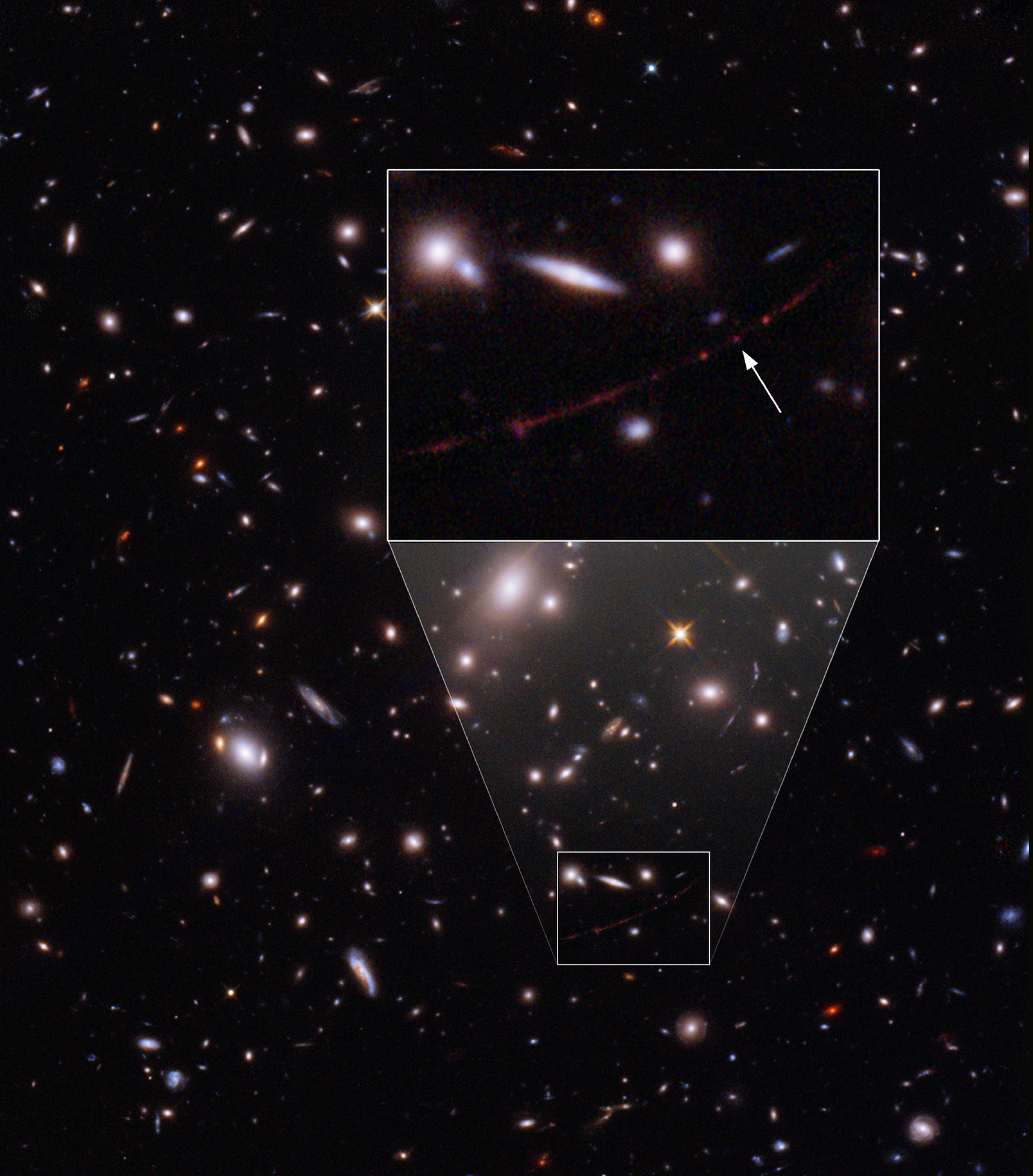


Hubble Breaking News!

