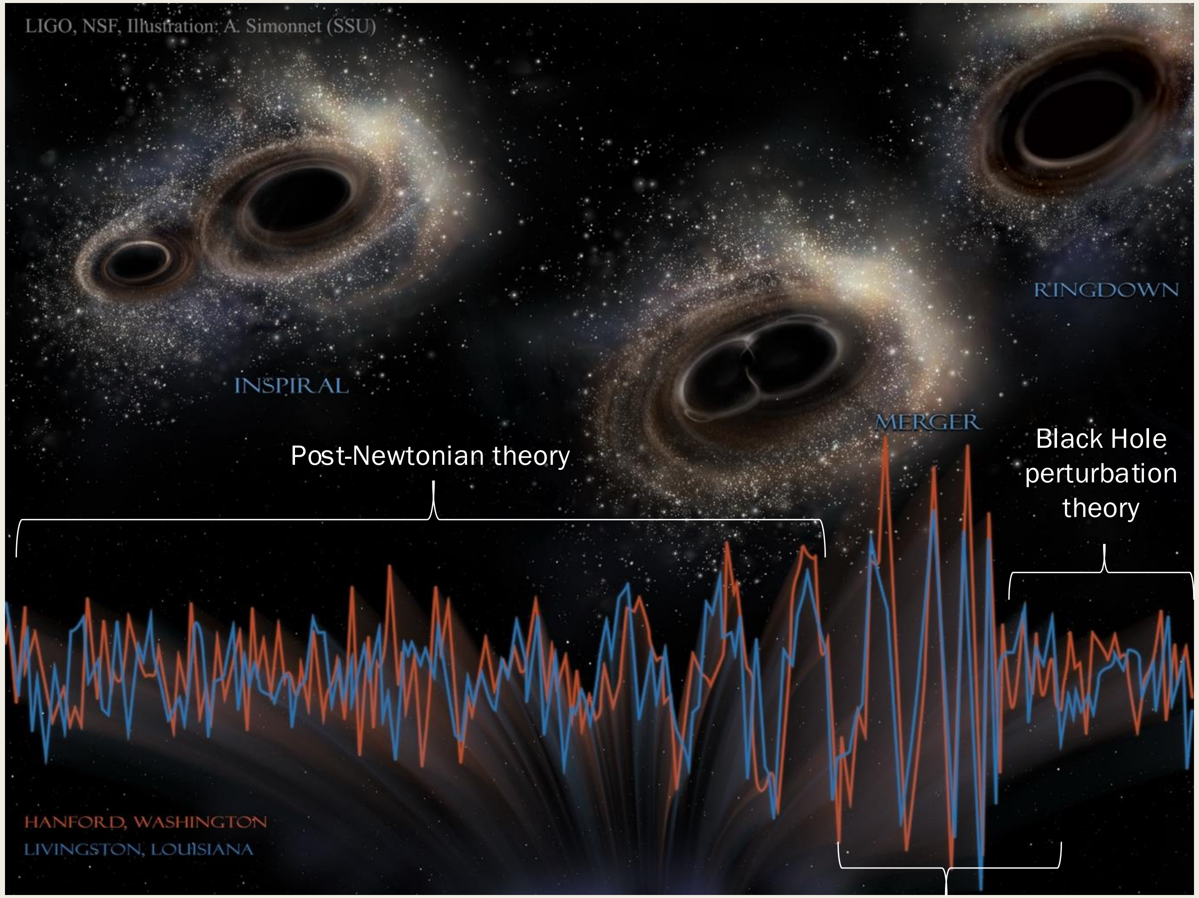
DYNAMICS OF BLACK HOLE BINARIES

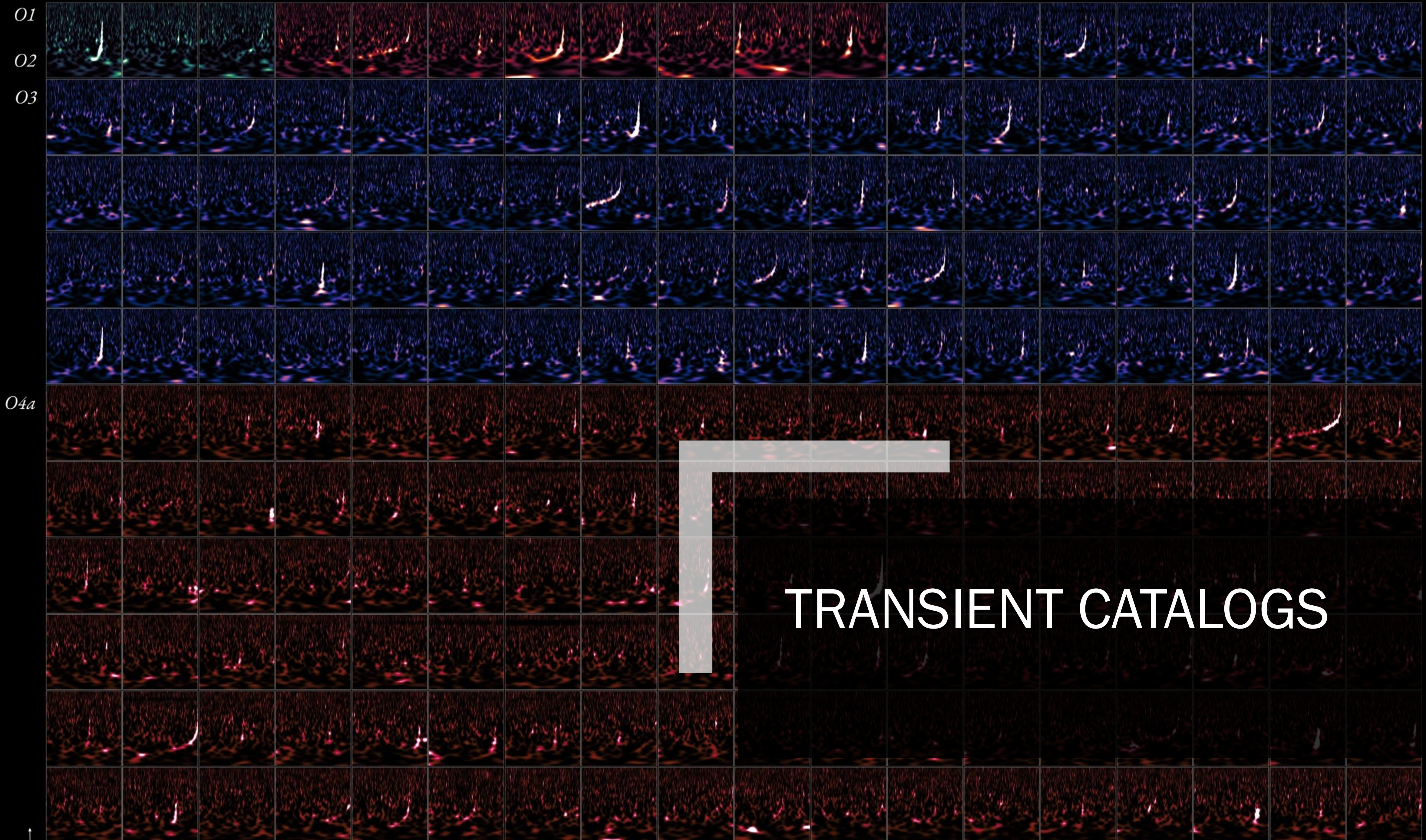
Matilde Garcia – BiCoQ conference 17/06



Numerical relativity

MERGING BINARIES OF COMPACT OBJECTS ACROSS THE COSMOS

10 Years of Detections (2015-2024) of Compact Binary Coalescences with Black Holes and Neutron Stars



TRANSIENT CATALOGS

Where do these binaries come from?

