Cluster Lensing in the JWST Era

—— Methodologies of lens modeling

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2023.3.3, Student seminar

Why is lens modeling important?

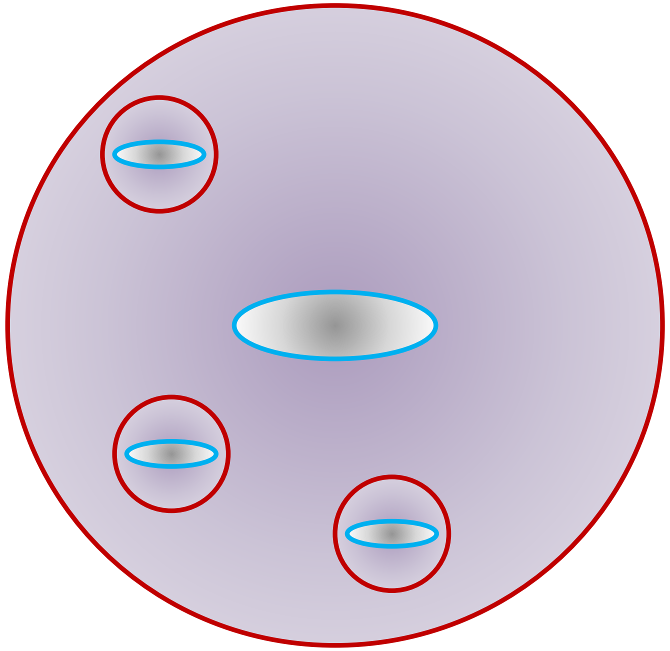
- Accurate lens model helps to correct lensing effects in source reconstruction
  - Luminosity, stellar mass, etc.
- Different results of lens modeling have great impact on source reconstruction
- Uncertainties from lens modeling can result in bias in source properties
  - E.g. image magnification

Models of cluster lens fitting

To fit $\Sigma(\vec{\theta})$

Parametric models

- Use analytical profiles to describe mass distribution



Pros

- Directly compares physically motivated models to data
- Less number of parameters, easy to fit

Cons

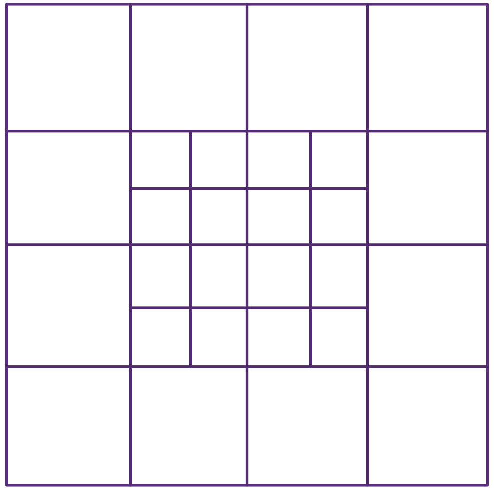
- Model assumptions may differ from reality (e.g. light-traces-mass)
- Lack of freedom introduces biases

Models of cluster lens fitting

To fit $\Sigma(\vec{\theta})$

Free-form (non-parametric) models

- Use pixelized mesh to describe mass distribution



Pros

- Free of model assumptions
- Positions of grid points can be chosen arbitrarily

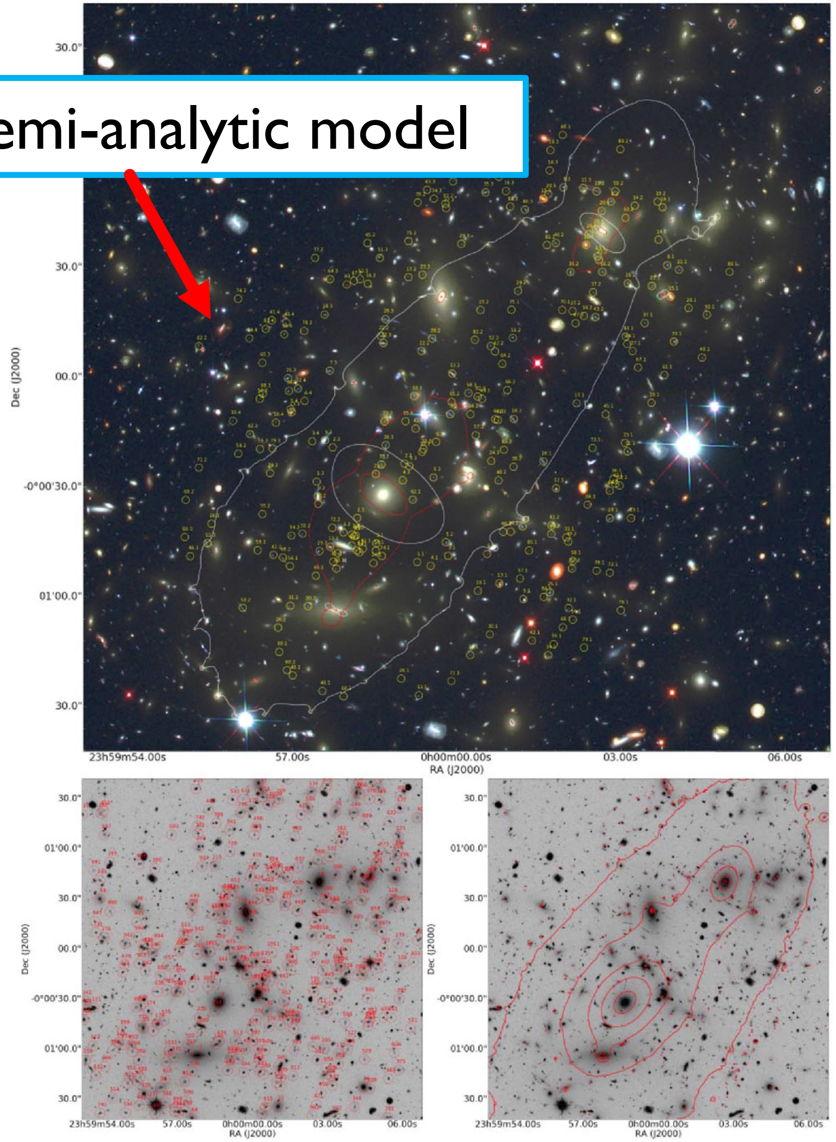
Cons

- Inherently unstable because of too many "parameters"
- Likely to diverge or get stuck in local minima

