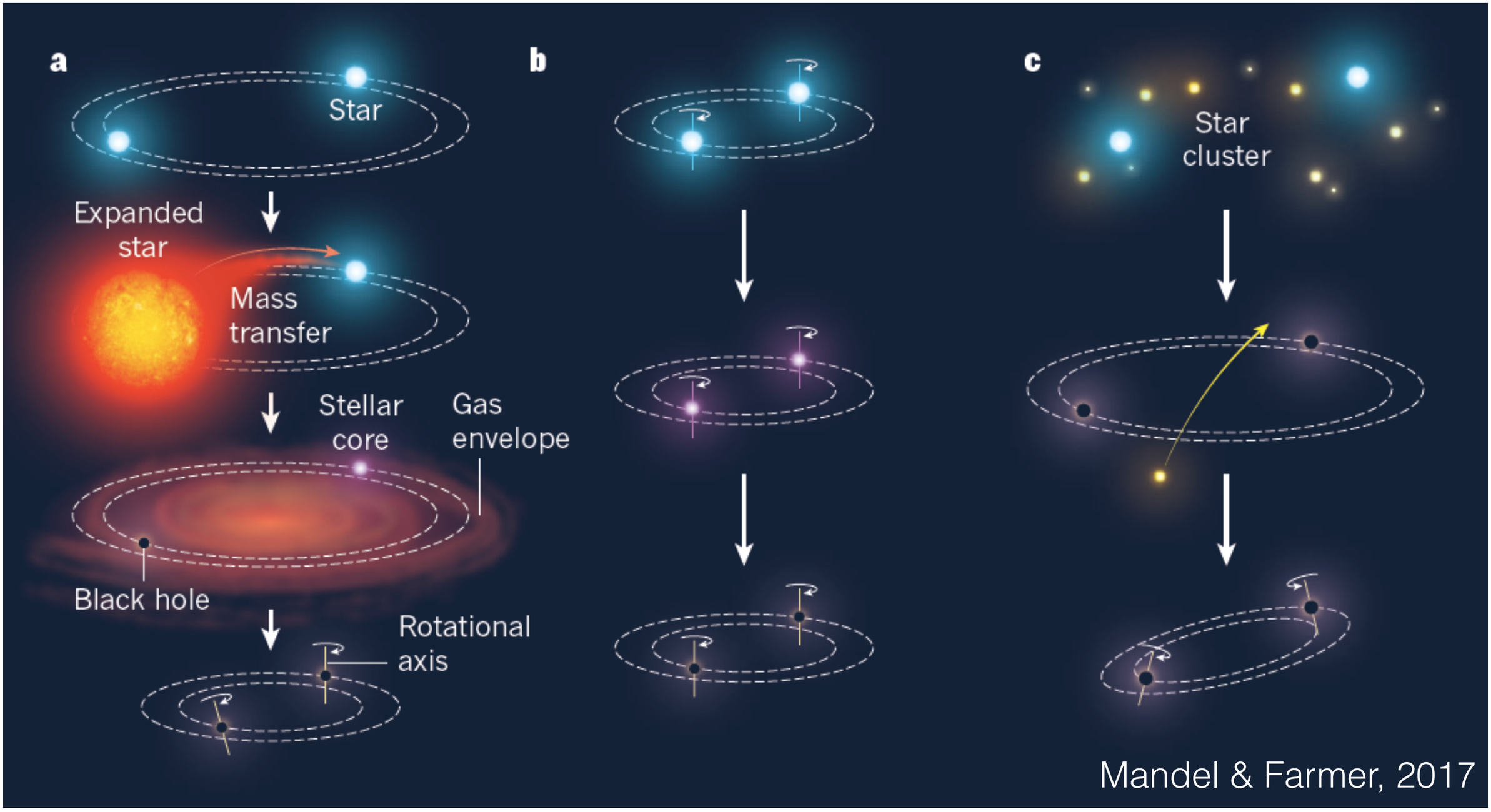
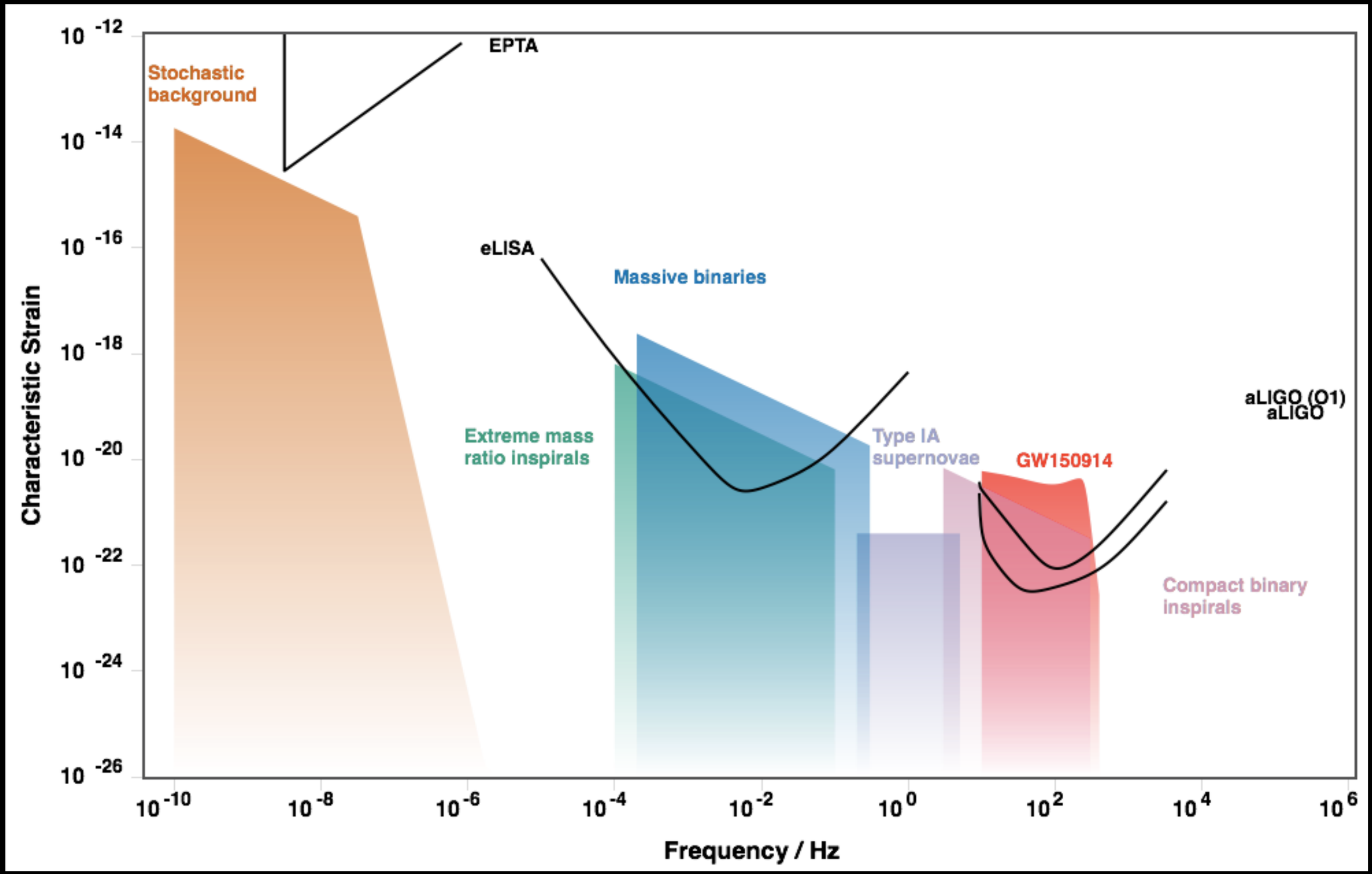
Astrophysical sources of GWs and future prospects for their detection

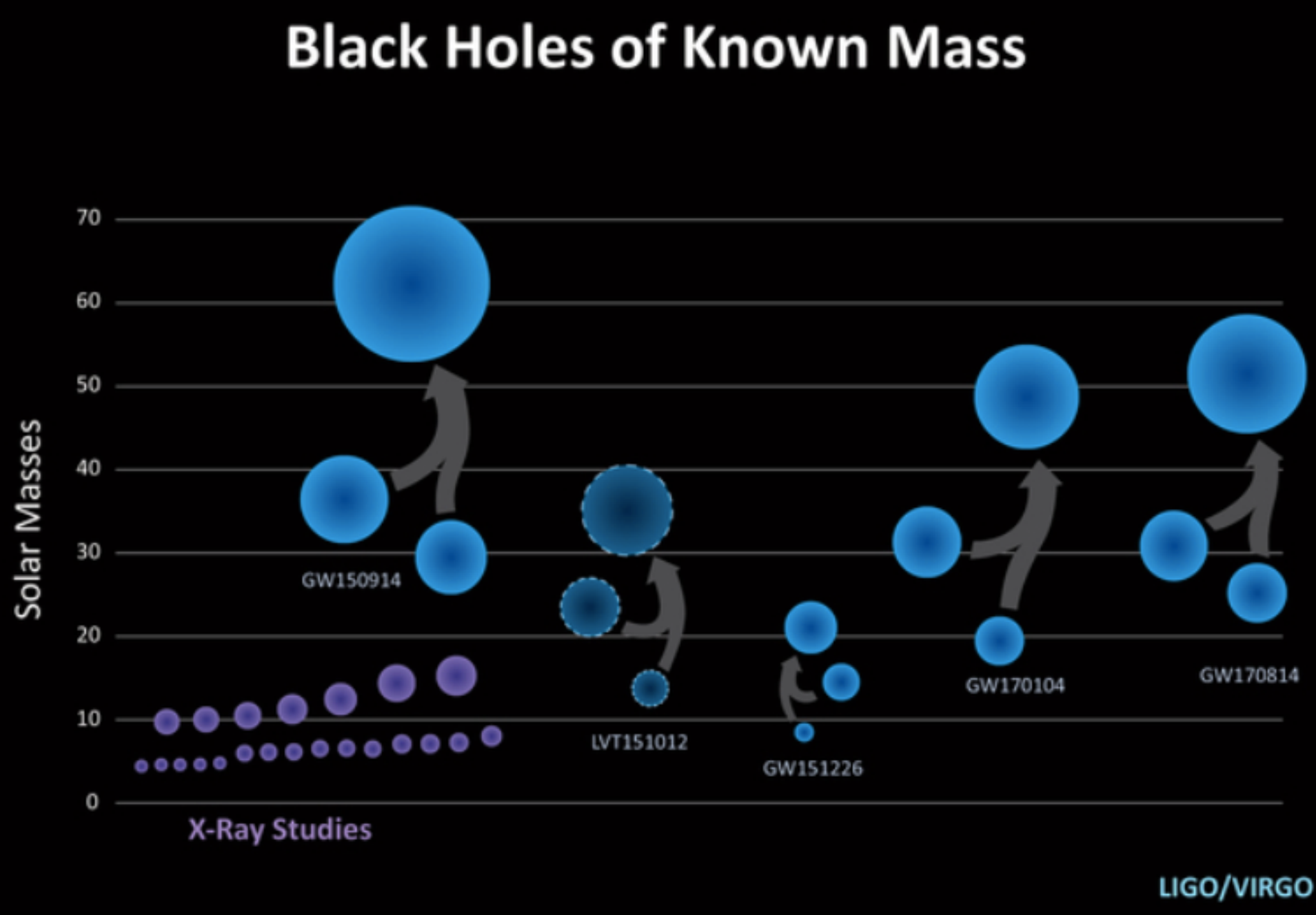


Ilya Mandel
University of Birmingham

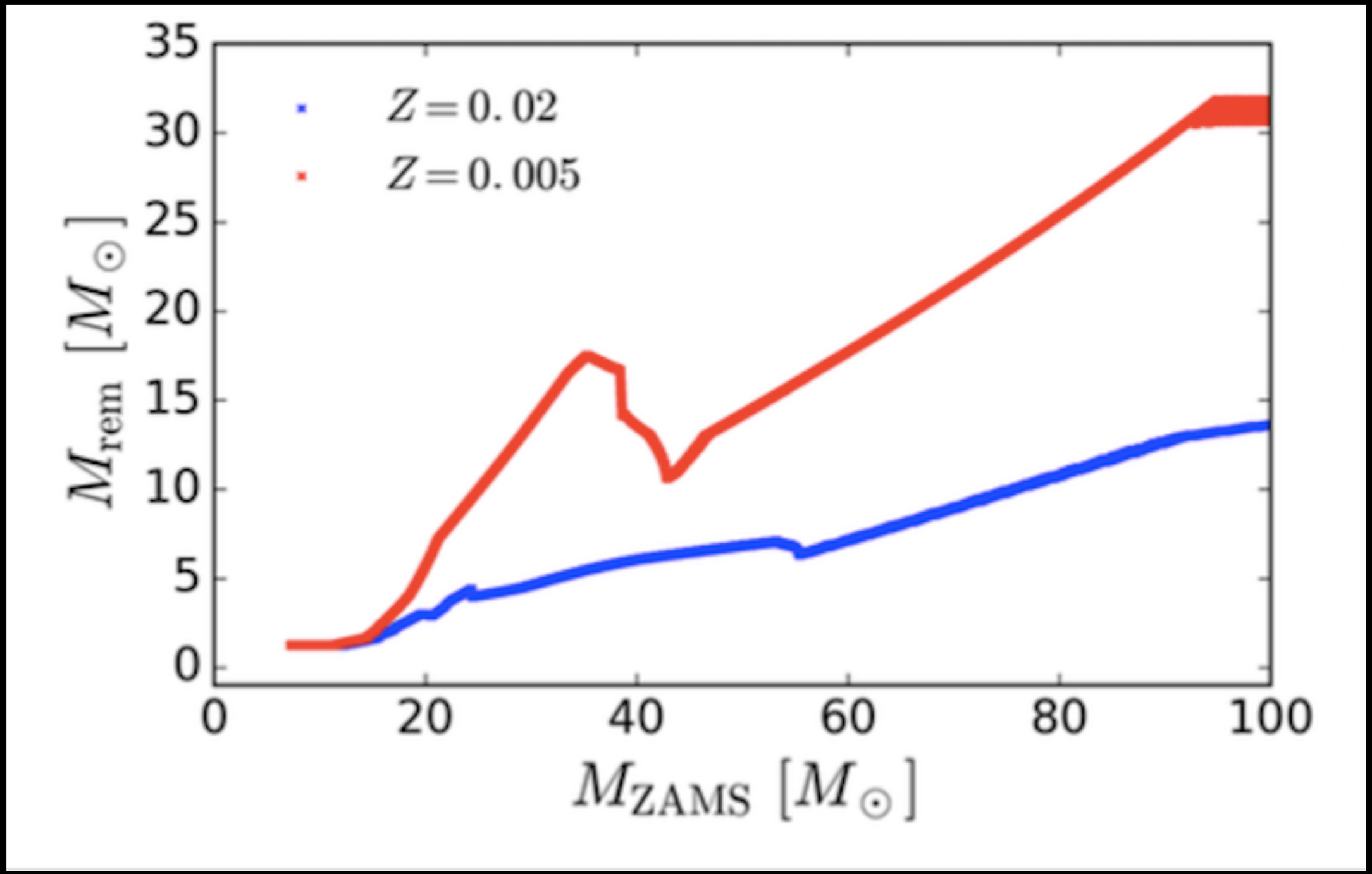


Moore, Berry, Cole

The mass problem



The mass problem



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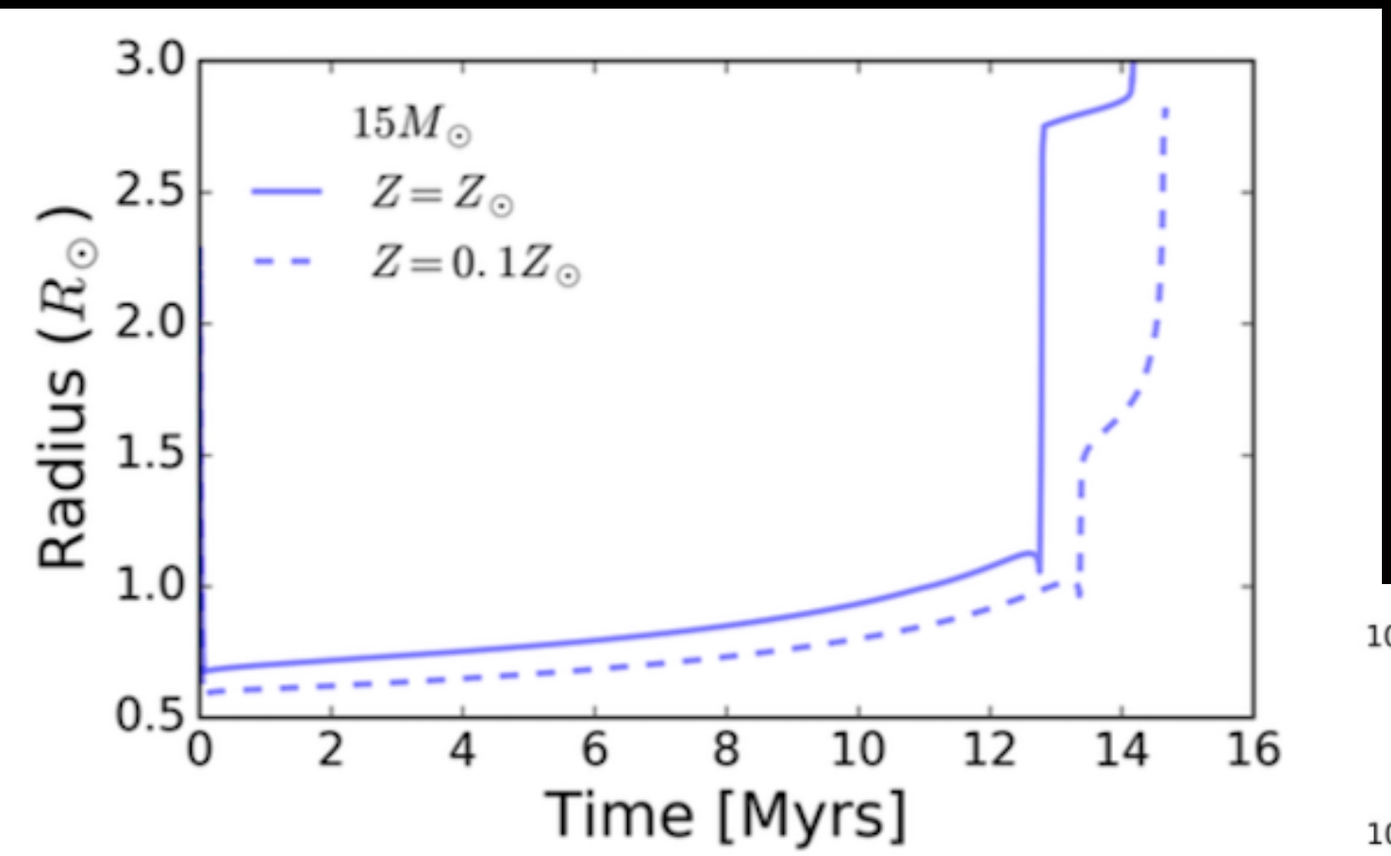
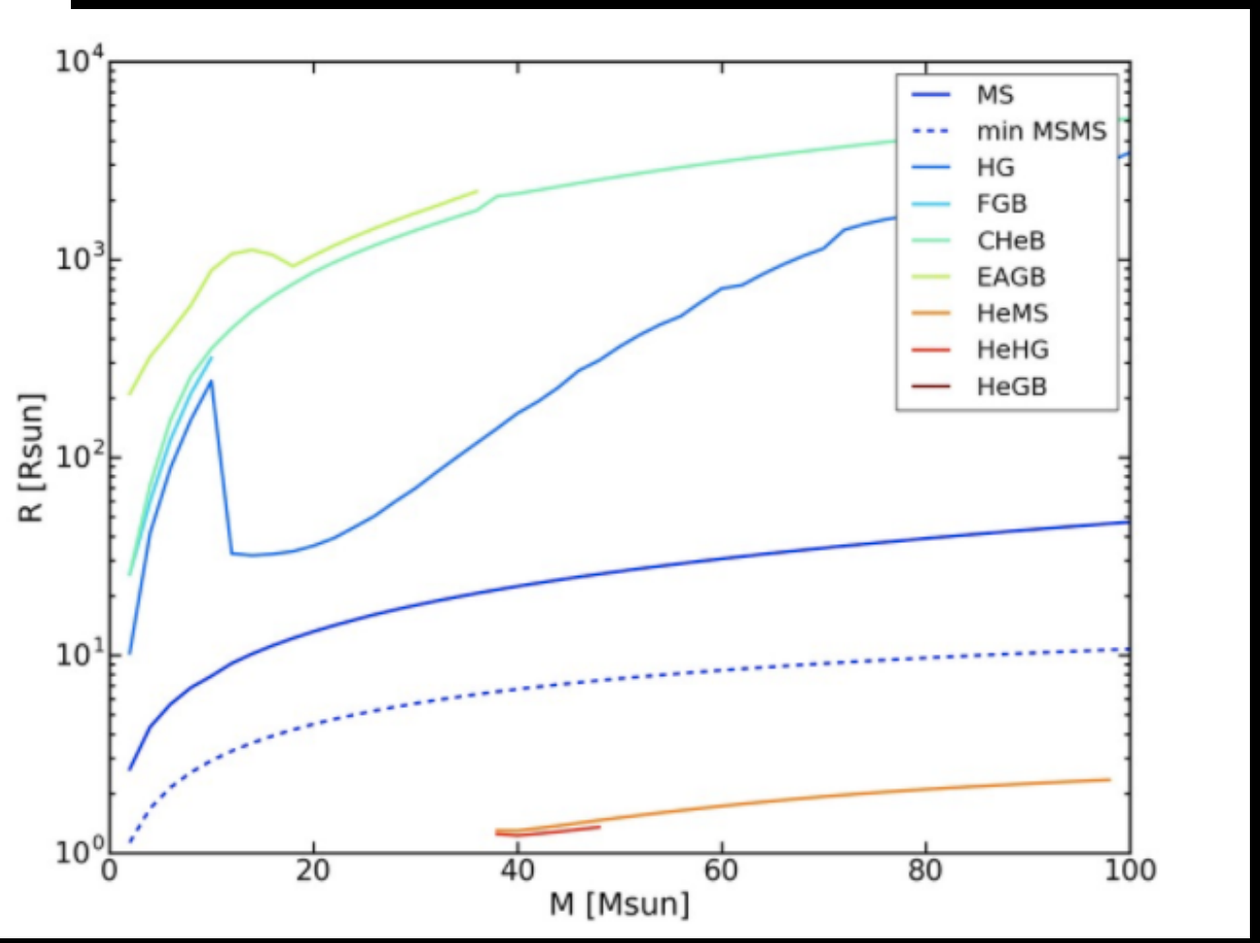
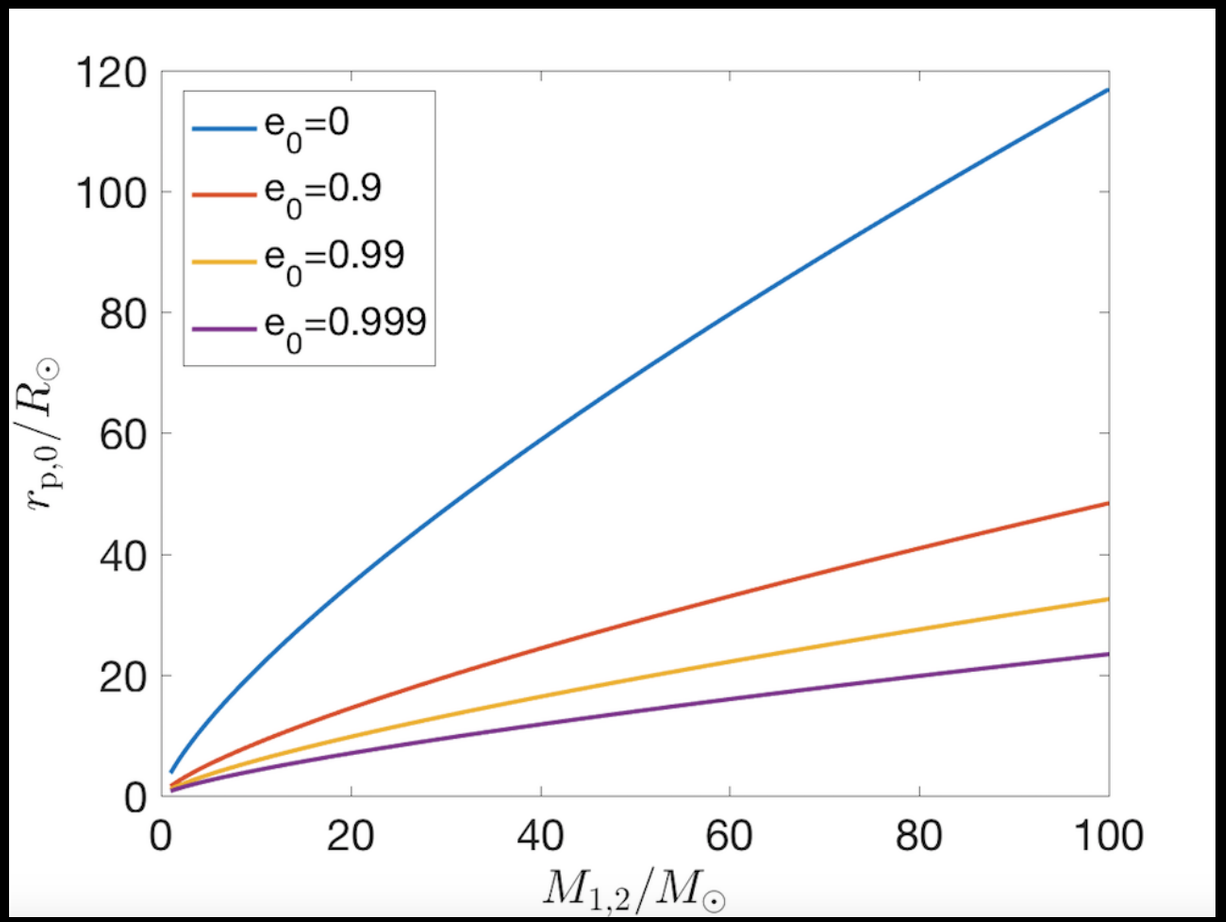
The separation problem

