



A fast and precise methodology to search for and analyze strongly lensed gravitational-wave events

Speaker: J. Janquart*

Collaborators: O. A. Hannuksela, K. Haris, C. Kalaghatgi, T. F. Li, E. Seo, C. Van Den Broeck



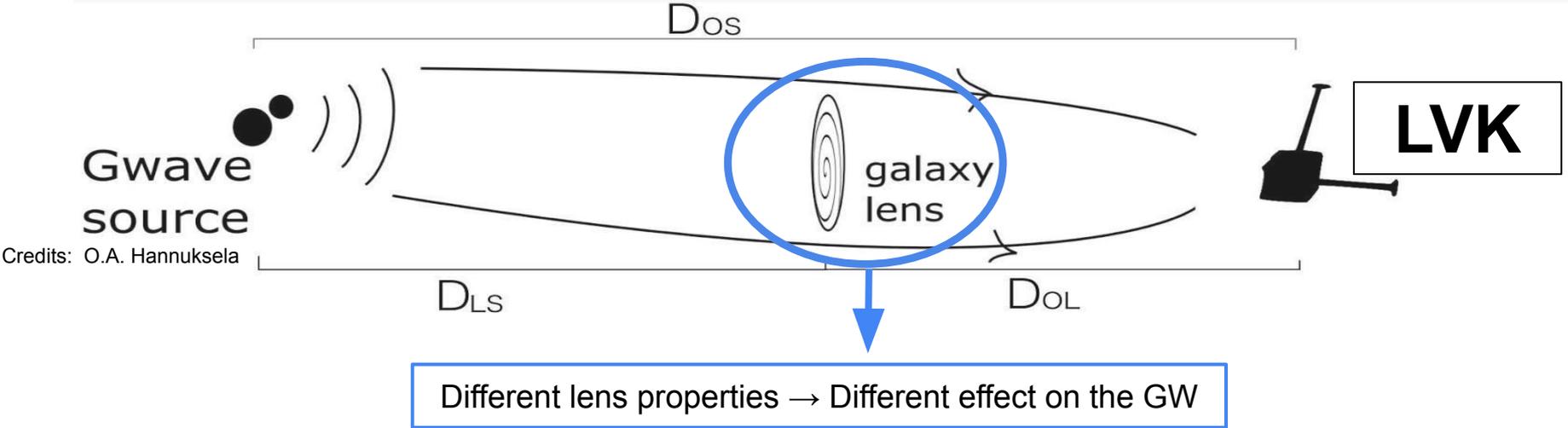
Utrecht University

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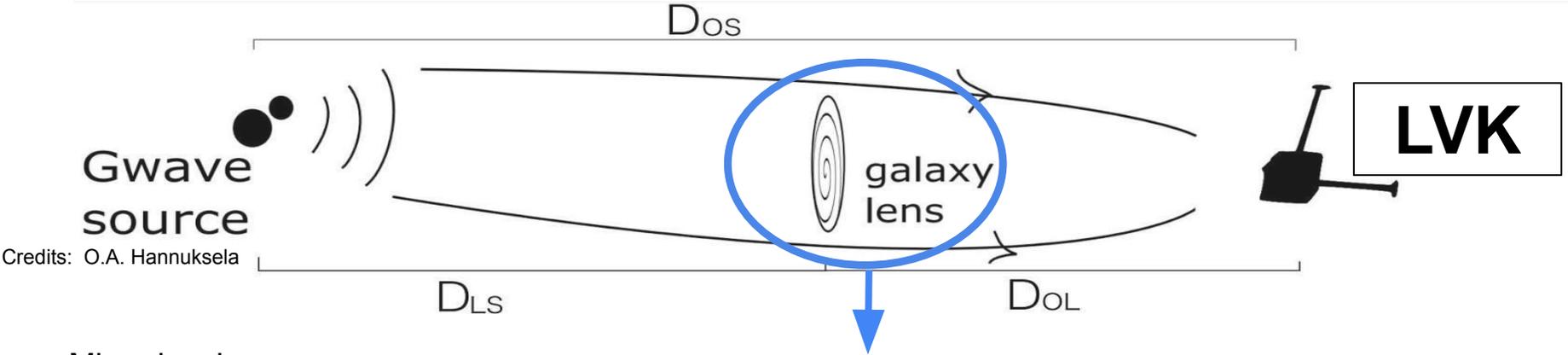
What is GW lensing?

→ Same principle as for light: a massive object along the path deflects the wave

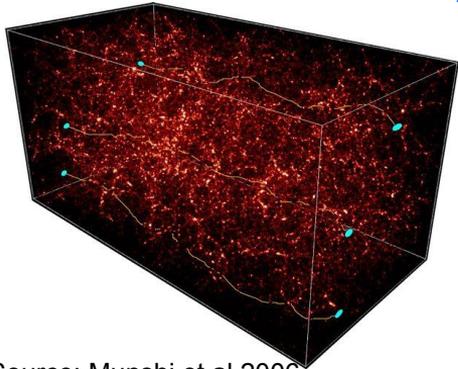


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Micro-lensing:



Different lens properties → Different effect on the GW

Weak lensing:

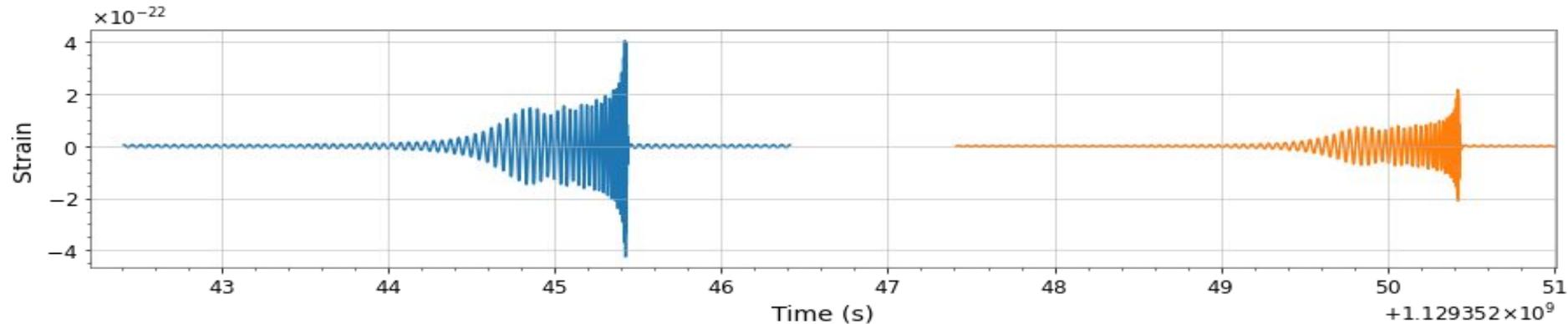


Strong lensing:



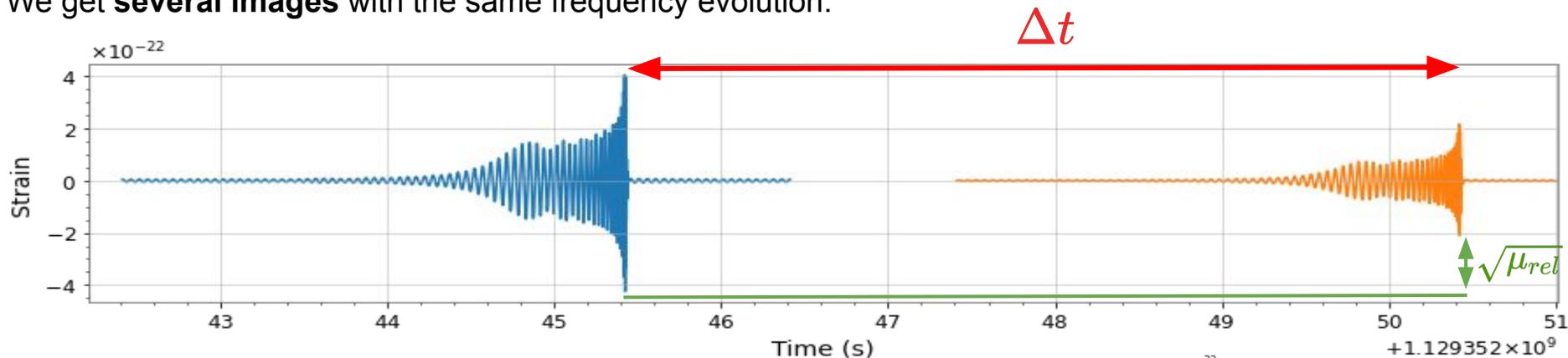
Focus on strong lensing:

In the **geometric optics limit** ($\lambda_{GW} \ll R_{lens}$): the frequency evolution of the wave is unchanged.
We get **several images** with the same frequency evolution.



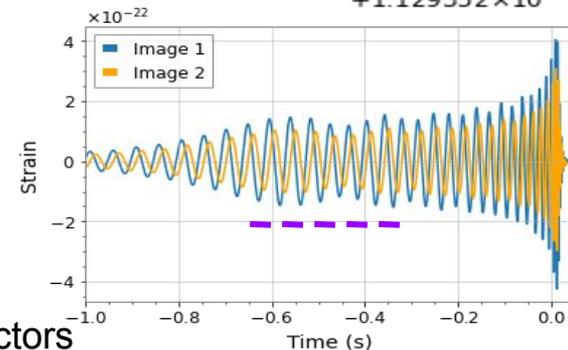
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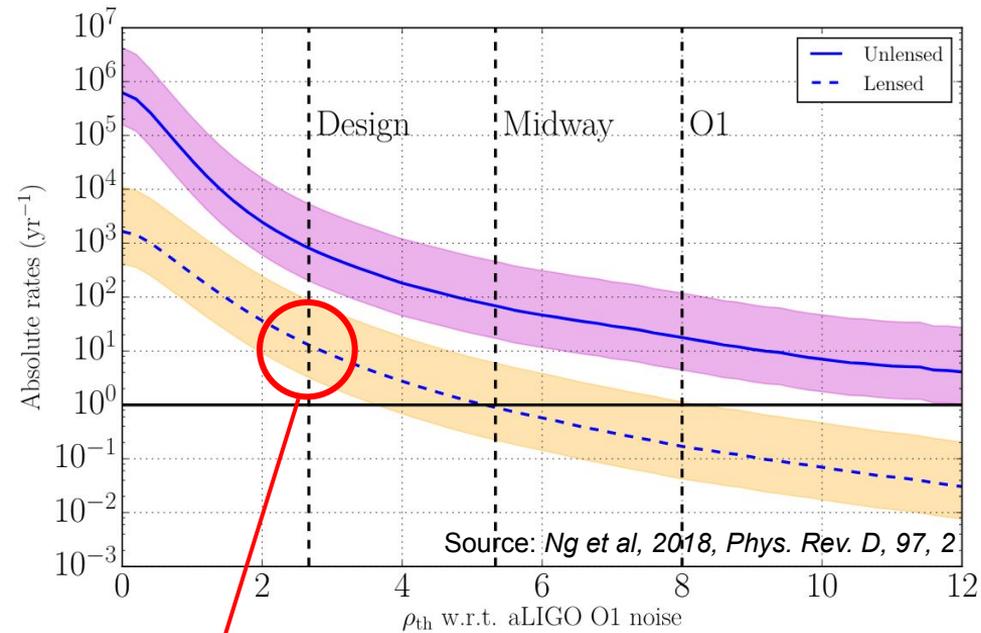


Differences between the images:

- **Relative magnification:** change in amplitude of the wave
- **Time delay:** different paths are take → different times of arrival at the detectors
- **Overall phase shift:** depending on the position of the image, we can get $\{0, \frac{\pi}{2}, \pi\}$.

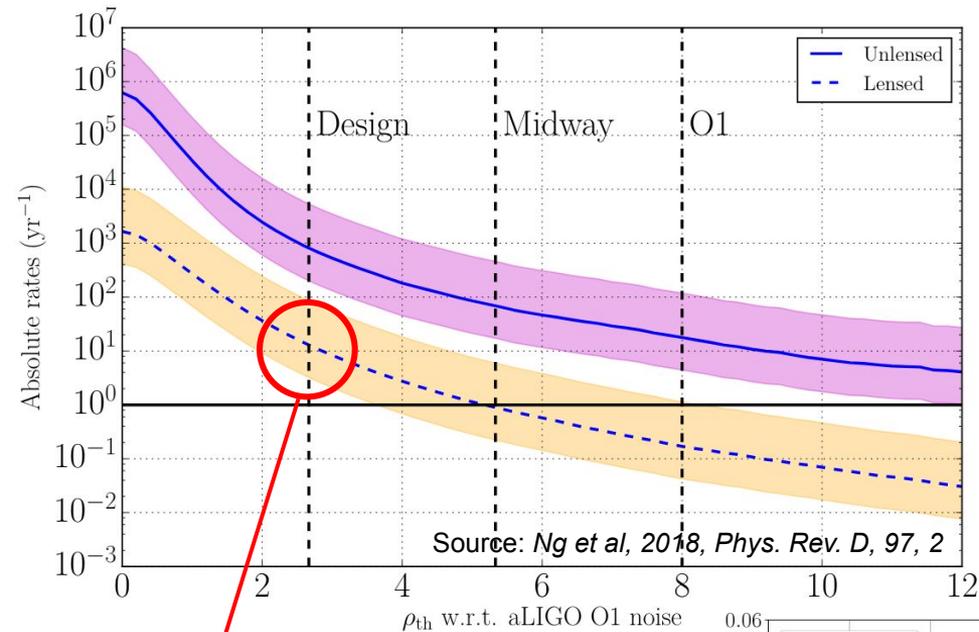


Why to we care about strong lensing?



Could be detected soon,
when detectors @ design
sensitivity

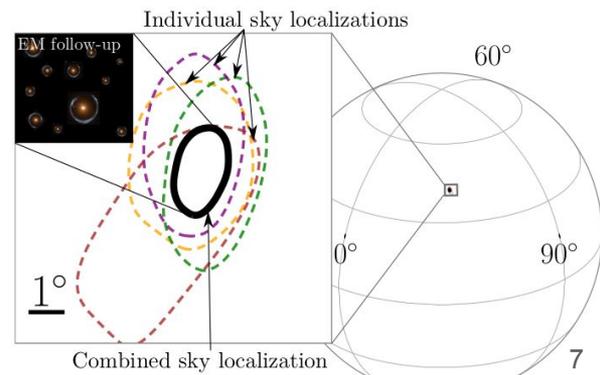
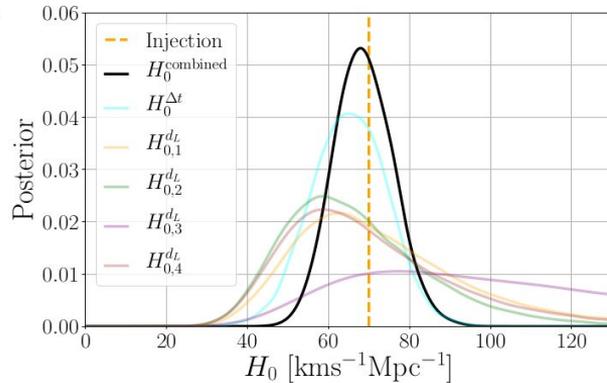
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Some interesting science cases:

- Origin of black holes (Hannuksela et. al, 2020)
 - Expansion of the Universe (Liao et. al 2017, Hannuksela et. al 2020)
 - Probe fundamental physics (Collett & Bacon 2017, Fan et al 2017)
 - Test GW polarizations (Goyal et al, 2021)
 - Probing of higher-order modes (Janquart et al 2021b)
 - Investigation of dark matter halos (Janquart et al, in prep)
- Huge impact due to the improved sky sensitivity: fiducial detector network of $N_{images} \times N_{detectors}$



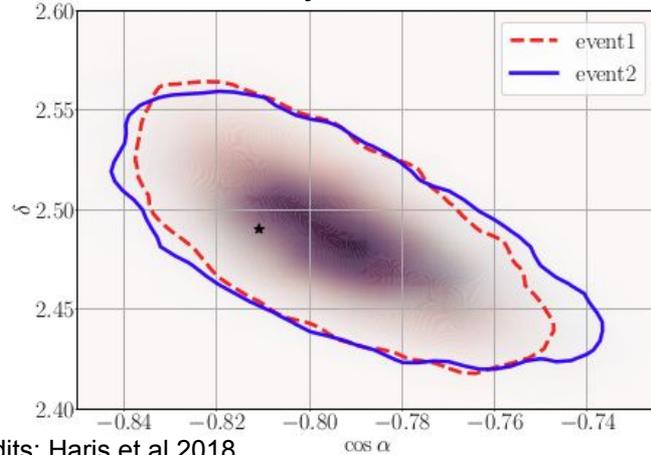
Credits: Hannuksela et al 2020

How do we search for strong lensing?

Two strongly lensed signals are dependant:

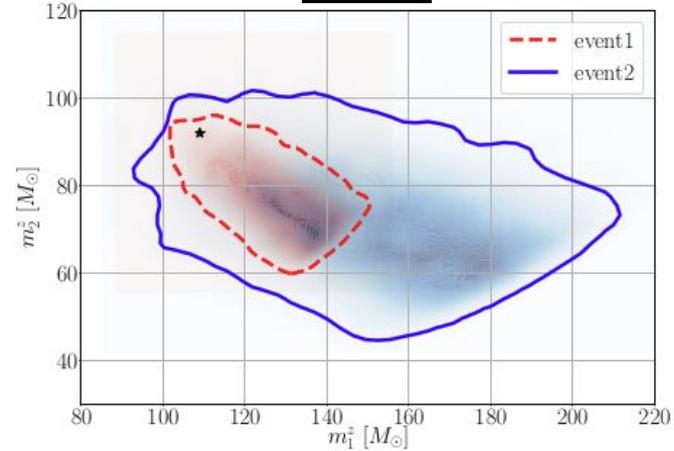
1. The parameters unaffected by lensing should be the same → Compatible distributions for these parameters

Sky location:



Credits: Haris et al 2018

Masses



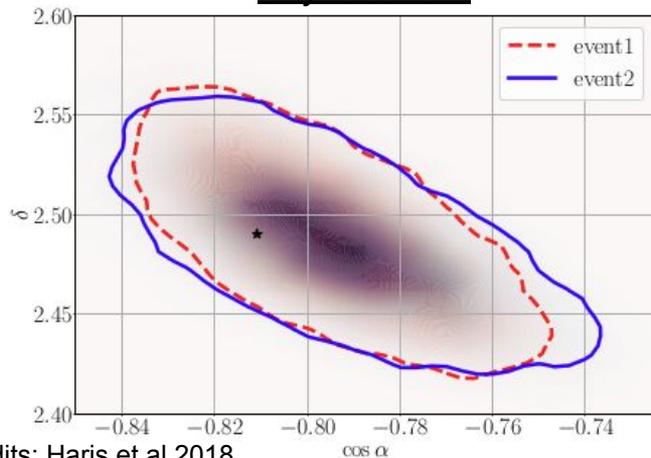
2. The lensing parameters link the distance, time and overall phase shift between the 2 images

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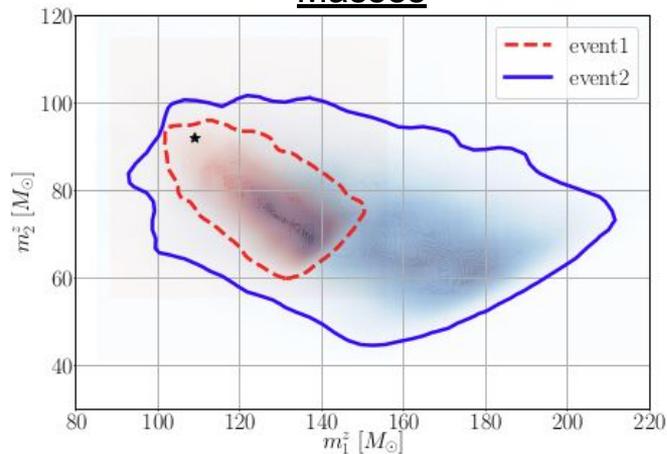
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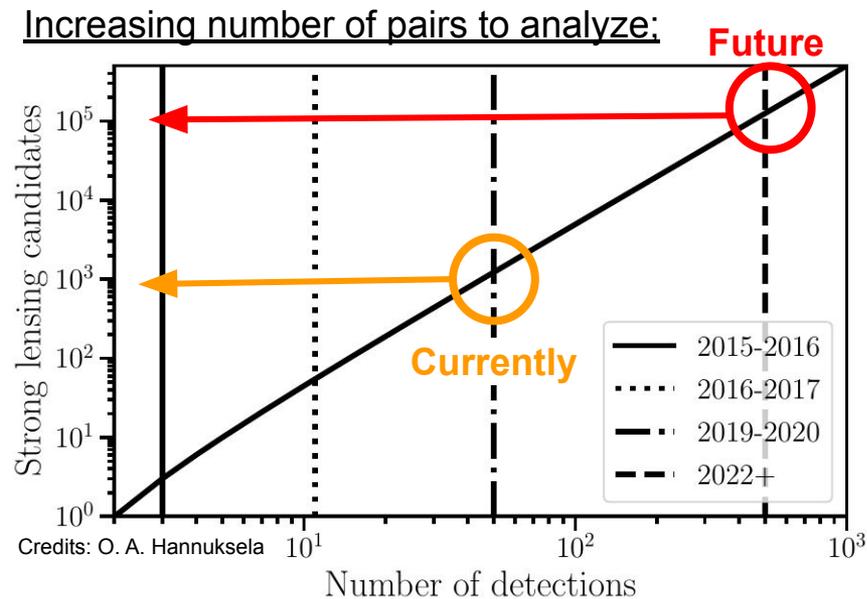


2. The lensing parameters link the distance, time and overall phase shift between the 2 images

Some methods:

- Using only 1. : Checking for consistent parameters (Haris et al 2018): Fast, but lead to many false alarms
- Using 1 and 2: Analyze the data from the images at the same time (Liu et al 2020, Lo & Hernandez 2021): Very precise, but slow, sometimes intractable

