
Image credit: LIGO/T. Pyle

# Gravitational Wave Astrophysics

## Pablo Marchant

Part 5: Astrophysics of observed GW sources

# Outline

## Today

- History of the field
- Types of detectors
- Types of sources
- Current state of the field
- Future advancements

## 12/5

- Ground based interferometers
- Production of GWs from compact object binaries

## 19/5

- Parameter estimation from observed compact object coalescences
- Astrophysics of observed GW sources

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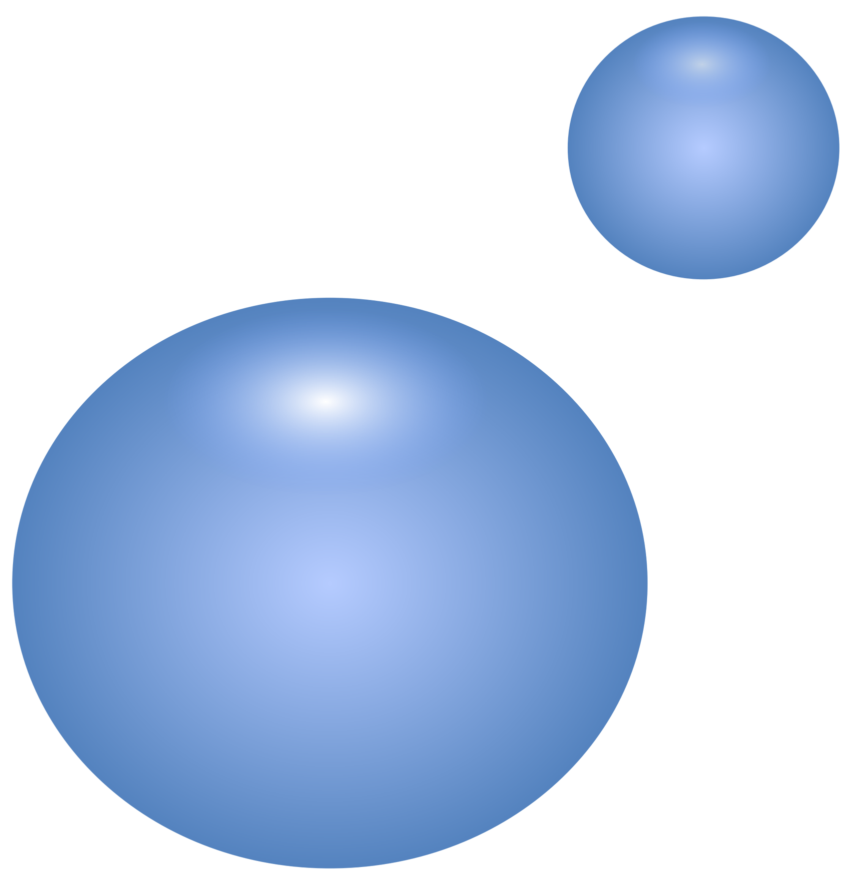
# Astrophysics from GR sources



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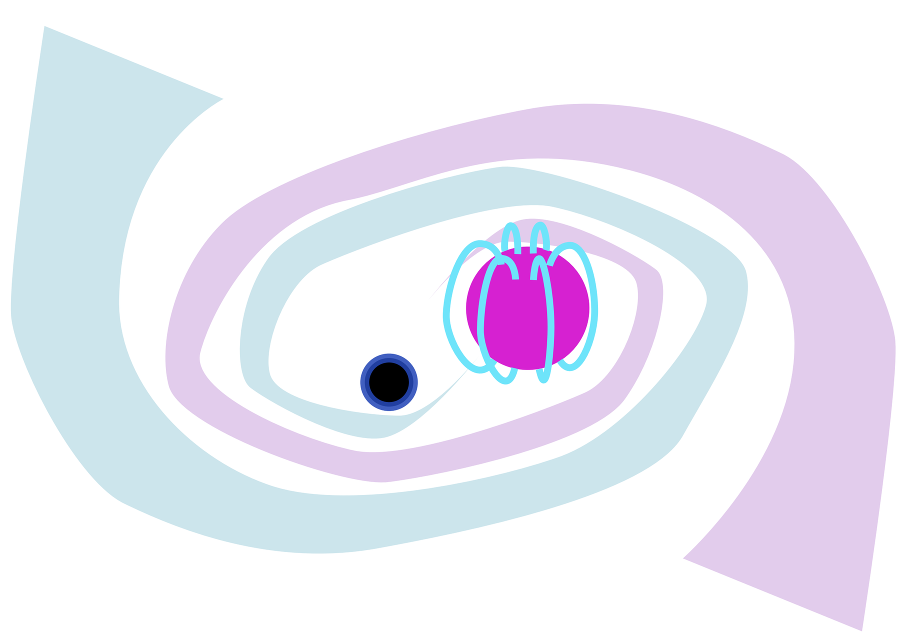
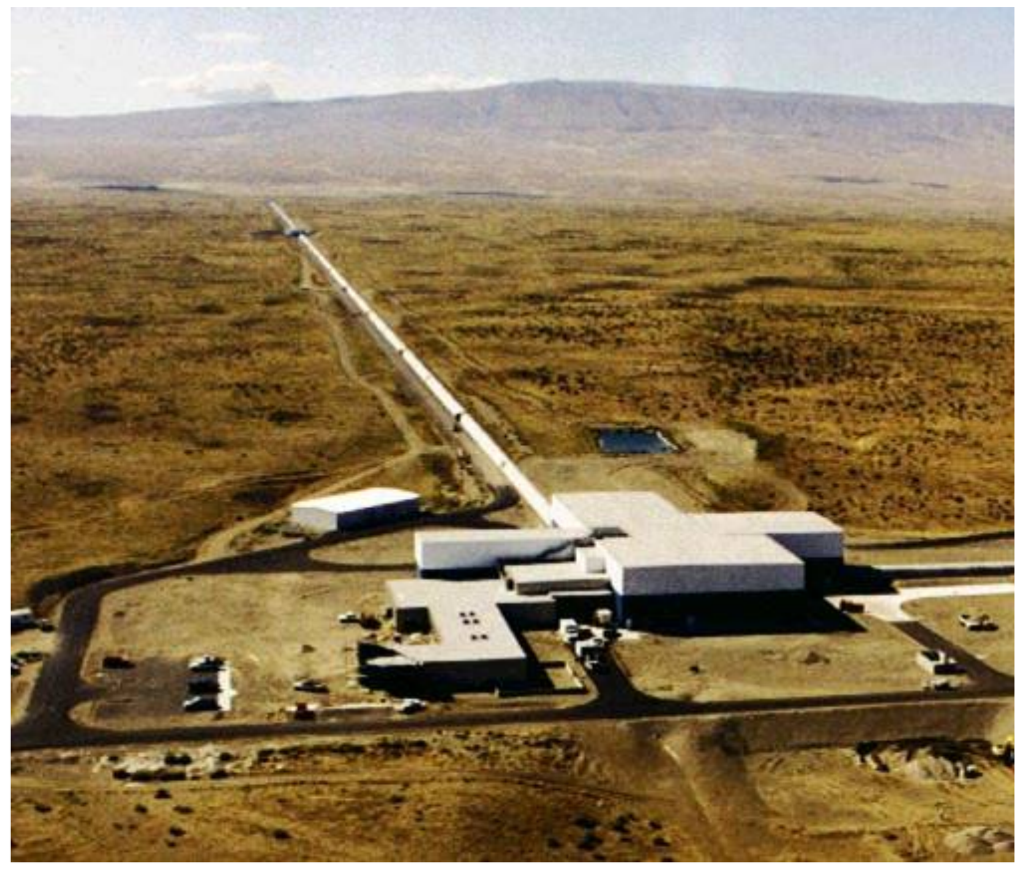
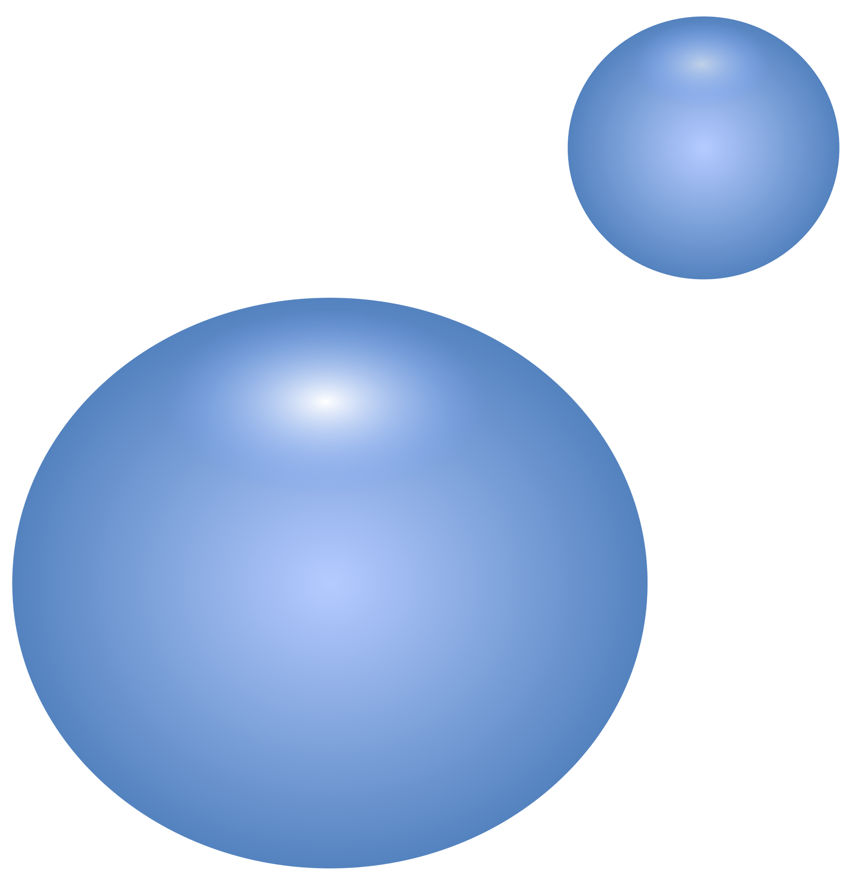




1. Form two stars
2. ?
3. Merge them
4. Detection

# Astrophysics from GR sources

What are the progenitors of
these sources?
(cf. Mandel & Farmer 2018)



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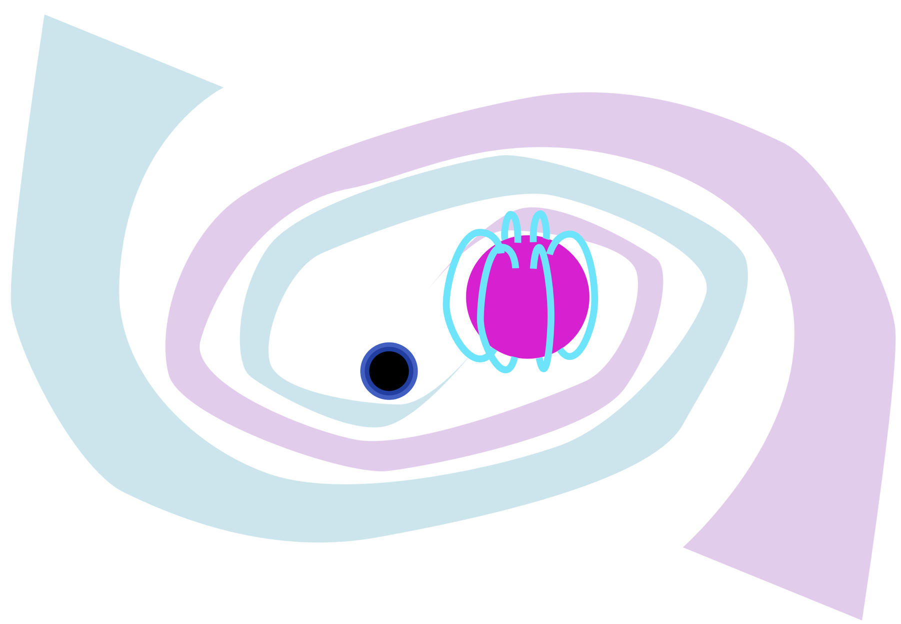

