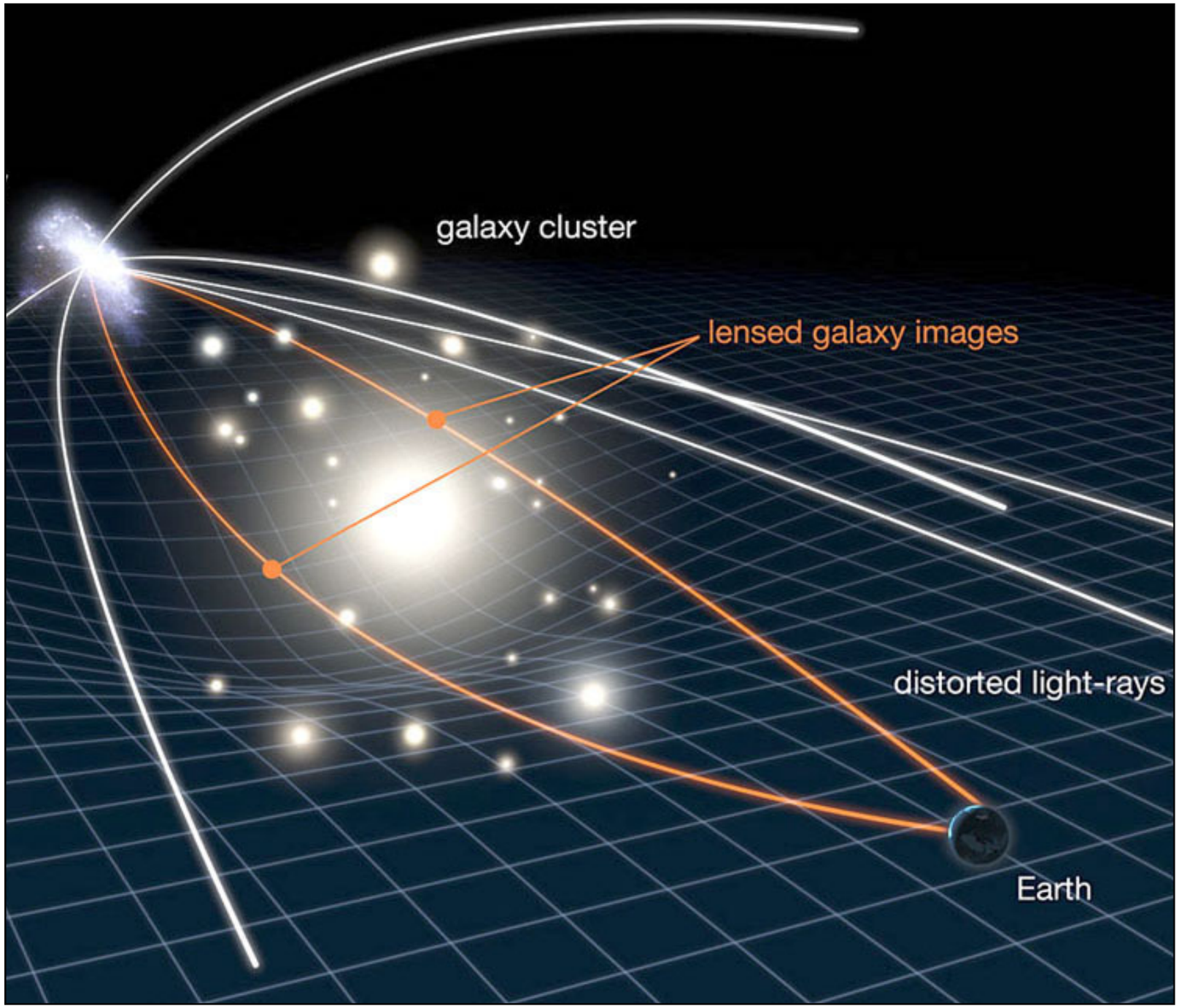
LENSING OF GRAVITATIONAL WAVES

COLUMBIA UNIVERSITY

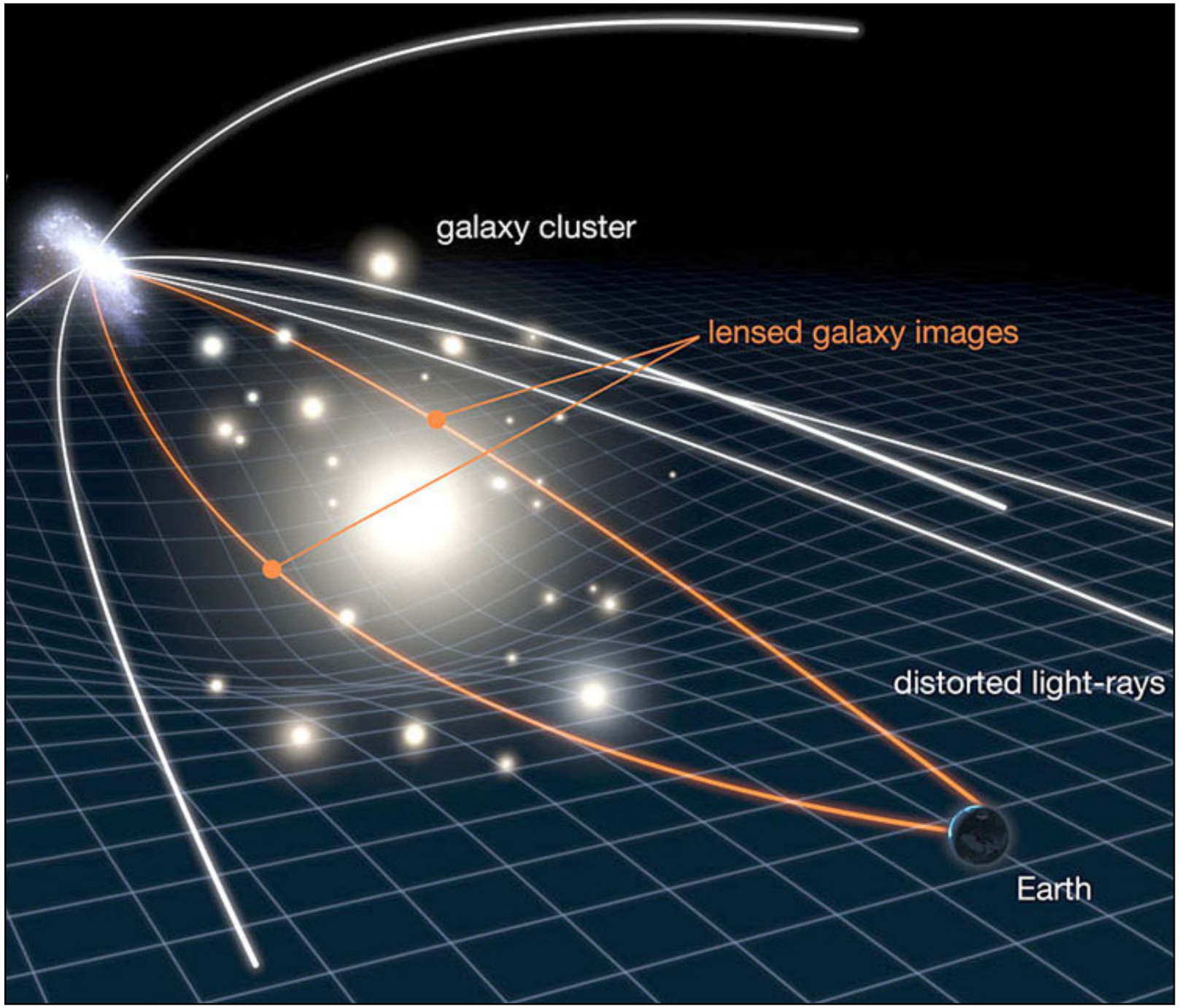
Macarena Lagos

LISA cosmology workshop — June 2023

GRAVITATIONAL LENSING



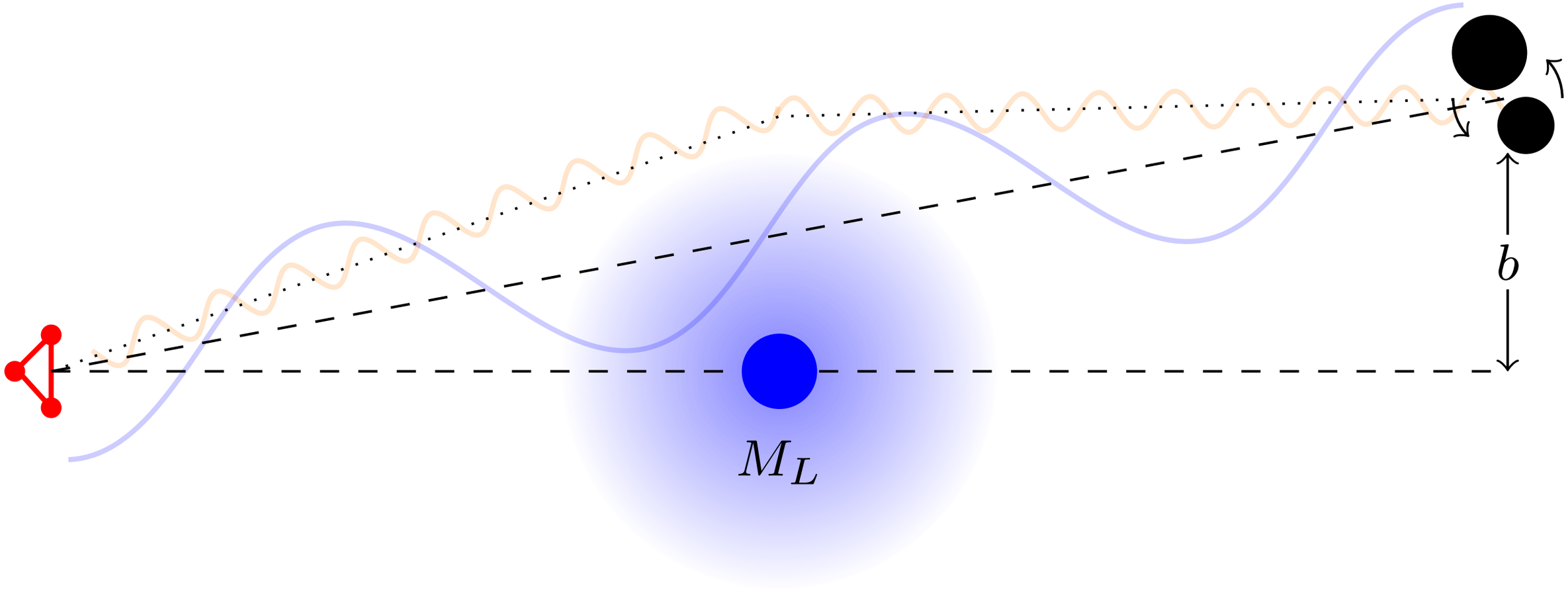
GRAVITATIONAL LENSING



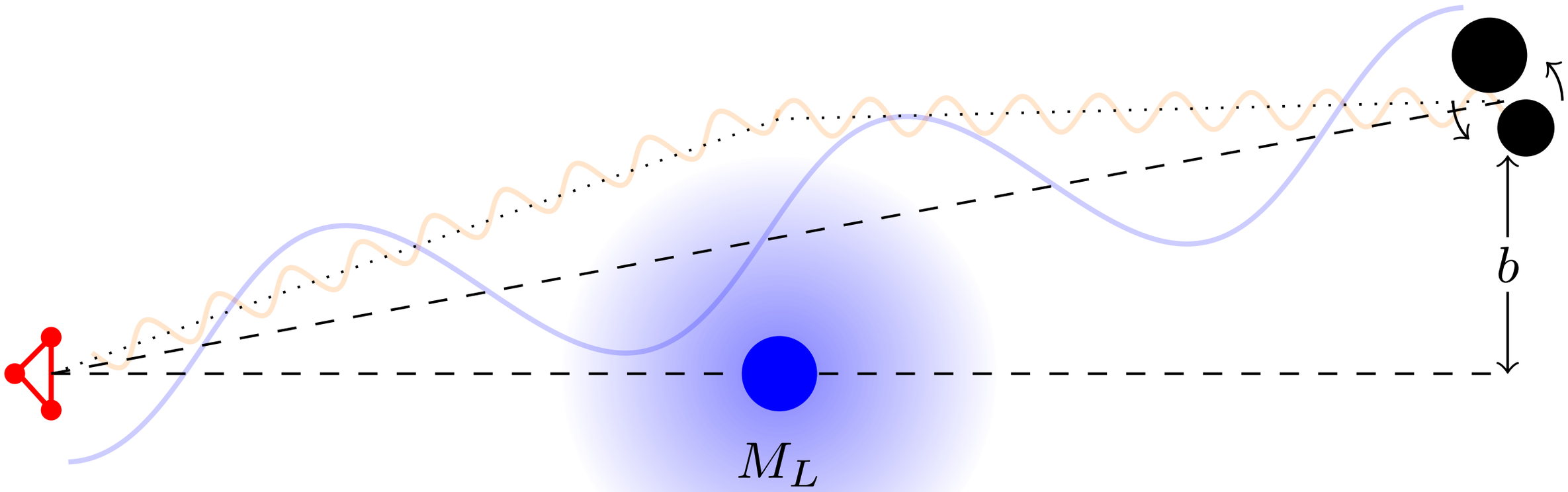
EM Lensing

- Probe Dark Matter
- Measure H_0
- See farther/lighter objects
- Exoplanets
- Primordial BHs

