Gravitational-wave lensing with ground-based gravitational-wave detectors

GdR Gravitational Waves, Cosmology talk (28-01-2021)

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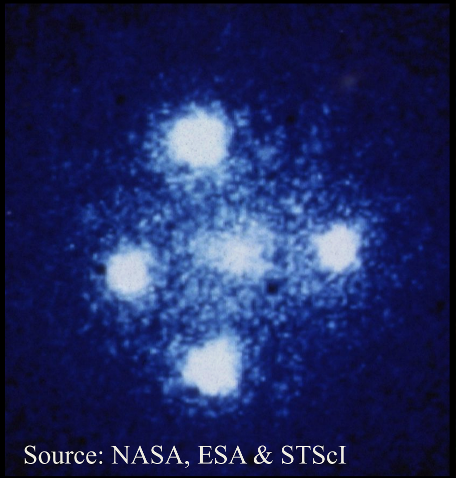
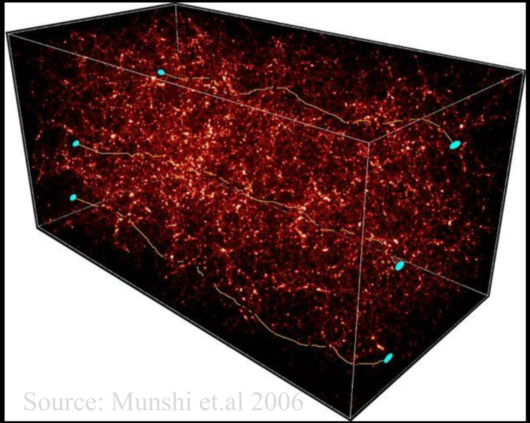
What I'll talk about

- What is gravitational-wave lensing and why is it interesting?
- GWTC-1 search for lensing
- Current status of methodologies
- What to do with a detection?
- Conclusions

