ARC Centre of Excellence for Gravitational Wave Discovery

Insights in binary black hole formation from gravitational waves
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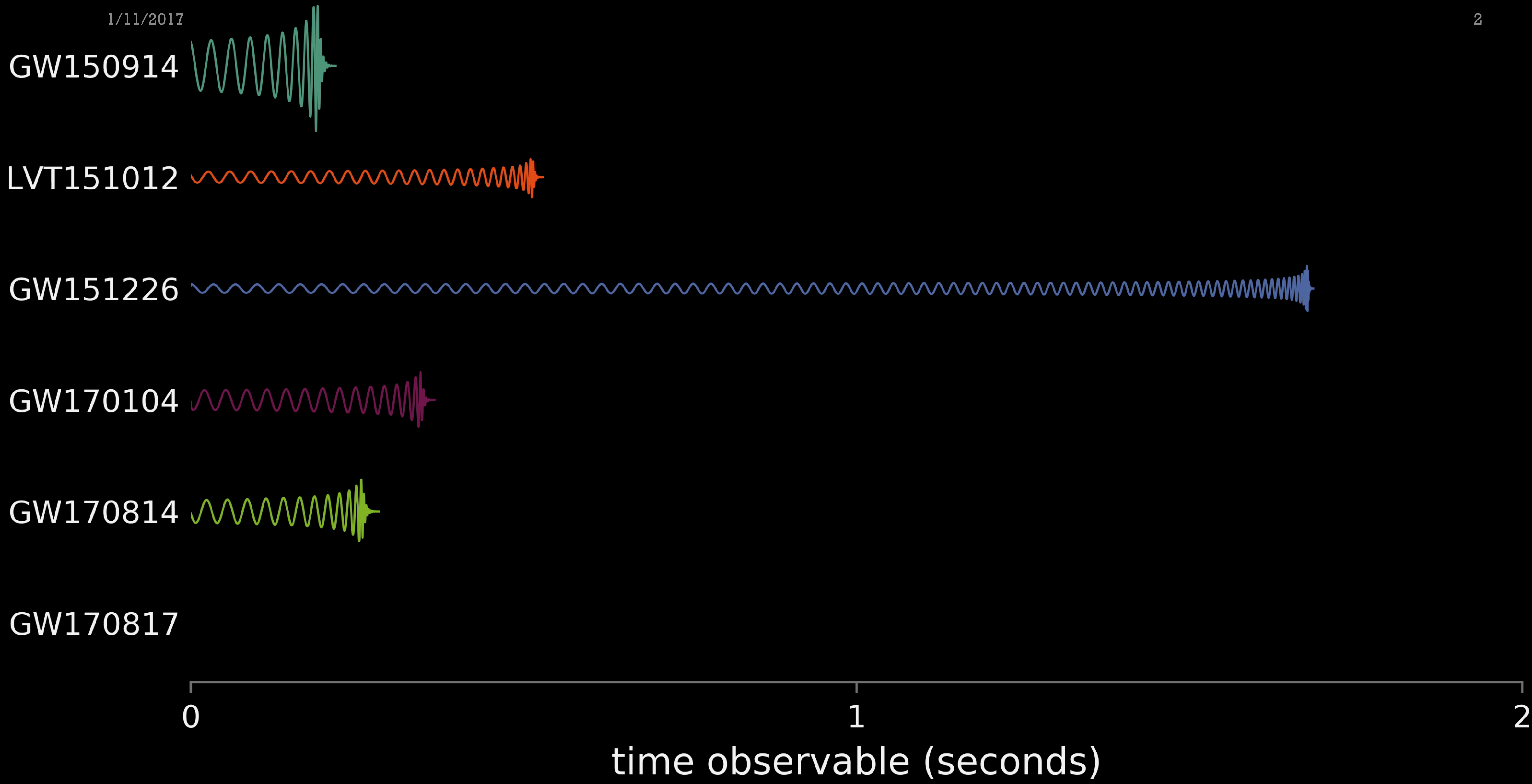
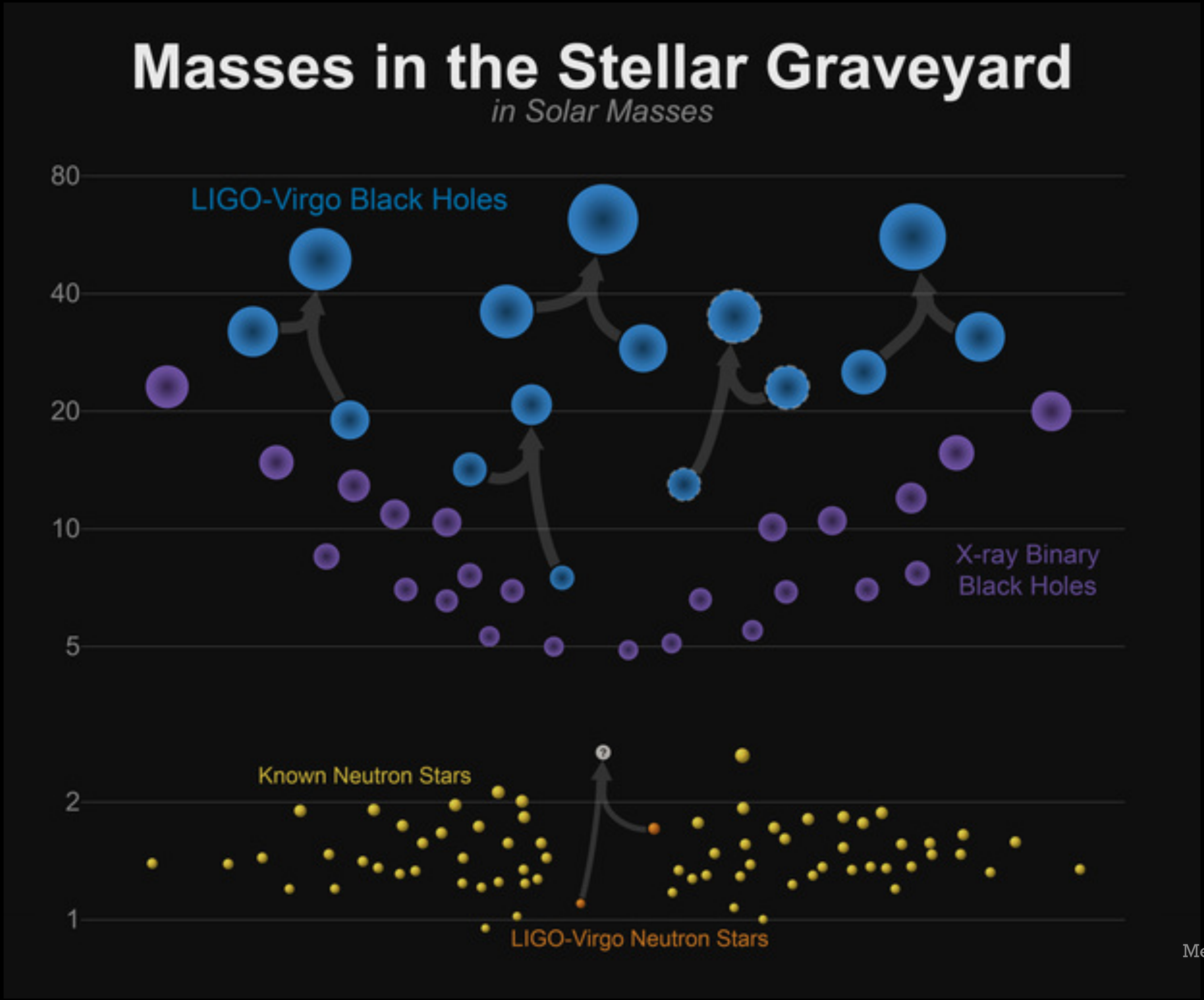
for the COMPAS team

Alejandro Vigna-Gómez, Coenraad J. Neijssel1, Jim W. Barrett, Ilya Mandel and more!

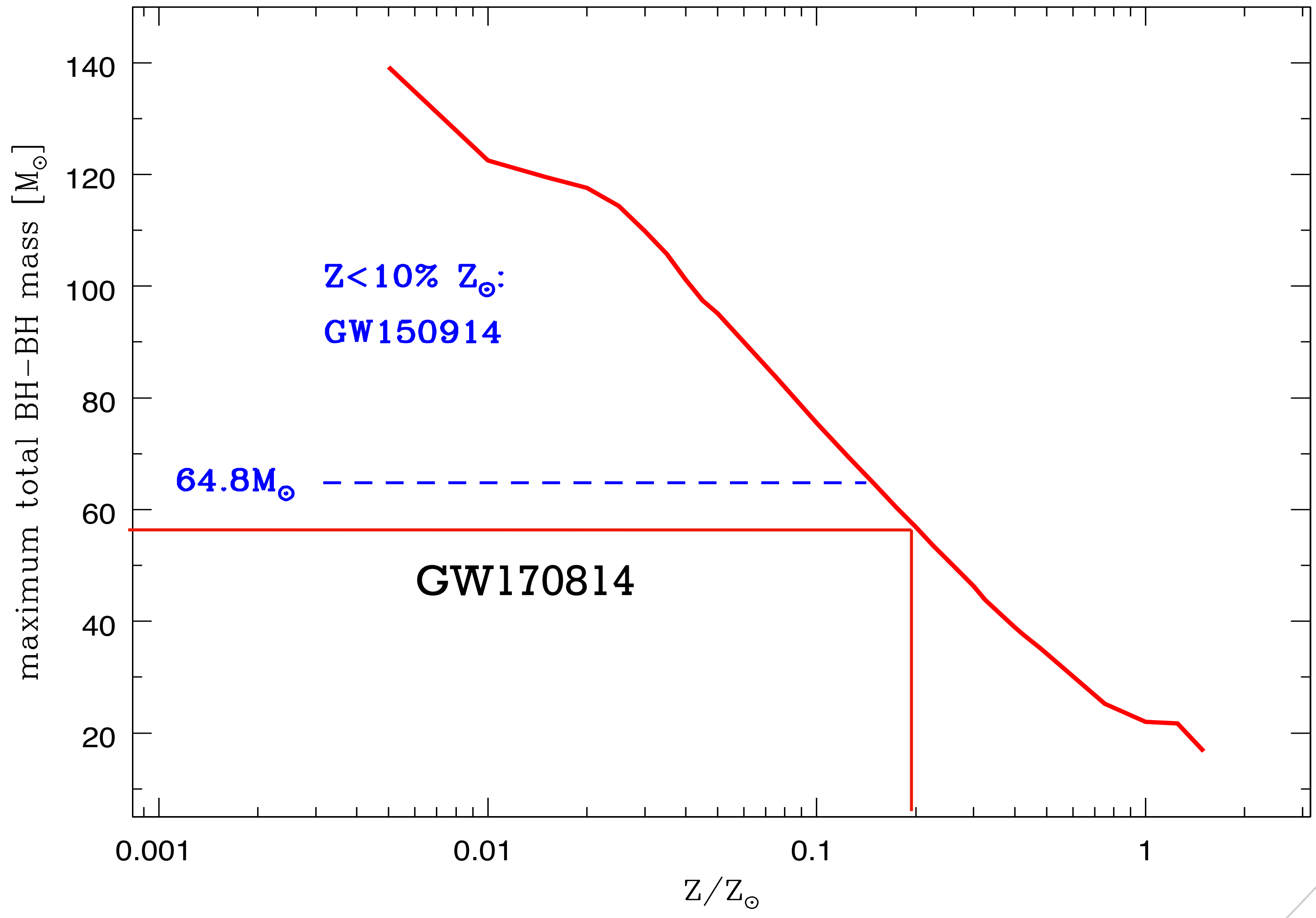


LIGO/University of Oregon/Ben Farr



Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary
Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars

Maximum total mass against metallicity



Adapted from Belczynski+ 2016 arXiv:1602.04531

Binary black hole mass distribution

Weak constraints on power law

$$p\left(m_1 \mid \alpha\right) \propto m_1^{-\alpha},$$

Weak evidence for maximum mass around 40 Msol. Pair-instability mass gap?

LVC 2016
arXiv:1606.04856

Fishbach & Holz
arXiv: 1709.08584

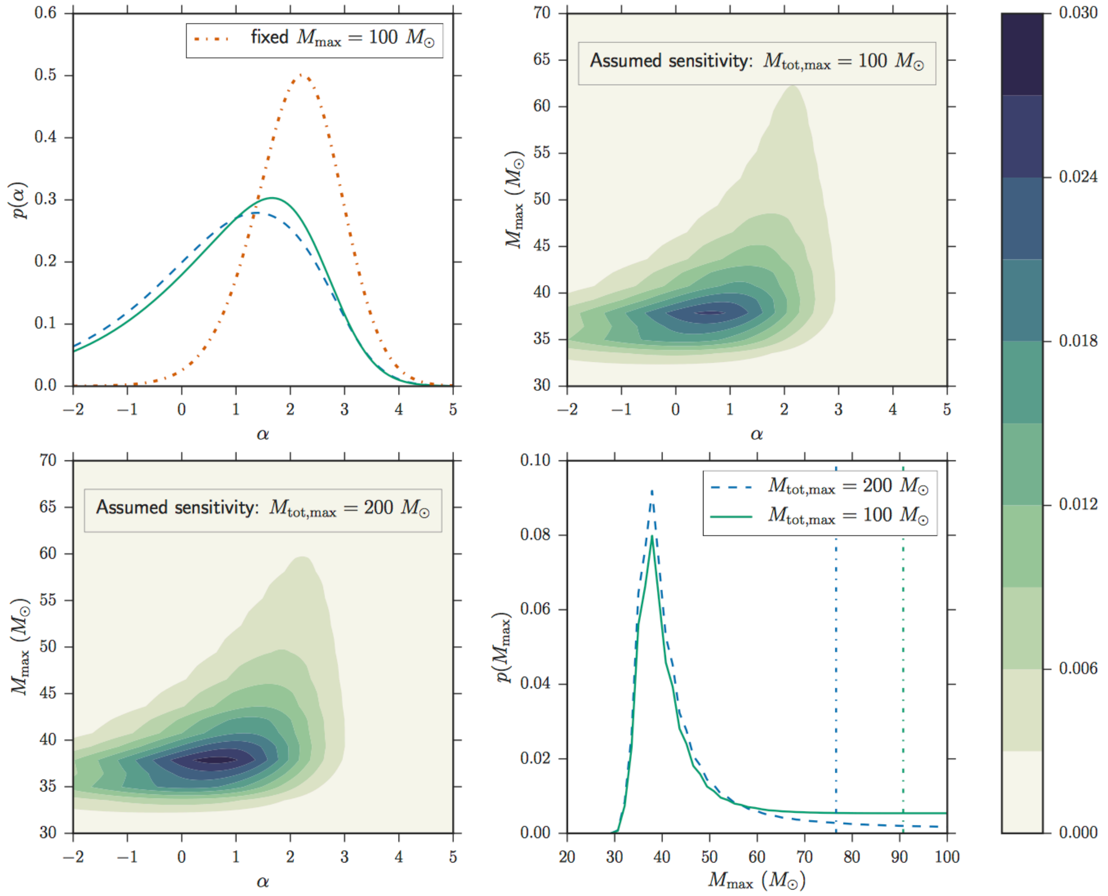
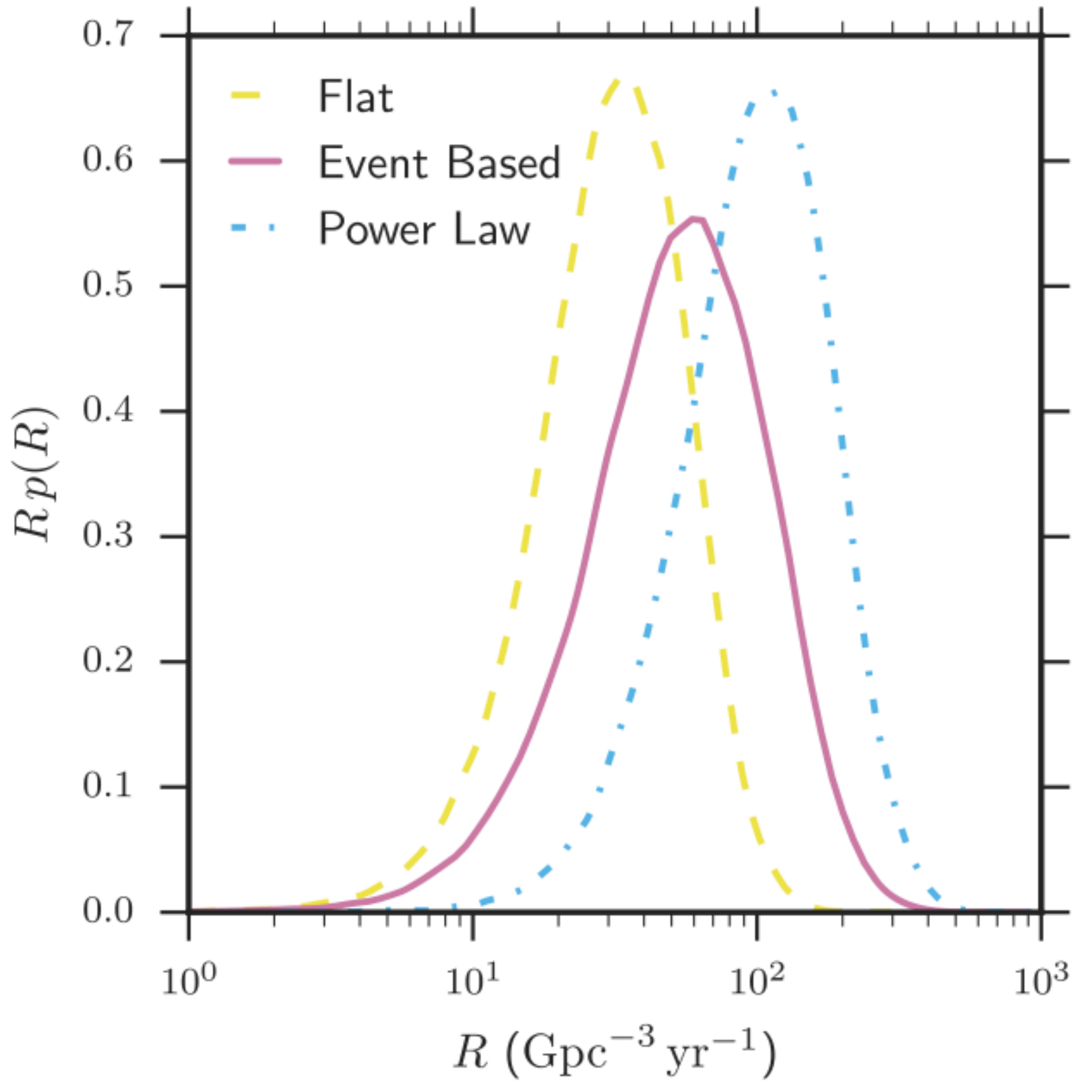


