GOLUM: A fast and precise methodology to search for strong gravitational wave lensing

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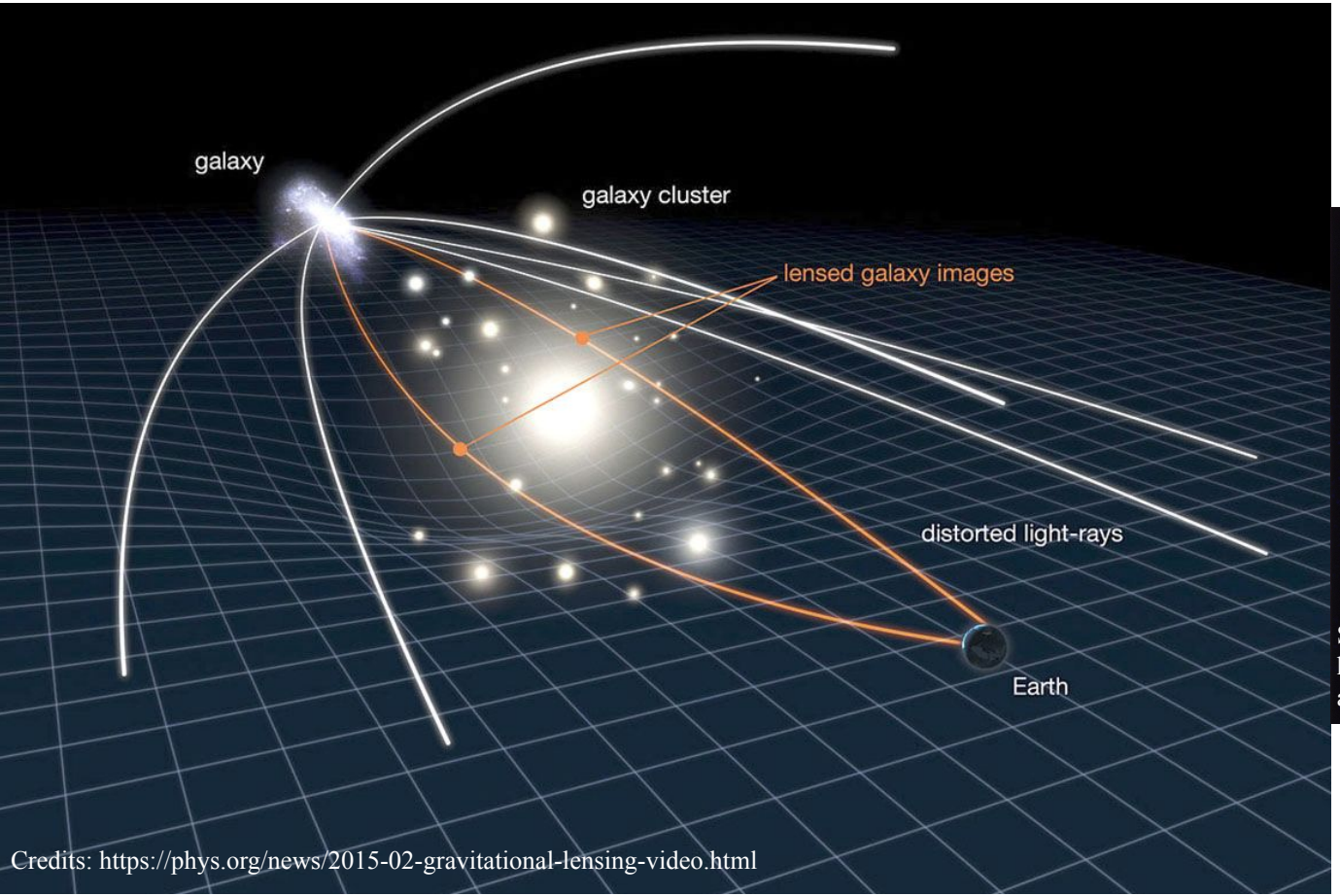
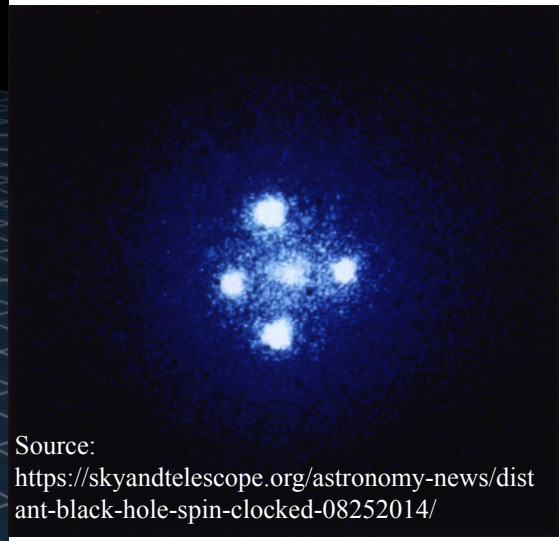
Utrecht University

Nikhef

What is lensing?



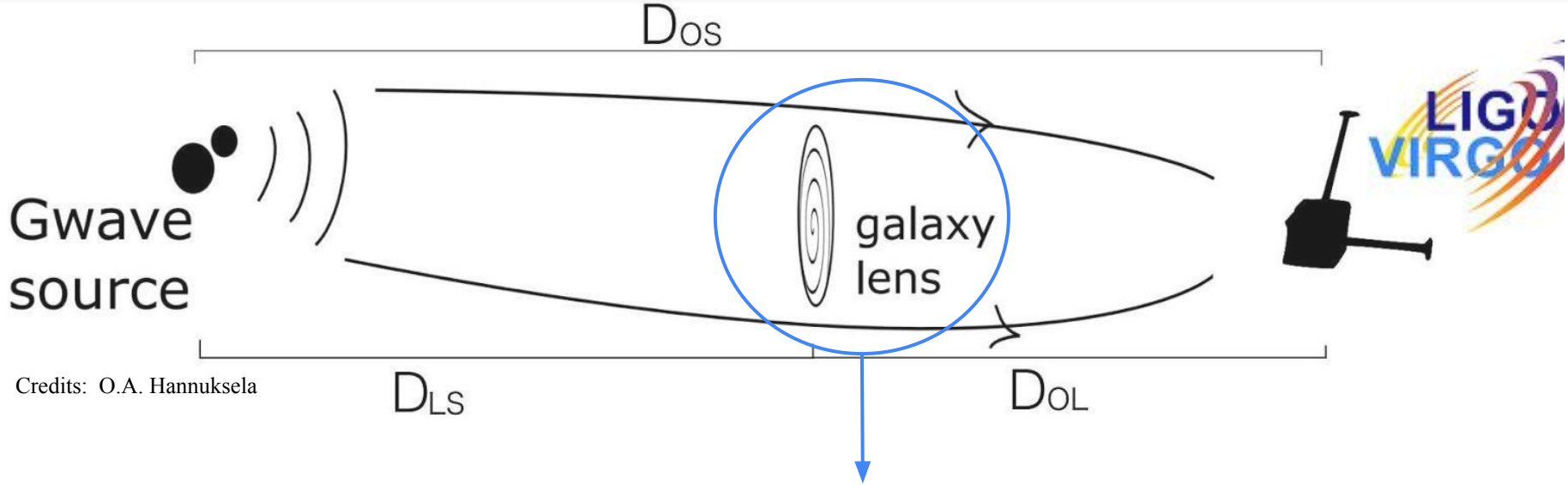
Credits: https://phys.org/news/2015-02-gravitational-lensing-video.html



Source: https://skyandtelescope.org/astronomy-news/distant-black-hole-spin-clocked-08252014/

What is lensing for GW?

→ Same principle as for light

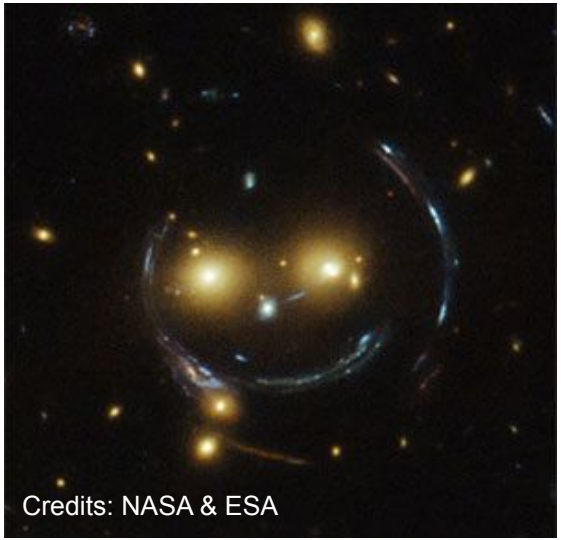


Credits: O.A. Hannuksela

If lens properties change, effects on GW change

What can lensing do?

Strong lensing: Multiple “images”

