Cluster Lensing in the JWST Era

Applications of Cluster Lensing

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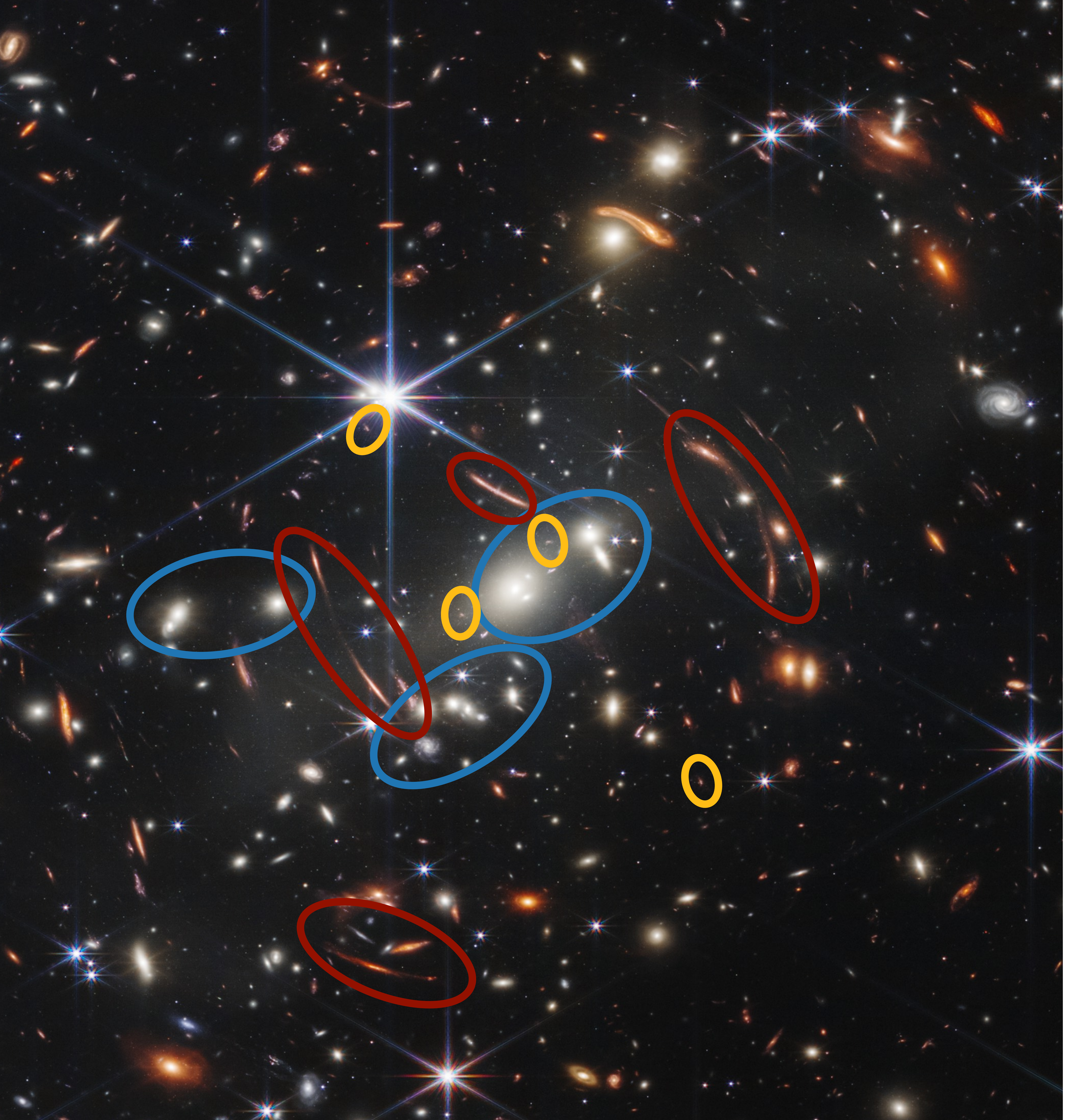