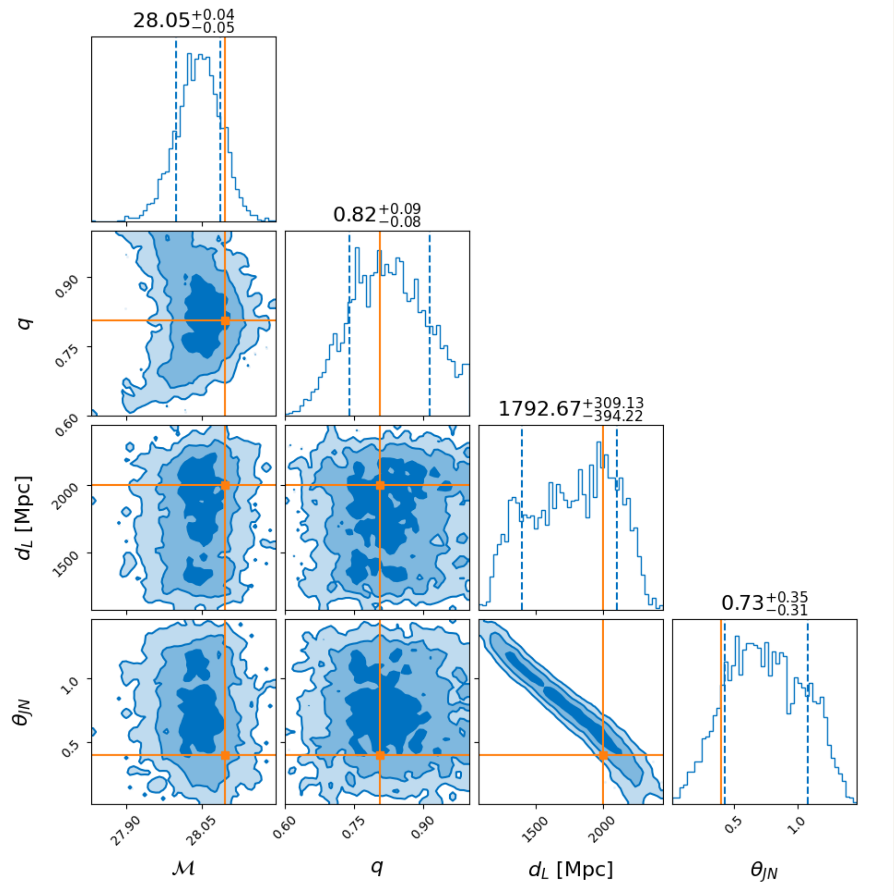
Different <u>formation channels</u> are predicted by theorists

- Dynamical formation channels – can leave imprints on gravitational wave signals
  - <u>Eccentricity</u> is smoking gun evidence that a binary was externally driven to form
  - Isolated binaries – expected to circularize by the time they reach LVK's frequency band

CRASH COURSE IN BAYESIAN INFERENCE FOR GWS

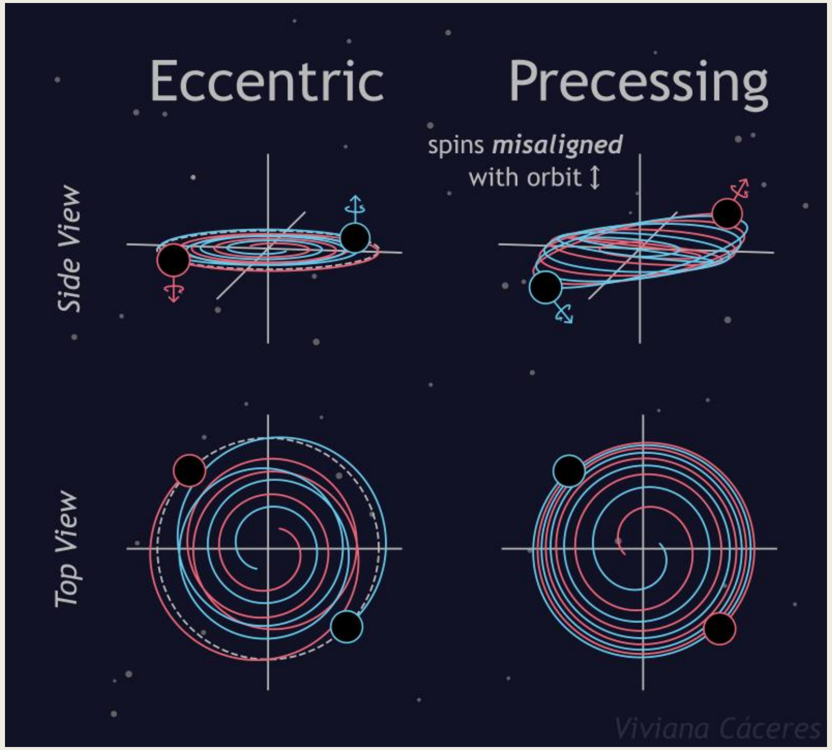
Gravitational wave data analysis

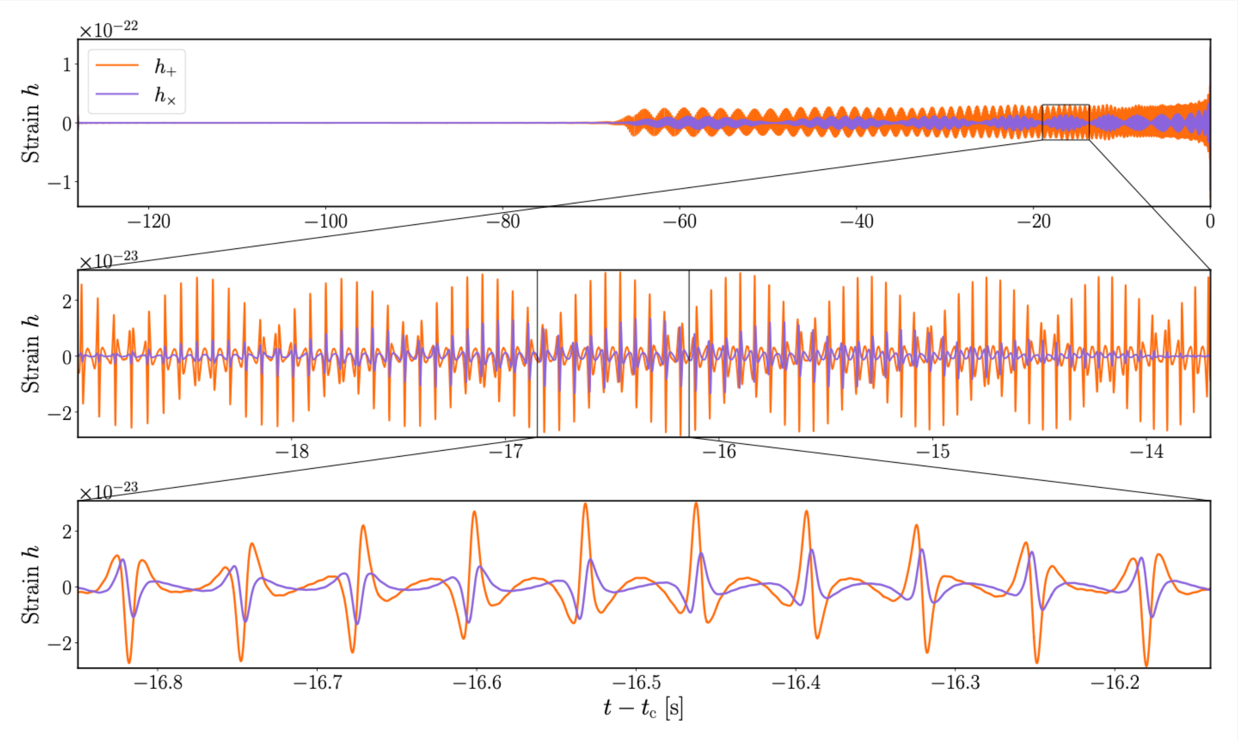
- $\mathcal{L}(d \mid \theta) = \frac{1}{2\pi\sigma^2}\exp\left(-\frac{1}{2}\frac{|\mathrm{d}-\mu(\theta)|^2}{\sigma^2}\right)$ - Likelihood, introduces a noise and waveform model
- $\pi(\theta)$ - Prior probability on the parameters
- $\mathcal{Z} = \int \mathrm{d}\theta \mathcal{L}(d \mid \theta)\pi(\theta)$ - Evidence, normalizing factor / model comparison
- $p(\theta \mid d)$ - Posterior probability , ultimate goal of bayesian inference



