Gravitational lensing applied to gravitational waves

Martina Toscani,
PostDoc @ UniMib

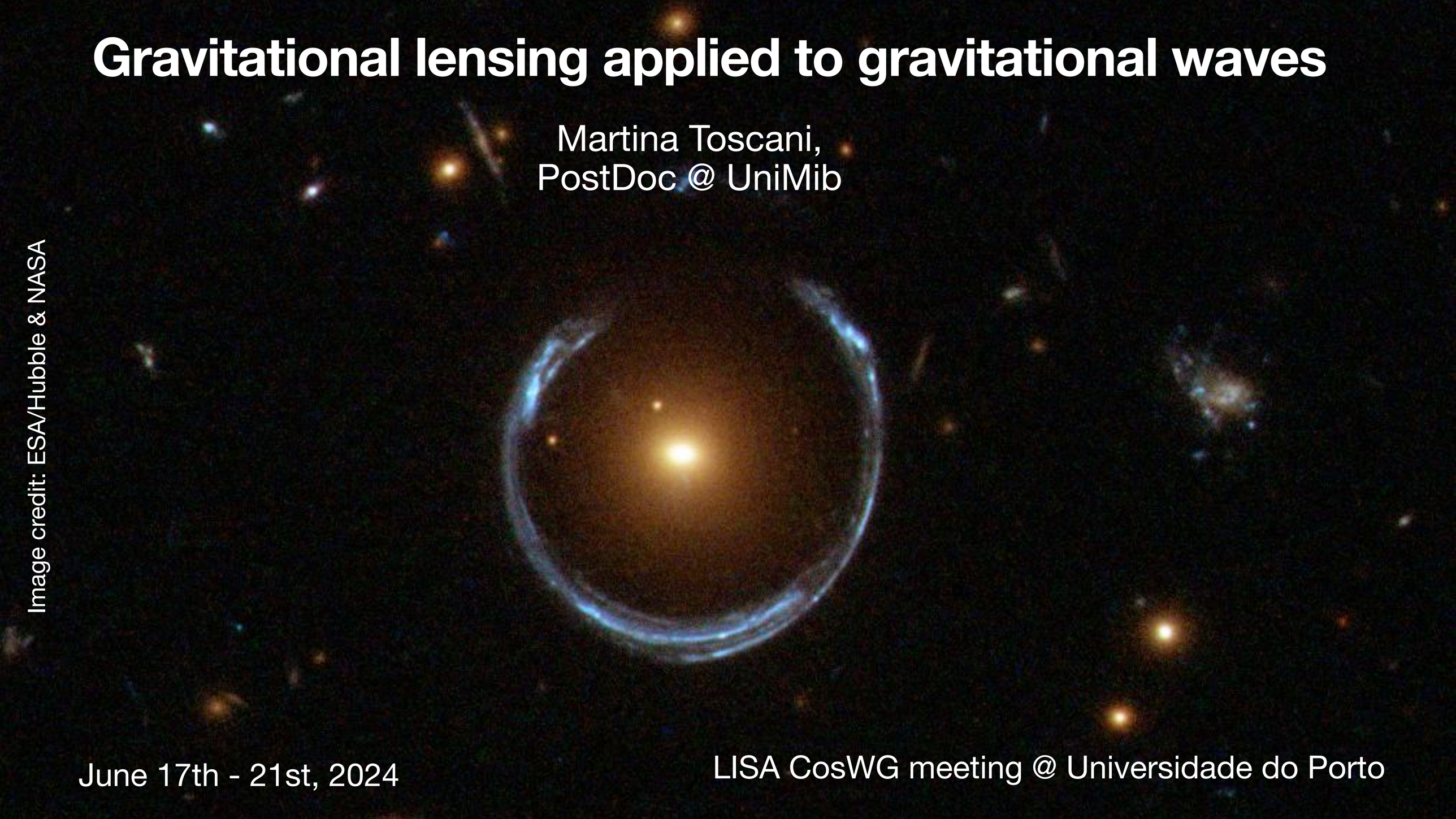


Image credit: ESA/Hubble & NASA

June 17th - 21st, 2024

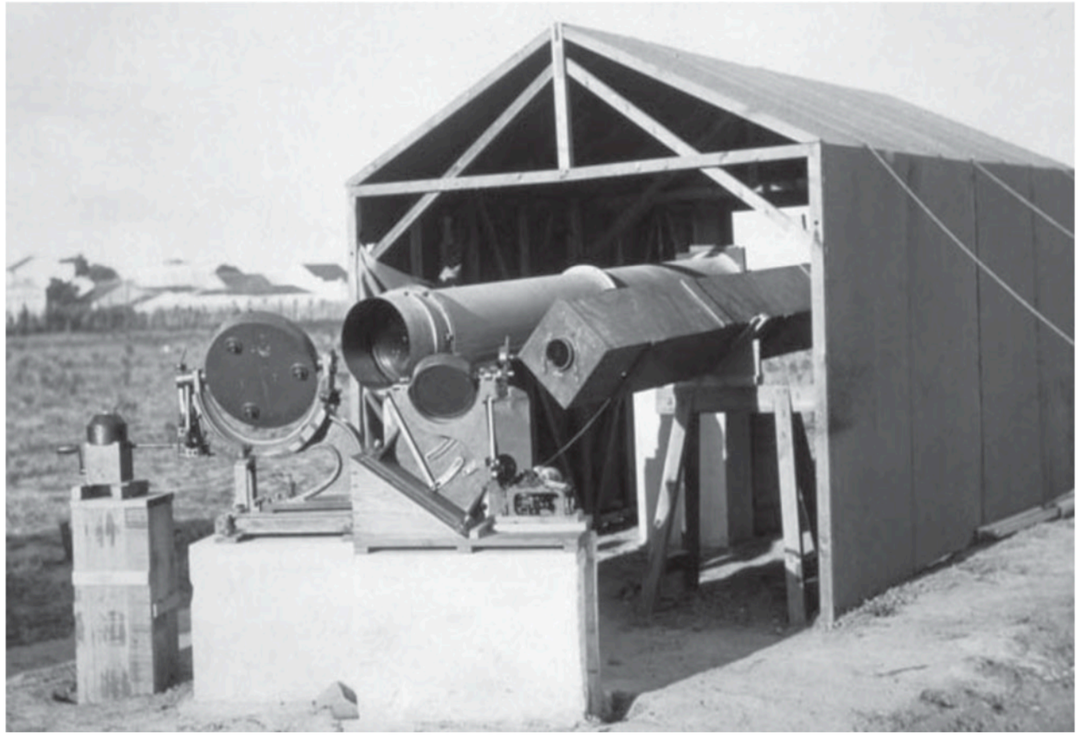
LISA CosWG meeting @ Universidade do Porto

What is lensing?

