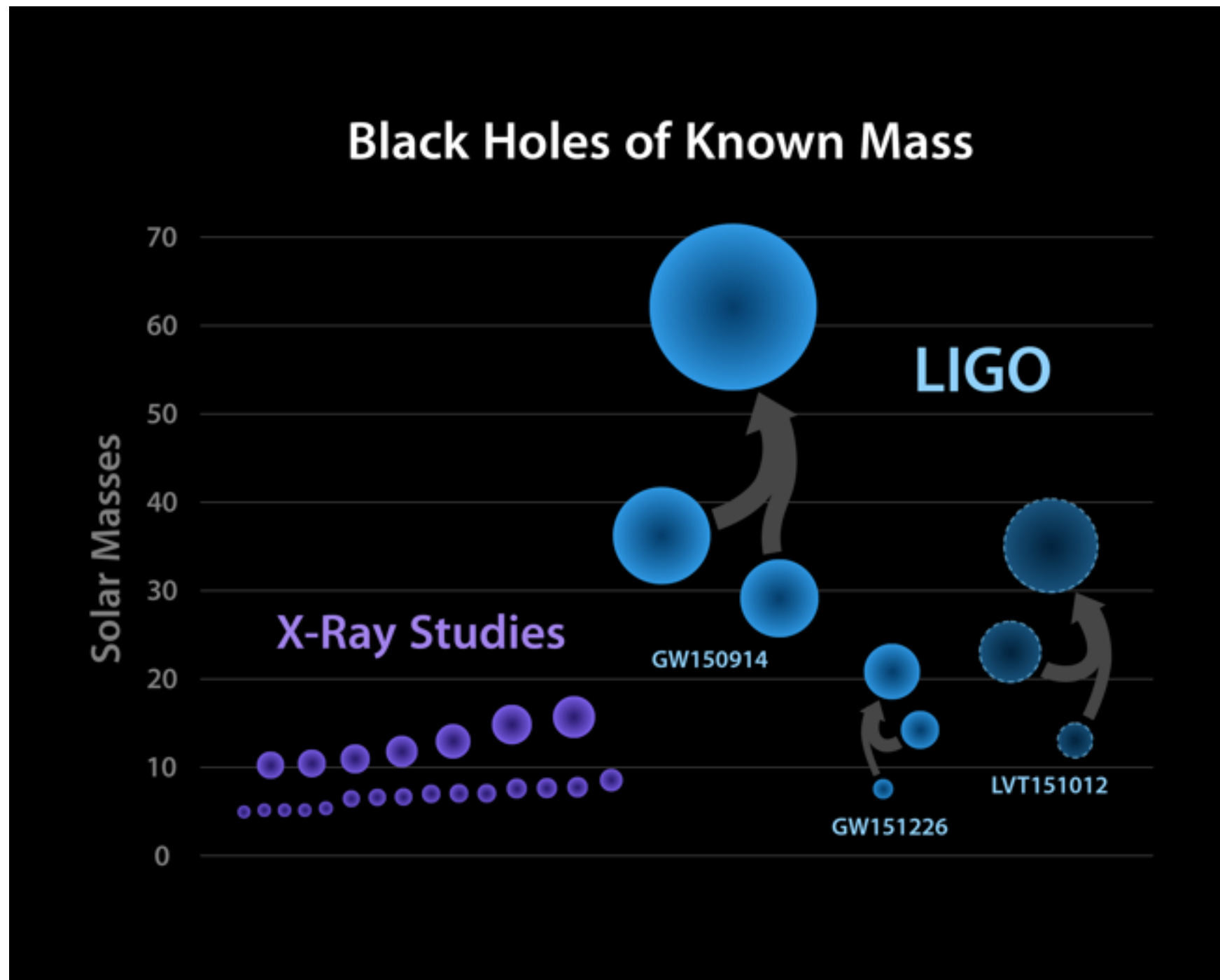
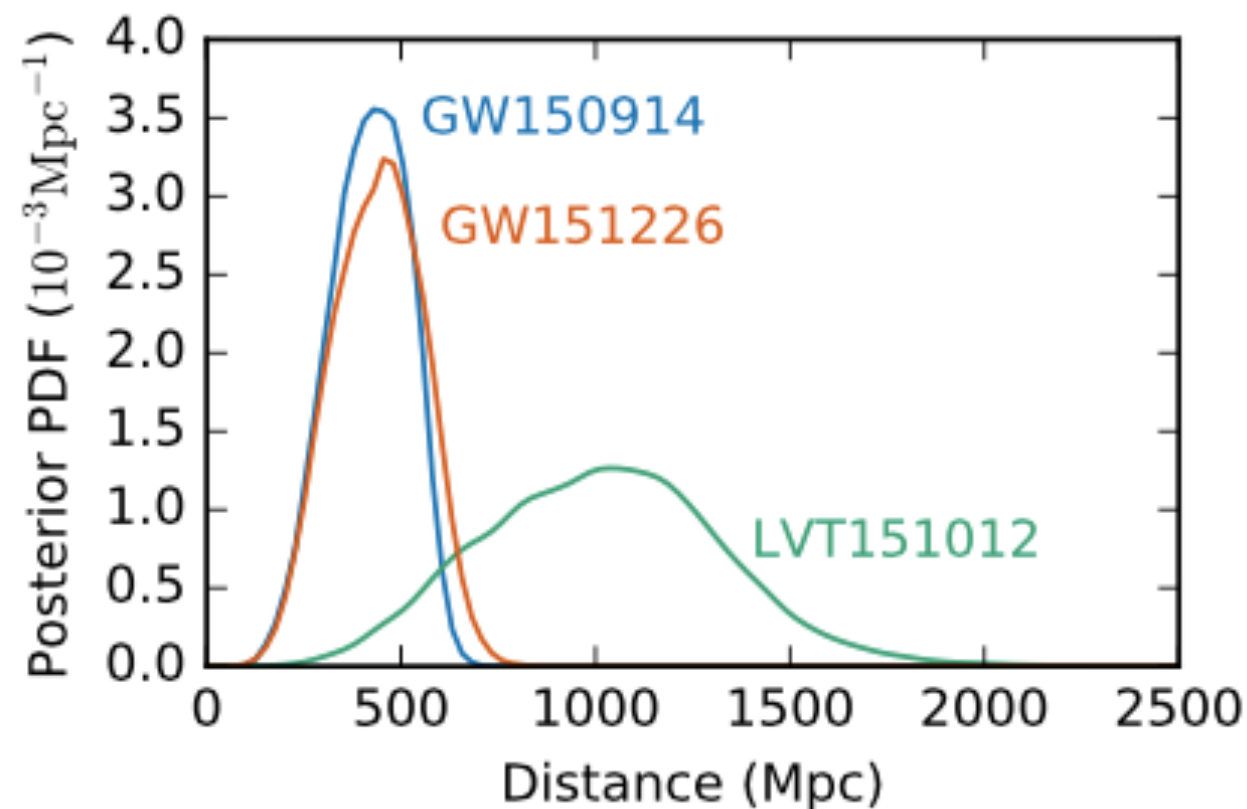
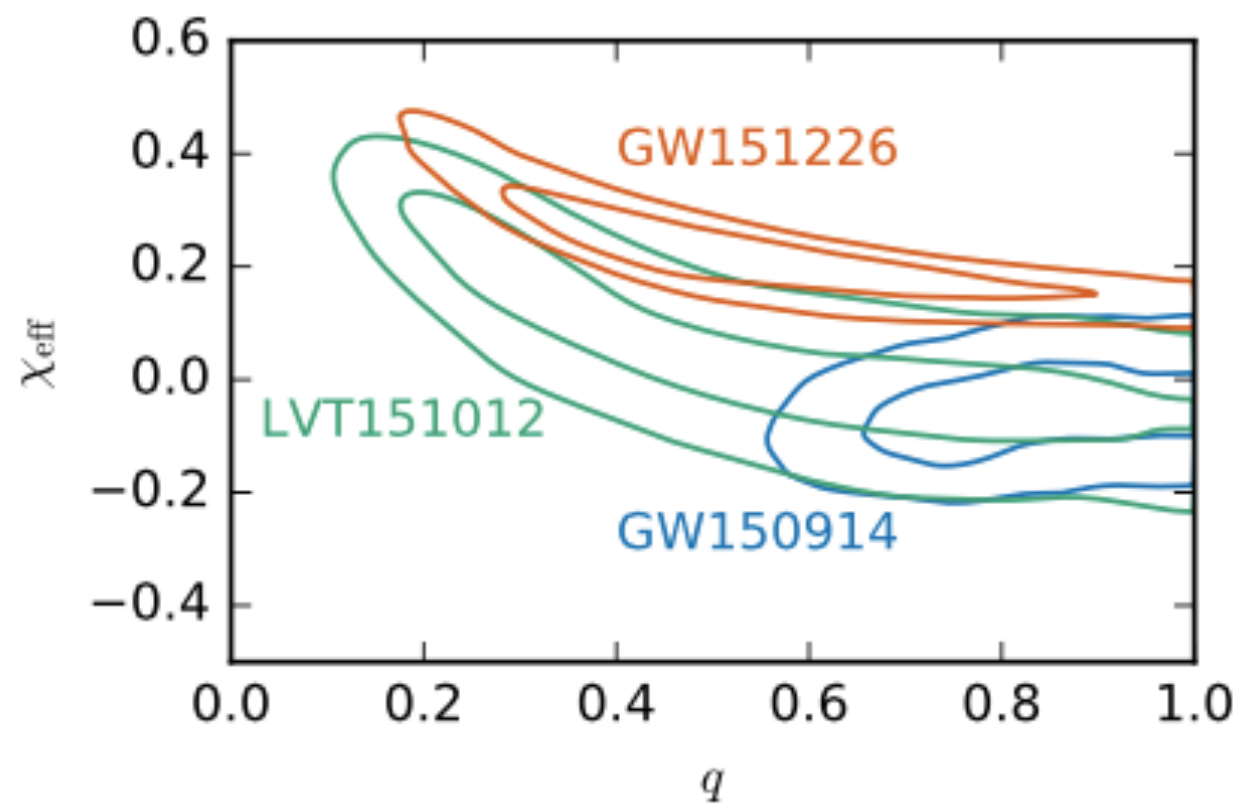
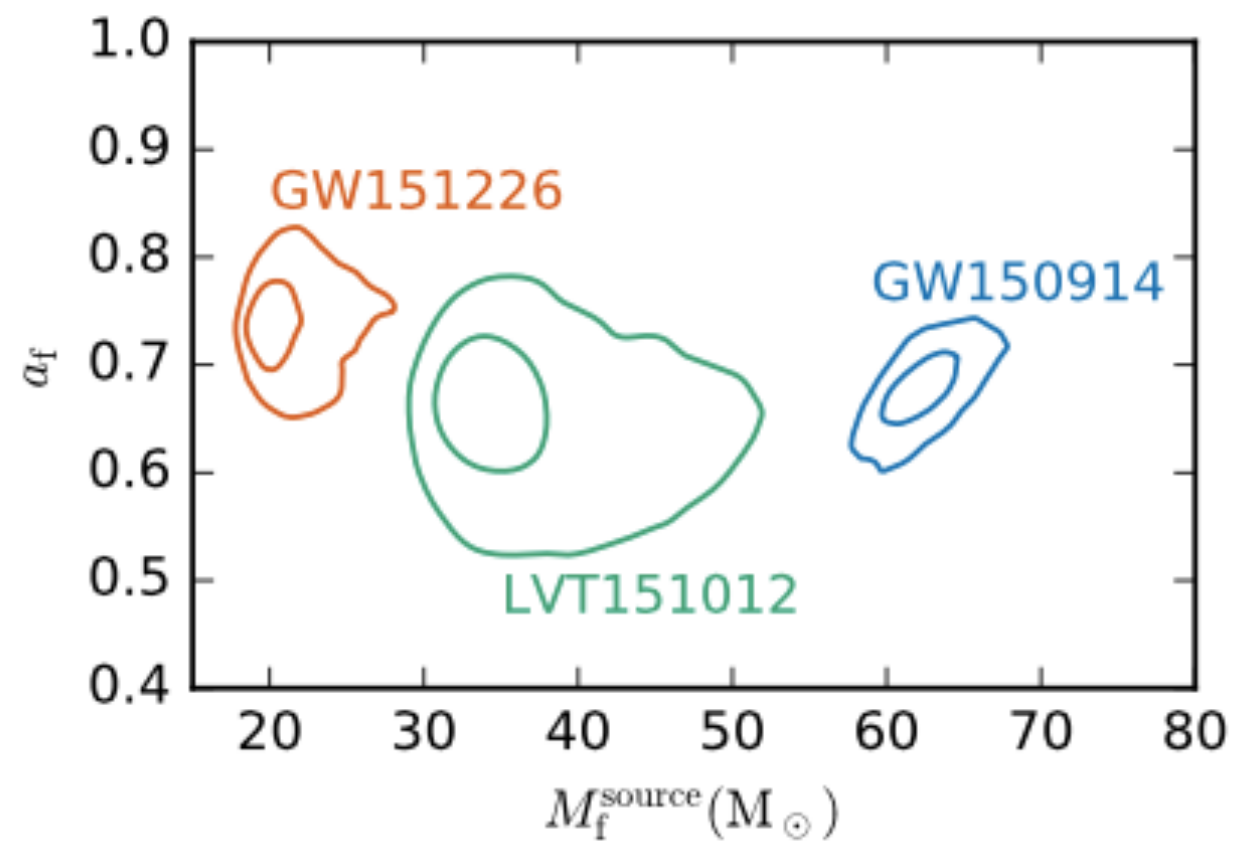
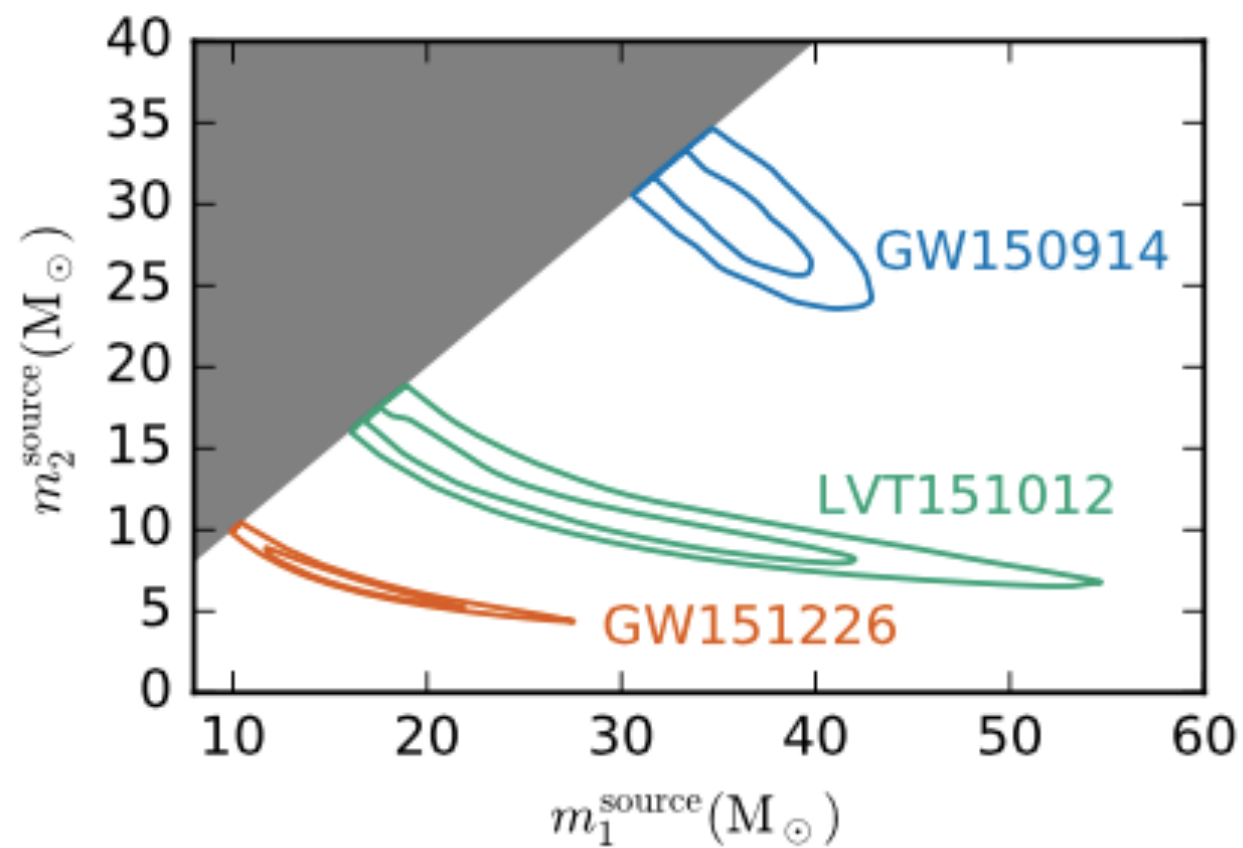


Astrophysical consequences of the LIGO discovery



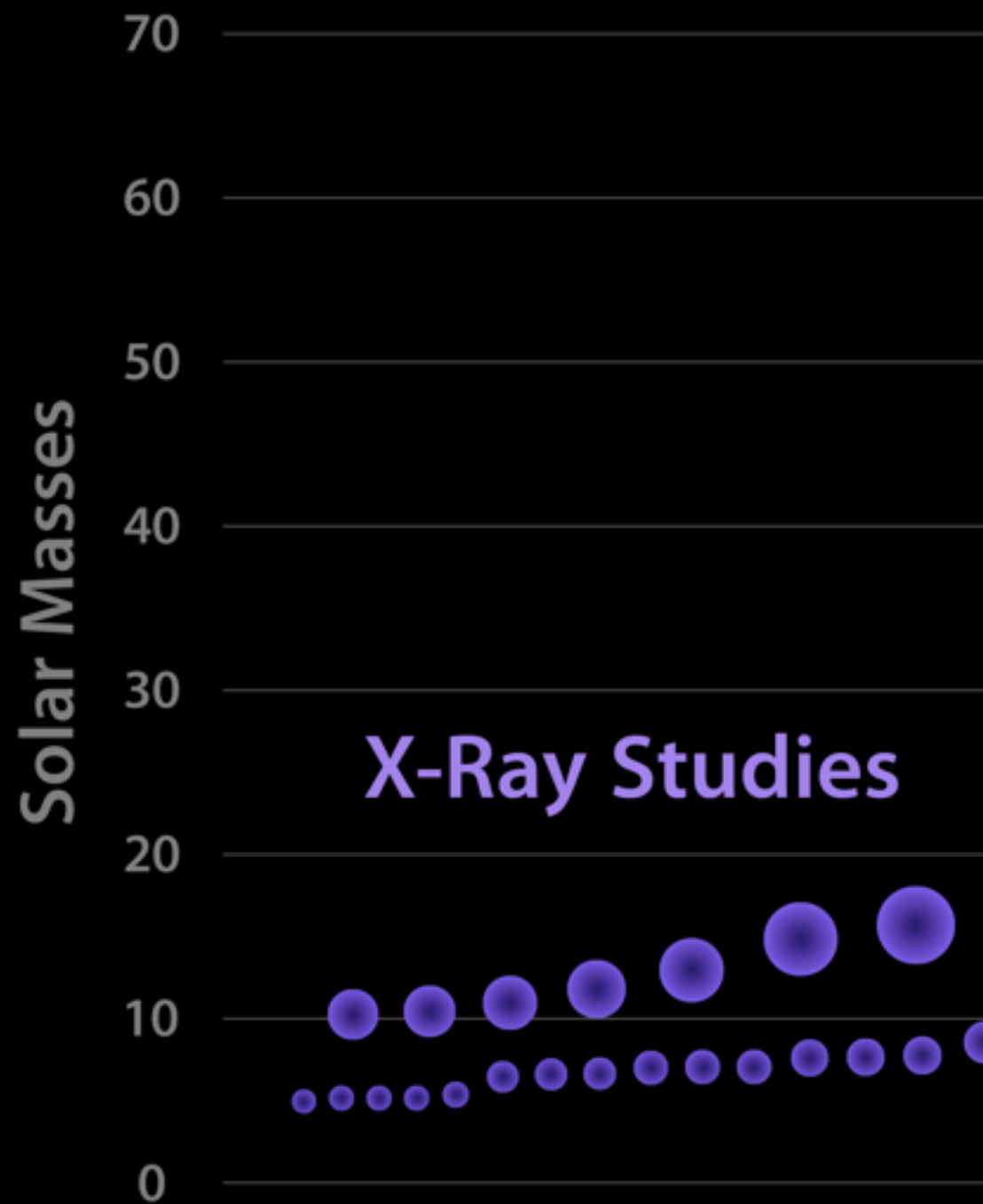
Ilya Mandel
University of Birmingham

- BBHs exist
- Merging BBHs exist
- stellar-mass BHs with mass above 30 solar masses exist (and take part in mergers)
- Don't know formation channel from single event — isolated binary with CE? chemically homogeneous evolution? dynamical formation?
- Likely formed in low metallicity environment (either locally, or at high z with long time delay)
- Primary has spin of <0.7 at 90% confidence; no evidence for spins being both large and strongly aligned

