Title: What Compact-Object (Re)mergers Can Tell Us About Astrophysics

Speakers: Chase Kimball

Series: Strong Gravity

Date: April 14, 2022 - 1:00 PM

URL: https://pirsa.org/22040115

Abstract: Among the discoveries in LIGO/Virgo/KAGRA's third observing run are a handful of compact binary coelescences (CBCs) that stand out for one reason or another -- exceptional either because they were the first entry in a previously undetected class of CBCs, or because of the mass, mass ratio, or spins of their component compact objects. After briefly discussing the implications of these observations and their merger rates, I will focus on the tension that has arisen from the discovery of the most massive binaries in LVK's catalog. These binaries have component black holes encroaching on the pair-instability mass gap, where black holes are not expected to be formed directly from stars. I'll discuss an alternate formation channel, where massive black holes are assembled dynamically from repeated binary black hole mergers, and an analysis that constructs a binary black hole population that allows for hierarchical formation in both globular cluster-like and nuclear star cluster-like environments.

Zoom Link: https://pitp.zoom.us/j/94867401133?pwd=bTJmVy8vUk9rb1RvTDlrMzl1ZHdEZz09

What Compact-Object (Re)mergers Can Tell Us About Astrophysics

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Northwestern University
Reidel Family Fellow

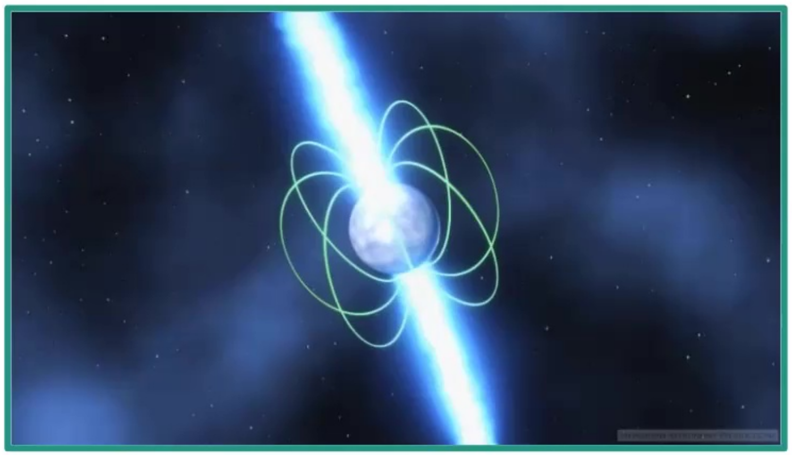
CIERA
Center for Interdisciplinary Exploration and Research in Astrophysics

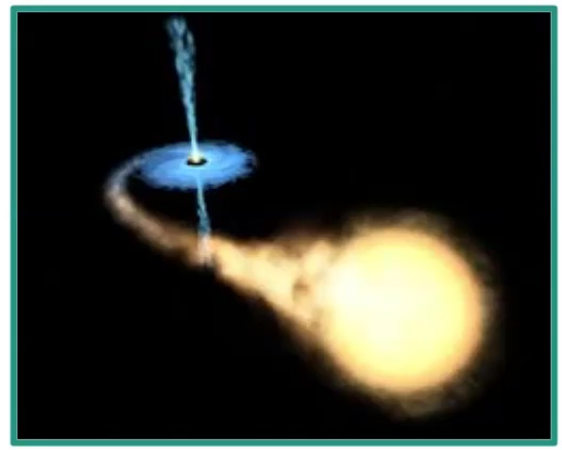
LSC LIGO Scientific Collaboration

Chase Kimball | CIERA

Perimeter Institute Strong Gravity Seminar April 2022

Observing Compact Objects with Gravitational Waves

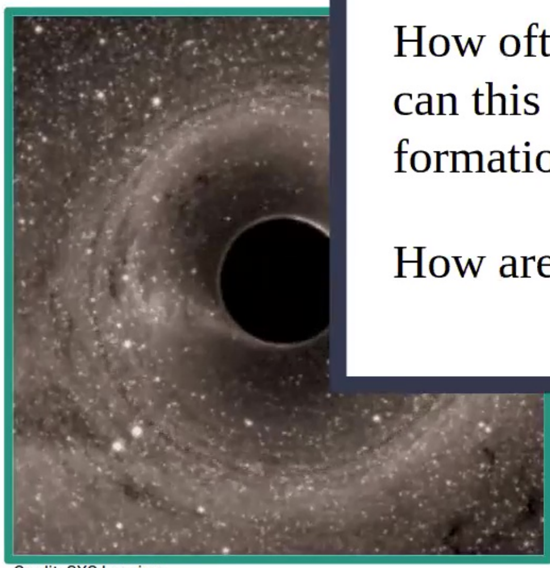




Swinburne/CAASTRO

ESA/Hubble

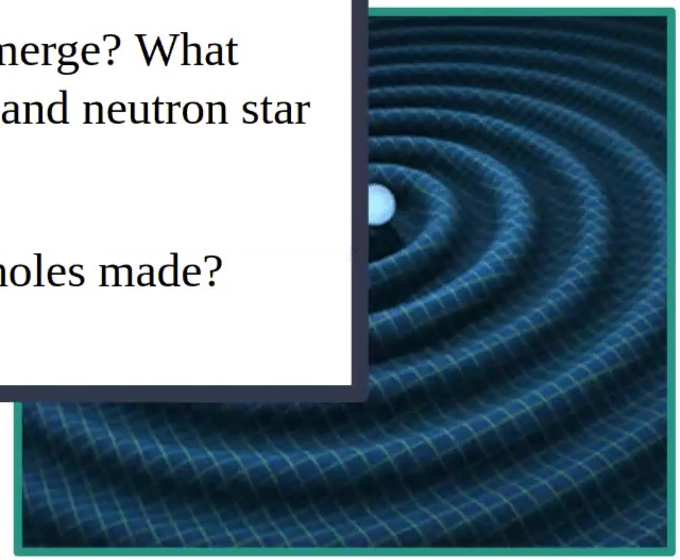
Observing Compact Objects with Gravitational Waves



Credit: SXS Lensing

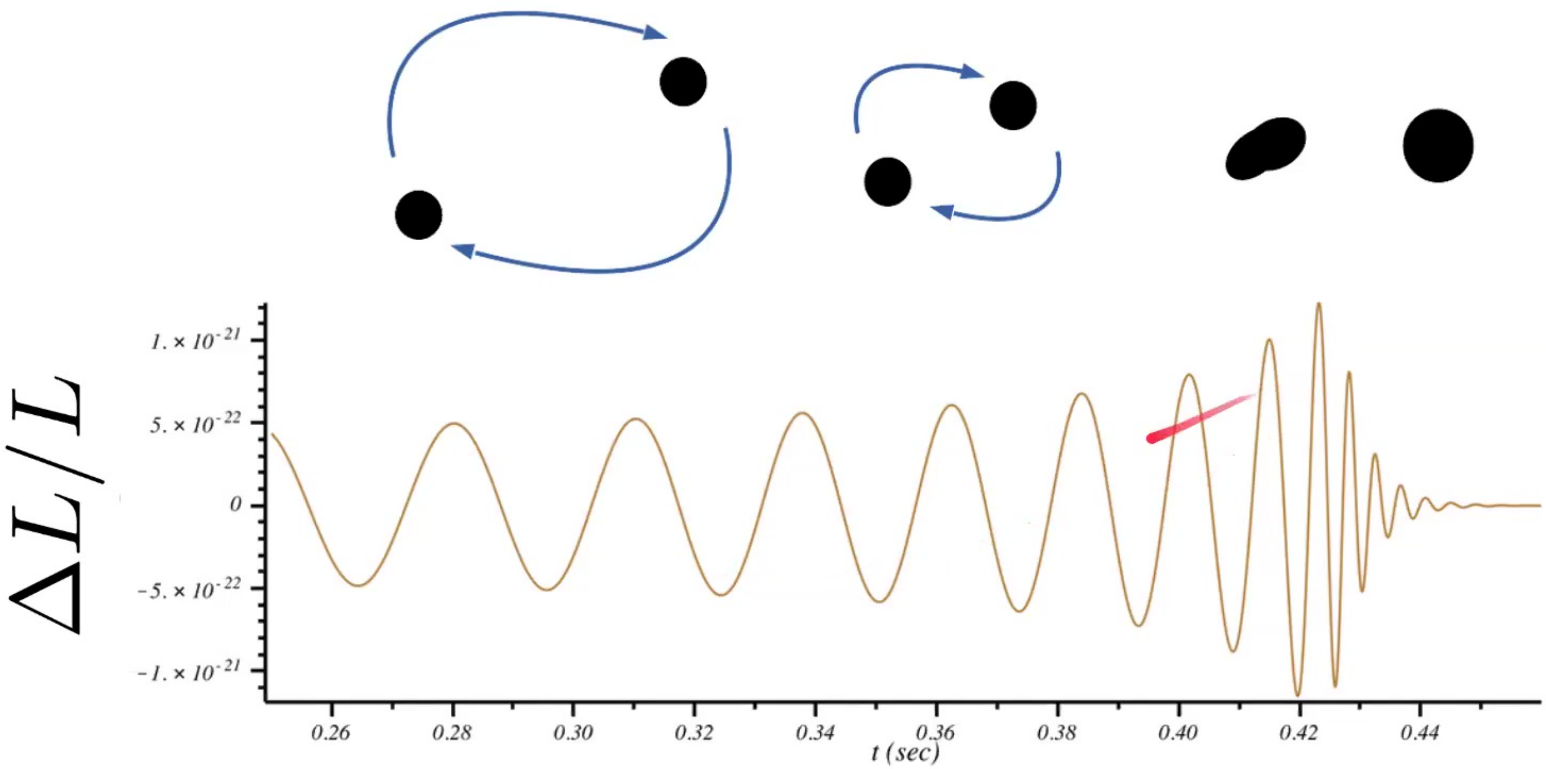
How often do compact objects merge? What can this tell us about black hole and neutron star formation?

How are LIGO's biggest black holes made?



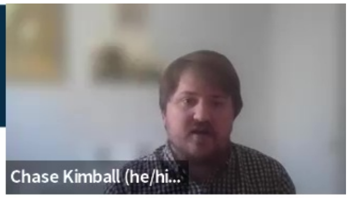
Credit: Nasa/JPL

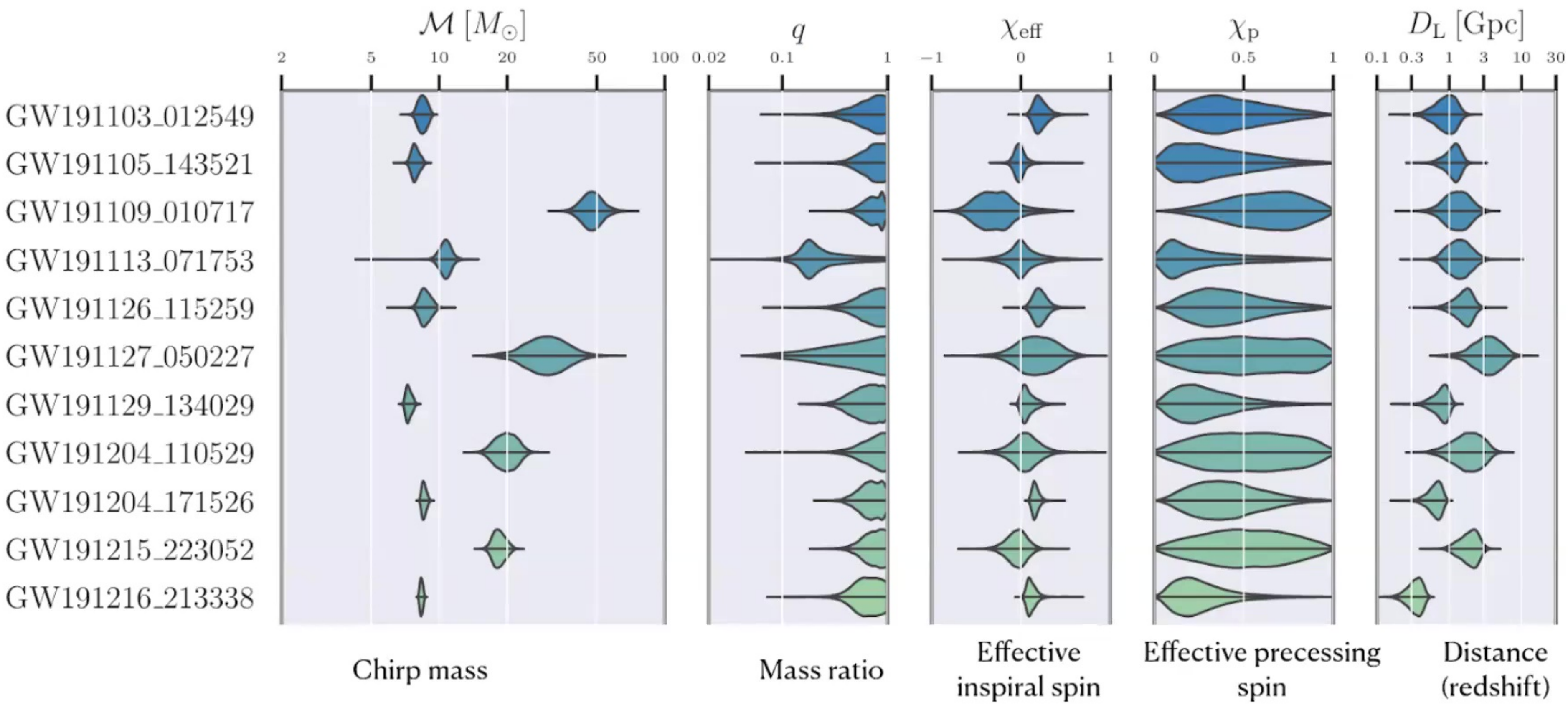
Observing Compact Objects with Gravitational Waves



Credit: SoundsOfSpacetime

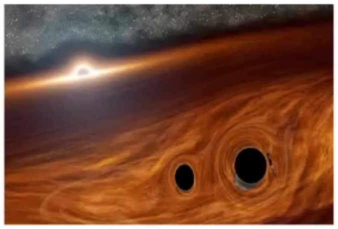
Observing Compact Objects with Gravitational Waves



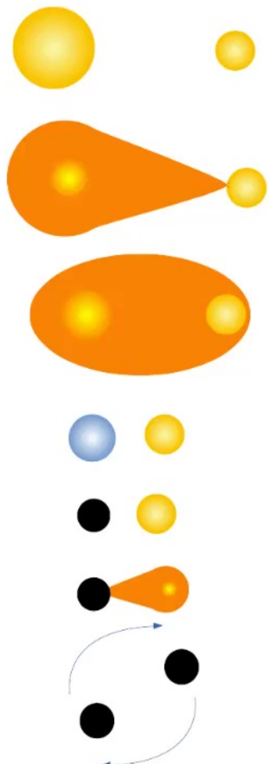


Observing Compact Objects with Gravitational Waves

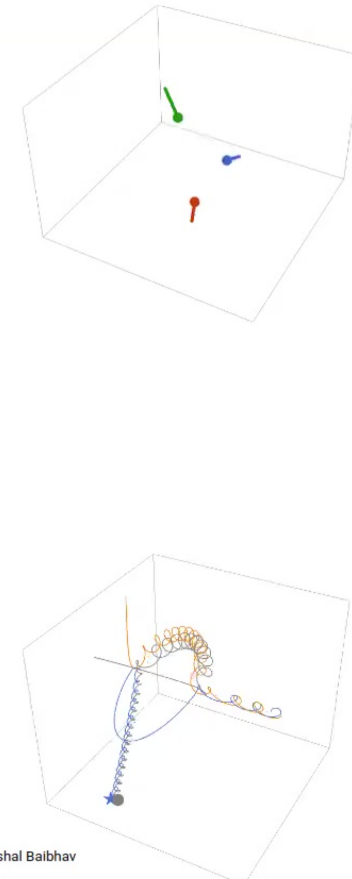
Isolated Binary Evolution

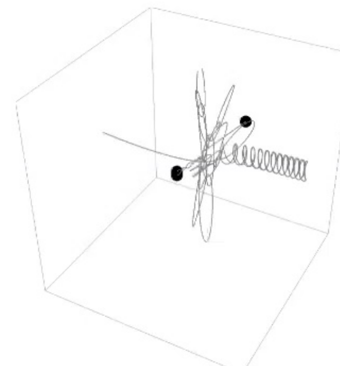


Credit: Caltech/R Hurt (IPAC)