Gravitational field of a massive object (lens) bends the path of the signal from a distant source

GR predicts double displacement wrt Newtonian gravity

Observationally confirmed by Dyson, Eddington and Davidson during the Solar eclipse of 1919



Instruments used for the experiment, picture by Science Museum of London. Longhair 2015.

What is lensing?

Shear: image stretched or compressed without changing the area

Convergence: change in the image size

Magnification factor μ

> 1, brighter

< 1, dimmer

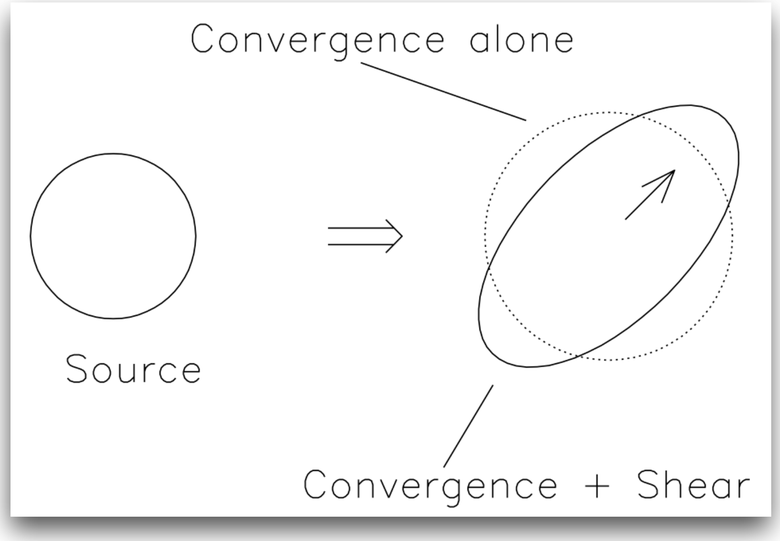


Image from Narayan & Bartelmann 1995

What is lensing?

Shear: image stretched or compressed without changing the area

Convergence: change in the image size

Magnification factor μ

- > 1, brighter
- < 1, dimmer

Multiple images: production of multiple images of the source

→ Positive or negative parity

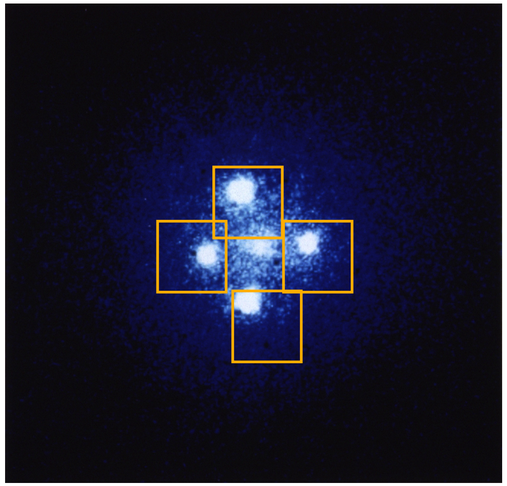
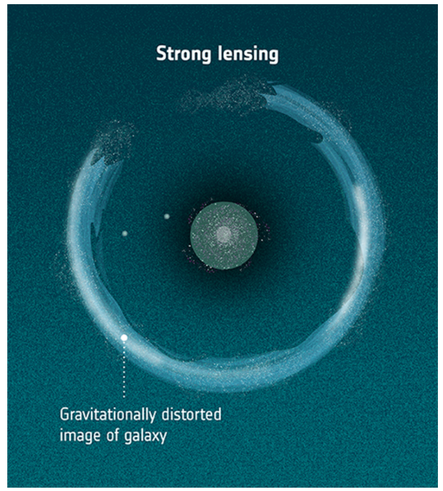


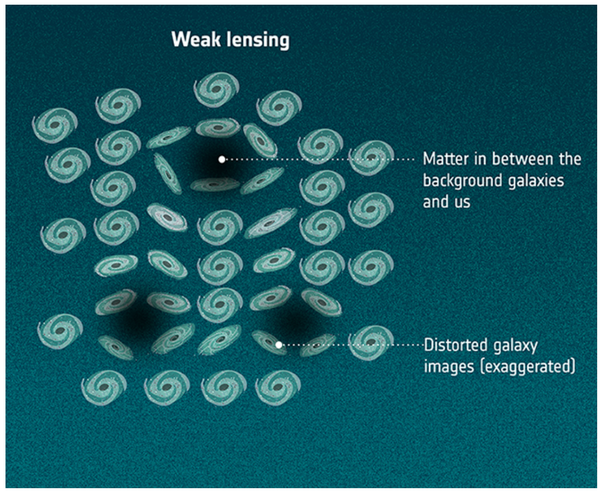
Image from NASA/ESA

4 images same quasar

What is lensing?

