Follow-up Analyses to the O3 LIGO-Virgo-KAGRA Lensing Searches

Editorial Team: *J. Janquart**, M. Wright, S. Goyal
Analysts: J. C. L. Chan, A. Ganguly, A. Garron, D. Keitel, A. K. Y. Li, A. Liu, R. K. L. Lo, A. Mishra, A. More, H. Phurailatpam, P. Prasia
Contributors: P. Ajith, S. Biscoveanu, P. Cremonese, J.R. Cudell, J. M. Ezquiaga, J. Garcia-Bellido, O. A. Hannuksela, K. Haris, I. Harry, M. Hendry, S. Husa, S. Kapadia, T. G. F. Li, I. Magana Hernandez, S. Mukherjee, E. Seo, C. Van Den Broeck, J. Veitch

Link to the paper: Janquart et al, 2023

* J.Janquart@uu.nl

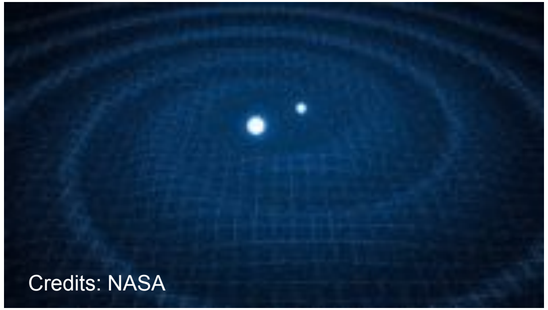
Utrecht University

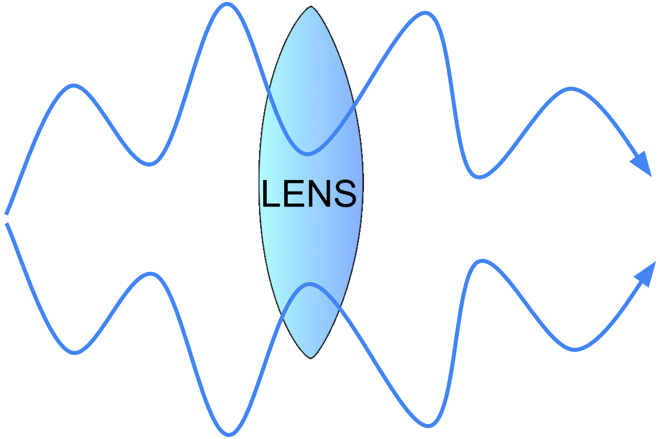
LIGO VIRGO KAGRA

Nikhef

What is Lensing of Gravitational Waves?

Same principle as for light: the wave is deflected by a massive object along its path

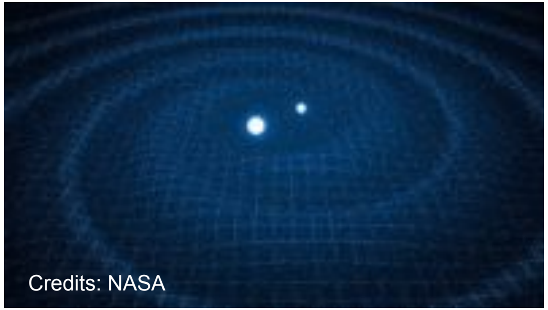


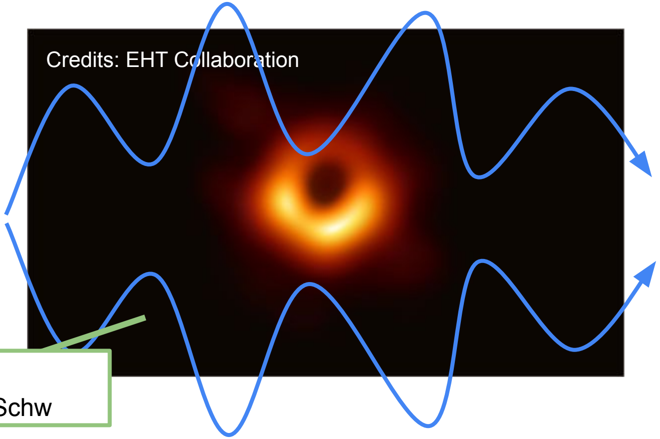


Different lens properties → Different effect on the GW

What is Lensing of Gravitational Waves?

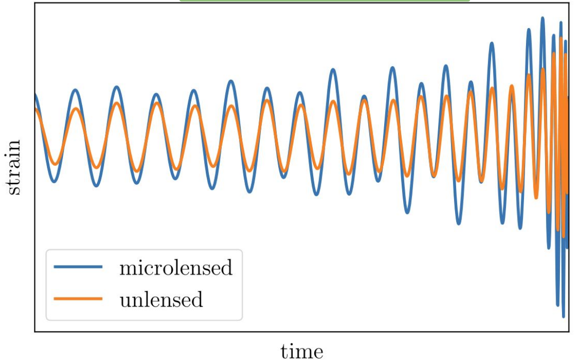
Same principle as for light: the wave is deflected by a massive object along its path





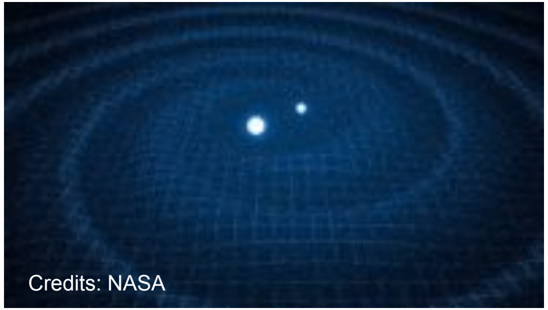
$\lambda_{GW} \gtrsim R_{Schw}$

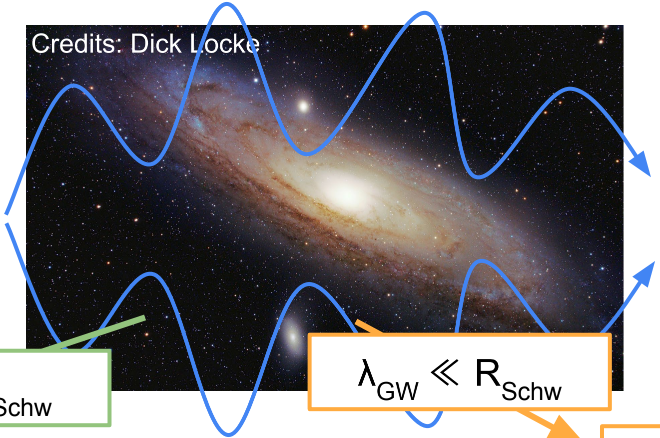
Microlensing



What is Lensing of Gravitational Waves?

Same principle as for light: the wave is deflected by a massive object along its path



