Strong gravitational lensing of gravitational waves: an upcoming new multi-messenger channel

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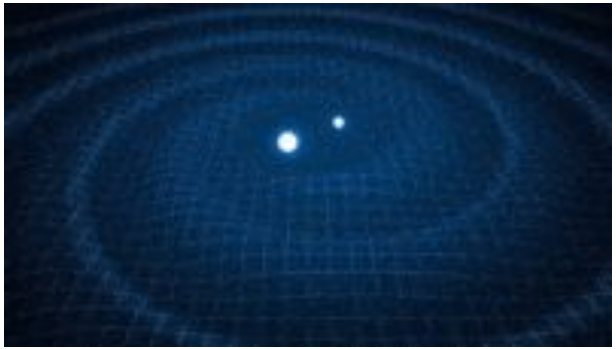
Nikhef

What are gravitational waves?



credits : NASA

Two massive objects (Black hole, neutron star, …) orbit each other

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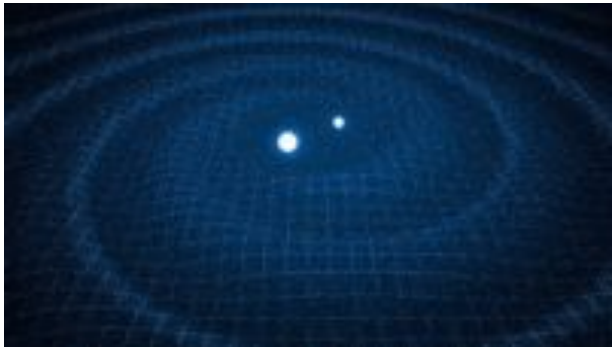

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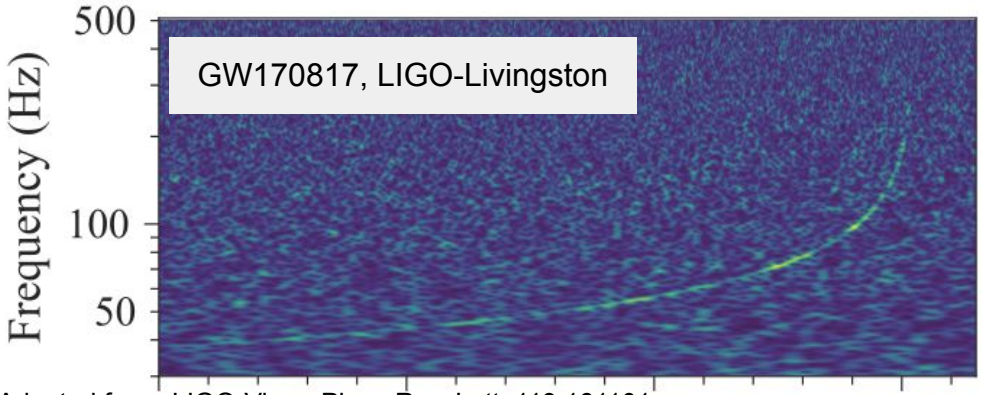
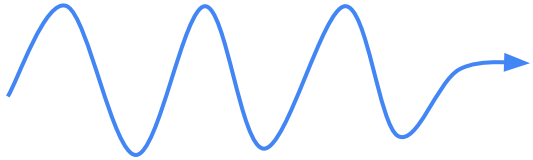


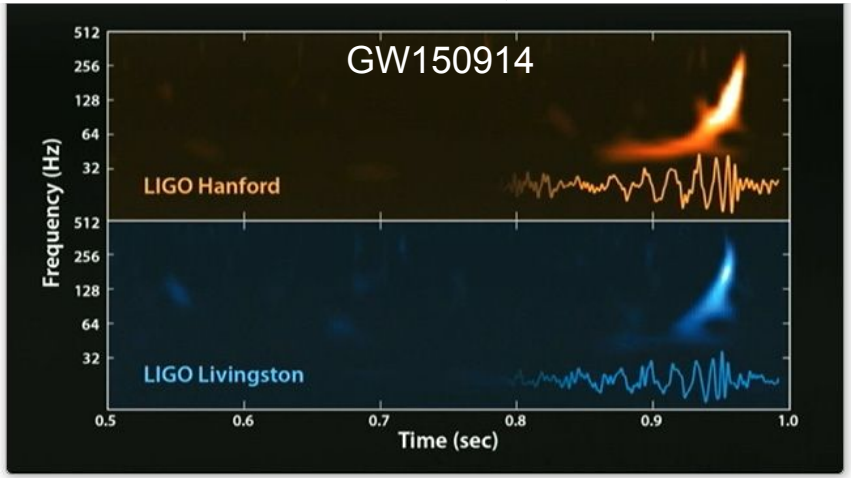
Adapted from: LIGO-Virgo, Phys. Rev. Lett. 119.161101



