Searching for boson-star mergers in LIGO-Virgo data

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… with Nicolas Sanchis-Gual, Alex Torres-Forne, Samson Leong, Koustav Chandra, Carlos Herdeiro, Tjonnie Li, Toni Font, Isaac Wong and Eugen Radu

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Fundació "la Caixa"

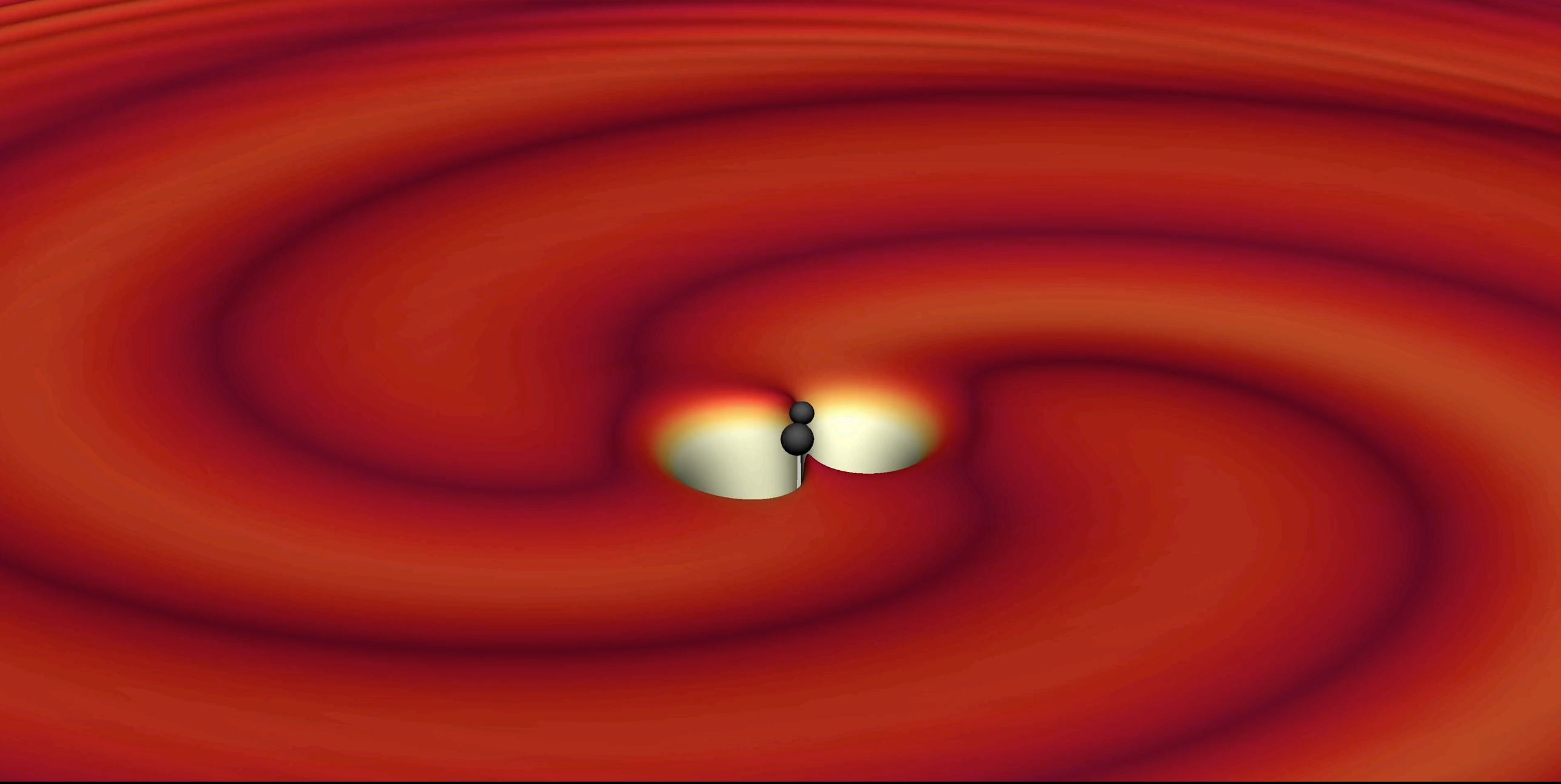
XUNTA DE GALICIA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

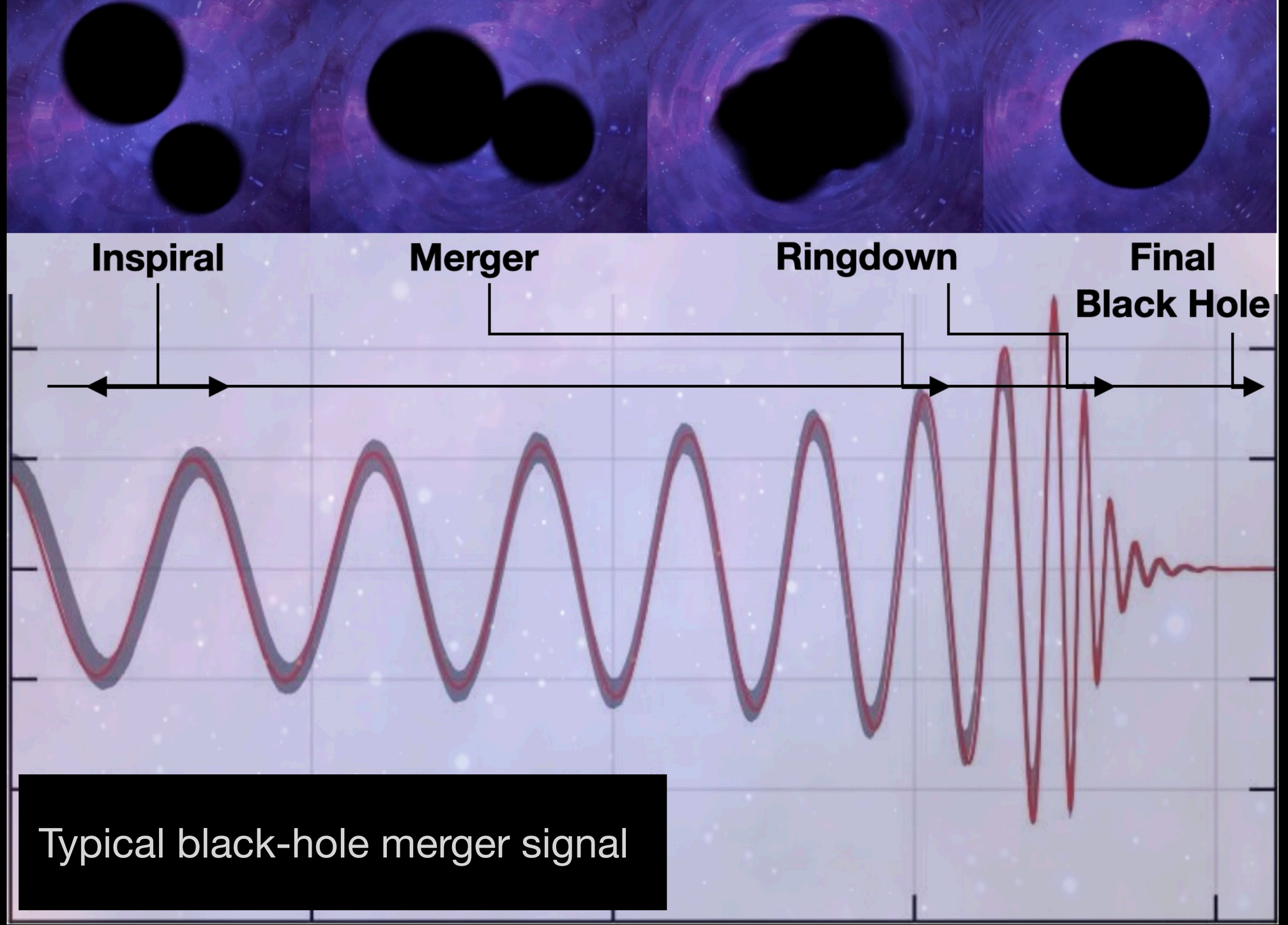
IGFAE Instituto Galego de Física de Altas Enerxías

GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA E INNOVACIÓN

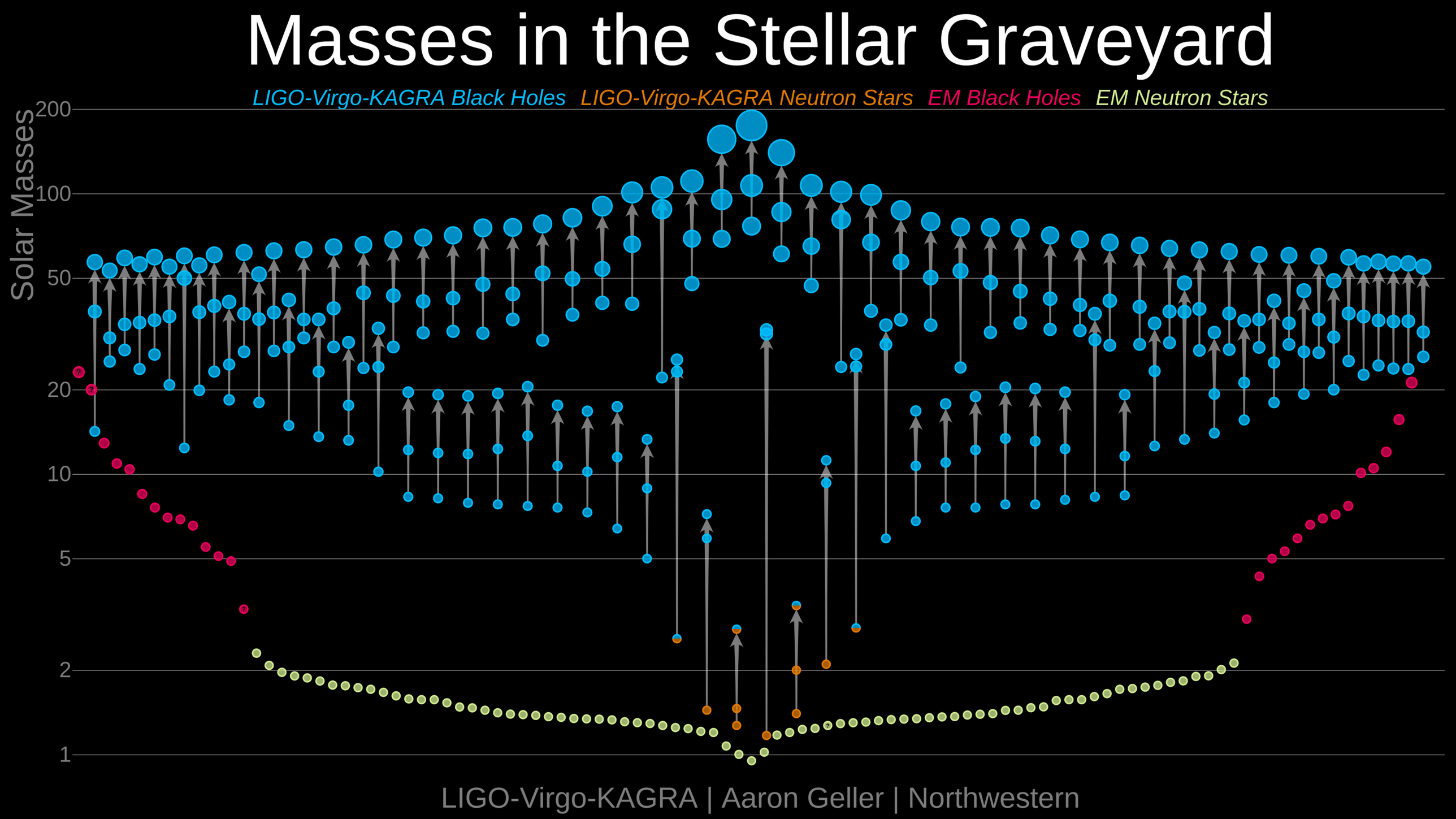


Max Planck Institute
for Gravitational Physics



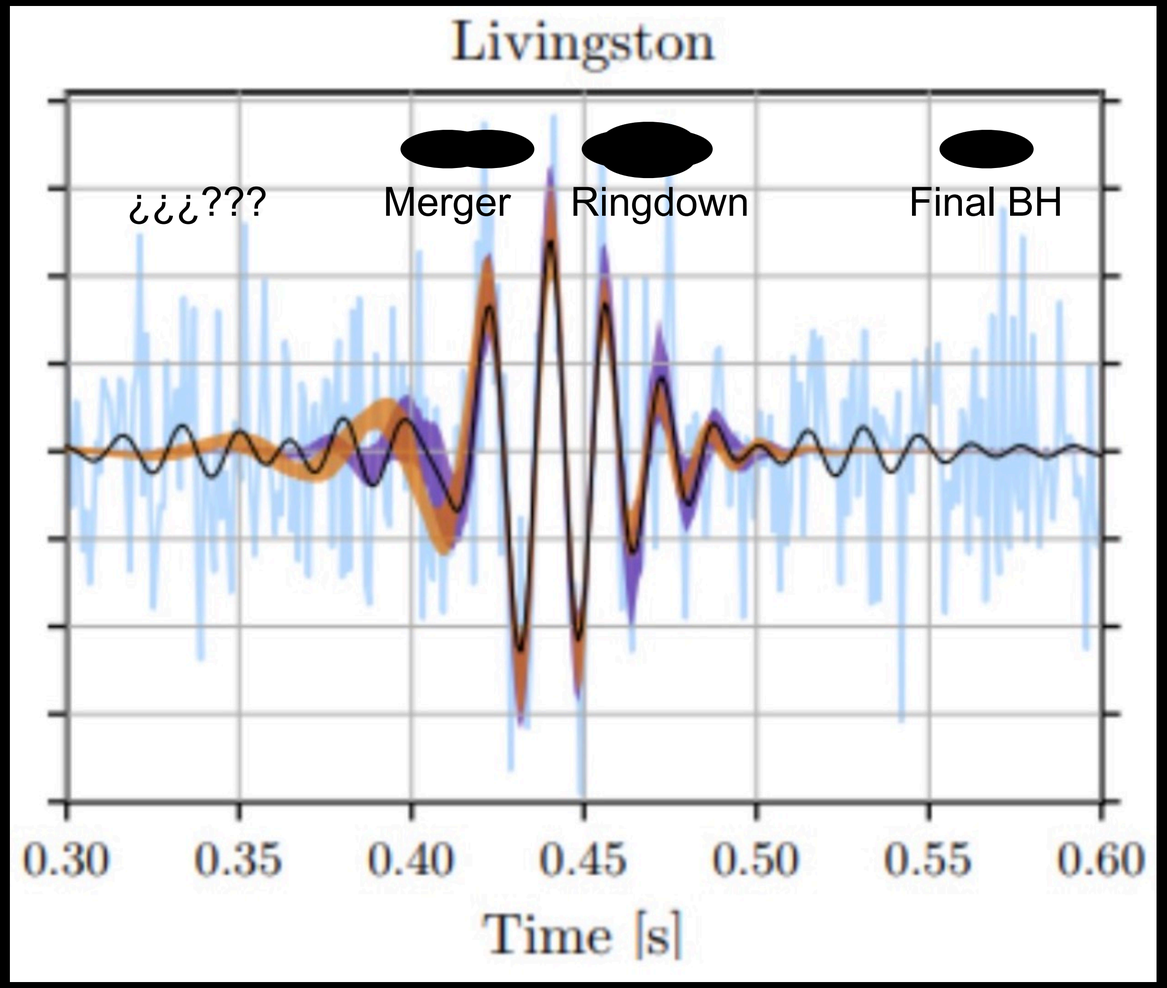
Typical black-hole merger signal

Masses in the Stellar Graveyard



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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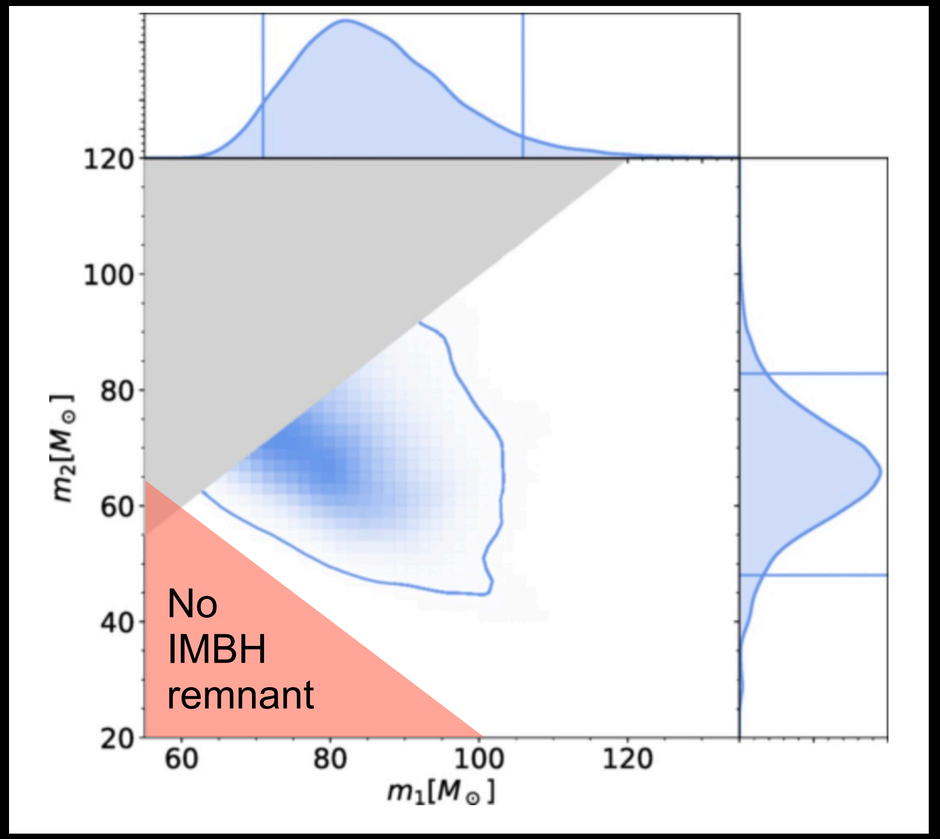
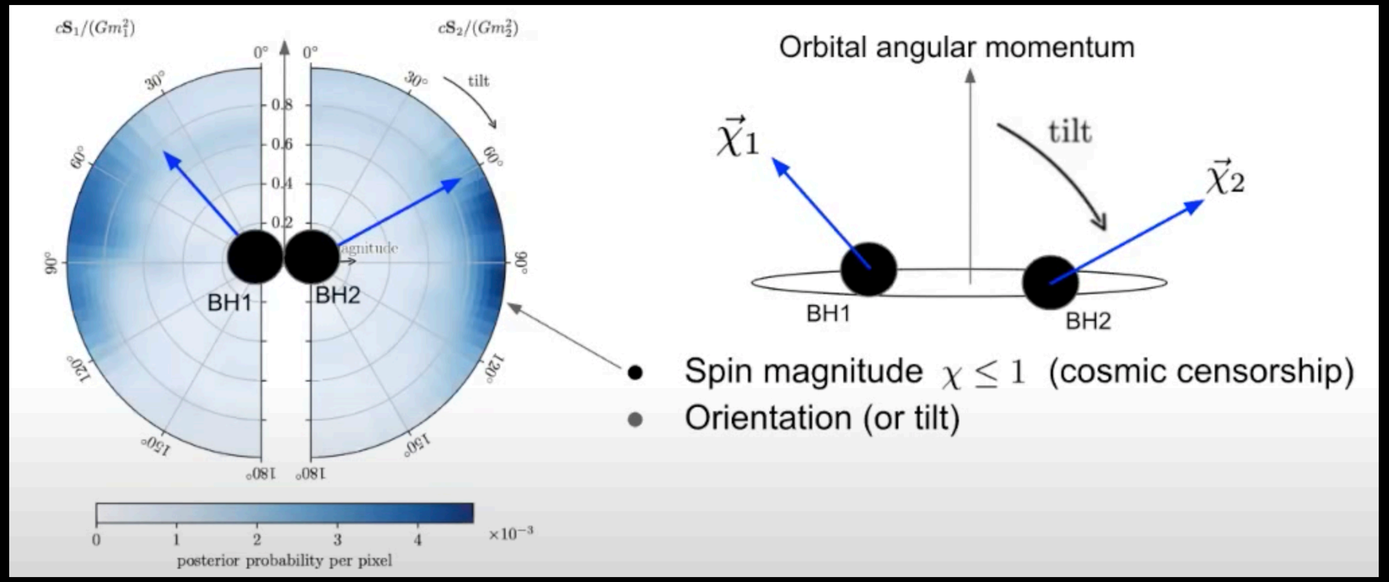


LVC 2020

- Barely any pre-merger emission
  - Remnant: intermediate-mass black hole.
  - If BBH: primary black hole in the pair instability supernova gap.
  - Mild precession signature



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

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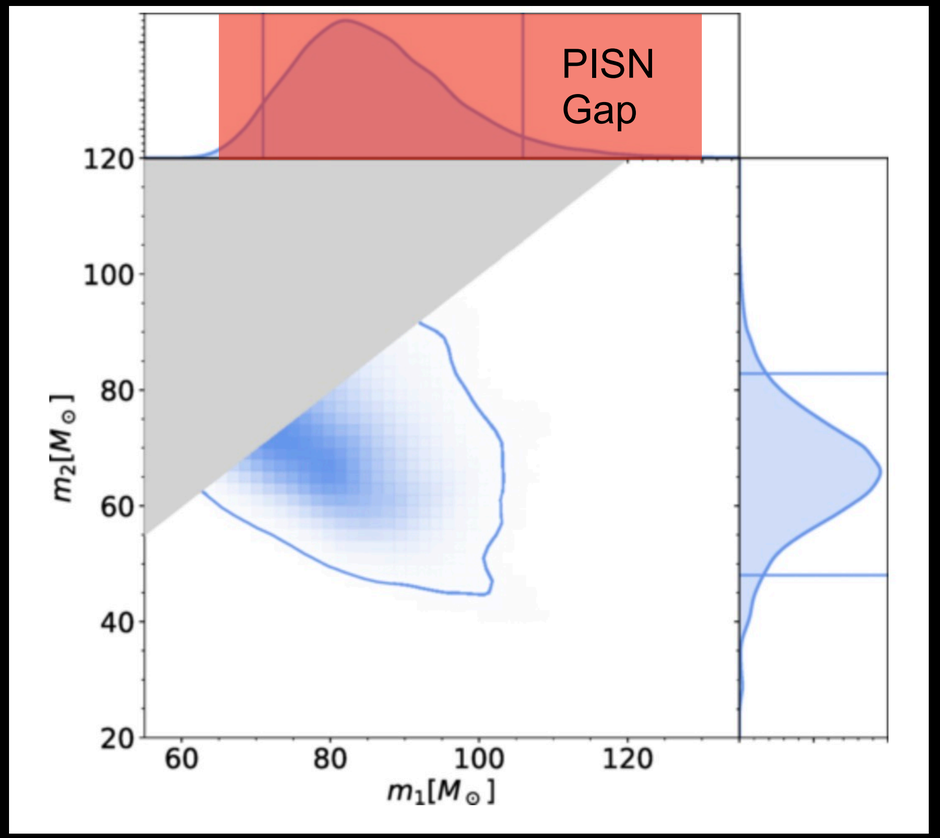

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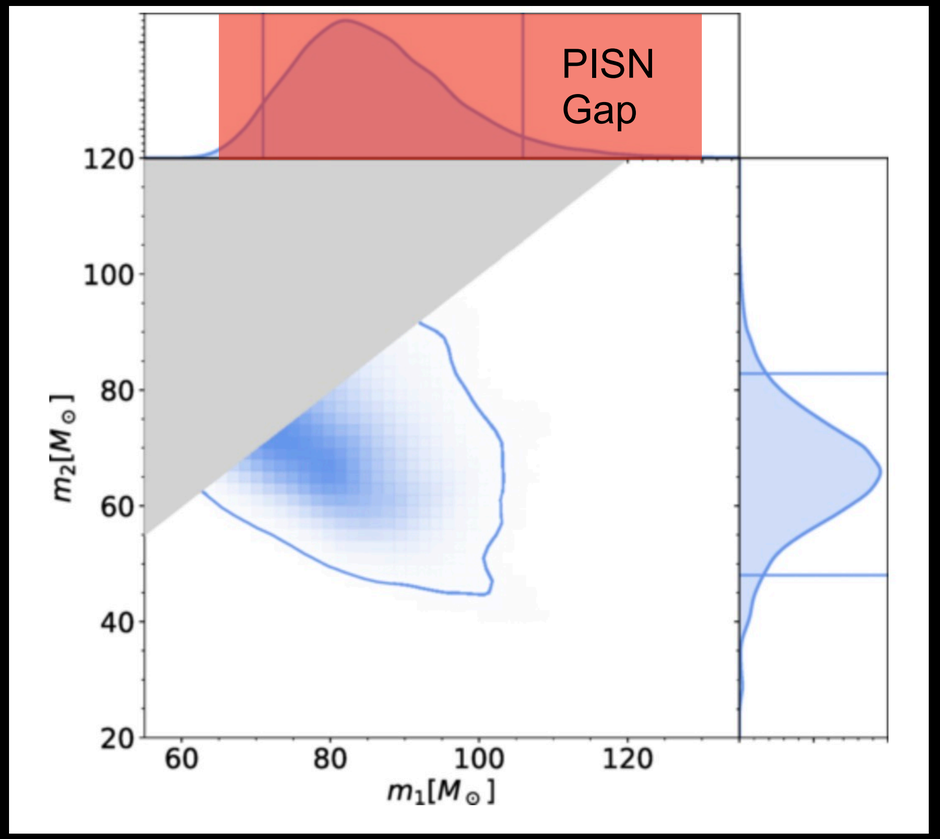

Self-gravitating Bose Einstein condensates of ultralight bosons

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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- **Considered good Dark Matter candidates**

	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.

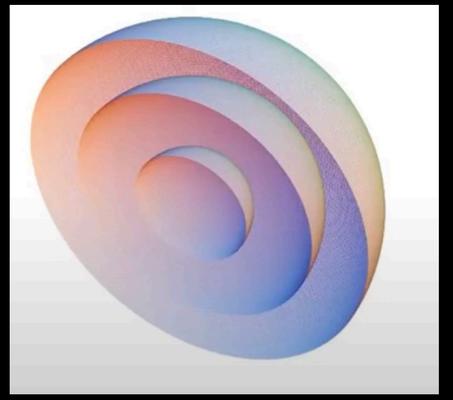
: Form stable cloud around black-holes. SR equilibrium, spin of the system is kept. No Continous waves.

Mergers:

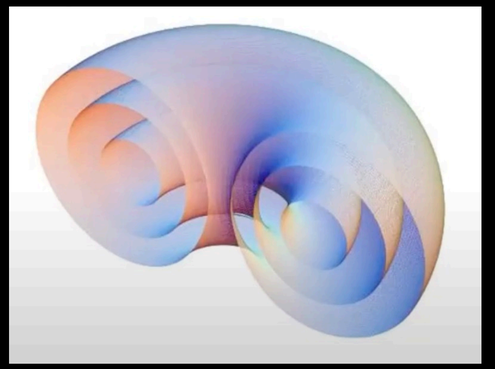
Quasi-circular

Only available for non-spinning stars

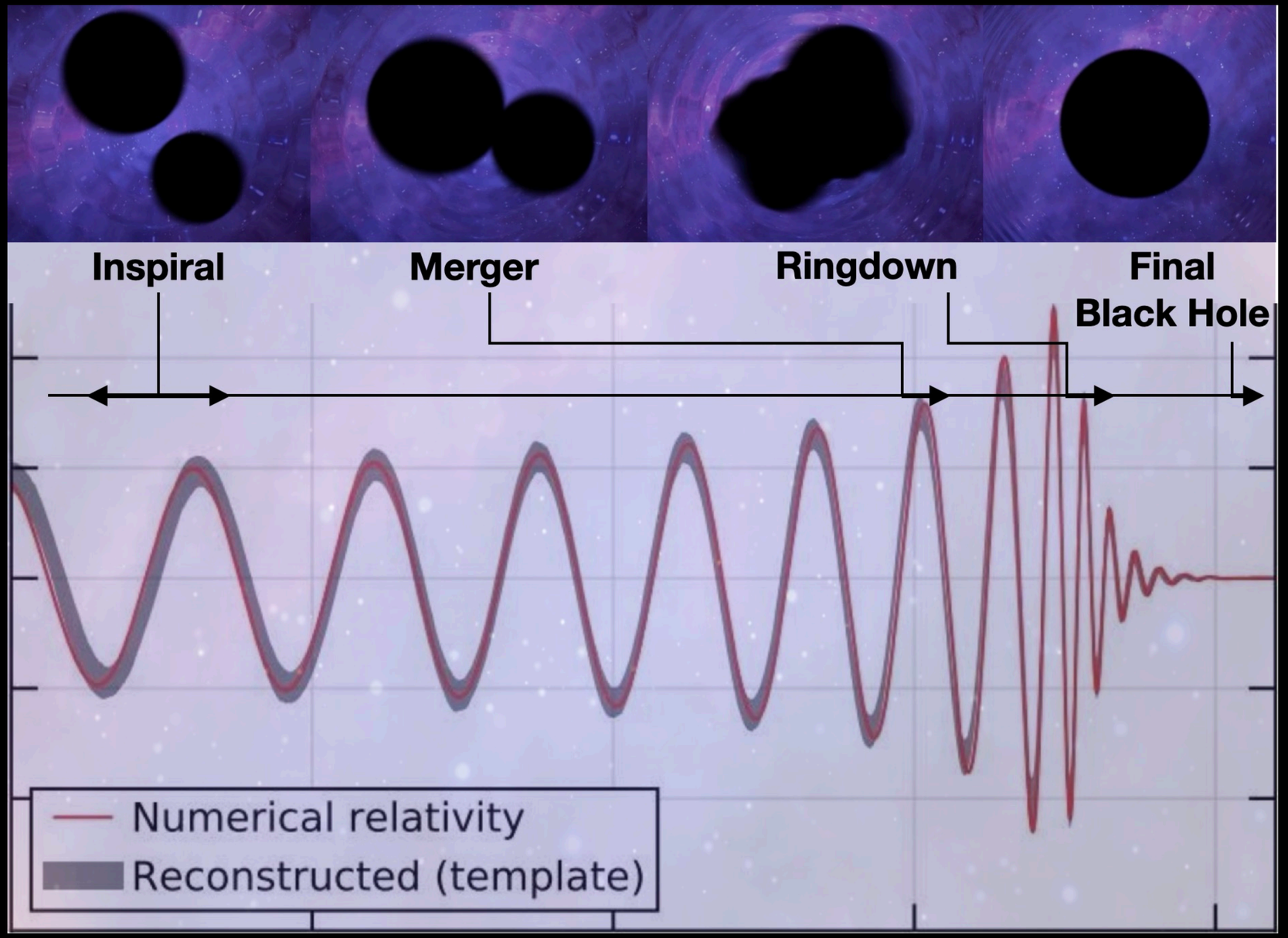
Head-on

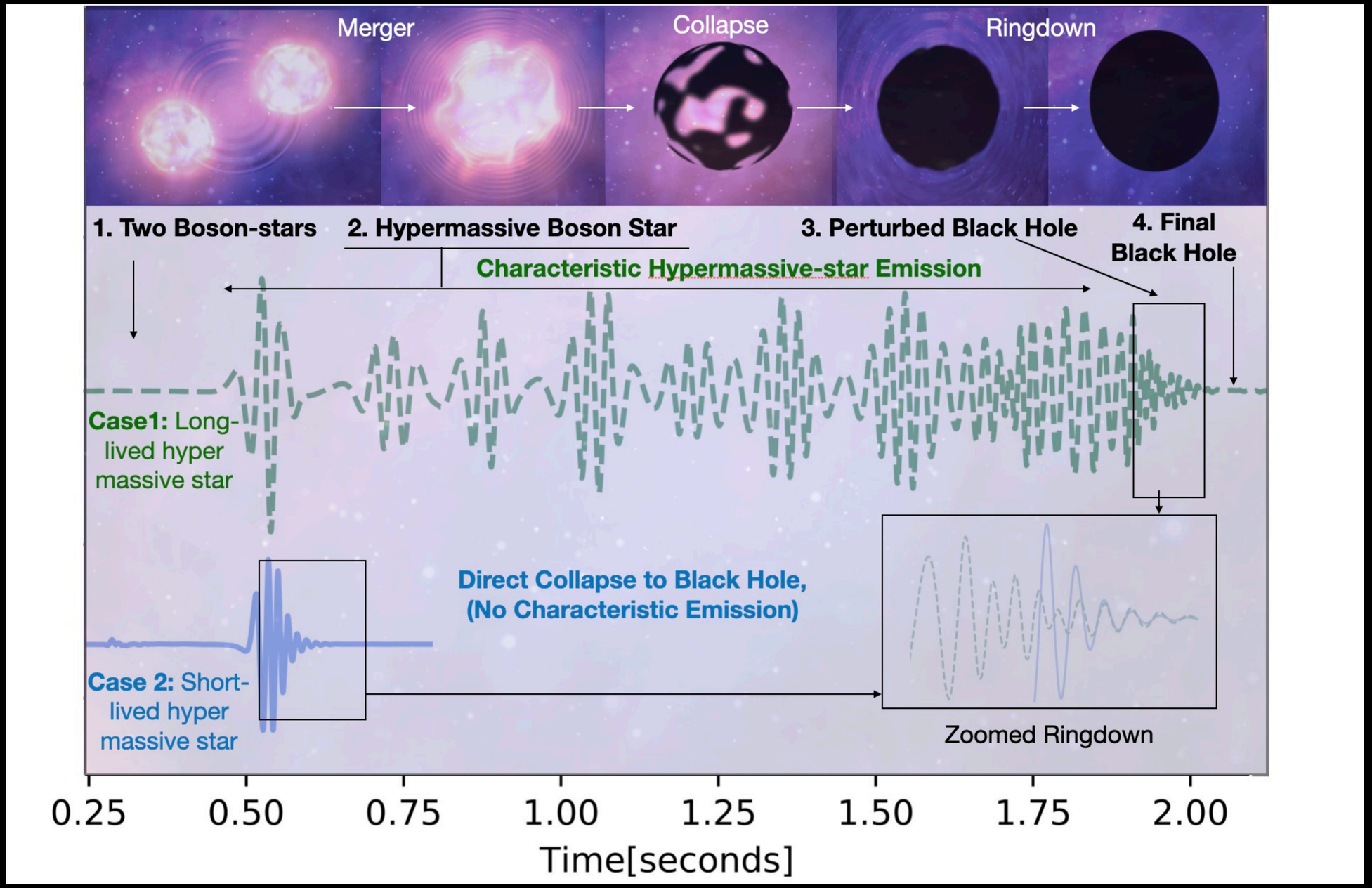


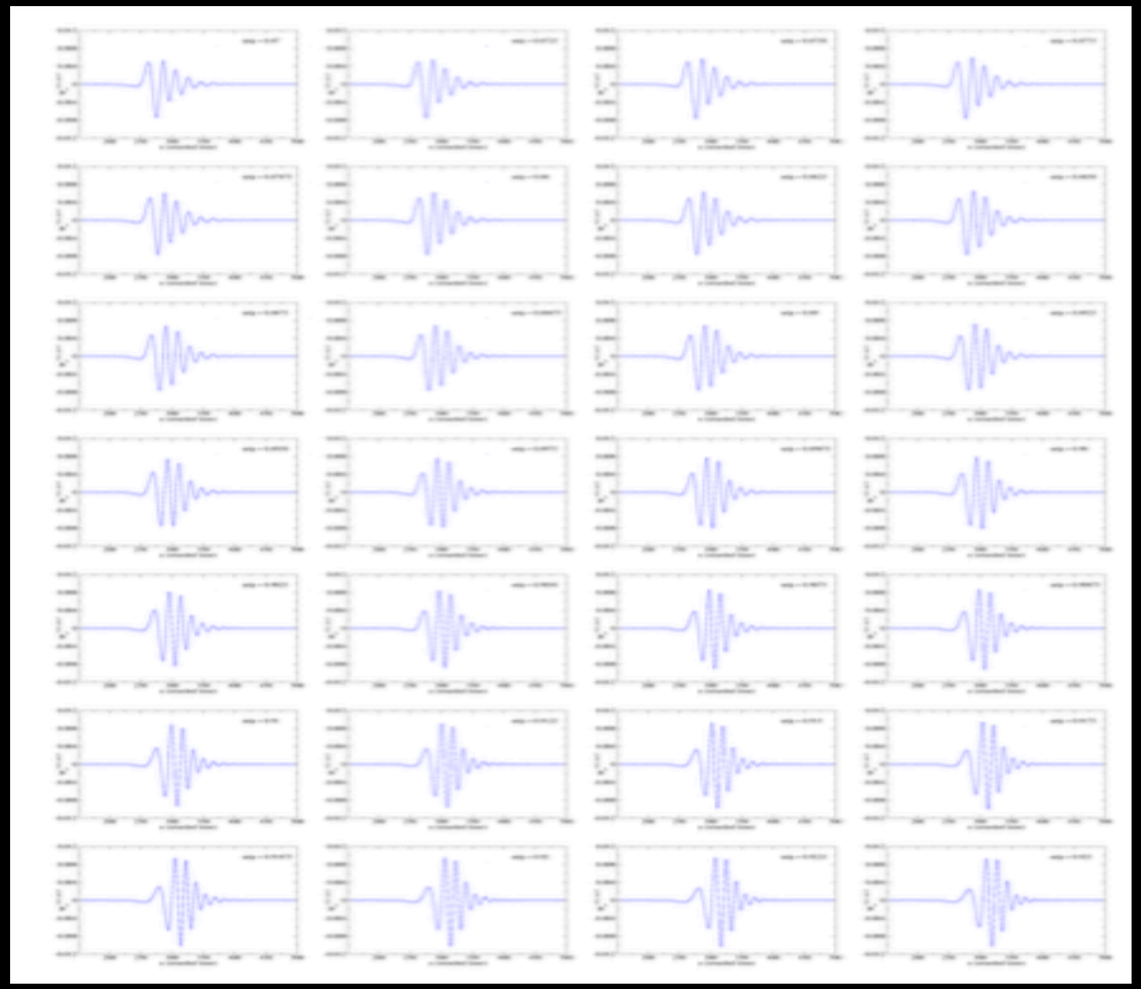
Spinning Proca star

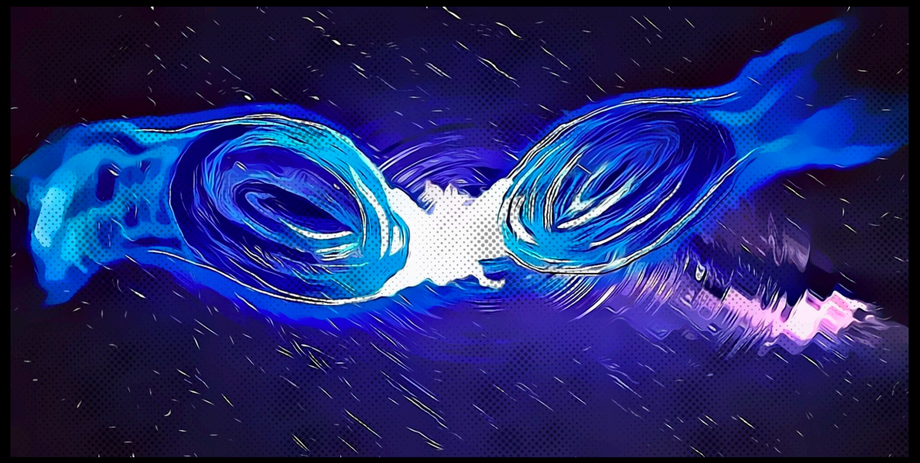


Spinning Scalar star (Unstable)


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]



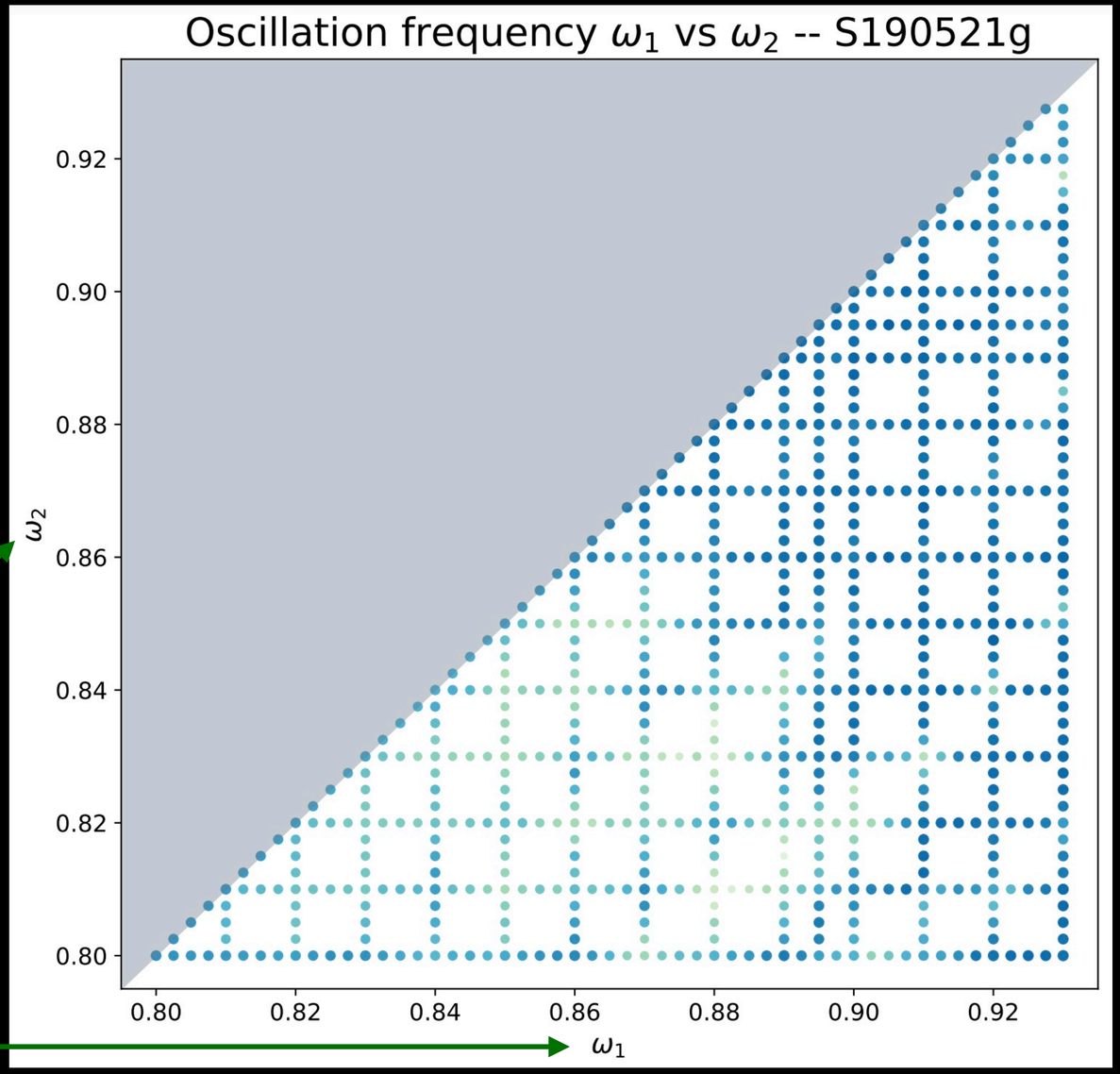


Equal-mass, equal field frequency (equal spin)

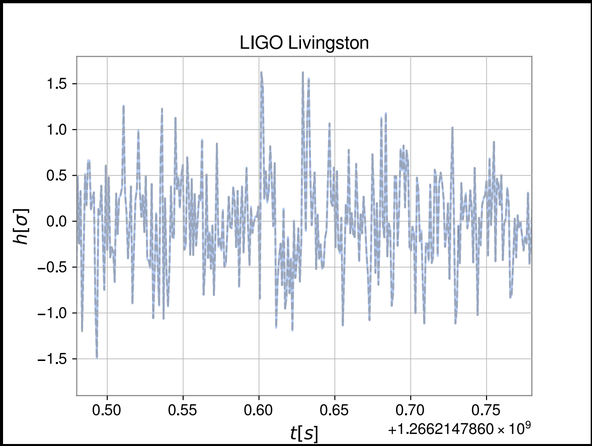
Initial separation = 100M

- 759 numerical (head-on) simulations
    - JCB+ 2020: reduced to 96 simulations
- Include (2,2), (2,0), (3,2), (3,3) modes

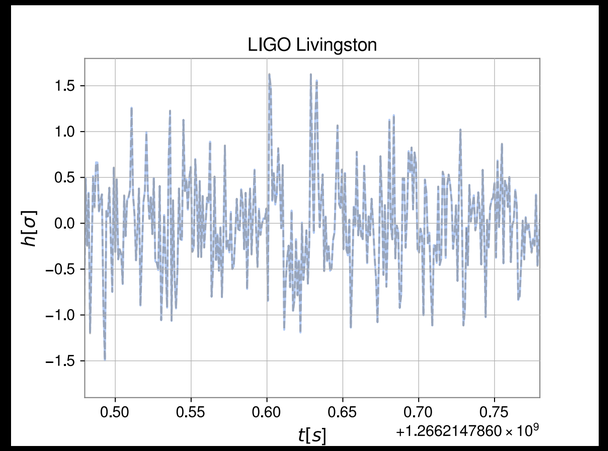
Star field frequencies



GW data


LIGO Livingston
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
h[σ]
0.50
0.55
0.60
0.65
0.70
0.75
t[s]
+1.2662147860 × 10^9