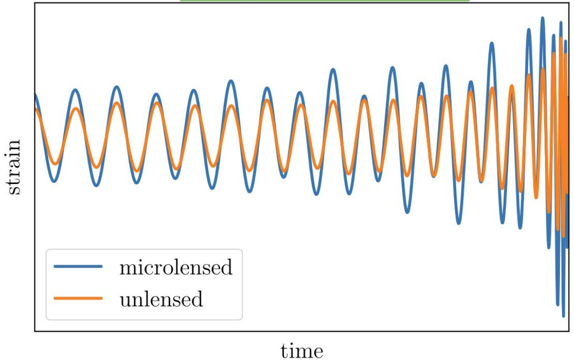


$\lambda_{GW} \gtrsim R_{Schw}$

Microlensing

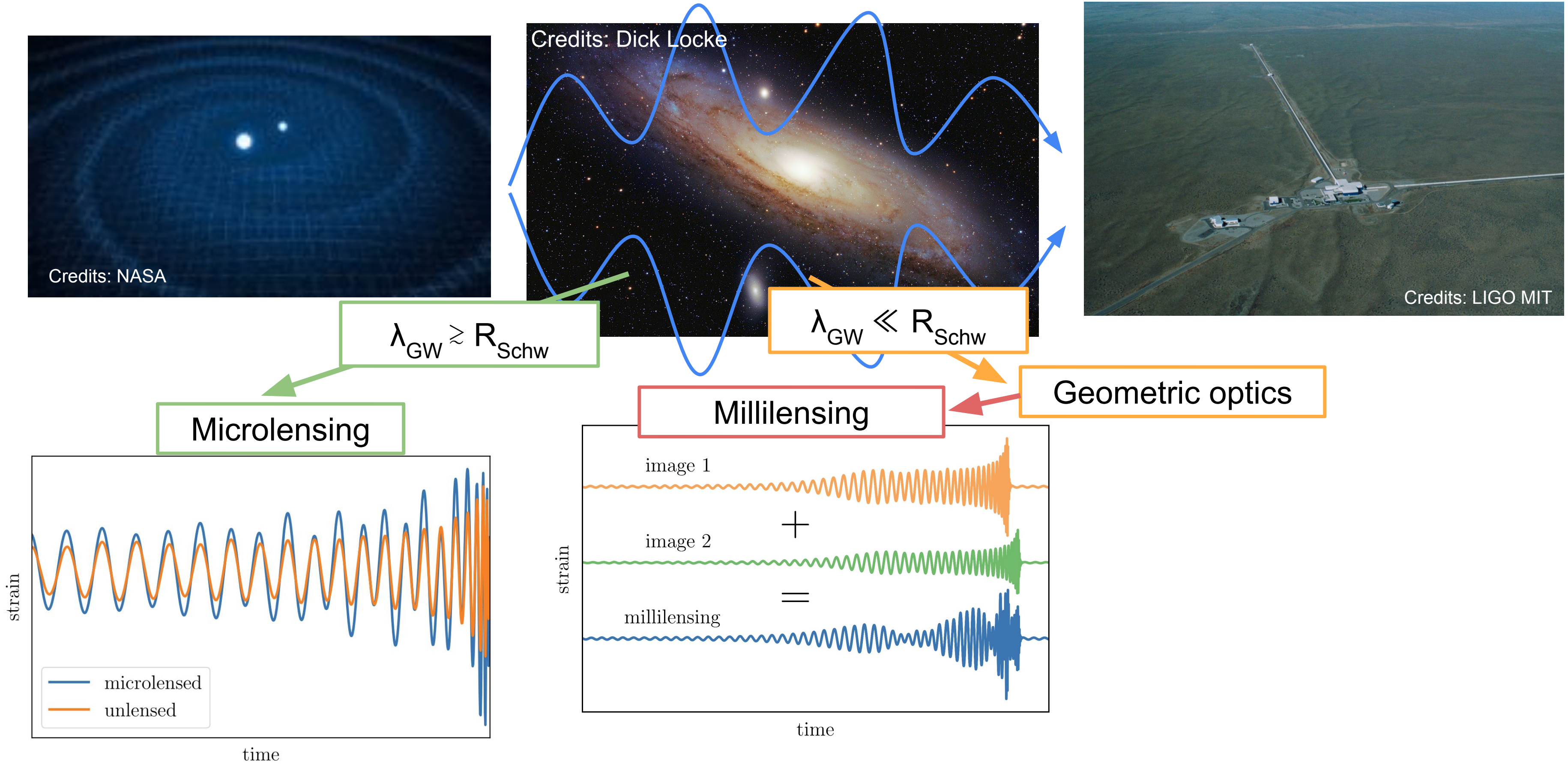
$\lambda_{GW} \ll R_{Schw}$

Geometric optics



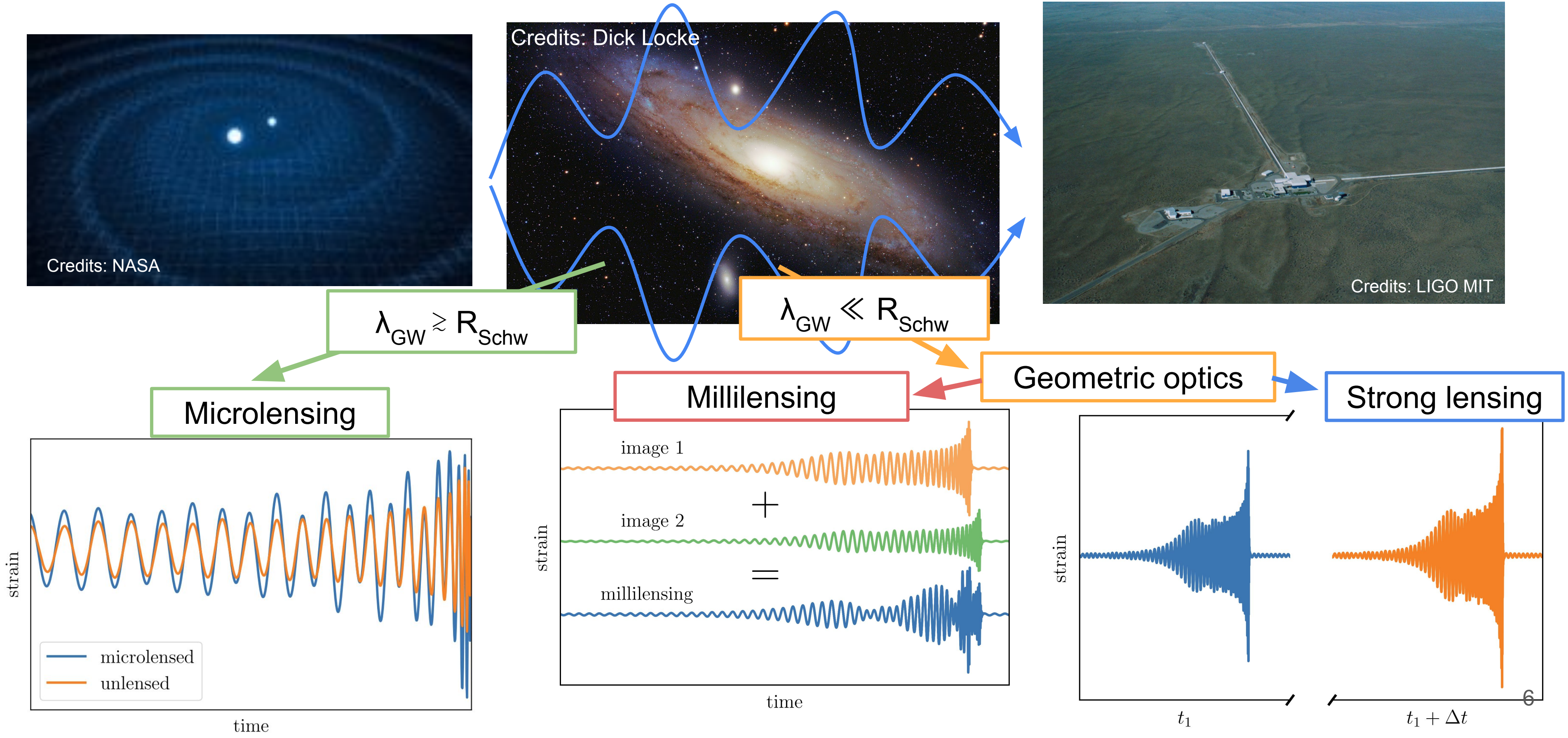
What is Lensing of Gravitational Waves?

Same principle as for light: the wave is deflected by a massive object along its path



What is Lensing of Gravitational Waves?

Same principle as for light: the wave is deflected by a massive object along its path



Current Status of Gravitational Wave Lensing Searches

O2 data: Hannuksela et al, 2019
O3a data: LVK Scientific Collaboration, 2021
O3 data: LVK Scientific Collaboration, 2023
More in depth analysis for some interesting events: Janquart et al, 2023 (large collaborative effort)

Current Status of Gravitational Wave Lensing Searches

O2 data: Hannuksela et al, 2019
O3a data: LVK Scientific Collaboration, 2021
O3 data: LVK Scientific Collaboration, 2023
More in depth analysis for some interesting events: Janquart, Wright et al, 2023 (large collaborative effort)

No confident detections have been made so far

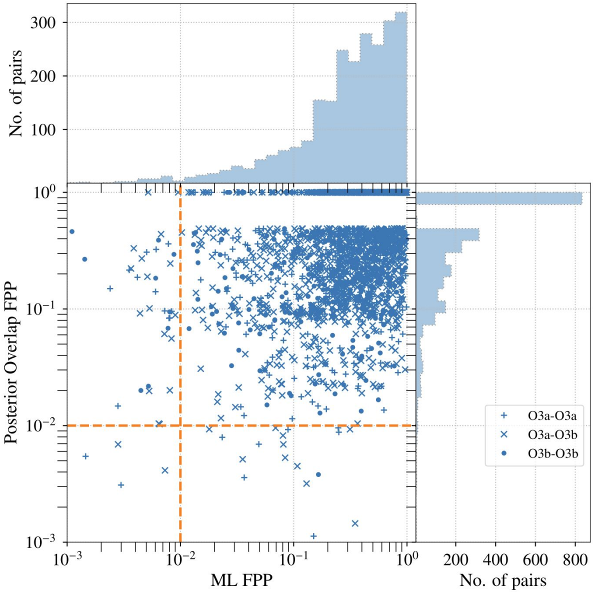
Searches for Strongly Lensed Event Pairs

3-step analysis

Low Latency

First filtering of the event pairs.

a) Posterior overlap
b) Machine learning



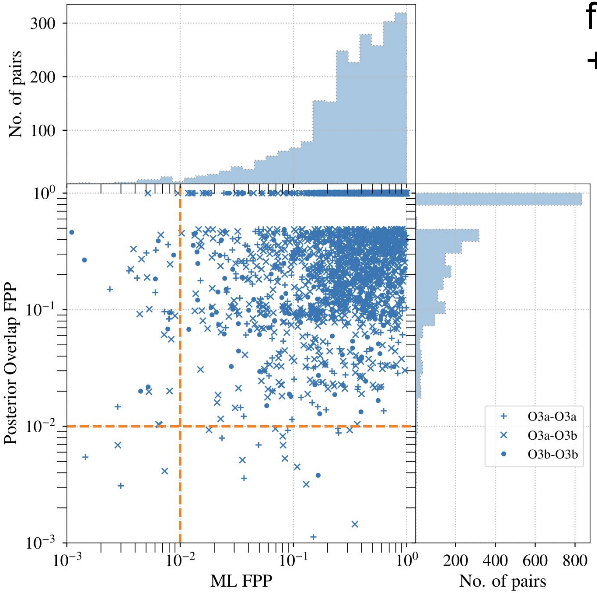
Searches for Strongly Lensed Event Pairs

3-step analysis

Low Latency → ~ 150 pairs → Medium Latency

First filtering of the event pairs.

a) Posterior overlap
b) Machine learning



GOLUM (Janquart et al, 2021; 2023)
More precise, reduces further the number of pairs
+ search for other effects

Searches for Strongly Lensed Event Pairs

3-step analysis

Low Latency → ~ 150 pairs → Medium Latency → 14 pairs → High Latency

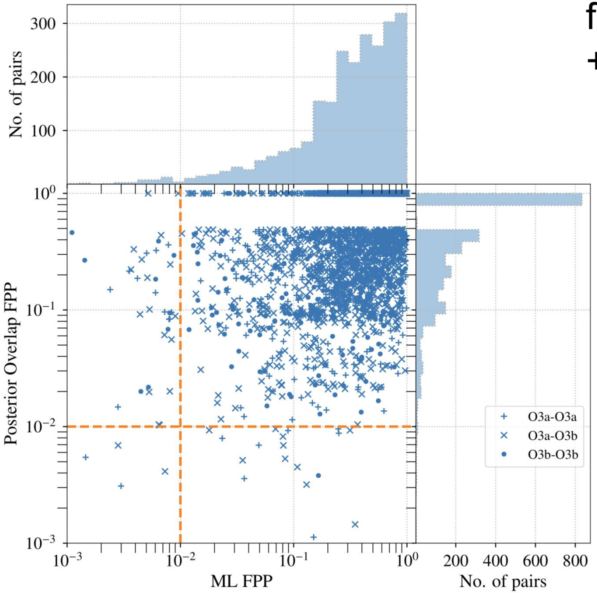
First filtering of the event pairs.

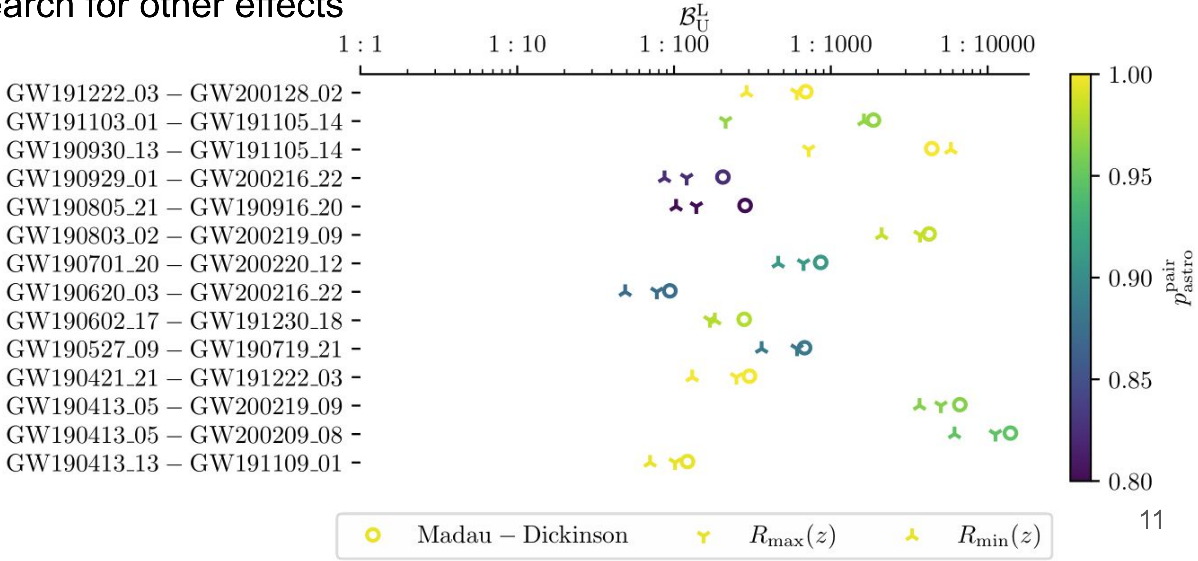
a) Posterior overlap
b) Machine learning

GOLUM (Janquart et al, 2021; 2023)
More precise, reduces further the number of pairs
+ search for other effects