Gravitational lensing of light



Source: NASA, ESA & STScI

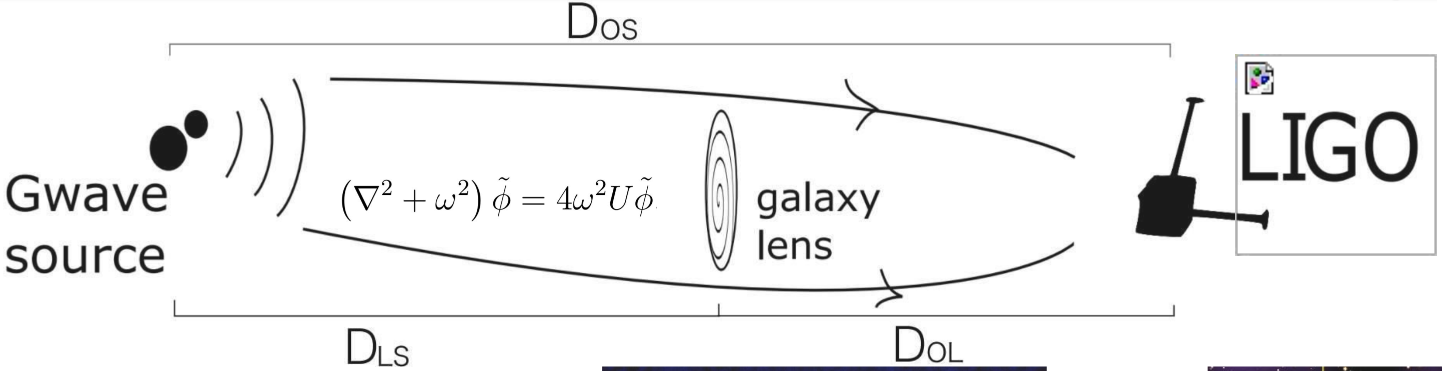


Source: Munshi et.al 2006

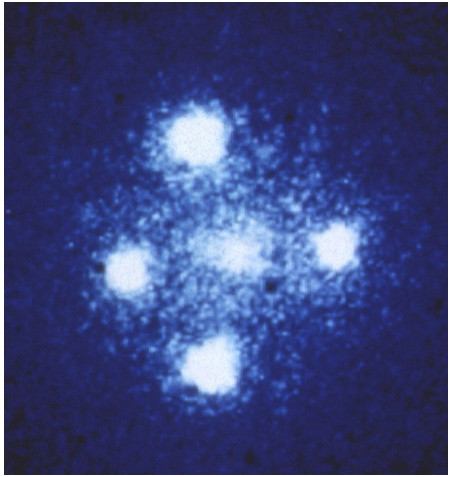
Source: NASA

Source: Chandra

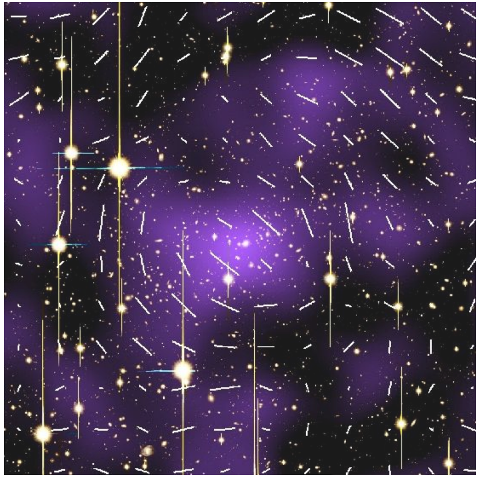
Gravitational wave lensing



ESA/Hubble & NASA

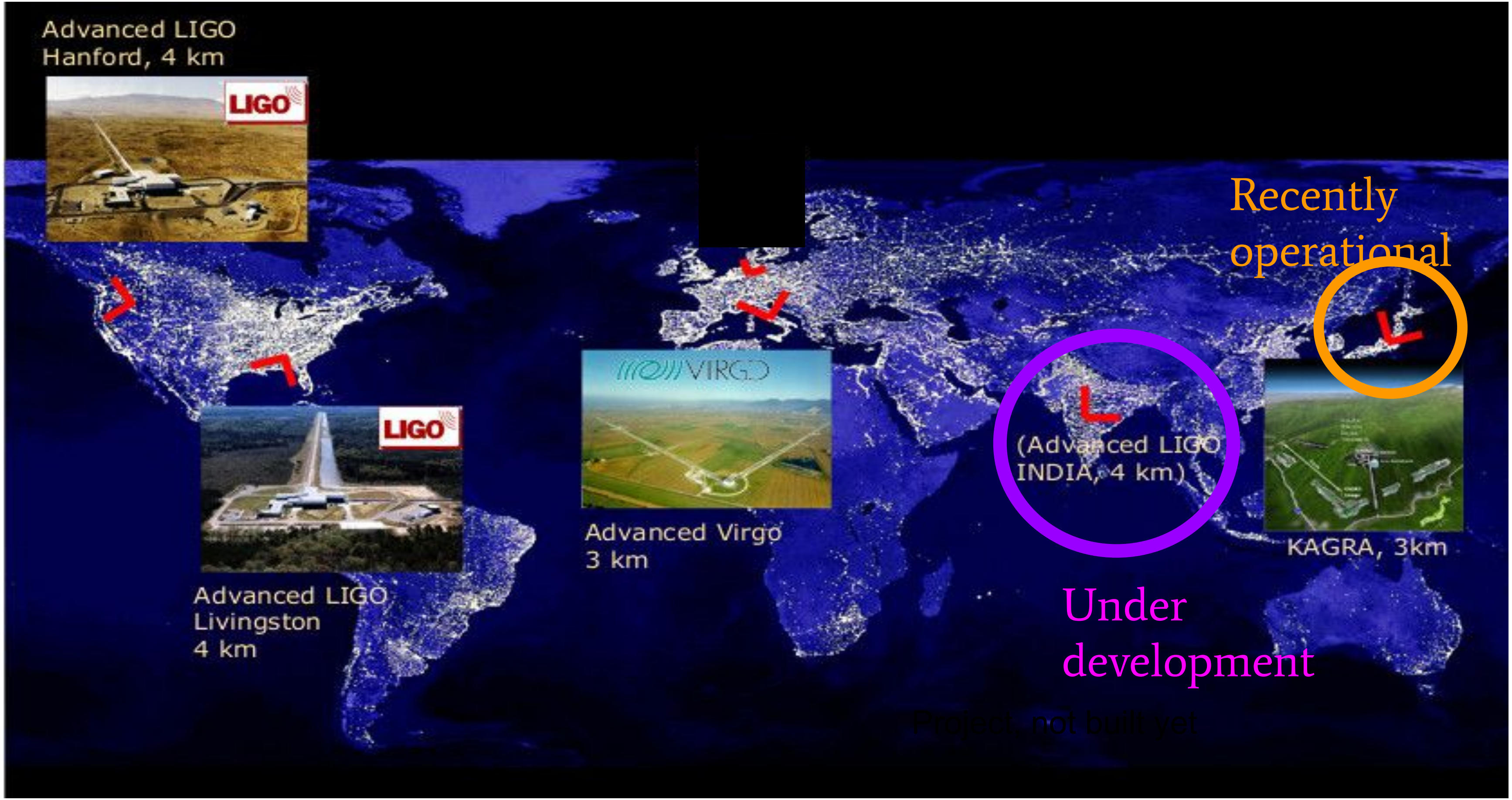


NASA, ESA & STScI

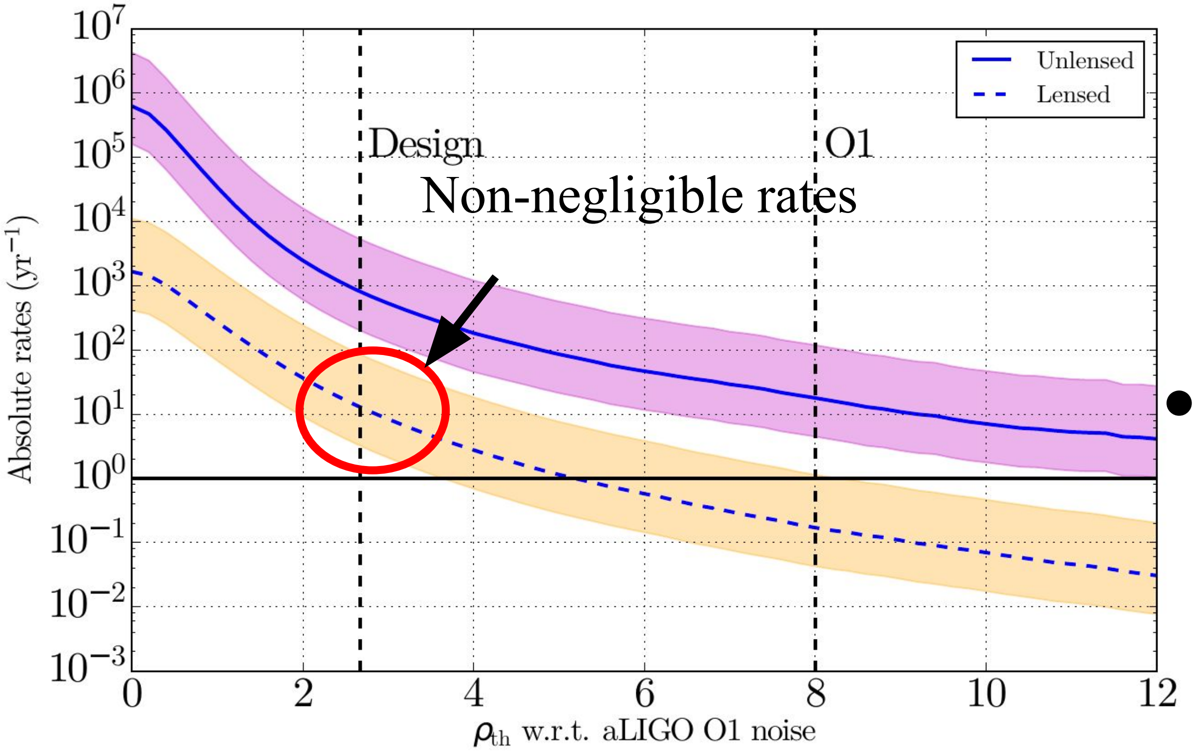


Oguri et al.

Why is gravitational-wave lensing exciting?



Why is gravitational-wave lensing exciting?



- Forecasts predict strong lensing at a reasonable rate

Ng et al. (2017); see also *Li et al. (2018)*, *Oguri (2018)*

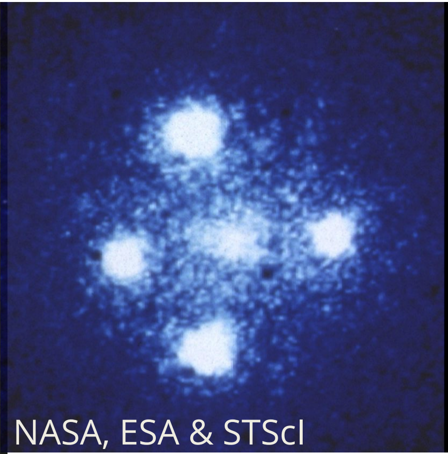
Why is gravitational-wave lensing exciting?

An entirely new avenue to probe gravitational lensing

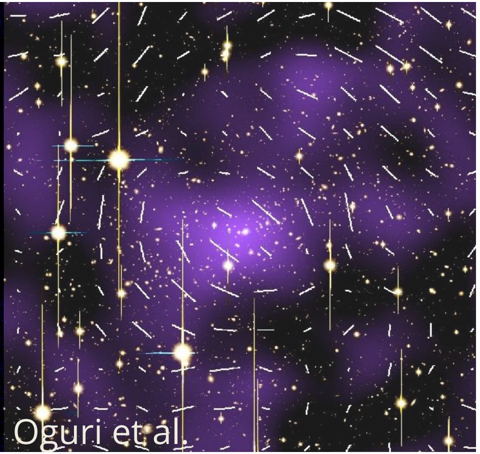
→new studies of astrophysics, cosmology, and fundamental physics

- **Study the origin of black holes** *(Hannuksela et al. 2020)*
- **Tests of fundamental physics** *(Collett & Bacon 2017,Wong et al., in prep)*
- **Study the expansion of the Universe** *(Baker & Trodden 2017, Liao et al. 2017, Hannuksela et al. 2020)*
- **Study microlens populations** *(Lai et al. 2018, Jung et al., 2019)*
- **Study wave optics** *(Cheung et al., 2020)*


ESA/Hubble & NASA


NASA, ESA & STScI

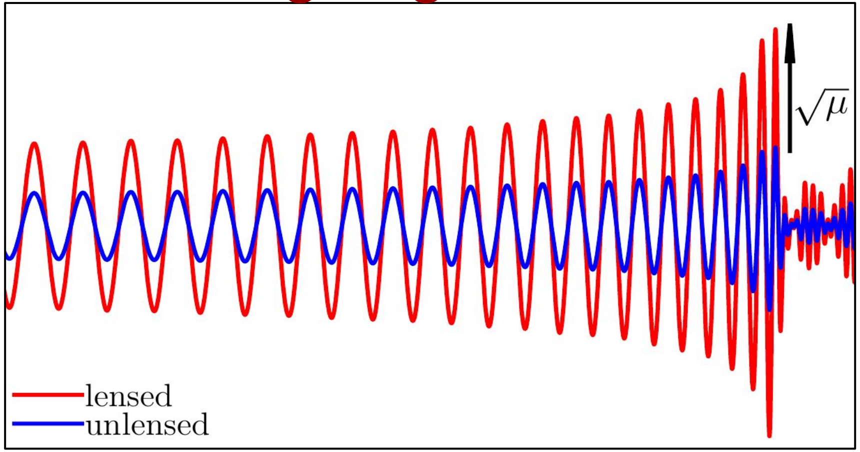
Chandra


Oguri et al.

