GW150914:
Astrophysical implications of the discovery

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Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

- LIGO-P1500229: Observing gravitational-wave transient GW150914 with minimal assumptions
- LIGO-P1500269: GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
- LIGO-P1500218: Properties of the binary black hole merger GW150914
- LIGO-P1500217: The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
- LIGO-P1500262: Astrophysical Implications of the Binary Black-Hole Merger GW150914
- LIGO-P1500213: Tests of general relativity with GW150914
- LIGO-P1500222: GW150914: Implications for the stochastic gravitational-wave background from binary black holes
- LIGO-P1500248: Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914
- LIGO-P1500238: Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
- LIGO-P1500227: Localization and broadband follow-up of the gravitational-wave candidate G184098
- LIGO-P1500271: High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES
- LIGO-P1500237: GW150914: The Advanced LIGO Detectors in the Era of First Discoveries

THE RATE OF BINARY BLACK HOLE MERGERS INFERRED FROM ADVANCED LIGO OBSERVATIONS SURROUNDING GW150914

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J. L. Wright,[36] G. Wu,[6] J. Yablon,[82] W. Yam,[10] H. Yamamoto,[1] C. C. Yancey,[62] M. J. Yap,[20] H. Yu,[10] M. Yvert,[7] A. Zadrożny,[110] L. Zangrando,[42] M. Zanolin,[97] J.-P. Zendri,[42] M. Zevin,[82] F. Zhang,[10] L. Zhang,[1] M. Zhang,[119] Y. Zhang,[112] C. Zhao,[50] M. Zhou,[82] Z. Zhou,[82] X. J. Zhu,[50] M. E. Zucker,[1,10] S. E. Zuraw,[101] and J. Zweizig[1]

[†]Deceased, May 2015. [‡]Deceased, March 2015.

(LIGO Scientific Collaboration and Virgo Collaboration)

ASTROPHYSICAL IMPLICATIONS OF THE BINARY BLACK-HOLE MERGER GW150914

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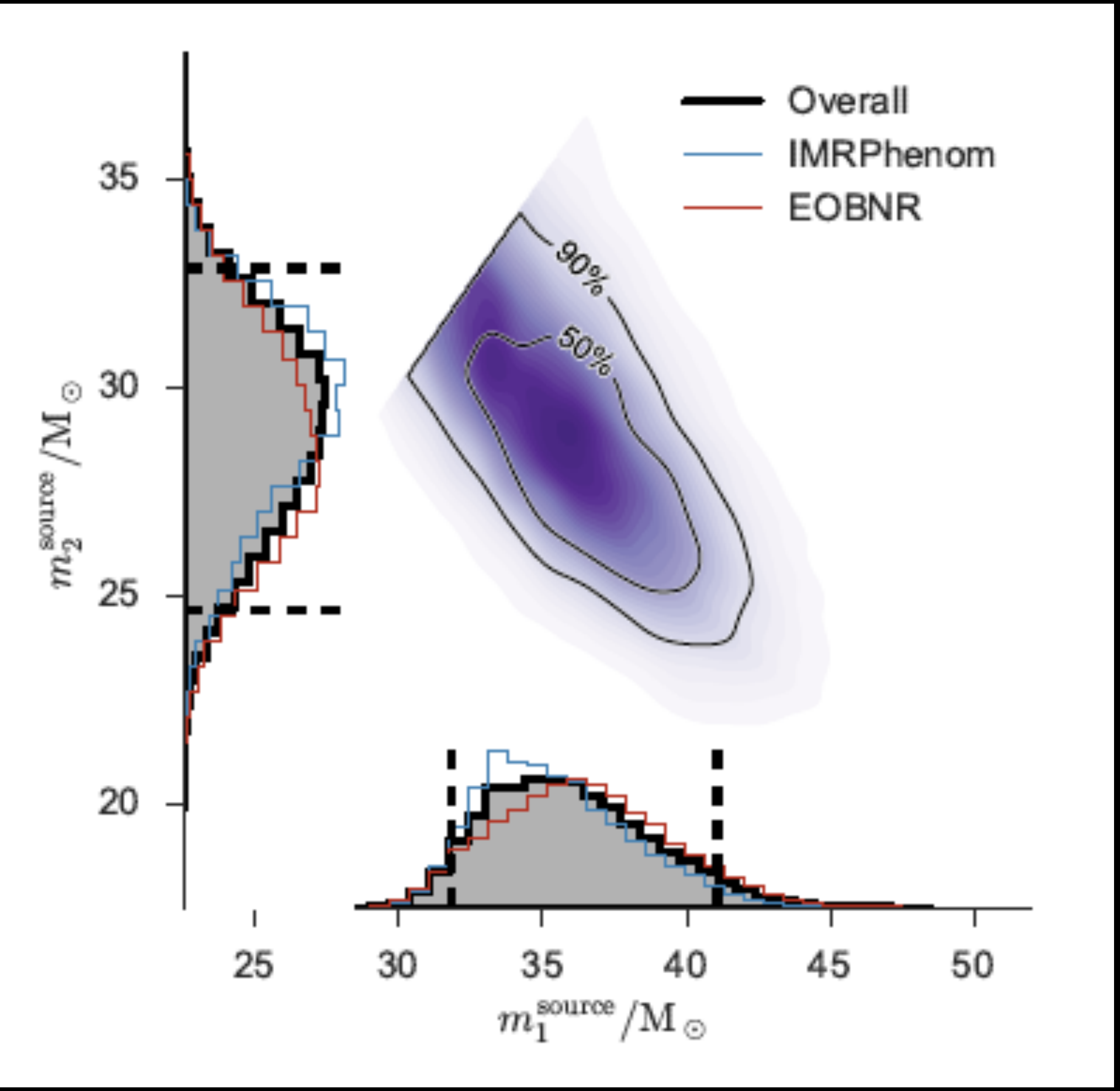
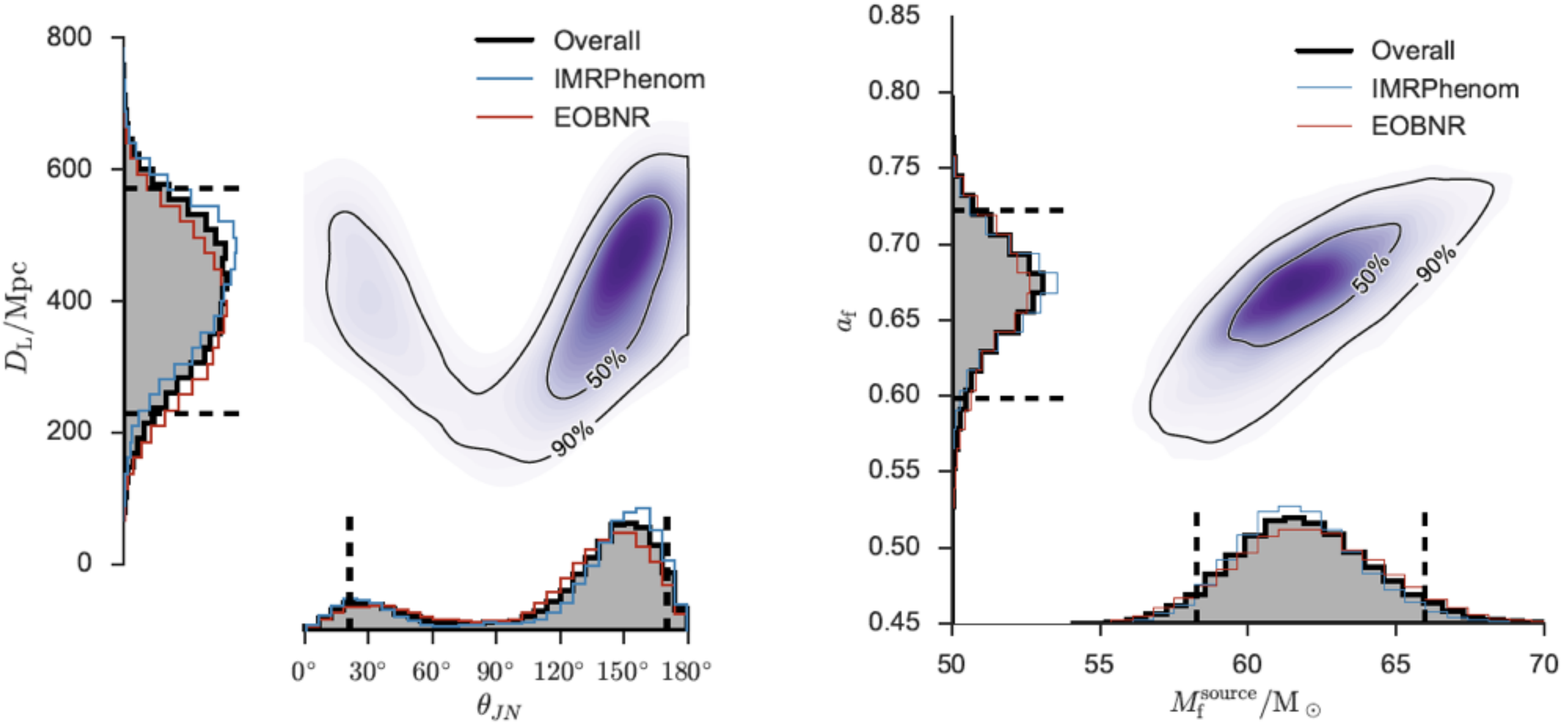
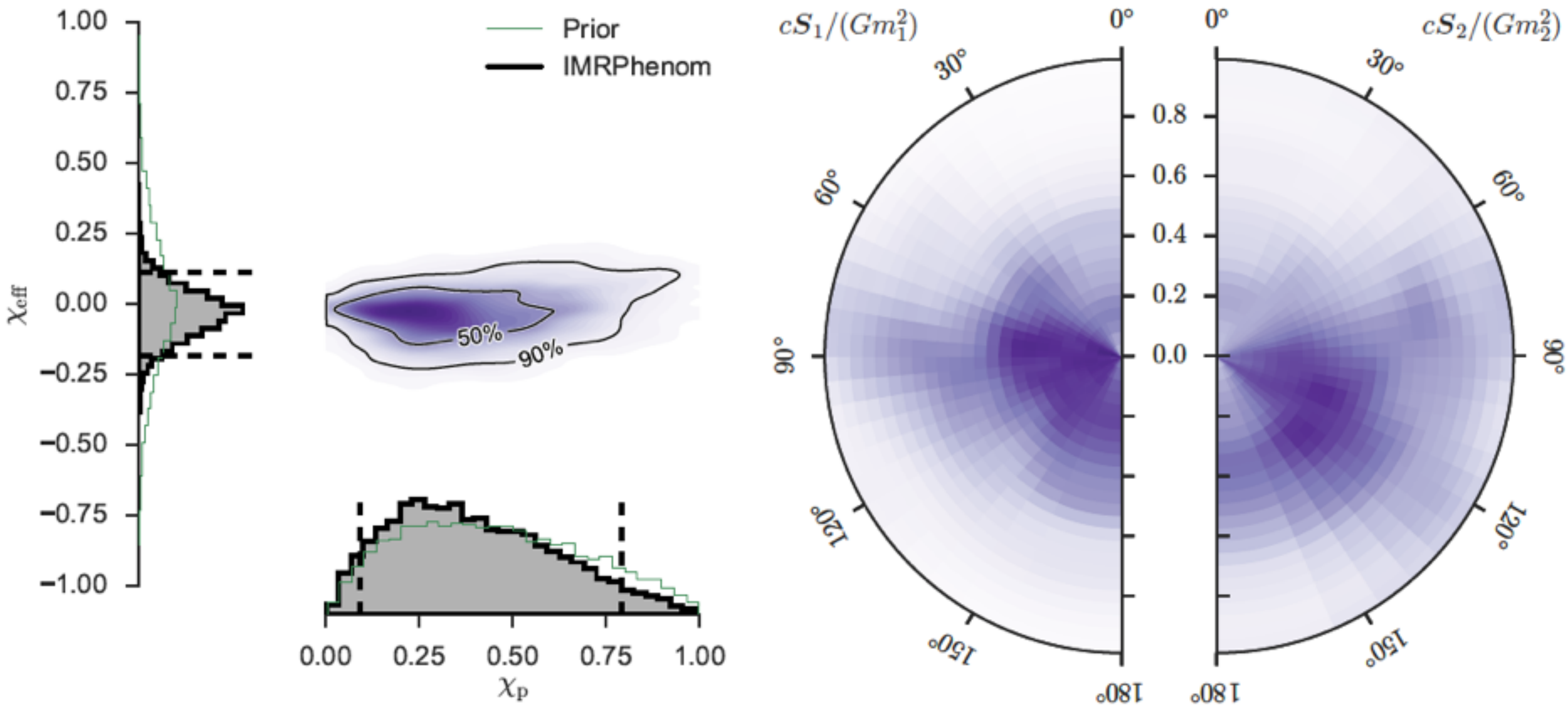
Properties of GW150914



Properties of GW150914





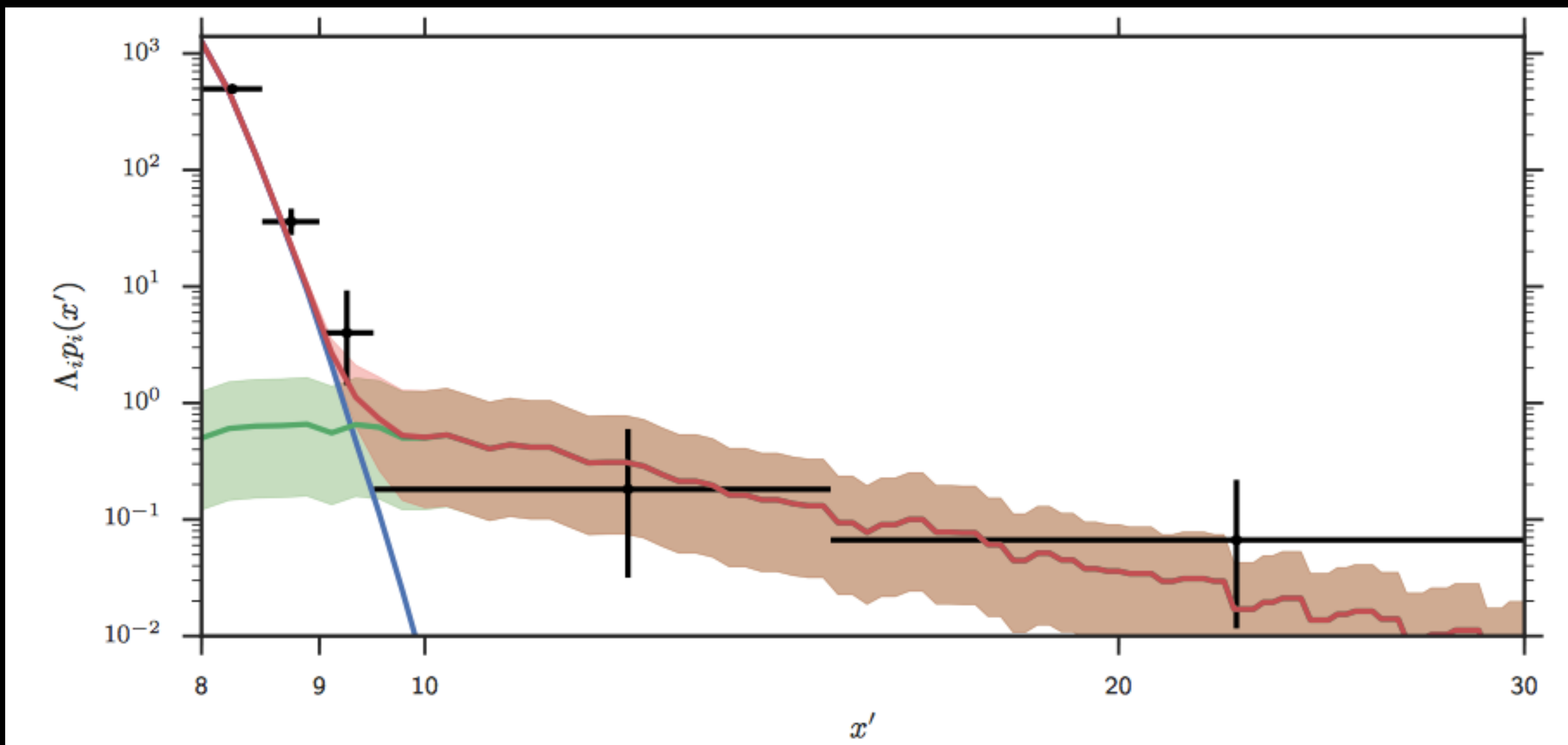
Prior
IMRPhenom
$\chi_{\rm eff}$
$\chi_{\rm p}$
50%
90%
$cS_1/(Gm_1^2)$
$cS_2/(Gm_2^2)$

	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/\mathrm{M}_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm0.9}_{-4.5\pm1.0}$
Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm0.4}_{-1.9\pm0.4}$
Detector-frame primary mass $m_1/\mathrm{M}_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm0.9}_{-4.1\pm0.3}$
Detector-frame secondary mass $m_2/\mathrm{M}_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm0.1}_{-4.9\pm0.6}$
Detector-frame final mass $M_\mathrm{f}/\mathrm{M}_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm0.8}_{-4.0\pm0.9}$
Source-frame total mass $M^\mathrm{source}/\mathrm{M}_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm0.01}_{-0.21\pm0.03}$
Effective inspiral spin parameter χ_eff	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm0.04}_{-0.28\pm0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm0.07}_{-0.42\pm0.01}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm0.00}_{-0.07\pm0.03}$
Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm20}_{-180\pm40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm0.004}_{-0.038\pm0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_{\mathrm{s/n}}$	288.7 ± 0.2	290.1 ± 0.2	—