Hanabi (Lo & Magana, 2021)
Full analysis with population effects

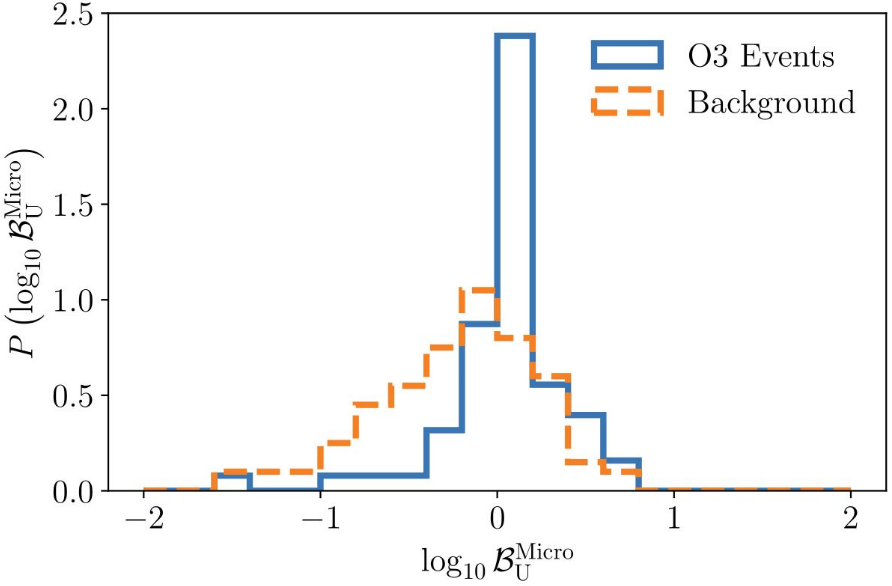
No evidence for strong lensing



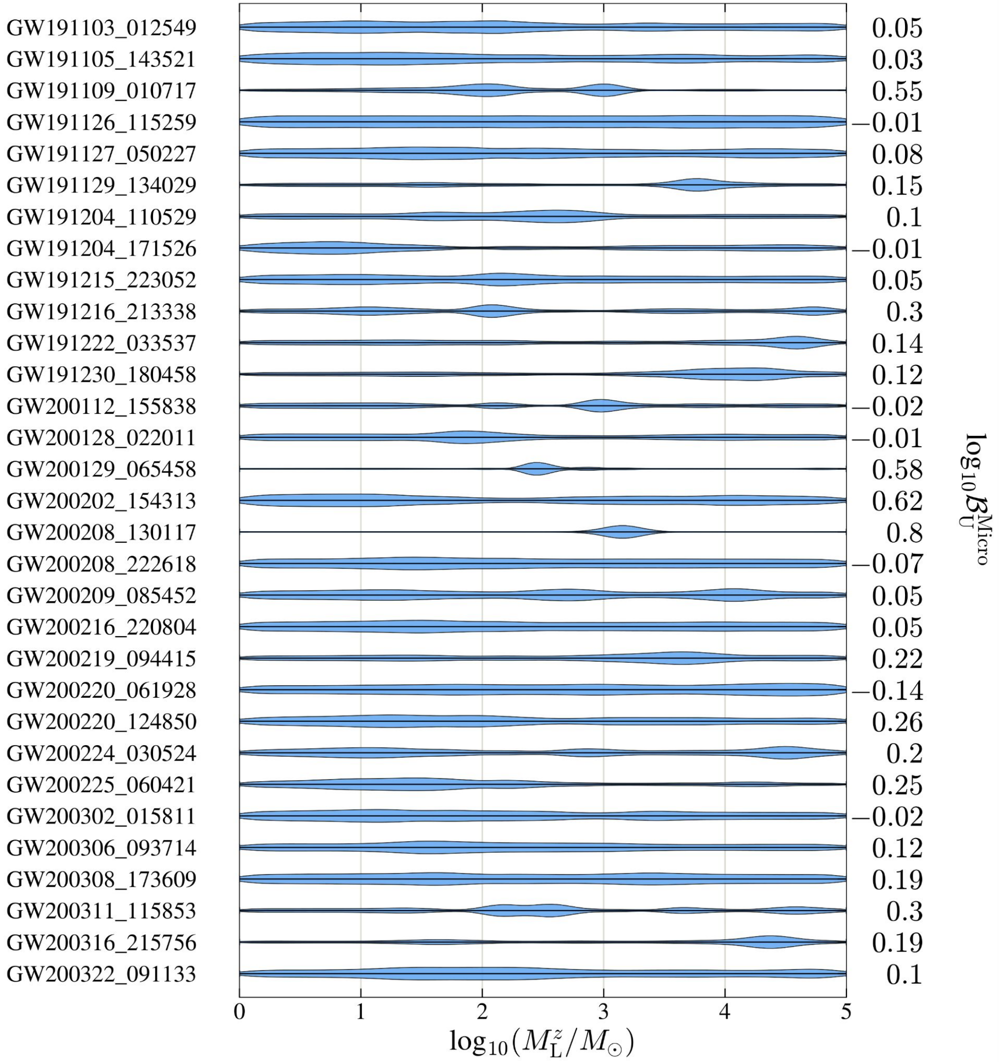


Microlensing Searches

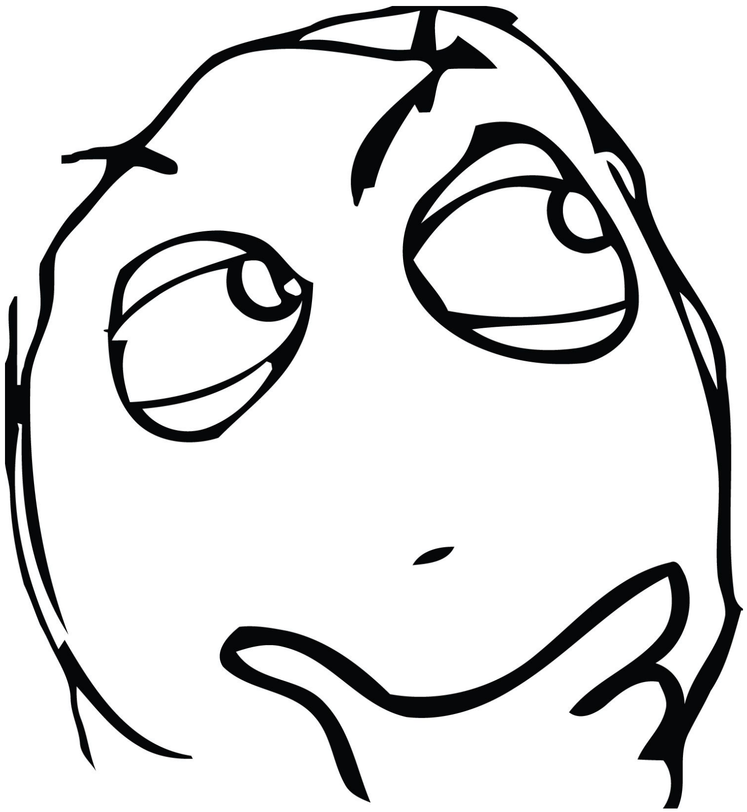
Allow for beating patterns from an isolated point mass



No evidence for microlensing

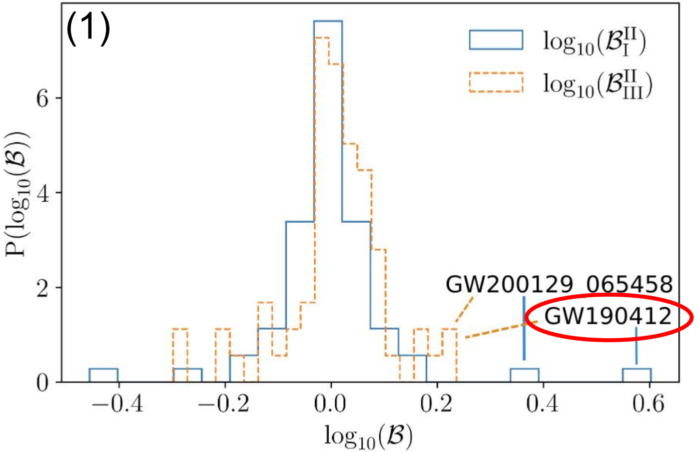


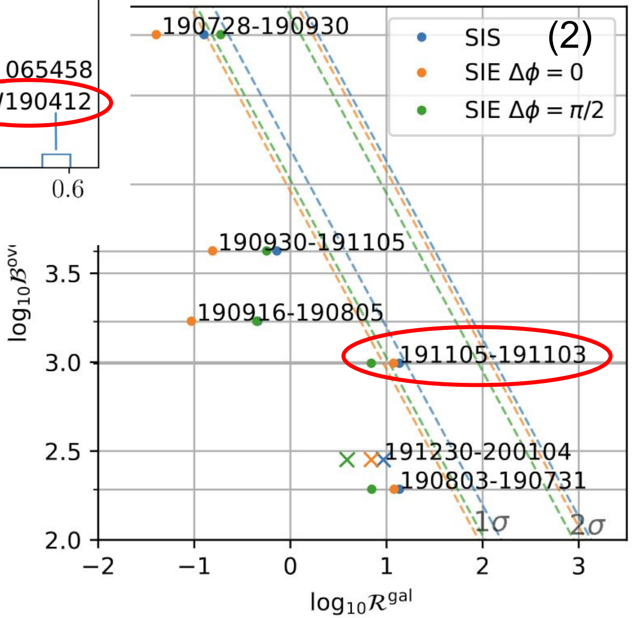
Did we really not see anything?

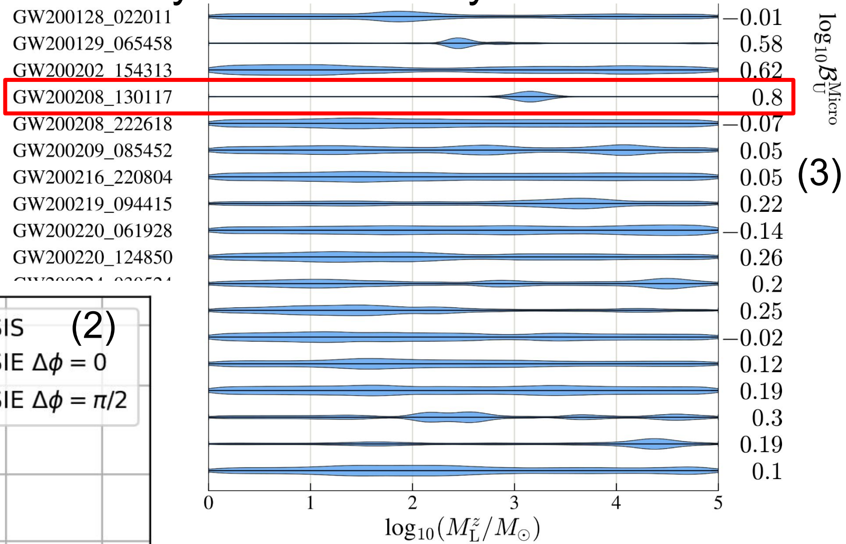


A Few Events Draw our Attention!

