

# GW190521 as a Boson-Star Merger

Juan Calderón Bustillo\*



Nicolás Sanchis-Gual, Samson Leong, Koustav Chandra, Alejandro Torres-Forné, Toni Font, Avi Vajpeyi, Rory Smith, Carlos Herdeiro & Eugen Radu

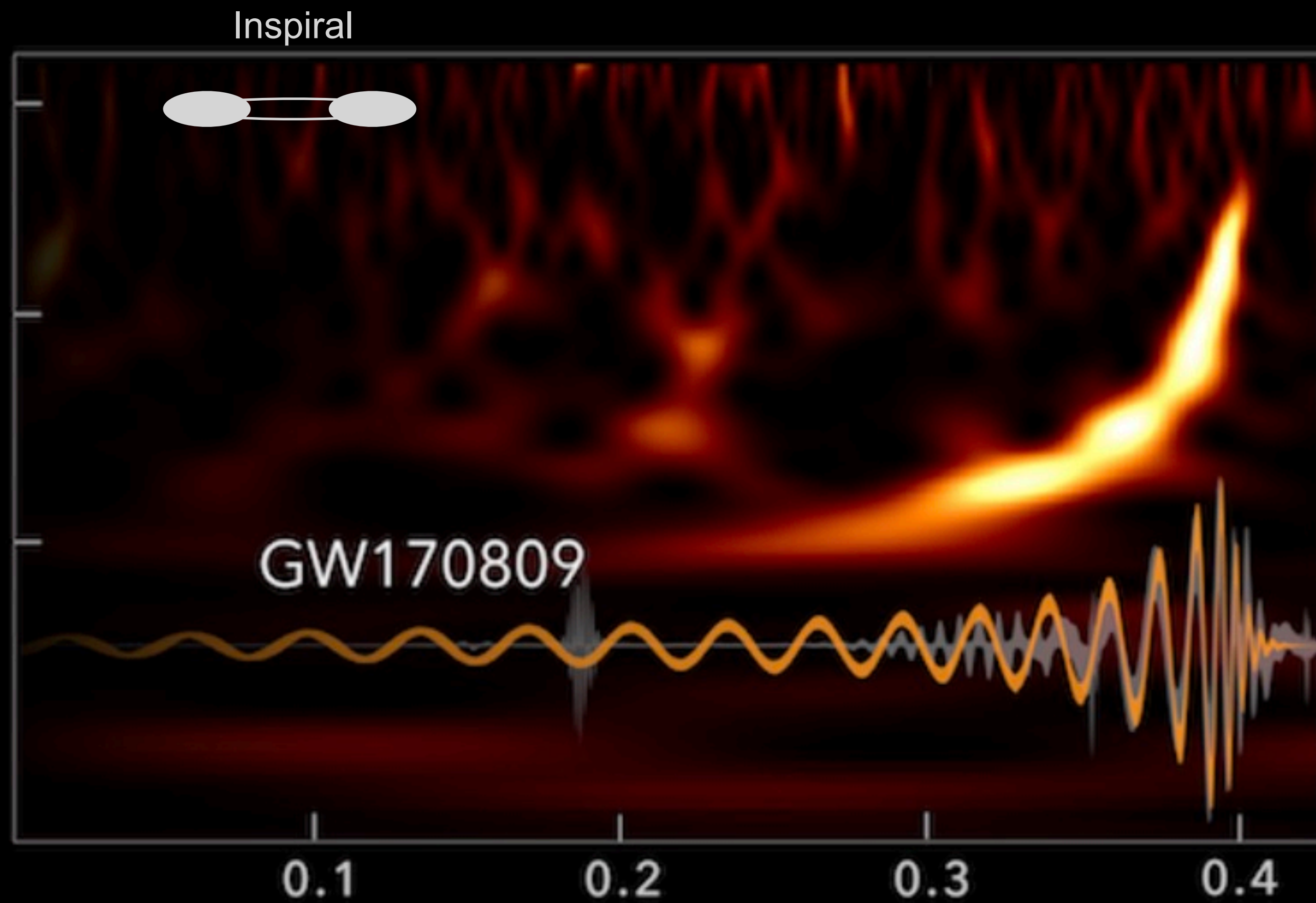


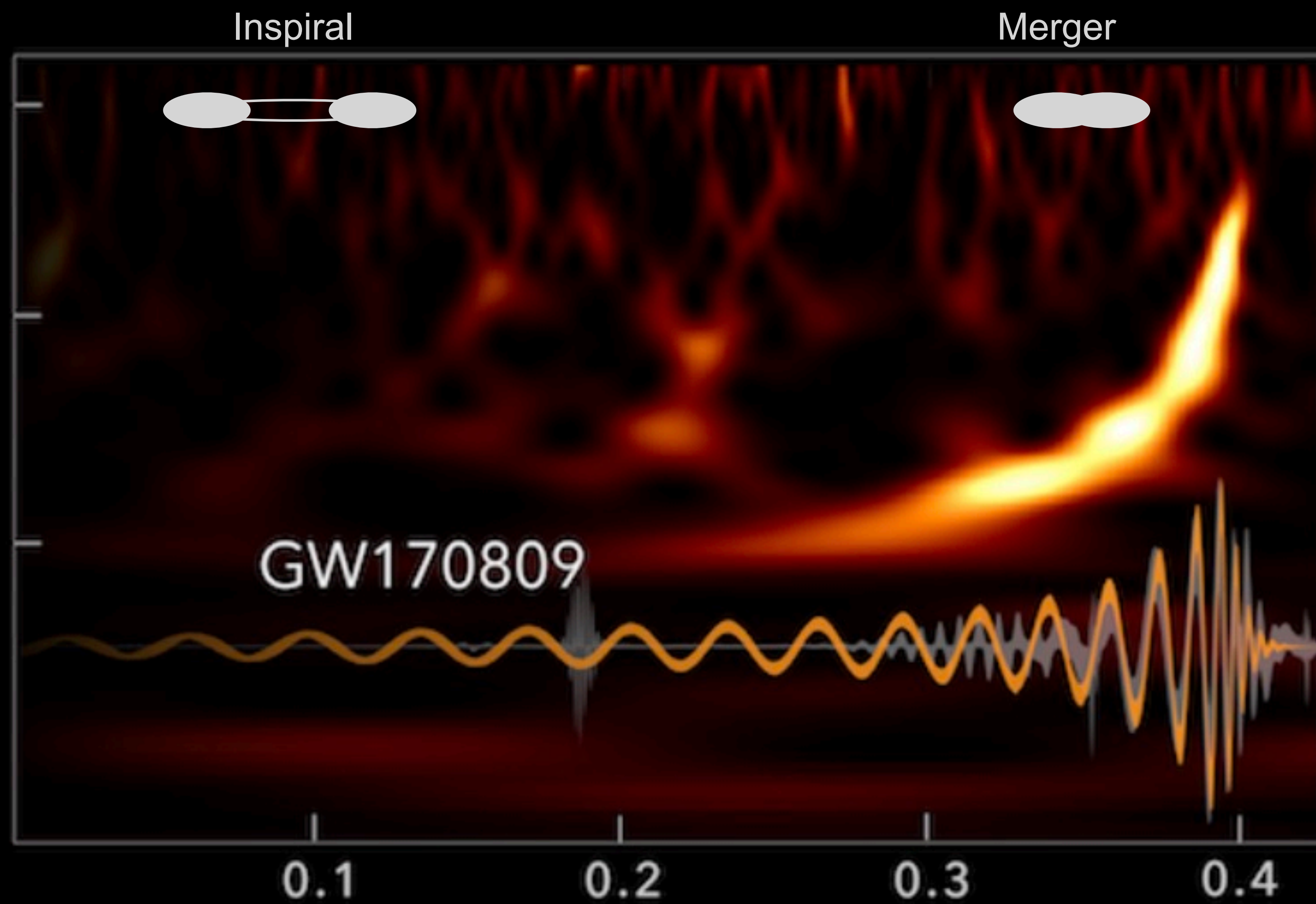
EPS-HEP Meeting, July 2021

Phys.Rev.Lett 126.081101 & Phys.Rev.Lett 126.201101 (2021)

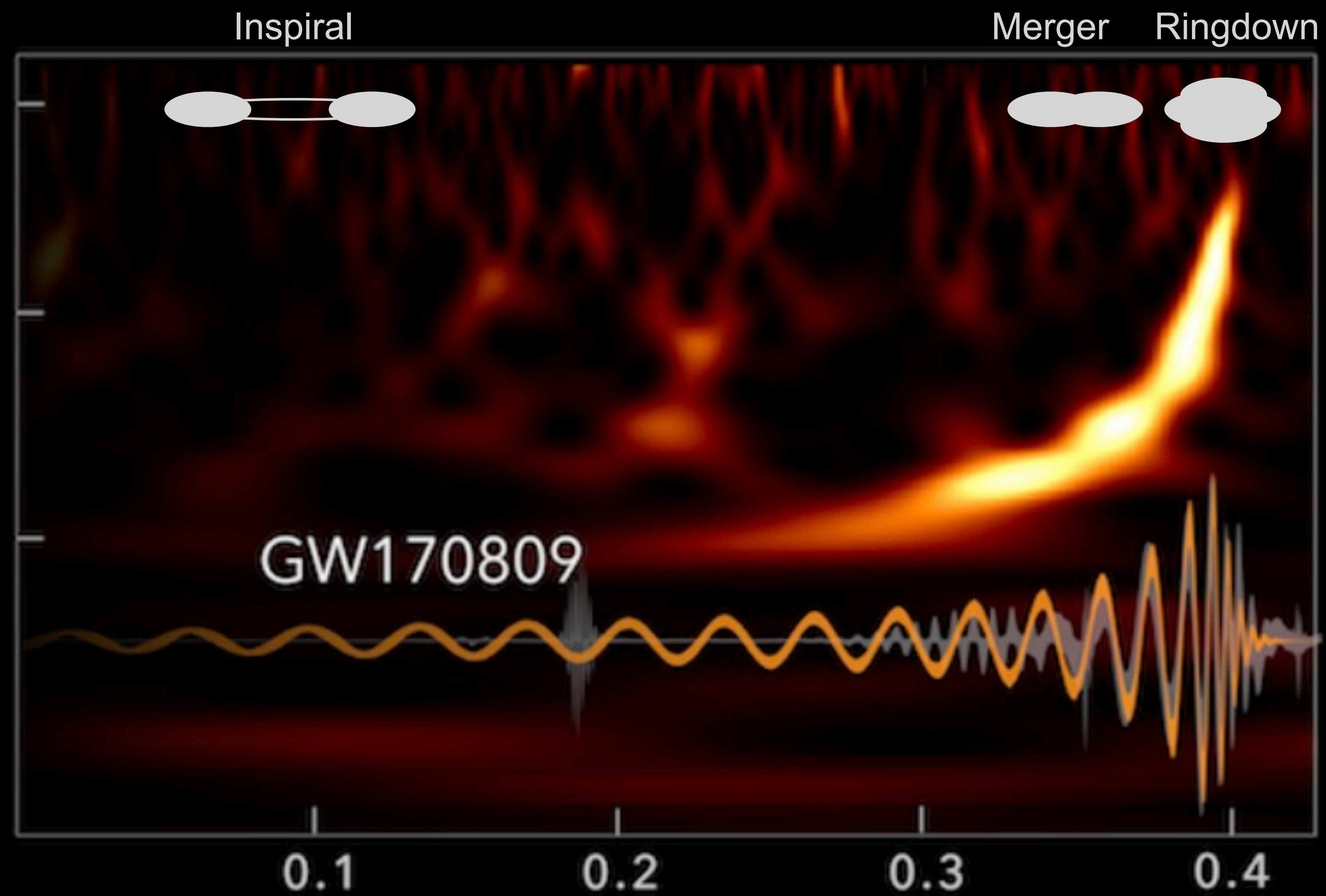
\*juan.calderon.bustillo@gmail.com





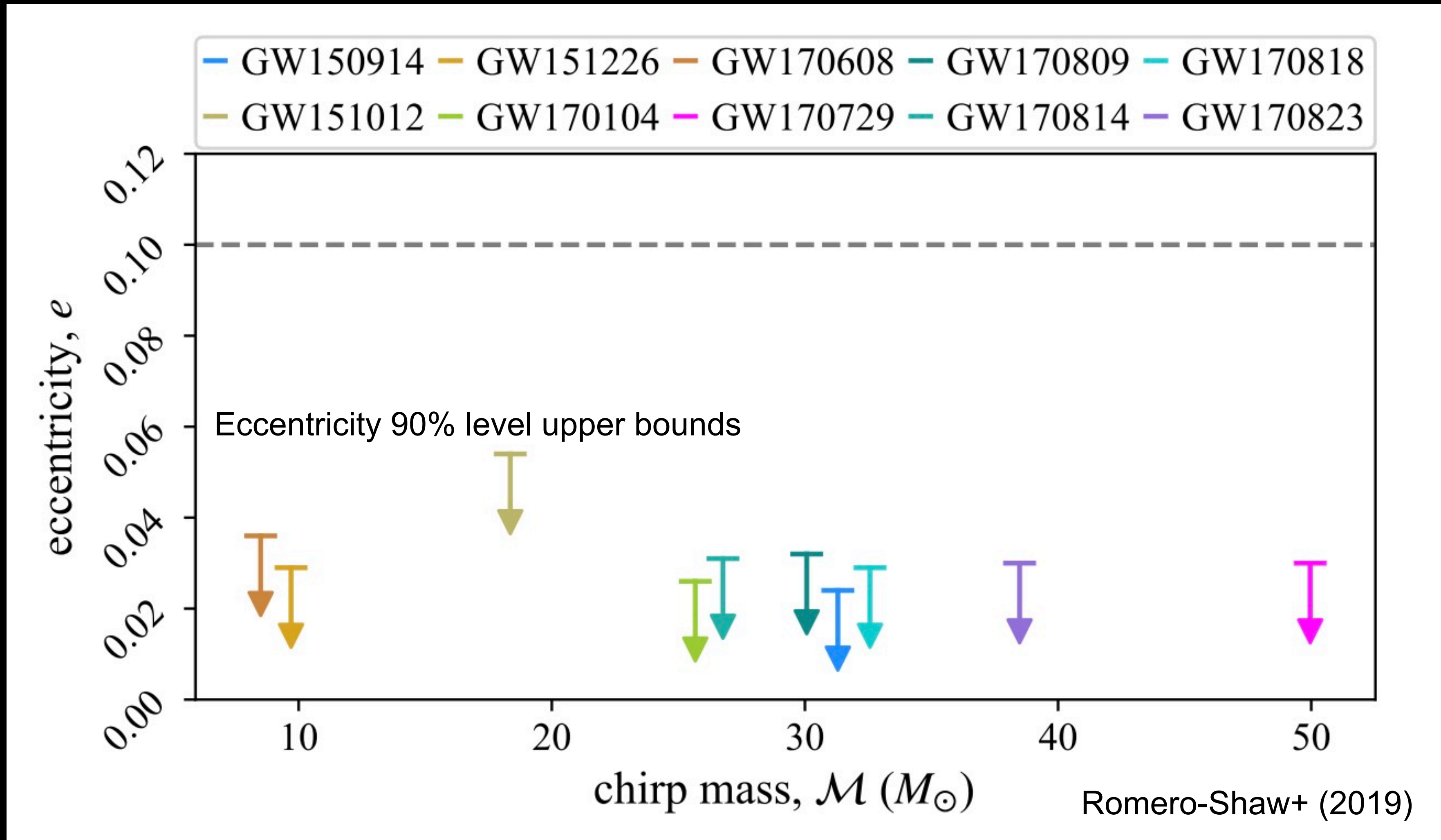




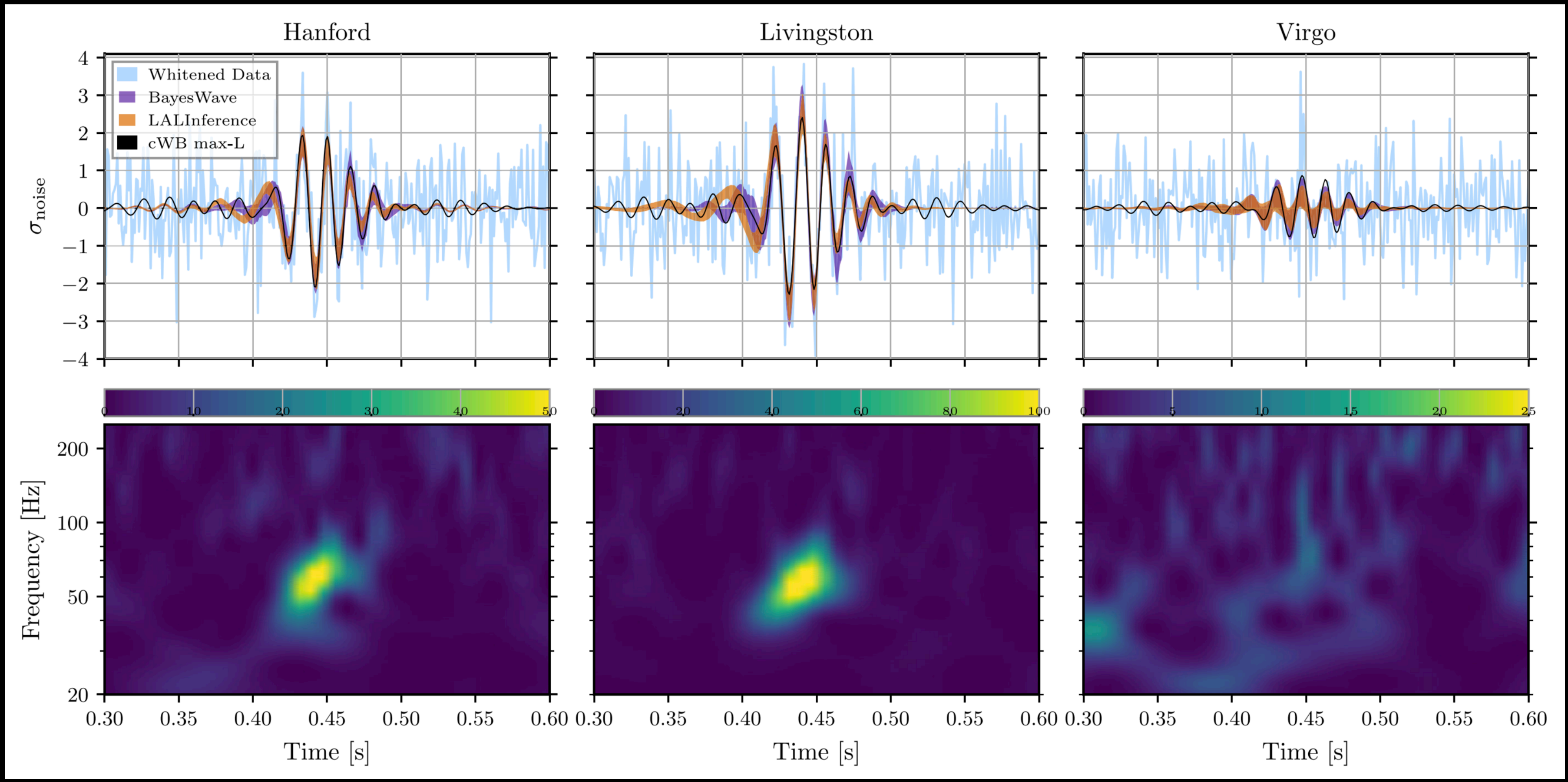


Safe to assume a “vanilla” quasi-circular inspiral process





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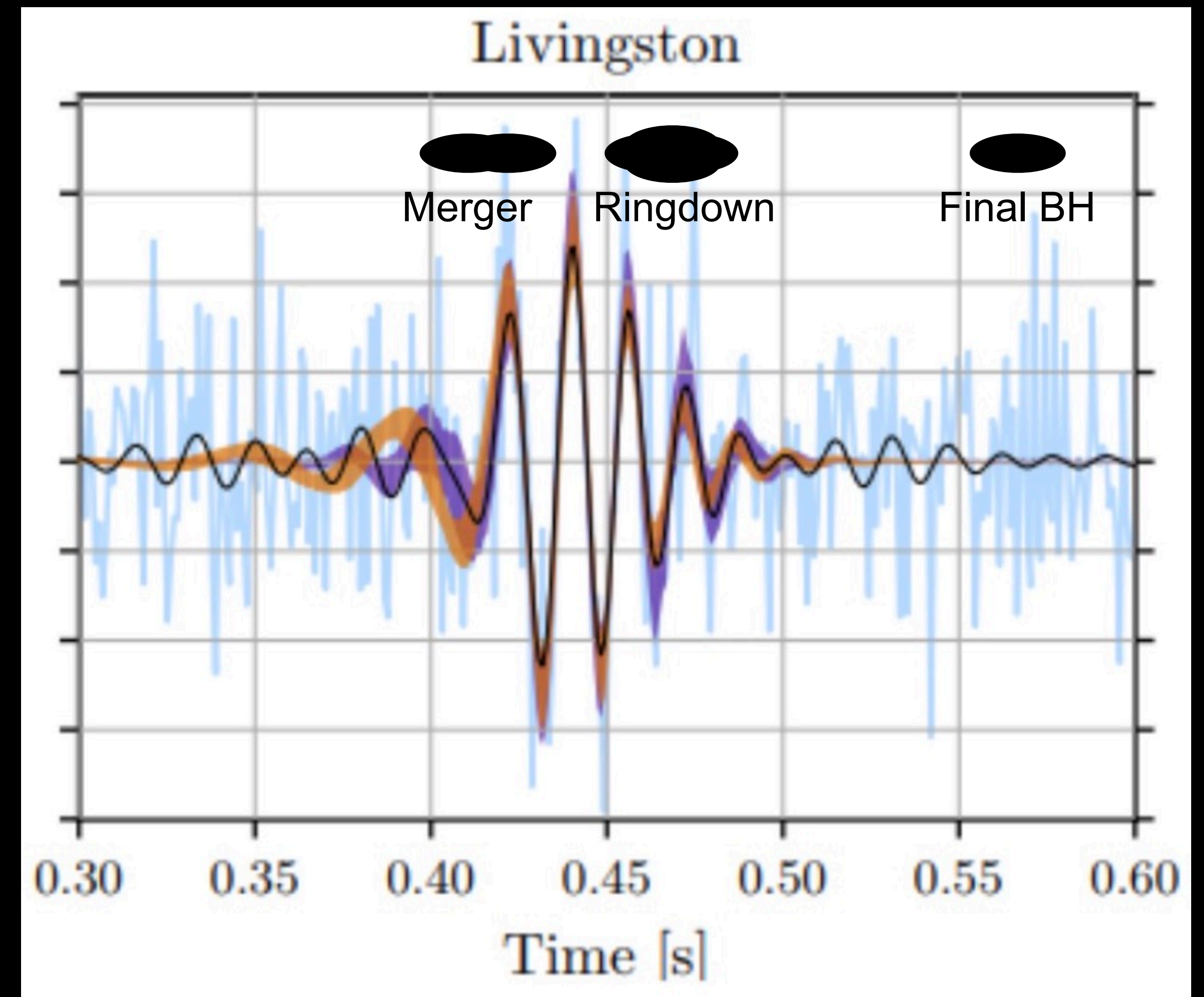


May 21st 2019

LIGO-Virgo (LVC) 2020

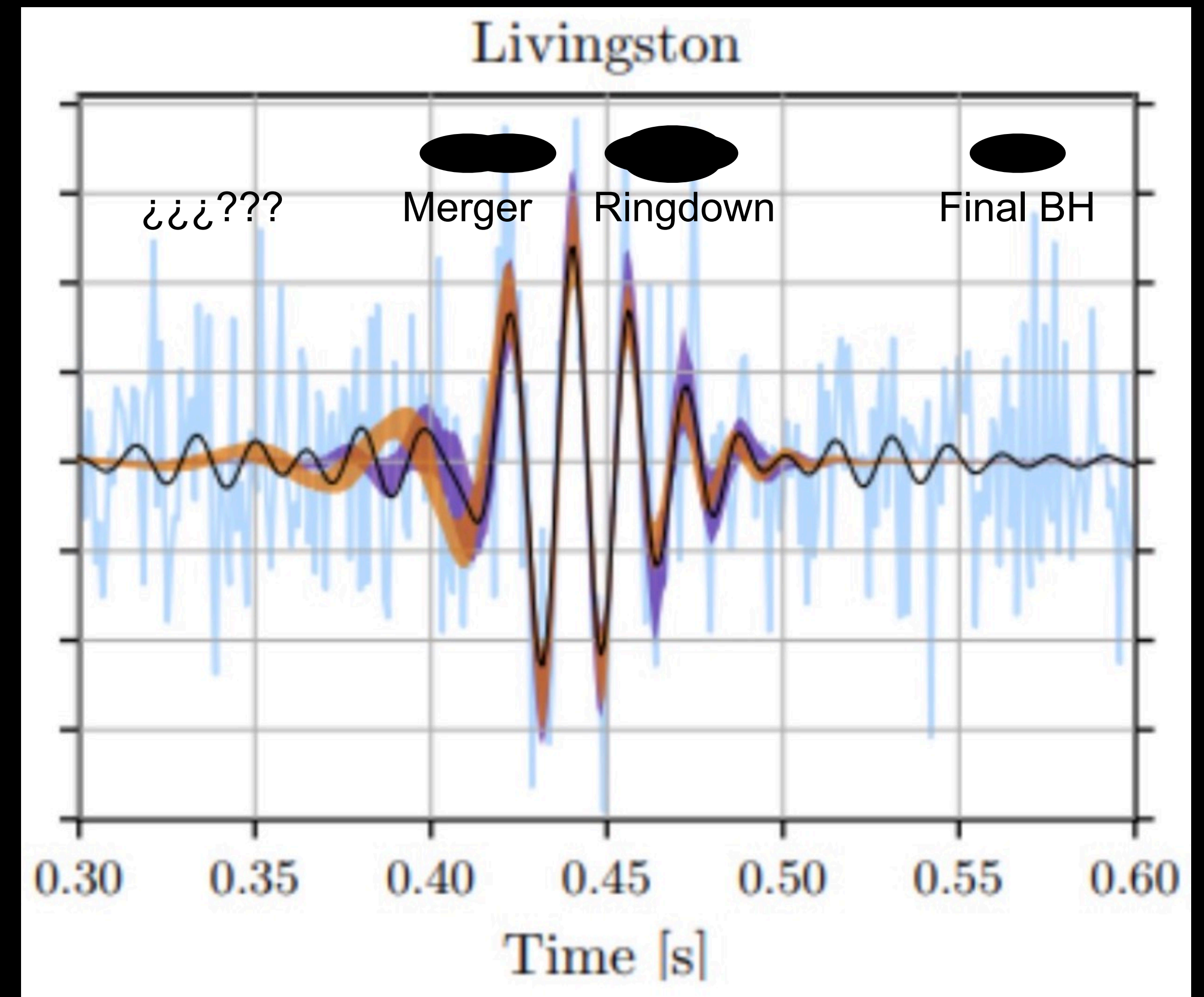


- Barely any (visible) pre-merger emission
  - Remnant: intermediate-mass black hole.
  - If BBH: primary black hole in the pair instability supernova gap.

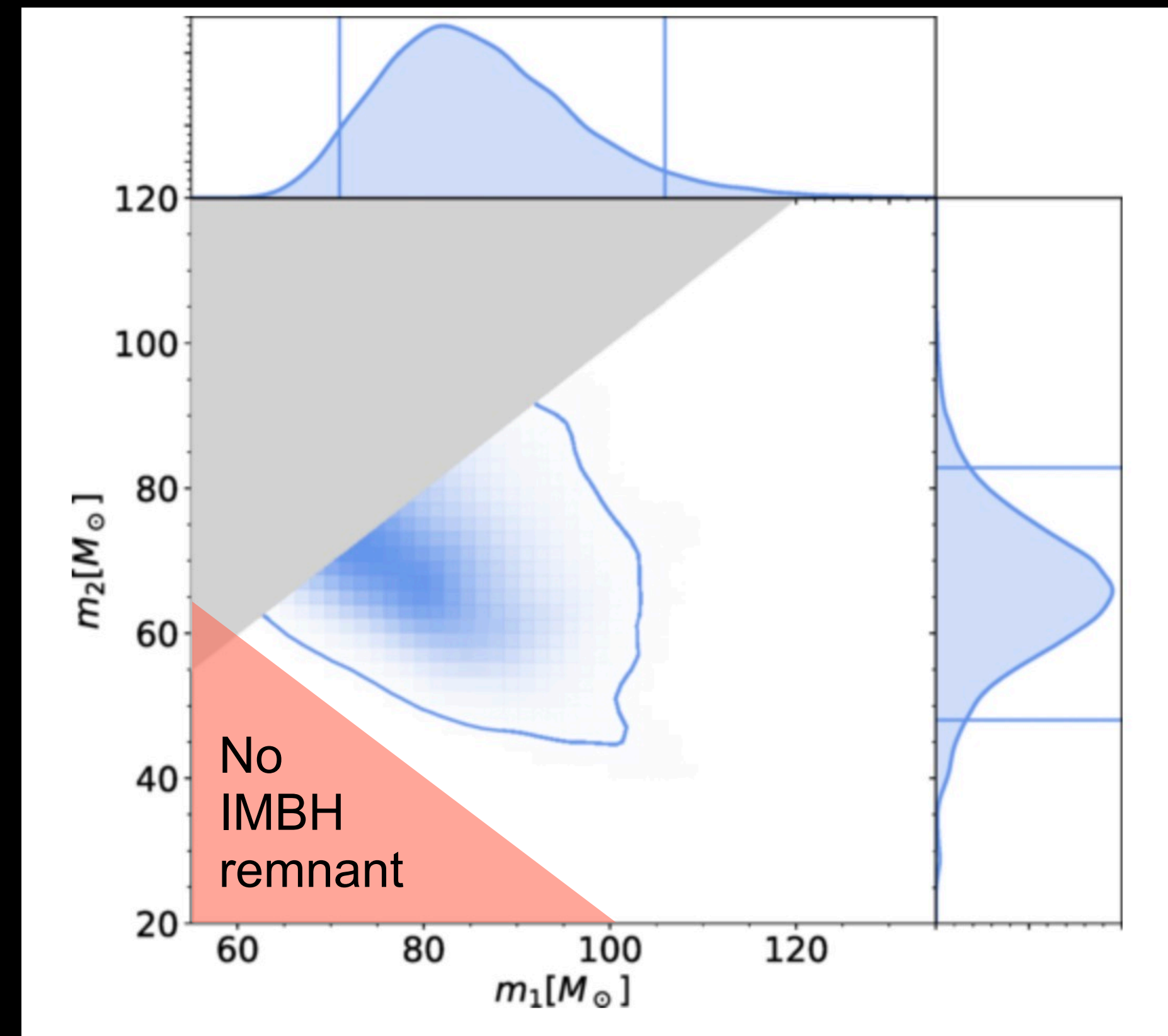




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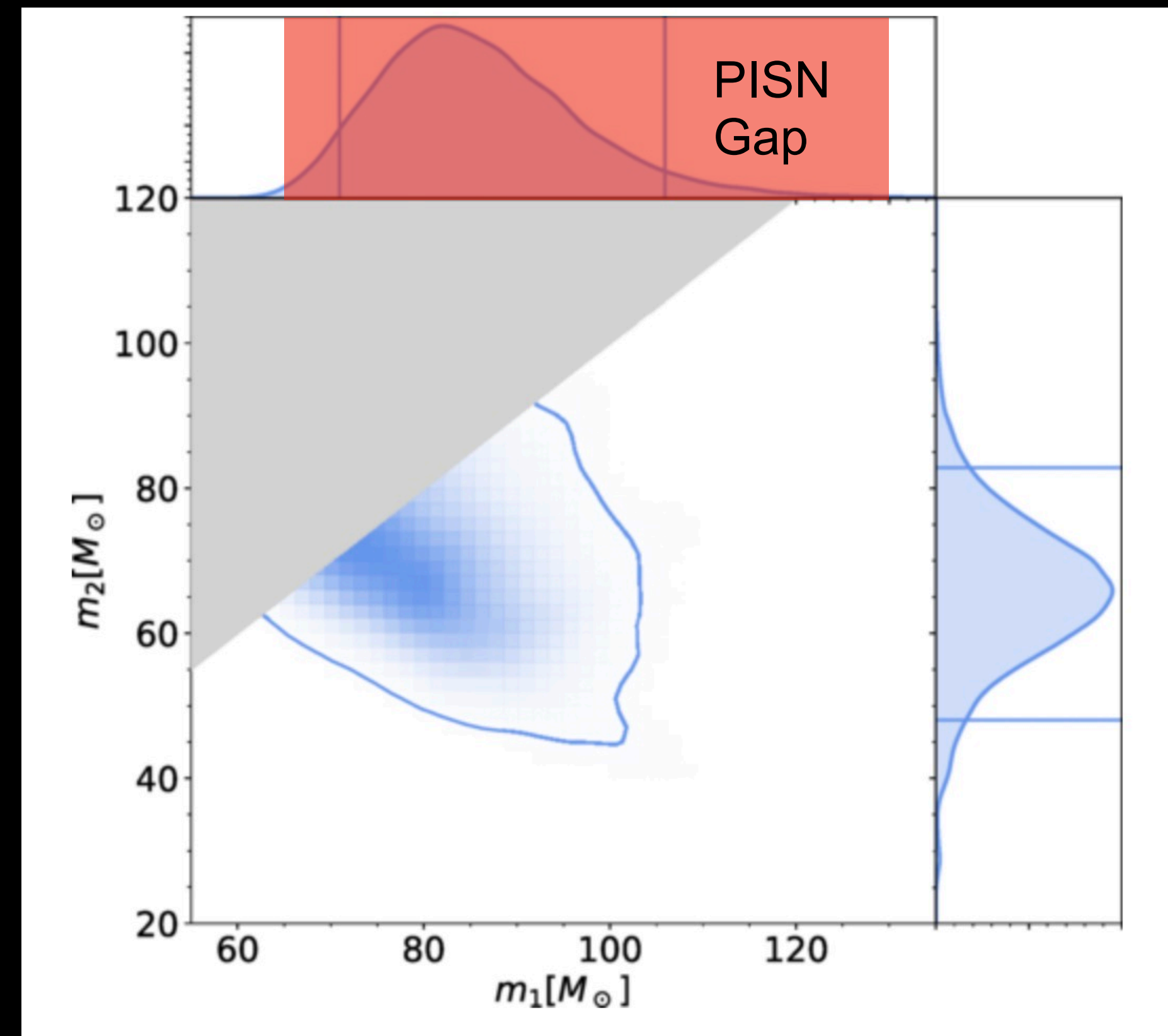


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LVC 2020  
Waveform Model NRSur7dq4 (Varma+ '19)

