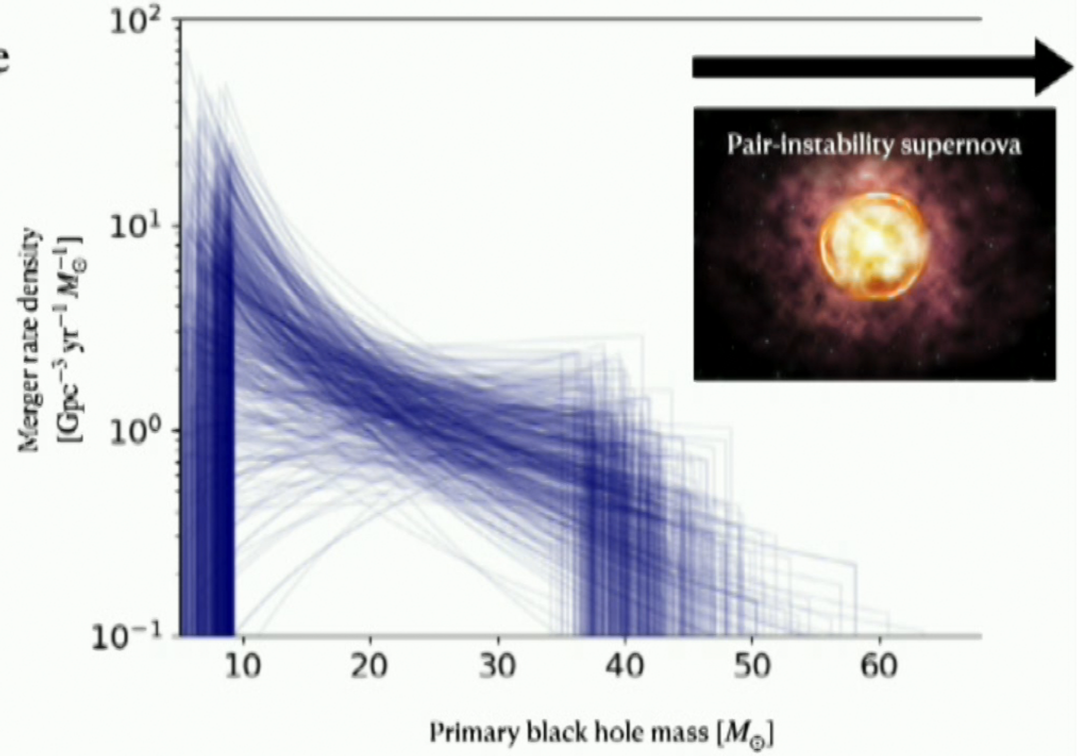
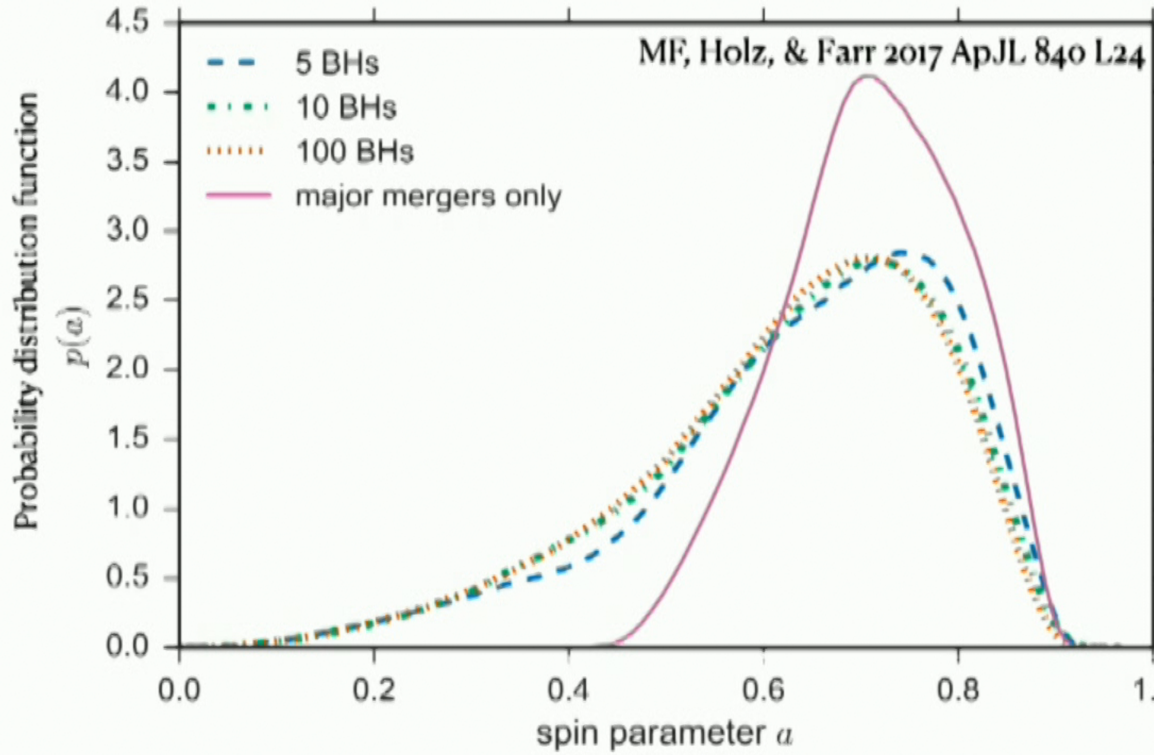


Image credit: Gemini Observatory/NSF/AURA/ Illustration by Joy Pollard

Are LIGO's Black Holes Made From Smaller Black Holes?

Distinct signature in the **spin distribution**: Previous mergers produce black holes spinning at a dimensionless spin parameter of $a \sim 0.7$



Black hole dimensionless spin magnitude

Also see recent Nature Astronomy review by Gerosa & MF

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Black holes in the mass gap? The case of GW190521

The New York Times

OUT THERE

These Black Holes Shouldn't Exist, but There They Are

On the far side of the universe, a collision of dark giants sheds light on an invisible process of cosmic growth.

