Towards a gravitational-wave catalogue of Proca-star mergers

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universidade de aveiro

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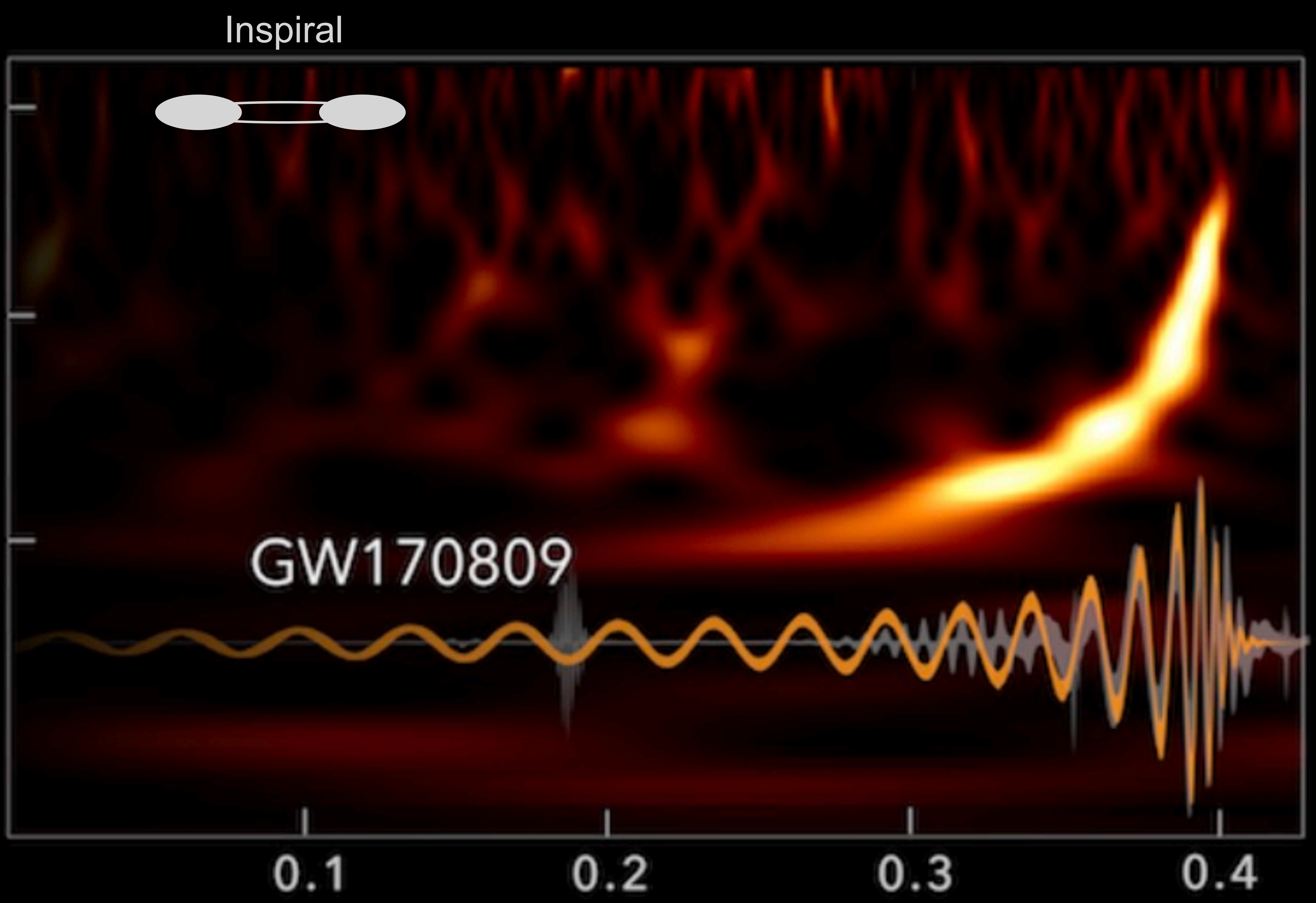
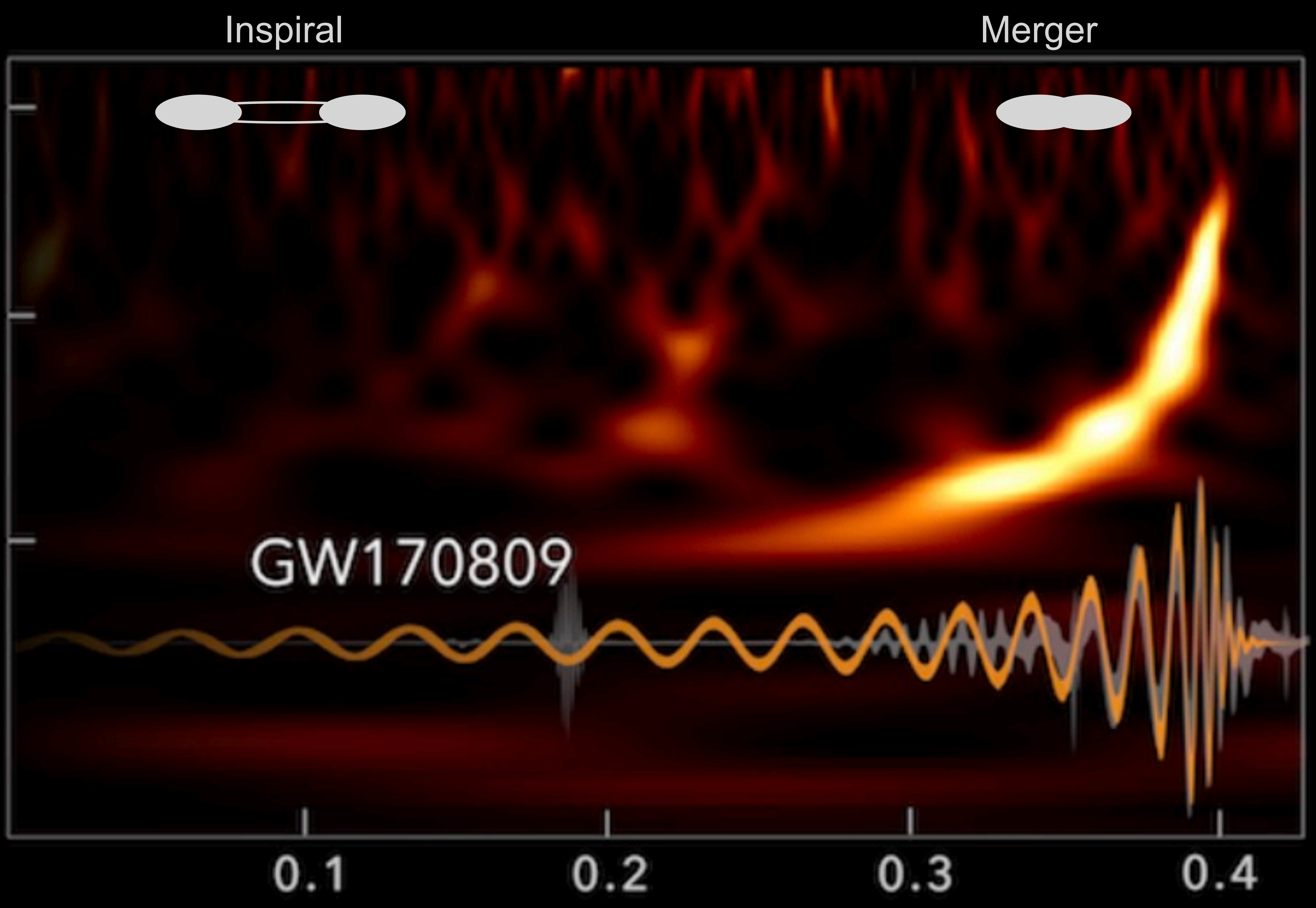
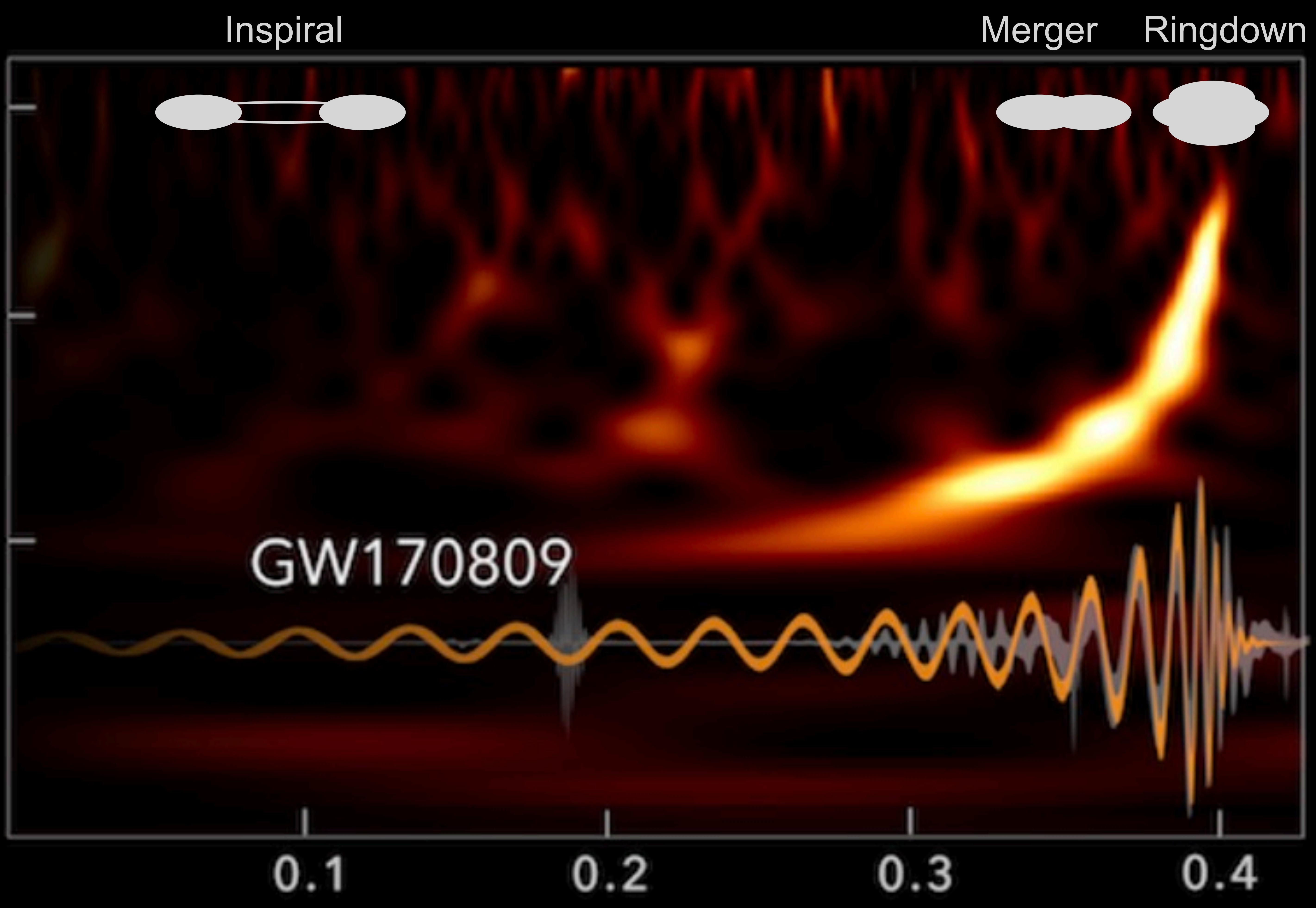
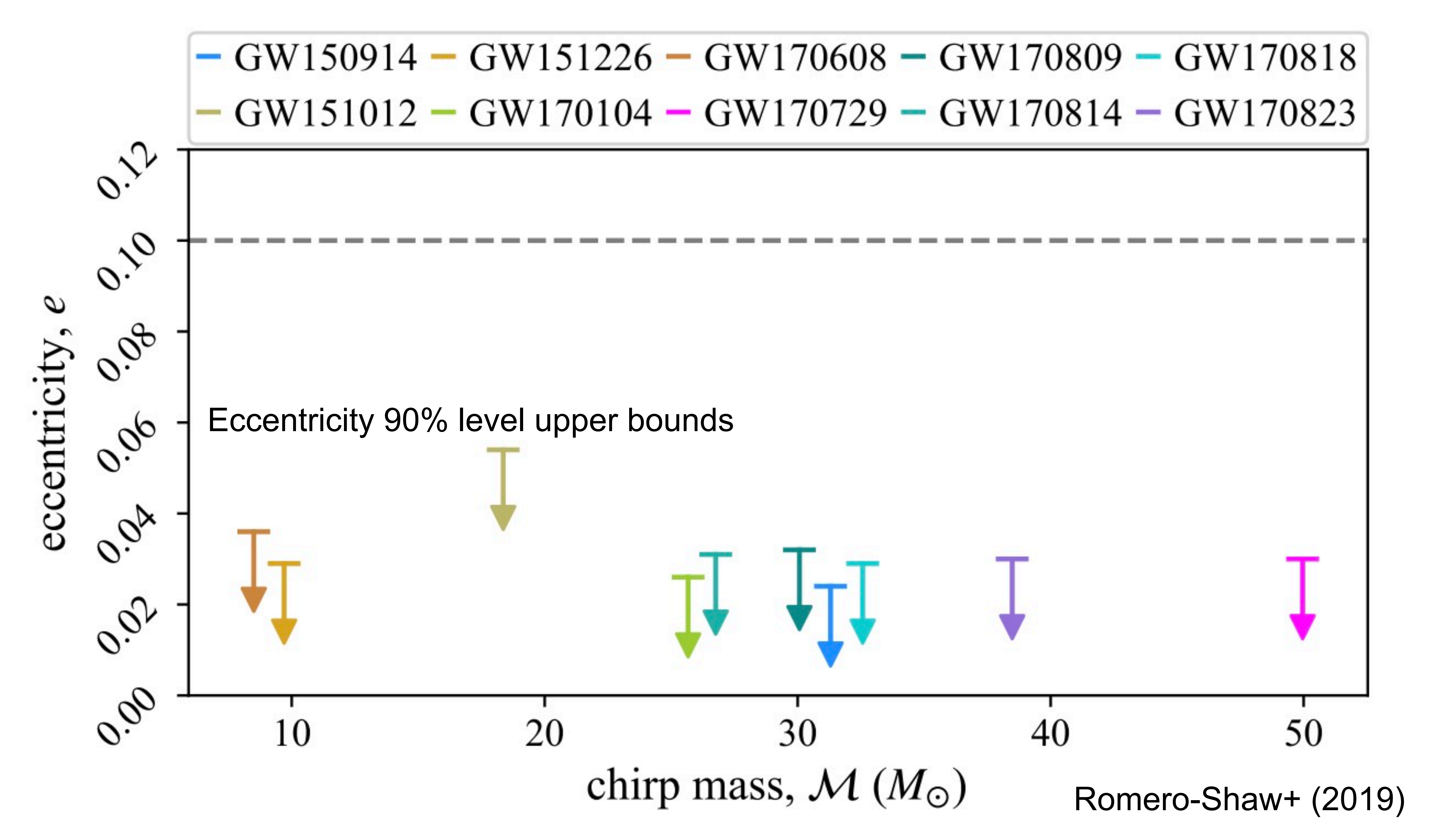
EXCELENCIA MARÍA DE MAEZTU


Inspiral
GW170809
0.1
0.2
0.3
0.4


Inspiral
Merger
GW170809
0.1
0.2
0.3
0.4



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



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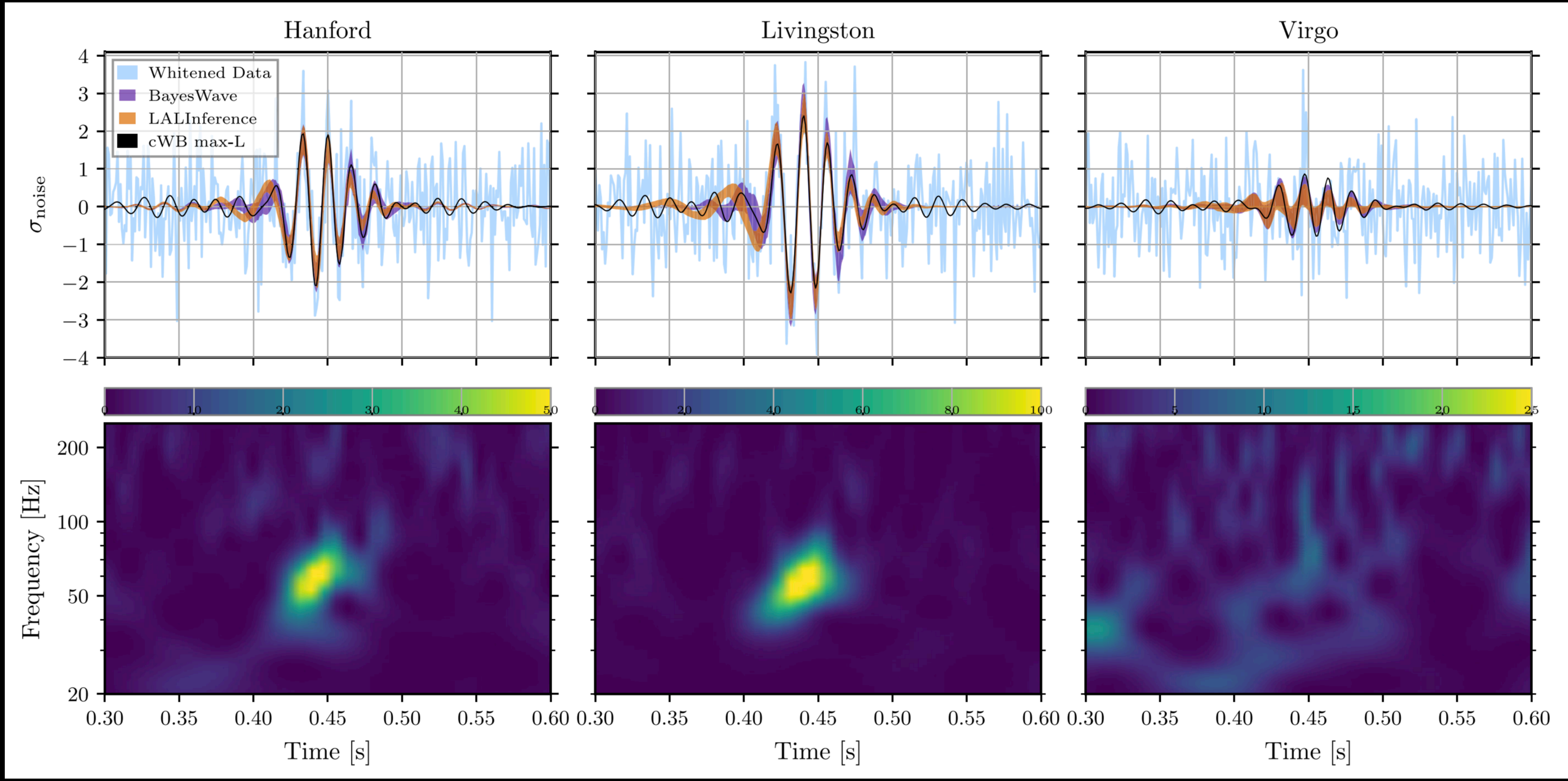
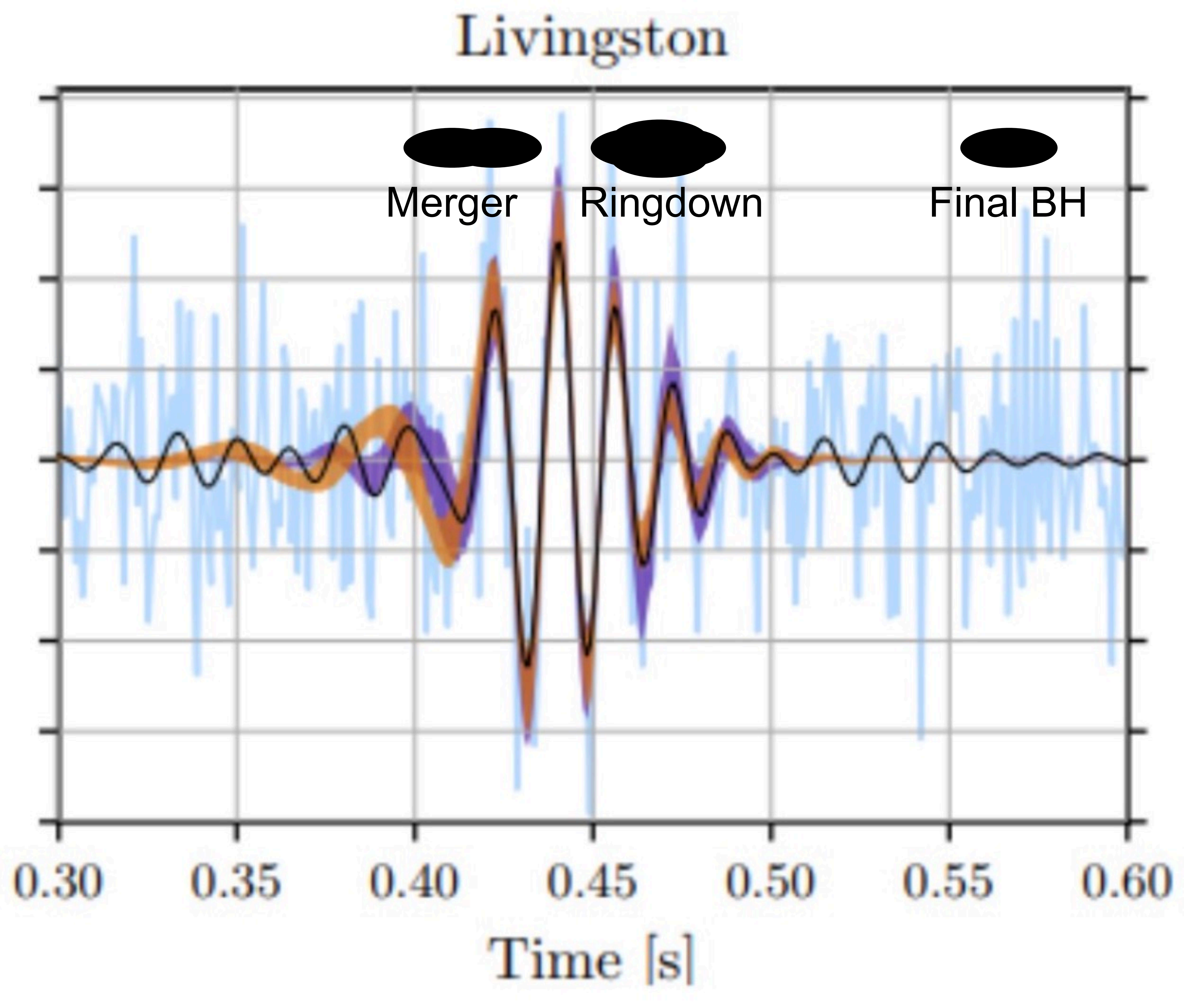


May 21st 2019

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.

LVC 2020



What produced GW190521?

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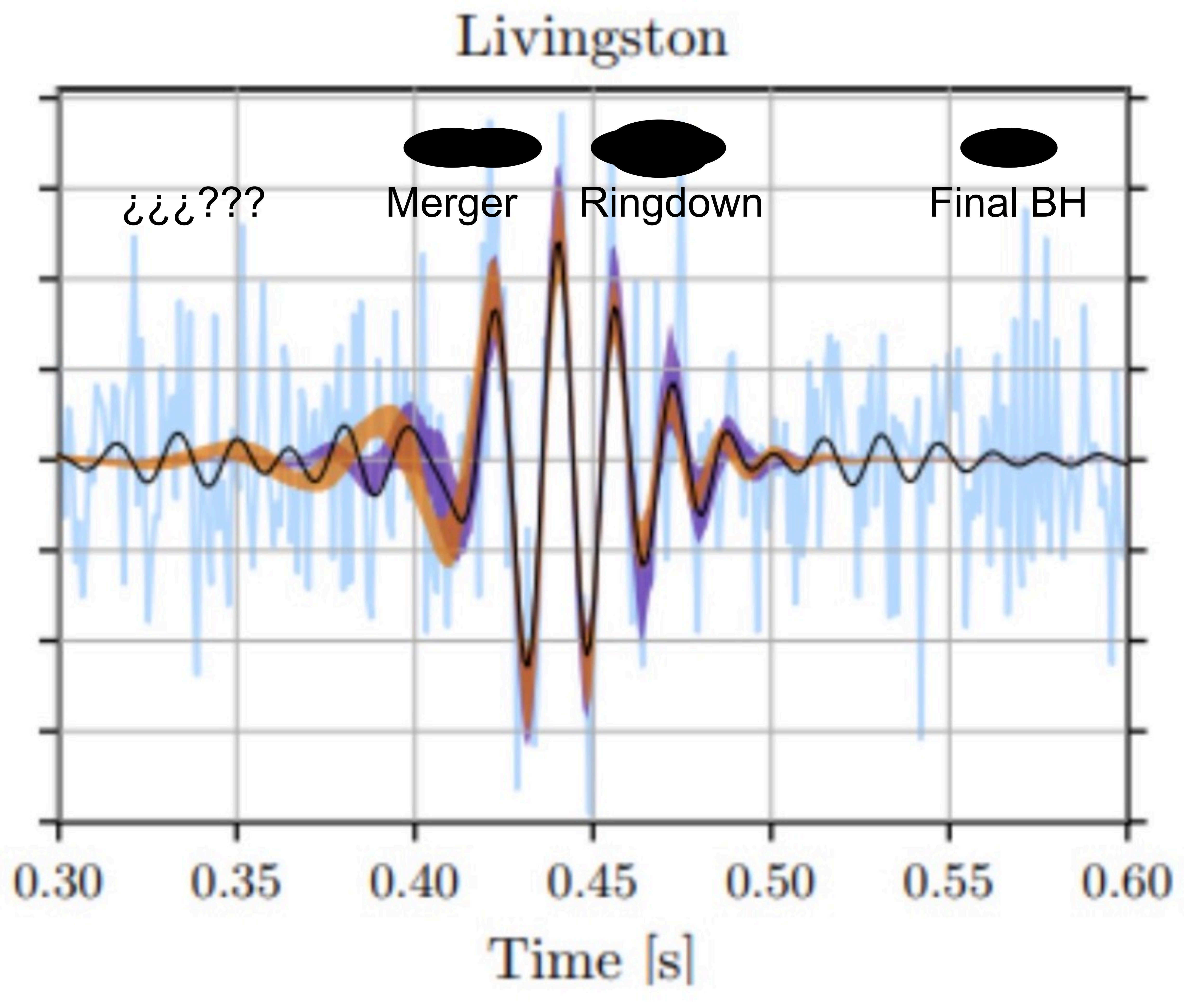
LVC 2020



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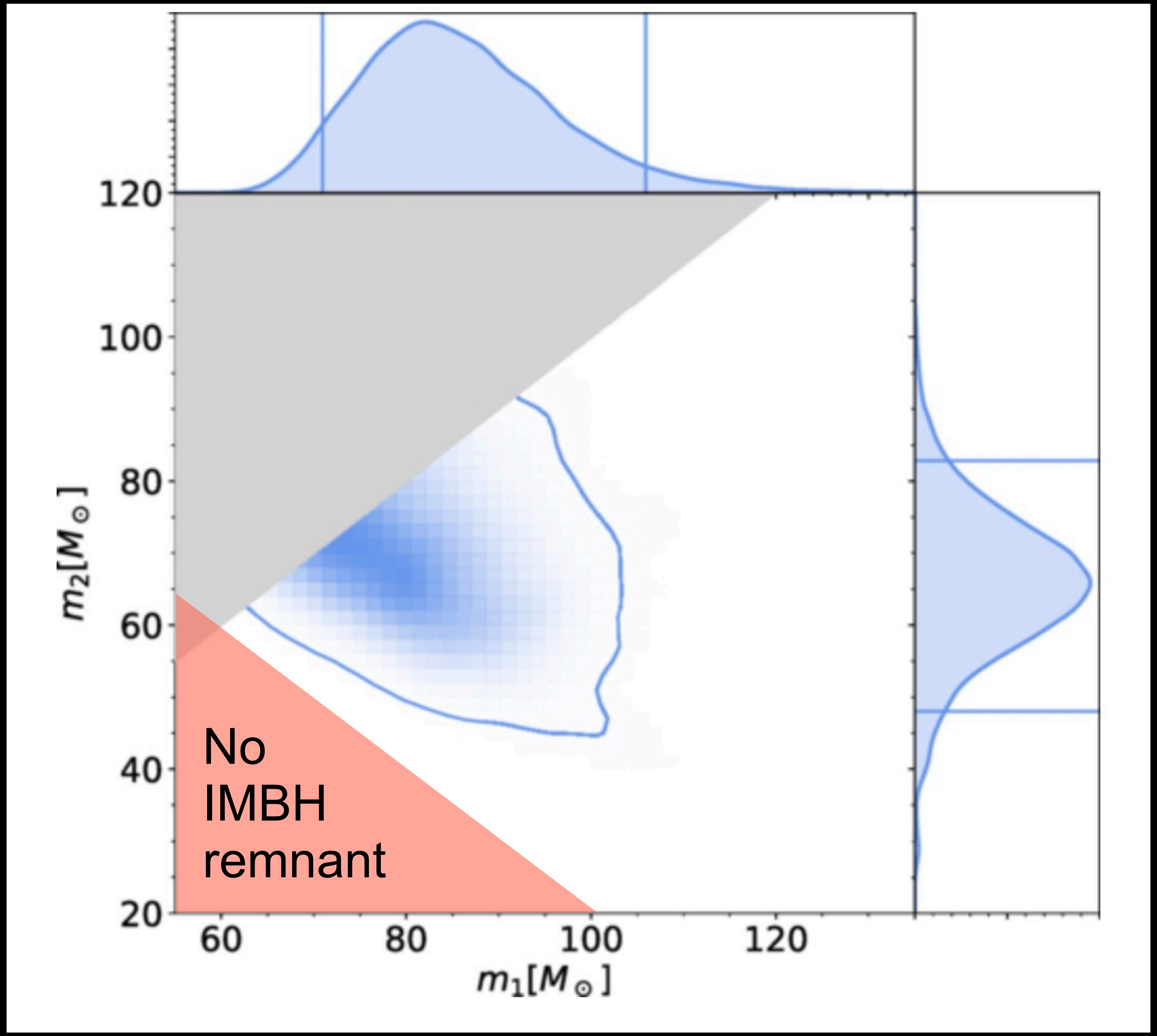

LVC 2020
Waveform Model NRSur7dq4 (Varma+ ’19)

- Barely any pre-merger emission
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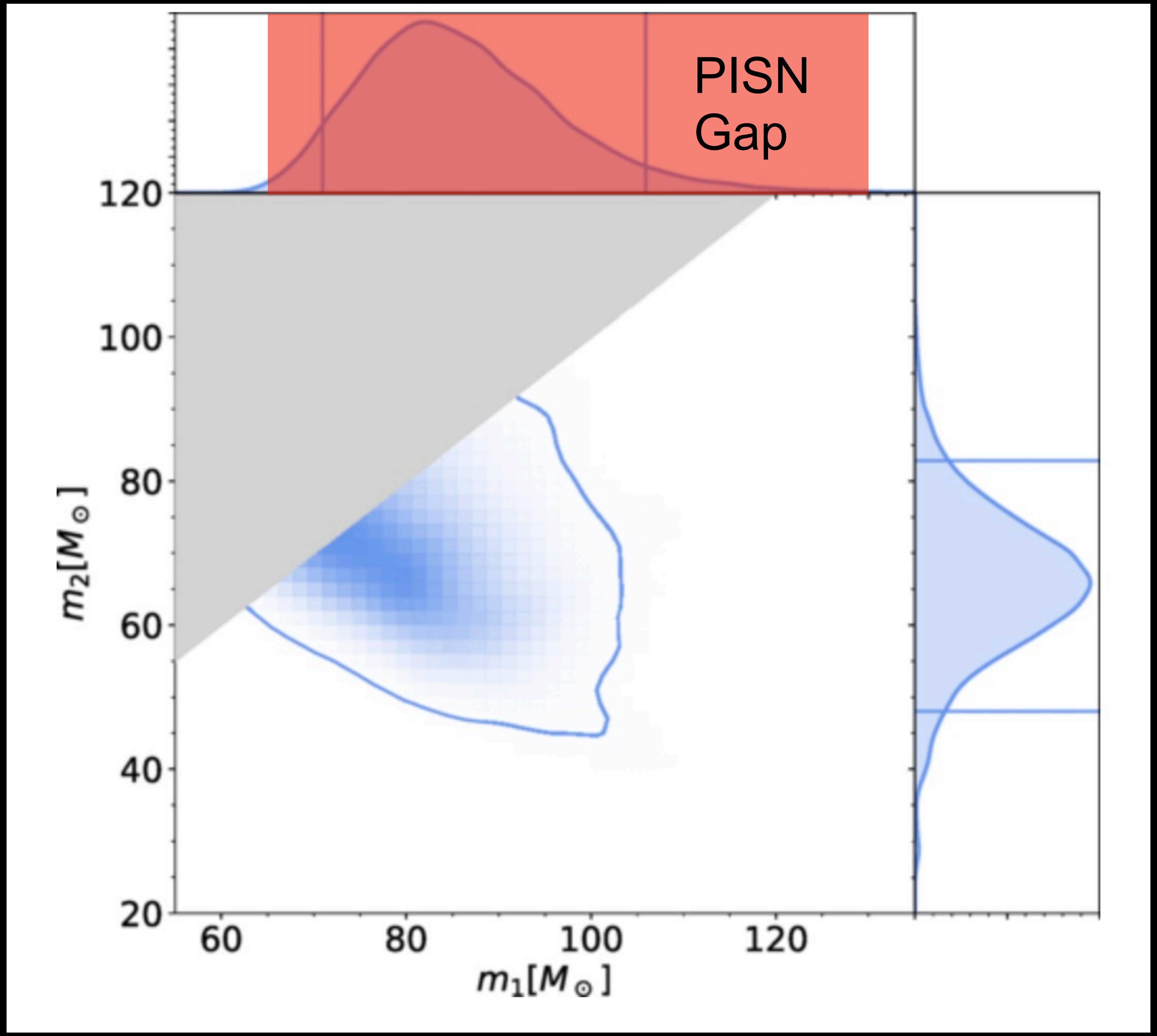
  - Mild precession signature