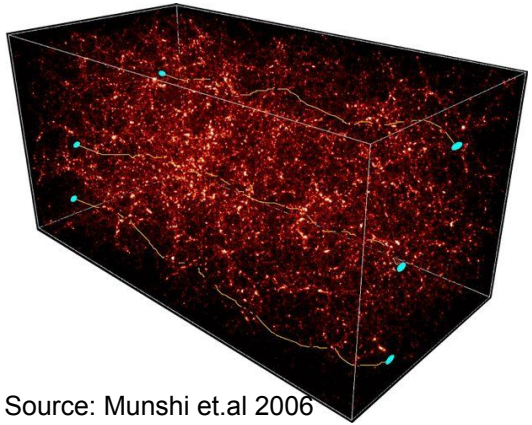


Heavy lenses
Ex: galaxies, galaxy clusters

Weak lensing: one magnified image

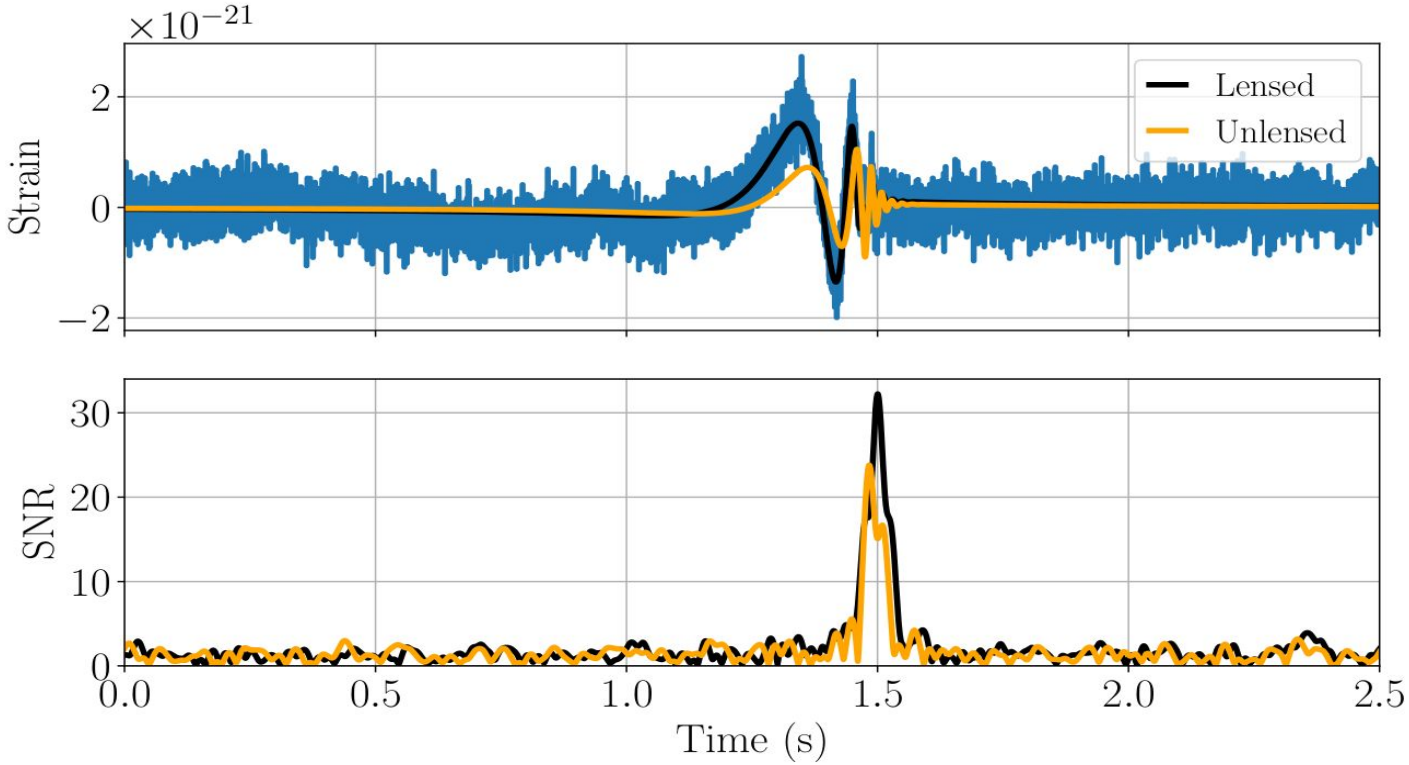
Median lenses
Ex: galaxies, black-holes

Micro-lensing: one distorted image



Any lenses
Ex: black-holes, neutron stars

What happens when a GW passes by a small compact object?



→ Lens characteristics can be studied via the GW distorsion

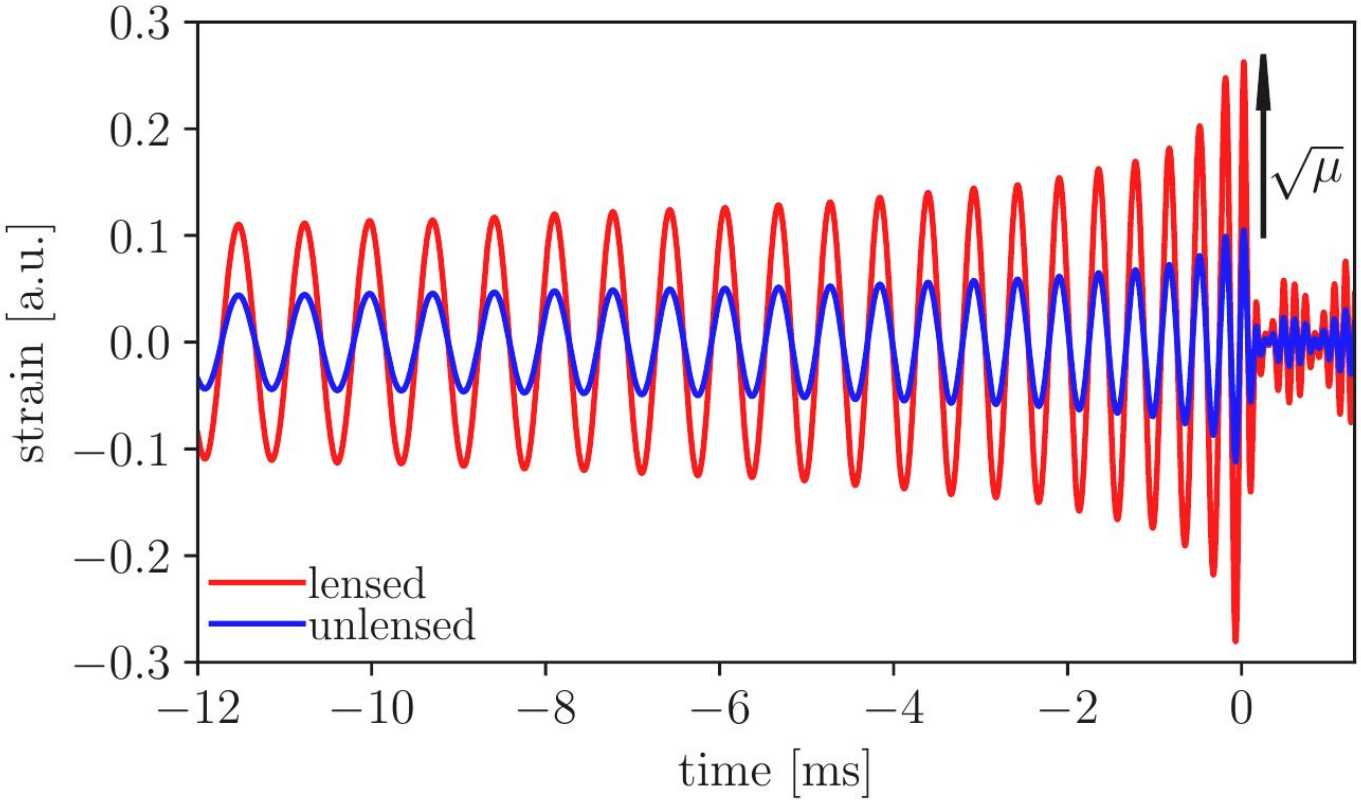
<u>Examples:</u>

- Study of primordial black holes (Jung et al., 2019)
- Detection of intermediate mass black holes (Lai et al., 2017)

Source: *"LensingGW: a Python package for lensing of gravitational waves"*, Pagano et. al

What happens when a GW is weakly lensed?

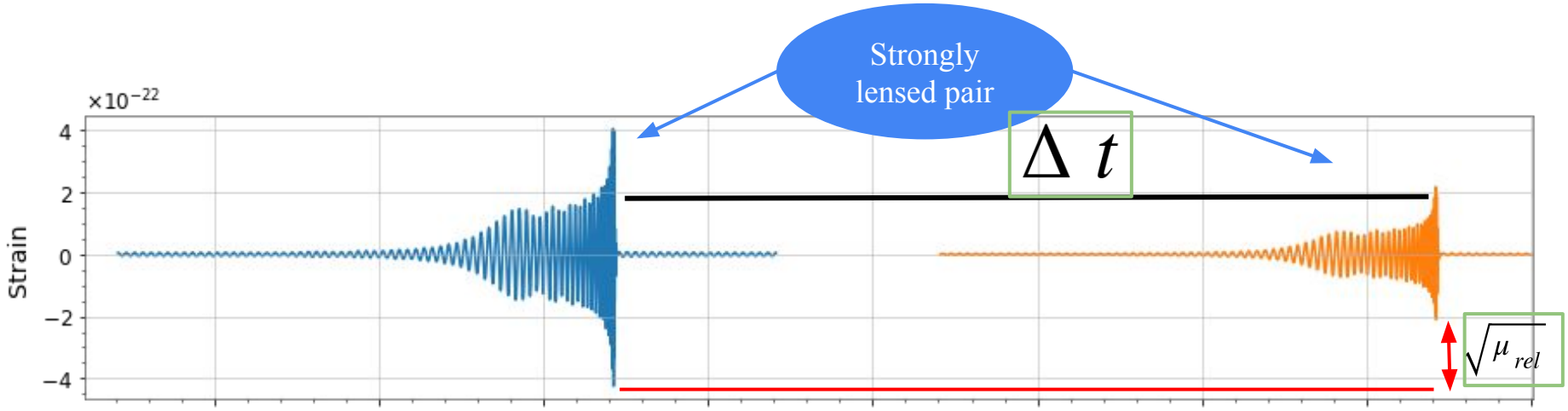
One magnified wave is observed (bias in detected luminosity distance)
Undetectable for BBH; can be used in BNS (luminosity distance and tidal deformability not matching) (Pang et al., 2020)



Credits: *"Lensed or not lensed: Determining lensing magnifications for binary neutron star mergers from a single detection"*, Pang et al., 2020

What happens when a GW is strongly lensed?

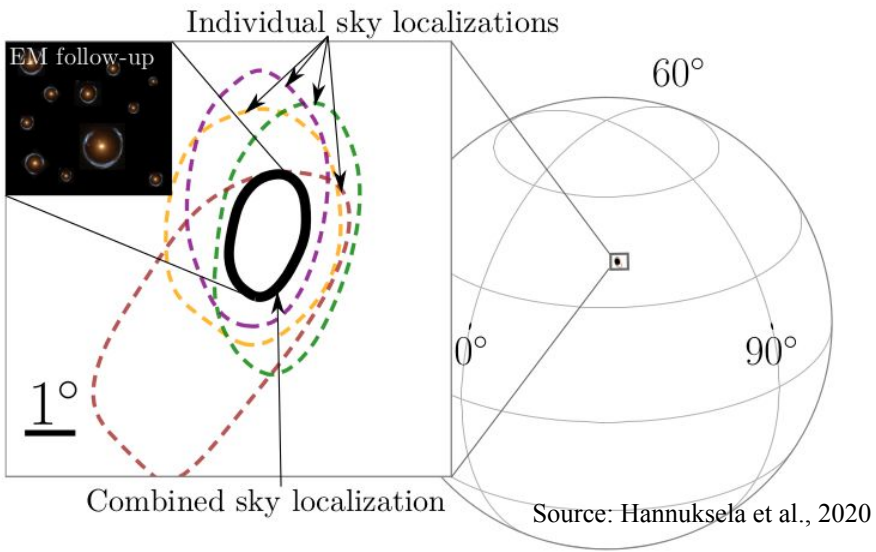
N (typically 2 or 4) repeated events, linked by 3 lensing parameters, with same frequency evolution



+ Overall phase shift → Morse factor n_{12}

Once we detect strong lensing, then what?

