Insights into binary evolution from gravitational waves

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For the COMPAS team

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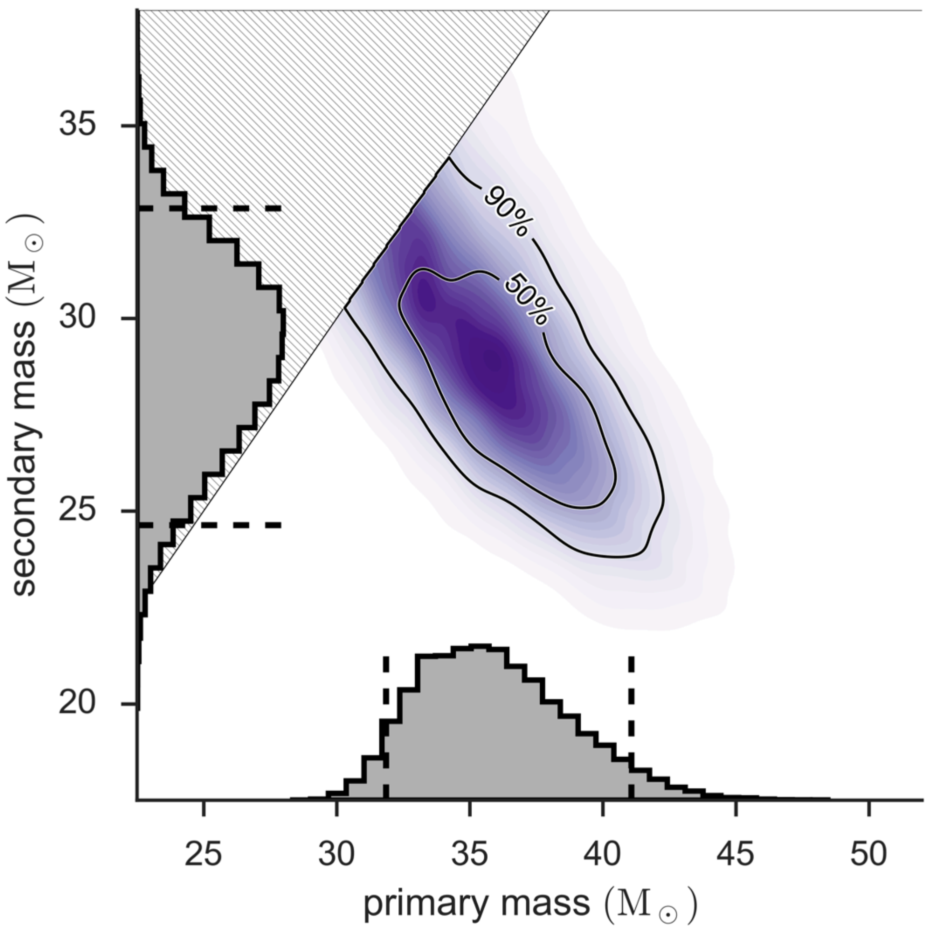
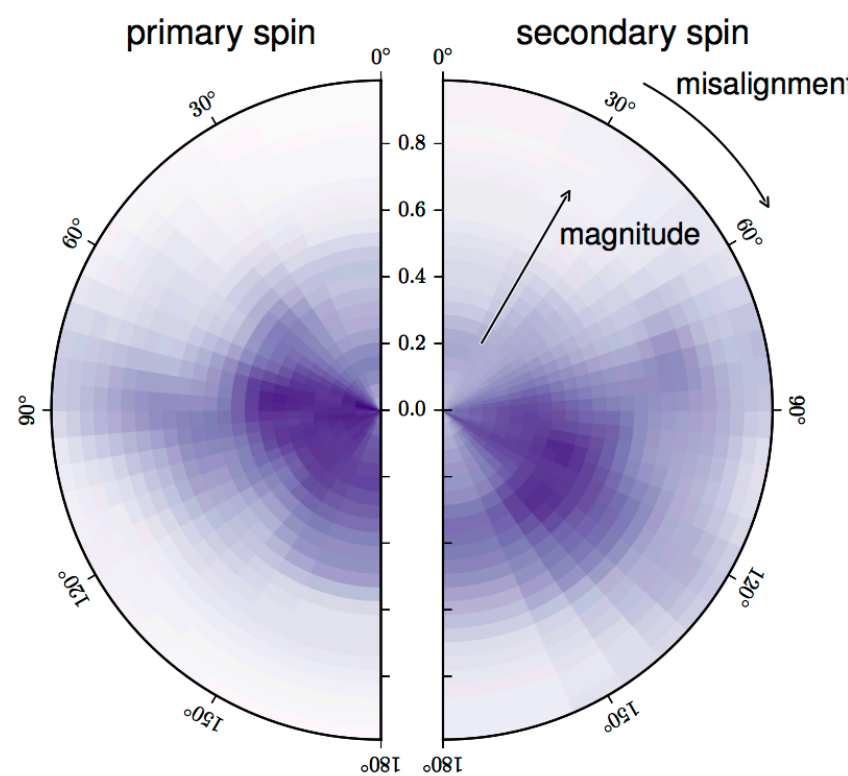
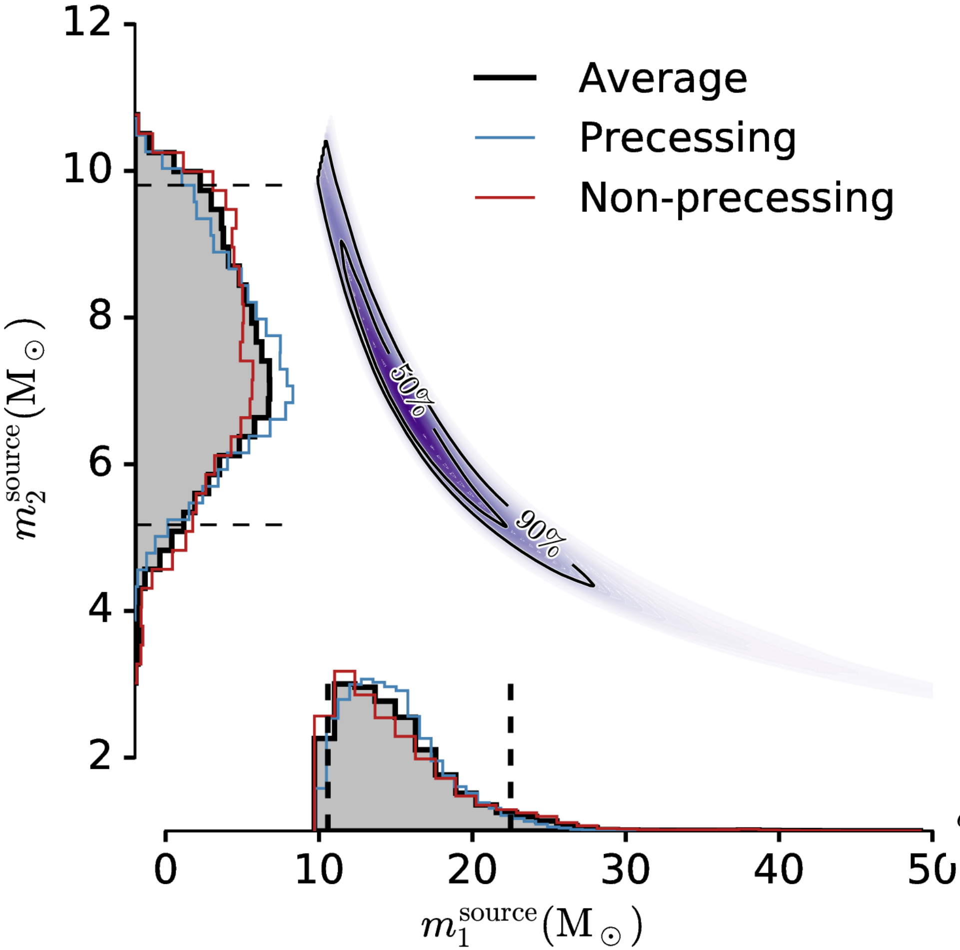
GW150914