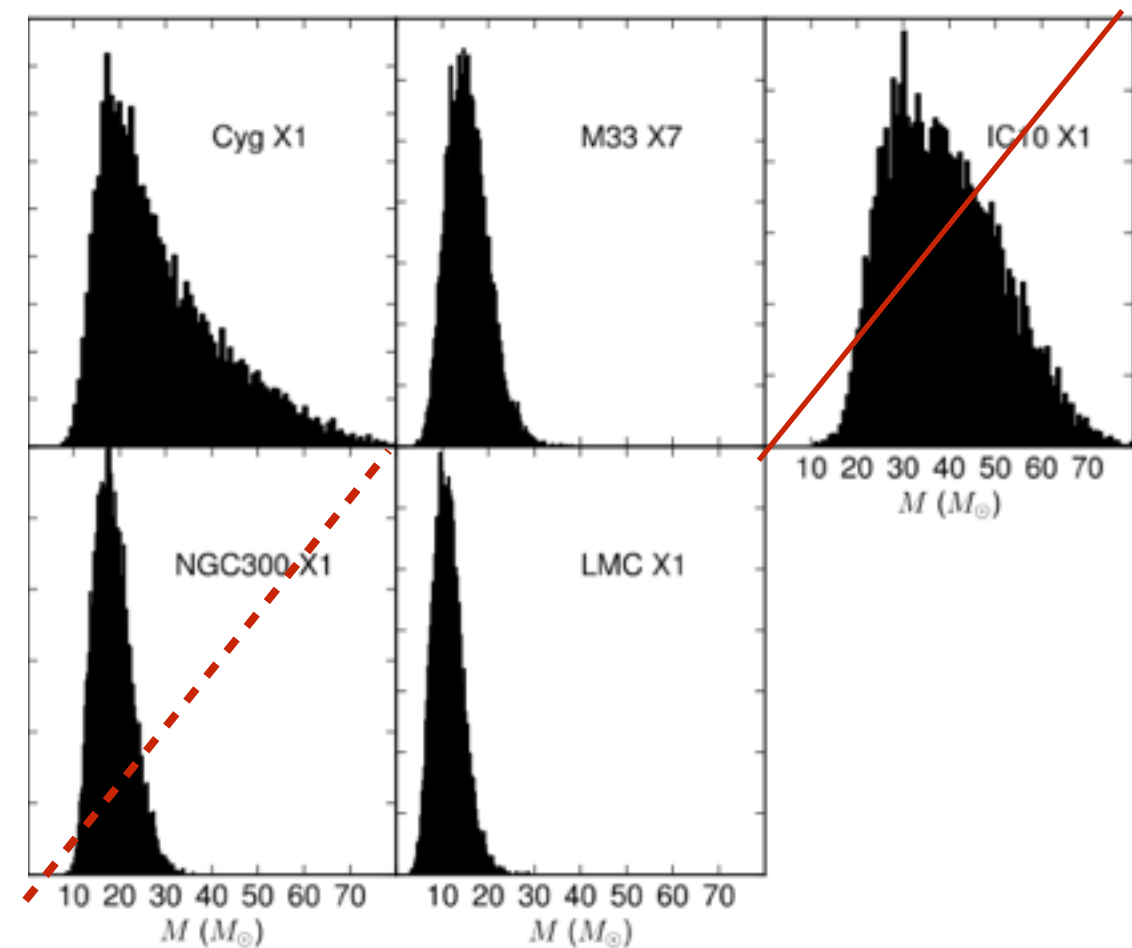
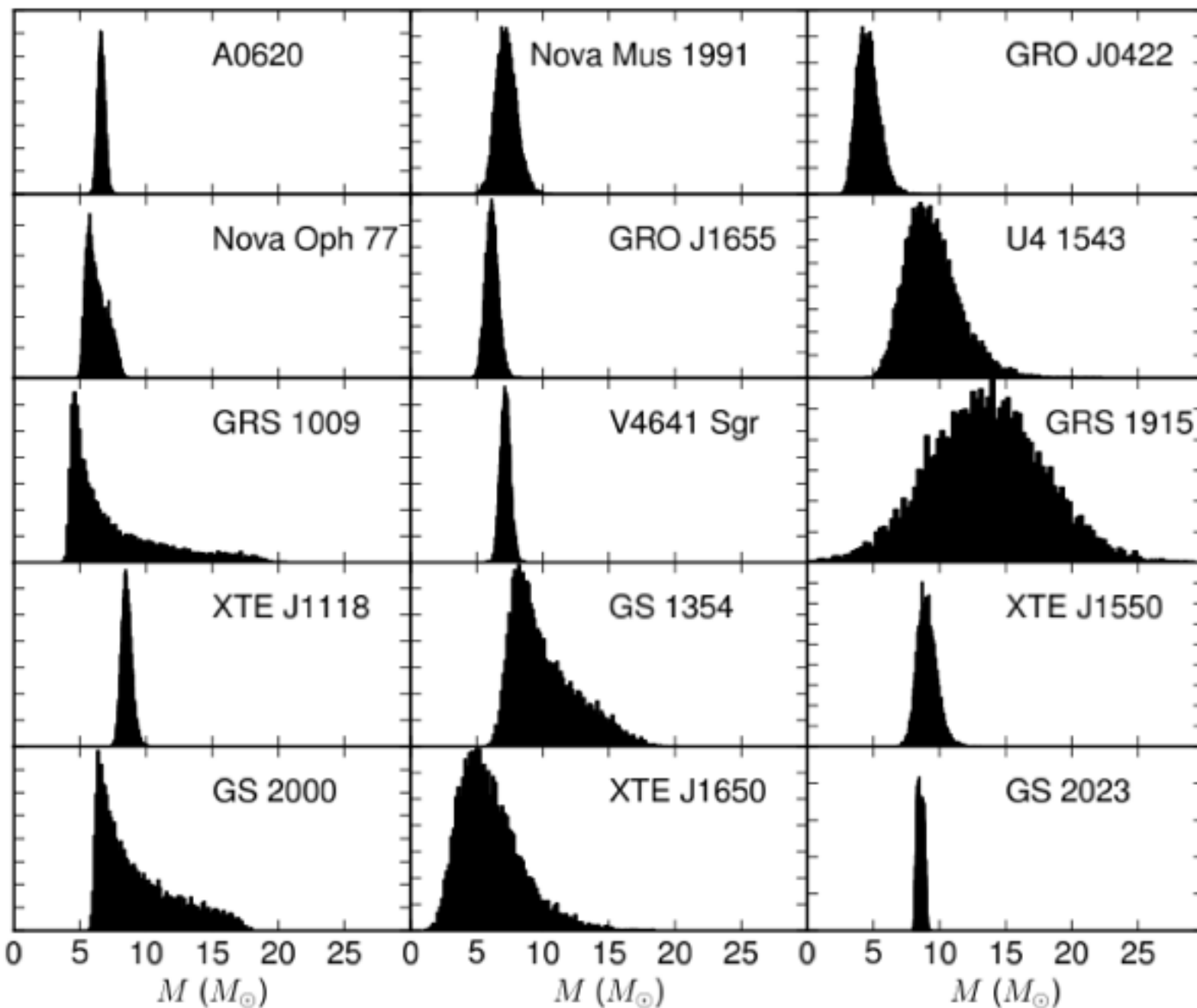


Abbott et al., 2016

Black Holes of Known Mass

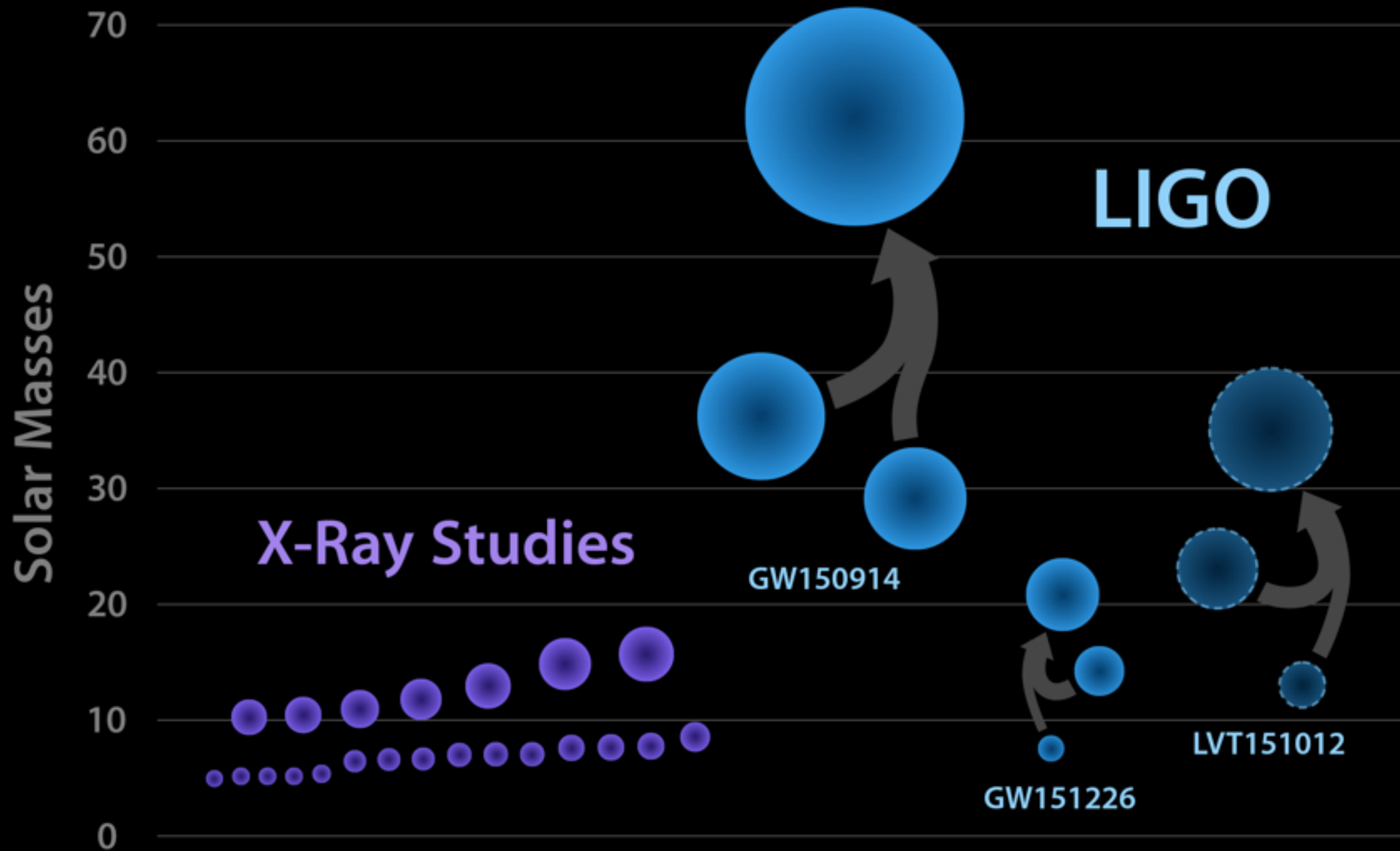


BH masses in X-ray binaries

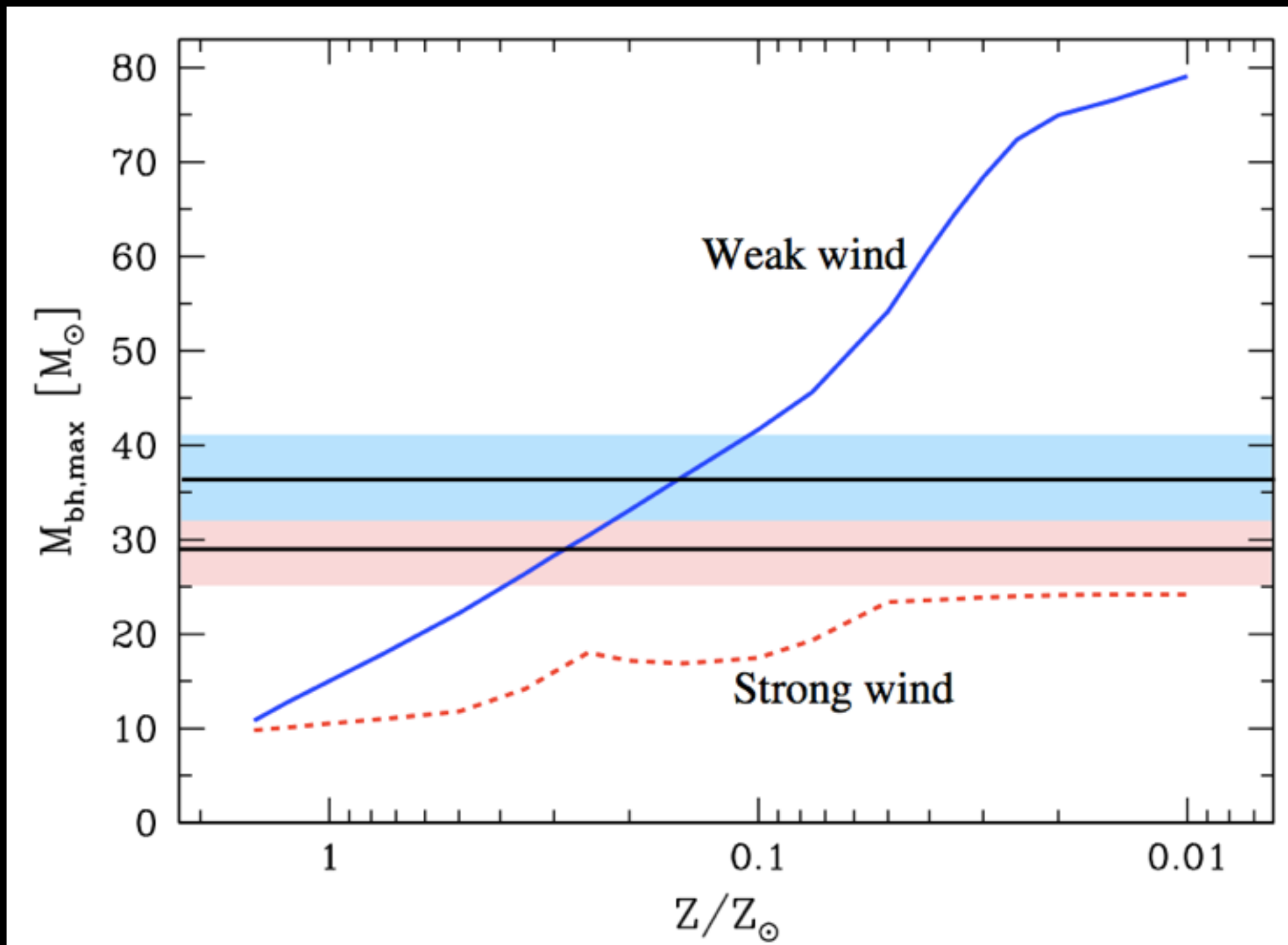


Black hole masses in low-mass
and high-mass X-ray binaries
[Farr+Mandel+, 2011 ApJ 741,
103]

Black Holes of Known Mass

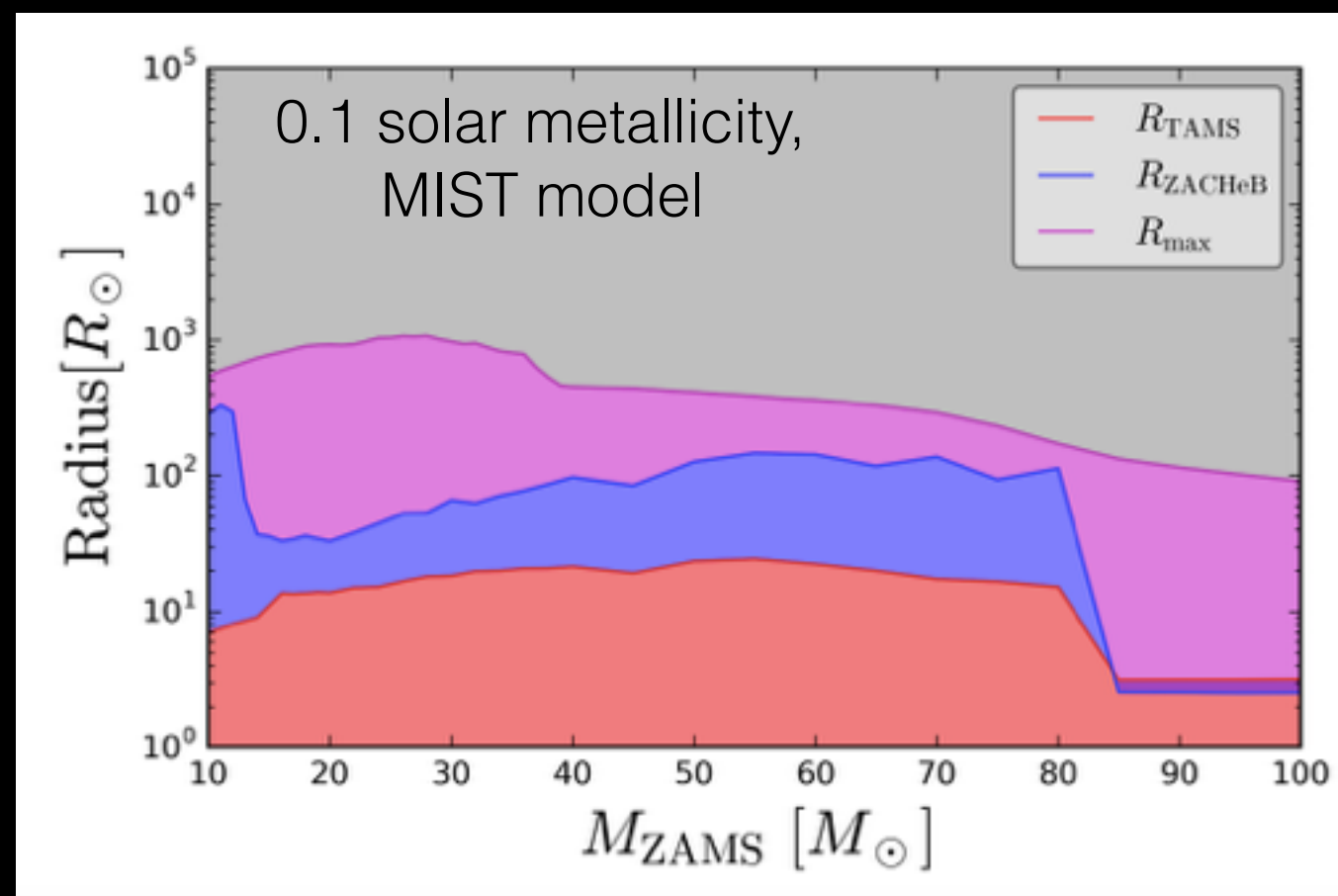
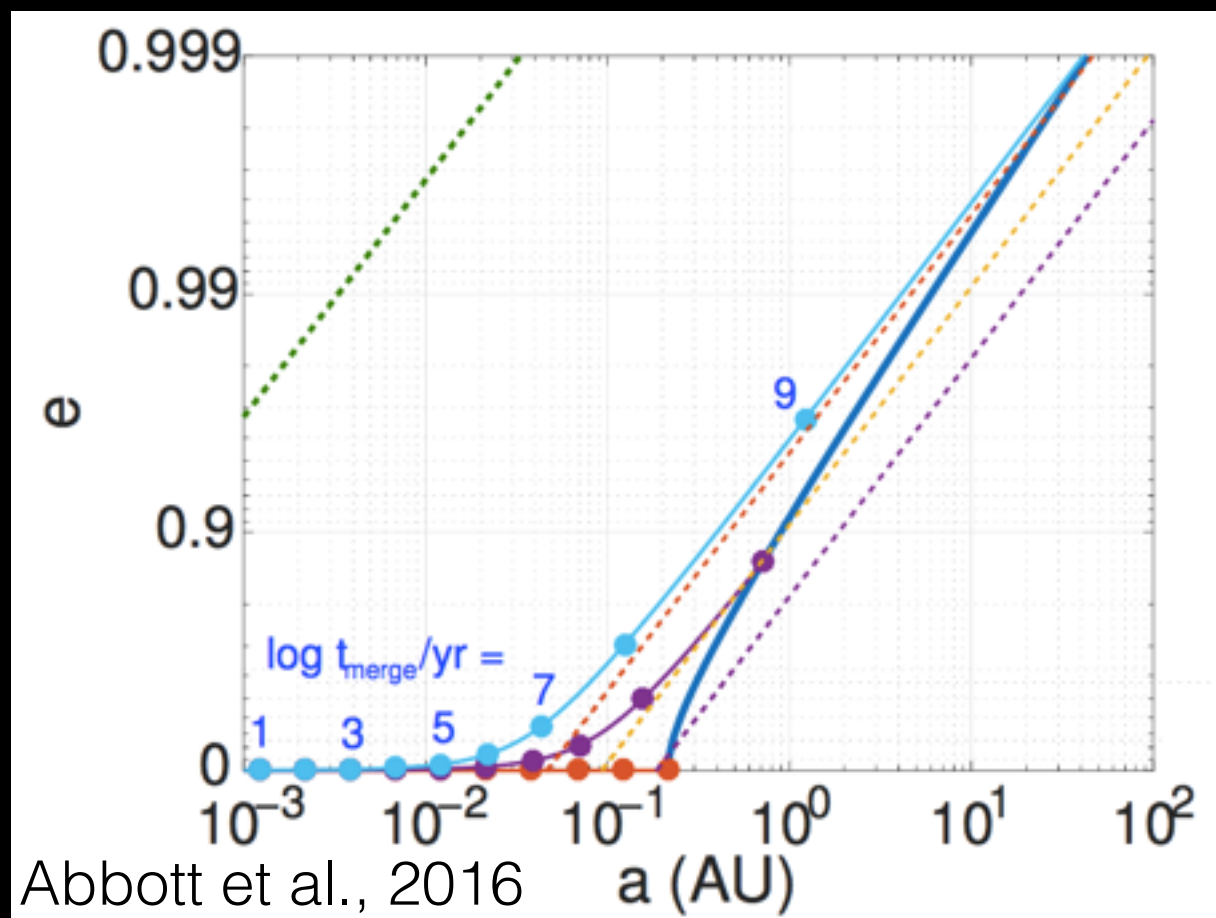