Credit: Carol & Mike Werner/Visuals Unlimited, INC./Science Photo Library

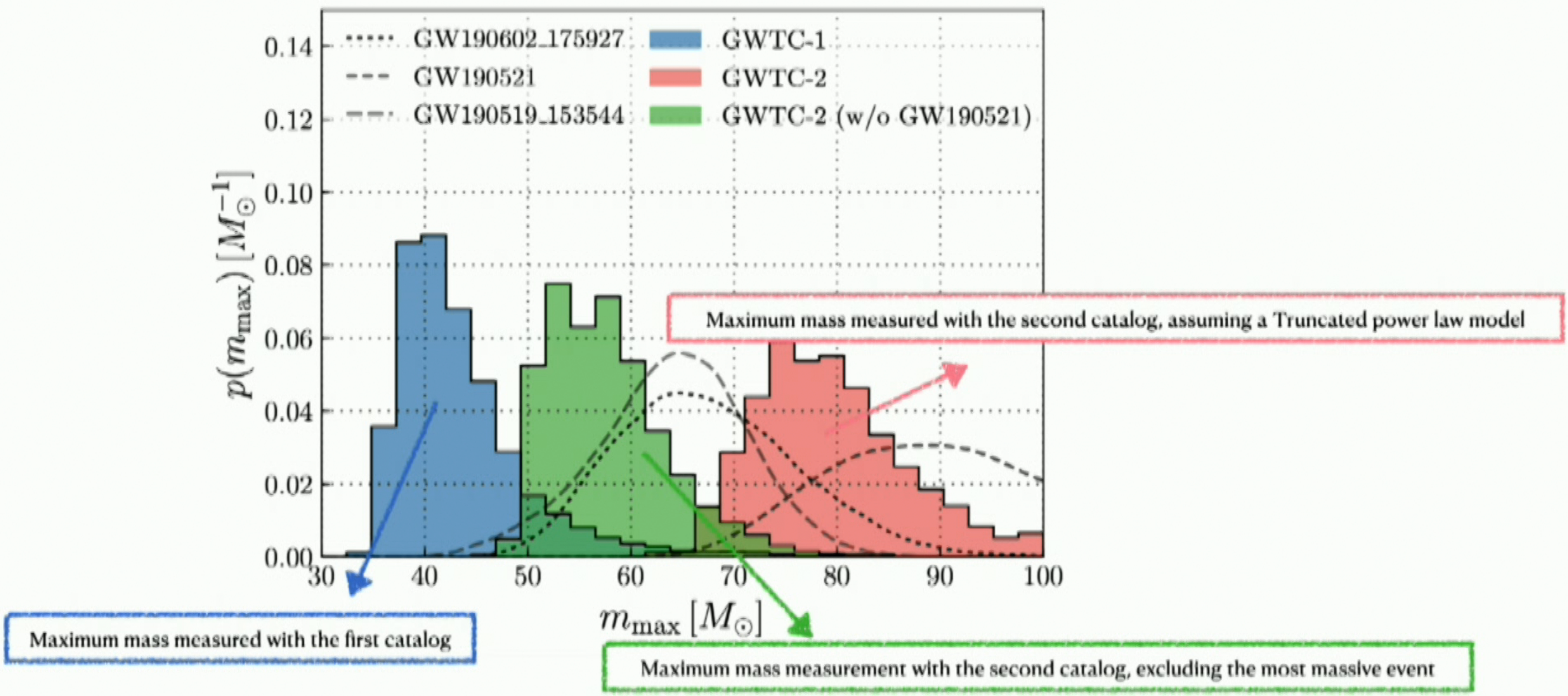
NEWS · 02 SEPTEMBER 2020

'It's mindboggling!': astronomers detect most powerful black-hole collision yet

Gravitational-wave detections suggest merging black holes fell into 'forbidden' range of masses.

LVK PRL 125, 101102

In addition to GW190521, there are other recently-discovered big black holes



LVK 2021 ApJL 913 L7 (chaired by MF)

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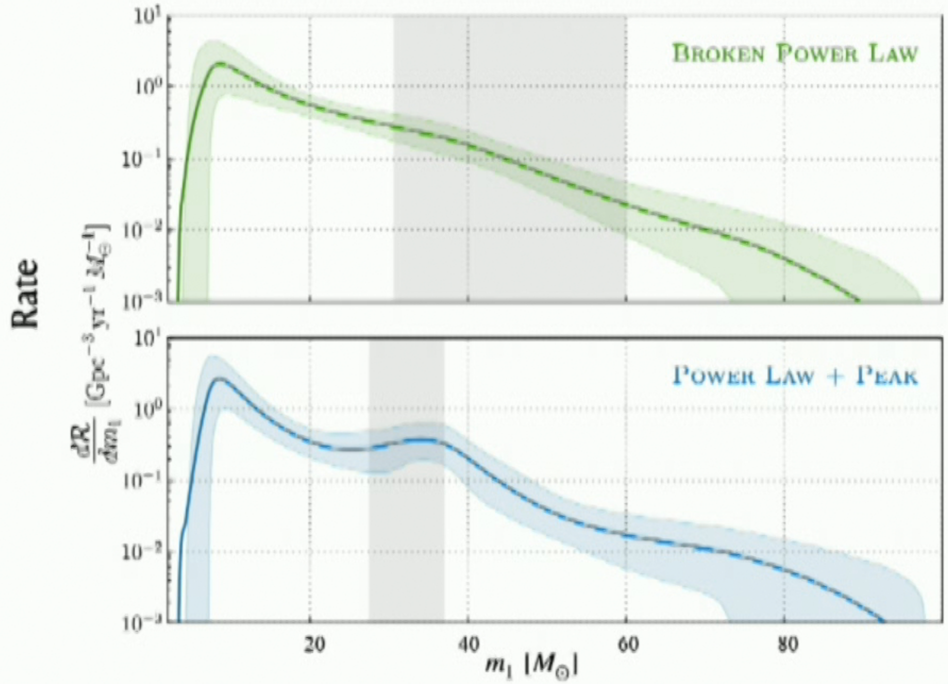
A population of big black holes, but a feature at ~40 solar masses persists

Are these big black holes inside the mass gap? (Made in a different formation channel that contaminates the gap, like hierarchical mergers?)

Is the lower edge of the gap represented by a gradual tapering-off, rather than a sharp cutoff? (Fallback of the hydrogen envelope, stellar mergers, accretion)

Does the mass gap start at higher core masses than previously thought? (Different nuclear reaction rates, new physics?)



Primary mass in solar masses

LVK 2021 ApJL 913 L7 (chaired by MF)