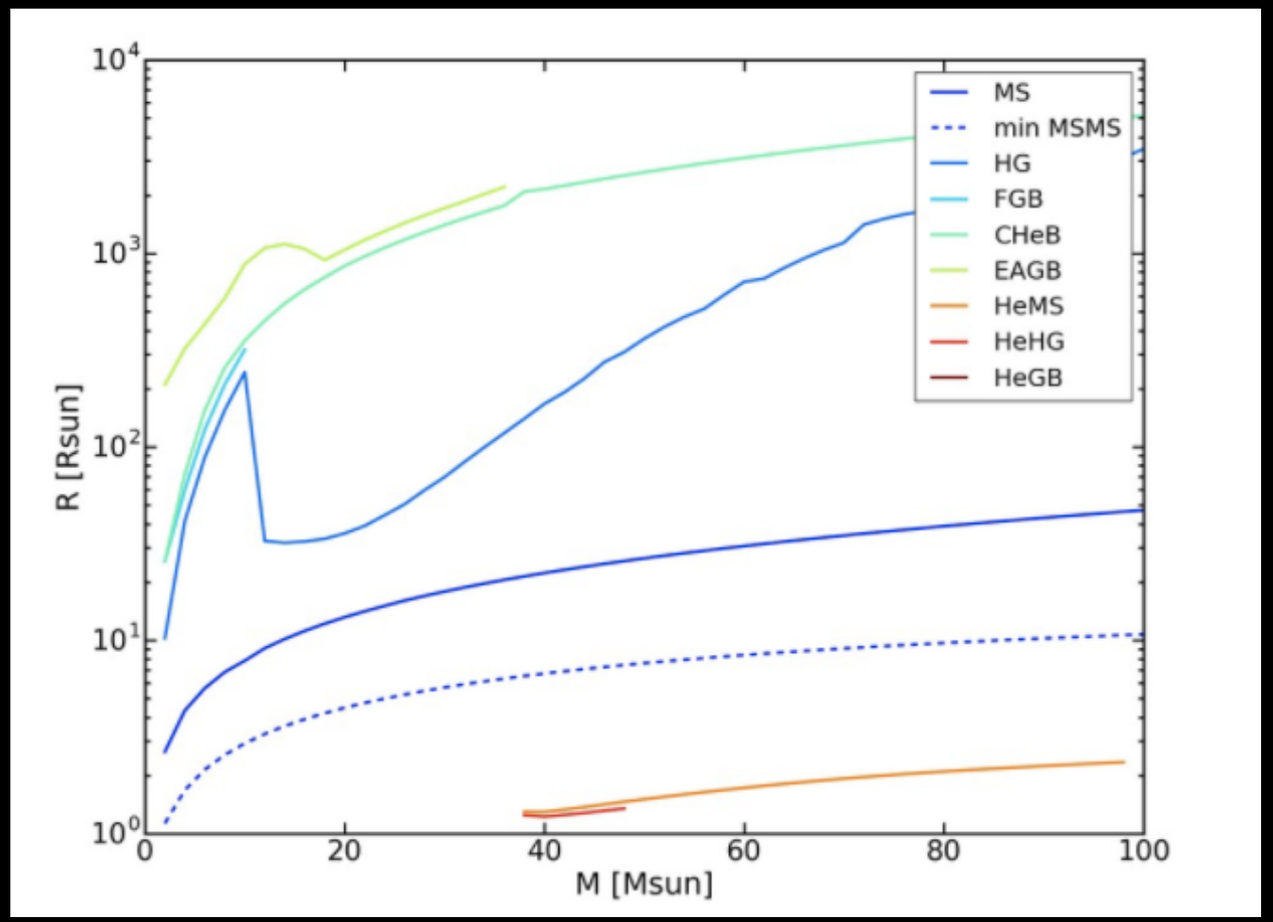


based on Hurley+, 2000



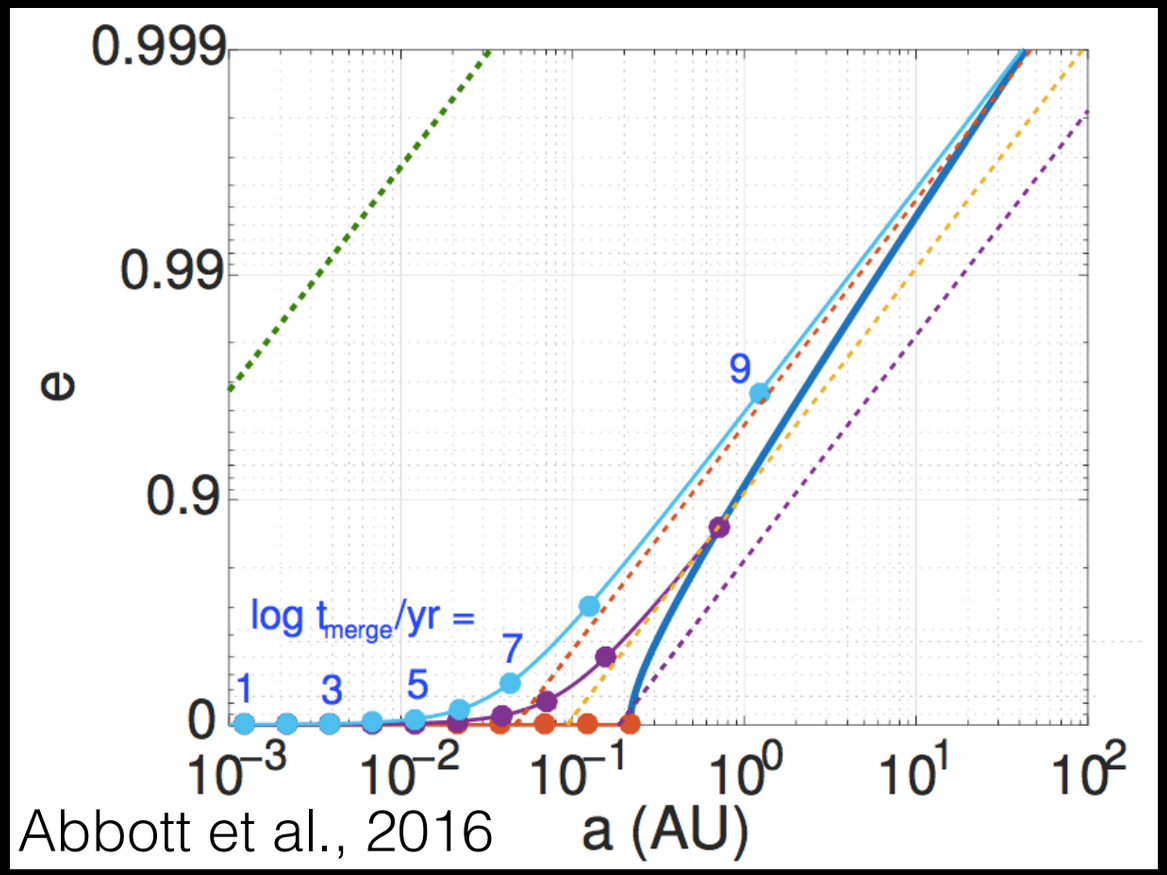
The separation problem



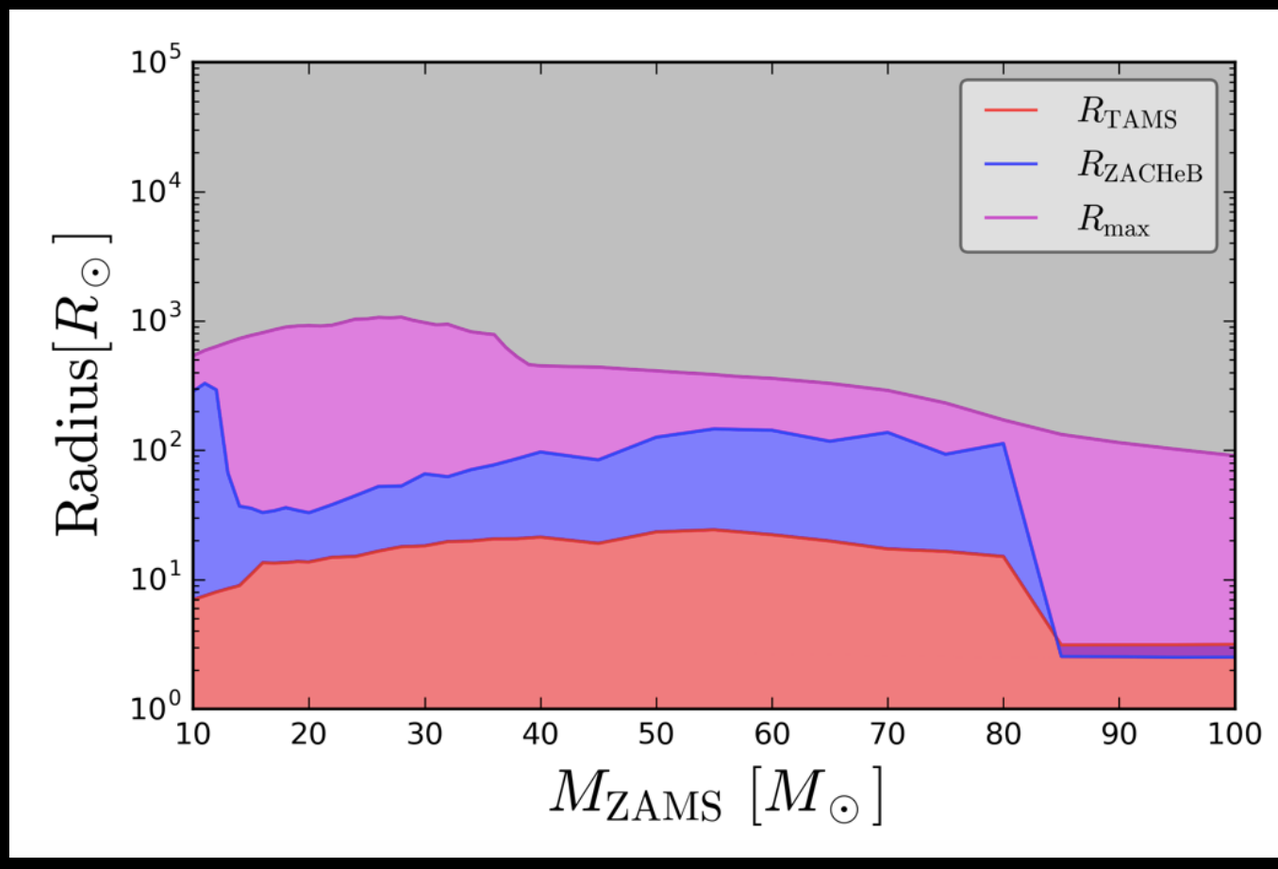


Mandel, in prep.

The separation problem

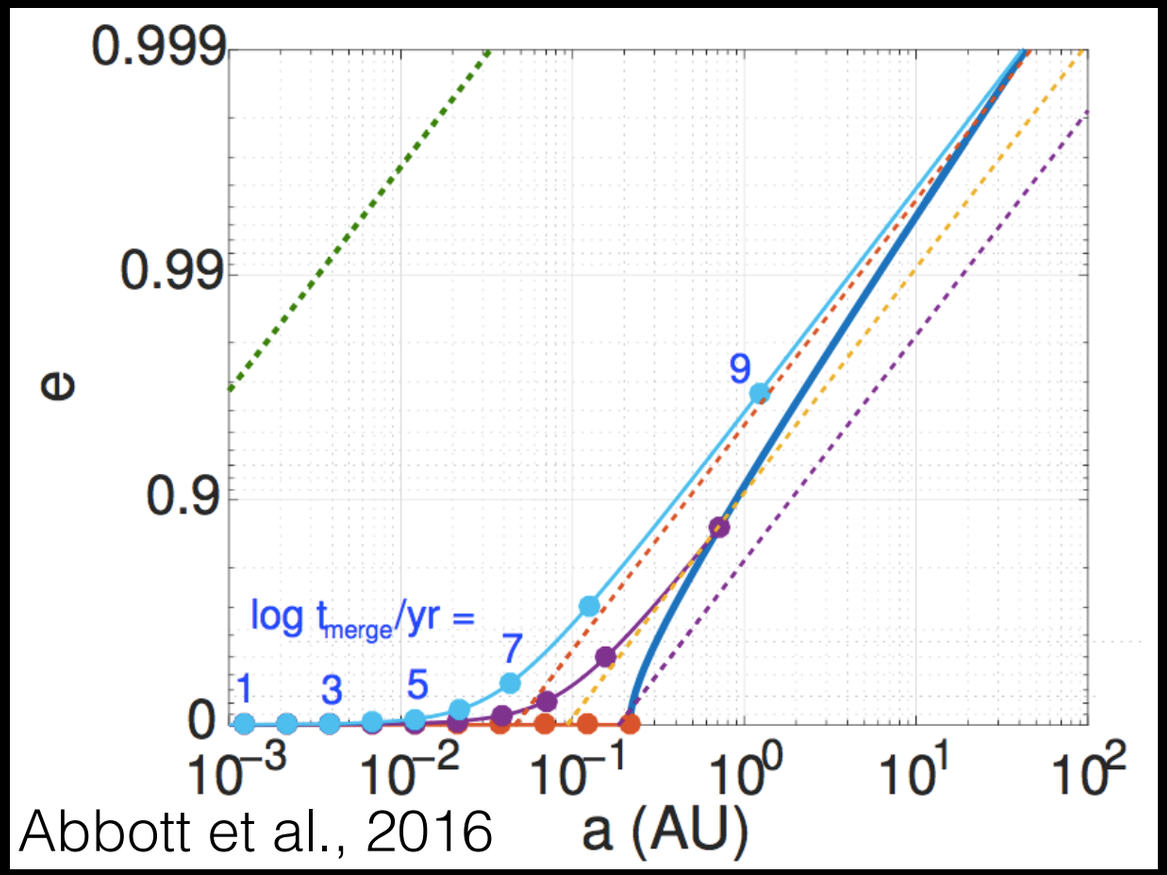


Abbott et al., 2016

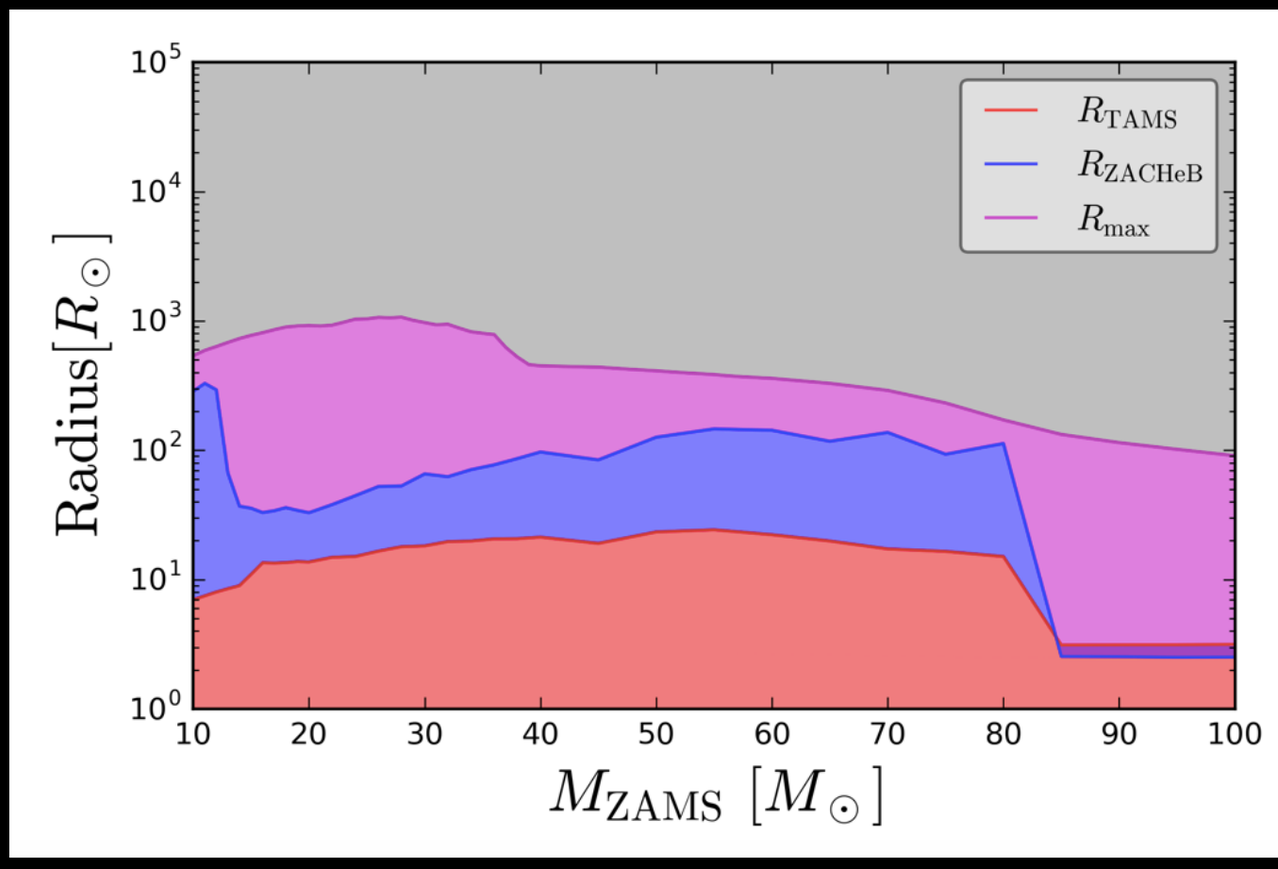


- Harden the binary after stars evolved
- Don’t let stars expand
- Let stars evolve before they make a binary

The separation problem



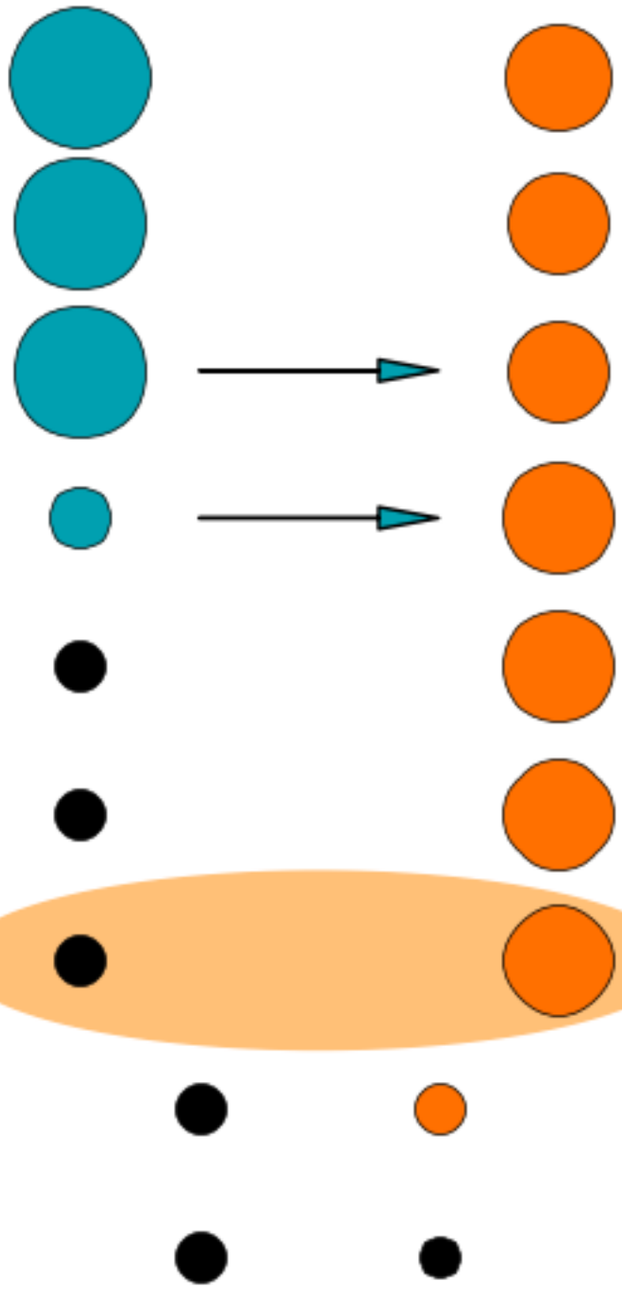
Abbott et al., 2016



- Harden the binary after stars evolved: classical binary evolution via a common envelope
  - Tutukov & Yungelson 1973, 1993; Lipunov, Postnov & Prokhorov (1997), Bethe & Brown (1998), Bloom, Sigurdsson & Pols (1999), De Donder & Vanbeveren (2004), Grishchuk et al. (2001), Nelemans (2003), Voss & Tauris (2003), Pfahl, Podsiadlowski & Rappaport (2005), Dewi, Podsiadlowski & Sena (2006), Kalogera et al. 2007; O'Shaughnessy et al. (2008), Mennekens & Vanbeveren (2014), Dominik et al. (2012, 2013, 2015), Belczynski et al. 2016, Eldridge & Stanway (2016), Lipunov+ (2016), …