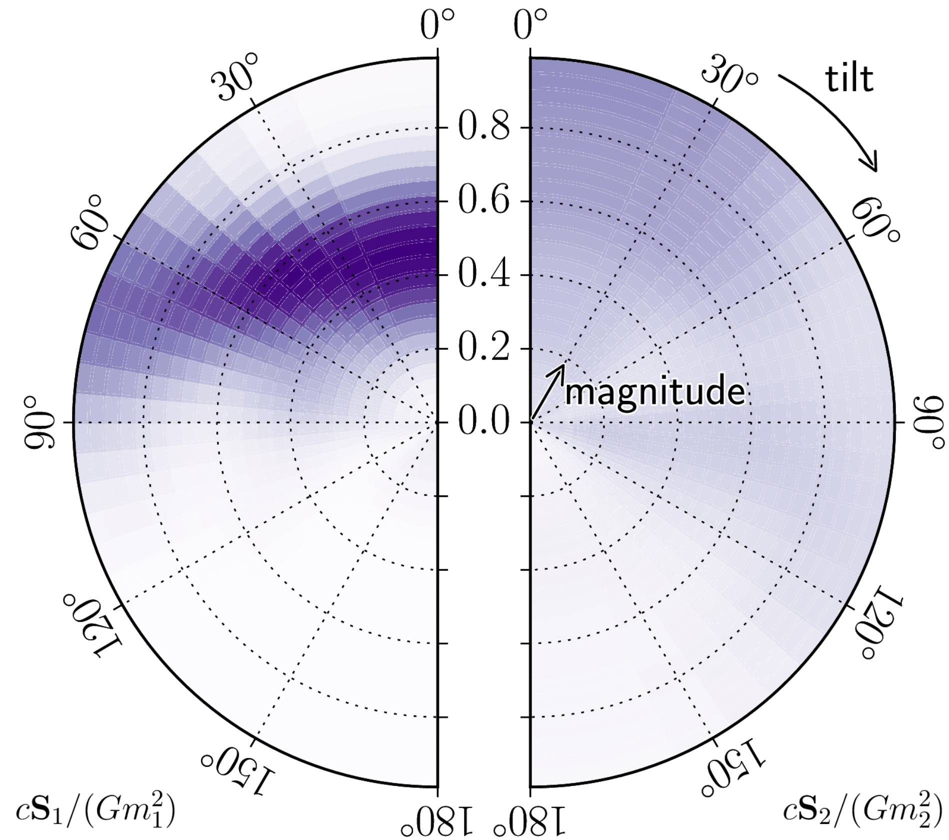




LVC 2016 arXiv:1602.03840

GW151226





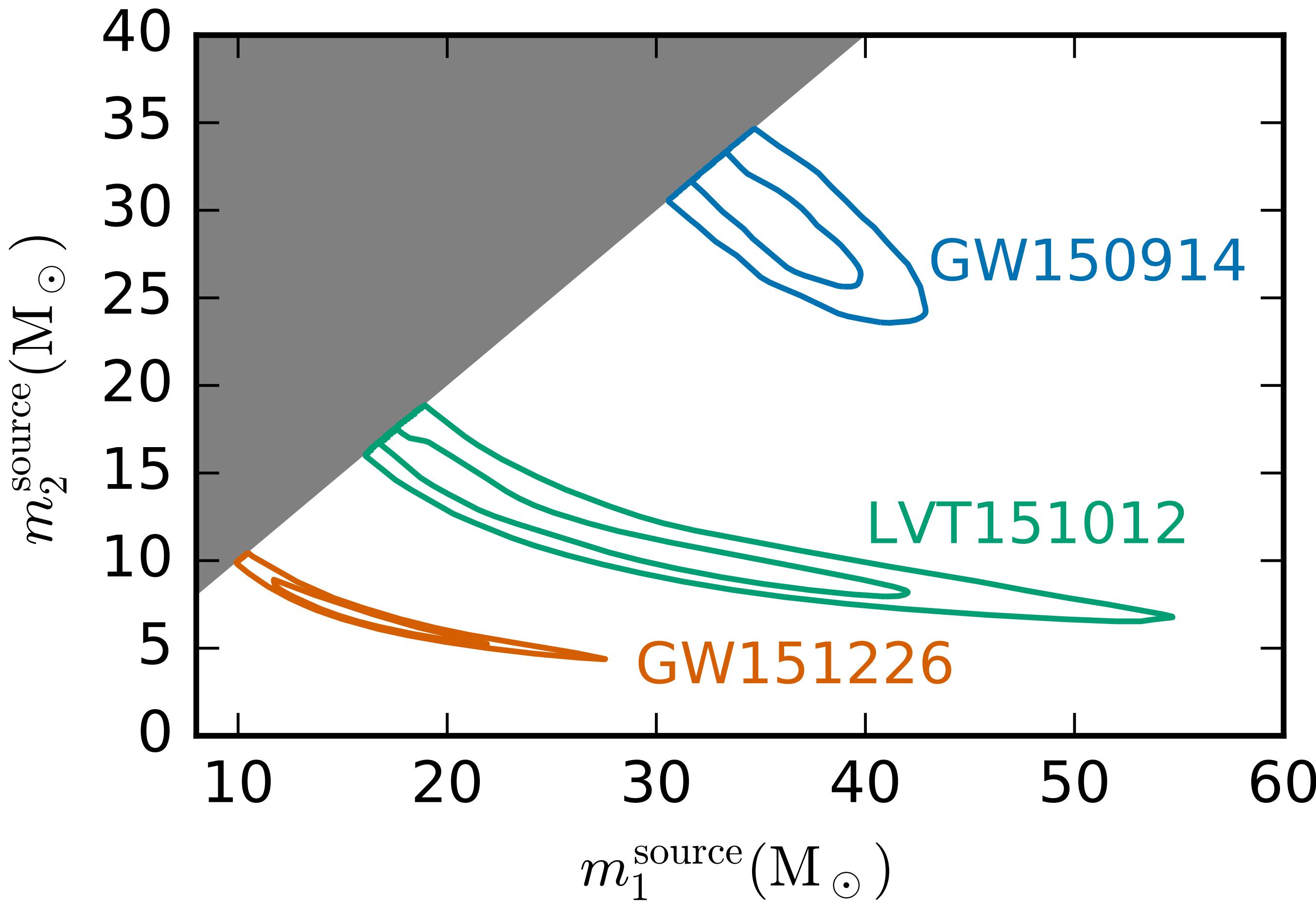
LVC 2016 arXiv:1606.04855

Masses

Stevenson+ 2015, Stevenson+ 2017 (in press), Mandel+ 2017

Measured masses

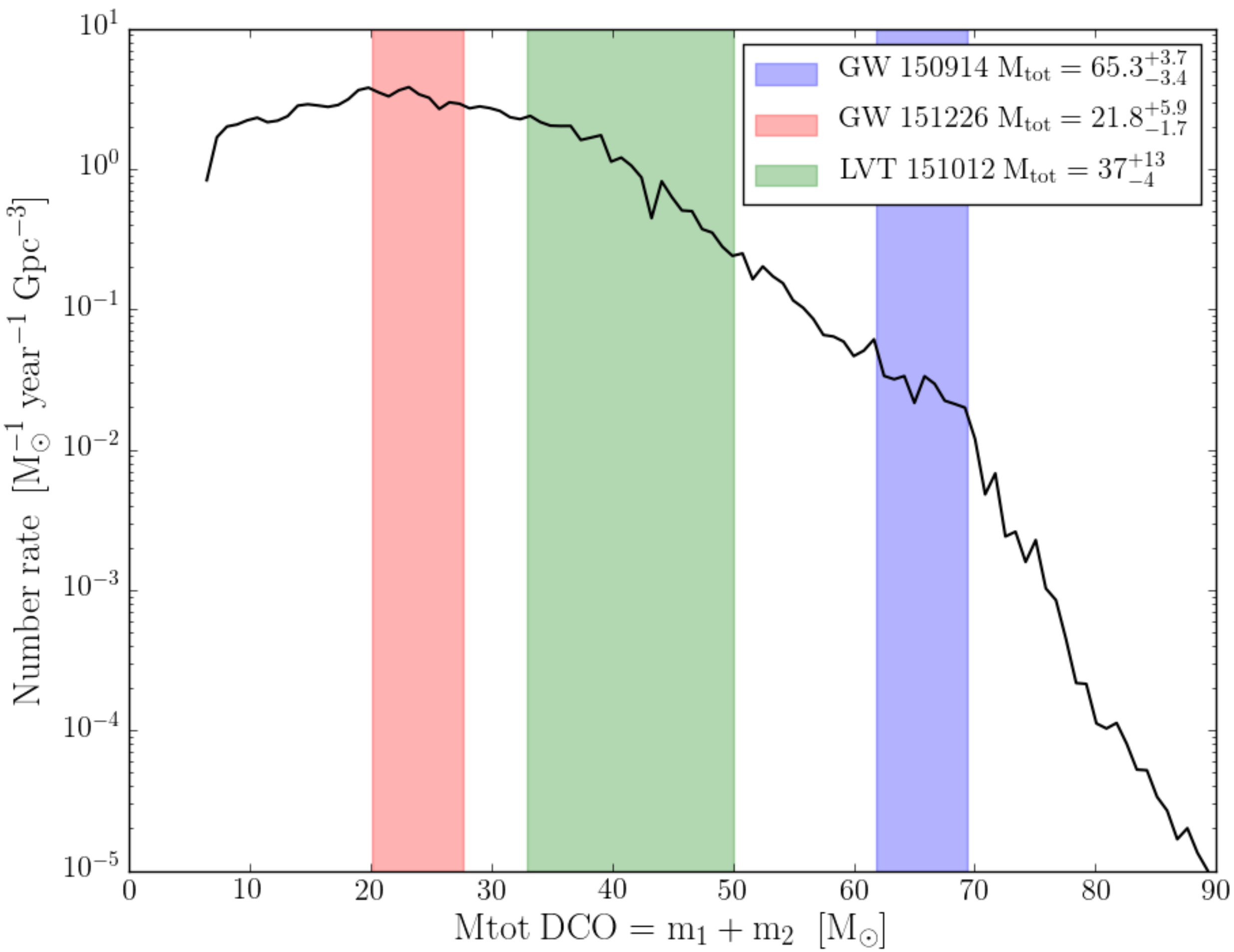
- Combination of component masses:
  - Chirp mass for low mass events
  - Total mass for high mass events



