Cleaning up the PISN Mass Gap:

Identifying Hierarchical Mergers

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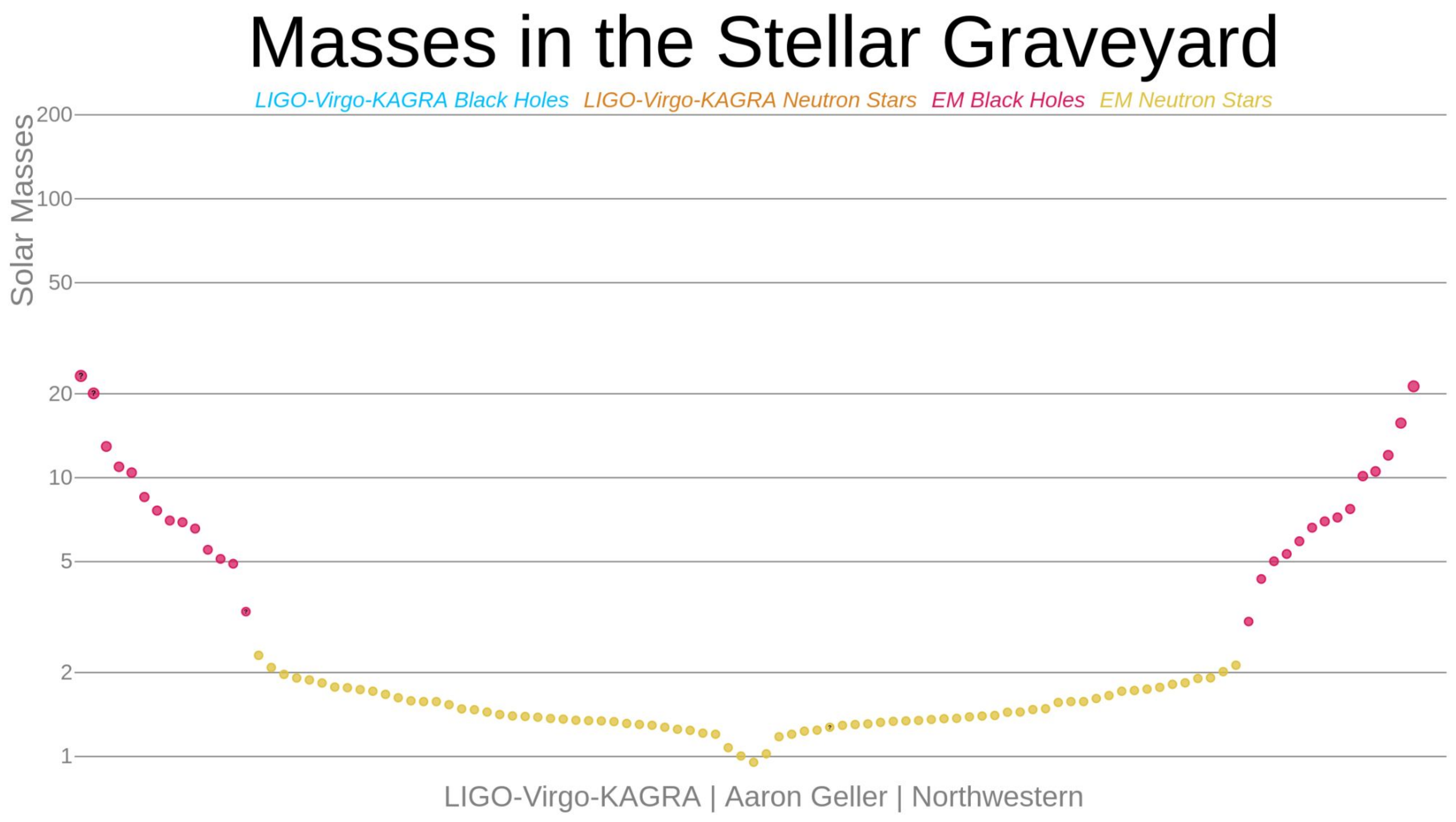
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

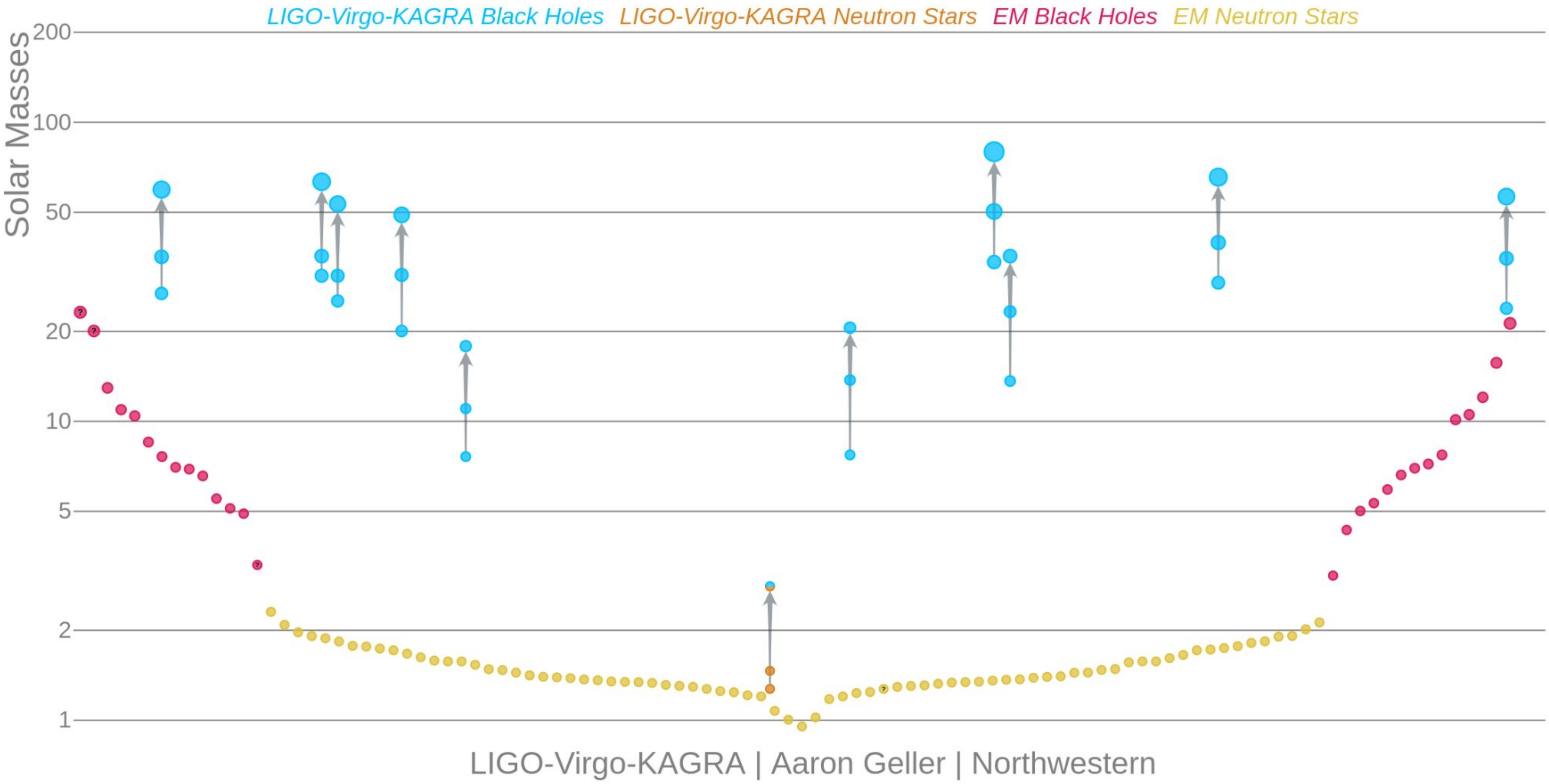
With Colm Talbot, Michael Zevin,
Eric Thrane, Vicky Kalogera and others

LSC LIGO Scientific Collaboration



Masses in the Stellar Graveyard
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

GWTC-1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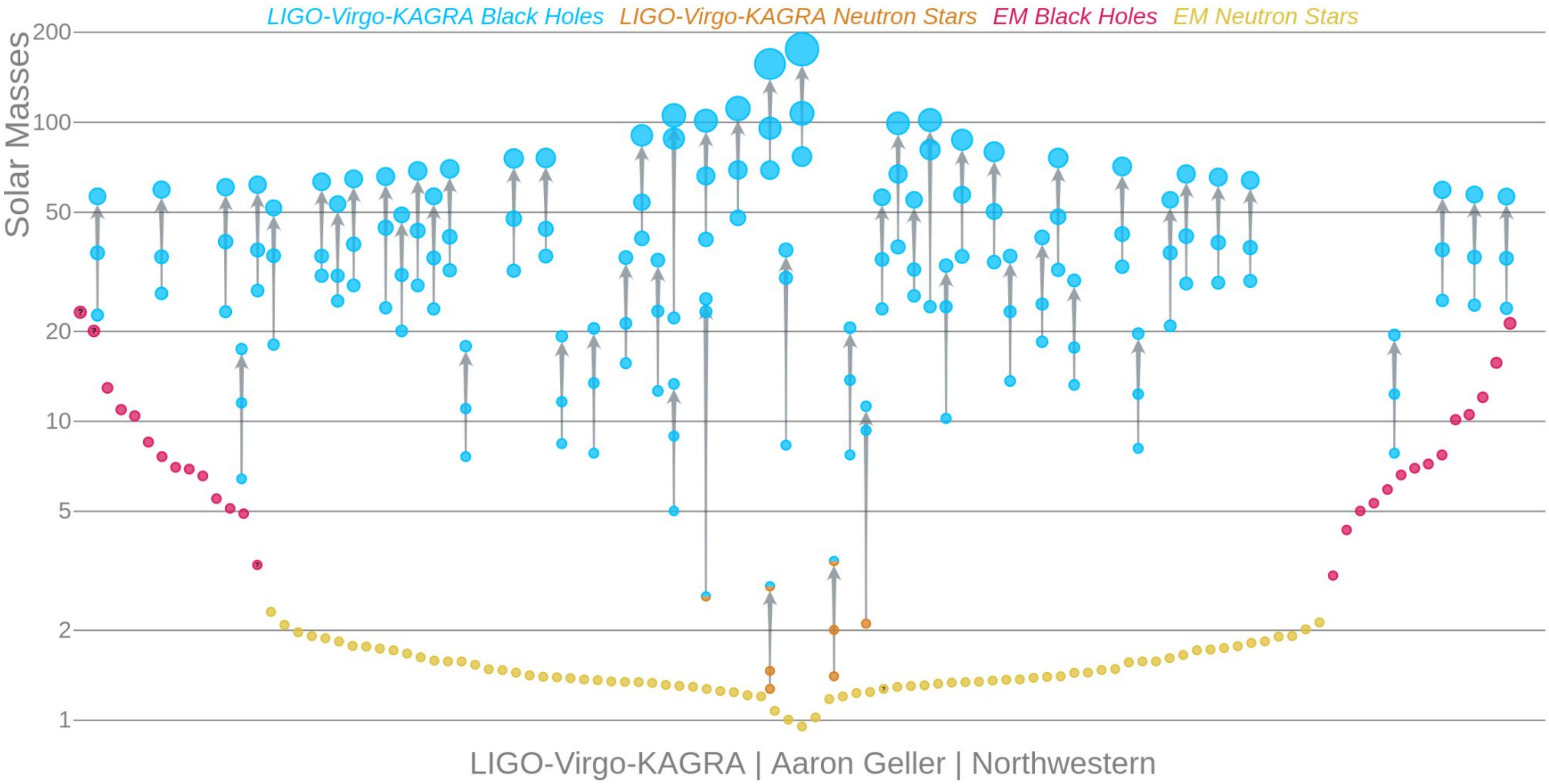
GWTC-2



LIGO-Virgo-KAGRA Black Holes
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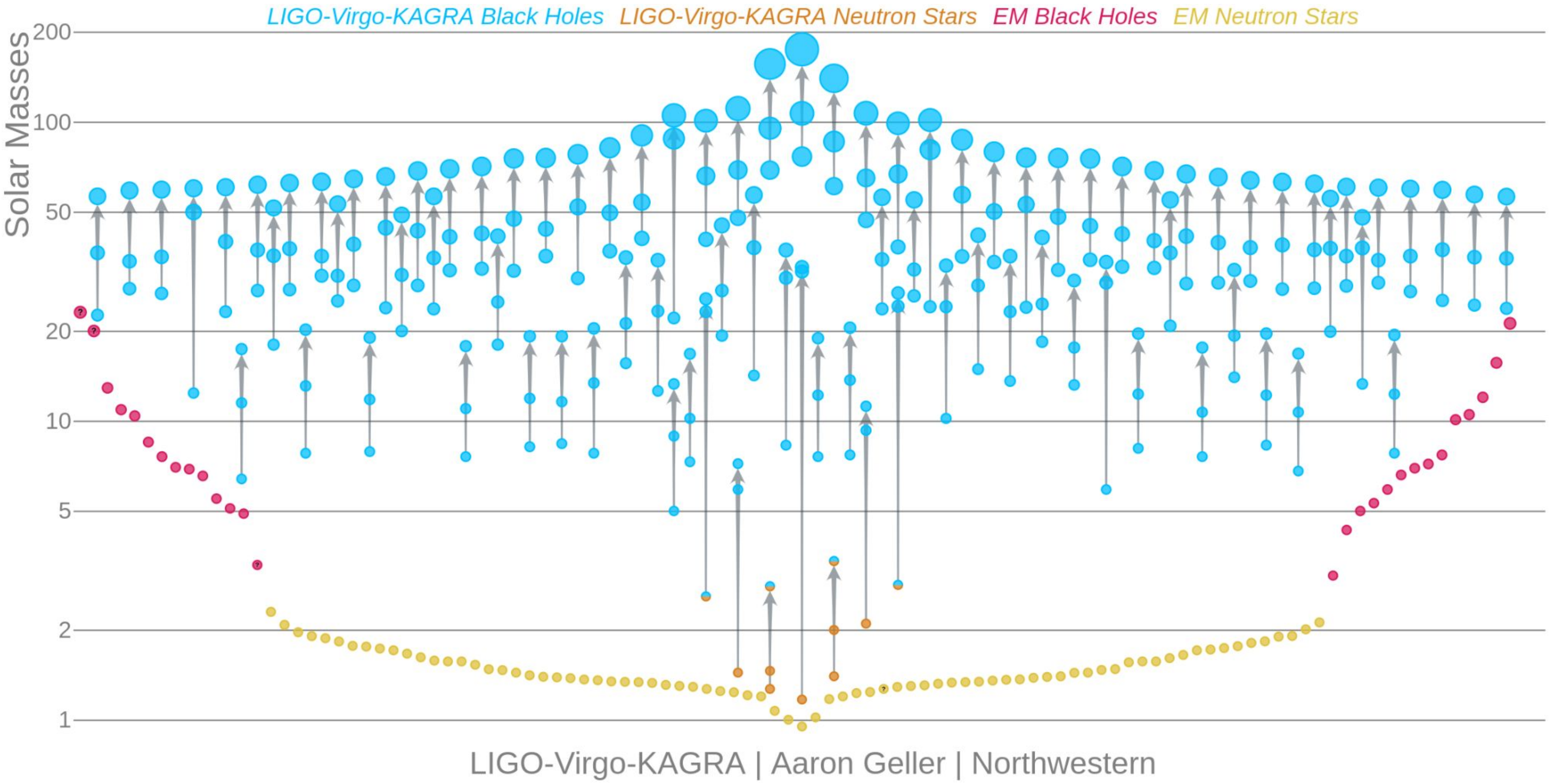
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GWTC-3


LIGO-Virgo-KAGRA Black Holes
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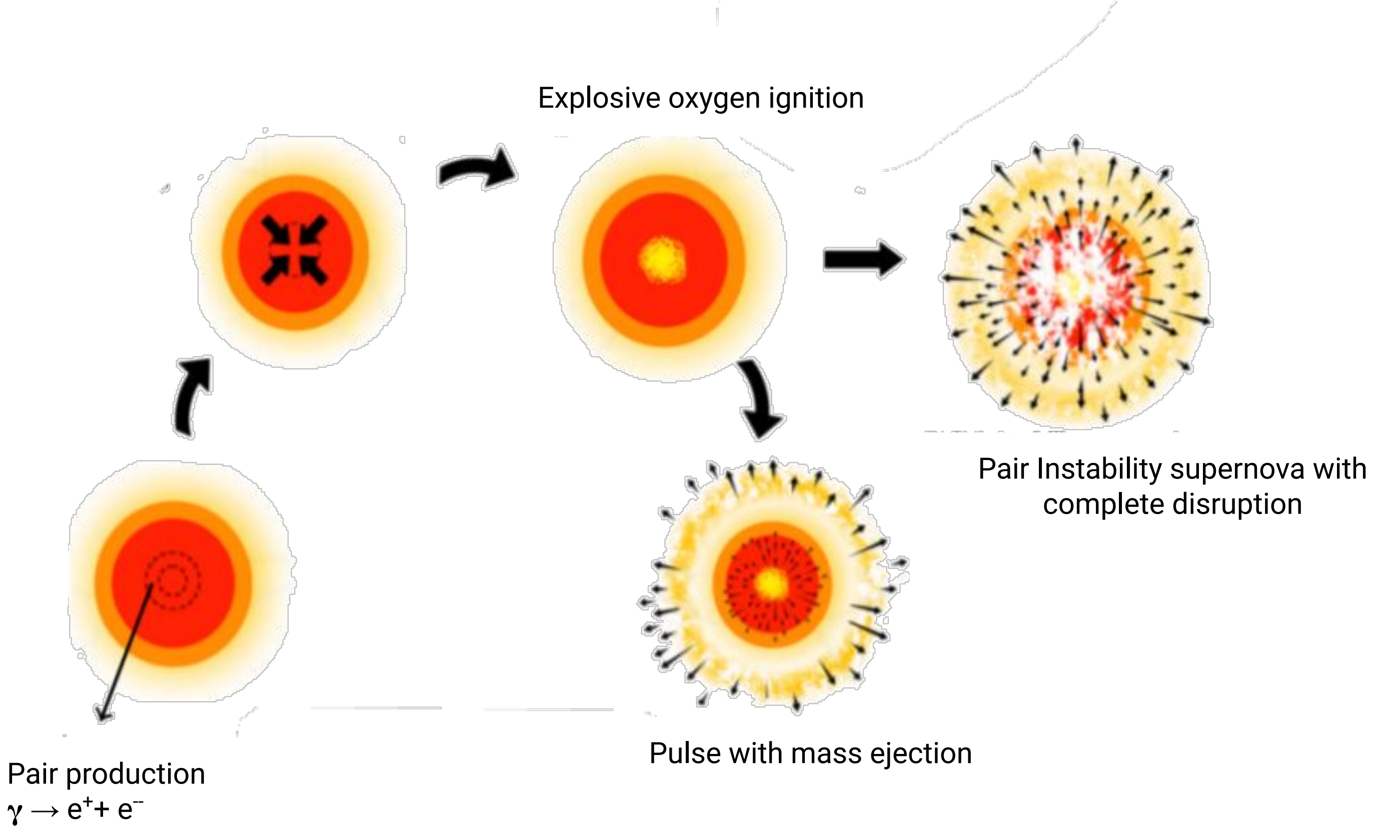
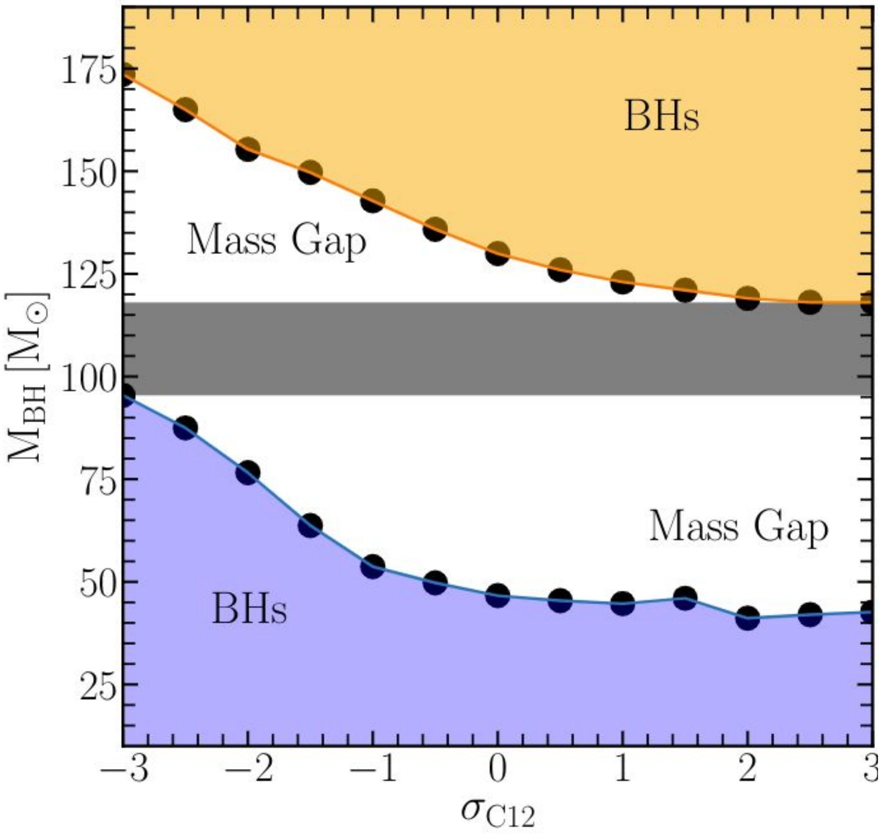
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