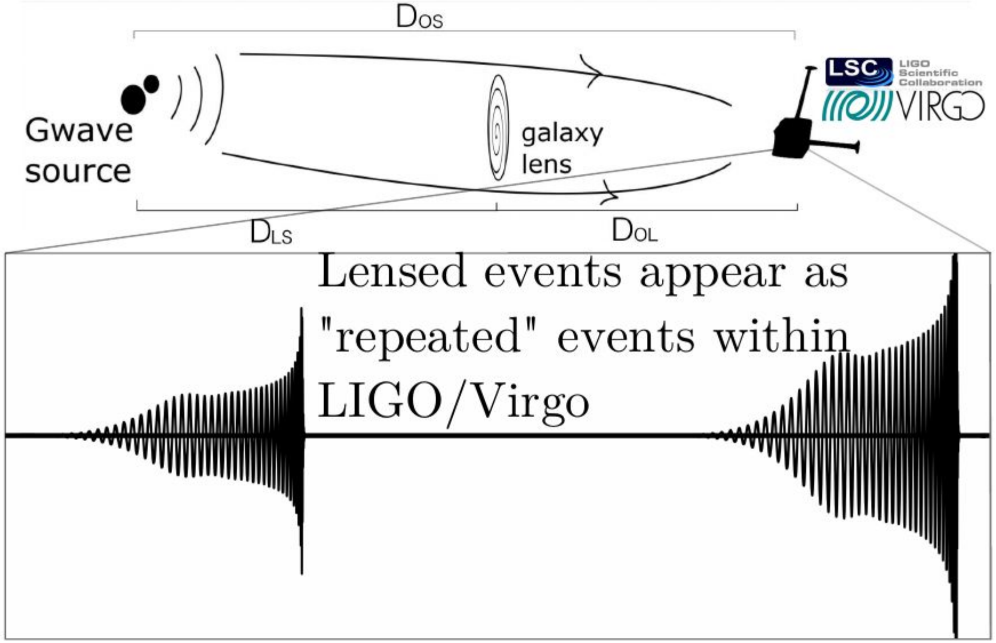
What signatures does lensing produce?

Transformation: $h(f) \to h_L(f) = F(f)h(f)$

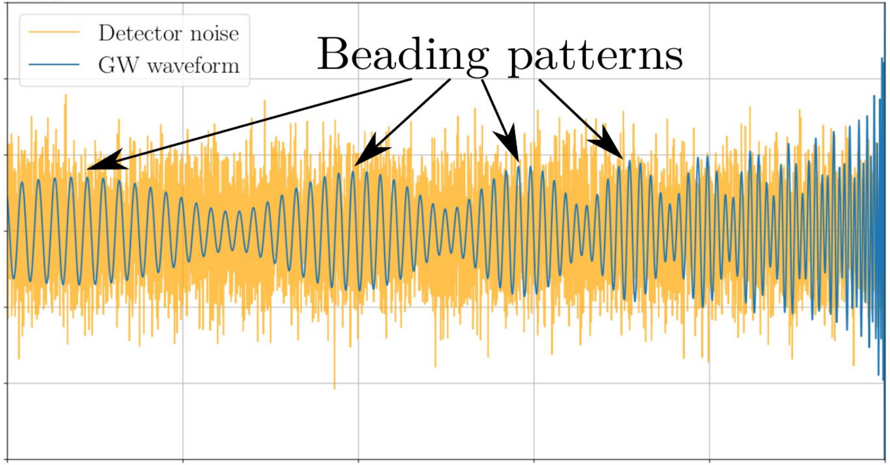
Lensing magnification



Strong lensing multi-images

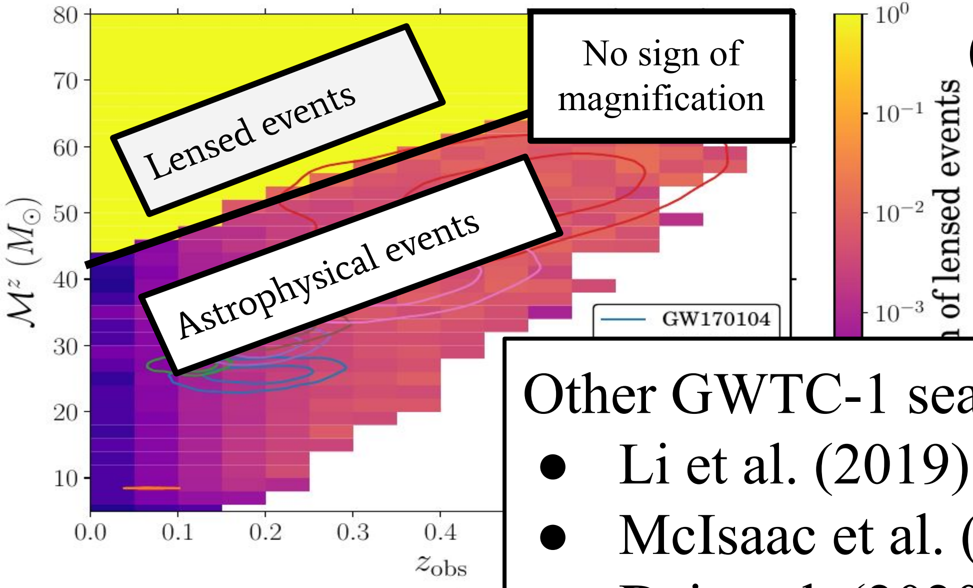


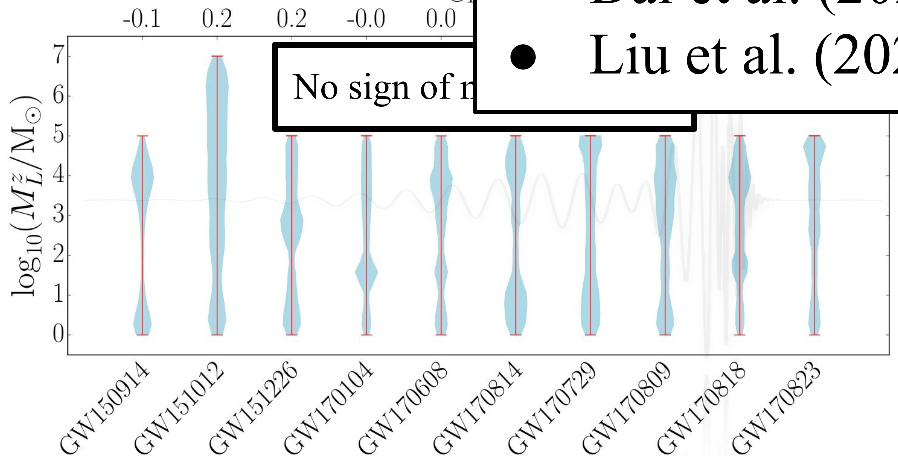
Microlensing distortions

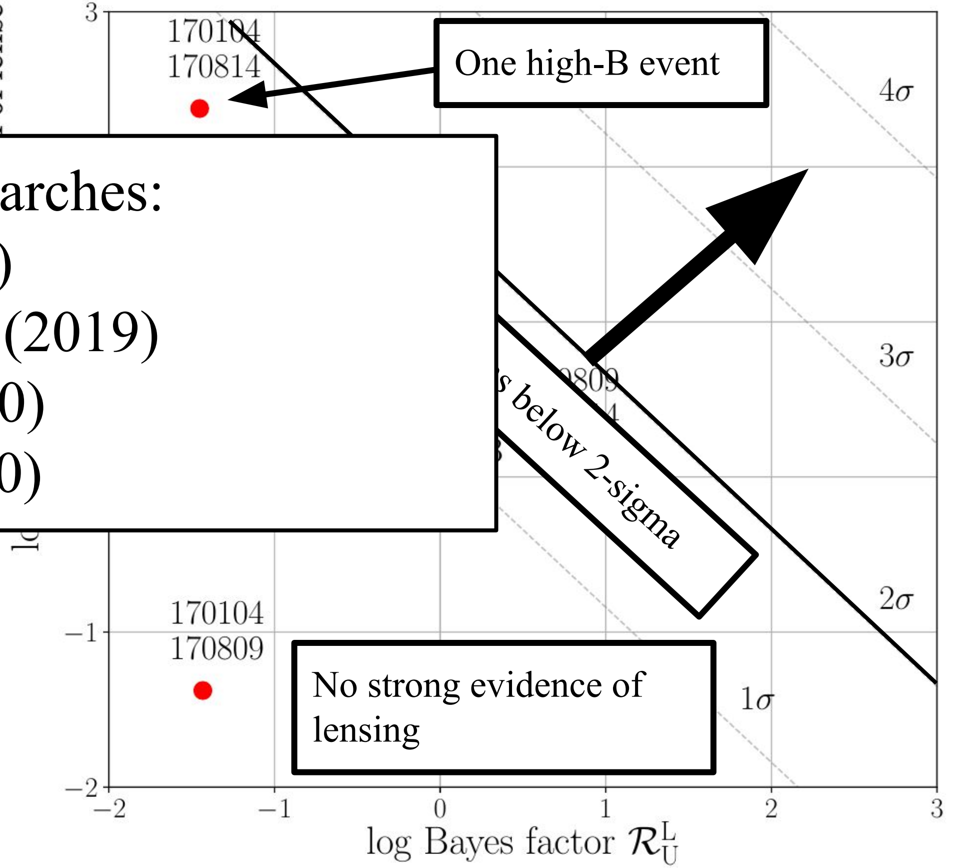


GWTC-1 lensing study

Hannuksela OA, Haris K, Ng KKY, Kumar S, Mehta AK, Keitel D, Li TGFL, Ajith P.
Astrophysical Journal Letters (2019)