__BAYES THEOREM__ $$p(\theta \mid d) = \frac{\mathcal{L}(d|\theta)\pi(\theta)}{\mathcal{Z}}$$

ECCENTRICITY MEASUREMENTS CHALLENGES





ECCENTRICITY – SPIN PRECESSION DEGENERACY

The two effects, in general, operate on different timescales

However…

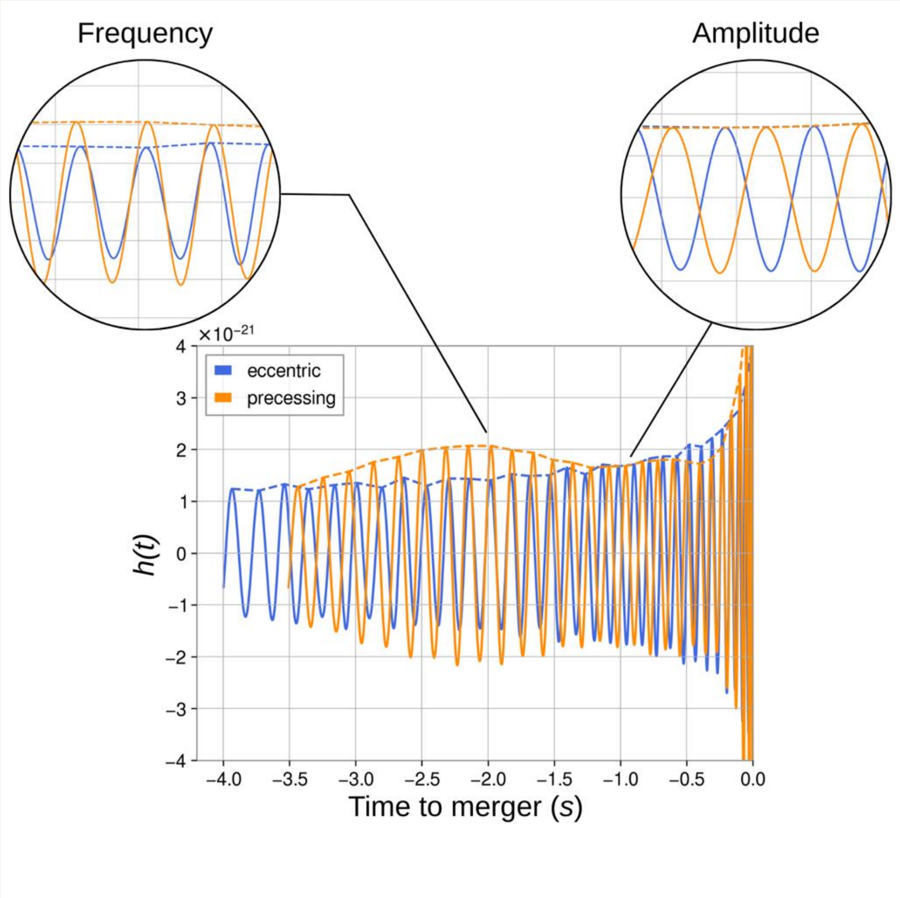
Eccentricity or spin precession? Distinguishing subdominant effects in gravitational-wave data

Isobel M. Romero-Shaw*[1,2,3], Davide Gerosa[4,5,6], Nicholas Loutrel[7]

For short signals, with only a few cycles in band, the two effects can become indistinguishable

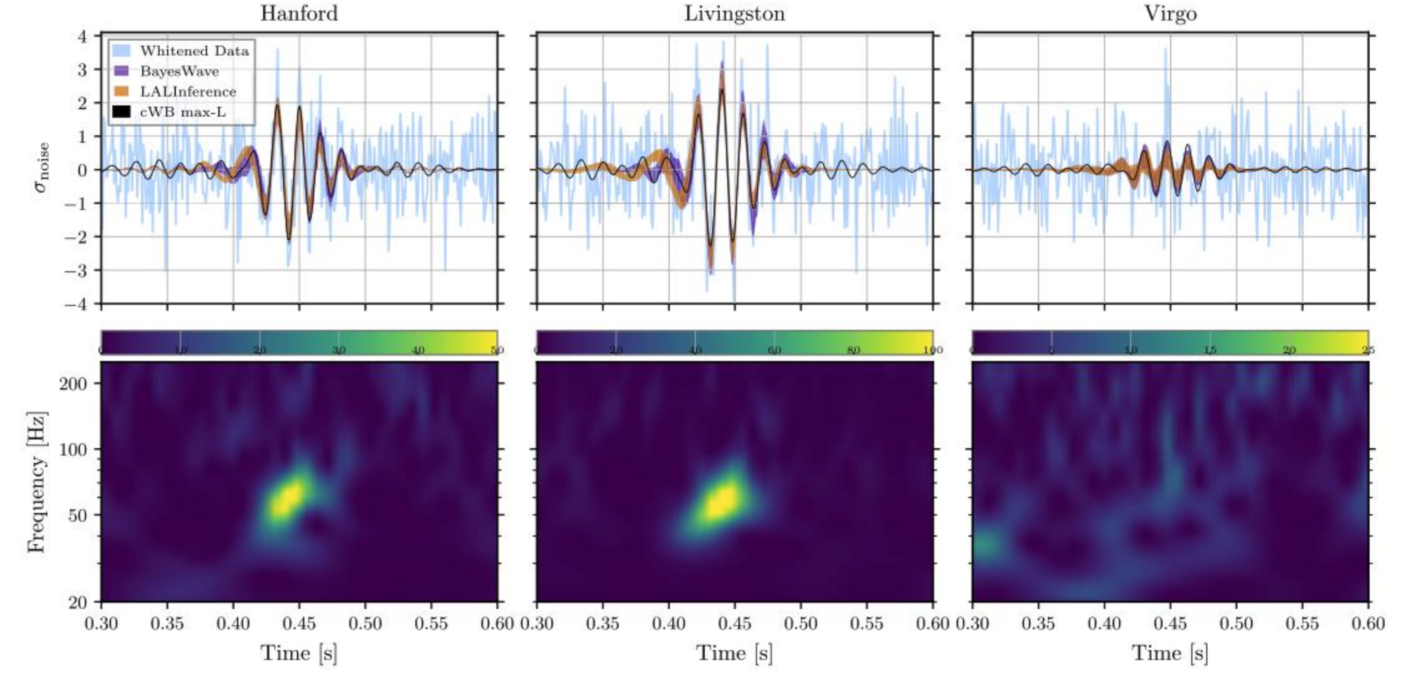
Misinterpreting Spin Precession as Orbital Eccentricity in Gravitational-Wave Signals