(Pulsational) Pair-Instability Supernovae



Adapted from Renzo et al. 2020

The mass gap encodes interesting physics

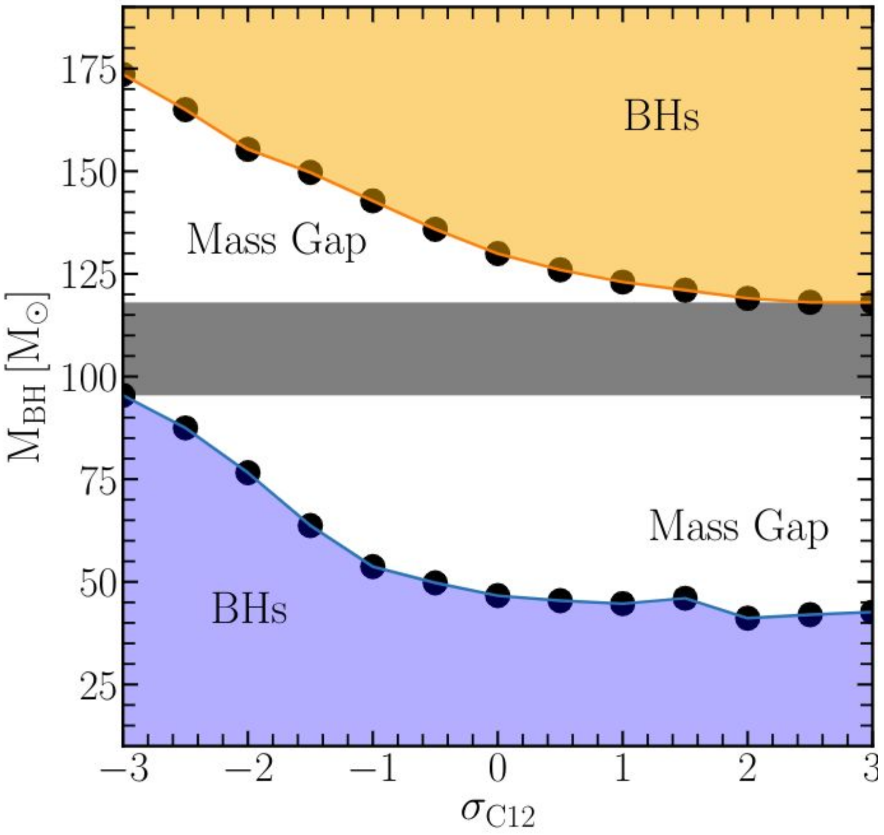


Farmer et al. 2020

Uncertainties in the lower edge of the mass gap from

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

The mass gap encodes interesting physics



Farmer et al. 2020

Uncertainties in the lower edge of the mass gap from

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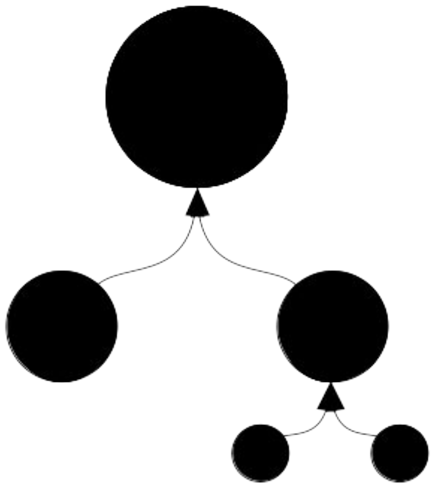
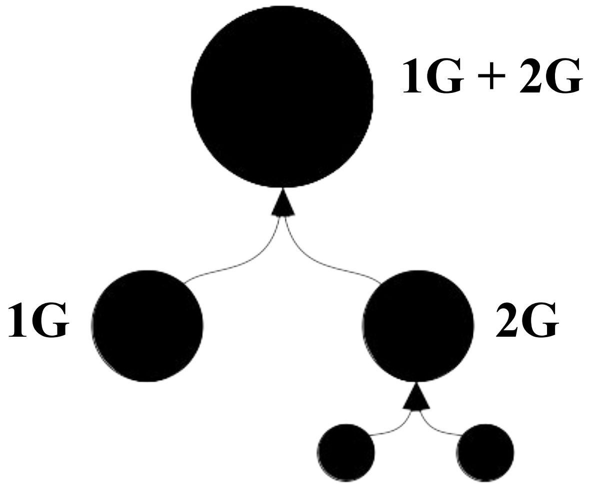
Wouldn't it be nice to use GW observations to constrain some of this physics?



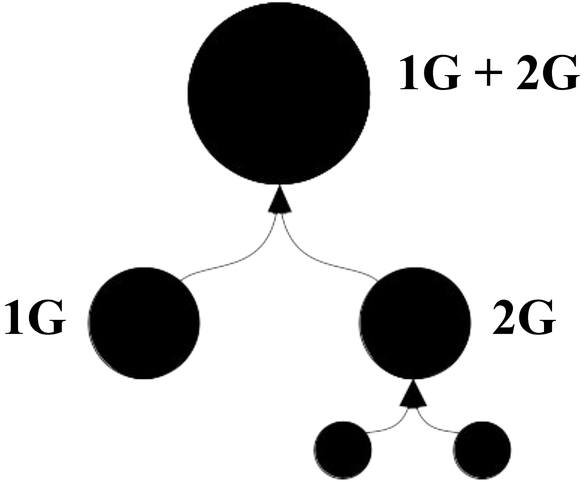

1G + 2G
1G
2G

Nuclear Star Clusters

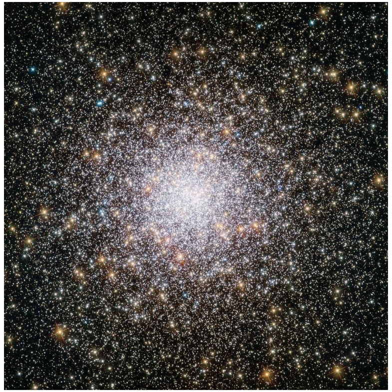
Credit: ESO

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

Active Galactic Nuclei



Globular Clusters



Credit: ESA / NASA / Hubble

Nuclear Star Clusters

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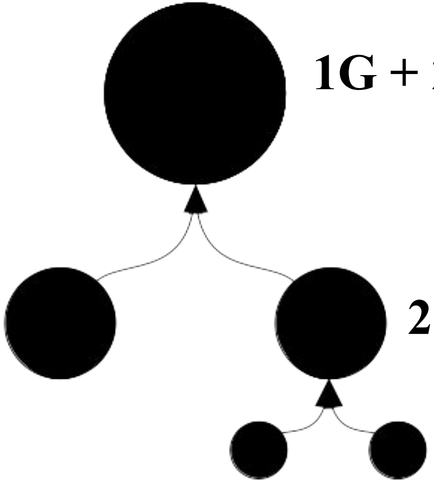
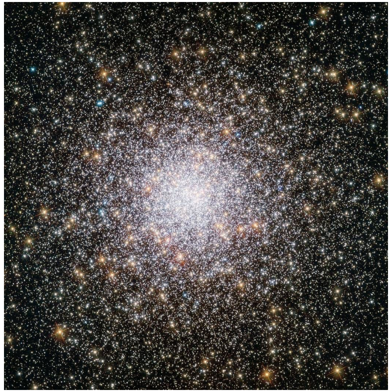
Active Galactic Nuclei

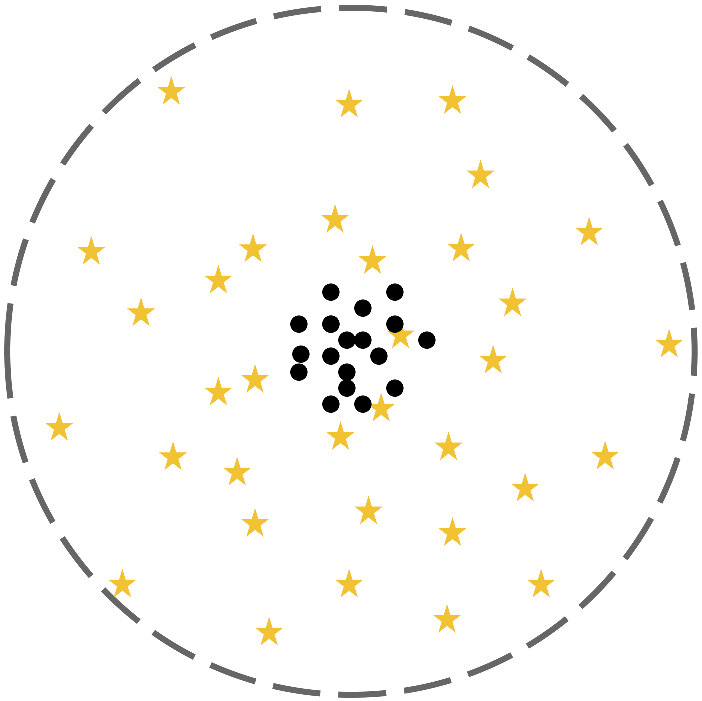


Globular Clusters

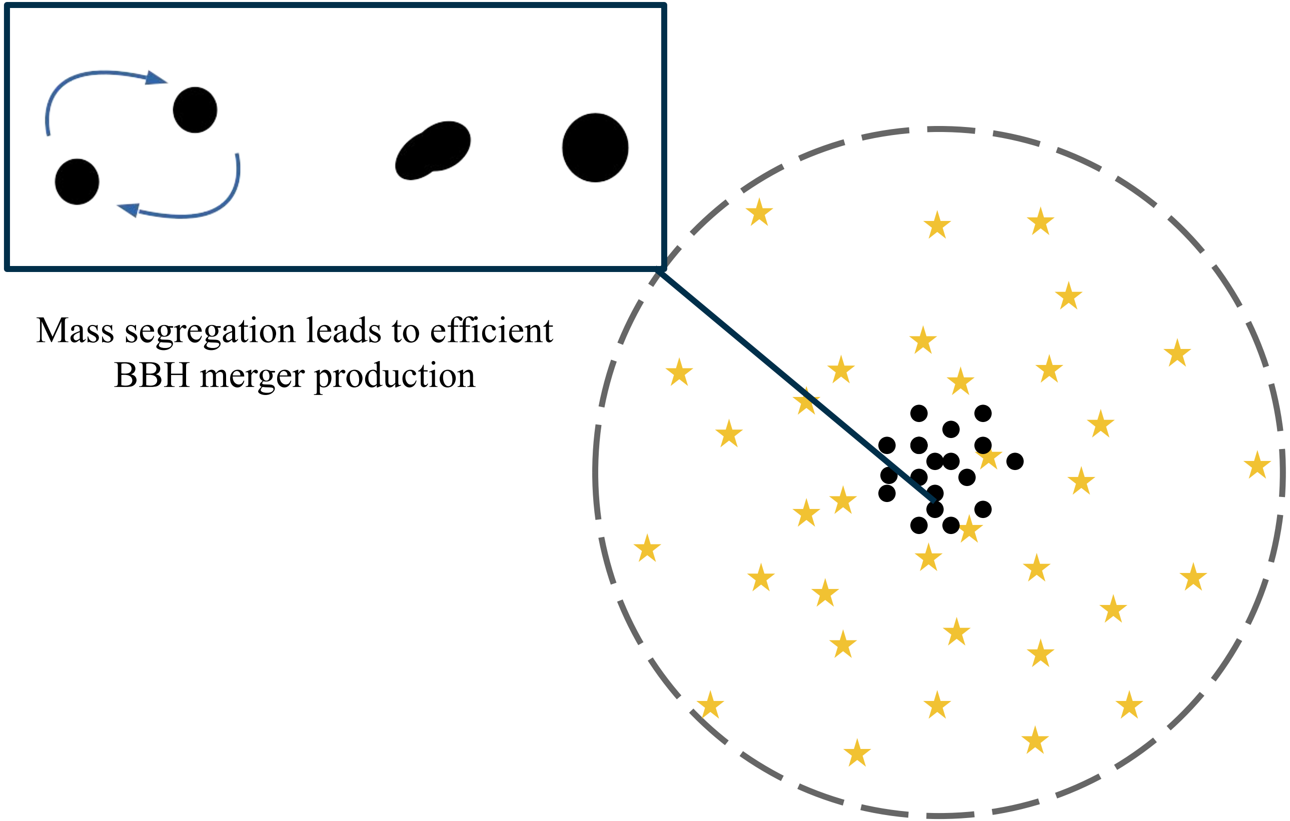


Credit: ESA / NASA / Hubble

Black Hole Mergers in Globular Clusters

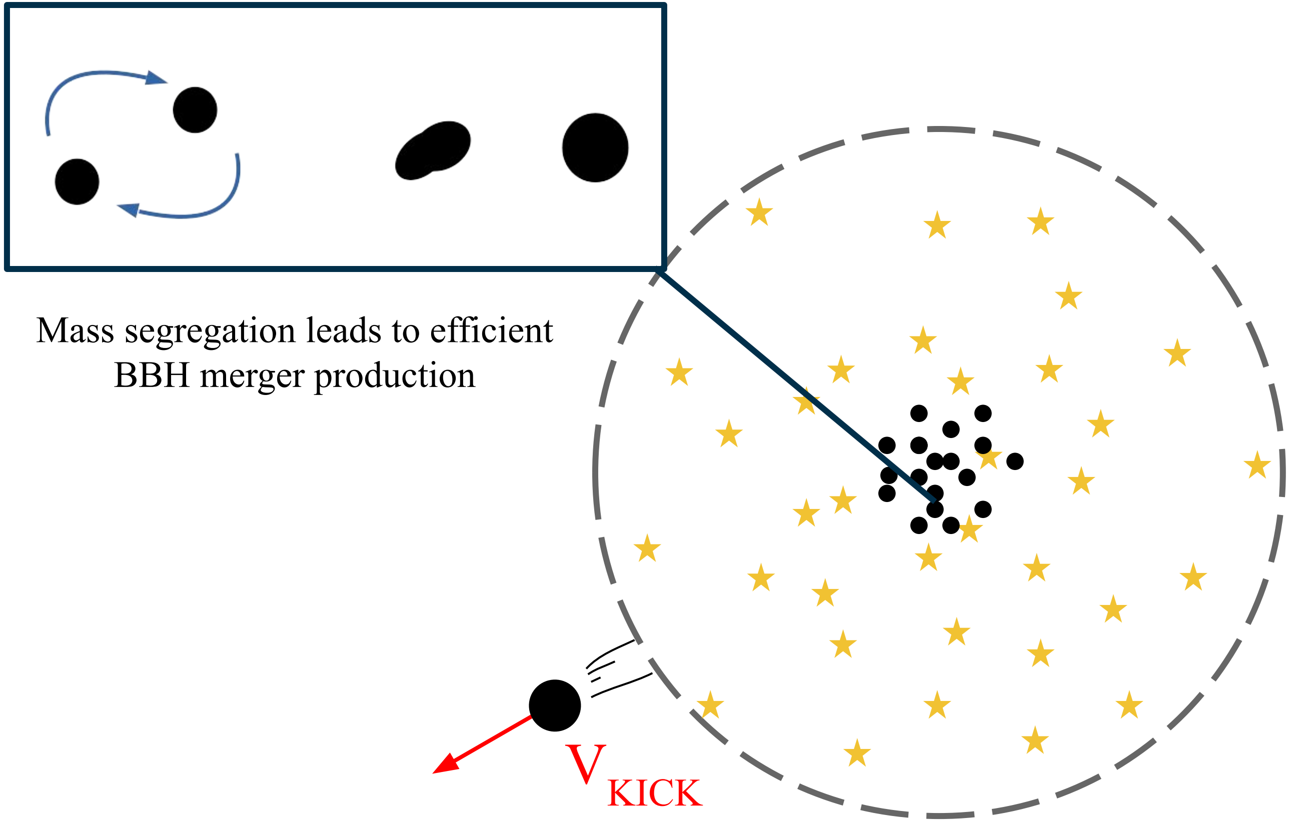


Black Hole Mergers in Globular Clusters



Mass segregation leads to efficient BBH merger production

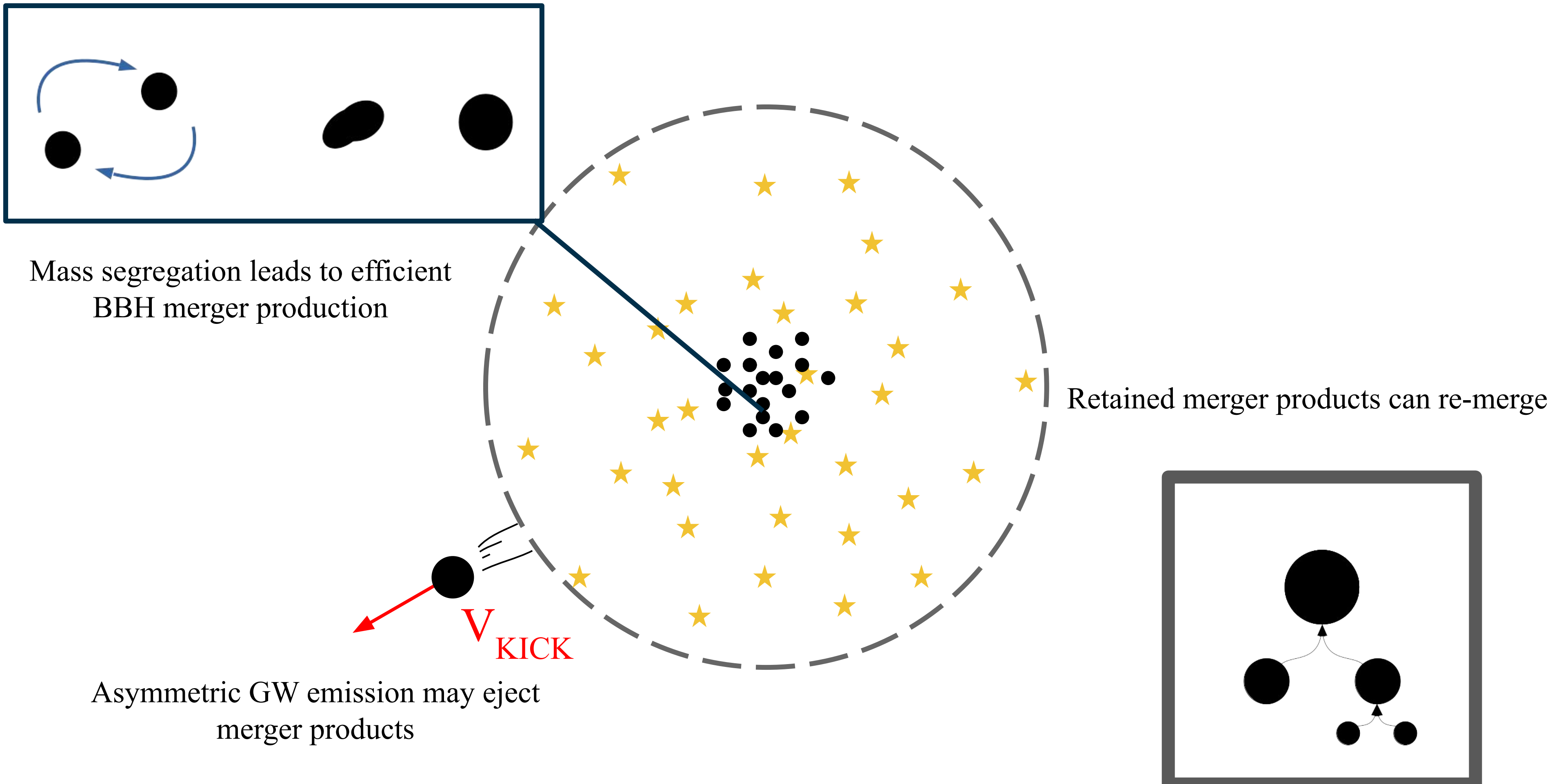
Black Hole Mergers in Globular Clusters



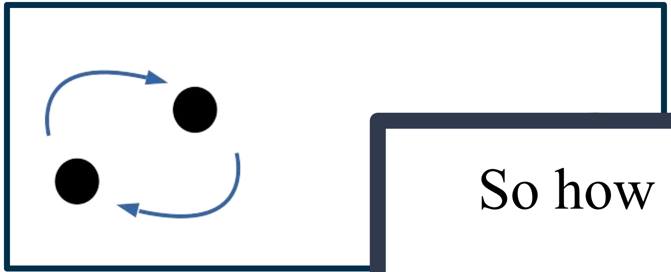
Mass segregation leads to efficient BBH merger production

Asymmetric GW emission may eject merger products

Black Hole Mergers in Globular Clusters



Black Hole Mergers in Globular Clusters



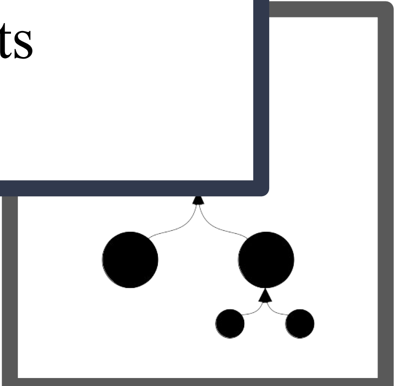
Mass segregation lead
BBH merger proc

So how can we:

- ❖ Infer details of the merging binary black hole population while accounting for this channel

- ❖ Identify potential mass gap pollutants

can re-merge



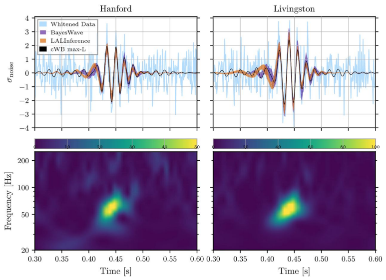
KICK

Asymmetric GW emission may eject merger products

Hierarchical Bayesian Inference (no relation)