For various reasons, some events draw our attention, even if they were ultimately seen as not lensed



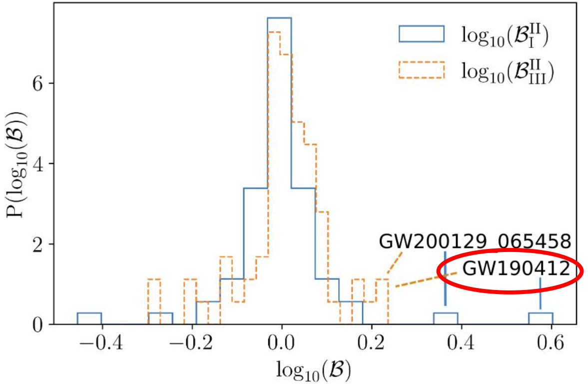


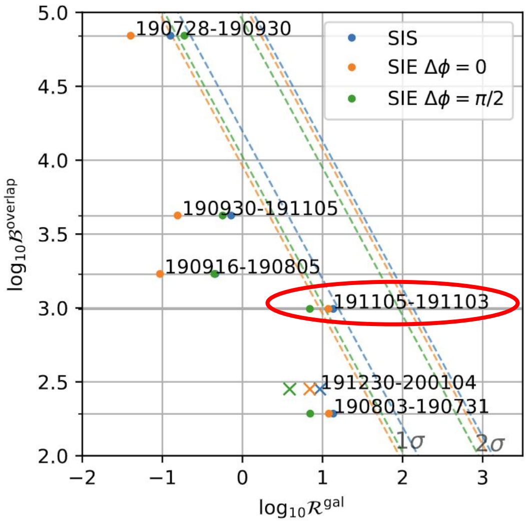


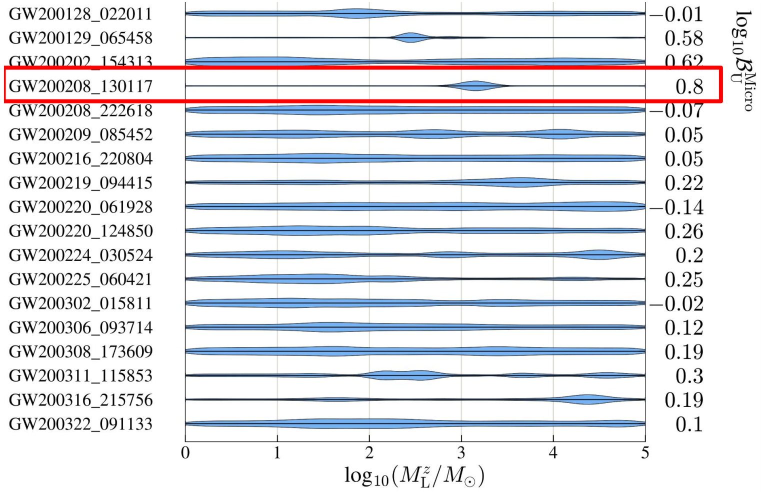
(1) Strong lensing type II image signature
(2) Strongly-lensed event pairs
(3) Microlensing signatures

A Few Events Draw our Attention!

For various reasons, some events draw our attention, even if they were ultimately seen as not lensed







Idea behind the paper: Look deeper into this events as a preparation to next observation runs, where more such events could be seen → We need to make sure we can distinguish between genuine lensed pairs and apparently lensed ones

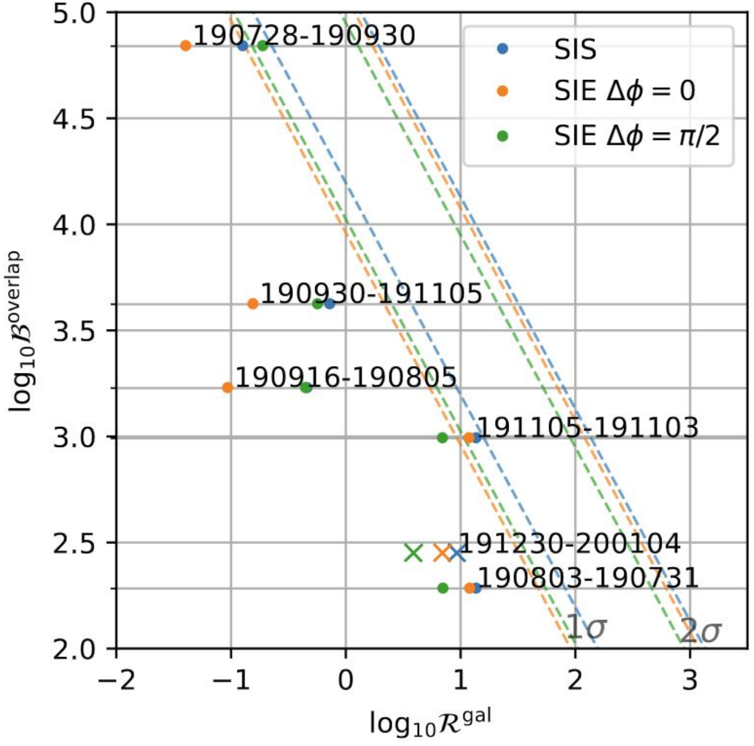
Many analyses done, see the paper for full details. Here, I will focus on one example: **the analyses done on strongly-lensed events**

Investigations for Apparent Strongly-Lensed Pairs

Two such pairs are analyzed: GW191103-GW191105 and GW191230-LGW200104.
The second is a new pair flagged in this paper using a new ranking method (Goyal et al, 2023) for sub-threshold events.
The same analyzes are done on the two pairs.

Apparent Strongly-Lensed Pairs – Posterior overlap

Posterior overlap investigations (low latency)

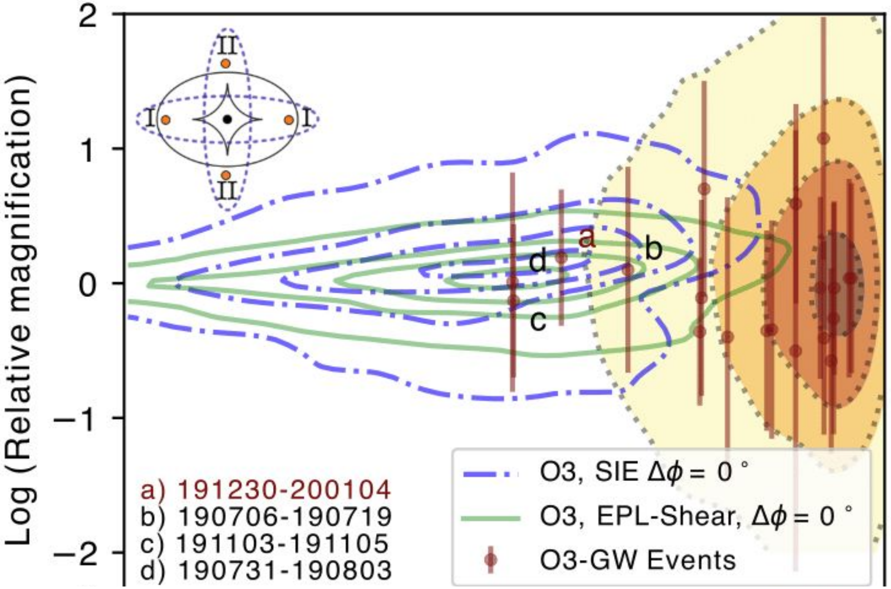


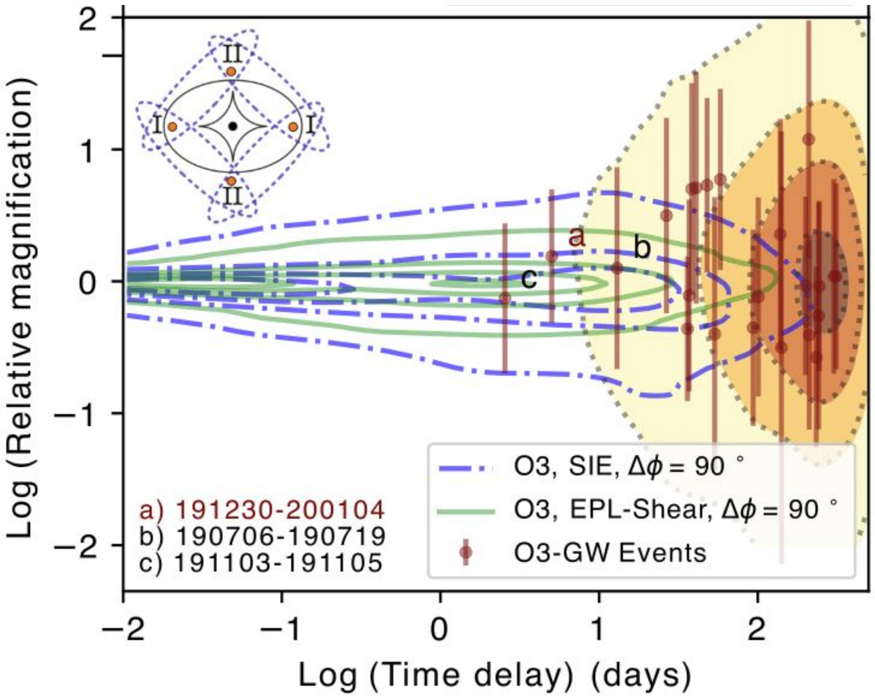
Verify if the results are consistent throughout different waveform models (more in depth study on waveform systematics in Garron et al, 2023)

Waveform	log(Blu) for GW191103–GW191105	log(Blu) for GW191230–LGW200104
IMRPhenomXAS	3.37	3.30
IMRPhenomXHM	3.48	3.13
IMRPhenomXP	3.08	2.52
IMRPhenomXPHM	3.03	2.45
IMRPhenomTPHM	2.70	2.55
SEOBNRv4PHM	2.65	N/A

Apparent Strongly-Lensed Pairs – Lensing Statistics

Compatibility with lensing models: compare the observed lensing characteristics with those expected depending on strong lensing simulations (Wierda et al, 2021 and More & More, 2022)

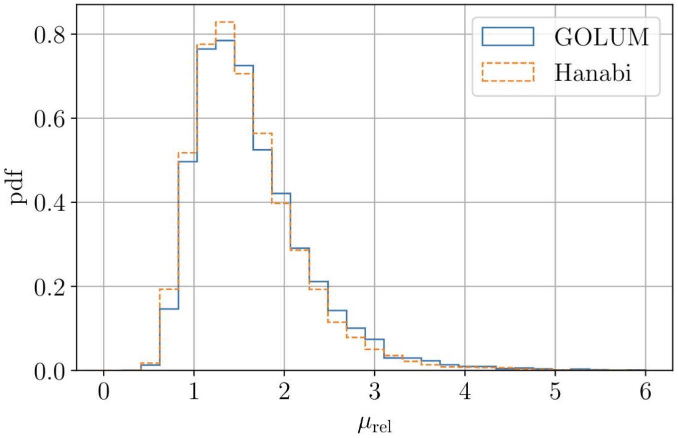




Apparent Strongly-Lensed Pairs – GOLUM

Compatibility with lensing models: include the lensing model in the lensing analysis framework (Janquart et al, 2022, Medium latency)

Measured relative lensing parameters for GW191230-LGW200104



GW191103–GW191105

Statistic	$\log_{10}$ value	$\mathrm{FAP}_{\mathrm{PP}}$
C_U^L	2.5	2.0×10^{-3}
$C_{\mathcal{M}_{\mu,t}}$	2.4	1.6×10^{-3}
$C_{\mathcal{M}_t}$	2.9	9.8×10^{-4}

GW191230–LGW200104

Statistic	$\log_{10}$ value	$\mathrm{FAP}_{\mathrm{PP}}$
C_U^L	1.105	1.401×10^{-2}
$C_{\mathcal{M}_{\mu,t}}$	3.427	1.167×10^{-3}
$C_{\mathcal{M}_t}$	1.915	2.017×10^{-3}

Lensing hypothesis is more favoured with the model, but FAP is still relatively low (~40 unlensed events are enough to get the same statistics!)

