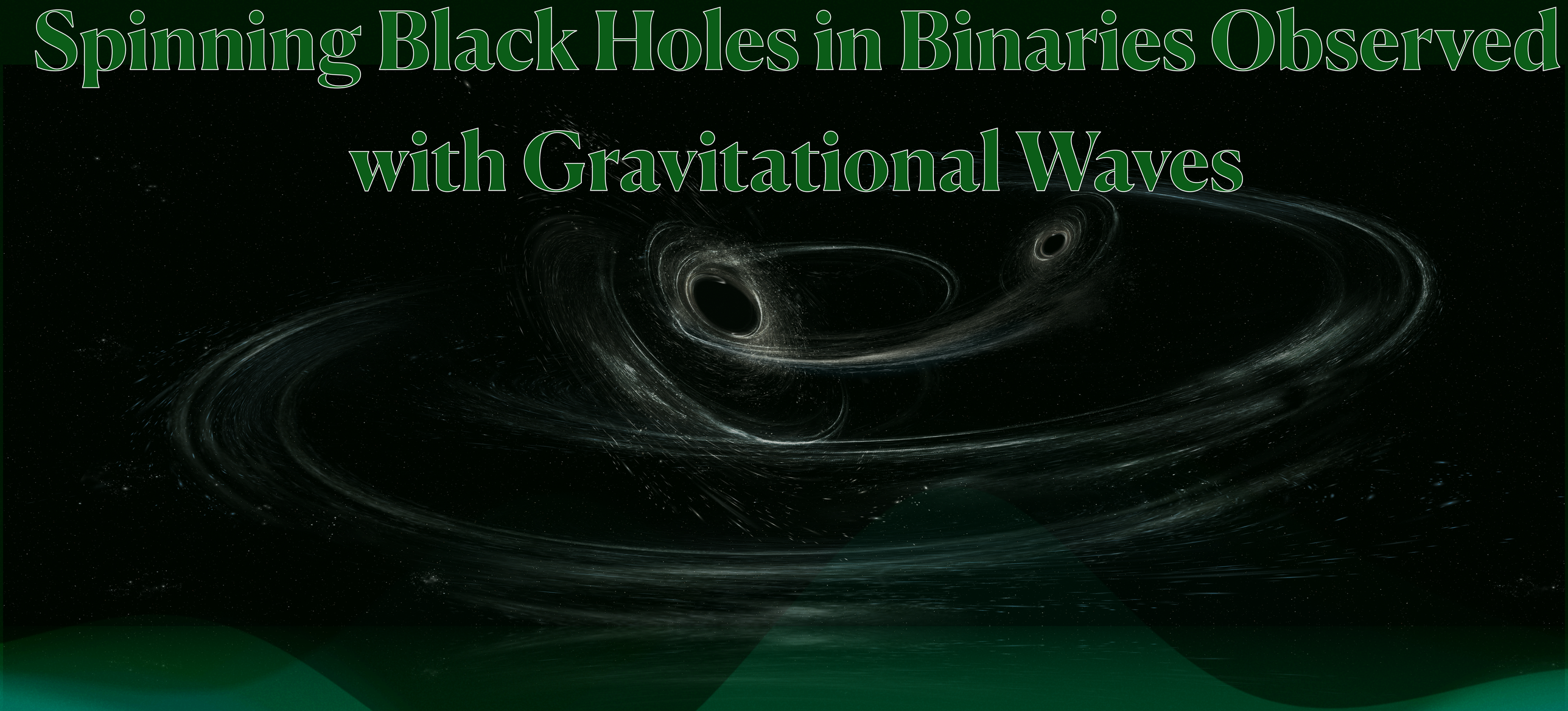
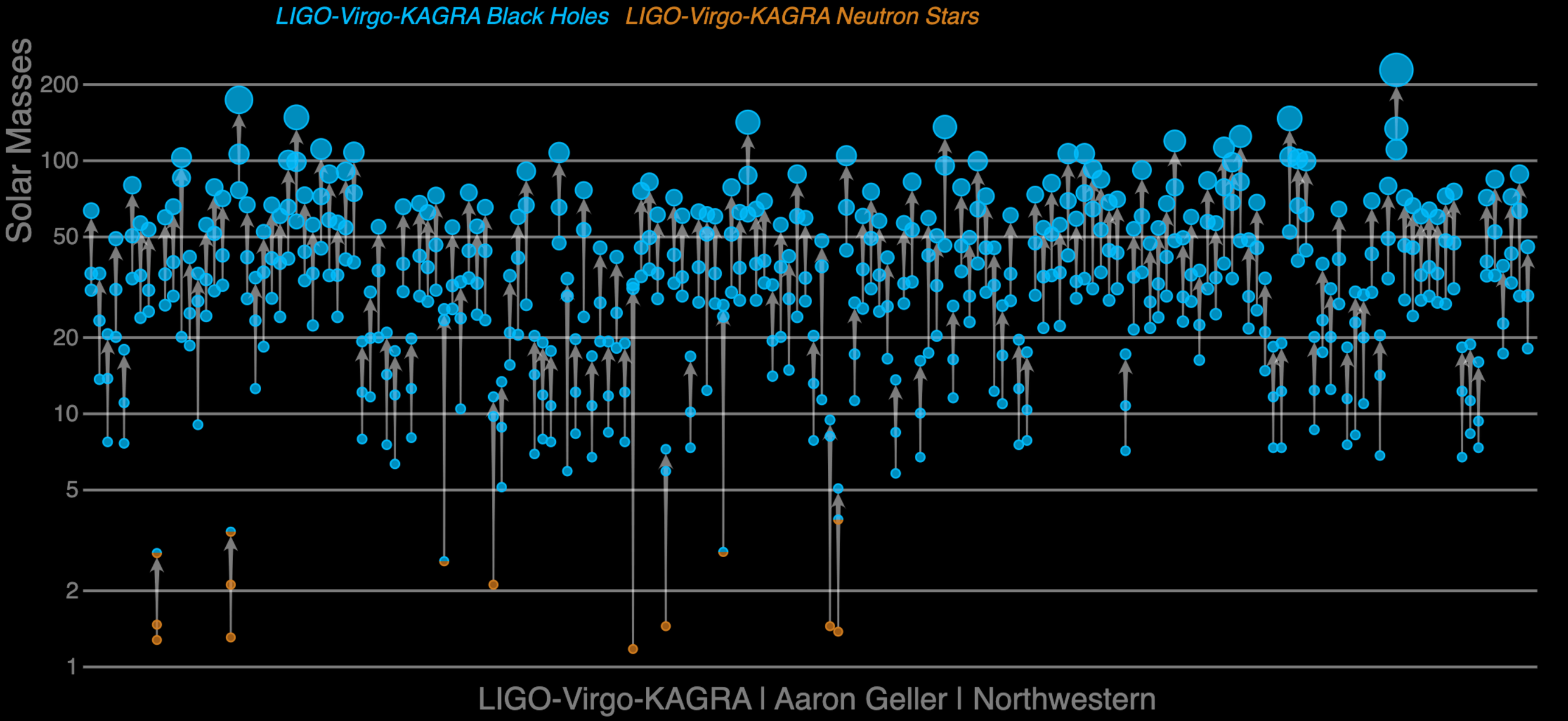
Spinning Black Holes in Binaries Observed with Gravitational Waves



Katerina Chatziioannou
Caltech

NEB-21
September 1, 2025

Masses in the Stellar Graveyard



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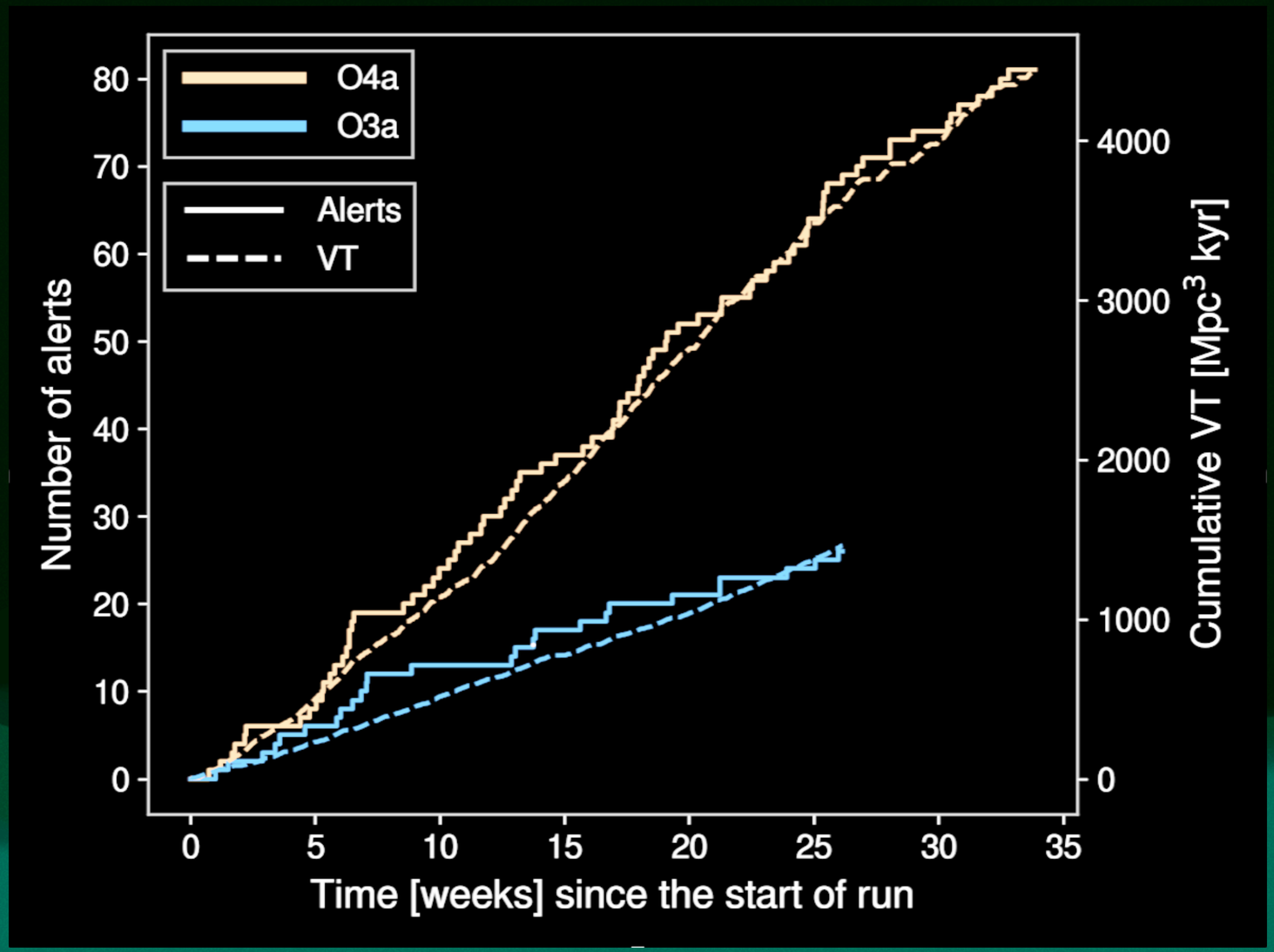
Accelerating Growth

$$\text{Sensitivity} \sim \frac{1}{R}$$

$$\#\,\text{of detections} \sim R^3$$

LVC/Derek Davis

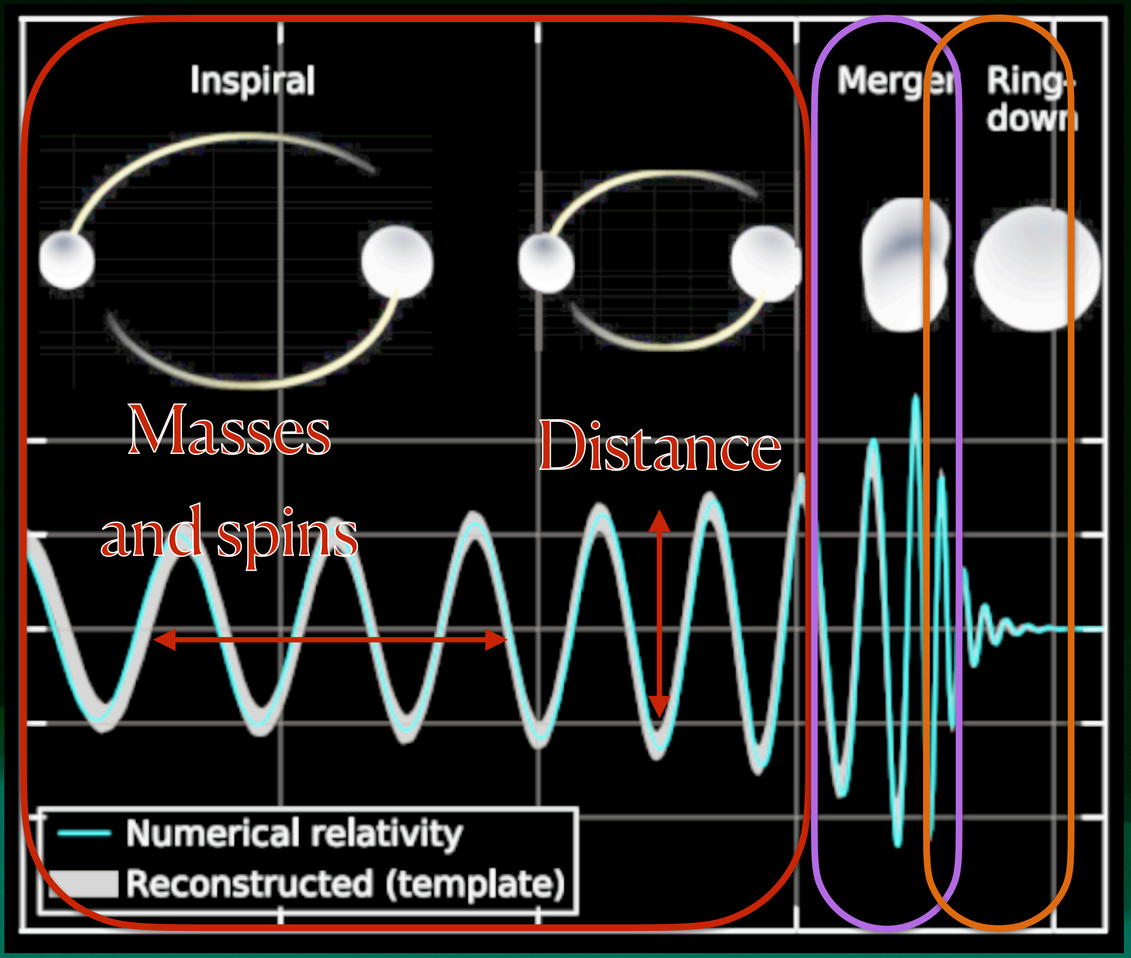


The signal

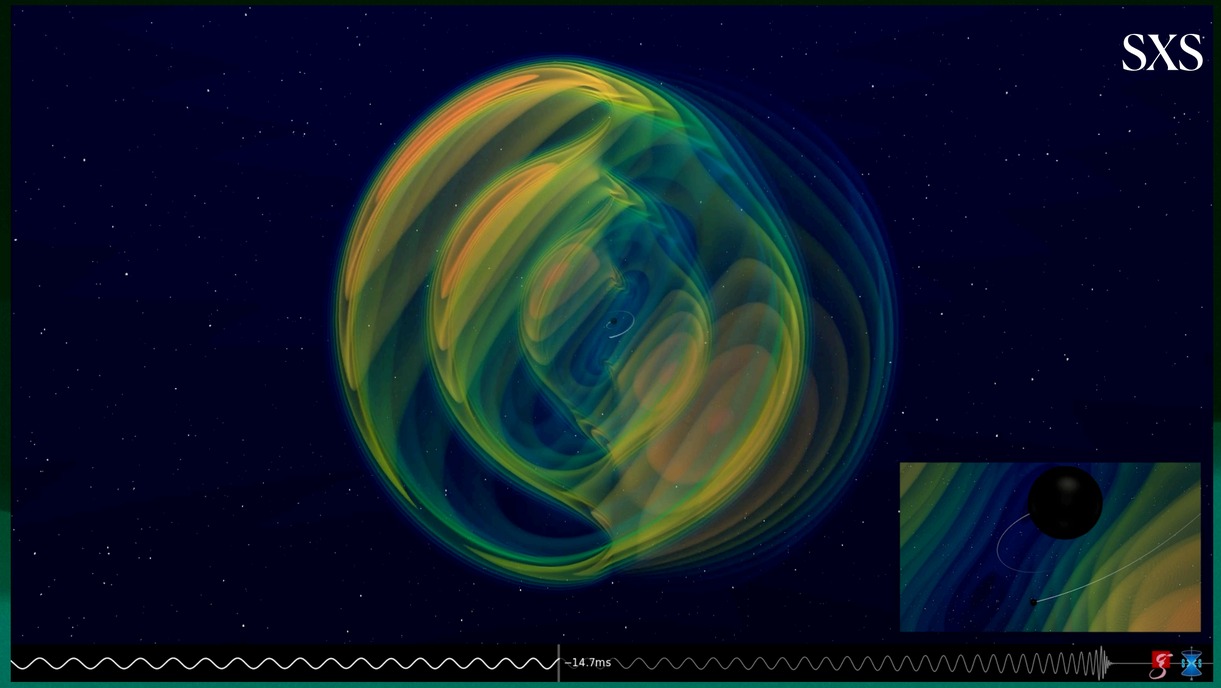
Inspiral: two distinct black holes orbiting each other