A highly magnified star at redshift 6.2

Nature Article published on 30 March 2022

Welch et al.

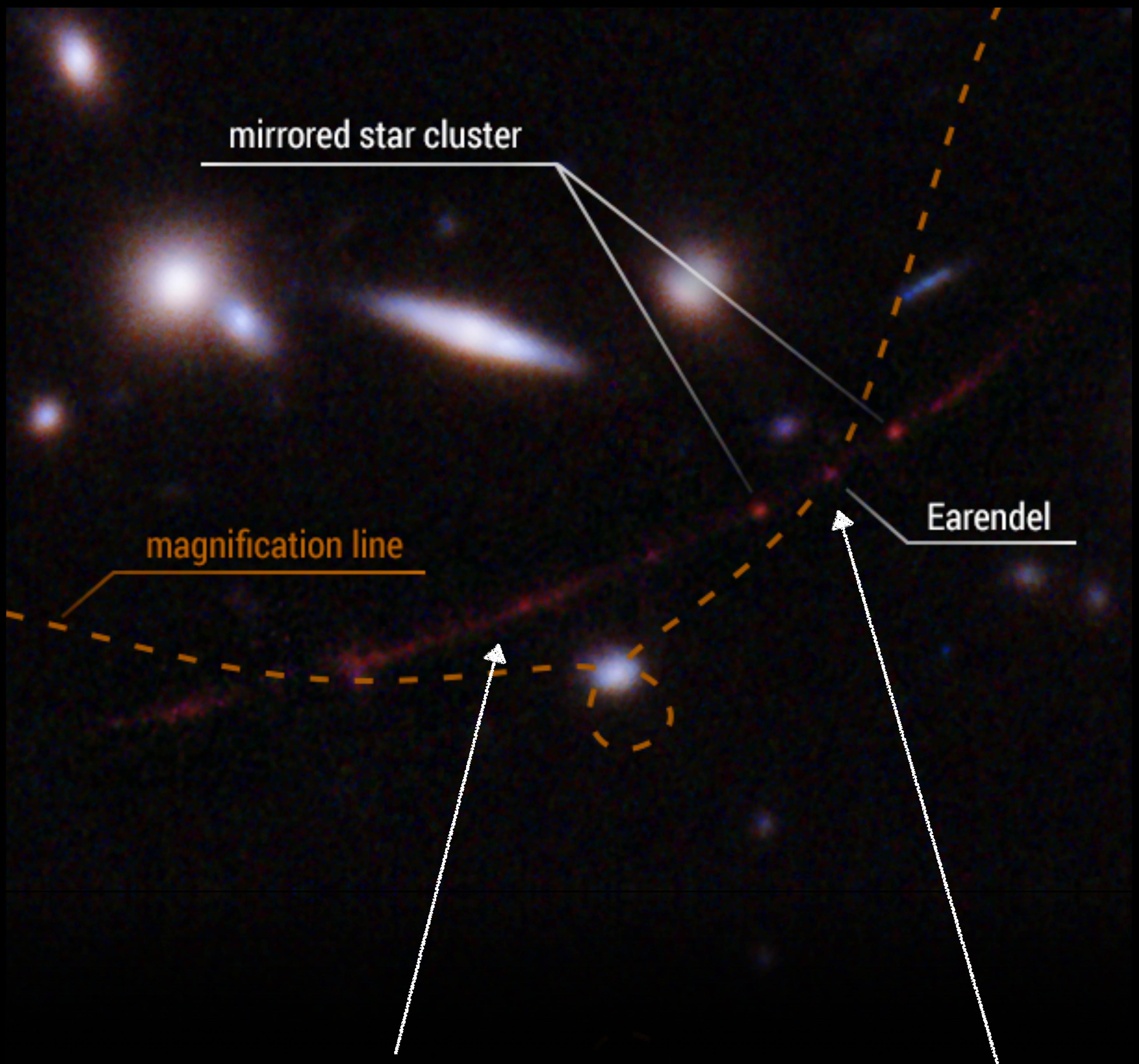
Student Seminar   Xiaojing Lin   1st April 2022