Astrophysical lessons in this talk

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   A. Upper Black Hole Mass Gap
   B. Lower Neutron Star Mass Gap
2. Evolution with cosmic time
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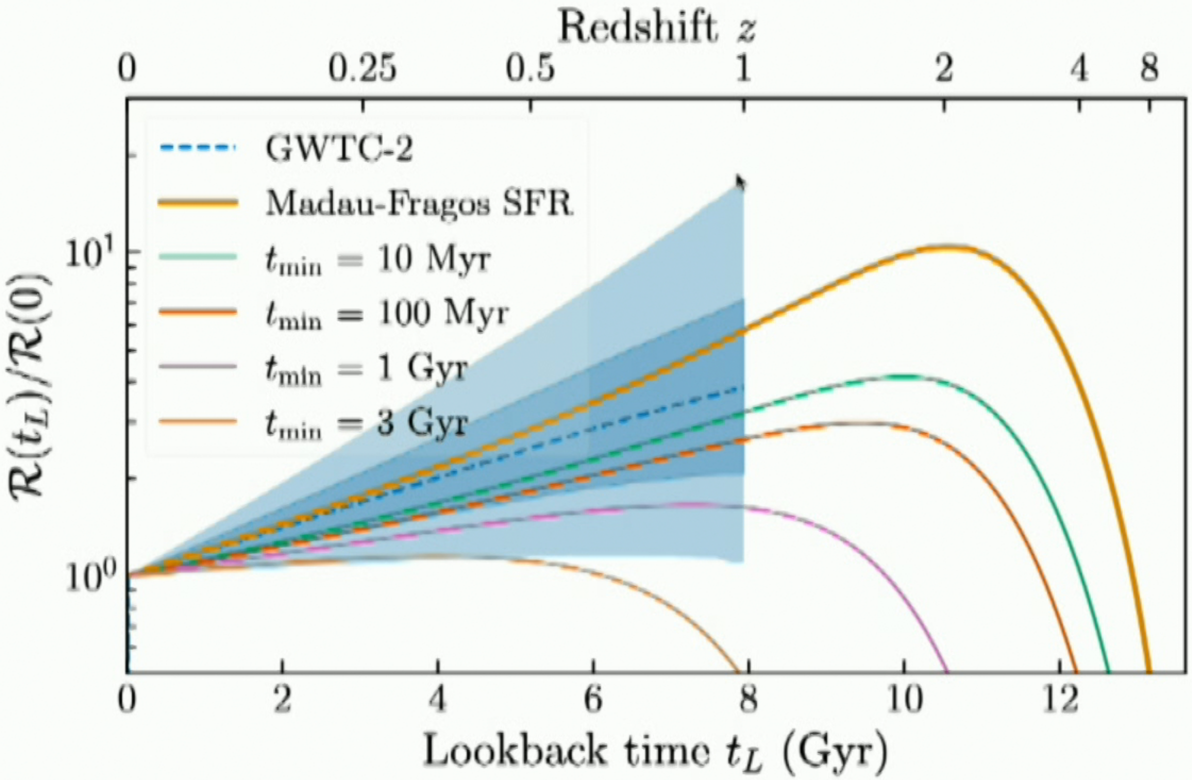
Comparing merger rate evolution to star formation + time delays



Blue: Inference of the black hole merger rate as a function of cosmic time

Solid lines: Predicted merger rate evolution from different time delay distributions

MF, Farr & Holz 2018 ApJL 863 L41
MF & Kalogera 2021, ApJL 914 L30

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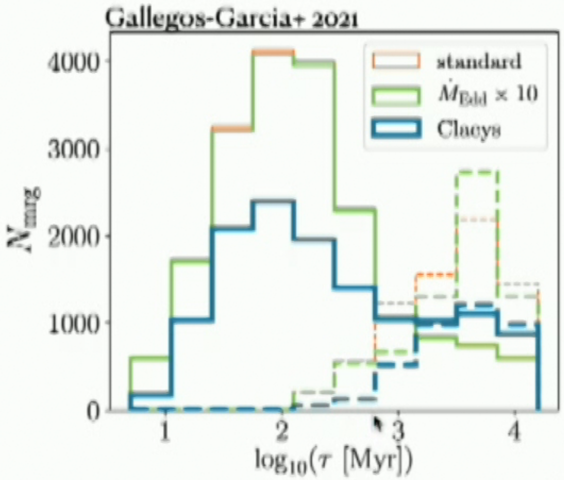
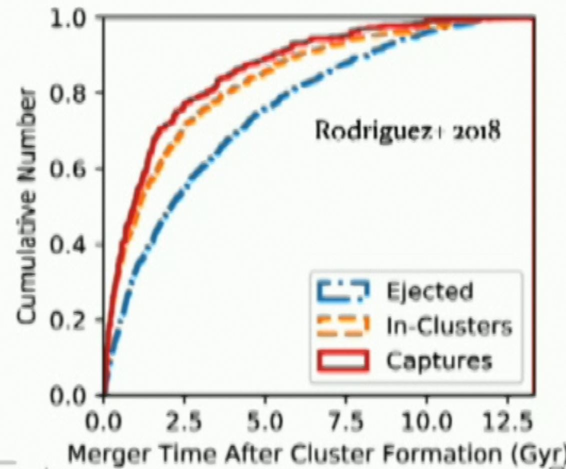
The delay time distribution tells us about the formation channel