- Study the origin of merging black holes (Hannuksela et al., 2020)



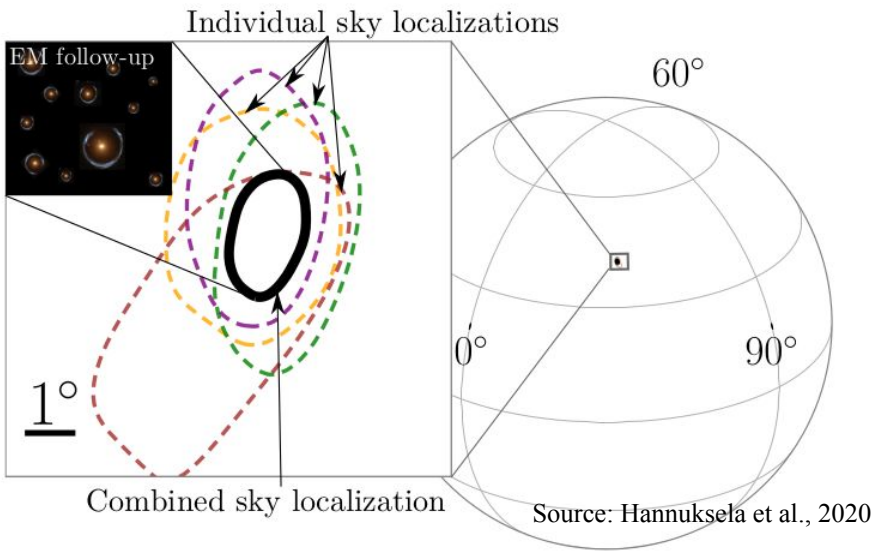
Source: Hannuksela et al., 2020

Combining sky locations and electromagnetic data
→ 1 possible host galaxy

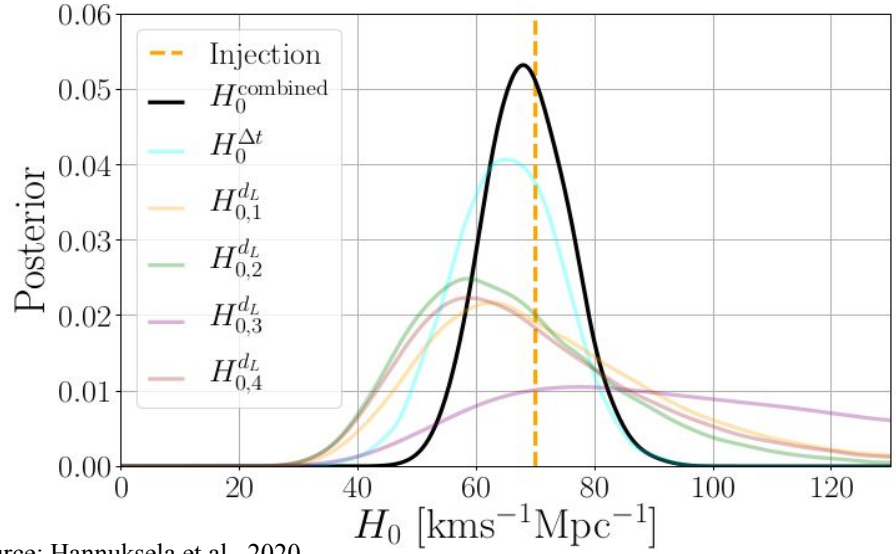
Source: Hannuksela et al., 2020

Once we detect strong lensing, then what?

- Study the origin of merging black holes (Hannuksela et al., 2020)
- Study the expansion of the Universe (Hannuksela et. al, 2020; Liao et. al, 2017)
- Probe fundamental physics (Collett & Bacon, 2017 ; Fan et al. 2017)



Source: Hannuksela et al., 2020



Source: Hannuksela et al., 2020

Combining sky locations and electromagnetic data
→ 1 possible host galaxy

→5 Hubble constant measure from 1 lensed event

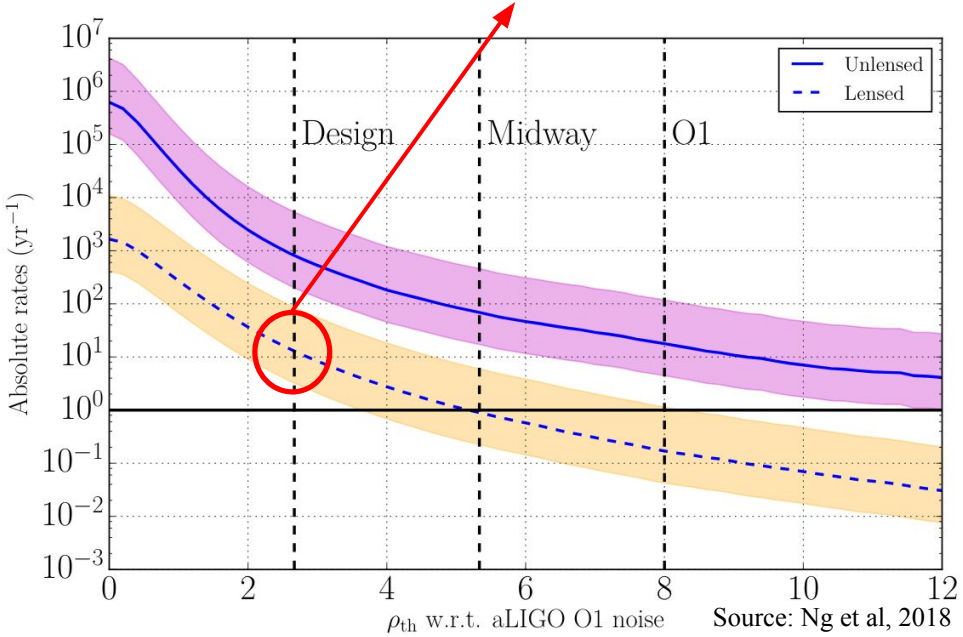
How do we search for strong lensing?

Non-negligible rate at design sensitivity

Already started as predicted in the coming years:

- For O2: https://arxiv.org/pdf/1901.02674.pdf
- For O3a: https://arxiv.org/pdf/2105.06384.pdf

→ So far, no evidence for lensing



Source: Ng et al, 2018

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- For O3b: https://arxiv.org/pdf/2105.06384.pdf

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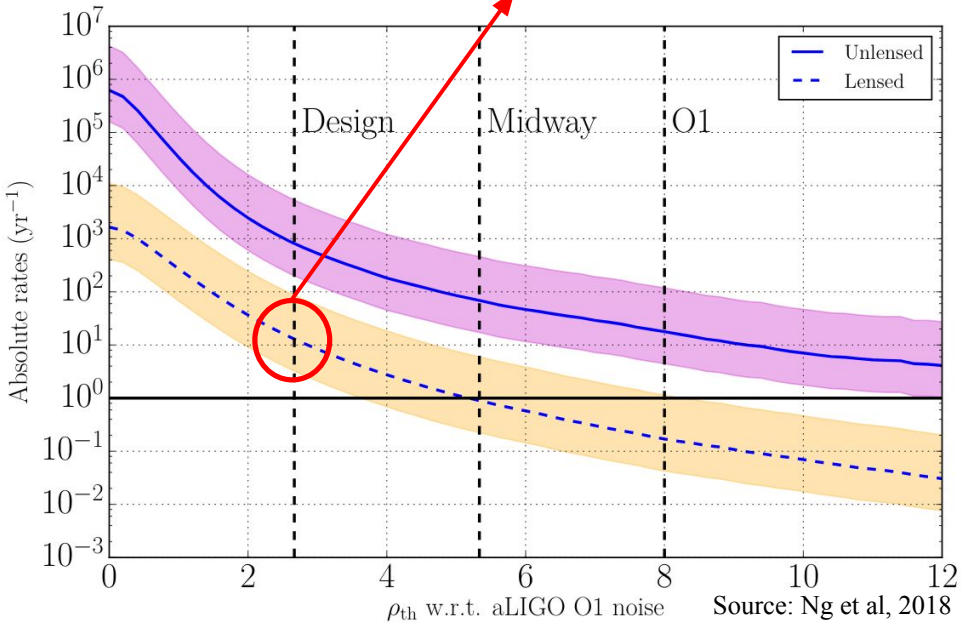
<u>Basic idea:</u>
Look for events with consistent posterior distributions and linked via the lensing parameters



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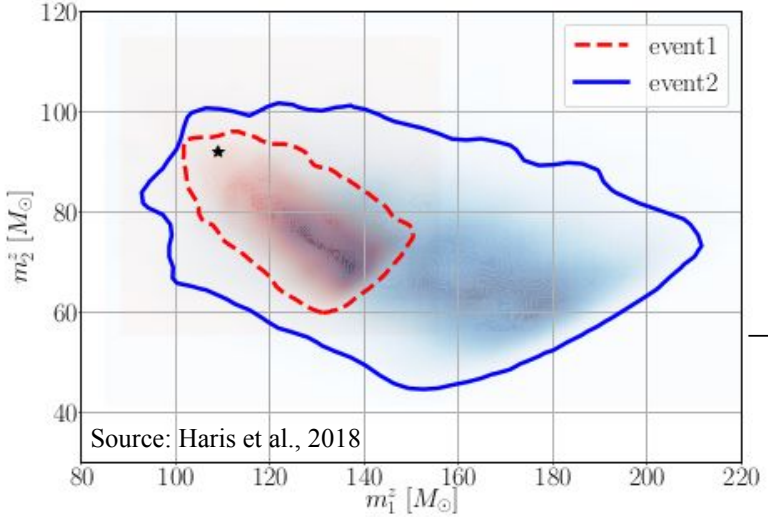
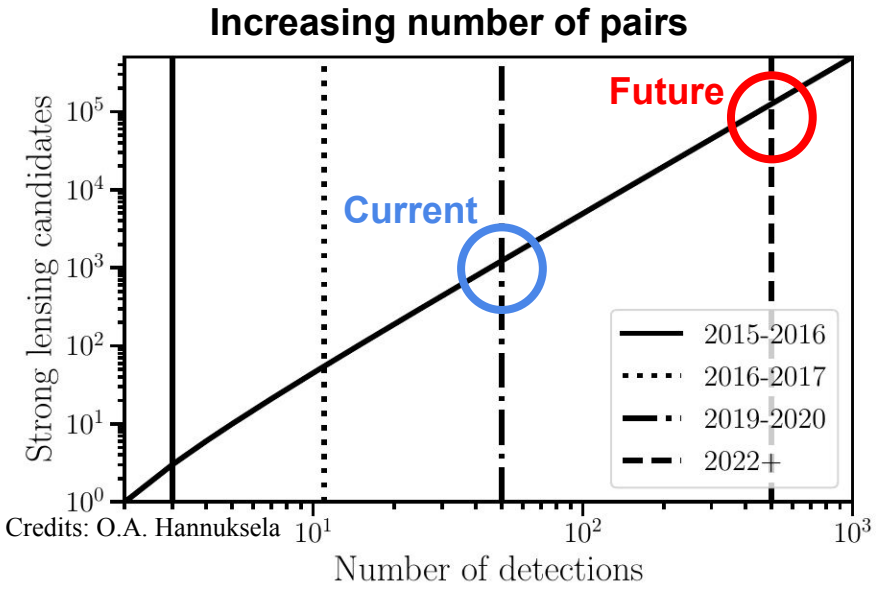


Source: Haris et al., 2018

→ Masses of the events are consistent

Why develop a new method?