Snehal Tibrewal,[1] Aaron Zimmerman,[1] Jacob Lange,[2,1] and Deirdre Shoemaker[1]



GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$

R. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)



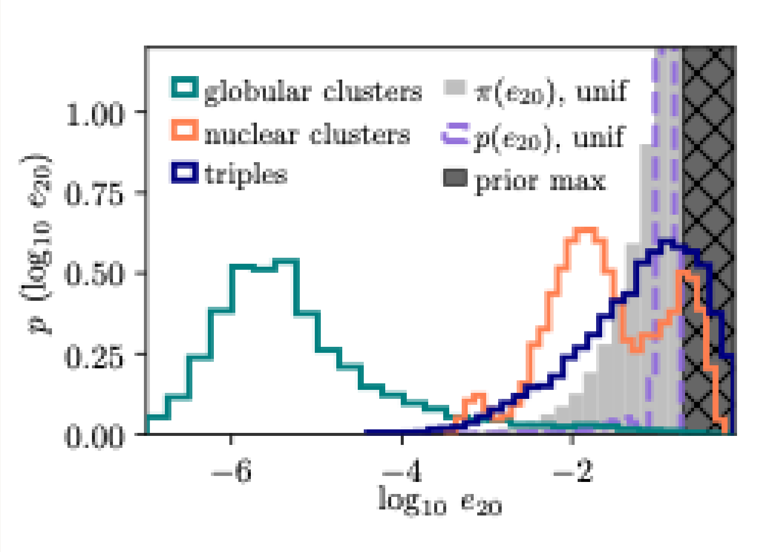
Furthermore…

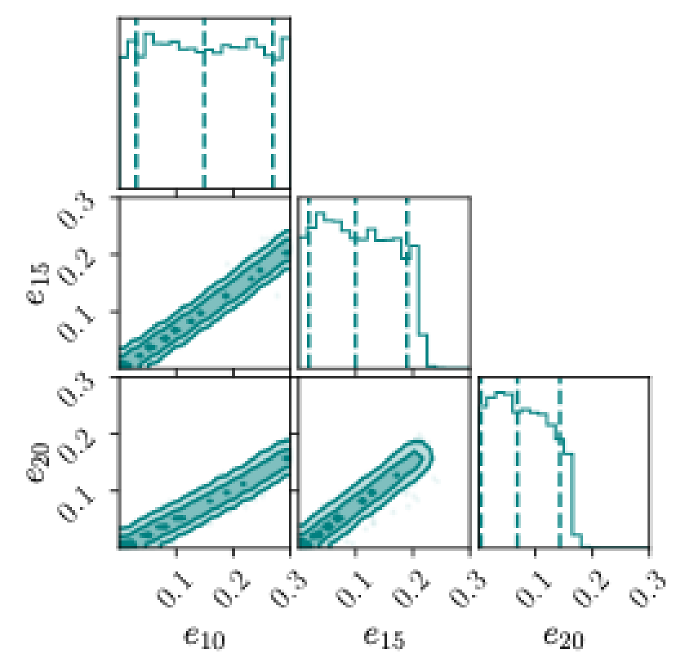
Recovered results are extremely prior dependent

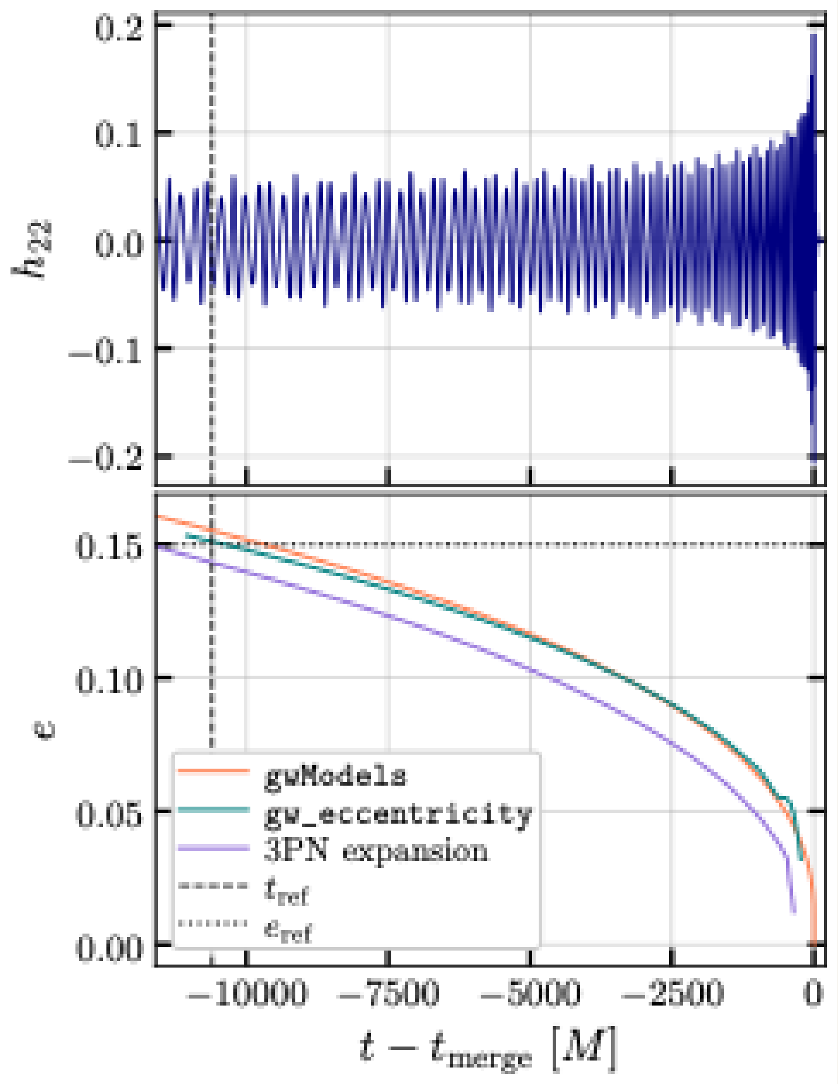
Choice of eccentricity reference frequency

Ambiguous definitions of eccentricity

…







ECCENTRICITY MEASUREMENTS ATTEMPTS

Eccentric VS Spin precessing hypothesis testing

- $\mathcal{Z} = \int d\theta \mathcal{L}(d \mid \theta)\pi(\theta)$ - Evidence, normalizing factor / <u>model comparison</u>

