Detection and characterization of strongly lensed gravitational-wave events

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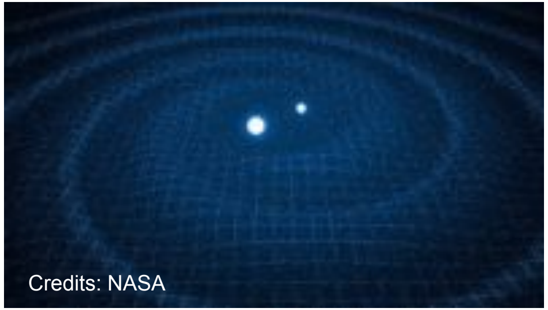
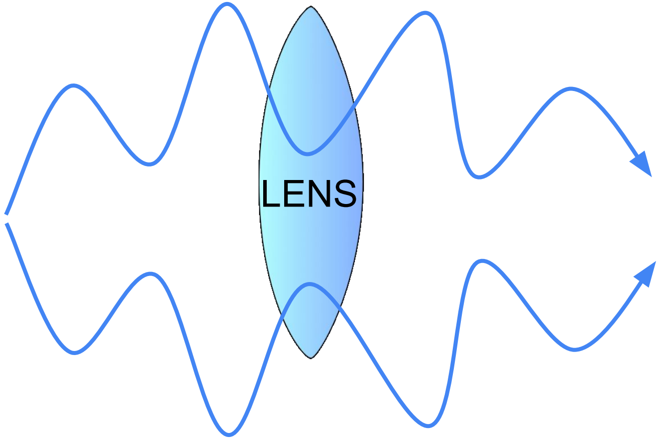
Nikhef

What is GW lensing?

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





Different lens properties → Different effect on the GW

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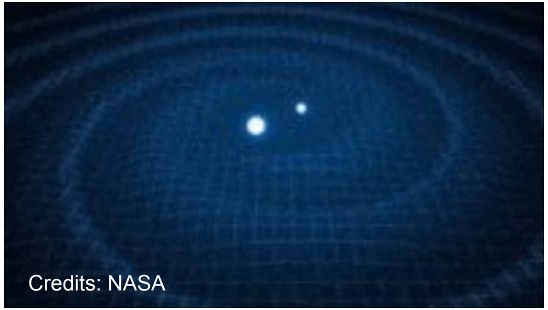
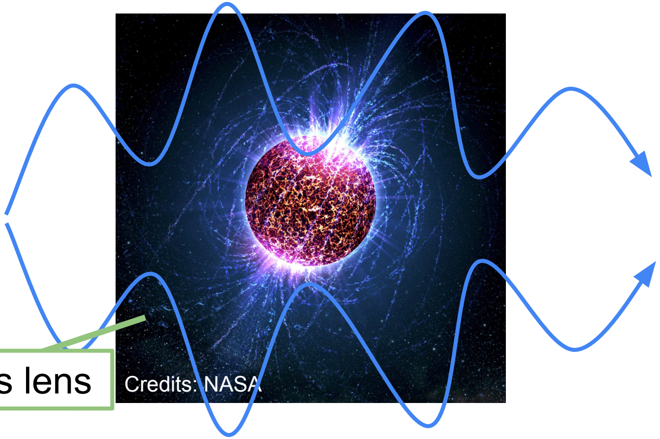
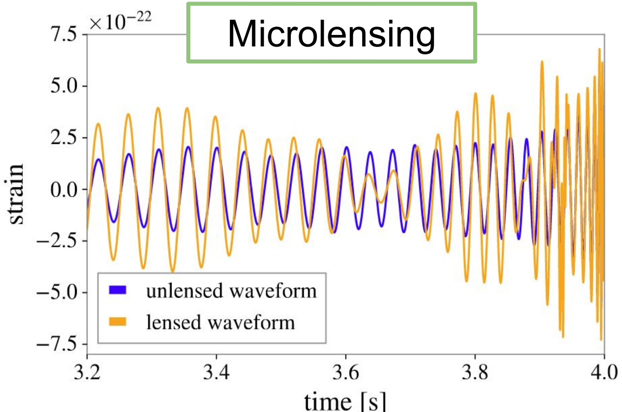




Low mass lens

Microlensing



Source: Seo et al., 2021, arxiv:2110.03308

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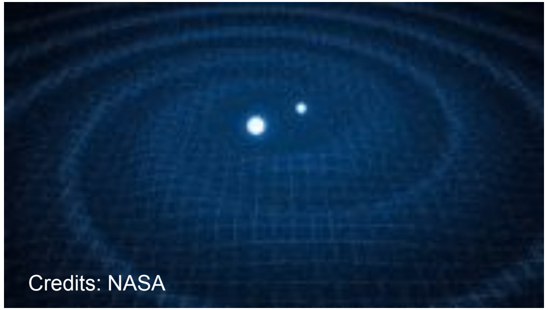

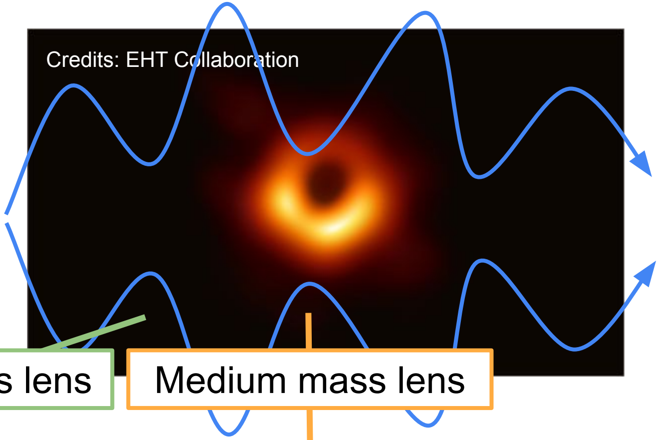

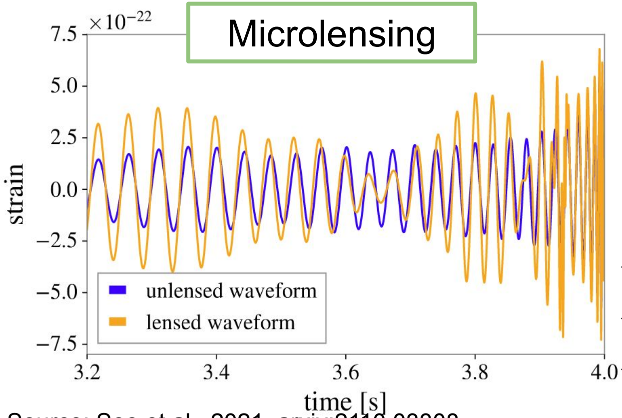

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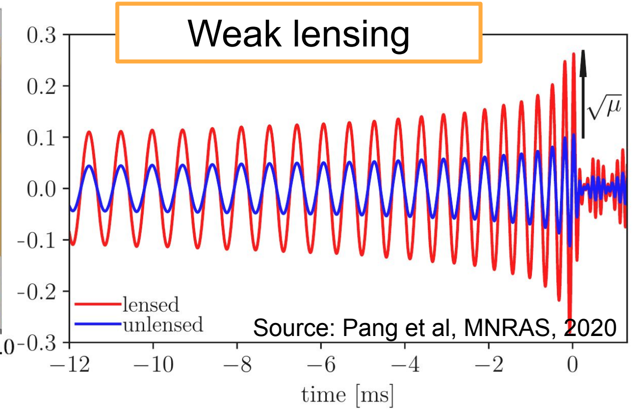

Source: Pang et al, MNRAS, 2020

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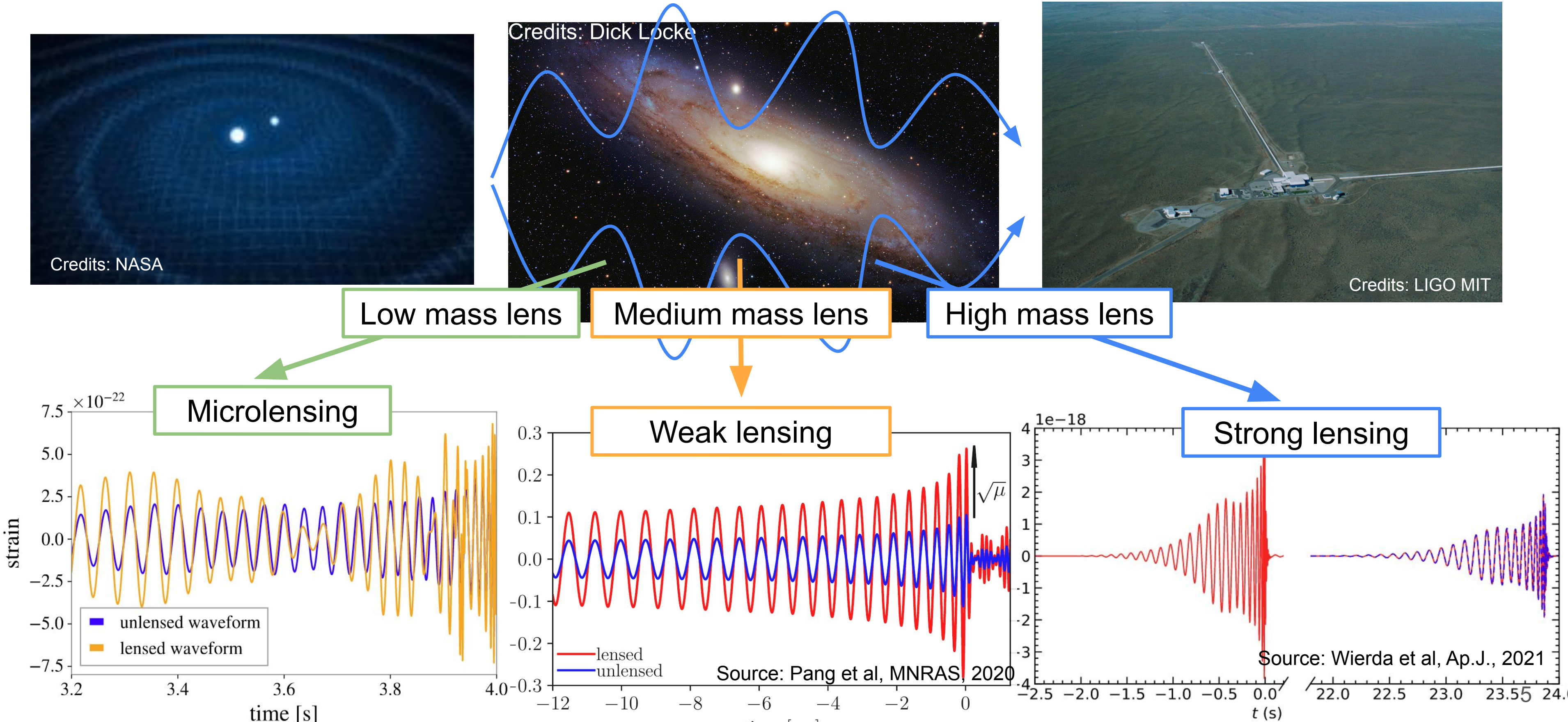