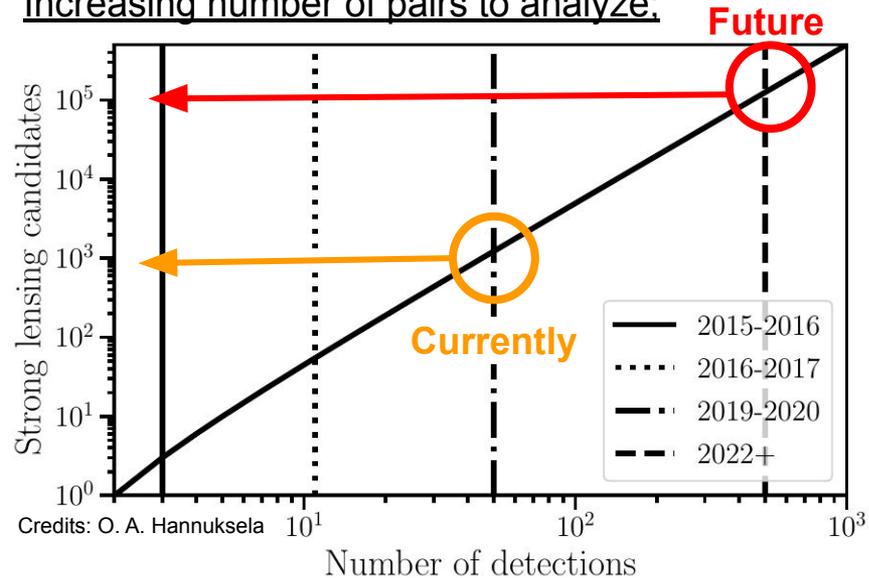
Why introduce a new method?



→ Need to be **fast** to follow the pace but also **precise** to avoid false alarms that require extensive follow ups.

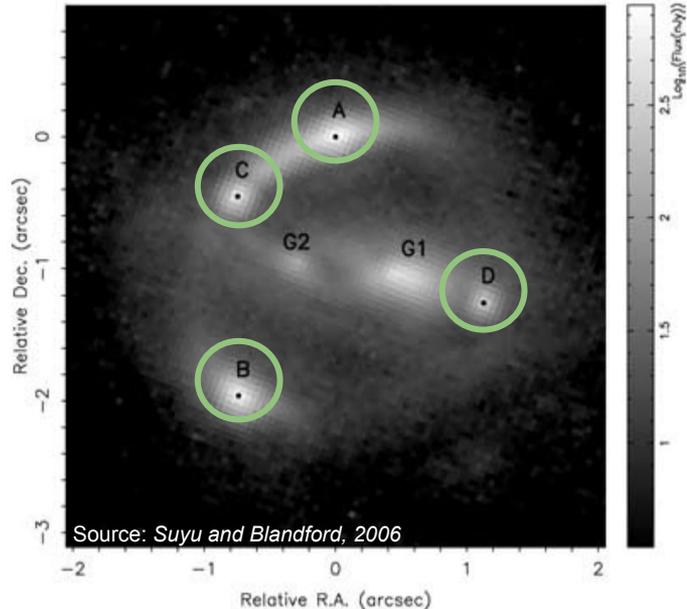
Why introduce a new method?

Increasing number of pairs to analyze:



→ Need to be **fast** to follow the pace but also **precise** to avoid false alarms that require extensive follow ups.

Joint analysis of multiple images:



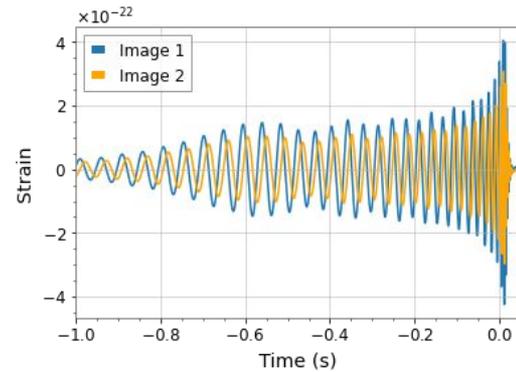
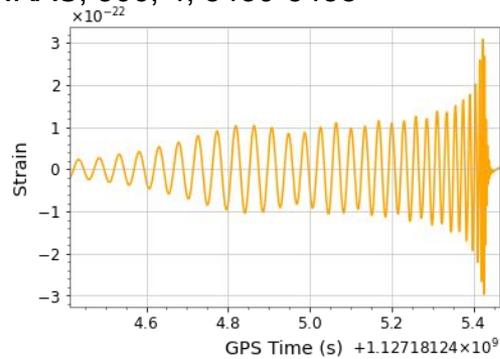
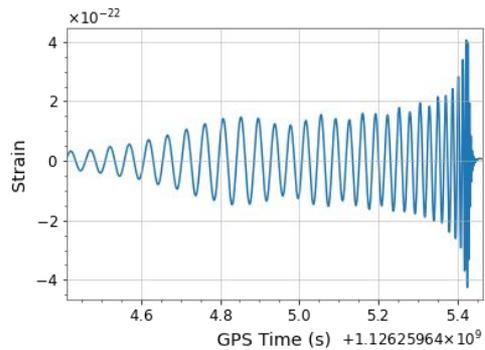
→ Prohibitively computationally expensive for joint analyses of four images

Study of science cases for strong lensing:

This often require the analysis of many (simulated or not) events and can be difficult to perform when having to analyze all images jointly.

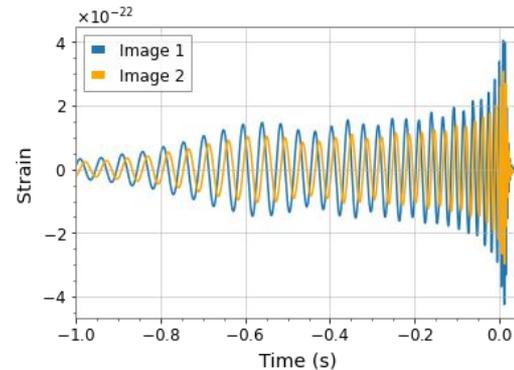
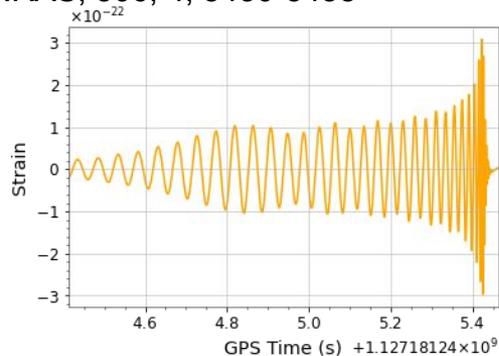
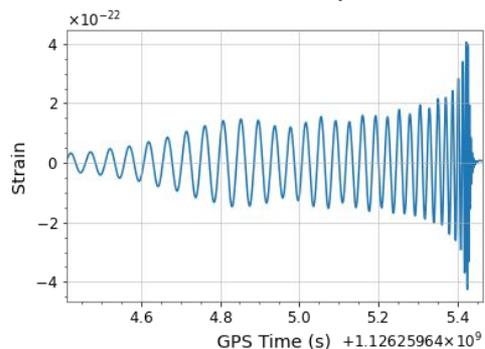
Our approach to search for strong lensing

Detailed method in Janquart et al, 2021a, MNRAS, 506, 4, 5430-5438



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Detailed method in Janquart et al, 2021a, MNRAS, 506, 4, 5430-5438