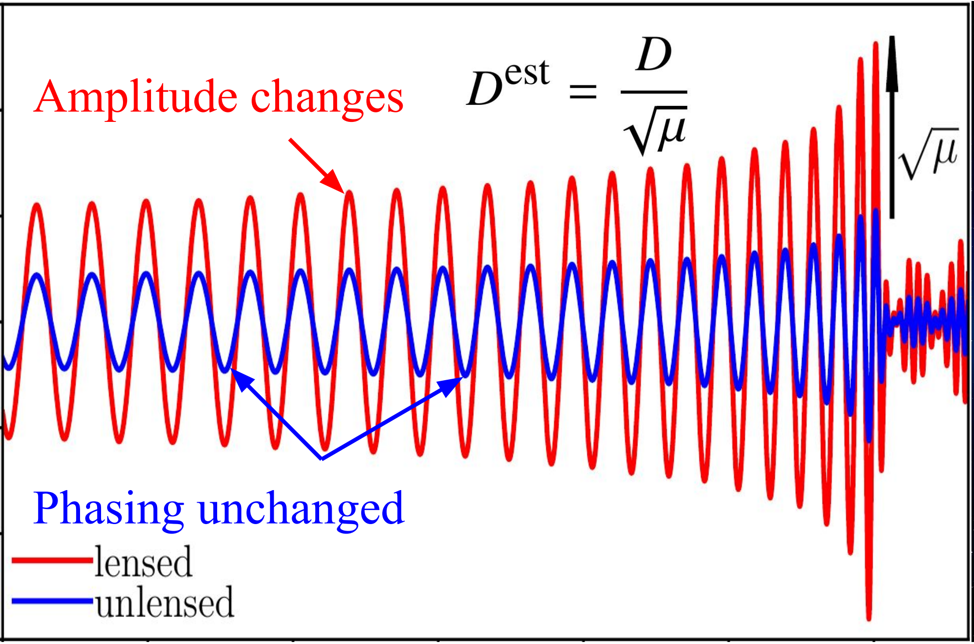


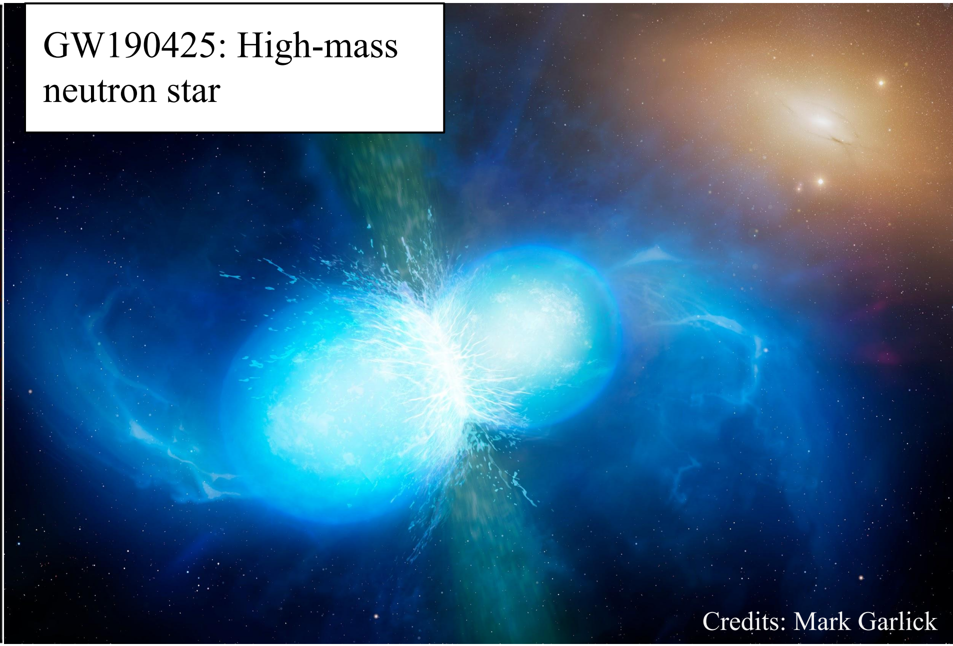


Other GWTC-1 searches:

- Li et al. (2019)
- McIsaac et al. (2019)
- Dai et al. (2020)
- Liu et al. (2020)

Methodologies to search for magnification



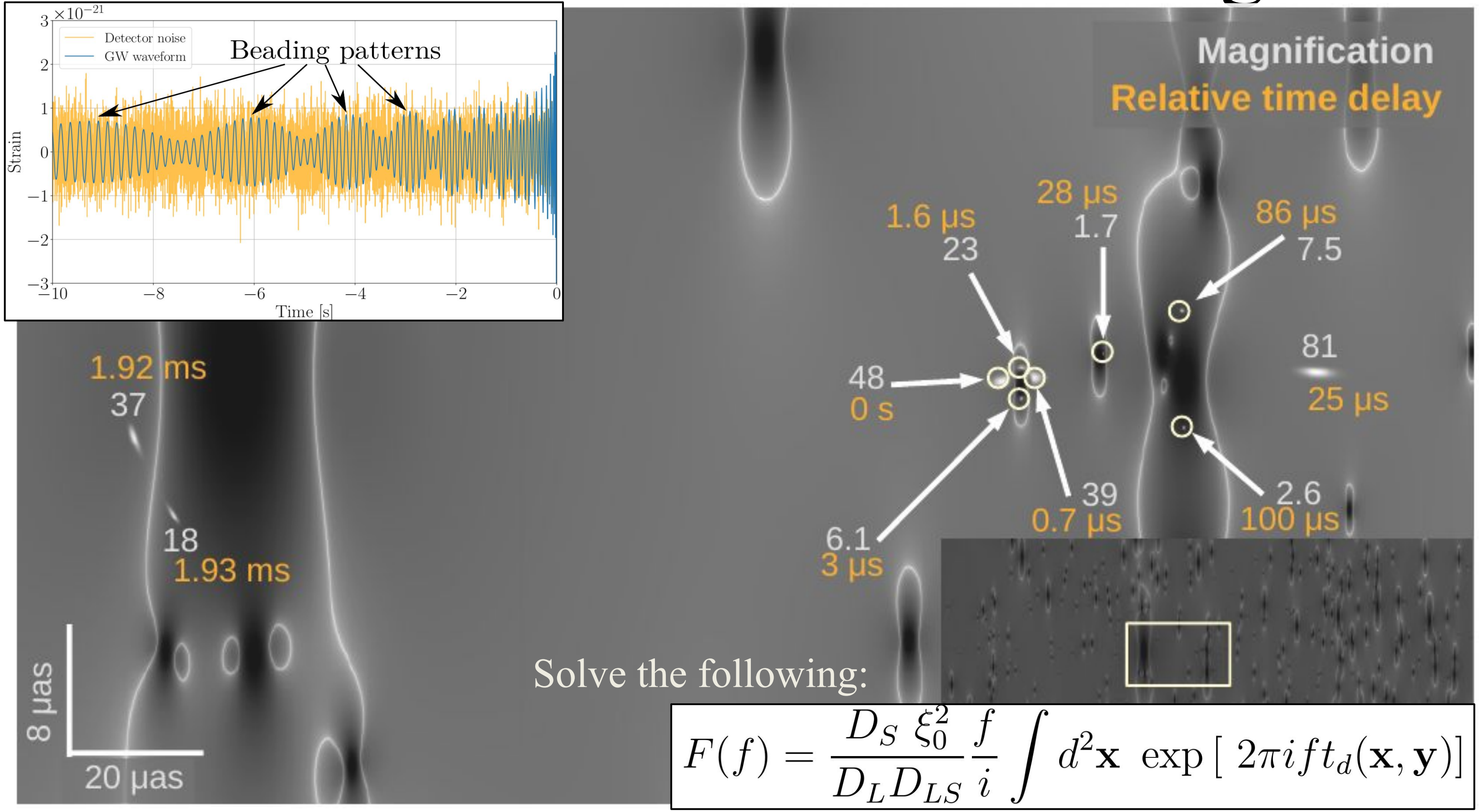


- A method to analyze the image properties of high-mass events
- A tidal test that allows for smoking-gun lensing evidence