Record Broken

Earendel

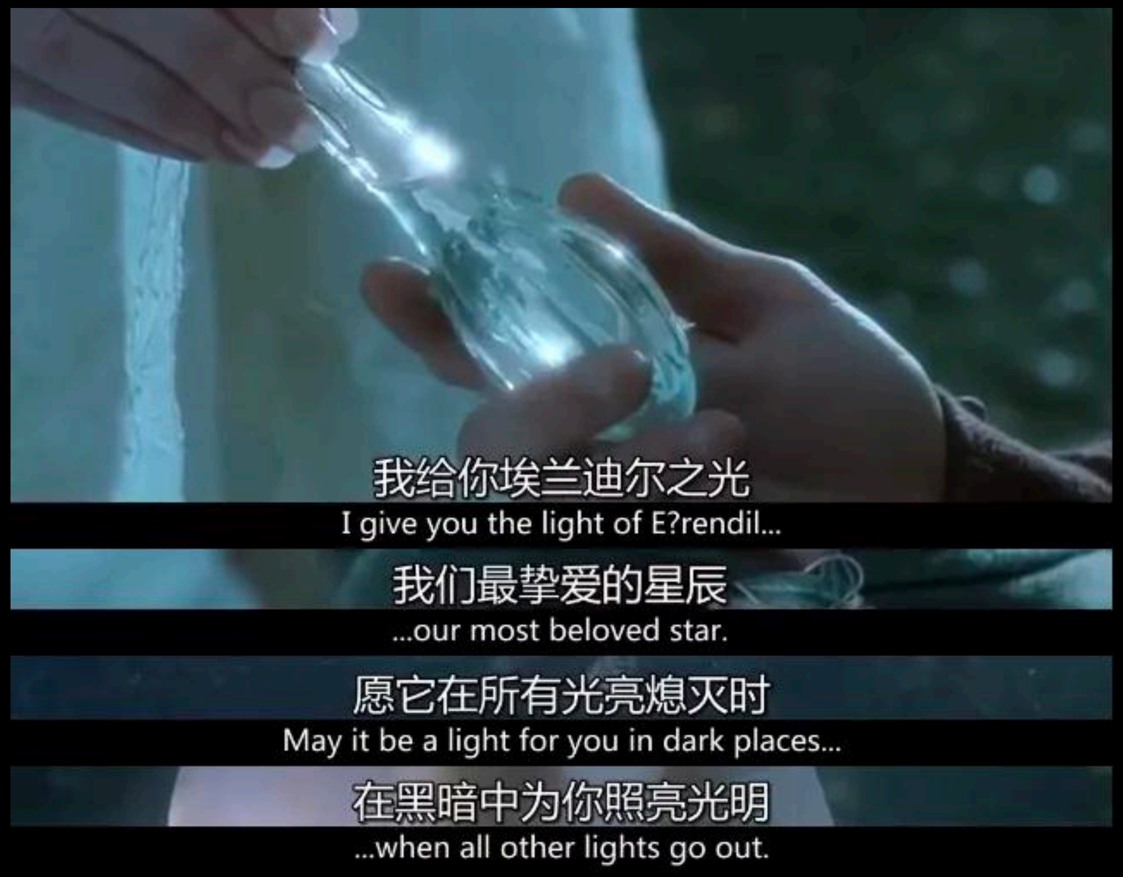
(WHL0137-LS)