Our method

GOLUM:
Gravitational-wave analysis Of
Lensed and
Unlensed
waveform
Models



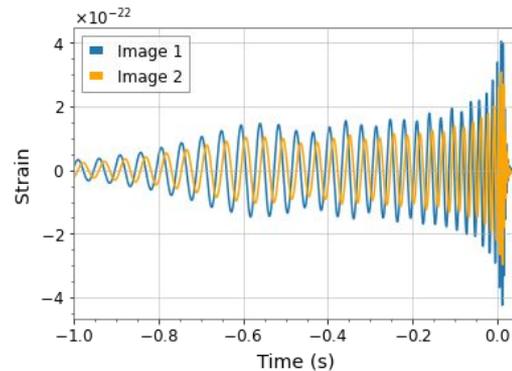
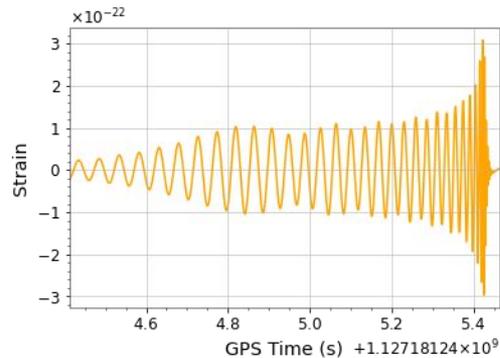
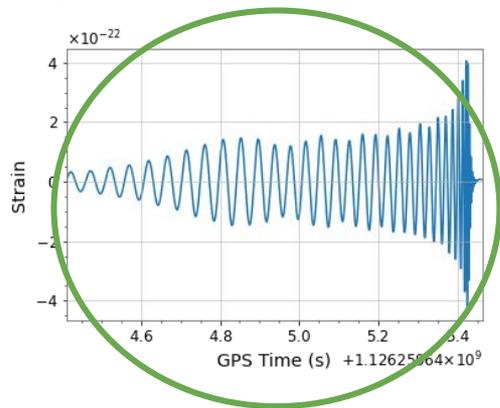
Main idea:

Distribute the runs instead of analyzing them jointly

Process:

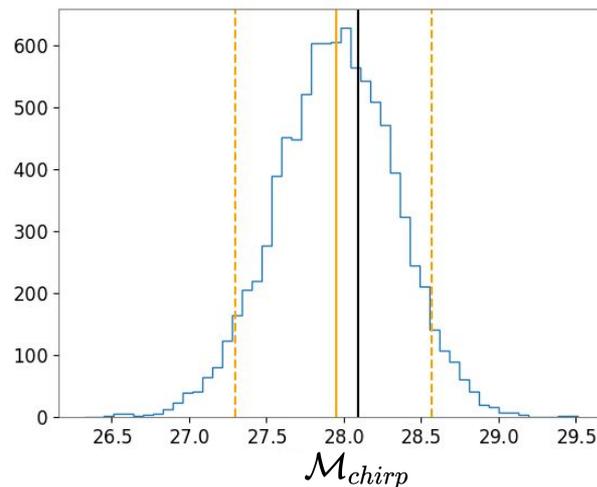
- 1) Analyze the first image
- 2) Use the posterior samples from 1) to analyze the next image
- 3) Reweigh the samples to account for lensing in all the parameters

A journey with GOLUM:

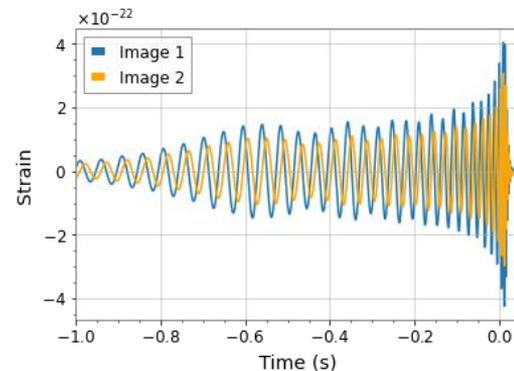
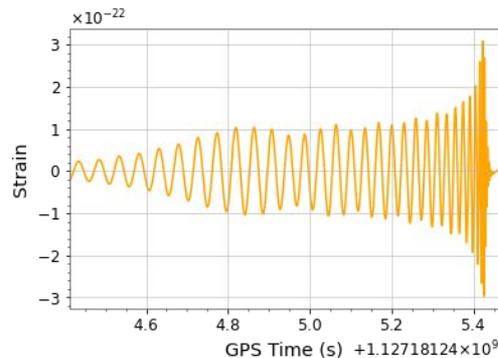
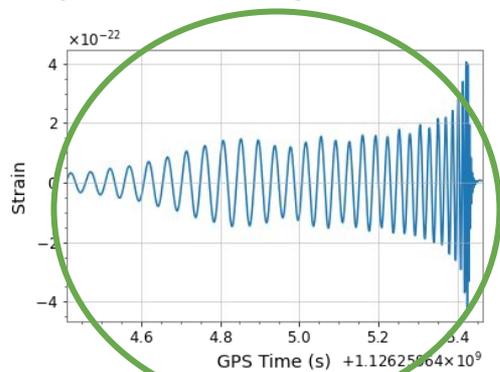


Analyze the first image

Done with usual GW
techniques and lensed
waveform
Time: \sim day(s)

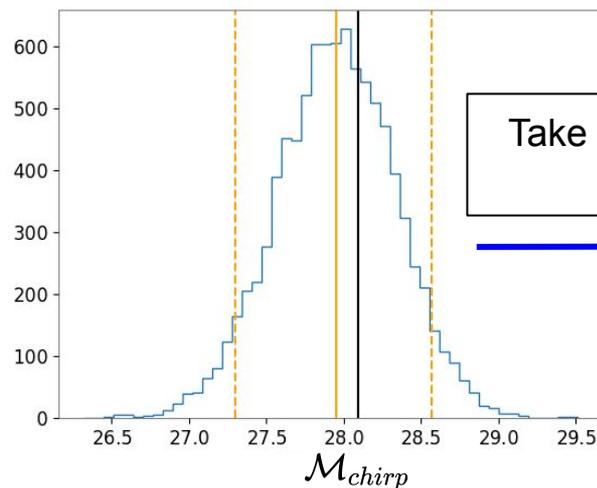


A journey with GOLUM:

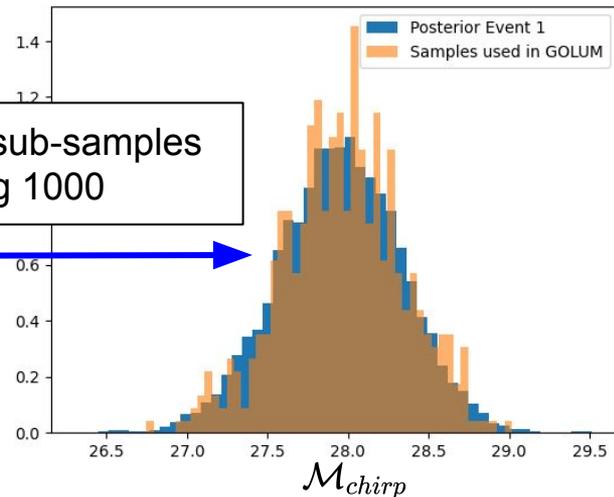


Analyze the first image

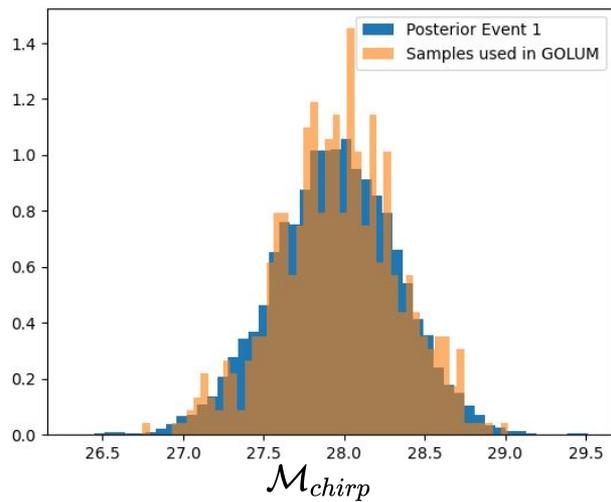
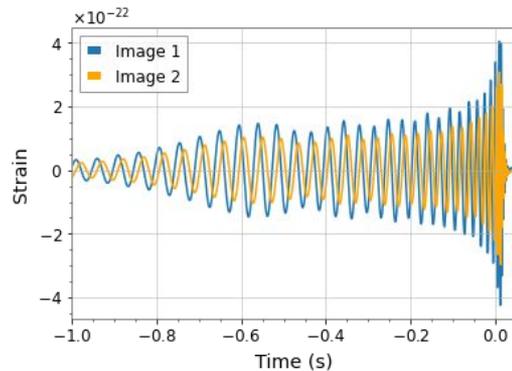
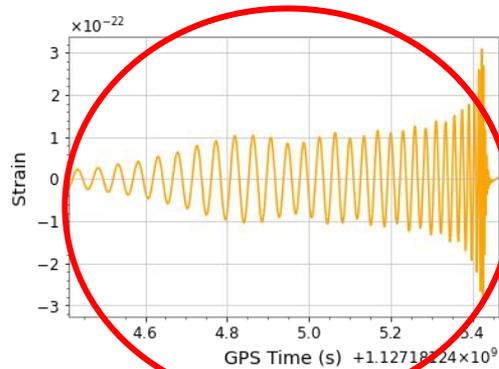
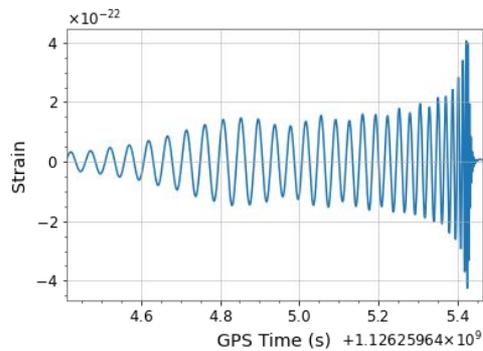
Done with usual GW techniques and lensed waveform
Time: \sim day(s)



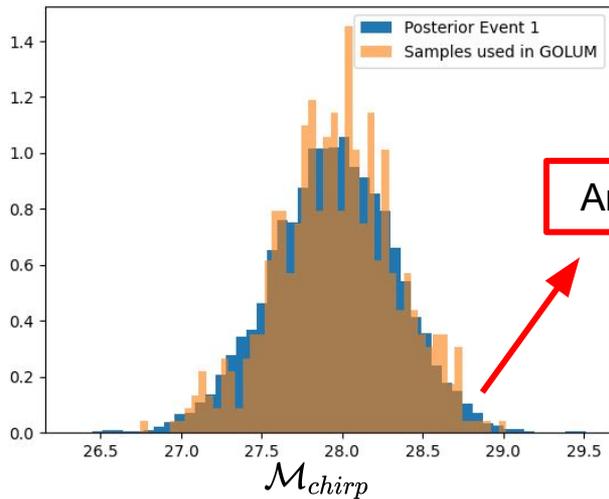
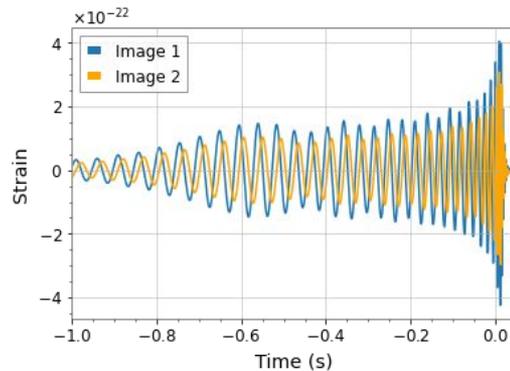
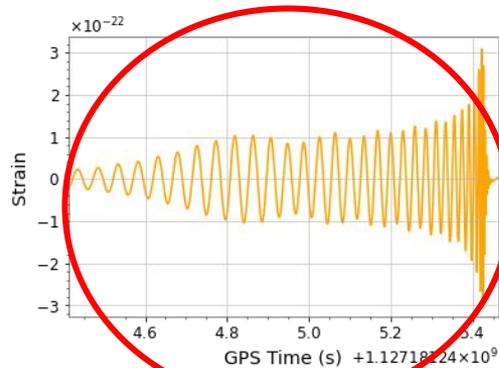
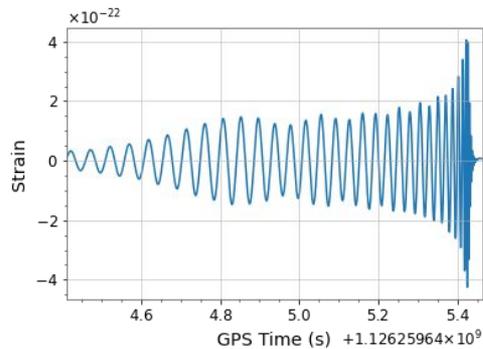
Take N sub-samples
e.g 1000



A journey with GOLUM:



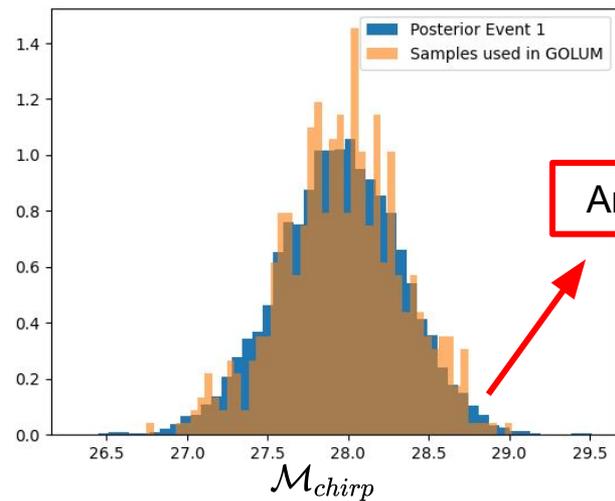
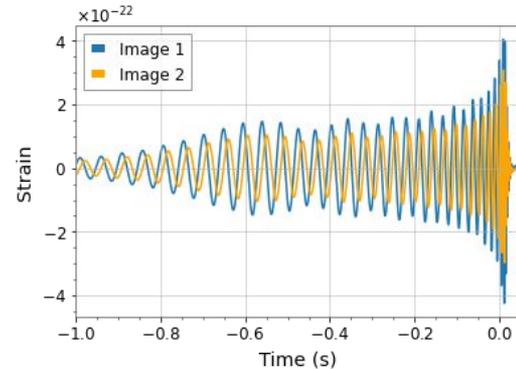
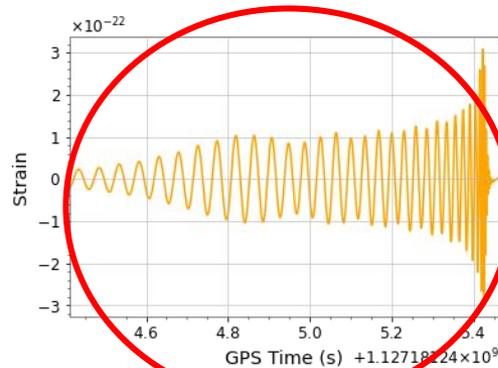
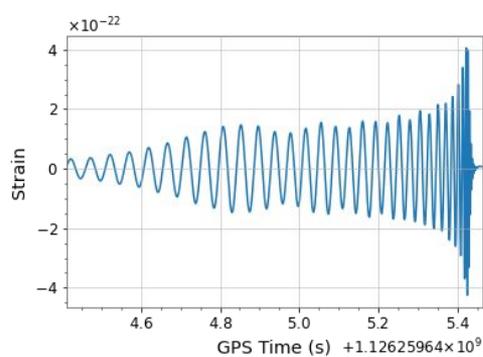
A journey with GOLUM:



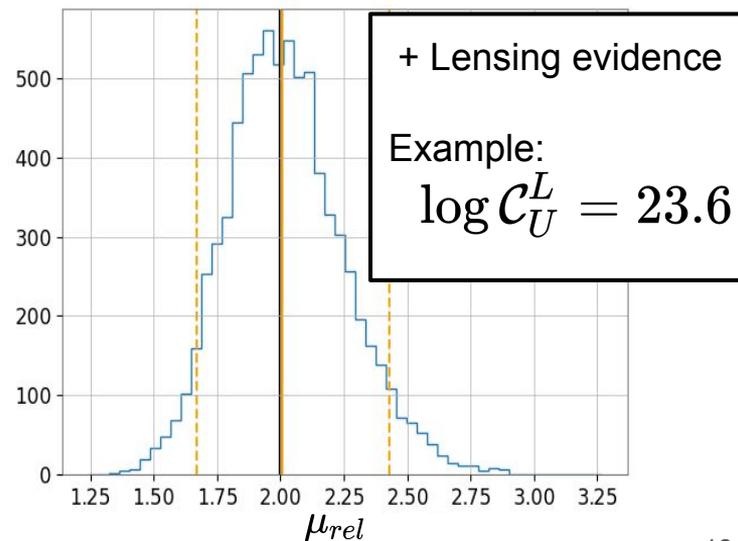
Analyze second image

Done with conditional likelihood
+ speed-up via a look-up table
Time: ~ 30 min

A journey with GOLUM:



Analyze second image



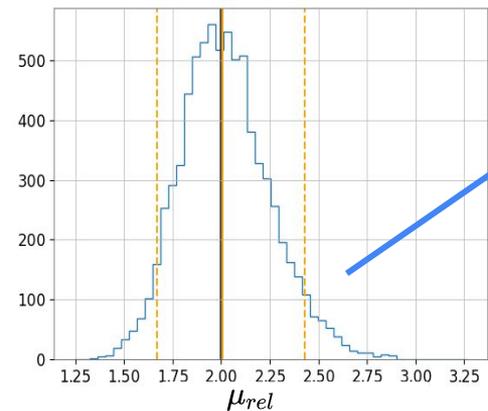
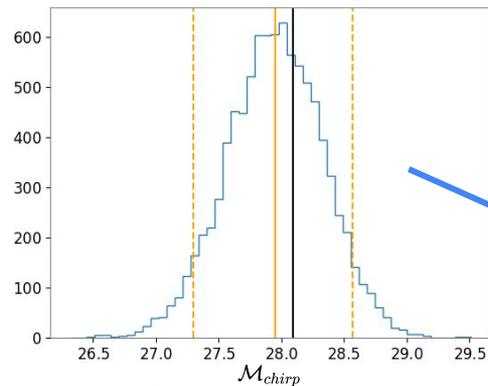
A journey with GOLUM:

At this stage: we **know it is lensed**, but we have **parameters for the first image** and the **lensing parameters**.

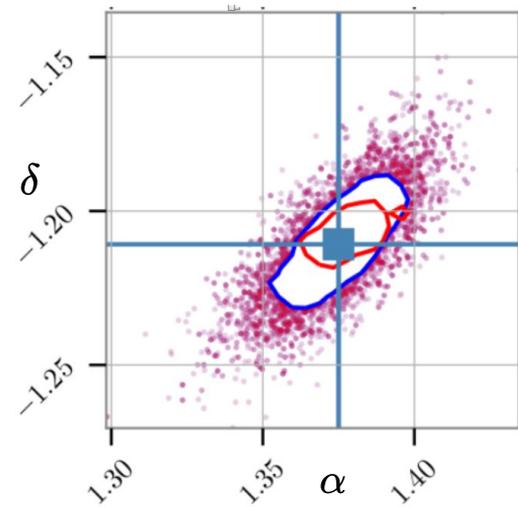
→ Need to have the **joint parameters** to get the enhanced constraints on the binaries' parameters.

Can be done with reweighing in post-processing.

Time ~ 5 min



Reweighting,
combining the
information of the
two images

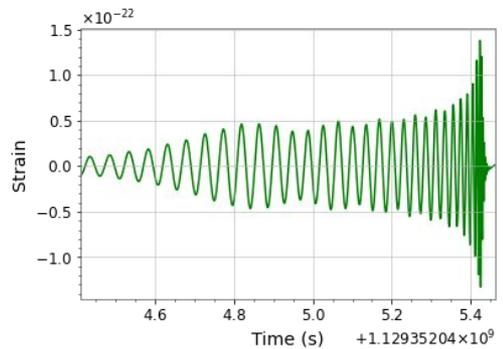
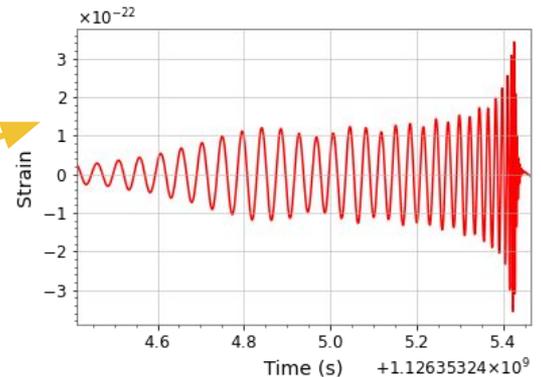
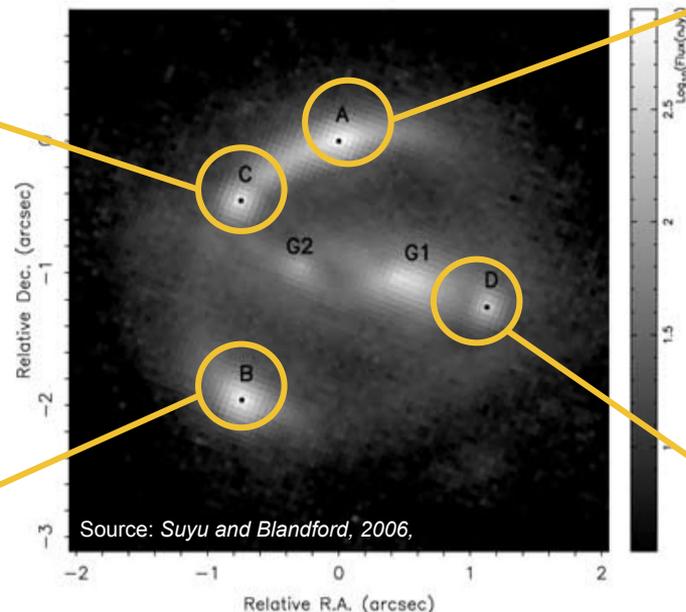
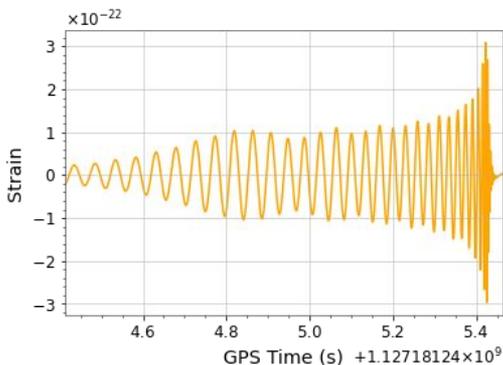
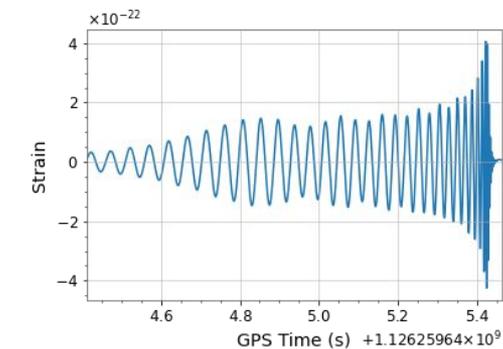


