

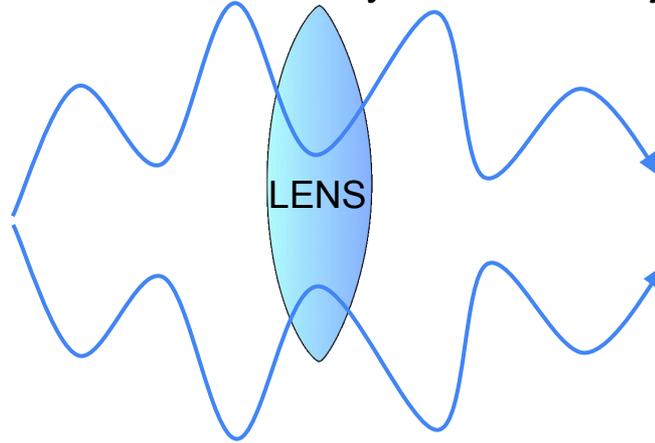
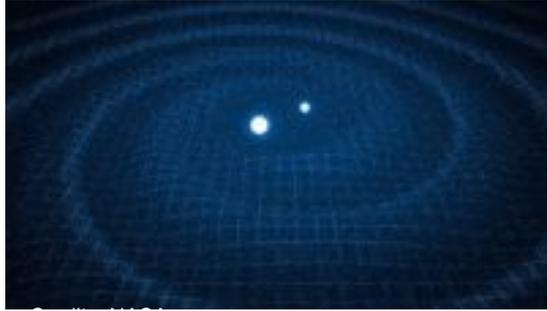
On the identification of strongly-lensed gravitational-waves

J.Janquart*, O.A. Hannuksela, K. Haris, T.G.F. Li, A. Moore, E. Seo, C. Van Den Broeck



What is GW lensing?

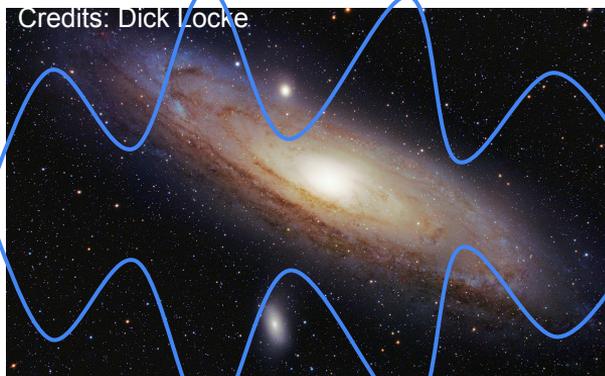
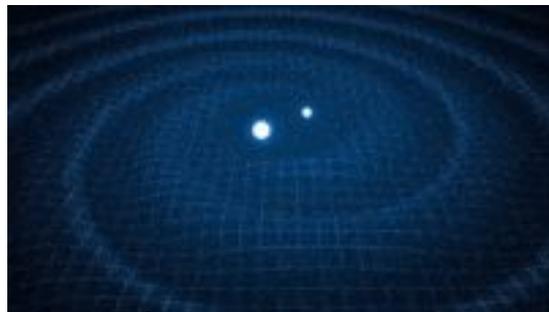
Same principle as for light: the wave is deflected by a massive object along its path



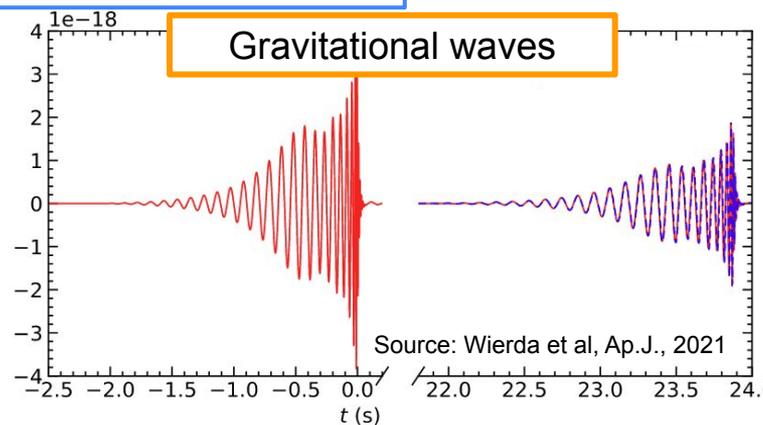
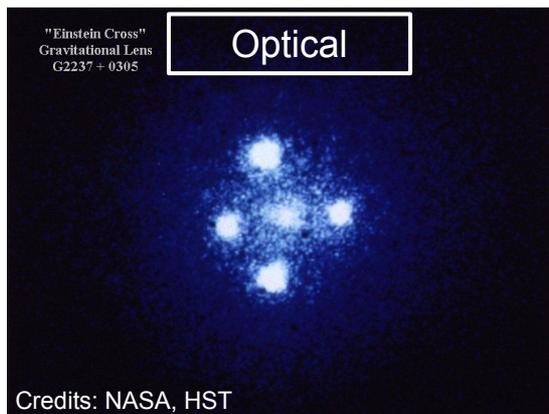
Different lens properties → Different effect on the GW

What is GW lensing?