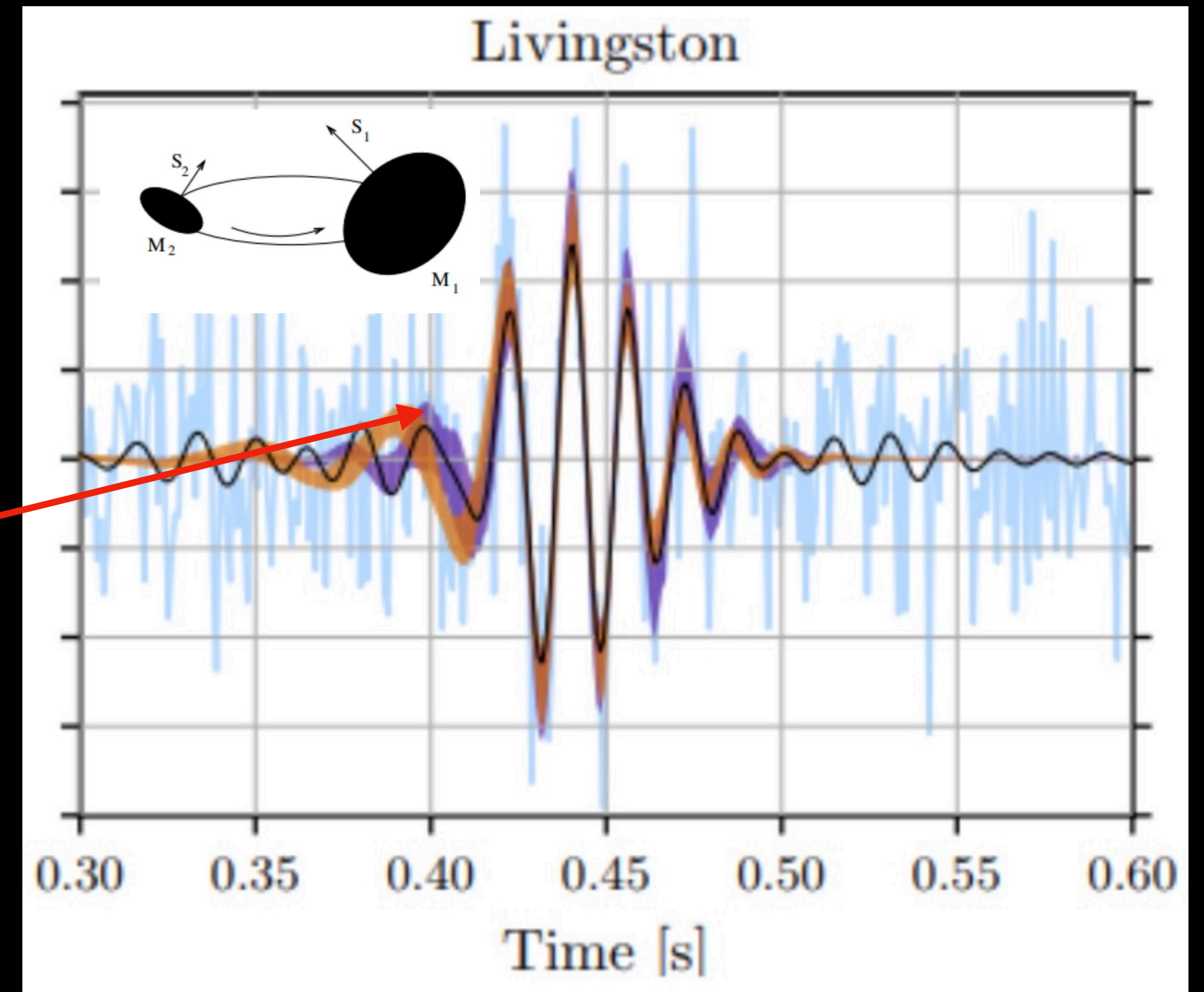
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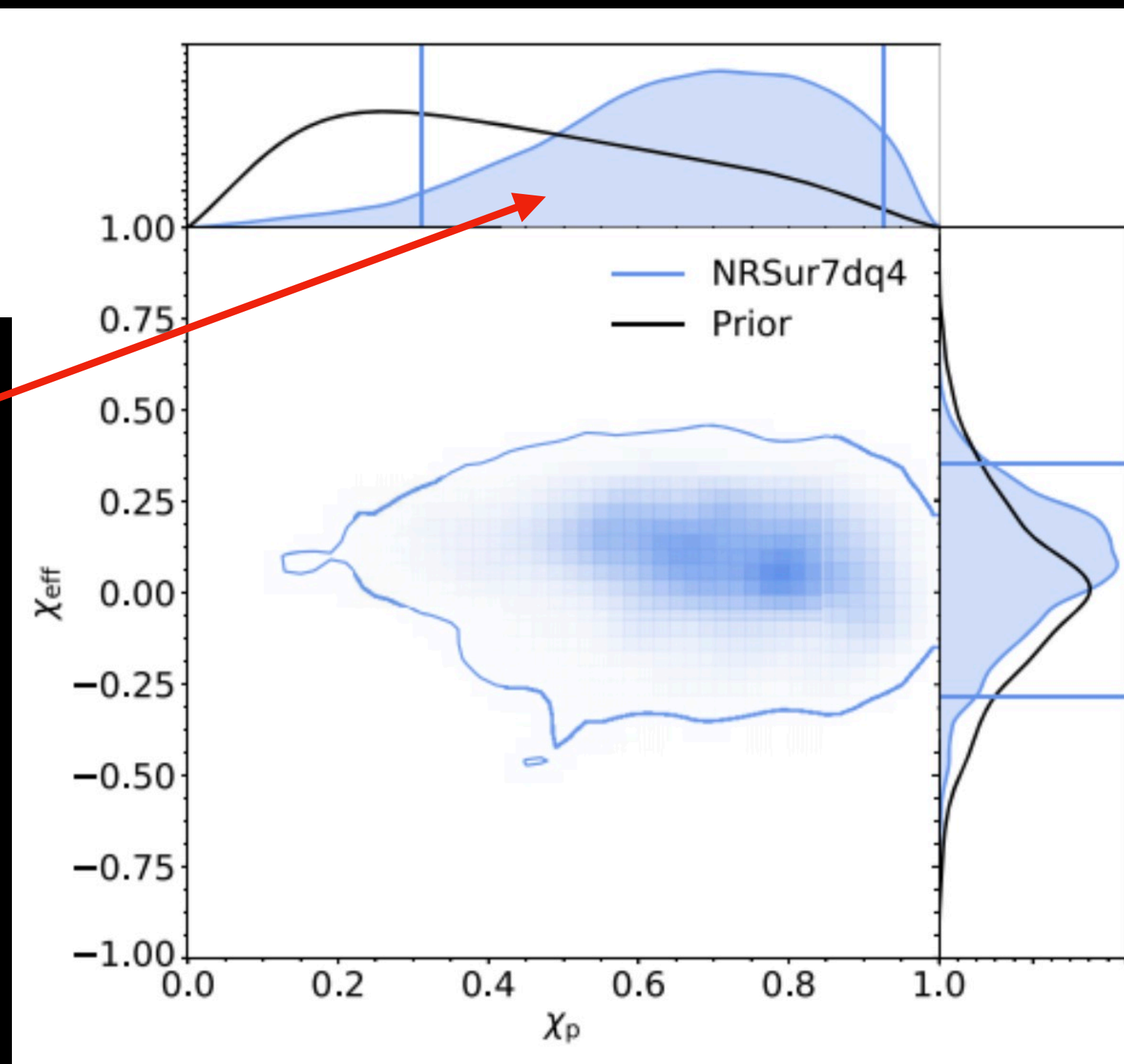
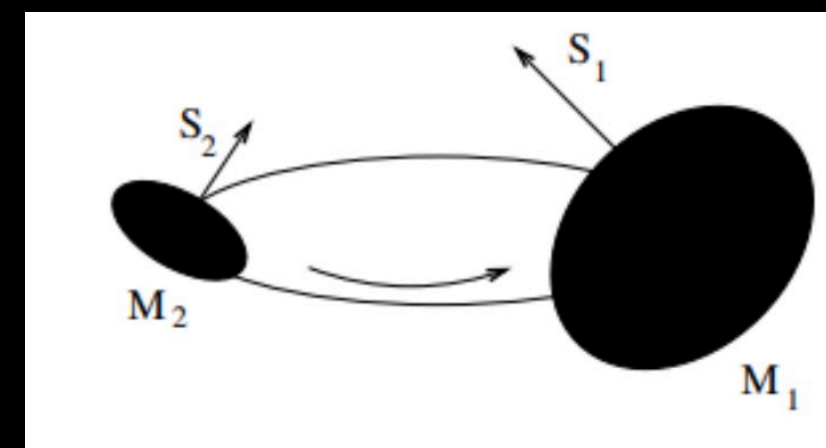
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Extremely detailed study: Estellés et. al. 2021



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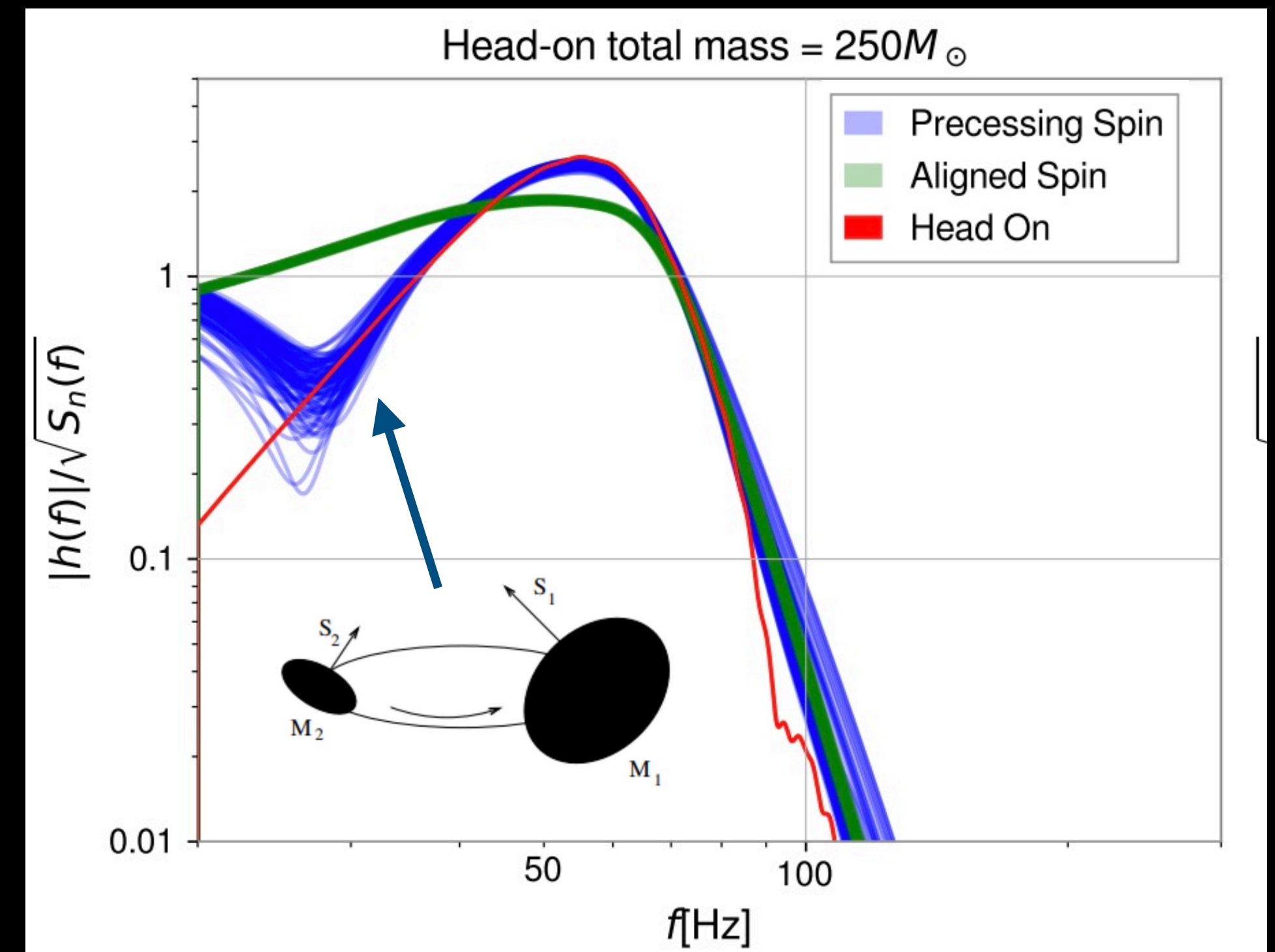
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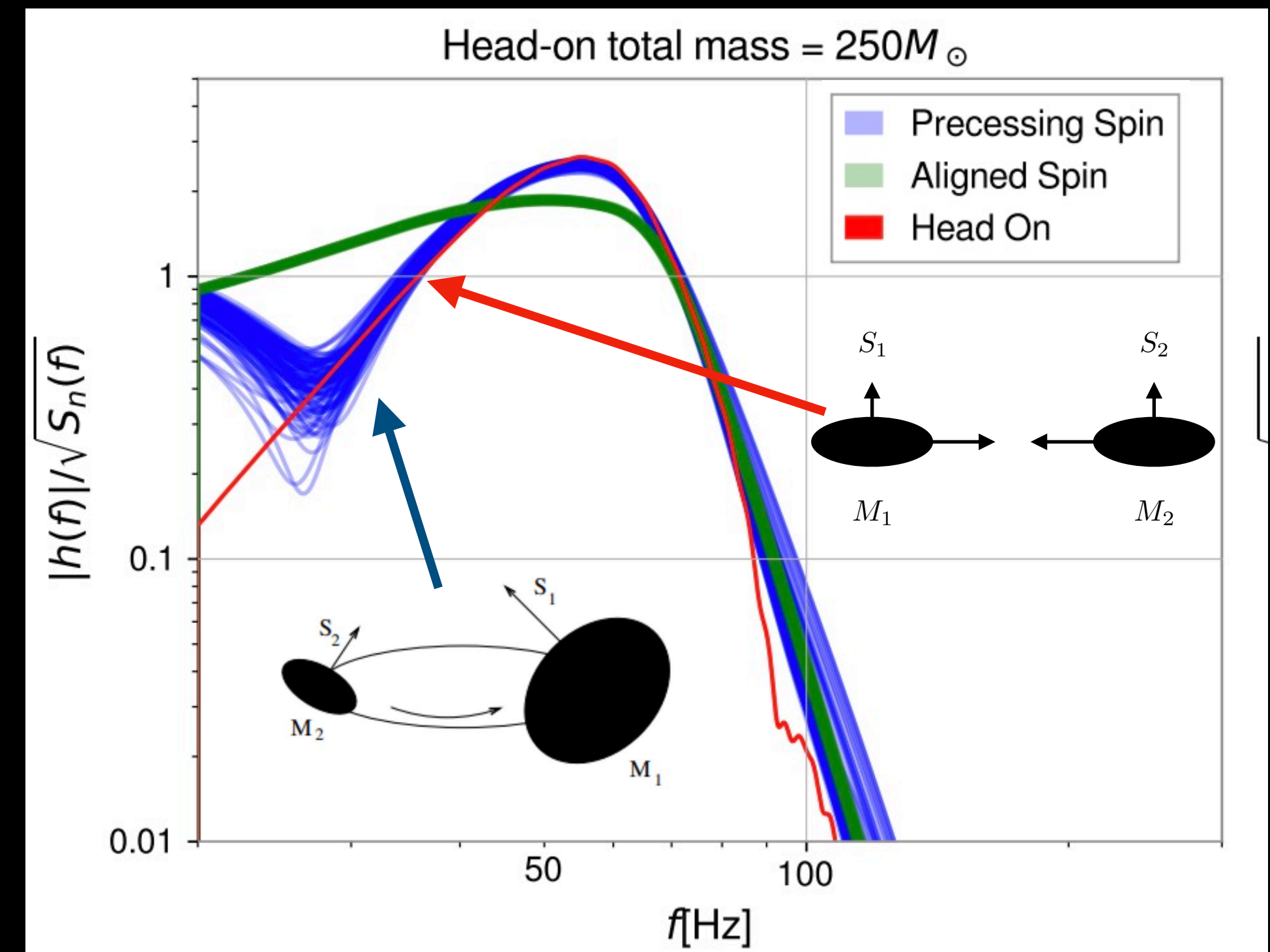
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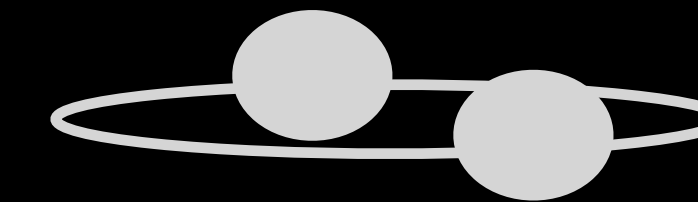
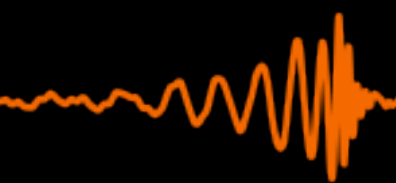
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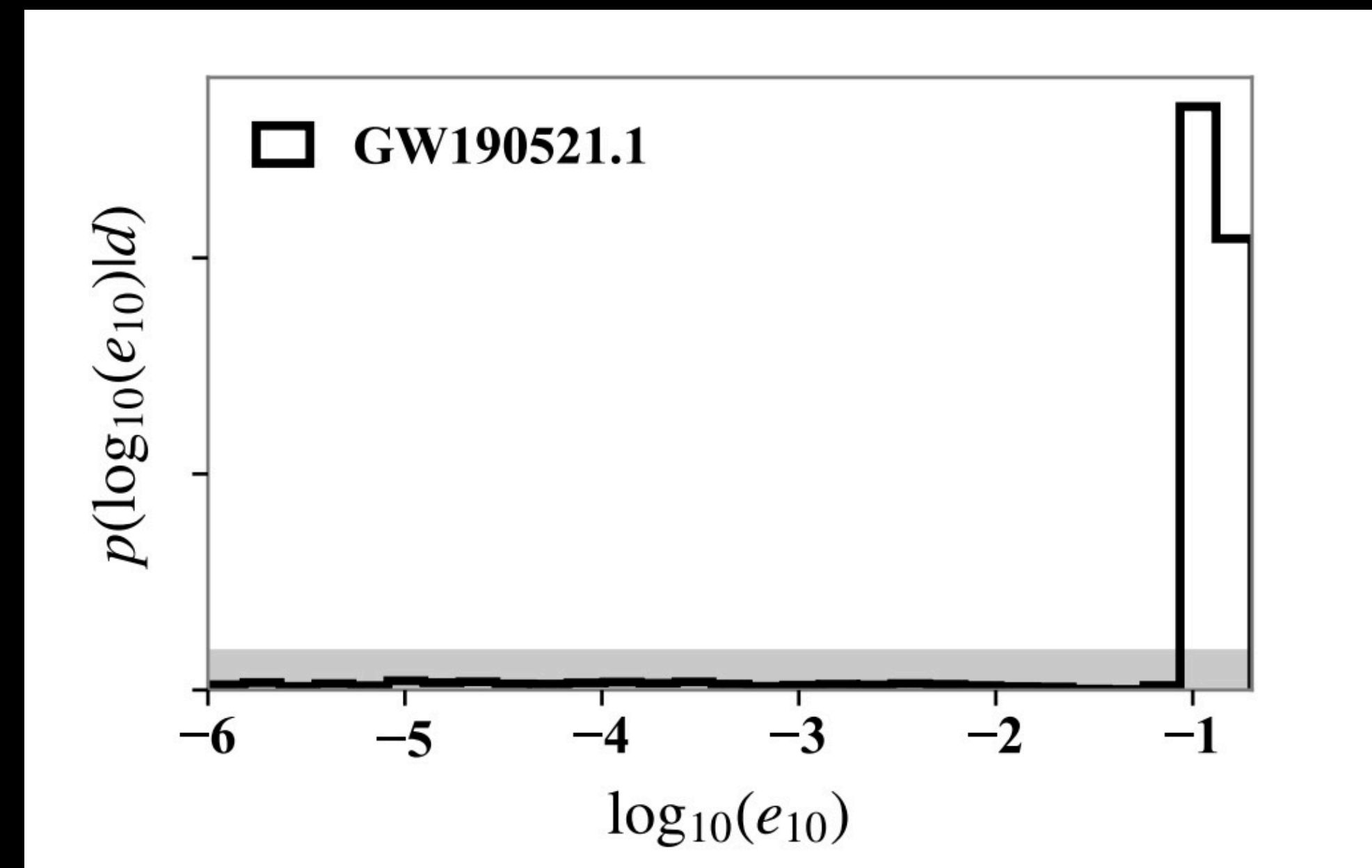
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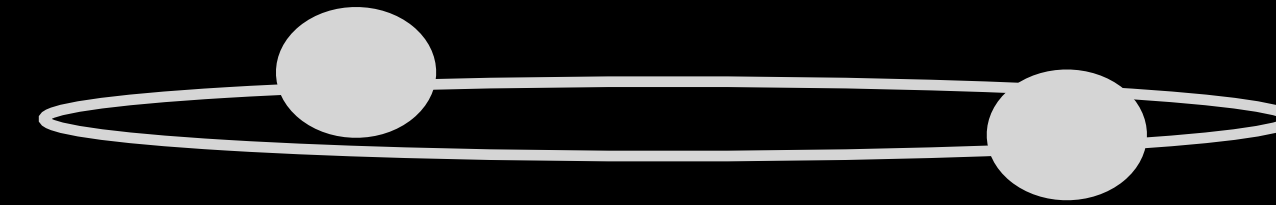


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Romero-Shaw+ (2020)



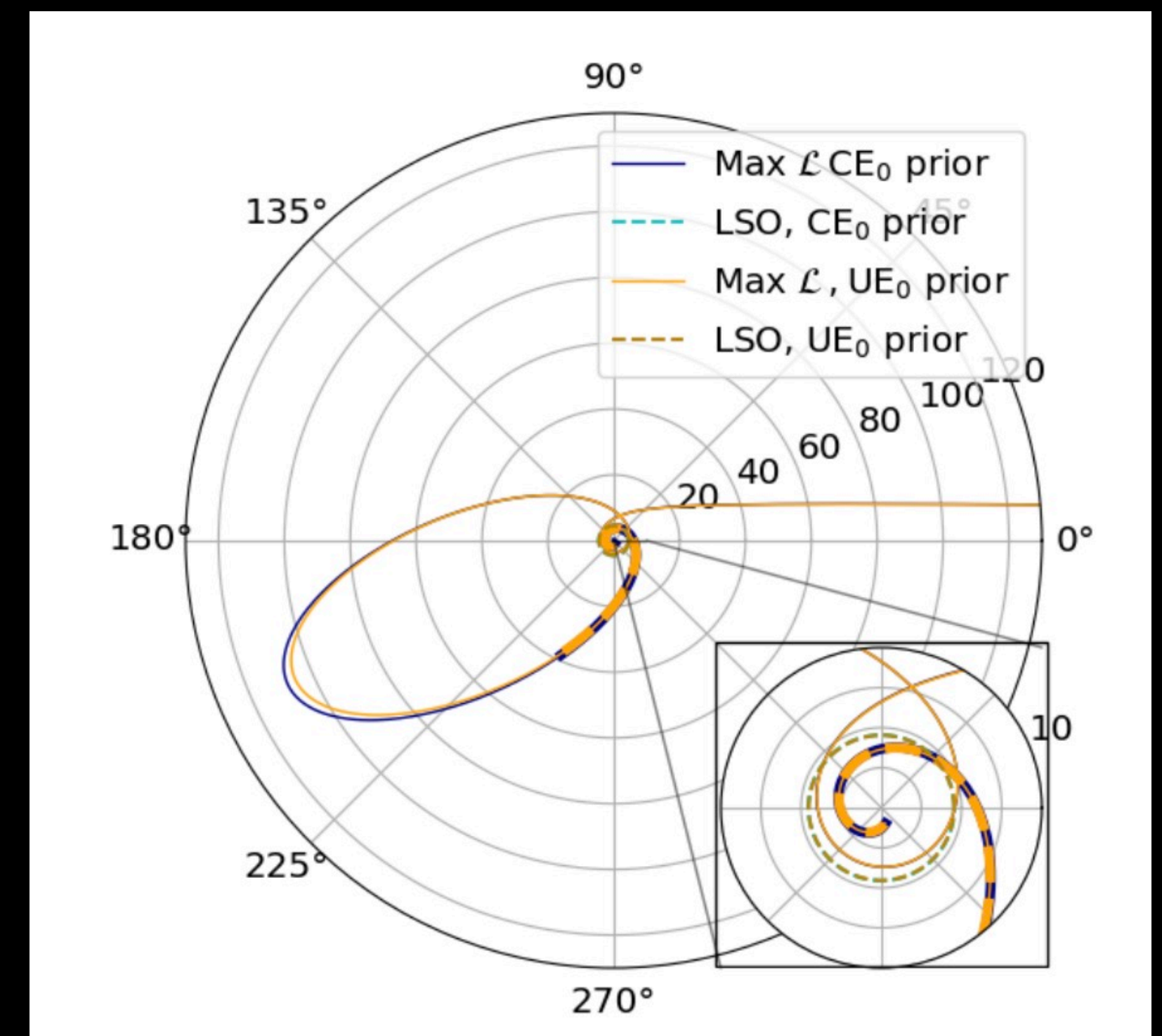


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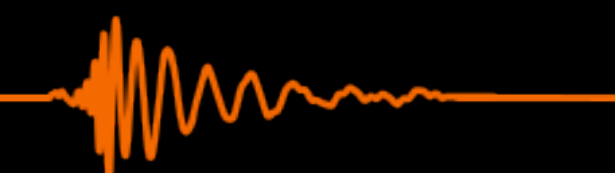
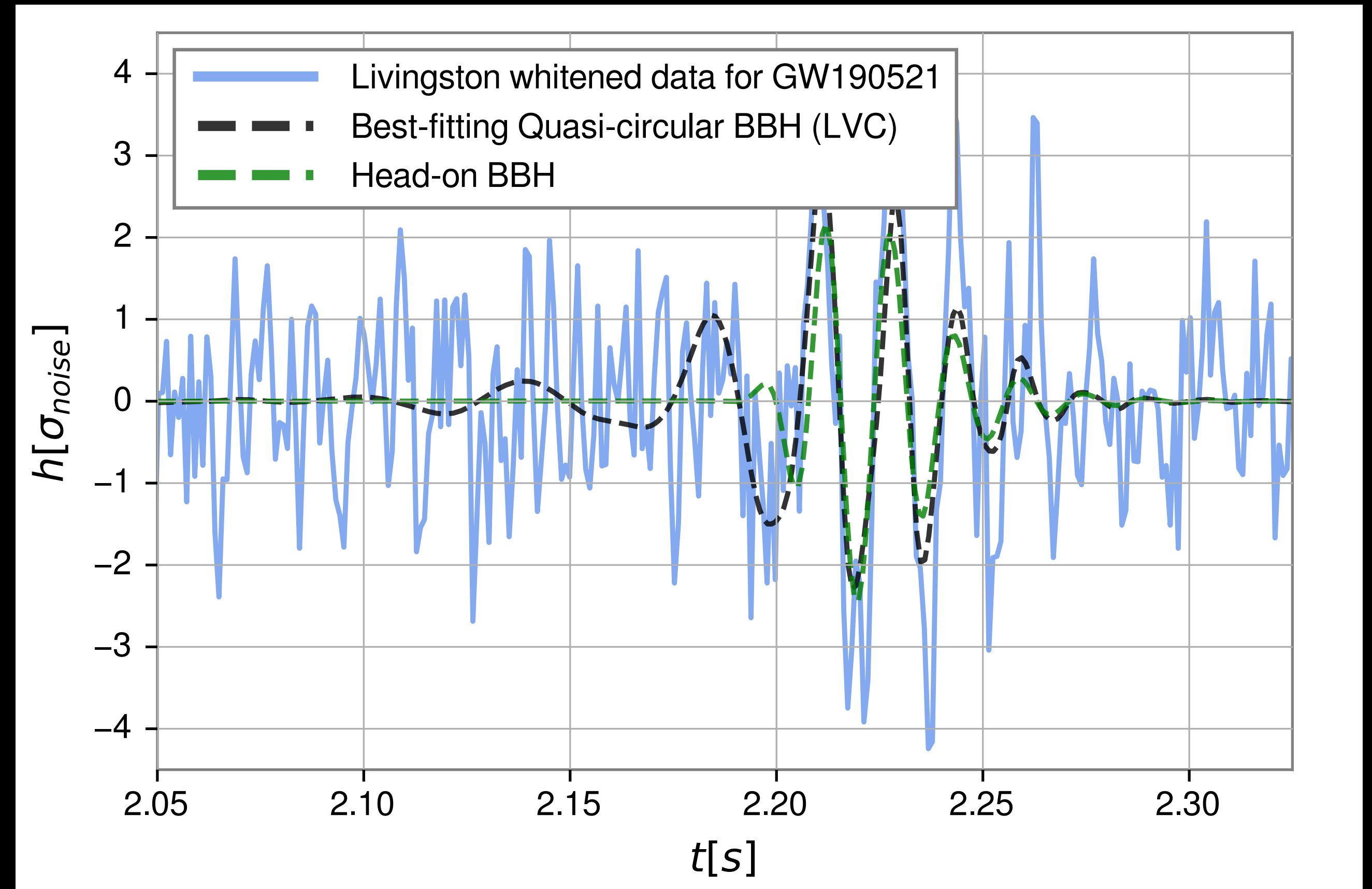
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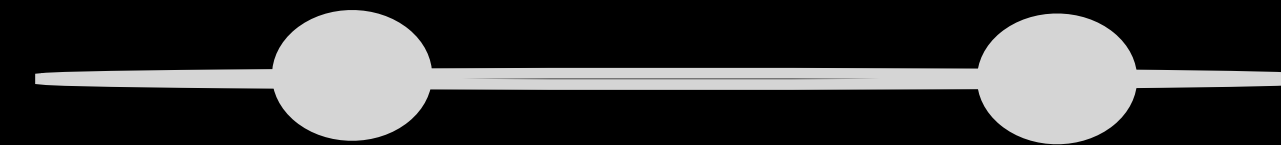


Gamba+ (Today)

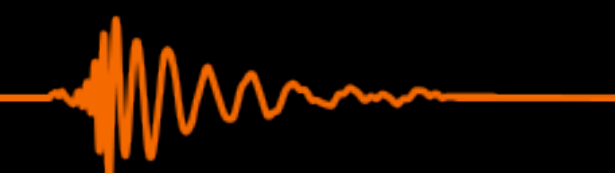
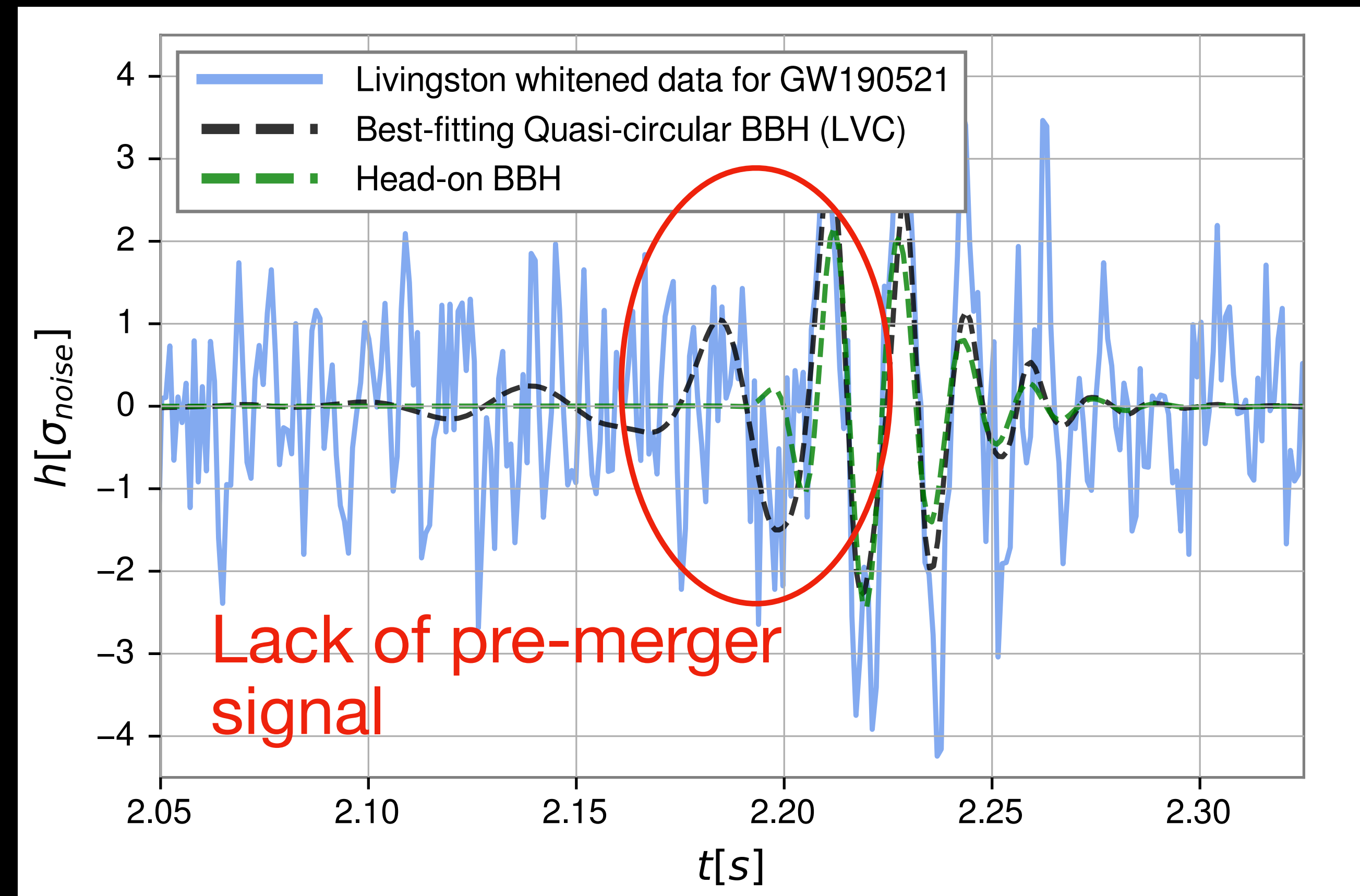
See also: Gamba et al (dynamical capture, on arxiv today) ←