Apparent Strongly-Lensed Pairs – Hanabi

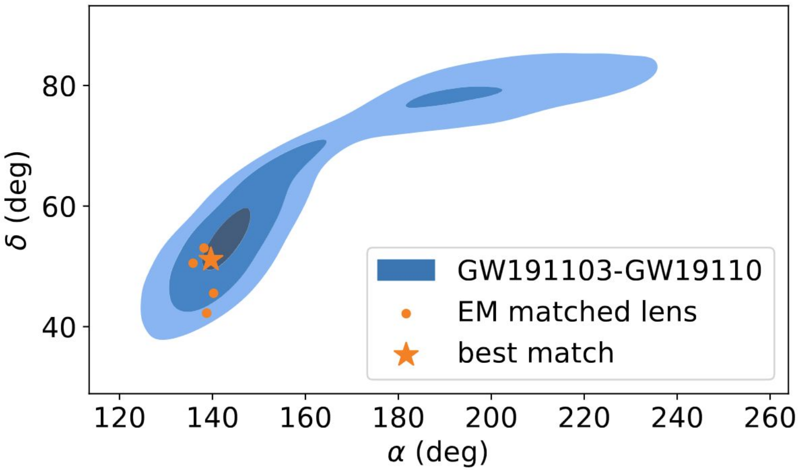
Log10 Bayes factors for the event pairs

	GW191103–GW191105			**GW191230–LGW200104**		
Merger rate *----------------* *Lens model*	*Madau-Dickinson*	*Rmin*	*Rmax*	*Madau-Dickinson*	*Rmin*	*Rmax*
SIS	-3.27	-3.21	-2.33	-0.76	-0.35	-0.57
SIE + shear	-2.69	-2.46	-1.28	0.14	0.57	0.30

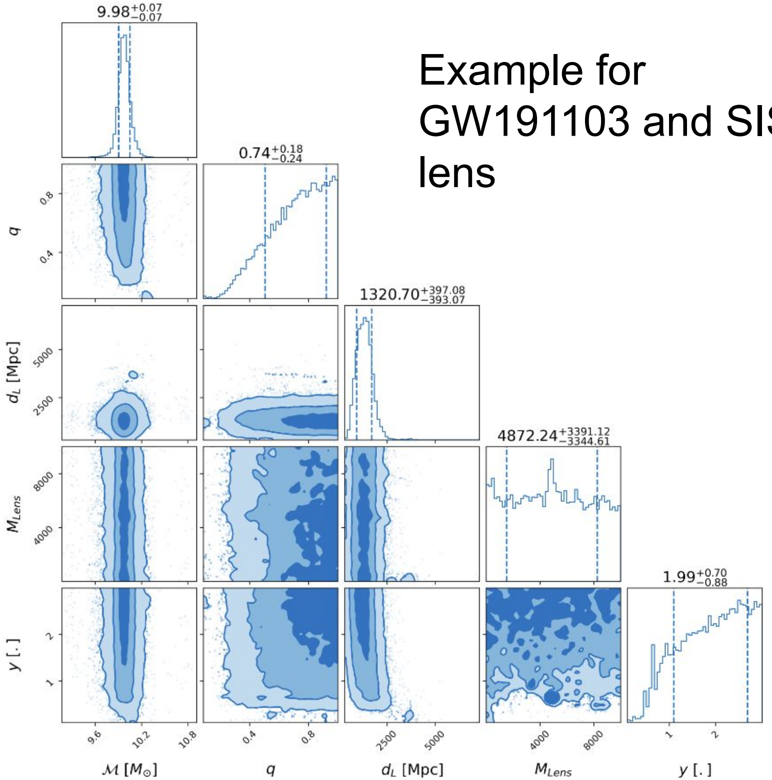
While we have a positive log10 Bayes factor for the most realistic lens model, it is not high enough to favor lensing in the odds ratio (lensing log10 prior odds ~ -3 to -4) – comparing the probability to be in the two hypotheses. In addition, the sub-threshold event has a high chance to not be a real event in the first place (p_astro ~ 1%)

Apparent Strongly-Lensed Pairs – Other Analyses

Search for the host galaxy in electromagnetic data. Here, by cross-matching with catalogs



Check if any of the images is microlensed



Example for GW191103 and SIS lens

Conclusions

In our work, we have built on the LVK lensing searches to perform more in-depth analysis of events displaying prototypical lensing signatures, even if they are not lensed in the end.
Here, I have presented the analyses done on two strongly-lensed candidates: GW191103-GW191105 and GW1913230-LGW200104. For these events, we have:

- Applied posterior overlap with lensing models, compared to a background
- Checked for waveform systematics
- Compared the observed lensing parameters with their expected values coming from lensing simulations
- Included the compatibility with lensing models in the detection statistics
- Computed the Bayes factor including more realistic models

→ The event pairs were not found to be lensed, but we tested important strategies for coming observing runs
In this work, we also looked into other events displaying other signatures:

- GW190412: possible type II images → Found to be probably noise + waveform feature
- GW200208_130117: displayed prototypical signature for microlensing → Residual power + injection tests + systematic analyses seem to indicate it is due to noise. It is also not a detection due to millilensing (search applied for the first time on real data, following the method from Liu et al, 2023)

General conclusion of this work: No additional evidence for lensing has been found. In some cases, we further confirmed the non-lensed status of the event. We have showed some important avenues to deal with high significance lensing triggers in the future. This is important as more such triggers are expected with an increasing detection rate and as we approach the detection of a lensed gravitational wave event.

Conclusions

In our work, we have built on the LVK lensing searches to perform more in-depth analysis of events displaying prototypical lensing signatures, even if they are not lensed in the end.

Here, I have presented the analyses done on two strongly-lensed candidates: GW191103-GW191105 and GW1913230-LGW200104. For these events, we have:

- Applied posterior overlap with lensing models, compared to a background
- Checked for waveform systematics
- Compared the observed lensing parameters with their expected values coming from lensing simulations
- Included the compatibility with lensing models in the detection statistics
- Computed the Bayes factor including more realistic models

→ The event pairs were not found to be lensed, but we tested important strategies for coming observing runs

In this work, we also looked into other events displaying other signatures:

- GW190412: possible type II images → Found to be probably noise + waveform feature
- GW200208_130117: displayed prototypical signature for microlensing → Residual power + injection tests + systematic analyses seem to indicate it is due to noise. It is also not a detection due to millilensing (search applied for the first time on real data, following the method from Liu et al, 2023)

General conclusion of this work: No additional evidence for lensing has been found. In some cases, we further confirmed the non-lensed status of the event. We have showed some important avenues to deal with high significance lensing triggers in the future. This is important as more such triggers are expected with an increasing detection rate and as we approach the detection of a lensed gravitational wave event.

Thank you for you attention!

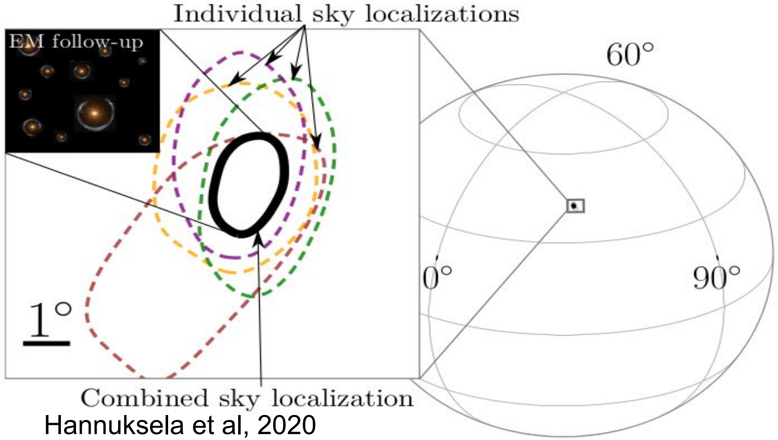
Extra Slides

Some more information about gravitational wave lensing

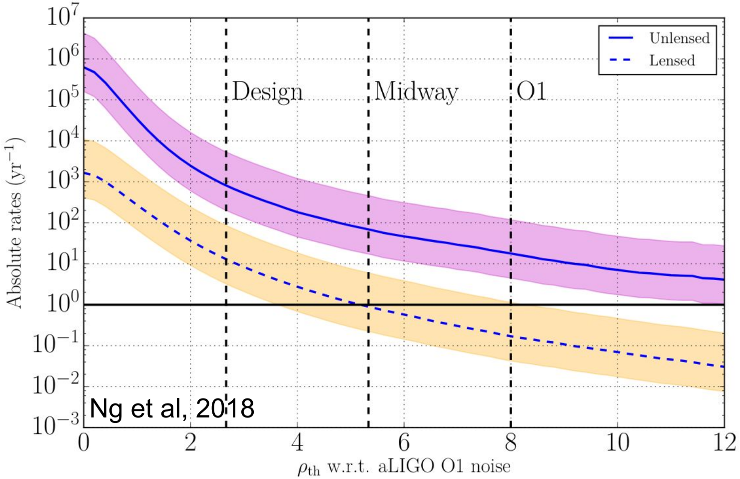
Why is gravitational wave lensing interesting?

Strong lensing:

- Interesting detection rates forecast for the coming years (e.g. Ng et al, 2018; Wierda et al, 2021; Xu et al, 2022)
- Additional science cases + possible synergies with electromagnetic studies (Hannuksela et al, 2020, Wempe et al, 2022)
    - Precise localization of binary black holes (Hannuksela et al, 2020)
    - Study of the expansion of the universe (Hannuksela et al, 2020, Narola et al, 2023, in prep)
    - Probe modified theory of gravity (Finke et al, 2022: Narola et al, 2023, in prep)
    - Probe GW polarization content (Goyal et al, 2021, Magana Hernandez, 2022)
    - Better probe the higher-order mode content (Janquart et al, 2021b)



Hannuksela et al, 2020



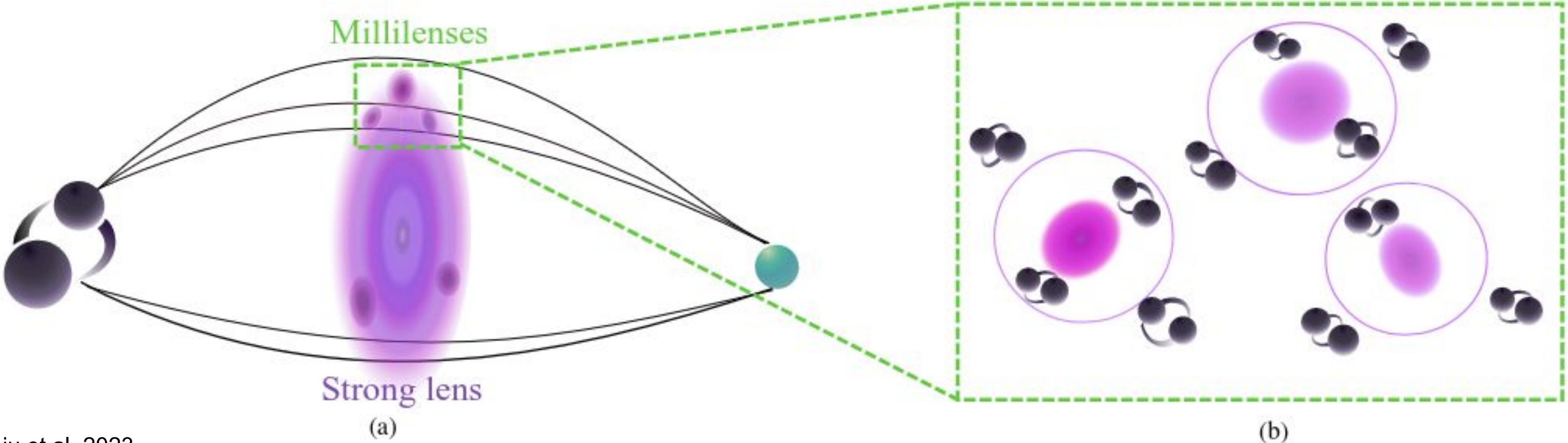
Ng et al, 2018

Why is gravitational wave lensing interesting?