- Gravitational-wave lensing tidal test
- Ruled out as a high-magnification event
- Found no evidence of lensing

Pang PTH, Hannuksela OA, Dietrich T, Pagano G, Harry IW. MNRAS *(2020)*

Searches for microlensing

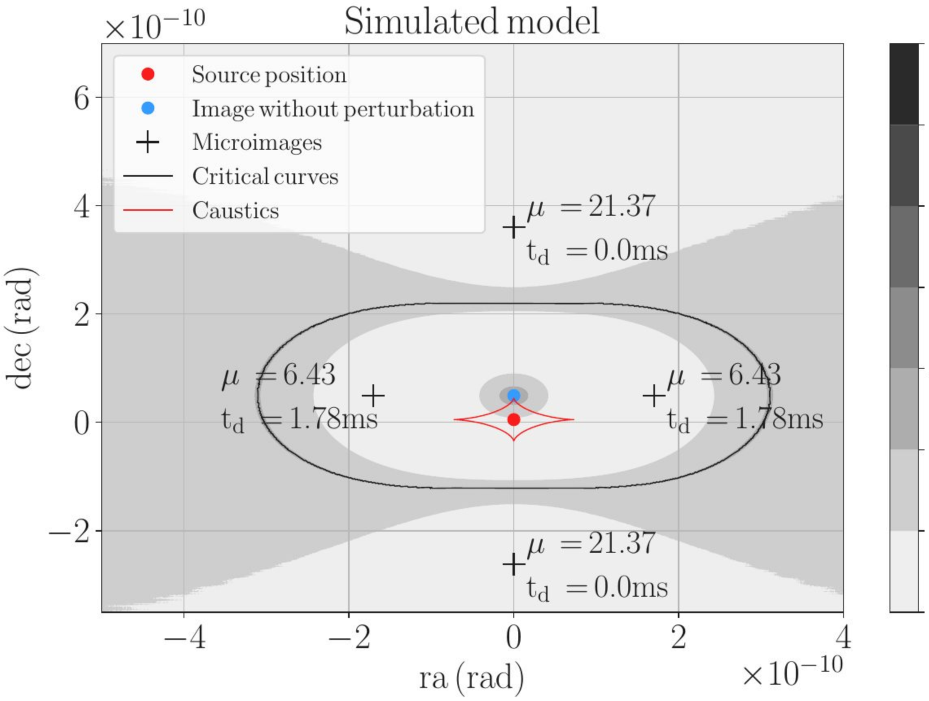


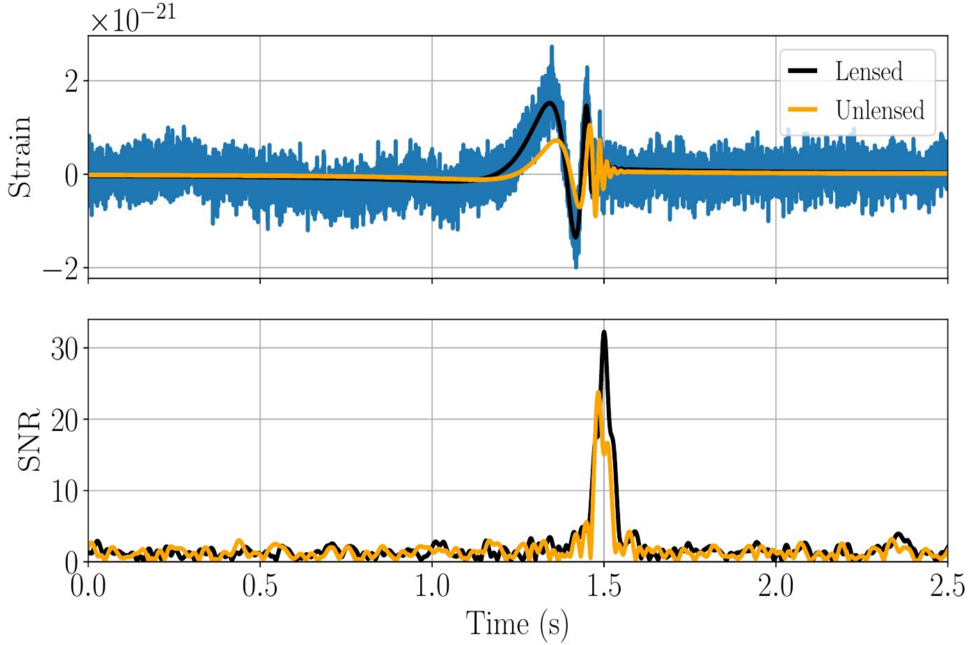
Solve the following:

$$F(f) = \frac{D_S\ \xi_0^2}{D_L D_{LS}} \frac{f}{i} \int d^2\mathbf{x}\ \exp\left[\ 2\pi i f t_d(\mathbf{x}, \mathbf{y})\right]$$

Diego et al. (2019)