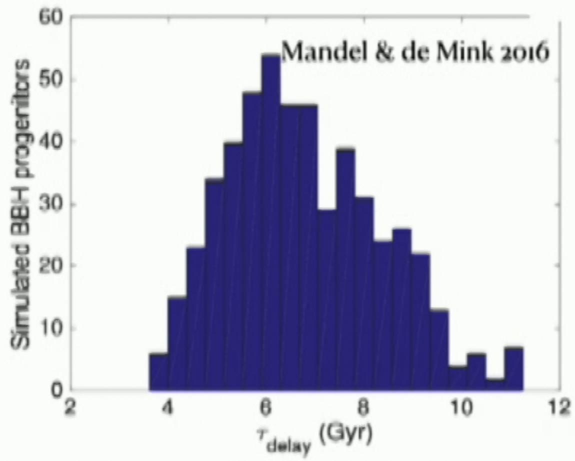


Left: Field binary evolution: common-envelope and stable mass transfer

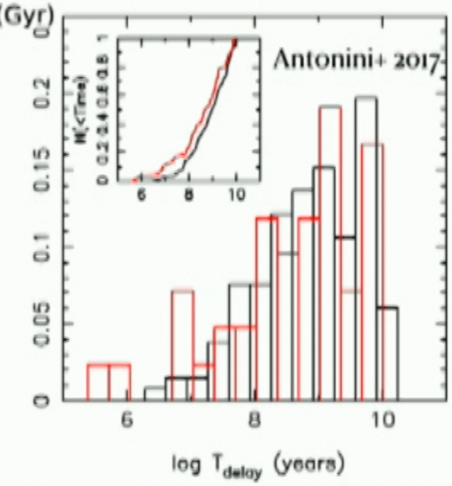


Left: Dynamical assembly in globular clusters

Right: Chemically homogeneous evolution



Right: Stellar triples



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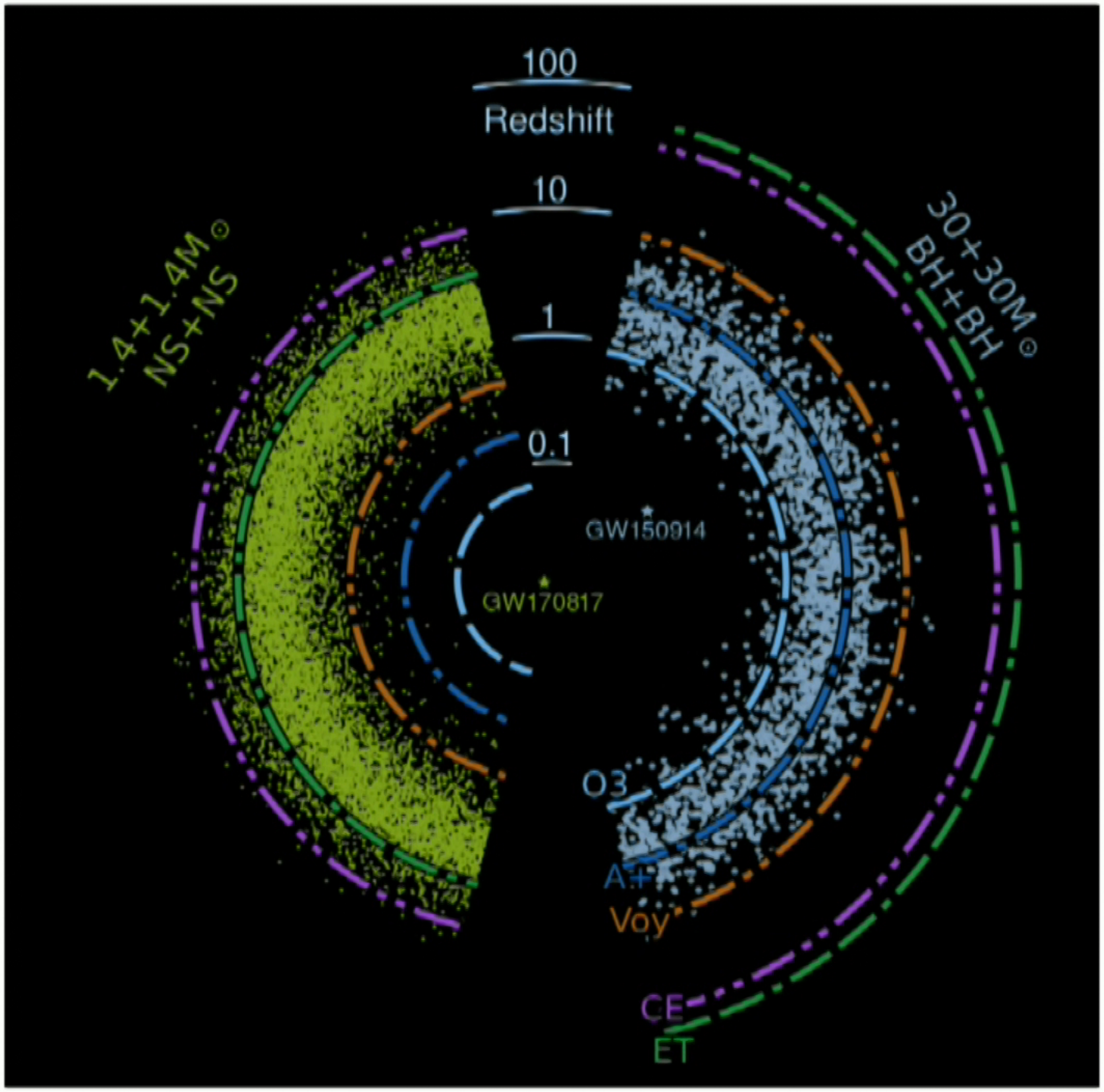
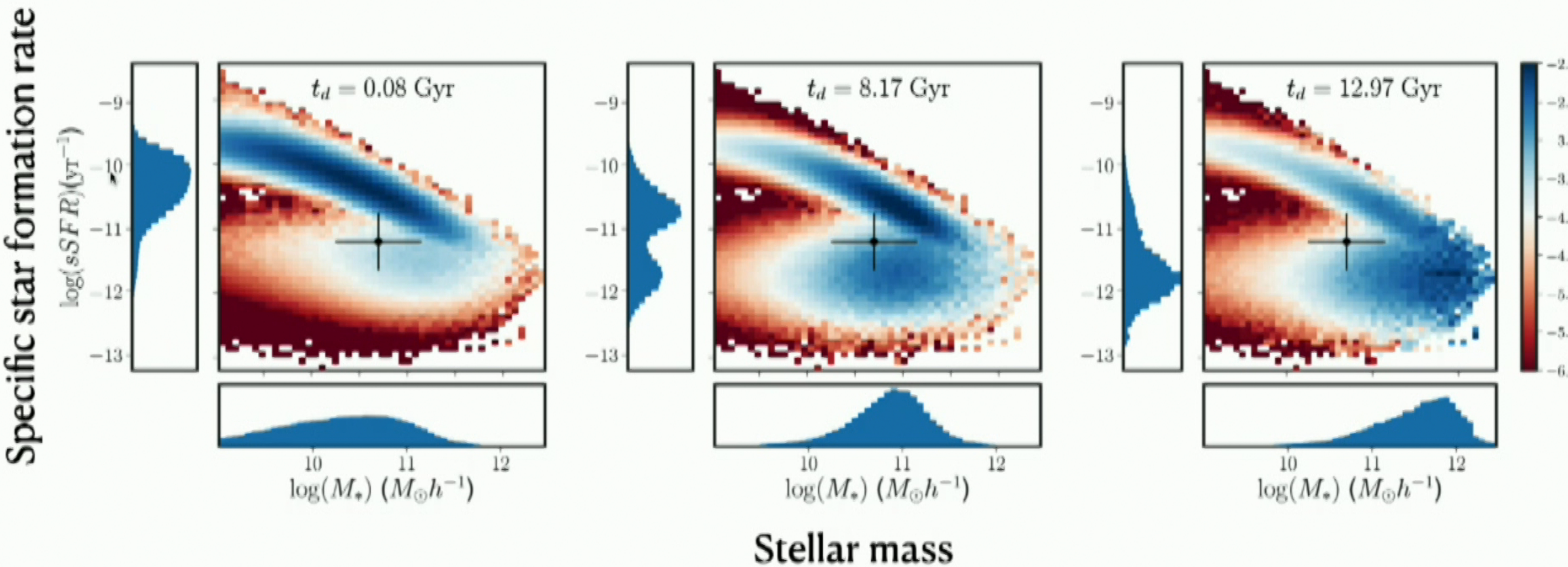
Next generation gravitational-wave detectors

Mapping the black hole merger rate across *all* of cosmic time, from the very first black holes

Evans et al., Cosmic Explorer Horizon Study, arXiv:2109.09882



Using host galaxy properties to infer time delays



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Adhikari, MF, Holz, Wechsler & Fang 2020, ApJ 905 21

Astrophysical lessons in this talk

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   A. Upper Black Hole Mass Gap
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2. Evolution with cosmic time

➡ Applications to cosmology

The black hole mass gap as a cosmological probe

Standard Sirens: Binary coalescences provide a direct measurement of the luminosity distance (Schutz 1986)...

frequency

position and orientation

GW strain

$$h(t) = \frac{\mathcal{M}_z^{5/3} f(t)^{2/3}}{D_L} F(\text{angles}) \cos(\Phi(t))$$

phase

redshifted chirp mass

luminosity distance

$$\mathcal{M}_z = \left(\frac{5}{96} \pi^{-8/3} \left(f(t)\right)^{-11/3} \dot{f}(t) \right)^{3/5}$$

...and the redshifted (detector-frame) masses.