Merger: two black holes combining

Ringdown: a single perturbed black hole ringing

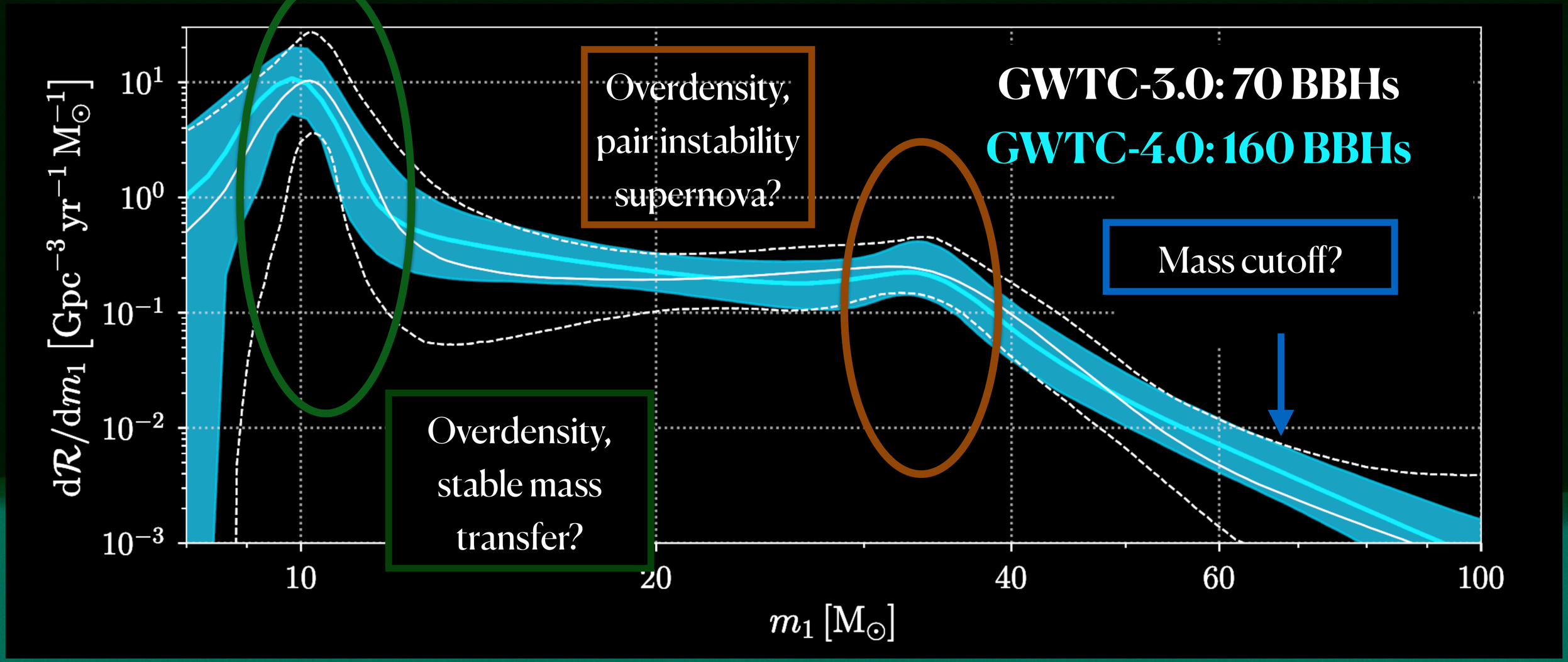


LVC (arxiv:1602.03837)



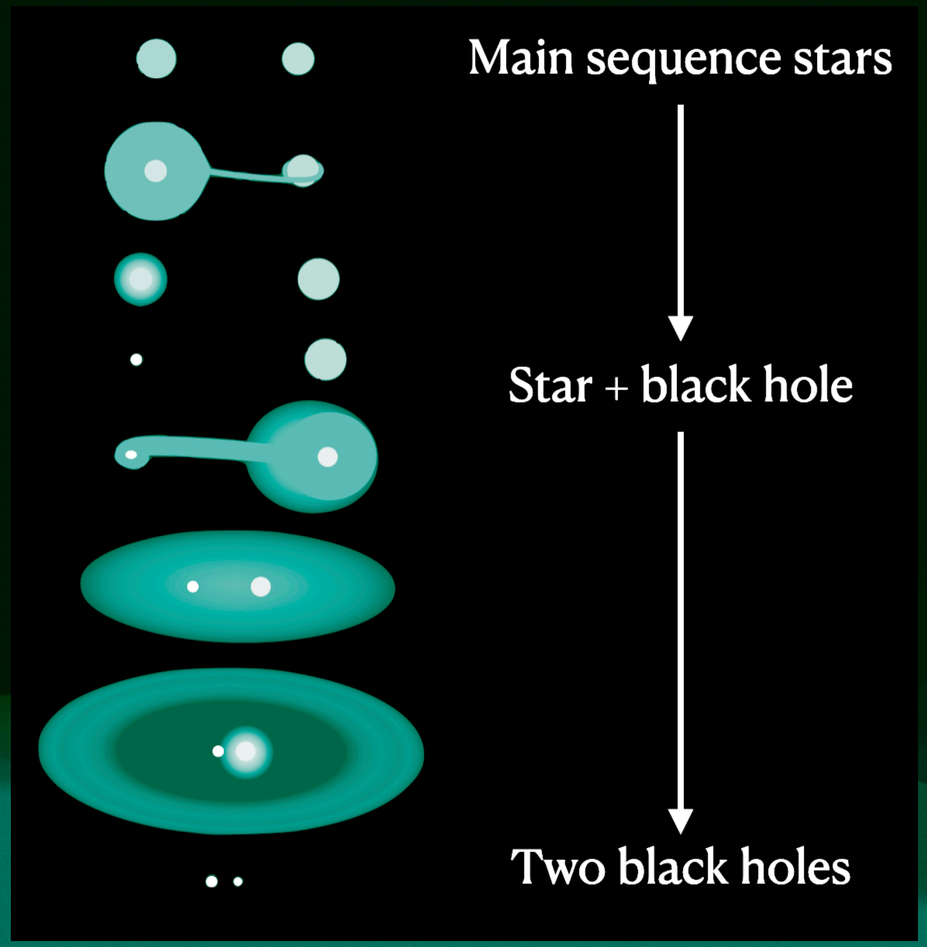
Black hole Masses

LVC w/ KC (arxiv:2508.18083)



Where do LIGO's black holes come from?

Isolated binary evolution



Mandel+ (arxiv:1806.05820)

vs

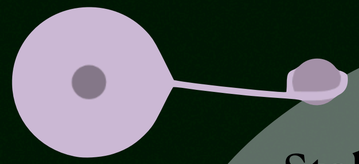
Dynamical formation

Credit: Carl Rodriguez

Slide adapted from Mike Zevin & Lieke Van Son

Actually...

Isolated binary formation



Common envelope

Stable mass transfer

Population III stars

Chemically homogeneous evolution

Dynamic formation

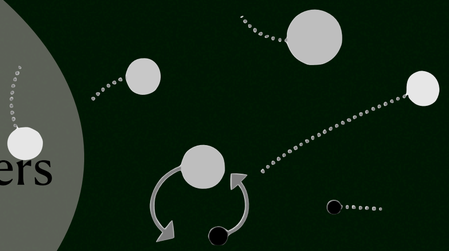
Globular clusters

Nuclear clusters

Open clusters

Young massive clusters

Ultra-dwarf galaxy mergers



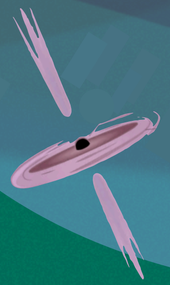
Wide binaries + flybys

Secular evolution of triples/ quadruples

Triples with common envelope

Active galactic nuclei

Gaseous Environments



Non-astrophysical

Primordial black holes

Dark matter

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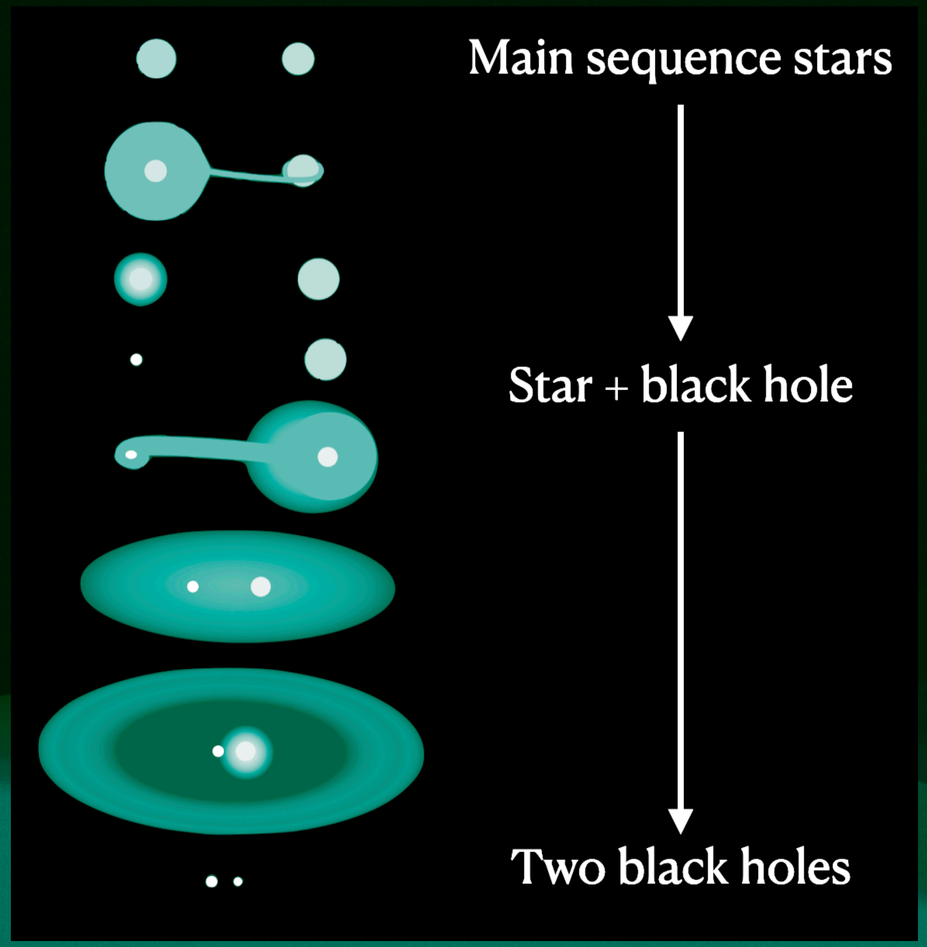


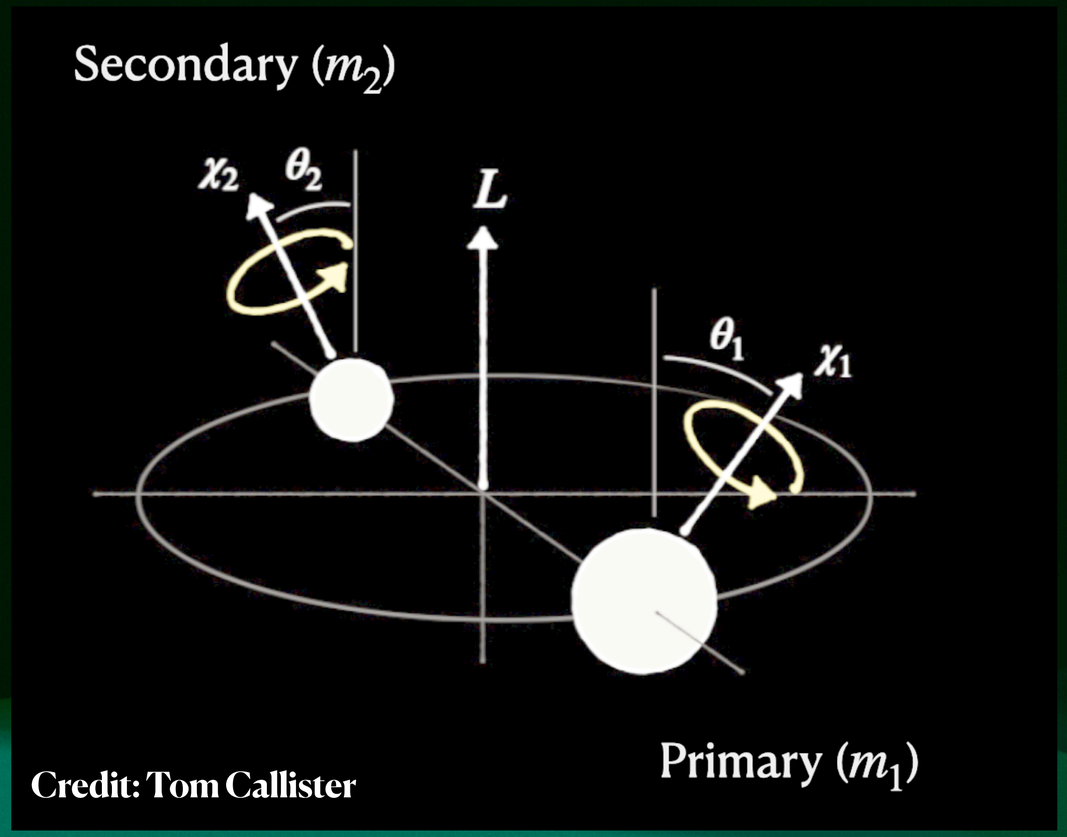
Mandel+ (arxiv:1806.05820)