Millilensing:

Helps probing the finer structure of the Universe (e.g stars, dark matter subhalos, …)(Liu et al, 2023)

Could be an extra feature present on one or several of the strongly-lensed images



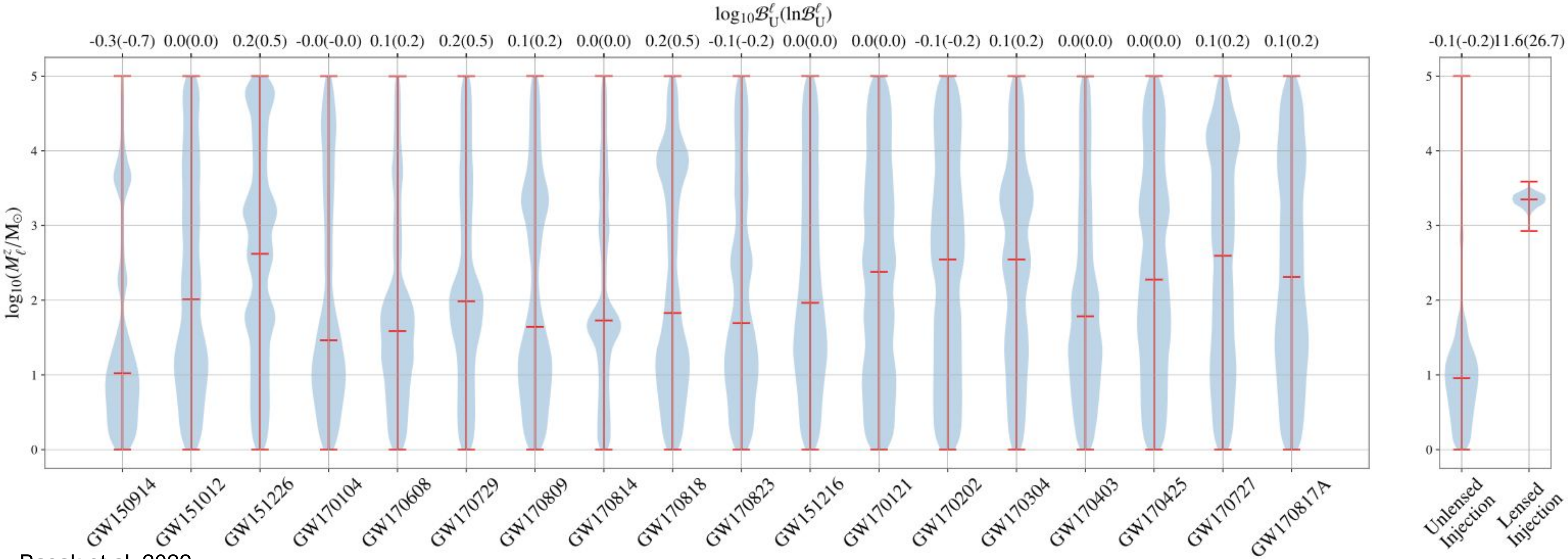
Liu et al, 2023

Why is gravitational wave lensing interesting?

Microlensing:

Helps probing the content of the Universe as the beating patterns give information about the lens (can be black holes (Lai et al, 2018), dark matter (Basak et al, 2022), …) (Wright & Hendry, 2022; Savastano et al, 2023)

Could be an additional effect on strongly-lensed images in up to 50% of the case (Meena et al, 2022, Shan et al, 2023)

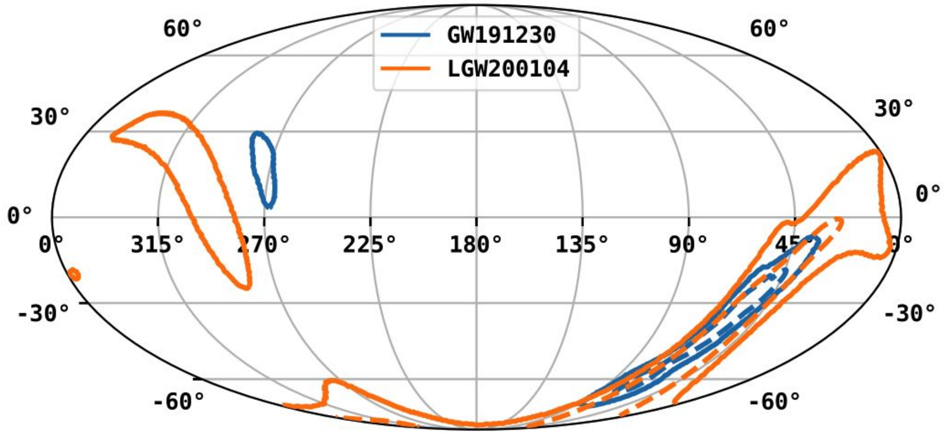


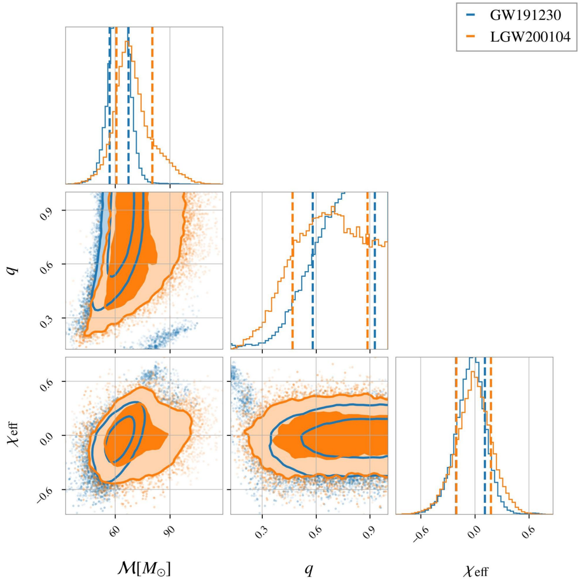
Basak et al, 2022

More analyses from the technical document

GW191230–LGW200104: Subthreshold investigations

During the O3 run, we use adapted method to search for subthreshold candidates (Li et al 2019; McIsaac et al, 2019). Basically, one makes a reduced template bank based on the posterior observed for the supra-threshold event taken as first image. This leads to a list of candidates.
In O3: triggers are ranked by individual FAP
Here, we use a ranking based on the distance in matched filtering chirp masses, skymap overlap, and compatibility of the time delay with lensing models (Goyal et al, 2023).



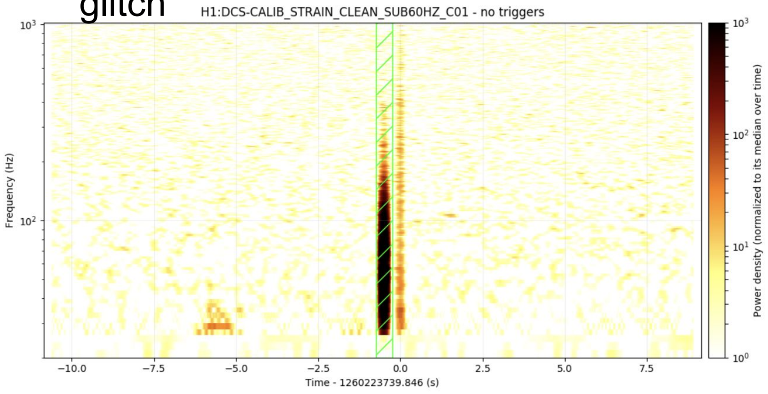


GW191230–LGW200104: Subthreshold investigations

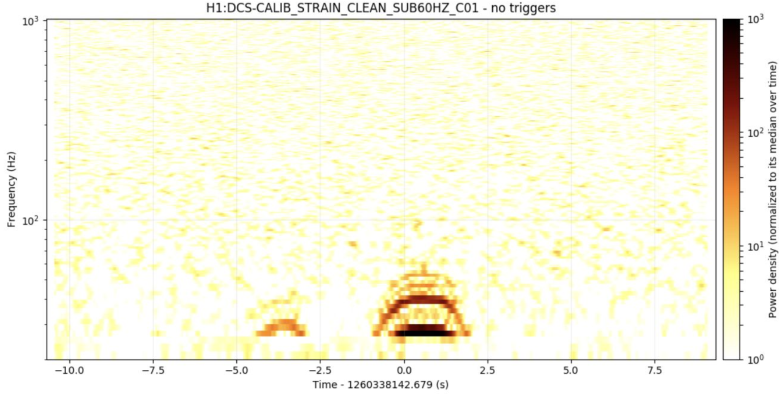
Verify the trigger using another method: use the PyCBC subthreshold search (McIsaac et al, 2019) to check if the trigger is recovered and matches what has been observed in the other pipelines. The results are consistent.

Rank	Name	Event	ΔT [days]	IFAR [yr]	SNR	90% CR Overlap
0	LGW191222_033537	GW191230	8.60	125822.11	10.99	0.00
1	LGW191230	GW191230	0.00	312.15	10.11	0.75
2	LGW191212_220841	GW191230	17.83	0.57	16.38	0.00
3	LGW191214_055524	GW191230	16.51	0.10	7.16	0.02
4	LGW200104	GW191230	5.02	0.09	8.02	0.62

glitch



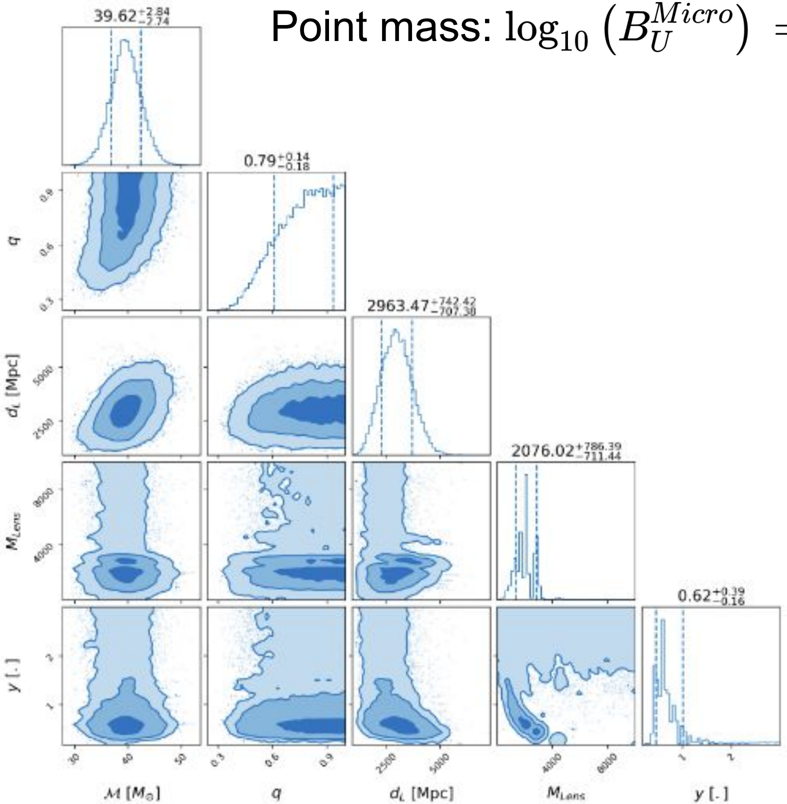
Scatter light glitch



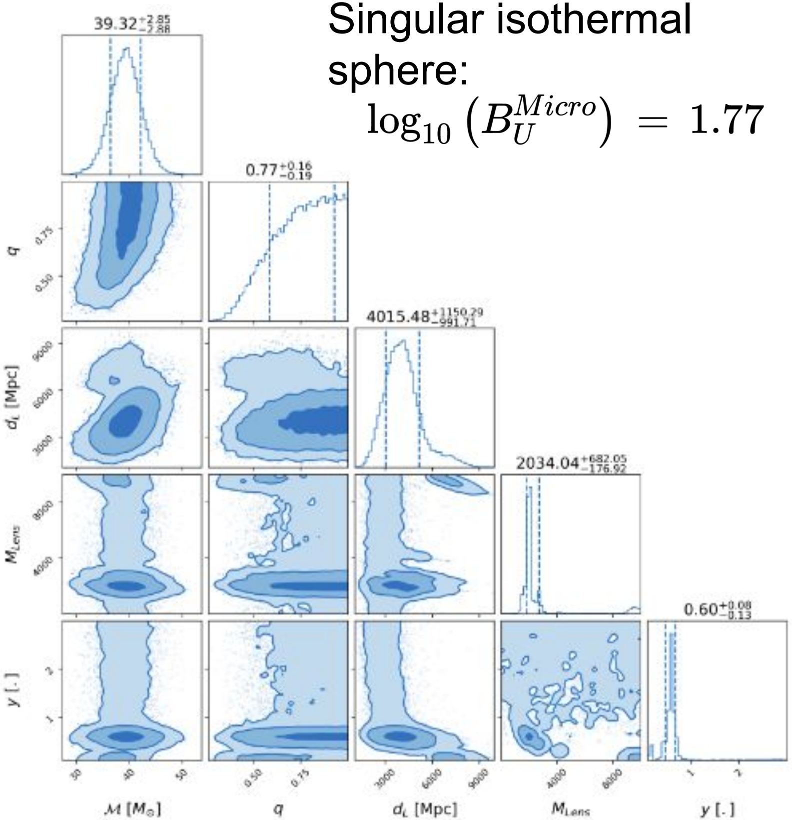
GW200208 – Model Selection

Asume different models for the lens and verify which is the most likely to generate the observed features and what would be the lens characteristics (Wright & Hendry, 2022)