Strong lensing:
massive lens, (near) perfect alignment, individual sources



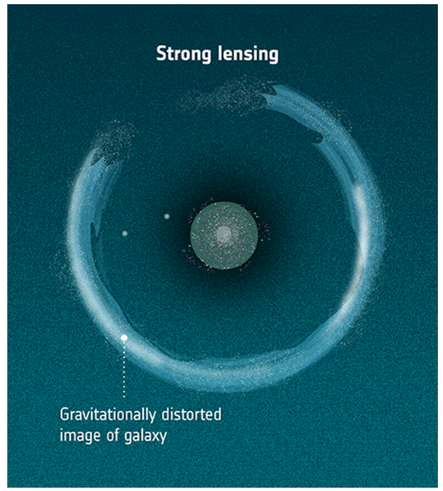


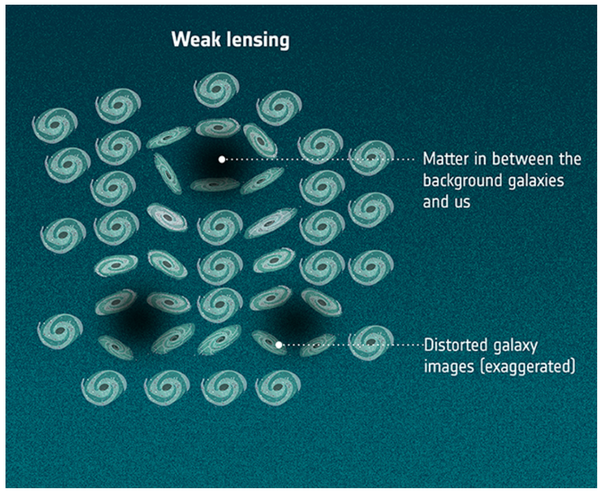
Weak lensing:
massive lens, moderate/poor alignment, statistical studies

Image from ATG under contract with ESA

What is lensing?

Strong lensing: massive lens, (near) perfect alignment, individual sources





Weak lensing: massive lens, moderate/poor alignment, statistical studies

Image from ATG under contract with ESA

Microlensing: compact lens, small scale alignment, temporary effect

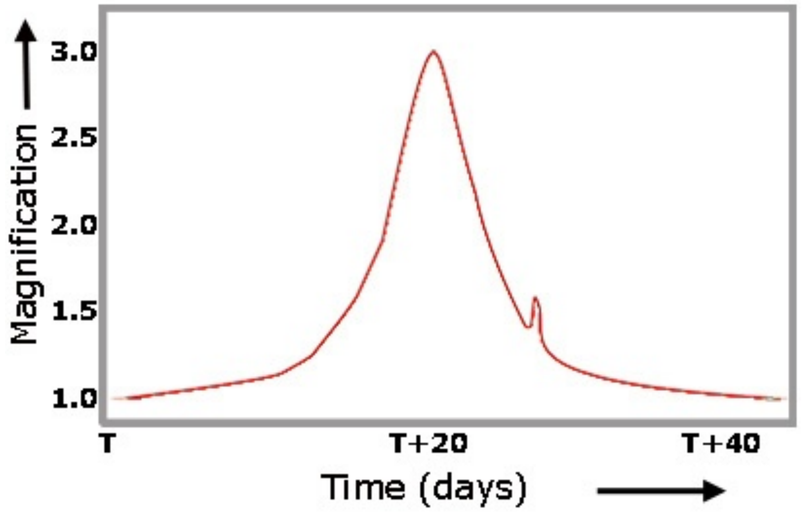
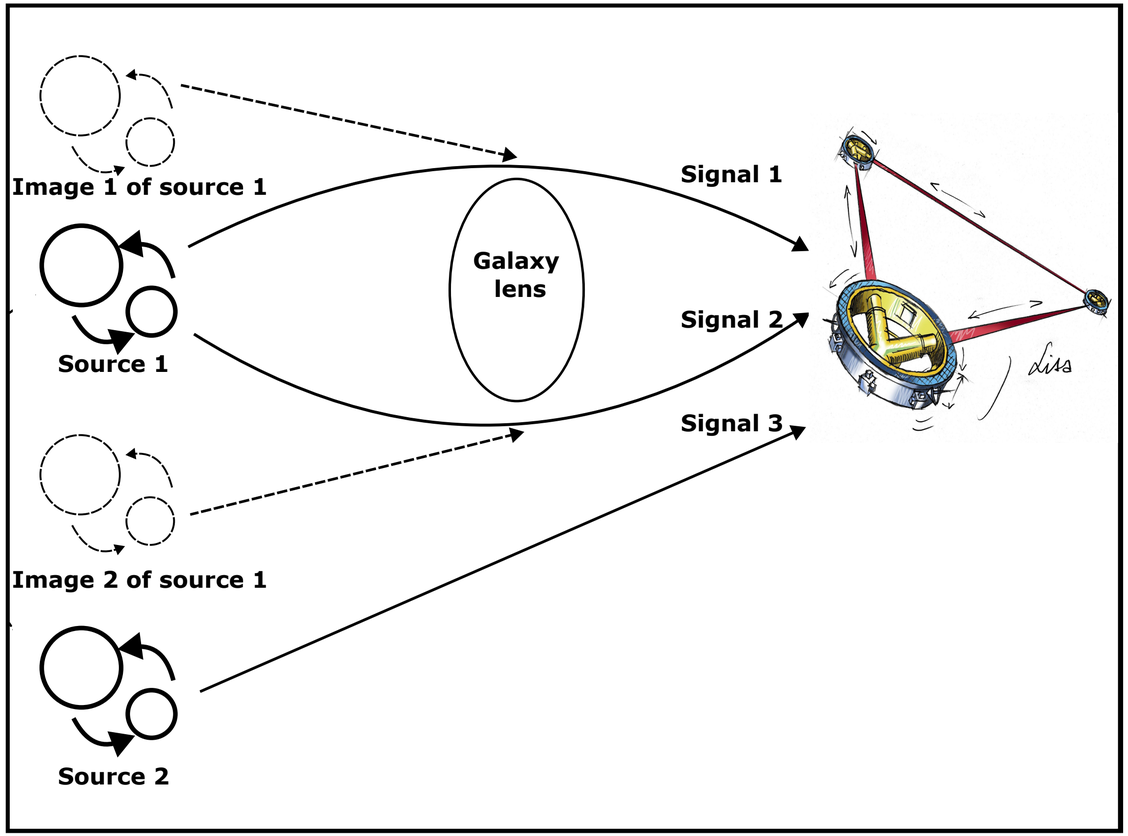