Figure 4. Joint fits for α, $M_{\rm max}$ from the four LIGO detections. Lower left panel: The posterior PDF $p(\alpha, M_{\rm max})$ under the conservative assumption that $M_{\rm tot,max} = 100 M_\odot$. Upper right panel: The posterior PDF $p(\alpha, M_{\rm max})$ assuming full matched-filter sensitivity up to $M_{\rm tot,max} = 200 M_\odot$. Upper left panel: The marginal posterior PDF for α under each assumption of $M_{\rm tot,max}$ (green solid and dashed blue curves). The orange dash-dotted curve shows the results of the canonical analysis (Eq. 3) in which $M_{\rm max}$ is fixed at $M_{\rm max} = 95 M_\odot$ and $M_{\rm tot,max} = 100 M_\odot$. Lower right panel: The marginal posterior PDF for $M_{\rm max}$ under each assumption of $M_{\rm tot,max}$. The vertical dotted lines denote 95% credible intervals. Throughout, we take a uniform prior on α in the range $-2 \leq \alpha \leq 7$ and on $M_{\rm max}$ in the range $M_{\rm max} < 100 M_\odot$, as described in the text.

Mass function with number of observations

Mandel…Stevenson+ 2016 arXiv:1608.08223

Binary black hole merger rates



- O1 empirically determined merger rates assuming a particular mass distribution
- “Power law” distribution favoured over “Flat-in-log” distribution (see next slide)
- Lower bounds including GW170104 are 40 and 12 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ respectively. Remain consistent including GW170814

LVC 2016 arXiv:1606.04856

How did these binary black holes form?

Formation channels

Mandel & Farmer 2017, Nature

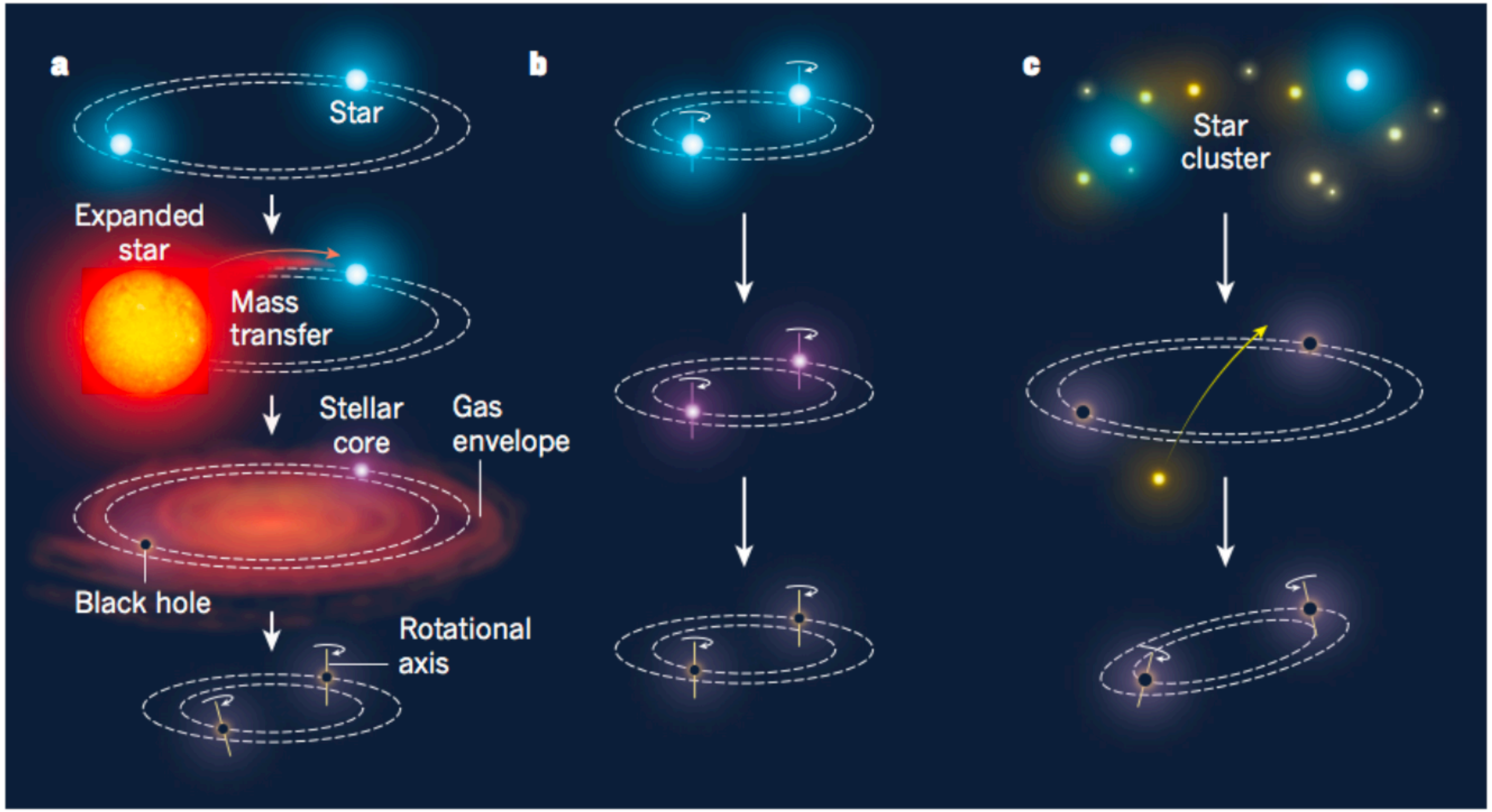
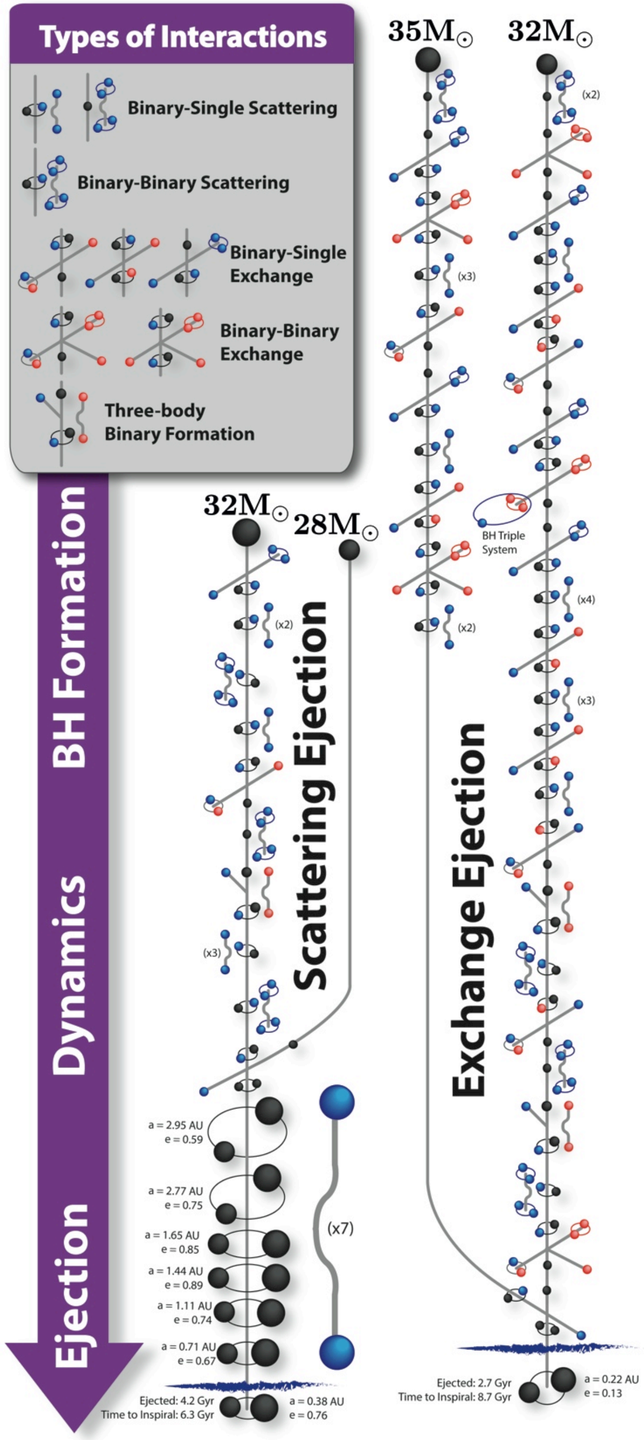


Figure 1 | Three possible mechanisms for the merger of black holes. **a,** In a binary star system that has a wide separation (orbit shown in broken lines), the expansion of one star as it evolves can lead to its outer layers being transferred to its companion. Further evolution of the system can lead to the formation of a gas envelope around the two objects, which are now a black hole and a stellar core. Friction between these objects and the envelope acts to bring the objects closer together. Eventually both stars collapse

Dynamical formation

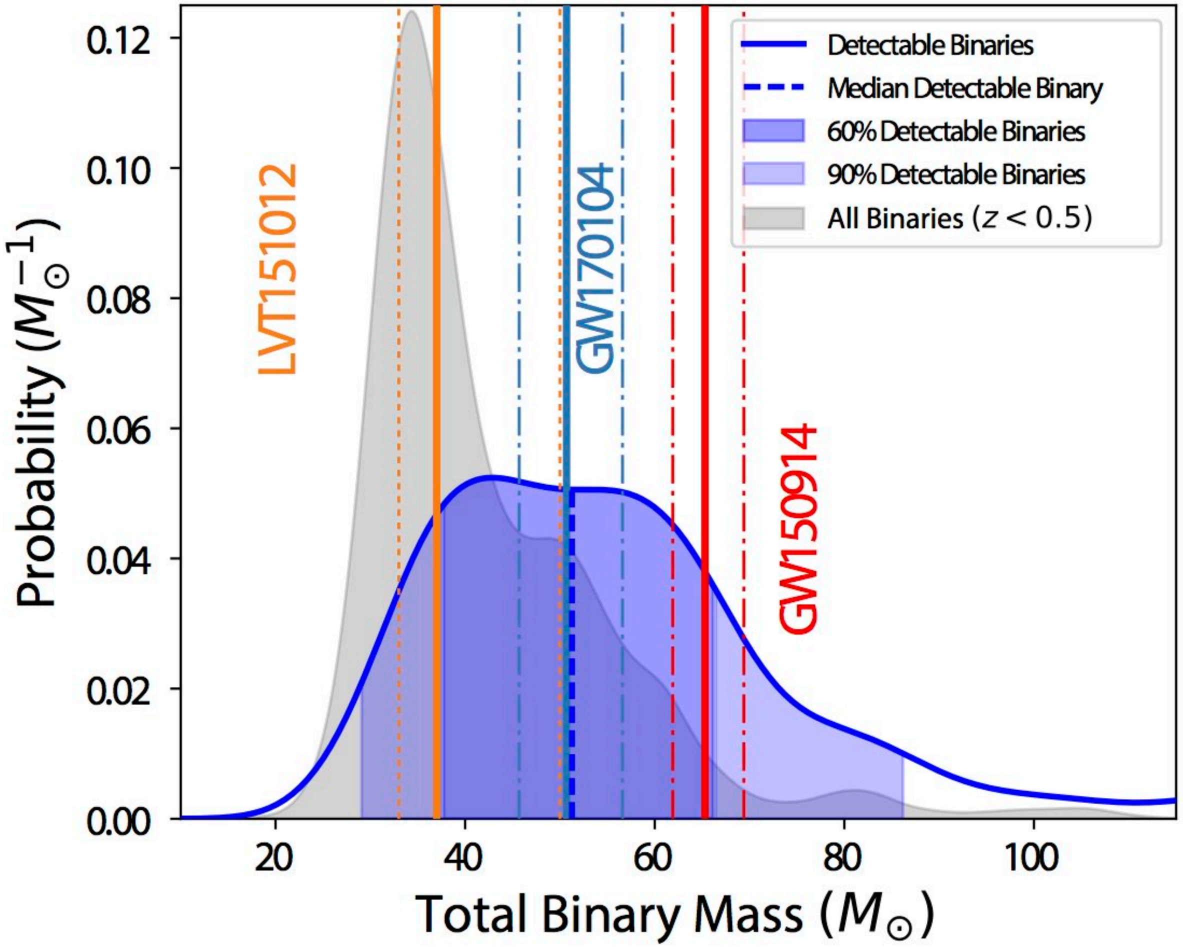
- Formation in a dense stellar environment such as a globular or nuclear cluster

