# *Black hole binaries: formation and merger rates*

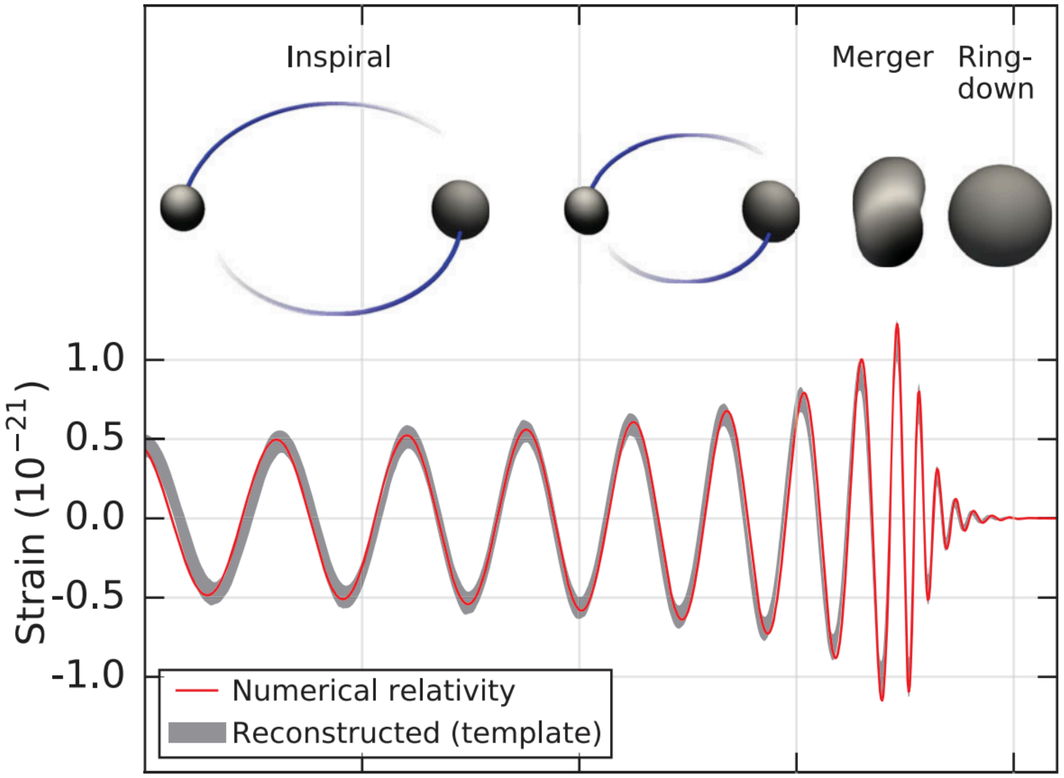
**Irina Dvorkin**

Max Planck Institute for Gravitational Physics (AEI, Potsdam)

With: Joe Silk, Jean-Philippe Uzan, Elisabeth Vangioni, Cyril Pitrou (Institut d'Astrophysique de Paris)
Giulia Cusin (Oxford), Keith Olive (U Minnesota)

SVOM Scientific Workshop, Les Houches, May 15, 2018

# The birth of gravitational-wave astronomy

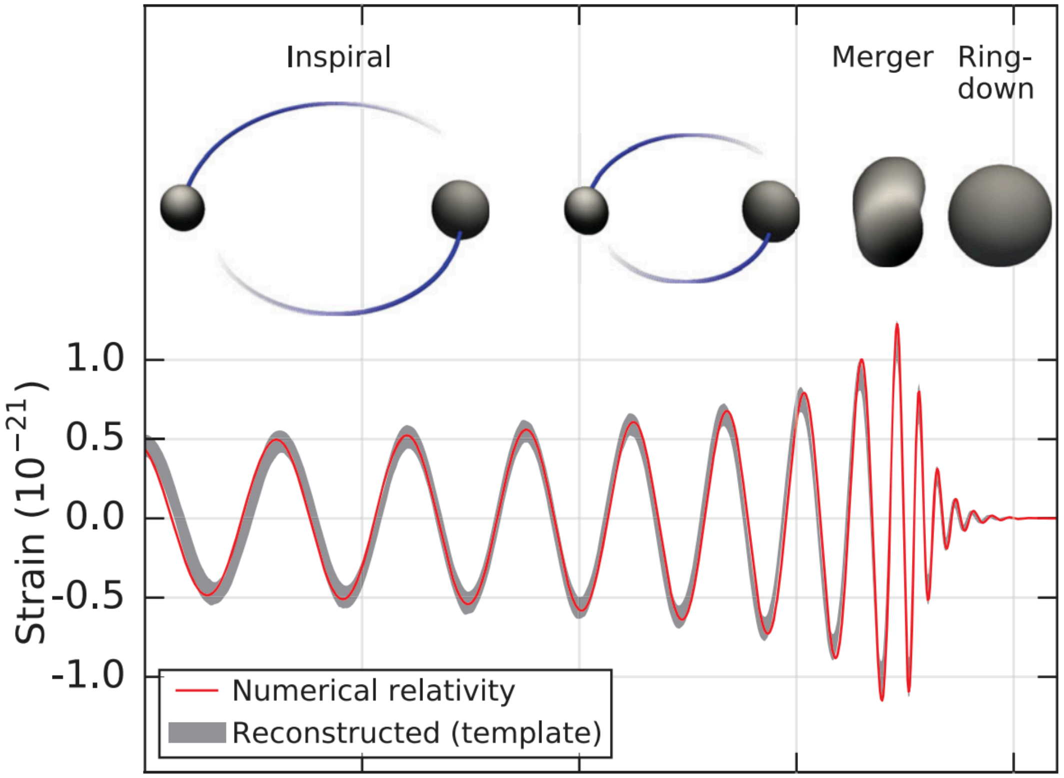


[Abbott et al. (2016)]

**September 2014:**

**GW150914:** The first merging binary black hole

# The birth of gravitational-wave astronomy



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**September 2014:**

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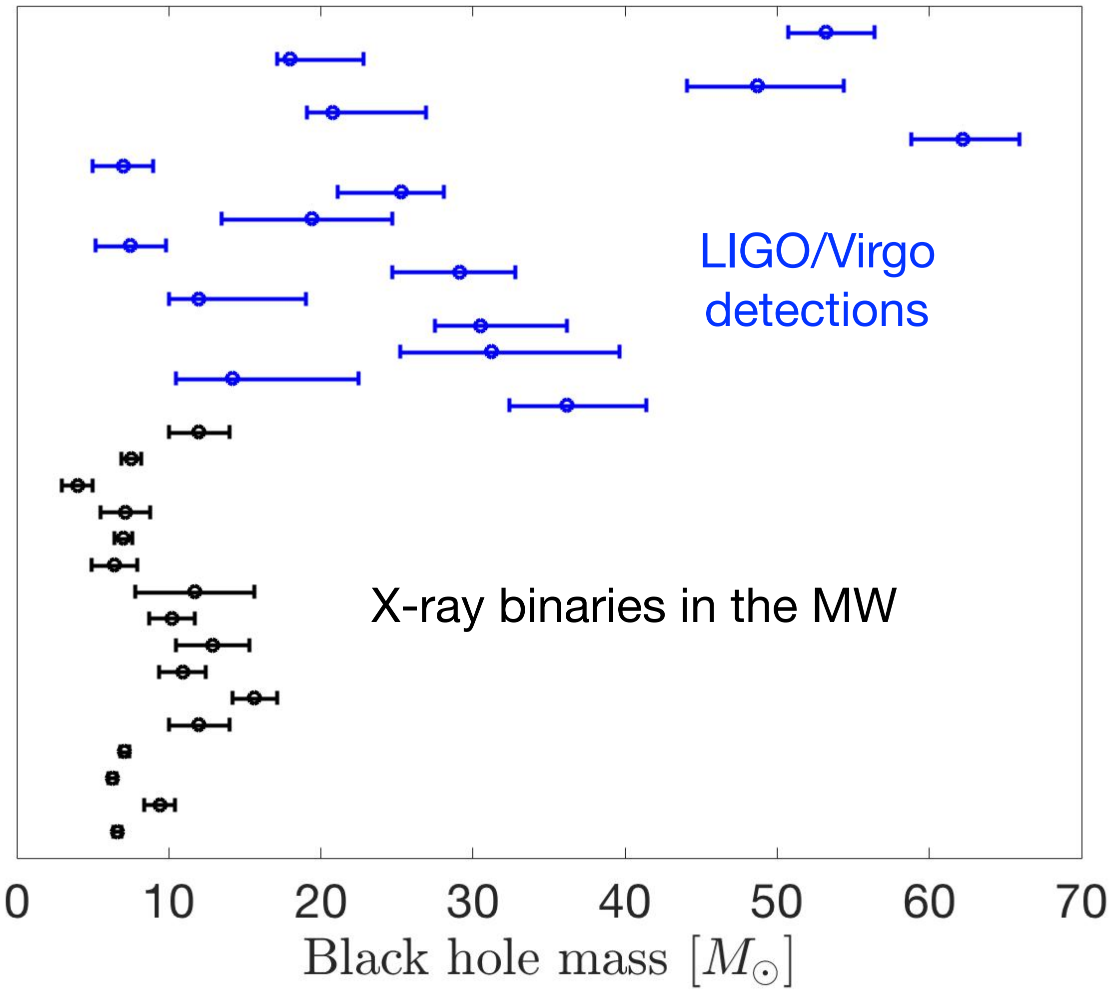
**Today (May 2018):** 5 binary black holes
1 binary neutron star



# How does a black hole binary form?

Core collapse SN / direct collapse to a BH

- Mass prior to core collapse: determined by stellar winds
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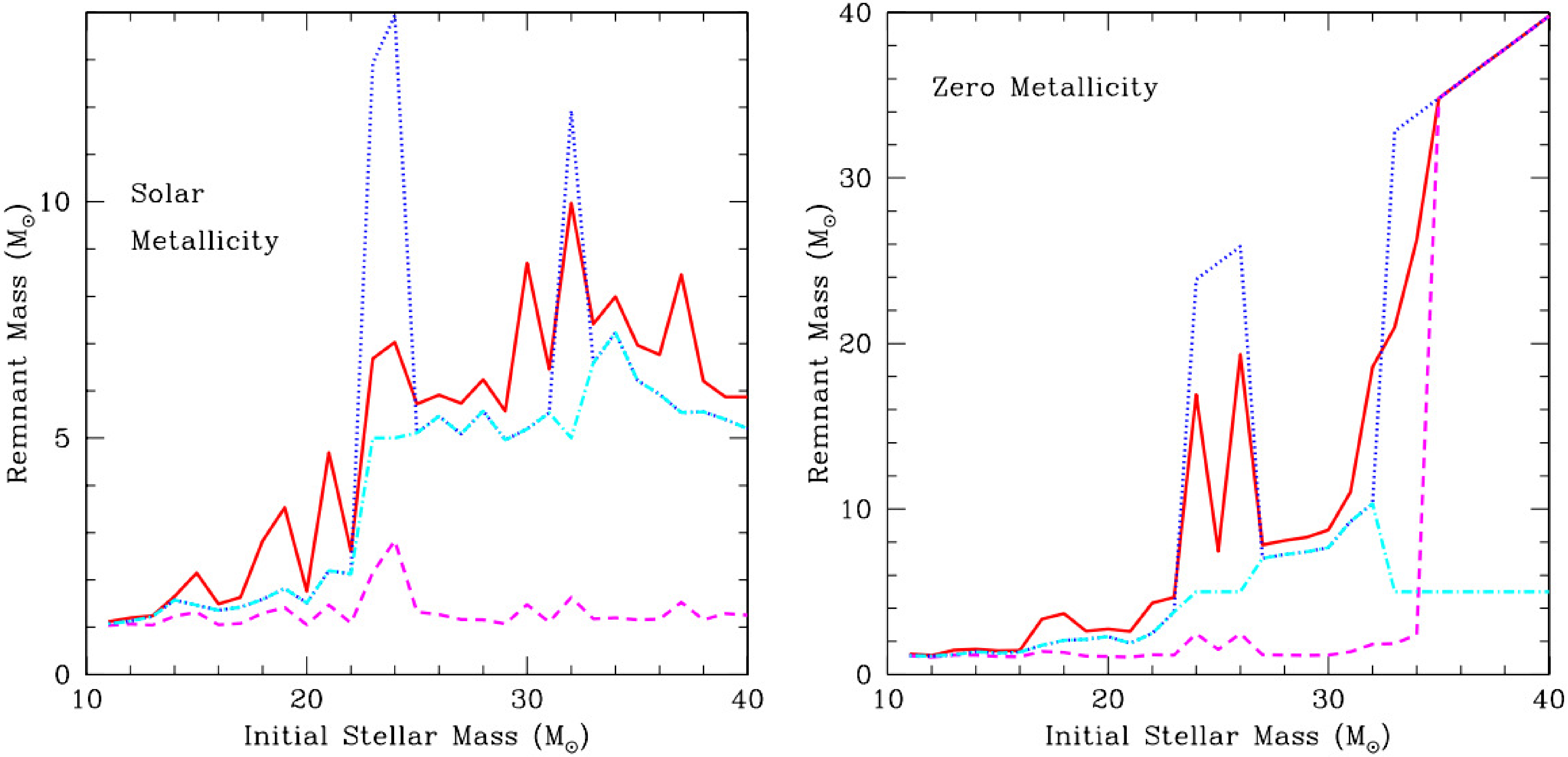
Remnant mass = *f*(stellar mass, **metallicity**, rotation)



