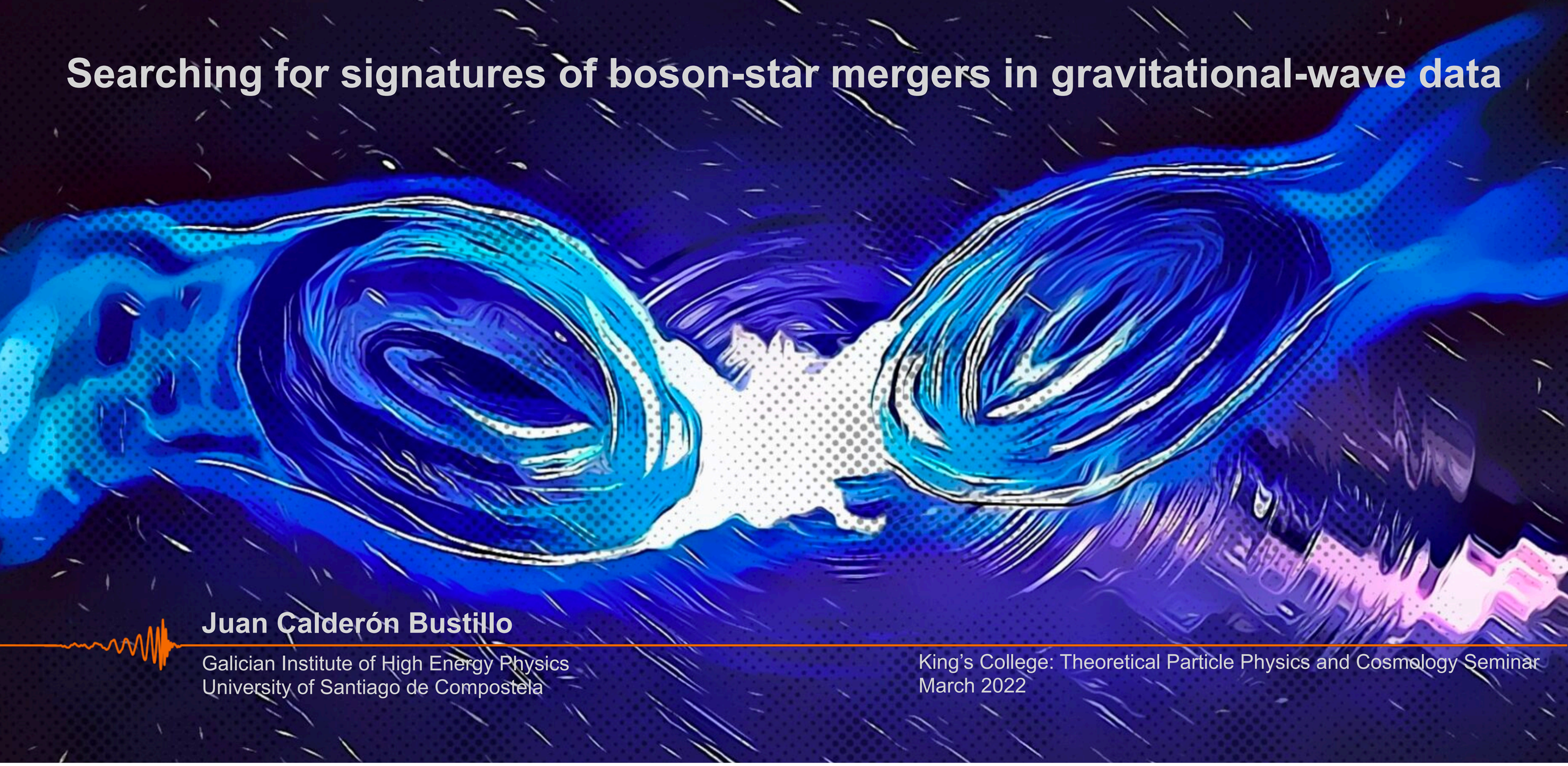
Searching for signatures of boson-star mergers in gravitational-wave data



Juan Calderón Bustillo

Galician Institute of High Energy Physics
University of Santiago de Compostela

King's College: Theoretical Particle Physics and Cosmology Seminar
March 2022

Fundació "la Caixa"

European Commission | Horizon 2020 European Union funding for Research & Innovation

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

IGFAE Instituto Galego de Física de Altas Enerxías

XUNTA DE GALICIA

EXCELENCIA MARÍA DE MAEZTU

- Parameter inference for gravitational waves
- High-mass mergers: gold mines tough to exploit
- Practical example: GW190521
- Boson-star mergers
    - GW190521 as a boson-star merger
        - … rather than a black-hole merger?
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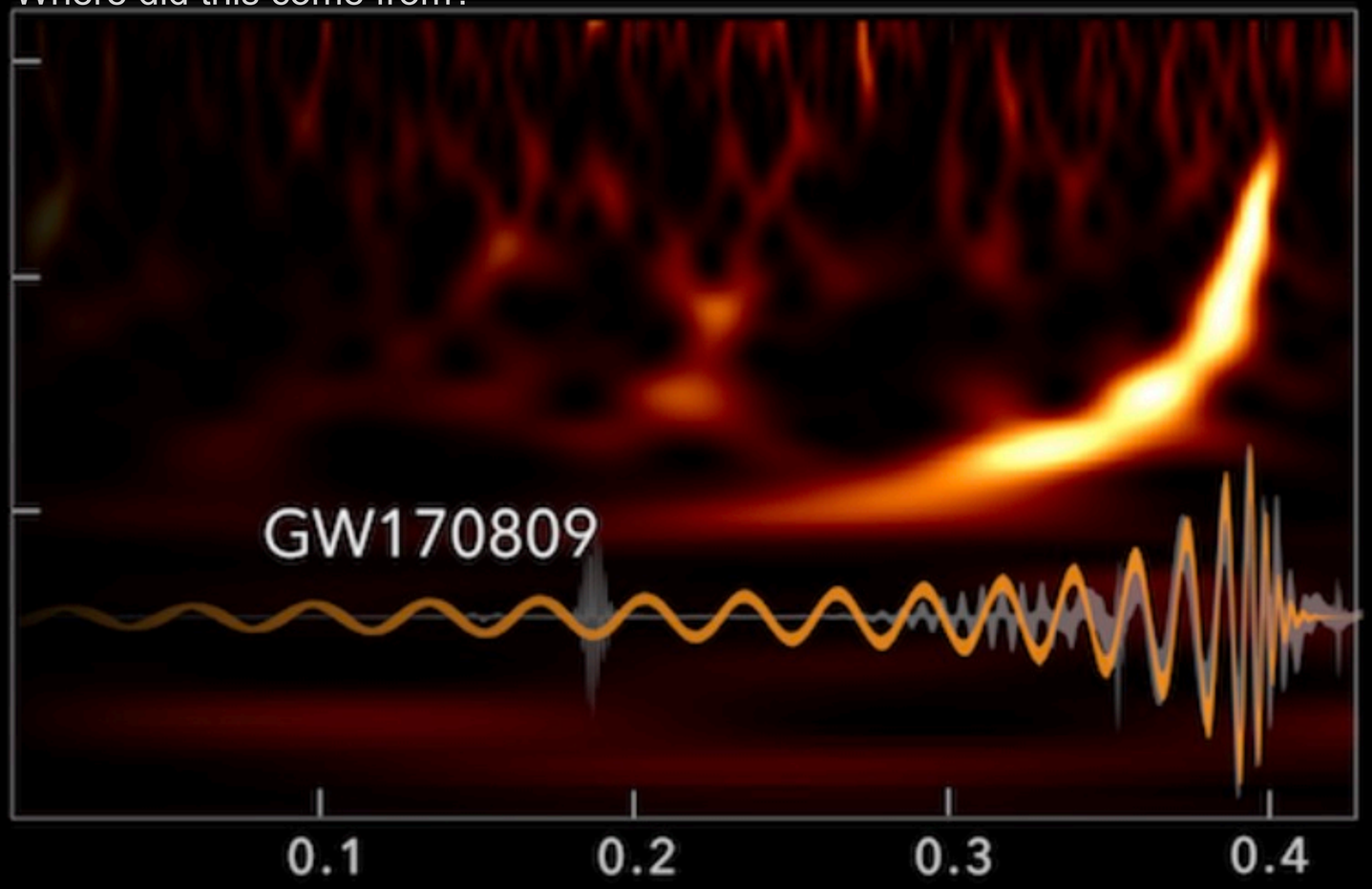
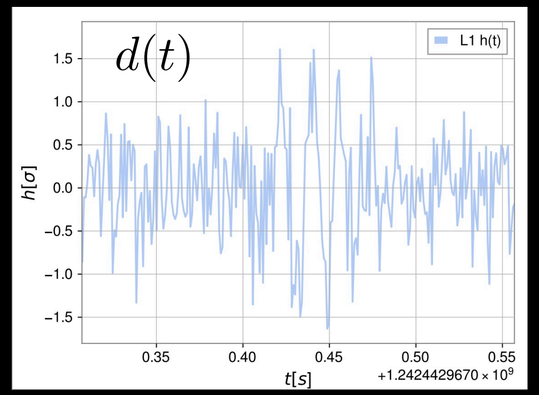
Estimating the parameters of gravitational-wave sources

Where did this come from?





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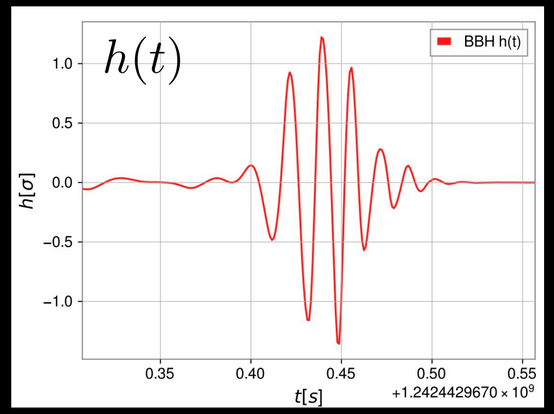
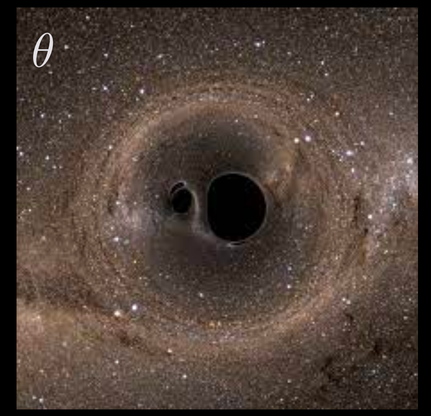


$+$

Noise

M

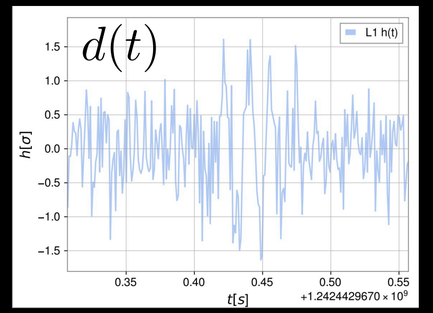


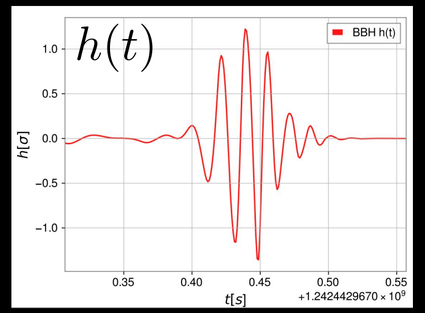
$$p(\theta|d)_M = \frac{\pi(\theta)\mathcal{L}(h_M(\theta)|d)}{Z_M(h_M(\theta)|d)}$$

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

$\pi(\theta)$: Prior Assumptions

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





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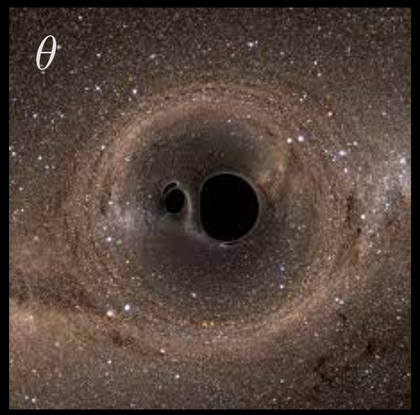

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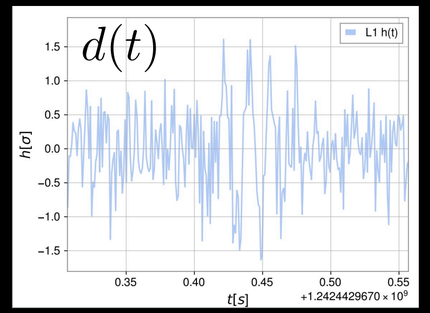

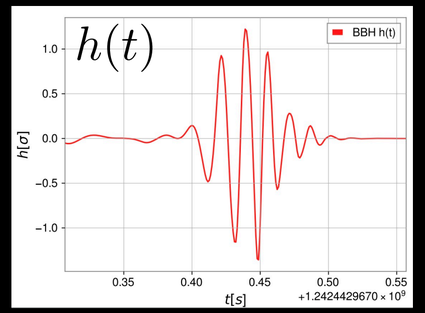

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↑: Large likelihood

↓: Useless parameters (Occam's Razor)

↑↓: Choice of priors

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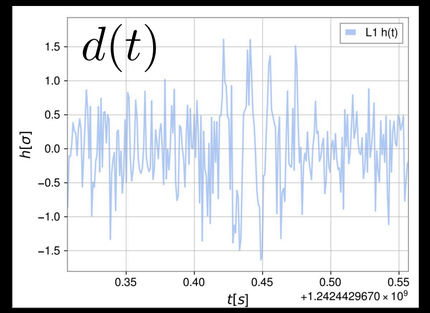

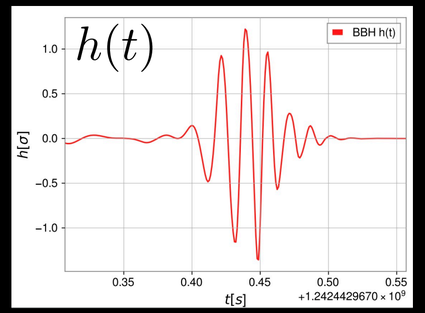

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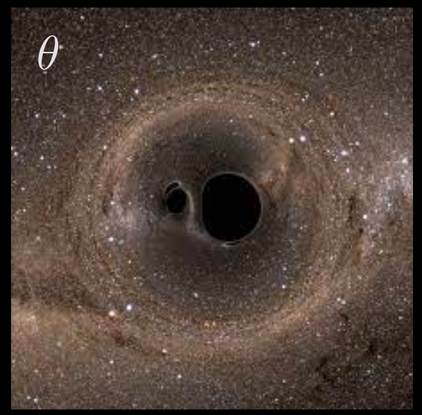


$$\frac{P(\text{Model A})}{P(\text{Model B})} = \frac{Z_A}{Z_B}$$

Many models for BBH mergers:

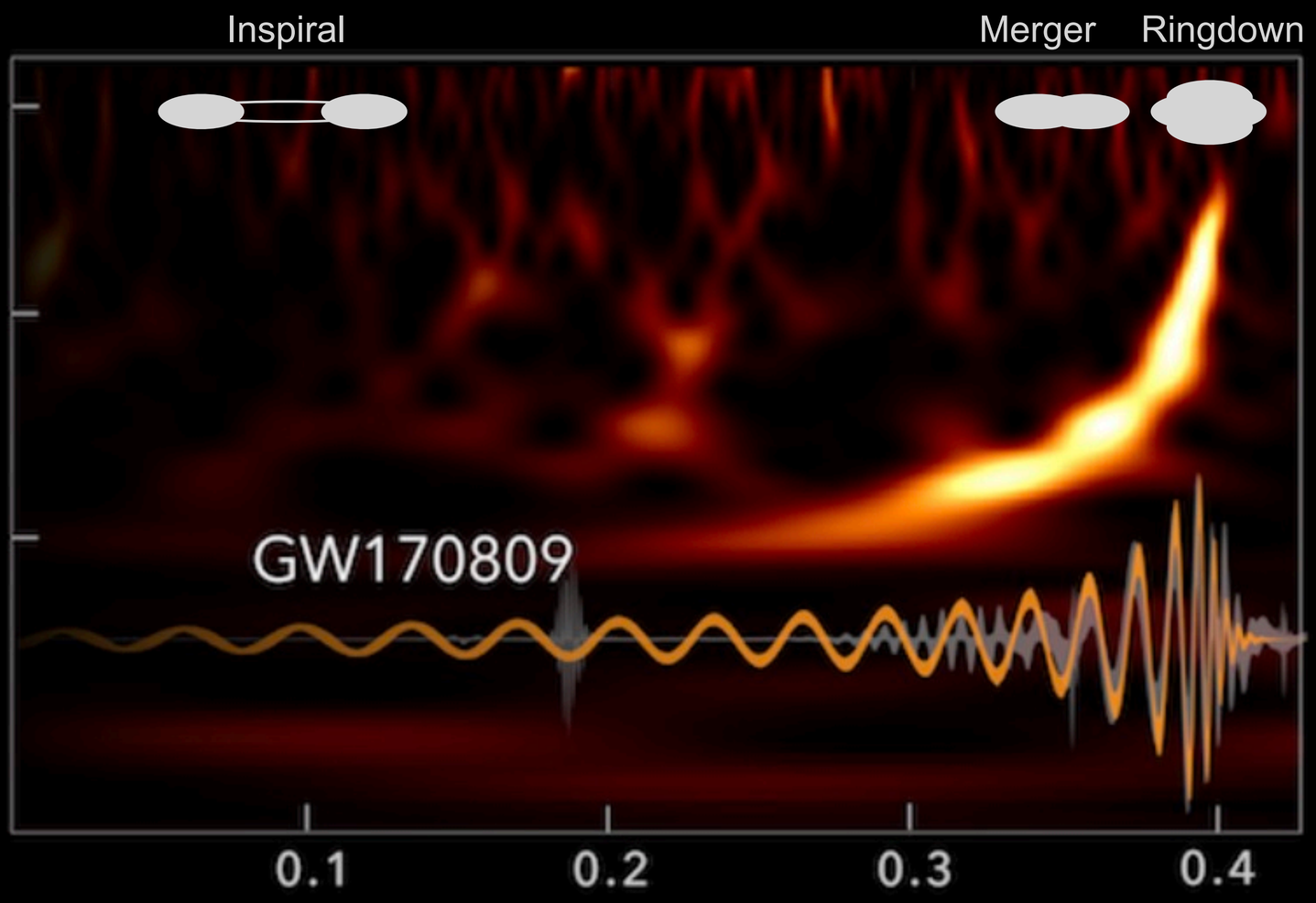
- Computed in different ways (EOB, Phenom, NRSurrogate, NR…)
- “Calibrated” to different regions of the parameter space
- Include different levels of refinement: Higher-harmonics, Memory, calibration to numerical relativity…

Models for different “types” of BBHs:

