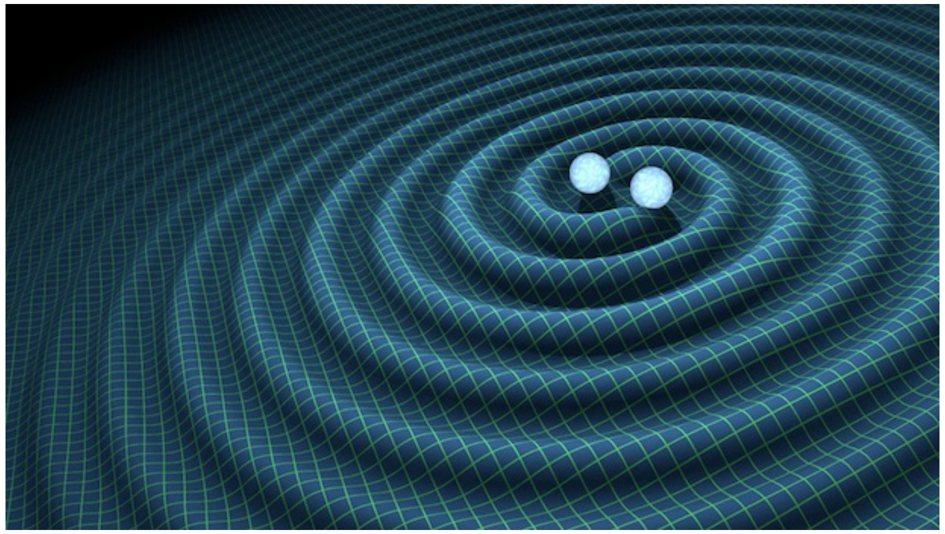
Constraining black hole formation models with gravitational-wave observations

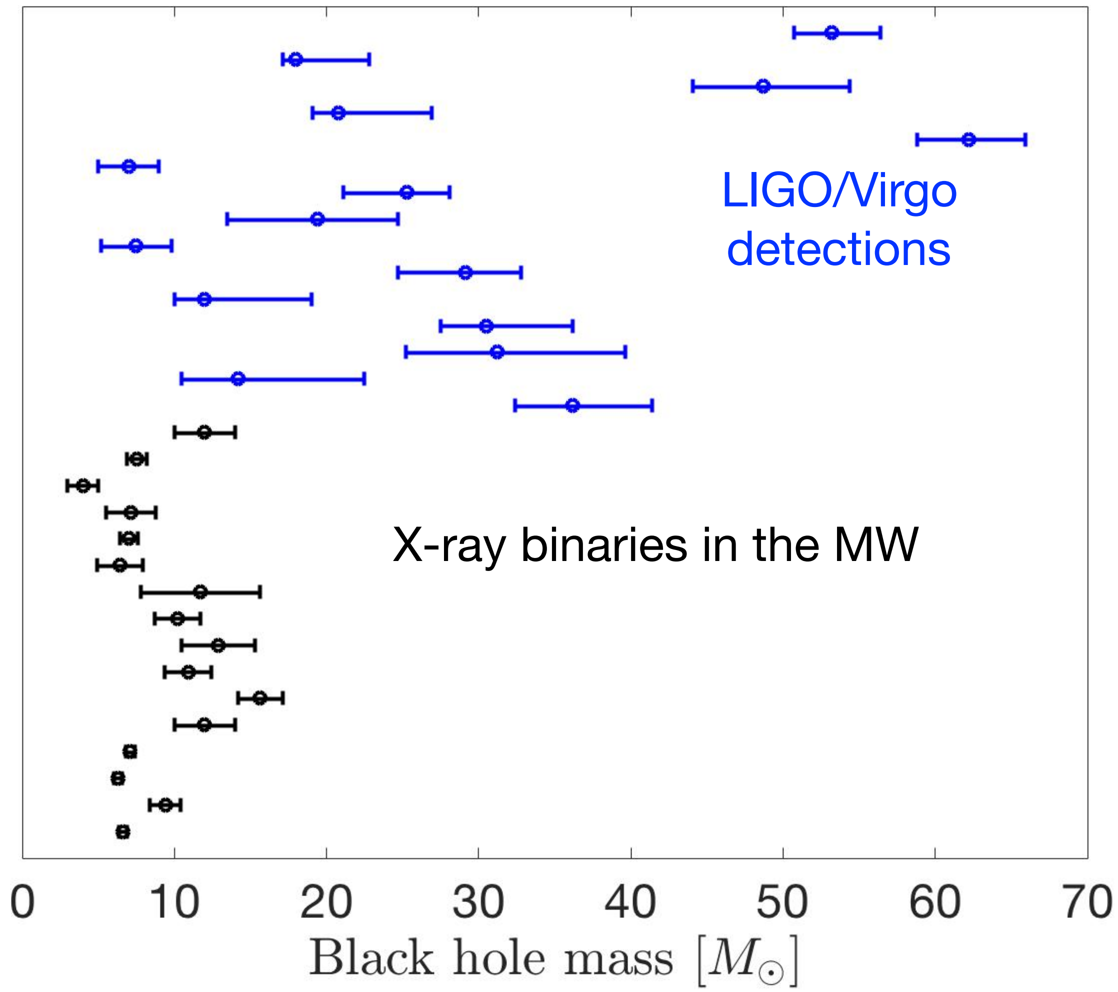
Irina Dvorkin

Max Planck Institute for Gravitational Physics (AEI, Potsdam)



CERN TH Workshop, May 18, 2018

Black holes observed with gravitational waves



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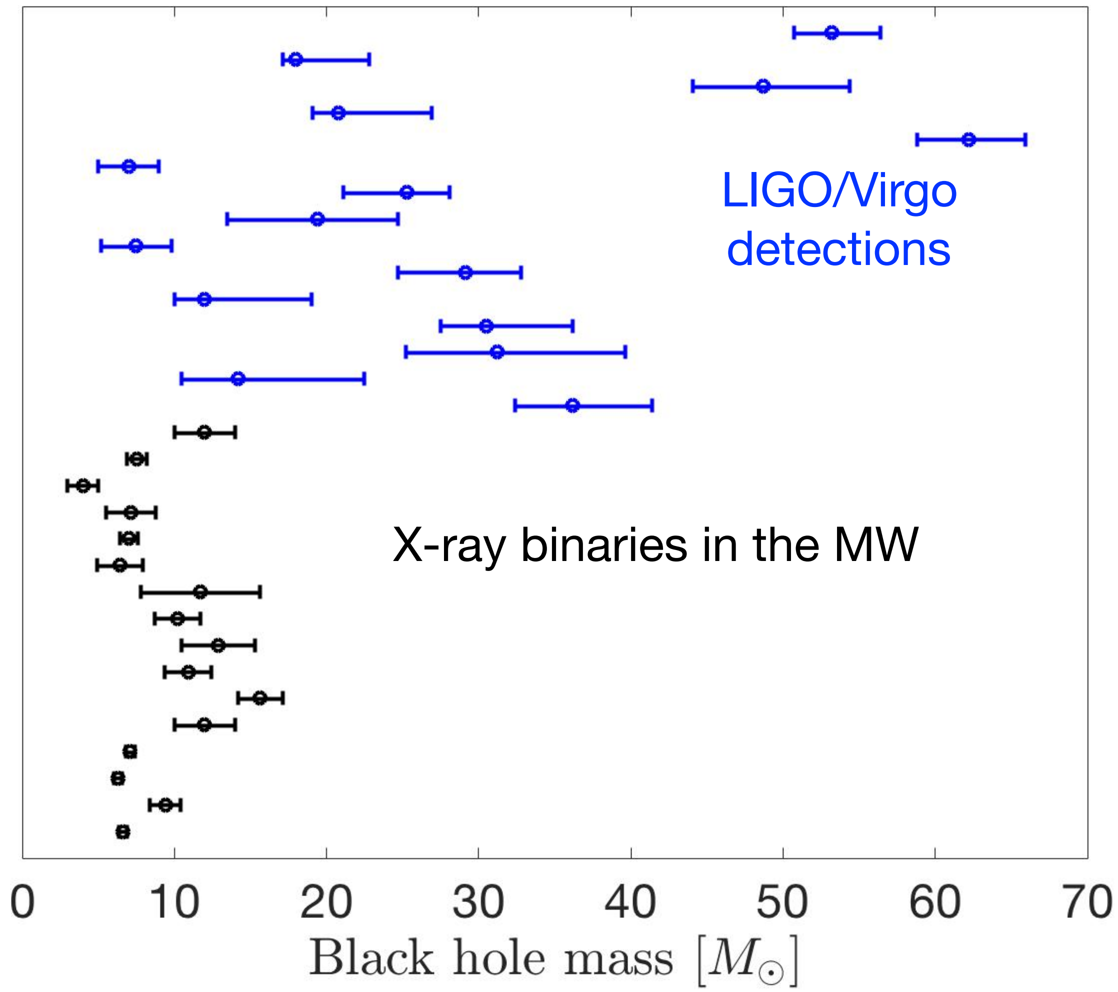
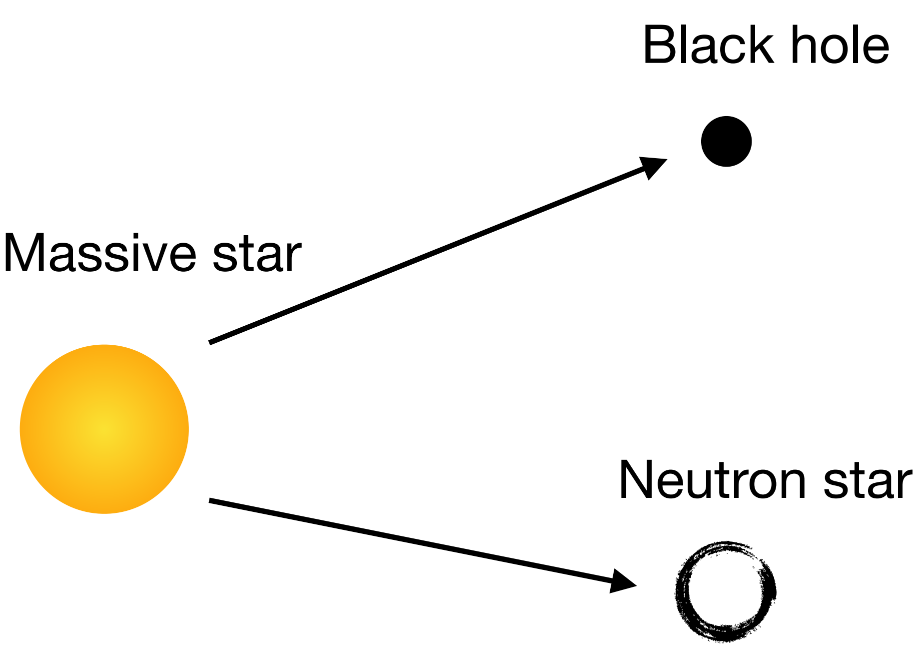


- How do black holes form?
- How do black hole binaries form and evolve?



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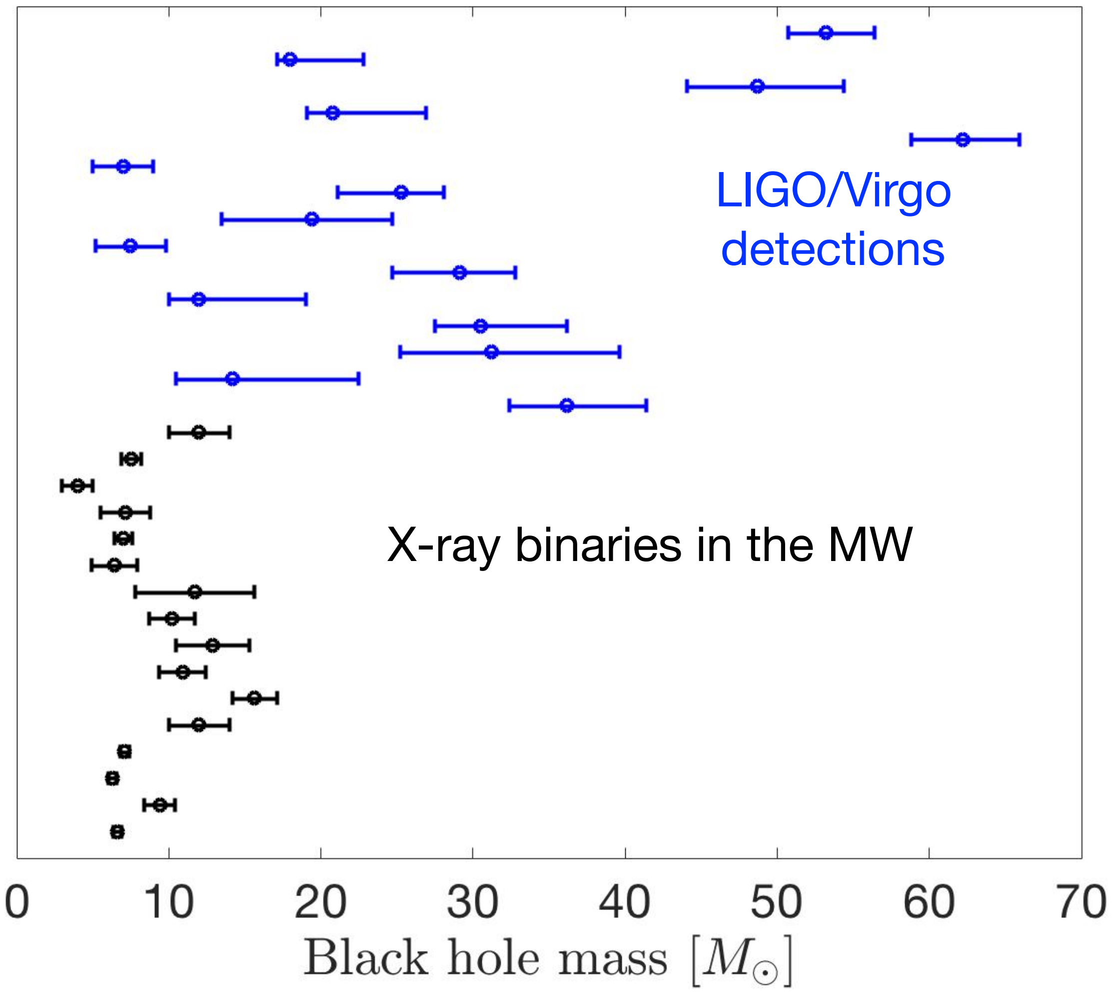
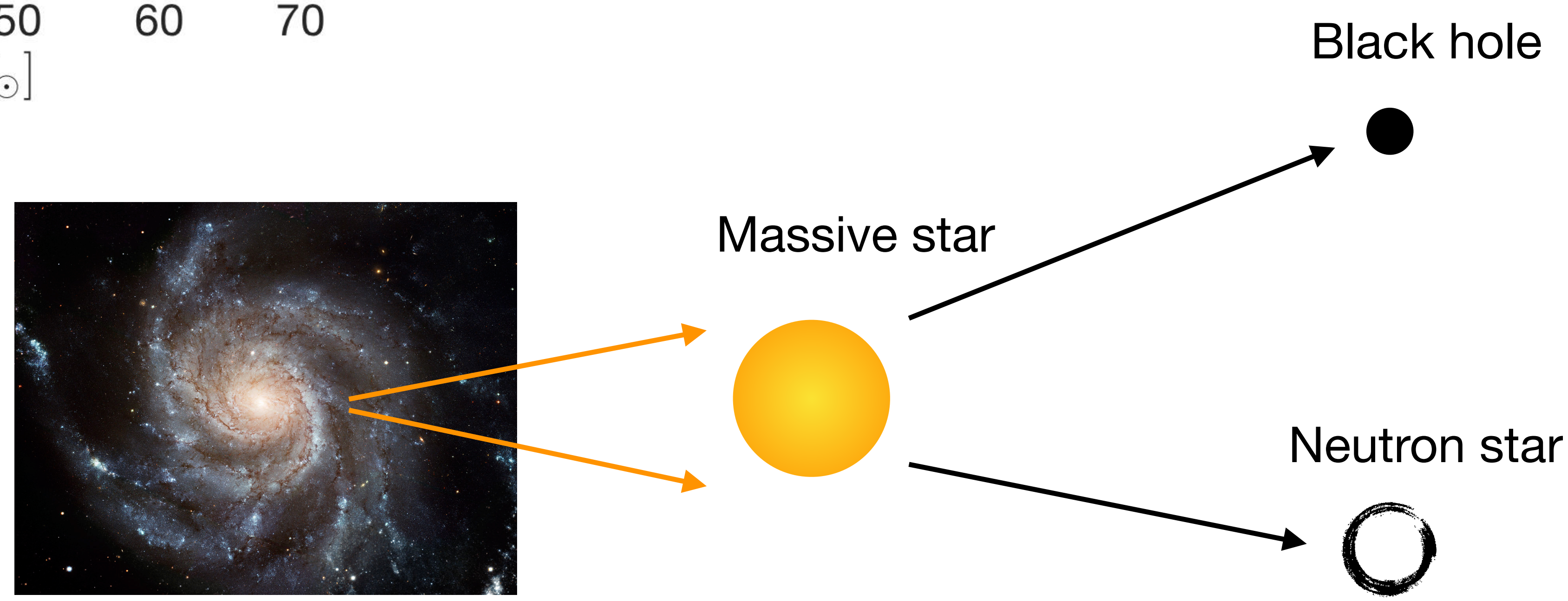


- How do black holes form?
- How do black hole binaries form and evolve?
- What are the properties of the stellar progenitors of the black holes observed in GW?
- What are the galactic environments of the stellar progenitors?