GW data



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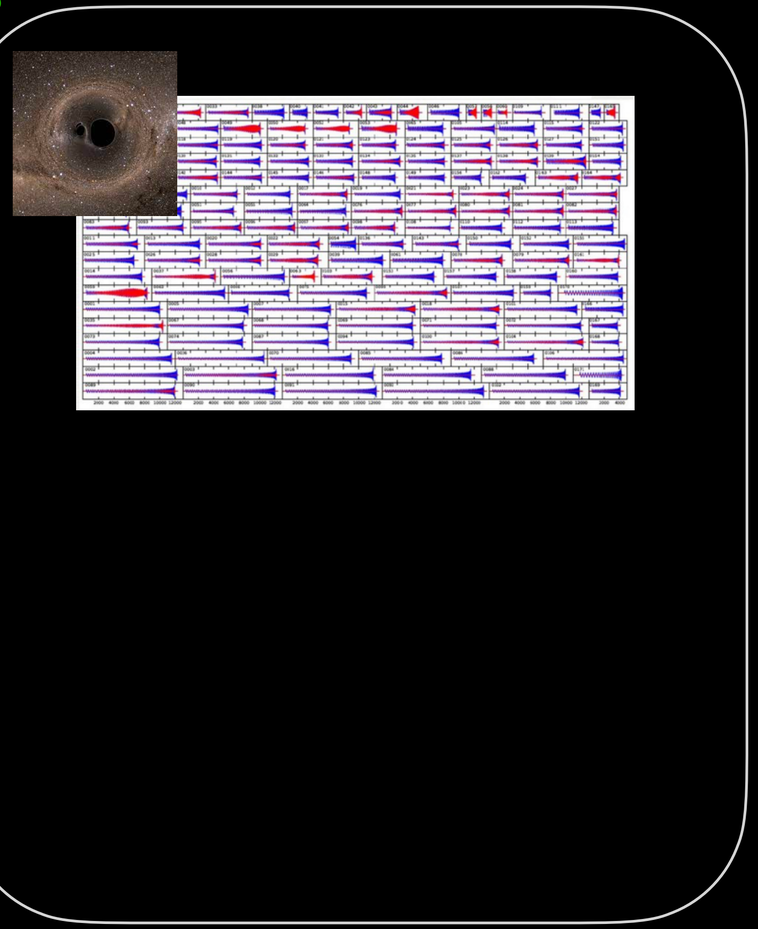
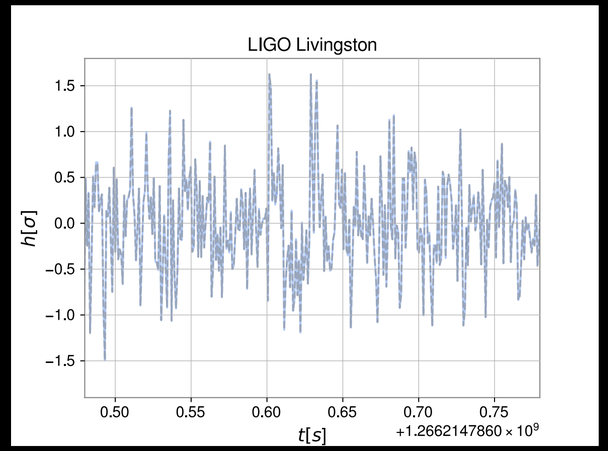
BBH Templates



GW data



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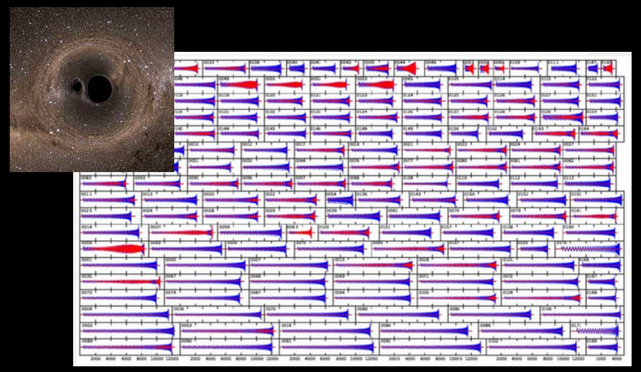
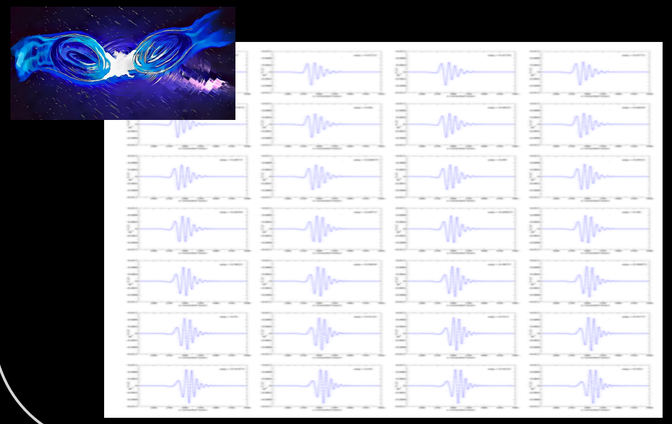
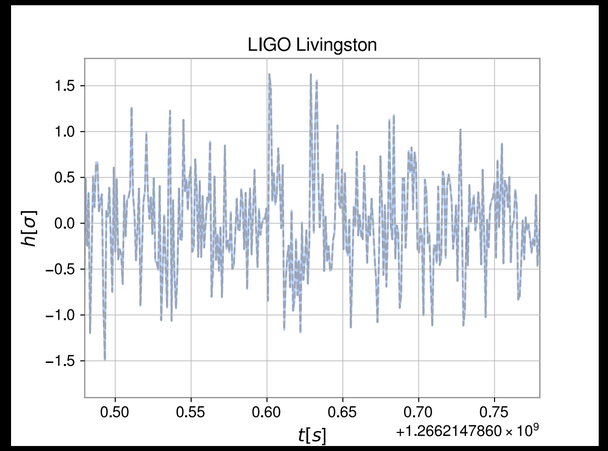


Proca-star Templates



GW data



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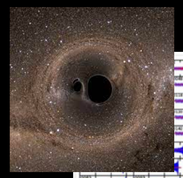
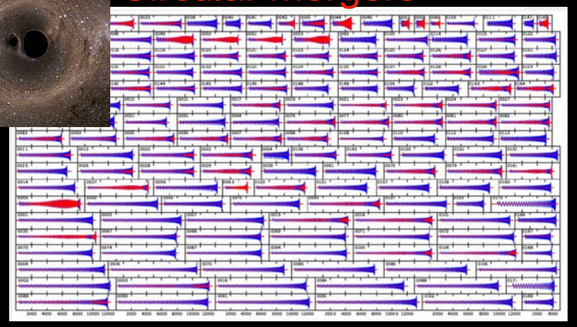
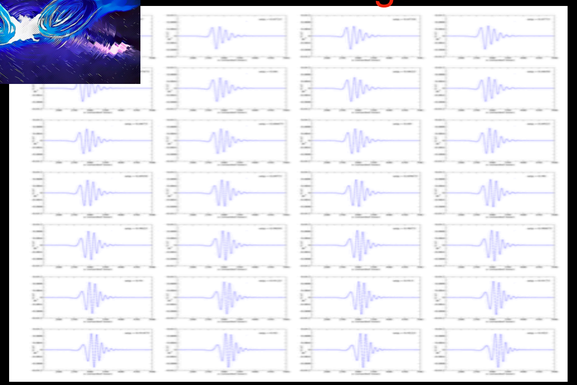
BBH Templates



Circular mergers



Head-on mergers



Proca-star Templates

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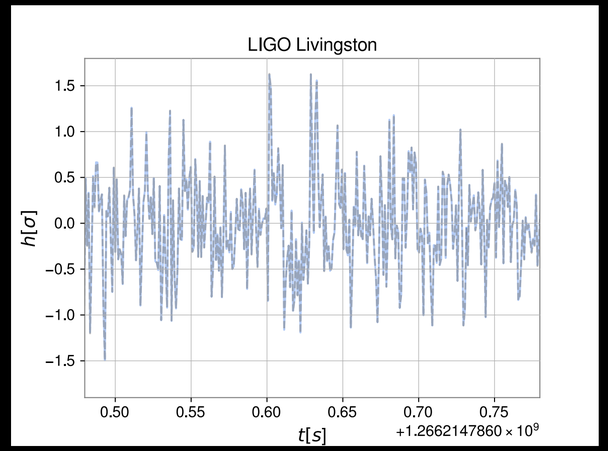

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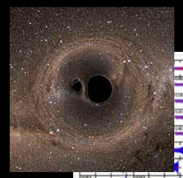

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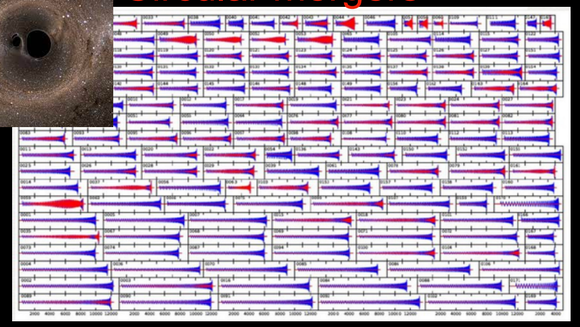

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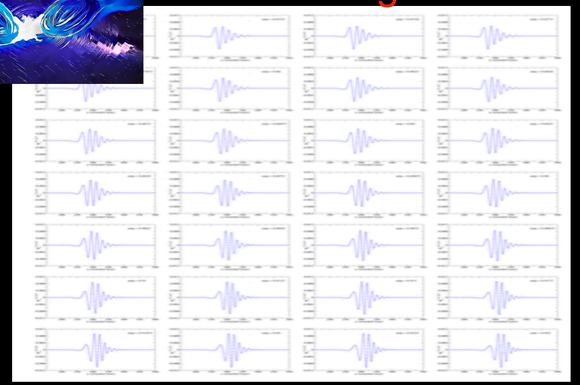


Proca-star Templates

=

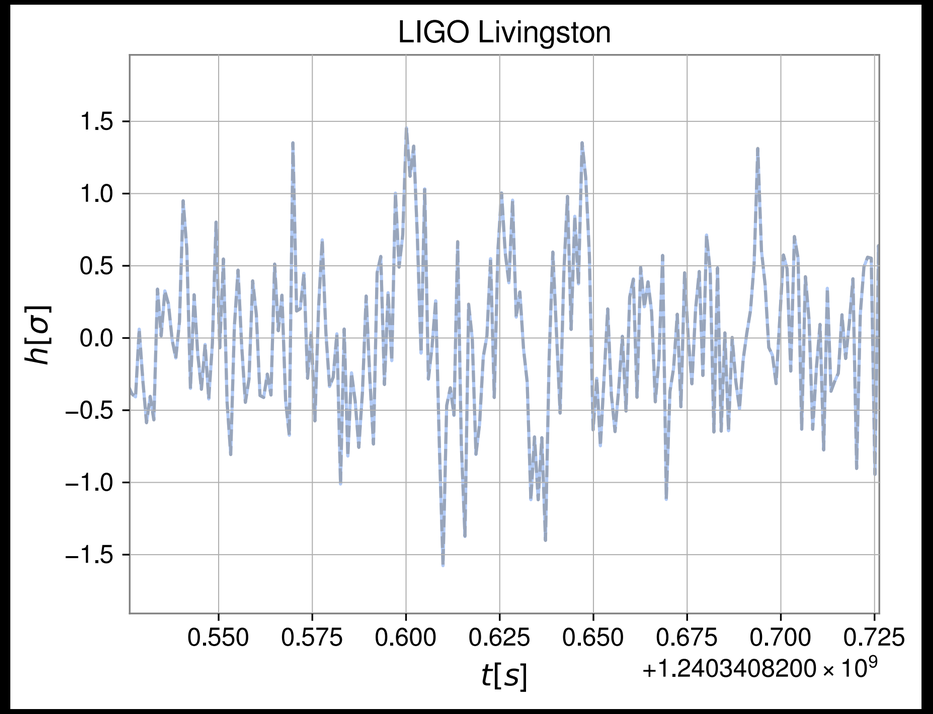
Results

Evidence

Proca-Star
vs.
Black-hole merger

Parameter estimates

- Analyse events beyond GW190521
  - GW200220 Part of the GWTC-3 catalogue (LVK 2021)
  - GW190426 Low significance (<1/year)
  - S200114f BBH estimate: 200Msun



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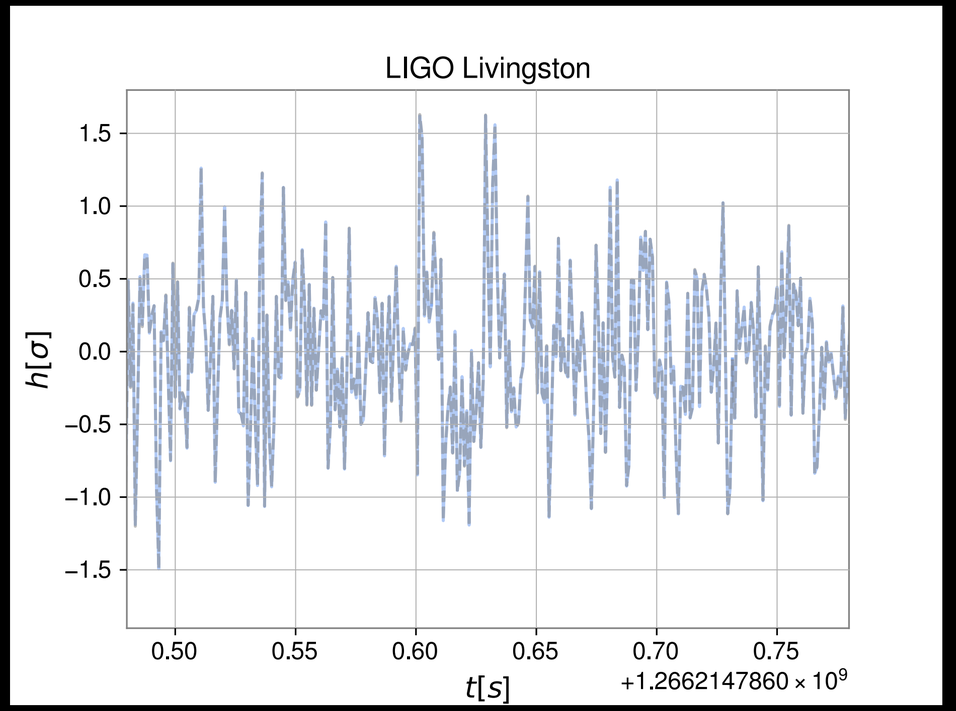
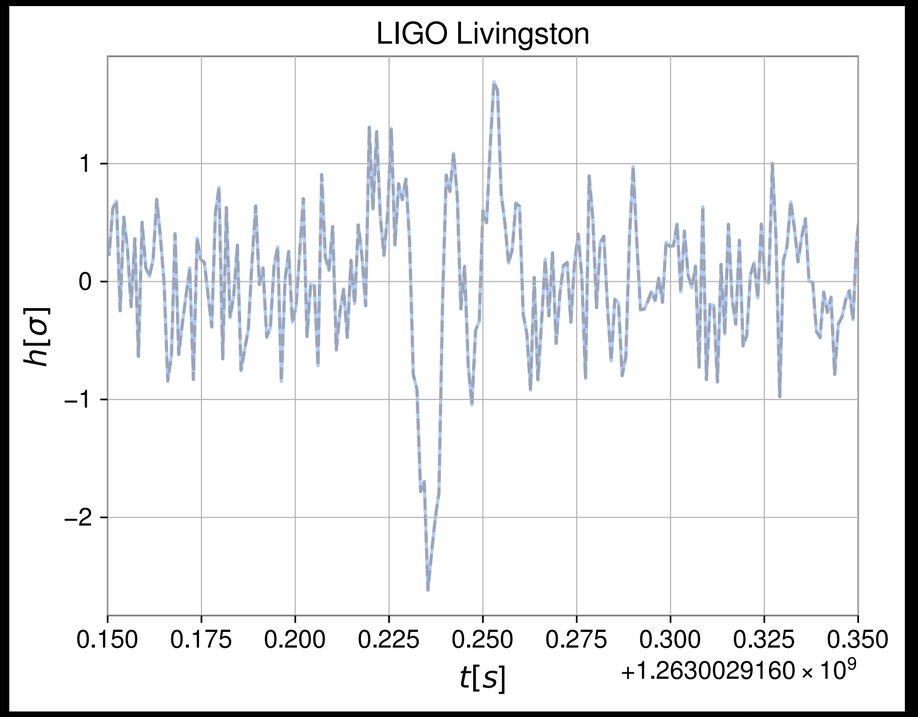
  - GW200220 Part of the GWTC-3 catalogue (LVK 2021)
  - GW190426 Low significance (<1/year)
  - S200114f Heaviest merger to date