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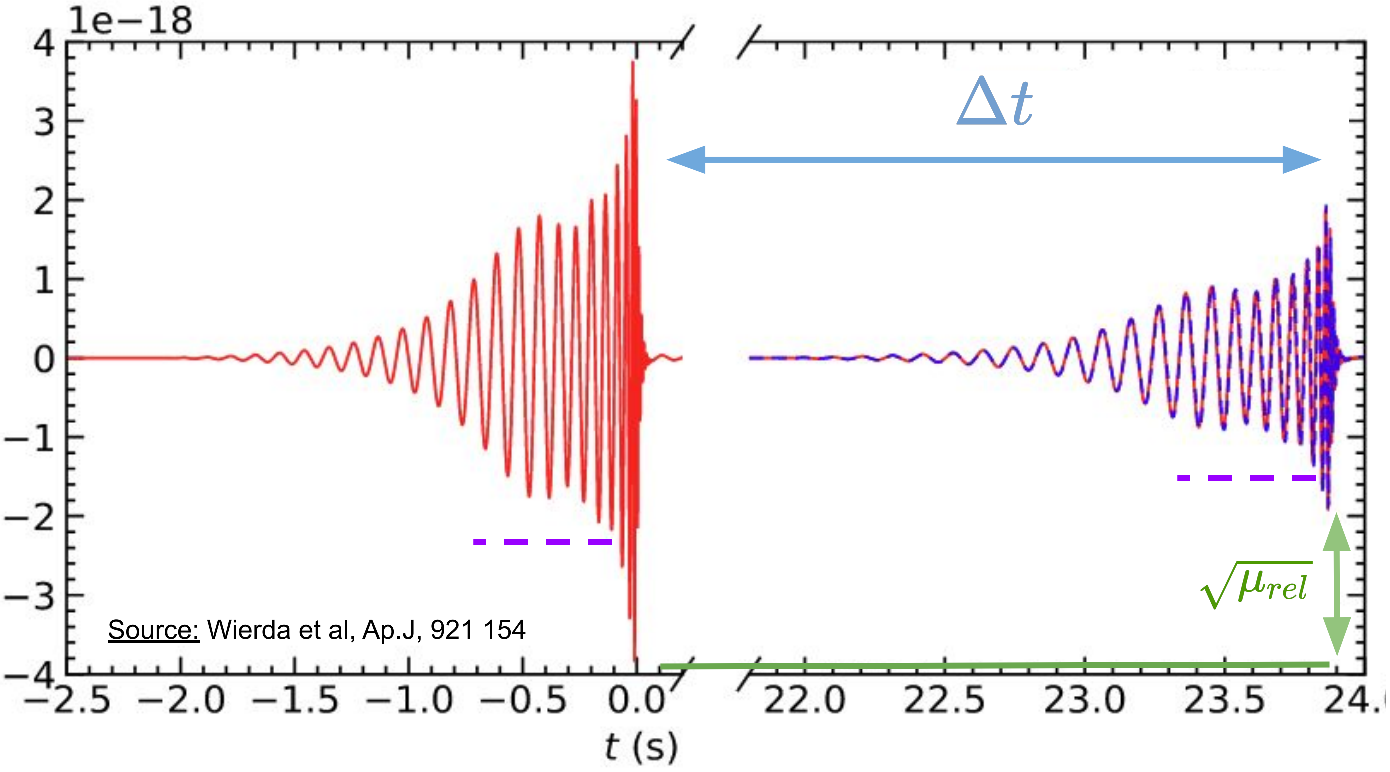
What is strong lensing?

Geometric optics limit $(\lambda_{GW} << R_{lens})$: the frequency evolution of the wave is unchanged.
→ **Several images** with the same frequency evolution.

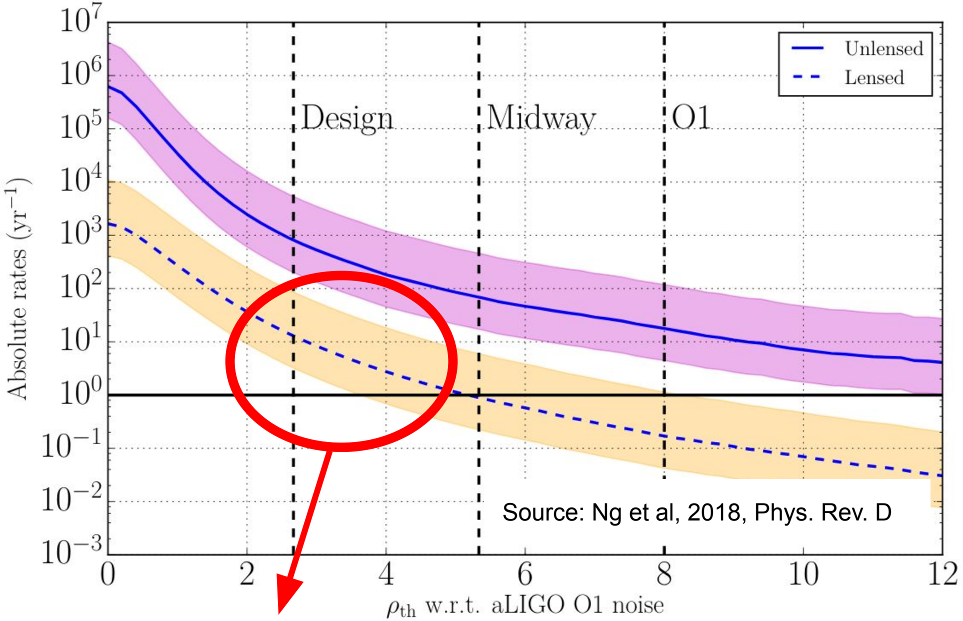


Time delay: different paths lead to different arrival time at the detectors.

Relative magnification: links the change in amplitude for each wave

Overall phase shift: depends on the position relative to the source, one can have $\{0, \frac{\pi}{2}, \pi\}$

Why care about strong lensing?



Improved detector sensitivity

↳ Increased rate

↳ **Could be detected soon**

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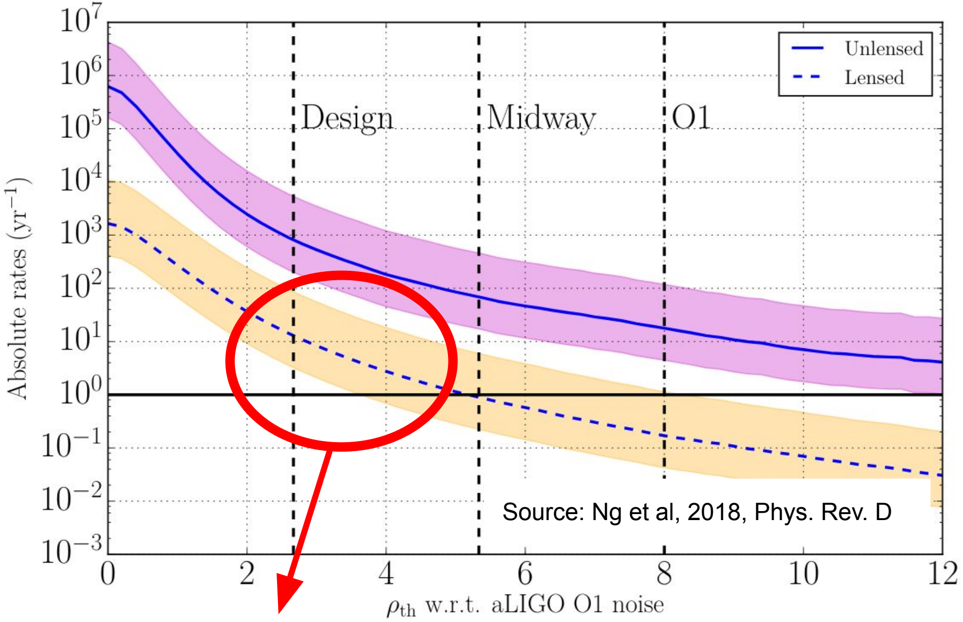