See Standard Siren chapter by MF in "Unveiling the Universe with Emerging Cosmological Probes," submitted to Living Reviews in Relativity

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...and the redshifted (detector-frame) masses.

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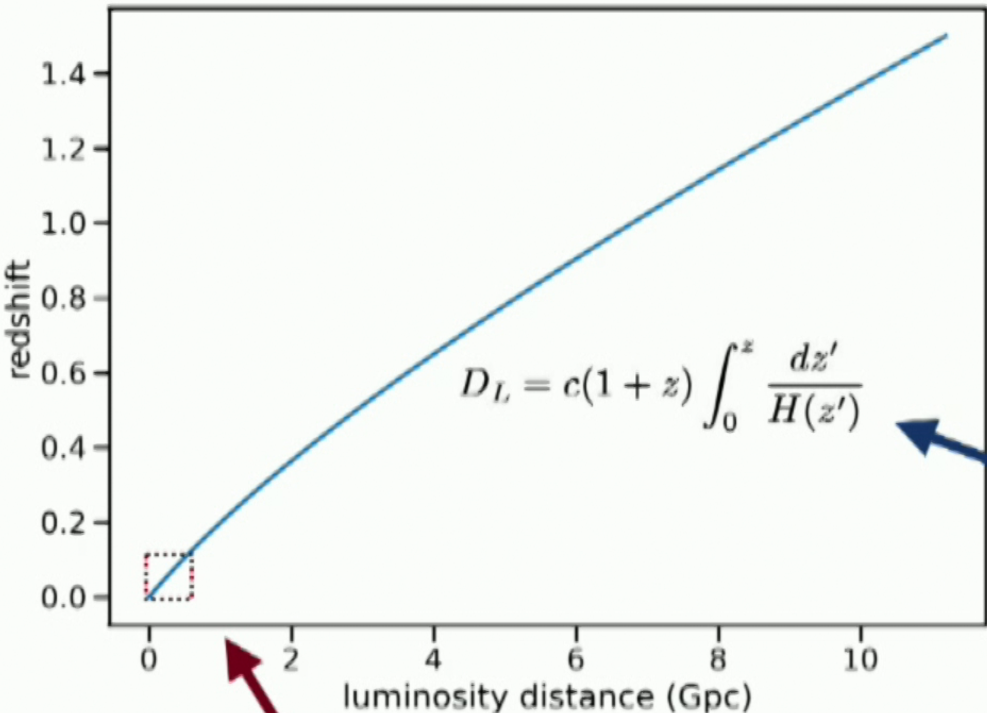
Goal: measure the redshift—distance relation



And thereby infer cosmological parameters

Depends on constituents of the Universe: matter density, dark energy density, dark energy equation of state

Local slope is the *Hubble constant*

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GW170817: A standard siren with an electromagnetic counterpart