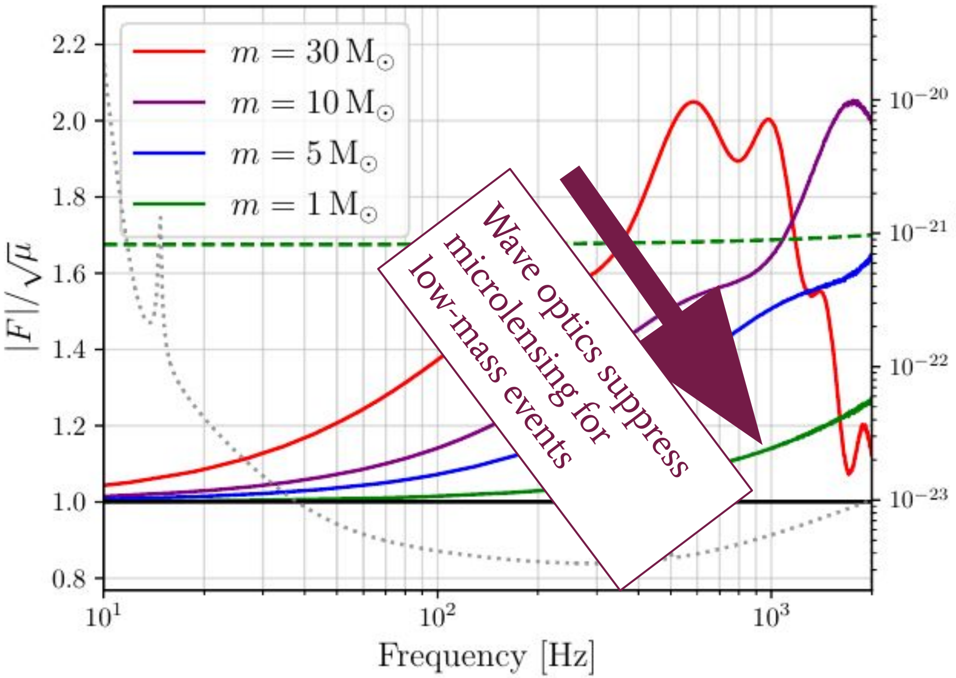
On-going microlens modeling

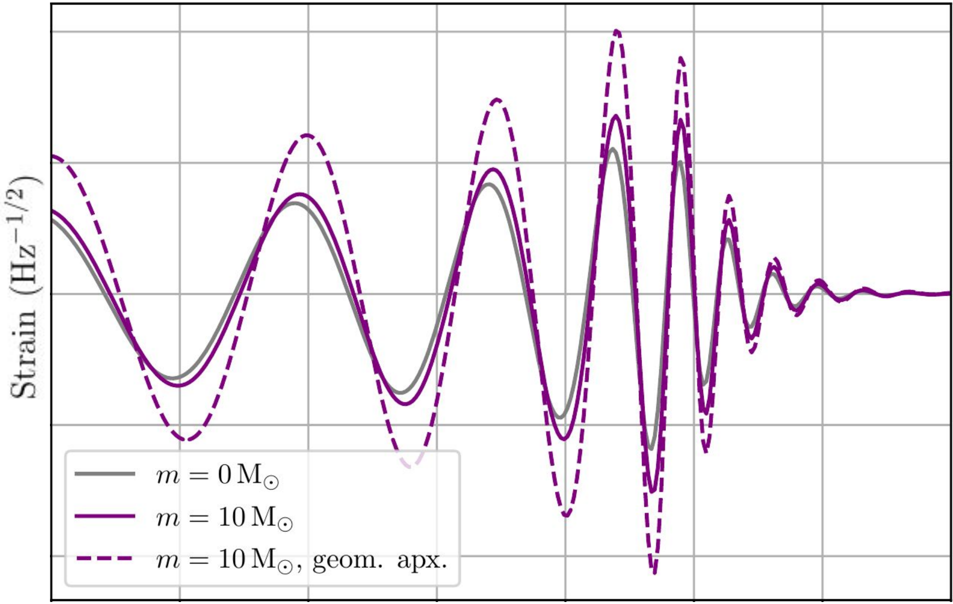




Pagano G, Hannuksela OA, Li TGF. *Astronomy & Astrophysics (2020)*

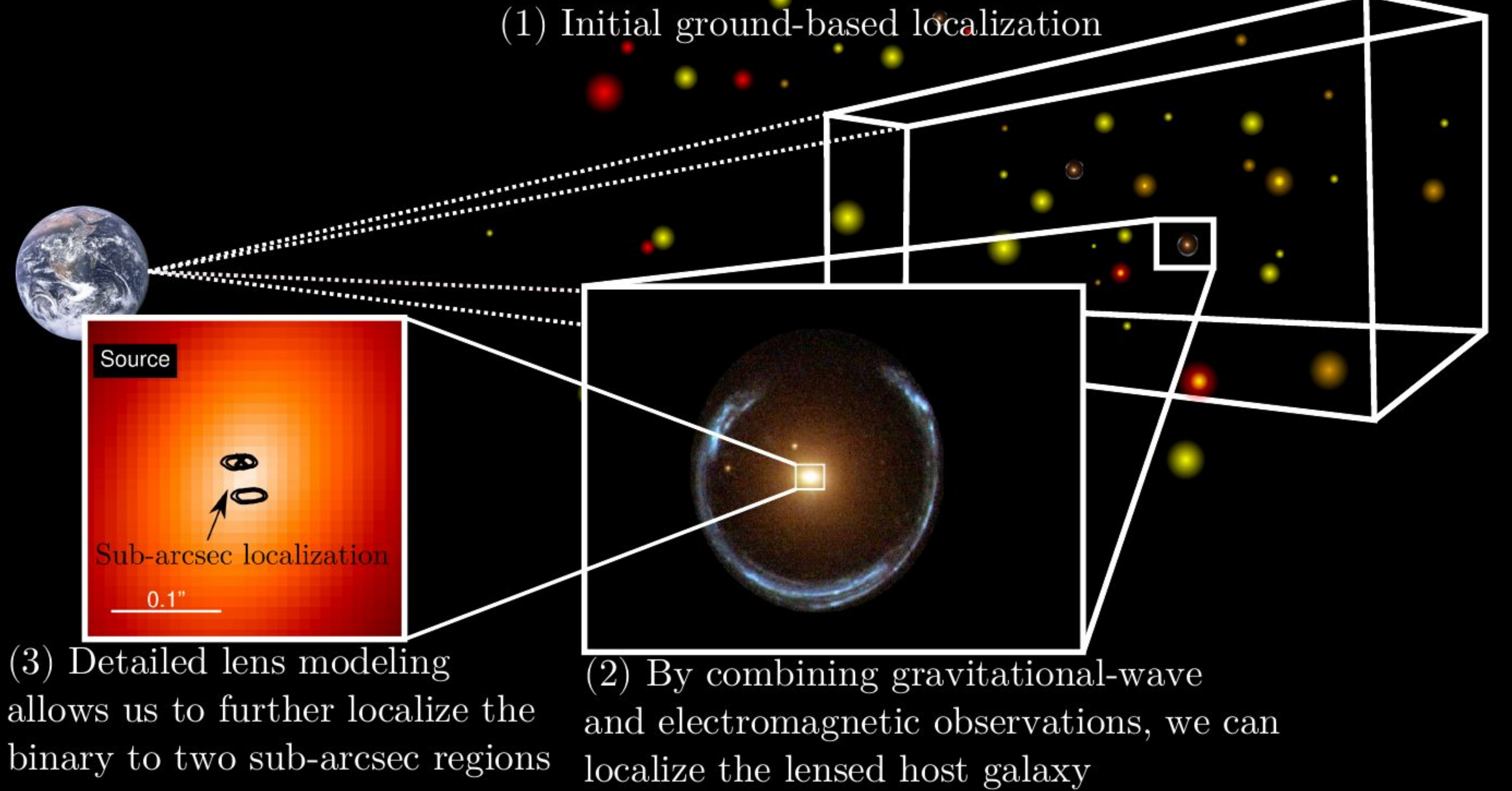
Microlensing: Wave optics effects





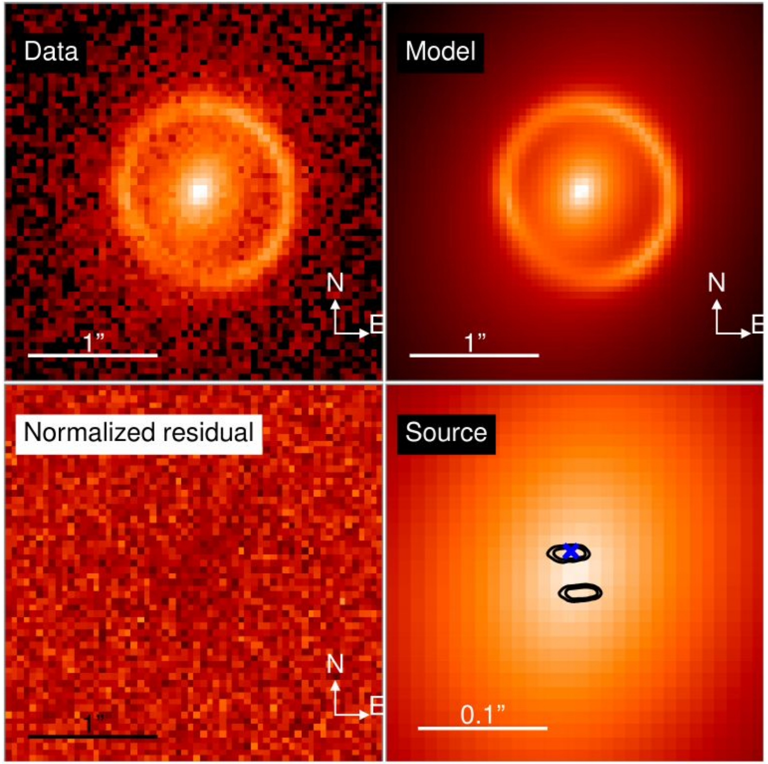
Cheung MHY, Gais J, Hannuksela OA, Li TGF. *arxiv:2012.07800*

Once we detect lensing, what do we do with it?