Comparison between different models

Meneghetti et al. 2017

Semi-analytic model

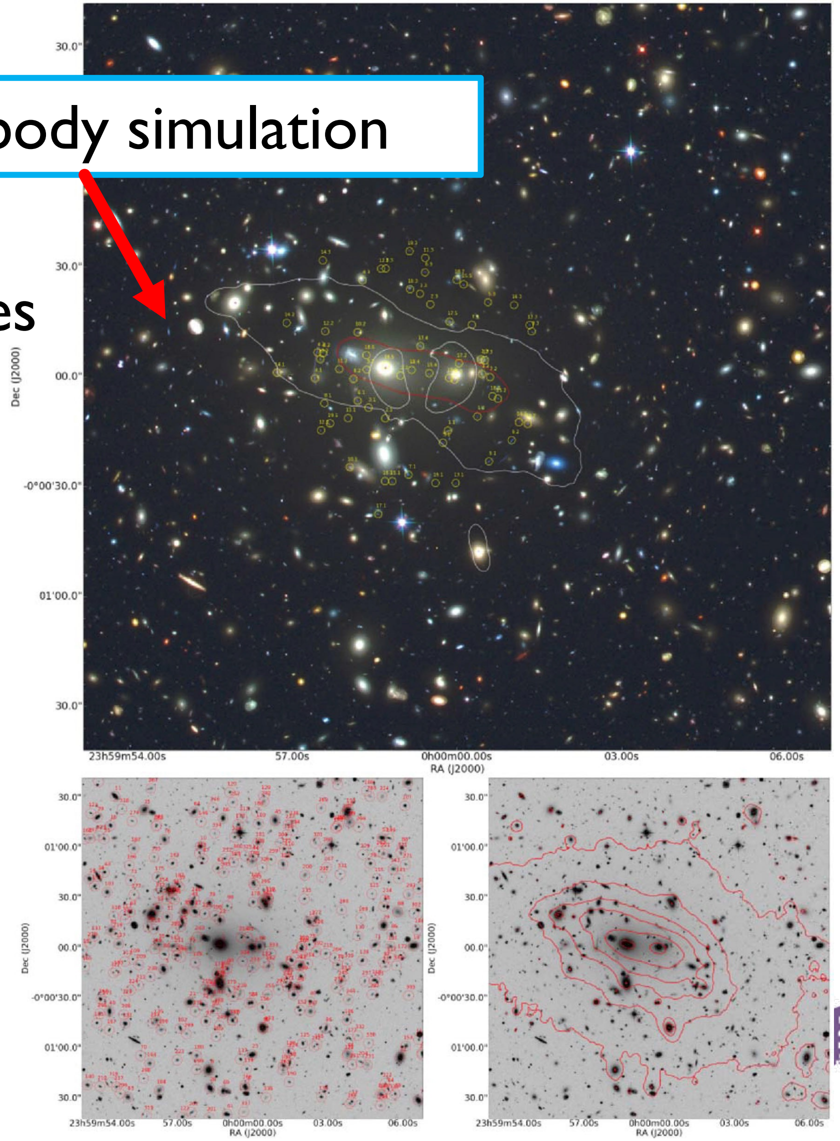


Mock cluster images

← Fig. 3

Fig. 4 →

N-body simulation



Comparison between different models

Meneghetti et al. 2017

Bradac-Hoag (Bradac+2009)
Diego-multires
Diego-overfit
Diego-reggrid (Diego+2016)
Lam (Lam+2014)
GRALE (Liesenborgs+2006)
Coe (Coe+2008)

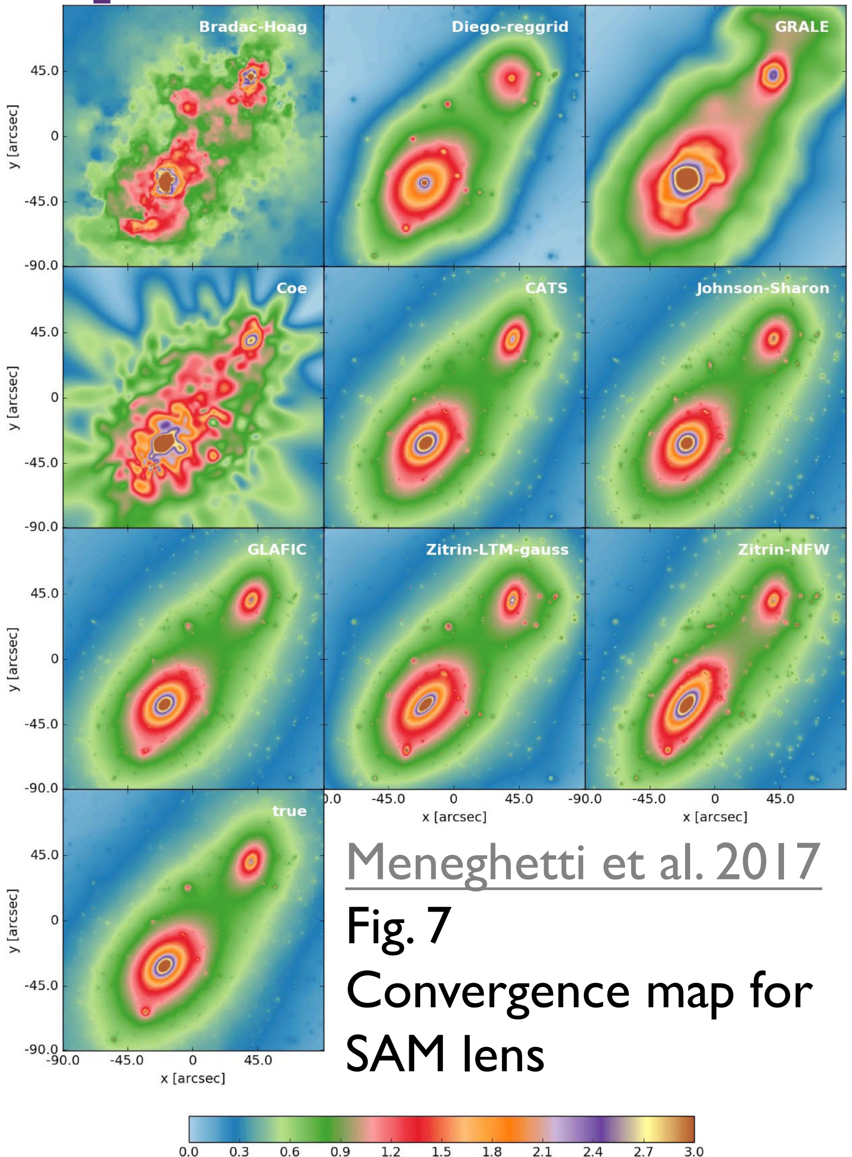
Free-form (including hybrid) models

CATS (Jullo & Kneib 2009)
Johnson-Sharon (Sharon+2012, Johnson+2014)
GLAFIC (Oguri 2010)
Zitrin-LTM-gauss (Zitrin+2009)
Zitrin-NFW (Zitrin+2013)