Stellar-mass black hole binaries

Stellar evolution

- Mass loss by stellar winds

Core collapse SN / direct collapse to a BH

- Explosion mechanism

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

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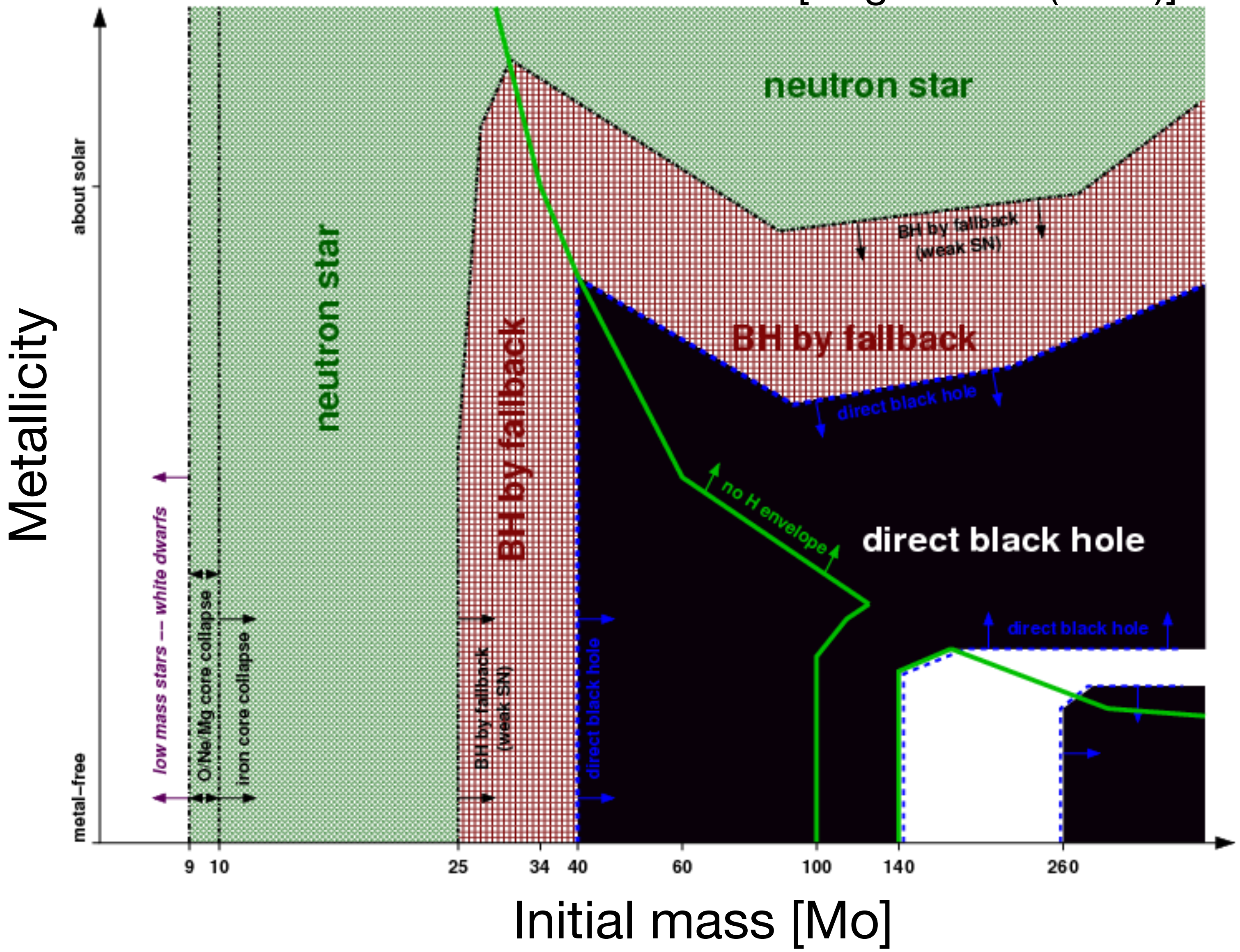
[Heger et al. (2003)]



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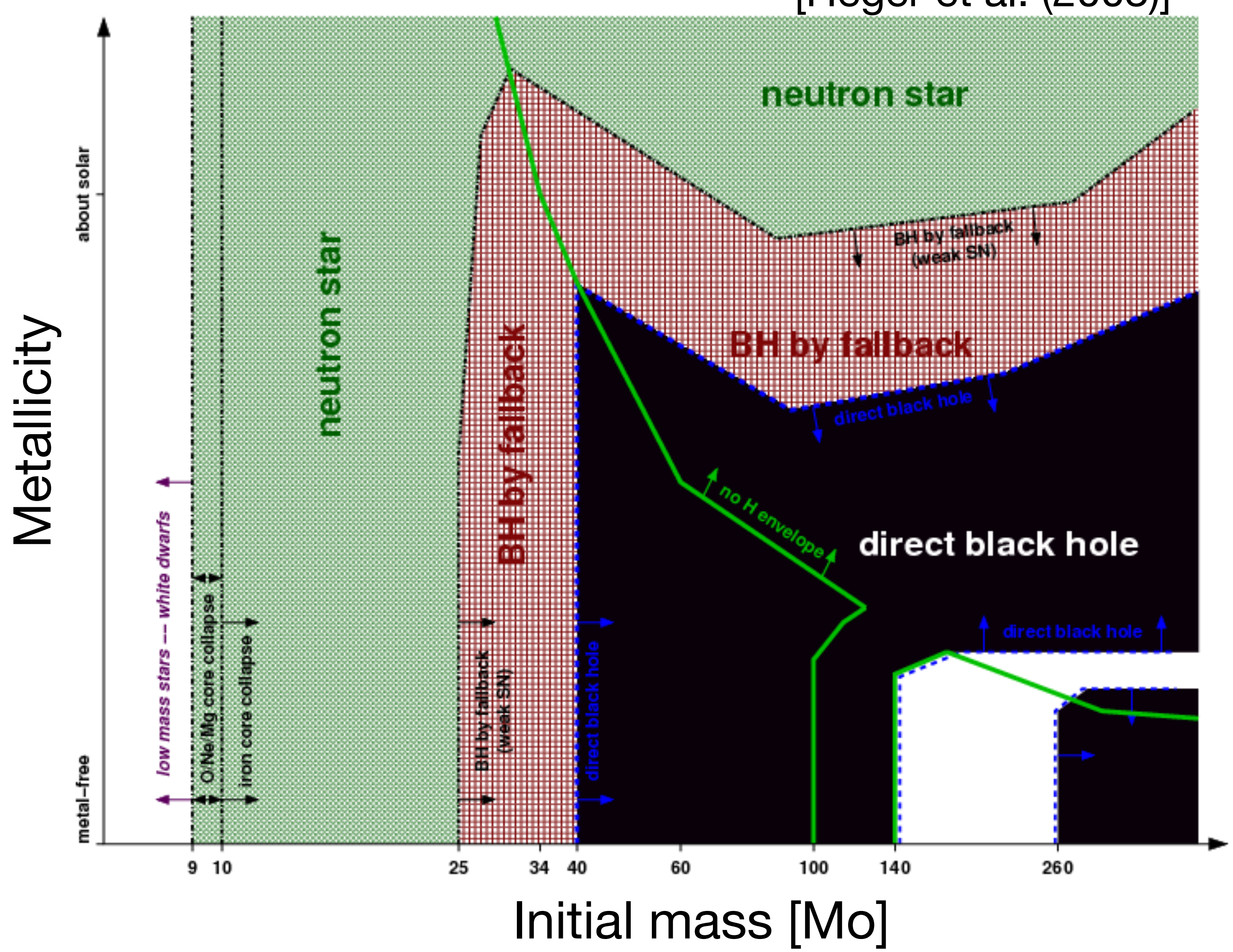
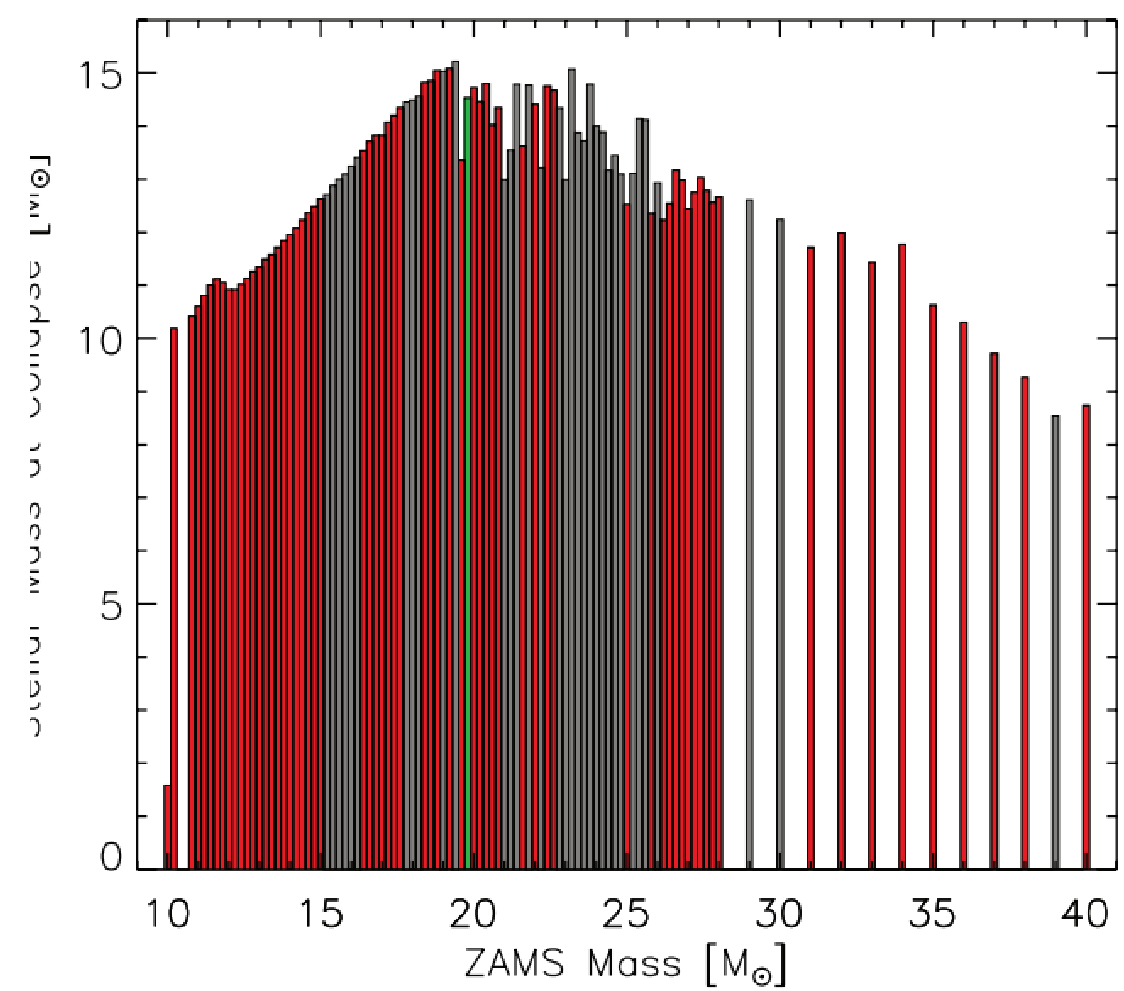
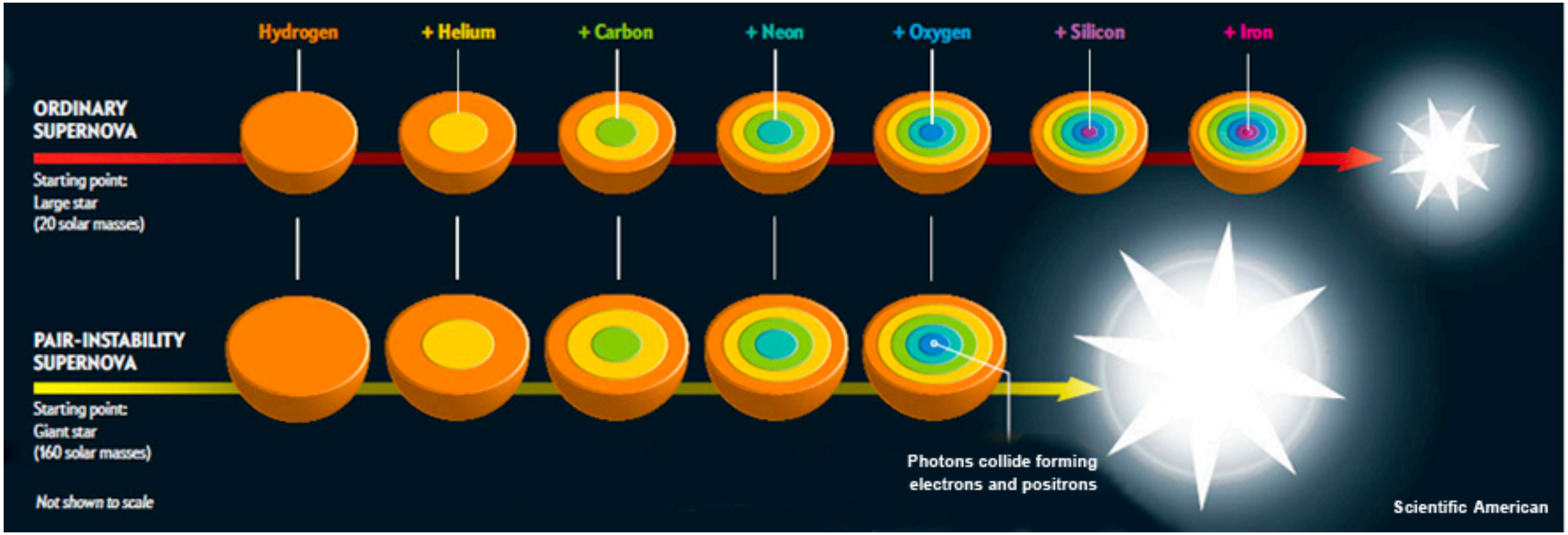


[Ertl et al. (2016); Sukhbold et al. (2016)]

[Ugliano et al. (2012)]



Pair-instability supernovae



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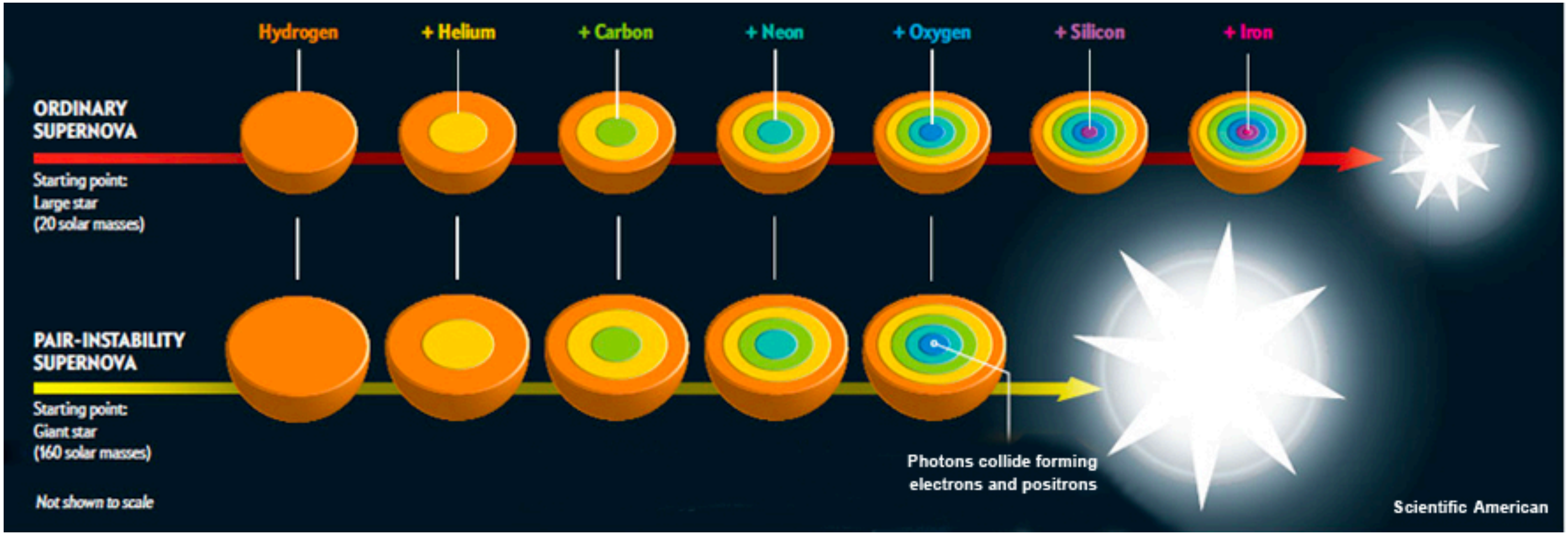
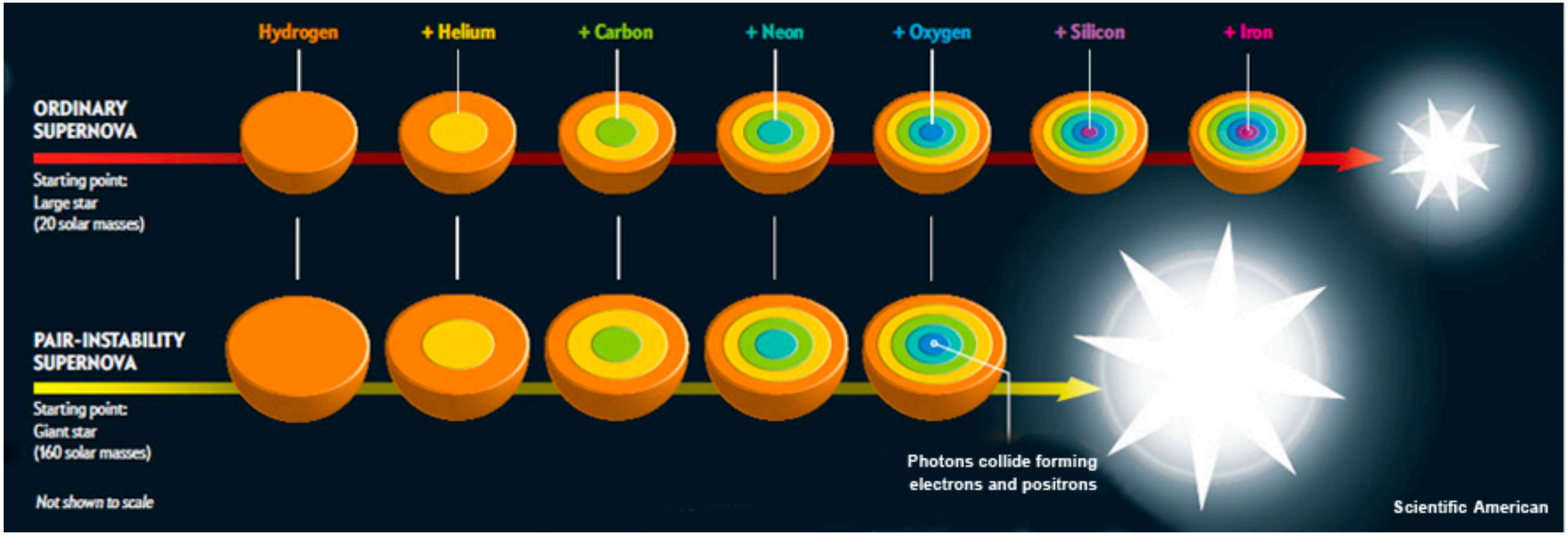


Table 1 Final evolution of stars of different initial mass[3]

Mass at birth (solar masses)	Helium core mass (solar masses)	Compact remnant	Event
10–95	2–40	Neutron star, black hole	Ordinary supernova
95–130	40–60	Neutron star, black hole	Pulsational pair-instability supernova
130–260	60–137	Explosion, no remnant	Pair-instability supernova
>260	>137	Black hole	?

[Woosley, Blinnikov, Heger (2007)]

Pair-instability supernovae



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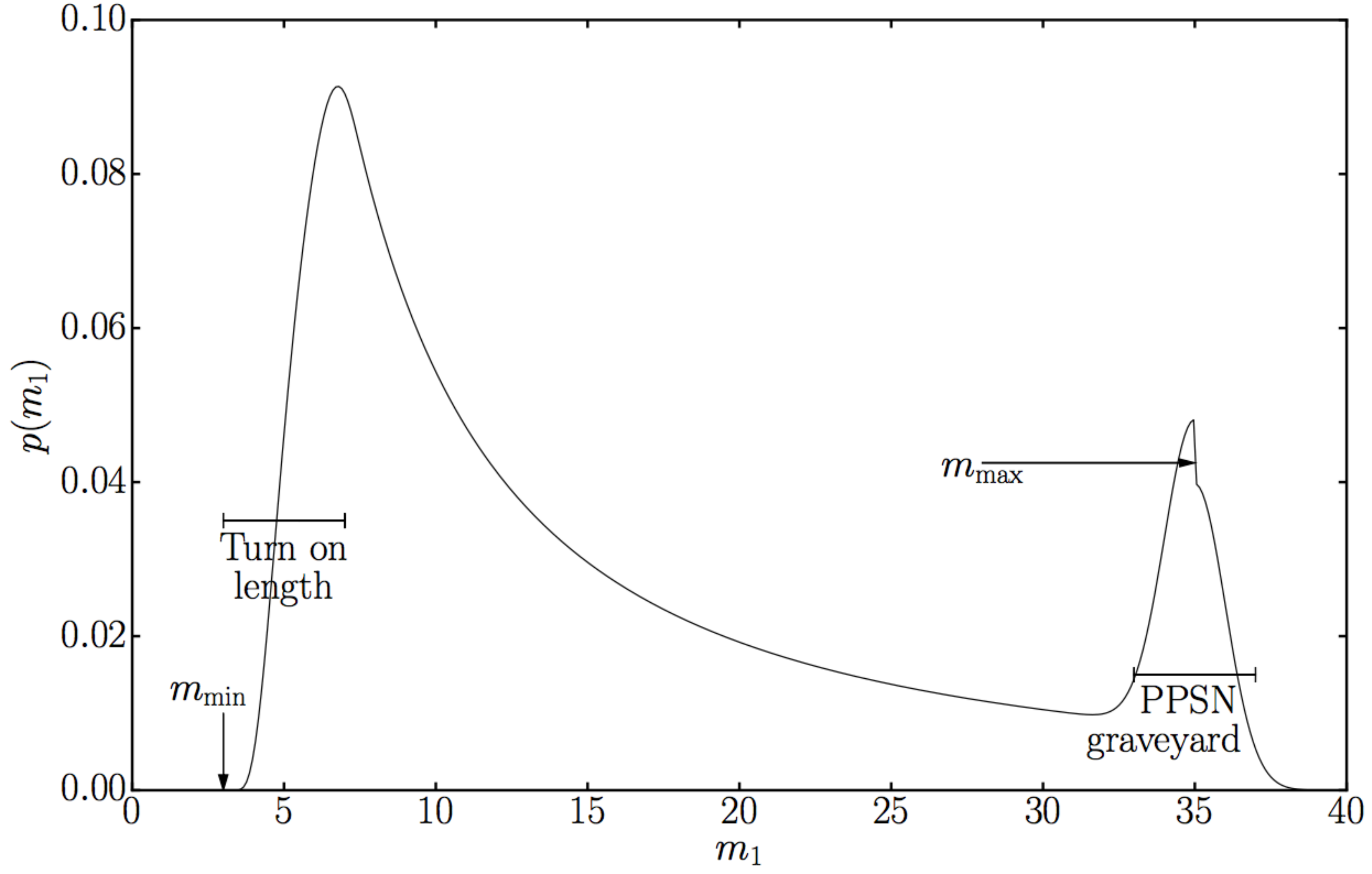
[Woosley, Blinnikov, Heger (2007)]