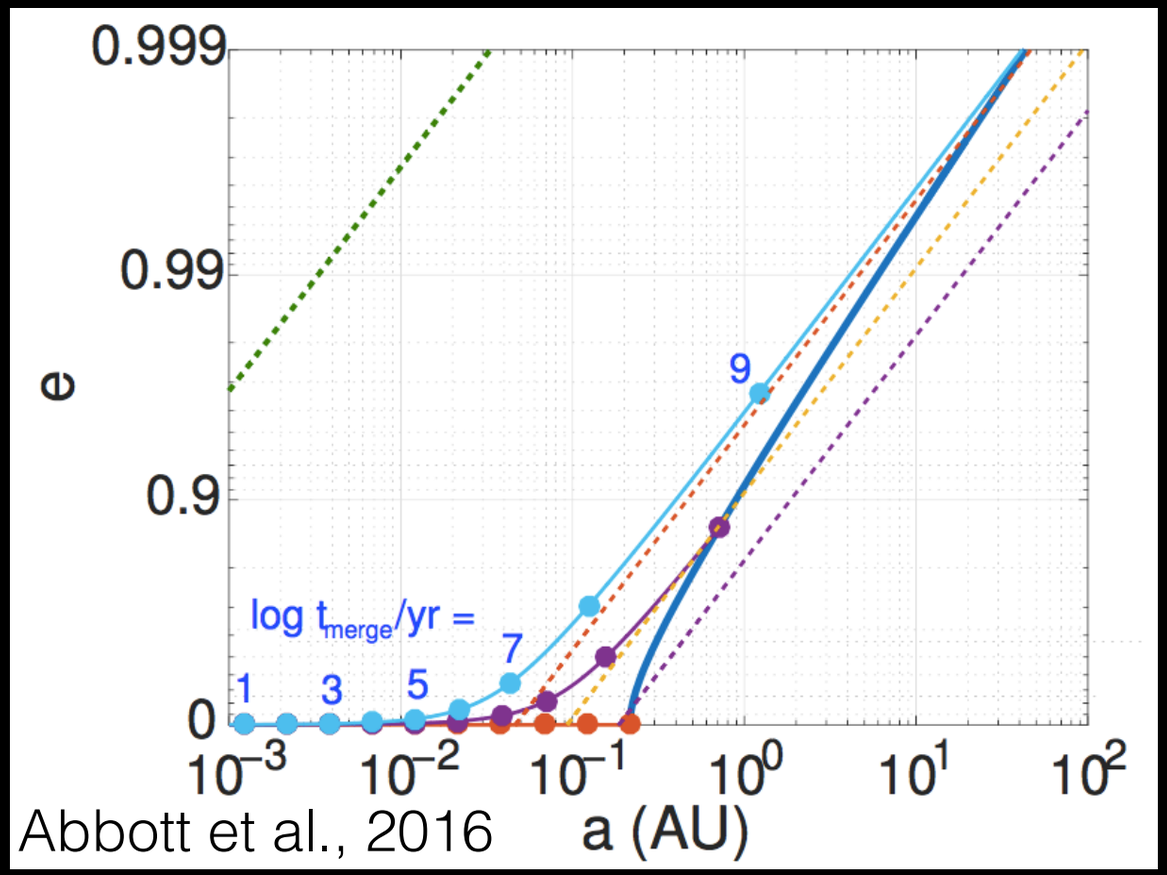
Isolated binary evolution

Time (Myr)	Mass 1 ($M_\odot$)		Mass 2 ($M_\odot$)		$a(R_\odot)$
0.0	MS	99.5	MS	75.8	2262.9
3.517	HG	95.2	MS	73.8	2348.5
3.5185	HG	95.0	MS	73.8	2351.1
3.5185	HeMS	43.3	MS	79.7	4031.5
3.8098	BH	34.3	MS	79.2	4372.8
4.0664	BH	34.3	HG	78.7	4391.4
4.0687	BH	34.3	CHeB	78.4	4402.3
4.0689	BH	34.3	HeMS	34.9	34.4
4.393	BH	34.3	BH	28.1	38.2

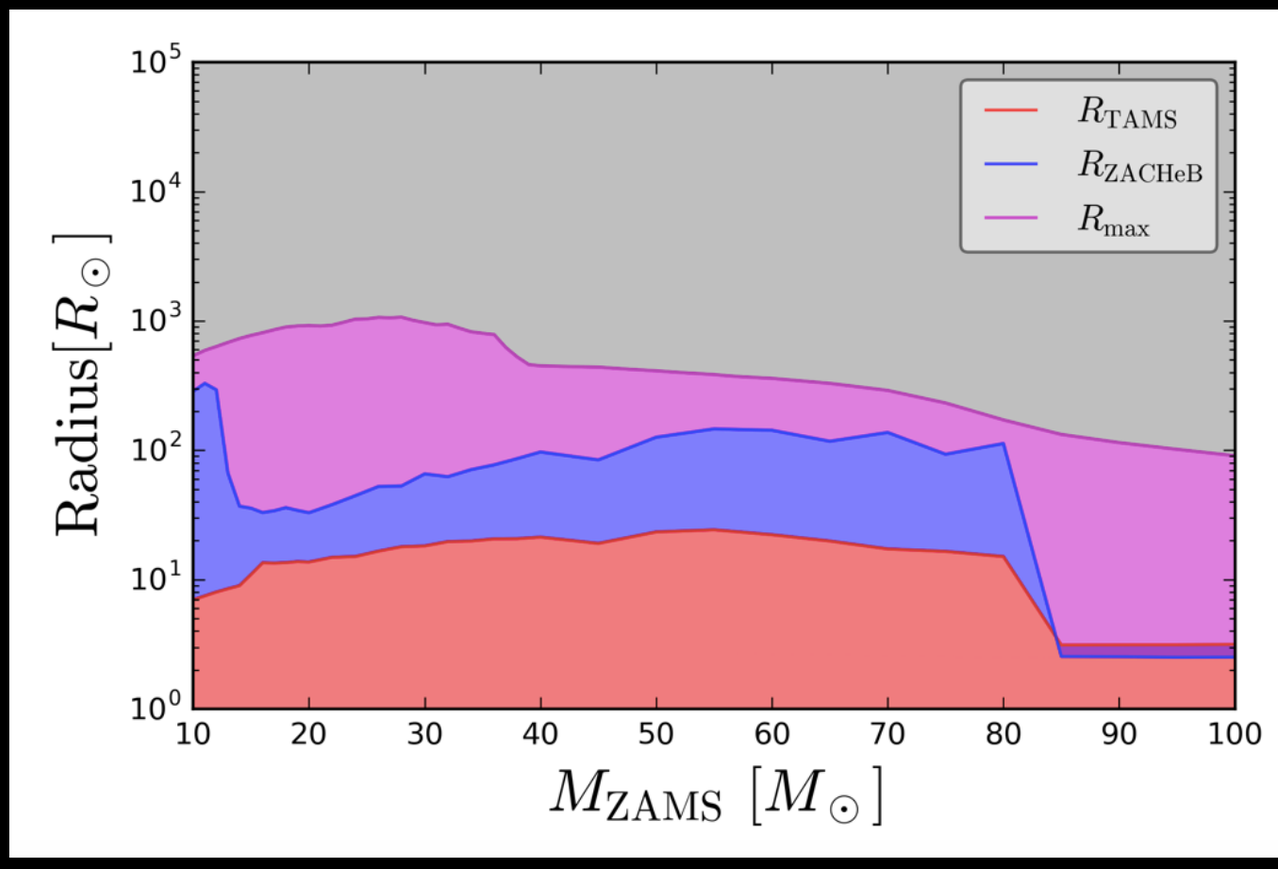


Stevenson, Vigna Gomez, Mandel+, Nat Comm, 2017

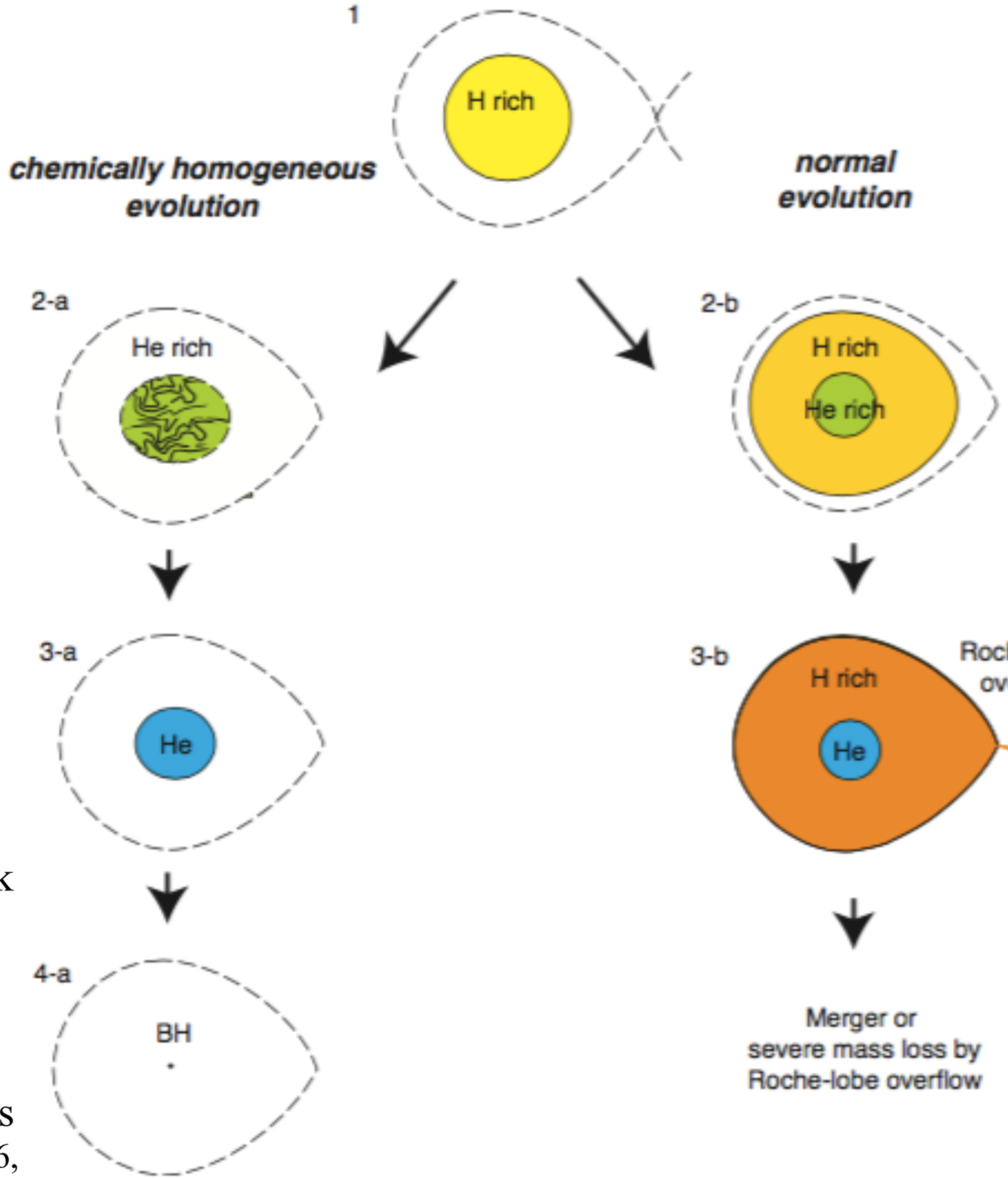
The separation problem



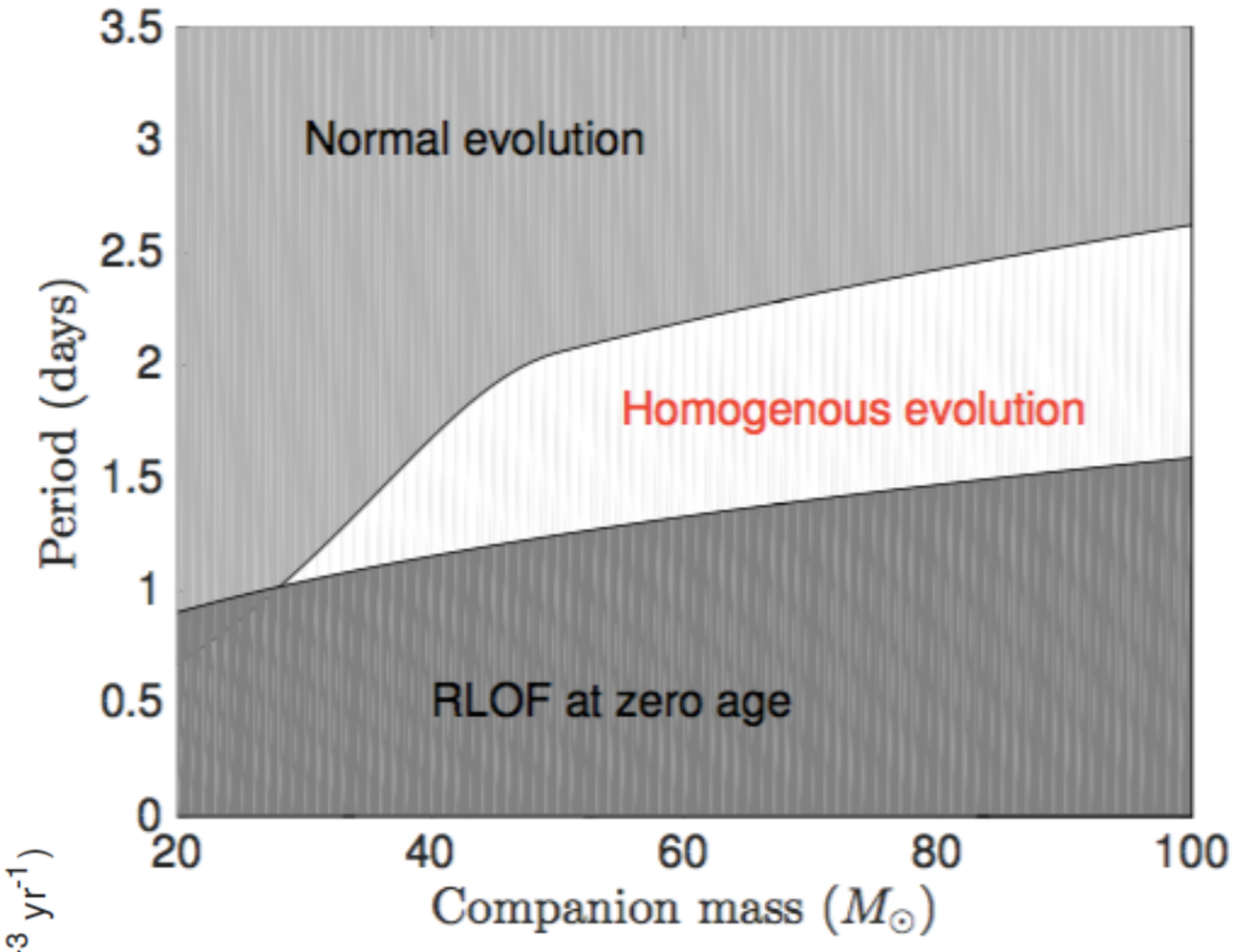
Abbott et al., 2016

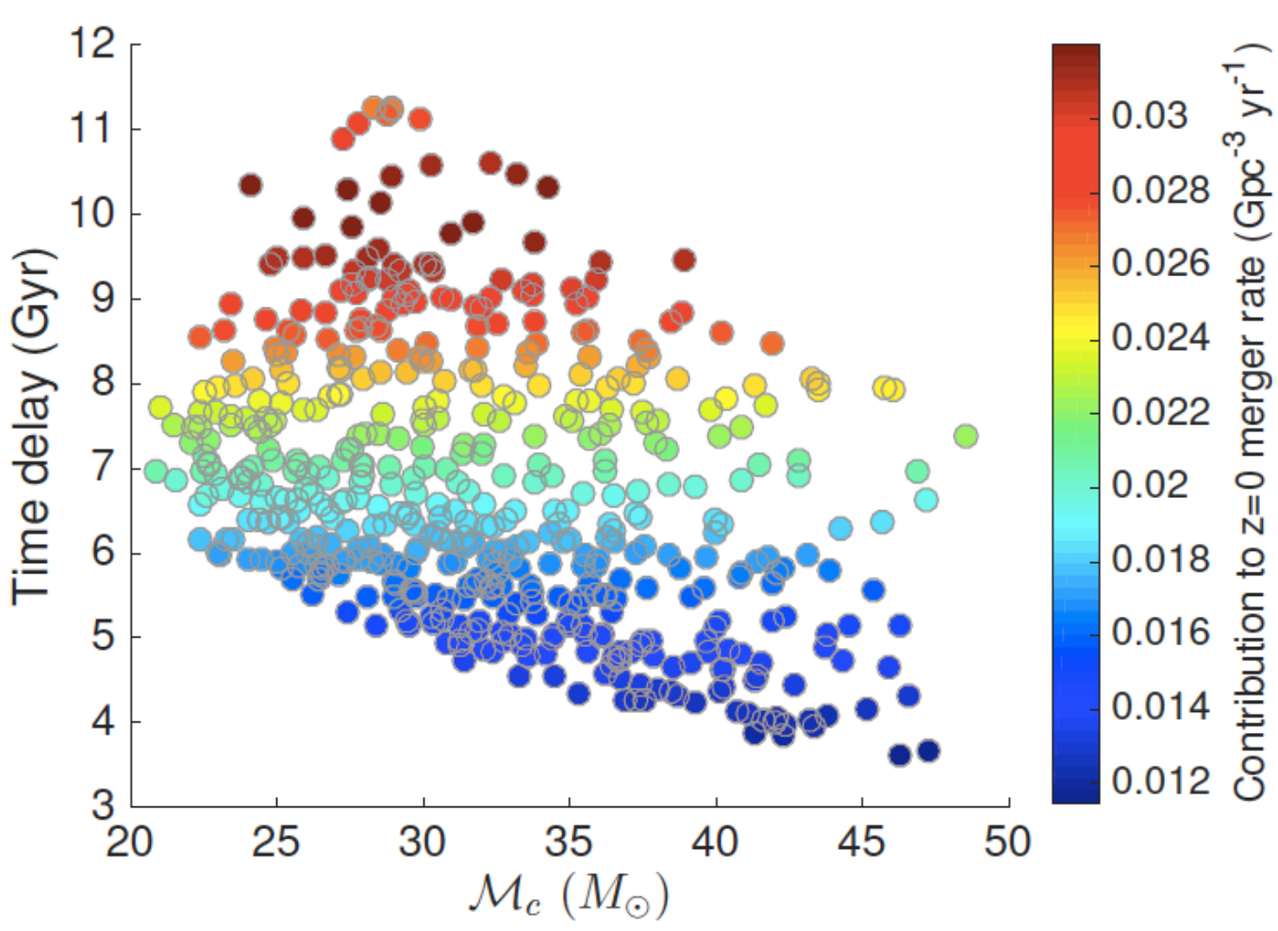


- Harden the binary after stars evolved
- Don’t let stars expand: chemically homogeneous evolution
  - Mandel & de Mink, 2016; Marchant+, 2016; de Mink & Mandel, 2016
- Let stars evolve before they make a binary

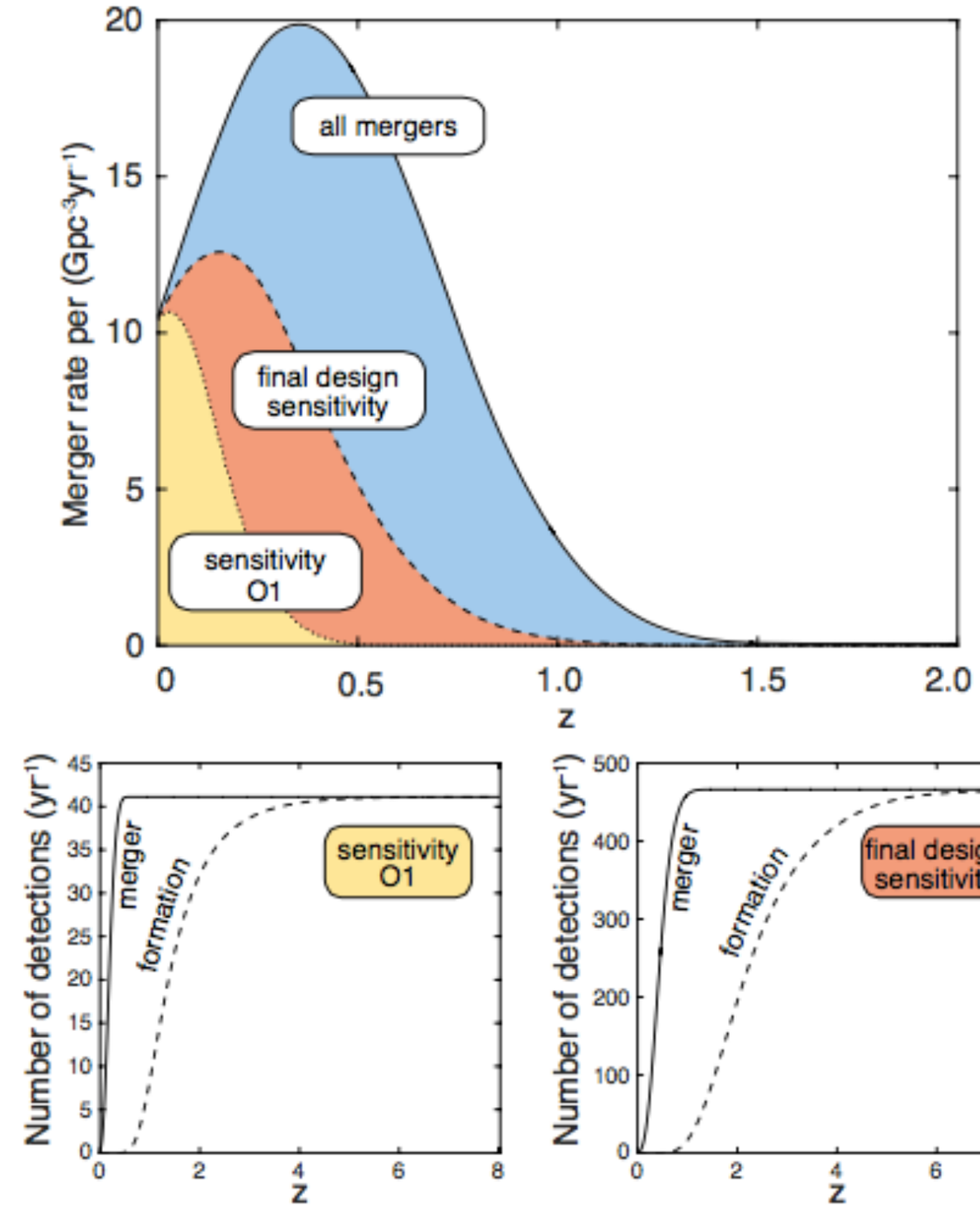


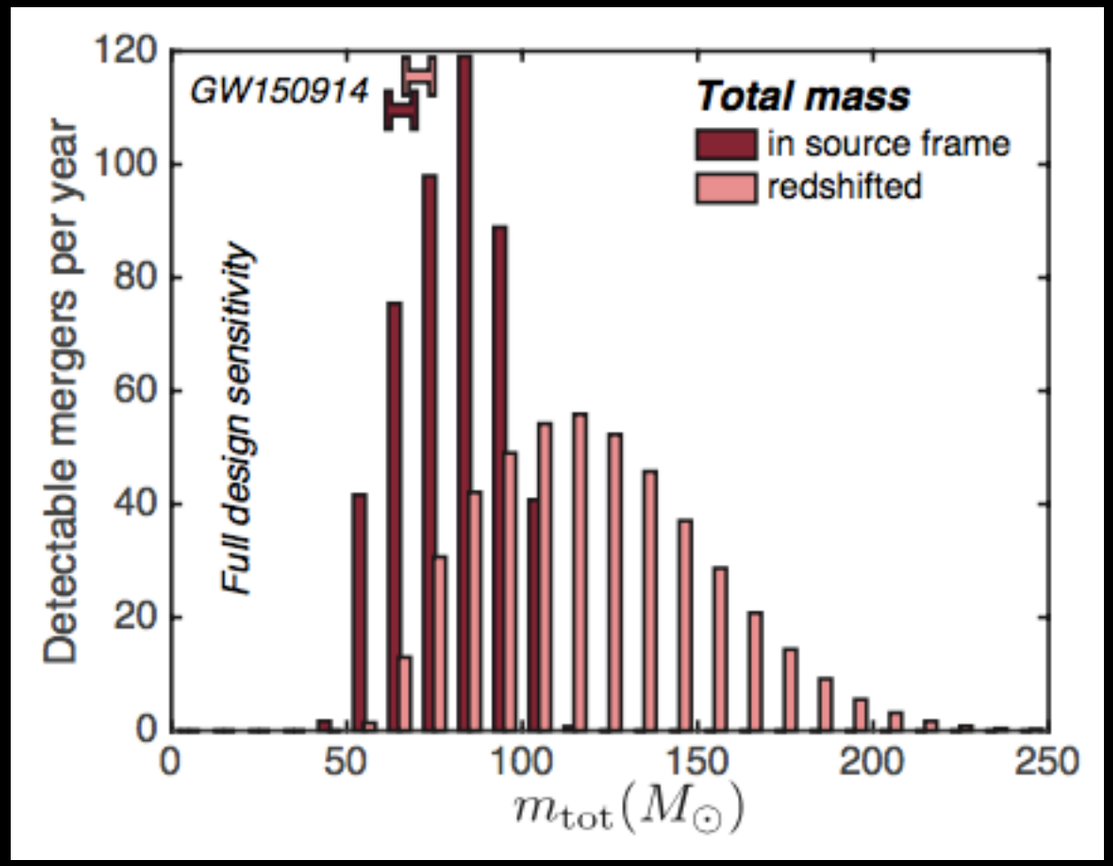
Merging binary black holes formed through chemically homogeneous evolution in short-period stellar binaries [Mandel & de Mink,2016, after de Mink+, 2009]