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

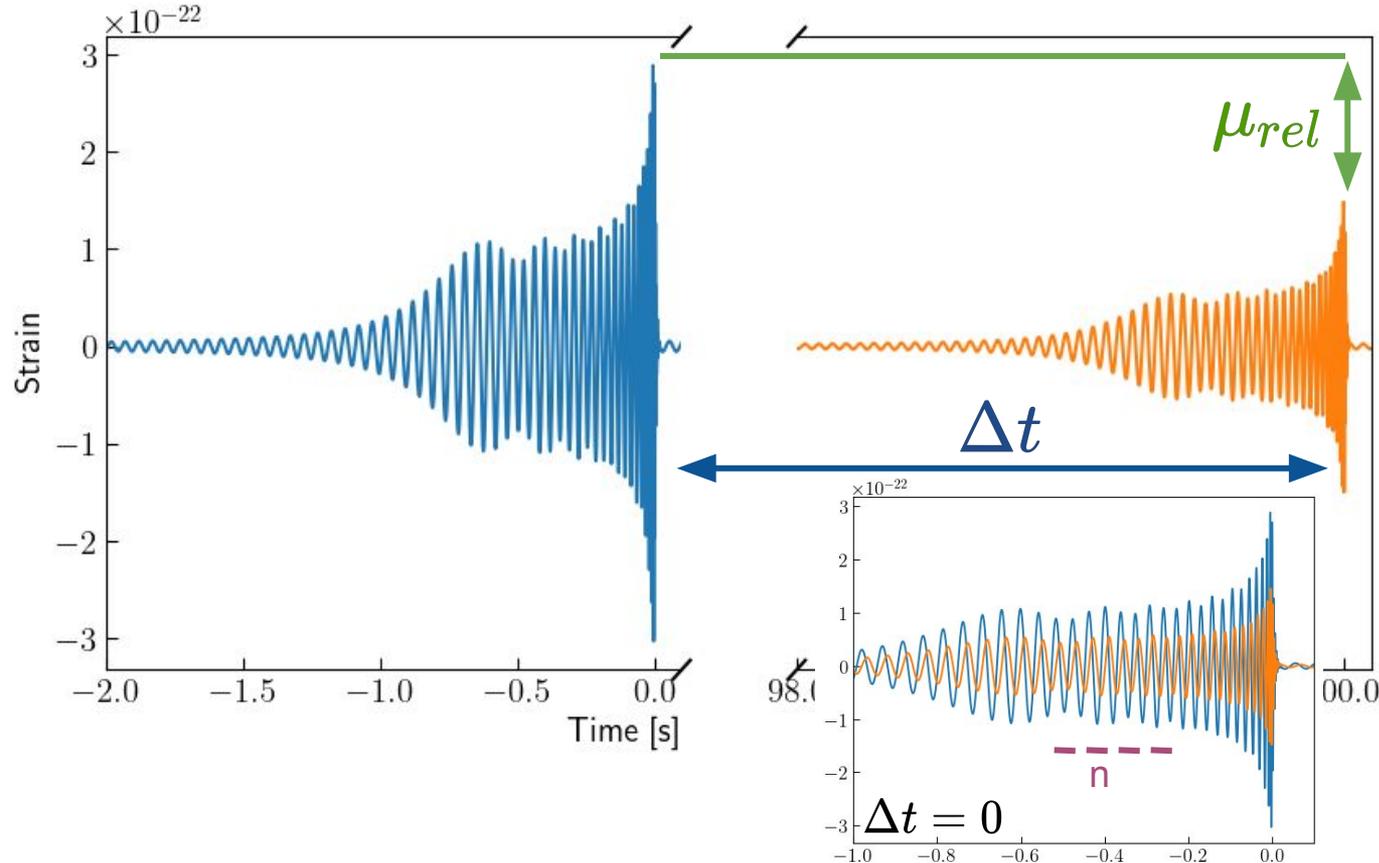


High mass lens (galaxy, galaxy cluster) → **Strong lensing**



What is 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.

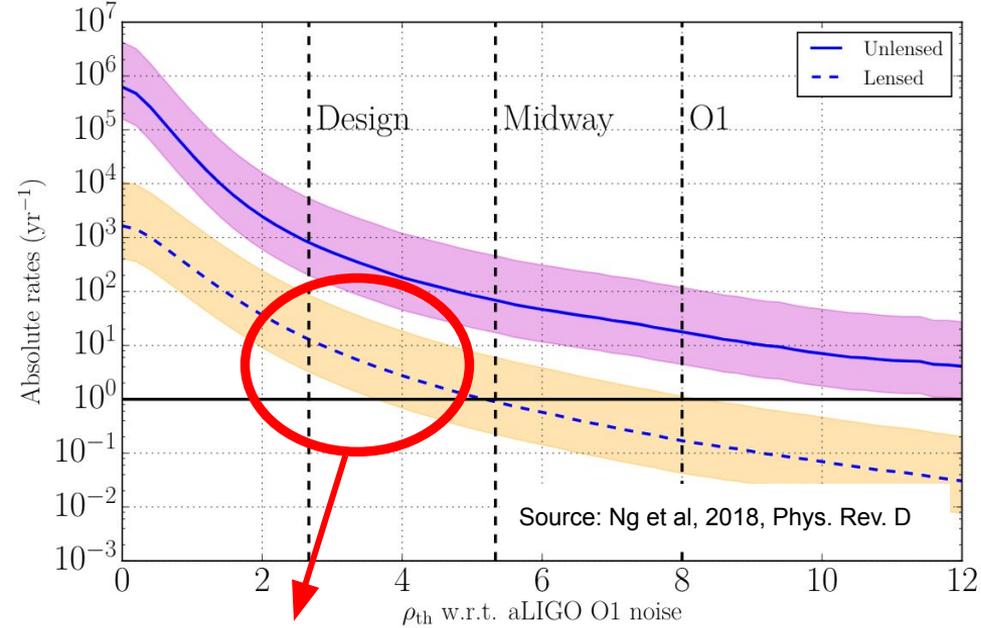


Differences between images:

- **Time delay:** waves take a different path \rightarrow different time of arrival
- **Relative magnification:** links the change in amplitude between the two waves
- **Morse phase:** each wave undergoes a global phase shift. Depending on the image position, we can get

$$n = \left\{ 0, \frac{\pi}{2}, \pi \right\}$$

Why care about strong lensing?

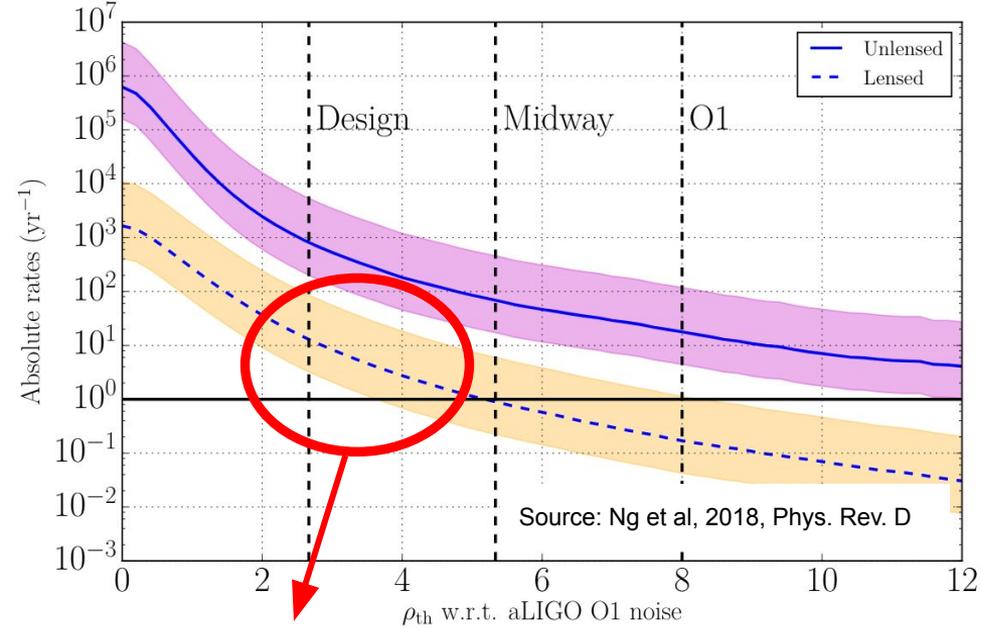


Improved detector sensitivity

↳ Increased rate

↳ Could be detected soon

Why care about strong lensing?