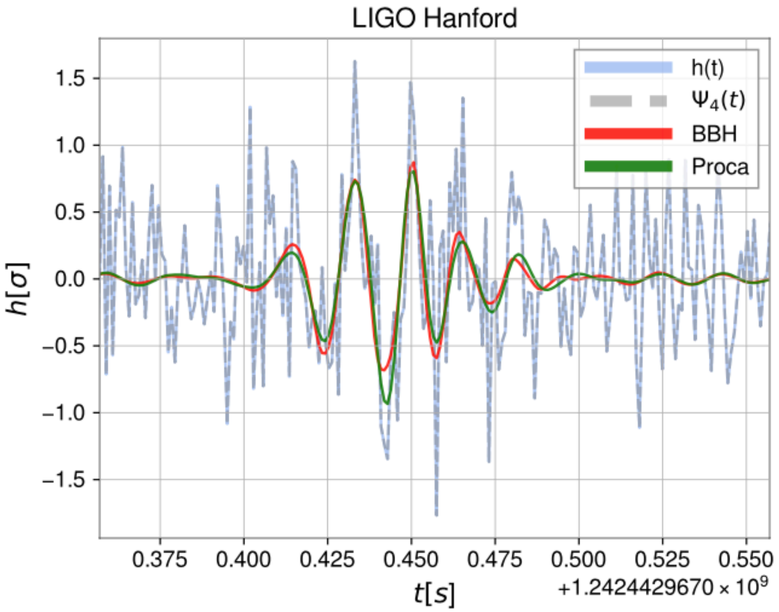


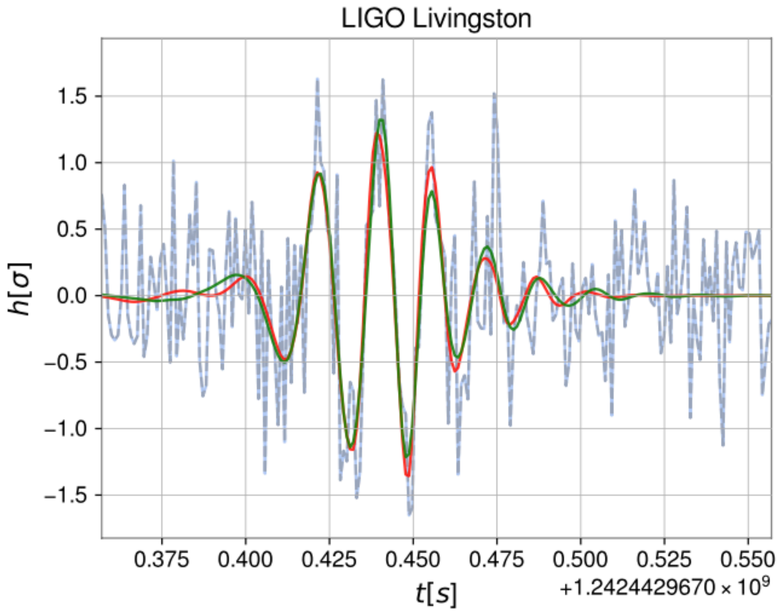
- Analyse events beyond GW190521
  - GW200220 — Not published as an event but as a loud trigger (Abbott+ 2022)
  - GW190426 — Significance much larger than other two events (1/30 year)
  - S200114f — Extremely challenging for our waveform models

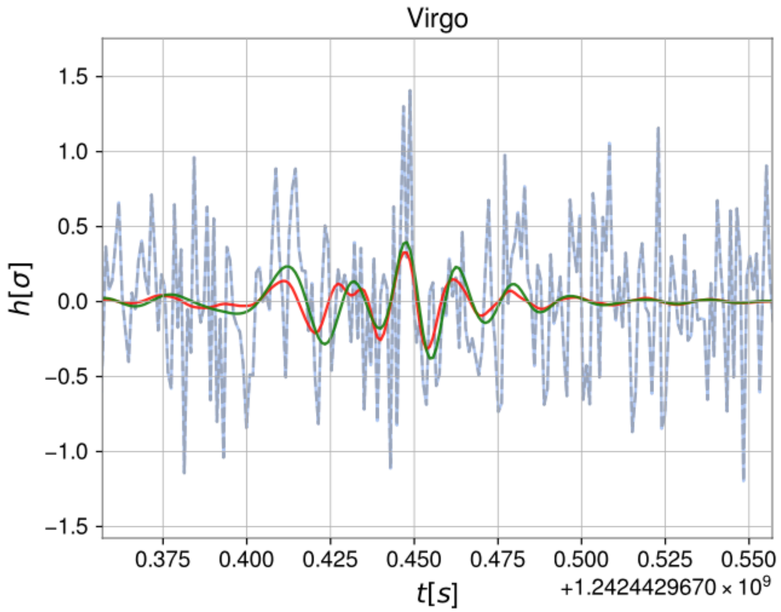
    Not ruled out as a gravitational-wave detection



Best-fit waveforms (GW190521)







Event	GW190521	GW190426	GW200220	S200114f
$\mathcal{B}^{\mathrm{Proca}}_{\mathrm{BBH}}$	2.5	2.0×10^{-4}	0.05	3.7

- Proca-Star mildly favoured: GW190521, S200114f
- Proca-Star mildly rejected: GW200220 (though see next)
- Proca-Star strongly rejected: GW190426

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	$173^{+19}_{-14}\ M_\odot$	$175^{+13}_{-11}\ M_\odot$

LVC (BBH)

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

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

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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	$173^{+19}_{-14}\ M_\odot$	$175^{+13}_{-11}\ M_\odot$

LVC (BBH)

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

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

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

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	$0.12^{+0.05}_{-0.04}$	$0.14^{+0.06}_{-0.05}$
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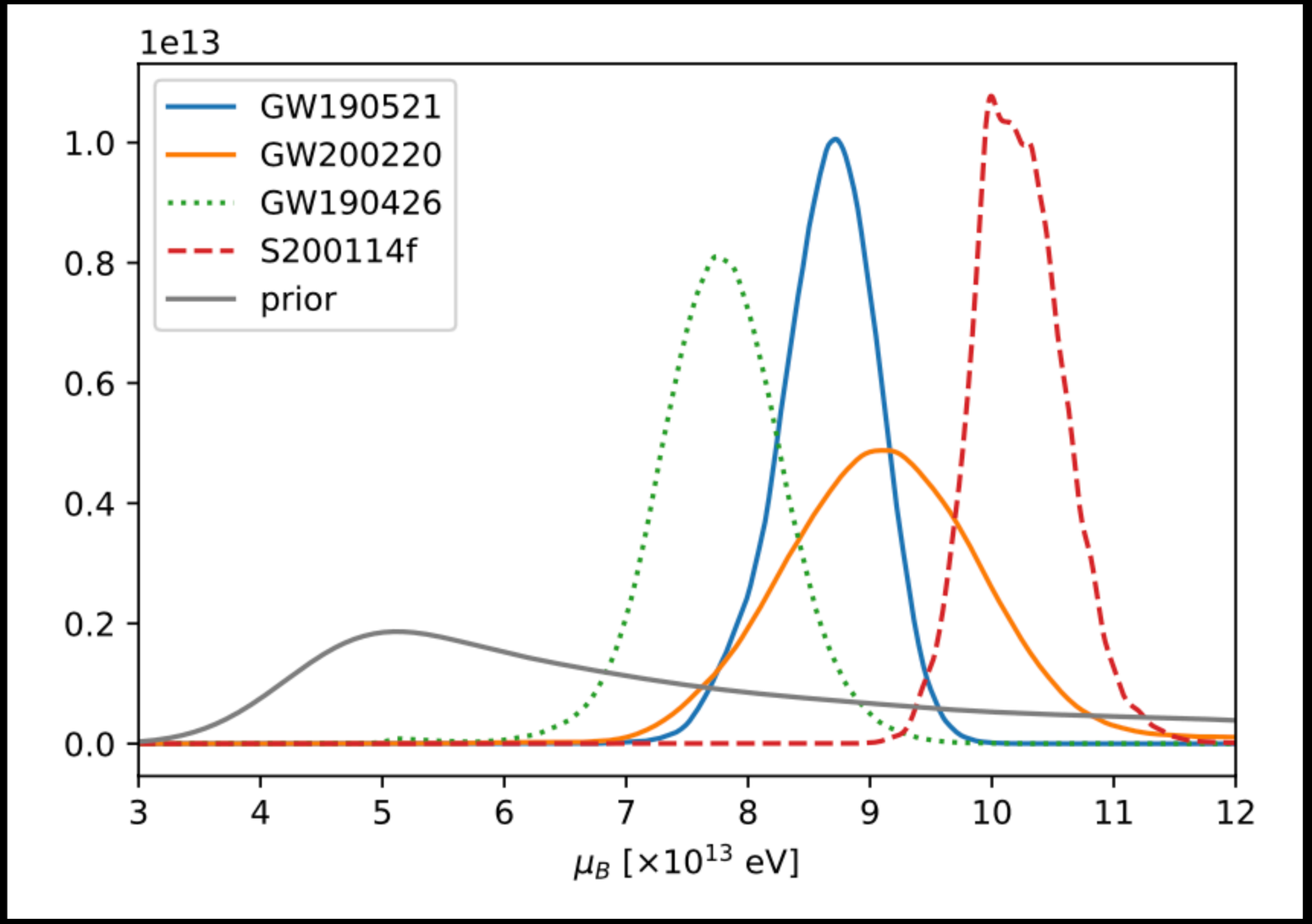
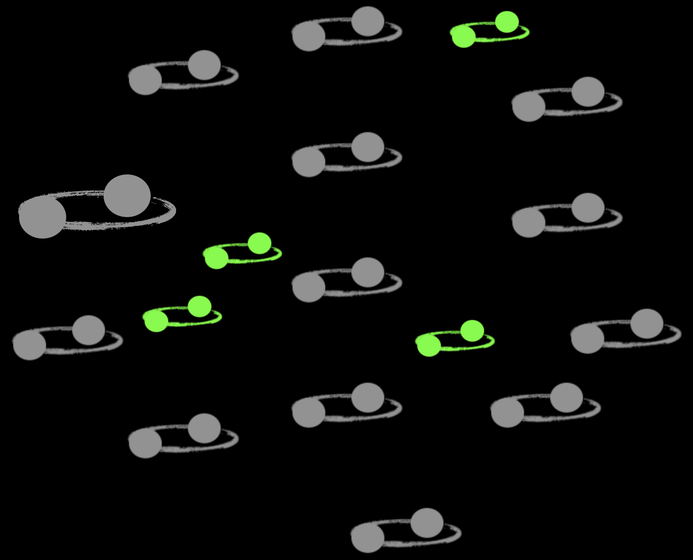
LVC (BBH)

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

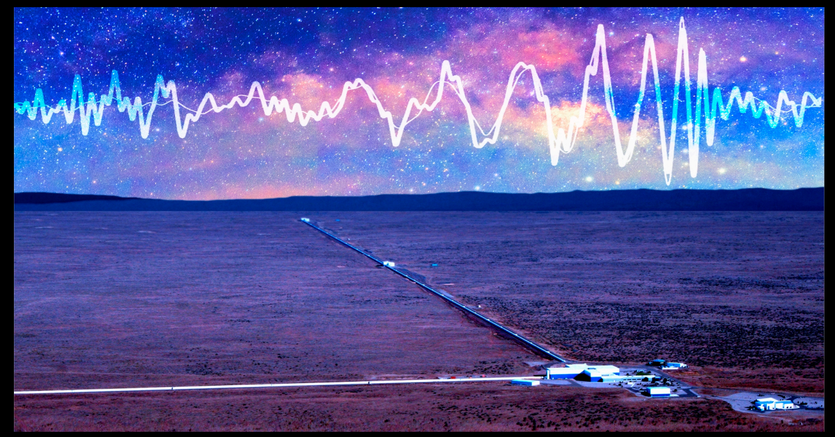
$5300^{+2600}_{-2400} Mpc$ Much closer than a BBH

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


1e13
GW190521
GW200220
GW190426
S200114f
prior
1.0
0.8
0.6
0.4
0.2
0.0
3
4
5
6
7
8
9
10
11
12
μ_B [$\times 10^{13}$ eV]