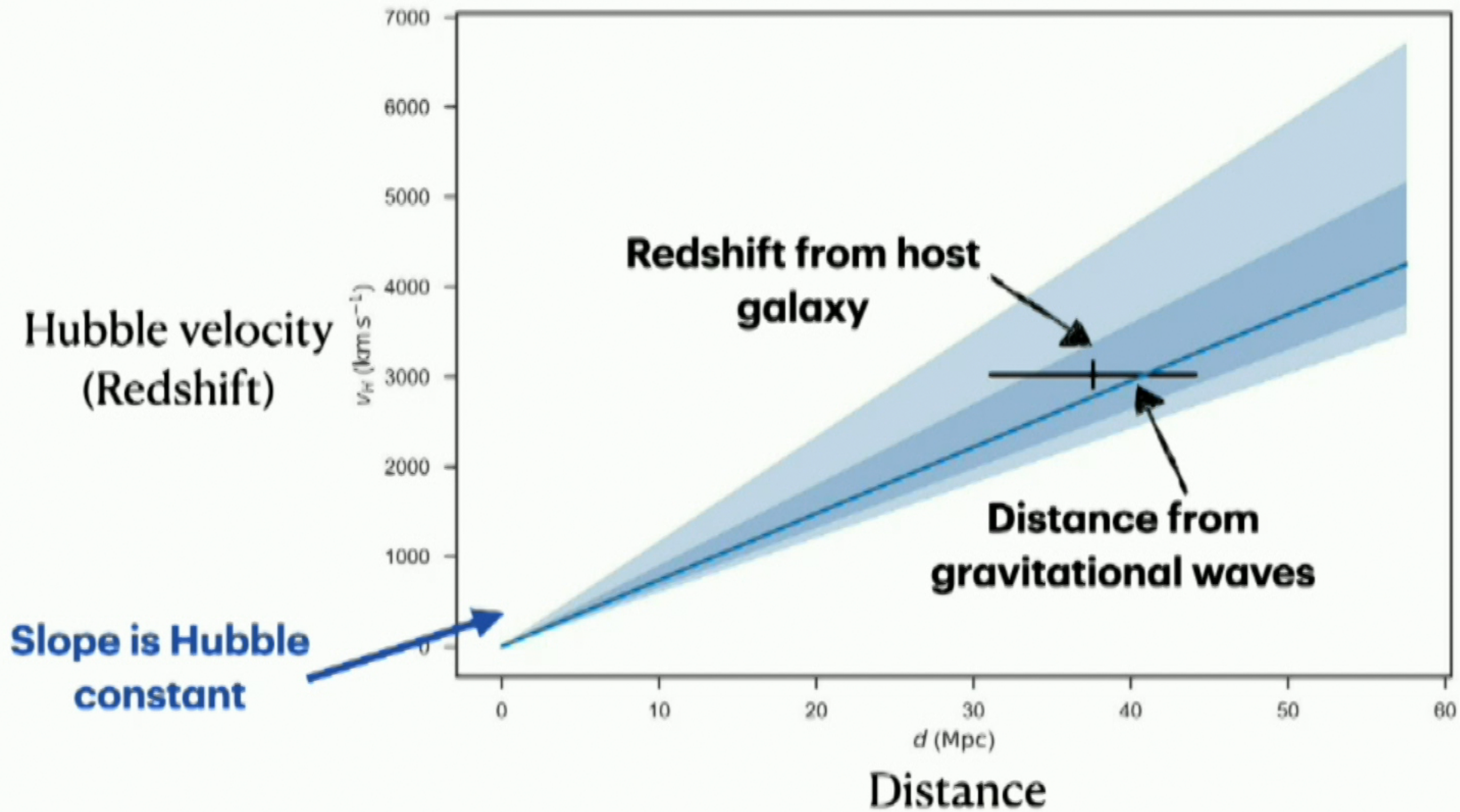

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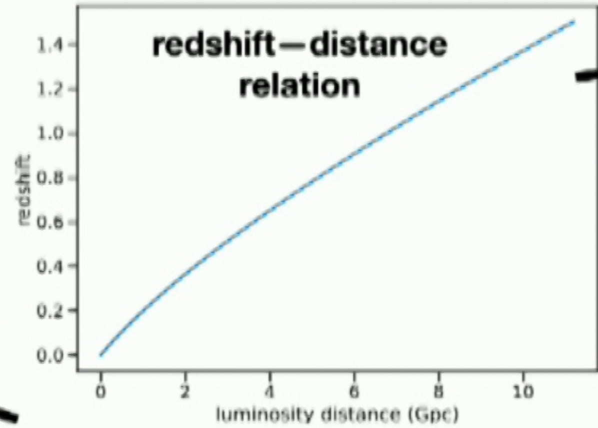
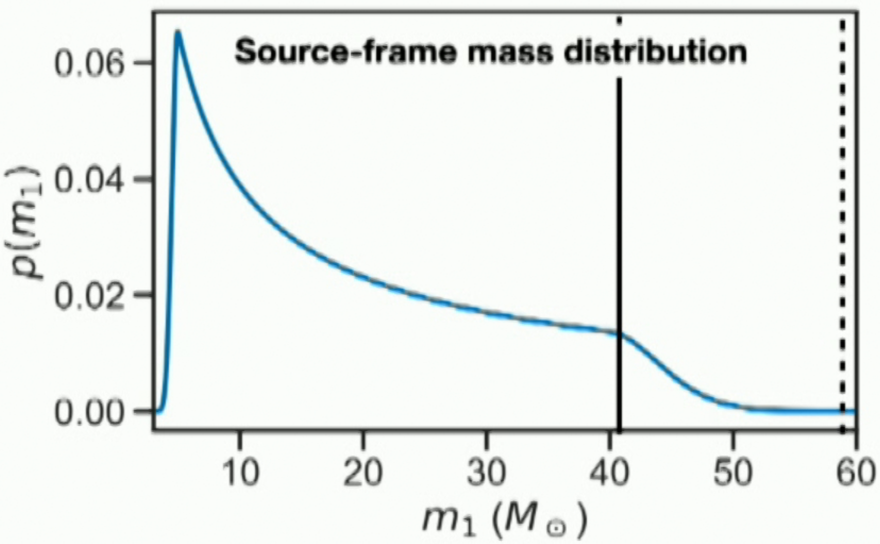
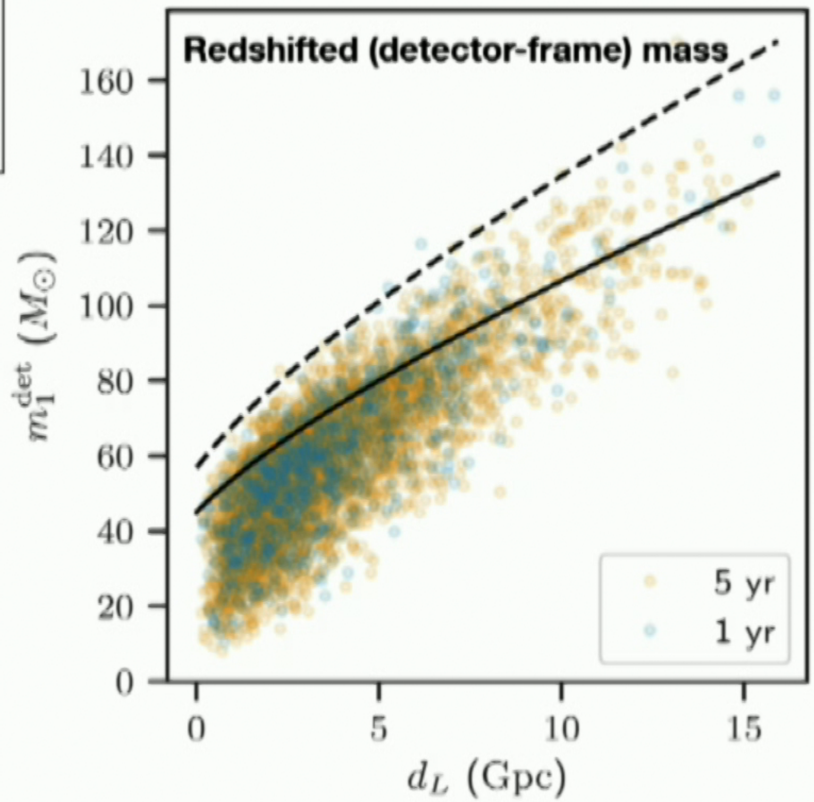
Figure Credit: Will Farr/ LIGO Scientific Collaboration

Simultaneously infer source population and redshift—distance relation







Farr, MF, Ye & Holz ApJL 883 L42 (2019)

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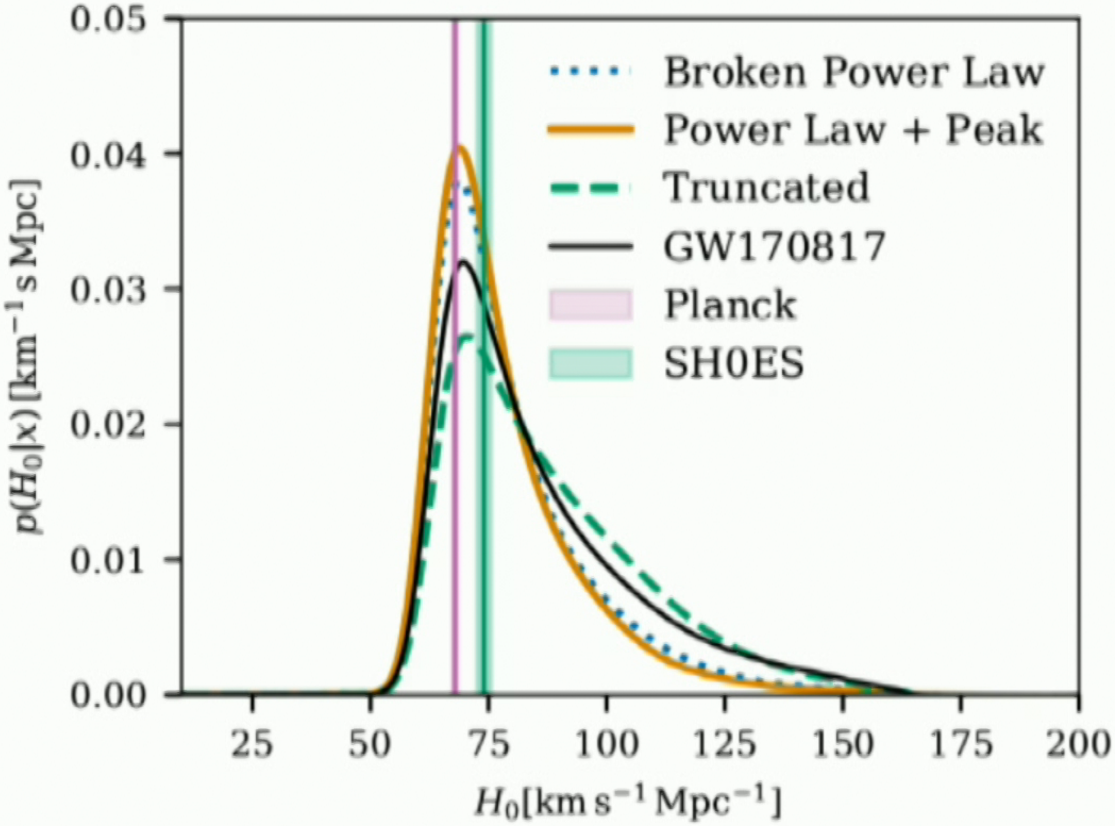
Application of mass distribution cosmology to GWTC-3