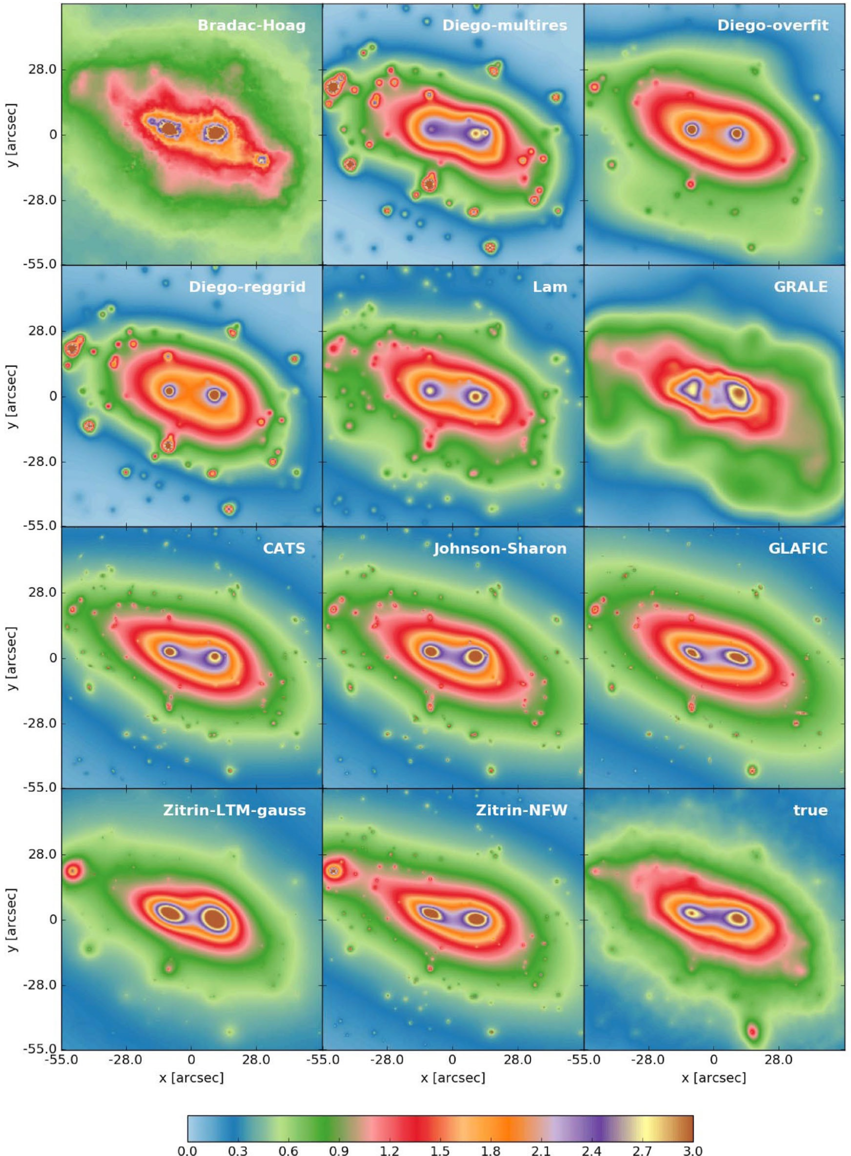
Parametric models

Different settings, fitting tools, profiles, …

Different models vary widely in reconstructed lens clusters



Meneghetti et al. 2017
Fig. 7
Convergence map for SAM lens



The major differences are found near substructures

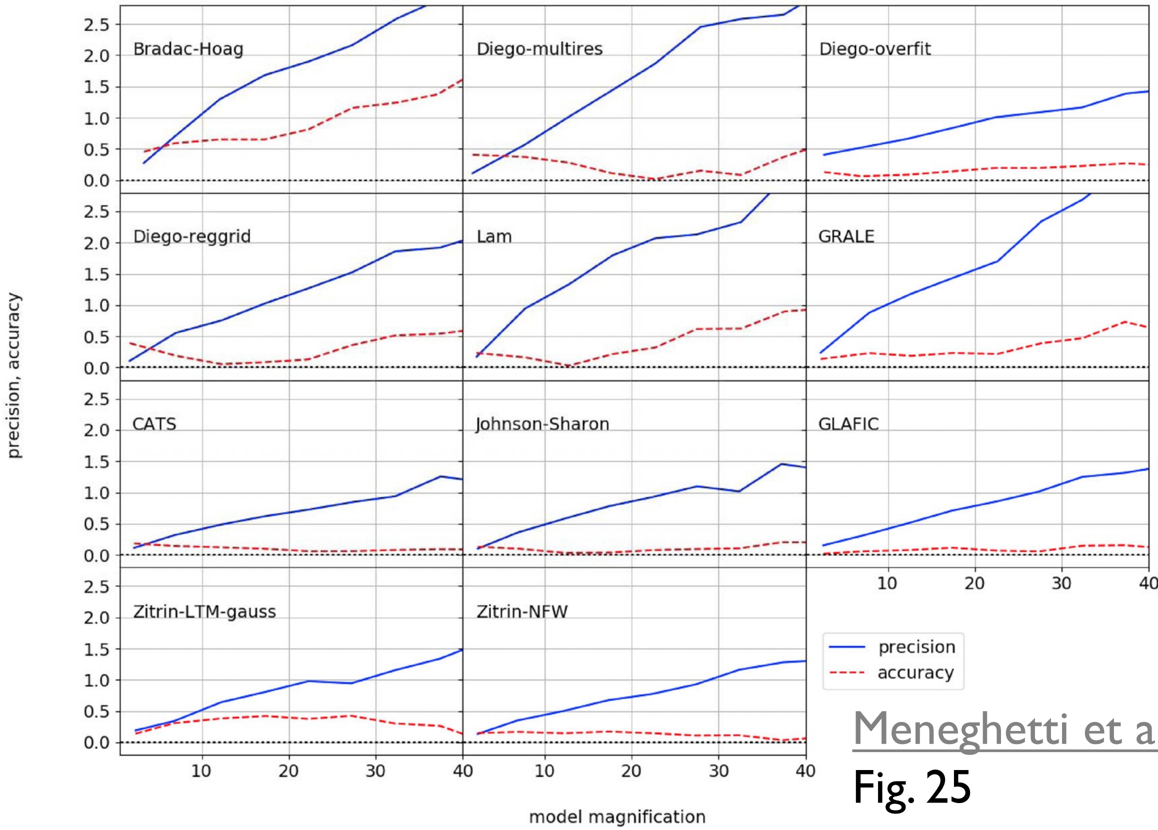
*Convergence:
$\kappa \equiv \Sigma(\vec{\theta})/\Sigma_{crit}$
Σ_{crit}: critical density dependent on lens and source redshifts only