The mass problem



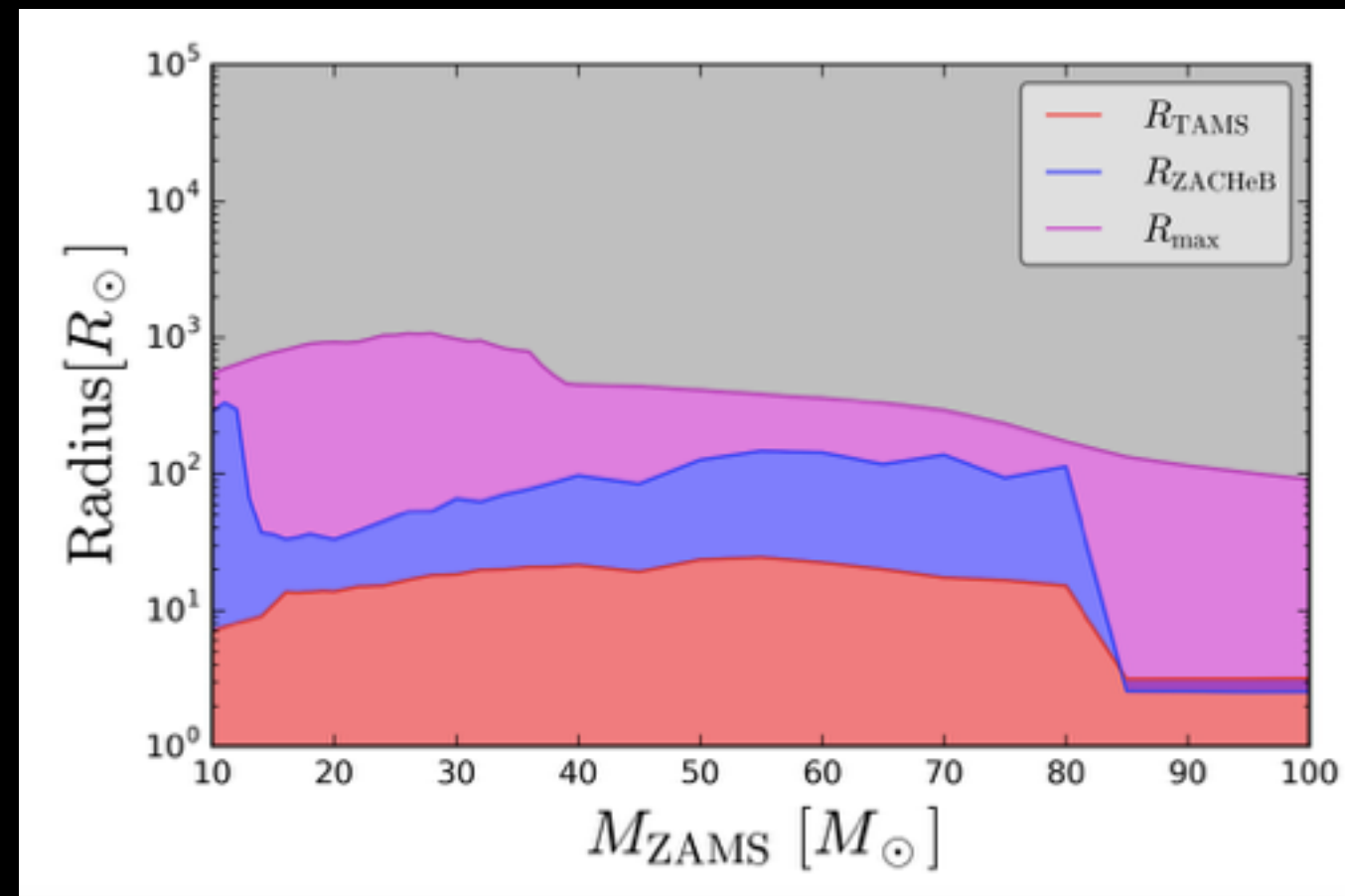
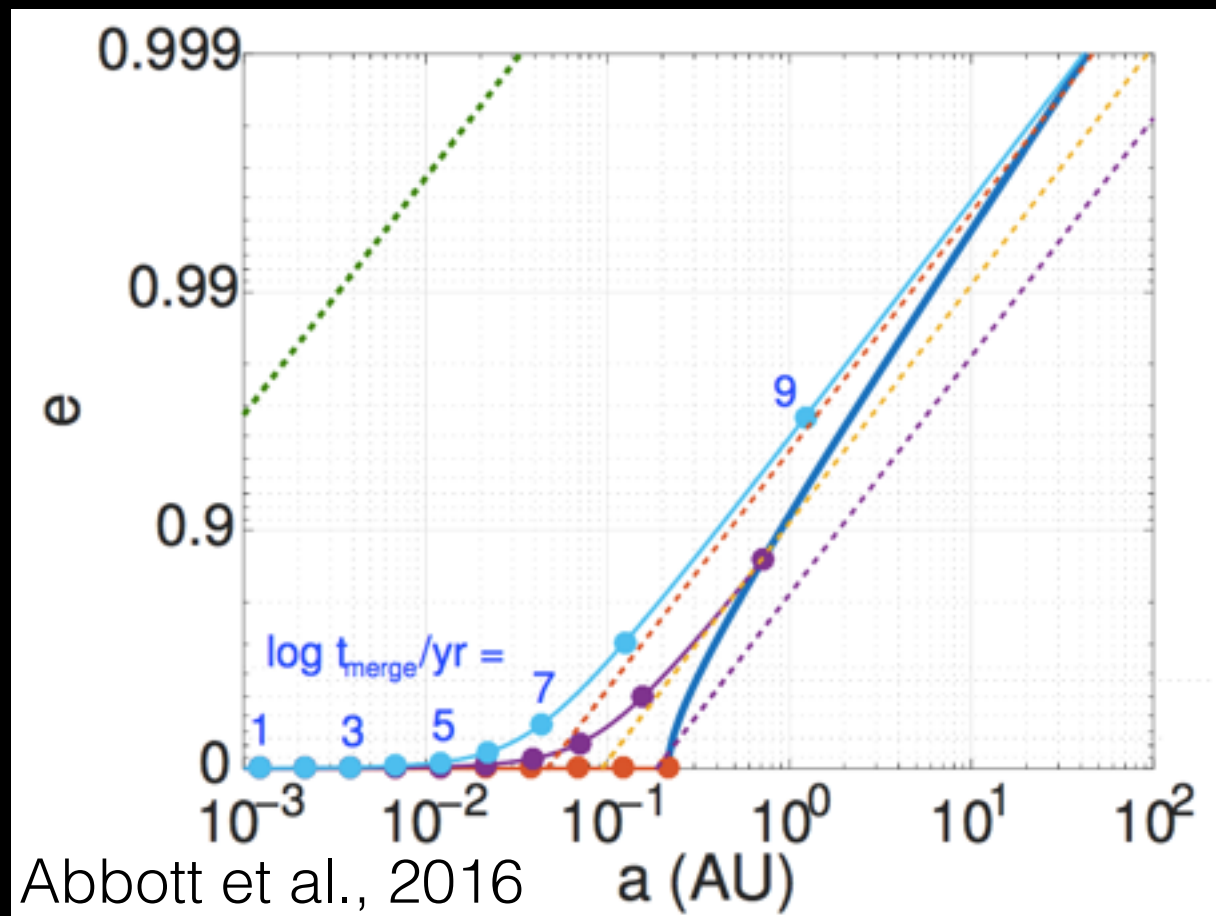
Belczynski+ (2010), adapted in Abbott+ (2016)

The separation problem



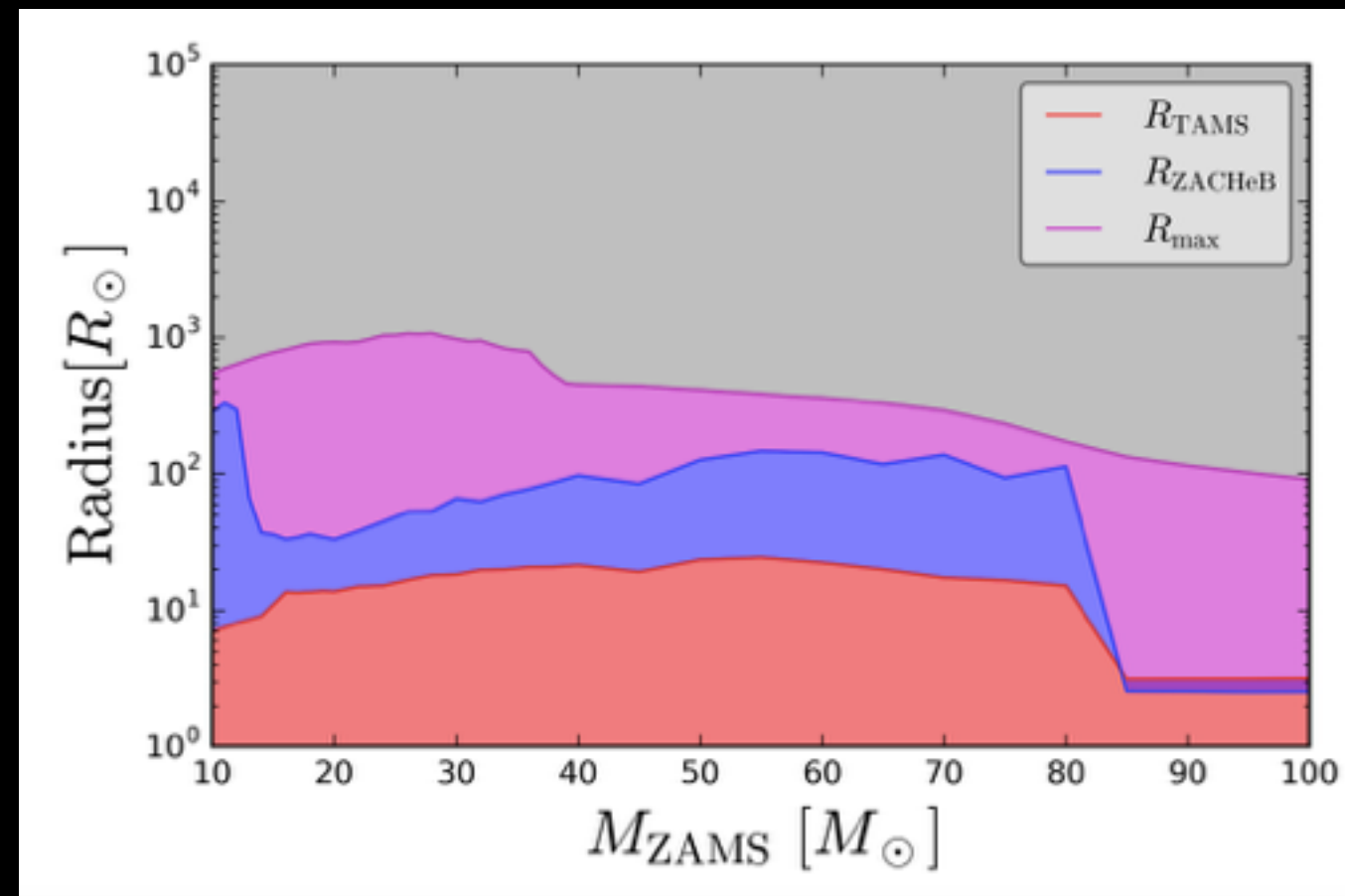
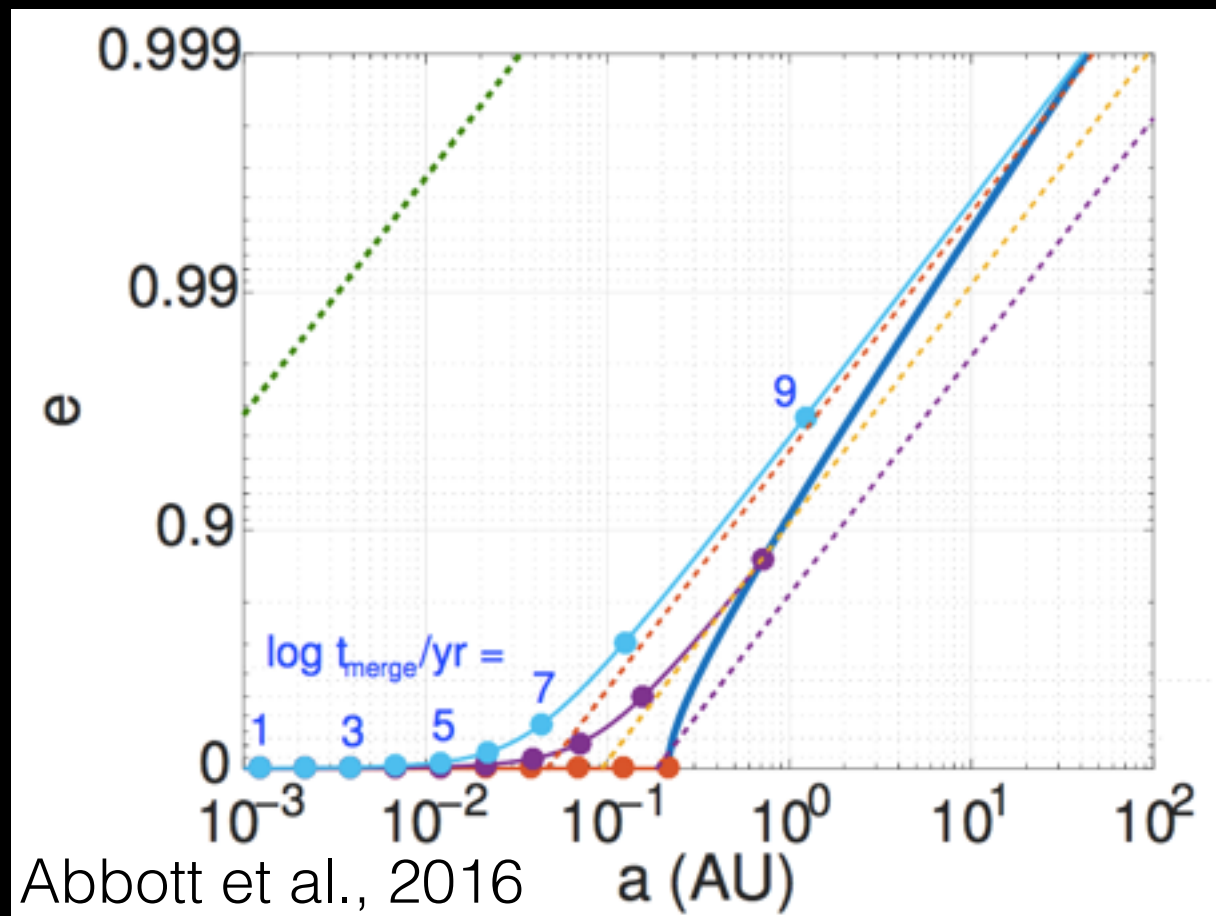
MIST: Dotter (2016), Choi+ (2016)
based on MESA, Paxton+ (2011, 2013, 2015)

The separation problem



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

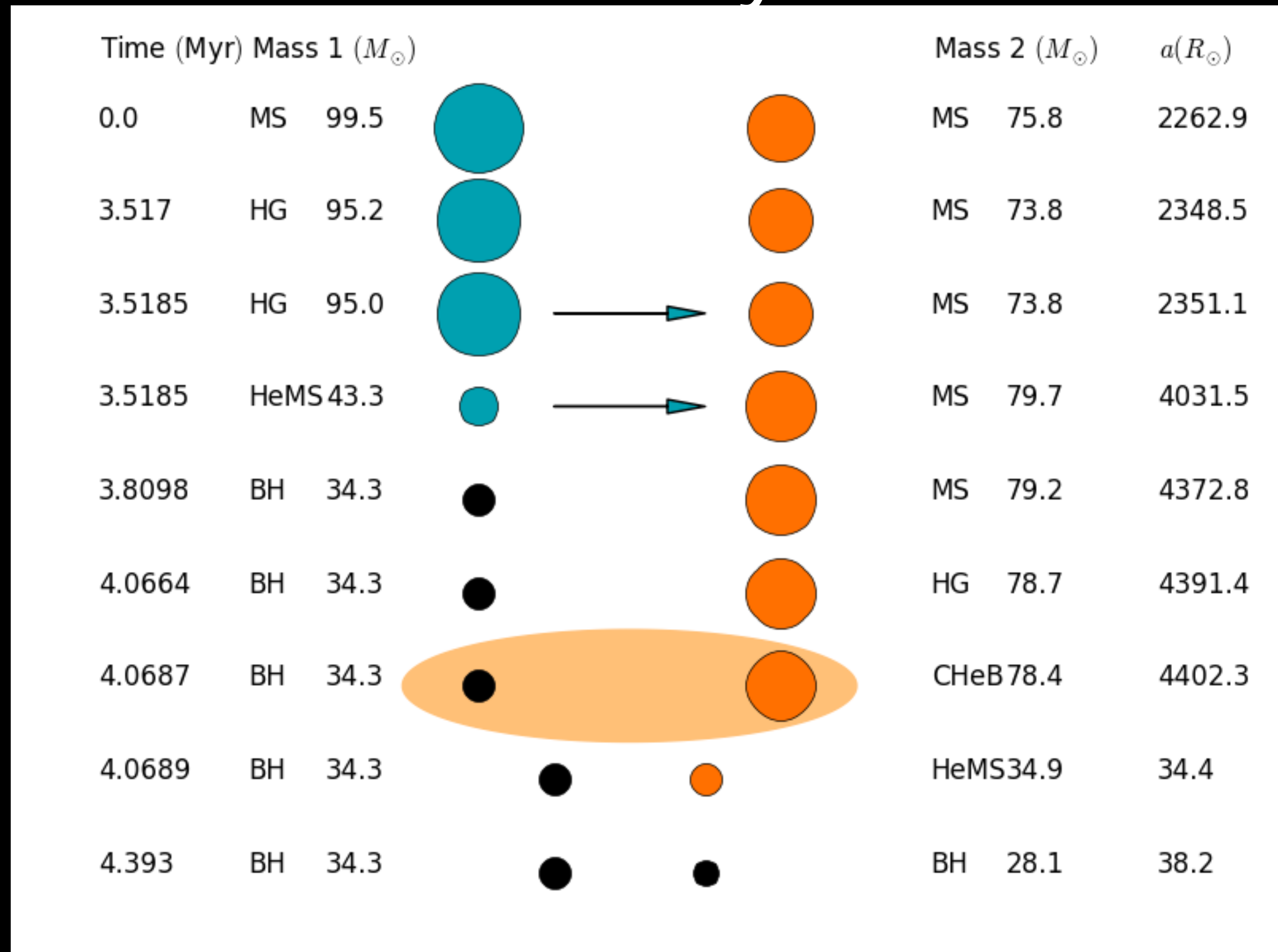
The separation problem



- Harden the binary after stars evolved: classical binary evolution via a common envelope

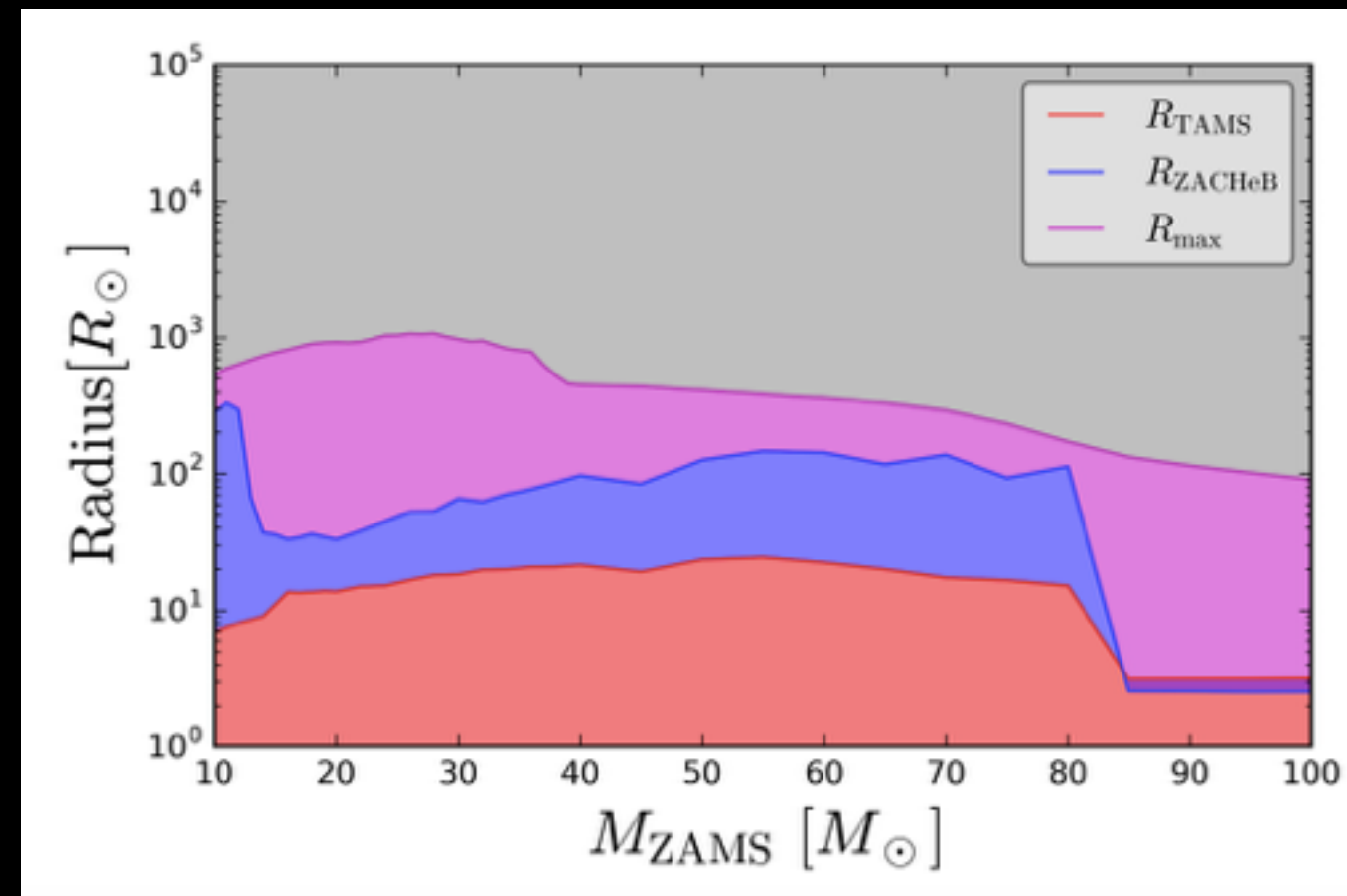
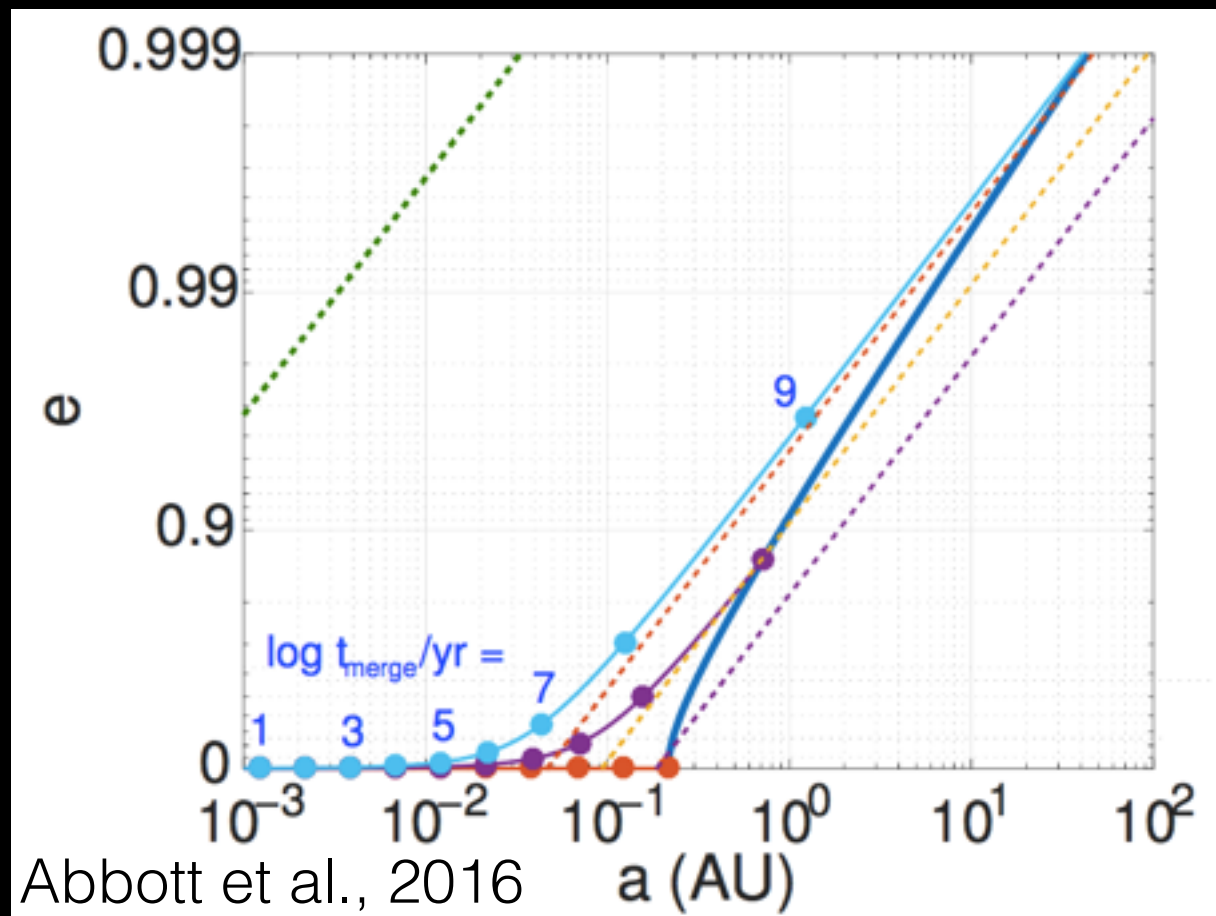
- Tutukov & Yungelson 1973, 1993; Lipunov, Postnov & Prokhorov (1997), Bethe & Brown (1998), Bloom, Sigurdsson & Pols (1999), De Donder & Vanbeveren (2004), Grishchuk et al. (2001), Nelemans (2003), Voss & Tauris (2003), Pfahl, Podsiadlowski & Rappaport (2005), Dewi, Podsiadlowski & Sena (2006), Kalogera 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