SMACS J0723

Foreground
Galaxy Cluster

Arclet Image

Multiple-Image
System

credit: NASA,
ESA, CSA, STScI

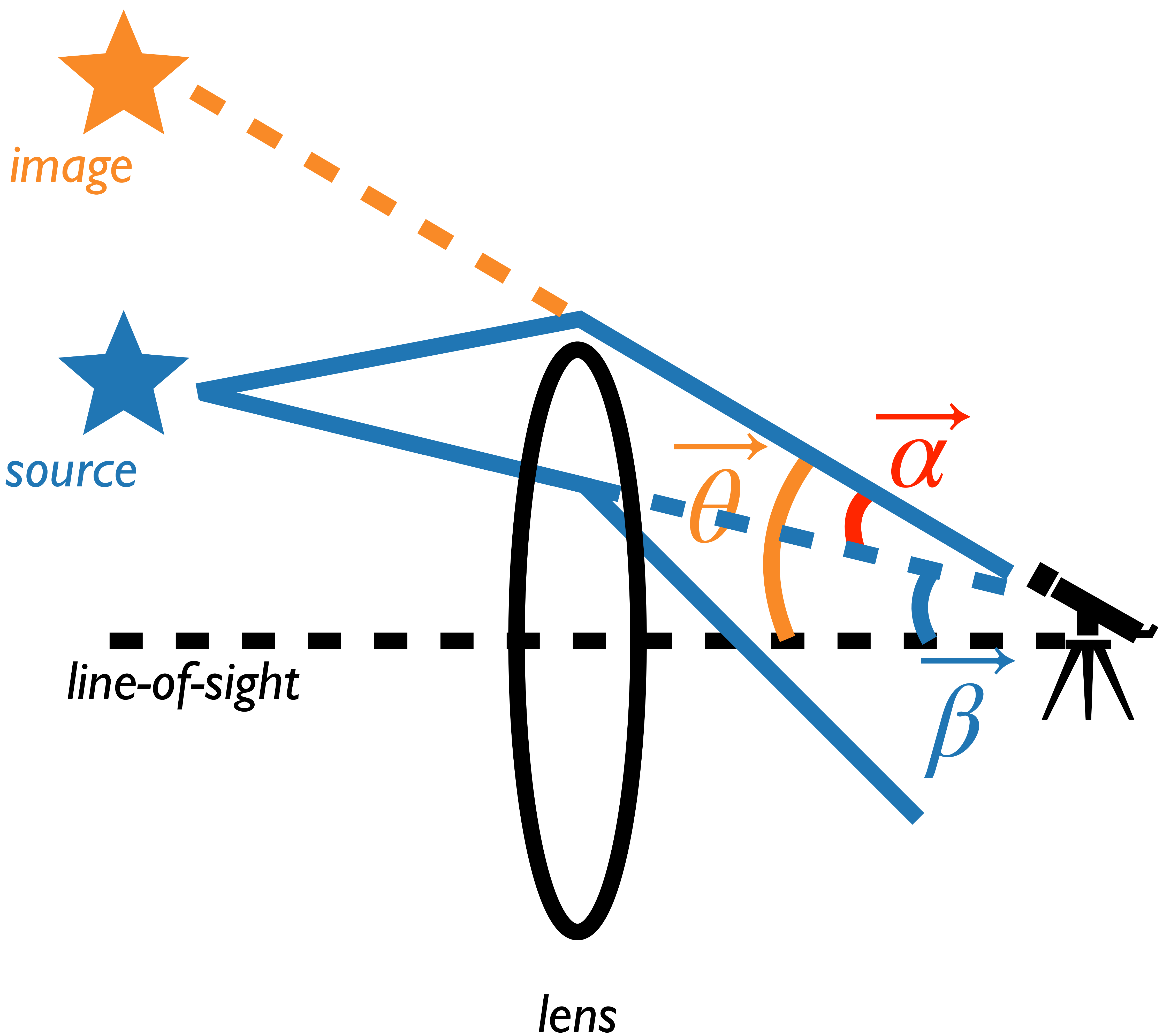
Outline

3 Steps to Be a "Strong Lensing Expert"

Study on Lens Properties

Study on Source Properties

Step 1 Deflection Effect



lens equation

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}$$

$\vec{\beta}$ *(source plane): angular position of source*

$\vec{\theta}$ *(image plane): obseved angular position of image*

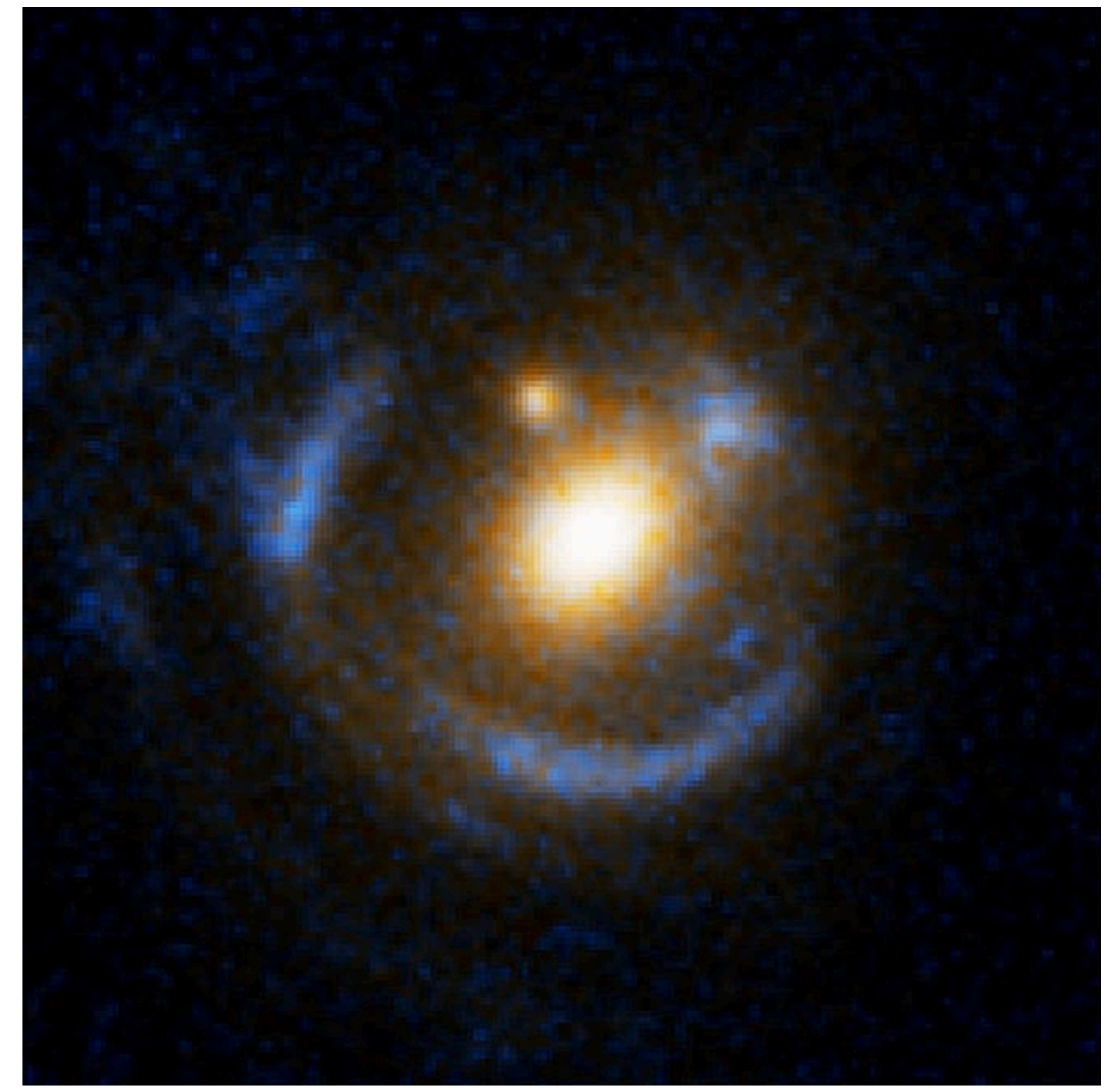
$\vec{\alpha}$ *: deflection angle*

$$\vec{\alpha}(\vec{\theta}, \Sigma(\vec{\theta}), z_s, z_l)$$

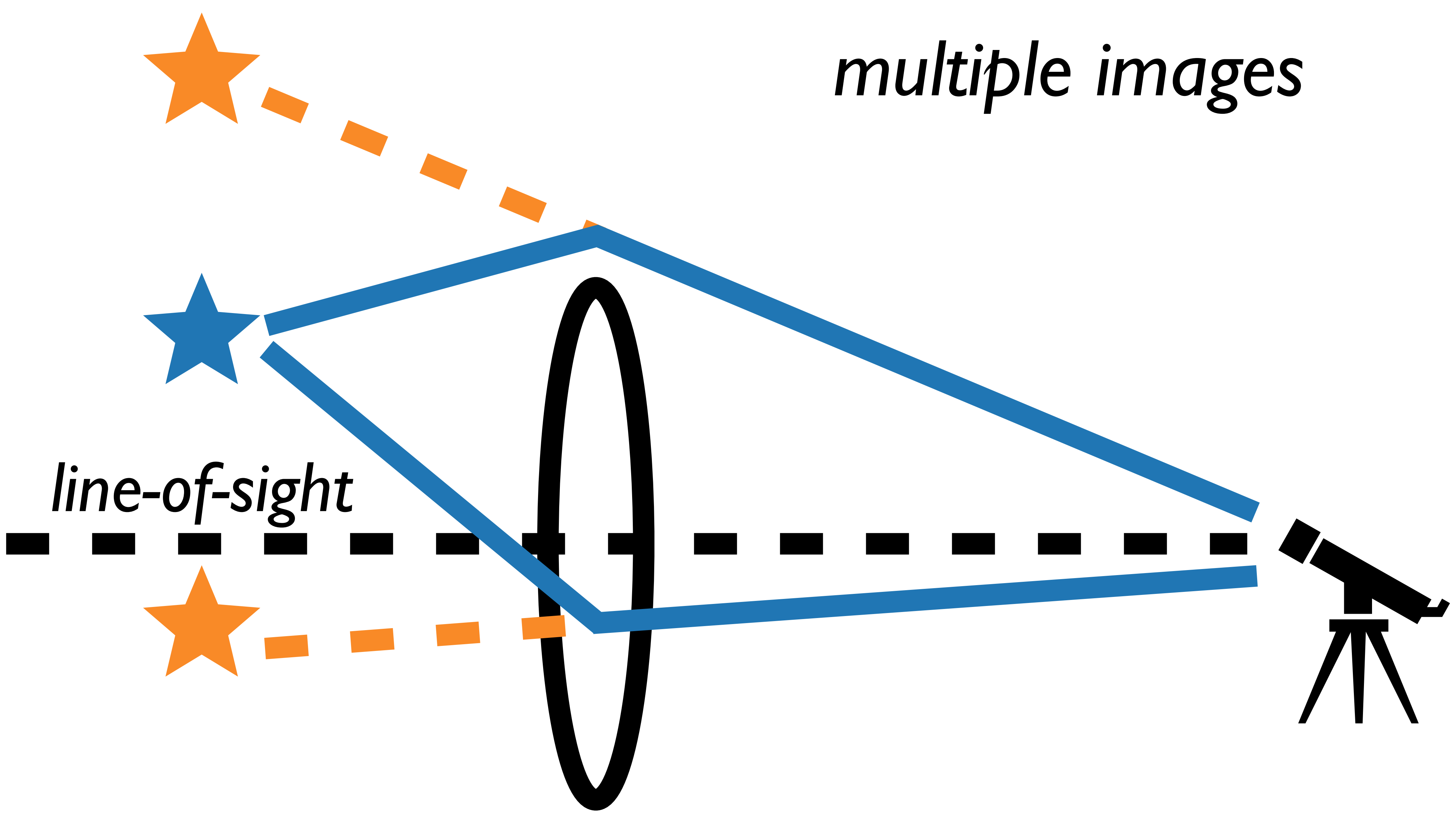
lens
surface density
distribution

Step I Deflection Effect

multiple images



arc-like image



- extended sources in the universe

Step II Magnification Effect

$$\text{Flux (F)} = \text{Surface Brightness (S)} \times \text{Area (A)}$$

- Gravitational lensing conserves the surface brightness of source
- Gravitational lensing magnifies the area of source

$$\bar{\mu}_{\text{image}} = \frac{F_{\text{image}}}{F_{\text{source}}}$$

→ *correct for source intrinsic flux*

→ *correct for source intrinsic size/area*

magnification factor
(extended source)

Step II Magnification Effect

$$\text{Flux (F)} = \text{Surface Brightness (S)} \times \text{Area (A)}$$

- Gravitational lensing conserves the surface brightness of source
- Gravitational lensing magnifies the area of source

$$\bar{\mu}_{\text{image}} = \frac{F_{\text{image}}}{F_{\text{source}}}$$

"hard to know"

magnification factor
(extended source)

usually approximated with $\mu(\vec{\theta})$
in cluster lens correction

$$\mu(\vec{\theta}, \Sigma(\vec{\theta}), z_s, z_l)$$

magnification factor
(infinitesimal source)