Long travel in space

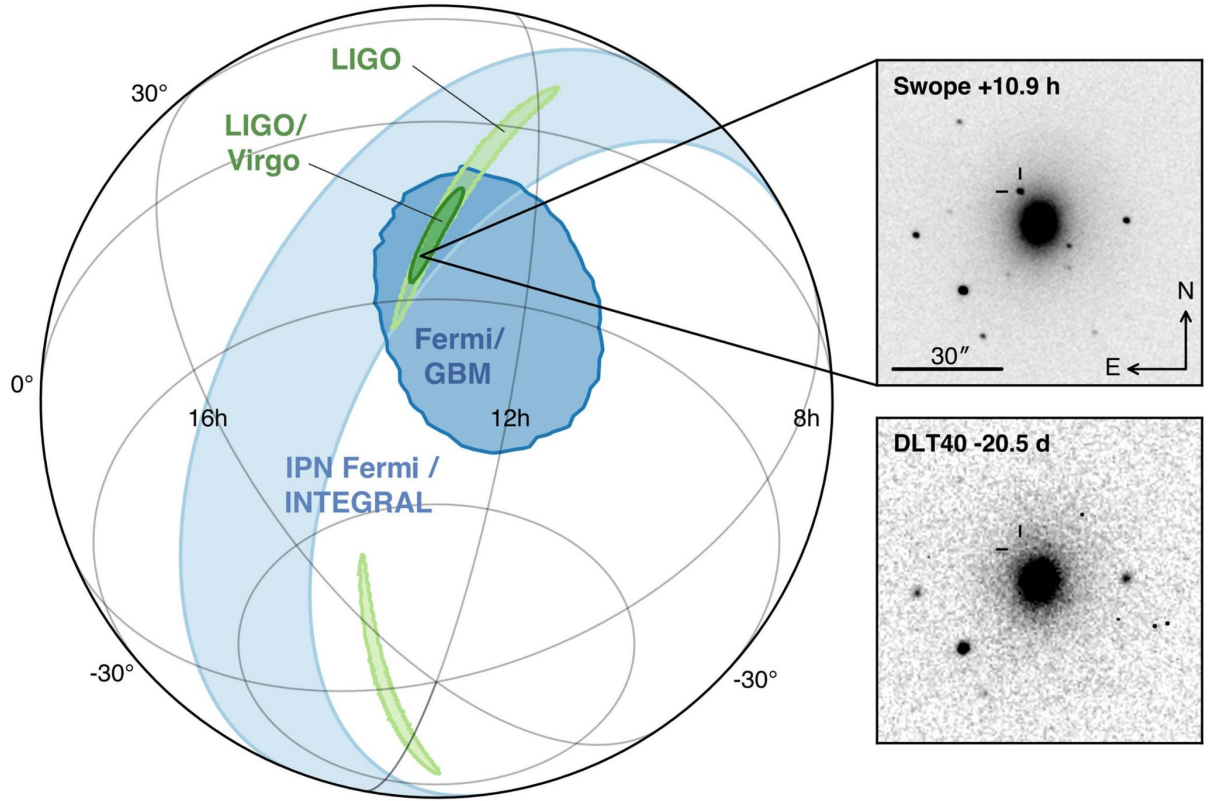
Credits: MIT

Reaches Earth, can be detected



Source: LIGO, Rev. Lett. 116 061102

GW170817, an example of a multi-messenger observation



Lead to (LIGO-Virgo, Phys. Rev. Lett. 161101):

- Study of neutron stars properties (masses, tidal deformability, …)
- Constraint on the equation of state for neutron star matter
- Using the **difference in time of travel between the photons and the gravitational wave signal**:
  - Test speed of gravity
  - Test for dispersive effects in gravitational waves
  - Test the equivalence principle
- Make **link between the GRBs and the object at their origin**
- Independent **measure of the Hubble constant**

Source: LIGO-Virgo-Fermi et al, Astroph. J. Letters, 848:L12

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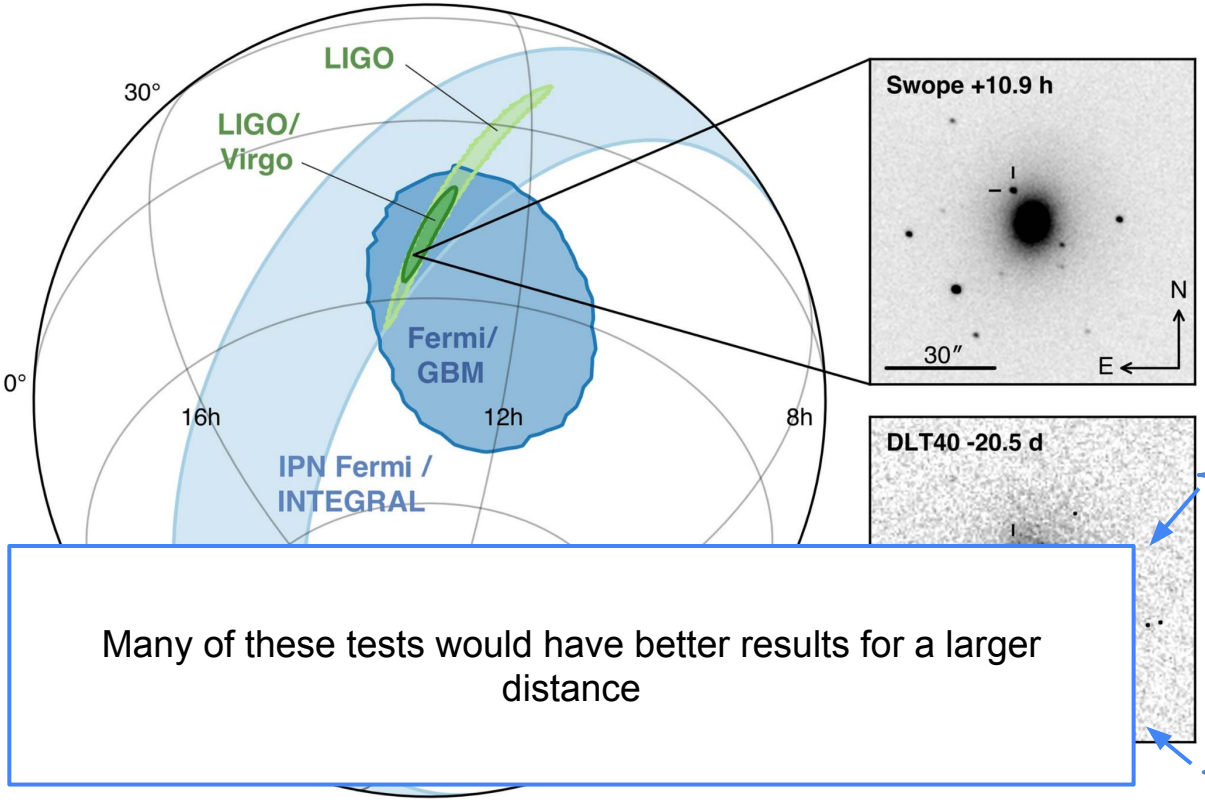

Many of these tests would have better results for a larger distance

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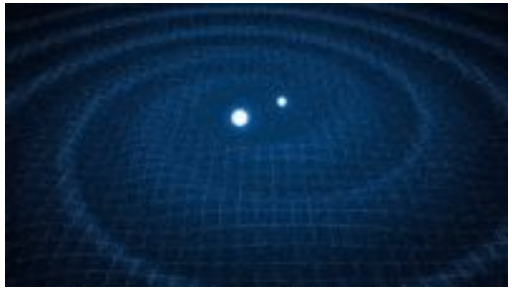
What is strong lensing?



credits : NASA

t_1

t_2

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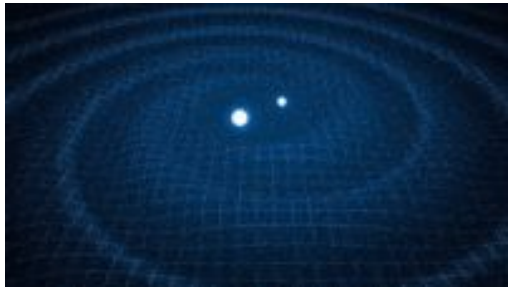

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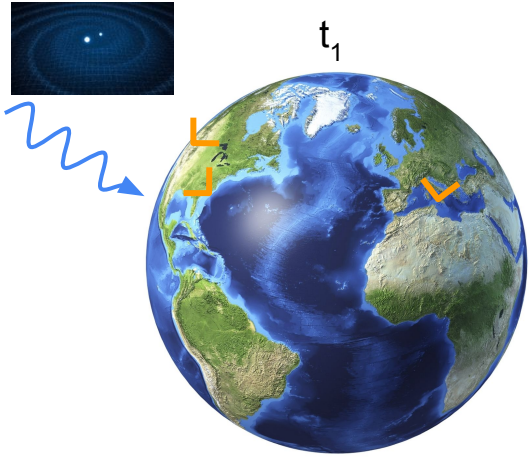
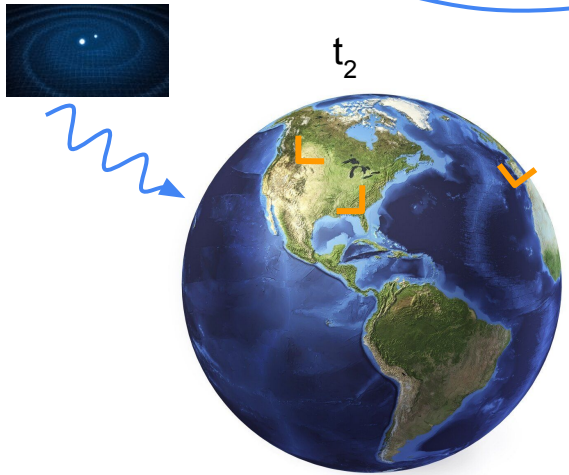


t_1

3 detectors



t_2

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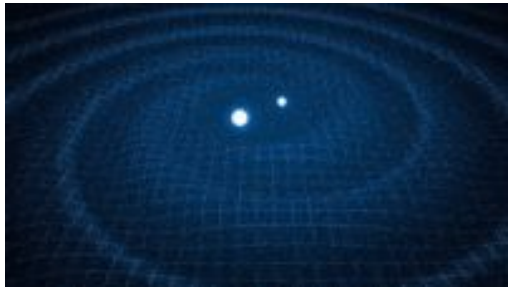