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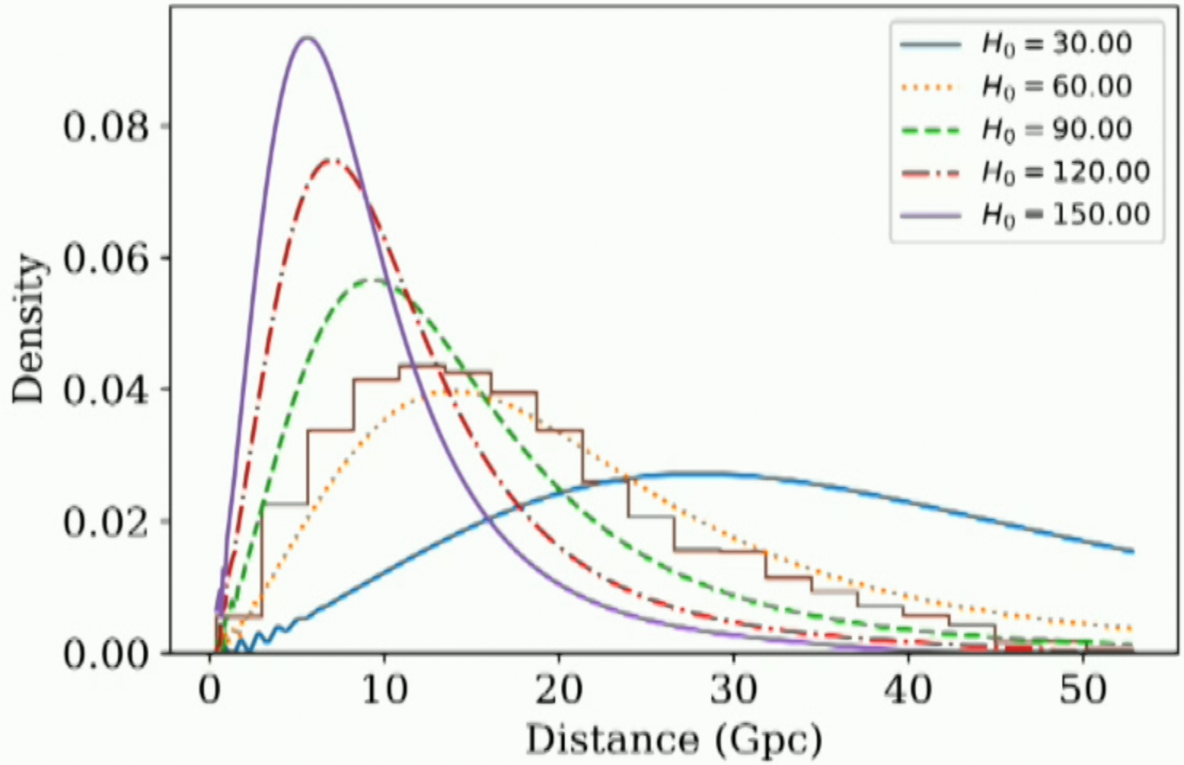
LVK 2021, arXiv:2111.03604 (Paper Writing Team includes MF)

Christine Ye
(Eastlake High School)

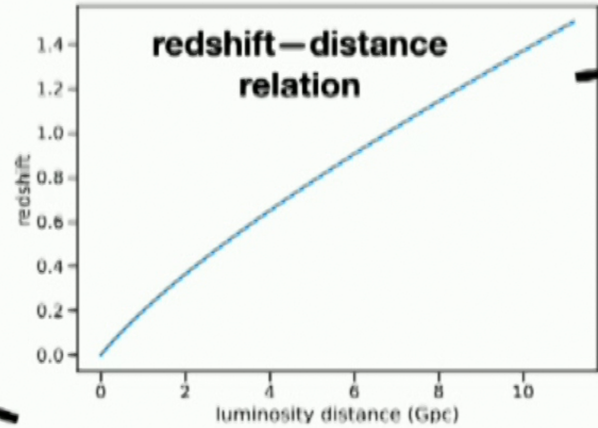
Cosmology with the redshift peak of the merger rate, measured by next-generation detectors

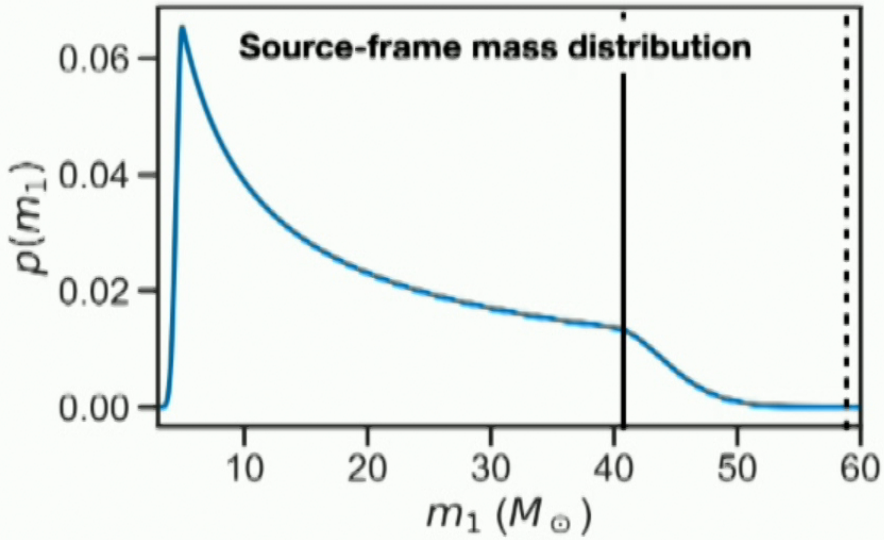
Standard Sirens at Cosmic Noon:
Leverage external knowledge of the merger rate as a function of *redshift* to derive cosmological information from the peak in the gravitational-wave *distance* distribution