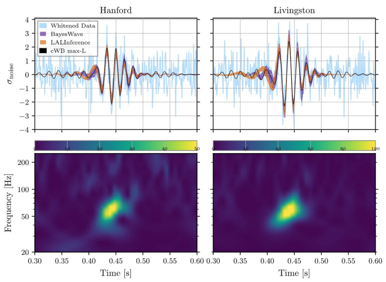
Hierarchical Bayesian Inference (no relation)

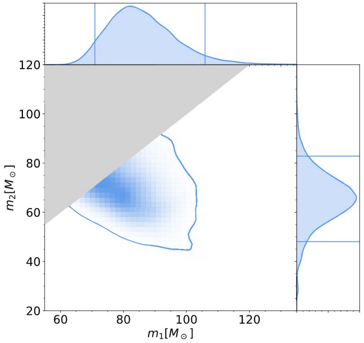
Data



Hierarchical Bayesian Inference (no relation)

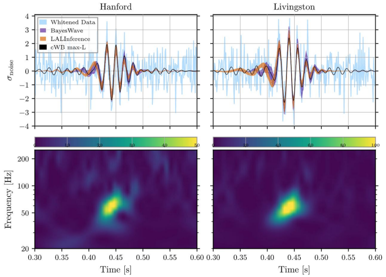
Data → **Source Parameters**

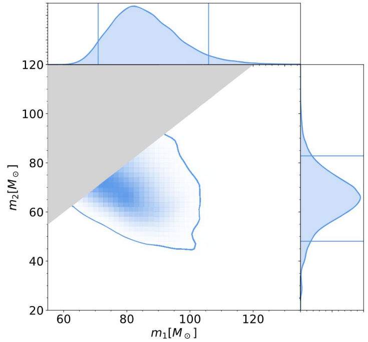


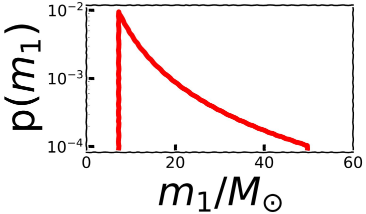


Hierarchical Bayesian Inference (no relation)

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





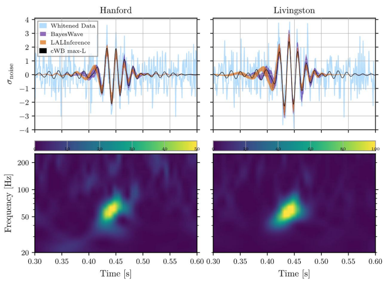


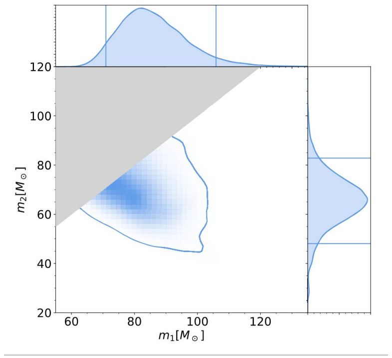
Hierarchical Bayesian Inference (no relation)

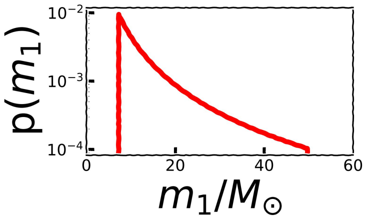
Sample likelihood with gwpopulation (Colm Talbot)

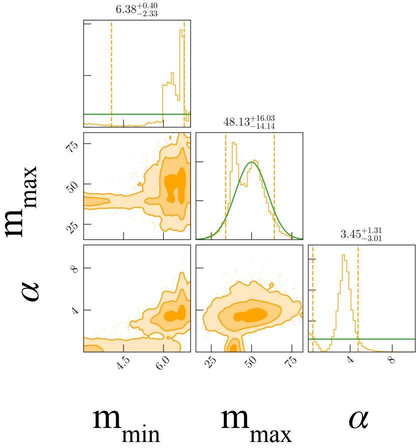
$$\mathcal{L}_{\text{tot}}(\vec{d}|\boldsymbol{\Lambda}) \simeq \prod_i^N \frac{1}{P_{\text{det}}(\boldsymbol{\Lambda})} \frac{Z_\varnothing(d_i)}{n_i} \sum_k^{n_i} \frac{\pi(\boldsymbol{\theta}^k|\boldsymbol{\Lambda})}{\pi(\boldsymbol{\theta}^k|\varnothing)}$$

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



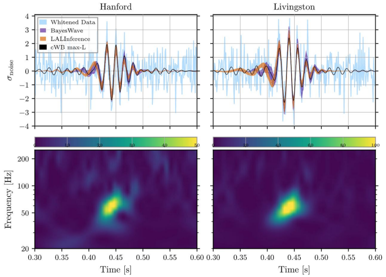




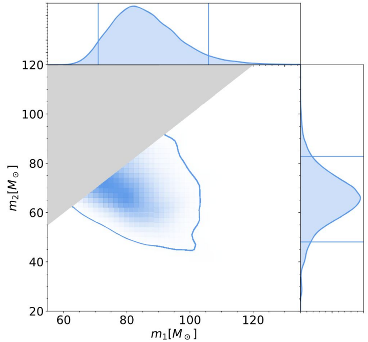


Hierarchical Bayesian Inference (no relation)

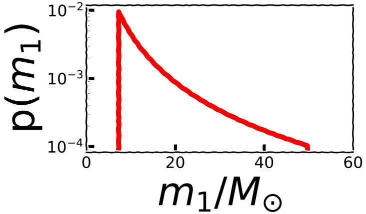
Data



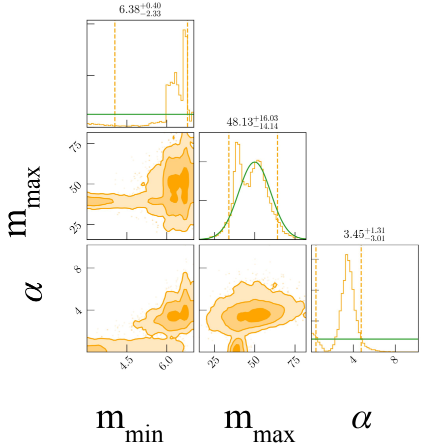
Source Parameters



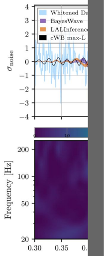
Population Model



Hyperposteriors



Hierarchical Bayesian Inference (no relation)

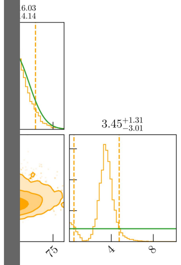


$$\mathcal{O}^{i}_{\mathrm{1G+2G}} = \frac{\int \mathrm{d}\boldsymbol{\Lambda} Z(d_i|\boldsymbol{\Lambda}, \mathrm{1G{+}2G})\zeta_{\mathrm{1G+2G}}(\boldsymbol{\Lambda})p(\boldsymbol{\Lambda}|\vec{d})}{\int \mathrm{d}\boldsymbol{\Lambda} Z(d_i|\boldsymbol{\Lambda}, \mathrm{1G{+}1G})\zeta_{\mathrm{1G+1G}}(\boldsymbol{\Lambda})p(\boldsymbol{\Lambda}|\vec{d})}$$

$$Z(d_i|\boldsymbol{\Lambda}, \mathrm{1G{+}2G}) = \int \mathrm{d}\boldsymbol{\theta} L(d_i|\boldsymbol{\theta})\pi(\boldsymbol{\theta}|\boldsymbol{\Lambda}, \mathrm{1G{+}2G})$$

Odds of hierarchical merger

osteriors

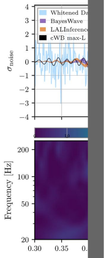


Hierarchical Bayesian Inference (no relation)

Hyperposterior

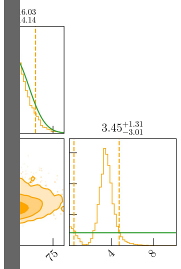
Branching fraction

osteriors



$$\mathcal{O}^{i}_{1G+2G} = \frac{\int d\boldsymbol{\Lambda} Z(d_i|\boldsymbol{\Lambda}, 1G+2G)\zeta_{1G+2G}(\boldsymbol{\Lambda})p(\boldsymbol{\Lambda}|\vec{d})}{\int d\boldsymbol{\Lambda} Z(d_i|\boldsymbol{\Lambda}, 1G+1G)\zeta_{1G+1G}(\boldsymbol{\Lambda})p(\boldsymbol{\Lambda}|\vec{d})}$$

$$Z(d_i|\boldsymbol{\Lambda}, 1G+2G) = \int d\boldsymbol{\theta} L(d_i|\boldsymbol{\theta})\pi(\boldsymbol{\theta}|\boldsymbol{\Lambda}, 1G+2G)$$



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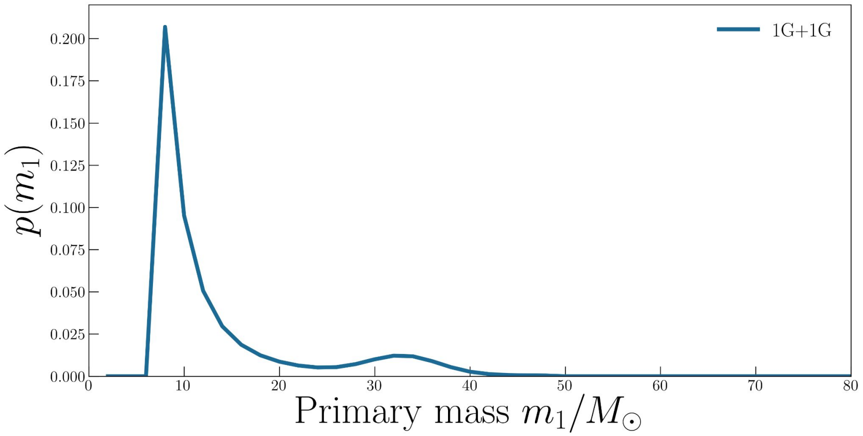
Parameter Likelihood

Population model

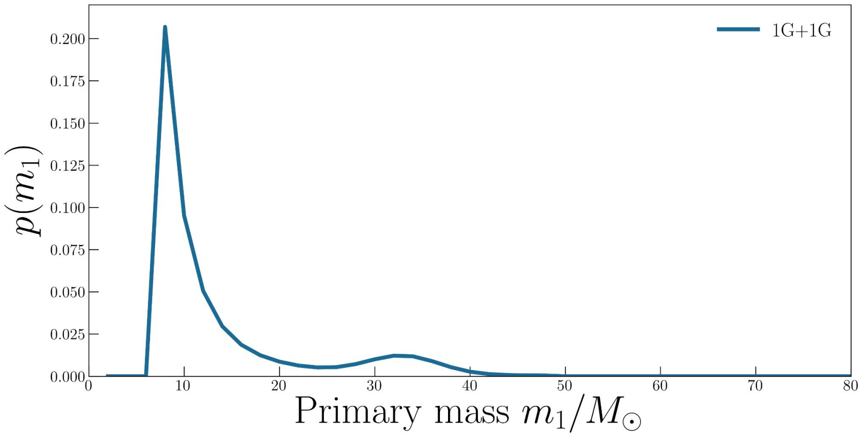
Odds of hierarchical merger

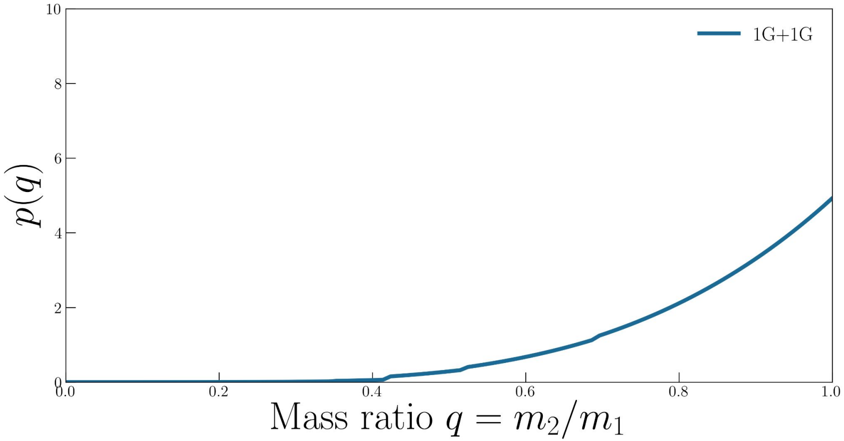
Parameterizing the hierarchical population

Parameterizing the hierarchical population



Parameterizing the hierarchical population





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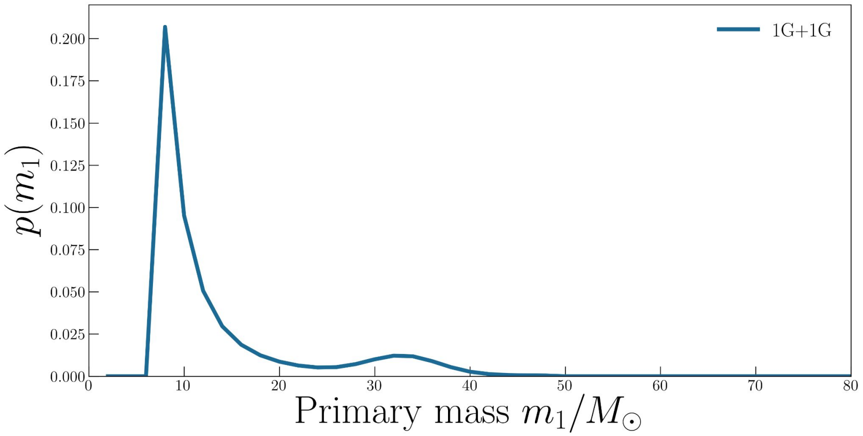
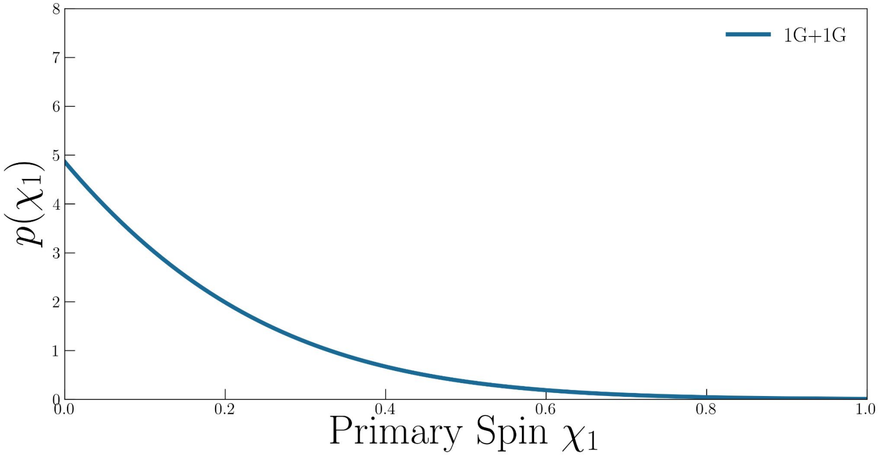
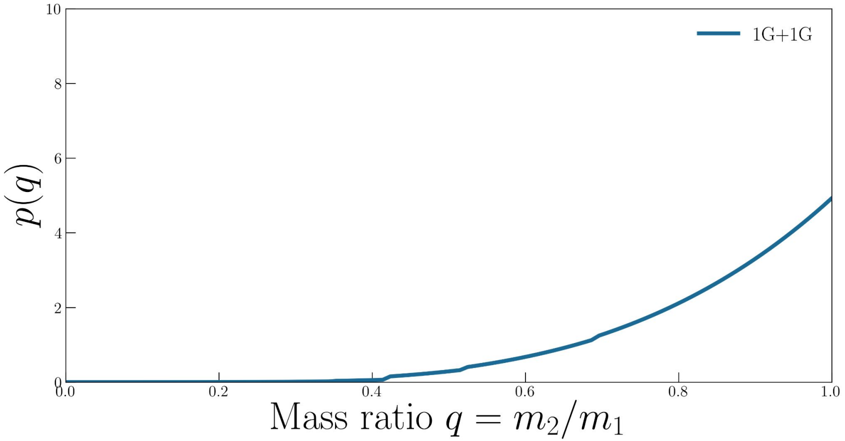
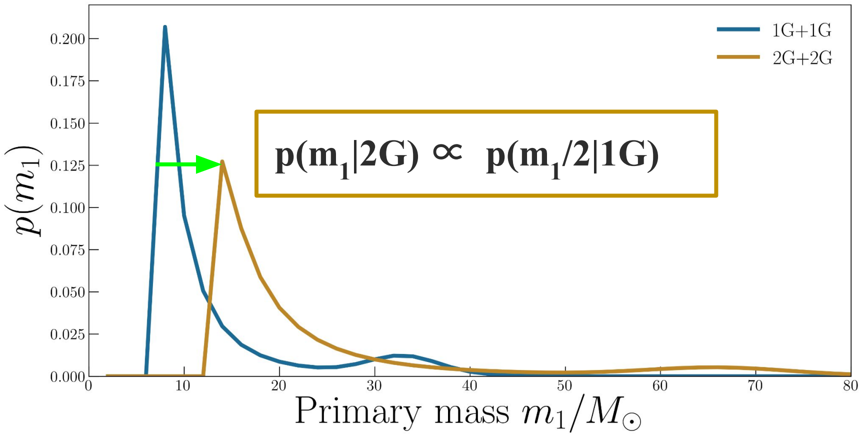
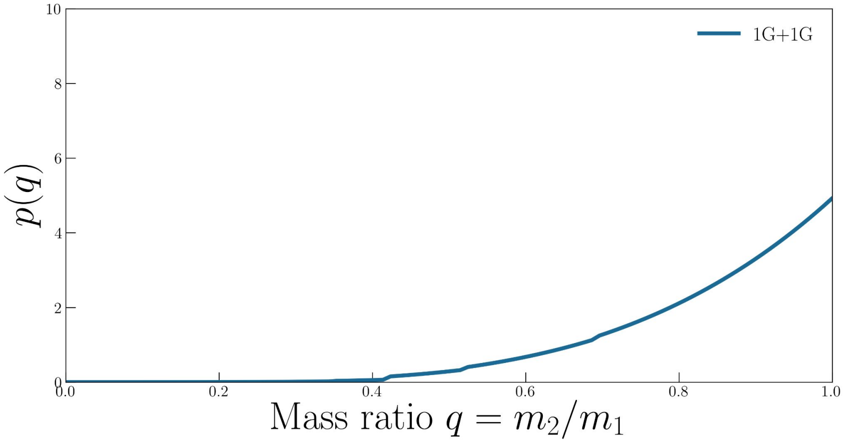


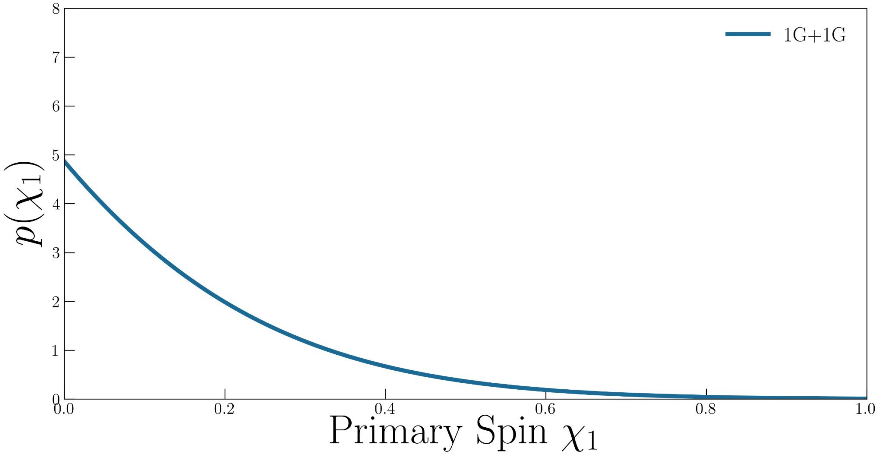




Parameterizing the hierarchical population







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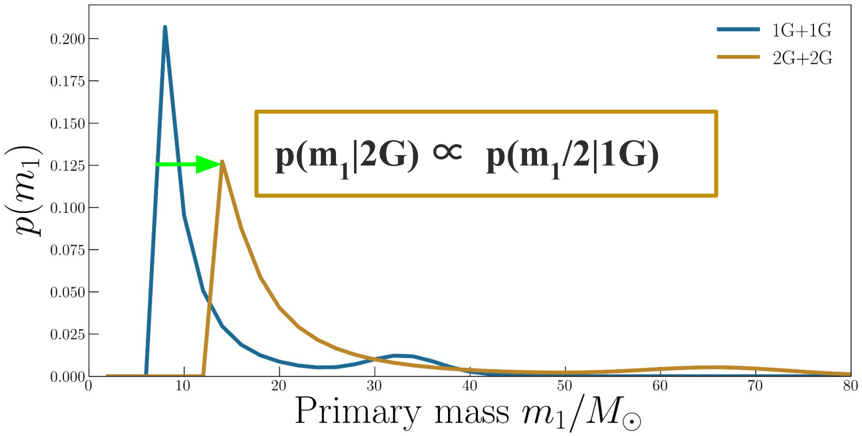