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t_1

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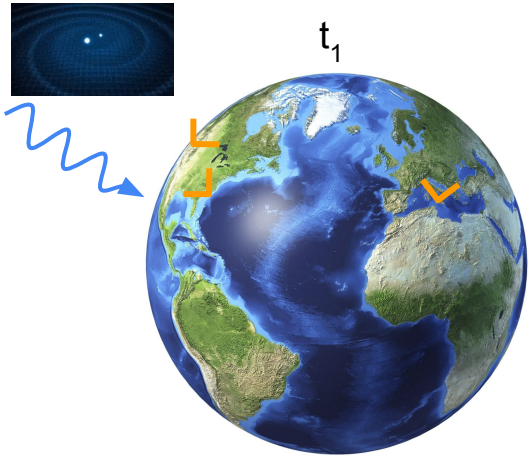


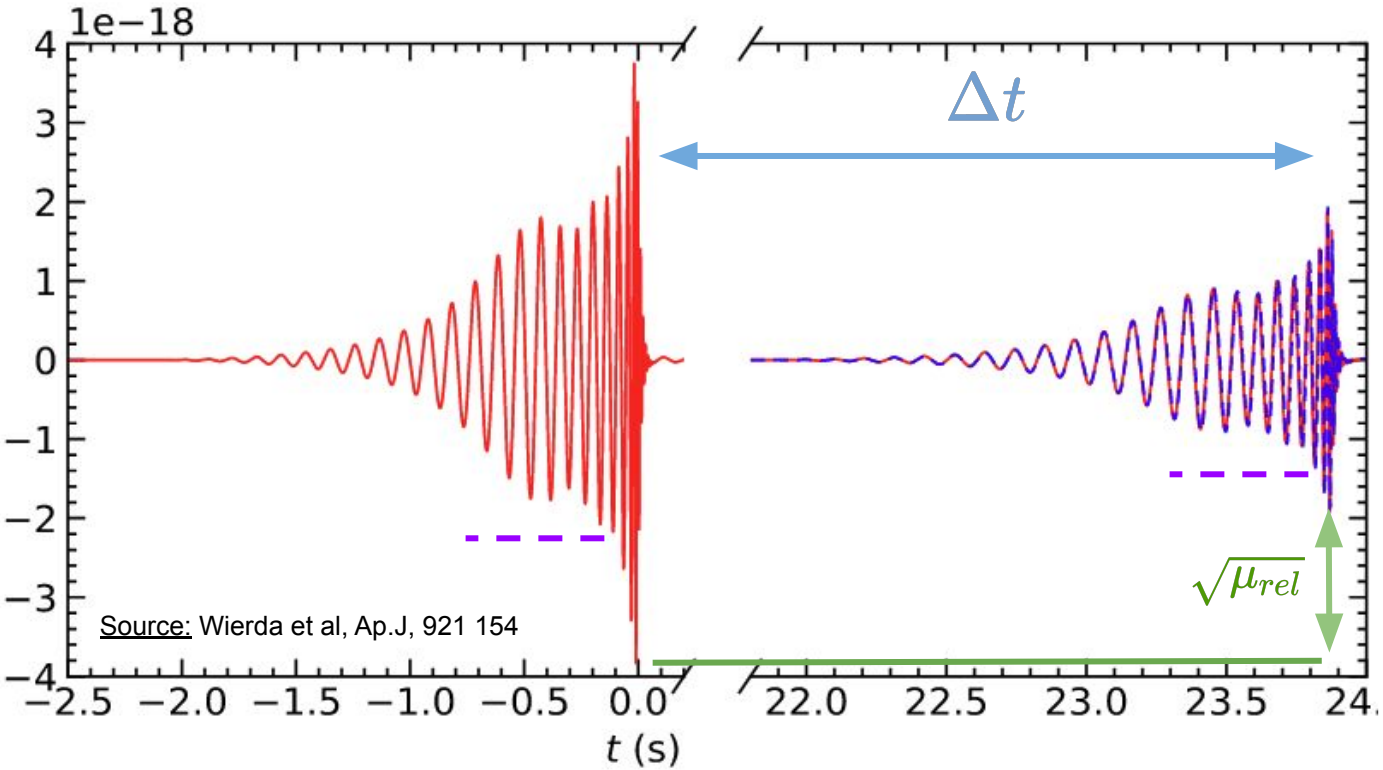
3 detectors

3 detectors

6 detectors

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.

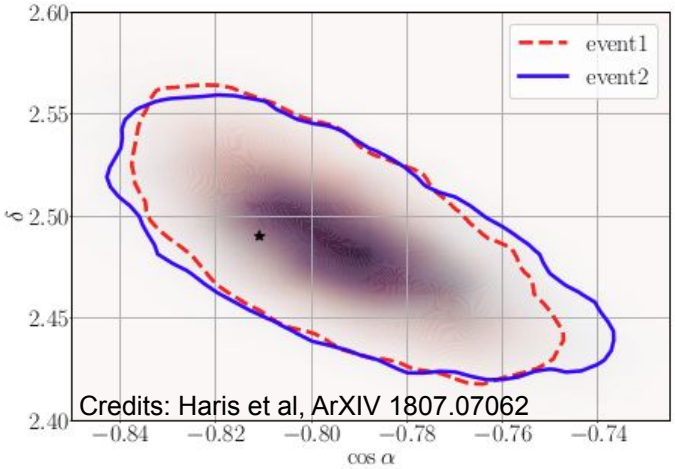
Relative magnification: links the change in amplitude for each wave

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

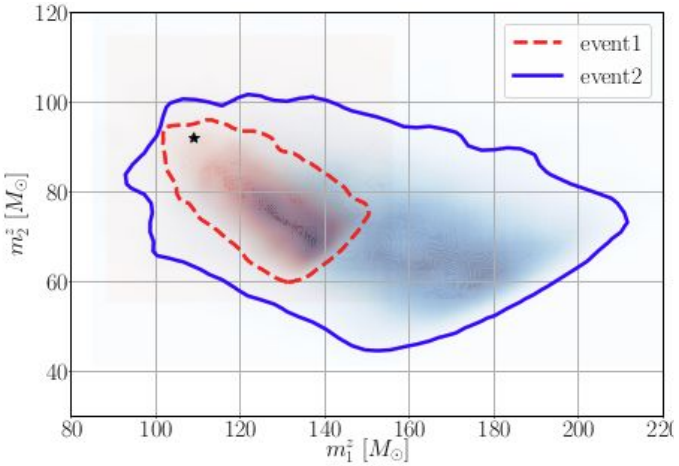
Finding the needle in the haystack

- How do we identify strong lensing?