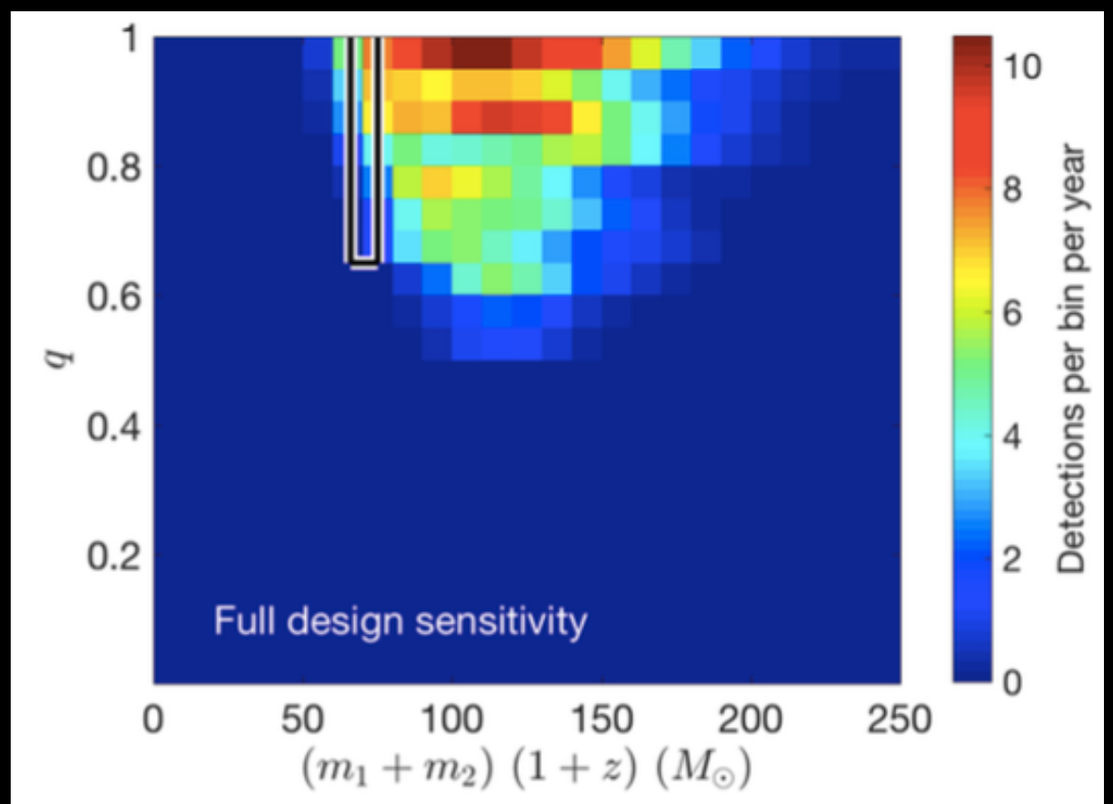




Mandel & de Mink, 2016

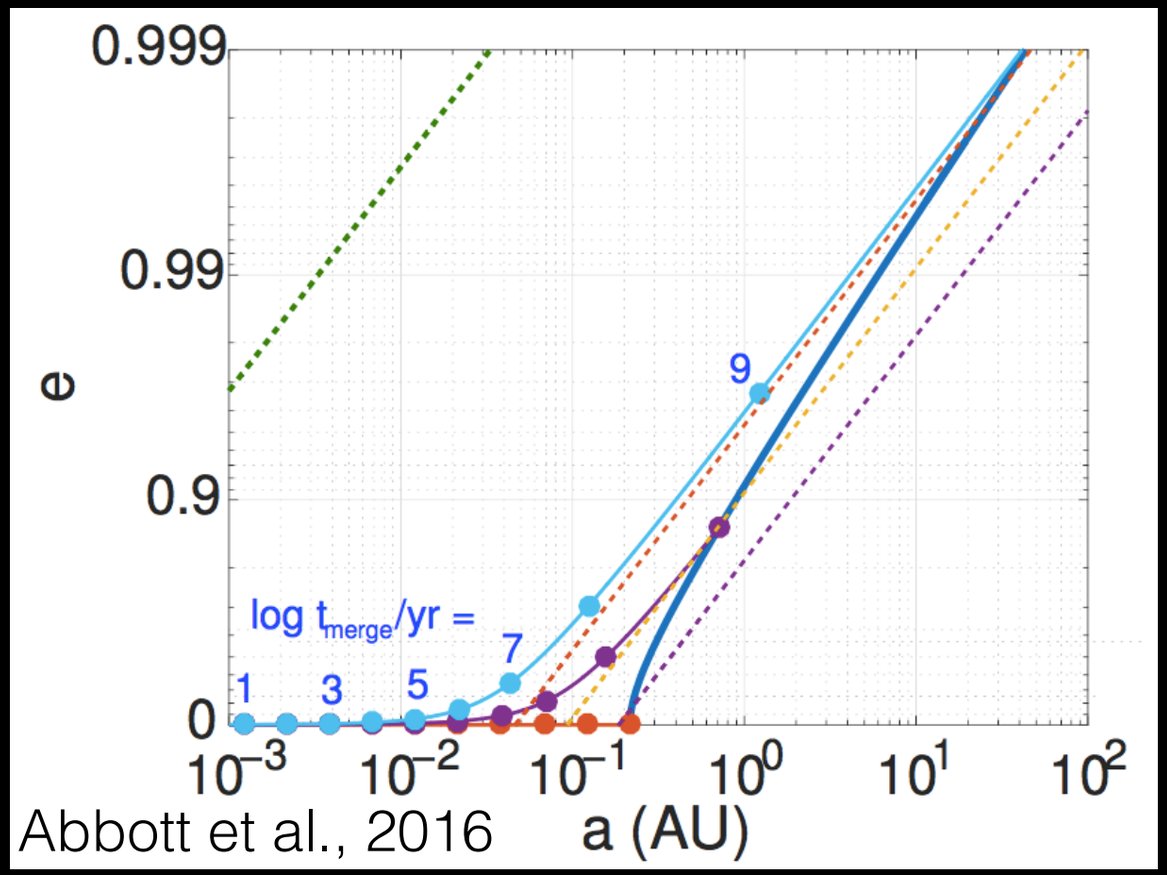




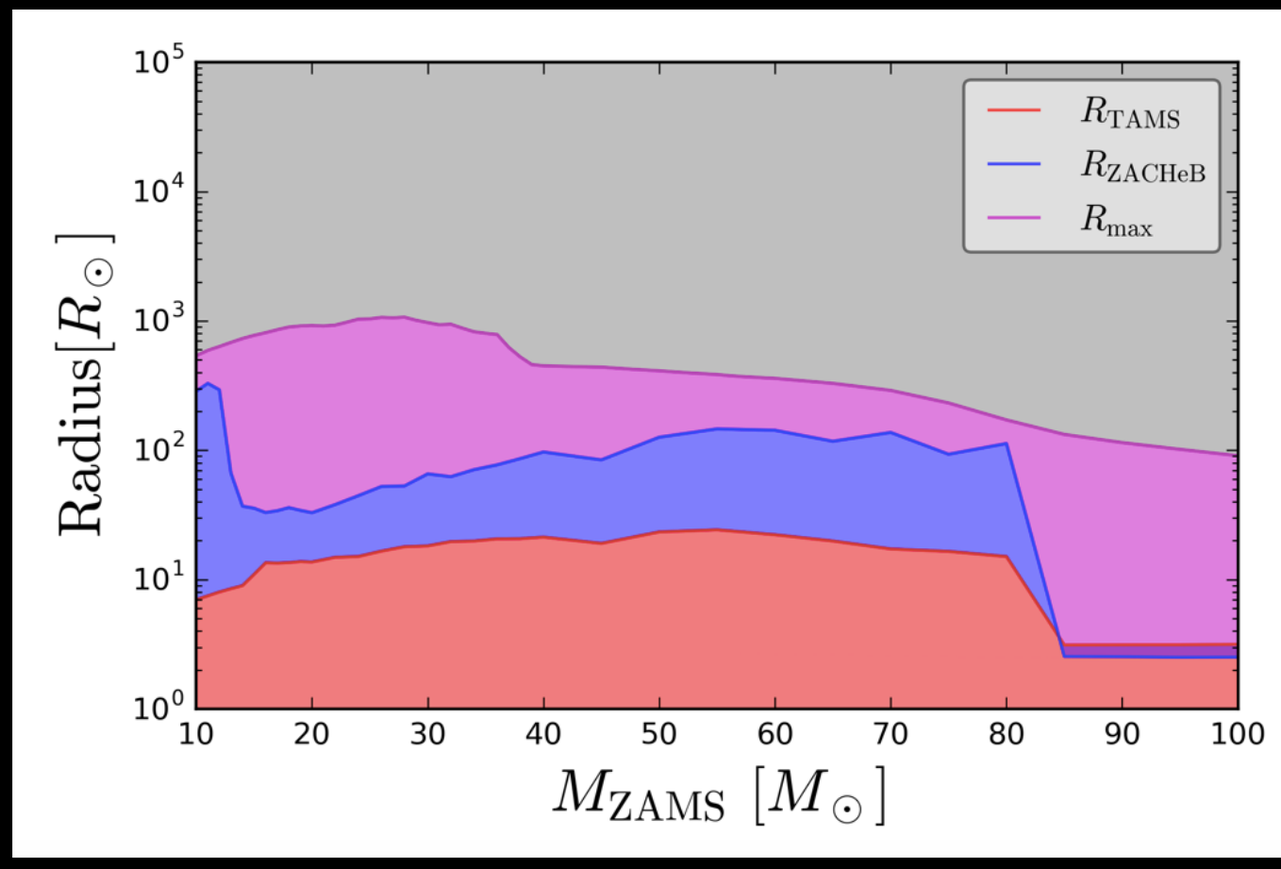


de Mink & Mandel, 2016

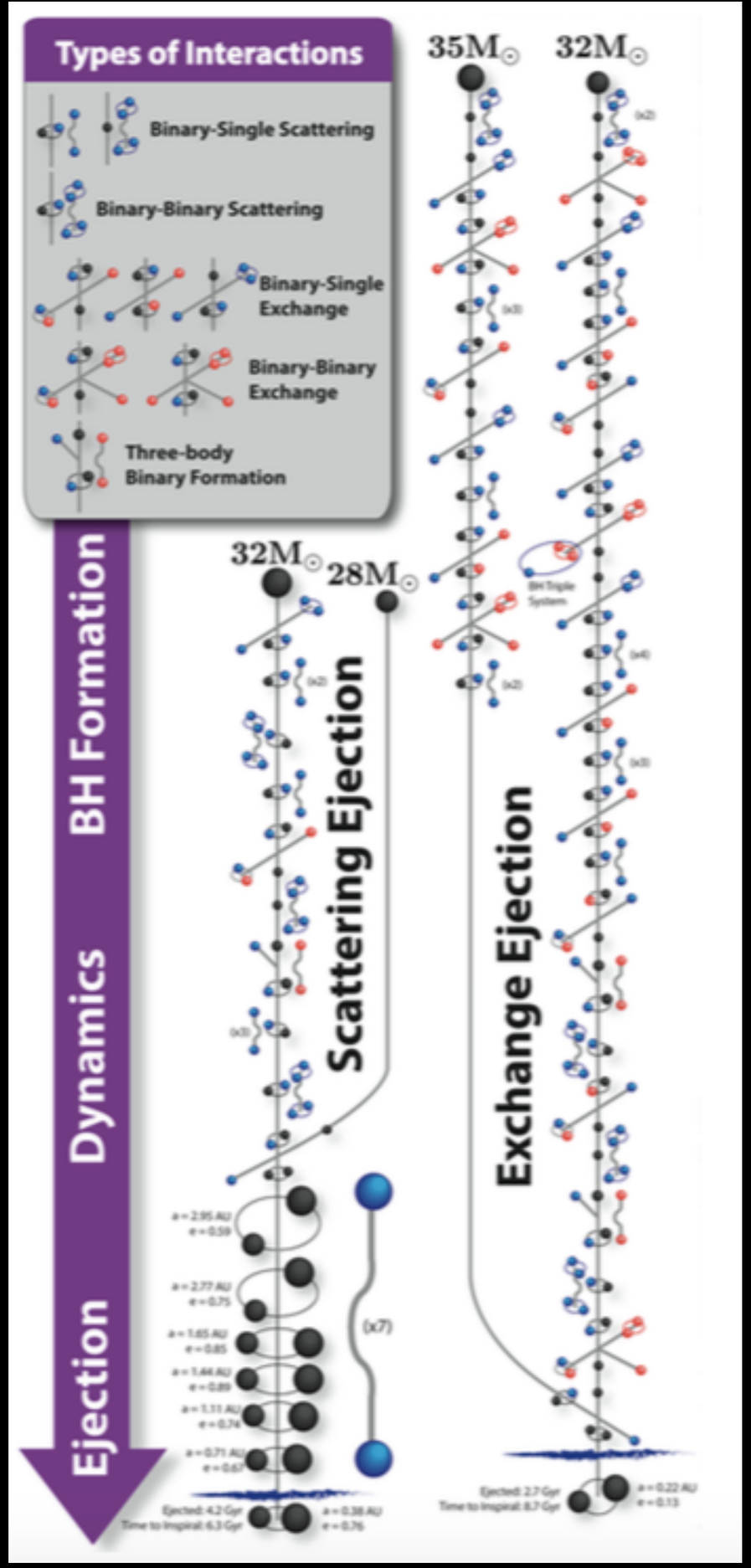
The separation problem



Abbott et al., 2016



- Let stars evolve before they make a binary: dynamical formation in clusters
  - Stellar and globular clusters: Sigurdsson & Hernquist (1993); Kulkarni+ (1993); Portegies Zwart & McMillan (2000); Gultekin+ (2004, 2006); Kocsis+ (2006); O'Leary+ (2006, 2007, 2016); Sadowski+ (2008); Banerjee+ (2010); Downing+ (2010, 2011); Morscher+ (2013, 2015); Mapelli+ (2016); Rodriguez+ (2015, 2016)
  - Galactic nuclear clusters: Miller & Lauburg (2009); O'Leary+ (2009); Kocsis & Levin (2012); Tsang (2013); Bae+ (2014); Bartos+ (2016); Stone+ (2016)



Rodriguez, Haster+, (2016)

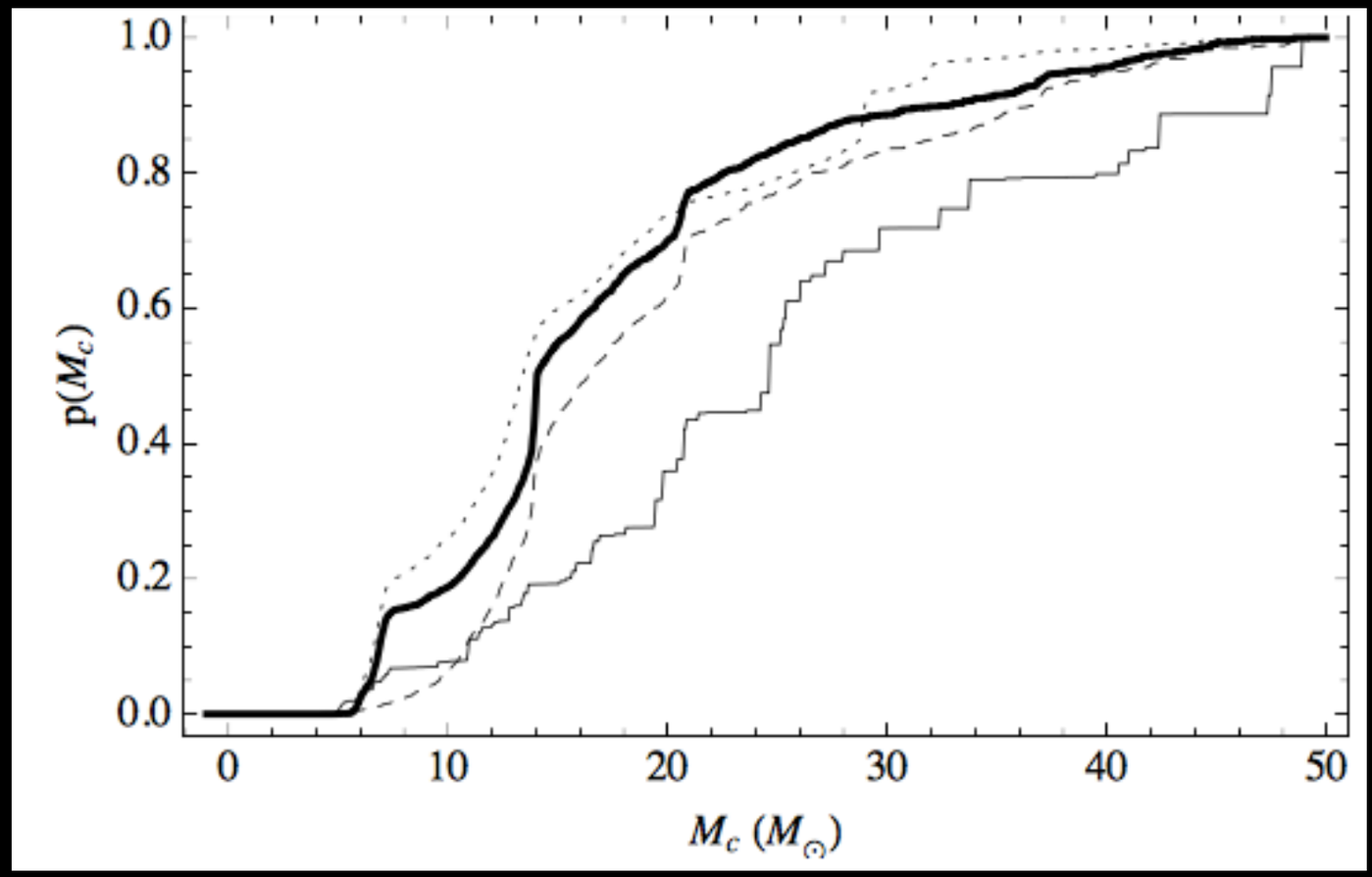
Are predictions borne out?

TABLE IV: Compact binary coalescence rates per Mpc^3 per Myr.[a]

Source	R_{low}	R_{re}	R_{high}	R_{max}
NS-NS (Mpc^{-3} Myr^{-1})	0.01 [1]	1 [1]	10 [1]	50 [16]
NS-BH (Mpc^{-3} Myr^{-1})	6×10^{-4} [18]	0.03 [18]	1 [18]	
BH-BH (Mpc^{-3} Myr^{-1})	1×10^{-4} [14]	0.005 [14]	0.3 [14]	

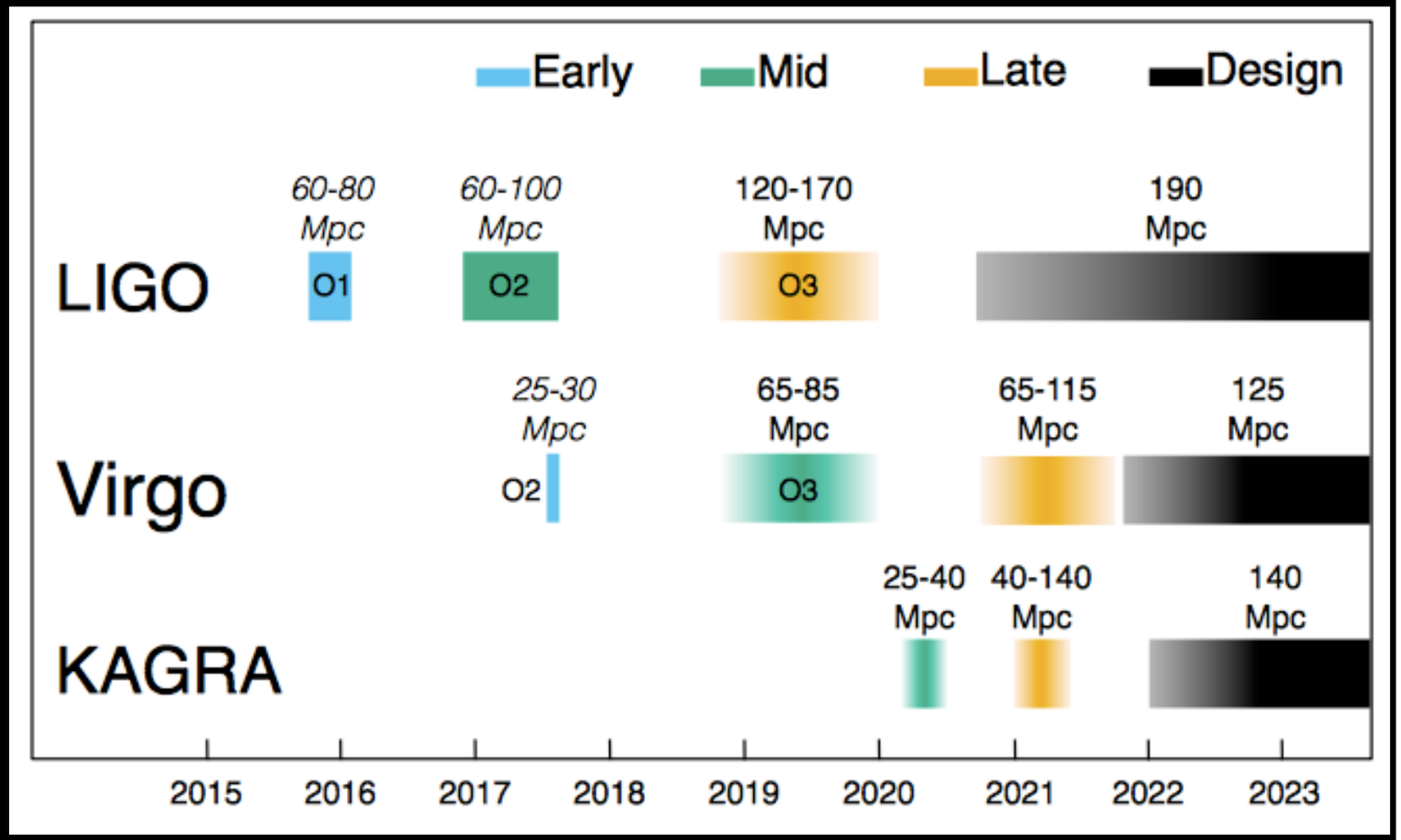
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