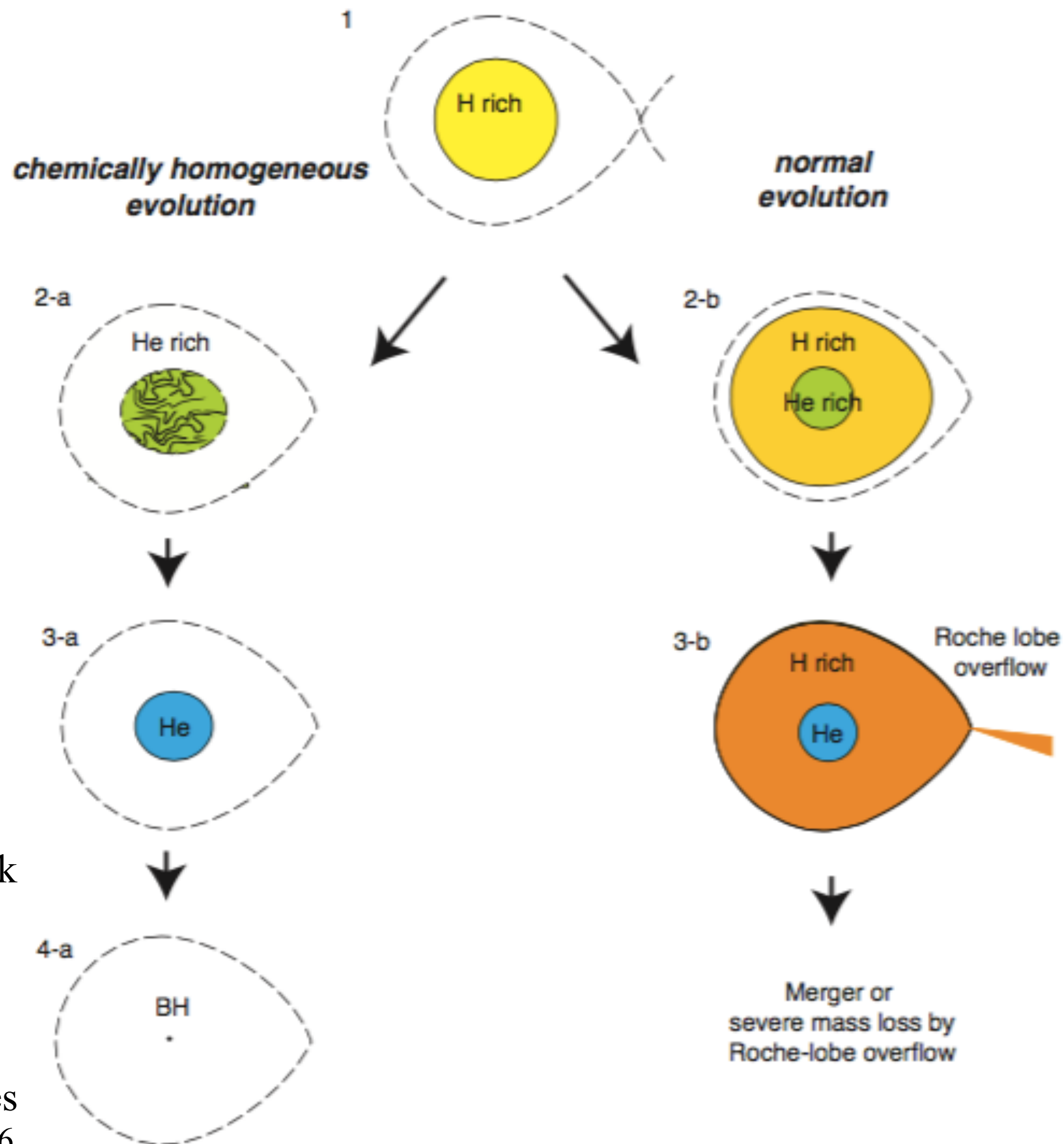


Stevenson, Vigna Gomez, Mandel, Perkins, Barrett, de Mink, 2016

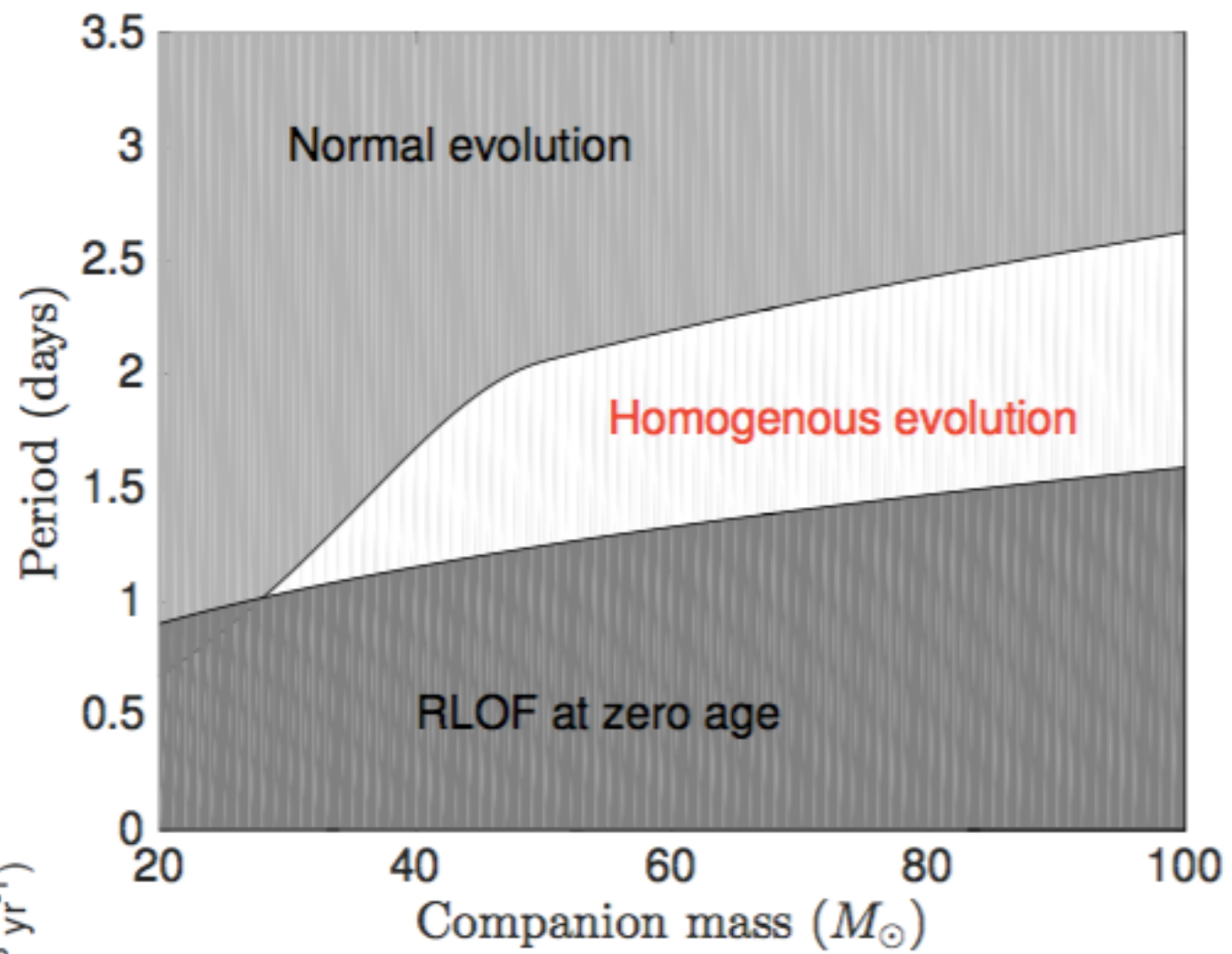
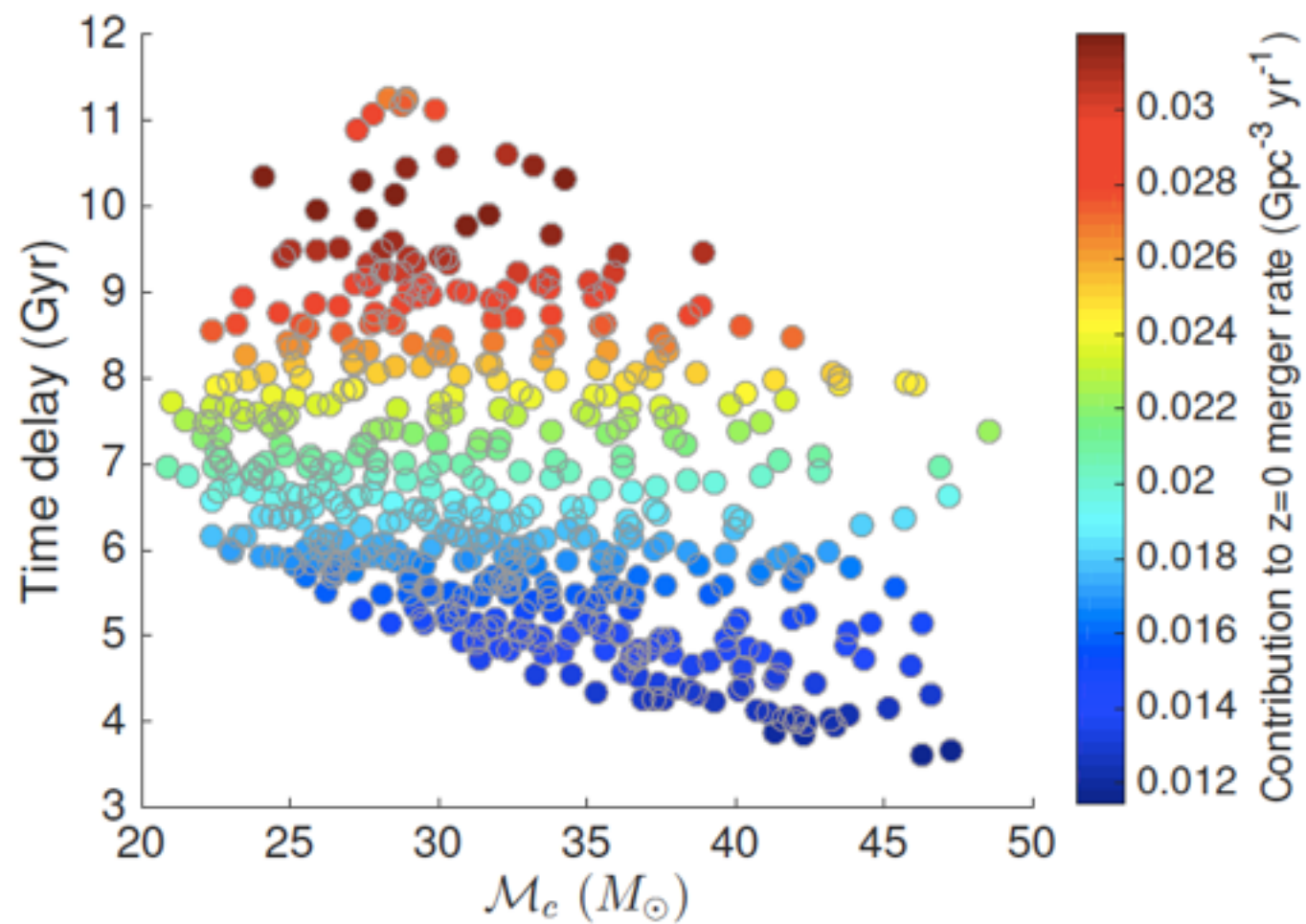
The separation problem



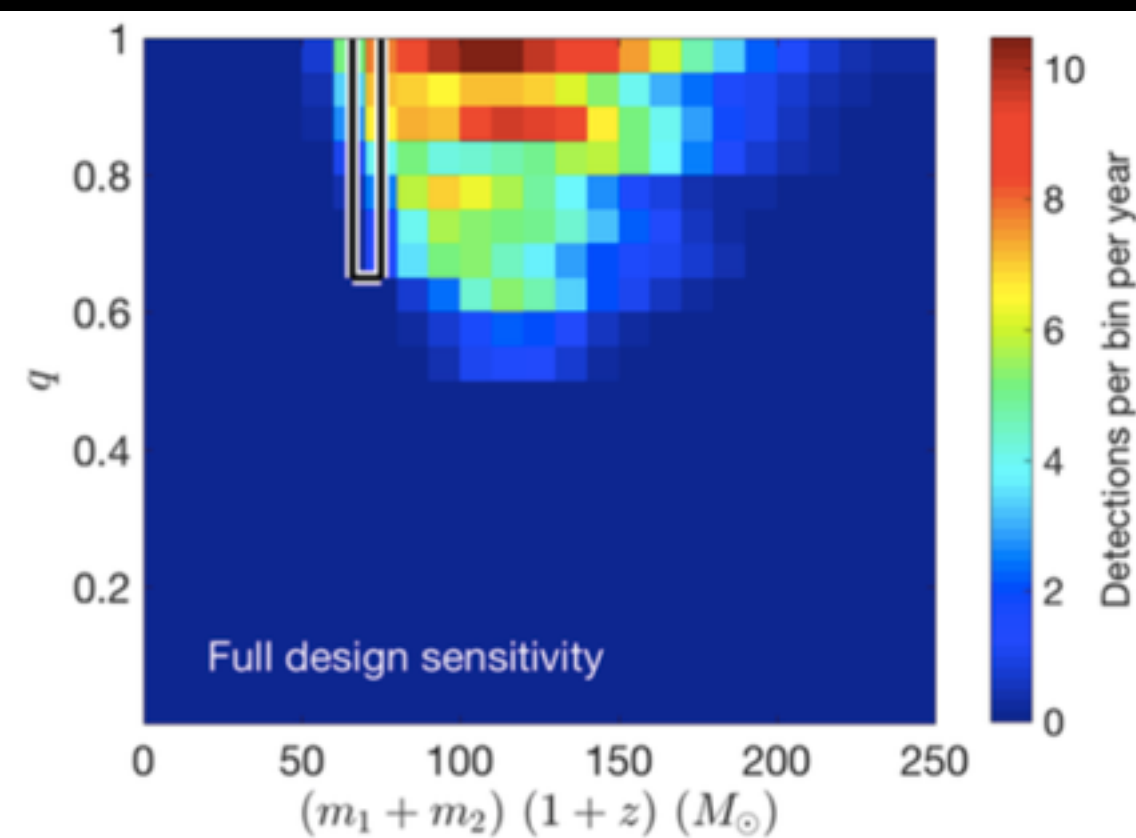
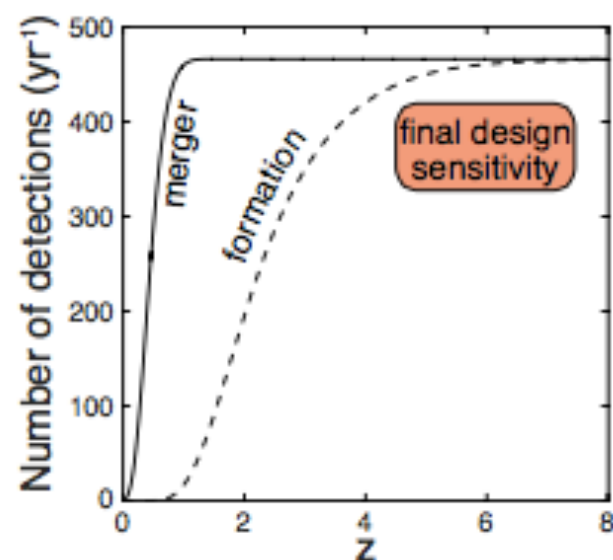
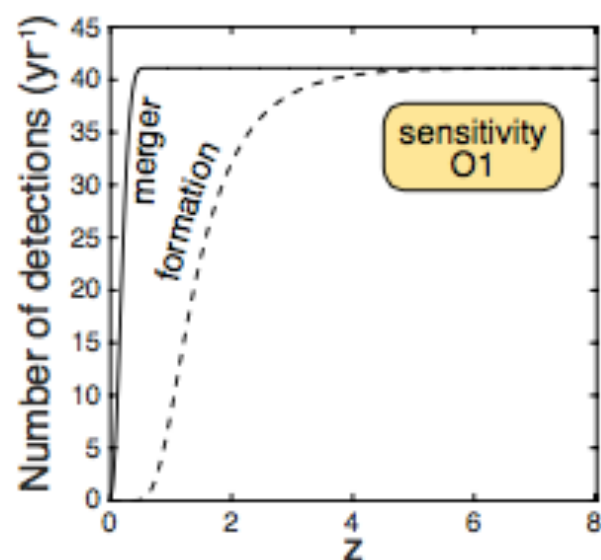
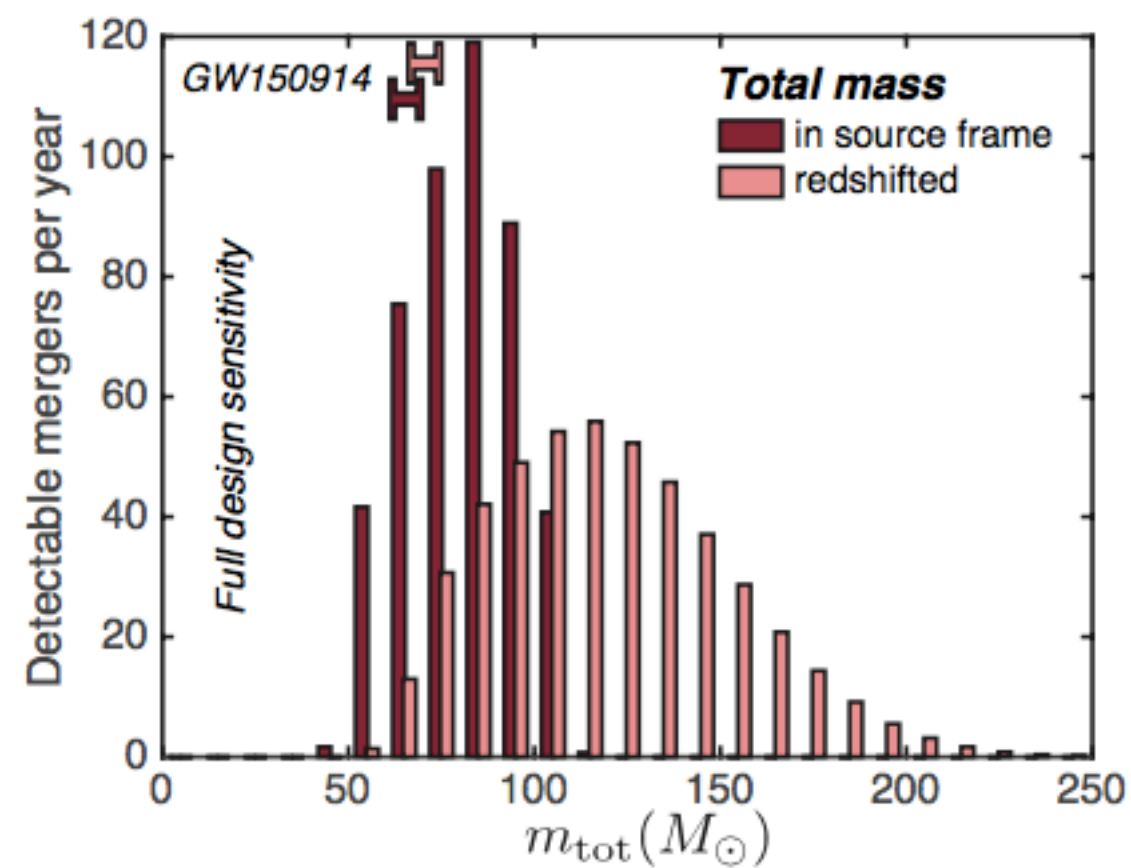
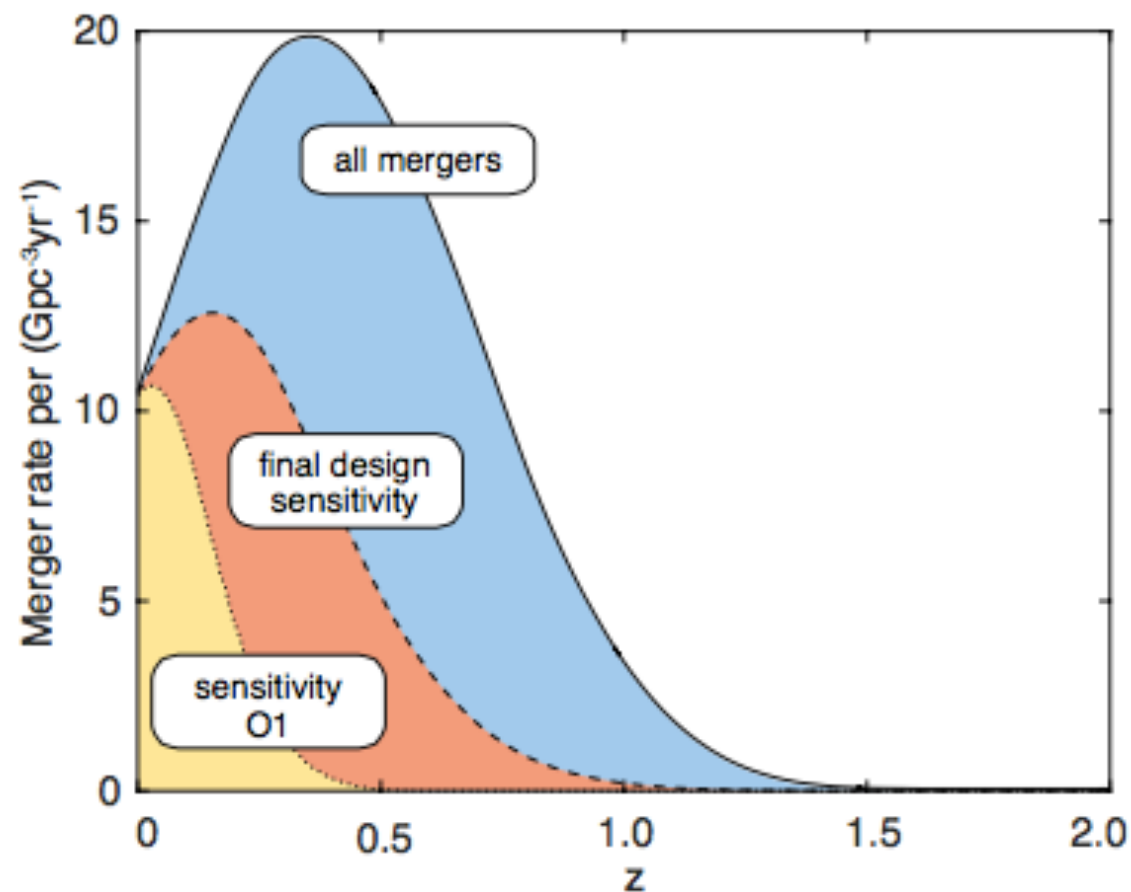
- Harden the binary after stars evolved
- Don't let stars expand: chemically homogeneous evolution
 - Mandel & de Mink, 2016; Marchant+, 2016; de Mink & Mandel, 2016
- Let stars evolve before they make a binary