GW LENSING



GW LENSING



Main parameters of interest: b, M_L, λ

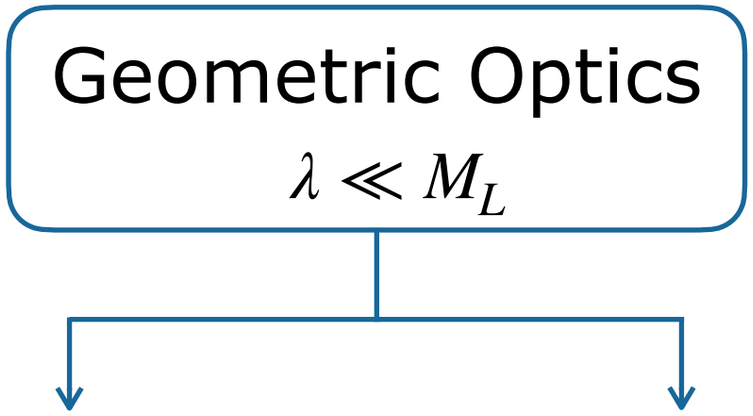
LENSING LANDSCAPE

LENSING LANDSCAPE

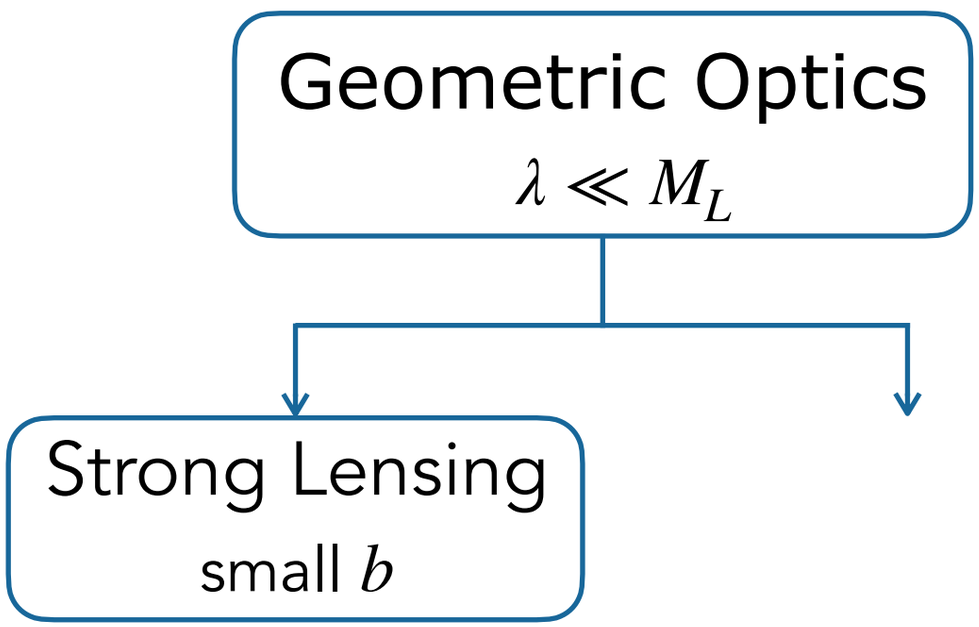
Geometric Optics

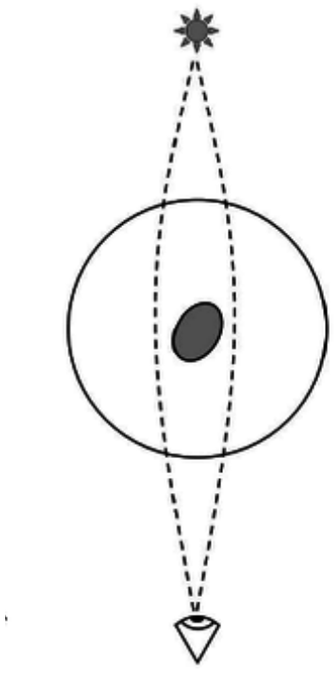
$$\lambda \ll M_L$$

LENSING LANDSCAPE



LENSING LANDSCAPE





Illustrations: Zackrisson+2010

LENSING LANDSCAPE

Geometric Optics

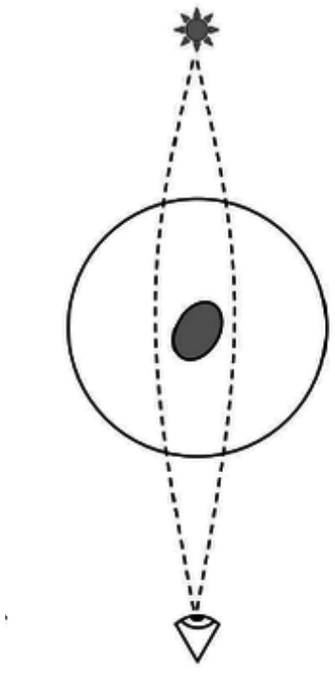
$\lambda \ll M_L$

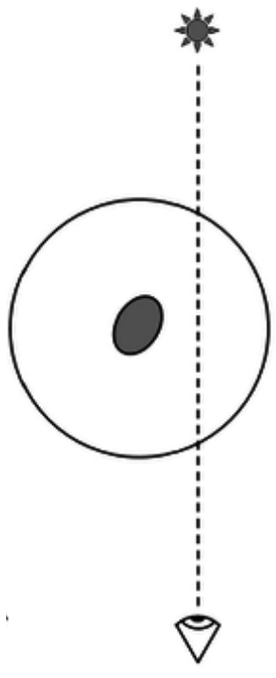
Strong Lensing

small b

Weak Lensing

large b





Illustrations: Zackrisson+2010

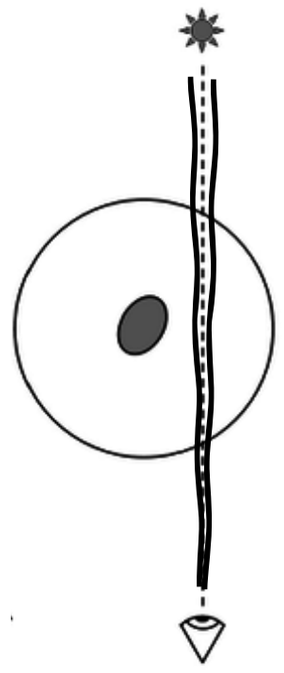
LENSING LANDSCAPE

Geometric Optics
$\lambda \ll M_L$

Strong Lensing
small b

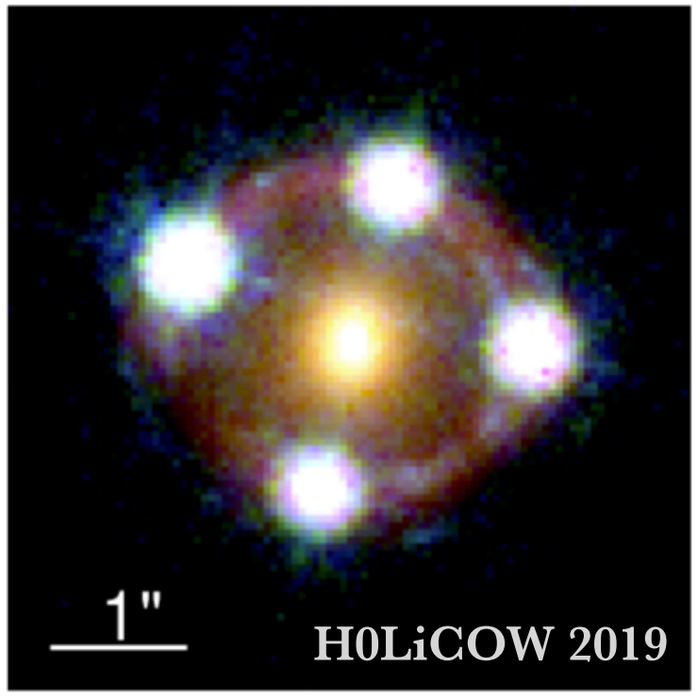
Weak Lensing
large b

Wave Optics
$\lambda \sim M_L$

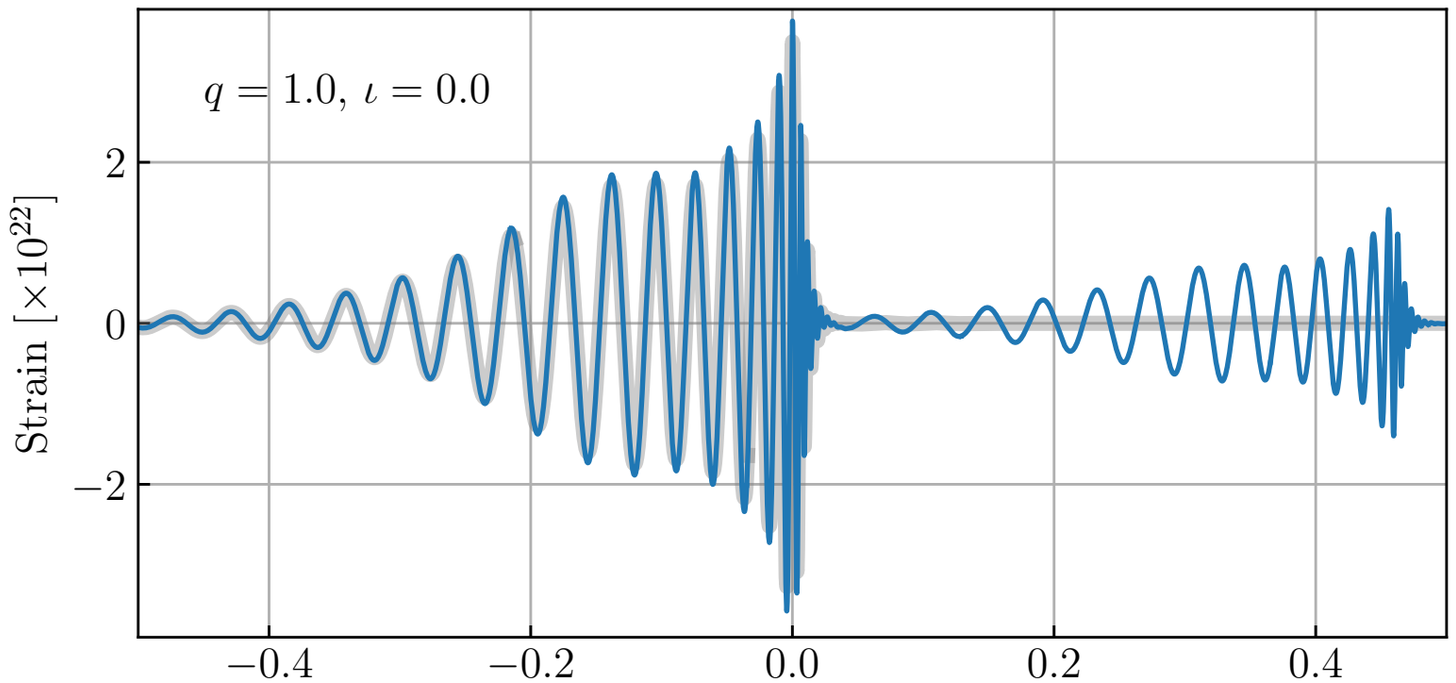


Illustrations: Zackrisson+2010