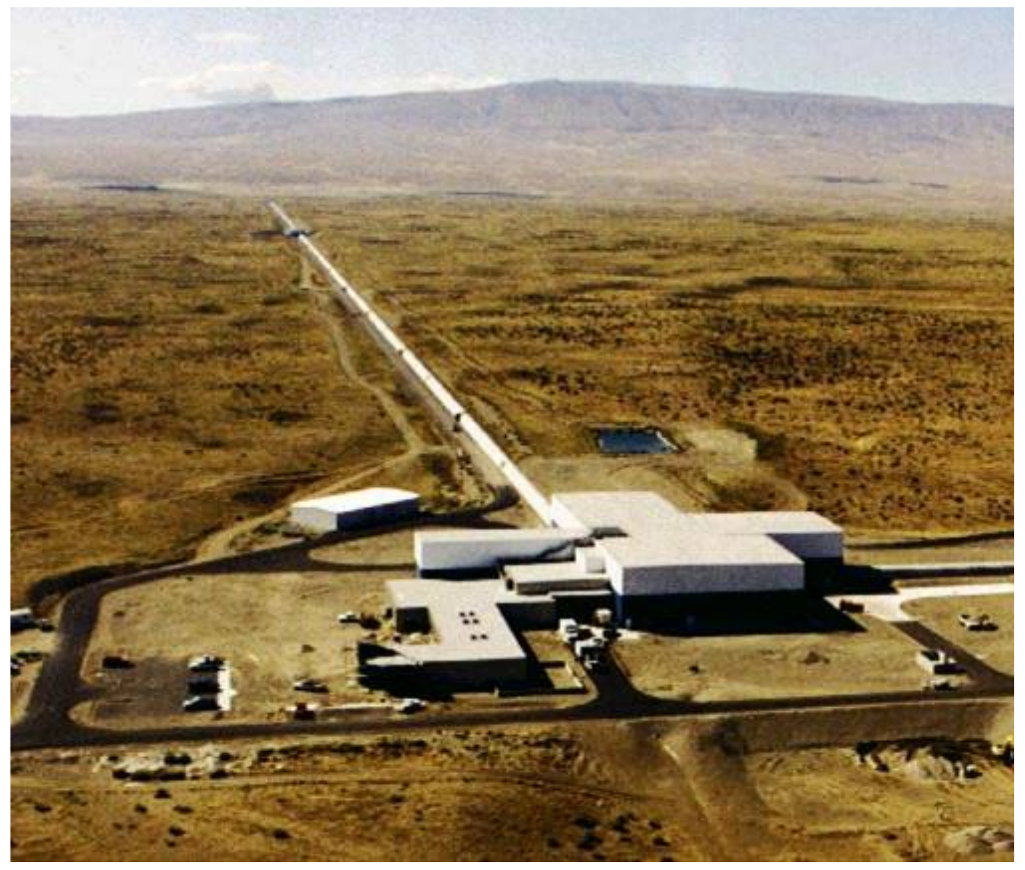

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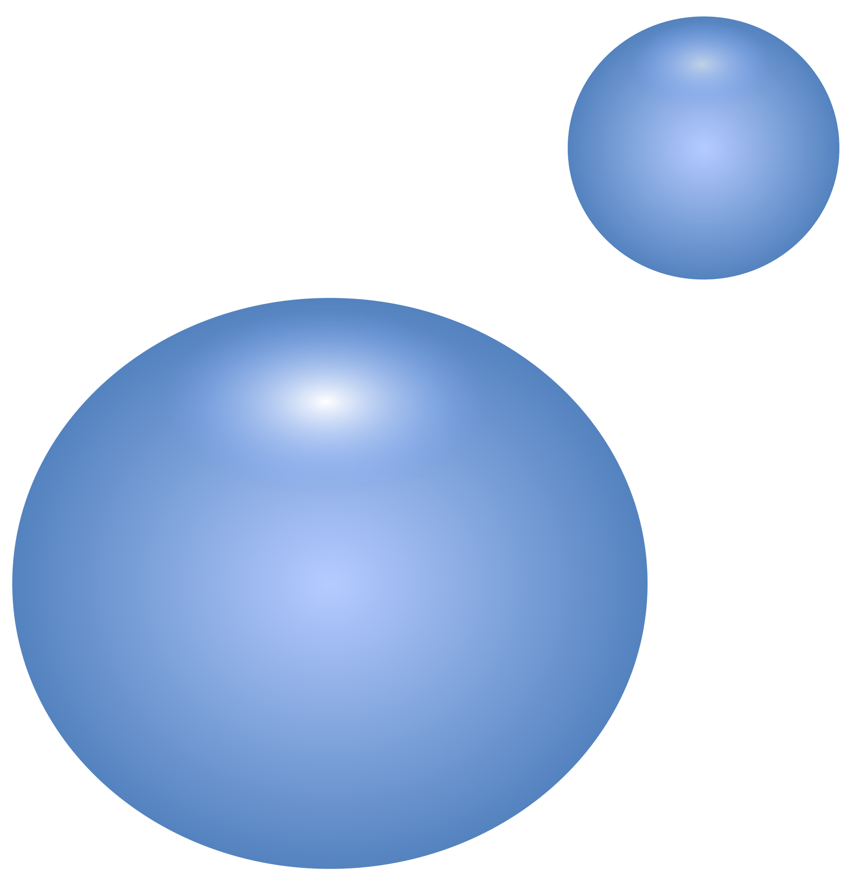

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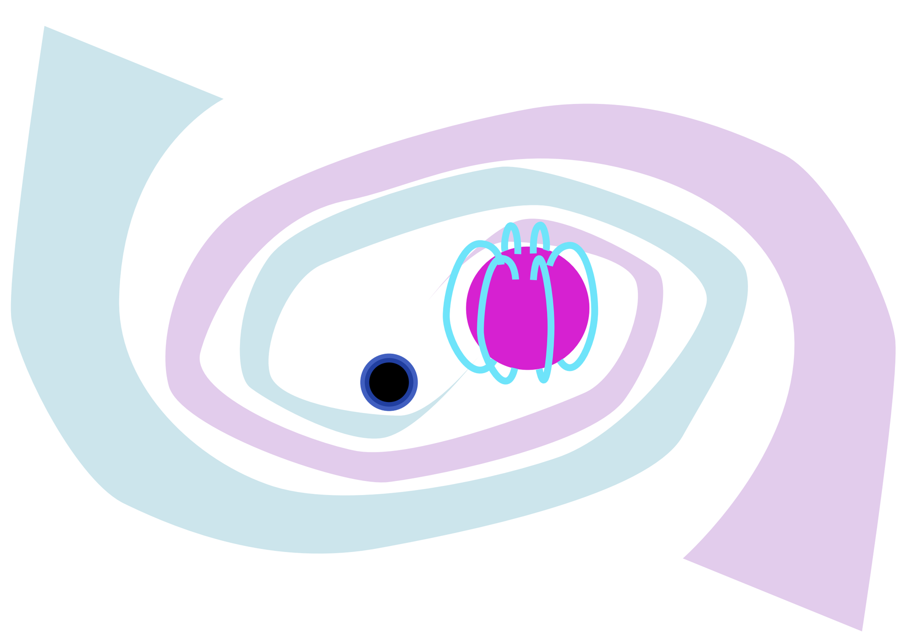

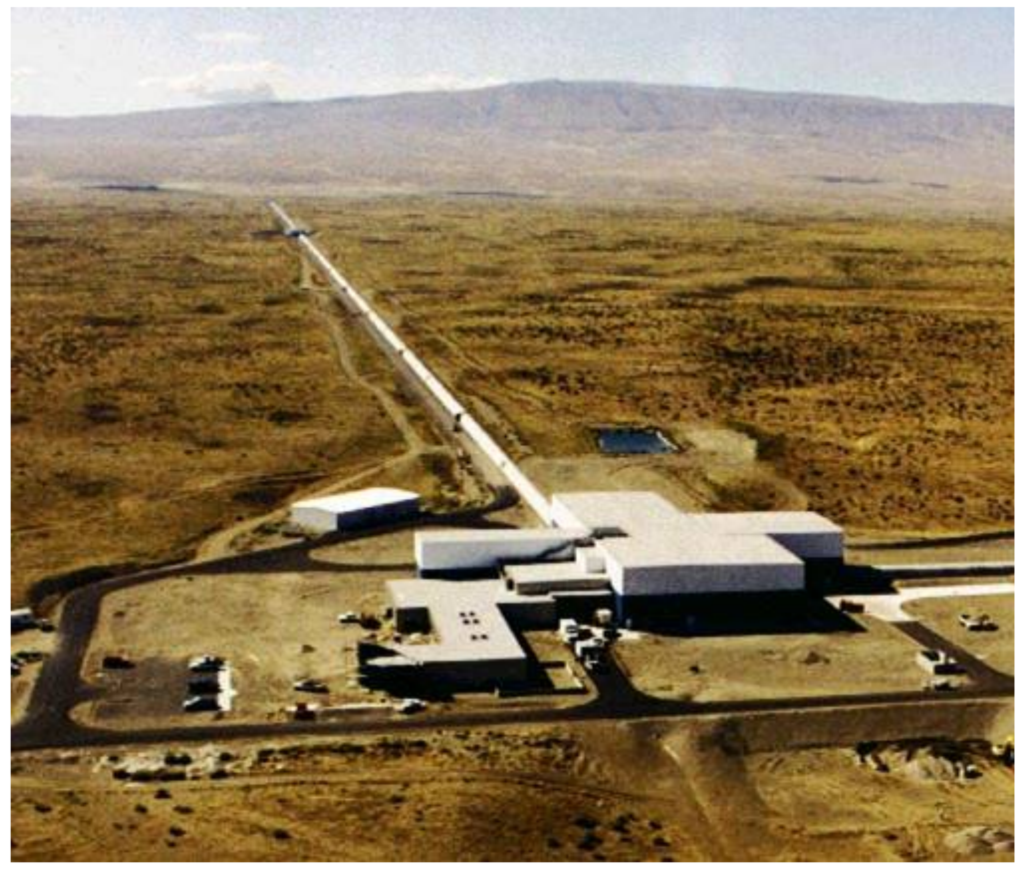

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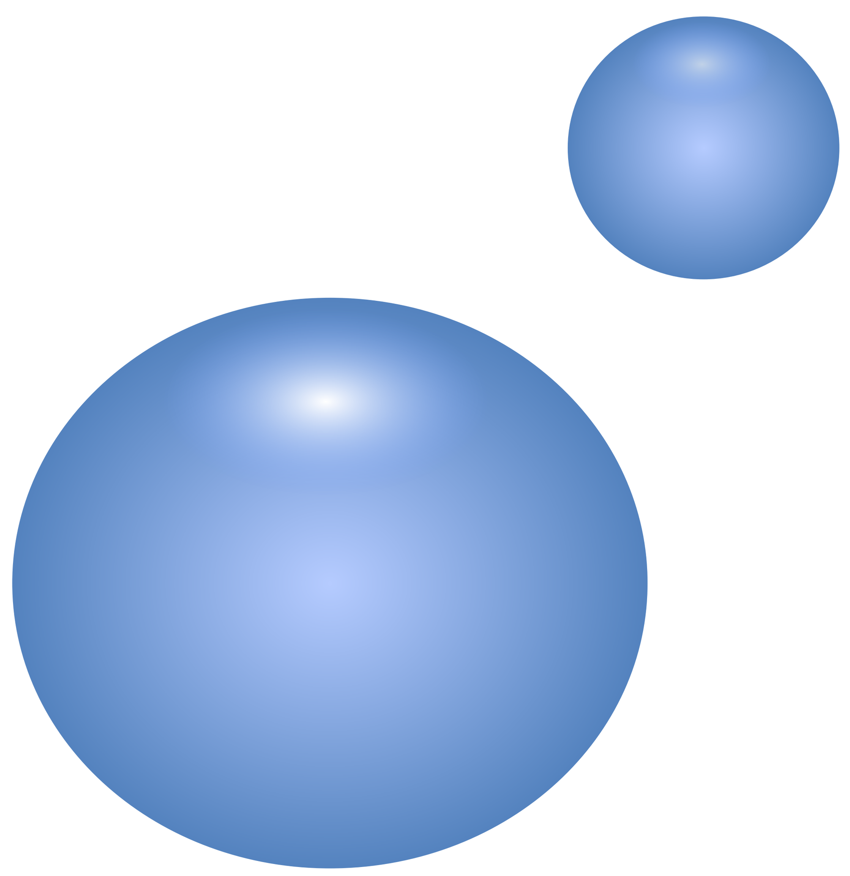

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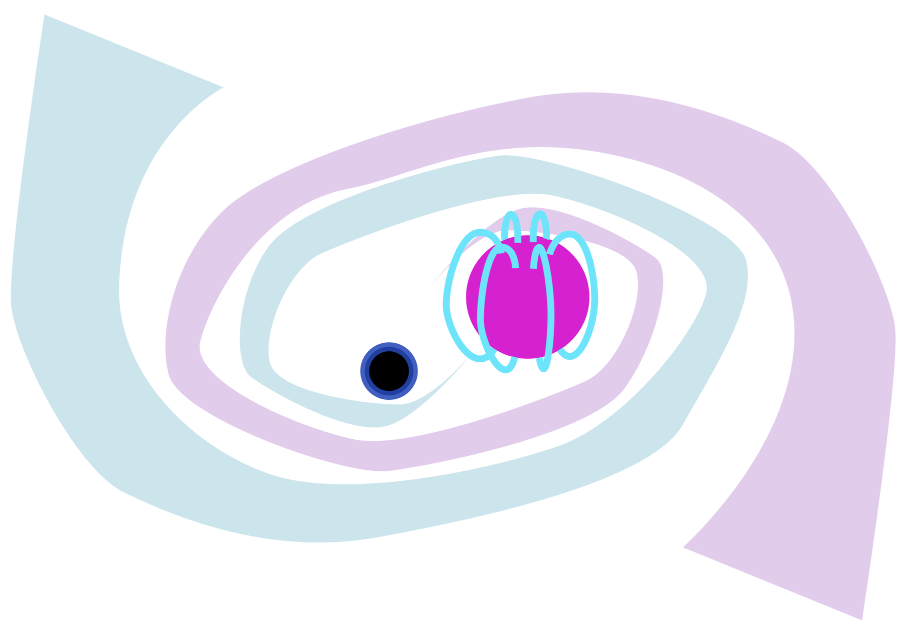