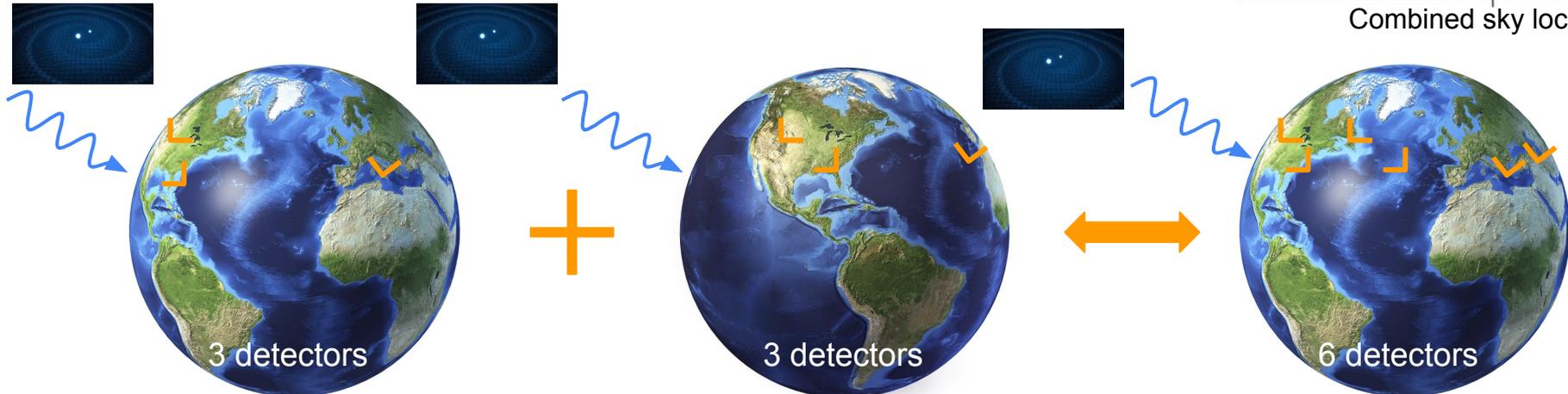
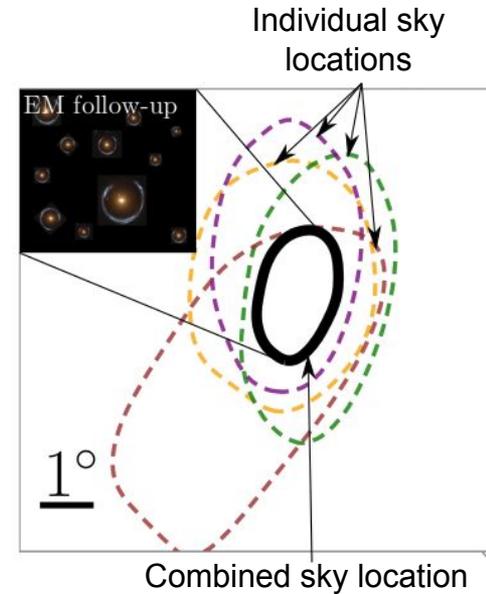
Searches already ongoing!
(GWTC-2 : [Hannuksela et al, 2019](#);
GWTC-2.1 : [LVK, ApJ., 2021](#))

Improved detector sensitivity
↳ Increased rate
↳ Could be detected soon

Why care about strong lensing?

Some interesting science cases (non-exhaustive):

- Origin of black holes ([Hannuksela et. al. 2020](#))
- Expansion of the Universe ([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](#))

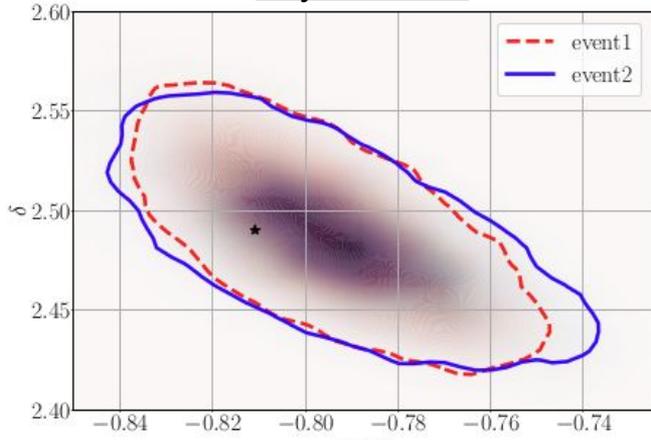


How do we search for strong lensing?

Two strongly lensed signals are dependent:

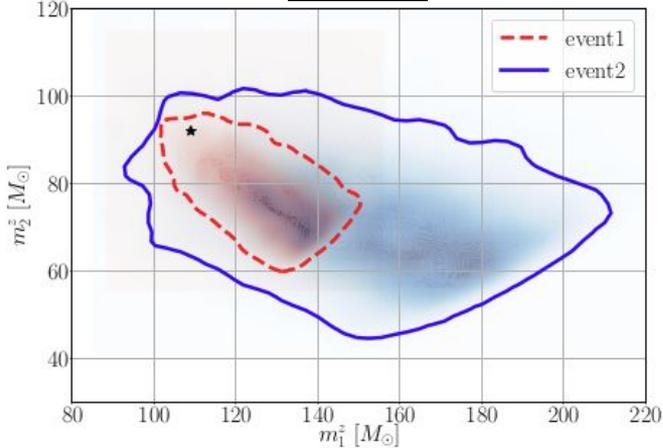
1. The parameters unaffected by lensing should be the same → Compatible probability distributions for these parameters

Sky location:



Source: Haris et al, 2018

Masses:



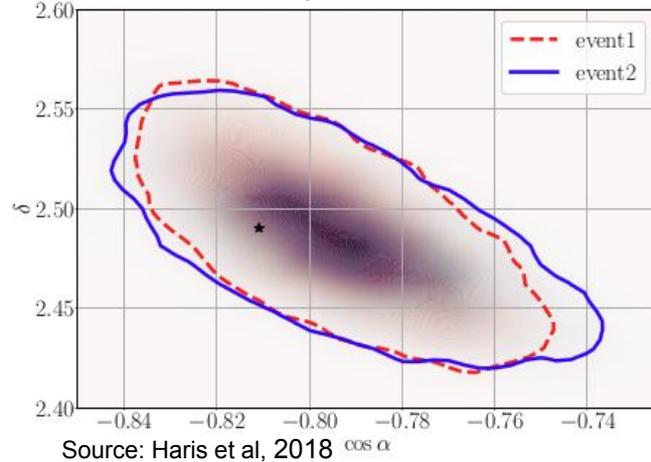
2. The lensing parameters link the distance, time and overall phase shift between the 2 images

