

SEARCHING FOR PROCA STAR MERGER

arXiv: <http://arxiv.org/abs/2206.02551>



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TODAY:

- * Why do we think so?
- * What have we done?
- * What can we learn from them?

A QUICK REVIEW ON PROCA STAR

- * Proca star \rightarrow Vector boson star
- * self-gravitating, Bose Einstein condensate of ultra-light bosons
- * Characterise by:
 - $\mu_{\text{Boson}} \rightarrow$ Boson mass
 - $\omega \rightarrow$ Oscillation frequency
- * no event horizon \rightarrow black hole mimickers
- * Head-on merger \rightarrow Direct collision into each other
 - * (Short-lived) Hypermassive star \rightarrow collapse into a Black hole

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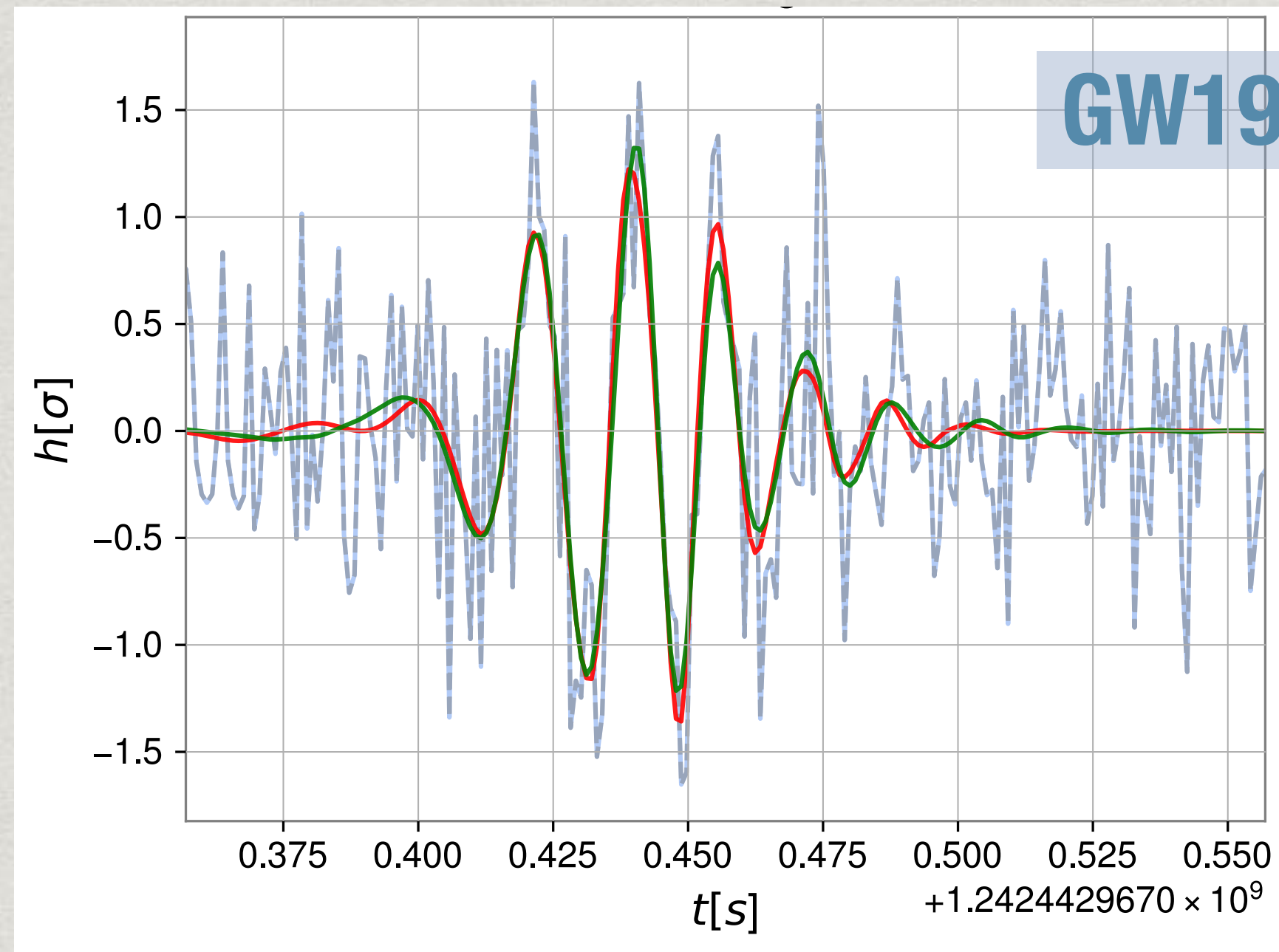
μ_{Boson} \longrightarrow Boson mass

ω \longrightarrow Oscillation frequency

Maximal star mass

Compactness

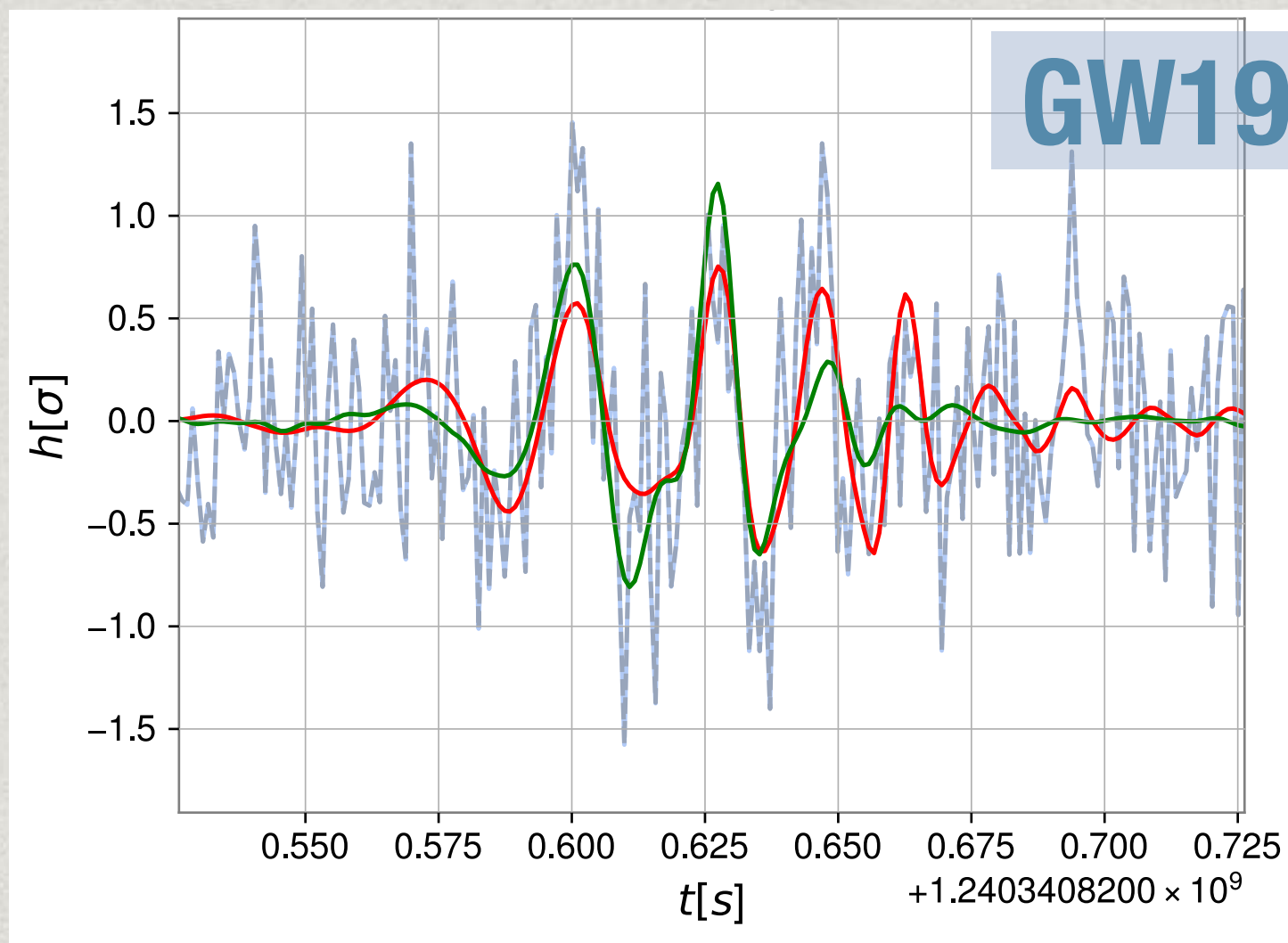
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GW190521

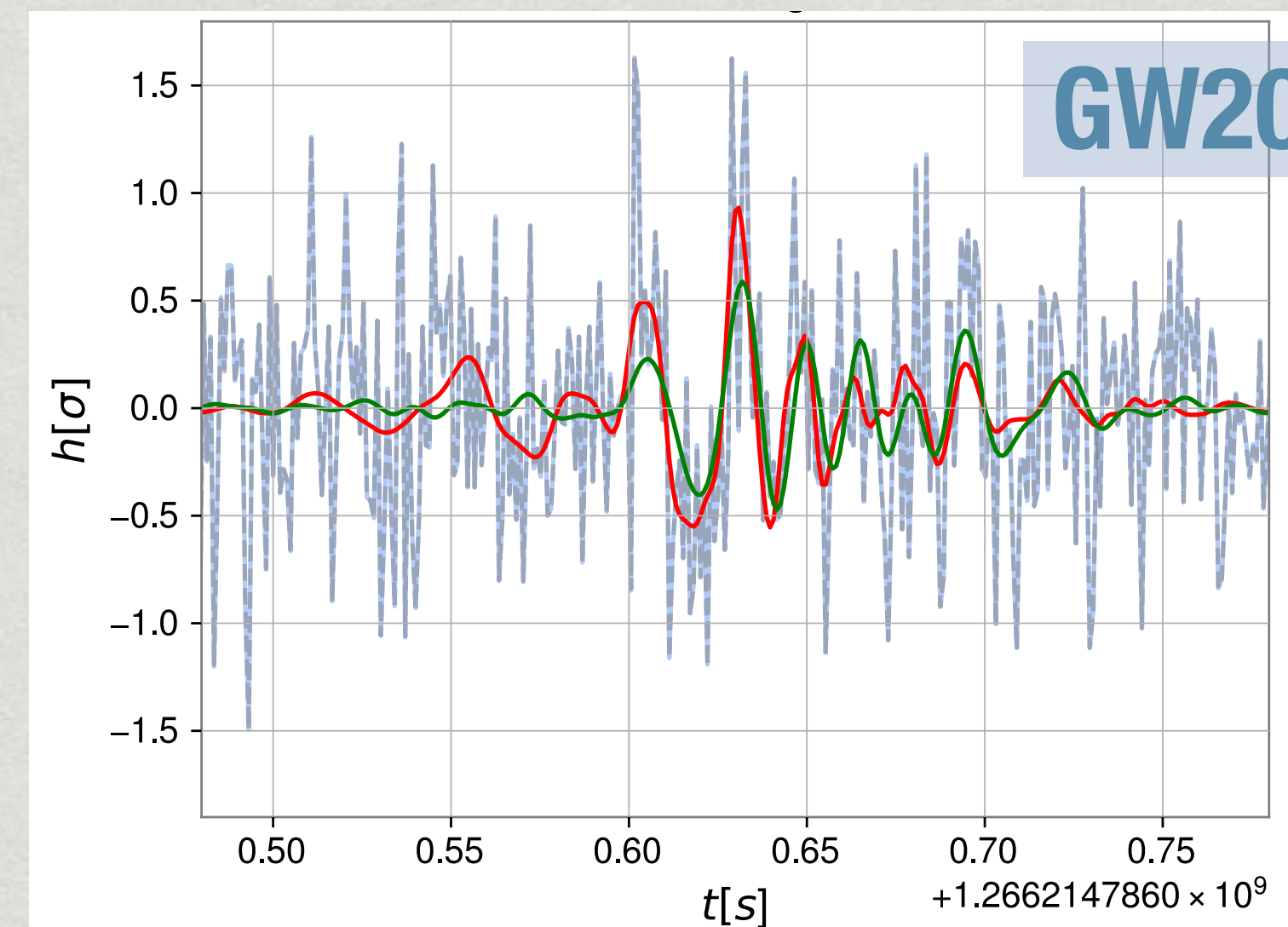
Bustillo+, 2022 (today)

- **Most significant high mass event detected by LIGO**
- **Short signal**
- **What its astrophysical origin??**
 - ◆ **Within PISN gap ?** [Nitz & Capano, 2021]
 - ◆ **“Straddling binary” ?** [Fishbach & Holz, 2020]
 - ◆ **Eccentric Binary ?** [Romero-Shaw, 2020; Gayathri, 2020]
 - ◆ **Proca star merger ?** [Bustillo+, 2020]