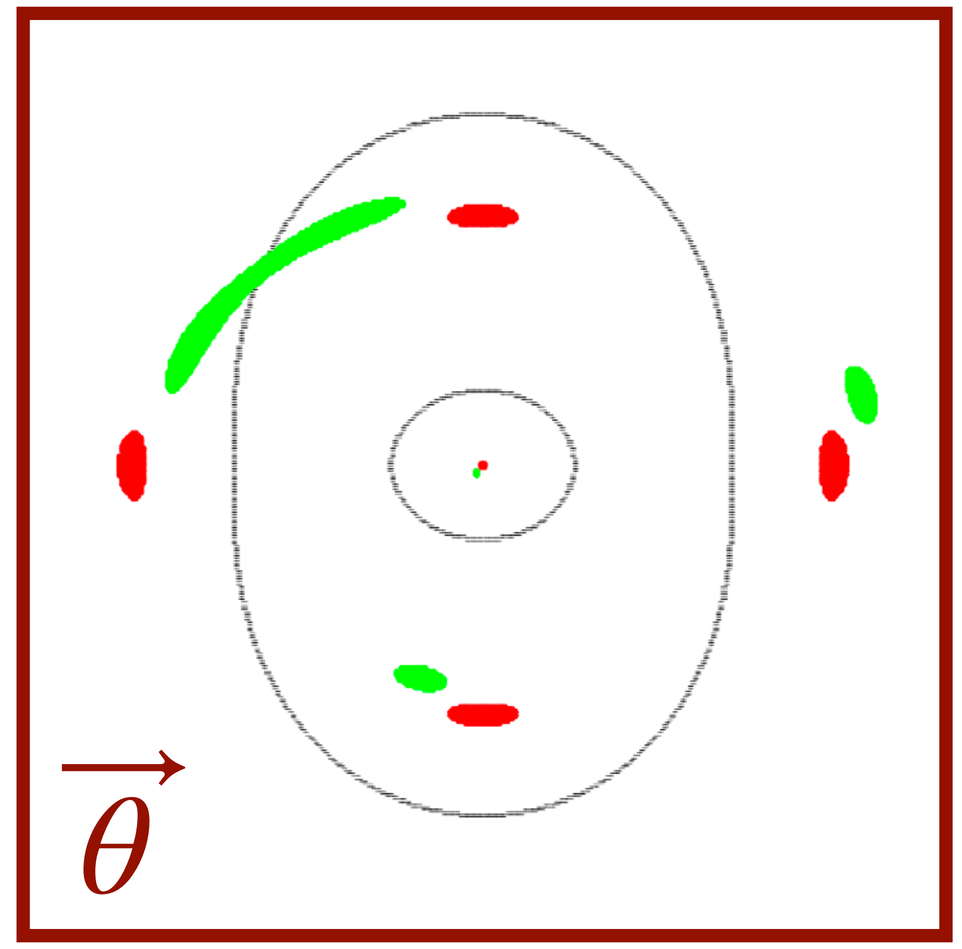
Step III Terminology

- critical curve and caustic

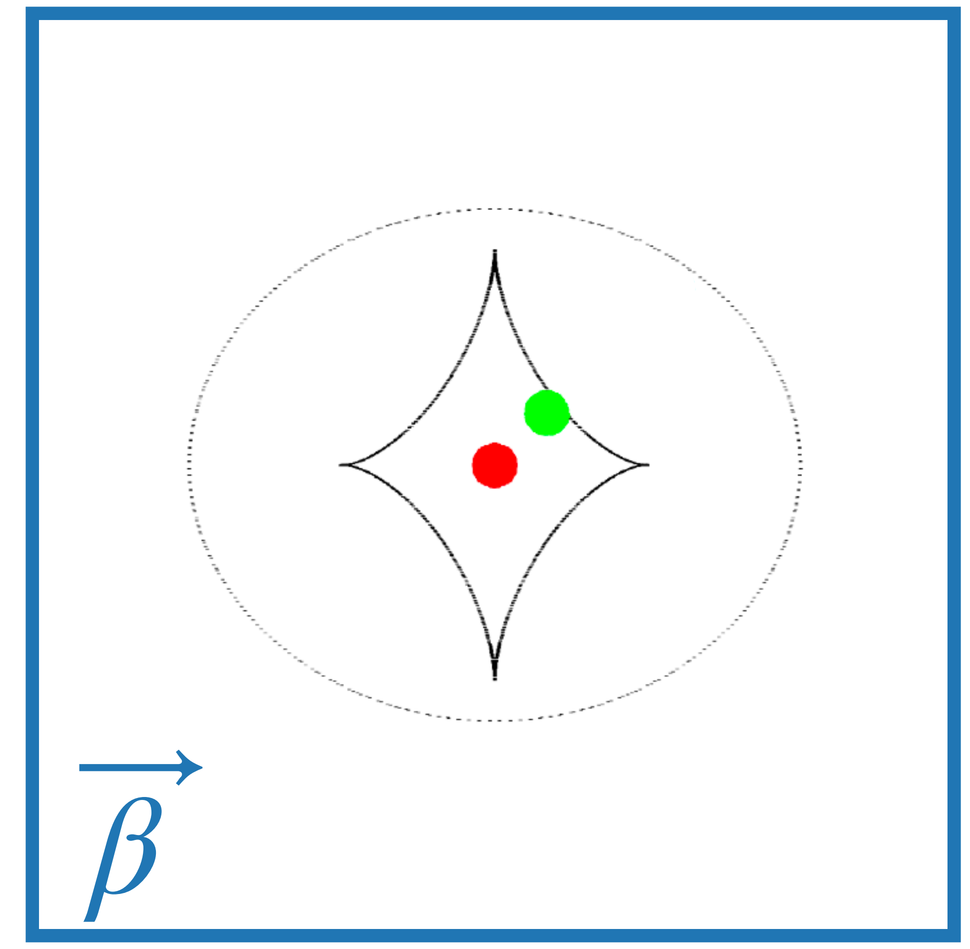
critical curve: positions on image plane $\{\vec{\theta}_c\}$ *with infinite analytic magnification factor* $\mu(\vec{\theta}_c) = \infty$

caustic : positions on source plane $\{\vec{\beta}_c\}$ *corresponding to critical curves*

critical curves
(image plane)



caustics
(source plane)



- The vicinity of critical curve has extreme magnification gradient
- Images merge around critical curves and form arclet
- Critical curve reveals the reach size of strong lensing effect
  galaxy lens: ~ 1 arcsec
  cluster lens: ~10 arcsec - 1 arcmin

Strong Lensing Effect

- Deflection angle ($\vec{\alpha}$) and magnification factor (μ) depend on the mass distribution of lens and redshift.

- Gravitational lensing conserves the surface brightness of source and magnifies the area.

- Critical curve represents the positions with extreme magnification factor on image plane.
  Images merge around critical curve and form arclet.

Methodology

lens equation: $\vec{\beta} = \vec{\theta} - \vec{\alpha}$ $\vec{\alpha}(\vec{\theta}, \Sigma(\vec{\theta}), z_s, z_l)$

Only image plane $\vec{\theta}$ is observable.

Ruizhe's talk

$\vec{\theta}$ *lens fitting* → $\Sigma(\vec{\theta})$ → $\vec{\alpha}(\vec{\theta})$ and $\mu(\vec{\theta})$

observed images · *lens mass distribution* · *deflection angle* · *magnification factor*