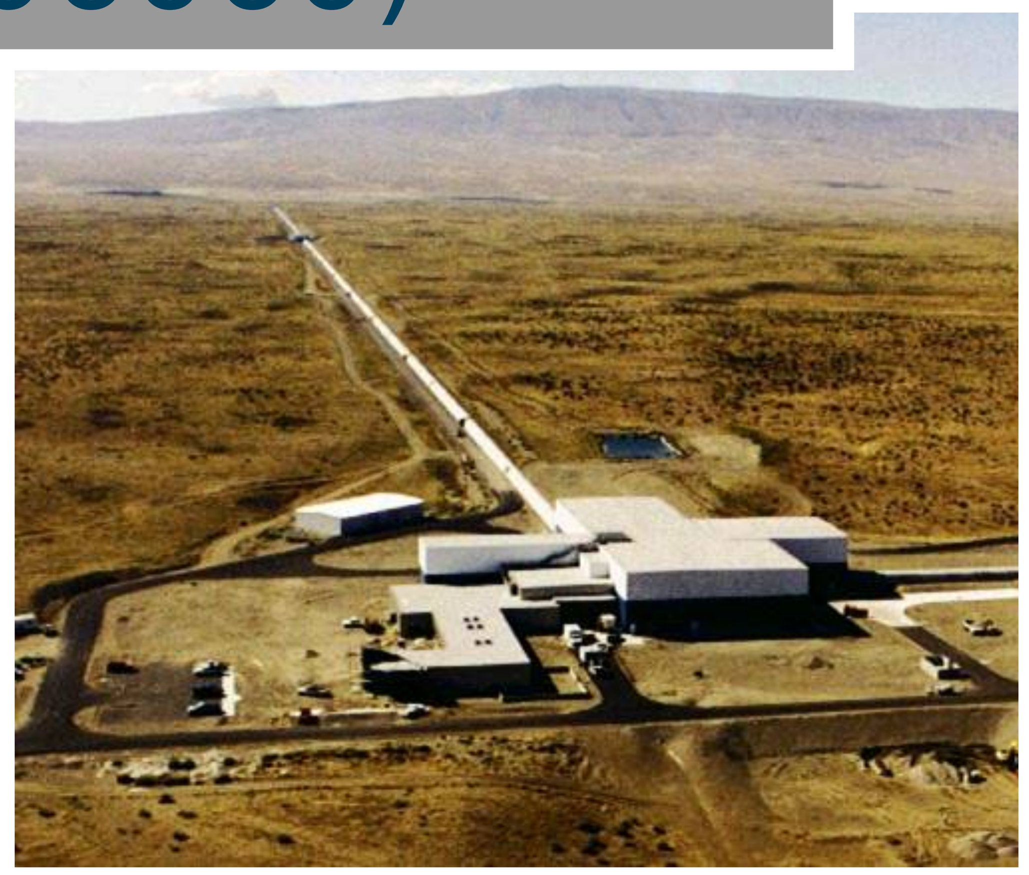

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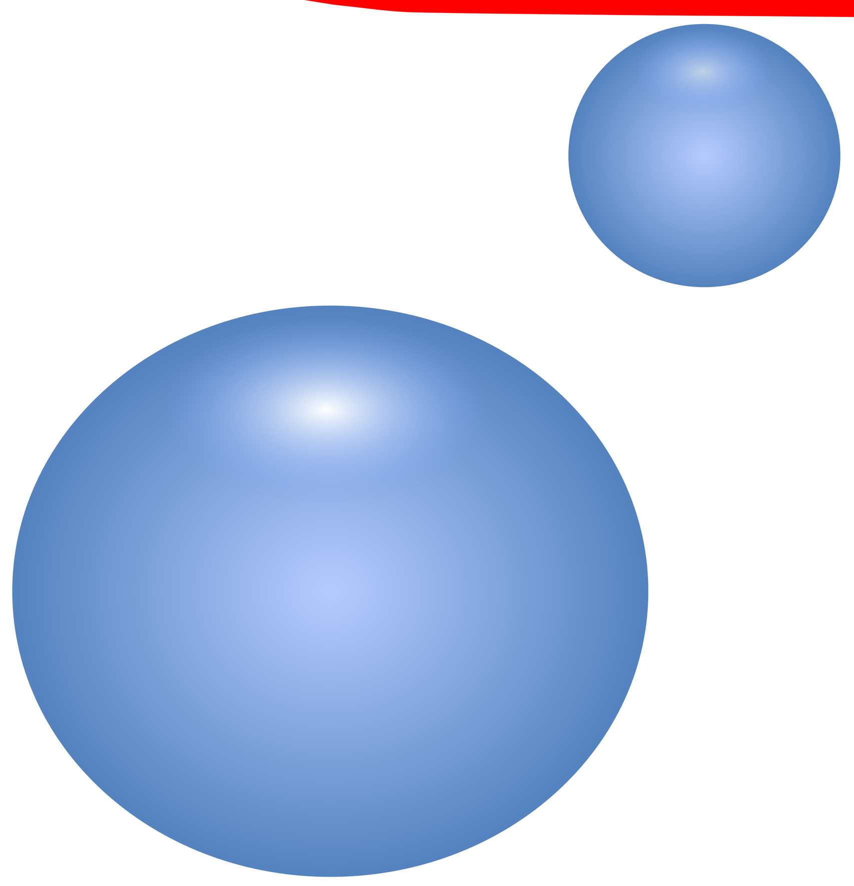

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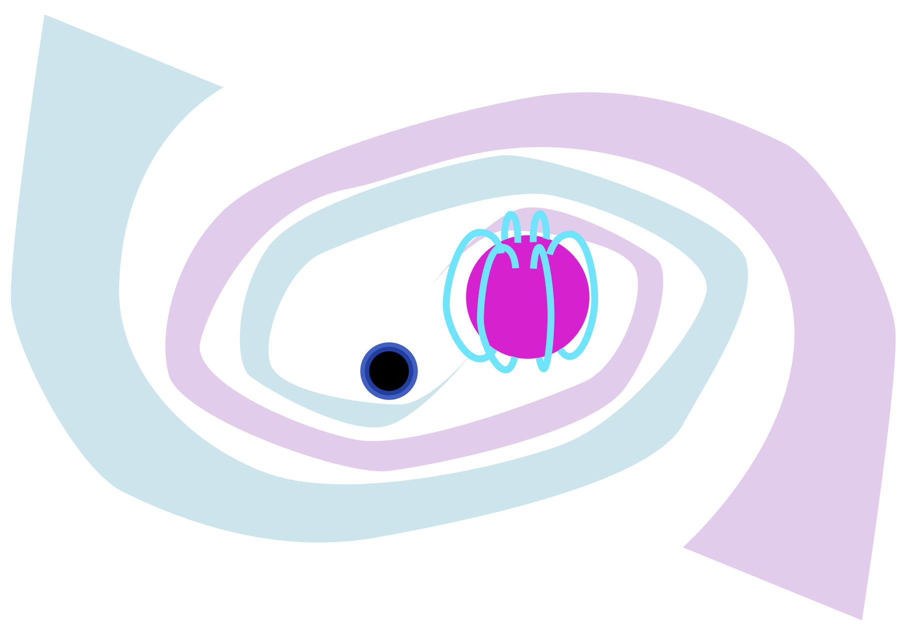

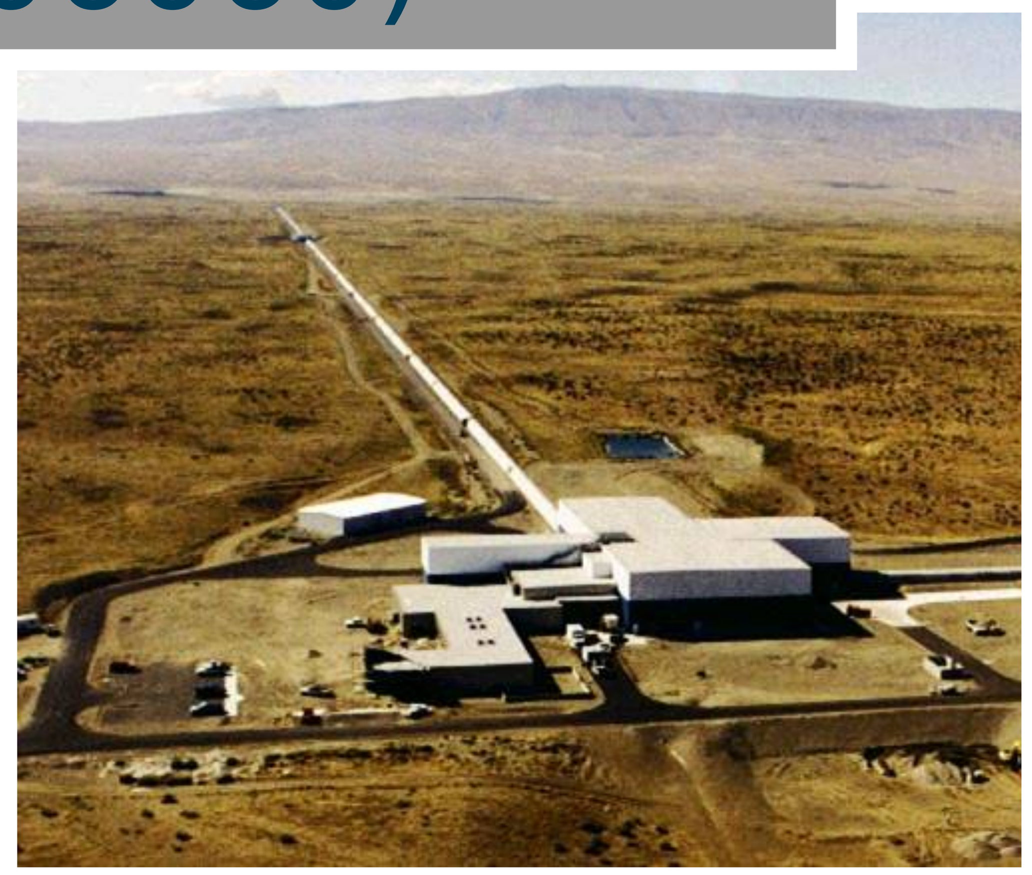

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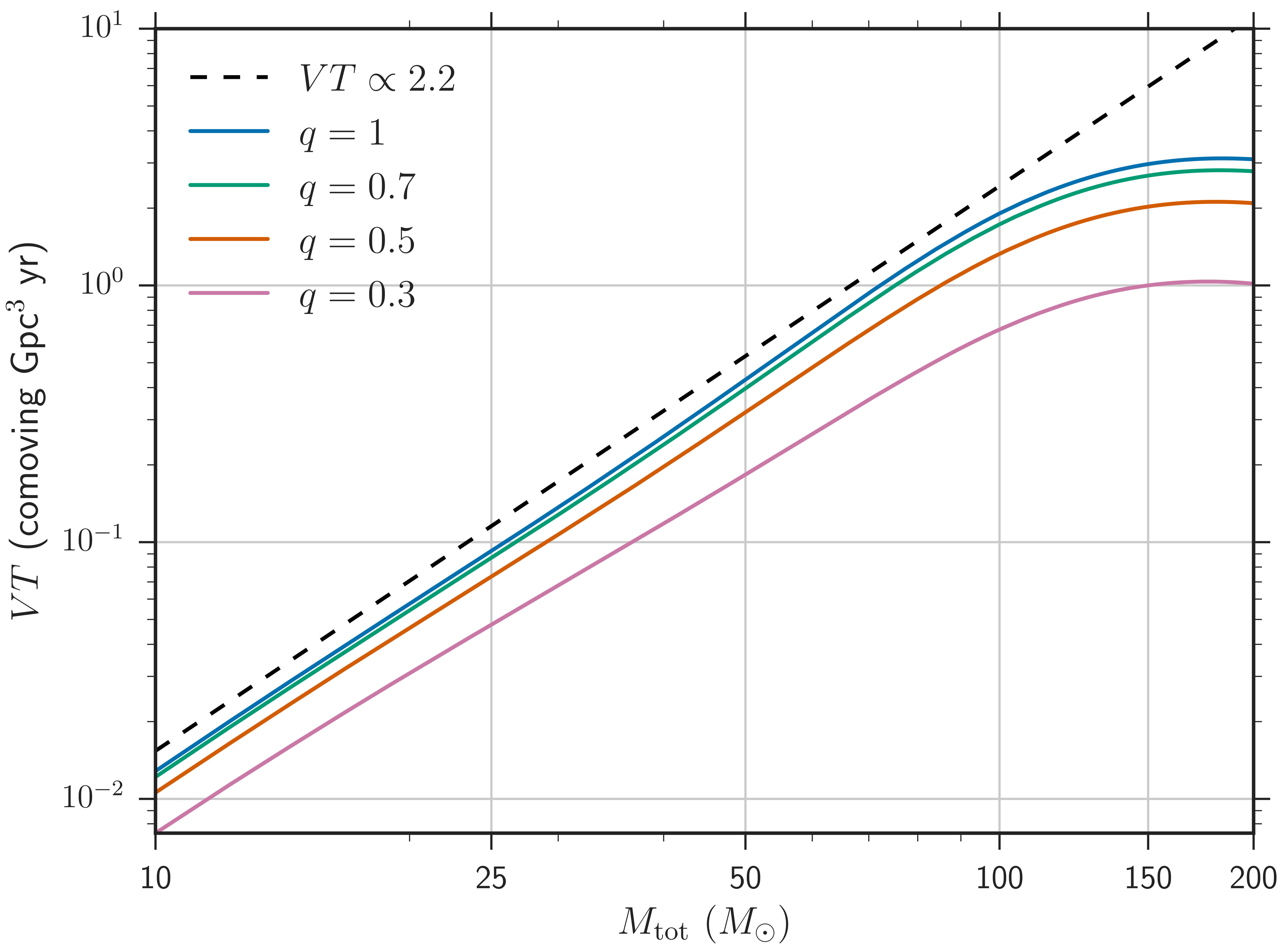
# Sources observed to date


| O1 | GWTC-1 | GWTC-2 |
|---|---|---|
| 3 BH+BH | 10 BH+BH, 1 NS+NS | 46 BH+BH, 2 NS+NS, 2 ? |
| astro-ph 1606.04856 | astro-ph 2010.14527 | astro-ph 2010.14527 |

# Sources observed to date

Detectors are strongly biased towards higher black hole masses. If BH mass function is similar to stellar mass function they nearly compensate.

Biggest surprise is the apparent lack of more massive BHs in the data, potentially indicative of the existence of exotic pair-instability SNe.




Fishbach & Holz (2017)

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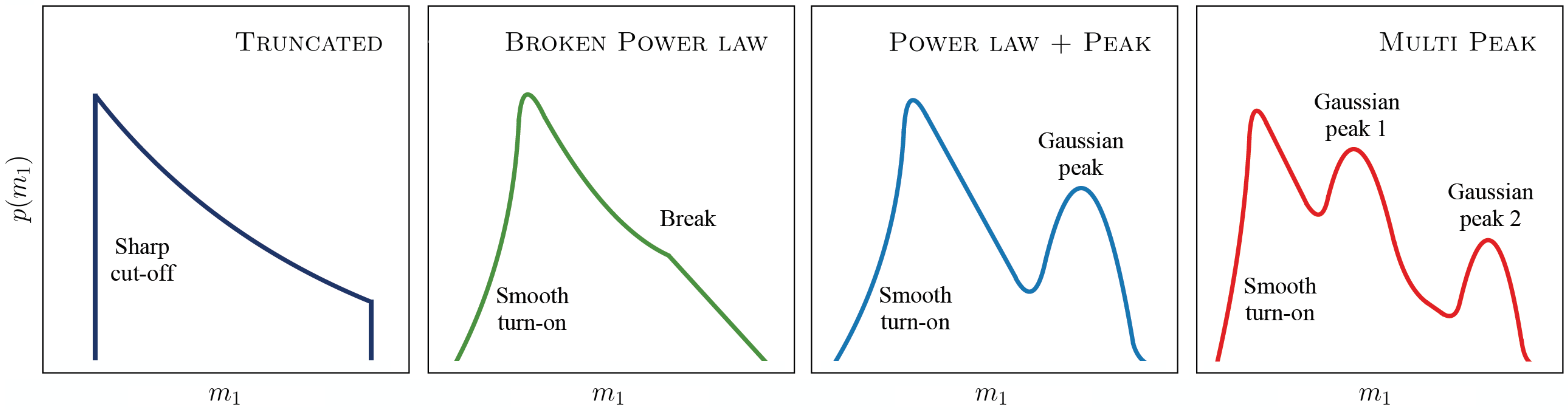


For comparison to formation models, one needs to understand intrinsic properties of the population. These are inferred from the observed population by a Bayesian analysis that accounts for the detector biases and uses parametrized distributions.
(astro-ph: 2010.14533)

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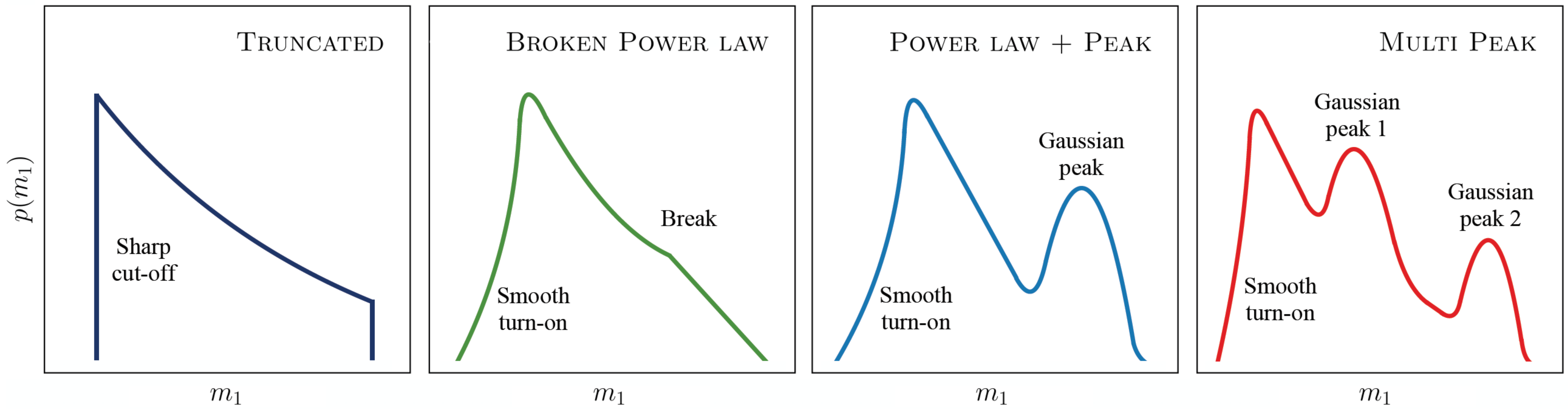