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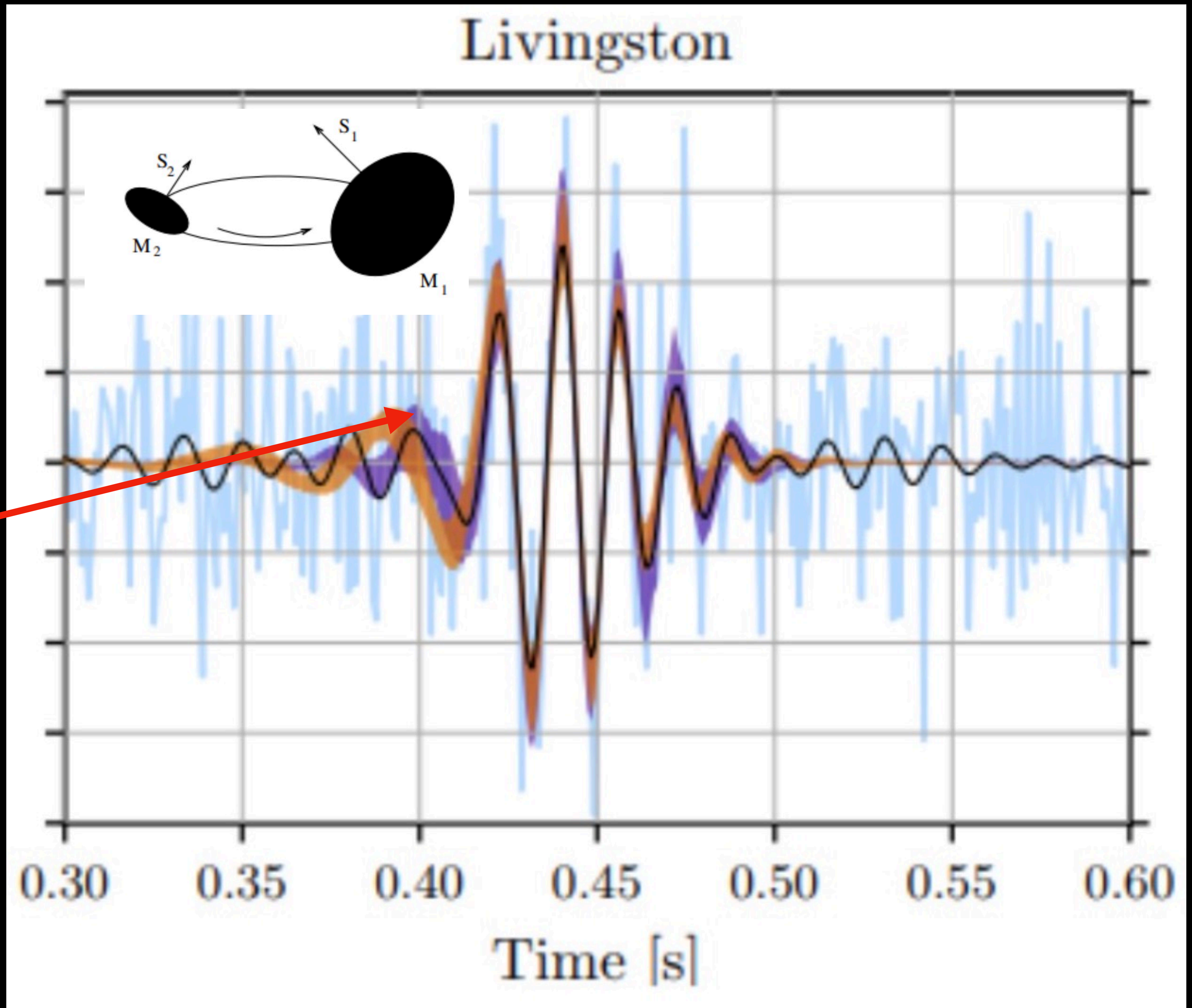
Extremely detailed study: Estellés et. al. 2021



$P(\text{precession}|\text{qBBH})$ 10 : 1

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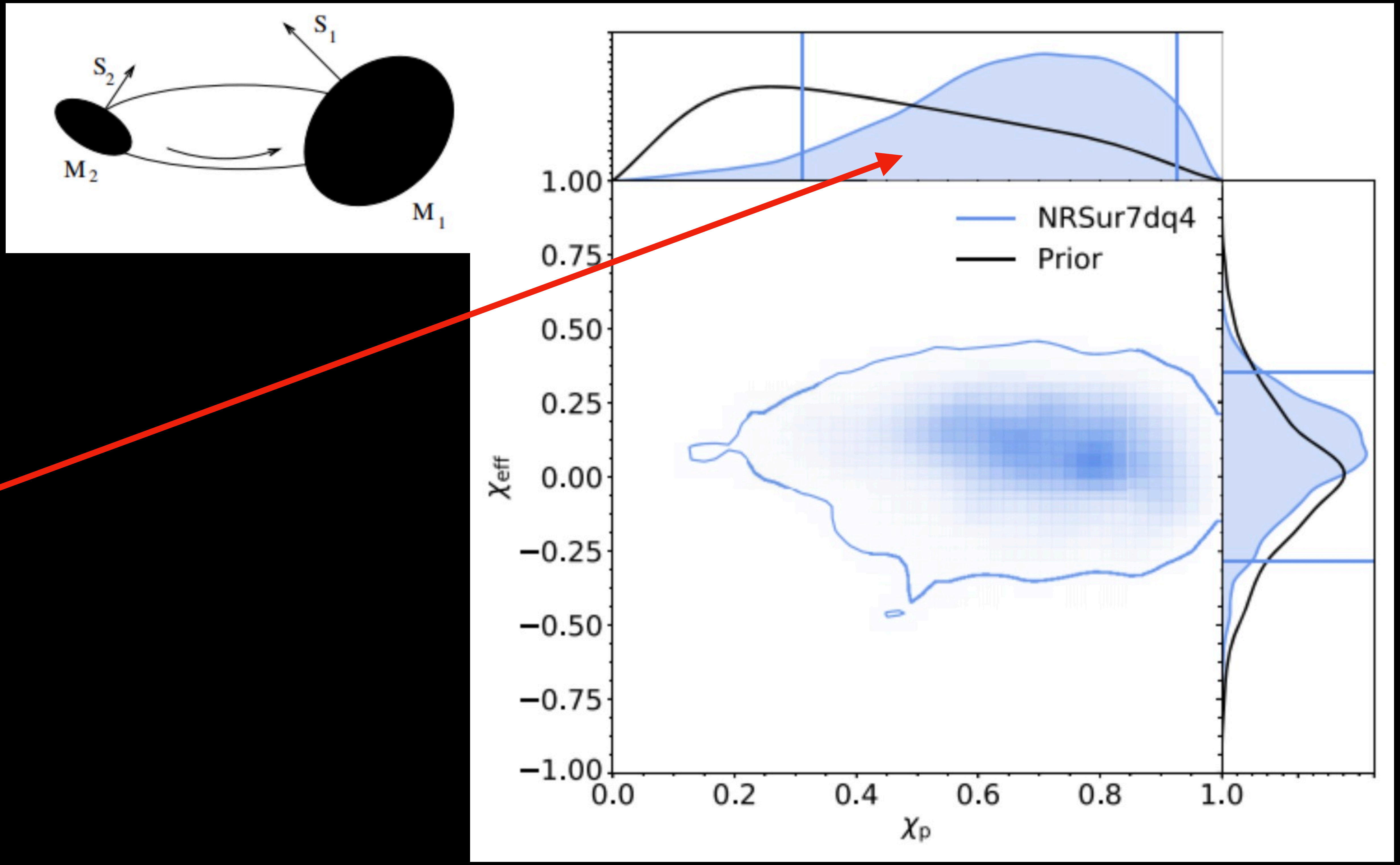

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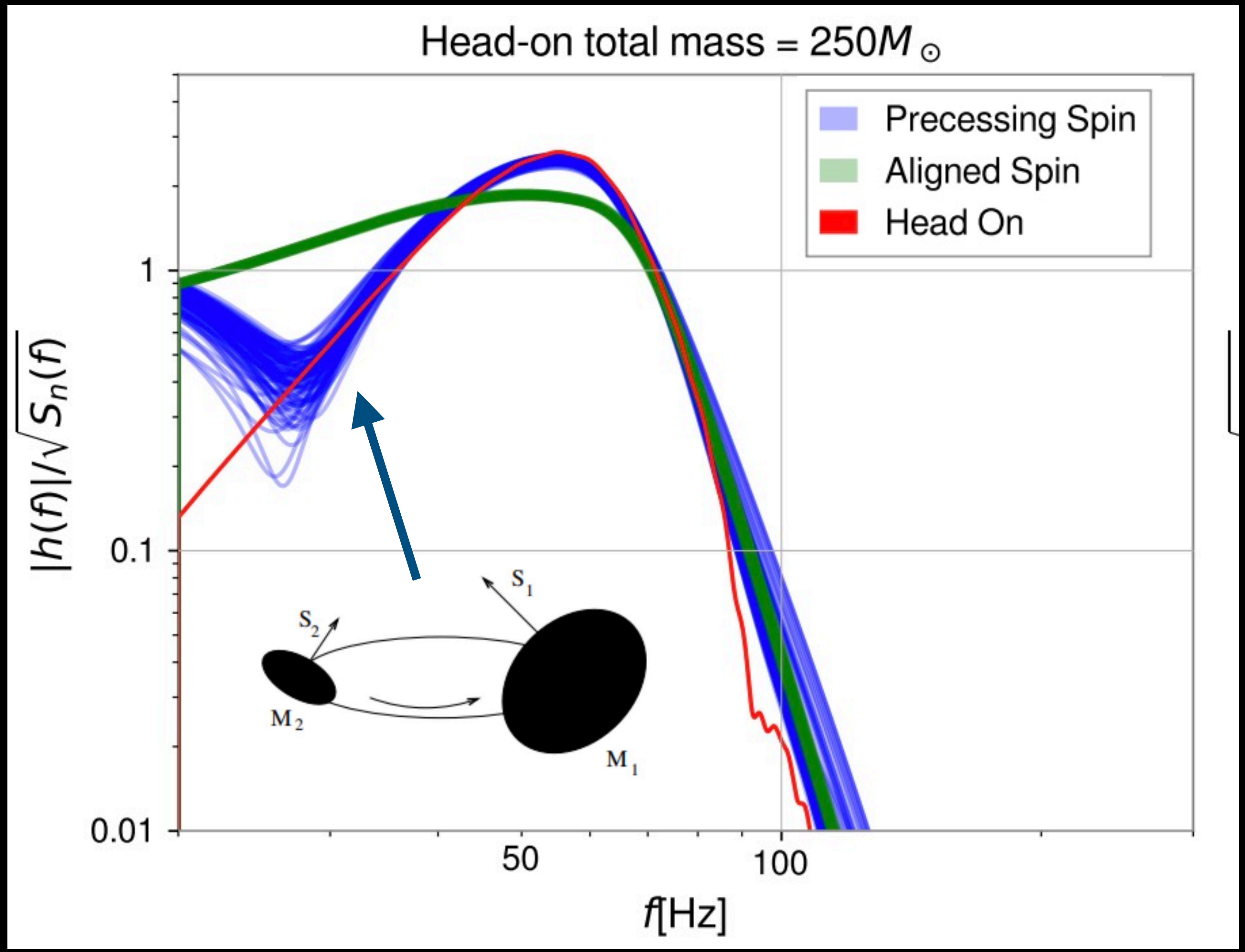
- But: Precession can mimic eccentricity! (JCB + 2021)



JCB+ 2021

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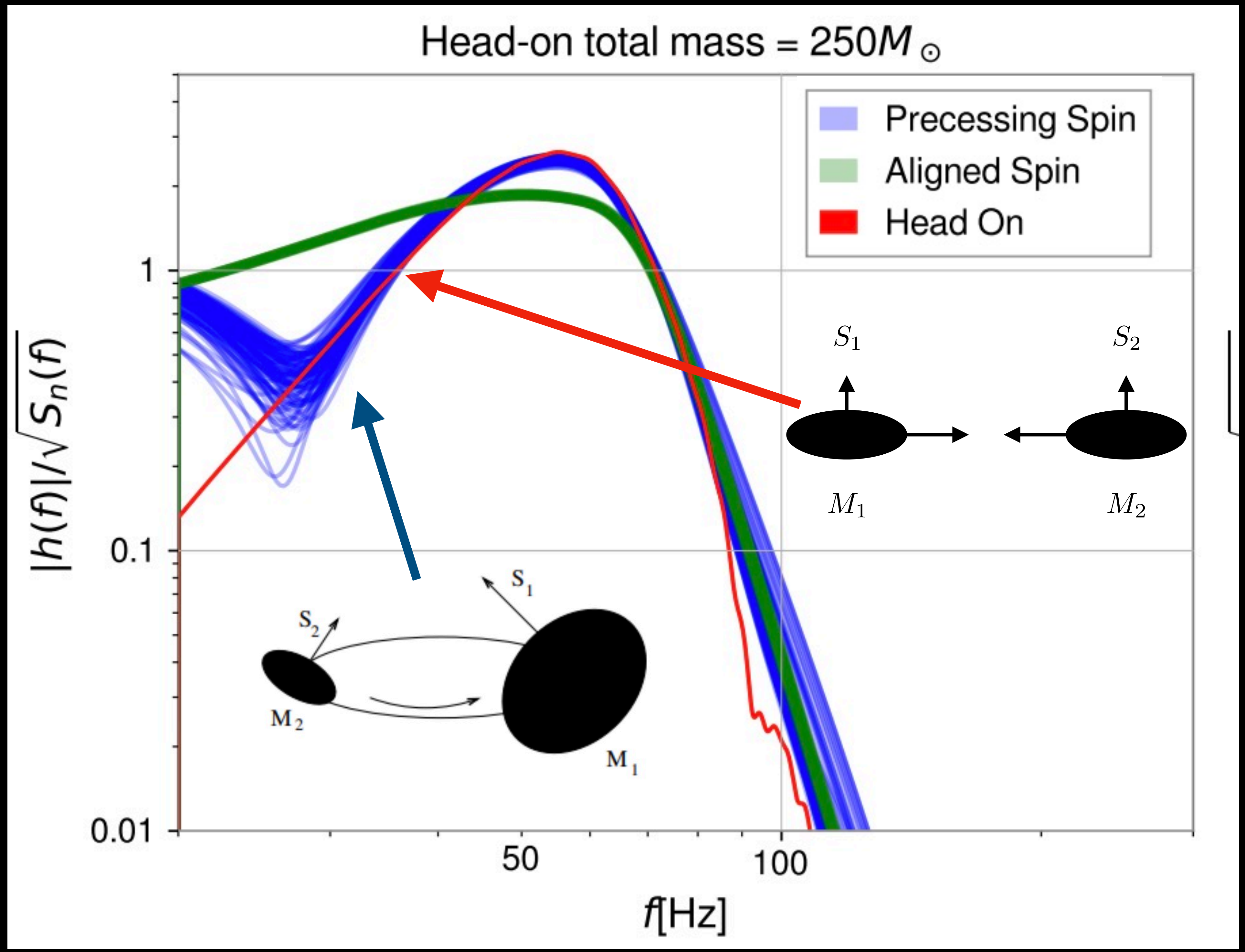
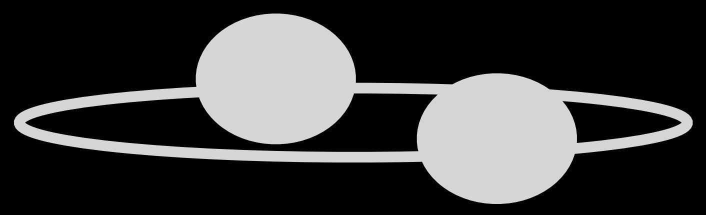


JCB+ 2021



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- Alternative interpretations
  - Small eccentricity (Romero-Shaw+) ✔
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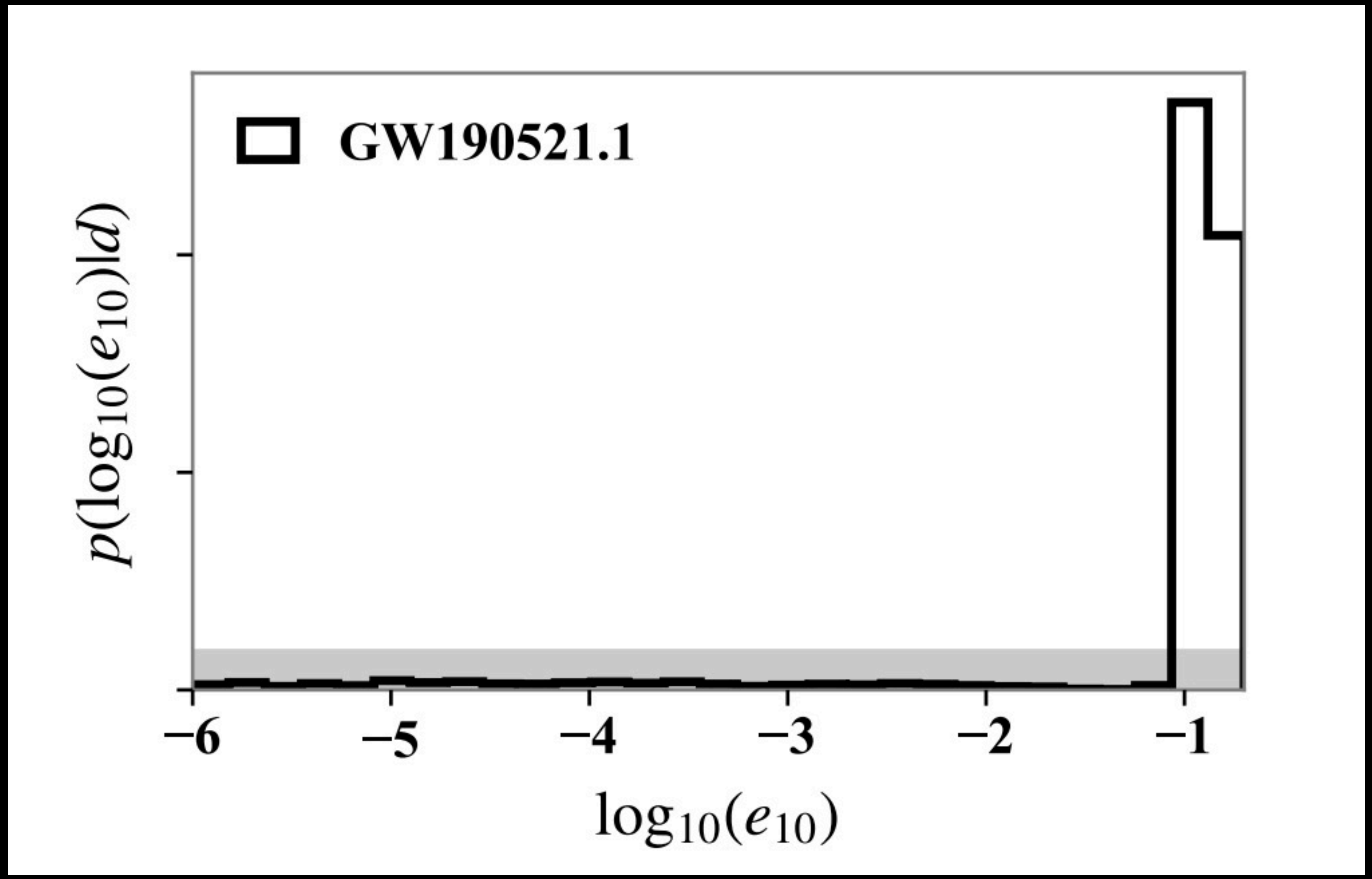
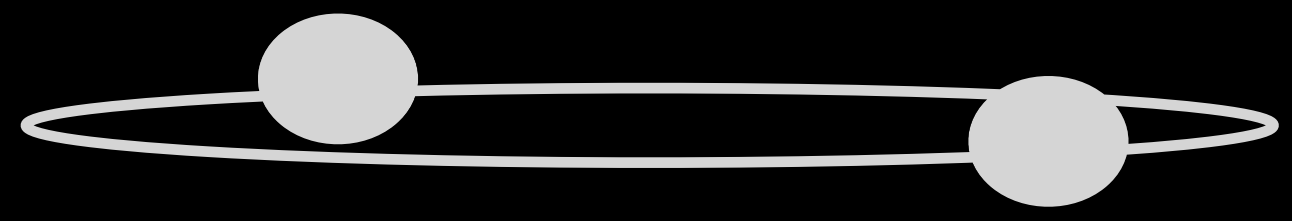
  - Head-on merger (JCB+)
  - Boson-star merger (this talk)



Romero-Shaw+ (2020)



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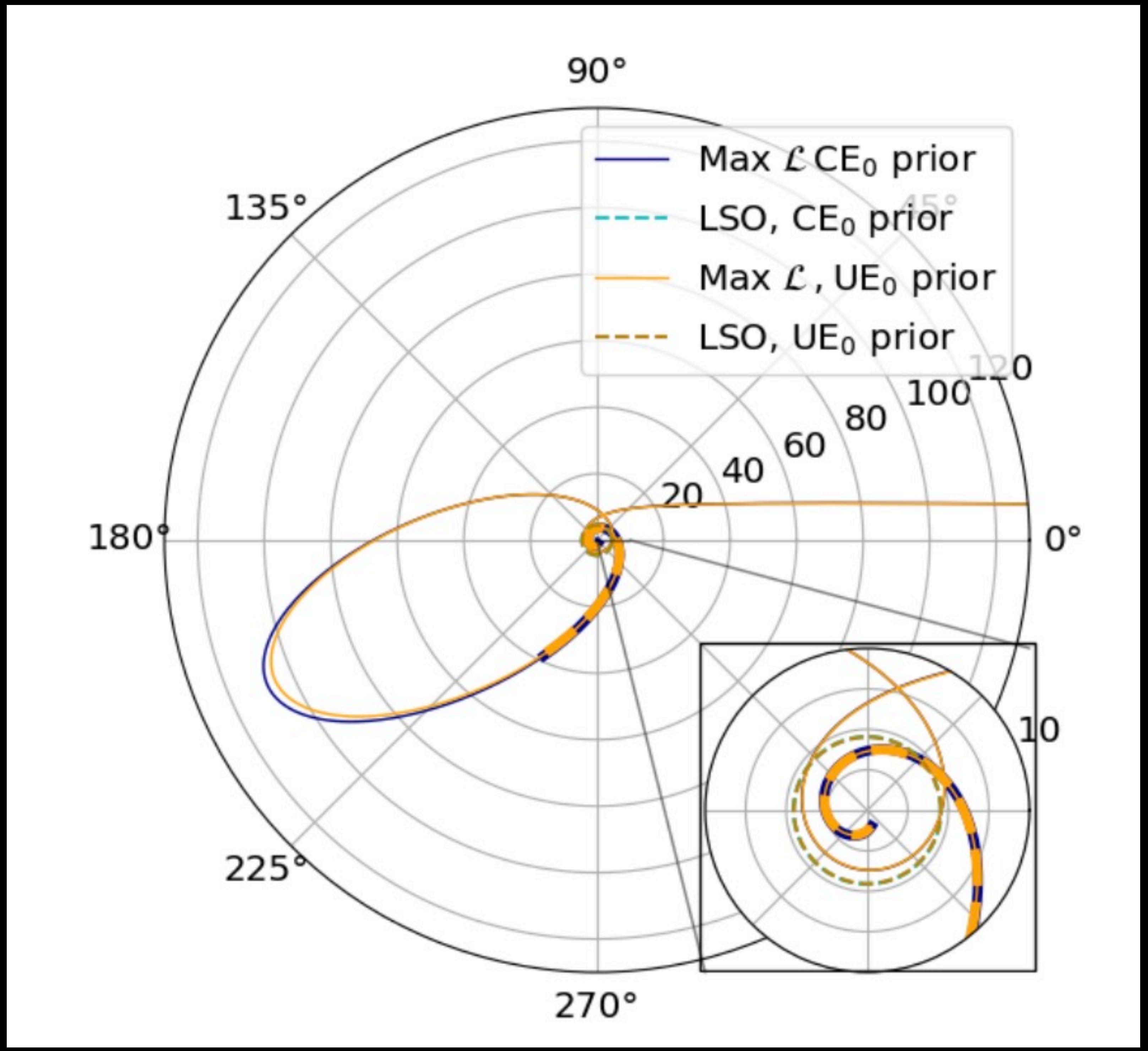

Gamba+ (Today)

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

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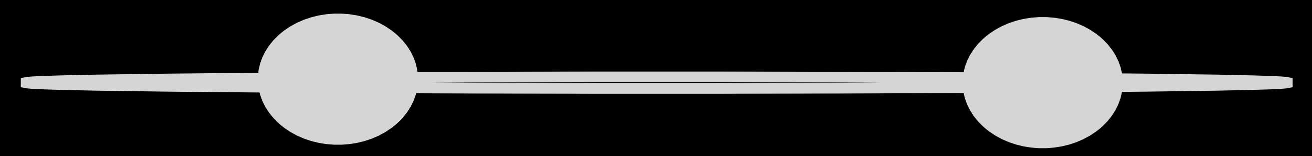

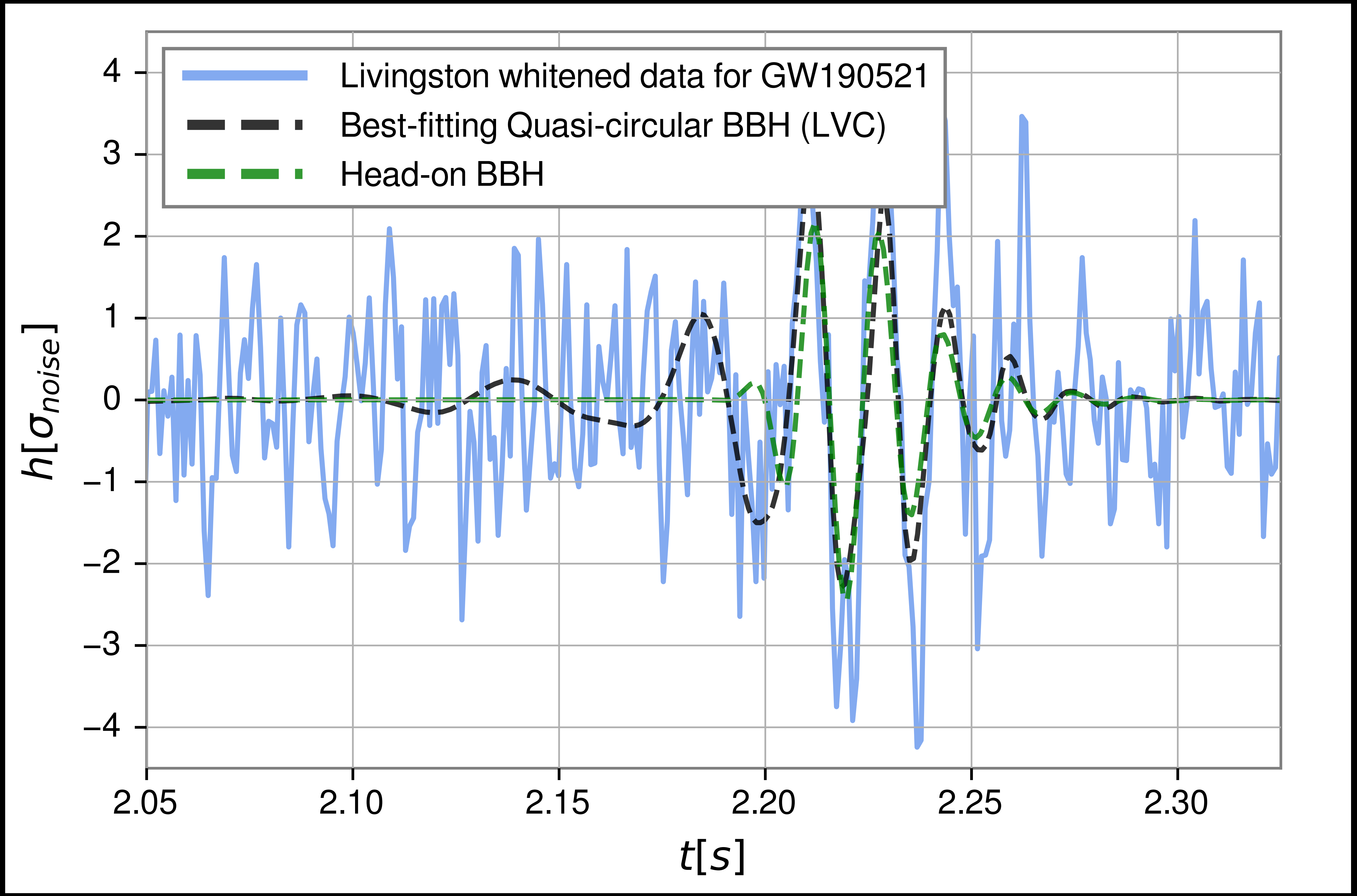

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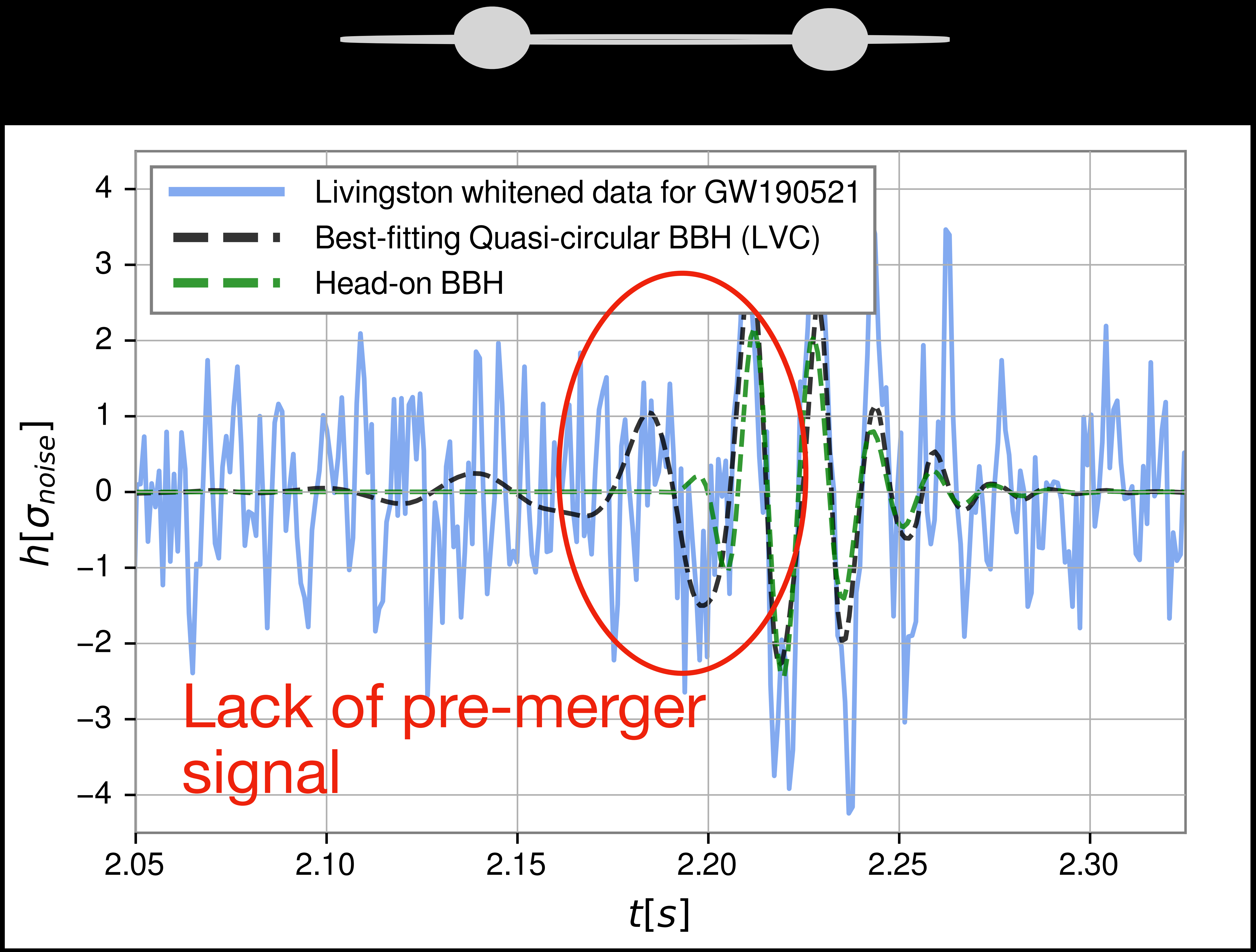
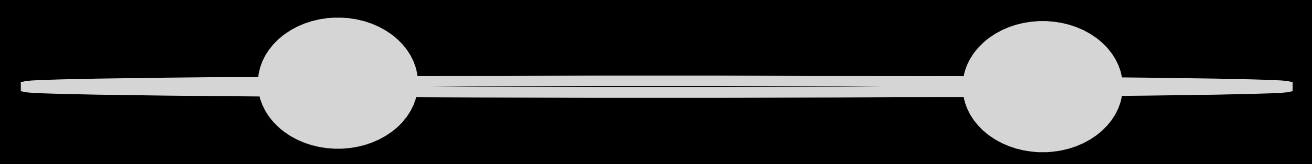
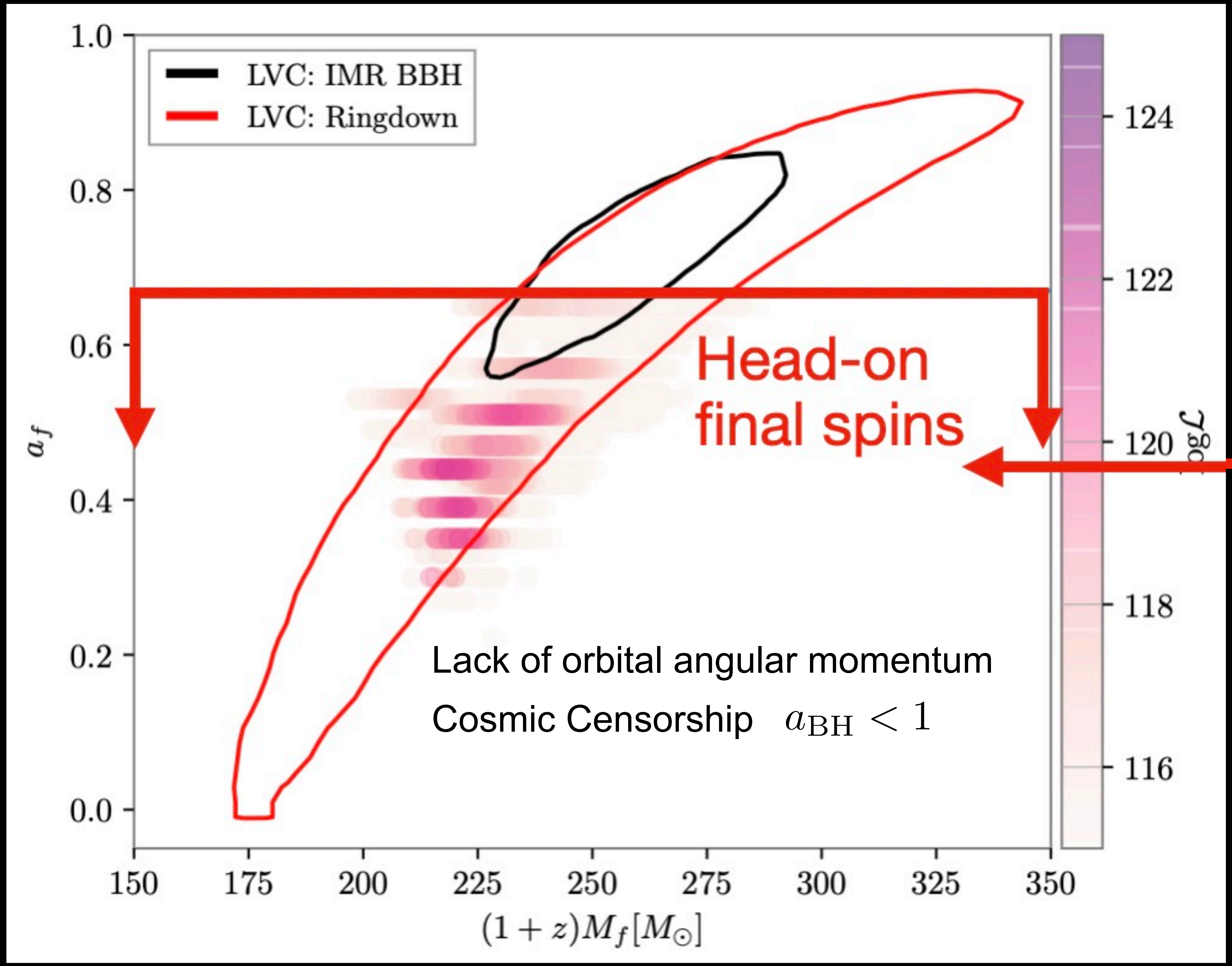
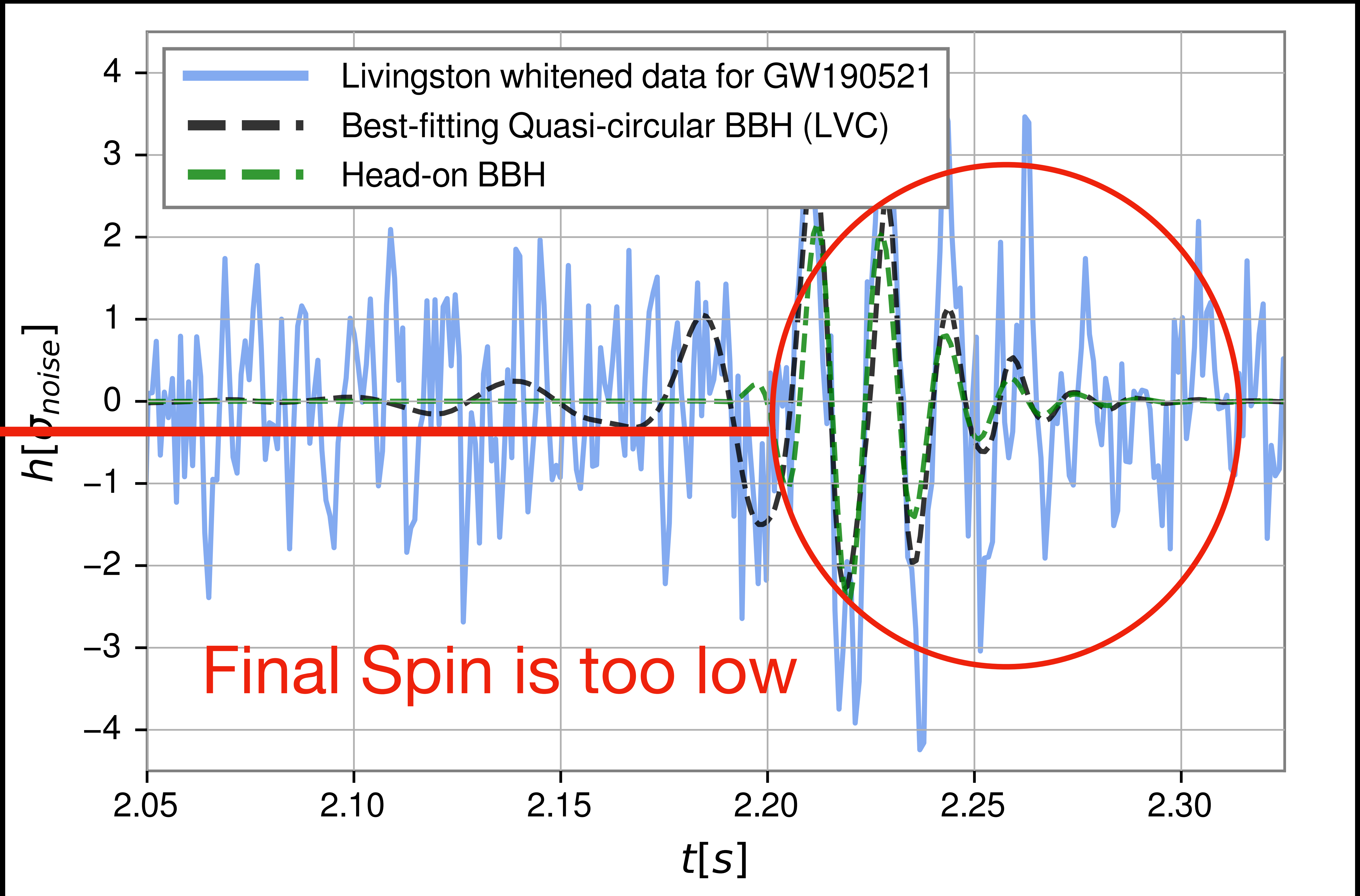