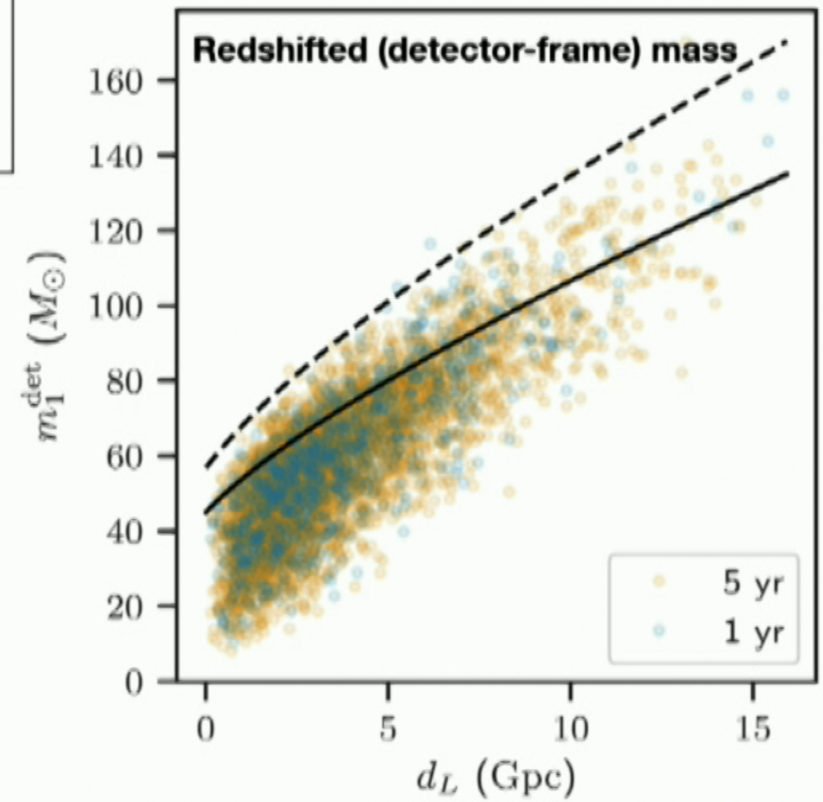


Ye & MF 2021, PRD 104, 043507

Simultaneously infer source population and redshift—distance relation







Farr, MF, Ye & Holz ApJL 883 L42 (2019)

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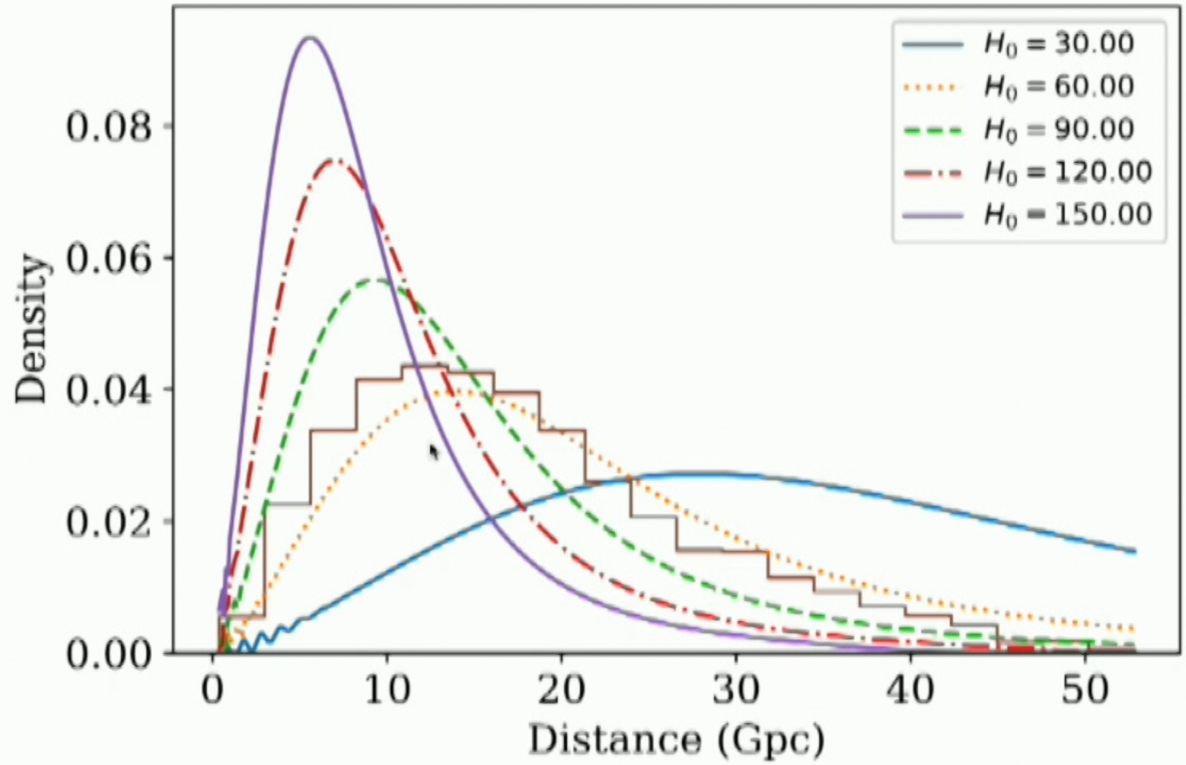
Christine Ye
(Eastlake High School)

Cosmology with the redshift peak of the merger rate, measured by next-generation detectors

Standard Sirens at Cosmic Noon: Leverage external knowledge of the merger rate as a function of *redshift* to derive cosmological information from the peak in the gravitational-wave *distance* distribution



Ye & MF 2021, PRD 104, 043507

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Learning from gravitational-wave populations

- **How are black holes and neutron stars made?**
  - Where is the **pair-instability mass gap**?
  - Is there a **mass gap between neutron stars and black holes**?
  - What are the **natal spins** of neutron stars and black holes?
  - How do neutron stars and black holes find **merger partners?**
- **Where and when do black holes and neutron stars merge?**
  - How does the population **evolve across cosmic time**?
  - Does their progenitor formation rate track the (low-metallicity?) **star formation rate**?
  - Synergy with observing the **host galaxies** of gravitational-wave sources
- **What are the cosmological implications of gravitational-wave sources?**
  - Standard sirens may help arbitrate the **Hubble constant tension**
  - Probe **dark energy** via background expansion and **modified gravitational-wave propagation**
  - Measure the three-dimensional **clustering** of sources, gravitational-wave **lensing**

Looking ahead: a multi-messenger effort

- Preparing for future gravitational-wave detectors: Cosmic Explorer, Einstein Telescope, and LISA
- Discovering electromagnetic counterparts, host galaxies, and redshifts
- Understanding how black holes in gravitational-wave sources fit in with the broader population of stellar-mass black holes
- Placing gravitational-wave sources in the cosmological context of the Hubble expansion, structure growth, and cosmic chemistry