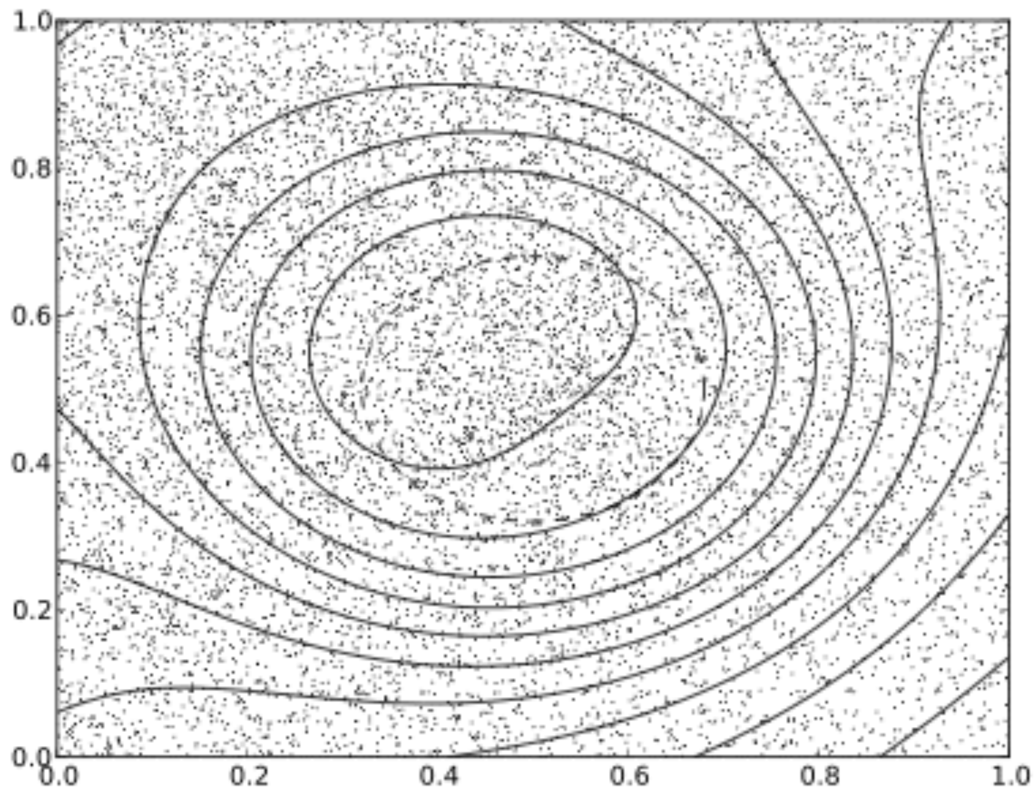
$3.0^{+0.5}_{-0.5}\ \mathrm{M}_\odot c^2$ in GWs,

$3.6^{+0.5}_{-0.4} \times 10^{56}\ \mathrm{erg\,s^{-1}} = 200^{+30}_{-20}\ \mathrm{M}_\odot c^2/\mathrm{s}$

Rates:
trigger number density



Counting and confusion



Globular cluster on top of a galactic background with a gradient [Farr, Gair, Mandel, Cutler, 2015, PRD 91, 023005]

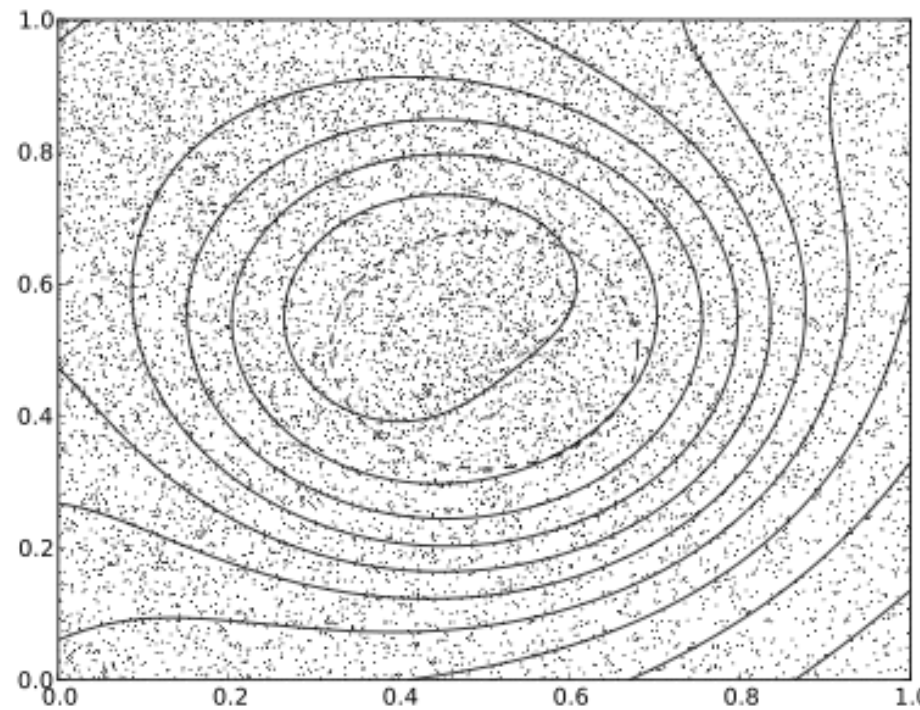
- Trouble distinguishing foreground and background signals

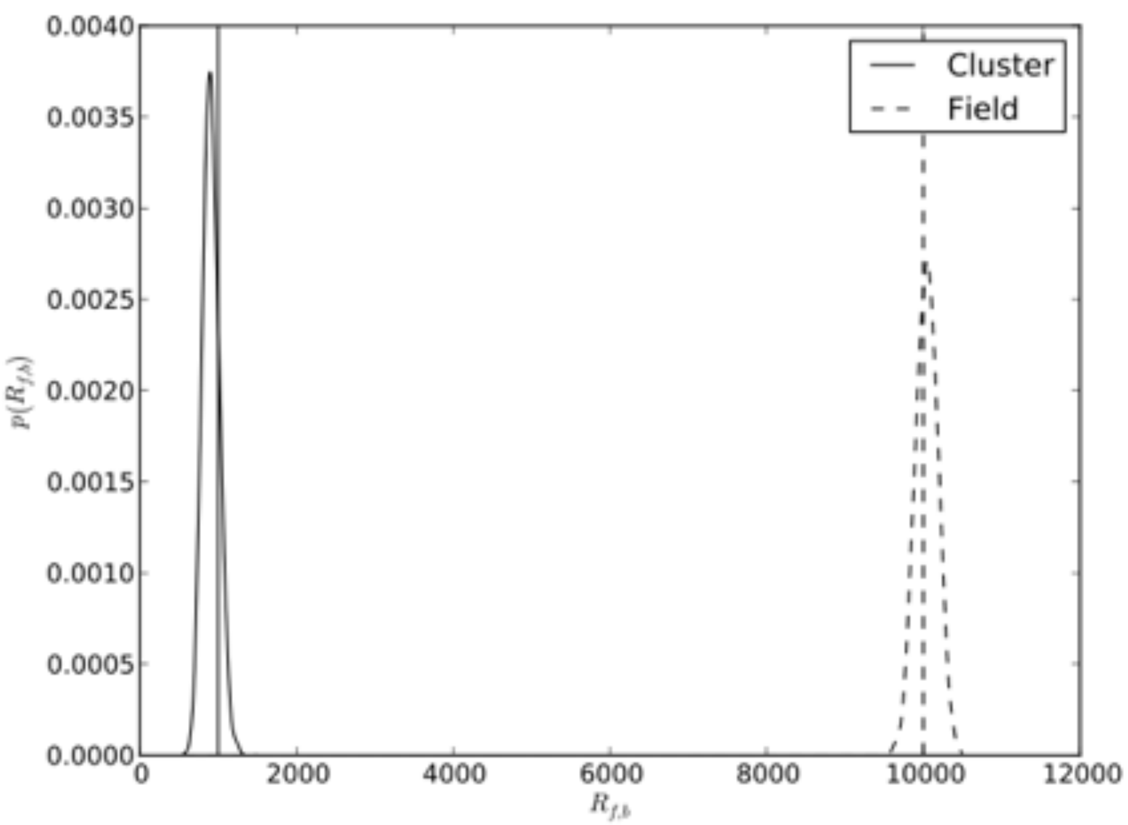
Counting and confusion, II

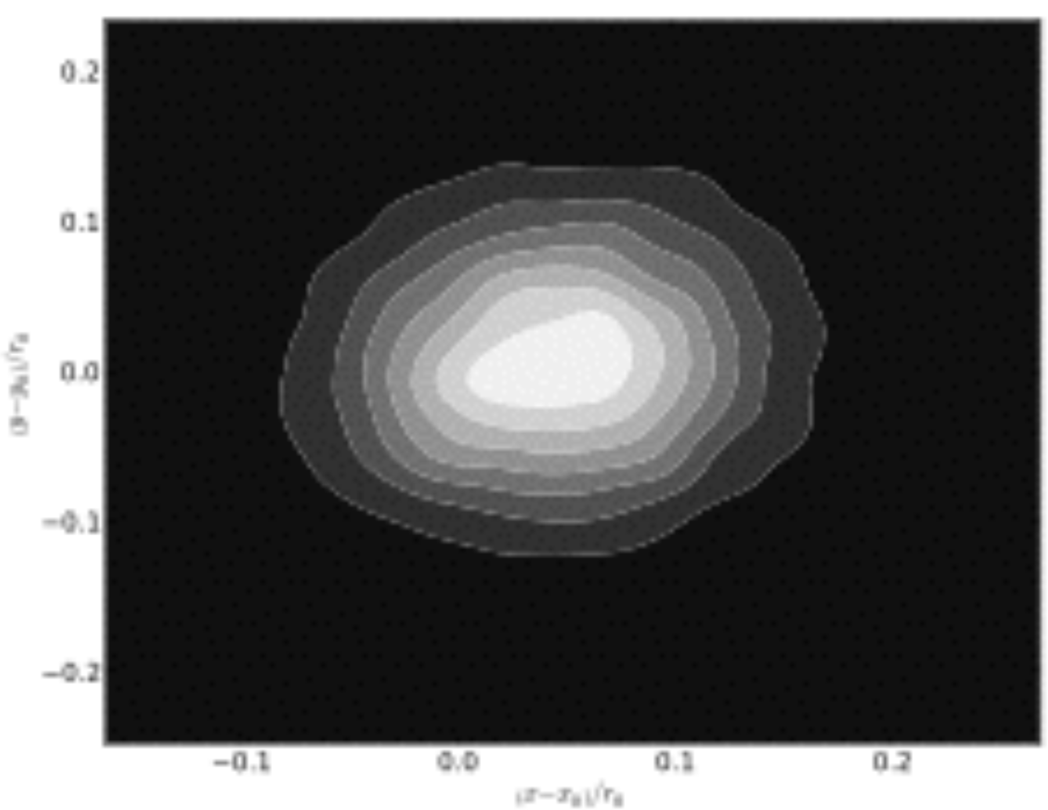
- Allow each “event” to be assigned to foreground or background.
- Parameterize the foreground and background distributions as you wish.
- MCMC over distribution parameters and fore/back status of each event.

$$
\begin{aligned}
p\left(\{g_i\}, R_f, R_b, \theta | d_{\text{to}}, N\right) = {} & \frac{\alpha}{p(d_{\text{to}}, N)\, N!} \\
& \times \left[\prod_{\{i|g_i=1\}} R_f \hat{f}\left(x_i, \theta\right)\right] \left[\prod_{\{i|g_i=0\}} R_b \hat{b}\left(x_i, \theta\right)\right] \\
& \times \exp\left[-\left(R_f + R_b\right)\right] \frac{p(\theta)}{\sqrt{R_f R_b}}.
\end{aligned}
$$