Rodriguez+ 2016 arXiv:1604.04254



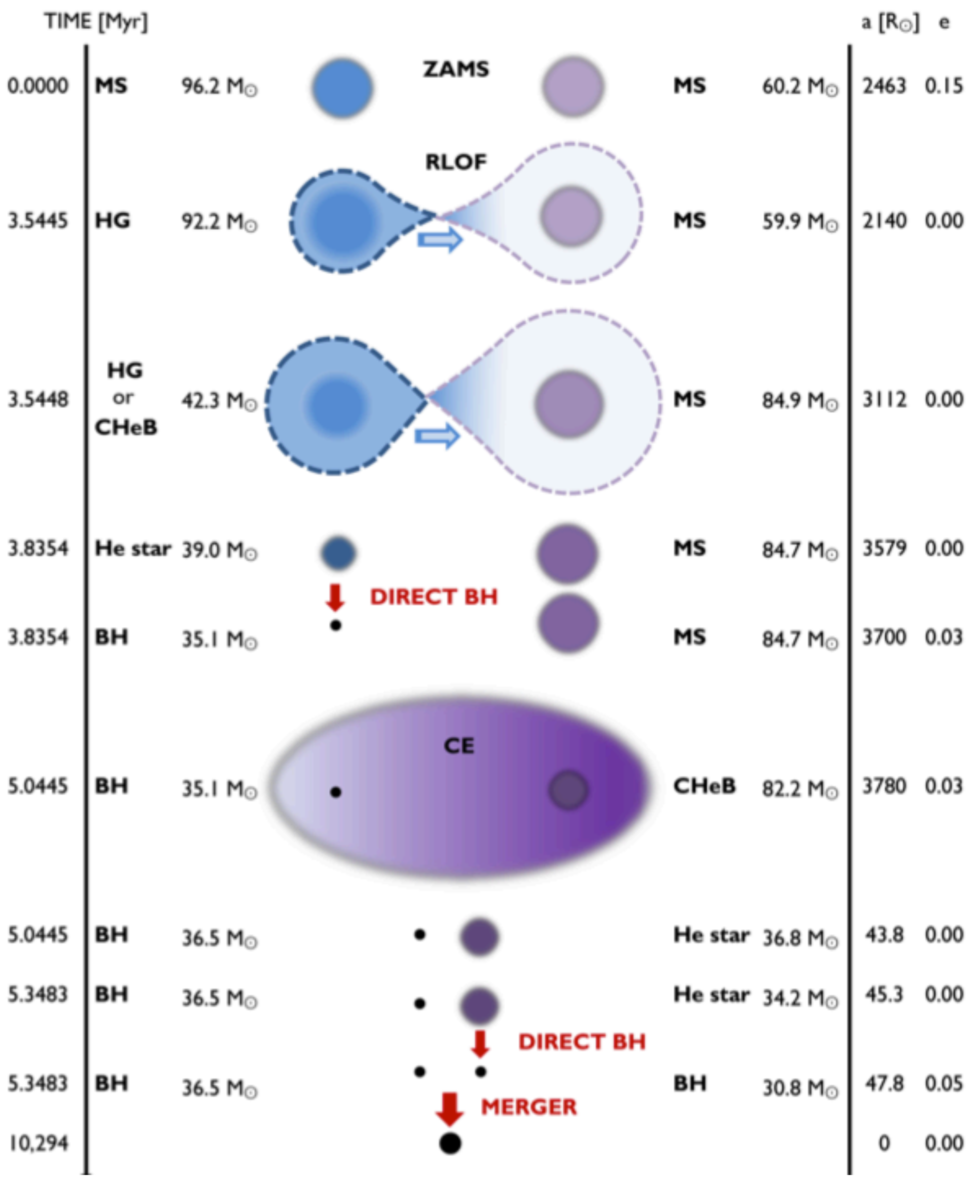
Dynamical formation - masses

- Predicted masses and spins consistent with observed events



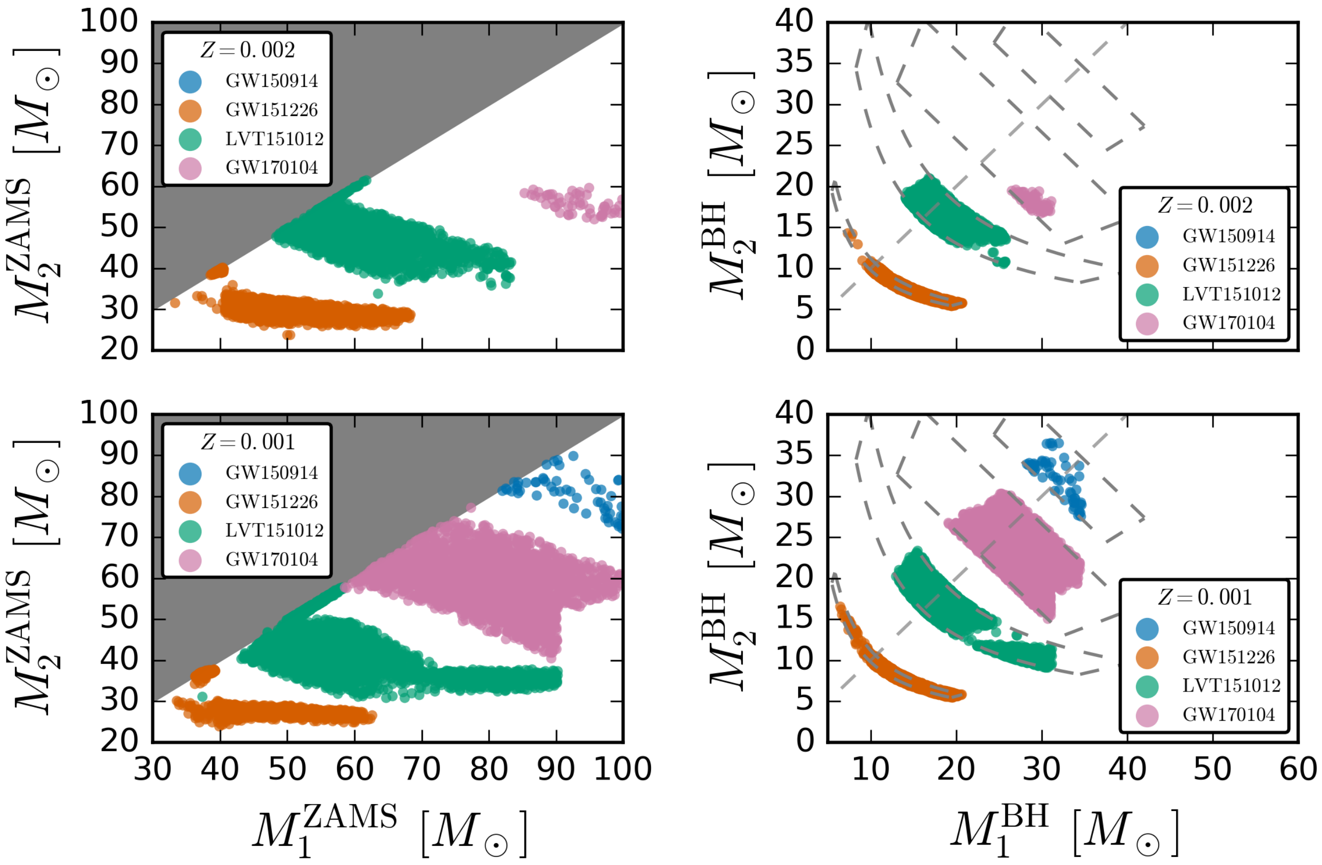
Carl Rodriguez https://twitter.com/aCarlRodriguez/status/870314010301935618
Adapted from Rodriguez+ 2016 arXiv:1604.04254

Isolated binary evolution



Belczynski+ 2016, Nature
arXiv:1602.04531

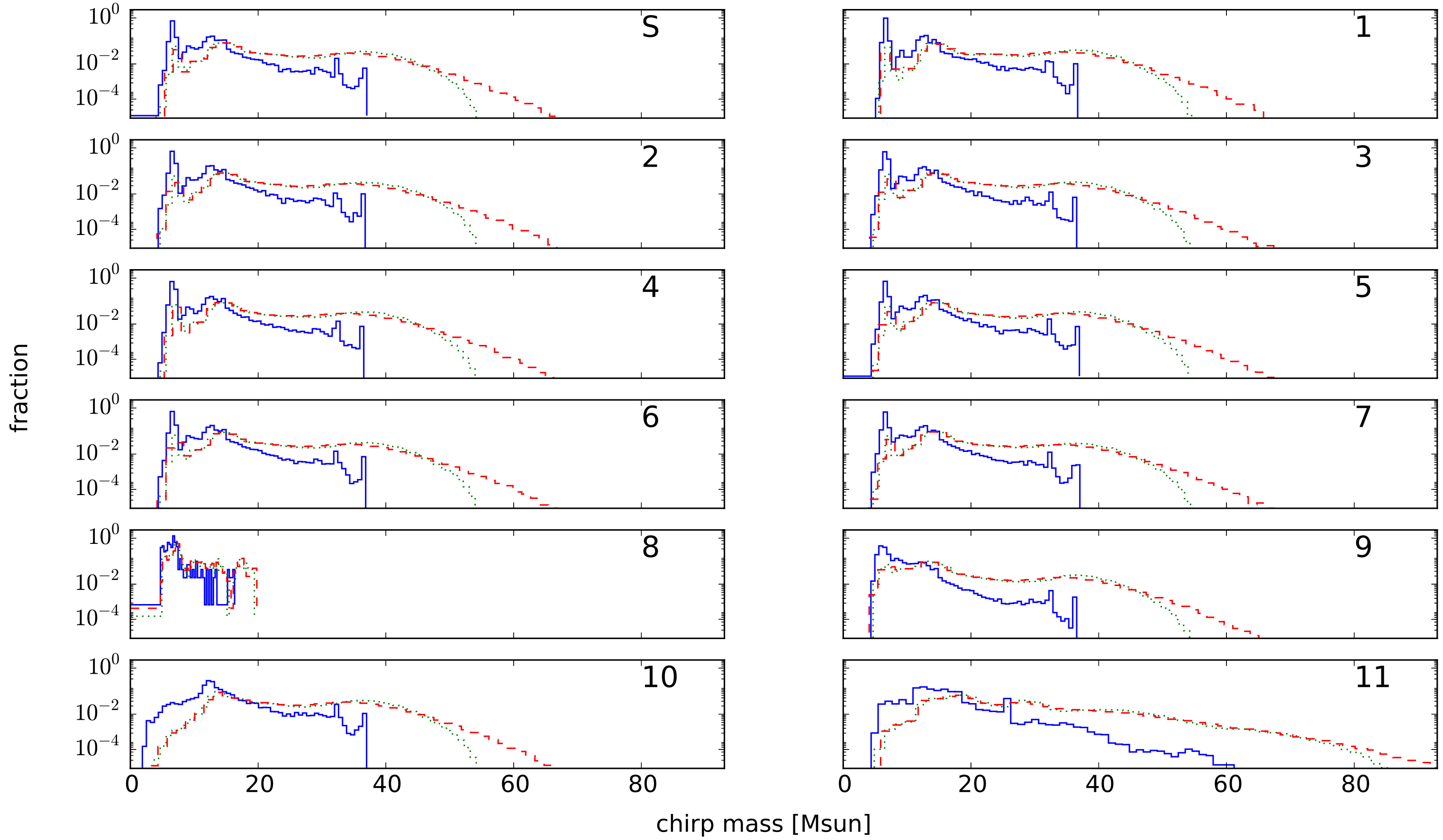
Isolated binary evolution - masses



Stevenson+ Nat. Commun. 8, 14906 (2017).
arXiv:1704.01352
Updated to include GW170104
(also consistent with GW170814, not shown)

Constrain binary evolution uncertainties with masses and rates

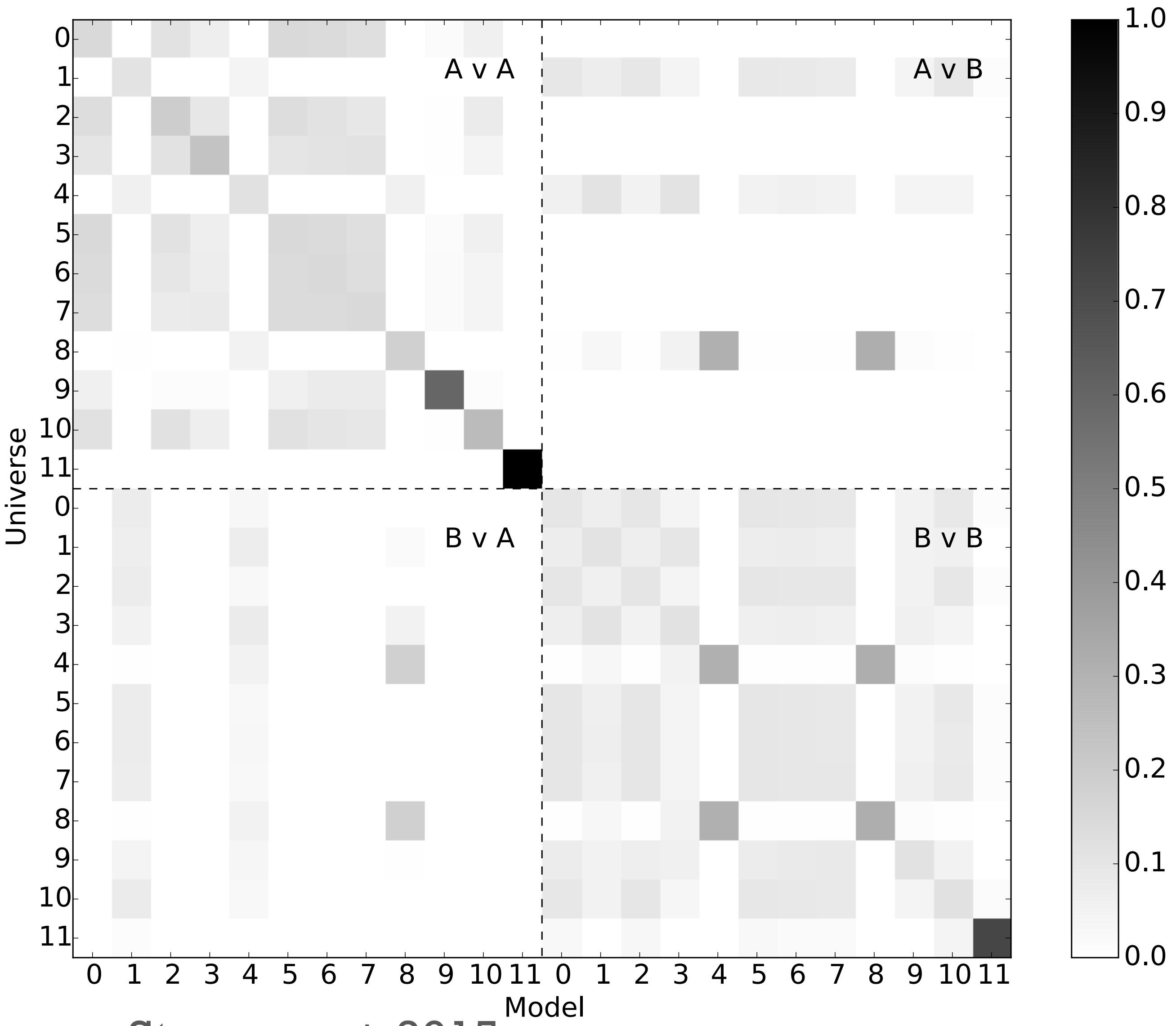
Uncertainties in binary evolution can be explored with pop synth



Stevenson+ 2015

arXiv:1504.07802

Model comparison to pop synth models (with mock observations)



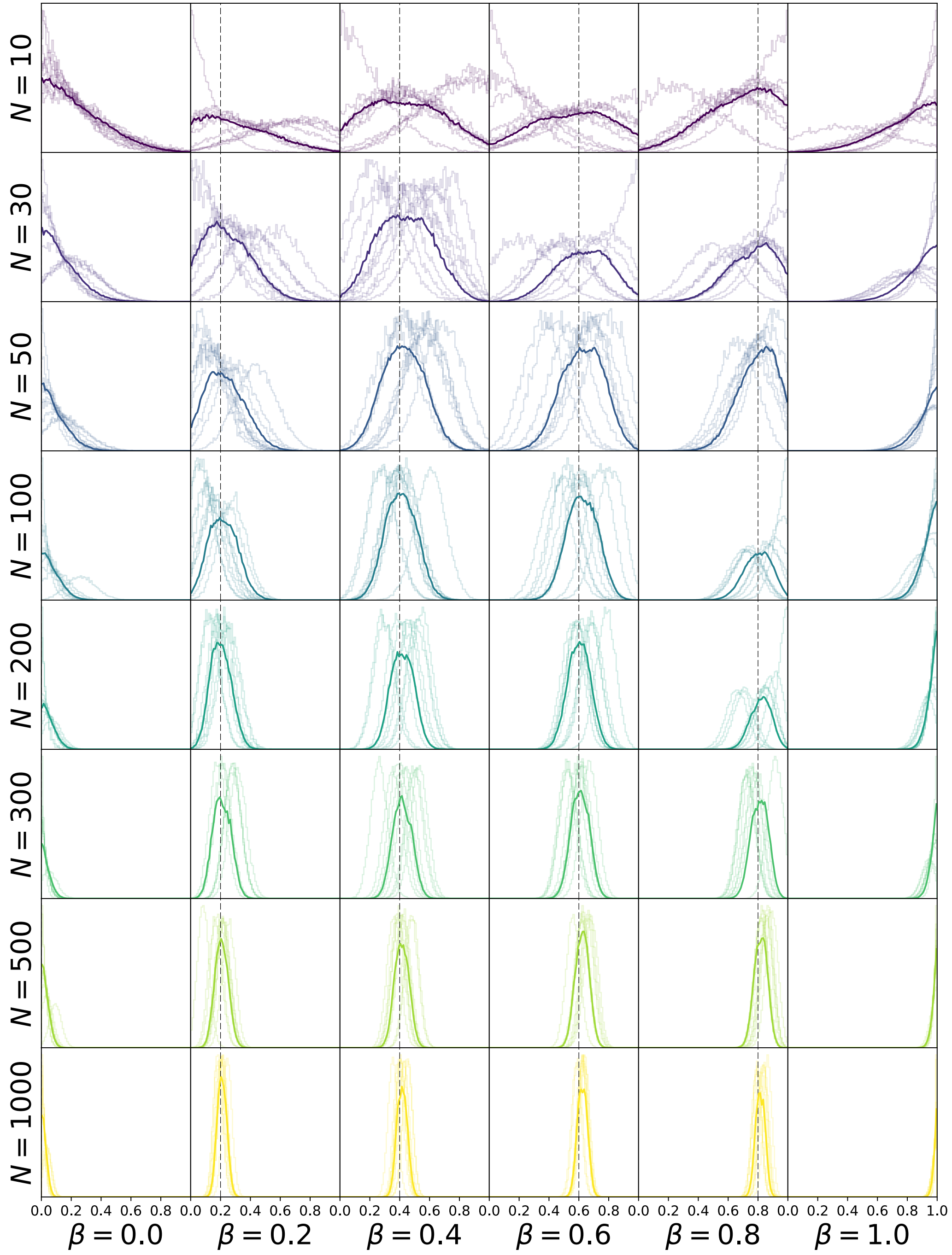
Stevenson+ 2015

arXiv:1504.07802

- Currently only include small set of isolated binary evolution models (Dominik et al 2012) – would like to include other channels