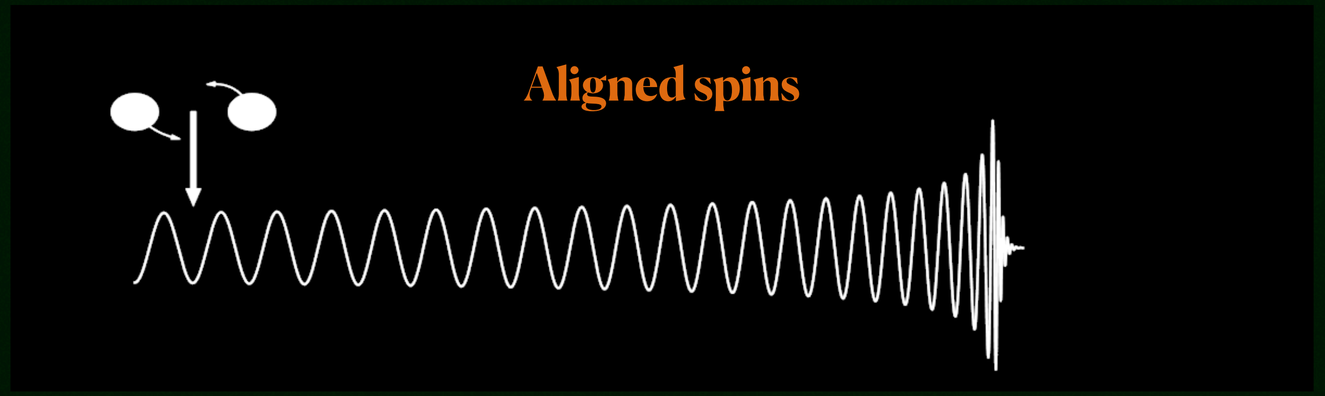
vs

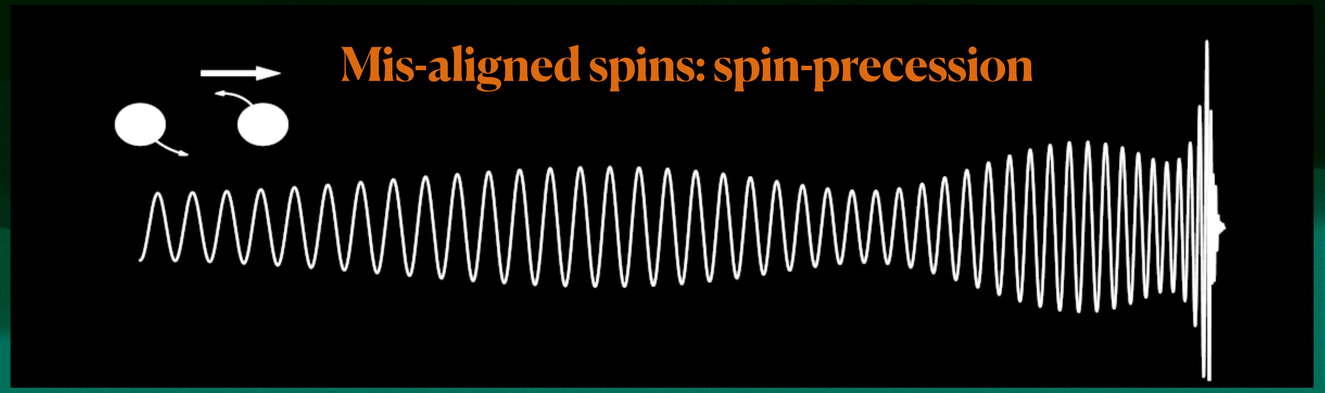
Dynamical formation

Credit: Carl Rodriguez

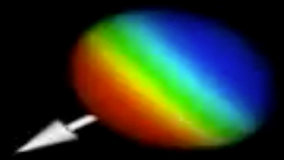
Black hole Spins





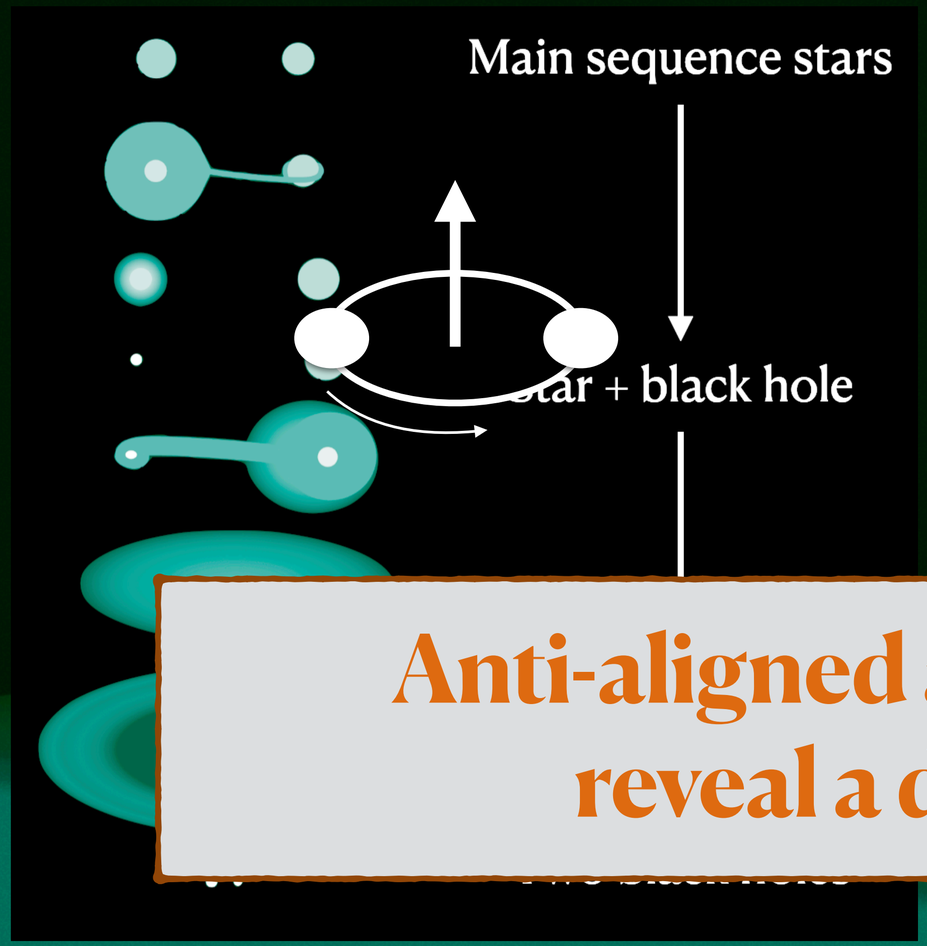


SXS



Where do LIGO's black holes come from?

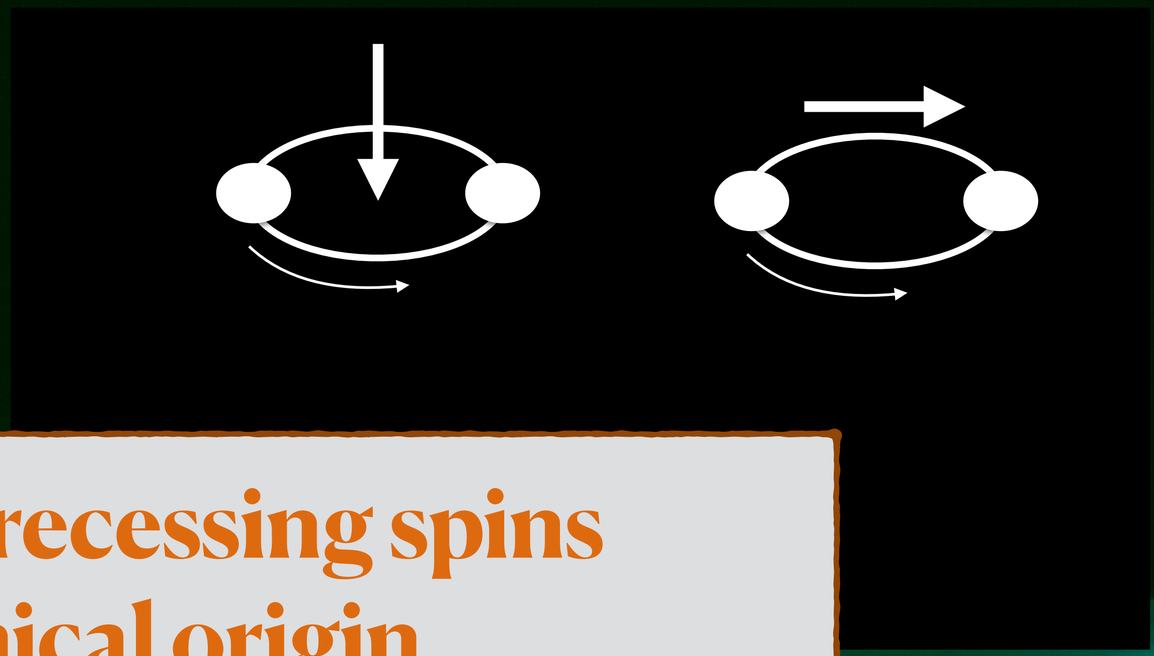
Isolated binary evolution



Mandel+ (arxiv:1806.05820)

vs

Dynamical formation



dit: Carl Rodriguez

Anti-aligned and precessing spins reveal a dynamical origin

Conclusions

Gravitational waves carry information about the spins of merging black holes that can reveal their astrophysical properties.

The imprint of spins on signals is extremely subtle and sensitive to the system configuration, especially for the majority of signals that are merger-dominated.

Spin inference is strongly affected by noise imperfections

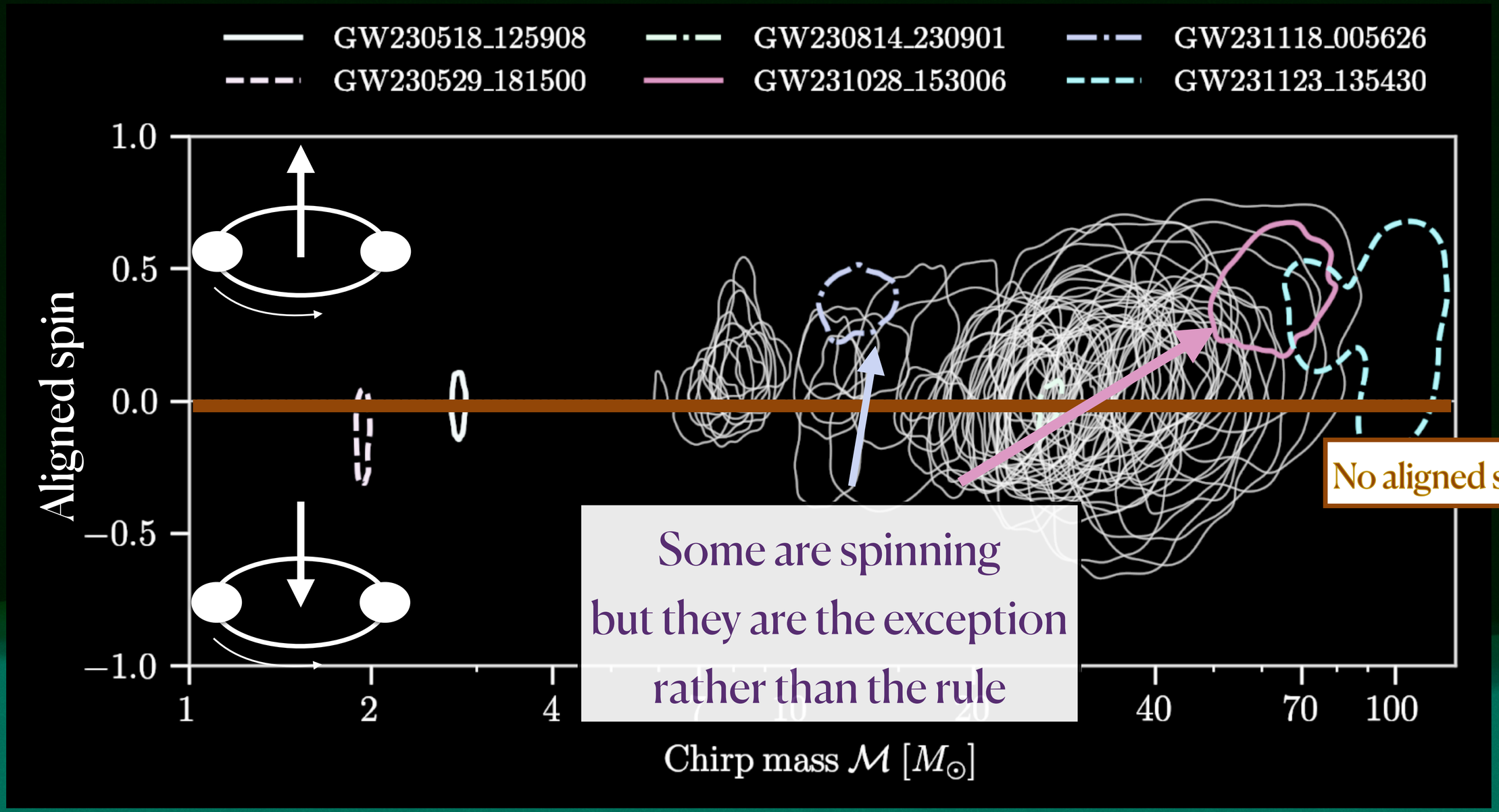
Most black holes have low spins with a range of misalignments, but combining many weakly informative measurements is subject to hard-to-diagnose model dependence

Measurement precision

Masses >> Aligned spins >> Precessing spins

(Frequency >> Length >> Modulation)

Observations



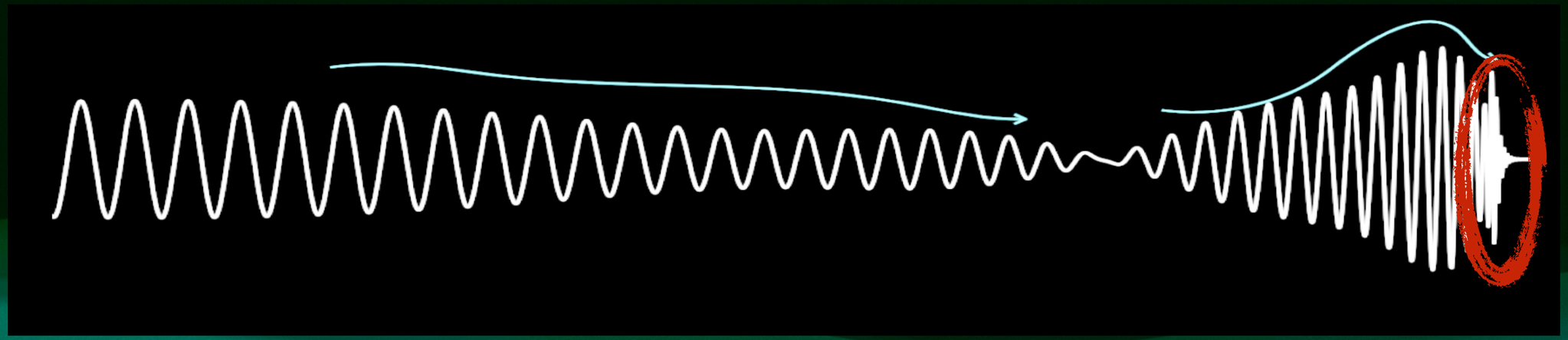
LVC w/KC (arxiv:2508.18082)

Forward models

$$(m_1, m_2, \vec{S}_1, \vec{S}_2, \ldots)$$

No missing physics...