GW190426

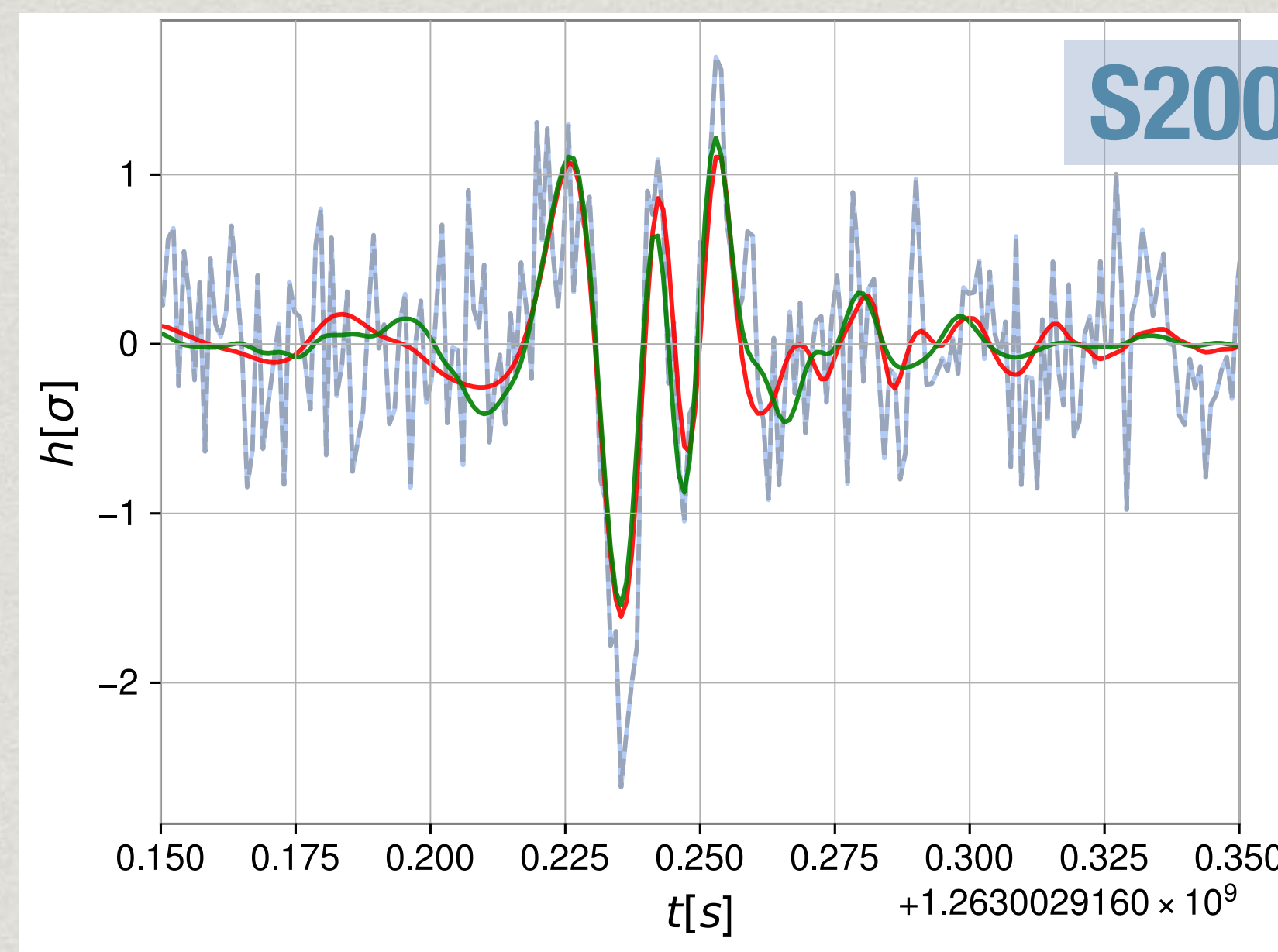
Bustillo+, 2022 (today)



GW200220

Bustillo+, 2022 (today)

— **Confirmed GW events**

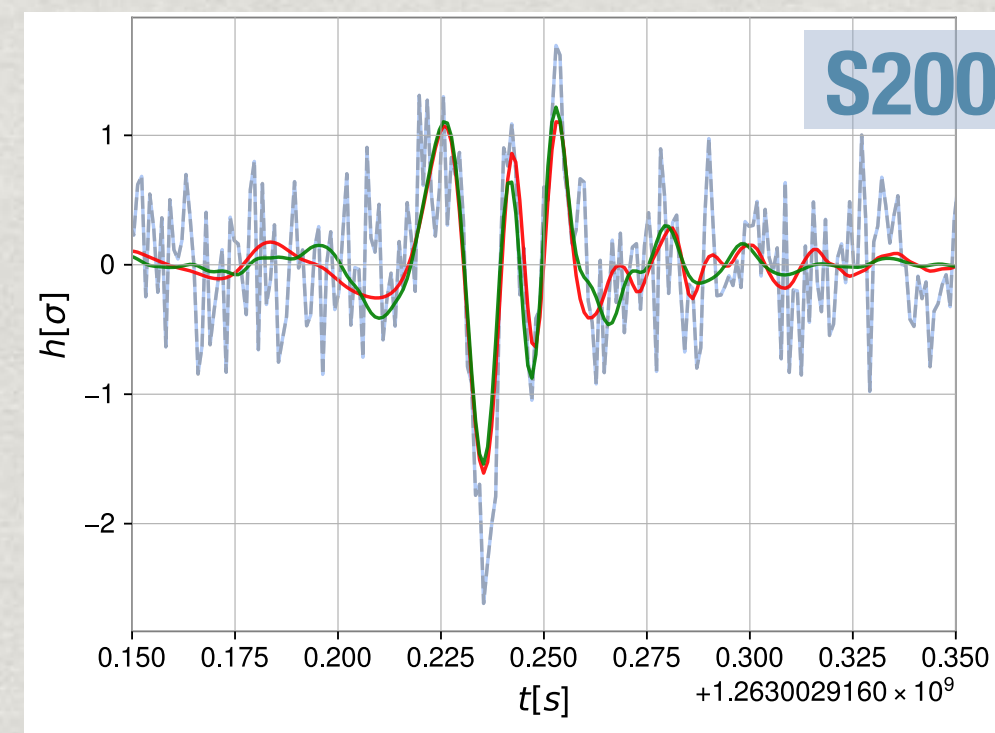
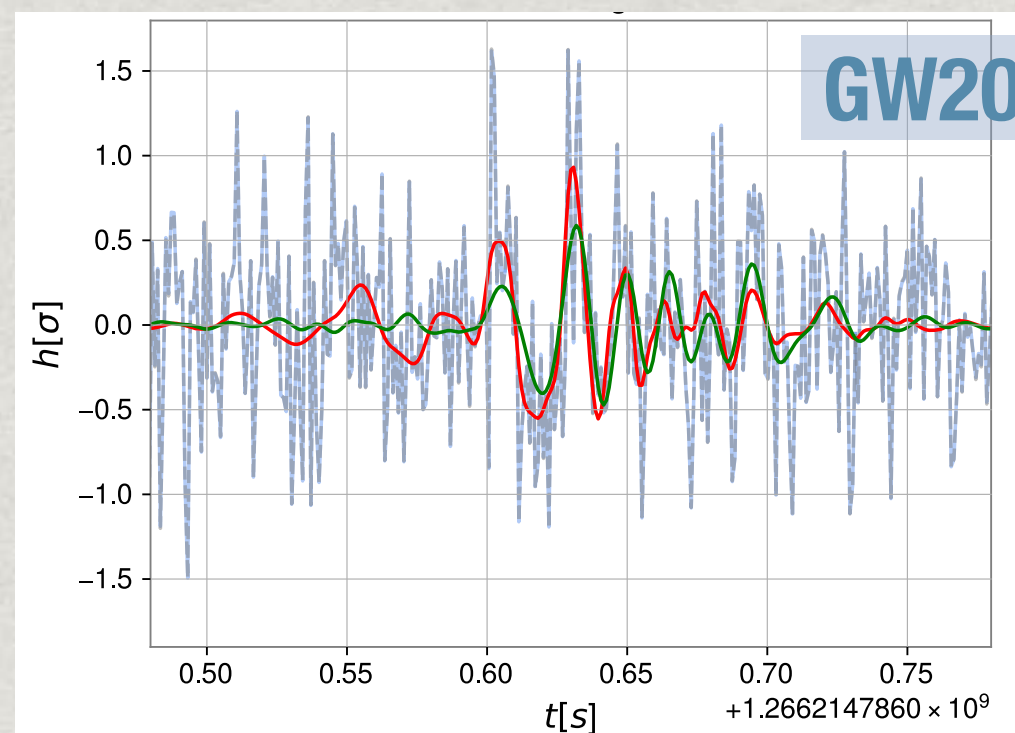
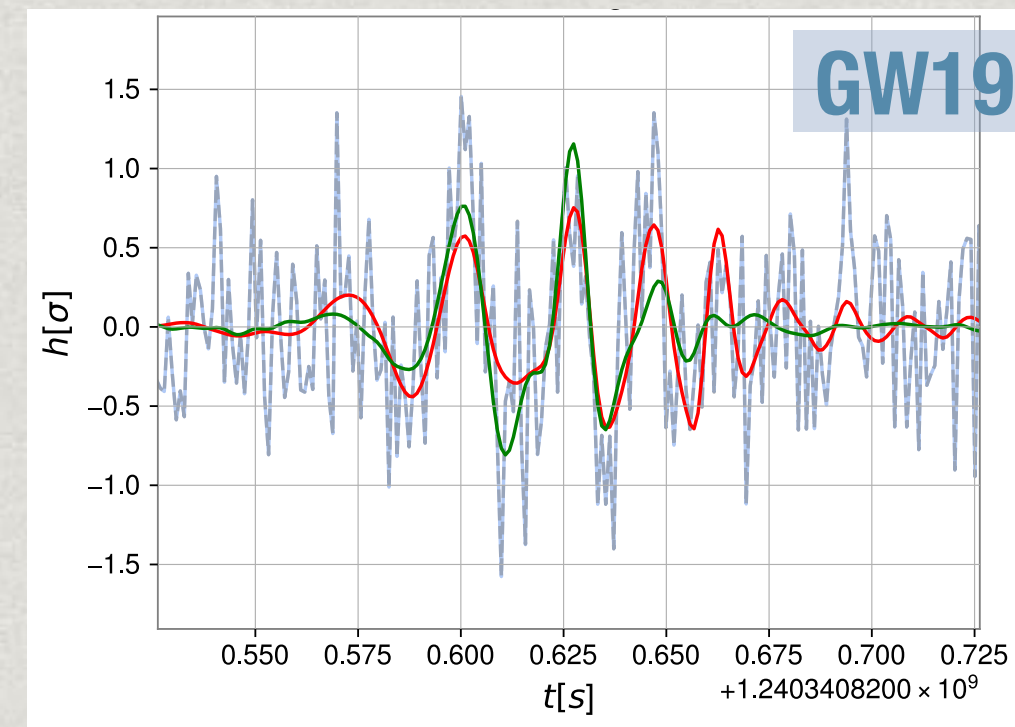
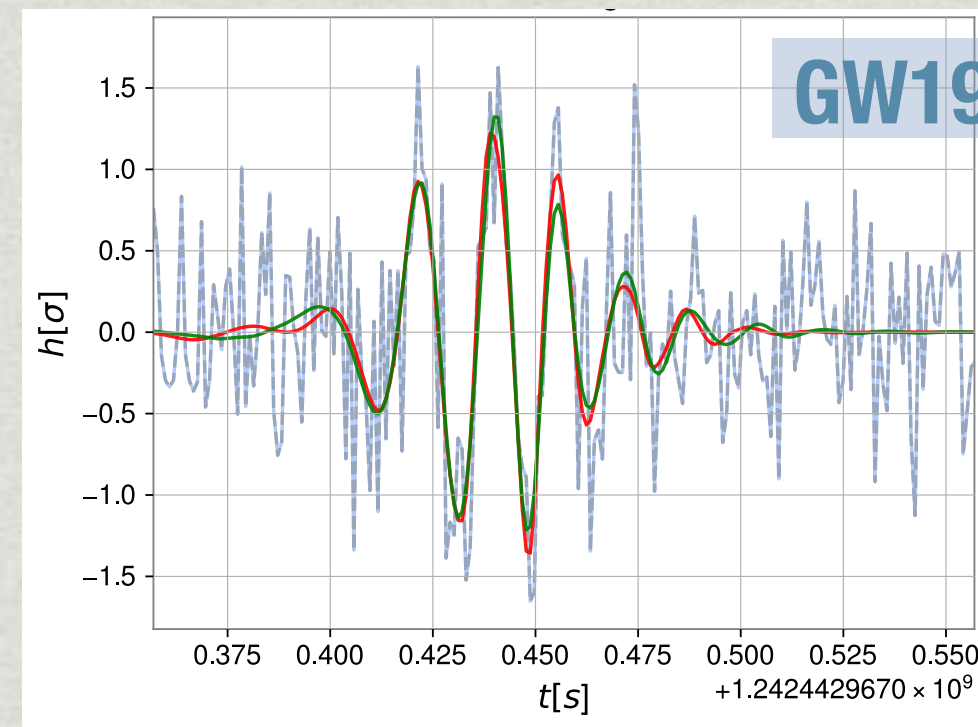


S200114f

Bustillo+, 2022 (today)

- **Short-duration transient**
- **Search from CWB** [Klimenko+, 2016]
- **Neither GW nor glitch**

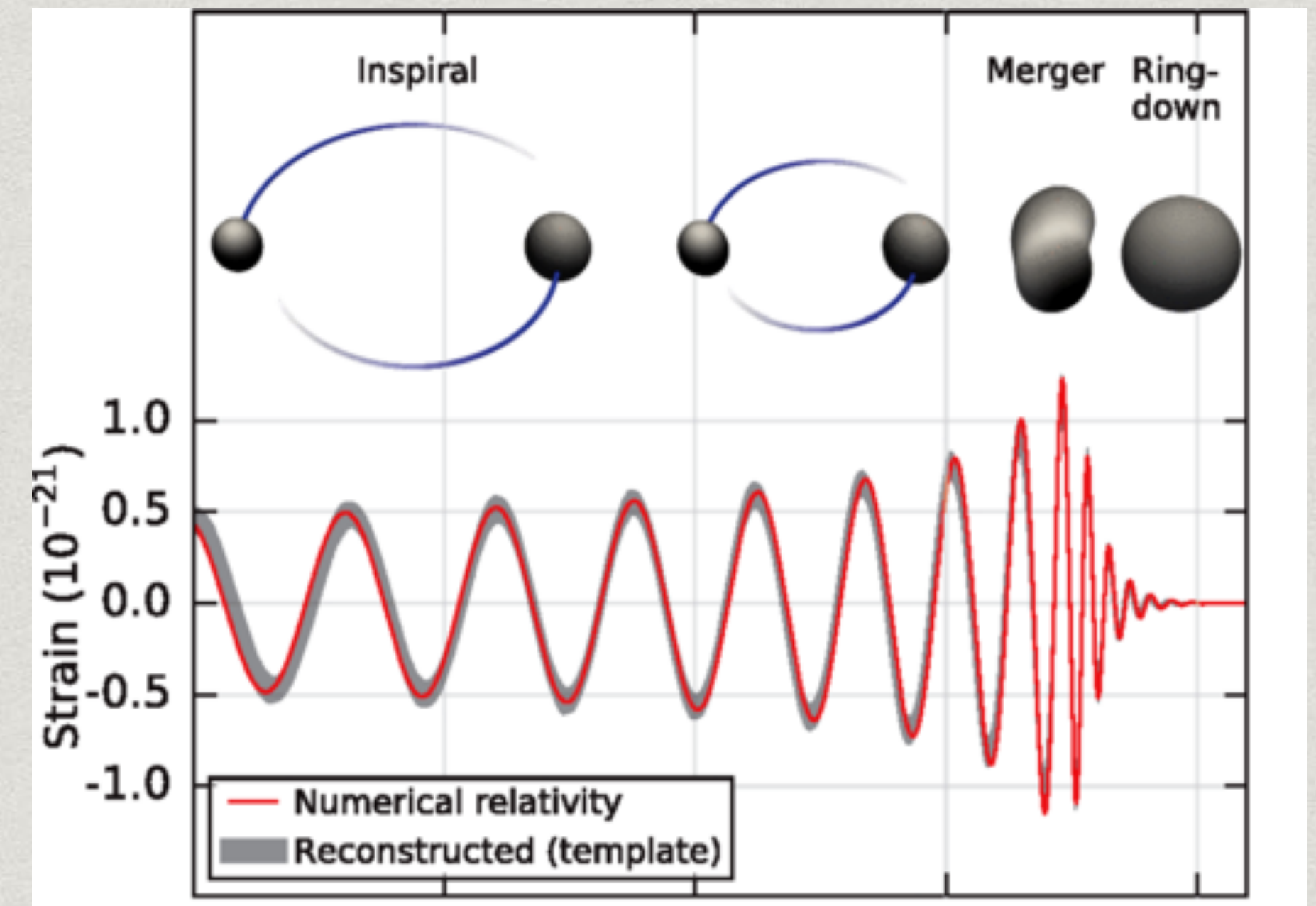
Strain data from Livingston (L1)