LVC 2016
arXiv:1606.04856

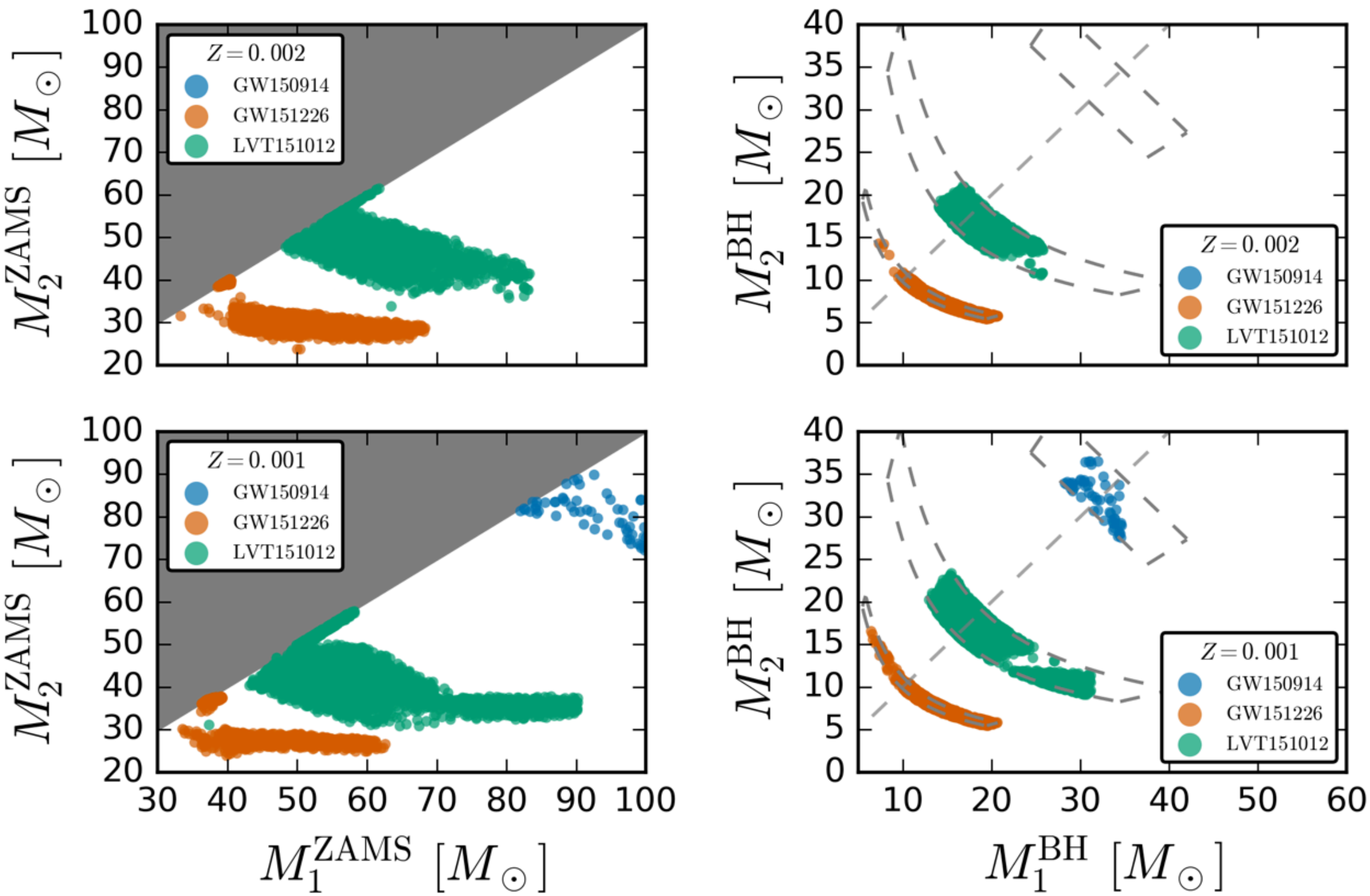
BBH (total) mass distribution

- Assumes our Fiducial model values of hyperparameters, integrated across cosmic history



- Data from Stevenson+ 2017 in press
- Evolution of BBH merger rate over cosmic history studied in Neijssel+ 2017 in prep

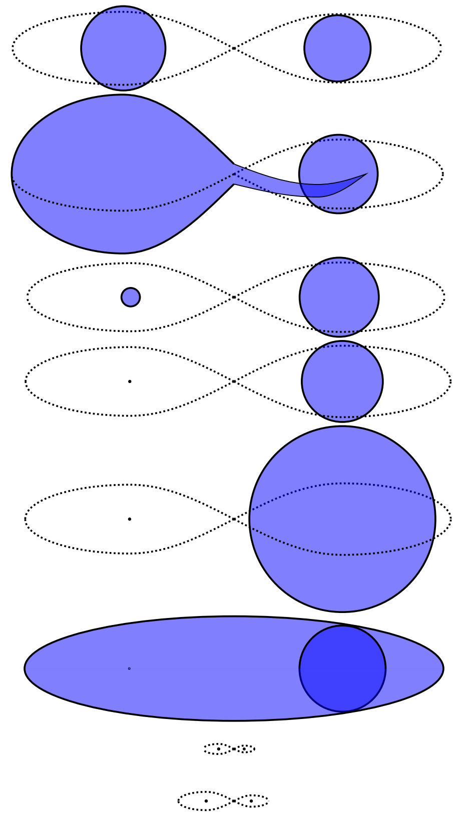
Progenitors of O1 events (maybe)



Stevenson et al 2017 in press

Typical evolutionary channel for GW151226

Time	M_1	ST_1	ST_2	M_2	a
[Myr]	[$M_\odot$]	–	–	[$M_\odot$]	[$R_\odot$]
0.0	63.6	MS	MS	27.8	729.93
4.1	60.4	HG	MS	27.7	757.5
4.12	24.6	HeMS	MS	30.6	622.07
4.49	19.1	BH	MS	30.6	692.7
7.21	19.1	BH	CHeB	30.3	697.48
7.42	19.1	BH	CHeB	29.7	706.33
7.42	19.1	BH	HeMS	10.6	5.18
7.88	19.1	BH	BH	5.7	8.82



Stevenson et al 2017 in press

Uncertainties in binary evolution

- Initial conditions (Recent progress e.g. Sana+ 2012, probably correlated as in Moe+ 2016)
- Stellar evolution (in particular for massive stars – e.g. expand or not? Overshooting -> core masses -> BH masses)
- Supernovae – NS/BH birth kicks – same or different? BH kicks large or small? NS/BH mass spectrum? Spin tilts?
- Stellar winds – absolute mass loss rates, extrapolation in metallicity
- Mass transfer – e.g. accretion efficiency, mass loss mode, response to mass loss (stable v unstable)
- Common envelope? Structure of massive stars and response to mass loss? Efficiency of common envelope ejection?