Meneghetti et al. 2017
Fig. 8
Convergence map for N-body lens

Uncertainties are large

The largest uncertainties are found near substructures and critical curves

- Uncertainties on the magnification grow as a function of the magnification itself
- For the best-performing methods, the accuracy in magnification is ∼10 percent at $\mu_{true} = 3$ and it degrades to ∼30 percent at $\mu_{true} \sim 10$



Meneghetti et al. 2017

Fig. 25

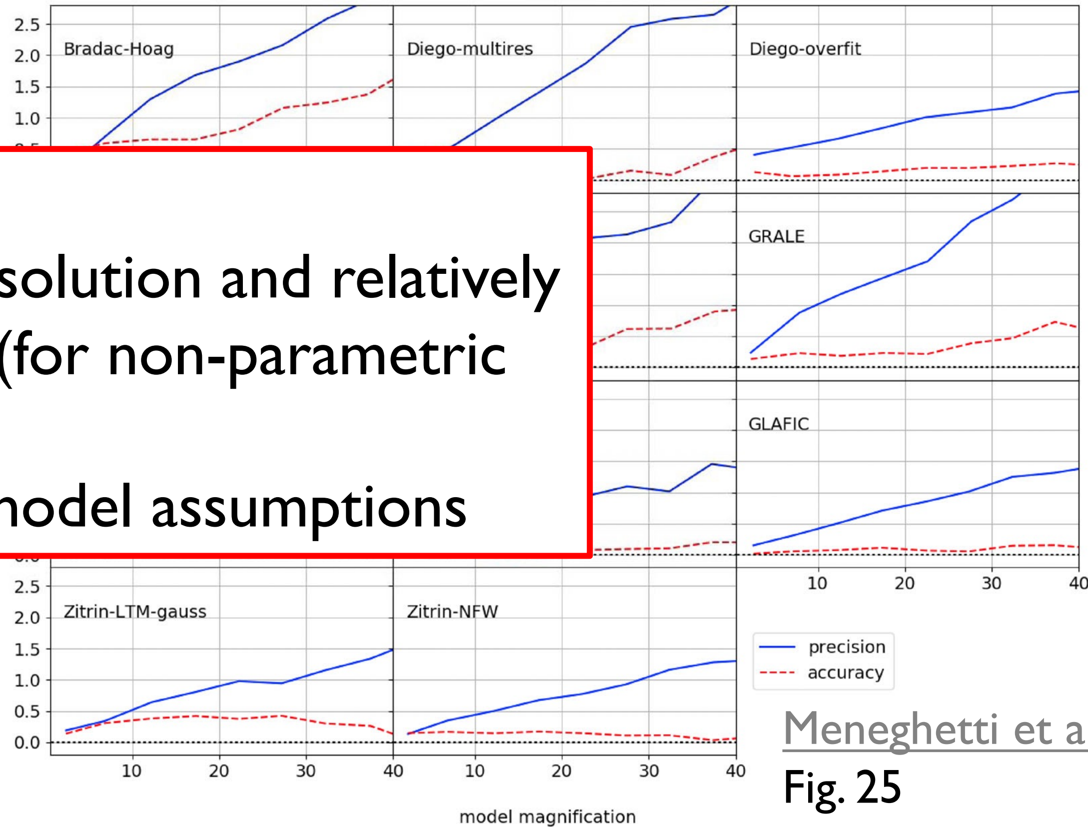
Uncertainties are large

The largest uncertainties are found near substructures and critical curves

- Uncertainties on the magnification grov of the magnificatio
- For the best-perfo methods, the accu magnification is ~ $\mu_{true} = 3$ and it degrades to ~30 percent at $\mu_{true} \sim 10$

Why?

- Lower spatial resolution and relatively less constraints (for non-parametric models)
- Oversimplified model assumptions



Meneghetti et al. 2017

Fig. 25

A specific example: SMACS J0723

Mahler et al. 2022

Data/Constraints

- The positions of prominent light peaks in each lensed image (catalogue data)
  - 16 new multi-image systems are discovered with JWST
- Spectroscopic redshifts (5 systems)
  - One is confirmed with JWST