Bustillo+, 2022 (today)

- Short, no inspiral phase
- Not informative Inspiral,
- Strong impact of prior

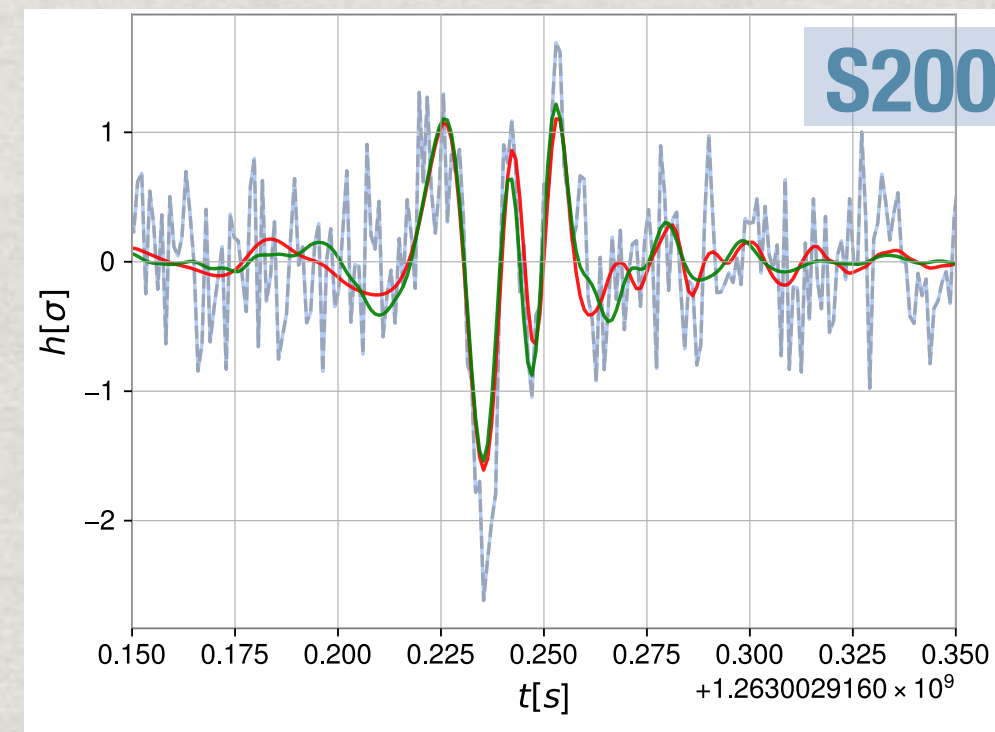
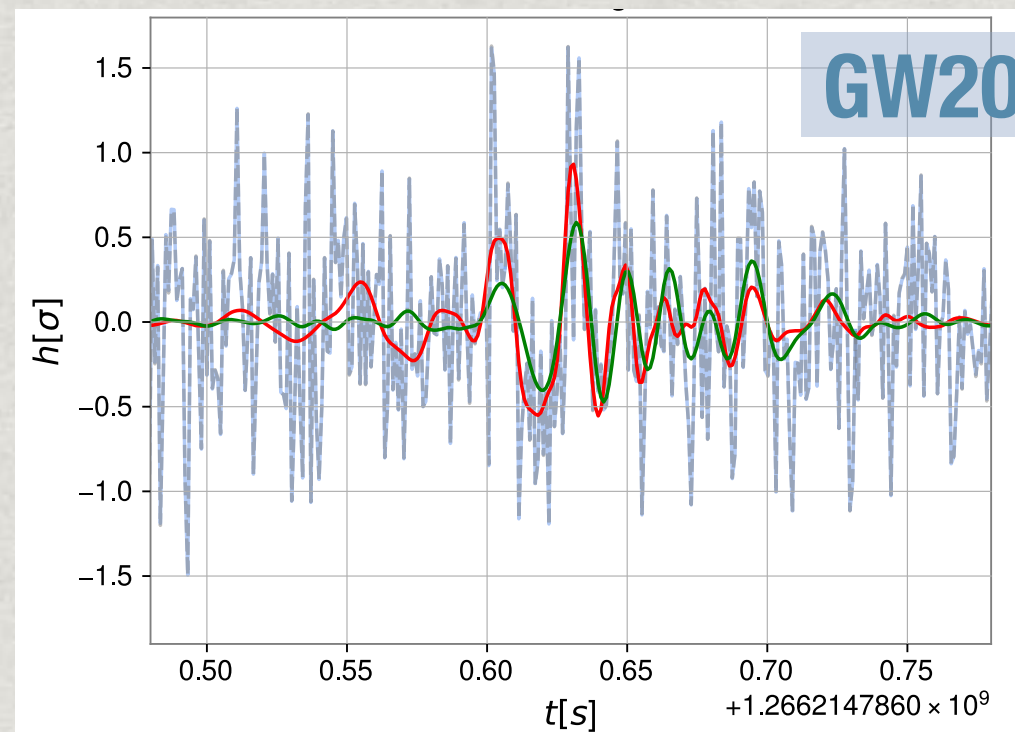
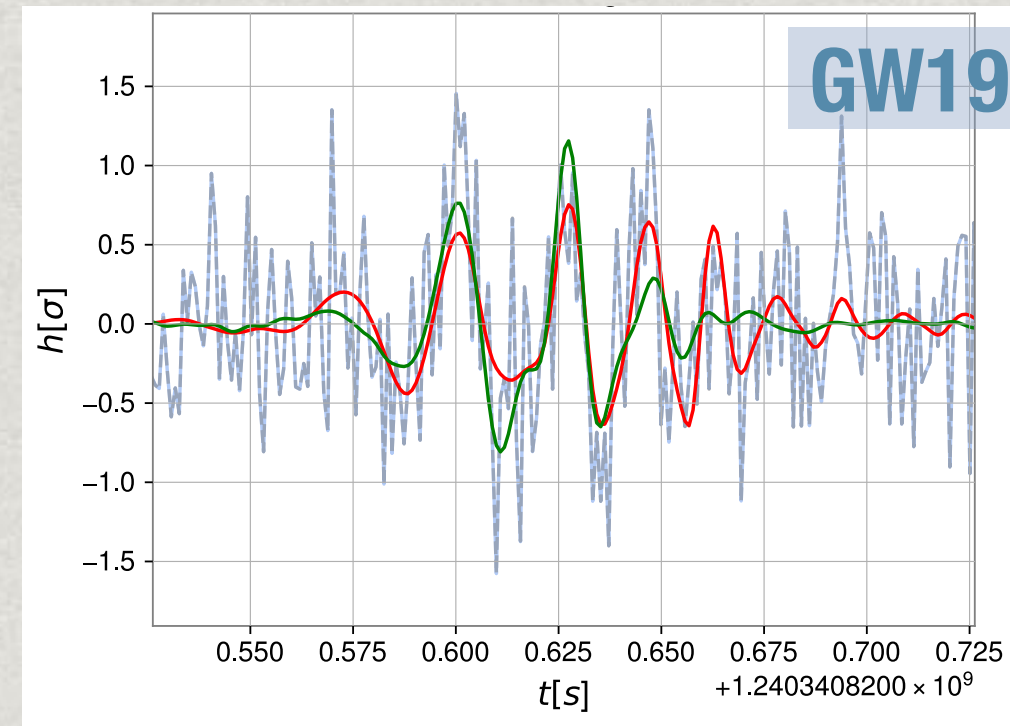
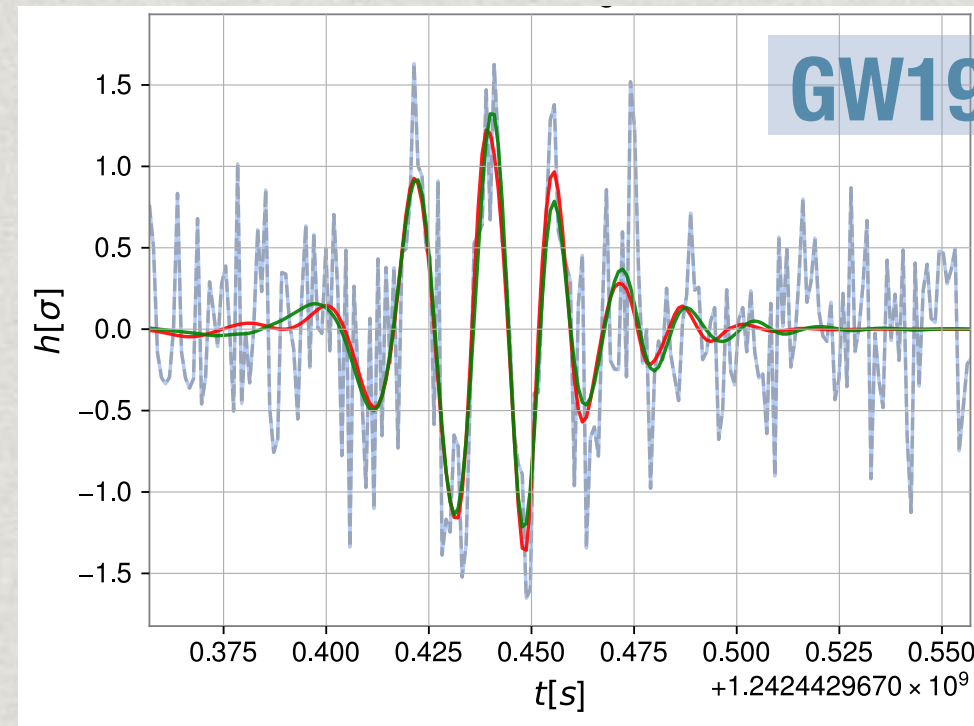
GW150914 (first detection) H1 strain data



LVC, 2016

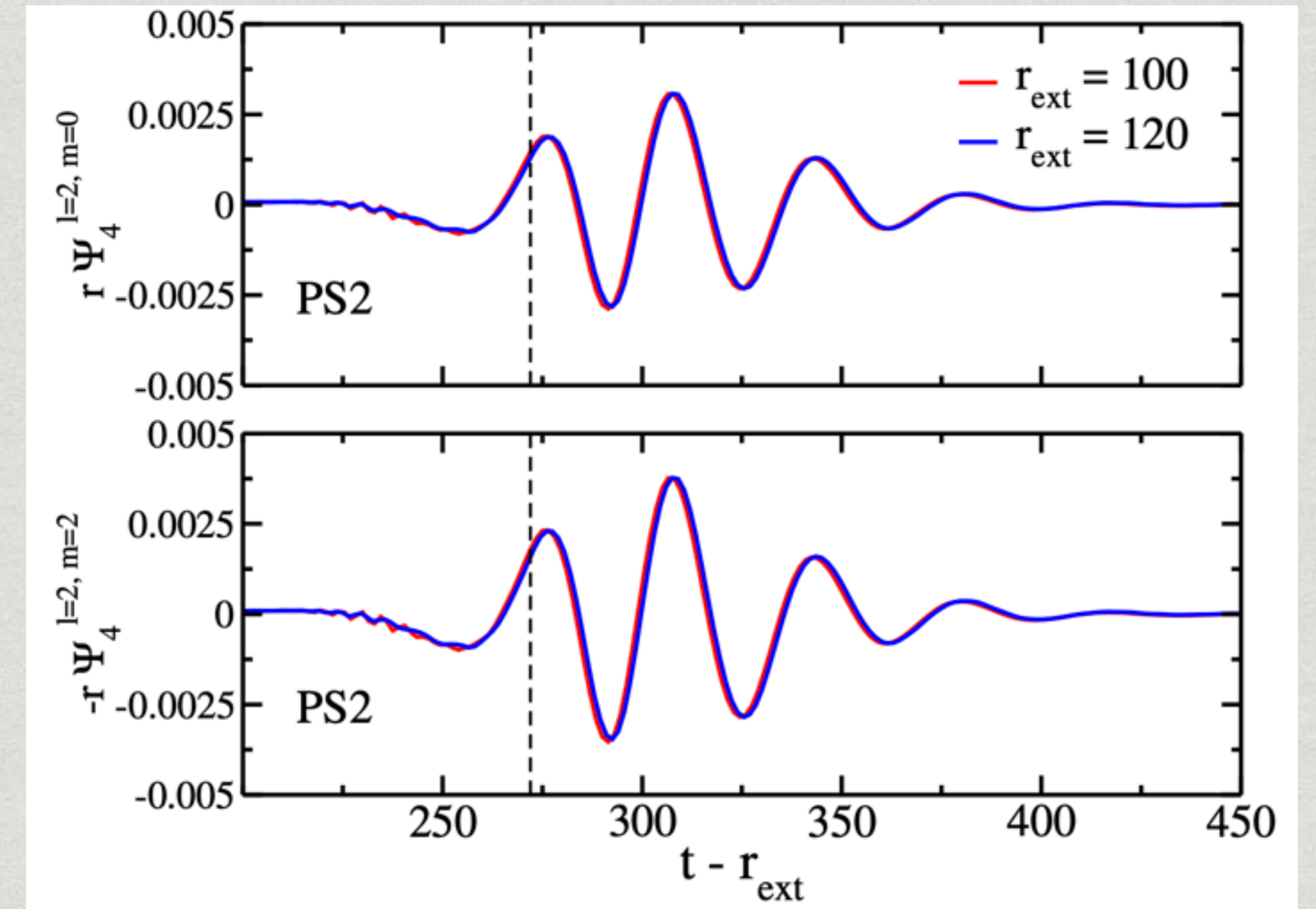
- Inspiral: total mass, mass ratio

Strain data from Livingston (L1)



Bustillo+, 2022 (today)

Typical Head-on, Proca stars merger



Sanchis-Gual+, 2019

- Short, no inspiral phase

EVIDENCE?