[Fryer et al. (2012)]

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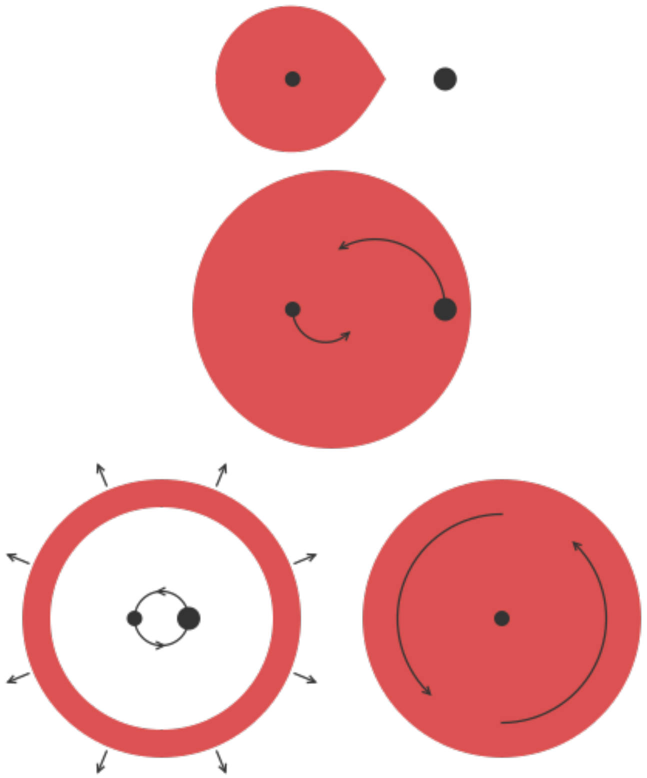
Evolution of stellar binary

- Common envelope



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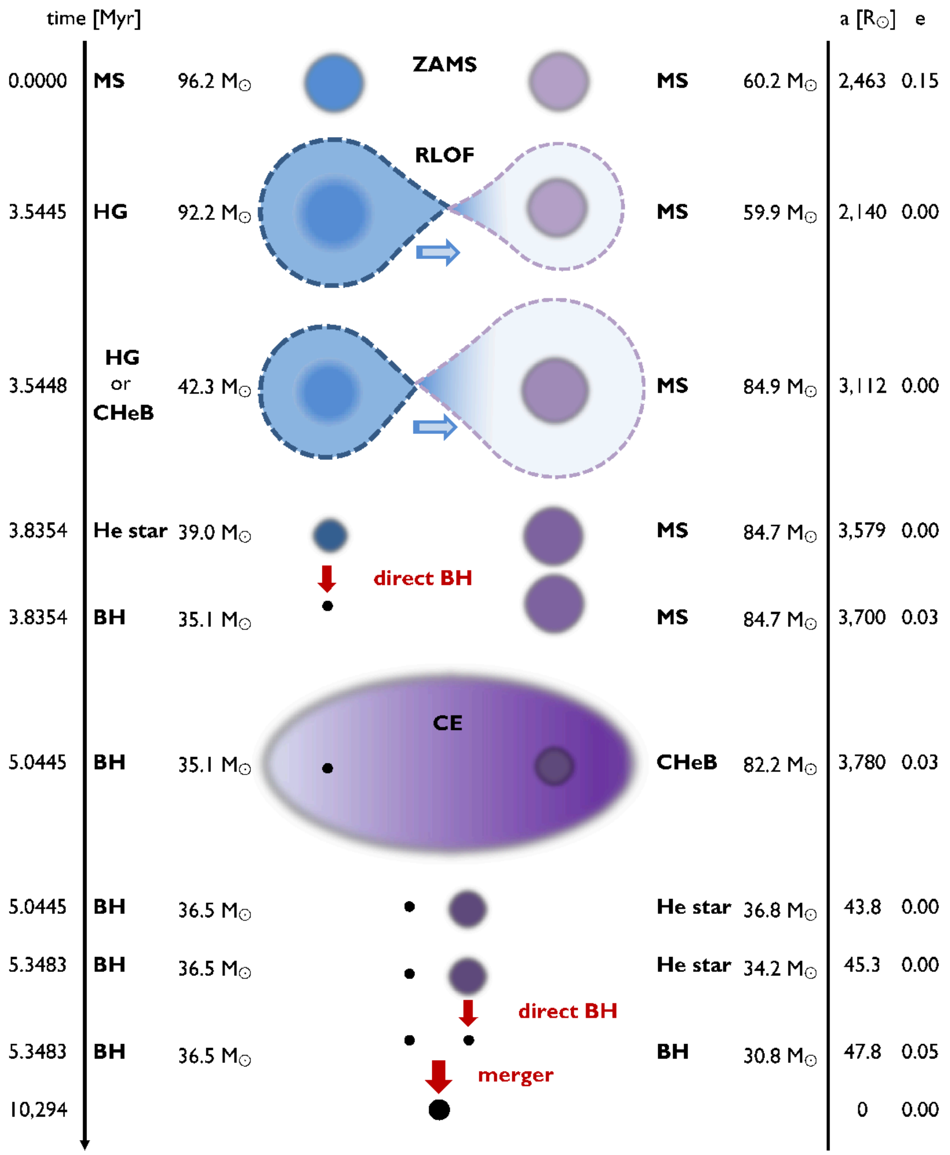

[Belczynski et al. (2016)]

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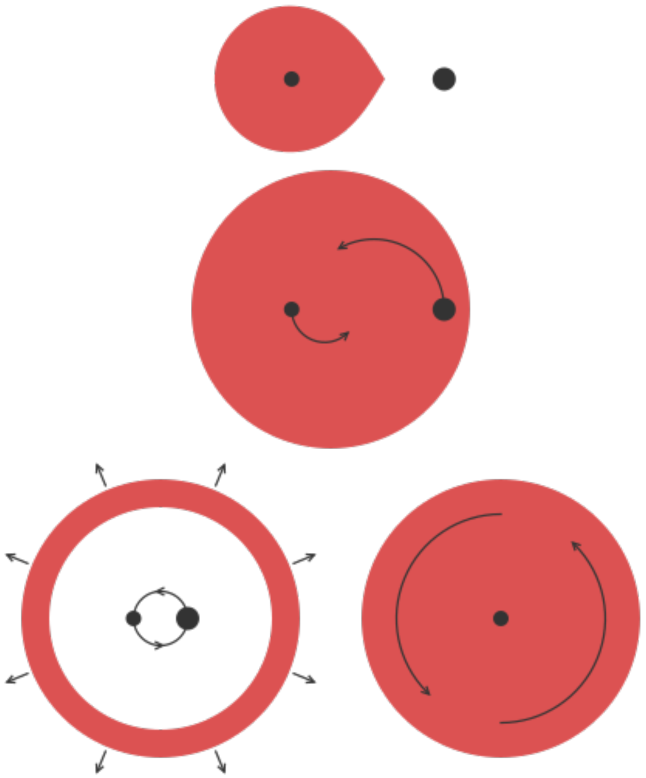

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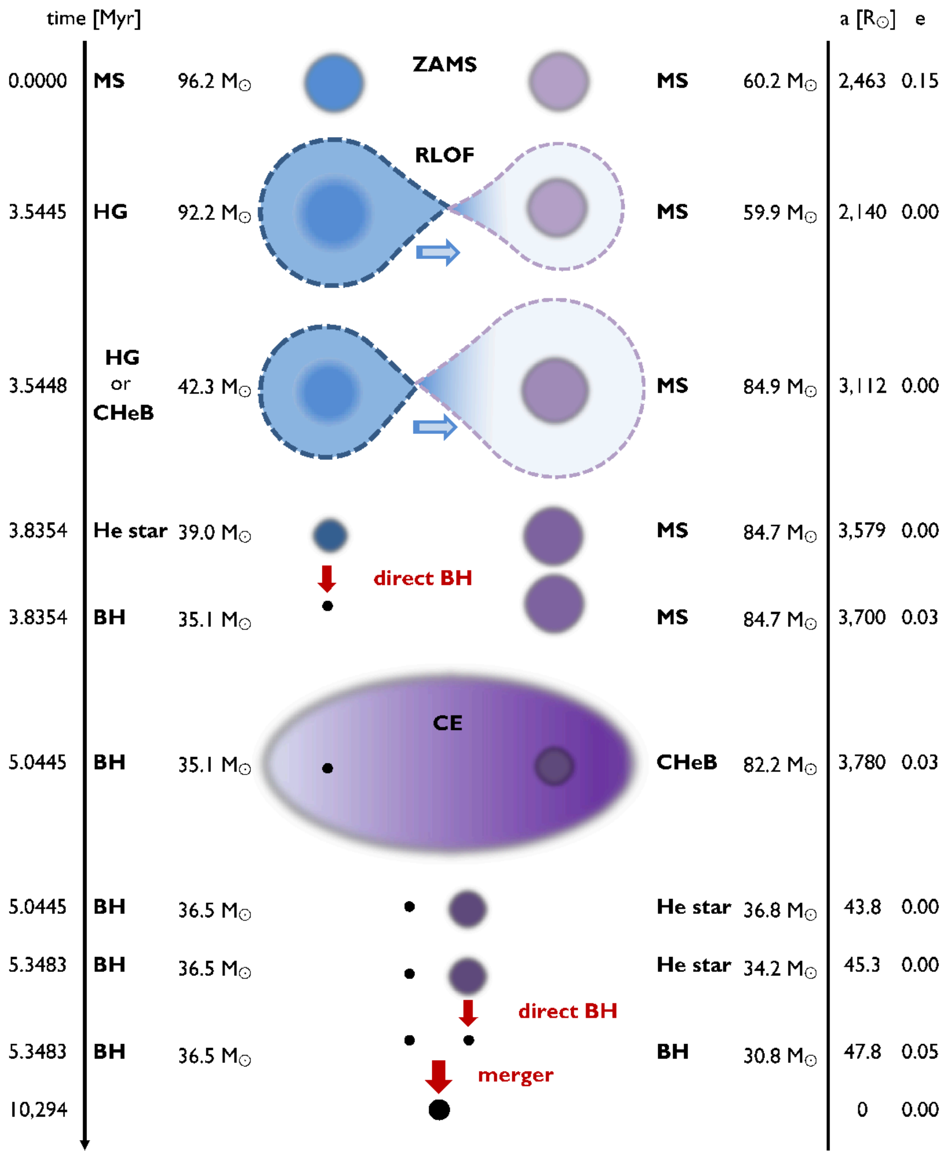