Credits: O.A. Hannuksela

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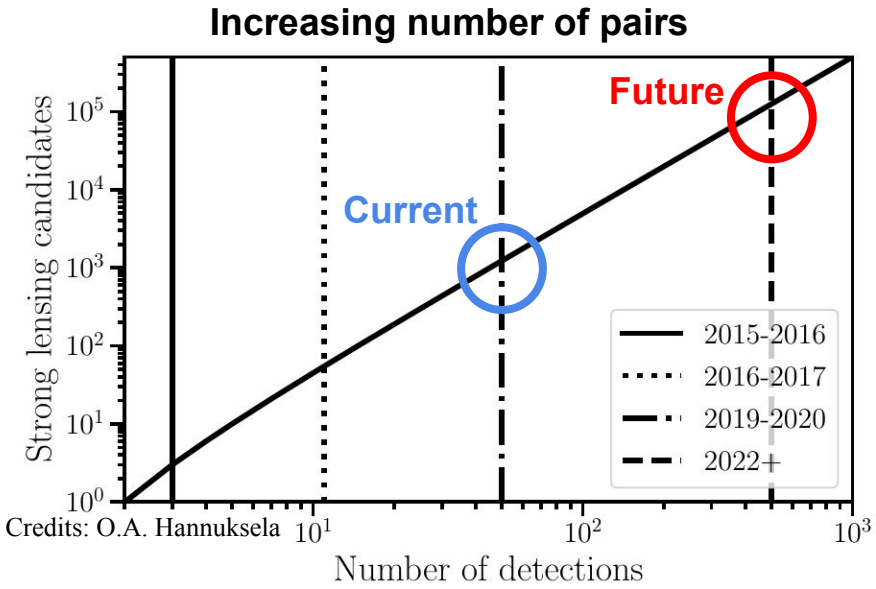

Credits: O.A. Hannuksela

Current methods:

- Posterior overlap[1]: Fast (CPU time ~ minutes), not very precise
- Full joint parameter estimation[2, 3]: computationally expensive (CPU time ~ month(s)), very precise

Goal: Evaluate the coherence ratio: $C_U^L = \frac{p(d_1, d_2 \mid H_L)}{p(d_1, d_2 \mid H_U)}$

~ evaluate the probability to have lensing against no lensing

1. *"Identifying strongly lensed gravitational wave signals from binary black hole mergers"*, Haris et. al 2018
2. *"Identifying strong gravitational-wave lensing during the second observing run of Advanced LIGO and Advanced Virgo"*, Liu et. al, 2020
3. *"A Bayesian statistical framework for identifying strongly-lensed gravitational-wave signals"*, Lok Lo & Magaña Hernandez, 2021

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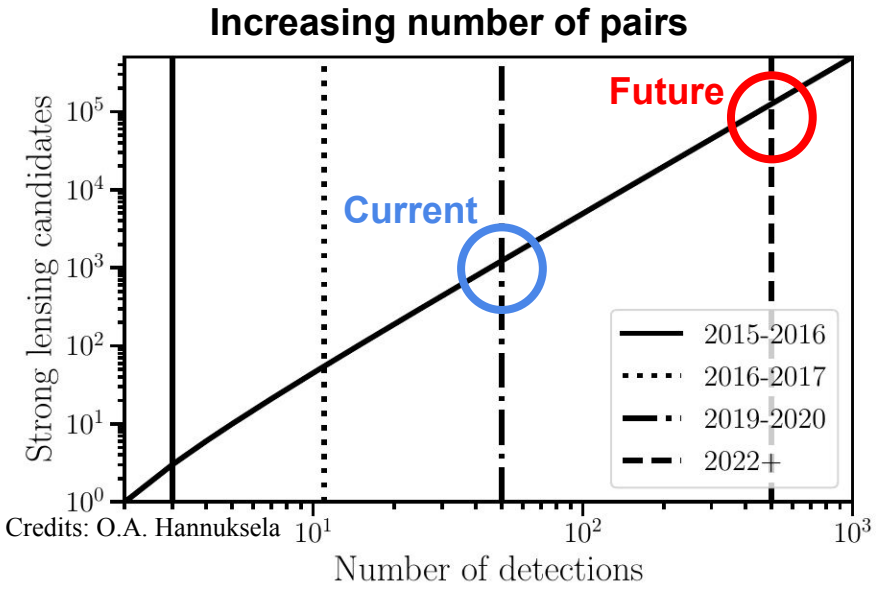

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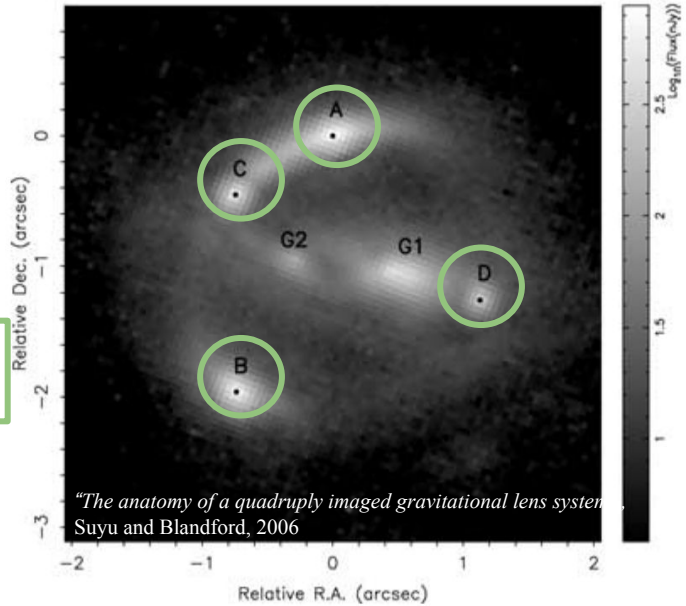
Joint analysis of multiple images



"The anatomy of a quadruply imaged gravitational lens system", Suyu and Blandford, 2006

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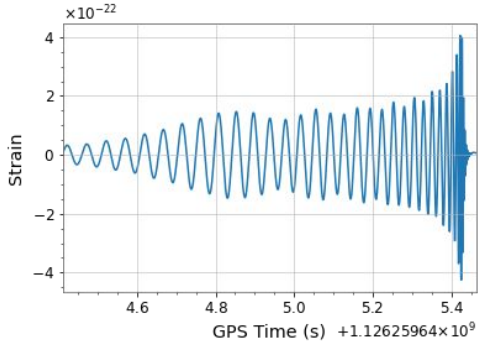
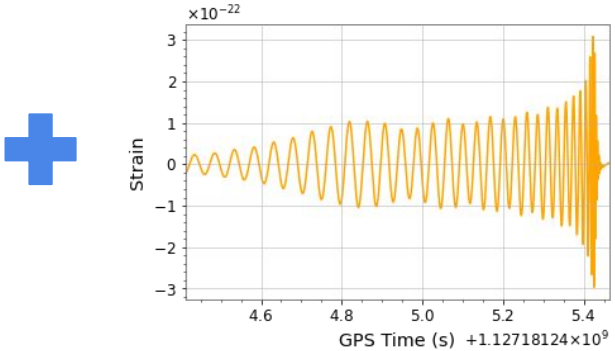
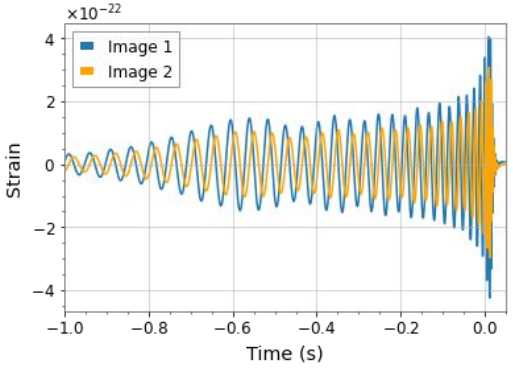
How do we analyze analyze strong lensing in practice?







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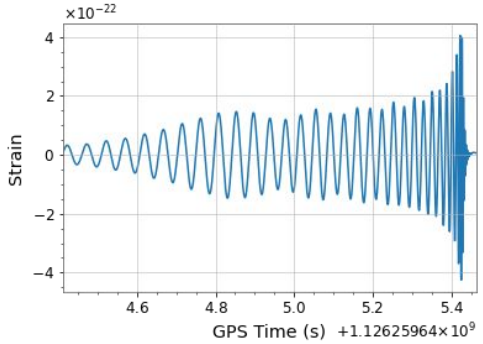
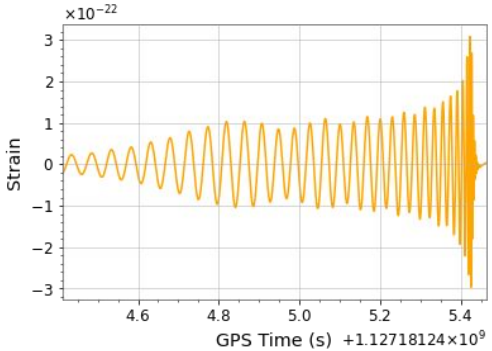
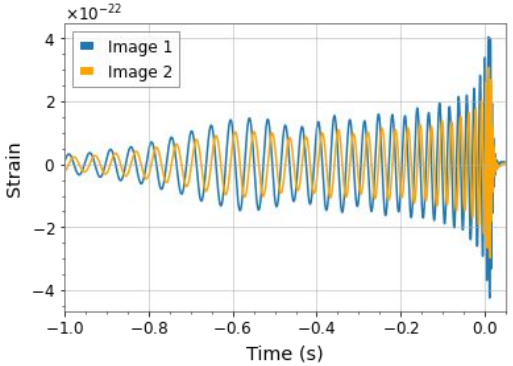