Image from ESA

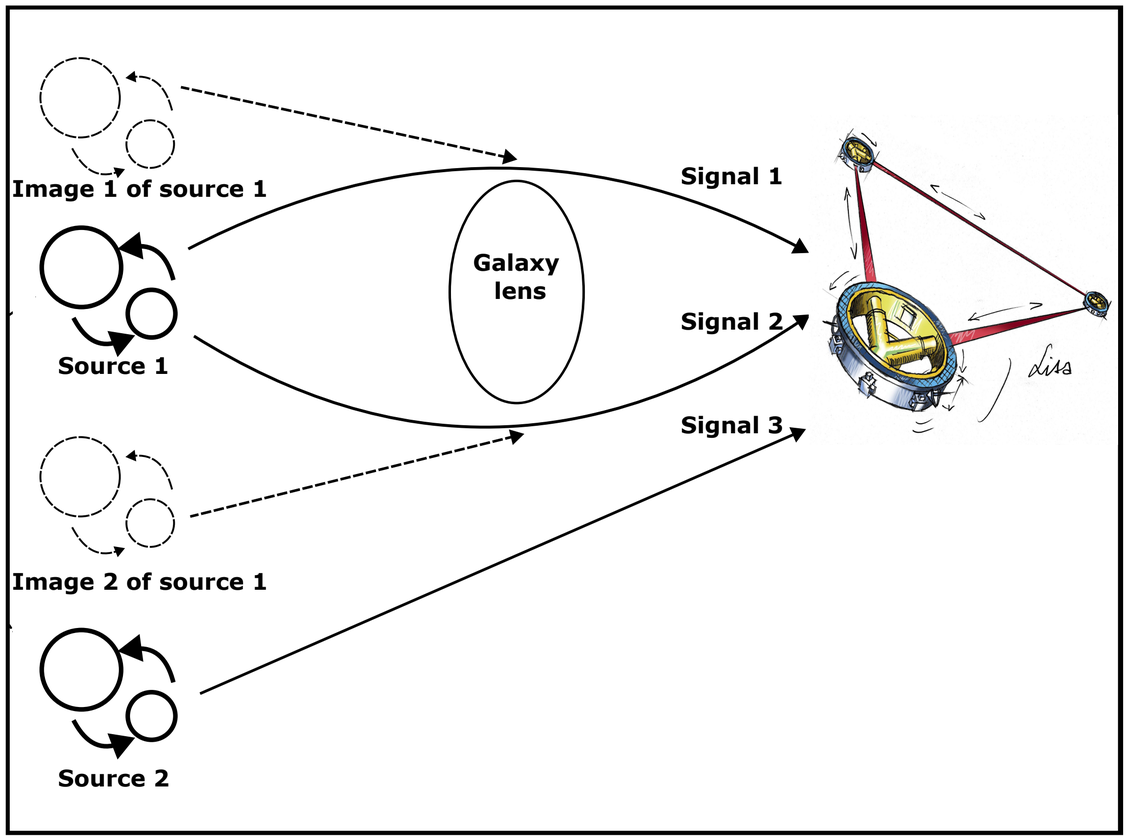
Why studying lensing?

Image from Cheung et al, preprint



Why studying lensing?

Image from Cheung et al, preprint



Proof of General Relativity

Understanding GWs propagation in strong gravity

Understanding the nature of the lens

Constrains cosmological parameters

Observing faint sources

martina.toscani@unimib.it

Lensing in the context of Lisa

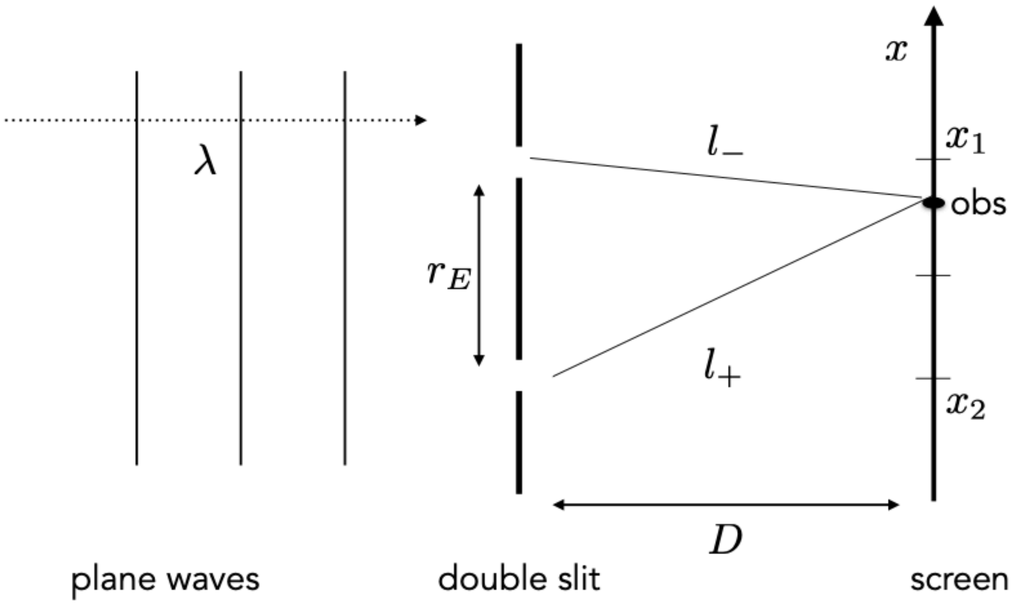


Image from Cusin & Lagos 2020

$$10^{-4}\mathrm{Hz} \lesssim \mathrm{f} \lesssim 10^{-1}\mathrm{Hz}$$

Diffraction becomes relevant for

$$\lambda \gtrsim R_{s,c} \rightarrow M_{\mathrm{L}} \lesssim 10^{8}\mathrm{M}_{\odot}\left(\frac{\mathrm{f}}{\mathrm{mHz}}\right)$$

Geometrical optics

Lensing by galaxy and galaxy clusters

Wave optics

Lensing by black holes

martina.toscani@unimib.it

Strongly lensed MBHBs

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

- Loudest sources
- Cosmological distances

Strongly lensed MBHBs

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

- Loudest sources
- Cosmological distances

Up to a few in LISA (Sereno et al 2010)