Can be explored with pop synth

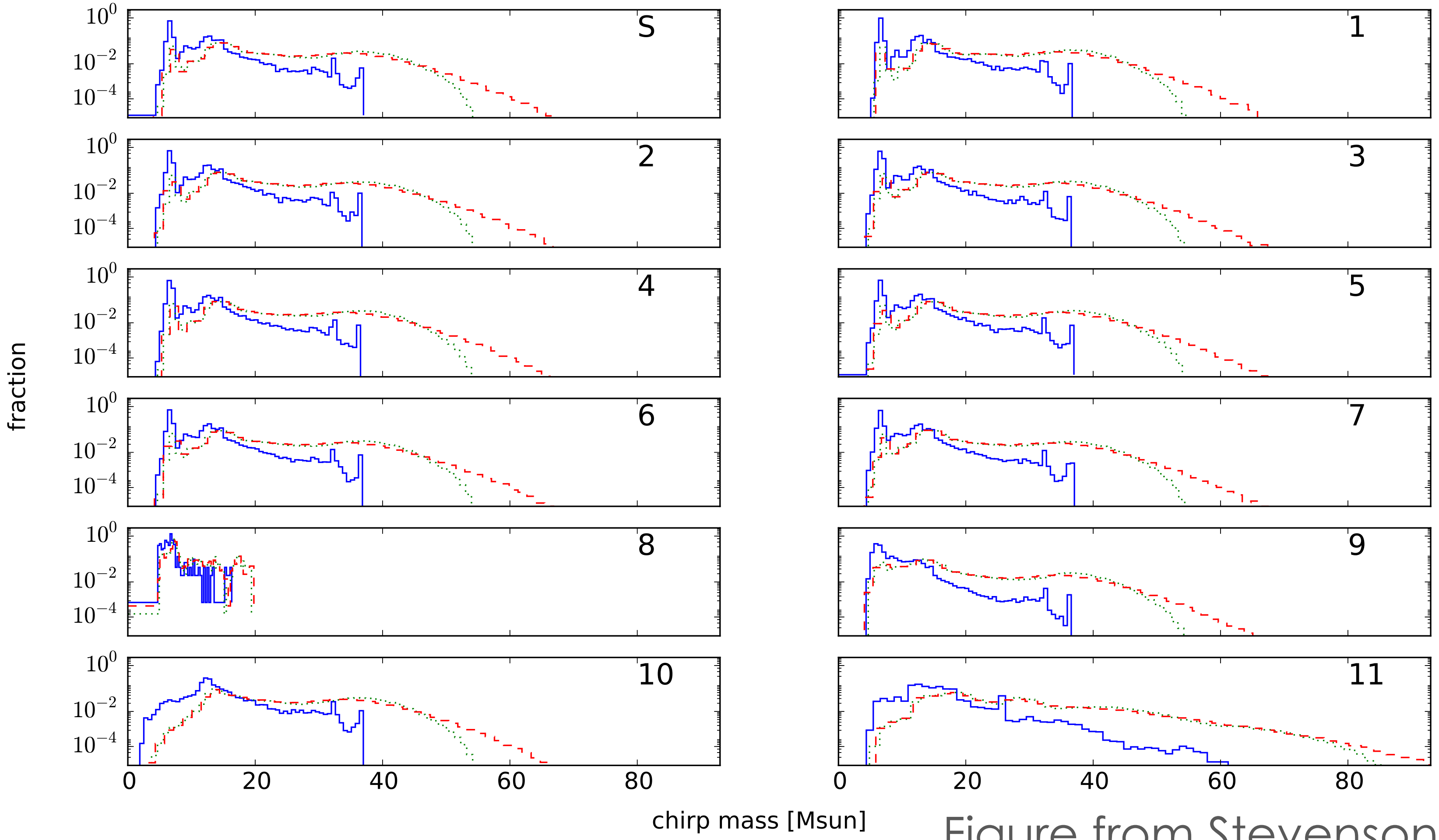


Figure from Stevenson+ 2015

Model comparison to pop synth models

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

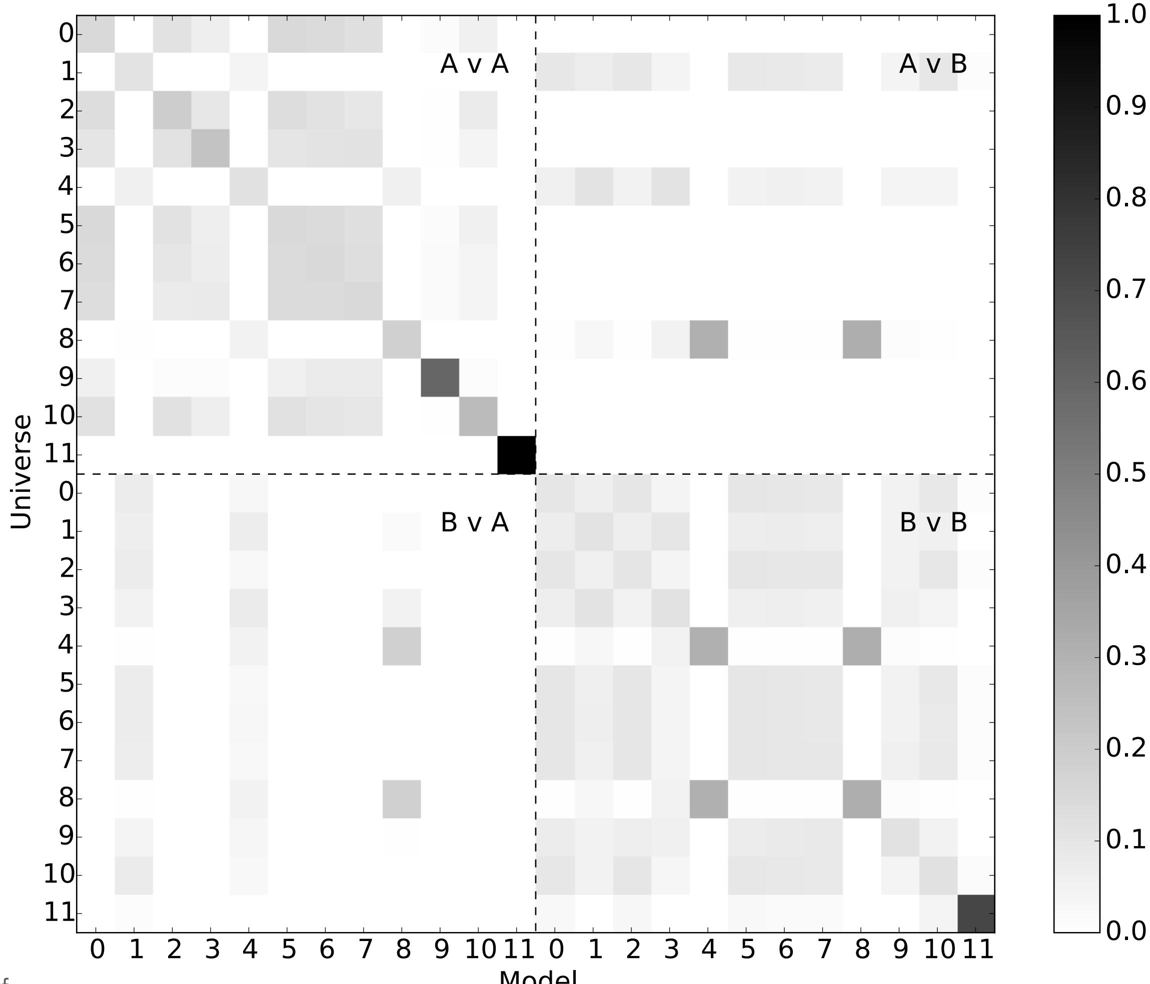
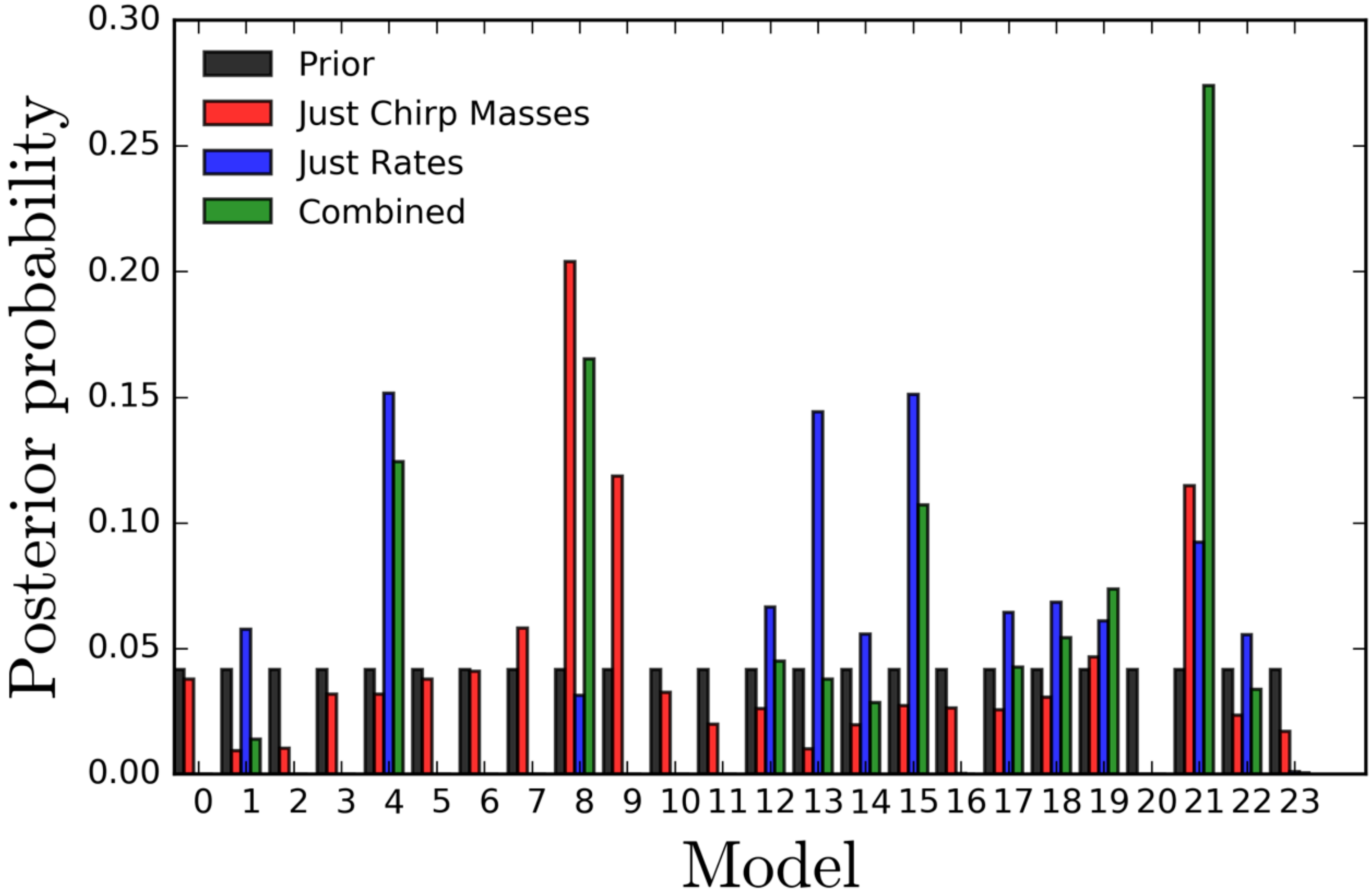