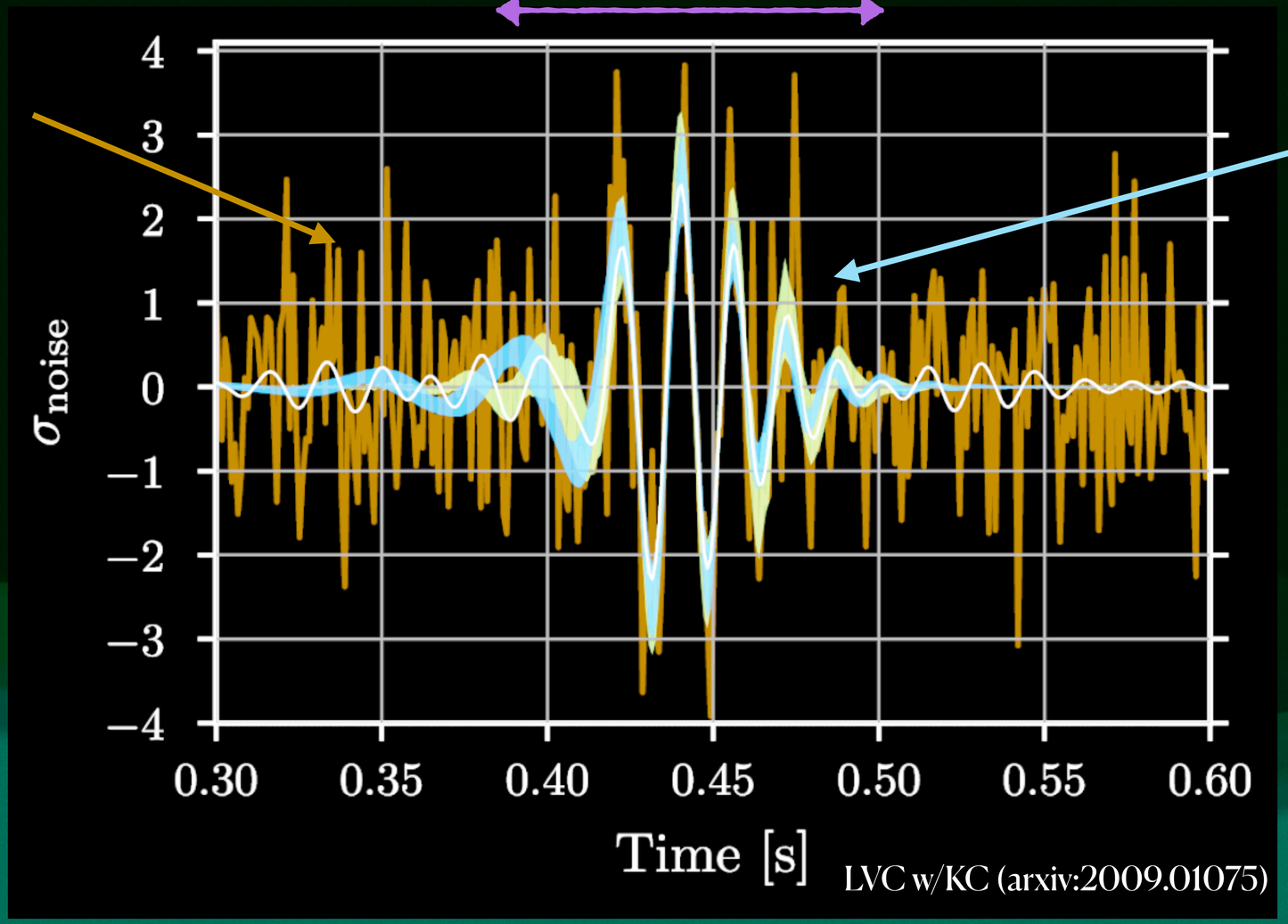
...but also little physical intuition especially for the merger



GW190521: A heavy black hole binary at $150\,M_\odot$

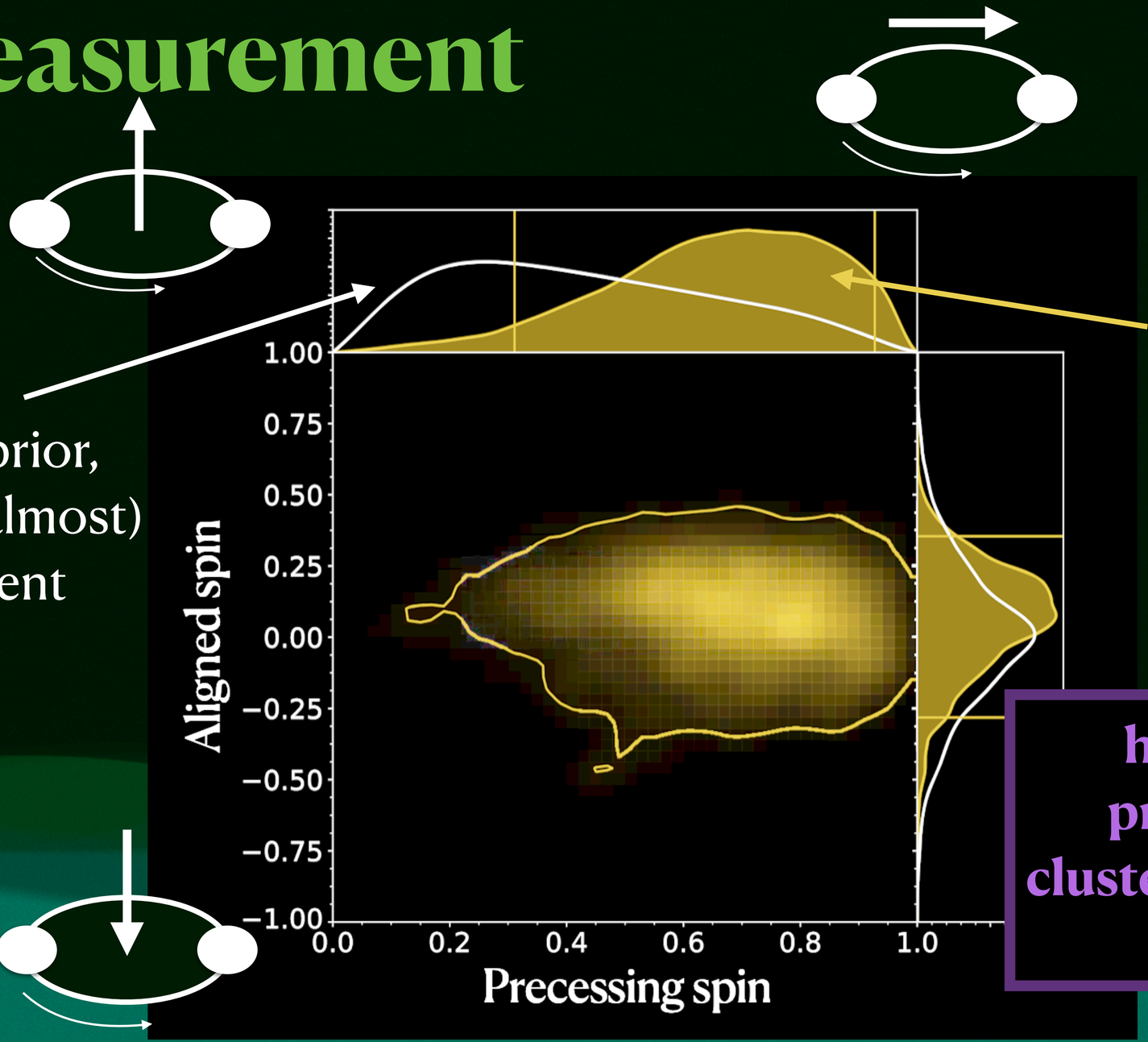
low frequency <-> short signal <-> merger-dominated <-> high mass

Data



Reconstructed gravitational-wave signal

Spin measurement



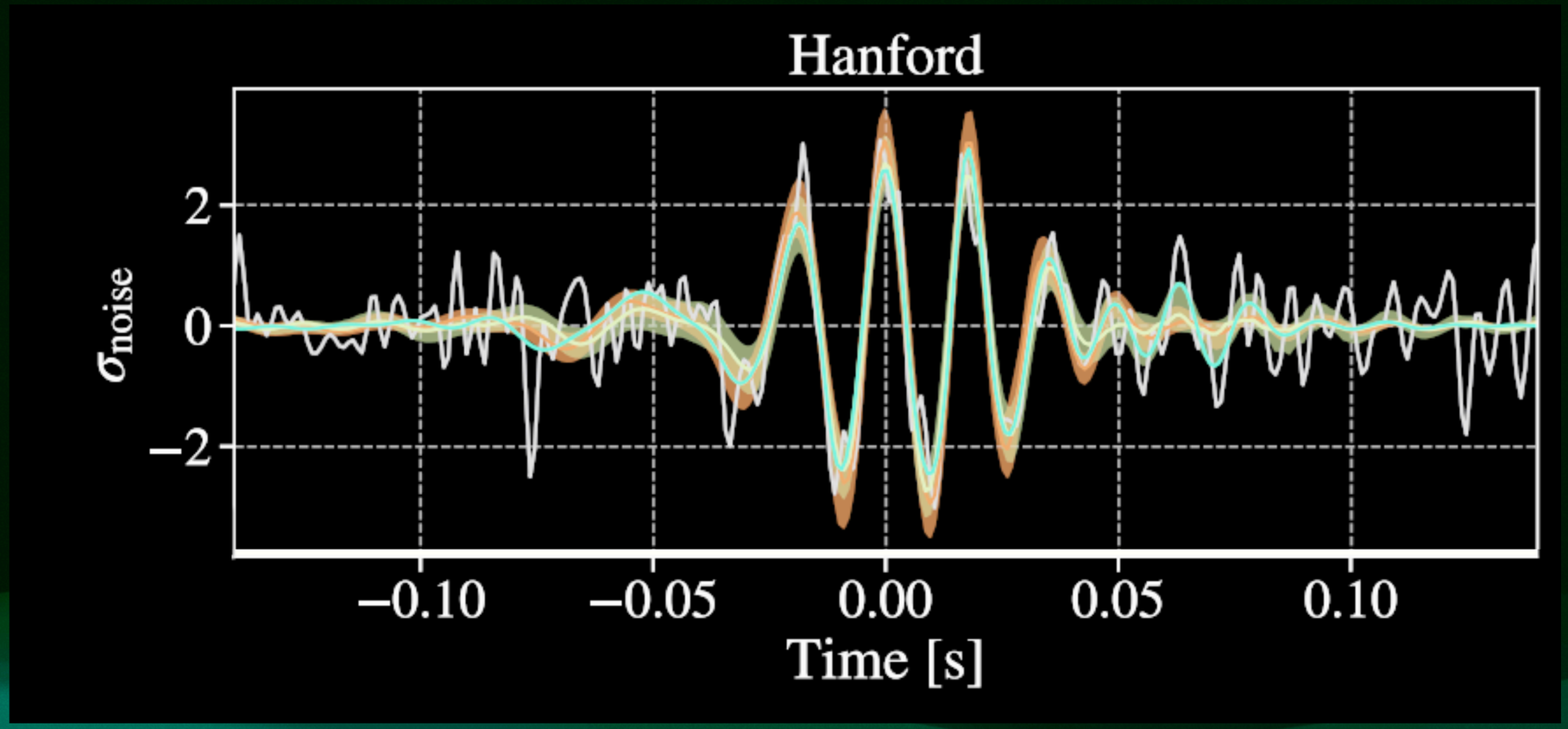
Uninformative prior, what we get for (almost) every other event

Constraint on precession

high mass+ precession-> cluster/hierarchical origin?

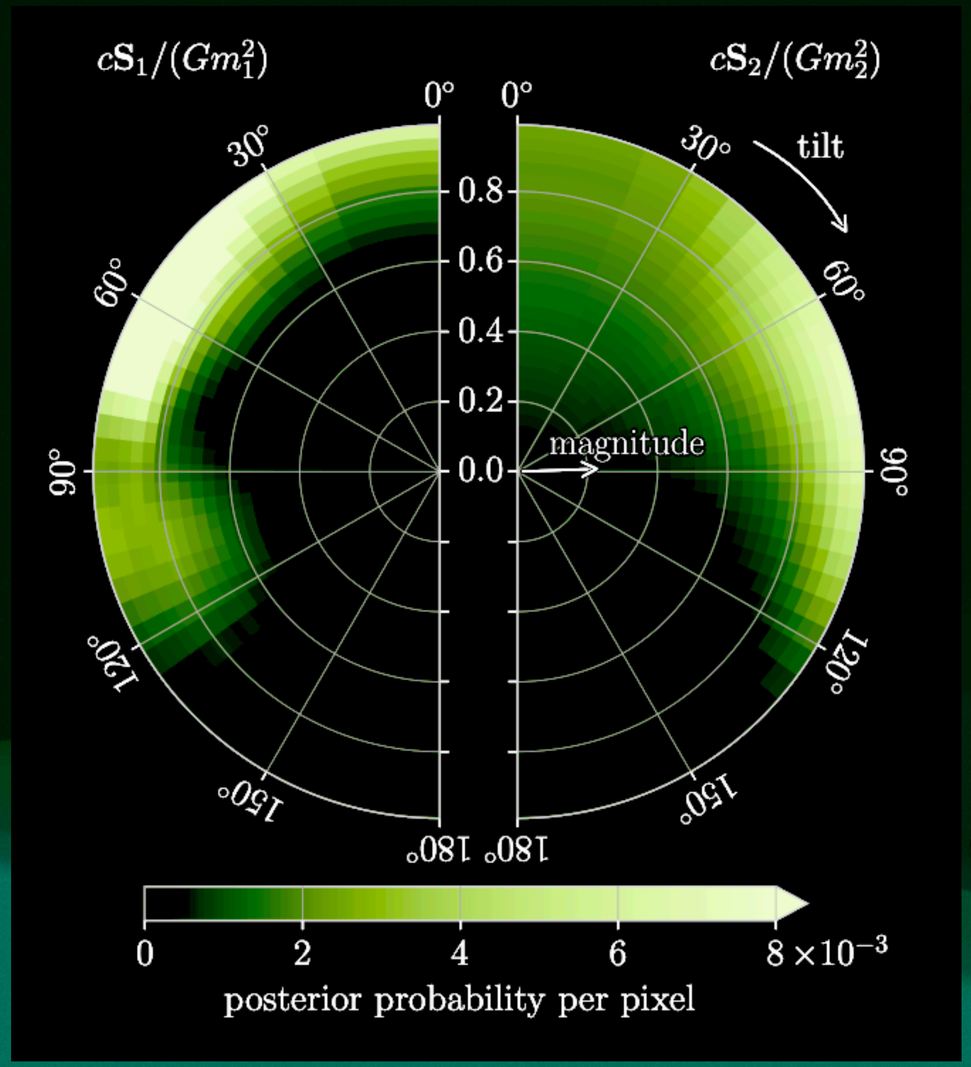
LVC w/KC (arxiv:2009.01075)

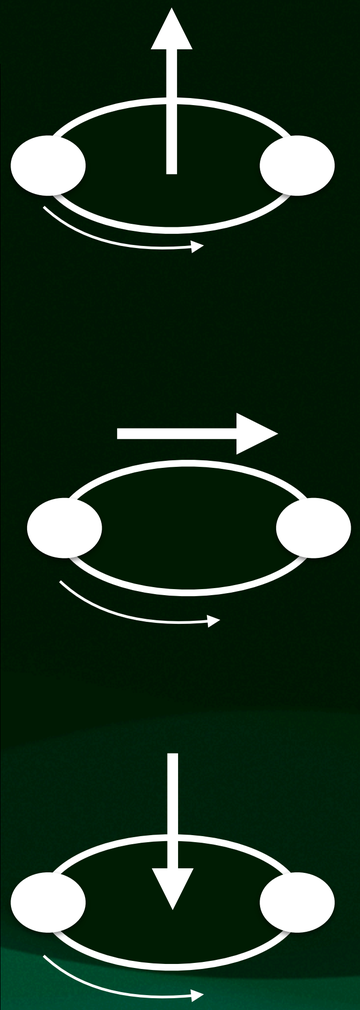
GW231123: The heaviest black hole binary at 240 $M_\odot$



LVK w/KC (arxiv:2507.08219)