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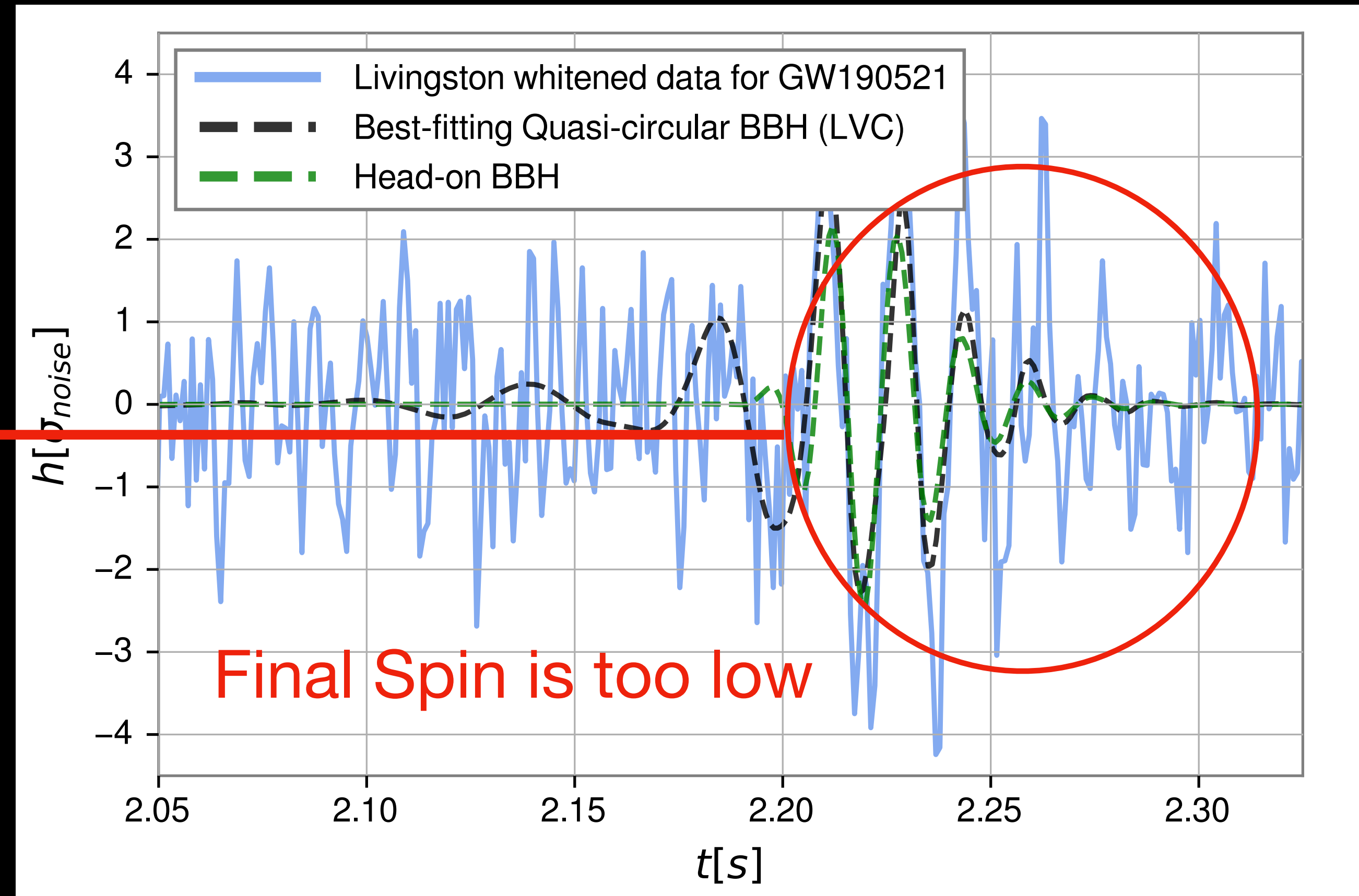
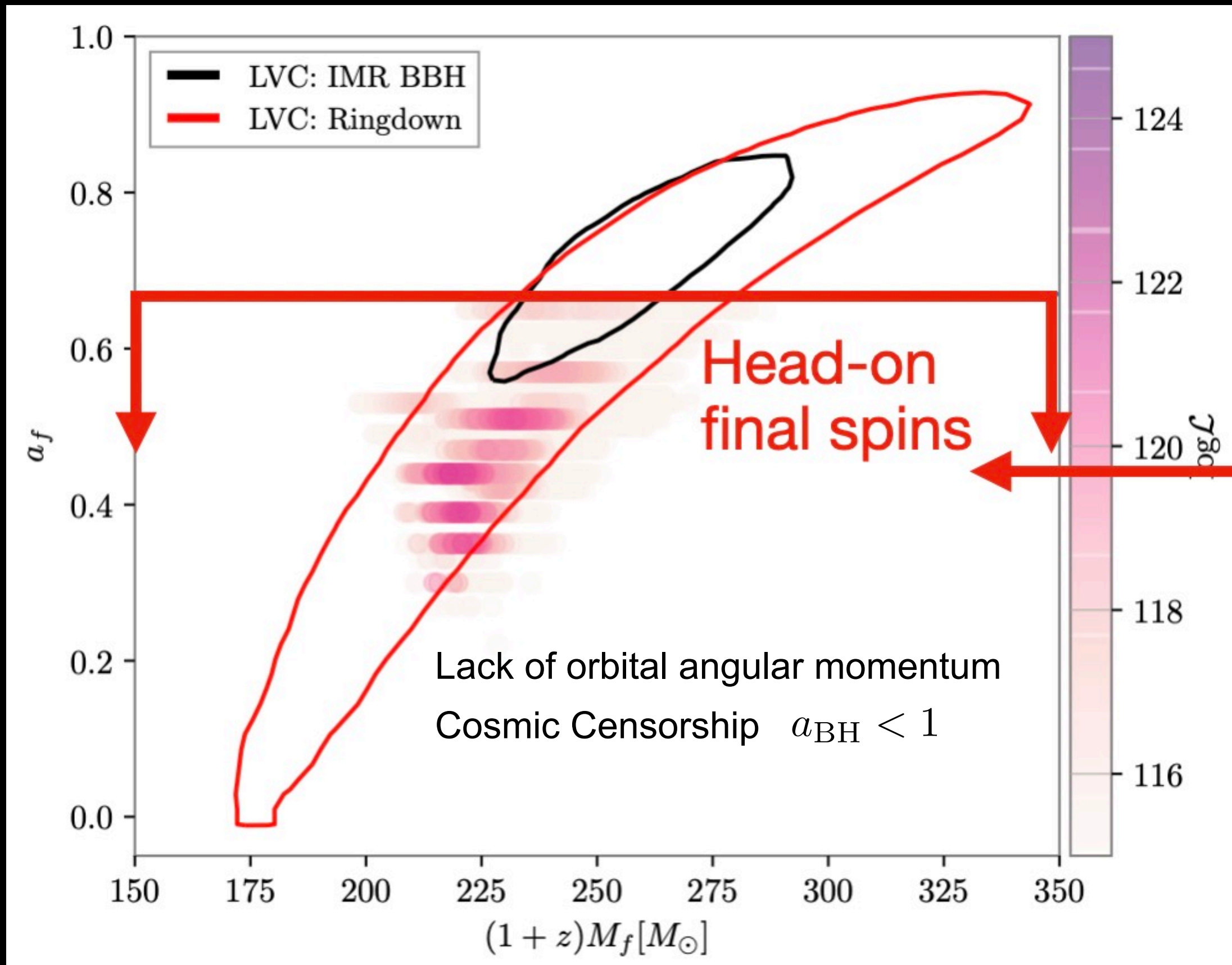
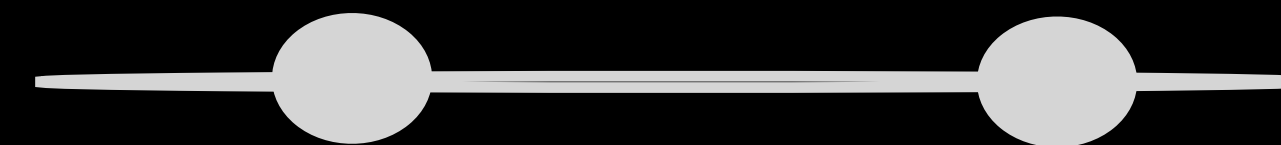




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Credit: Nicolás Sanchis-Gual, Rocío García-Souto



## Self-gravitating Bose Einstein condensates of ultralight bosons

Compact objects with no event horizon (black hole mimickers)

- Can have spins larger than 1!!!
- Can produce highly spinning remnant black holes!

Two “new physics” parameters

- **Oscillation frequency of the field:**
  - Determines the “compactness” of the star
- **Boson mass:**
  - Determines the maximum mass of the star (before collapsing to a black hole)
- **Dark-Matter candidates**





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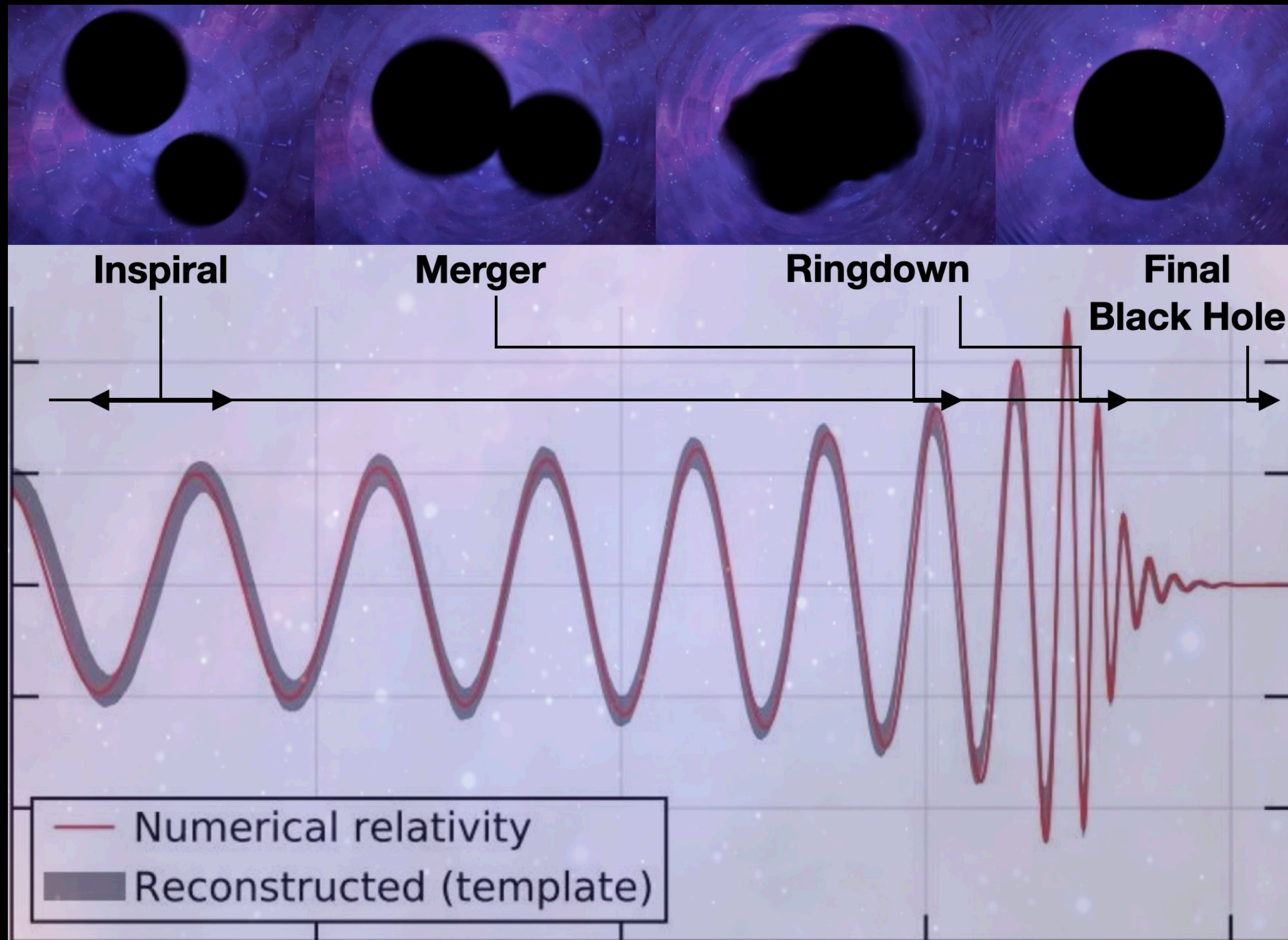
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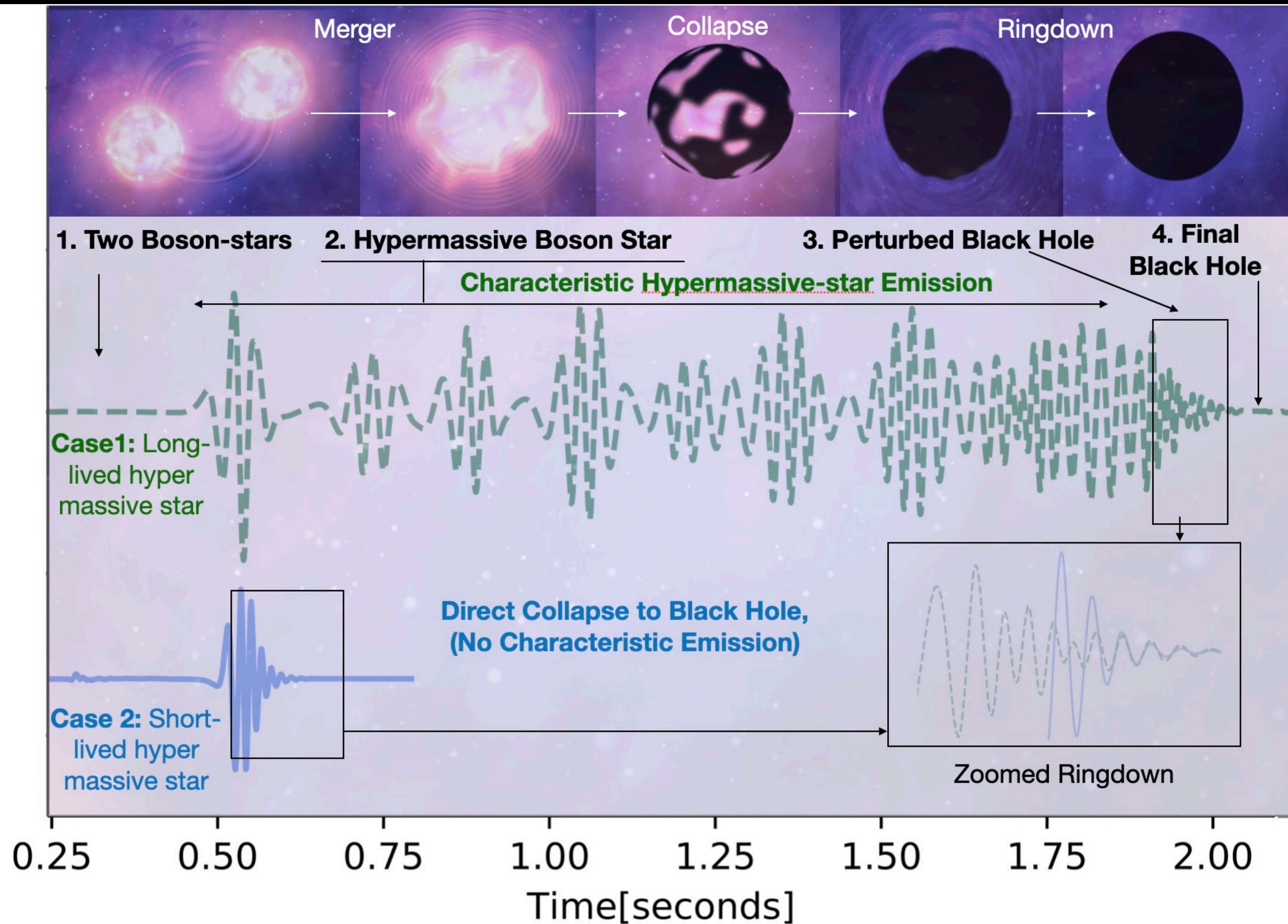
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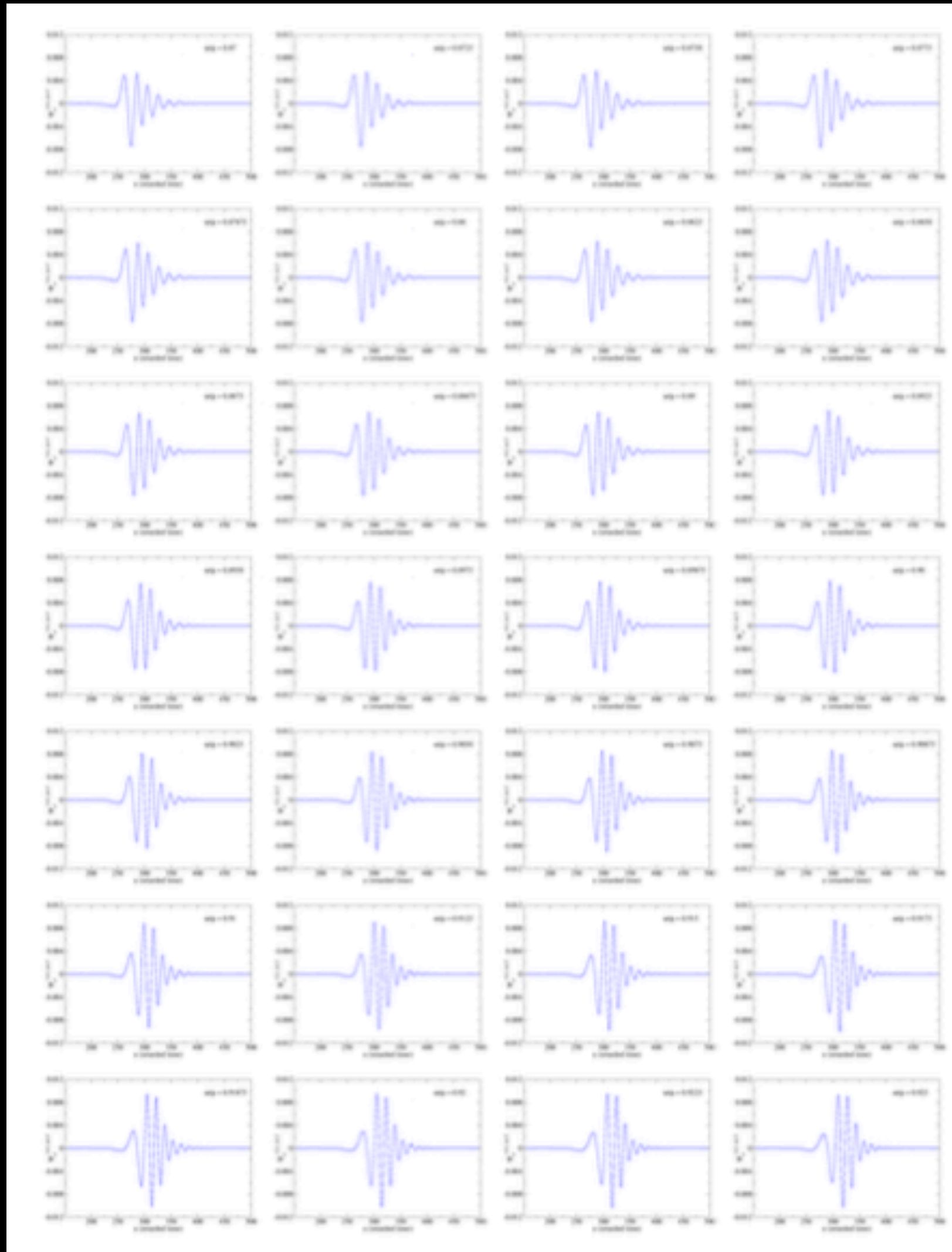




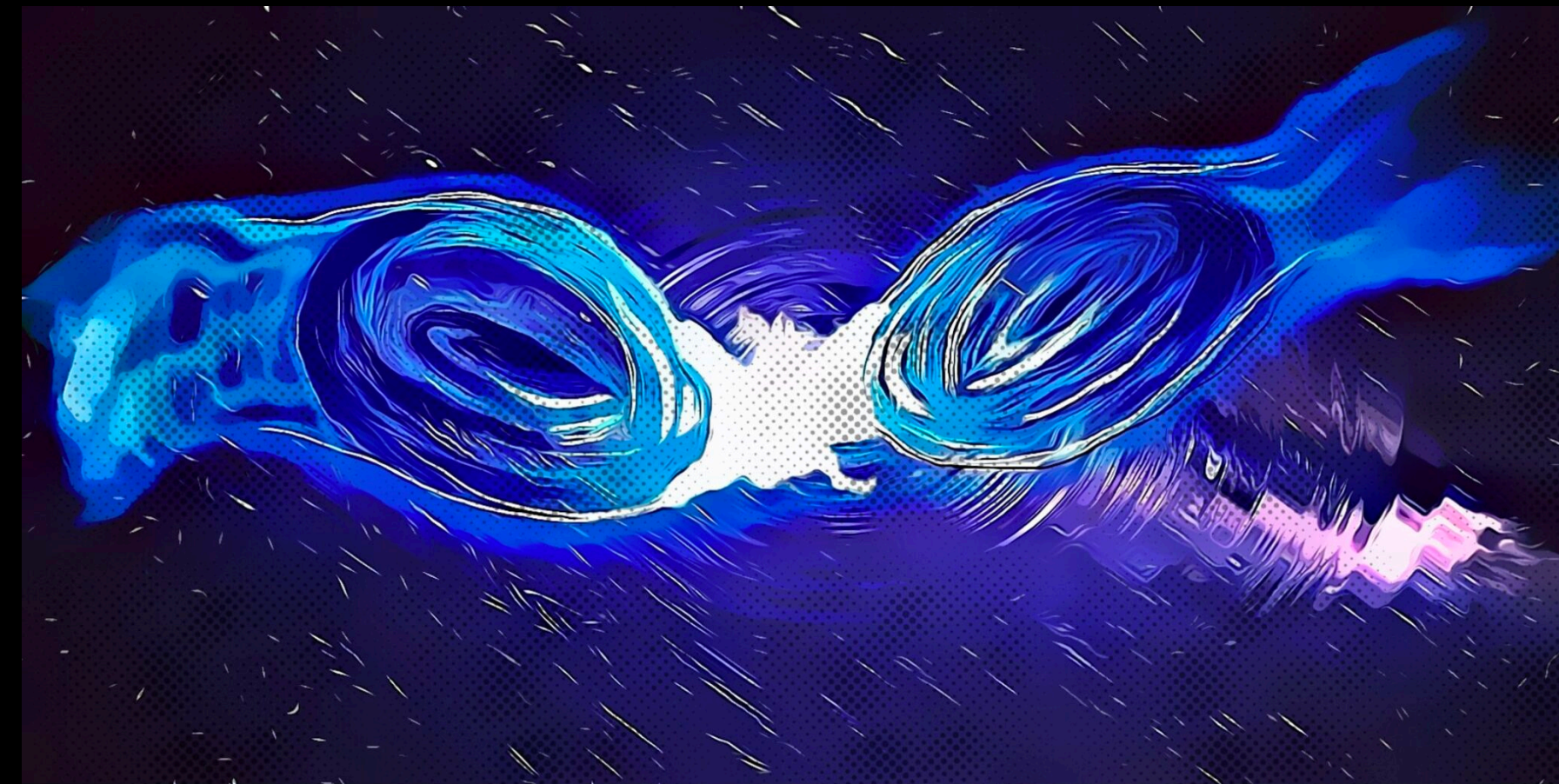




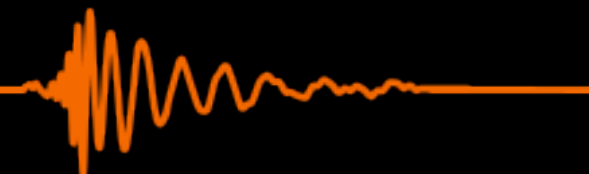




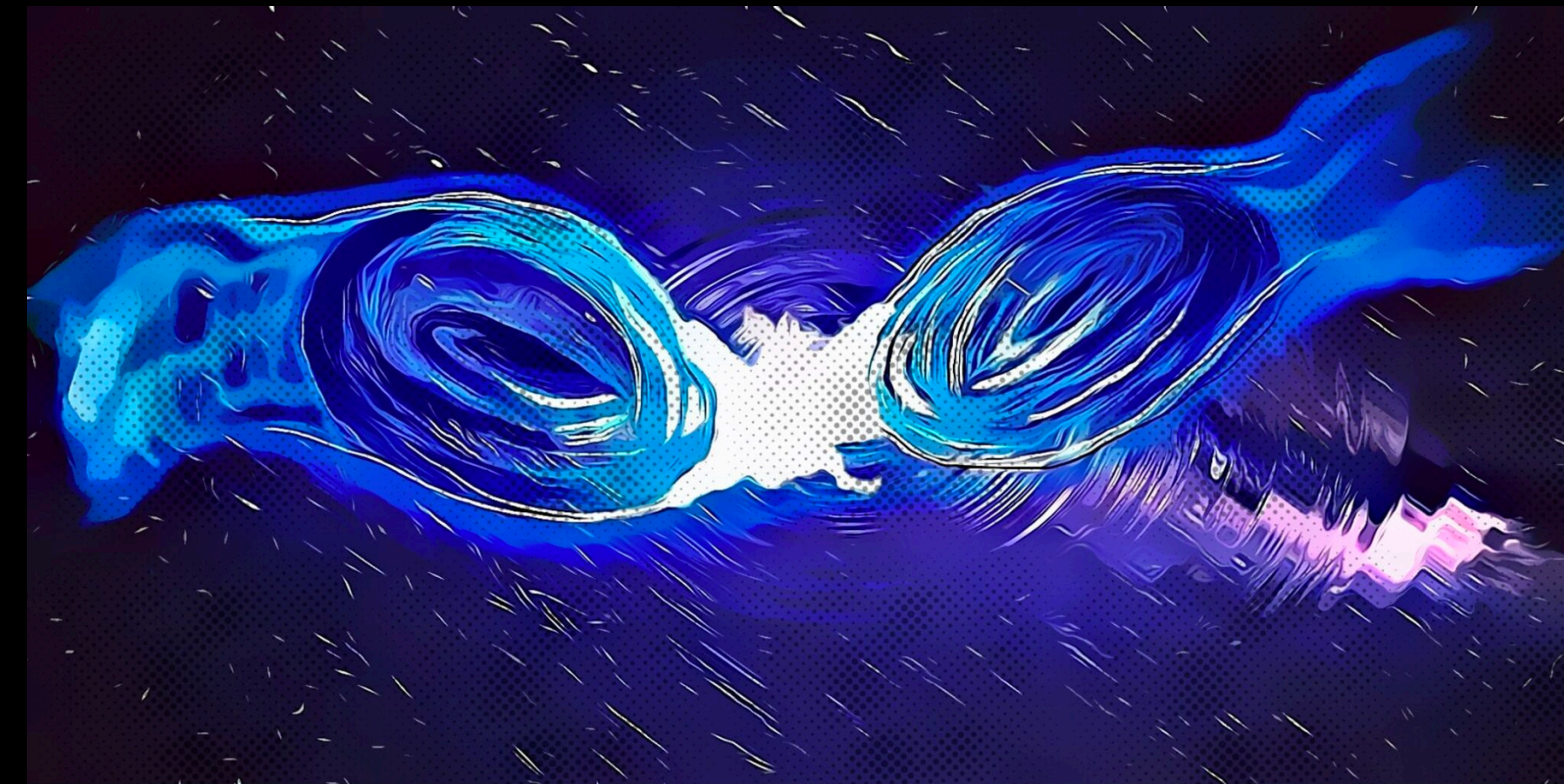
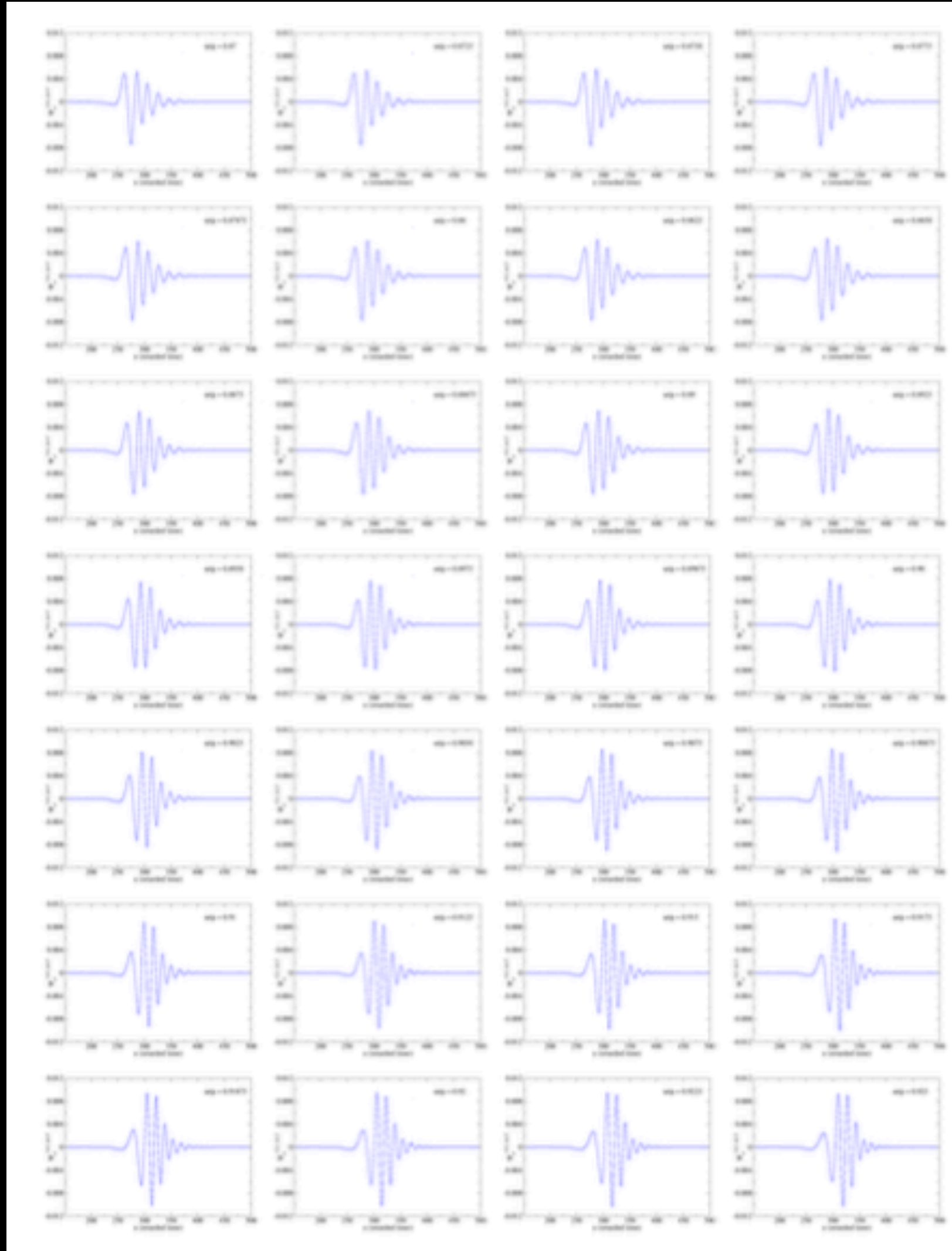
Credit: Nicolás Sanchis-Gual



einstein  
toolkit







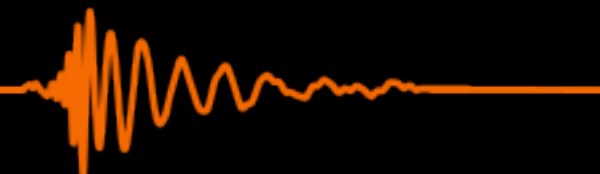
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Equal-mass, equal field frequency (equal spin)

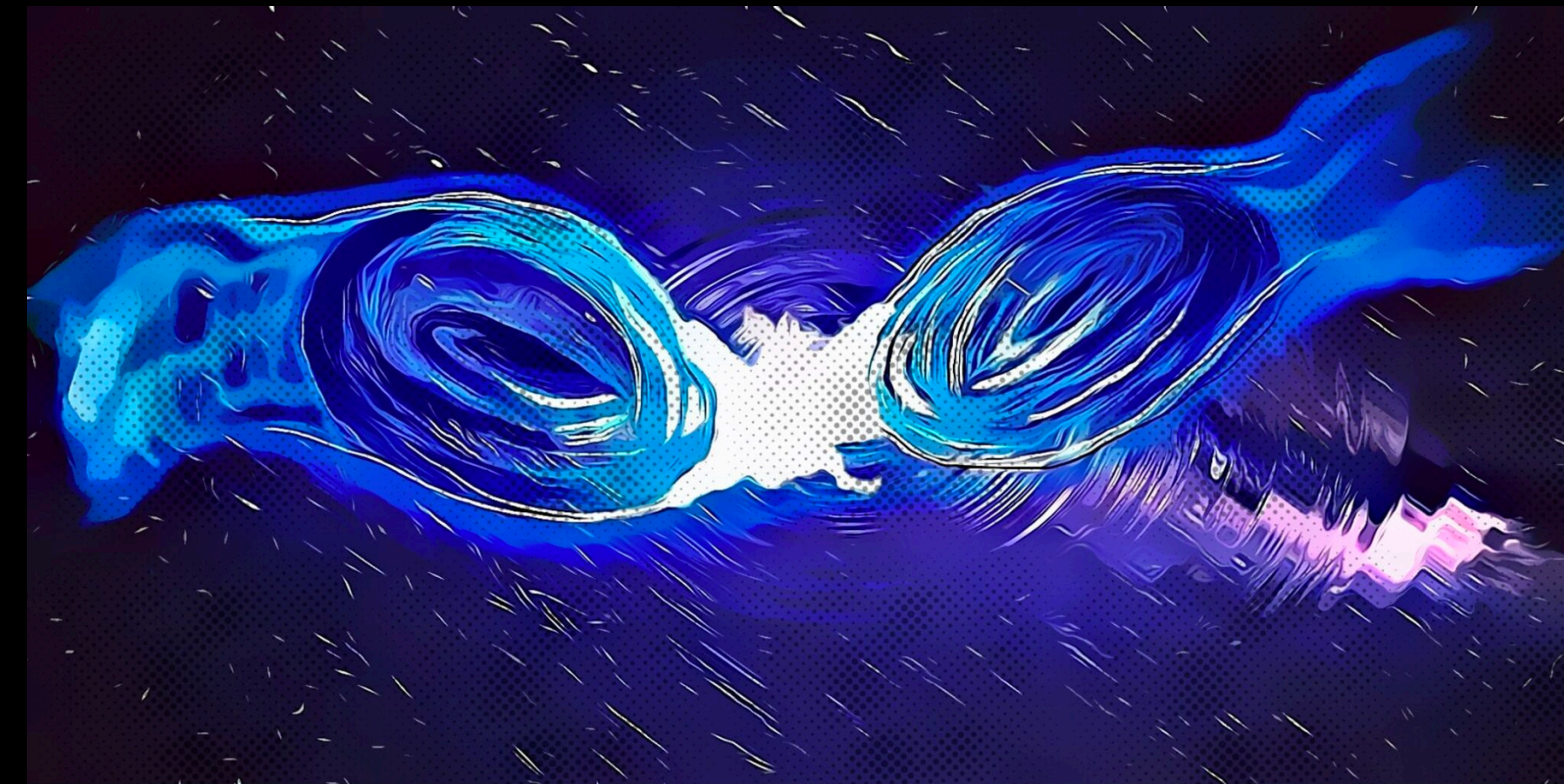
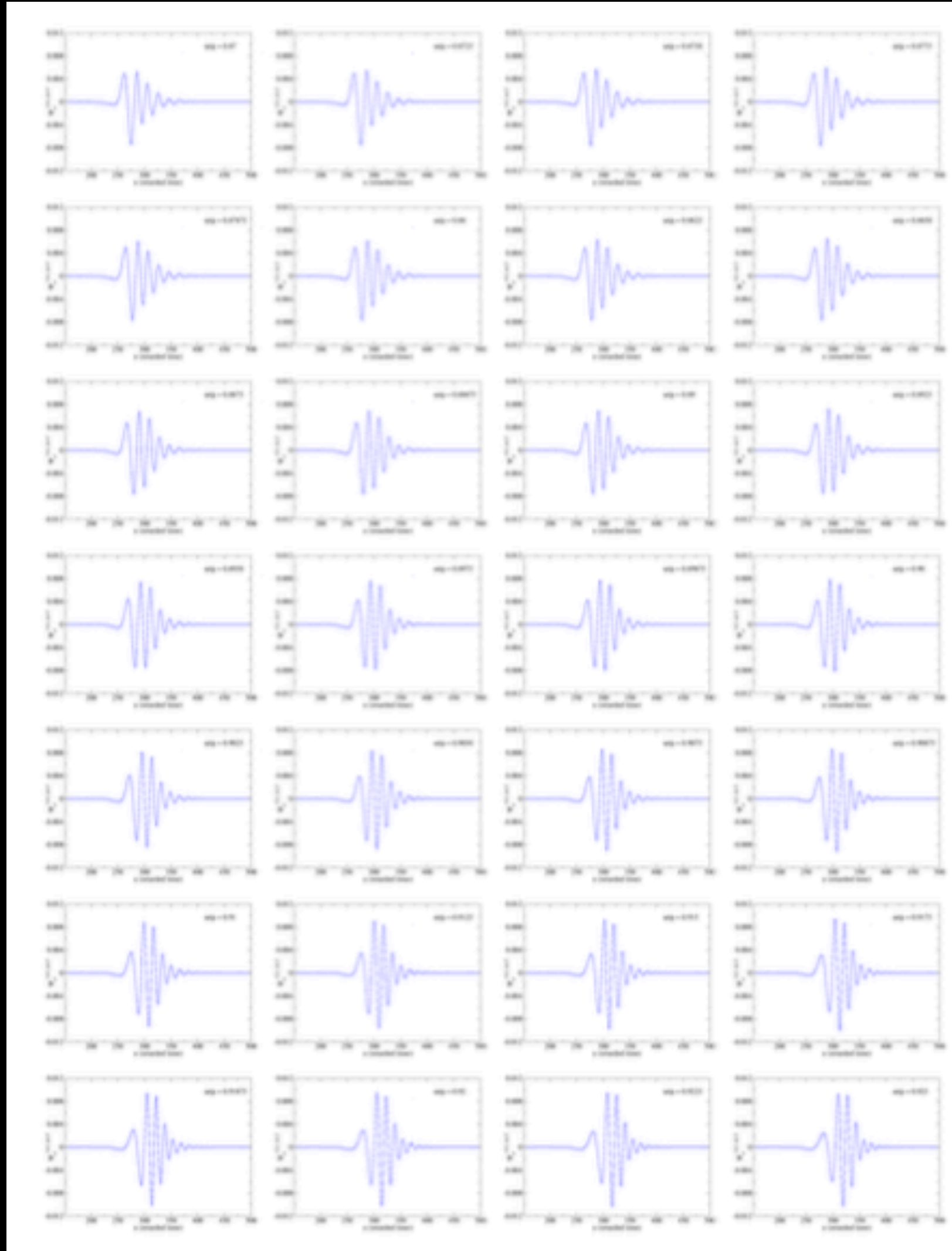
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We include (2,0), (2,2), (3,2) modes