↓ lens properties ↓ source properties

this talk

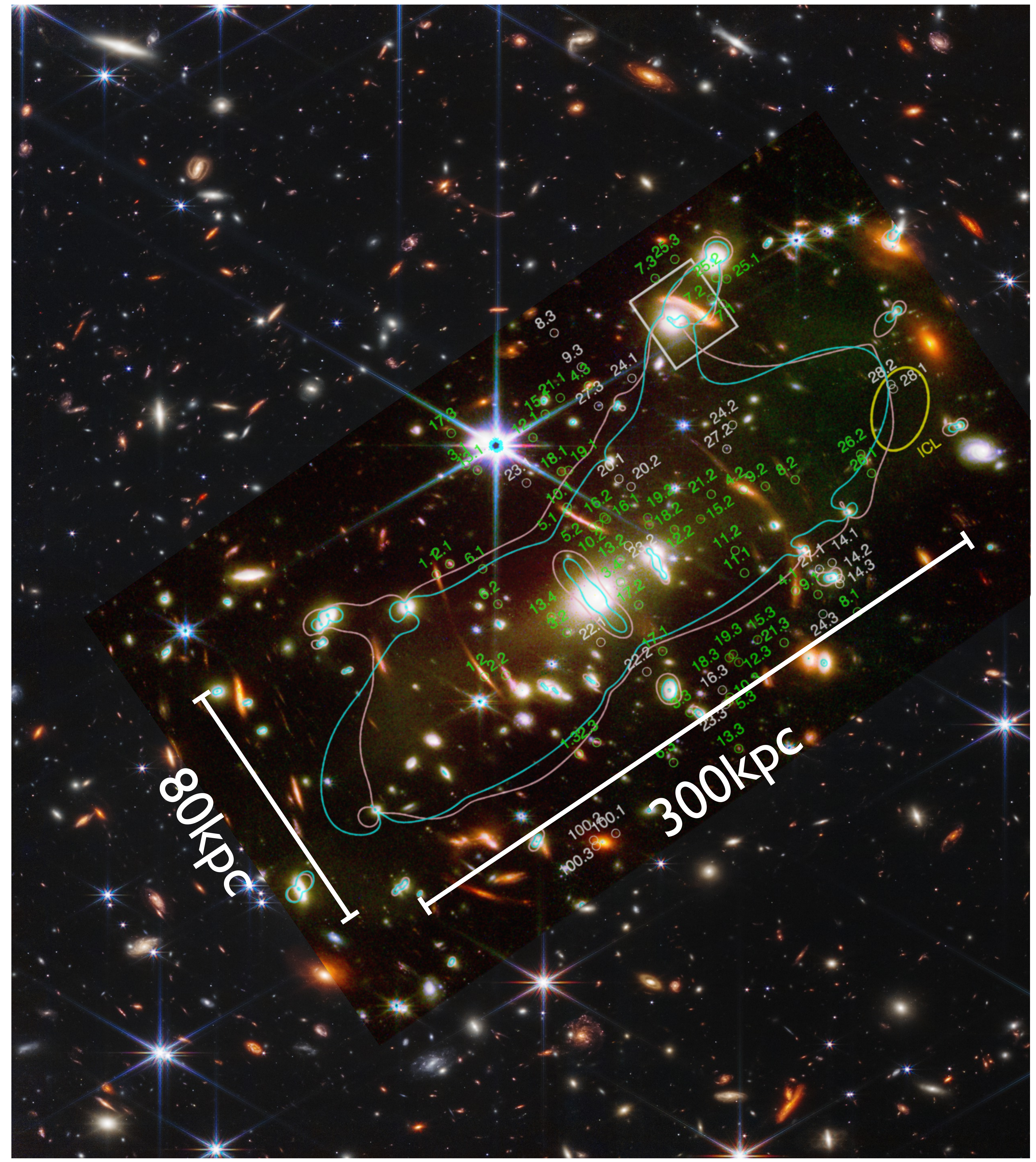
Study on Lens

- Gravitational lensing traces the distribution of total mass.

➡ *luminous matter, dark matter*

- Strong lensing only constrains the mass distribution at the core of cluster.

➡ *combine with other methods (e.g. weak lensing, X-ray) to study large-scale mass distribution*



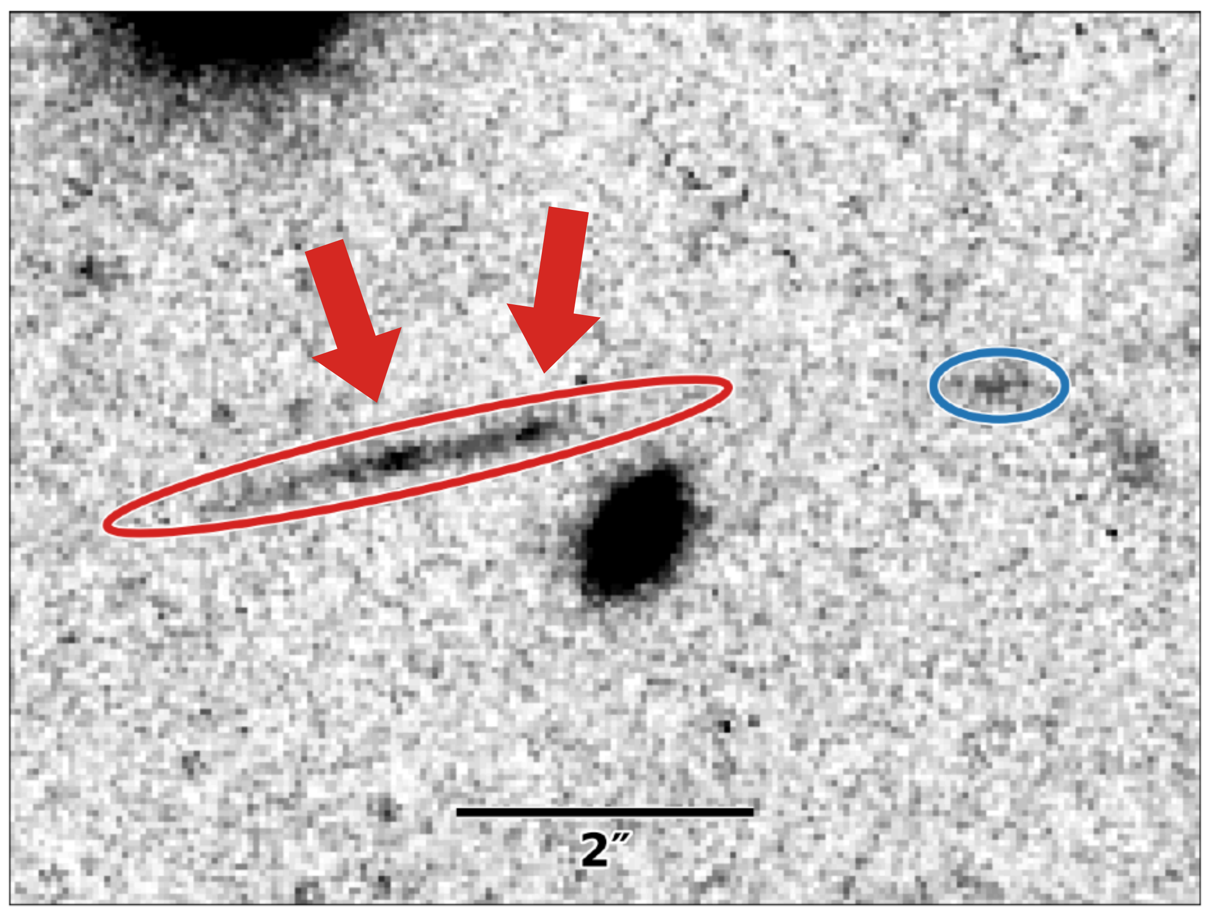
(Mahler et al. 2022)

Study on Background Sources

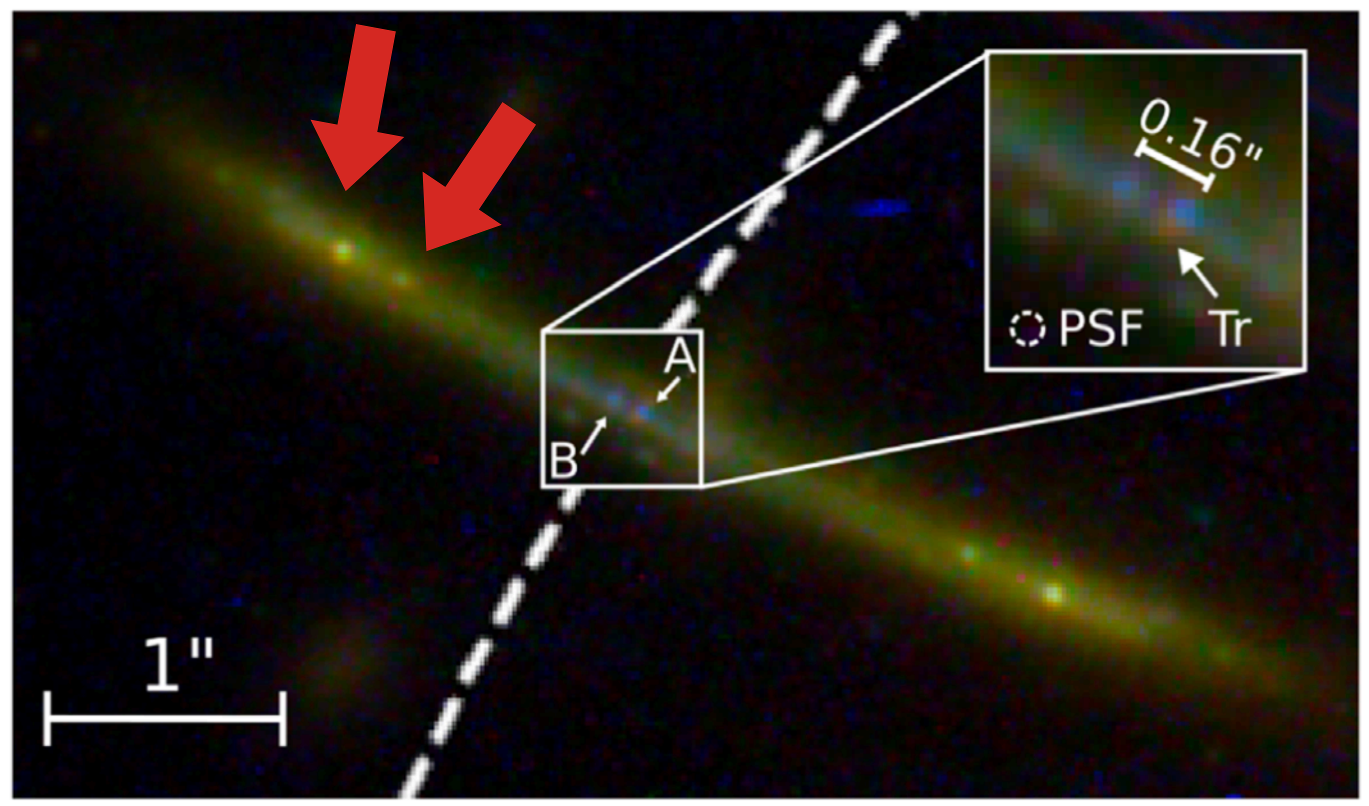
- Zoom in to study substructures of high-z objects
- Facilitate identifying extremely high-z objects