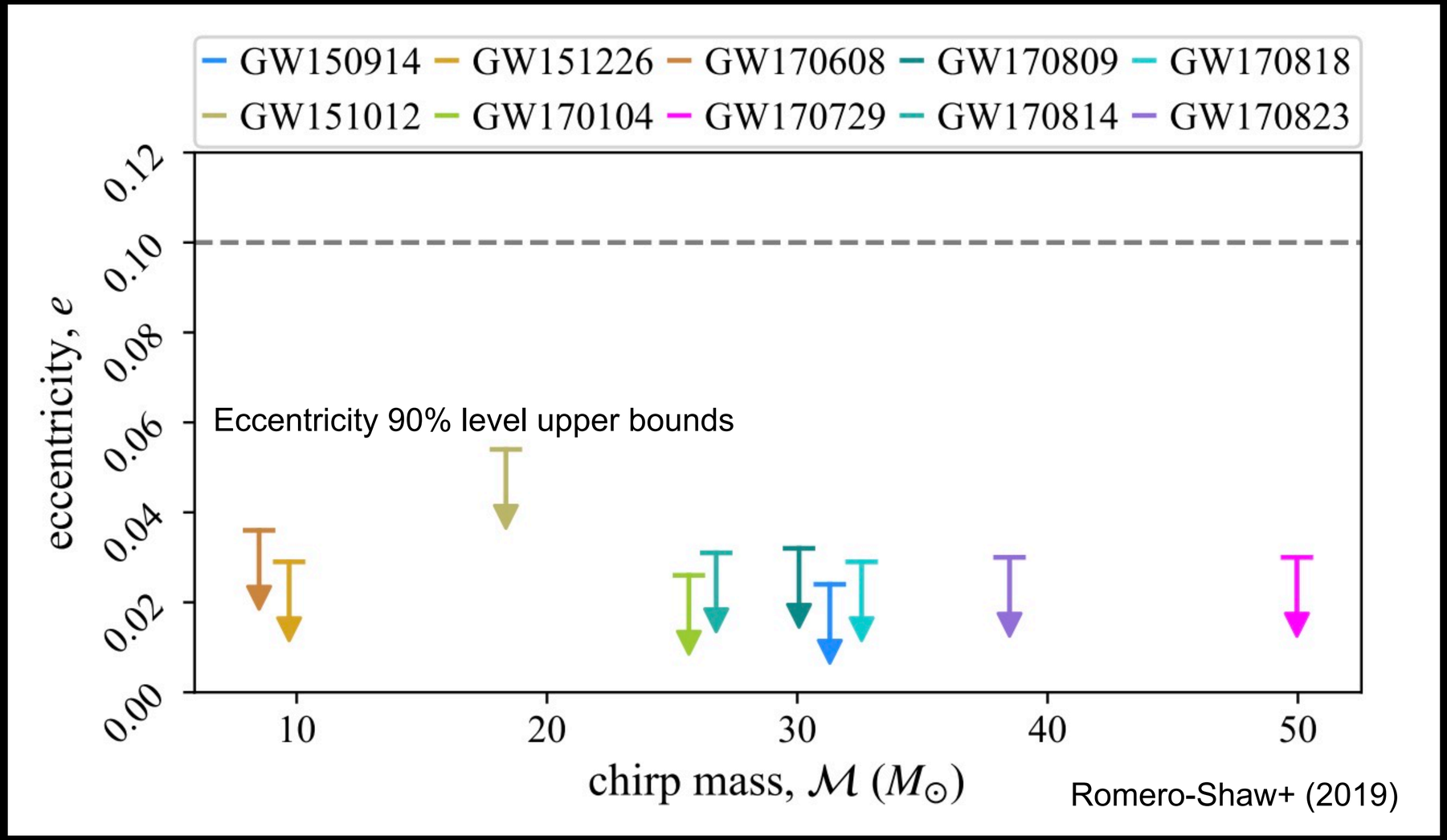
- Quasi-circular binaries
- Eccentric binaries
- Dynamical captures

And even different types of CBCs:

- Boson-star mergers
- BBHs + scalar fields



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



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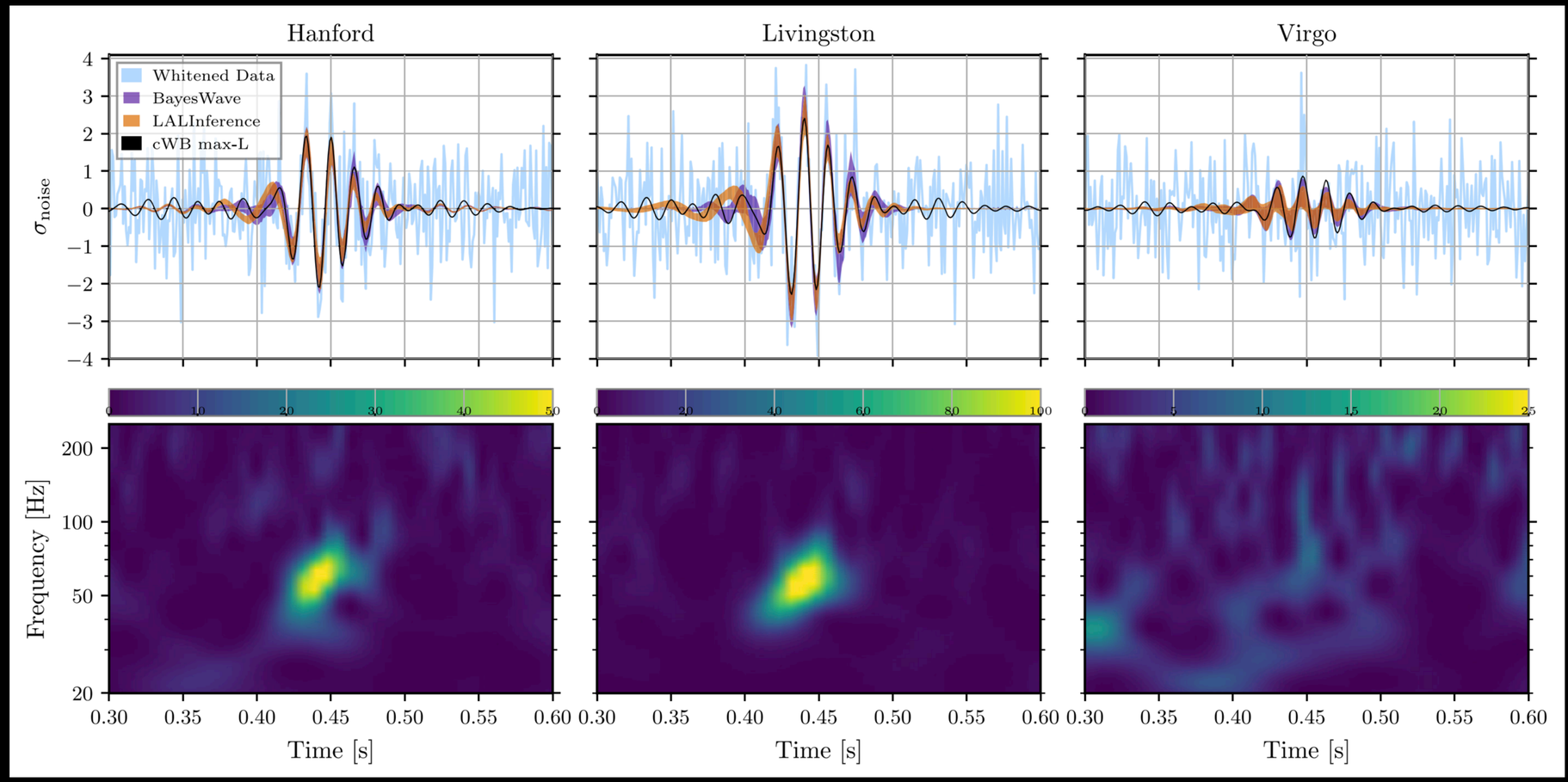
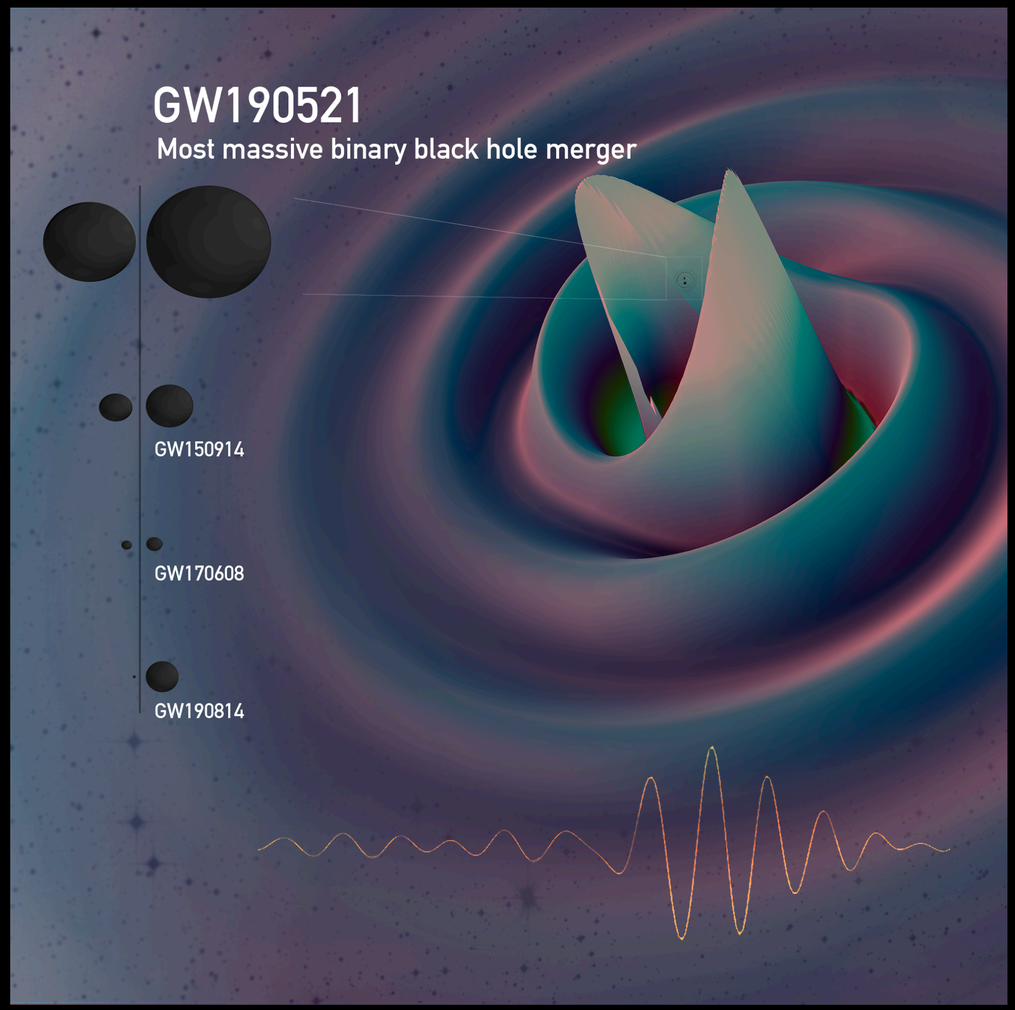
High-mass mergers



May 21st 2019

LIGO-Virgo (LVC) 2020

- Pros:
  - Strong-field gravity at its best
  - Higher GW harmonics: Varma+14,17, JCB+16,17, Pekowski+13,Graff+15
  - Tests of General Relativity e.g., No-Hair Theorem: Isi+19, Giesler+19, JCB+21, Capano+21, Carullo+19
  - Strong-field phenomena: kicks, memory, lensing.. Varma+20, JCB+18, Huebner+20 …



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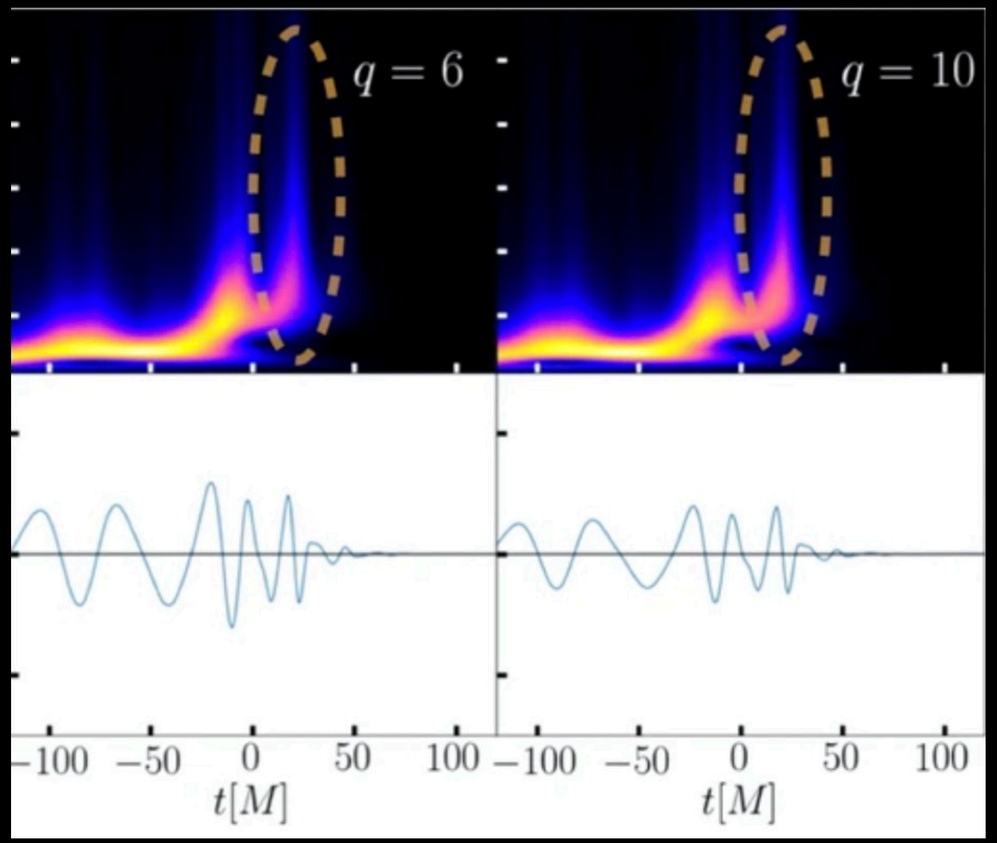

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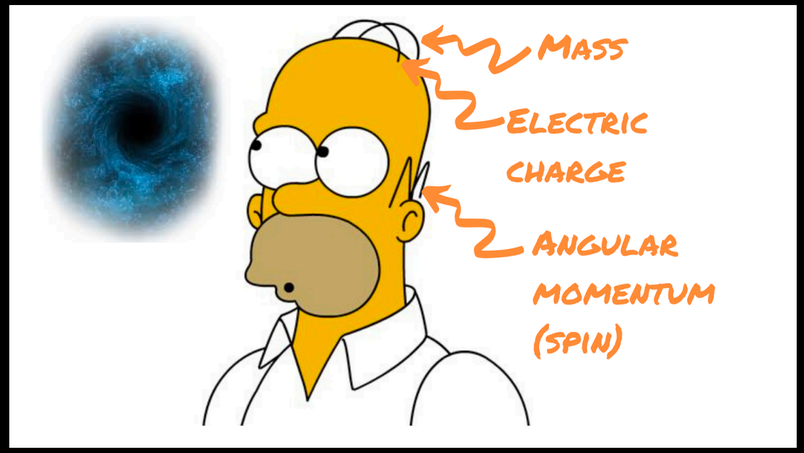

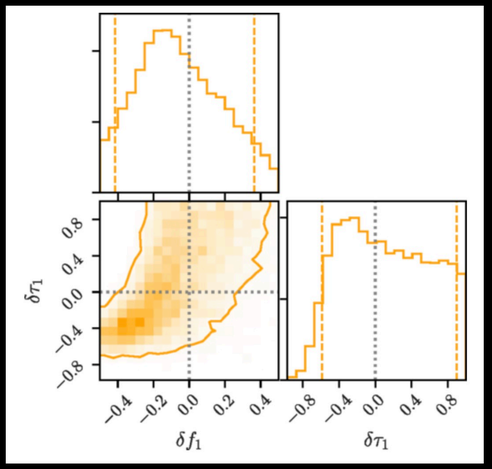

Isi+ 2019

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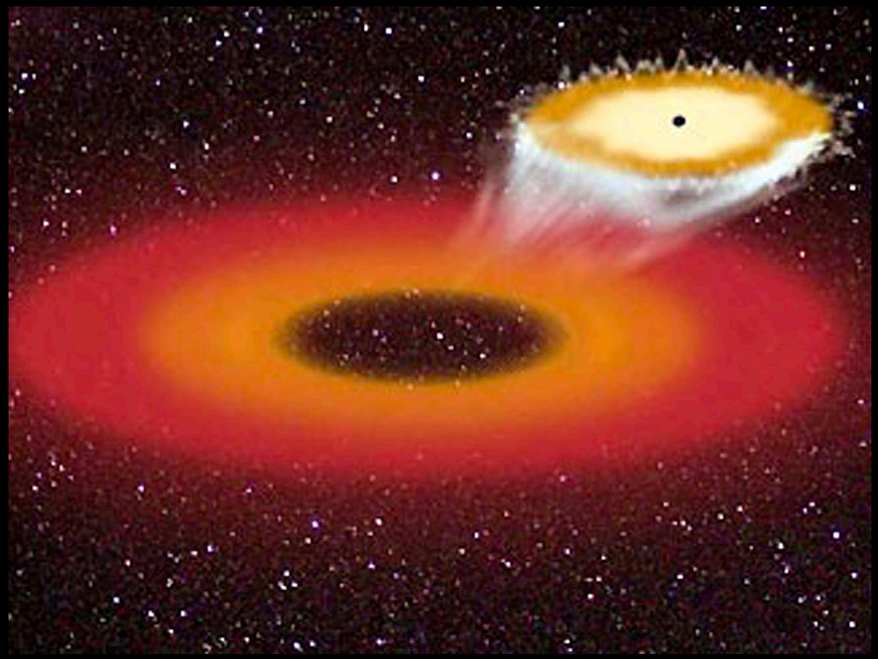

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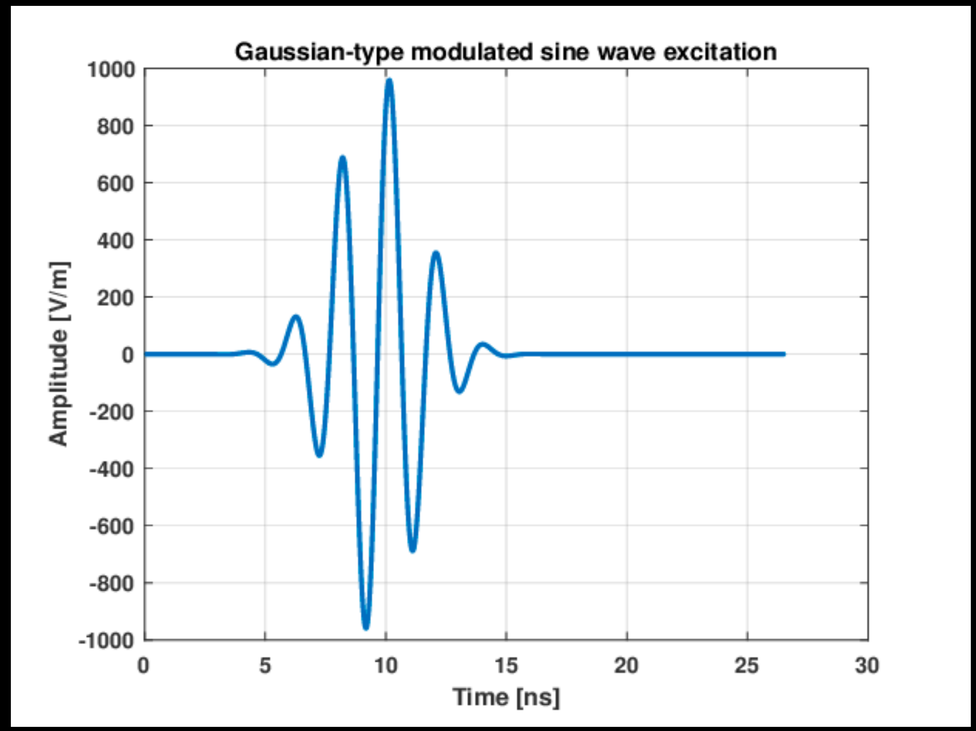
  - Involve objects in the PISN gap Woosley & Heger +21, DiCarlo+20..
  - Search for ultralight-boson effects: Chung+21, Baumann+19, Ng+20 …

- Con 1: Detection
  - Short signals: confused with glitches
  - Strong higher harmonics: not targeted by searches
    - Ongoing searches including higher modes
    - Non-modelled searches
- Con 2: Interpretation
  - Little information on pre-merger
  - Waveform models not fully reliable
  - Results strongly influenced by priors