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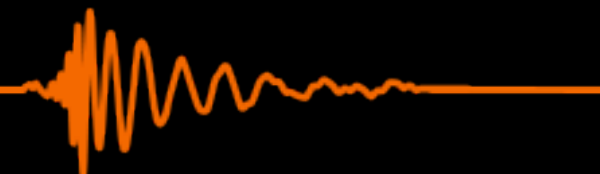
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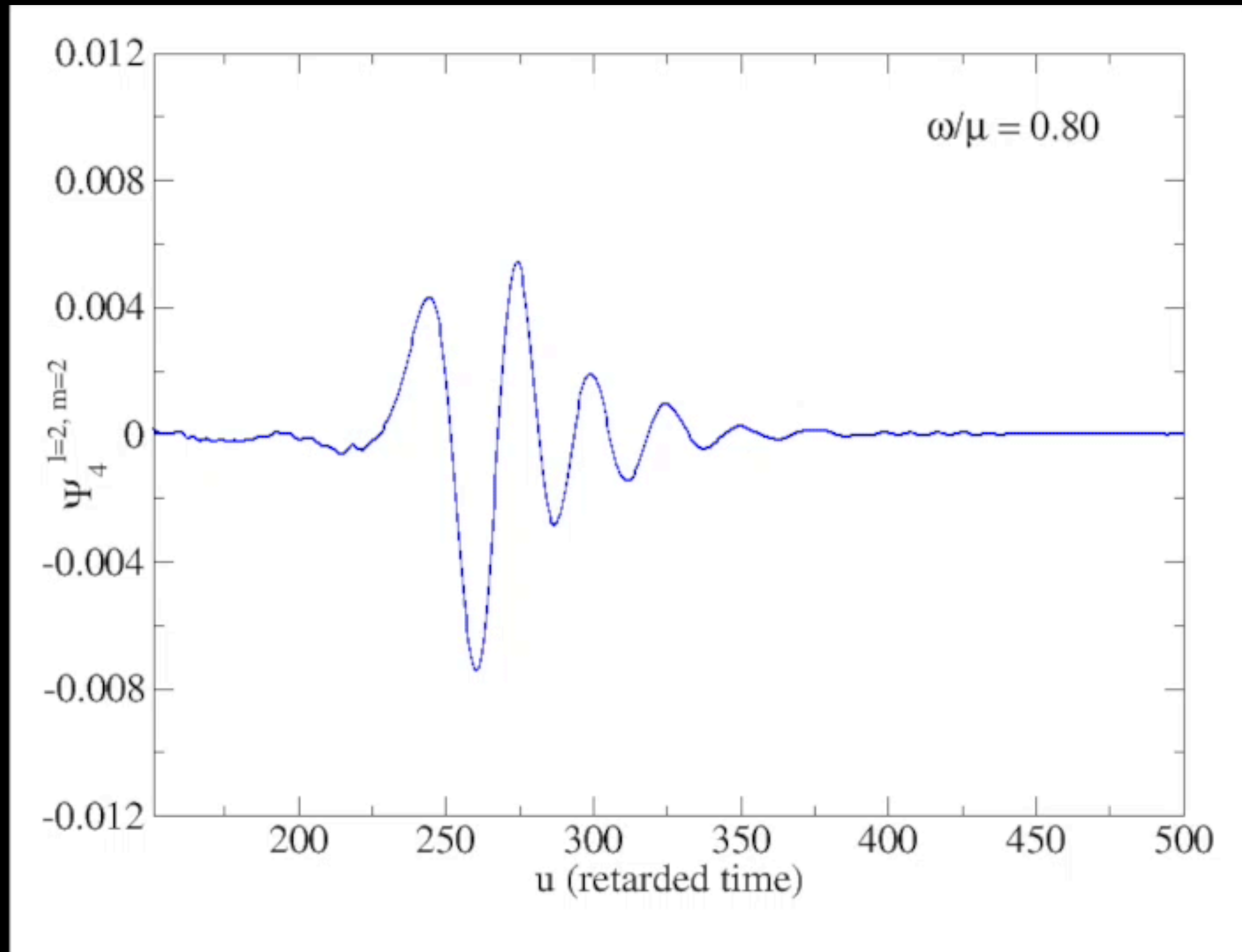
**Secondary set:**

First frequency fixed, second varies

einstein  
toolkit

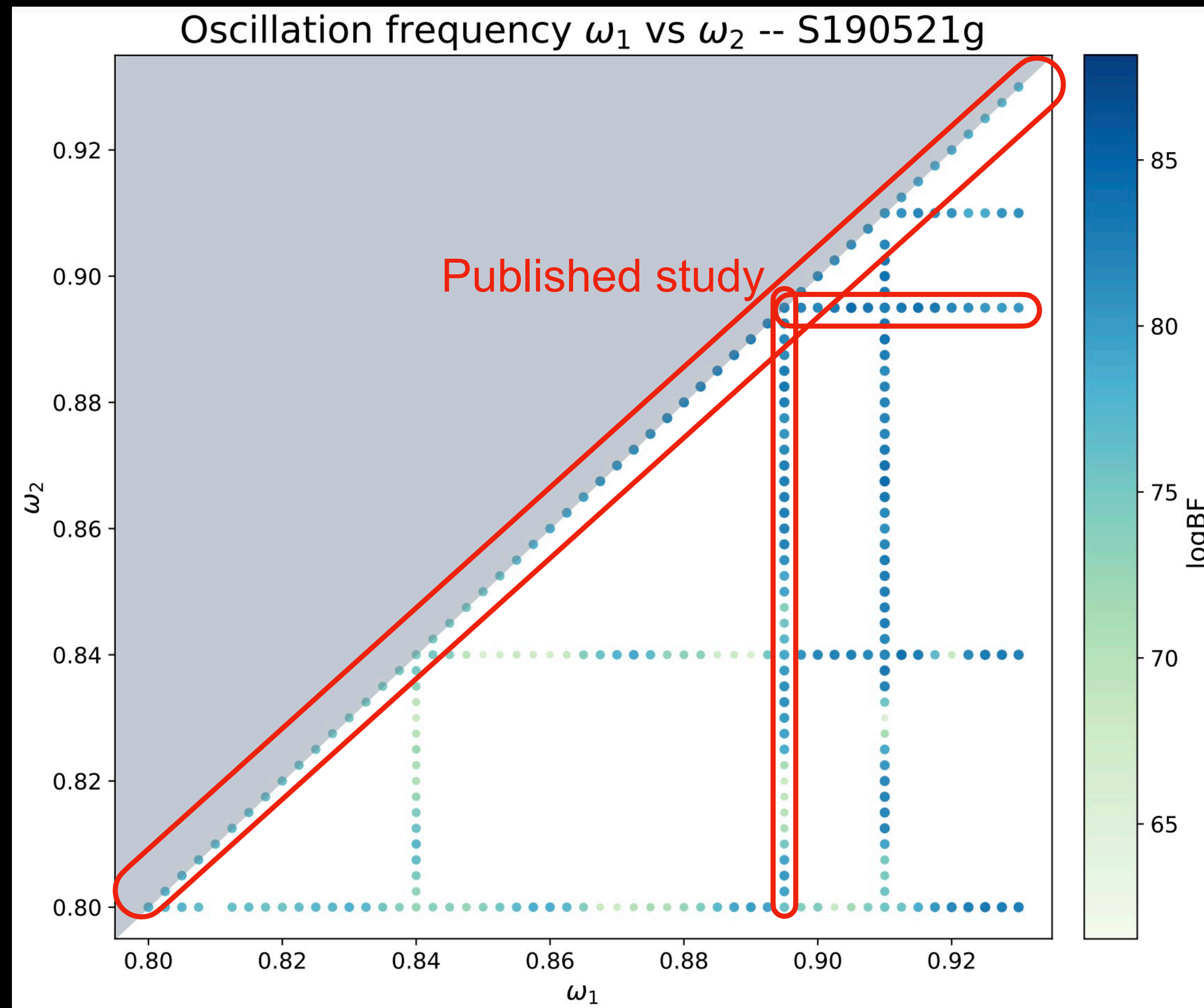






Credit: Nicolás Sanchis-Gual







## GW190521 Parameters (Proca-star merger)

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Primary mass	$115_{-8}^{+7} M_{\odot}$	$115_{-8}^{+7} M_{\odot}$
Secondary mass	$115_{-8}^{+7} M_{\odot}$	$111_{-15}^{+7} M_{\odot}$
Total or final mass	$231_{-17}^{+13} M_{\odot}$	$228_{-15}^{+17} M_{\odot}$
Final spin	$0.75_{-0.04}^{+0.08}$	$0.75_{-0.04}^{+0.08}$
Inclination $\pi/2 -  \iota - \pi/2 $	$0.83_{-0.47}^{+0.23}$ rad	$0.58_{-0.39}^{+0.40}$ rad
Azimuth	$0.65_{-0.54}^{+0.86}$ rad	$0.78_{-1.20}^{+1.23}$ rad
Luminosity distance	$571_{-181}^{+348}$ Mpc	$700_{-279}^{+292}$ Mpc
Redshift	$0.12_{-0.04}^{+0.05}$	$0.14_{-0.05}^{+0.06}$
Total or final redshifted mass	$258_{-9}^{+9} M_{\odot}$	$261_{-11}^{+10} M_{\odot}$
Bosonic field frequency $\omega/\mu_V$	$0.893_{-0.015}^{+0.015}$	(*) $0.905_{-0.042}^{+0.012}$
Boson mass $\mu_V$ [ $\times 10^{-13}$ ]	$8.72_{-0.82}^{+0.73}$ eV	$8.59_{-0.57}^{+0.58}$ eV
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Circular mergers are louder  
Larger initial mass needed to get same final BH



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Much closer than a BBH

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Bosonic field frequency $\omega/\mu_V$	$0.893_{-0.015}^{+0.015}$	(*) $0.905_{-0.042}^{+0.012}$
Boson mass $\mu_V$ [ $\times 10^{-13}$ ]	$8.72_{-0.82}^{+0.73}$ eV	$8.59_{-0.57}^{+0.58}$ eV
Maximal boson star mass	$173_{-14}^{+19} M_{\odot}$	$175_{-11}^{+13} M_{\odot}$

## LVC (BBH)

$150_{-17}^{+29} M_{\odot}$

Much heavier than the BBH estimation

$5300_{-2400}^{+2600} Mpc$

Much closer than a BBH

$272_{-27}^{+26} M_{\odot}$

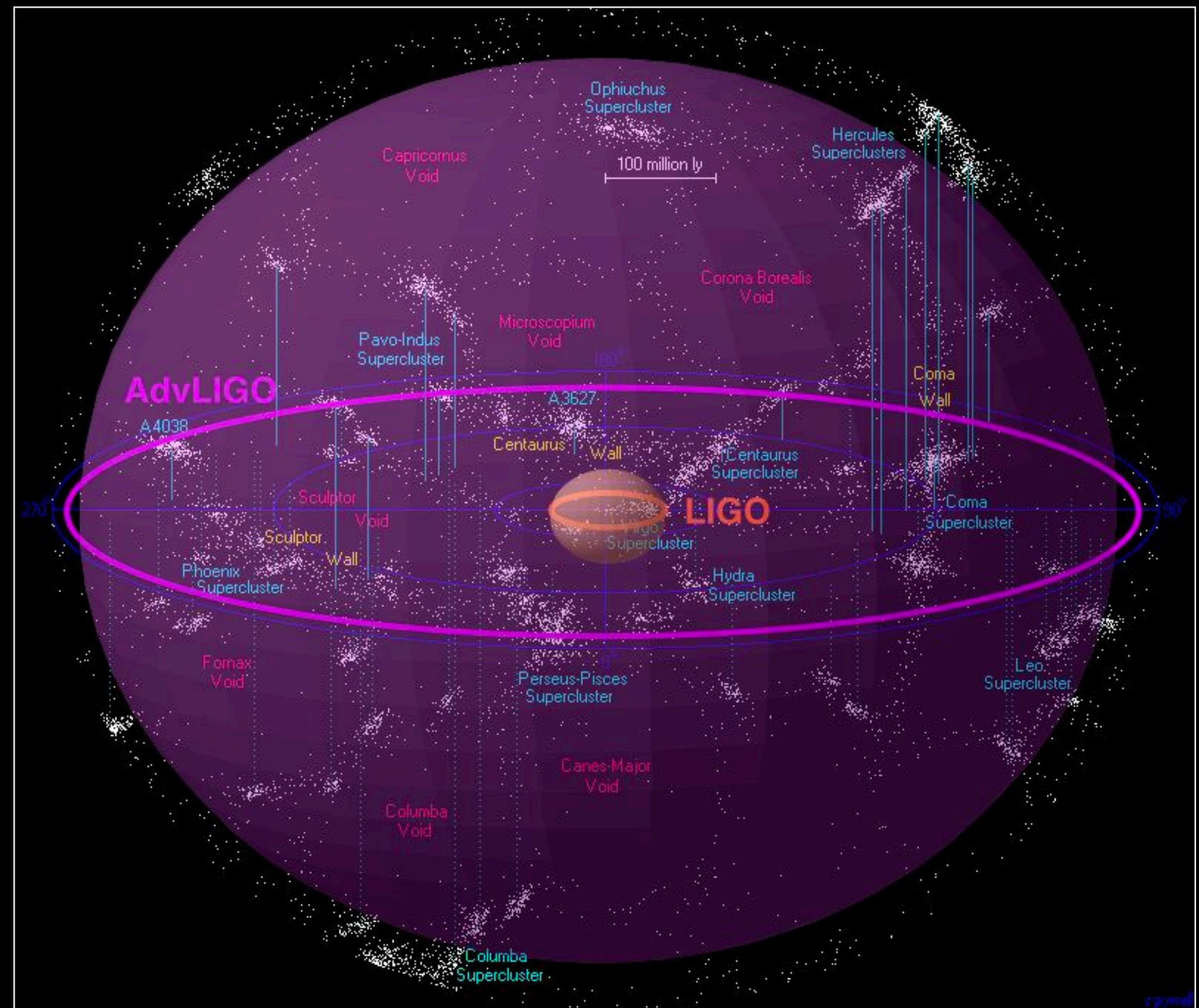
Circular mergers are louder  
Larger initial mass needed to get same final BH



## Initial study: Model Selection

Distance prior: Uniform in-comoving volume

Waveform model	$\log \mathcal{B}$	$\log \mathcal{L}_{\max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	80.9	106.7
Head-on Unequal-mass Proca Stars	82.0	106.5
Head-on Binary Black Hole	75.9	103.2





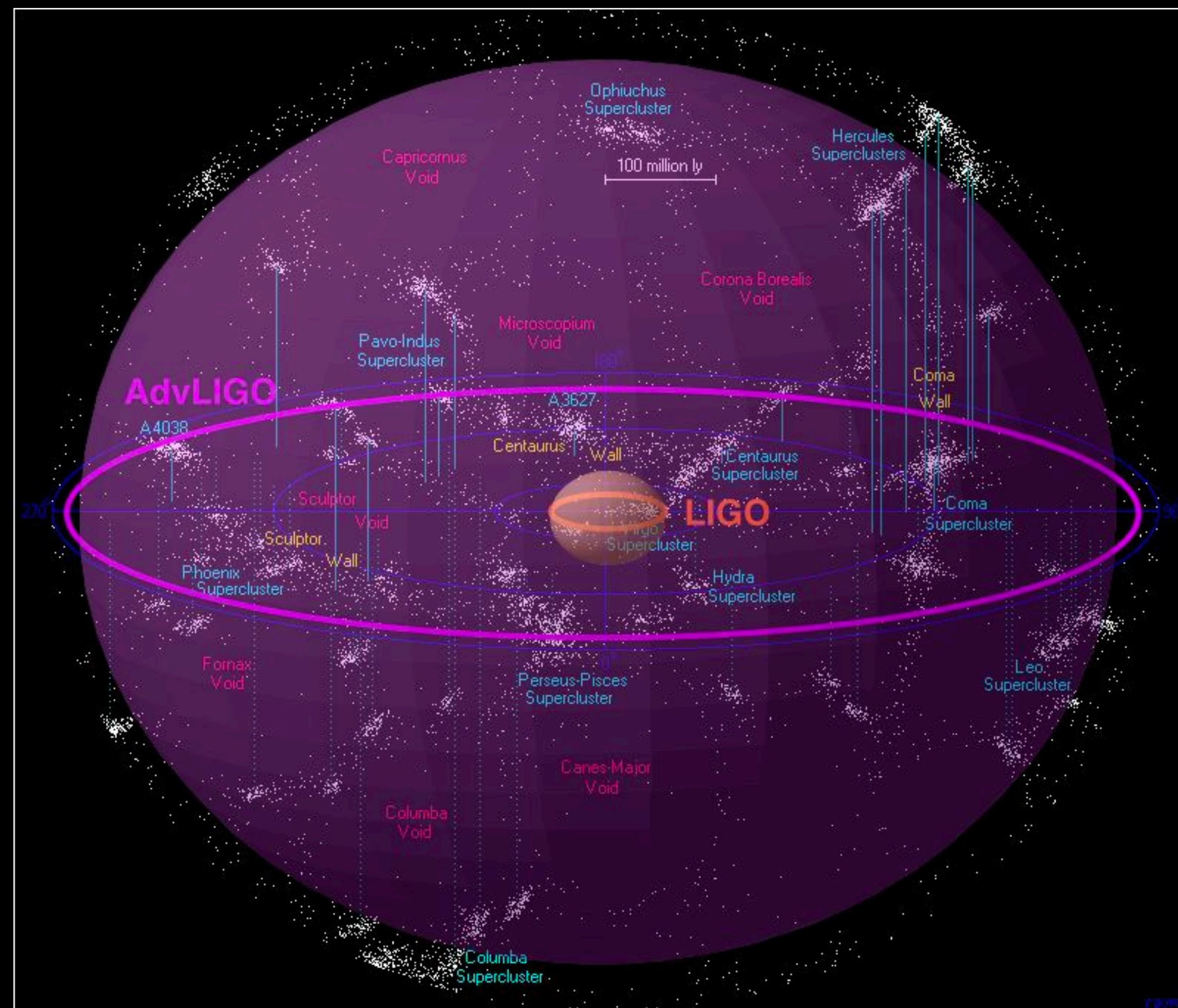
### Initial study: Model Selection

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Head-on Binary Black Hole	75.9	103.2

$$\frac{P(\text{Proca } q=1)}{P(\text{BBH})} = e^{(80.9-80.0)} \simeq 2.5 \quad \frac{P(\text{Proca } q \neq 1)}{P(\text{BBH})} \simeq 6.7$$

Reasonable, but this favours loud BBH sources



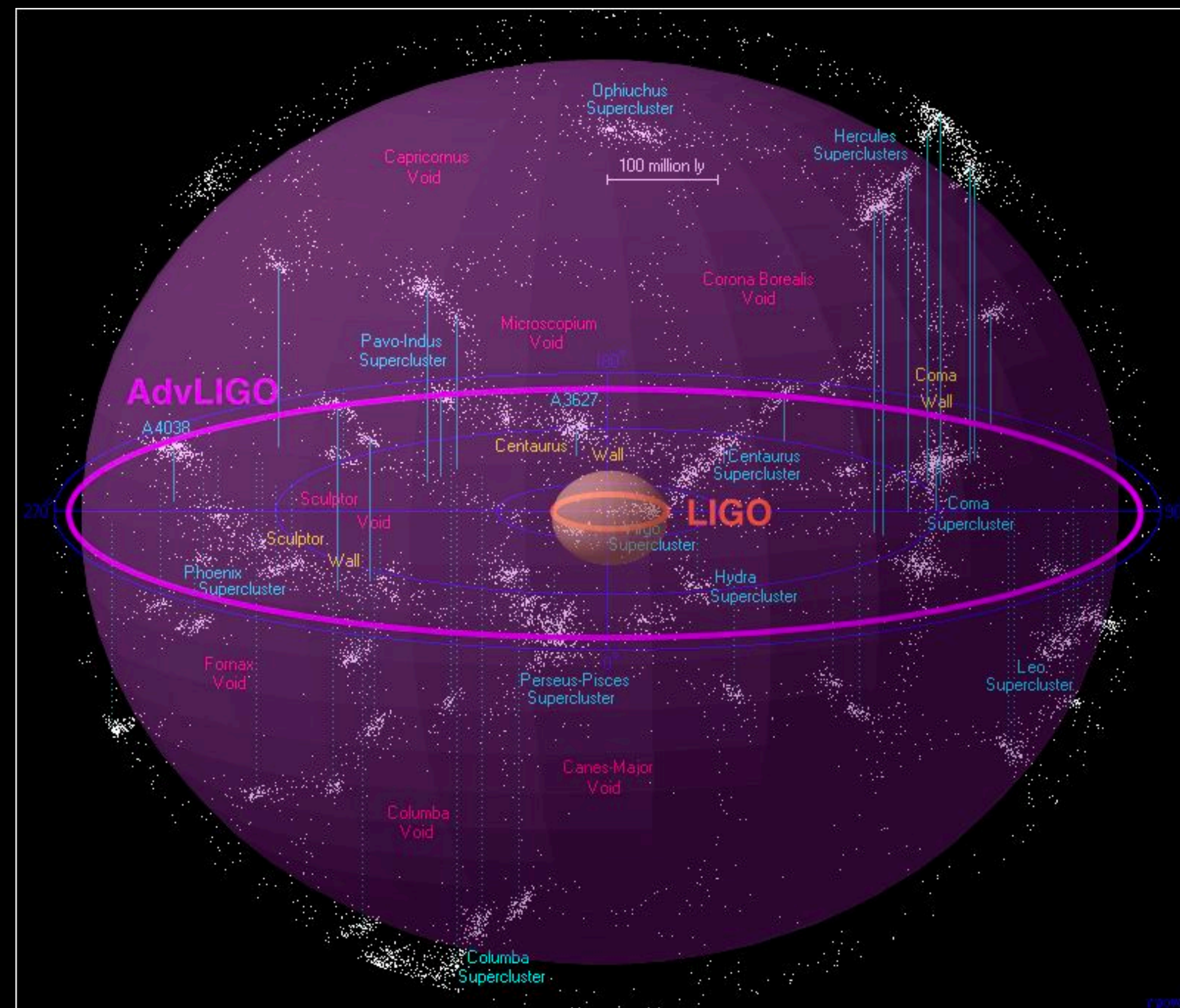


## Initial study: Model Selection

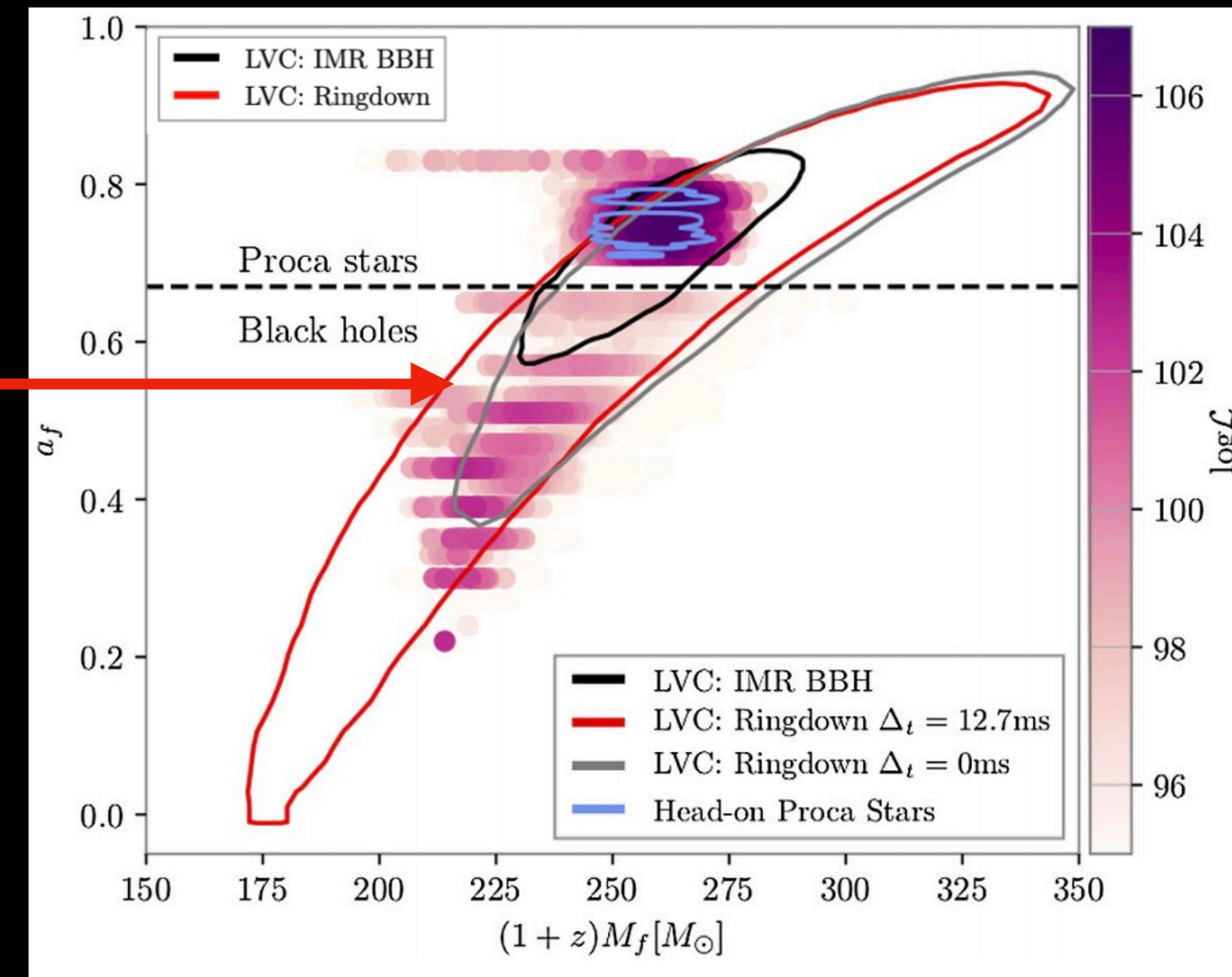
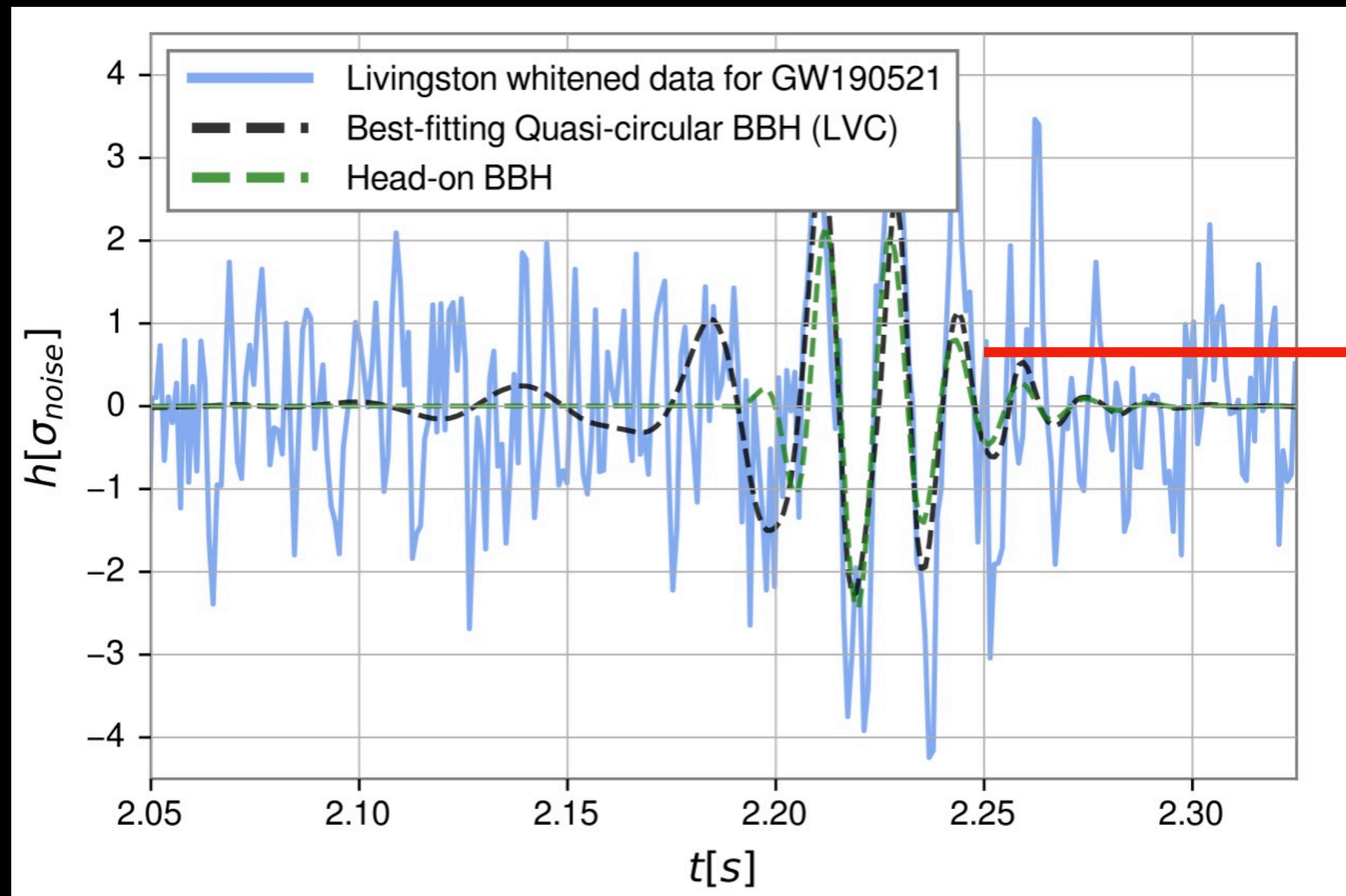
Distance prior: Uniform in-comoving volume

Waveform Model	$\log \mathcal{B}$	$\log \mathcal{L}_{Max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	83.5	106.7
Head-on Unequal-mass Proca Stars	84.3	106.5
Head-on Binary Black Hole	78.0	103.2

$$\frac{P(\text{Proca } q \neq 1)}{P(\text{BBH})} \simeq 70 \quad \frac{P(\text{Proca } q = 1)}{P(\text{BBH})} \simeq 30$$

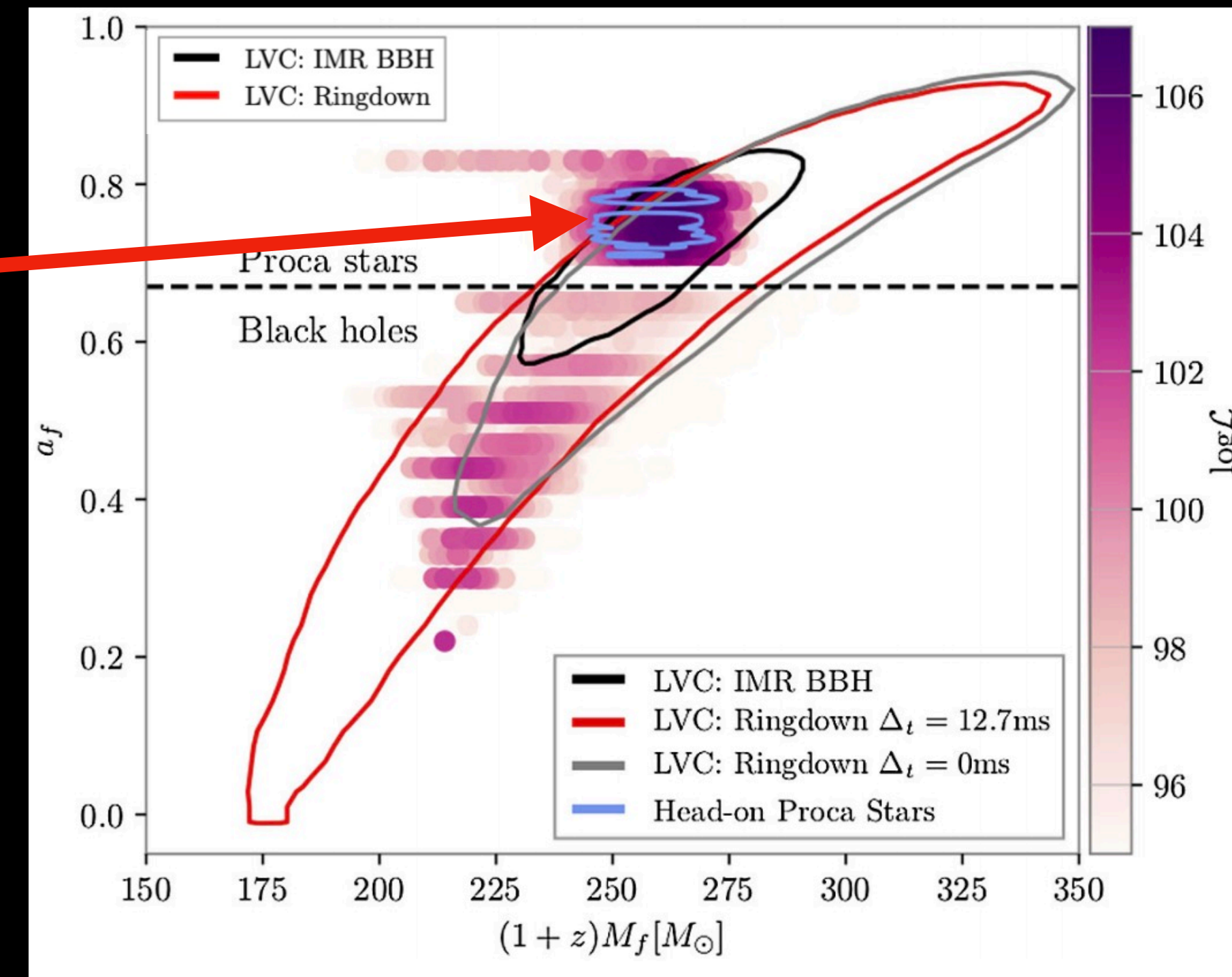
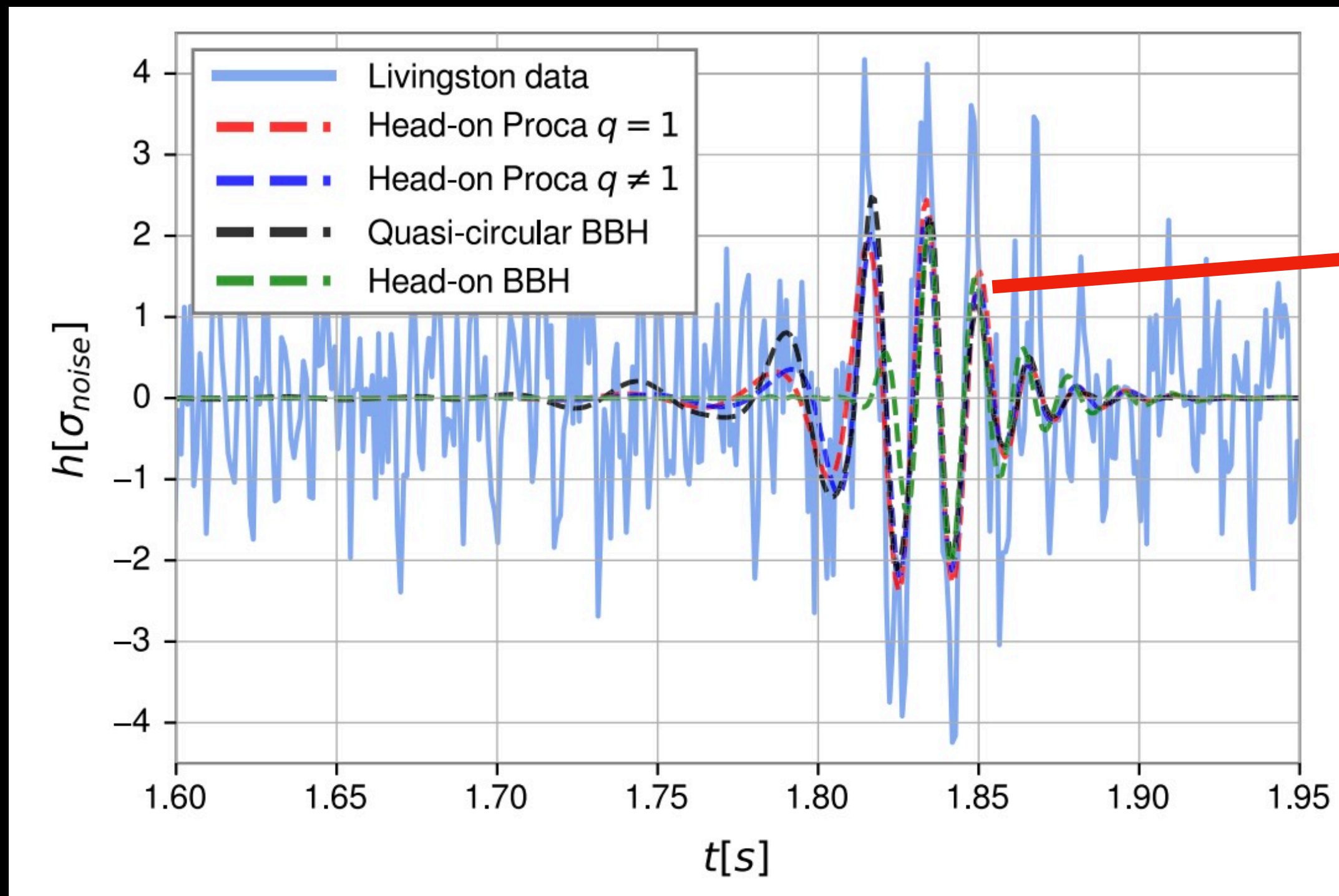






