Title: Singing and dancing with black holes

Speakers: Vishal Baibhav

Series: Strong Gravity

Date: December 14, 2023 - 1:00 PM

URL: https://pirsa.org/23120052

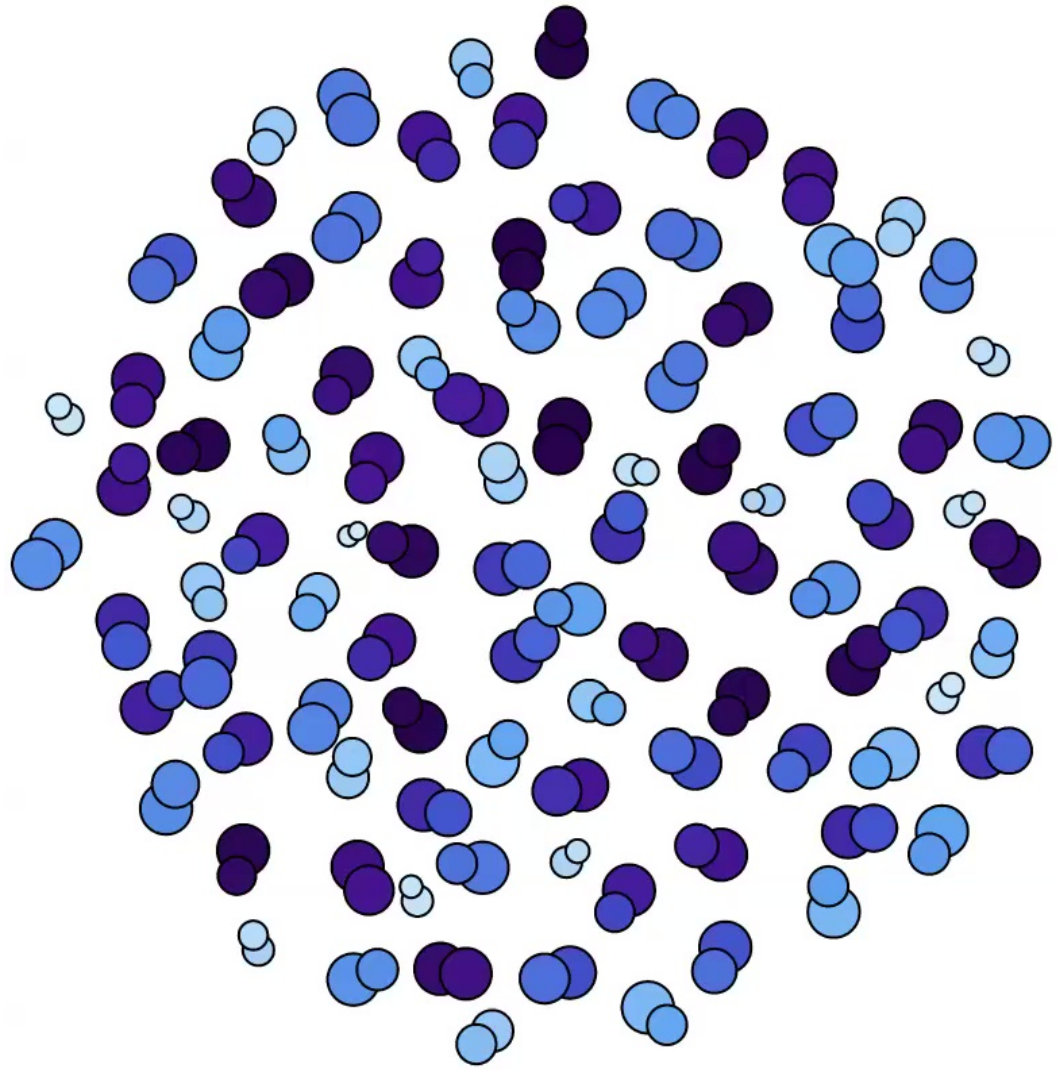
Abstract: Gravitational waves have uncovered a treasure trove of nearly 90 merging black holes and neutron stars, each with its own unique story to tell. In the first part of the talk, our focus will center on black hole spins, seeking to decipher the secrets hidden within, including their origins, hometowns, and the forces driving their mergers. We will challenge the belief that isolated binary black holes should have spins aligned with orbital angular momentum. We will explore the mechanisms influencing these spins, from their origins to the forces driving their mergers.

Zoom link https://pitp.zoom.us/j/95680635803?pwd=Yll6NjFPbmpMZ1lTS0JtdUp6dG1RZz09

Dancing with Black Holes

Vishal Baibhav
Vicky Kalogera, Emanuele Berti, Sharan Banagiri,
Davide Gerosa, Matthew Mould, Thomas Helfer, Kaze Wong

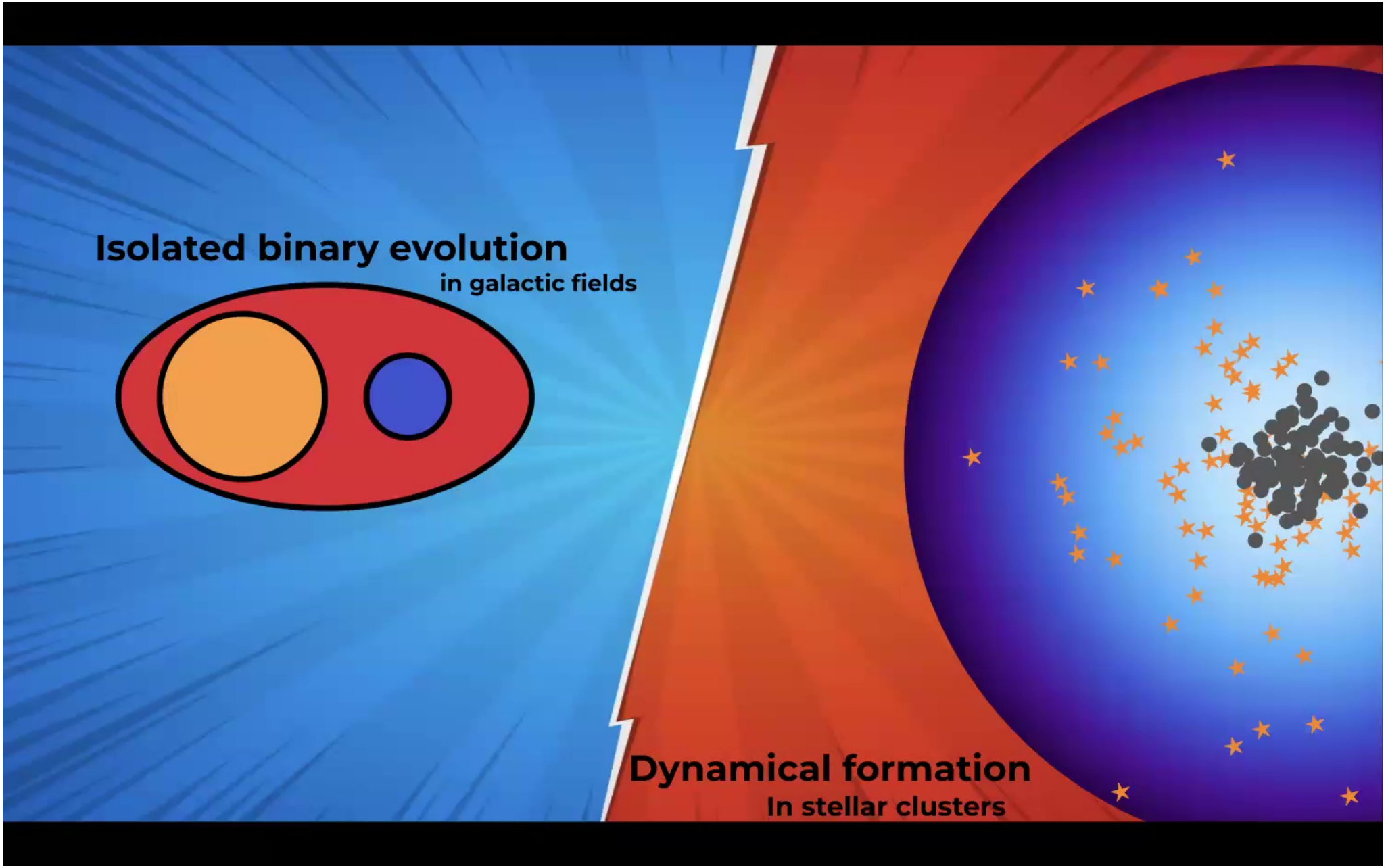
CIERA
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS
Northwestern



LIGO-Virgo-Kagra have detected

90 mergers

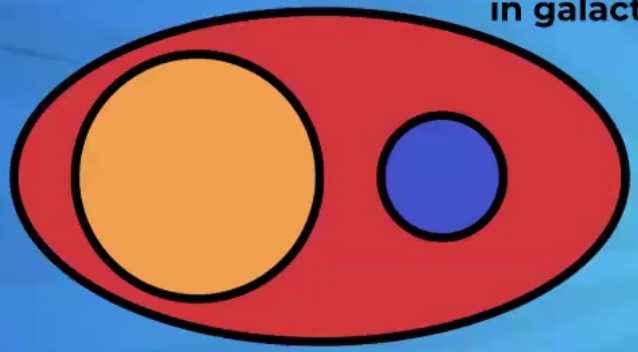
involving black holes and neutron stars


Isolated binary evolution
in galactic fields
Dynamical formation
In stellar clusters


Masses
Redshift
Eccentricity
Spins

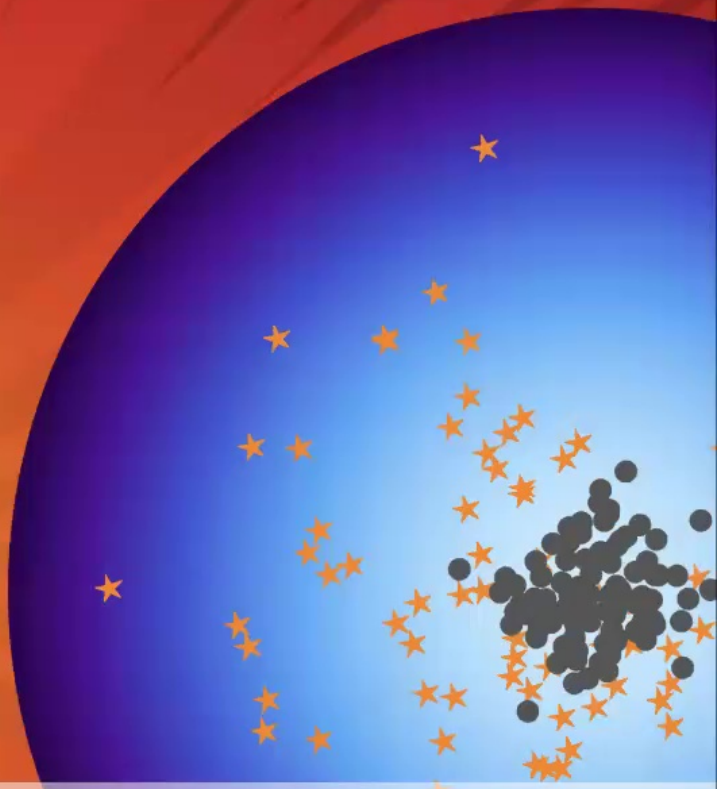
Part I: OUTLINE

Isolated binary evolution
in galactic fields

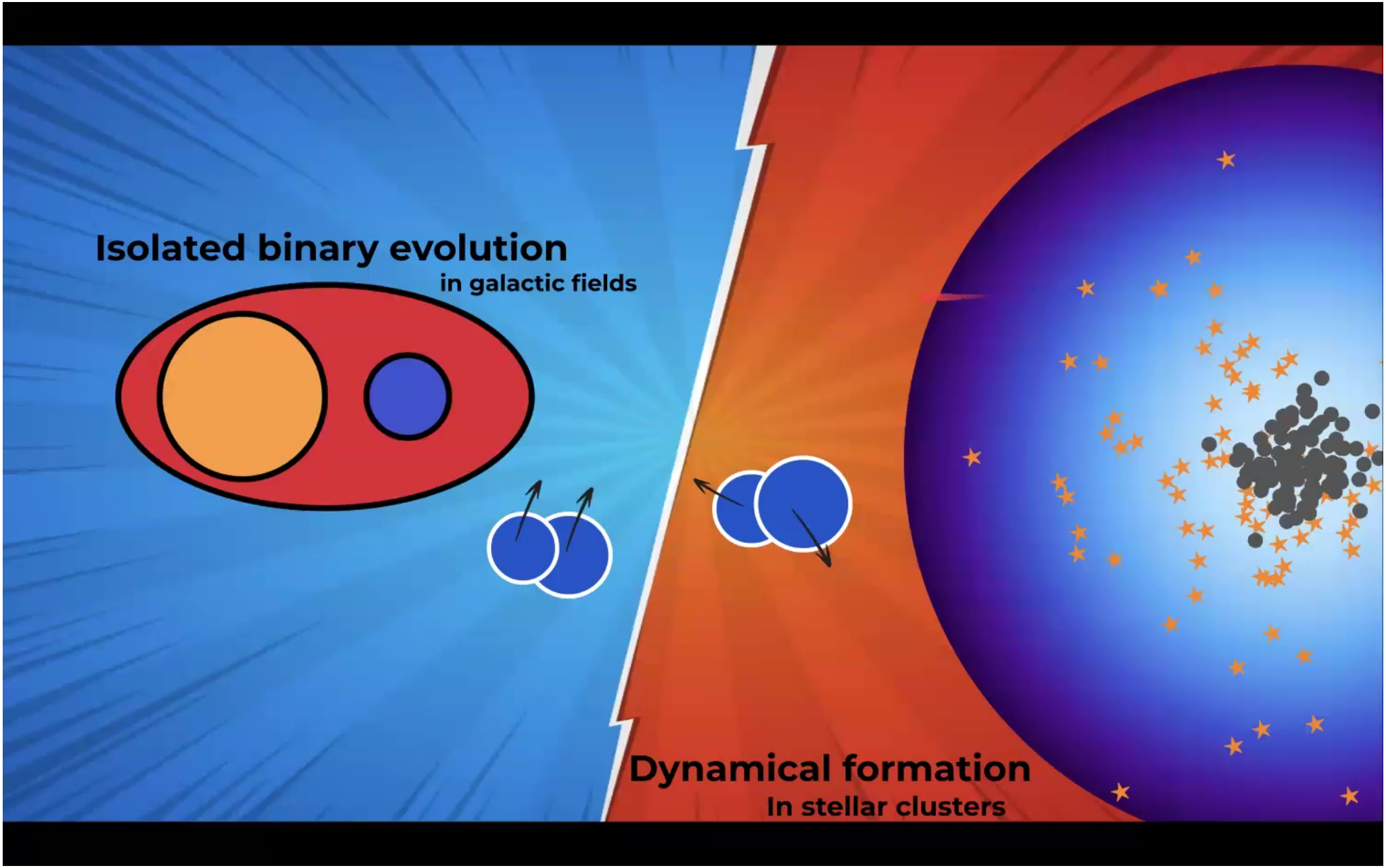


Which came first? Black spin or supernova kick
Lessons from LMXBs and Young pulsars
BBHs that would have been impossible
Insights from BBH population

Dynamical formation
In stellar clusters



Parents and Hometown of Repeated Mergers
Spin Gap & GW190521
Parents of GW190412


Isolated binary evolution
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Dynamical formation
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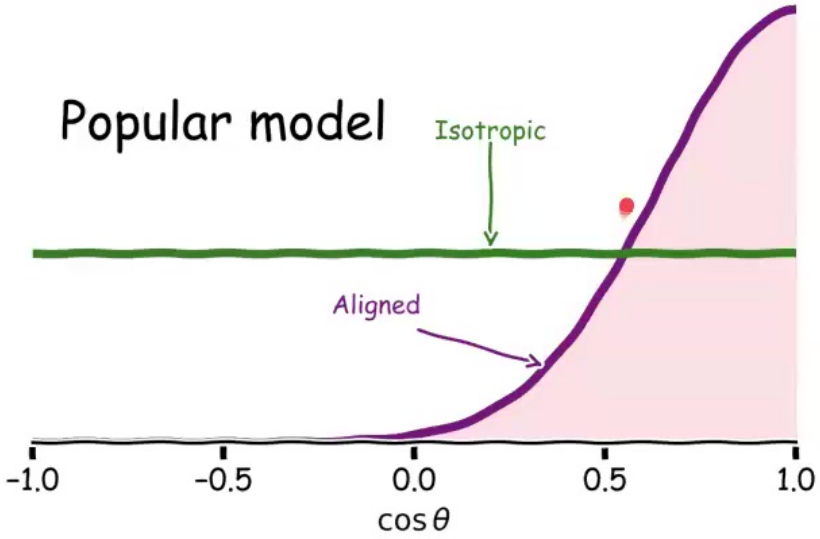
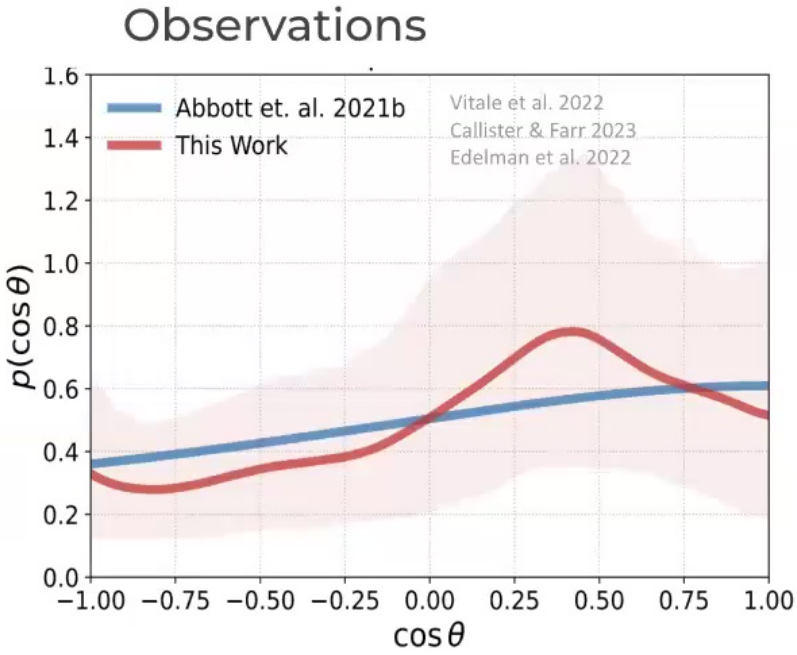
Conclusion

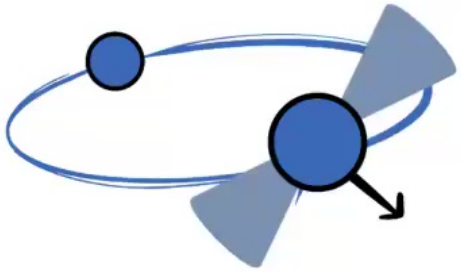

Only dynamical environments can
produce highly misaligned binaries

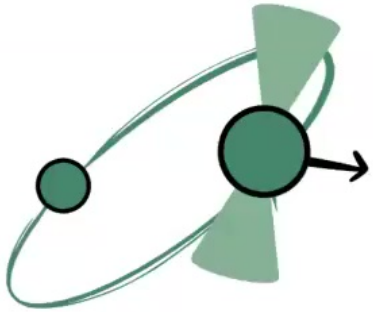

NO





Problem 1. GW observations do not support the popular theory





PSR J0737-3039:	130 ± 1°	Breton et al. 2008
PSR J1906+0746:	104± 10°	Desvignes et al. 2019
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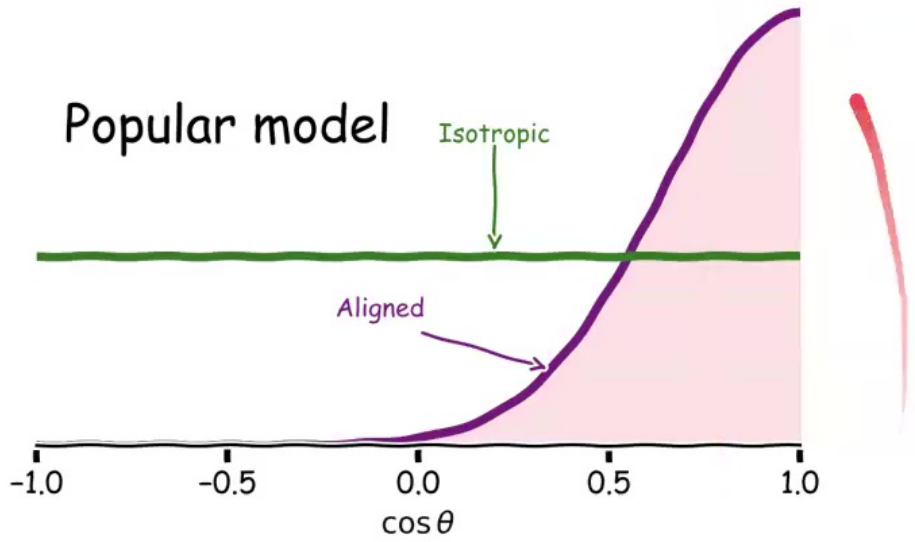
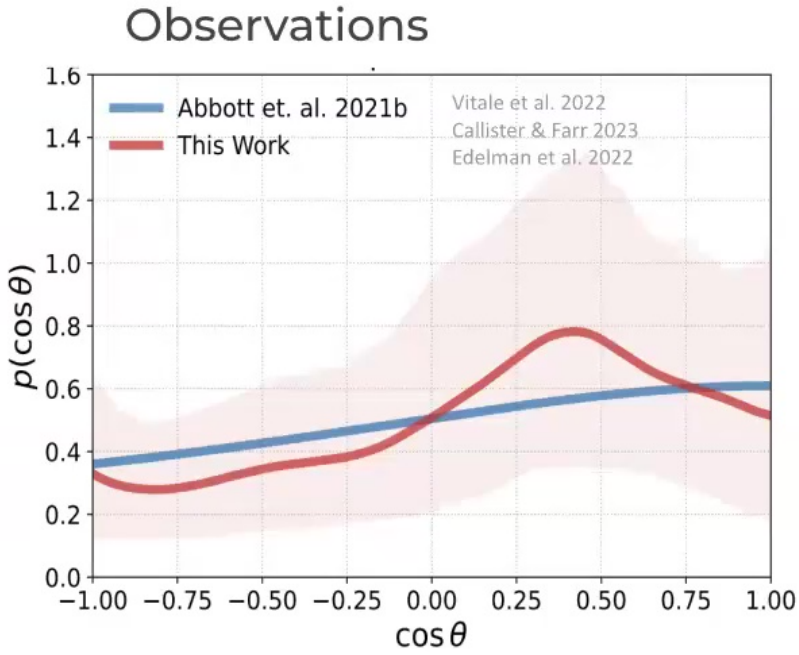
MAXI J1820+070:	42°, 63°, 117°, 138°	Poutanen et al. (2022)

Problem 2. EM observations do not support the popular theory





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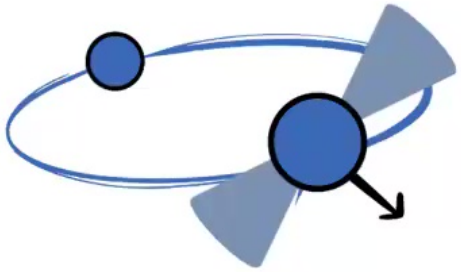