Counting and confusion, III

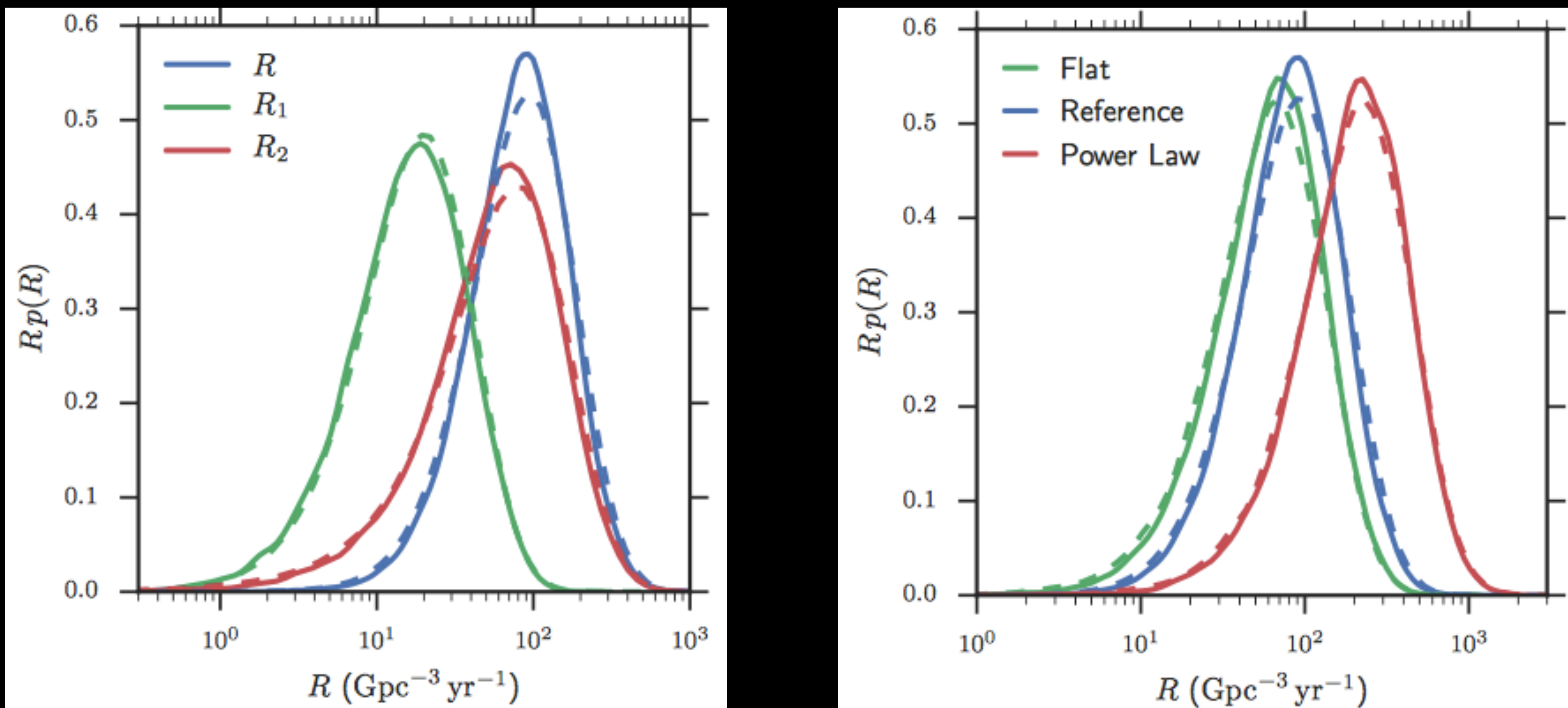




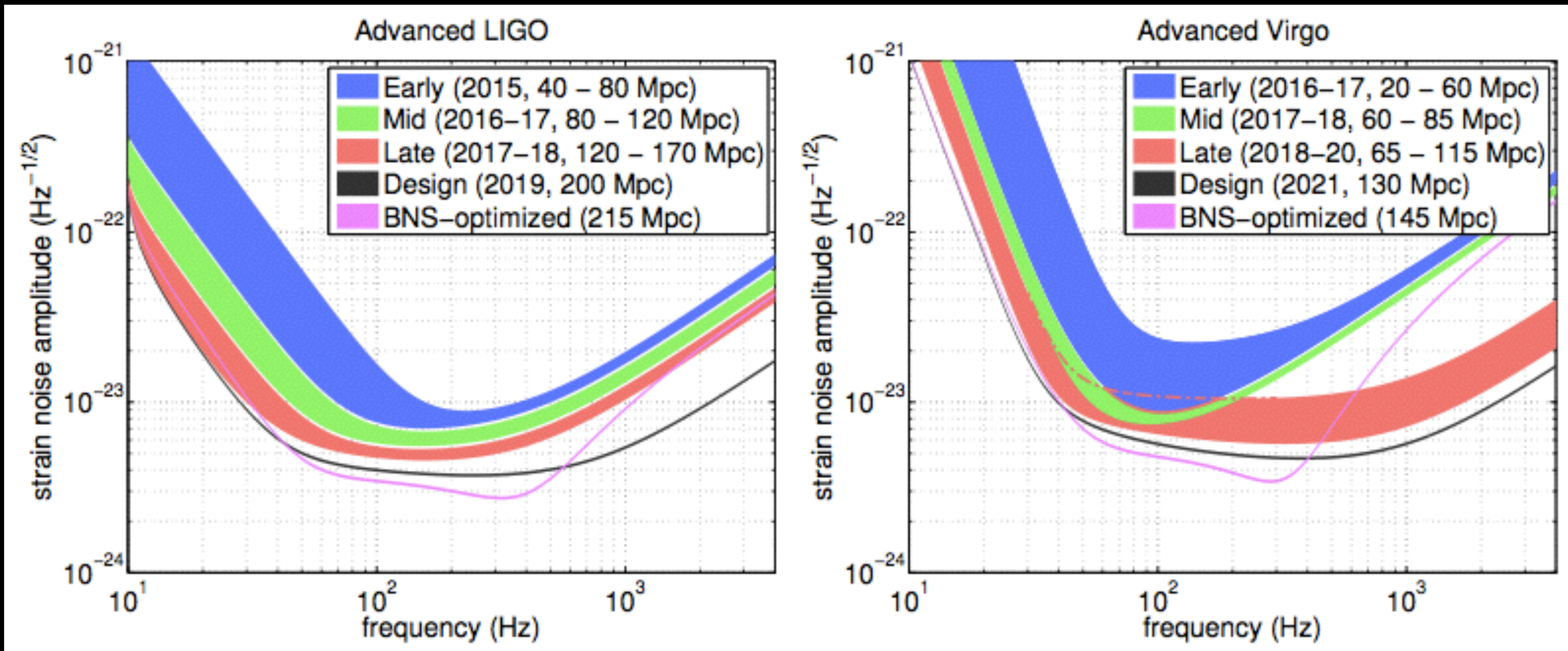


Rates:
candidate events

Rates: population assumptions



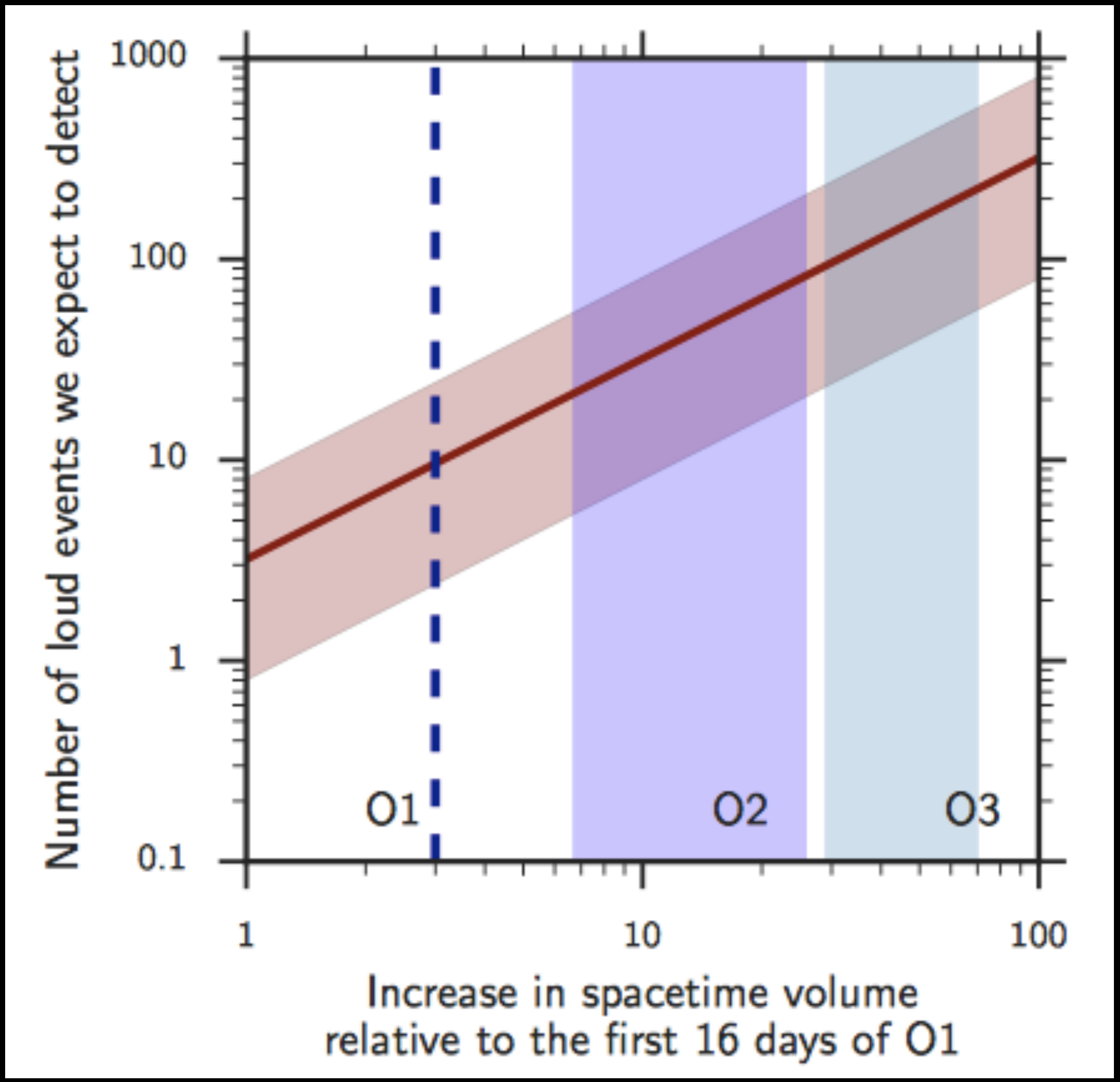
Advanced detector timelines



Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within $5\,\text{deg}^2$	$20\,\text{deg}^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

[Aasi+ (LSC+Virgo), arXiv:1304.0670]

Rates:
Future expectations



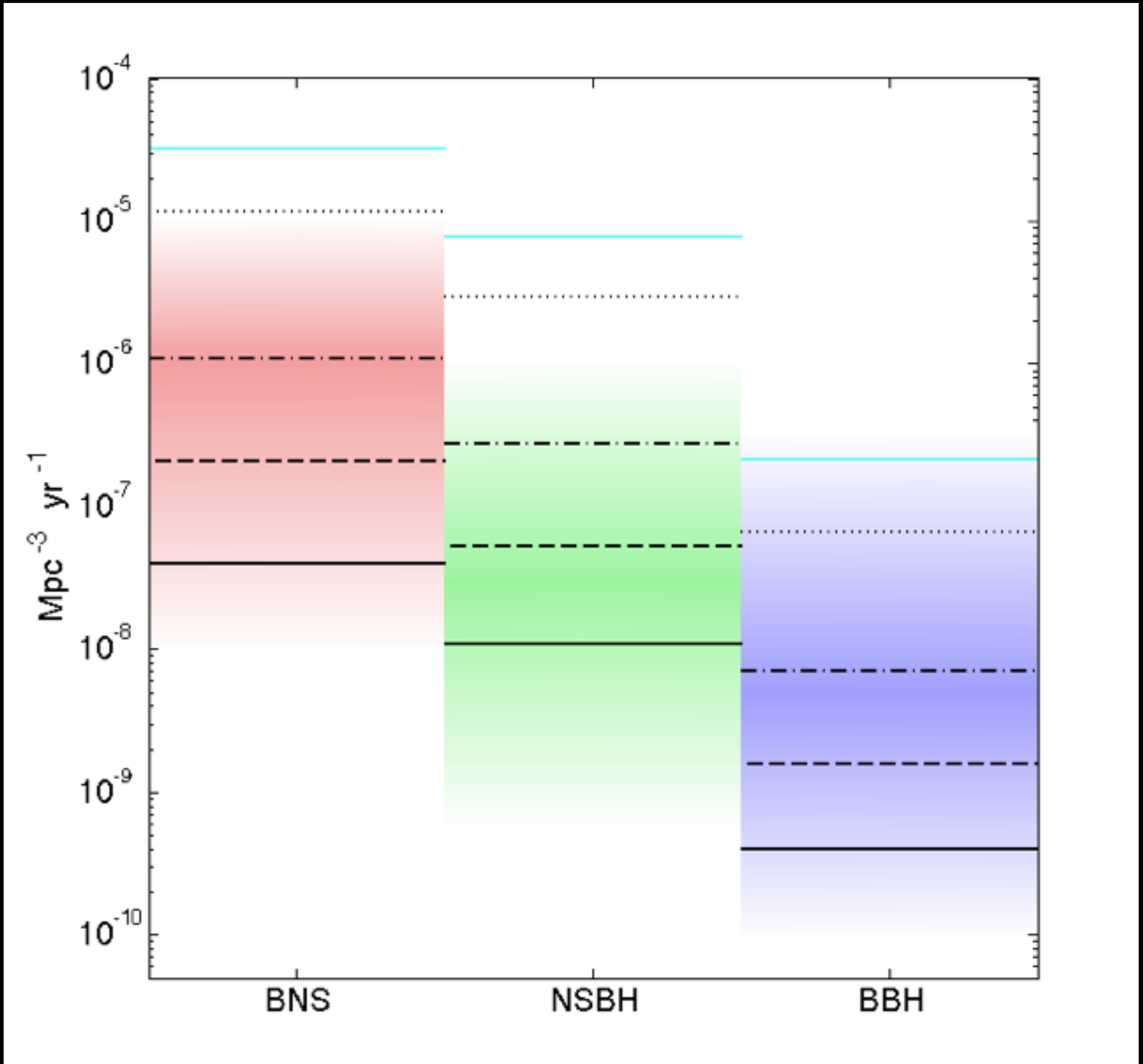
Rates vs. past predictions

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

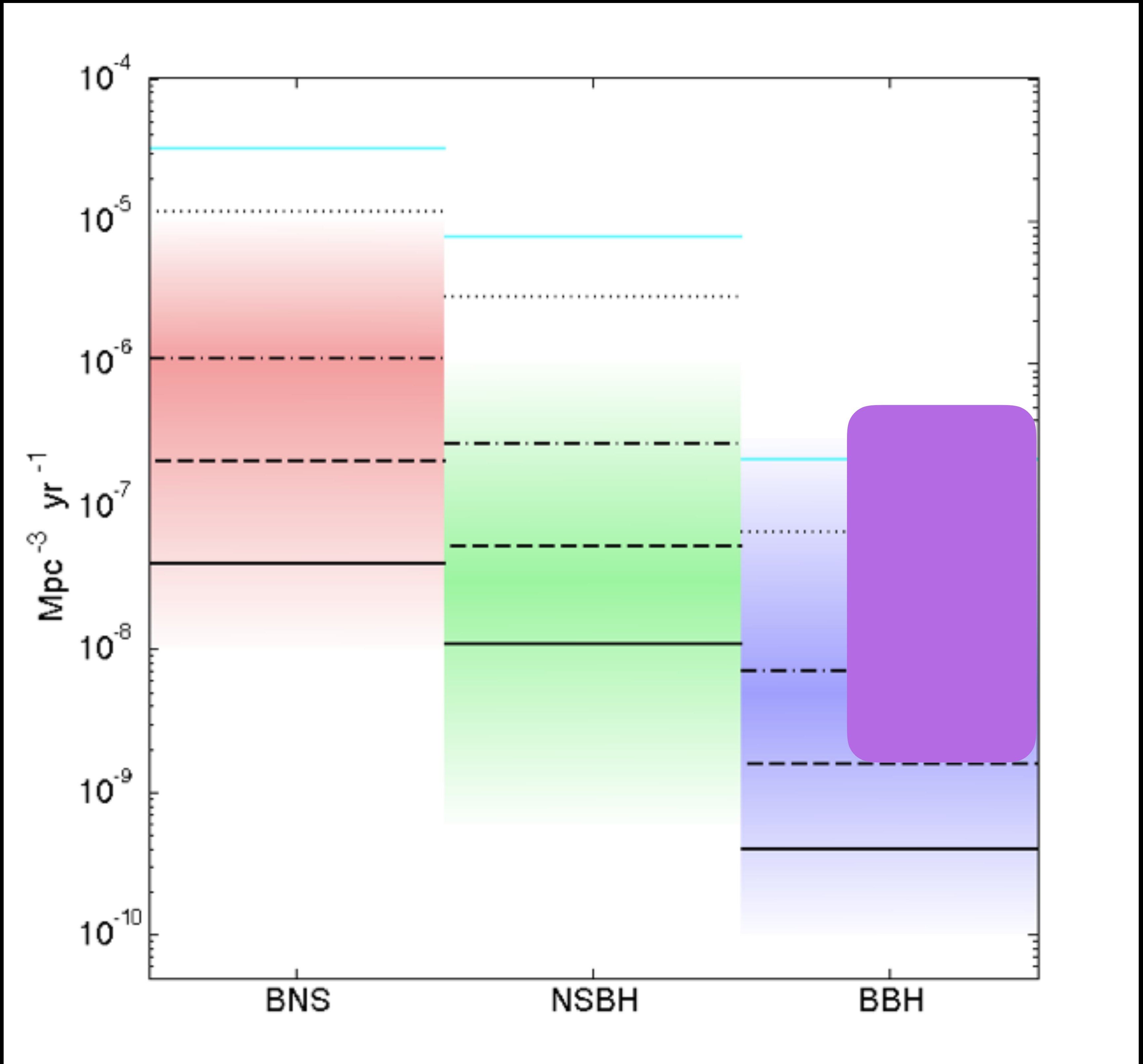
Source	R_{low}	R_{re}	R_{high}	R_{max}
NS-NS (Mpc^{-3} Myr^{-1})	0.01 [1]	1 [1]	10 [1]	50 [16]
NS-BH (Mpc^{-3} Myr^{-1})	6×10^{-4} [18]	0.03 [18]	1 [18]	
BH-BH (Mpc^{-3} Myr^{-1})	1×10^{-4} [14]	0.005 [14]	0.3 [14]	

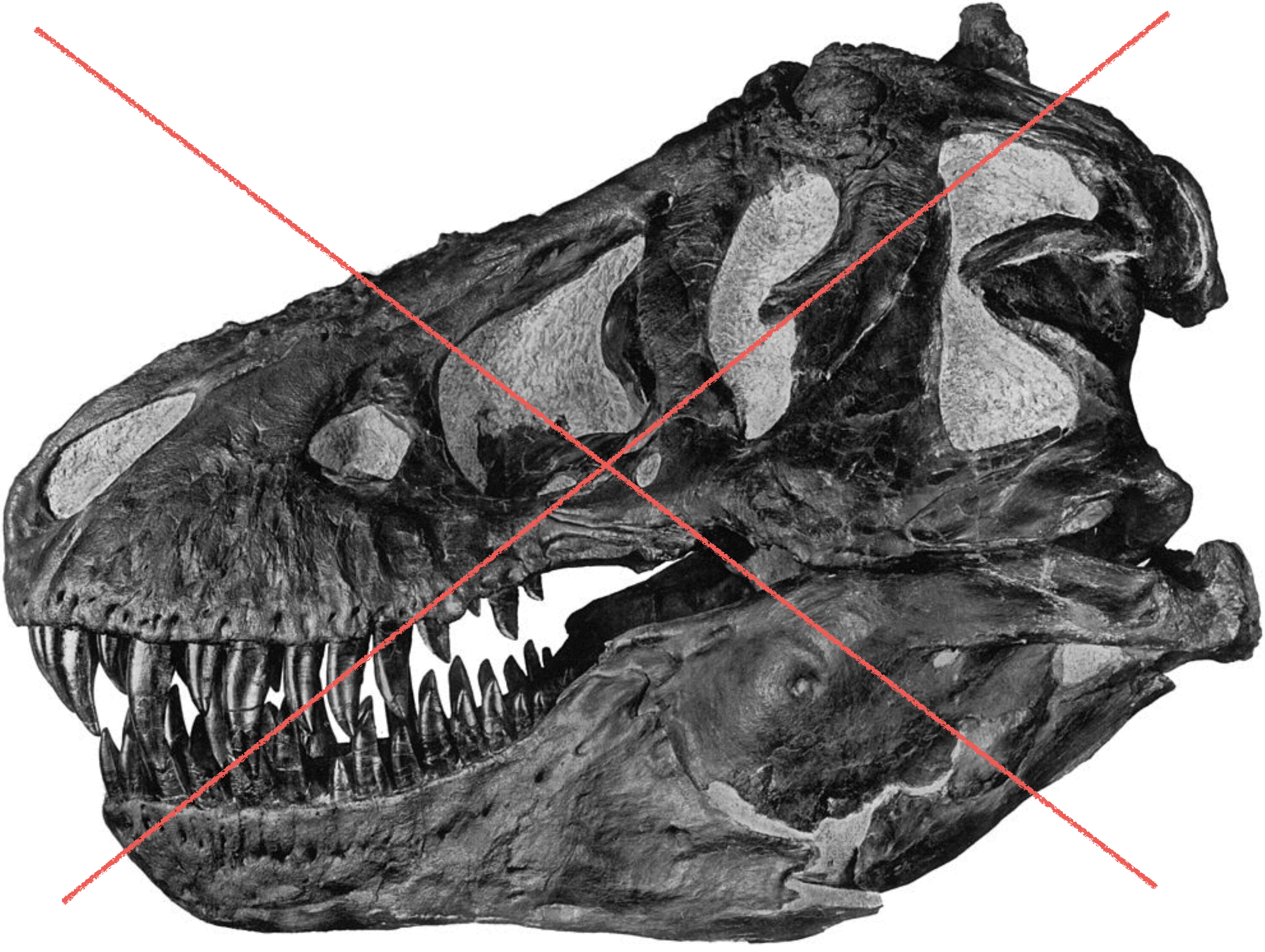
[Abadie et al., CQG 27:173001,2010]

Rates vs. predictions



Rates vs. predictions





Key lessons learned

1. BBHs exist

First prediction

ЭВОЛЮЦИЯ МАССИВНЫХ ТЕСНЫХ ДВОЙНЫХ СИСТЕМ

А. В. Тутуков, Л. Р. Юнгельсон

После выгорания ядерного горючего в ядре WR, она взрывается, теряя часть массы. Остаток – релятивистский объект имеет массу $-\beta\alpha(2-\alpha)^{1.4}\mathfrak{m}$. Поскольку мы не знаем зависимости β от массы, мы принимаем β для первой и второй WR одинаковыми, дальнейшие оценки подтверждают это приближение. Рассмотрим вопрос о распаде системы WR+R в момент взрыва компоненты WR, Конечно, в принципе возможно, что на предшествующих стадиях эволюции обе звезды потеряют большую часть массы, и коллапс не будет сопровождаться большой потерей вещества. Система останется связанной, и можно будет получить системы типа пульсар + пульсар или коллапсар + коллапсар. Но изучение обнаруженных пульсаров не дает ни одного примера двойственности, поэтому такую возможность следует считать маловероятной, по крайней мере, для большинства систем.