→ By looking to event pairs with similar intrinsic parameters and sky location



Credits: Haris et al, ArXIV 1807.07062



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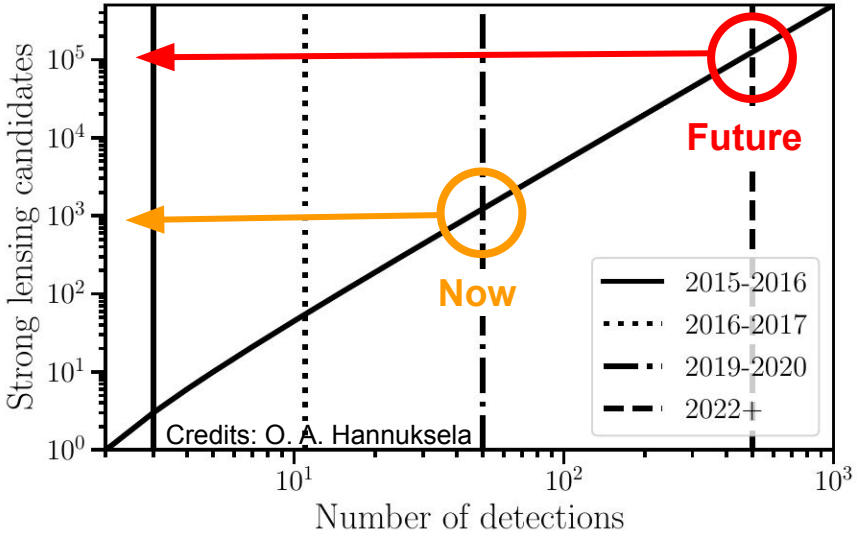
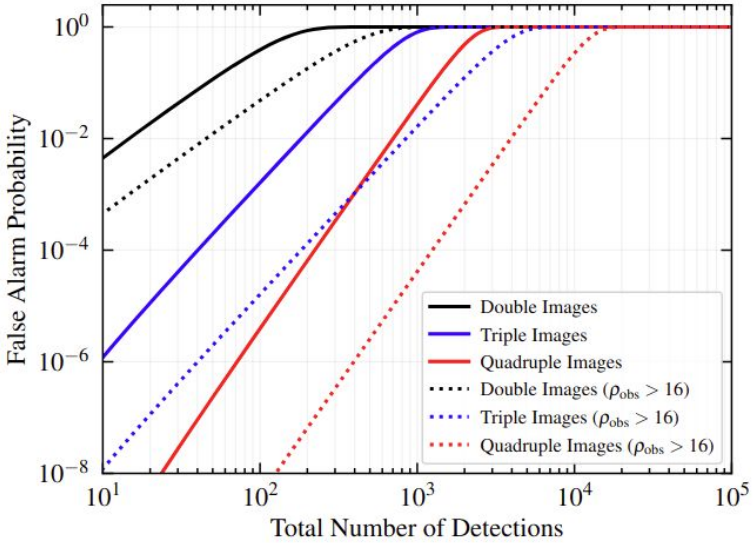
  → Need to analyze all the pairs of events in the data, matching posteriors can happen by chance





Çalişkan et al, arXIV 2201.04619

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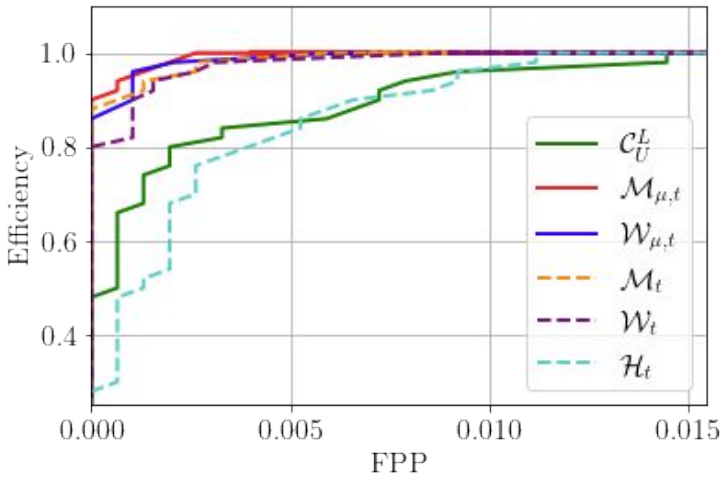
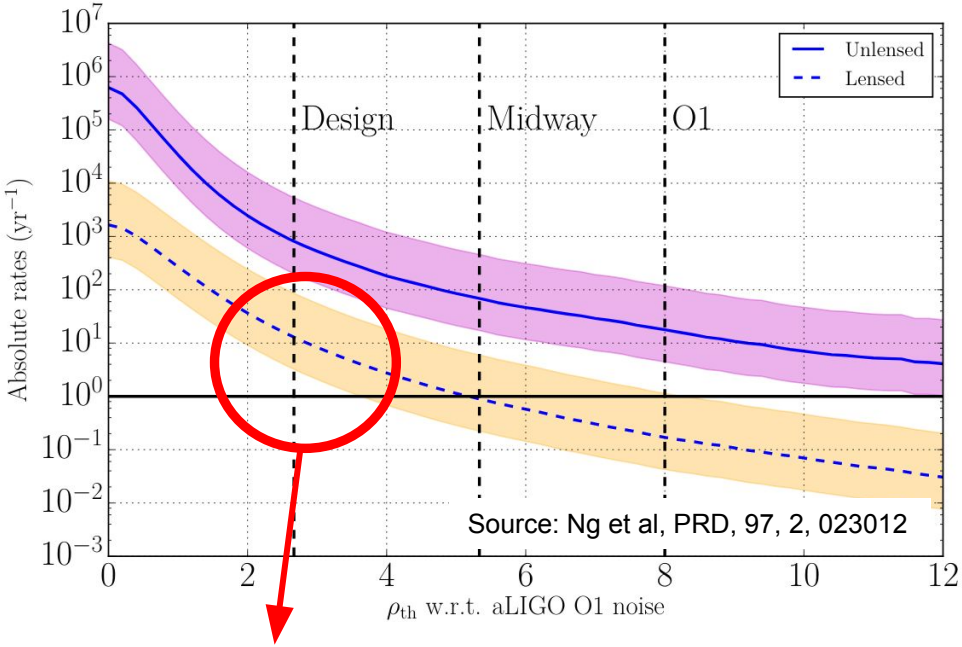
Several methods developed over the years:

- Fast but not very precise:
  - Posterior overlap (Haris et al, ArXIV 1807.07062)
  - Machine learning based (Goyal et al, PRD, 104, 12)
- Very precise but slow:
  - Full joint parameter estimation (Liu et al, ApJ, 908, 1; Lo & Hernandez, arXIV 2104.09339)
- Fast and precise:
  - GOLUM (Janquart et al, MNRAS, 506, 4)

Possibility to constrain more the similarities based on the expected lenses (Janquart et al, ArXIV 2205.11499):



Why is this interesting?