Multiple near-identical images

Difference only in

- amplitude
- overall phase
- arrival time

Same sky location

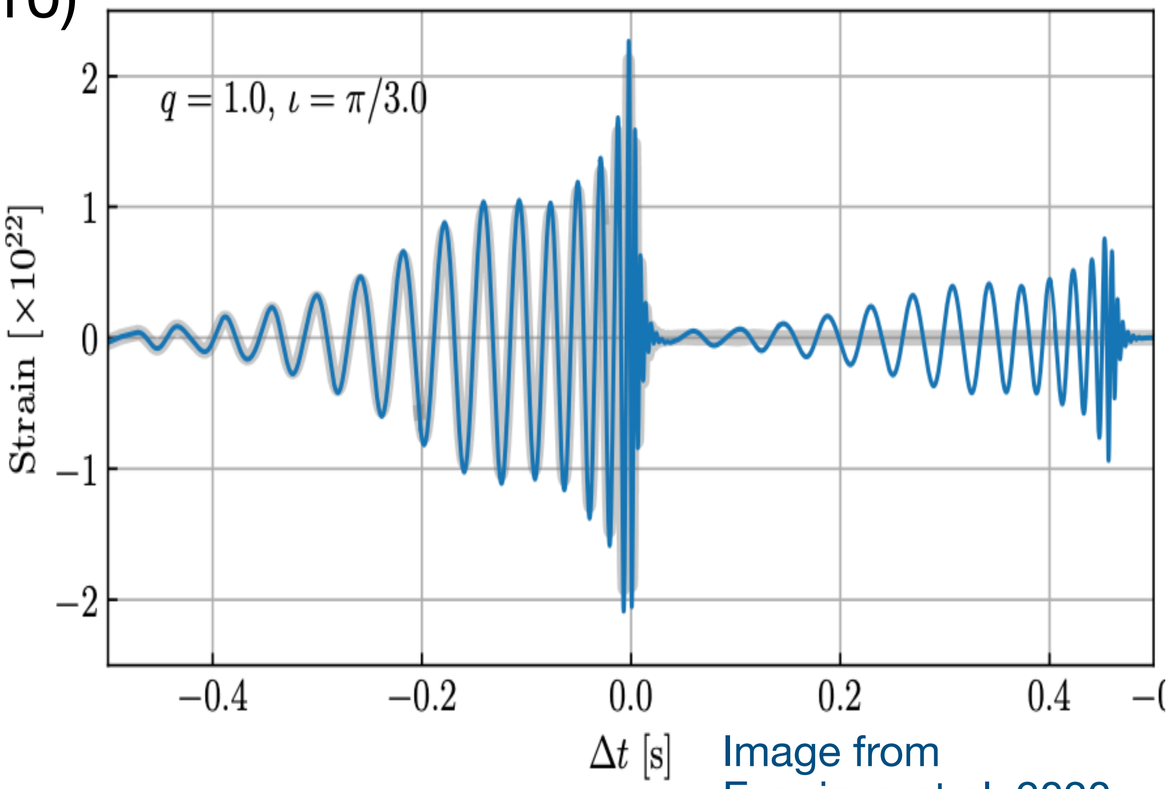


Image from Ezquiaga et al. 2020

Strongly lensed MBHBs

$$h \propto \frac{\sqrt{\mu}}{d_L}$$

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

Strongly lensed MBHBs

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

$$h \propto \frac{\sqrt{\mu}}{d_L}$$

Selection effects shift mean magnification and introduce distance bias

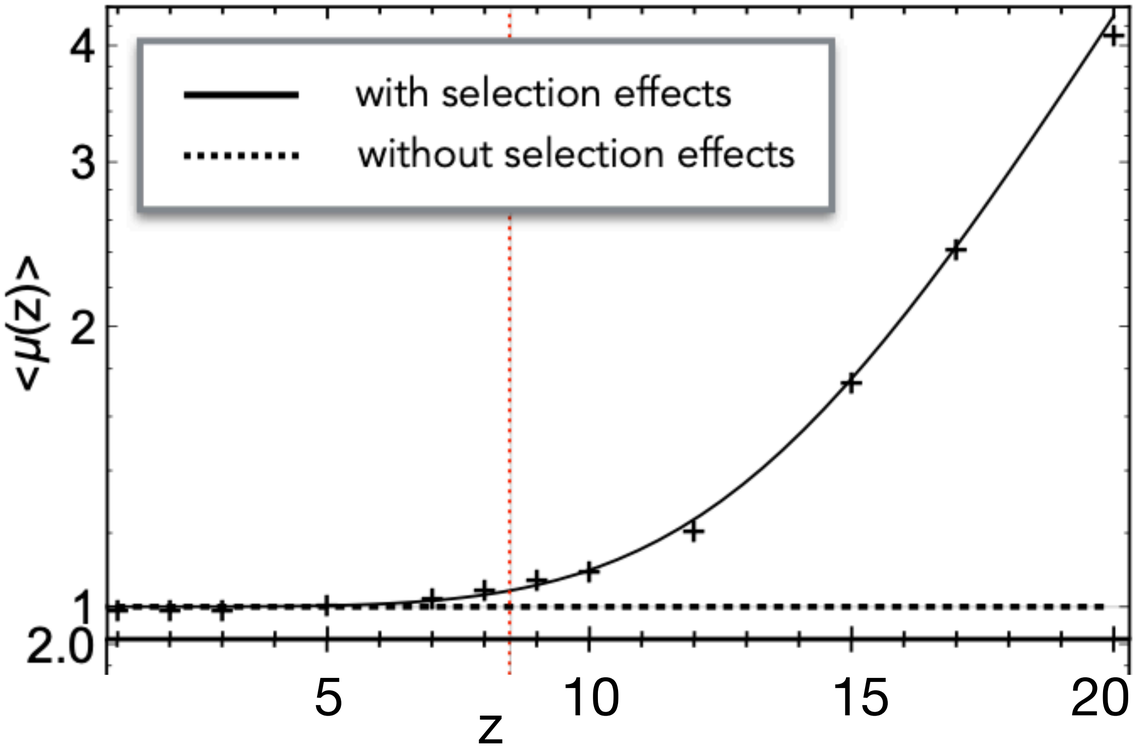


Image from Cusin & Tamanini 2021

Strongly lensed MBHBs

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

Cosmological probes: time delay analysis, strong lensing statistics

- time delay analysis → Hubble constant