Abadie+ (2010)



Dominik+, 2015

Prospects



Abbott+, 2017,
Living Reviews

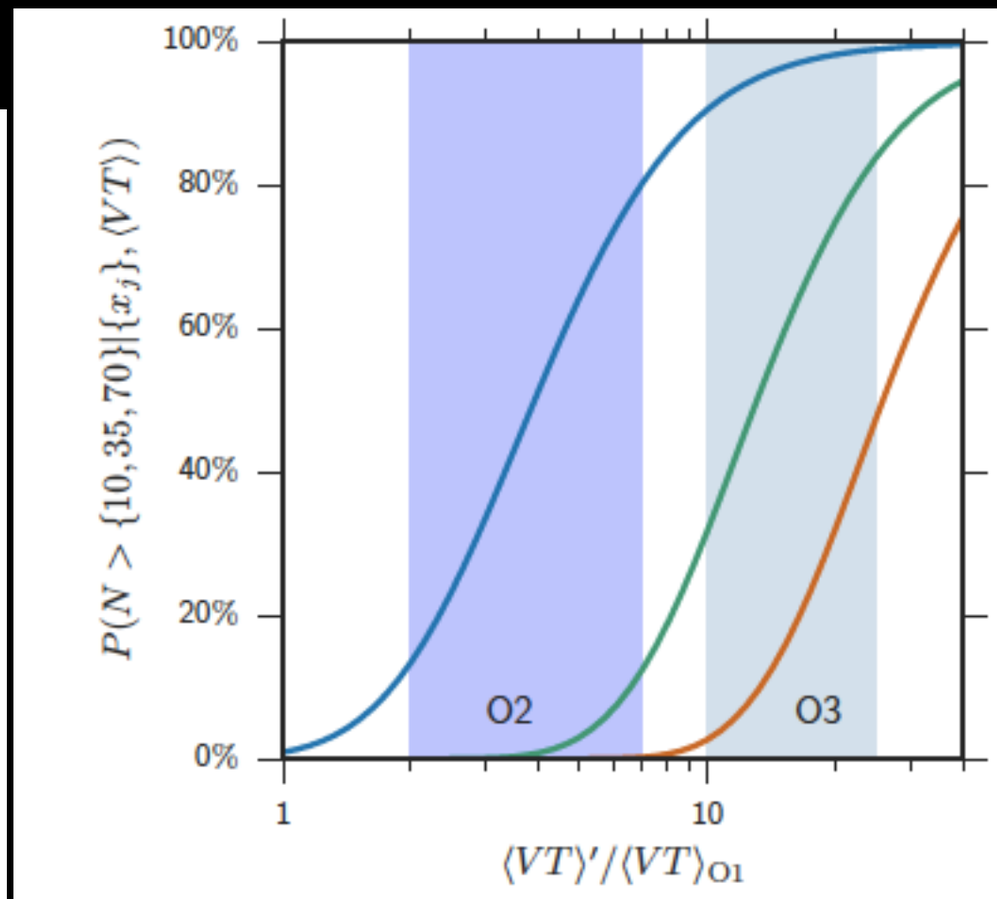


FIG. 12. The probability of observing $N > 10$, $N > 35$, and $N > 70$ highly significant events, as a function of surveyed time-volume. The vertical line and bands show, from left to right, the expected sensitive time-volume for the second (O2) and third (O3) advanced detector observing runs.

Abbott+, 2016

COMPAS

The inverse problem of gravitational-wave astrophysics:
how to go from a population of observed sources to understanding key uncertainties about binary evolution?

COMPAS

Simon Stevenson

Alejandro Vigna Gómez

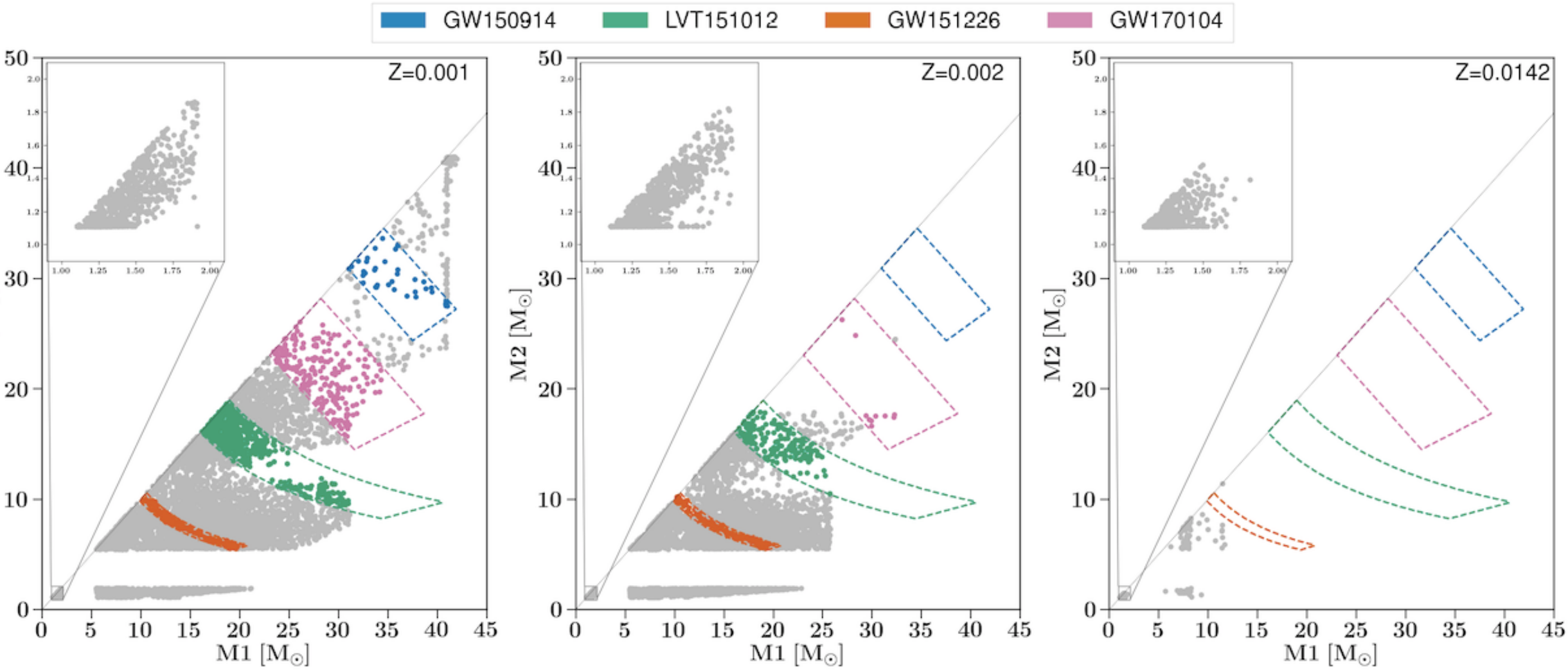
Jim Barrett

Coenraad Neijssel

Key collaborators / consultants: Christopher Berry, Will Farr, Sebastian Gaebel, Selma de Mink, Stephen Justham, Natasha Ivanova, Vicky Kalogera, Chris Belczynski, Gijs Nelemans, Philipp Podsiadlowski…

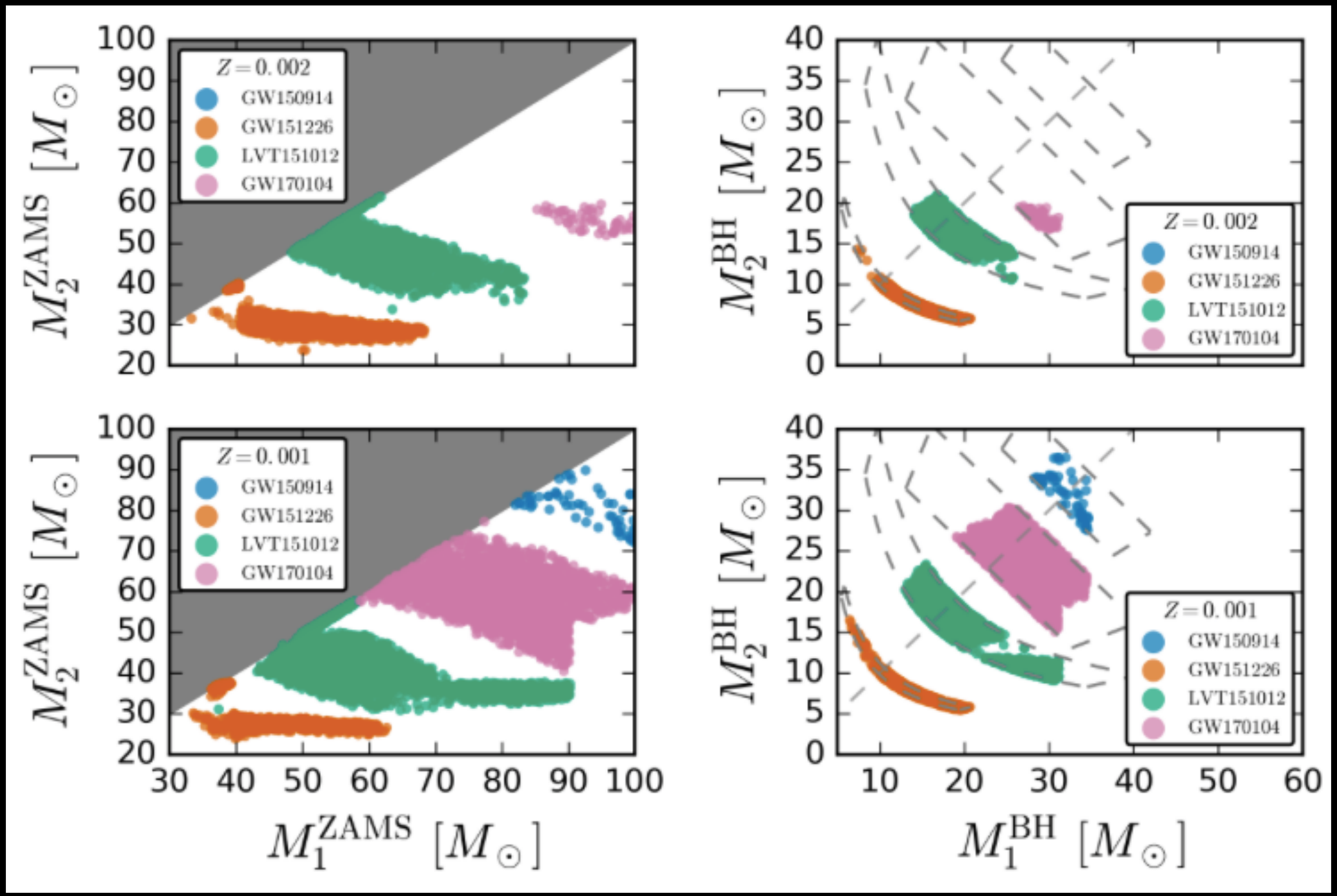
YOUR NAME COULD BE HERE!

Population Synthesis



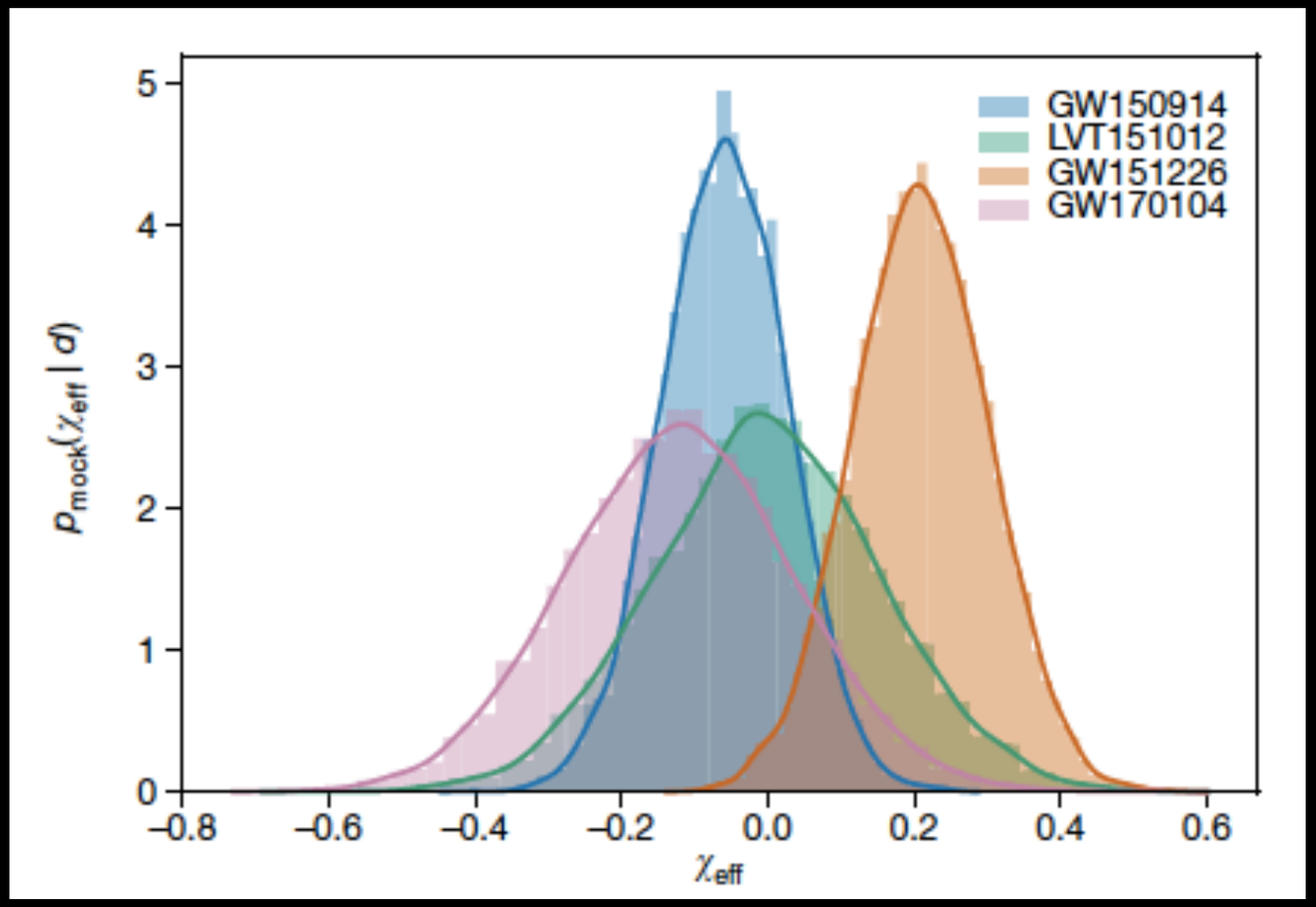
Vigna Gomez+, in prep.

Population Synthesis

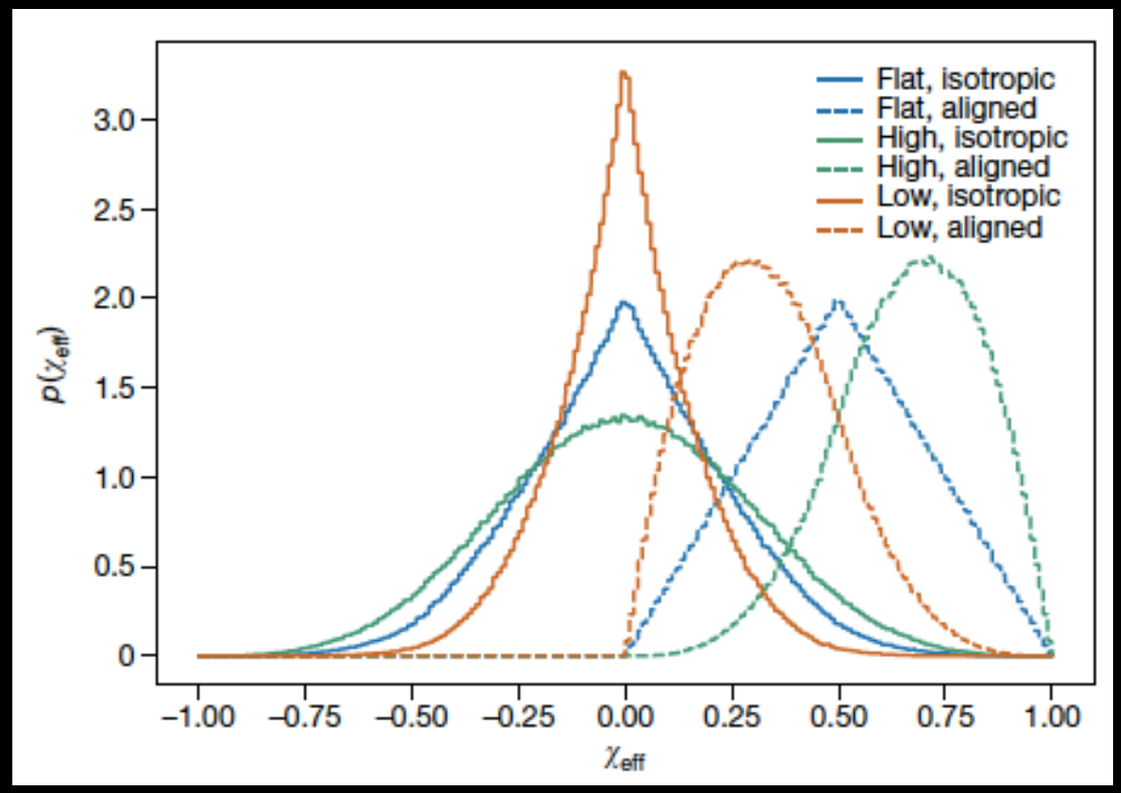


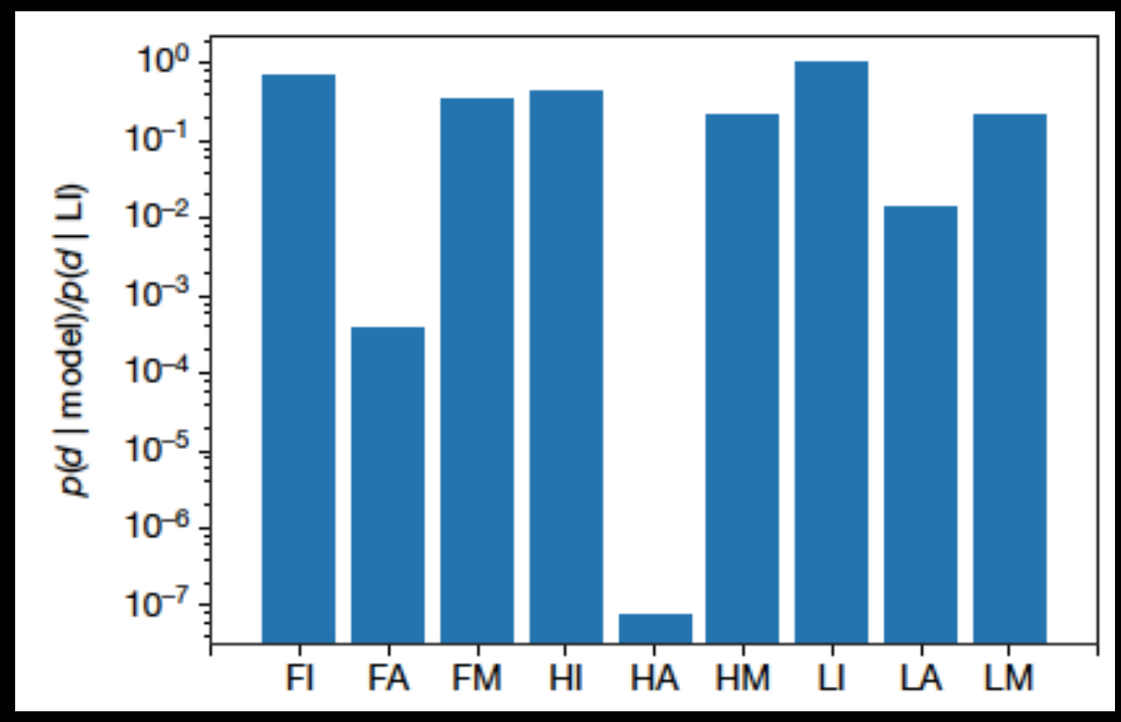
Stevenson, Vigna Gomez, Mandel, Barrett, Neijssel, Perkins, de Mink, 2017