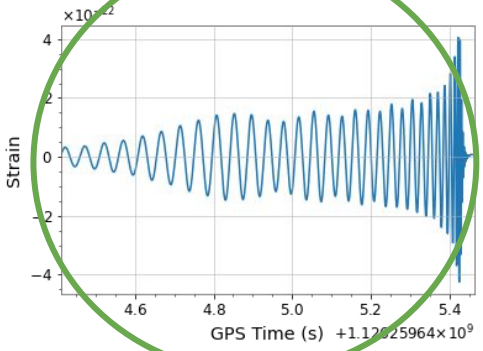


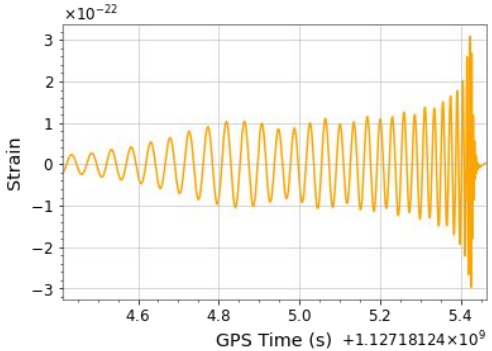


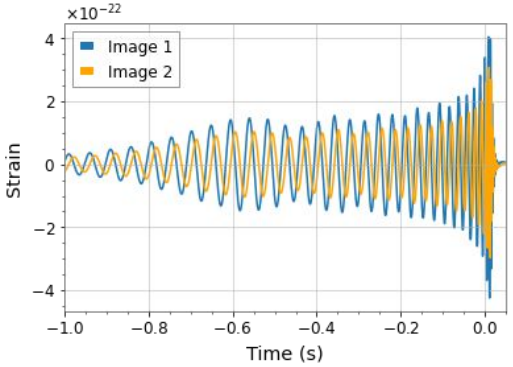
GOLUM: Gravitational-wave analysis **O**f **L**ensed and **U**nlensed waveform **M**odels

<u>Idea:</u> Use the posteriors of the first image analysis as priors for the second image

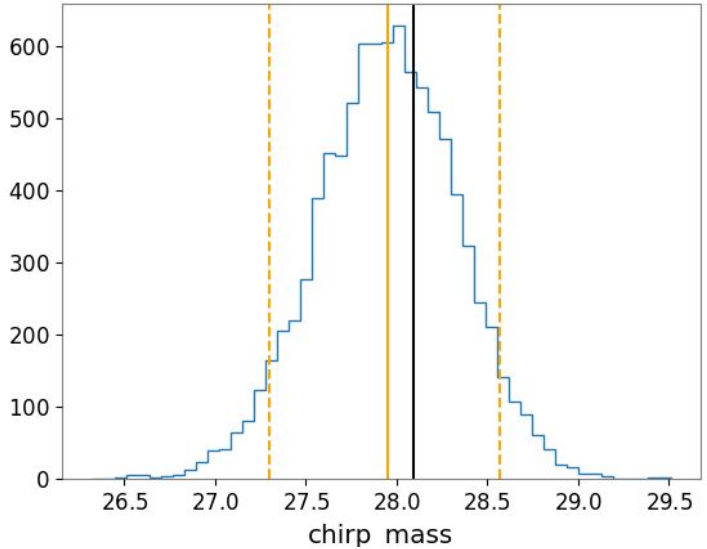
How do we analyze strong lensing in practice?







Analyze the first image



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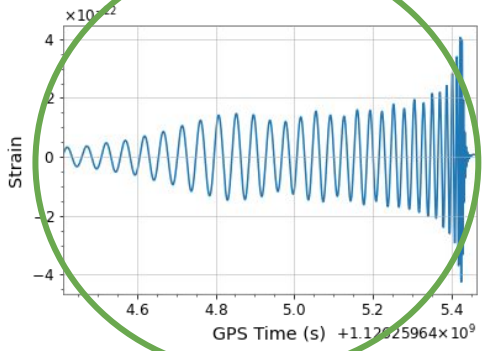

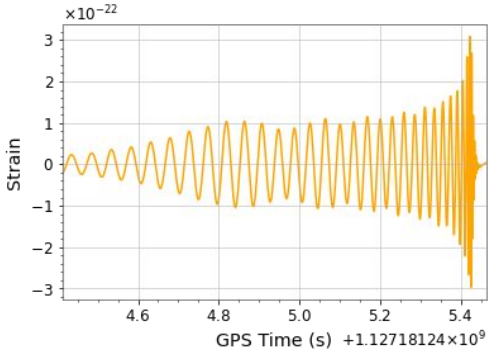

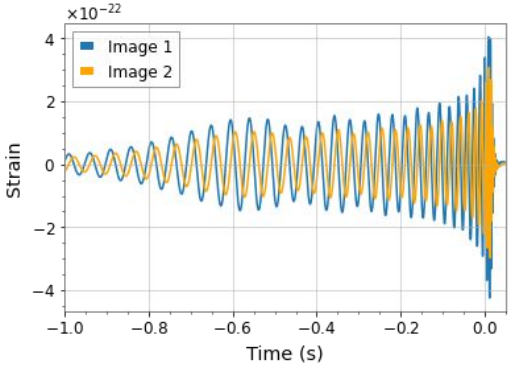

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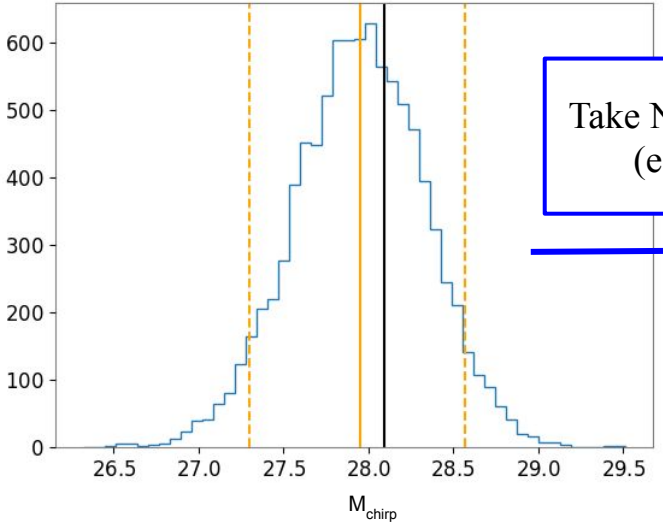
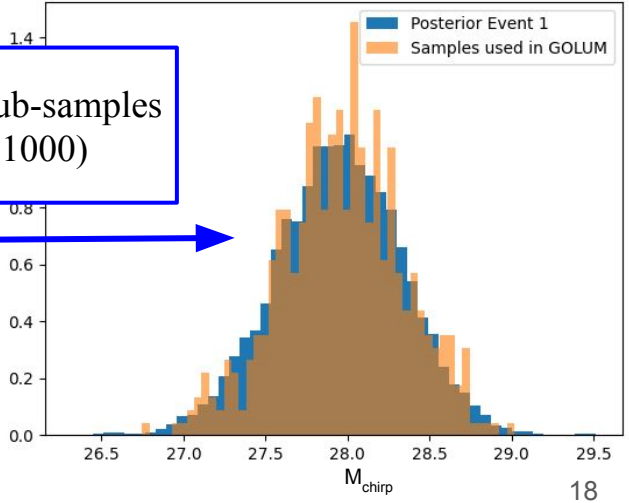


Take N sub-samples (e.g. 1000)



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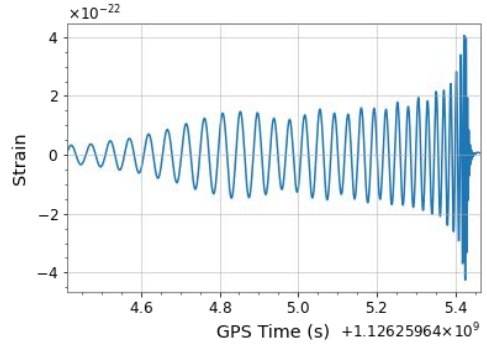
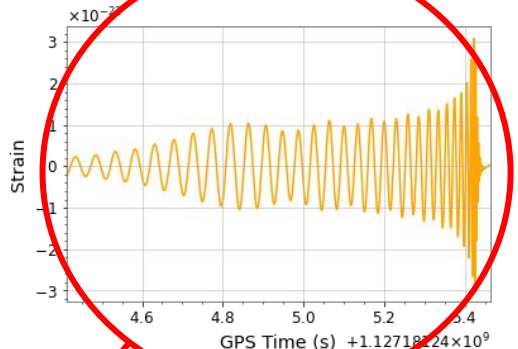
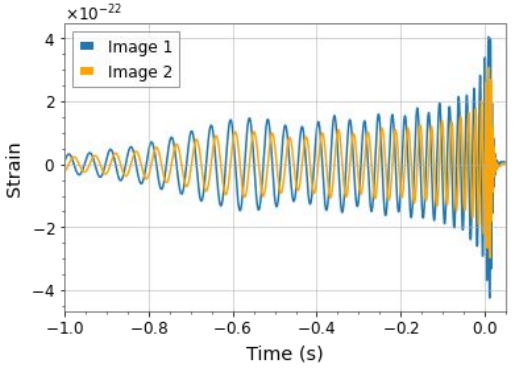
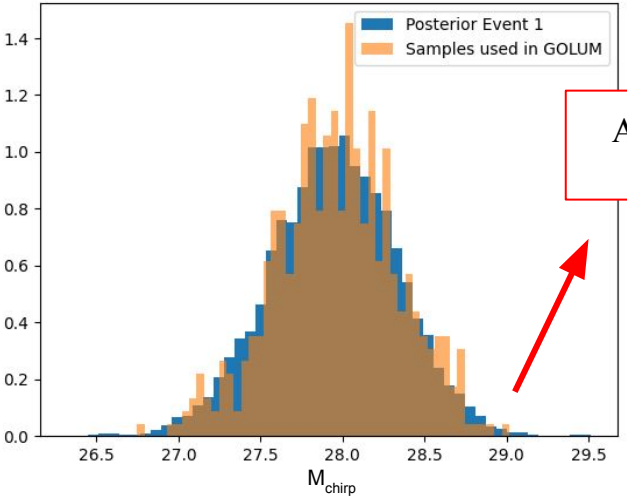