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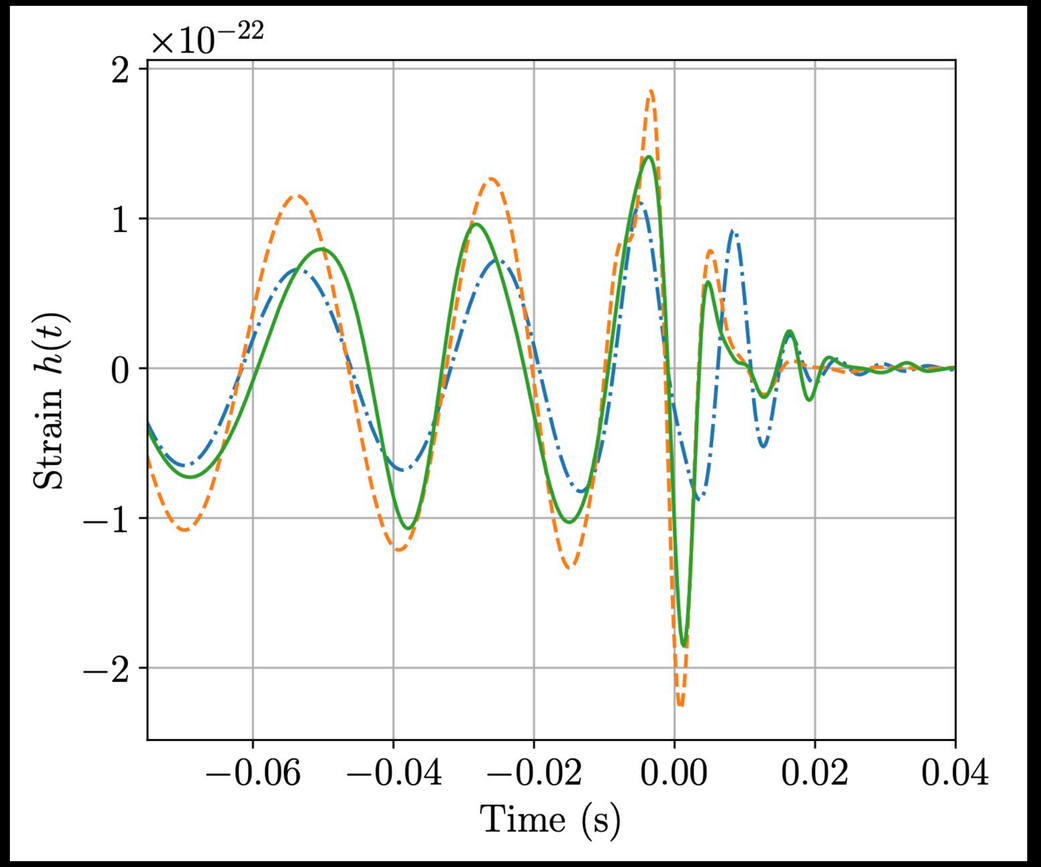

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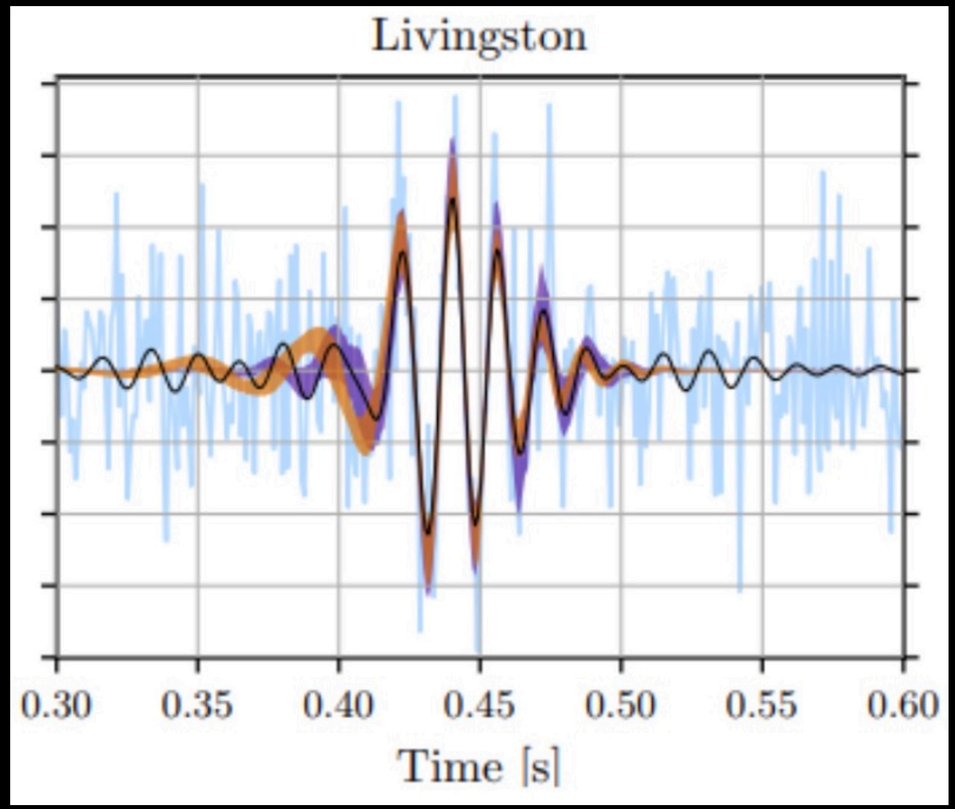
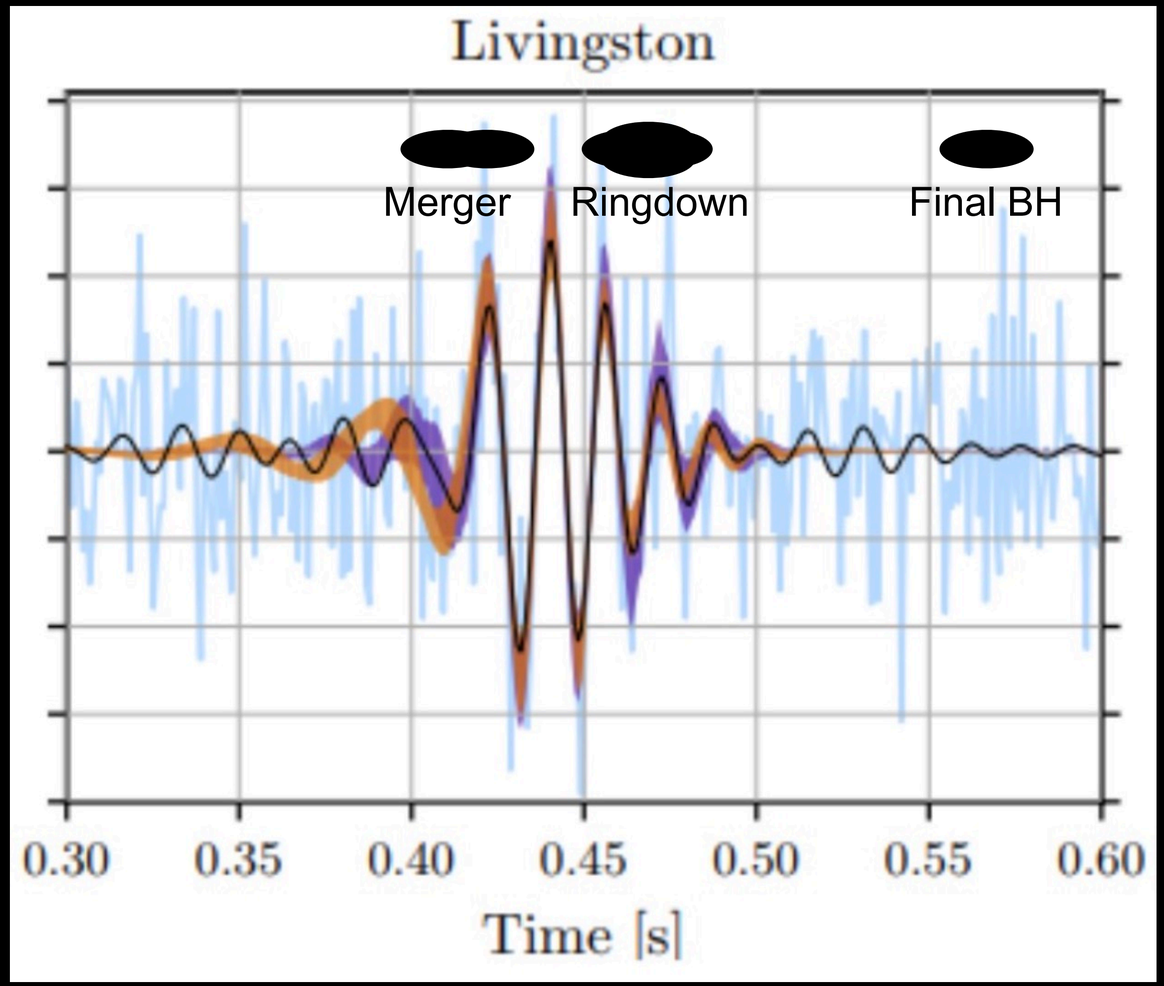


GW190521: “Canonical interpretations”

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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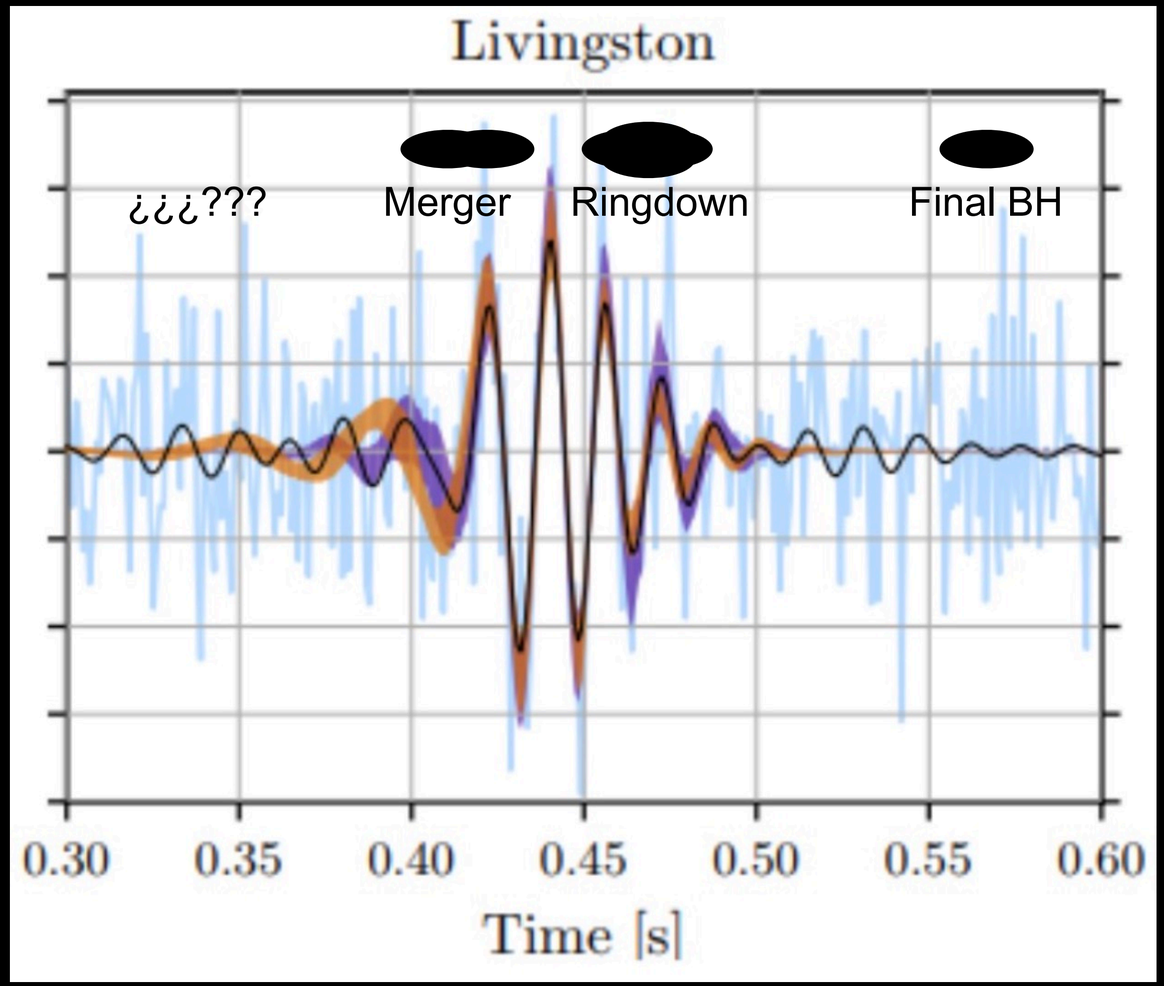

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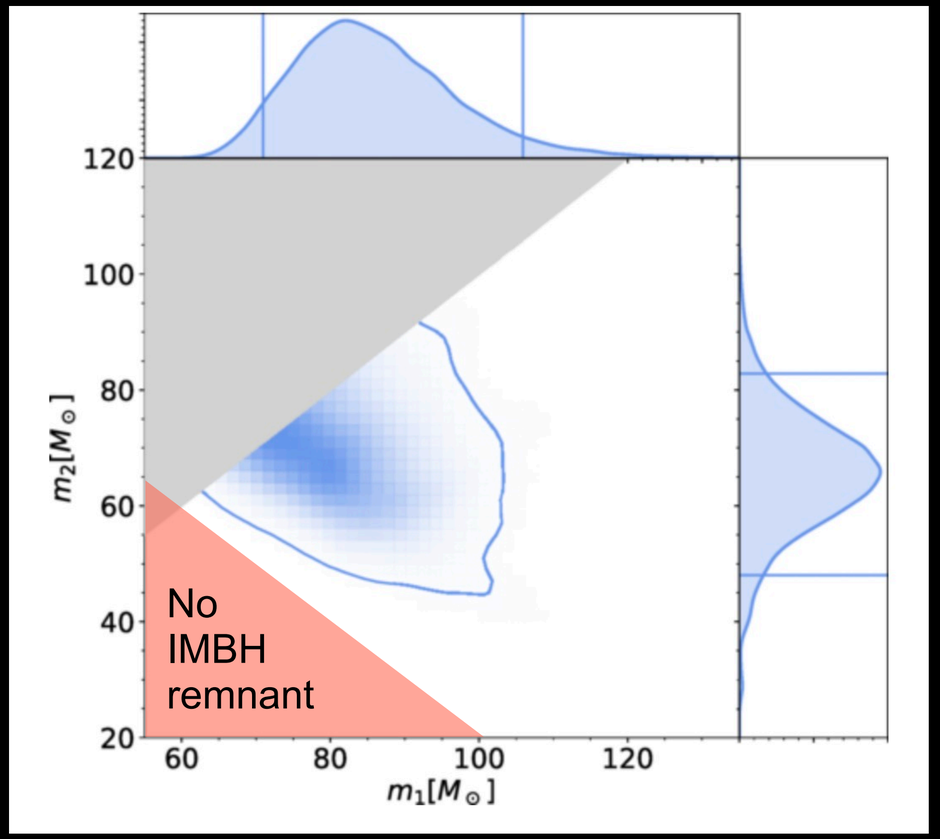

LVC 2020
Waveform Model NRSur7dq4 (Varma+ ’19)

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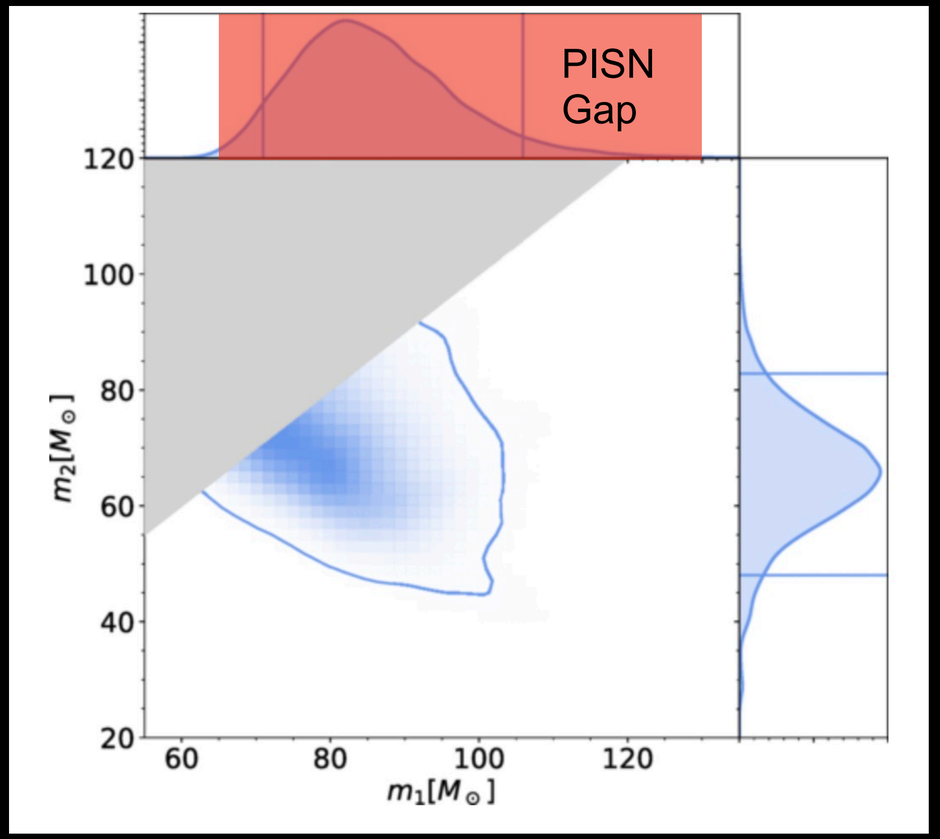

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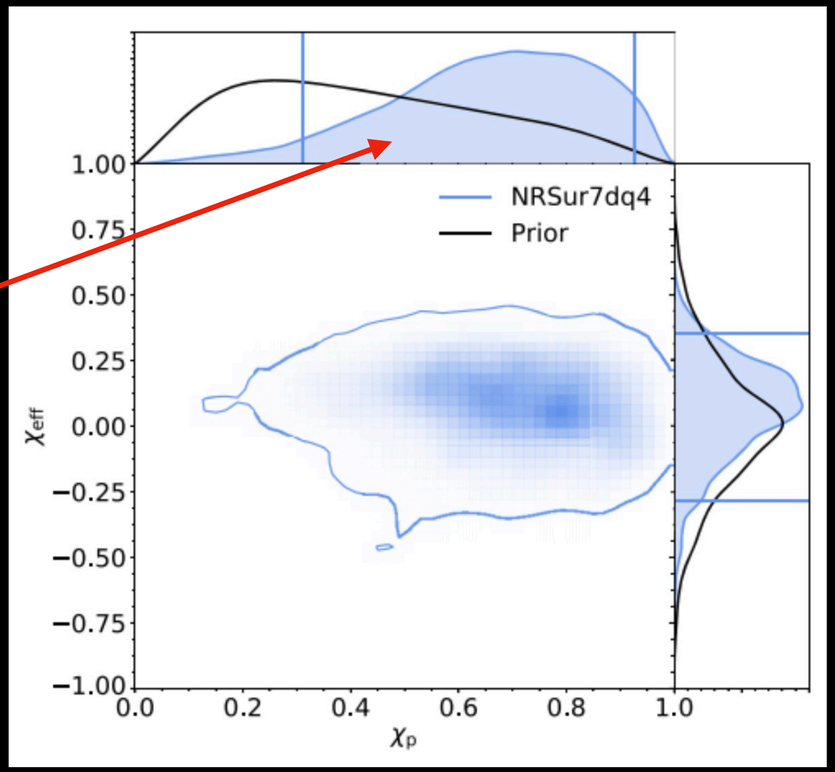