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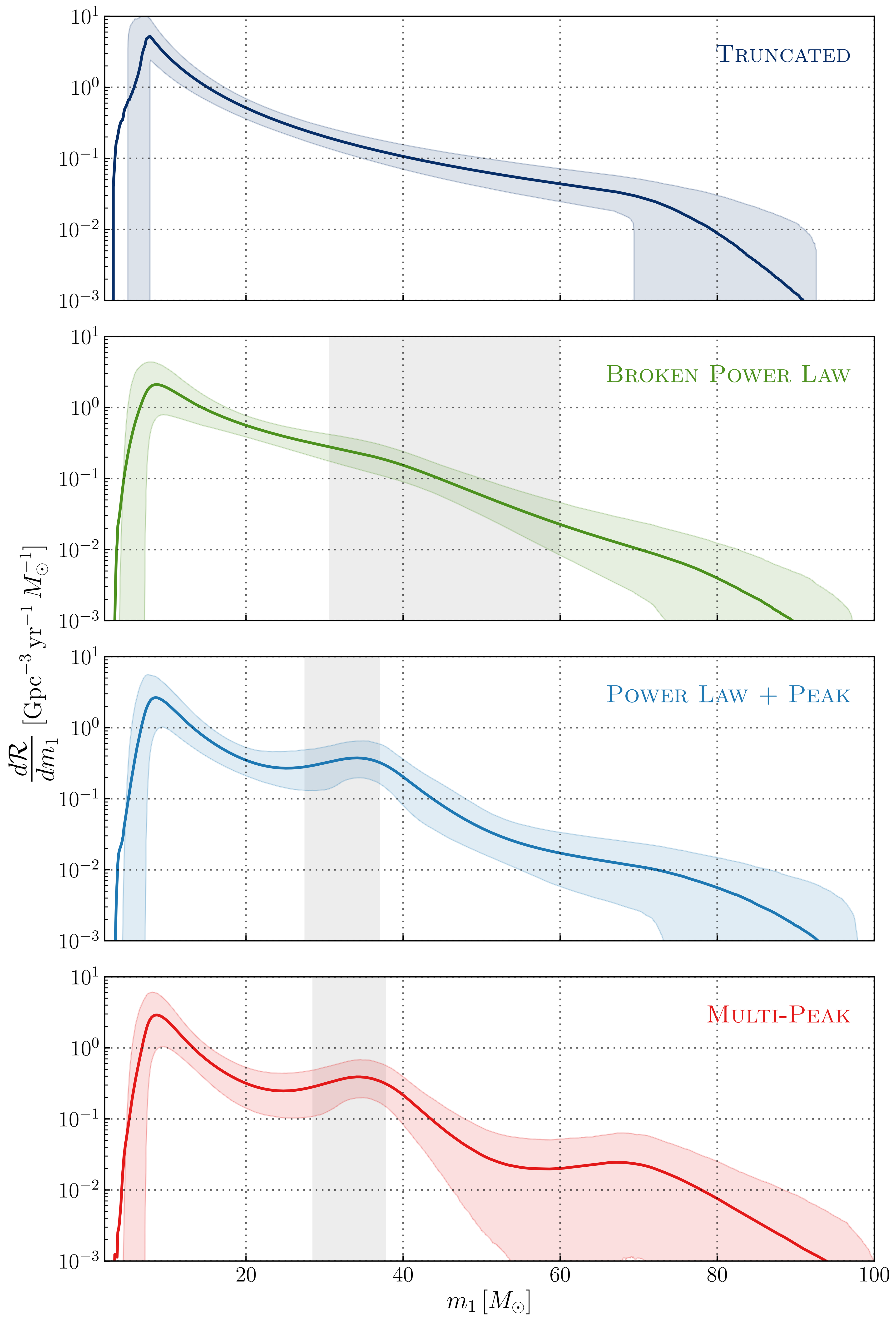
$$\mathcal{R}_{\rm BBH} = 23.9^{+14.3}_{-8.6}\ [\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}],\ \mathcal{R}_{\rm NS} = 320^{+490}_{-240}\ [\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}]$$

$$p(m_1 > 45 M_\odot) = 2.9^{+3.5}_{-1.7}\%$$

# Sources observed to date

Parametrized models indicate the apparent preference for more massive BHs is biased.



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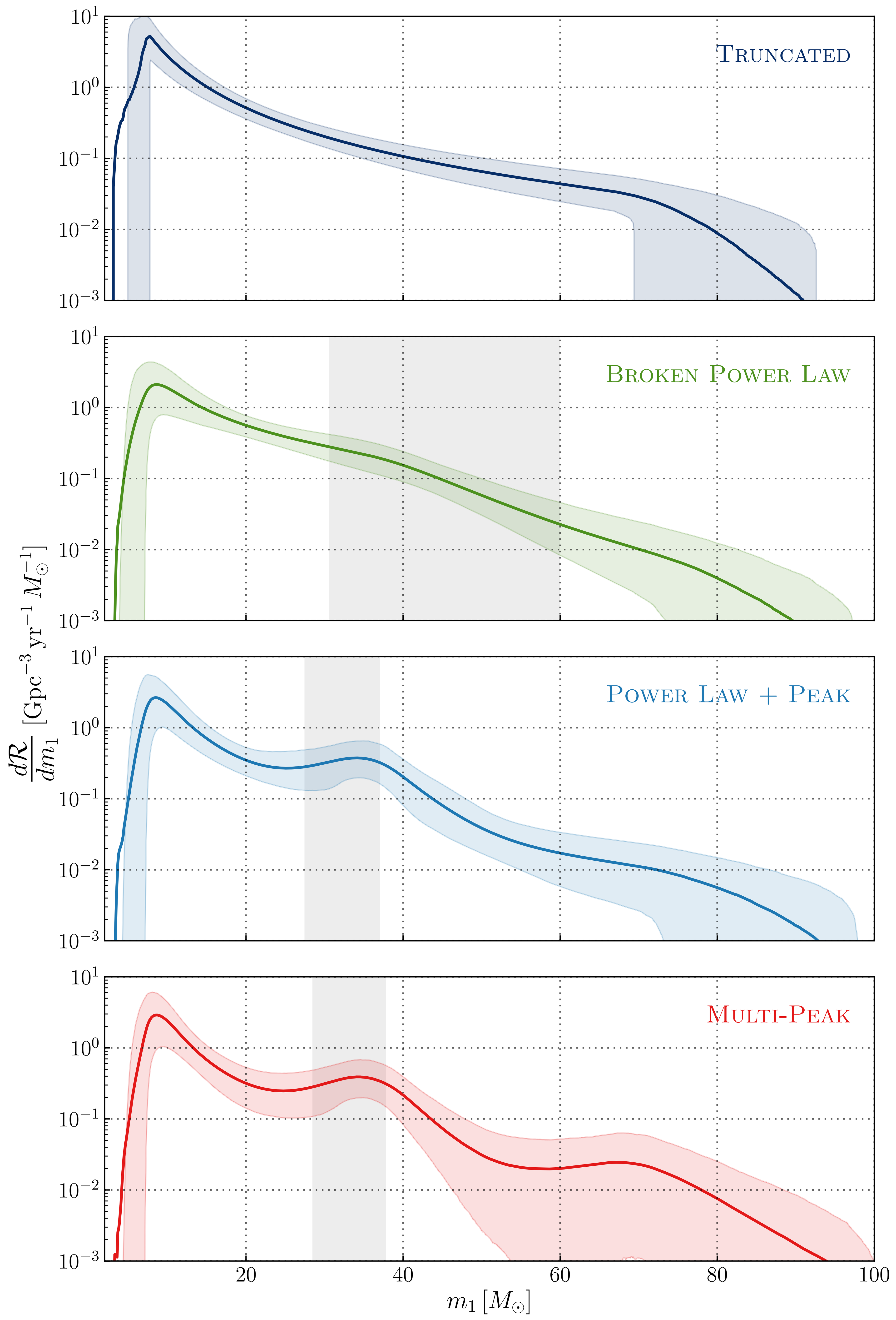
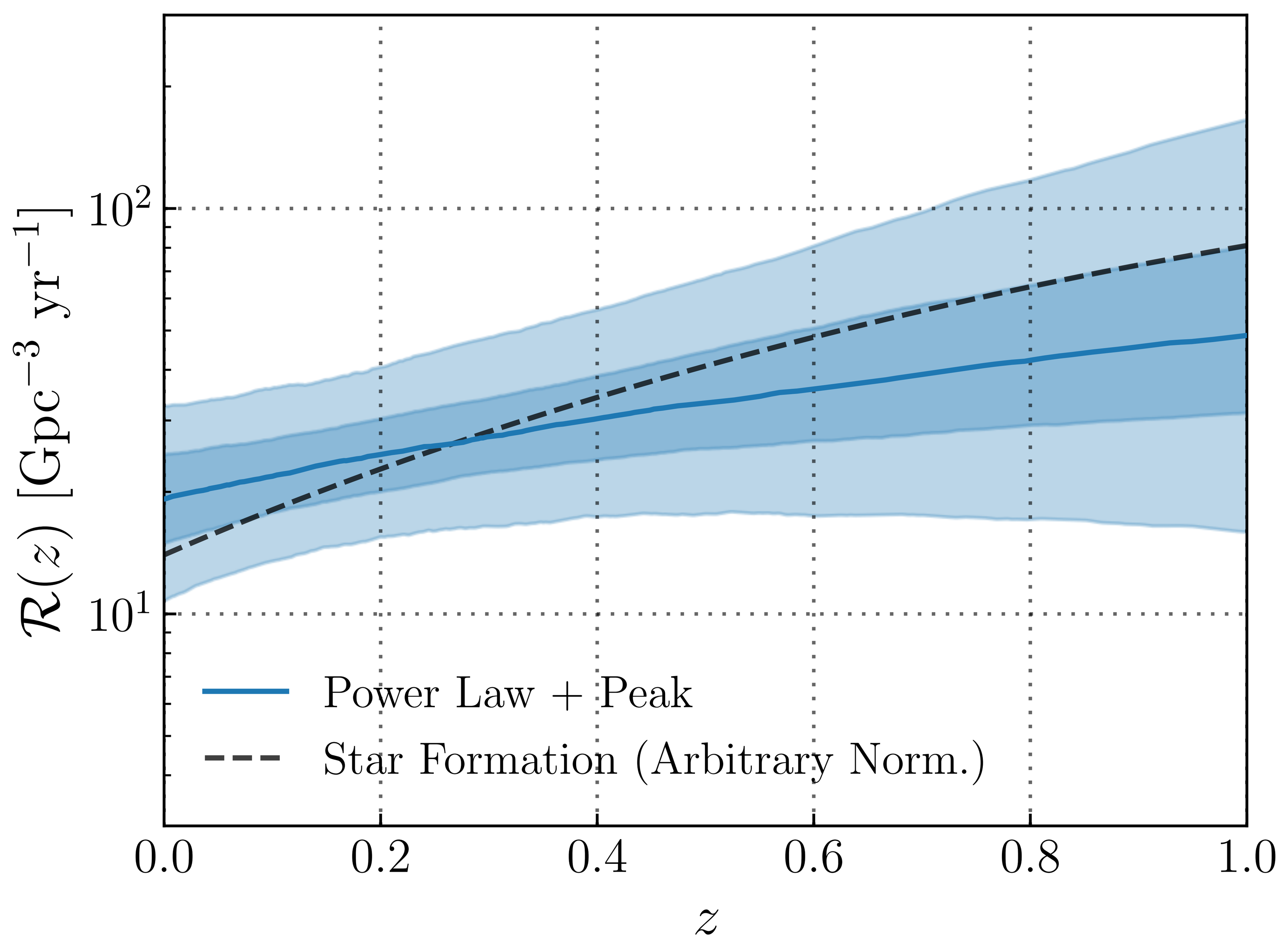



Indications that the volumetric BBH merger rate increases with redshift.