Dynamical Formation



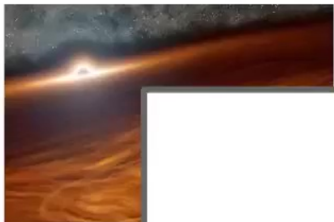


Credit: Vishal Baibhav

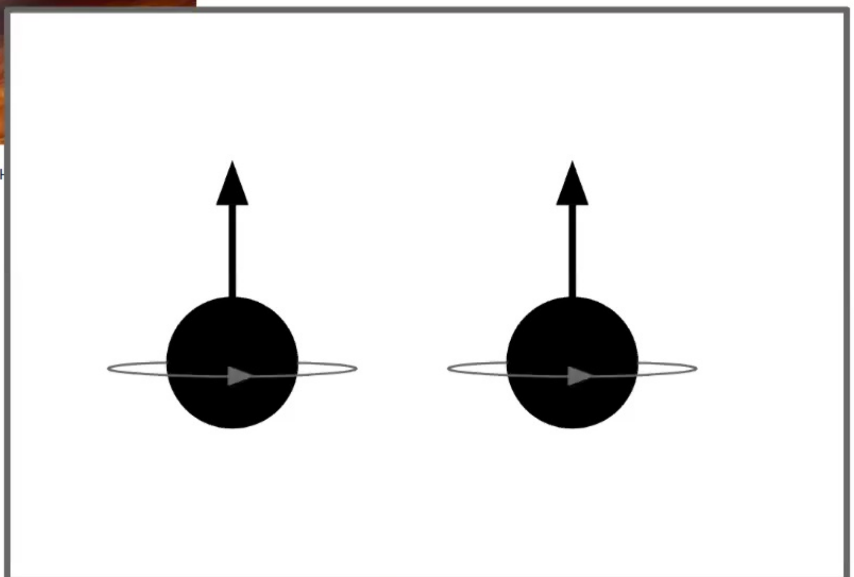
Credits: NASA, ESA, T. Brown, S. Casertano, and J. Anderson (STScI)

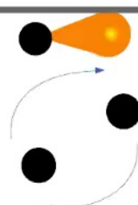
Observing Compact Objects with Gravitational Waves

Isolated Binary Evolution



Credit: Caltech/R H
(IPAC)





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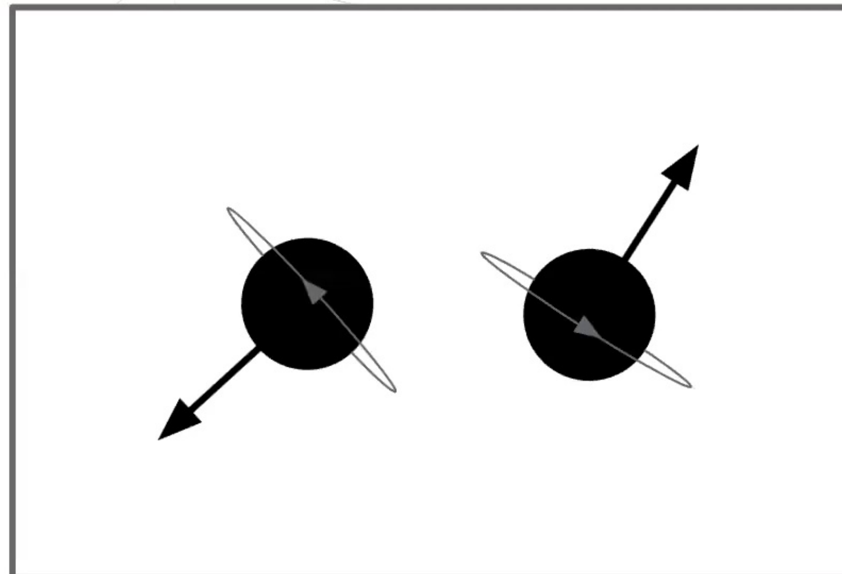

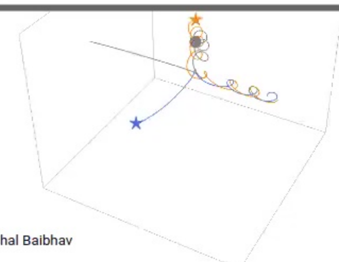

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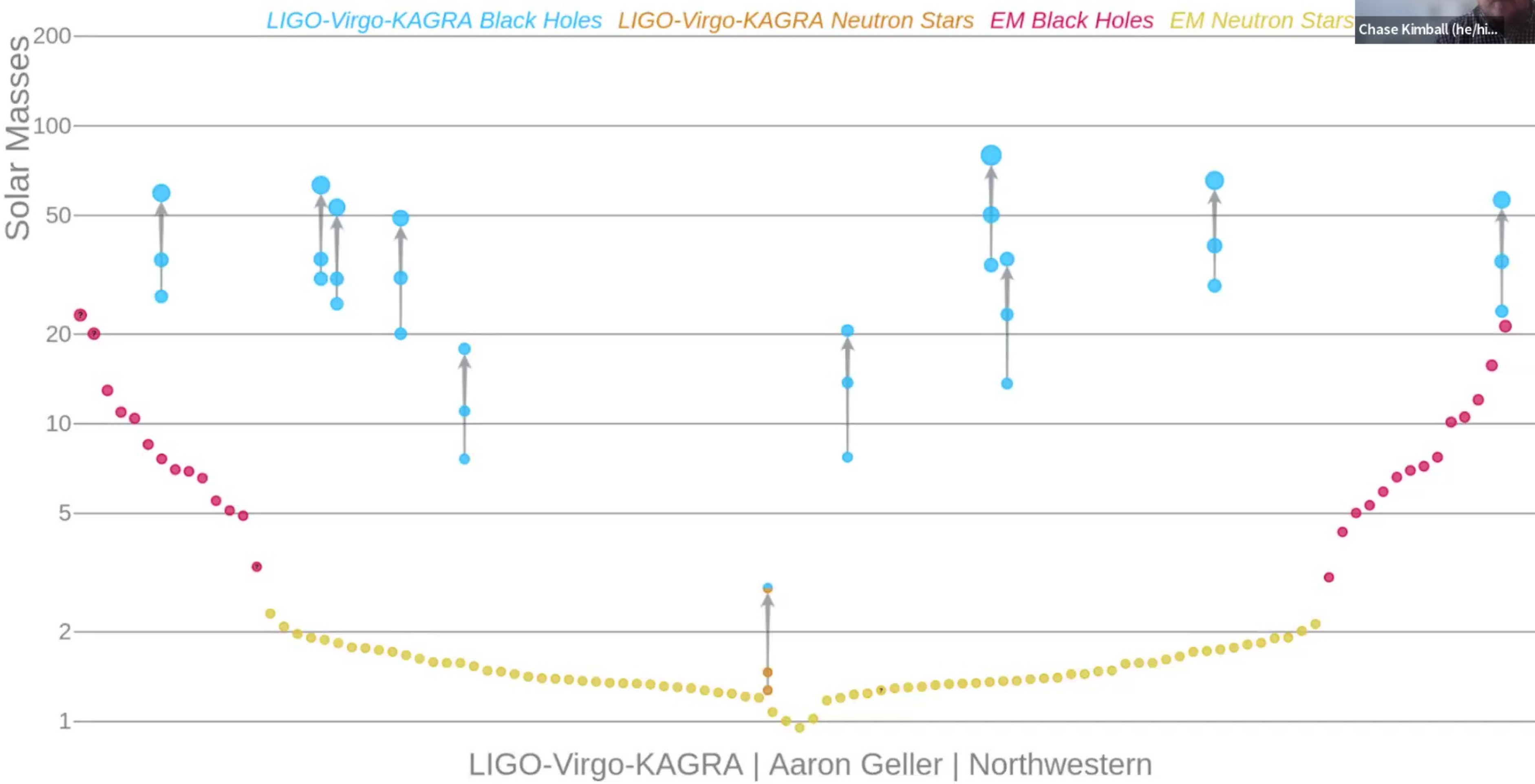
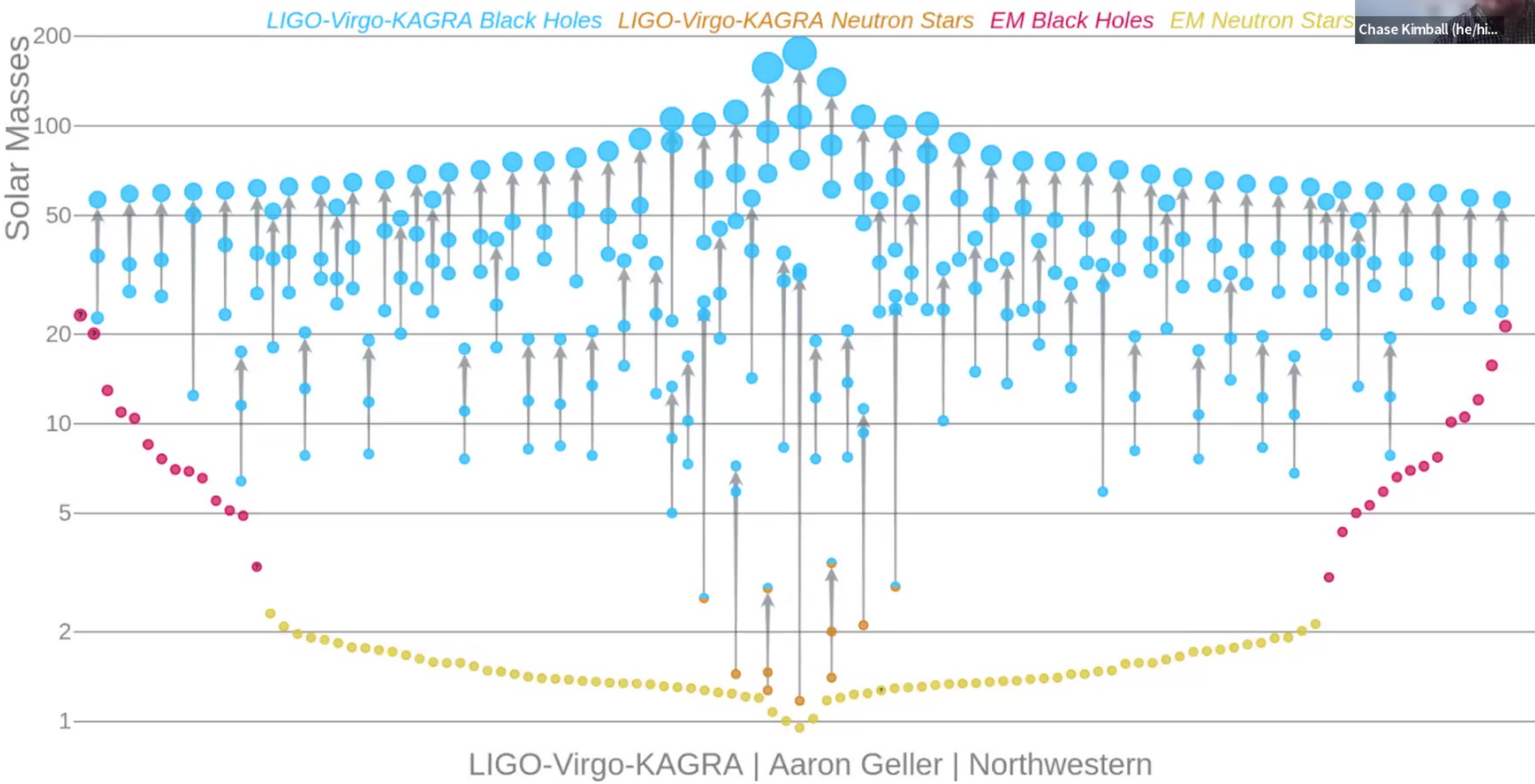
GWTC-1



LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Chase Kimball (he/hi...

GWTC-3



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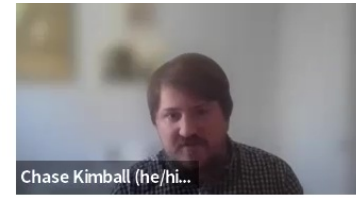
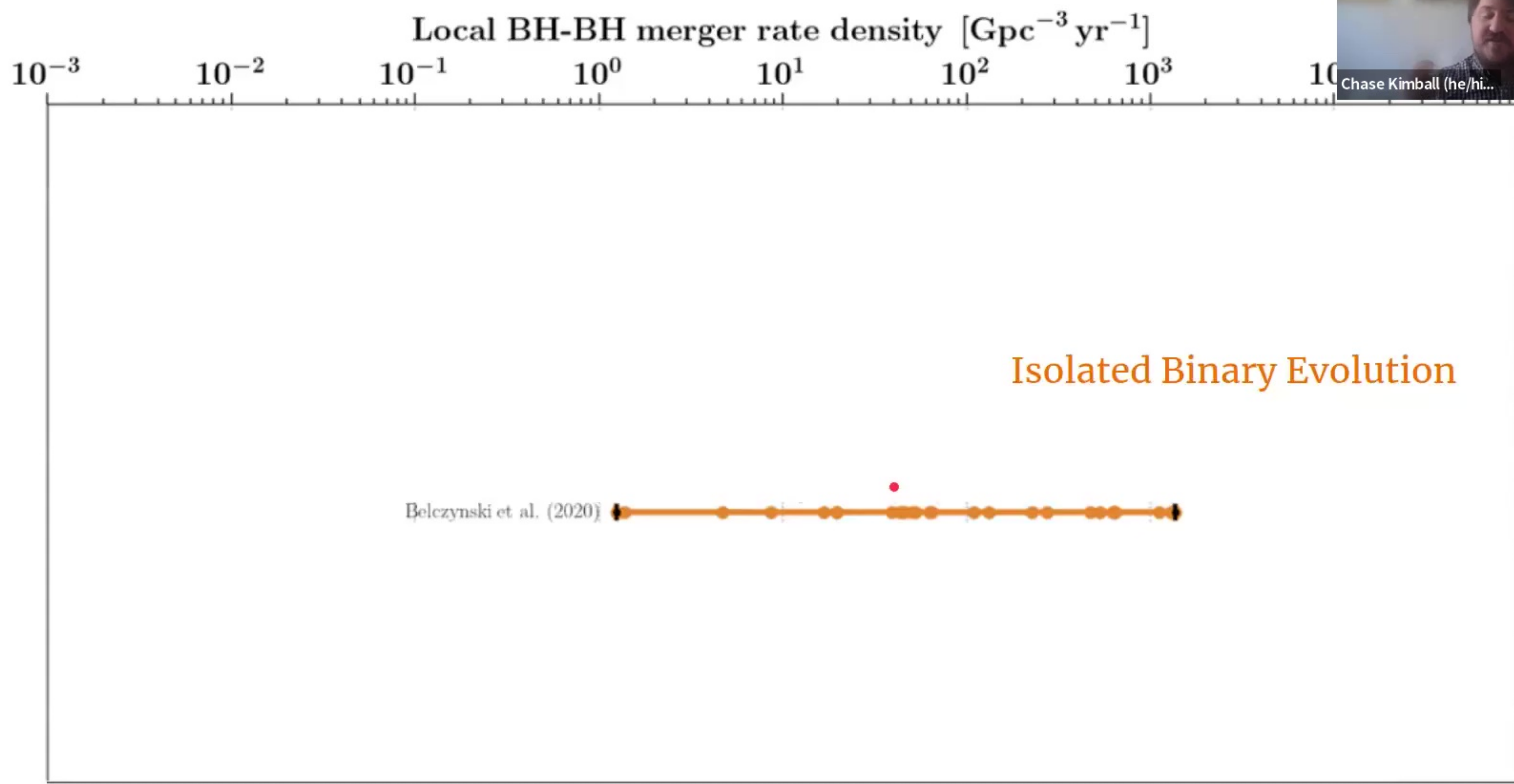
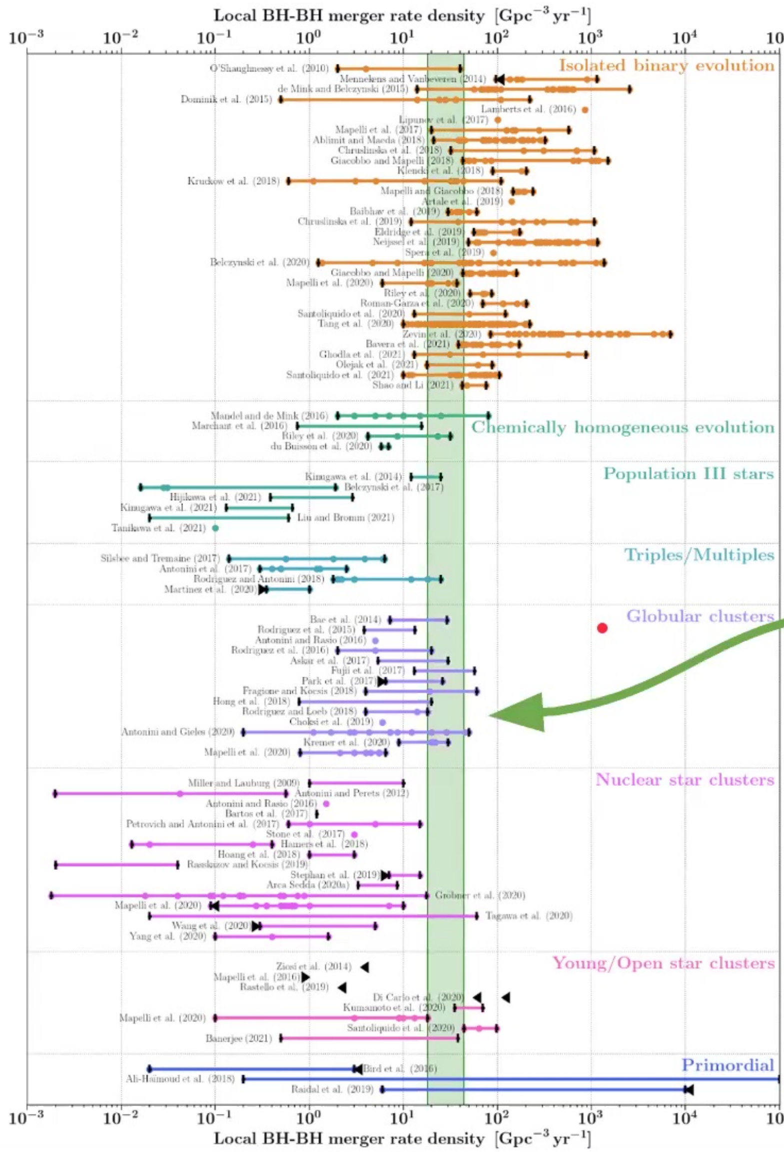