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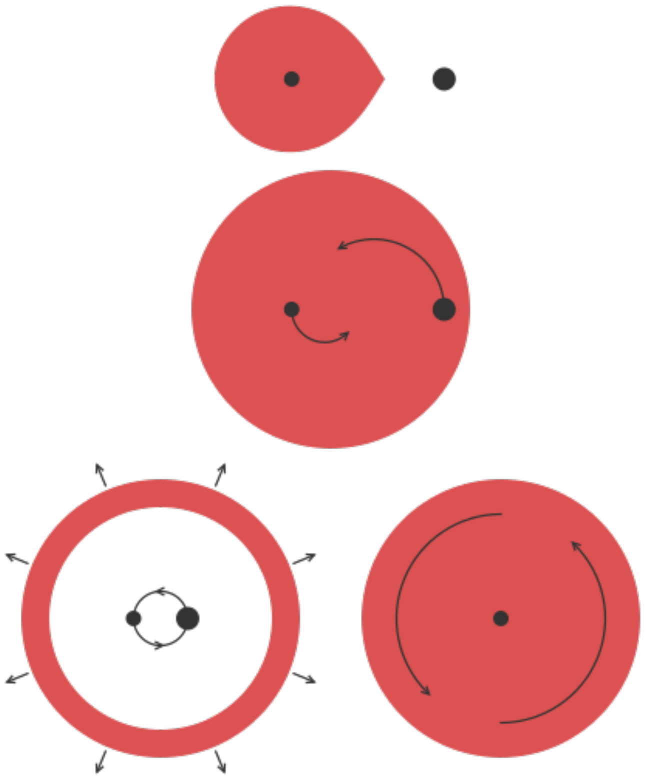


Other channels:

- PopIII stars
- Dynamic binary formation in dense stellar clusters
- Primordial black holes

# How to study BH formation with GW?

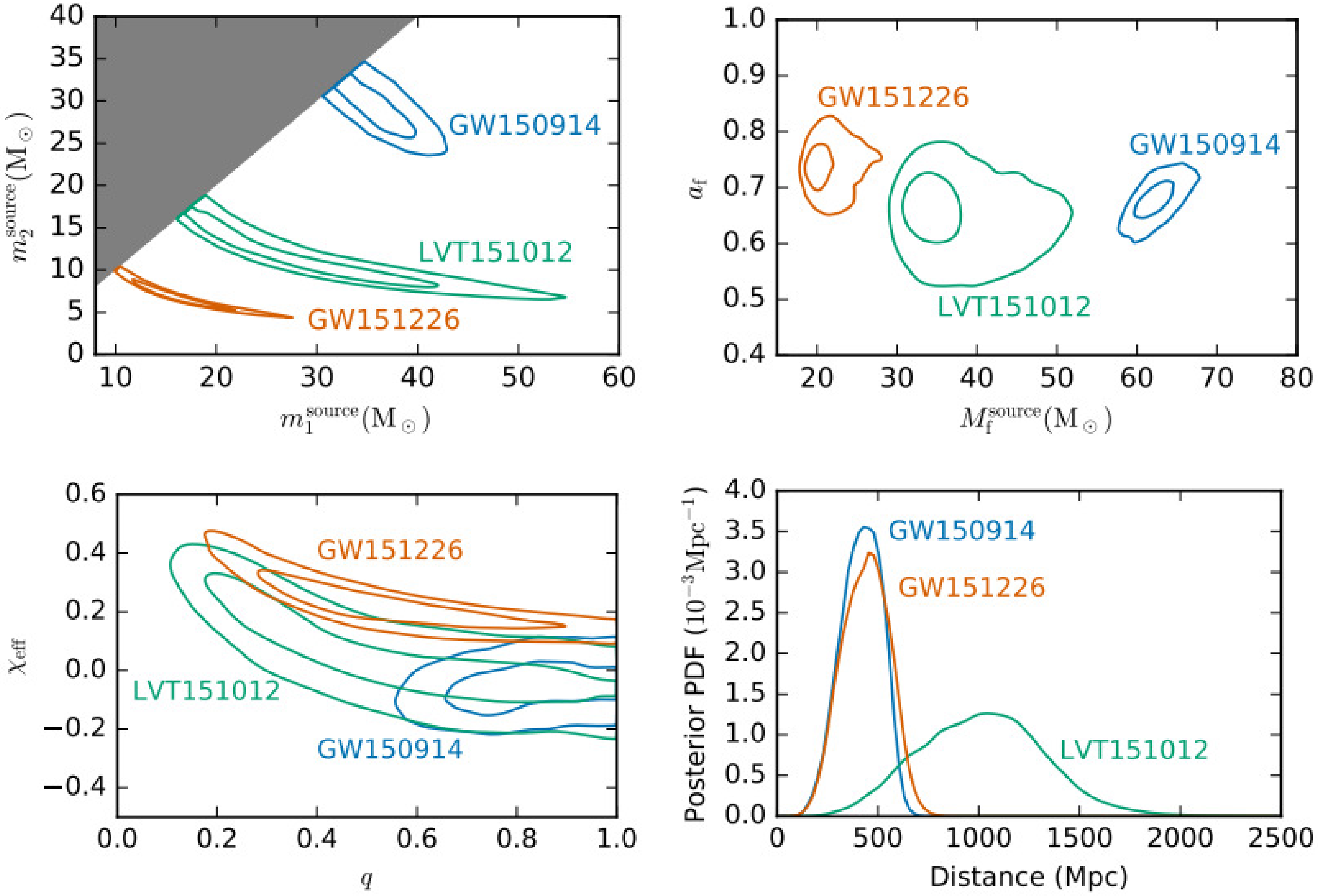
**What we can observe:**

- Masses
- Spins
- Redshifts

**What we need to constrain:**

- Black hole formation scenario
- Specific model parameters

[Abbott et al. (2016)]



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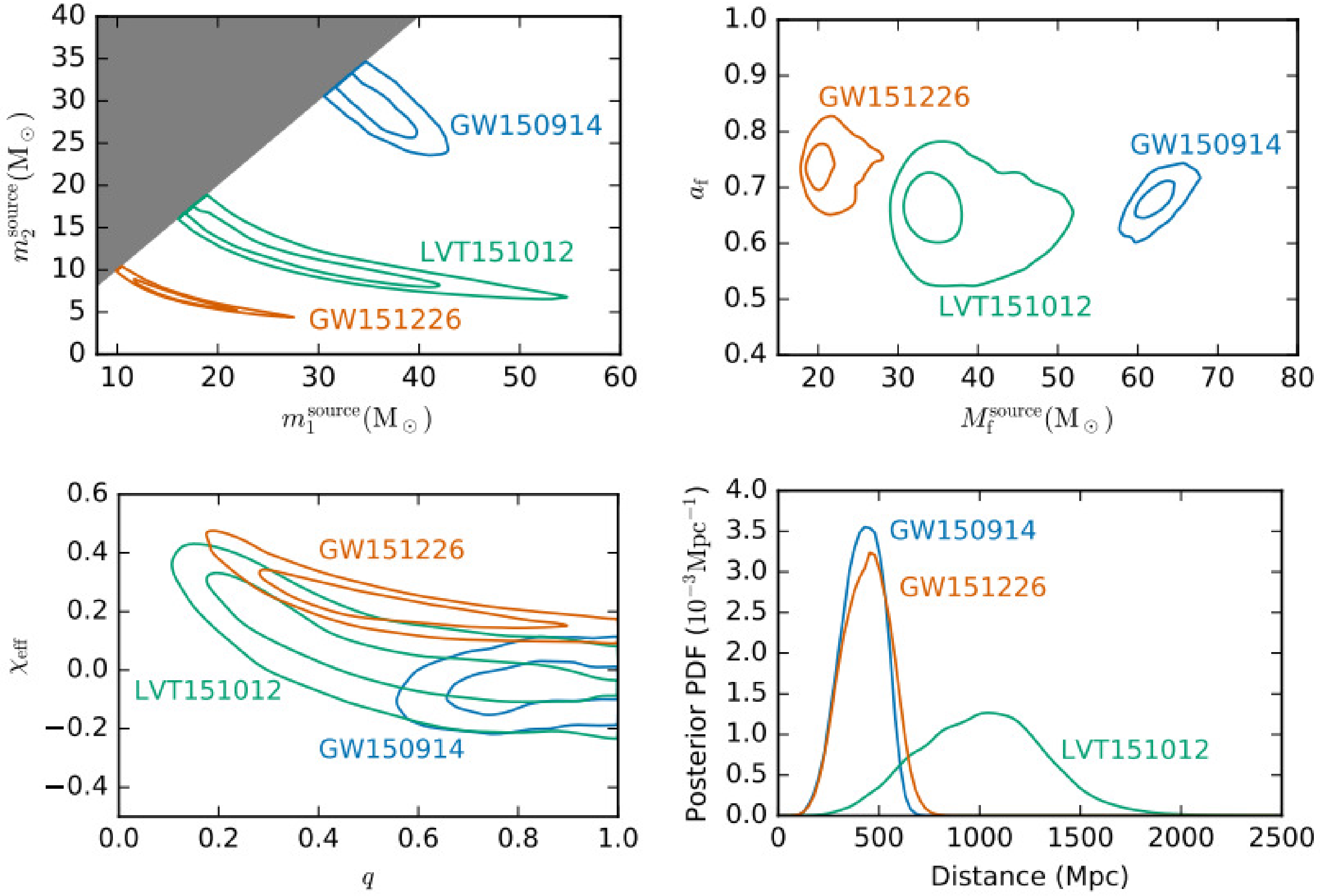

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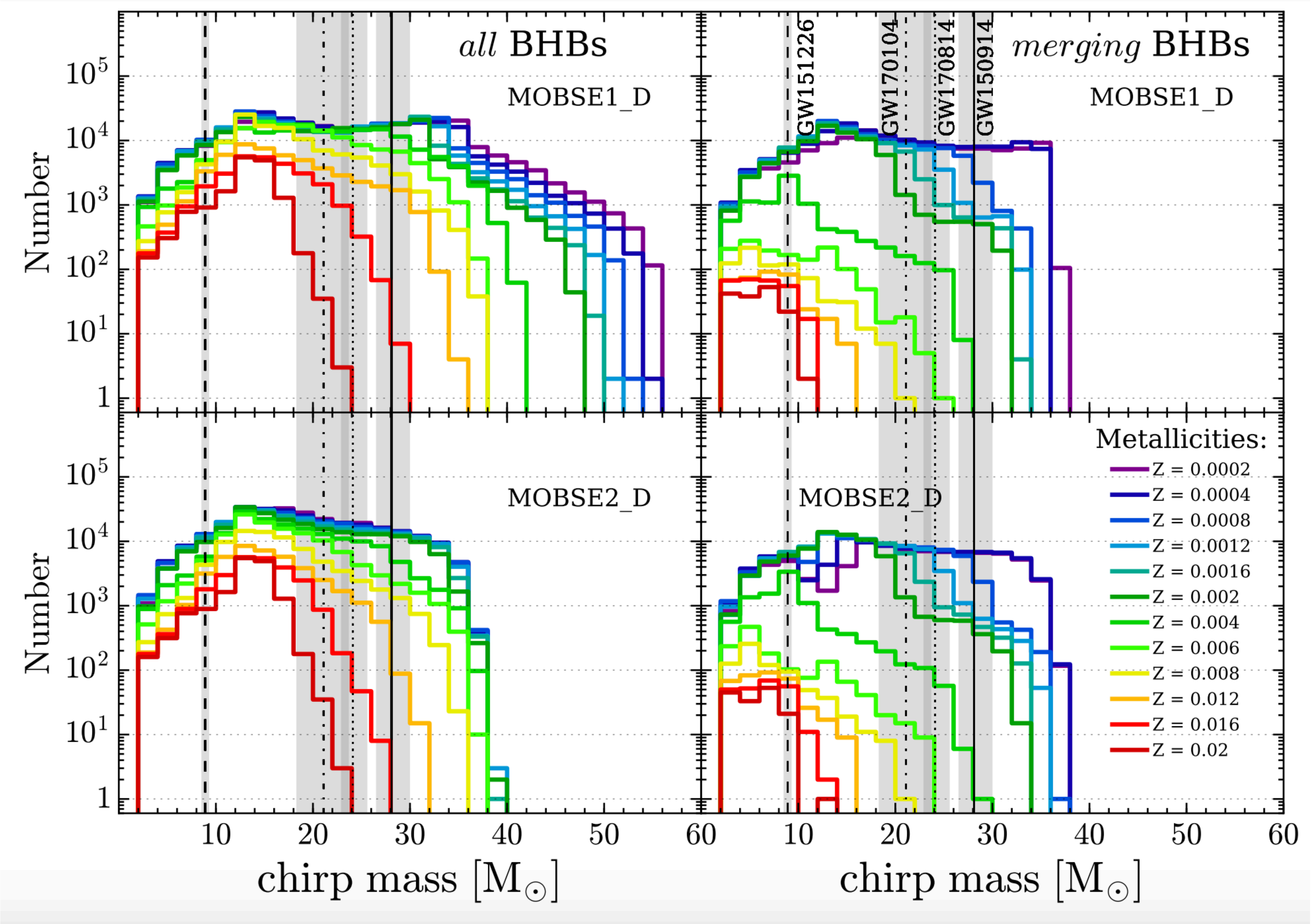
[**ID** et al. (2016a,b; 2018); Lamberts et al. (2016); Belczynski et al. (2016), Mapelli et al. (2017); Zevin et al. (2017); Schneider et al. (2017); Kovetz et al. (2017); Hotokezaka & Piran (2017); Giacobbo et al. (2017)]