- strong lensing statistics → Dark matter distribution

No need for EM counterparts

Strongly lensed MBHBs

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

Host galaxy will be lensed → Follow up EM observations

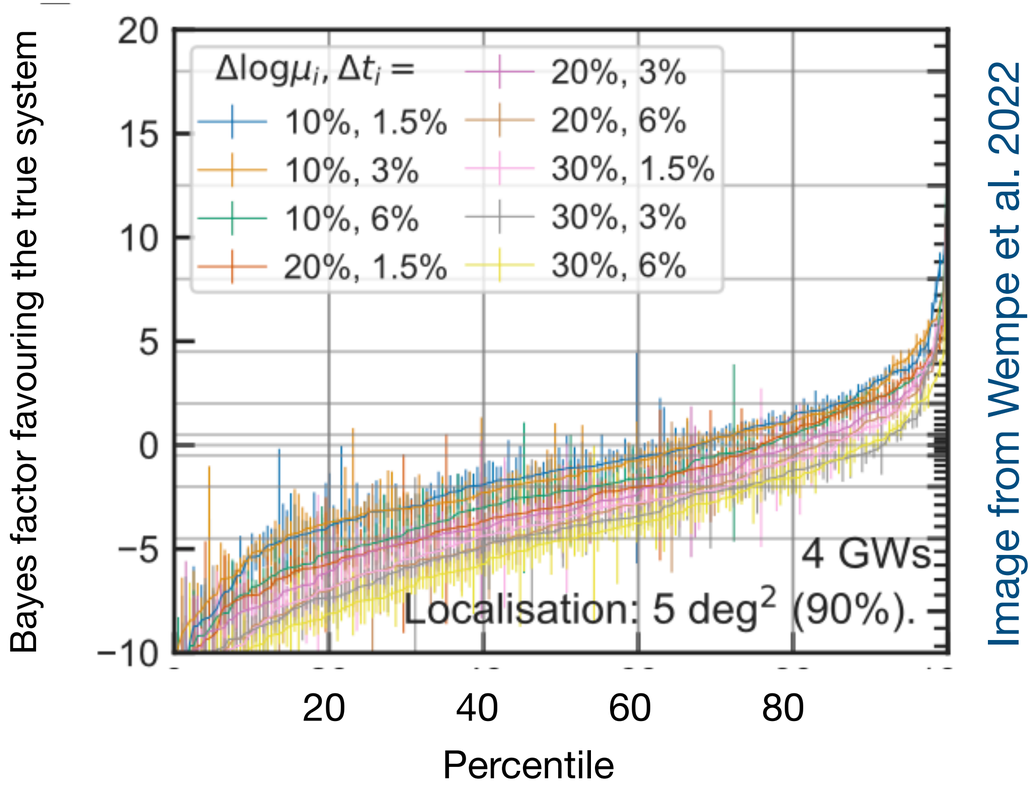


Image from Wempe et al. 2022

2 detected GWs: correct identification for 10ish% events

4 detected GWs: correct identification for 30ish% events

Strongly lensed EMRIs

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

- Excellent probes for strong field gravity
- Uncertain detection rates

Strongly lensed EMRIs

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

- Excellent probes for strong field gravity

Up to 40 in LISA (Toscani et al. 2024)