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

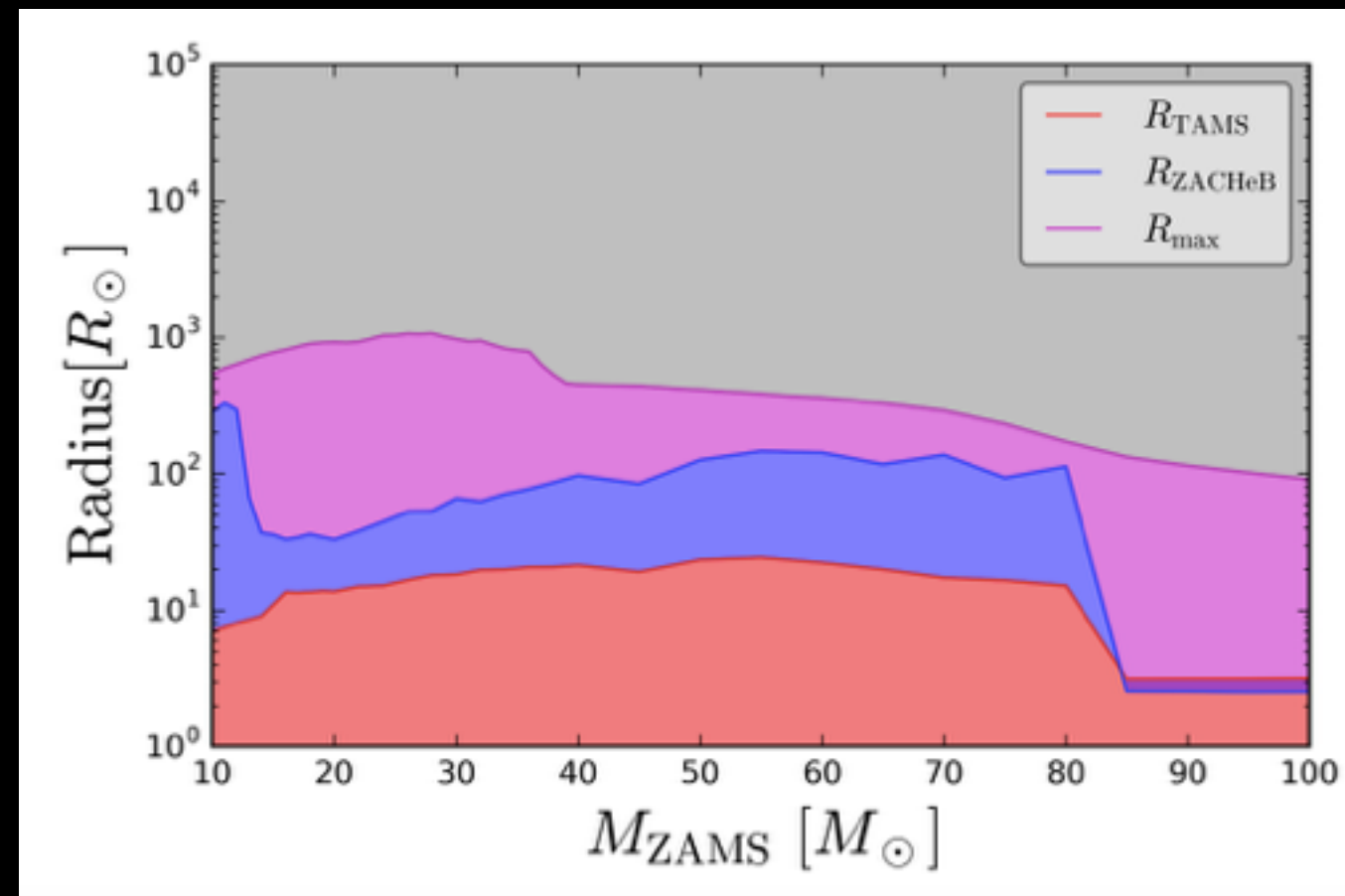
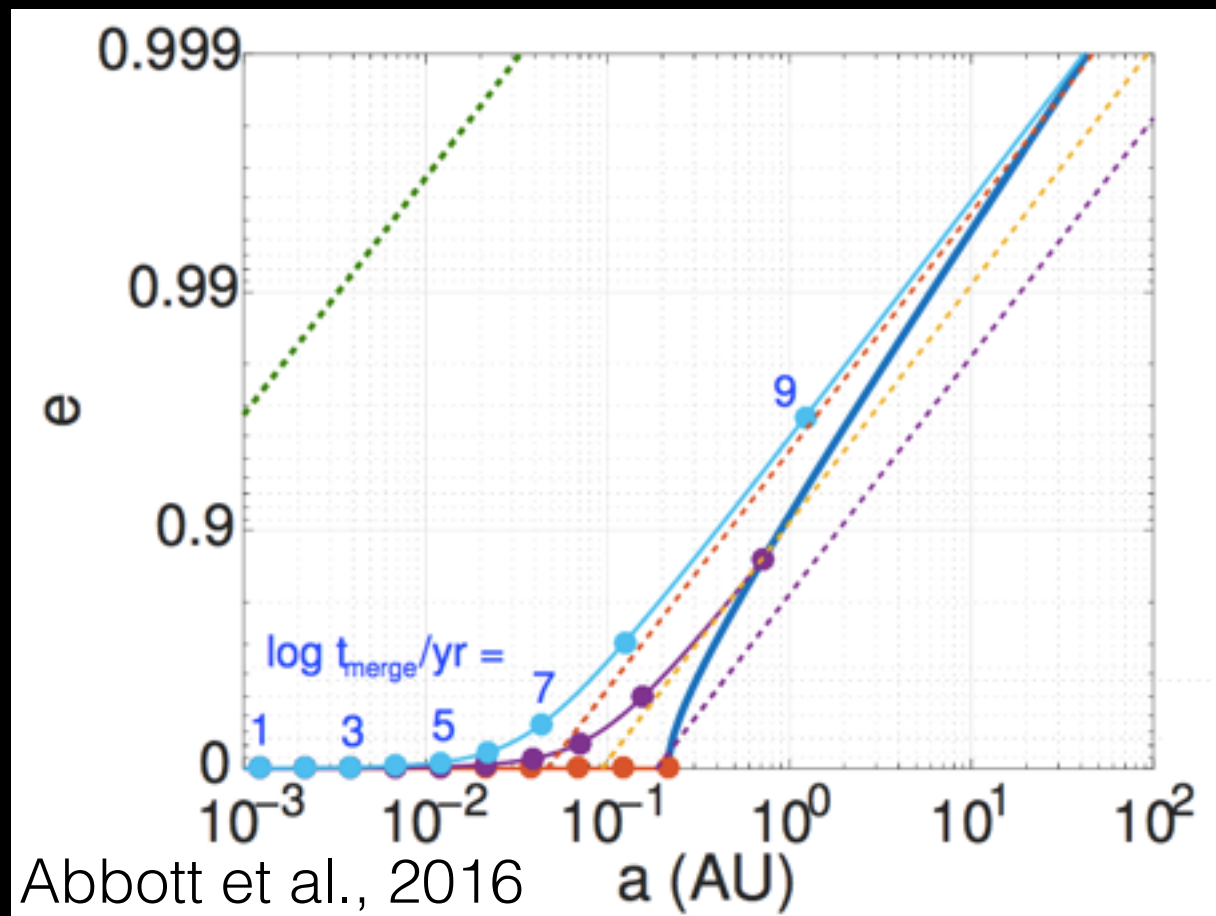


Mandel & de Mink, 2016

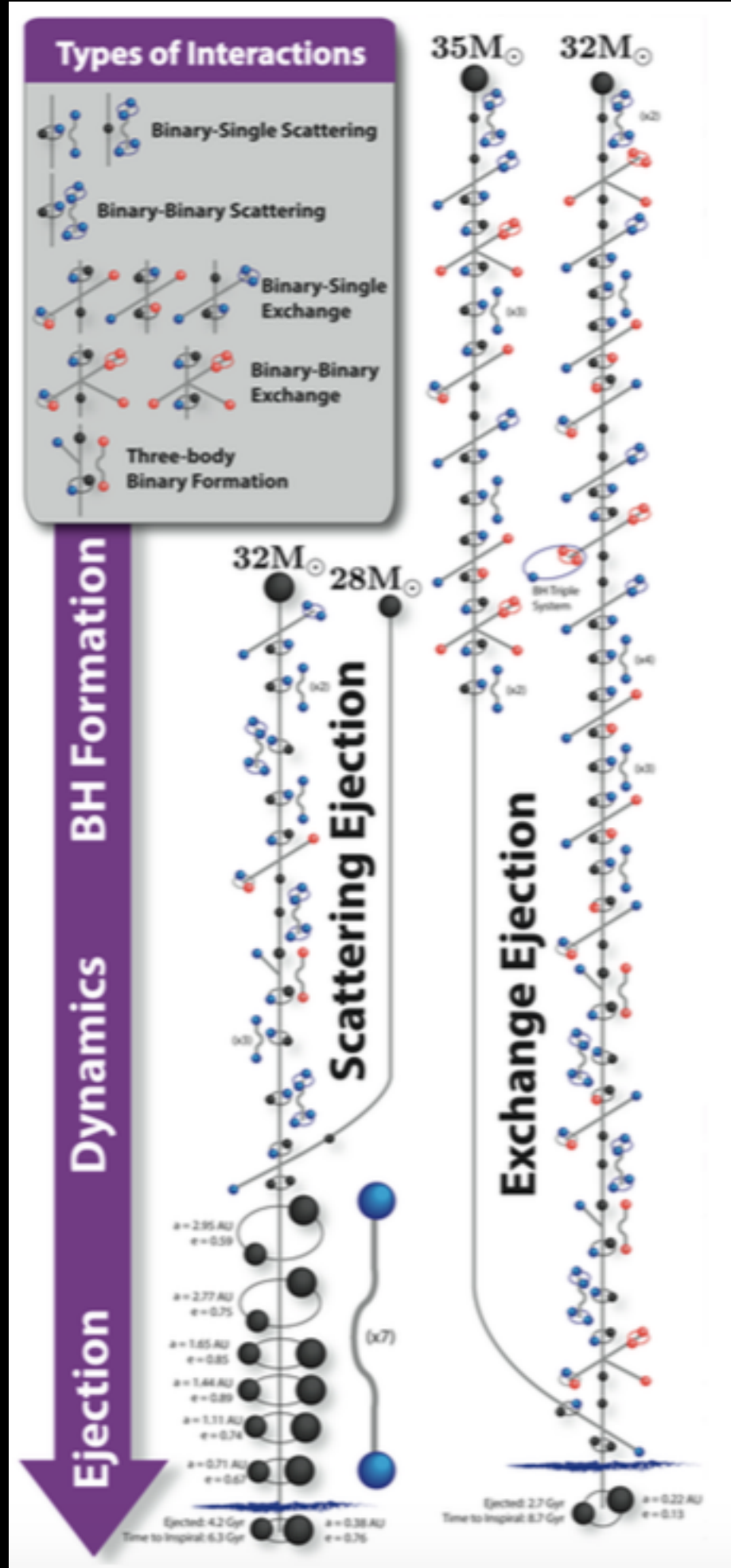


de Mink & Mandel, 2016

The separation problem



- Let stars evolve before they make a binary: dynamical format in clusters
 - Stellar and globular clusters: Sigurdsson & Hernquist (1993); Kulkarni+ (1993); Portegies Zwart & McMillan (2000); Gültekin+ (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)

C 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



Alejandro Vigna Gómez



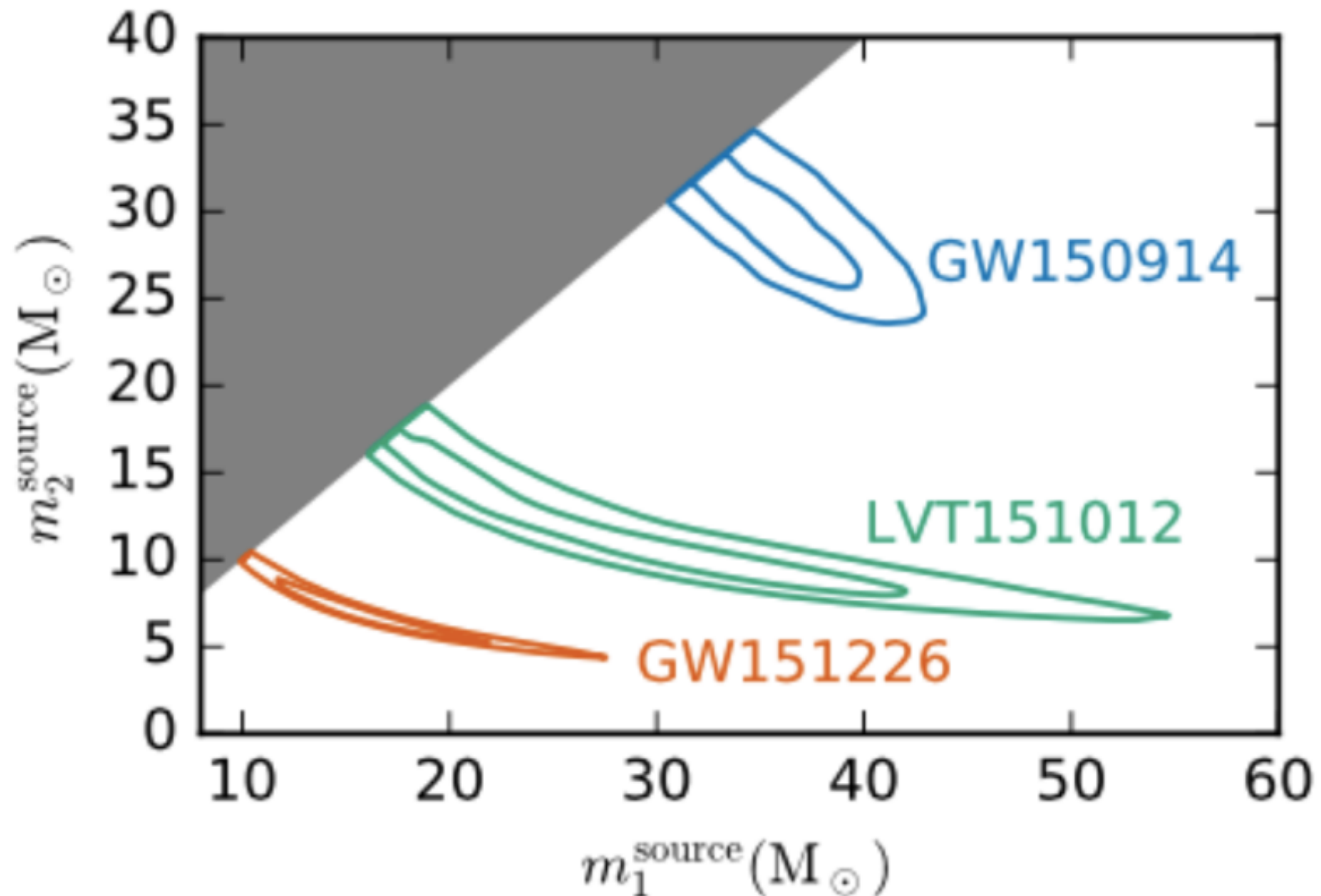
Simon Stevenson



Jim Barrett

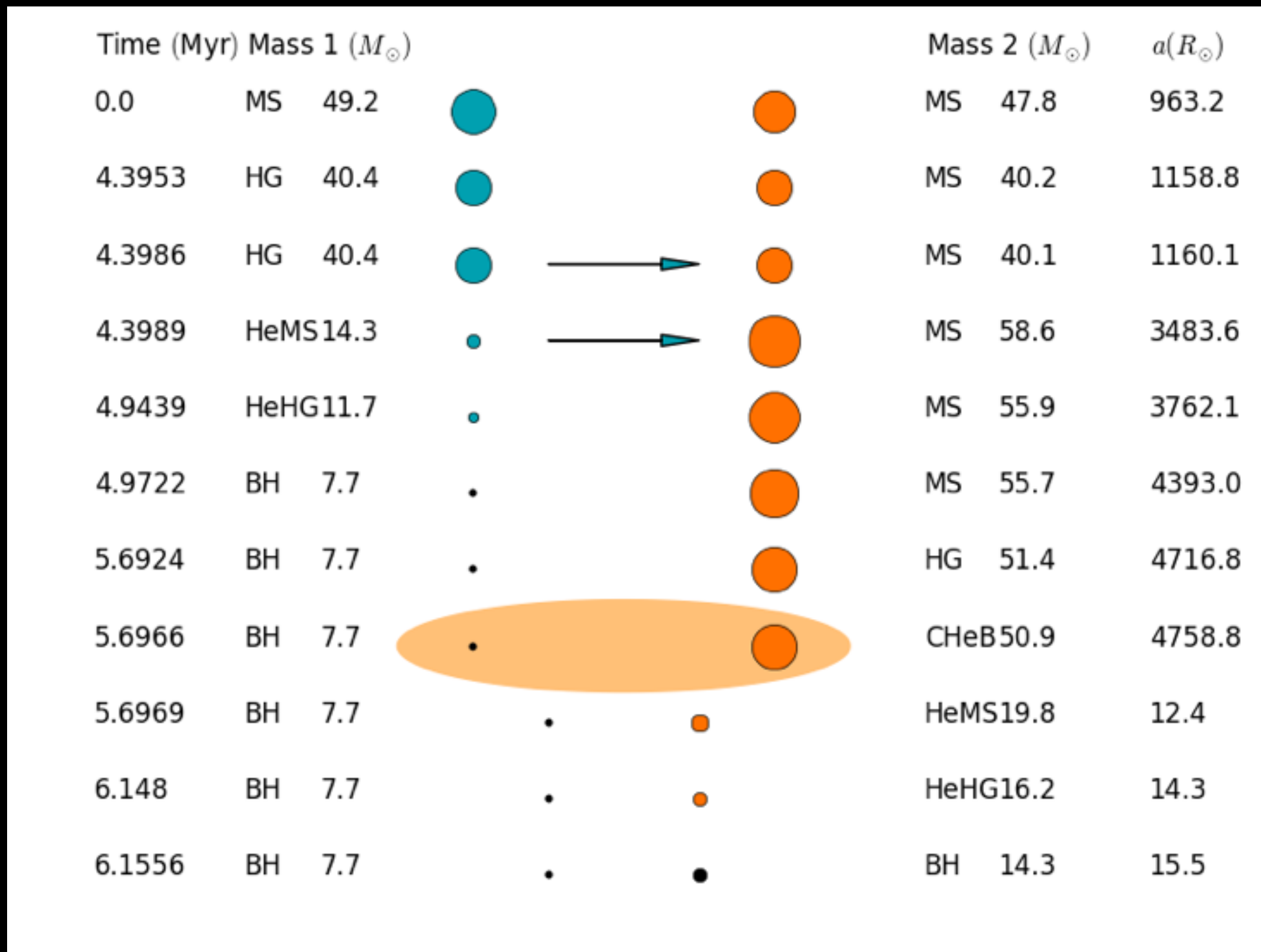
Key collaborators / advisors: Christopher Berry, Will Farr, Selma de Mink, Natasha Ivanova, Vicky Kalogera, Chris Belczynski, Gijs Nelemans, Philipp Podsiadlowski... **YOUR NAME COULD BE HERE!**