Could be detected soon!

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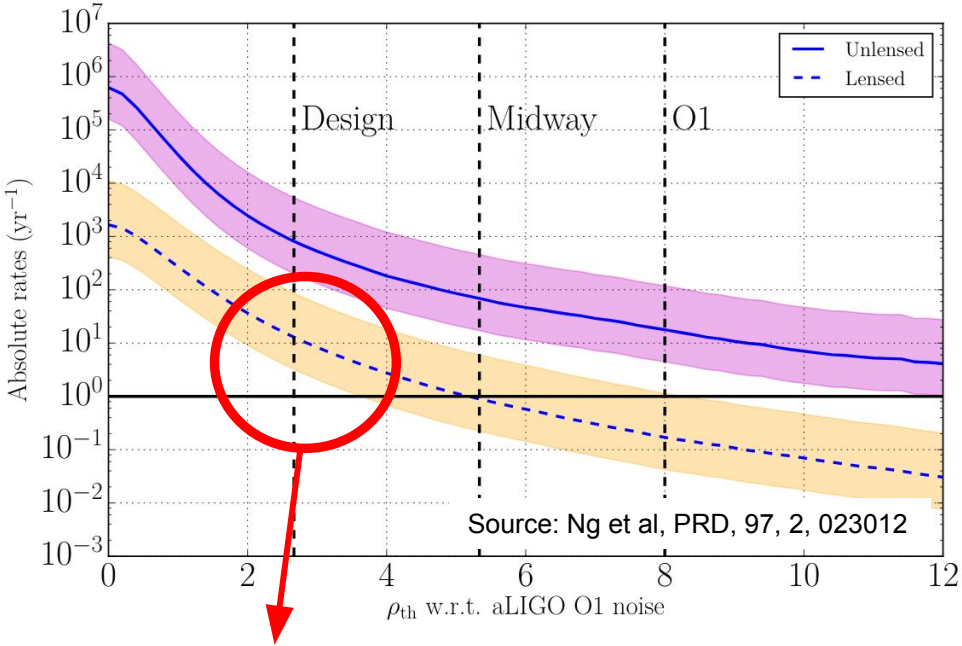


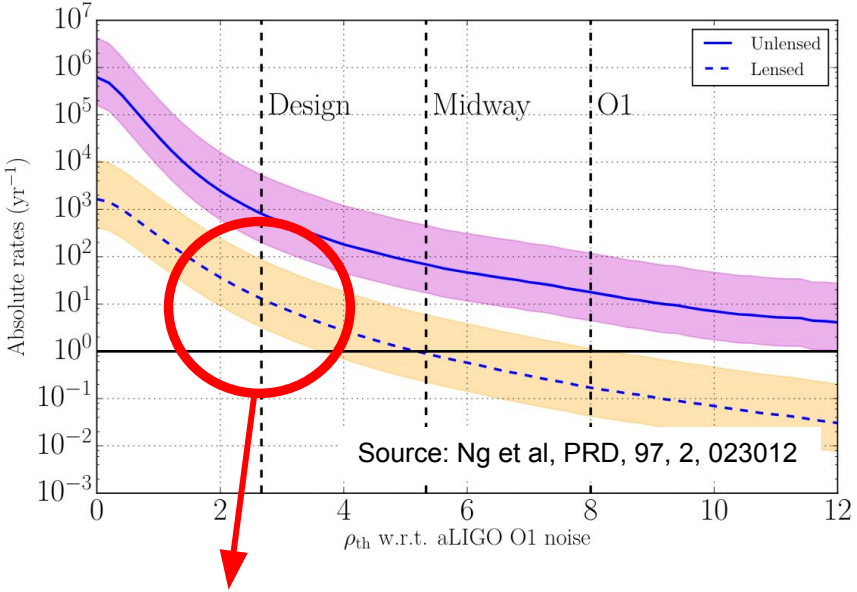
Could be detected soon!

Searches are already ongoing:

- In GWTC-2: Hannuksela et al, 2019
- In GWTC-3.1: LIGO & Virgo, 2021

} No signs of lensing yet

Why is this interesting?

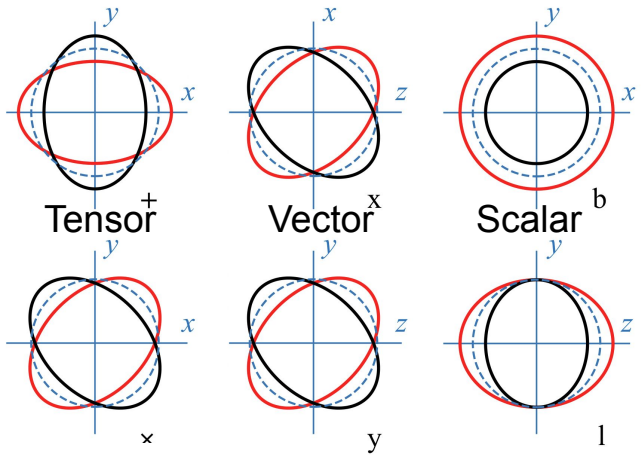


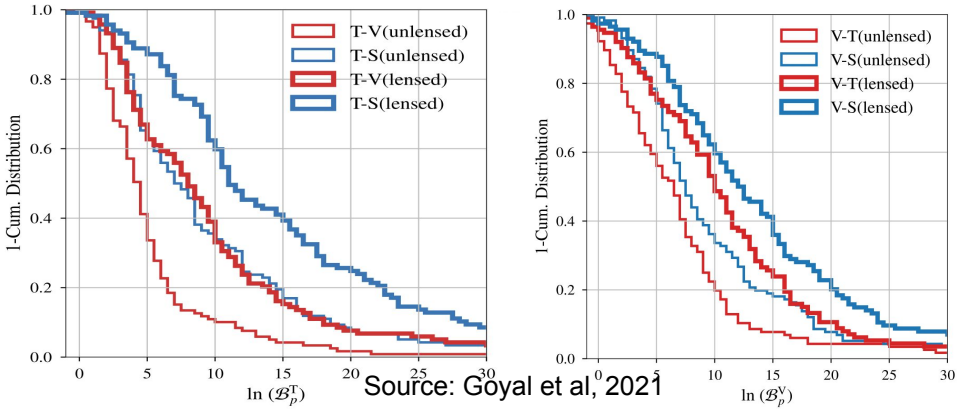
Could be detected soon!