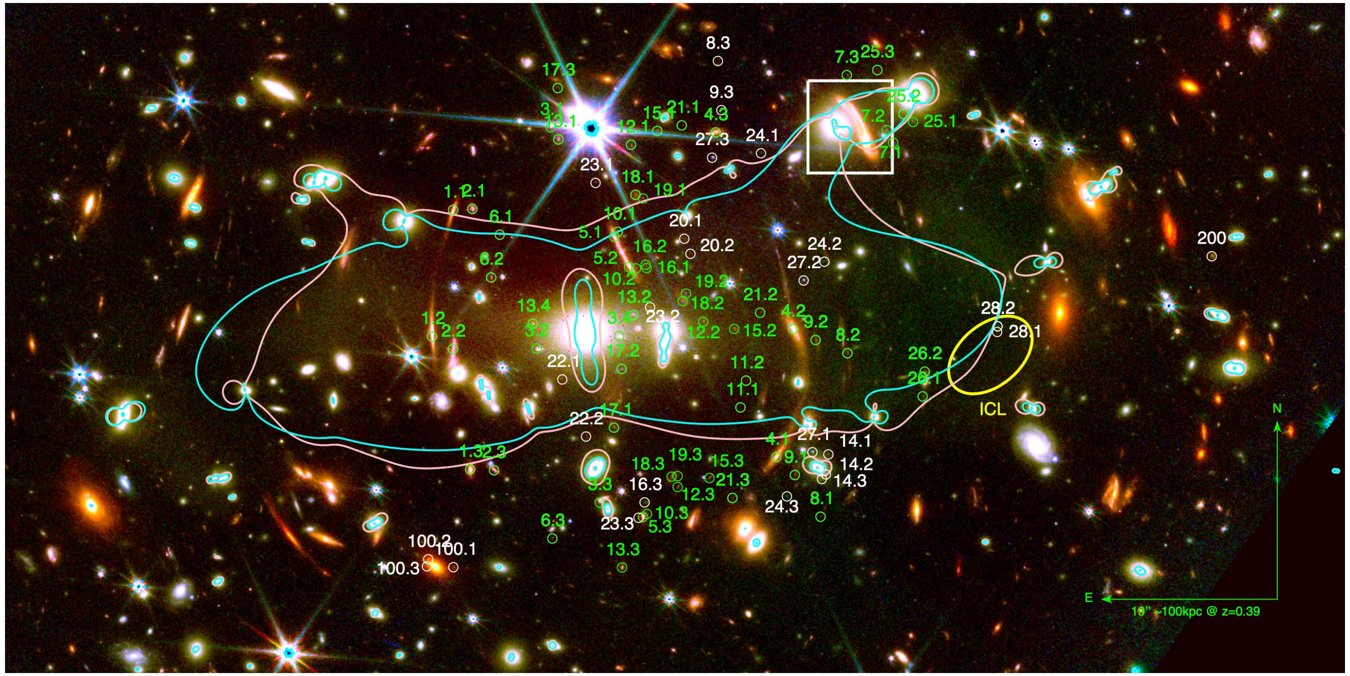
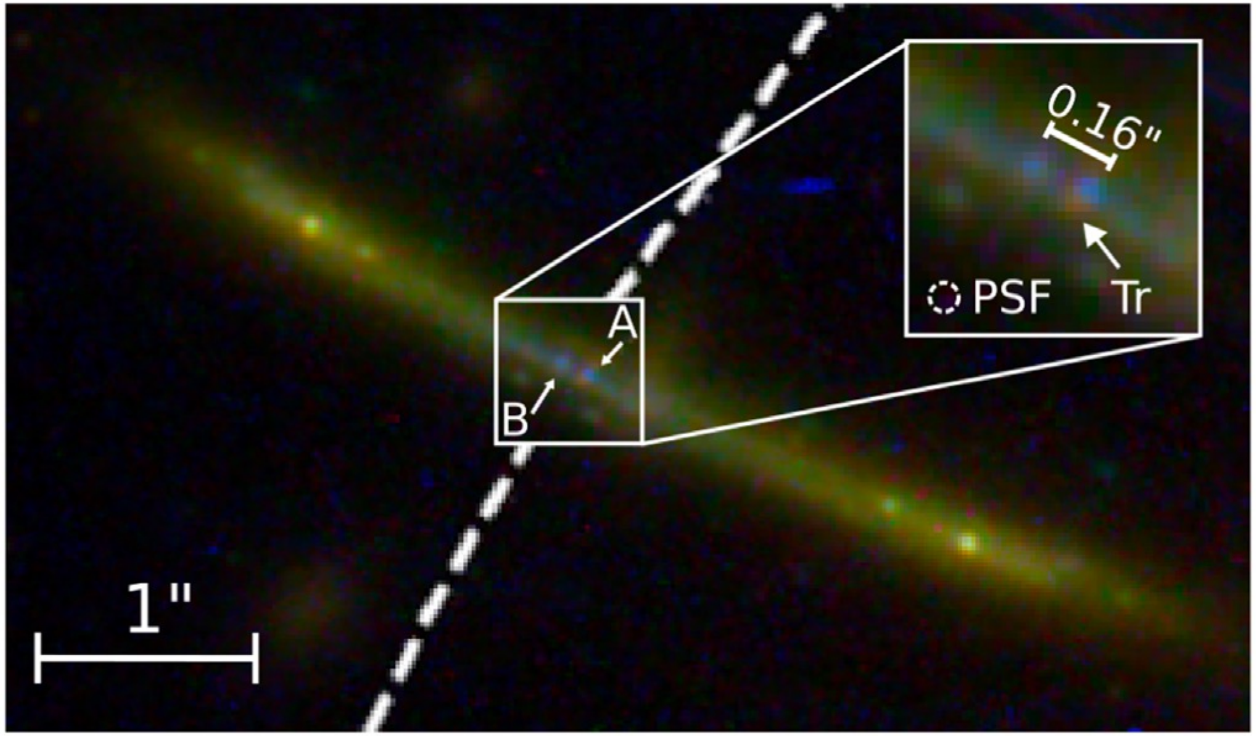


Fig. 4, top panel

How JWST plays a role

High resolution

- Able to see previously unseen substructures in images
  - identify new multi-image systems
- Constrain the local critical curve precisely
  - Critical curves directly depend on mass distribution