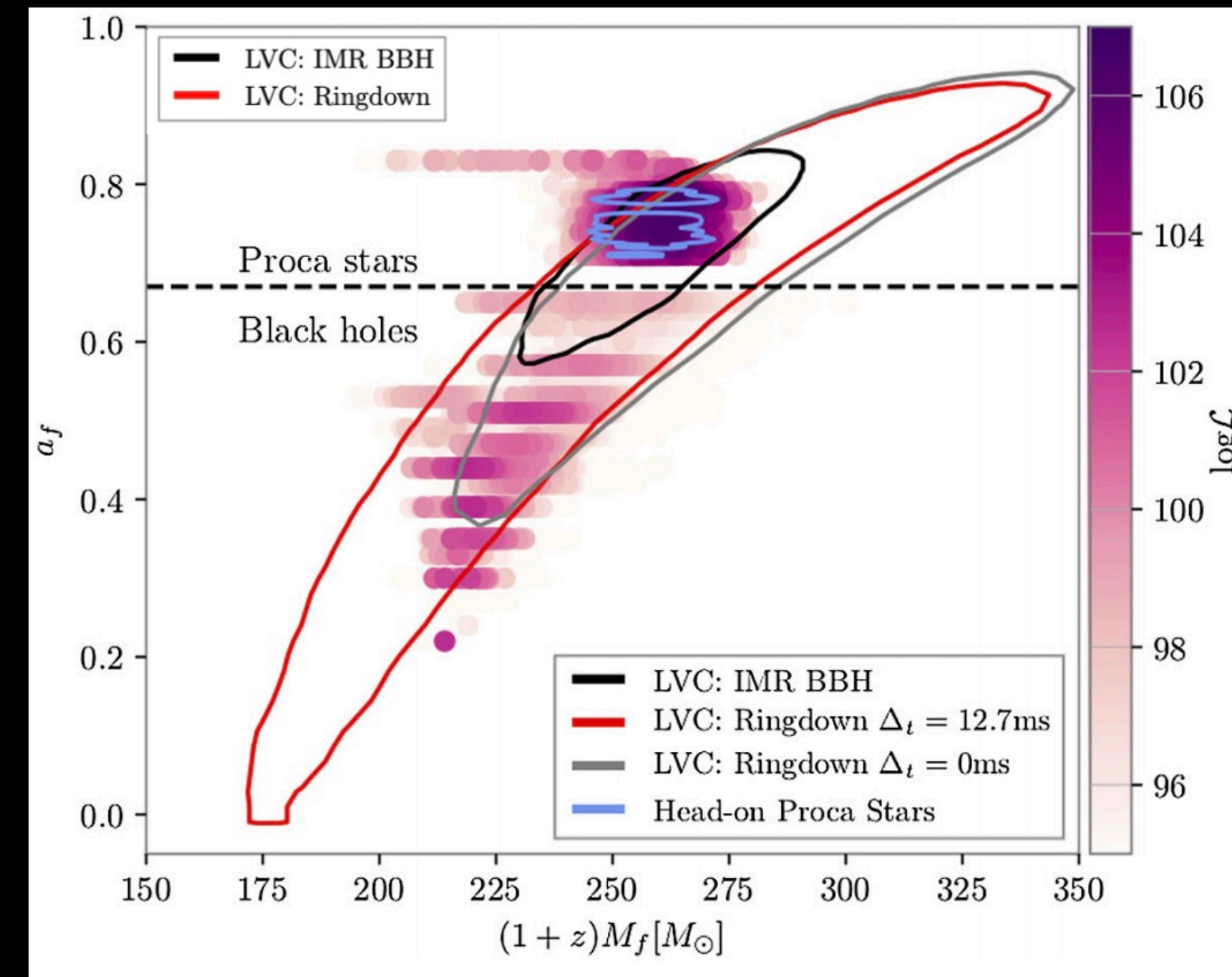
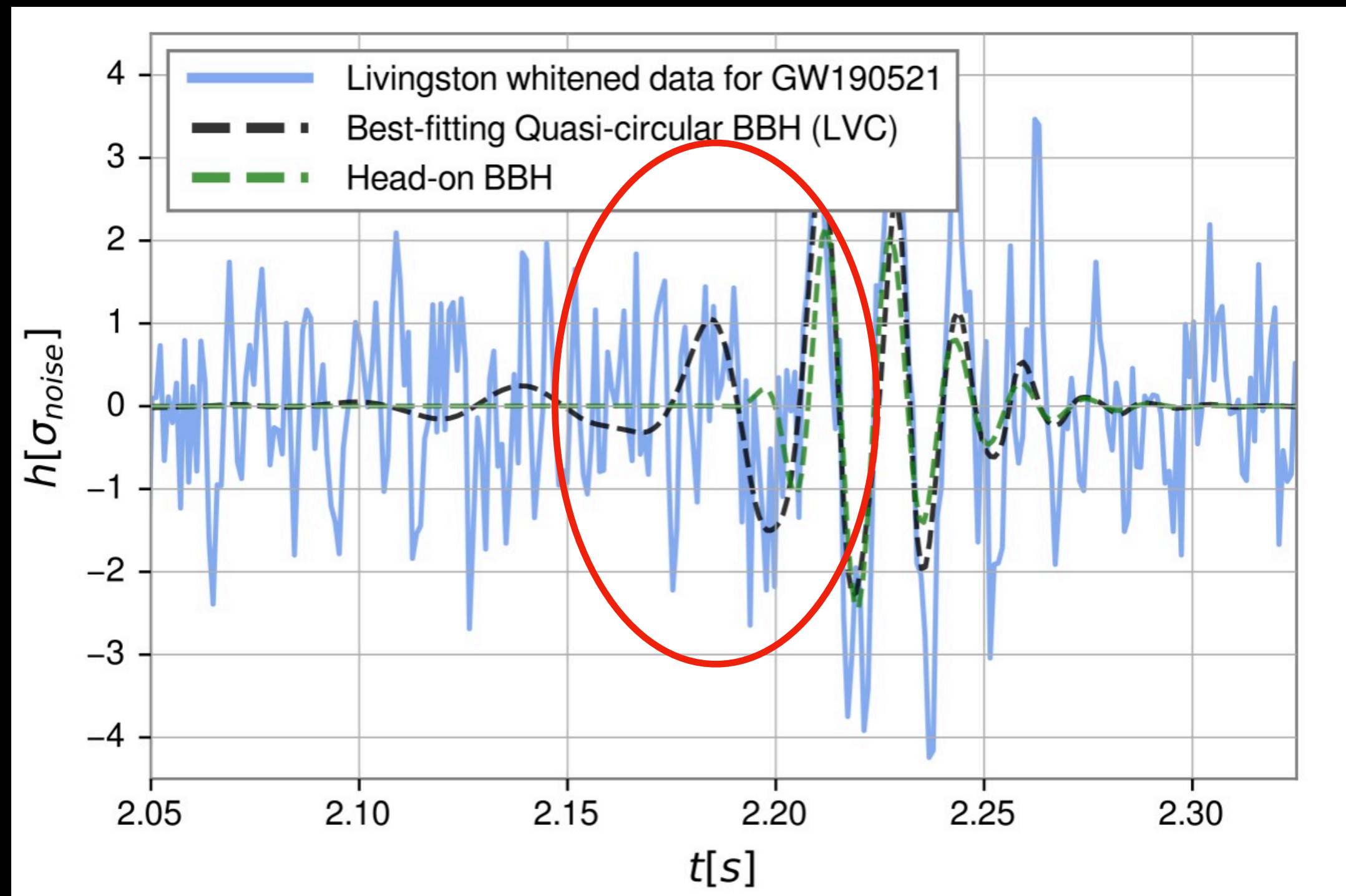
Head-on black-holes could not provide us with enough final spin





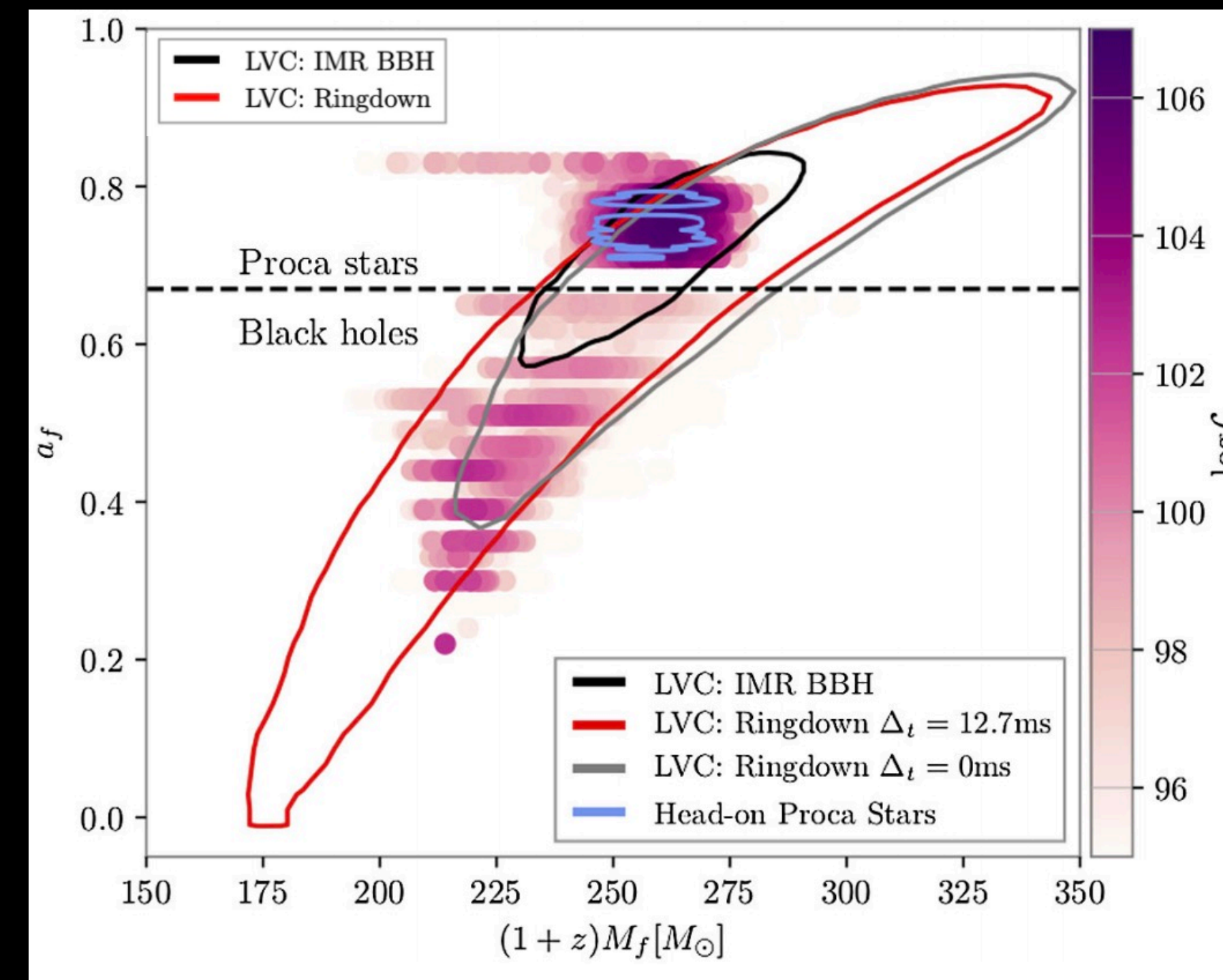
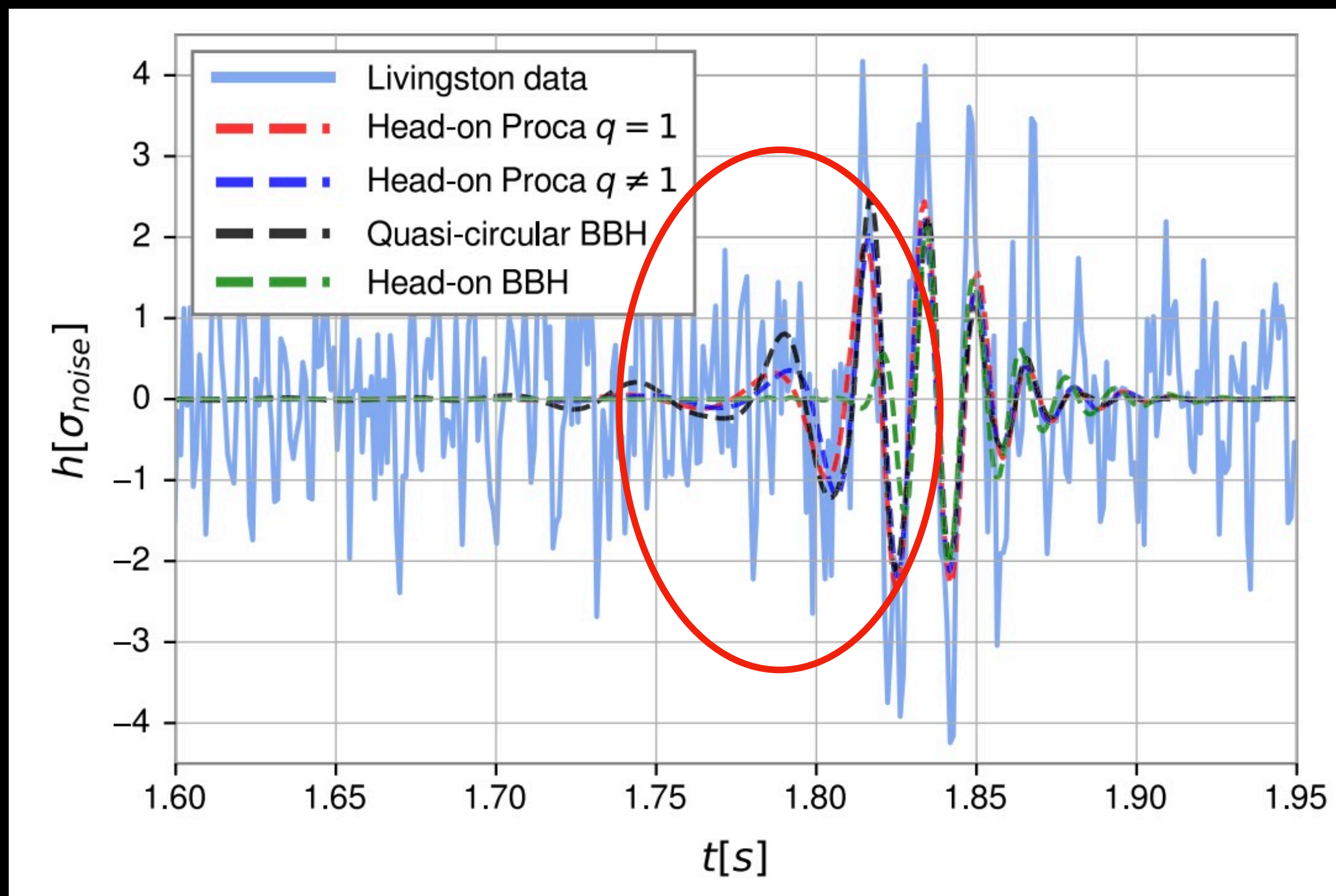
Head-on Proca stars can





Lack of power before signal peak: immediate ringdown of final black hole

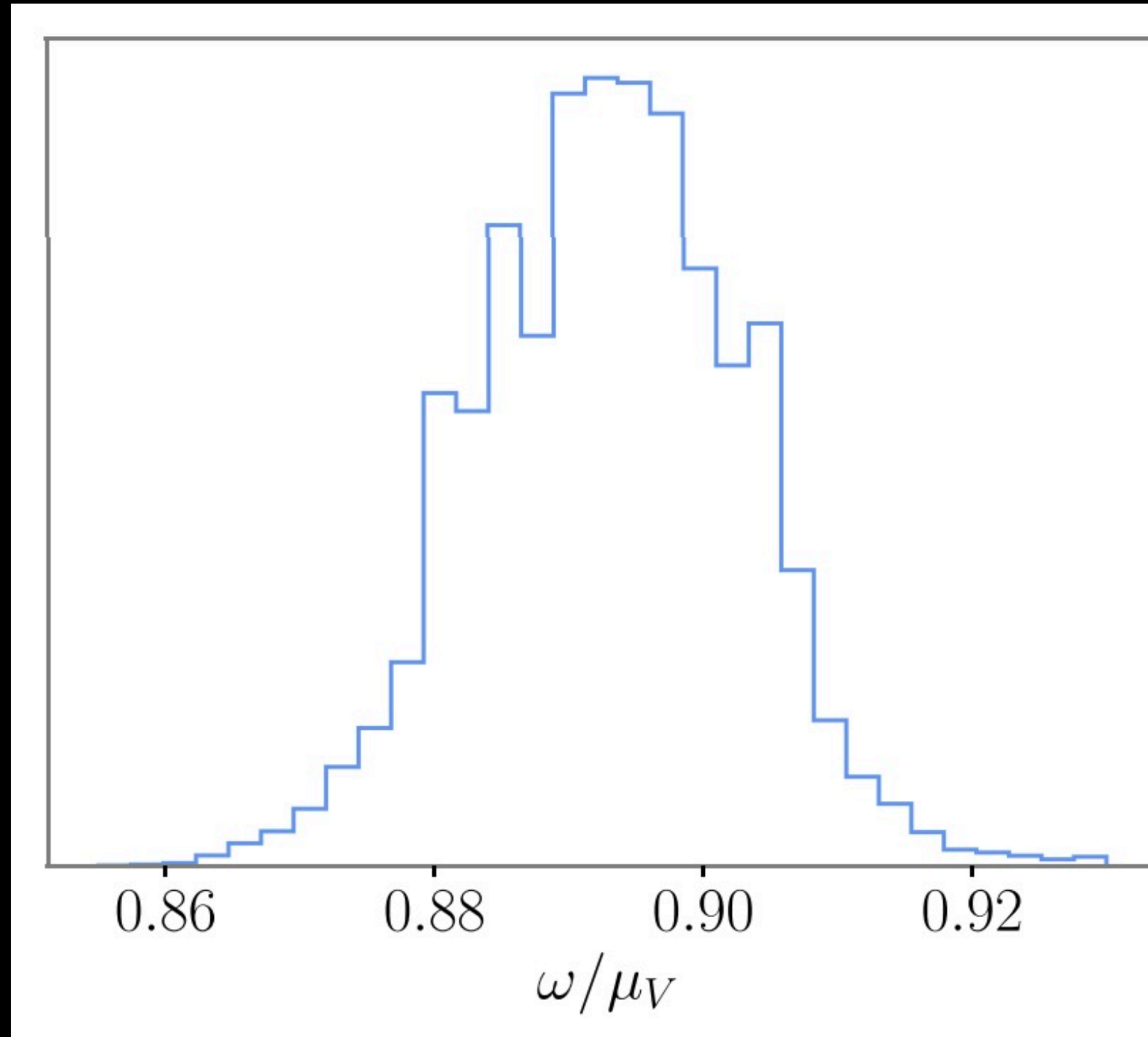




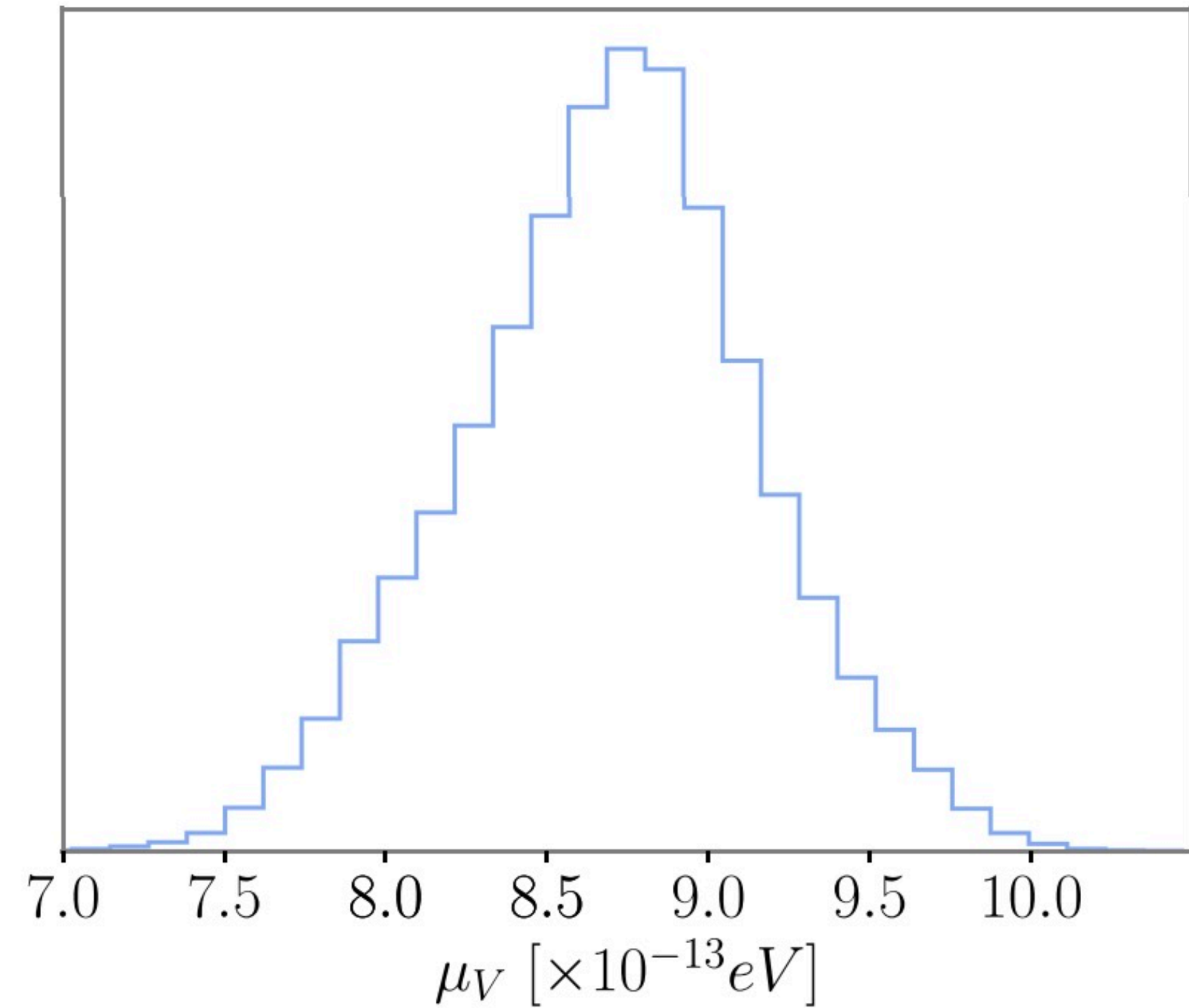
Transient hypermassive Proca star: power before signal peak



Bosonic field frequency

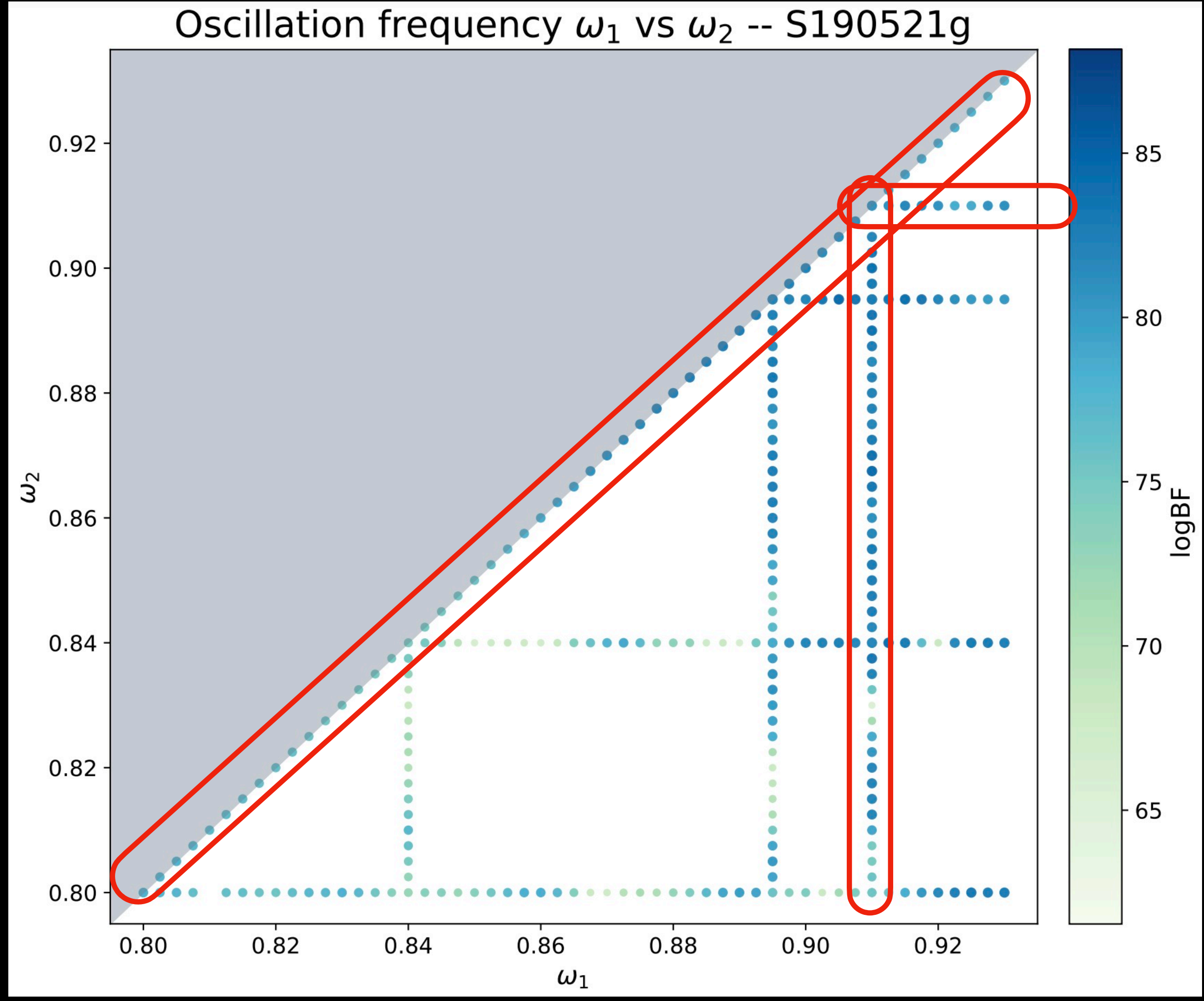


Boson mass

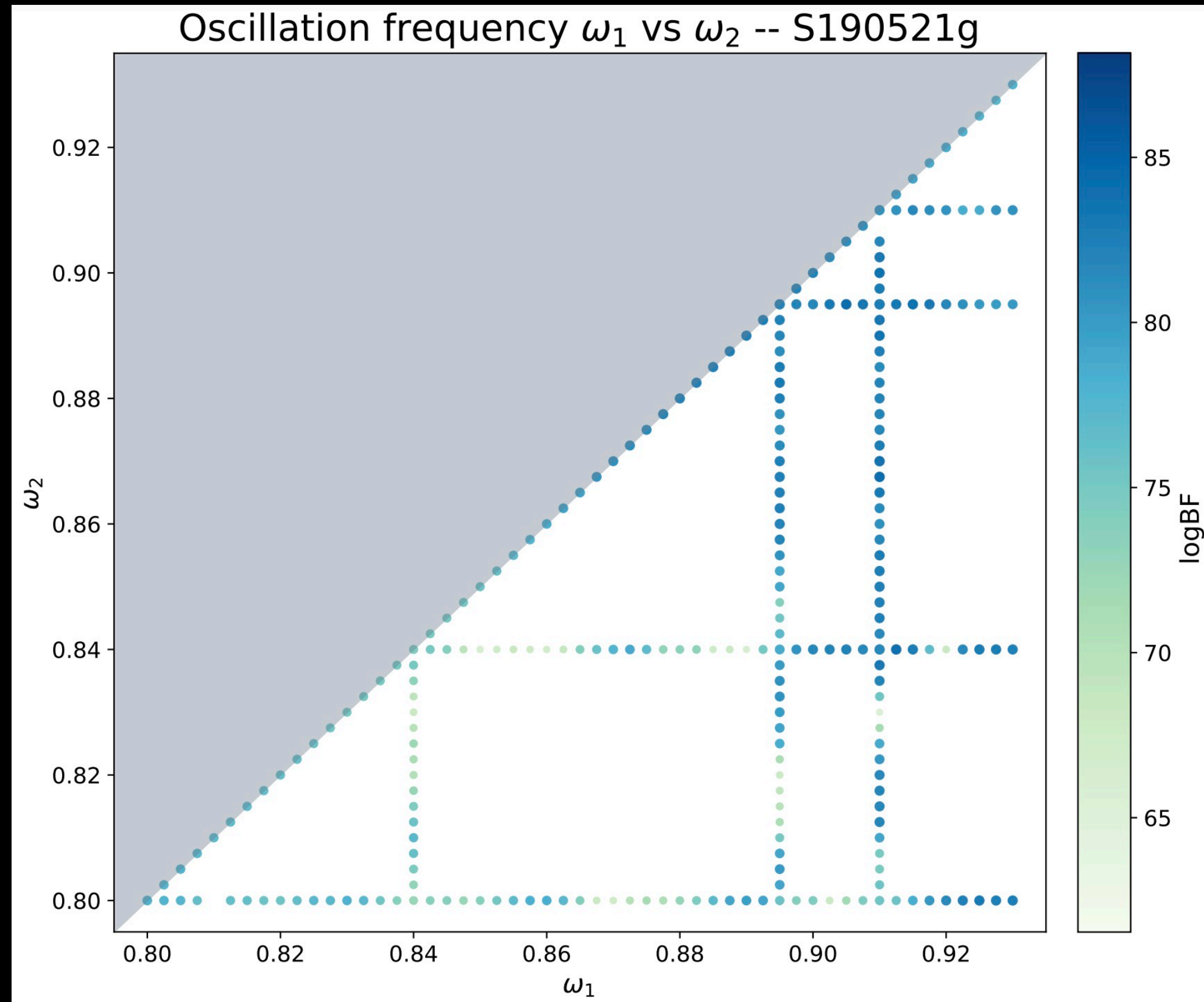


$$\mu_V^{\text{GW190521, } q=1} = 8.67_{-0.82}^{+0.73} \times 10^{-13} eV$$









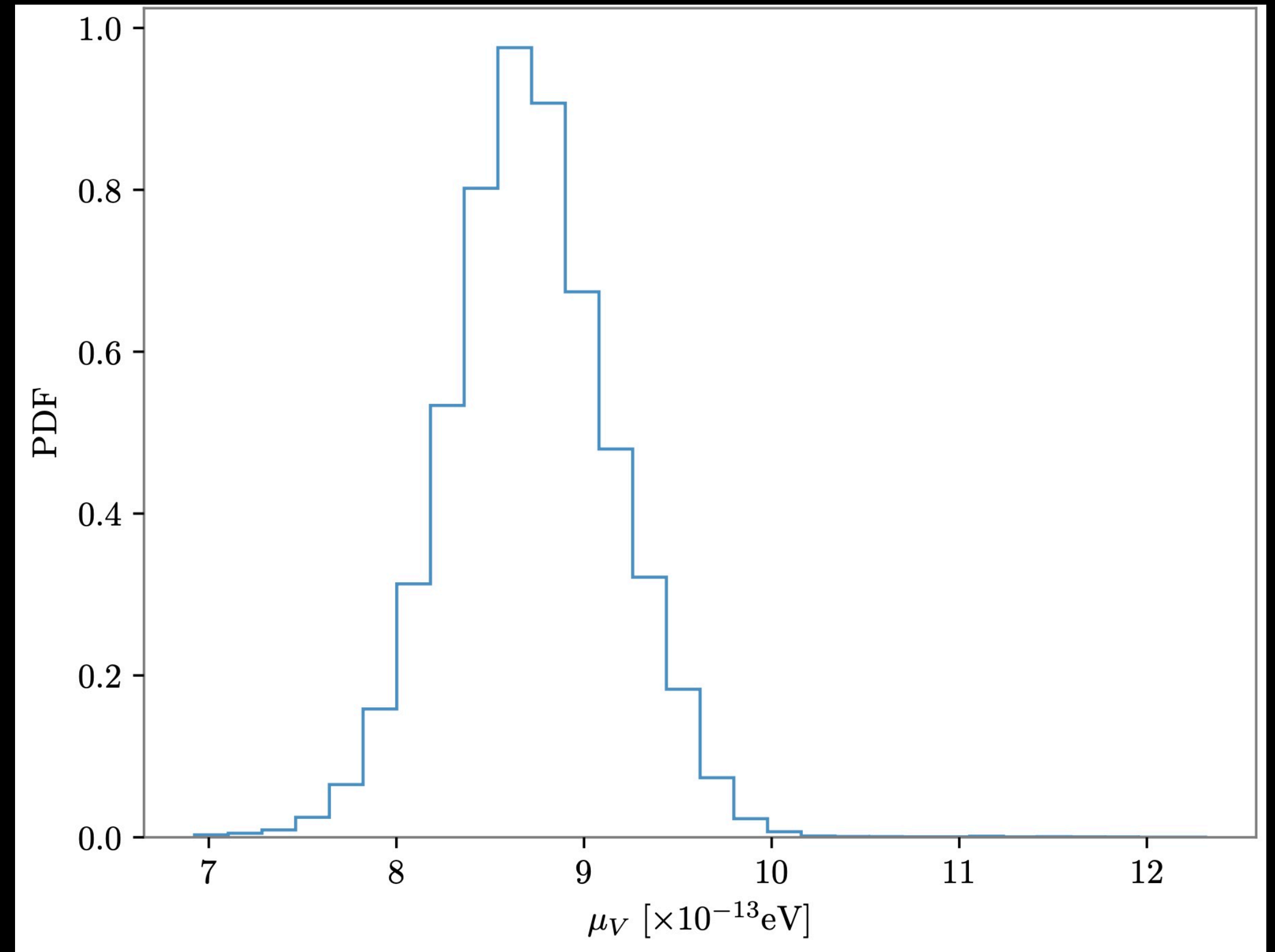
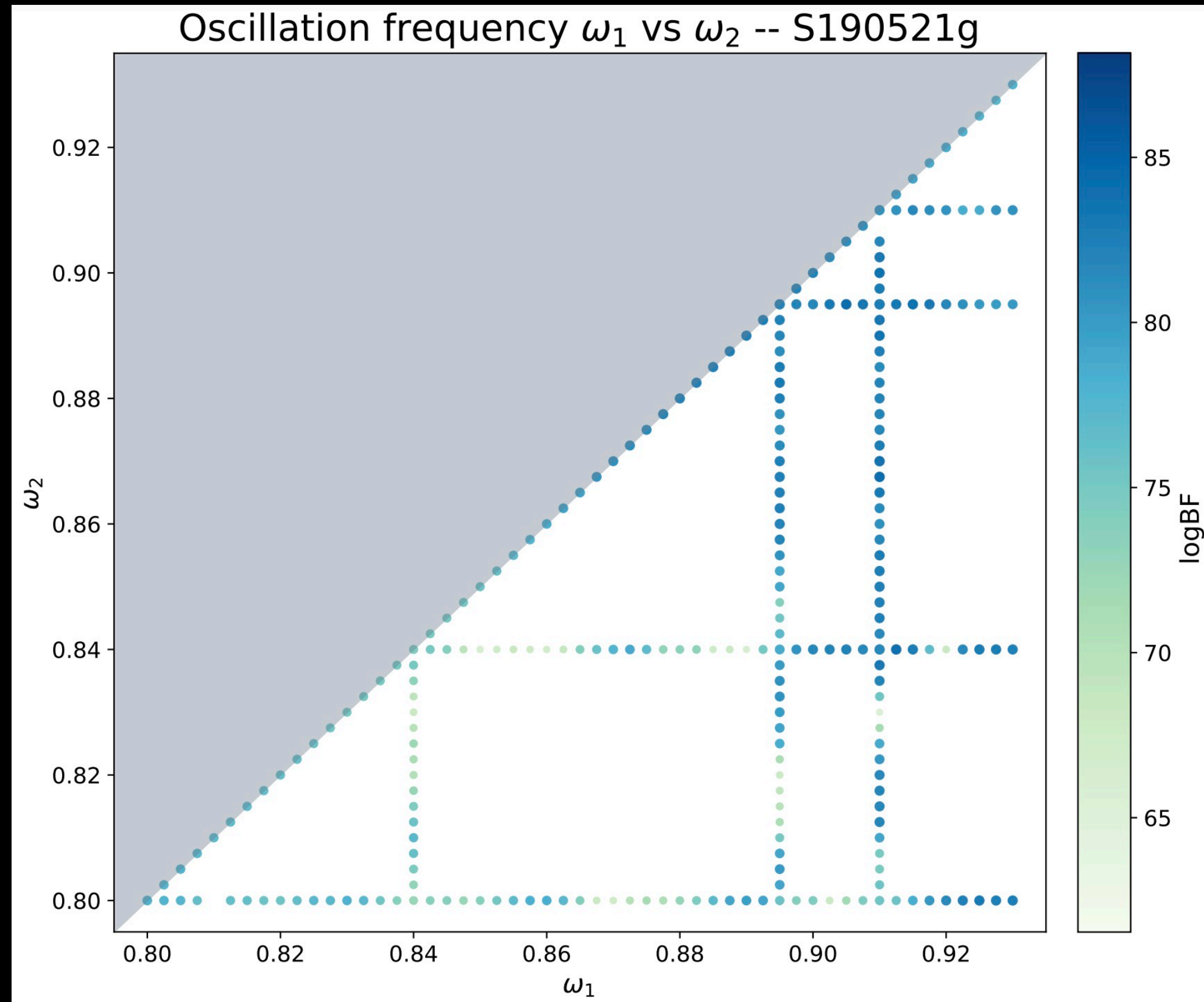
### Enlarged waveform family