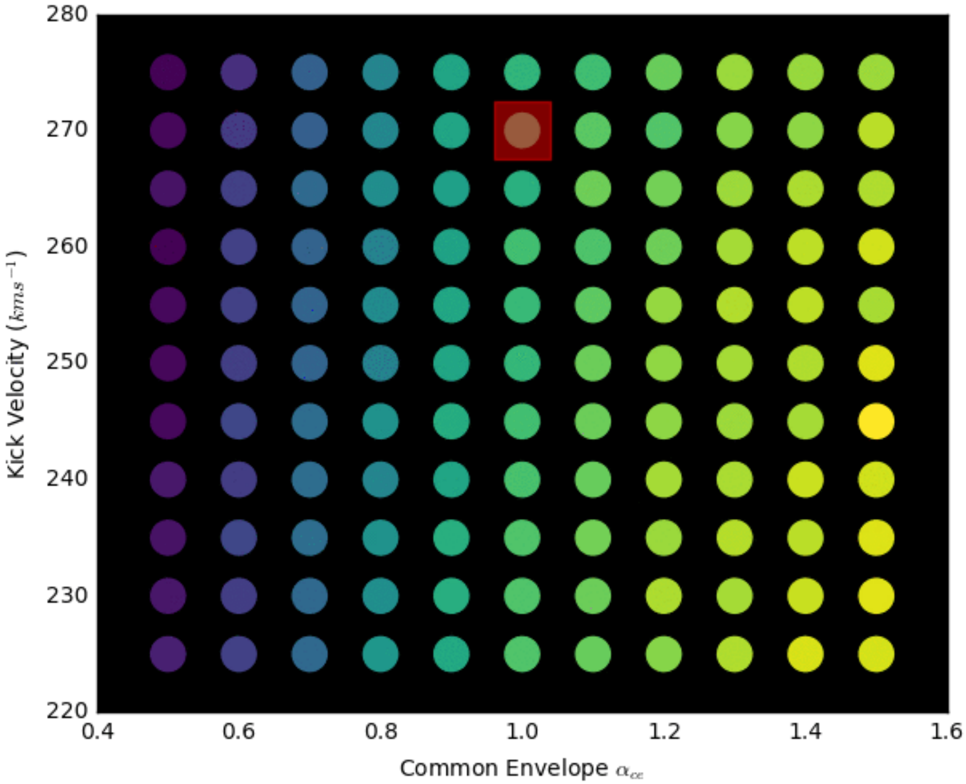
Figure from Stevenson+ 2015

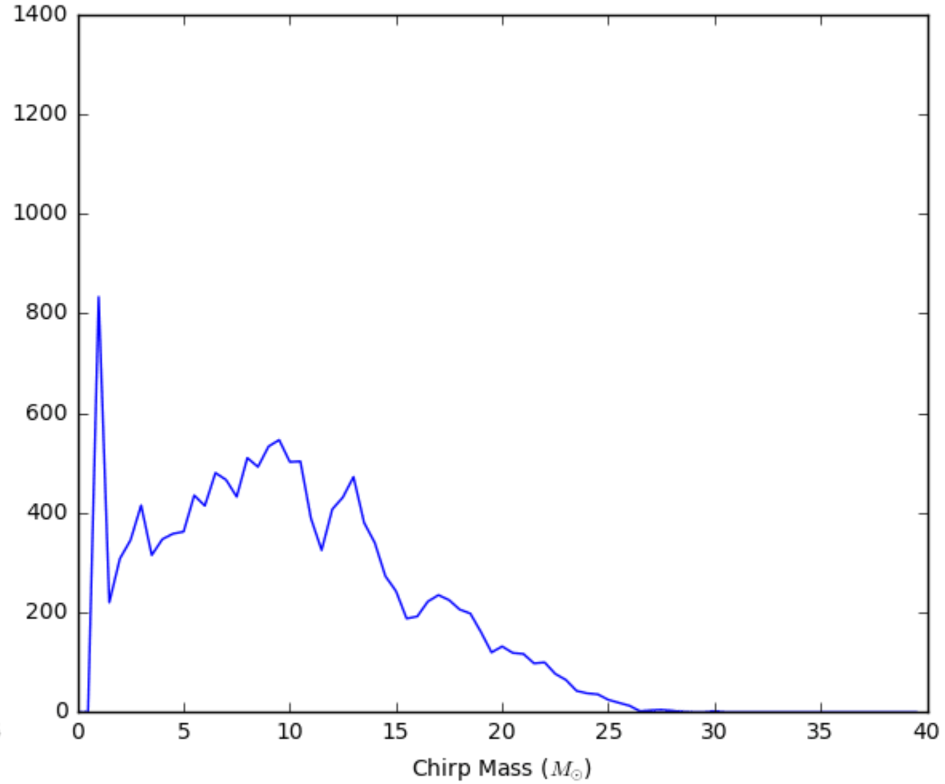
After O1



Unpublished, after Stevenson+ 2015

Chirp mass changes with hyper parameters of pop synth models

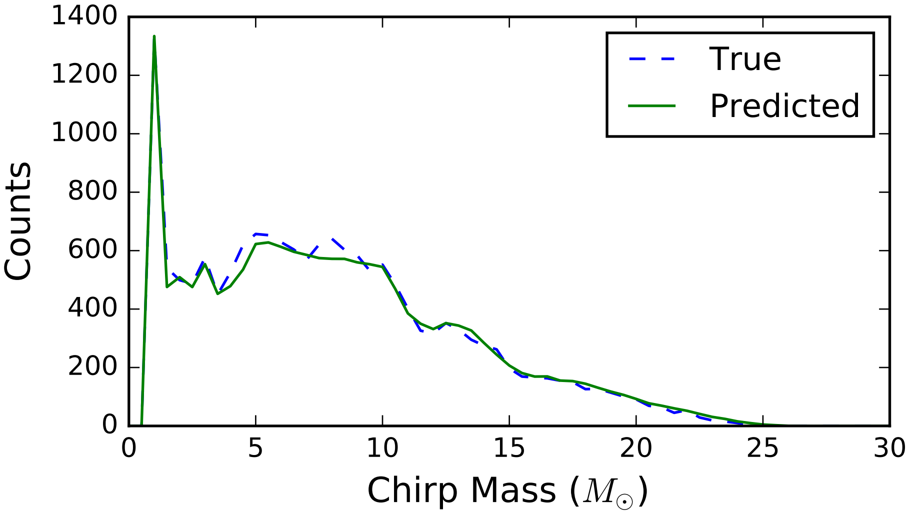


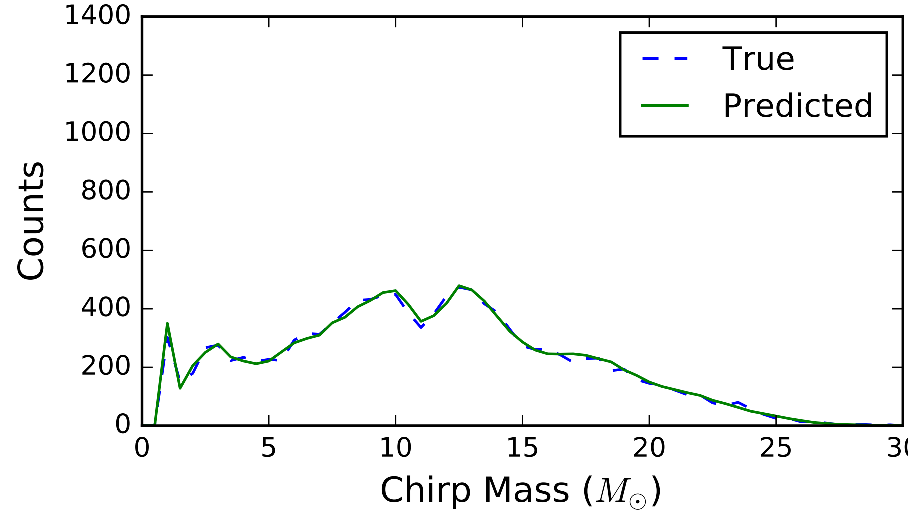


Barrett et al 2017 in prep

Interpolate chirp mass distribution

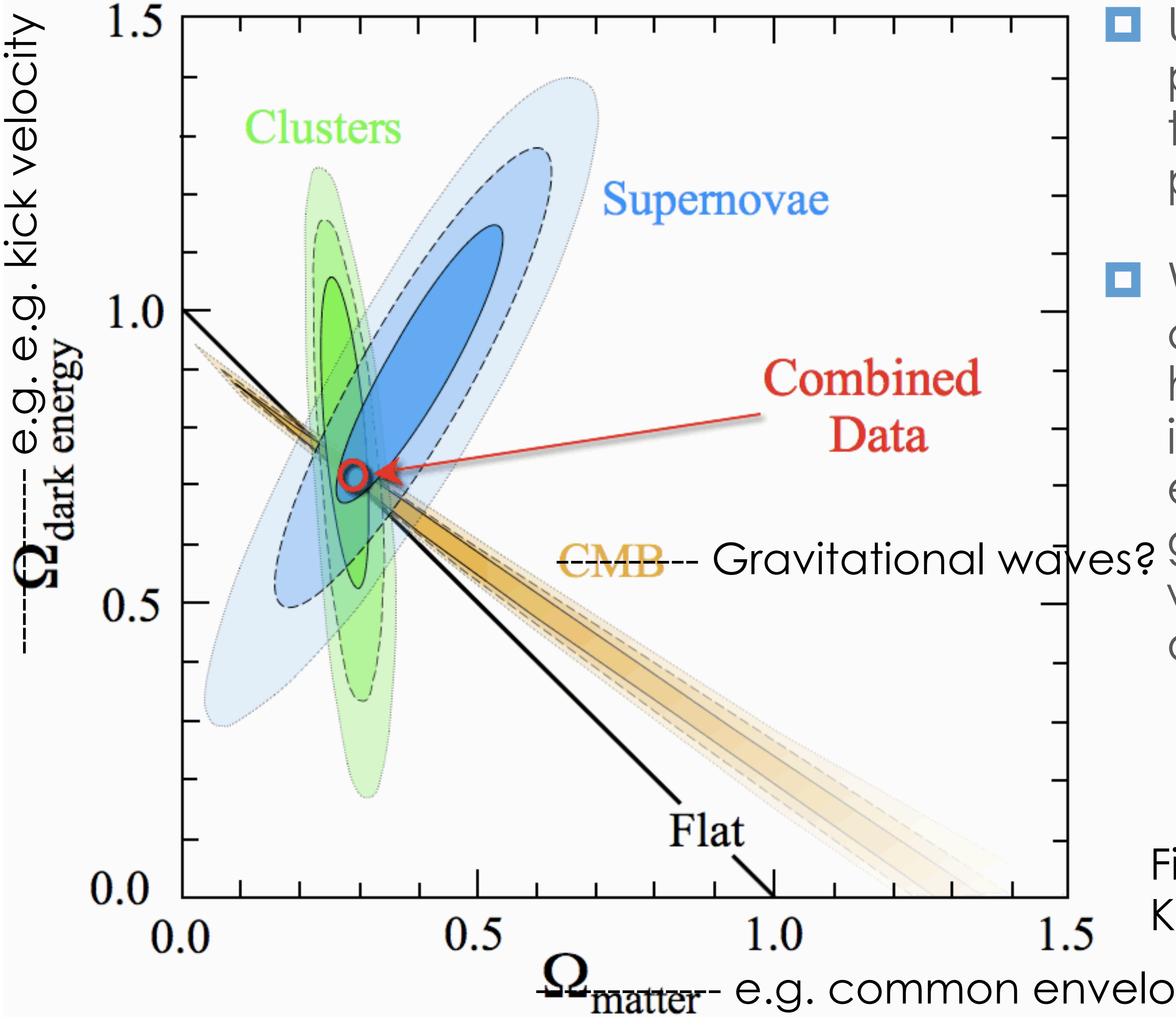
- Previous work by O'Shaughnessy in interpolating pop synth rate in high dimensions
- We bin chirp mass distribution, calculate principle component analysis and then interpolate coefficients using Gaussian Process
- Similar method to Taylor+ 2016 for PTAs (1612.02817)





Barrett et al 2017a, Barrett et al 2017b in prep

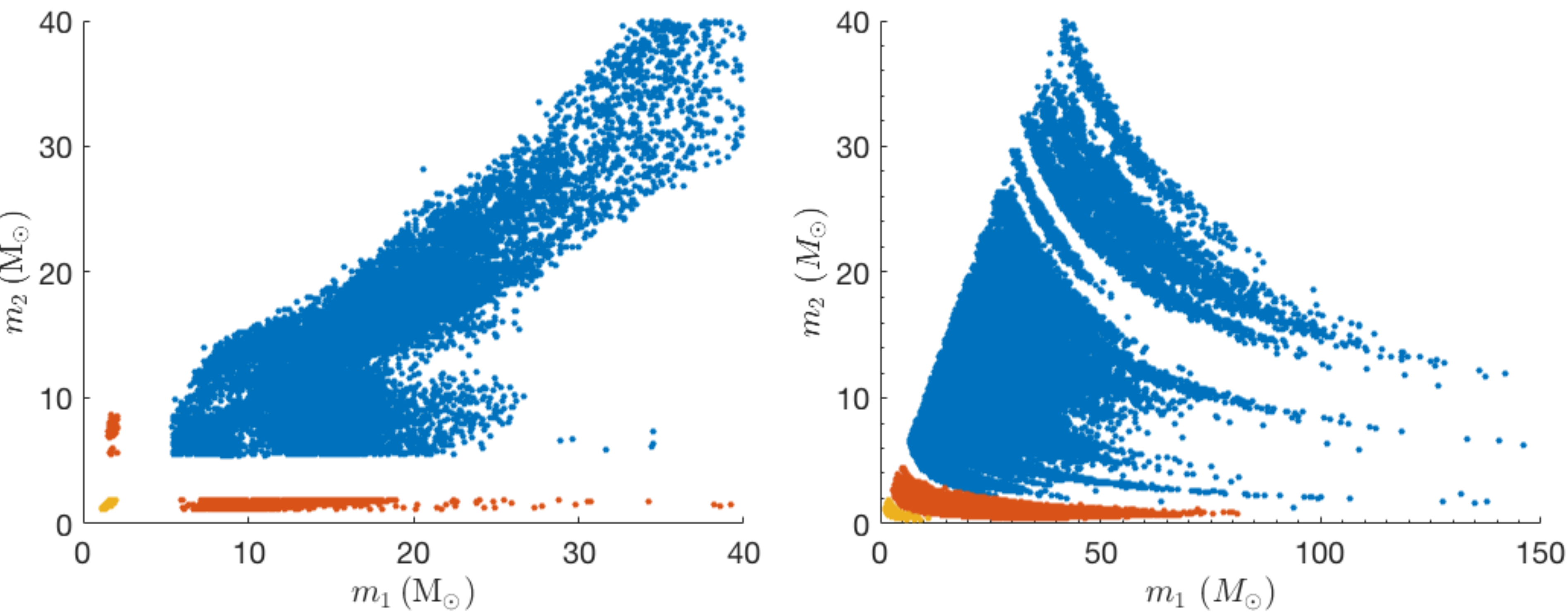
Concordance ~~cosmology~~ binary evolution



- Use interpolated pop synth models to solve inverse problem;
- Which combination of hyperparameters in our model best explains the gravitational wave observations?

Figure adapted from Kowalski et al 2008

Model independent methods



Mandel…Stevenson+ 2016

Mass function with number of observations

Mandel…Stevenson+ 2016