Sky area is ~ halved
with 2 images

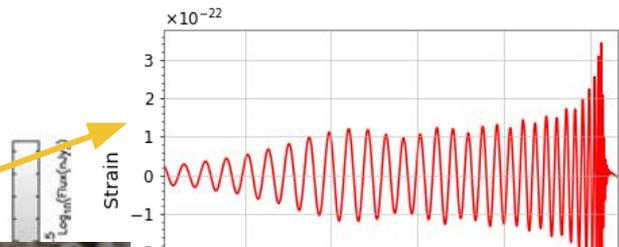
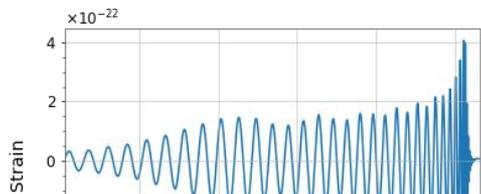
The final information is the same as for the joint analysis of the images, except that this takes the time of a usual single event analysis

And if quadruplet?

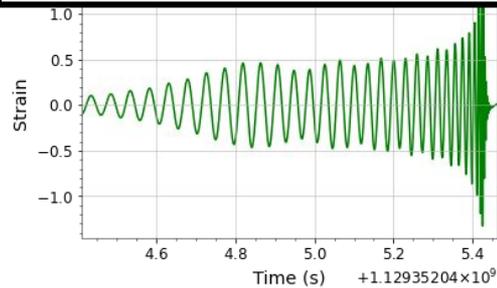
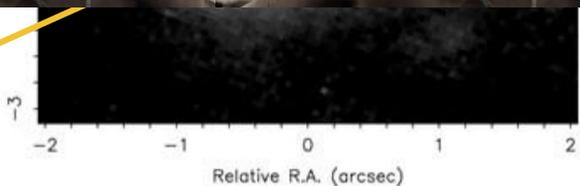
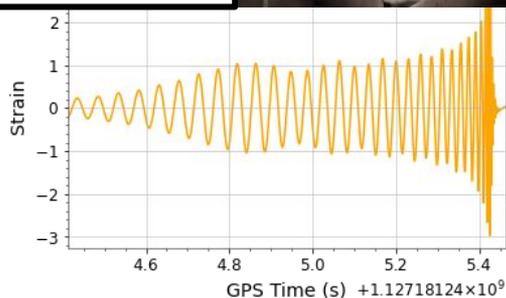
Are these linked?
Location host galaxy of the BBH?
Lens?



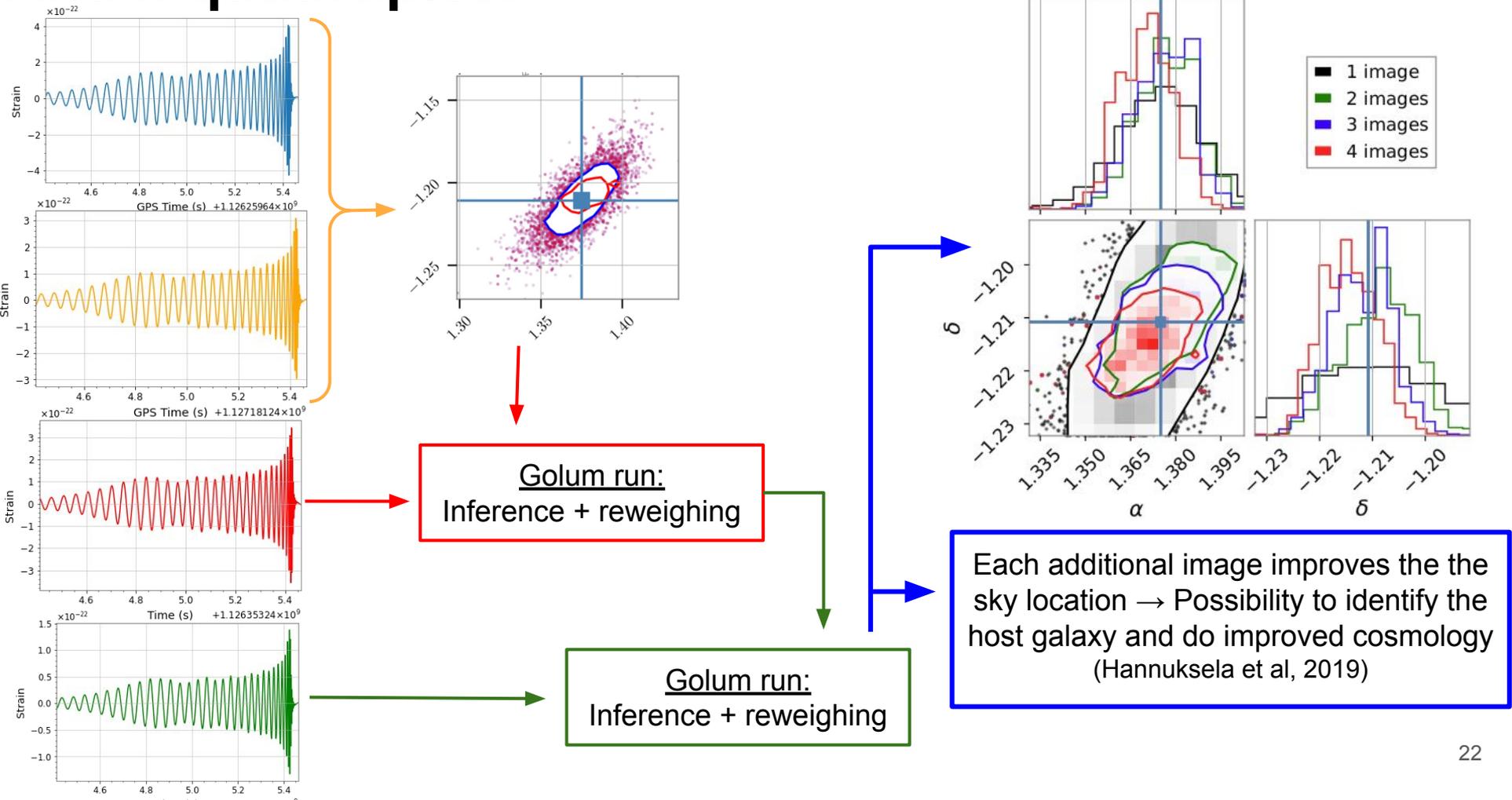
And if quadruplet?



For image i , sample from the reweighted samples obtained for the $(i-1)^{th}$ image.
After first image, each additional image is ~ 35 min



And if quadruplet?



Conclusions and outlooks:

Strong lensing is **upon us** and give some **interesting prospects**.

Our GOLUM approach is fast while remaining precise.

- Enables **future strong lensing studies**, when massive amount of data has to be analyzed
- Enables to do more **extensive injection studies**, leading to a **better understanding of strong lensing**
- Makes **multiple-image analyses** studies possible



We would be happy to answer any questions.