Why care about merger rates?

Mandel & Broekgaarden, 2021

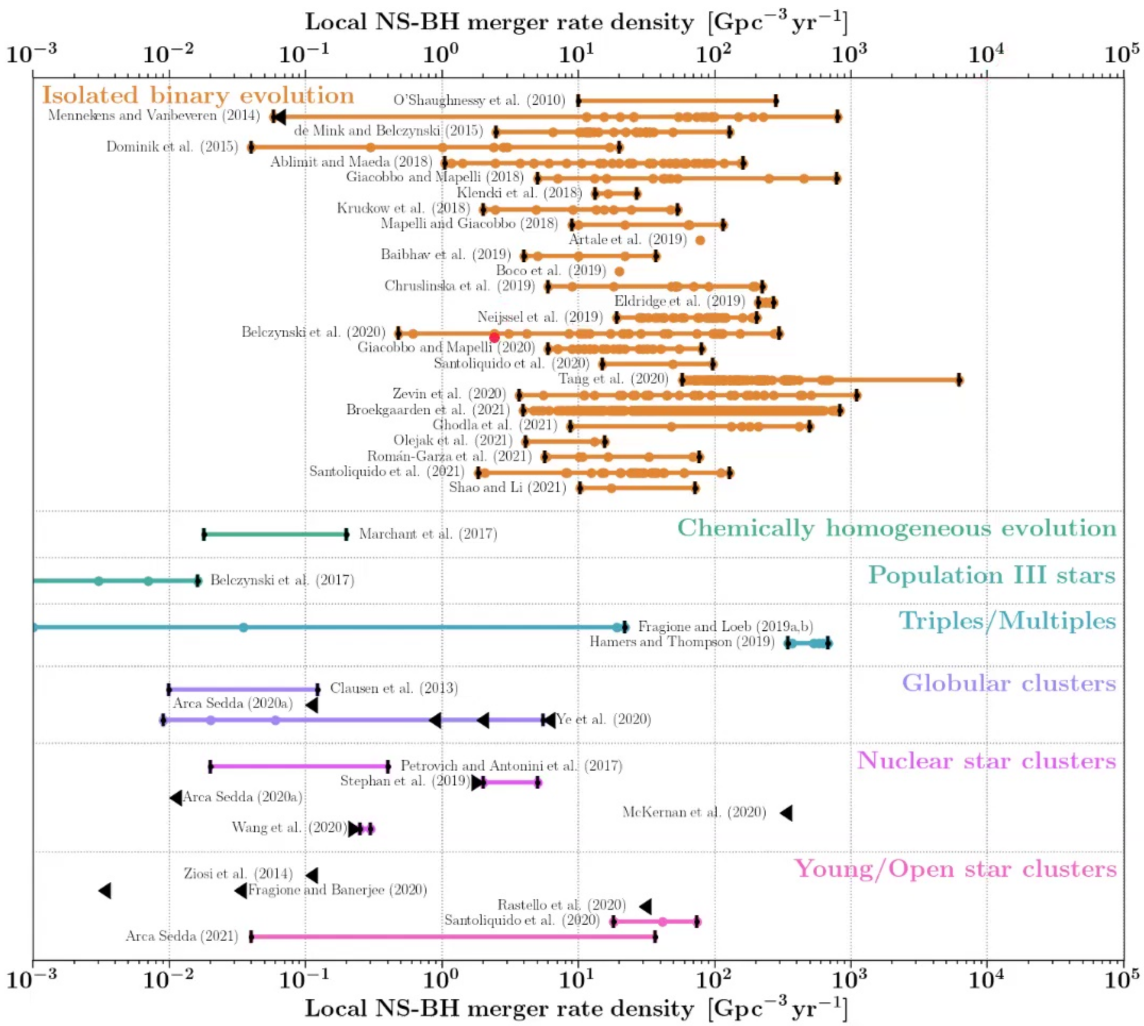


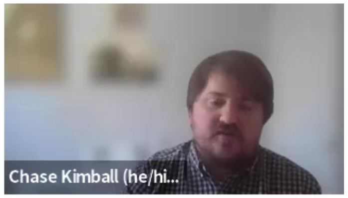
[Mandel & Broekgaarden, 2021](#)



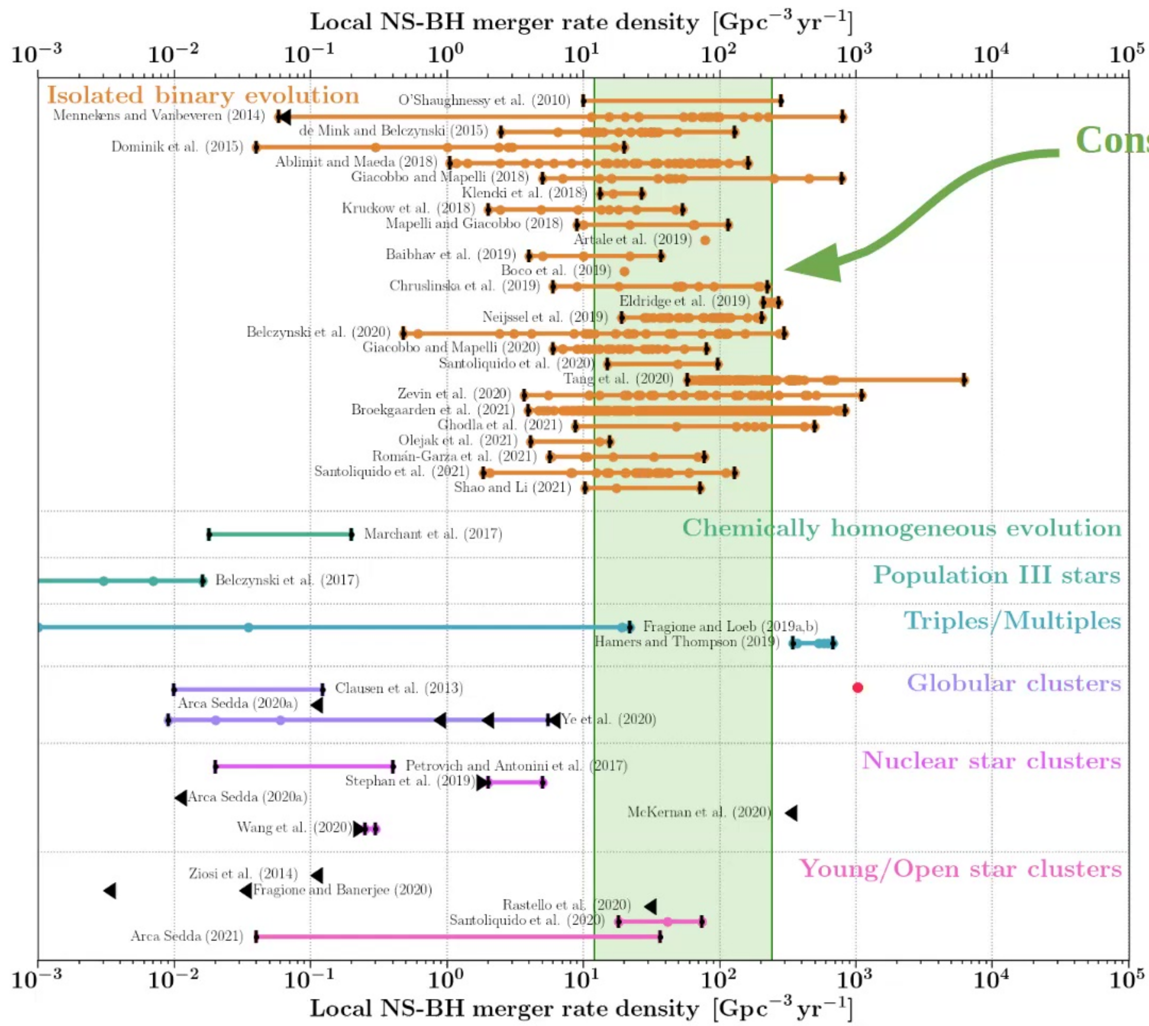
Constraint from Gravitational Wave Observations

Mandel & Broekgaarden, 2021



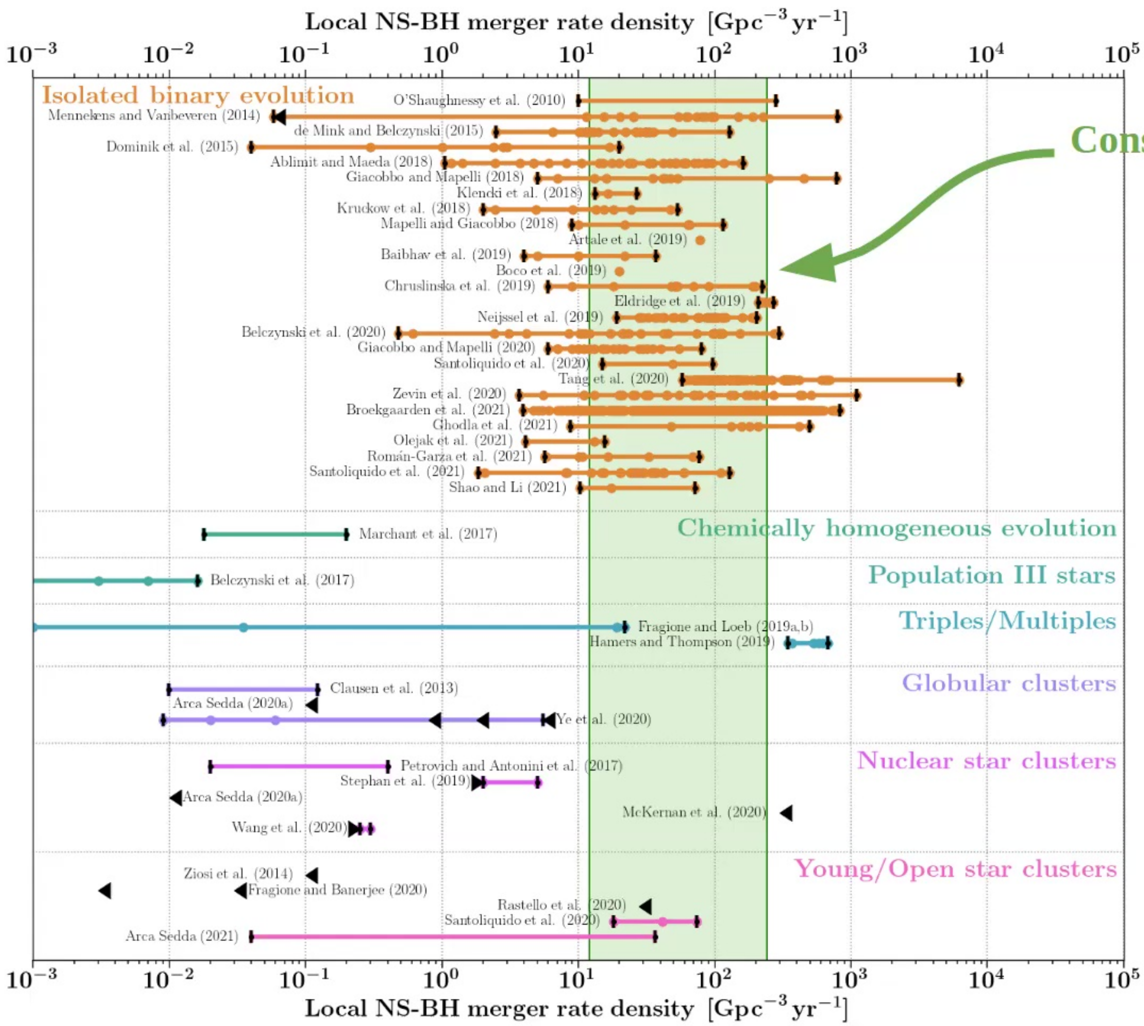


Mandel & Broekgaarden, 2021



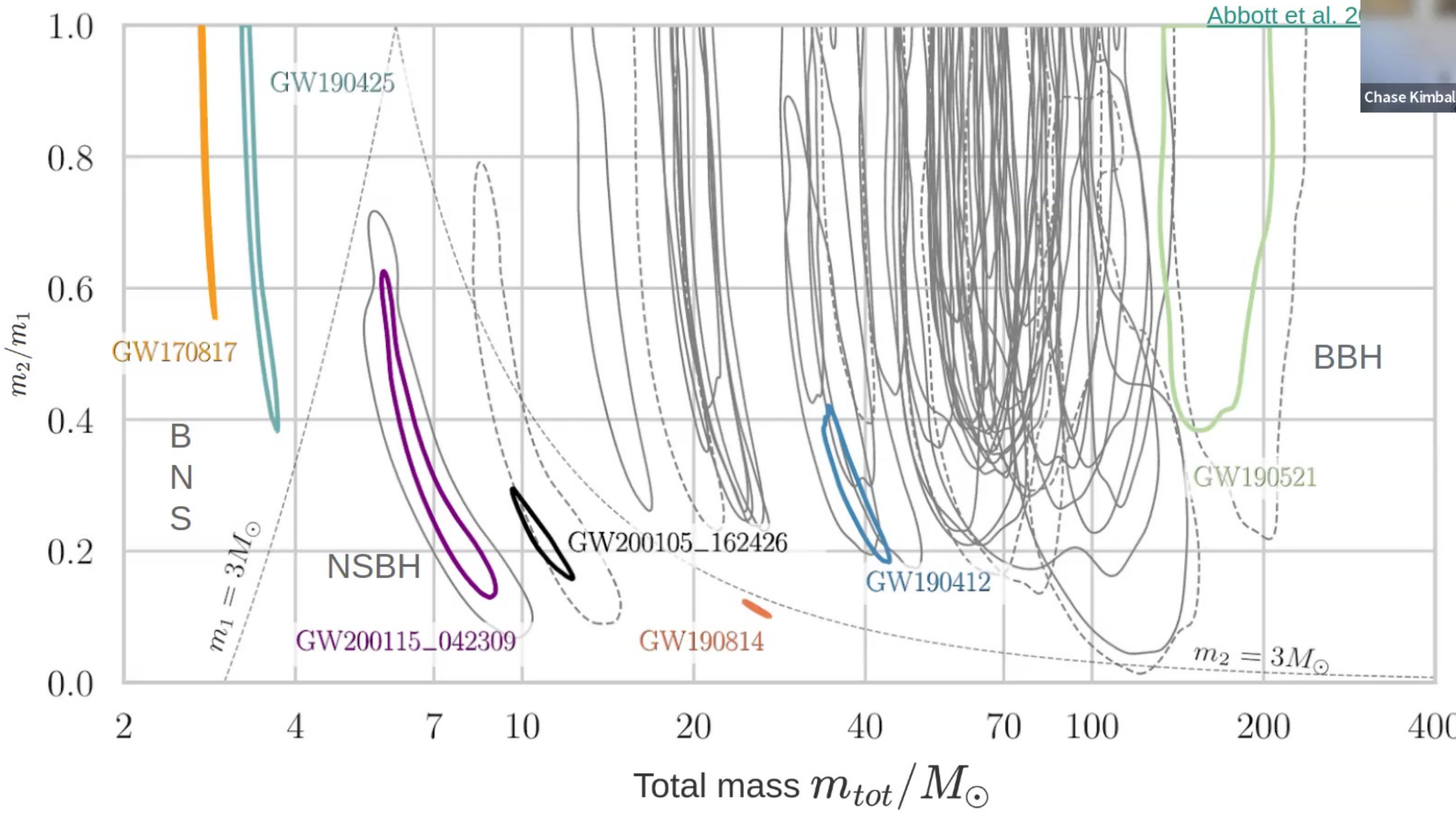
Constraint
Wave Observations

[Mandel & Broekgaarden, 2021]