# BBH formation rates

Population synthesis codes with different prescriptions for stellar winds:

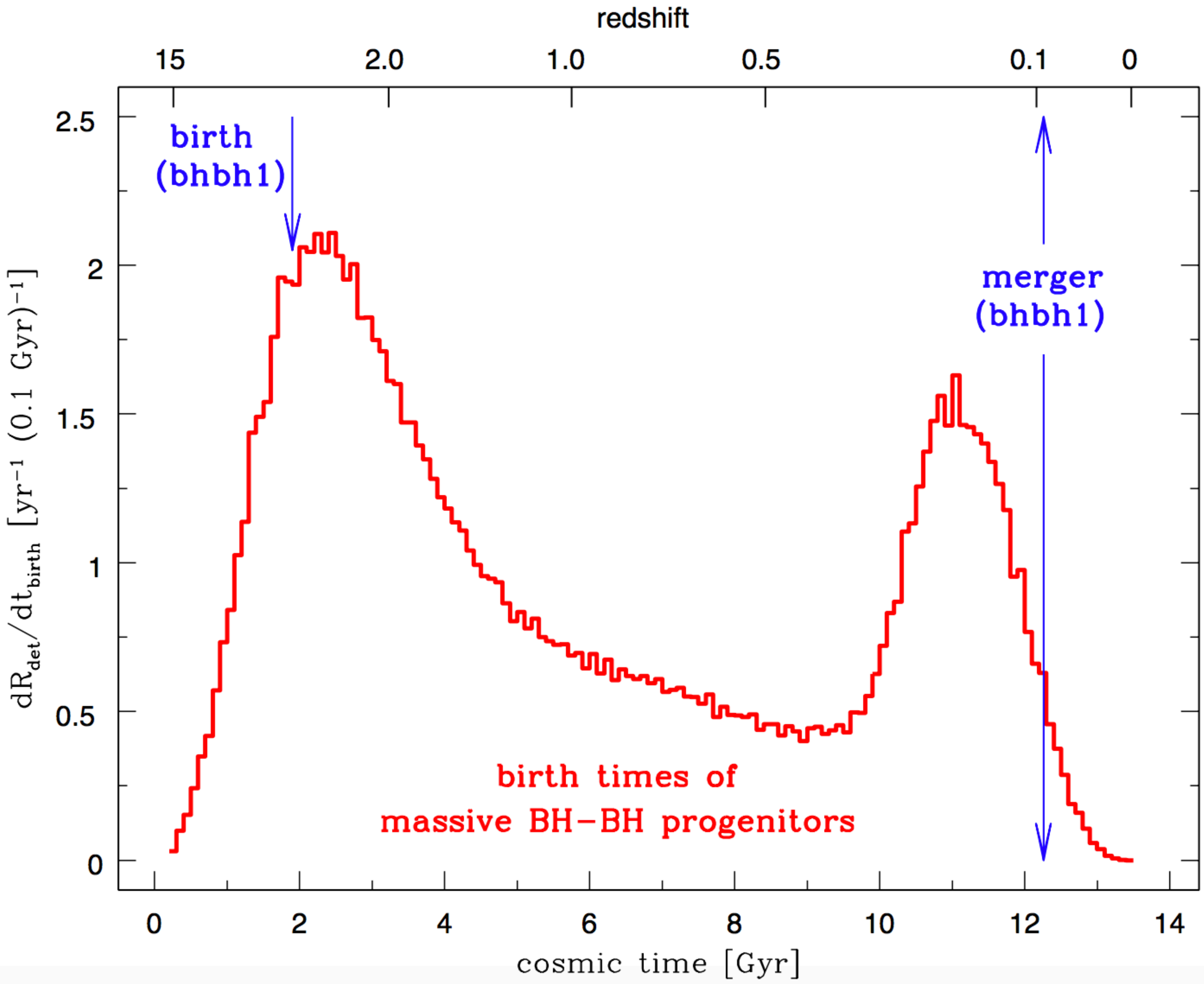
[Giacobbo et al. (2017)]



# BBH formation rates

Birth times of GW150914-like progenitors across cosmic time

[Belczynski et al. (2016)]

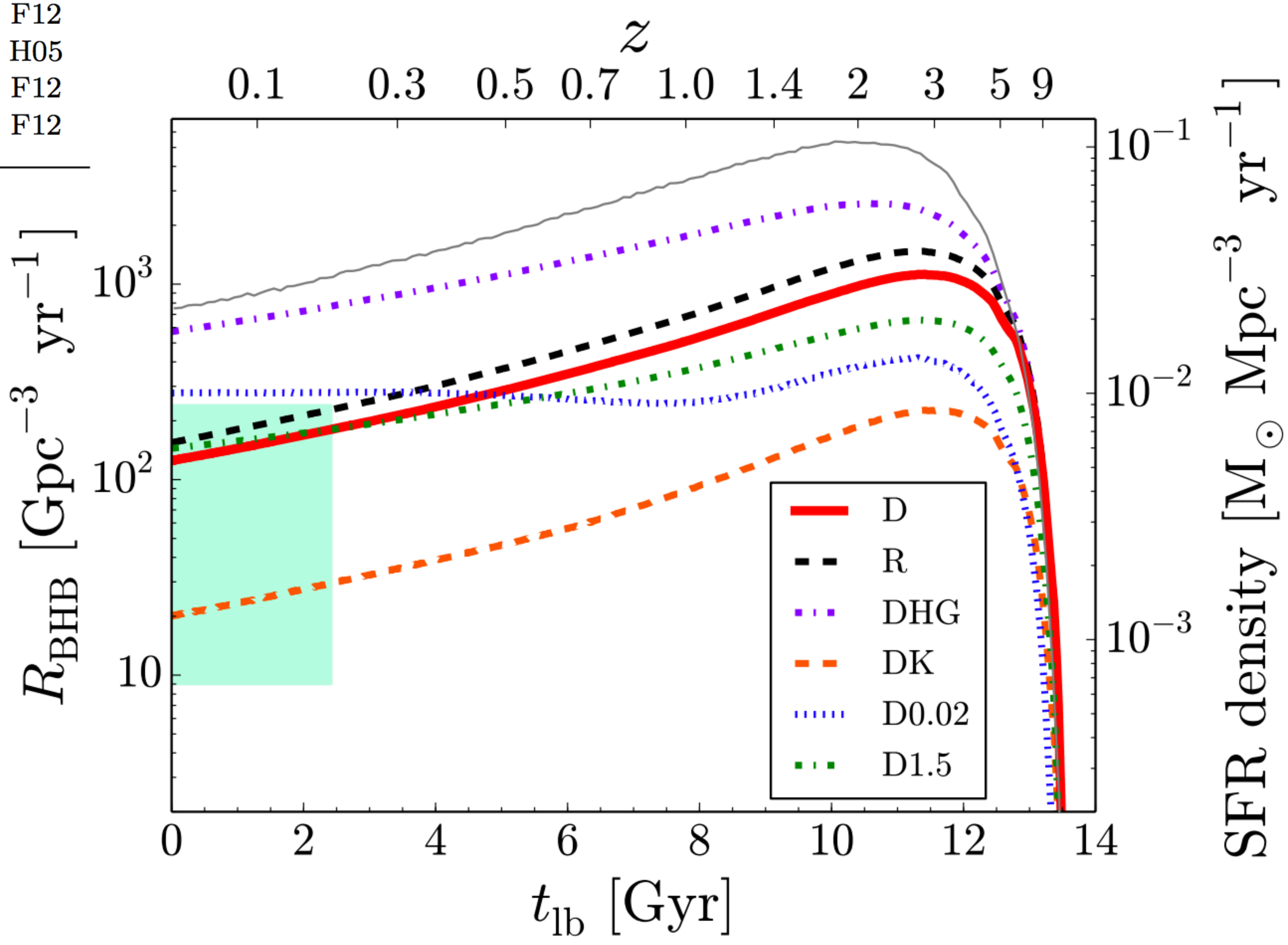


# BBH merger rates

Remnant mass = $f$(stellar mass, **metallicity**, rotation) **+** **Galaxy evolution model**

| Name | SN | $\alpha$ | $\lambda$ | HG | Kick |
|---|---|---|---|---|---|
| D | Delayed | 1.0 | 0.1 | new | F12 |
| R | Rapid | 1.0 | 0.1 | new | F12 |
| DHG | Delayed | 1.0 | 0.1 | BSE | F12 |
| DK | Delayed | 1.0 | 0.1 | new | H05 |
| D0.02 | Delayed | 0.2 | 0.1 | new | F12 |
| D1.5 | Delayed | 3.0 | 0.5 | new | F12 |

[Mapelli et al. (2017)]