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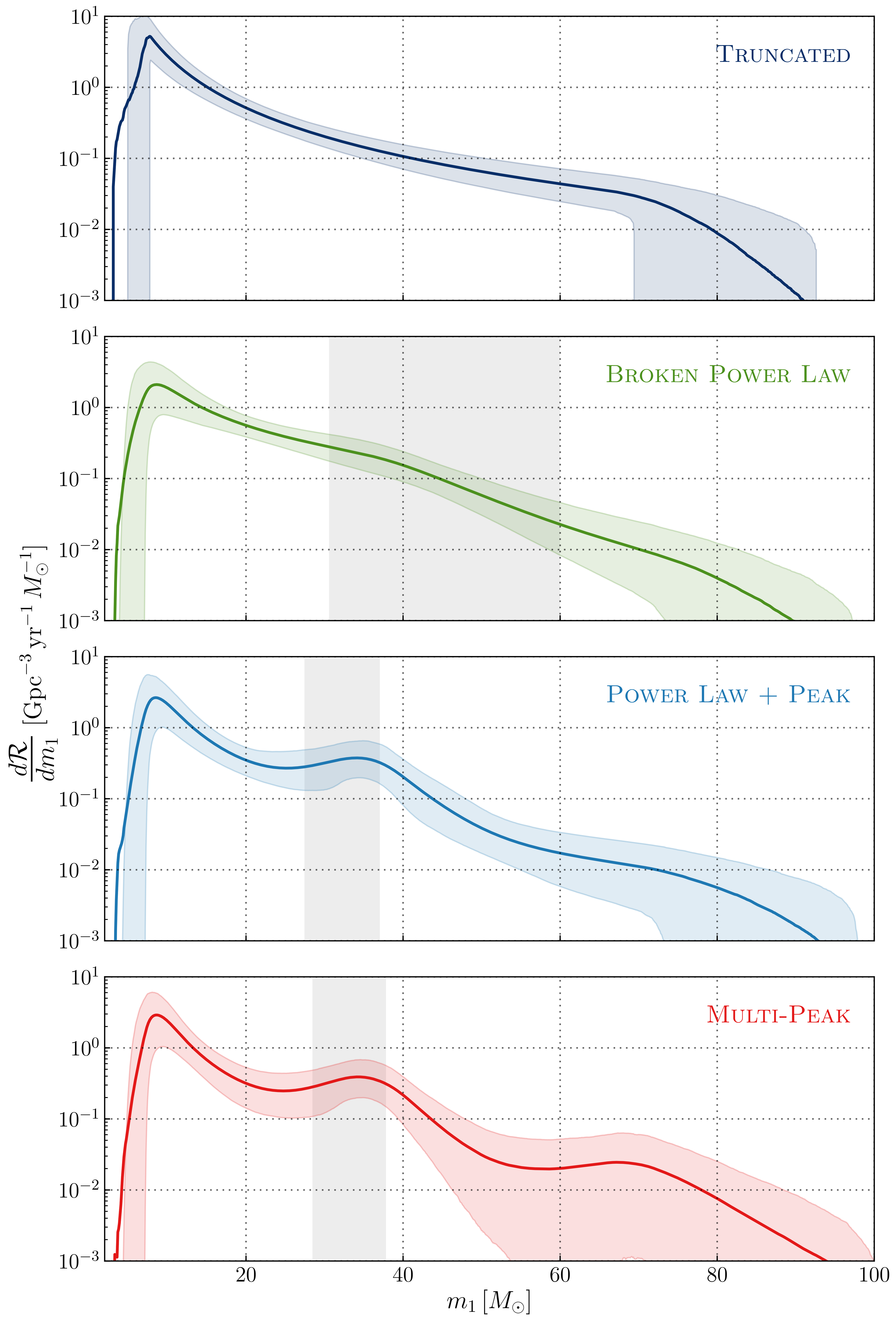


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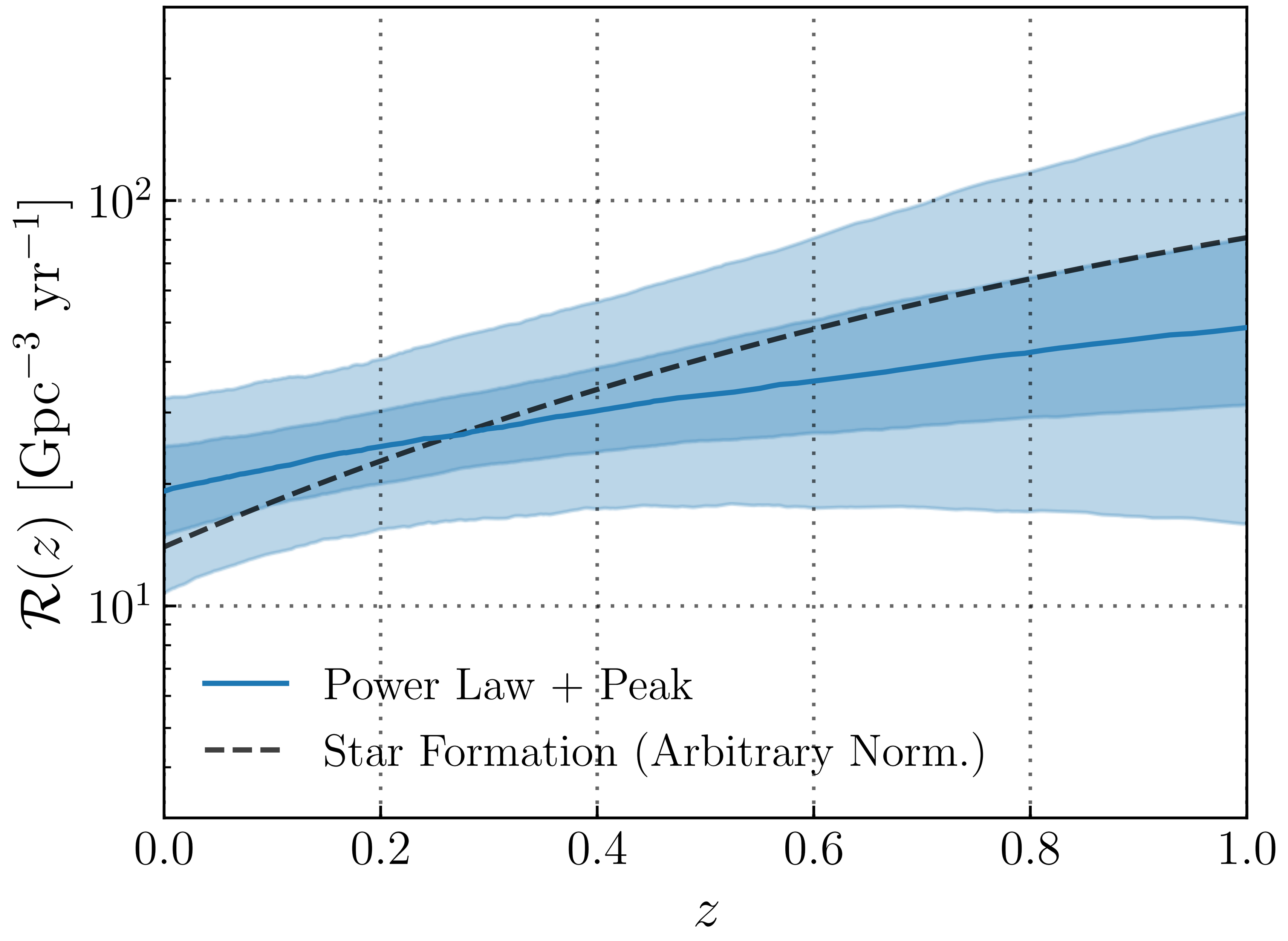
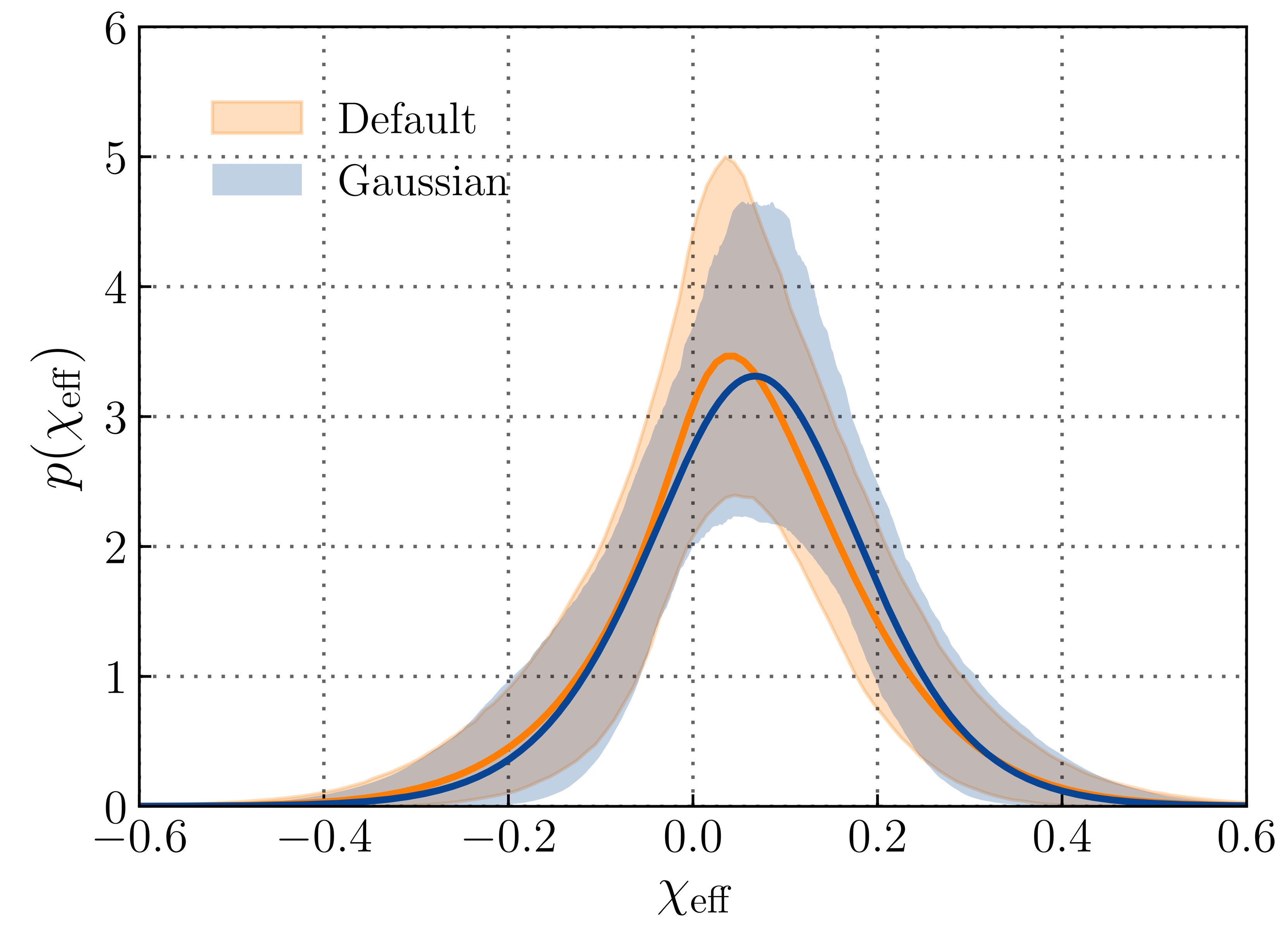
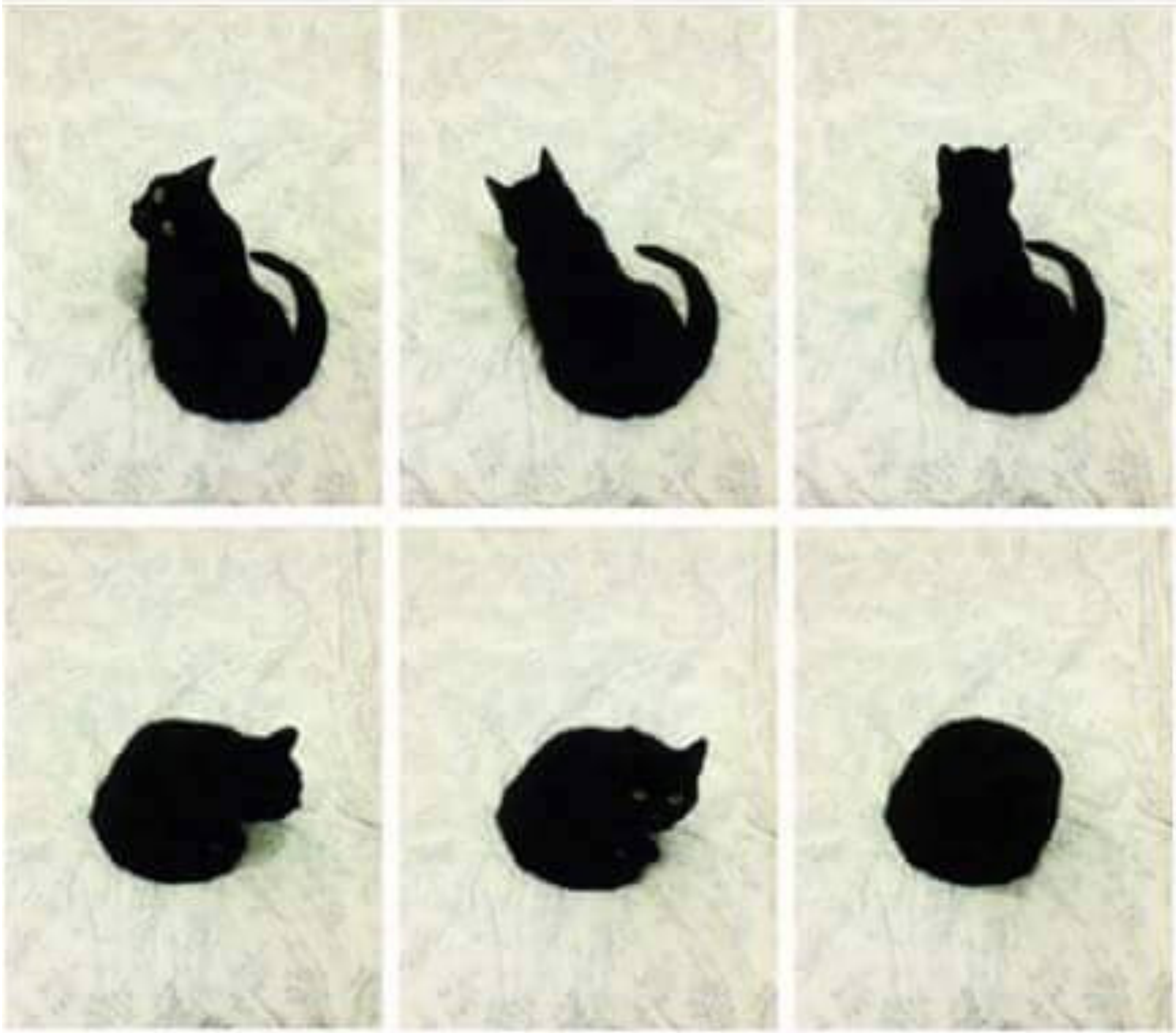
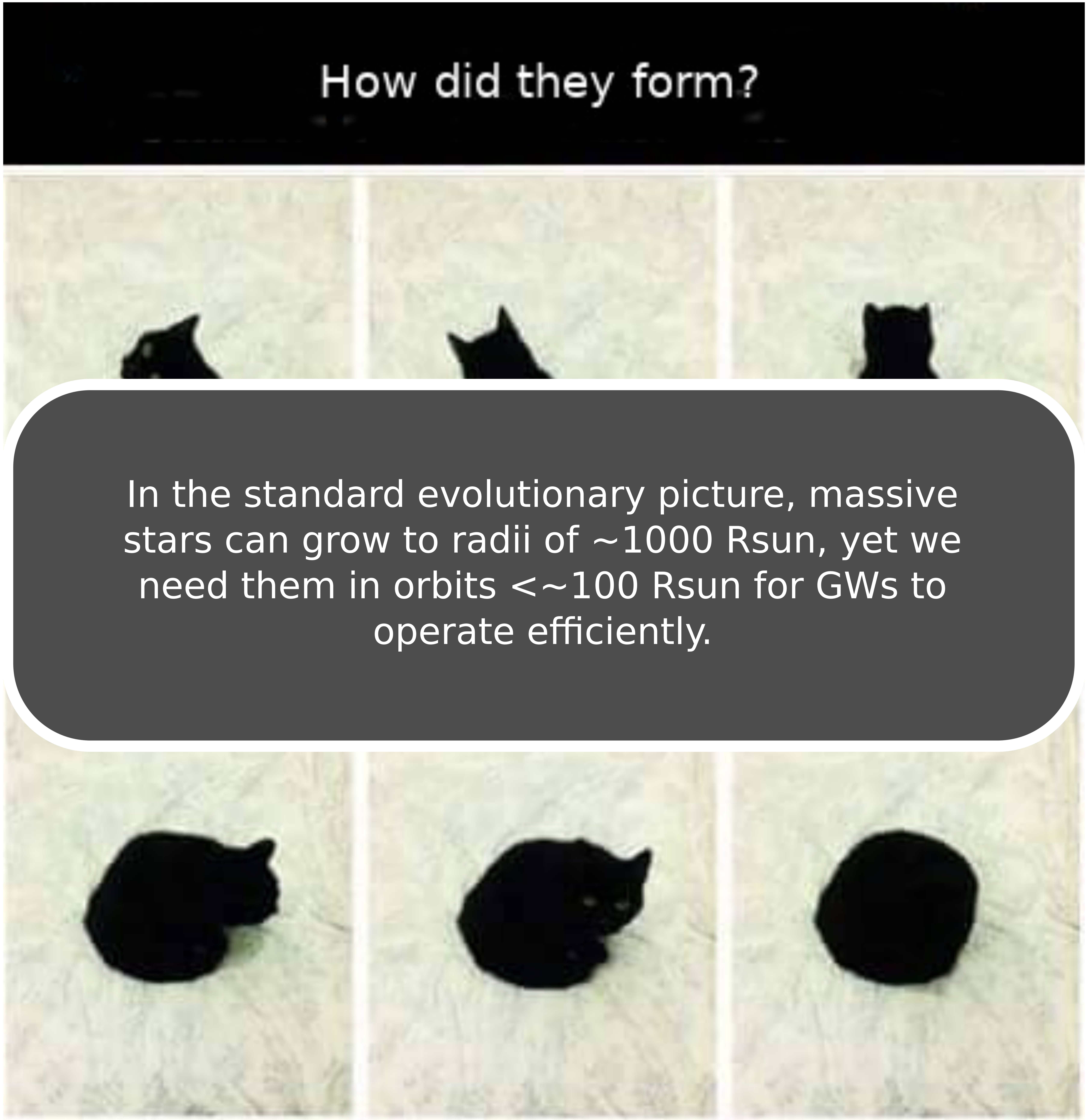