$P(\text{precession}|\text{qBBH})$ 10 : 1

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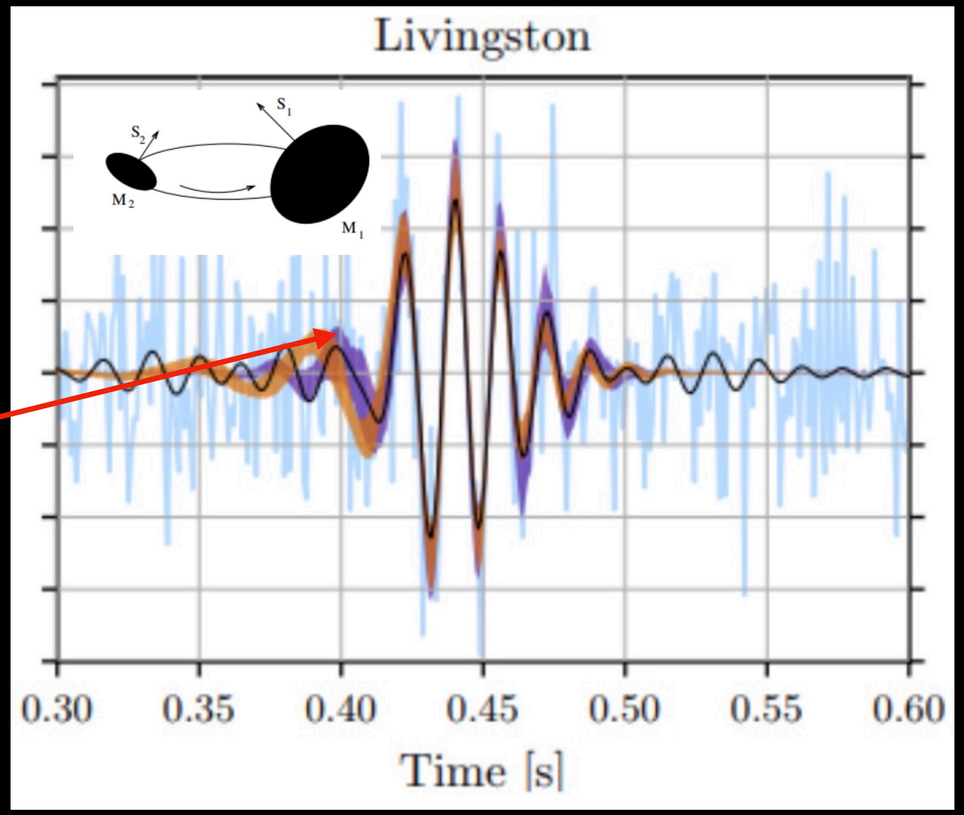

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Extremely detailed study: Estellés et. al. 2021

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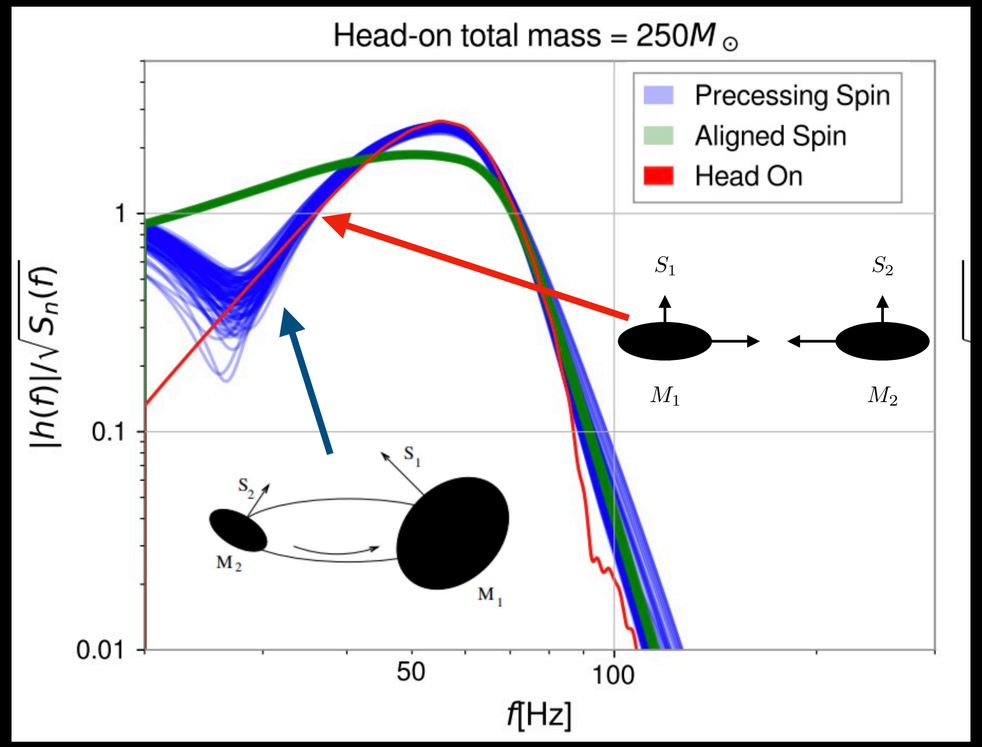
- But: Precession can mimic eccentricity!



JCB+ Phys. Rev. Lett. 126, 201101 (2021)

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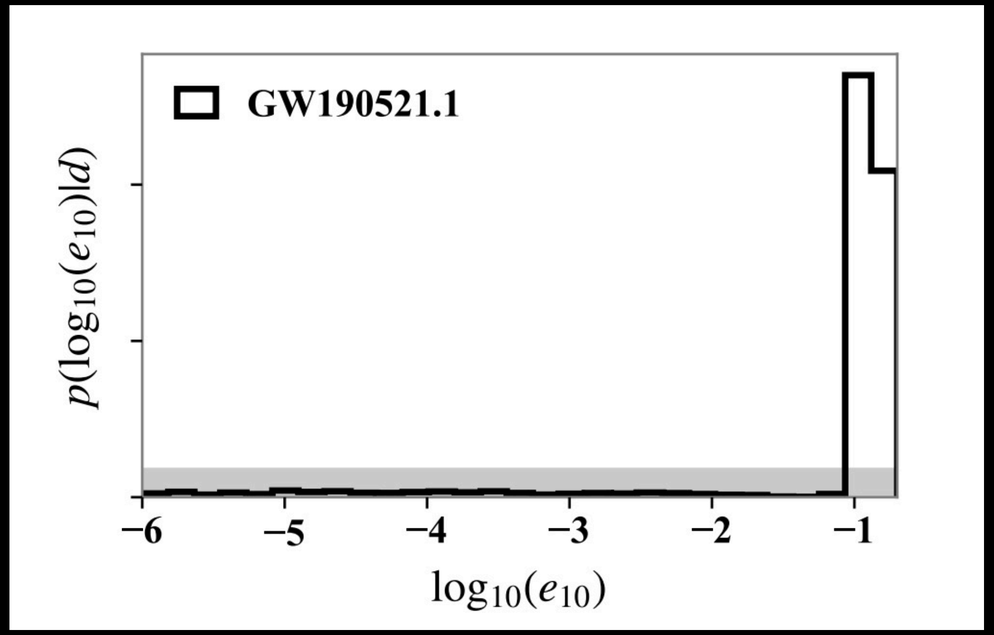

Romero-Shaw+ APjL 901, 1 (2020)

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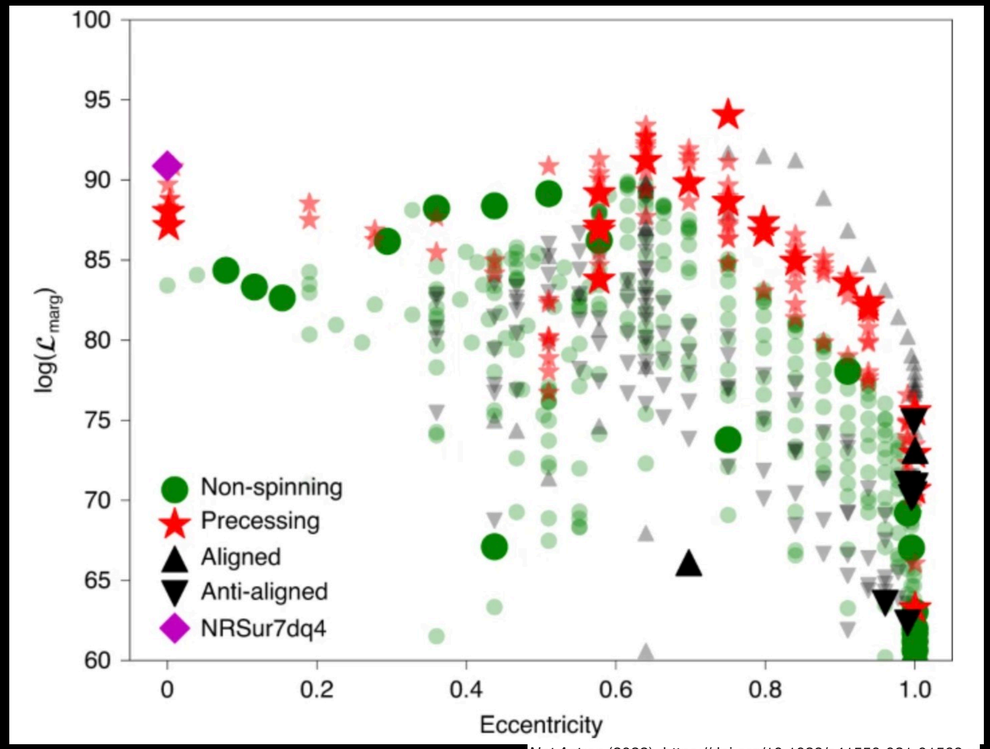

Nat Astron (2022). https://doi.org/10.1038/s41550-021-01568-w

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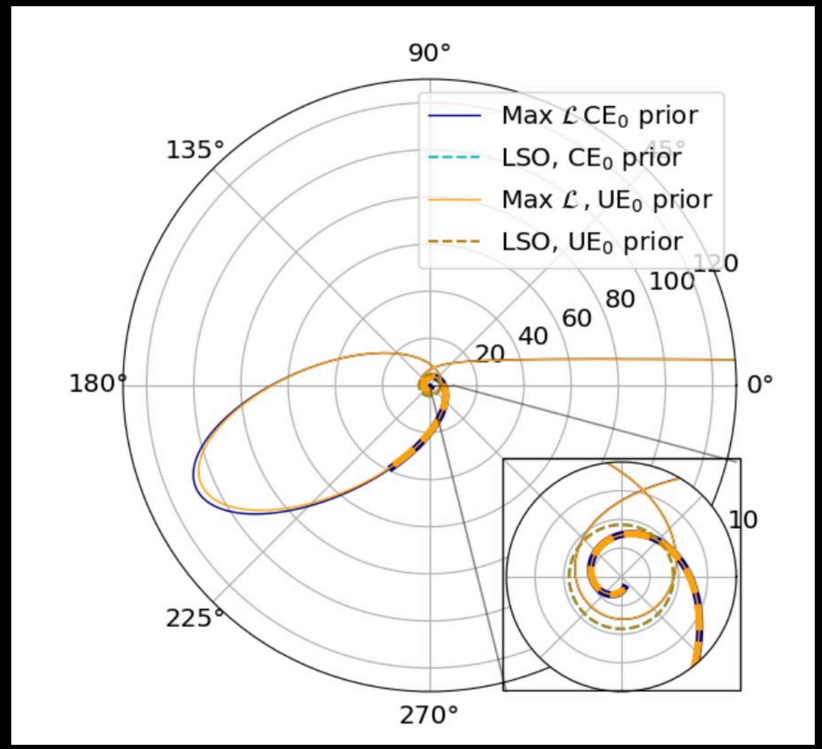

Gamba arXiv:2106.05575 (2021)

See also: Gamba et al (dynamical capture)

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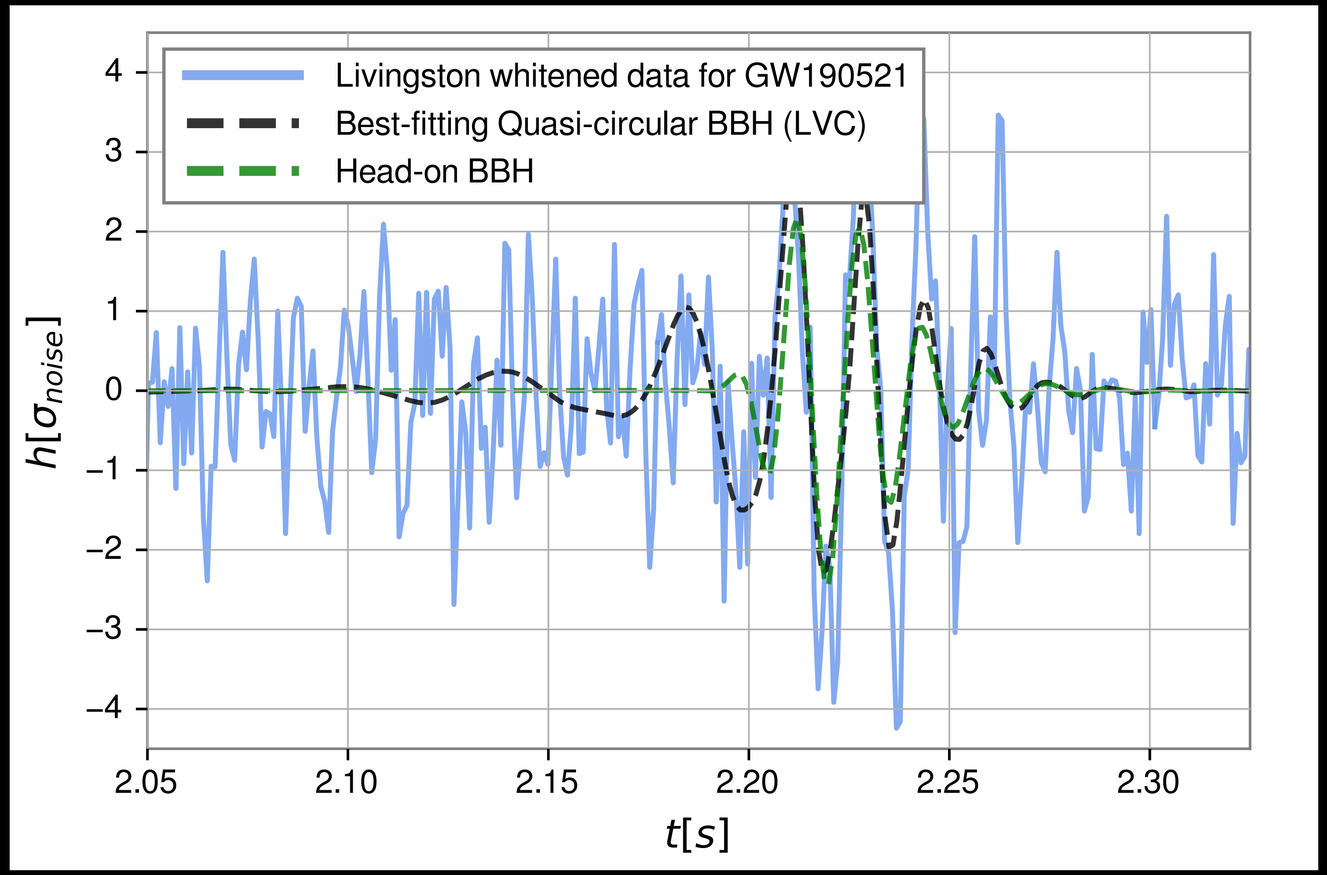