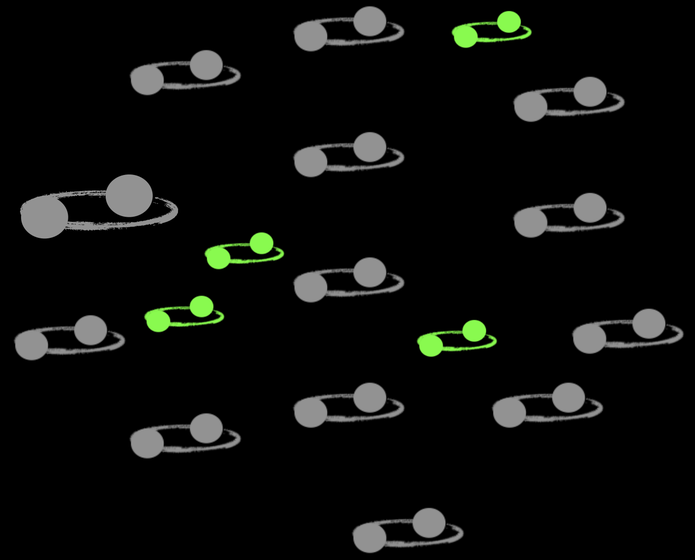


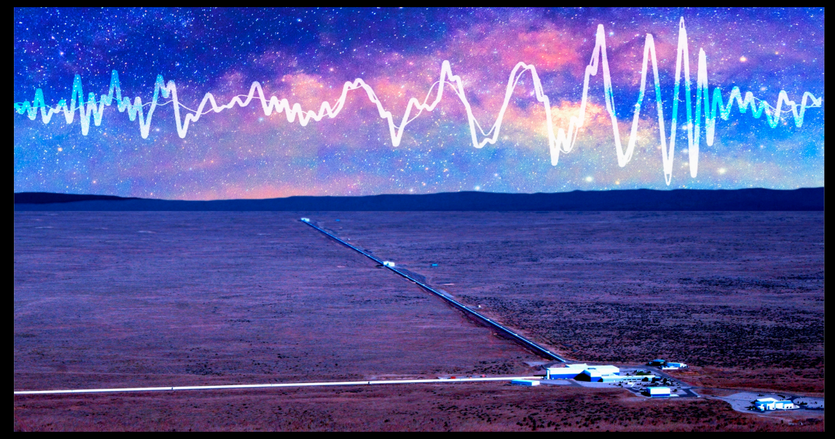
Event	GW190521	GW190426	GW200220	S200114f
$\mathcal{B}^{\text{Proca}}_{\text{BBH}}$	2.5	2.0×10^{-4}	0.05	3.7



- **Model:** population with given fraction ζ of Proca-star mergers.

$$p(\{d_i\}|\zeta) = \prod_{i=1}^{N} p(d_i|\mathrm{PSM})\zeta + p(d_i|\mathrm{BBH})(1-\zeta)$$
$$\propto \prod_{i=1}^{N} \mathcal{B}^{\mathrm{PSM}}_{\mathrm{BBH}}\zeta + (1-\zeta),$$





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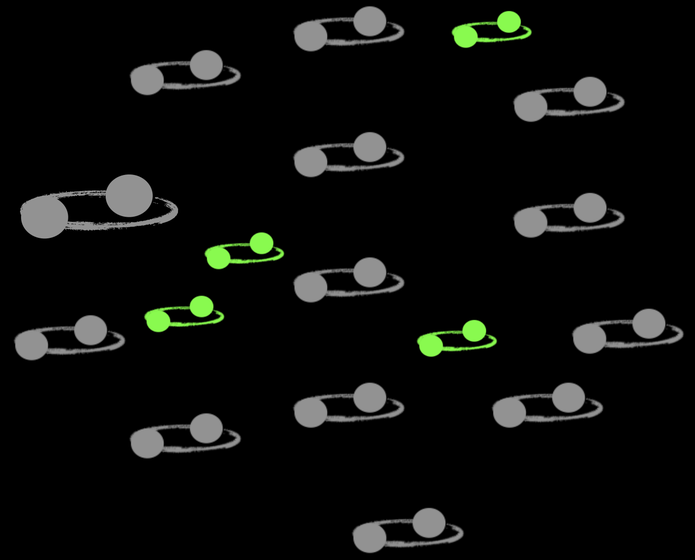

Figure out ζ

Event	GW190521	GW190426	GW200220	S200114f
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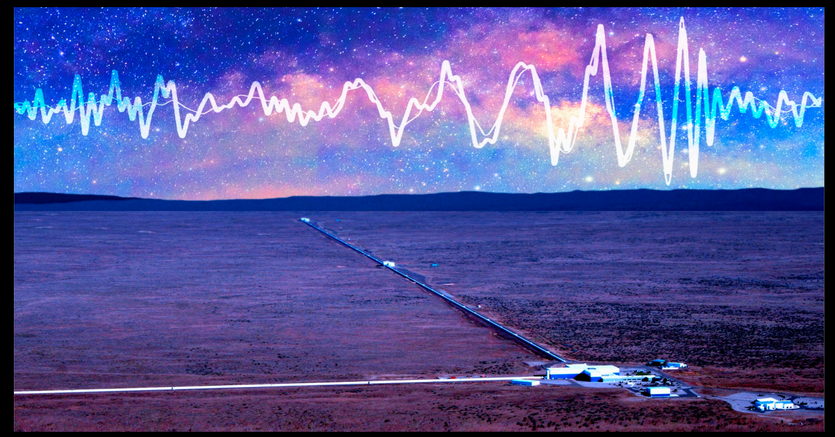

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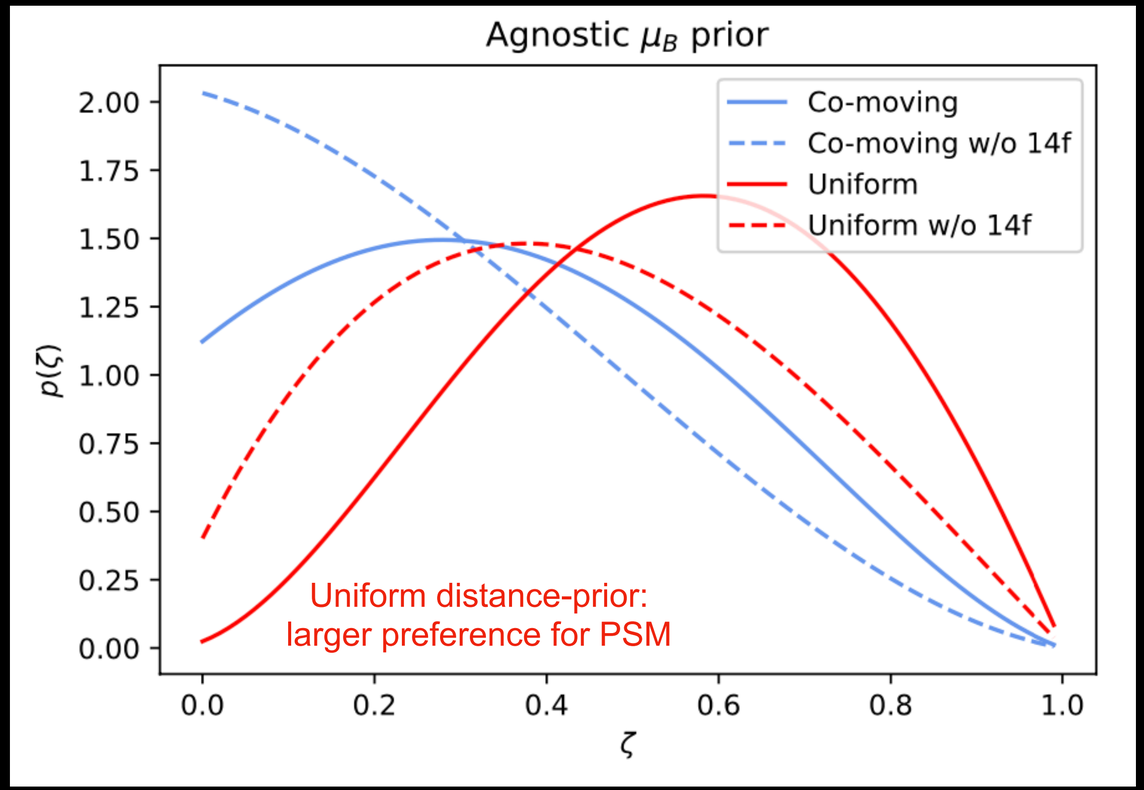
- Obtain **posterior distribution** for ζ
  - **Ignore** s200114f:
    - Only one event prefers PSM, population peaks at zero
    - Removing loudness bias: peaks at ~0.3



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  - **Ignore** s200114f:
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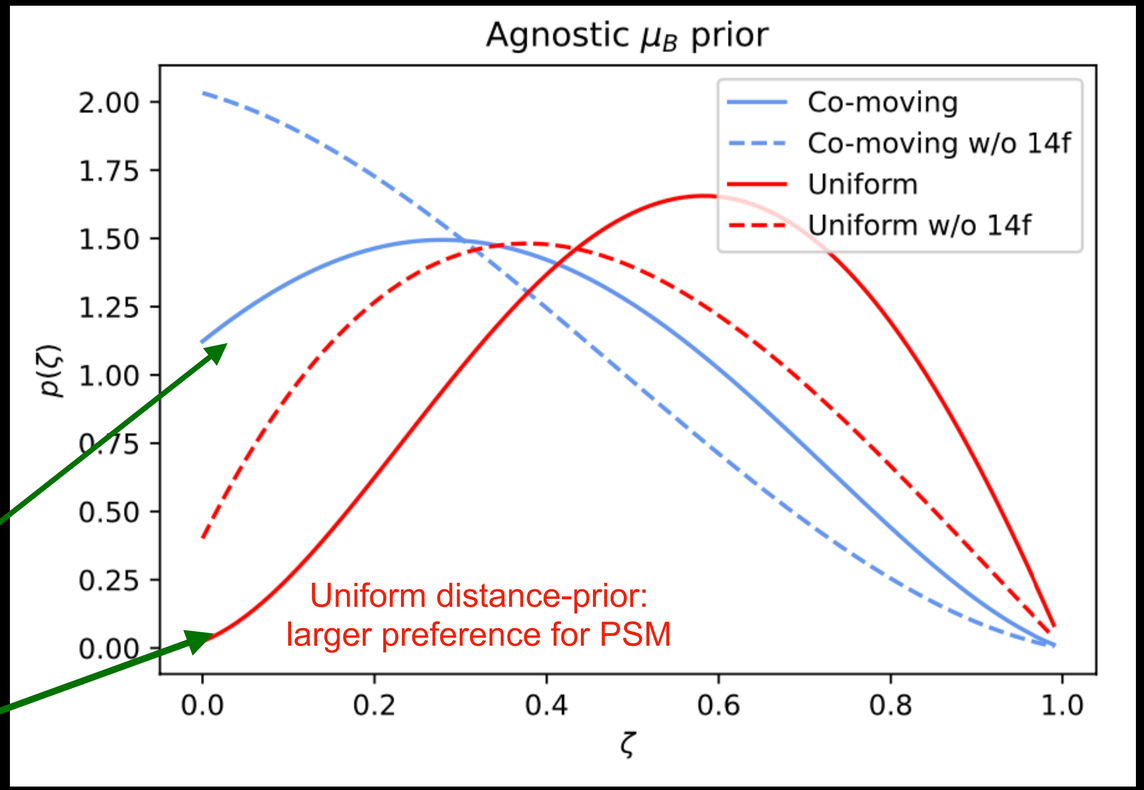
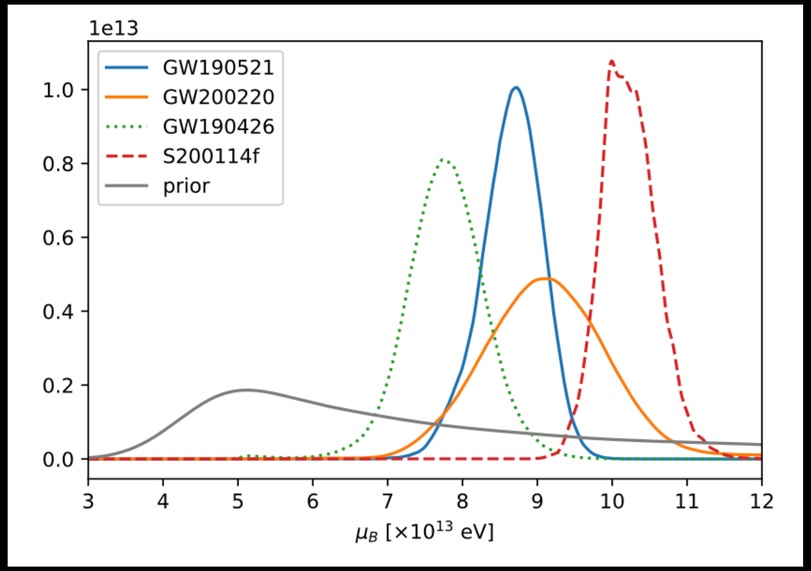
    - Removing loudness bias: peaks at ~0.3
  - Include s200114f:
    - Preference for PSM increases population fraction



- Can we **exploit mass-consistencies**? If so, one less parameter
  - Smaller Occam penalty for PSM model
  - Raise evidence for PSM vs. BBH model



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- **Proposal**: use the posterior for GW190521 (most significant event) as our prior
  - New PSM-evidence for each individual event:

GW190521 posterior

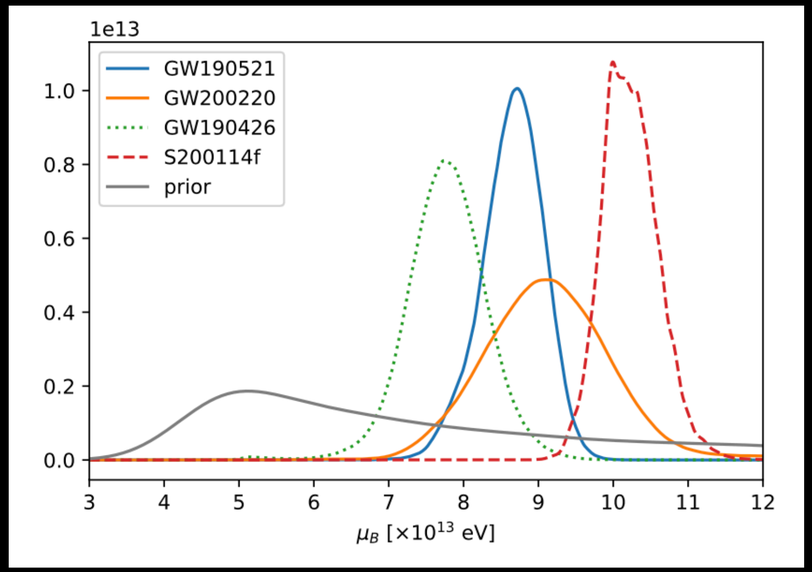
Original event posterior

Mass-Overlap integral (Ashton+ 20)

$$\mathcal{Z}_i^* = \mathcal{Z}_i \int p^{\mathrm{GW190521}}(\mu_\mathrm{B}) \frac{p(\mu_\mathrm{B})}{\pi(\mu_\mathrm{B})} \mathrm{d}\mu_\mathrm{B} = \mathcal{I}_{\mu_\mathrm{B}}^{\mathrm{GW190521},i} \mathcal{Z}_i$$

Original evidence

Original prior



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GW190521 posterior — Original event posterior — Mass-Overlap integral (Ashton+ 20)

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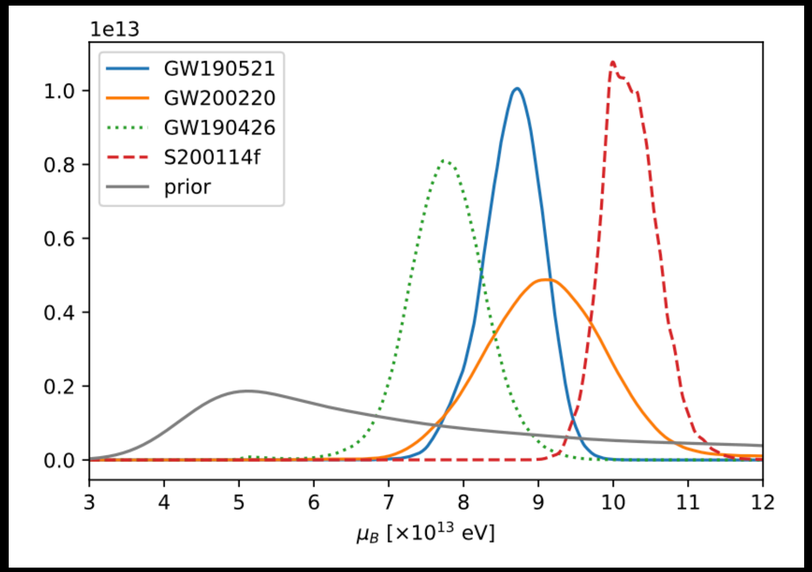
Original evidence — Original prior