GW STRONG LENSING

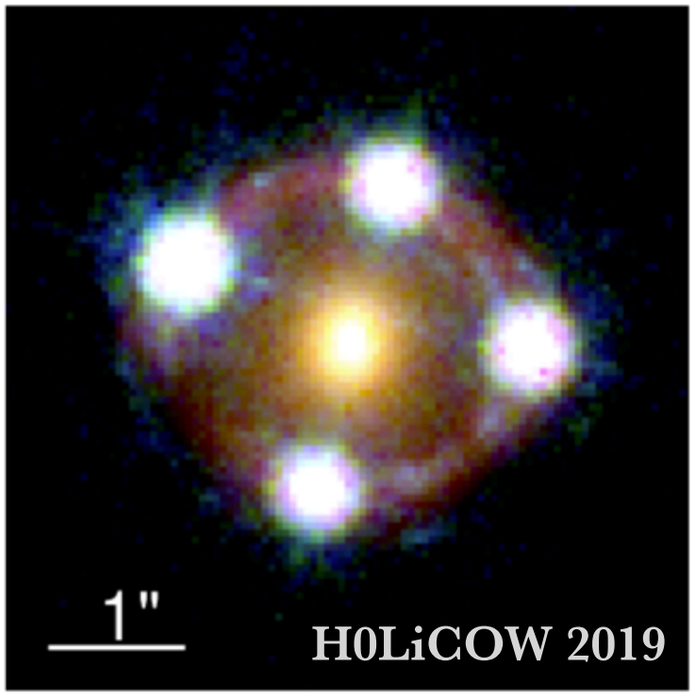


(c) HE 0435−1223

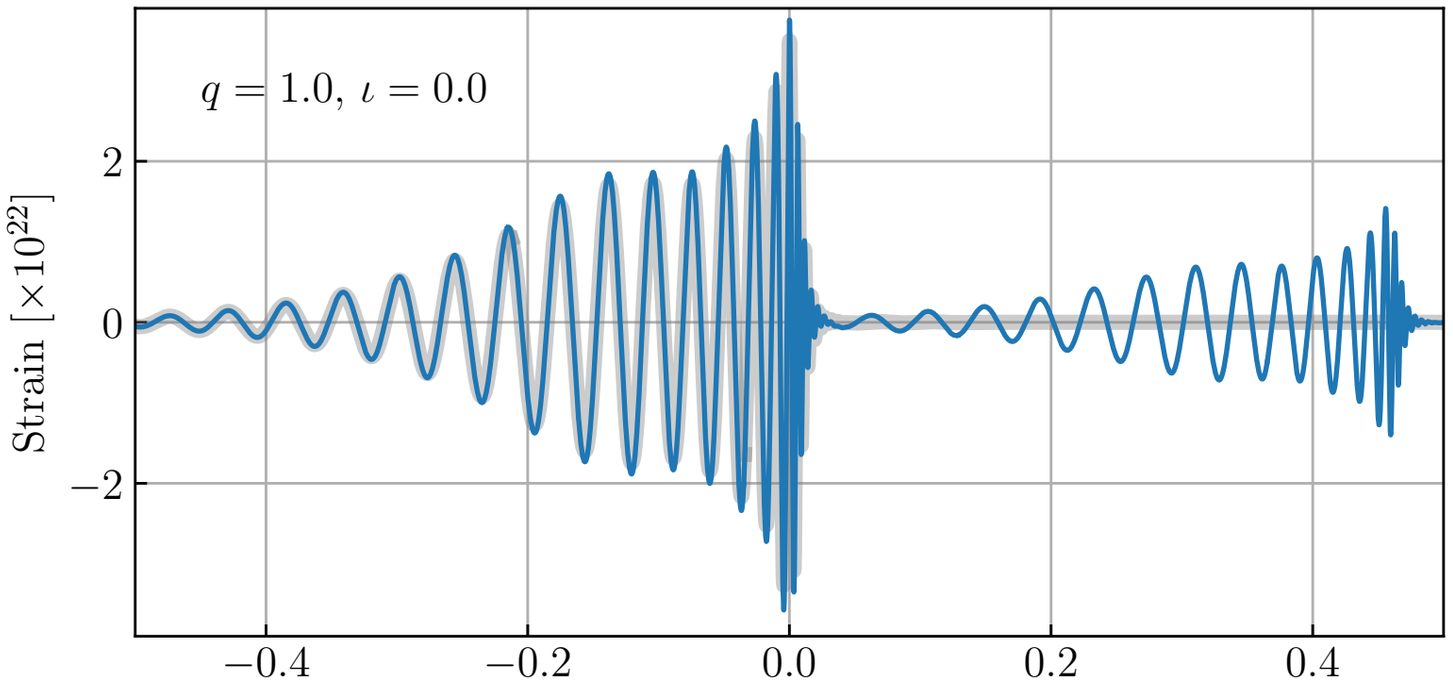


Ezquiaga, Holz, Hu, Lagos+ 2020

GW STRONG LENSING



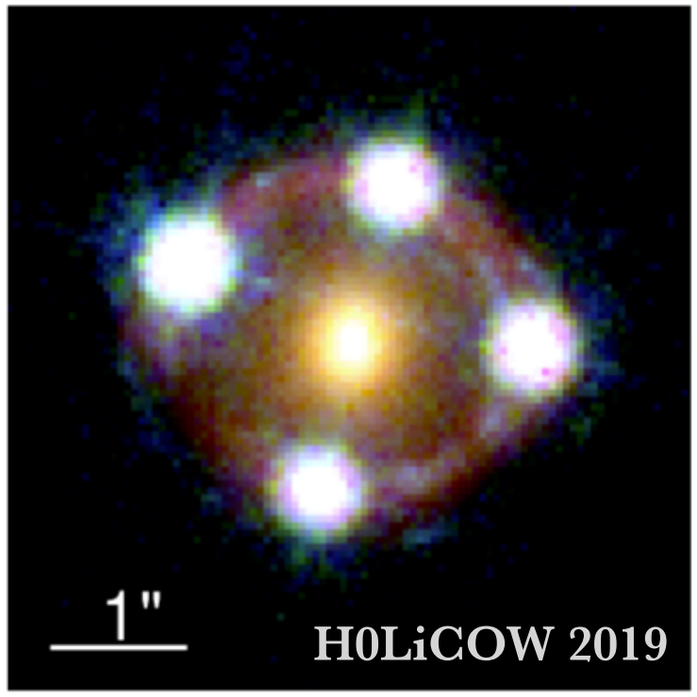
(c) HE 0435−1223



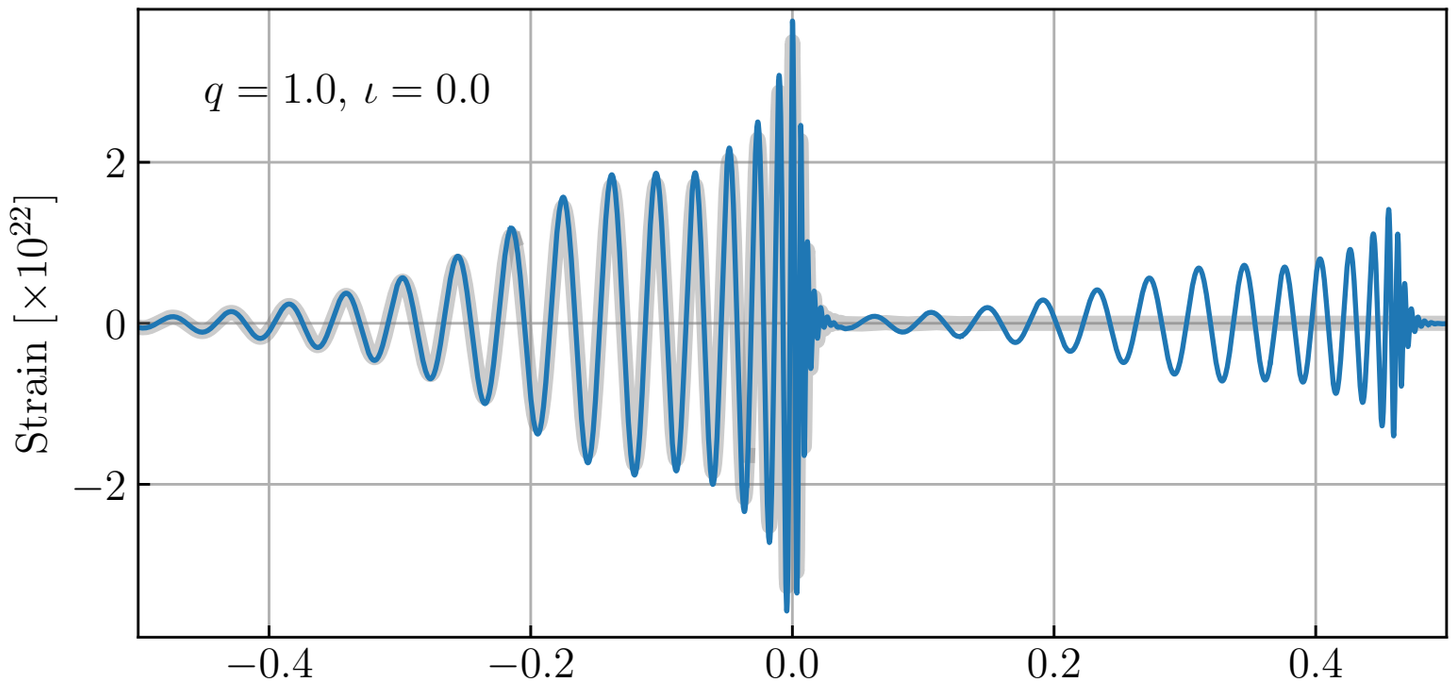
Ezquiaga, Holz, Hu, Lagos+ 2020

- Events: up to a few in LISA [Sereno+2010] (vs ~100 with ET/CE)

GW STRONG LENSING



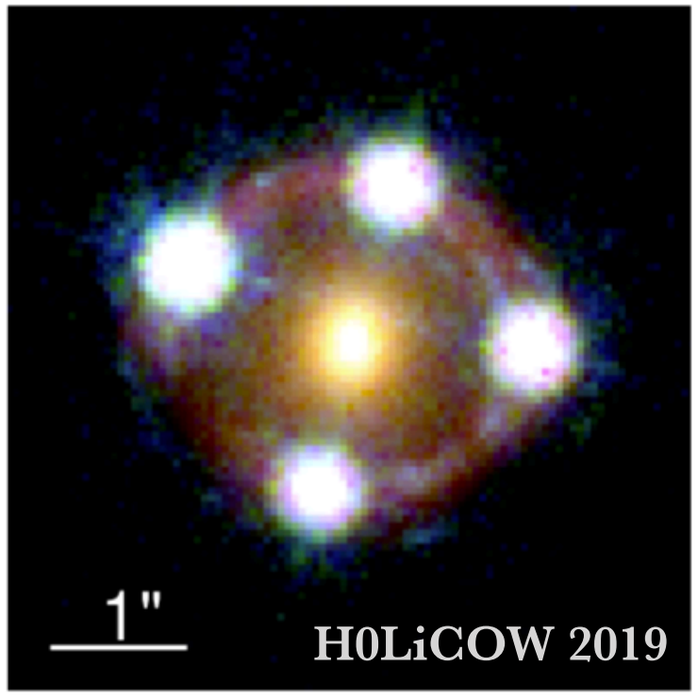
(c) HE 0435−1223



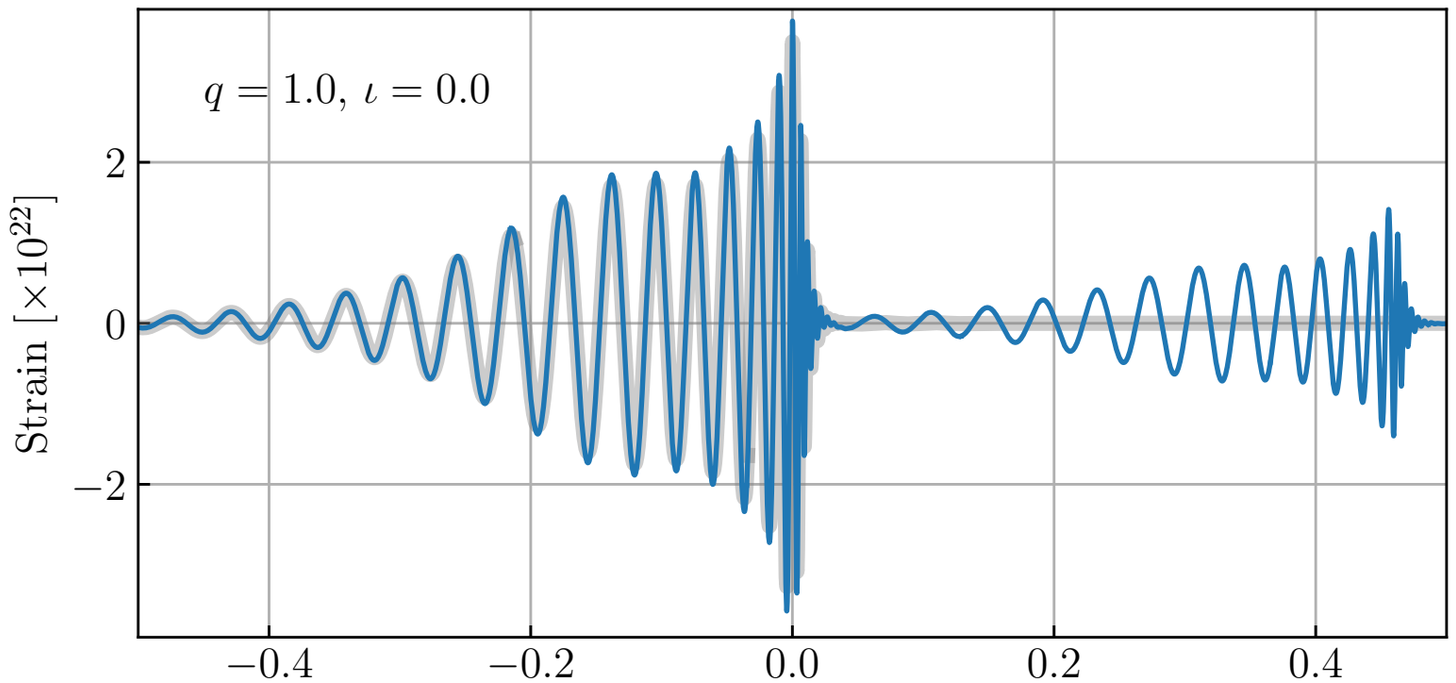
Ezquiaga, Holz, Hu, Lagos+ 2020

- Events: up to a few in LISA [Sereno+2010] (vs ~100 with ET/CE)
- Science:

GW STRONG LENSING



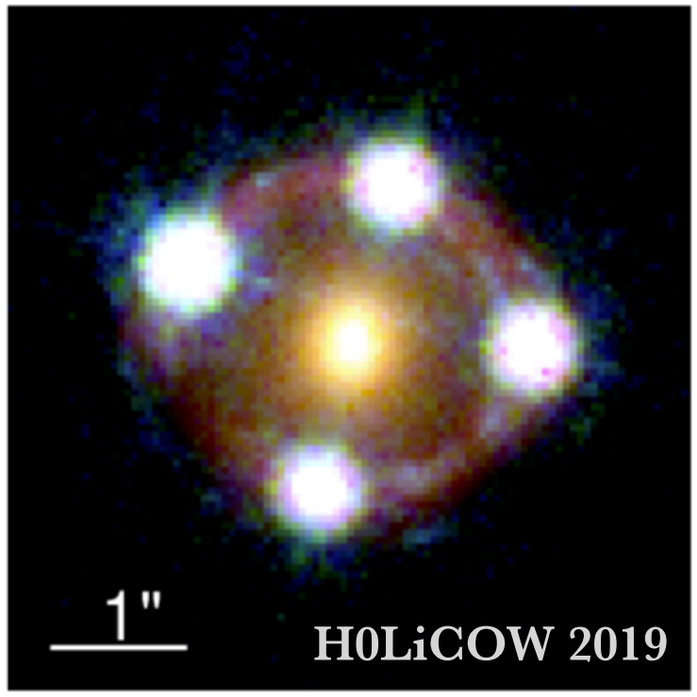
(c) HE 0435−1223



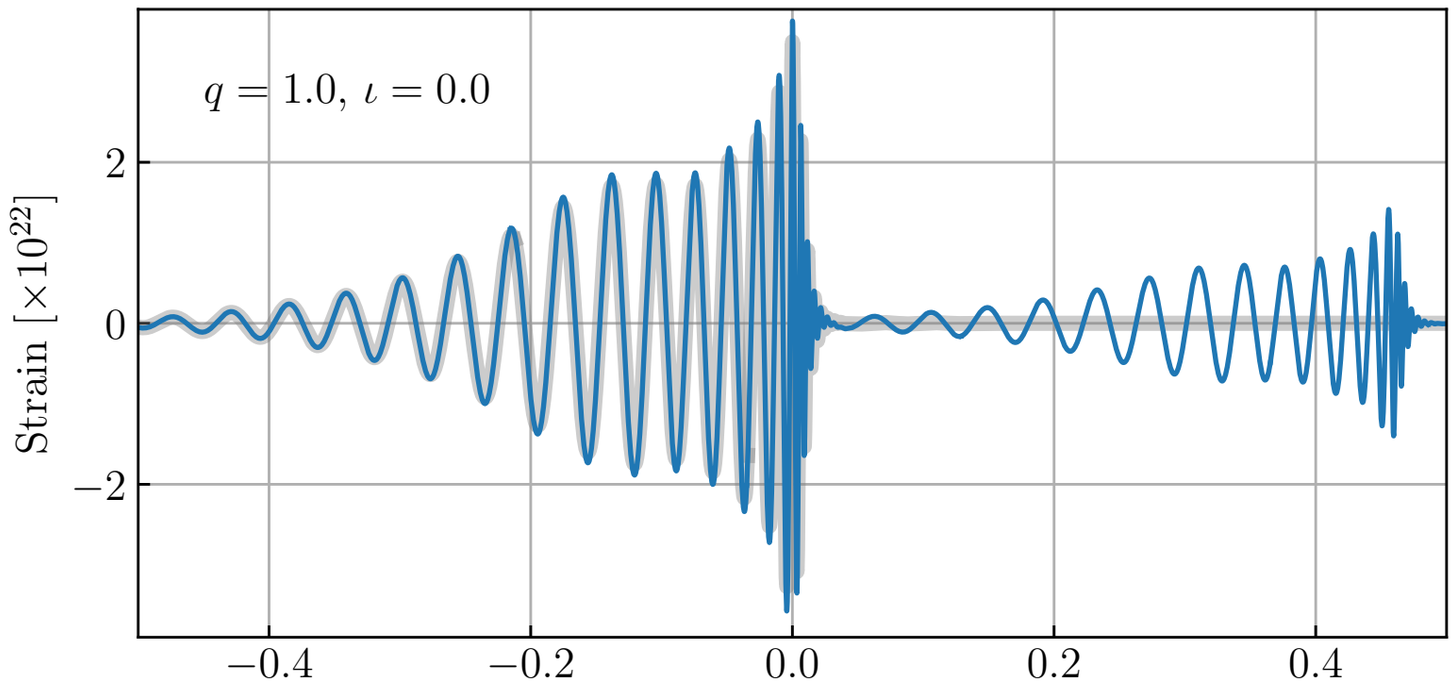
Ezquiaga, Holz, Hu, Lagos+ 2020

- Events: up to a few in LISA [Sereno+2010] (vs ~100 with ET/CE)
- Science:
  - DM distribution