We add the (3,3) mode See Capano+ 2021

Increased Max LogLikelihood: from 106 to 110

Mildly increased Log Bayes Factor: from 80.9 to 81.46





$$\mu_\nu^{\text{GW190521, Updated, Preliminary}} = 8.70_{-0.69}^{+0.75} \times 10^{-13} \text{eV}$$



Too massive Proca star: collapse to black hole

$$\frac{M_{max}}{M_{\odot}} = 1.125 \times \frac{1.34 \times 10^{-10} eV}{\mu_V}$$

Final Proca star less massive: no collapse, no ringdown

Previous LVC events discarded as head-on Proca star mergers (with same boson mass)

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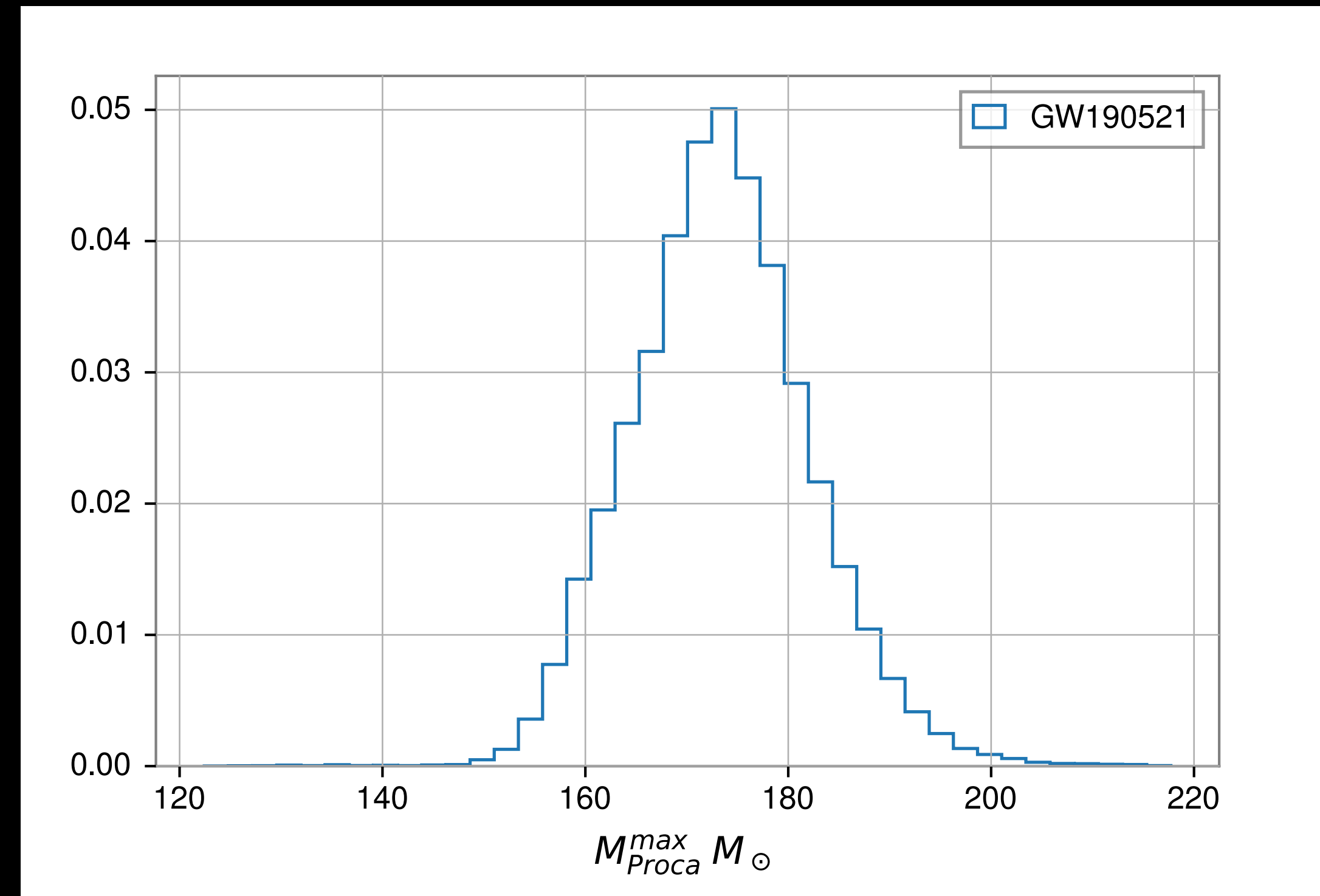
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Previous LVC events discarded as head-on Proca star mergers (with same boson mass)

$$M_{max}^{Proca} = 174_{-14}^{+15} M_{\odot}$$



This talk:

GW190521 has brought us in the realm of ¿what are we observing?

Consistent with a head-on merger of Proca stars

Second, low significance trigger S200114 (ongoing)

Consistent masses at 90% C.I.

$$\mu_B^{190521} = 8.70_{-0.69}^{+0.75} \times 10^{-13} eV \quad \mu_B^{200114} = 10.19_{-0.55}^{+0.69} \times 10^{-13} eV$$







This talk:

GW190521 has brought us in the realm of ¿what are we observing?

Consistent with a head-on merger of Proca stars

$$\mu_B^{190521} = 8.70_{-0.69}^{+0.75} \times 10^{-13} eV$$

Waveforms models very limited!



The future:

Simulations for less eccentric configurations: large room for improvement!!!!

Targeted search for boson-star mergers

Mass consistency across events: population studies. How many ultralight bosons are there, if any?

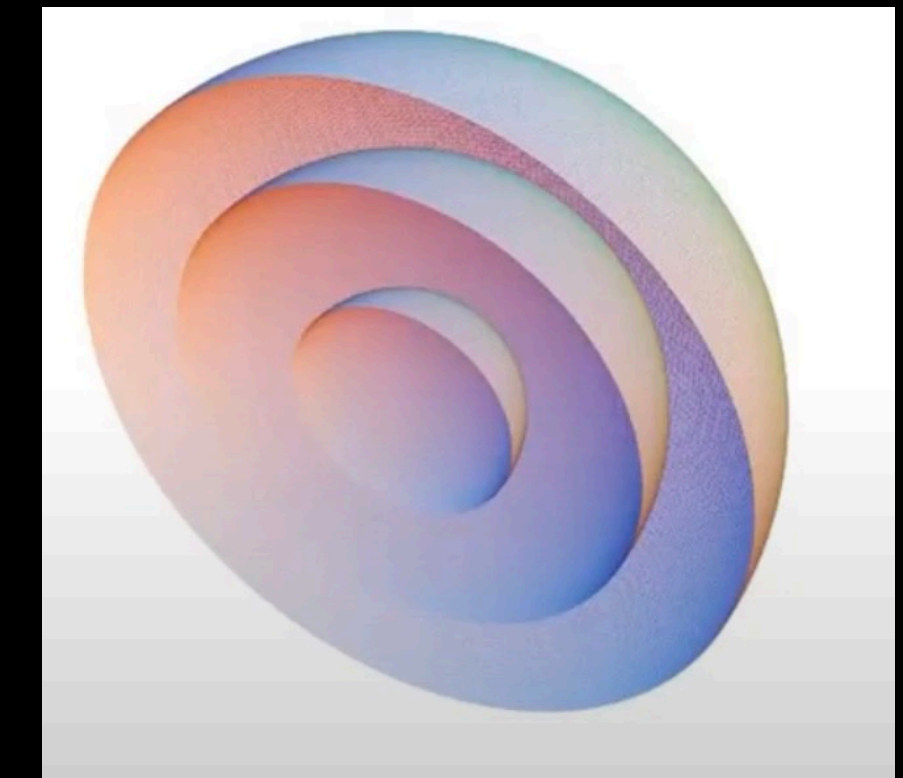
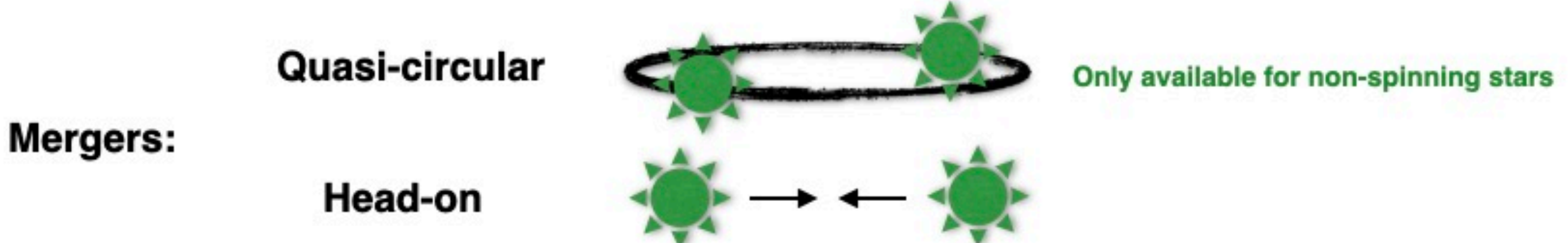




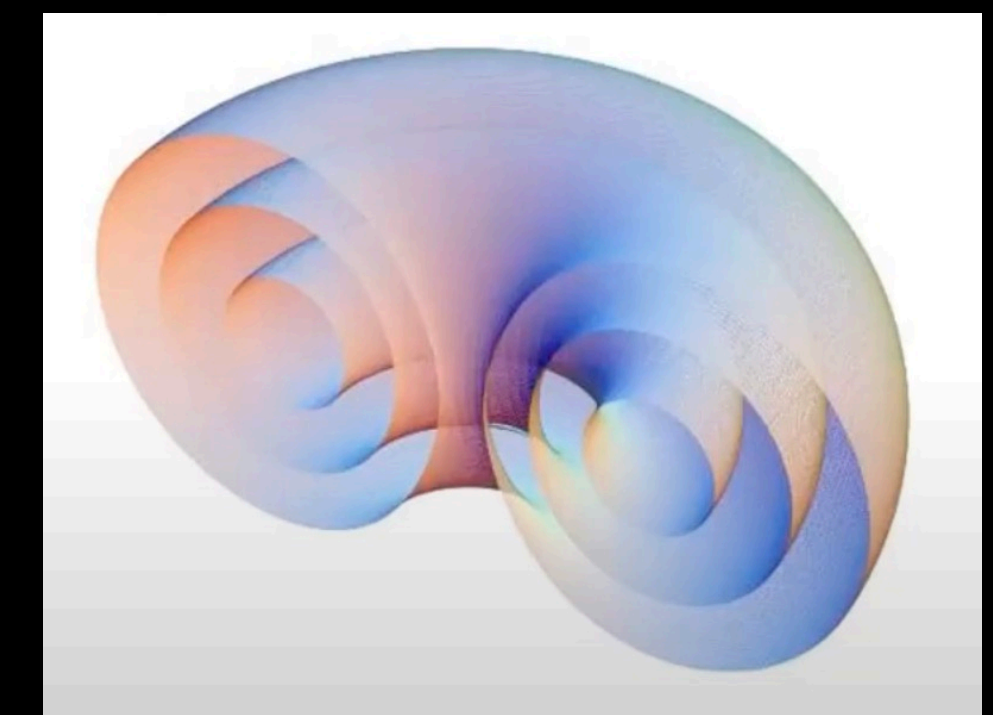
	Scalar (s=0)		Vector (Proca) (s=1)		Tensor (s=2)	
Star	Real	Complex	Real	Complex	Real	Complex
Non-Spinning						
Spinning						

: Form **unstable** cloud around black-holes. SR instability. System spins-down, Continous waves. Current mass constraints.

: Form **stable** cloud around black-holes. SR equilibrium, spin of the system is kept. No Continous waves.



Spinning Proca star



Spinning Scalar star (Unstable)



	Scalar (s=0)		Vector (Proca) (s=1)		Tensor (s=2)	
Star	Real	Complex	Real	Complex	Real	Complex
Non-Spinning						
Spinning						

: Form **unstable** cloud around black-holes. SR instability. System spins-down, Continous waves. Current mass constraints.

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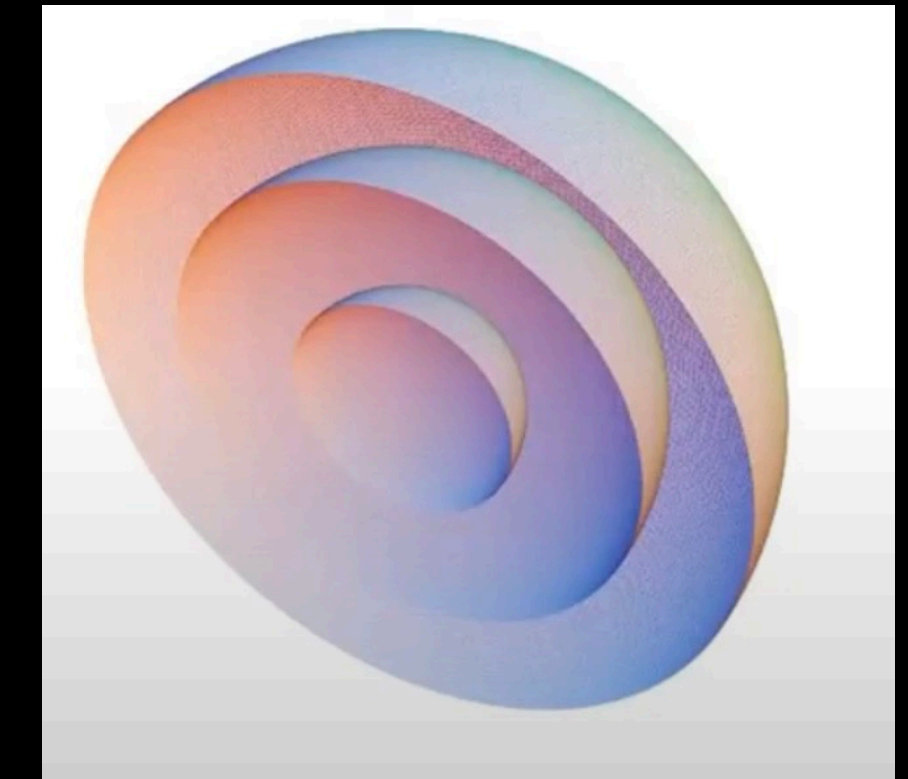
Quasi-circular



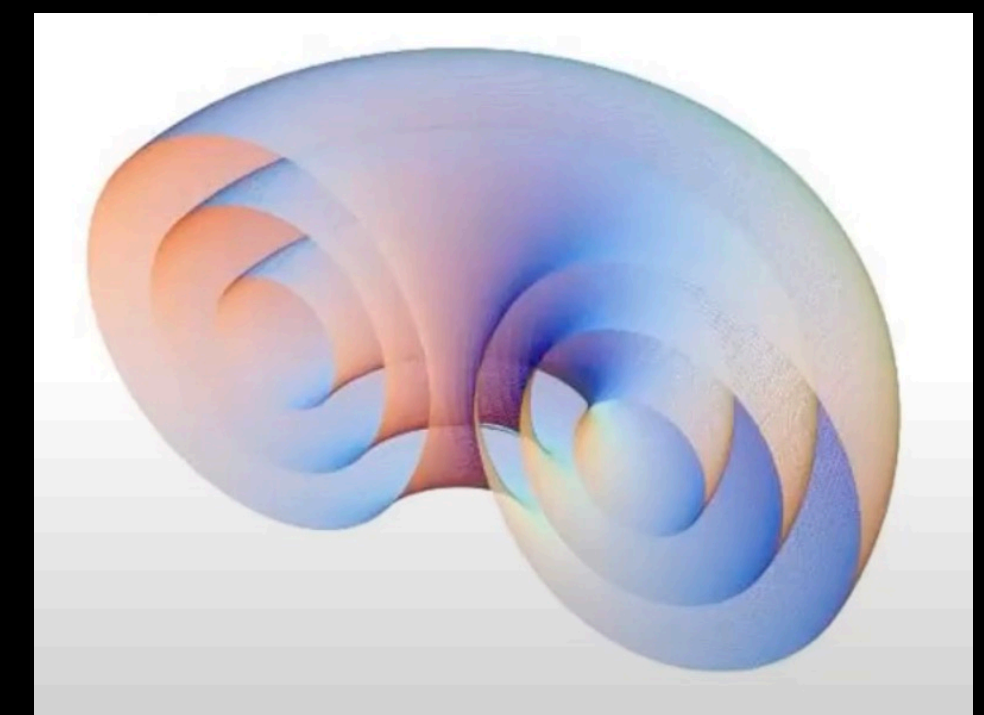
Only available for non-spinning stars

Mergers:


Head-on



Spinning Proca star



Spinning Scalar star  
(Unstable)



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Gravitational-wave data analysis with the Newmann-Penrose scalar

$$\Psi_4$$

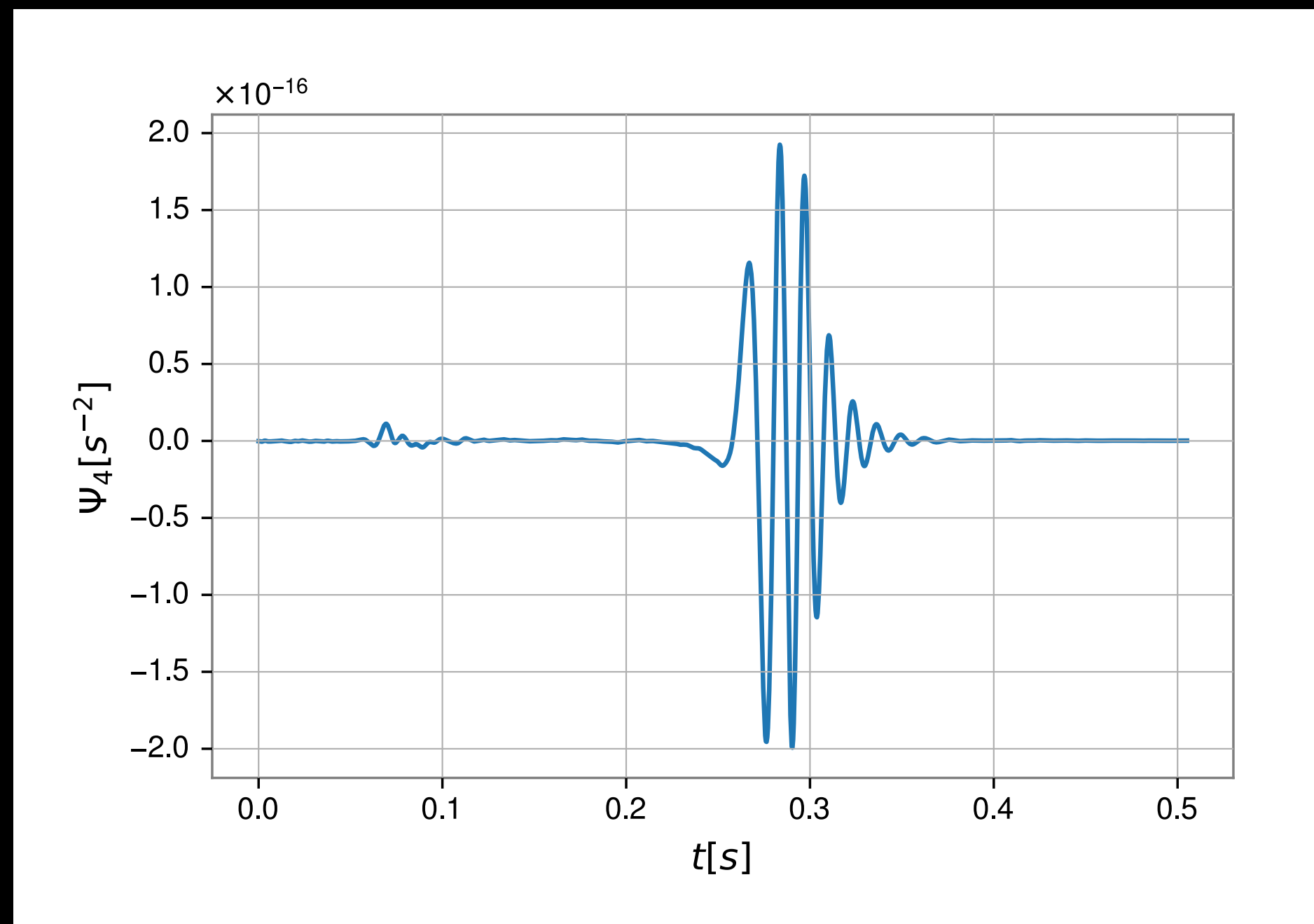




Numerical Relativity simulations extract GWs in form of  $\Psi_4 = \frac{d^2 h}{dt^2}$

Obtention of strain requires of double integration plus cleaning procedure

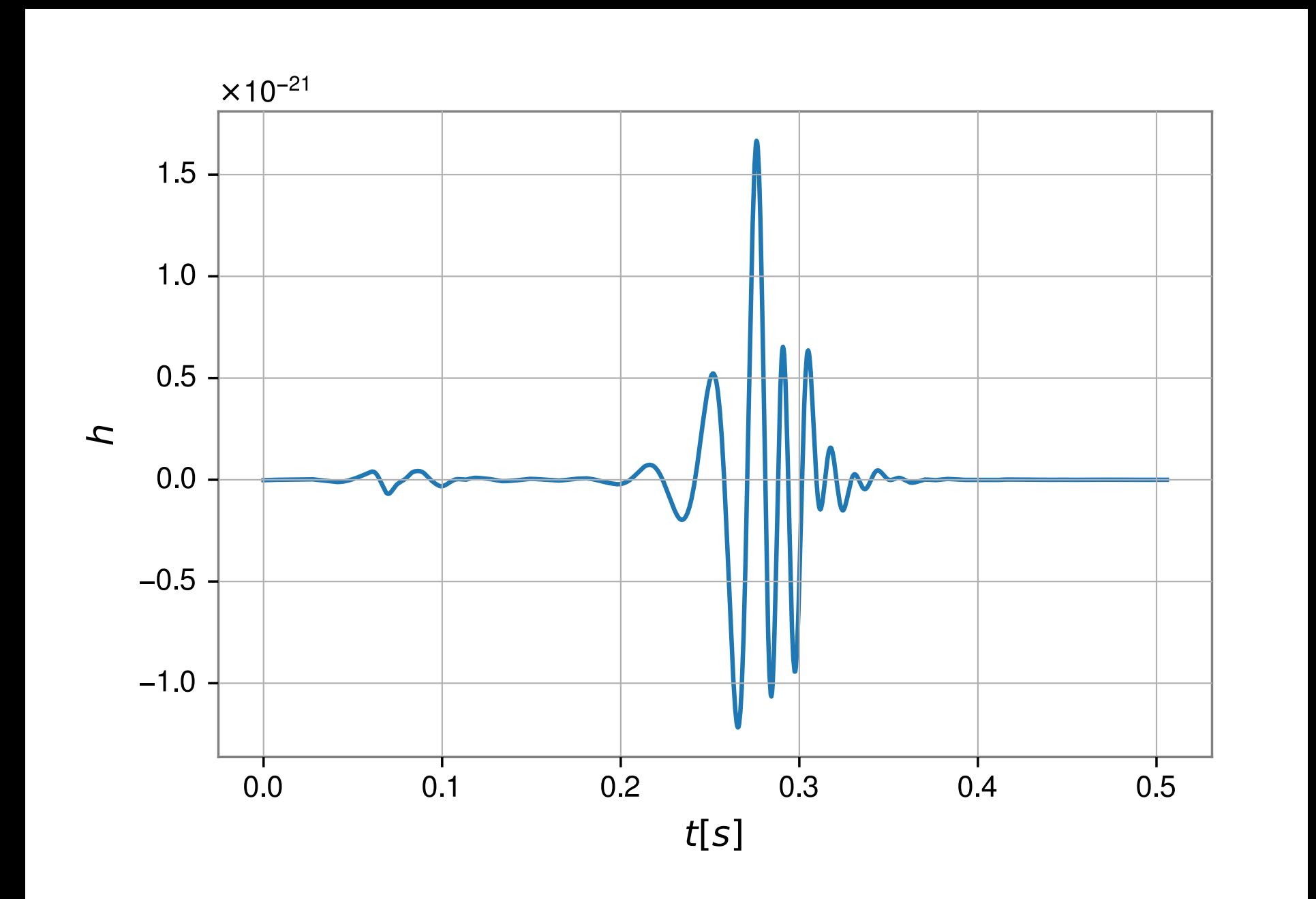
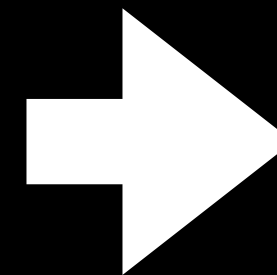
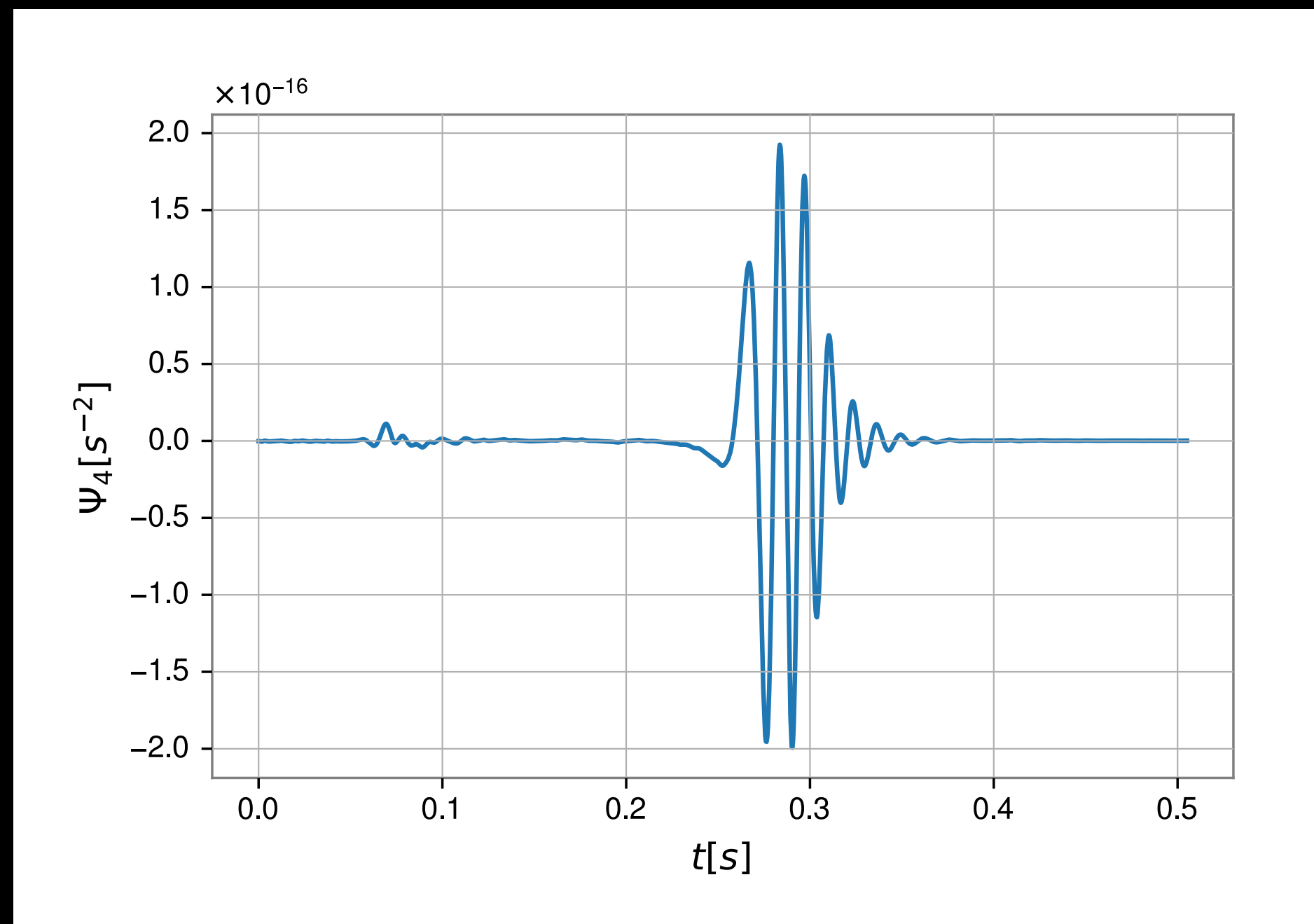
Short numerical simulations may suffer from artefacts