Pair-instability supernovae and pulsational pair-instability

Pulsations may cause an overabundance of BHs at ~35 Msun

[Talbot & Thrane (2018)]



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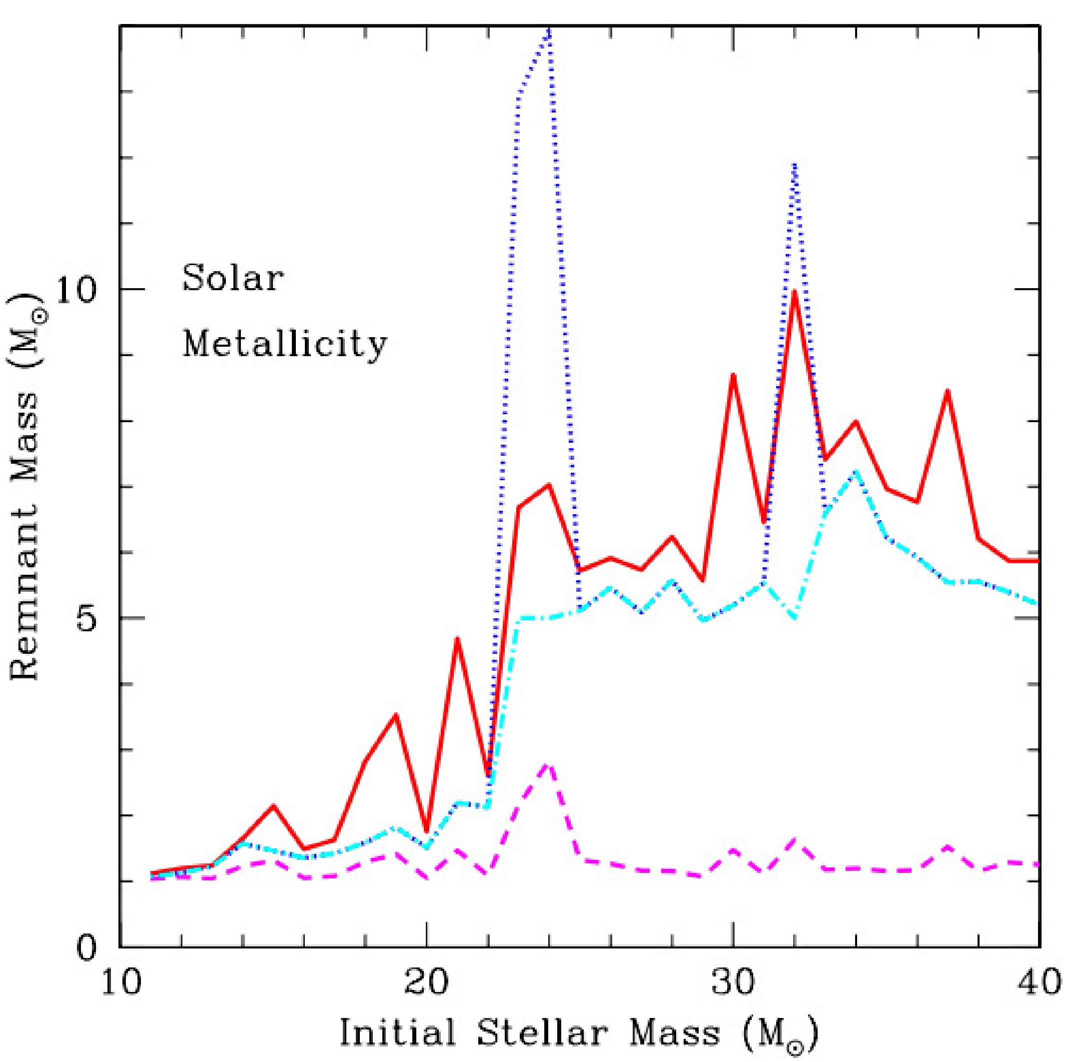

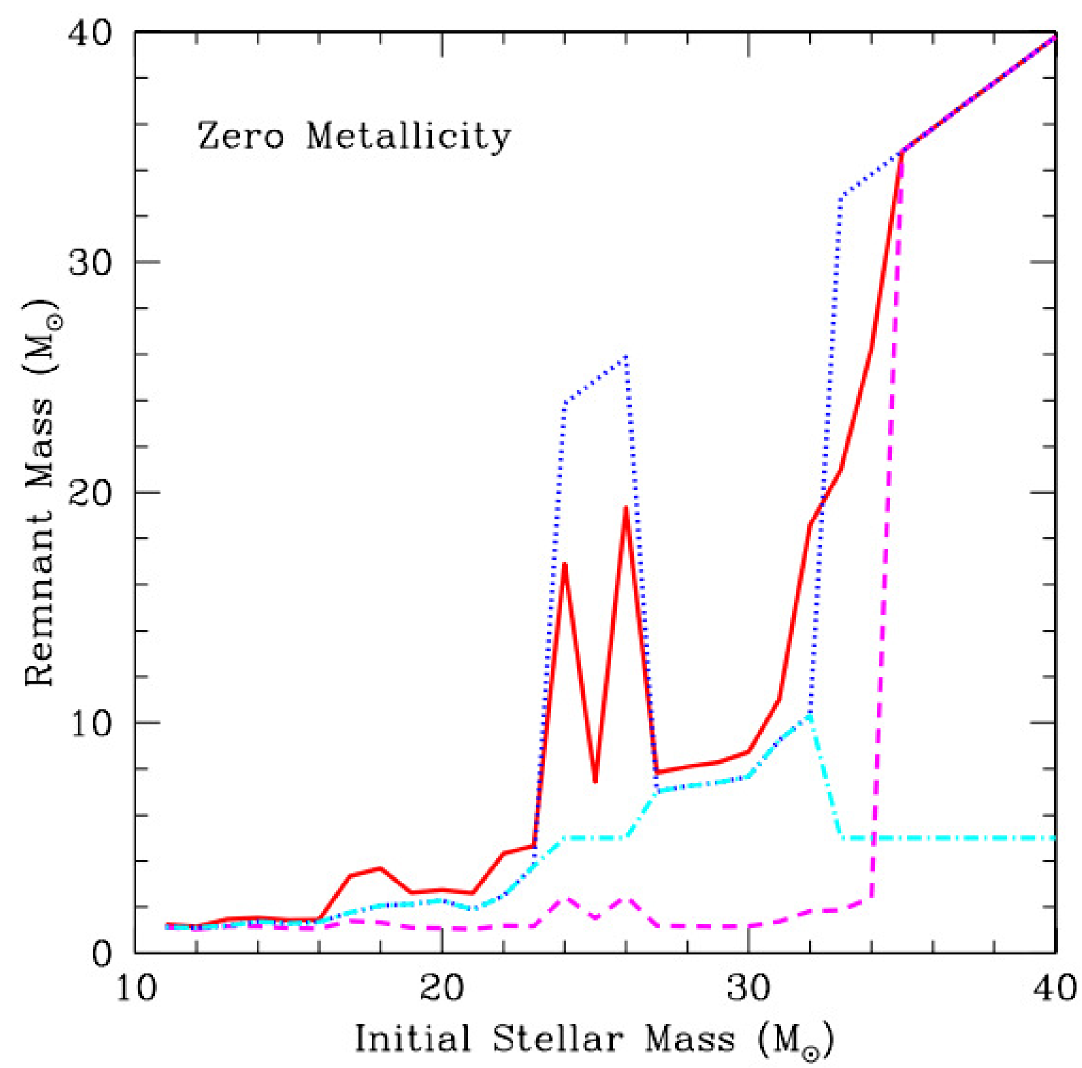

[Fryer et al. (2012)]

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Evolution of stellar binary

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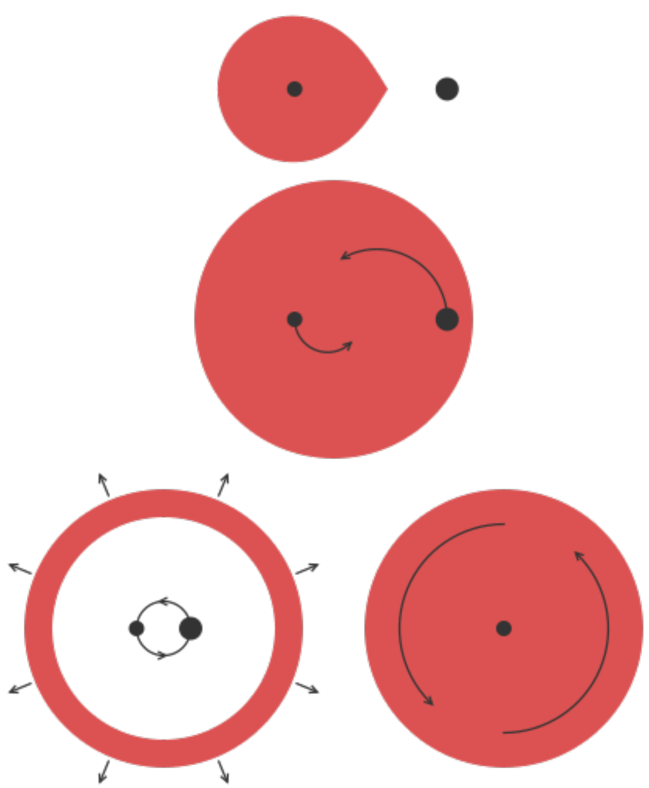

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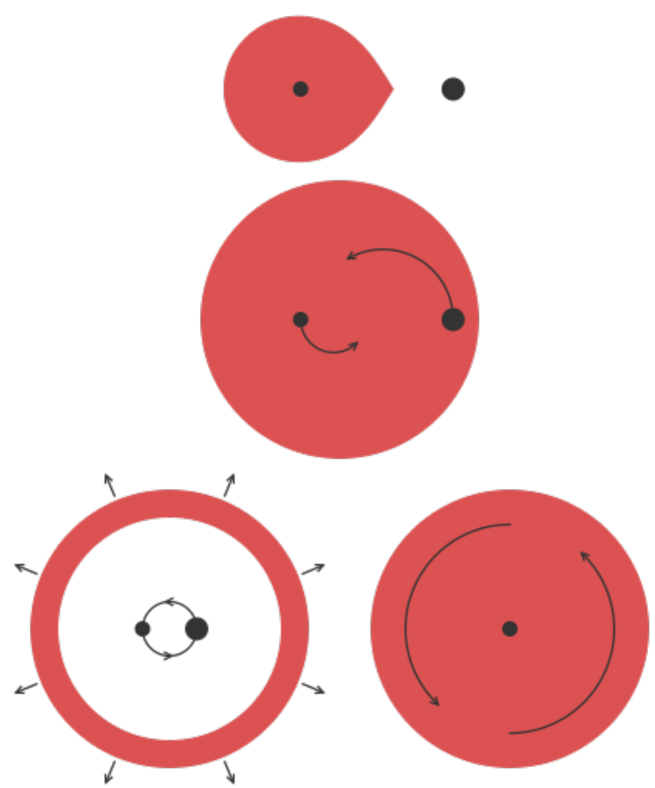

Other channels:

- PopIII stars
- Dynamic binary formation in dense stellar clusters

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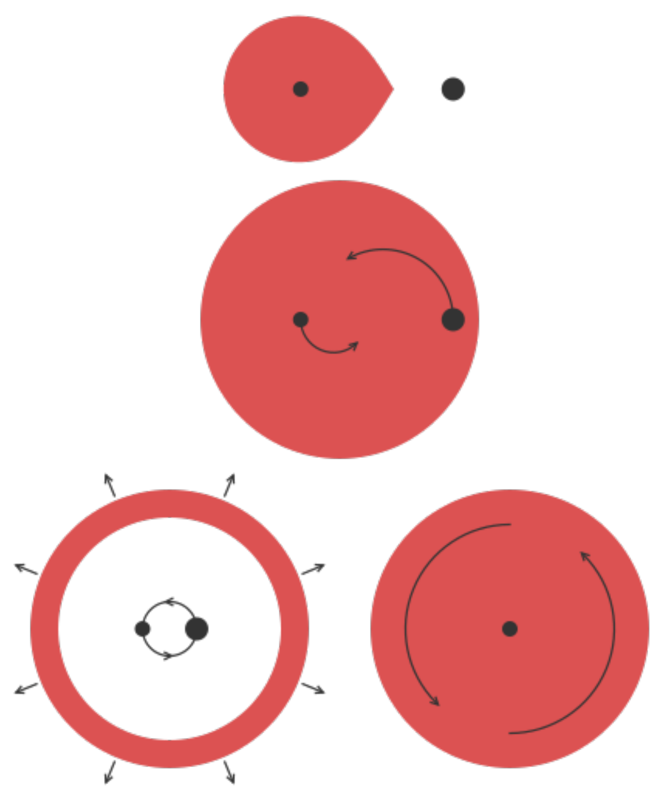
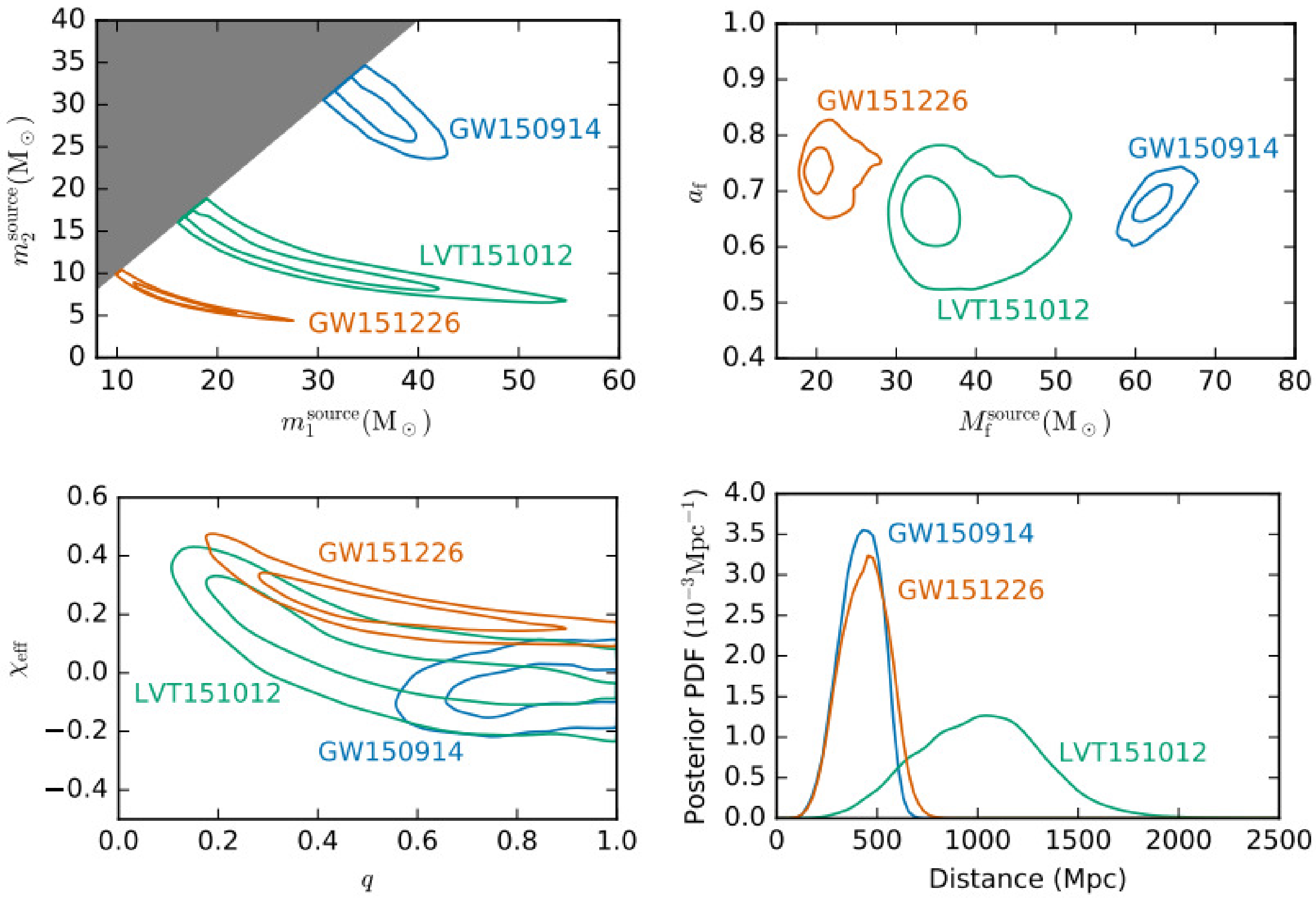


Other channels:

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

How to study BH formation models with GW?

[Abbott et al. (2016)]



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- Masses
- Spins
- Redshifts

What we need to constrain:

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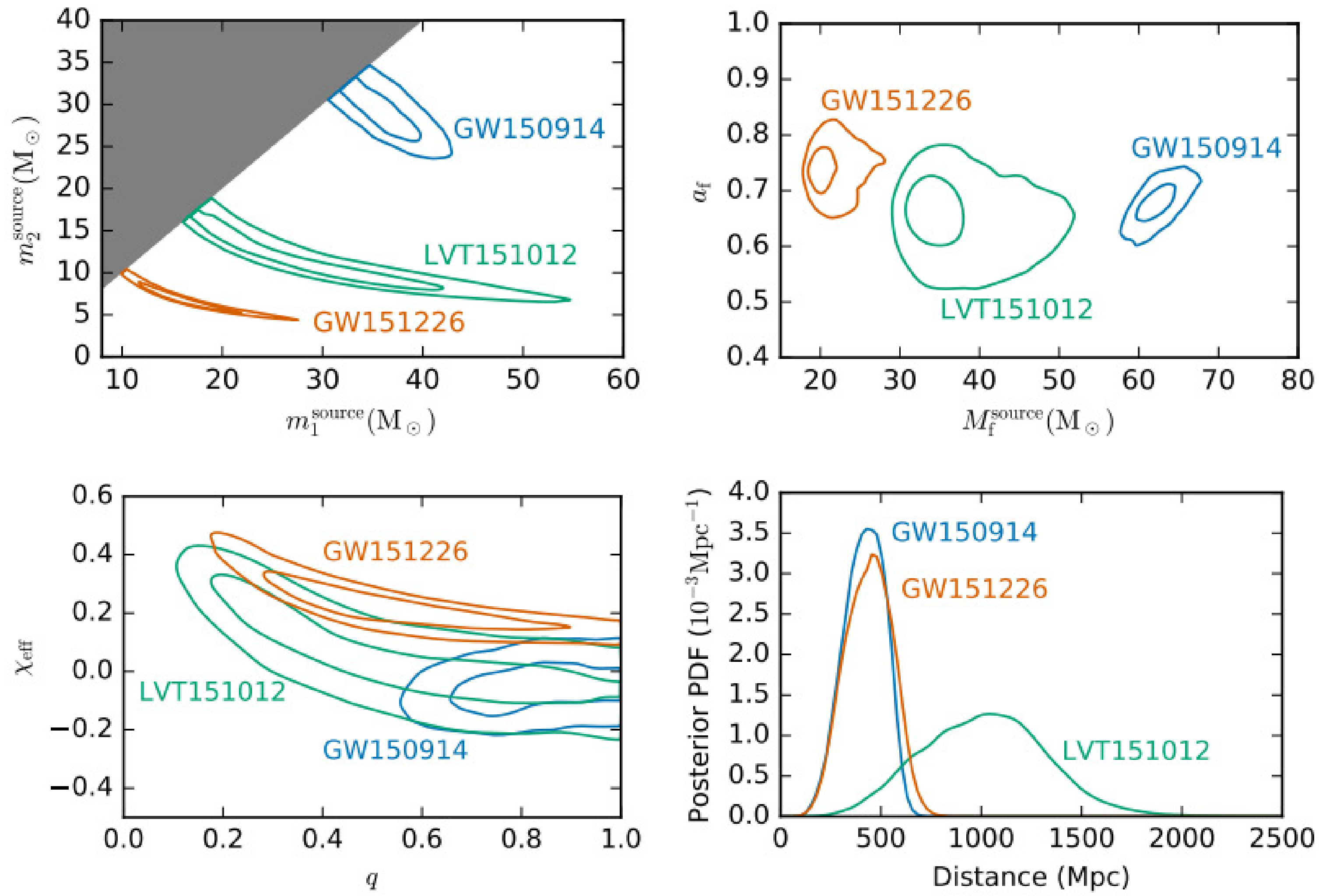