Key lessons learned

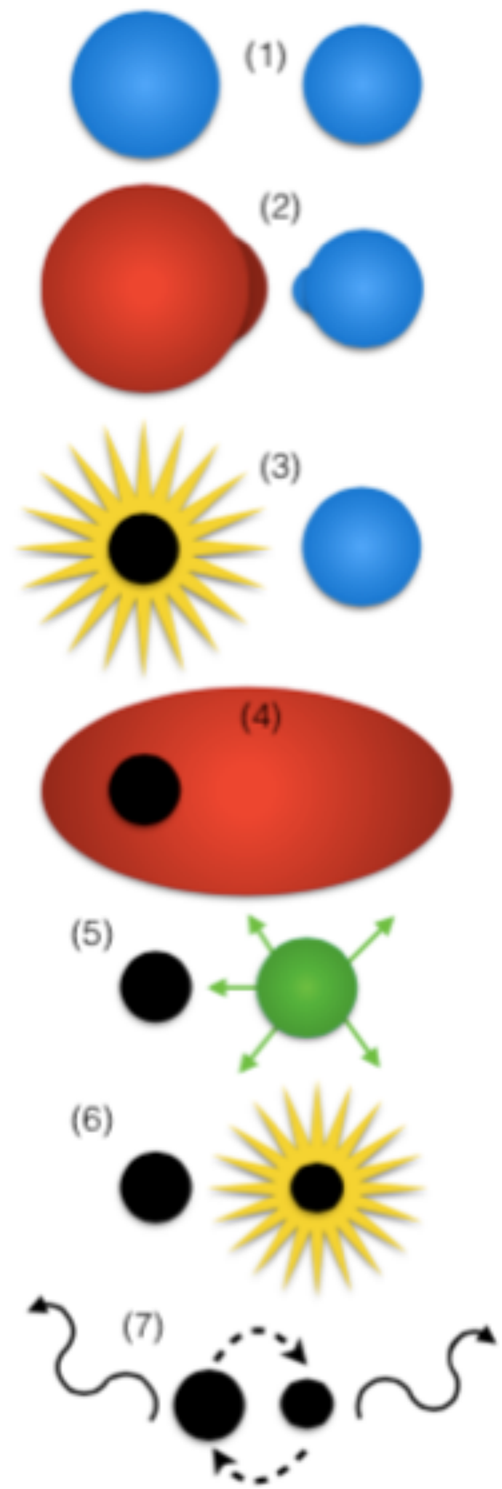
1. BBHs exist
2. Merging BBHs exist

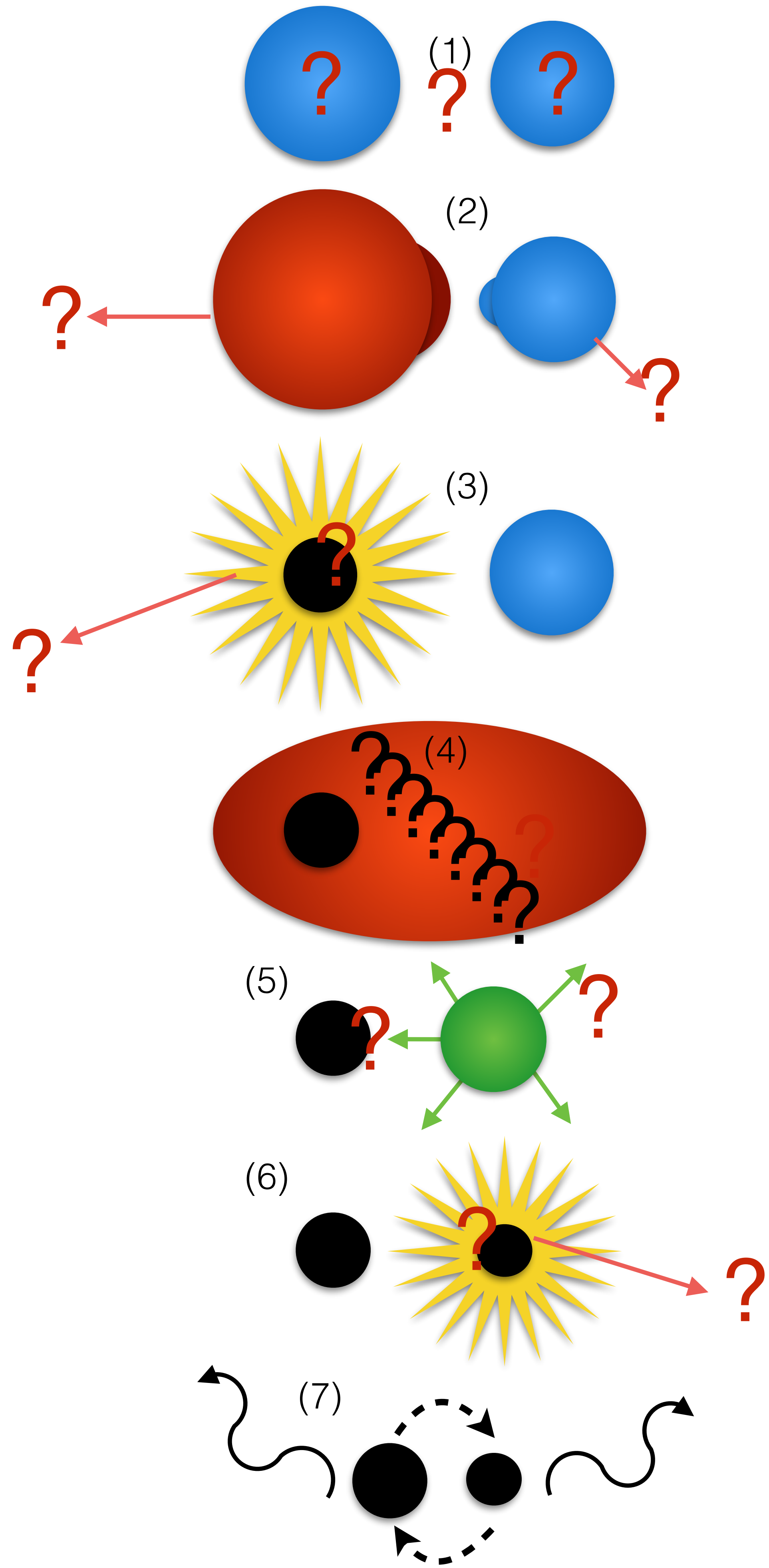
How do you get a BBH to merge?

A. Isolated binary evolves and merges through GW emission

B. Dynamical processes form the binary and/or help it harden

Isolated binary





(1)
(2)
(3)
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(5)
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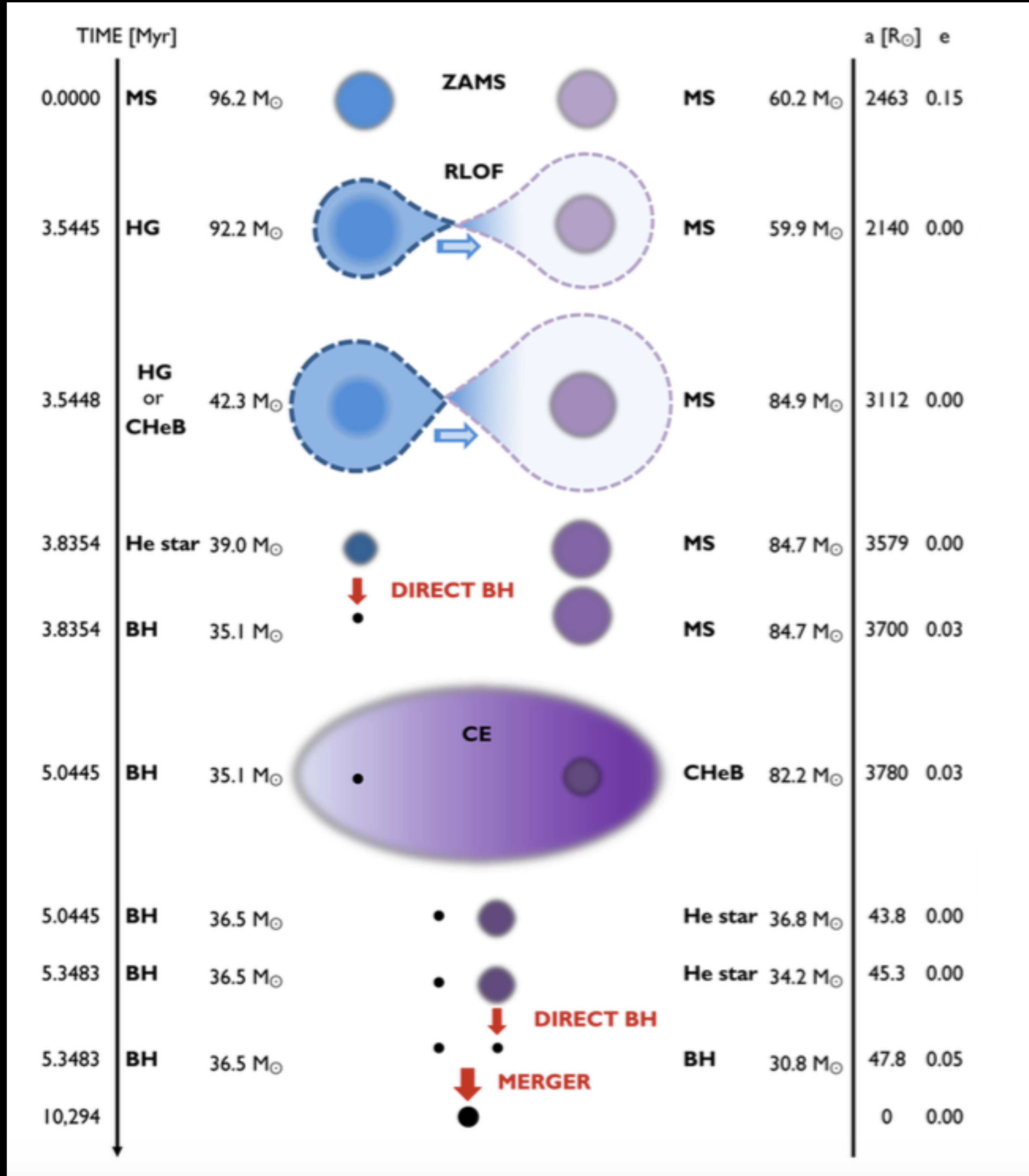
(7)

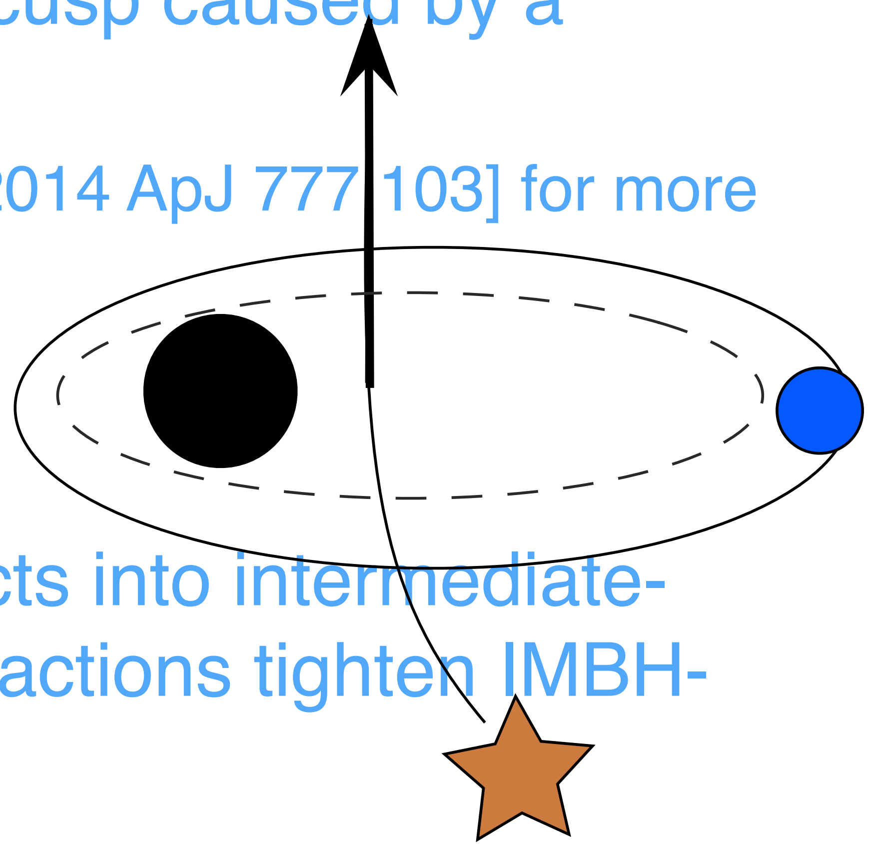


Belczynski+, arXiv:1602.04531

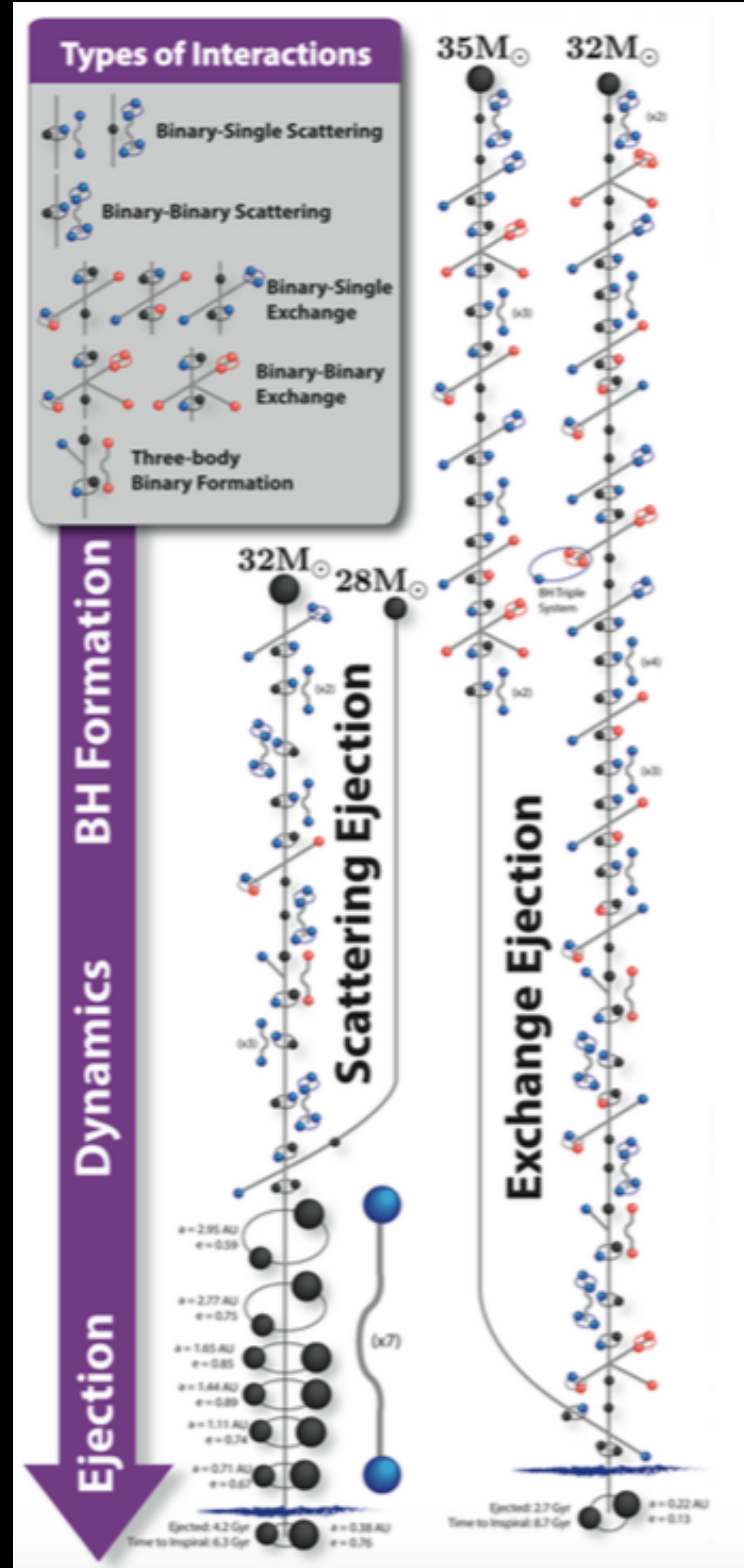
see also Eldridge & Stanway, arXiv:1602.03790; Inayoshi+, arXiv:1603.06921

Dynamical Formation

- BH-BH mergers in dense black-hole subclusters of globular clusters
  - [e.g., O'Leary, O'Shaughnessy, Rasio, 2007 PRD 76 061504; Downing et al., 2011 MNRAS 416 133; Bannerjee et al., 2010 MNRAS 402 371, Morscher et al., 2013 ApJL 763 L15, 2015 ApJ 800 9; Rodriguez et al. arXiv:1505.00792]
- BH-BH scattering in galactic nuclei with a density cusp caused by a massive black hole (MBH)
  - [O'Leary, Kocsis, Loeb, 2009 arXiv:0807.2638; Tsang, 2014 ApJ 777 103] for more conservative estimate]
- BH-BH mergers in nuclei without an MBH
  - [Miller and Lauburg, 2009, ApJ 692 917]



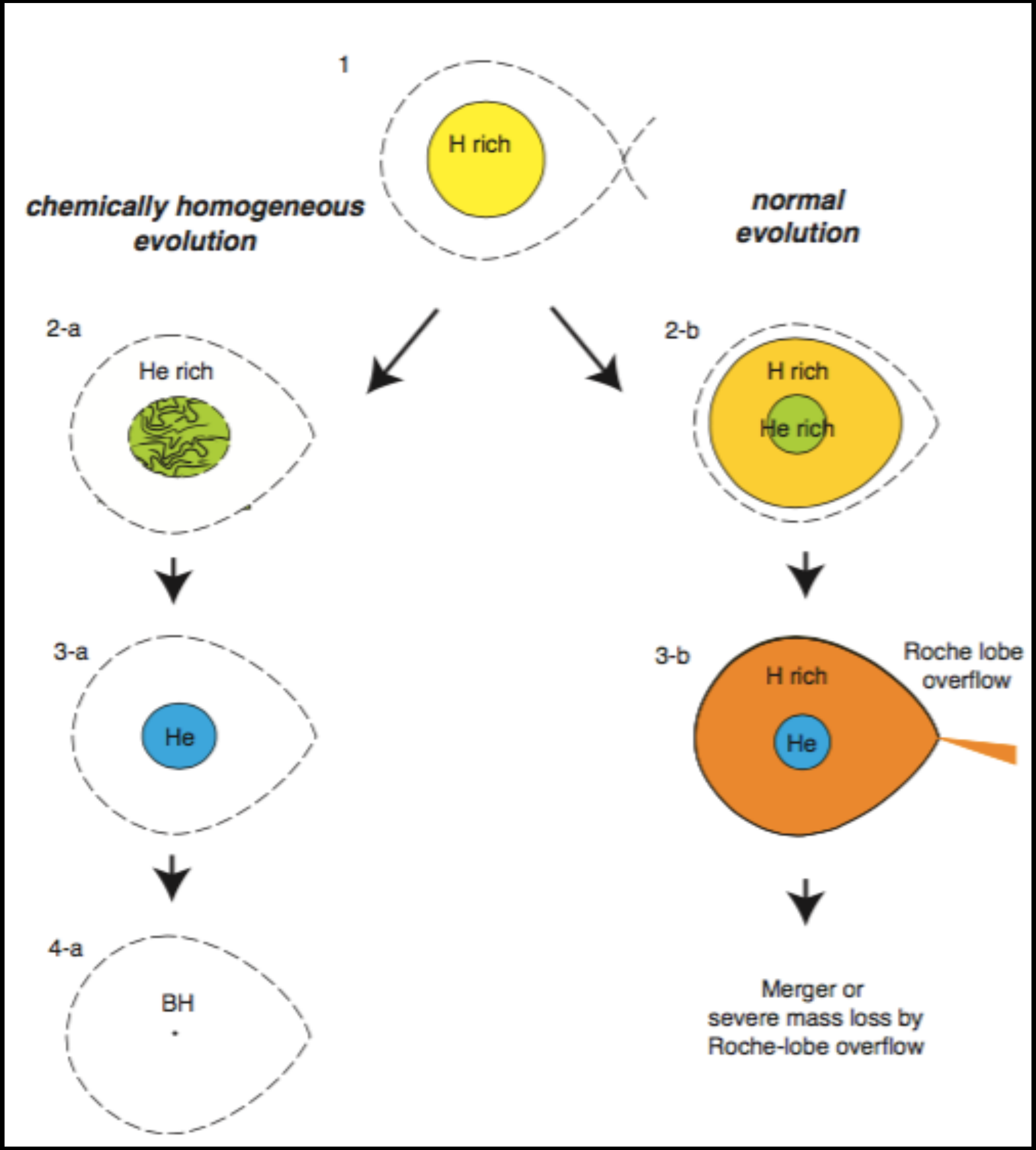
- Intermediate-mass-ratio inspirals of compact objects into intermediate-mass black holes in globular clusters; 3-body interactions tighten IMBH-CO binary [Mandel et al., 2008 ApJ 681 1431]
- Still no confident IMBH detections… but recent detection of very massive (several hundred solar masses) stars [e.g., Crowther et al., 2010 MNRAS L11]
  - Direct formation of IMBH binaries? [Belczynski et al., 2014 ApJ 789 120]