Between 12% and 44% of BBHs have a counteraligned spin.



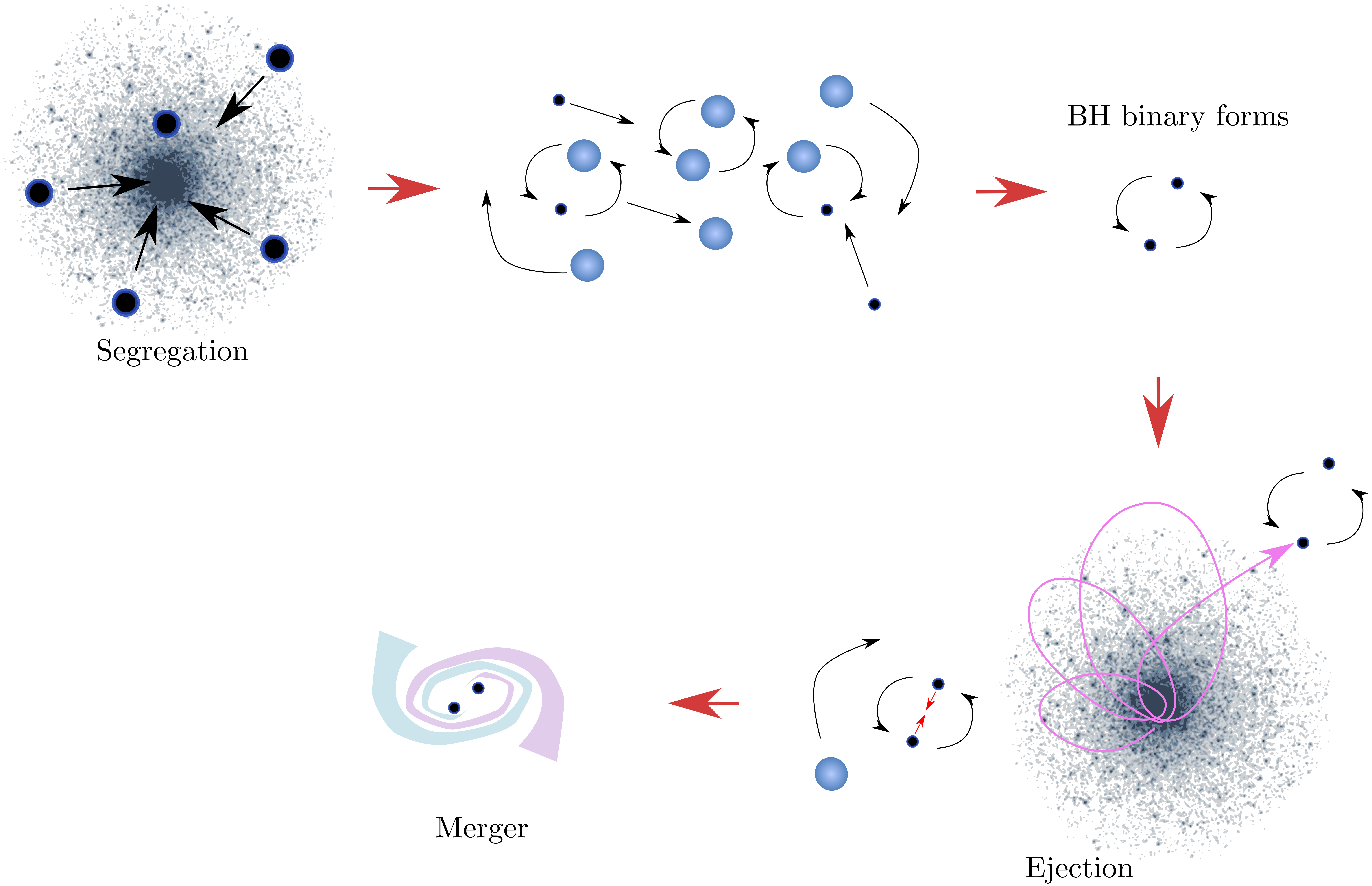
How did they form?





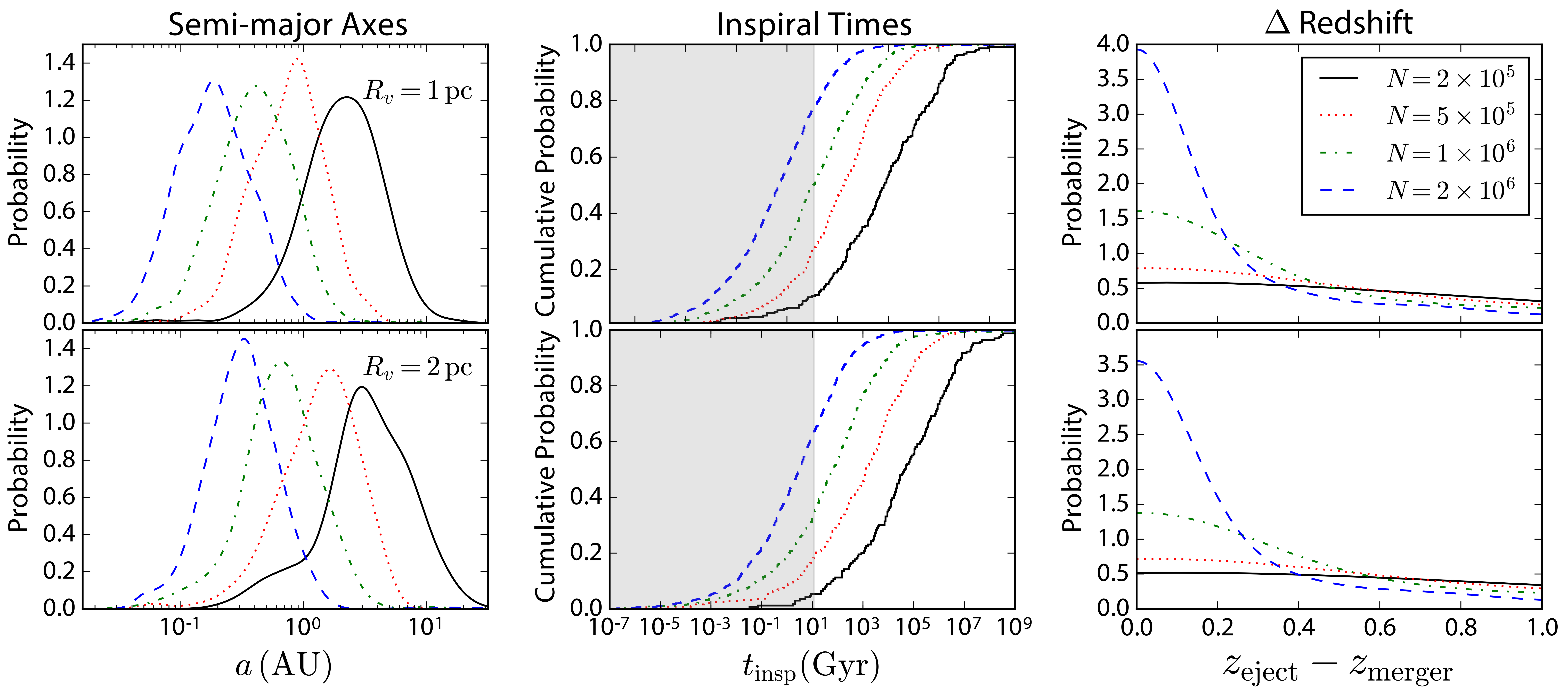

In the standard evolutionary picture, massive stars can grow to radii of ~1000 Rsun, yet we need them in orbits <~100 Rsun for GWs to operate efficiently.

# Dynamical formation




Sigurdsson & Hernquist 1993

# Dynamical formation

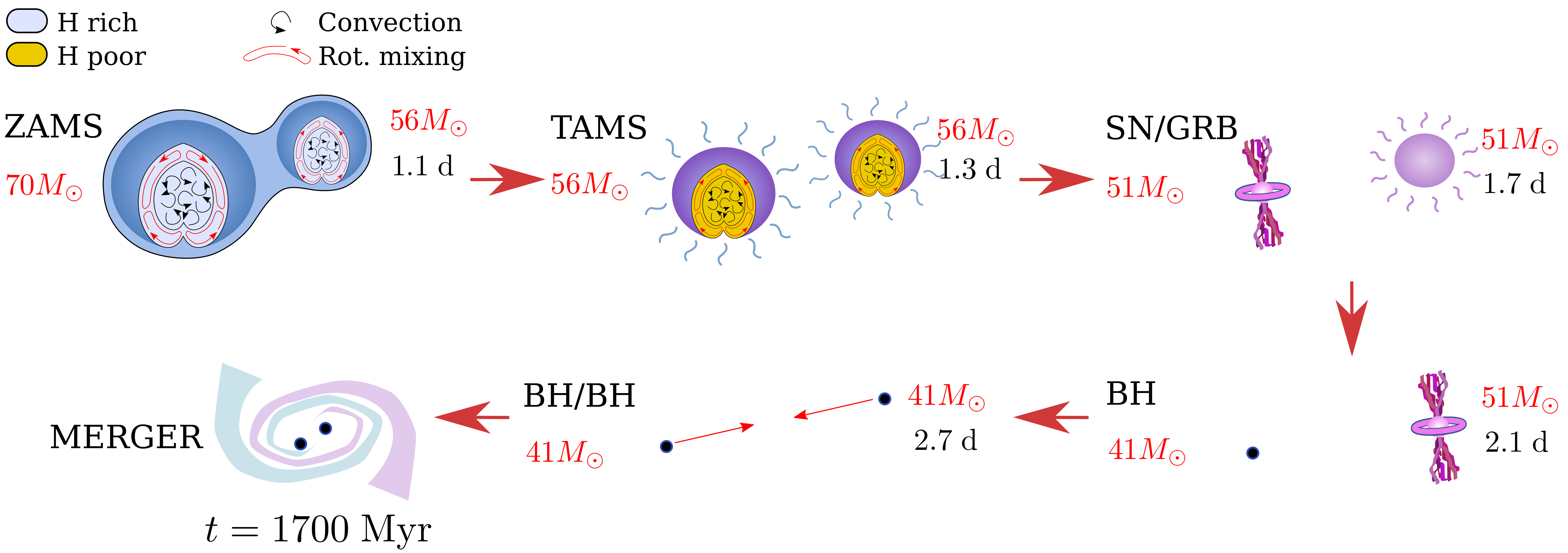



Rodriguez et al. (2016a)

Higher mass and smaller clusters produce harder binaries
- spins expected to be misaligned with orbits
- Potential for second generation mergers

# Chemically homogeneous evolution

Mandel & de Mink (2016), Marchant et al. (2016)
More recent: du Buisson et al. (2020), Ryley et al. (2021)