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[Lamberts et al. (2016); Belczynski et al. (2016; 2017), Mapelli et al. (2017); Zevin et al. (2017); Schneider et al. (2017); Kovetz et al. (2017); Hotokezaka & Piran (2017); Fishbach & Holz (2017); **ID** et al. (2018), …]

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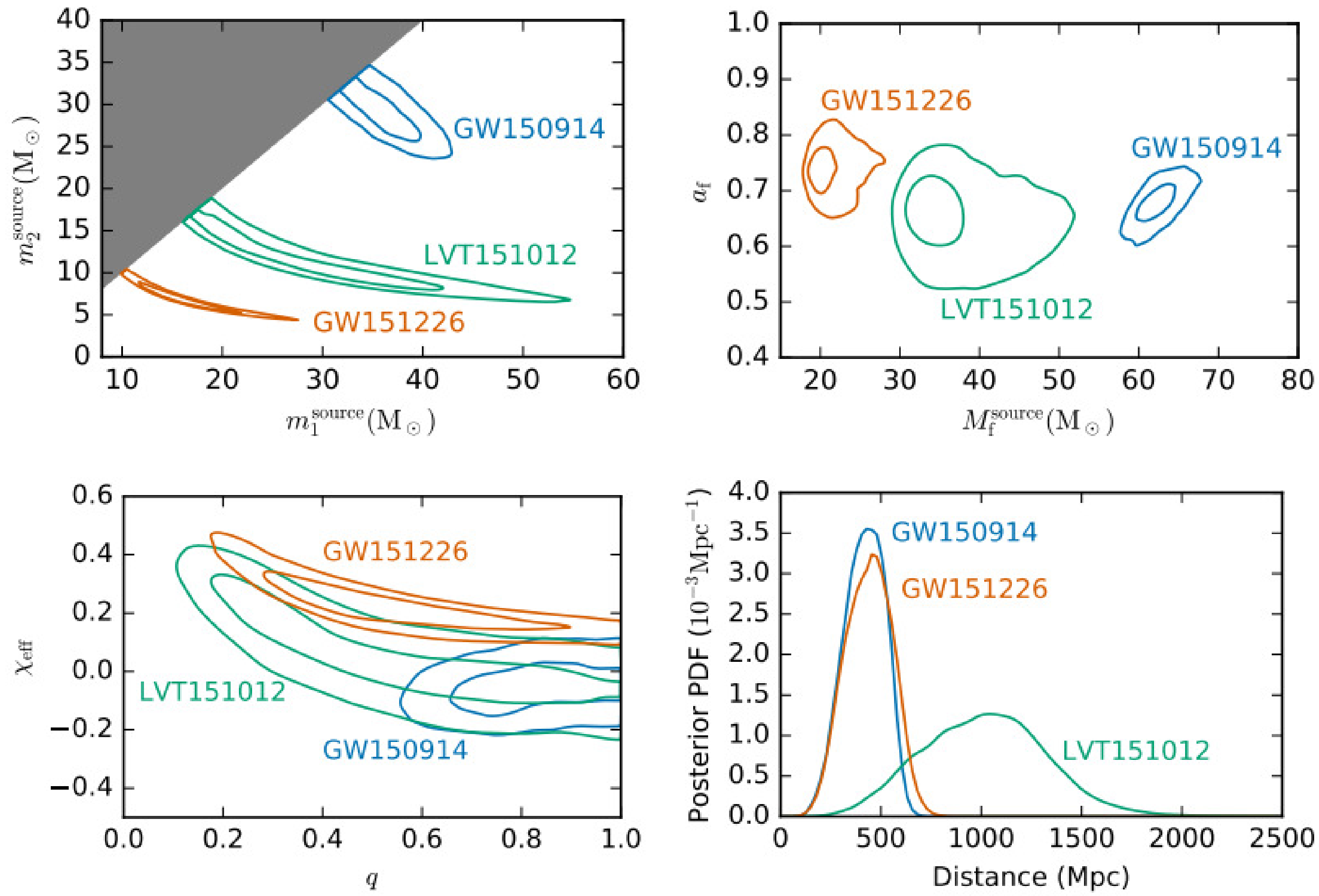

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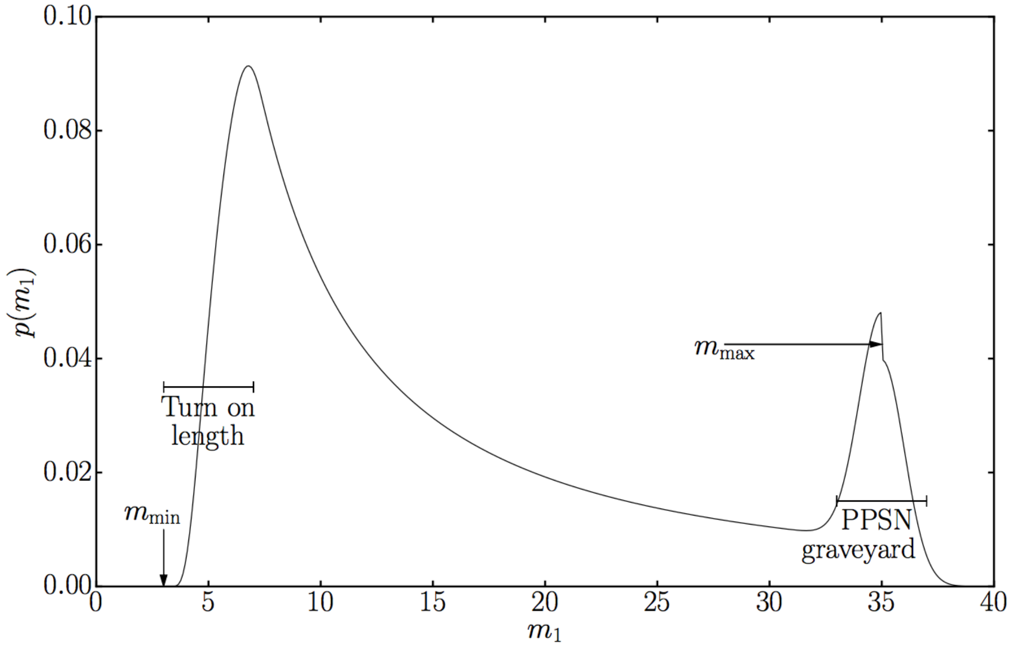
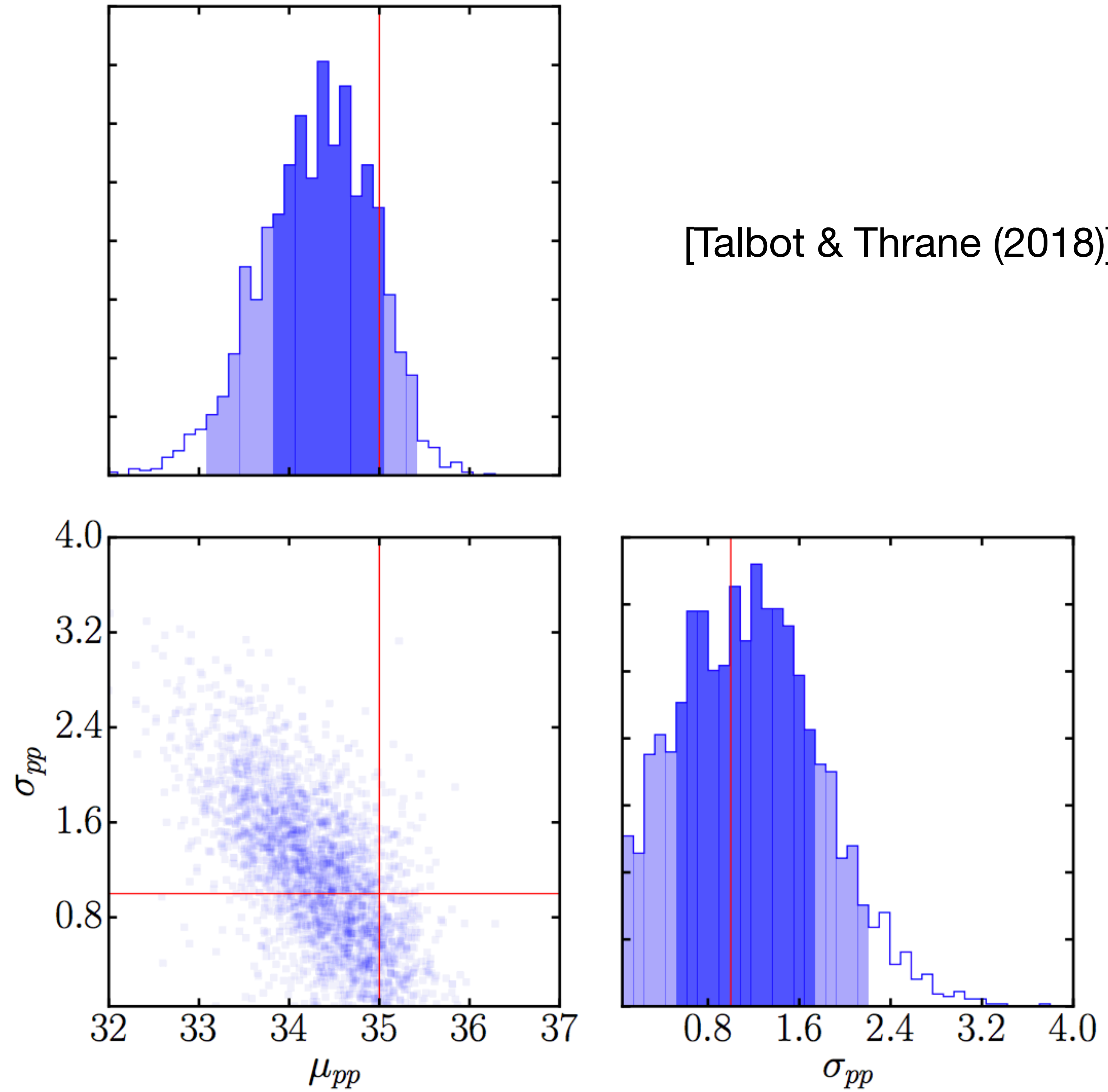
Constraining black hole formation using the mass distribution

Constraining the position and width of the pulsational PISN peak with 200 events



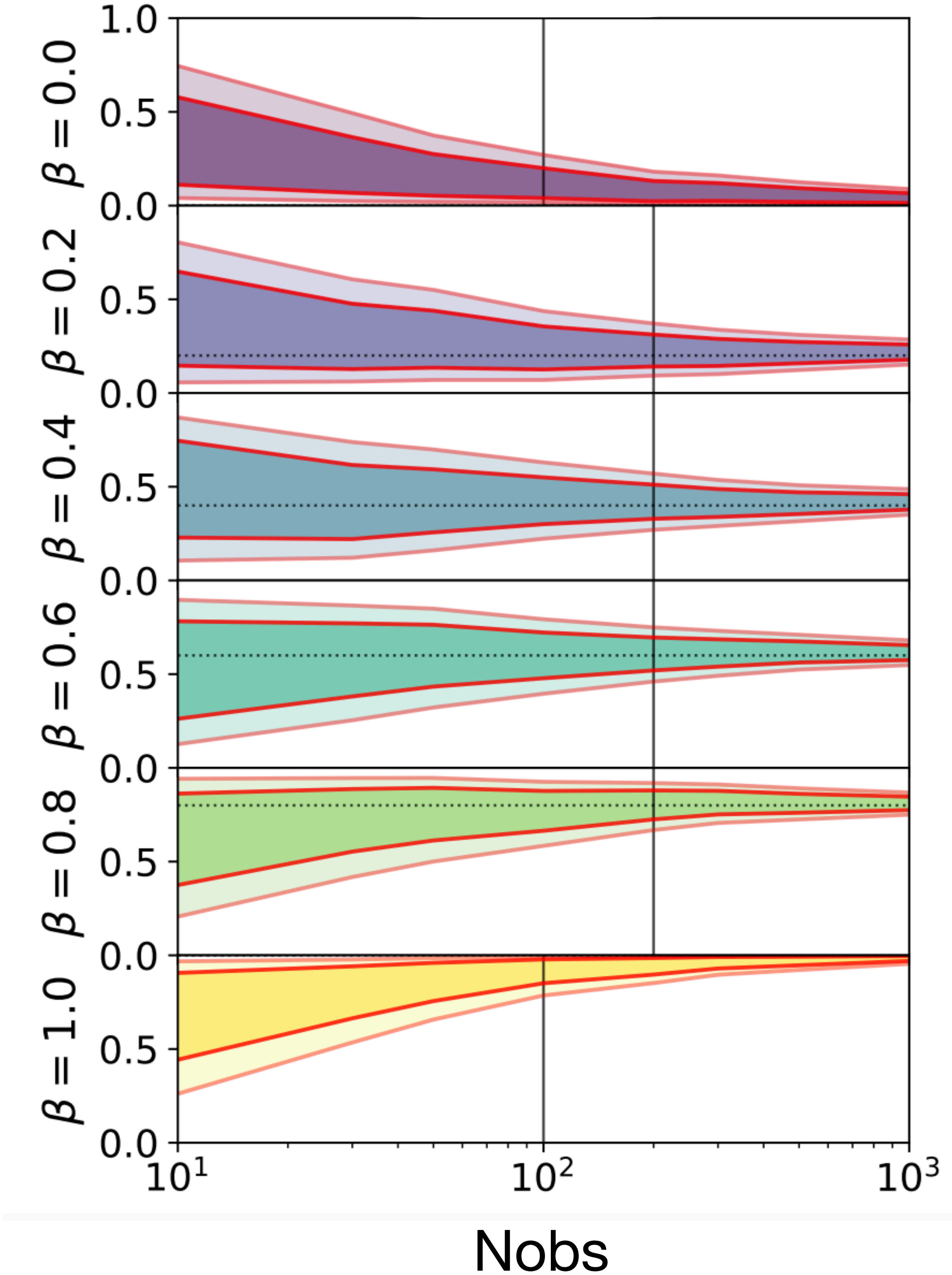


[Talbot & Thrane (2018)]

Constraining black hole formation using the mass distribution

Constraints on the branching ratio of two models:
'Field' vs. 'Cluster'

[Zevin et al. (2016)]

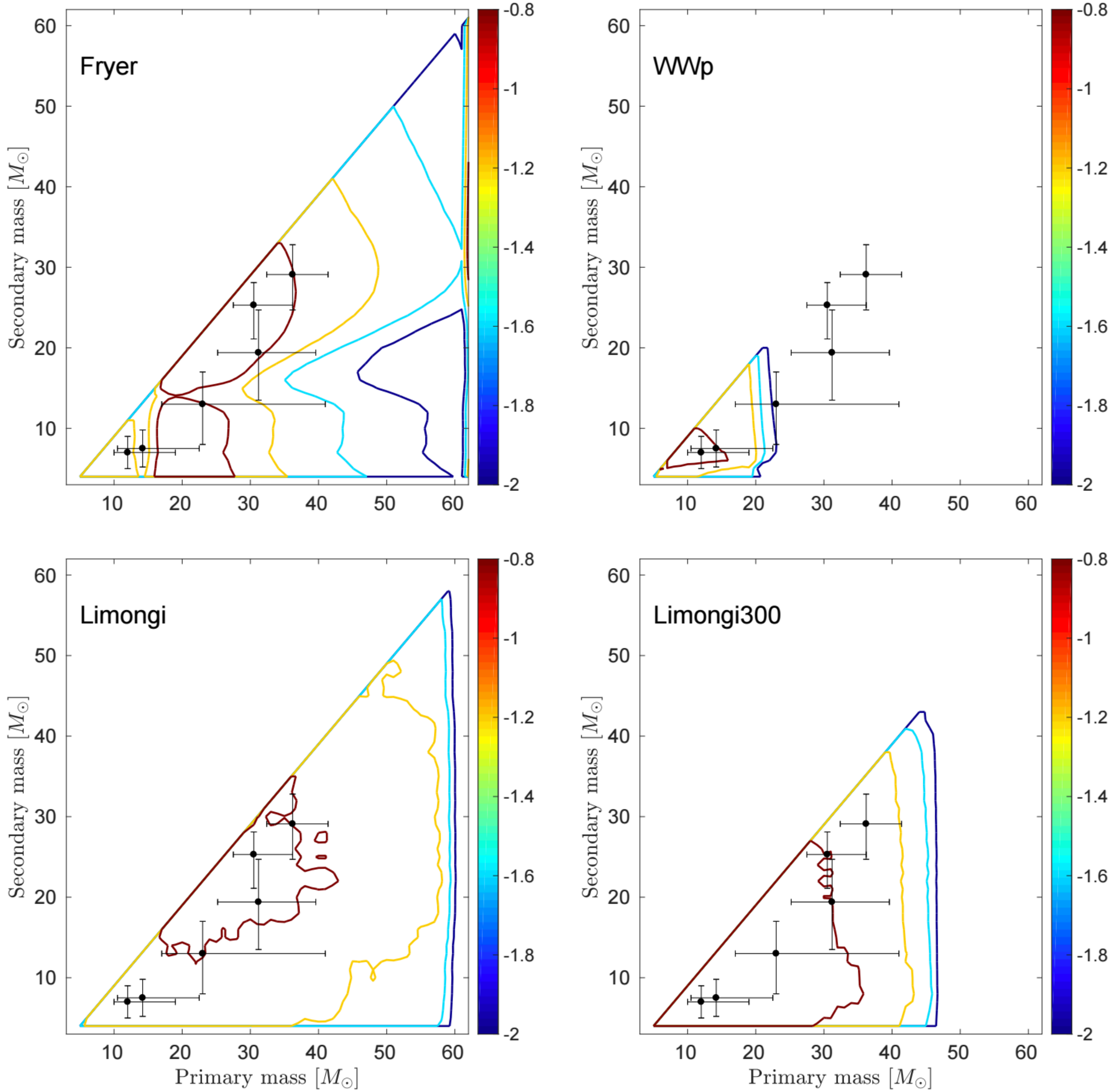


None are formed in clusters

All are formed in clusters

Constraining black hole formation using the mass distribution

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

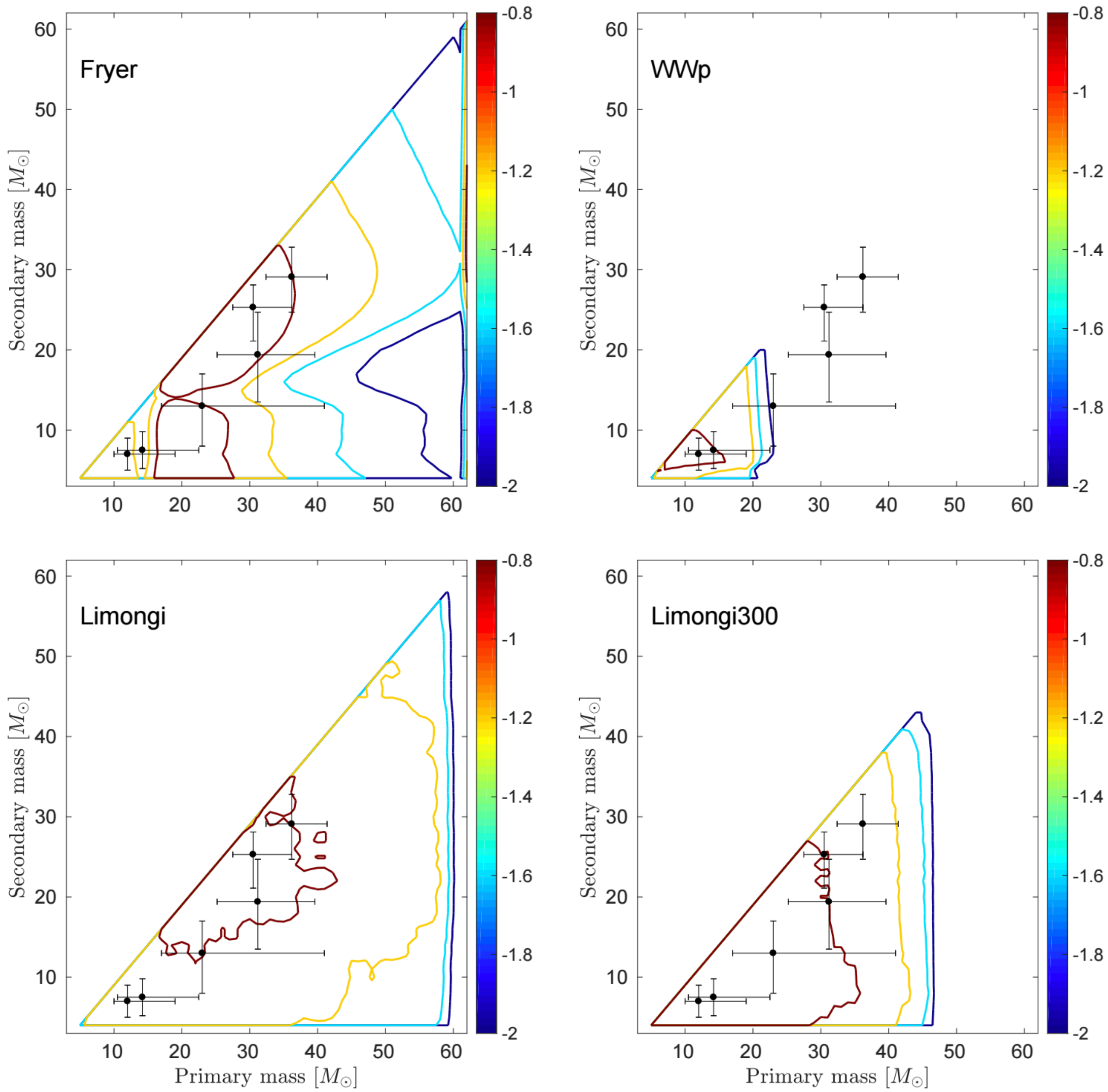


[**ID** et al. (2018)]