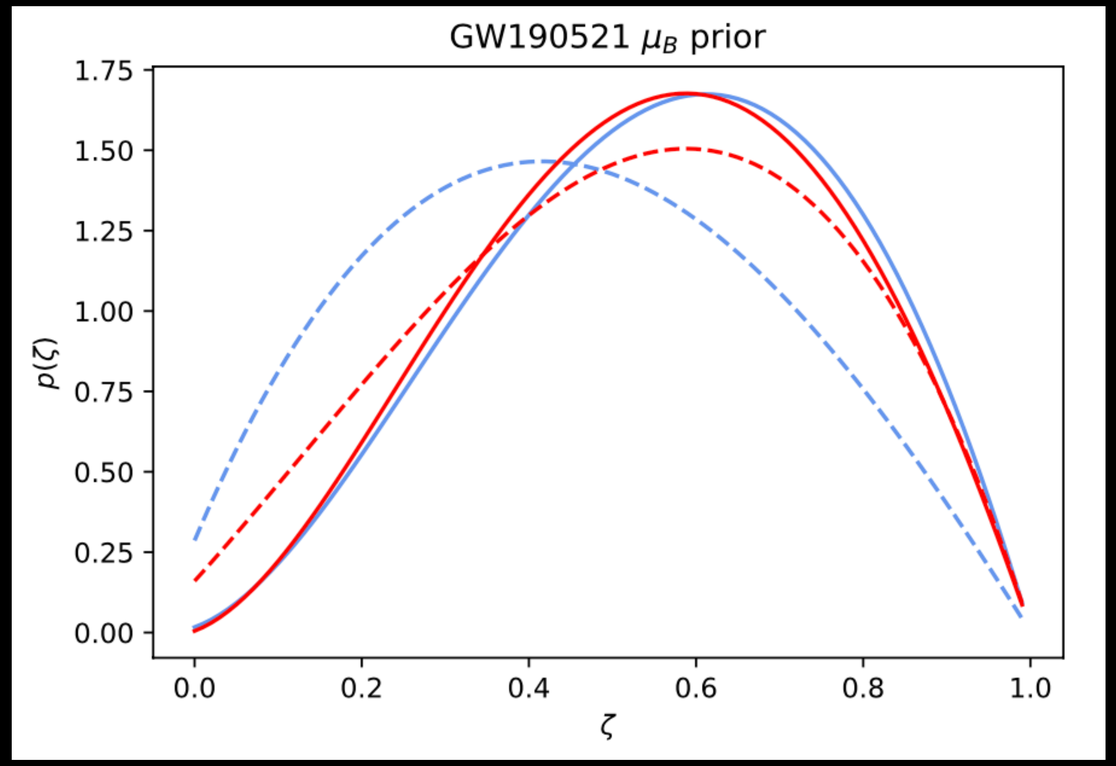


GW190521 + GW200220: $\mathcal{I} = 5.5$

GW190521 + GW190426: $\mathcal{I} = 3.1$

GW190521 + S200114f: $\mathcal{I} = 0.1$

- **Consistent mass across all events except 200114f**
  - Pushes PSM evidence
    - Pop. Fraction peaks away from zero
- **Inconsistent mass for s200114f**:
  - Penalises s200114f
  - Not much difference between including and including it
- **Also:** evidence for GW190521 “artificially” increased due to using its posterior as its own prior
  - Just a proof-of-concept study to exploit mass-consistencies



- **Next step** (working on it): more agnostic approach. Sample over population fraction(s) and boson mass(es)

- Some LIGO-Virgo detections are challenging to interpret as black-hole mergers

  Boson (Proca)-stars are one of the simplest black-hole mimickers

  Ultralight bosons are good candidates to form dark matter

- Catalog of boson-star simulations available (restricted to head-on mergers)

- Analysed GW190521: consistent with boson-star merger + boson mass estimate

  First systematic comparison of LIGO-Virgo events to beyond BH models

- Will analyse future events: exploit boson-mass consistencies

- Targeted searches

- Proca field is complex: there is a phase $\phi(t)$ characterising the star
  - Relative phase $\Delta\phi(t) = \phi_1(t) - \phi_2(t)$ controls how stars interact, specially at merger
  - In all previous cases $\Delta\phi(t = 0) = 0$
  - However $\Delta\phi(t_{merger})$ varies across our catalog

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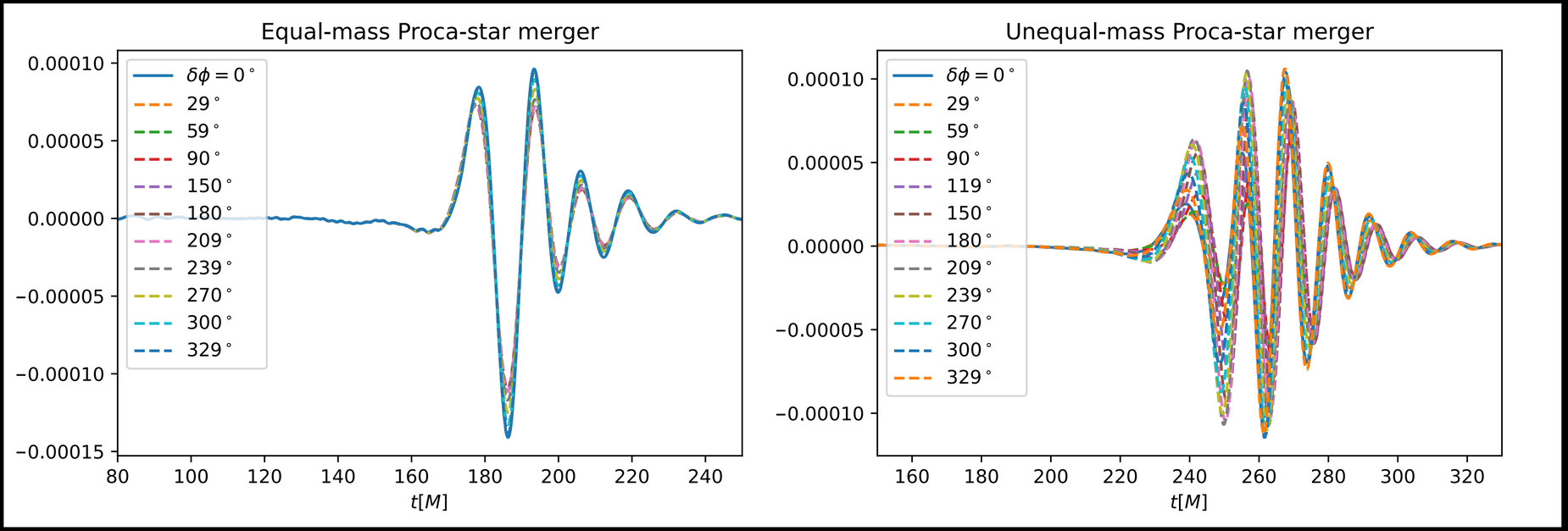

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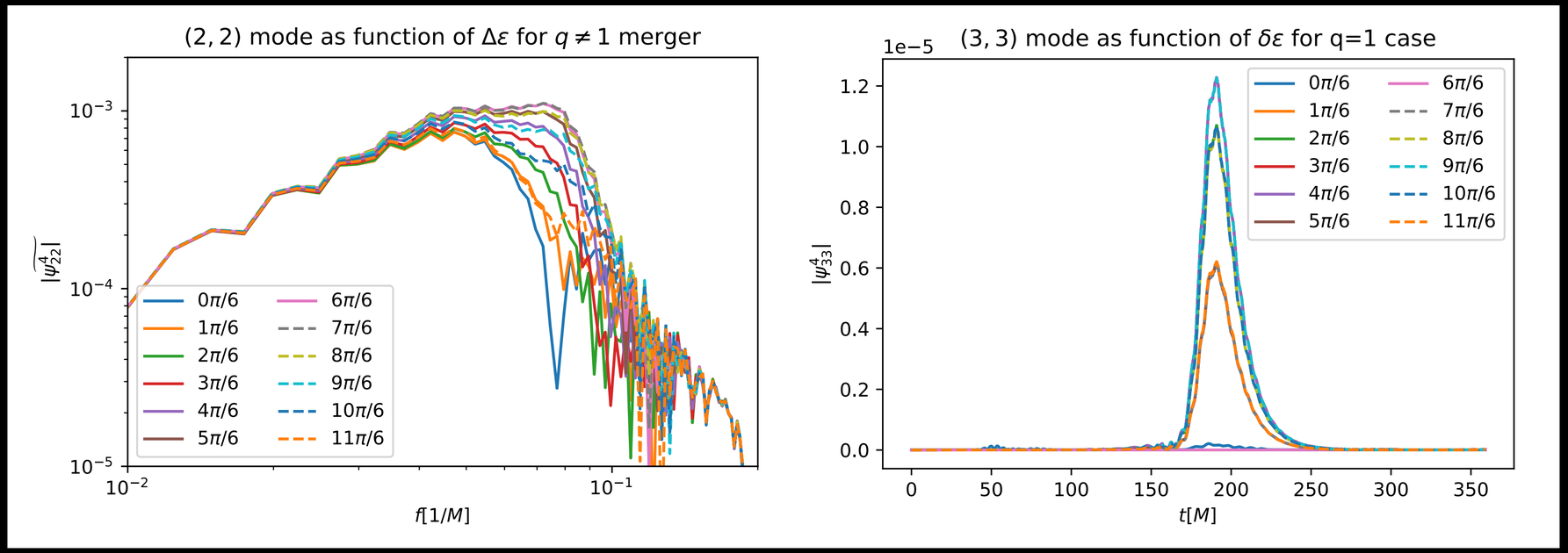
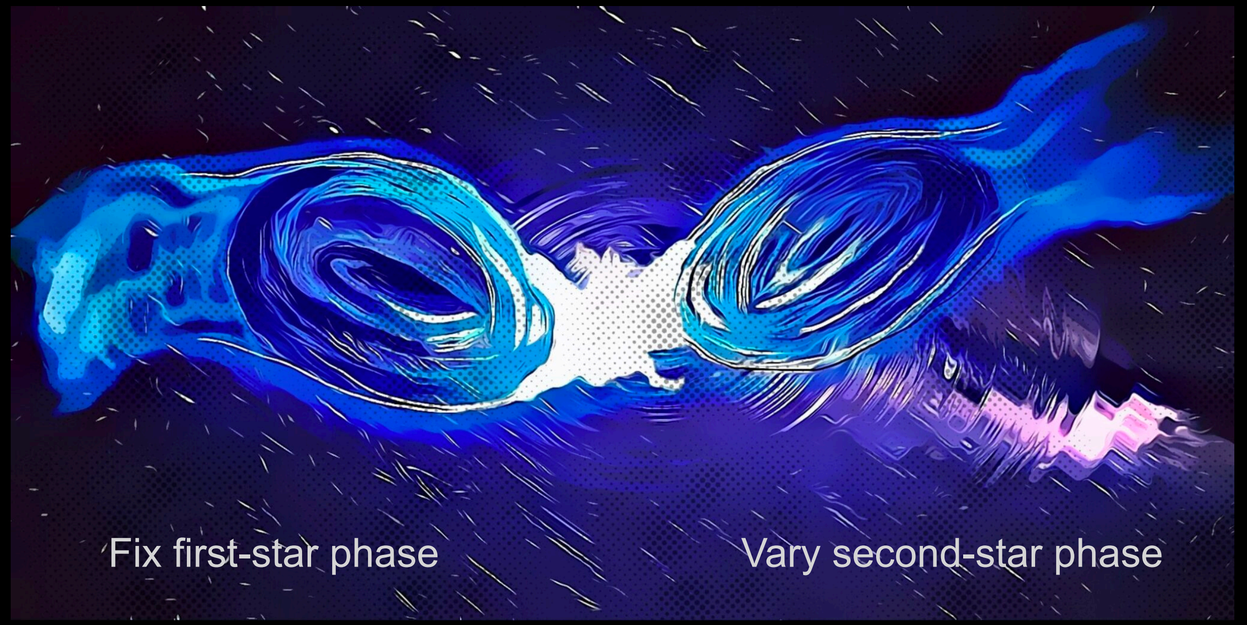


- Perform simulations for varying $\Delta\phi(t_{initial})$
  - Ideally, do this for all of our initial catalog
  - For now: 12 selected cases
    - Working on a ~3000 simulation catalog
  - Bayesian inference on GW190521



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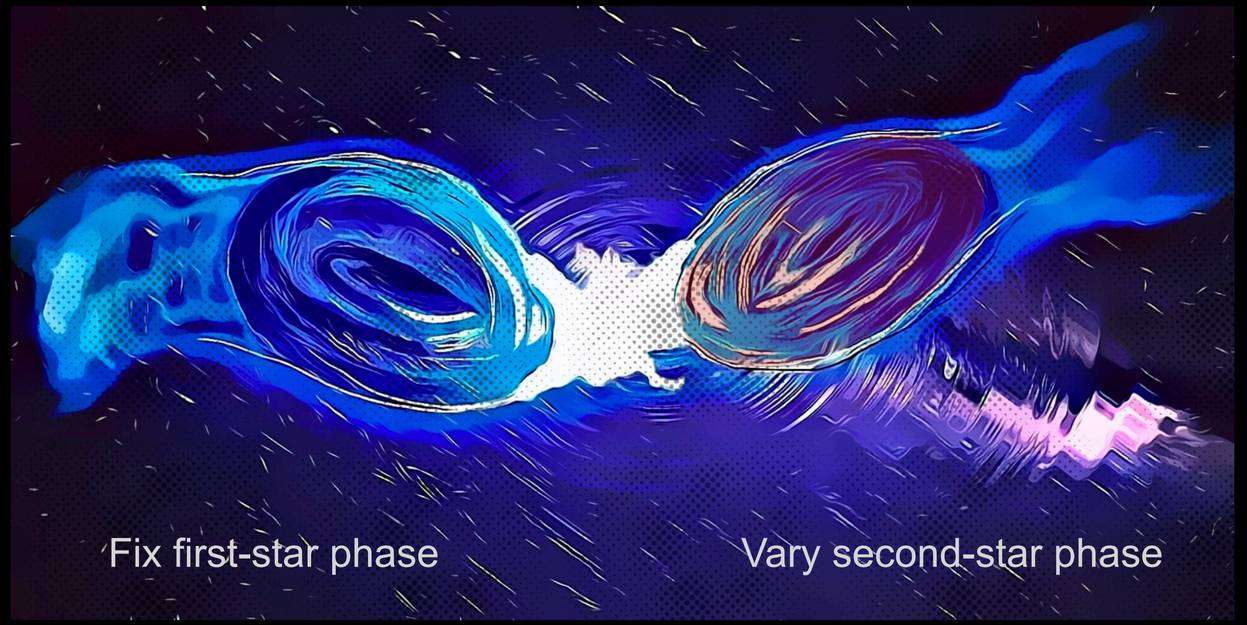