LVC: IMR BBH
LVC: Ringdown
Head-on final spins
Lack of orbital angular momentum
Cosmic Censorship $a_{\mathrm{BH}} < 1$
a_f
$(1+z)M_f[M_\odot]$
$\log\mathcal{L}$
1.0
0.8
0.6
0.4
0.2
0.0
150
175
200
225
250
275
300
325
350
124
122
120
118
116



Livingston whitened data for GW190521
Best-fitting Quasi-circular BBH (LVC)
Head-on BBH
Final Spin is too low
$h[\sigma_{noise}]$
$t[s]$
4
3
2
1
0
−1
−2
−3
−4
2.05
2.10
2.15
2.20
2.25
2.30

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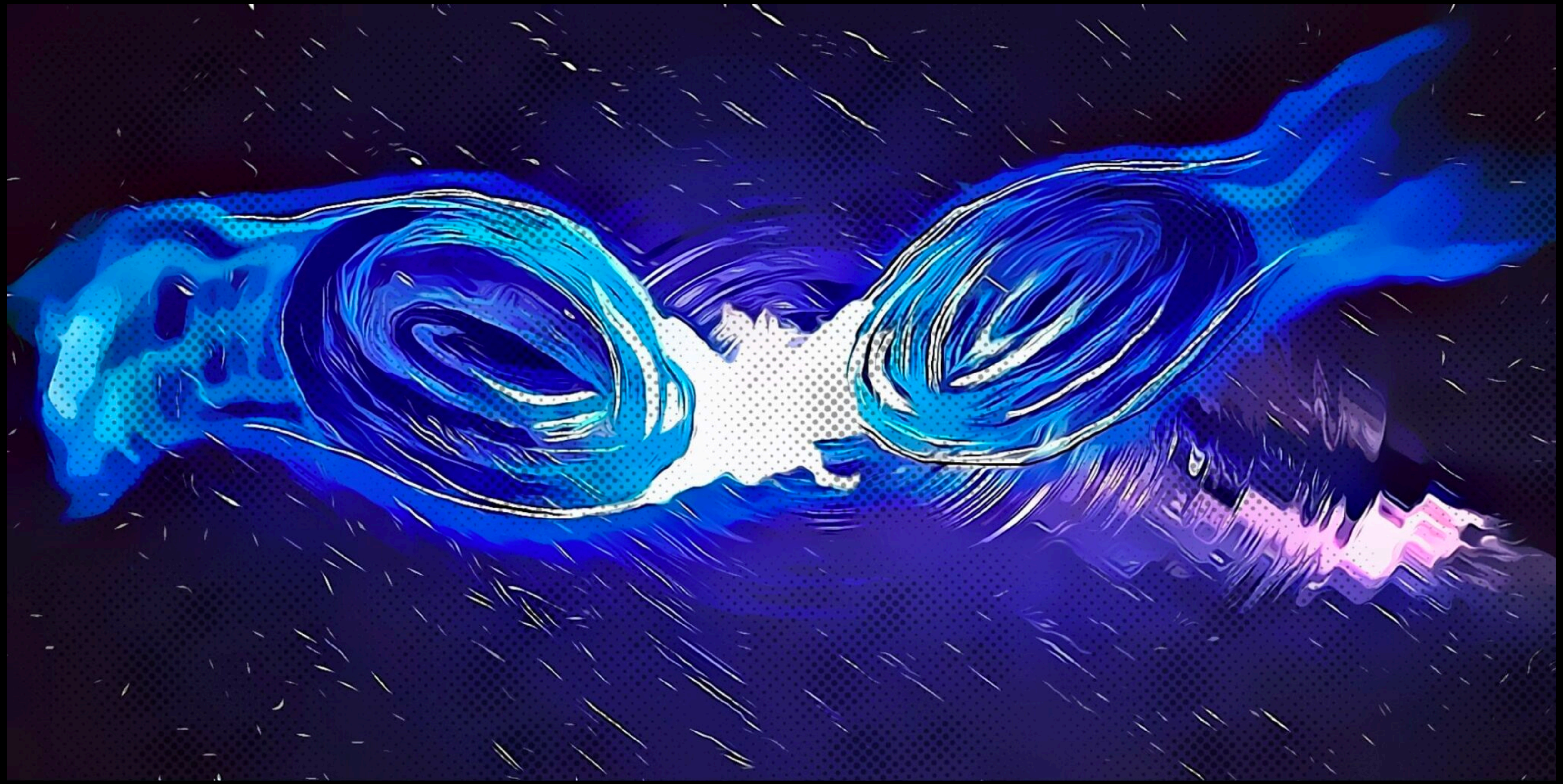

Credit: Nicolás Sanchis-Gual, Rocío García-Souto

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 candiates**

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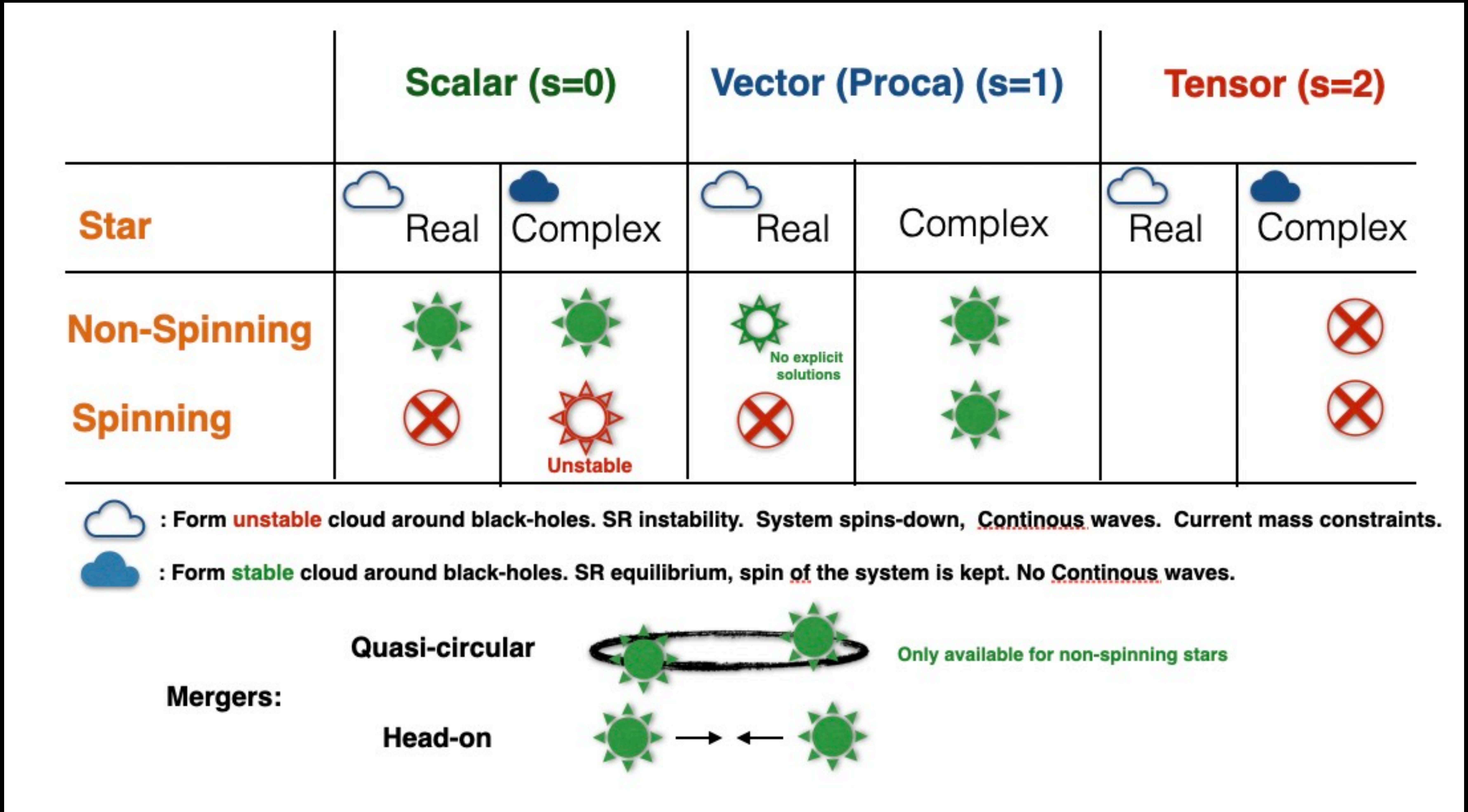
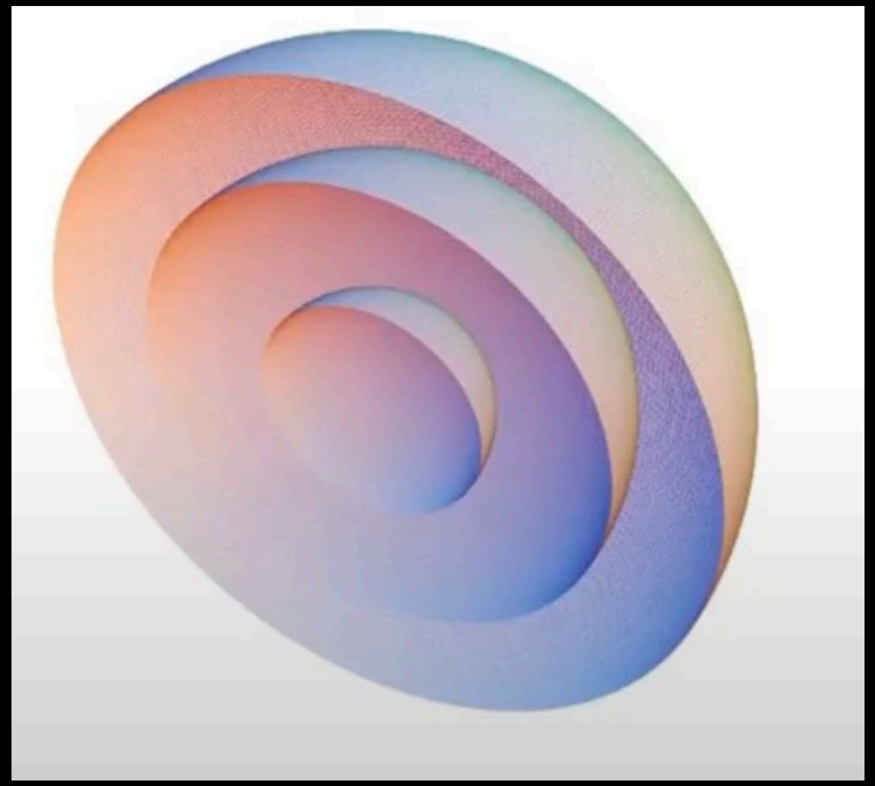
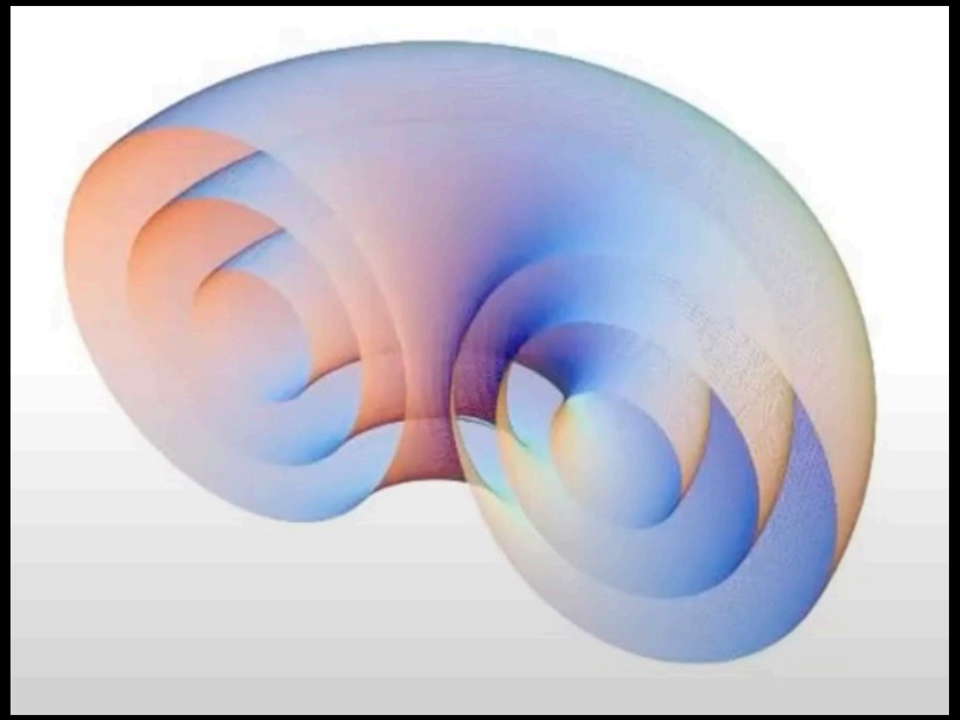
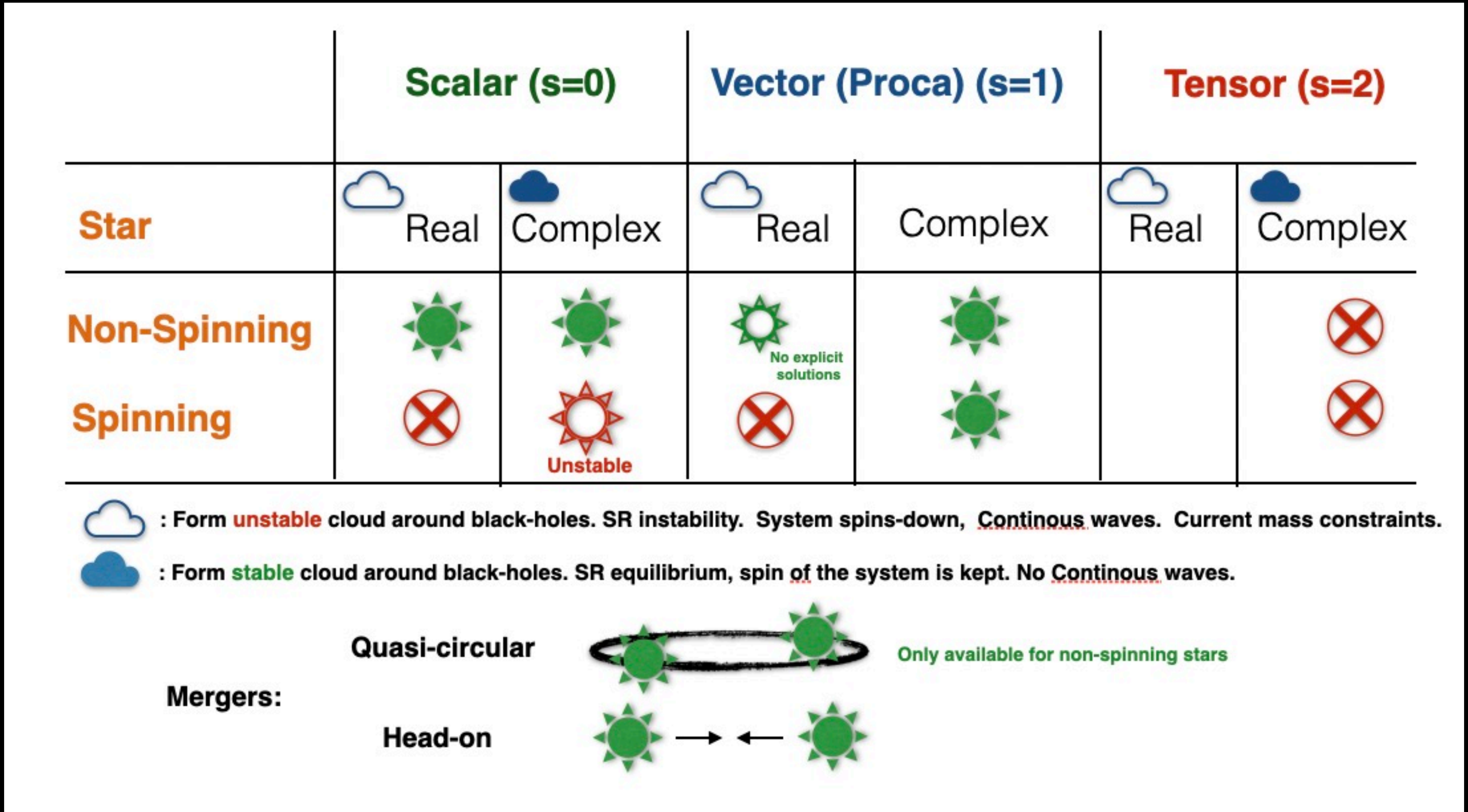


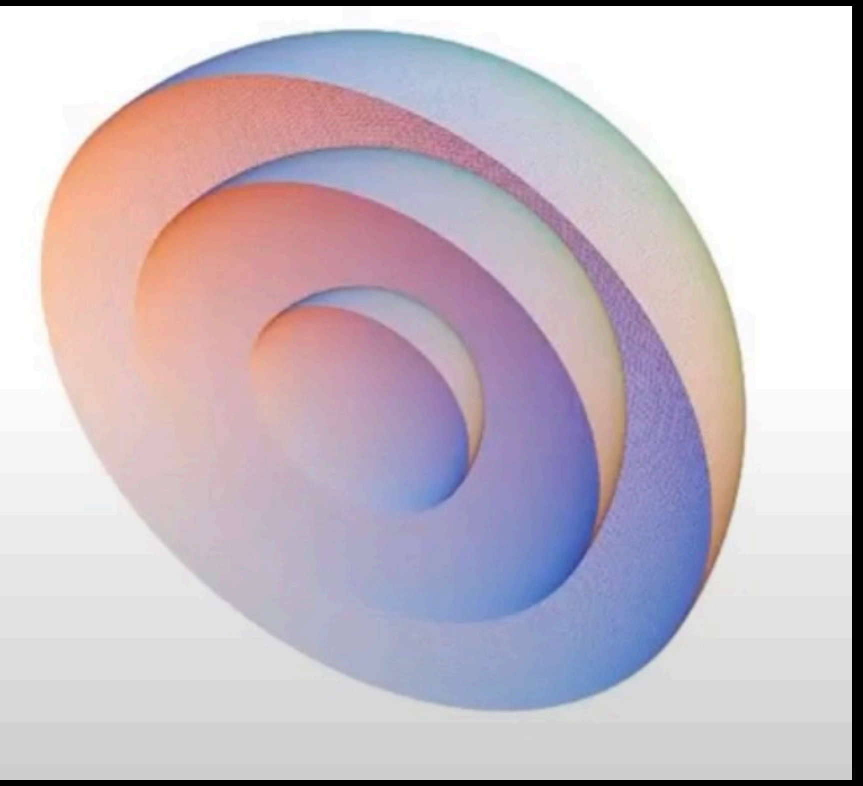


Spinning Proca star



Spinning Scalar star (Unstable)





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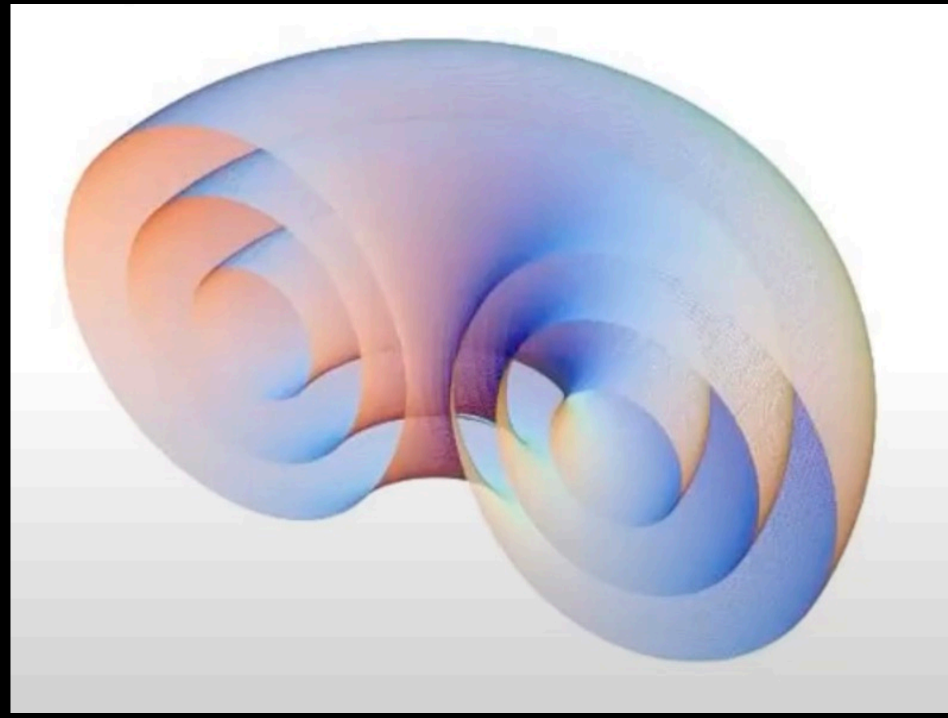

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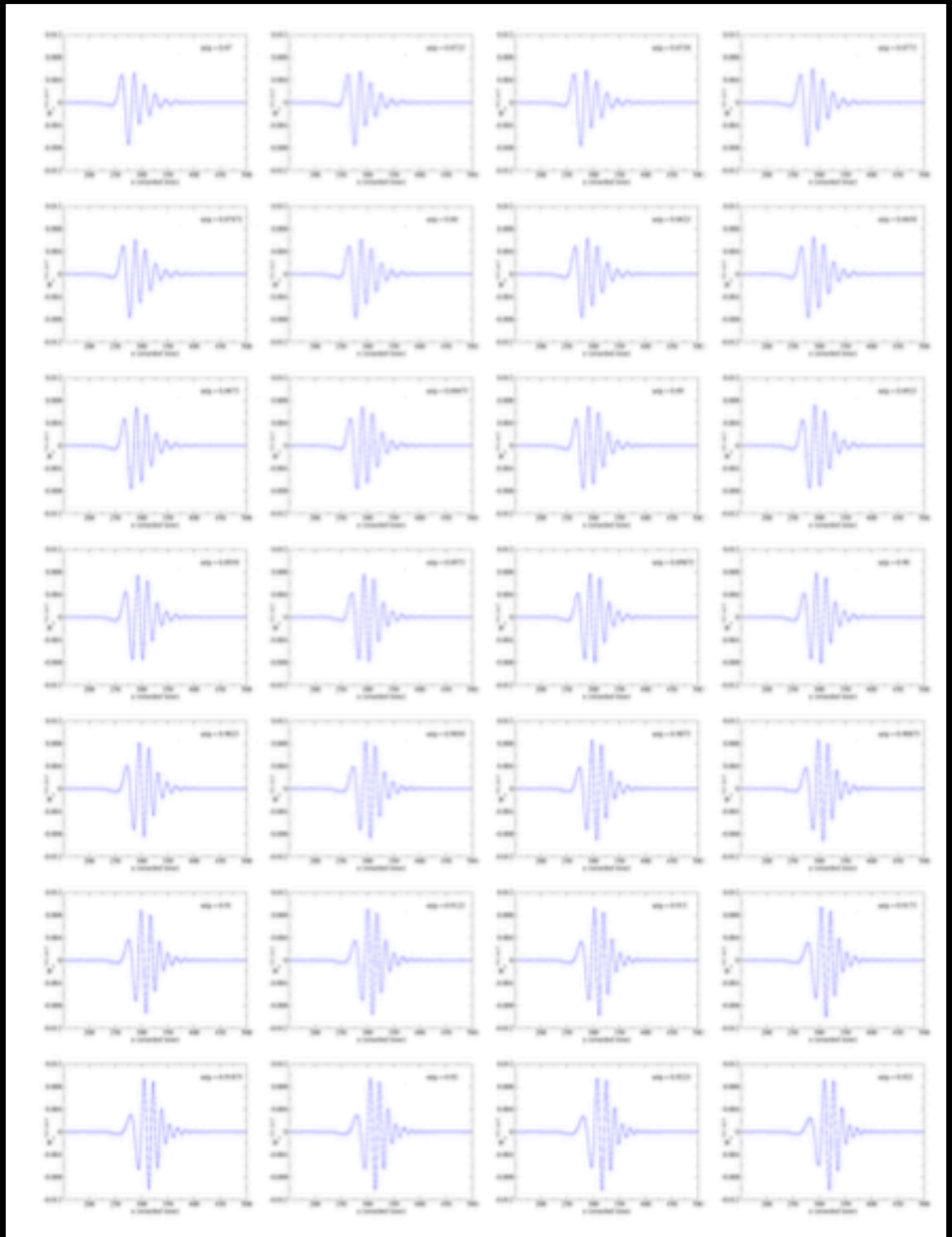
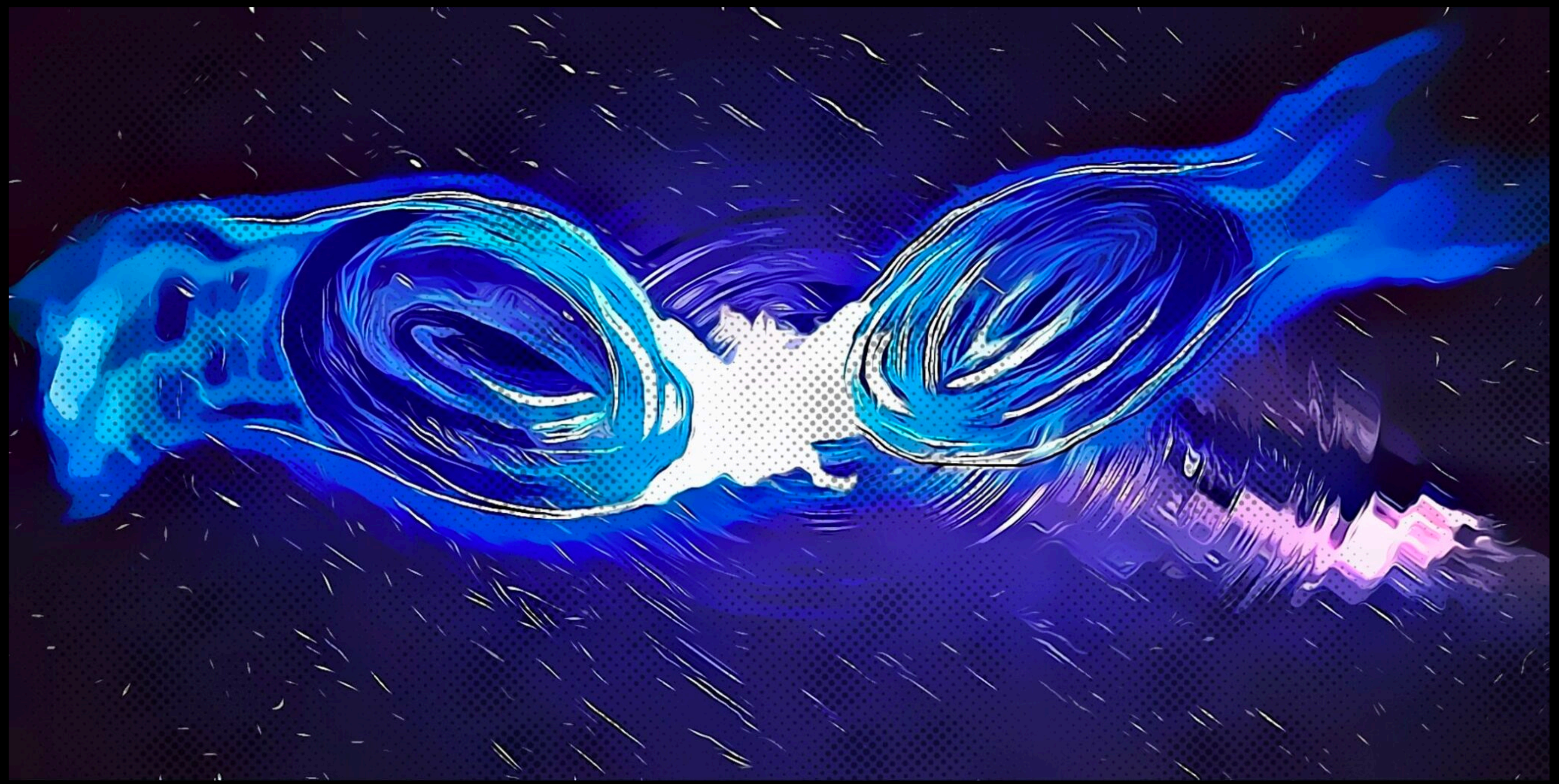
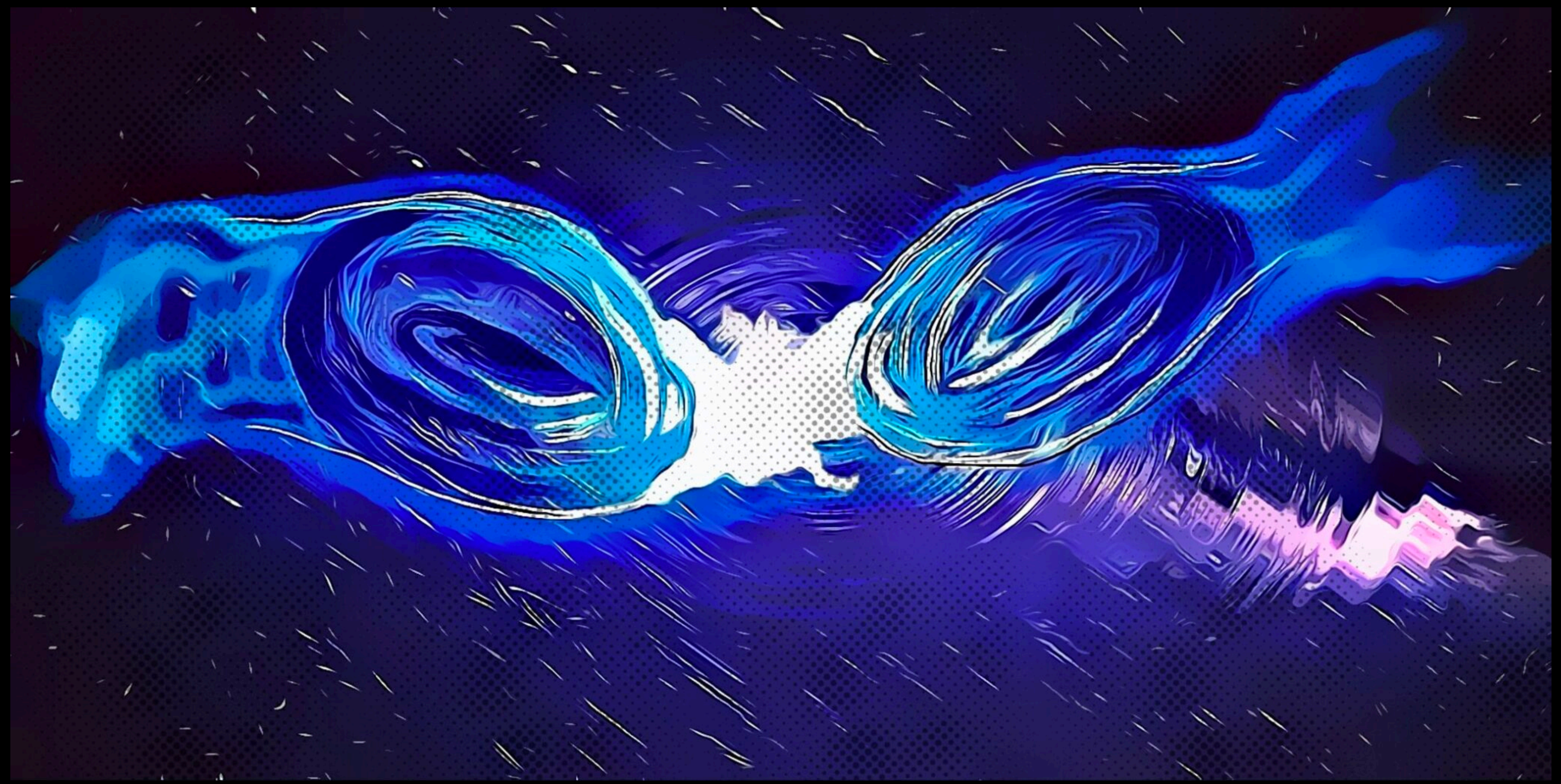