Constraint

Wave Observations


Abbott et al. 2
GW190425
GW170817
B
N
S
$m_1 = 3M_\odot$
NSBH
GW200115_042309
GW200105_162426
GW190814
GW190412
GW190521
BBH
$m_2 = 3M_\odot$
m_2/m_1
Total mass $m_{tot}/M_\odot$
1.0
0.8
0.6
0.4
0.2
0.0
2
4
7
10
20
40
70
100
200
400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GW190814 -

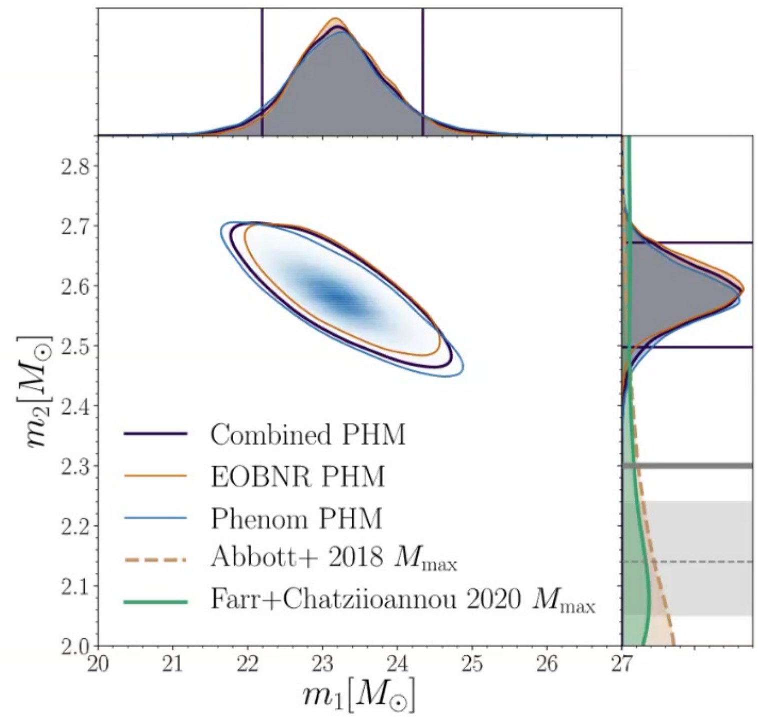
Taken *together:*

Small mass ratio (≈ 0.1)

Secondary mass (≈ 2.6 $M_{\odot}$)

Inferred merger rate (≈ 1-23 Gpc^{-3} yr^{-1})

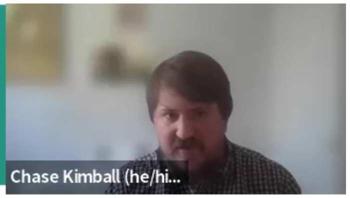
GW190814 is challenging for standard formation scenarios



Abbott et al. 2020, ApJ Letters, 896, L44

GW190521

A Massive BBH Merger



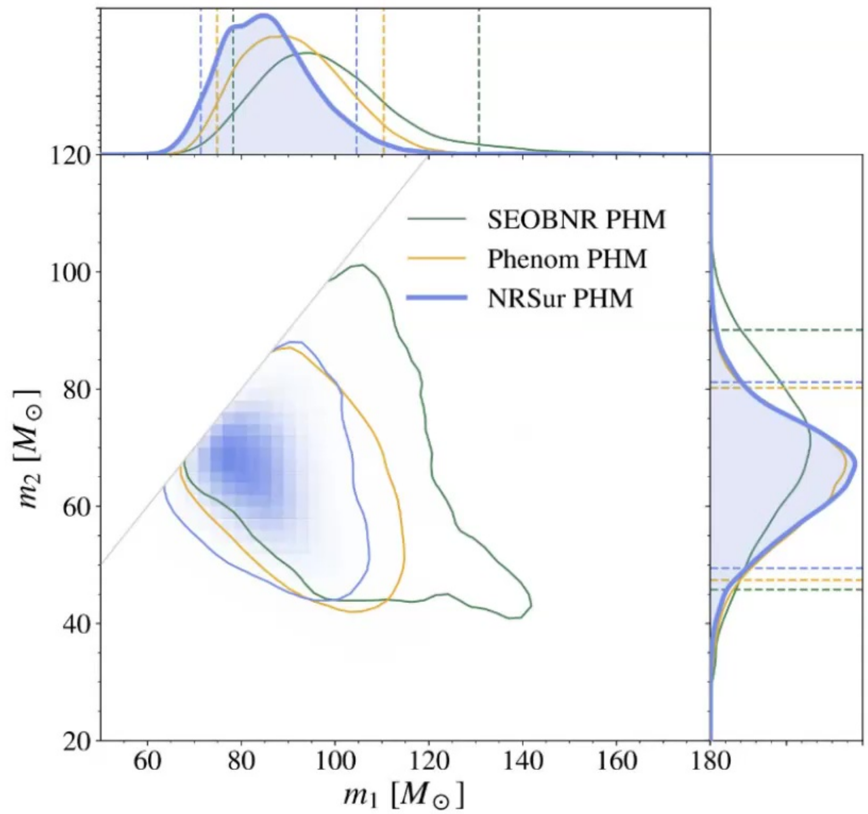
Most massive binary ever detected at the time

$$m_{tot} = 150^{+29}_{-17}\, M_{\odot}$$

$$m_1 = 85^{+21}_{-14}\, M_{\odot} \quad m_2 = 66^{+17}_{-18}\, M_{\odot}$$

Remnant is **first ever observed intermediate-mass black hole**

$$M_f = 142^{+28}_{-16}\, M_{\odot}$$



Abbott et al. 2020, Apj Letters 900, L13

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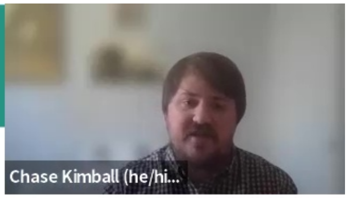
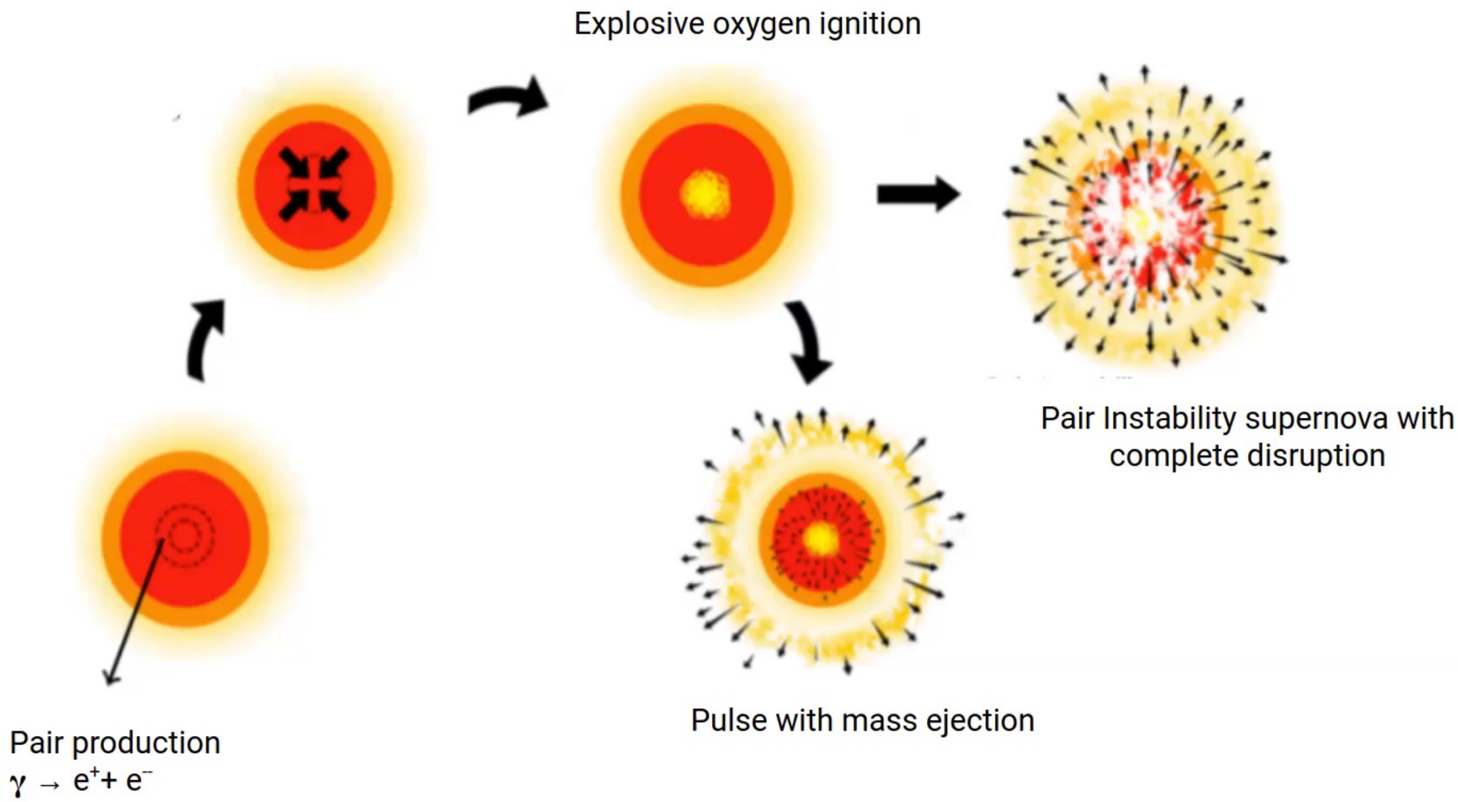
(Pulsational) Pair-Instability Supernovae



Adapted from Renzo et al. 2020



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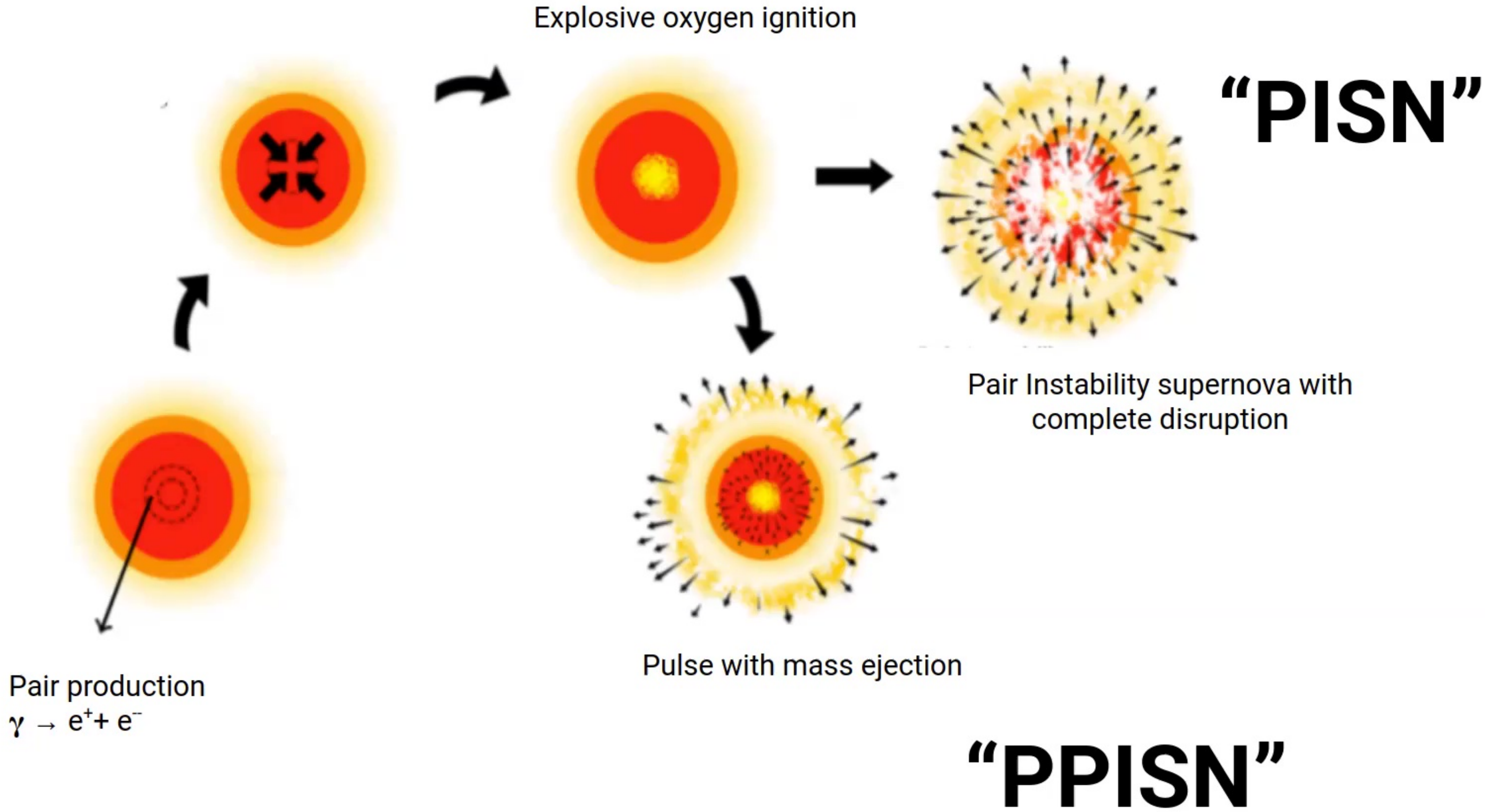
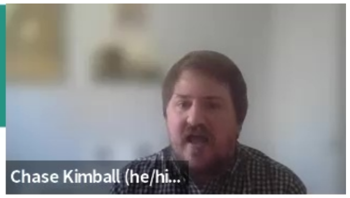
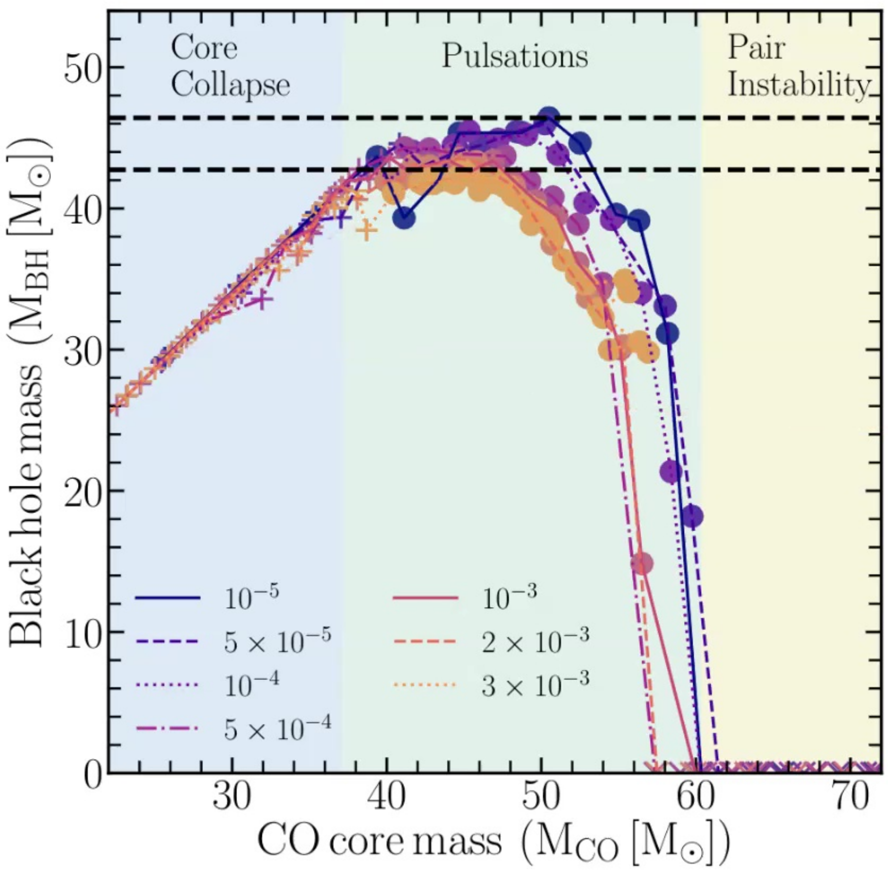