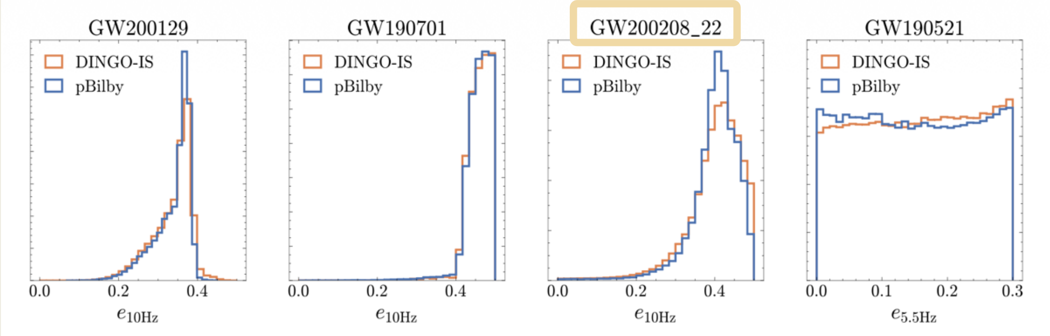
$\mu_1(\theta) \Rightarrow \mathcal{Z}_1$
eccentric, splin aligned hypothesis

$\mu_2(\theta) \Rightarrow \mathcal{Z}_2$
Quasi-circular, splin precessing hypothesis

Bayes factor $\mathcal{Z}_1/\mathcal{Z}_2$

Evidence for eccentricity in the population of binary black holes observed by LIGO-Virgo-KAGRA

Nihar Gupte,[1,2] Antoni Ramos-Buades,[3,1] Alessandra Buonanno,[1,2] Jonathan Gair,[1] M. Coleman Miller,[4] Maximilian Dax,[5] Stephen R. Green,[6] Michael Pürrer,[7,8] Jonas Wildberger,[5] Jakob Macke,[5] Isobel M. Romero-Shaw,[9,10] and Bernhard Schölkopf[5]



FOUR ECCENTRIC MERGERS INCREASE THE EVIDENCE THAT LIGO–VIRGO–KAGRA'S BINARY BLACK HOLES FORM DYNAMICALLY

Isobel Romero-Shaw,[1,2,3] Paul D. Lasky,[1,2] and Eric Thrane[1]

Event	$\ln \mathcal{B}_{E/P}(e_{10} \geq 0.1)$	$\ln \mathcal{B}_{E/P}(e_{10} \geq 0.05)$
GW190521	3.06	2.30
GW190620	2.52	2.10
GW191109	-1.74	-2.14
GW200208_22	1.51	0.96

Accurate inspiral-only waveform models

- In theory:

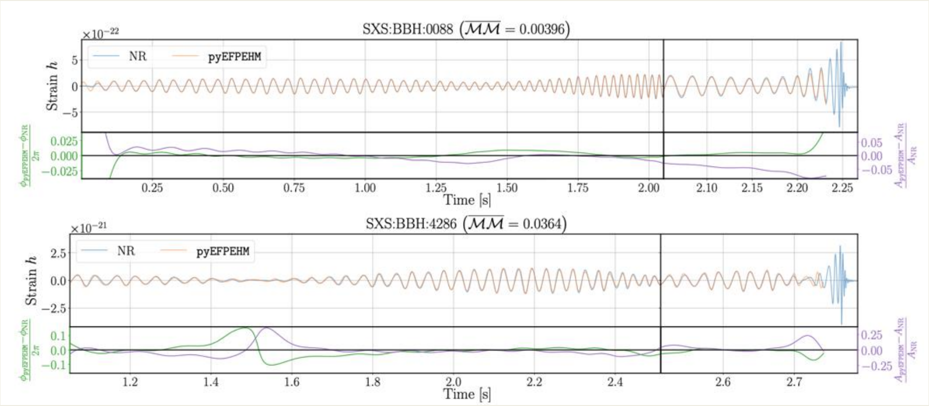
Long enough signal (many inspiral cycles) + Accurate waveform models $\mu(\theta)$ – both eccentric and spin precessing + Appropriate choice of priors, data glitch mitigation … = Somewhat confident eccentricity measurement

- It has been done!

(For very light systems of NS and BHNS)

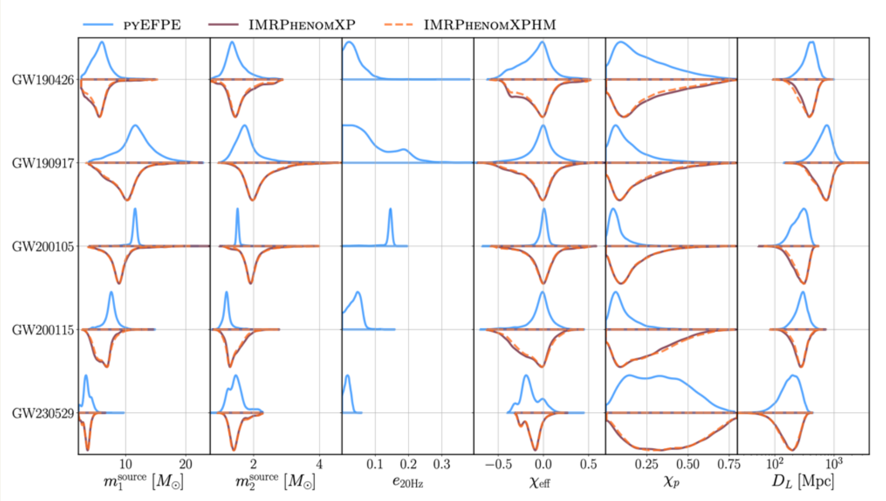
Post-Newtonian inspiral waveform model for eccentric precessing binaries with higher-order modes and matter effects

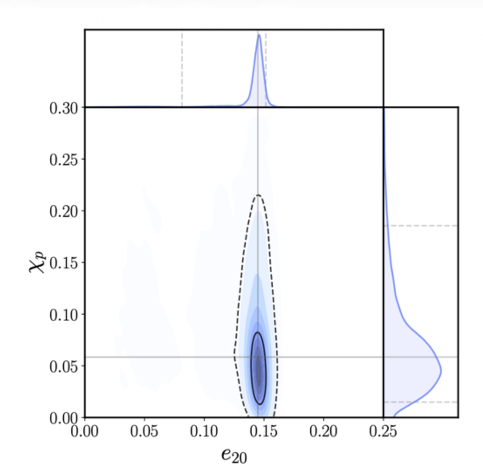
Gonzalo Morras,[1,2,*] Geraint Pratten,[3] Patricia Schmidt,[3] and Alessandra Buonanno[1,4]



Impact of eccentricity on the population properties of neutron star – black hole mergers

Gonzalo Morras,[1,2] Geraint Pratten,[3] and Patricia Schmidt[3]





Accurate inspiral-only waveform models

- For NS and BH-NS binaries, there are a lot of inspiral cycles within band

(in fact, the merger is often too high-frequency to be visible)

→ Using inspiral-only waveforms is not a problem

- For BBH binaries …

GW200208_222617 as an eccentric black-hole binary merger: properties and astrophysical implications