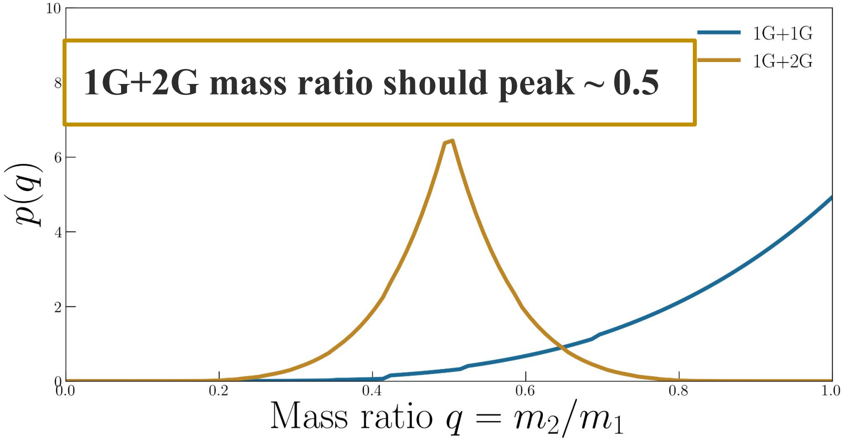

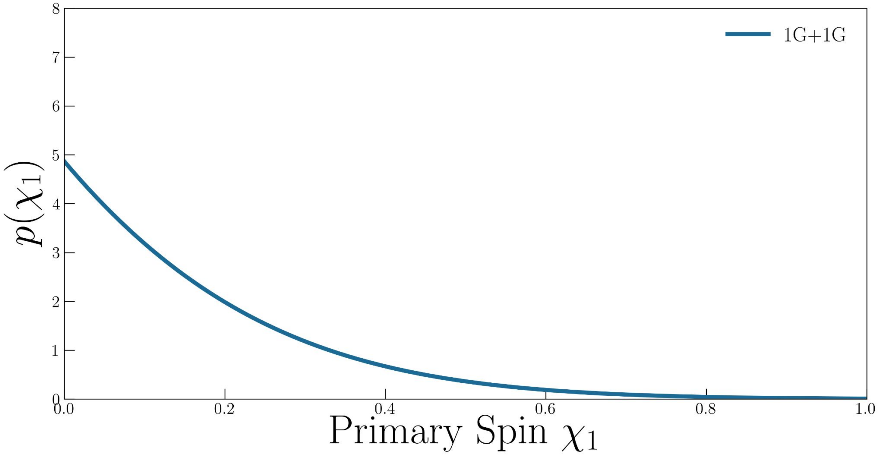

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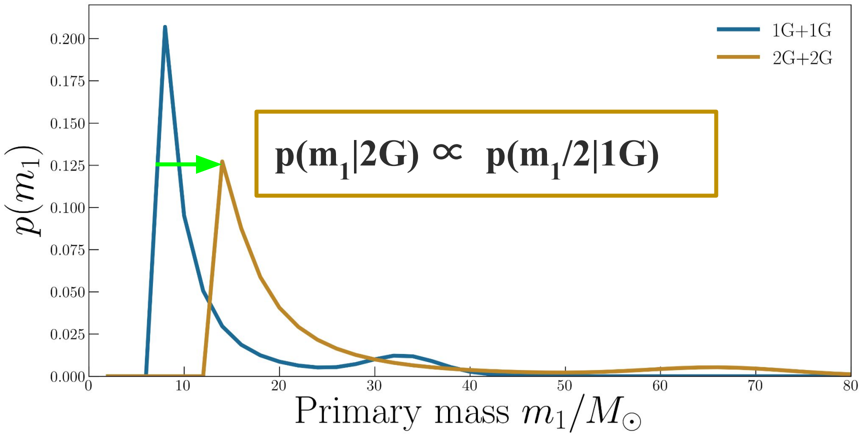
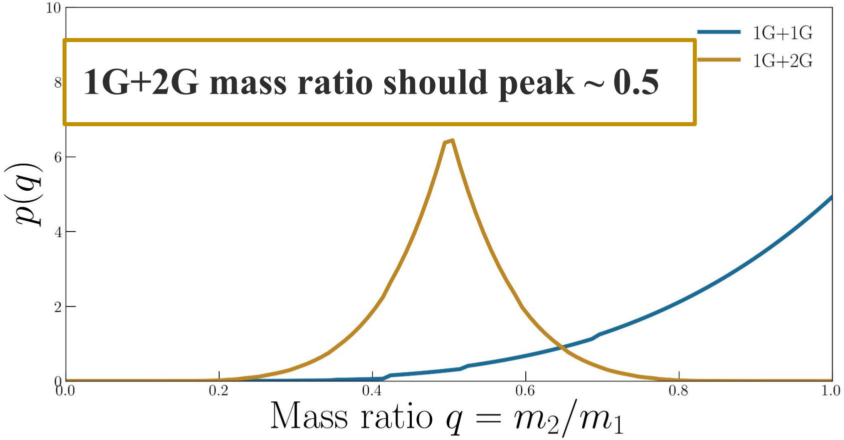
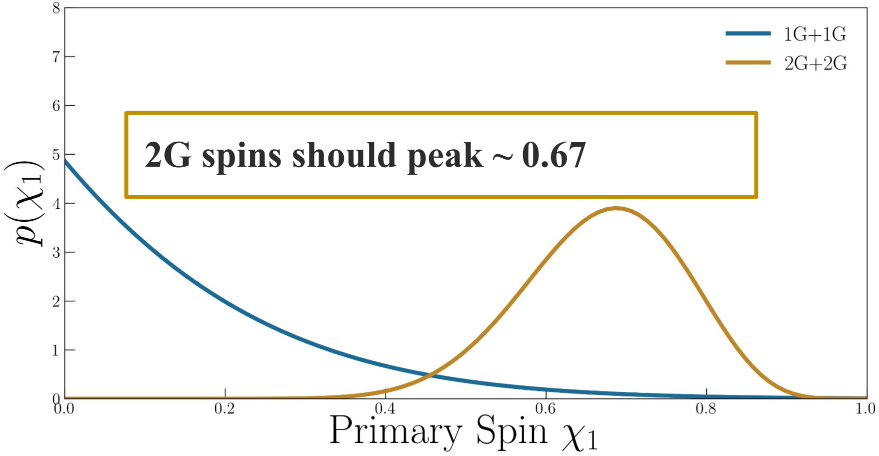
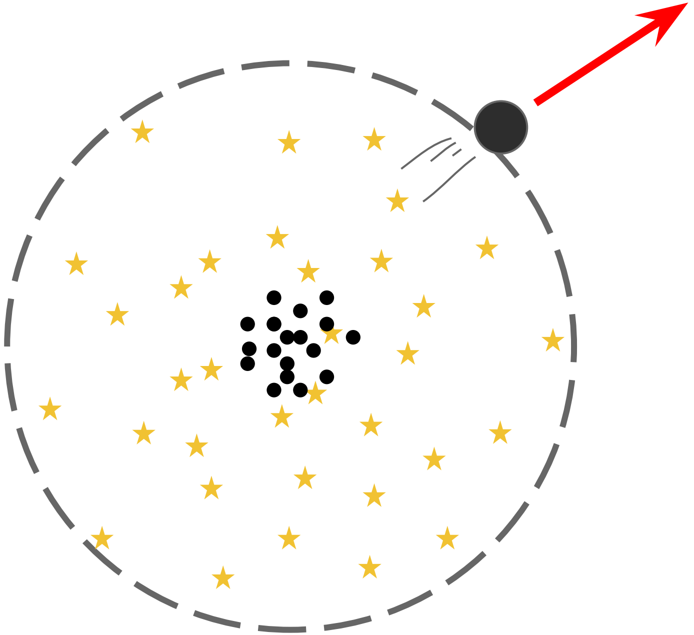




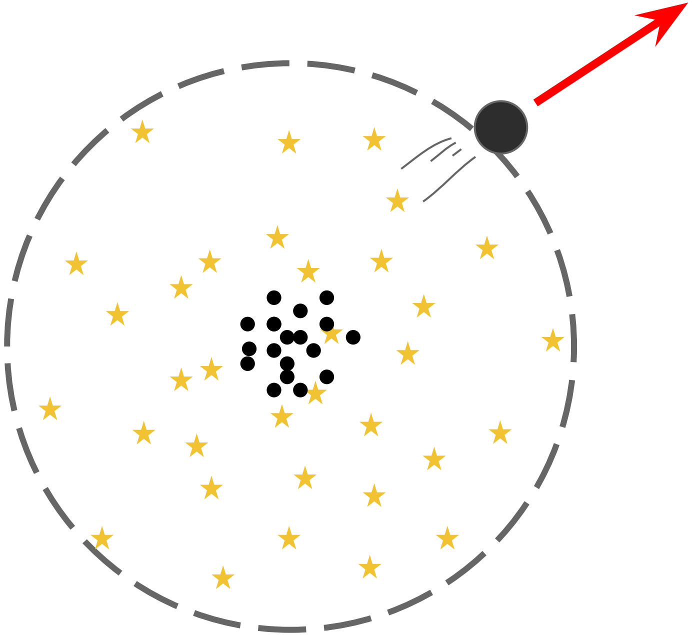


Calculating branching fractions



Calculating branching fractions

$$(\mathbf{x}_1, \mathbf{x}_2, \mathbf{q})$$



Calculating branching fractions

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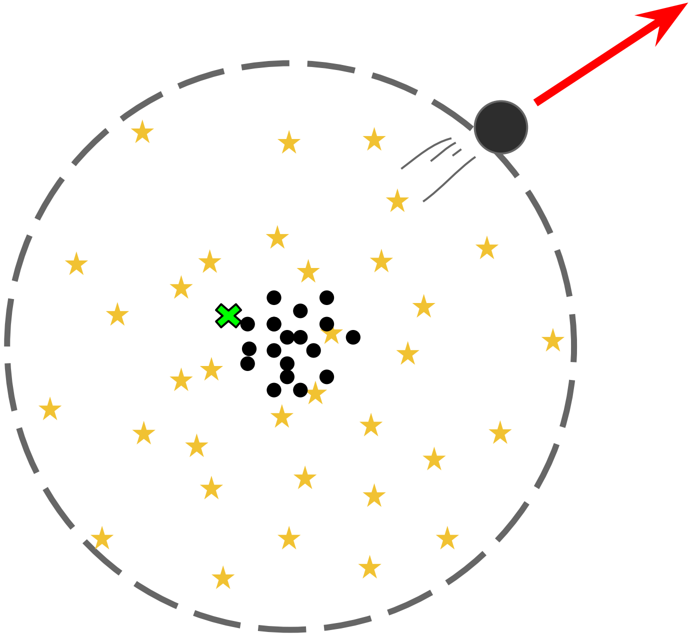

Calculating branching fractions

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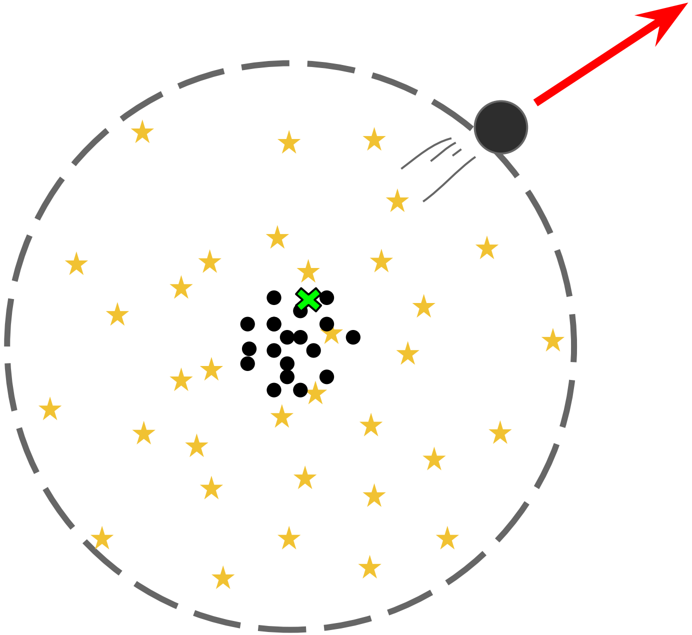
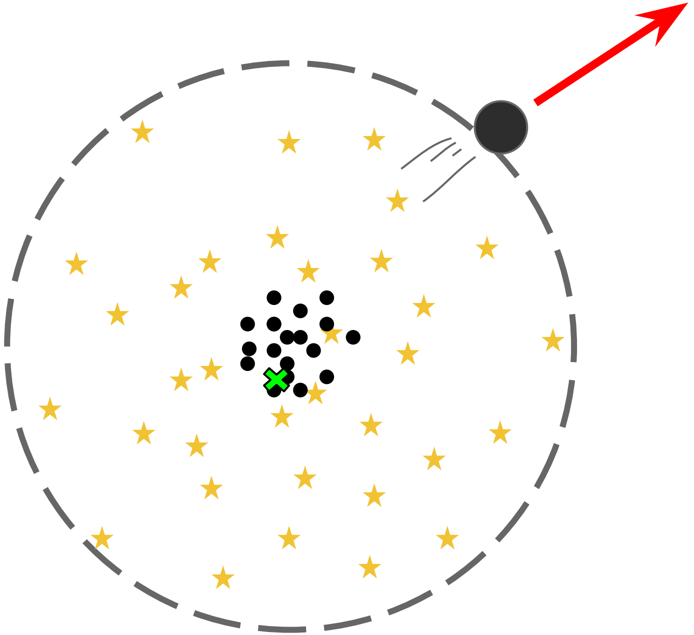