Credit: Nicolás Sanchis-Gual



einstein toolkit

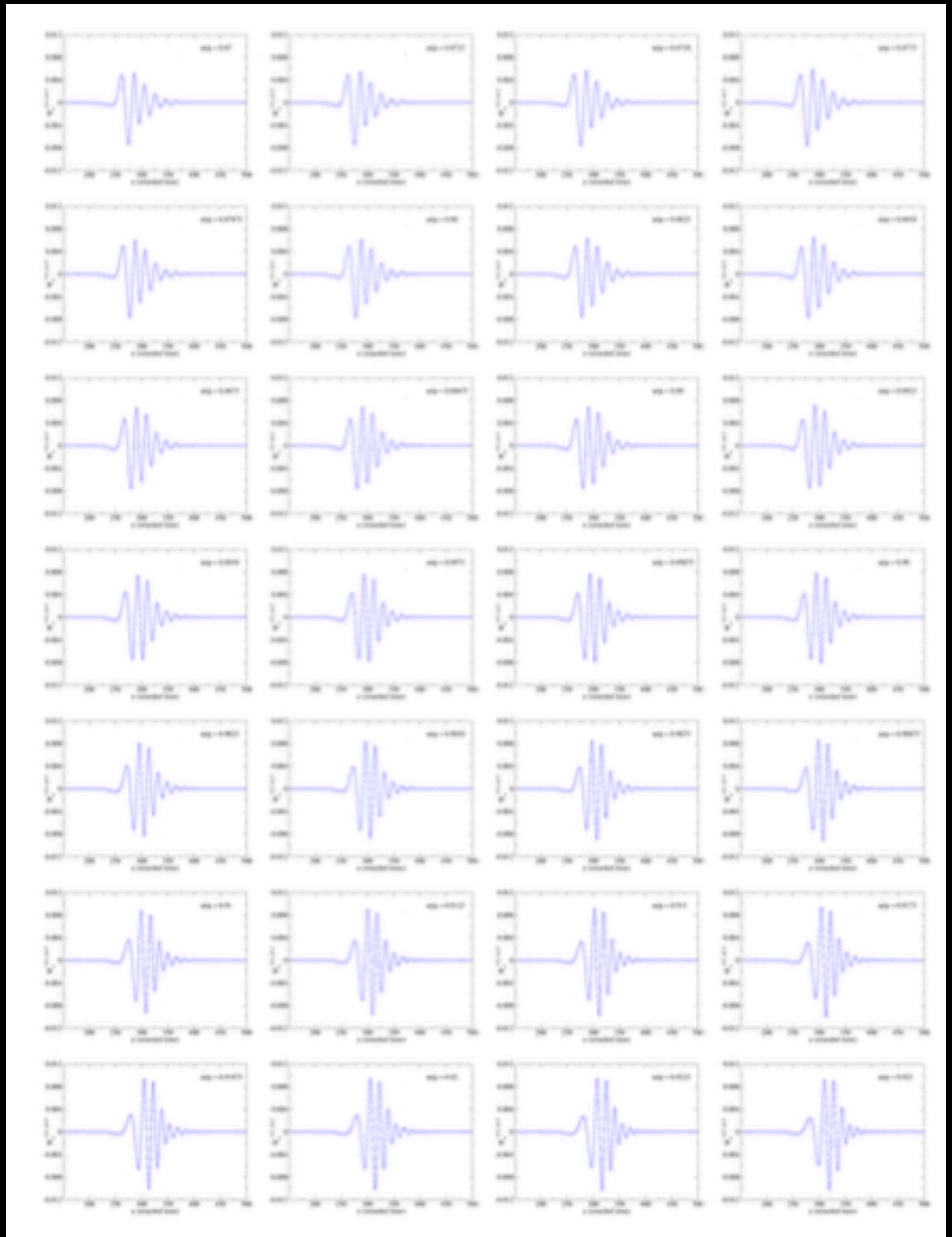


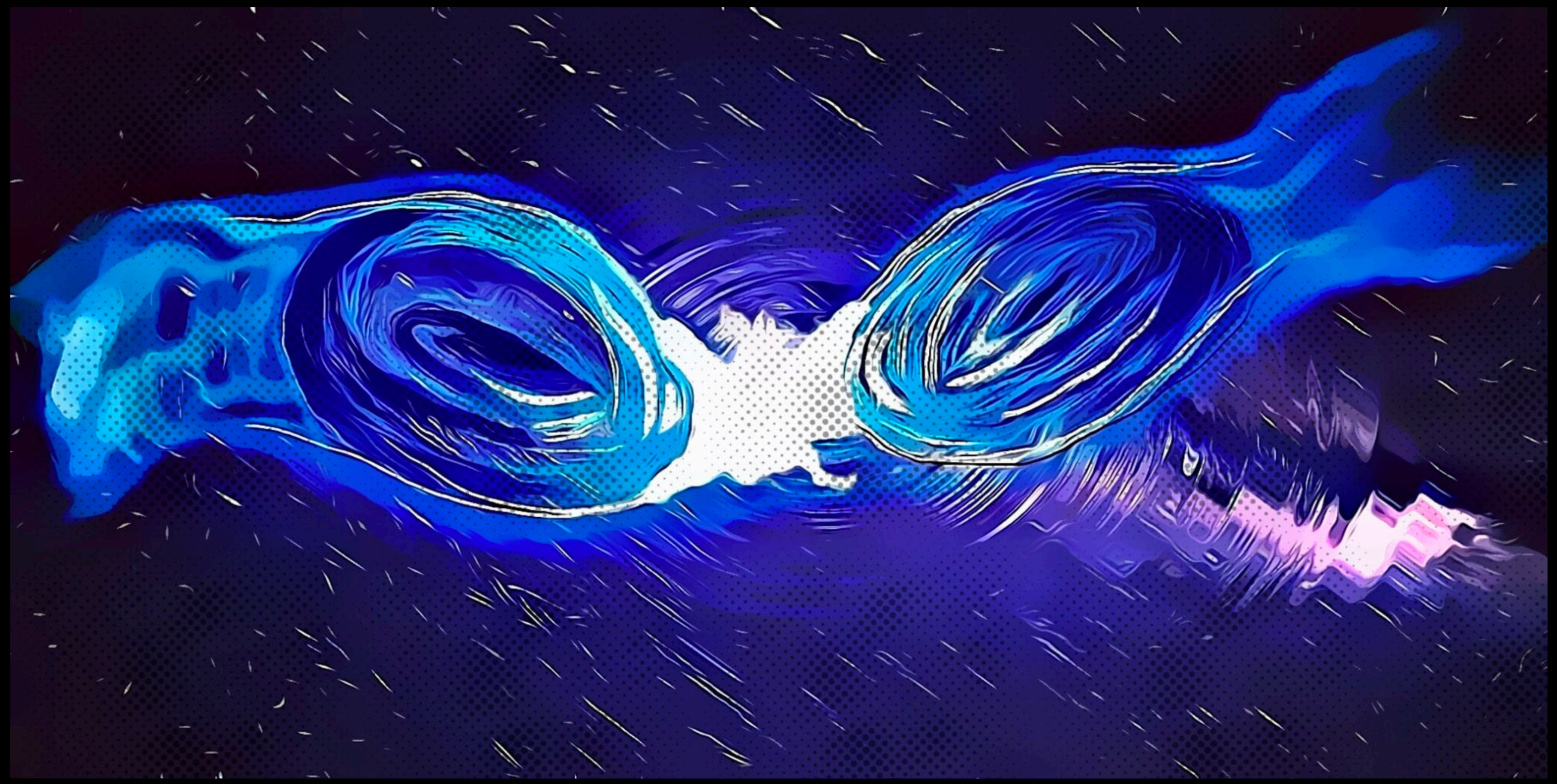
Initial set:

Equal-mass, equal field frequency (equal spin)

Initial separation = 100M

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





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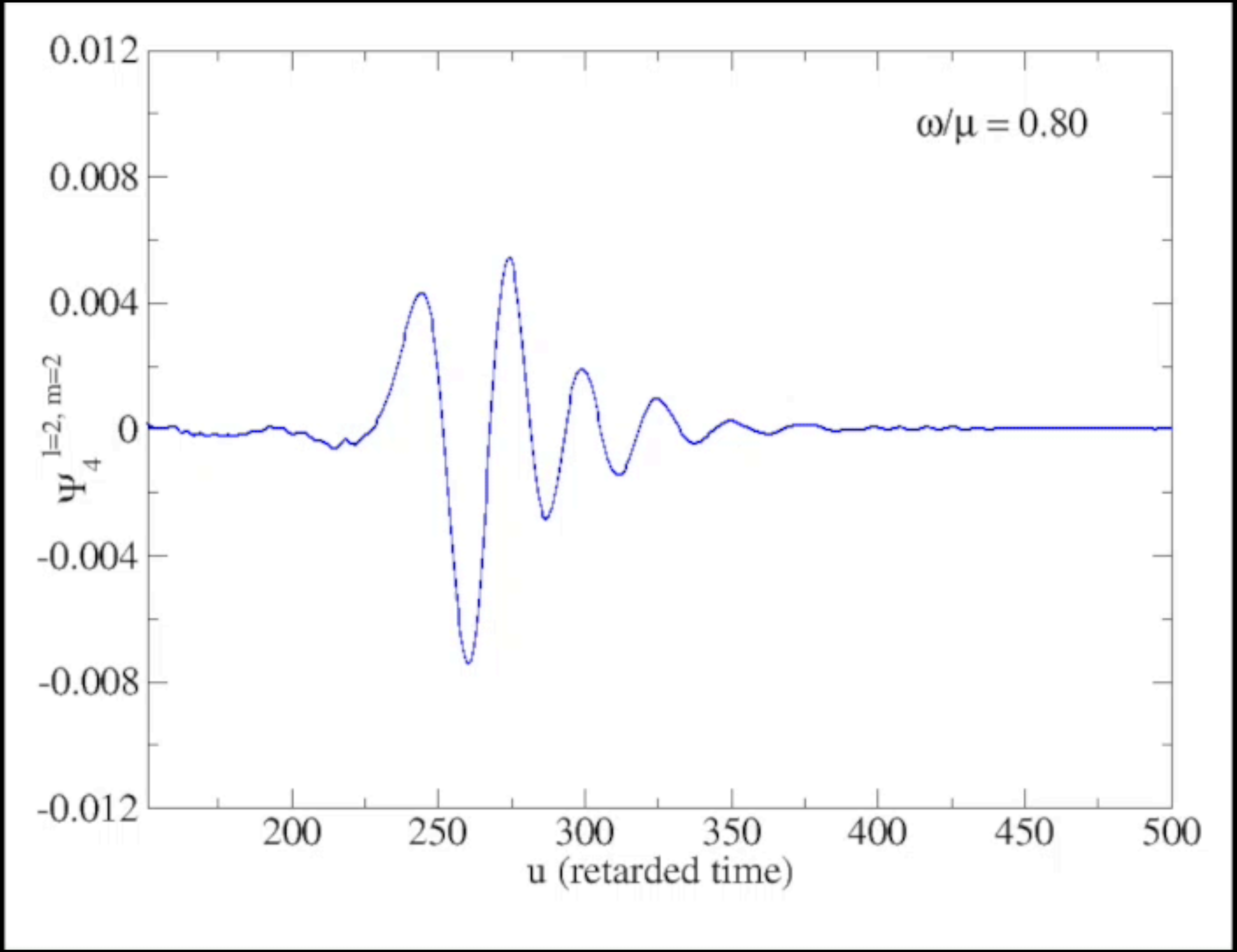
Secondary set:

First frequency fixed, second varies



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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

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

$\uparrow$: Large likelihood

$\downarrow$: Useless parameters (Occam's Razor)

$\uparrow\downarrow$: 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

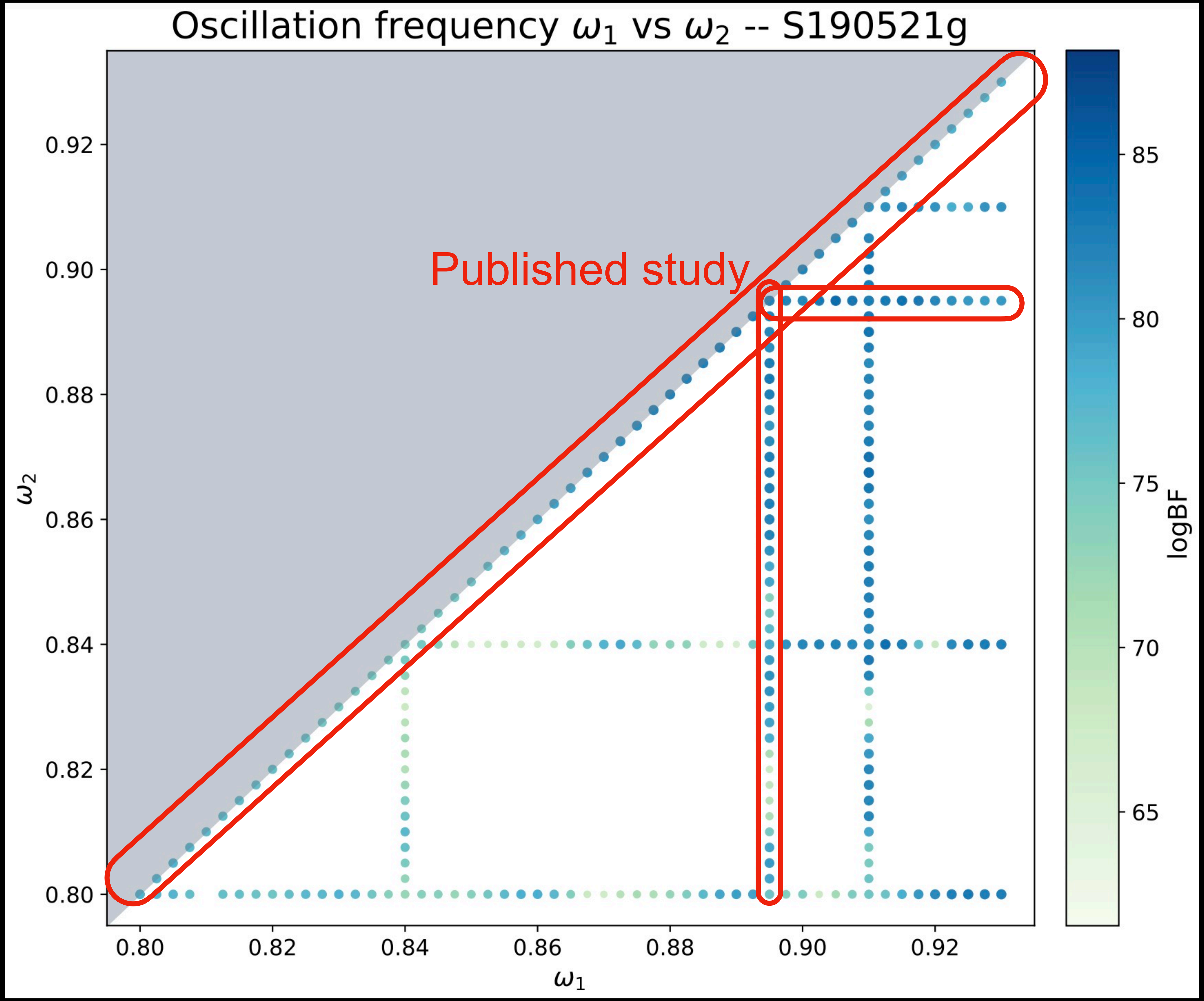
Sampler: CPNest Veitch+ (Dynesty ongoing)

Priors:

Uniform in Total Mass and Mass Ratio

Standard for the spins, source orientation, sky-location

Uniform in Co-moving volume


Oscillation frequency ω_1 vs ω_2 -- S190521g
Published study
ω_2
0.80
0.82
0.84
0.86
0.88
0.90
0.92
ω_1
0.80
0.82
0.84
0.86
0.88
0.90
0.92
logBF
65
70
75
80
85

GW190521 Parameters (Proca-star merger)

Parameter	$q = 1$ model	$q \neq 1$ model
Primary mass	$115^{+7}_{-8}\ M_\odot$	$115^{+7}_{-8}\ M_\odot$
Secondary mass	$115^{+7}_{-8}\ M_\odot$	$111^{+7}_{-15}\ M_\odot$
Total or final mass	$231^{+13}_{-17}\ M_\odot$	$228^{+17}_{-15}\ M_\odot$
Final spin	$0.75^{+0.08}_{-0.04}$	$0.75^{+0.08}_{-0.04}$
Inclination $\pi/2 - \lvert\iota - \pi/2\rvert$	$0.83^{+0.23}_{-0.47}$ rad	$0.58^{+0.40}_{-0.39}$ rad
Azimuth	$0.65^{+0.86}_{-0.54}$ rad	$0.78^{+1.23}_{-1.20}$ rad
Luminosity distance	571^{+348}_{-181} Mpc	700^{+292}_{-279} Mpc
Redshift	$0.12^{+0.05}_{-0.04}$	$0.14^{+0.06}_{-0.05}$
Total or final redshifted mass	$258^{+9}_{-9}\ M_\odot$	$261^{+10}_{-11}\ M_\odot$
Bosonic field frequency ω/μ_V	$0.893^{+0.015}_{-0.015}$	$(*)0.905^{+0.012}_{-0.042}$
Boson mass μ_V [$\times 10^{-13}$]	$8.72^{+0.73}_{-0.82}$ eV	$8.59^{+0.58}_{-0.57}$ eV
Maximal boson star mass	$173^{+19}_{-14}\ M_\odot$	$175^{+13}_{-11}\ M_\odot$

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

GW190521 Parameters (Proca-star merger)

Parameter	$q = 1$ model	$q \neq 1$ model
Primary mass	$115^{+7}_{-8}\ M_\odot$	$115^{+7}_{-8}\ M_\odot$
Secondary mass	$115^{+7}_{-8}\ M_\odot$	$111^{+7}_{-15}\ M_\odot$
Total or final mass	$231^{+13}_{-17}\ M_\odot$	$228^{+17}_{-15}\ M_\odot$
Final spin	$0.75^{+0.08}_{-0.04}$	$0.75^{+0.08}_{-0.04}$
Inclination $\pi/2 - \lvert\iota - \pi/2\rvert$	$0.83^{+0.23}_{-0.47}$ rad	$0.58^{+0.40}_{-0.39}$ rad
Azimuth	$0.65^{+0.86}_{-0.54}$ rad	$0.78^{+1.23}_{-1.20}$ rad
Luminosity distance	571^{+348}_{-181} Mpc	700^{+292}_{-279} Mpc
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LVC (BBH)

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

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

GW190521 Parameters (Proca-star merger)

Parameter	$q = 1$ model	$q \neq 1$ model	LVC (BBH)	
Primary mass	$115^{+7}_{-8}\ M_\odot$	$115^{+7}_{-8}\ M_\odot$		
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Luminosity distance	571^{+348}_{-181} Mpc	700^{+292}_{-279} Mpc	$5300^{+2600}_{-2400} Mpc$	Much closer than a BBH
Redshift	$0.12^{+0.05}_{-0.04}$	$0.14^{+0.06}_{-0.05}$		
Total or final redshifted mass	$258^{+9}_{-9}\ M_\odot$	$261^{+10}_{-11}\ M_\odot$	$272^{+26}_{-27} M_\odot$	Circular mergers are louder Larger initial mass needed to get same final BH
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Total or final mass	$231^{+13}_{-17}\ M_\odot$	$228^{+17}_{-15}\ M_\odot$	$150^{+29}_{-17} M_\odot$	Much heavier than the BBH estimation
Final spin	$0.75^{+0.08}_{-0.04}$	$0.75^{+0.08}_{-0.04}$		
Inclination $\pi/2-\lvert\iota-\pi/2\rvert$	$0.83^{+0.23}_{-0.47}$ rad	$0.58^{+0.40}_{-0.39}$ rad		
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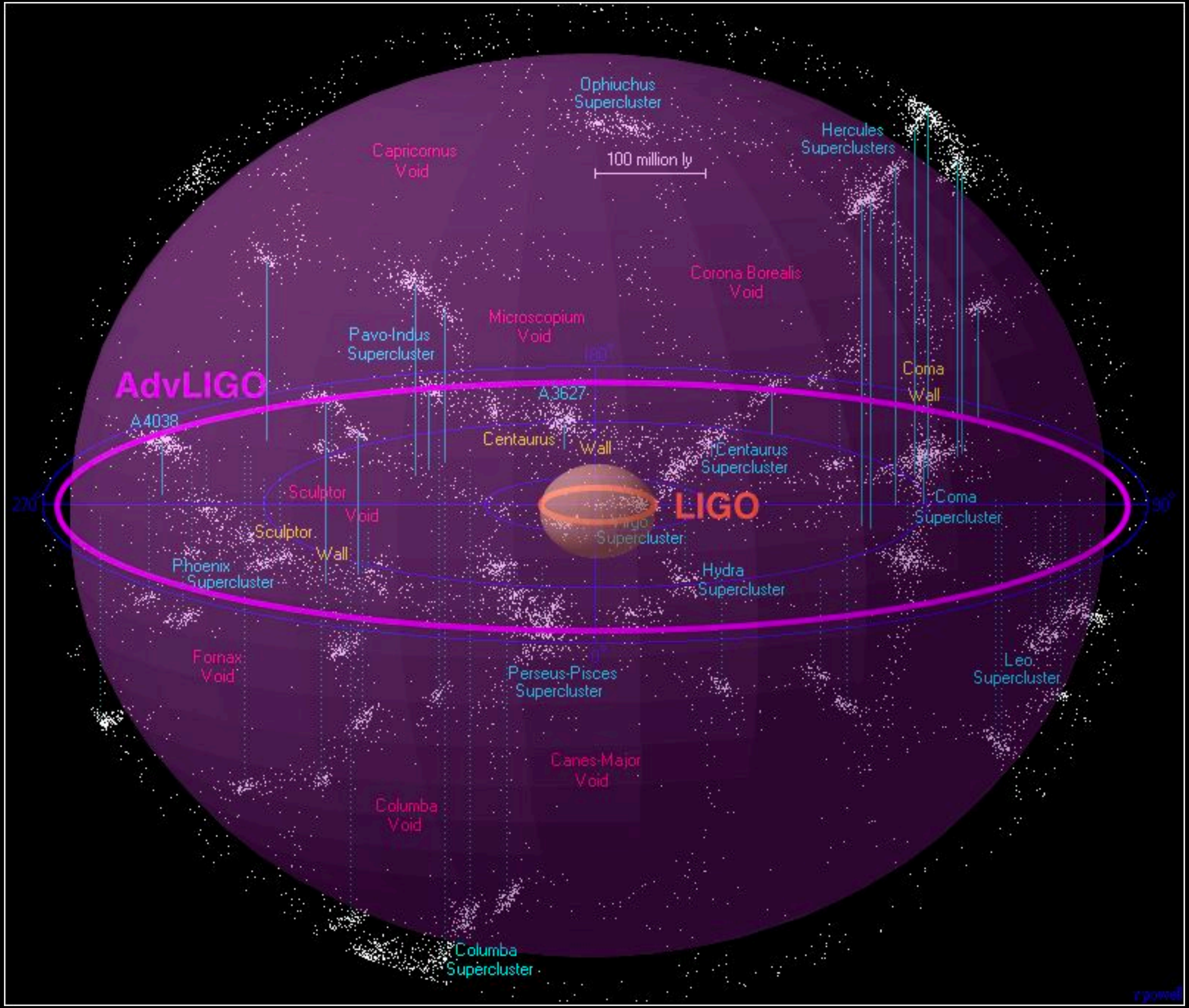
Initial study: Model Selection

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



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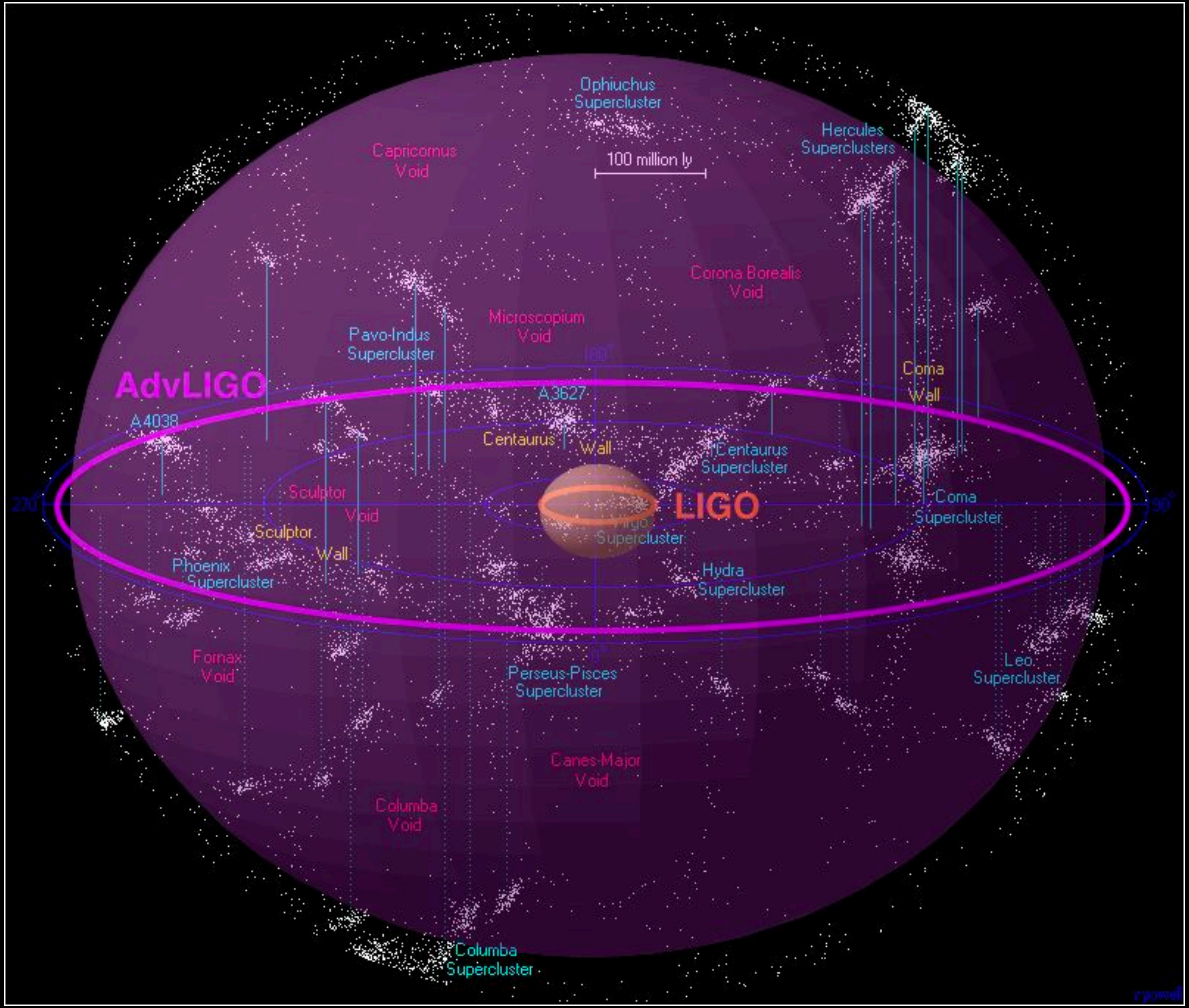
Head-on Binary Black Hole	75.9	103.2

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

Reasonable, but this favours loud BBH sources

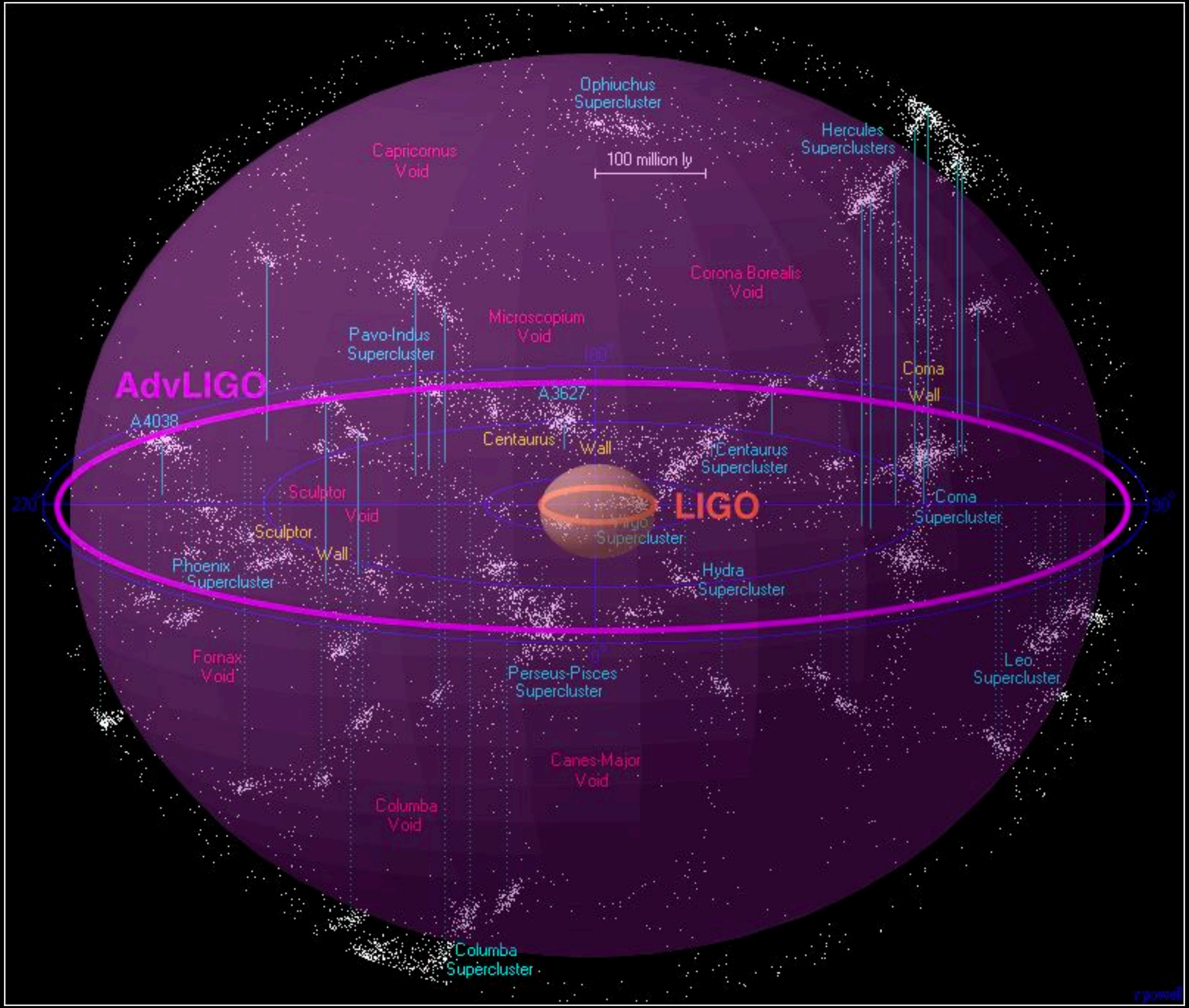


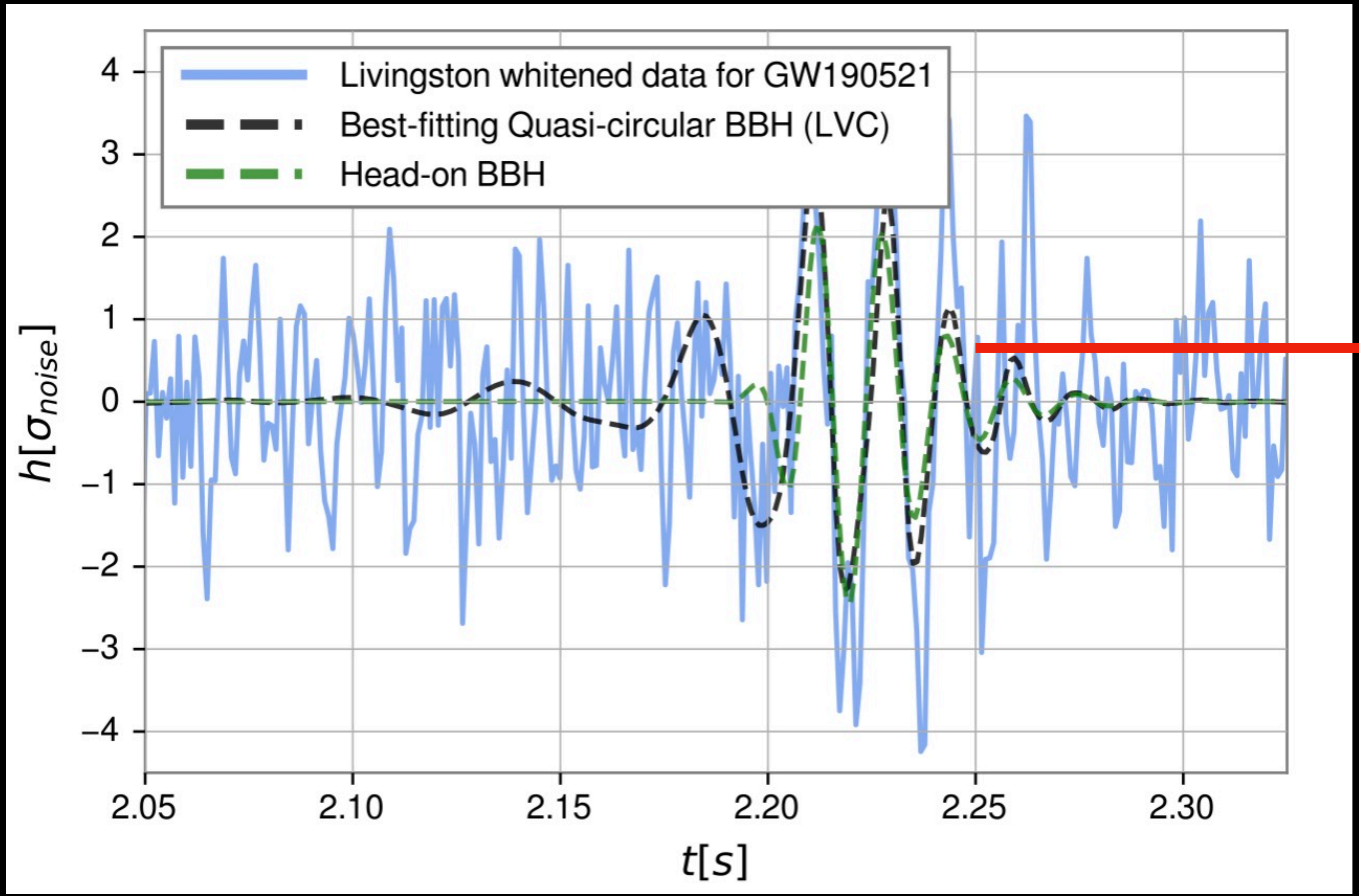
Initial study: Model Selection

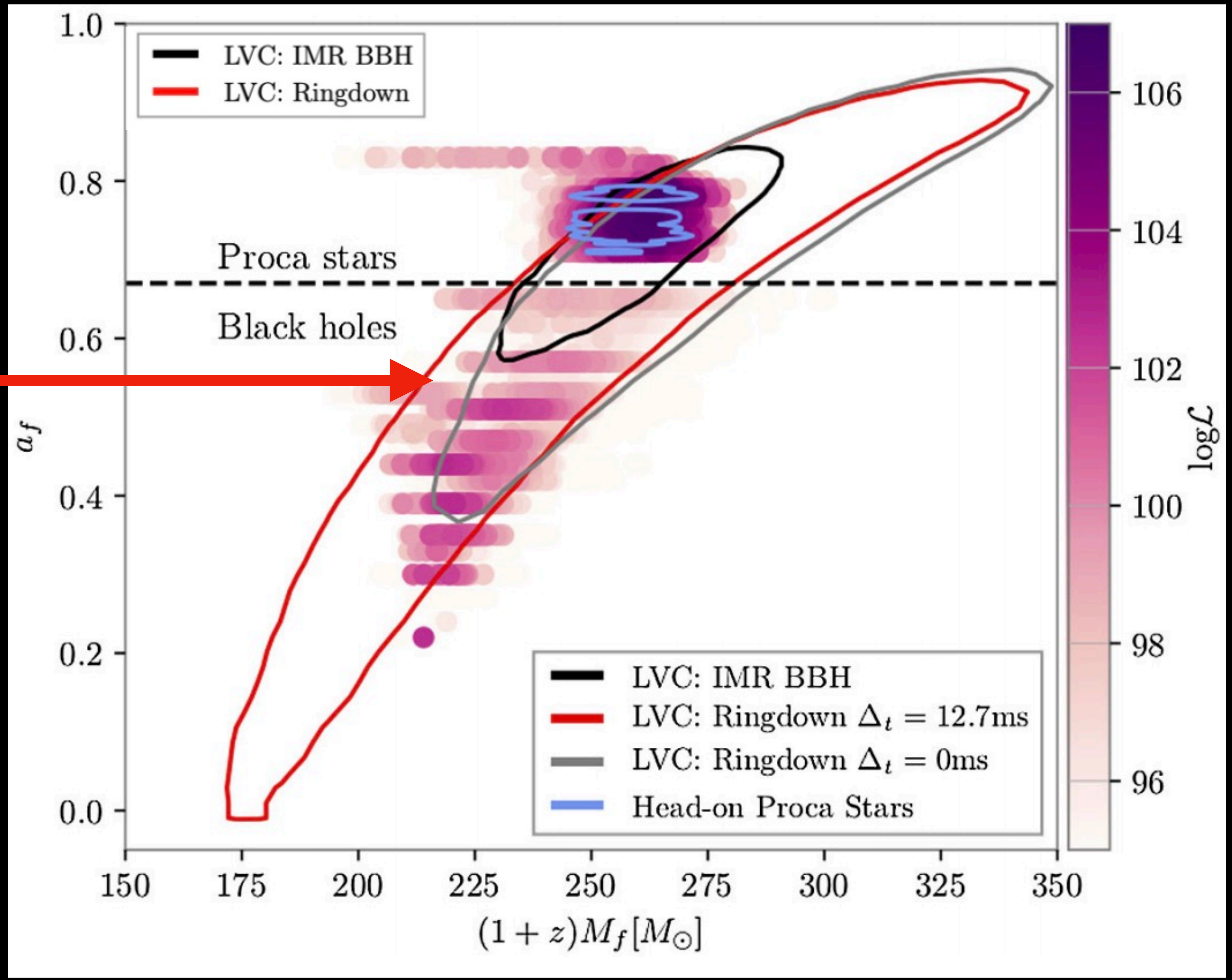
Distance prior: Uniform in-comoving volume