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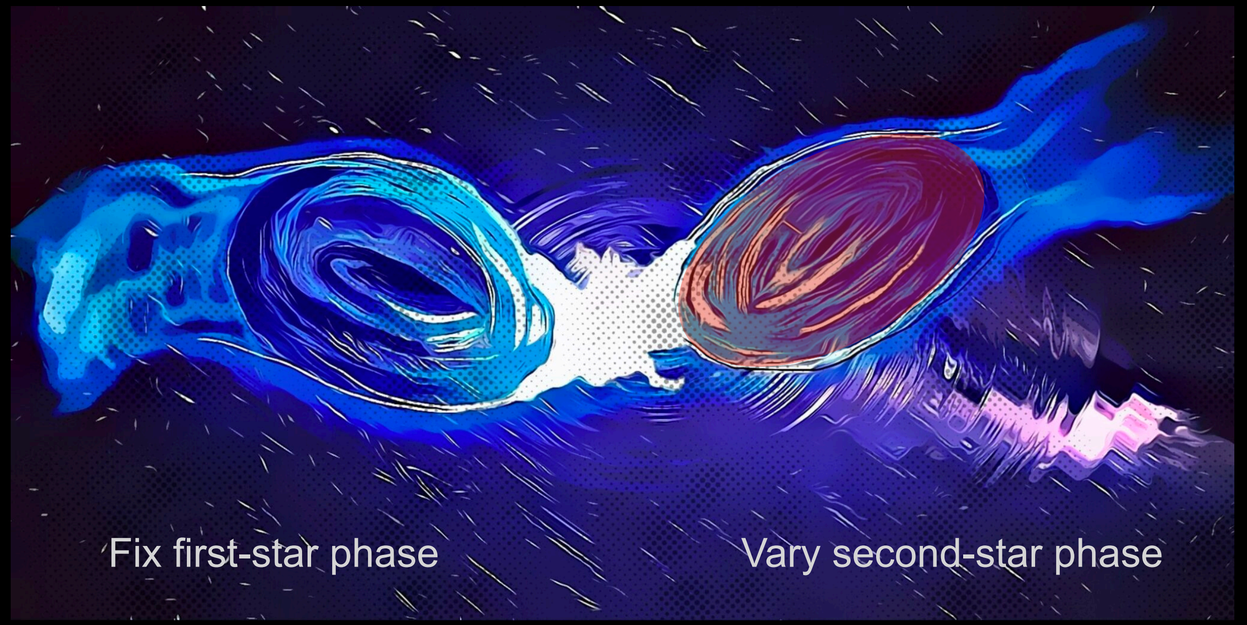

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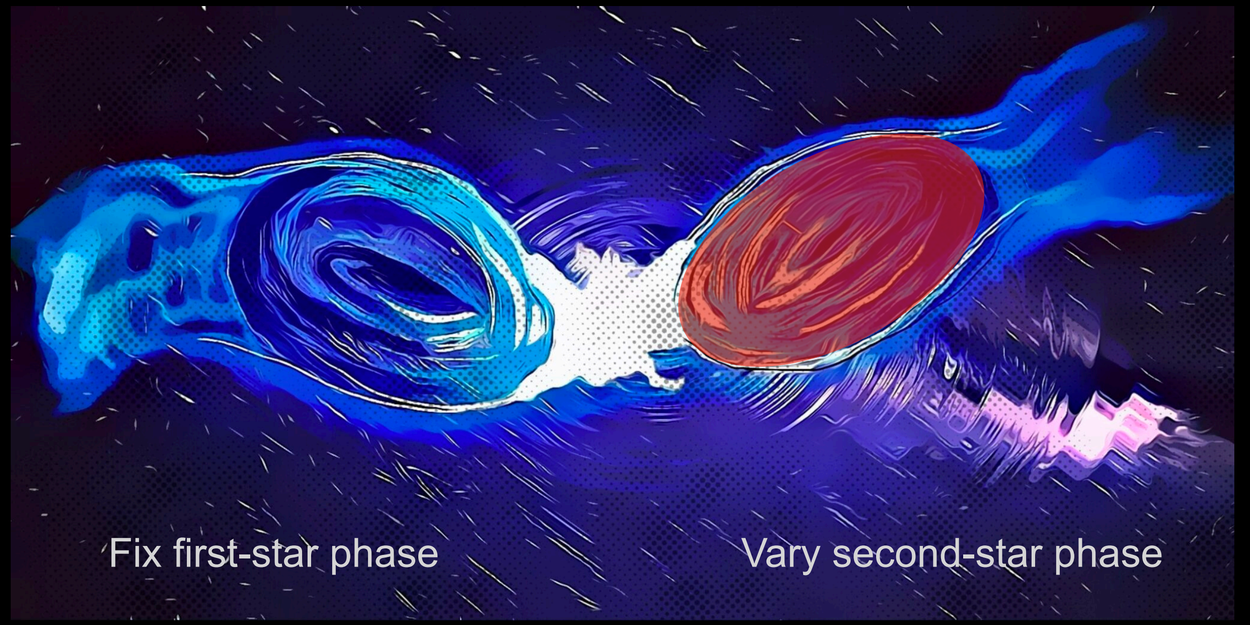

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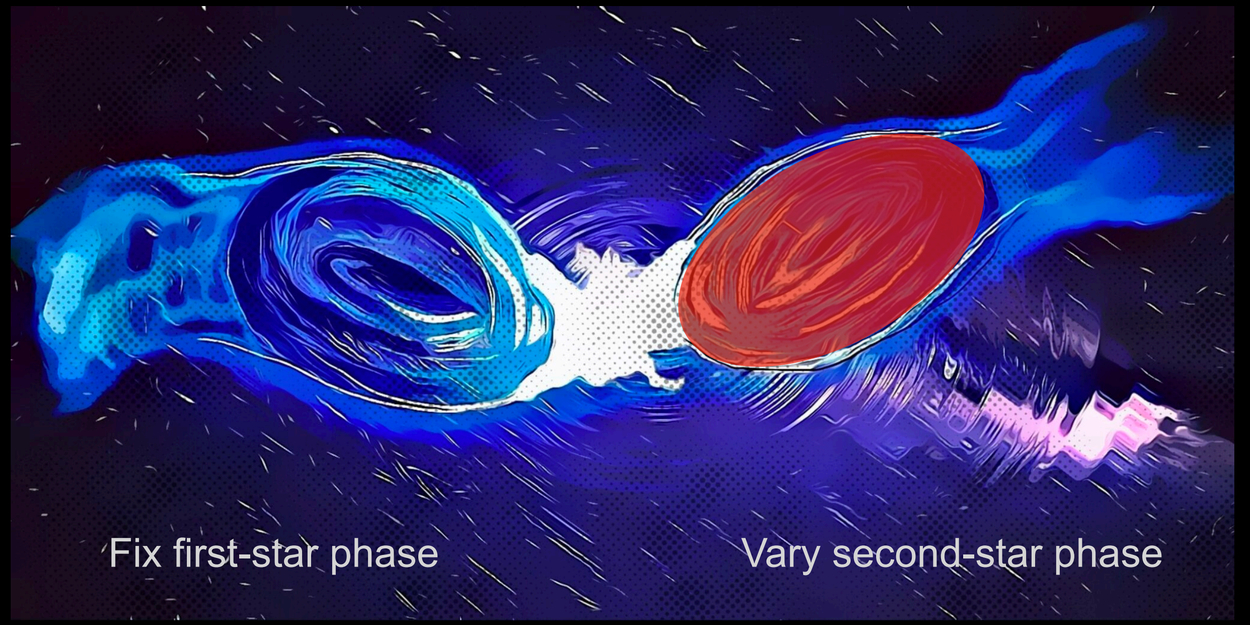

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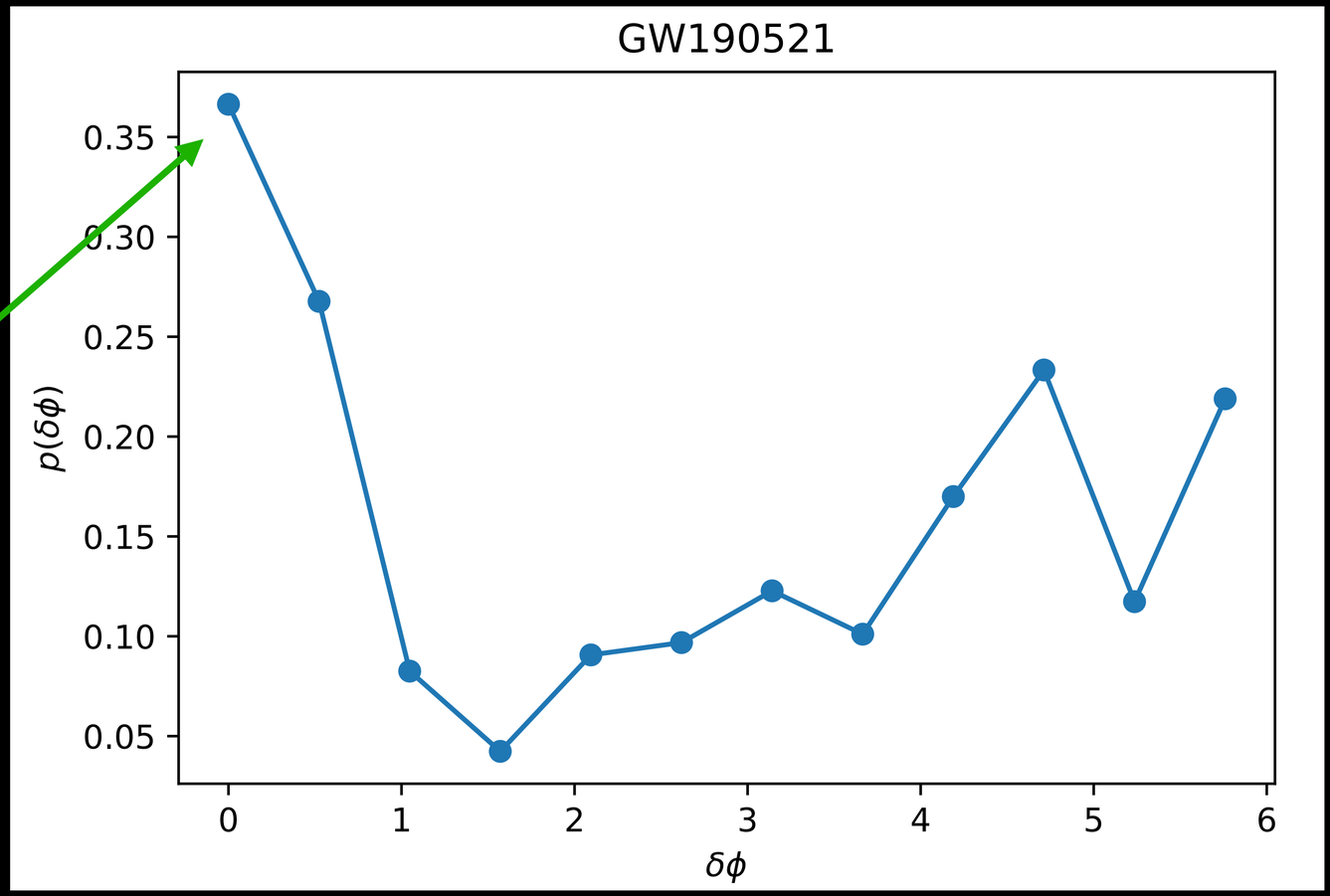
Preference for null phase difference: “no wave-nature” evidence



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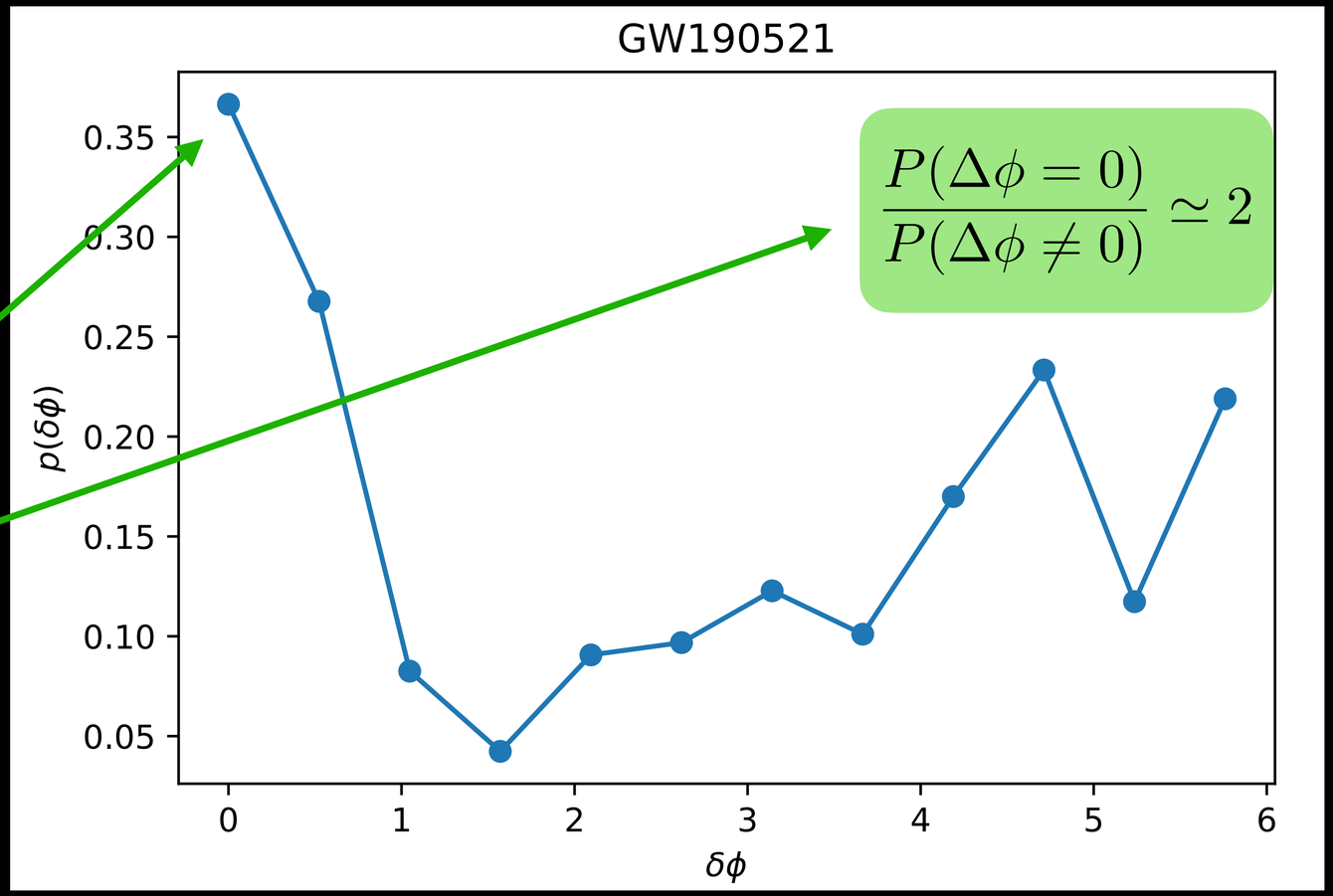
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