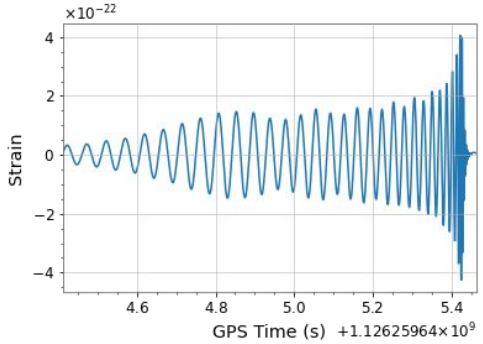


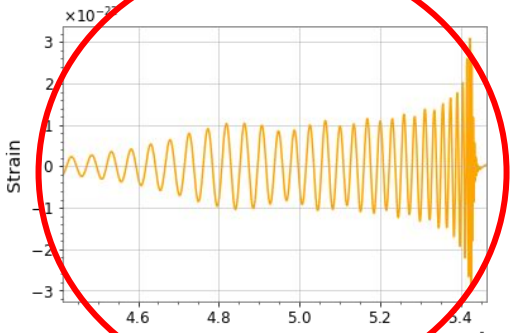


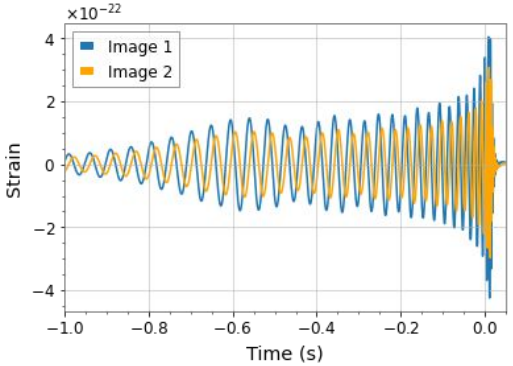


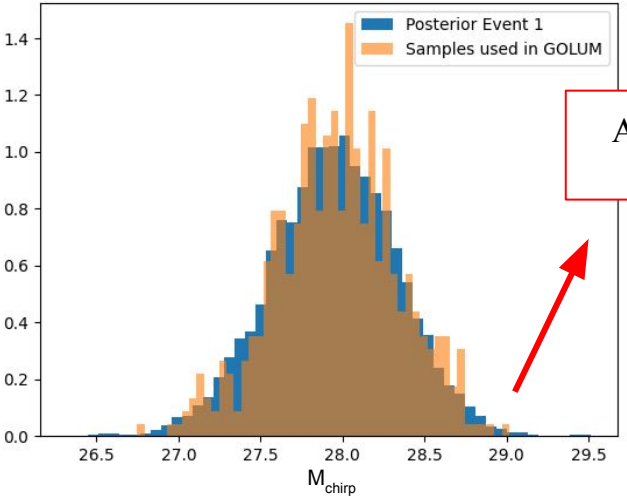
Analyze the second image

How do we analyze analyze strong lensing in practice?









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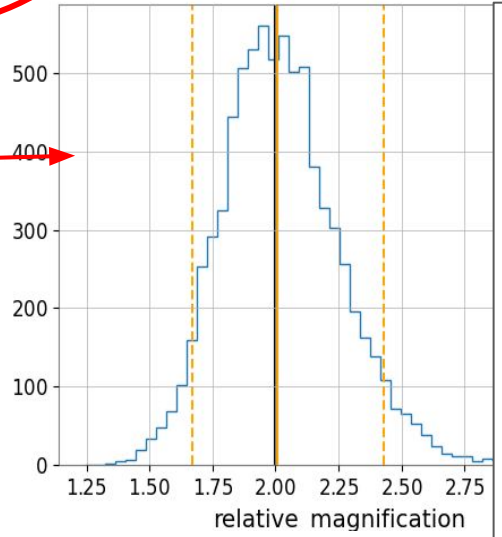


$\log(C_U^L) = 23.6$

Time: $\theta(1\ hr)$

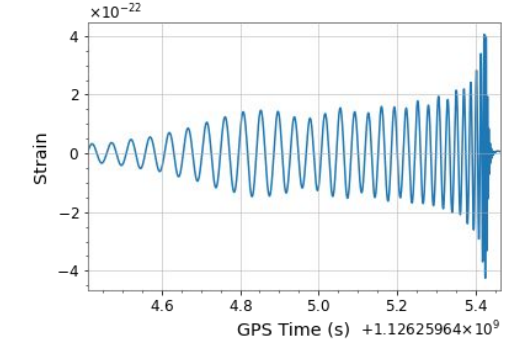
If unlensed pair

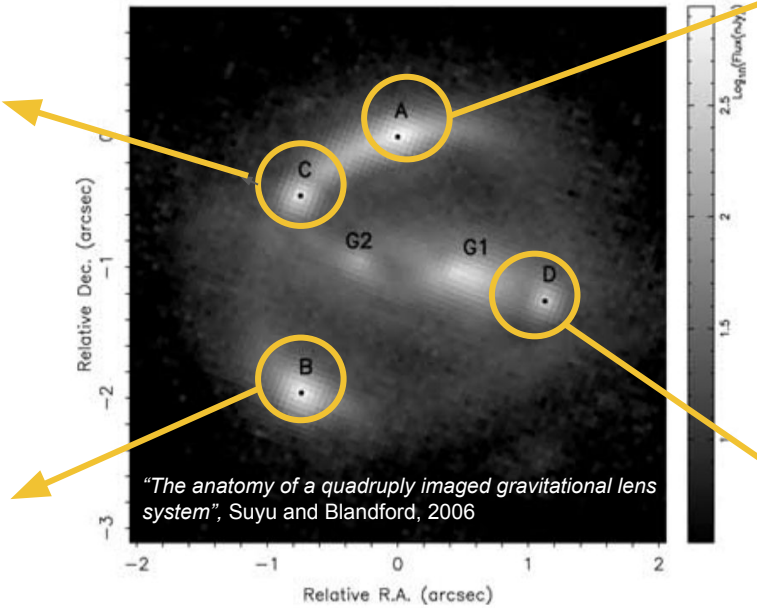
$\log(C_U^L) = -14$

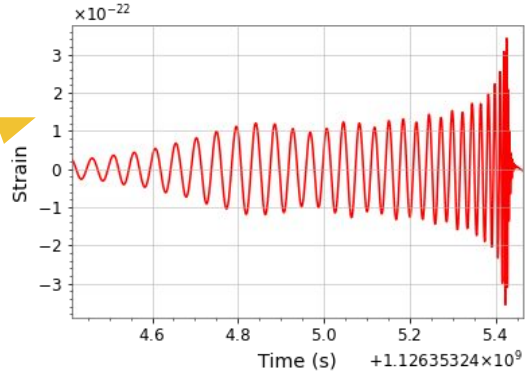
Follow-up analysis for sub-threshold pairs possible (and faster)

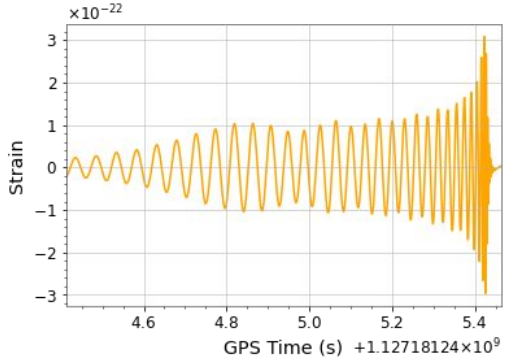
And if quadruplet?

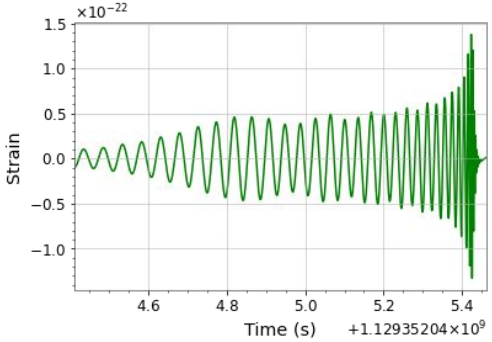
Are these linked?
Location host galaxy of the BBH?
Lens?











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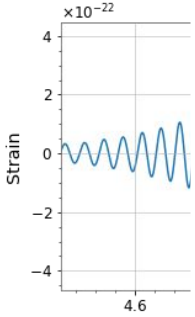
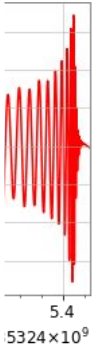
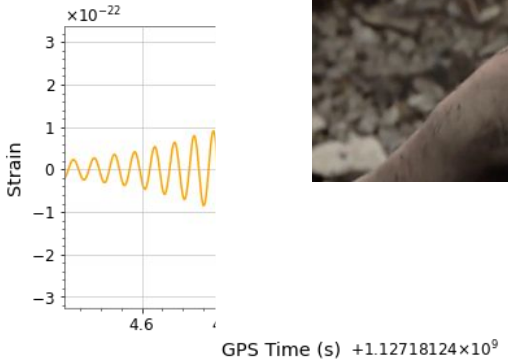
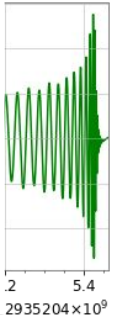


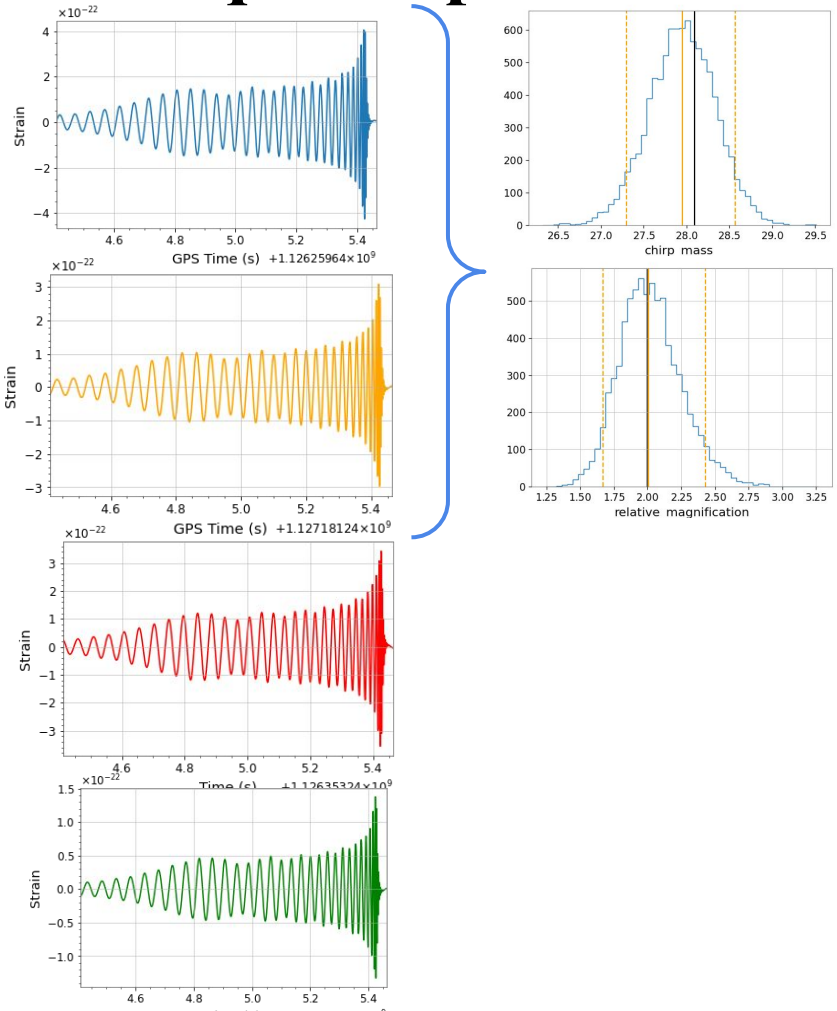
× 3







And if quadruplet?