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

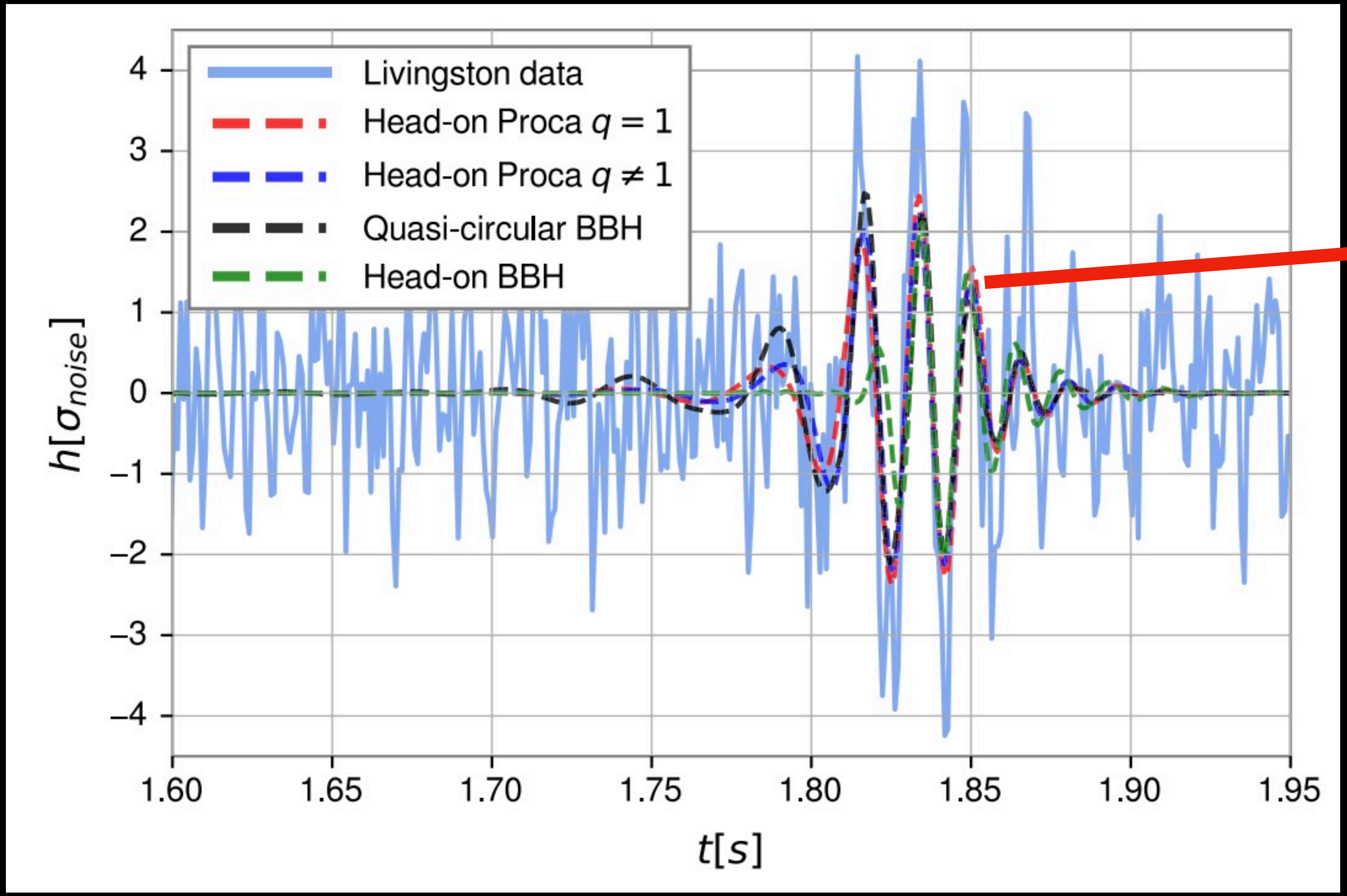
$$\frac{P(\text{Proca } q{\neq}1)}{P(\text{BBH})} \simeq 70 \qquad \frac{P(\text{Proca } q{=}1)}{P(\text{BBH})} \simeq 30$$

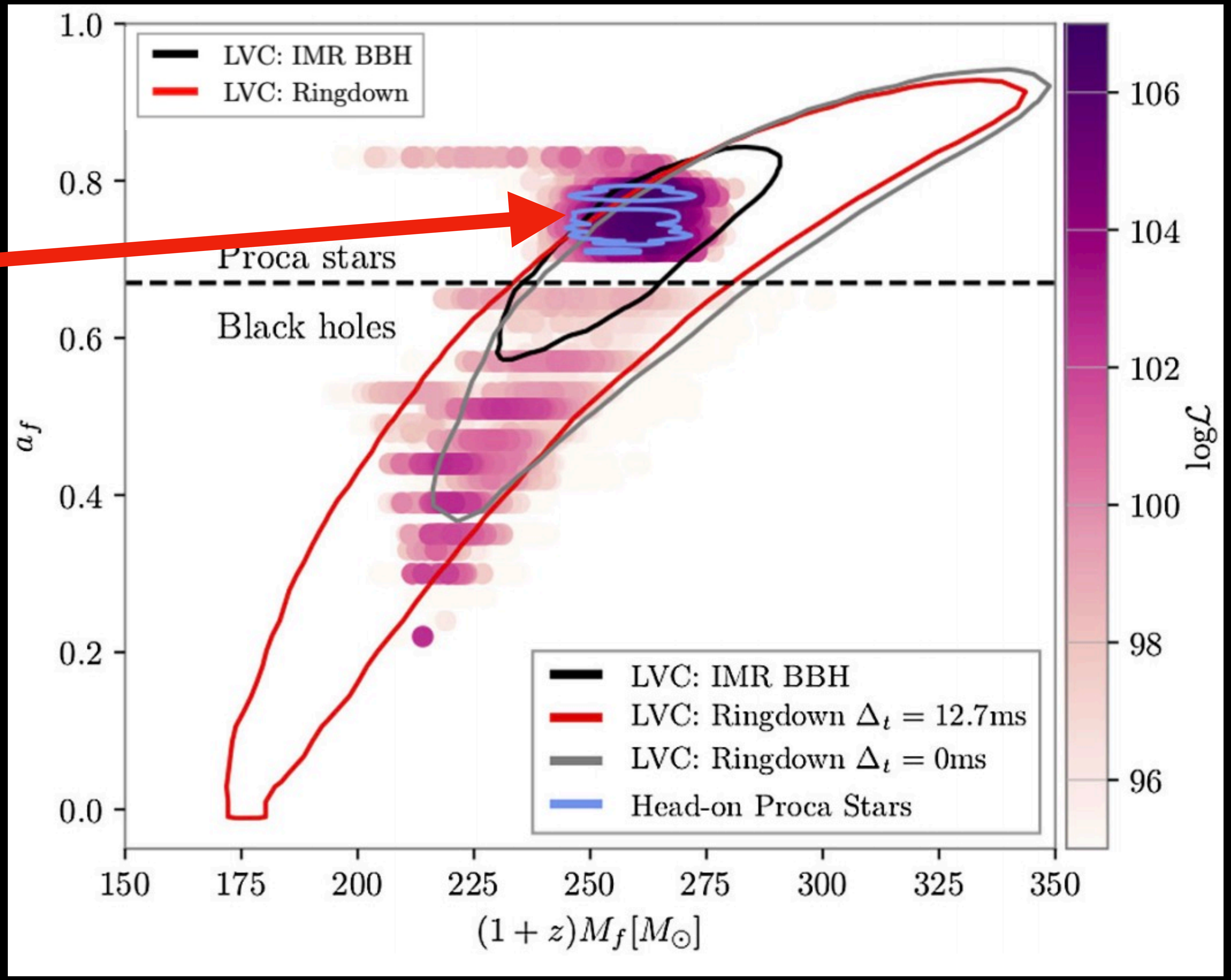




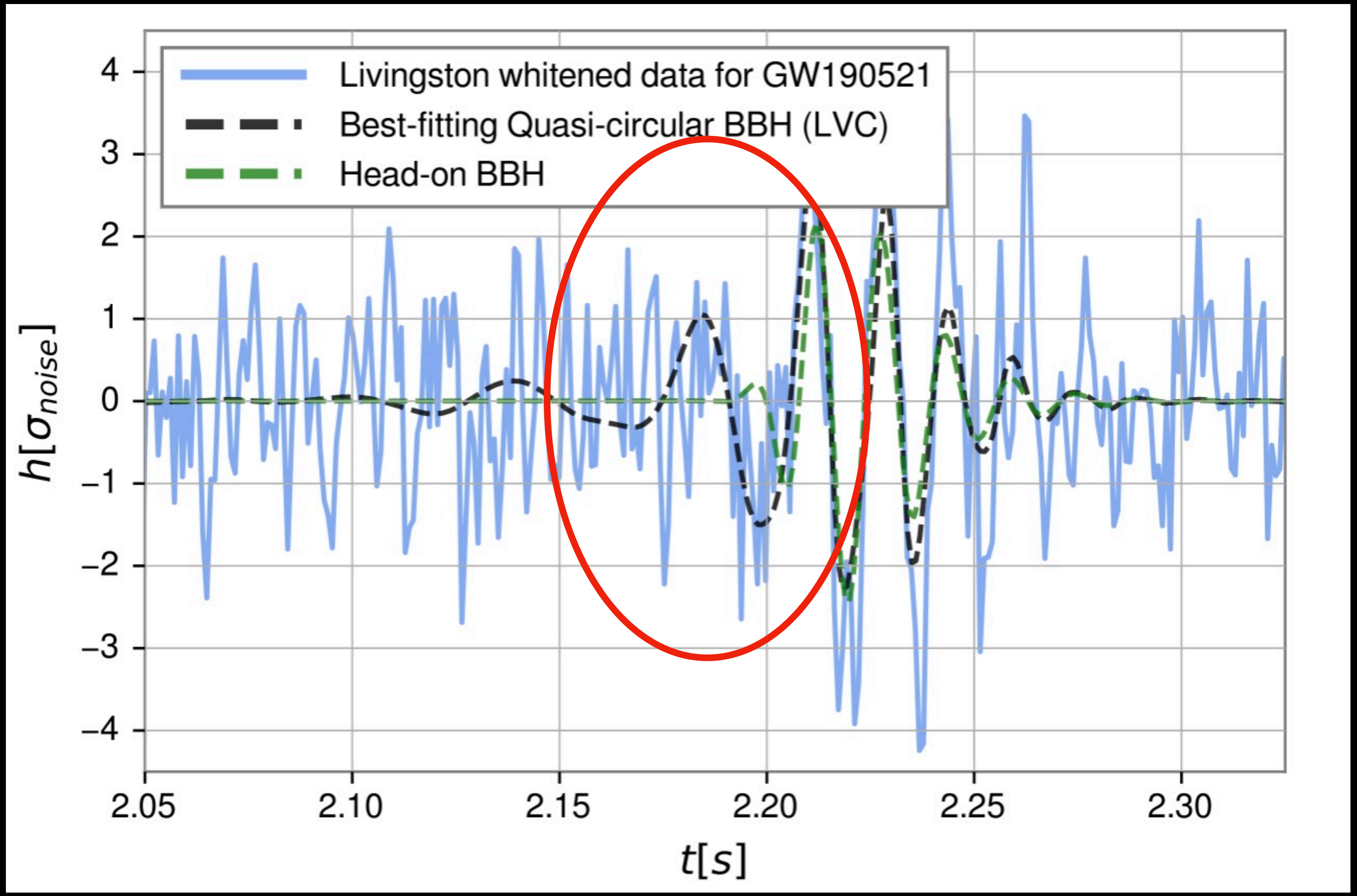


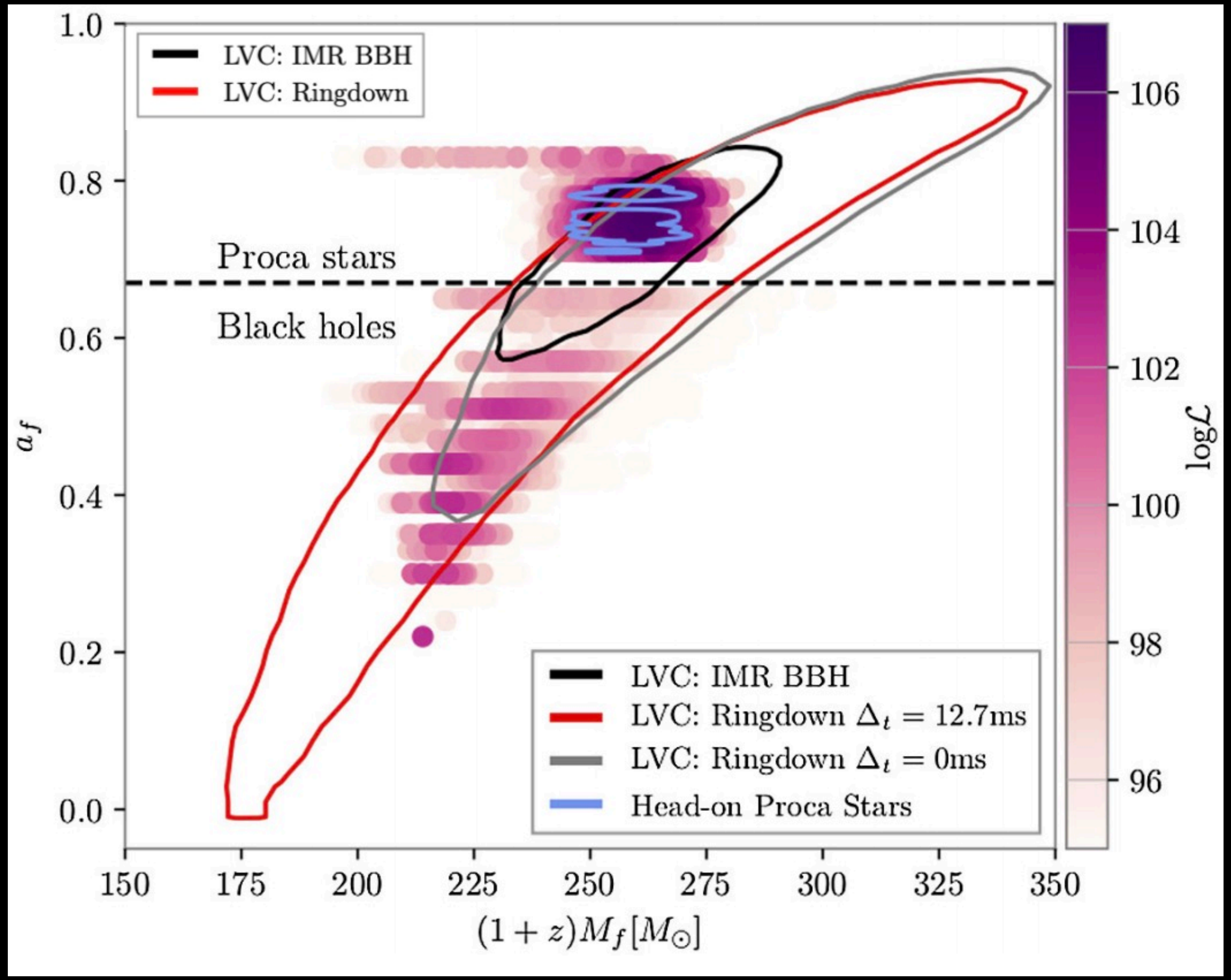
Head-on black-holes could not provide us with enough final spin



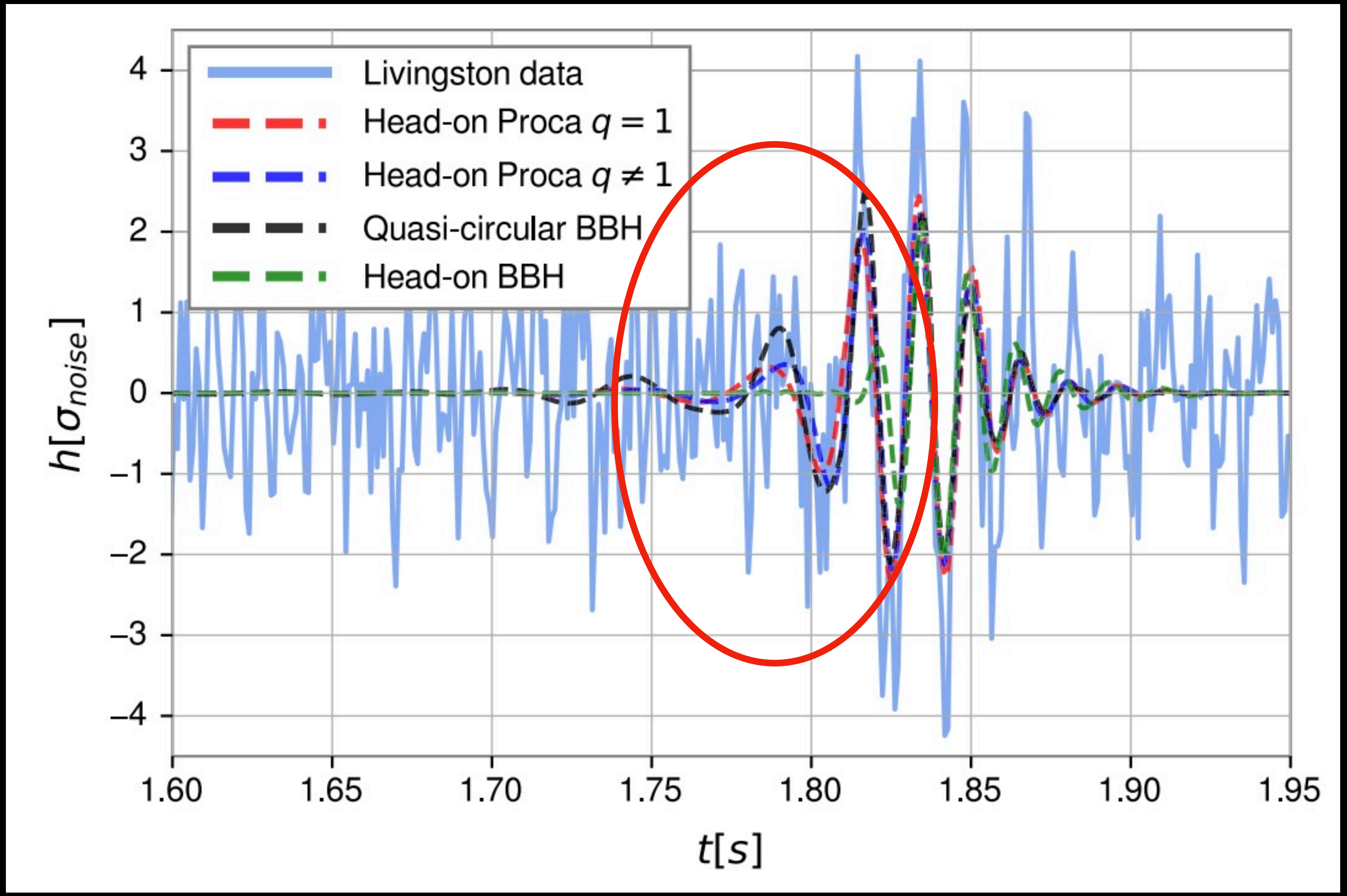


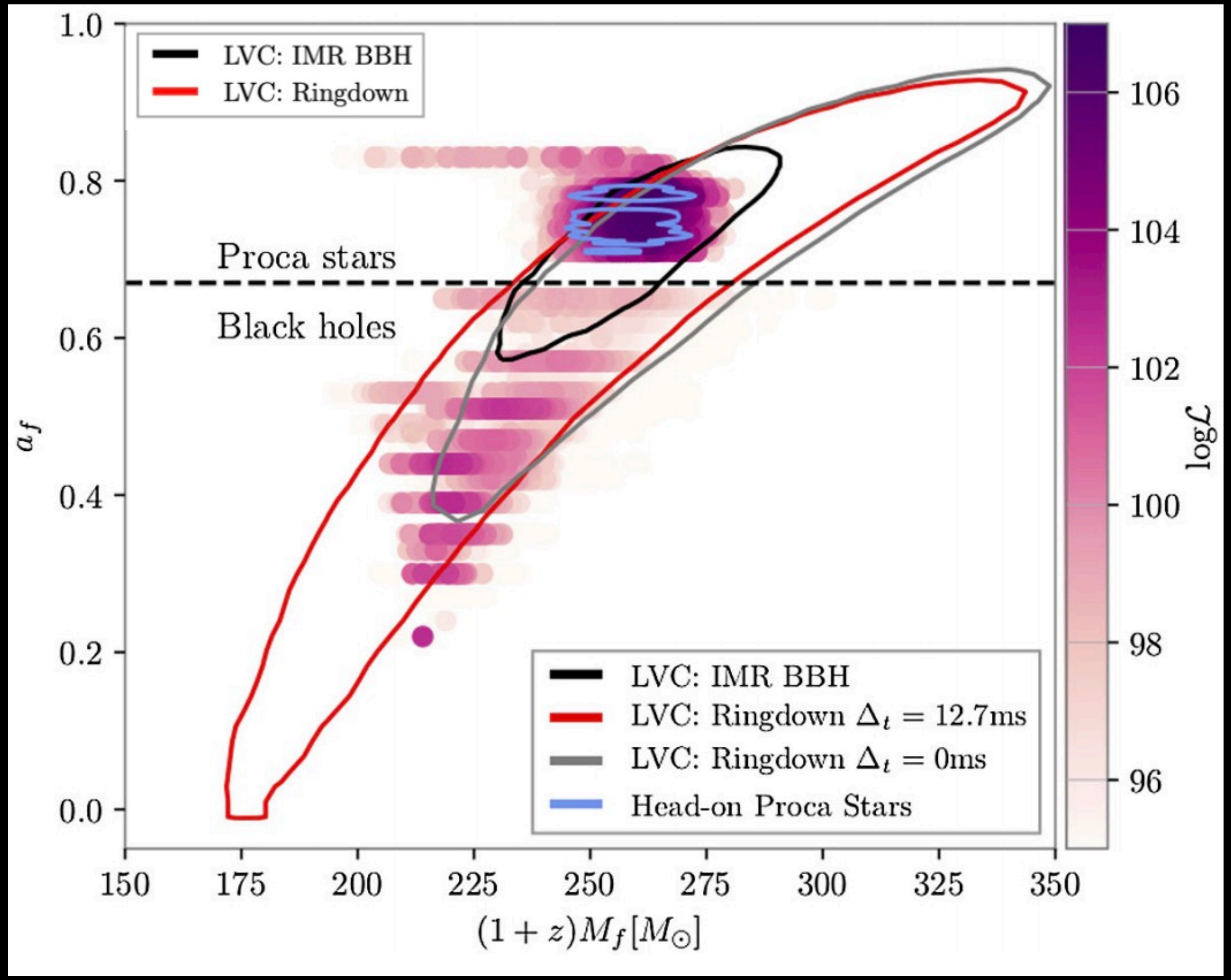
Head-on Proca stars can





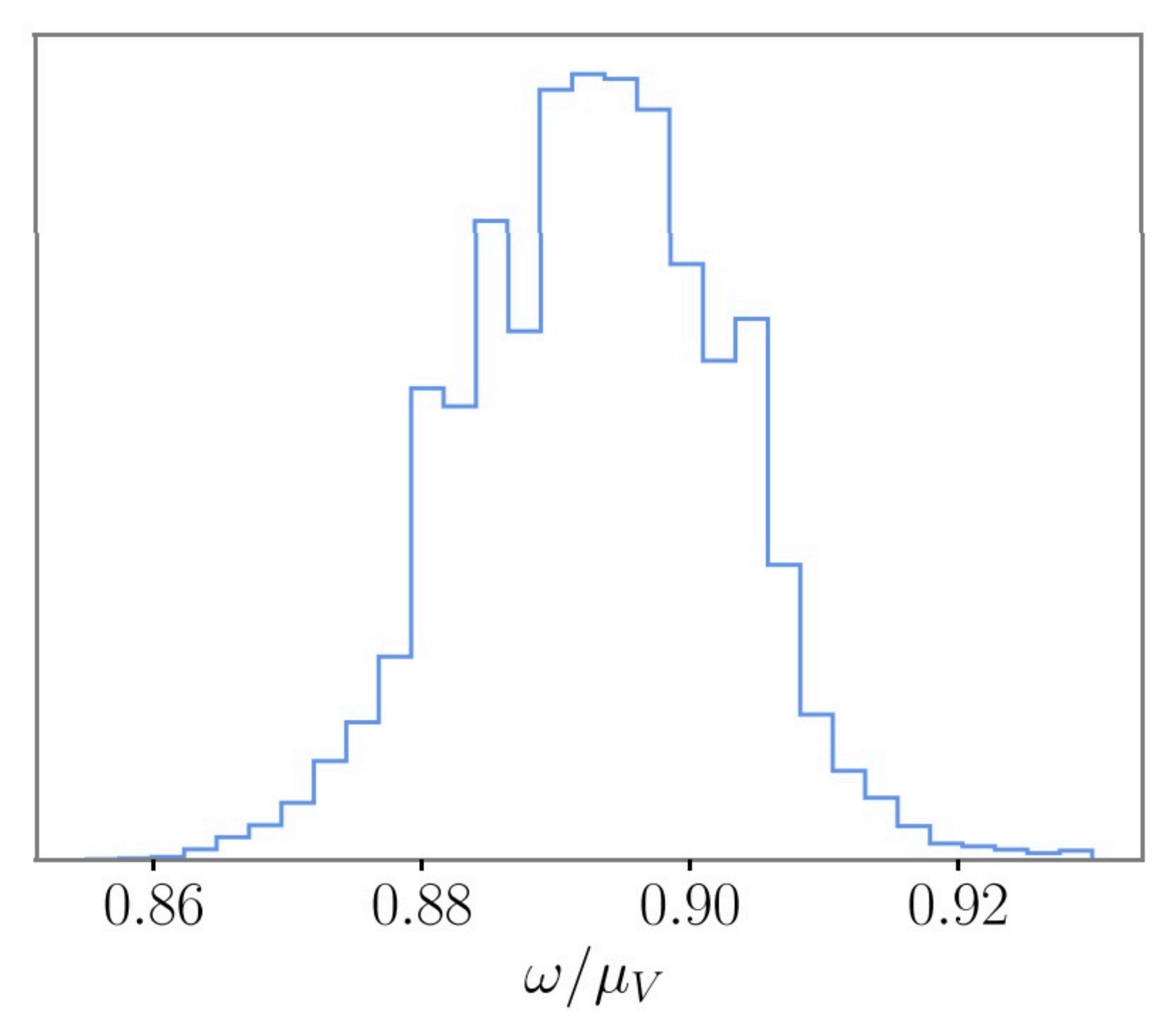
Lack of power before signal peak: immediate ringdown of final black hole