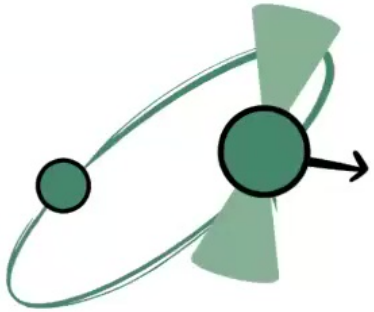

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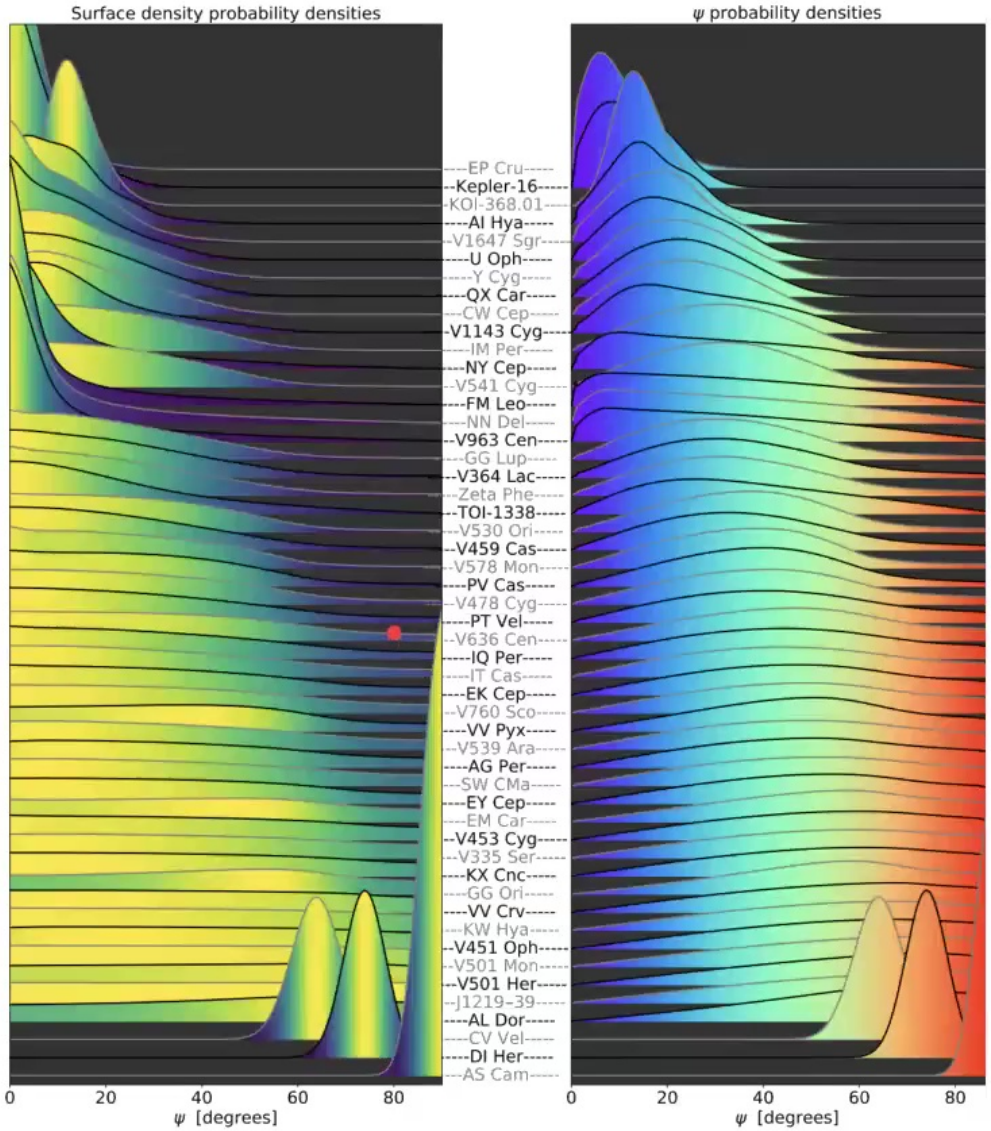
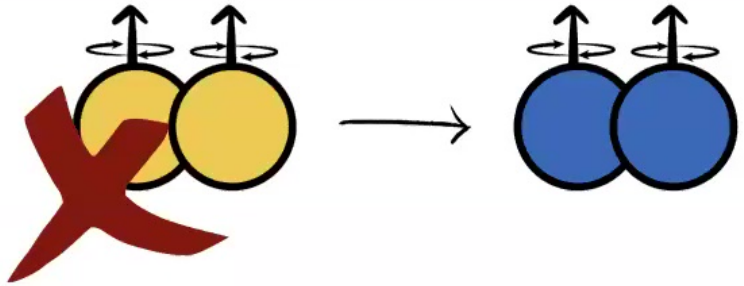


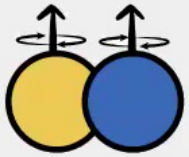


BANANA Project

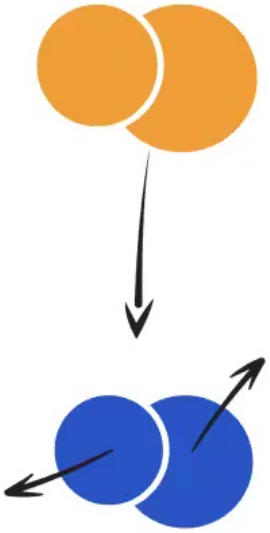
Binaries Are Not Always Neatly Aligned

Albrecht+ 2010
Albrecht+ 2012
Albrecht+ 2014
Marcussen, Albrecht. 2021

1. Natal spins



2. Isotropic spins



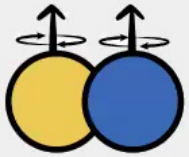
When black holes don't inherit spins from the star:

internal gravity waves, accreting convective layers, SASI

Fuller et al 2014
McNeill Muller 2020
Antoni, Quataert 2021, 2023

See Tauris 2022

1. Natal spins



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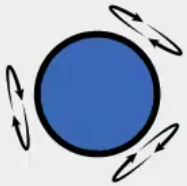
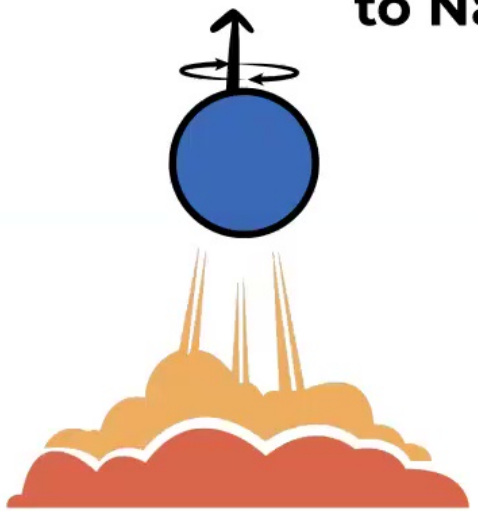


3. Spin parallel to Natal Kick



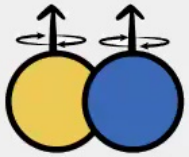
Pulsar observations

Johnston et al. 2005
Ng & Romani 2007
Noutsos et al. 2012, 2013

Hydrodynamical mechanisms

Janka et al 2021

1. Natal spins



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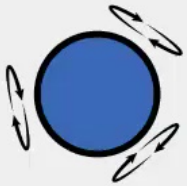

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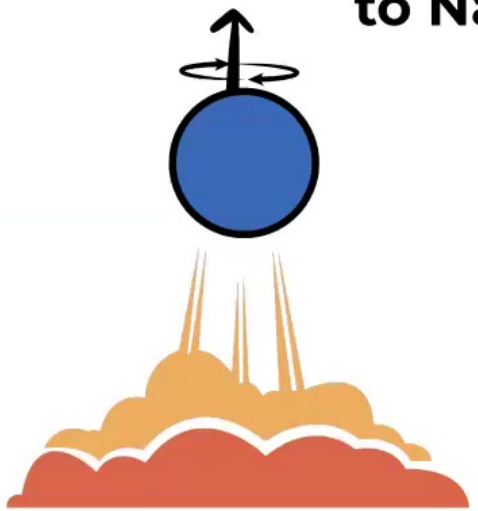

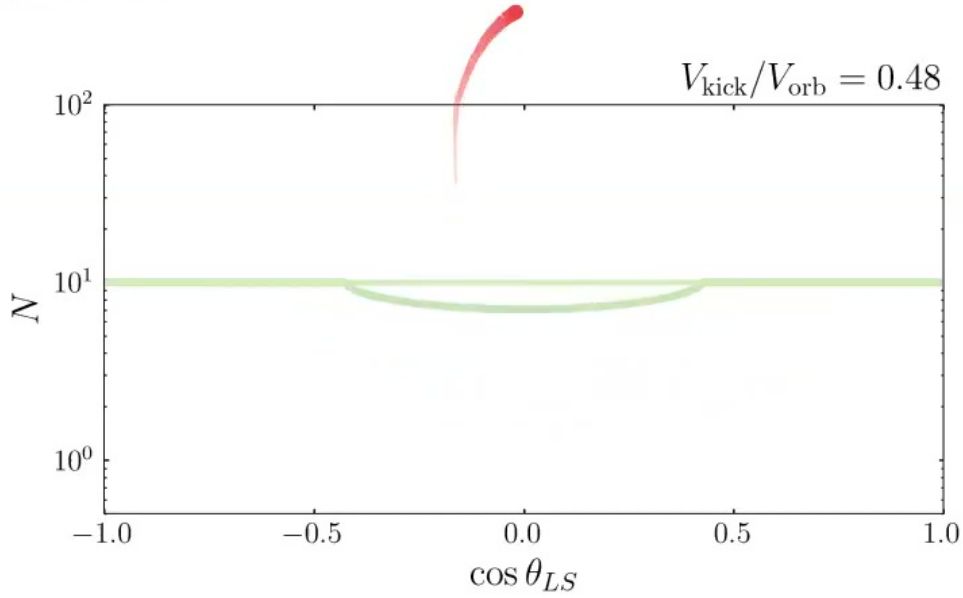

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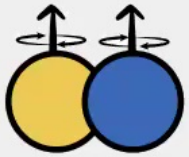
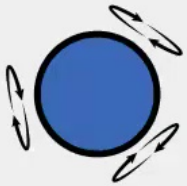


2. Isotropic spins



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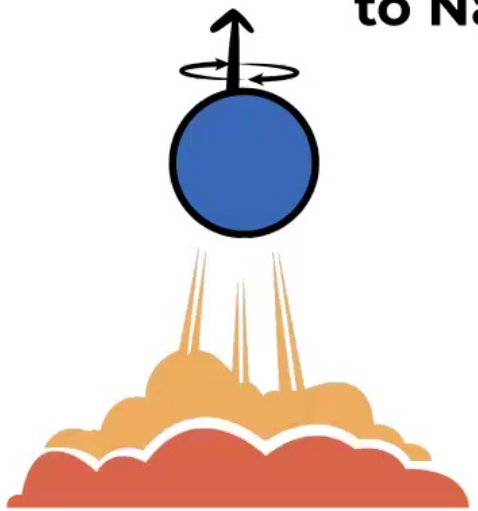

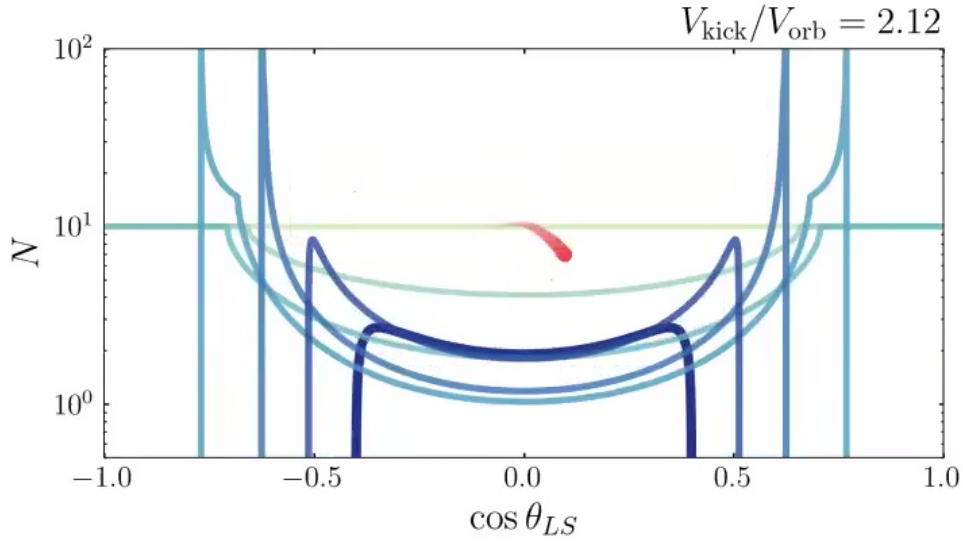

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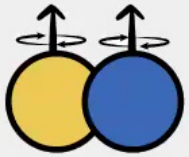

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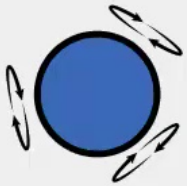
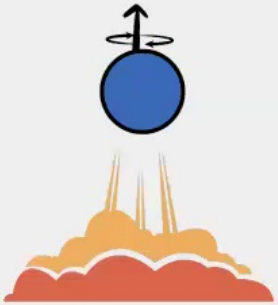
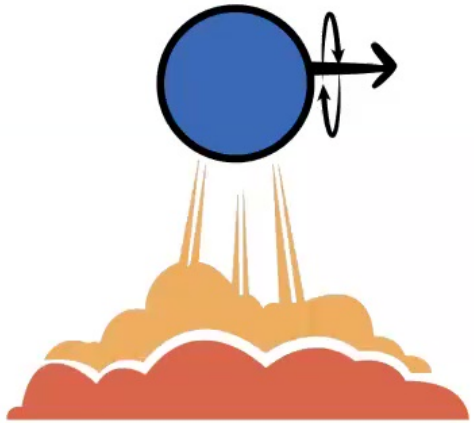


3. Spin ll Kick

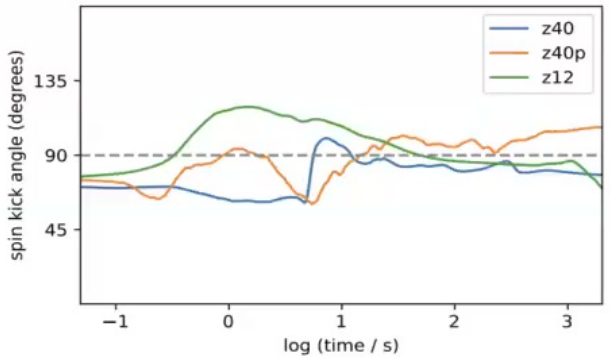


4. Spin perpendicular to Natal Kick

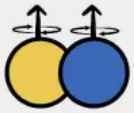


Off-center explosions, Asymmetric fallback of ejecta

- Phinney Spruit 1998
- Farr et al 2011
- Muller et al 2018
- Chan Muller Heger 2020

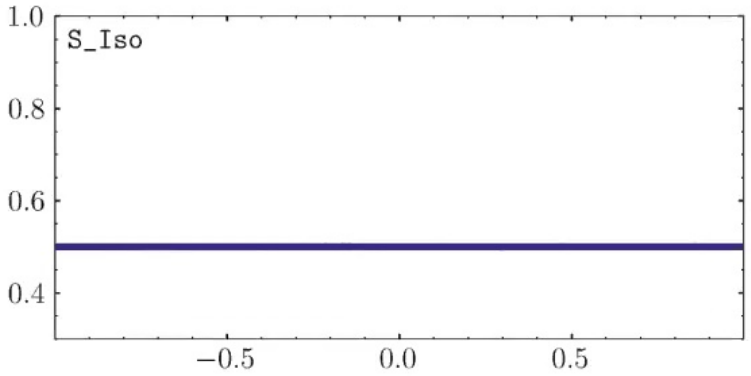


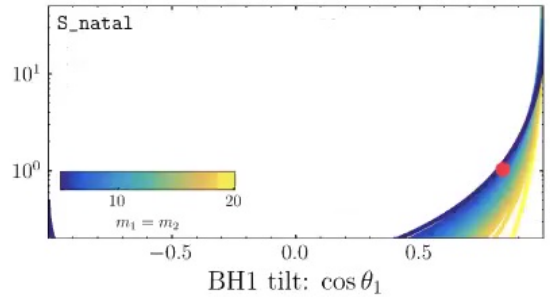
How spin mechanisms shape
spin-orbit tilt Distribution

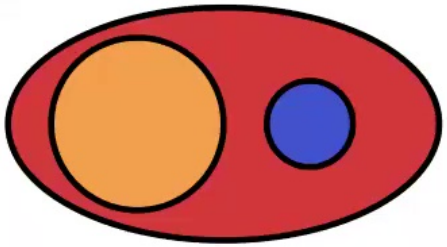


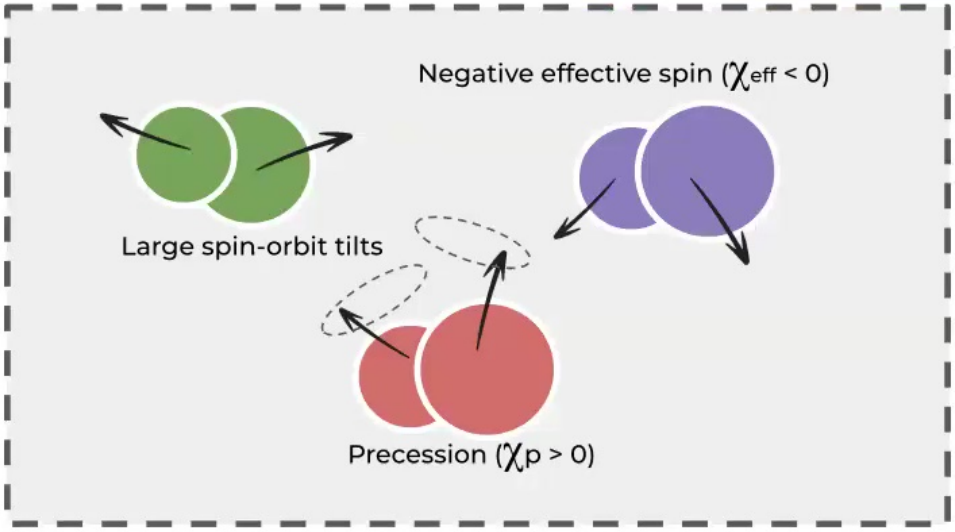
Isotropic spins

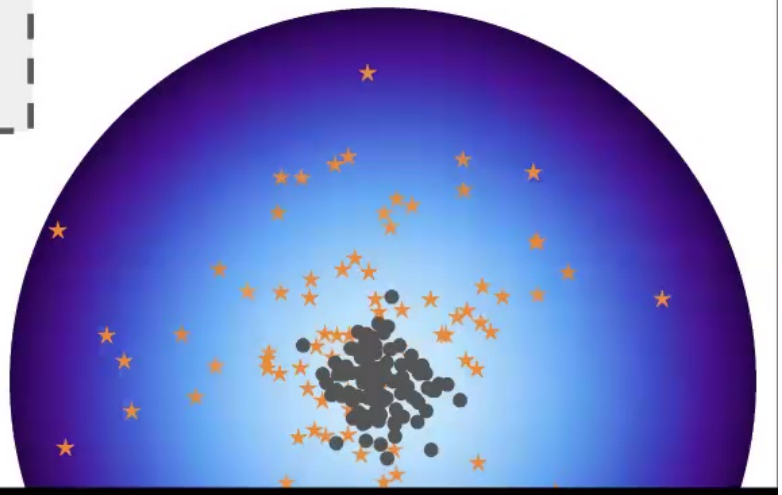
Natal spins



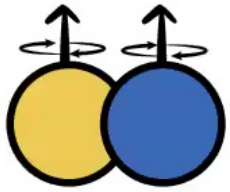





Negative effective spin ($\chi_{eff} < 0$)
Large spin-orbit tilts
Precession ($\chi_p > 0$)

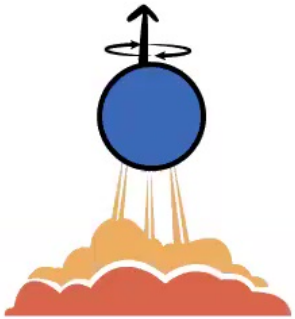


GW191109_010717



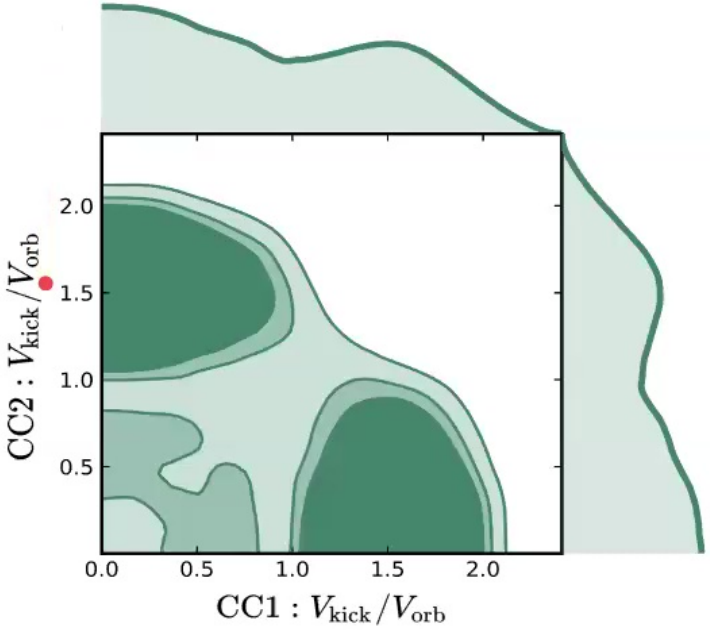
Natal spins

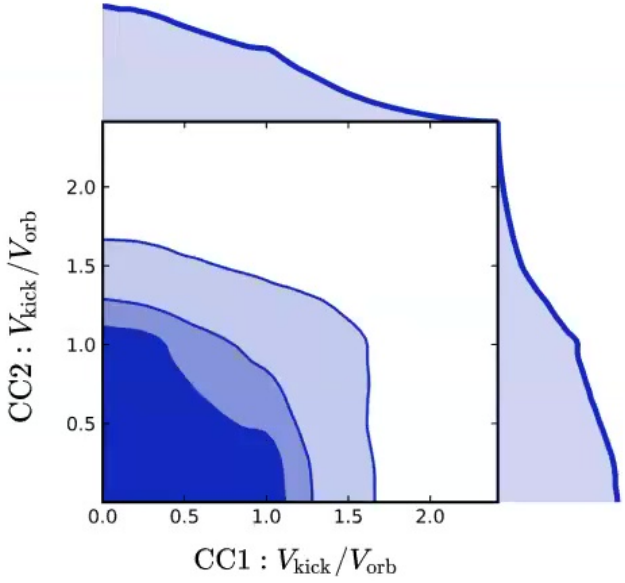
Need large natal kicks to explain large misalignments

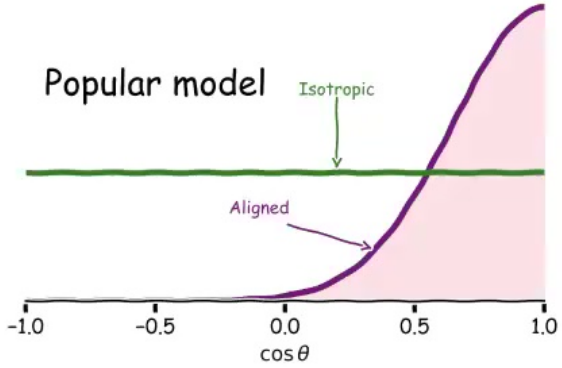


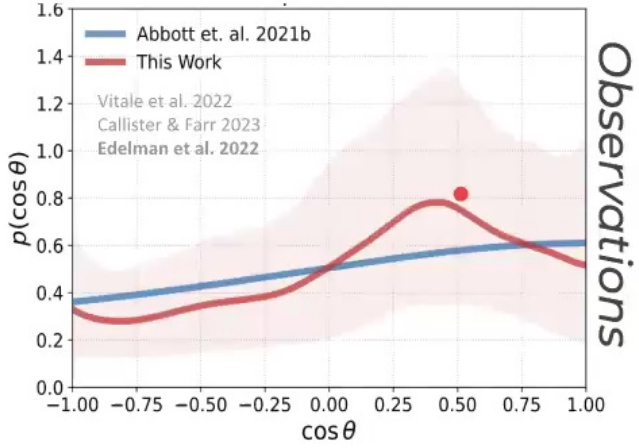
Spin parallel to kicks

large natal kicks are not required

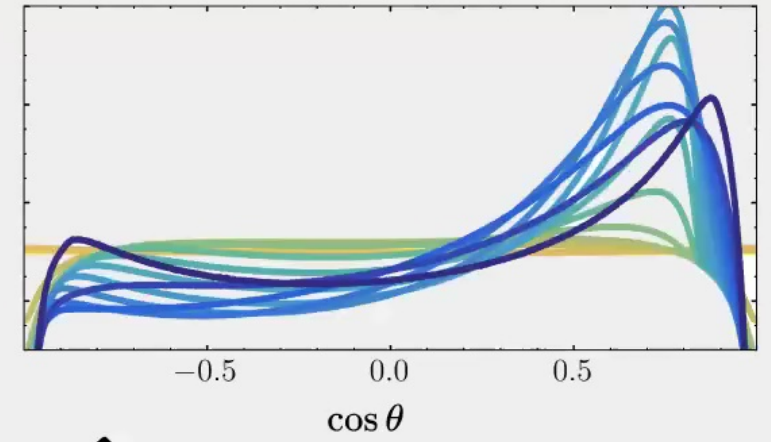


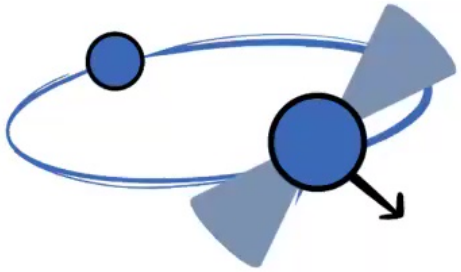


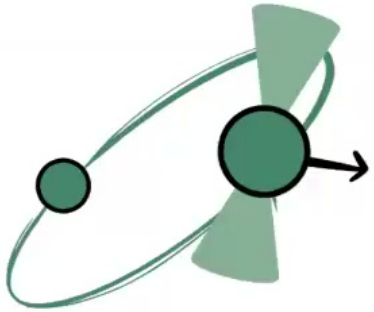




Problem 1. GW observations do not support the popular theory







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What can we learn from young pulsar in binaries or LMXBs?