Point mass: $\log_{10}\left(B_U^{Micro}\right) = 1.20$



Singular isothermal sphere:
$\log_{10}\left(B_U^{Micro}\right) = 1.77$



GW200208 – Investigating the Lensed Nature

Injection test: Inject the microlensed maximum likelihood parameters and run the analysis to s see what values would be observed for the Bayes factor. We find $\log_{10}\left(B_U^{Micro}\right) = 0.37 \, \mathrm{and} \, 0.79$ for the point mass and the SIS.

⇒ Should the event be genuinely lensed, it would be very hard to confirm its true nature

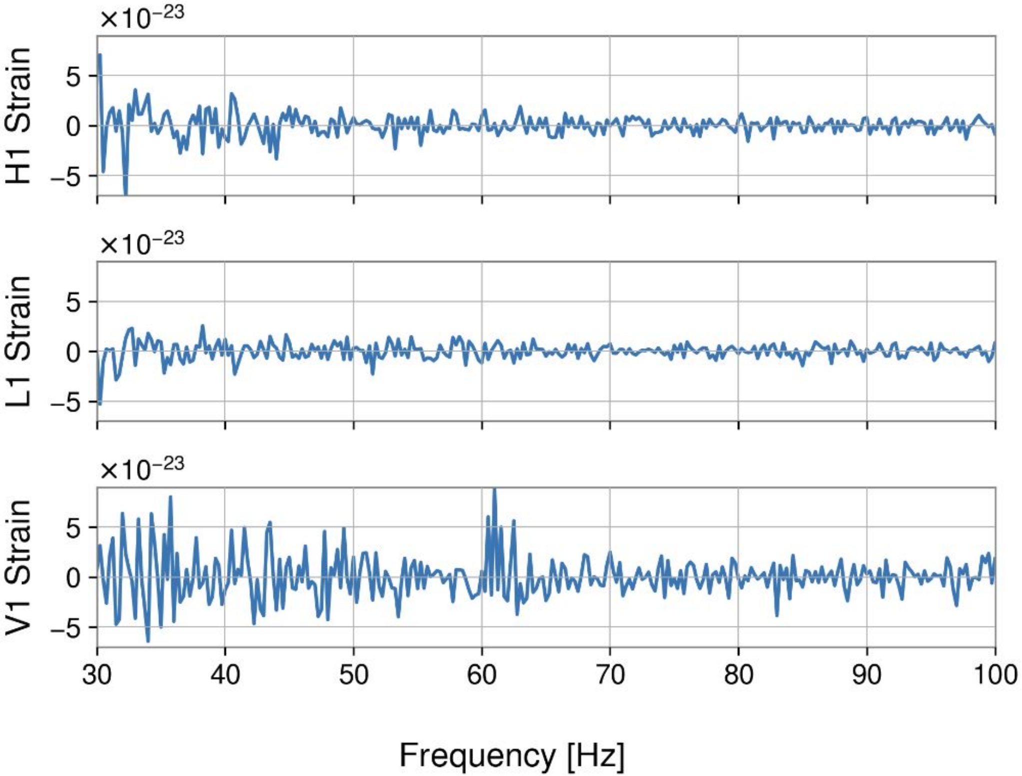
GW200208 – Investigating the Lensed Nature

Injection test: Inject the microlensed maximum likelihood parameters and run the analysis to s see what values would be observed for the Bayes factor. We find $\log_{10}\left(B_U^{Micro}\right) = 0.37$ and 0.79 for the point mass and the SIS.

⇒ Should the event be genuinely lensed, it would be very hard to confirm its true nature

Search for residual power in the data by subtracting the maximum likelihood unlensed parameters (similar to the TestingGR tests in LVK Scientific Collaboration, 2022).

Residual power p-value: 0.97
(~ probability that the event is unlensed based on the coherent power in the detectors).



GW200208 – Waveform Systematics and Analysis Settings

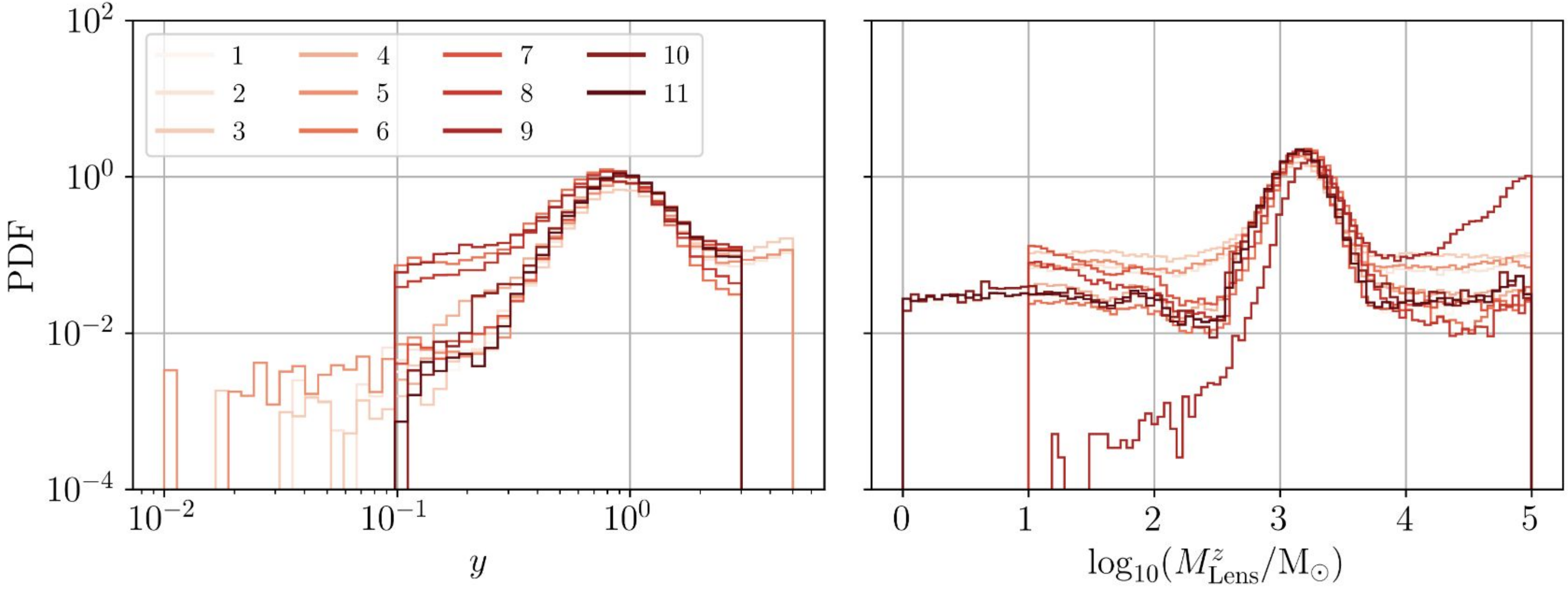
Analysis performed with GWMAT (Mishra et al, 2023, in prep.) using different priors, waveforms, and settings

Waveform	$f_{\rm low}$	$f_{\rm high}$	duration	$p(M^z_{\rm Lens})$	$p(y)$	$\log_{10} \mathcal{B}^{\rm L}_{\rm U}$
IMRPhenomXPHM	20	448	4	L.U (min=1, max=10^5)	P.L (α = 1, min=0.1, max=3.0)	0.89
IMRPhenomXPHM	20	1024	4	L.U (min=10, max=10^5)	P.L (α = 1, min=0.01, max=5.00)	0.63
IMRPhenomXPHM	20	896	8	L.U (min=10, max=10^5)	P.L (α = 1, min=0.01, max=5.00)	0.46
IMRPhenomXPHM	15	448	4	L.U (min=10, max=10^5)	P.L (α = 1, min=0.1, max=3.0)	1.02
IMRPhenomXPHM	15	448	4	L.U (min=10, max=10^5)	P.L (α = 1, min=0.01, max=5.00)	0.53
IMRPhenomXPHM	15	448	4	L.U (min=10, max=10^5)	Uniform (min=0.1, max=3.0)	1.04
IMRPhenomXPHM	15	448	4	L.L.U (min=10, max=10^5)	P.L (α = 1, min=0.1, max=3.0)	0.70
IMRPhenomXPHM	15	448	4	L.L.U (min=10, max=10^5)	Uniform (min=0.1, max=3.0)	0.95
IMRPhenomXPHM	15	448	4	Uniform (min=10, max=10^5)	Uniform (min=0.1, max=3.0)	0.50
NRSur7dq4	20	448	4	L.U (min=1, max=10^5)	P.L (α = 1, min=0.1, max=3.0)	0.96
NRSur7dq4	18	448	4	L.U (min=1, max=10^5)	P.L (α = 1, min=0.1, max=3.0)	0.90

The Bayes factor show some variability. In principle, for a genuinely microlensed event, less variability is expected.

GW200208 – Waveform Systematics and Analysis Settings

Analysis performed with GWMAT (Mishra et al, 2023, in prep.) using different priors, waveforms, and settings



The posteriors also show variability depending on the prior that is used. This shows that the support for lensing cannot be strong. In the latter case, the effect of the prior should be reduced.