Localizing strongly lensed events: *Hannuksela et al. (2020)*

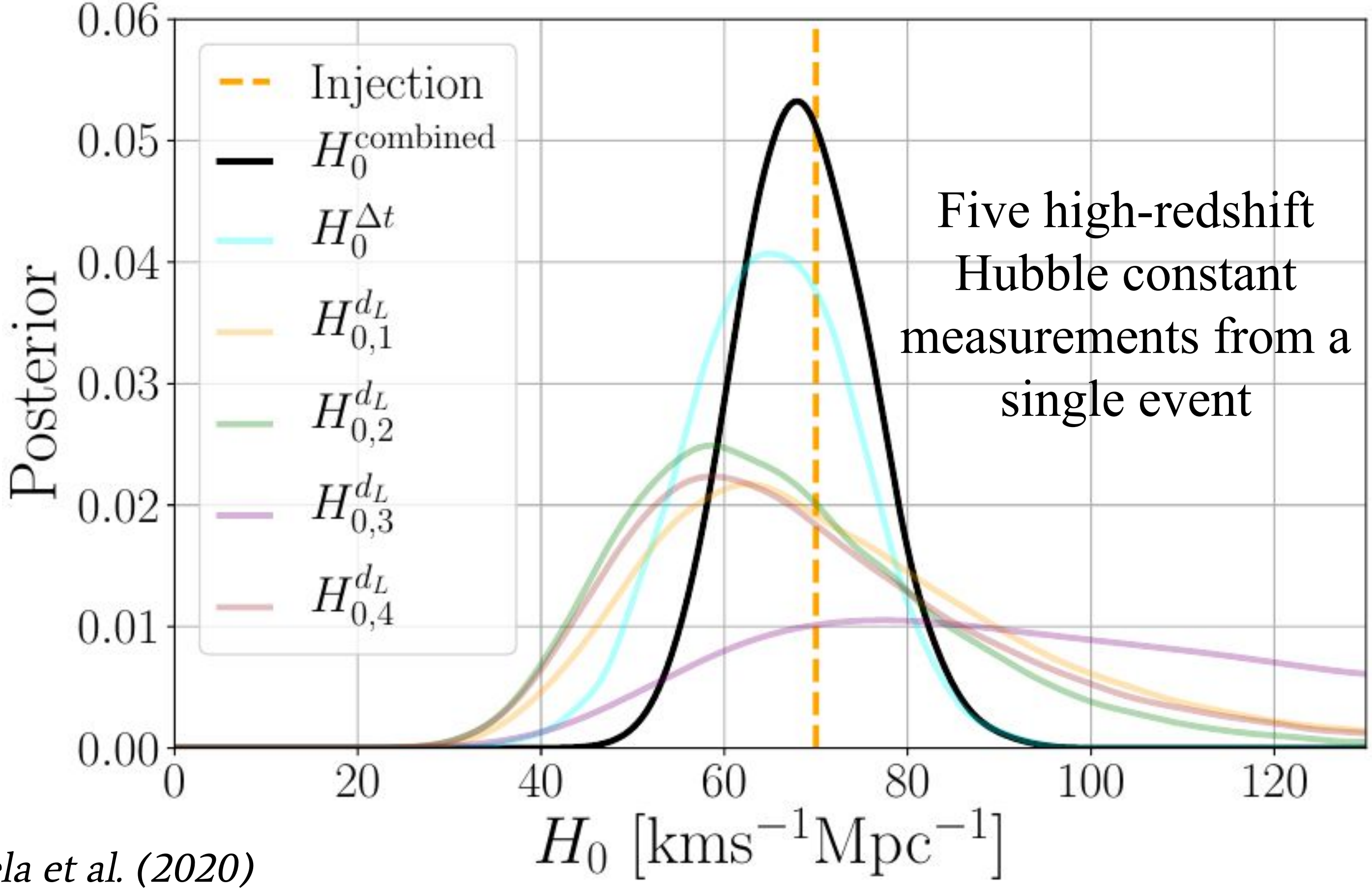
Combine gravitational-wave and electromagnetic measurements



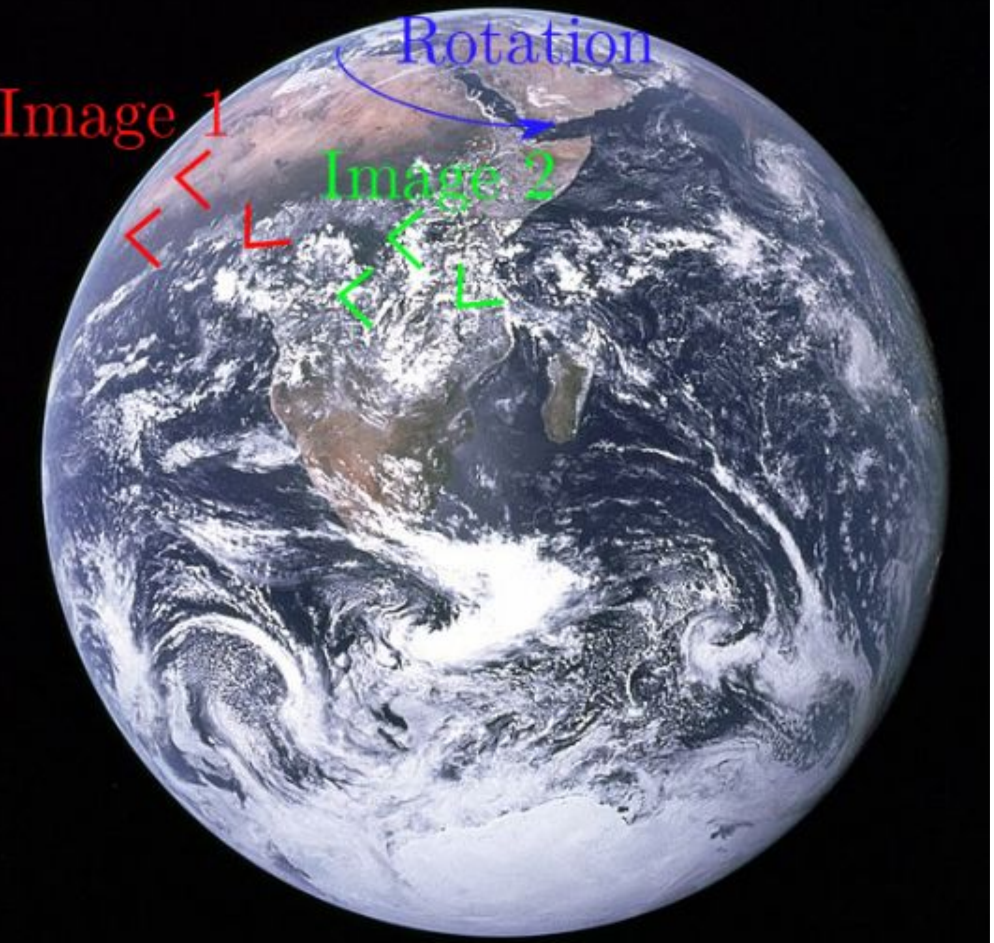
- Model gravitational waves and electromagnetic observations in unison

Hannuksela et al., *Monthly Notices of Royal Astronomical Society* (2020)