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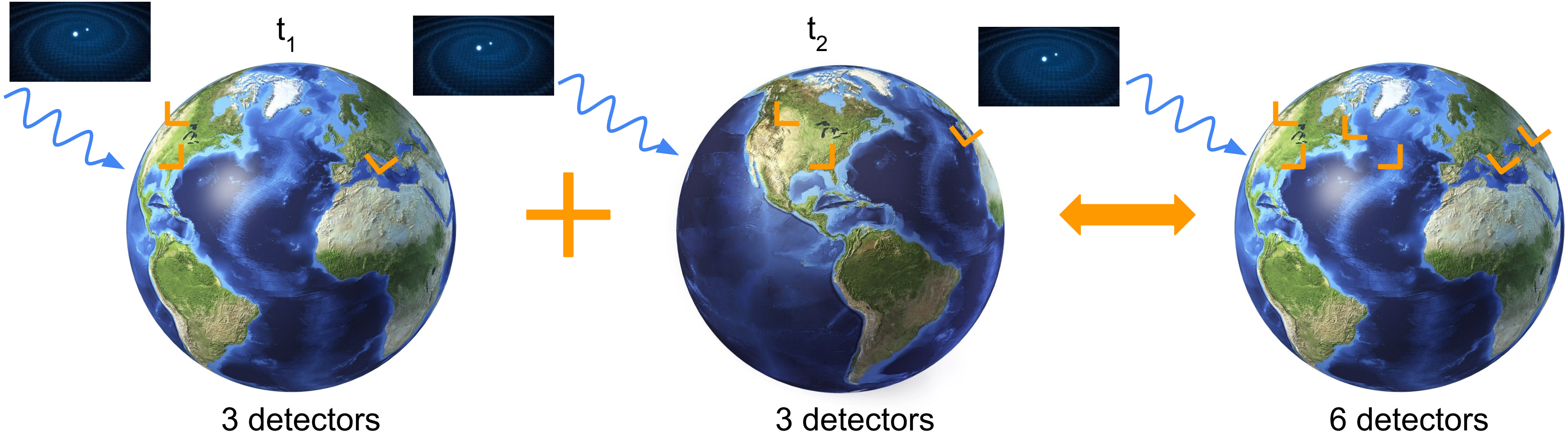
Searches already ongoing!
(GWTC2 : Hannuksela et al, 2019;
GWTC-2.1 : LVK, ApJ., 2021)

Why care about strong lensing?

Some interesting science cases:

- **Origin of black holes** (Hannuksela et. al, 2020)



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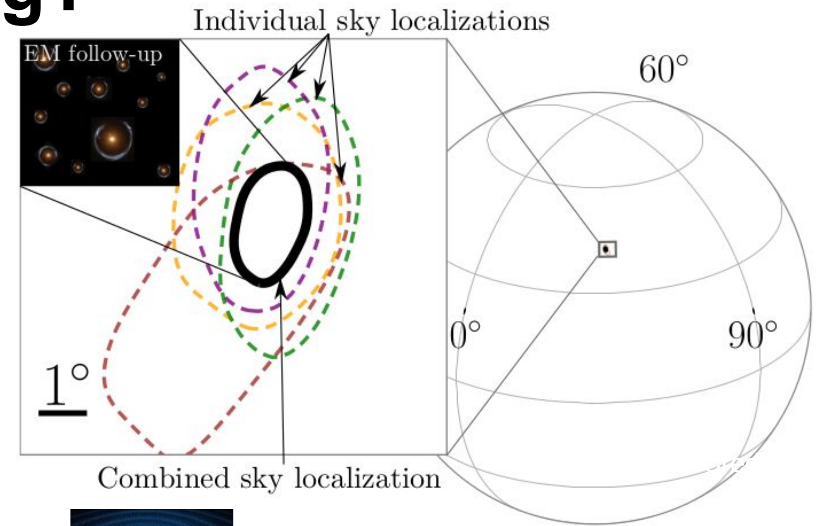
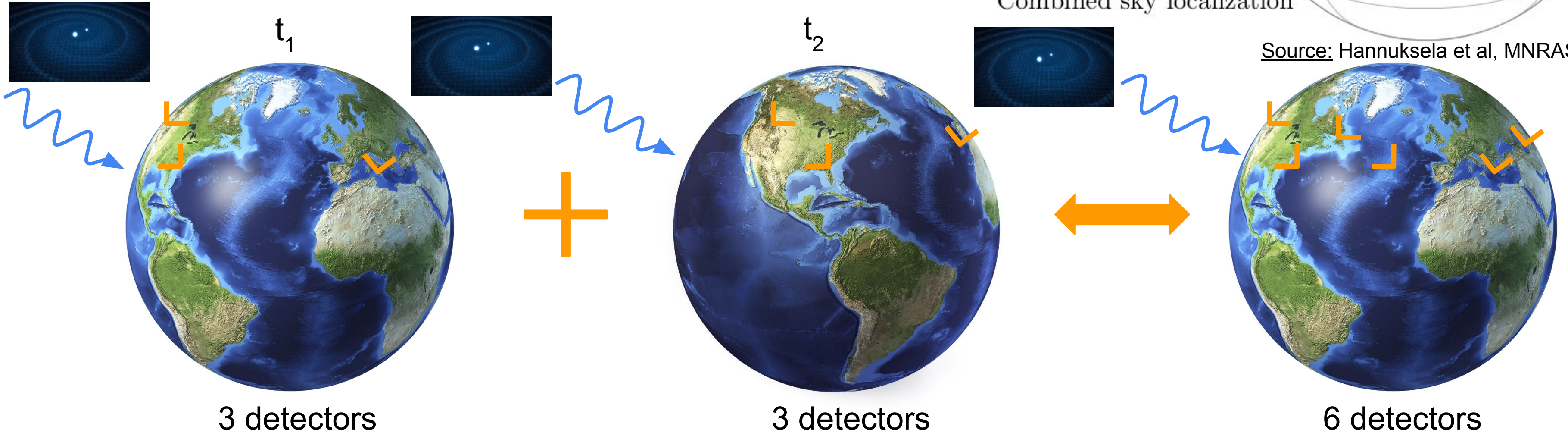


Source: Hannuksela et al, MNRAS, 2020



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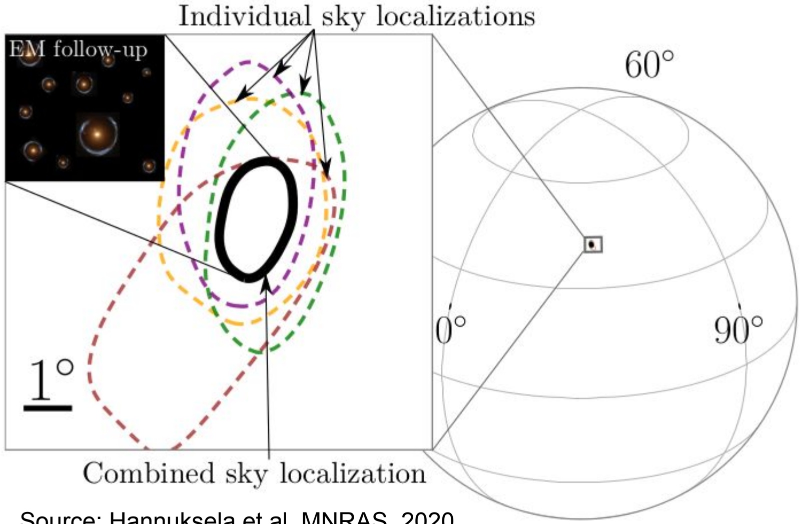

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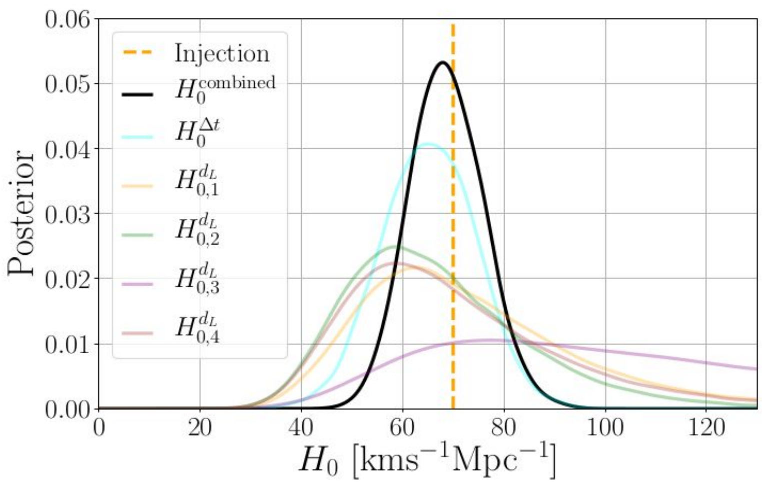