Rodriguez, Haster+, arXiv:1604.04254

see also Mapelli, arXiv:1604.03559

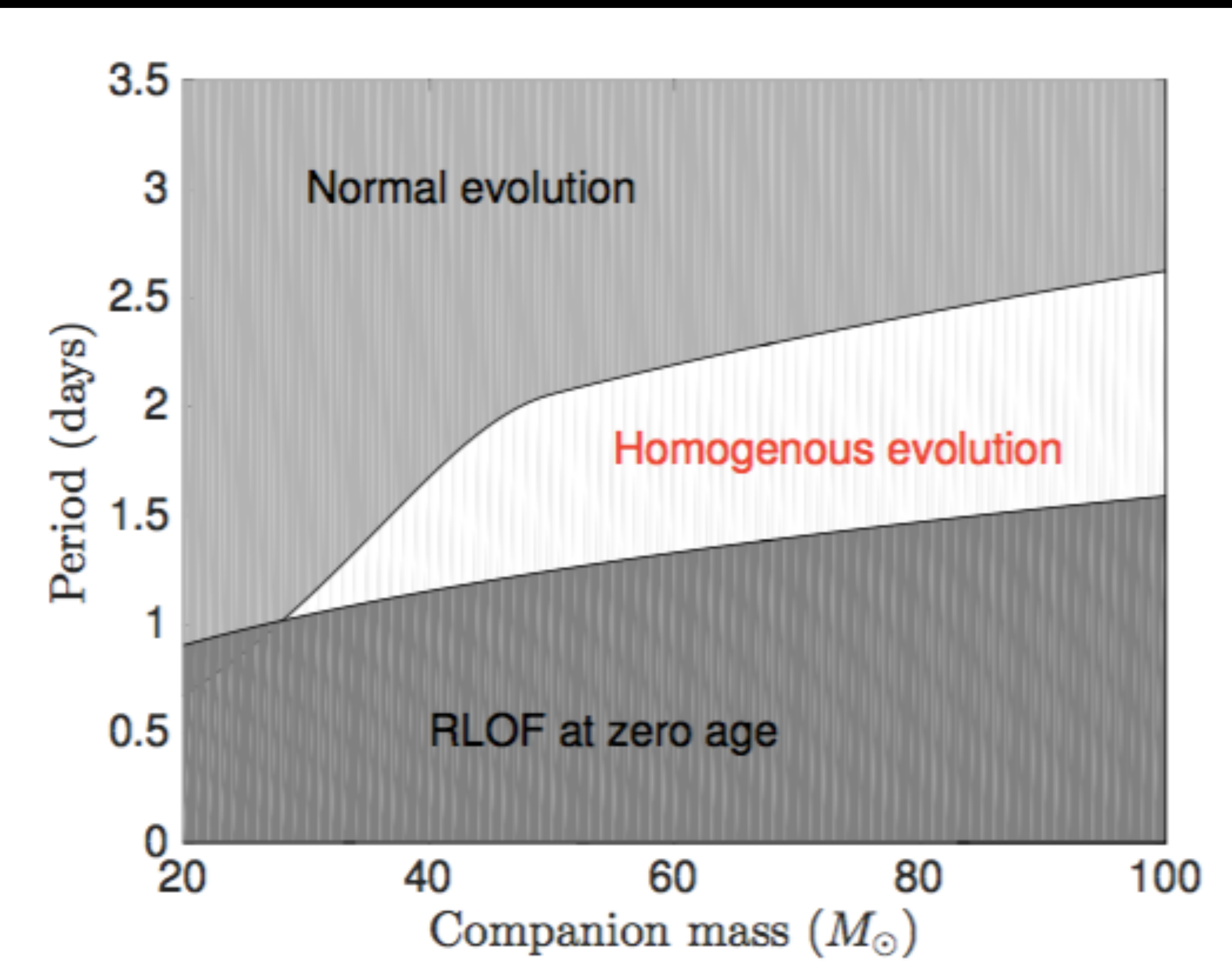
Chemically homogeneous evolution?

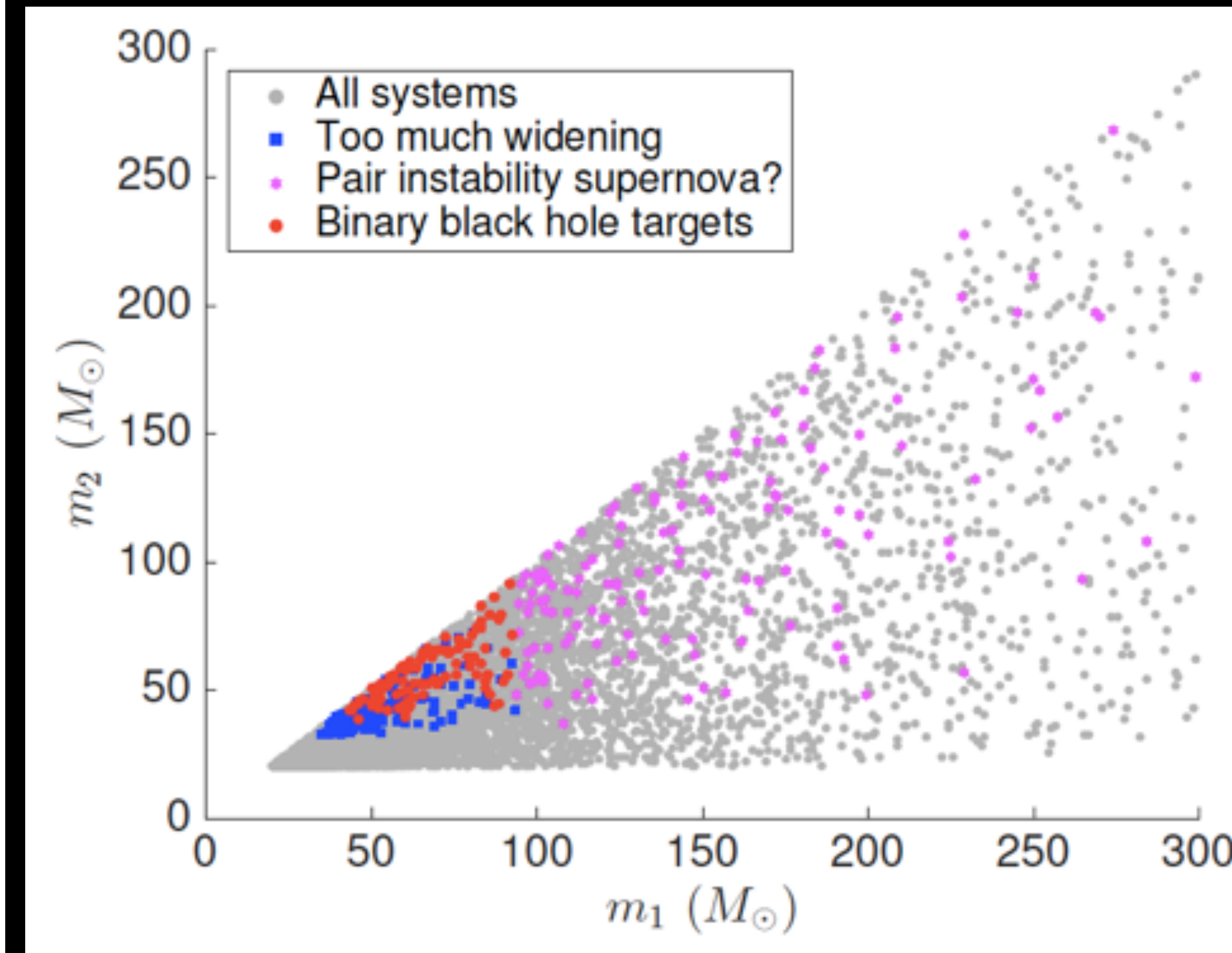


Mandel & de Mink, arXiv:1601.00007, MNRAS

see also Marchant+, arXiv:1601.03718, A&A; de Mink & Mandel, arXiv:1603.02291, MNRAS

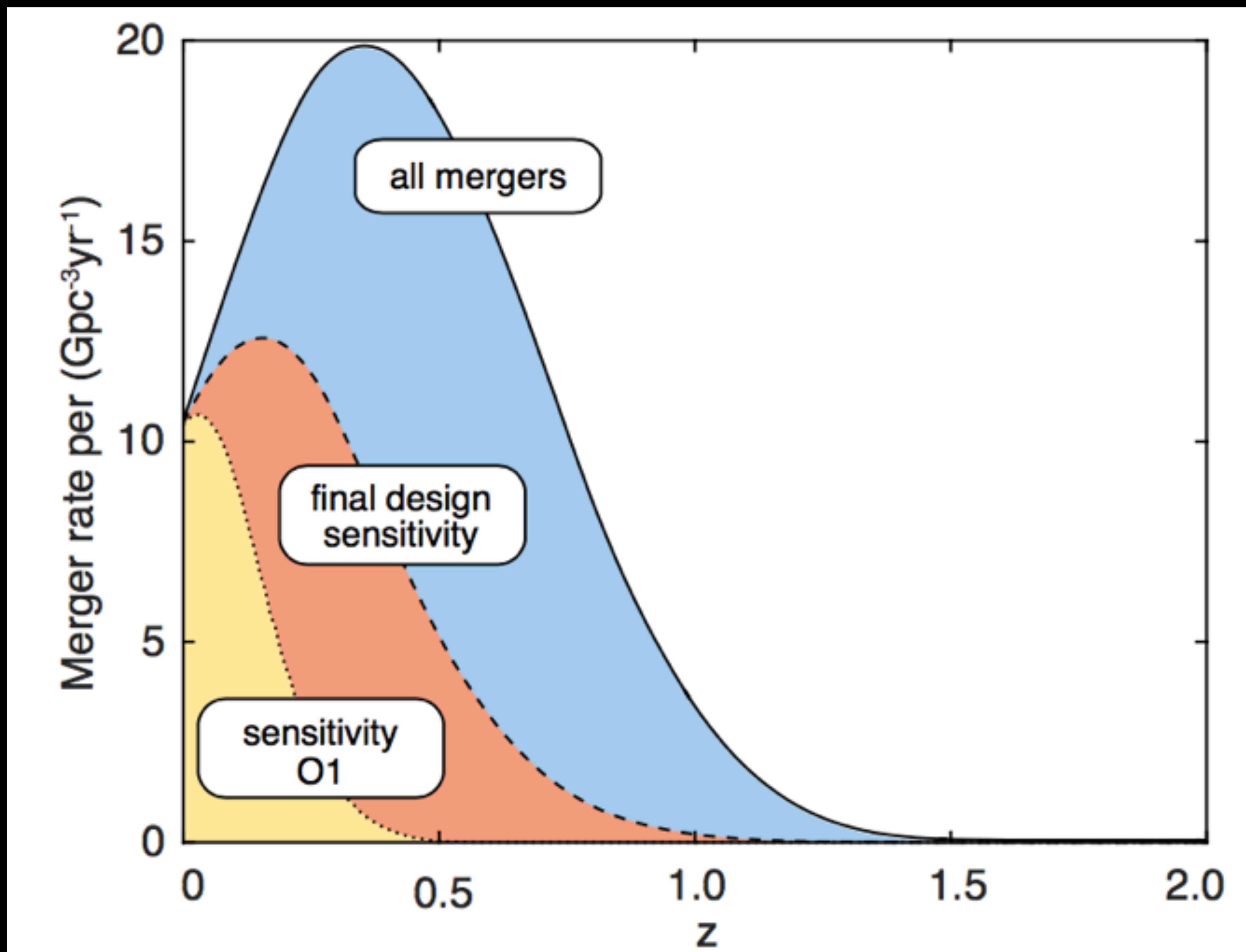
Chemically homogeneous evolution





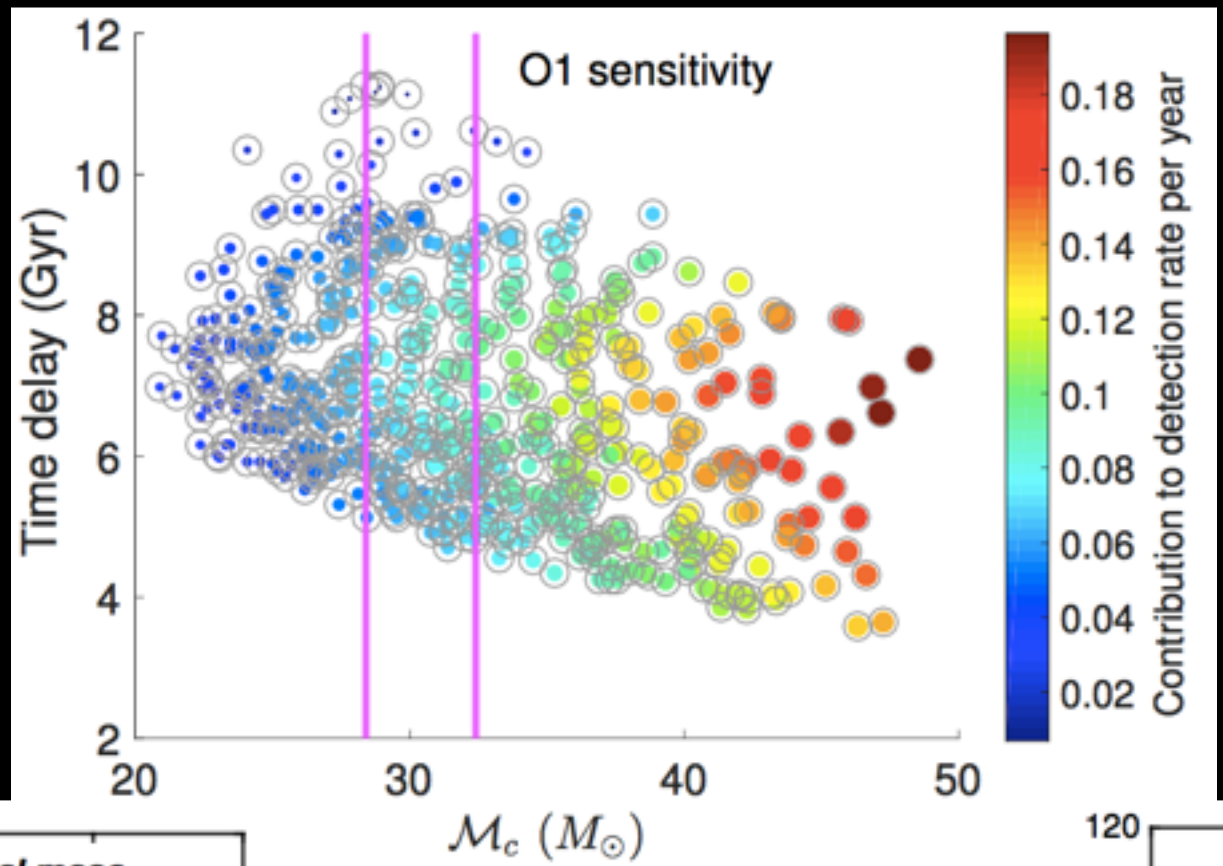
see mock catalogs at
http://www.sr.bham.ac.uk/~imandel/CaseM/