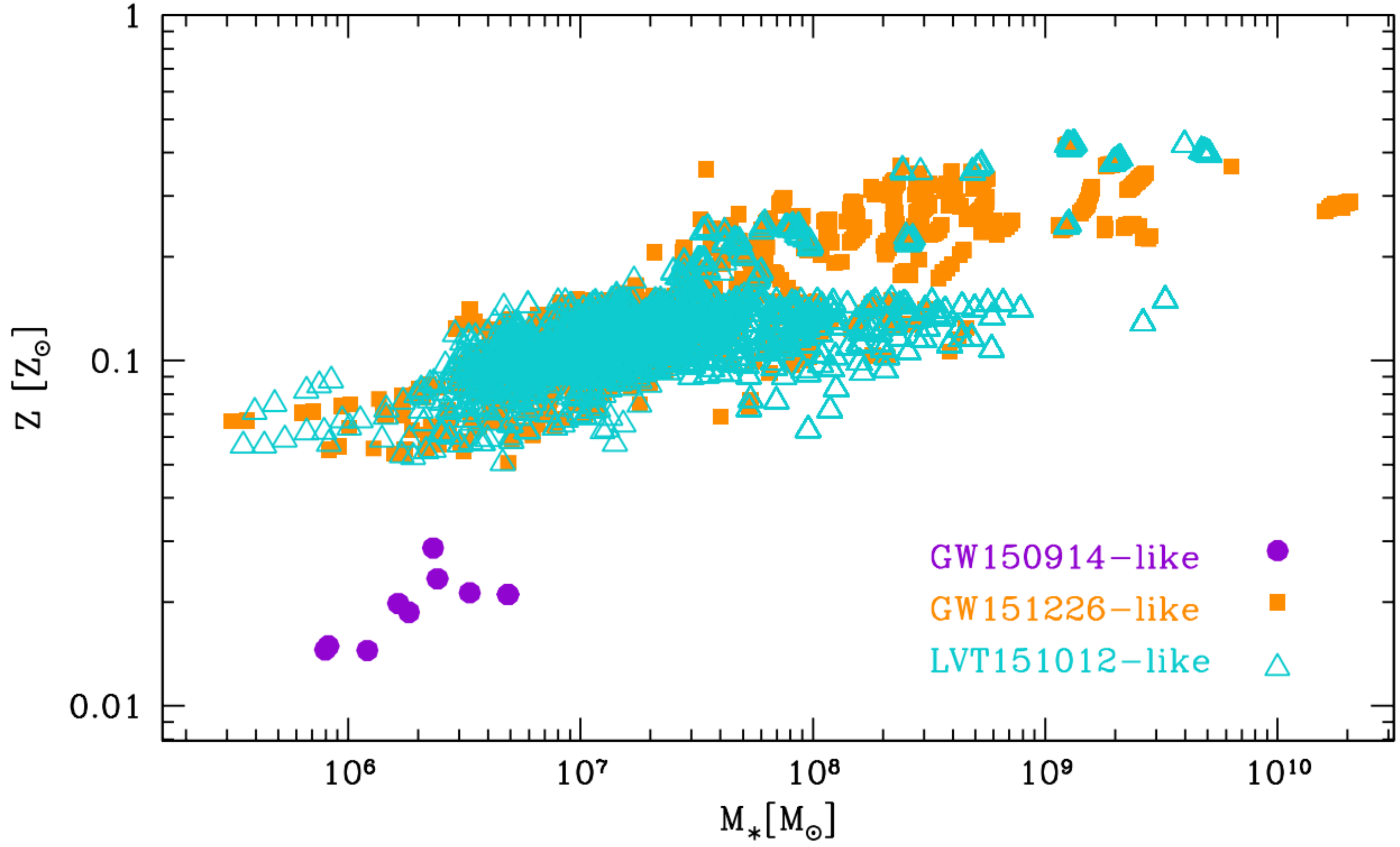
# Studying the host galaxies of GW events

Remnant mass = *f*(stellar mass, **metallicity**, rotation)

+

**Galaxy evolution model**

[Schneider et al. (2017)]



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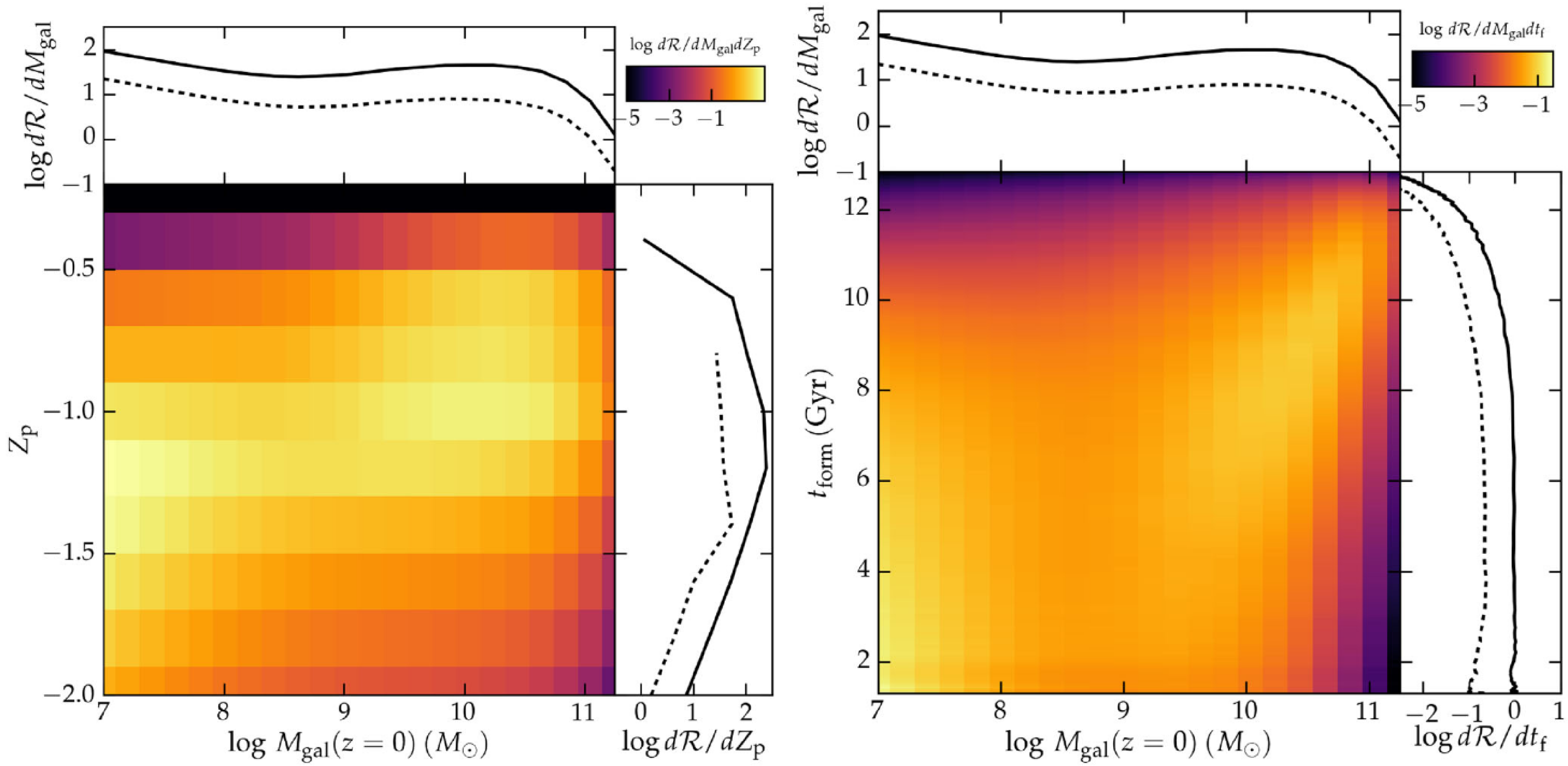

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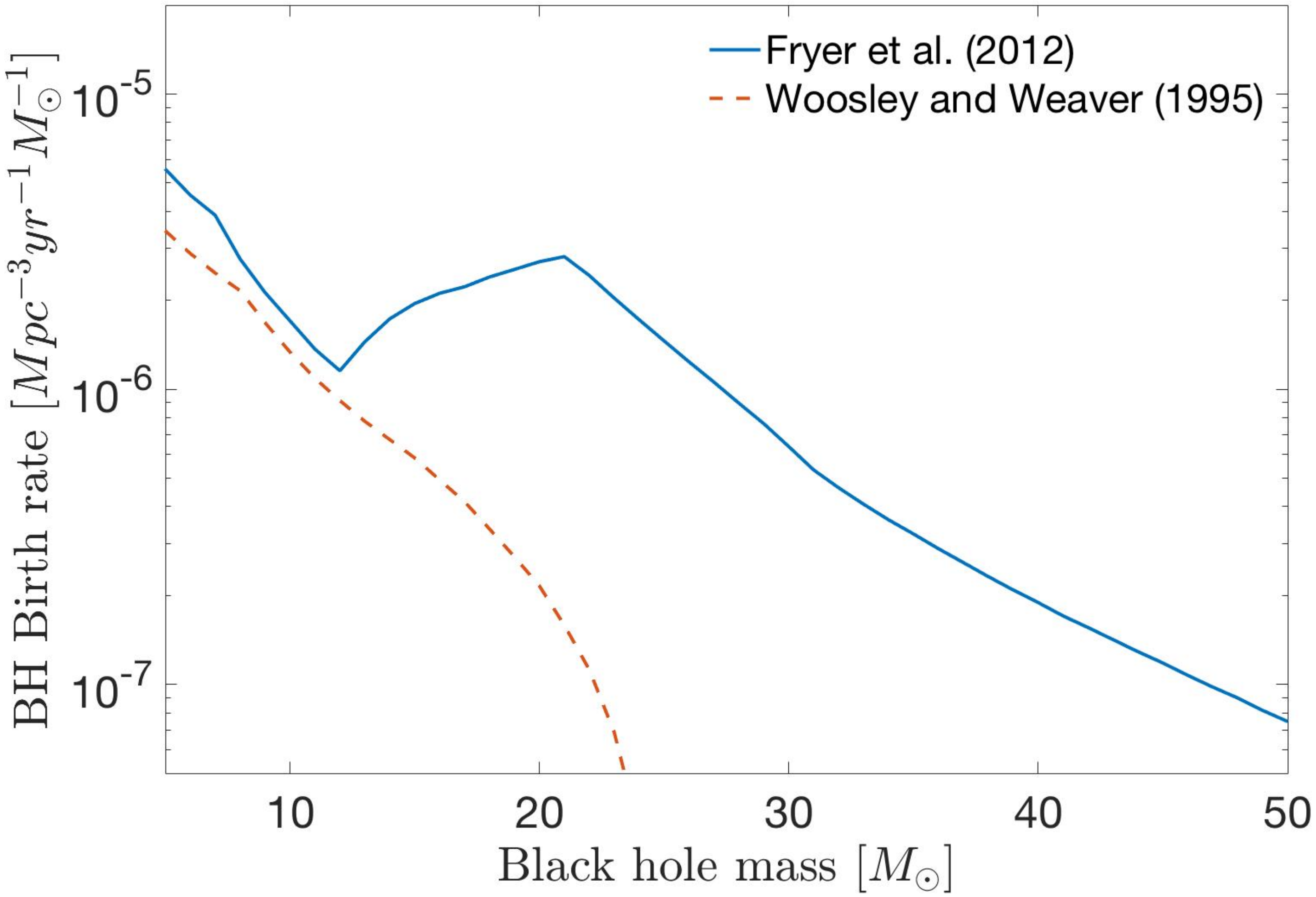
# Constraining black hole formation with GW observations

Semi-analytic model [Daigne et al. (2006); **ID** et al. (2015)]