Many observational cycles

Signal lasts longer than typical lensing time delay

Multiple images superimpose

- Uncertain detection rates

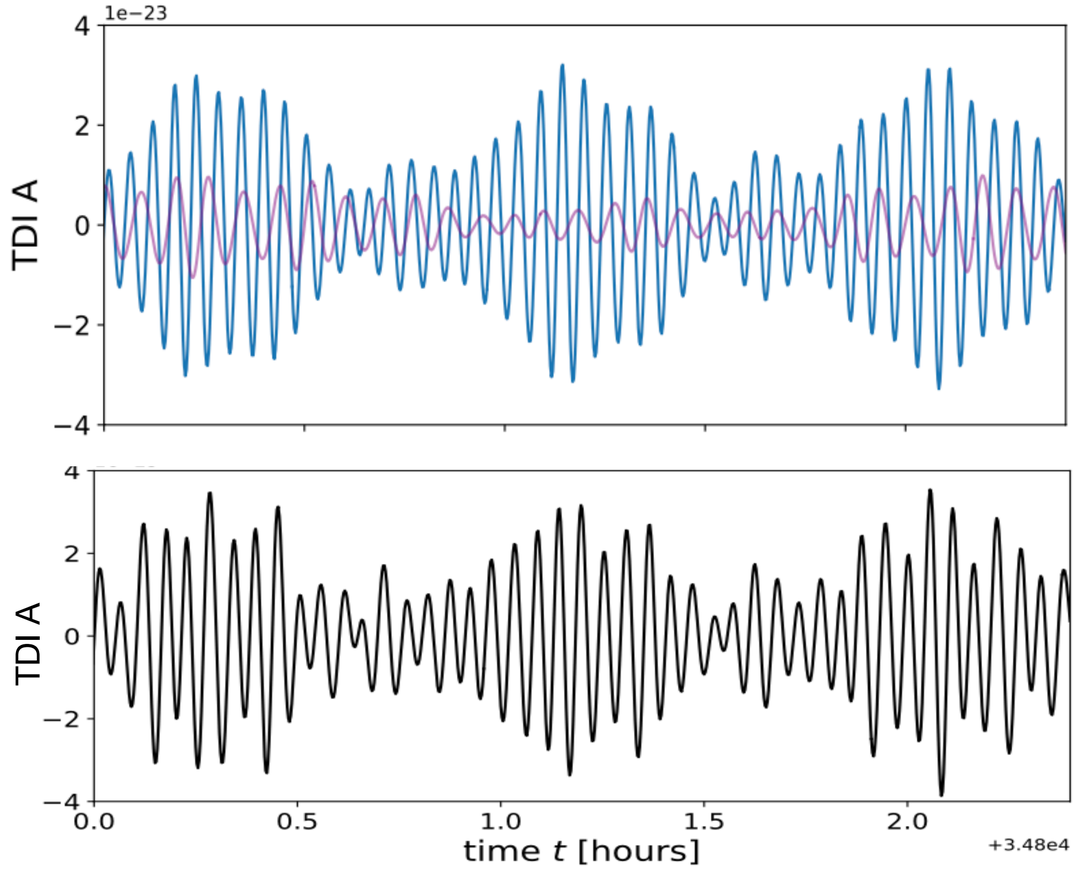


Image from Toscani et al. 2024

martina.toscani@unimib.it

Strongly lensed EMRIs

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

Inject an unlensed EMRI waveform in the LISA data stream

Time shift operation

Maximise noise-weighted inner product

Inject a lensed EMRI waveform

Strongly lensed EMRIs

Dai 2007, Sereno et al. 2010, Sereno et al. 2011, Ezquiaga et al. 2020, Goyal et al. 2020, Hannuksela et al. 2020, Cusin and Tamanini 2021, Wang 2021, Vijaykumar 2022, Wempe et al. 2022, Toscani et al. 2023, Toscani et al. 2024…

Inject an unlensed EMRI waveform in the LISA data stream

Time shift operation

Maximise noise-weighted inner product

Inject a lensed EMRI waveform

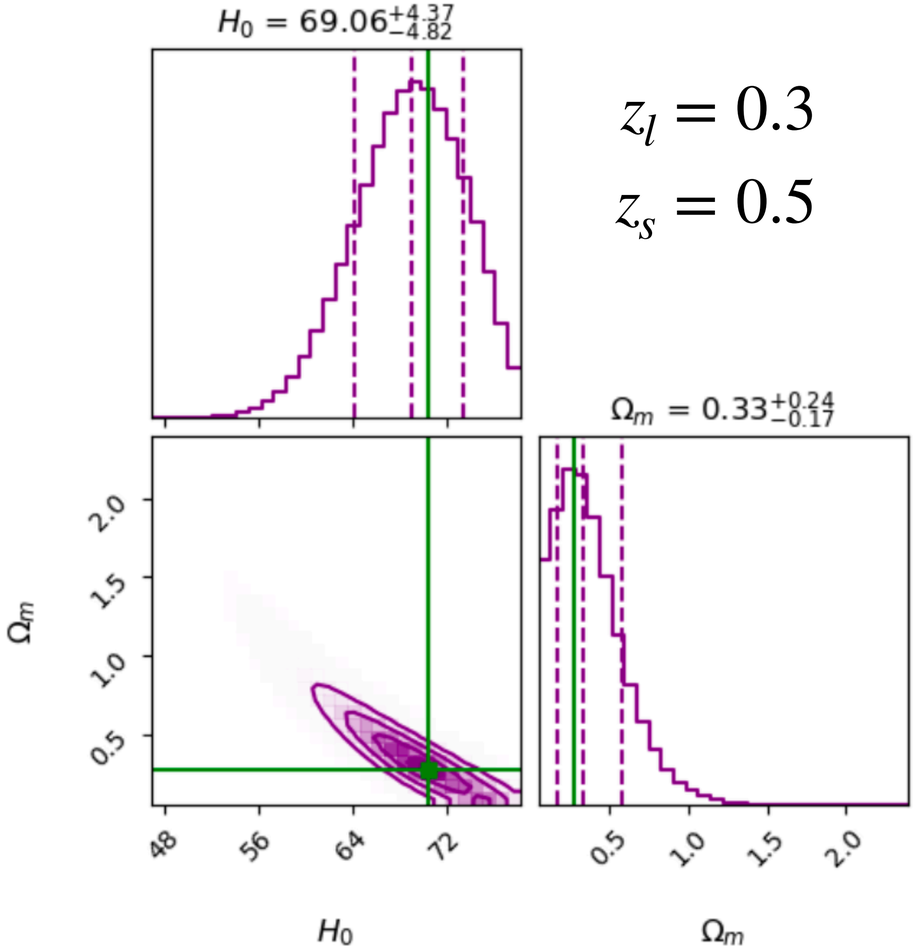


Image from Toscani et al. 2024

martina.toscani@unimib.it

Weak lensing by LSS

Cutler 2009, Shang 2010, Mpetha 2022, Balaudo et al. 2022

Large scale structures will induce small perturbations in the path of the propagating wave

Weak lensing will introduce some scatter in the measure of the luminosity distance