Population Synthesis

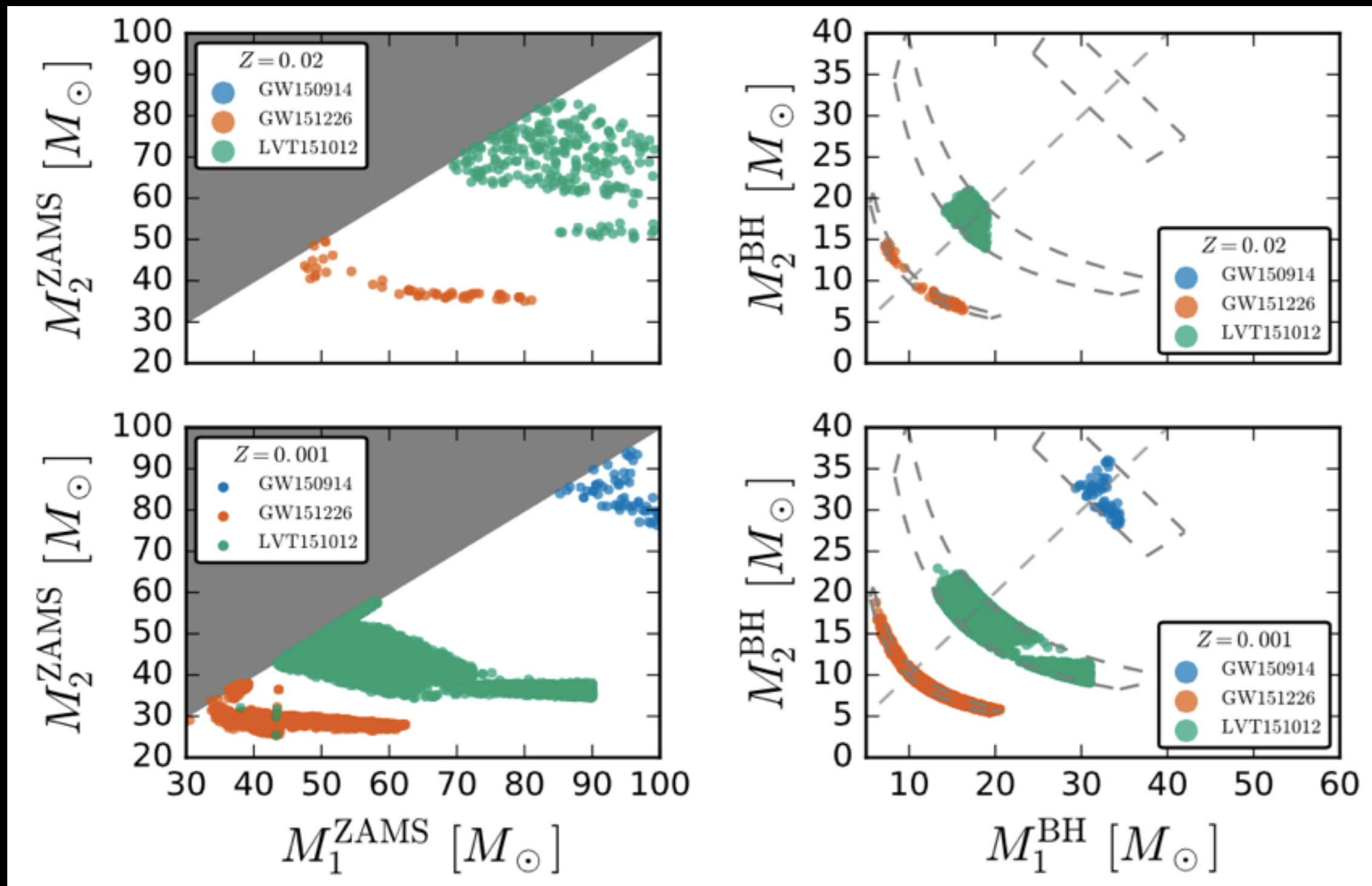


Abbott+ (LVC), 2016

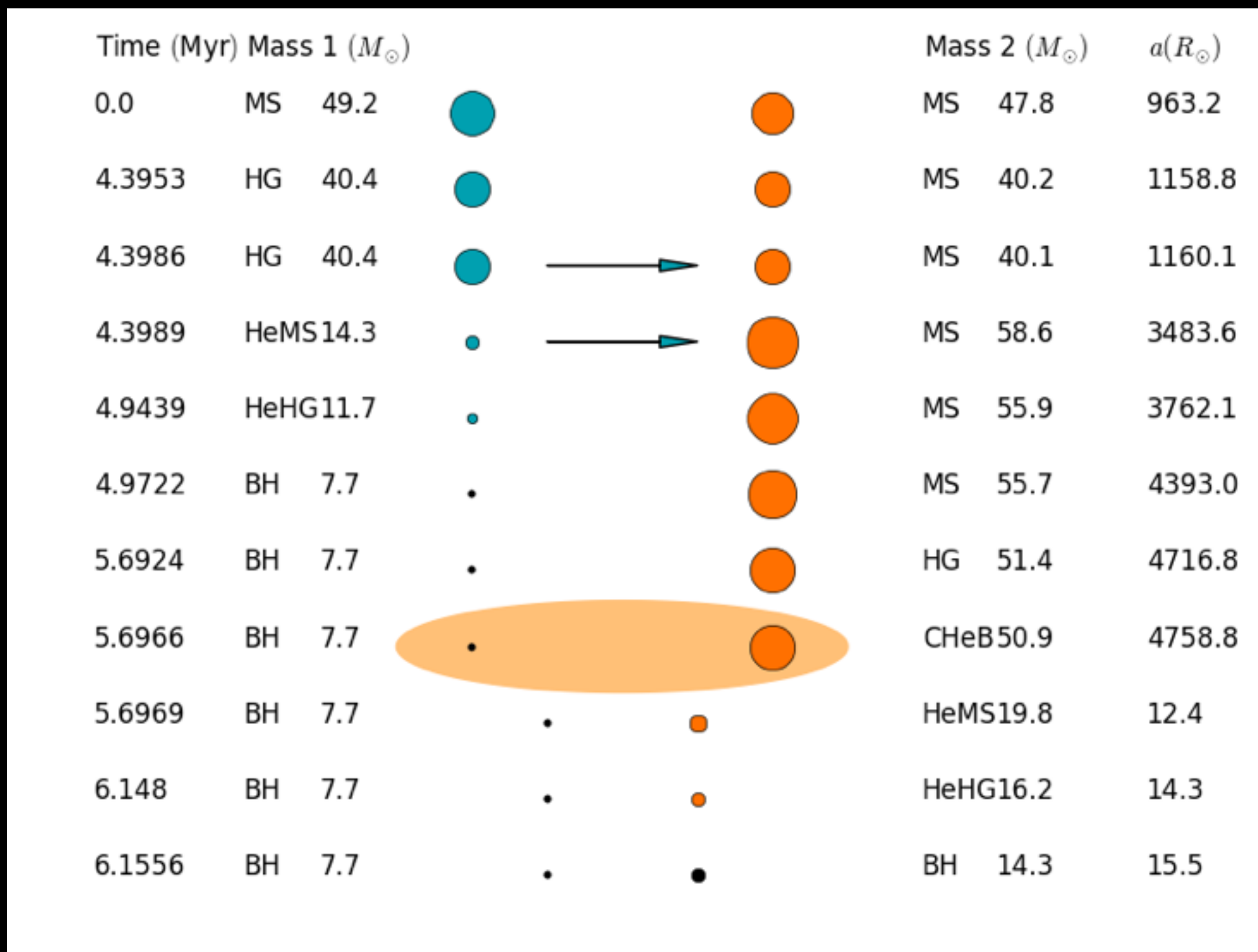
Population Synthesis

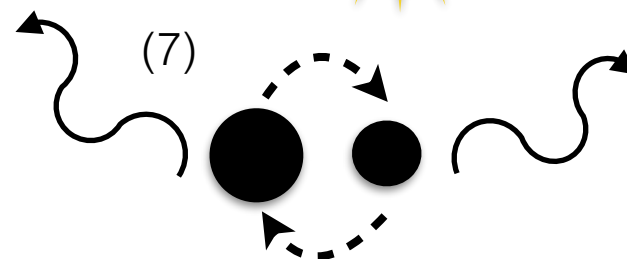
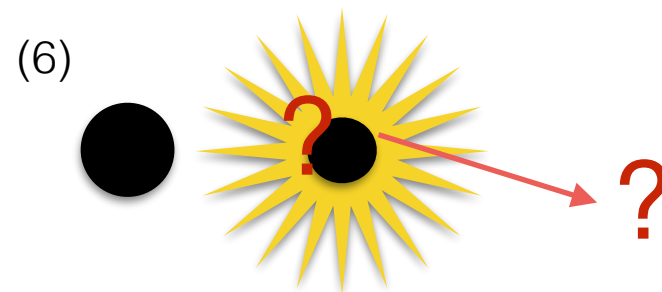
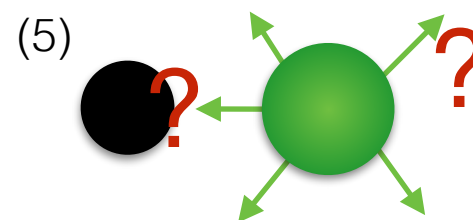
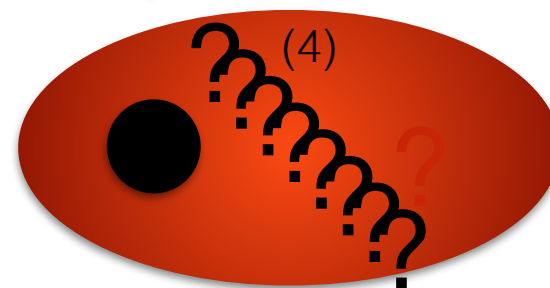
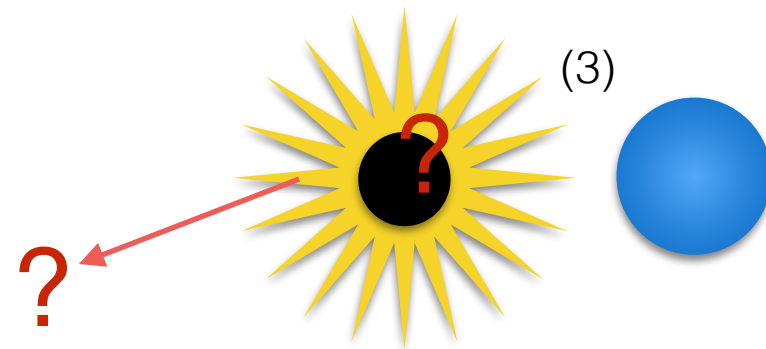
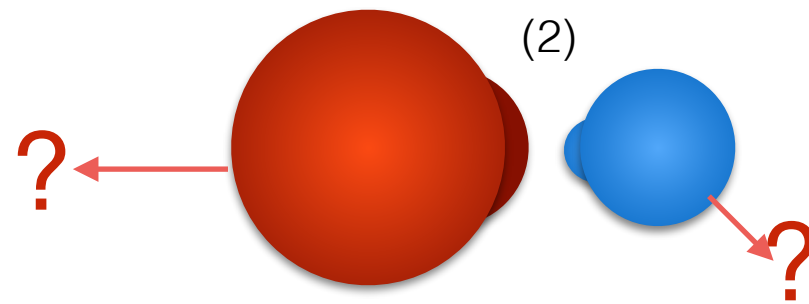
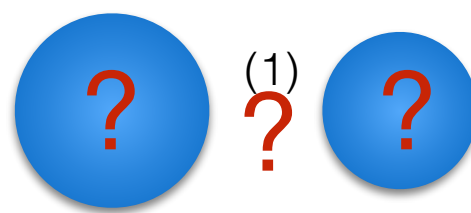