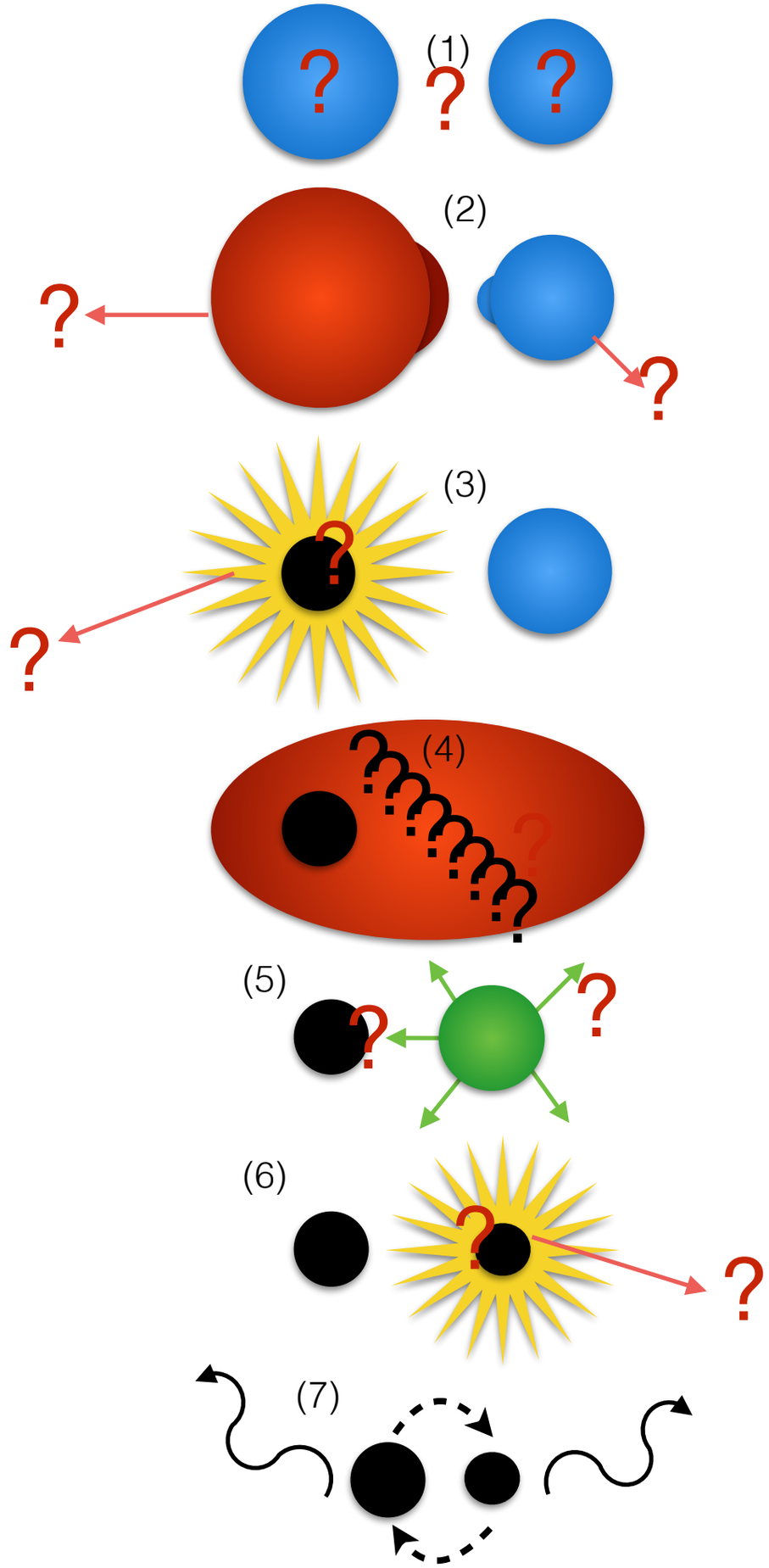
Learning from detections



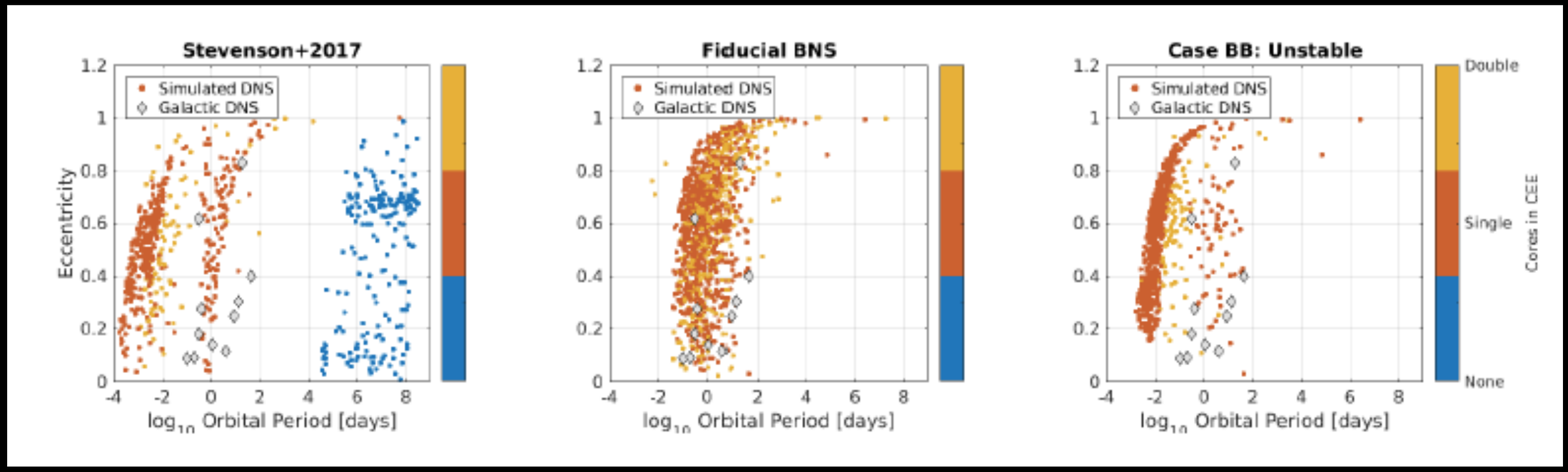
Farr+, Nature, 2017

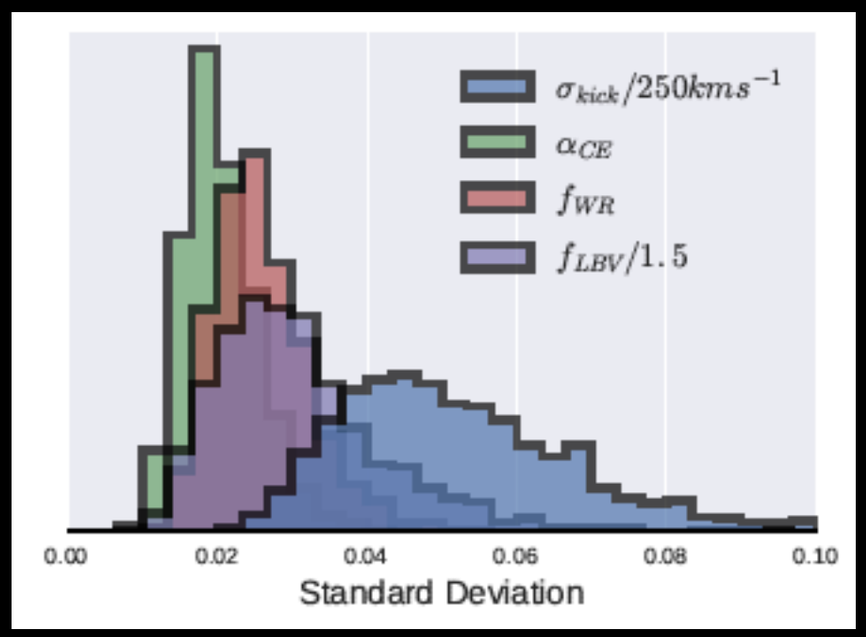


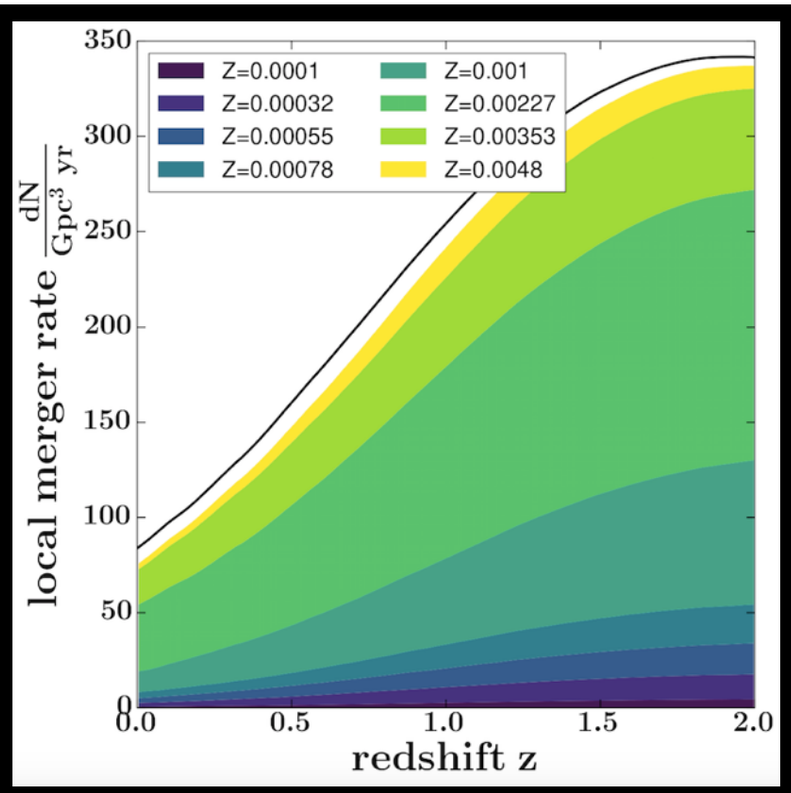



(1)
(2)
(3)
(4)
(5)
(6)
(7)

Predictions: what can we learn?

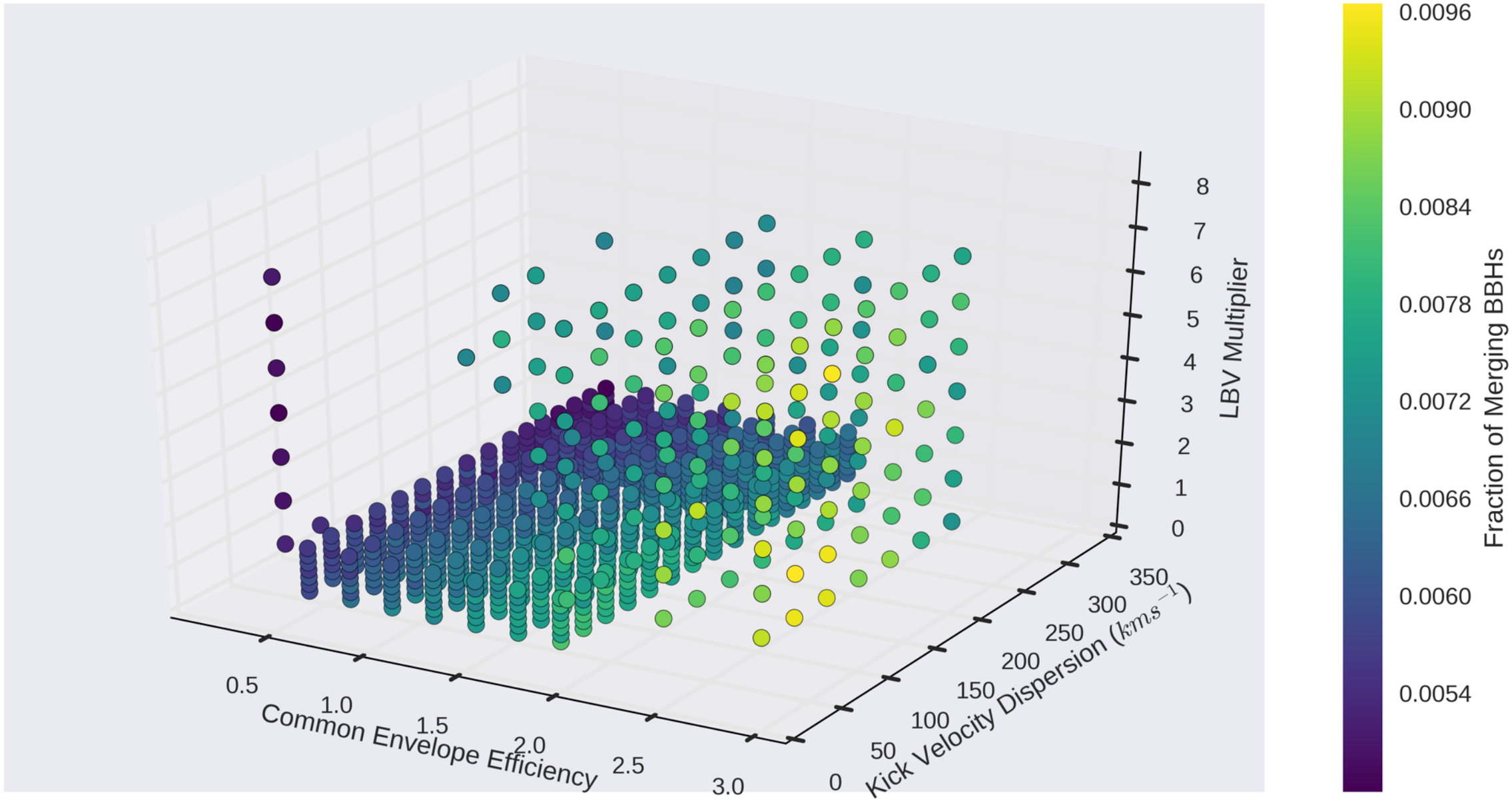




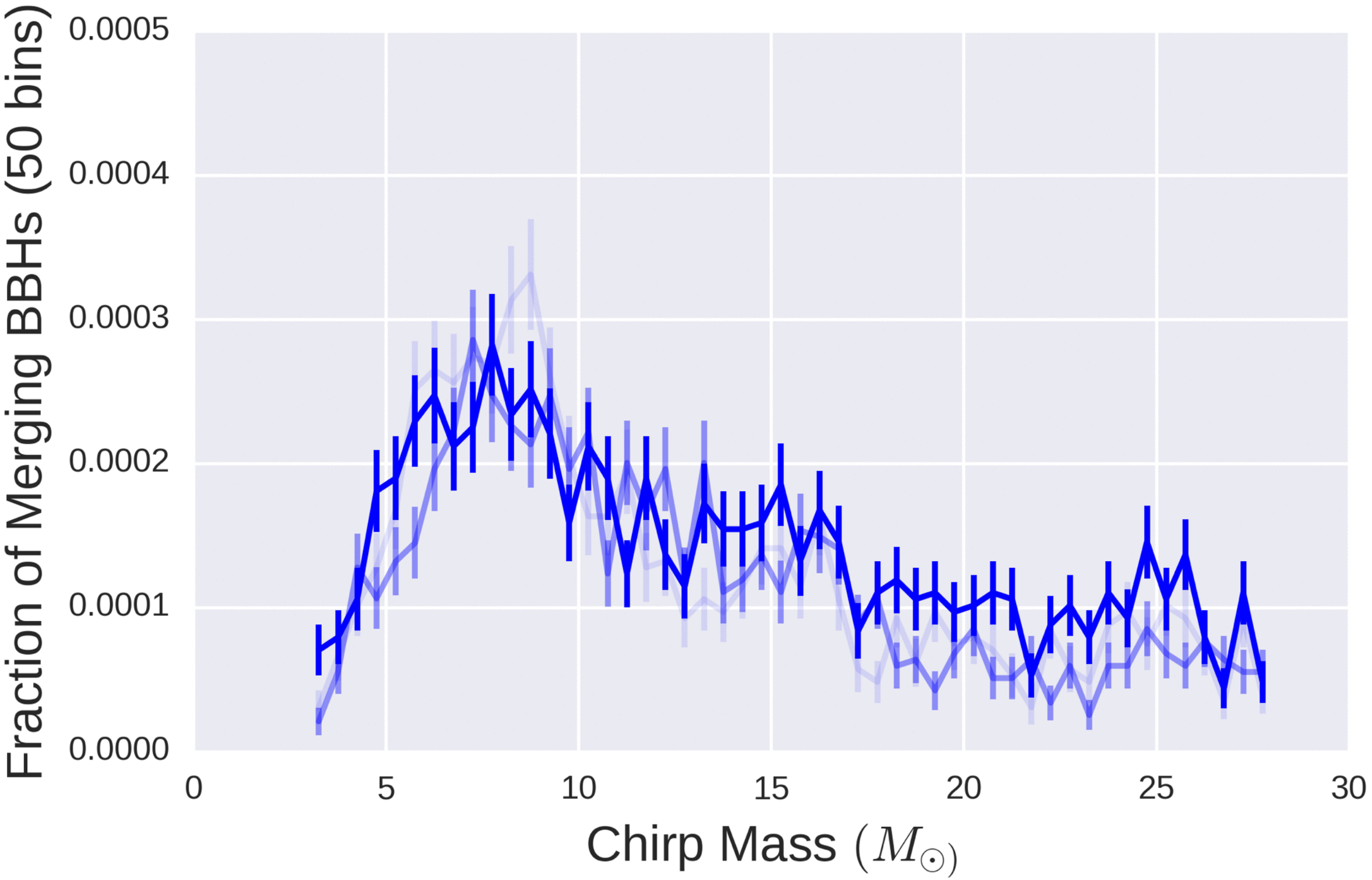


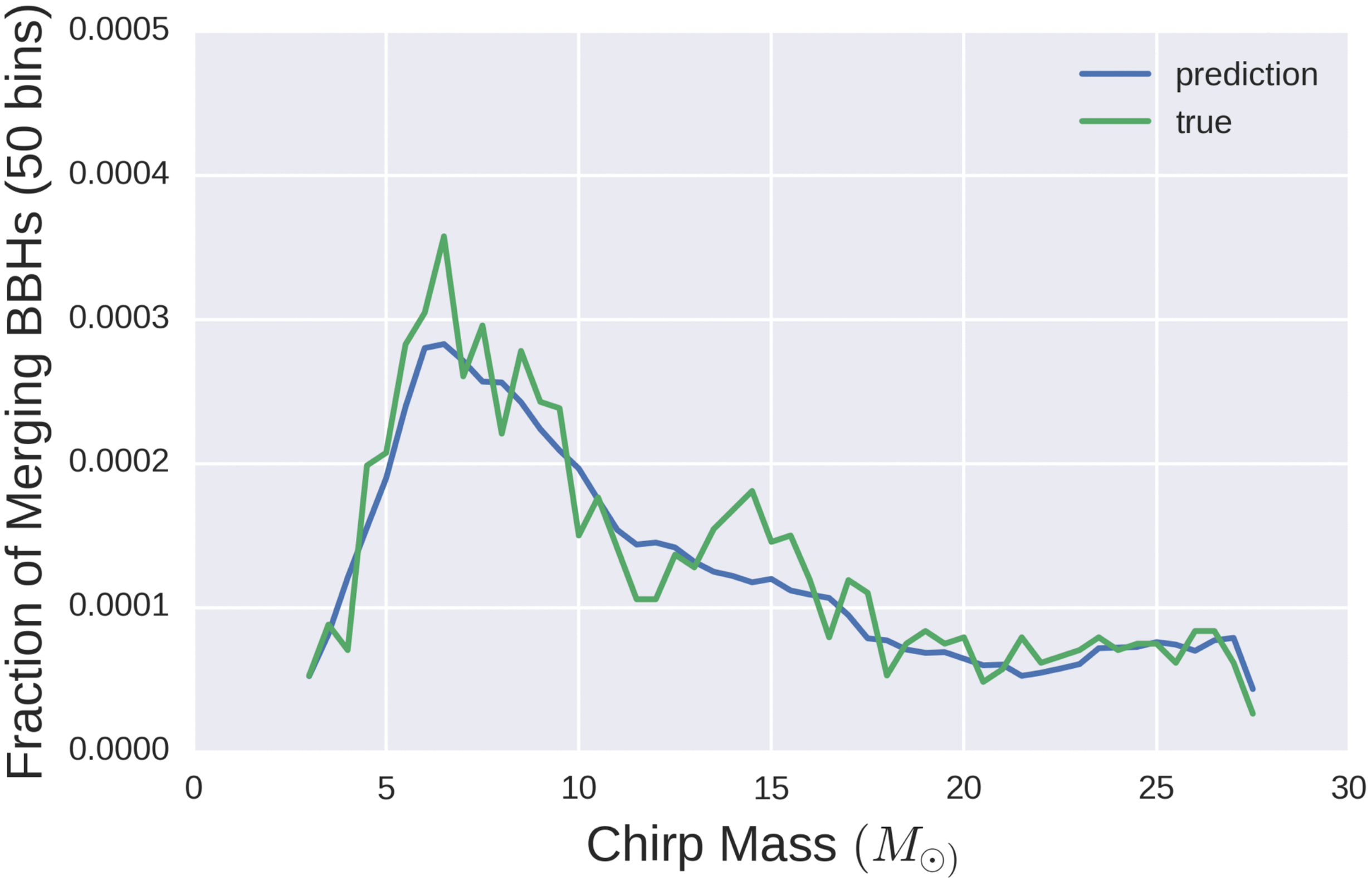
Vigna Gomez+;
Barrett+;
Neijssel+;
in prep.

Model interpolation

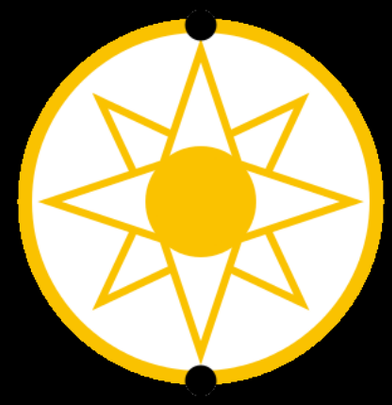


Barrett et al., in prep.


Fraction of Merging BBHs (50 bins)
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
0
5
10
15
20
25
30
Chirp Mass $(M_\odot)$


Fraction of Merging BBHs (50 bins)
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
0
5
10
15
20
25
30
Chirp Mass $(M_\odot)$
prediction
true

Population Reconstruction



- Selection effects and measurement uncertainty

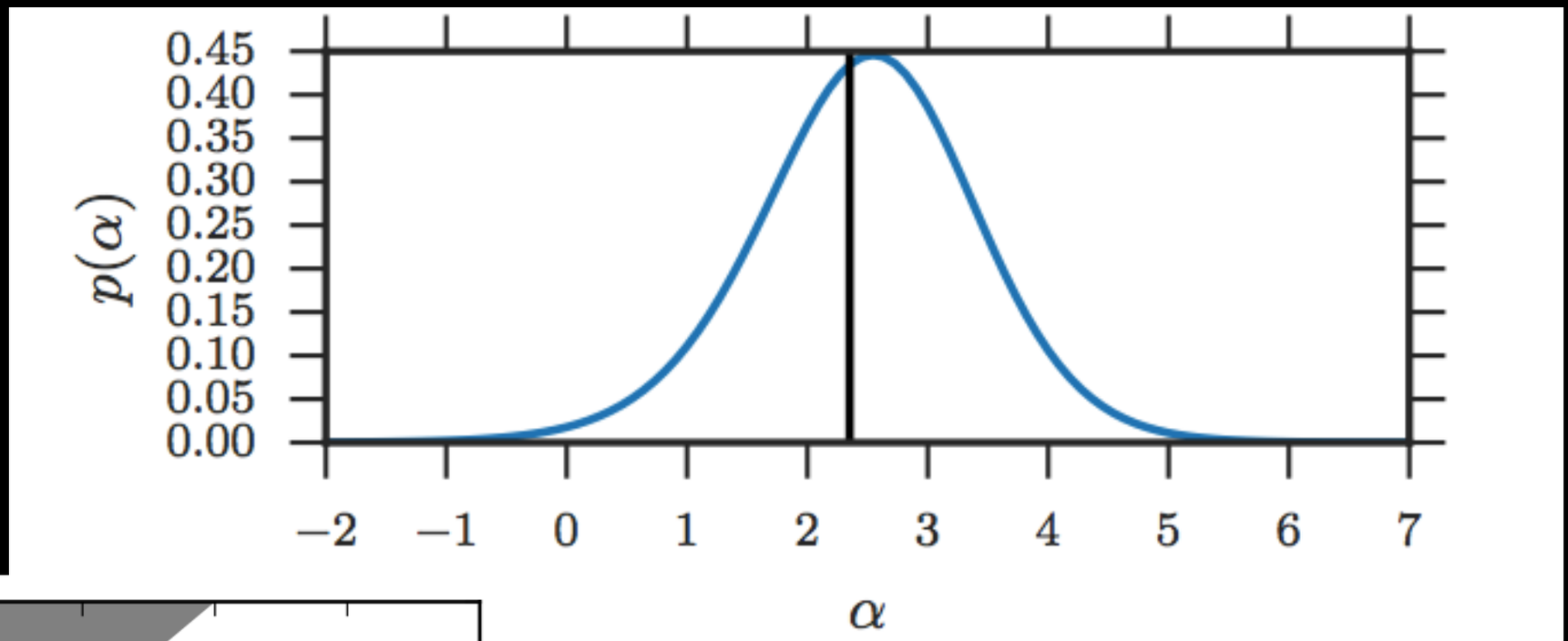
$$p(\{\vec{d}^{(i)}\}|\vec{\lambda}) = \prod_{i=1}^{k} \frac{\int d\vec{\theta} p(\vec{d}^{(i)}|\vec{\theta}) p_{\rm pop}(\vec{\theta}|\vec{\lambda})}{\int d\vec{\theta} p_{\rm det}(\theta) p_{\rm pop}(\vec{\theta}|\vec{\lambda})}$$

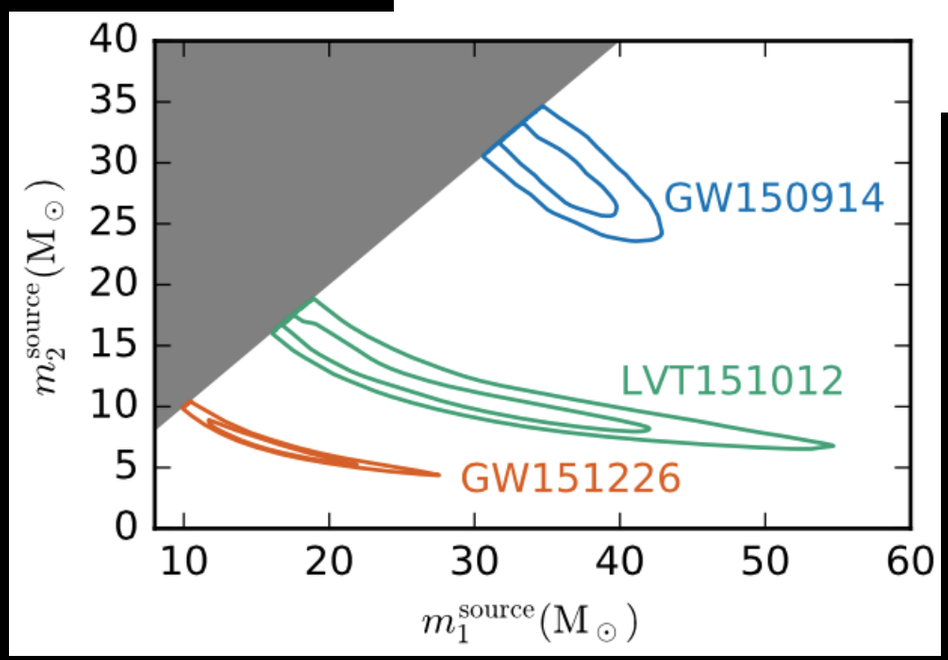
Mandel, Farr, Gair, in prep.