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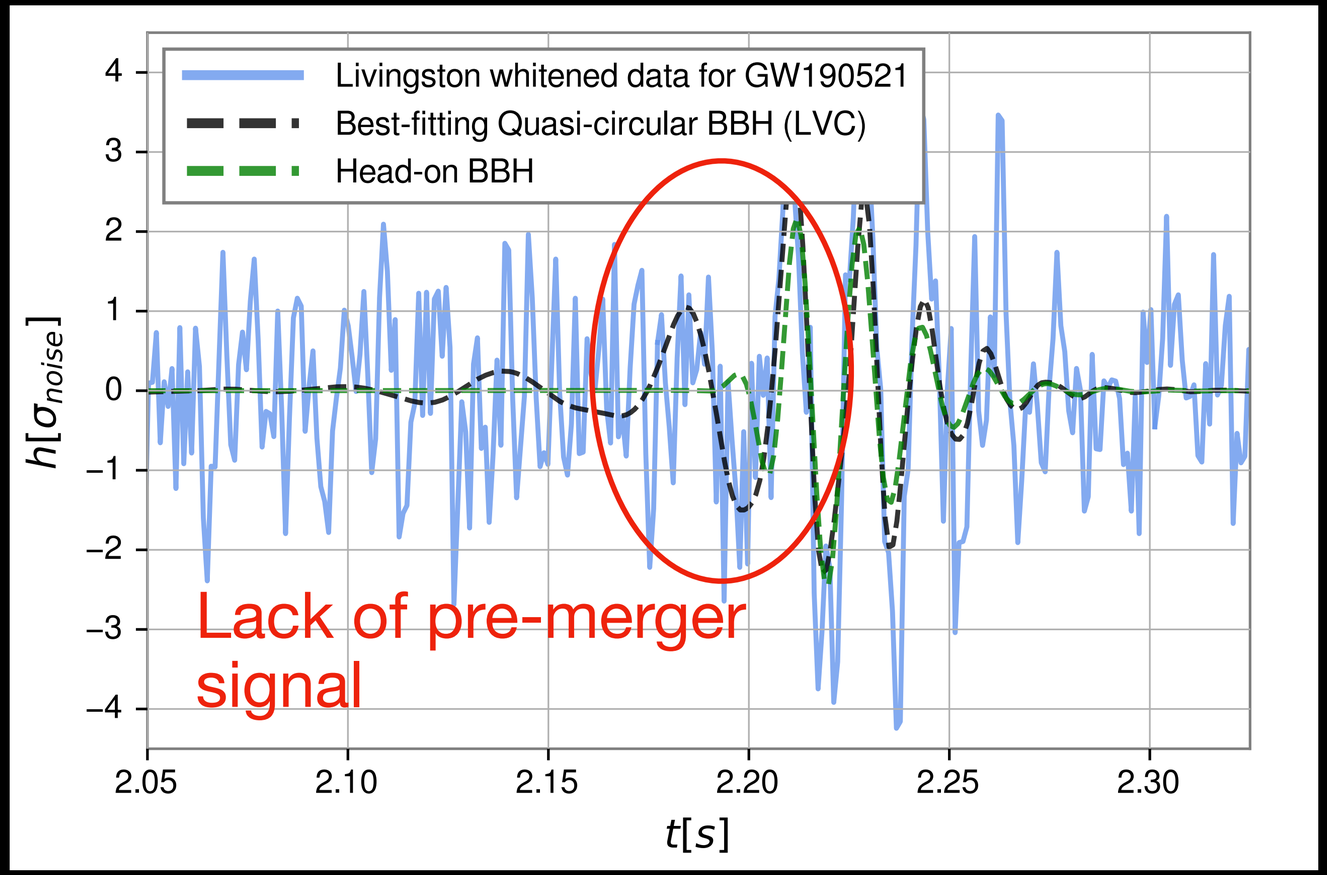
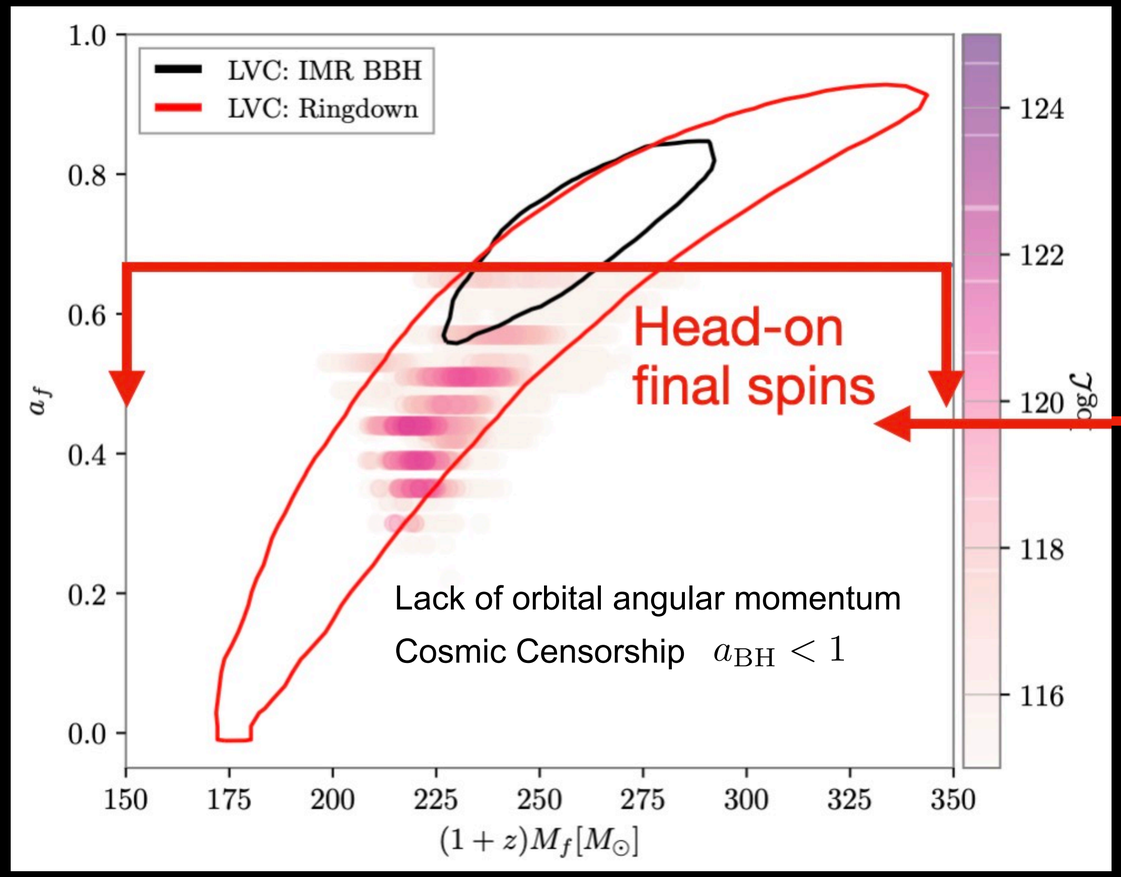
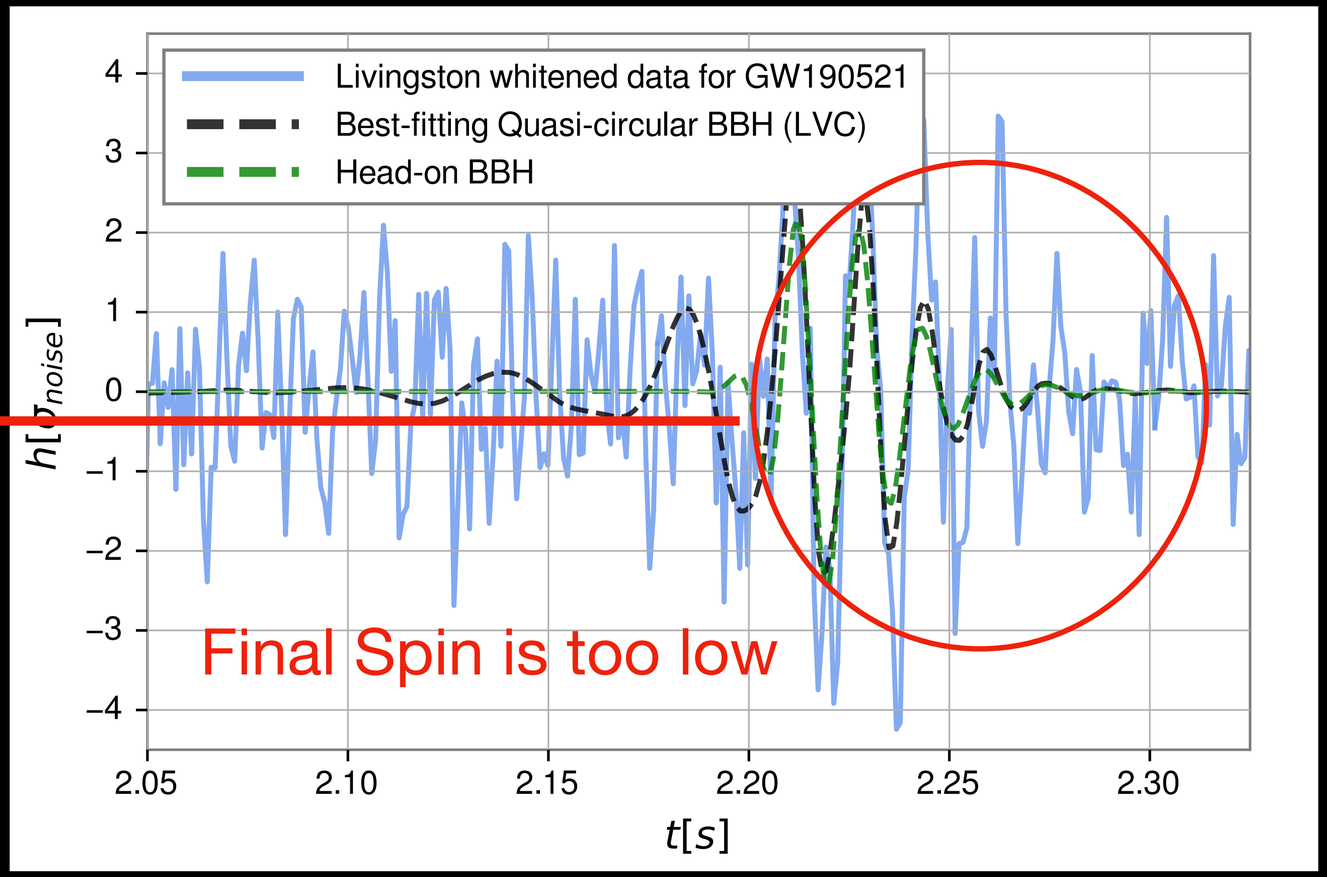
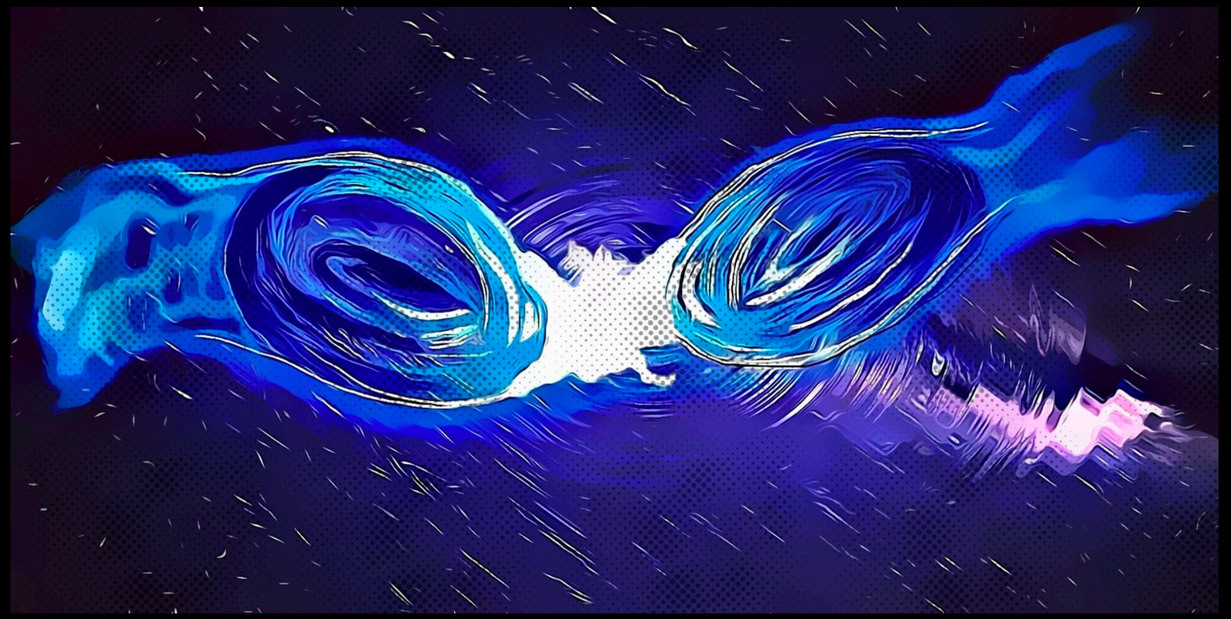



LVC: IMR BBH
LVC: Ringdown
Head-on
final spins
Lack of orbital angular momentum
Cosmic Censorship $a_{\rm BH} < 1$
a_f
$(1+z)M_f[M_\odot]$
$\log\mathcal{L}$


Livingston whitened data for GW190521
Best-fitting Quasi-circular BBH (LVC)
Head-on BBH
Final Spin is too low
$h[\sigma_{noise}]$
$t[s]$

Boson-star mergers

- Barely any pre-merger emission
  - Remnant: intermediate-mass black hole.
  - If BBH: primary black hole in the pair instability supernova gap.
- Alternative interpretations
  - Small eccentricity (Romero-Shaw+) ✓
  - High Eccentricity (Gayahtri+) ✓
  - Head-on merger (JCB+) ✗
  - Boson-star merger (this talk) ?



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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- **Boson mass:** μ_V

  Determines the maximum mass of the star
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  (before collapsing to a black hole)

- **Dark-Matter candiates**

	Scalar (s=0)		Vector (Proca) (s=1)		Tensor (s=2)	
Star	Real	Complex	Real	Complex	Real	Complex
Non-Spinning	✓	✓	✓ No explicit solutions	✓		✗
Spinning	✗	✓ Unstable	✗	✓		✗

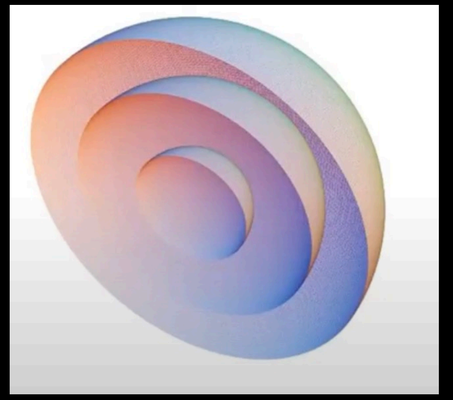
: Form unstable cloud around black-holes. SR instability. System spins-down, Continous waves. Current mass constraints.

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

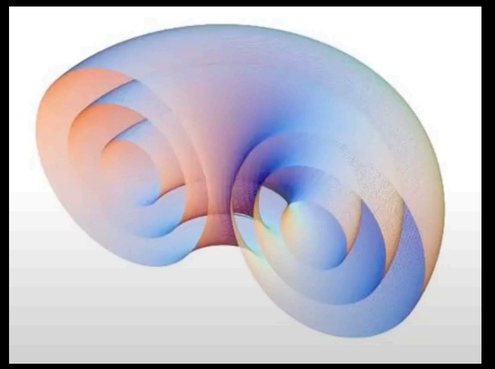
Mergers:

Quasi-circular — Only available for non-spinning stars

Head-on



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	✓	✓	✓ No explicit solutions	✓		✗
Spinning	✗	✓ Unstable	✗	✓		✗

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

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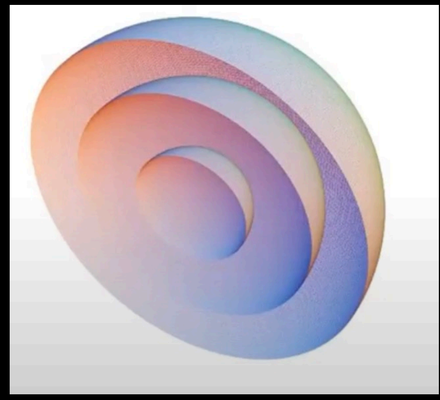
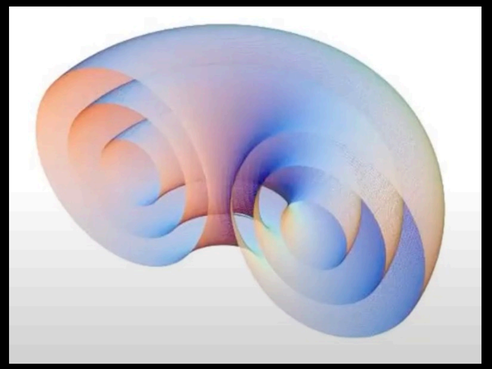
Mergers:

Quasi-circular  Only available for non-spinning stars

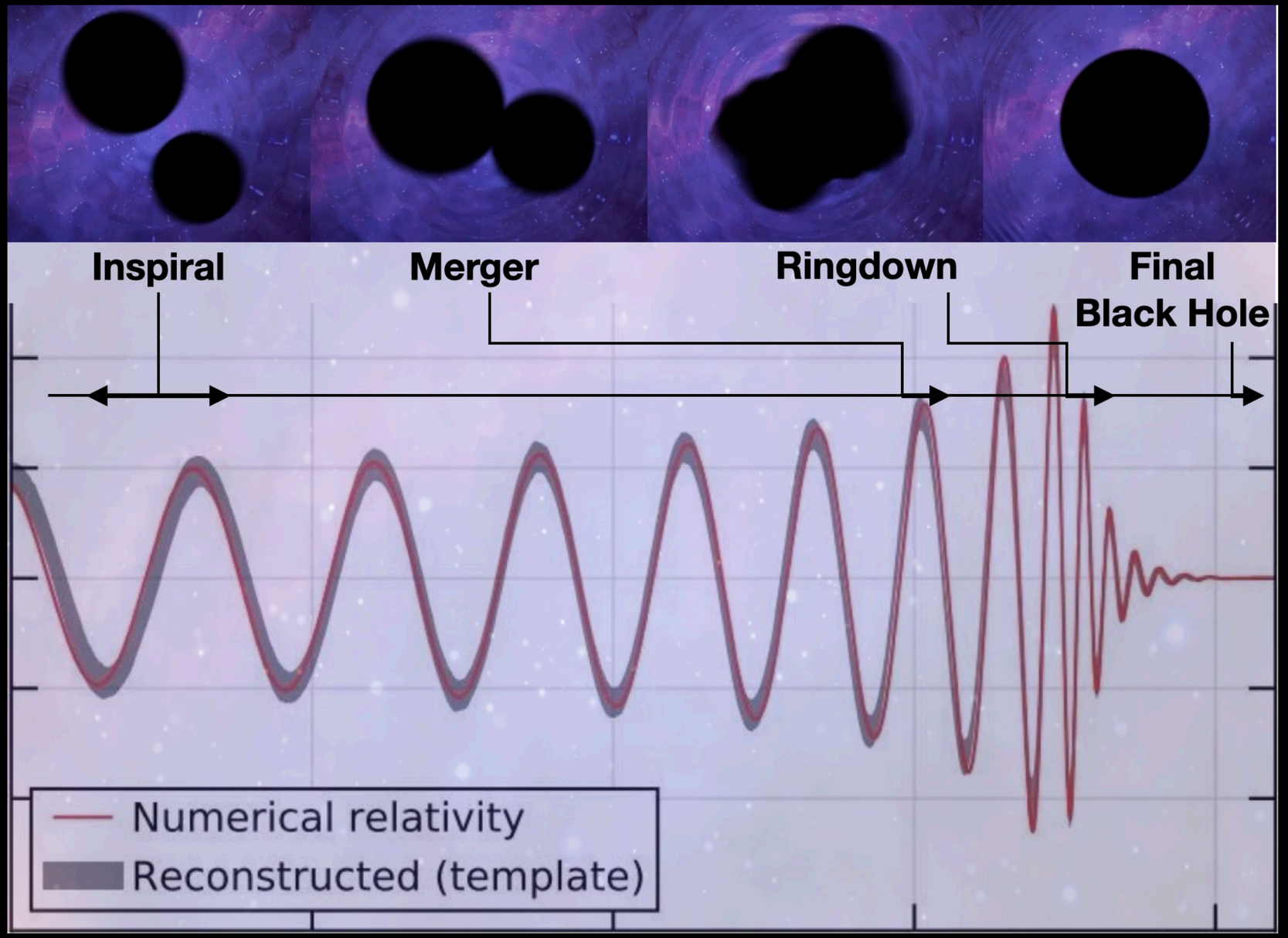
Head-on 

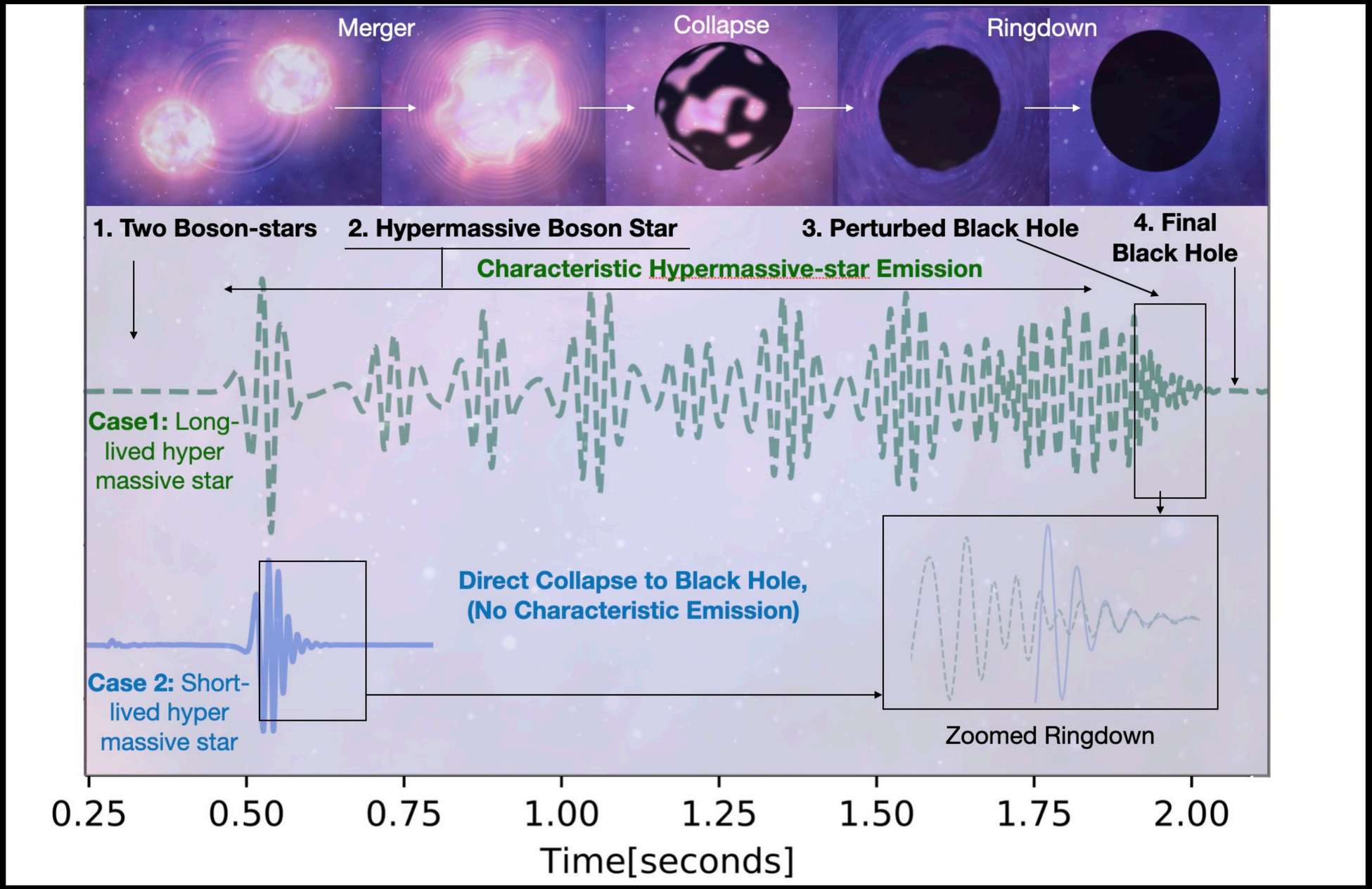


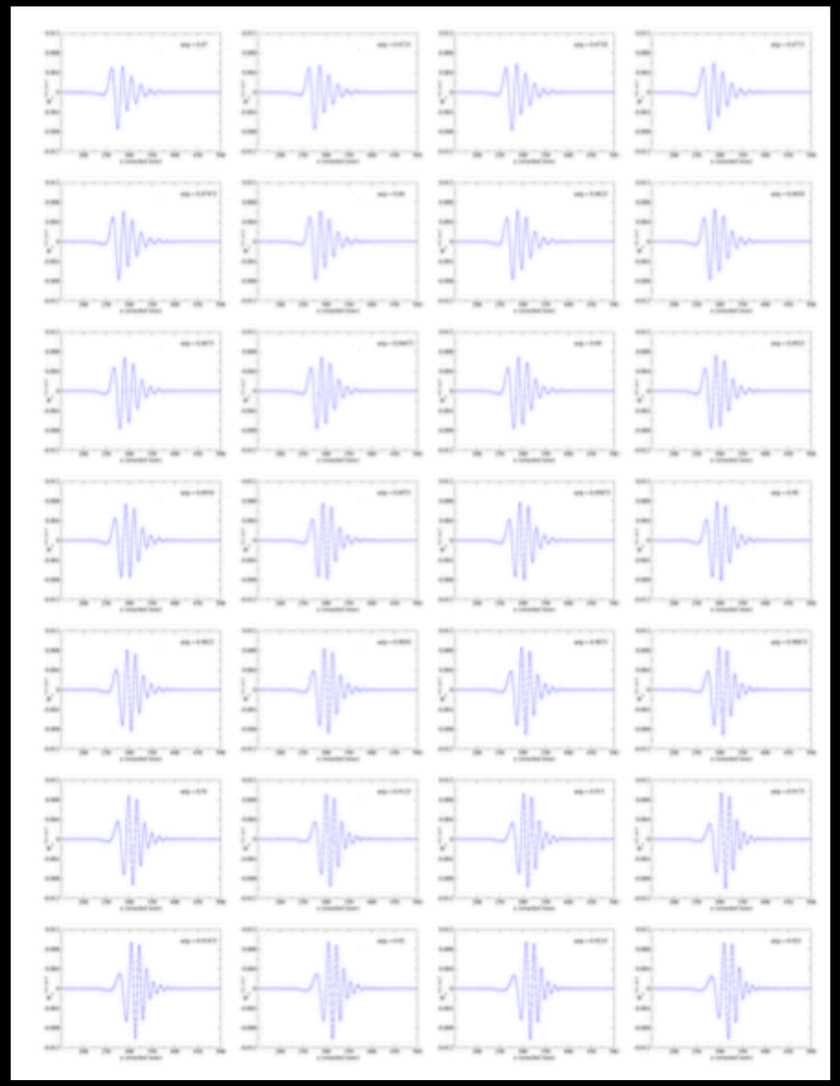
Spinning Proca star

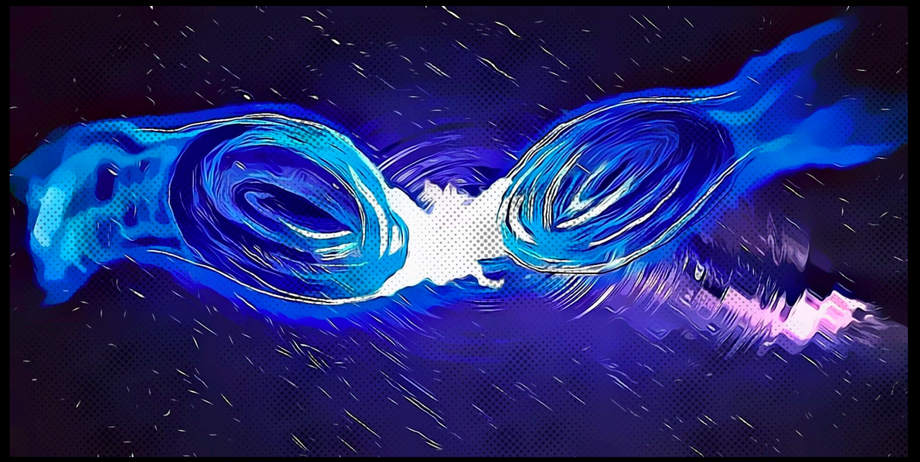


Spinning Scalar star (Unstable)


Inspiral
Merger
Ringdown
Final
Black Hole
Numerical relativity
Reconstructed (template)


Merger
Collapse
Ringdown
1. Two Boson-stars
2. Hypermassive Boson Star
3. Perturbed Black Hole
4. Final Black Hole
Characteristic Hypermassive-star Emission
Case1: Long-lived hyper massive star
Direct Collapse to Black Hole, (No Characteristic Emission)
Case 2: Short-lived hyper massive star
Zoomed Ringdown
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Time[seconds]

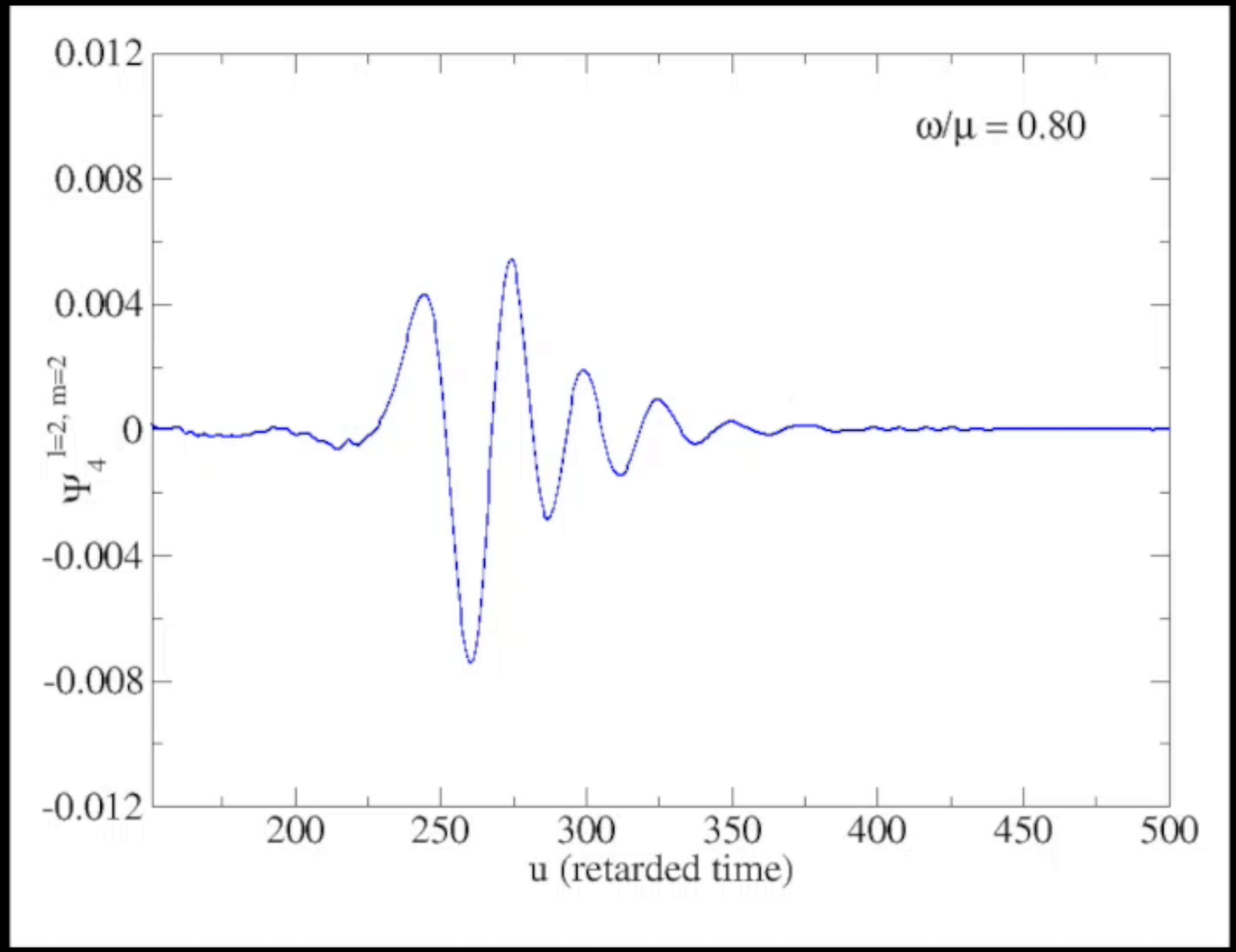




Equal-mass, equal field frequency (equal spin)

Initial separation = 100M

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



Credit: Nicolás Sanchis-Gual

GW190521 as a boson-star merger

Phys.Rev.Lett. **126**, 081101 (2021)

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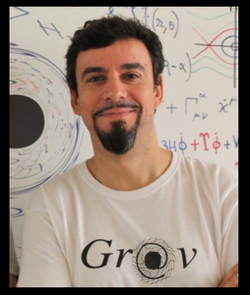

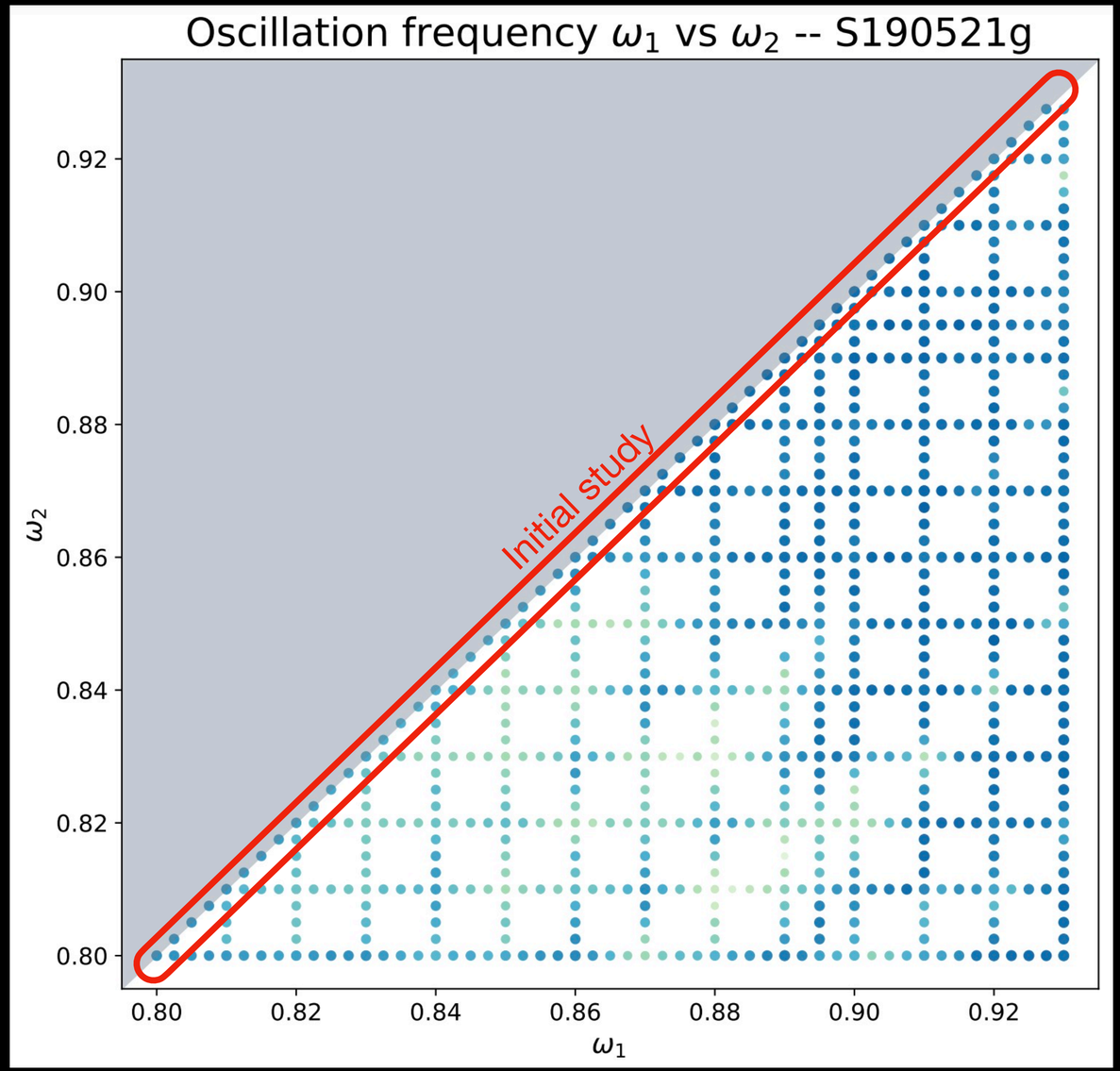

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GW190521 Parameters (Proca-star merger)

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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LVC (BBH)

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

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

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LVC (BBH)

$5300^{+2600}_{-2400} Mpc$ Much closer than a BBH

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

Circular mergers are louder
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LVC (BBH)

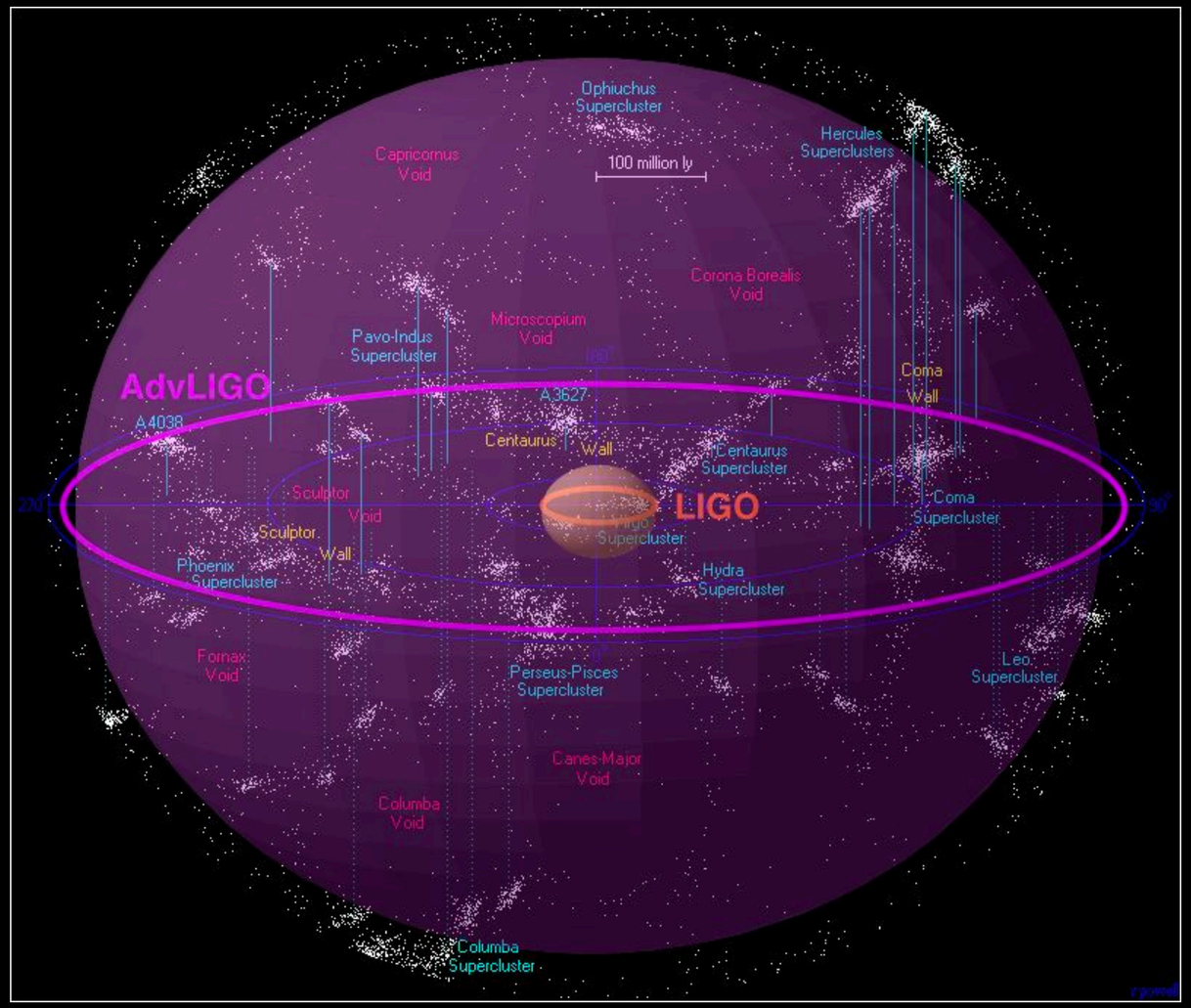
$150^{+29}_{-17} M_\odot$ Much heavier than the BBH estimation

$5300^{+2600}_{-2400} Mpc$ Much closer than a BBH

$272^{+26}_{-27} M_\odot$ Circular mergers are louder
Larger initial mass needed to get same final BH