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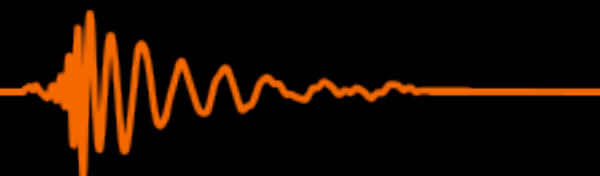
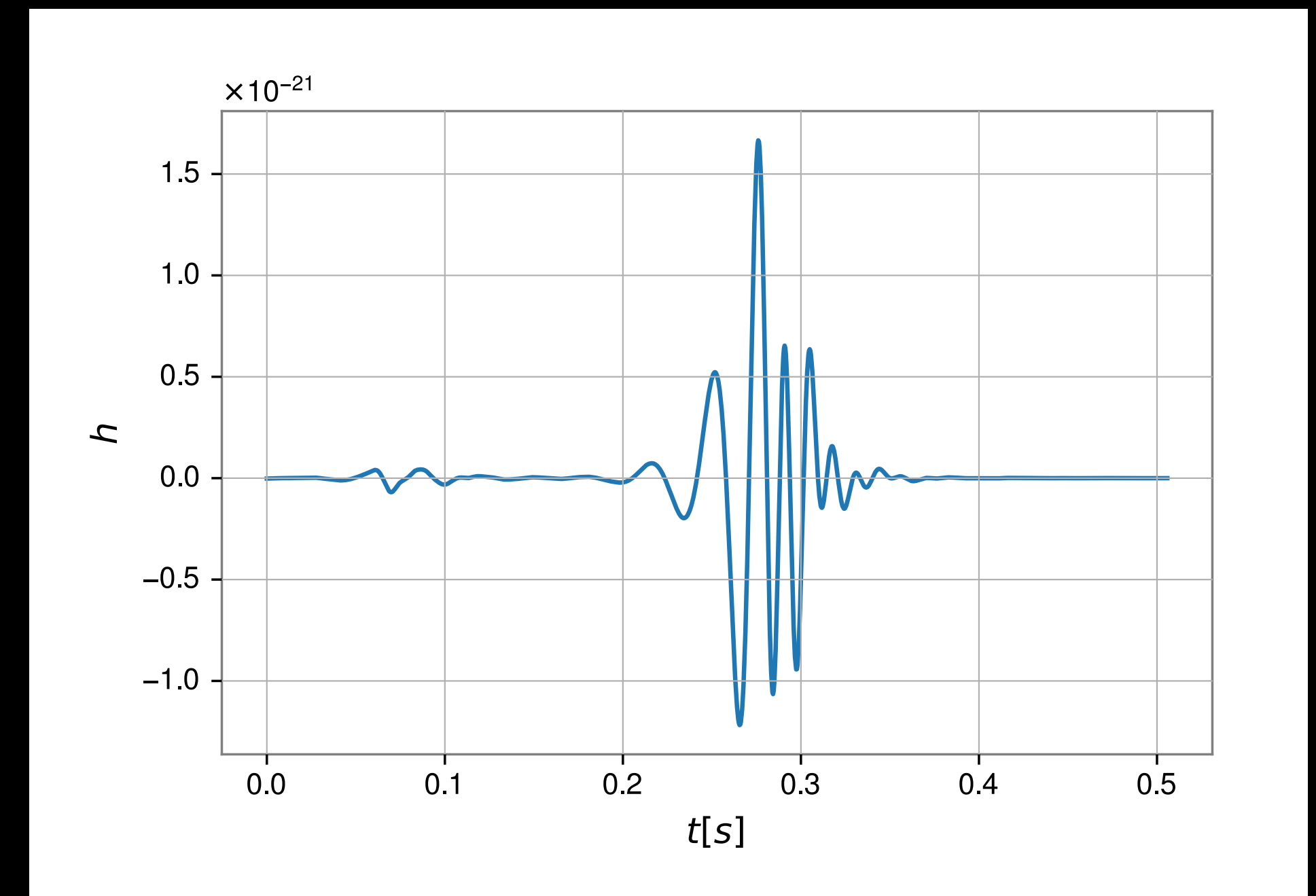
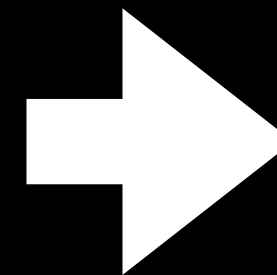
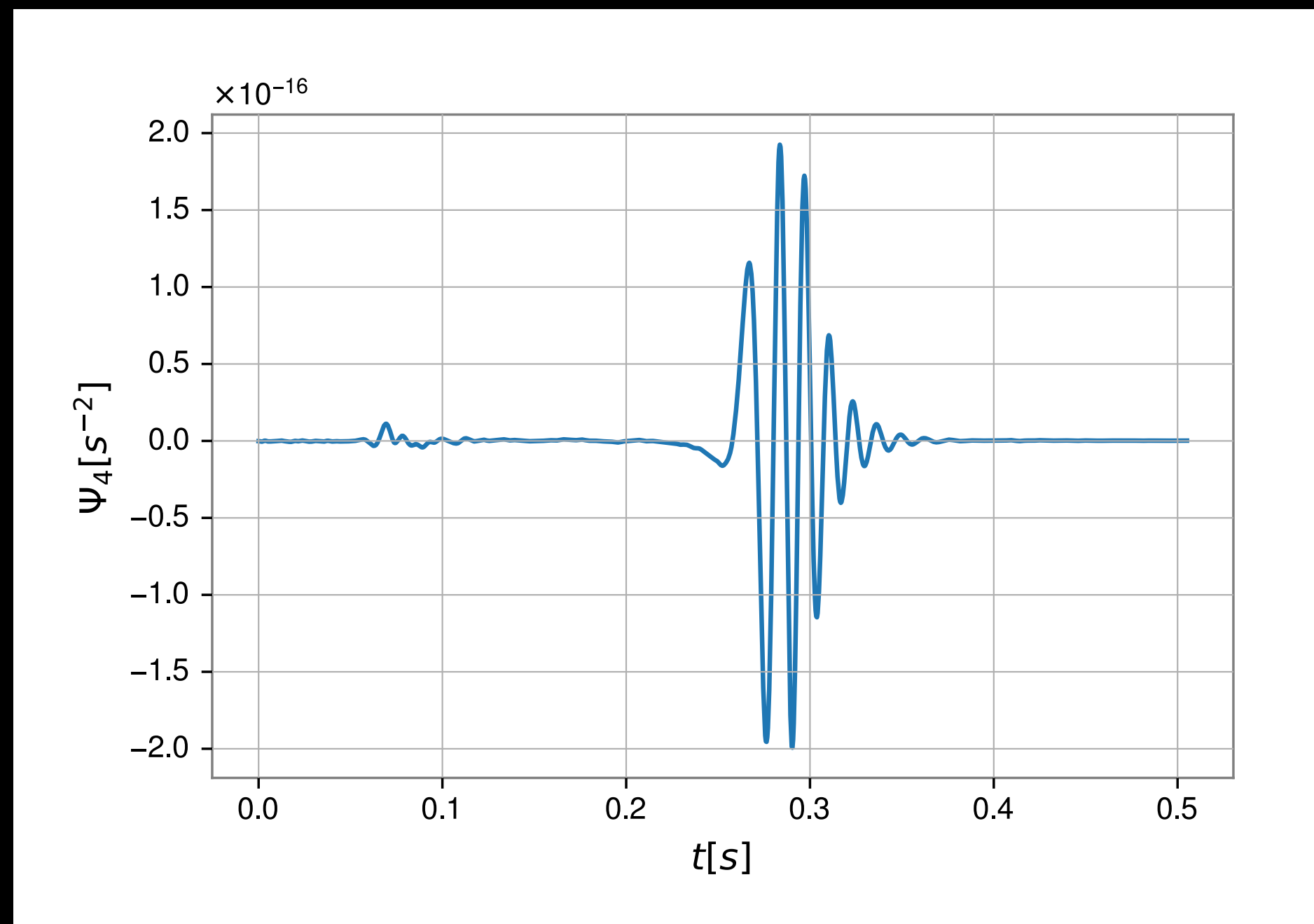




Numerical Relativity simulations extract GWs in form of  $\Psi_4 = \frac{d^2 h}{dt^2}$

Obtention of strain requires of double integration plus cleaning procedure

Short numerical simulations may suffer from artefacts





**Strategy:**

Perform second-order differencing of GW strain data

Use as templates  $\Psi_4$  directly extracted from NR simulations

**Compute the  $\Psi_4$ -PSD as:**

Run parameter estimation as usual







**Strategy:**

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**Compute the  $\Psi_4$ -PSD as:**

$$S^{(\psi_4)}[k] = \frac{1}{(\Delta t)^4} (6 - 8 \cos(2\pi k/N) + 2 \cos(4\pi k/N)) S^h[k] \quad \text{Isaac Wong (CUHK)}$$

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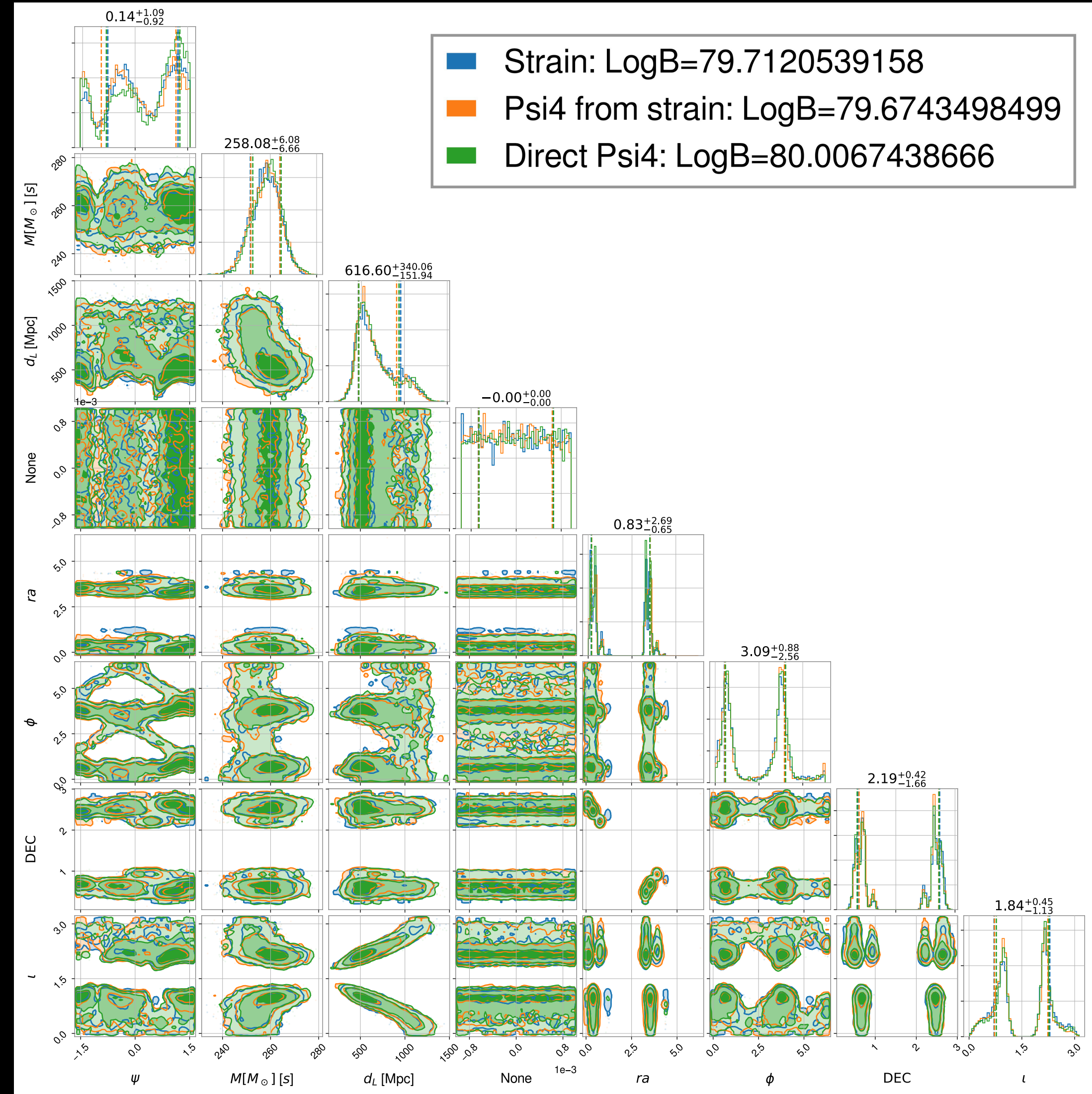
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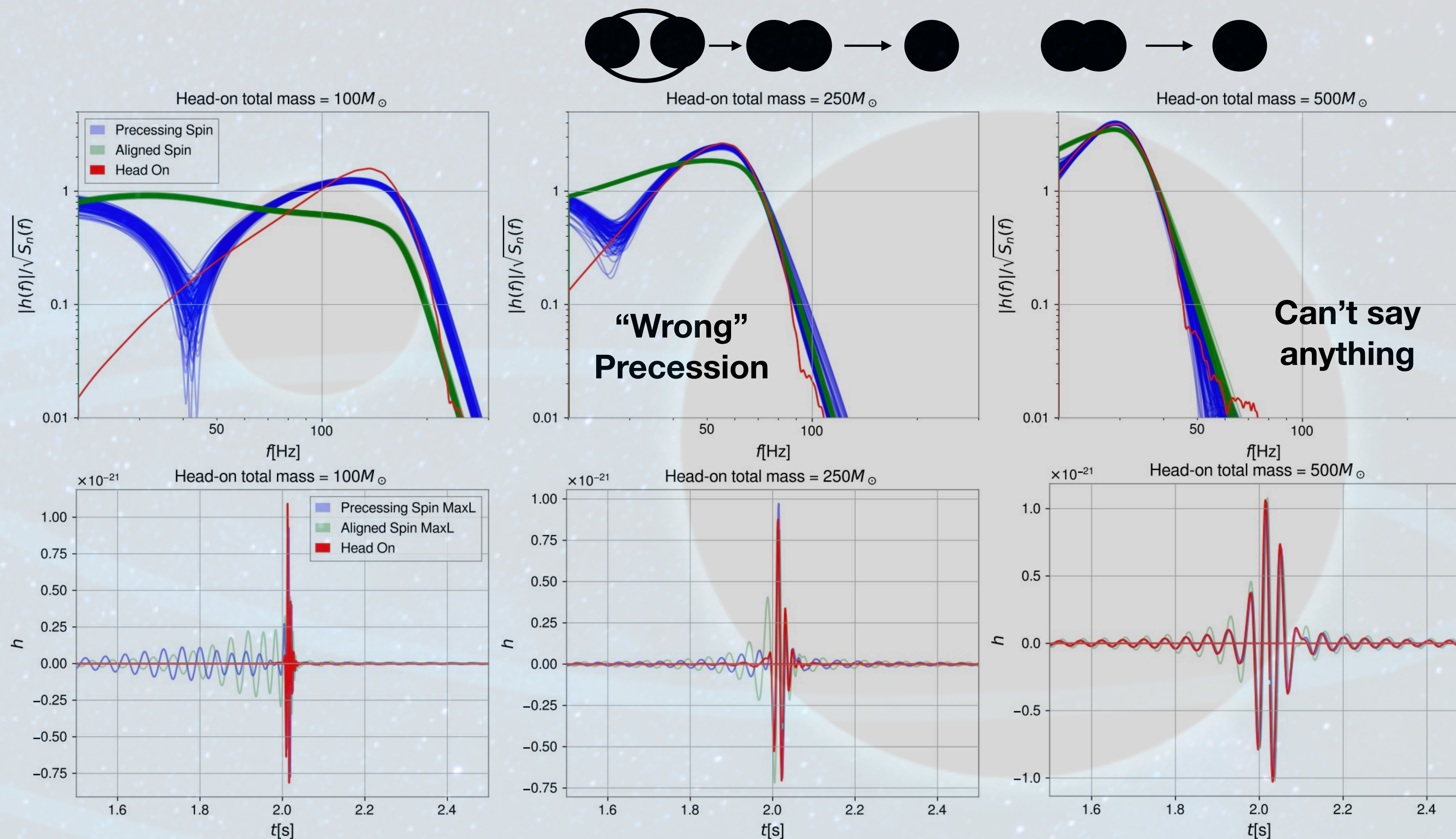
$$S^{(\psi_4)}[k] = \frac{1}{(\Delta t)^4} (6 - 8 \cos(2\pi k/N) + 2 \cos(4\pi k/N)) S^h[k]$$

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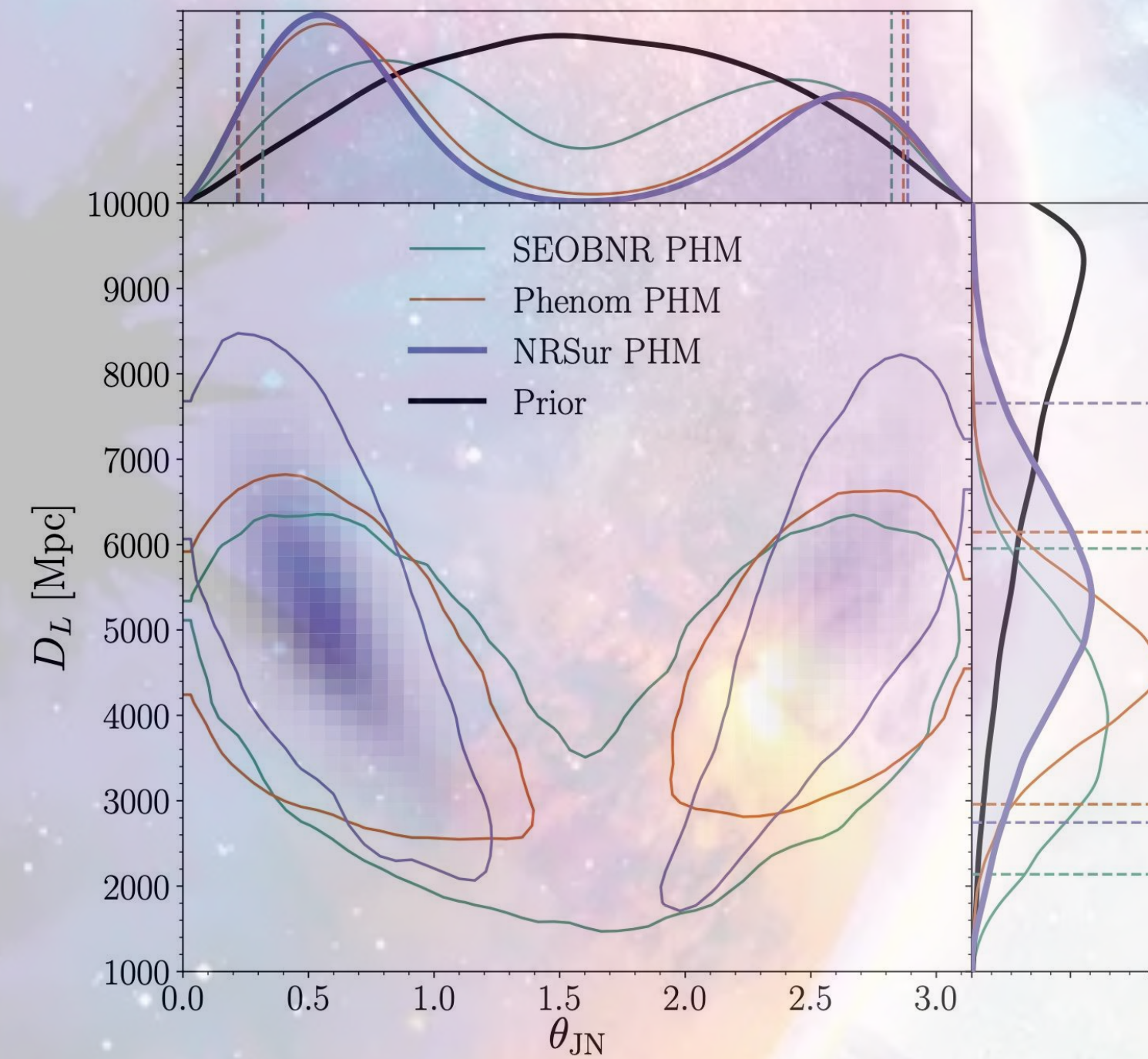
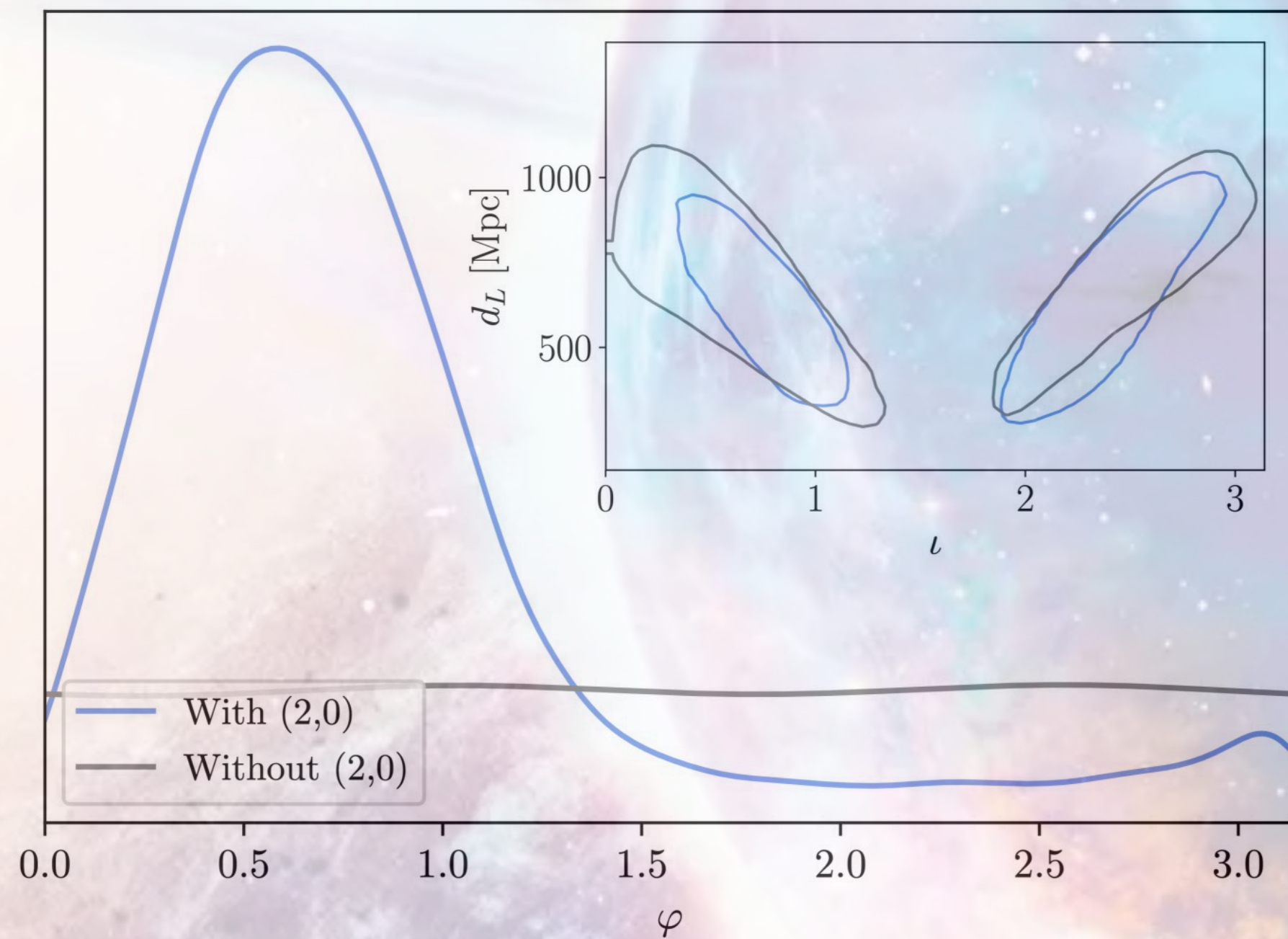


# In which situations can one mistake precession by eccentricity?





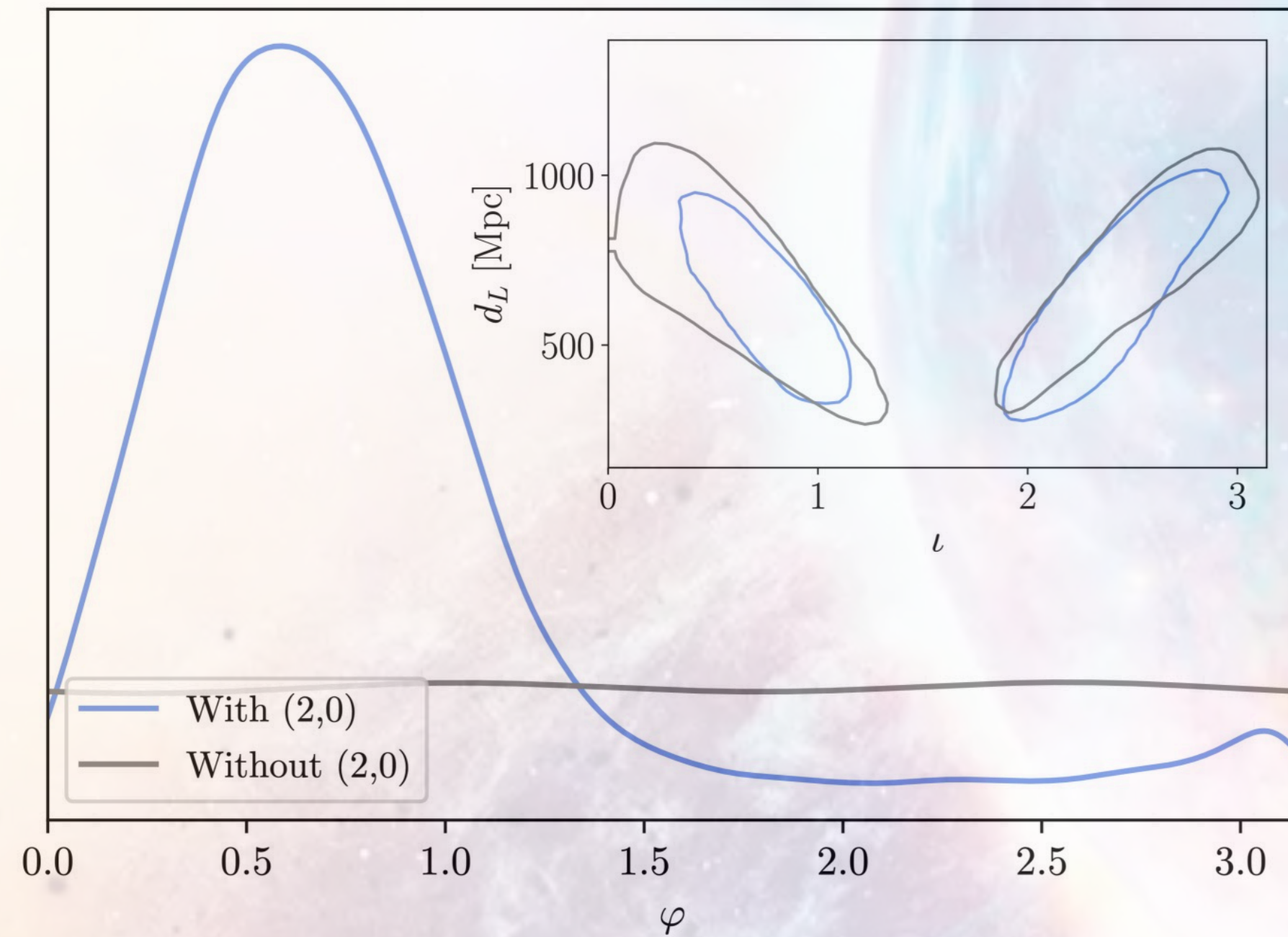
- Distance of  $\sim 500$  Mpc (5 Gpc for LIGO-Virgo)
- Much lower redshift: much larger source frame mass  $M_{source} = M_{det}/(1+z)$
- Discard edge-on inclinations



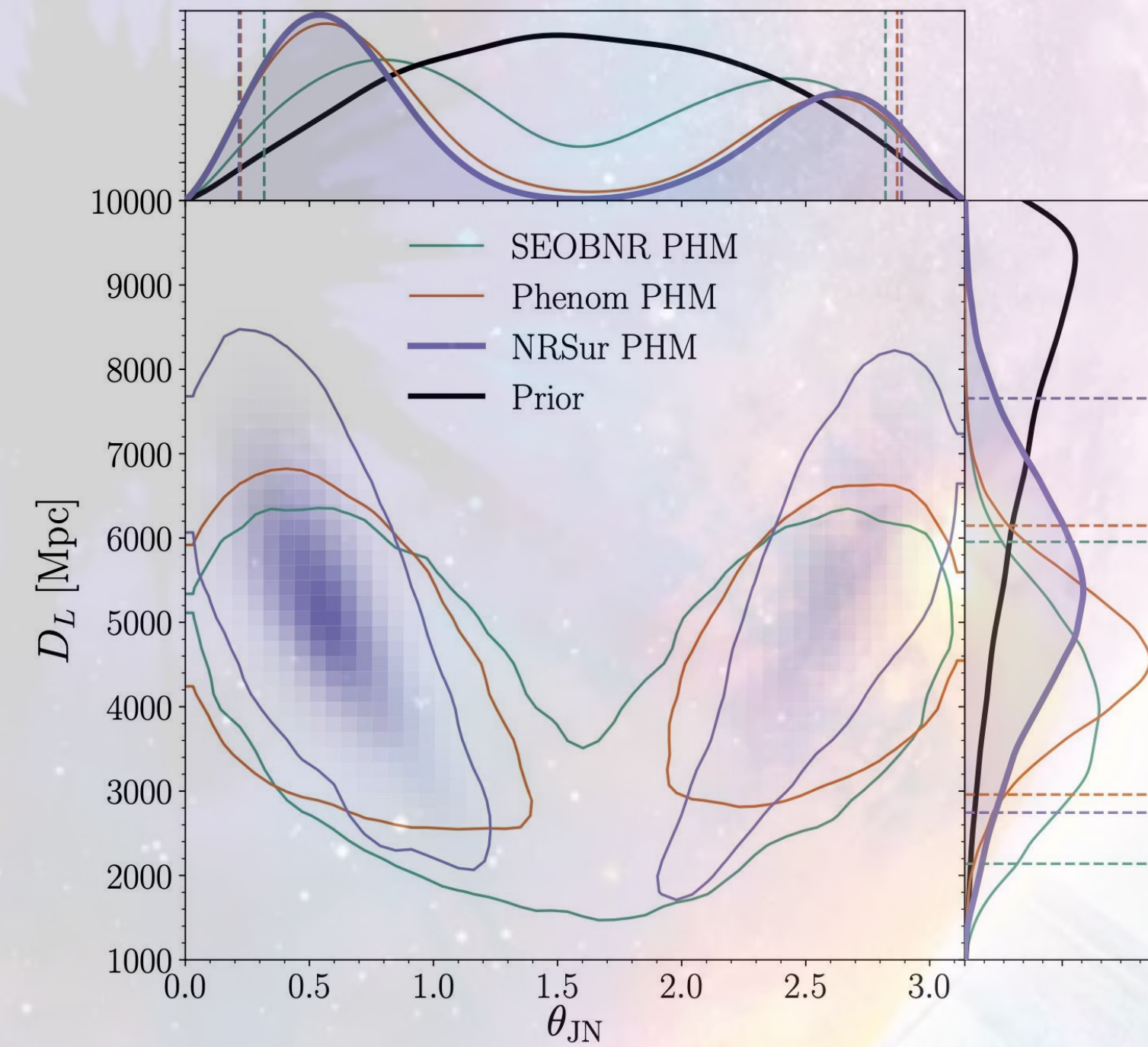
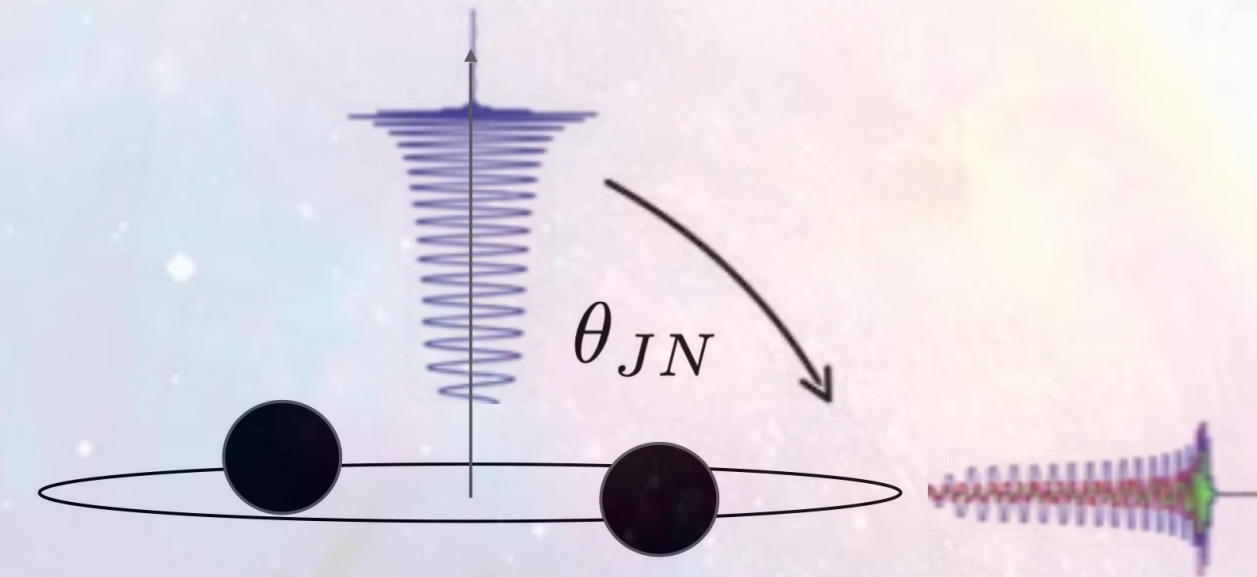


# GW190521: Proca-star parameters

- Distance of  $\sim 500$  Mpc (5 Gpc for LIGO-Virgo)
- Discard edge-on inclinations
- (2,0) mode helps to constrain inclination

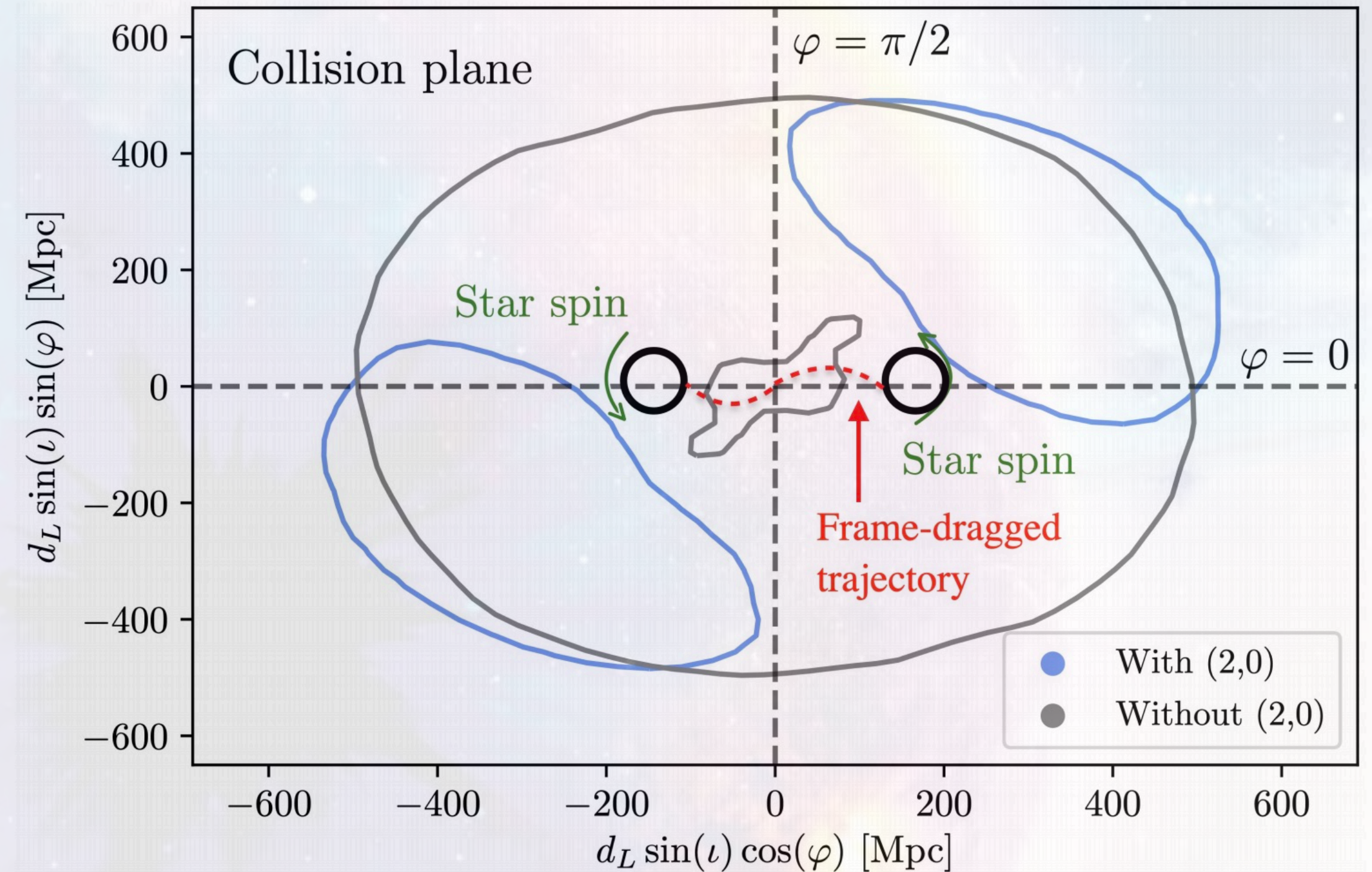


- GWs: sum of many emission modes (multipoles)





- We can measure the azimuthal angle
- (2,0) mode introduces asymmetries in the GWs
- Star's trajectories curved by frame-dragging
- Repeat analysis without (2,0) mode
  - Evidence of (2:1) for presence of (2,0) mode
- First measurement of frame dragging in GWs





## Impact of Occam Penalty

$$Z(\theta|d) = \int \pi(\theta) \mathcal{L}(\theta|d) d\theta$$

“Averaged” likelihood x Prior

“Bad” regions of parameter space reduce Z

Waveform Model	$\log \mathcal{B}$	$\log \mathcal{L}_{Max}$
Quasi-circular Binary Black Hole	80.1	105.2
Quasi-circular Non-precessing Binary Black Hole	77.1	98.8
Quasi-circular Binary Black Hole ( $q \leq 2$ )	80.7	105.2
Quasi-circular Binary Black Hole ( $q = 1$ )	81.2	105.2
Head-on Equal-mass Proca Stars	80.9	106.7
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Head-on Binary Black Hole	75.9	103.2

No support for  $q > 2$



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Precession is a necessary complication

## Impact of Occam Penalty

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Removing  $q > 2$  helps BBHs