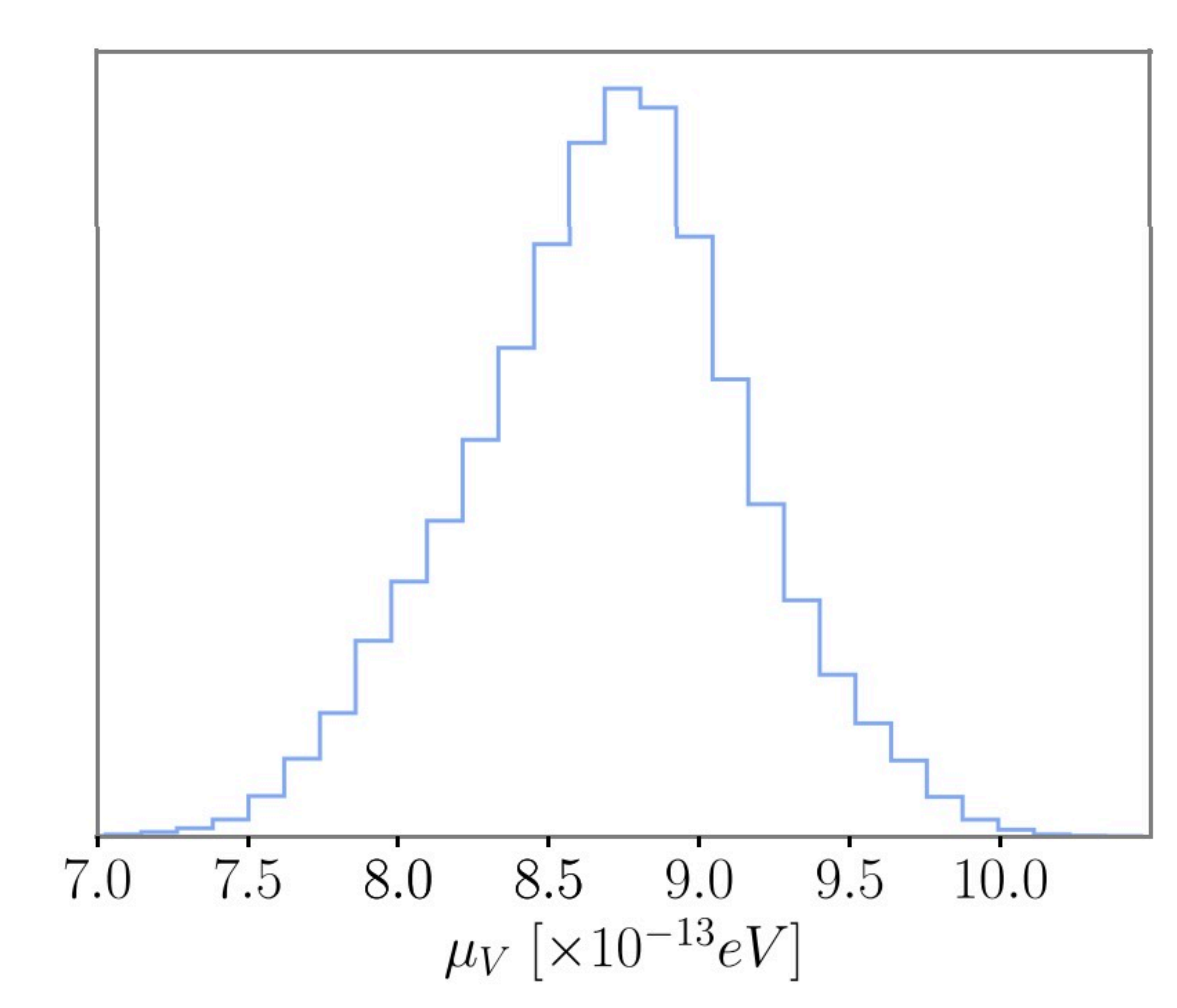


Transient hypermassive Proca star: power before signal peak

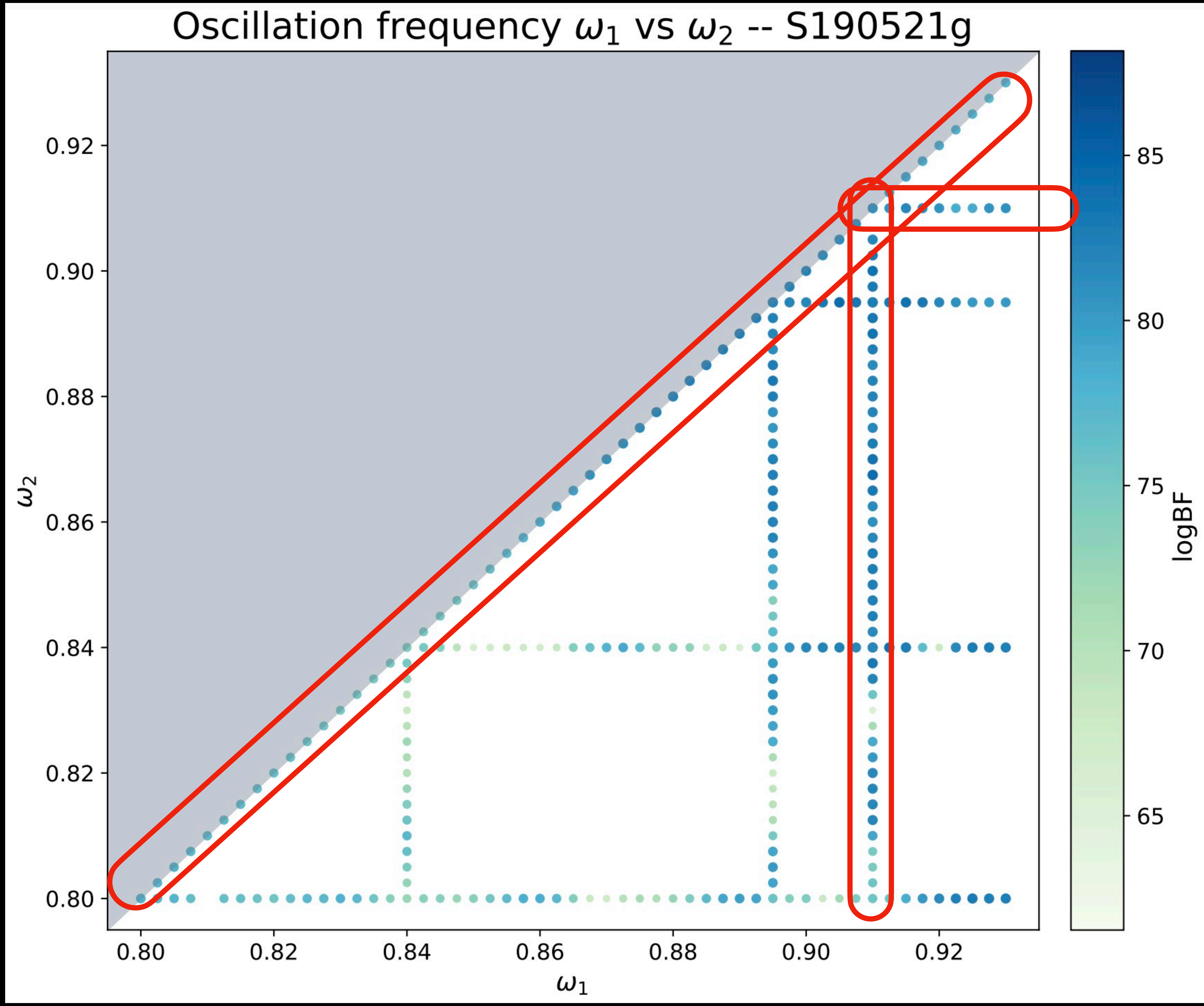
Bosonic field frequency



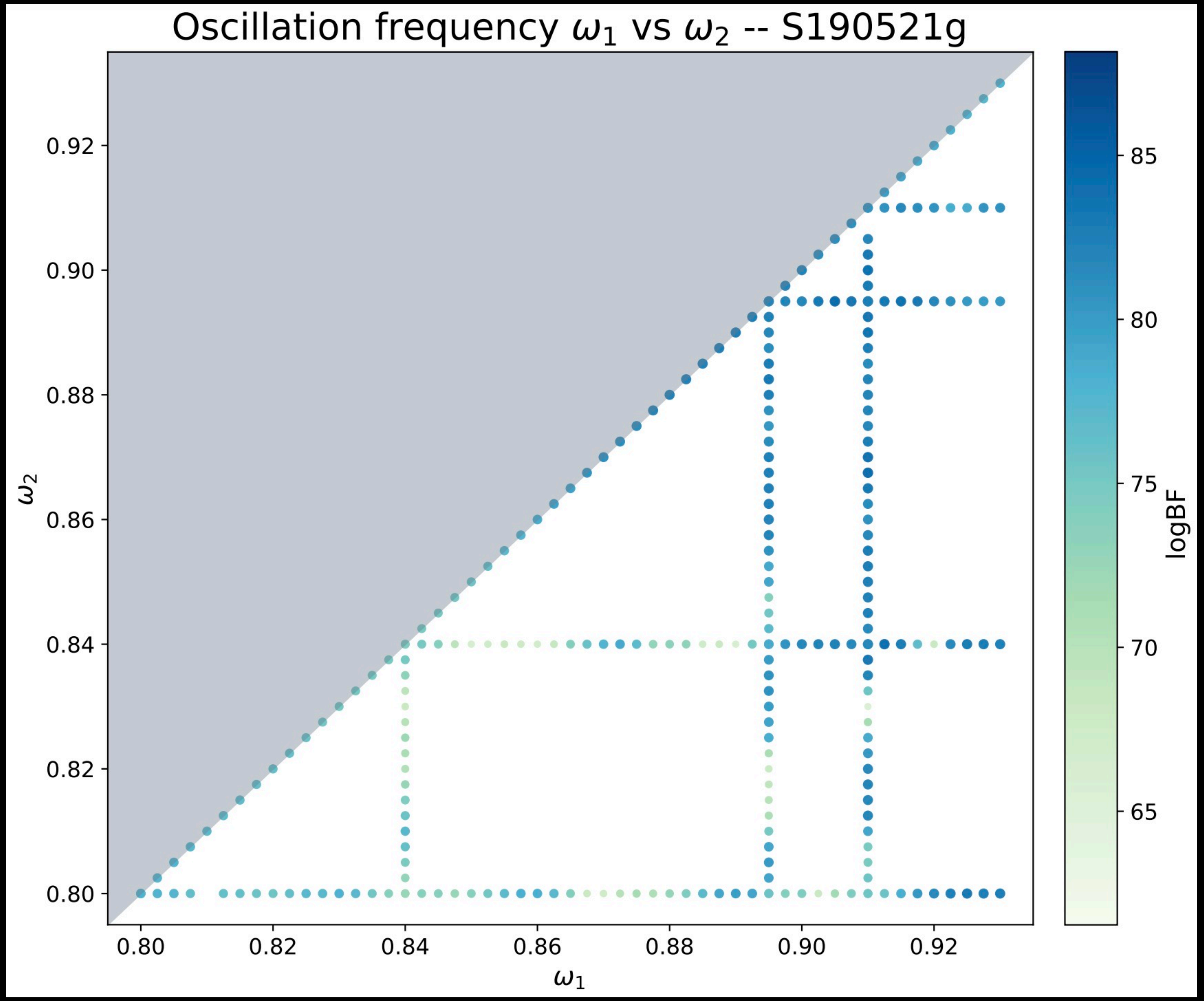
Boson mass



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



Oscillation frequency ω_1 vs ω_2 -- S190521g
ω_2
0.92
0.90
0.88
0.86
0.84
0.82
0.80
ω_1
0.80
0.82
0.84
0.86
0.88
0.90
0.92
logBF
85
80
75
70
65

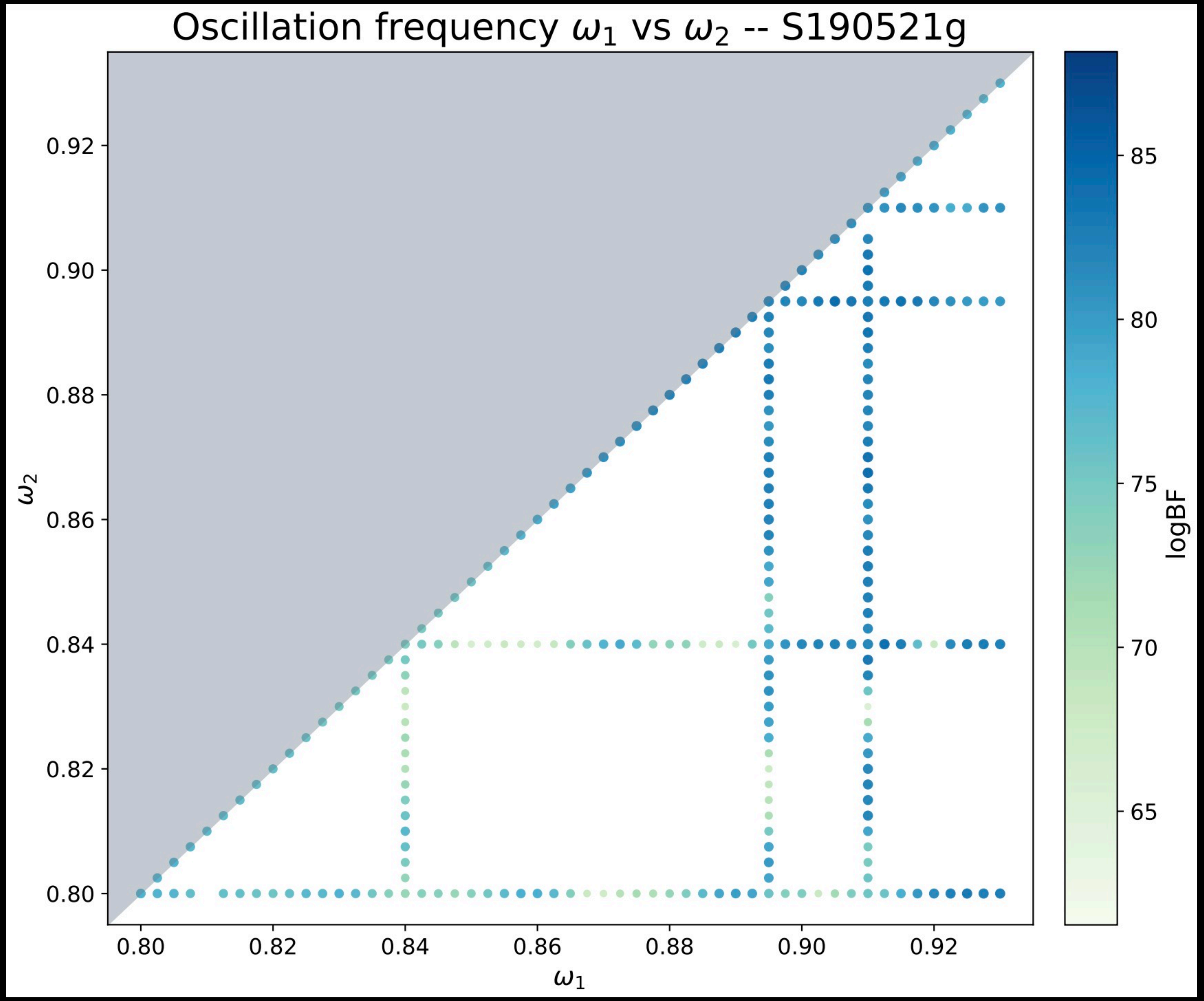


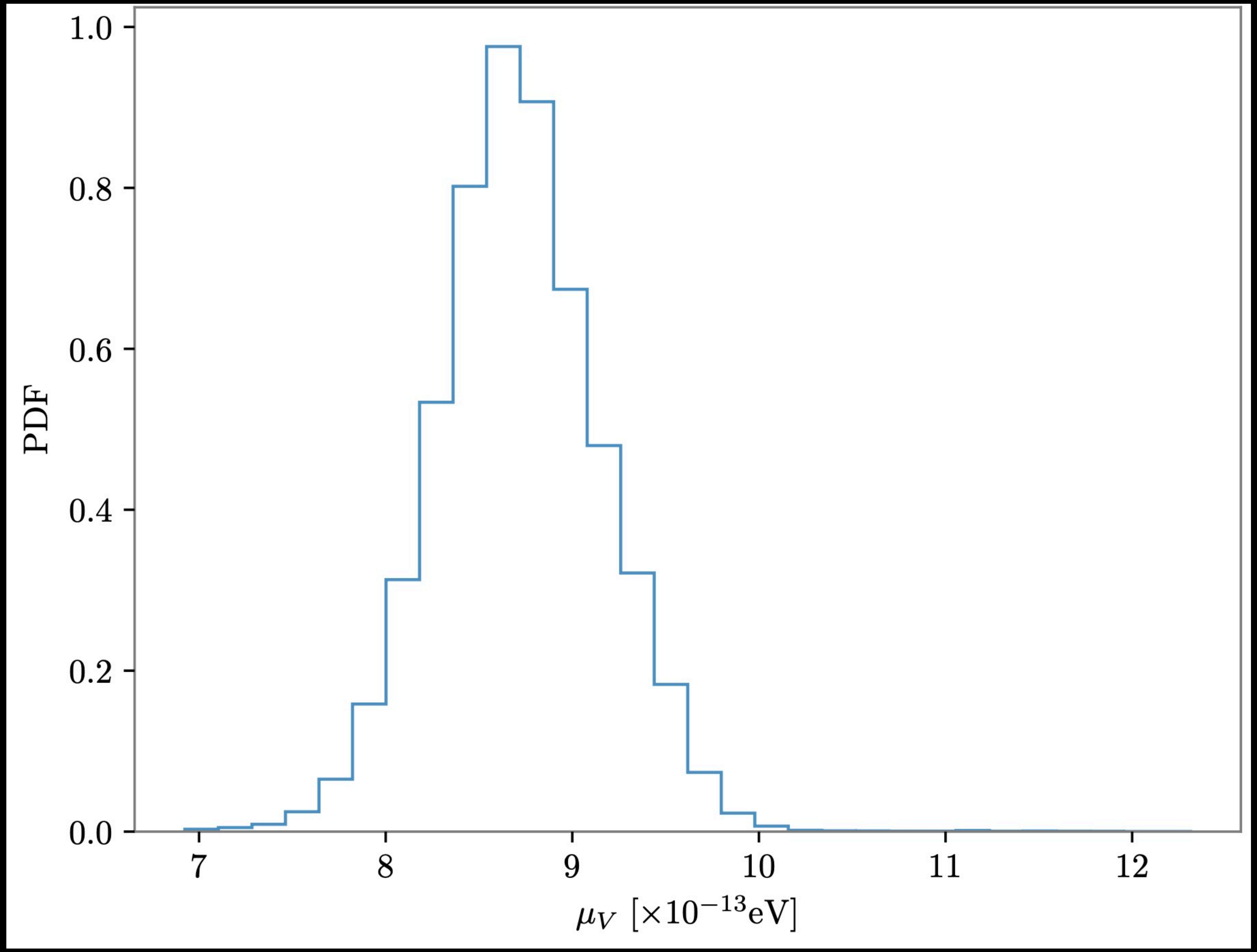
Enlarged waveform family

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





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

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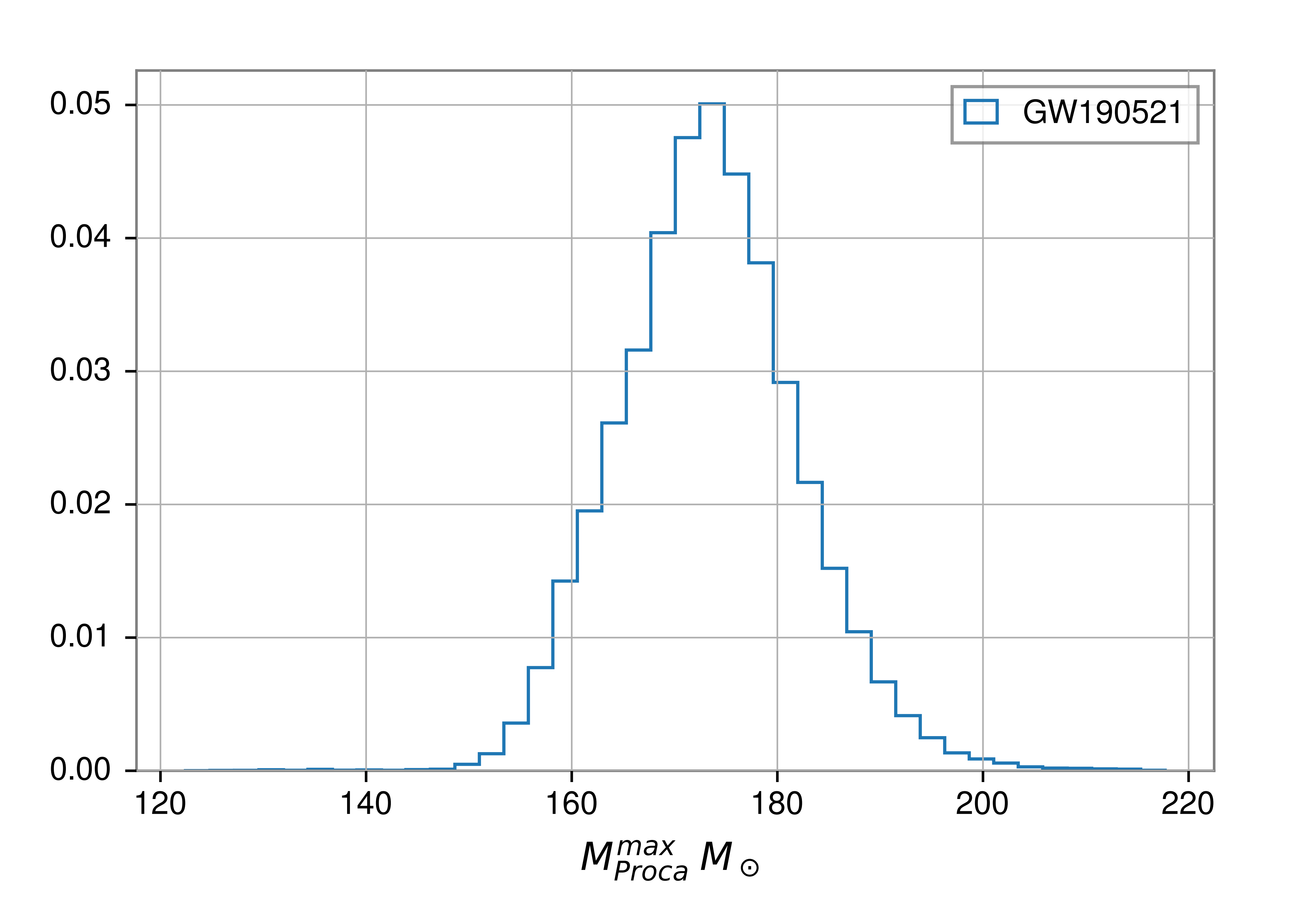
$$M^{\rm Proca}_{\rm max} = 174^{+15}_{-14} M_\odot$$



PRELIMINAR

Take with a grain of salt

Second-most significant IMBH trigger reported by LVC

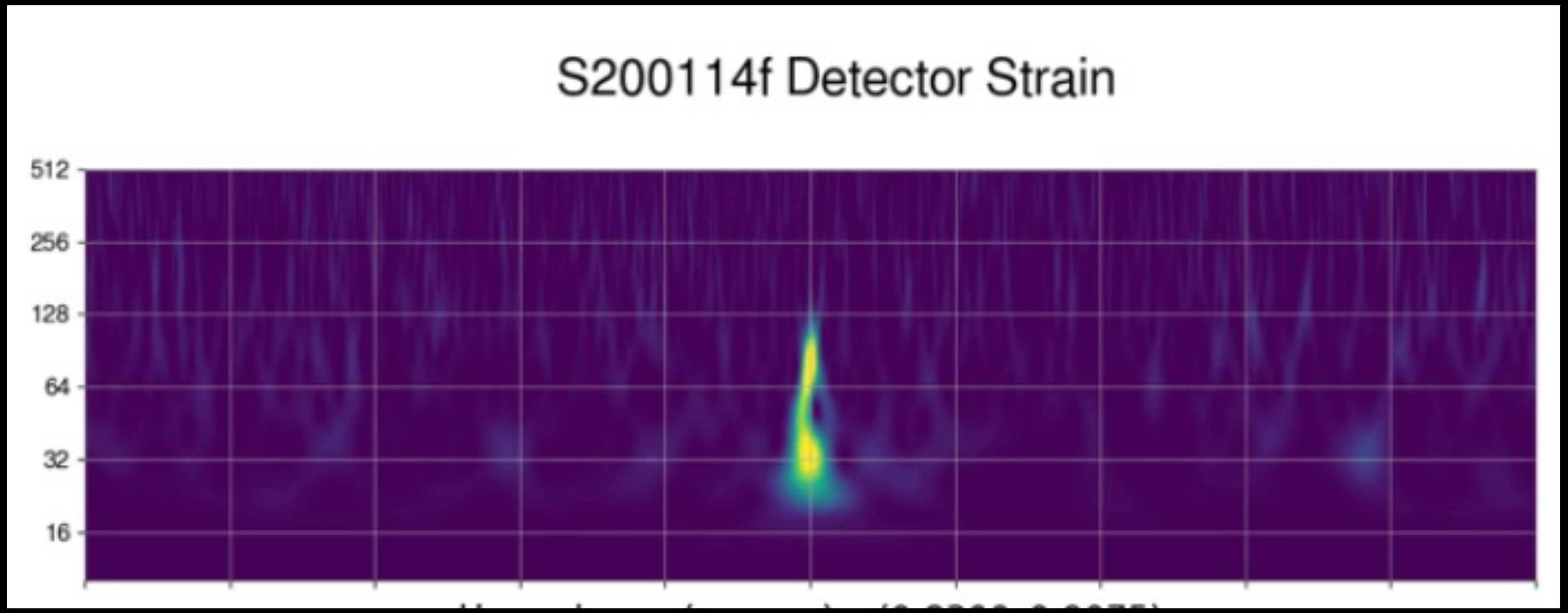
Parameter inconsistency across BBH models

Not ruled out as Proca star merger

LogB ~ 0 (as probable as a BBH)

Boson mass:

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



False Alarm Rate ~ 1/17yr

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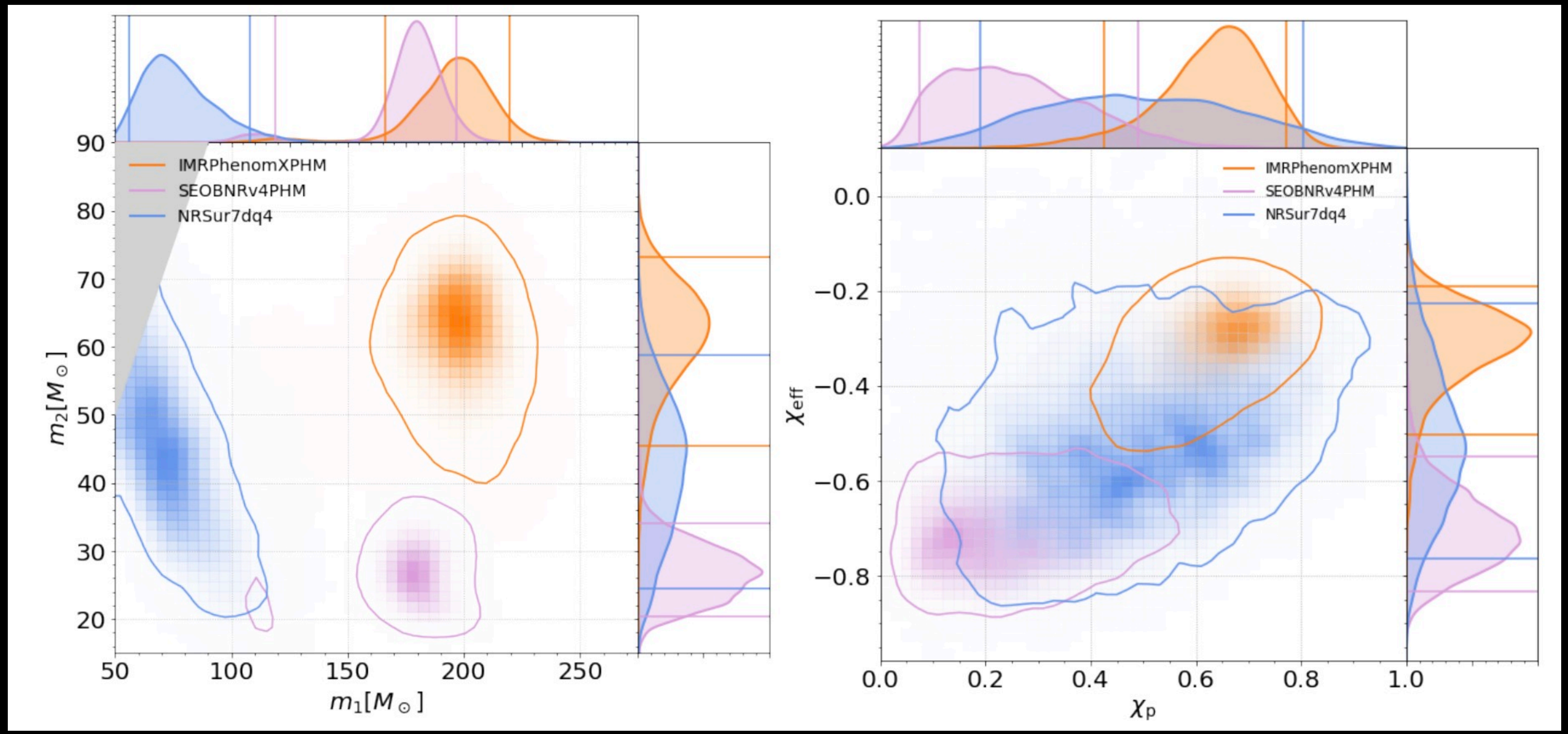

LIGO+Virgo (2021)

- Second-most significant IMBH trigger reported by LVC
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- Boson mass:

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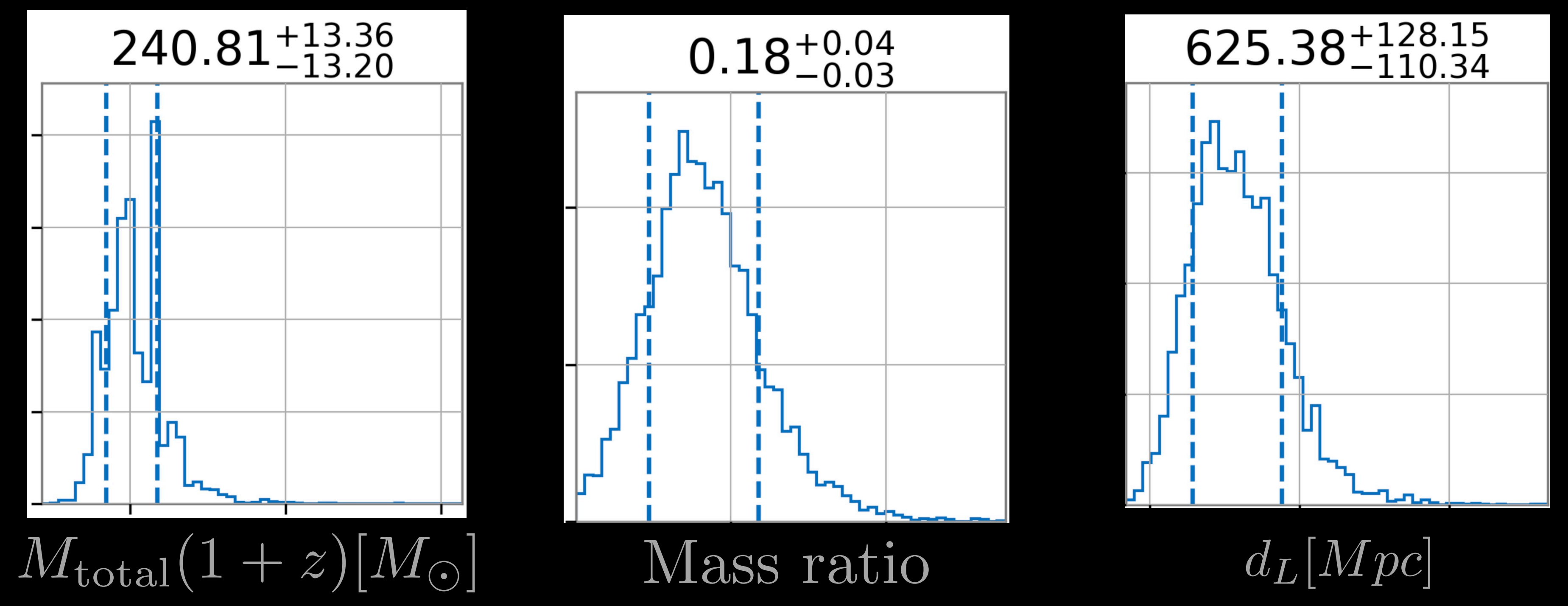
BBH run: IMRPhenomTPHM (Pratten+ 21): MaxLogL = 103

Tried also NRSur7dq4 (Varma+ 20), IMRPhenomXPHM



Large individual spin magnitudes Large spin tilts: precession

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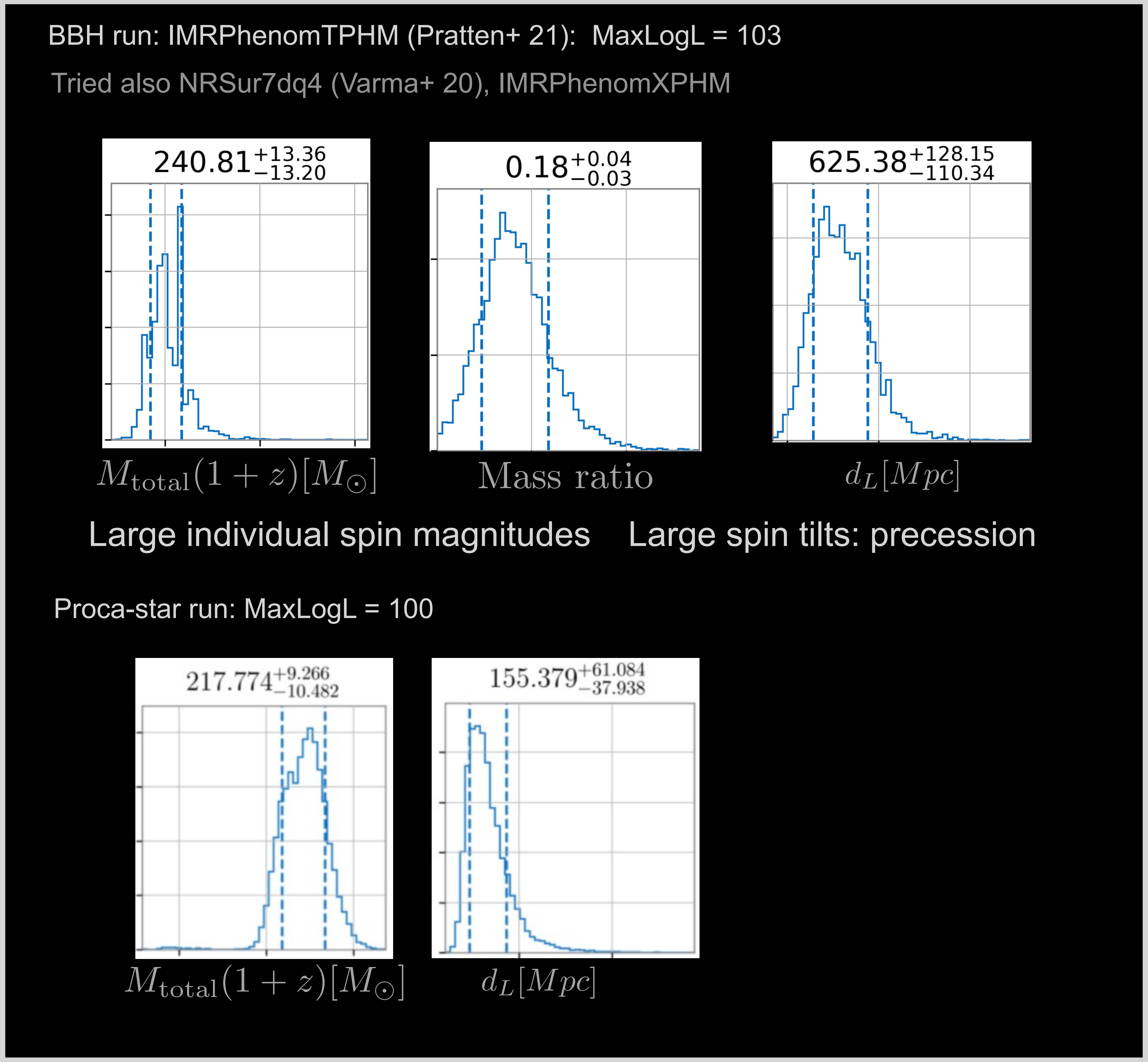