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Two strongly lensed signals are dependent:

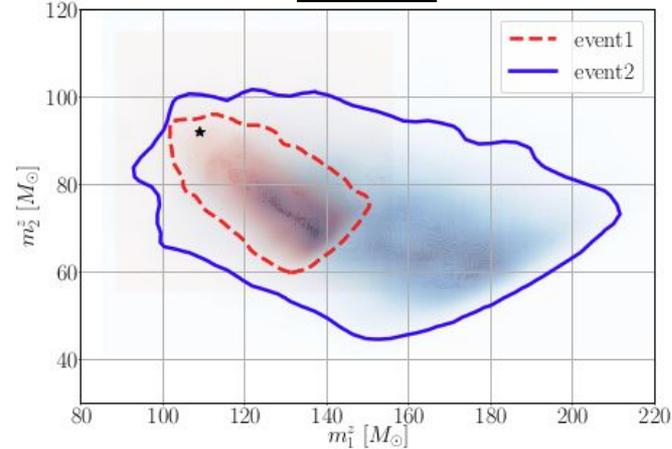
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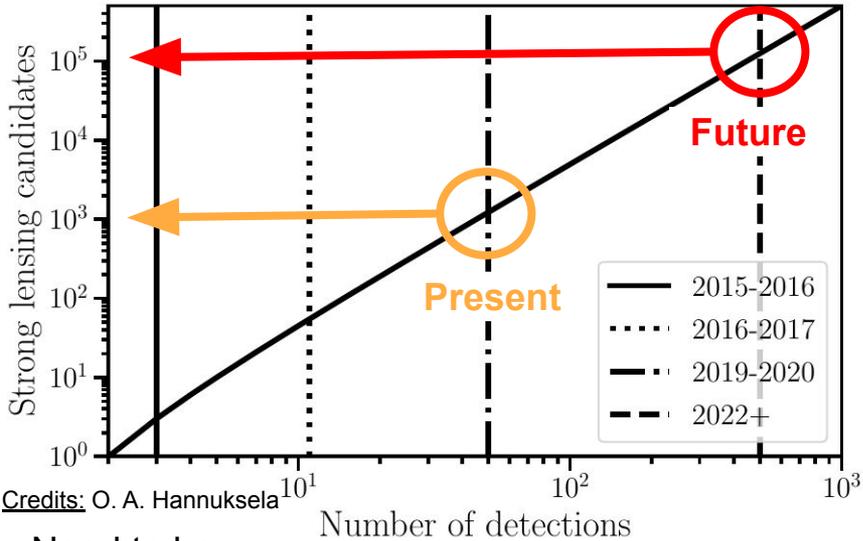
2. The lensing parameters link the distance, time and overall phase shift between the 2 images

Some methods:

- Using only 1: Checking for consistent parameters ([Haris et al, 2018](#)): Fast, but leads 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
- Other: Using machine learning ([Goyal et al. 2021](#); Only for detection)

What are possible issues for these methods?

Increasing number of pairs to analyze:



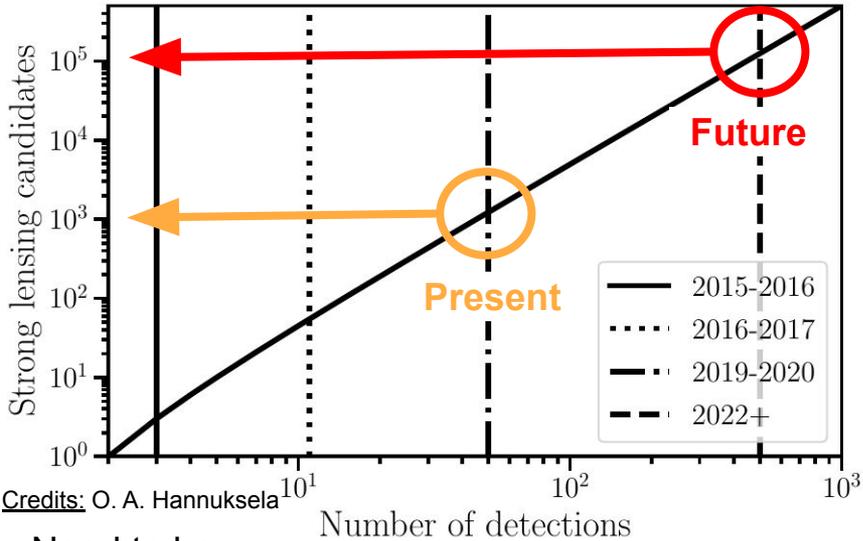
Credits: O. A. Hannuksela

Need to be:

- **FAST** → follow the detection rate
- **PRECISE** → Avoid false alarms leading to expensive follow-up studies

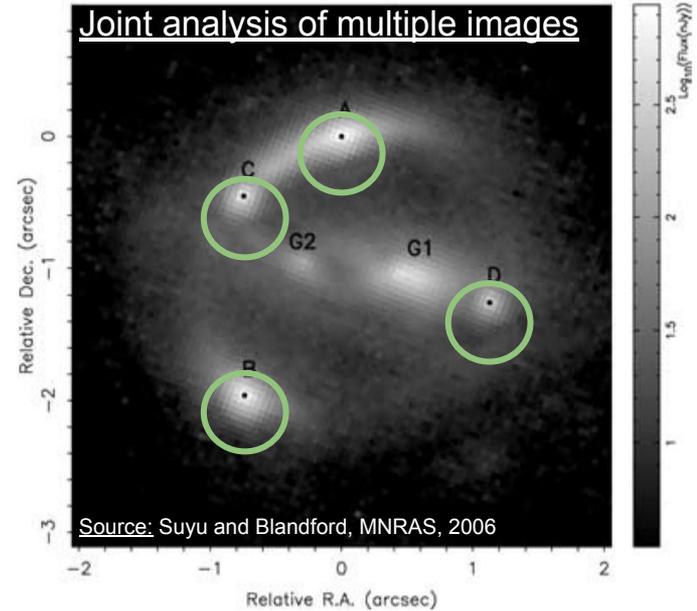
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Increasing number of pairs to analyze:



Need to be:

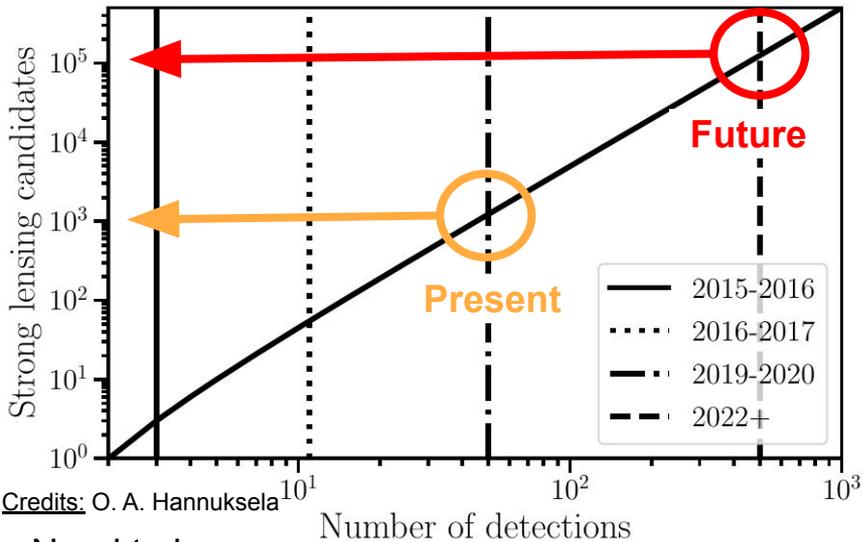
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→ Prohibitively **computationally expensive** for joint analyses of four images

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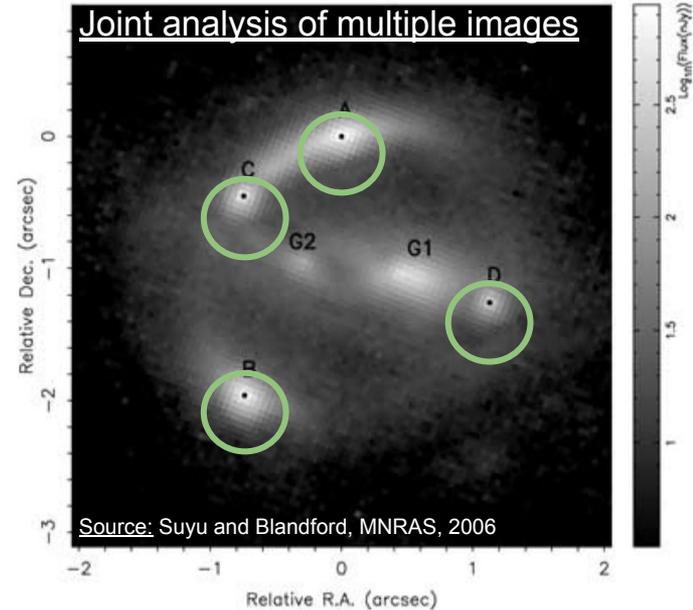


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Need to be:

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Joint analysis of multiple images



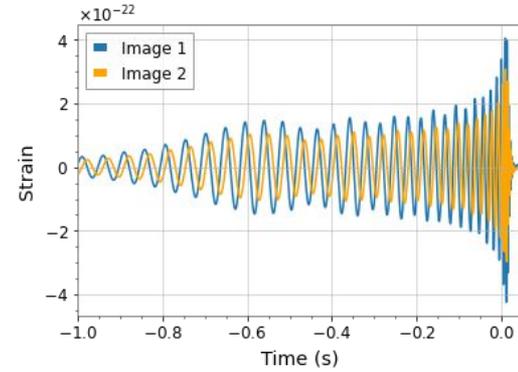
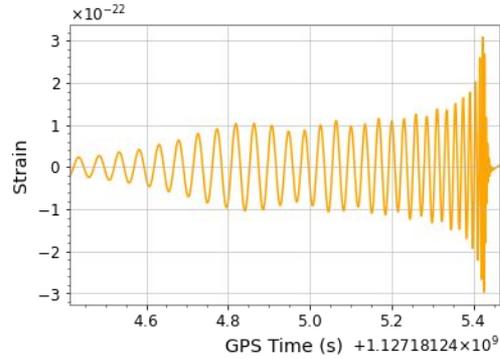
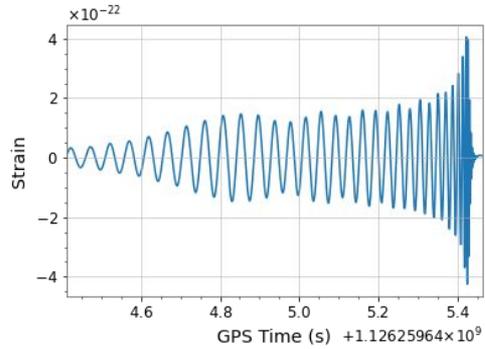
→ Prohibitively **computationally expensive** for joint analyses of four images

Science cases for strong lensing:

- Requires often the analysis of **many event pairs**
 - Often asks for the **joint information** between images
- } Difficult for joint analysis

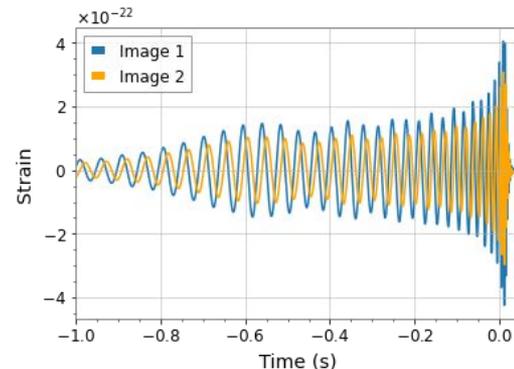
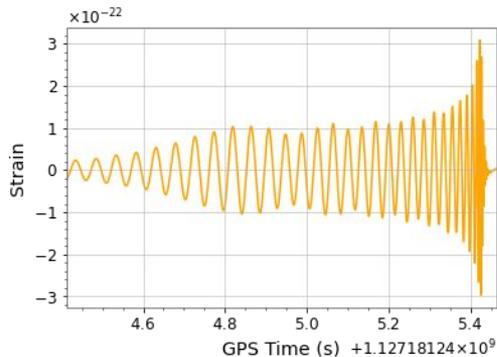
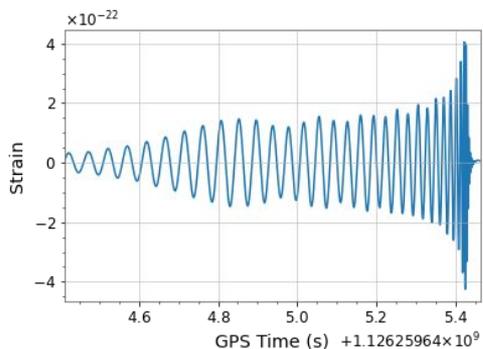
GOLUM to the rescue!