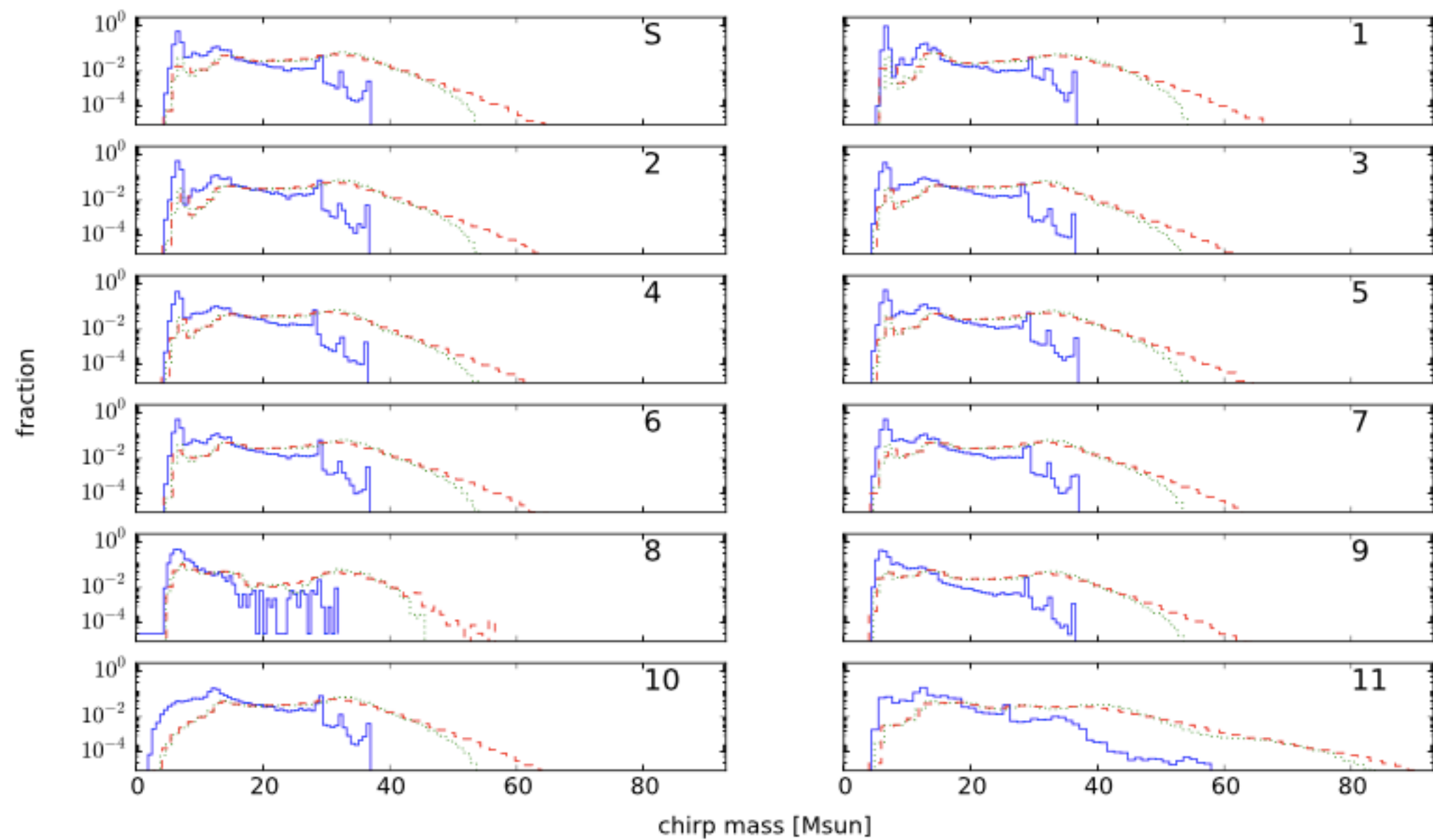
Population Synthesis



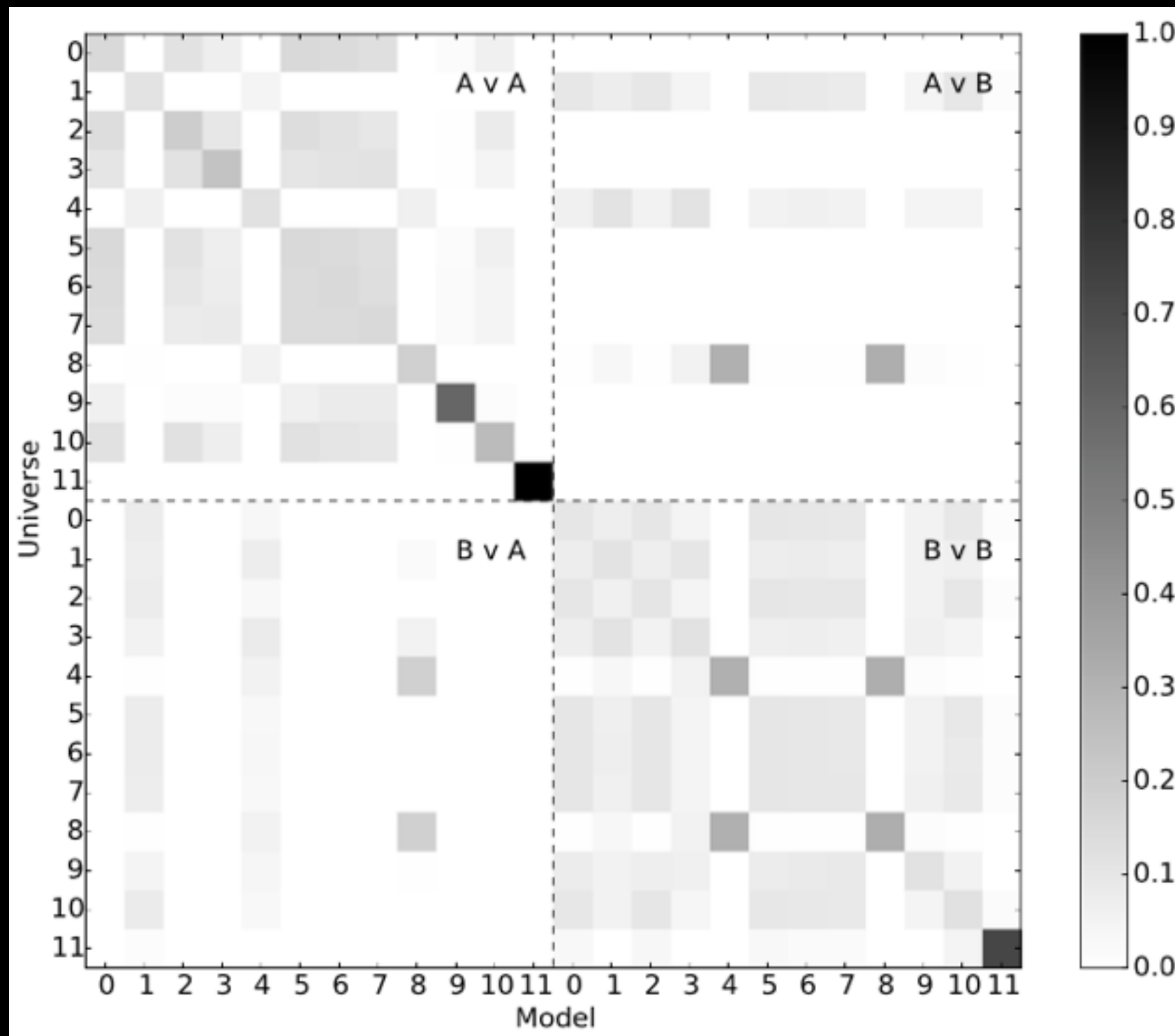
Interpolation

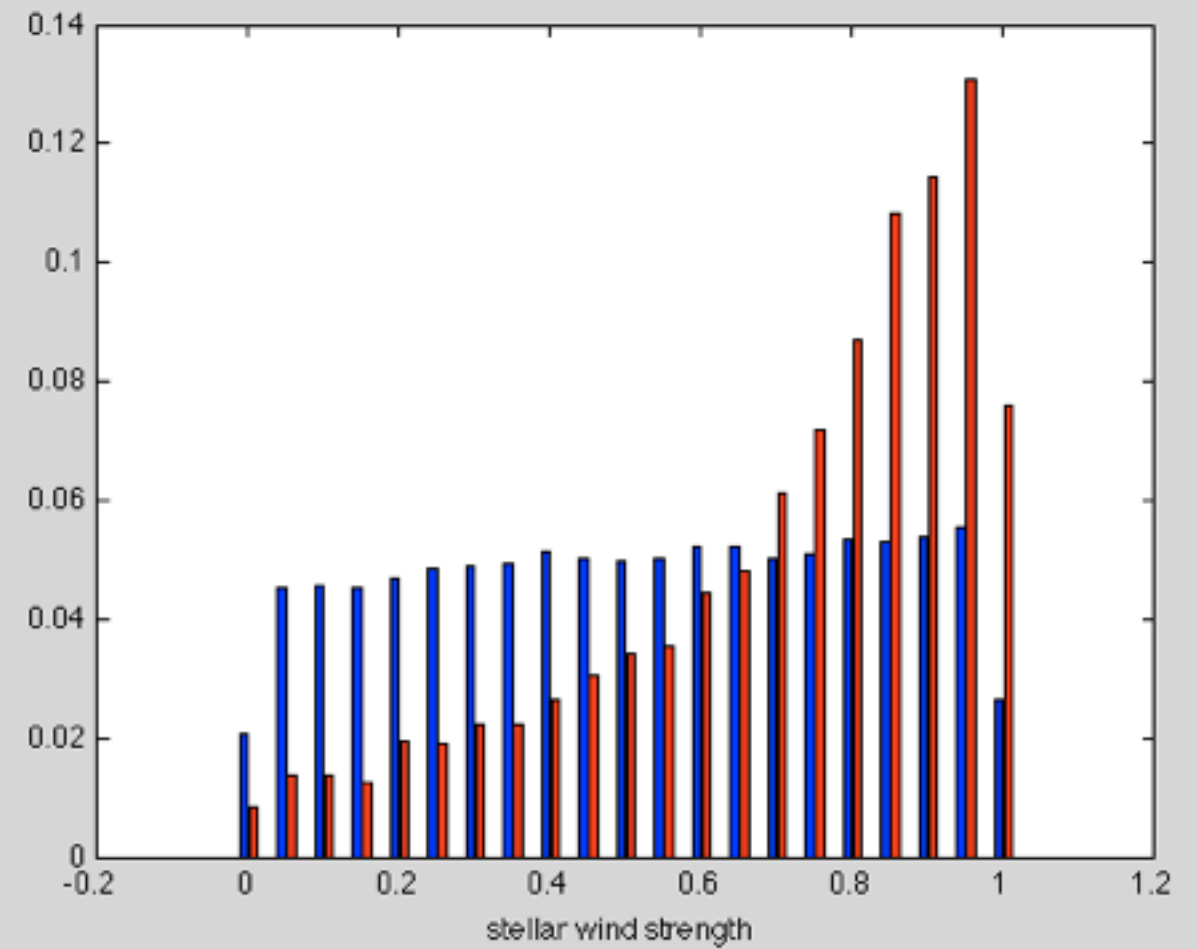
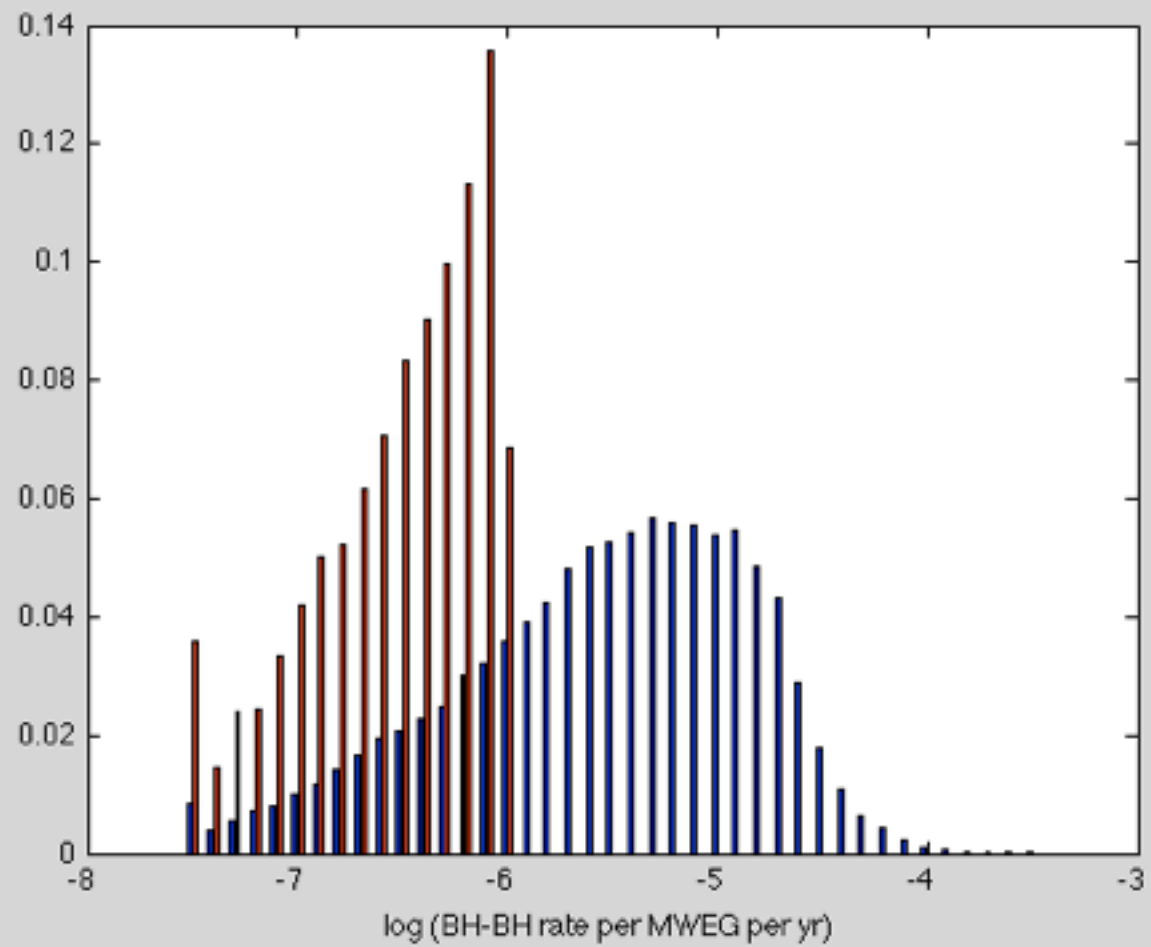






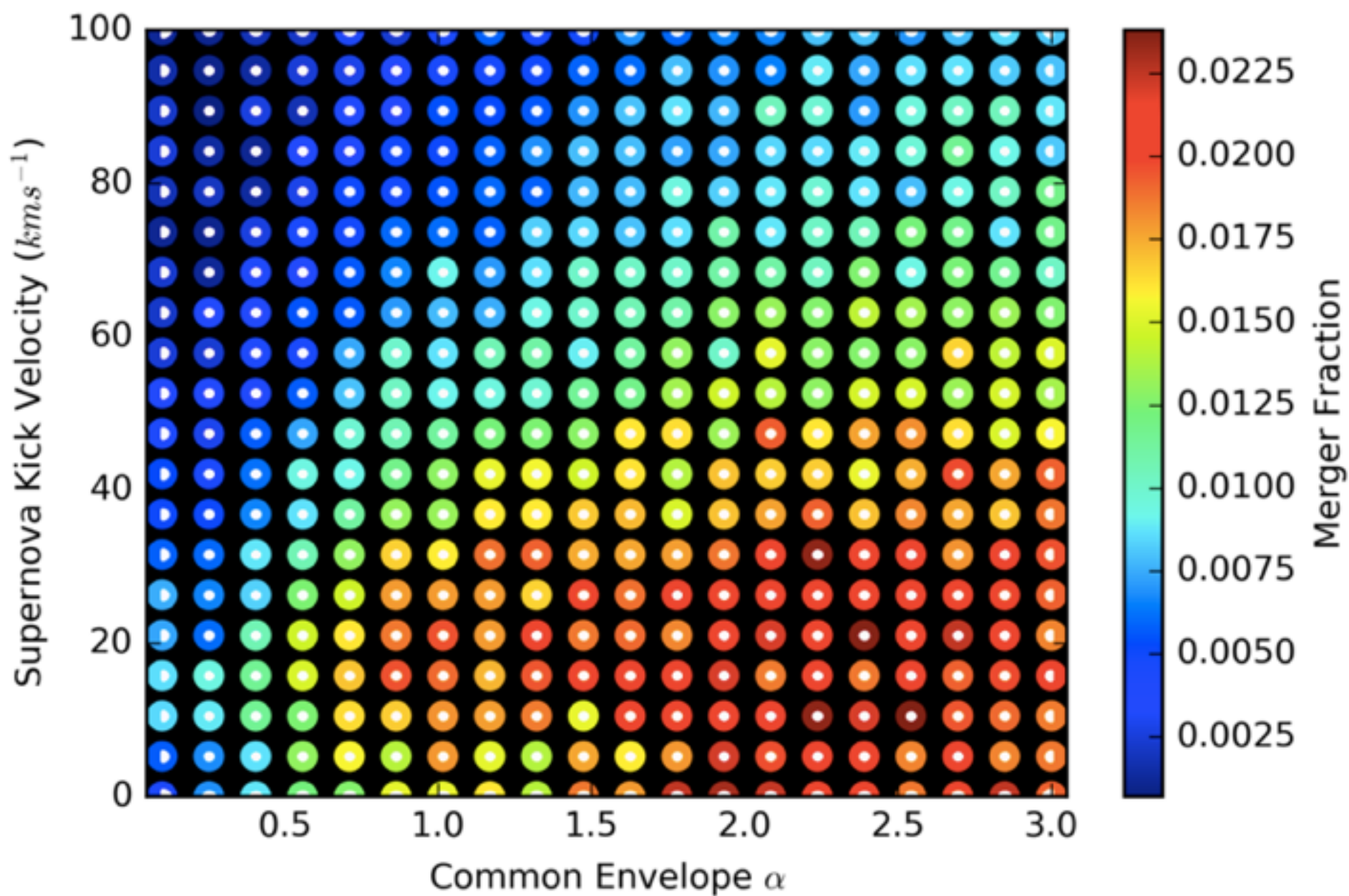
Stevenson+ 2015, from Dominik+ 2012





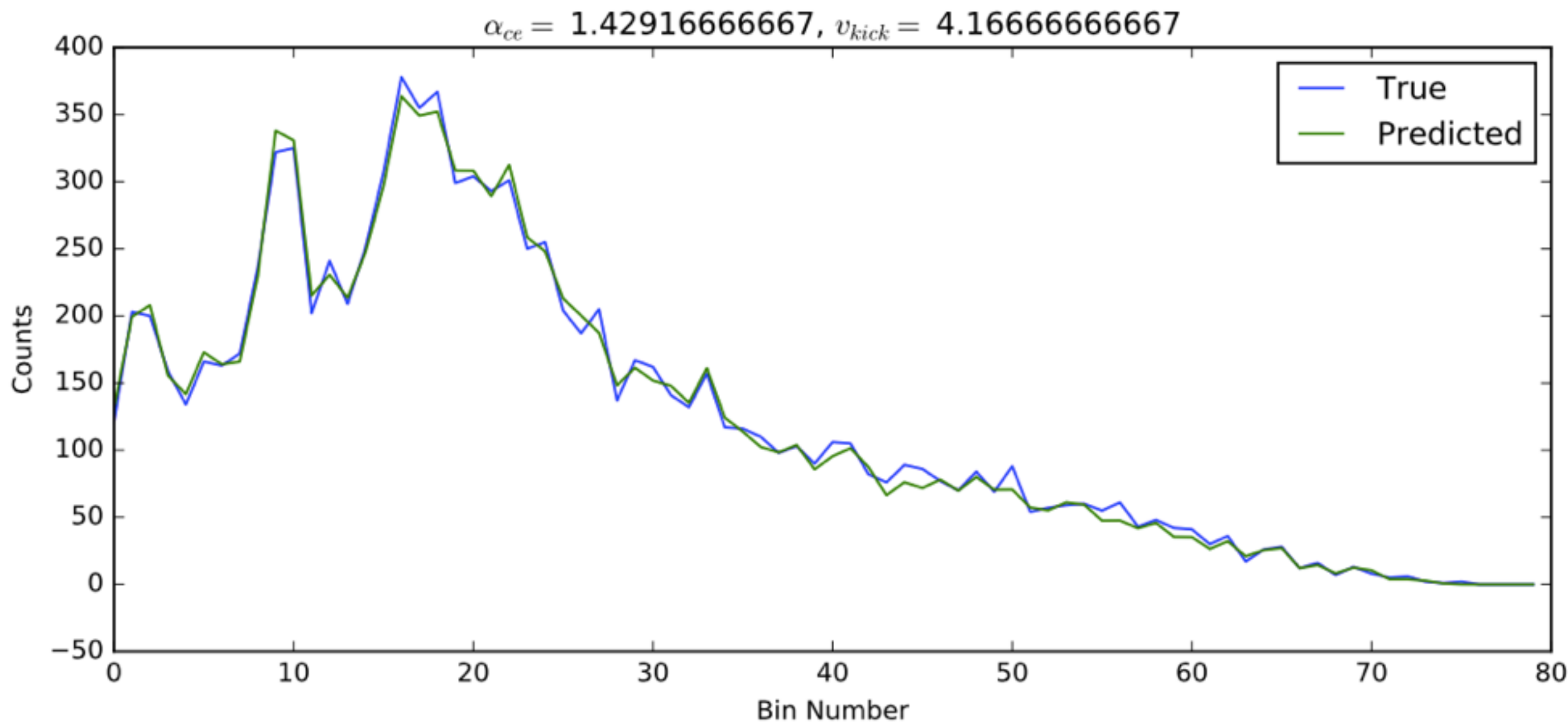
Mandel & O'Shaughnessy, 2010

Interpolation



Barrett et al., in prep.

Interpolation



Barrett et al., in prep.

Population Reconstruction



- Selection effects and measurement uncertainty

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

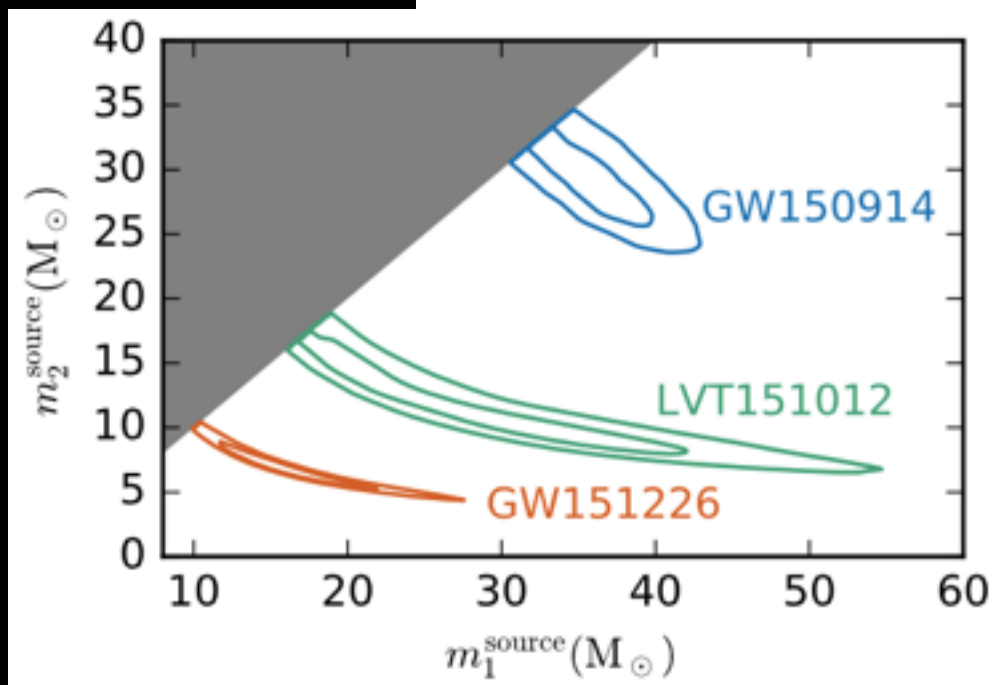
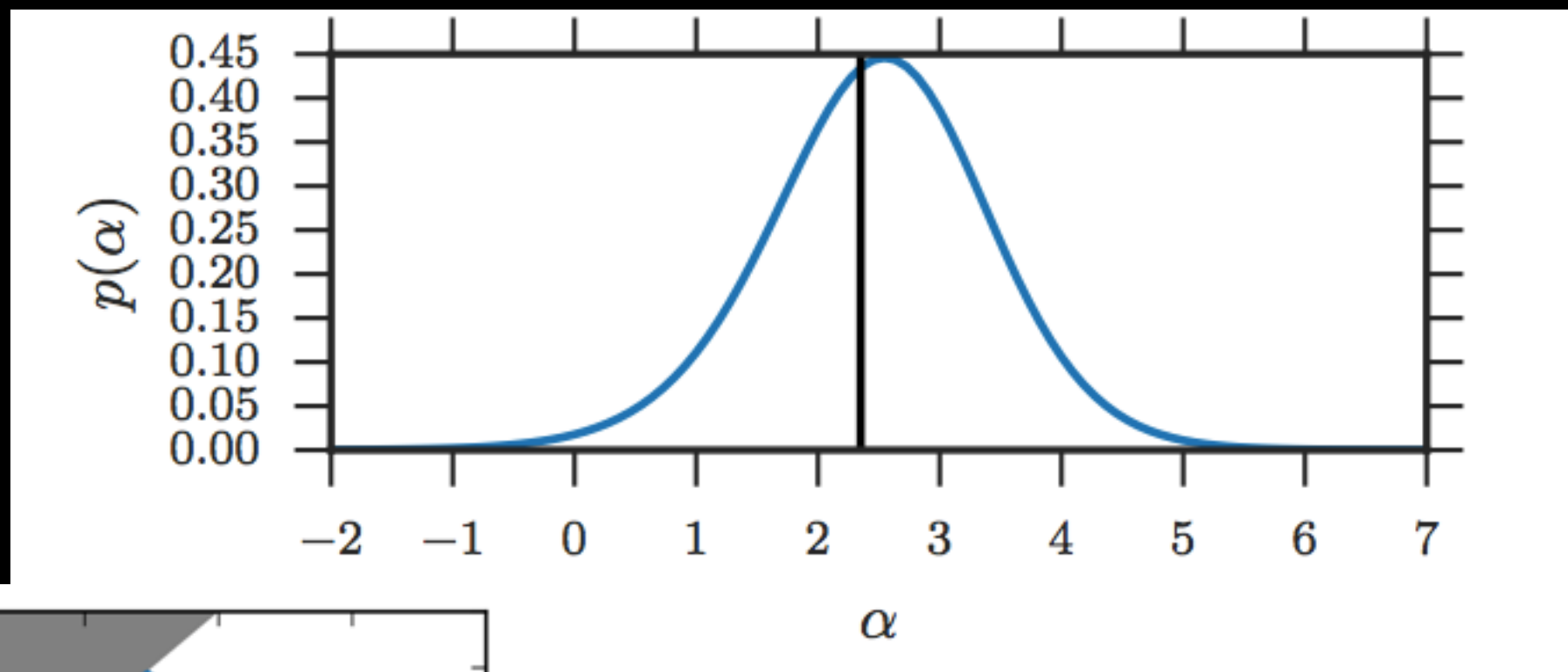
Mandel, Farr, Gair, in prep.

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

Population Reconstruction



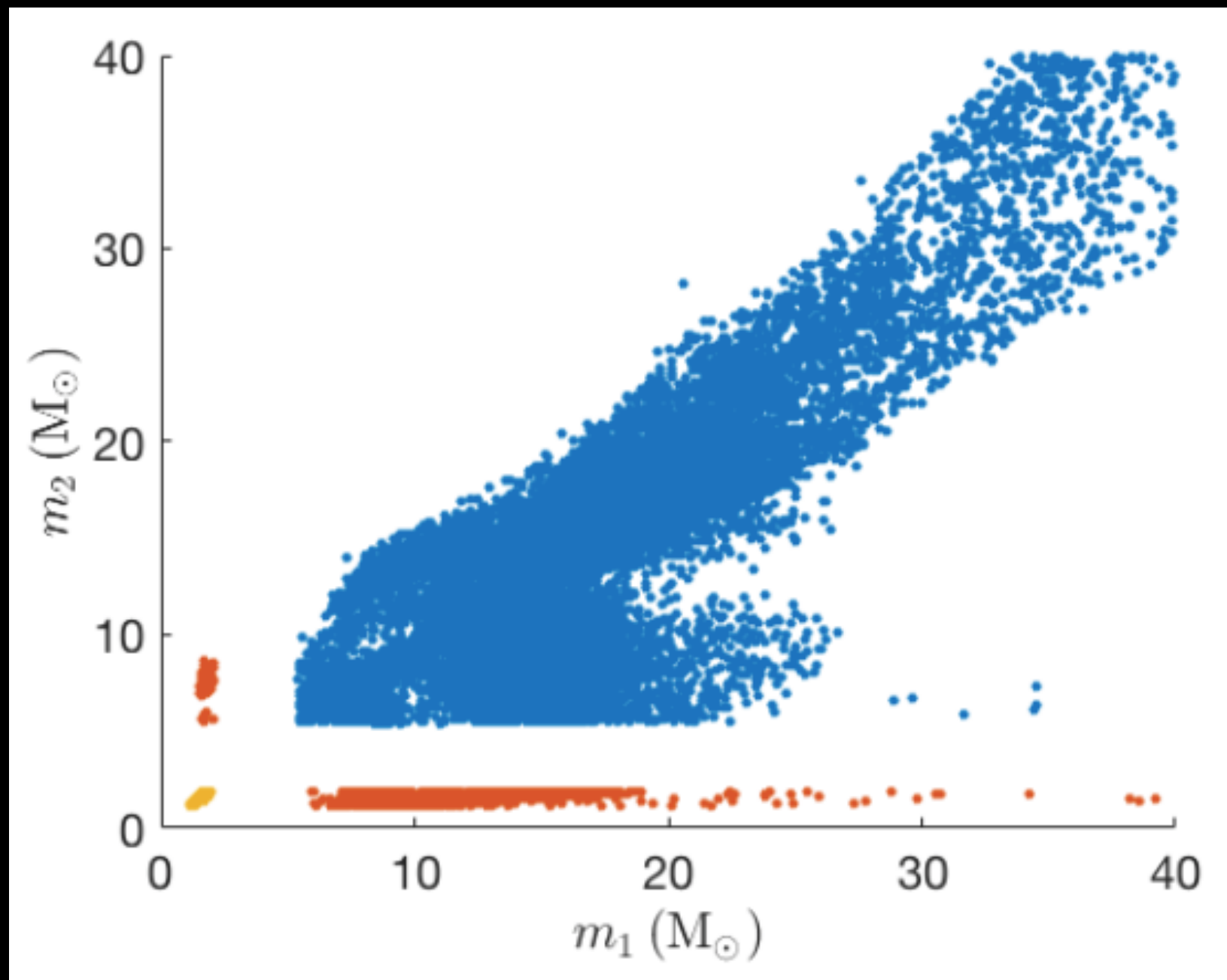
$$p(m_1) \propto m_1^{-\alpha} \quad \text{flat } q$$