Spin measurement

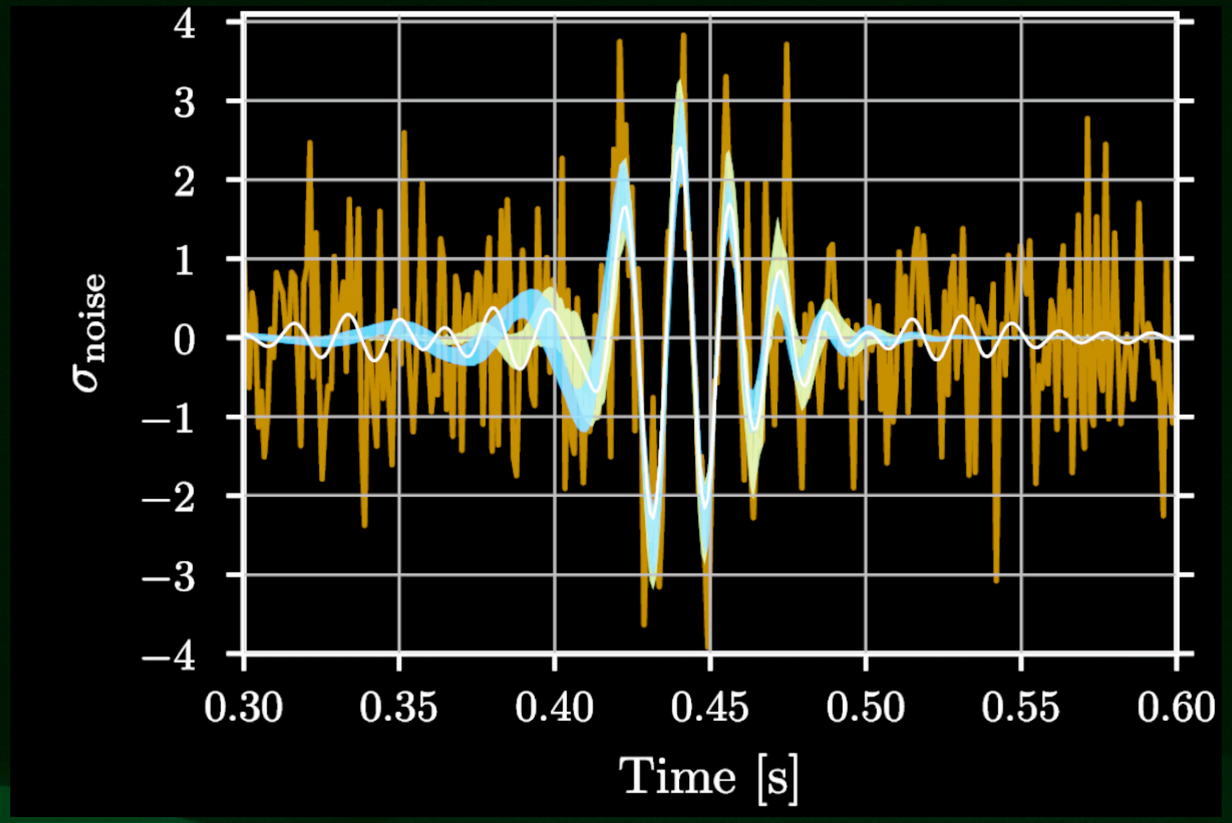




high mass+spin-> cluster/hierarchical origin?

LVK w/KC (arxiv:2507.08219)

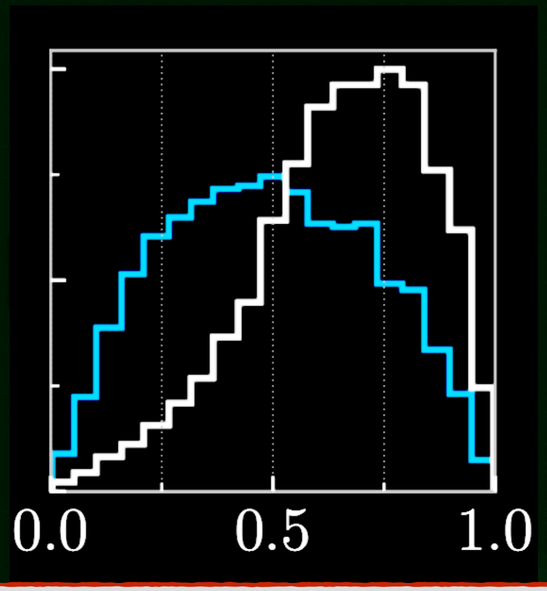
Inference

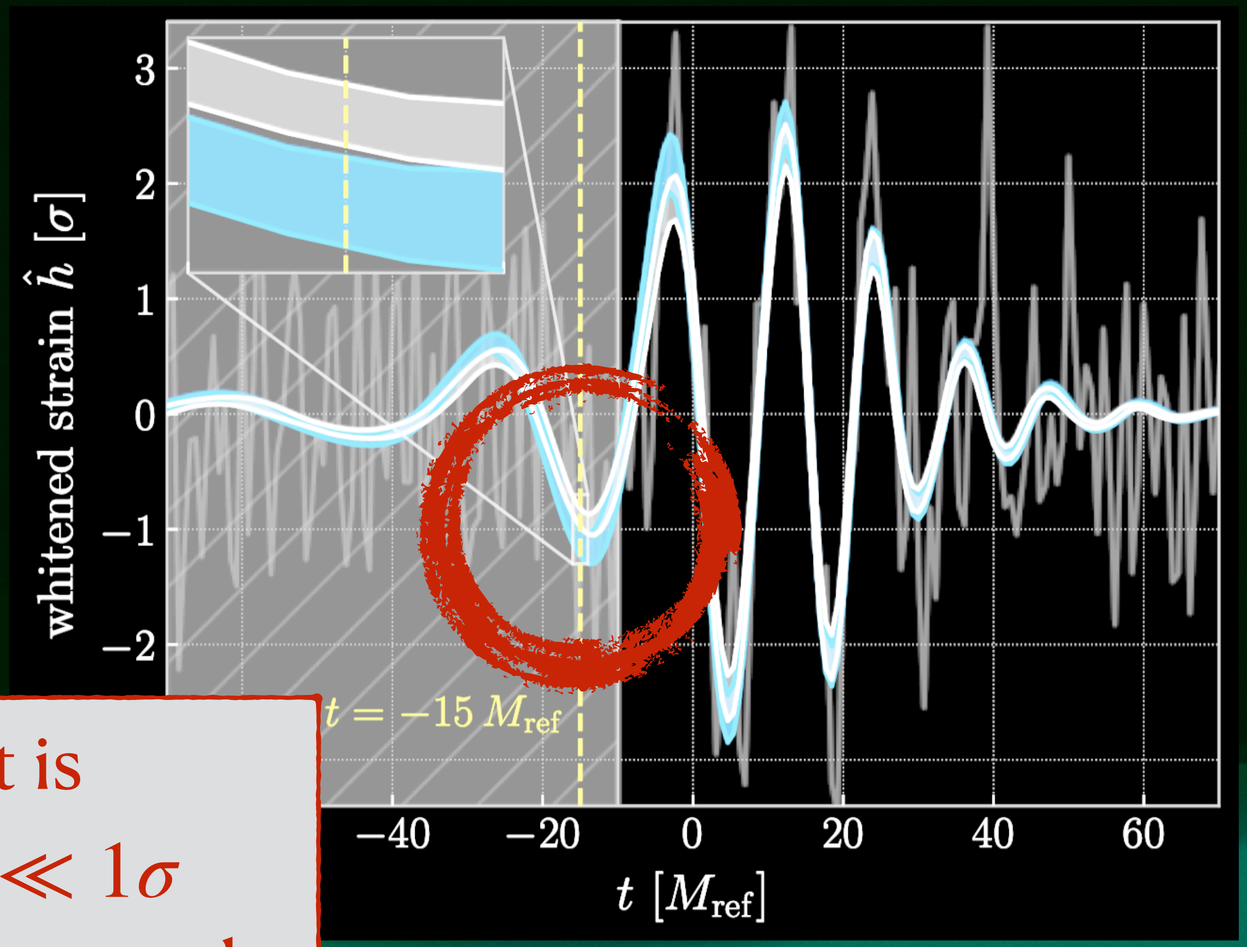


Robust inference includes understanding the morphological imprint of precession on the signal

Precession Morphology

Miller+ w/KC (arxiv:2310.01544)





The precession constraint is morphologically linked to a $\ll 1\sigma$ suppression of the final pre-merger cycle

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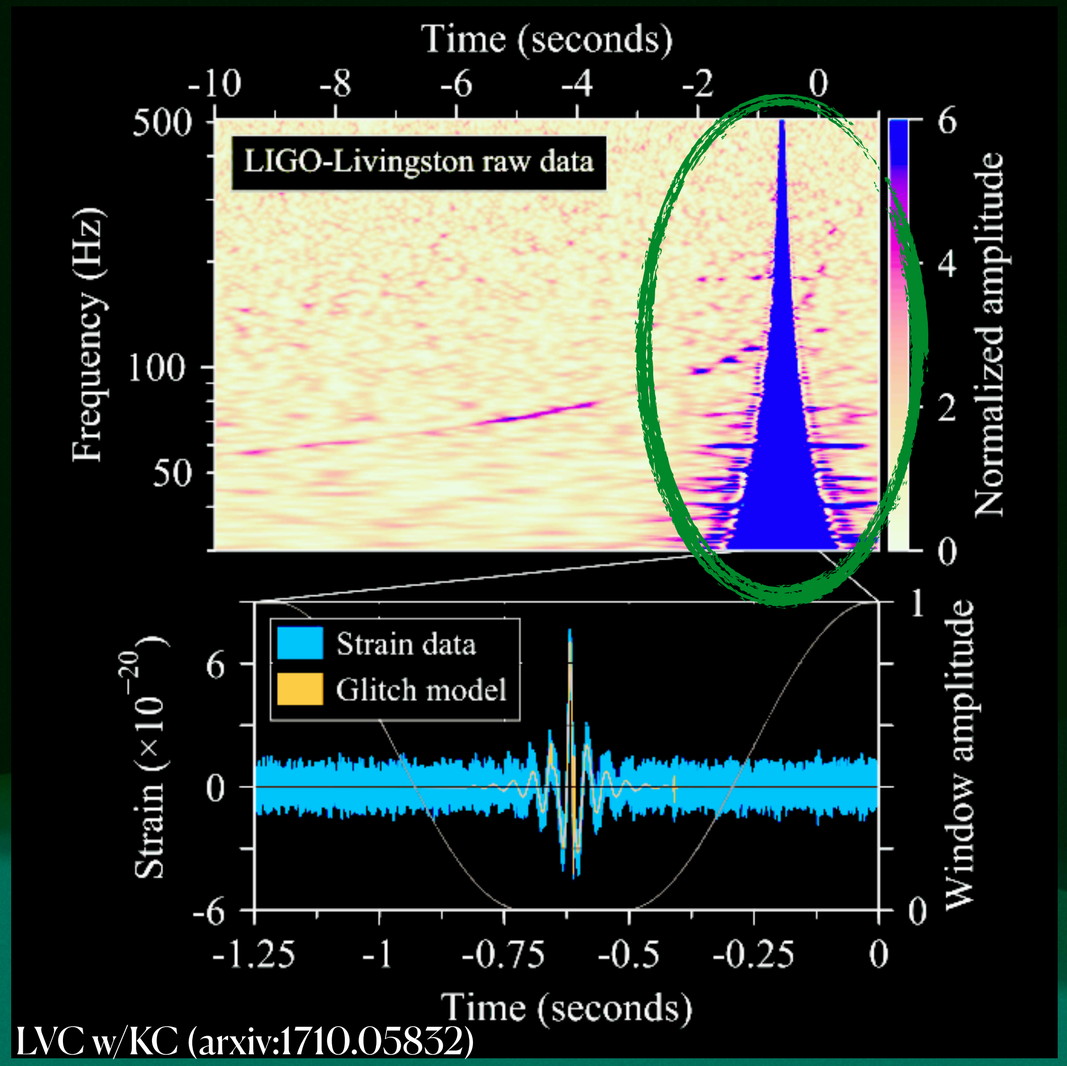
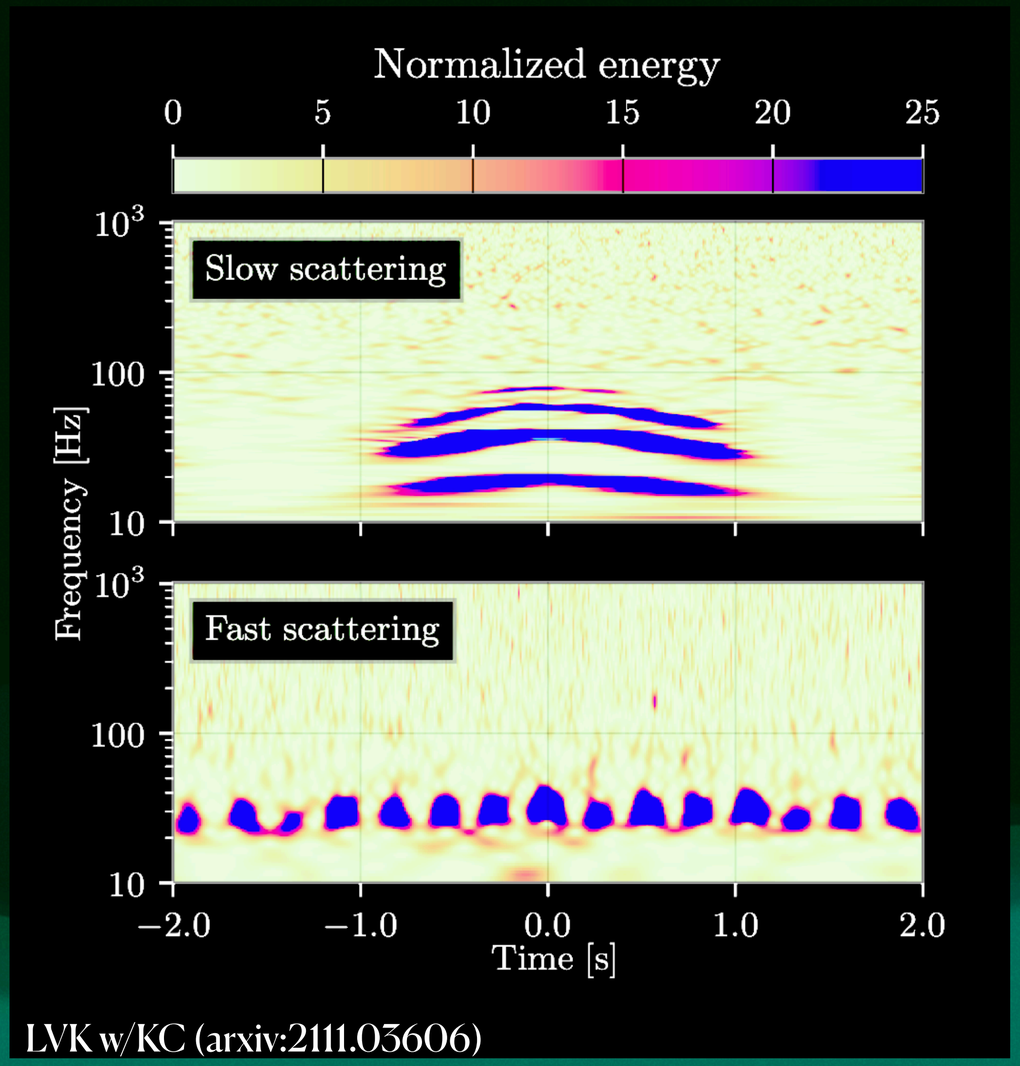
Subtle measurements vs Systematics