Isobel Romero-Shaw[1,2,3,*] Jakob Stegmann[4] Hiromichi Tagawa[5] Davide Gerosa[6,7] Johan Samsing[8] Nihar Gupte[9,10] and Stephen R. Green[11]

- ☑ Relatively low mass
- ☑ Many visible inspiral cycles
- ☑ No (known) data issues (glitch-free)

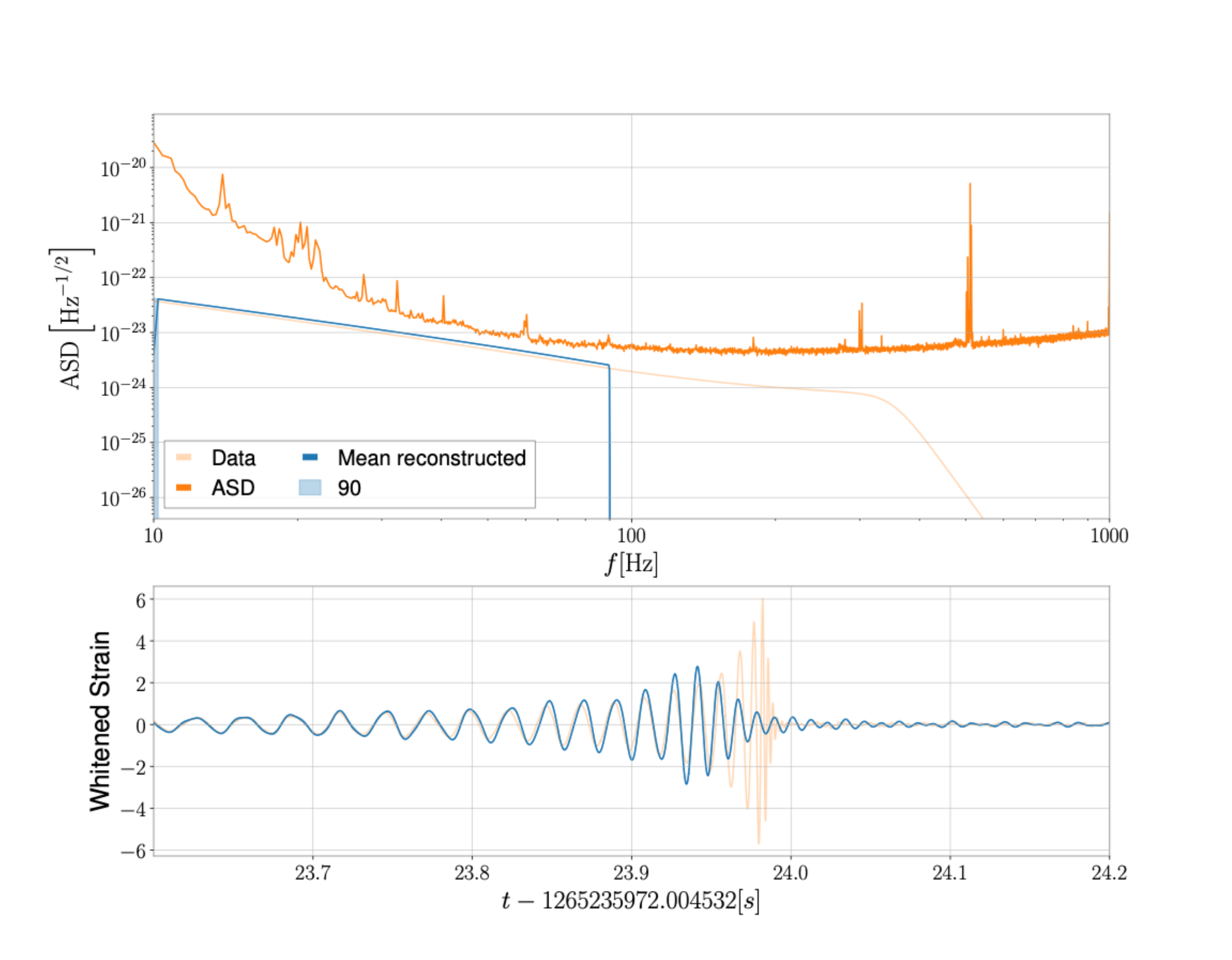
→ however → Using inspiral-only waveforms **is** a problem!!

The problem of inspiral-only waveforms

- **Even for relatively light BBH**– in the same frequency range, we have inspiral-merger-ringdown data, but only inspiral model…

$$\mathcal{L}(\, d \mid \theta \,) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{1}{2}\frac{|\mathrm{d}-\mu(\theta)|^2}{\sigma^2}\right)$$

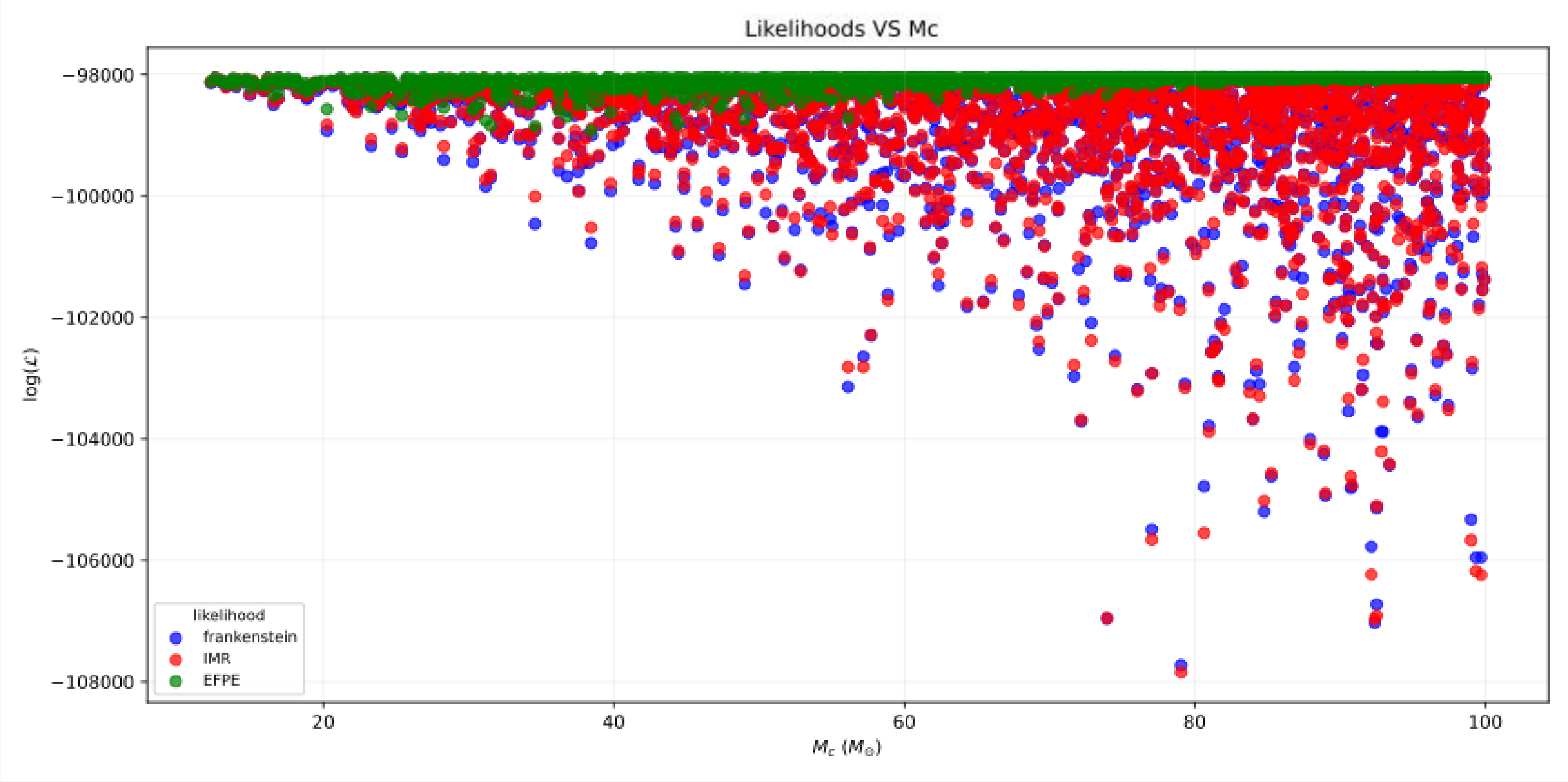
an integral across frequencies of the noise weighted inner product of the signal with the model