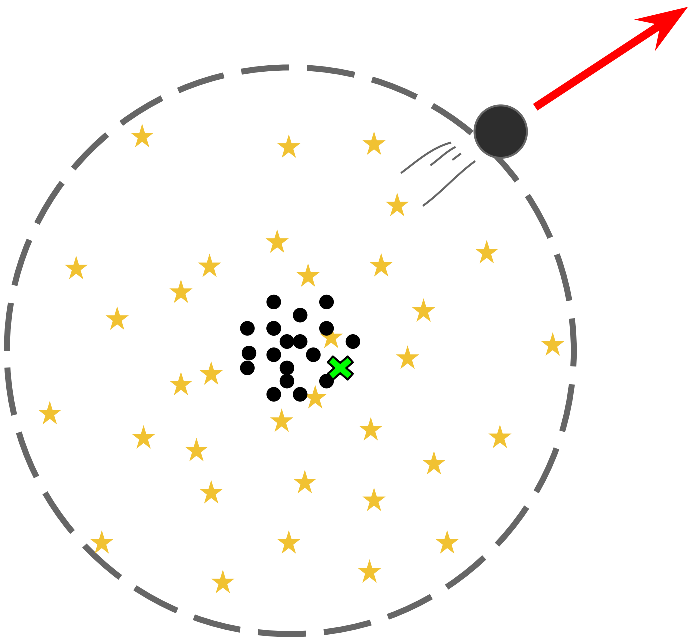
Calculating branching fractions

$$(\mathbf{x}_1, \mathbf{x}_2, \mathbf{q})$$



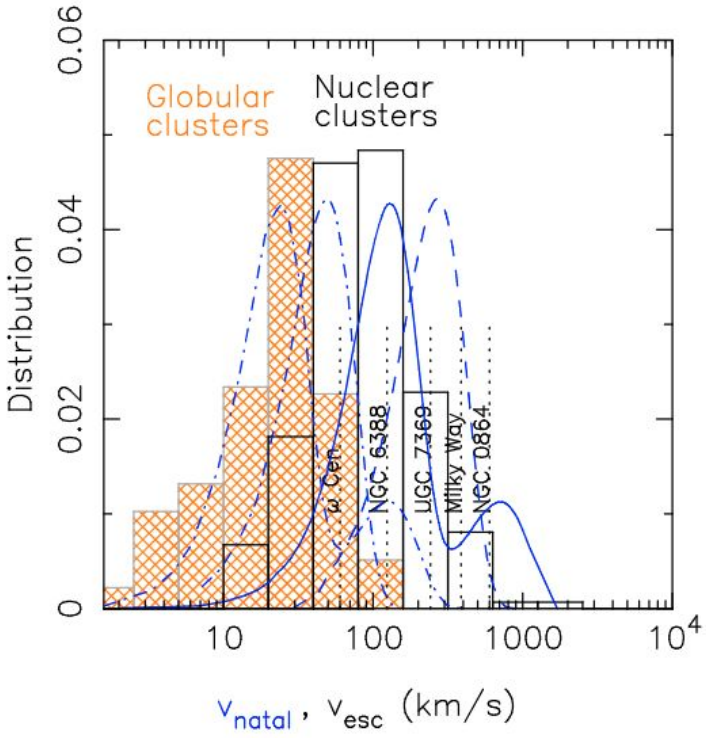
Calculating branching fractions

$$(\mathbf{x}_1, \mathbf{x}_2, \mathbf{q})$$

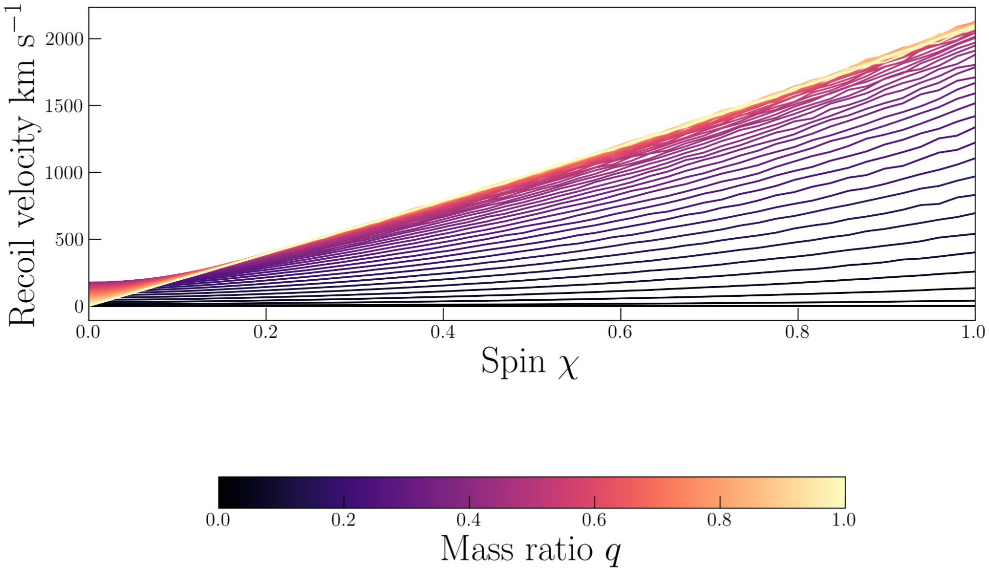


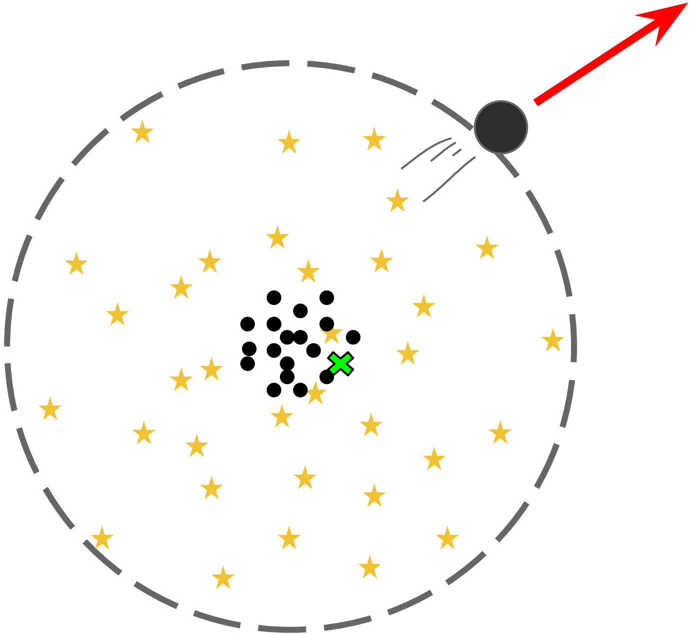
Calculating branching fractions

$$(\chi_1, \chi_2, q)$$



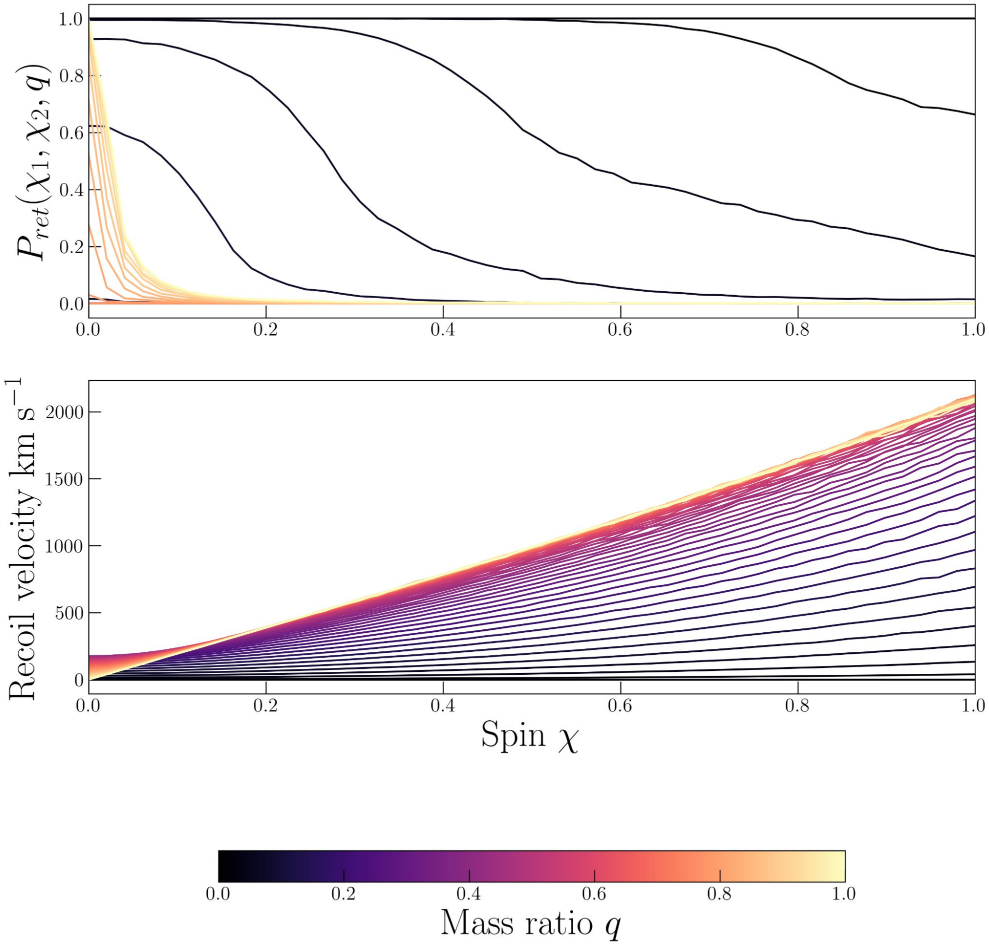
Calculating branching fractions

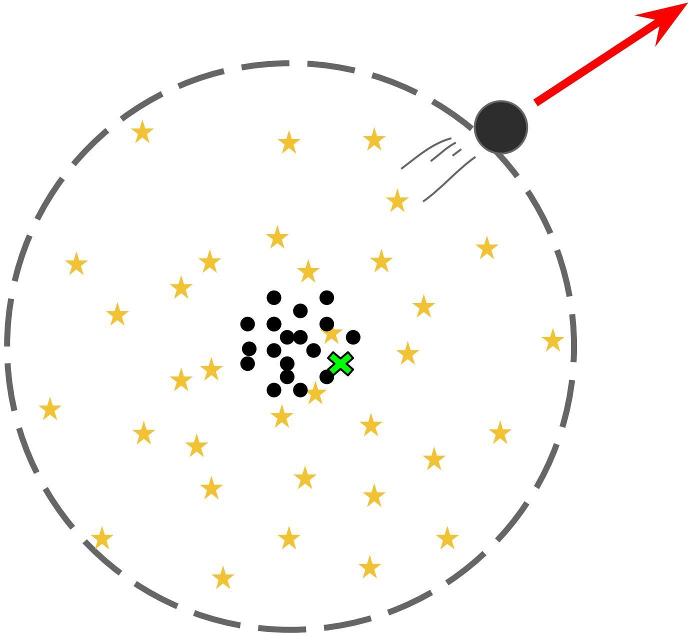




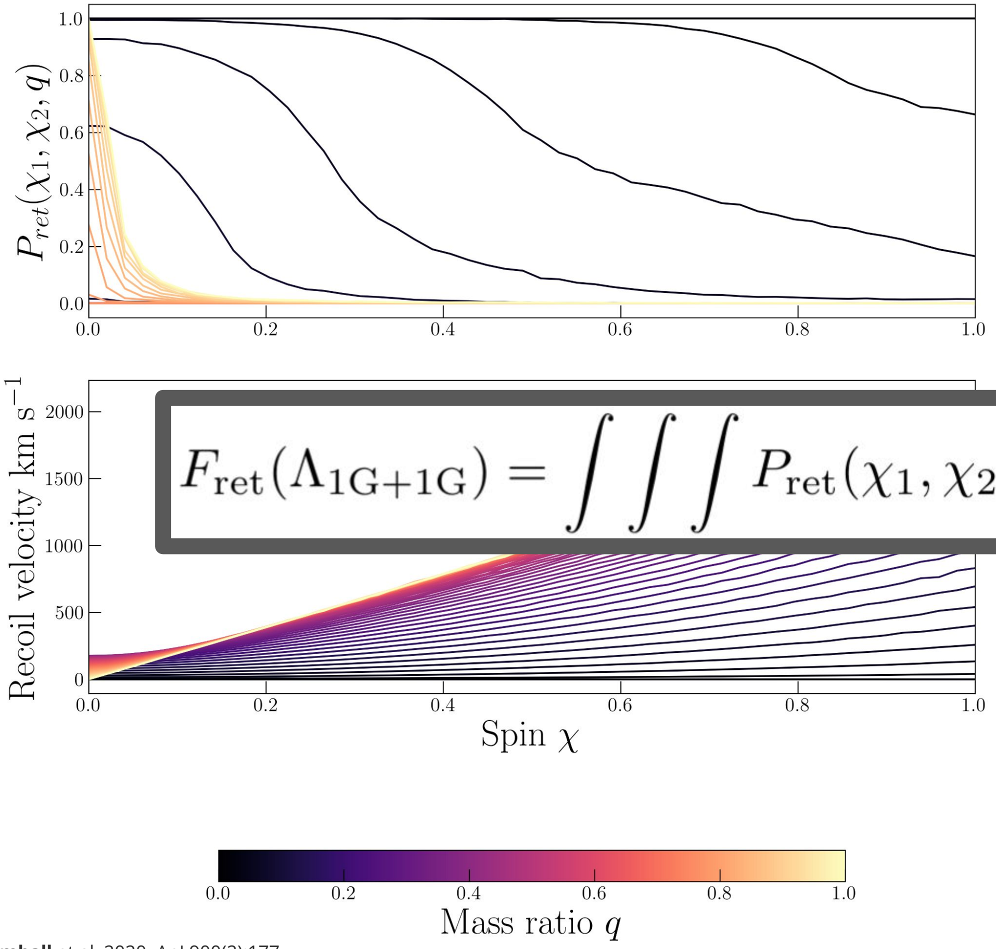
Kimball et al. 2020, ApJ 900(2):177

Calculating branching fractions

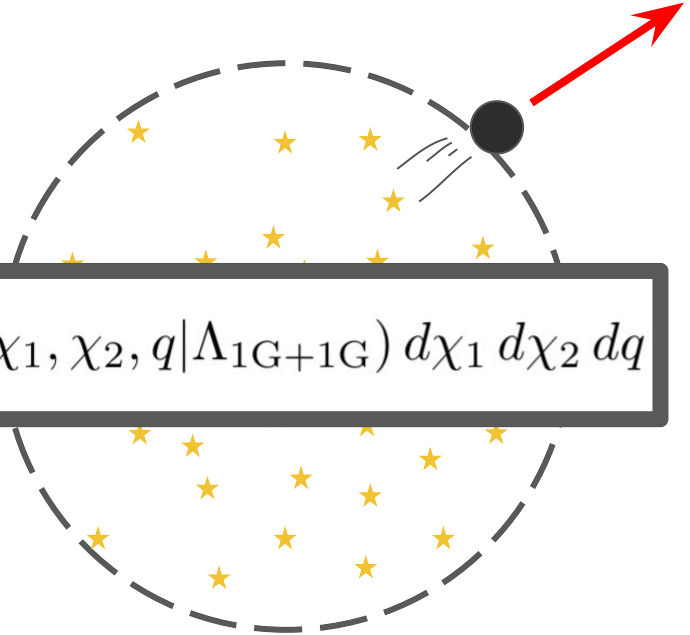




Kimball et al. 2020, ApJ 900(2):177



$$F_{\rm ret}(\Lambda_{\rm 1G+1G}) = \int\int\int P_{\rm ret}(\chi_1, \chi_2, q)\, \pi(\chi_1, \chi_2, q|\Lambda_{\rm 1G+1G})\, d\chi_1\, d\chi_2\, dq$$



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

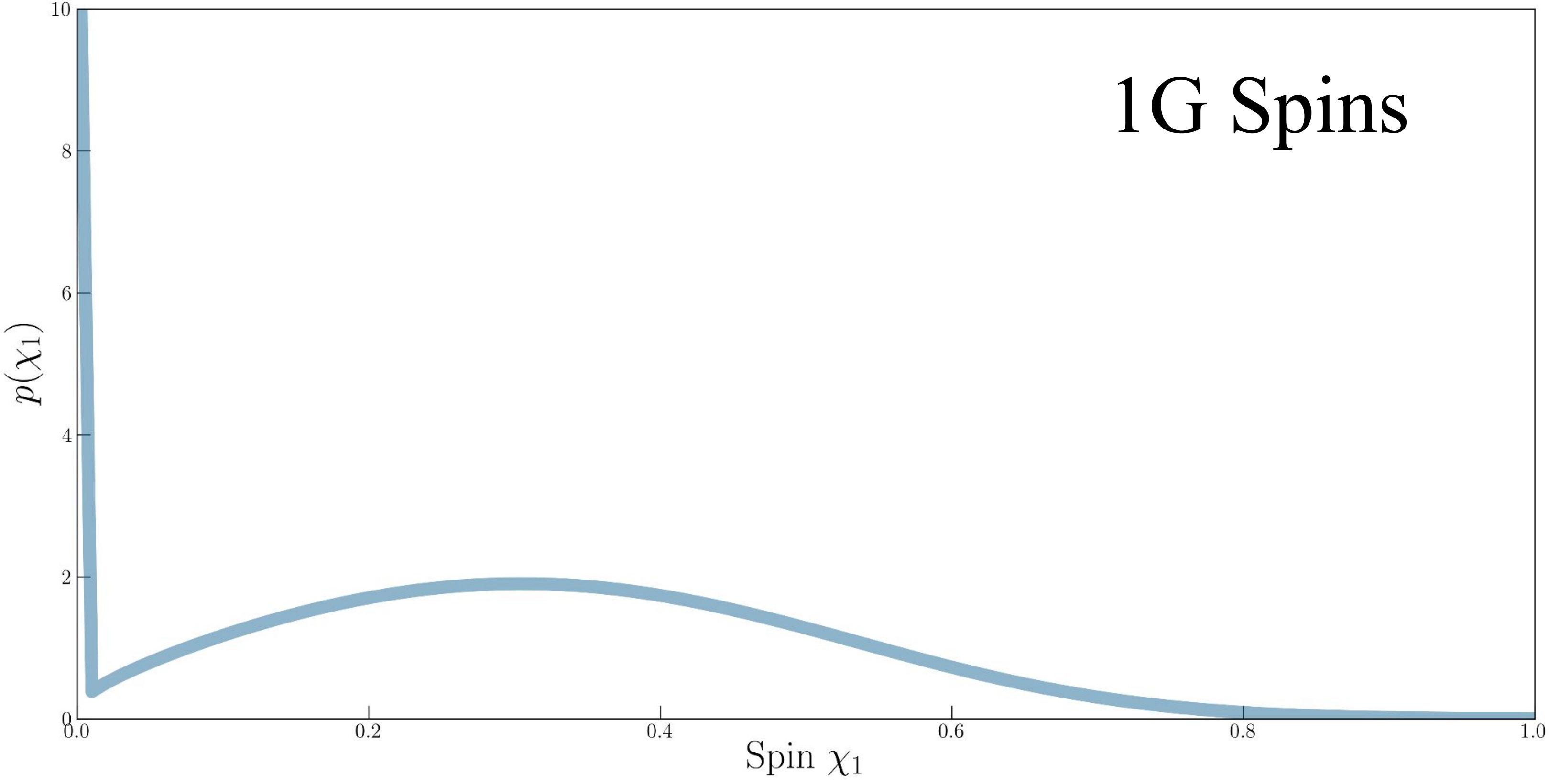
Key Results

Lessons from GWTC-1

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

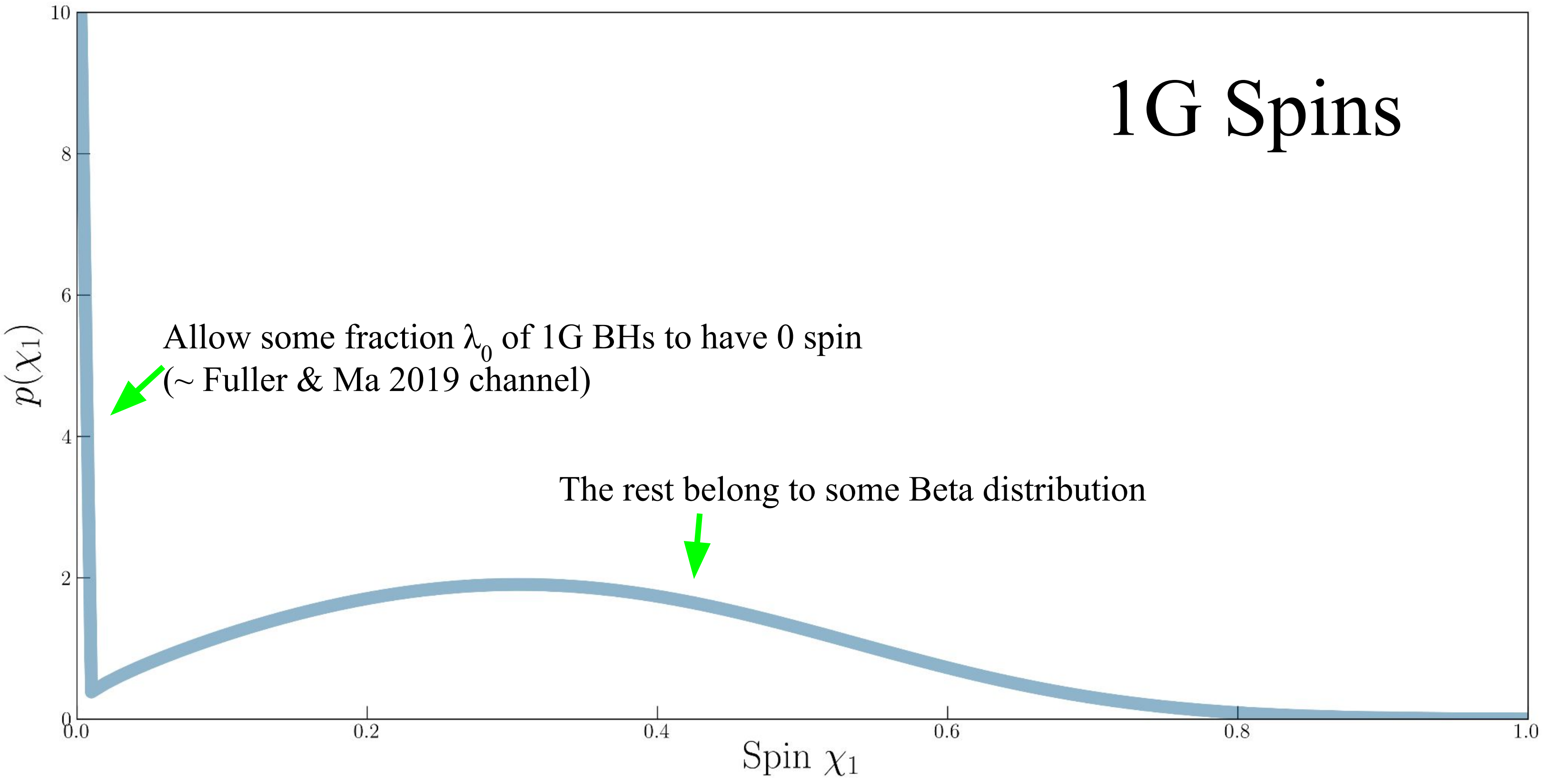
Lessons from GWTC-1

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



Lessons from GWTC-1

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



Lessons from GWTC-1

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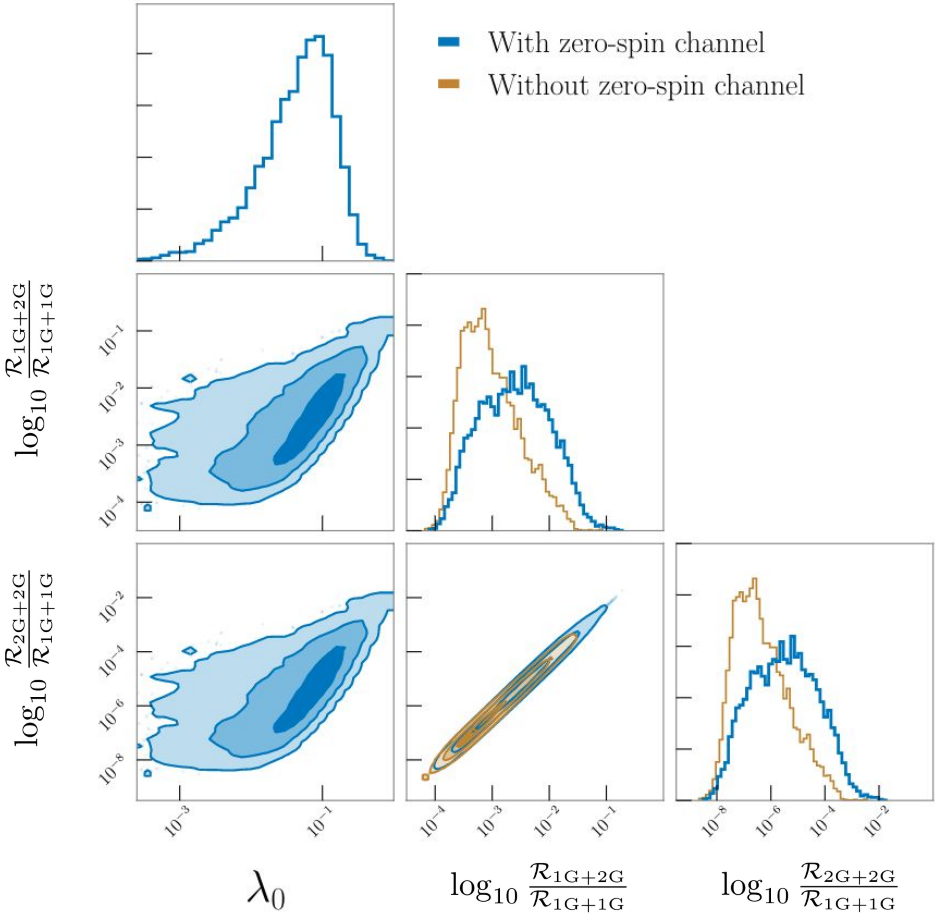

Lessons from GWTC-1

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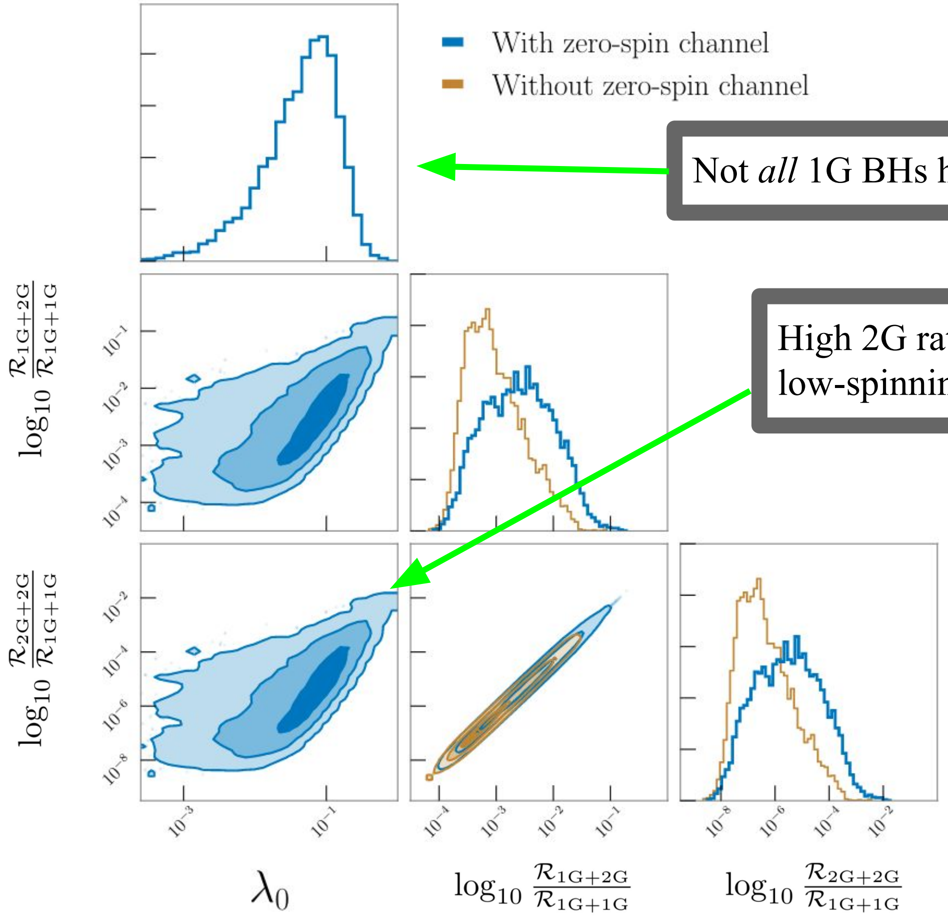
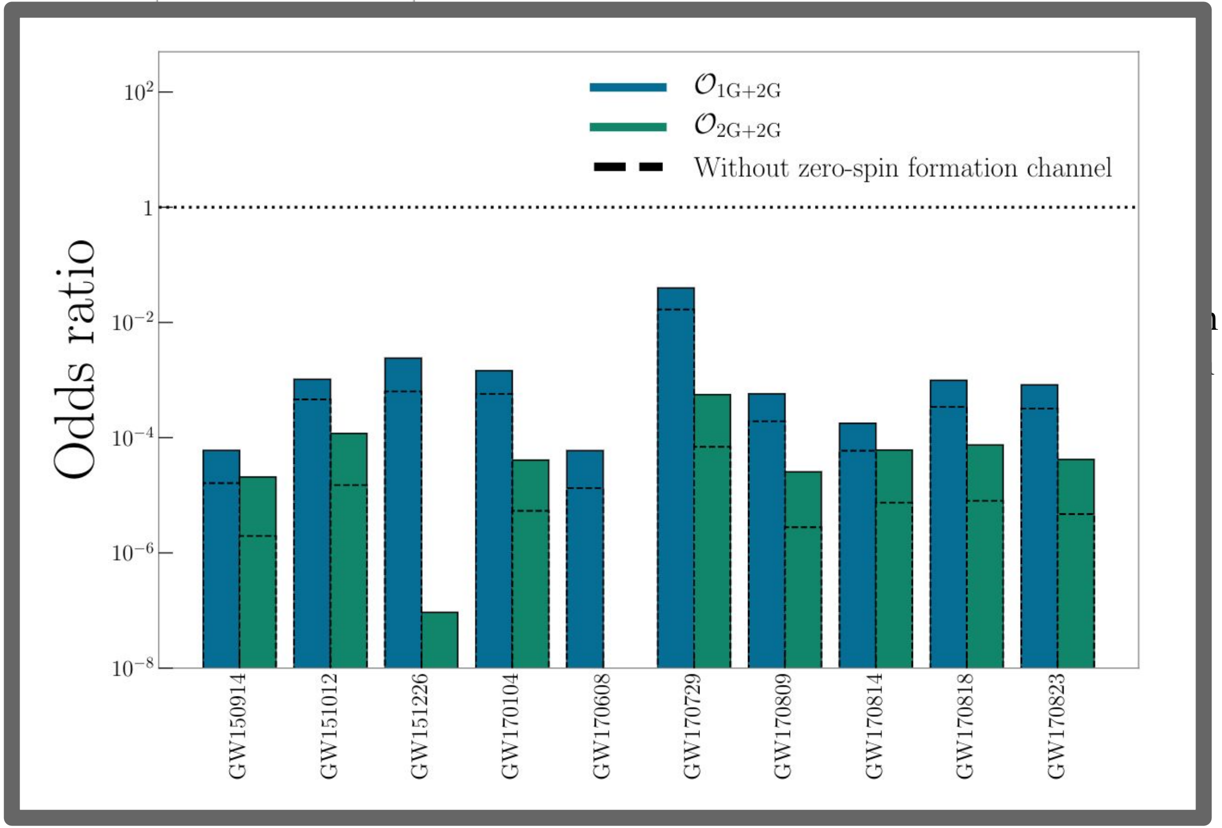


Not *all* 1G BHs have 0 spin

High 2G rates correlate with low-spinning 1G population

Lessons from GWTC-1

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



λ_0 $\log_{10}\frac{\mathcal{R}_{1G+2G}}{\mathcal{R}_{1G+1G}}$ $\log_{10}\frac{\mathcal{R}_{2G+2G}}{\mathcal{R}_{1G+1G}}$

Less

The Astrophysical Journal Letters, 900:L13 (27pp), 2020 September 1 Abbott et al.