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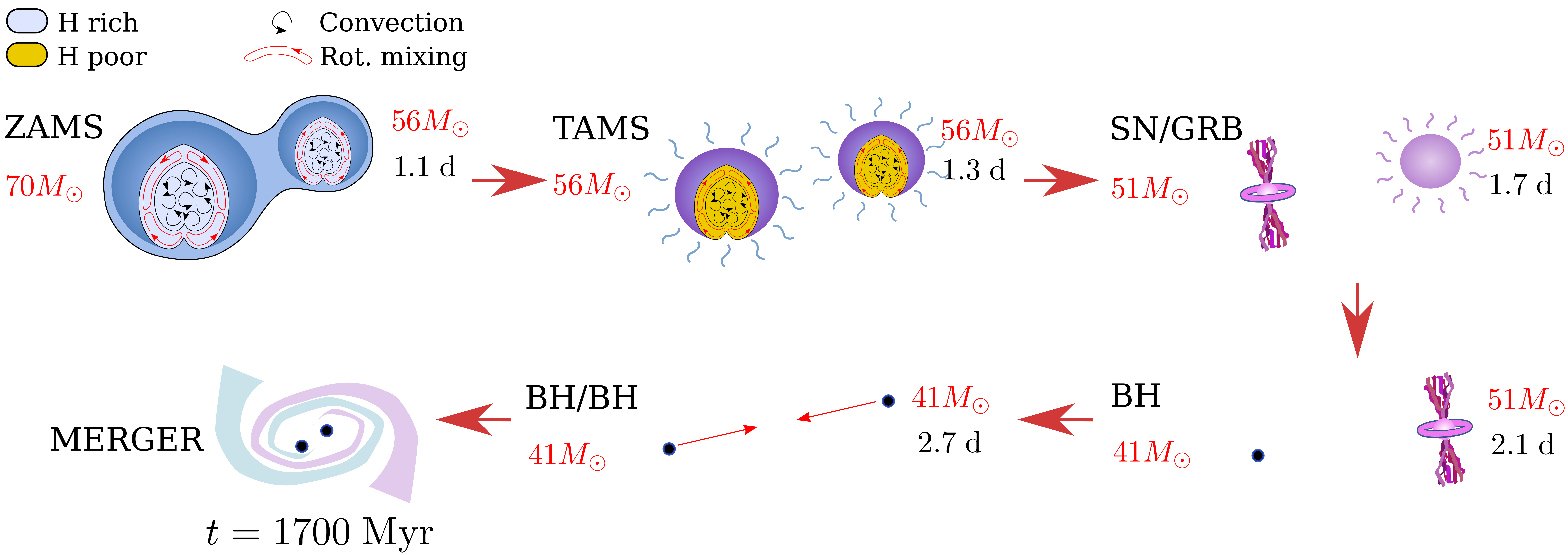
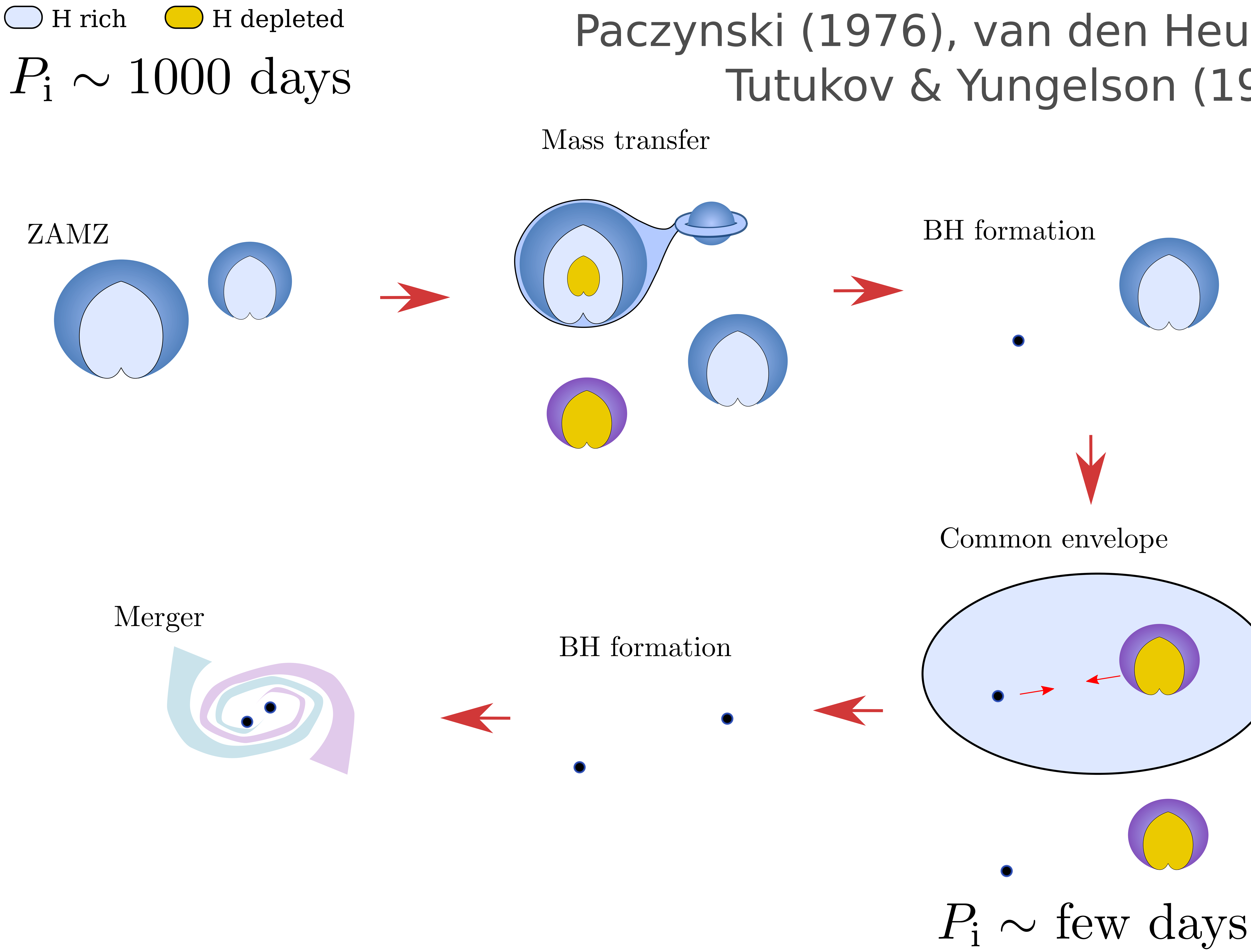



- Large (chi_eff>~0.3) aligned spins
- Potentially a large number of near unity mass ratio systems

# Common envelope evolution

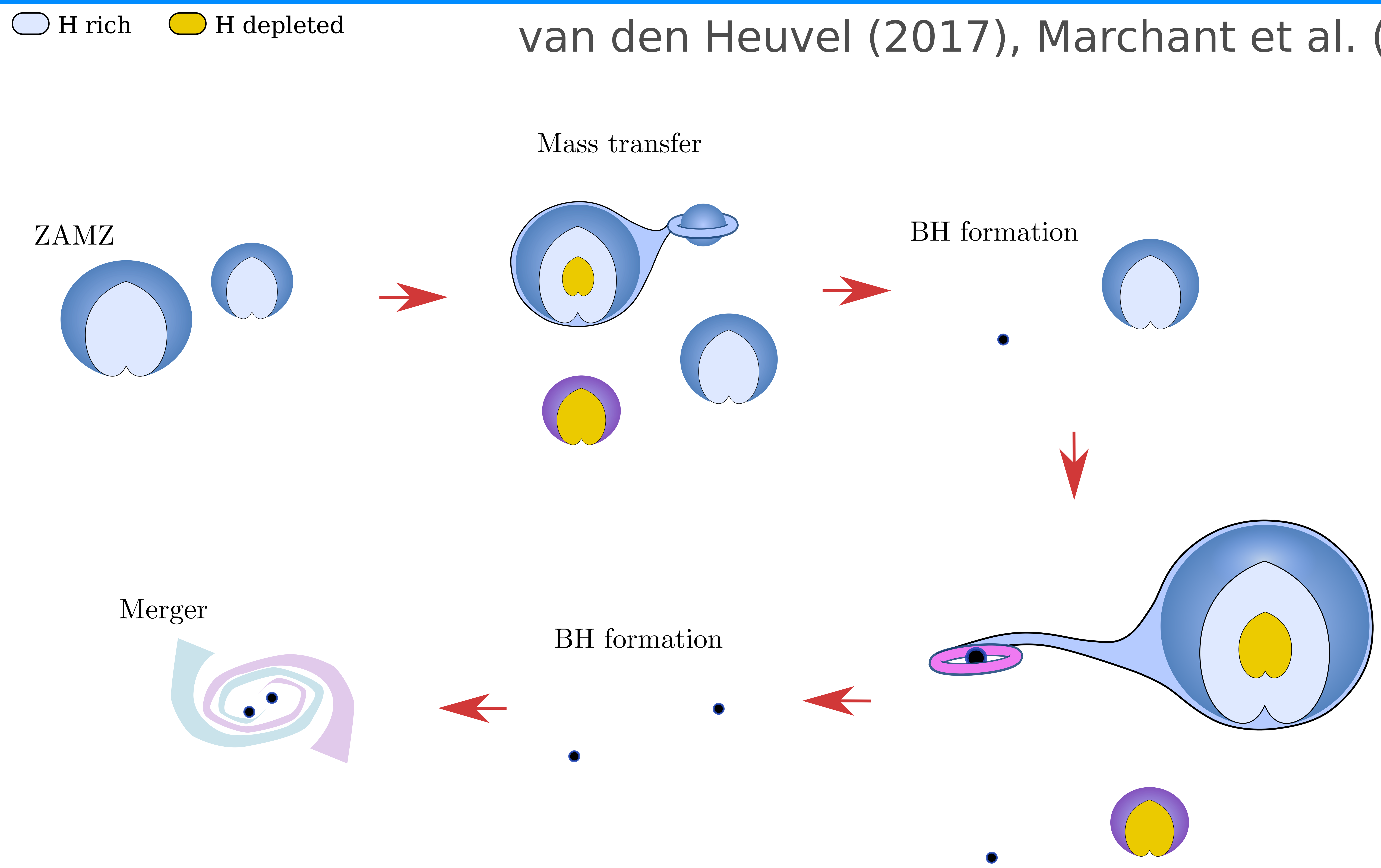
Paczynski (1976), van den Heuvel (1976),
Tutukov & Yungelson (1993)




- Preference for mass ratios >~0.5
- possibility for one of the BHs to have a large spin (cf. Bavera et al. 2020)

# Stable mass transfer

van den Heuvel (2017), Marchant et al. (2021)




$P_{\mathrm{i}} \sim$ few days

- Standard binary evolution estimates might significantly overestimate the contribution from the CE channel, with stable mass transfer being dominant
- General expected properties still under study (see Bavera et al. 2021).

# How do we disentangle this?

This is not even a comprehensive list of channels. And most channels predict rates comparable to the observed one. How do we disentangle their relative contributions?

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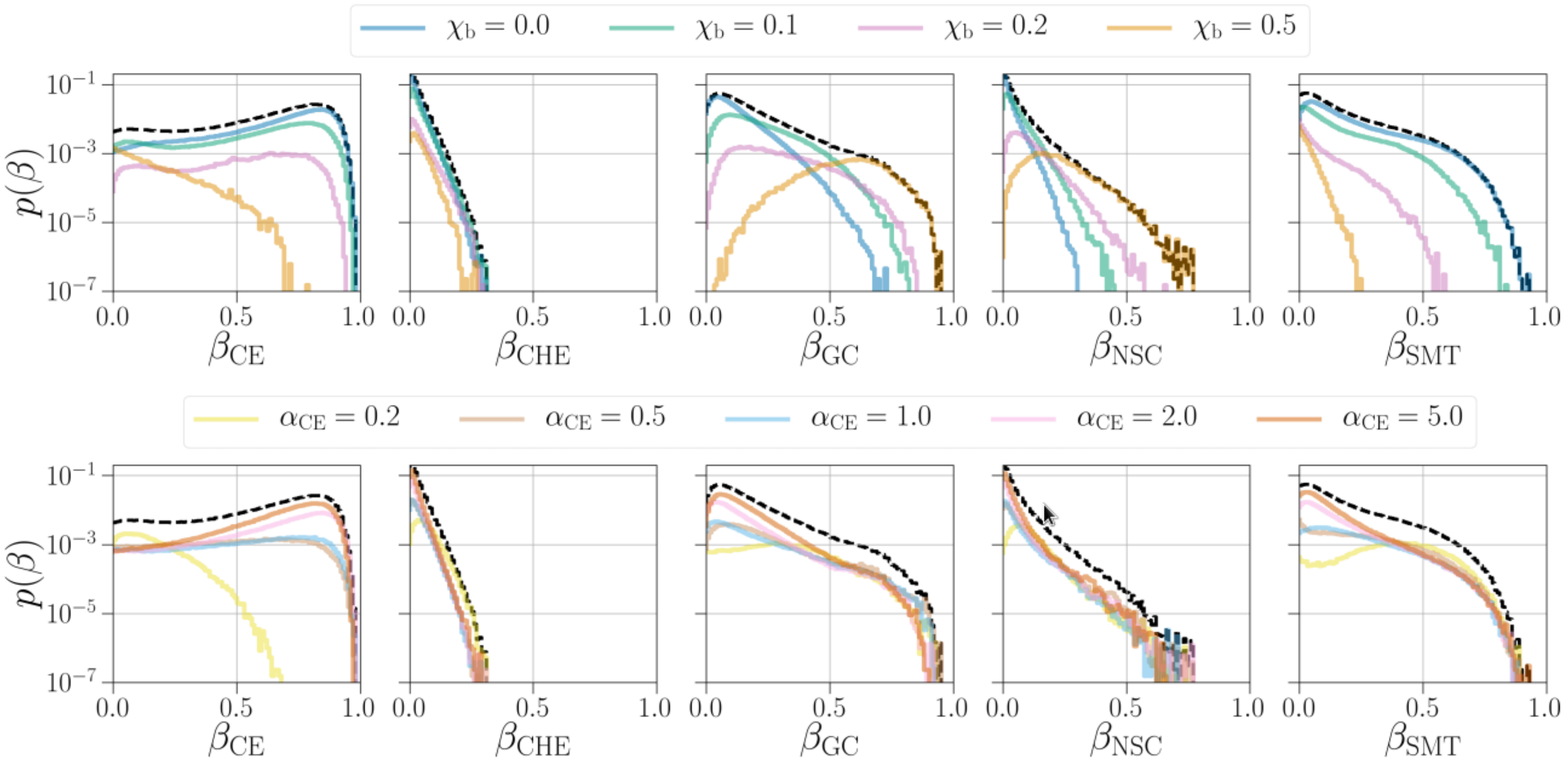


Current attempts doing Bayesian inference to disentangle relative fractions (cf. Zevin et al. 2021). Large uncertainties, important caveats, but if anything the community is mostly convinced that there is more than one channel in operation.

# Want to know more?

*Living Rev. Relativity*, **12**, (2009), 2
http://www.livingreviews.org/lrr-2009-2

LIVING REVIEWS *in relativity*

## Physics, Astrophysics and Cosmology with Gravitational Waves

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*Living Reviews in Relativity*
ISSN 1433-8351

Accepted on 29 January 2009
Published on 4 March 2009

**Abstract**

Gravitational wave detectors are already operating at interesting sensitivity levels, and they have an upgrade path that should result in secure detections by 2014. We review the physics of gravitational waves, how they interact with detectors (bars and interferometers), and how these detectors operate. We study the most likely sources of gravitational waves and review the data analysis methods that are used to extract their signals from detector noise. Then we consider the consequences of gravitational wave detections and observations for physics, astrophysics, and cosmology.

Really a good review for both parts of today's lecture.

# Want to know more?

## Merging stellar-mass binary black holes

Ilya Mandel*

*Institute of Gravitational Wave Astronomy and School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom*
*and*
*Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Clayton, Victoria 3800, Australia*

Alison Farmer

*kW Engineering, Oakland, California, 94612, USA*

The LIGO and Virgo detectors have recently directly observed gravitational waves from several mergers of pairs of stellar-mass black holes, as well as from one merging pair of neutron stars. These observations raise the hope that compact object mergers could be used as a probe of stellar and binary evolution, and perhaps of stellar dynamics. This colloquium-style article summarizes the existing observations, describes theoretical predictions for formation channels of merging stellar-mass black-hole binaries along with their rates and observable properties, and presents some of the prospects for gravitational-wave astronomy.

Mandel & Farmer (2018), plenty of information on the formation of merging binary black holes.