The problem of inspiral-only waveform models

$$\mathcal{L}(d \mid \theta) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{1}{2}\frac{|\mathrm{d}-\mu(\theta)|^2}{\sigma^2}\right)$$

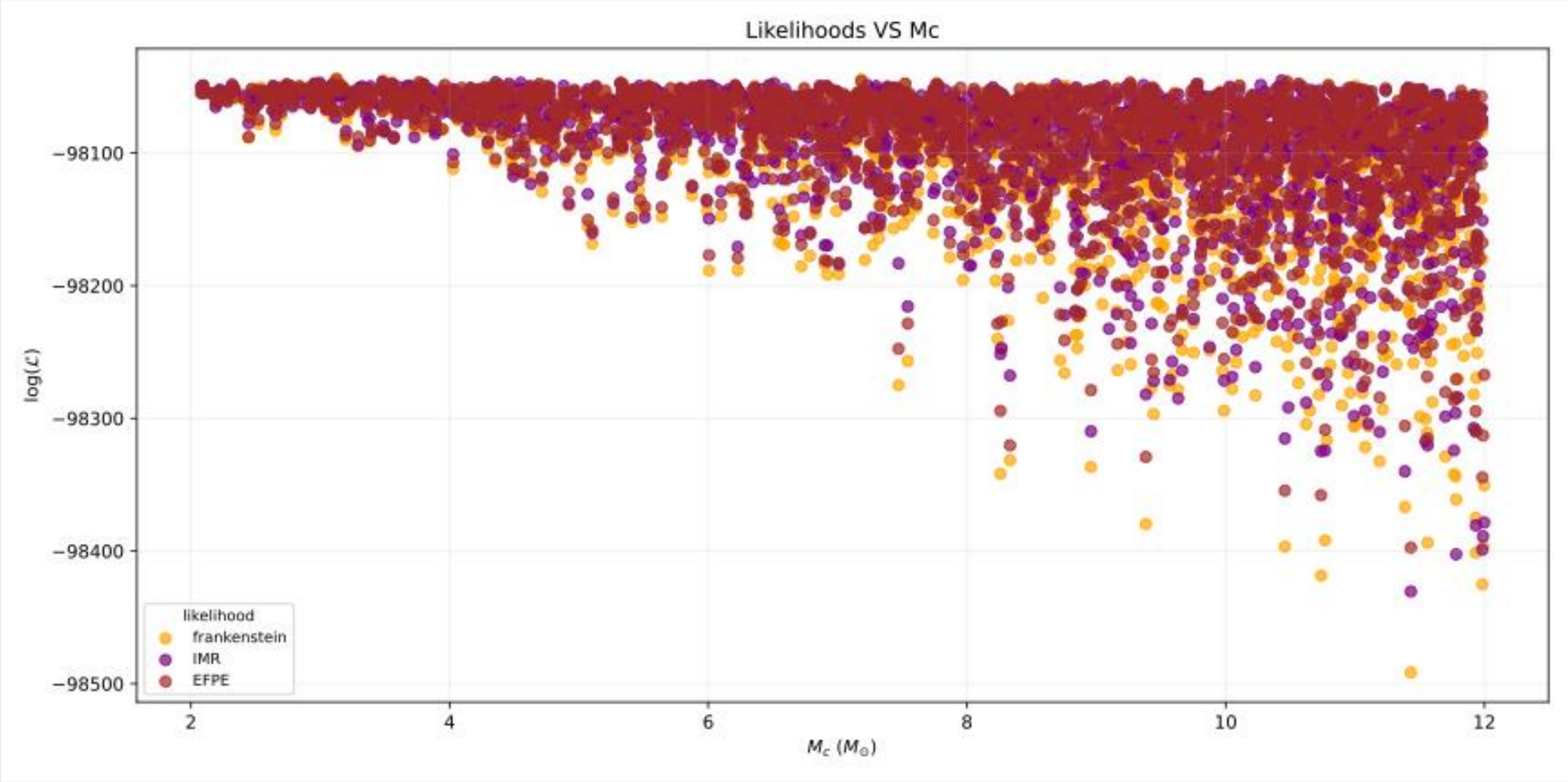
- A large amount of the frequency range has model $\mu = 0$ for BBH
- $\mathcal{L}(\mathrm{d}_1 \mid \mathcal{M}_\mathrm{c})$ - BBH data set, inspiral only model



The problem of inspiral-only waveform models

- **For lighter binaries** – in the same frequency range, we have only inspiral data, and only inspiral model…

- $\mathcal{L}(\mathrm{d}_2 \mid \mathcal{M}_\mathrm{c})$ - BNS data set, inspiral only model