Measure mixing fraction with masses

- Can distinguish between/measure fractions of these two formation channels using the rate and mass distribution

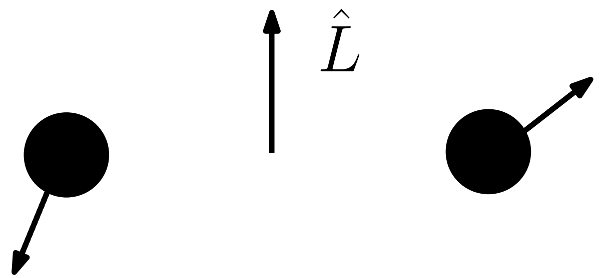


Zevin+ 2017 arXiv:1704.07379

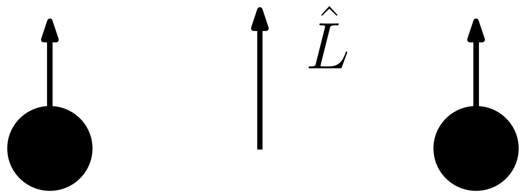
Can also use spins!

Spin-orbit (mis)alignment

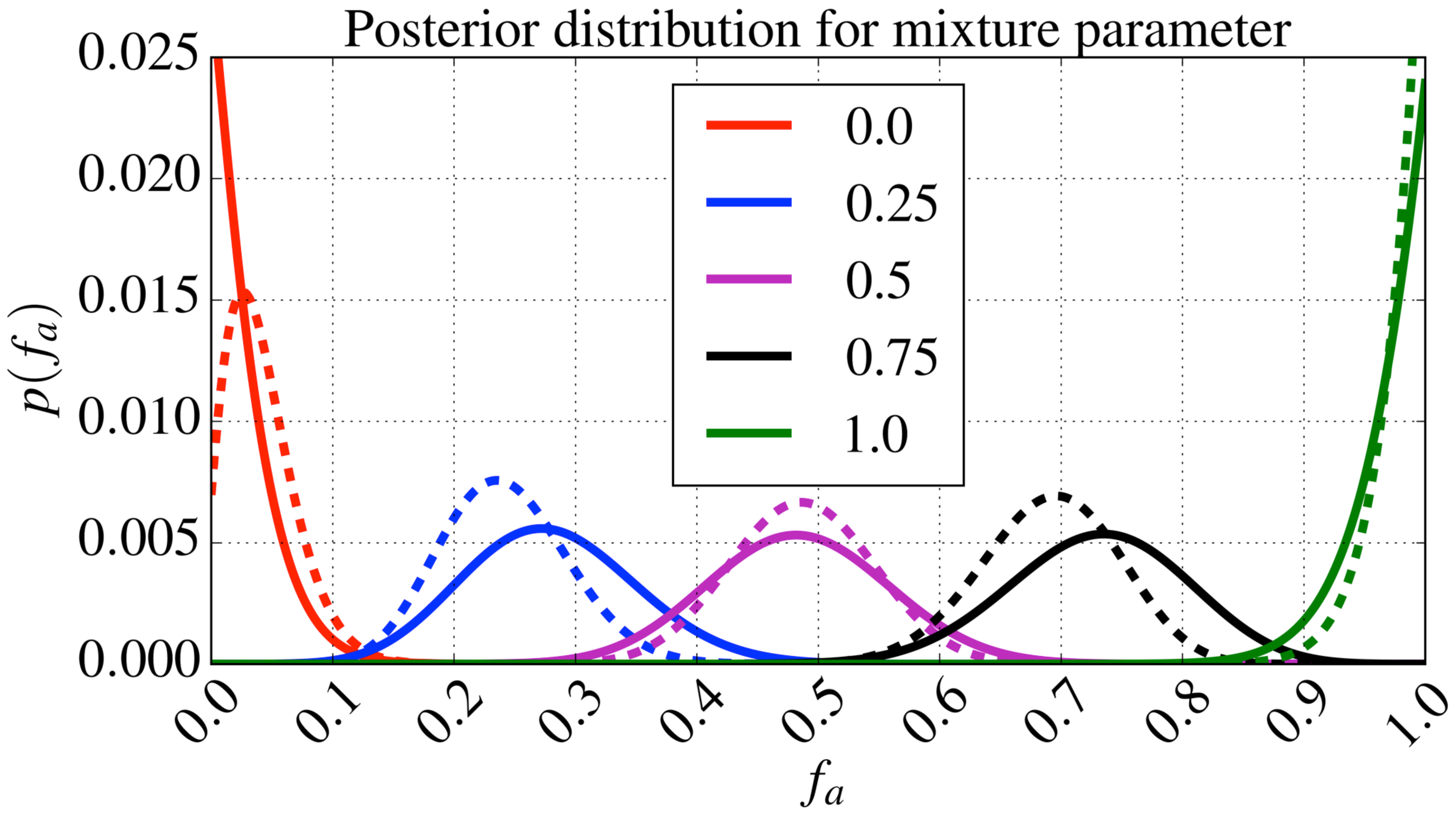
- Dynamics



- Isolated binary evolution

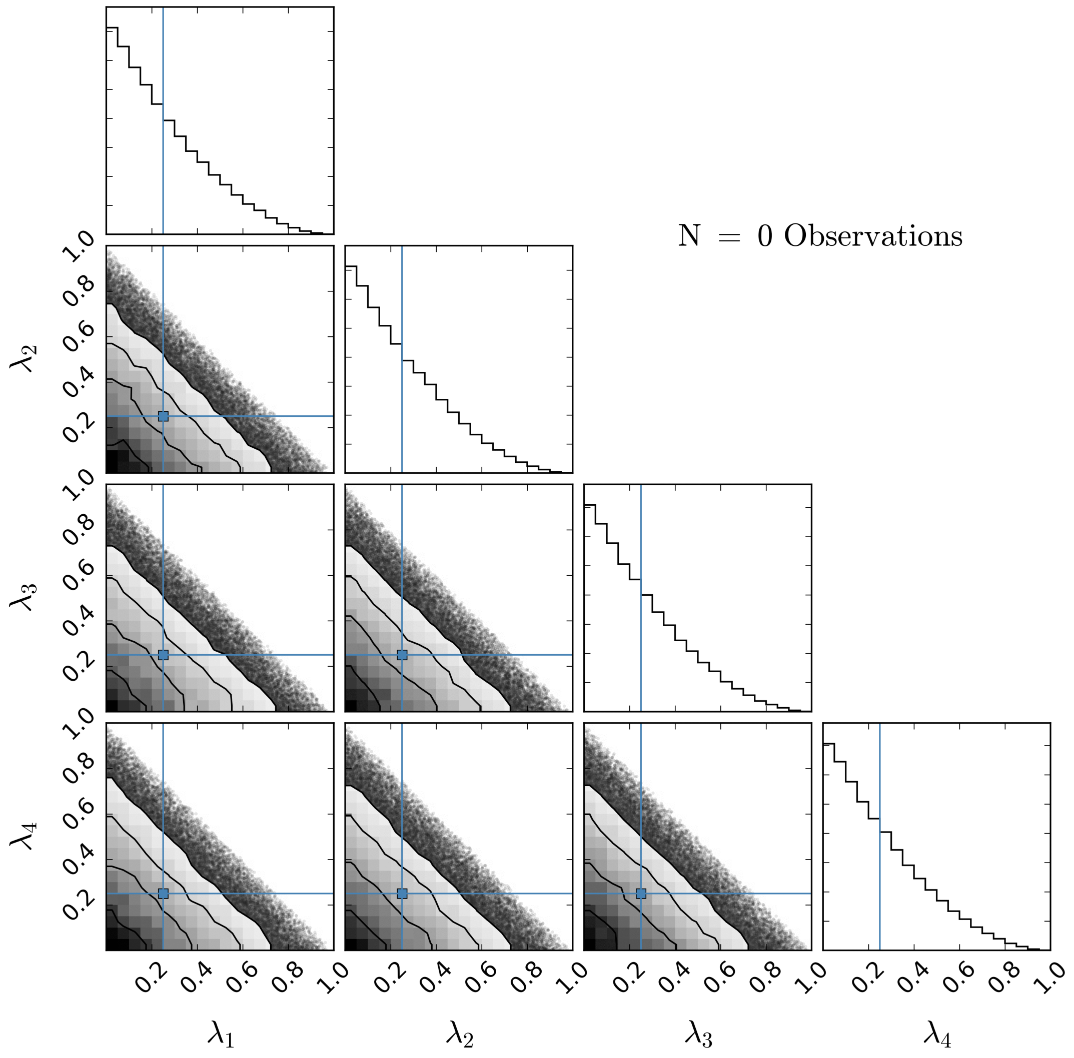


Vitale+ 2015 (1503.04307)



Solid lines are 200 BBH detections, true fraction is colour

How constraints on model fractions improves with number of observations

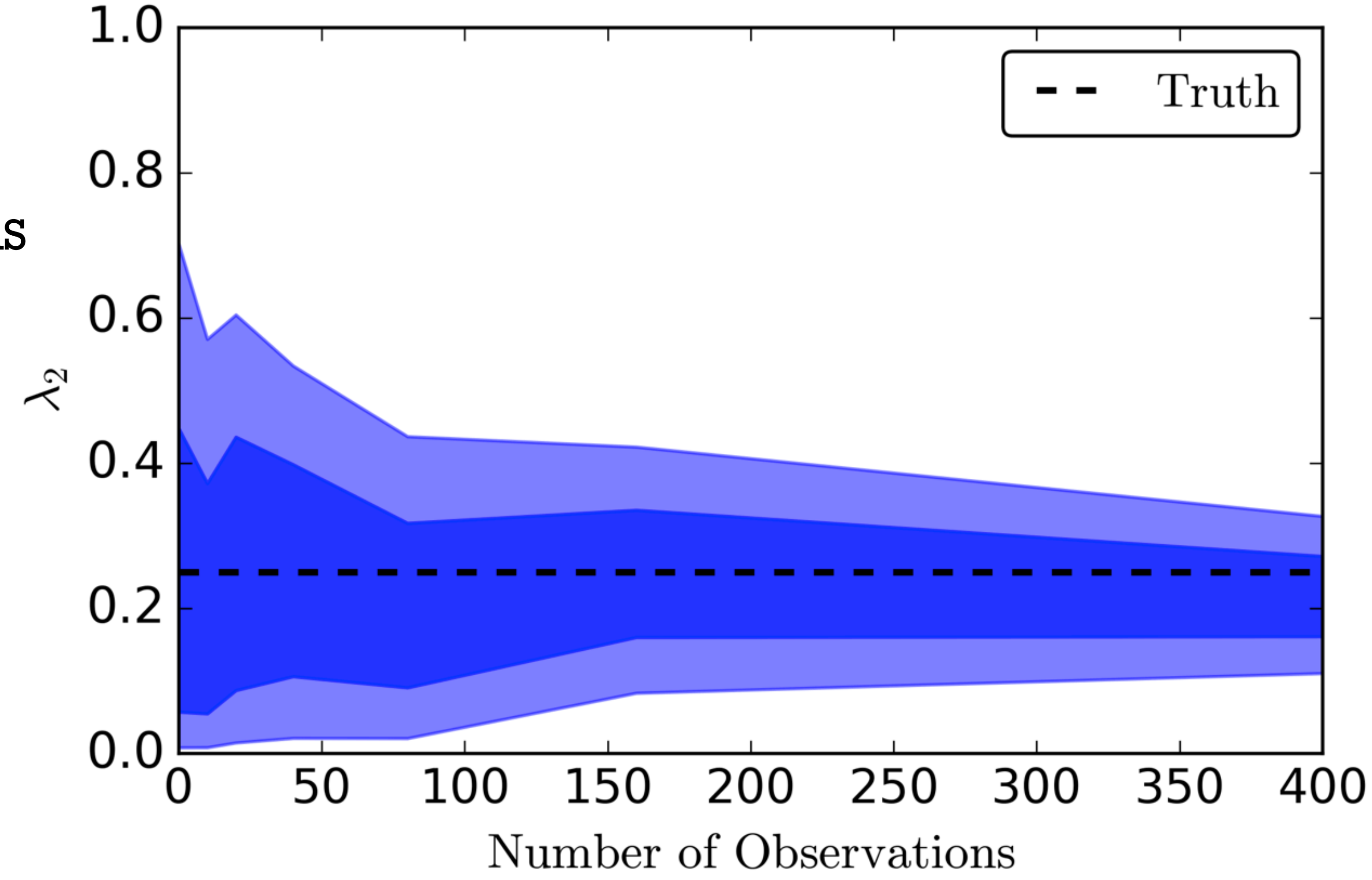


- Including realistic measurement uncertainties
- Drawing increasing number of observations from a multinomial distribution
- True fractions shown in blue
- Rule out extreme models at > 5σ with ~5 observations

Stevenson+ 2017 MNRAS arXiv: 1703.06873

How constraint on fraction of dynamically formed BBHs evolves with the number of observations

Stevenson+ 2017 MNRAS
arXiv: 1703.06873



Dark shaded region is 1 sigma, light is 2 sigma Roughly 1/sqrt(nObservations) in the tail

What can we learn from the detections so far?