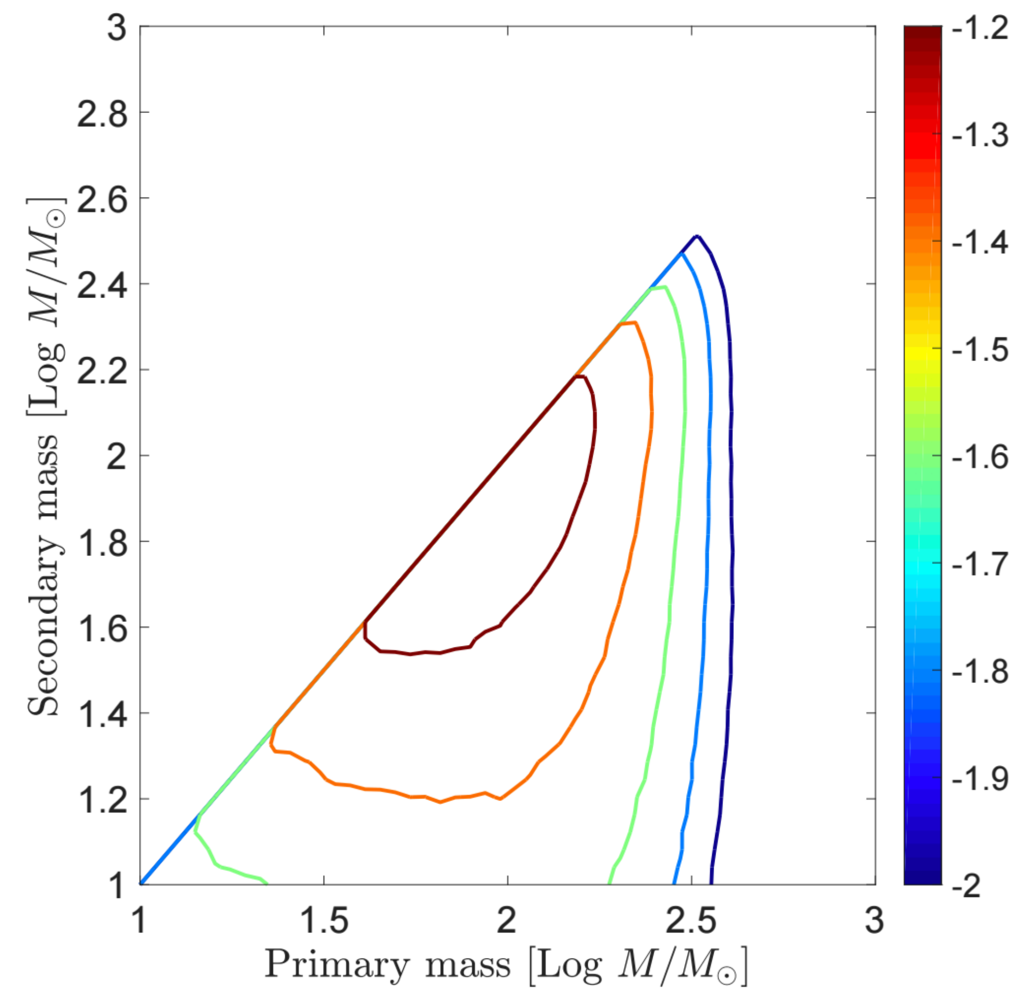
Constraining black hole formation using the mass distribution

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

Stellar-origin black holes



PBH-like toy model



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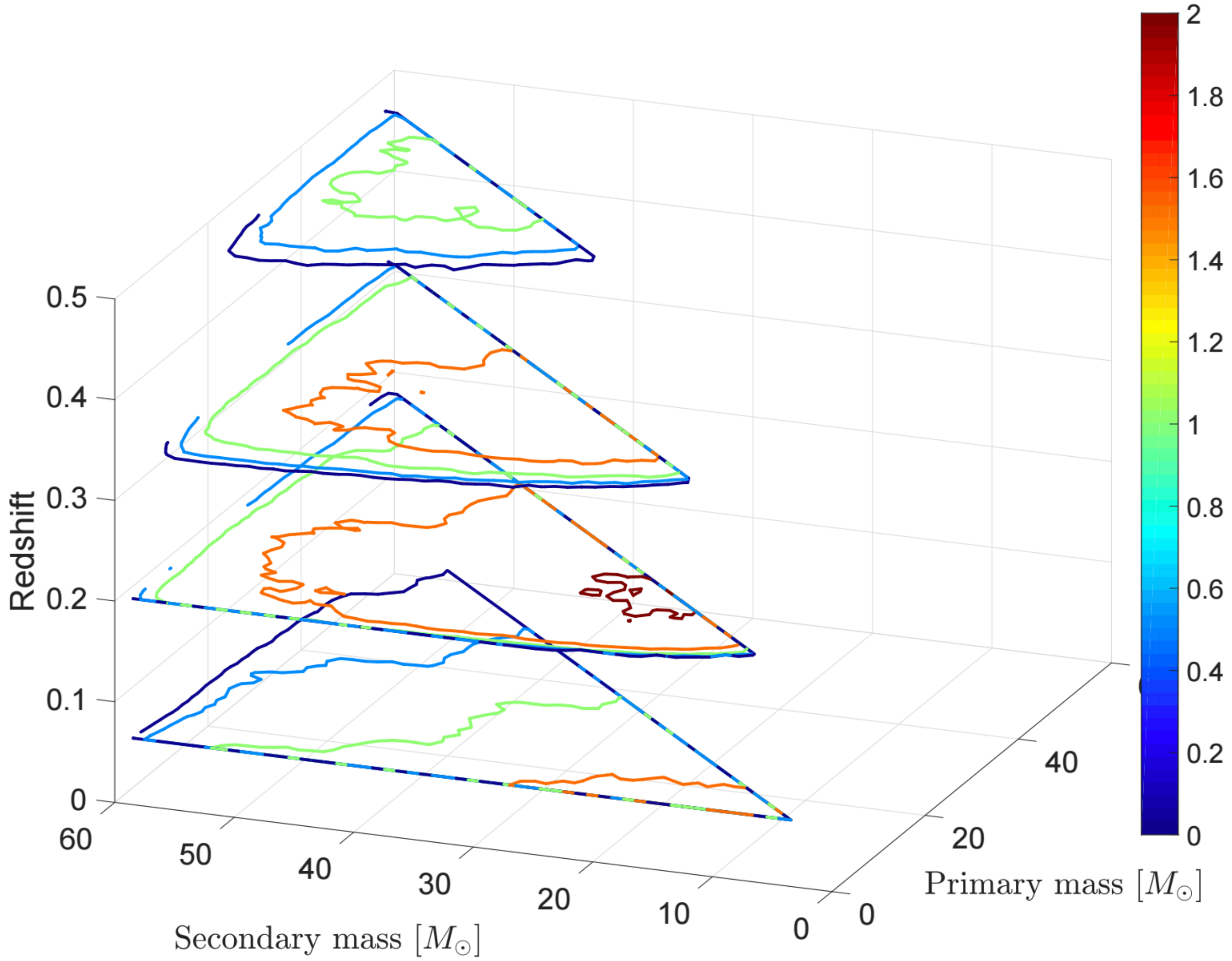

Detection rates Log[Mo^{-2} yr^{-1}] per unit redshift

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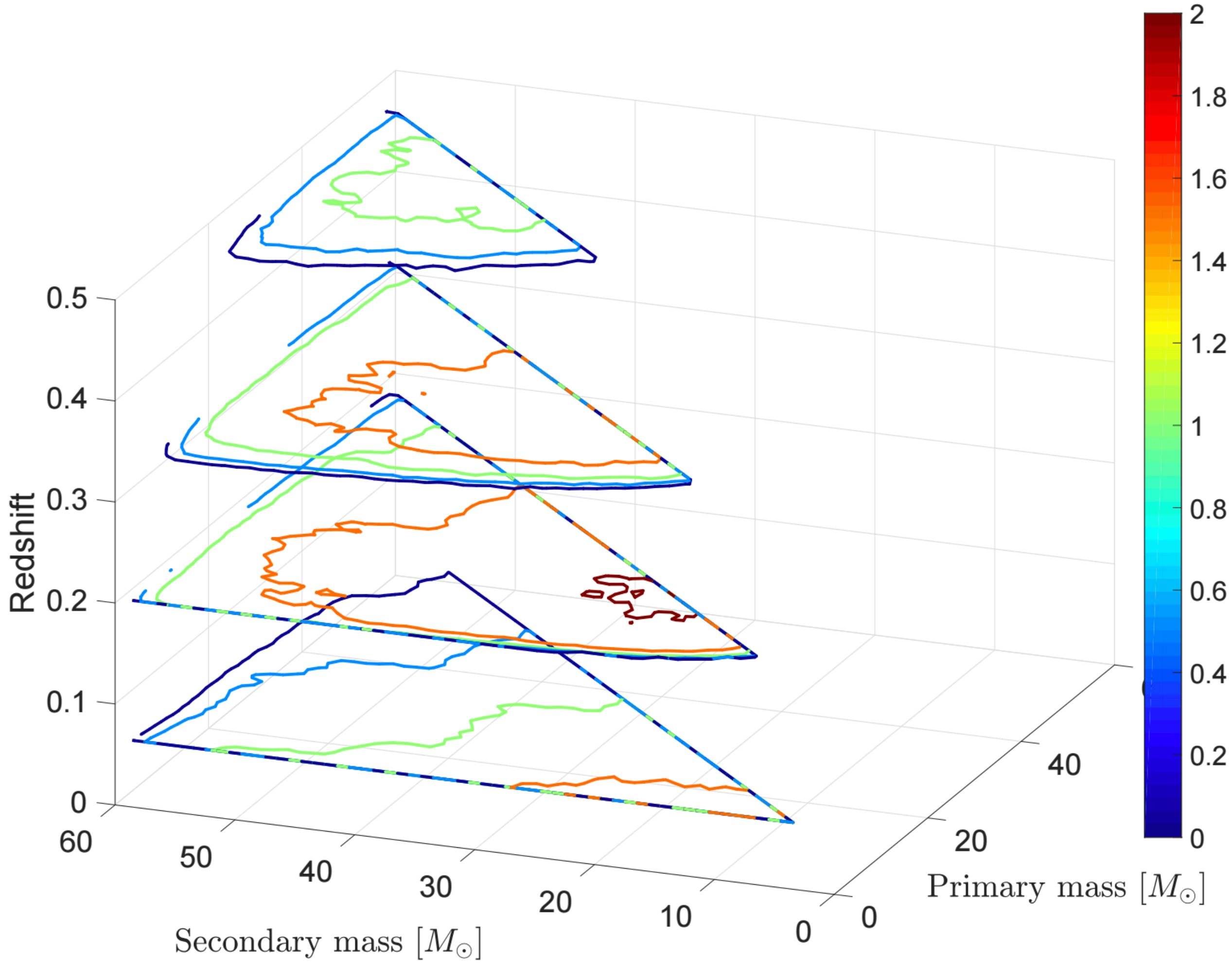

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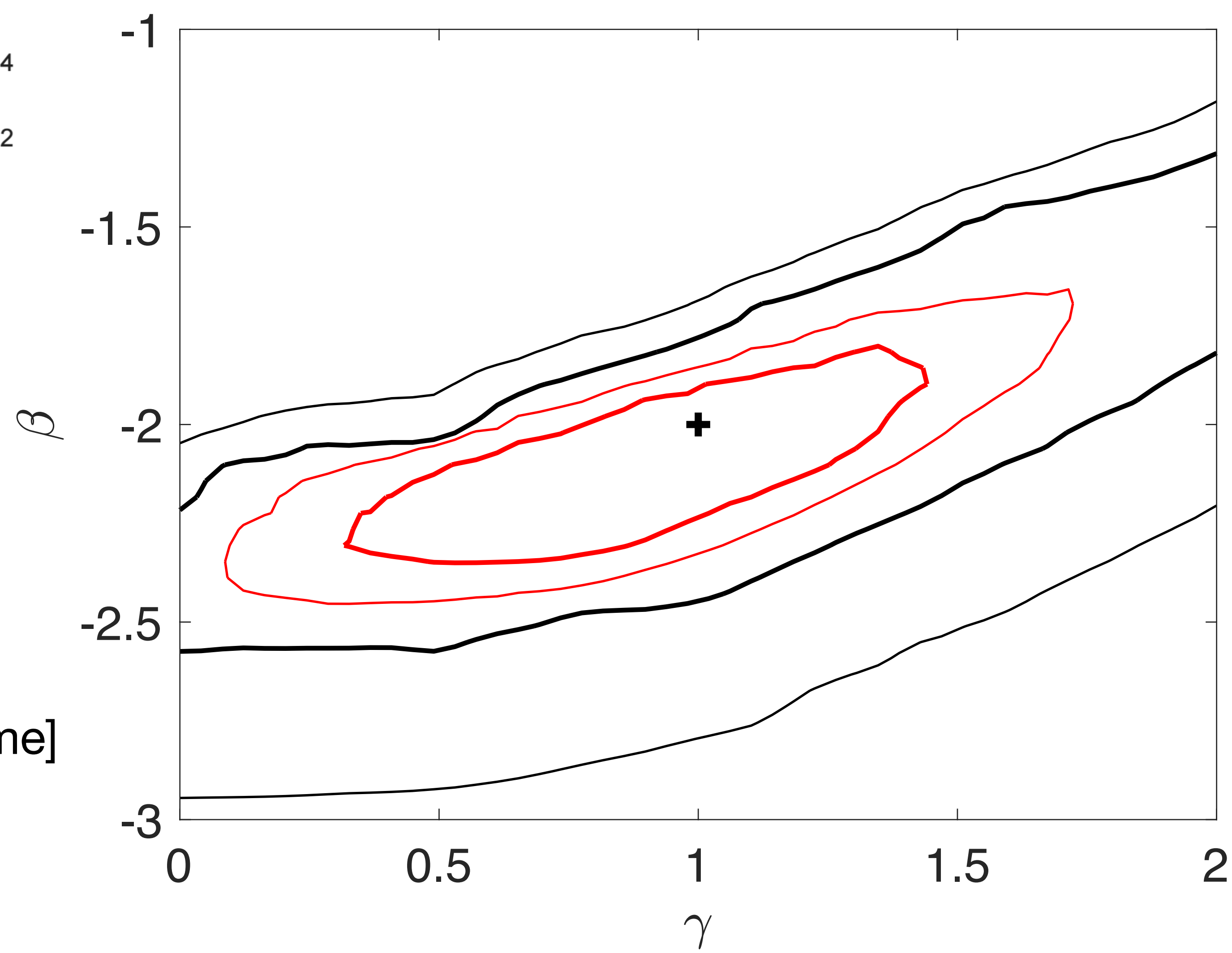


Constraining model parameters:

- 100 detections
- 500 detections

β = Log[Fraction of BHs that merge within Hubble time]

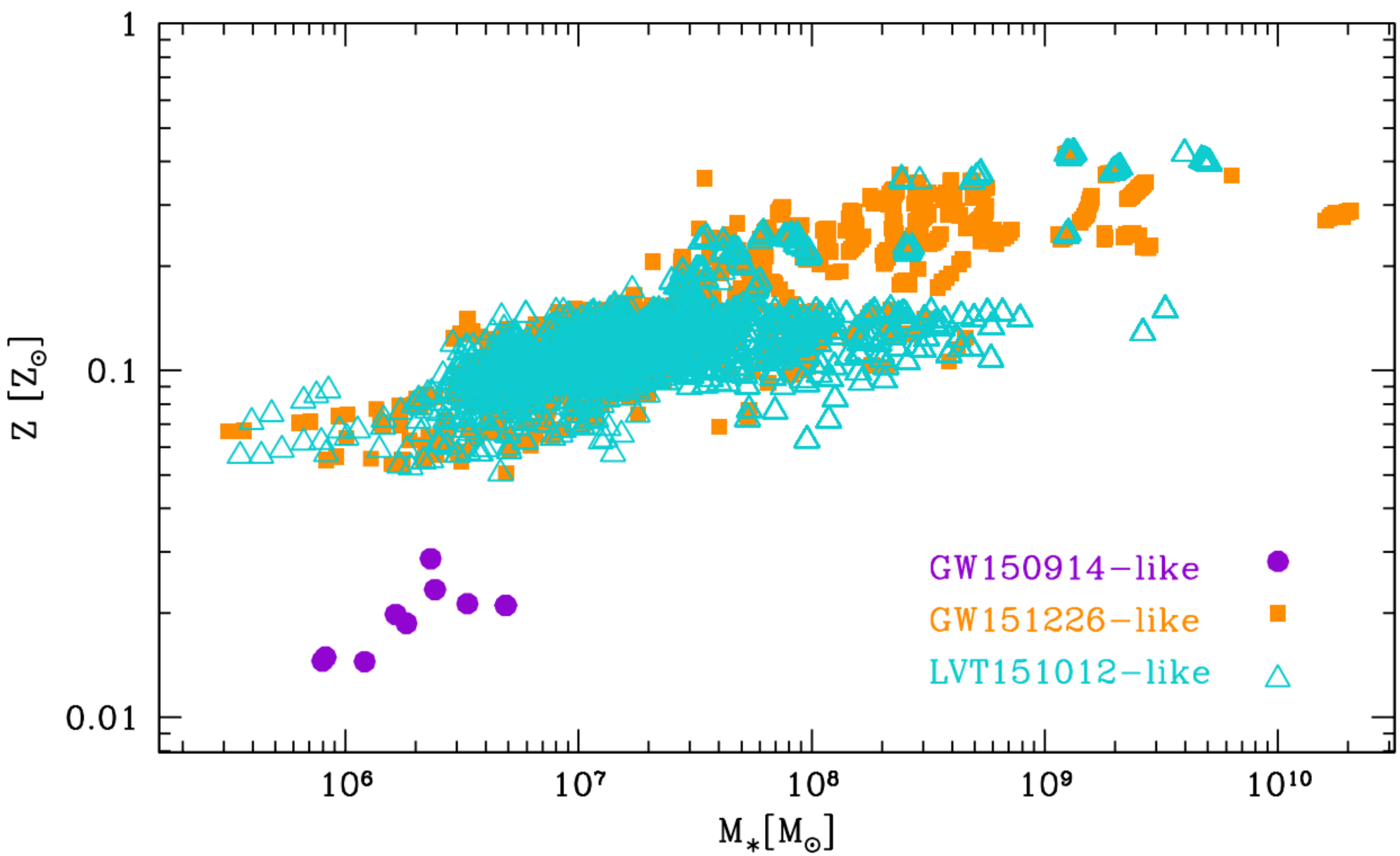
γ = Slope of time delay distribution

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

Studying the host galaxies of GW events

'Heavy' BHs are formed in low-mass low-metallicity galaxies

[Schneider et al. (2017)]