Abbott+ (LVC), 2016

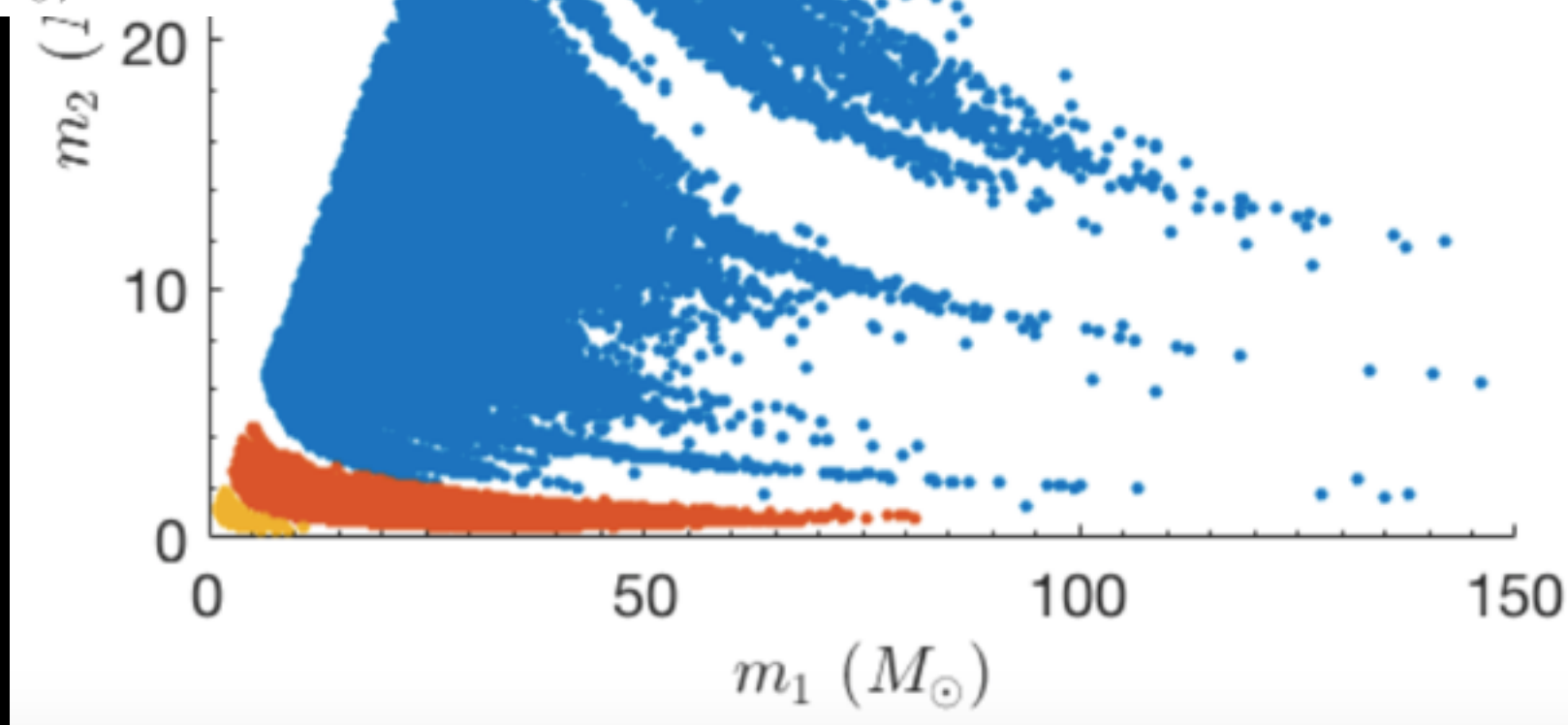
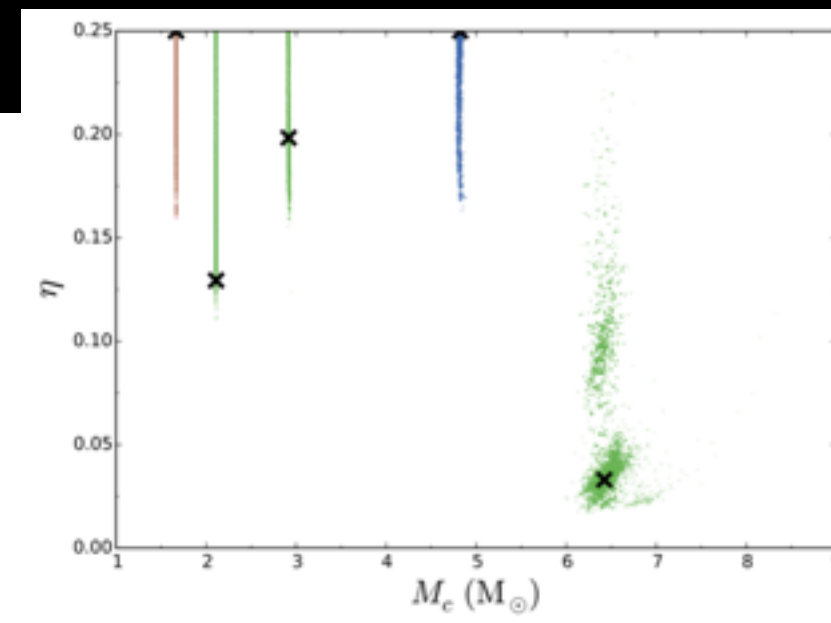
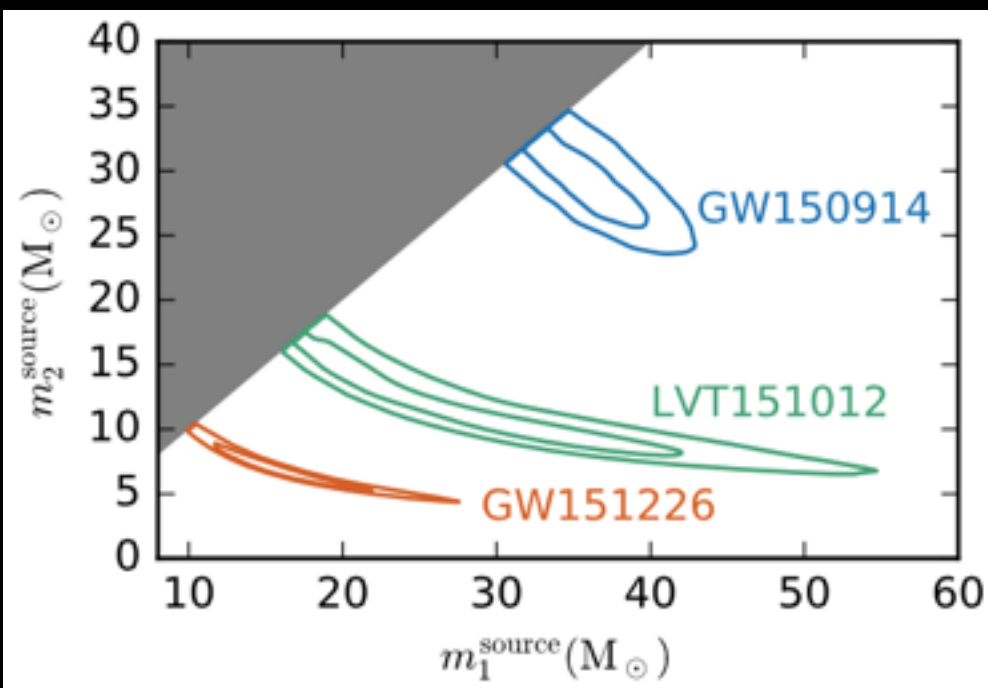
$$h(f) \sim M^{5/6} \Rightarrow V \sim M^{2.5}$$

Unmodeled Inference: Binary population clustering



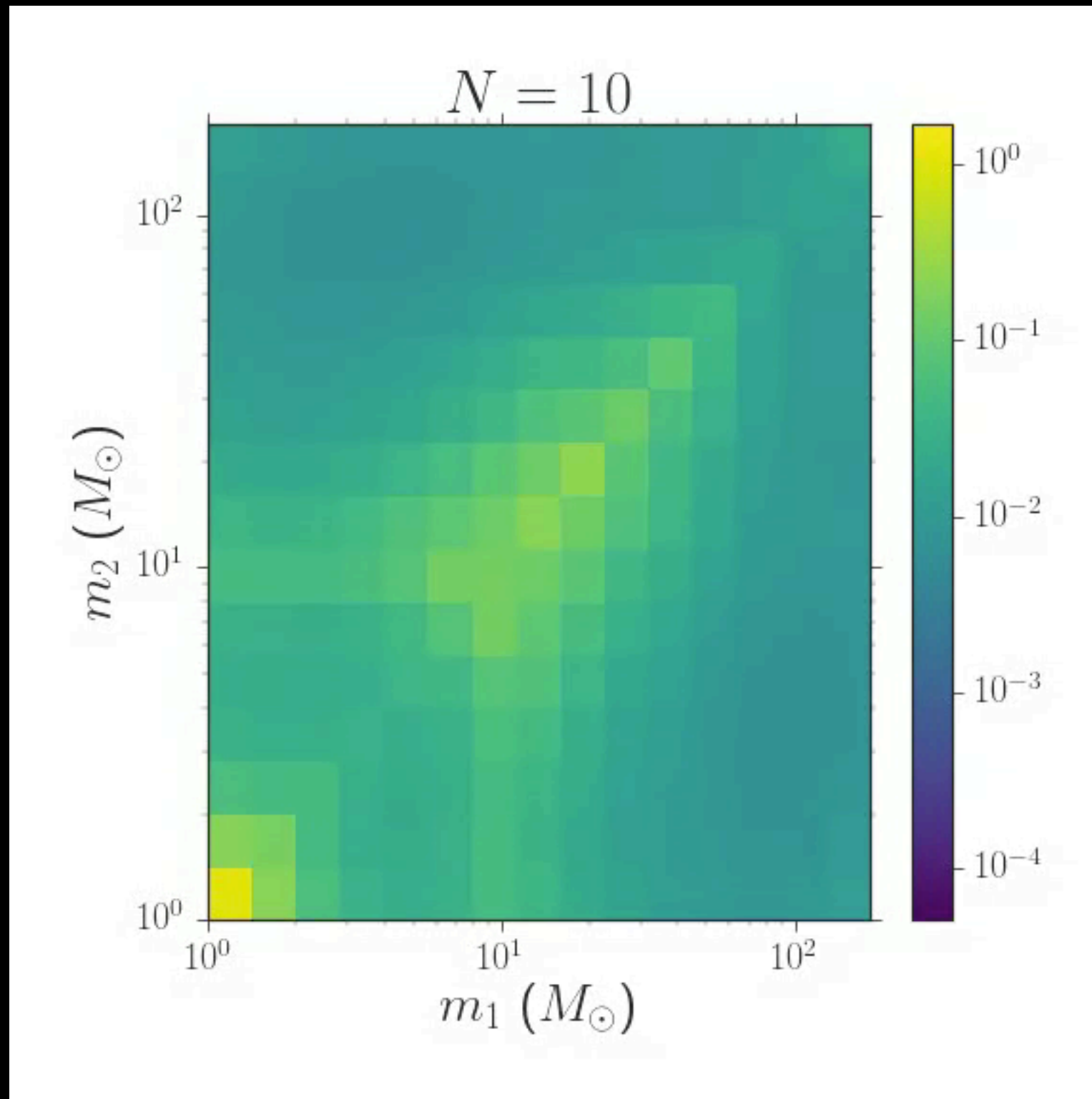
[Mandel et al., 2015; Dominik et al., 2015; Stevenson et al., 2016]

Measurement uncertainty



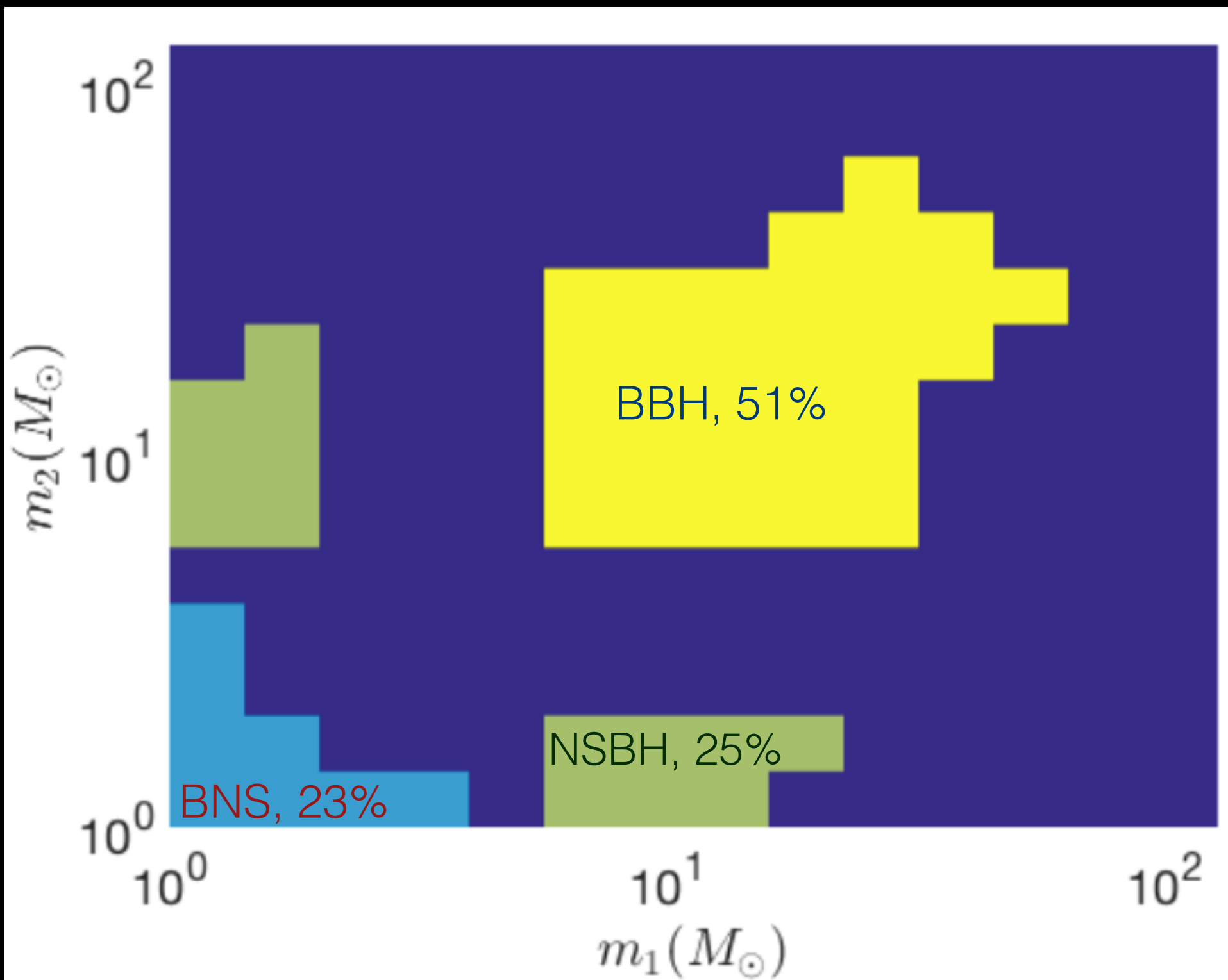
[Abbott et al., 2016; Mandel et al., 2015; see also Littenberg et al., 2015]

Unmodeled Inference: Binary population clustering

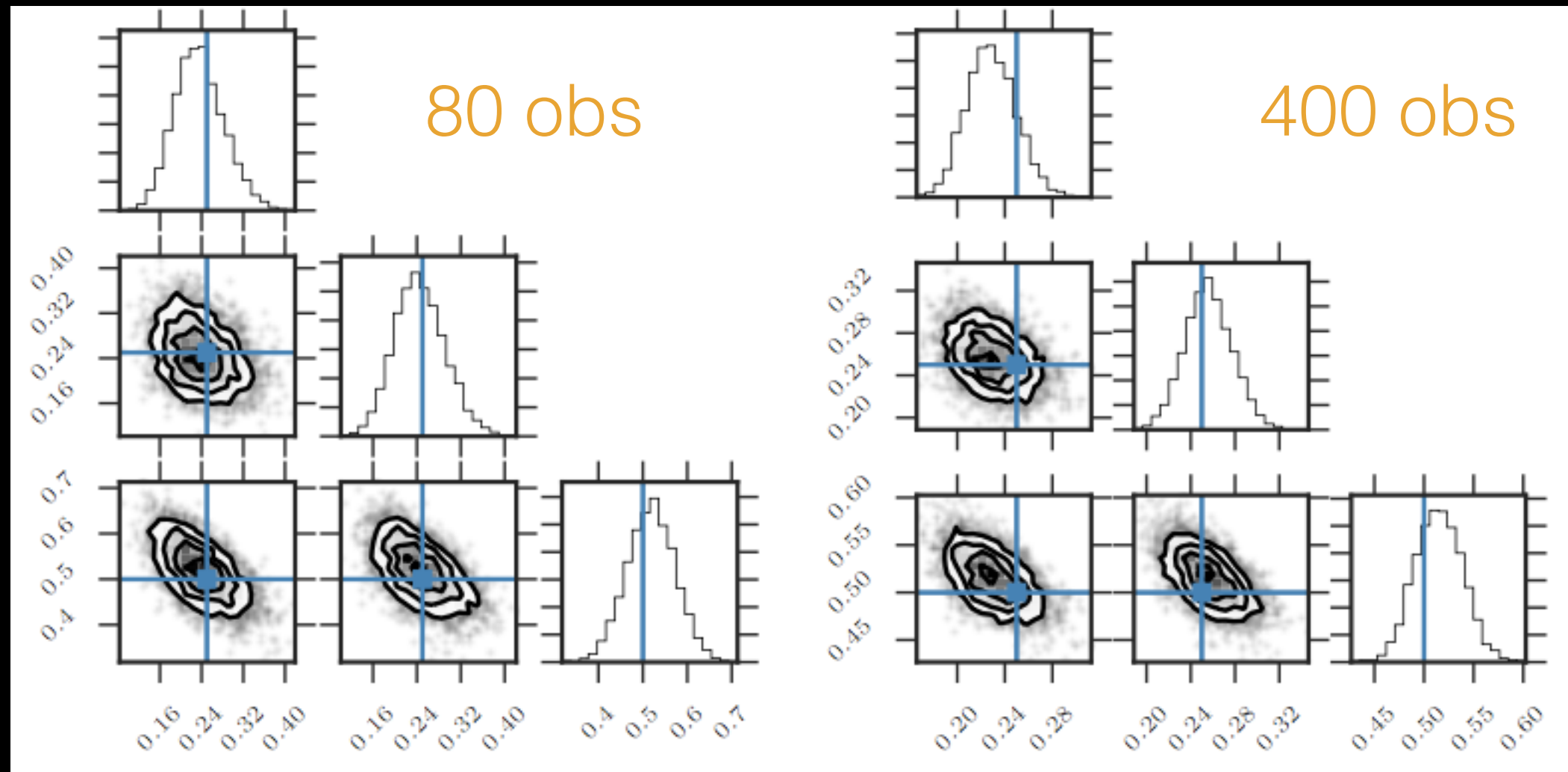


Mandel+,
2016

Water filling on mean density



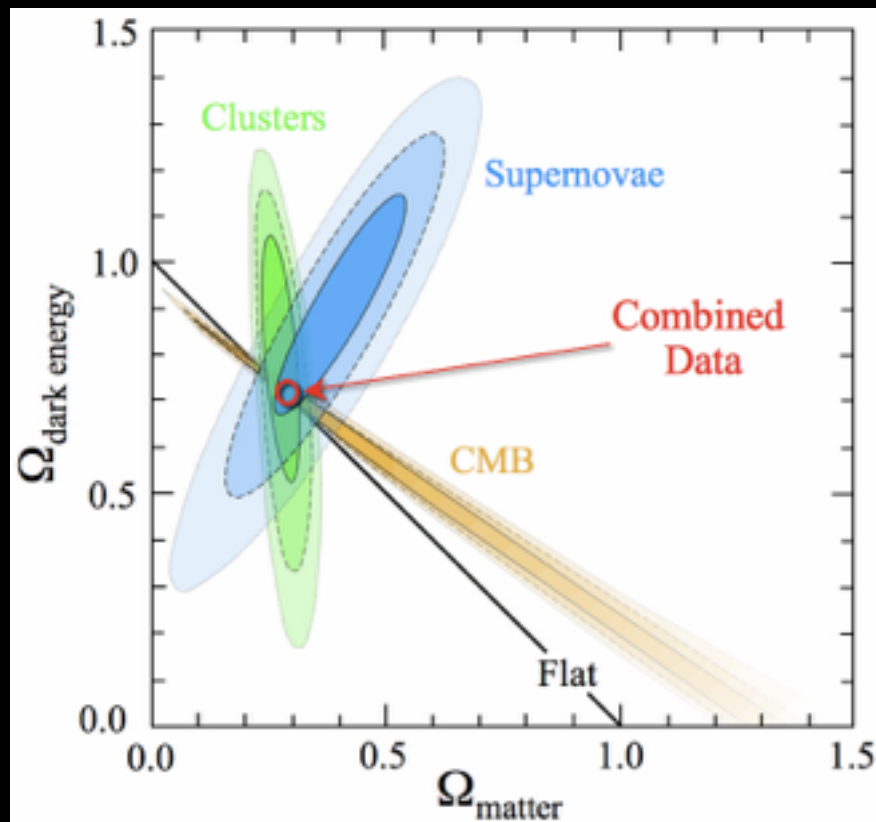
Unmodeled Inference





Future

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



THE GRAVITATIONAL WAVE
DETECTOR WORKS! FOR THE
FIRST TIME, WE CAN LISTEN
IN ON THE SIGNALS CARRIED
BY RIPPLES IN THE FABRIC
OF SPACE ITSELF!



EVENT: BLACK HOLE MERGER IN CARINA ($30 M_{\odot}$, $30 M_{\odot}$)
EVENT: ZORLAX THE MIGHTY WOULD LIKE TO CONNECT ON LINKEDIN
EVENT: BLACK HOLE MERGER IN ORION ($20 M_{\odot}$, $50 M_{\odot}$)
EVENT: MORTGAGE OFFER FROM TRIANGULUM GALAXY
EVENT: ZORLAX THE MIGHTY WOULD LIKE TO CONNECT ON LINKEDIN
EVENT: MEET LONELY SINGLES IN THE LOCAL GROUP TONIGHT!



GW150914: our first Binary BH merger

-0.76s