GW STRONG LENSING



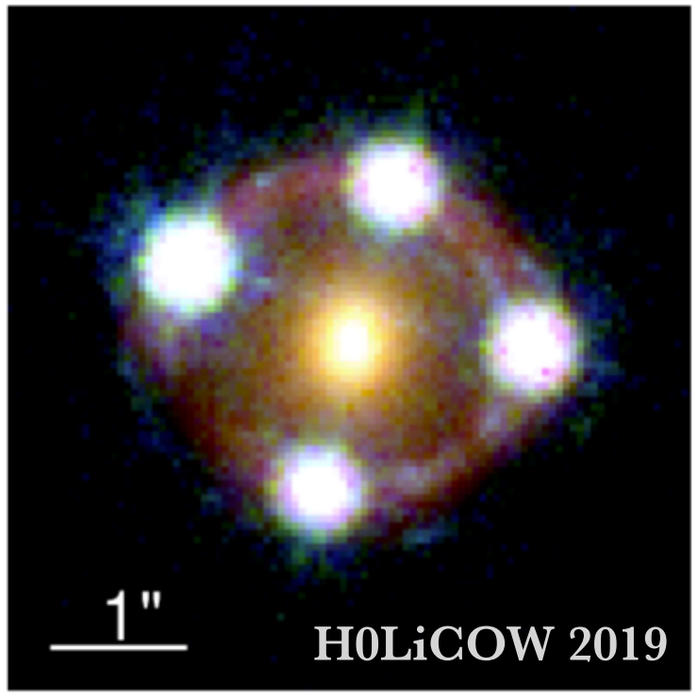
(c) HE 0435−1223



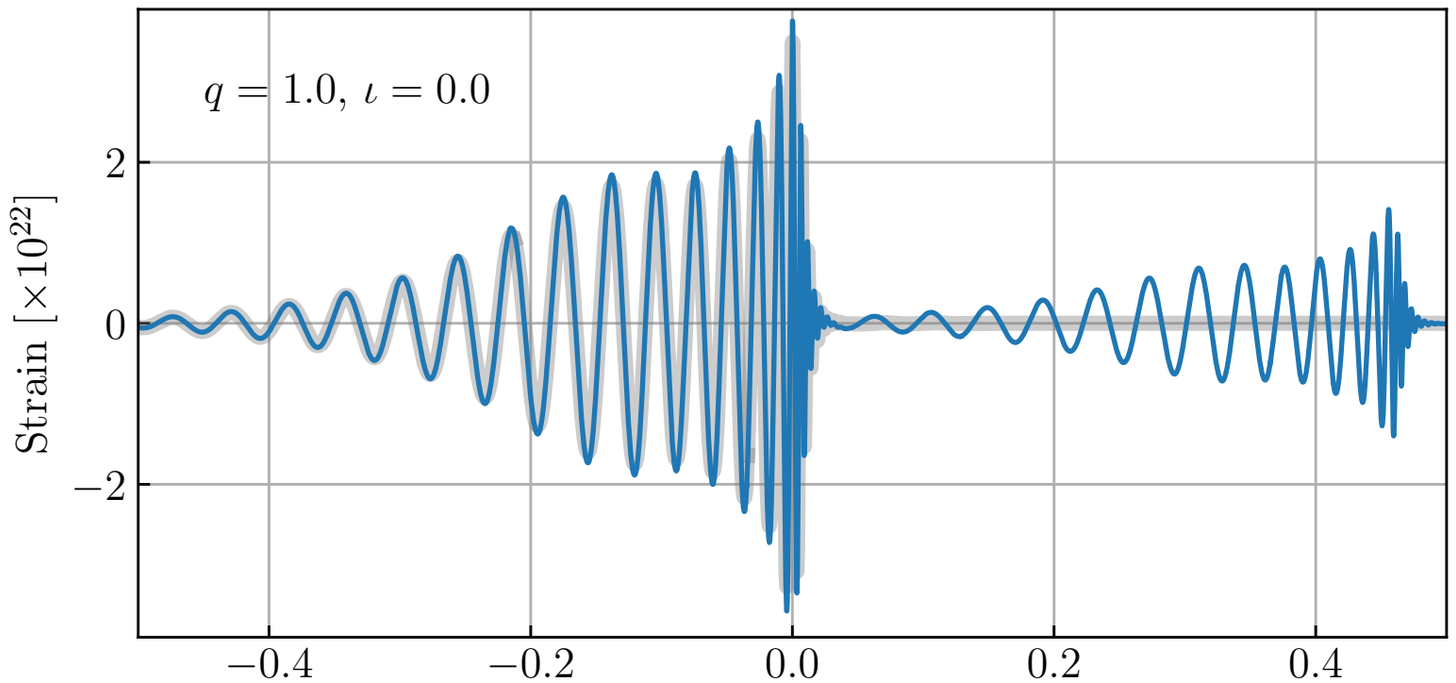
Ezquiaga, Holz, Hu, Lagos+ 2020

- Events: up to a few in LISA [Sereno+2010] (vs ~100 with ET/CE)
- Science:
  - DM distribution
  - H0 constraints [Sereno+2011; Hannuksela+ 2020; Wempe+2022]

GW STRONG LENSING



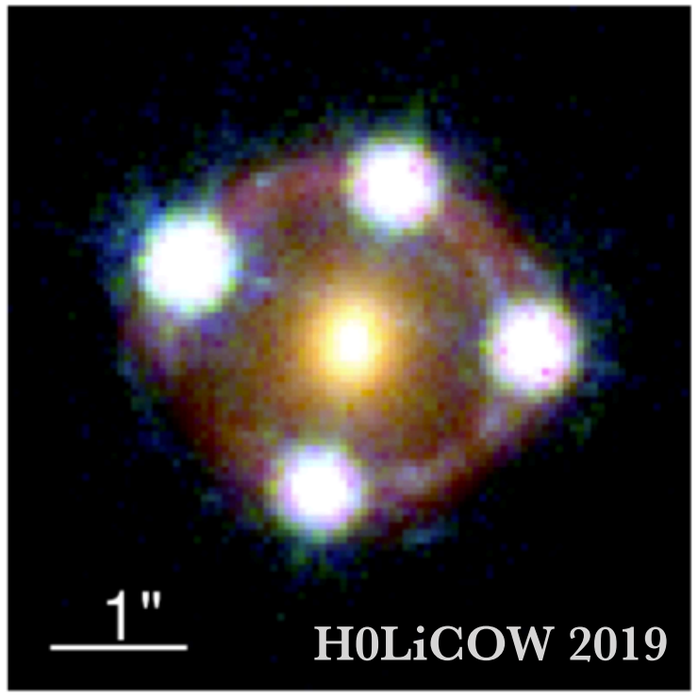
(c) HE 0435−1223



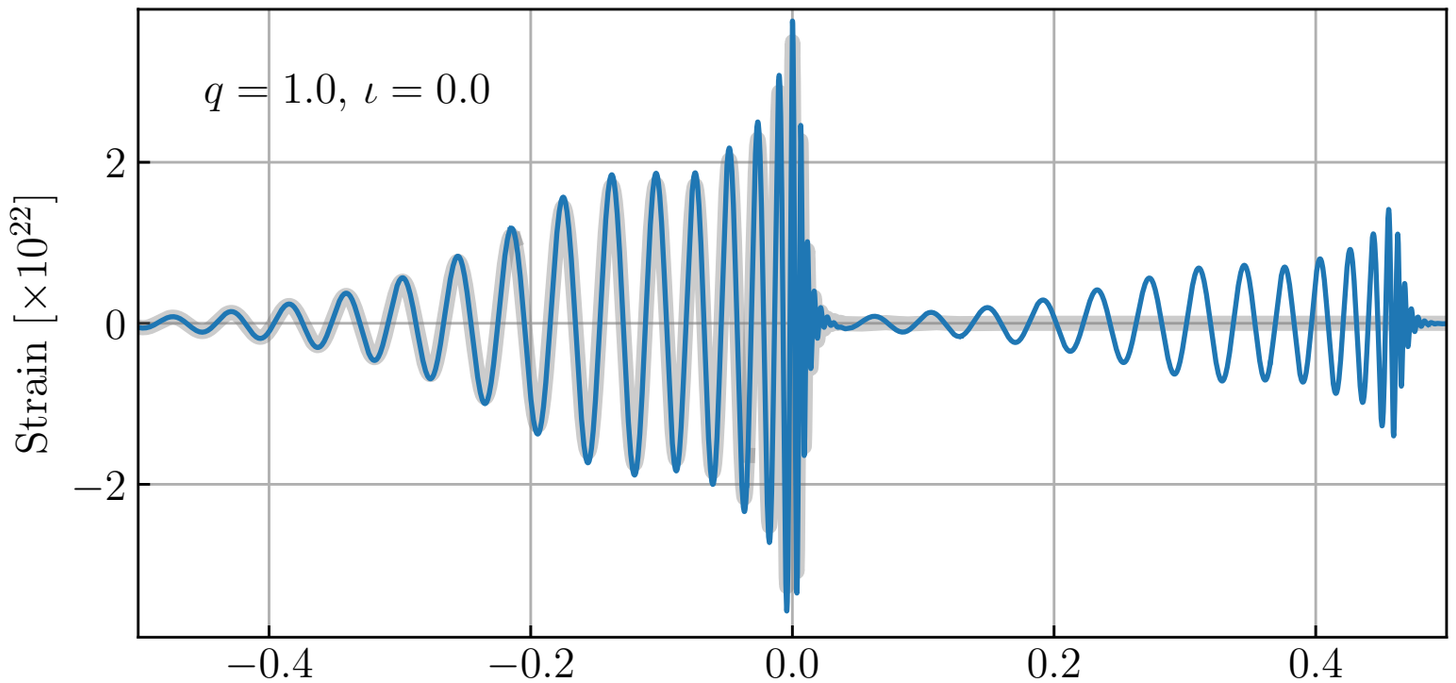
Ezquiaga, Holz, Hu, Lagos+ 2020

- Events: up to a few in LISA [Sereno+2010] (vs ~100 with ET/CE)
- Science:
  - DM distribution
  - H0 constraints [Sereno+2011; Hannuksela+ 2020; Wempe+2022]
  - Better localization and polarization (combine multiple time-delayed events) [Hannuksela+2020; Goyal+2020]

GW STRONG LENSING



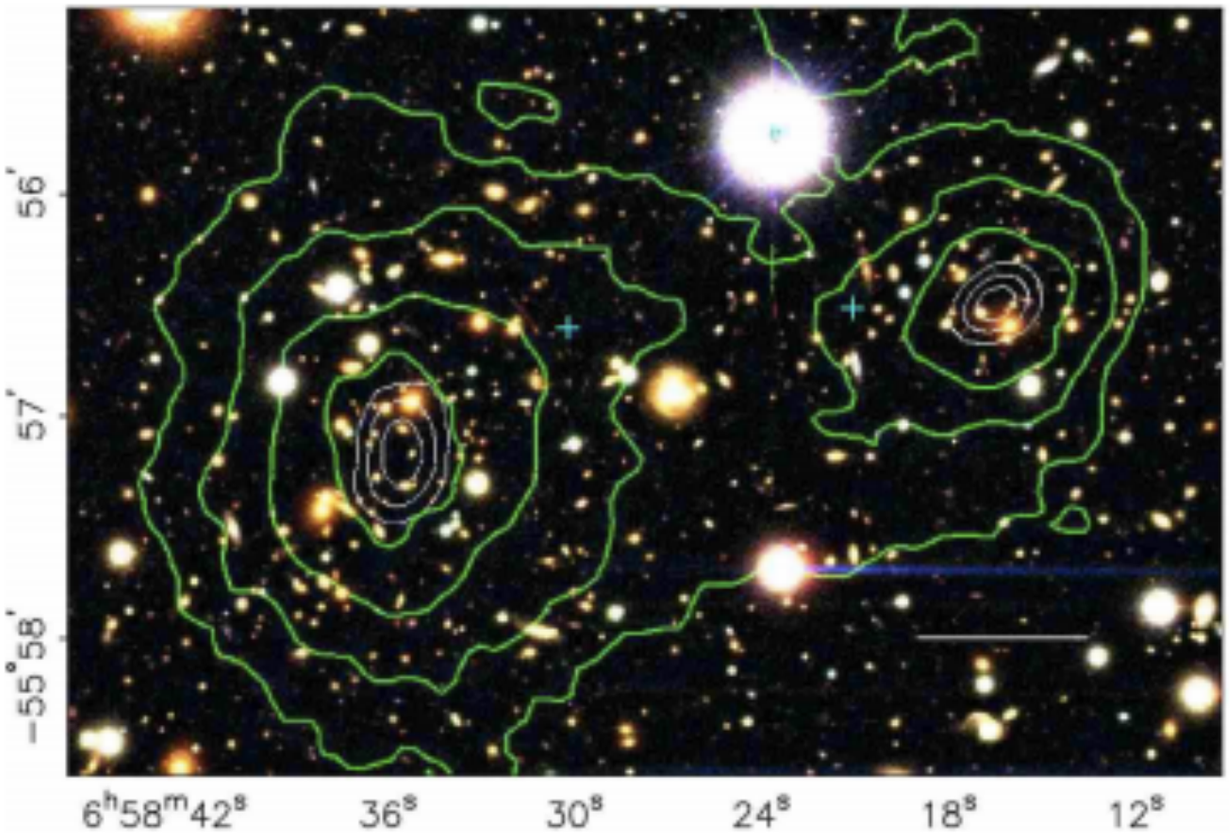
(c) HE 0435−1223



Ezquiaga, Holz, Hu, Lagos+ 2020

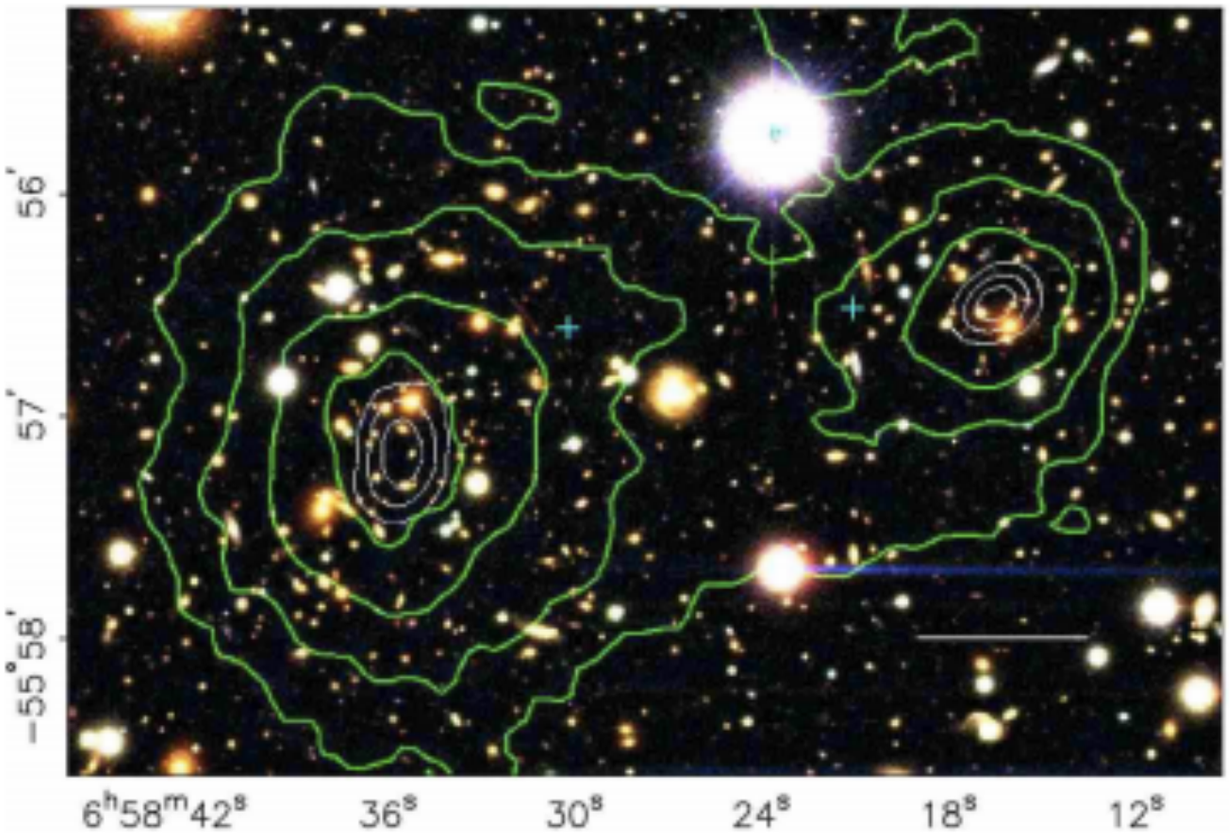
- Events: up to a few in LISA [Sereno+2010] (vs ~100 with ET/CE)
- Science:
  - DM distribution
  - H0 constraints [Sereno+2011; Hannuksela+ 2020; Wempe+2022]
  - Better localization and polarization (combine multiple time-delayed events) [Hannuksela+2020; Goyal+2020]
- Phase shift signature creates distortions for unequal mass ratios (IMRs, EMRIs) [Dai+2007; Ezquiaga, Holz, Hu, Lagos+2020; Wang+2021; Vijaykumar+2022]