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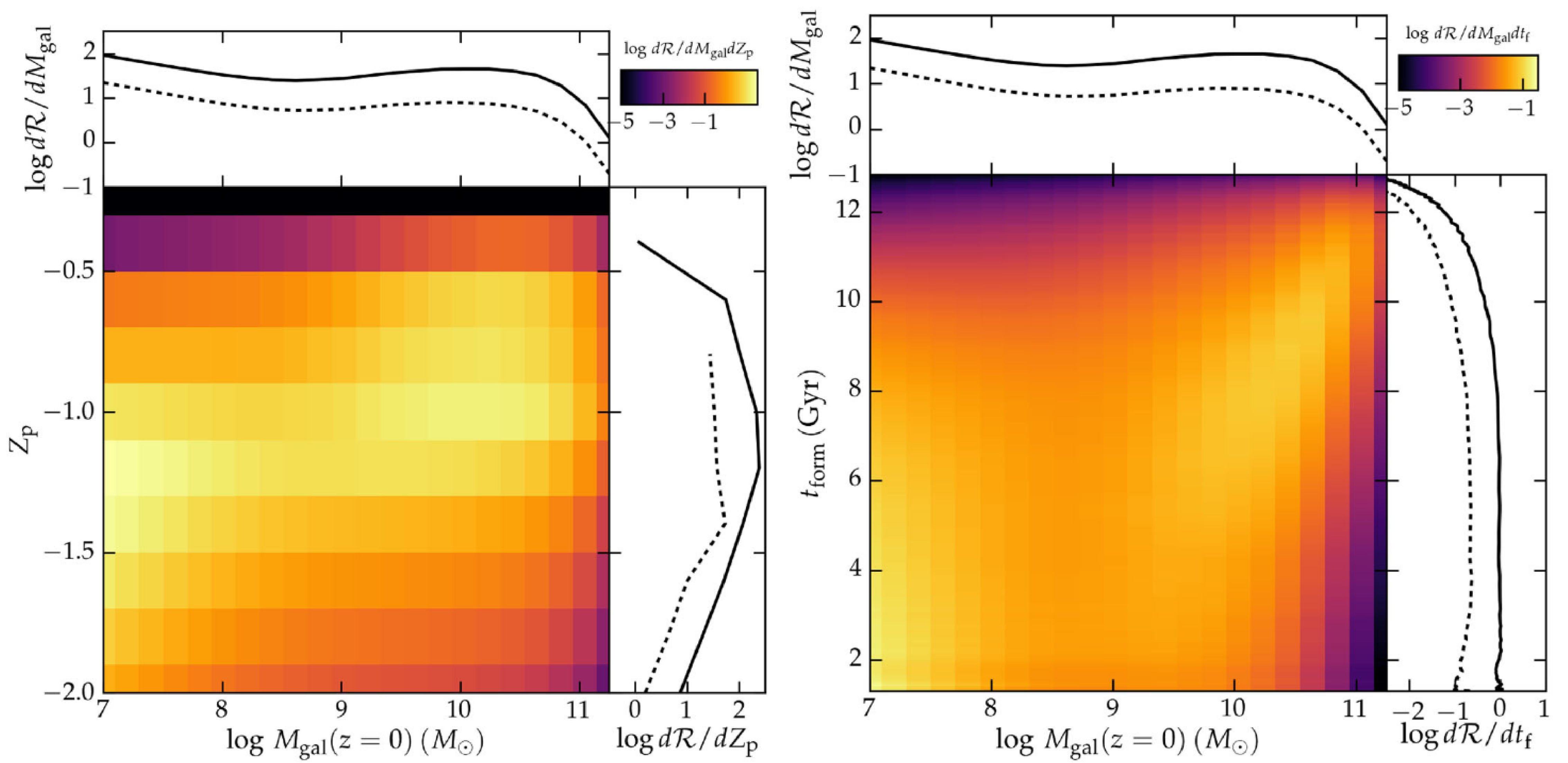
[Lamberts et al. (2016)]



How to study BH formation models with GW?

[Abbott et al. (2016)]

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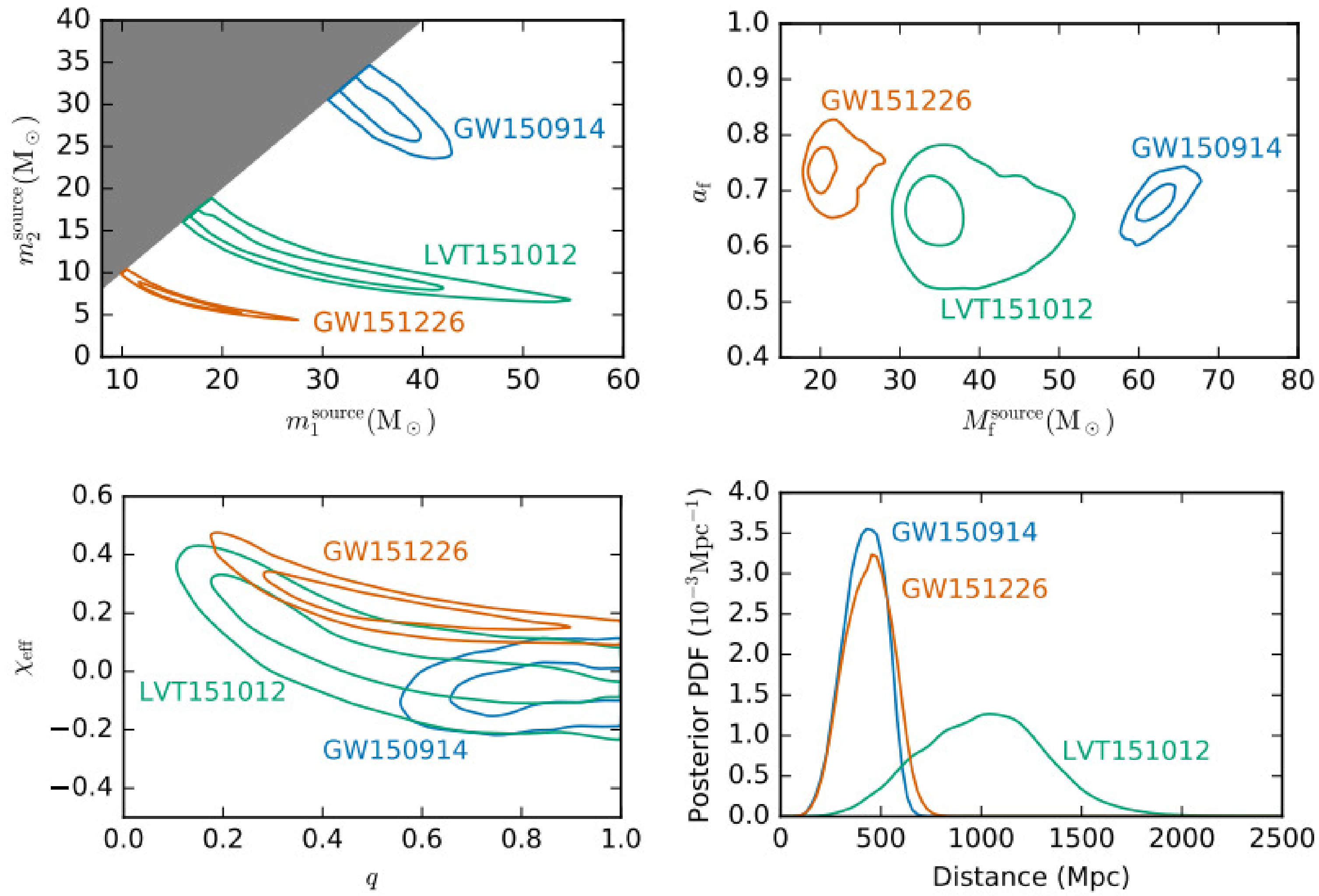

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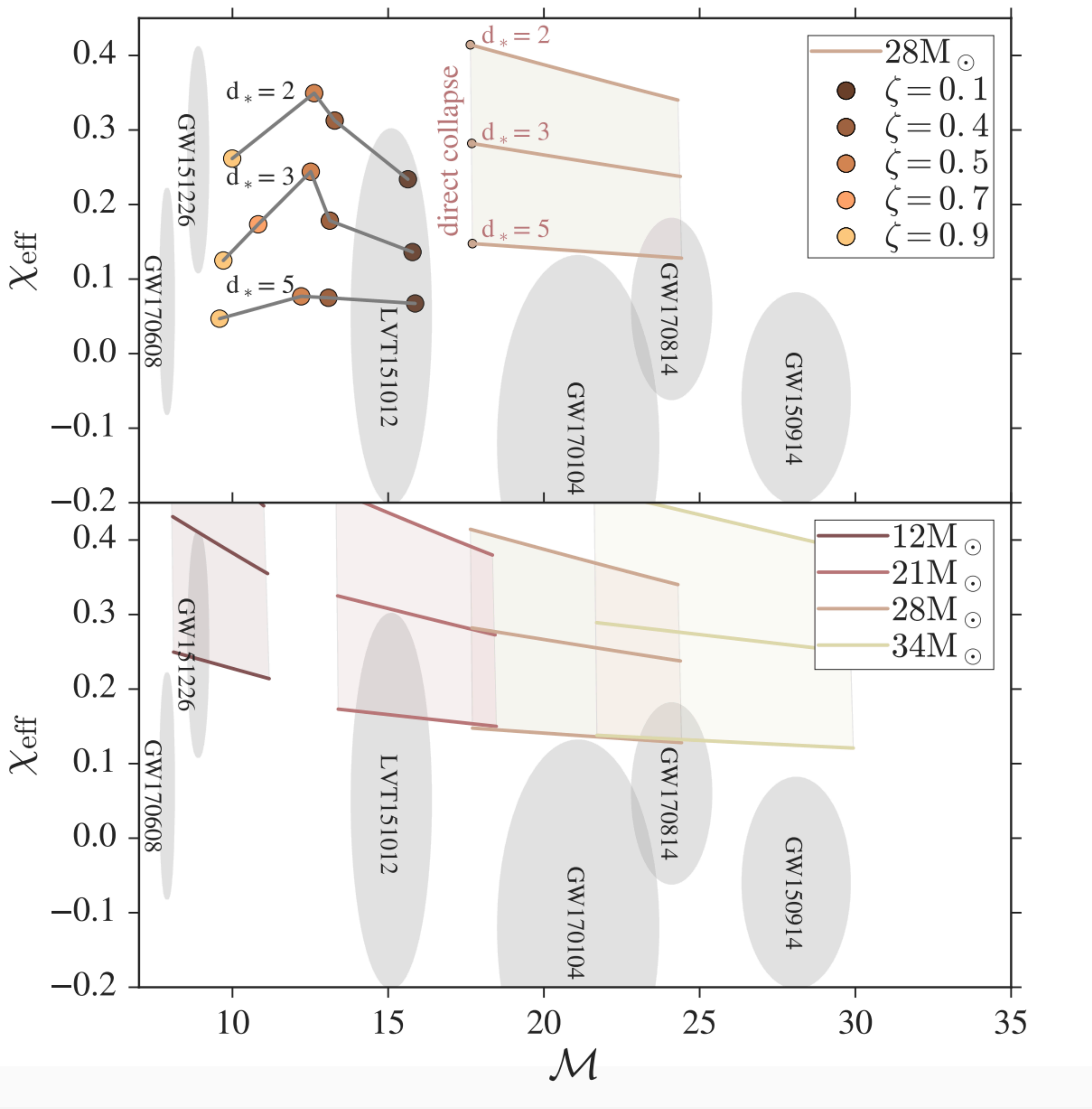
Constraining black hole formation using the spin distribution

What are the expectations for BH spins?

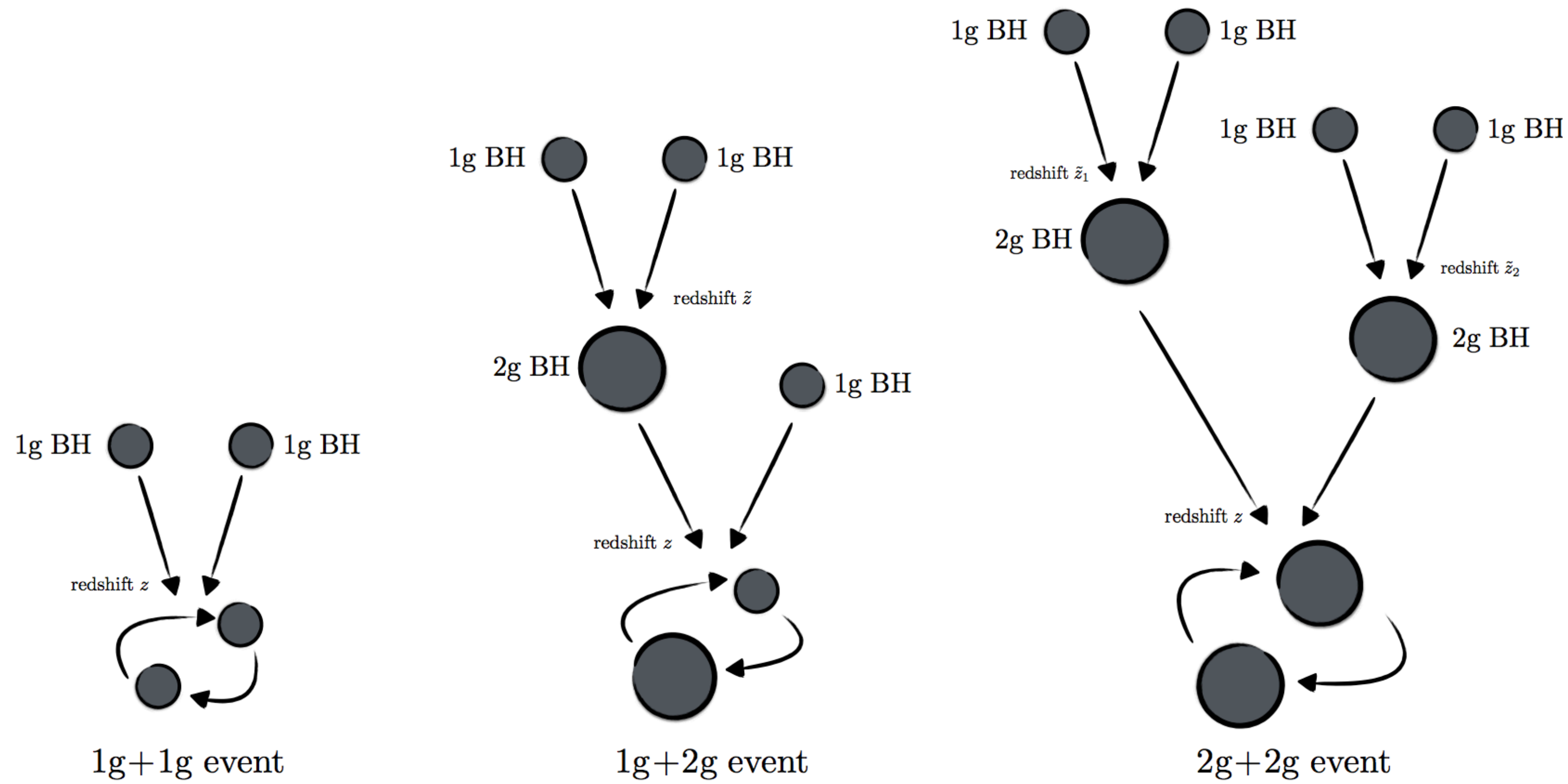


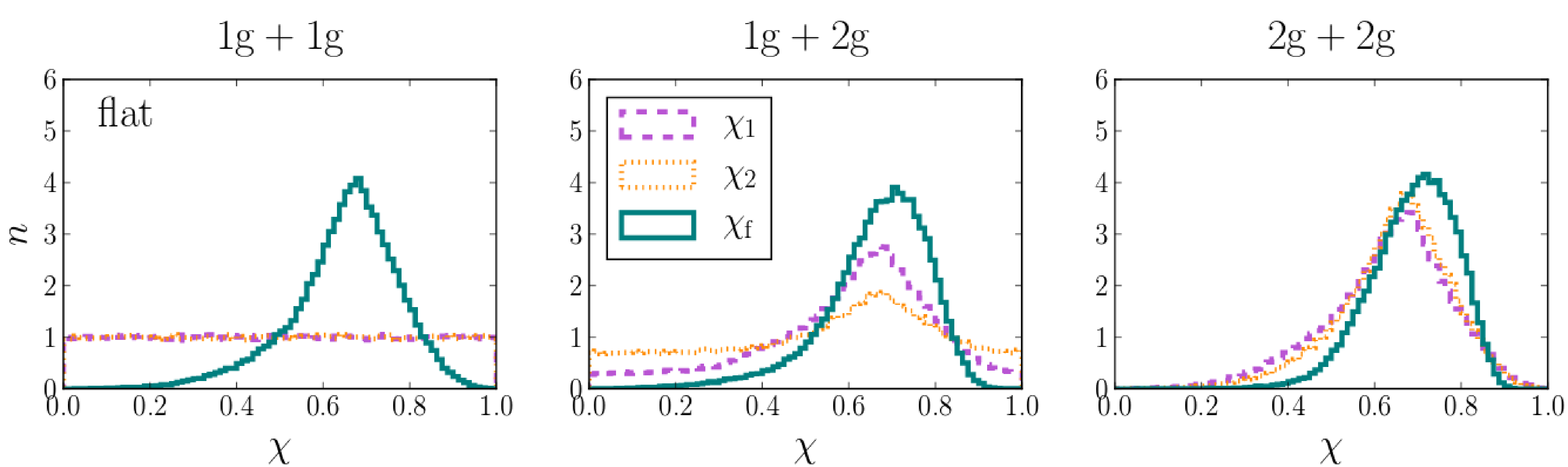
[Schroeder et al. (2018)]

[See also: Kushnir et al. (2016); Hotokezaka & Piran et al. (2017); Zaldarriaga et al. (2018); Qin et al. (2018)]

Constraining black hole formation using the spin distribution

[Gerosa & Berti (2017)]





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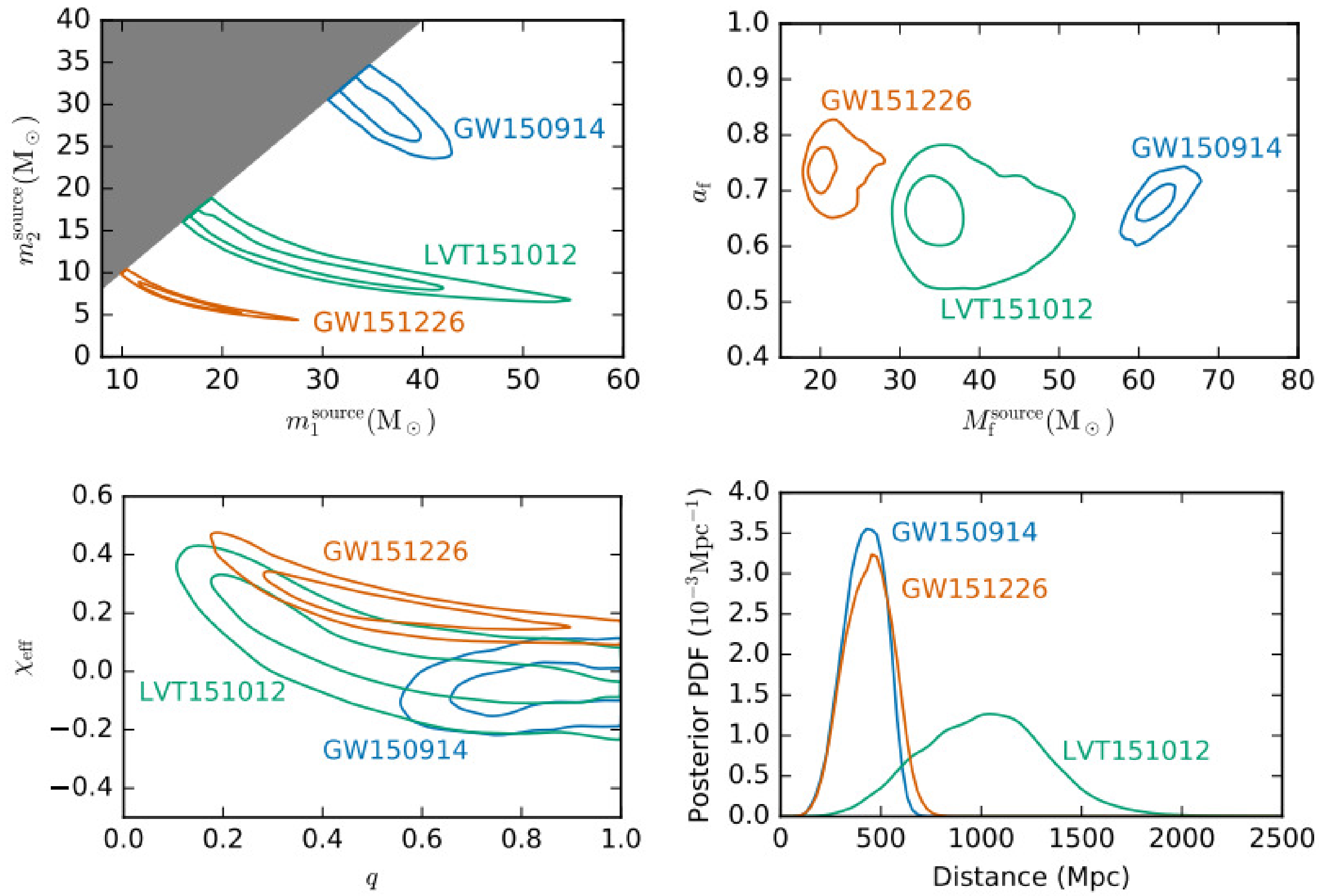