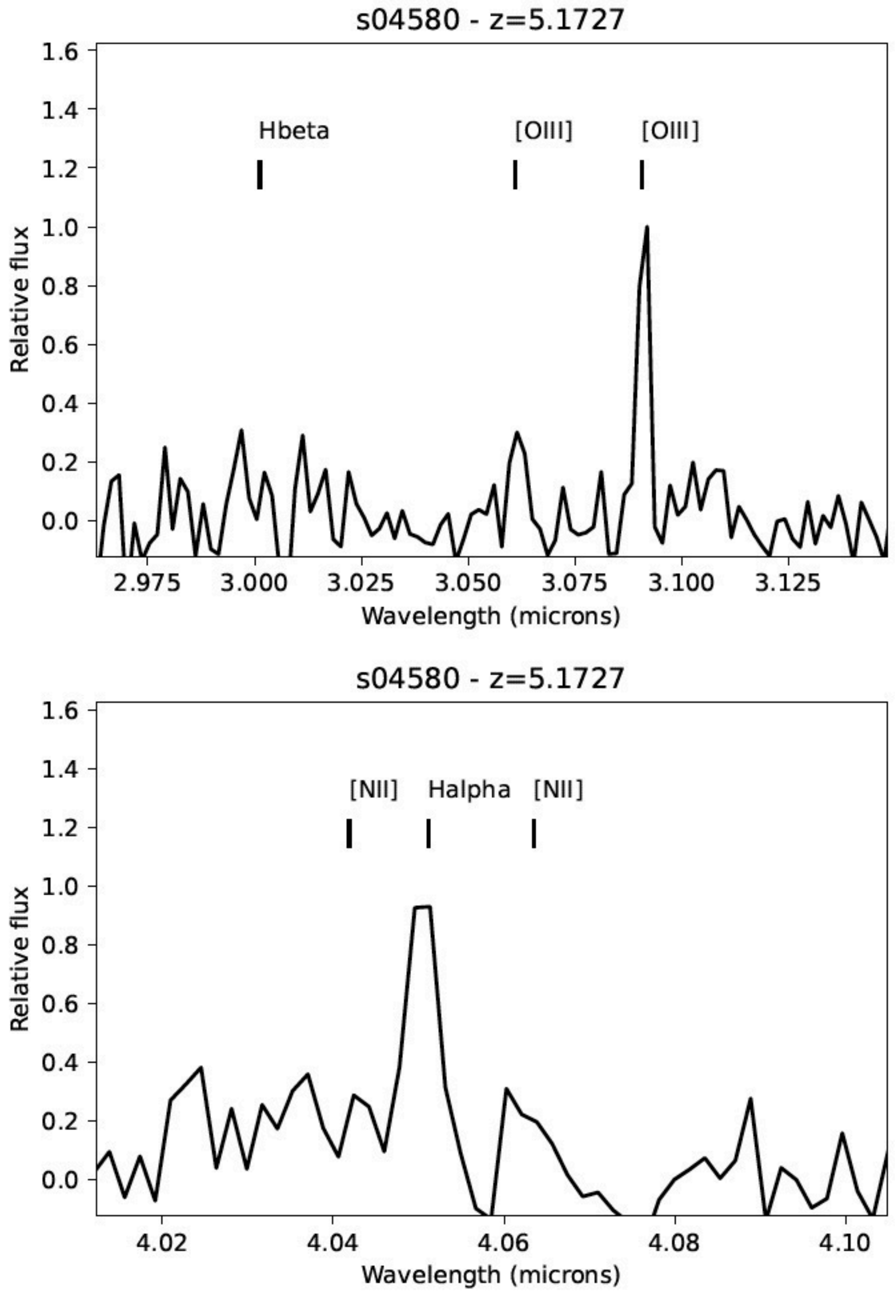


Pascale et al. 2022, Fig. 2

How JWST plays a role

Robust spectroscopic redshifts

- The redder wavelength range of JWST makes it possible to determine spectroscopic redshifts for high-z galaxies



Mahler et al. 2022 , Fig. 5

A specific example: SMACS J0723

Mahler et al. 2022

Model

- Cluster mass distribution
  - dual pseudo-isothermal ellipsoid (dPIE), 7 parameters: $\Delta\alpha, \Delta\delta, \epsilon, \theta, \sigma_0$, r_{core}, r_{cut} (fixed at 1500 kpc)
- Member galaxies
  - ~ 150 galaxies
  - Each is modeled with a dPIE
  - Too many parameters!!
  - Fix positional parameters
  - Scaling relation

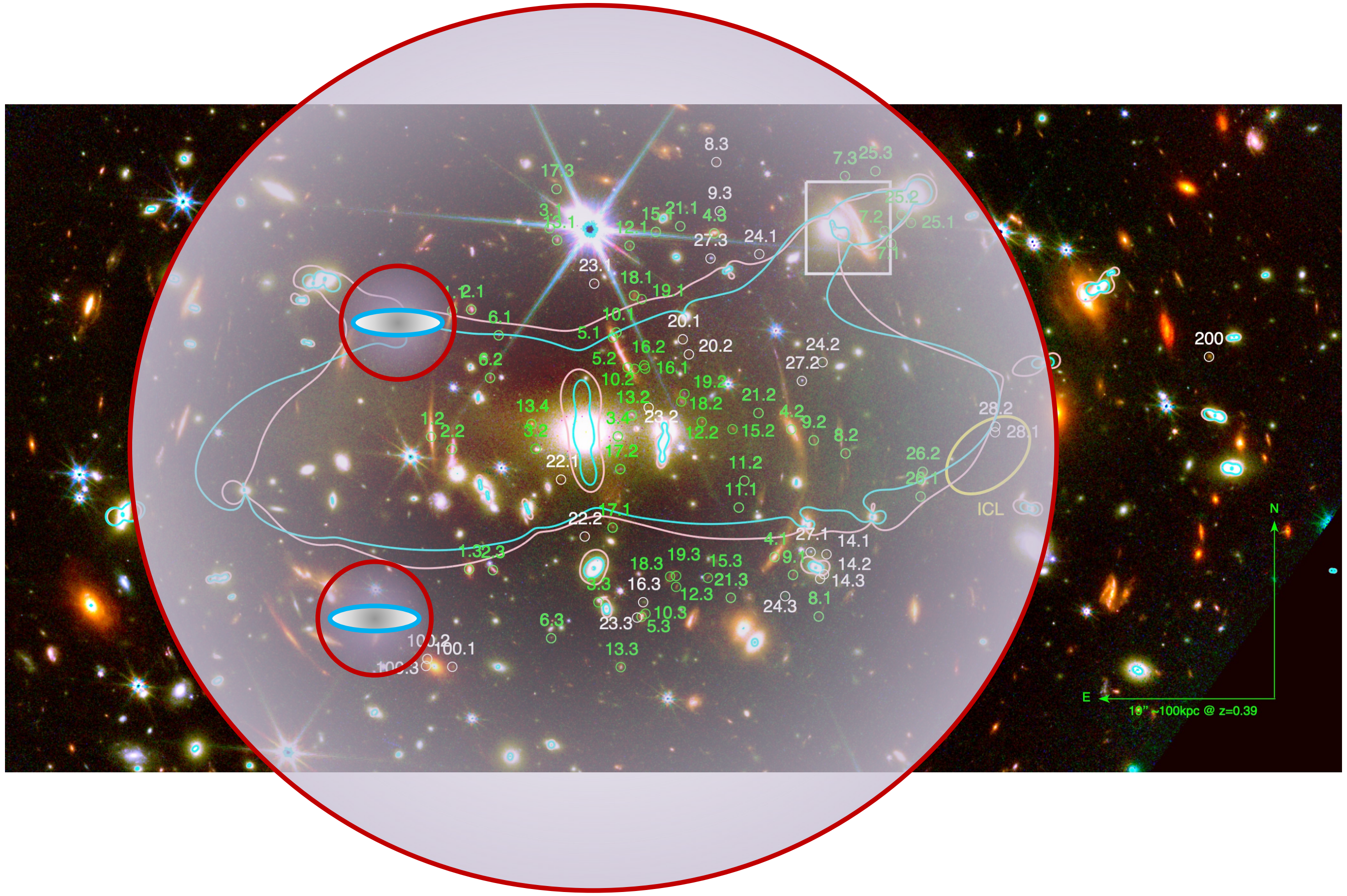


Fig. 4, top panel

Scaling relation

- $\sigma = \sigma^* \left(\frac{L}{L_*}\right)^{\frac{1}{4}}$, $\mathrm{r}_{\mathrm{cut}} = r^*_{cut} \left(\frac{L}{L_*}\right)^{\alpha}$, $\mathrm{r}_{\mathrm{core}} = r^*_{core} \left(\frac{L}{L_*}\right)^{\frac{1}{4}}$
- L_*: a standard luminosity
- $\alpha = 0.5$: the assumed galaxy model has constant mass-to-light ratio for each galaxy (case in Mahler et al. 2022)
- If $\alpha > 0.5$ ($\alpha < 0.5$), brighter galaxies have larger (smaller) haloes than the fainter ones (see Natarajan&Kneib 1997)
- Huge number of parameters of member galaxies → 3 parameters