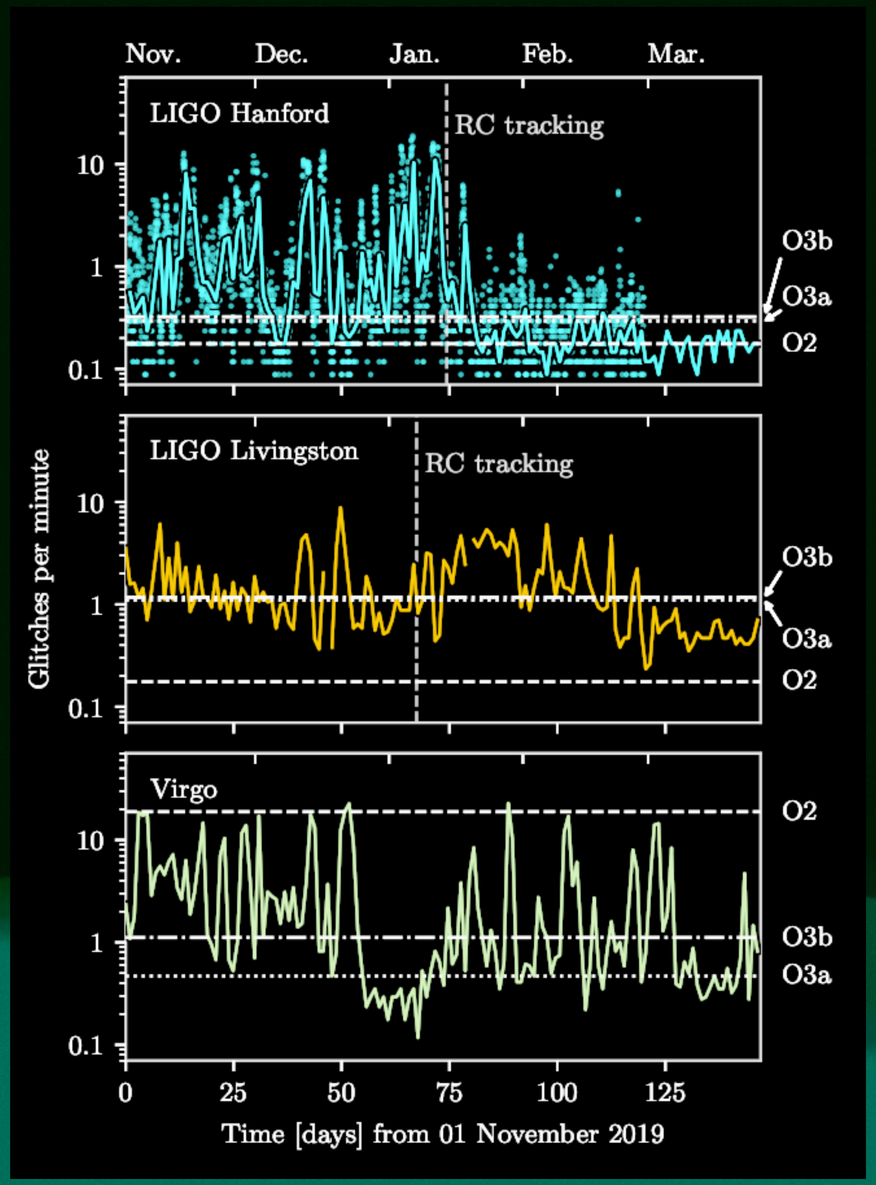
LVC w/KC (arxiv:1710.05832)



LVK w/KC (arxiv:2111.03606)

Detector glitches

LVK w/KC (arxiv:2111.03606)

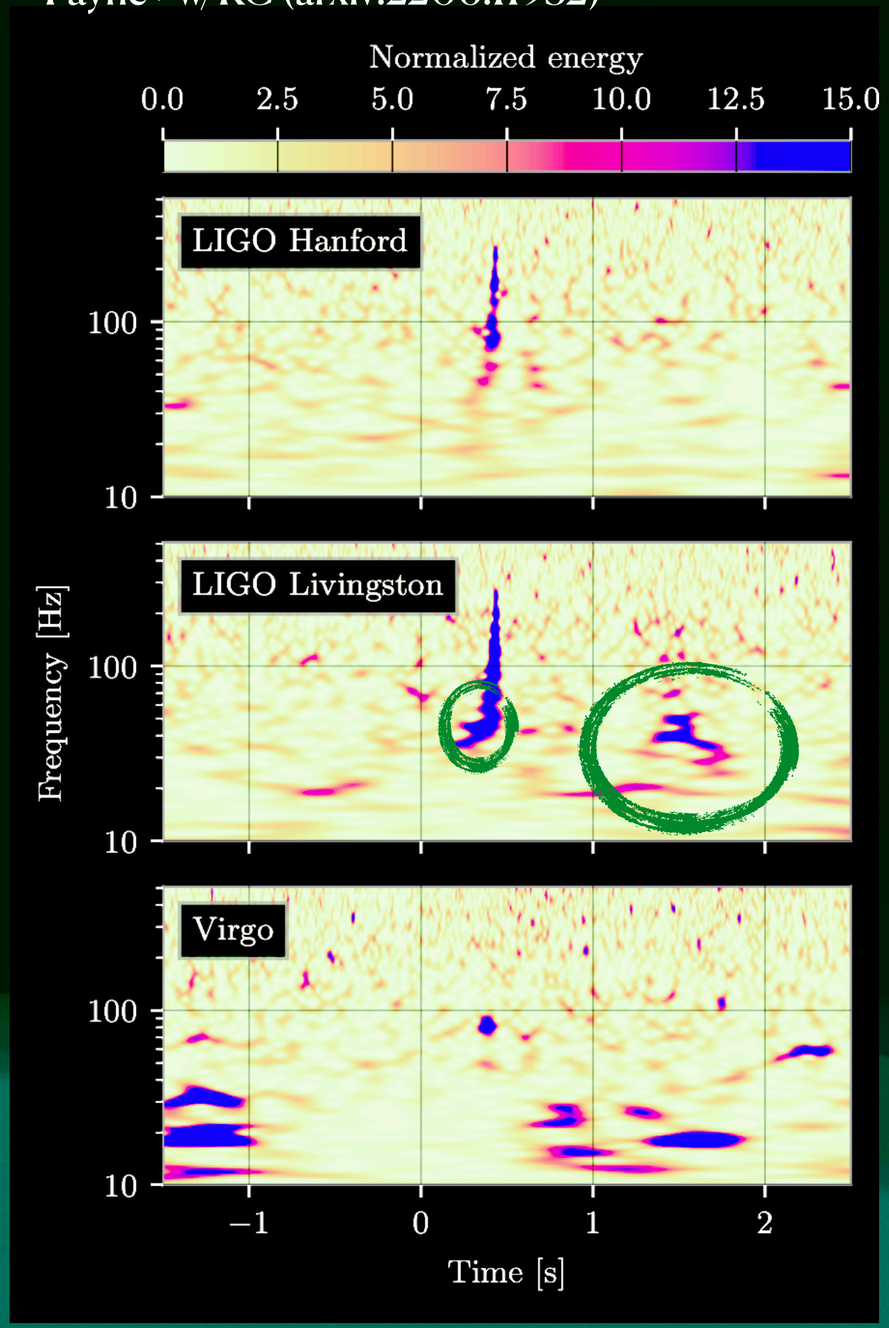


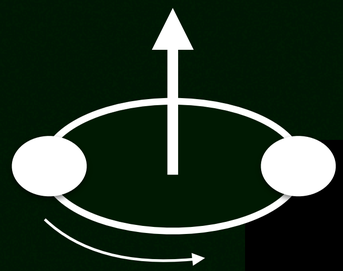
20 binary black hole mergers
out of ~90 have overlapped with glitches...

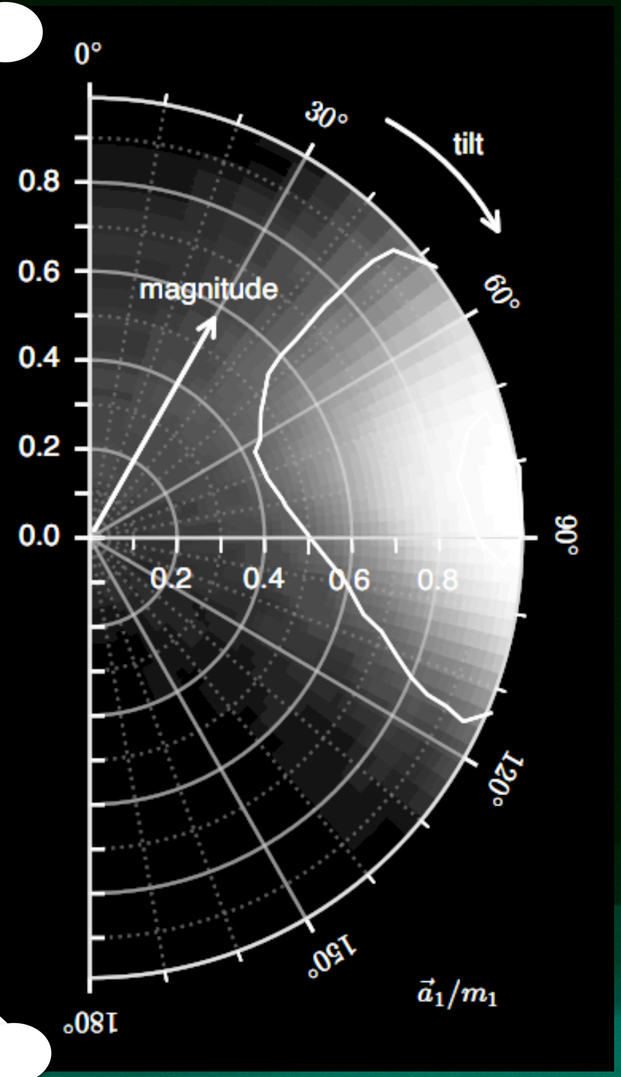
...including the remaining
two signals with evidence for
negative-aligned or precessing spins

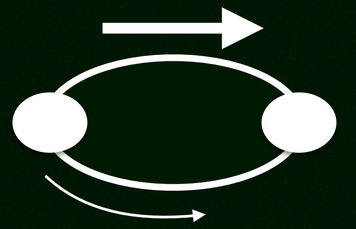
GW200129

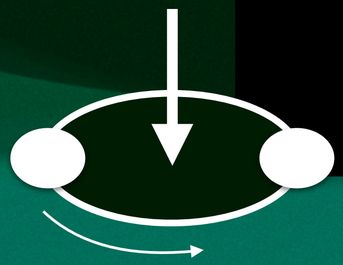
Payne+ w/KC (arxiv:2206.11932)











LVK w/KC (arxiv:2111.03606)
Hannam+ (arxiv:2112.11300)

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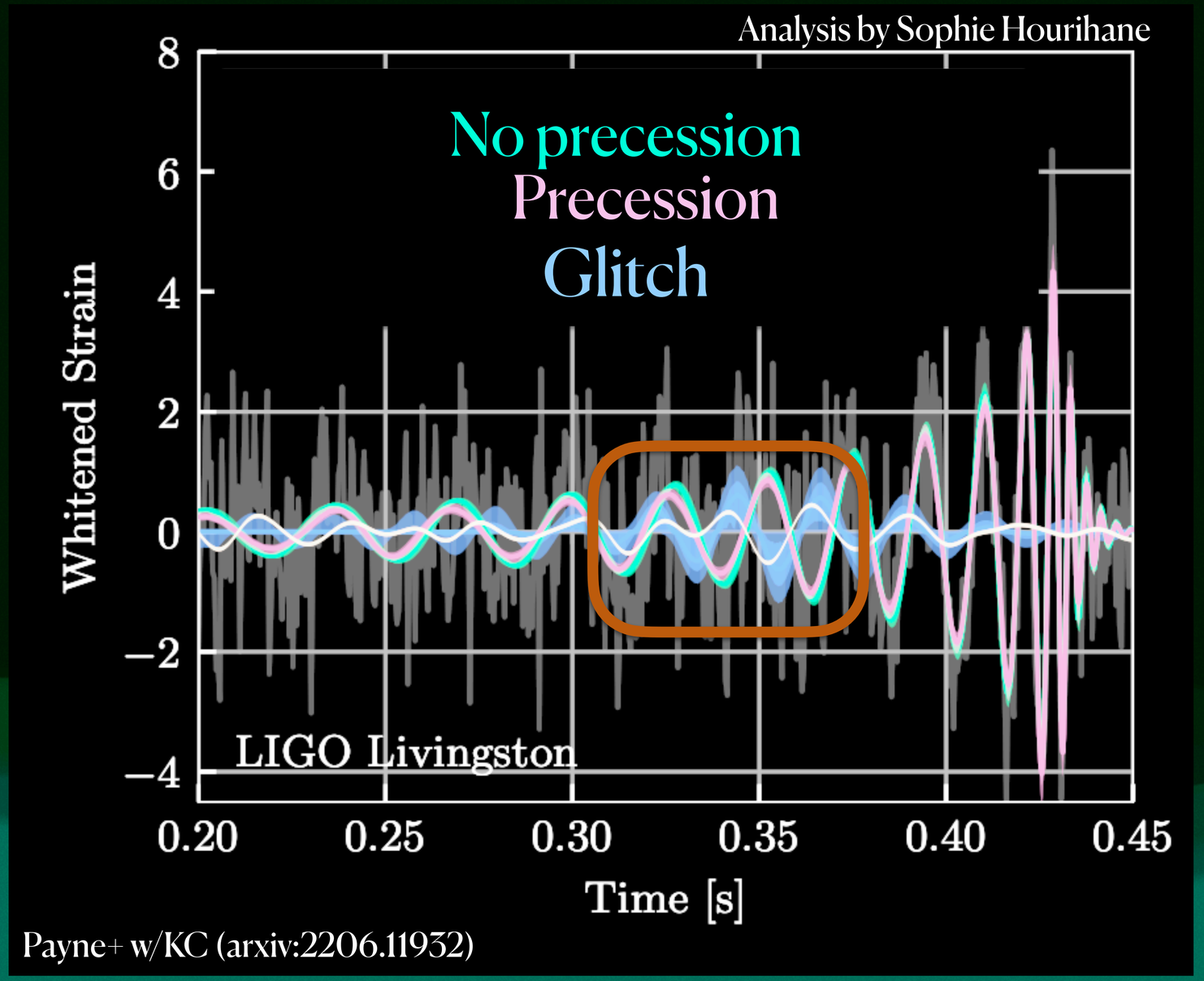
GW200129



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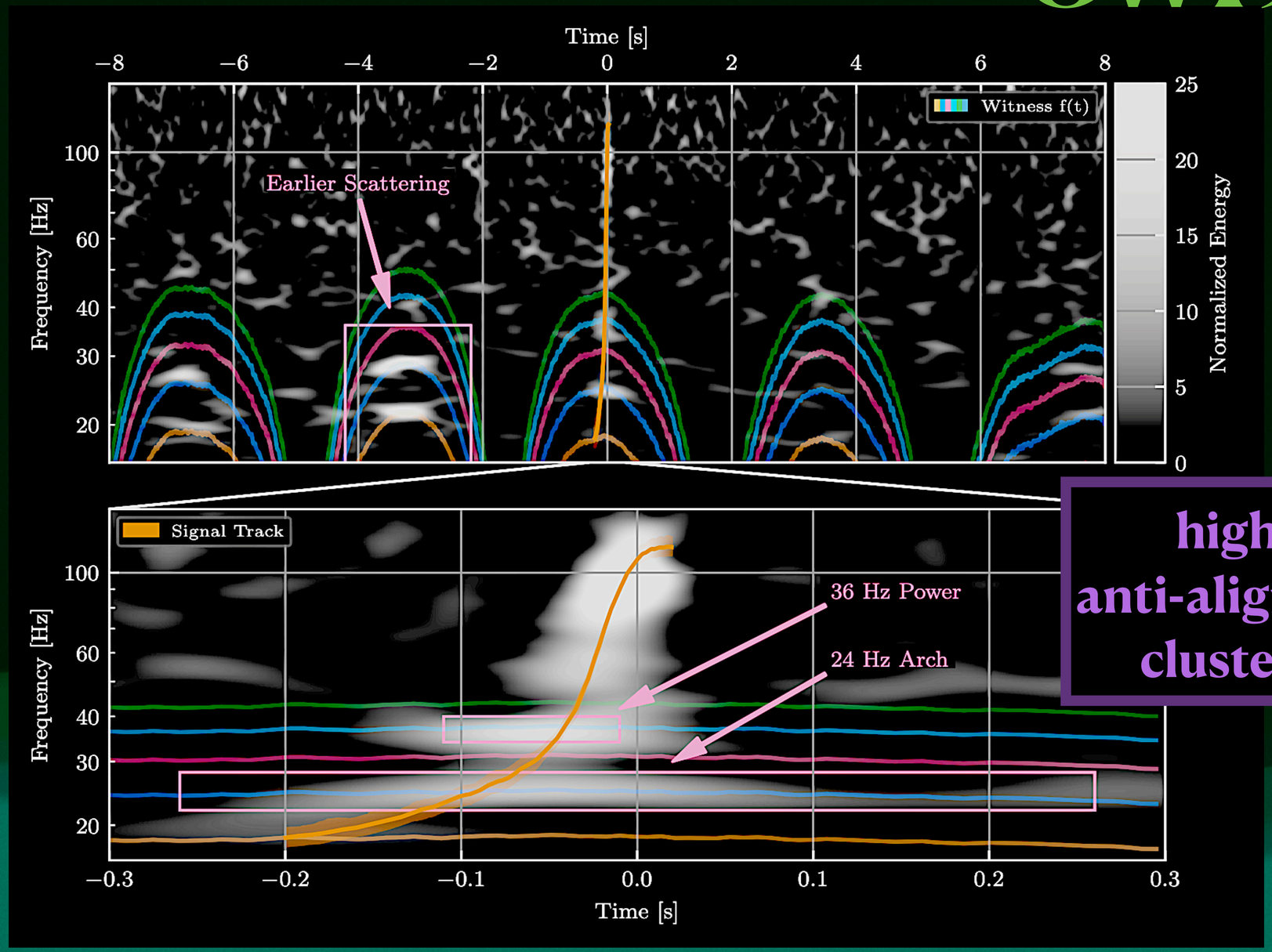
GW191109



high mass+ anti-aligned spin—> cluster origin?