Problem 2. EM observations do not support the popular theory

Do black holes and neutron stars
really **inherit the spins from stars?**

observations say otherwise.....

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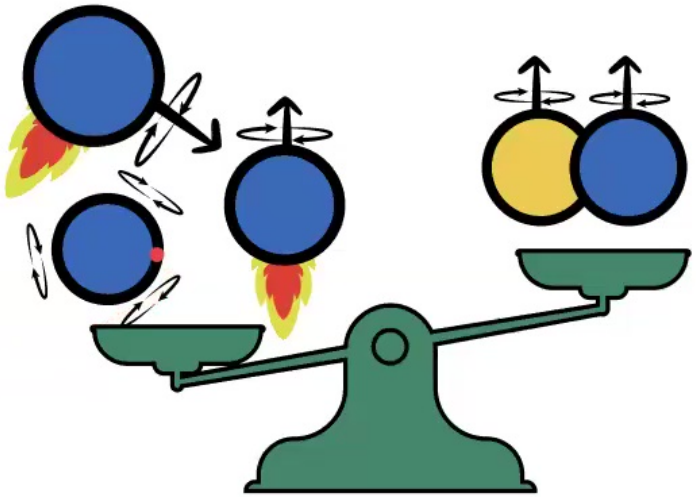
PSR J1141−6545:	38°± 13 , 150± 20°	Krishnan al. (2019)
MAXI J1820+070:	>40°	Poutanen et al. (2022)

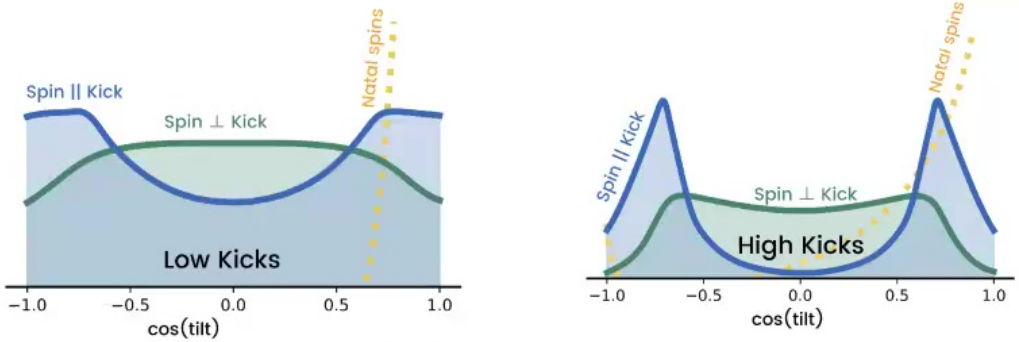


Natal spin model is disfavored with a

Bayes factor >10

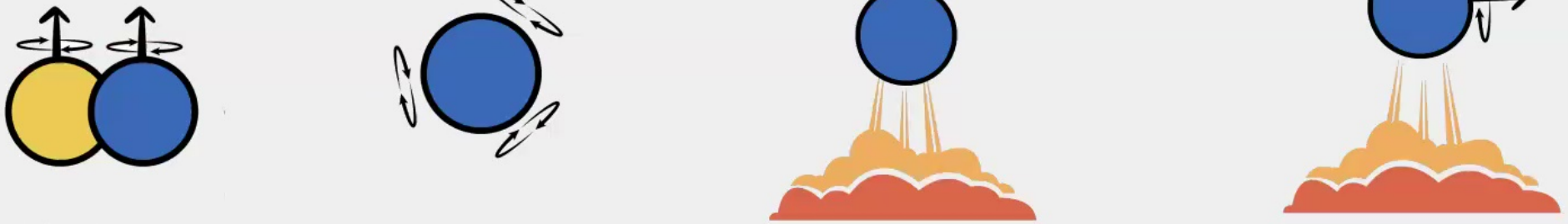
Problem 2. EM observations do not support the popular theory