The Upper Mass Gap



Farmer et al. 2019



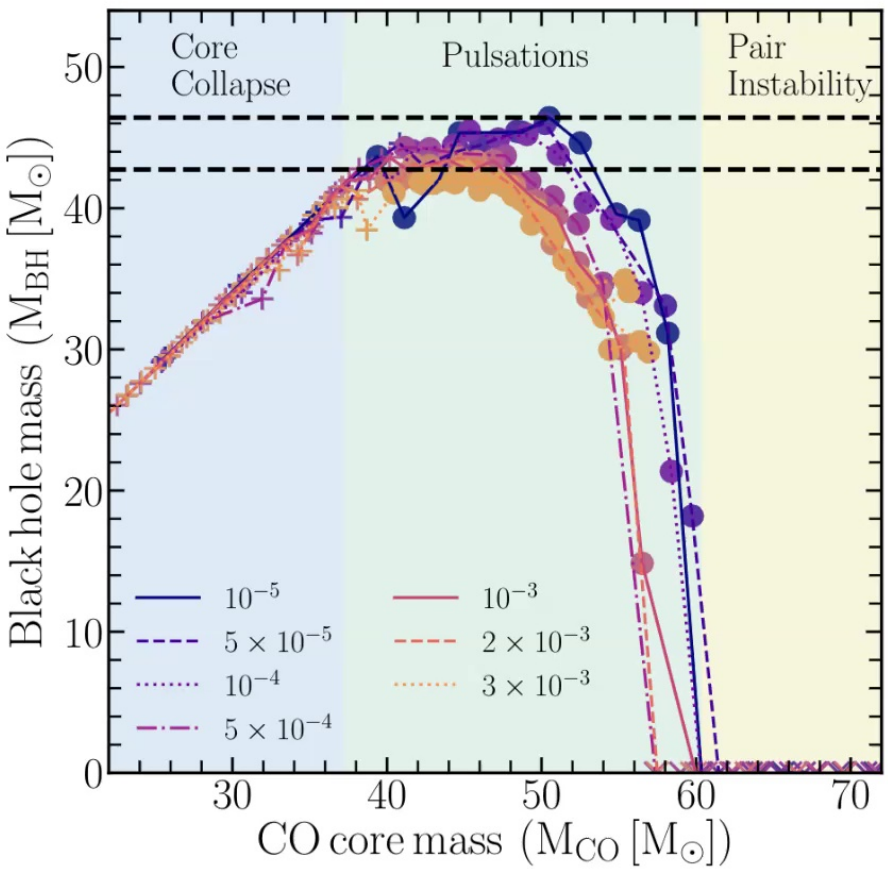
Mass gap ~50-120 $M_\odot$

Uncertainties in the lower edge of the mass gap from

- Nuclear reaction rates ($^{12}C^{16}O$)
- Stellar rotation
- Convection
- Stellar collisions

The Upper Mass Gap

Farmer et al. 2019



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Uncertainties in the lower edge of the mass gap from

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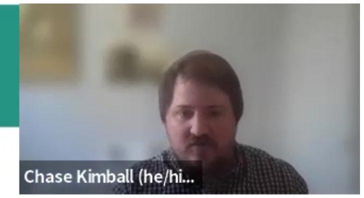
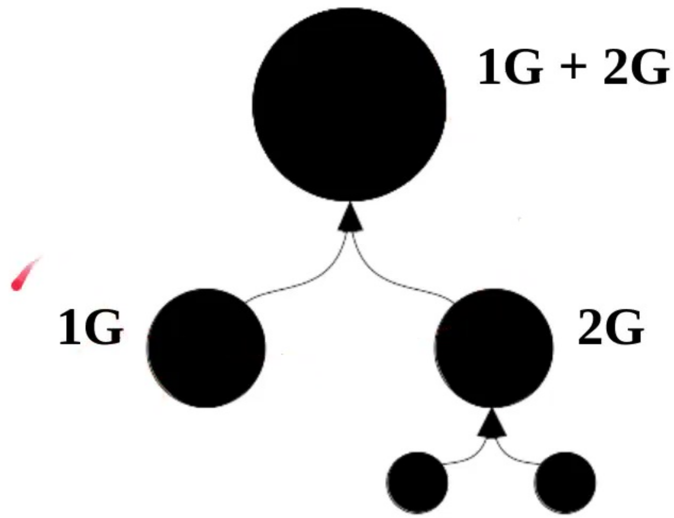
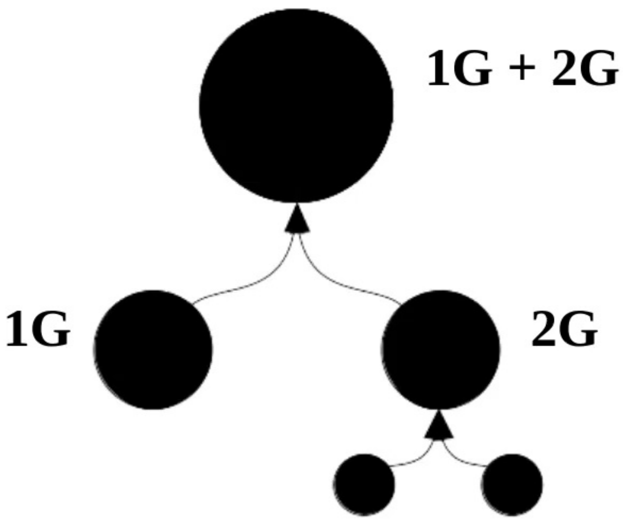
If we want to use BH populations to infer stellar physics, we need to account for mass gap "pollutants"

Sneaking Into The Mass Gap





Retaining Merger Products



Active Galactic Nuclei

Credit: ESA / NASA / Hubble / Rosario et al.

Globular

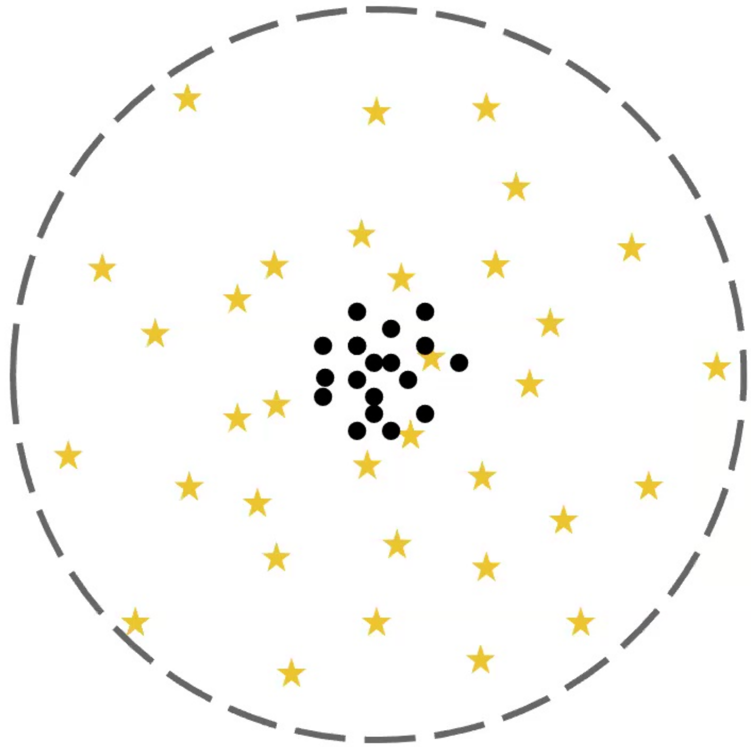
Credit: ESA / NASA / Hubble

Nuclear Star Clusters

Credit: ESO

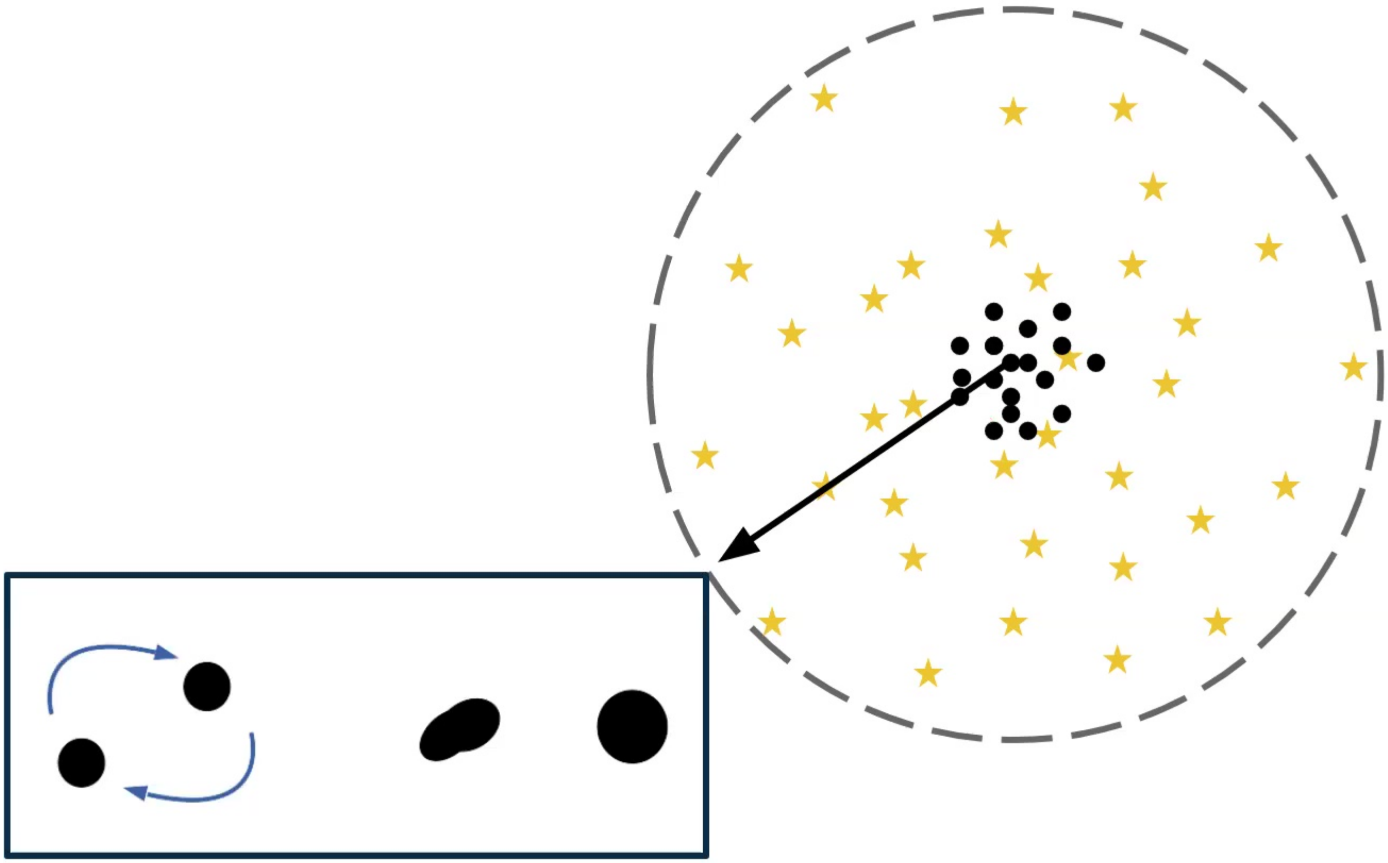
Globular Clusters

Hie



Globular Clusters

Hie



Globular Clusters

Hie

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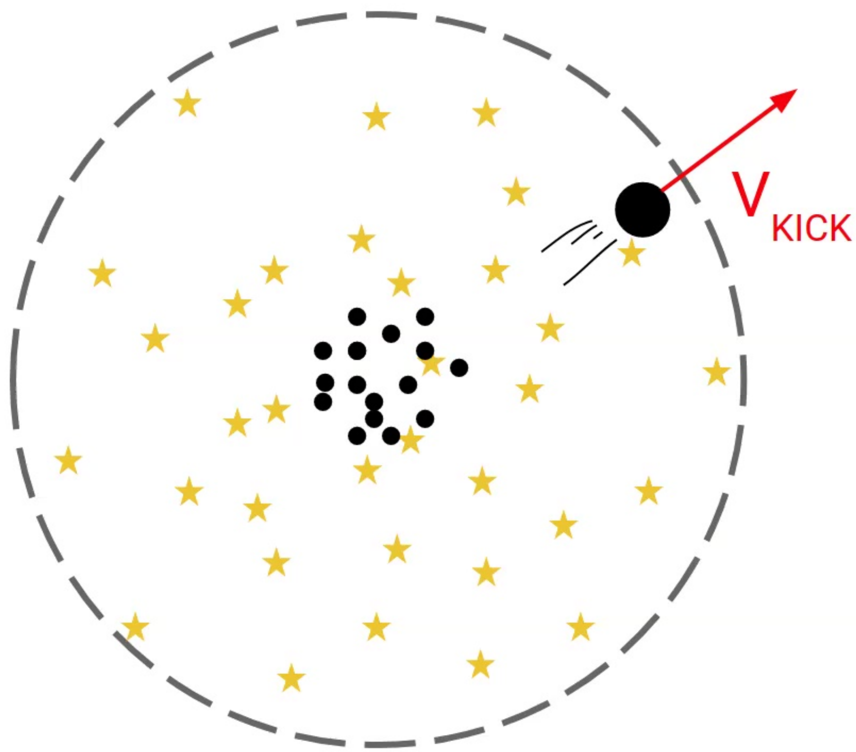


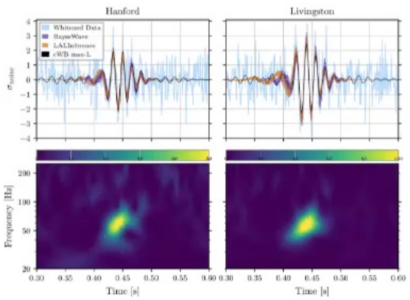
Globular Clusters

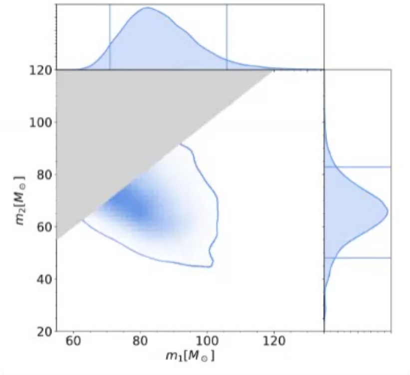
Hie

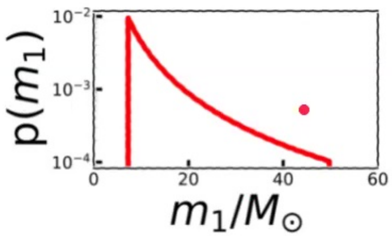
- What does the inferred binary black hole population (mass + spin) look like when we allow this formation channel?
- What happens to the edge of the mass gap?
- Can we identify >1G mergers in GW catalogs?