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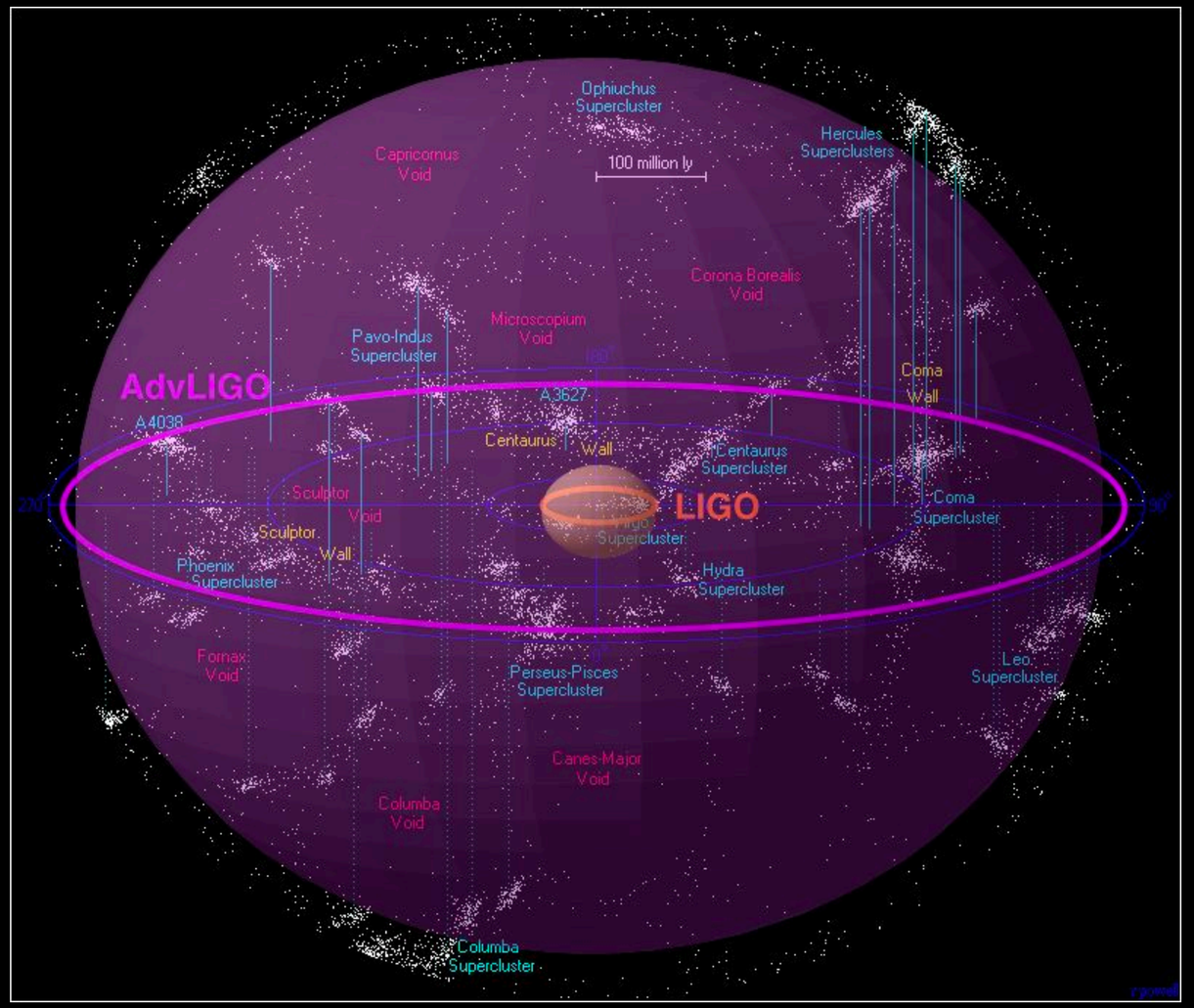
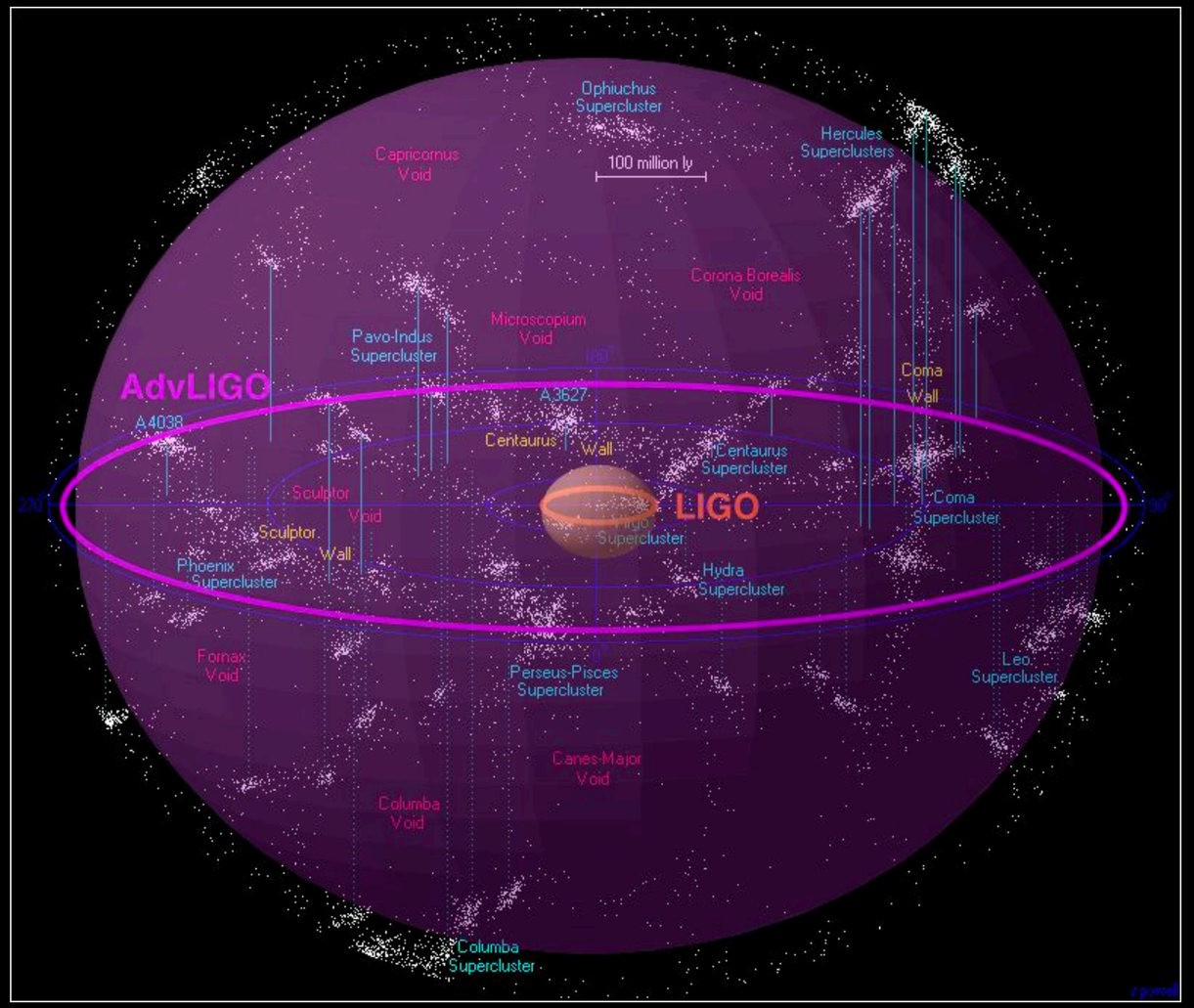
$$\frac{P(\text{Proca q=1})}{P(\text{BBH})} = e^{(80.9-80.0)} \simeq 2.5 \quad \frac{P(\text{Proca } q\neq 1)}{P(\text{BBH})} \simeq 6.7$$



Distance prior: Uniform in luminosity distance

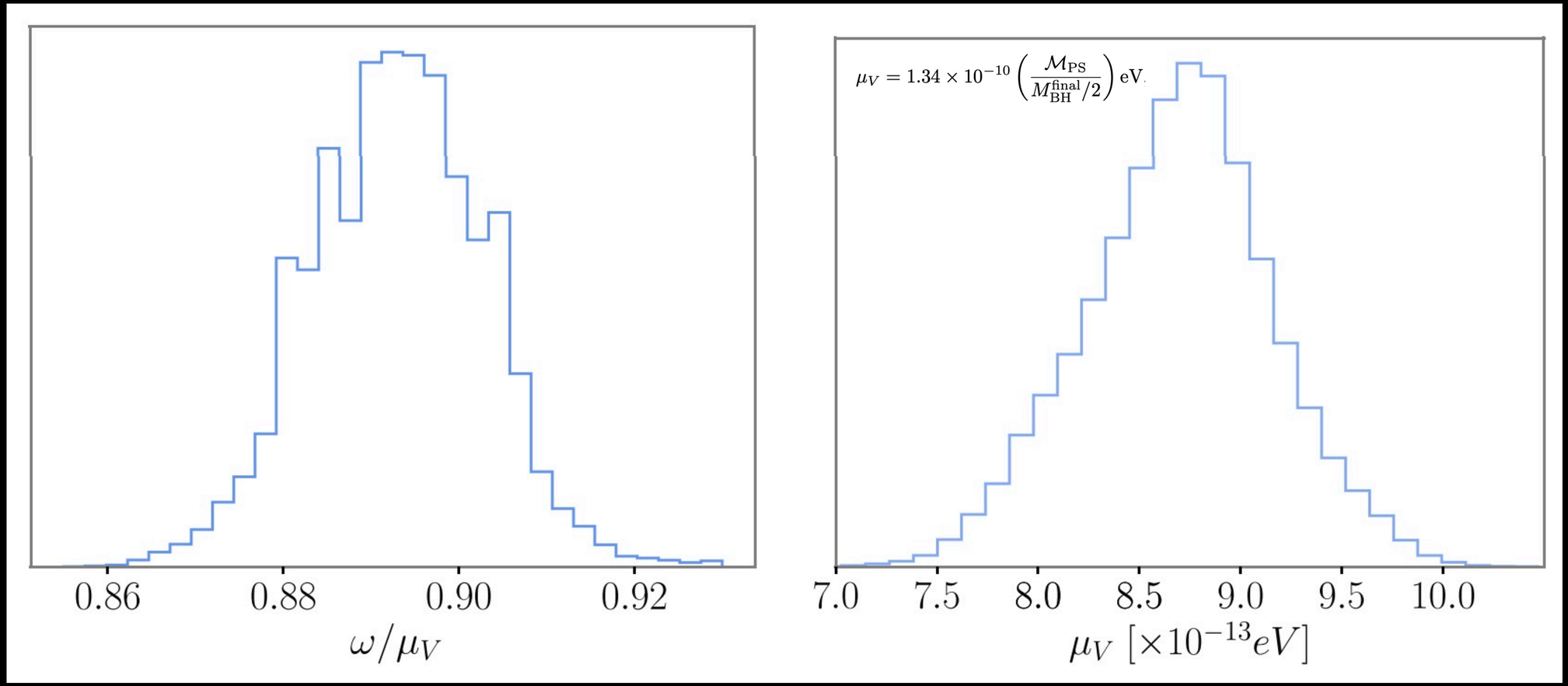
Waveform Model	$\log \mathcal{B}$	$\log \mathcal{L}_{Max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	83.5	106.7
Head-on Unequal-mass Proca Stars	84.3	106.5
Head-on Binary Black Hole	78.0	103.2

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



Bosonic field frequency

Boson mass



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

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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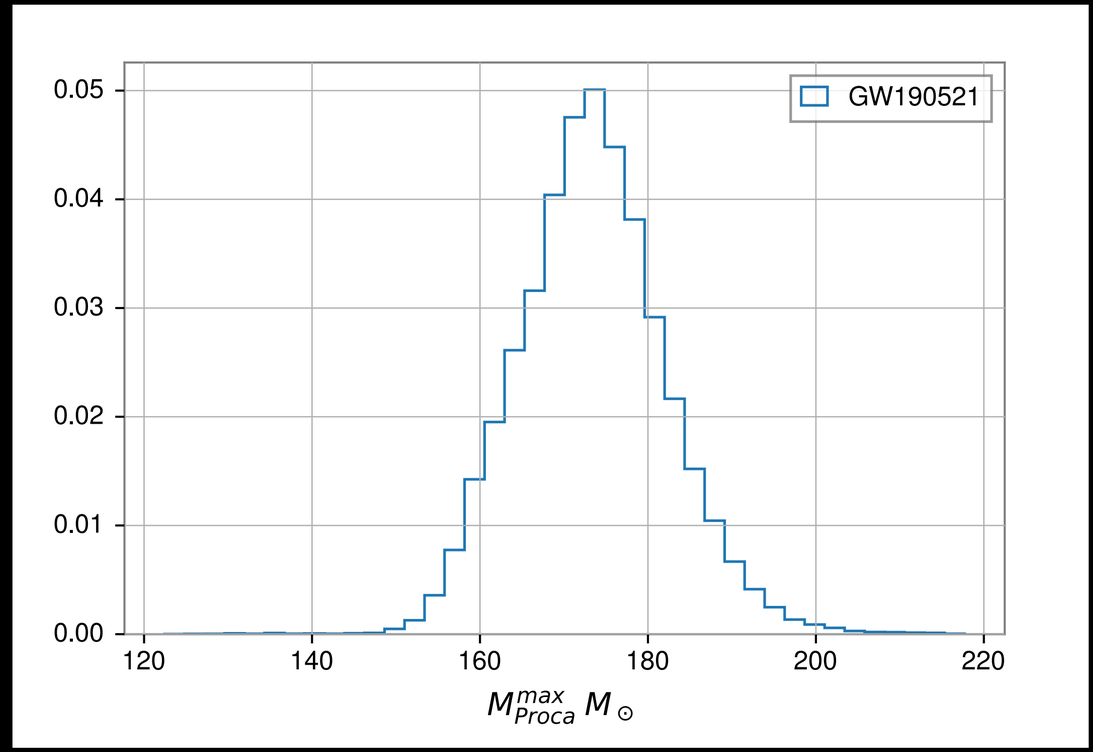
Final Proca star less massive: no collapse, no ringdown

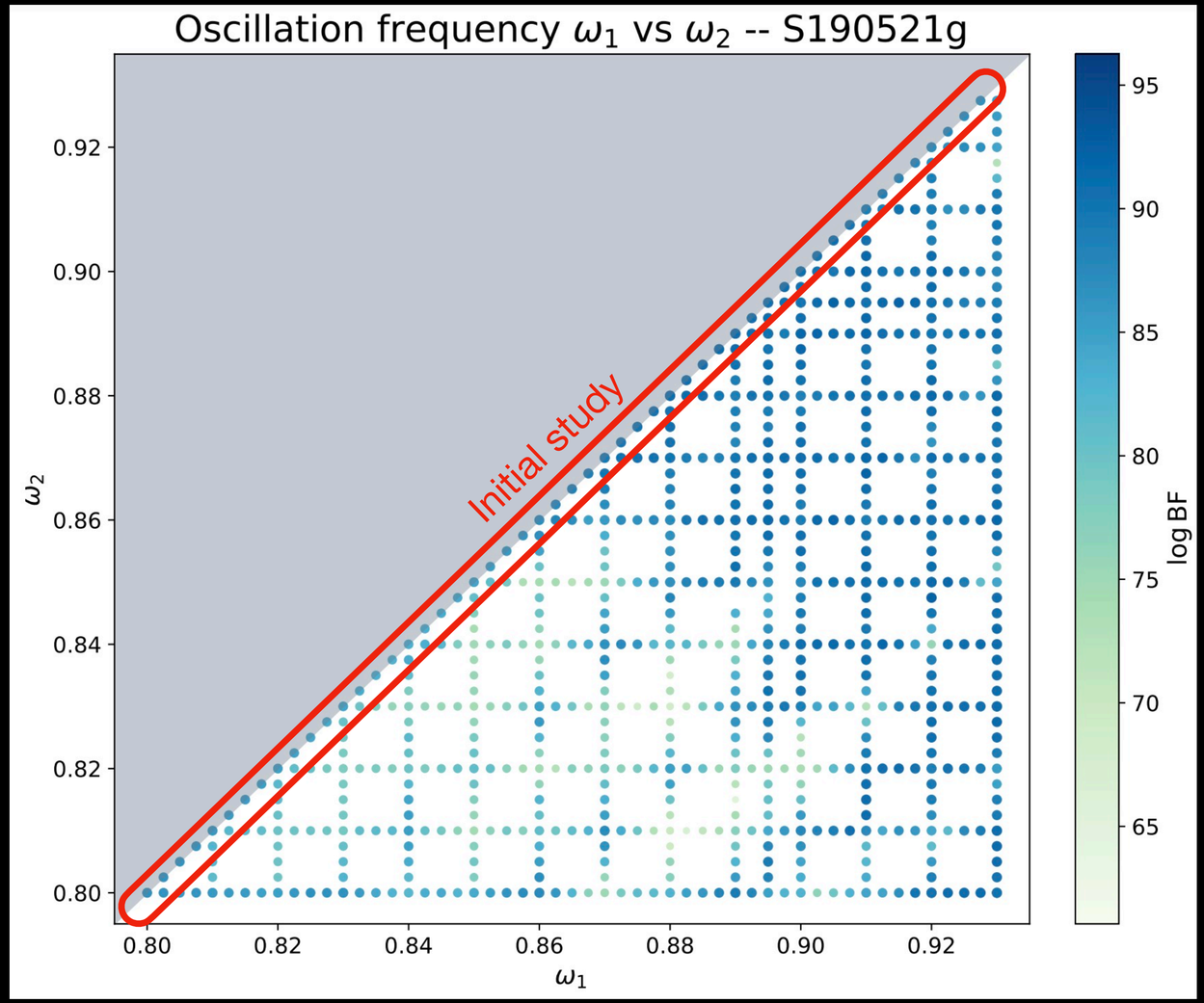
Previous LVC events discarded as head-on Proca star mergers (with same boson mass)

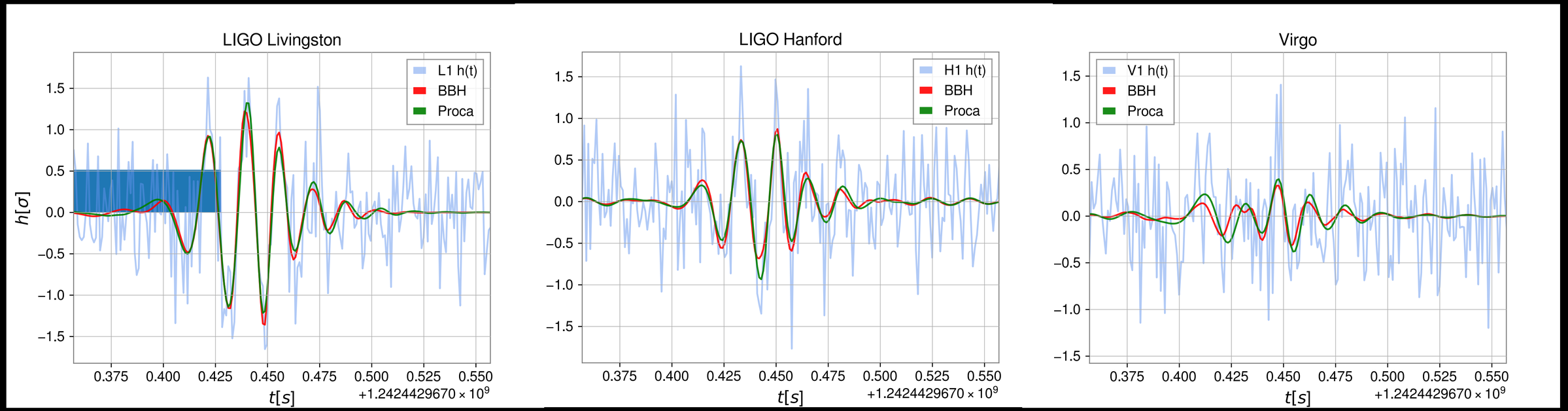
$$M_{\rm max}^{\rm Proca} = 174^{+15}_{-14} M_\odot$$



GW190521 as a boson-star merger (Updated)

Extended to 759 numerical simulations




LIGO Livingston
L1 h(t)
BBH
Proca
h[σ]
t[s]
+1.2424429670 × 10^9
LIGO Hanford
H1 h(t)
BBH
Proca
t[s]
+1.2424429670 × 10^9
Virgo
V1 h(t)
BBH
Proca
t[s]
+1.2424429670 × 10^9

Results essentially un-altered

Mild evidence in favour of Proca-star merger

All parameters consistent with initial study

$$\mu_B^{GW190521} = 8.73^{+0.65}_{-0.78} \times 10^{-13} eV$$

Parameter	GW190521
Primary mass $[M_\odot]$	125^{+14}_{-13}
Secondary mass $[M_\odot]$	108^{+11}_{-15}
Total / Final mass $[M_\odot]$	232^{+16}_{-16}
Final spin	$0.69^{+0.04}_{-0.04}$
Inclination $\pi/2 - \lvert\iota - \pi/2\rvert$ [rad]	$0.69^{+0.32}_{-0.45}$
Luminosity distance [Mpc]	577^{+357}_{-270}
Redshift	$0.12^{+0.07}_{-0.05}$
Total / Final redshifted mass $[M_\odot]$	261^{+9}_{-10}
Primary field frequency ω/μ_V	$0.88^{+0.04}_{-0.07}$
Secondary field frequency ω/μ_V	$0.91^{+0.03}_{-0.04}$
Boson mass μ_V $[\times 10^{-13}\mathrm{eV}]$	$8.73^{+0.65}_{-0.78}$
Maximal boson star mass $[M_\odot]$	172^{+17}_{-12}
$\Delta\mathrm{Log}\mathcal{L}^{\mathrm{Proca}}_{\mathrm{BBH,NRSur7dq4}}$	0.4
$\mathrm{LogBayesFactor}^{\mathrm{Proca}}_{\mathrm{BBH,NRSur7dq4}}$	0.9

Third Advanced LIGO -Virgo run has delivered more events like GW190521

- GW190426 (heaviest event to date)
- GW200220

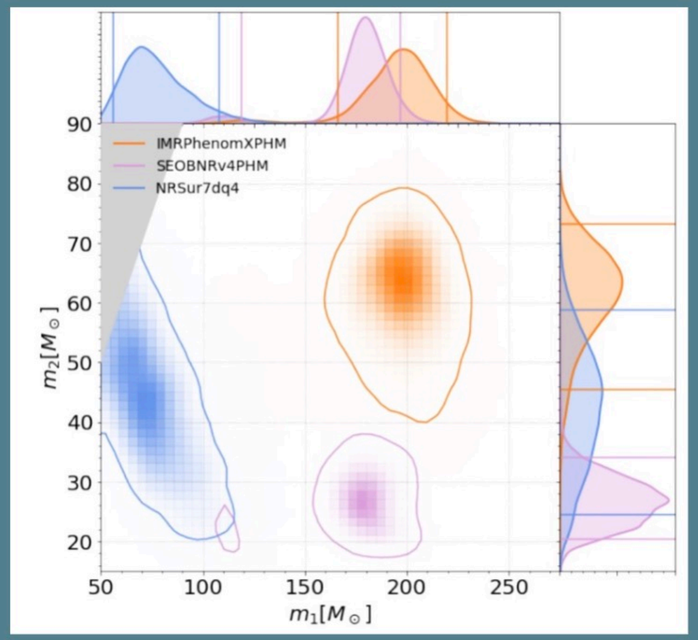
Also, interesting trigger from the second observing run: S200114f

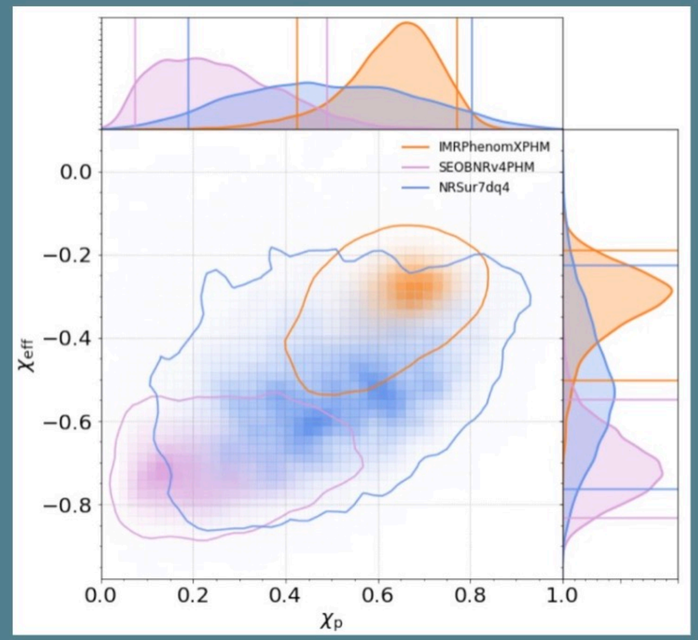
Could these be also consistent with Proca-star mergers?