Study on Background Sources

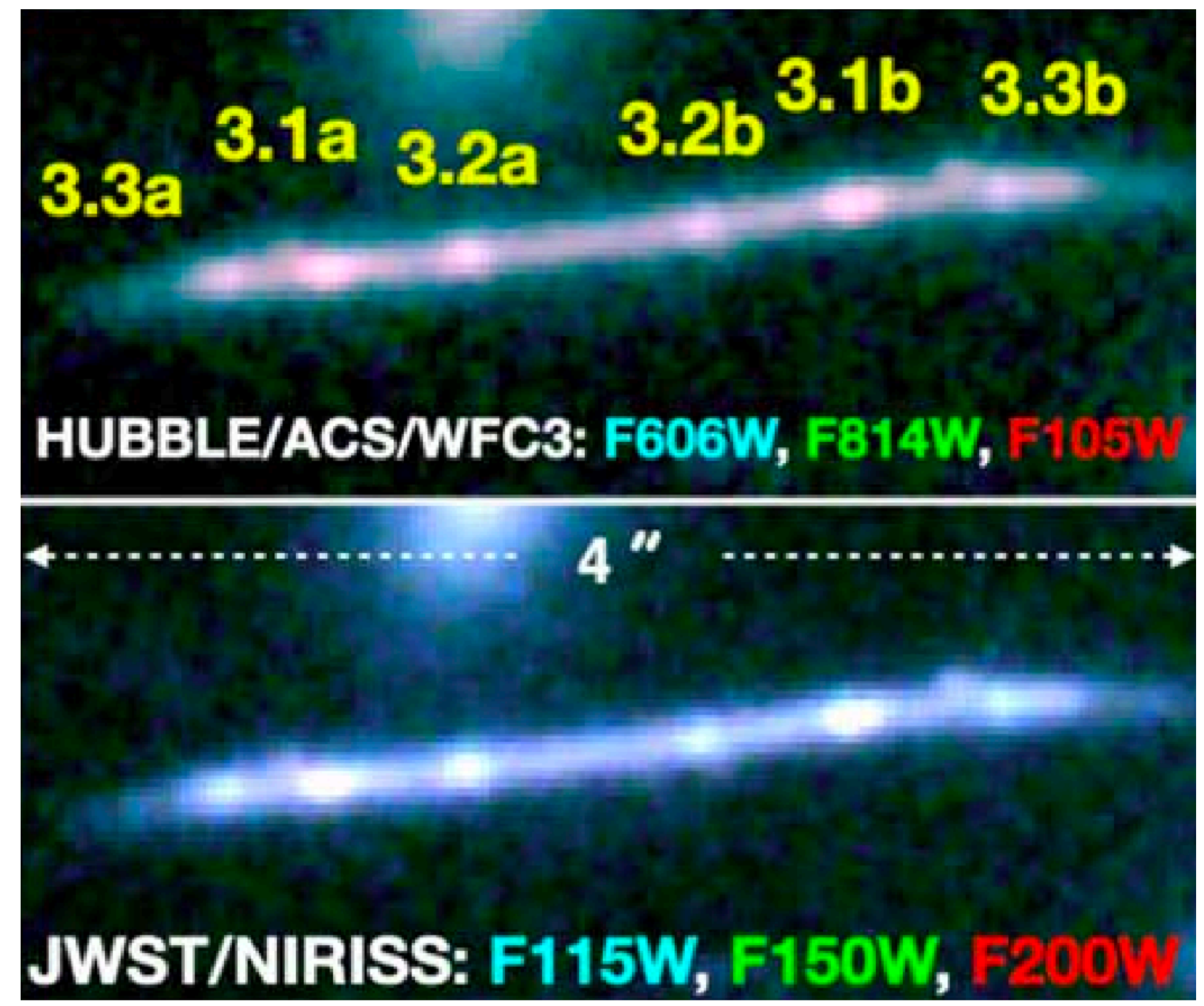
- Zoom in to study substructures of high-z objects



WHL0137-08 cluster field
photometric $z_p \sim 9$
(Bradley et al. 2022)



SMACS 0723 cluster field
spectroscopic $z_s = 1.43$
(Pascale et al. 2022)



Abell 2744 cluster field
spectroscopic $z_s = 4.0$
(Vanzella et al. 2022)

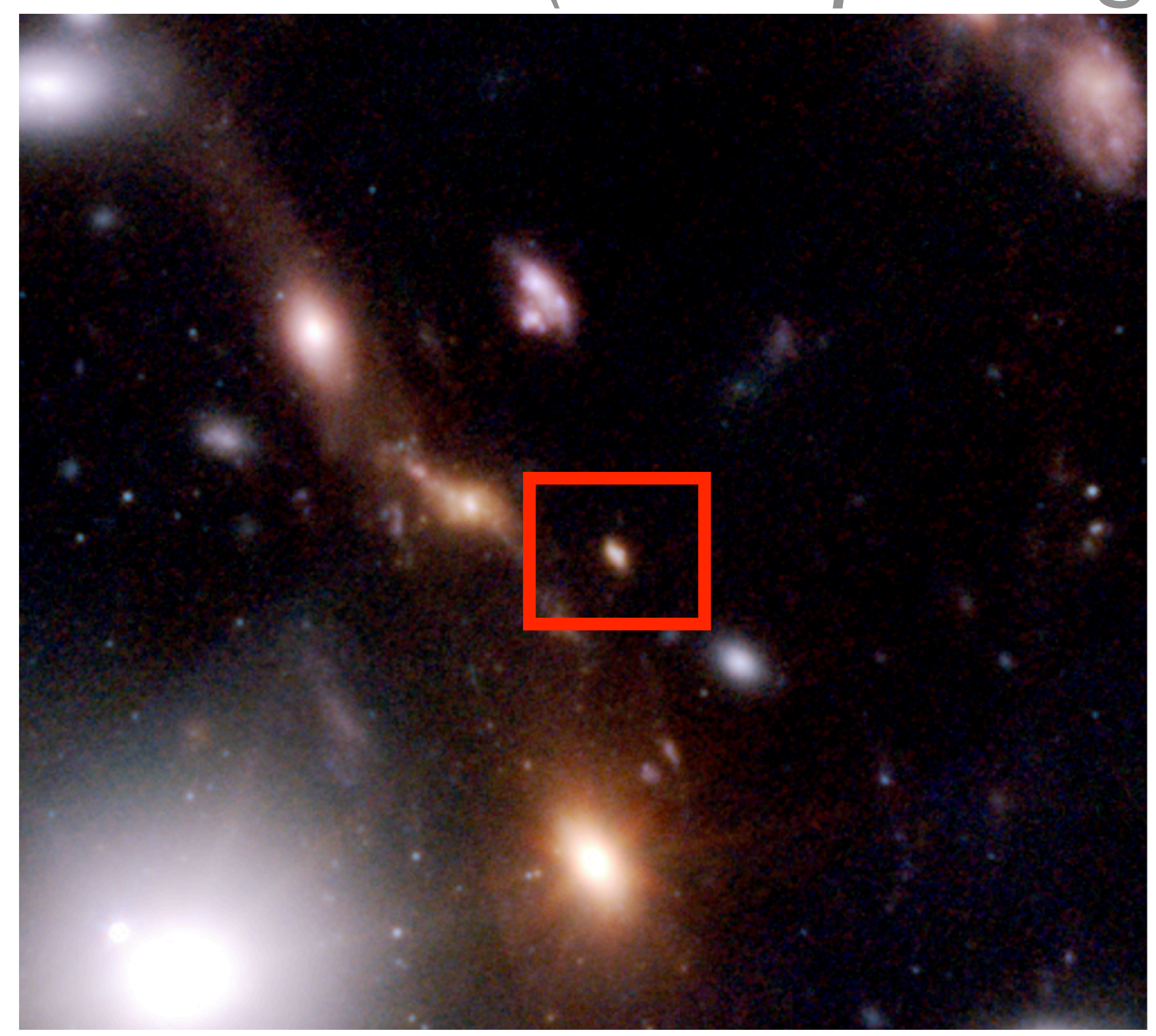
- Facilitate identifying extremely high-z objects