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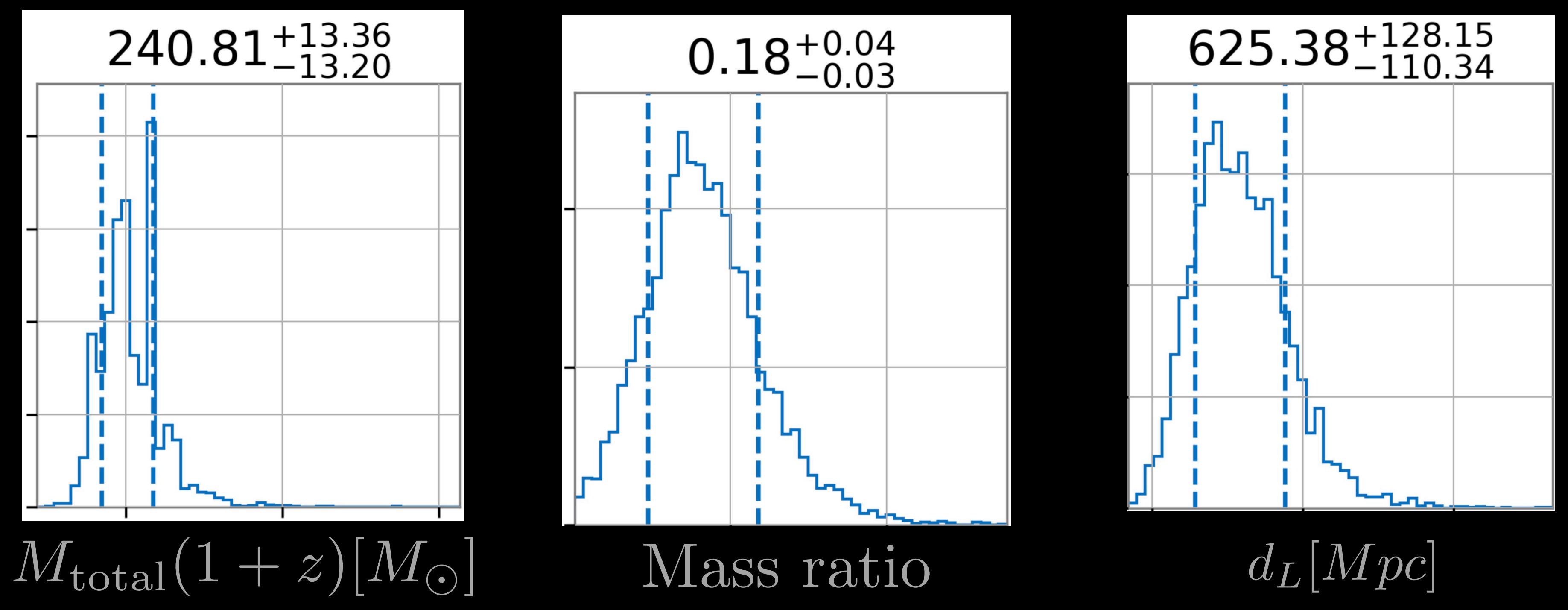
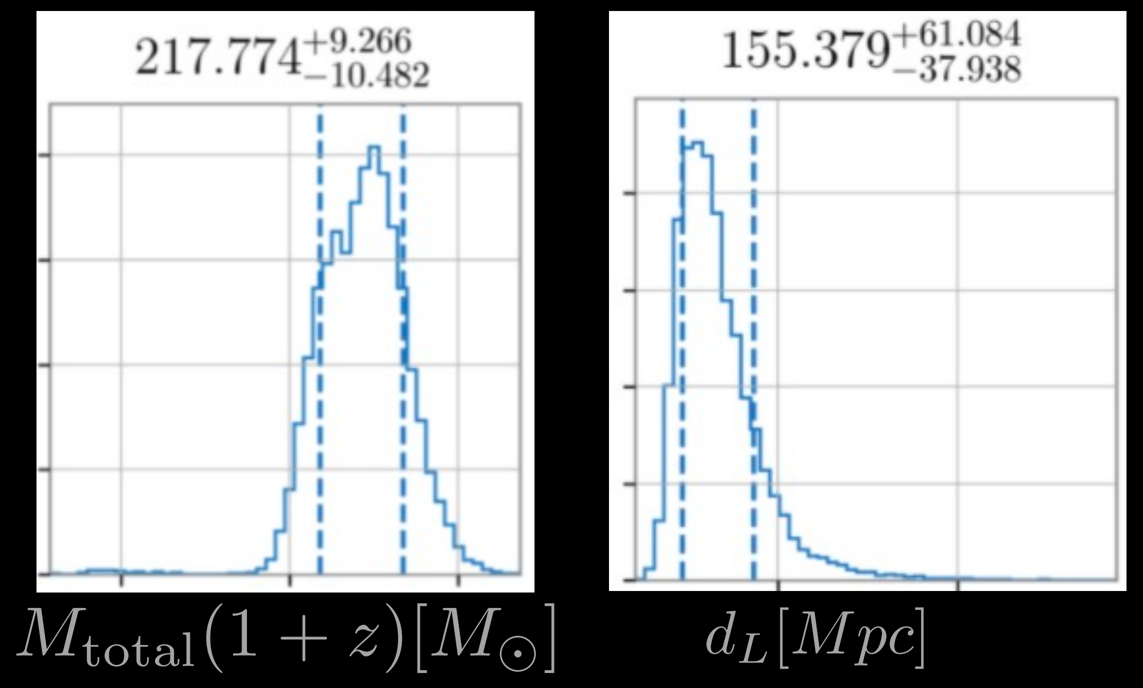


Large individual spin magnitudes   Large spin tilts: precession

Proca-star run: MaxLogL = 100



We use Newmann-Penrose scalar as template

Second-most significant IMBH trigger reported by LVC

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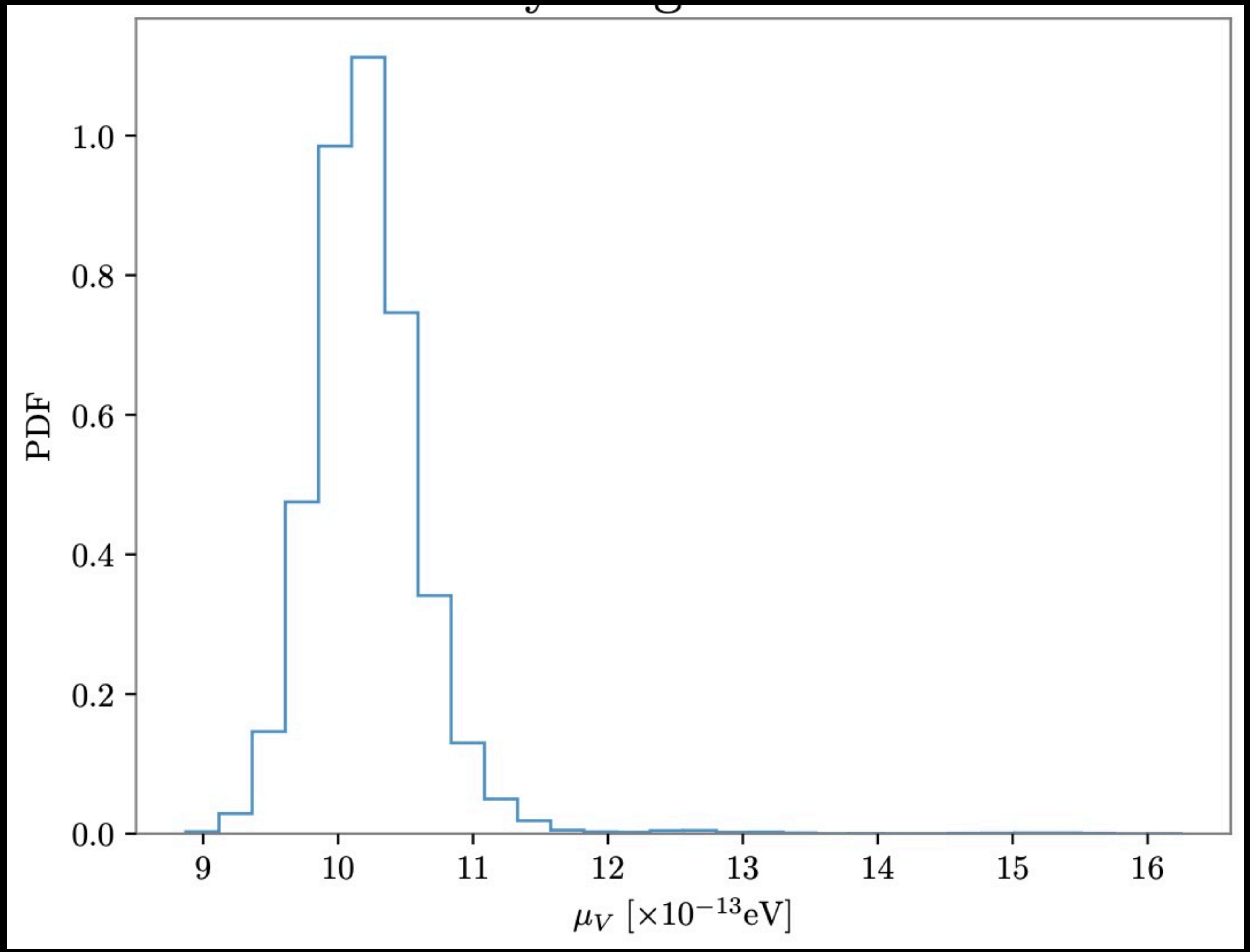
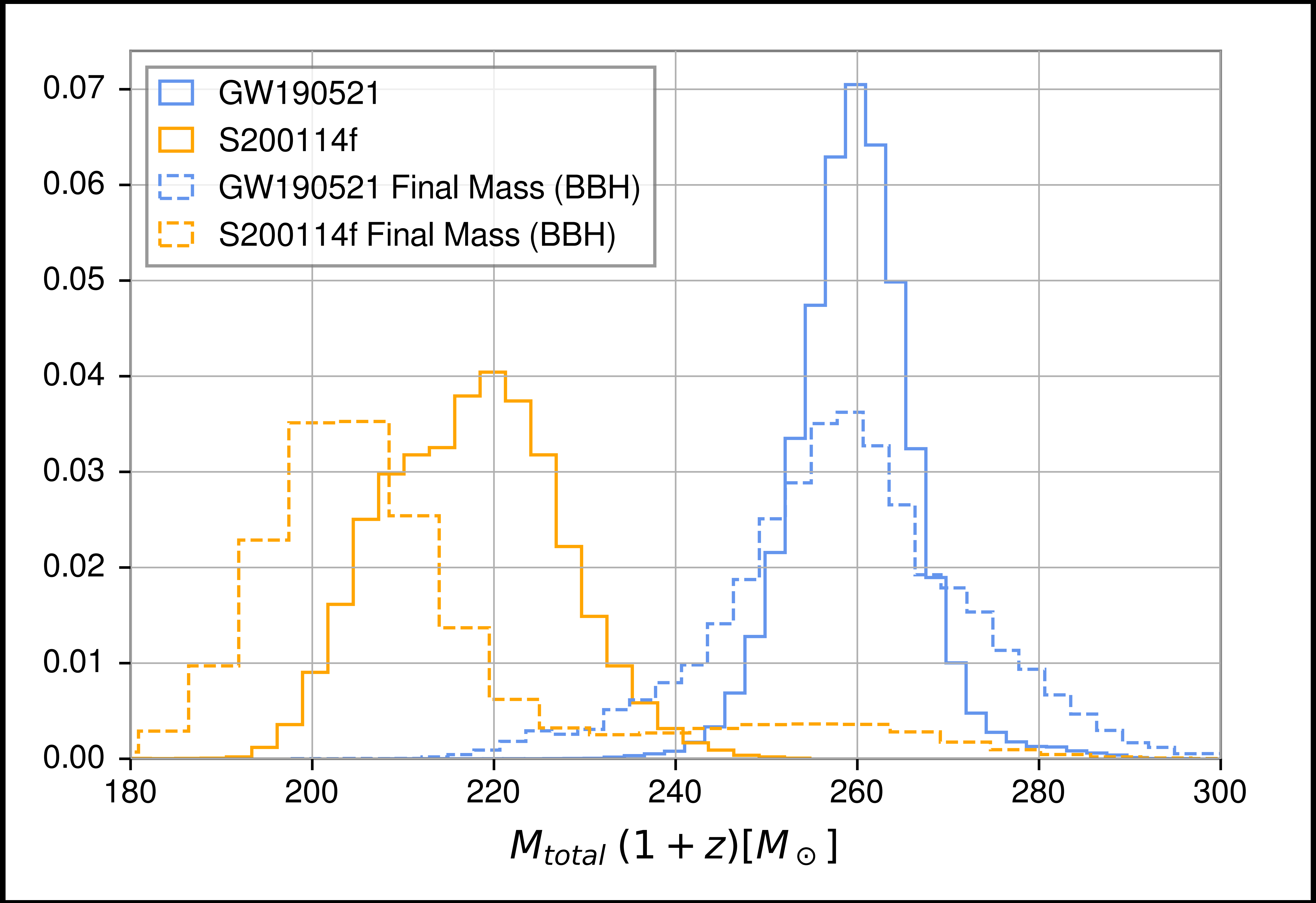
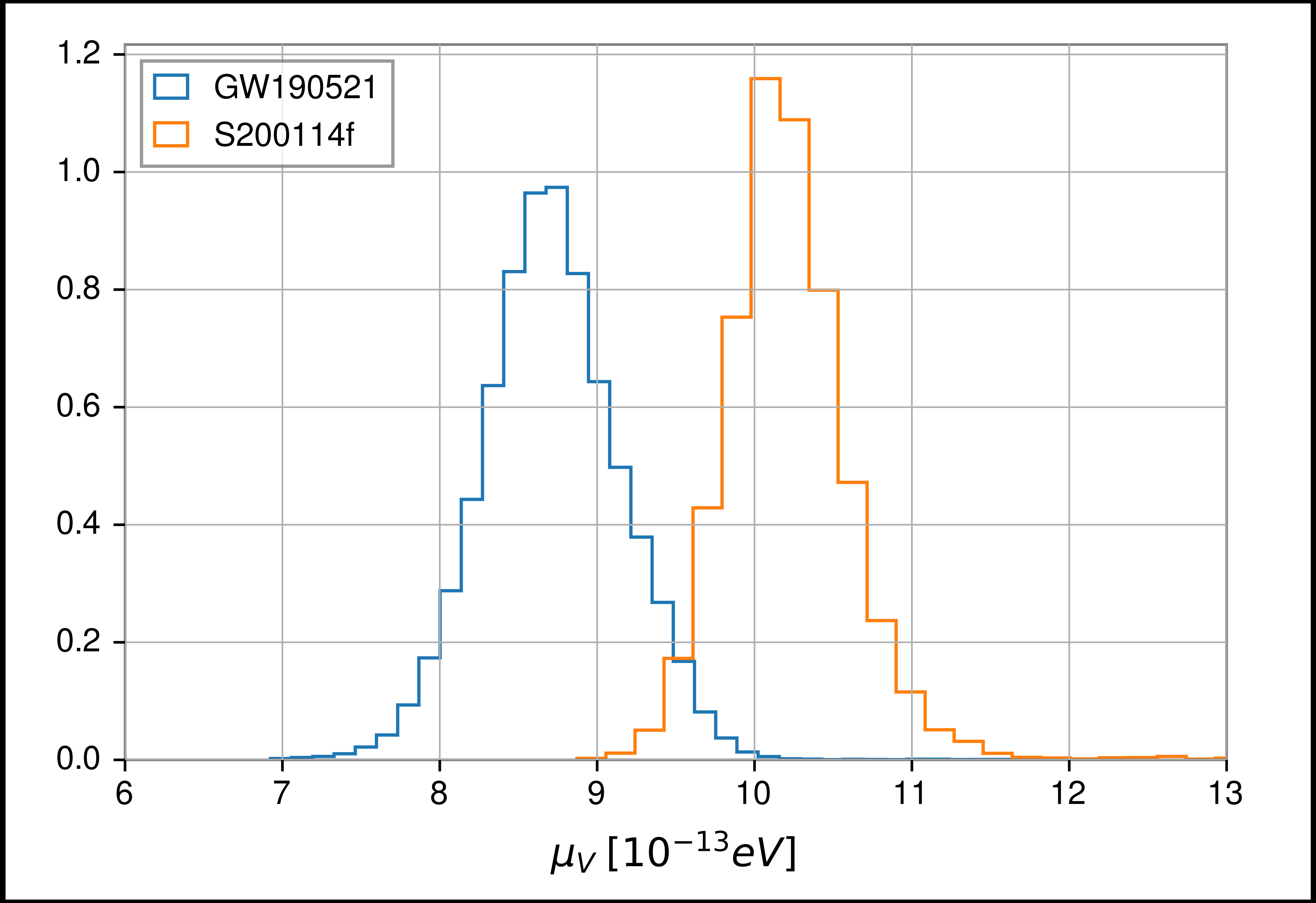


GW190521 and S200114: mass consistency with BBH



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



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This talk:

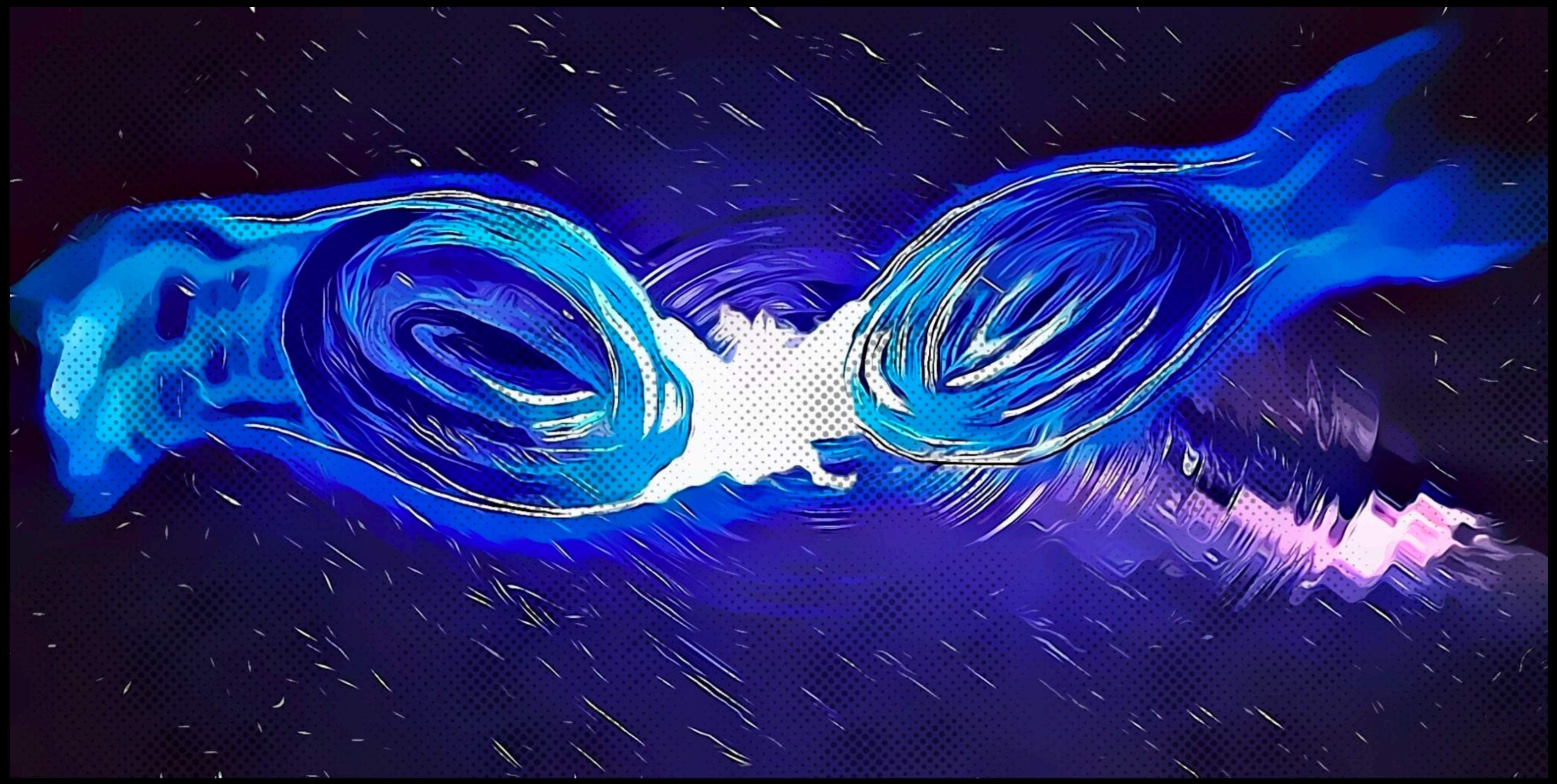
GW190521 has brought us in the realm of ¿what are we observing?

Consistent with a head-on merger of Proca stars

Second, low significance trigger S200114 (ongoing)

Consistent masses at 90% C.I.

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



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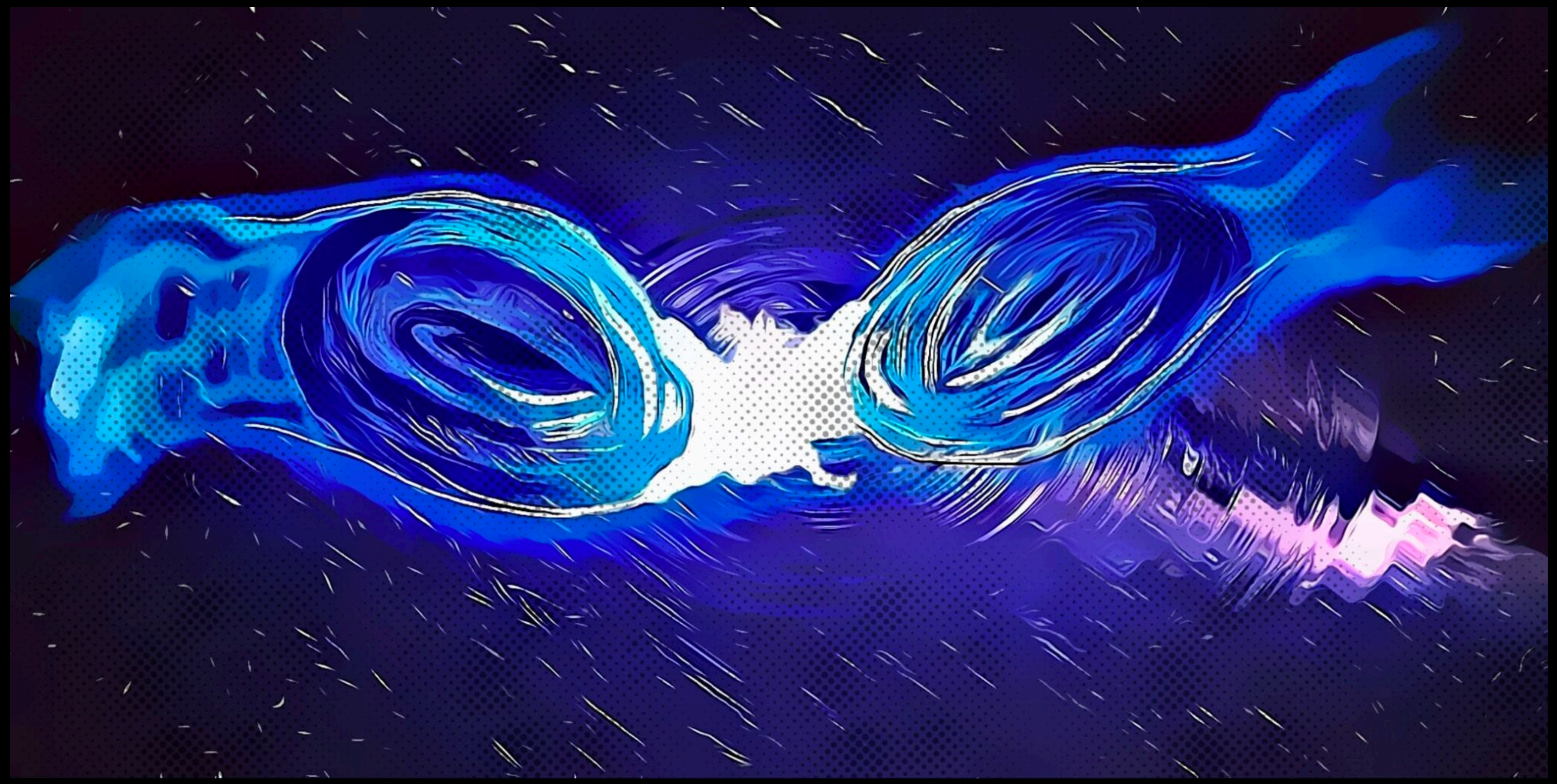


The future:

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?

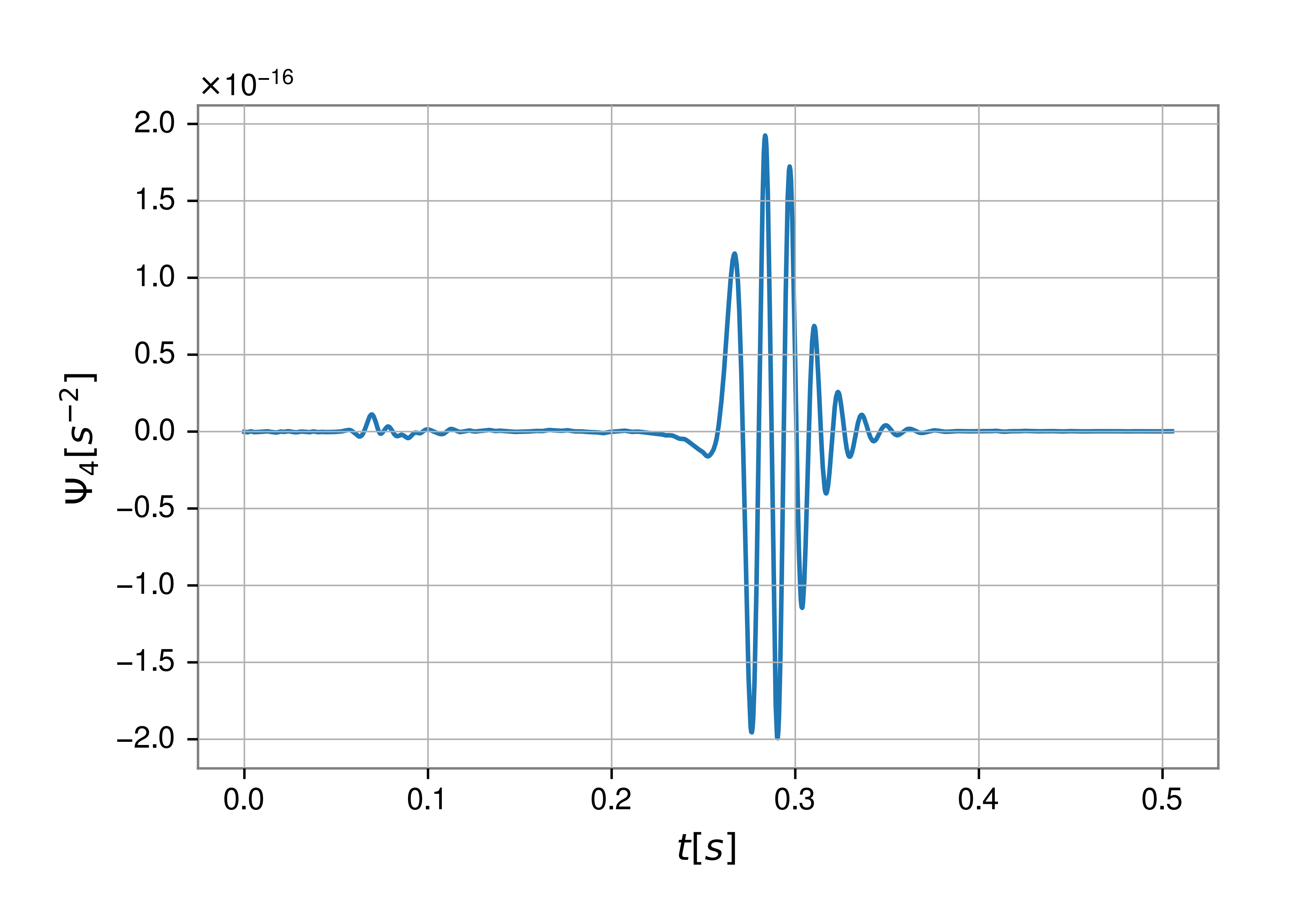
Gravitational-wave data analysis with the Newmann-Penrose scalar

$$\Psi_4$$

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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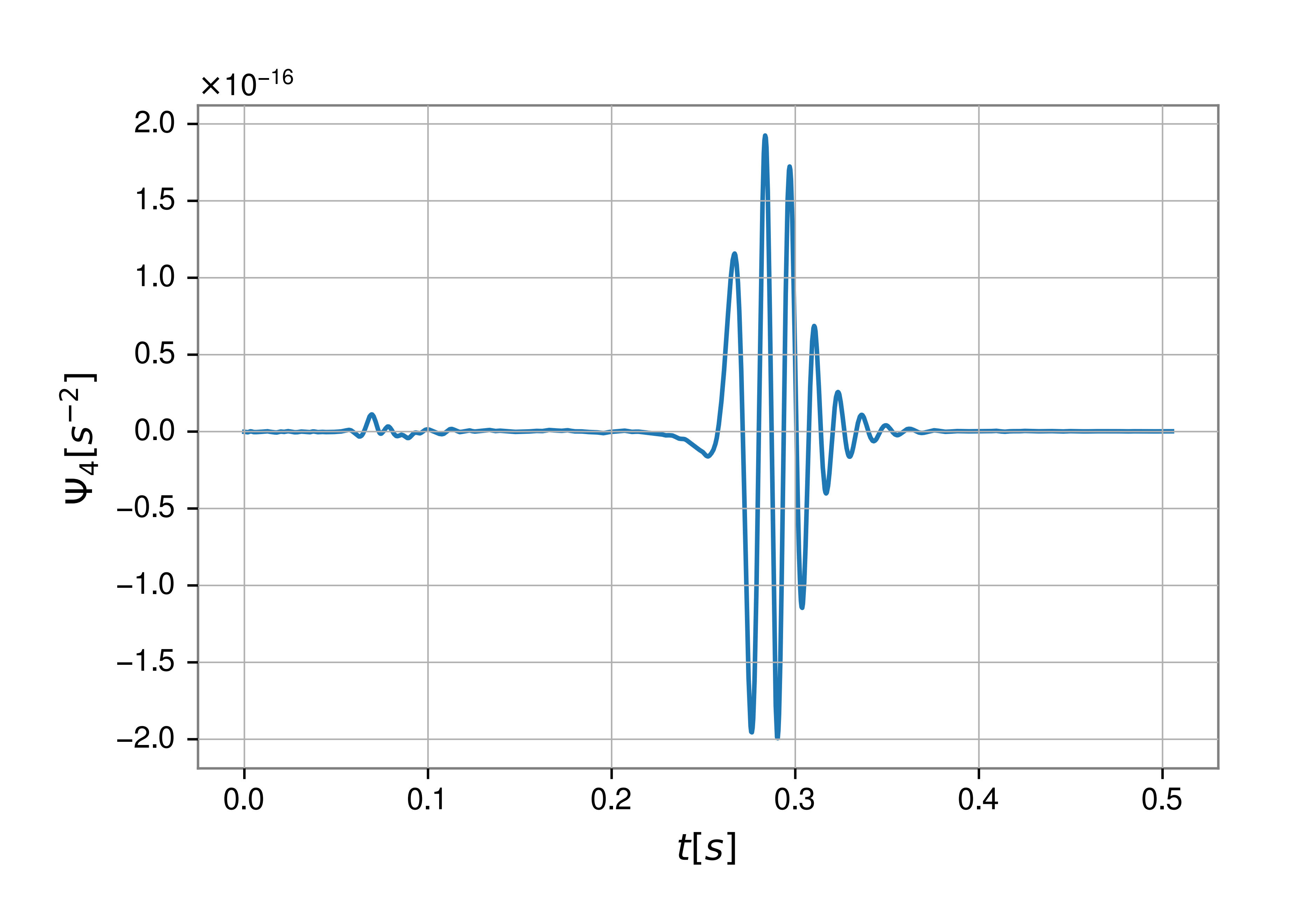
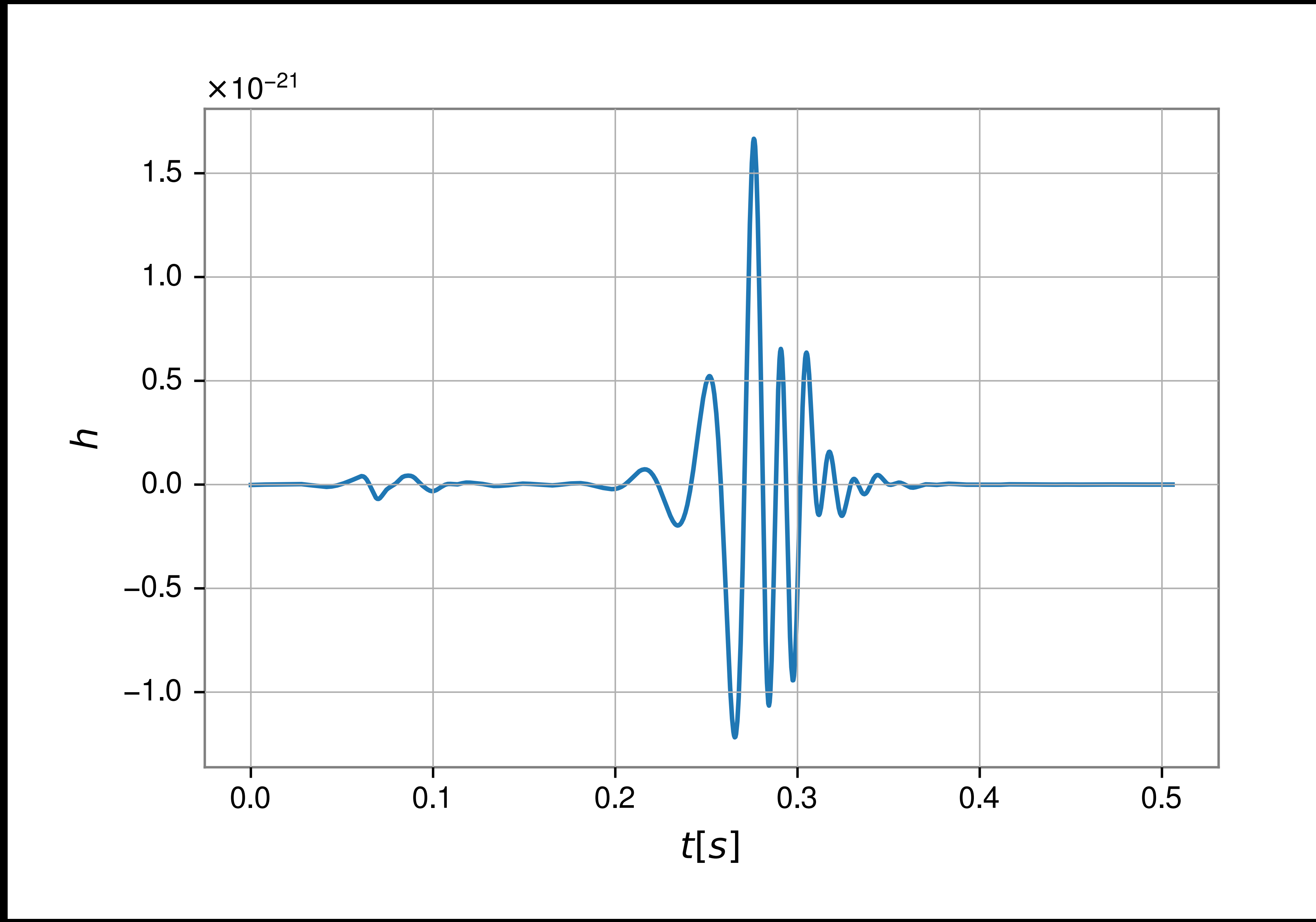
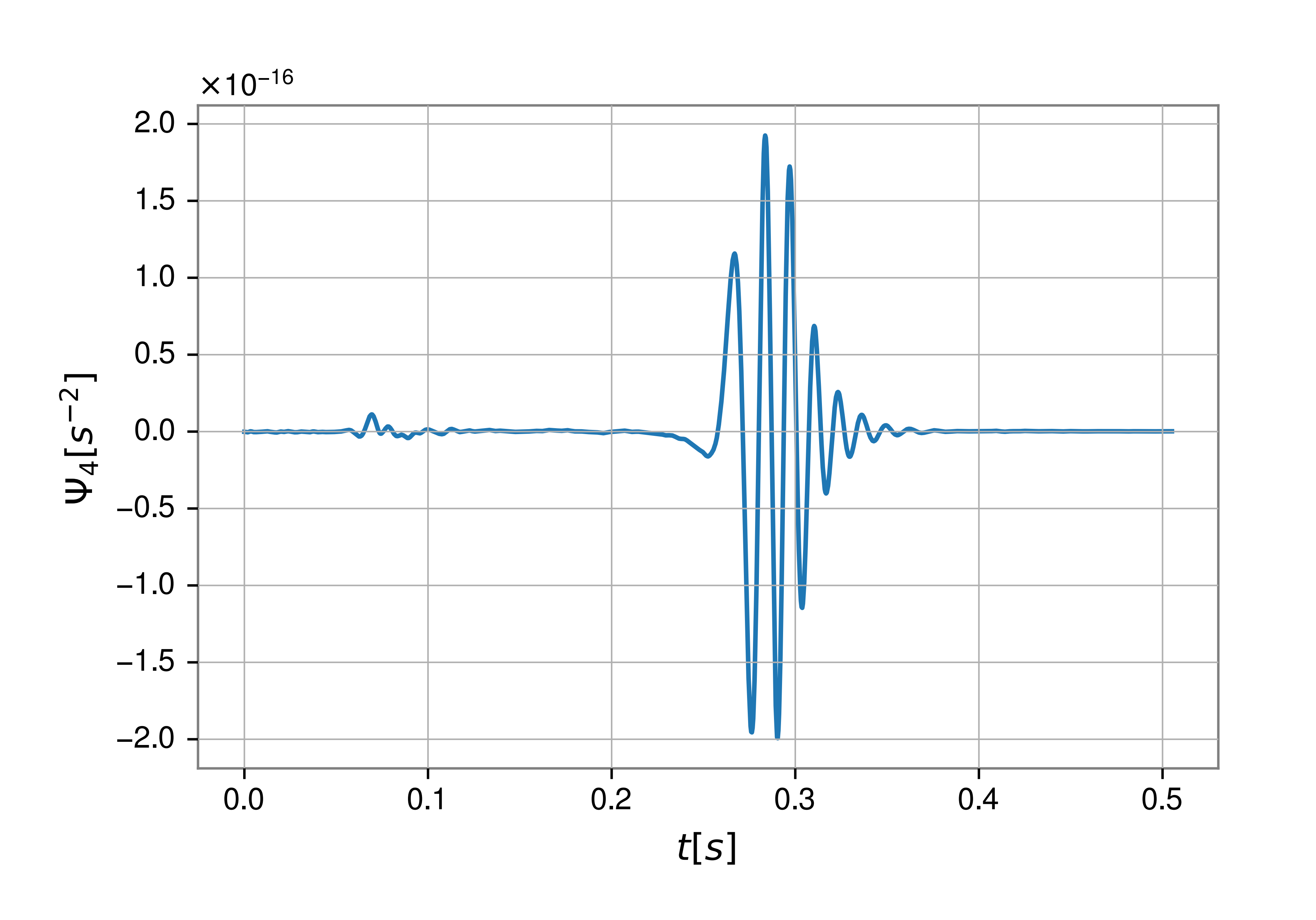