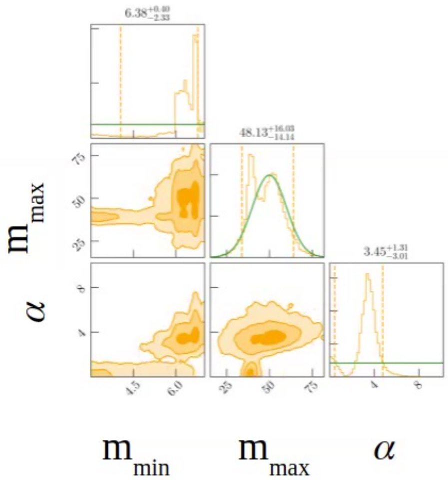
Hierarchical Mergers via Hierarchical Inference

Data → **Source Parameters** + **Population Model** → **Hyperposteriors**



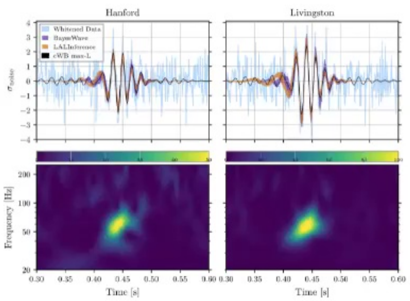




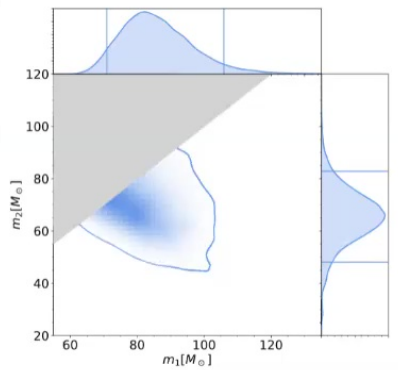


Hierarchical Mergers via Hierarchical Inference

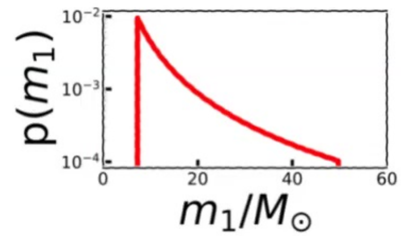
Data



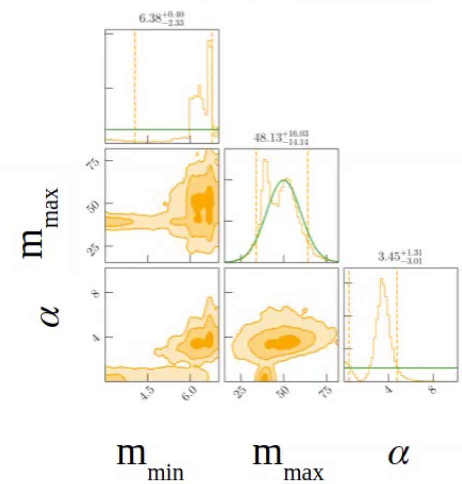
Source Parameters



Population Model

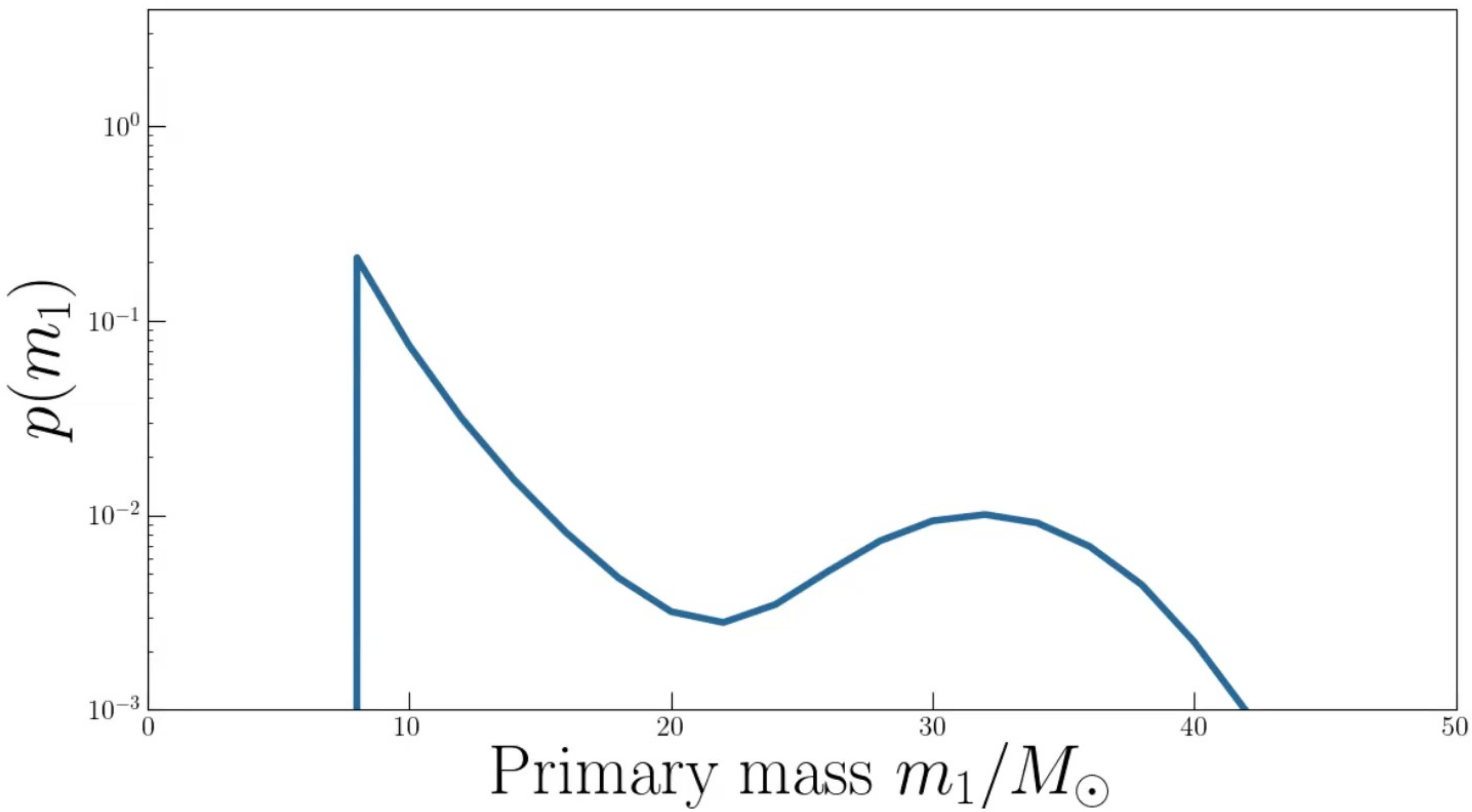


Hyperposteriors

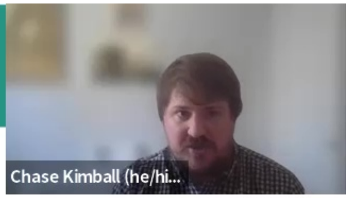


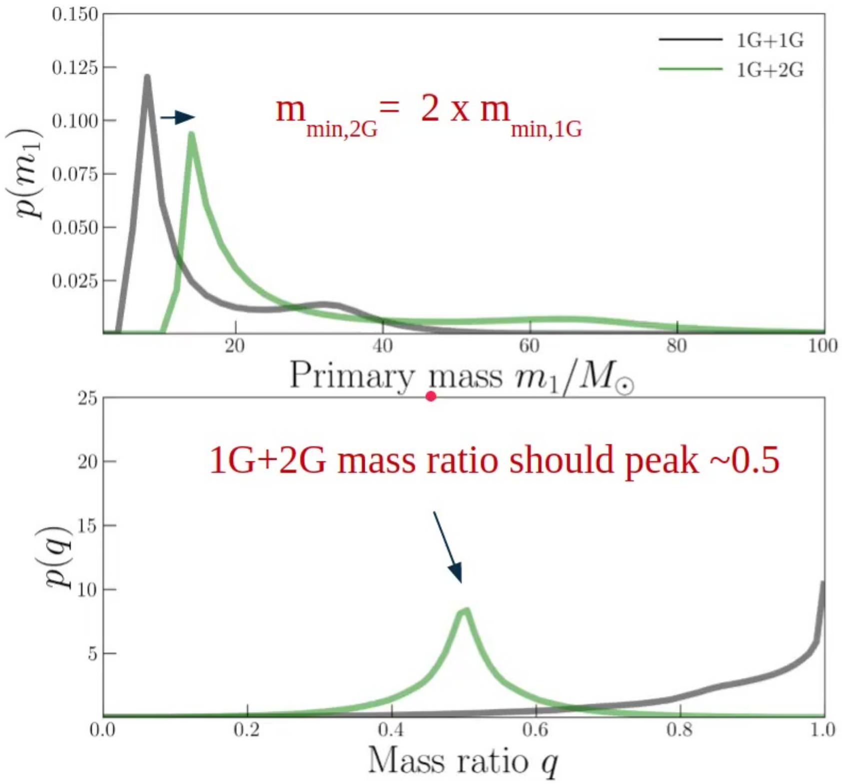
P(Hierarchical Merger|D)

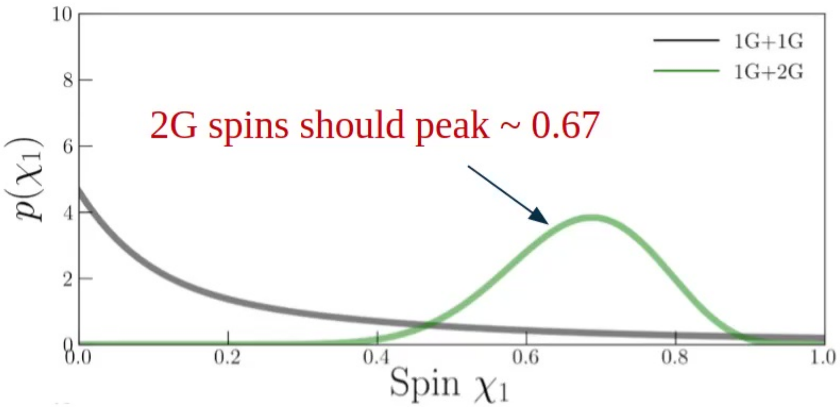
1G + 1G Mass Model



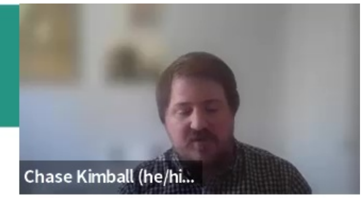
xG + 2G Populations

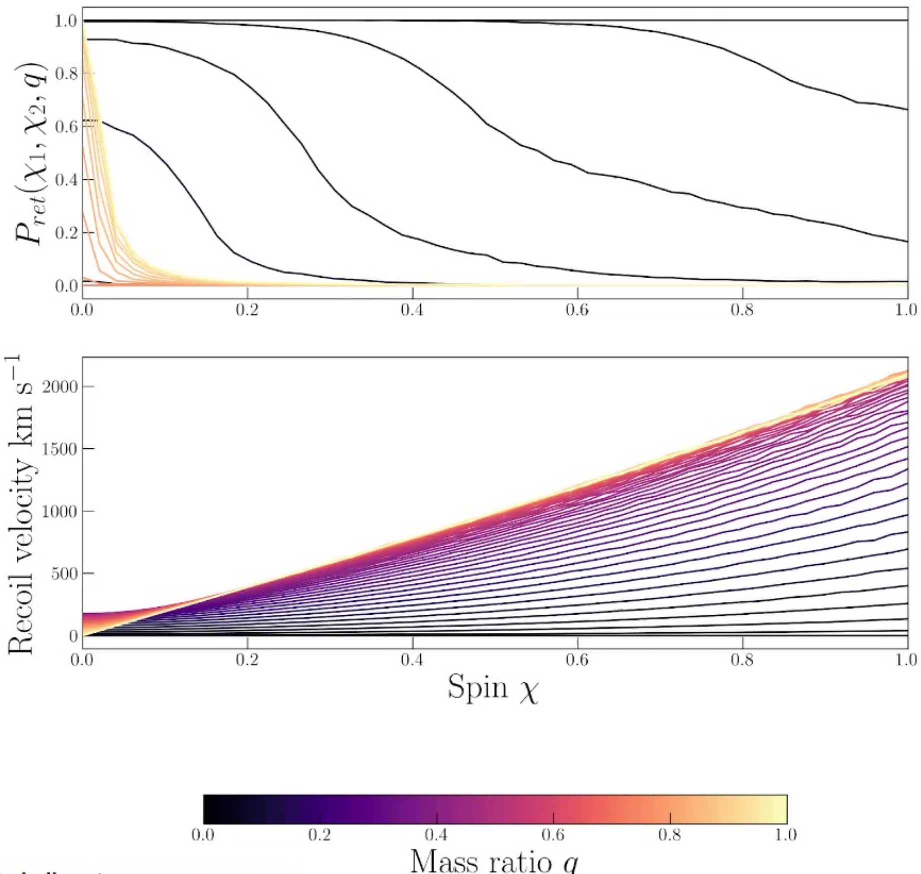


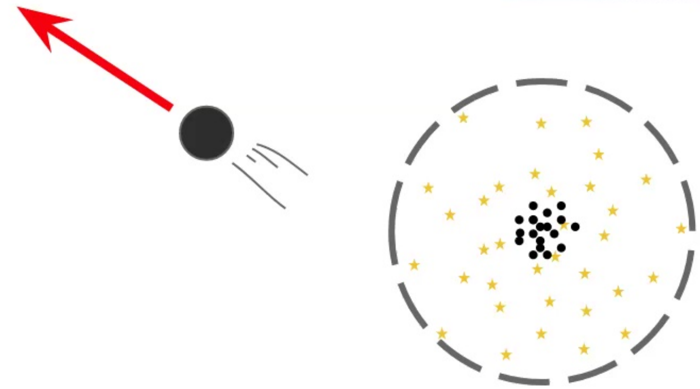




Retaining Merger Products







Strong spin dependence

Kimball et al. 2020, ApJ 900(2):177

GWTC-1

Kimball et al. 2020, Ap

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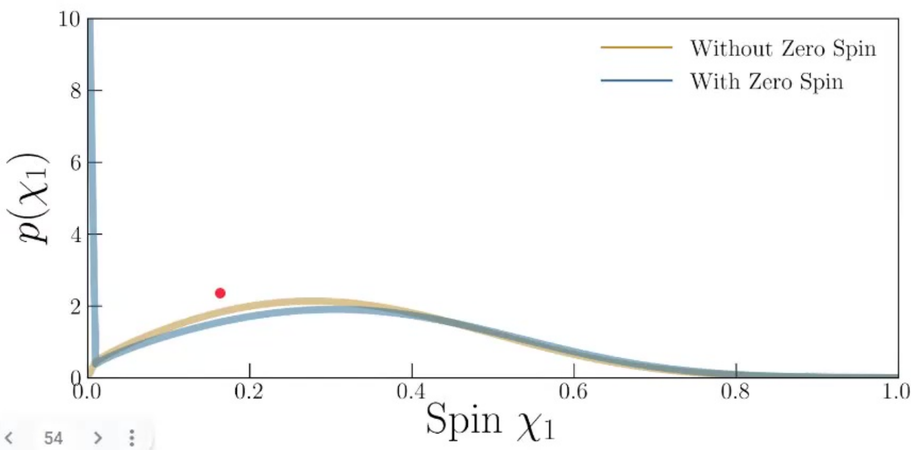
Not *all* 1G BHs have 0 spin