Effective spin parameter

Dimensionless Spin magnitudes

Misalignments

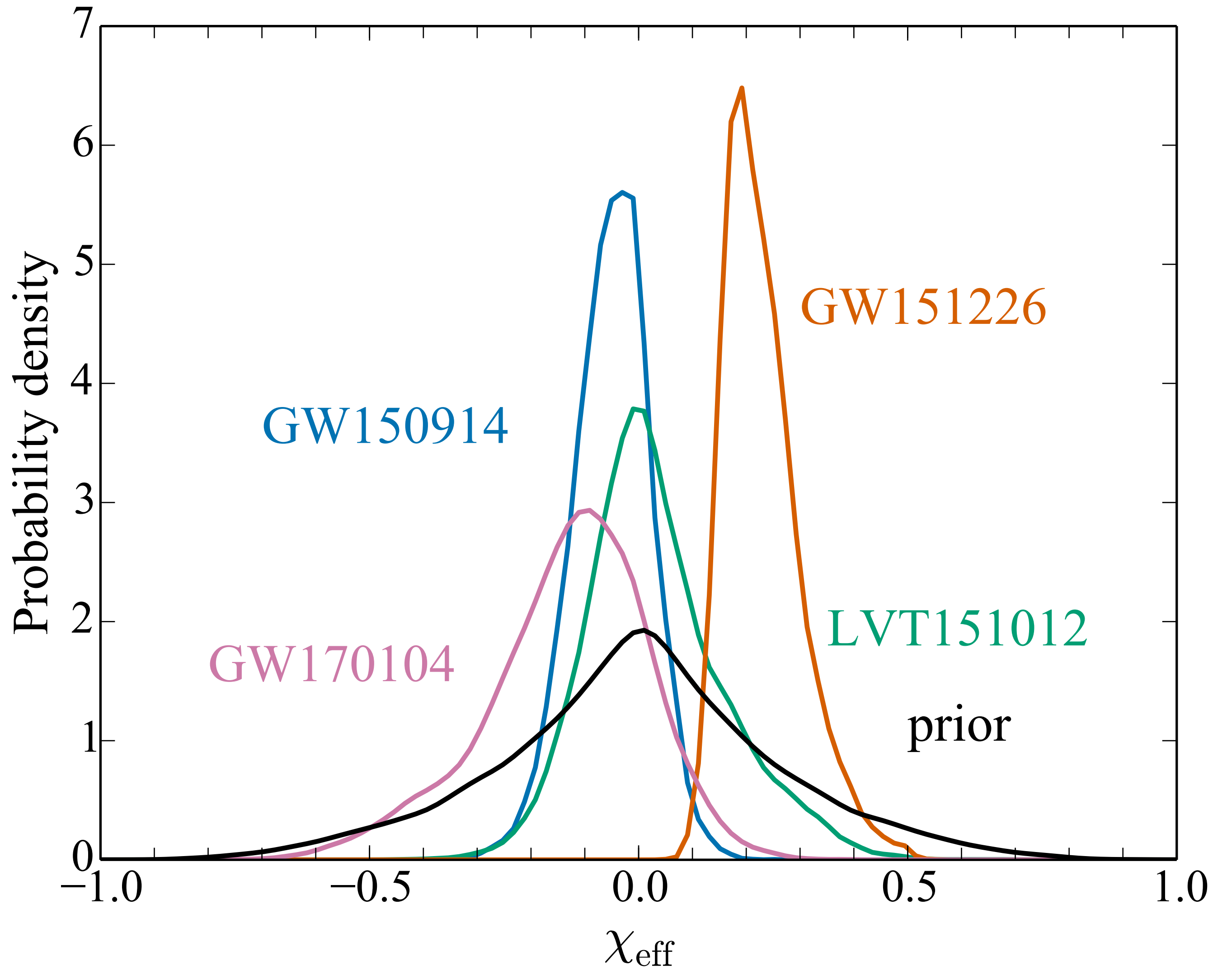
$$\chi_{\text{eff}} = \frac{a_1 \cos\theta_1 + q a_2 \cos\theta_2}{1+q}$$

Mass ratio

$$-1 \leq \chi_{\text{eff}} \leq 1$$

Effective spin parameter measurements

$$\chi_{\rm eff} = \frac{a_1 \cos\theta_1 + q a_2 \cos\theta_2}{1+q}$$

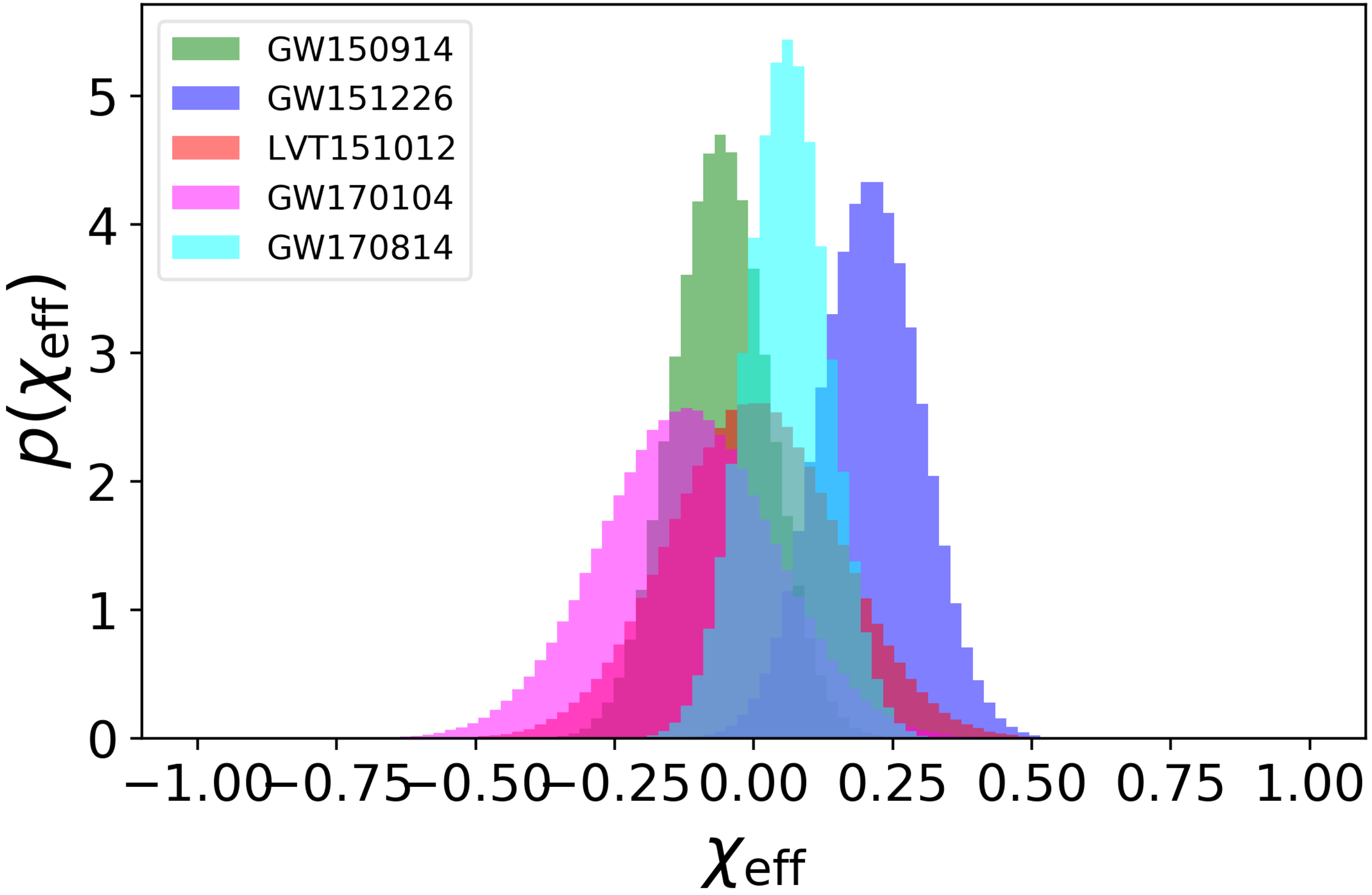


$\chi_{\rm eff} \sim 0$ ($|\chi_{\rm eff}| < 0.35$)

LVC 2017
arXiv:1706.01812

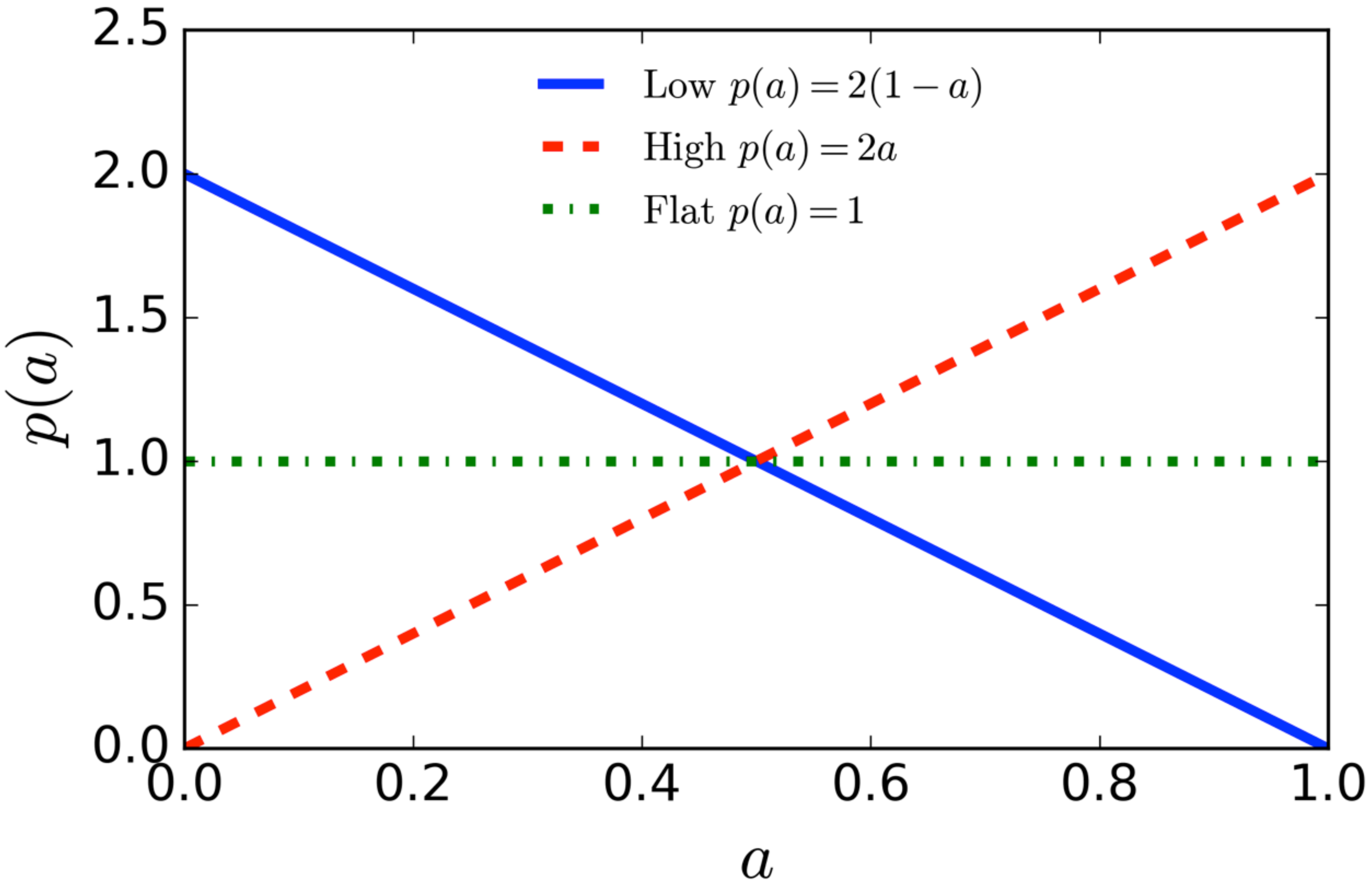
$$\chi_{\rm eff} = \frac{a_1 \cos\theta_1 + q a_2 \cos\theta_2}{1+q}$$

Our approximation



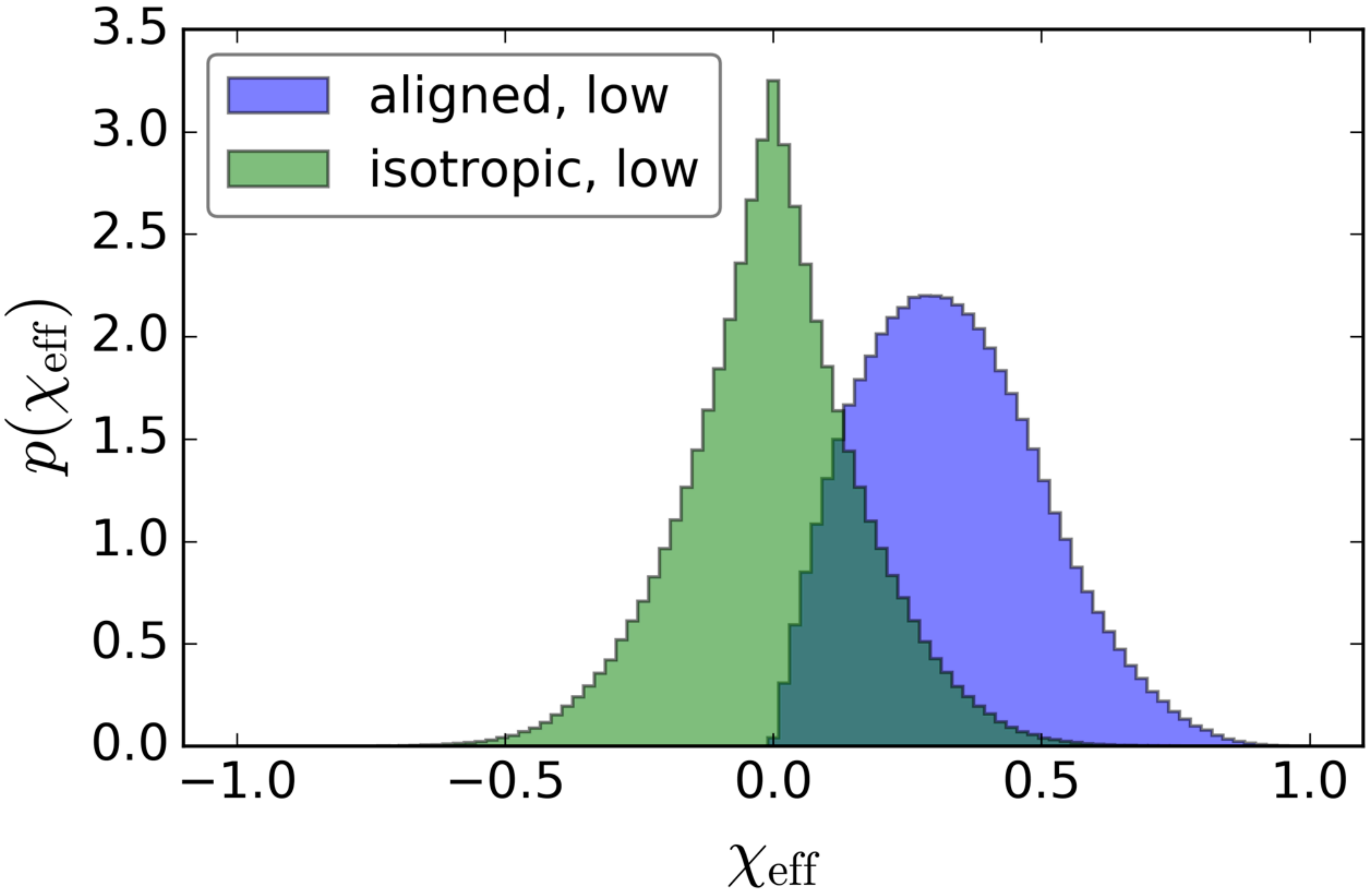
Farr, Stevenson+ 2017 Nature
arXiv:1706.01385