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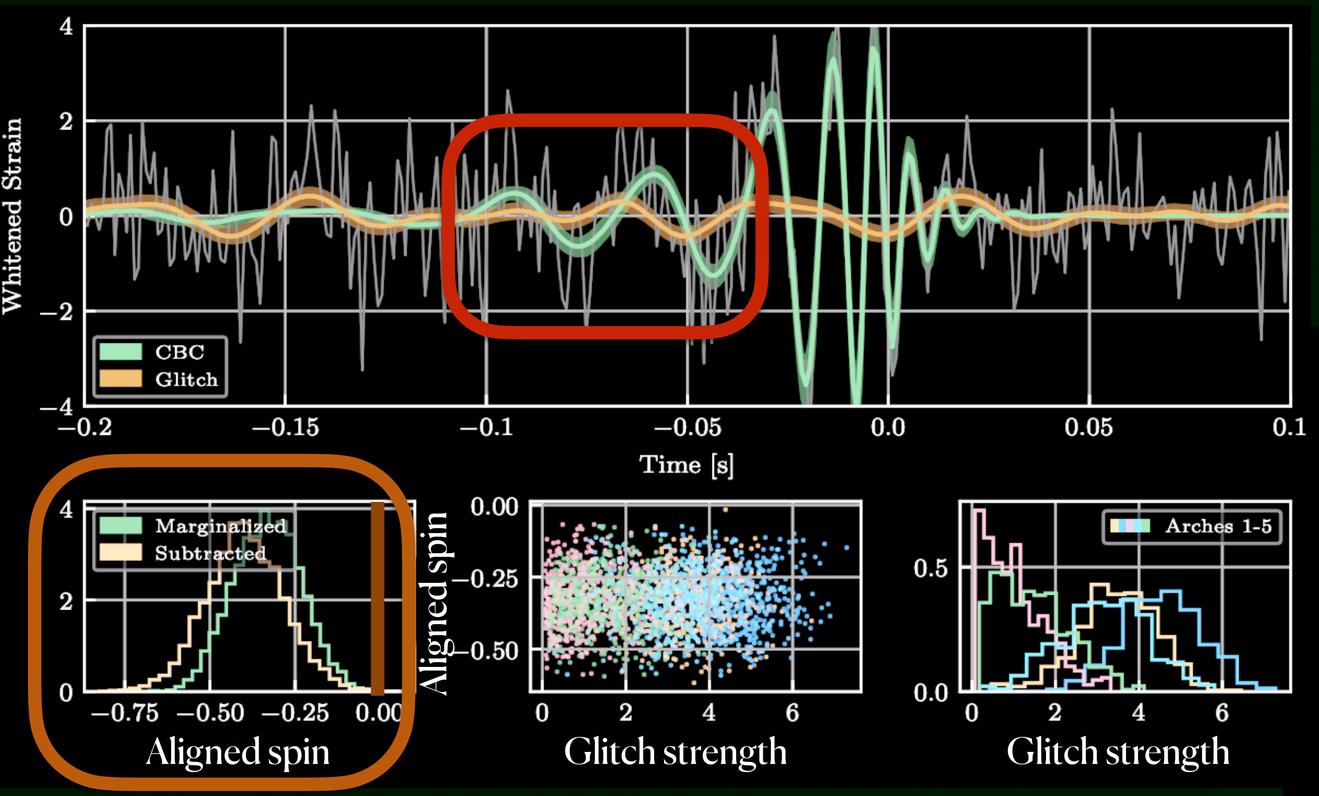
Udall+ w/KC (arxiv:2409.03912)

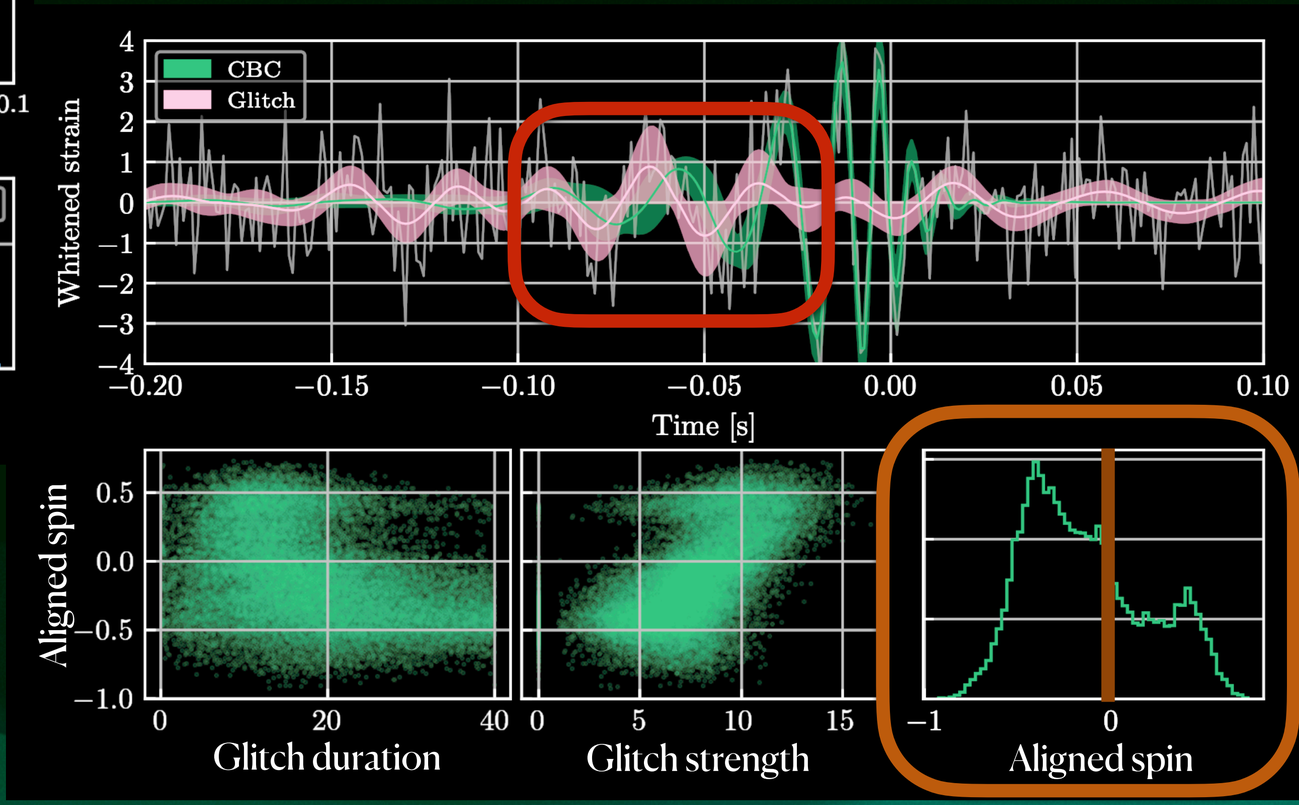
GW191109

Targeted glitch model



Analysis by Rhiannon Udall

Phenomenological glitch model



Analysis by Sophie Hourihane

K. Chatziioannou

Udall+ w/KC (arxiv:2409.03912)

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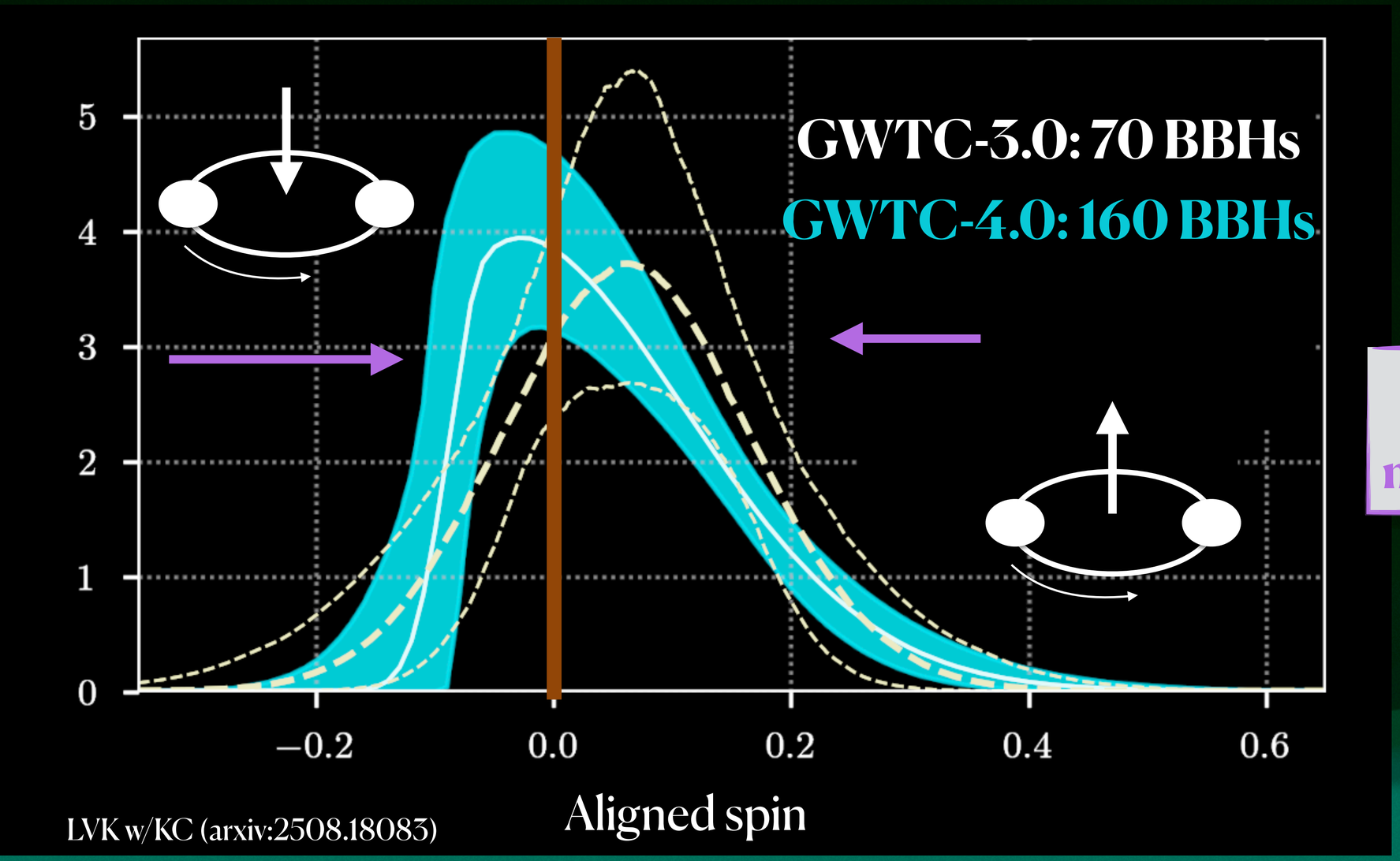
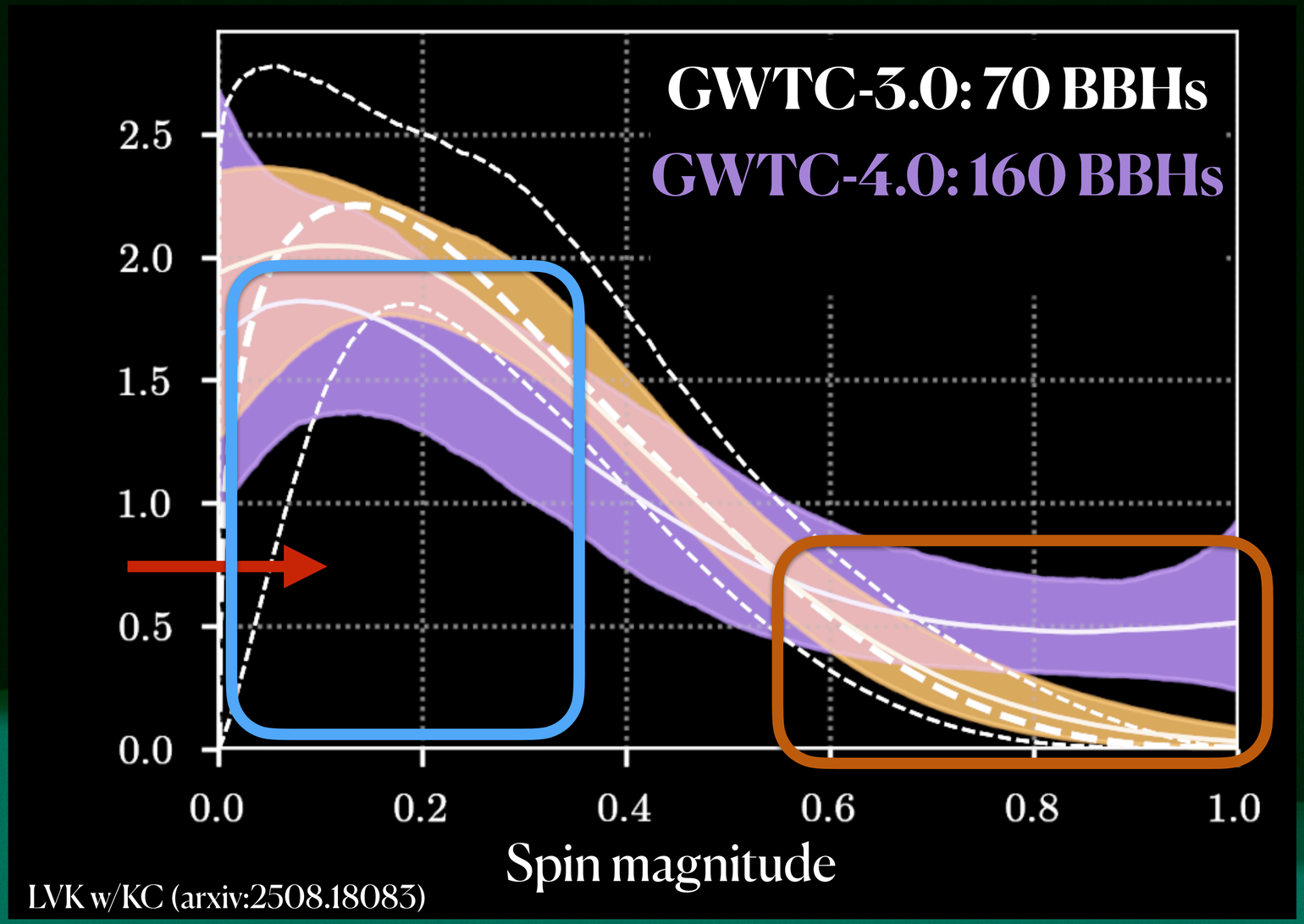
Black hole population: Aligned spin



LVK w/KC (arxiv:2508.18083)

Spins are not isotropic, multiple origin scenarios?