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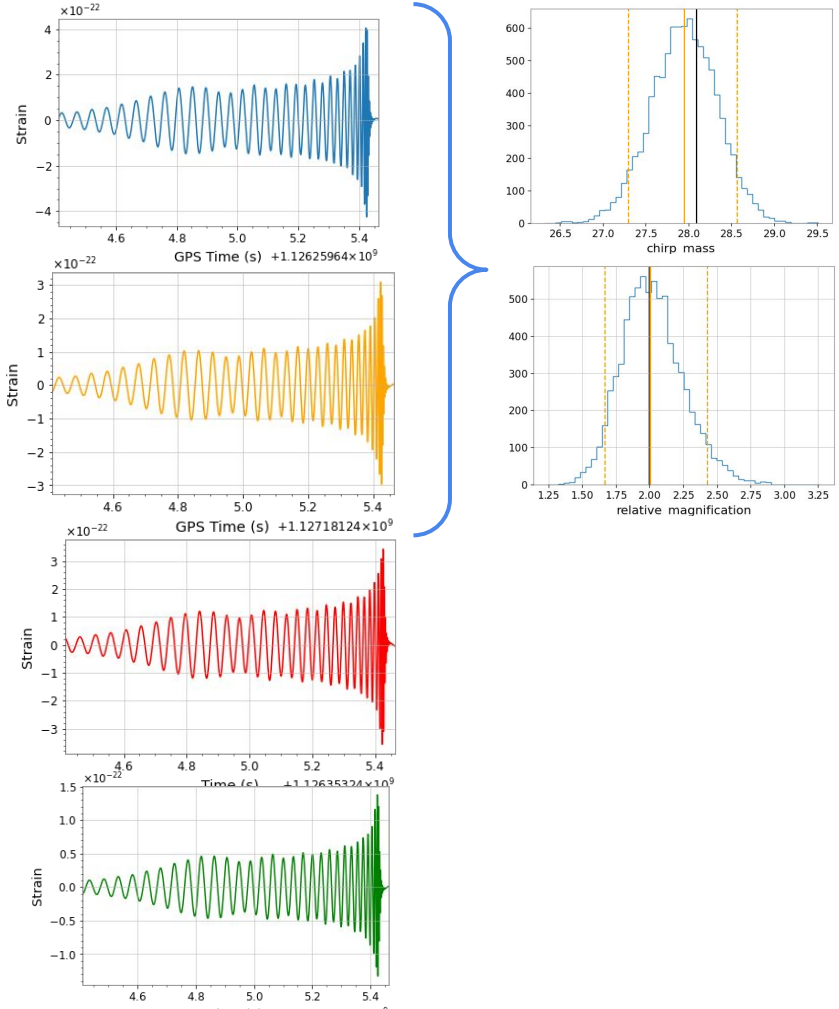
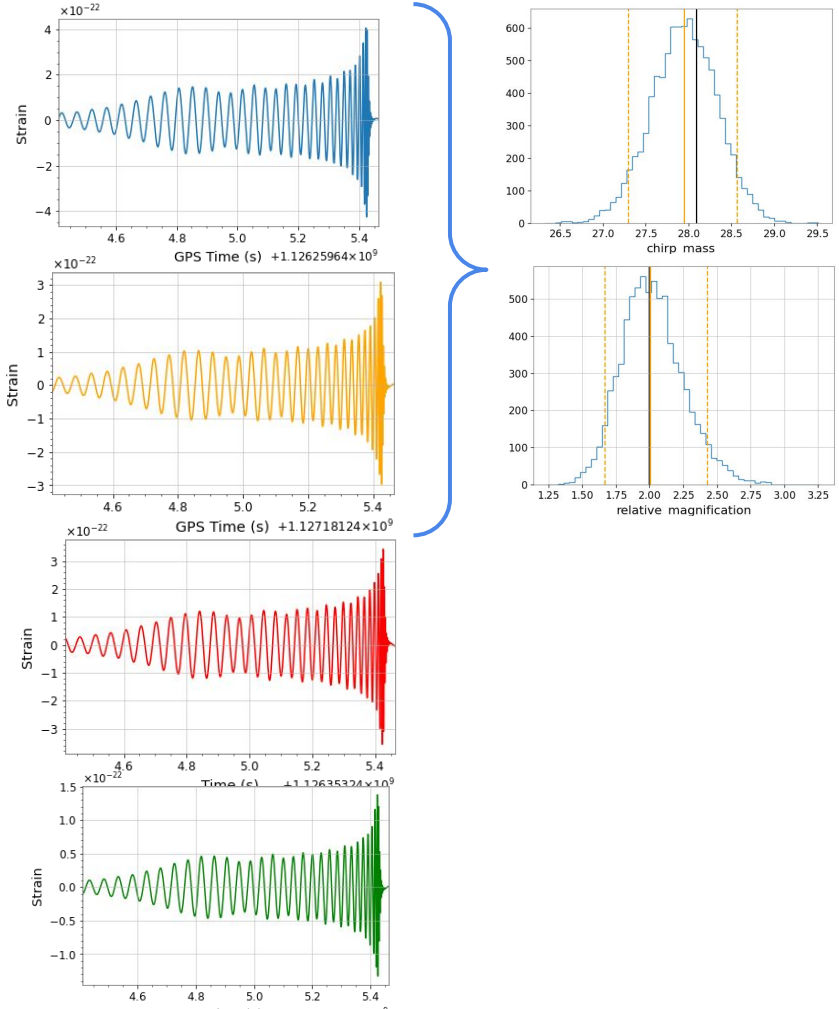
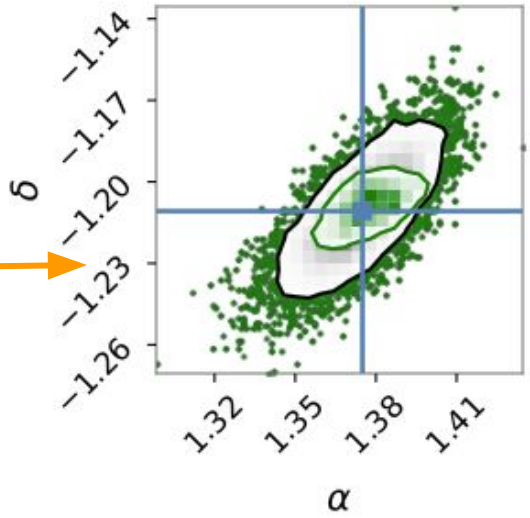


Reweighing

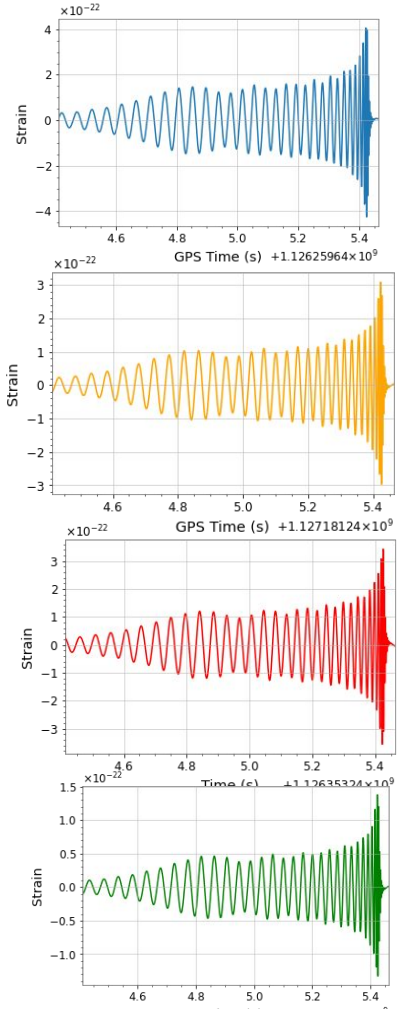
And if quadruplet?

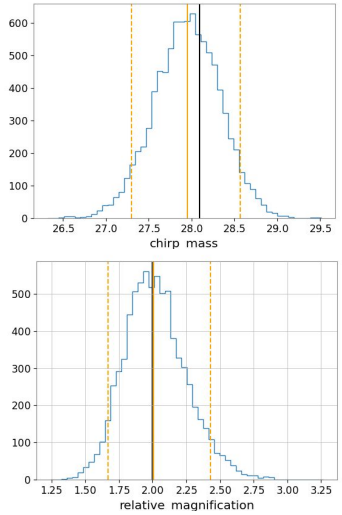


Reweighing



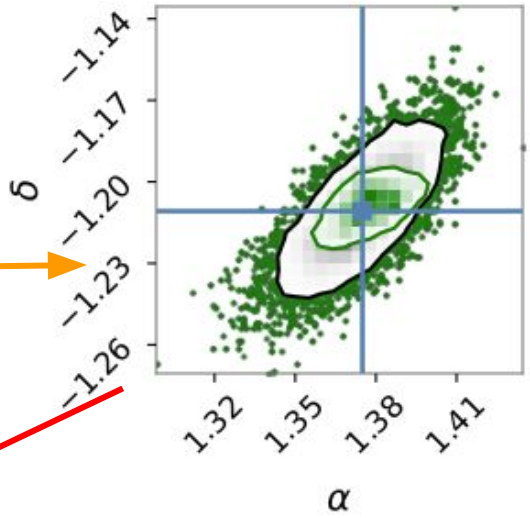
And if quadruplet?