* Evidence:

Signal data **Proca model**

$$\mathcal{Z}_{\text{Proca}} = p(\underline{\text{data}} \mid \underline{M_{\text{Proca}}})$$
$$\mathcal{Z}_{\text{Proca}} = \int \mathcal{L}(\text{data} \mid \theta, M_{\text{Proca}}) \pi(\theta \mid M_{\text{Proca}}) d\theta$$

EVIDENCE?

$$Z_{\text{Proca}} = p(\text{data} \mid M_{\text{Proca}})$$

* Evidence:

$$Z_{\text{Proca}} = \int \mathcal{L}(\text{data} \mid \theta, M_{\text{Proca}}) \pi(\theta \mid M_{\text{Proca}}) d\theta$$

Likelihood:

how well model is fitting data

Prior:

Prior distribution of
the parameter

MODEL SELECTION

BAYES' FACTOR

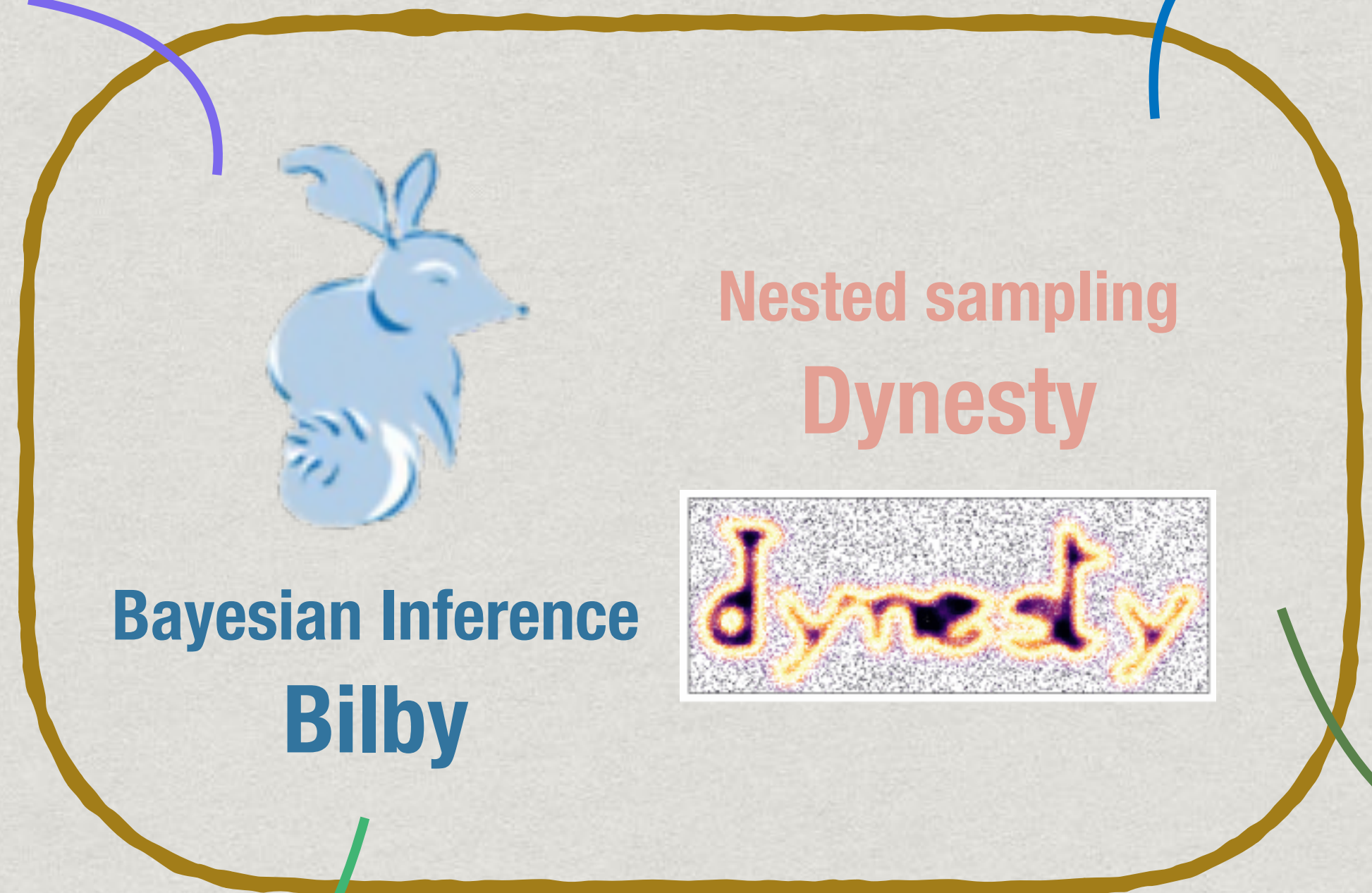
$$\mathcal{B}_{\text{BBH}}^{\text{Proca}} = \frac{\mathcal{Z}_{\text{Proca}}}{\mathcal{Z}_{\text{BBH}}}$$

Evidence of Proca stars merger model

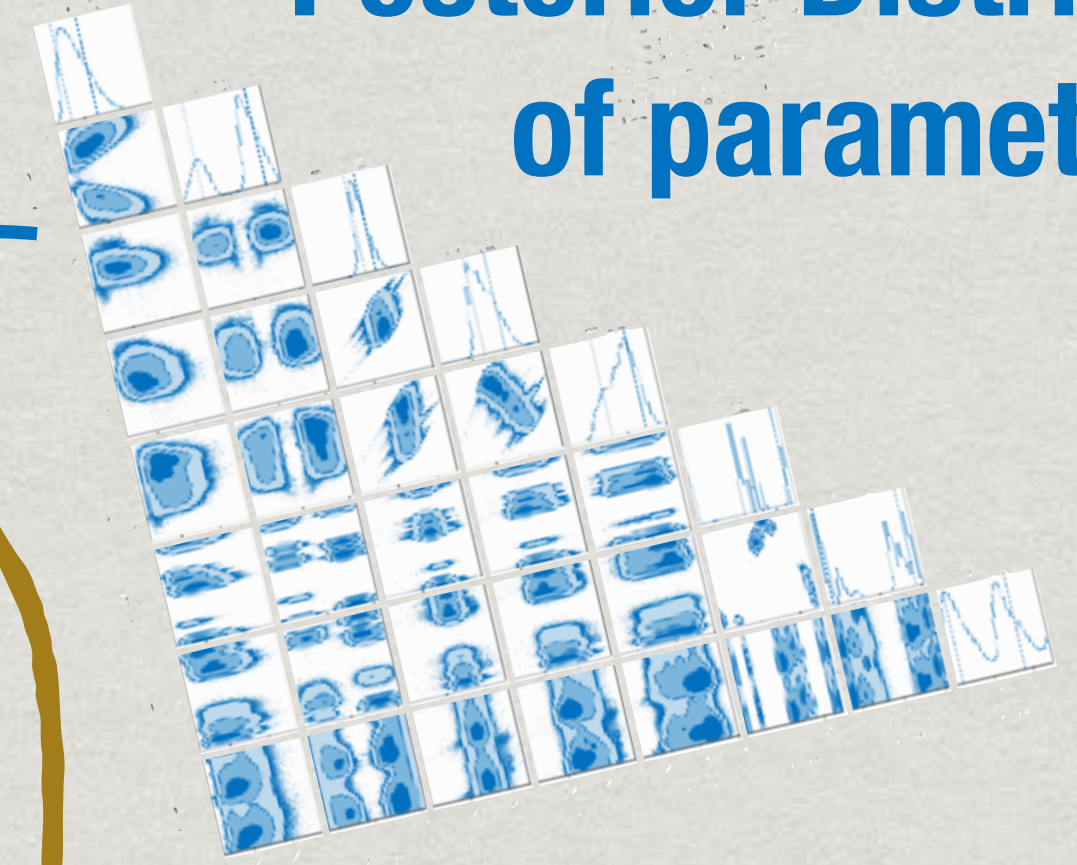
Evidence of Binary Black Hole model

WHAT WE DID:

759 numerical simulations of Proca star merger

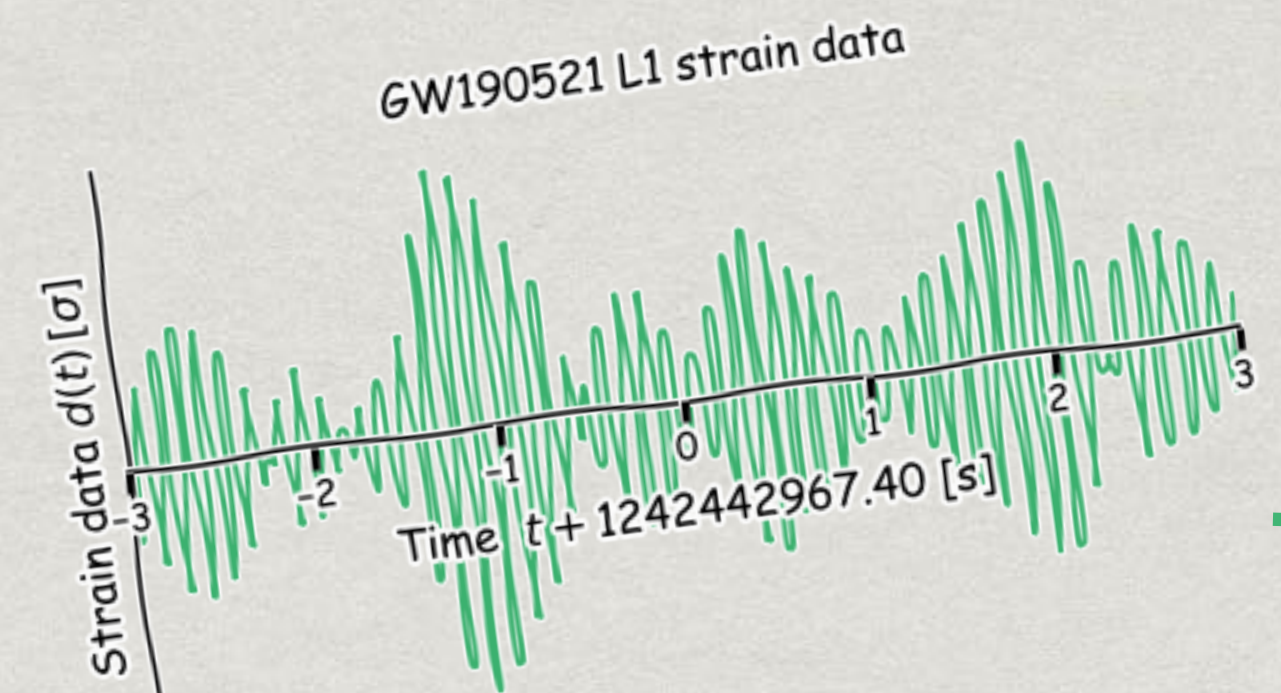


Posterior Distributions of parameters



d_L
 $M_{\text{final}}^{\text{BH}}$
 ω_1, ω_2

Evidence of Proca stars merger model



LIGO Data

$$\mathcal{B}_{\text{BBH}}^{\text{Proca}} = \frac{\mathcal{Z}_{\text{Proca}}}{\mathcal{Z}_{\text{BBH}}}$$

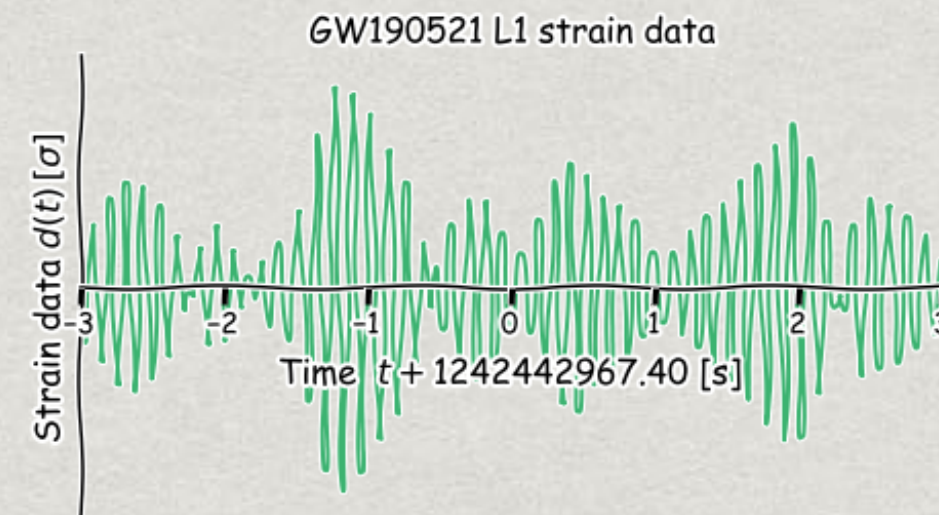
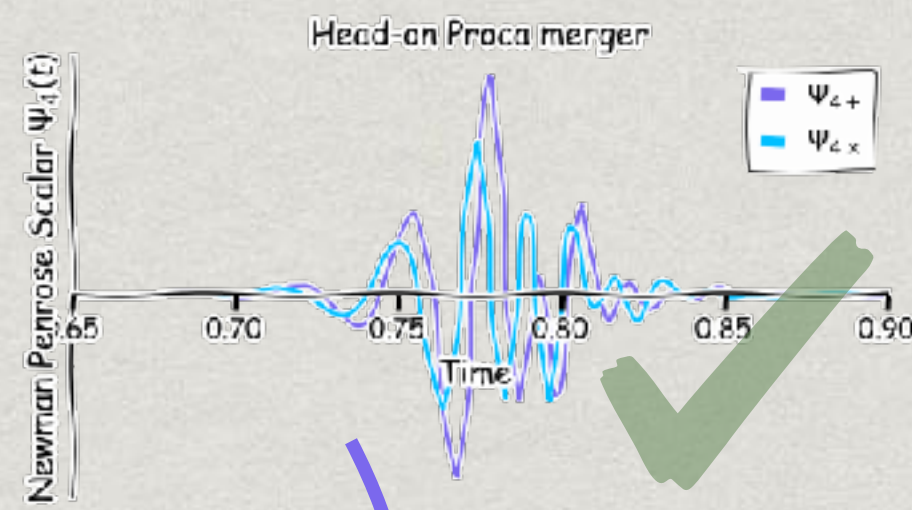
BAYES' FACTOR