# Want to know more?

**Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1**

The LIGO Scientific Collaboration and the Virgo Collaboration
(compiled October 10, 2019)

The detection of gravitational waves by Advanced LIGO and Advanced Virgo provides an opportunity to test general relativity in a regime that is inaccessible to traditional astronomical observations and laboratory tests. We present four tests of the consistency of the data with binary black hole gravitational waveforms predicted by general relativity. One test subtracts the best-fit waveform from the data and checks the consistency of the residual with detector noise. The second test checks the consistency of the low- and high-frequency parts of the observed signals. The third test checks that phenomenological deviations introduced in the waveform model (including in the post-Newtonian coefficients) are consistent with zero. The fourth test constrains modifications to the propagation of gravitational waves due to a modified dispersion relation, including that from a massive graviton. We present results both for individual events and also results obtained by combining together particularly strong events from the first and second observing runs of Advanced LIGO and Advanced Virgo, as collected in the catalog GWTC-1. We do not find any inconsistency of the data with the predictions of general relativity and improve our previously presented combined constraints by factors of 1.1 to 2.5. In particular, we bound the mass of the graviton to be $m_g \leq 4.7 \times 10^{-23}$ eV$/c^2$ (90% credible level), an improvement of a factor of 1.6 over our previously presented results. Additionally, we check that the four gravitational-wave events published for the first time in GWTC-1 do not lead to stronger constraints on alternative polarizations than those published previously.

Current status of GR tests done with LIGO data. At the moment there are no inconsistencies found (astro-ph:1903.04467).

# Want to know more?

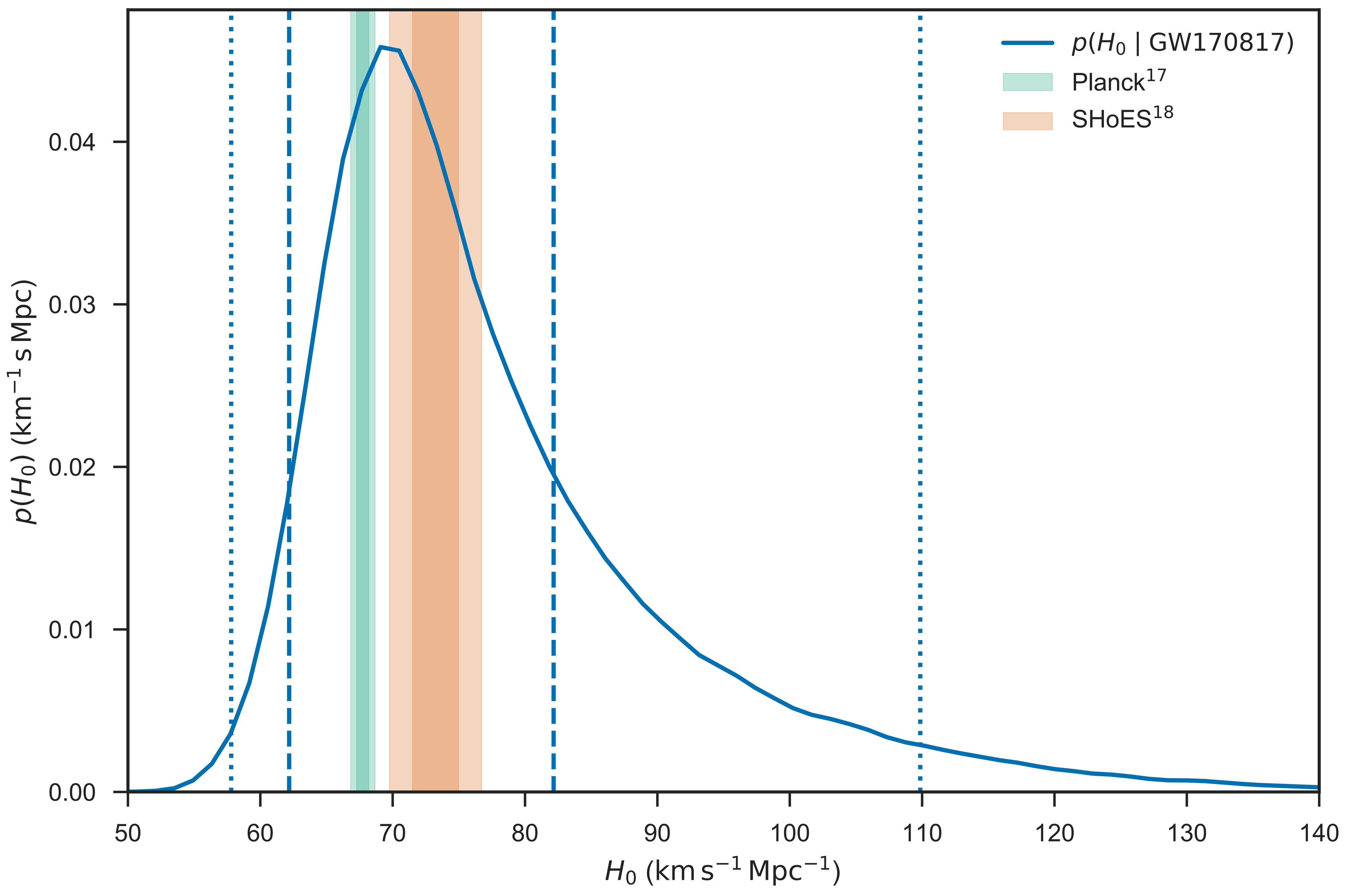
DRAFT VERSION OCTOBER 17, 2017
Typeset using LaTeX **preprint2** style in AASTeX61

A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE 1M2H COLLABORATION,
THE DARK ENERGY CAMERA GW-EM COLLABORATION AND THE DES COLLABORATION,
THE DLT40 COLLABORATION, THE LAS CUMBRES OBSERVATORY COLLABORATION,
THE VINROUGE COLLABORATION, THE MASTER COLLABORATION, et al.

Hubble constant measurements, not yet useful to sort out the discrepancy on the measurement of the Hubble constant but will be competitive in the coming decade. (astro-ph: 1710.05835).

See also Farr et al. (2019) for a different method to use GR signals as standard sirens (astro-ph:1908.09084).



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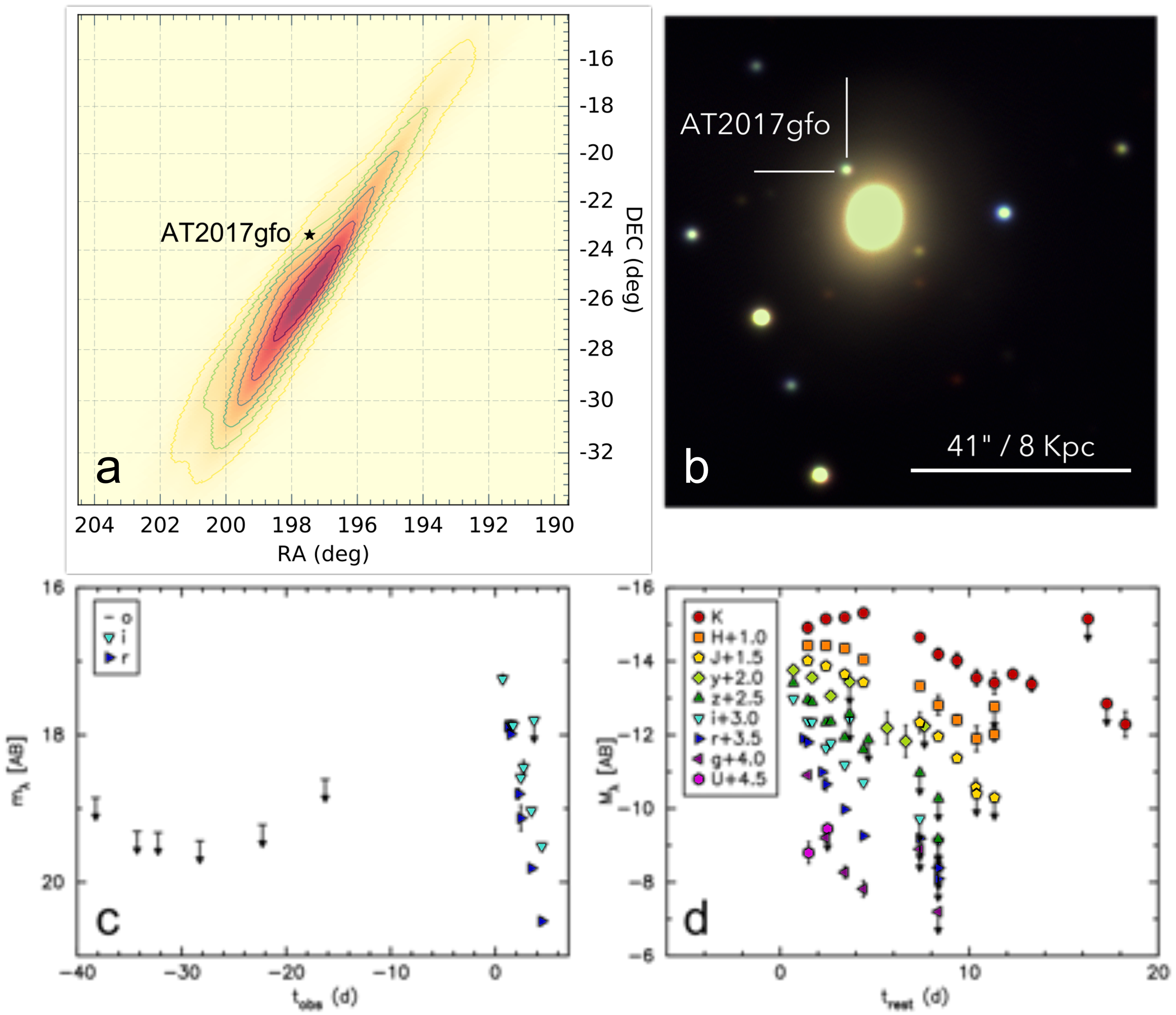
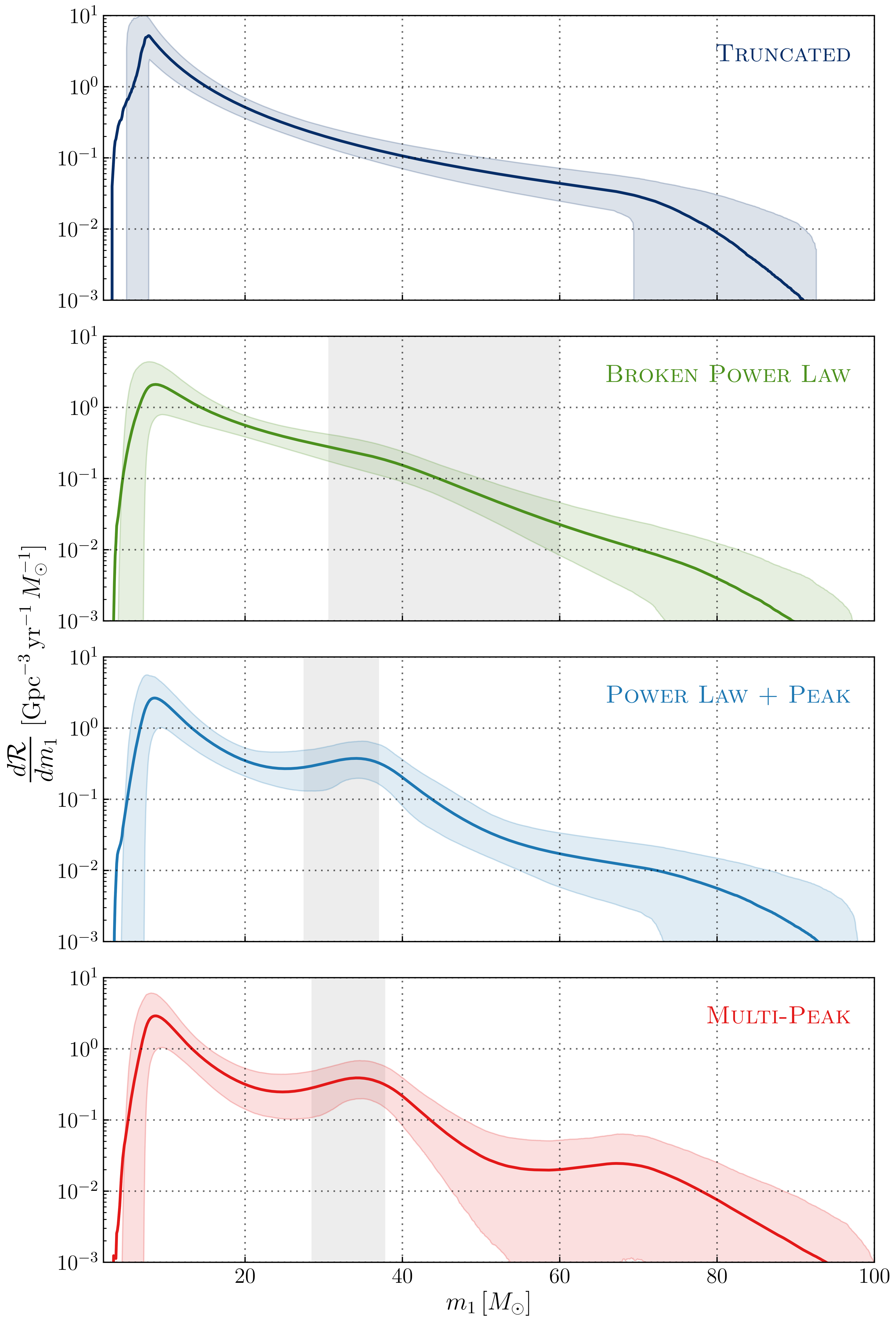



Figure 1: | **Observational data summary a:** The position of AT2017gfo lying within the Ligo-Virgo skymap[11, 6] **b:** Color composite image of AT2017gfo from GROND on 2017 Aug 18 (MJD 57983.969, 1.44 days after GW170817 discovery. The transient is 8.50″ North, 5.40″ East of the centre of NGC4993, an S0 galaxy at a distance of $40 \pm 4$ Mpc. This is a projected distance of 2 kpc. The source is measured at position of RA=13:09:48.08 DEC=−23:22:53.2 J2000 (±0.1″ in each) in our Pan-STARRS1 images. **c:** ATLAS limits between 40 and 16 days before discovery (orange filter), plus the Pan-STARRS1 and GROND $r$ and $i$-band light curve. **d:** Our full light curve data, which provides a reliable bolometric light curve for analysis. Upper limits are $3\sigma$ and uncertainties on the measured points are $1\sigma$.

Smartt et al. (2017), on the observation of the electromagnetic counterpart to GW170817.

astro-ph: 1710.05841

# Want to know more?




Second catalogue of GW transients, GWTC-2 (astro-ph: 2010.14527)

Inferred population properties from GWTC-2 (astro-ph: 2010.14533)