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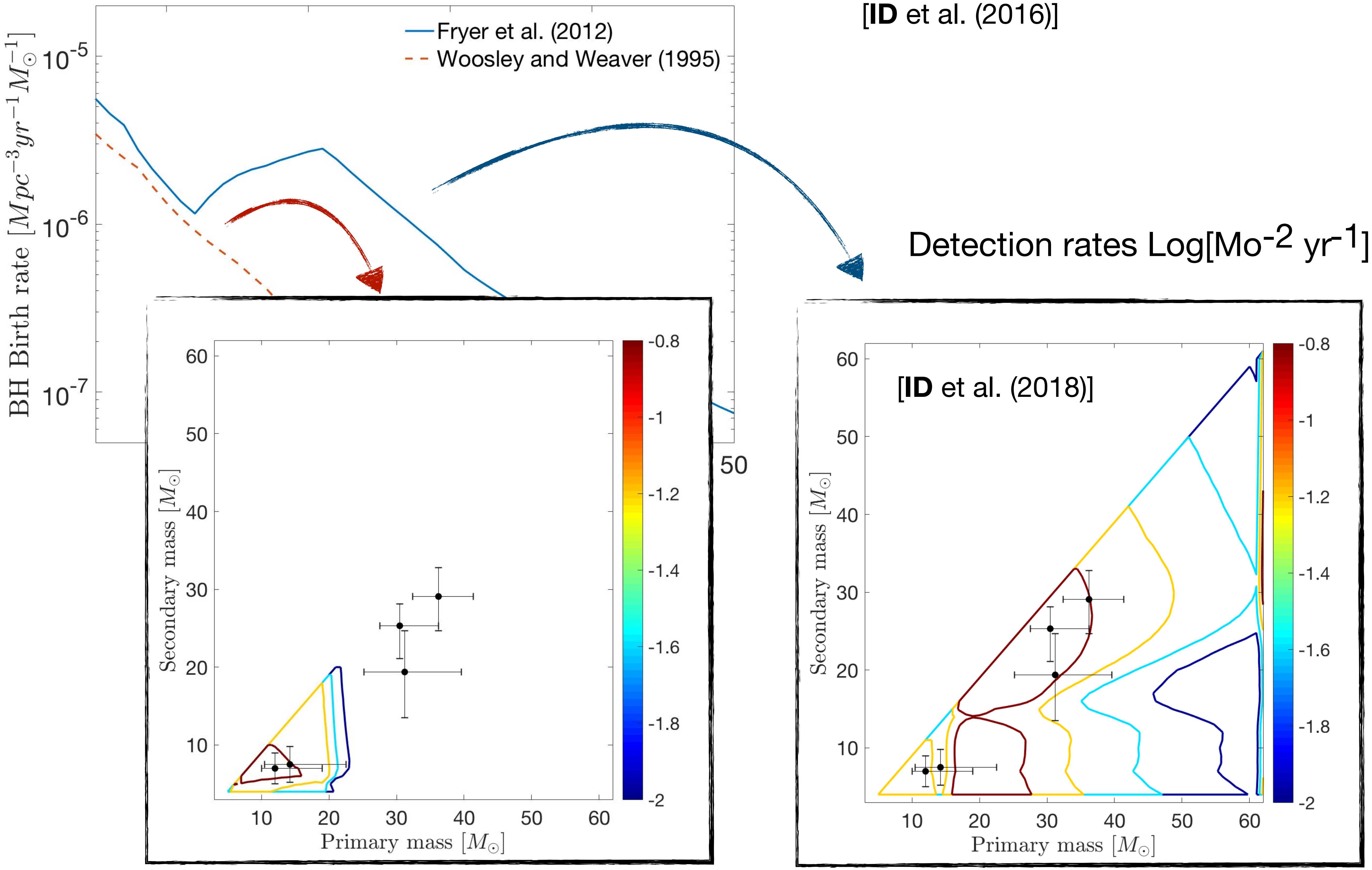

[**ID** et al. (2016)]

Detection rates Log[Mo$^{-2}$ yr$^{-1}$]

[**ID** et al. (2018)]

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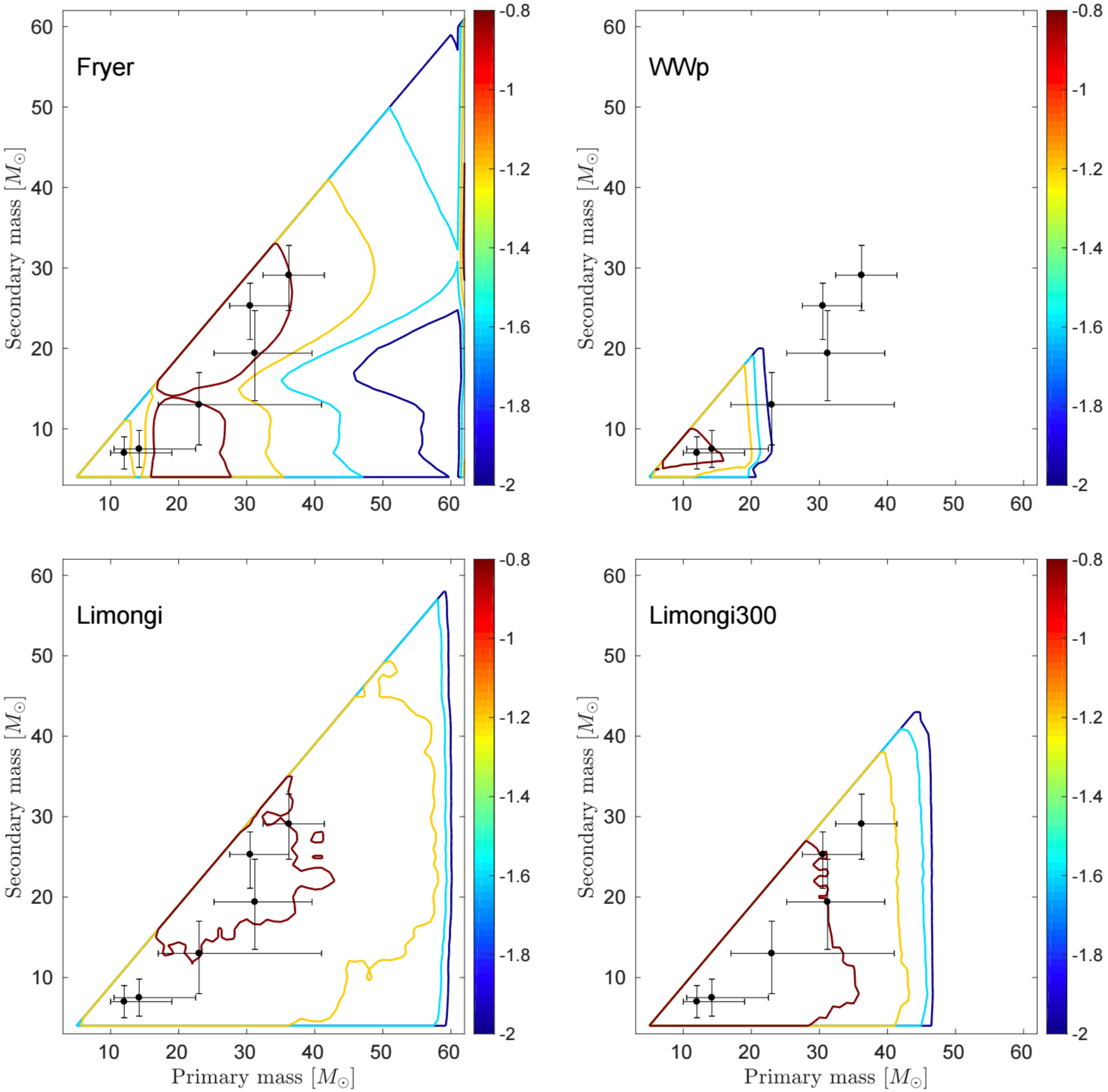

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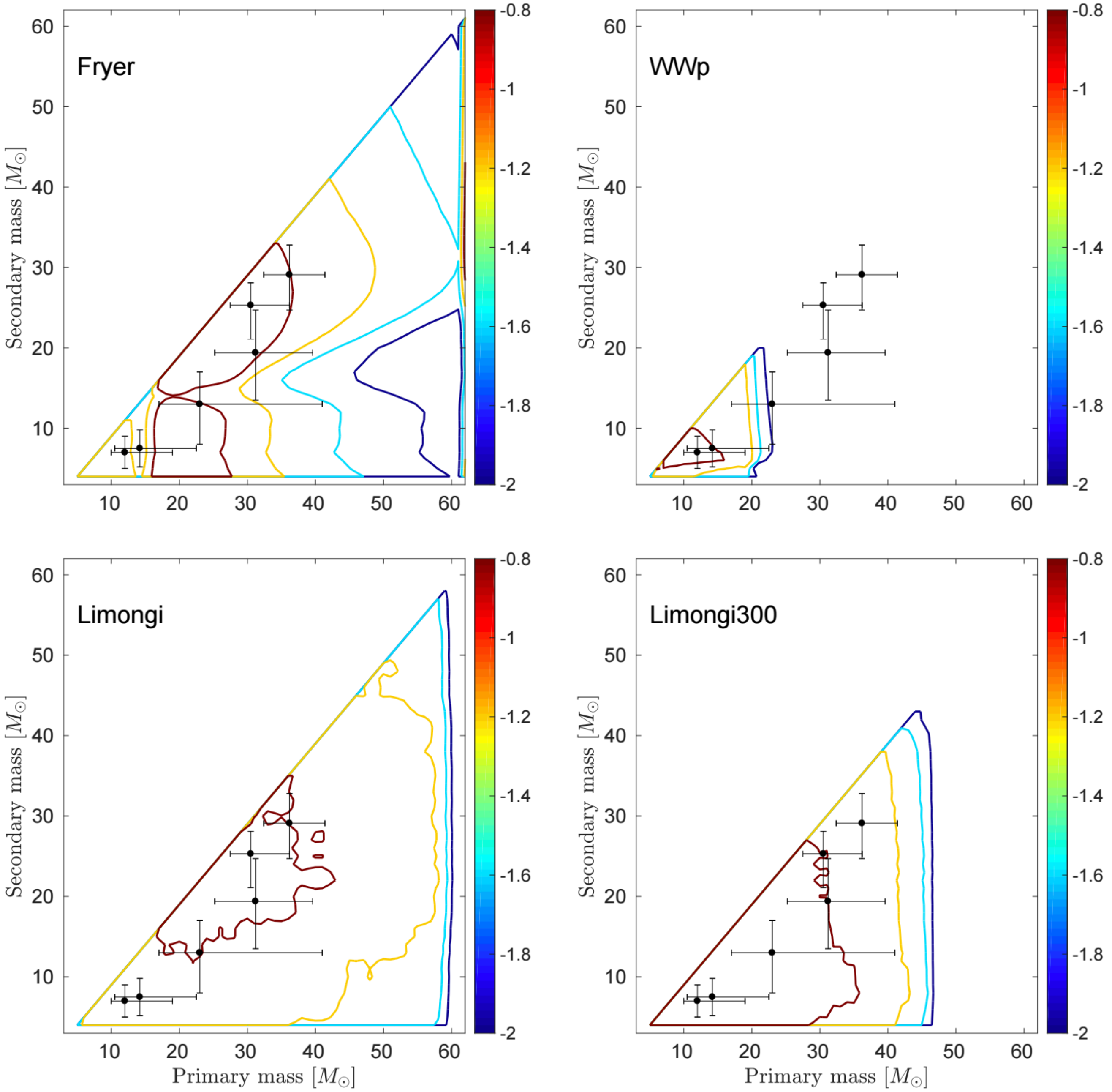
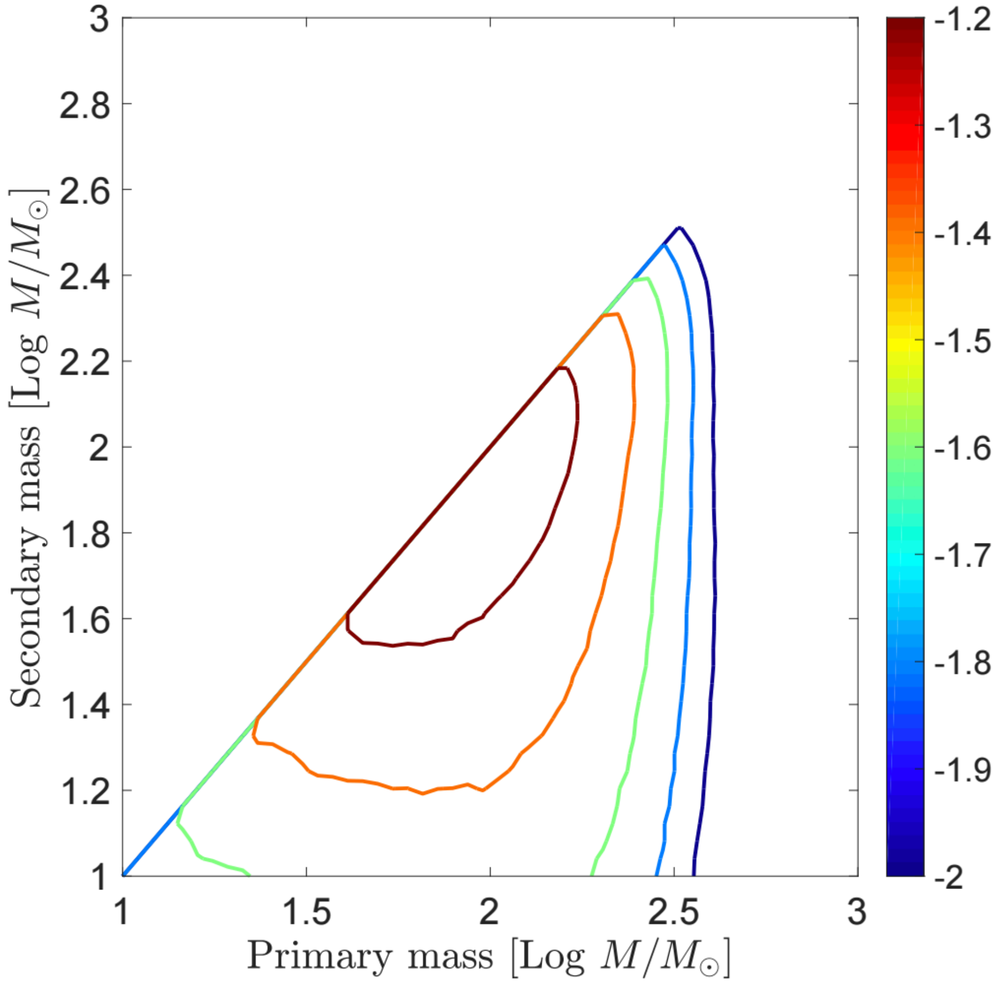
# Constraining black hole formation with GW observations