Spins

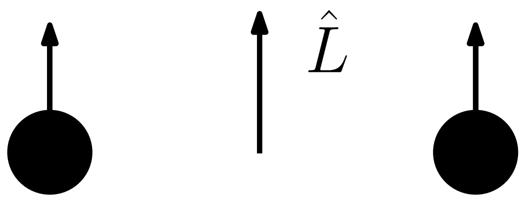
Stevenson+ 2017 in prep (see also Salvo's talk earlier)

Models for black hole spin-orbit misalignment angles

- We use a simplified population synthesis code (COMPAS) to model the binary black hole population
- We vary our assumptions about spin-orbit misalignments
- For all of our models we assume:
  - The magnitude of both black hole spins is 0.7
  - Black holes receive linear kicks in a similar way to neutron stars during a supernova
  - The mass distribution is identical for all channels
  - All binaries form with spins aligned to orbital angular momentum

Isolated binary evolution

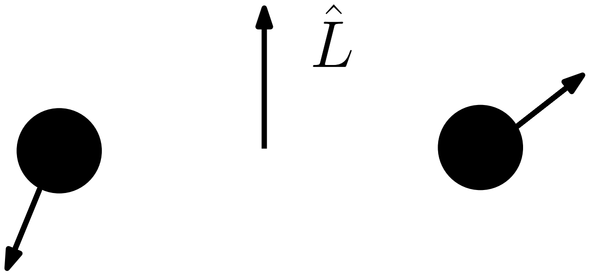
1)



- Many (but not all) binaries formed spin-aligned
- Many astrophsyical processes (tides, mass transfer etc) act to realign spins with the orbital angular momentum
- We assume that both black holes are aligned when they merge
- Possible if no kicks in BH formation and stars form aligned
- Also have 2 additional models 3) and 4) that vary assumption of both spins being exactly aligned

Dynamical formation

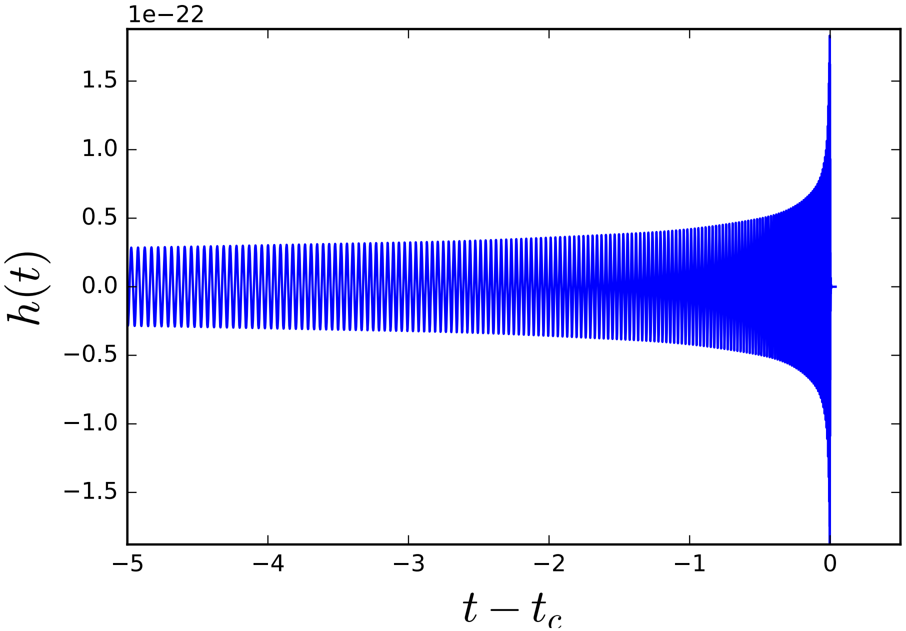
2)