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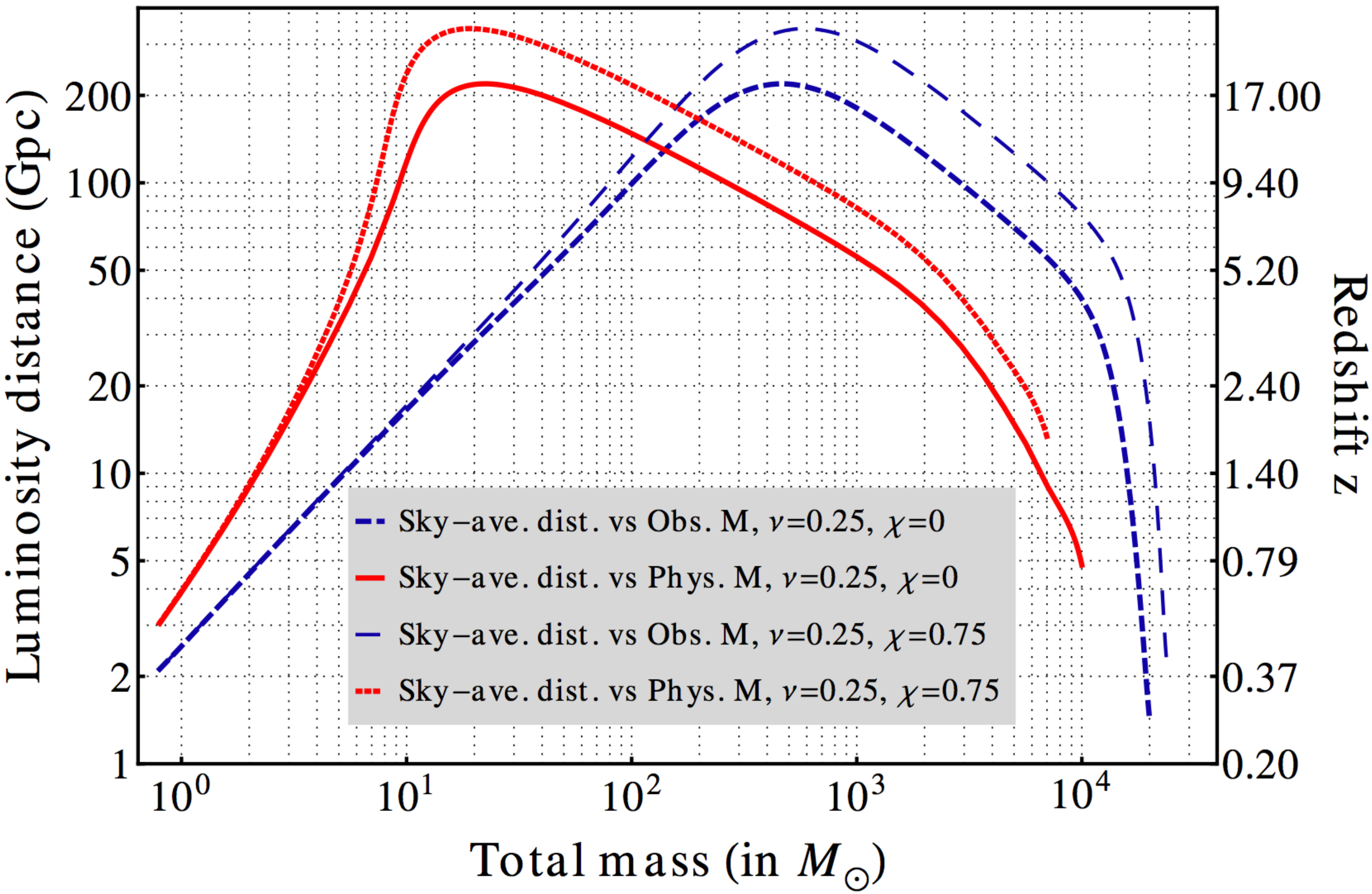
Constraining black hole formation using the redshift distribution

[ET Design Study; ET-0106C-10]



Stochastic gravitational-wave background

Gravitational-wave signal from unresolved sources:

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

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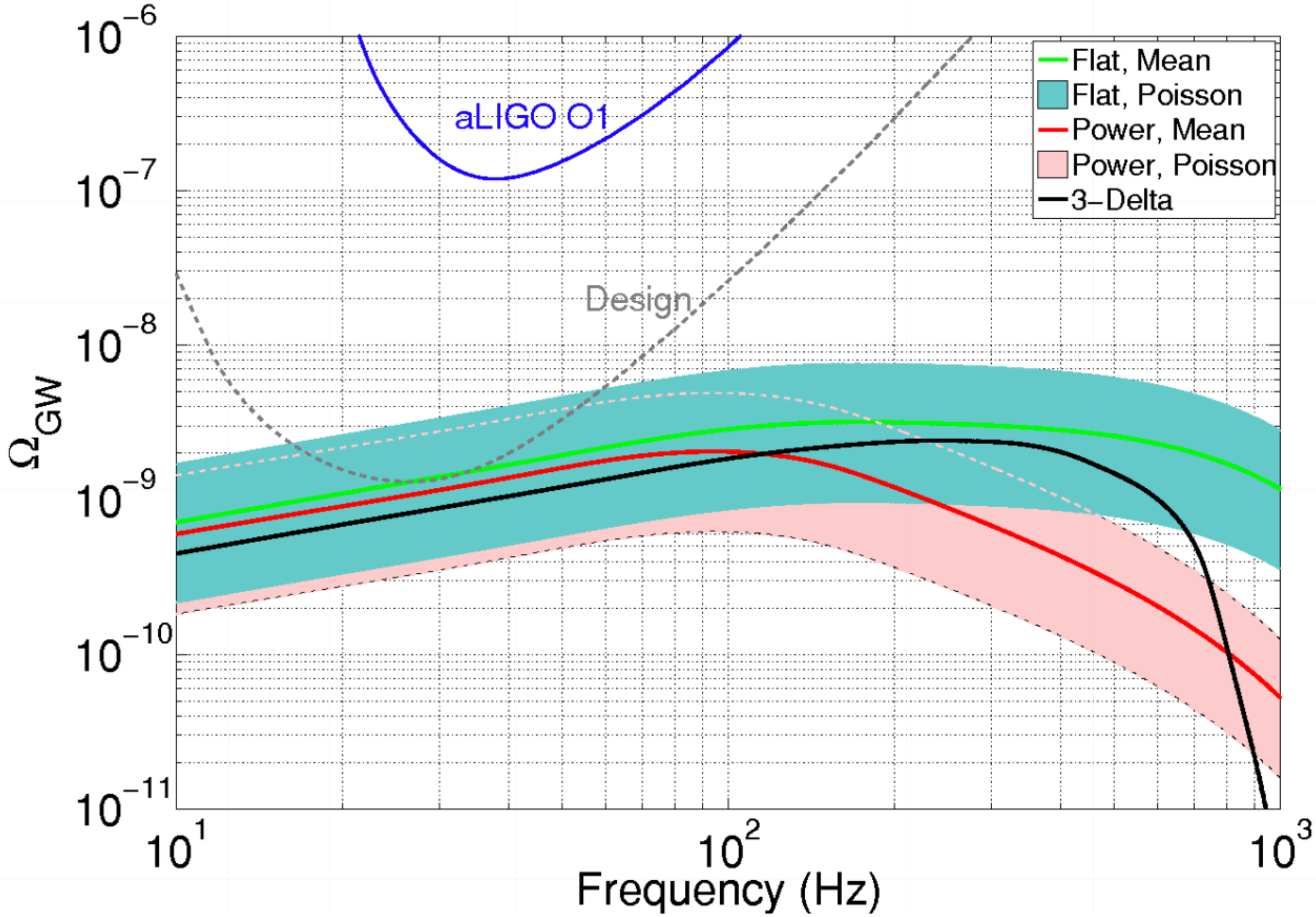

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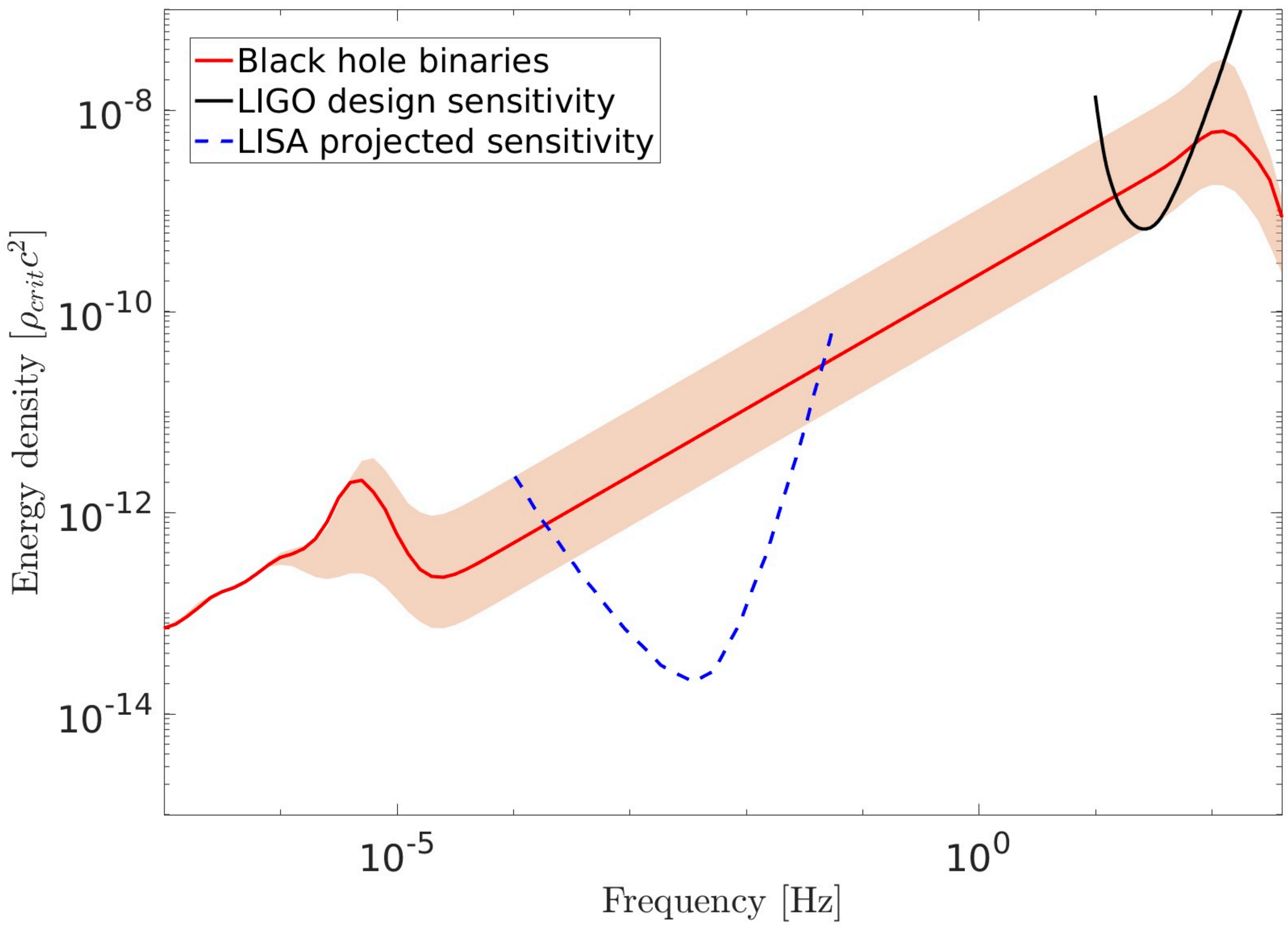
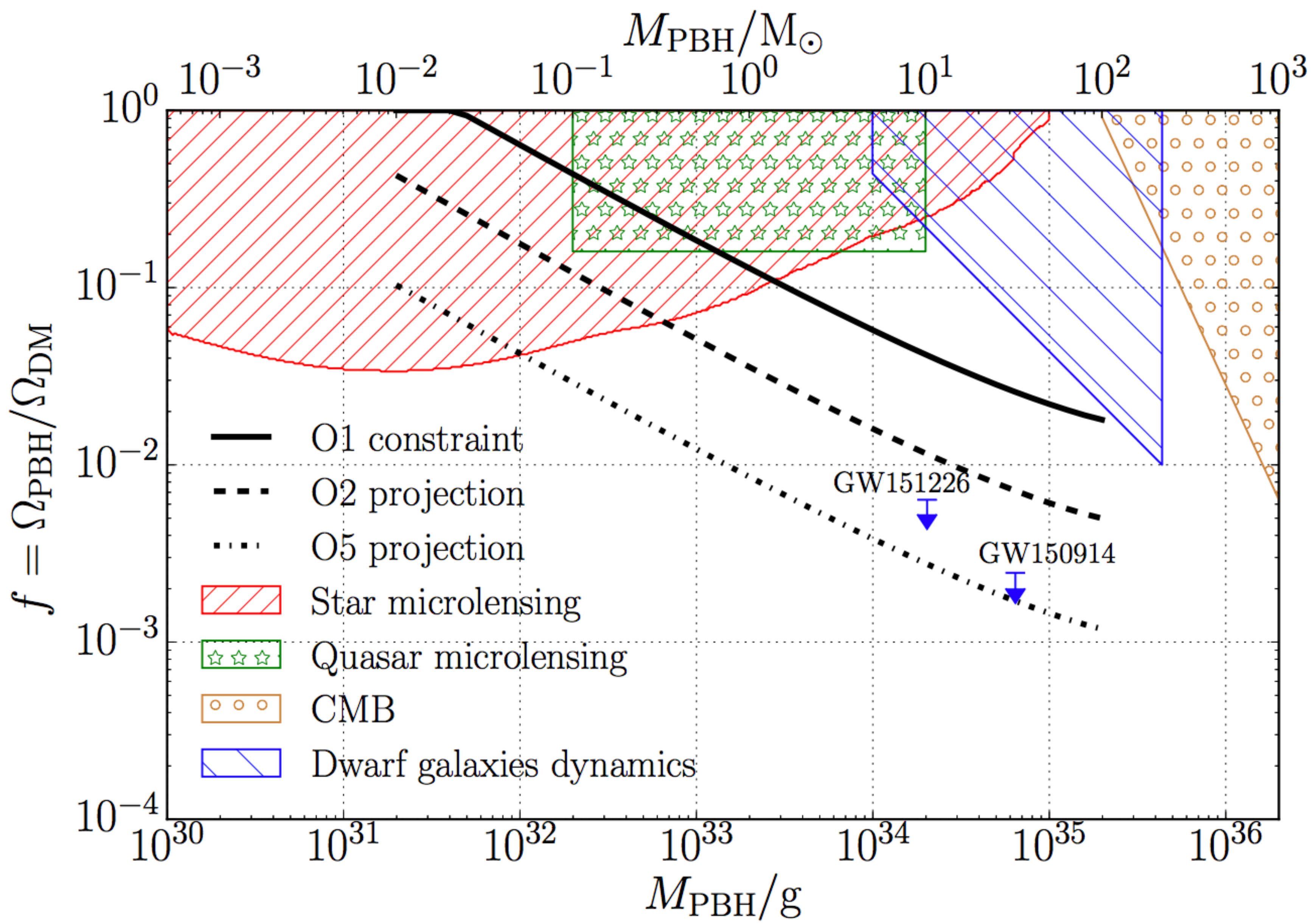


[**ID** et al. (2016)]

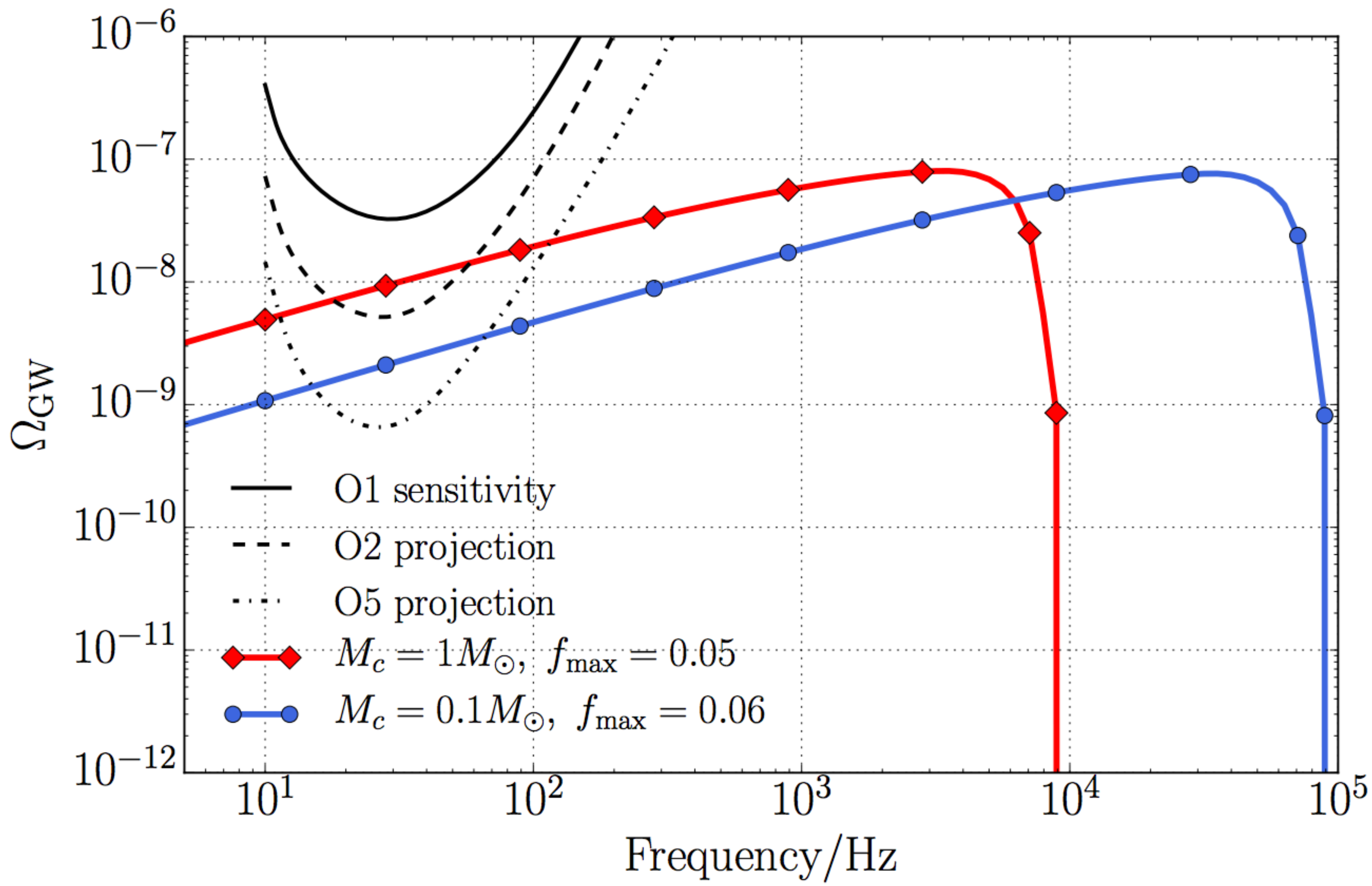
Constraints on PBH abundance with LIGO O1

PBH model as in Sasaki et al. (2016)



[Wang et al. (2018)]

Stochastic background from subsolar BHs



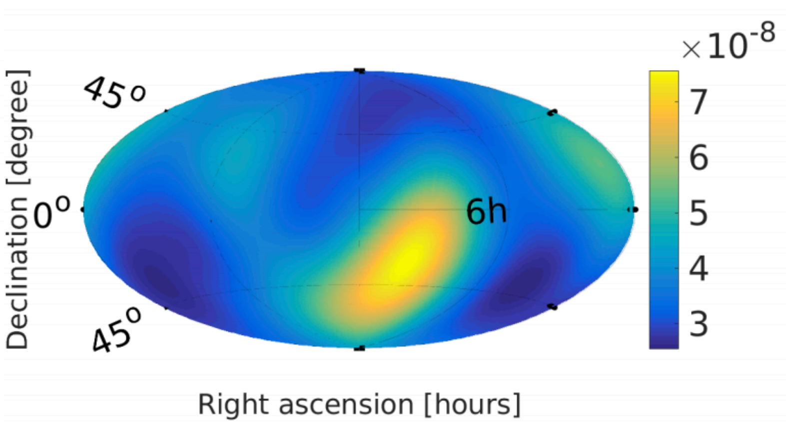
[Wang et al. (2018)]