Some interesting science cases:

For example:

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





Source: Goyal et al, 2021

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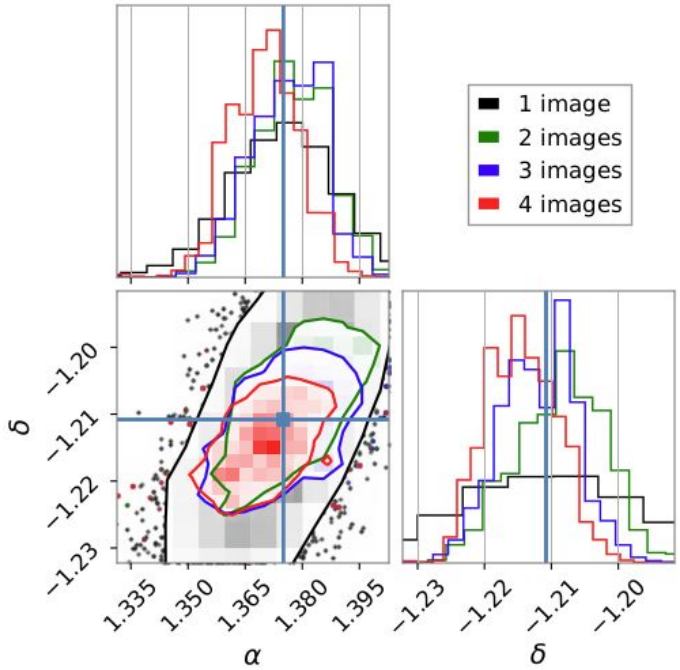
Where is the multi-messenger?

→ The increase in effective number of detectors lead to an improved sky location!



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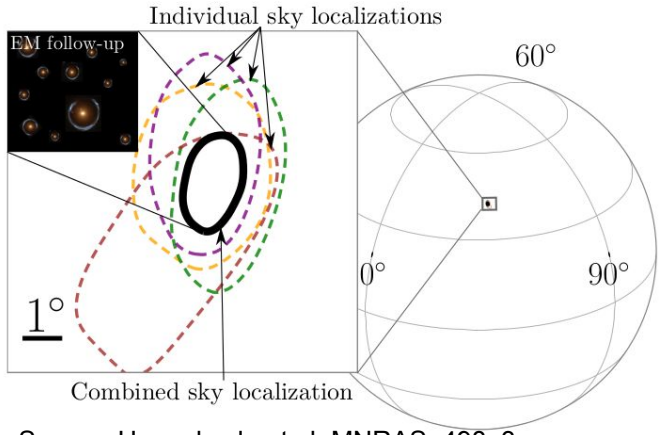
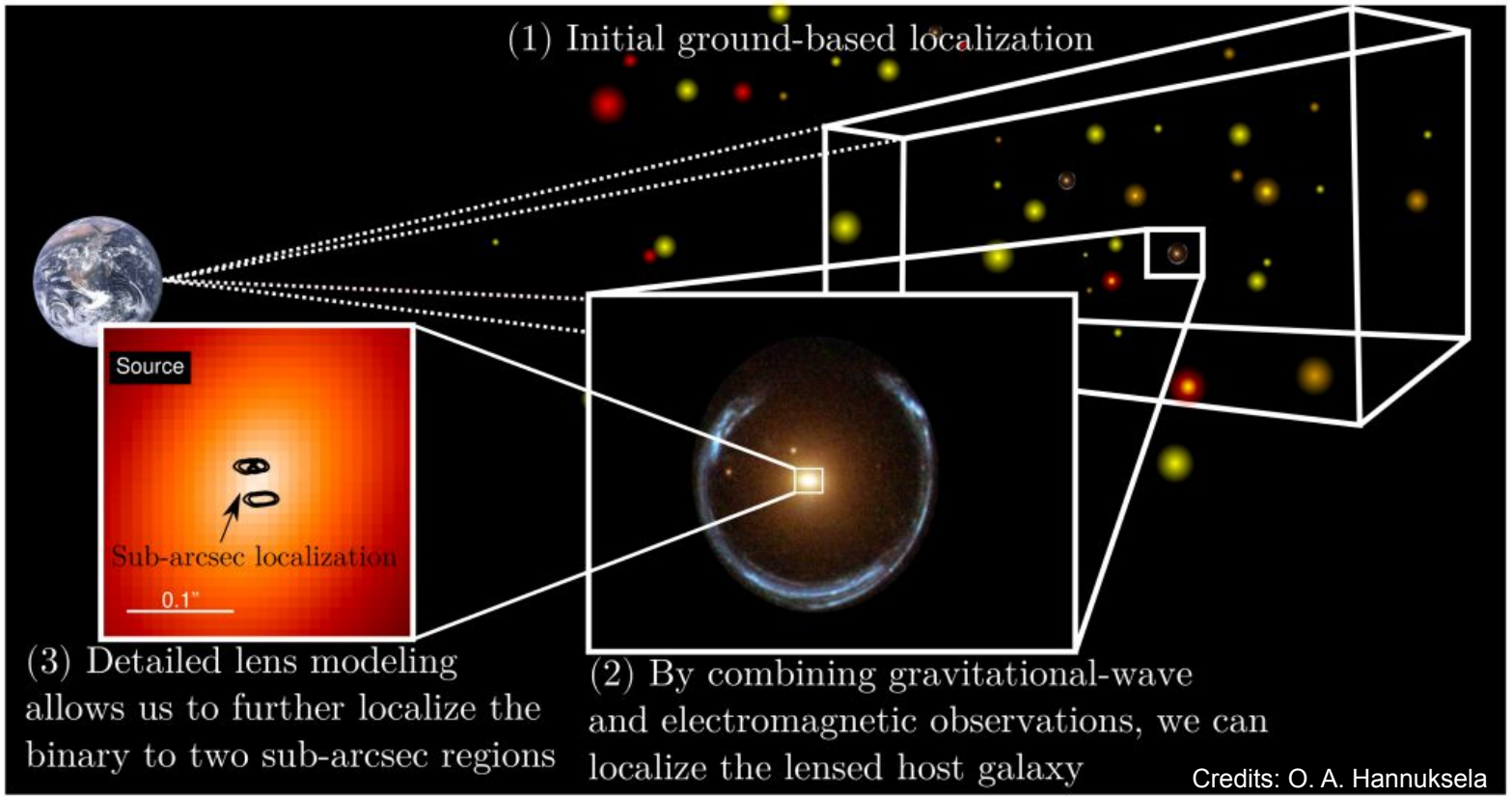


Source: Hannuksela et al, MNRAS, 498, 3

Where is the multi-messenger?

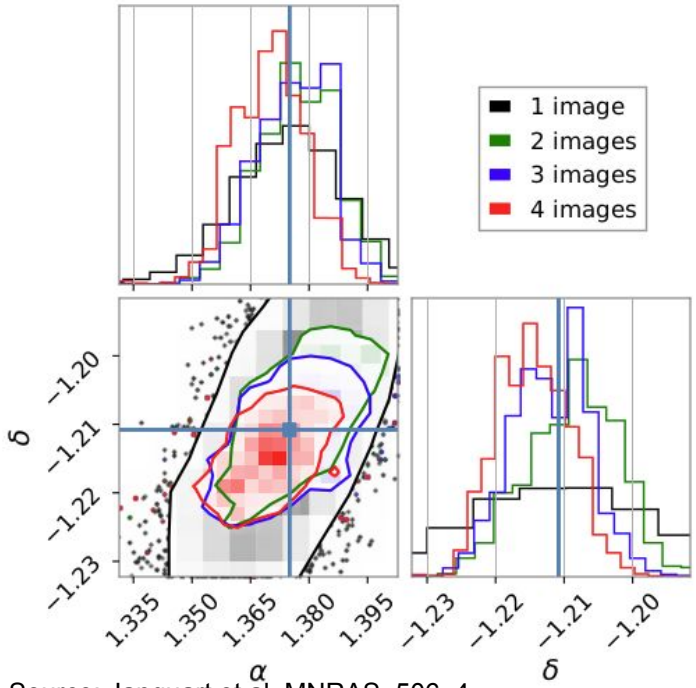
Assuming the merger happens in a Galaxy, the electromagnetic signal should also be lensed → Using this and gravitational wave information, one can identify the lens and the host galaxy in the reduced sky area.