High 2G rates correlate with low spin



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GWTC-1

Kimball et al. 2020, Ap

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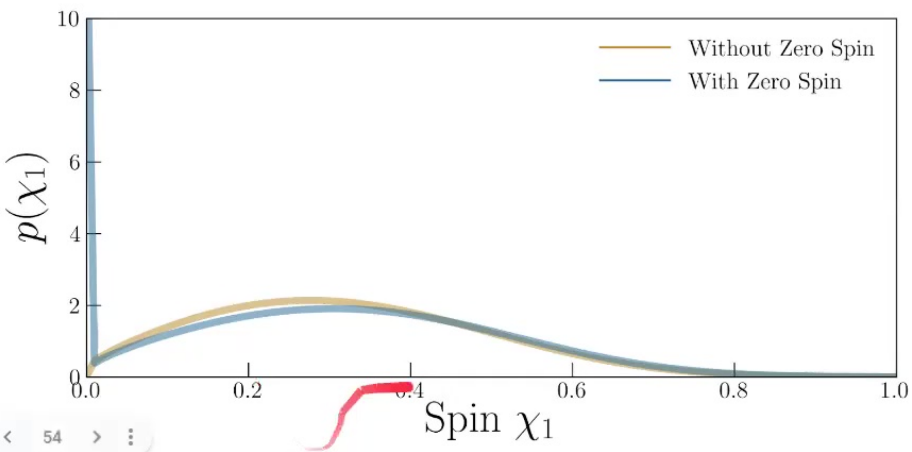
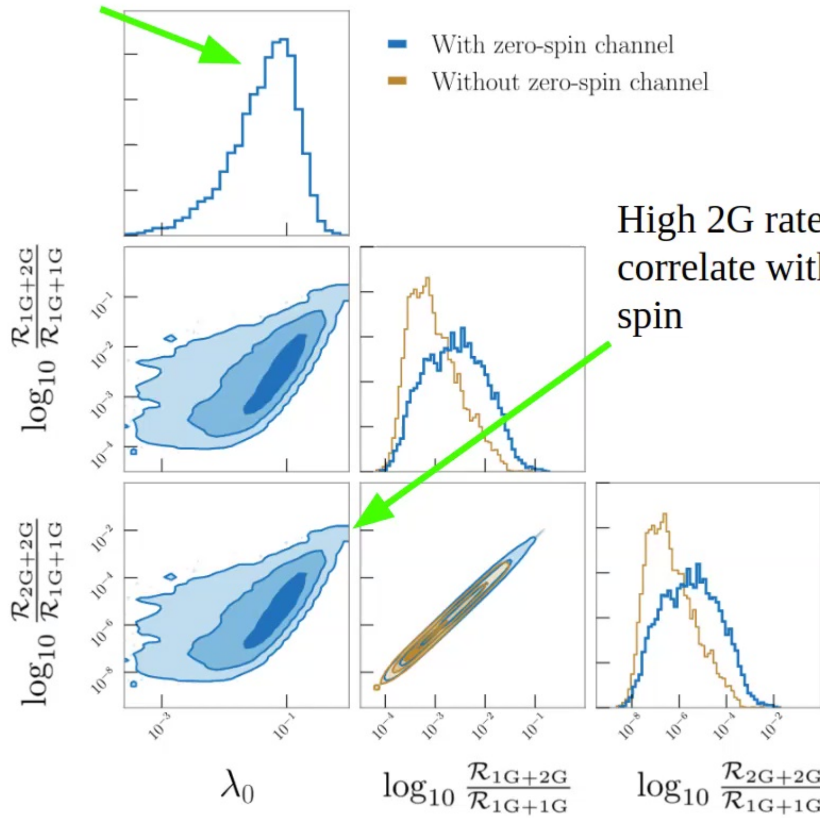
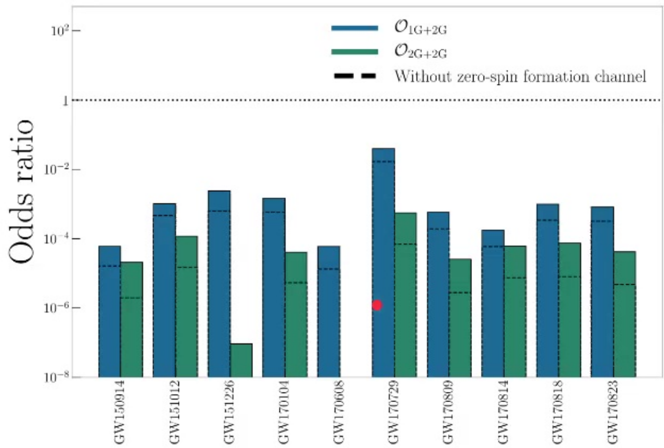