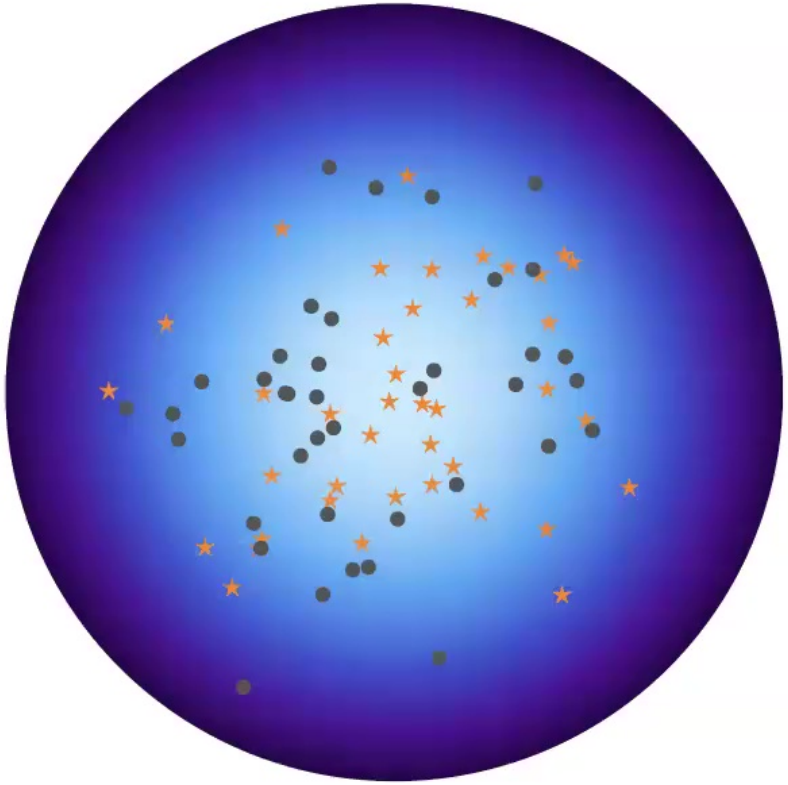
RECAP



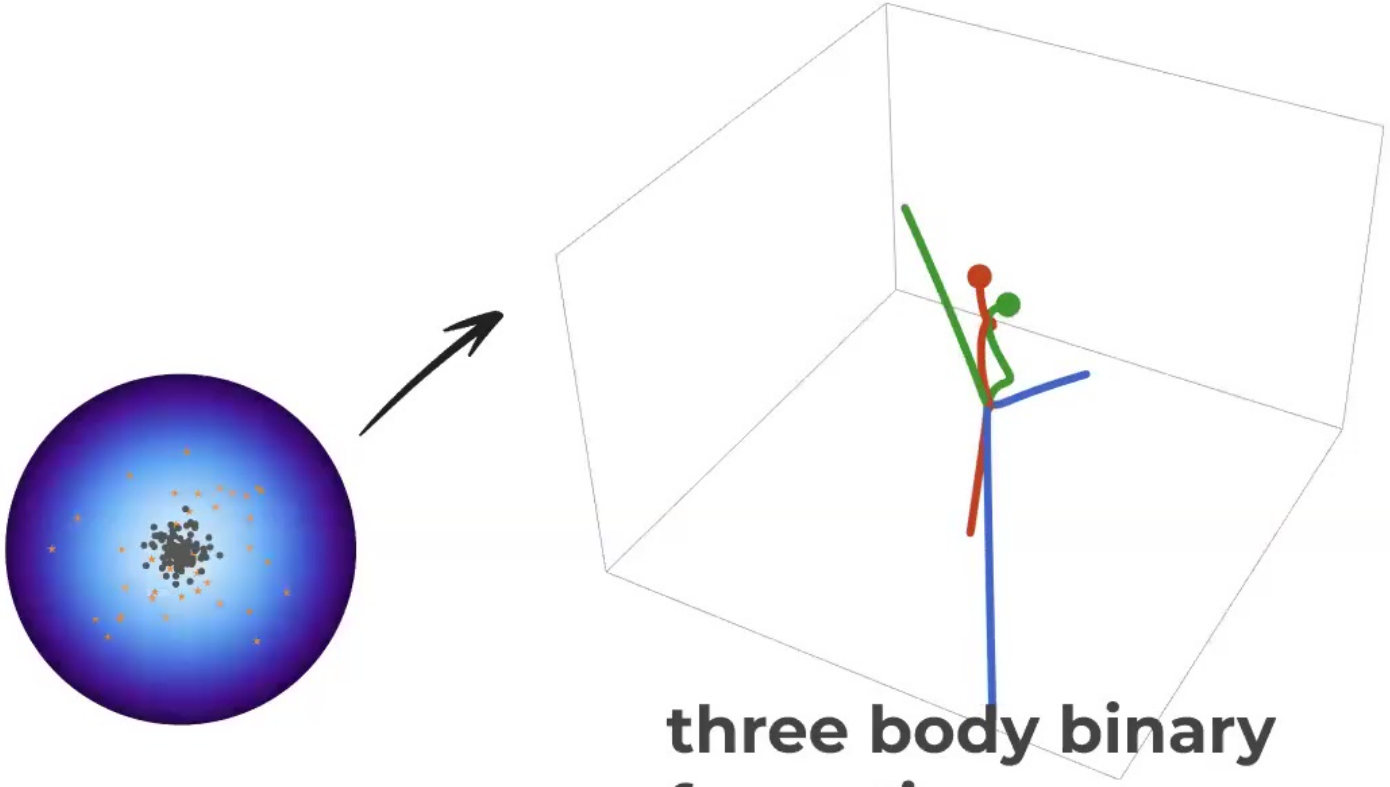
Distribution of spin tilts

Natal spins | Isotropic spins | Spin ∥ Kick | Spin ⊥ Kick



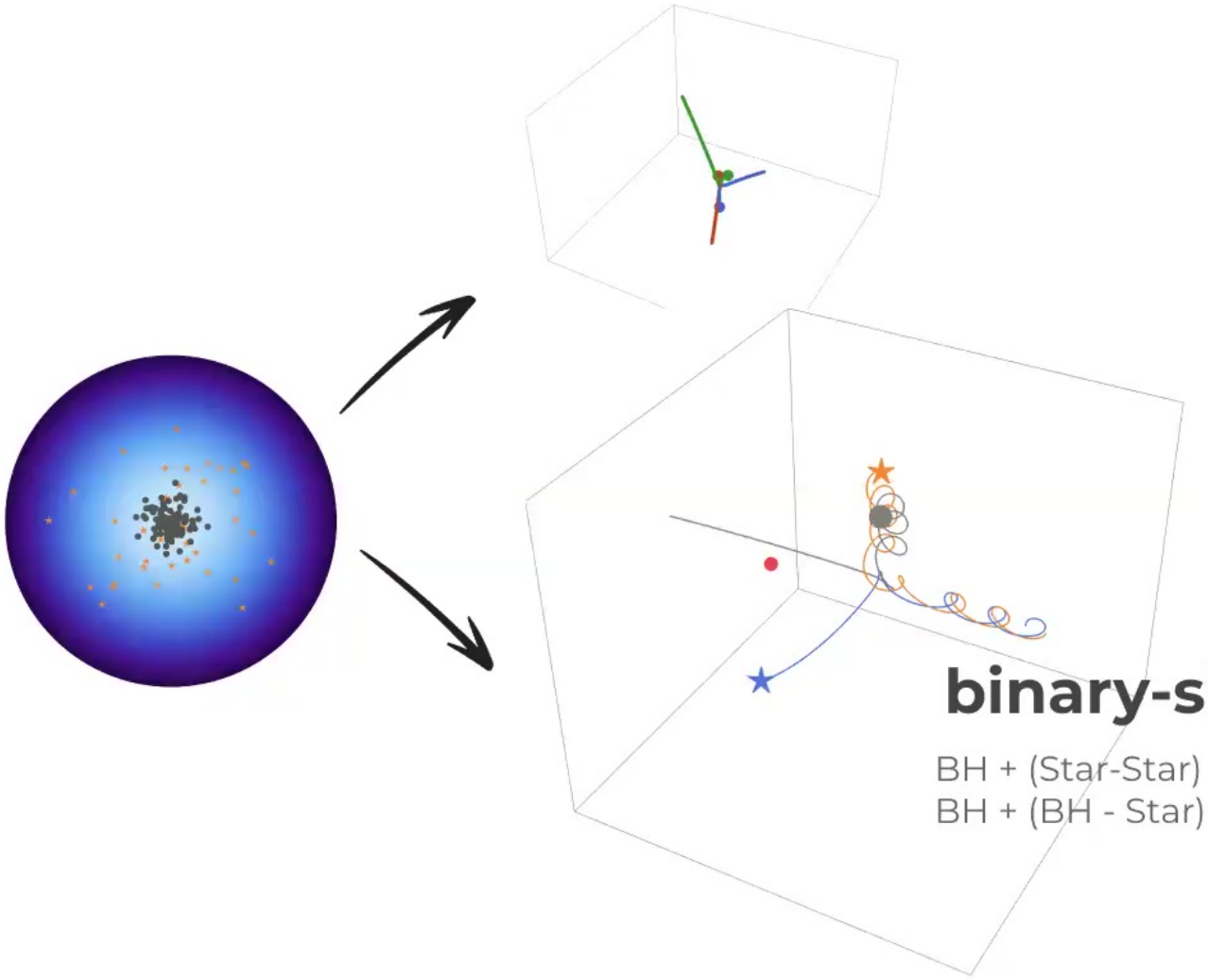


Black hole binary formation in star clusters



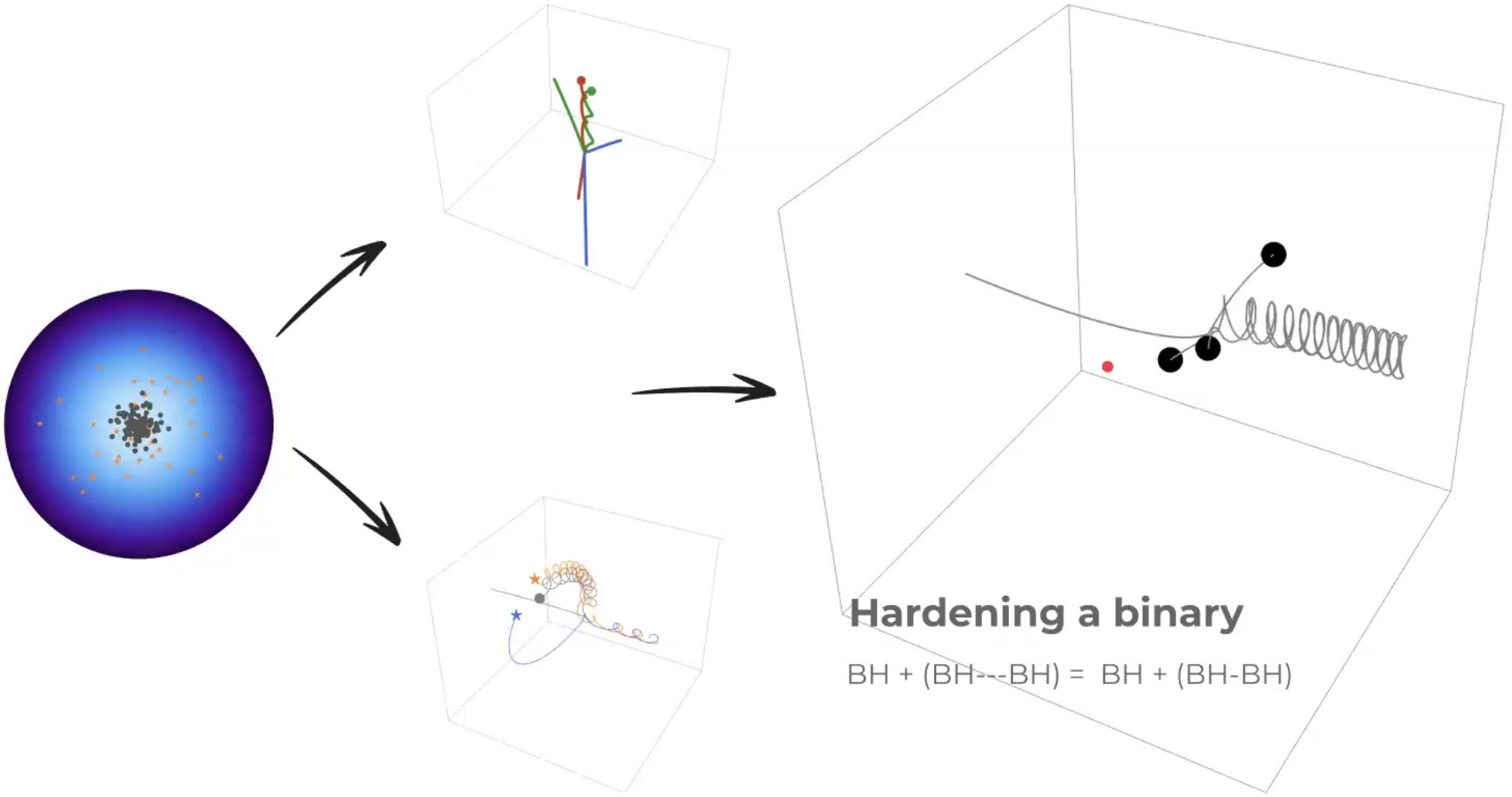
three body binary formation

BH + BH + BH → (BH-BH) + BH

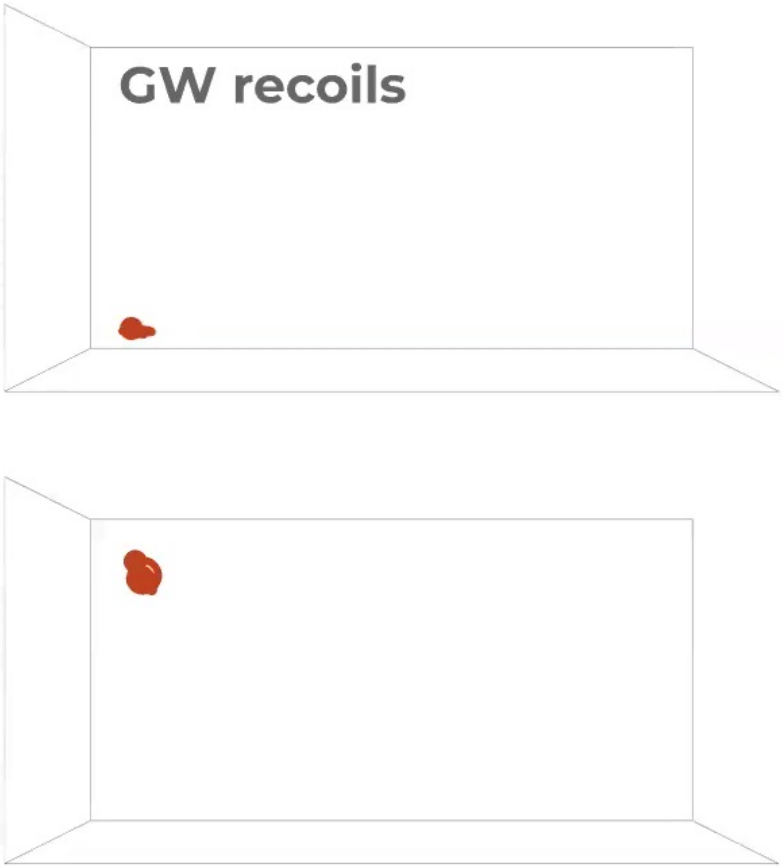


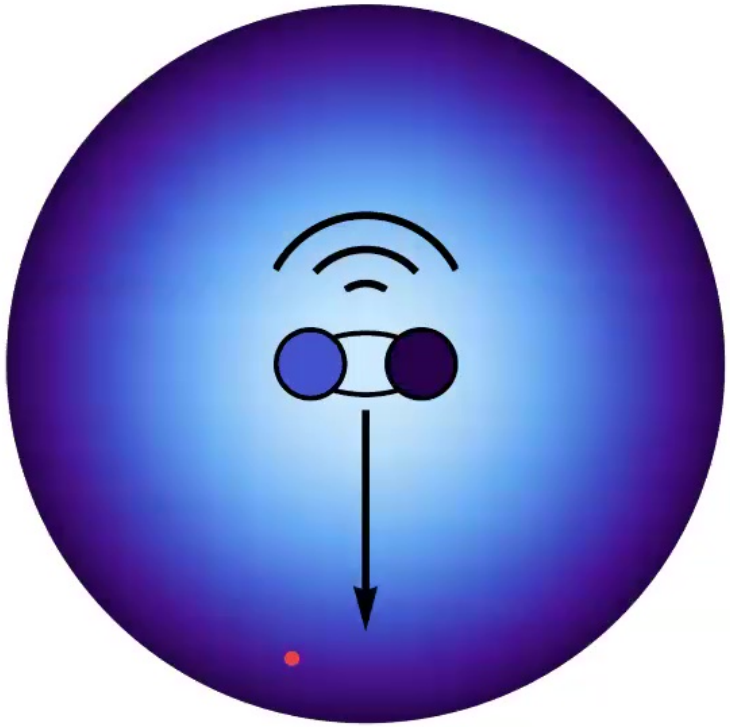
binary-single exchanges

BH + (Star-Star) ⟶ (BH-Star) + Star
BH + (BH - Star) ⟶ (BH-BH) + Star

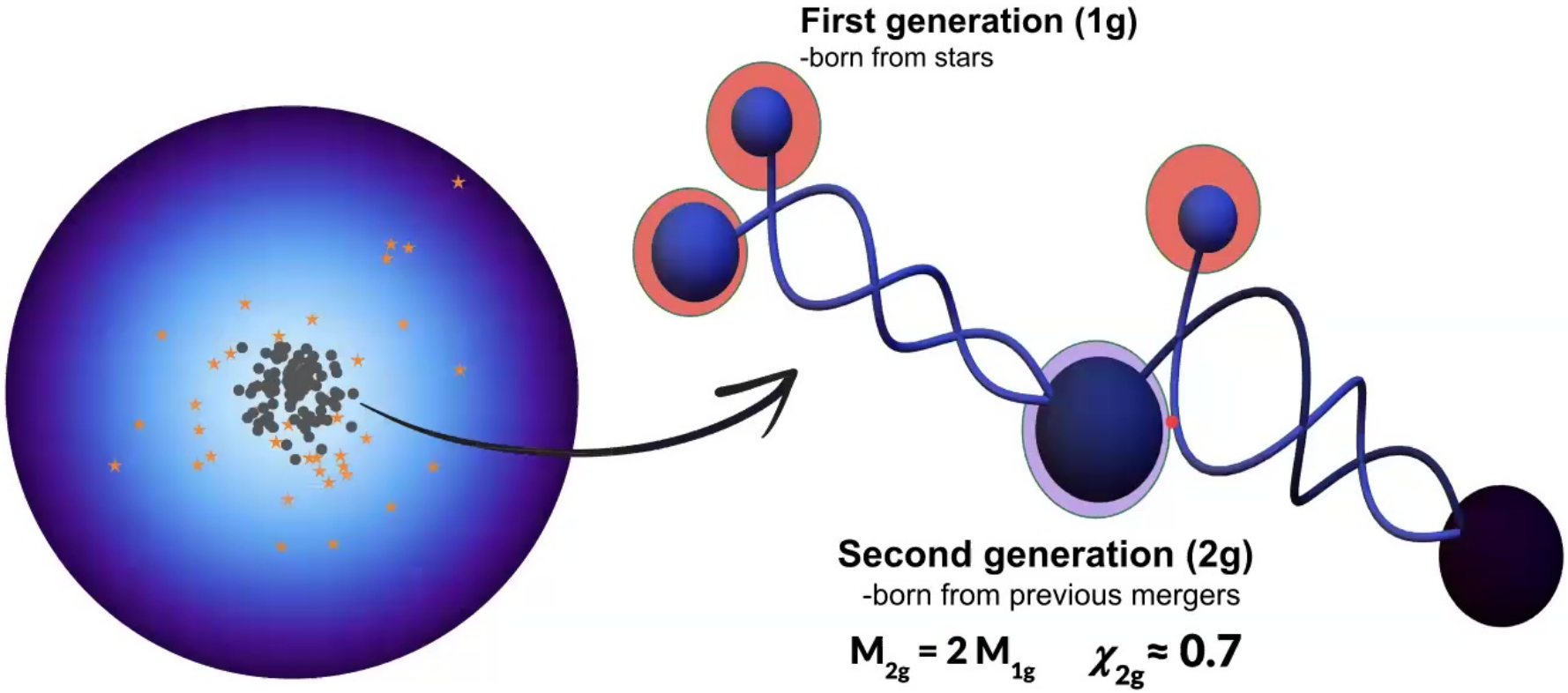

Hardening a binary
BH + (BH---BH) = BH + (BH-BH)

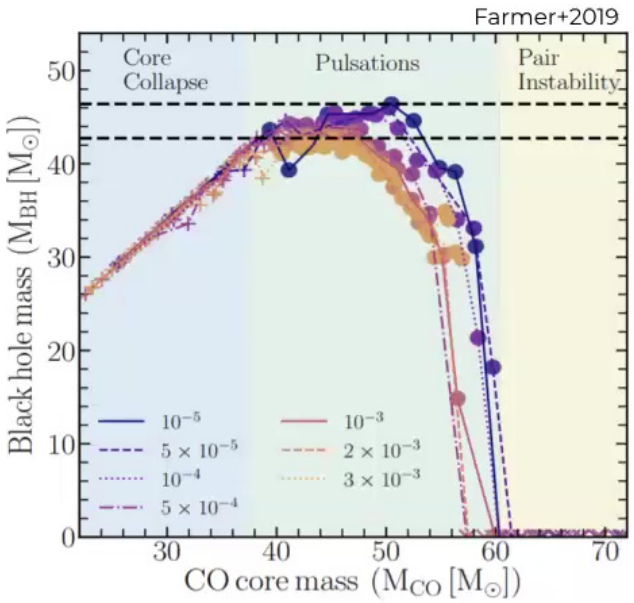
Can clusters retain their BHs?





Repeated mergers in clusters





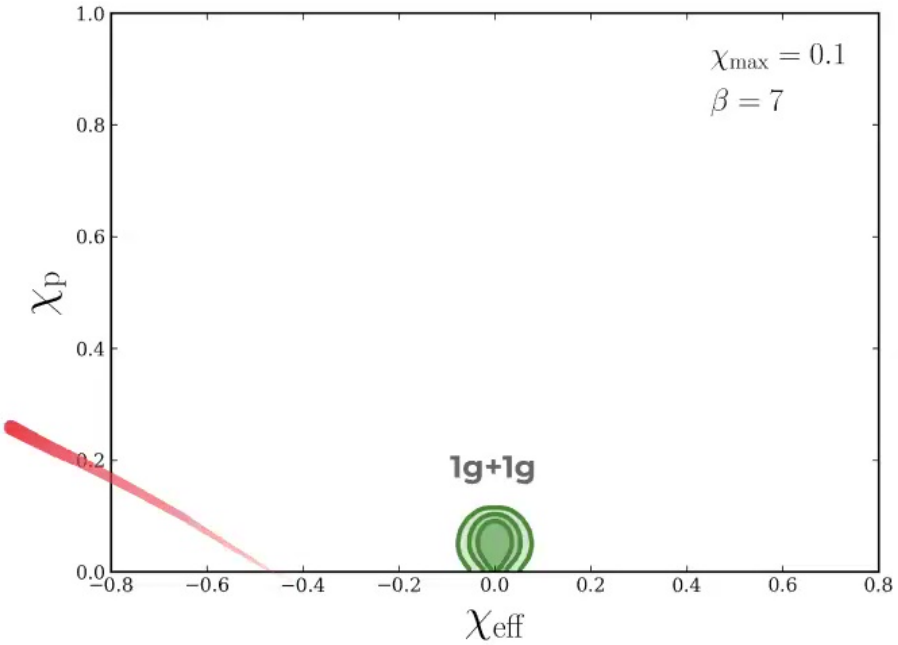
Mass Gap

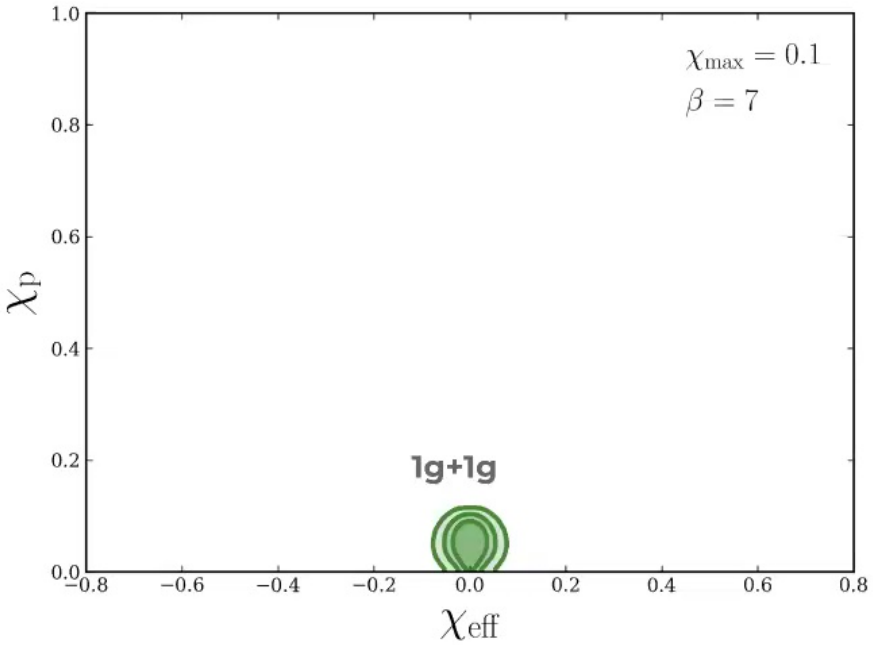
60 – 120 solar masses


GW190521
Mass Gap
60 – 120 solar masses
Black Hole Masses (M_{sun})
160
140
120
100
80
60
40
20
0
Adapted from
LIGO/Caltech/MIT
R. Hurt (IPAC)

Baibhav+ 2021

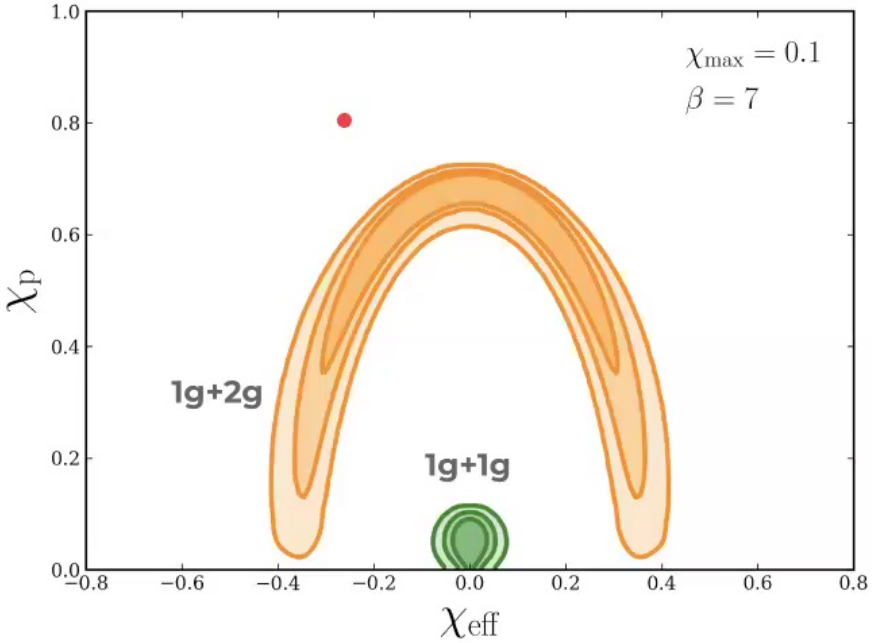
Repeated Mergers can fill the SPIN GAP



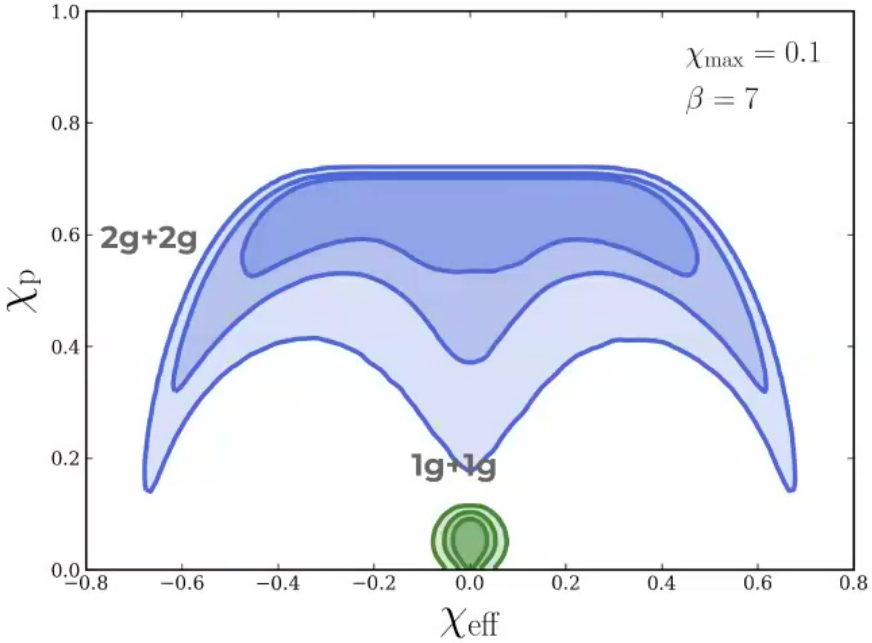


Baibhav+ 2021

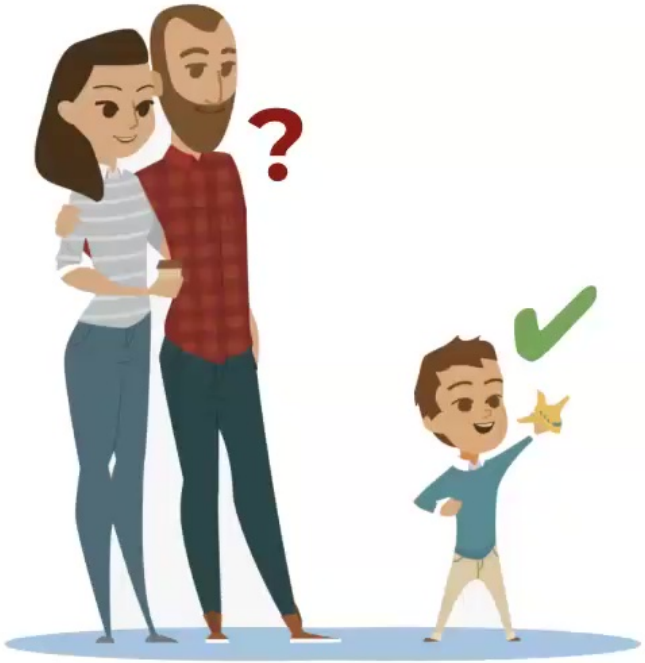
Repeated Mergers can fill the SPIN GAP



1g+2g

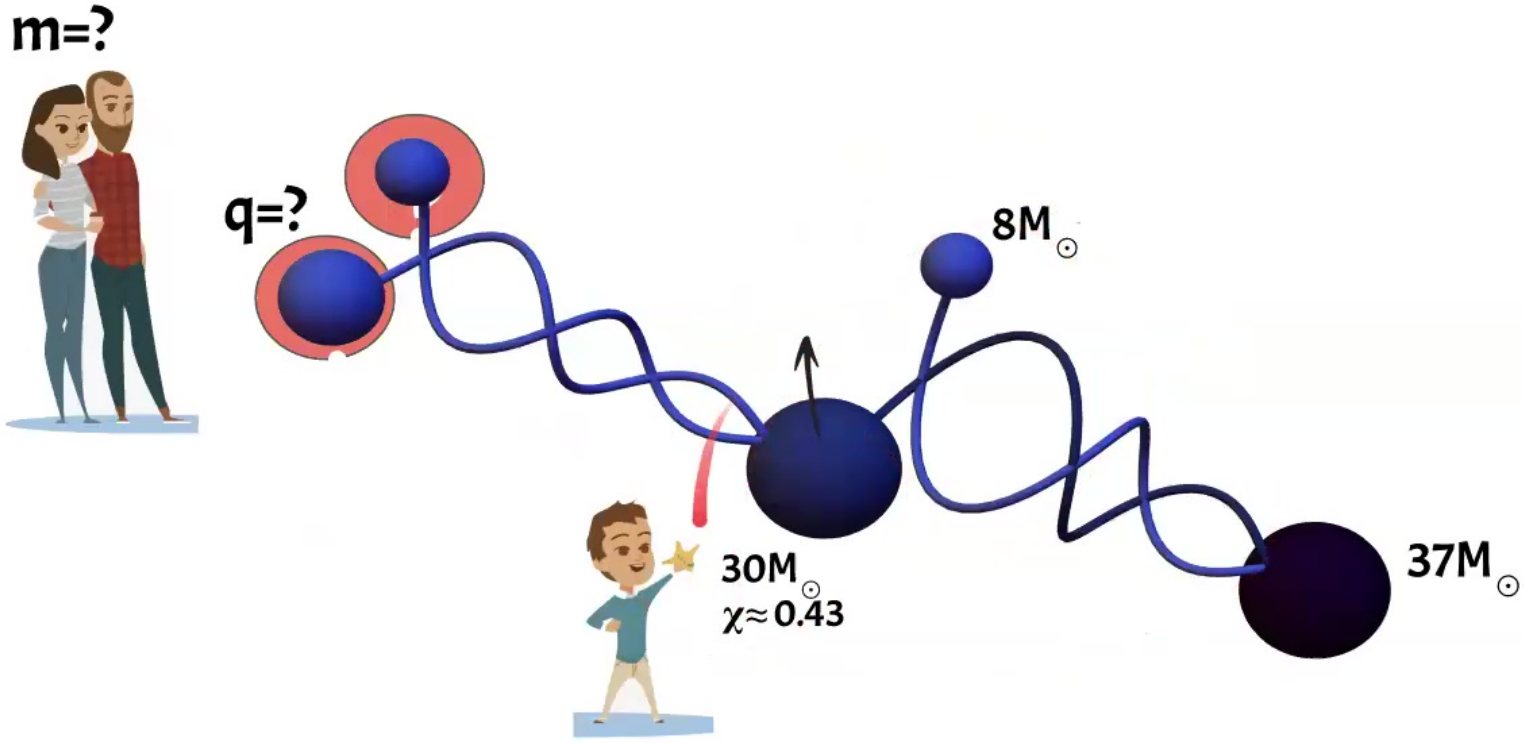


2g+2g



Parents
of second-generation
black holes

Parents of GW190412

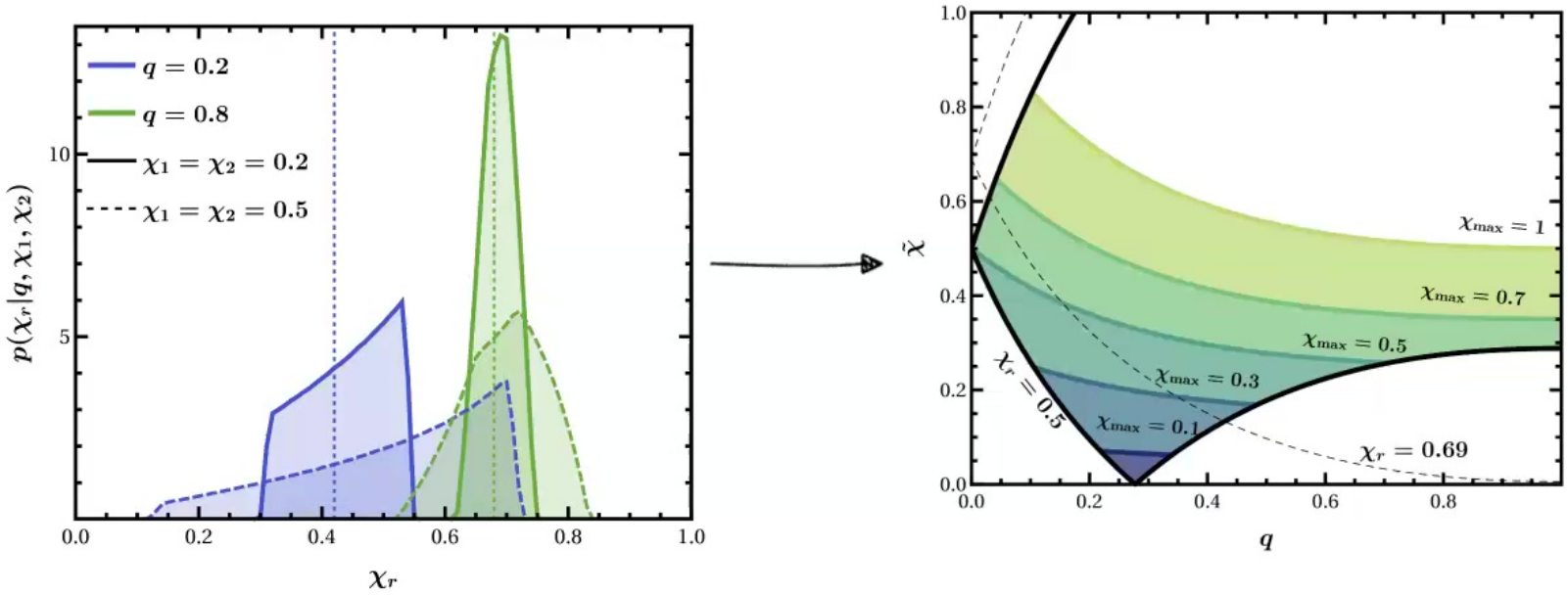


Gerosa, Vitale, Berti 2020 (PRL)
Rodriguez et al 2020 (ApJL)

Baibhav+ 2021

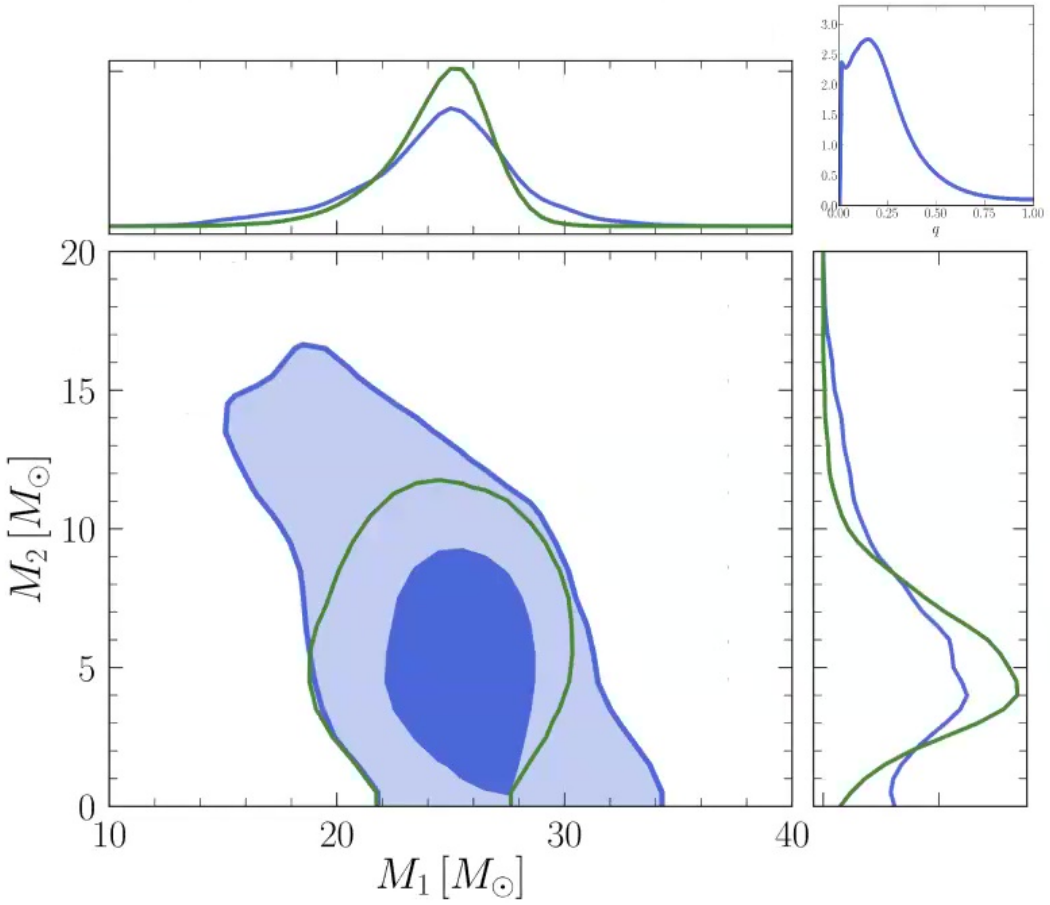
Parents of GW190412

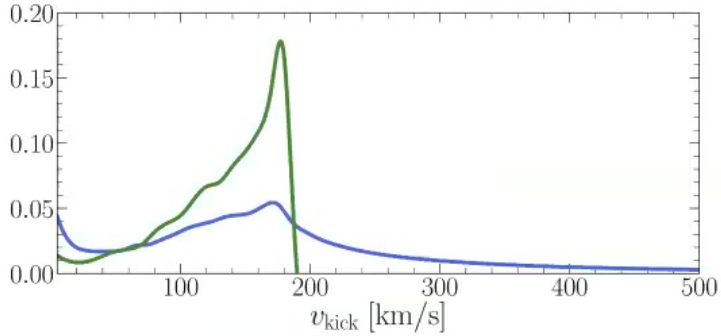
Reconstructing parents from the remnant's spin