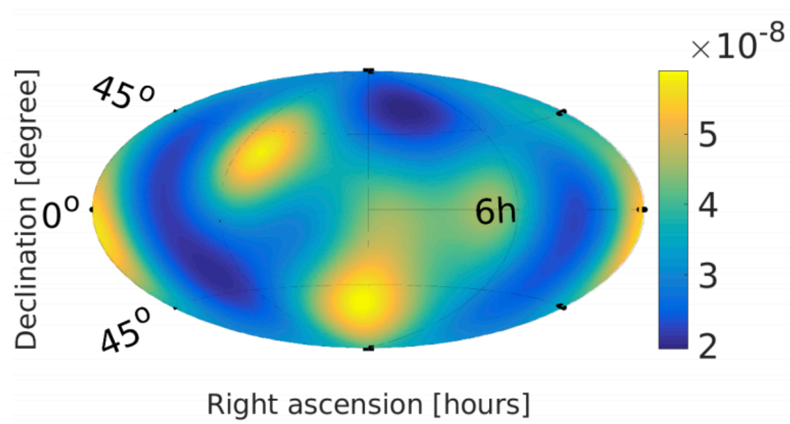
Stochastic gravitational-wave background

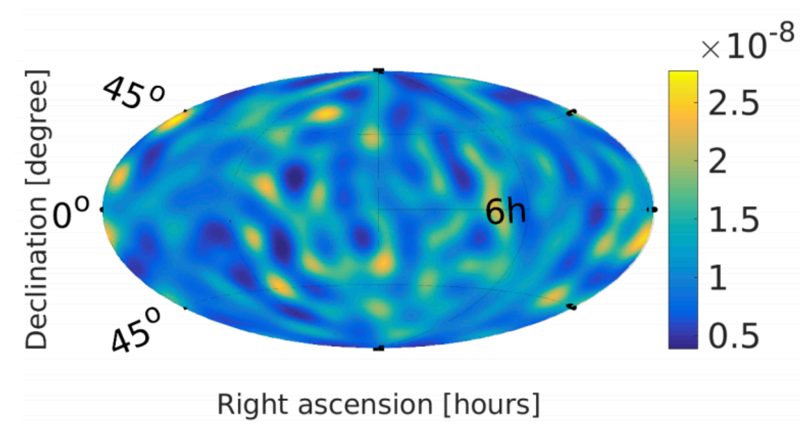
Anisotropic background: *[In analogy with the cosmic infrared background]*

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]	[Compact binary coalescences]	[Flat strain power spectrum density]
α=0	α=2/3	α=3







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

f_ref=25 Hz

First predictions of anisotropic background from binary BH mergers:

[Cusin, Pitrou, Uzan (2017a;b)]

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

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

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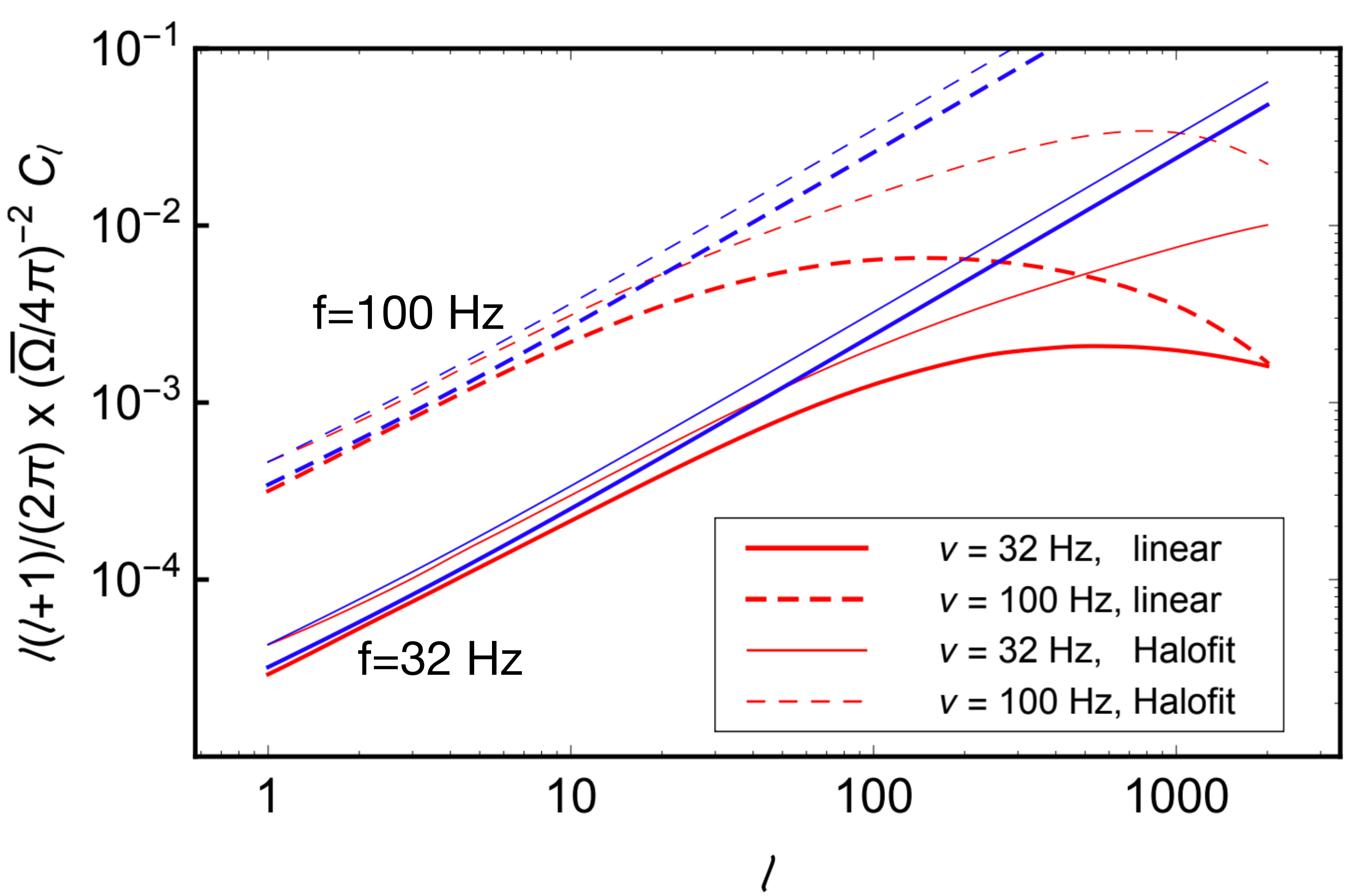
[Cusin, **ID**, Pitrou, Uzan (2018)]



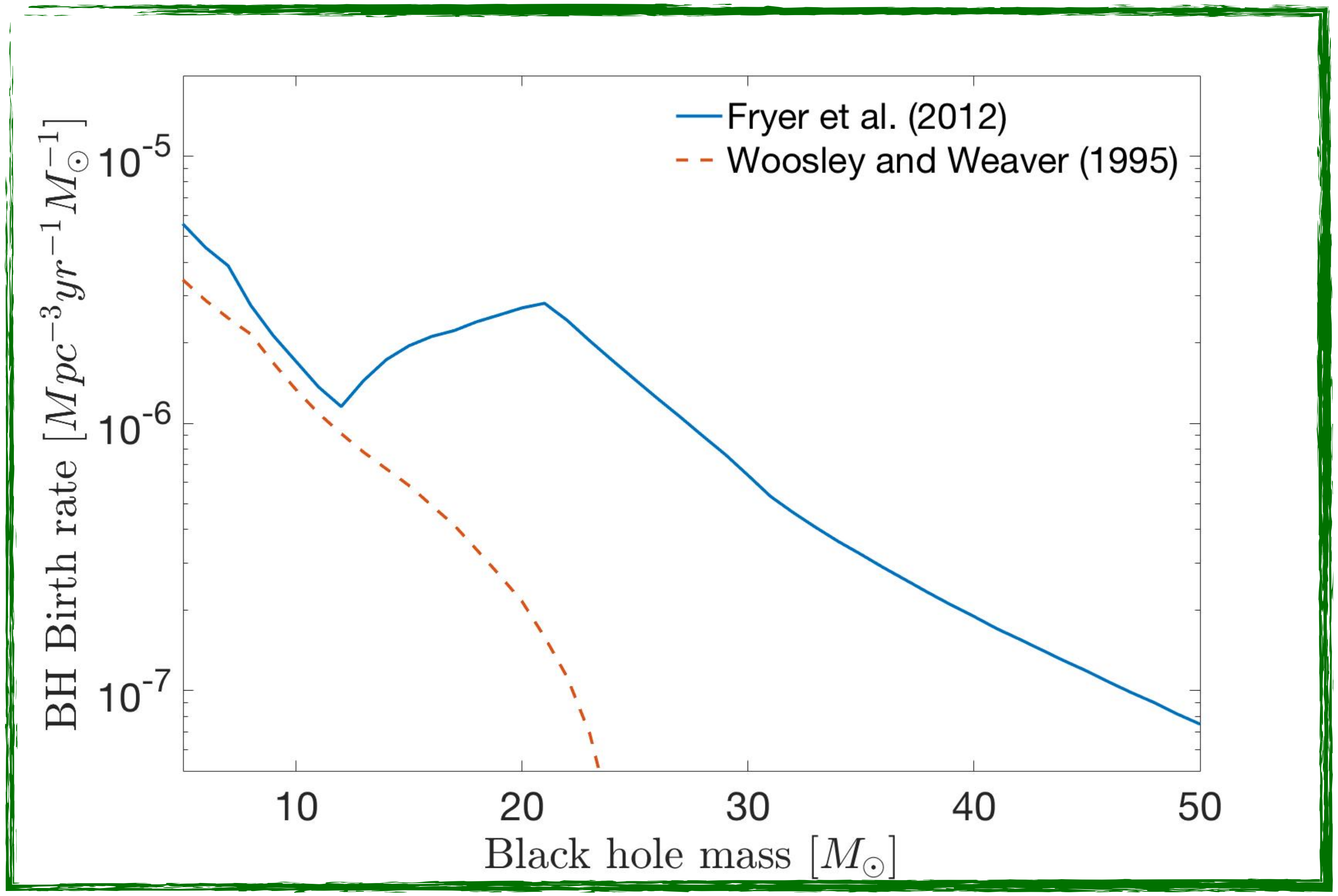
Conclusions

What can we say about the black hole formation scenario?

- **Individual merger events**
  - Mass distribution: need O(100) events to constrain stellar models, but single detections in interesting mass limits (subsolar mass or the PISN gap) may suffice
  - Spin distribution: possibly need O(10) but measurement is difficult
  - Redshift: need to wait for LIGO Voyager and Einstein Telescope
- **Stochastic background**
  - Amplitude may already constrain the fraction of PBHs
- **Anisotropies in the stochastic background**
  - Potentially very informative but detection will take some years…

Additional slides

Constraining black hole formation using the mass distribution



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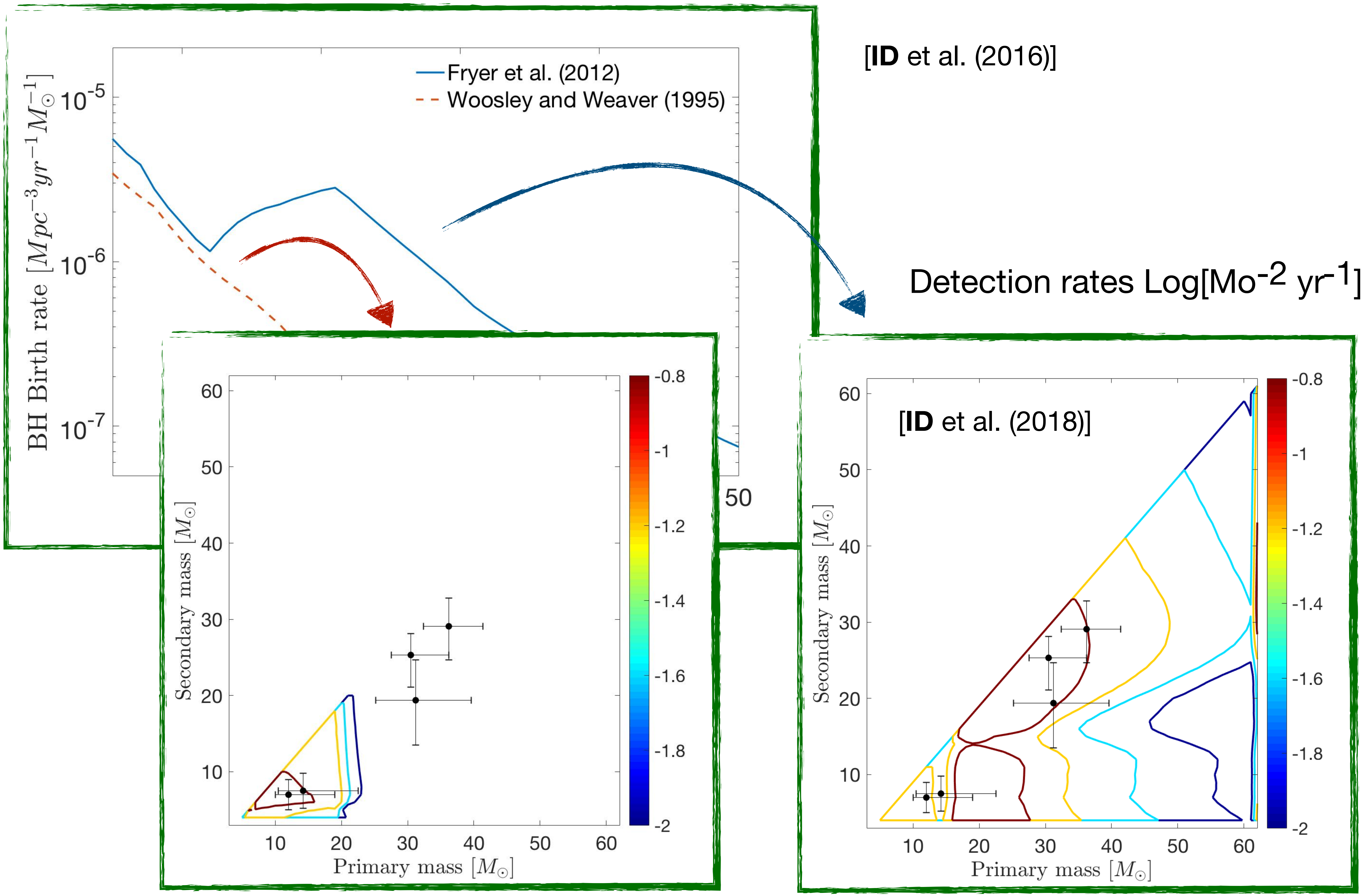


$$
\begin{aligned}
\delta\Omega_\ell(k,\nu_\mathrm{O}) \quad &= \frac{\nu_\mathrm{O}}{4\pi\rho_c}\int_{\eta_*}^{\eta_\mathrm{O}} \mathrm{d}\eta\,\mathcal{A}(\eta,\nu_\mathrm{O})\left[\left(4\Phi_k(\eta)+b\delta_{\mathrm{m,k}}(\eta)+(b-1)3\mathcal{H}\frac{v_k(\eta)}{k}\right)j_\ell(k\Delta\eta)-2kv_k(\eta)j'_\ell(k\Delta\eta)\right] \\
&+\frac{\nu_\mathrm{O}}{4\pi\rho_c}\int_{\eta_*}^{\eta_\mathrm{O}} \mathrm{d}\eta\,\mathcal{B}(\eta,\nu_\mathrm{O})\left[-\Phi_k(\eta)j_\ell(k\Delta\eta)+kv_k(\eta)j'_\ell(k\Delta\eta)\right] \\
&+\frac{\nu_\mathrm{O}}{4\pi\rho_c}\int_{\eta_*}^{\eta_\mathrm{O}} \mathrm{d}\eta\left[6\mathcal{A}(\eta,\nu_\mathrm{O})-2\mathcal{B}(\eta,\nu_\mathrm{O})\right]\int_{\eta}^{\eta_\mathrm{O}} \mathrm{d}\tilde\eta\Phi'_k(\tilde\eta)j_\ell(k\Delta\tilde\eta)\,.
\end{aligned}
$$

[Cusin et al. (2017a;b)]

First predictions of anisotropic background from binary BH mergers:

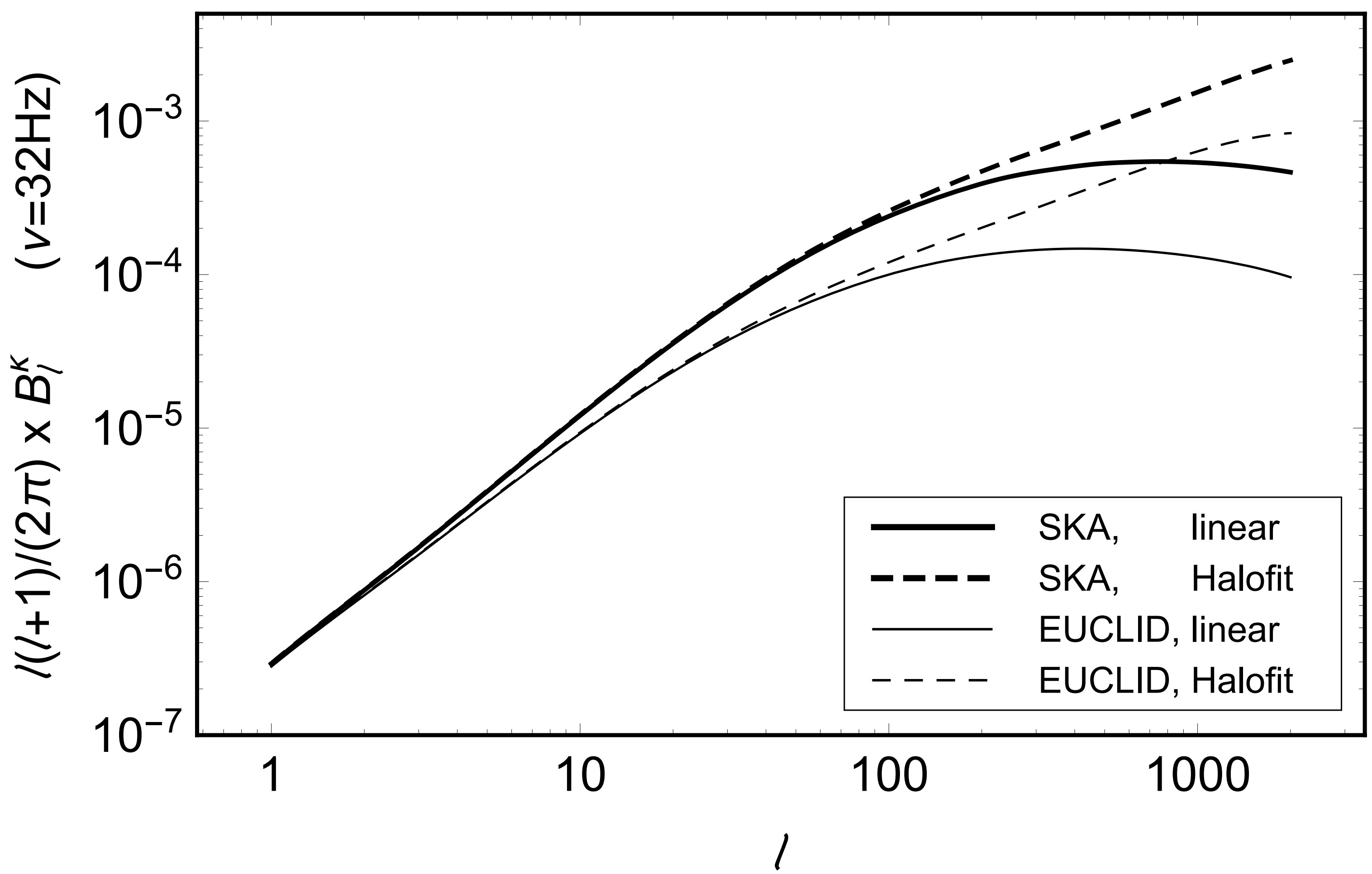
[Cusin, Pitrou, Uzan (2017a;b)]

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

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

Cross-correlations with galaxy number counts:

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



[Sasaki et al. (2016)]