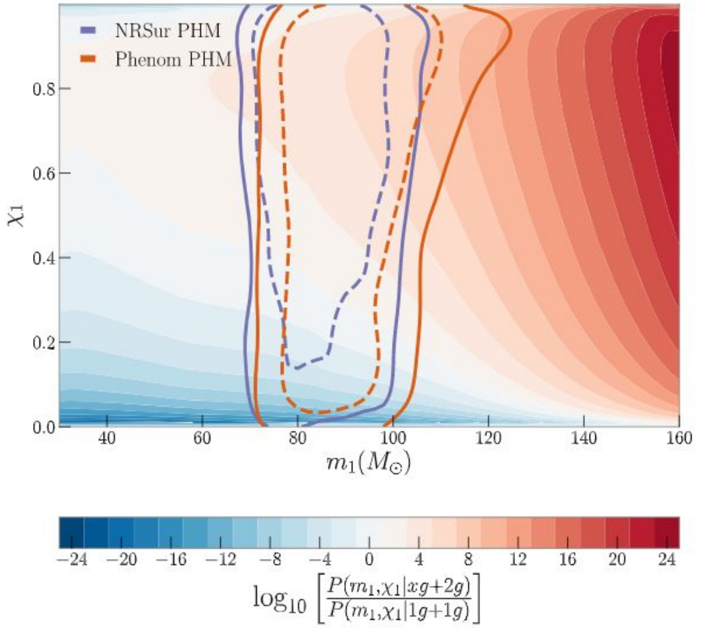


Figure 11. Marginalized Bayes factor for a BBH to be a second-generation merger (1g+2g or 2g+2g) as opposed to a first-generation BH merger, as a function of primary mass and spin, in the globular cluster analysis of Section 5.2.1 using a physically motivated prior cutoff on 1g BH masses. The Bayes factor contours correspond to component masses and spins inferred using the NRSur PHM model for GW190521 and differ only slightly from those found using the Phenom PHM model. We show the 90% and 68% posterior credible regions for GW190521 as solid and dashed contours, respectively, for both the NRSur PHM and Phenom PHM models.

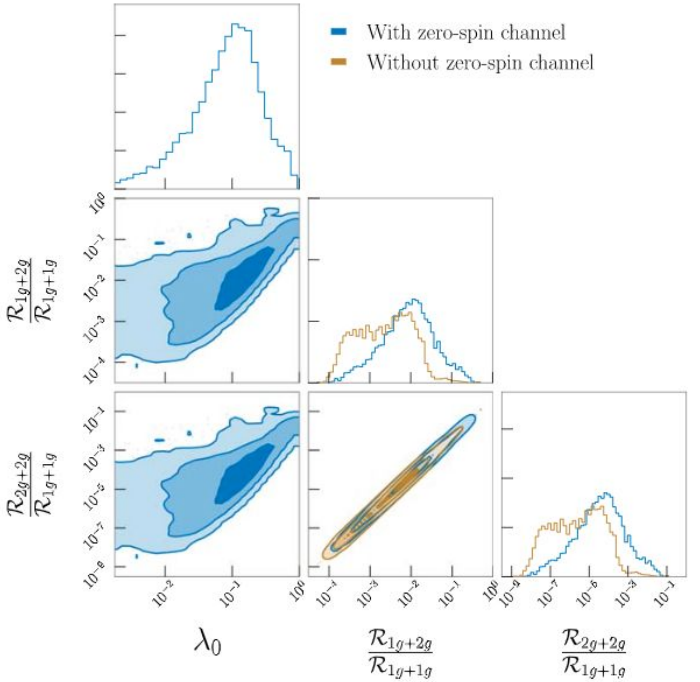


Figure 12. Relative rates of 1g+2g and 2g+2g as compared to first-generation mergers, in globular cluster models with (blue) and without (orange) a zero-spin stellar BH population (see Section 5.2.1), using GW190521 source parameters derived from NRSur PHM. In the model with zero-spin population, we also plot the fraction λ_0 of 1g+1g binary components belonging to this population.

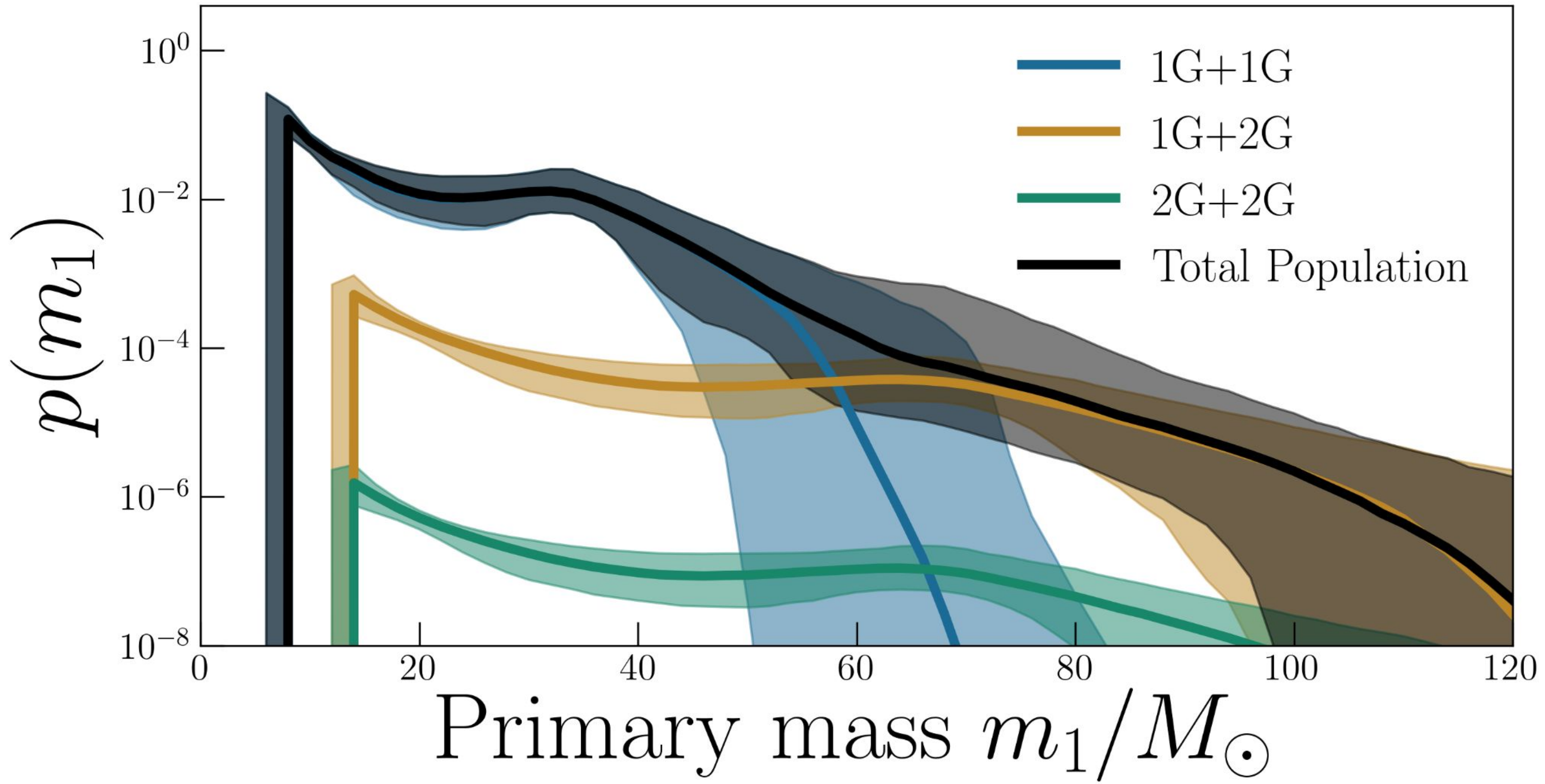
λ_0 $\log_{10}\frac{\mathcal{R}_{1G+2G}}{\mathcal{R}_{1G+1G}}$ $\log_{10}\frac{\mathcal{R}_{2G+2G}}{\mathcal{R}_{1G+1G}}$

Lessons from GWTC-2

Kimball et al. 2021, ApJ Letters 915(2), L35

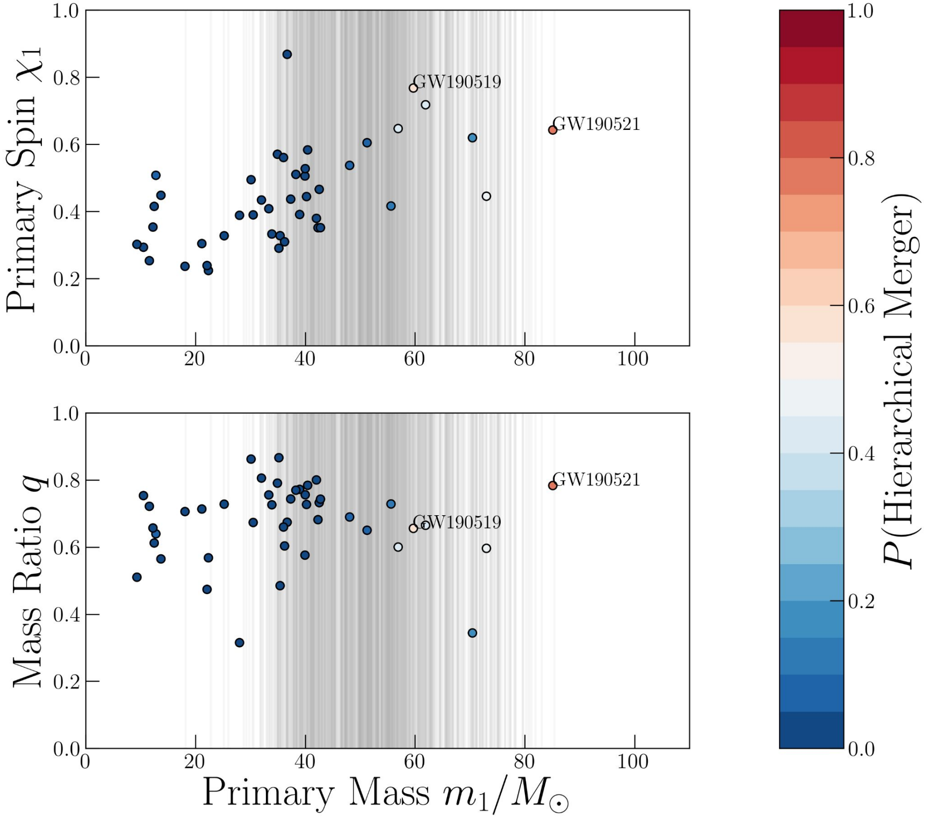
Lessons from GWTC-2

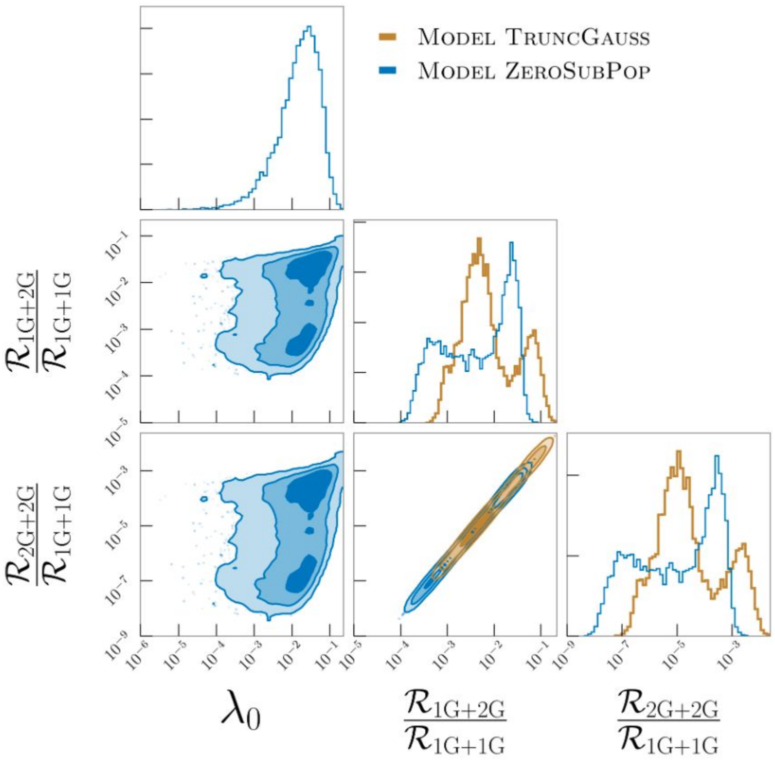
Kimball et al. 2021, ApJ Letters 915(2), L35



Lessons from GWTC-2

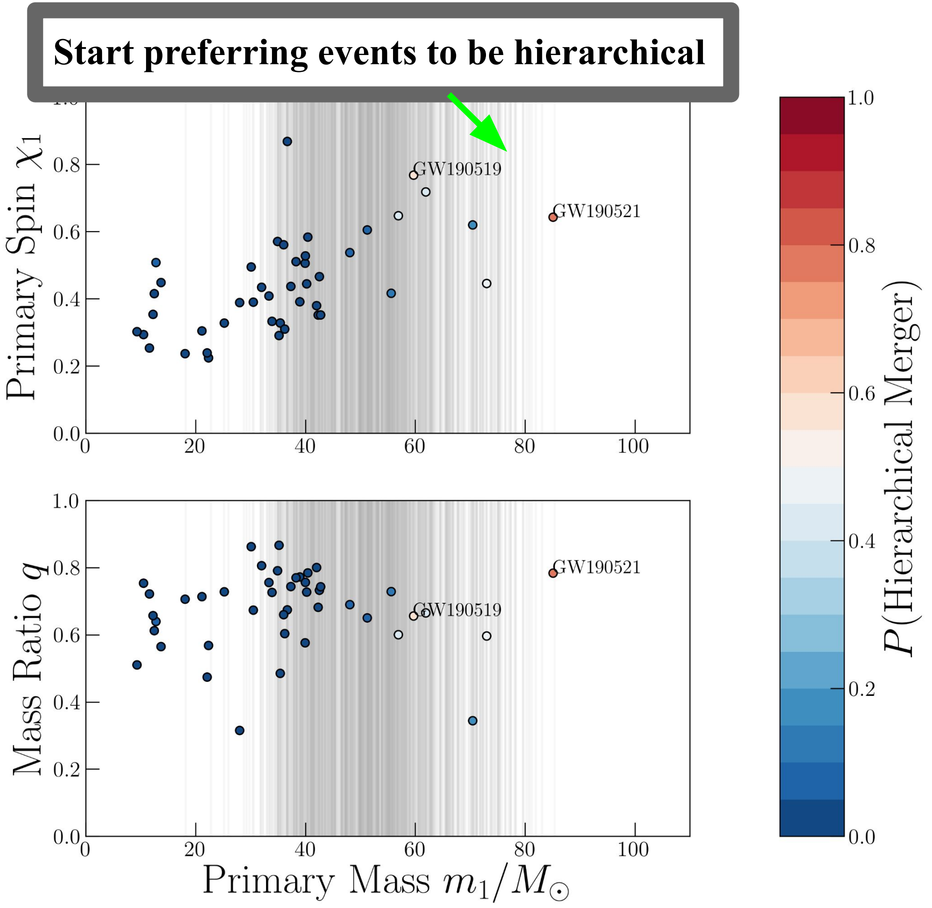
Kimball et al. 2021, ApJ Letters 915(2), L35