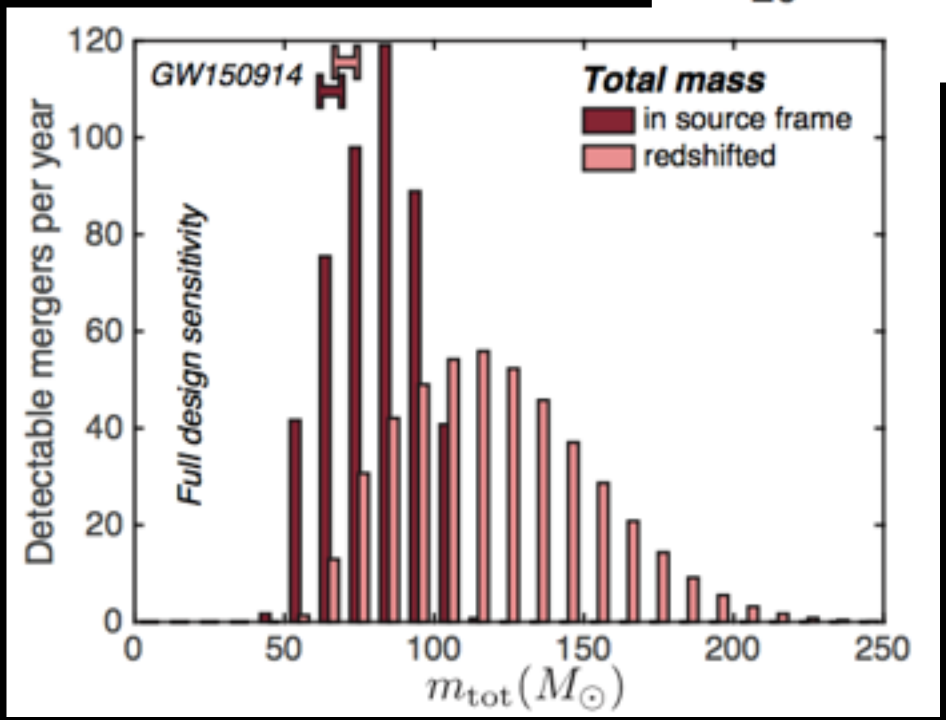
Chemically homogeneous evolution

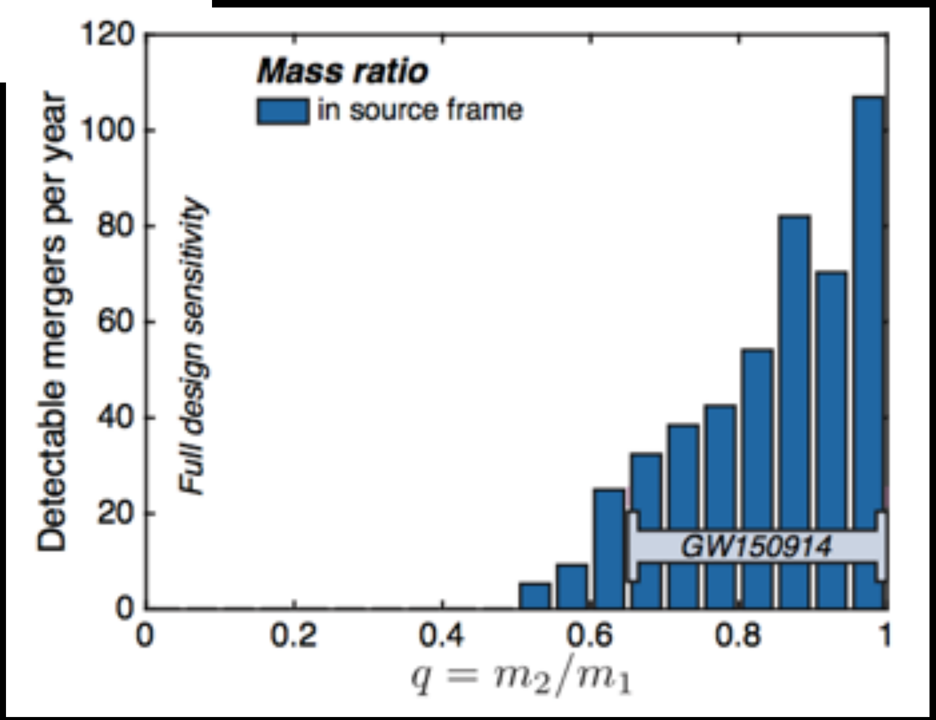


de Mink & Mandel, arXiv:1603.02291, MNRAS

Chemically homogeneous evolution







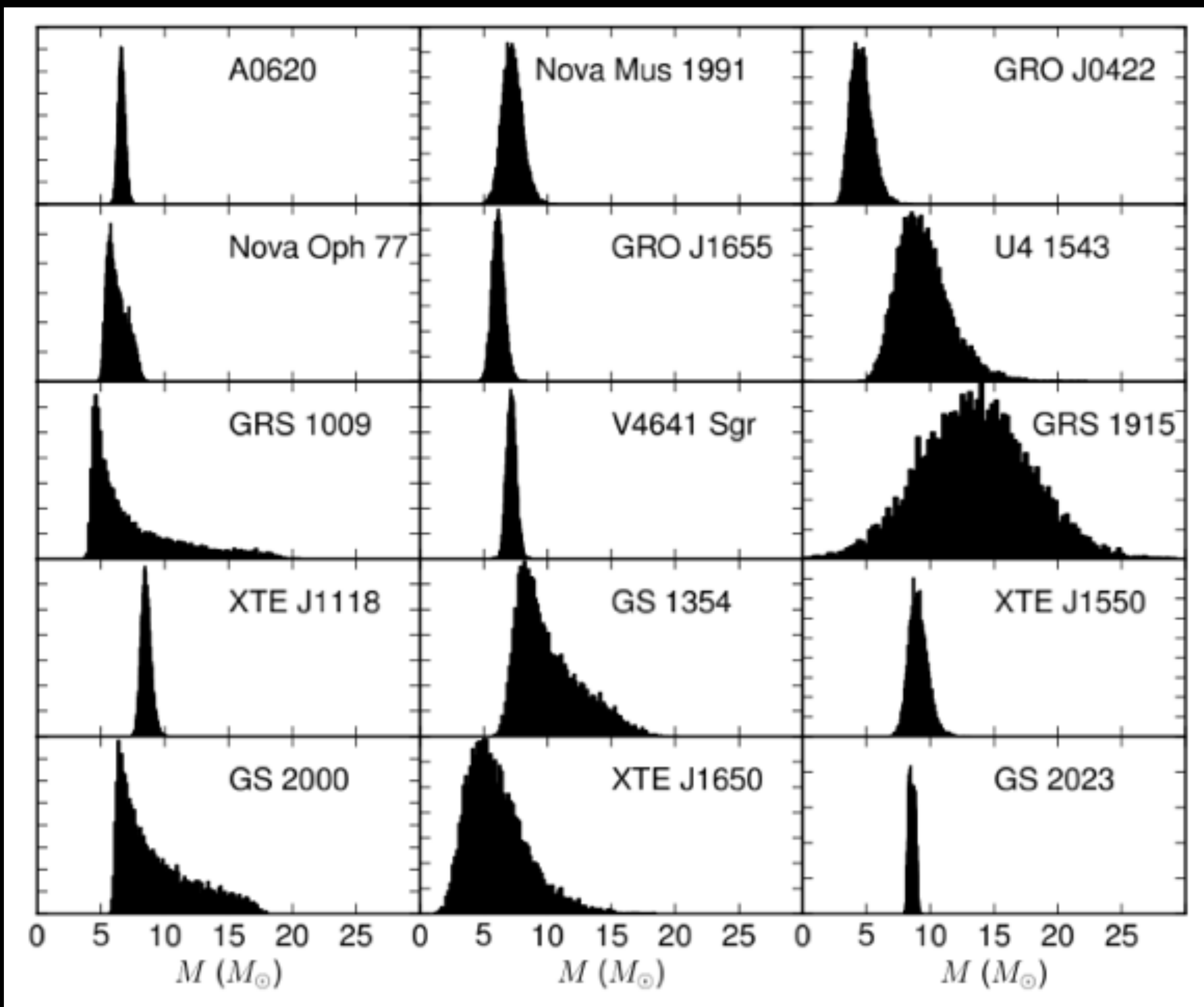
Key lessons learned

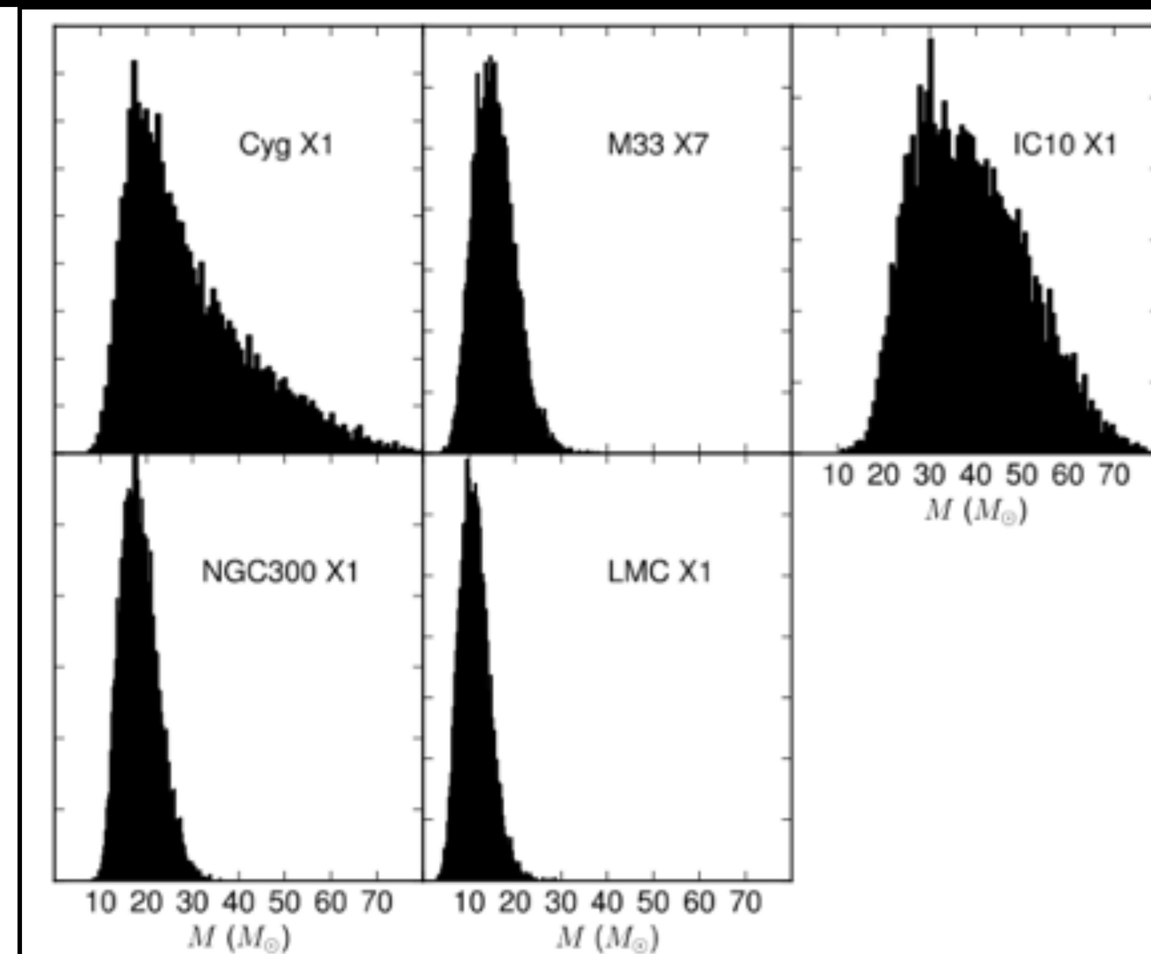
1. BBHs exist

2. Merging BBHs exist

3. Stellar-mass BHs with mass above 30 solar masses exist (and take part in mergers)

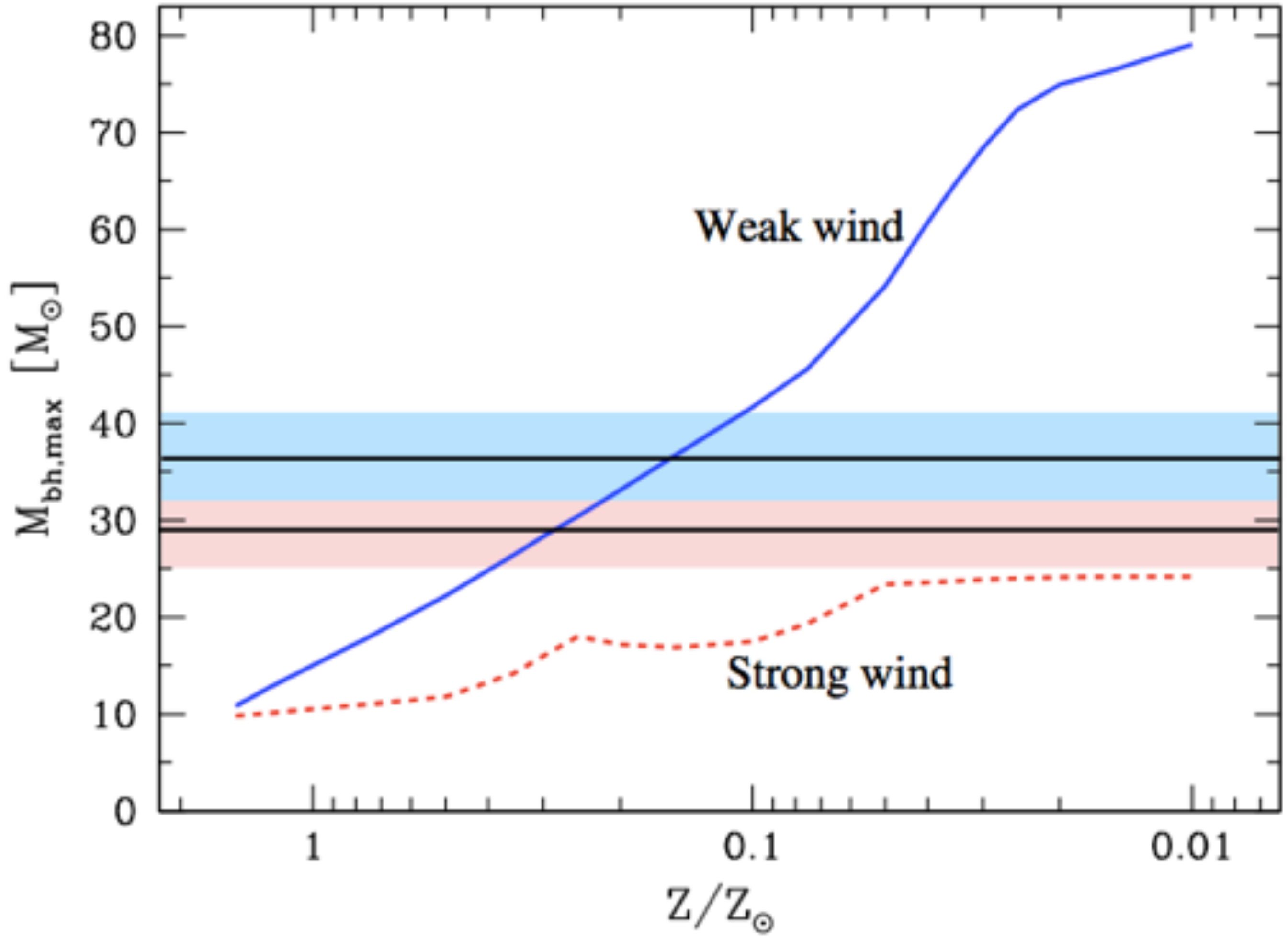
BH mass distribution

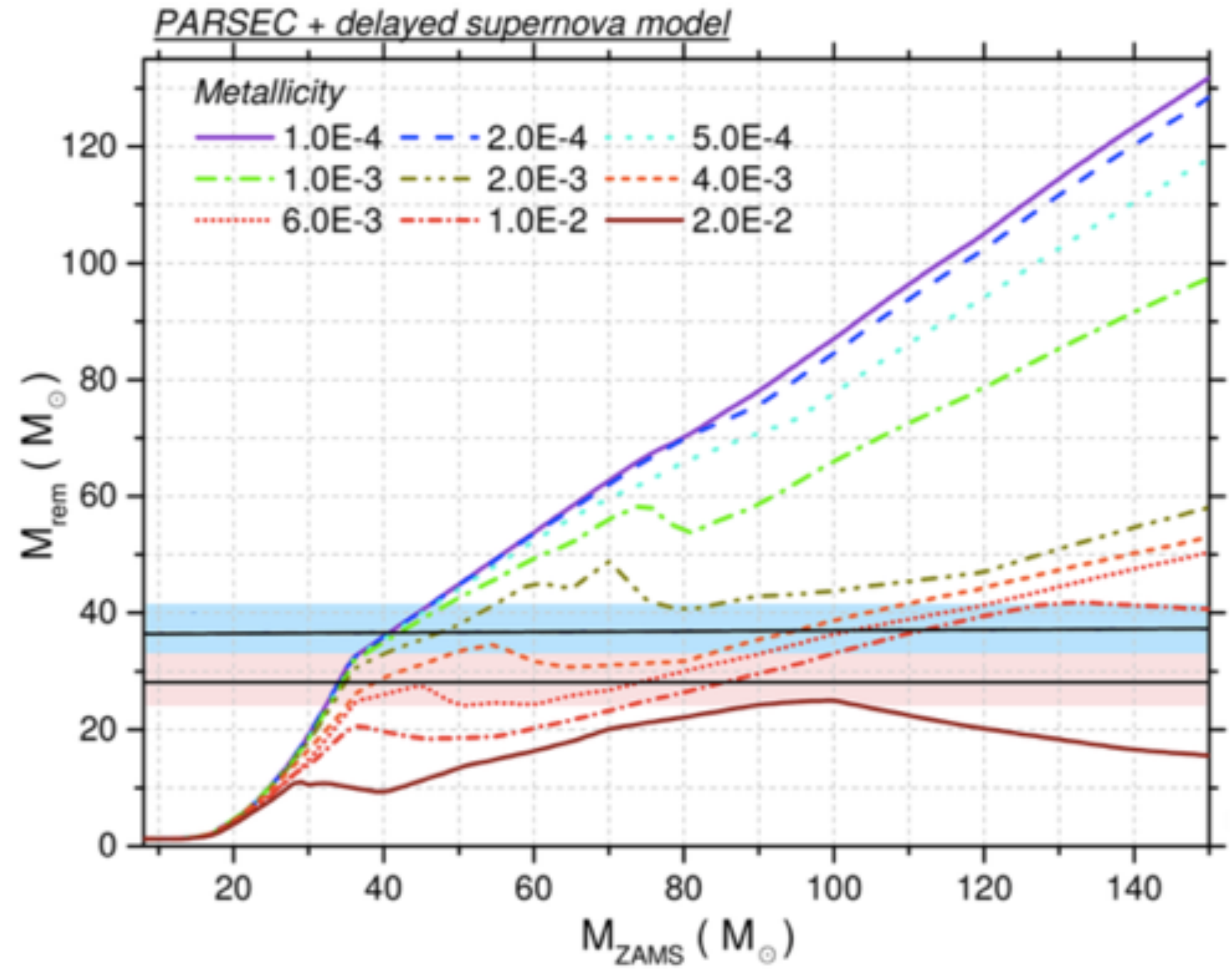




Black hole masses in low-mass and high-mass X-ray binaries [Farr et al., 2011 ApJ 741, 103]; see also Ozel+, 2010 ApJ 725, 1918