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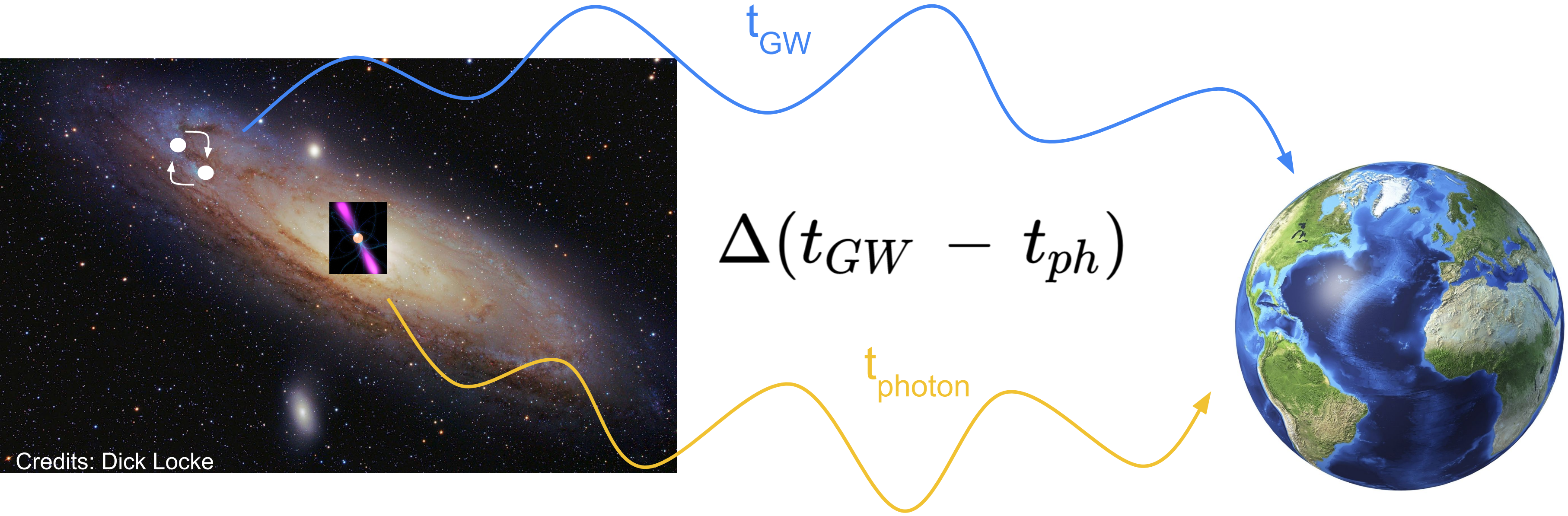

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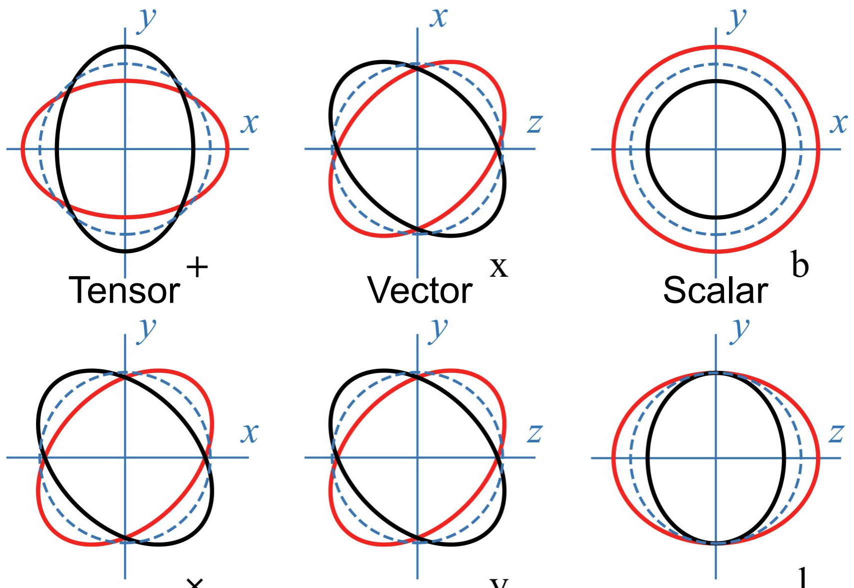
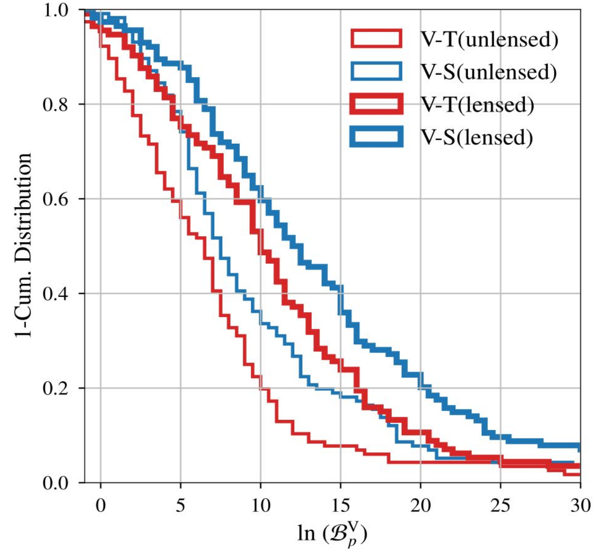
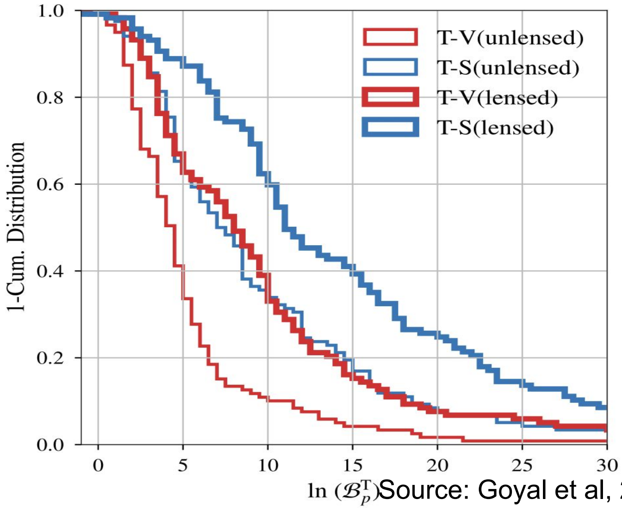


Source: Goyal et al, 2021





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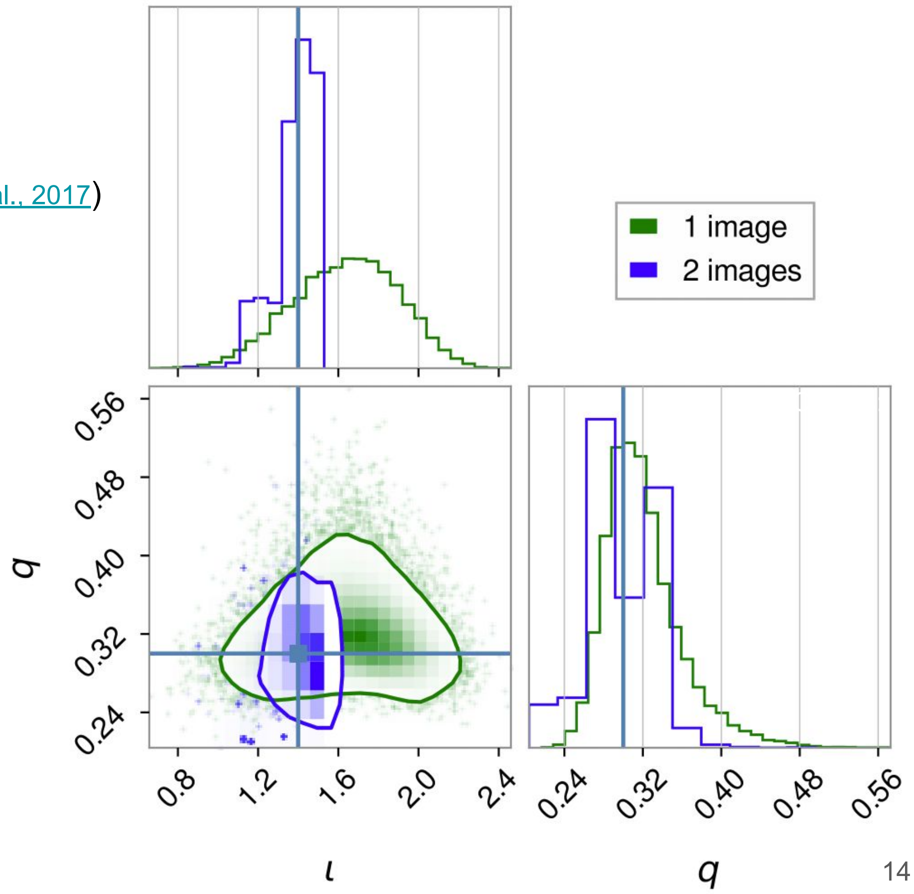
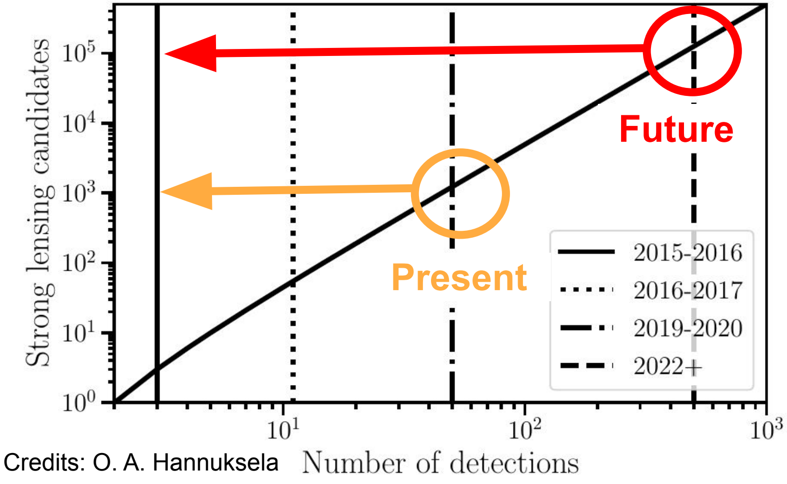
- Test GW polarizations (Goyal et al., 2021)
- **Probing of higher-order modes** (Janquart et al., 2021b)

Better constraint on HOM means better localization capabilities, better understanding of the binary, enhanced tests of General Relativity, …