Evidence of Binary Black Hole model

759 numerical simulations

WHAT WE ACTUALLY DID:

~~Strain $h_{+,x}(t)$~~



LIGO Data

NRSur7dq4

(with Precession + HM)

Nested sampling
Dynesty

Bayesian Inference
Bilby_psi4

Nested sampling
Dynesty

Bayesian Inference
Bilby

Evidence of Proca stars merger model

Evidence of Binary Black Hole model

$$\mathcal{B}_{\text{BBH}}^{\text{Proca}} = \frac{\mathcal{Z}_{\text{Proca}}}{\mathcal{Z}_{\text{BBH}}}$$

BAYES' FACTOR

BAYES' FACTOR OF EACH EVENT

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

- **GW190521, S200114f** → Prefer Proca stars merger
- **GW190426, GW200220** → (strongly, mildly) Prefer binary black holes

INTRINSIC LOUDNESS → POSSIBLE BIAS

Head-on Proca star merger

Quasi-circular binary black holes



Inspiral

No

Long

Loudness

Weaker

Intrinsically louder

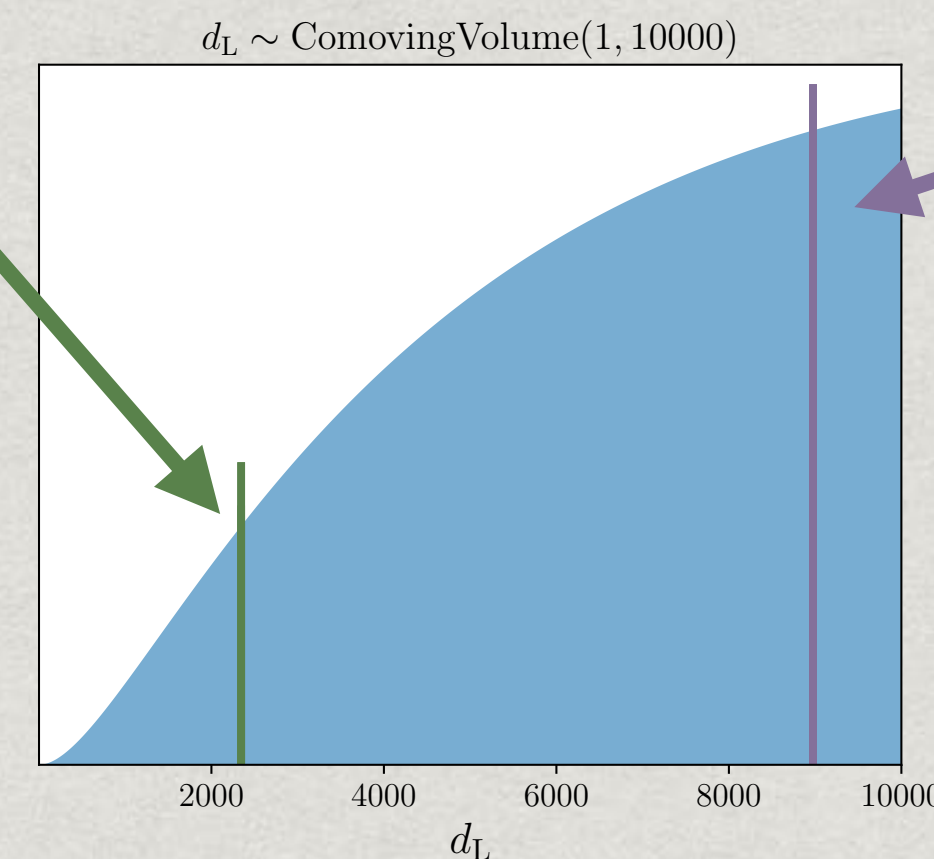
Inferred distance

much **closer**

can be placed **farther** away

Effect of distance prior

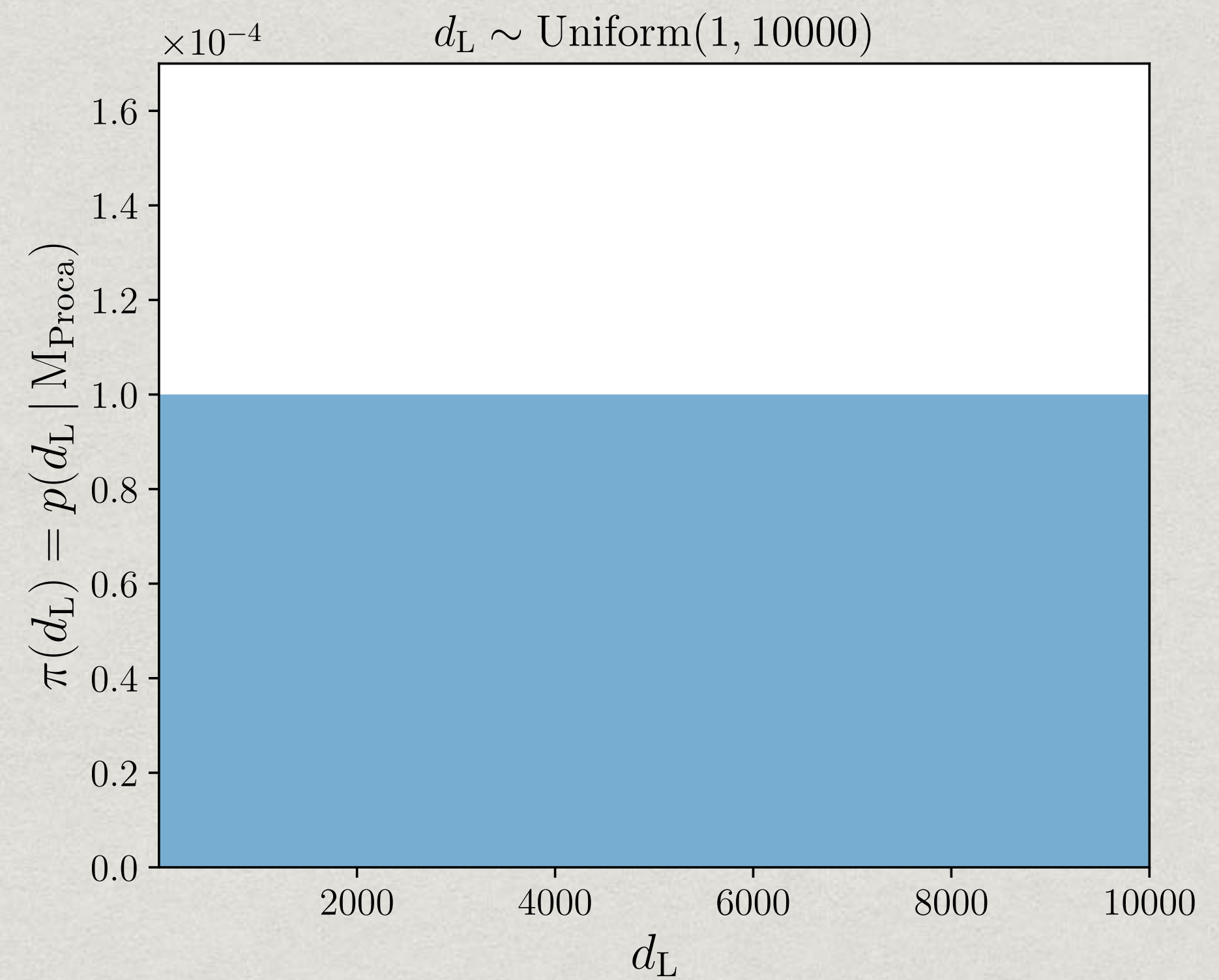
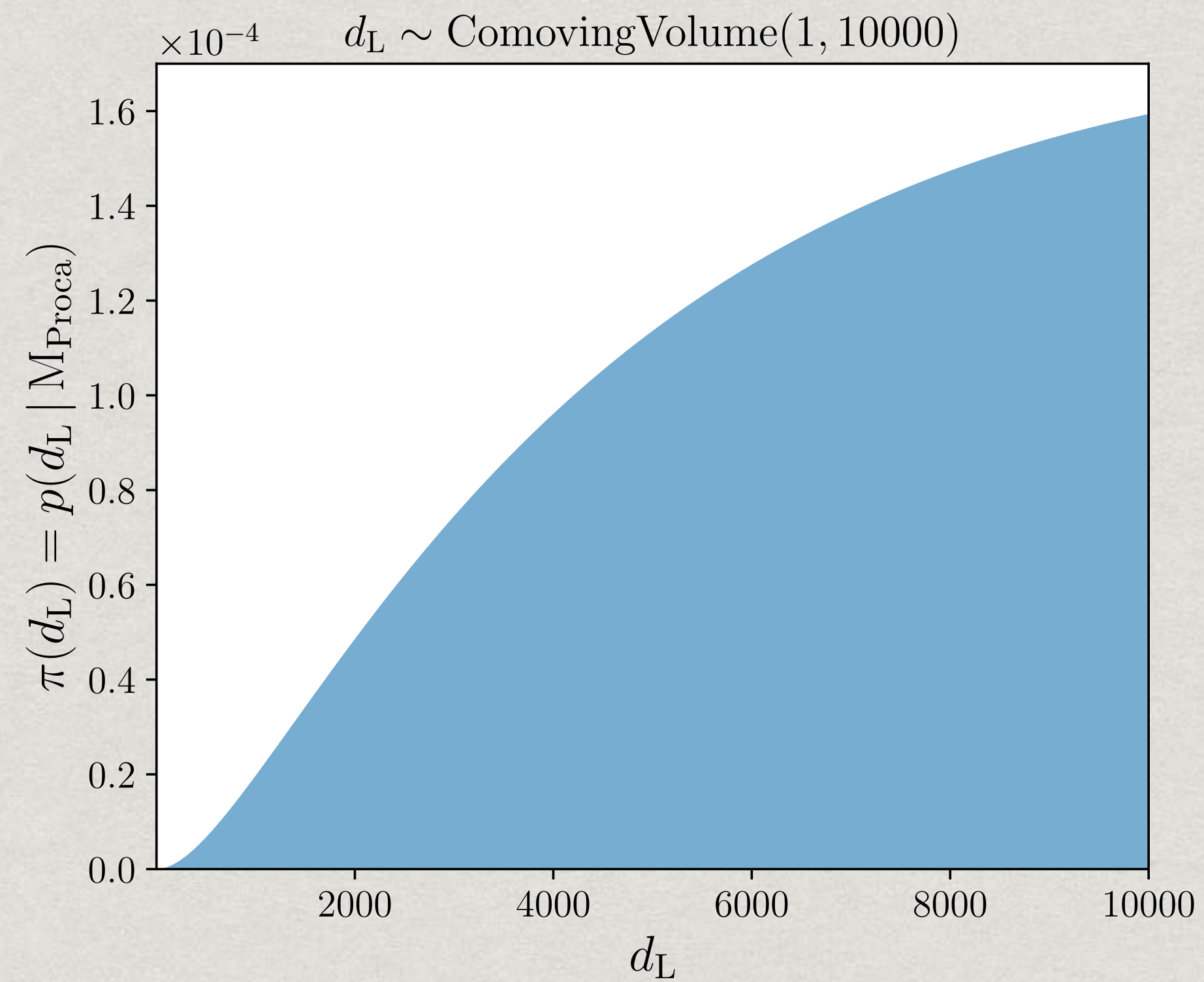
Uniform in Comoving Volume