Parents of GW190412 and their **Hometown**

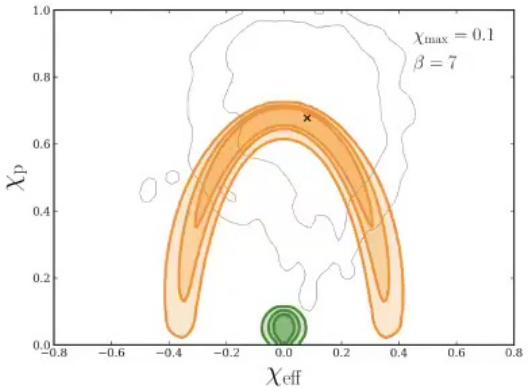
Baibhav+ 2021

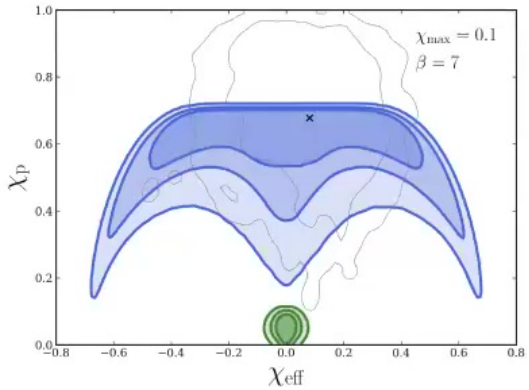


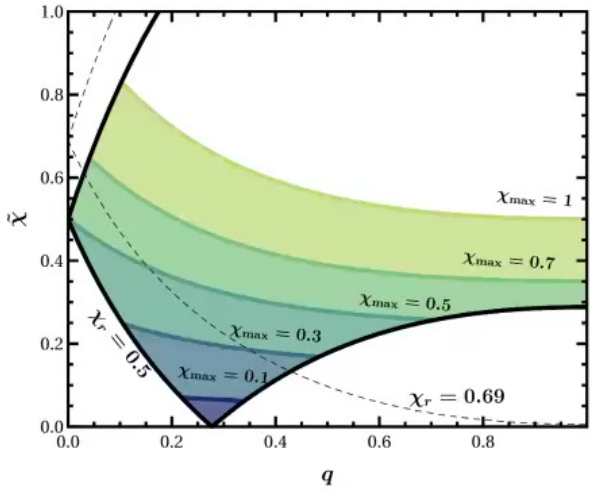


KEY TAKEAWAYS

Repeated mergers can
populate the SPIN GAP







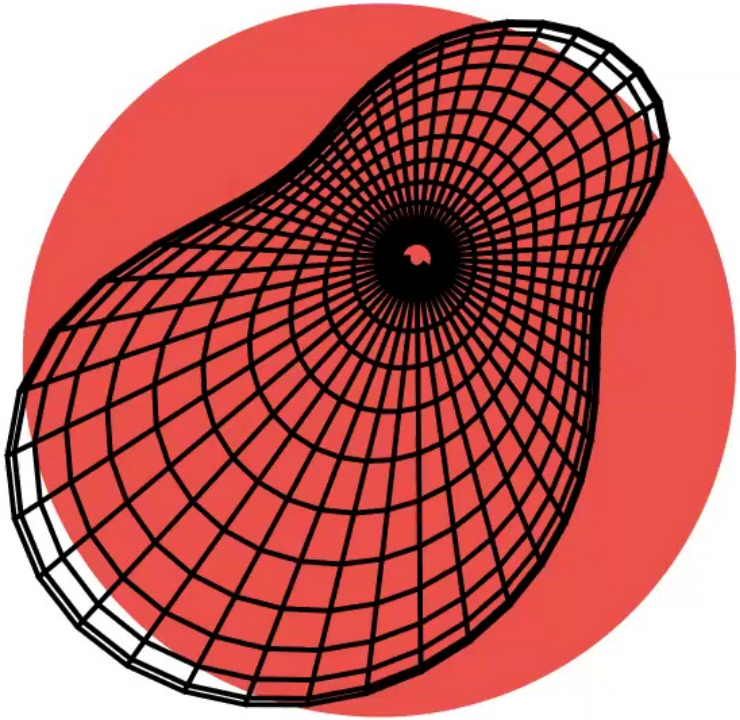
For some *lucky* events, we can
find their PARENTS

Singing with Black Holes

Do black holes play overtones?

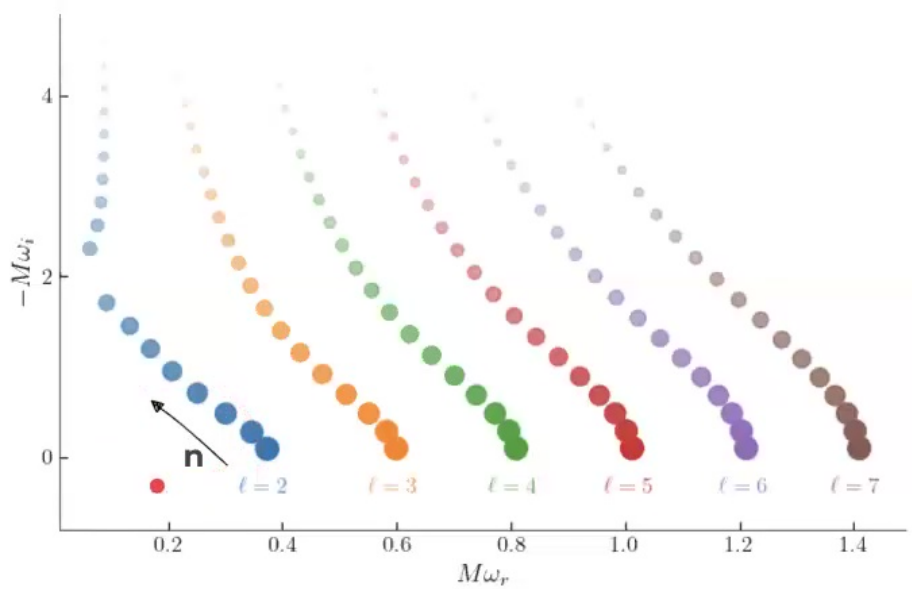
Baibhav, Berti, Cardoso et al 2017
Baibhav, Berti, 2018
Baibhav, Berti, Cardoso 2020
Cheung, Baibhav, Berti et al 2022
Baibhav, Cheung, Berti et al 2023
Cheung, Berti, Baibhav, et al 2023

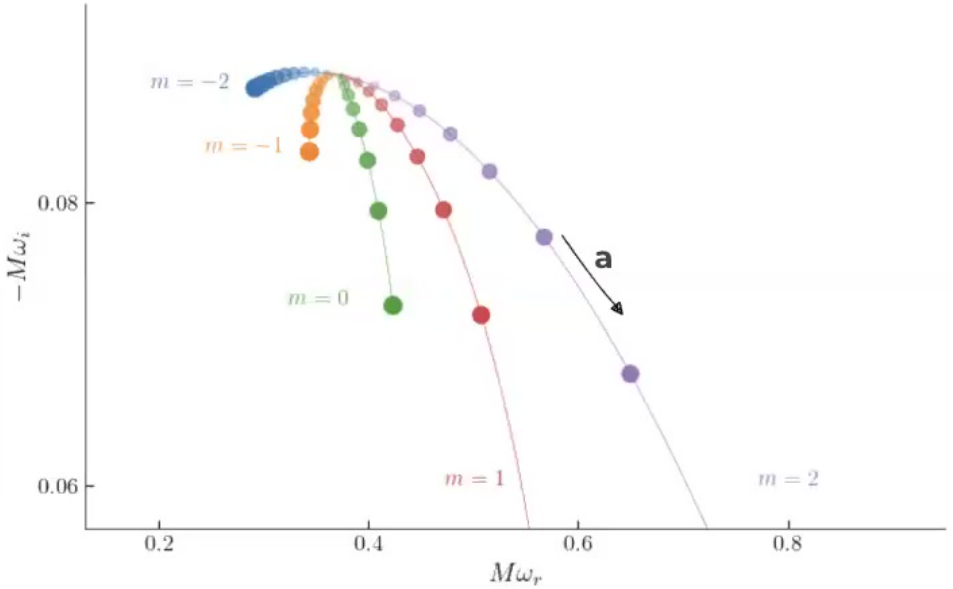
Vishal Baibhav, Mark Cheung, Emanuele Berti, Vitor Cardoso,
Roberto Cotesta, Gregorio Carullo, Walter del Pozzo, Francisco Duque



Sounds of black-hole spacetimes

What tones can the black holes play?





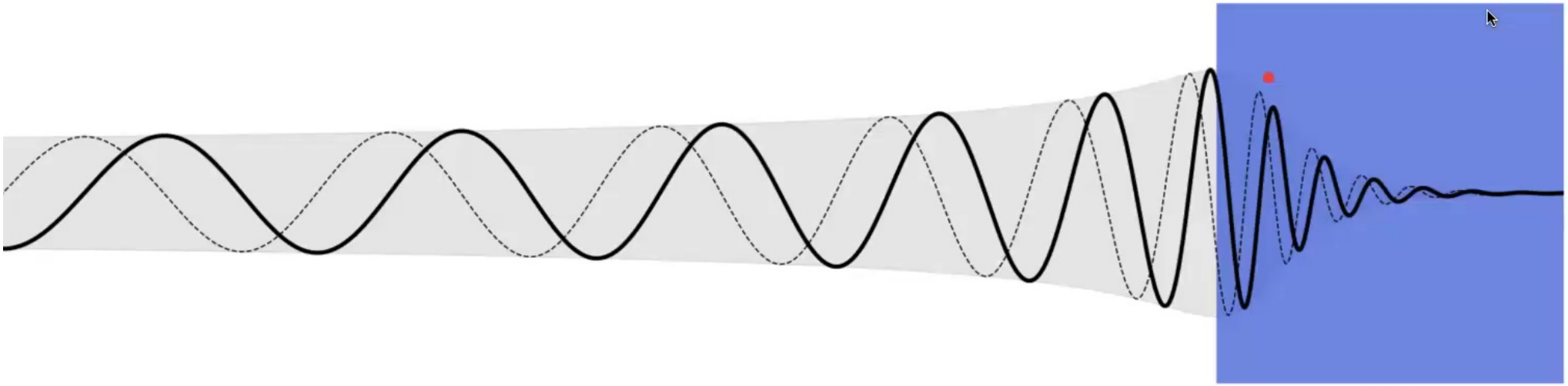
How musical are **ringing black holes?**

Buonanno, Cook, Pretorius 2007
London, Healy, Shoemaker 2014
Baibhav, Berti, Cardoso, Khanna 2017
..... and others

1-3 overtones

Giesler et al 2019
Cook 2020
Dhani 2020
Finch & Moore 2021
Magana Zertuche et al 2021
Ma et al 2021
..... and many others

7 or more overtones



Linear (N=7) model

Fundamental mode + 7 overtones

assume a priori that these QNMs exist (fixed complex frequencies)

N=7 offers smaller mismatches than N=0

N=7 extracts remnant properties better than N=0

Is post-peak waveform completely linear?

Which overtones are real?

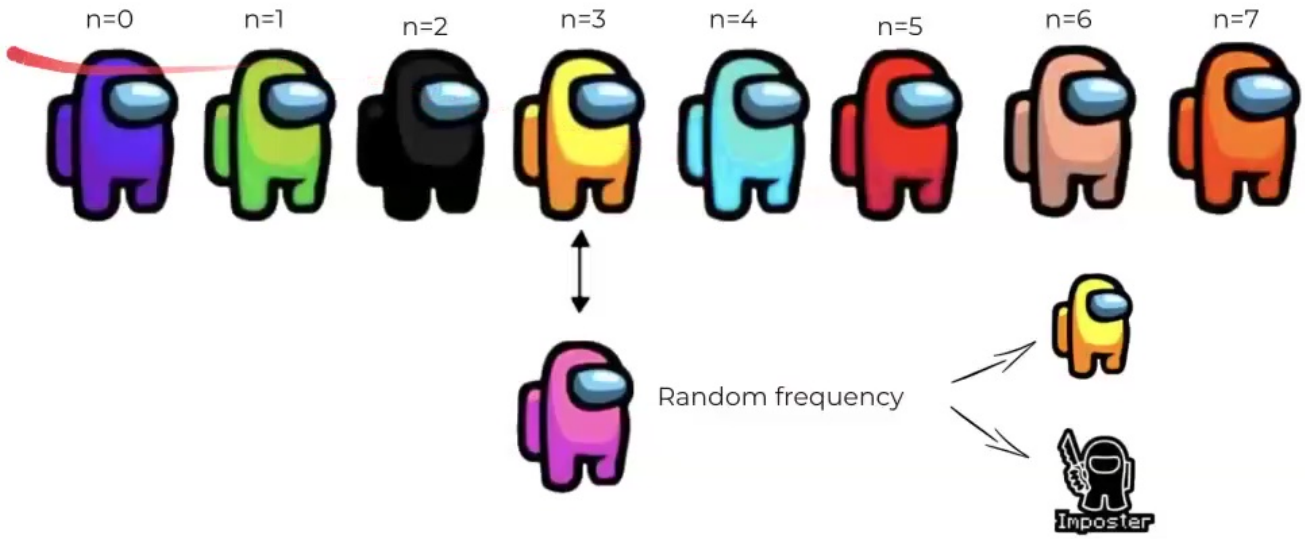
Are some overtones overfitting non-linearities?

Do overtones really offer best fits?

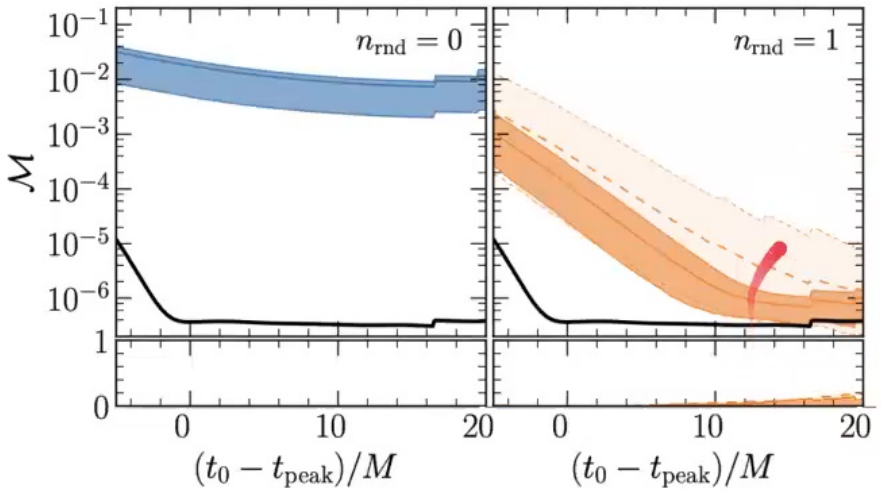
$$h = \underbrace{\sum A e^{-\omega_i(\chi,M)t}}\cos(\omega_r(\chi,M)t+\phi)$$

$$\mathcal{M} = 1 - \frac{\langle h_{\rm NR}|h_{\rm fit}\rangle}{\sqrt{\langle h_{\rm NR}|h_{\rm NR}\rangle\langle h_{\rm fit}|h_{\rm fit}\rangle}}$$

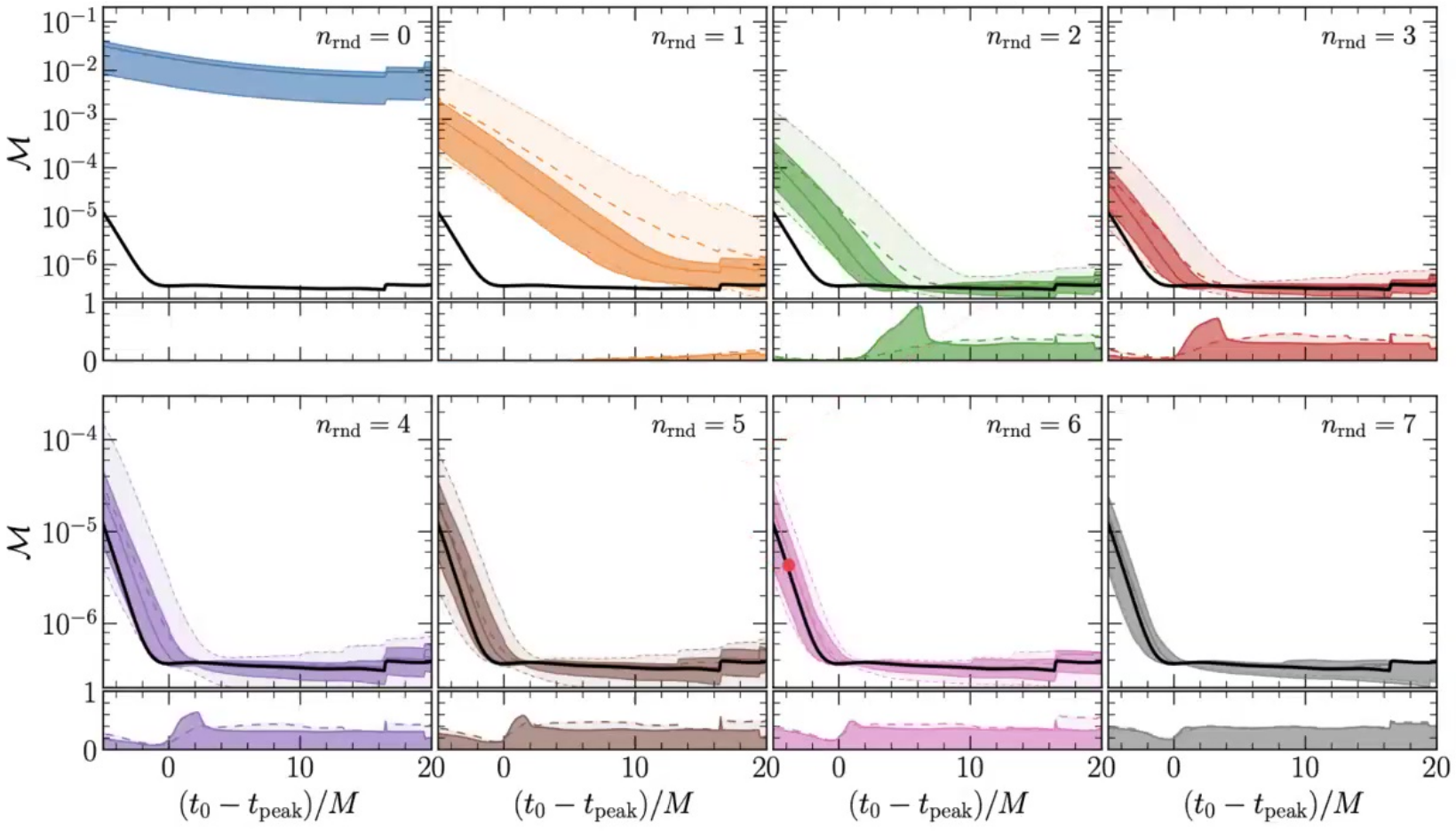
There are ___ imposters among us (overtones)!



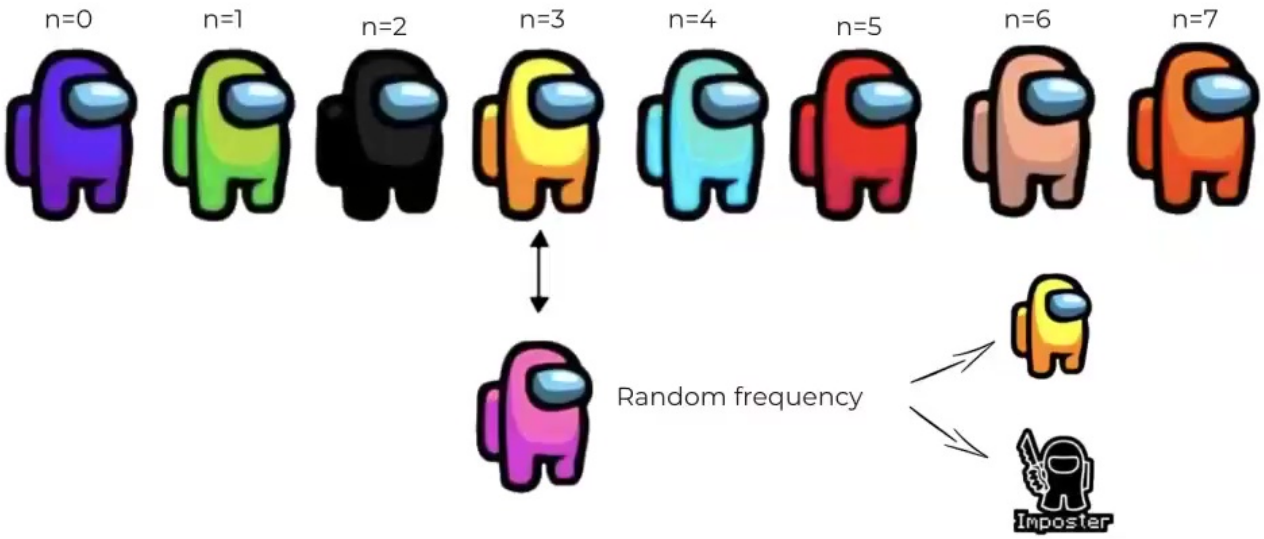
Do overtones really offer best fits?