GW WEAK LENSING



Clowe+2006

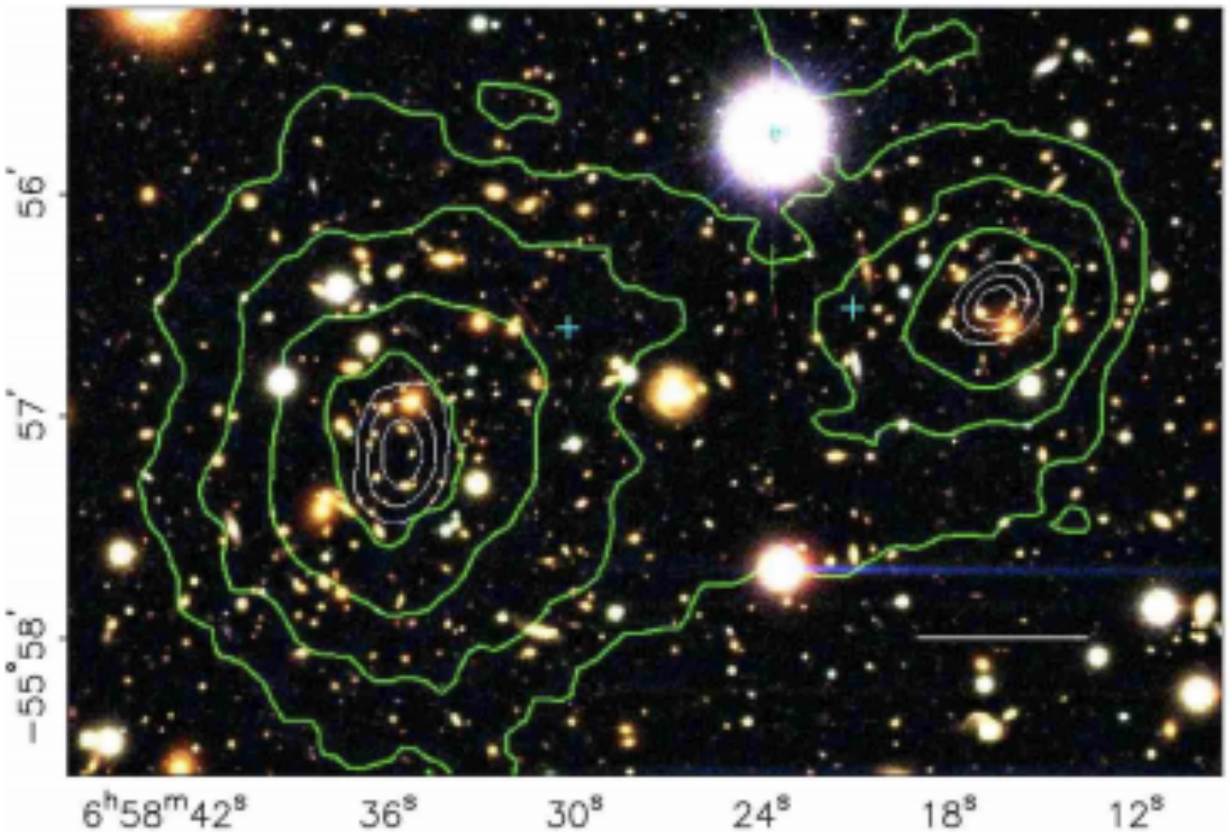
GW WEAK LENSING



Clowe+2006

- Single image with small magnification: $d_L^{obs} = d_L(z; H_0, \Omega_m) \times (1 - \kappa)$

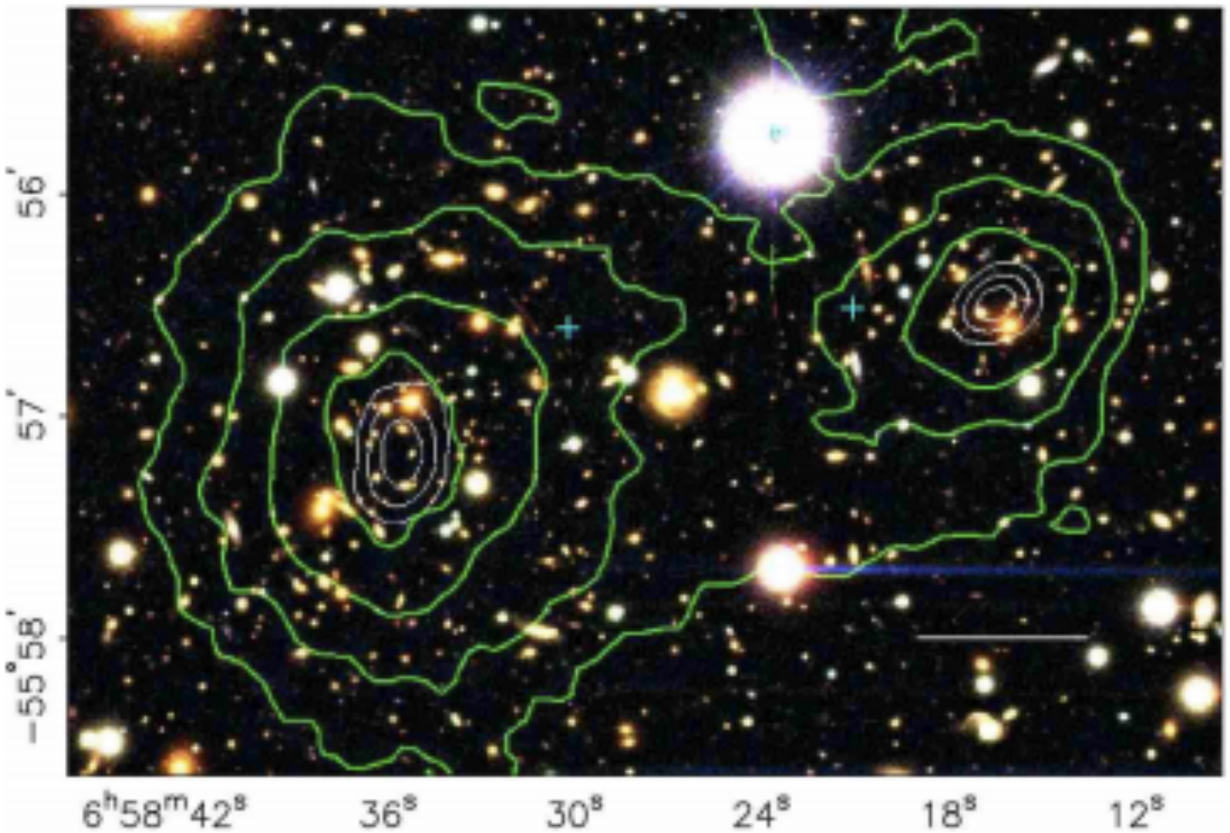
GW WEAK LENSING



Clowe+2006

- Single image with small magnification: $d_L^{obs} = d_L(z; H_0, \Omega_m) \times (1 - \kappa)$
- $\kappa < 1$ traces LSS matter distribution

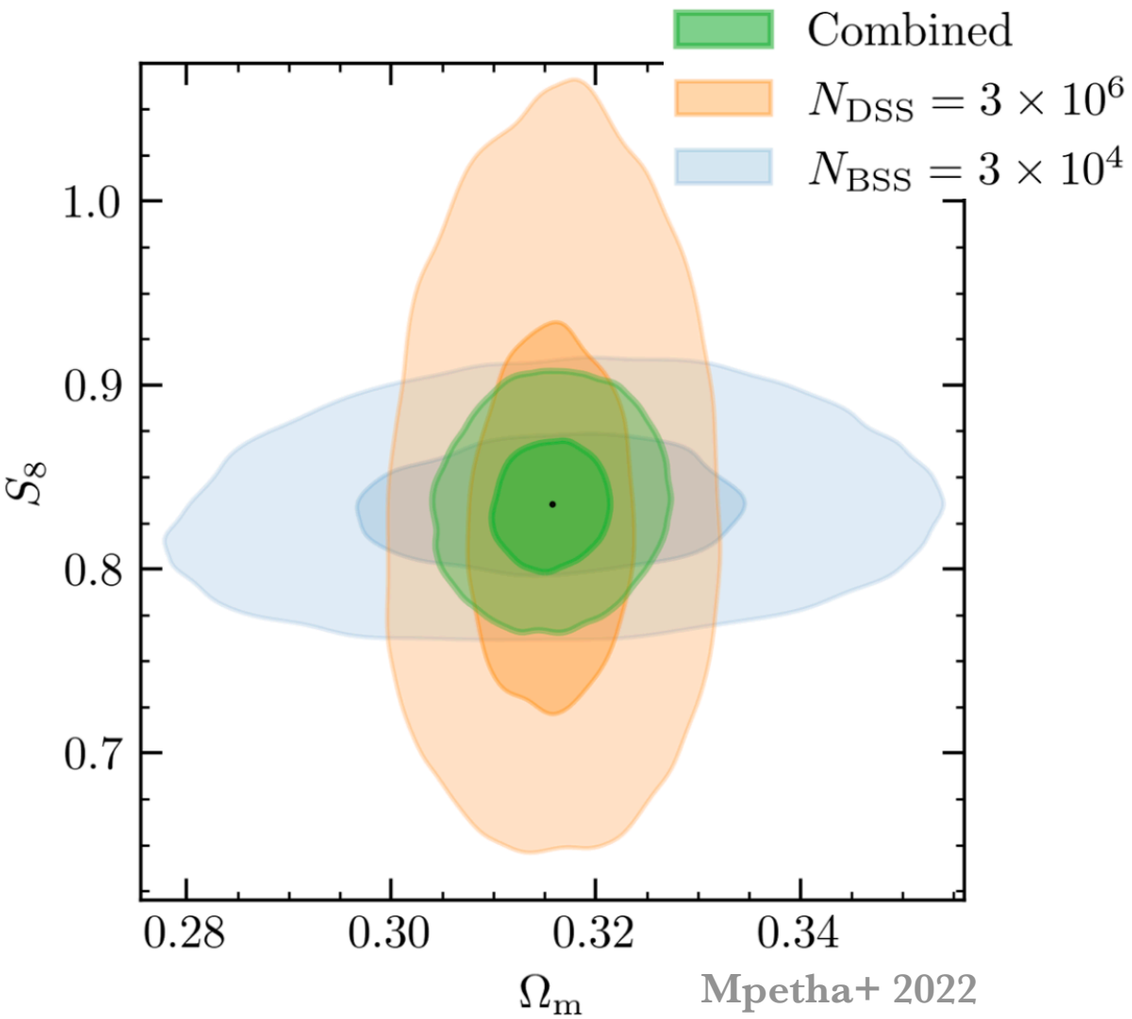
GW WEAK LENSING



Clowe+2006

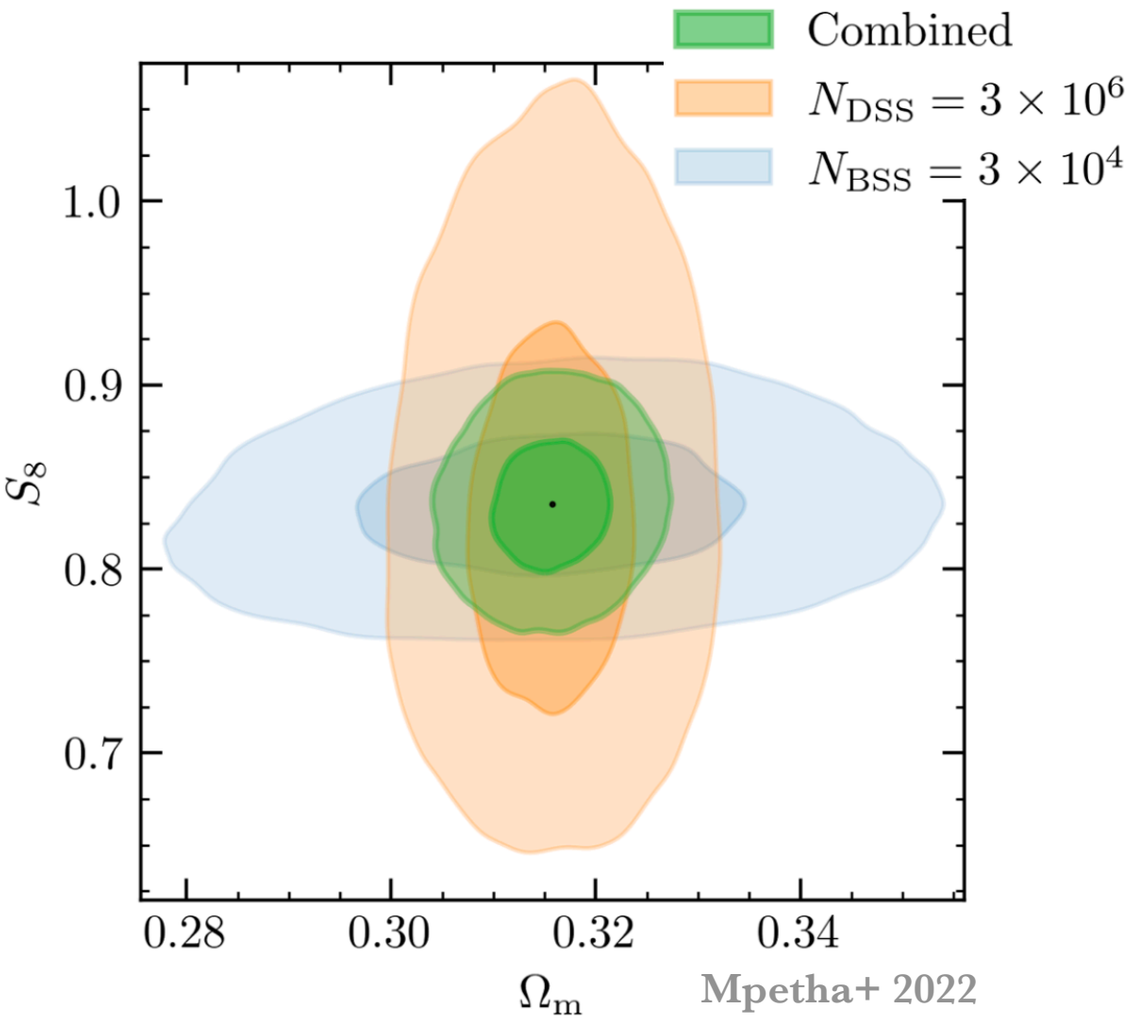
- Single image with small magnification: $d_L^{obs} = d_L(z; H_0, \Omega_m) \times (1 - \kappa)$
- $\kappa < 1$ traces LSS matter distribution
- Ideal case: GW distances with angular correlations + z [Cutler+2009; Shang+2010, Congedo+2019; Mpetha+ 2022]