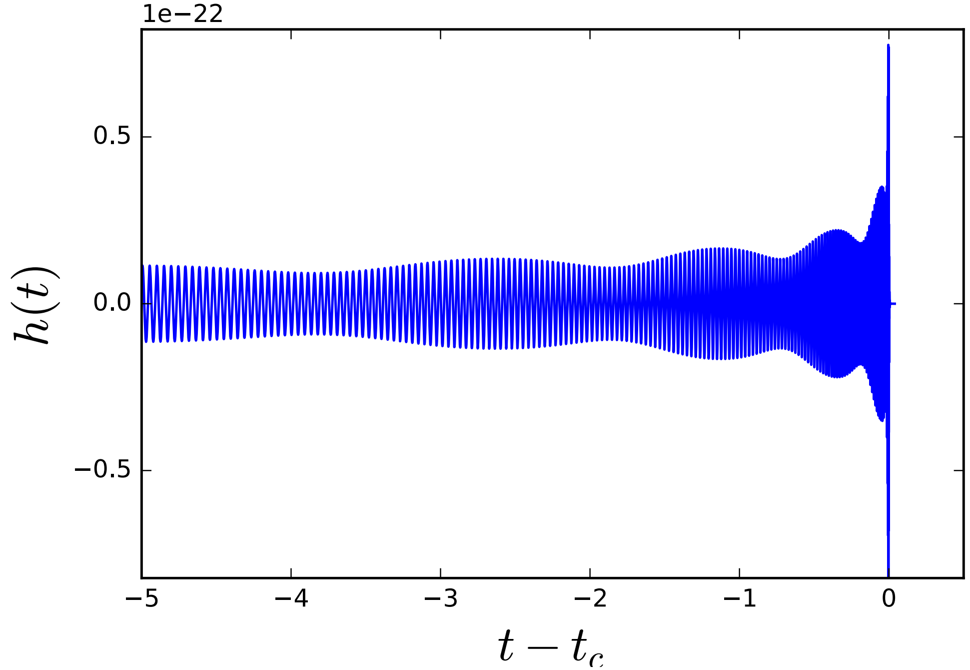
- We assume that the binary black hole is formed dynamically
- Both spins are misaligned isotropically and uncorrelated (e.g. Rodriguez+ 2016) and remains isotropic into LIGO band
- Possible for both stellar dynamics e.g. globular clusters and dynamically formed primordial black hole binaries

Measuring misaligned spins with GWs

Aligned spins



Misaligned spins

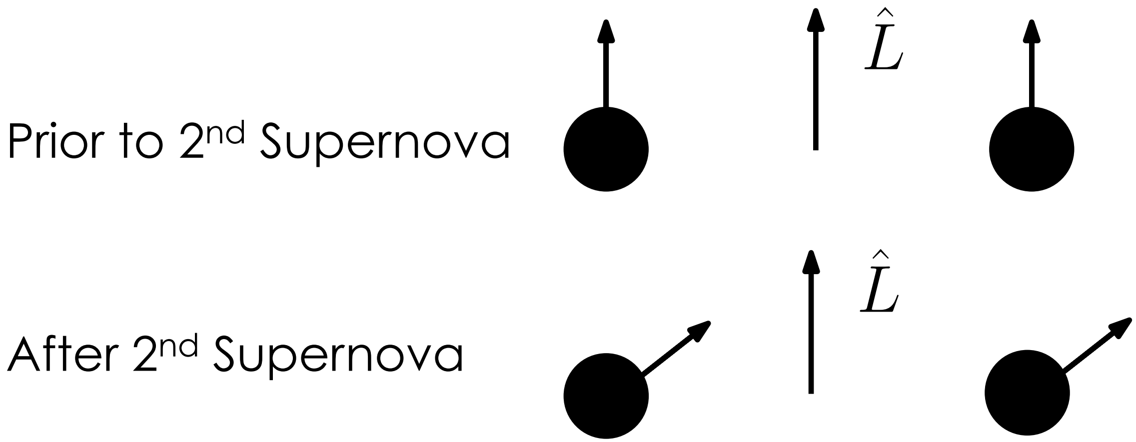


$M_1 = 16.29\ M_\odot$ $M_2 = 7.52\ M_\odot$ $a_1 = a_2 = 0.7$

Calculate for Advanced LIGO at design sensitivity

Model 3 – Isolated binary evolution

3)



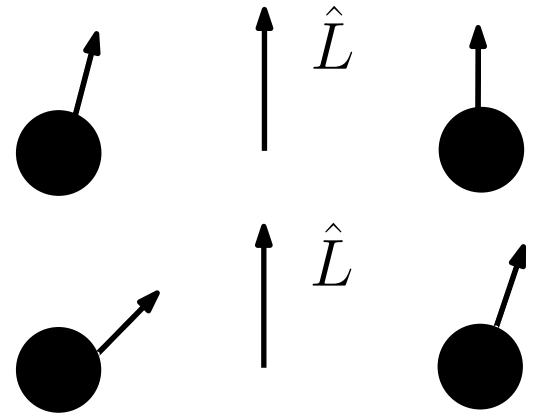
- We assume both aligned prior to the second supernova via CE
- Since misalignment set by second supernova kick, both BH spins are typically only **modestly and equally misaligned**, causing them to freely precess (Kalogera 2000, Schnittman 2004, Apostolatos 1994)

Model 4 – Isolated binary evolution

4)

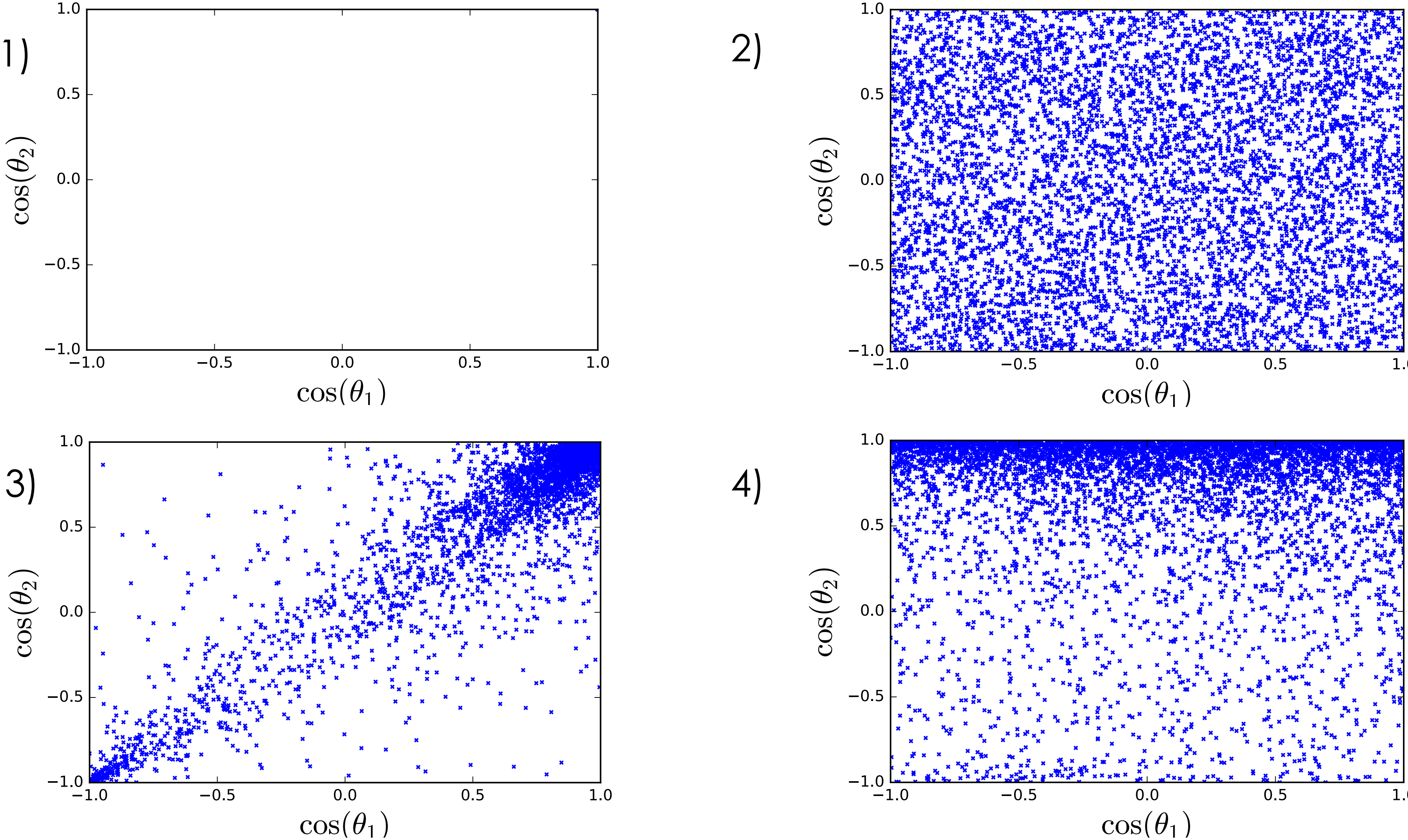
Prior to 2nd Supernova

After 2nd Supernova



- We assume the secondary is aligned prior to the second supernova via tides, with the primary misaligned via a supernova kick
- After second supernova, primary can be misaligned by a large angle, secondary by a more modest one
- This leaves the **primary misaligned and secondary aligned** (as in Gerosa et al 2013).