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



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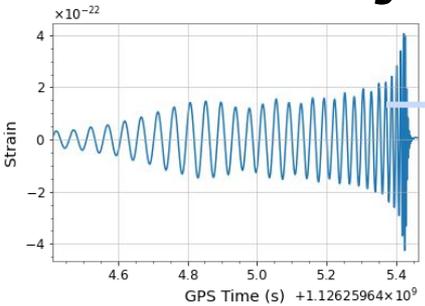


GOLUM:
Gravitational-wave analysis Of
Lensed and
Unlensed
waveform
Models

Process:

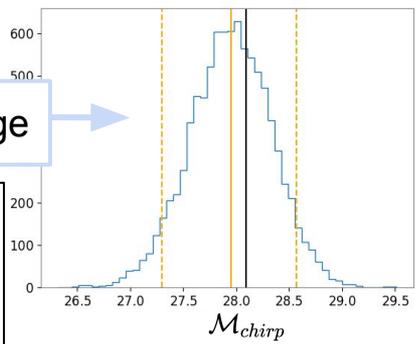
- 1) Analyze the first image
- 2) Use the posterior samples from 1) to analyze the next image
- 3) Reweight the samples to account for lensing in all the parameters

GOLUM's journey

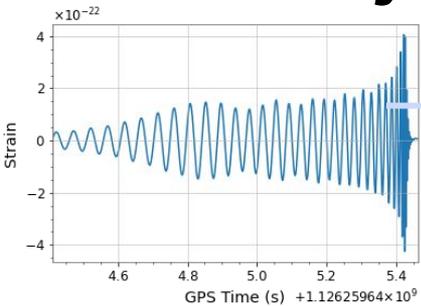


1) Analyze first image

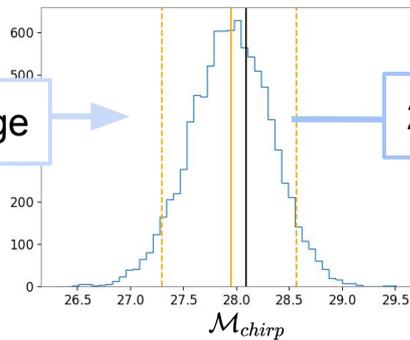
Done with usual
GW techniques
and lensed
waveform
Computational
time: ~ day(s)



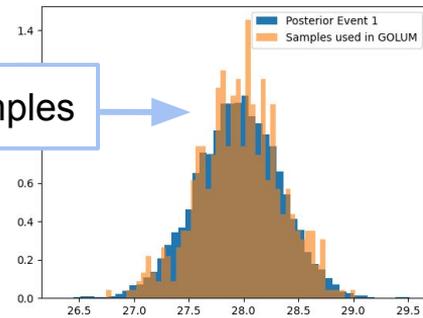
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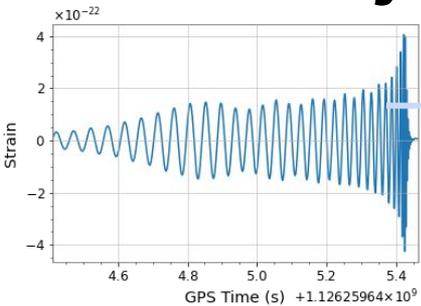
1) Analyze first image



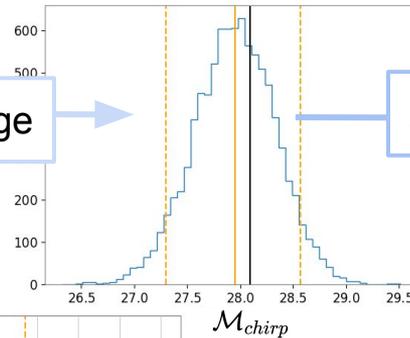
2) Take N sub-samples



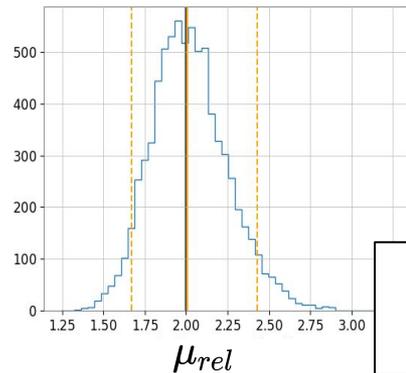
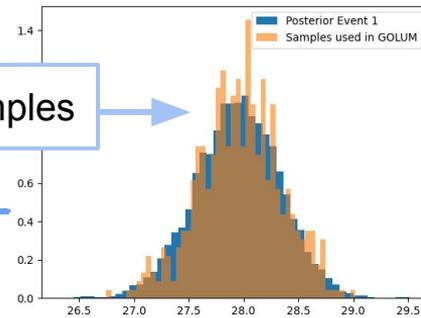
GOLUM's journey