Black hole population: Spin magnitude

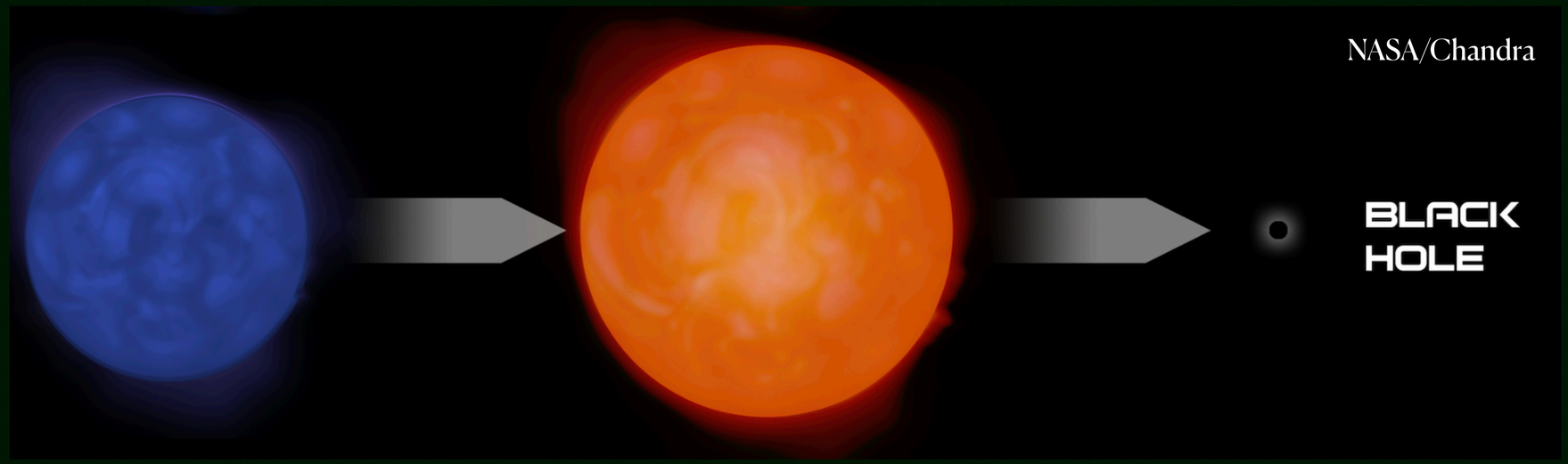


Spins are not all zero

Spins are not all maximal

Most black holes have low spins

Do most black holes have zero spin?

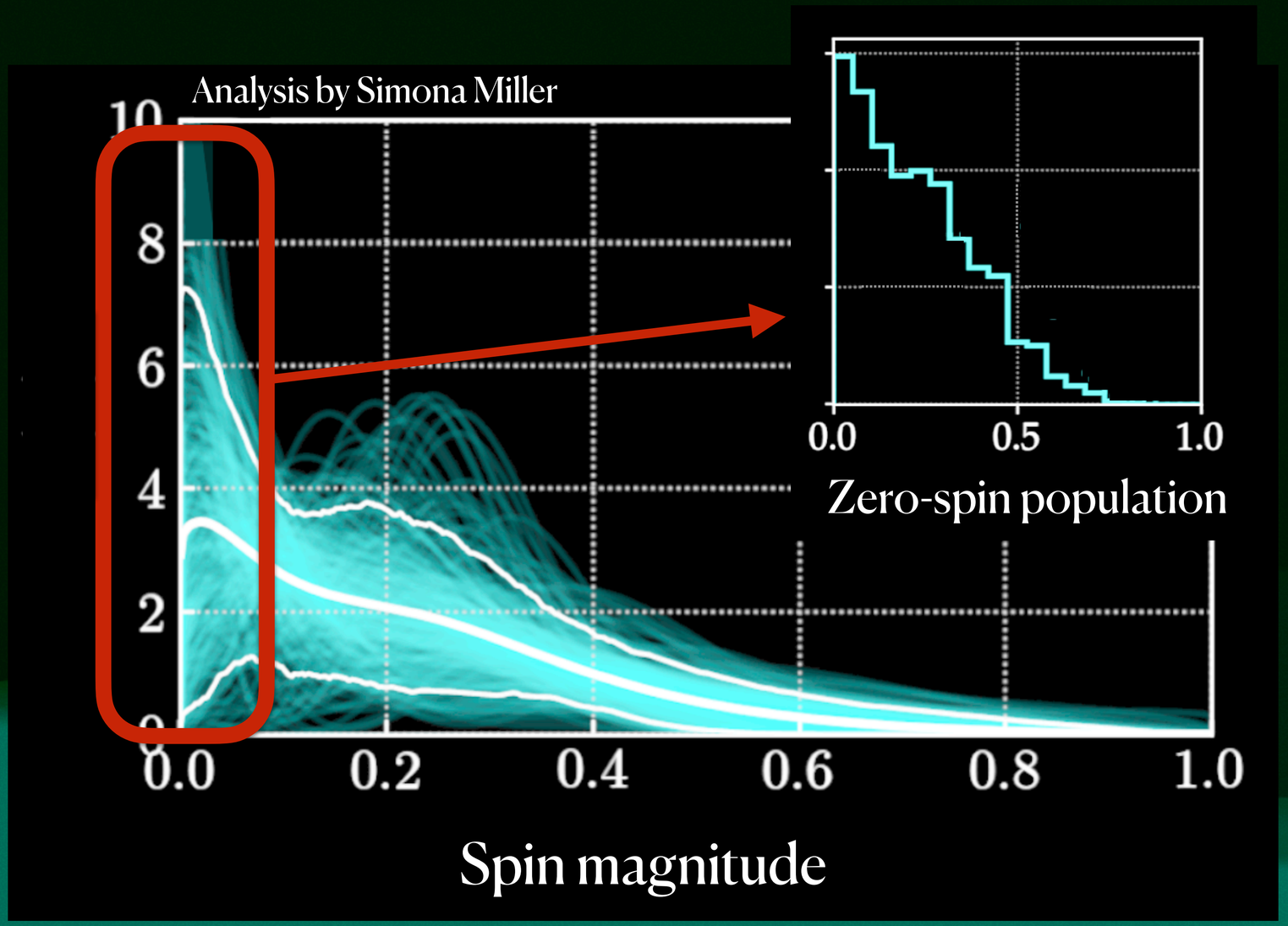


Stellar evolution predicts vanishingly small black hole spins.

Alternative: inefficient angular momentum transport, hierarchical mergers...

Fuller+ (arxiv:1907.03714)

Do most black holes have zero spin? No



Callister+ w/KC (arxiv:2205.08574)

Combining ~100 mostly uninformative measurements to assess something of measure zero is technically challenging

Model assessment is more challenging for weakly informative measurements

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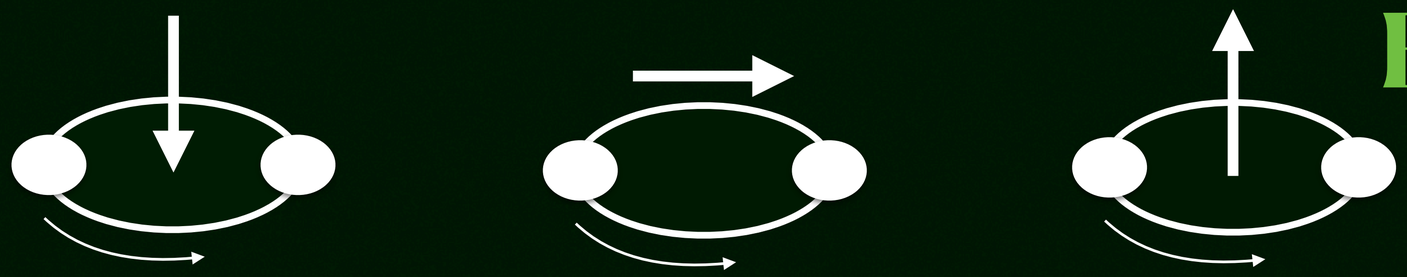
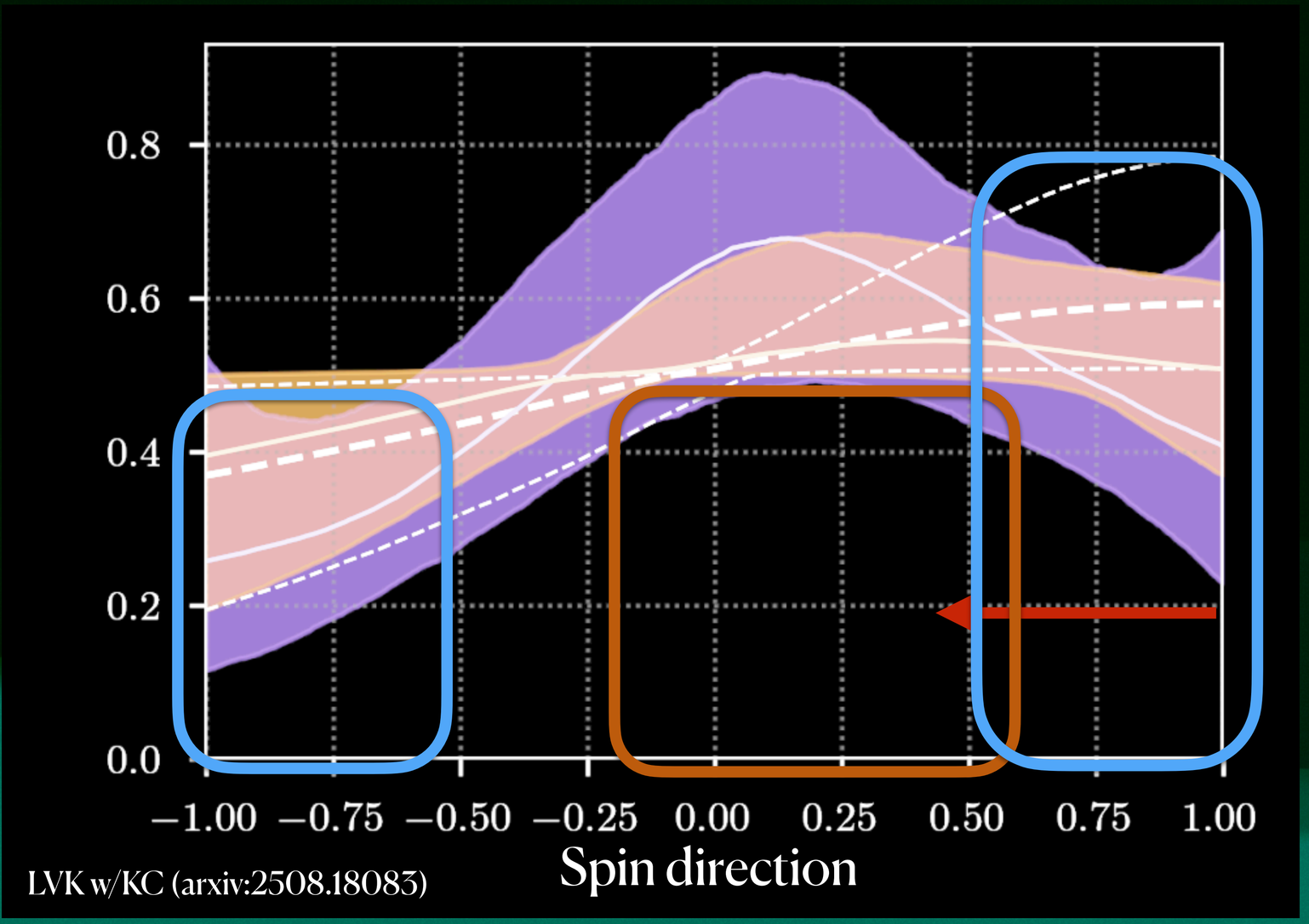


Black hole population: Spin direction



Spins are not all aligned

There is a wide range of misalignement

More spins are positively-aligned than negatively-aligned

Conclusions

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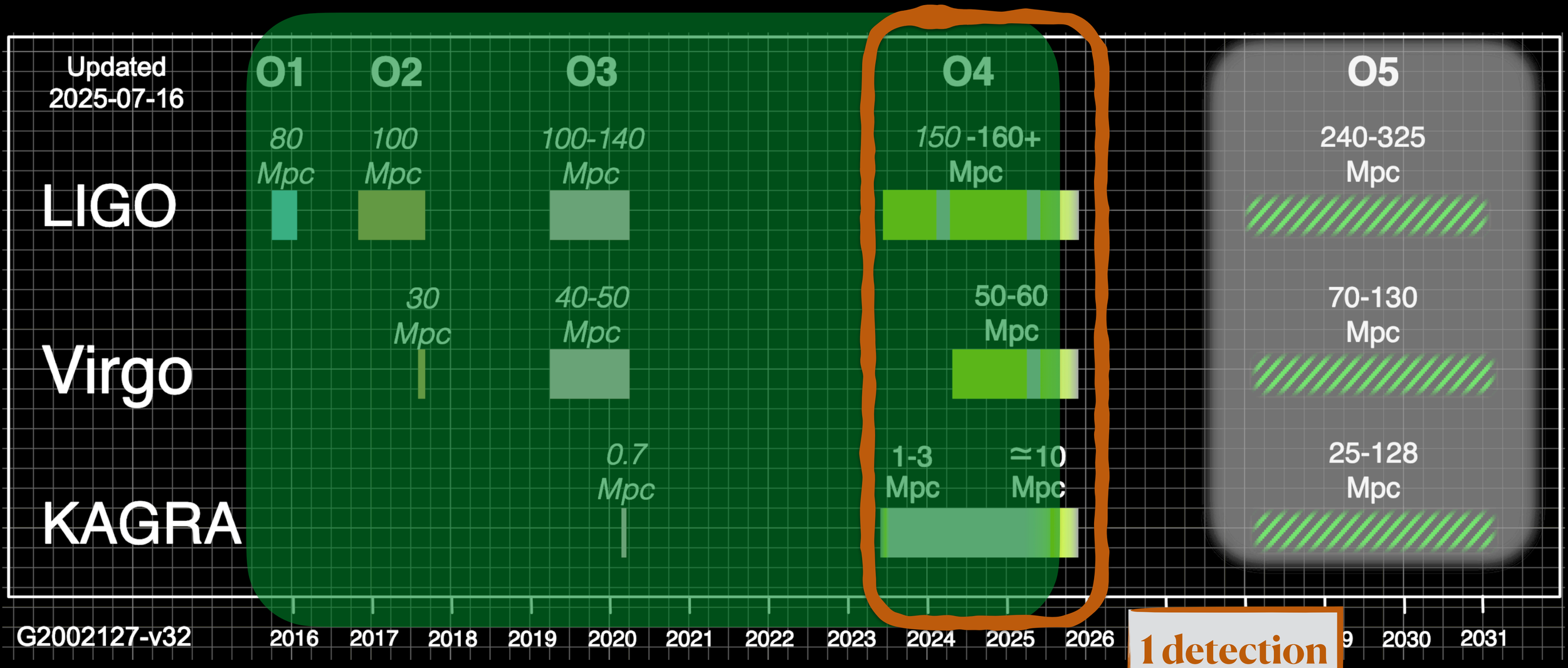
The next steps

LVC (G2002127 Tech Doc)



1 detection per ~3 days

K. Chatziioannou