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

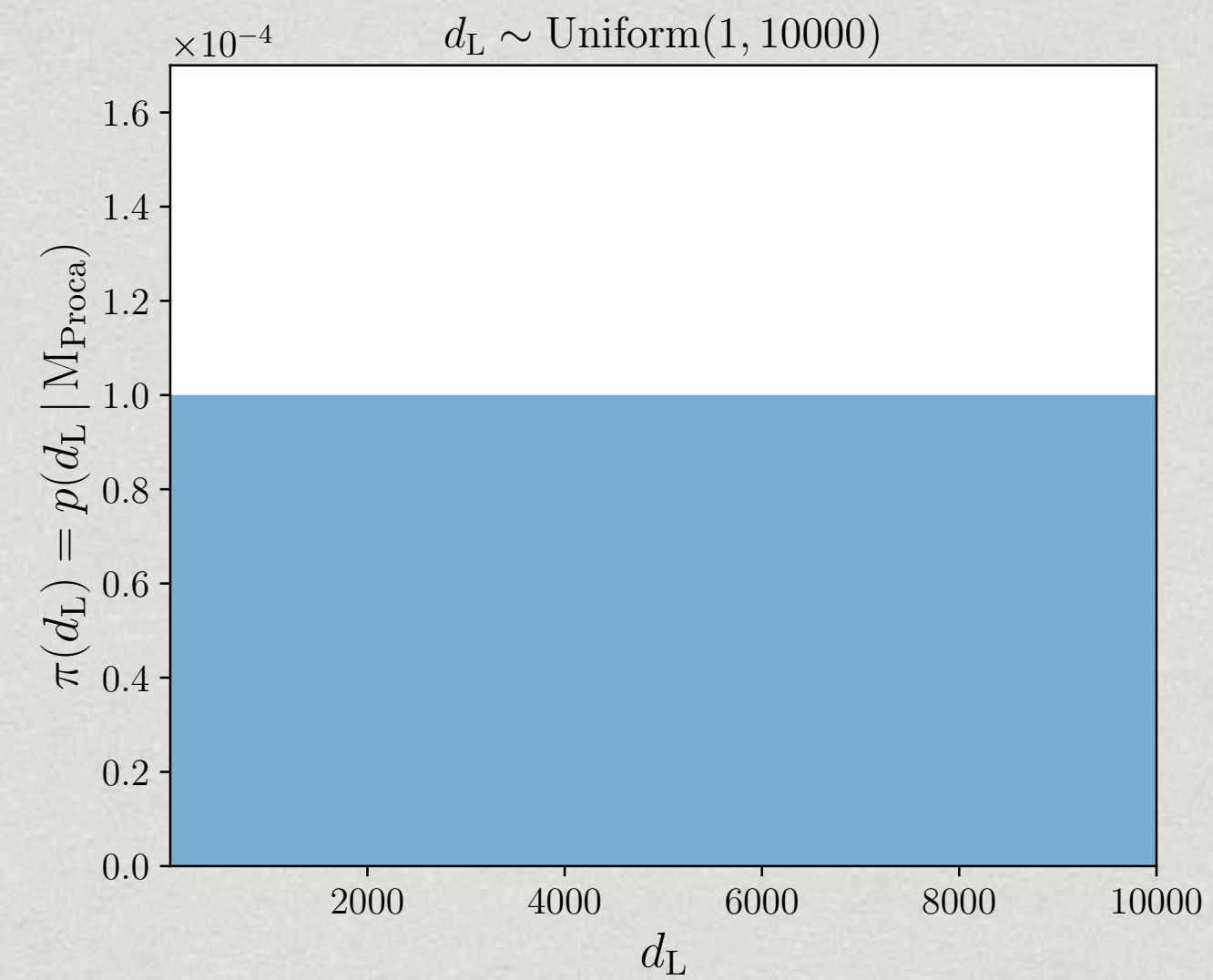
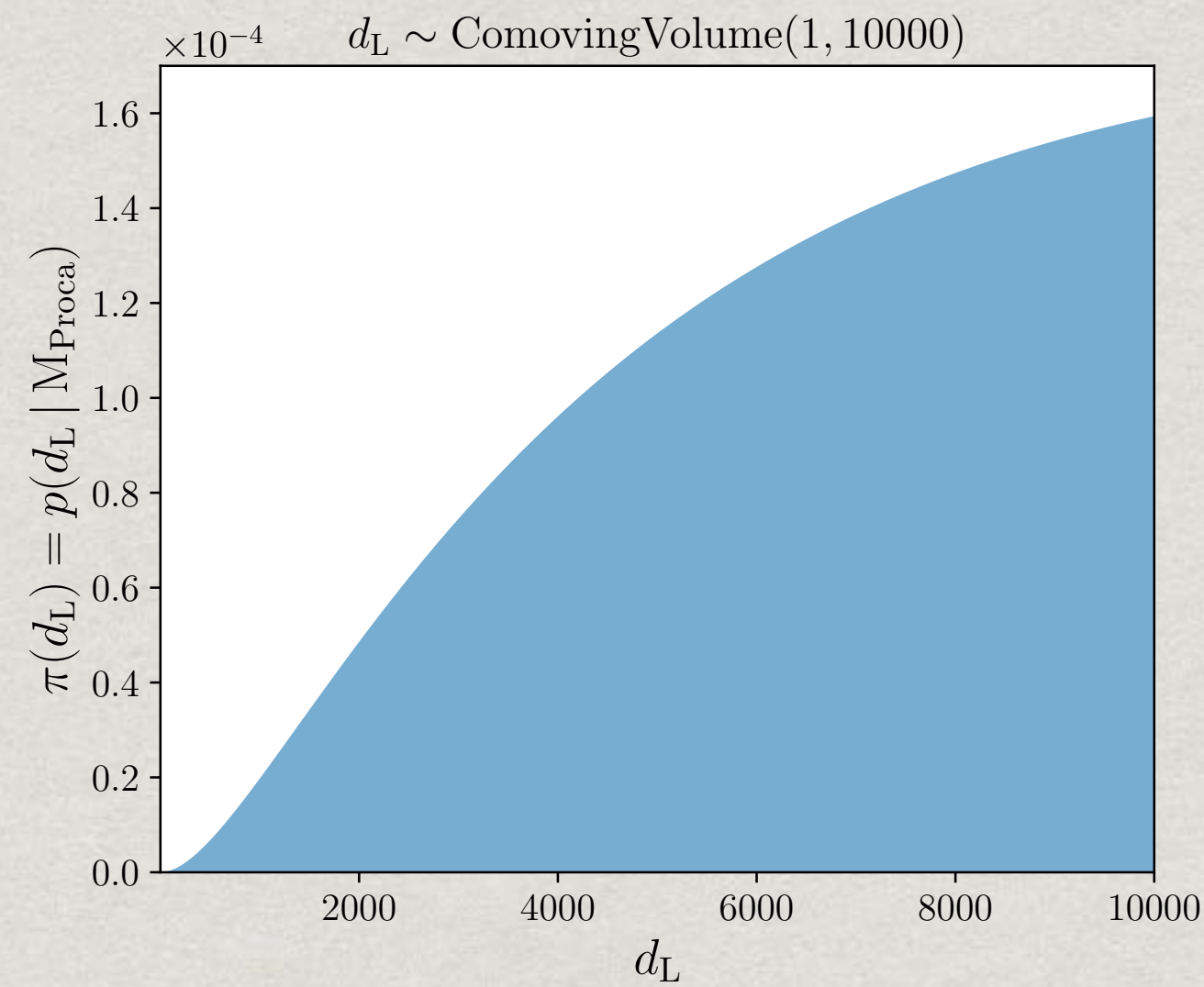
WHAT IF WE CHANGE PRIOR?

$$\pi(d_L) \propto \text{Comoving volume} \longrightarrow \pi(d_L) \propto \text{Uniform}(d_L)$$



WHAT IF WE CHANGE PRIOR?

$$\pi(d_L) \propto \text{Comoving volume} \longrightarrow \pi(d_L) \propto \text{Uniform}(d_L)$$



1. **Remove the bias**
2. **Glimpse at prospective circular Proca star mergers**

AFTER CHANGING THE PRIOR

- GW190521, S200114f → Prefer Proca stars merger
- GW190426, GW200220 → (Strongly, mildly) Prefer binary black holes

Event	GW190521	GW190426	GW200220	S200114f
(Comoving Volume) $\mathcal{B}_{\text{BBH}}^{\text{Proca}}$	2.5	2.0×10^{-4}	0.05	3.7
(Uniform distance) $\mathcal{B}_{\text{BBH}}^{\text{Proca}}$	18.2	2.0×10^{-3}	0.4	36.6

- **Significant improvements for all events**
- **In particular, S200114f**

WHAT DO WE KNOW ABOUT THE BOSON?

Inferred from analysis

Explicitly sampled from
Parameter estimation

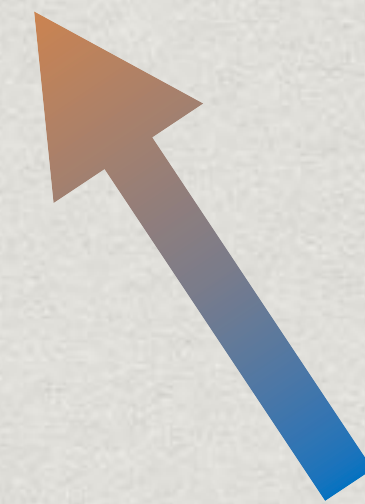
Boson masses

μ_{Boson}



ω_1, ω_2

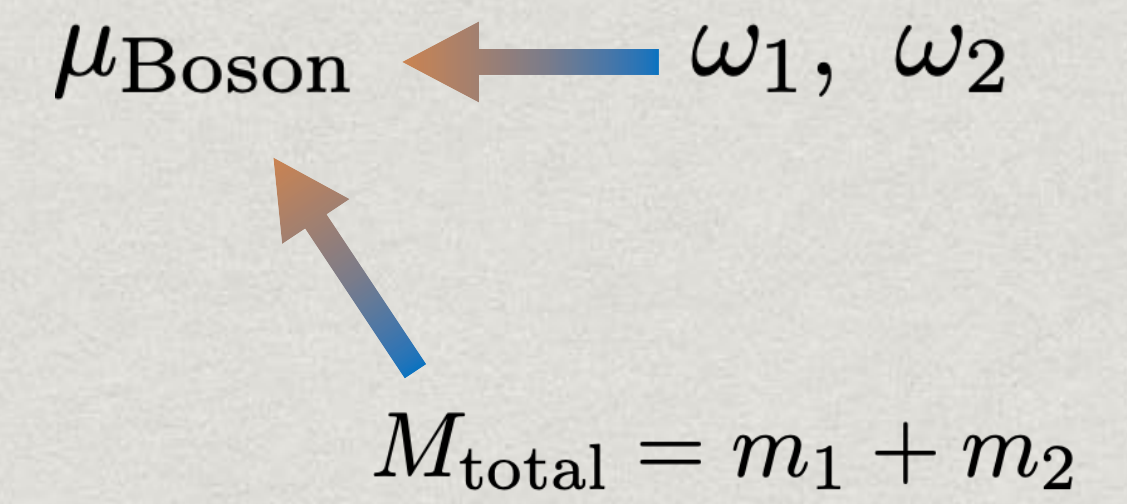
**Bosonic field
oscillation frequency**



$M_{\text{total}} = m_1 + m_2$

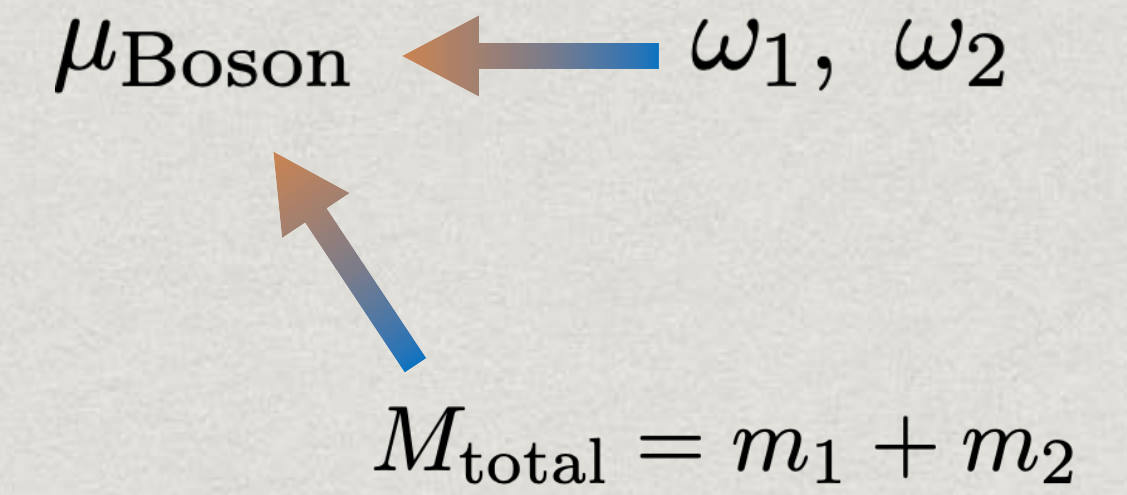
Total stars mass

MORE SPECIFICALLY...



$$M_{\text{final}}^{\text{BH}} = (\mathcal{M}_1 + \mathcal{M}_2) \frac{M_{\text{Pl}}}{\mu_{\text{Boson}}} M_{\text{Pl}}$$

MORE SPECIFICALLY...



Final BH mass $M_{\text{final}}^{\text{BH}} = (\mathcal{M}_1 + \mathcal{M}_2) \frac{M_{\text{Pl}}}{\mu_{\text{Boson}}} M_{\text{Pl}}$

Characteristic Proca star masses $\mathcal{M}_1, \mathcal{M}_2$

Planck mass M_{Pl}

the Boson mass μ_{Boson}

MORE SPECIFICALLY...

Determined by the oscillation frequency $\omega_{1,2}$

It's a constant

Characteristic

Proca star masses

Planck mass

Final BH mass

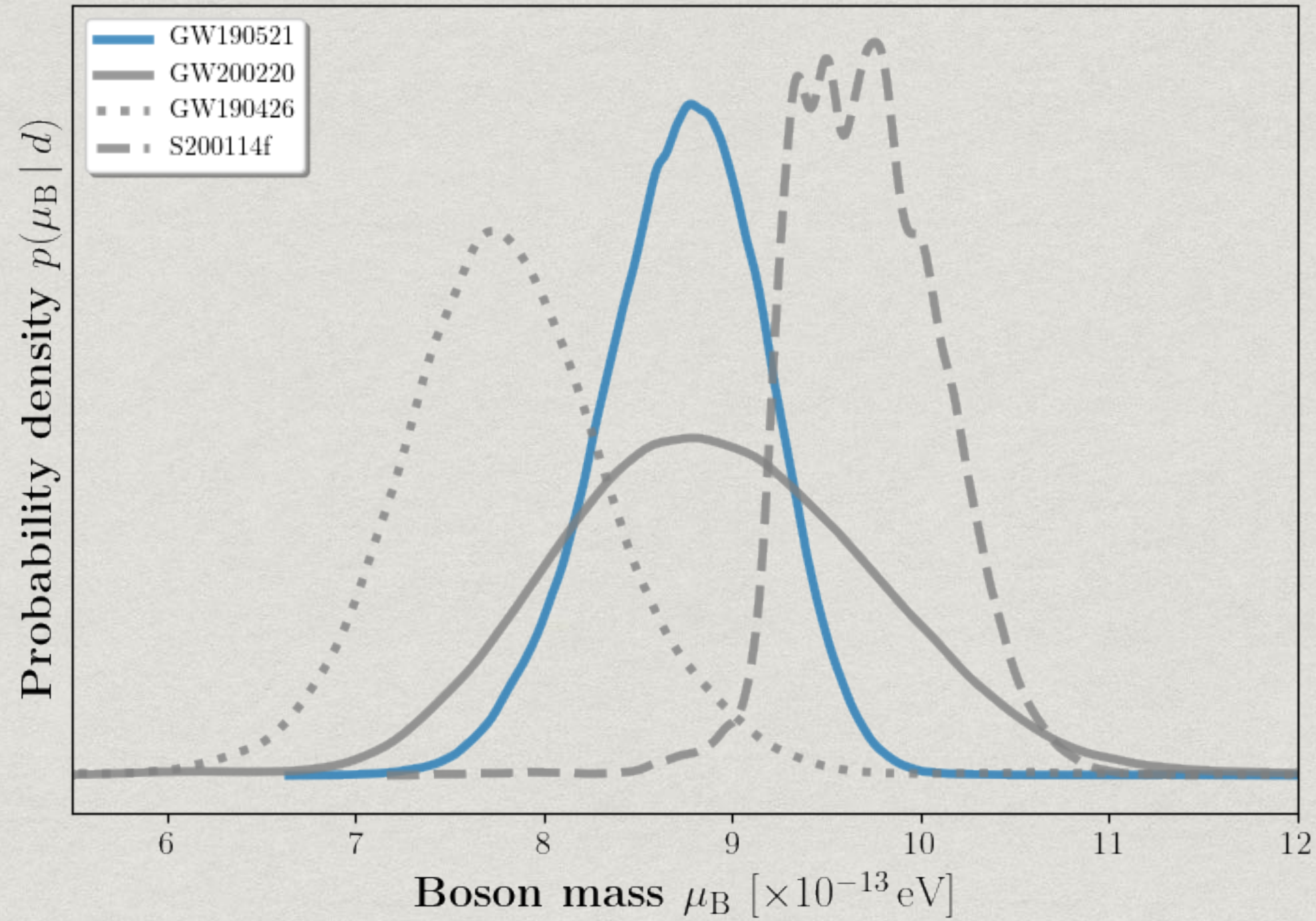
$$M_{\text{final}}^{\text{BH}} = (\mathcal{M}_1 + \mathcal{M}_2) \frac{M_{\text{Pl}}}{\mu_{\text{Boson}}} M_{\text{Pl}}$$