Study on Background Sources

- Zoom in to study substructures of high-z objects

(same plotting scale)

arclet formed by two merging images



third image

- Facilitate identifying extremely high-z objects

**original image credit to Fengwu Sun, UA*

Source Properties: Clumpy Star-Forming Regions

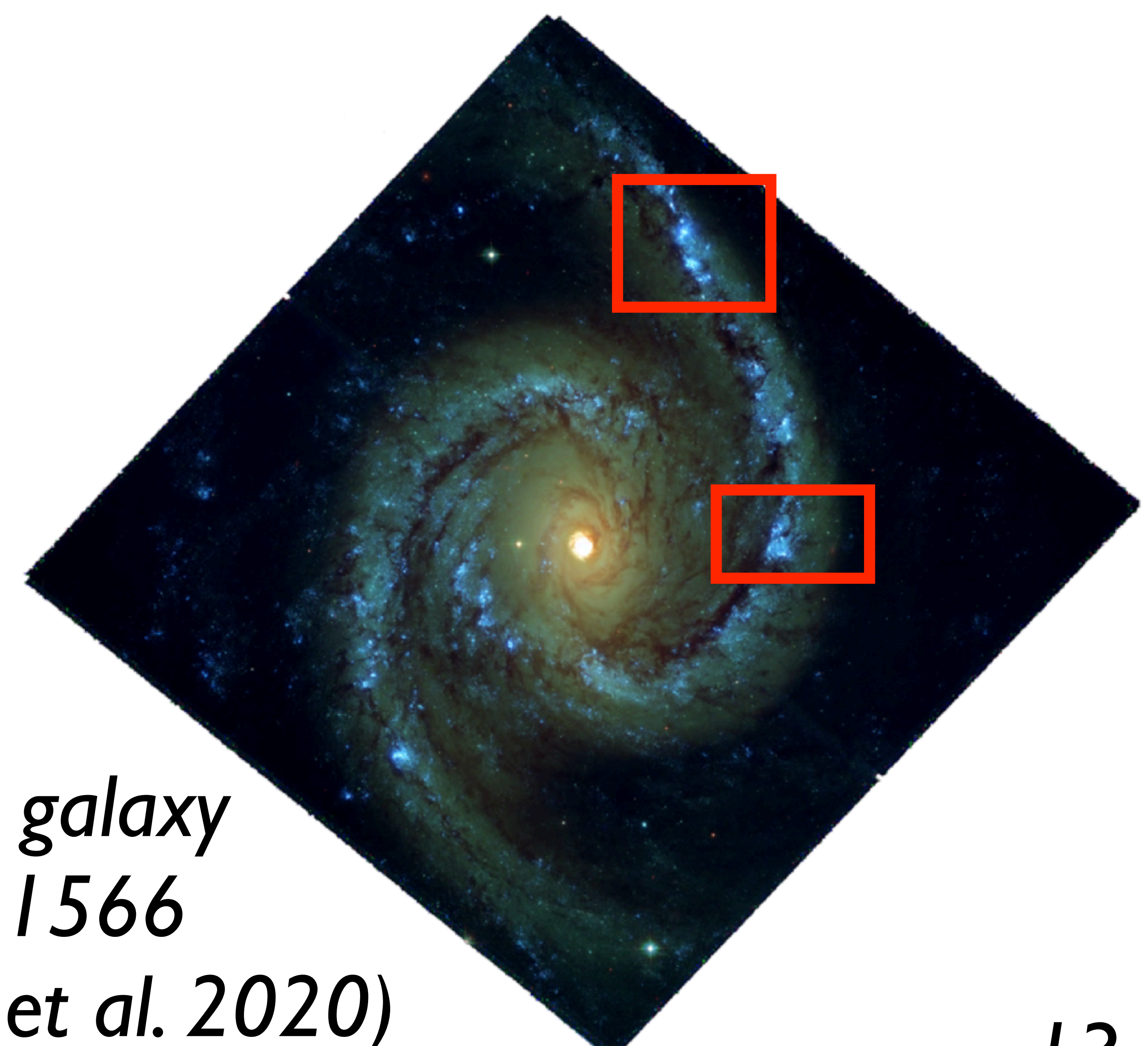
- JWST near-infrared observation waveband: $0.6\ \mu\text{m} - 5\ \mu\text{m}$ (imaging&spectroscopic)

➡ *correspond to rest-frame UV & visible band for high-z galaxies*

- Observations in local universe indicates a hierarchical organization of star formation.

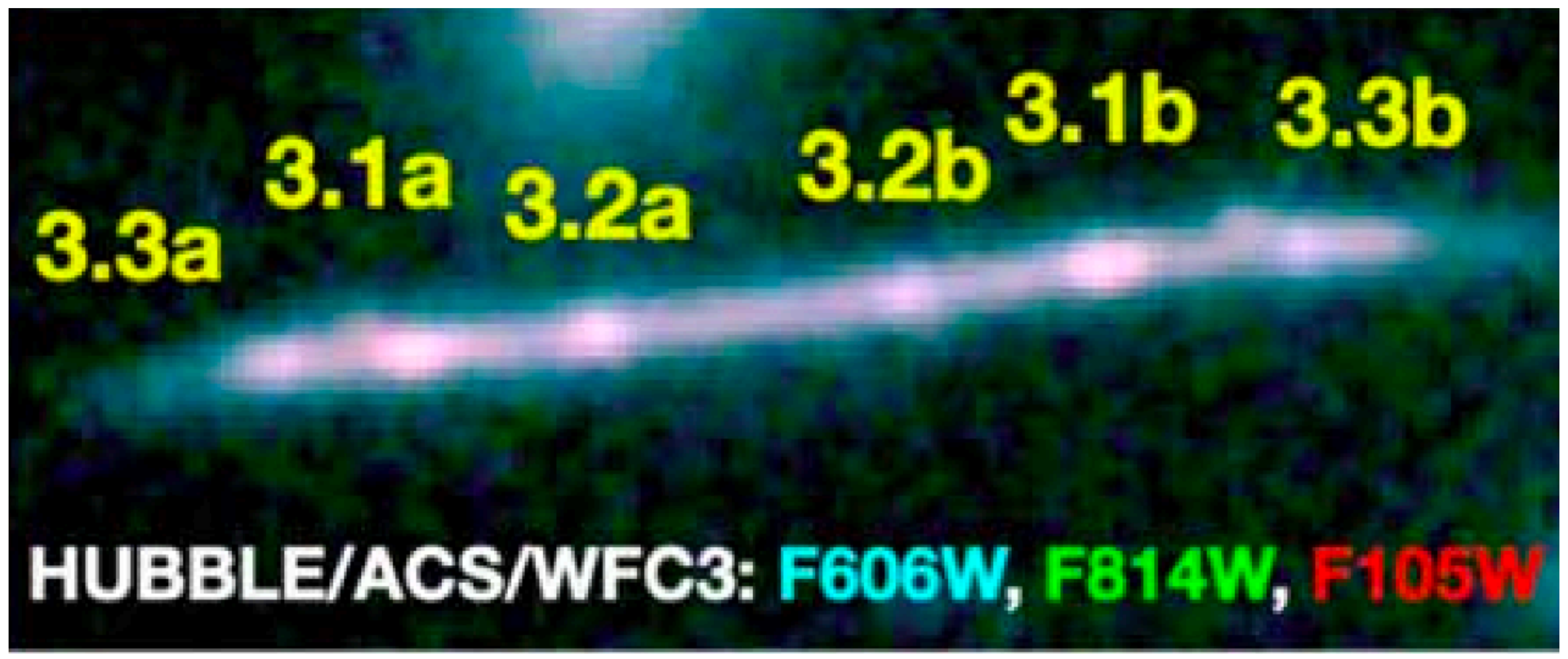
➡ *sub-kpc clumps, pc-scale stellar clusters*

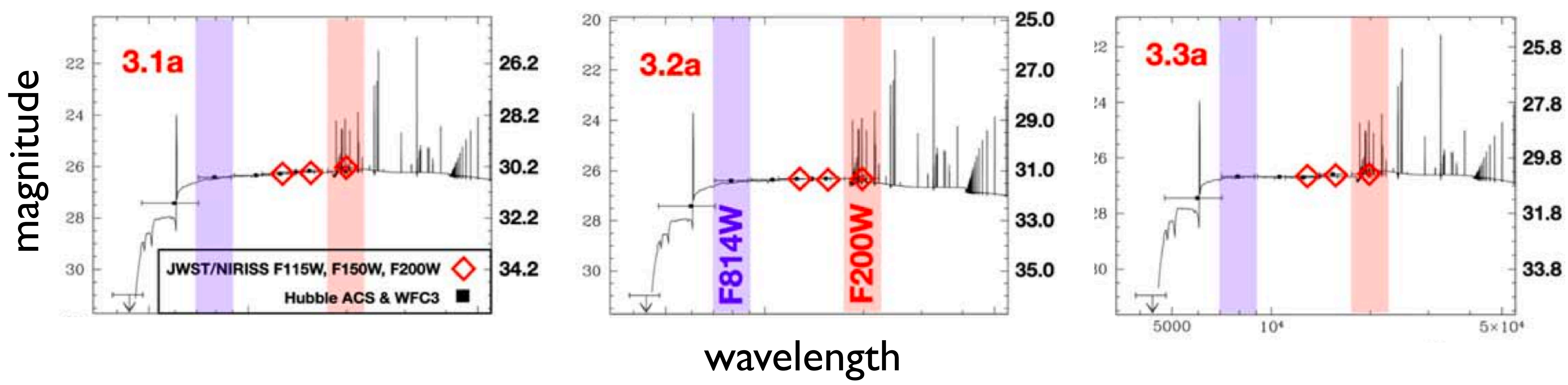
need extremely high resolution, cluster lensing HELPs!