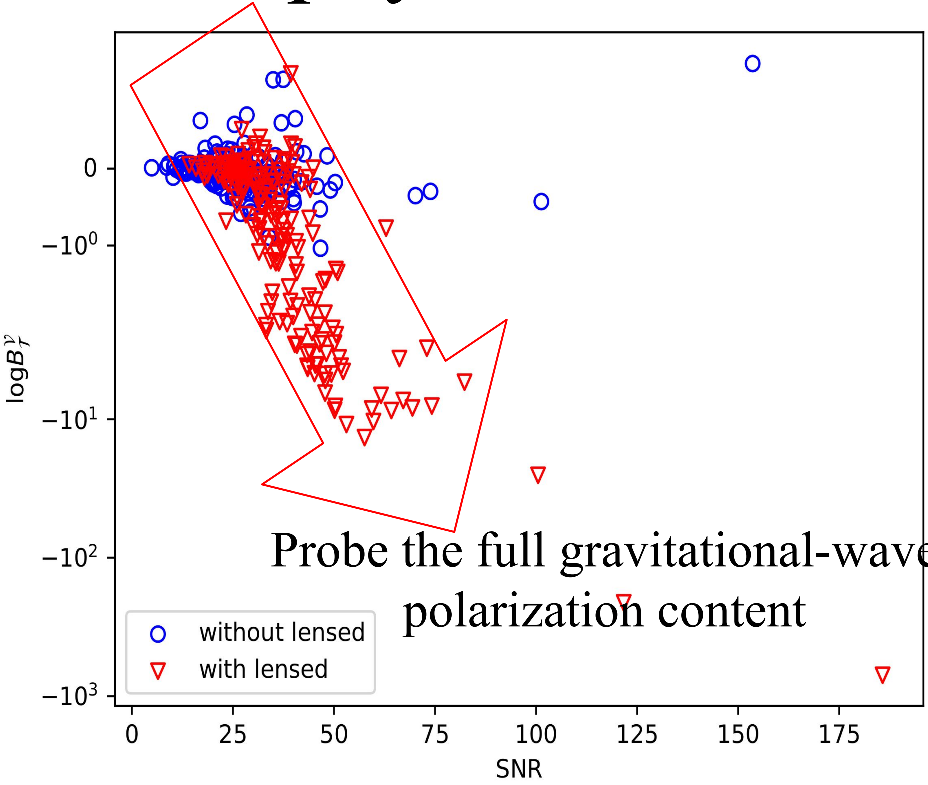
Study the expansion of the Universe



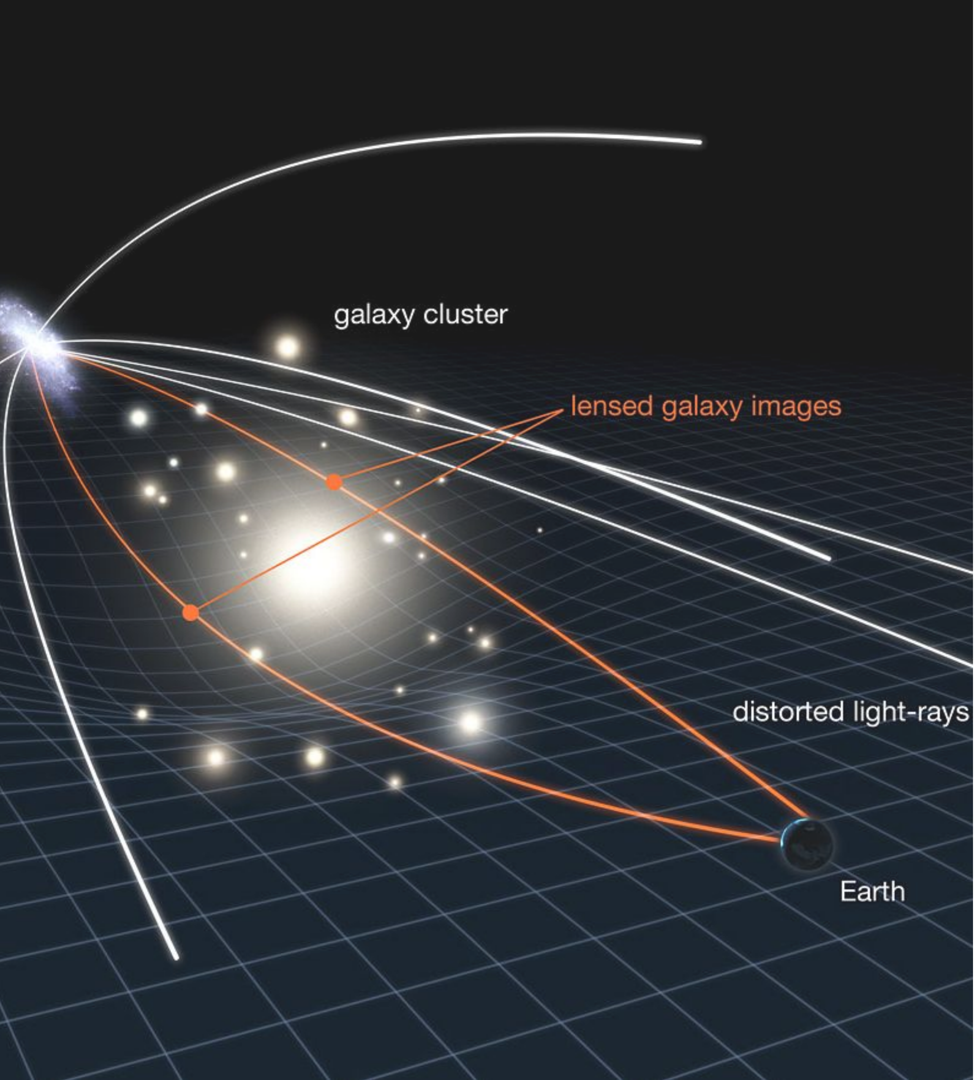
Hannuksela et al. (2020)



Study fundamental physics

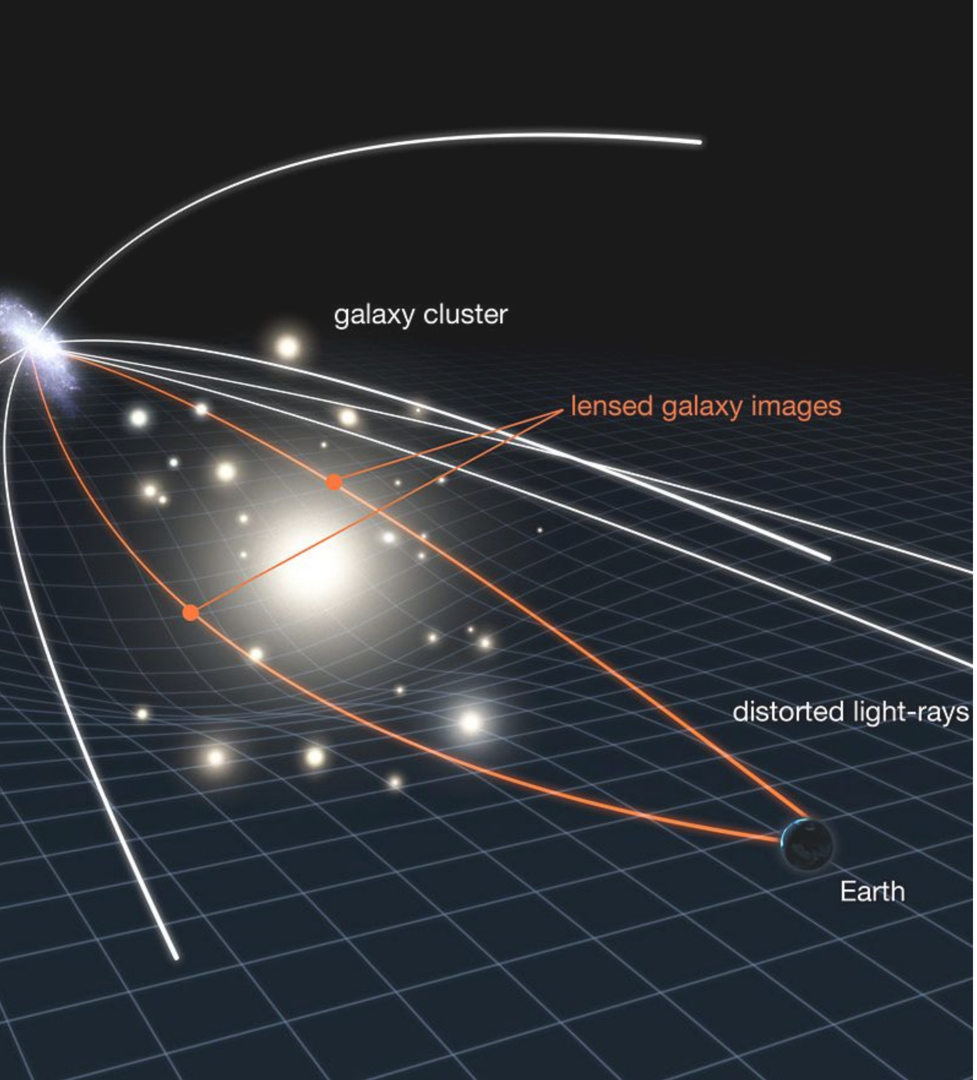


Wong et al. (in prep)



Other select science cases

- Test the speed of gravity *(Collett & Bacon 2017)*
- Probe fundamental physics *(Baker & Trodden 2017)*
- Expansion of the Universe *(Sereno et al. 2011, Liao et al. 2017)*
- Study microlens populations *(Lai et al. 2018, Jung et al., 2019)*



Presentation summary

- What is gravitational-wave lensing and why is it interesting?
- GWTC-1 search for lensing
- Methodologies
  - Lensing magnification
  - Microlensing beating patterns
  - Multiple images
- Science case
  - Localization
  - Expansion
  - Other select science cases