the Boson mass

\approx total mass
from parameter estimation

Ta-da

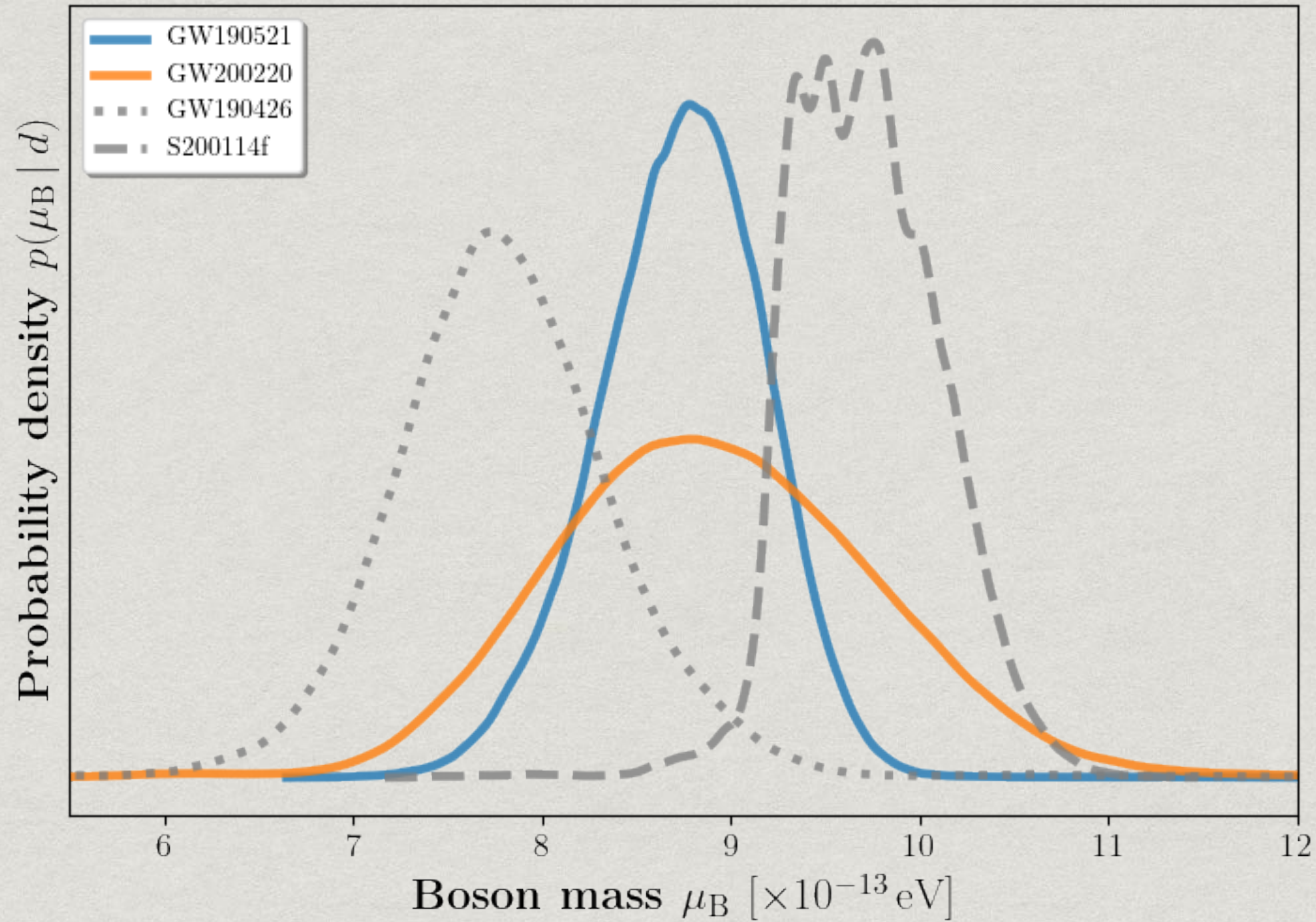
BOSON MASS DISTRIBUTION



GW190521:

- Consistent with result from last year

BOSON MASS DISTRIBUTION



GW190521:

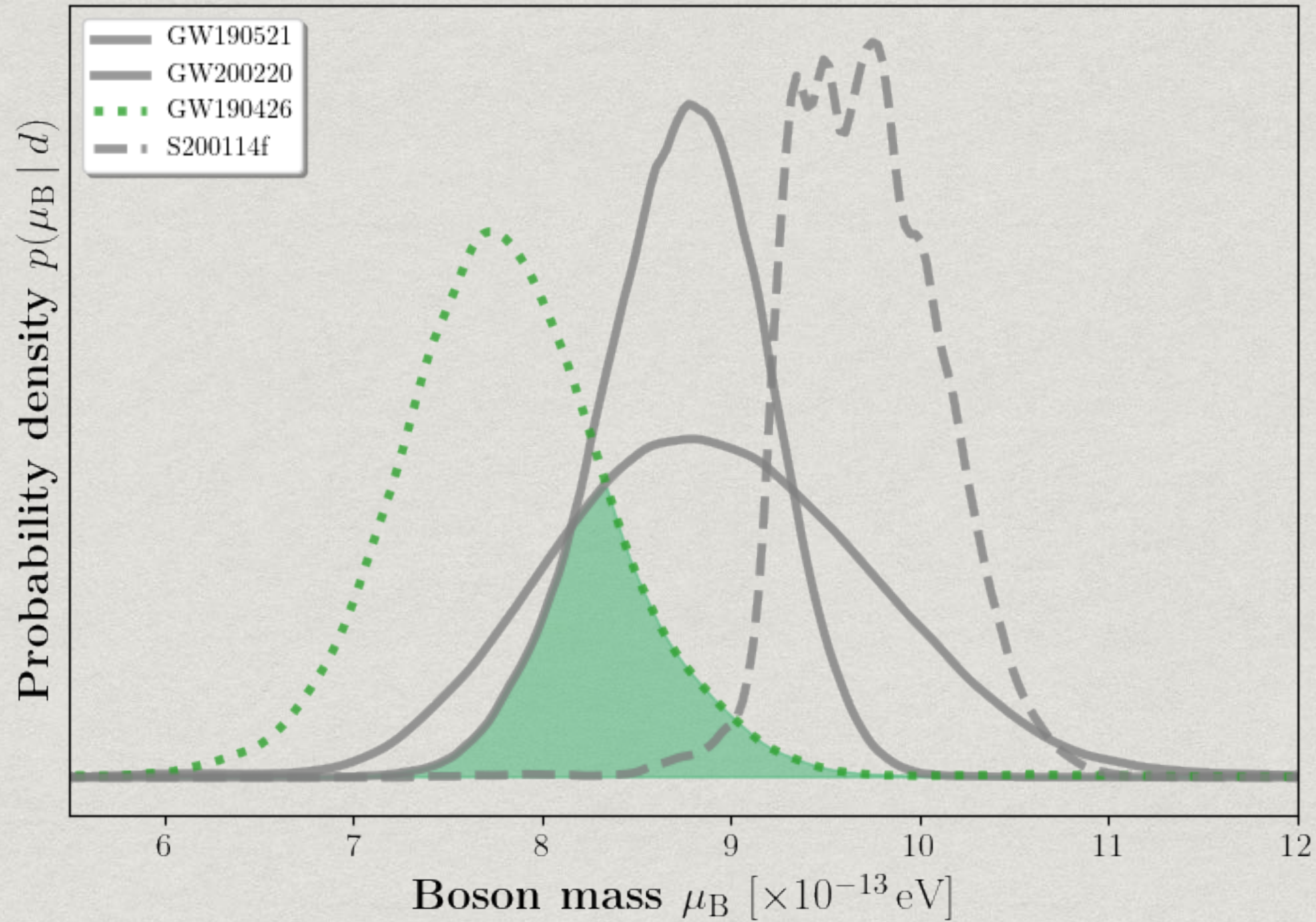
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GW200220:

- Good overlap with GW190521

- Mass coincidence in population study

BOSON MASS DISTRIBUTION



GW190521:

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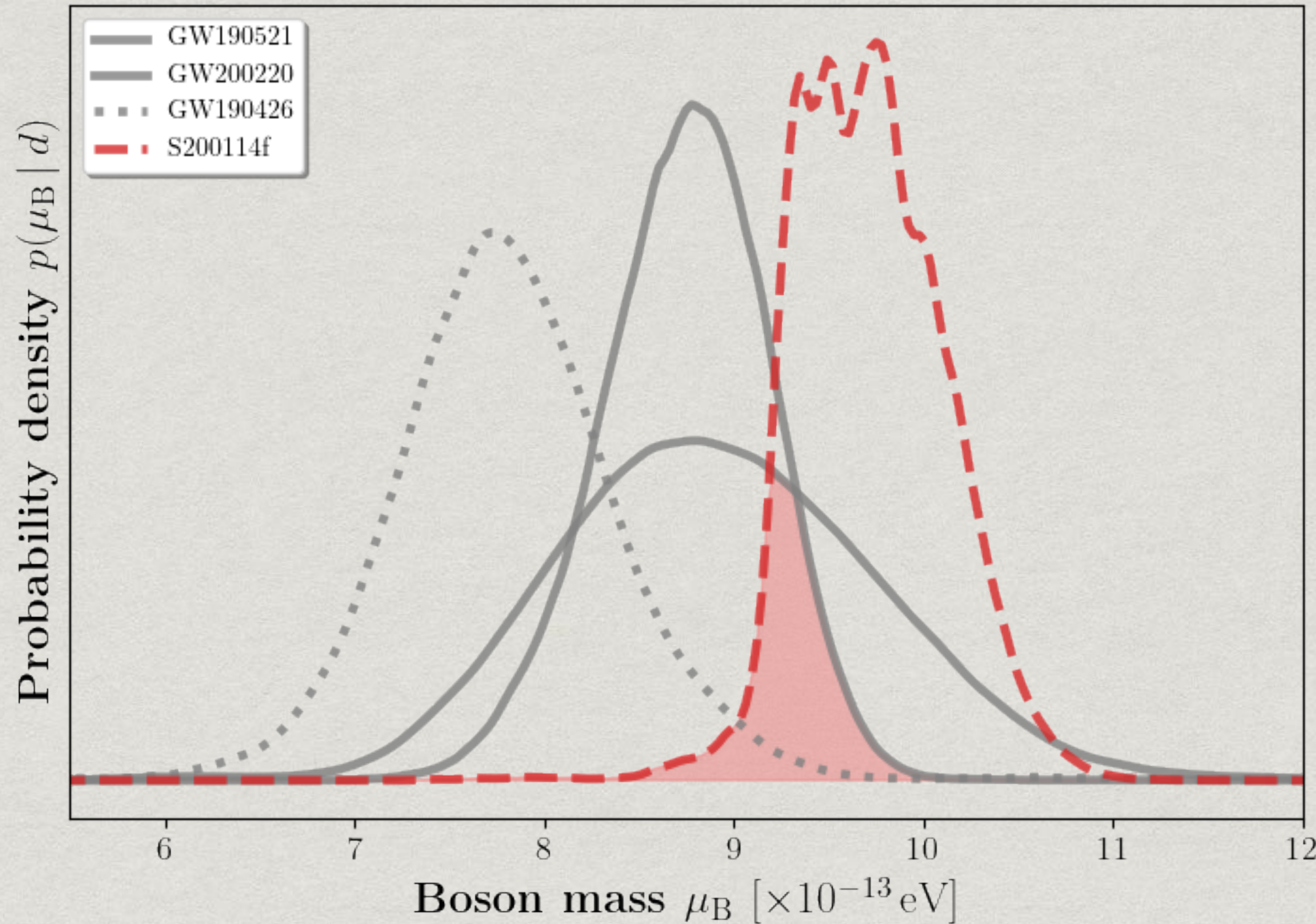
GW200220:

- Good overlap with GW190521
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GW190426:

- Not a good Proca candidate
- Not much overlap with the other two

BOSON MASS DISTRIBUTION



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- Consistent with result from last year

GW200220:

- Good overlap with GW190521
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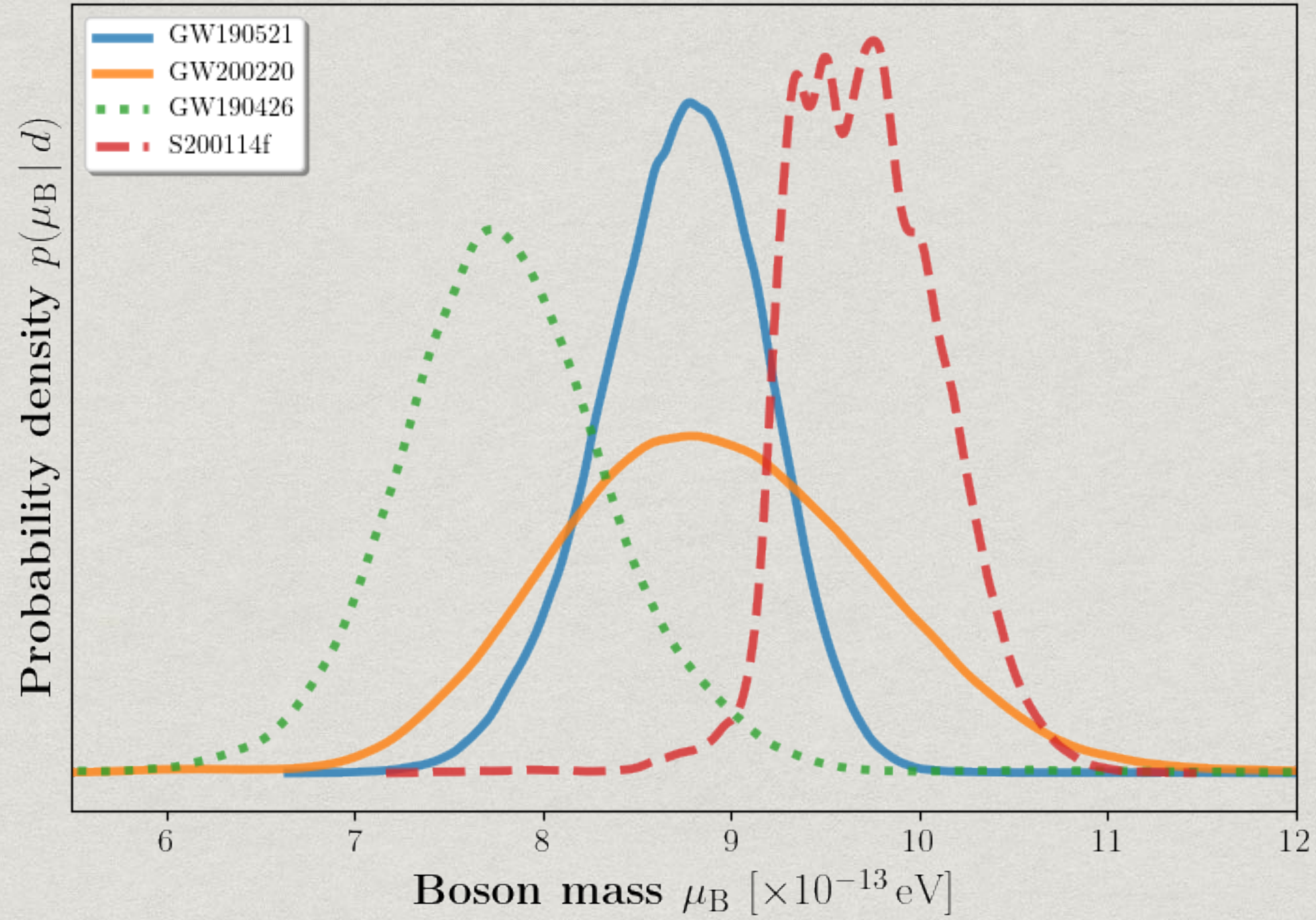
S200114f:

- Most favoured signal as a Proca star merger
- Quite different boson mass

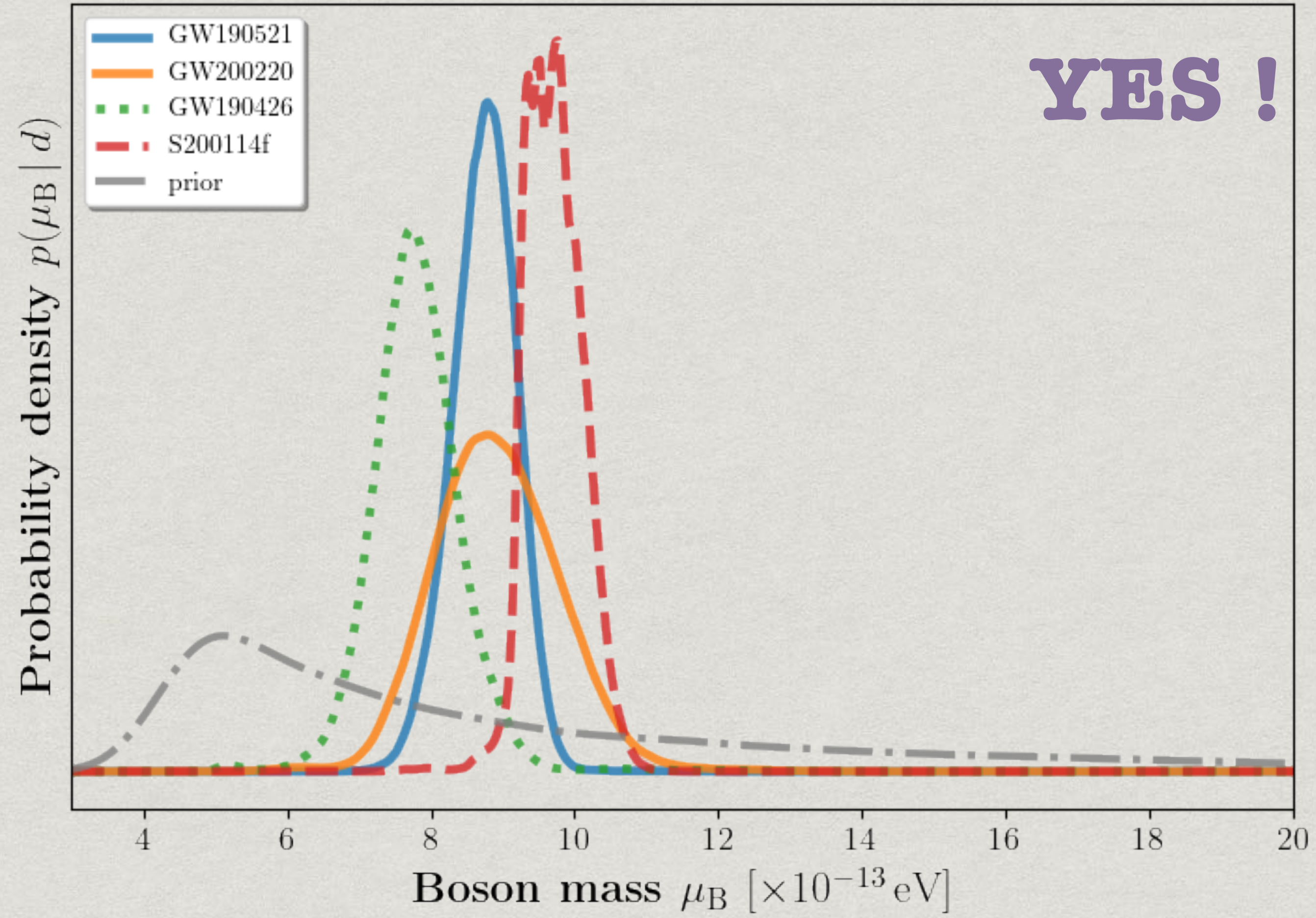
GW190426:

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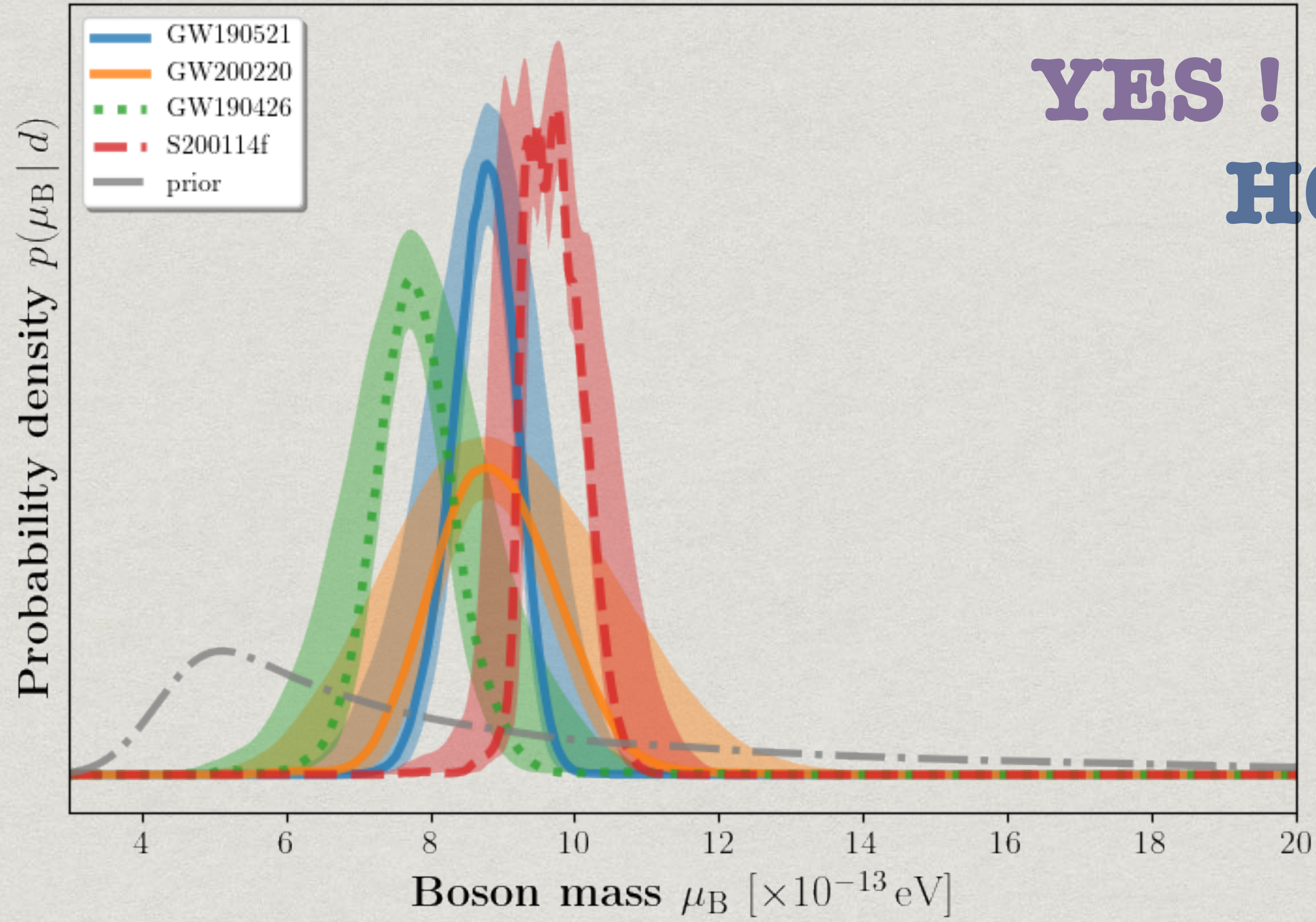
ARE WE REALLY RETRIEVING INFORMATION?



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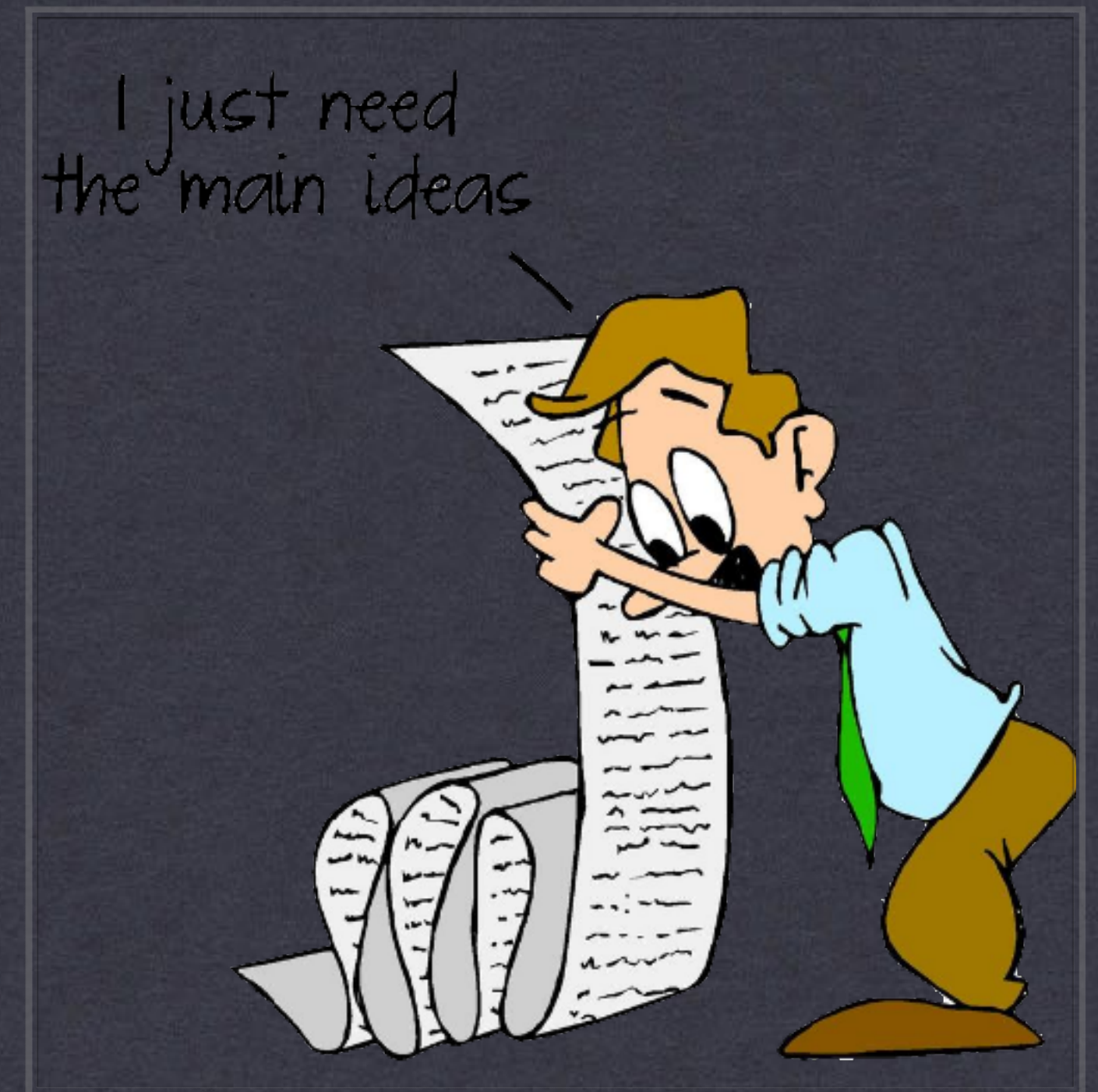


YES !

HOWEVER !

SUMMARY

- Improved study, with a much larger catalogue of **96** → **759 simulations**
- Analyse 4 events from the latest LIGO data using the **new Ψ_4 formalism** (and it works!!)
- Two of them, **GW190521** and **S200114f**, are **mildly favoured** as Proca star mergers
- **Boson masses** inferred are **consistent**



REFERENCES

- * **Bustillo+, 2022 (Today): <http://arxiv.org/abs/2206.02551>**
- * **Bustillo+, 2020: <https://doi.org/10.1103/PhysRevLett.126.081101>**
- * **Sanchis-Gual+, 2019: <https://doi.org/10.1103/PhysRevD.99.024017>**
- * **Nitz & Capano, 2021: <https://doi.org/10.3847/2041-8213/abccc5>**
- * **Fishbach & Holz, 2020: <https://doi.org/10.3847/2041-8213/abc827>**
- * **Romero-Shaw+, 2020: <https://doi.org/10.3847/2041-8213/abbe26>**
- * **Gayathri+, 2020: <https://doi.org/10.1038/s41550-021-01568-w>**
- * **Klimenko+, 2016: <https://doi.org/10.1103/PhysRevD.93.042004>**
- * **LVC, 2016: <https://doi.org/10.1103/PhysRevLett.116.061102>**