Combining bright and dark sirens with weak lensing gives better constraints

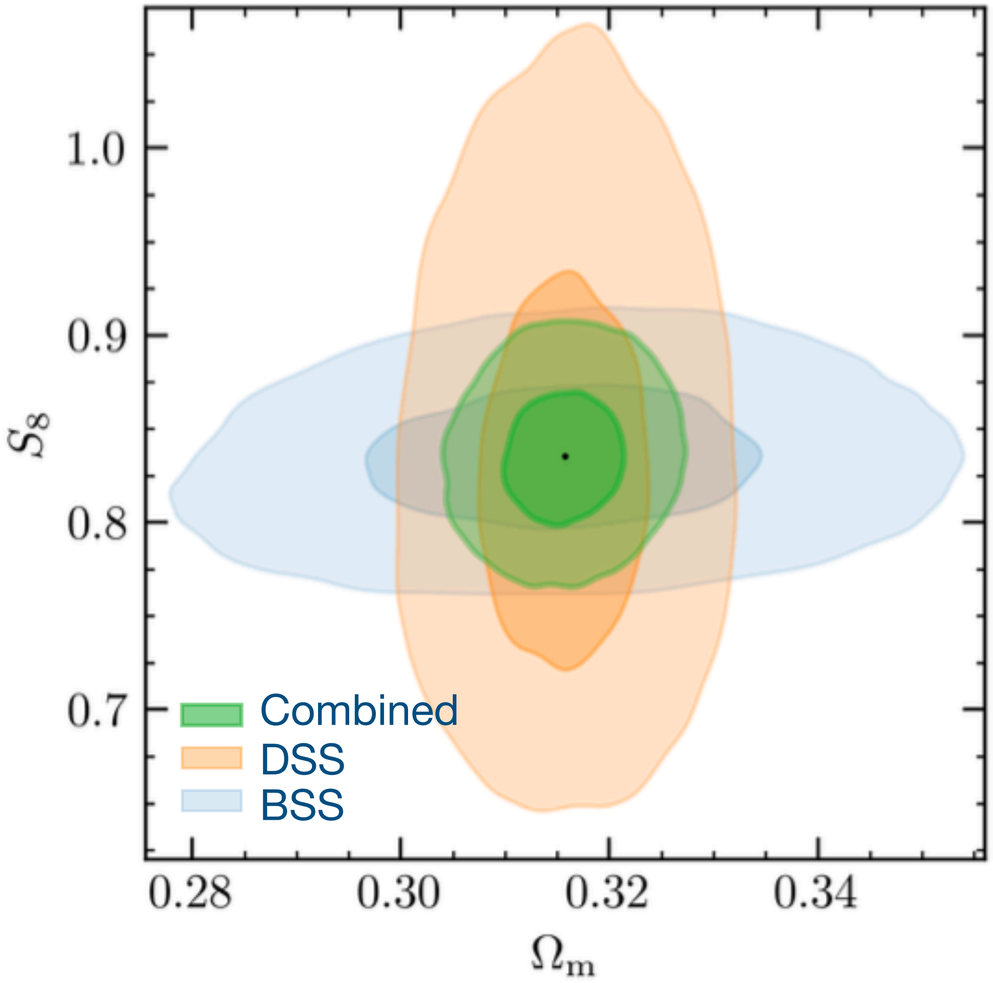


Image from Mpetha et al. 2022

martina.toscani@unimib.it

Wave effects

Takahashi & Nakamura 2003, Gao et al. 2022, Caliskan et al. 2022, Garoffolo 2023

$$M_{\rm L} \lesssim 10^8 {\rm M}_\odot \left(\frac{\rm f}{\rm mHz}\right)$$

Lenses like BHs, stars..

Oscillatory behaviour due to interference of multiple images

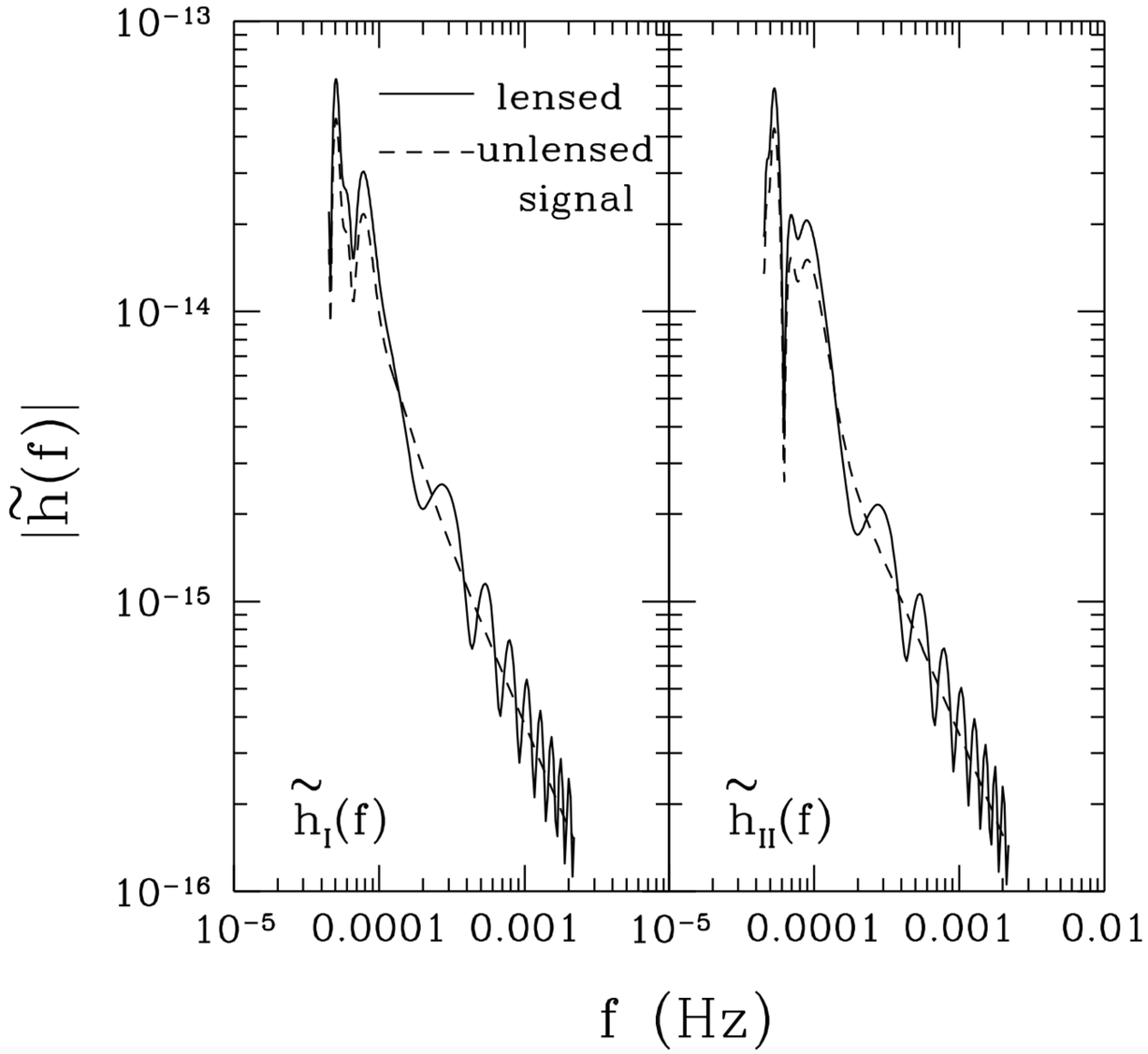


Image from Takahashi & Nakamura 2003

Conclusions

In the upcoming years we will see lensed GWs :-)!!

Important to recognise lensing effect to properly reconstruct astrophysical properties of the source population

Useful to constrain cosmological parameters

The End

Any questions … ?