Spin magnitude distributions



Farr, Stevenson+ 2017 Nature
arXiv:1706.01385

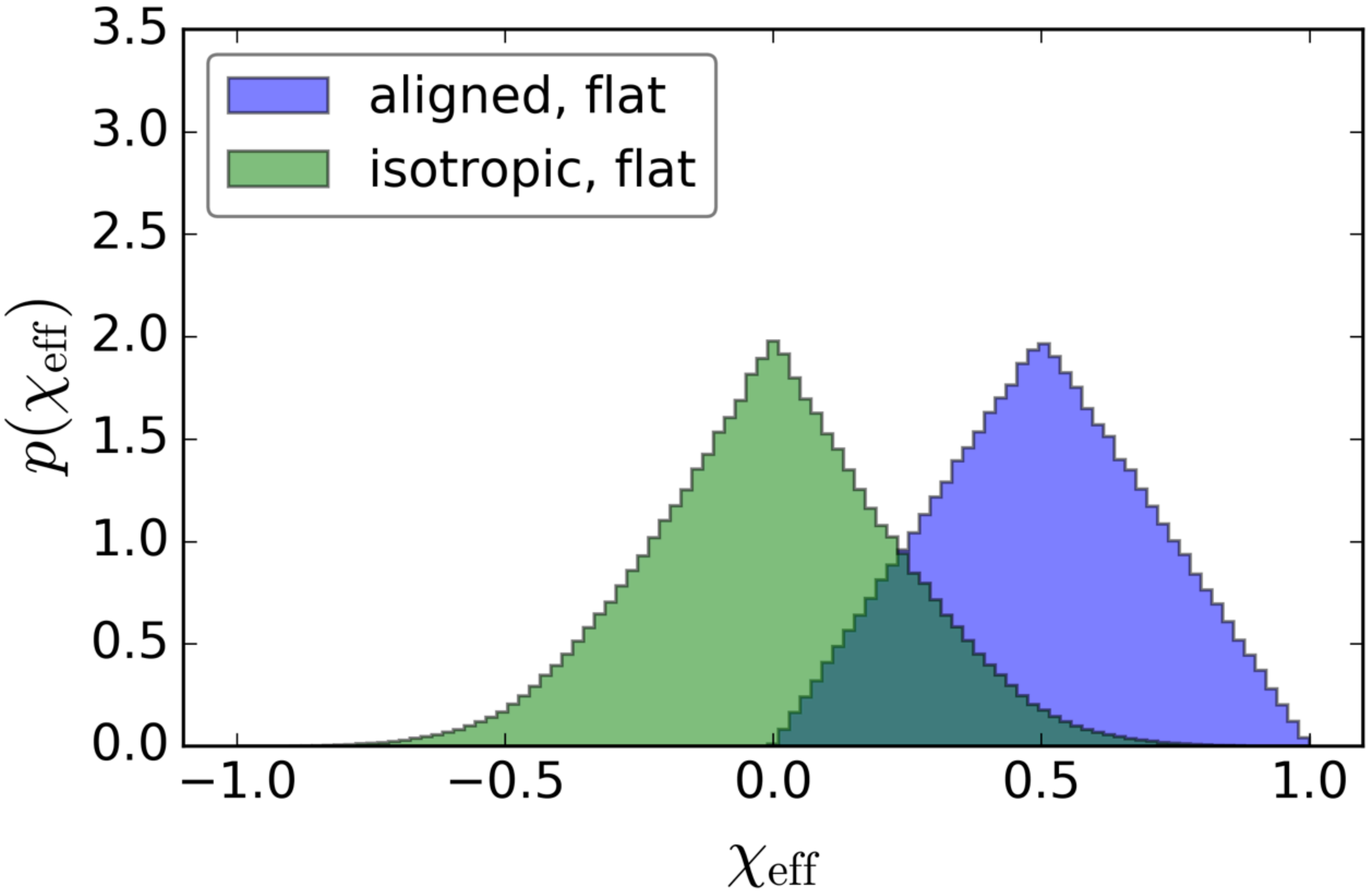
Our models



Assumes equal masses q=1

Farr, Stevenson+ 2017 Nature
arXiv:1706.01385

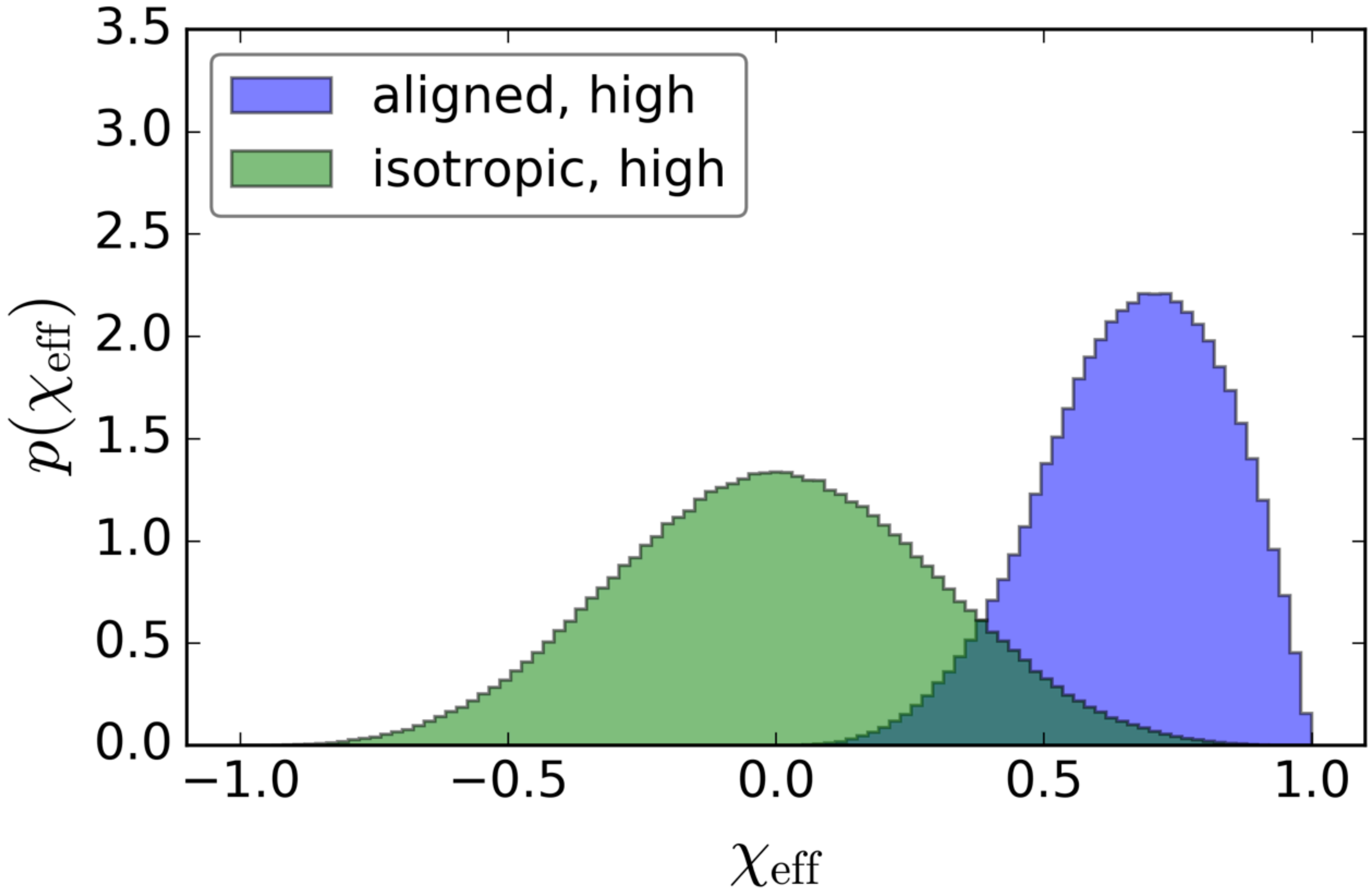
Our models



Assumes equal masses q=1

Farr, Stevenson+ 2017 Nature
arXiv:1706.01385

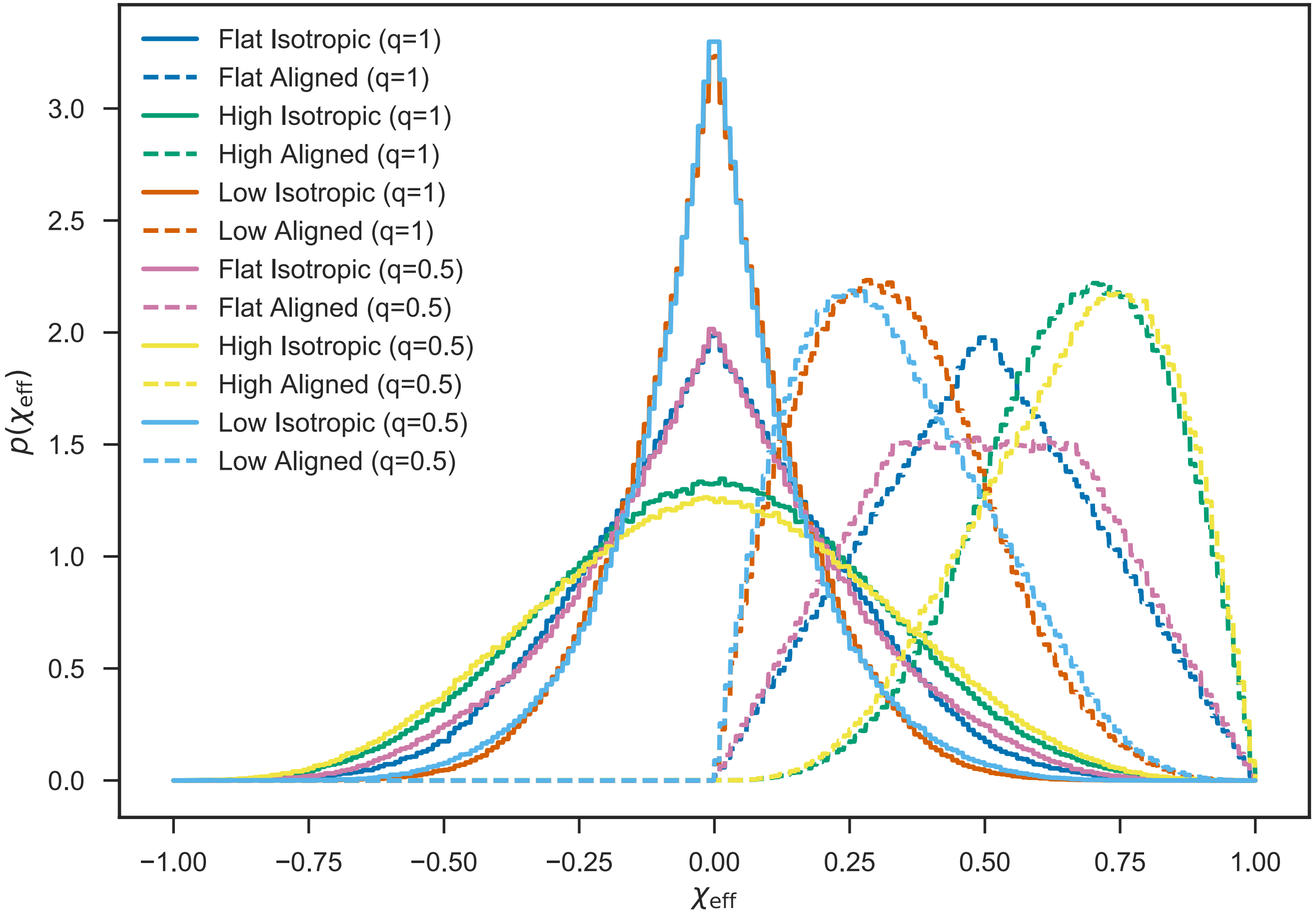
Our models



Assumes equal masses q=1

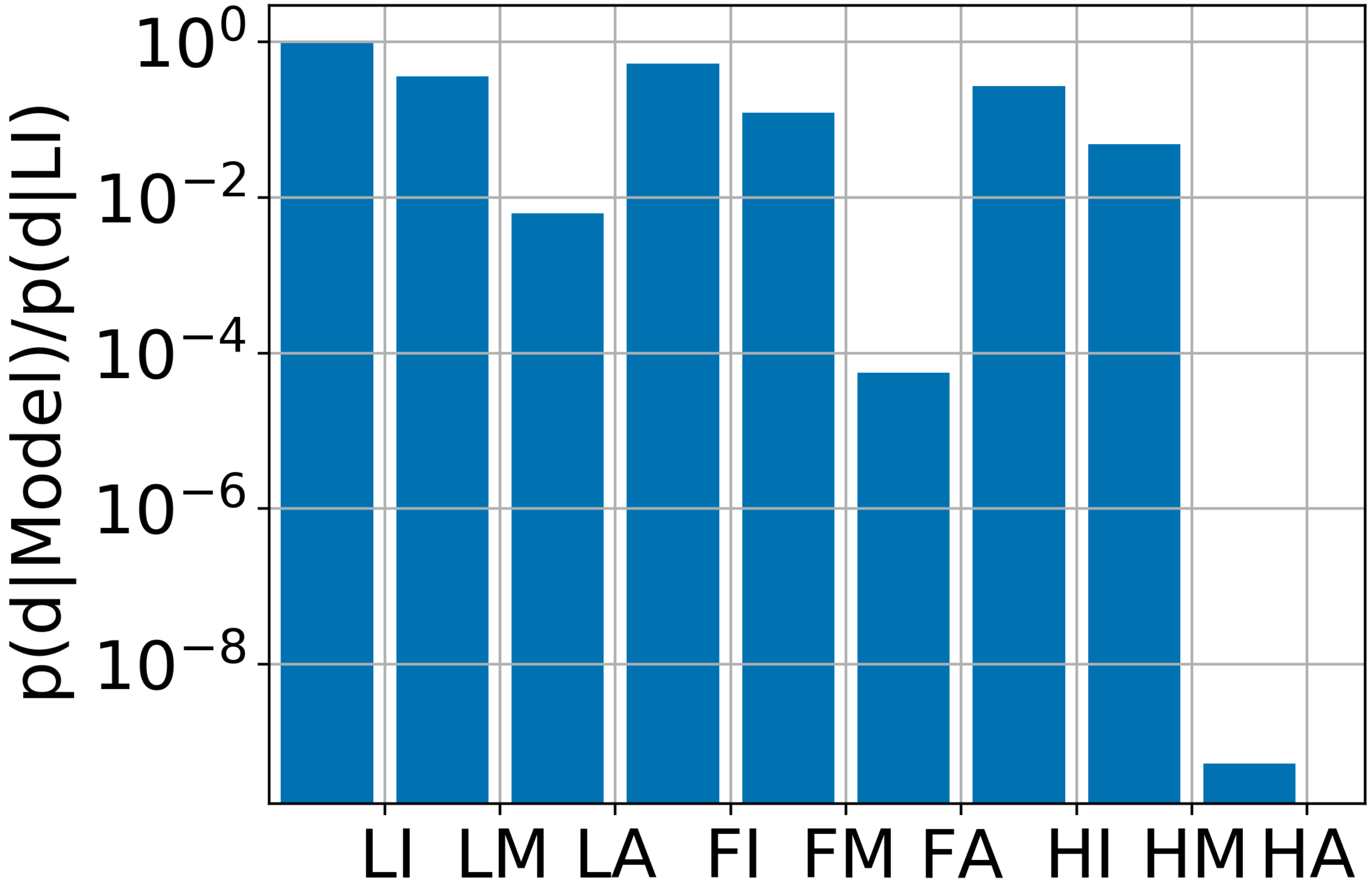
Farr, Stevenson+ 2017 Nature
arXiv:1706.01385