Metallicity and winds



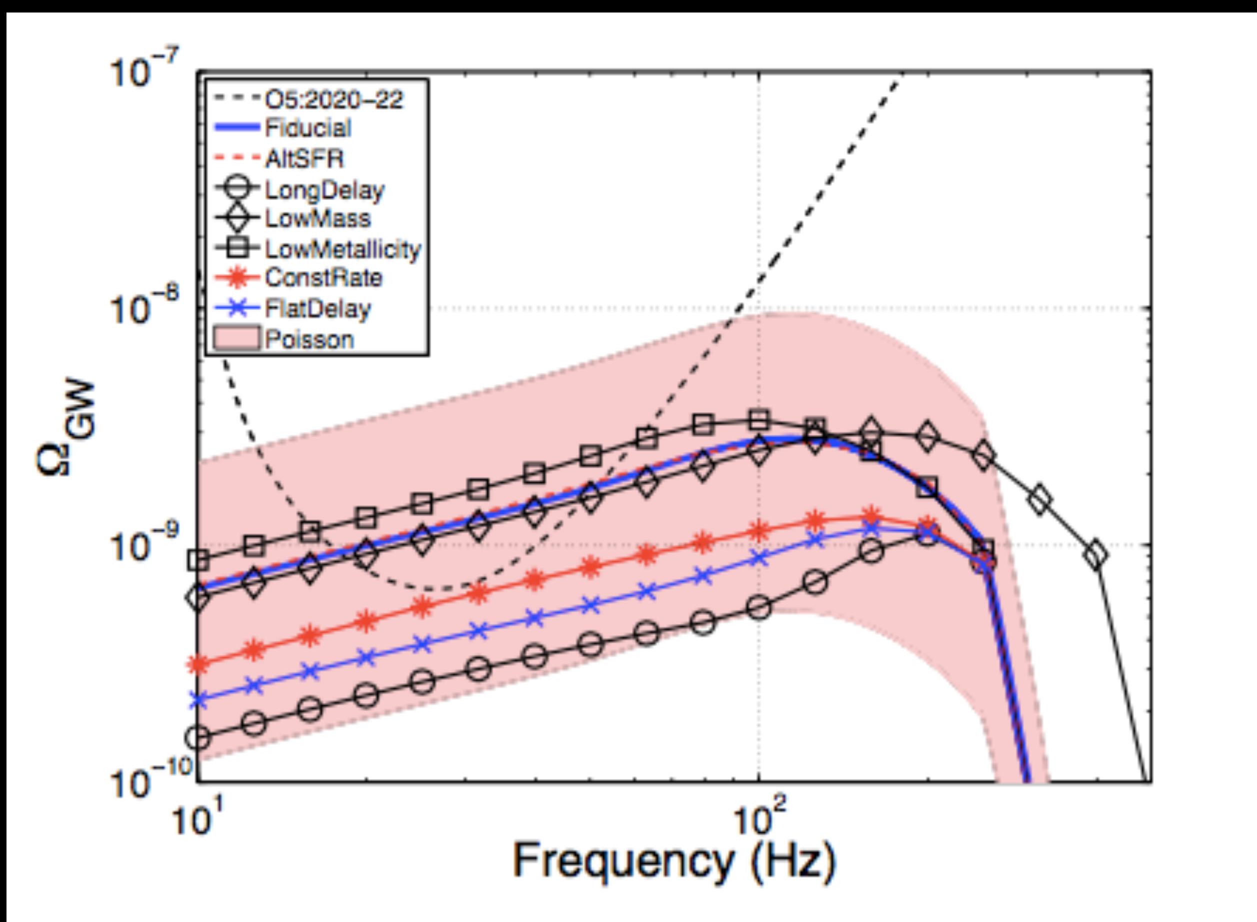


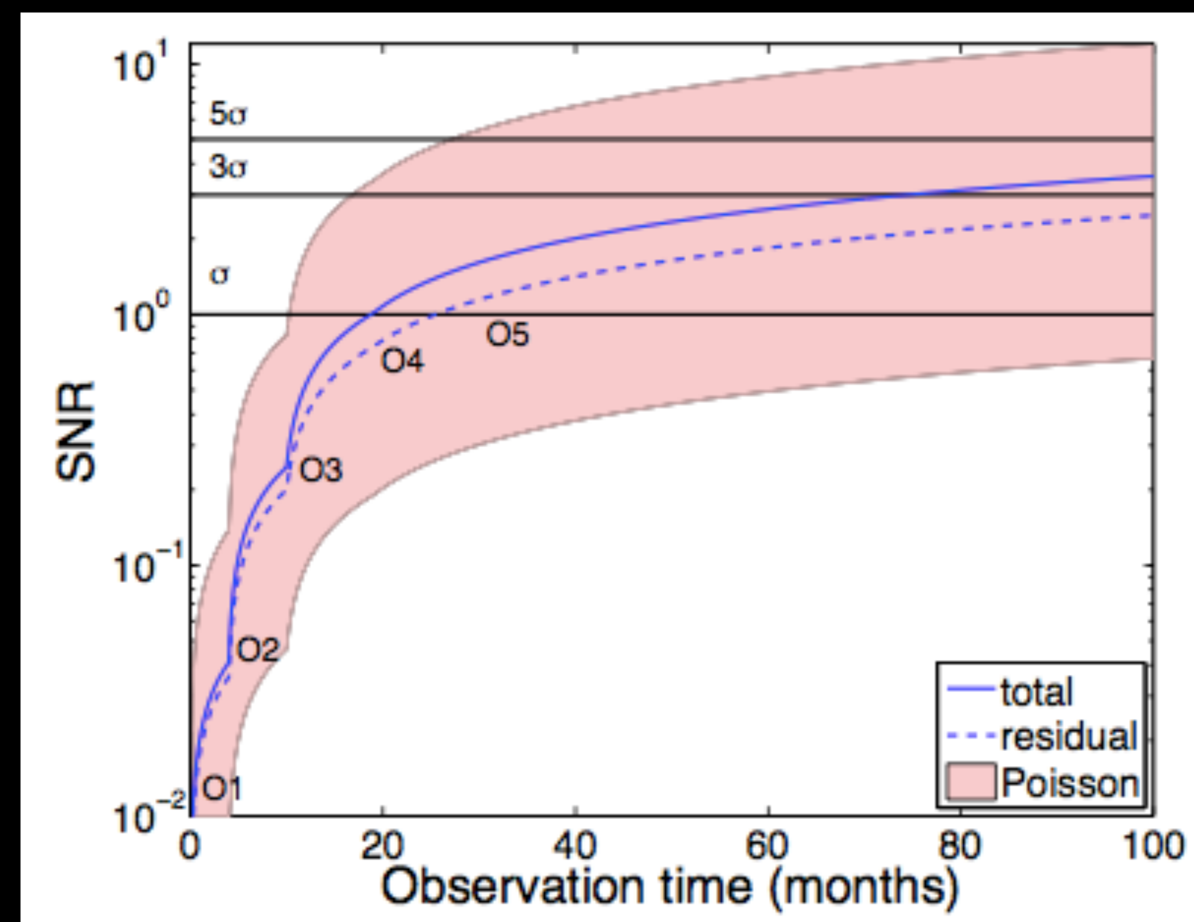
adapted from
Belczynski+, 2010

adopted from
Spera+, 2016

Stochastic background

GW150914: Implications for the stochastic gravitational-wave background from binary black holes





[but see, e.g., Callister+, arXiv:arXiv:1604.02513]

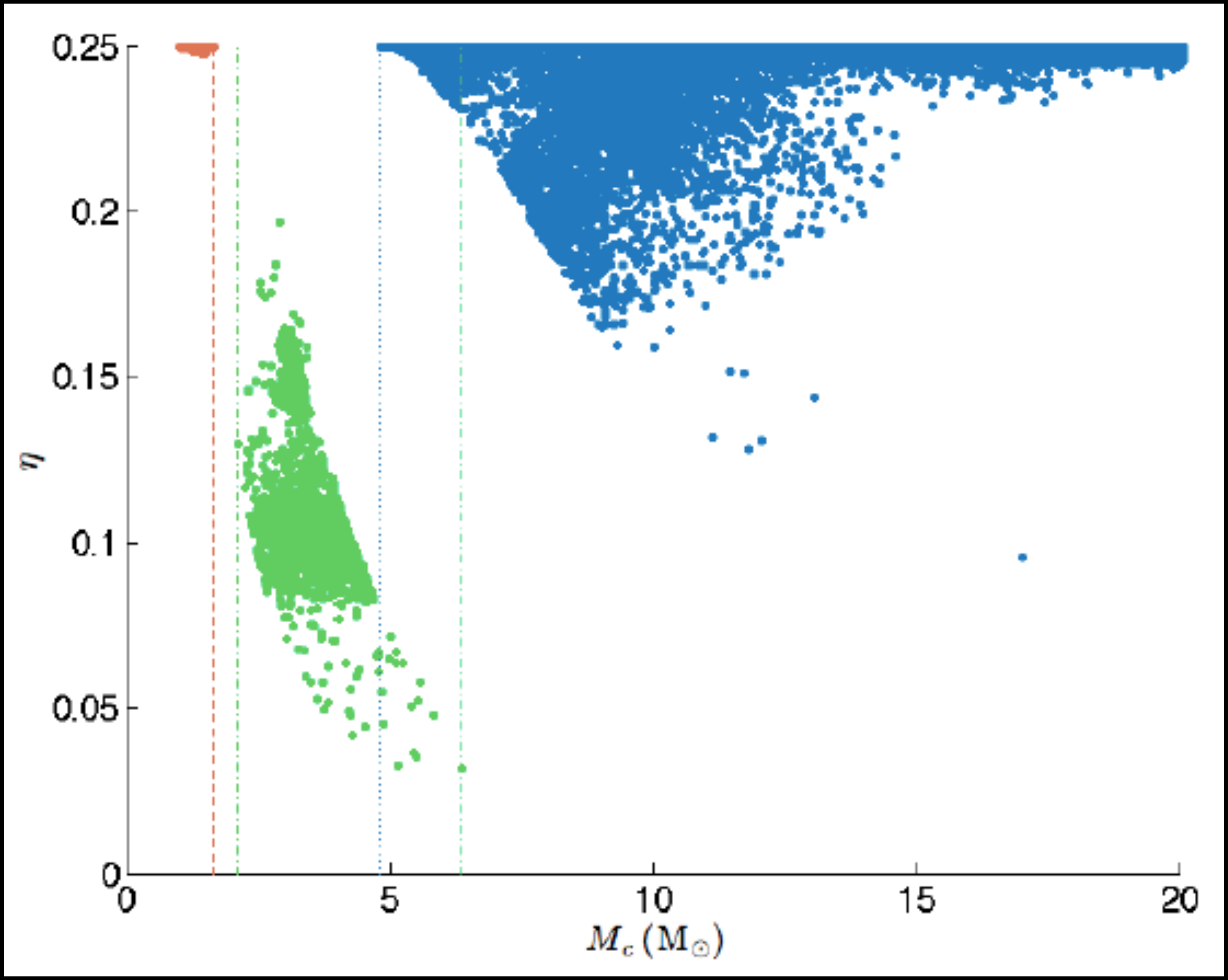
Key lessons learned

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

Inverse problem of gravitational-wave astrophysics

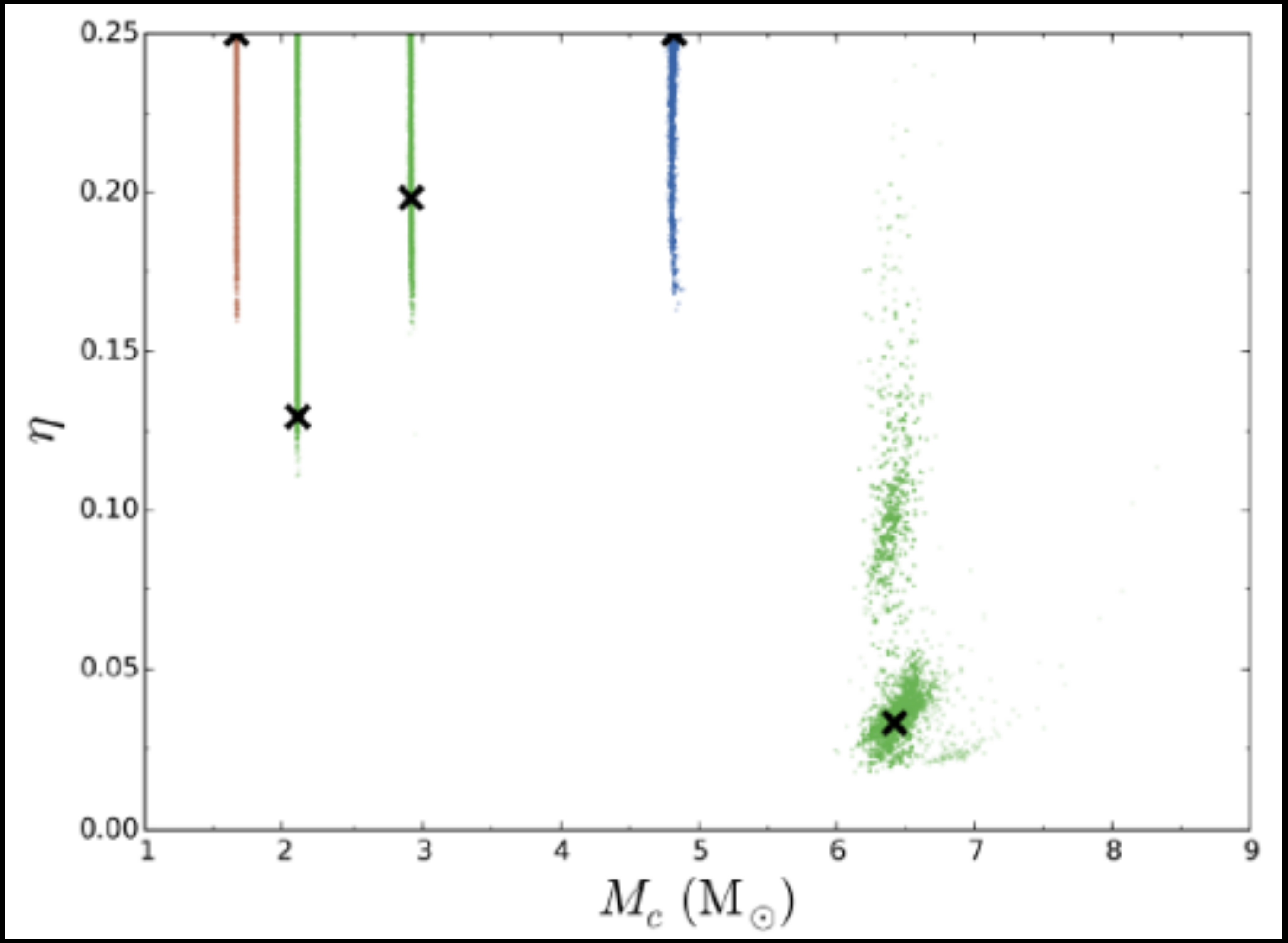
- Unmodeled approach:
  - Searching for clusters in observable parameter space
- Modeled approach
  - Compare observed rates and distributions against model predictions
  - Requires building a catalog of models which explore a broad hyper-parameter space (e.g., common-envelope physics, BH natal kicks, etc.), interpolating, comparing to reconstructed source population

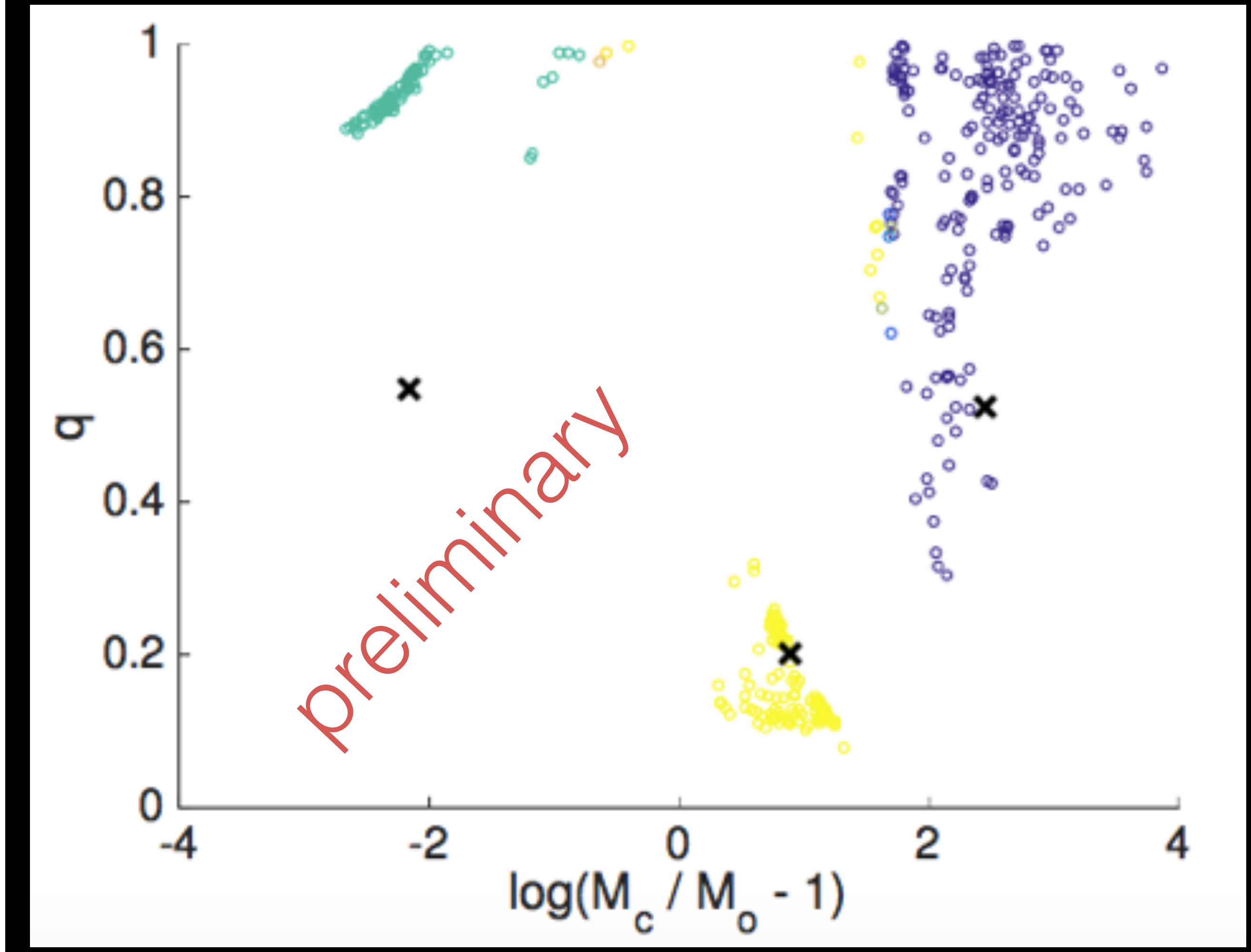
Clustering on observations



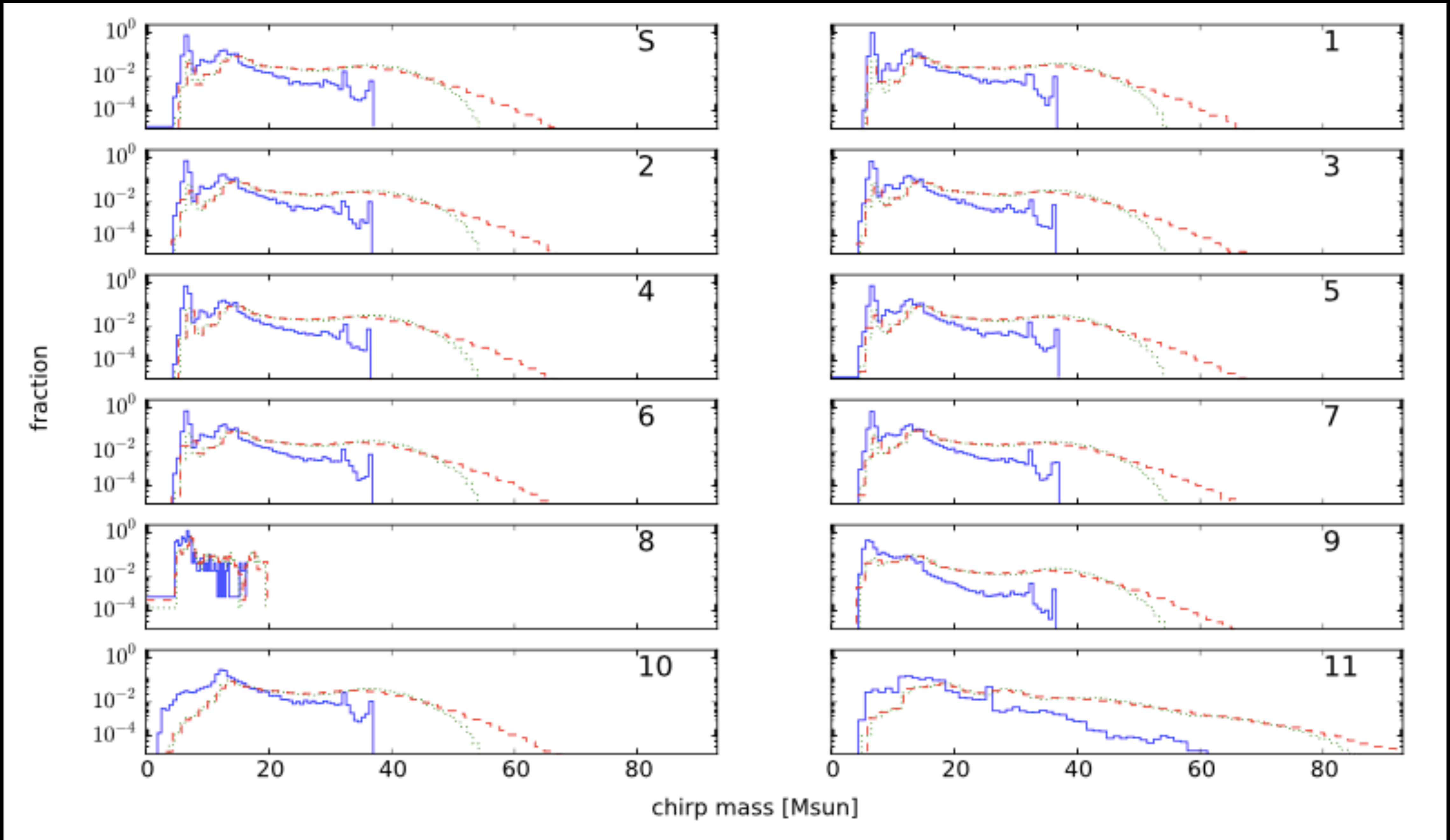
[Mandel+, 2015, MNRAS Letters, arXiv:1503.03172]