Detection rates Log[Mo$^{-2}$ yr$^{-1}$]

## Stellar-origin black holes



## Primordial black holes



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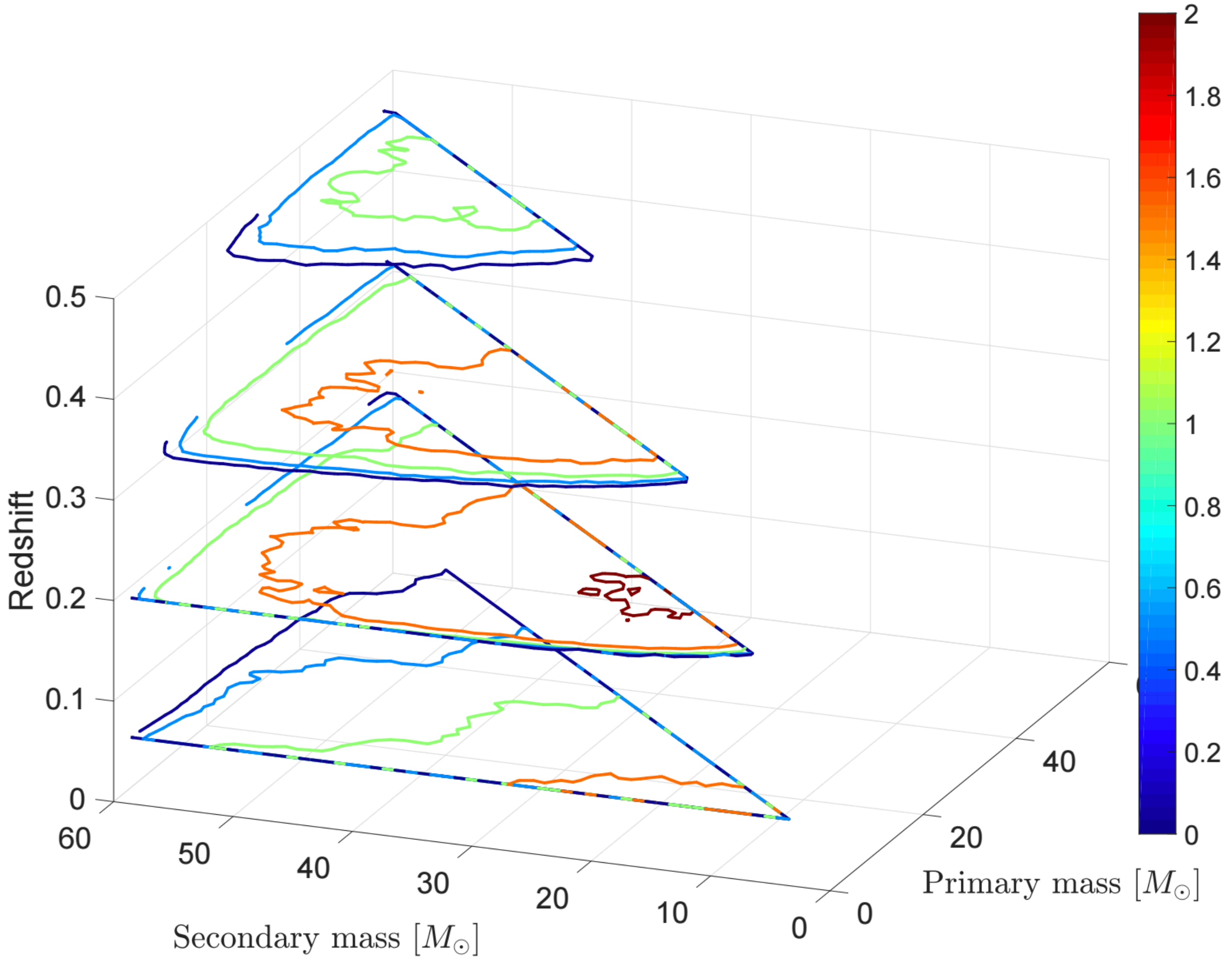

Detection rates Log[Mo$^{-2}$ yr$^{-1}$] per unit redshift

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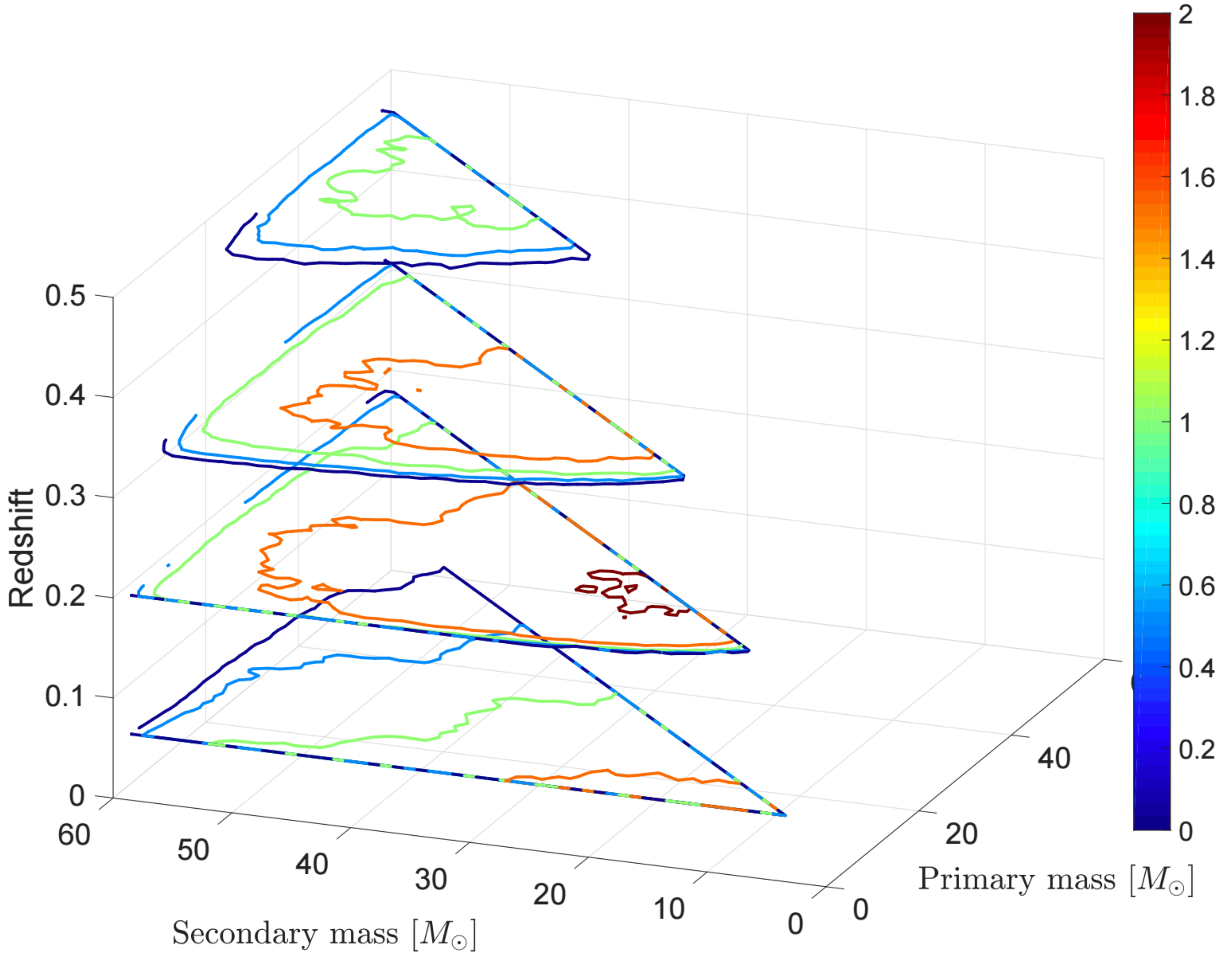

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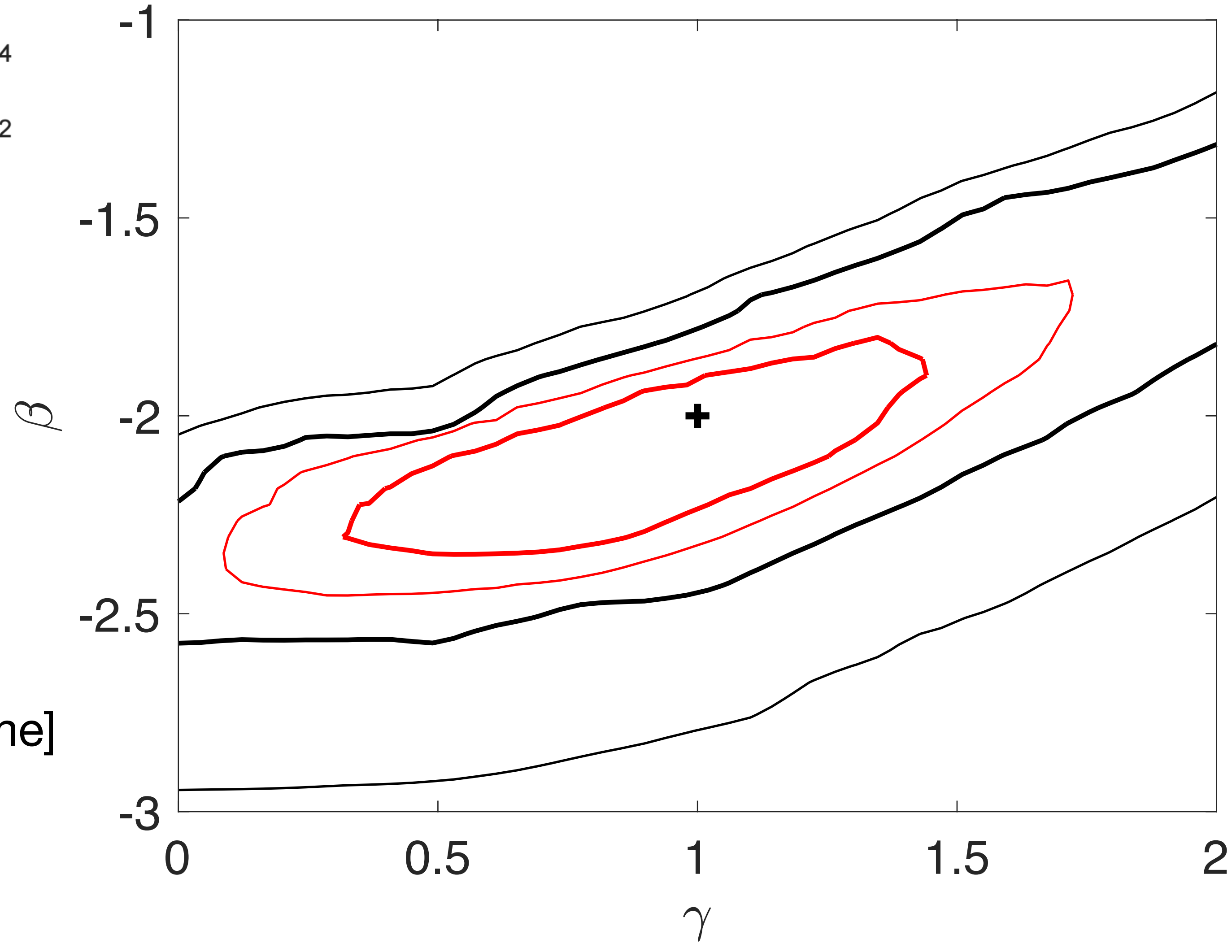