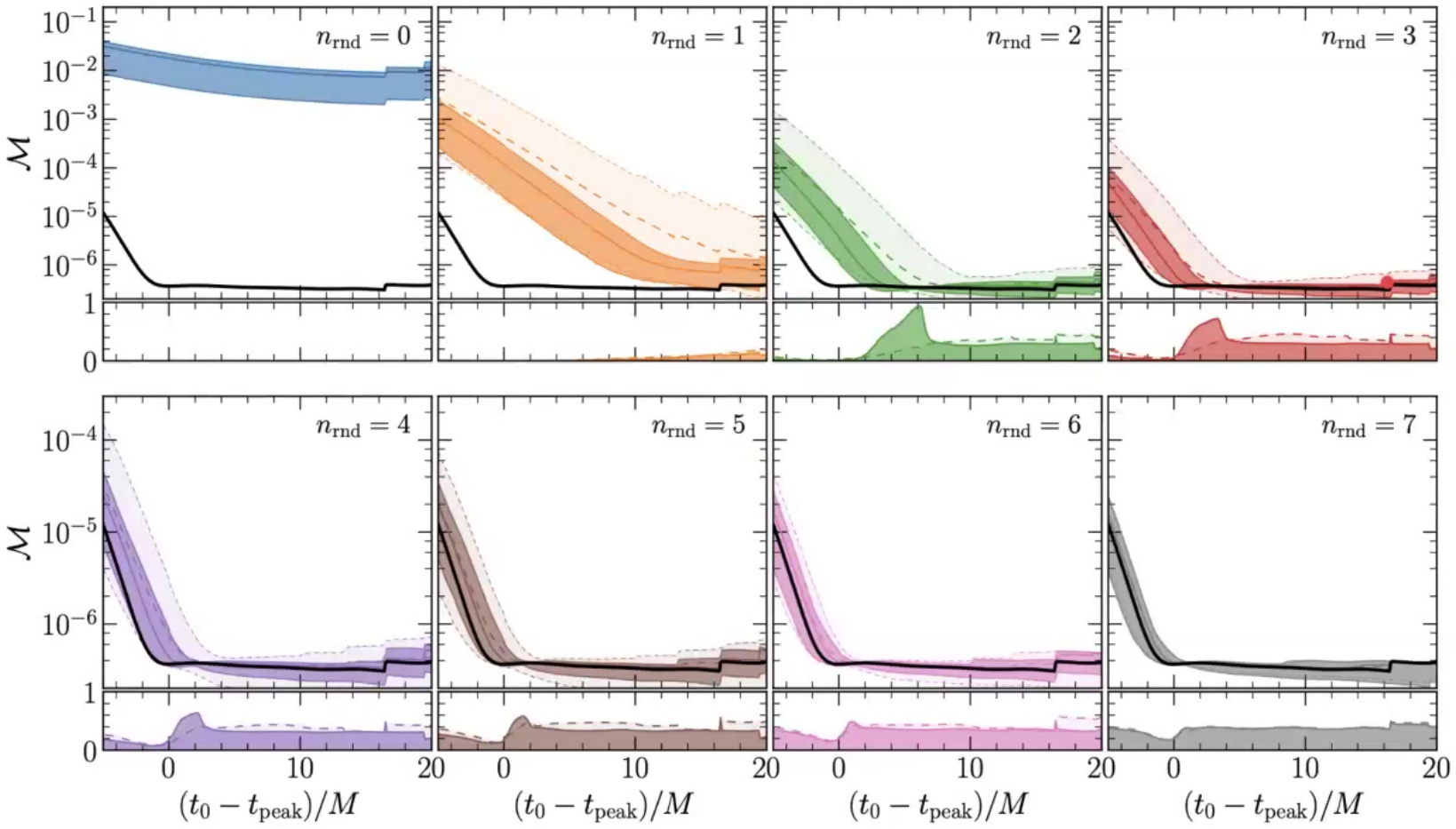
Do overtones really offer best fits?



There are ___ imposters among us (overtones)!

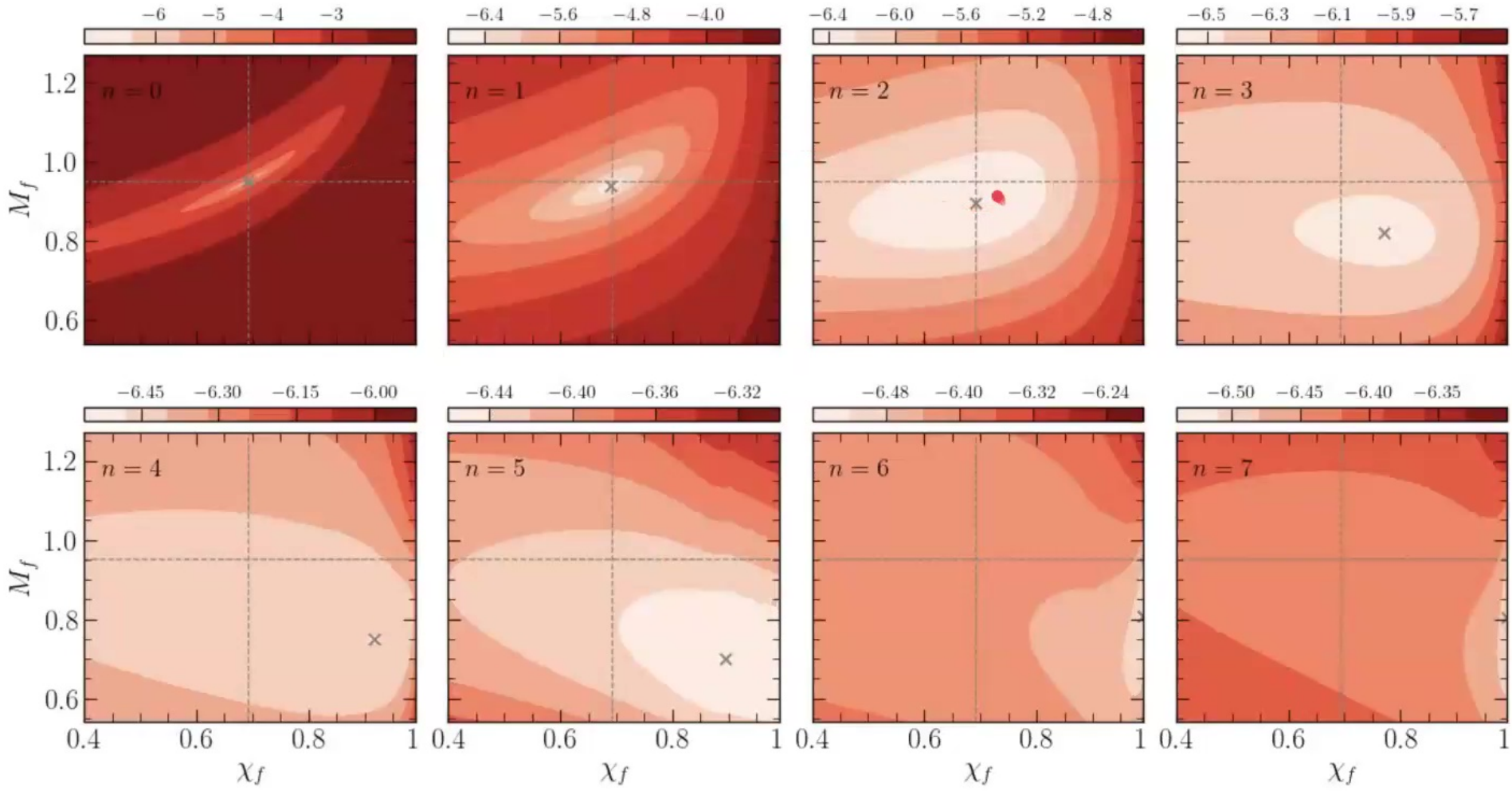


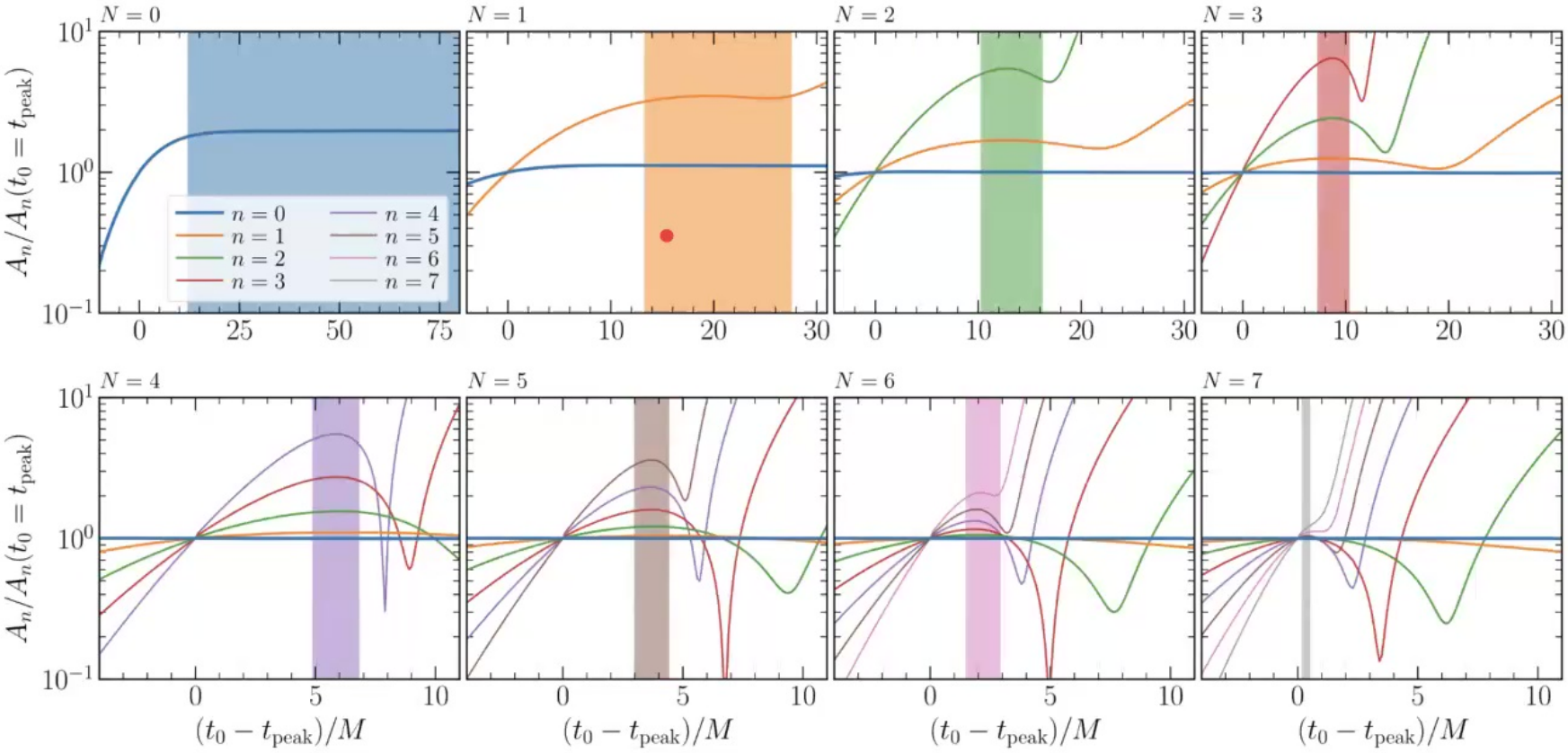
Do overtones really offer best fits?



Can “overtones” extract the correct values of remnant spin and mass?

$$h = \sum A e^{-\omega_i(\chi,M)t} \cos(\omega_r(\chi,M)t + \phi)$$


−6 −5 −4 −3
−6.4 −5.6 −4.8 −4.0
−6.4 −6.0 −5.6 −5.2 −4.8
−6.5 −6.3 −6.1 −5.9 −5.7
n = 0
n = 1
n = 2
n = 3
−6.45 −6.30 −6.15 −6.00
−6.44 −6.40 −6.36 −6.32
−6.48 −6.40 −6.32 −6.24
−6.50 −6.45 −6.40 −6.35
n = 4
n = 5
n = 6
n = 7
M_f
1.2
1.0
0.8
0.6
0.4 0.6 0.8 1
χ_f


$N = 0$
$N = 1$
$N = 2$
$N = 3$
$N = 4$
$N = 5$
$N = 6$
$N = 7$
$A_n/A_n(t_0 = t_{\rm peak})$
$(t_0 - t_{\rm peak})/M$
$n = 0$
$n = 1$
$n = 2$
$n = 3$
$n = 4$
$n = 5$
$n = 6$
$n = 7$

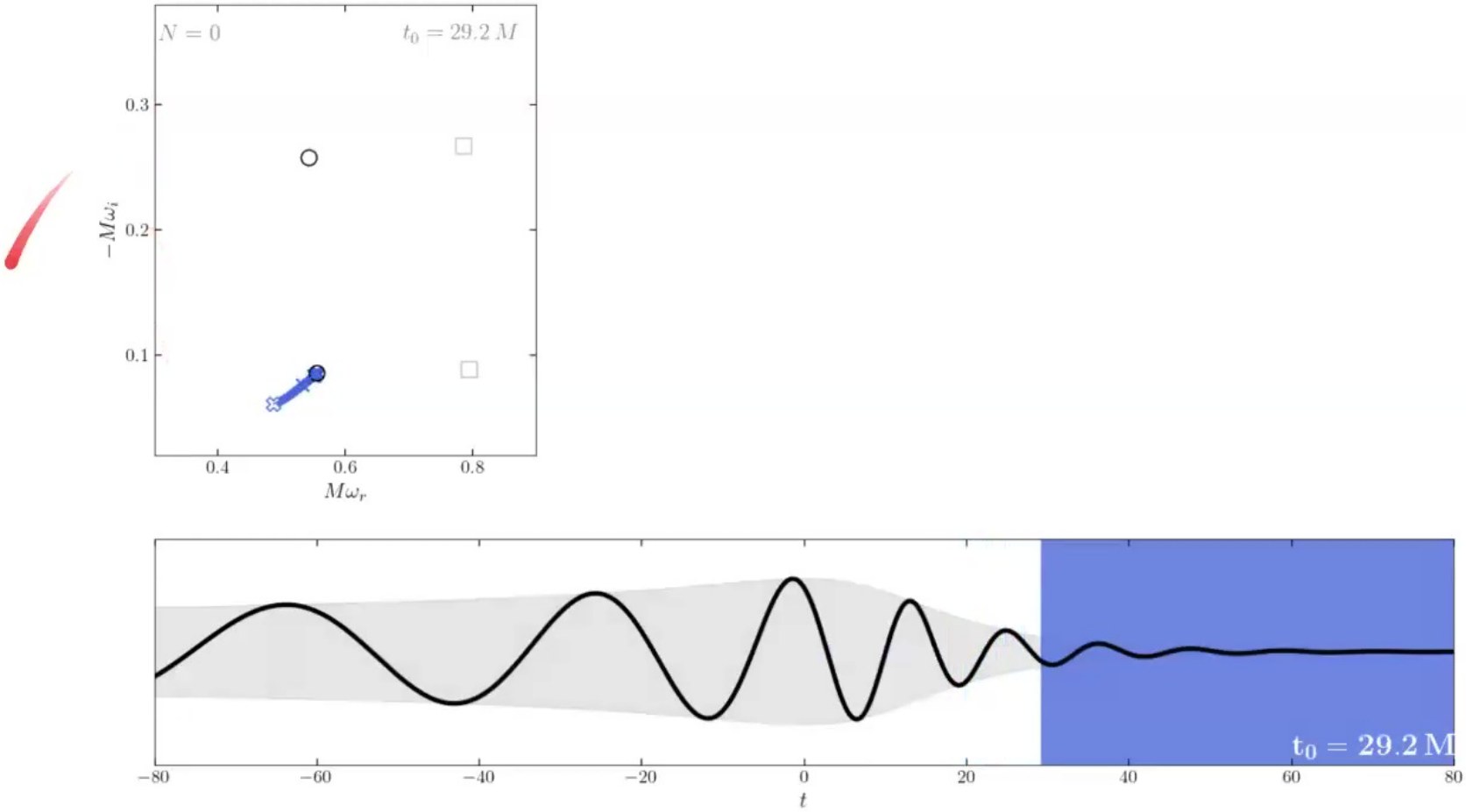
Do black holes play (higher) overtones?

Most of the higher overtones are **not real**!

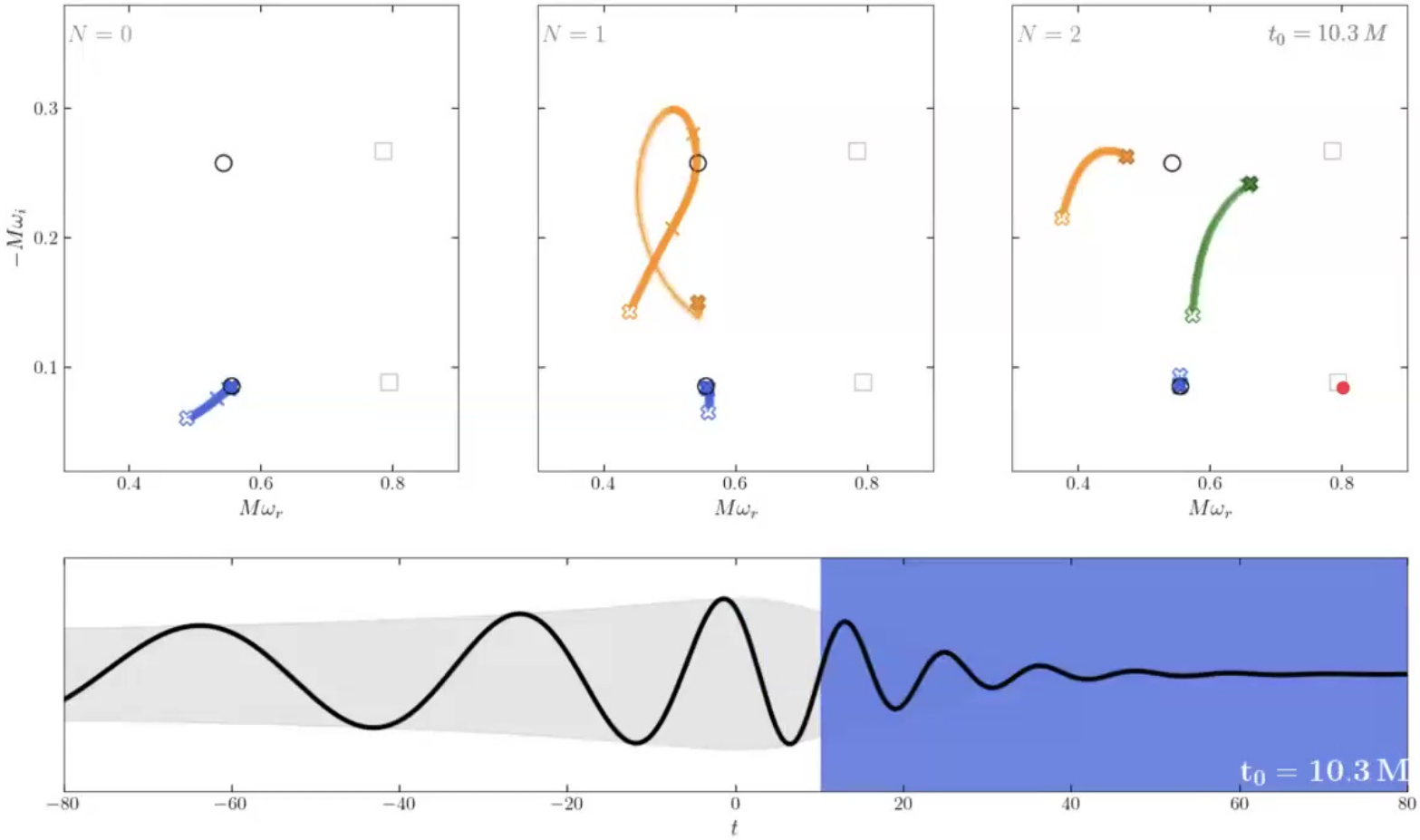
> They do not give the smallest mismatches
> They do not extract spin mass very well
> Inconsistent amplitudes

So, what tones do BHs play?

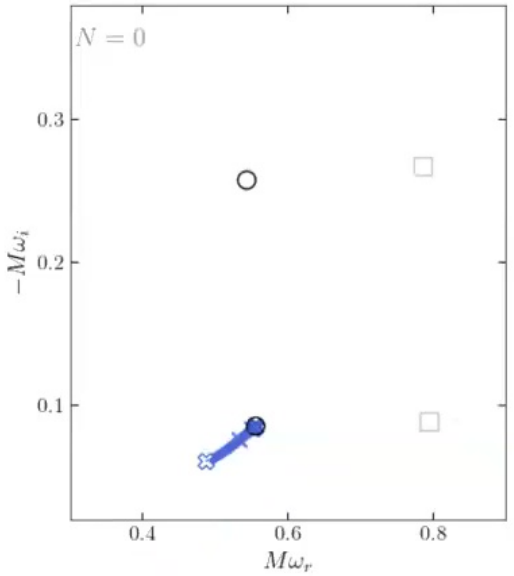
Quasinormal frequencies *extracted from* NR waveforms

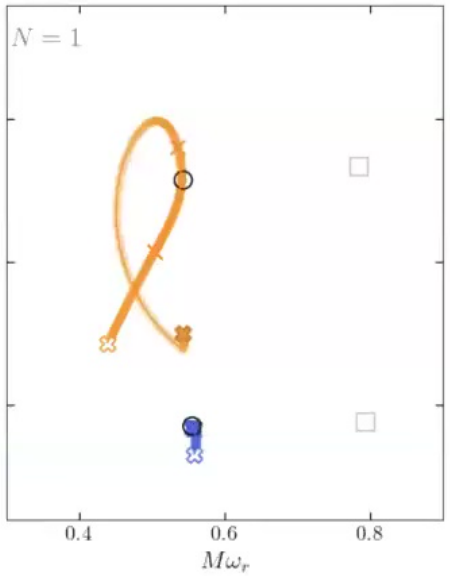


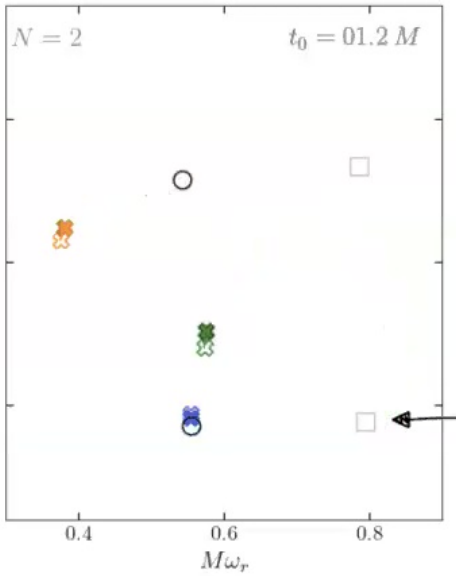
Quasinormal frequencies *extracted from* NR waveforms



Quasinormal frequencies *extracted from* NR waveforms







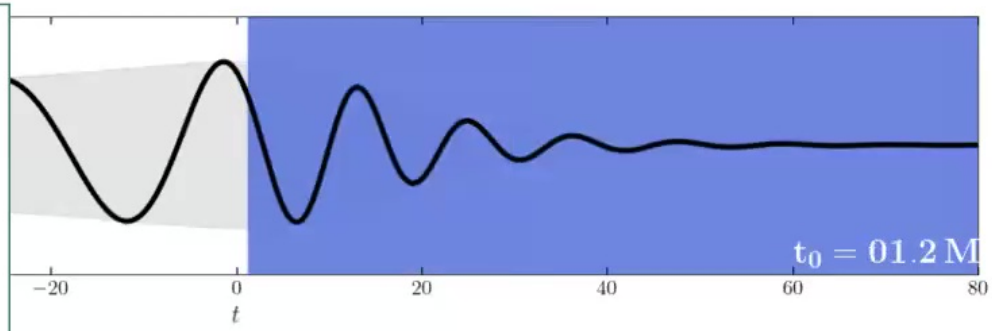
(3,2,0)