1) Analyze first image

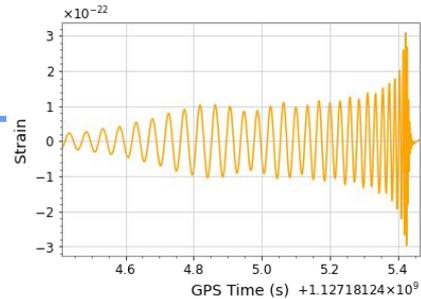


2) Take N sub-samples

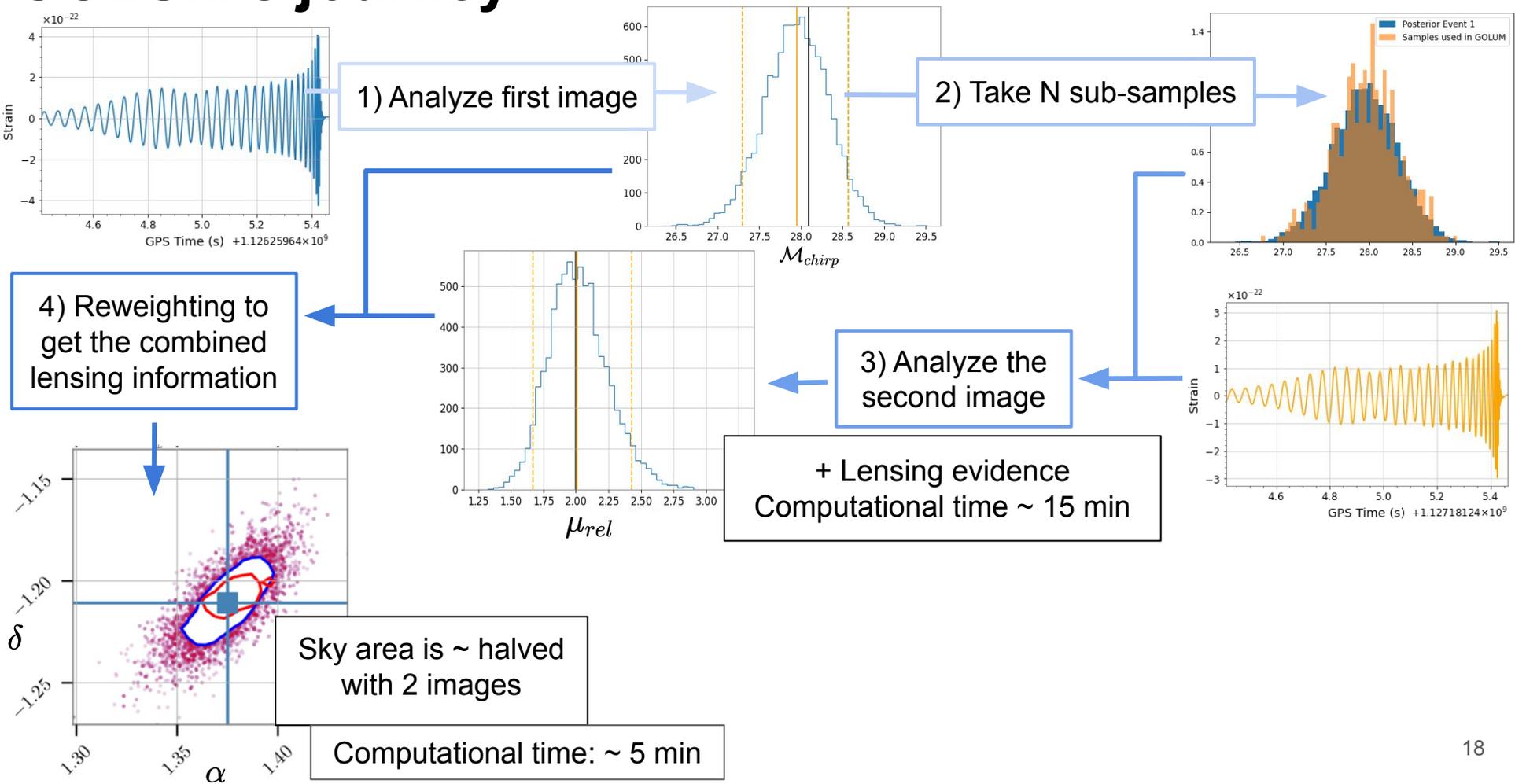


3) Analyze the second image

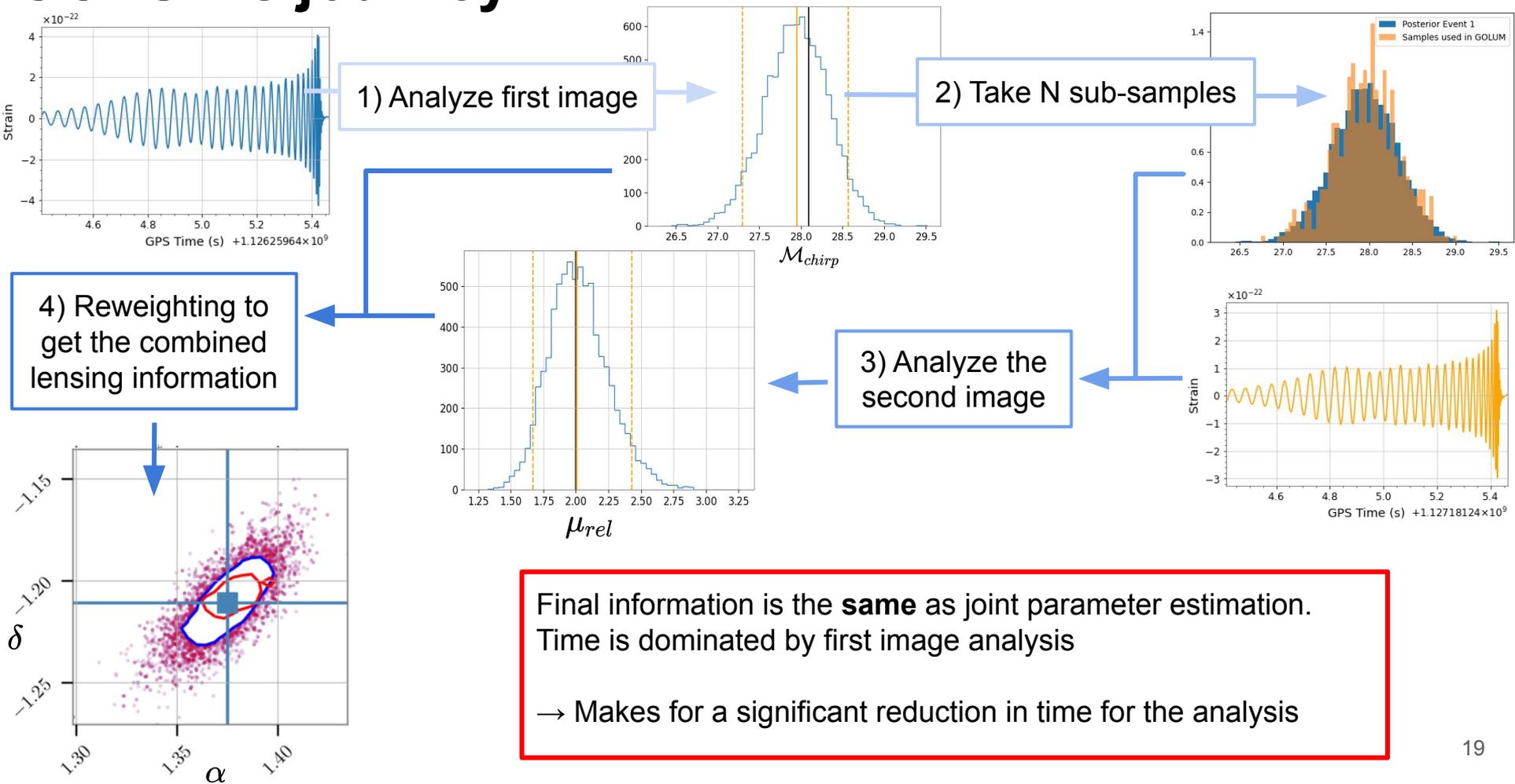
+ Lensing evidence
Computational time ~ 15 min