Effect of mass ratio



Farr, Stevenson+ 2017 Nature
arXiv:1706.01385

Results – model comparison



$$\mathrm{LI/LA} = 2.7\sigma$$

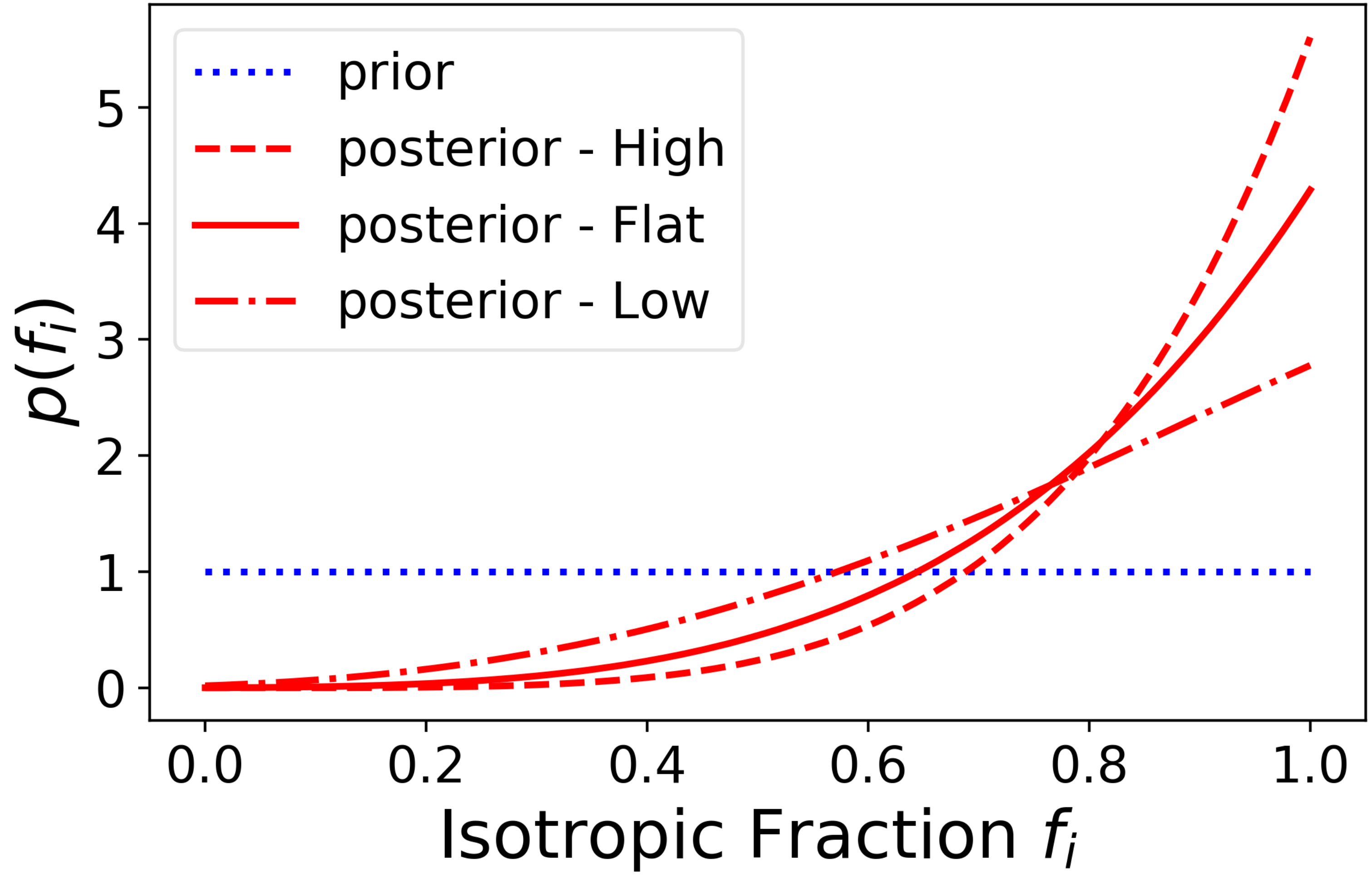
L=Low F=Flat H=High

I = Isotropic, M=Mixture (see next slide) A=Aligned

Farr, Stevenson+ 2017 Nature arXiv:1706.01385

Updated to include GW170814

Mixture fraction



Farr, Stevenson+ 2017 Nature arXiv:1706.01385
Updated to include GW170814

Accumulation of significance

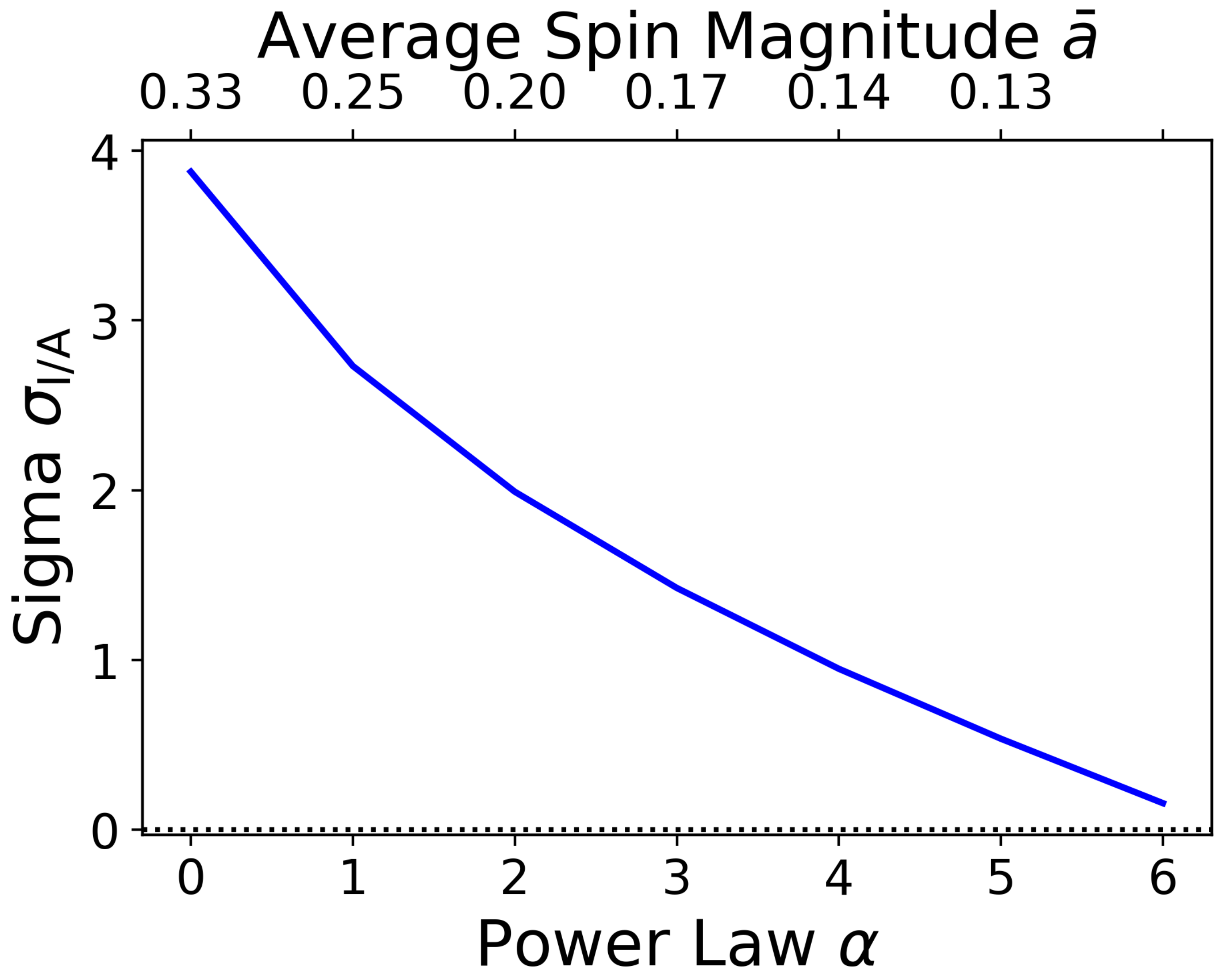
Events	$\sigma_{I/A}$ "Low"	$\sigma_{I/A}$ "Flat"	$\sigma_{I/A}$ "High"
GW150914 and GW151226	1.3	2.2	3.7
All O1 events	**1.7**	2.7	4.4
All O1 events and GW170104	2.4	3.6	5.4

Updated to include GW170814: $\mathrm{LI/LA} = 2.7\sigma$

Farr, Stevenson+ 2017 Nature arXiv:1706.01385
Updated to include GW170814

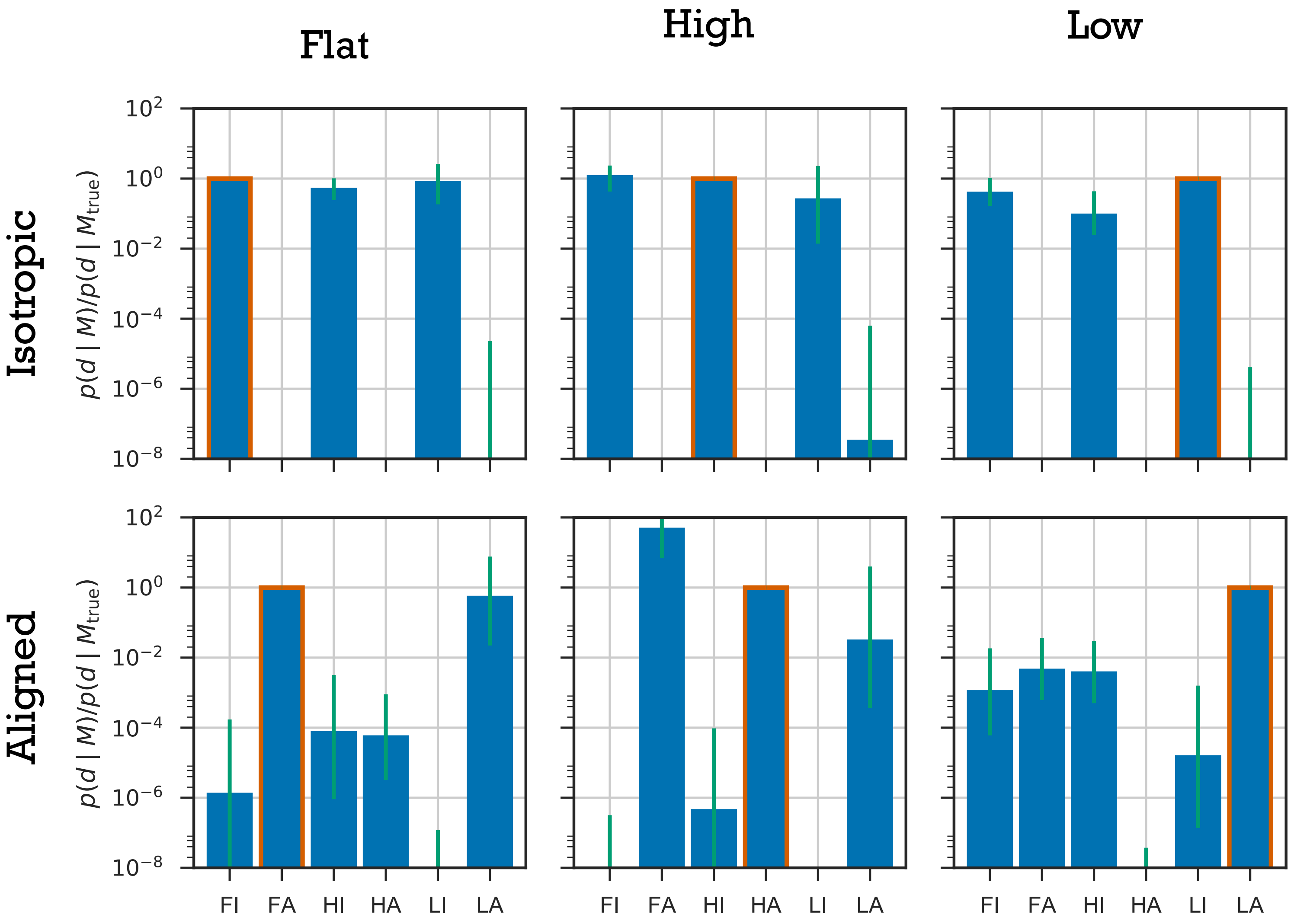
$$p(a) \propto (1 - a)^{\alpha}$$

Effect of small spins



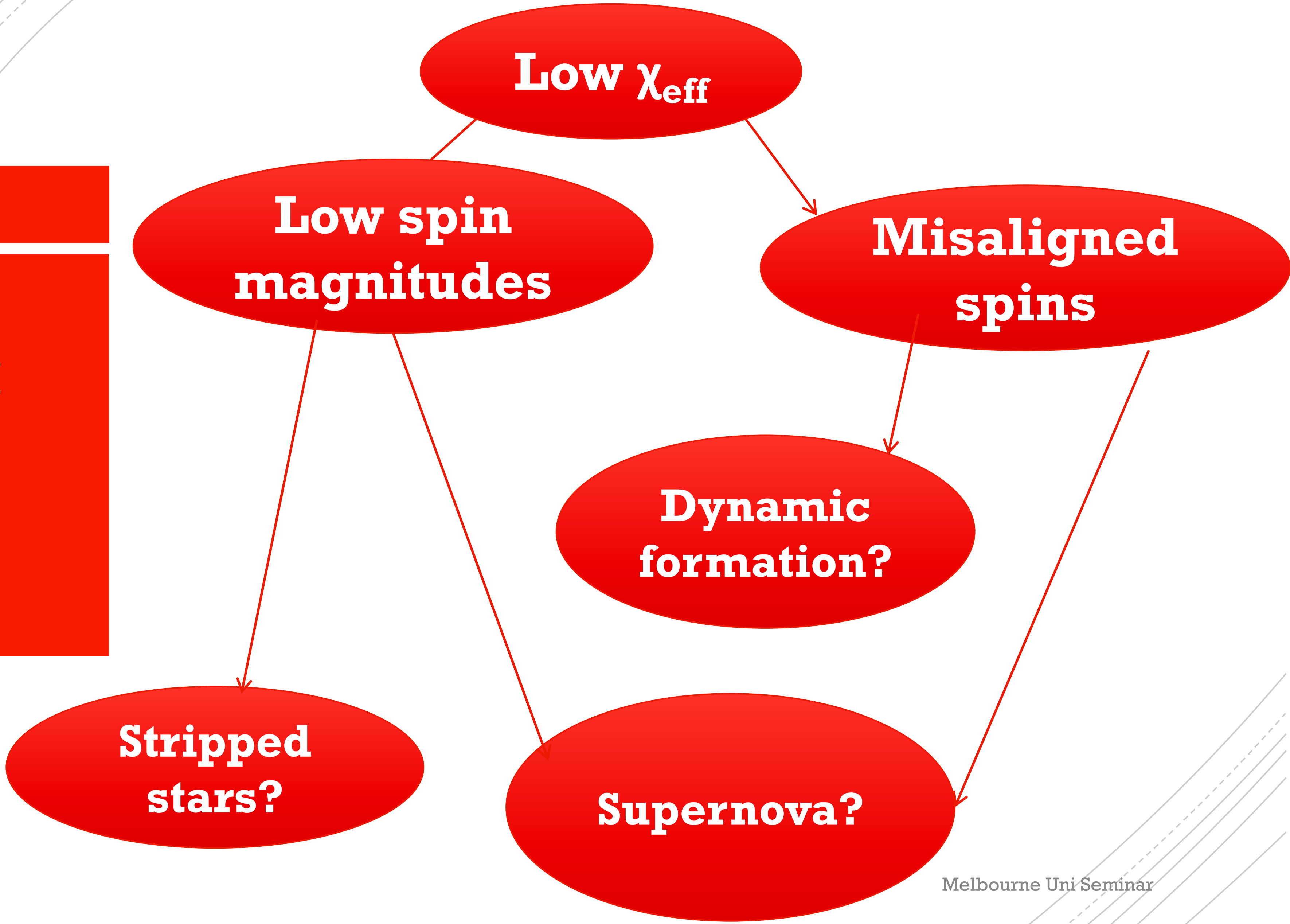
Farr, Stevenson+ 2017 Nature arXiv:1706.01385
Updated to include GW170814

Future predictions



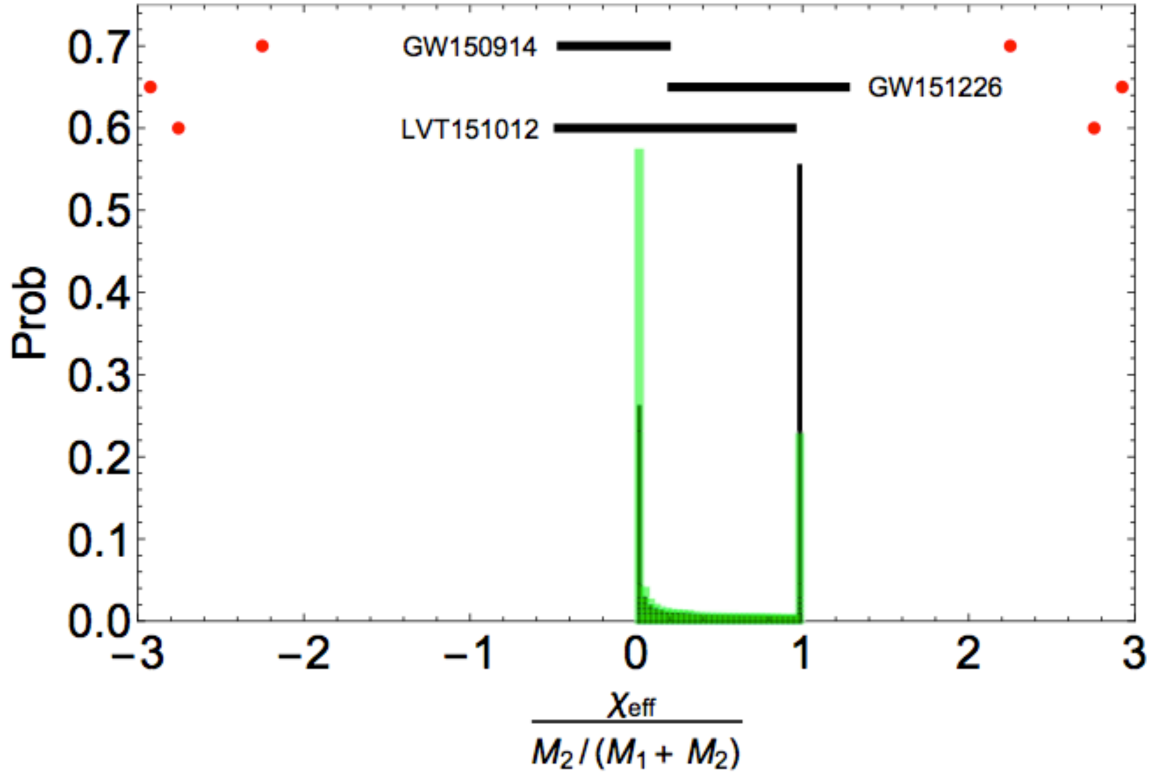
Farr, Stevenson+ 2017 Nature arXiv:1706.01385
Updated to include GW170814

Implications: Some wild speculation



Stripped WR stars?