Spheroidal Harmonics — Spherical Harmonics

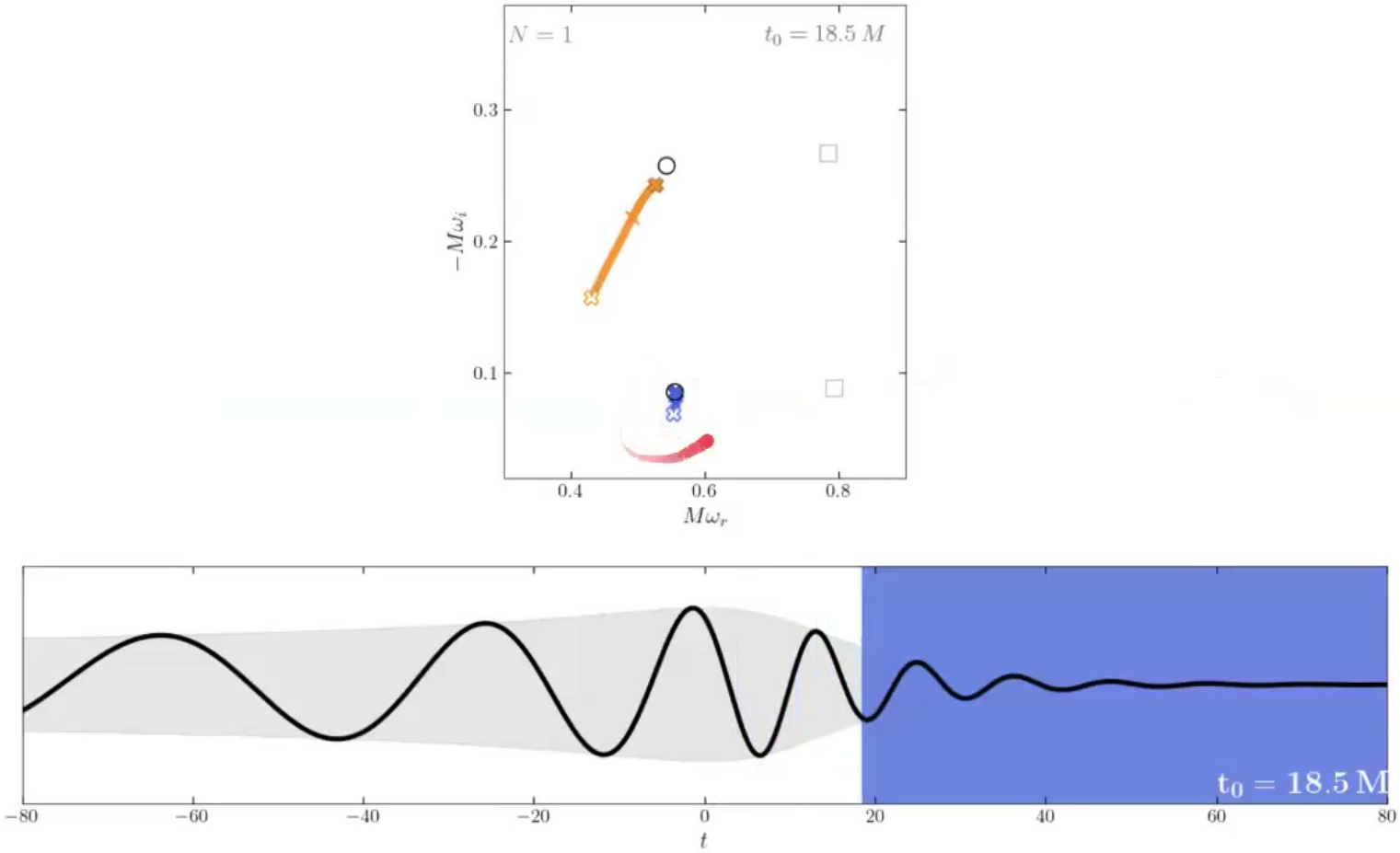
$$ {}_{-2}S_{lm} = {}_{-2}Y_{lm} + j_f\, \tilde{\omega}_{lmn} \sum_{l \neq l'} {}_{-2}Y_{l'm}\, c_{l'lm} $$

Black Hole perturbation theory

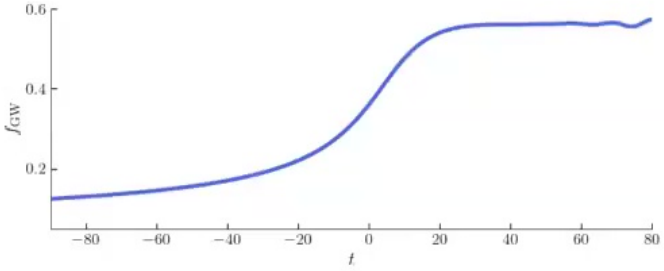
Numerical Relativity

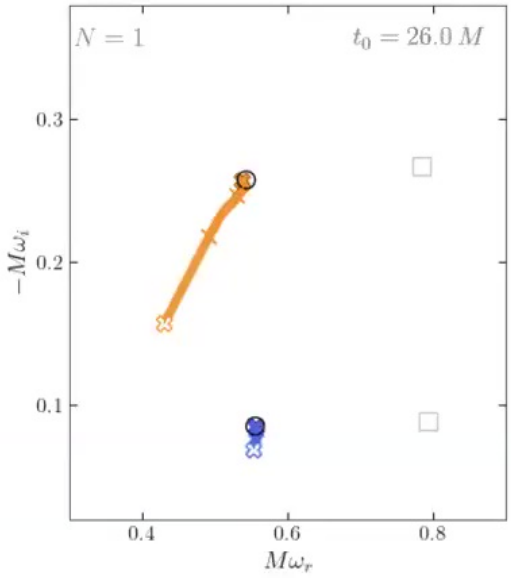


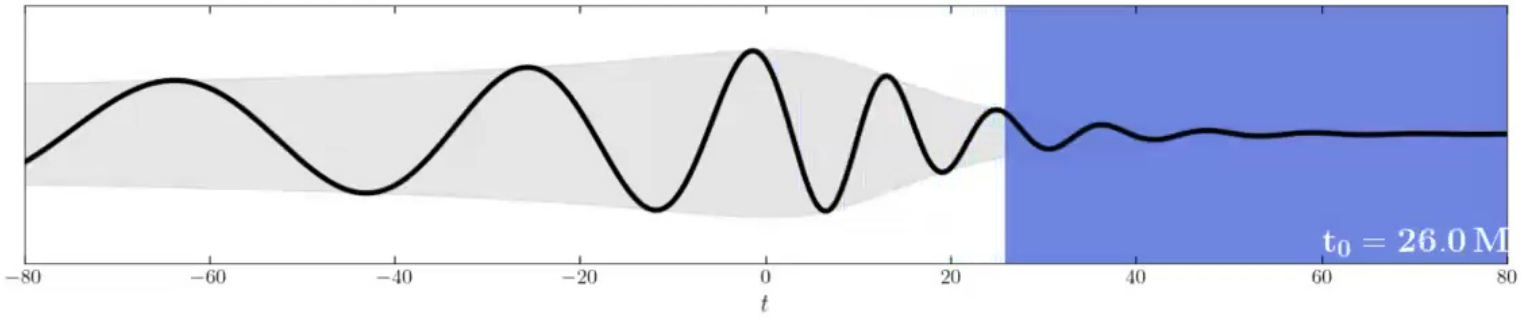
Quasinormal frequencies *extracted from* NR waveforms