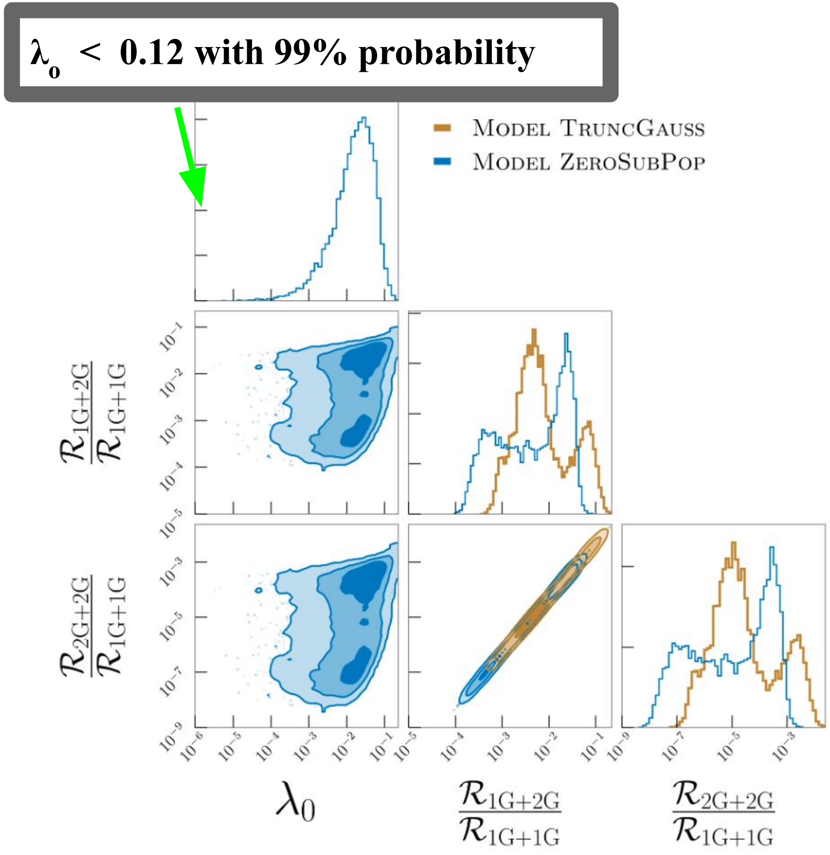




Lessons from GWTC-2

Kimball et al. 2021, ApJ Letters 915(2), L35



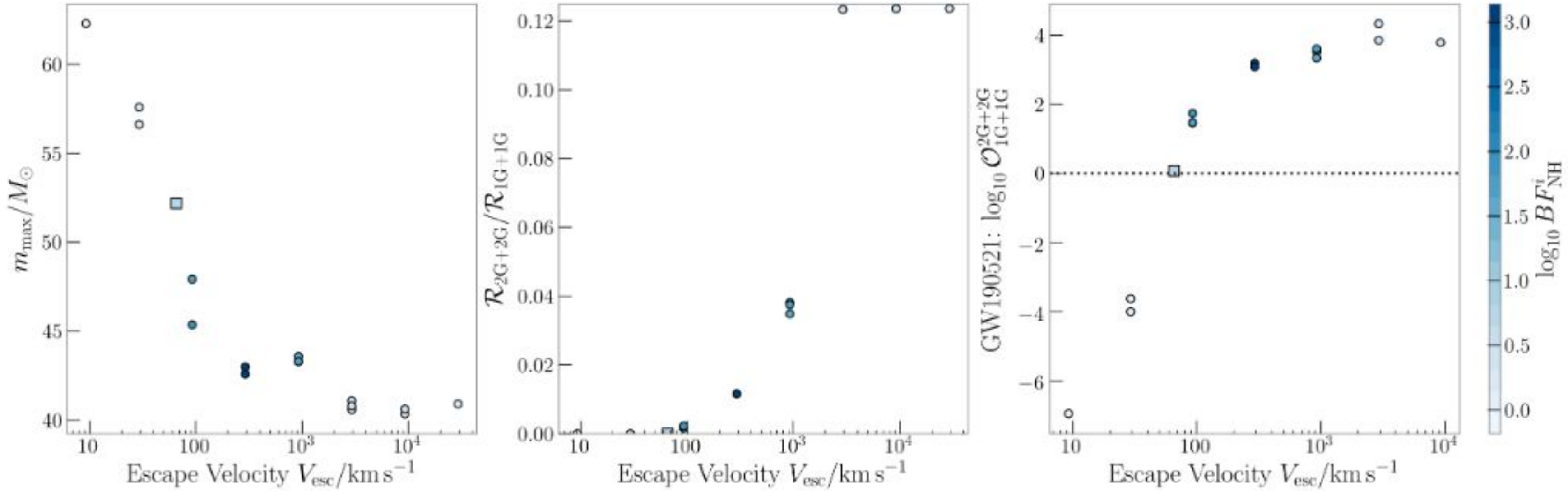


Lessons from GWTC-2

Kimball et al. 2021, ApJ Letters 915(2), L35

Increasing escape velocity

More reasonable m_{max} → More next gen mergers → GW190521 solidly 2G+2G



Lessons from GWTC-2

Kimball et al. 2021, ApJ Letters 915(2), L35

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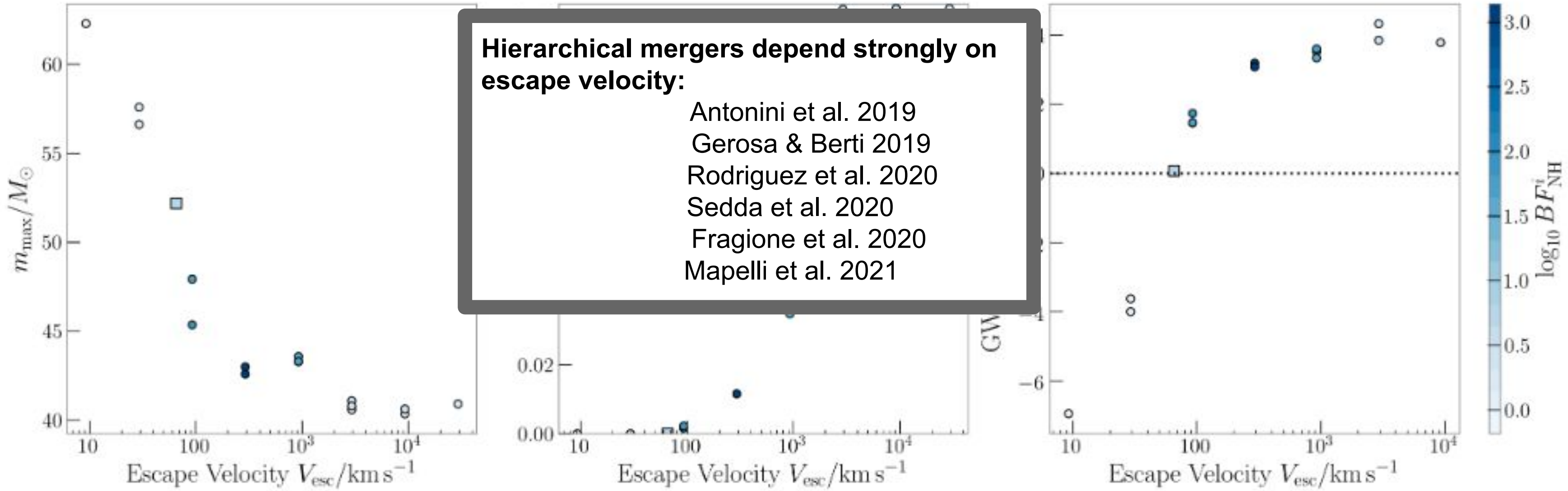
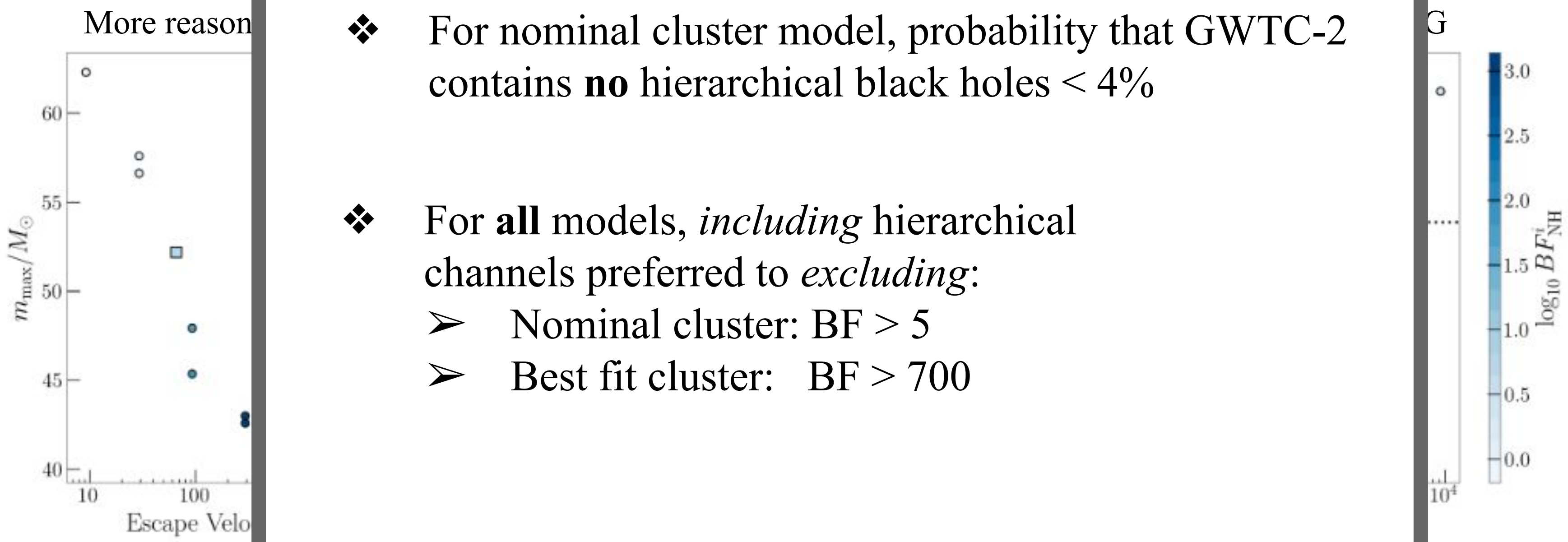


Hierarchical mergers depend strongly on escape velocity:

Antonini et al. 2019
Gerosa & Berti 2019
Rodriguez et al. 2020
Sedda et al. 2020
Fragione et al. 2020
Mapelli et al. 2021

Lessons from GWTC-2

Kimball et al. 2021, ApJ Letters 915(2), L35



- ❖ For nominal cluster model, probability that GWTC-2 contains **no** hierarchical black holes < 4%

- ❖ For **all** models, *including* hierarchical channels preferred to *excluding*:
  - ➢ Nominal cluster: BF > 5
  - ➢ Best fit cluster: BF > 700