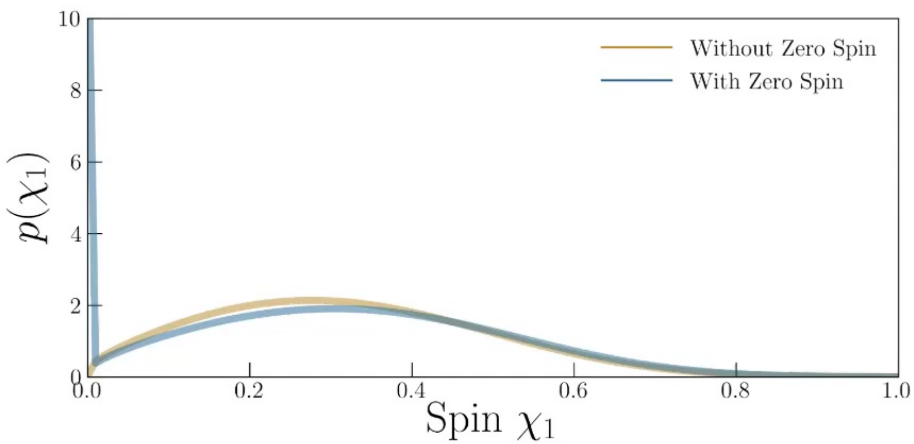
High 2G rates correlate with low spin

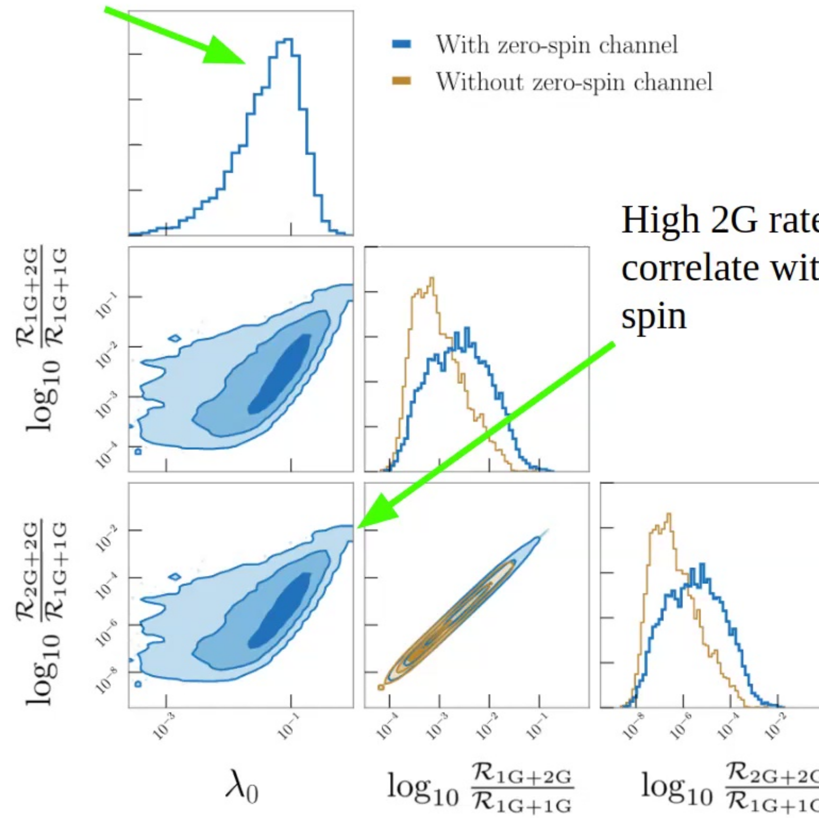
GWTC-1

Kimball et al. 2020, Ap



Not *all* 1G BHs have 0 spin

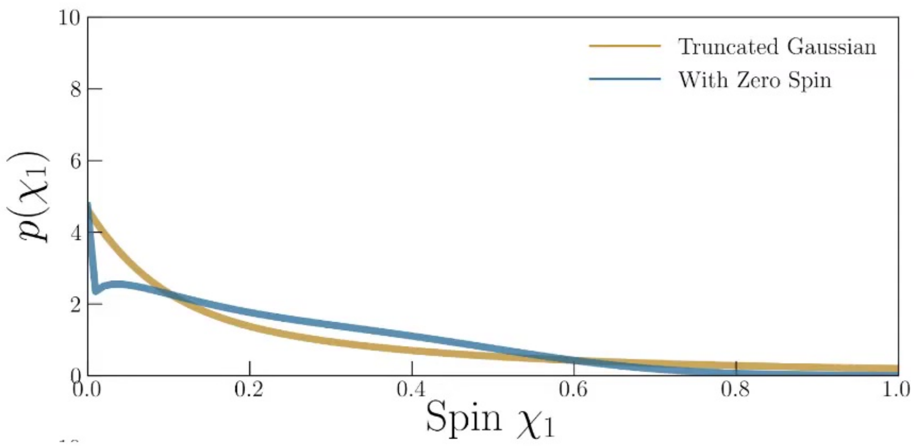


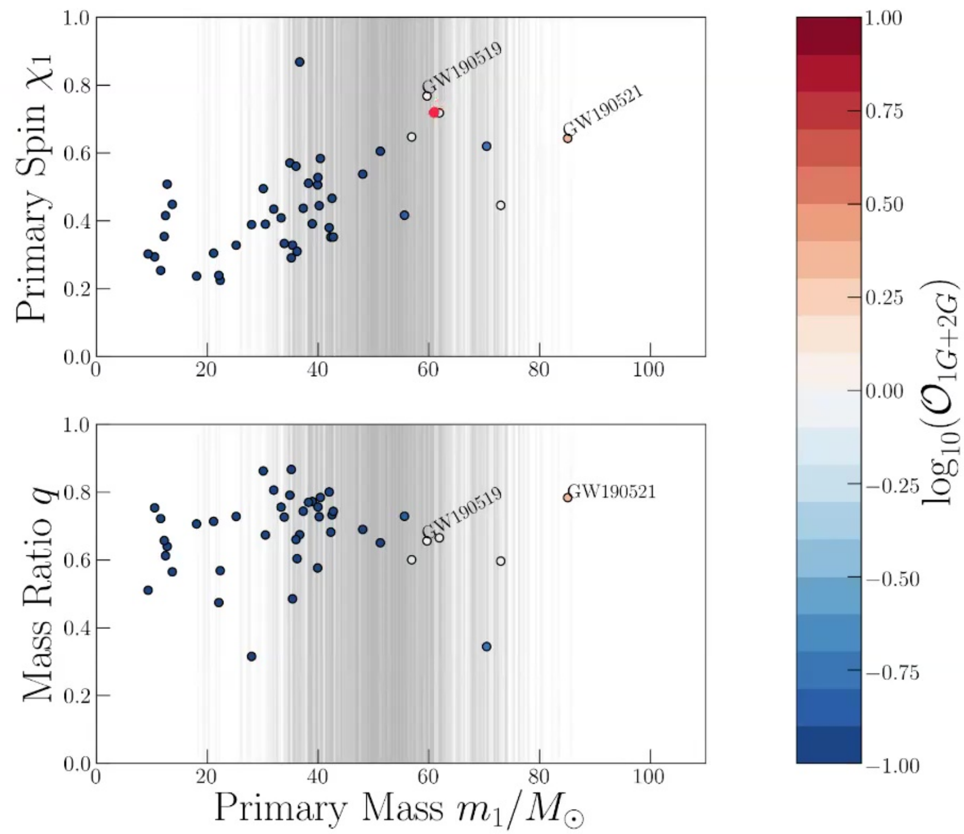


High 2G rates correlate with low spin

GWTC-2

Kimball et





Found GWTC-2 contains a 2G BH with >96% probability

Prefer including hierarchical channels with BF >5

GWTC-2

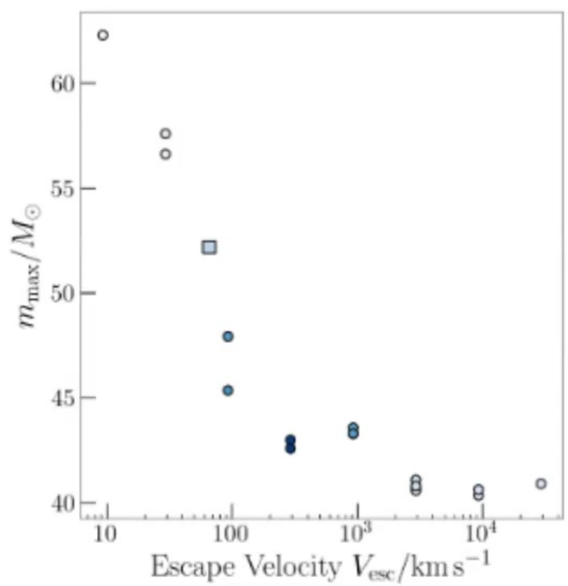
Higher escape velocity

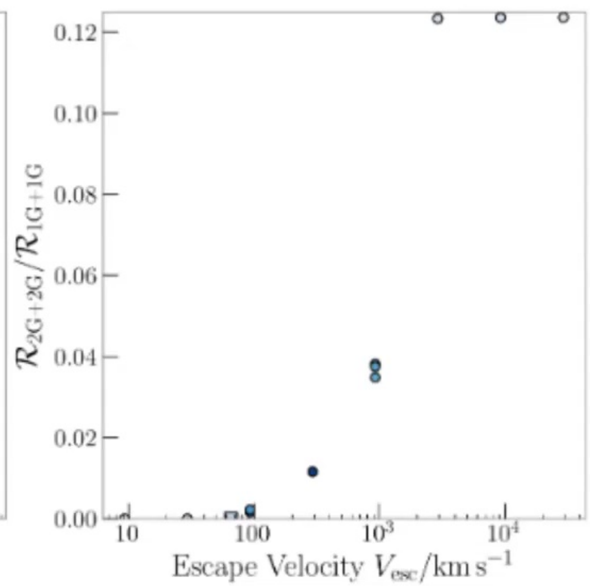
Kimball et

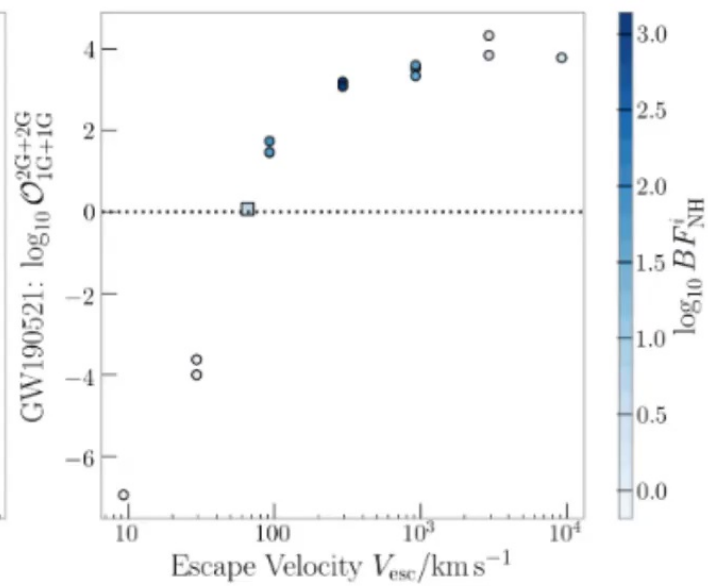
More reasonable m_{max}

More next gen mergers

GW190521 solidly 2G+2G



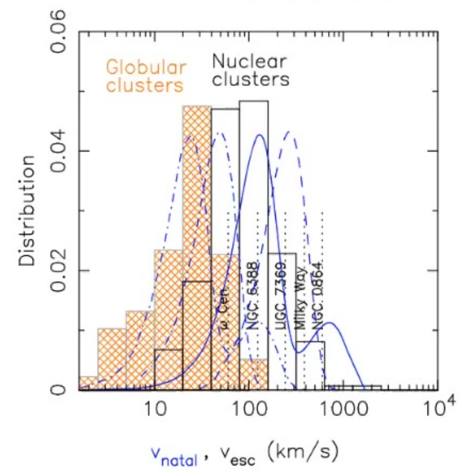


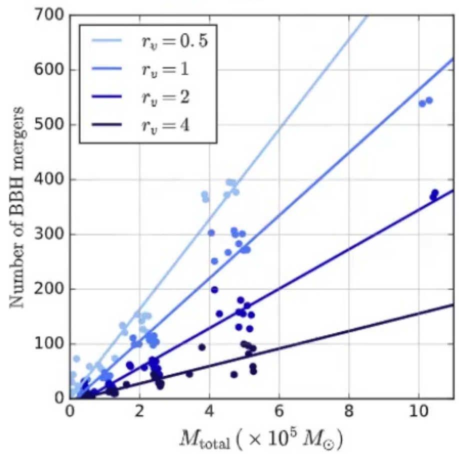


GWTC-3 + Model Extension

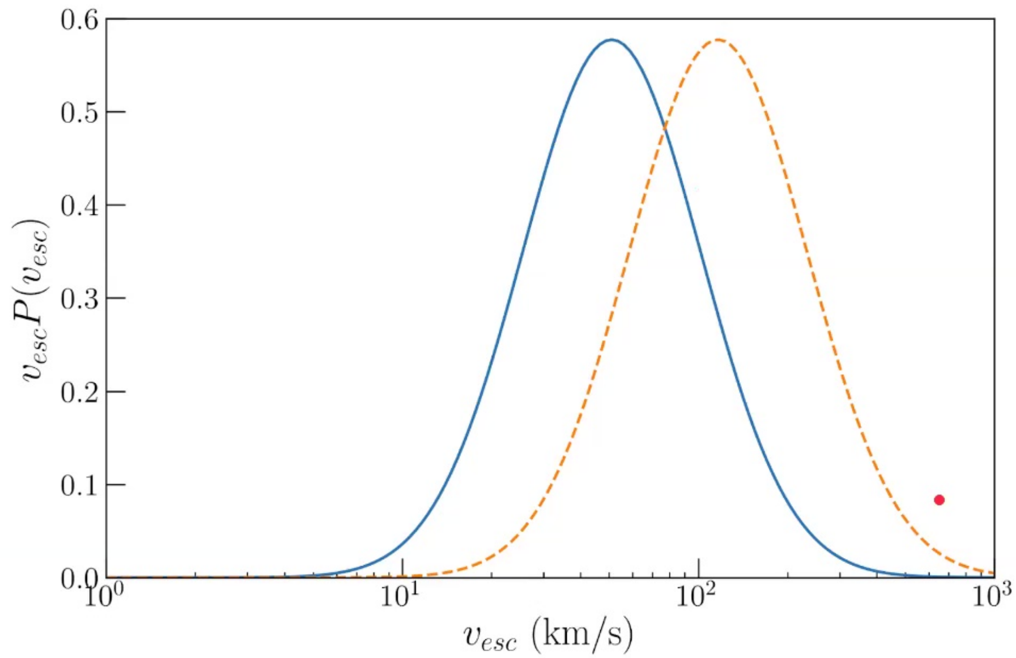
Preliminary

Antonini & Rasio 2016





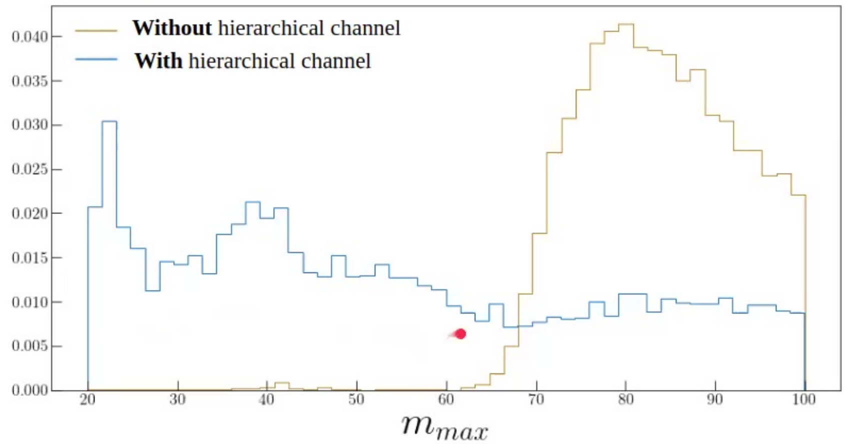
Kremer et al. 2020

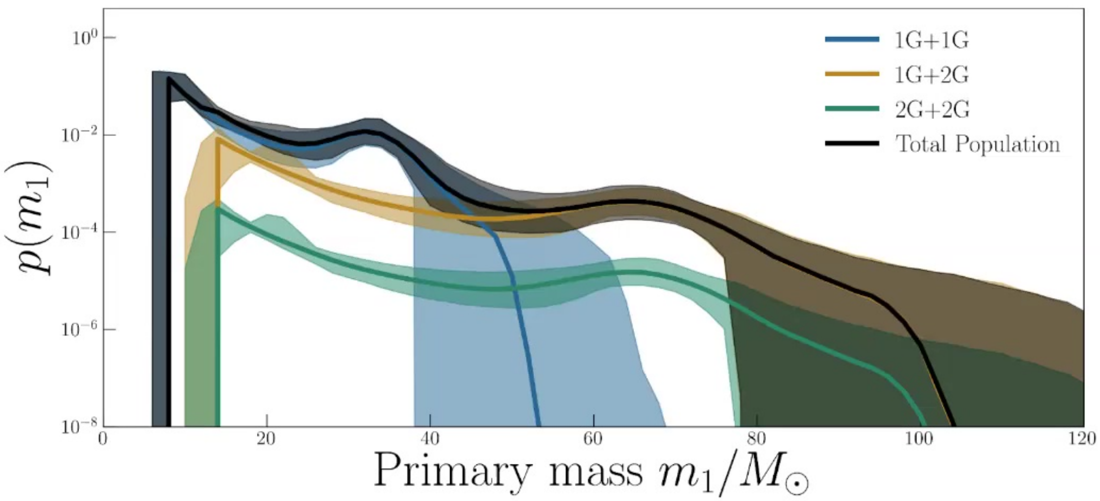


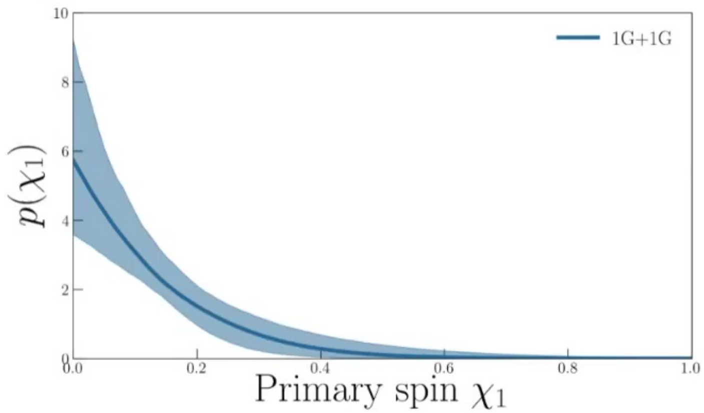
GWTC-3 + Model Extension

Kimball et al. 2022, In-prep

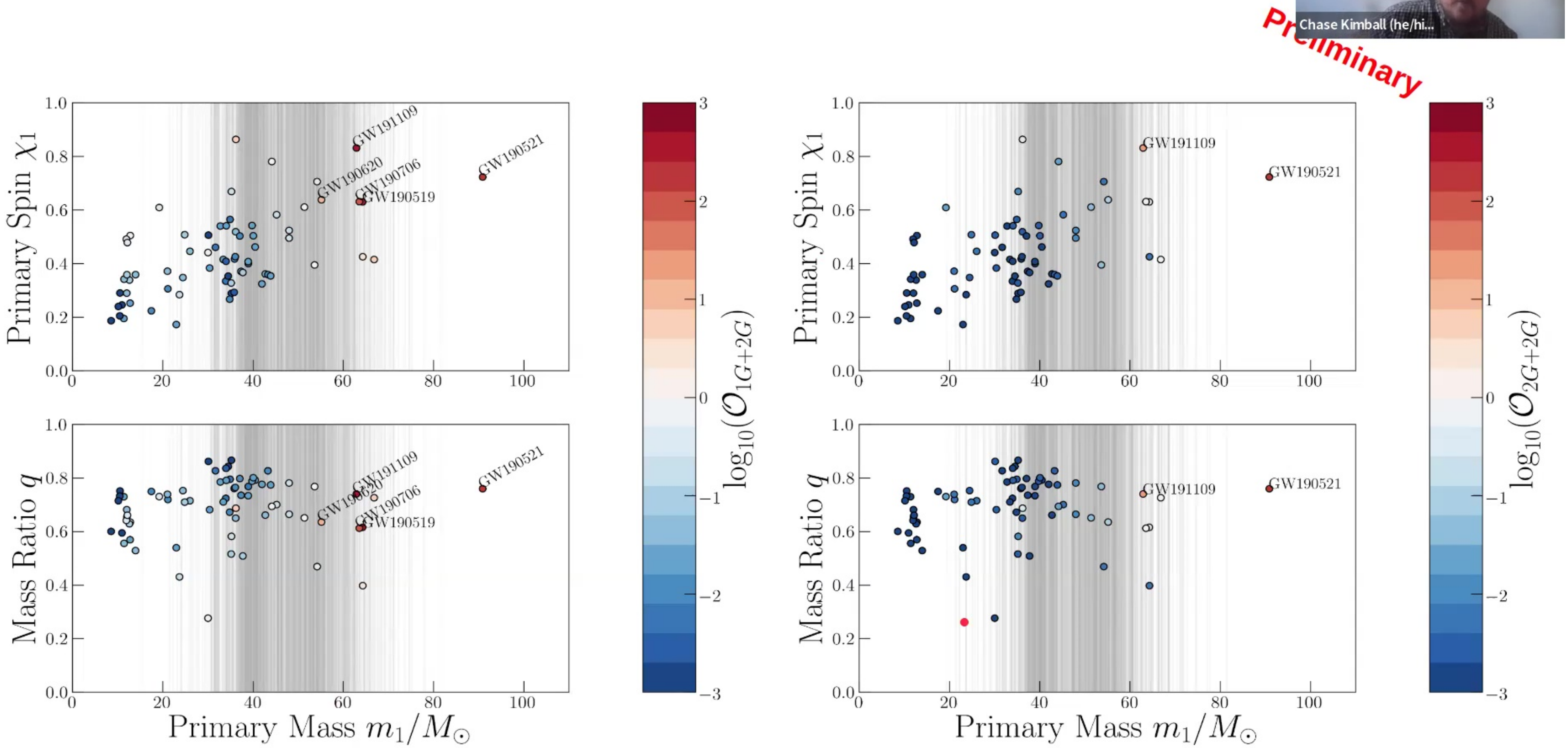
Preliminary







GWTC-3 + Model Extension



GWTC-3 + Model Extension

To Do:

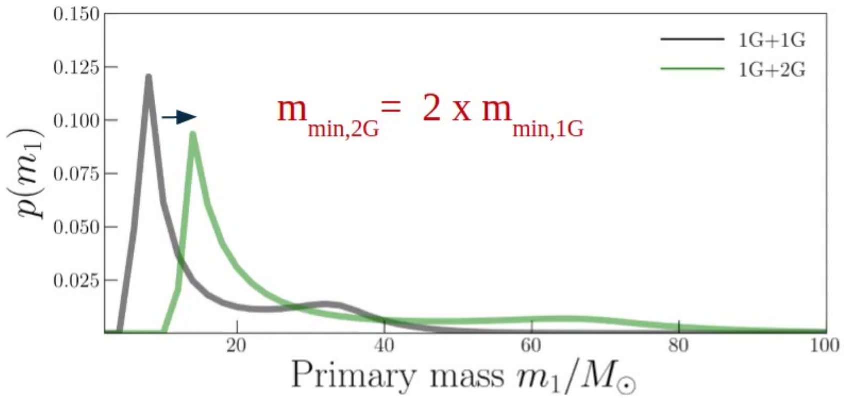
- Extend 1G + 1G mass distribution “beyond the gap”
  - Test GW190521 “straddling-the-gap” scenario (See Fishbach and Holtz 2020)

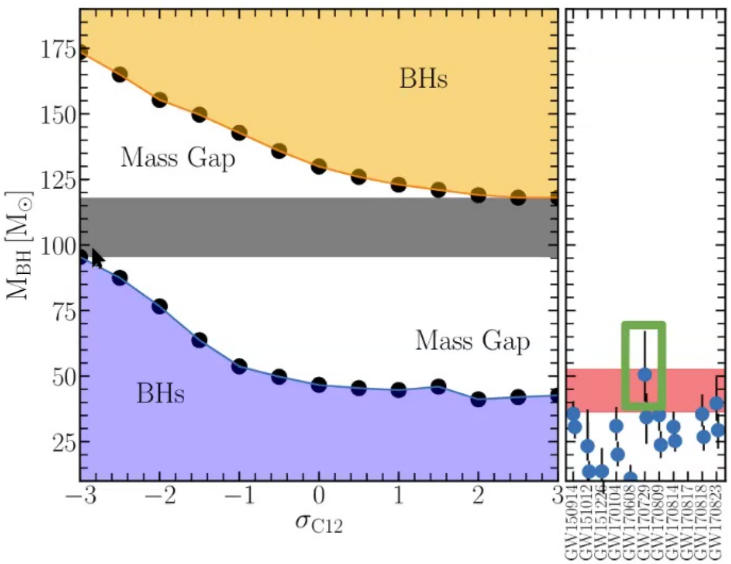
- Include other dynamical environments with respective branching fractions
  - Immediately, Nuclear Star Clusters
  - Eventually, Active Galactic Nuclei

Conclusions

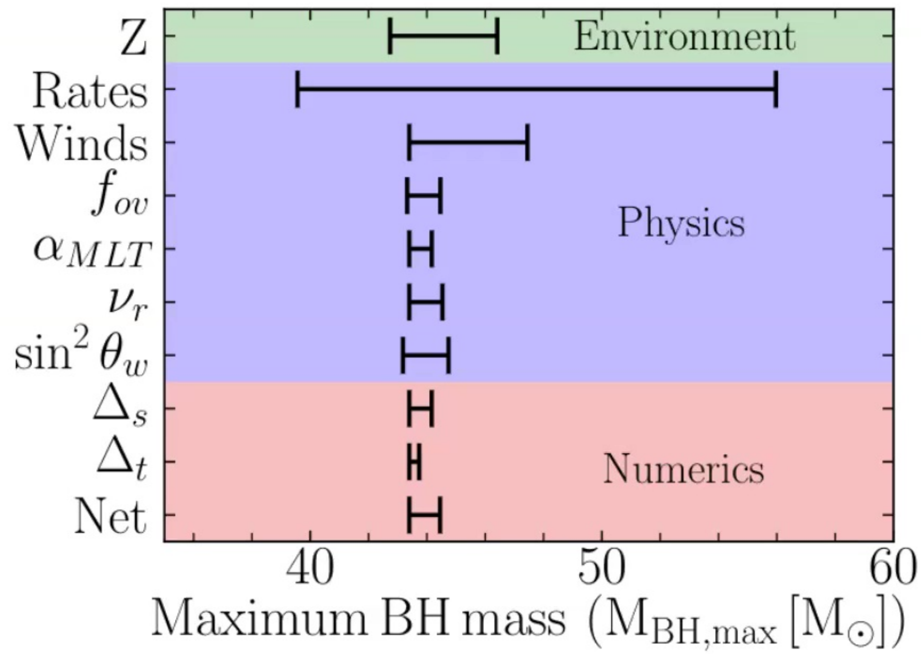
- GW Merger rates can help constrain our astrophysical models
  - *Can't* pin down formation channels
  - *Can* rule out some channels as dominant
- Dynamical channels are needed to explain *some* of our observations
  - Black holes in the pair-instability mass gap can be explained by hierarchical mergers
  - For wide range of assumptions, models including hierarchical mergers are preferred
  - Inference depends strongly on escape velocity of dynamical environment

xG + 2G Populations





R. Farmer *et al* 2020 *ApJL* 902 L36



R. Farmer *et al* 2019 *ApJ* 887 53