- In isolated binary evolution, second black hole forms from a stripped star (WR star)
- Binary is either close enough to spin the star up (to maximal) or wide enough to form a black hole with the natal (stellar) spin (since tides are very sensitive to separation)

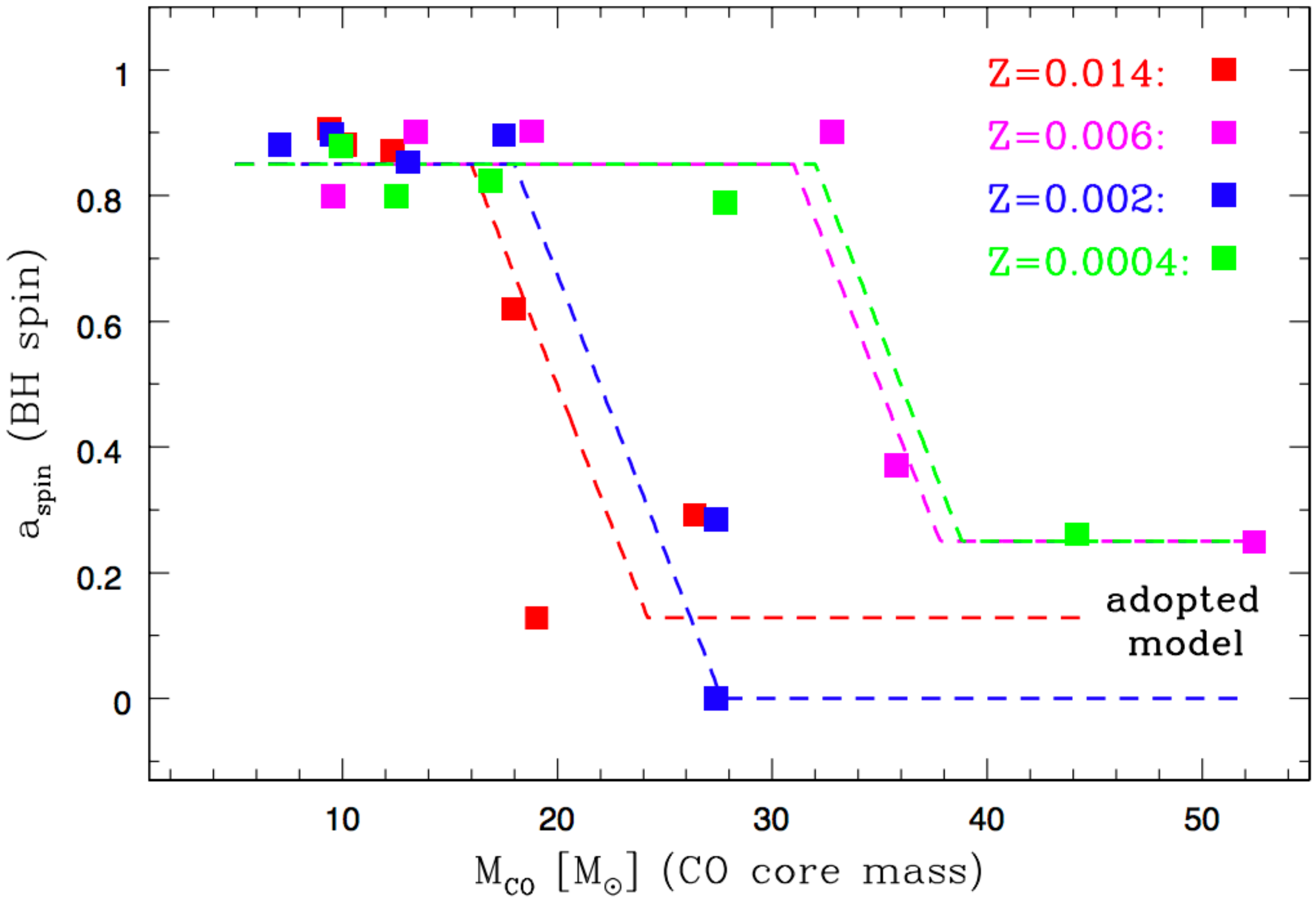


Zaldarriaga + arXiv:1702.00885
See also
Hotokezaka and Piran arXiv:1702.03952

Low spin magnitude from supernova?

- How to link pre-supernova spin of star to remnant spin?
- In many cases, need to eject some excess angular momentum. Why not eject it all?
- Unlikely since we see high spins in HMXBs (e.g. Miller & Miller arXiv:1408.4145). These are most likely the birth spins (unaltered by accretion) -> maybe HMXBs are not BBH progenitors?
- Different formation pathway for BBH than HMXB – Evolutionary reasons for different spins?
- Issue with HMXB measurements? Agreement between Fe line and continuum fitting methods for some systems.
- Low spin from SN e.g. Chan et al arXiv:1710.00838

Low spin magnitude from supernova?

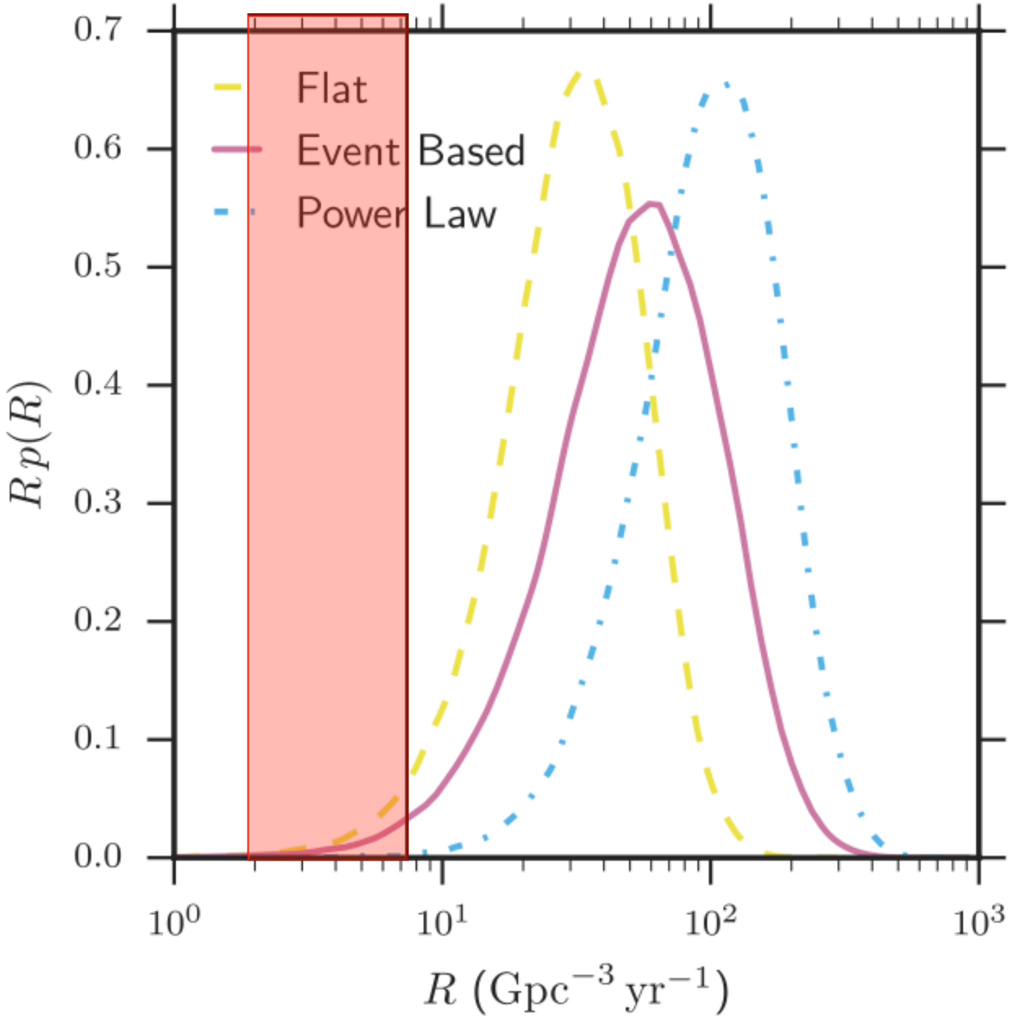


Belczynski et al 2017 arXiv:1706.07053

Dynamical formation

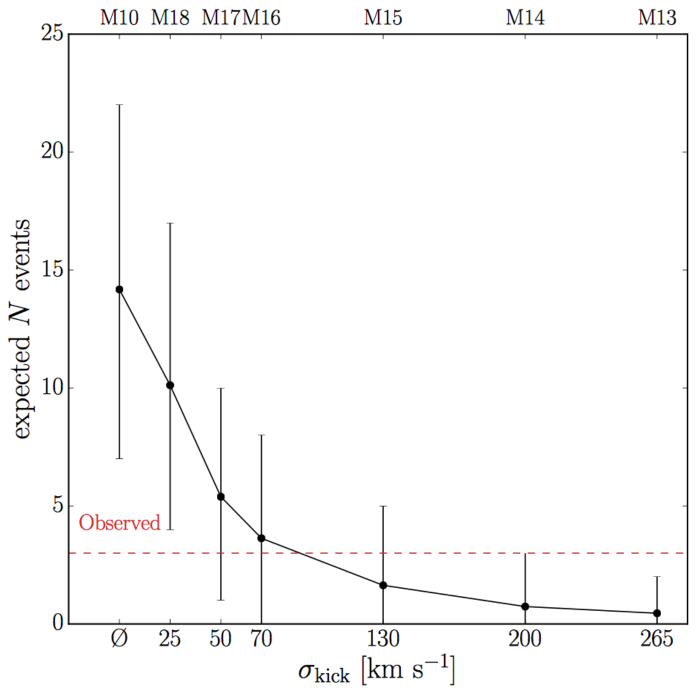
Dynamics $\sim 5\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

- Naturally expect an isotropic distribution of spins (e.g. Rodrgiuez+ 2016 arXiv:1609.05916)
- However, predicts too low merger rate to explain all observed events?



Rate from Rodriguez+ 2016 arXiv:1602.02444
Figure adapted from arXiv:1606.04856

Black hole natal kicks



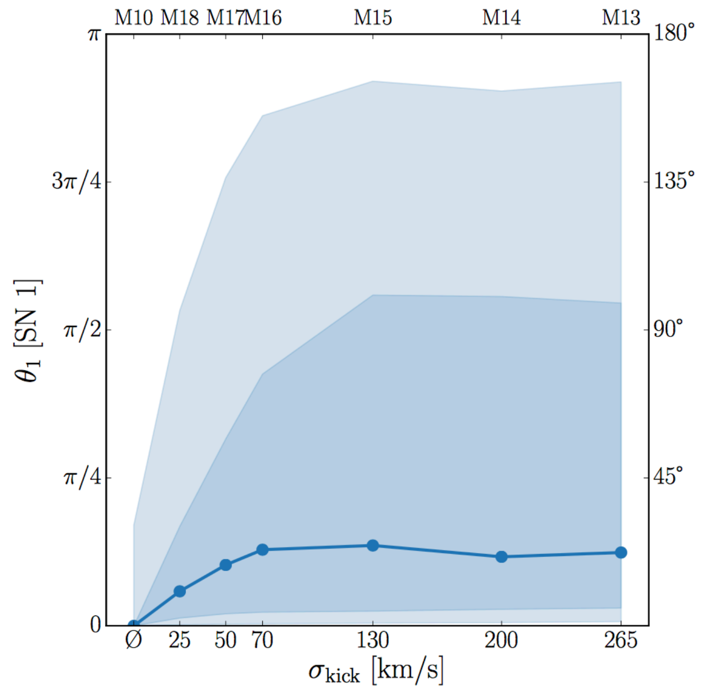


FIG. 1. **Expected number of events versus kick strength:** Expected number of BH merger detections pre-

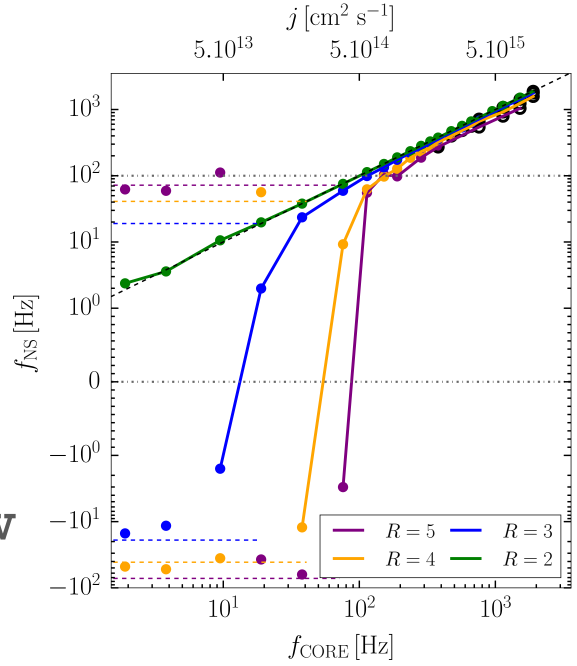
FIG. 2. **Spin-orbit misalignment versus kick strength:** The misalignment $\theta_{1,SN1}$ after the first SN event, as a function

- BH kicks bounded from above by inferred BBH merger rates
- Bounded from below by need for misalignment to explain low effective spins (if BH spins are generally large)

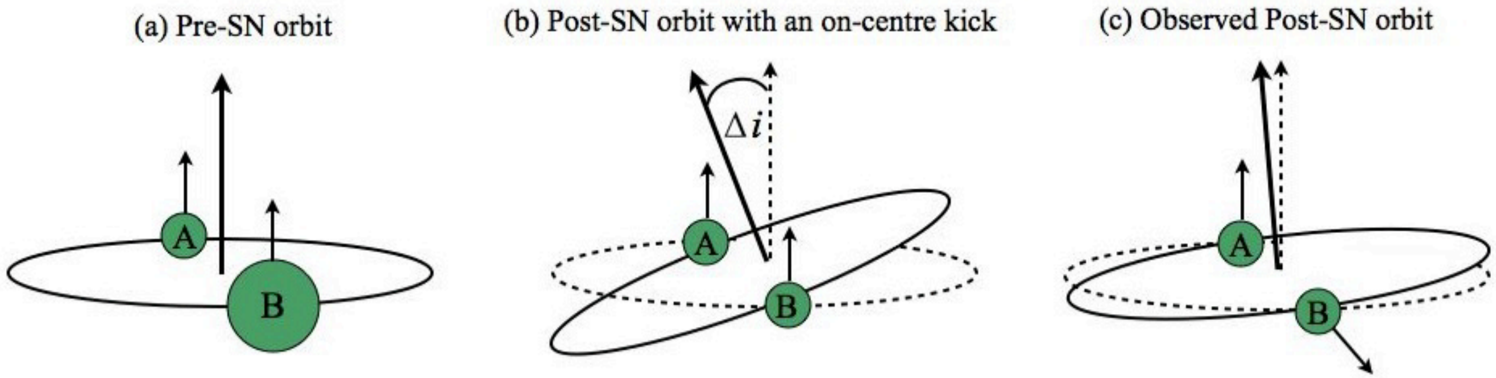
Wysocki et al 2017 arXiv: 1709.01943

Spin tilts during supernovae

- Spin tilts during supernova as in the Double Pulsar J0737-3039 (e.g. Farr+ 2011)
- Also shown by supernova modellers (e.g. Kazeroni+ 2017)
- No statements in literature for black hole formation (that I know about)



Kazeroni+ 2017 arXiv:1701.07029



Farr+ 2011 arXiv:1104.5001

Conclusions

- Gravitational waves measurements of binary black hole **masses**, **spins** and **merger rates** give us insight into their formation
- Effective spin for GW150914, GW151226, GW170104, GW170814 and LVT151012 are all clustered around 0
- Either black holes are **misaligned** with respect to the orbital angular momentum, or else they have intrinsically **low spins**
- We showed that given our simple models, the data favour misalignment (provided spins are at least sometimes large)
- Misalignment can originate from a linear **kick** or **tilt** during a supernova in **isolated** binaries, and is natural for **dynamically** formed binary black holes