→ **We have our counterpart!**

How much does lensing actually help?

For the **sky location** itself: Depends on the number of images but can be significant depending on the individual images



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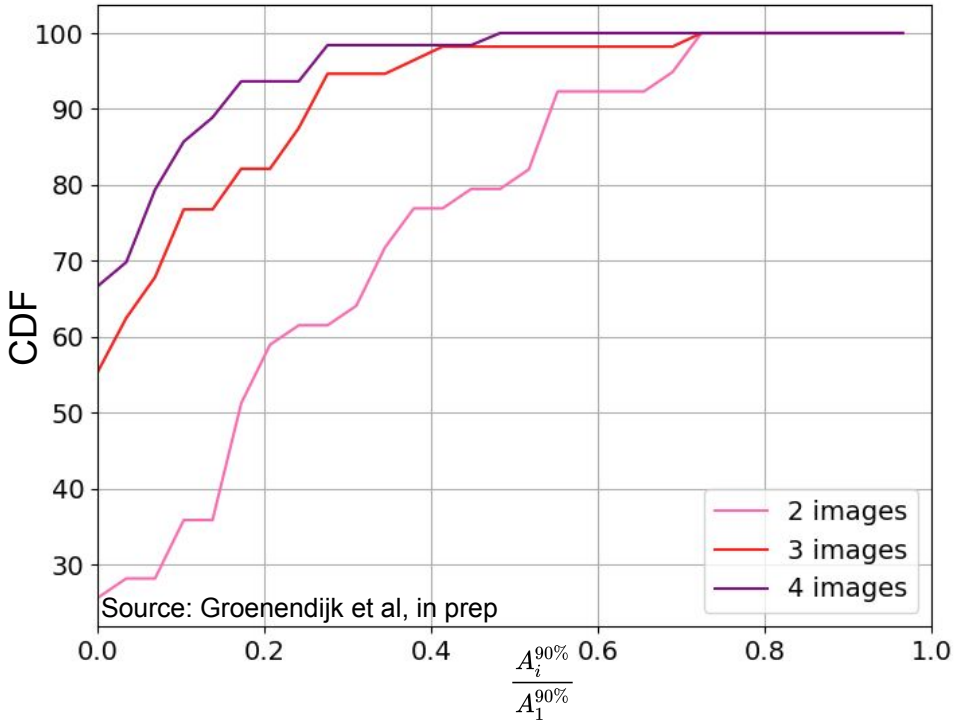

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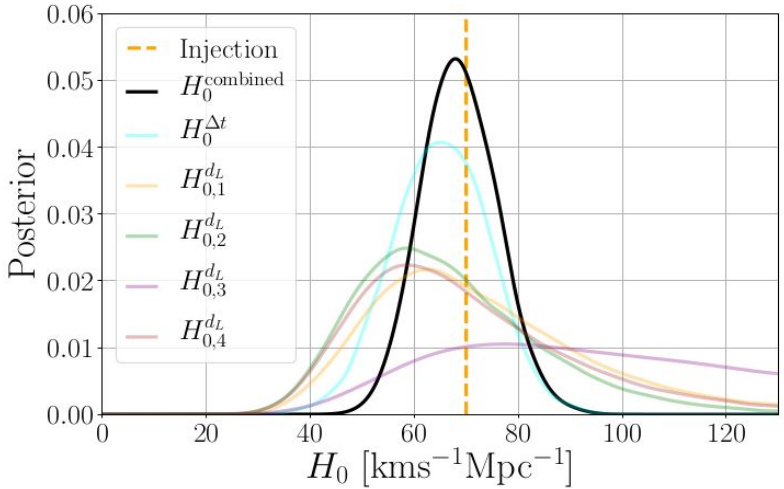
For **science cases**:

- Since black hole mergers can be seen further than neutron star mergers, any cumulative effect (speed of gravity, dispersion, …) can accumulate more and lead to a stronger effect
- The multiple images can lead to several measure of the same information, leading to a better measurement



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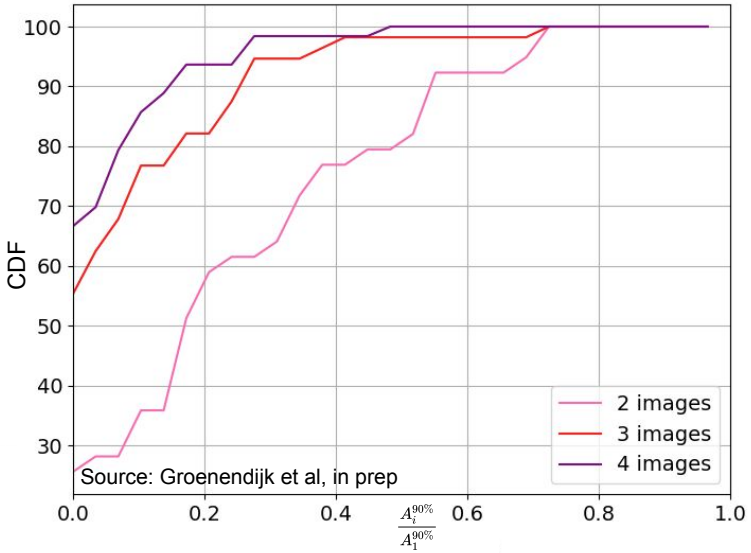

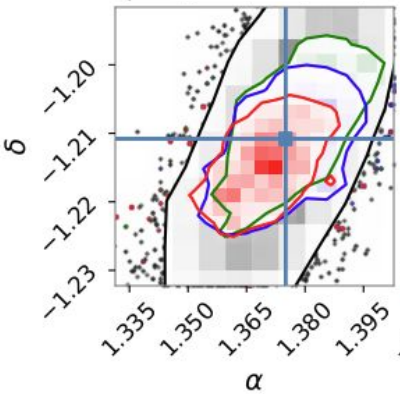

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What can we do in the end?