GW WEAK LENSING



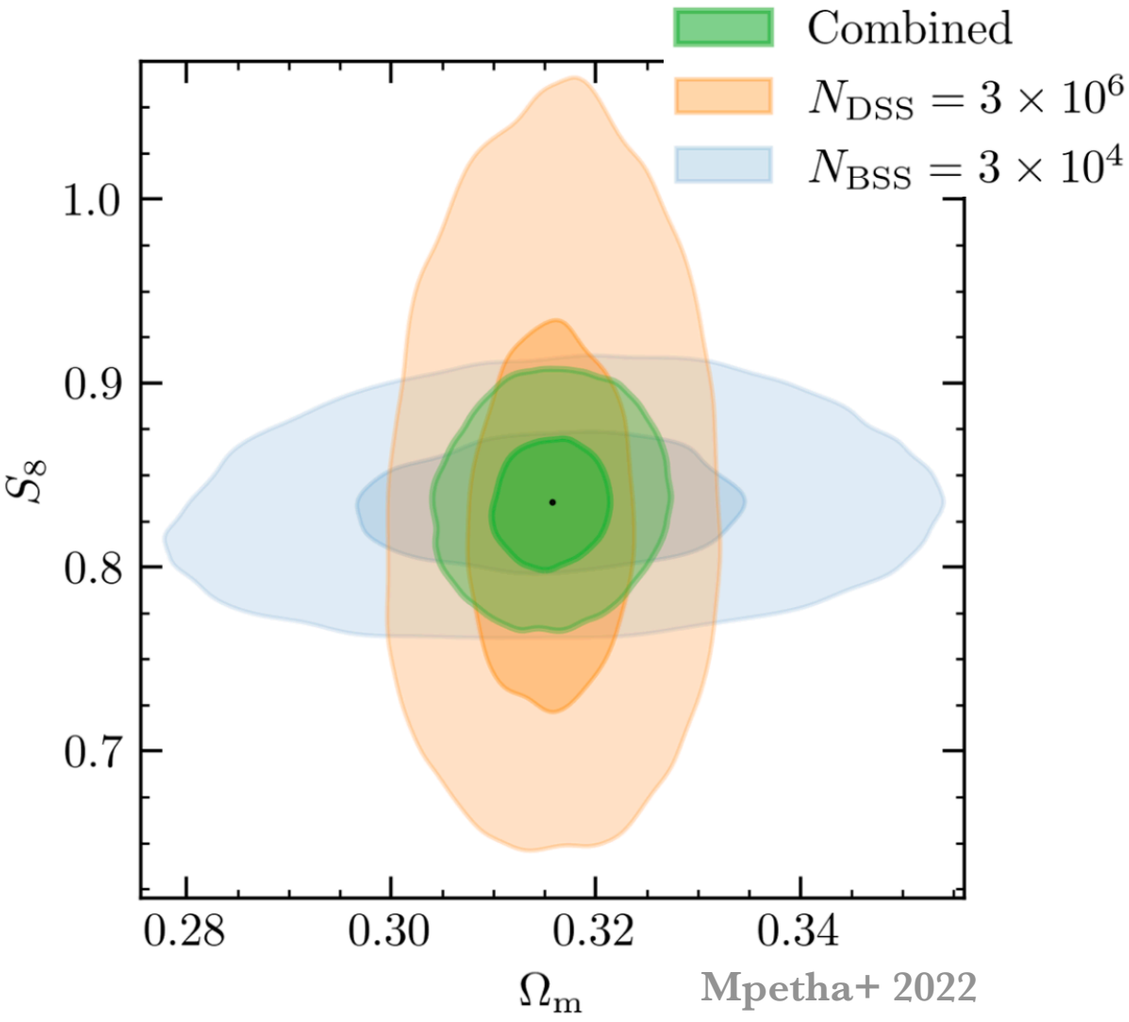
Mpetha+ 2022

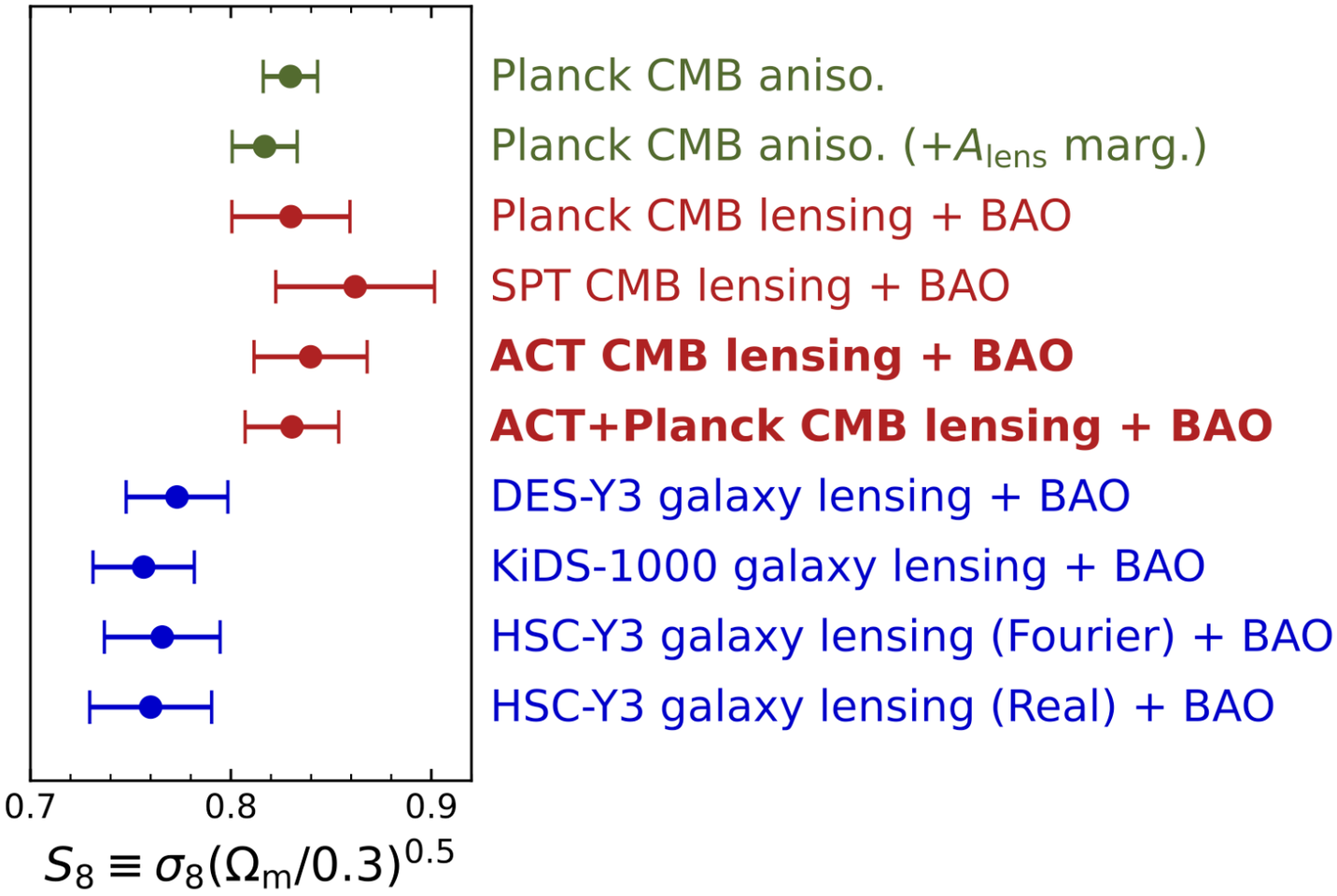
GW WEAK LENSING



- Independent measurement with less systematics

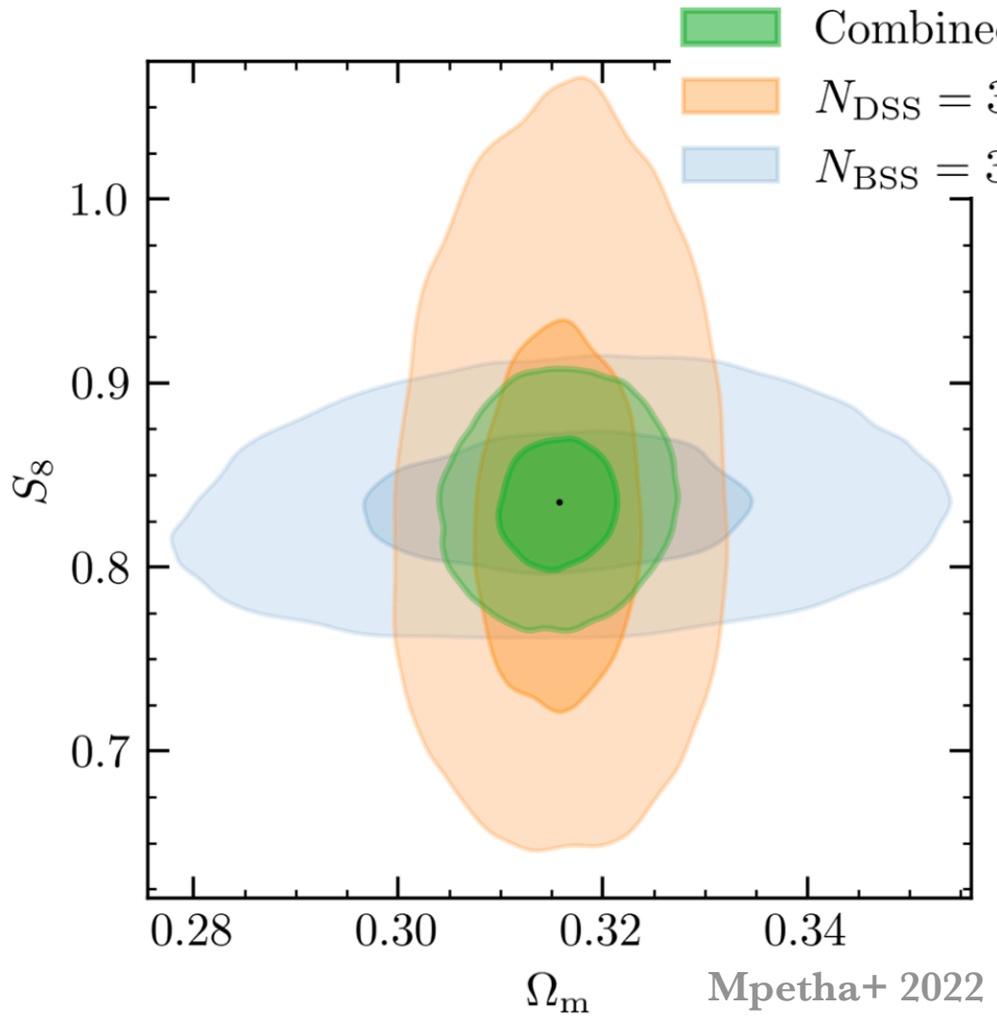
GW WEAK LENSING

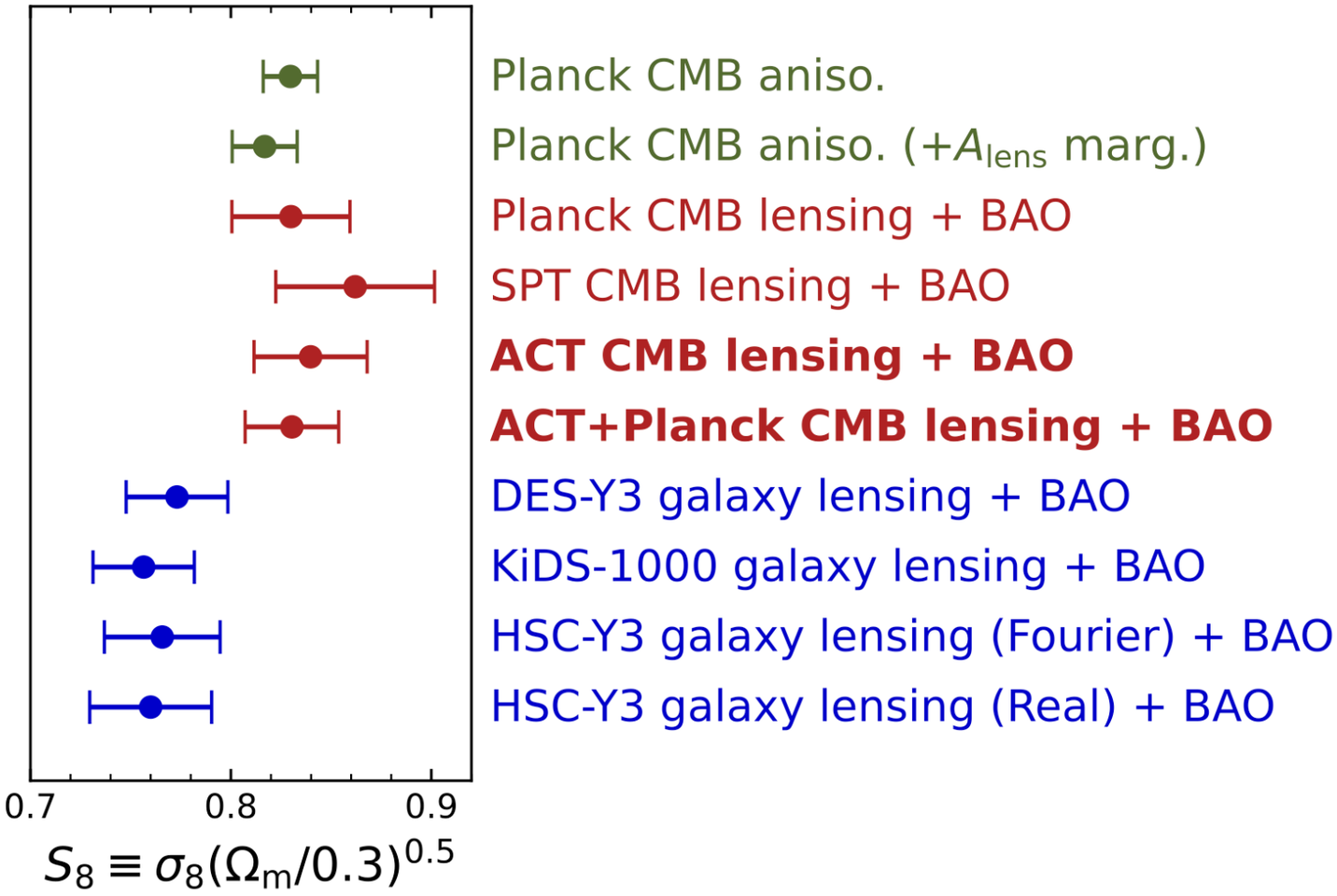




- Independent measurement with less systematics

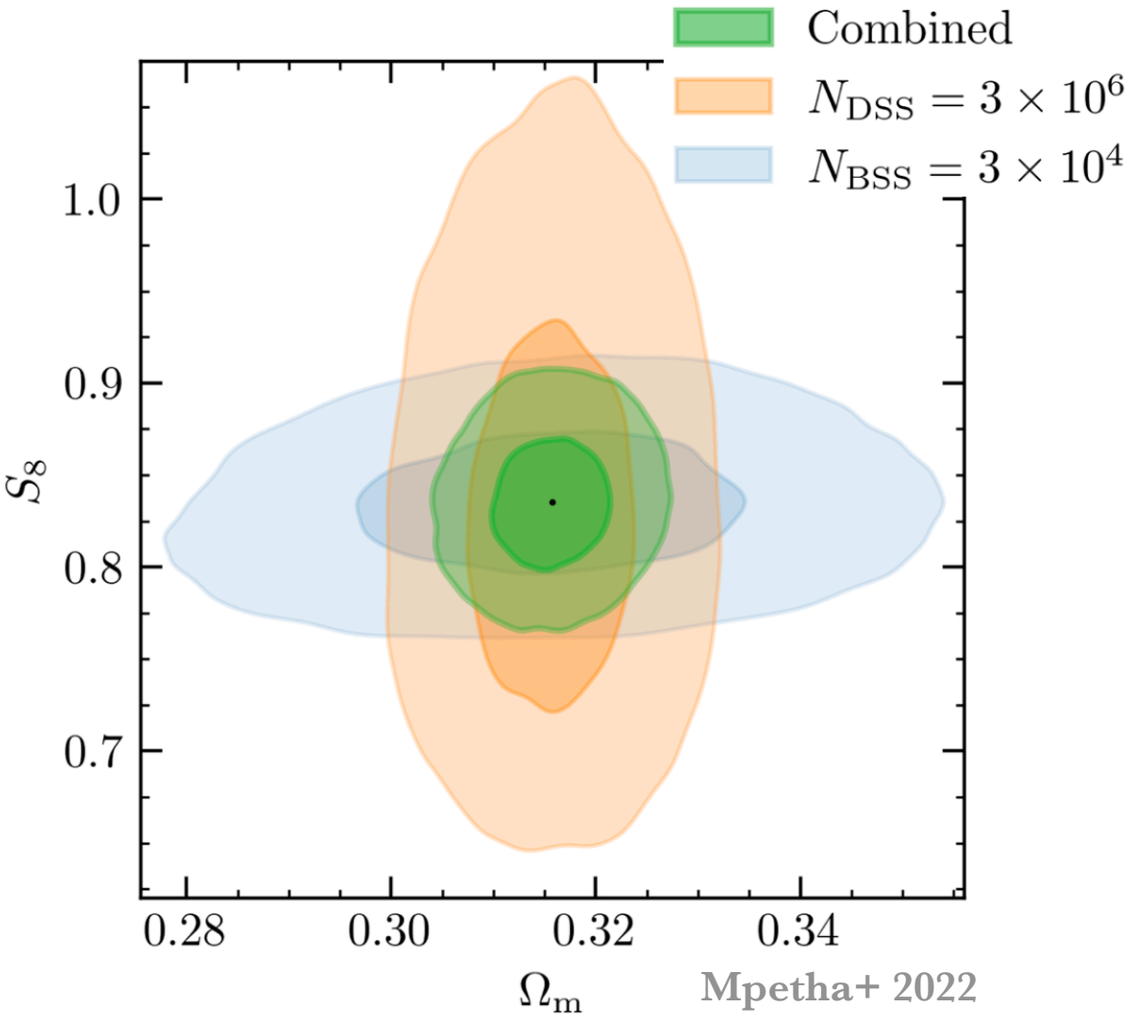
GW WEAK LENSING

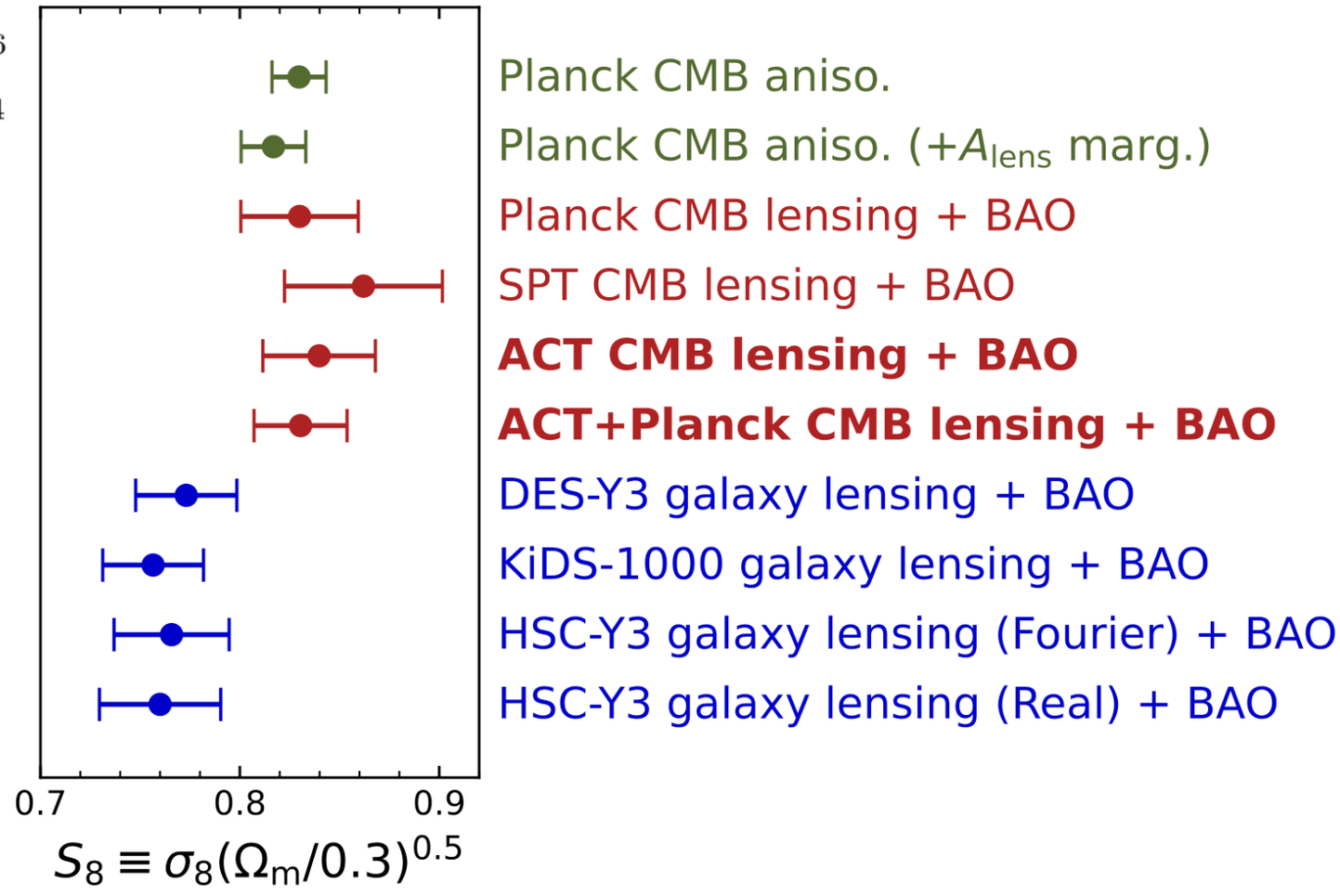