Constraining model parameters:

- 100 detections
- 500 detections

$\beta$ = Log[Fraction of BHs that merge within Hubble time]

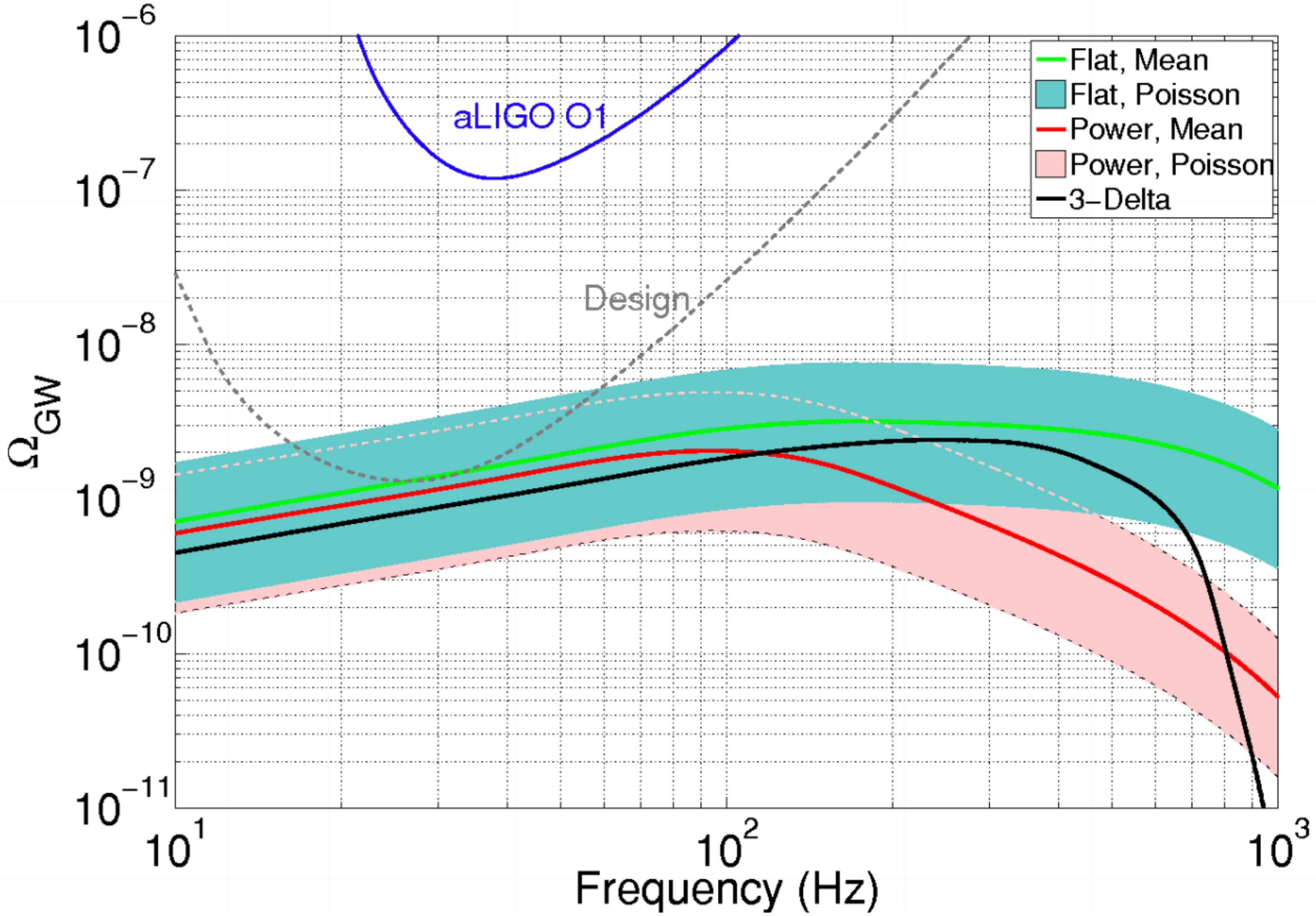
$\gamma$ = Slope of time delay distribution

$$P_\mathrm{d}(t_\mathrm{delay}) \propto t_\mathrm{delay}^{-\gamma}$$

# Stochastic gravitational-wave background

Gravitational-wave signal from unresolved sources:

$$\Omega_{\rm gw}(f) = \frac{f}{\rho_c c^2} \int dM_c dz \frac{d^2 n}{dM_c dz} \frac{dE}{df}$$



[Abbott et al. (2017)]

# Stochastic gravitational-wave background

**Anisotropic background:** *[In analogy with the cosmic infrared background]*

Energy density in gravitational waves at each point in the sky: $\Omega(f,\Theta) = \Omega_\alpha(\Theta)\left(\frac{f}{f_{\mathrm{ref}}}\right)^{\alpha}$

[Flat energy density spectrum]

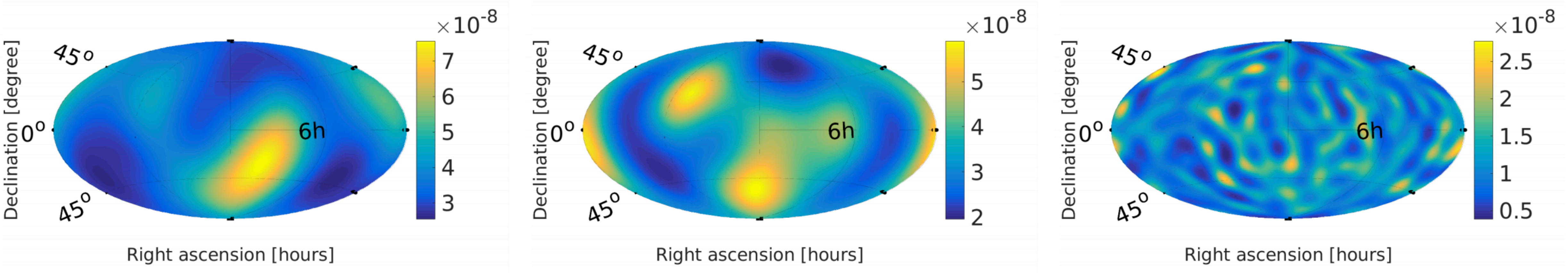
$\alpha$=0

[Compact binary coalescences]

$\alpha$=2/3

[Flat strain power spectrum density]

$\alpha$=3



Upper limits from LIGO O1 (90% CL) [Abbott et al. (2017)]

f_ref=25 Hz

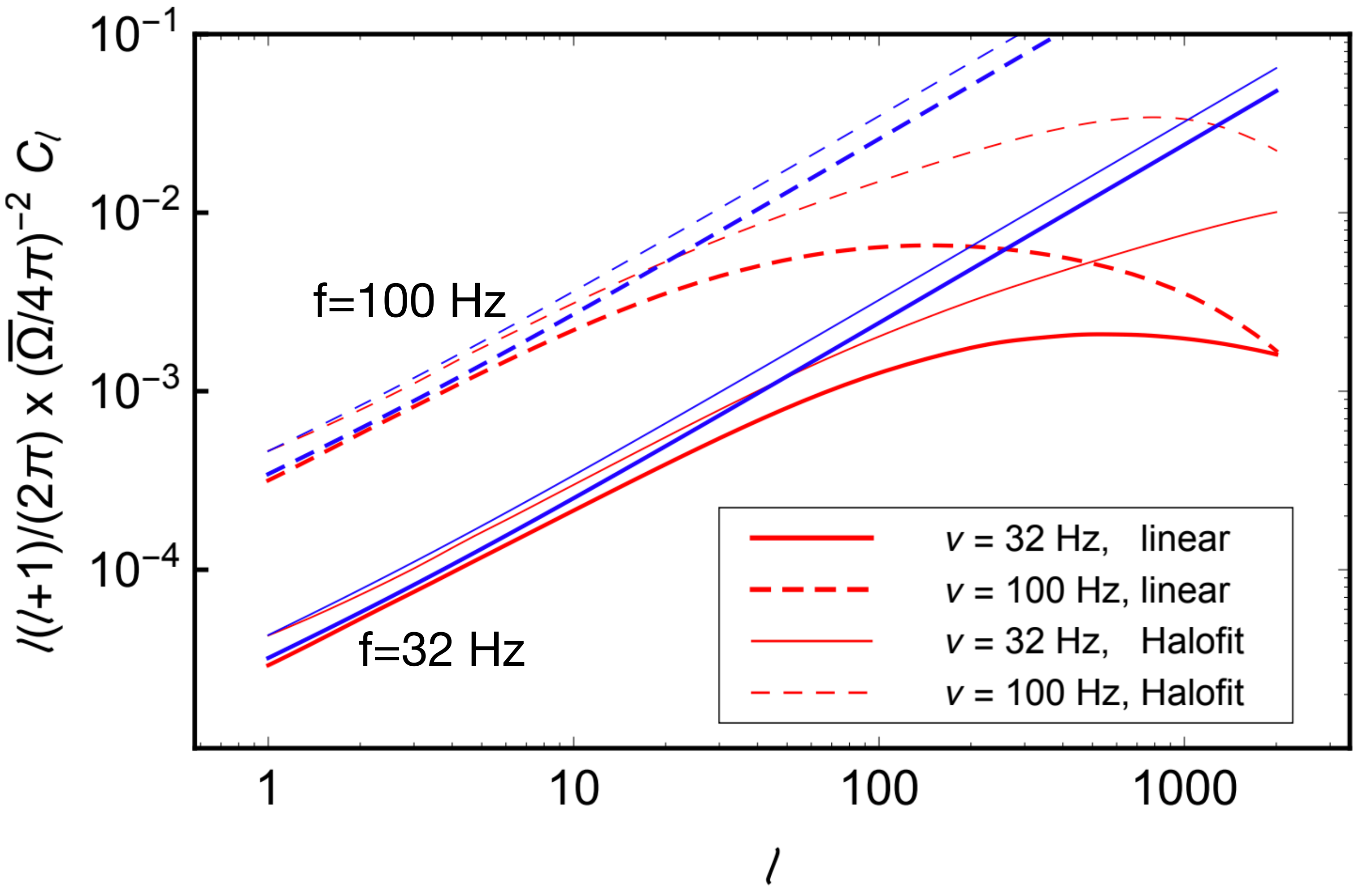
# Stochastic gravitational-wave background

**First predictions of anisotropic background from binary BH mergers:**

Anisotropic part: $\delta\Omega_{\mathrm{GW}}(\boldsymbol{e}, \nu_{\mathrm{O}})$

Decomposition of the angular correlation function: $C_\ell(\nu_{\mathrm{O}}) = \frac{2}{\pi}\int \mathrm{d}k\, k^2 |\delta\Omega_\ell(k, \nu_{\mathrm{O}})|^2$

[Cusin, **ID**, Pitrou, Uzan (2018)]



# Conclusions

**Future work:**

- Predictions for binary BH merger rates
  - Include predictions for X-ray binaries
  - Add neutron star formation rates
    - NS-BH
    - NS-NS

- Stochastic background anisotropies
  - Dependence on astrophysical and cosmological models
  - Include NS-NS

- **Need more detections and more sophisticated analysis tools!**

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[Chruslinska et al. (2017): inconsistencies between BBH and BNS merger rates]

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