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Restricting to  $q=1$  brings BBH closer to Proca

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Second-most significant IMBH trigger reported by LVC

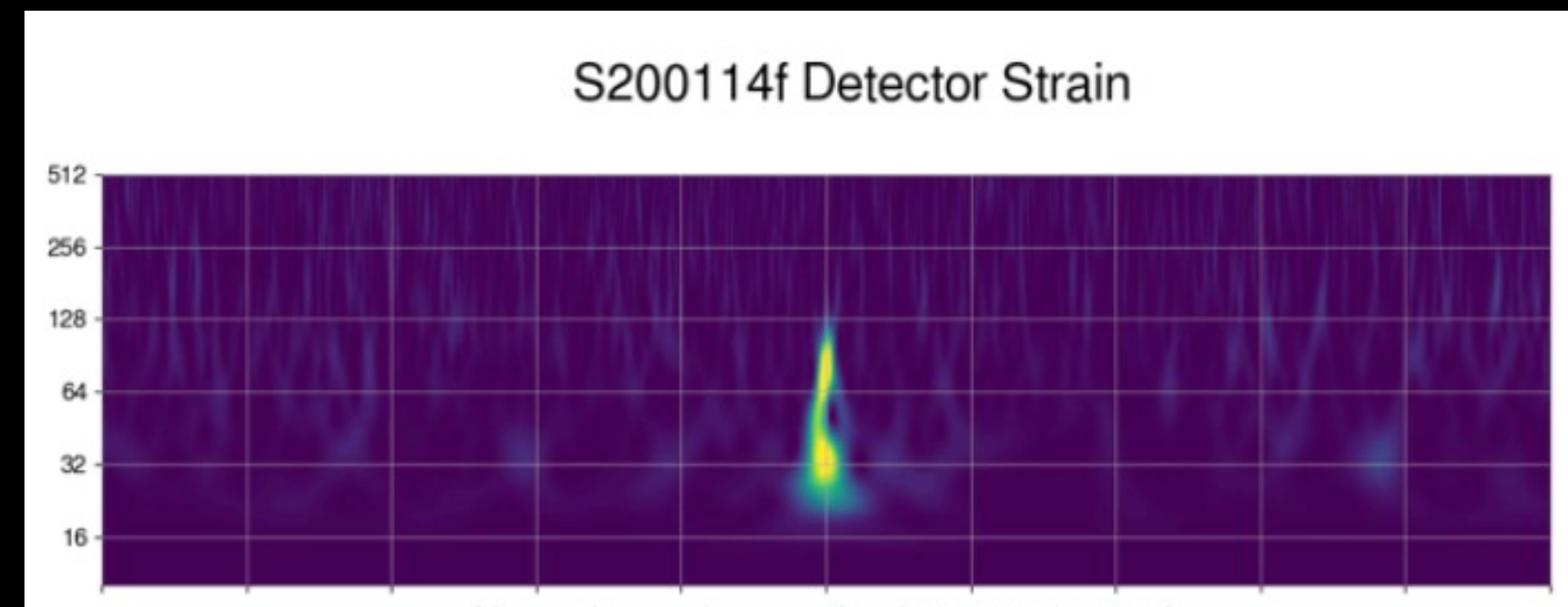
Parameter inconsistency across BBH models

Not ruled out as Proca star merger

LogB  $\sim 0$  (as probable as a BBH)

Boson mass:

$$\mu_B^{200114} = 10.19_{-0.55}^{+0.69} \times 10^{-13} eV$$



False Alarm Rate  $\sim 1/17$ yr

Second-most significant IMBH trigger reported by LVC

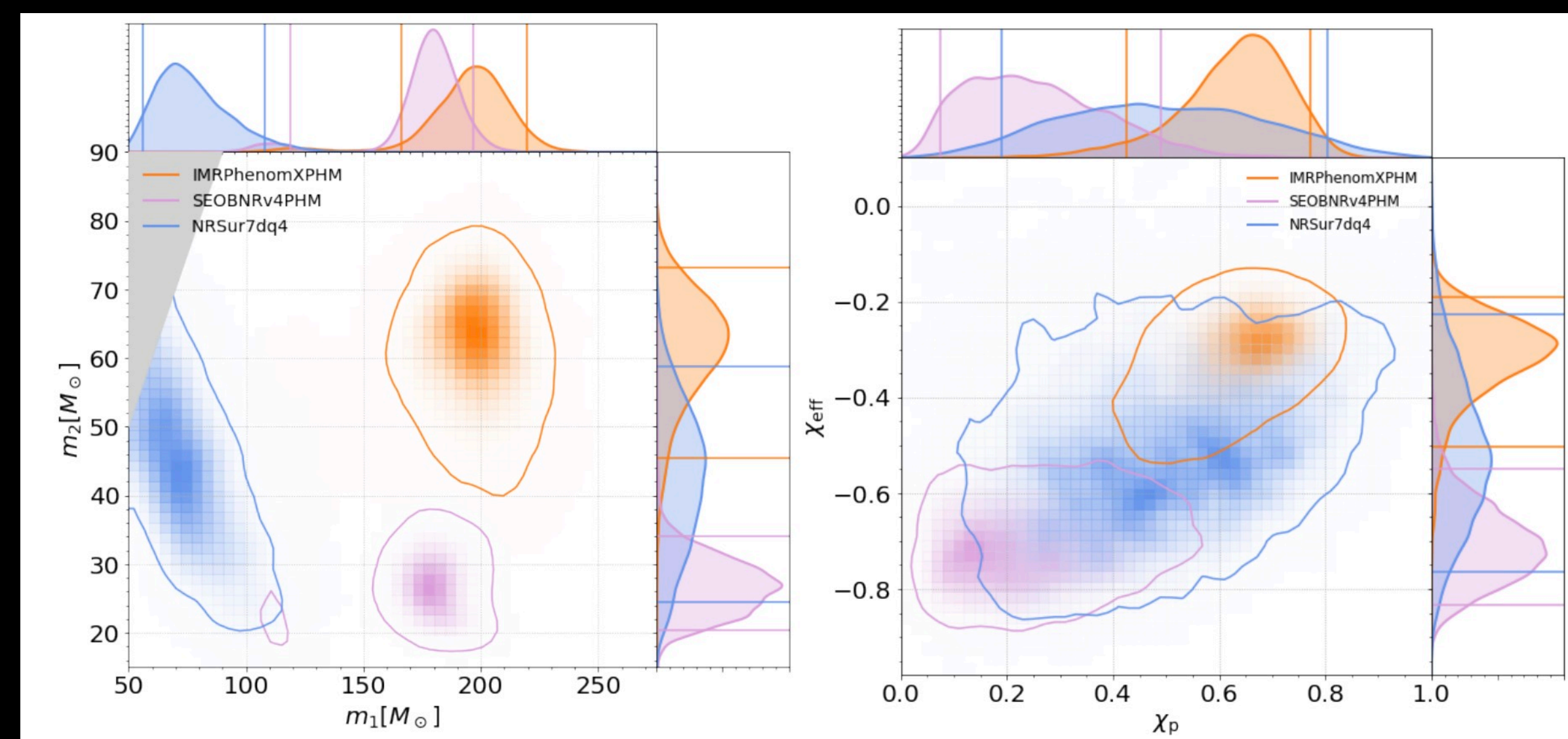
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LIGO+Virgo (2021)



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Parameter inconsistency across BBH models

Not ruled out as Proca star merger

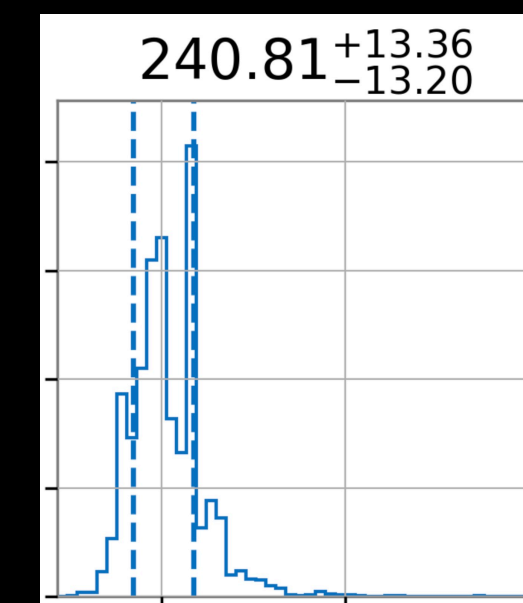
LogB (BBH vs. Proca Star)  $\sim 0$  (as probable as a BBH)

Boson mass:

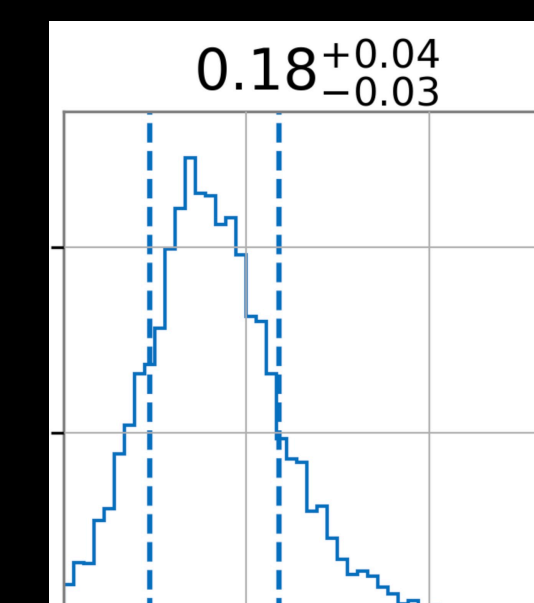
$$\mu_B^{200114} = 10.19_{-0.55}^{+0.69} \times 10^{-13} eV$$

BBH run: IMRPhenomTPHM (Pratten+ 21): MaxLogL = 103

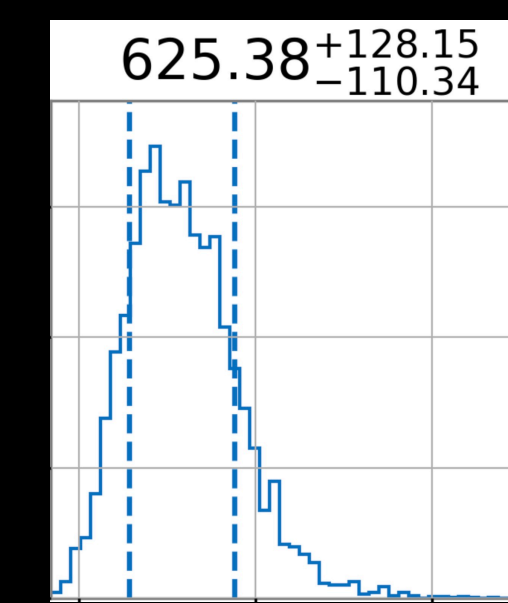
Tried also NRSur7dq4 (Varma+ 20), IMRPhenomXPHM



$M_{\text{total}}(1+z)[M_{\odot}]$



Mass ratio



$d_L[Mpc]$

Large individual spin magnitudes    Large spin tilts: precession

Second-most significant IMBH trigger reported by LVC

Parameter inconsistency across BBH models

Not ruled out as Proca star merger

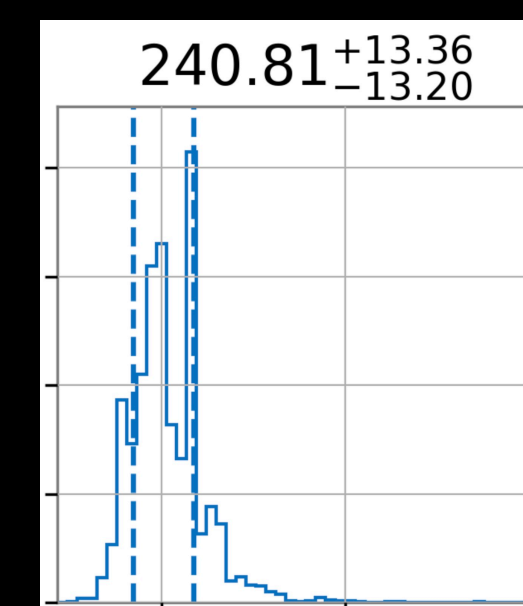
LogB (BBH vs. Proca Star)  $\sim 0$  (as probable as a BBH)

Boson mass:

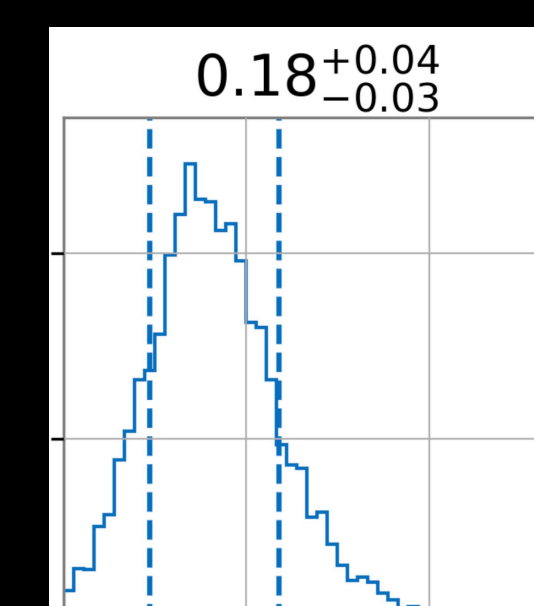
$$\mu_B^{200114} = 10.19_{-0.55}^{+0.69} \times 10^{-13} eV$$

BBH run: IMRPhenomTPHM (Pratten+ 21): MaxLogL = 103

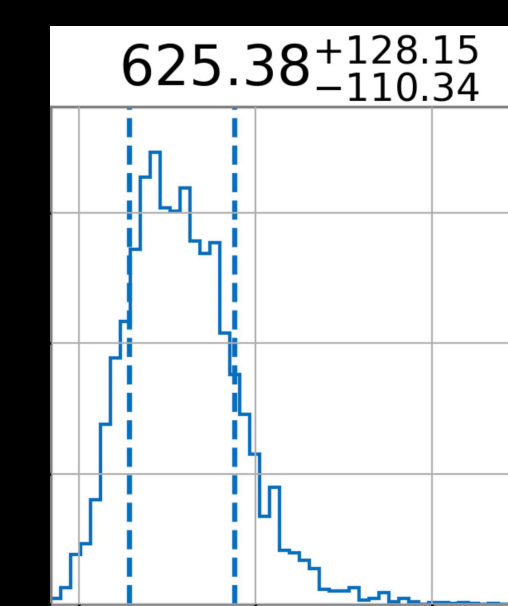
Tried also NRSur7dq4 (Varma+ 20), IMRPhenomXPHM



$M_{\text{total}}(1+z)[M_{\odot}]$



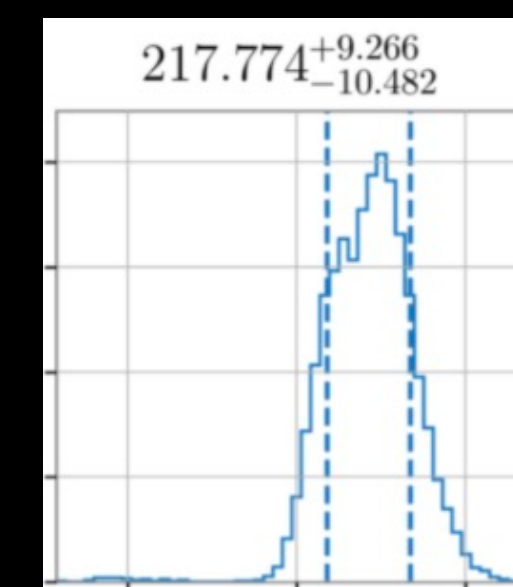
Mass ratio



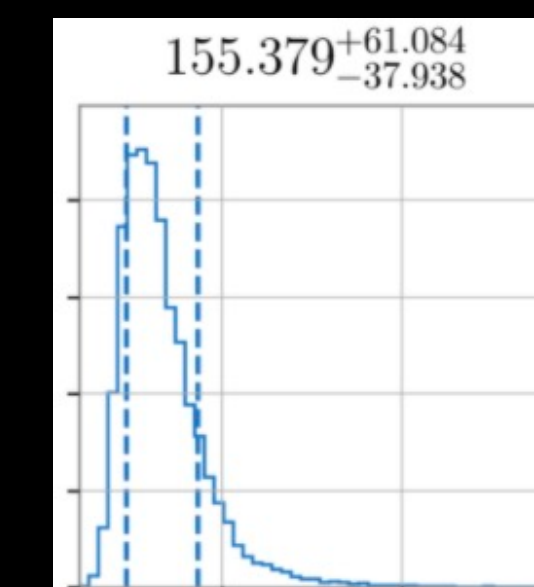
$d_L[Mpc]$

Large individual spin magnitudes    Large spin tilts: precession

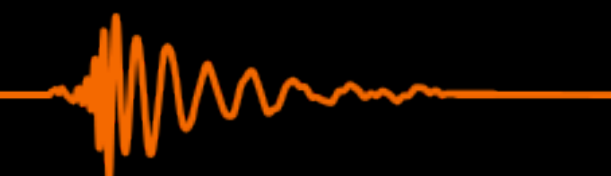
Proca-star run: MaxLogL = 100



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$d_L[Mpc]$





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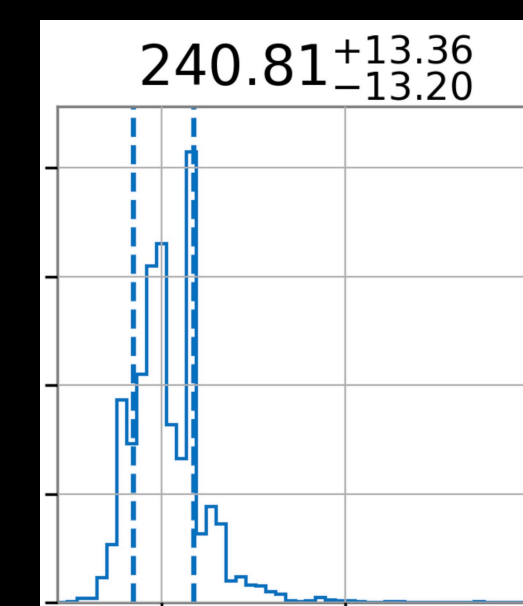
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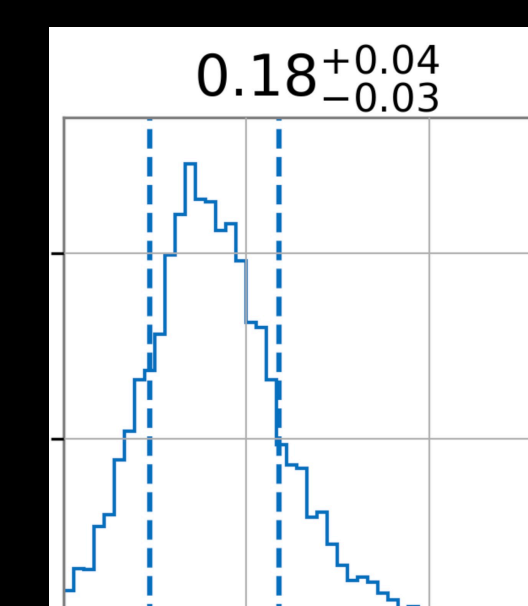
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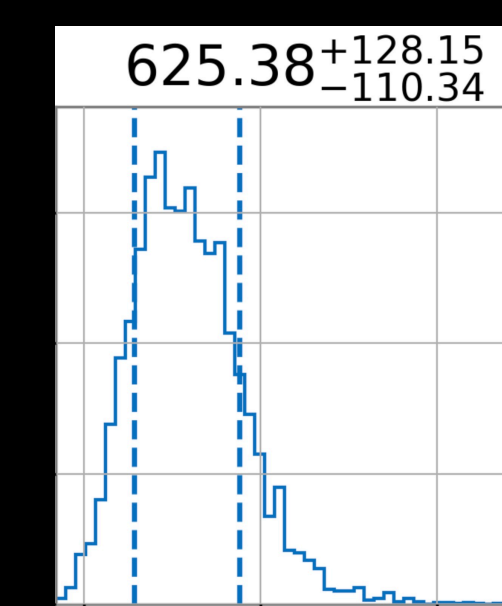
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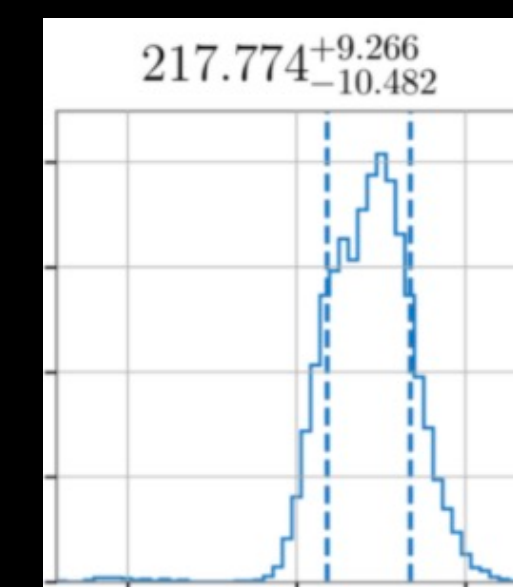
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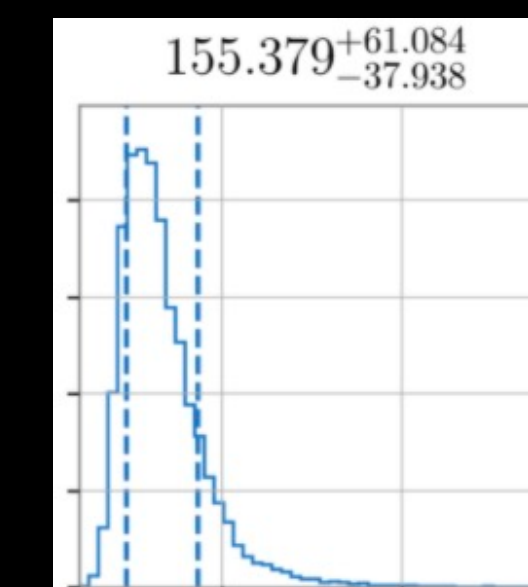
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We use Newmann-Penrose scalar as template

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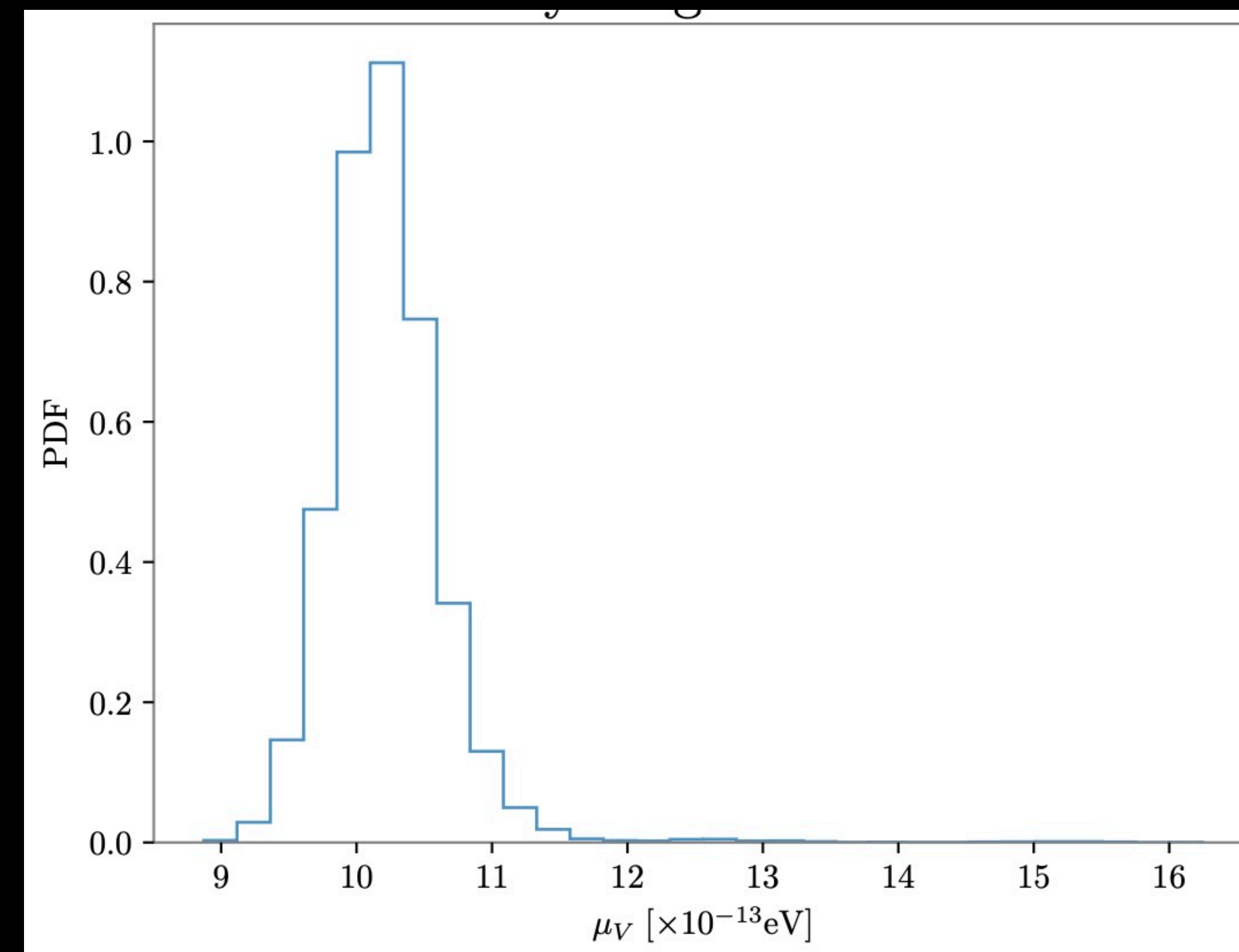
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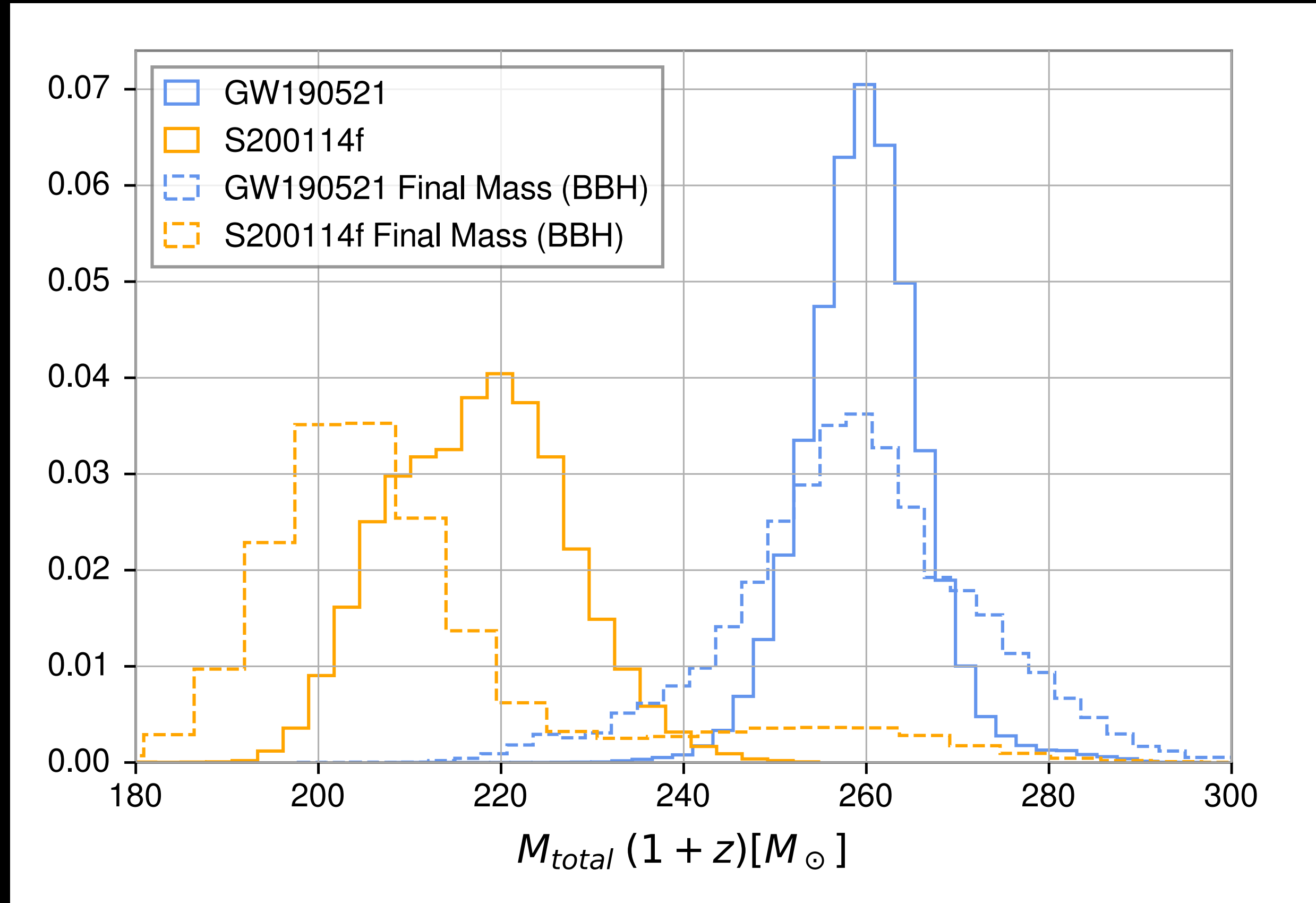
LogB  $\sim 0$  (as probable as a BBH)

Boson mass:

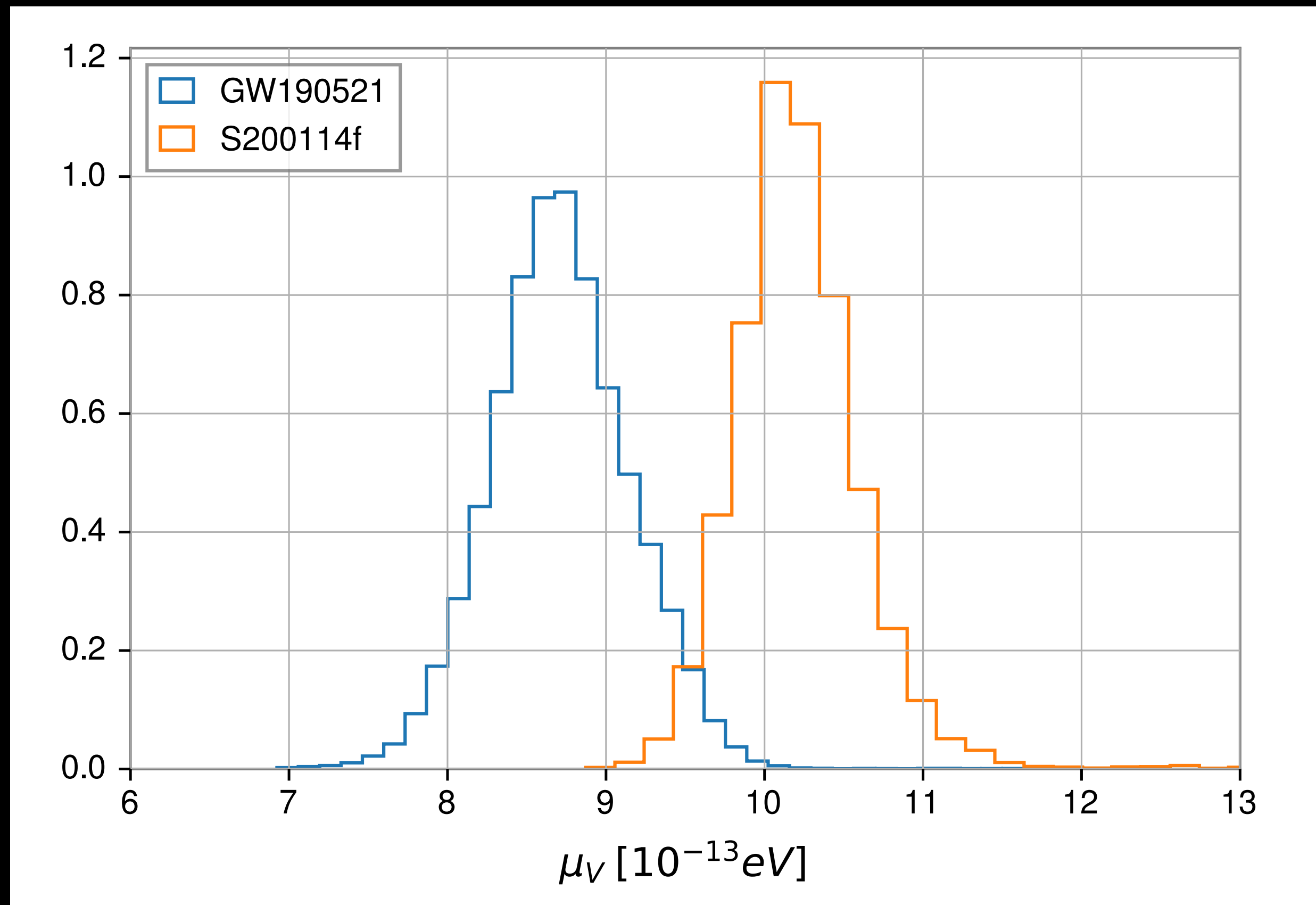
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Parameter	GW190521	S200114f
Primary mass	$124_{-12}^{+17} M_{\odot}$	$113_{-9}^{+9} M_{\odot}$
Secondary mass	$95_{-13}^{+10} M_{\odot}$	$97_{-10}^{+8} M_{\odot}$
<b>Total / Final mass</b>	<b><math>231_{-16}^{+15} M_{\odot}</math></b>	<b><math>217_{-16}^{+16} M_{\odot}</math></b>
Final spin	$0.75_{-0.04}^{+0.08}$	$0.75_{-0.04}^{+0.08}$
Inclination $\pi/2 -  \iota - \pi/2 $	$0.66_{-0.45}^{+0.37}$ rad	$0.93_{-0.29}^{+0.39}$ rad
Azimuth	$0.65_{-0.54}^{+0.86}$ rad	$0.78_{-1.20}^{+1.23}$ rad
Luminosity distance	$571_{-181}^{+348}$ Mpc	$155_{-52}^{+80}$ Mpc
Redshift	$0.12_{-0.05}^{+0.07}$	$0.034_{-0.012}^{+0.025}$
Total / Final redshifted mass	$259_{-10}^{+10} M_{\odot}$	$217_{-16}^{+16} M_{\odot}$
Primary boson field frequency $\omega/\mu_V$	$0.880_{-0.080}^{+0.032}$	$0.845_{-0.035}^{+0.020}$
Secondary boson field frequency $\omega/\mu_V$	$0.910_{-0.015}^{+0.015}$	$0.895_{-0.015}^{+0.017}$
Boson mass $\mu_V [\times 10^{-13}]$	$8.70_{-0.69}^{+0.75}$ eV	$10.19_{-0.55}^{+0.65}$ eV
Maximal boson star mass	$173_{-14}^{+15} M_{\odot}$	$147_{-9}^{+8} M_{\odot}$



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## Model Selection Fundamentals

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

$\mathcal{L}(\theta|d)$  : Likelihood (fit)

$\pi(\theta)$  : Prior Assumptions

$Z(\theta|d)$  : Evidence for the model

$$Z(\theta|d) = \int \pi(\theta)\mathcal{L}(\theta|d)d\theta$$

↑: Large likelihood

↓: Useless parameters (Occam's Razor)

↑↓: Choice of priors

$$\frac{P(\text{Model A})}{P(\text{Model B})} = \frac{Z_A}{Z_B}$$



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## Settings:

Frequency range: 11-512Hz

Code: Bilby Ashton+ 18 Romero-Shaw+ 20

Sampler: CPNest Veitch+ (Dynesty ongoing)

## Priors:

Uniform in Total Mass and Mass Ratio

Standard for the spins, source orientation, sky-location

Uniform in Co-moving volume