Quasinormal frequencies *extracted from* NR waveforms







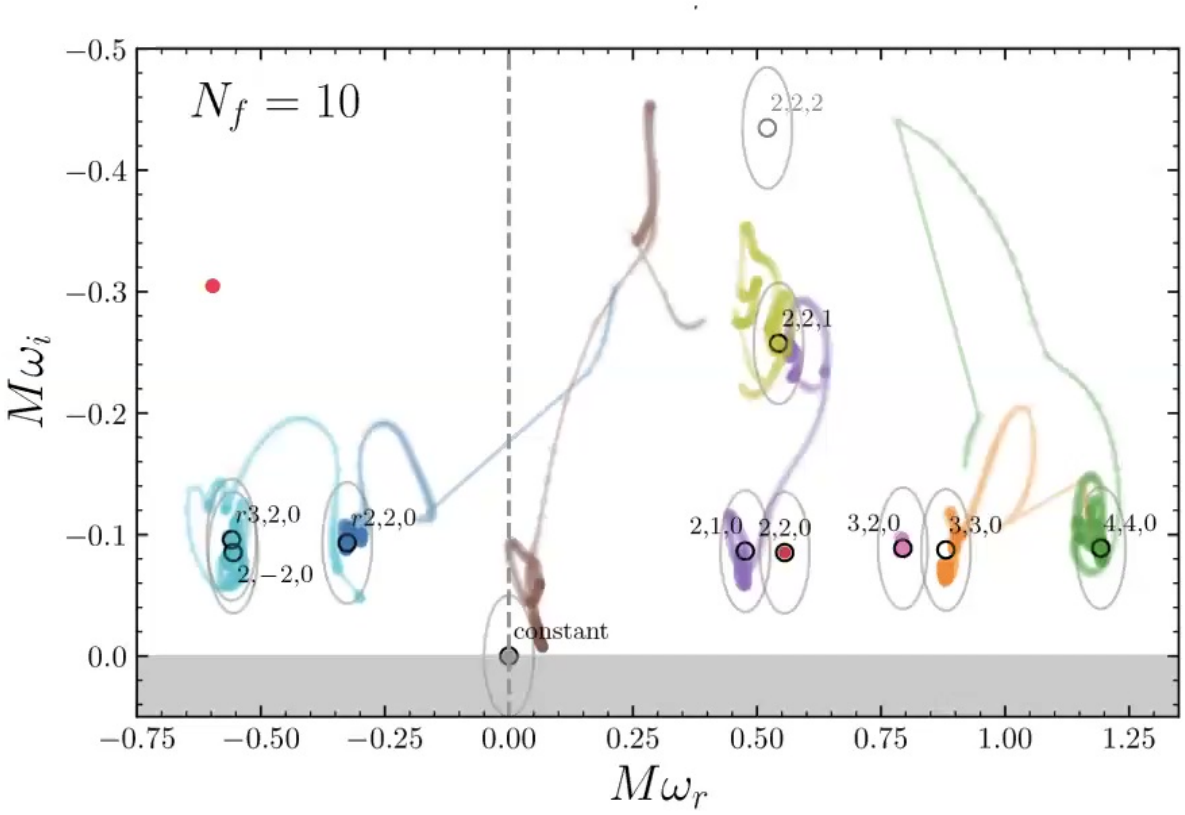
Quasinormal frequencies

extracted from NR waveforms

mhycheung.github.io/jaxqualin/

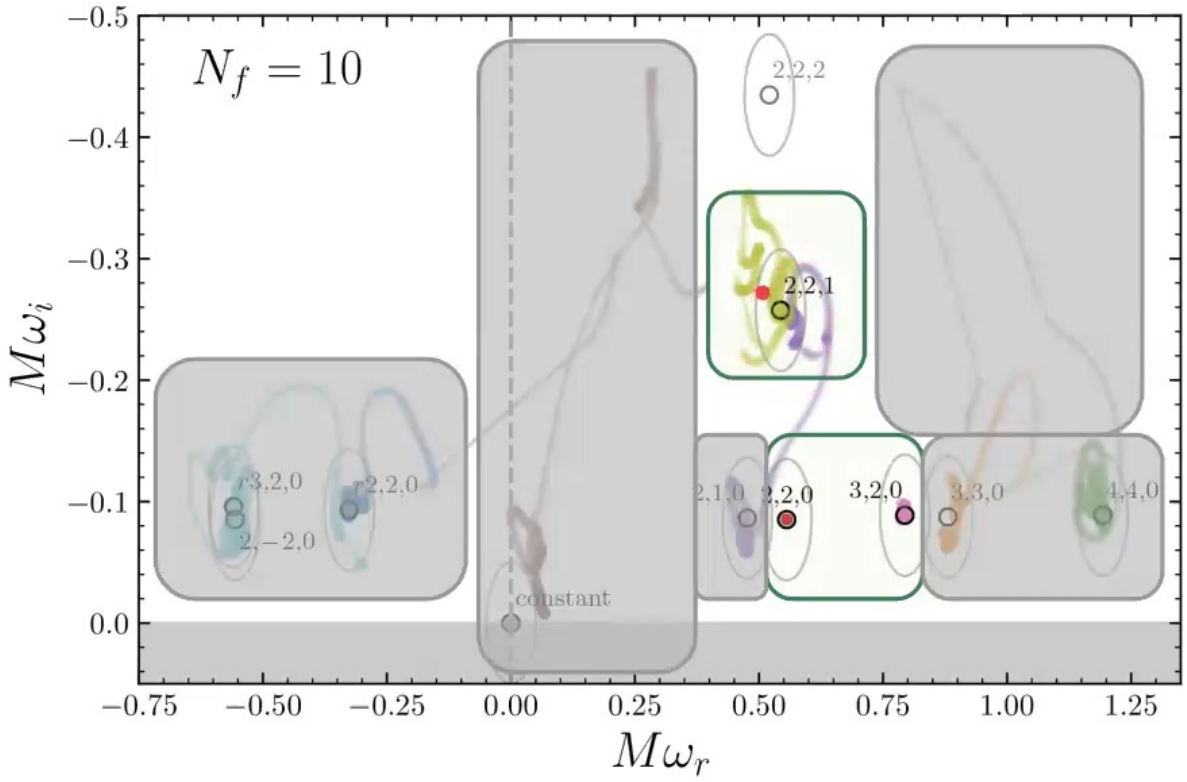
GitHub

Cheung+ 2023

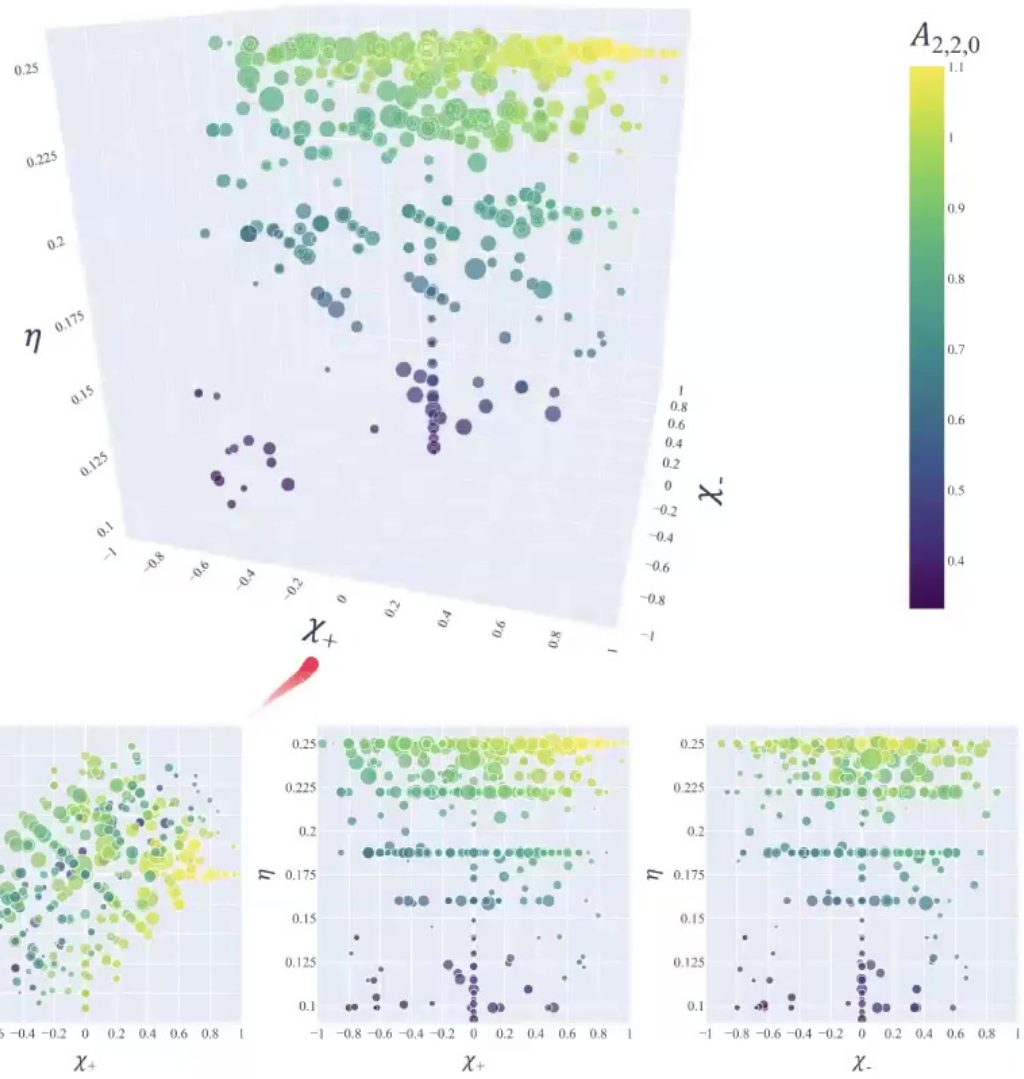


Quasinormal frequencies

extracted from NR waveforms



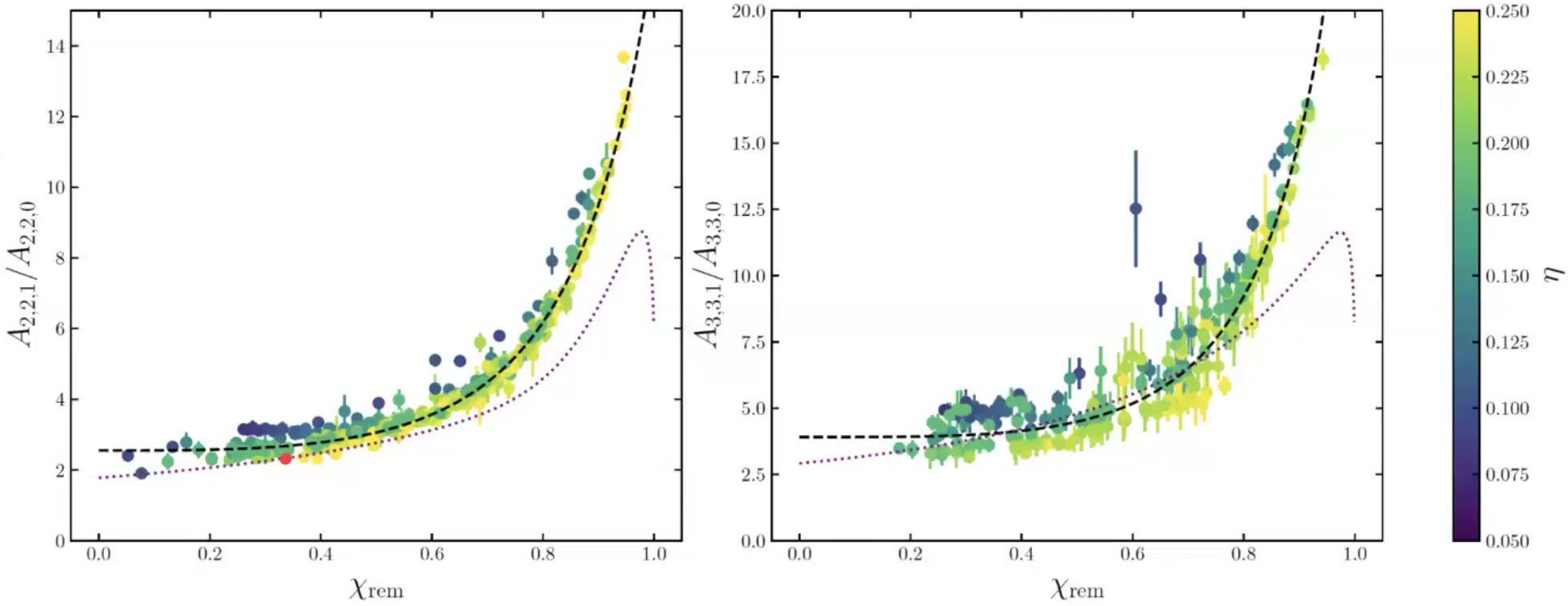
Cheung+ 2023

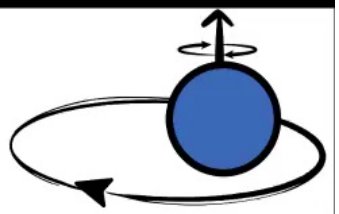


mhycheung.github.io/jaxqualin/

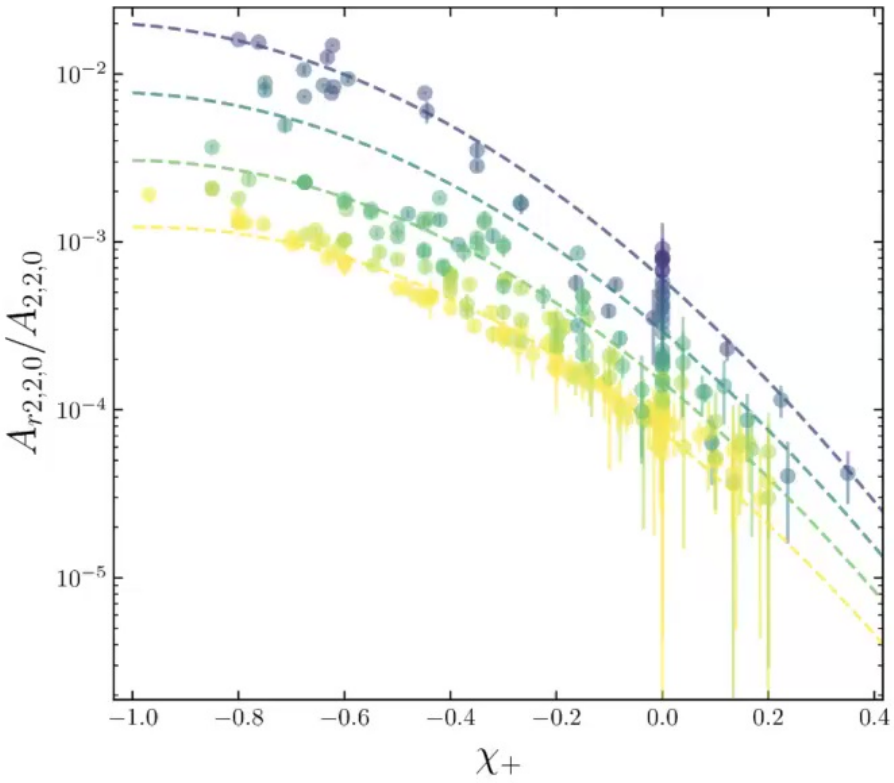
GitHub

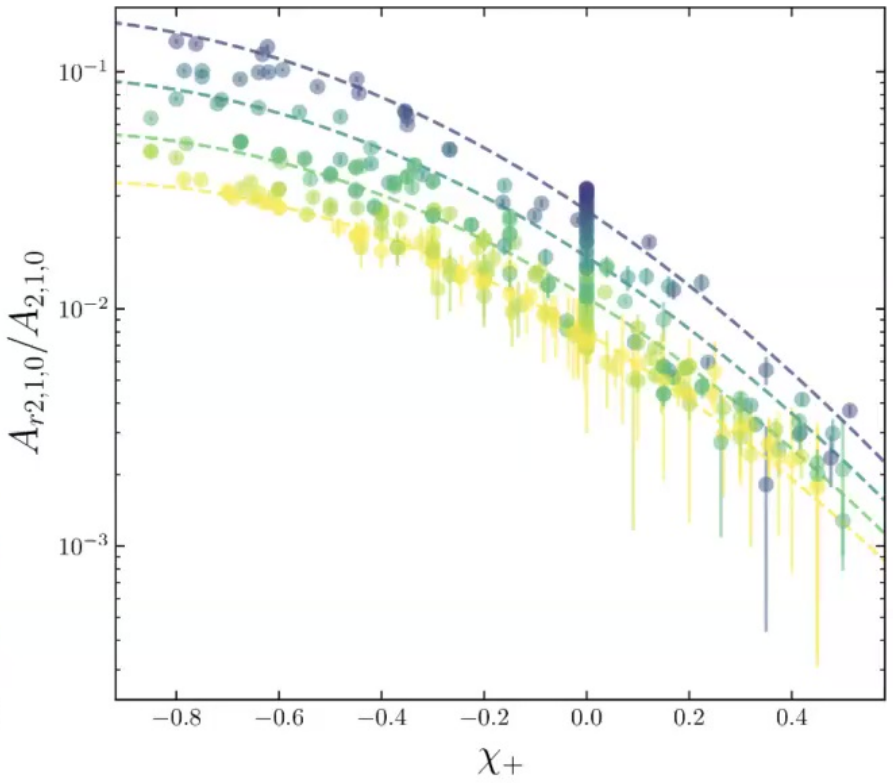
Excitation of the first overtone

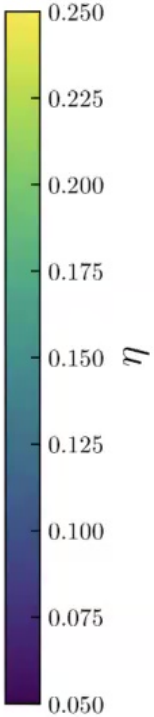




Excitation of retrograde modes

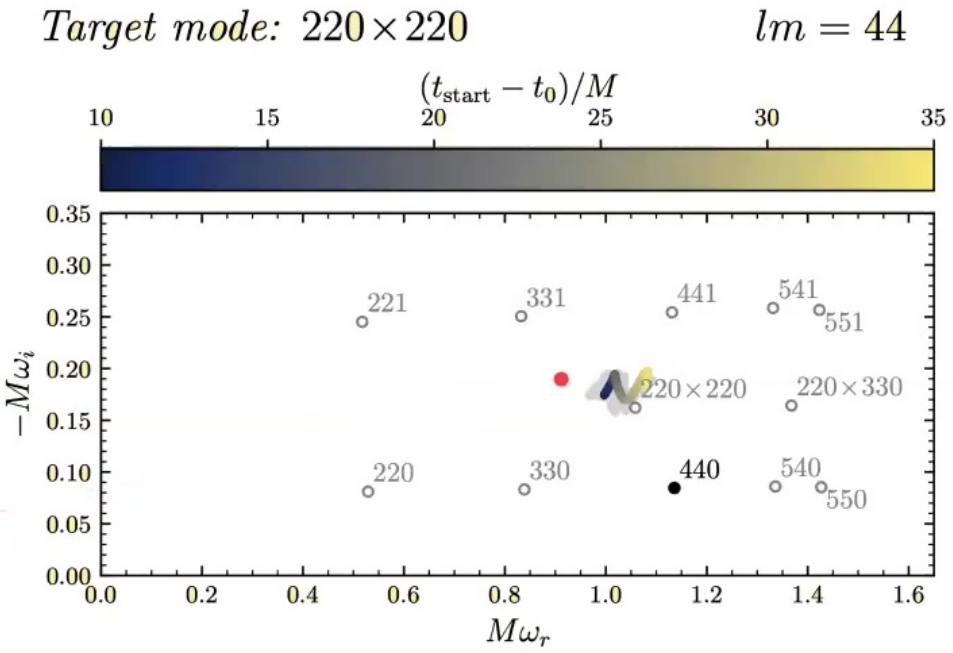






Quadratic modes

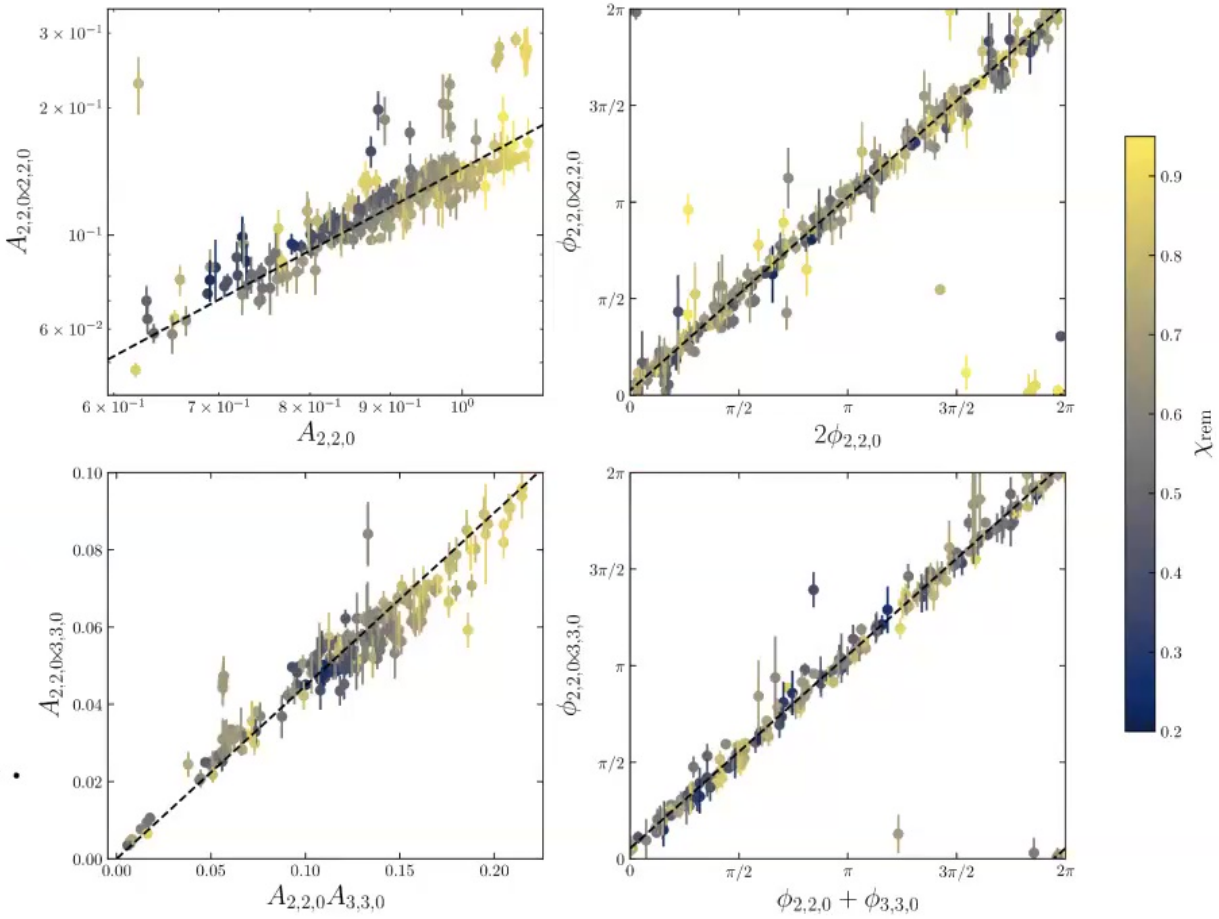
$$\omega_{\text{quadratic}} = \omega_{\text{linear},1} + \omega_{\text{linear},2}$$



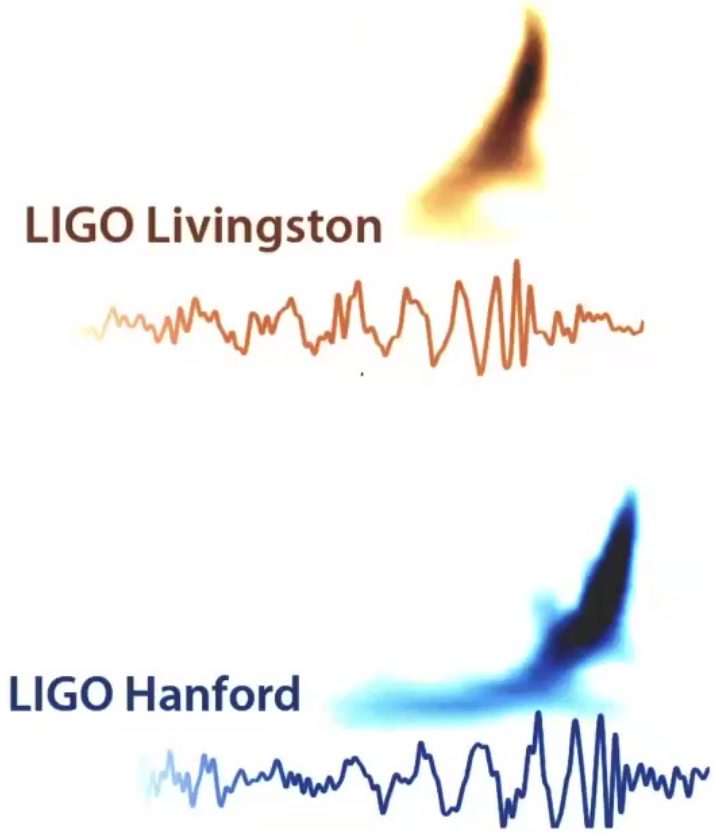
Quadratic modes

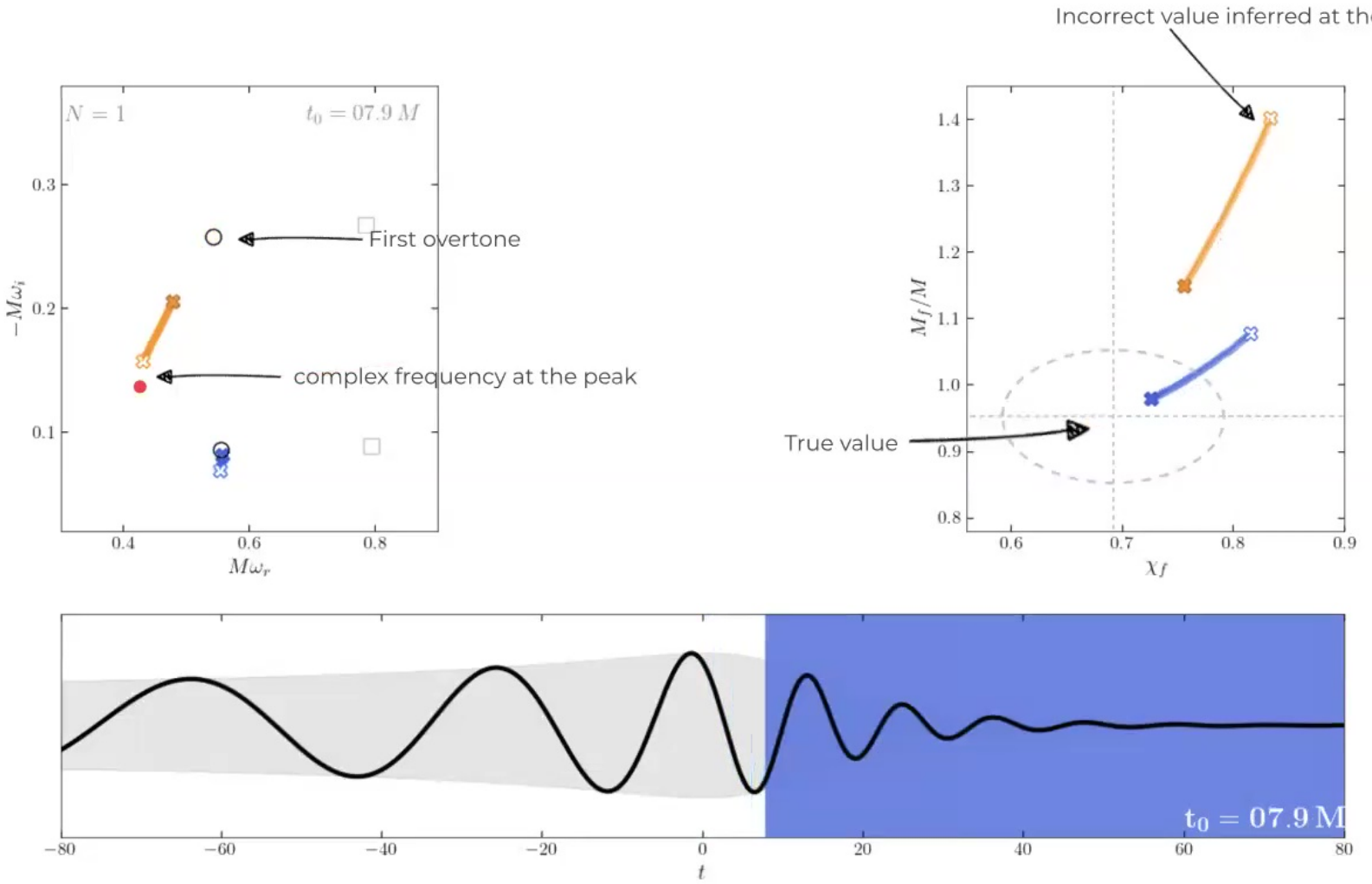
$$A_{\text{quadratic}} \propto A_{\text{linear},1} \times A_{\text{linear},2}$$

$$\phi_{\text{quadratic}} = \phi_{\text{linear},1} + \phi_{\text{linear},2} + \dots$$

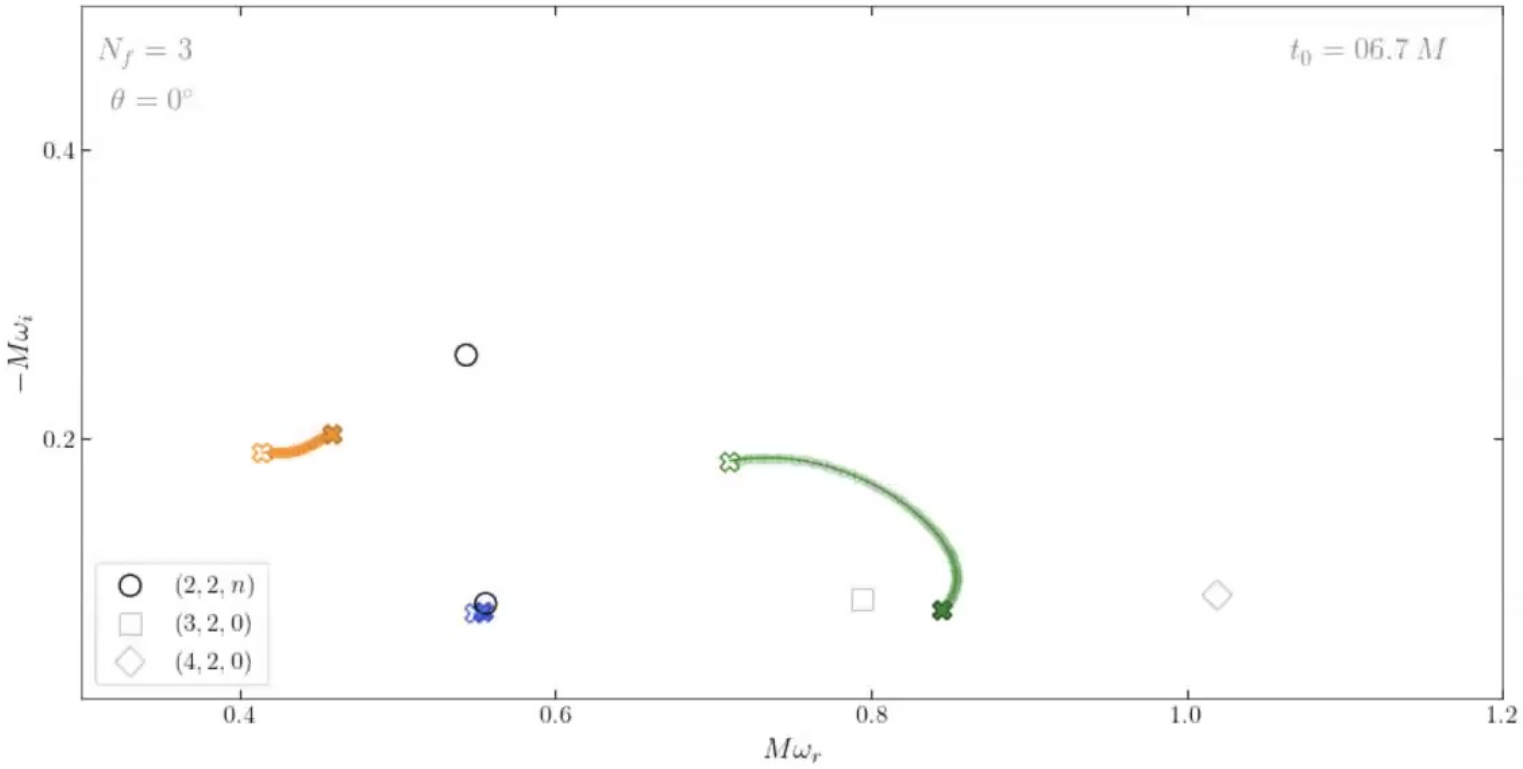


Have we detected any overtones?




Incorrect value inferred at the peak
$N = 1$
$t_0 = 07.9\,M$
First overtone
complex frequency at the peak
True value
$-M\omega_i$
$M\omega_r$
M_f/M
χ_f
t
$t_0 = 07.9\,M$

Extracting QNMs from a face-on binary



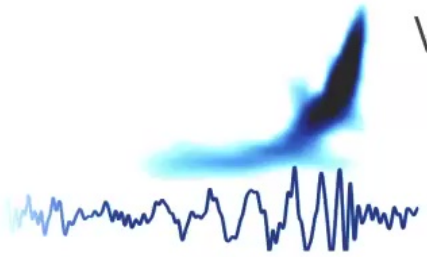
Do black holes play (higher) overtones?

Most of the higher overtones are **not real**!

> They do not give the smallest mismatches
> They do not extract spin mass very well
> Inconsistent amplitudes

So, what tones do BHs play?

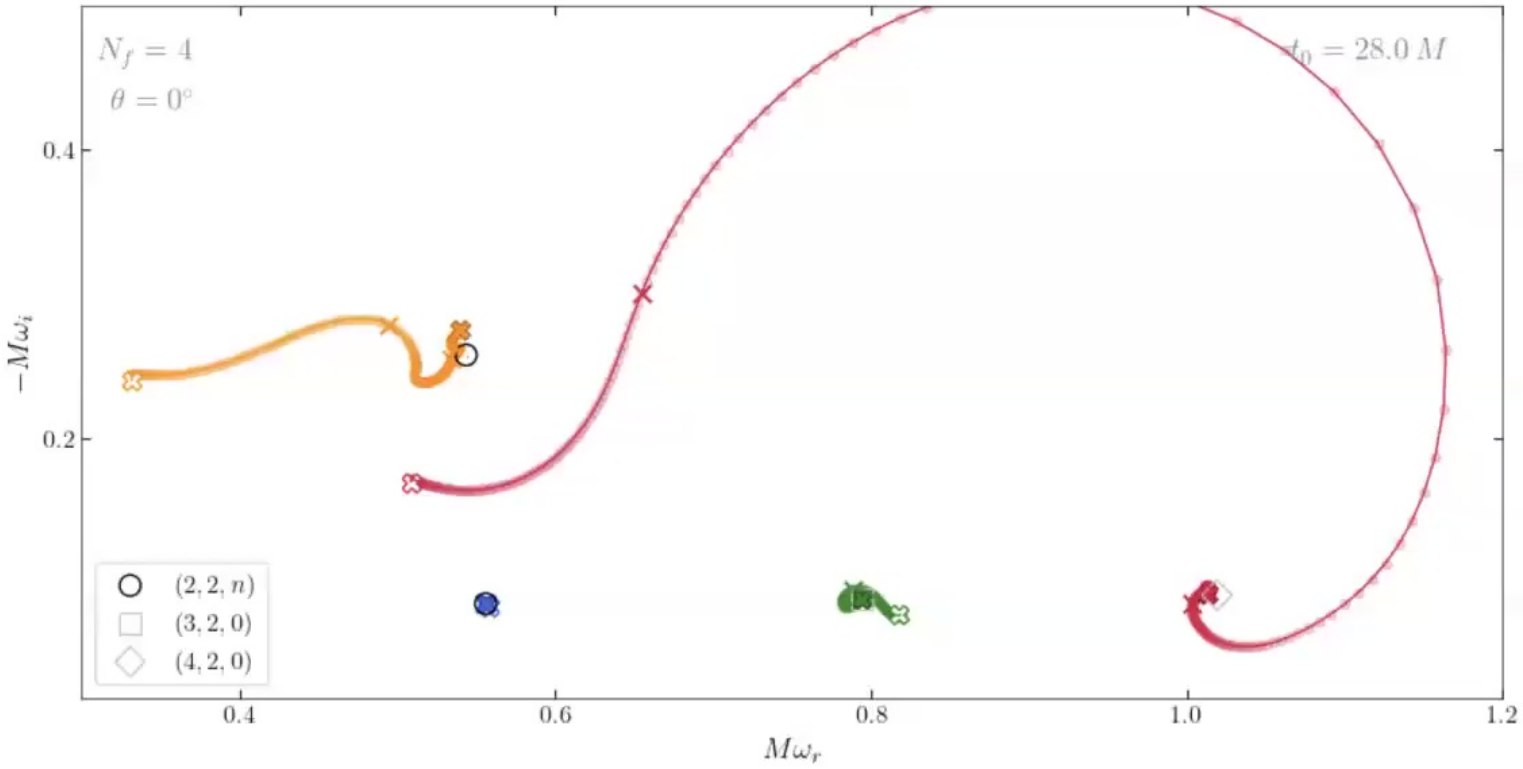
Fundamental mode
First overtone



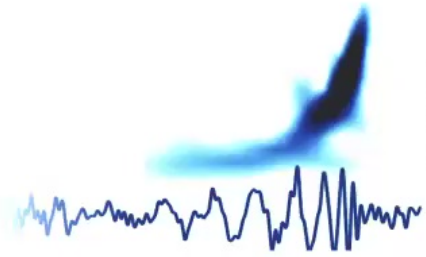
What does this mean for data analysis?

> It's not easy to extract the first overtone if other harmonics are present
> First overtone can only be extracted **10-15 M after the waveform peak**

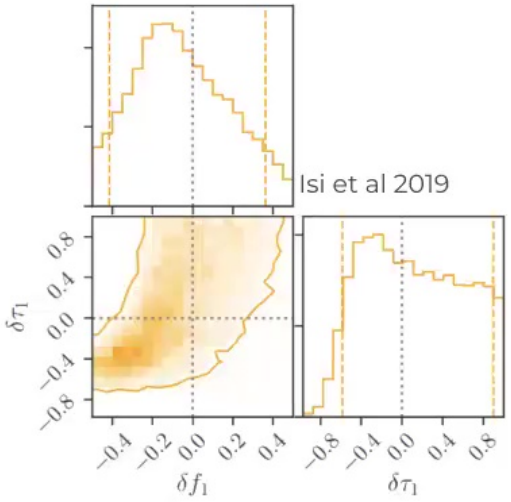
Extracting QNMs from a face-on binary

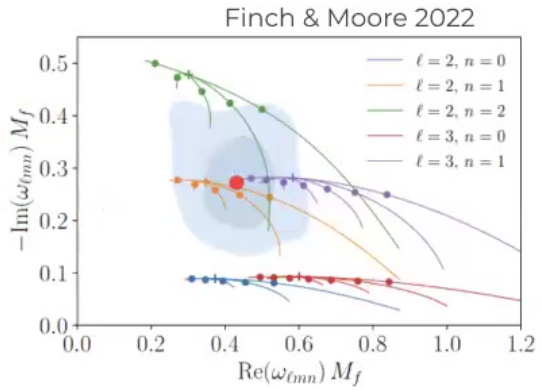


Have we detected any overtones?



Isi et al 2019
Cotesta et al 2022
Isi & Farr 2022
Finch & Moore 2022
.... and many others





Extracting QNMs from a face-on binary