- [Counting and confusion — Farr, Gair, Mandel, Cutler, 2015]

Population Reconstruction

$p(m_1) \propto m_1^{-\alpha}$ flat q

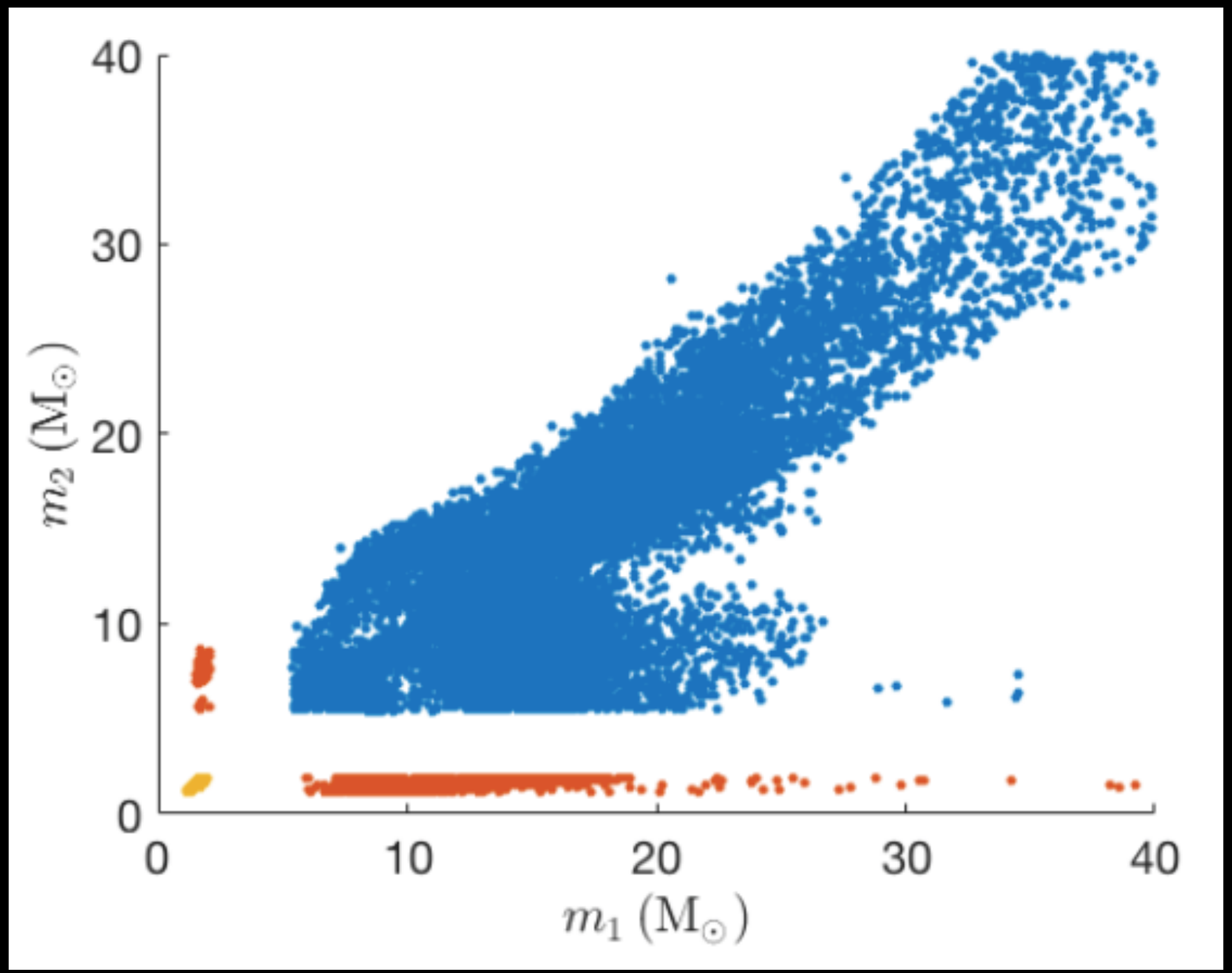




Abbott+ (LVC), 2016

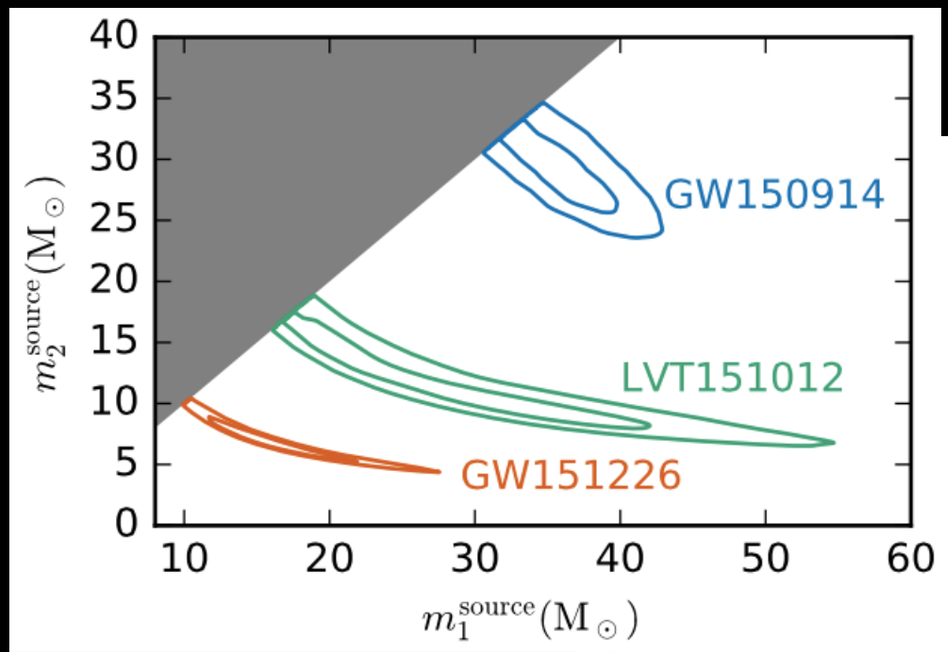
$h(f) \sim M^{5/6} \Rightarrow V \sim M^{2.5}$

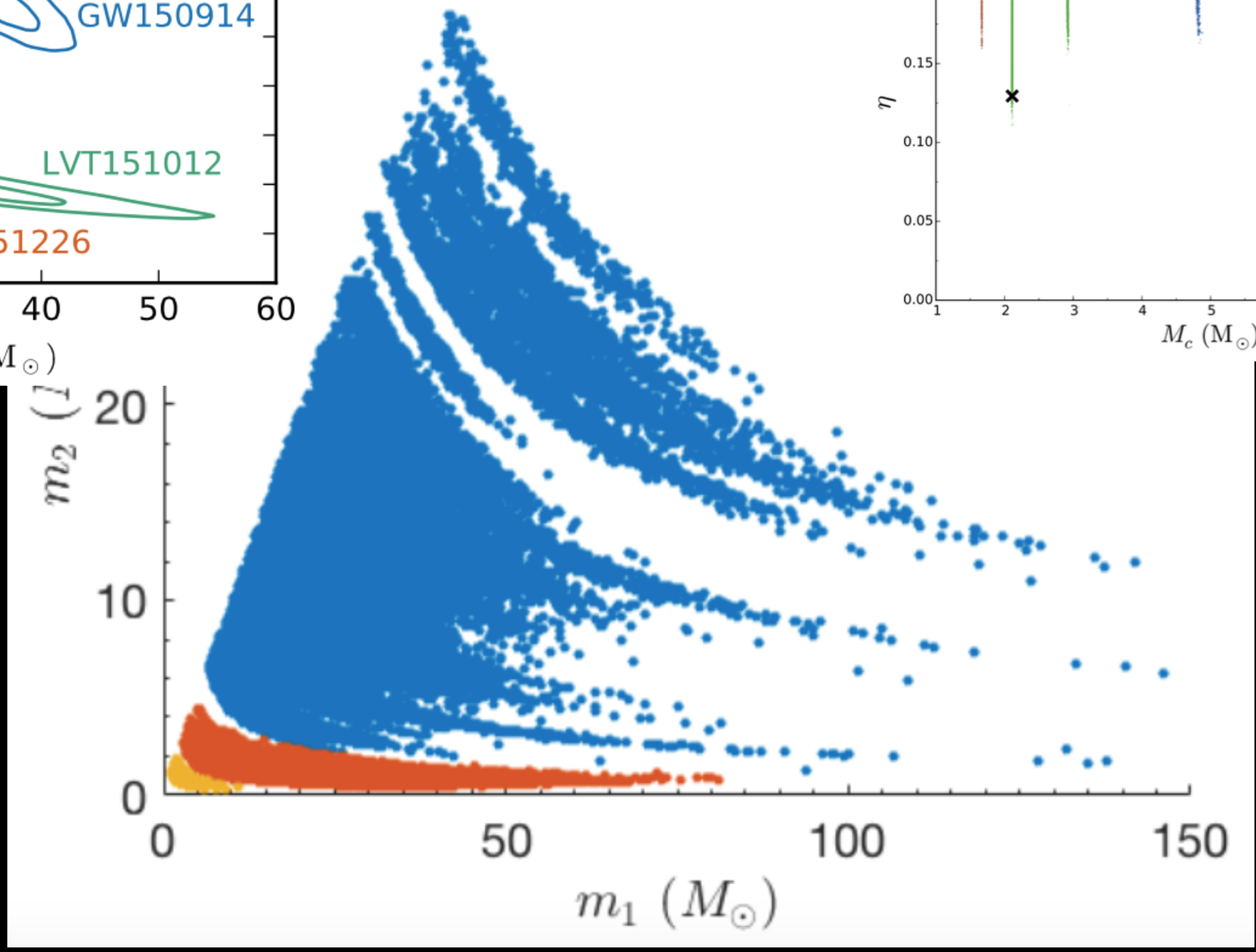
Unmodeled Inference: Binary population clustering

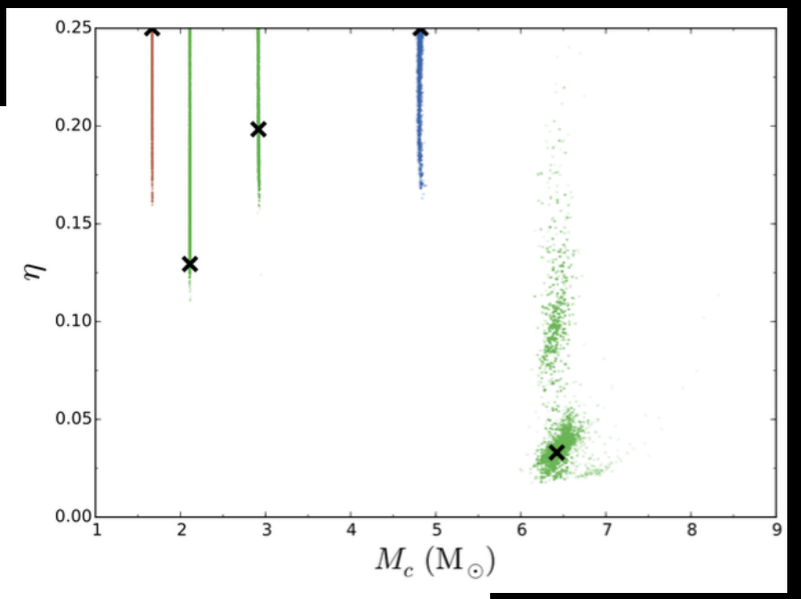


[Mandel et al., 2015 based on Dominik et al., 2015]

Measurement uncertainty

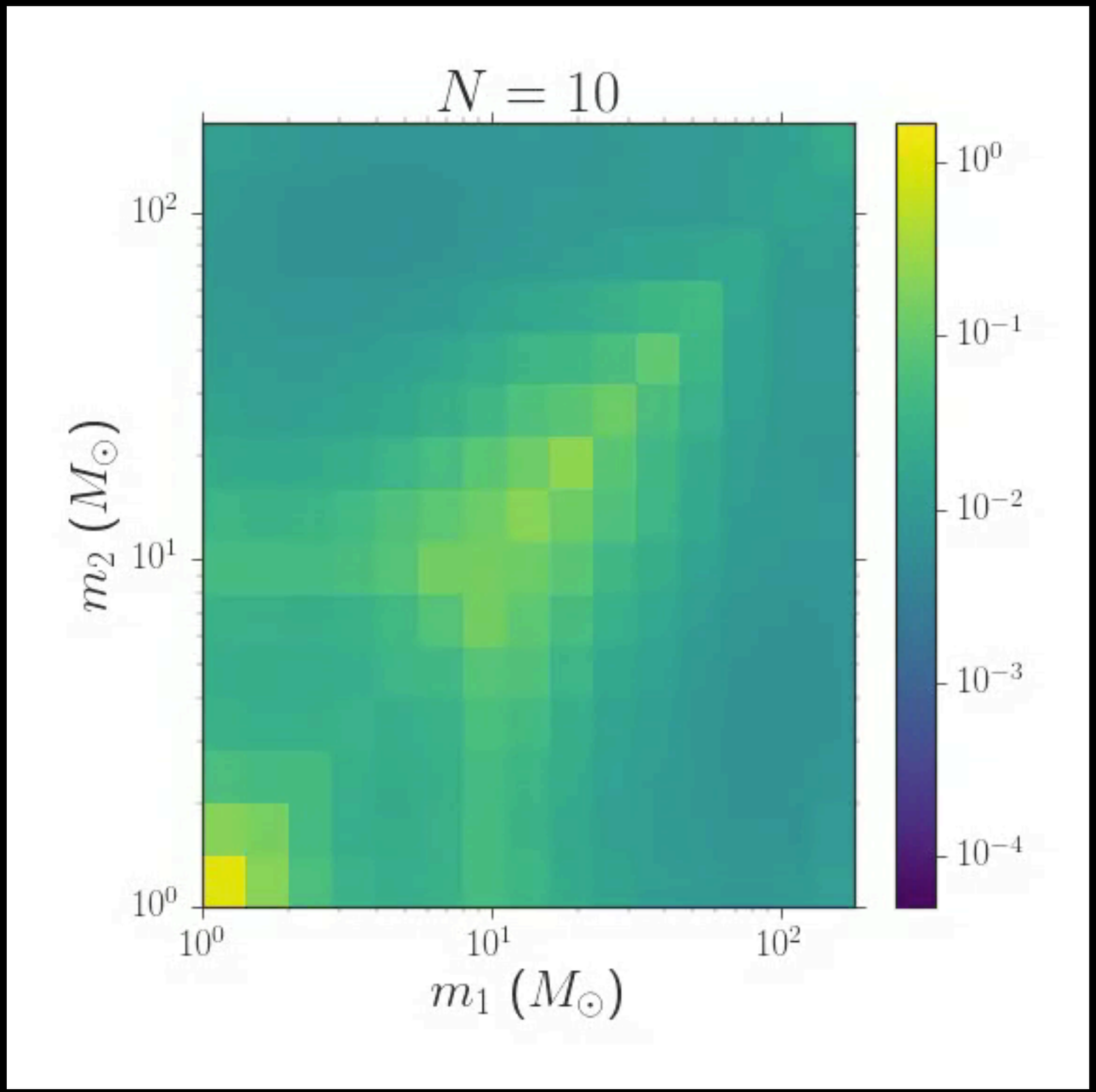




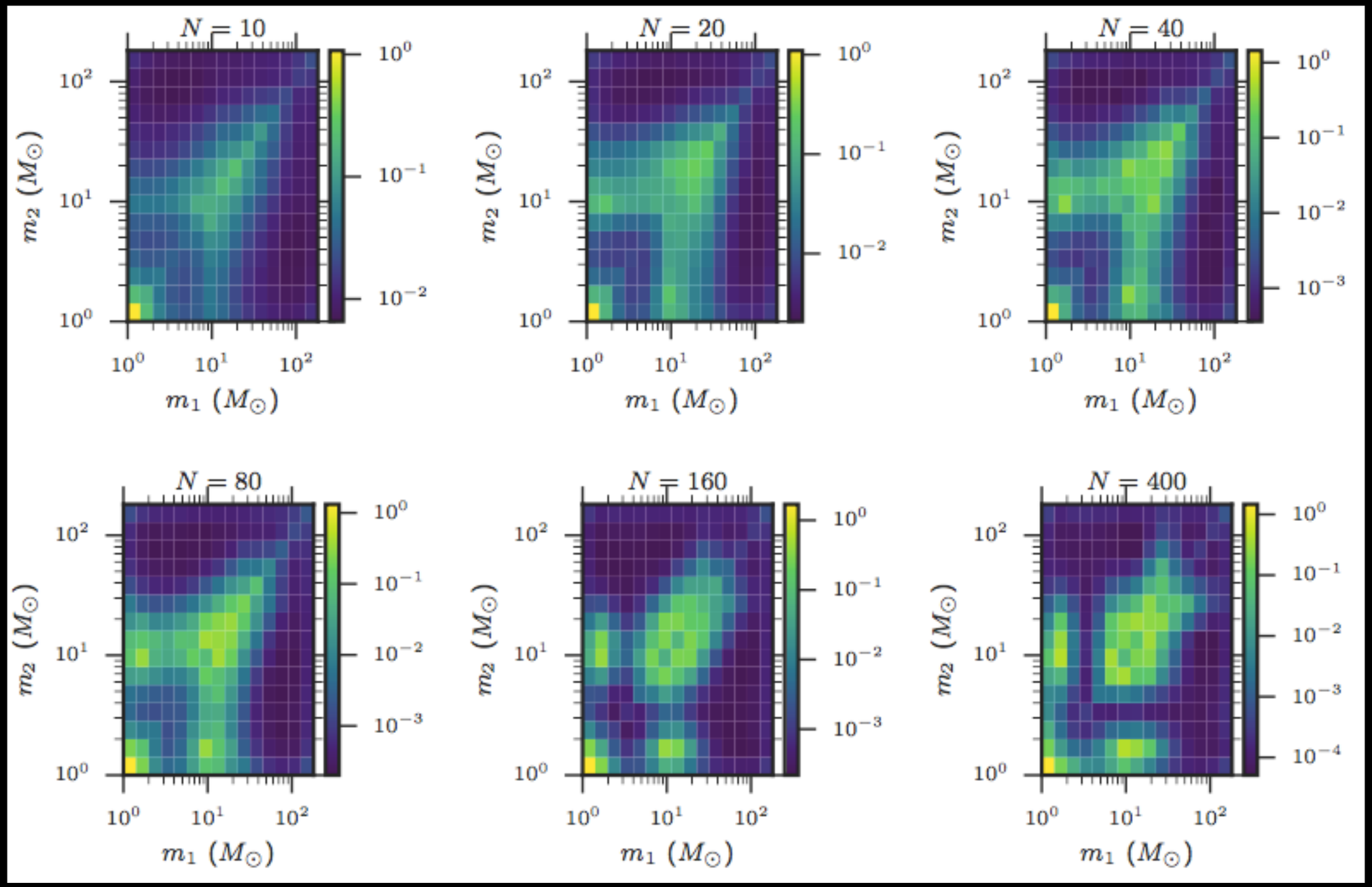


[Abbott et al., 2016; Mandel et al., 2015; see also Littenberg et al., 2015]