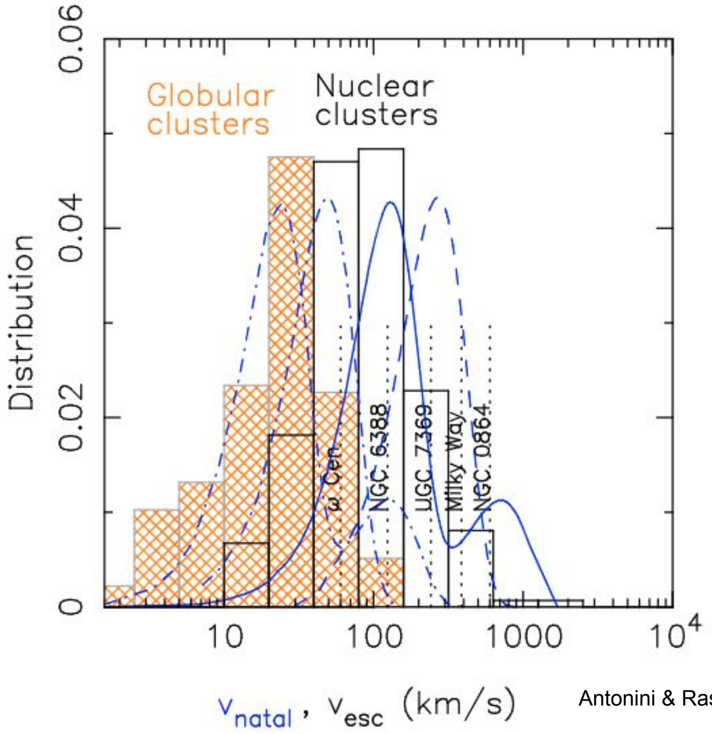
Preview of GWTC-3

Kimball et al. 2022, In-prep

Preview of GWTC-3

Kimball et al. 2022, In-prep

PRELIMINARY

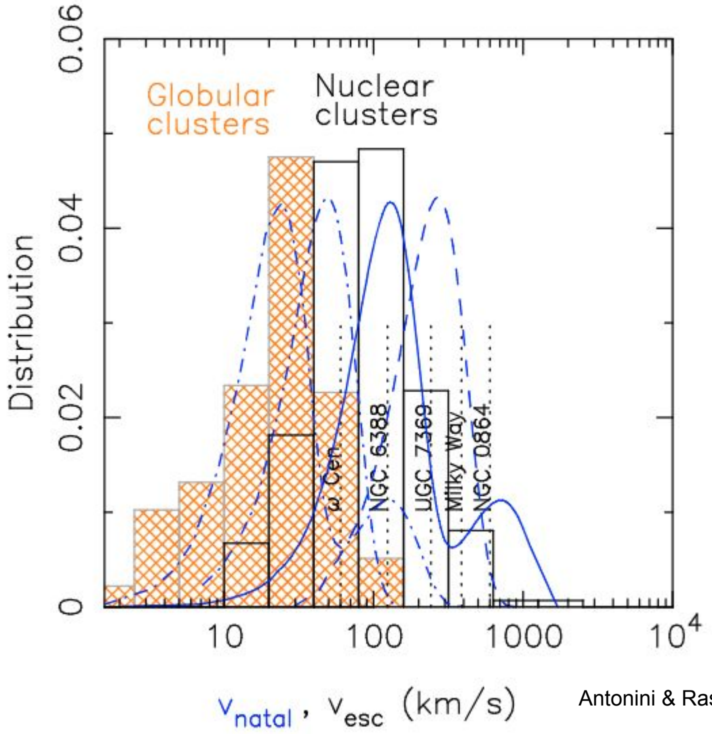


Antonini & Rasio 2016

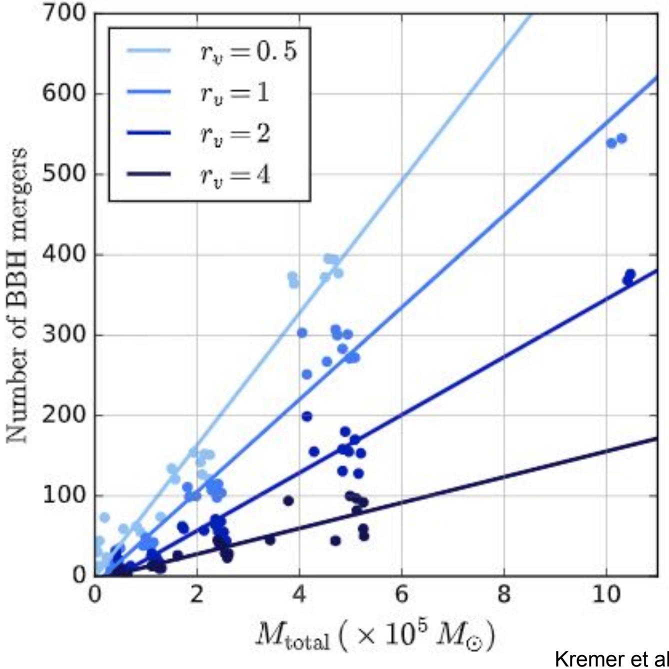
Preview of GWTC-3

Kimball et al. 2022, In-prep

PRELIMINARY



Antonini & Rasio 2016

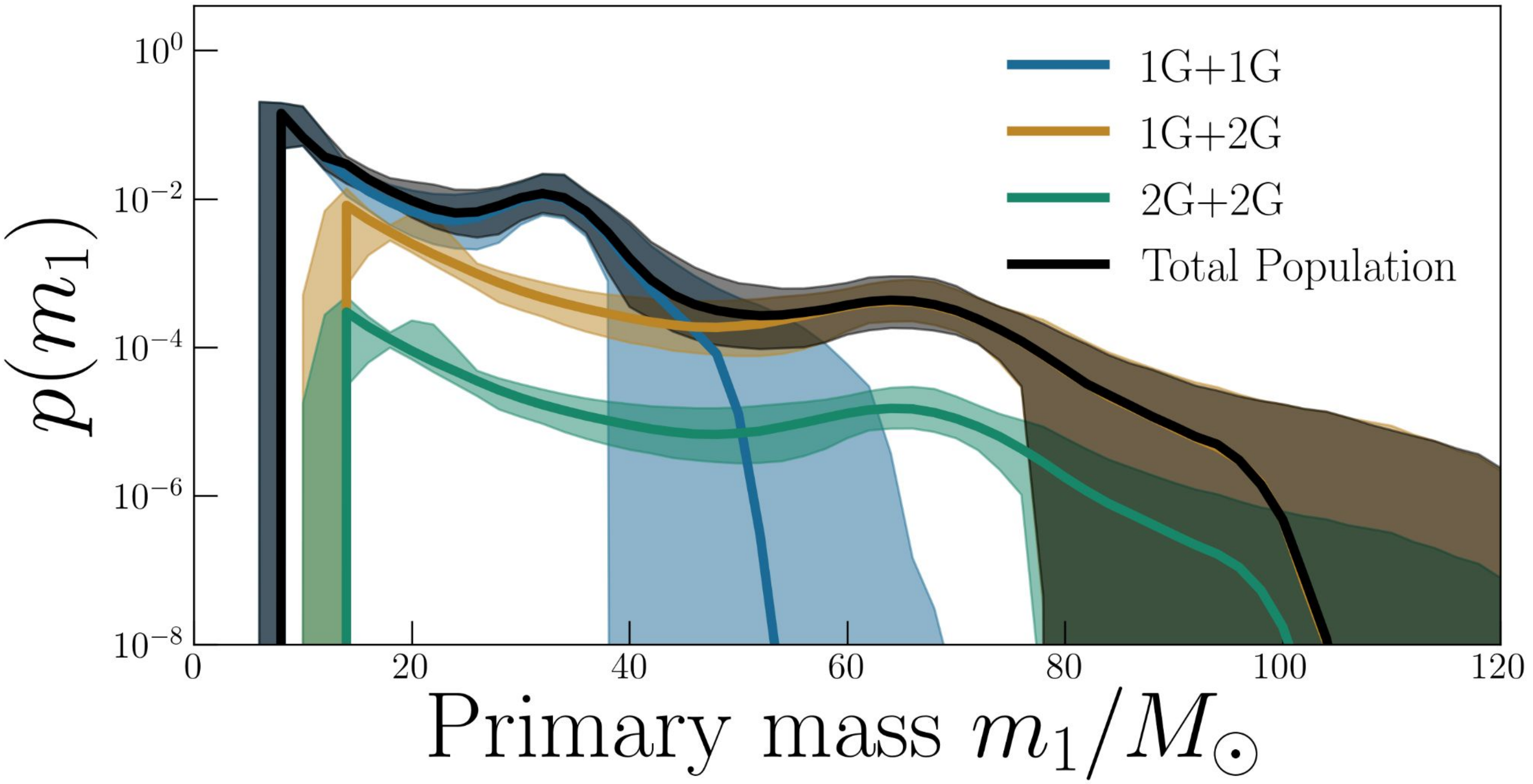


Kremer et al. 2020

Preview of GWTC-3

Kimball et al. 2022, In-prep

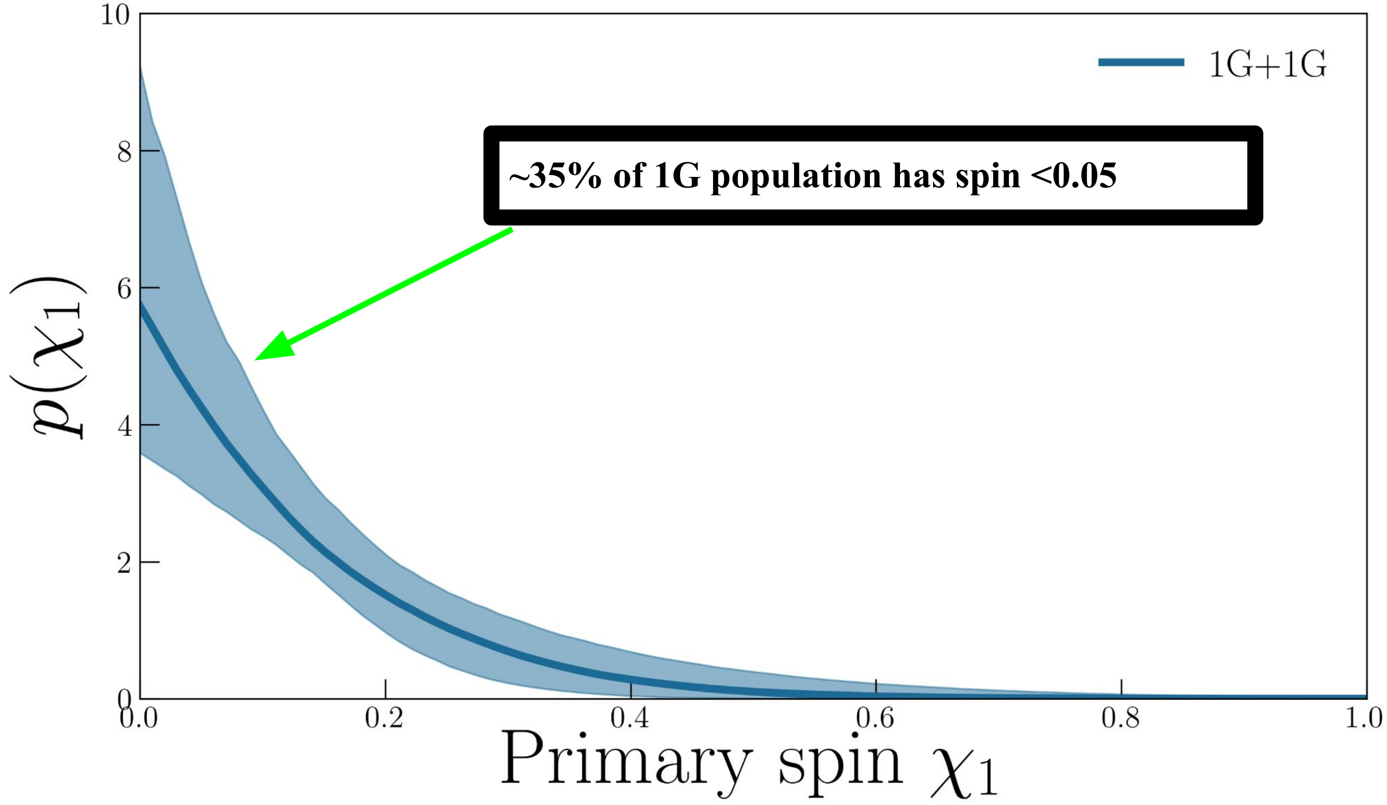
PRELIMINARY



Preview of GWTC-3

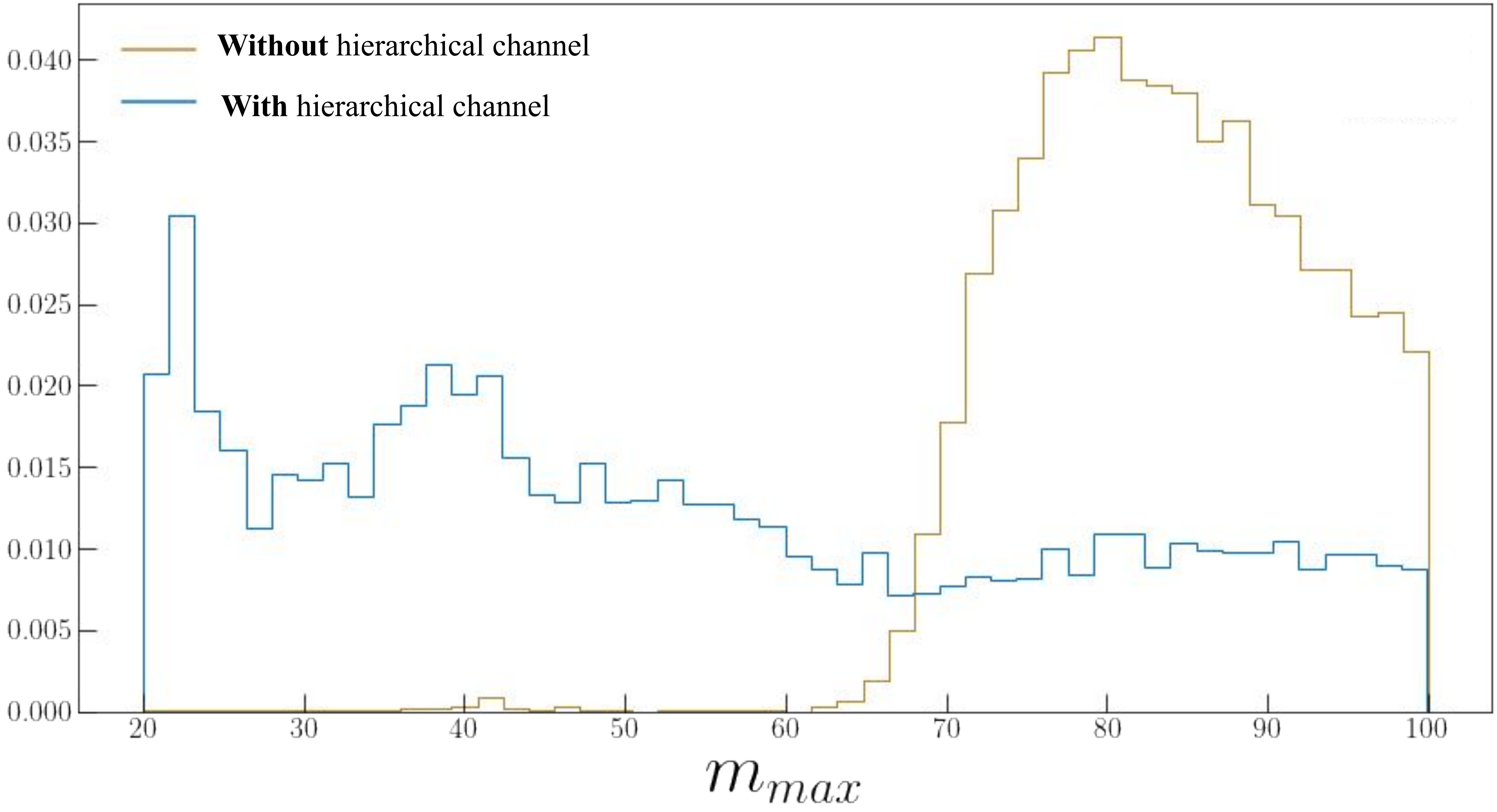
Kimball et al. 2022, In-prep

PRELIMINARY



Preview of GWTC-3

Kimball et al. 2022, In-prep



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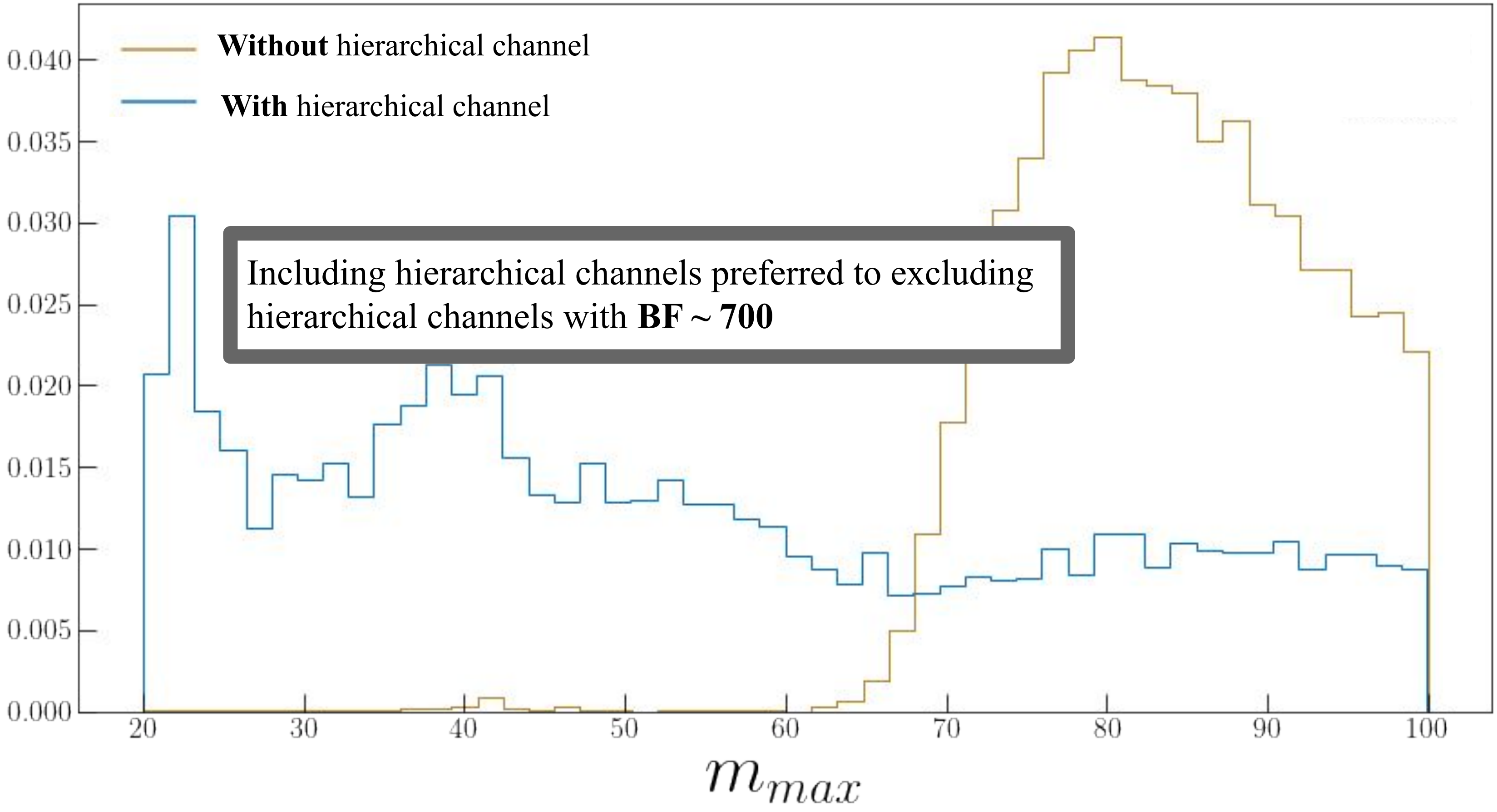
Kimball et al. 2022, In-prep

PRELIMINARY

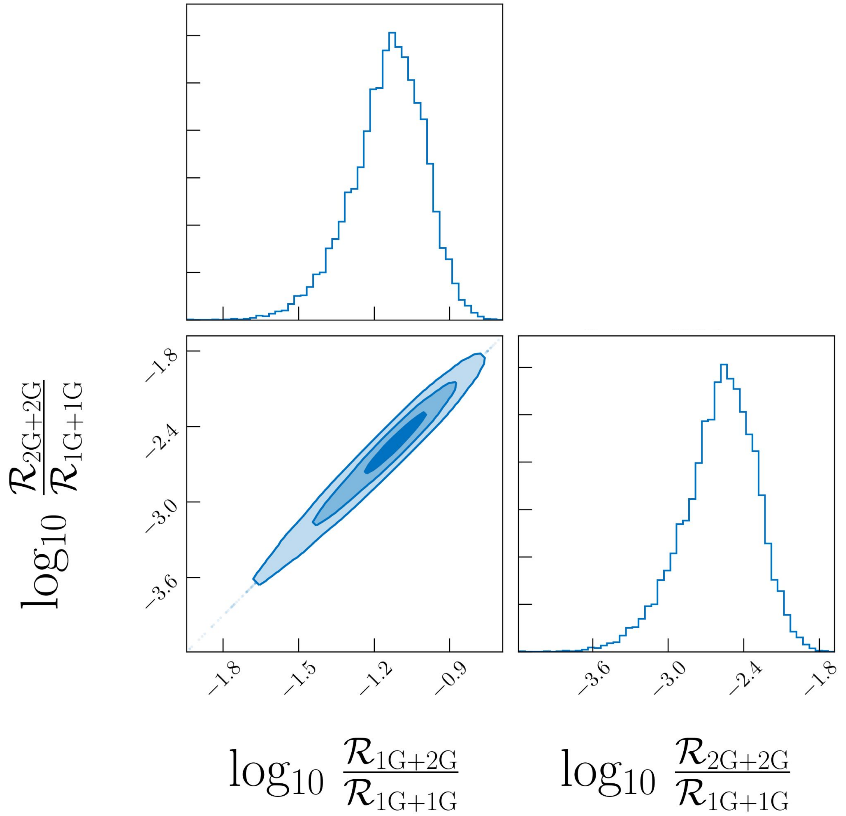


Including hierarchical channels preferred to excluding hierarchical channels with **BF ~ 700**

Preview of GWTC-3

Kimball et al. 2022, In-prep

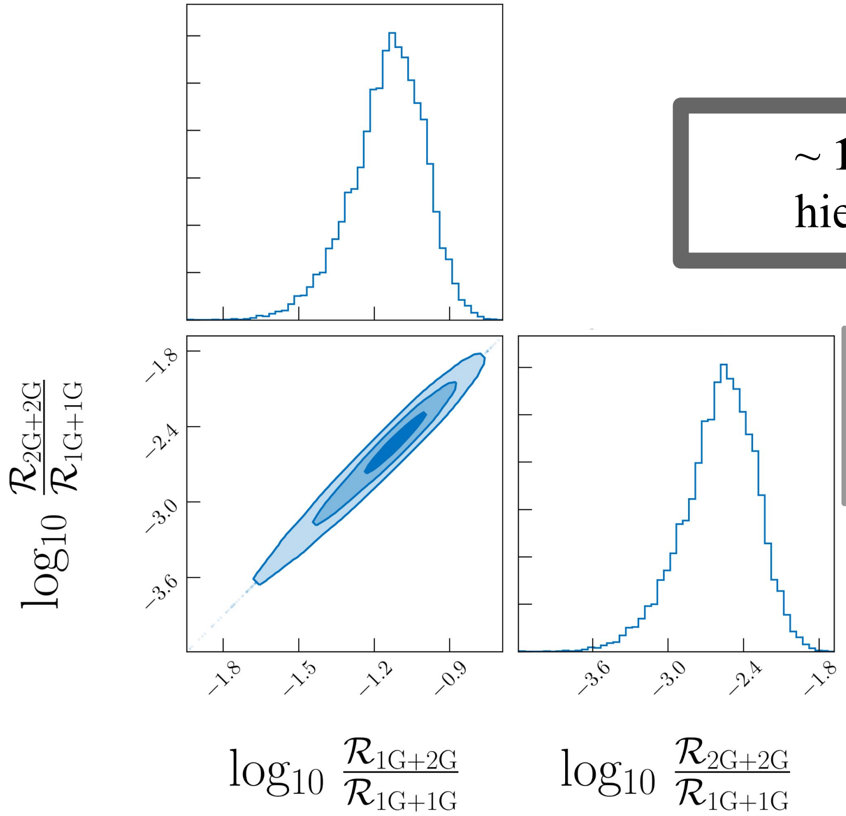
PRELIMINARY



Preview of GWTC-3

Kimball et al. 2022, In-prep

PRELIMINARY



$\sim$ **12%** of the merger rate is contributed by hierarchical mergers

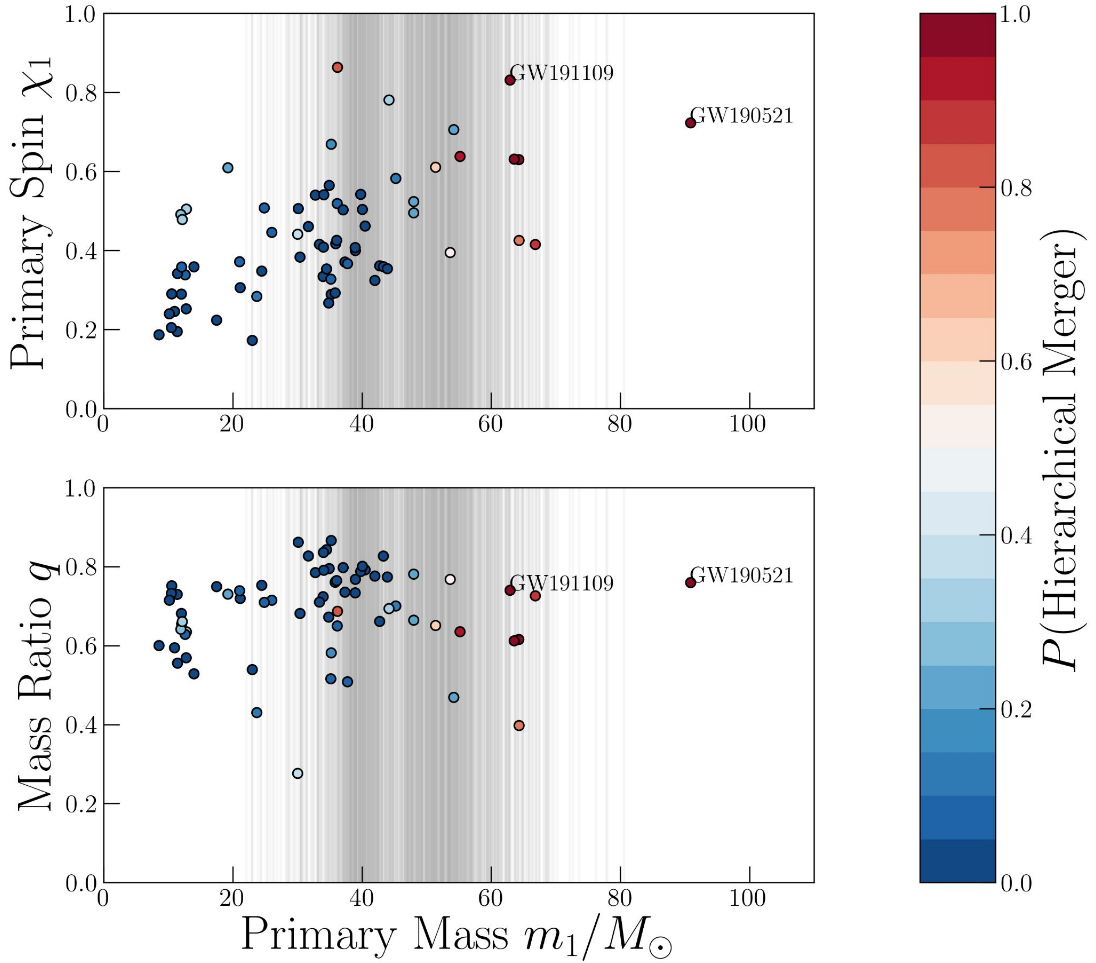
General agreement with Mould, Gerosa, and Taylor 2022

- Discrepancy due to treatment of retained merger products?

Preview of GWTC-3

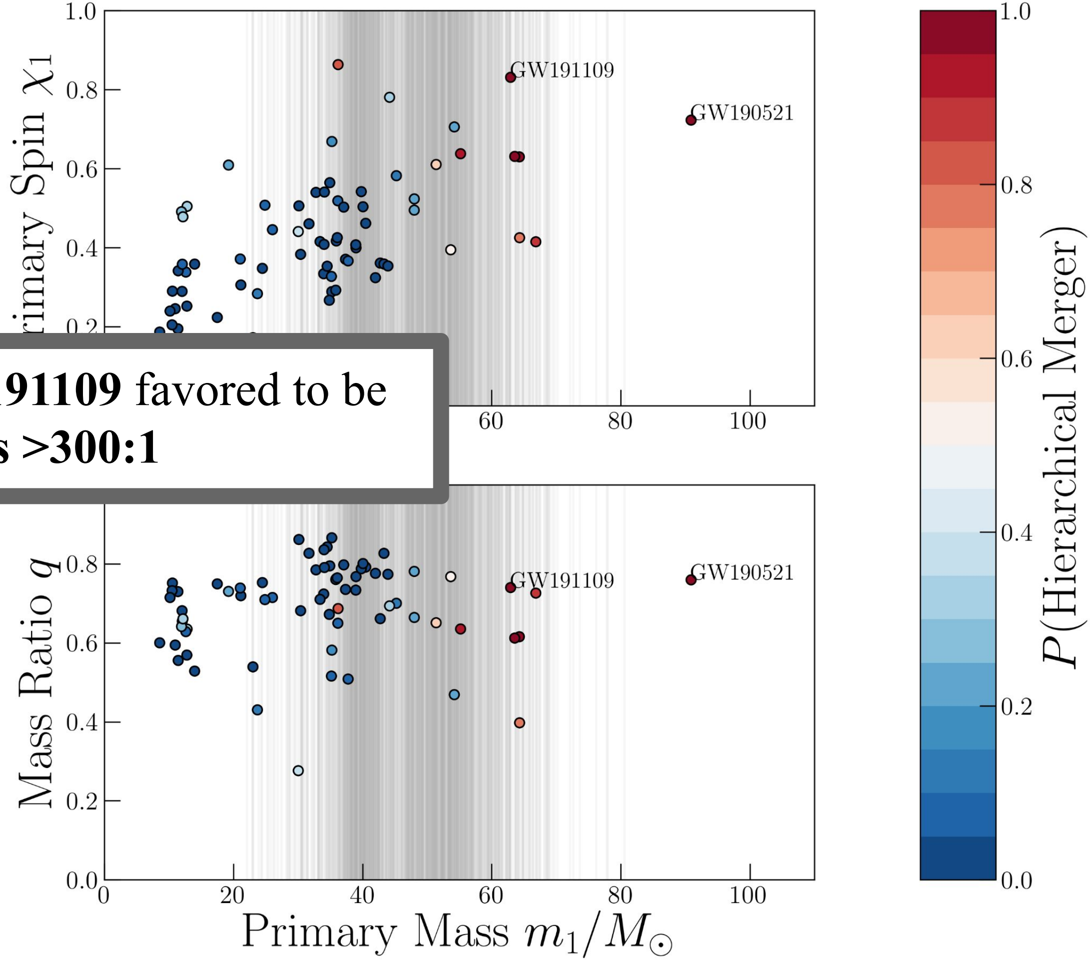
Kimball et al. 2022, In-prep

PRELIMINARY



Preview of GWTC-3

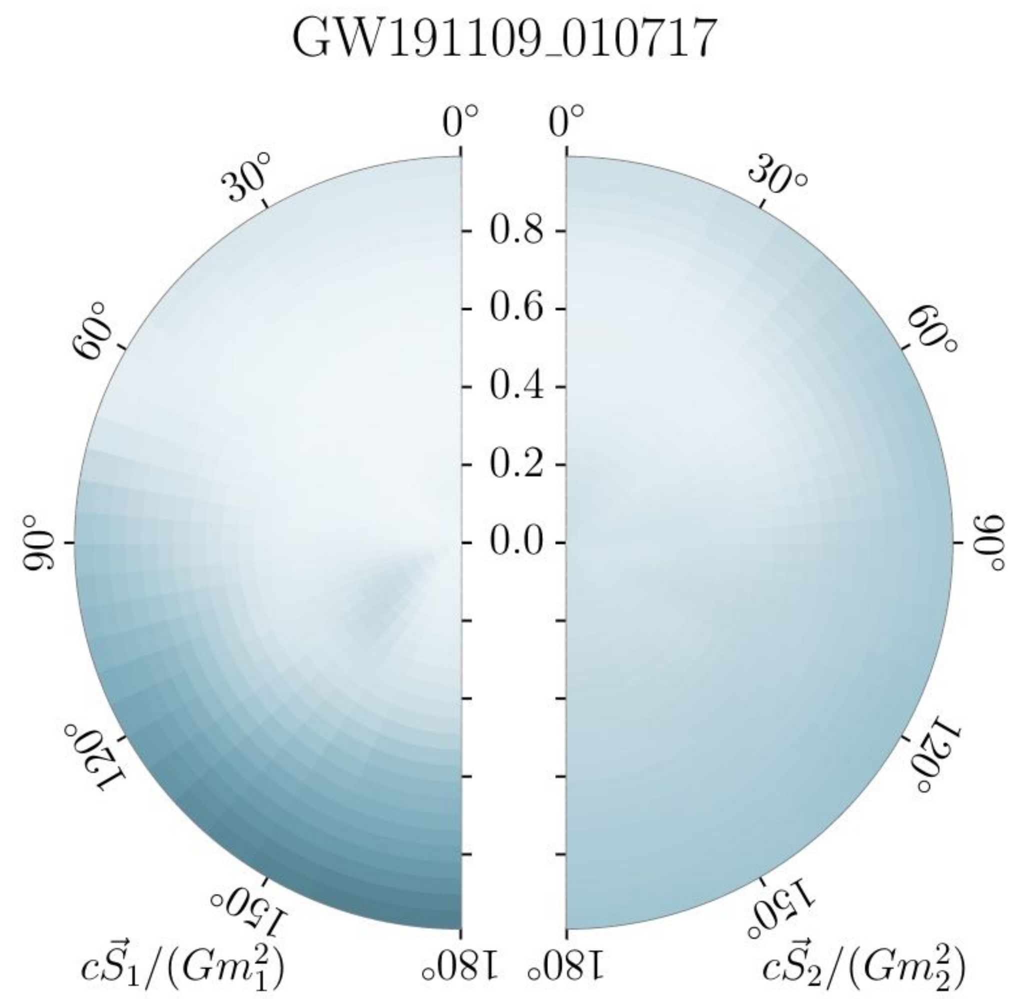
Kimball et al. 2022, In-prep



GW190521 and **GW191109** favored to be hierarchical with **odds >300:1**

PRELIMINARY

Preview



GW191109_010717
0°
30°
60°
90°
120°
150°
180°
0.8
0.6
0.4
0.2
0.0
$c\vec{S}_1/(Gm_1^2)$
$c\vec{S}_2/(Gm_2^2)$

Preview of GWTC-3

Kimball et al. 2022, In-prep

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
  - Nuclear Star Clusters
  - Active Galactic Nuclei

Primary Mass $m_1/M_\odot$

Summary

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- We need to **identify hierarchical mergers** if we want to use GW observations to infer anything about the mass gap

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  - Our model heavily **favors GW190521** and **GW191109** (among others) **being hierarchical mergers**

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  - ➢ Our model heavily **favors** **GW190521** and **GW191109** (among others) **being hierarchical mergers**

- We need to be careful about **1G black hole spins** and how we model dynamical environments