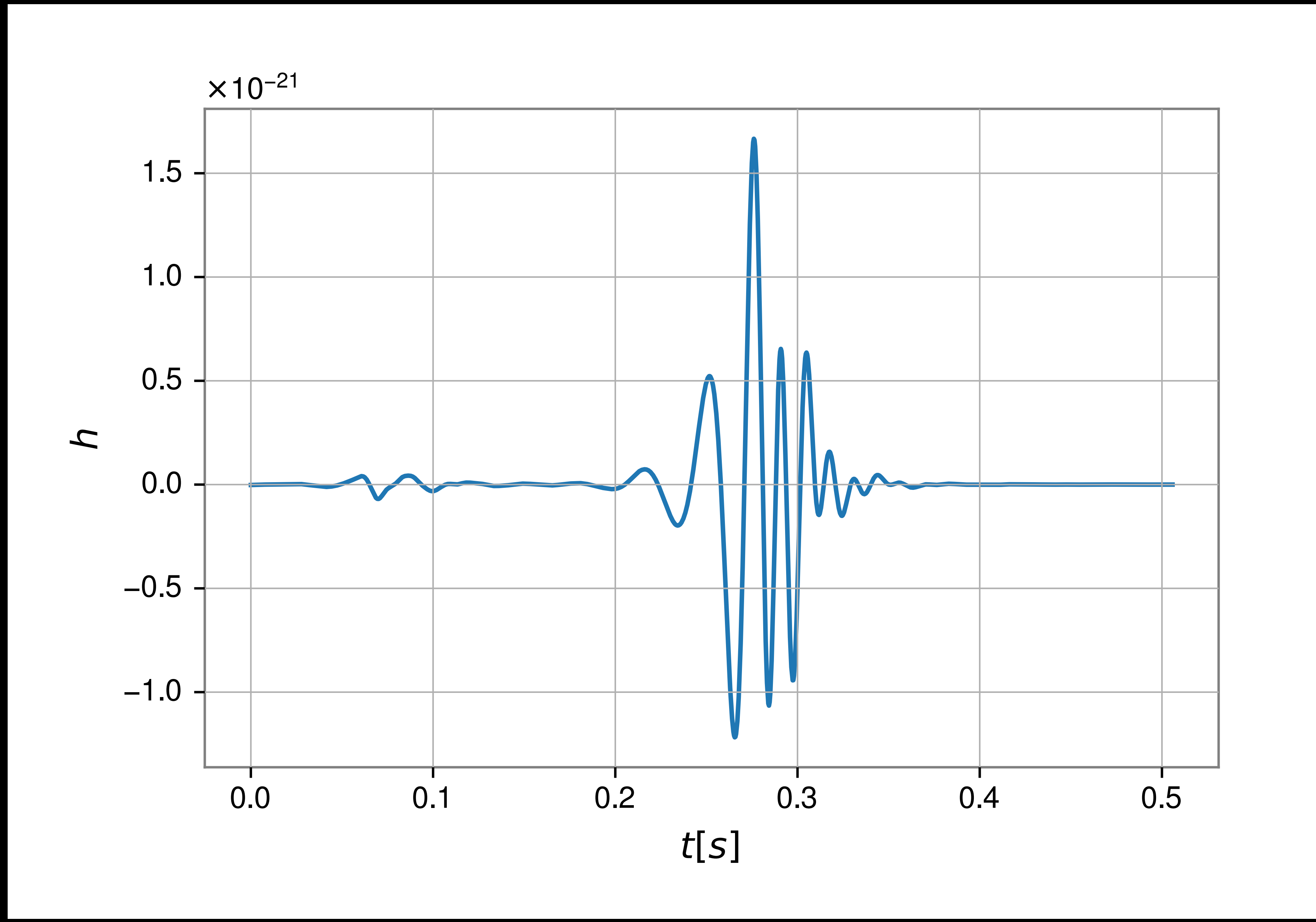


Numerical Relativity simulations extract GWs in form of $\Psi_4 = \frac{d^2h}{dt^2}$

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 Ψ_4 directly extracted from NR simulations

Compute the Ψ_4 - PSD as:

Run parameter estimation as usual

Strategy:

Perform second-order finite differencing of GW strain data

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Strategy:

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

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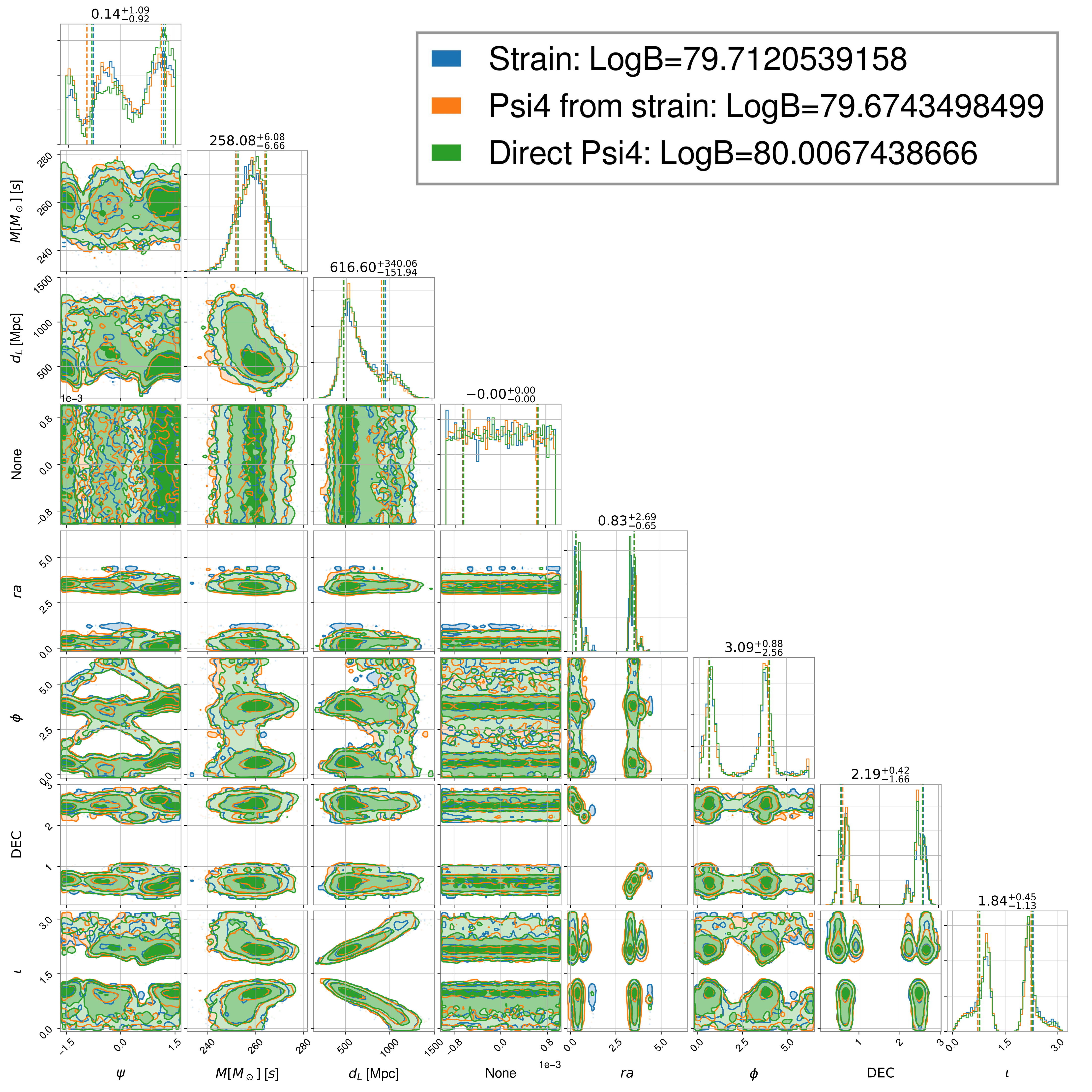
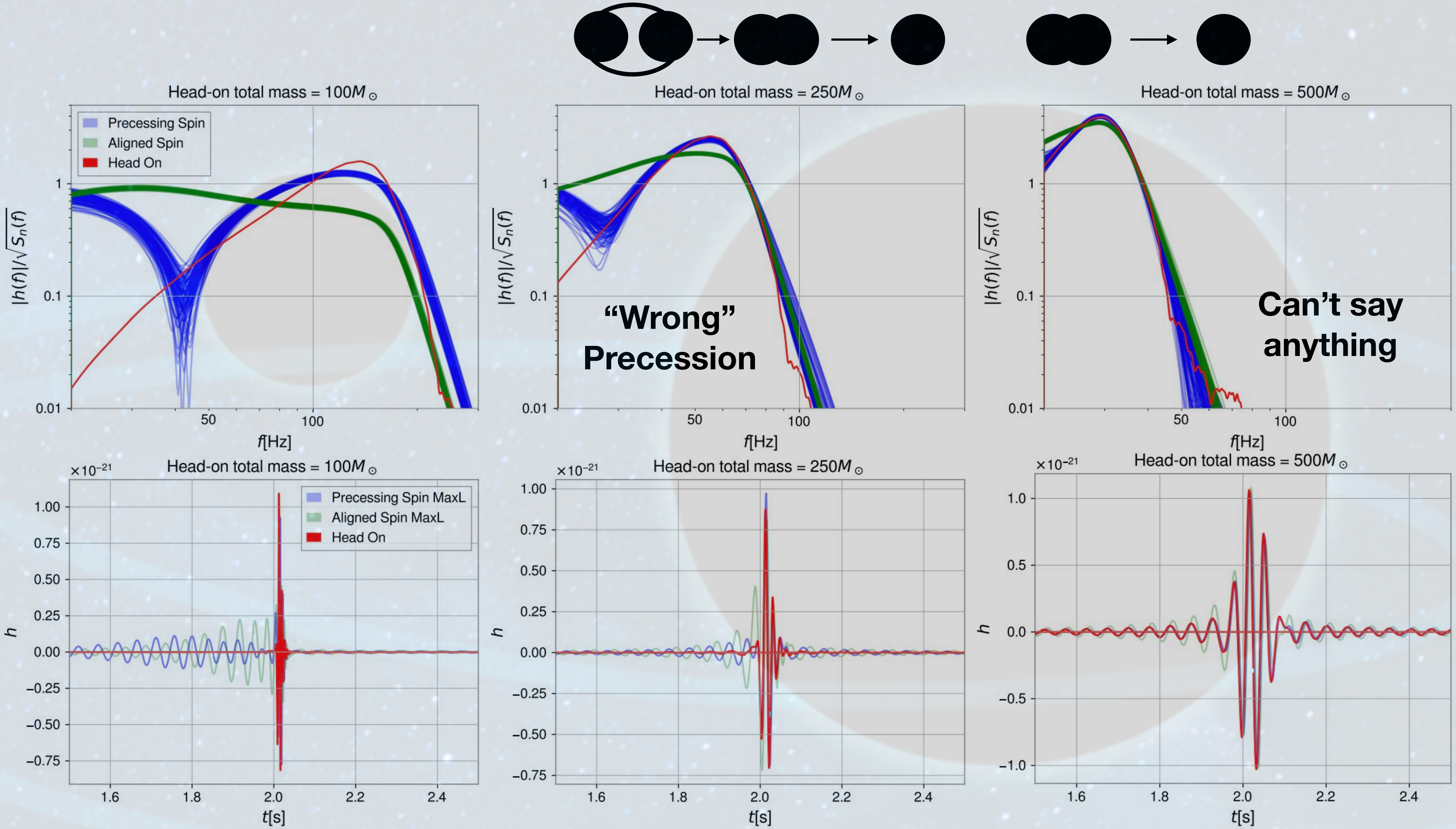


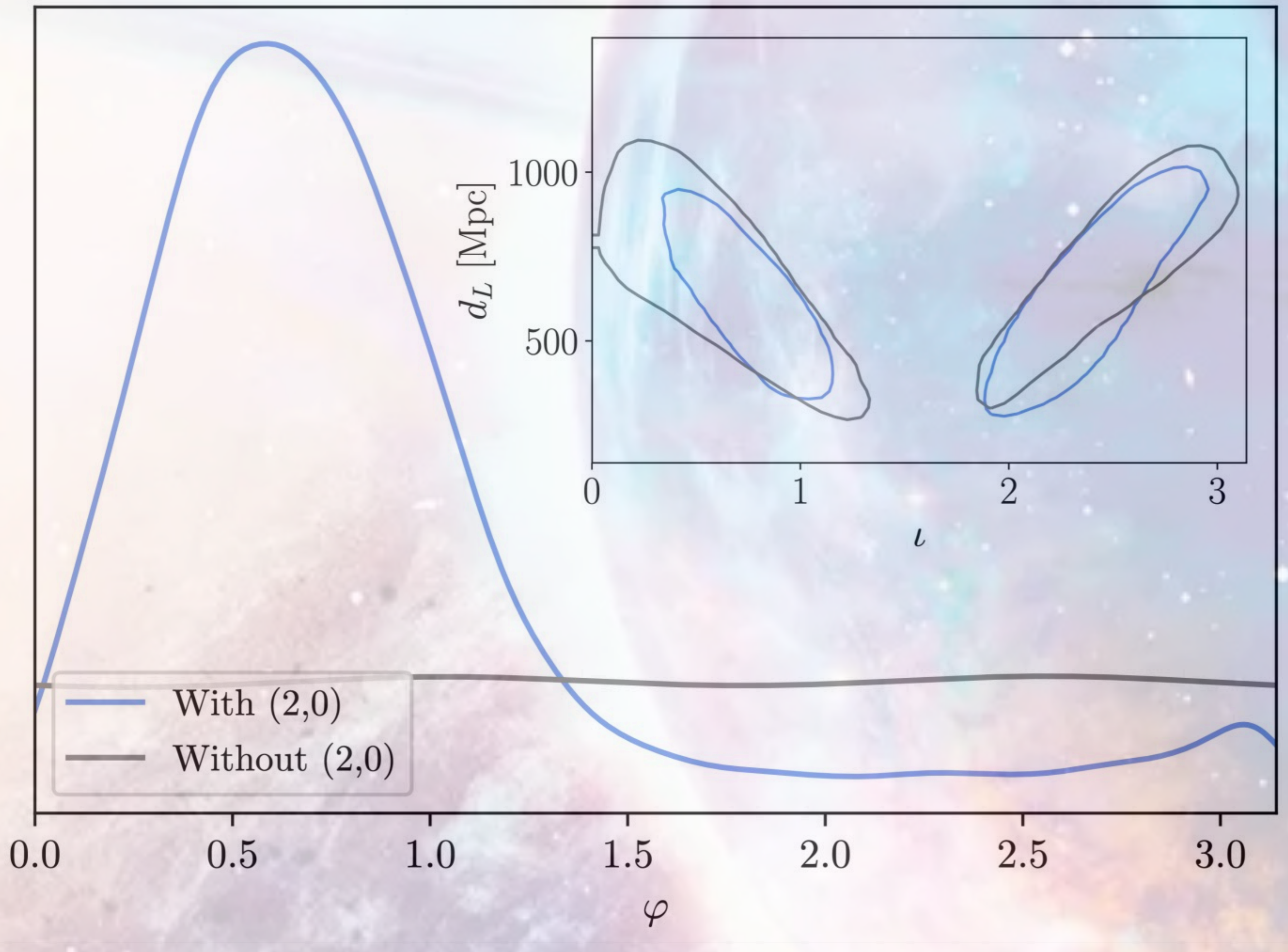
In which situations can one mistake precession by eccentricity?

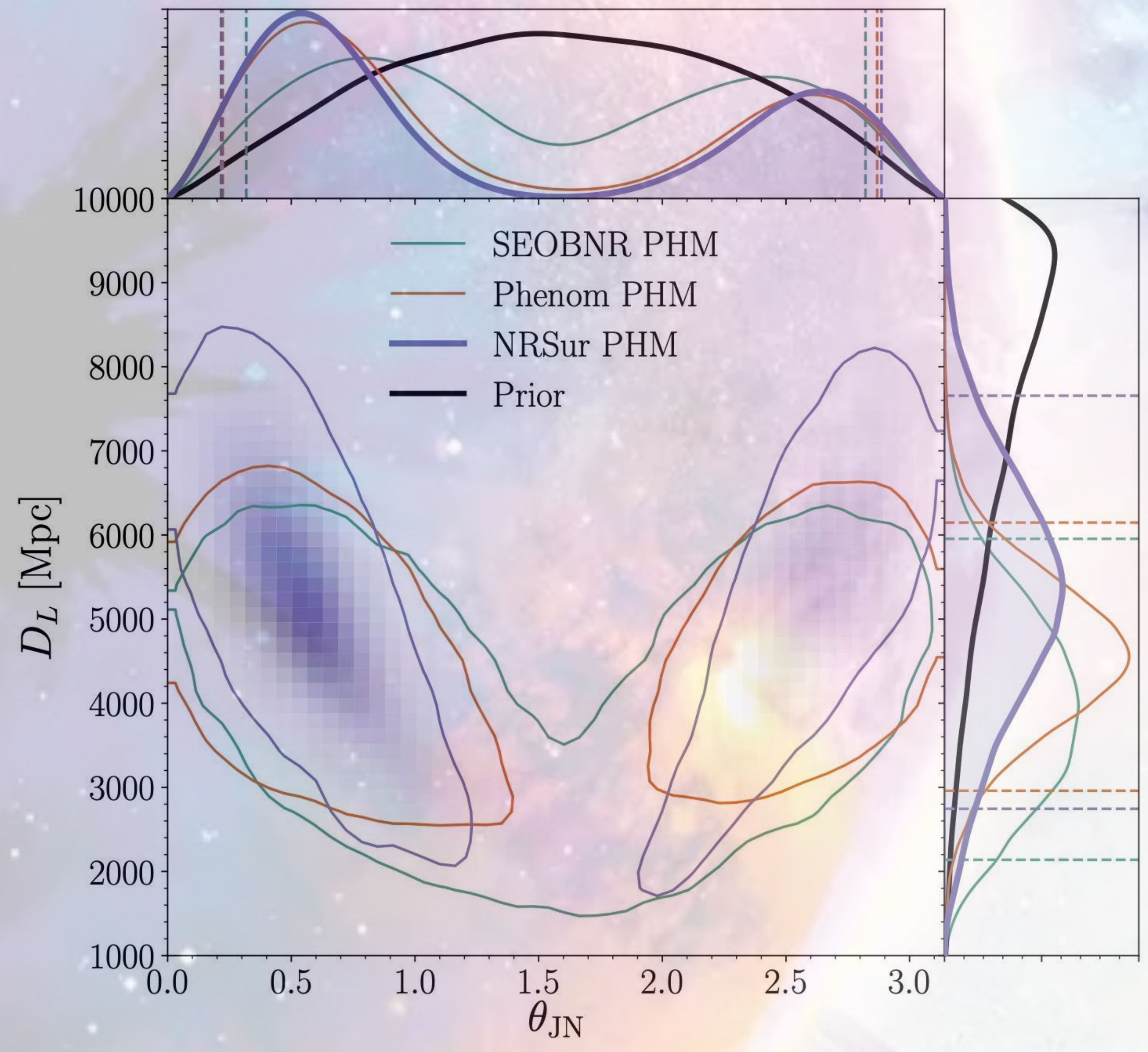


JCB, Sanchis-Gual, Torres-Forne and Font: arXiv 2009.01066 (2020), Accepted in Phys. Rev. Lett

GW190521: Proca-star parameters

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

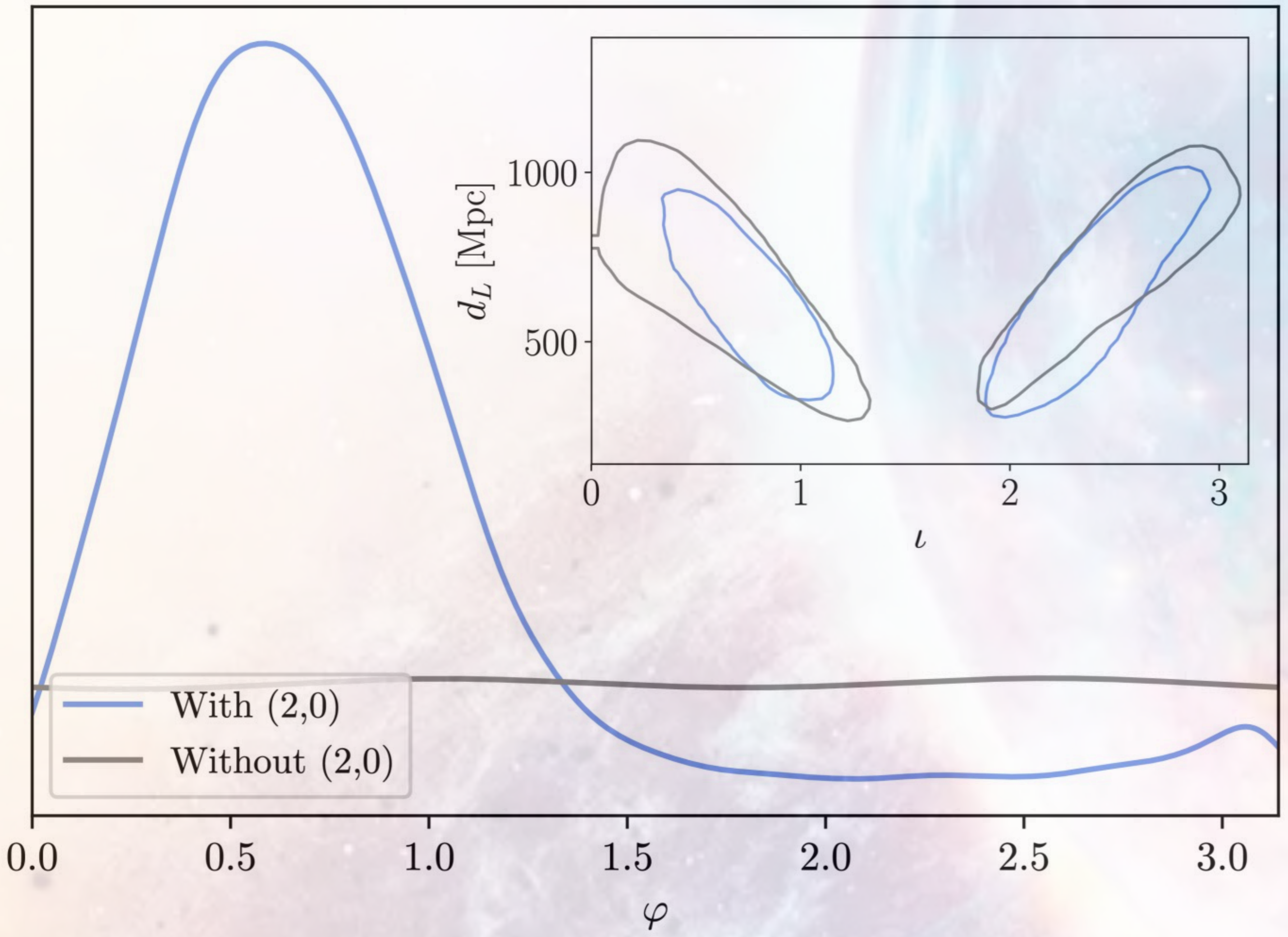




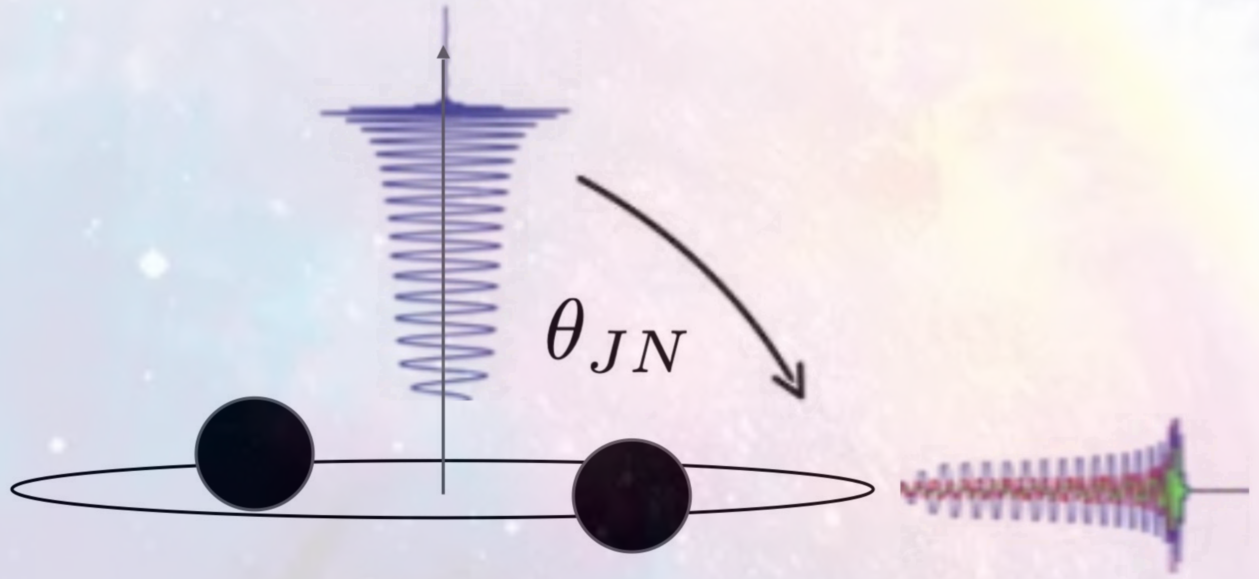
JCB, Sanchis-Gual et. al.,Phys. Rev. Lett. **126**, 081101 (2021)

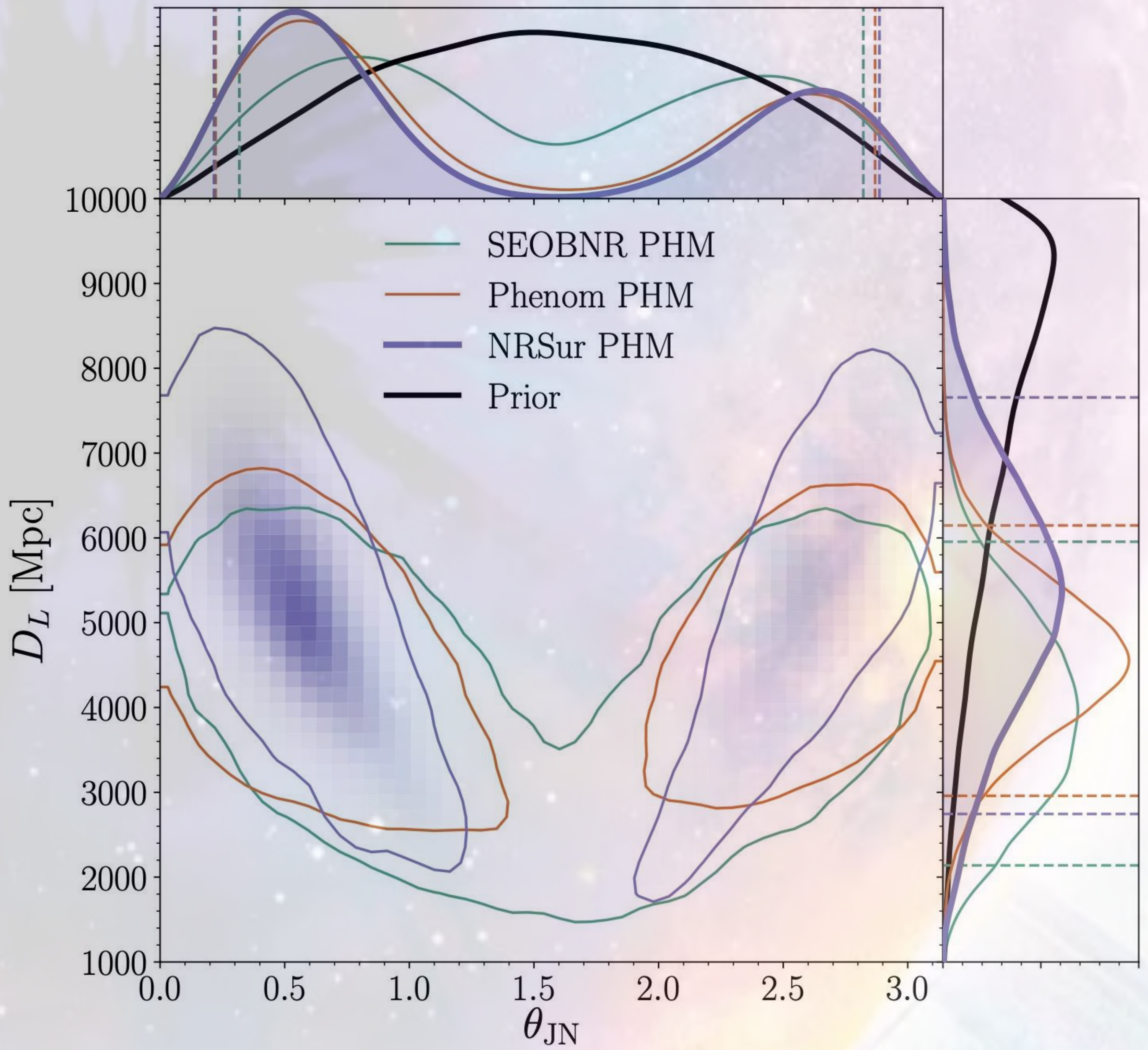
GW190521: Proca-star parameters

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



- GWs: sum of many emission modes (multipoles)

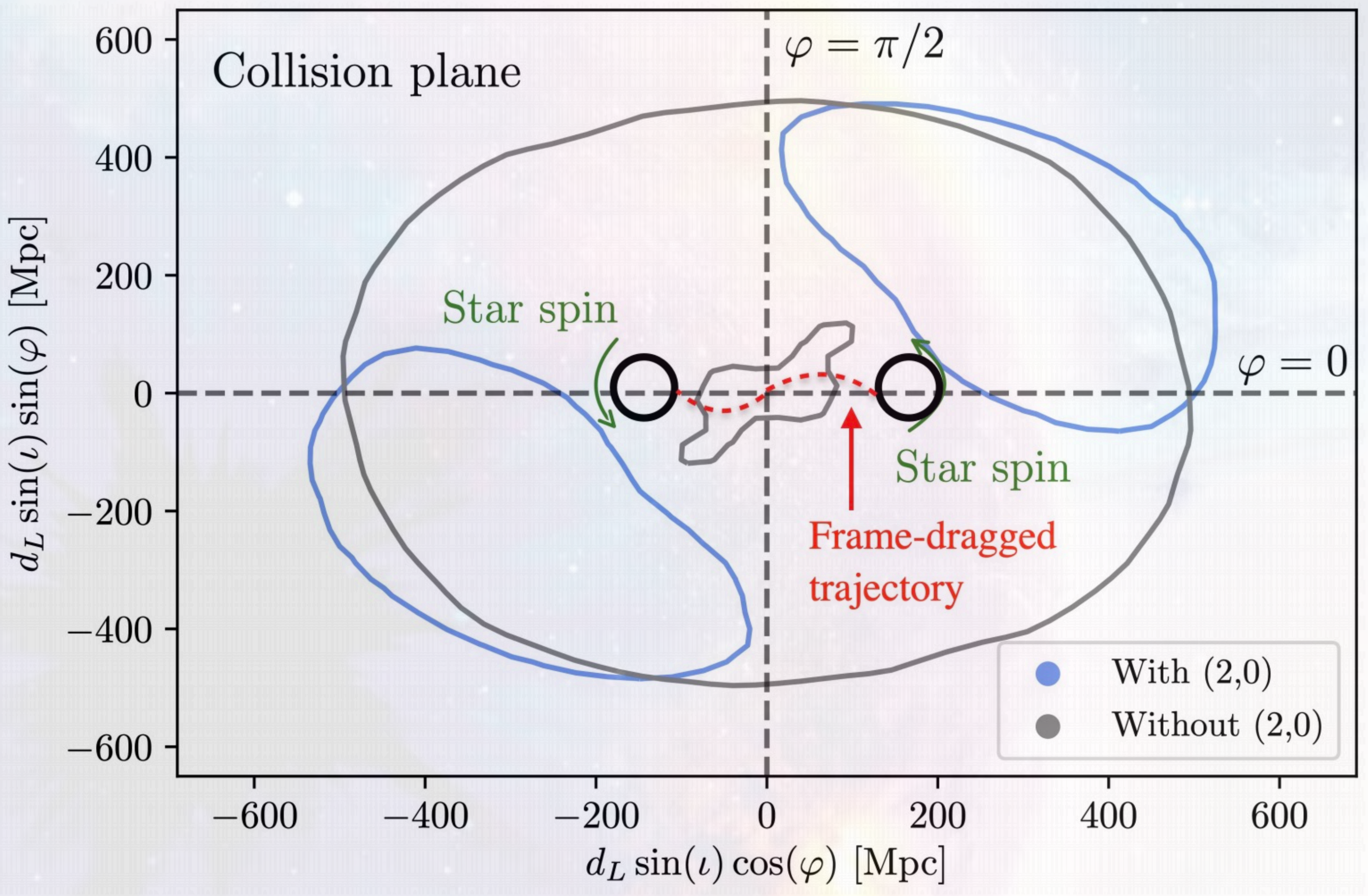




JCB, Sanchis-Gual et. al.,Phys. Rev. Lett. **126**, 081101 (2021)

GW190521: Proca-star parameters

- 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



JCB, Sanchis-Gual et. al.,Phys. Rev. Lett. **126**, 081101 (2021)

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
Head-on Unequal-mass Proca Stars	82.0	106.5
Head-on Binary Black Hole	75.9	103.2

No support for q > 2

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Precession is a necessary complication

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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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