Clustering on observations



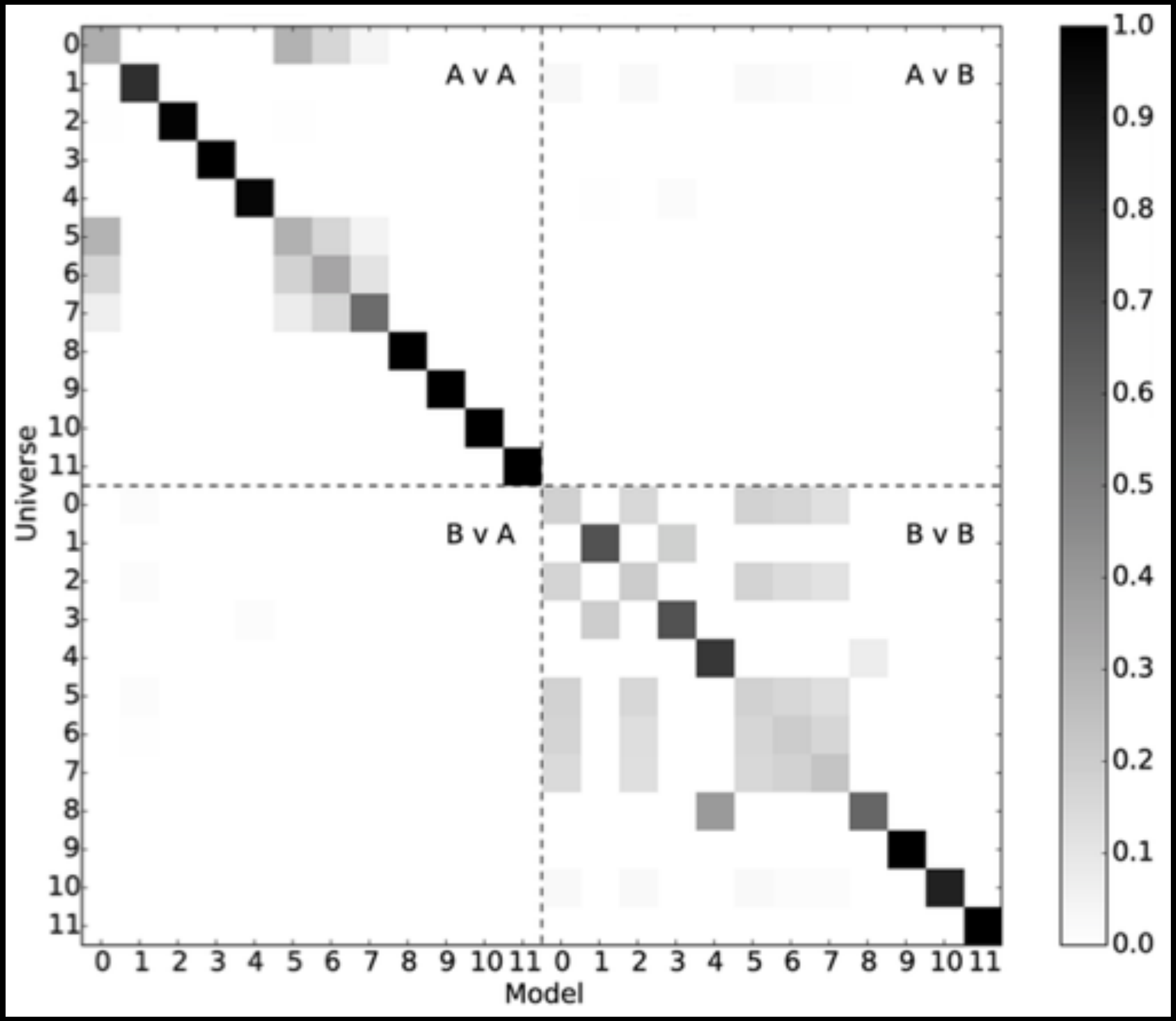


Model comparison



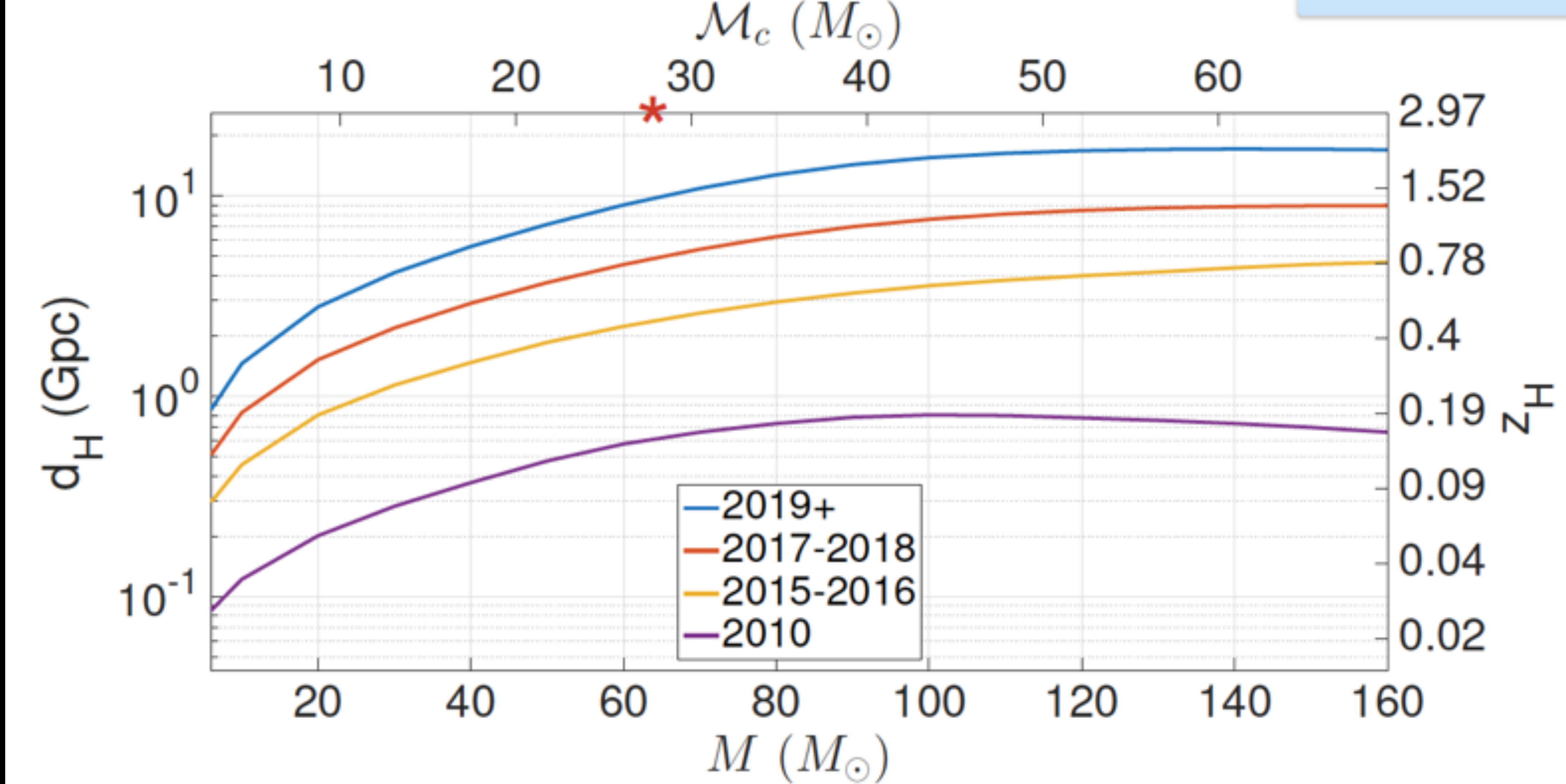
[Stevenson+, arXiv:1504.07802; based on data from Dominik+, 2012 — see syntheticuniverse.org]

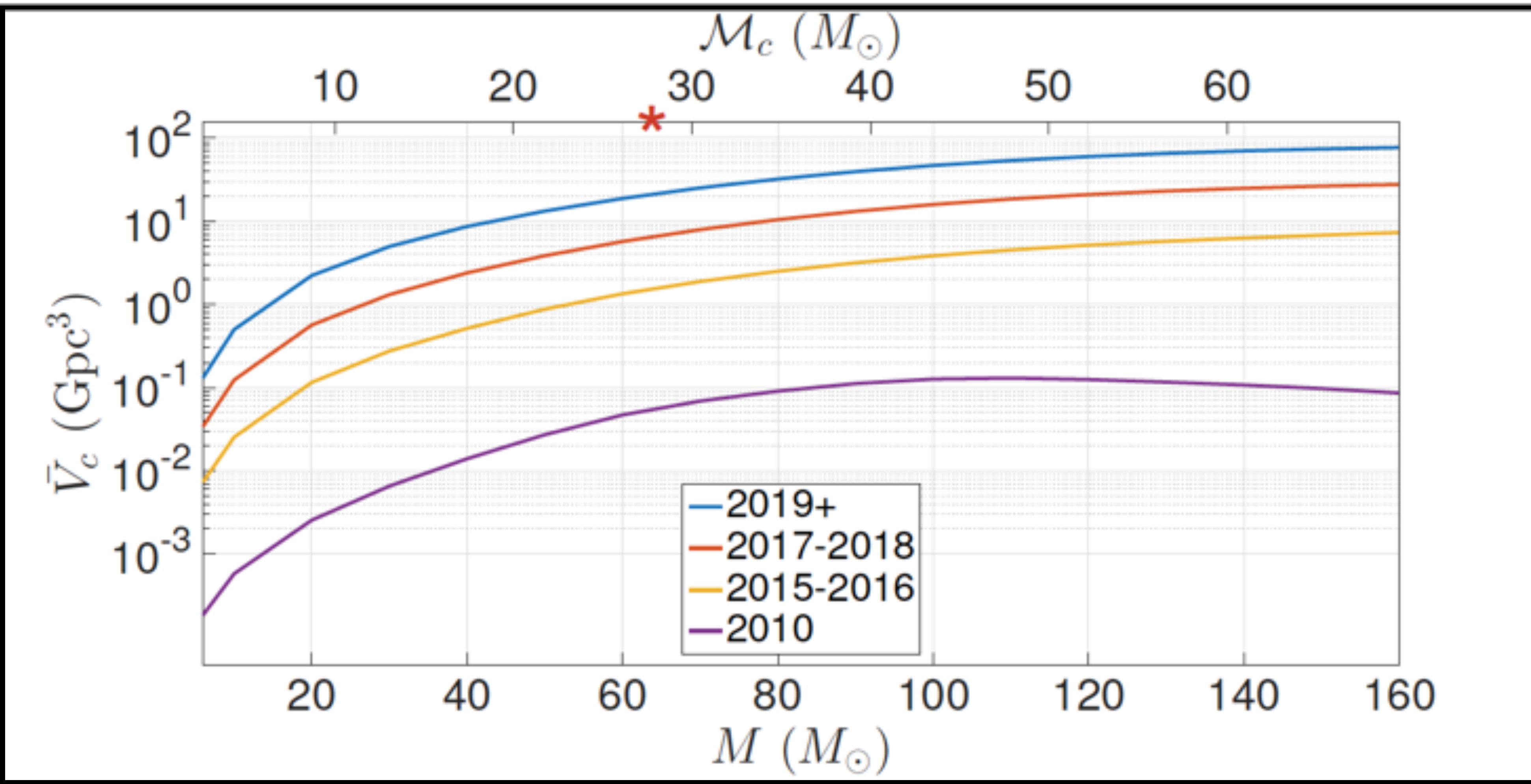
Model comparison

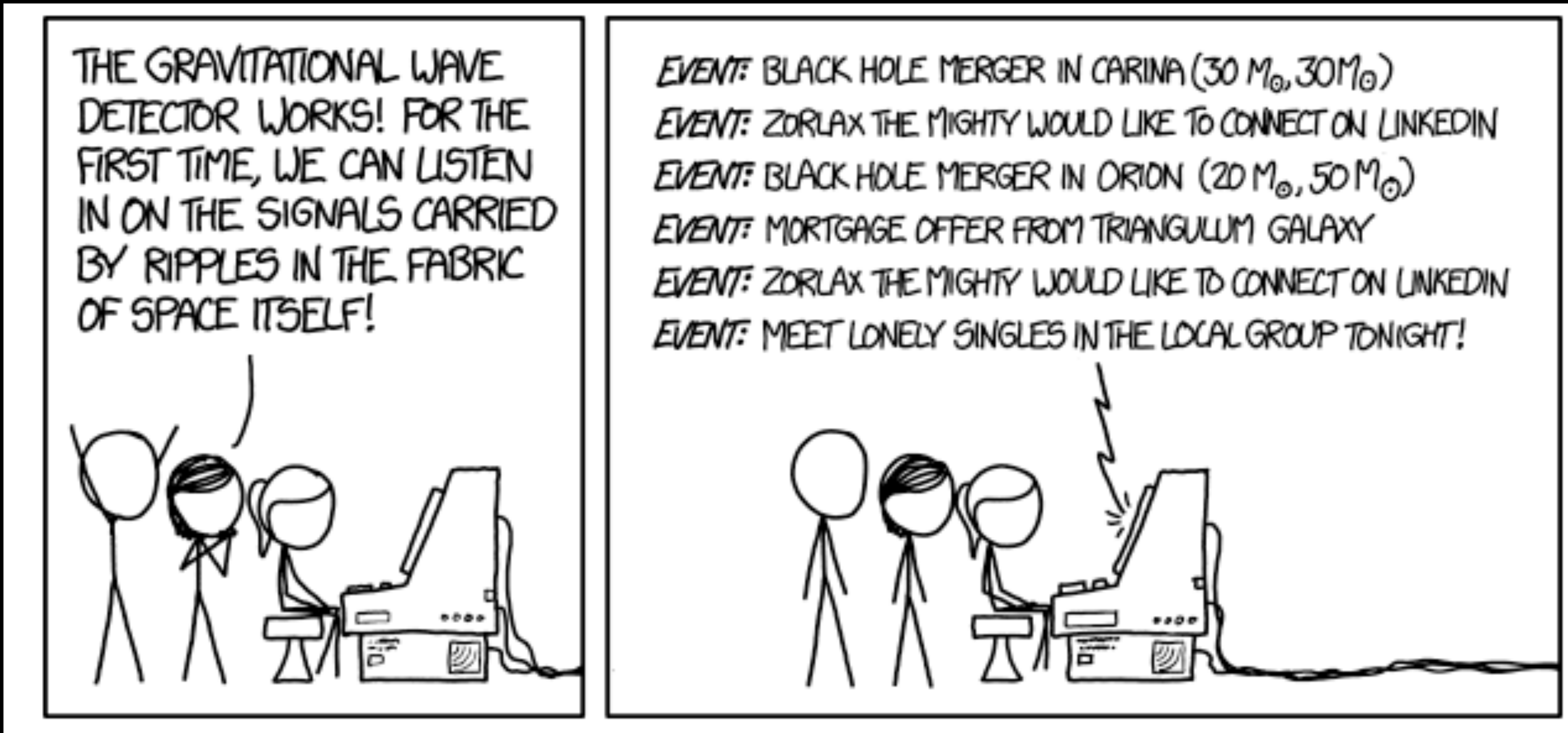


Stevenson+, arXiv:1504.07802

Compact Object Mergers: Population Assembly Statistics


$\mathcal{M}_c\ (M_\odot)$
10 20 30 40 50 60
d_H (Gpc)
10^1 10^0 10^{-1}
z_H
2.97 1.52 0.78 0.4 0.19 0.09 0.04 0.02
2019+
2017-2018
2015-2016
2010
20 40 60 80 100 120 140 160
$M\ (M_\odot)$


$\mathcal{M}_c\ (M_\odot)$
10 20 30 40 50 60
$\bar{V}_c\ (\mathrm{Gpc}^3)$
10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3}
2019+
2017-2018
2015-2016
2010
20 40 60 80 100 120 140 160
$M\ (M_\odot)$


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!