A specific example: SMACS J0723

Mahler et al. 2022

Model

- Cluster mass distribution
- Member galaxies
- BCG and another member galaxy modeled separately
  - Extreme luminosity and sensitive proximity can bias the overall scaling relation
- Intracluster light (ICL) clump

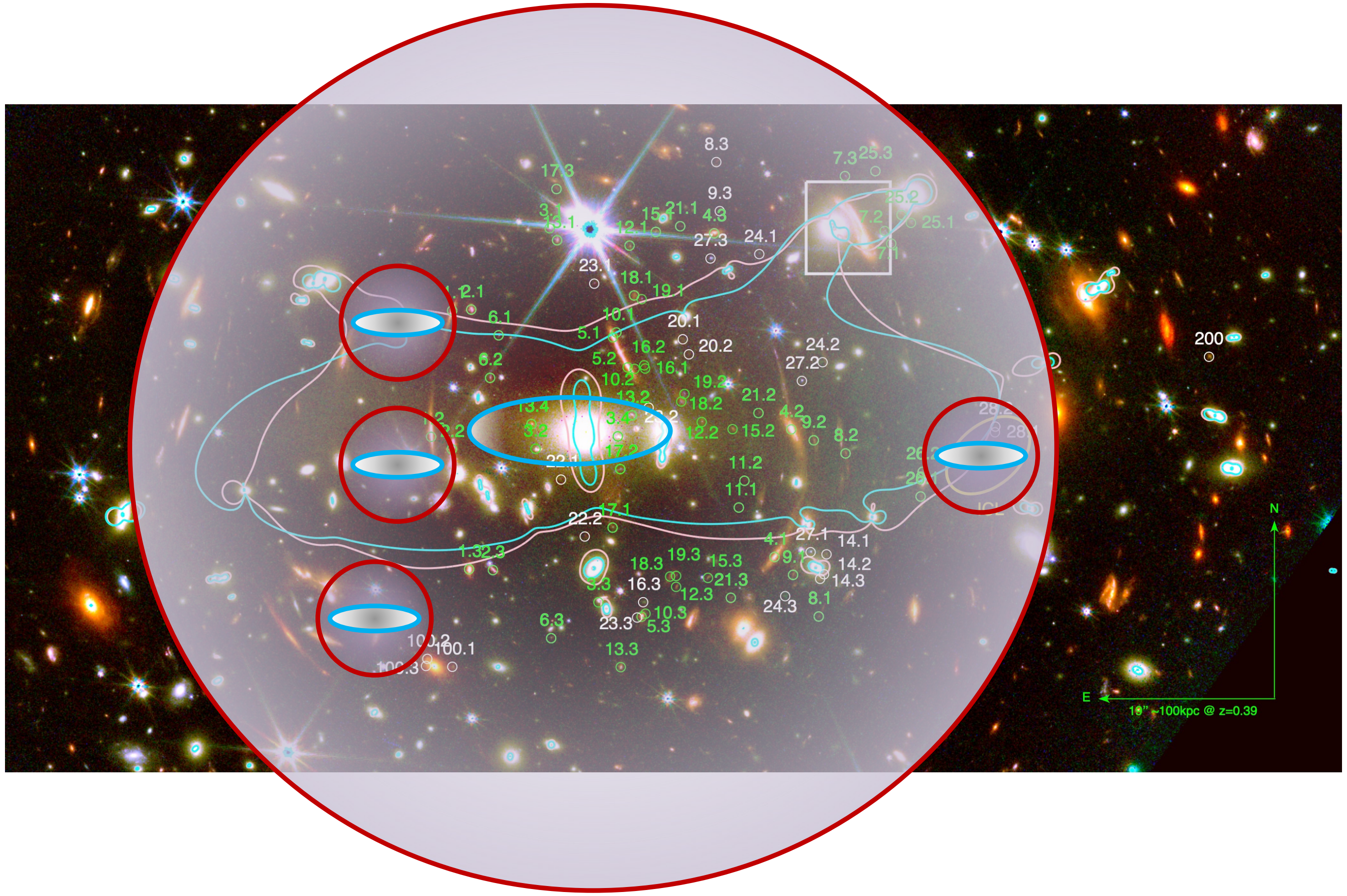
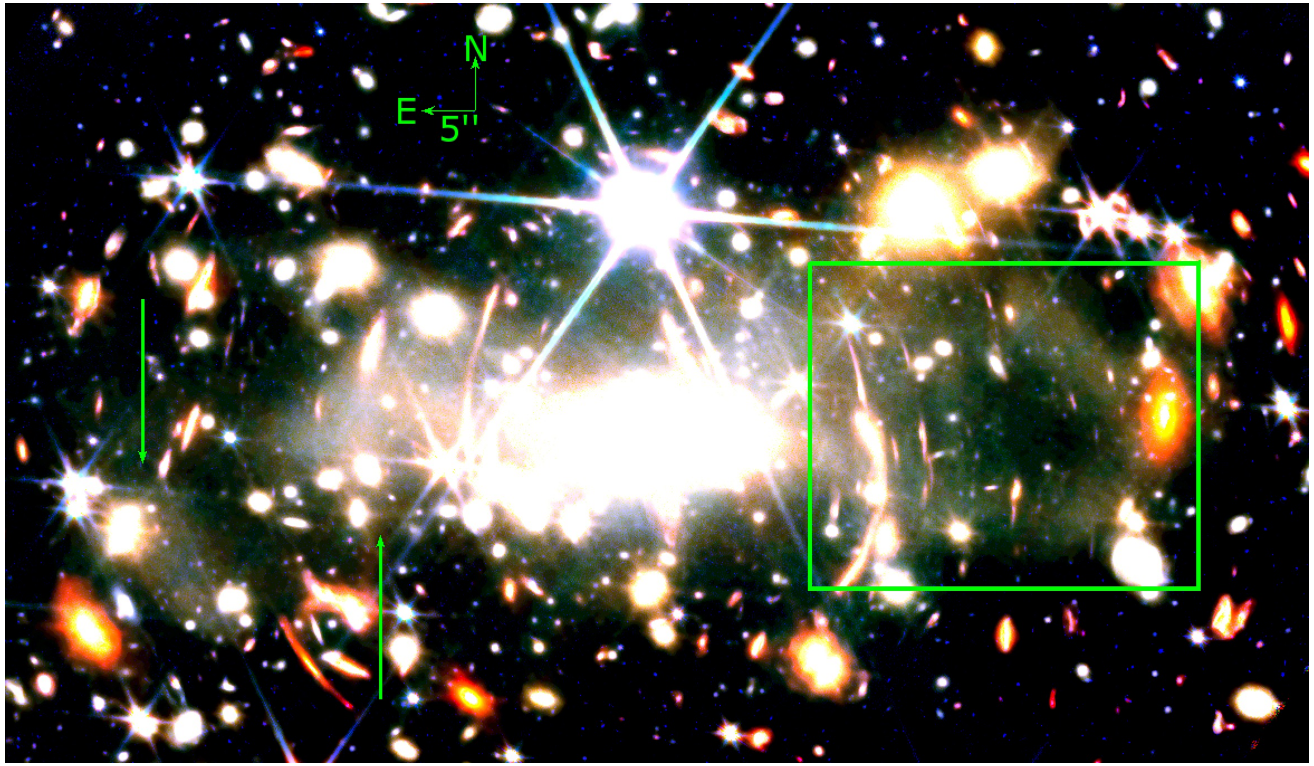