GOLUM's journey

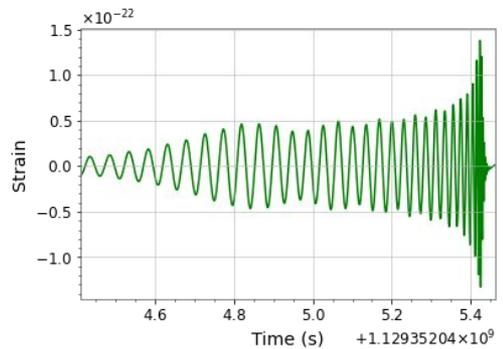
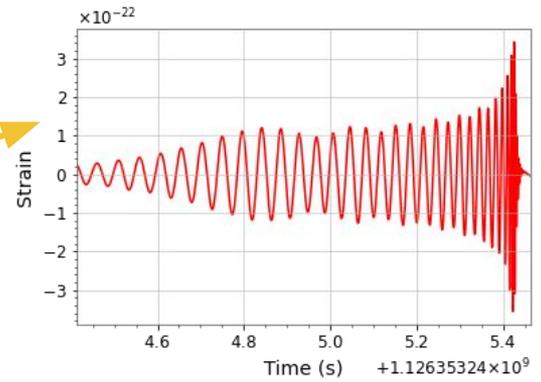
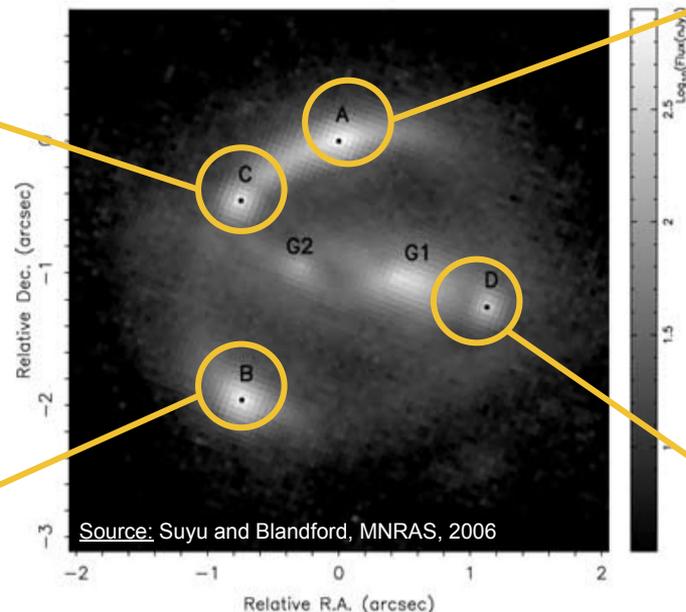
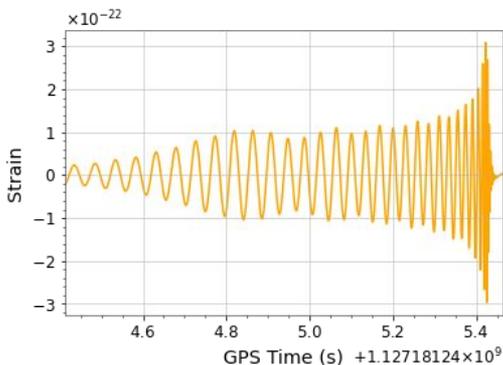
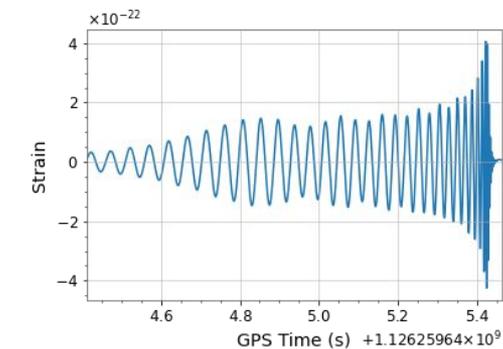


GOLUM's journey

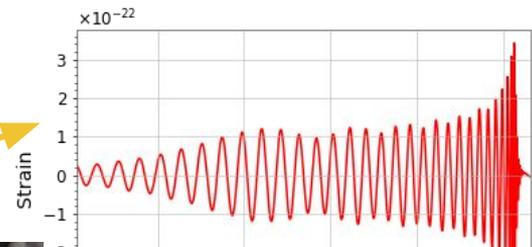
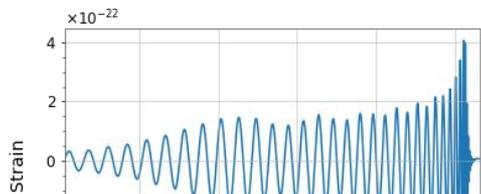


And if quadruplet?

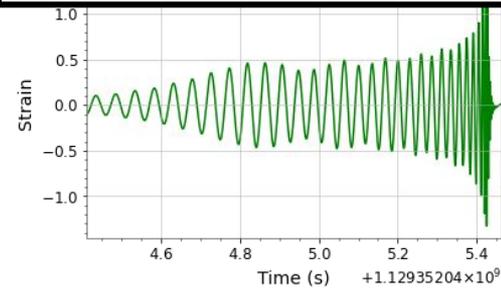
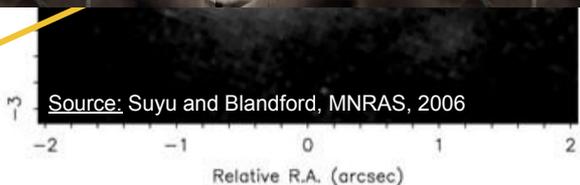
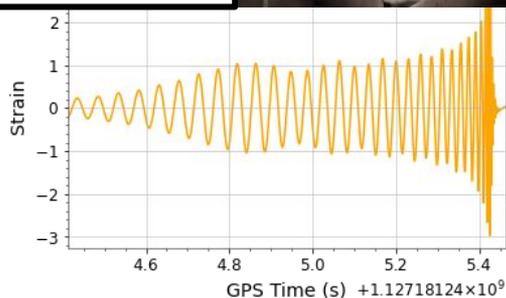
Are these linked?
Location host galaxy of the BBH?
Lens?



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



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 injections**, leading to a **better understanding of strong lensing**,

example in [Janquart et al, 2021](#)

- Makes **multiple-image analyses** studies possible
- Some bottlenecks not treated here:
 - High False Alarm probability:
 - resembling parameters can happen by chance ([Wierda et al 2021](#); [Çalışkan et al, 2022](#); [Janquart et al, 2022](#))
 - Can be reduced using lens models ([Wierda et al 2021](#); [Janquart et al, 2022](#))

Thank you for your attention!
I would be happy to answer any questions (now or later)