Possible issues when searching for strong lensing

A) Rapid increase in the number of pairs to analyze



Credits: O. A. Hannuksela

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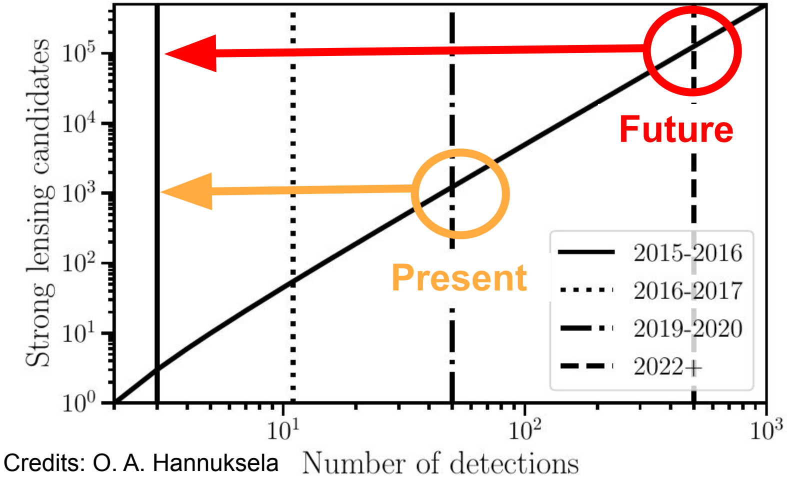

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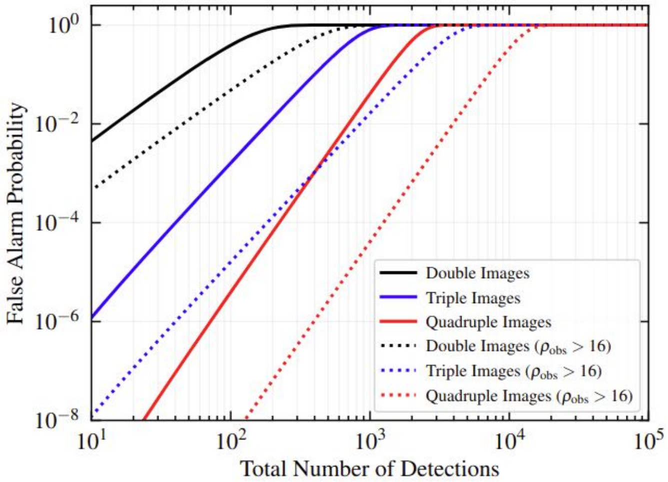
B) False alarm rate increases rapidly with the number of detections



Çalişkan et al, arXIV 2201.04619

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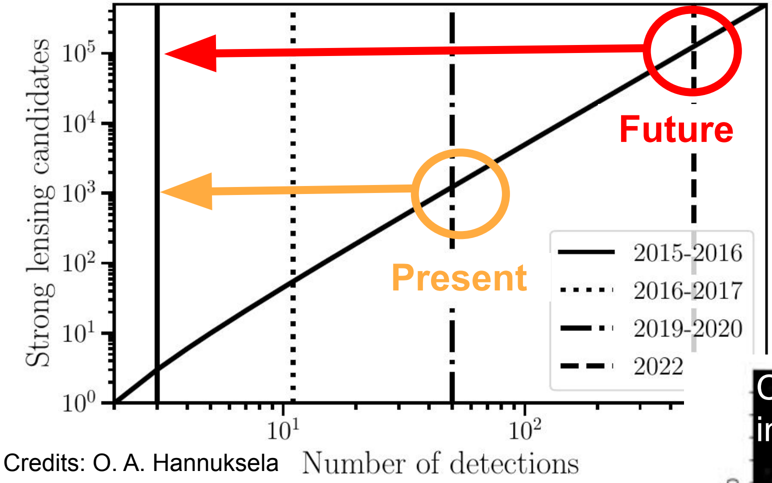

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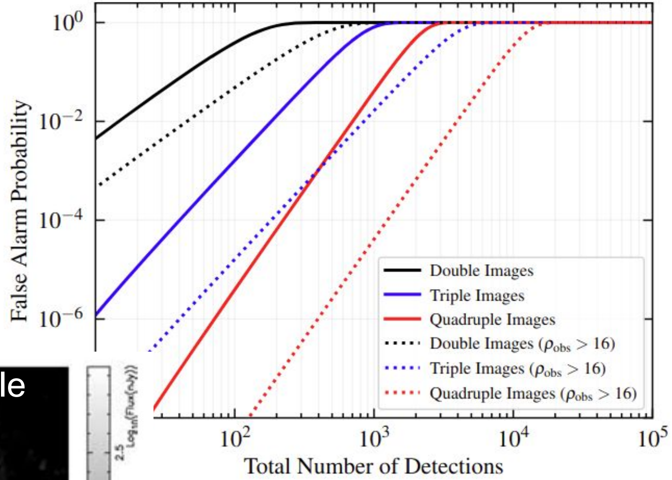
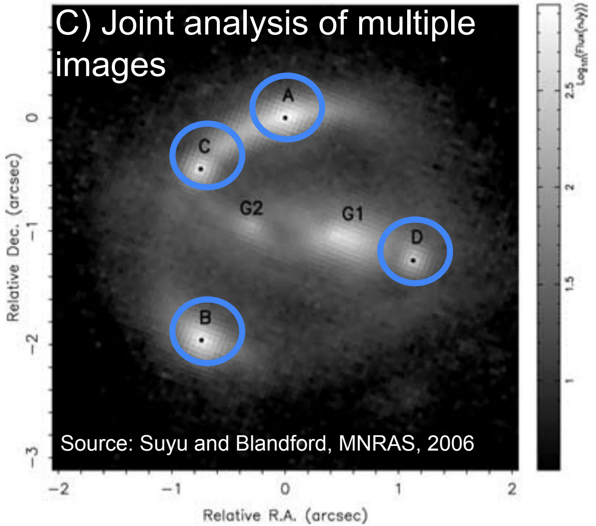


Çalişkan et al, arXIV 2201.04619

C) Joint analysis of multiple images

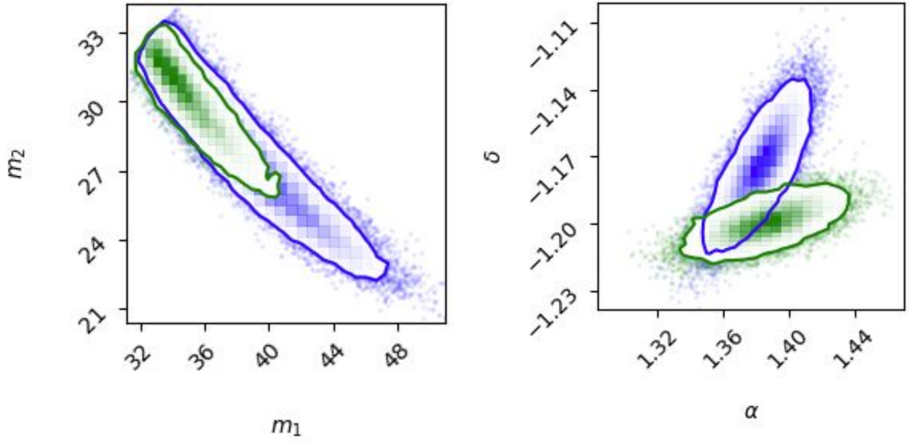


Source: Suyu and Blandford, MNRAS, 2006

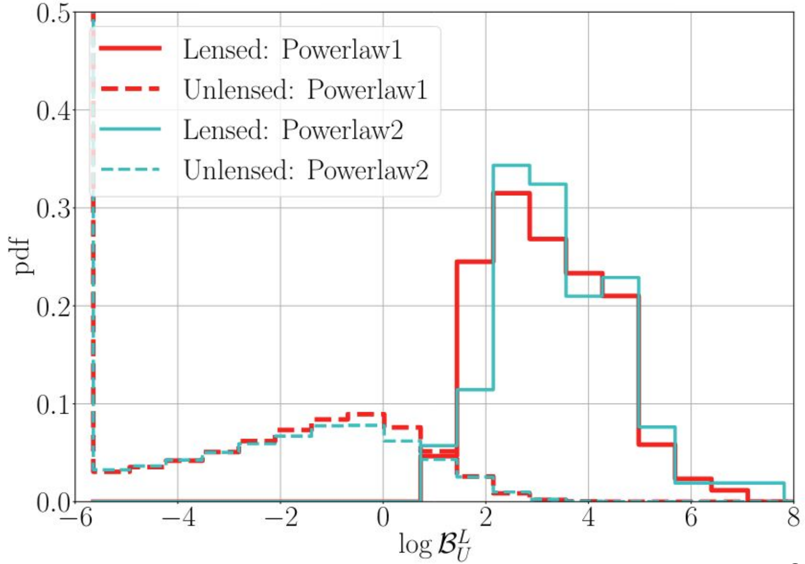
How do we search for strong lensing?

→Lensed events should have the same intrinsic parameters.

a) Check consistency between (a subset of) the recovered distributions for individual events (= **Posterior overlap**, Haris et al, 2018) → Fast but not very accurate



Lensed or not?