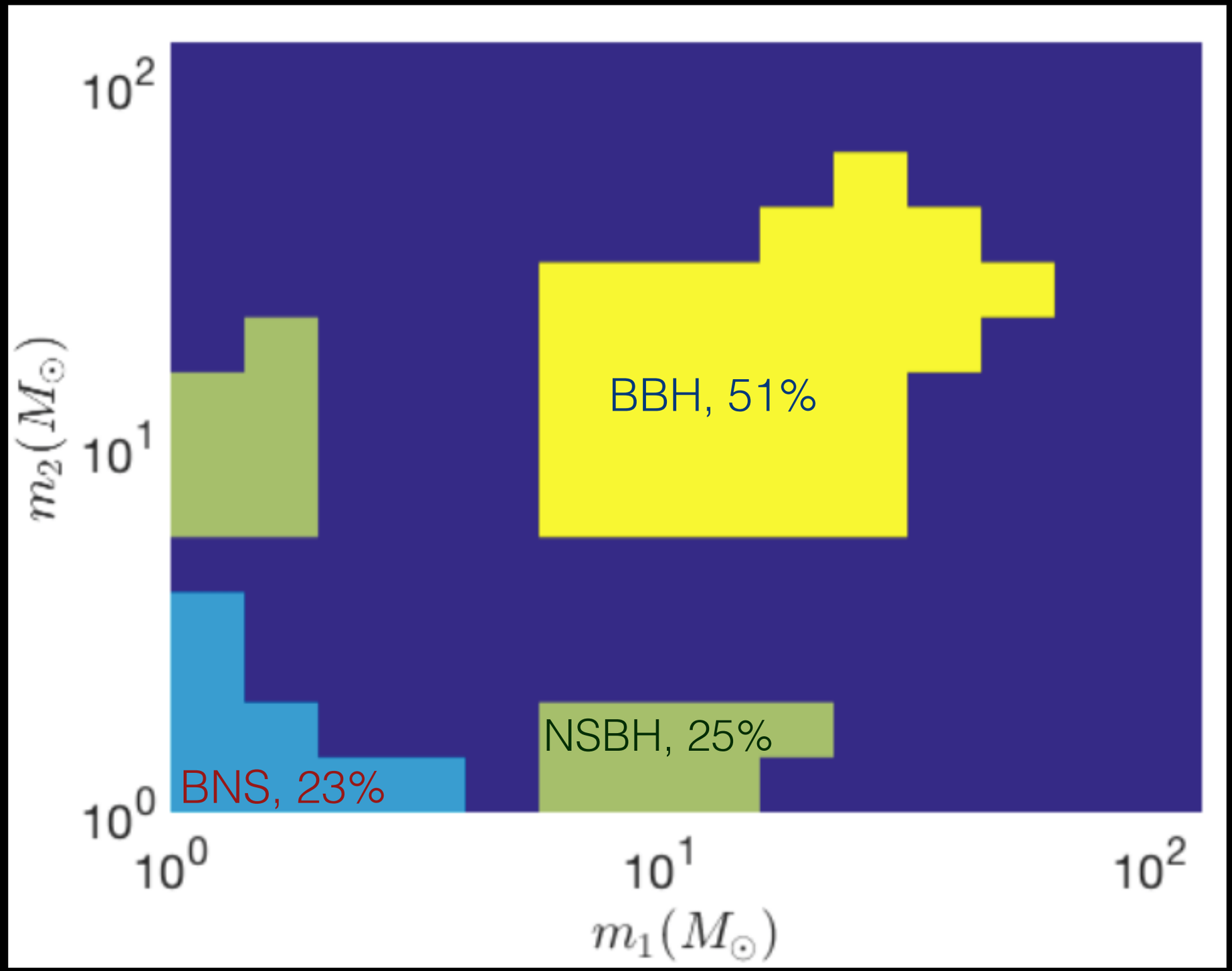
Mean inferred bin density



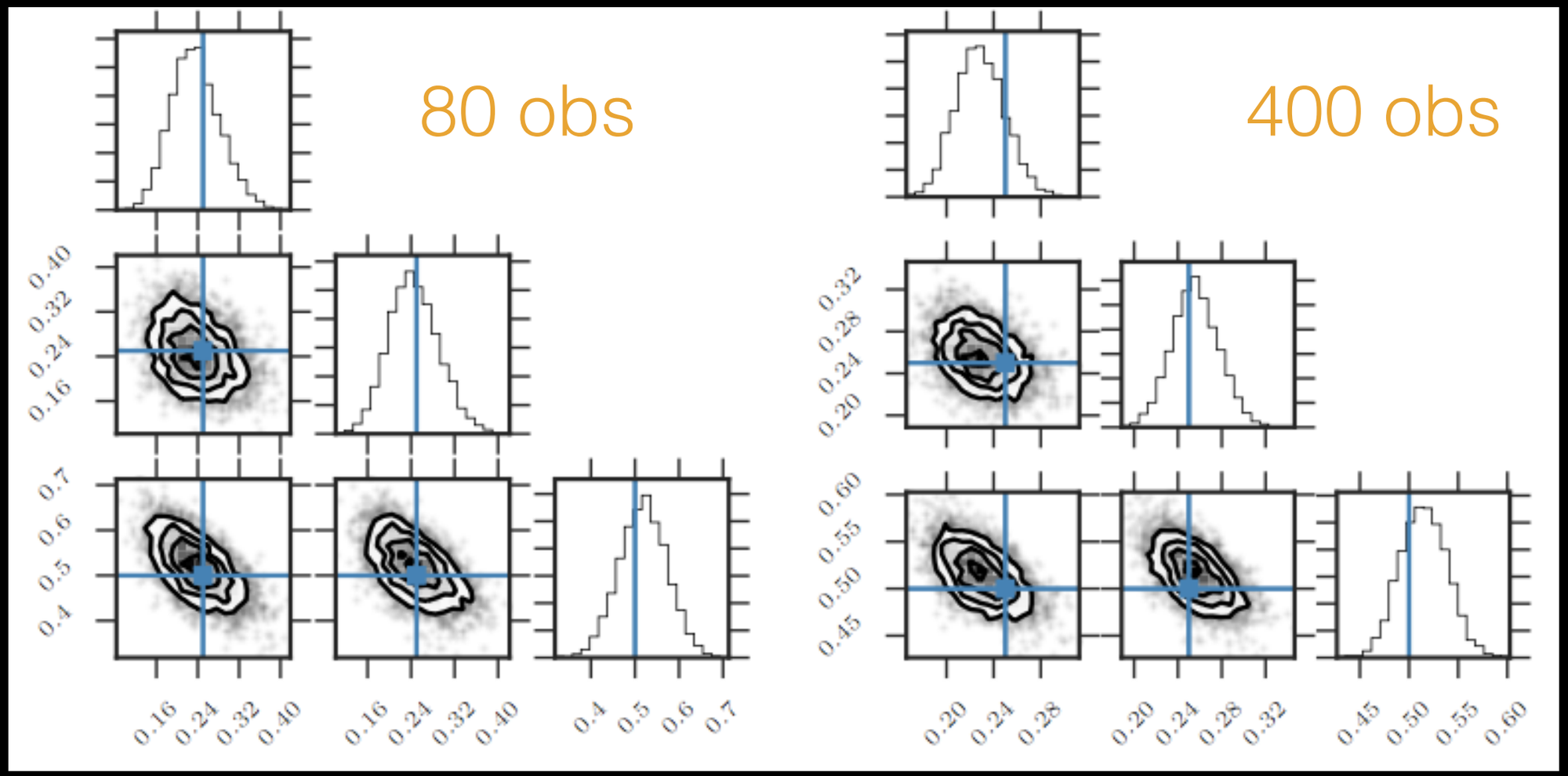
Mean inferred bin density



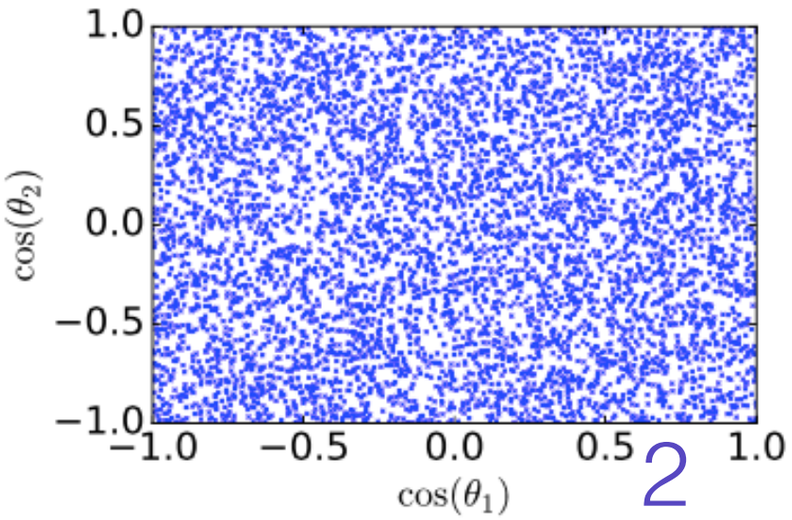
Water filling on mean density



Unmodeled Inference



Hierarchical modeling



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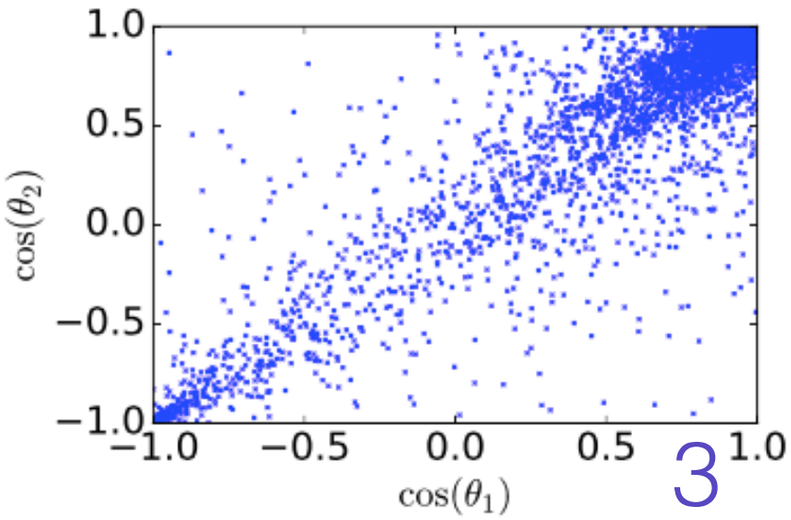

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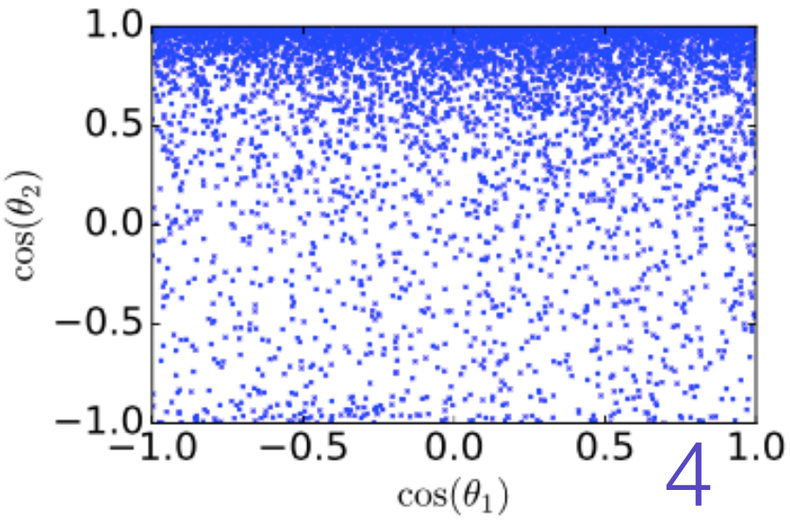

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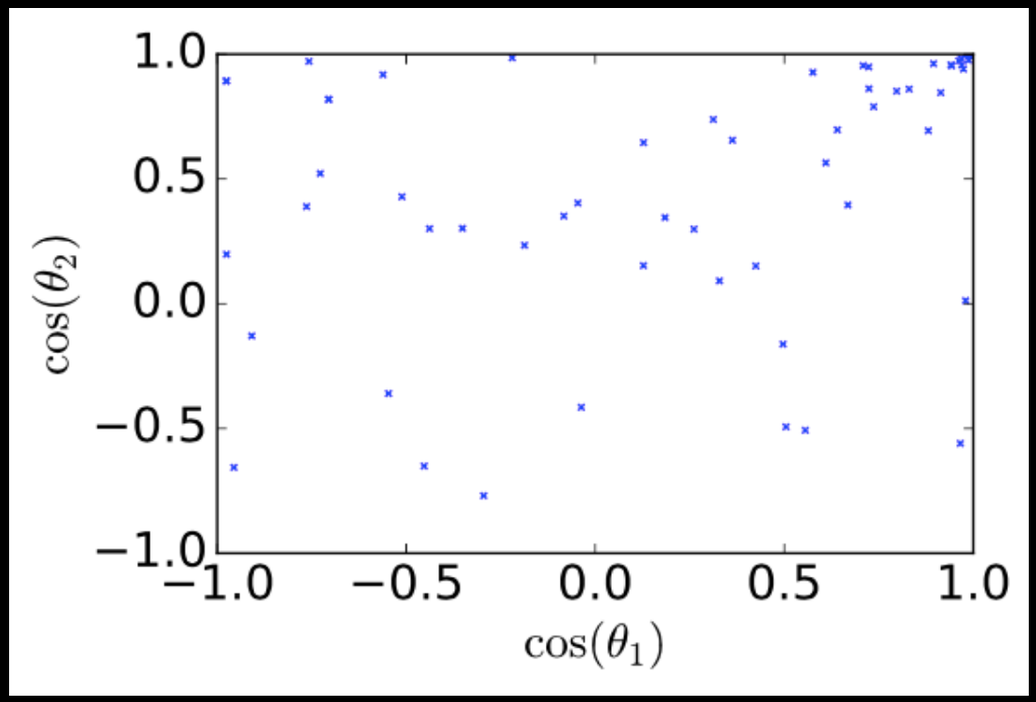
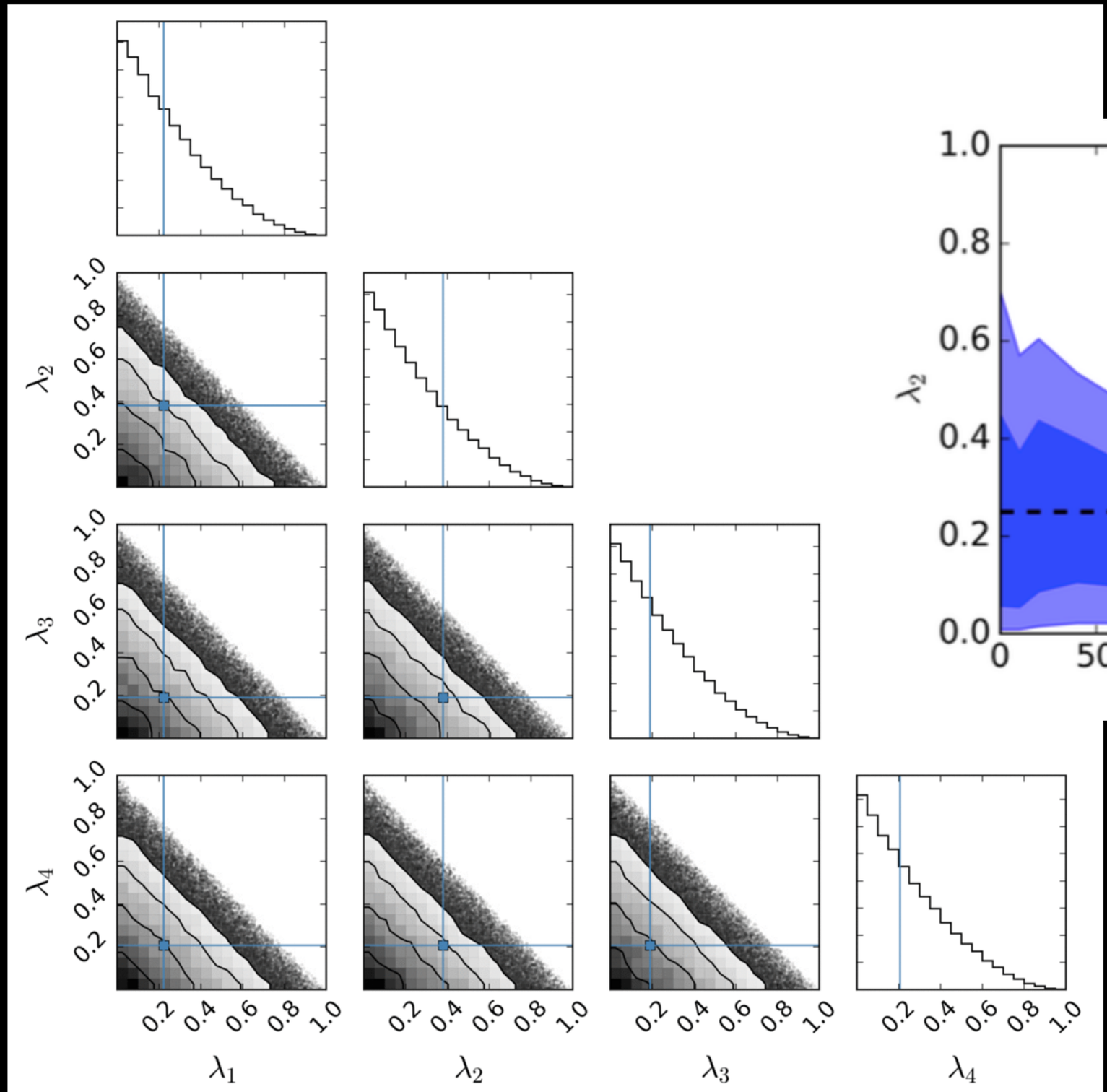
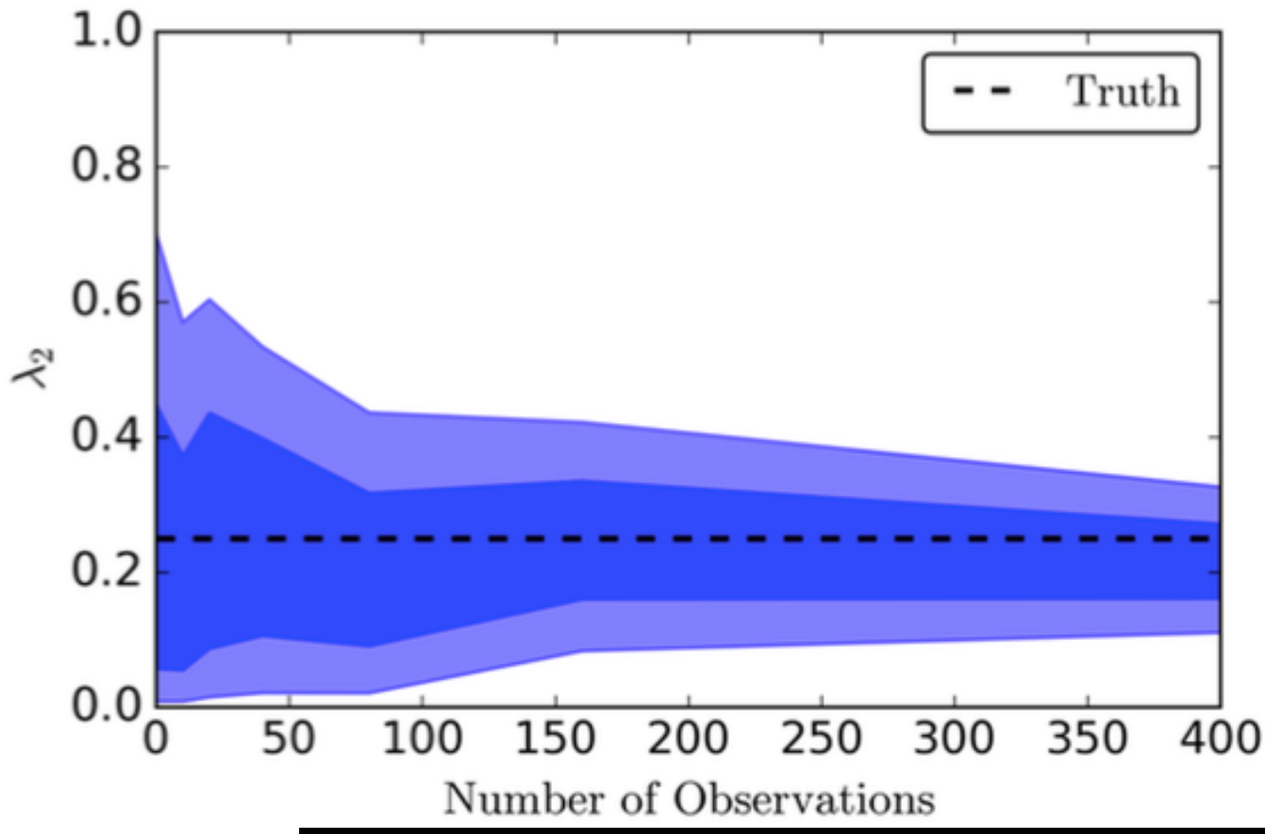


Stevenson, Berry, Mandel, 2017

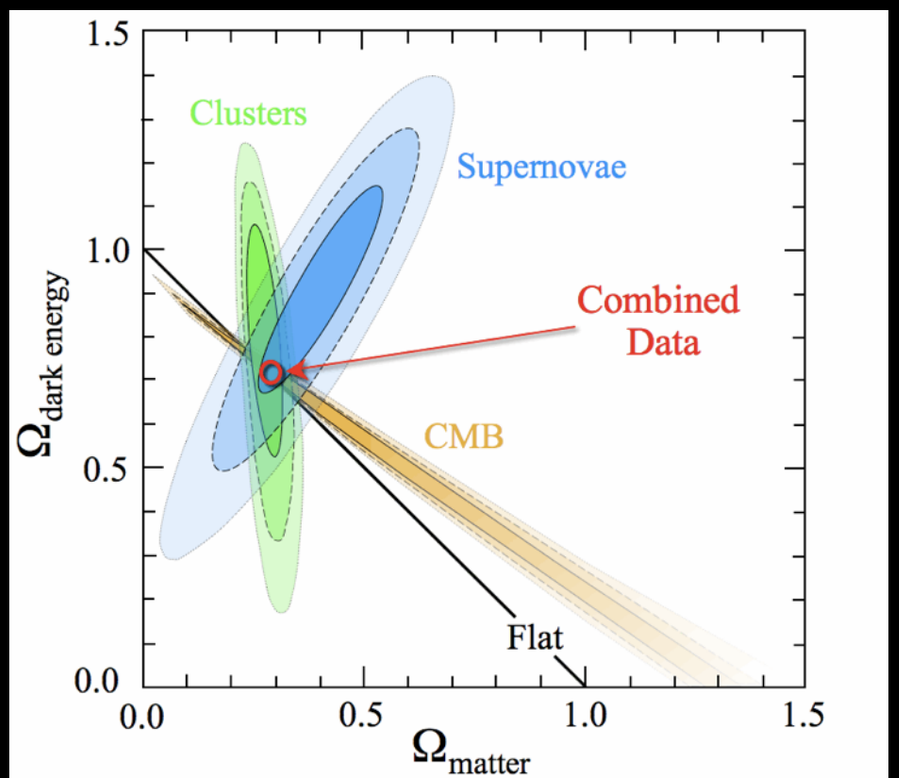
Hierarchical modeling



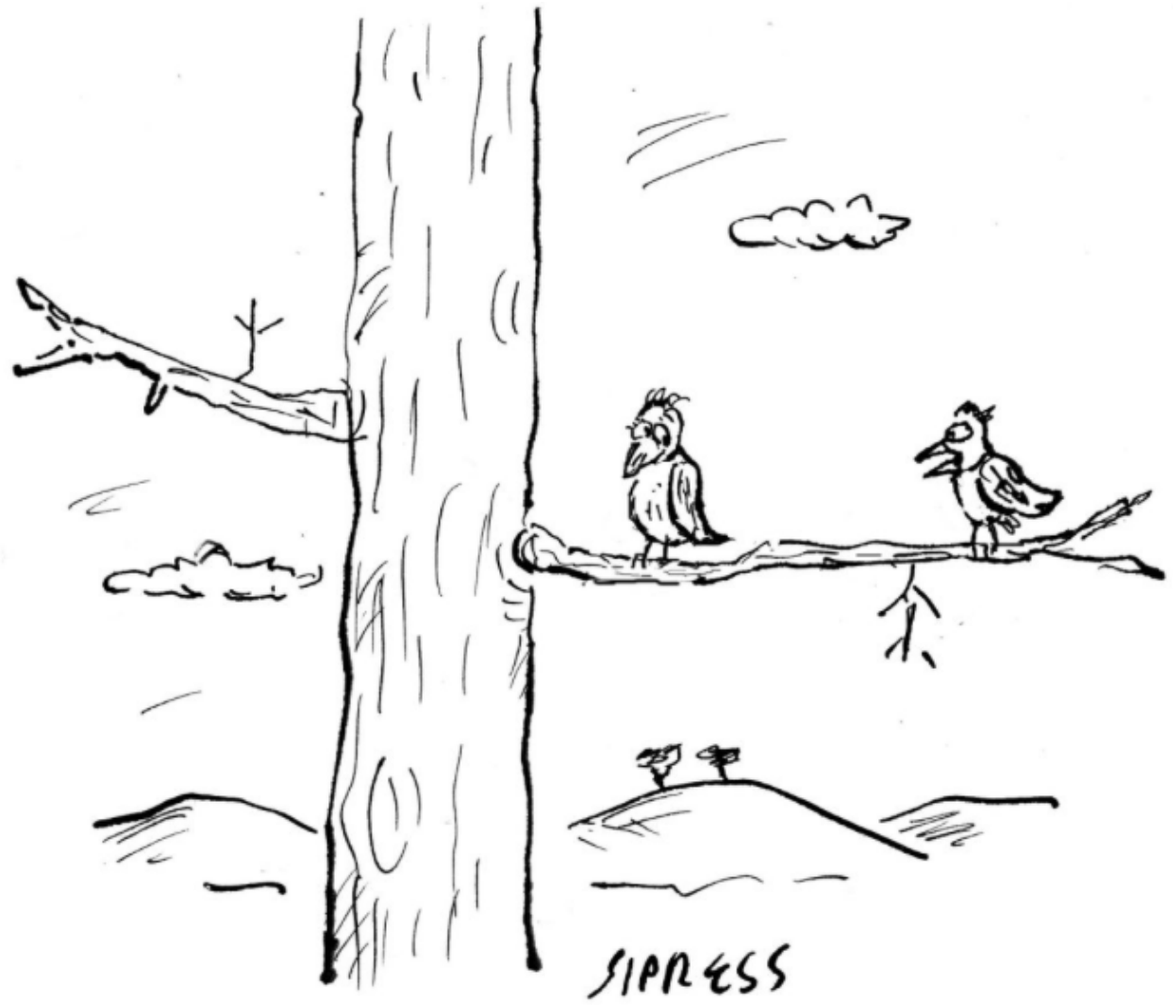


Future

- Bring together modelling and astrostatistics
- Figure out what questions we can realistically answer… and answer them!
- Use full observation set — concordance binary evolution?



Gravitational-wave astrophysics: the future is *now*



"Was that you I heard just now, or was it two black holes colliding?"

Ilya Mandel
University of Birmingham