Possible solutions

1. Cropping the high frequency content of the data (questionable approach)

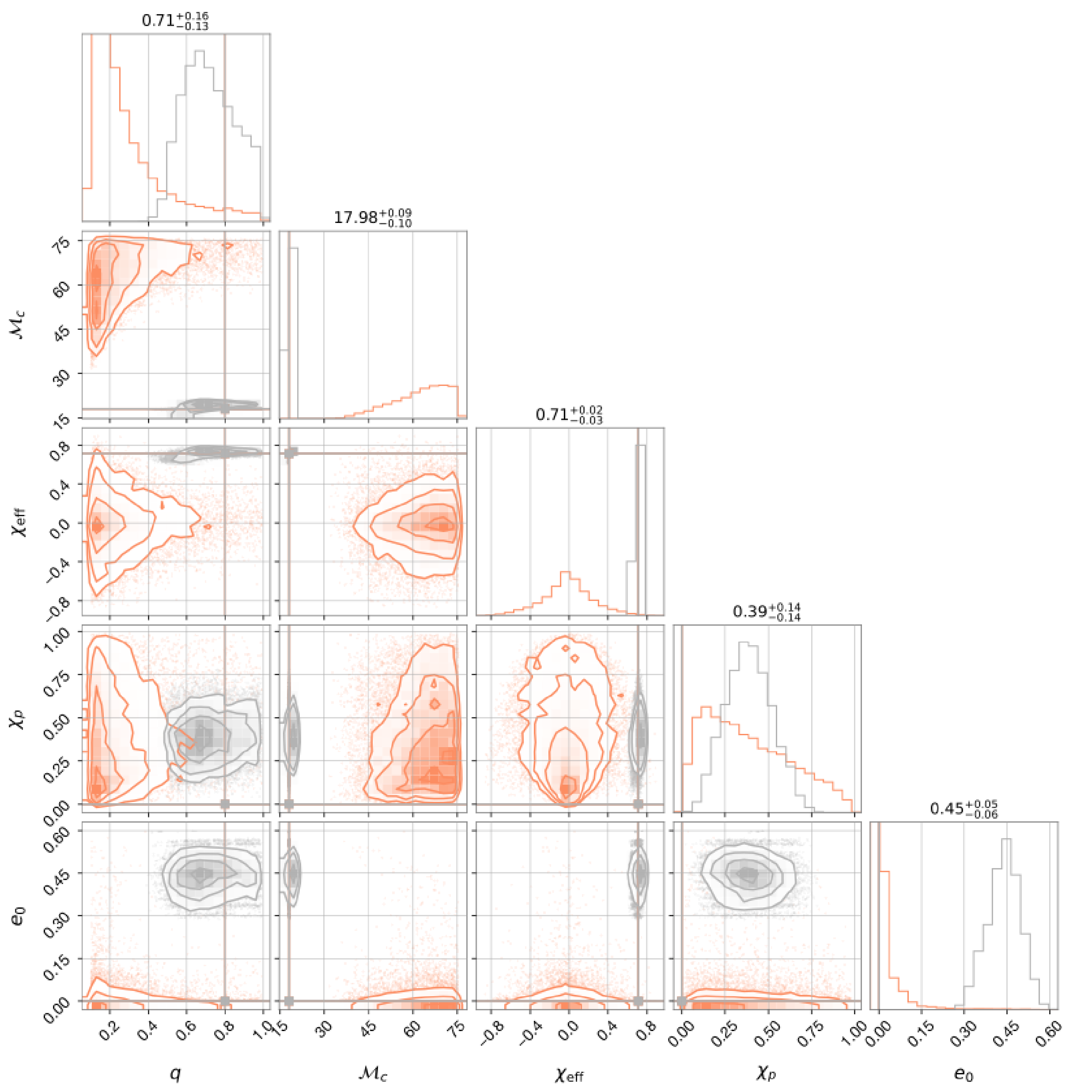
2. “Patching” a similar but non eccentric waveform to analyze the merger-ringdown part of the signal (to be determined, biased results?)

3. “Patching” a non physical model (spline) (to be determined, model complexity?)

Preliminary results

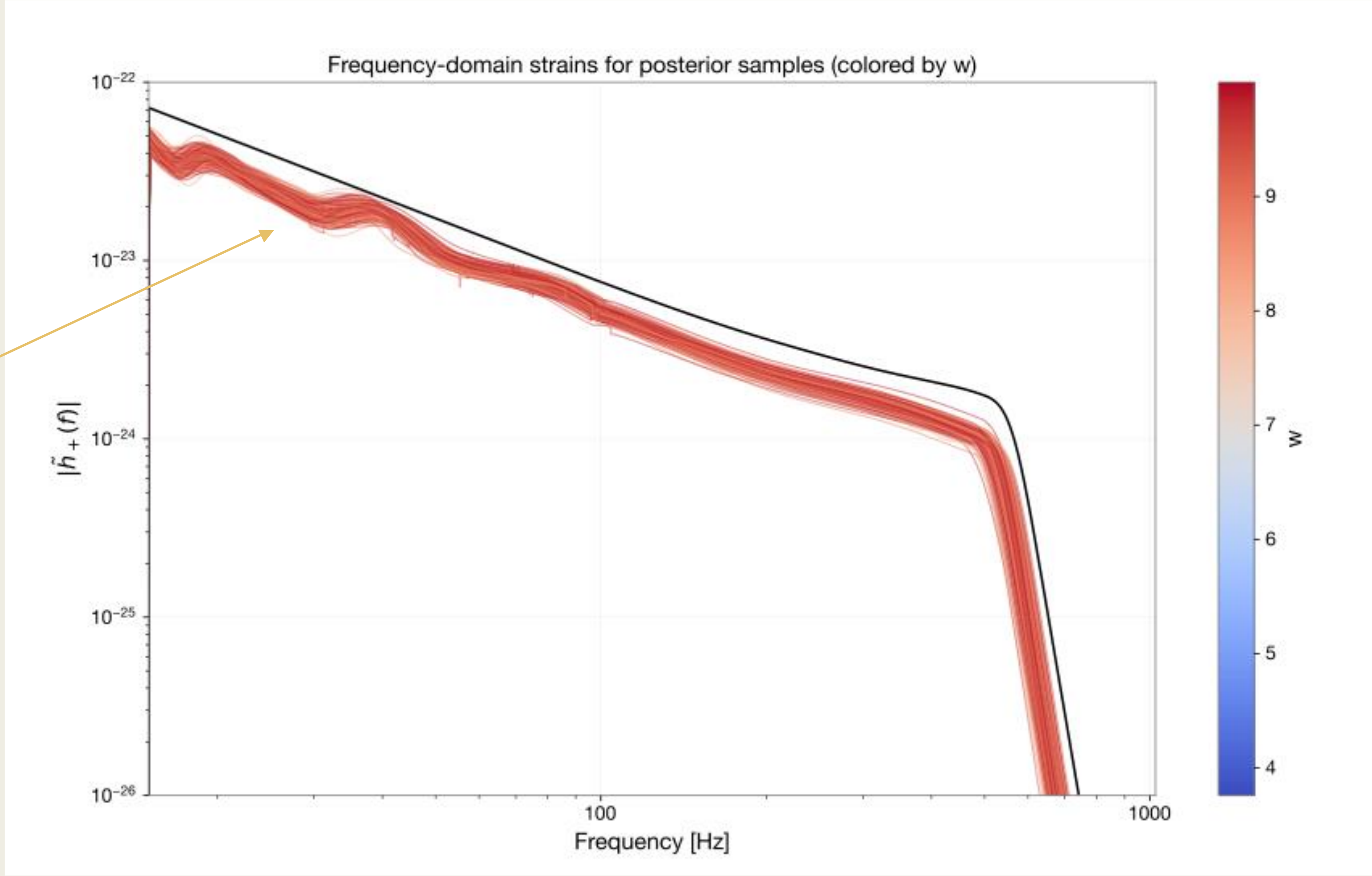
- Patching a precessing (non eccentric) waveform to our waveform model for the Merger-Ringdown part of the signal

- Biased results - common inspiral-merger-ringdown parameters are extremely different from the inspiral parameters of the inspiral + merger ringdown model



Preliminary results – bad news

- Inspiral model seems to prefer precessing dynamics



HOPEFULLY, MORE AND BETTER RESULTS TO COME …

Conclusions

- Eccentricity is smoking gun evidence of dynamical formation of binary black holes

- It's very hard to measure it in GW signals (for several other reasons, but):
  - *We can have IMR (inspiral-merger-ringdown) + only eccentric analysis*
  - *We can have IMR + only precessing analysis*
  - *We can have eccentric + precessing but no MR analysis*

- Attempts have been and are being made, but so far there has not been an eccentricity claim on a BBH signal that direct tackled of the eccentricity – spin precession degeneracy

THANK YOU!