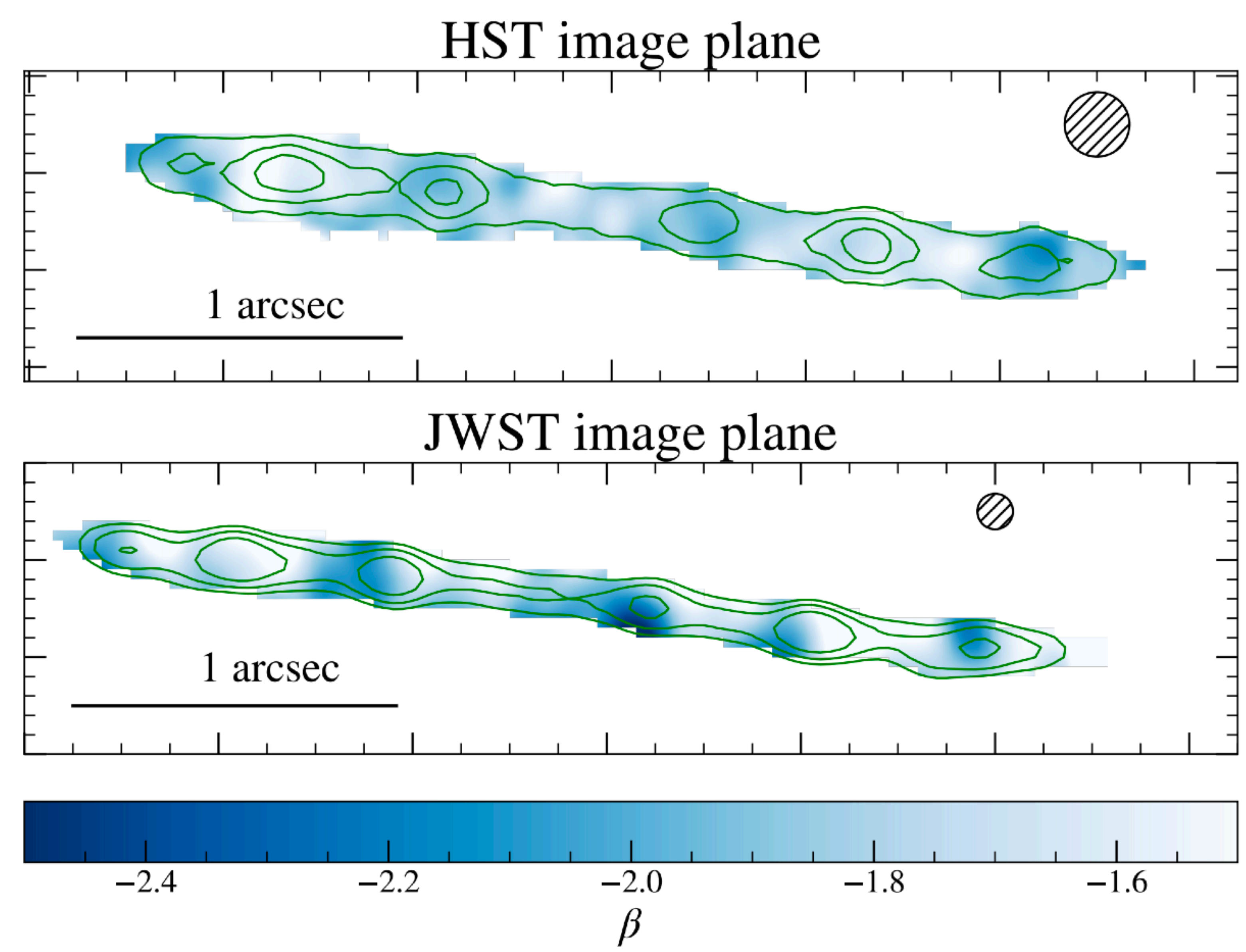
nearby galaxy NGC 1566 (Gouliermis et al. 2020)

Source Properties:
Clumpy Star-Forming Regions





SED fitting of the 3 knots
(Vanzella et al. 2022)

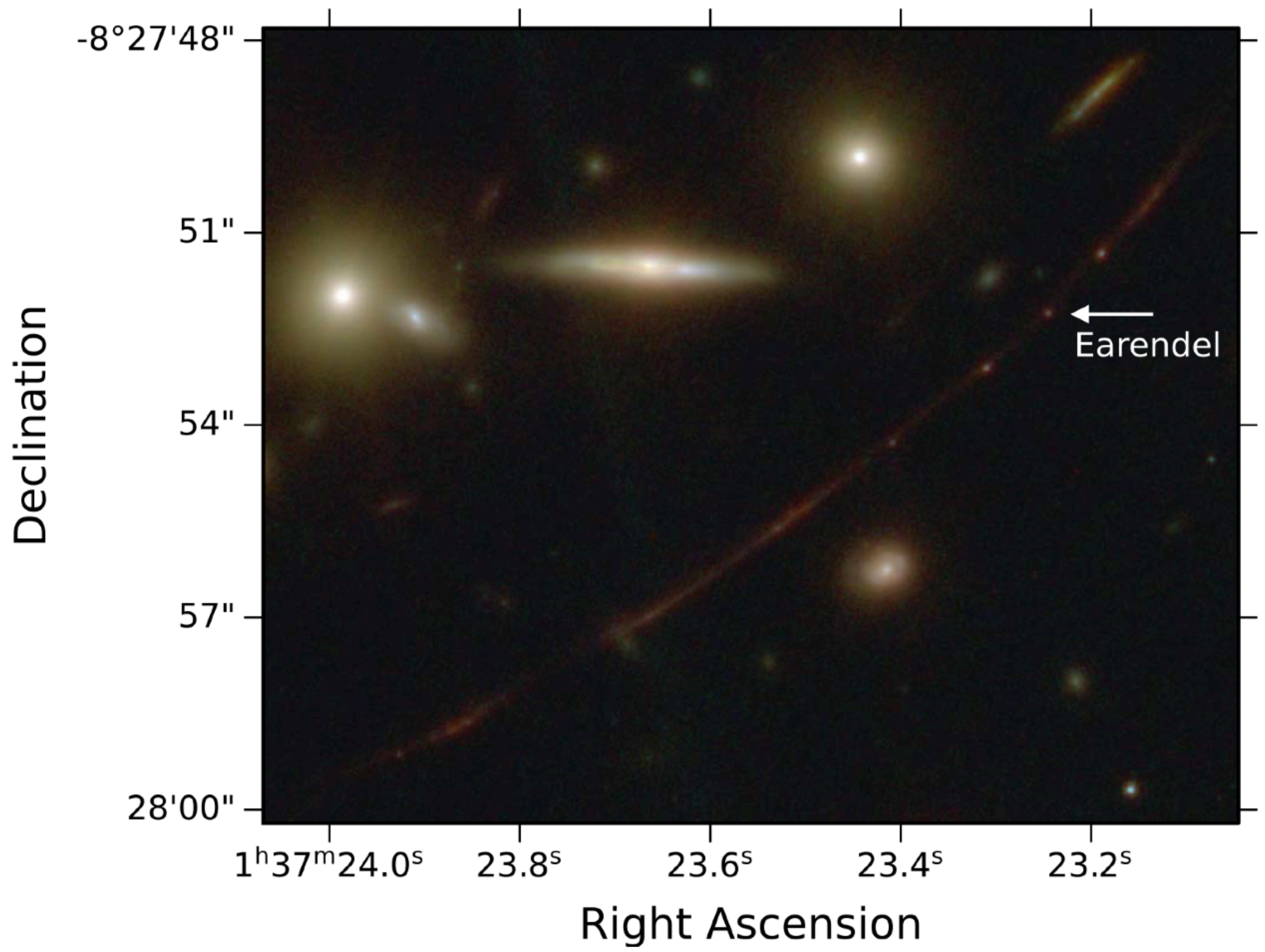


UV slope(β) map of the lensed arclet
(Lin et al. 2022)