Already a good discriminator but still some region of overlap between the lensed and unlensed events → Risk of false alarms

+ All the correlations are not accounted for

Source: Haris et al, arXiv:1807.07062 2018

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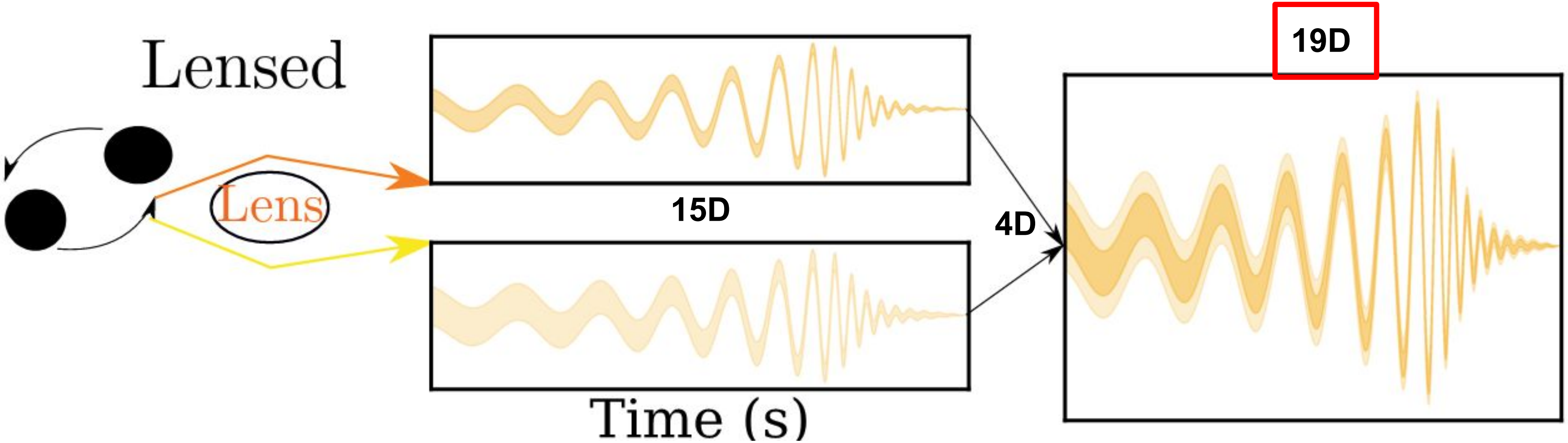
a) Check consistency between (a subset of) the recovered distributions for individual events (= **Posterior overlap**, Haris et al, 2018)
b) Analyze the two data streams jointly in a Bayesian framework (Liu et al., 2020, Lo & Hernandez, 2021)
→ Much more accurate but much slower



→ Characterises fully the event but is not usable for large-scale studies due to computational resources

Adapted from Çalişkan et al., 2022

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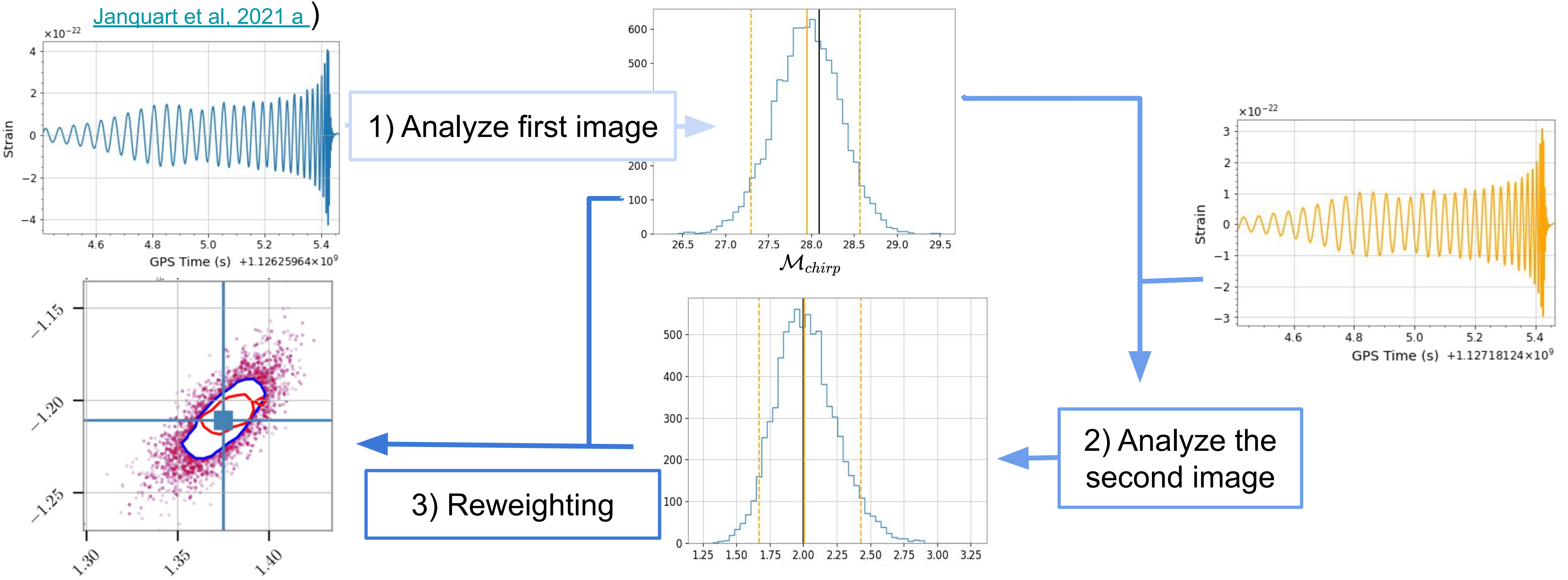
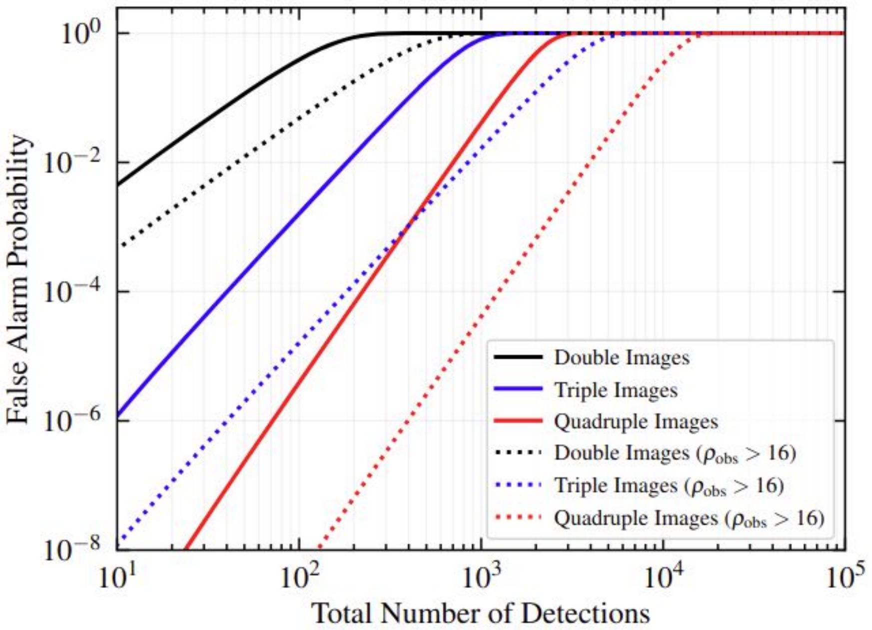
c) “Distributed” joint-analysis: decreases computational cost while preserving most of the accuracy (**GOLUM**, Janquart et al, 2021 a)



With these tools, can we identify strong lensing?

Unlensed events can mimic lensed onse: false-alarm probability issues (Wierda et al. 2021, Çalişkan et al. 2022; Janquart et al. 2022) → Need to find one lensed multiplet in a large pool of unlensed events



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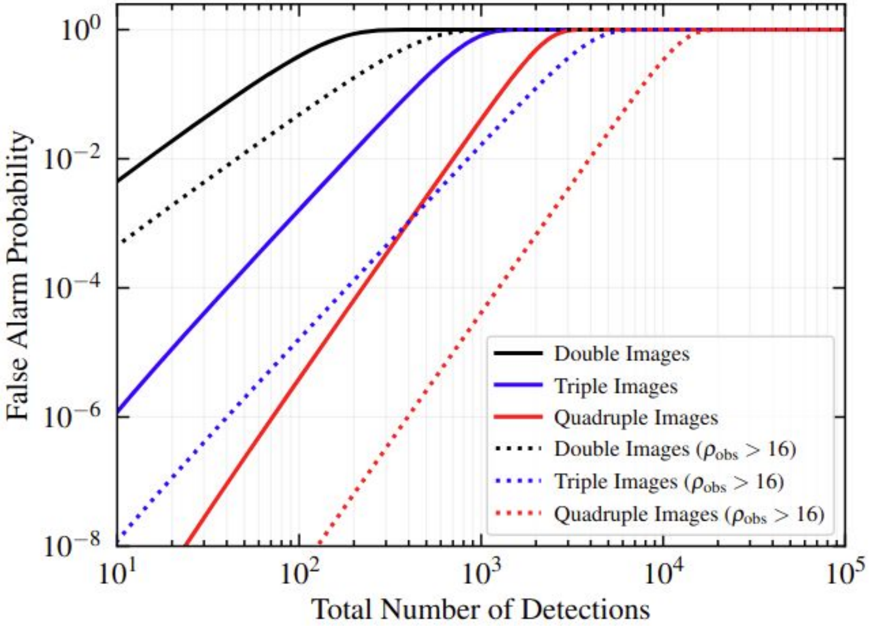
First improvement: Use more precise techniques able to account for all the dependencies → Not enough…