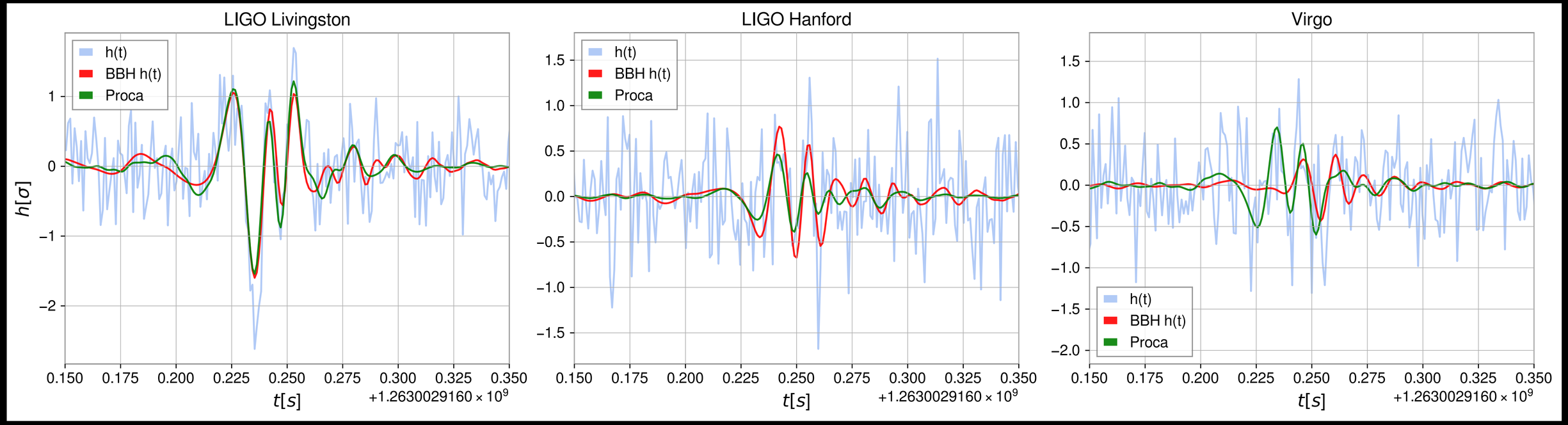
More events!

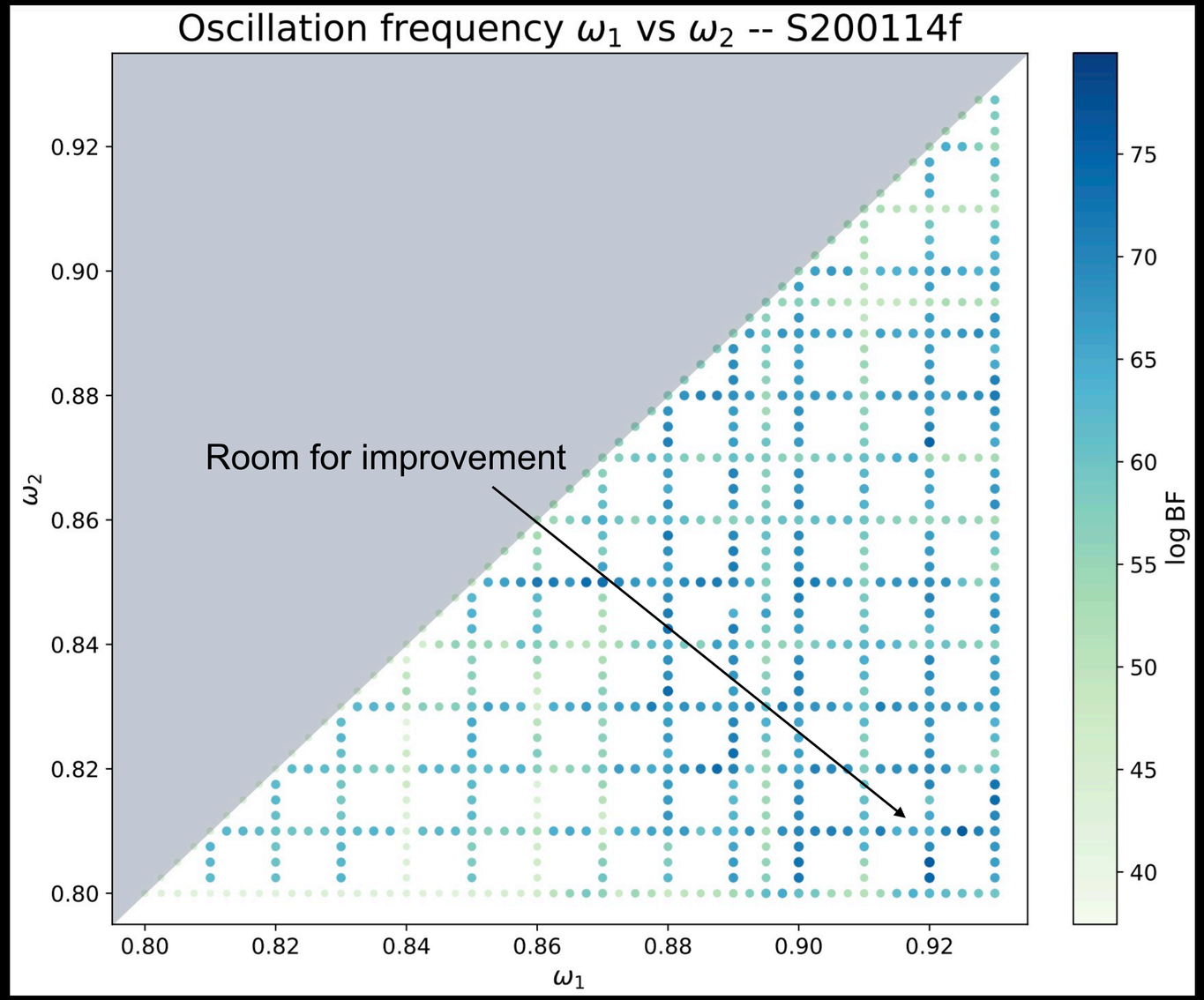
Most significant trigger within the O3 IMBH search

- cWB significance: 1/32 years
- Combined search significance: 1/17 years
- No two BBH models provide consistent PE
- Say something else….?



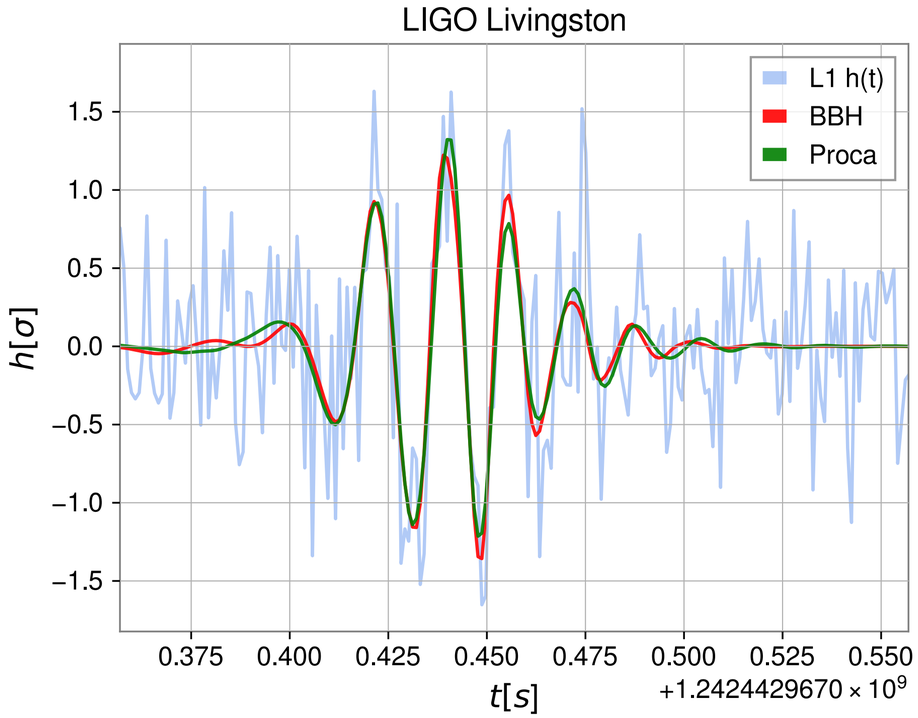


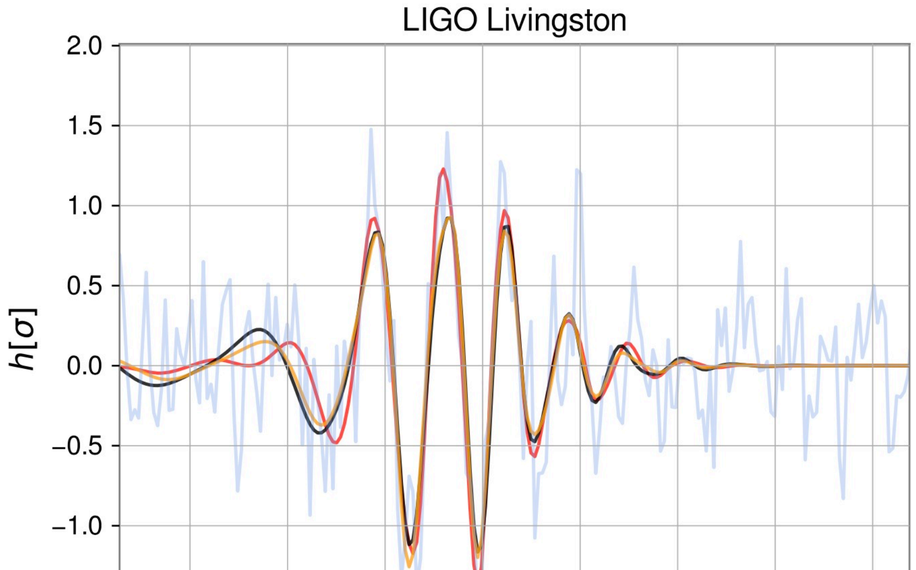

LIGO Livingston
h(t)
BBH h(t)
Proca
h[σ]
t[s]
+1.2630029160 × 10^9
LIGO Hanford
h(t)
BBH h(t)
Proca
t[s]
+1.2630029160 × 10^9
Virgo
h(t)
BBH h(t)
Proca
t[s]
+1.2630029160 × 10^9


Oscillation frequency ω_1 vs ω_2 -- S200114f
Room for improvement
ω_2
ω_1
0.80
0.82
0.84
0.86
0.88
0.90
0.92
log BF
40
45
50
55
60
65
70
75

Event	GW190521			GW190426			GW200220			S200114f		
Waveform model	$\log\mathcal{L}_{\max}$	V	D	$\log\mathcal{L}_{\max}$	V	D	$\log\mathcal{L}_{\max}$	V	D	$\log\mathcal{L}_{\max}$	V	D
Black-hole merger	121.1	89.9	90.6	62.8	38.3	38.6	46.2	15.7	16.3	114.7	71.2	71.7
Proca-star merger	121.0	90.8	93.5	62.5	29.6	32.2	36.7	14.5	16.8	107.4	71.0	76.0
$\mathcal{B}^{\rm PSM}_{\rm BBH}$		2	18		2×10^{-4}	2×10^{-3}		0.3	1.6		0.8	74.0

- Only for GW190521 Proca-star mergers beat (marginally) vanilla BBHs
- GW190426 completely ruled out as a Proca-star merger with our current catalogue

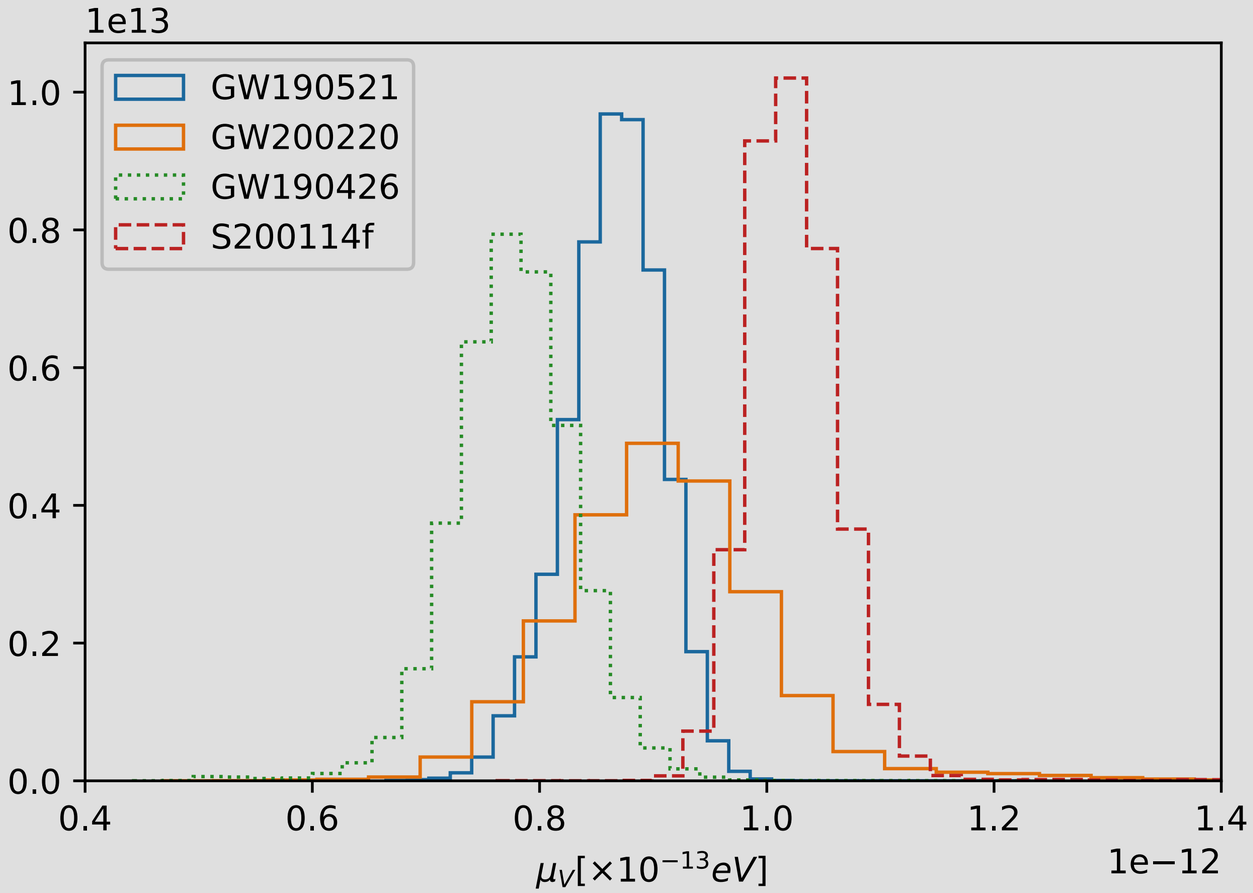

LIGO Livingston
L1 h(t)
BBH
Proca
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
h[σ]
0.375
0.400
0.425
0.450
0.475
0.500
0.525
0.550
t[s]
+1.2424429670 × 10^9


LIGO Livingston
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
h[σ]

Removing intrinsic loudness

Event	GW190521			GW190426			GW200220			S200114f		
Waveform model	$\log\mathcal{L}_{\max}$	V	D	$\log\mathcal{L}_{\max}$	V	D	$\log\mathcal{L}_{\max}$	V	D	$\log\mathcal{L}_{\max}$	V	D
Black-hole merger	121.1	89.9	90.6	62.8	38.3	38.6	46.2	15.7	16.3	114.7	71.2	71.7
Proca-star merger	121.0	90.8	93.5	62.5	29.6	32.2	36.7	14.5	16.8	107.4	71.0	76.0
$\mathcal{B}^{\rm PSM}_{\rm BBH}$		2	18		2×10^{-4}	2×10^{-3}		0.3	1.6		0.8	74.0

- GW190521 and S200114f do “strongly” the Proca-star merger model. GW200220 does marginally.
- GW190426 completely ruled out as a Proca-star merger with our current catalogue



- No pair of masses is completely inconsistent
- GW190521 and GW200220 consistent at the ~85% level.

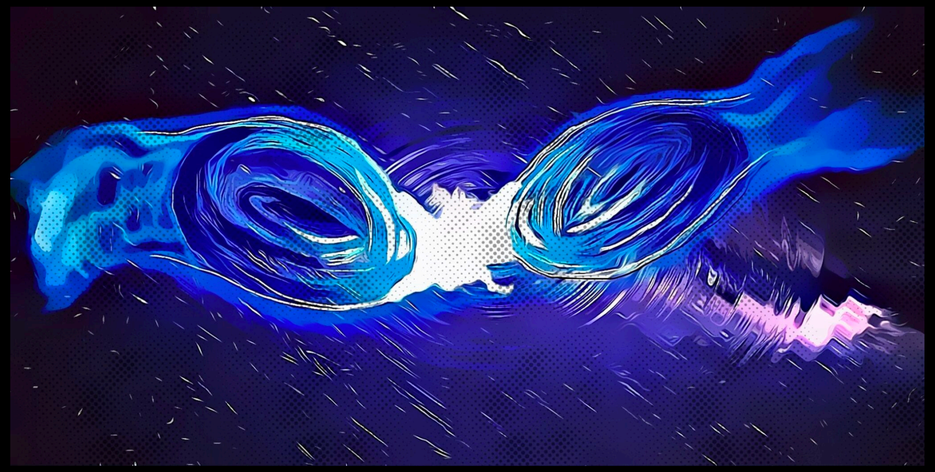
GW190521 has brought us in the realm of ¿what are we observing?

Origin unclear, strong influence of priors

Consistent with a Proca-star merger

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

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?