Fig. 4, top panel

How JWST plays a role

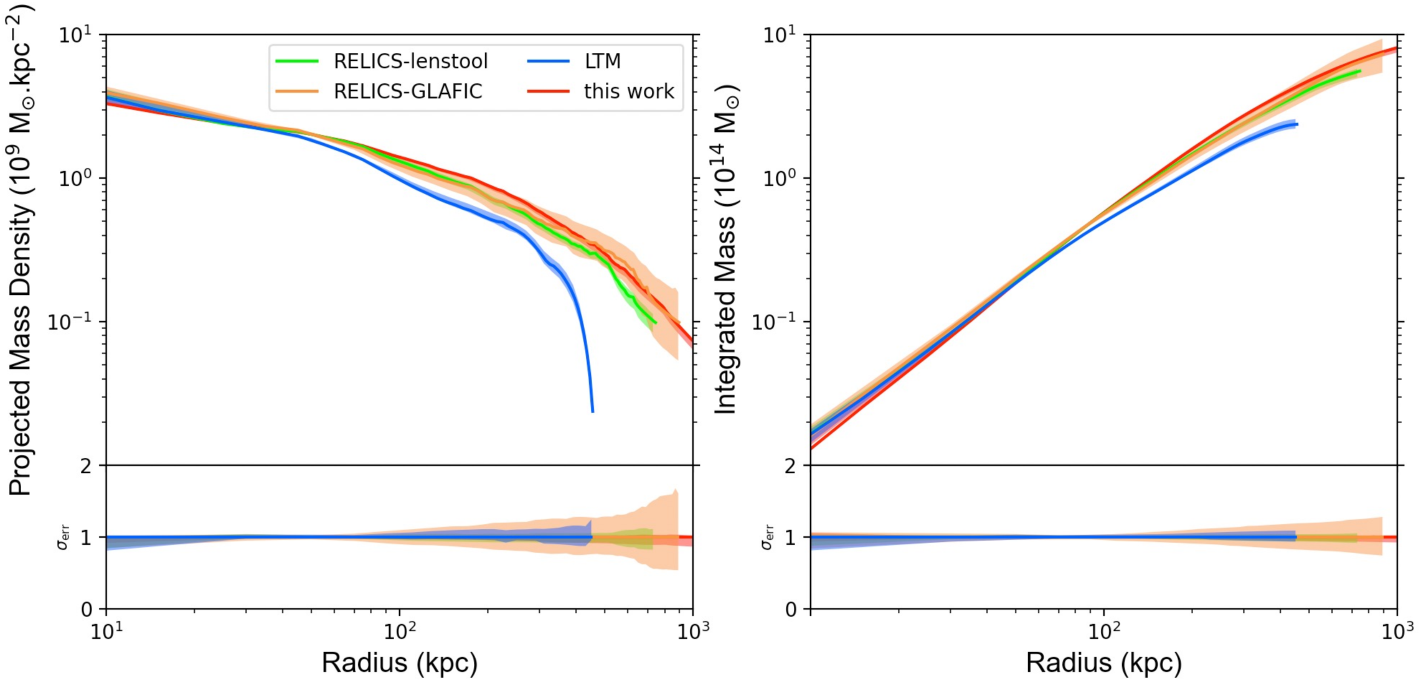
High sensitivity

- Able to detect low-surface-brightness features like ICL
- Improvement for mass model



Mahler et al. 2022 , Fig. 2

- Method
  - Monte Carlo Markov Chain
  - minimize the scatter (RMS) between the observed and predicted image-plane positions
- Result
  - Model with ICL clump: rms=0.3”, BIC=273
  - Model without ICL clump: rms=0.85”, BIC=471



Mahler et al. 2022 , Fig. 6

Limitations

Why could model assumptions bring large uncertainties?

Mismatch between model and data

- Hard to find an adequate model
  - Model is too simple: can only put constraints roughly
  - Model is too complex: the method is inherently unstable, likely to diverge or land in local minima; overfitting
- Data quality needs to get improved:
  - catalogue data rather than image data
  - lack of spectroscopic redshifts

Take-home messages

Feedback form →

- Accurate lens modeling is of great significance for source reconstruction
- There are parametric and non-parametric models in cluster lens modeling, and different models vary widely in reconstructed lens clusters
- Cluster lens modeling has large uncertainties and is not very precise because of too many model assumptions and the mismatch between model and data
- Multi-imaged systems are used as best constraints to cluster lens model. JWST has higher angular resolution, higher image sensitivity, and redder wavelength range, comparing to previous mission. These provide crucial information to allow identification of multi-imaged systems and better constraints to lens modeling.