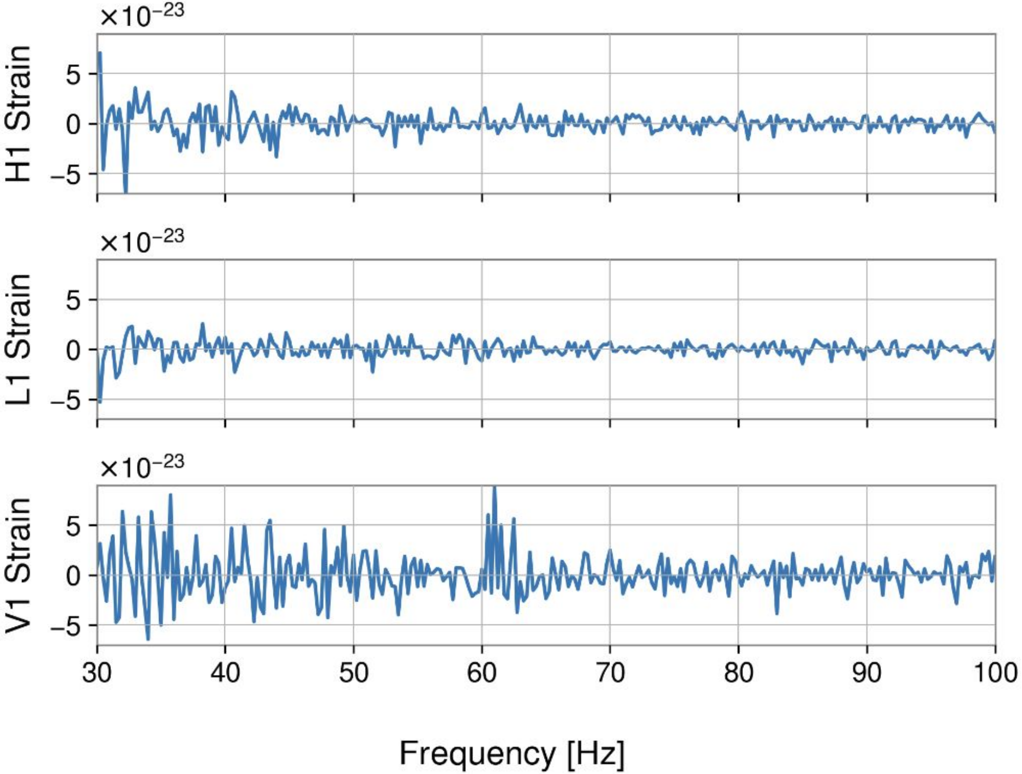
GW200208 – Investigating the Lensed Nature

Injection test: Inject the microlensed maximum likelihood parameters and run the analysis to s see what values would be observed for the Bayes factor. We find $\log_{10}\left(B_U^{Micro}\right) = 0.37$ and 0.79 for the point mass and the SIS.

⇒ Should the event be genuinely lensed, it would be very hard to confirm its true nature

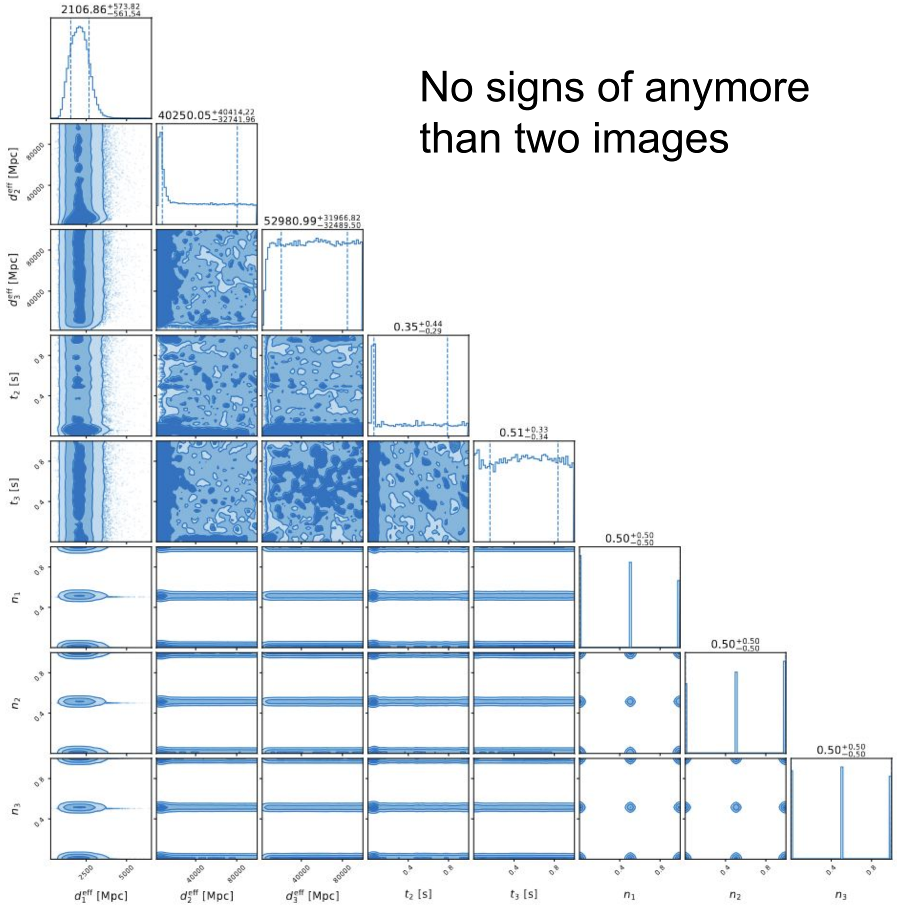
Residual power p-value: 0.97
(~ probability that the event is unlensed based on the coherent power in the detectors).

⇒ It seems more likely that the pair is unlensed. An extended injection campaign would be needed to have an even more confident idea about this.

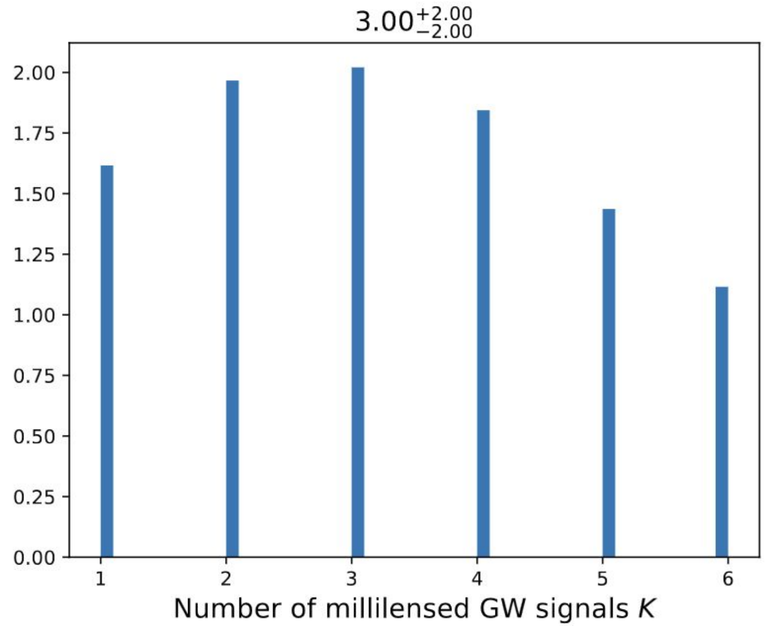


GW200208 – Millilensing Analyses

Since the microlensing analyses seem to pick something up, could it be millilensing features that show up?



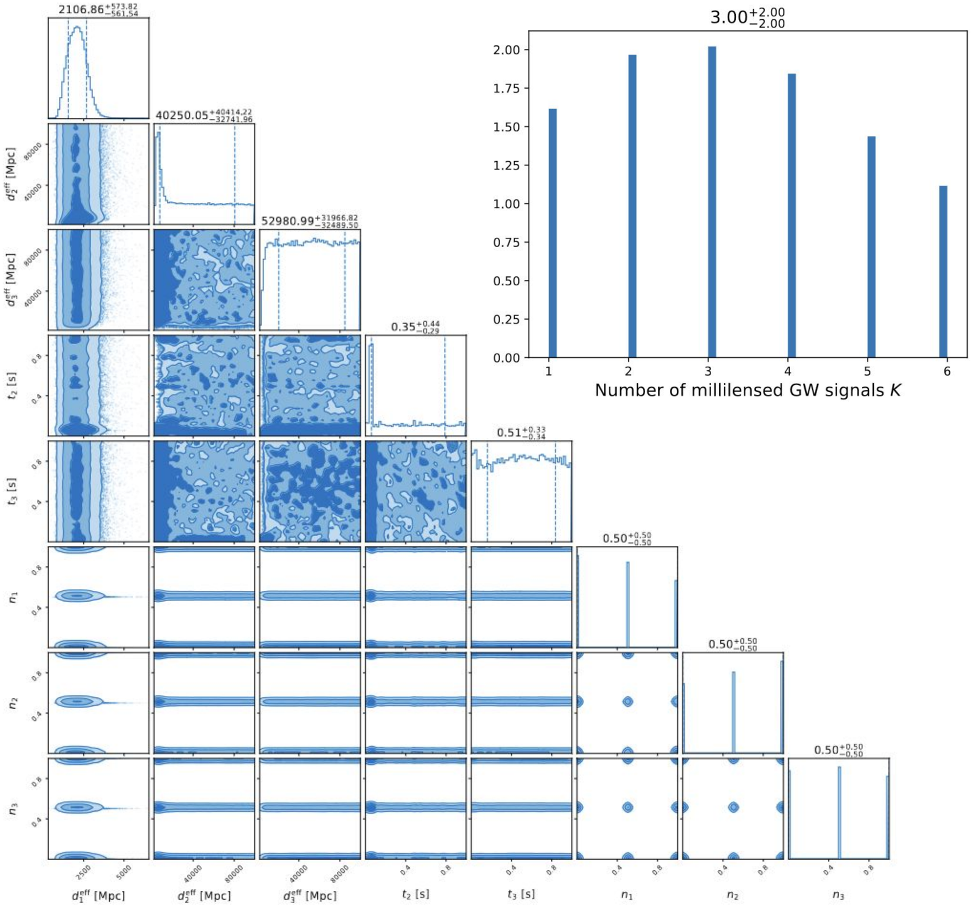
No signs of anymore than two images



Impossible to determine the number of images that would be overlapped (not expected for a genuinely millilensed image)

GW200208 – Millilensing Analyses

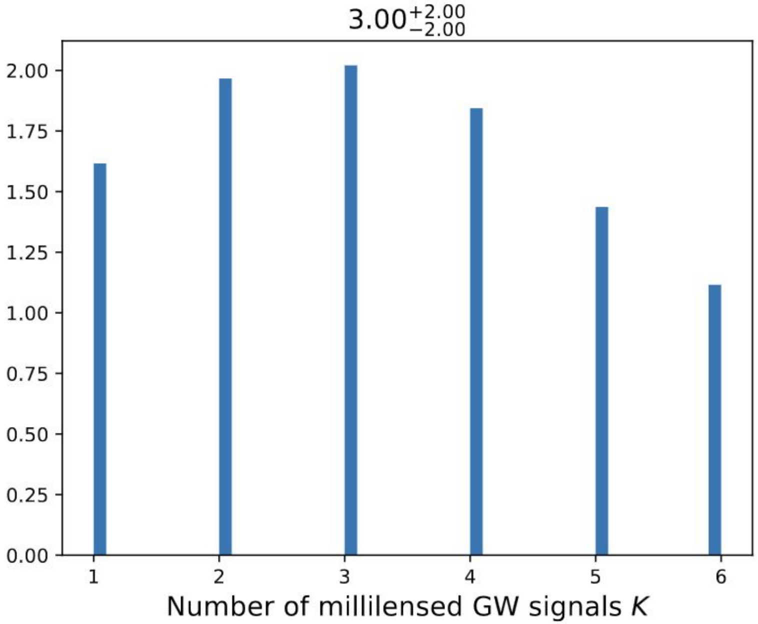
Since the microlensing analyses seem to pick something up, could it be millilensing features that show up?



Seems to indicate that the event is probably not millilensed either.

GW200208 – Millilensing Analyses

Model	$\log_{10}(\mathcal{B}_{\mathrm{U}}^{\mathrm{Milli}})$
Two signals	0.86
Three signals	0.92
Four signals	0.96
Multi-signal	1.10



Bayes factors are relatively high, in line with the microlensing results.
⇒ Probably an attempt to fit non-stationarity in the noise.

Impossible to determine the number of images that would be overlapped (not expected for a genuinely millilensed image)