Mixture model - distributions of black hole spin misalignments



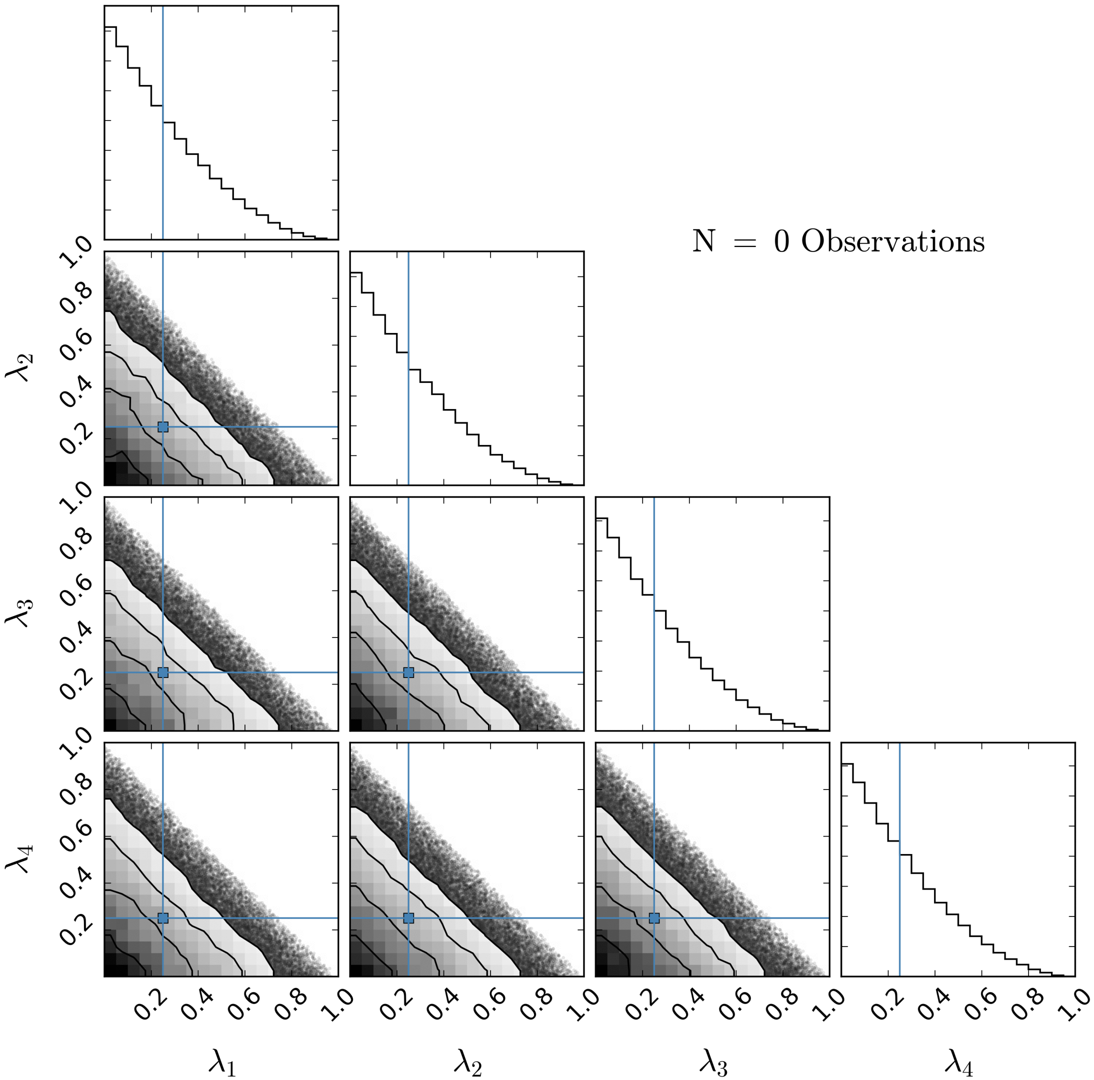
Hierarchical analysis

- Our models overlap significantly in parameter space.
- The spin-orbit misalignment angles are poorly measured for individual events
- A la Hogg 2010, Mandel 2010, we sample from the posterior given by the likelihood:

$$p\left(\{d_\alpha\}_{\alpha=1}^{N}\middle|\boldsymbol{\lambda}\right) = \prod_{\alpha=1}^{N}\frac{1}{\nu_\alpha}\sum_{k=1}^{\nu_\alpha}\frac{p(\boldsymbol{\Theta}_\alpha|\boldsymbol{\lambda})}{p(\boldsymbol{\Theta}_\alpha)}.$$

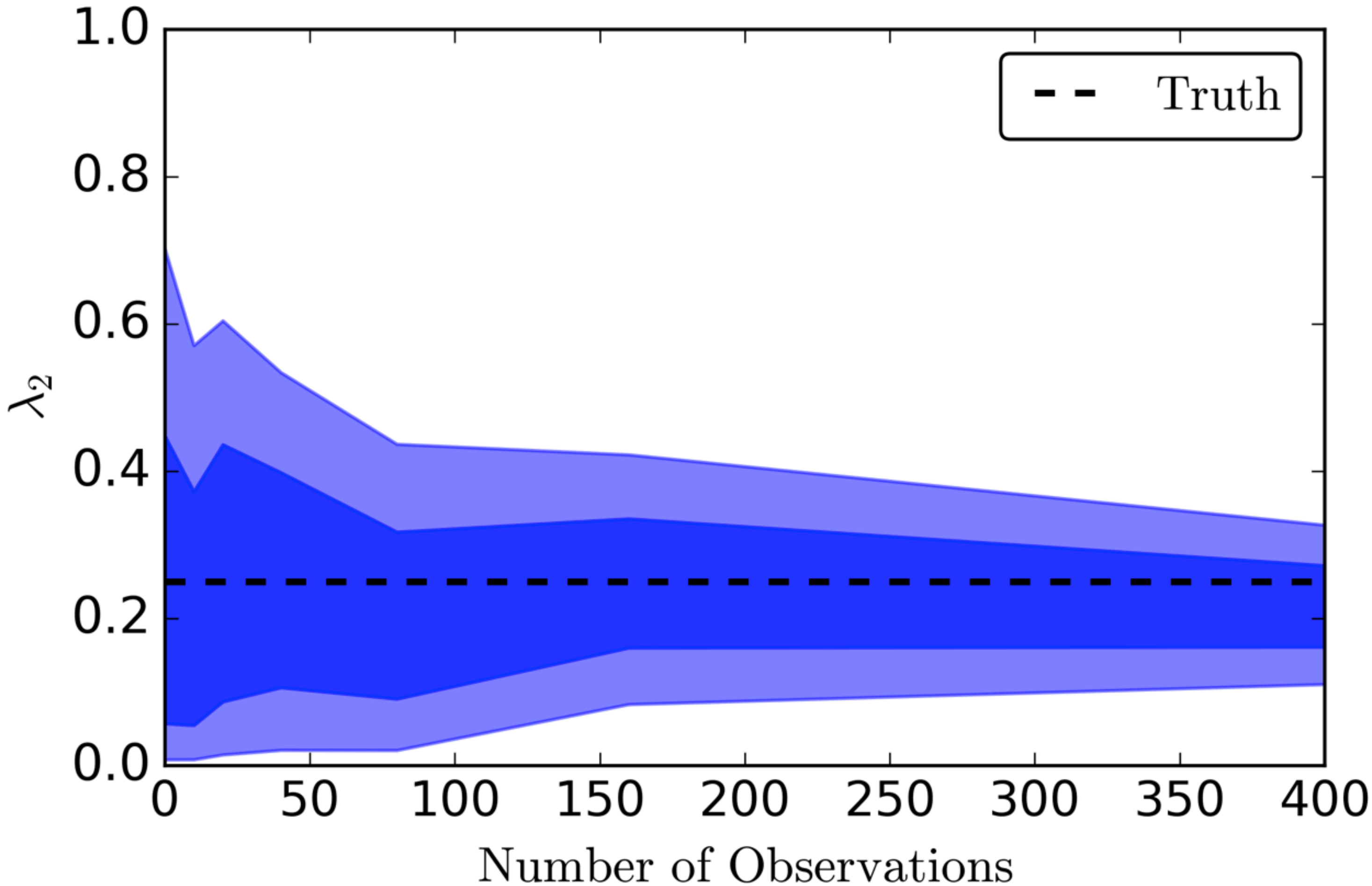
- Introduced by Chris earlier

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



- Including realistic measurement uncertainties
- Drawing increasing number of observations from a multinomial distribution
- True fractions shown in blue

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



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

Do misaligned spins really correspond to different formation channels?

- Possibility of spin tilts in supernovae (a la double pulsar Farr et al 2011 1104.5001) – cause binaries to lose "memory" of formation.
- From a modelling point of view:
  - Can we relate pre-SN stellar spin to post-SN BH spin?
  - How well do we understand realignment in e.g. common envelope?

Conclusions

- Isolated binary evolution is highly uncertain corresponding to uncertainty in **supernovae** and **mass transfer** (inc **common envelope** evolution)
- **Gravitational waves** provide a way to probe binary evolution and we now have observations!
- Can determine **fractions** of systems coming from isolated binary evolution v other channels
- Can use observations of GW masses, spins and rates to place **constraints on astrophysical *hyperparameters*** which go into our model, corresponding to uncertain astrophysics