- Independent measurement with less systematics
- Challenge: needs large number of sources, good distance, sky and z information

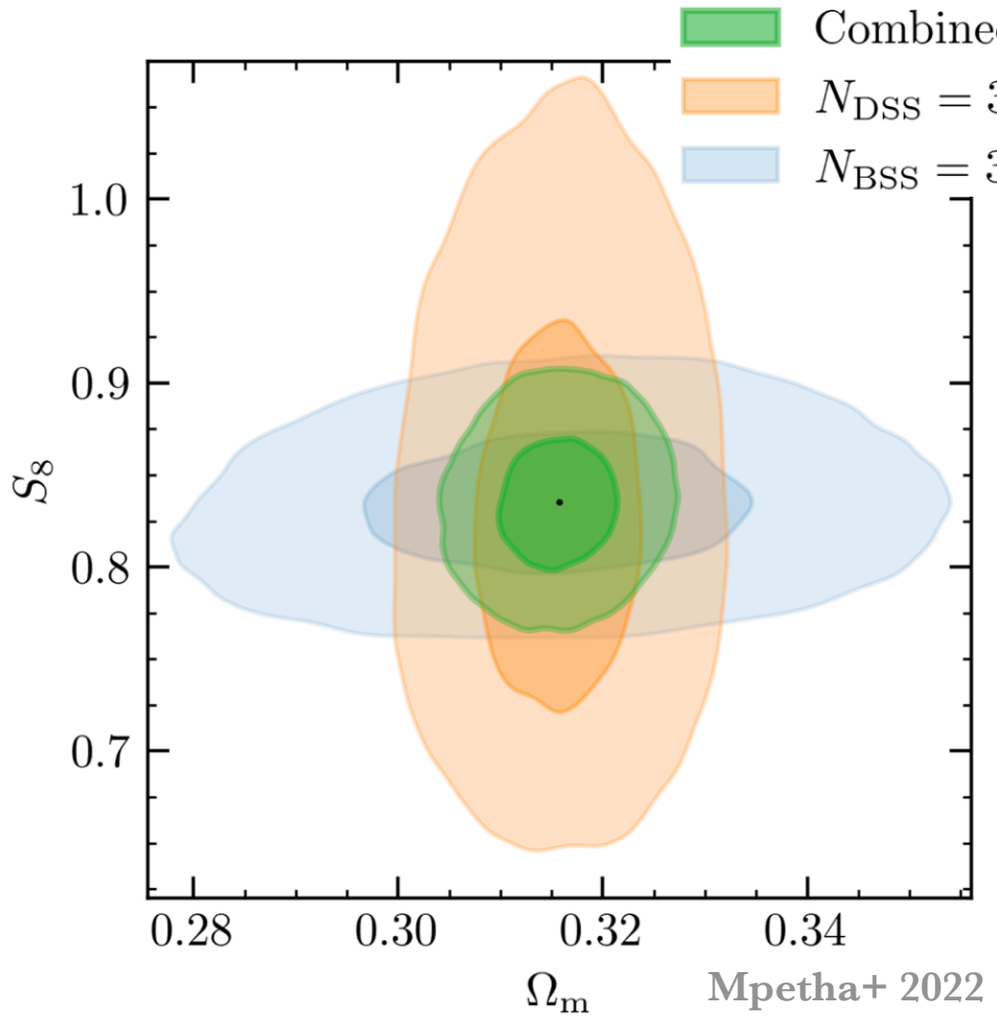
GW WEAK LENSING

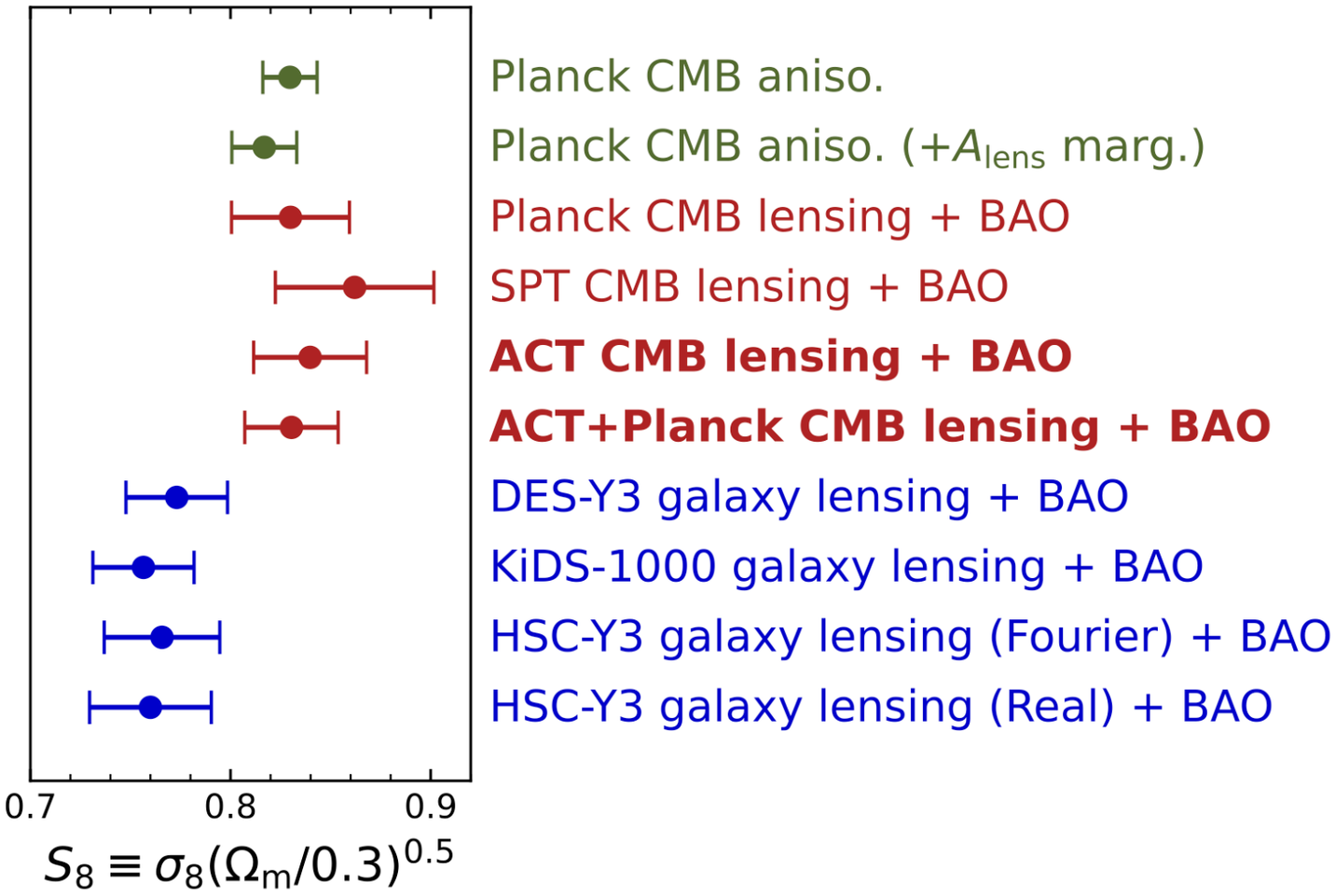




- Independent measurement with less systematics
- Challenge: needs large number of sources, good distance, sky and z information
  - Used in complementary way to EM