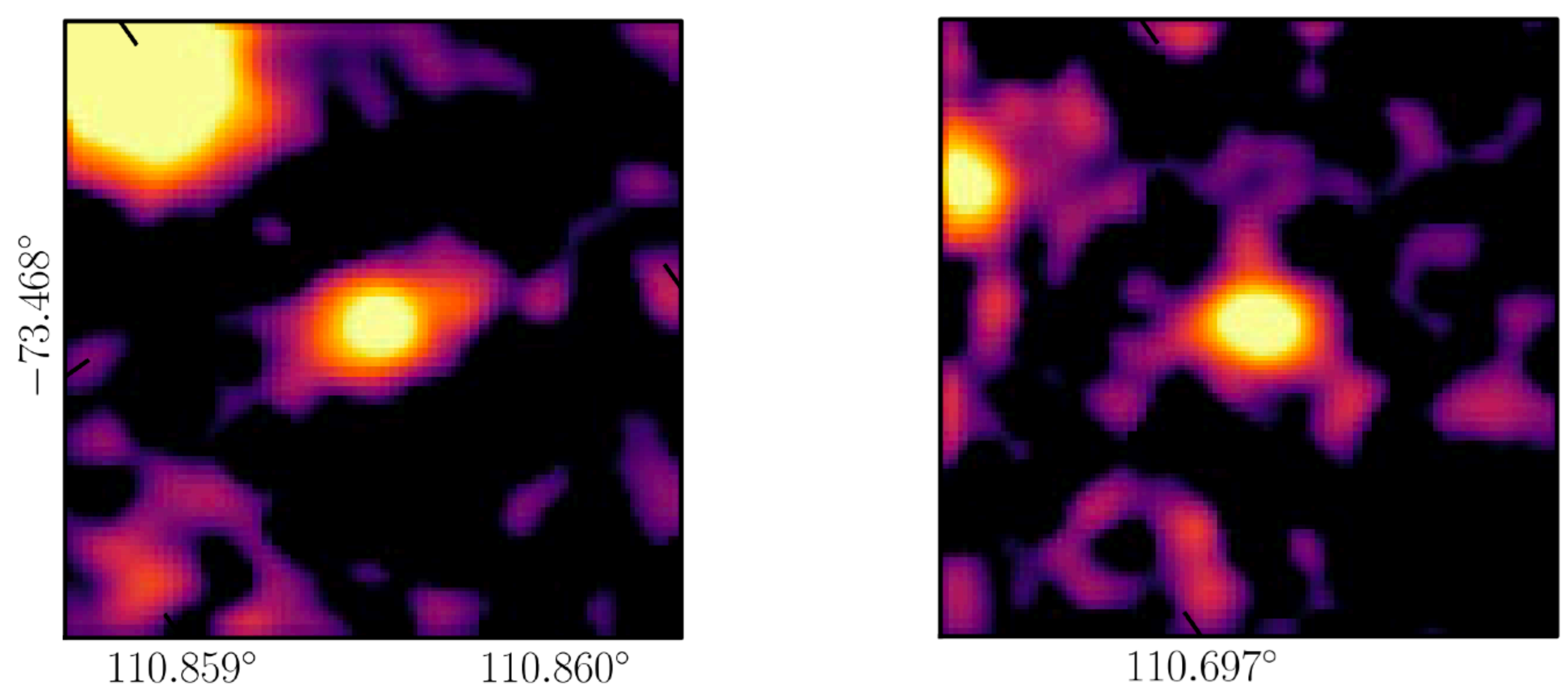
- physical properties of the substructure
- spatial distribution of properties

Study on Background Sources

- Zoom in to study substructures of high-z objects
- Facilitate identifying extremely high-z objects



most distant star Earendel
(Welch et al. 2022)



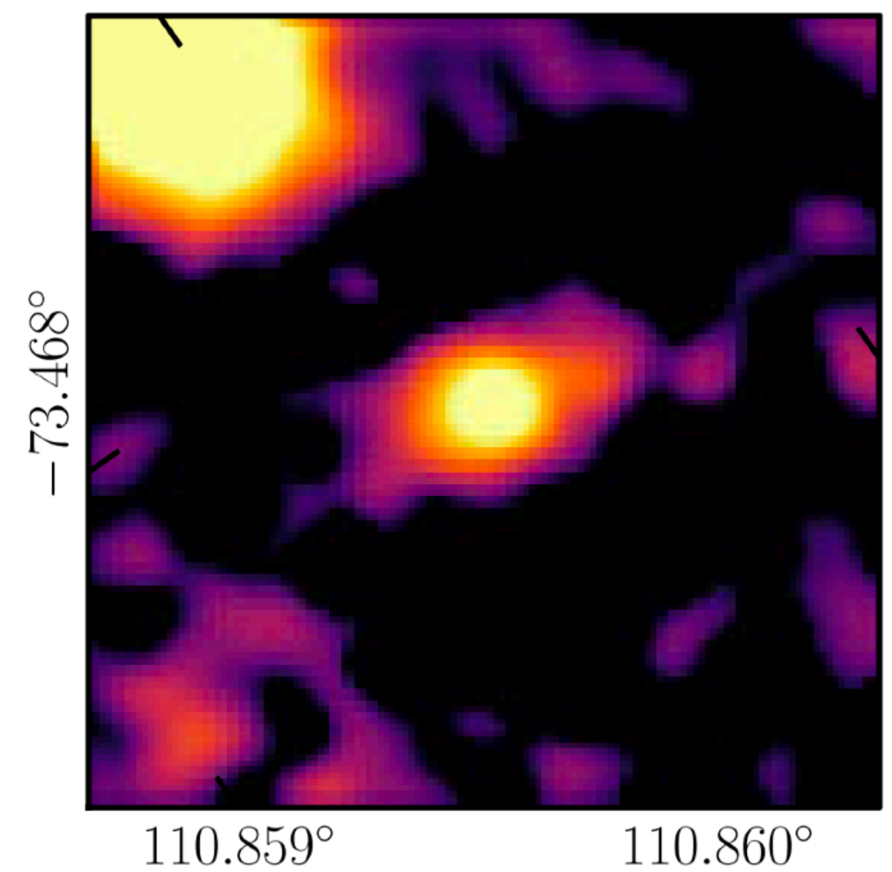
SMACS0723_z16a
$z_{\rm pho} \sim 16$
$\mu \sim 2.18$

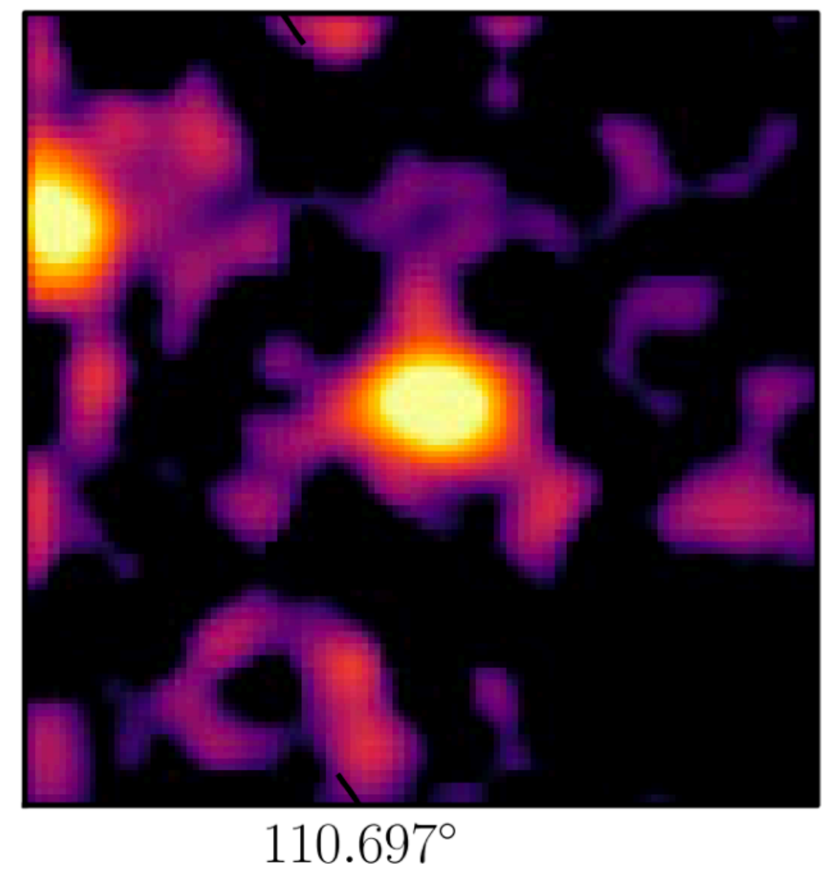
SMACS0723_z12a
$z_{\rm pho} \sim 12$
$\mu \sim 1.15$

extremely distant galaxy candidates
(Atek et al. 2022)

Source Properties: Biases from Lensing Effect

SMACS0723_z16a
$z_{\rm pho} \sim 16$
$\mu \sim 2.18$





SMACS0723_z12a
$z_{\rm pho} \sim 12$
$\mu \sim 1.15$

- Gravitational lensing magnifies the total flux of high-z galaxies and modifies intrinsic properties.

➡ *intrinsic luminosity, stellar mass, scaling relations at high redshift*

- Correction of lensing magnification effect depends on $\Sigma(\overrightarrow{\theta})$.

➡ *bias and scatter in different lens models*

Summary

- Cluster lensing plays an essential role in the JWST era. It helps to study the properties of foreground cluster and background source.

- Magnification effect of cluster lensing greatly facilitate identifying and studying high redshift galaxies.

- Correction for magnification effect is a must, and it depends on the fitting of lens mass distribution. The improved capability of JWST can help to model the mass distribution of lens much more precisely.

Magnification Factor

- more natural to define magnification factor for extended sources as area ratio

$$\mu = \frac{\delta^2 \overrightarrow{\theta}}{\delta \overrightarrow{\beta}^2}$$

(variation)

- use differentiation to approximate for infinitesimal soure

$$\mu = \frac{\overrightarrow{\theta} \, \mathrm{d} \overrightarrow{\theta}}{\overrightarrow{\beta} \, \mathrm{d} \overrightarrow{\beta}}$$

(differentiation)

+

$$\overrightarrow{\beta} = \overrightarrow{\theta} - \overrightarrow{\alpha}$$

$$\overrightarrow{\alpha}(\overrightarrow{\theta}, \Sigma(\overrightarrow{\theta}), z_s, z_l)$$

→

$$\mu(\overrightarrow{\theta}, \Sigma(\overrightarrow{\theta}), z_s, z_l)$$