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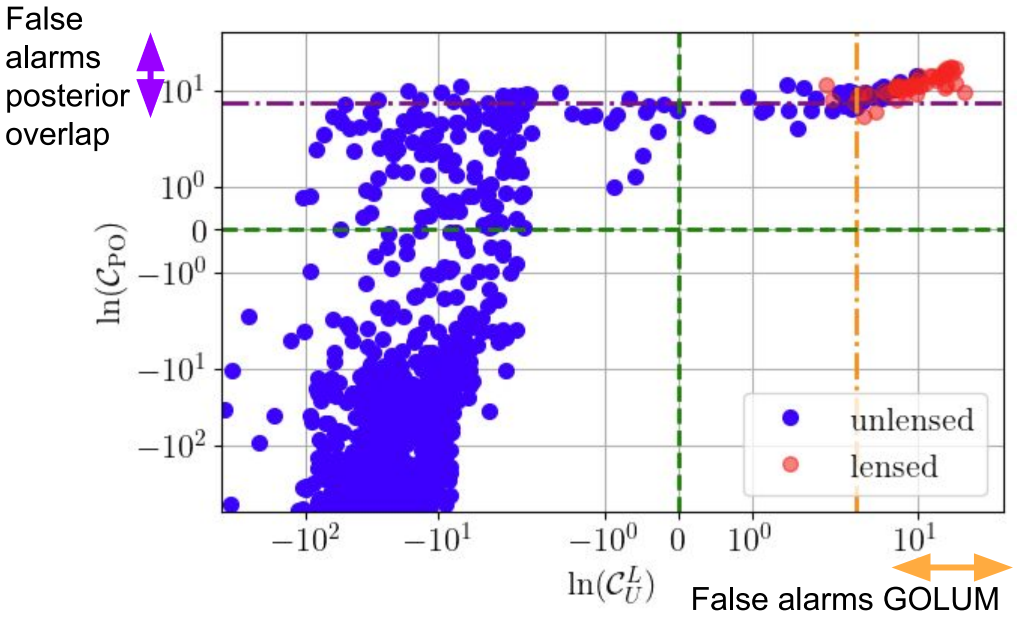
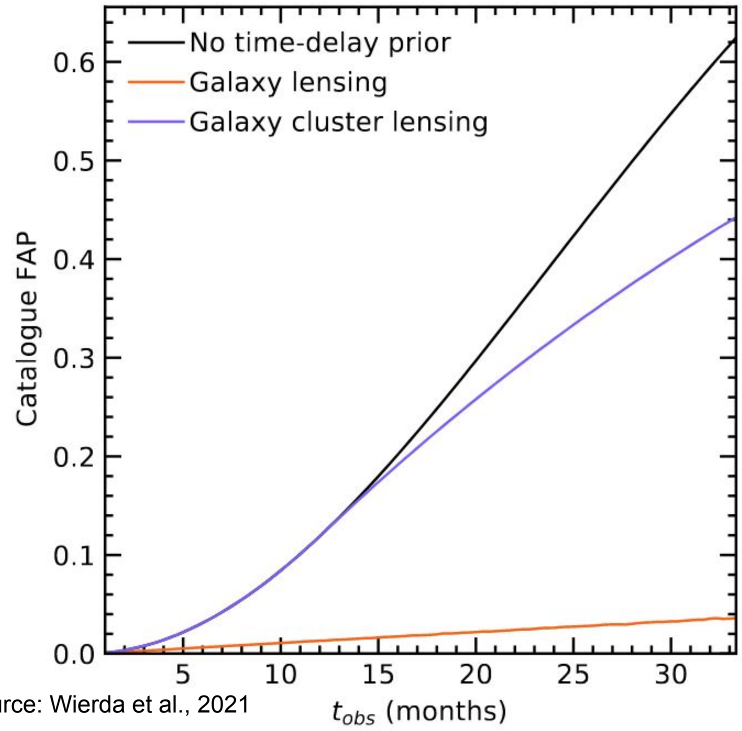
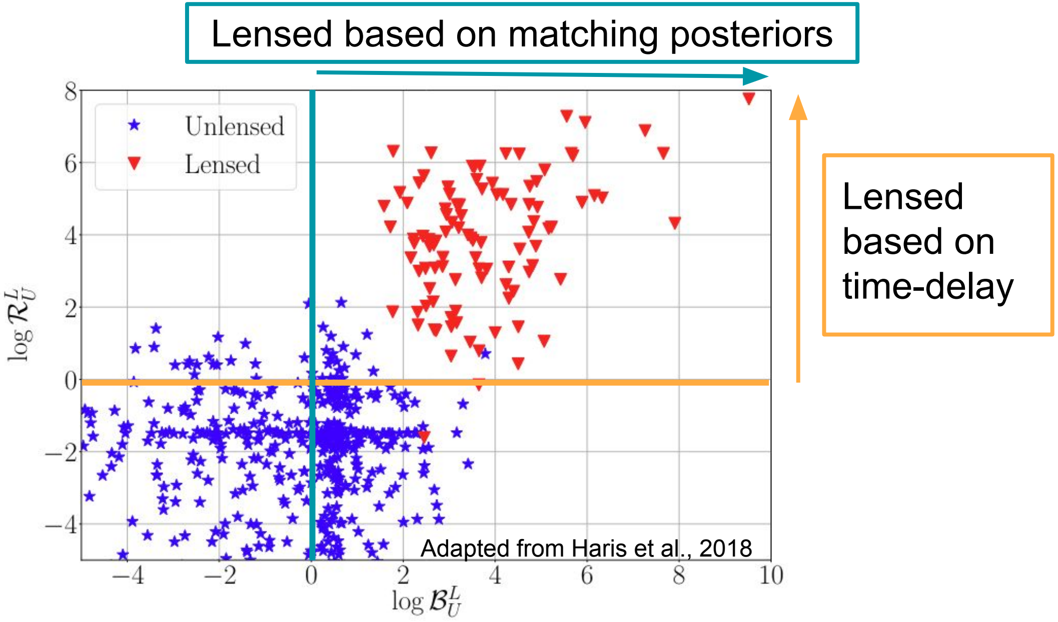


Can we decrease the false-alarm probability more?

Methods are generally agnostic about the lens model → Lens parameters can be “anything”
→ Enforcing the lensing parameters to match expected values can help but usually the lens is unknown…



Source: Wierda et al., 2021



→ Already helps for posterior overlap methods but assumes the lens to be known.

Can we do better?

Combine the lens model and the more accurate method should decrease the false alarm probability further.
We also need to know what would be the impact of mismodeling and inclusion of different information.
→ Effect of model can be included in post-processing for GOLUM: 1 run and several models can be tested

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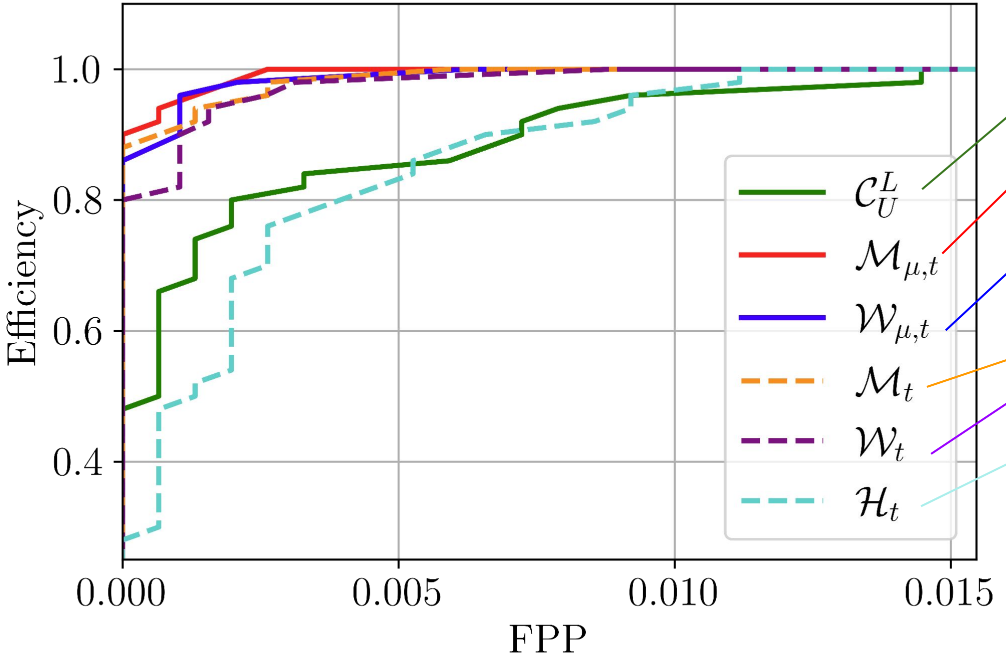


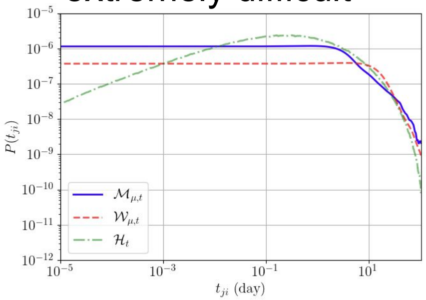
No model: Identification is difficult

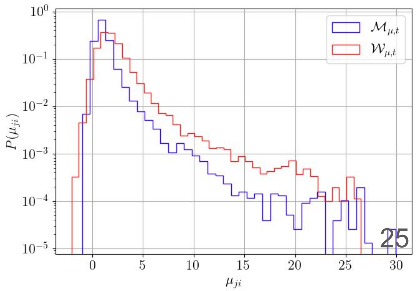
Correct model: Identification is made easier