GW WEAK LENSING

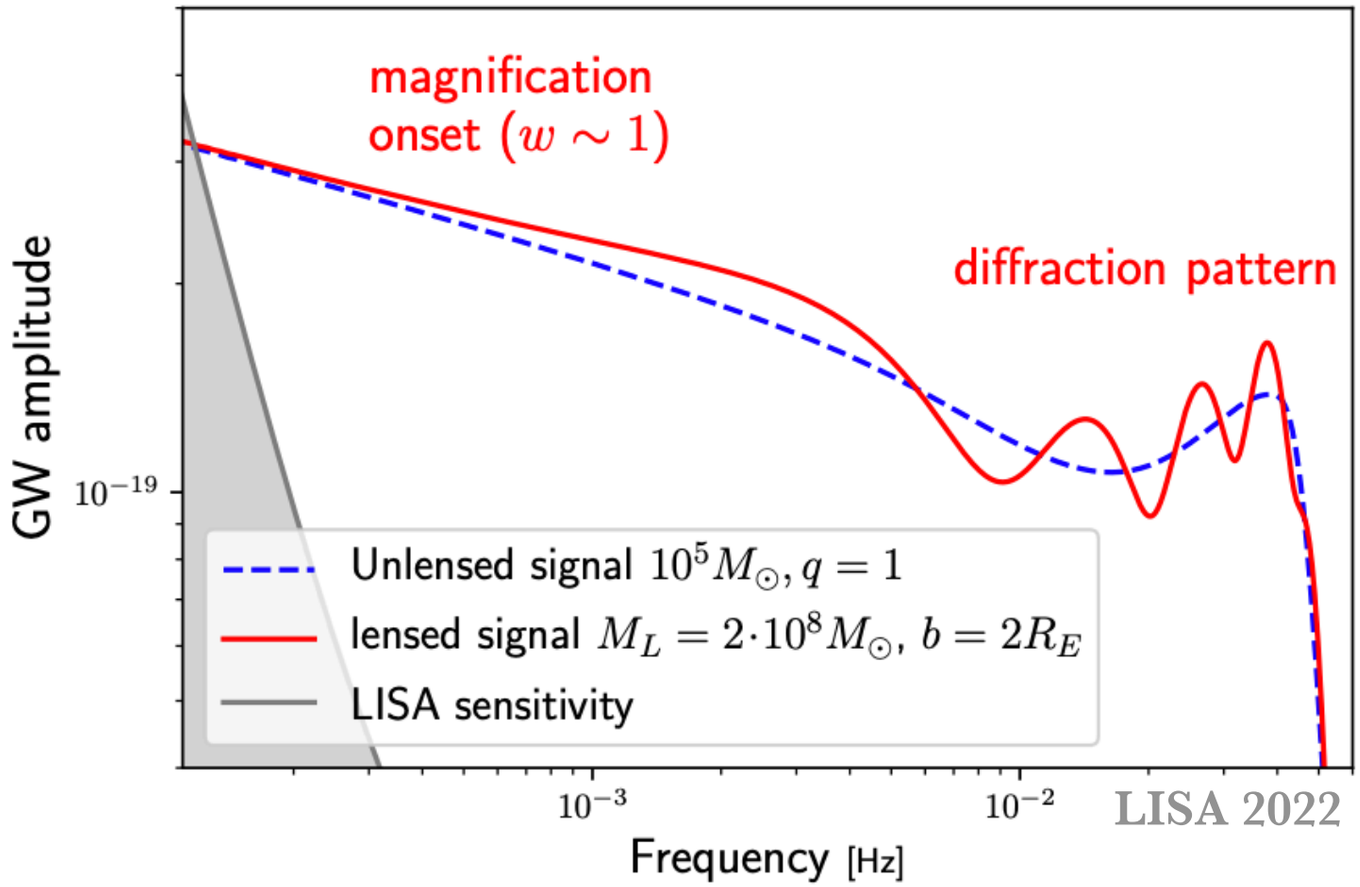




- Independent measurement with less systematics
- Challenge: needs large number of sources, good distance, sky and z information
  - Used in complementary way to EM
- It is a bias for low number of sources

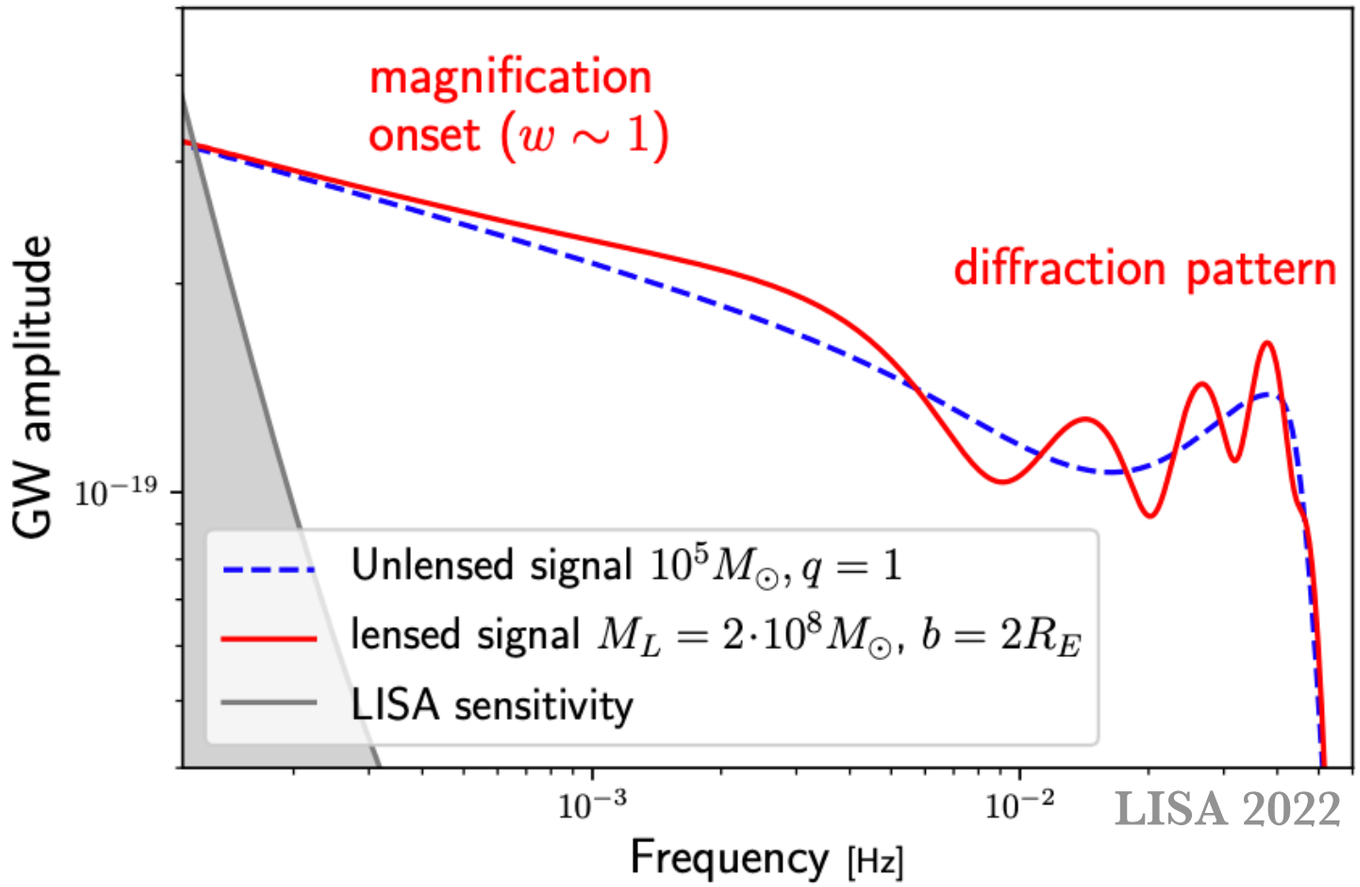
GW MICROLENSING

GW MICROLENSING



- Frequency-dependent distortions when $\lambda \sim M_L$ [Takahashi+2003]

GW MICROLENSING



- Frequency-dependent distortions when $\lambda \sim M_L$ [Takahashi+2003]
  - Ground: $M_L \sim 10 - 10^3 M_\odot$
  - LISA: $M_L \sim 10^6 - 10^8 M_\odot$

GW MICROLENSING

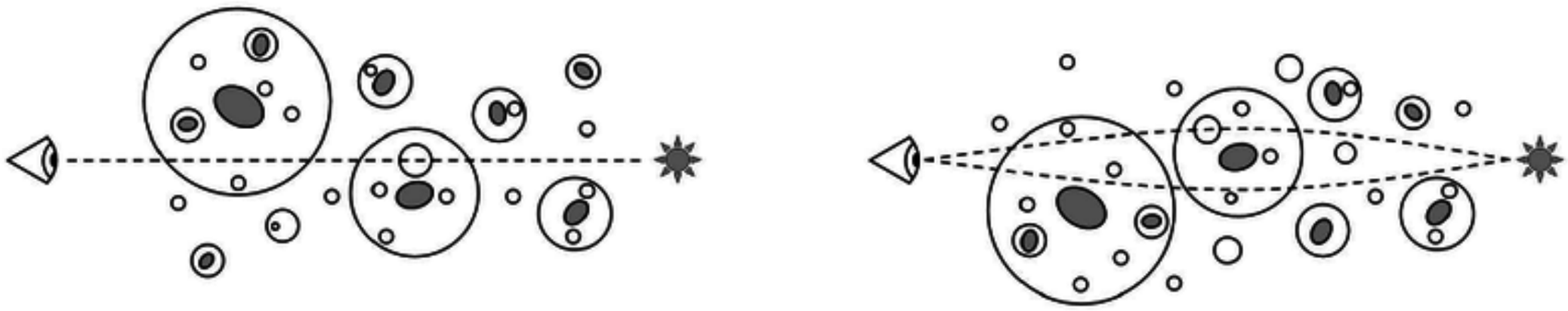
- Up to 2% mergers with detectable distortions by low-mass DM halos in CDM [Gao+ 2022]

GW MICROLENSING

- Up to 2% mergers with detectable distortions by low-mass DM halos in CDM [Gao+ 2022]
- Challenge: realistic lens models and LoS structures

GW MICROLENSING

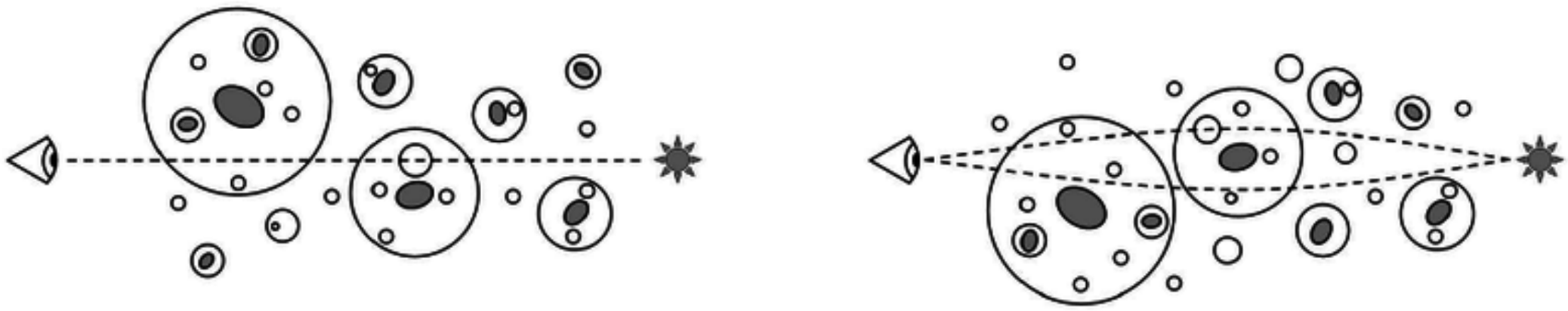
- Up to 2% mergers with detectable distortions by low-mass DM halos in CDM [Gao+ 2022]
- Challenge: realistic lens models and LoS structures
  - Does not need high alignment: $b/R_E \sim \mathcal{O}(10)$ [Gao+ 2022, Caliskan+2022]



Illustrations: Zackrisson+2010

GW MICROLENSING

- Up to 2% mergers with detectable distortions by low-mass DM halos in CDM [Gao+ 2022]
- Challenge: realistic lens models and LoS structures
  - Does not need high alignment: $b/R_E \sim \mathcal{O}(10)$ [Gao+ 2022, Caliskan+2022]
  - Different for individual strongly-lensed images [Tambalo+2023]



Illustrations: Zackrisson+2010

LISA LENSING OUTLOOK

LISA LENSING OUTLOOK

- Probe DM from large to small scales

- GWs lensing is free of many astrophysical systematics

LISA LENSING OUTLOOK

- Probe DM from large to small scales
- GWs lensing is free of many astrophysical systematics
- To Do:
  - Prepare joint EM analyses
  - Quantify realistic weak lensing constraints with EM

LISA LENSING OUTLOOK

- Probe DM from large to small scales
- GWs lensing is free of many astrophysical systematics
- To Do:
  - Prepare joint EM analyses
  - Quantify realistic weak lensing constraints with EM
- Use realistic lenses

LISA LENSING OUTLOOK

- Probe DM from large to small scales
- GWs lensing is free of many astrophysical systematics
- To Do:
  - Prepare joint EM analyses
    - Quantify realistic weak lensing constraints with EM
  - Use realistic lenses
  - Advantages of individual strong-lensed signals

LISA LENSING OUTLOOK

- Probe DM from large to small scales
- GWs lensing is free of many astrophysical systematics
- To Do:
  - Prepare joint EM analyses
    - Quantify realistic weak lensing constraints with EM
  - Use realistic lenses
  - Advantages of individual strong-lensed signals
  - Other signatures—e.g. polarization in microlensing [Cusin, Lagos+2020; Andersson+2021; Dahal+2021; Dalang, Cusin, Lagos 2022; Oancea+2022]

LISA LENSING OUTLOOK

- Probe DM from large to small scales
- GWs lensing is free of many astrophysical systematics
- To Do:
  - Prepare joint EM analyses
    - Quantify realistic weak lensing constraints with EM
- Use realistic lenses
- Advantages of individual strong-lensed signals
- Other signatures—e.g. polarization in microlensing [Cusin, Lagos+2020; Andersson+2021; Dahal+2021; Dalang, Cusin, Lagos 2022; Oancea+2022]
- Use for tests of GR [Ezquiaga, Zumalacarregui+2020; Dalang+2021; Goyal+2023]

LISA LENSING OUTLOOK

- Probe DM from large to small scales
- GWs lensing is free of many astrophysical systematics
- To Do:
  - Prepare joint EM analyses
    - Quantify realistic weak lensing constraints with EM
  - Use realistic lenses
  - Advantages of individual strong-lensed signals
  - Other signatures—e.g. polarization in microlensing [Cusin, Lagos+2020; Andersson+2021; Dahal+2021; Dalang, Cusin, Lagos 2022; Oancea+2022]
  - Use for tests of GR [Ezquiaga, Zumalacarregui+2020; Dalang+2021; Goyal+2023]
  - More pressing questions?

LISA LENSING OUTLOOK

- Probe DM from large to small scales
- GWs lensing is free of many astrophysical systematics
- To Do:
  - Prepare joint EM analyses
  - Quantify realistic weak lensing constraints with EM
- Use realistic lenses
- Advantages of individual strong-lensed signals
- Other signatures—e.g. polarization in microlensing [Cusin, Lagos+2020; Andersson+2021; Dahal+2021; Dalang, Cusin, Lagos 2022; Oancea+2022]
- Use for tests of GR [Ezquiaga, Zumalacarregui+2020; Dalang+2021; Goyal+2023]
- More pressing questions?