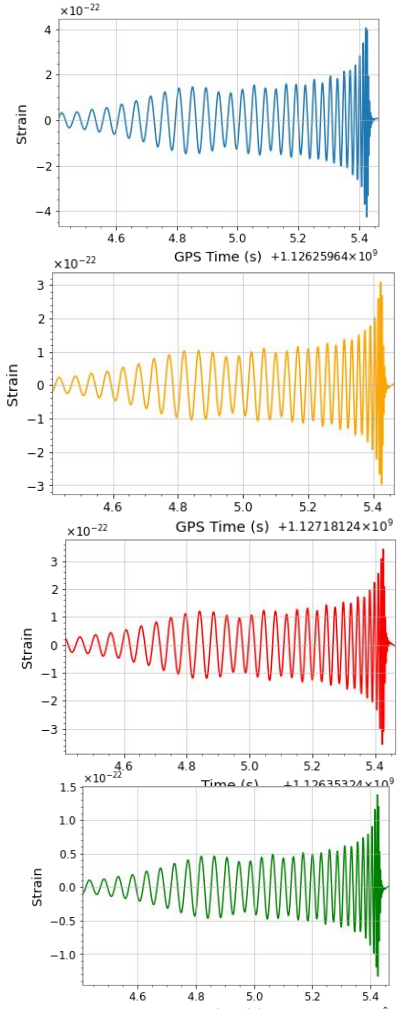


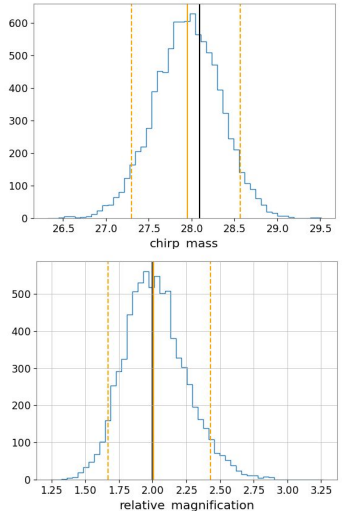
Reweighing

Golum + Reweighing



And if quadruplet?

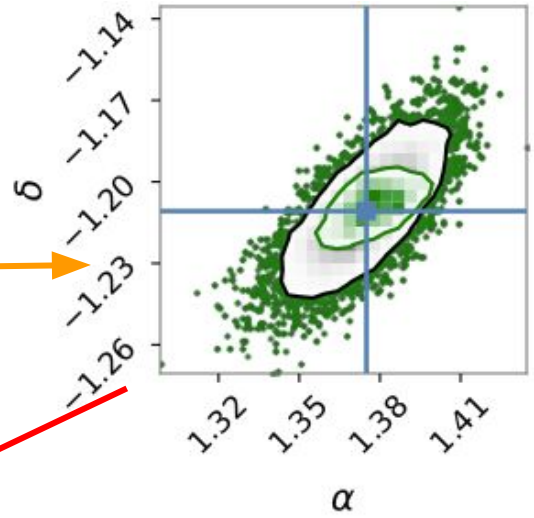




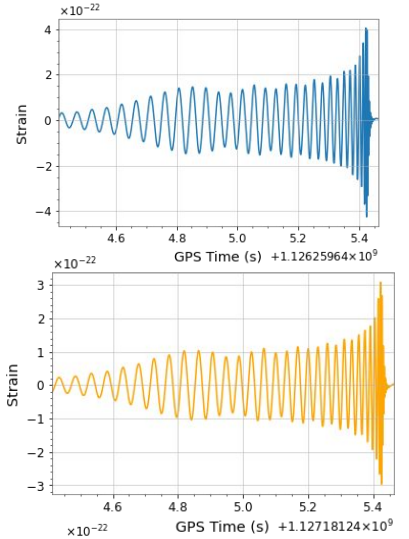
Reweighing

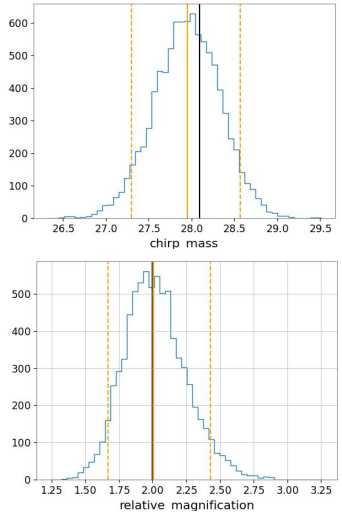
Golum + Reweighing

Reweighed samples for 3 images



And if quadruplet?





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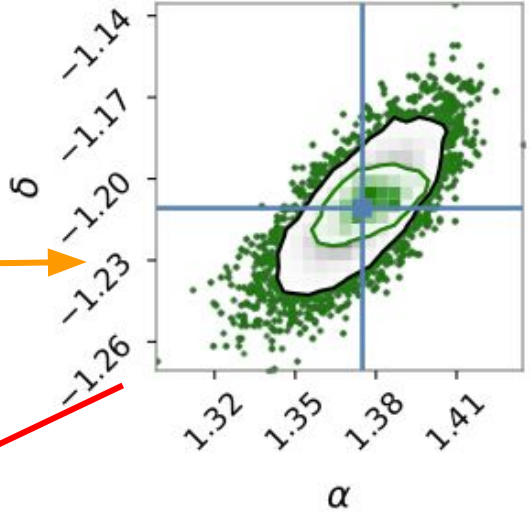
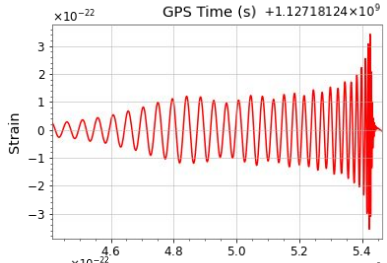
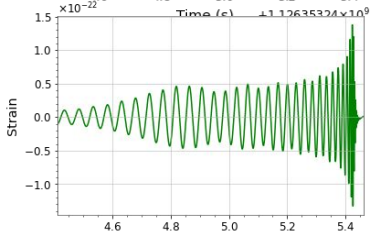


Golum + Reweighing

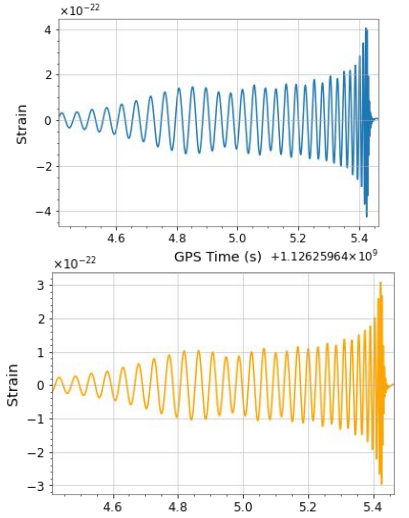


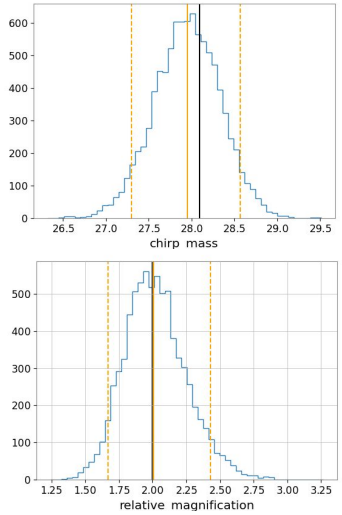
Reweighed samples for 3 images



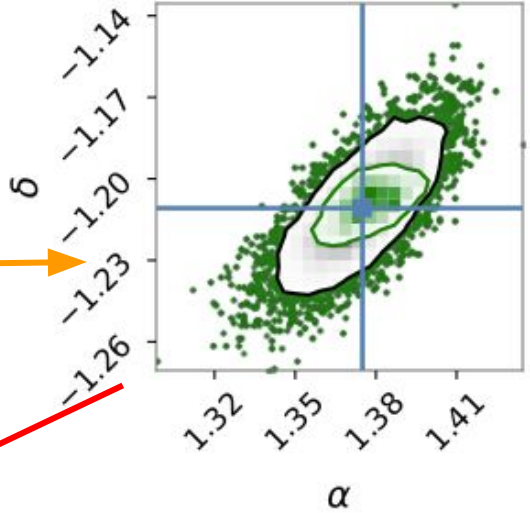
Golum + Reweighing

And if quadruplet?

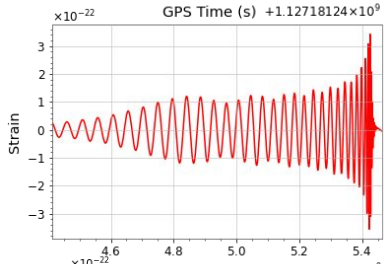




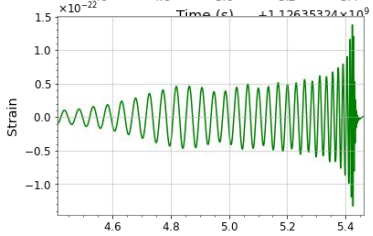
Reweighing



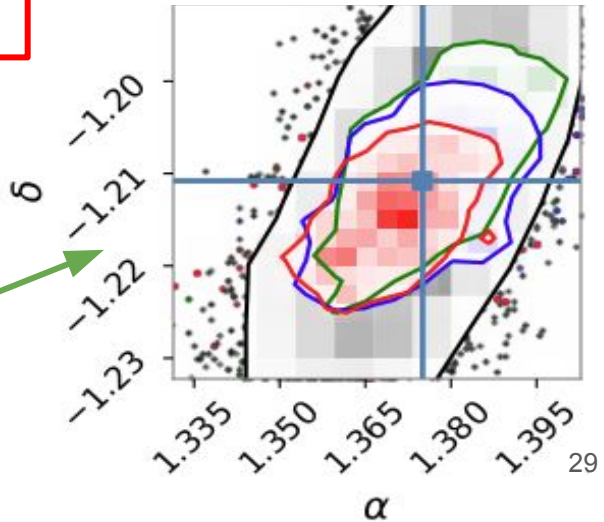
Golum + Reweighing



Reweighed samples for 3 images



Golum + Reweighing



Conclusions:

	Posterior overlap	GOLUM	Full joint PE
Speed	O(CPU minute)	O(CPU hour)	O(CPU month(s))
Precision	low	high	very high
Discriminatory power	weak	good	very good
Extended injection studies	computationally tractable	computationally tractable	computationally expensive

GOLUM is **fast** while remaining sufficiently **precise.**

Expected to **enable future strong lensing studies**, when **massive amount** of data to analyze

Enables us to perform fast **injection studies** and easy **multiple-image analyses.**

For more details, see the corresponding paper: https://arxiv.org/abs/2105.04536