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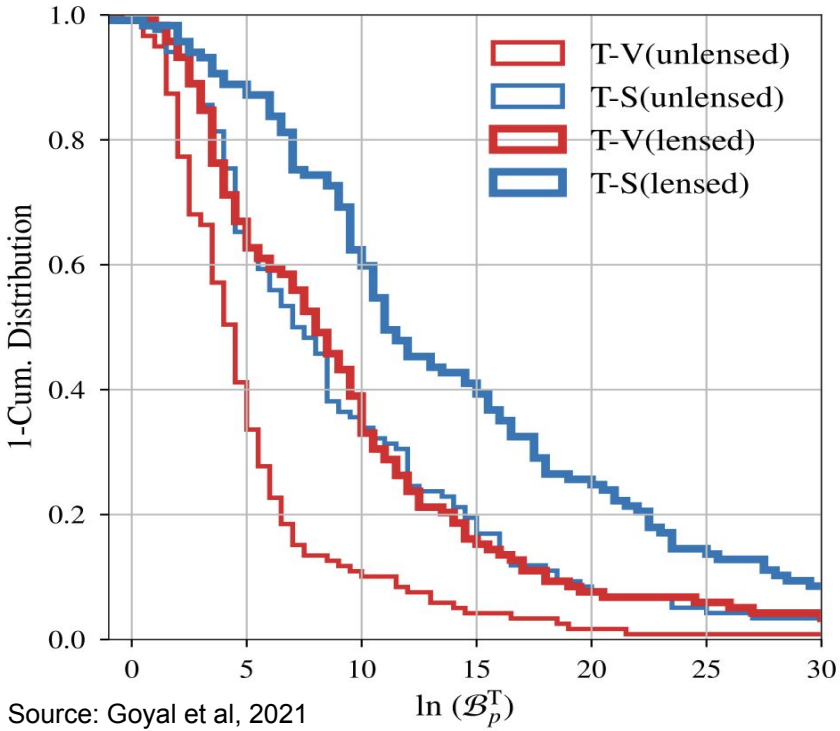
- Probing of higher-order modes (Janquart et al, 2021)



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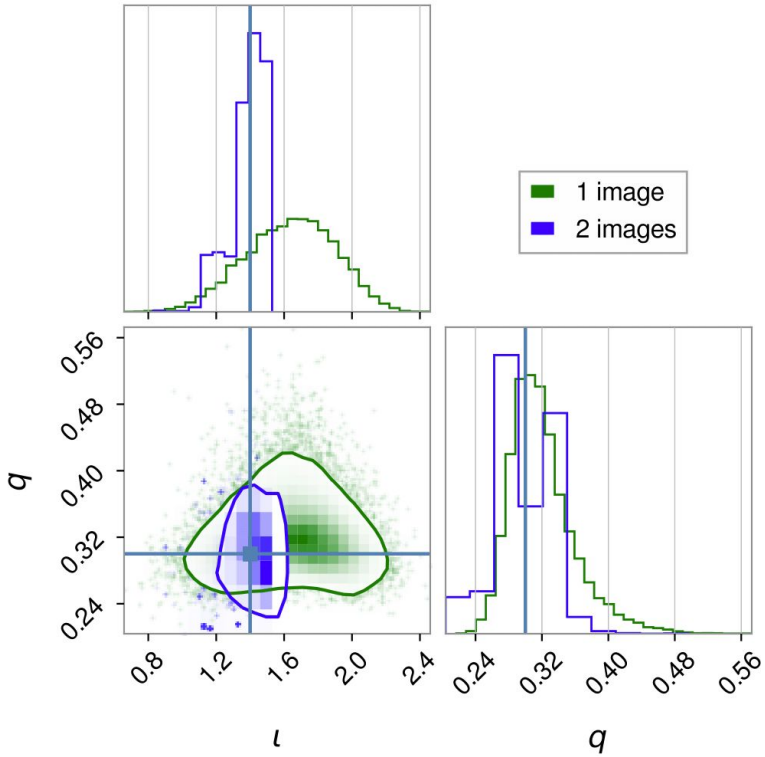

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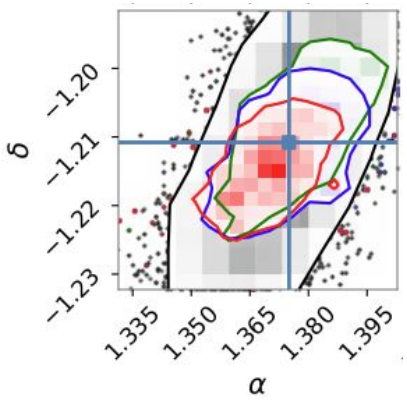
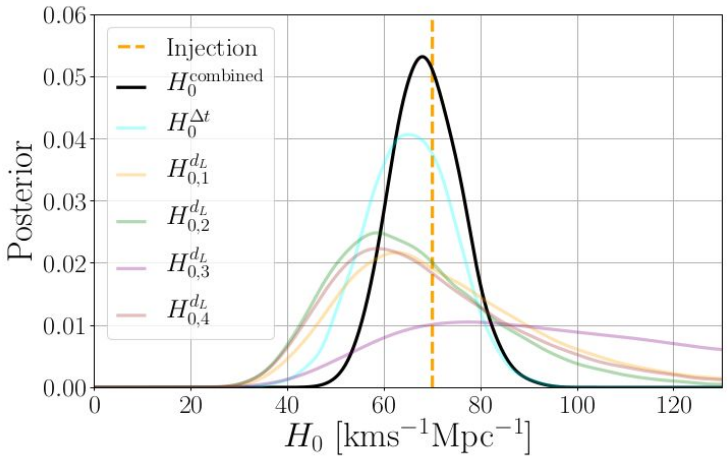
What can we do in the end?

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





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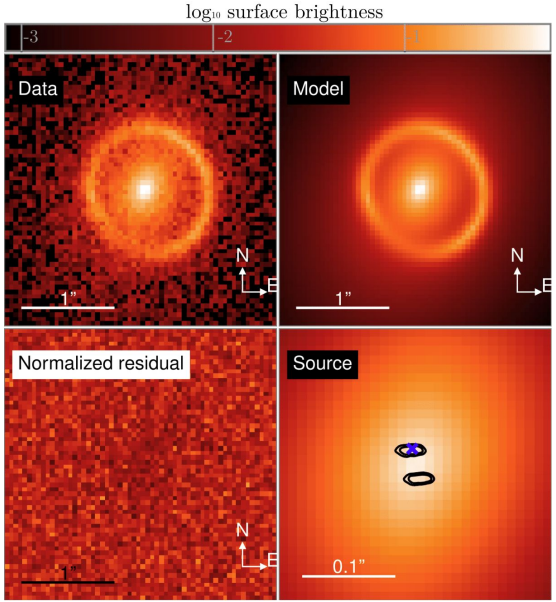

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And in the end?

- Gravitational waves **can be lensed**
- Gravitational wave lensing is an **active field** of research
- Strong lensing of gravitational waves **is upon us** and they would manifest themselves as **repeated events with the same frequency evolution**
- There are **still some challenges to confidently identify** strongly-lensed gravitational wave events
- If identified, strong lensing would open the door to **many interesting science cases** such as a better study of the events themselves based on their higher-order mode content, investigation of the gravitational wave polarization content, … without electromagnetic counterpart
- If, in addition, there is an **electromagnetic counterpart identified, even more tests would be possible**, such as the study of the origin of binary black holes, tests for cosmology, tests of general relativity.

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Thank you for your attention!