Very small variations in model: No significant impact

Only time delay: Slight decrease in performance

Wrong model: Identification would become extremely difficult





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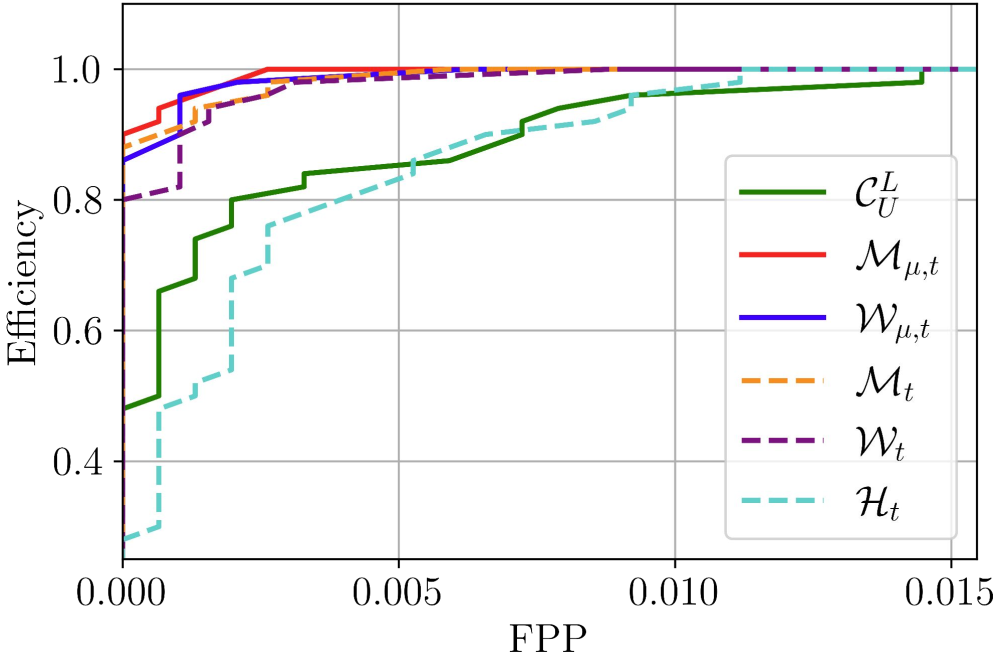


The inclusion of a lens model helps decreasing the false alarm probability

The effect of the models should become even more important when considering triples or quadruples. Work in progres…

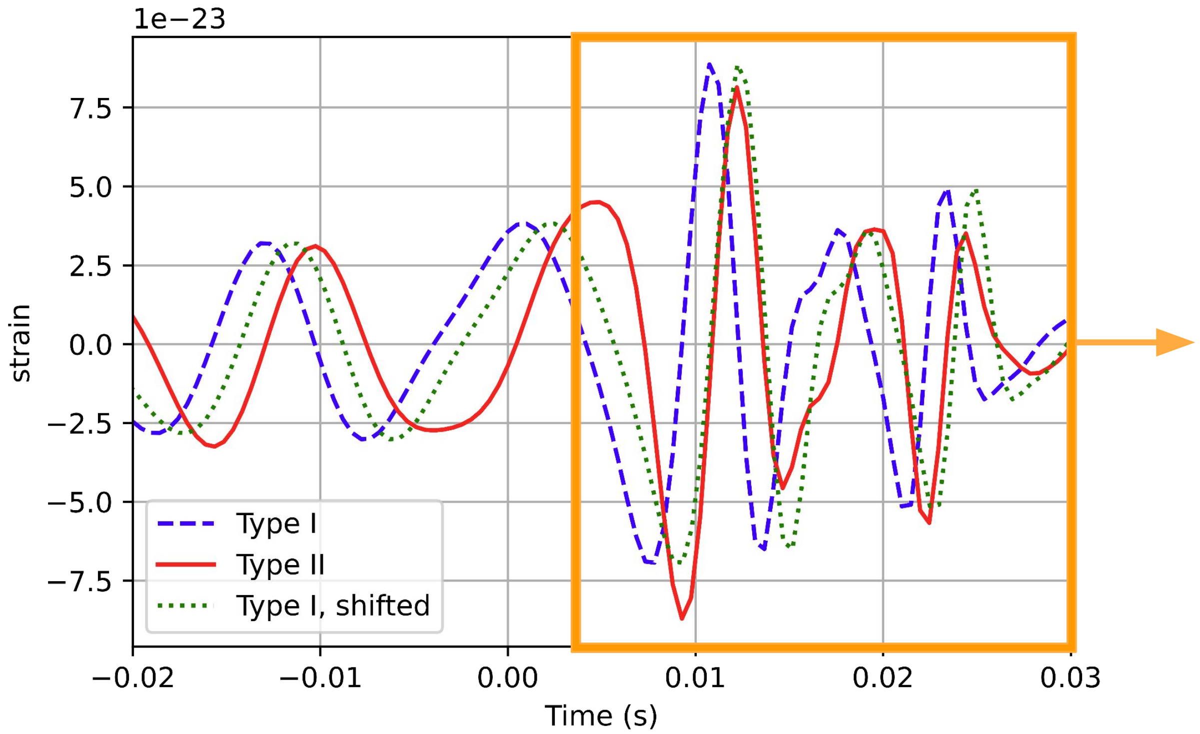
Morse factor difference can be accounted for, and should help (Janquart et al, 2021 b)

Even more extended studies are needed to prove detectability. Also work in progress.

The effect of higher-order modes

Depending on the image types present in the data, higher-order modes can help in the identification:

- For type I and III: no
- For type II images (phase shift = pi/2): yes … but need to have significant higher order modes



Type II images lead to additional distorsions. No shift can compensate for this
→ We can identify the type II images, if HOM effect is strong enough (Wang et al., 2021; Janquart et al., 2021b; Vijaykumar et al., 2022).
Smoking-gun evidence for lensing

The effect of higher-order modes

For very strong contributions (and 3G detectors), 1 image could be enough, but for 2 images or more, HOM helps for lower HOM content (Janquart et al., 2021b).

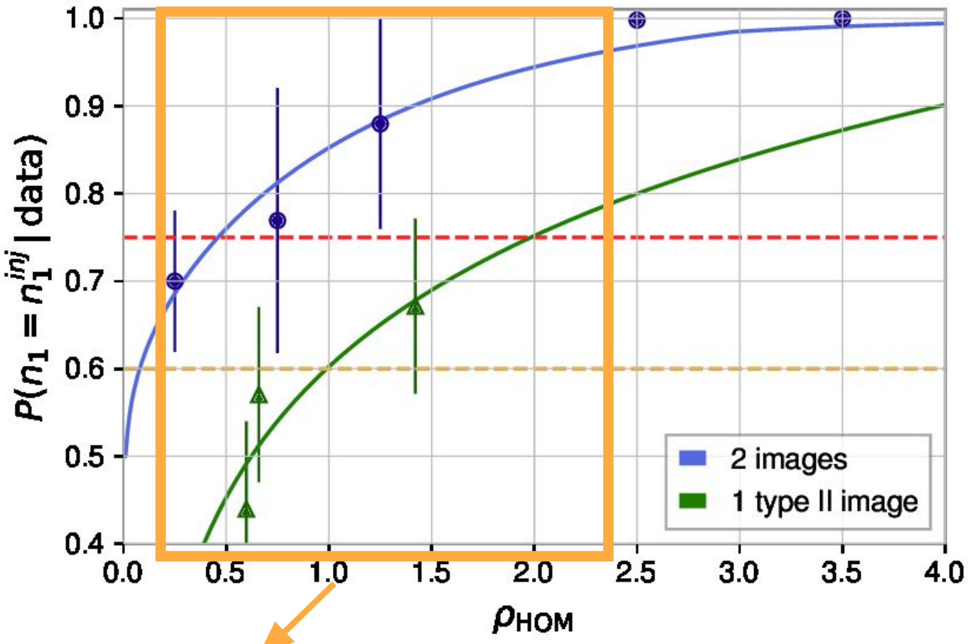
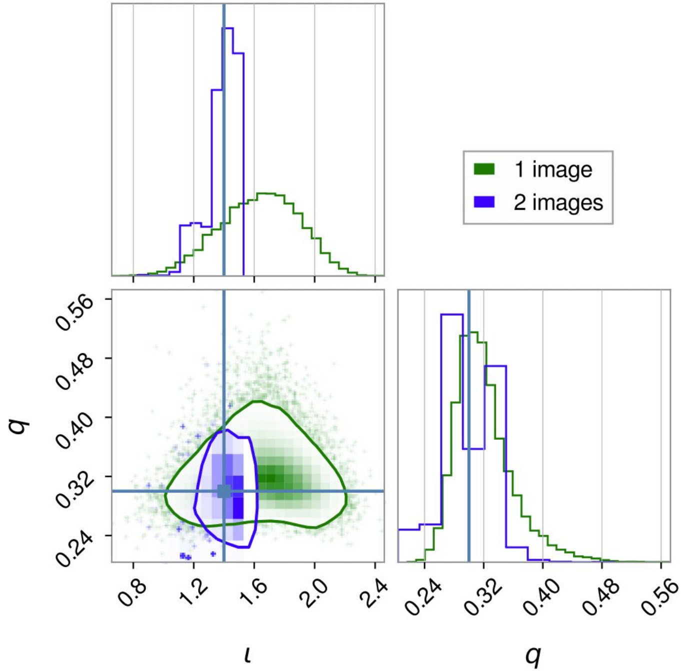


Image identification is crossed at a lower threshold for 2 images → smoking gun evidence!



Better probing of the HOMs, better sky location, enhanced tests of General Relativity

Conclusions and outlooks

- Gravitational wave lensing is an active field of research
- Strong gravitational wave lensing is upon us, manifesting itself as repeated events with the same frequency evolution
- Strong lensing has many interesting and exciting science cases.
- There are many challenges to search for strong lensing and to identify the lensed images:
    - Increasing number of pairs to analyze → Requires speed
    - Analysis of multiplets → Requires precision and tractability
    - High false-alarm probabilities
- Methods exists to search for and analyze strongly lensed events:
    - Very fast analysis method, e.g. posterior overlap
    - Very precise analysis method: joint parameter estimation
    - Precise and fast: GOLUM
- Higher order modes can help in having clear signatures for lensing with one or multiple images
- Using lens models and associated expected values for the lensing parameters, one can decrease the false-alarm probability.