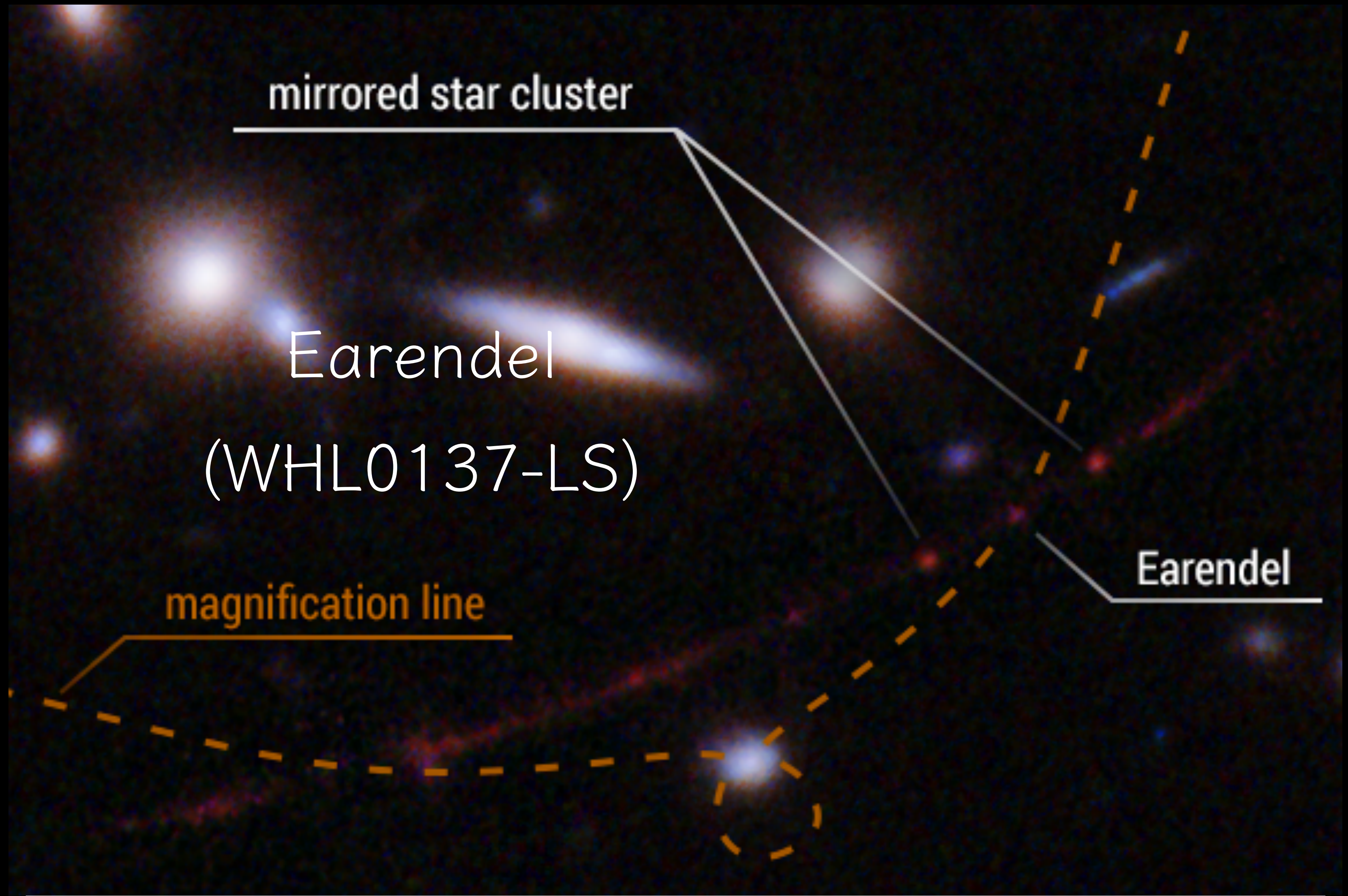
- A distant and persistent magnified star at a redshift of 6.2 ± 0.1; 900 million years after the Big Bang.
- Foreground: WHL0137–08 (z=0.566)
- 2μ = 1,000–40,000



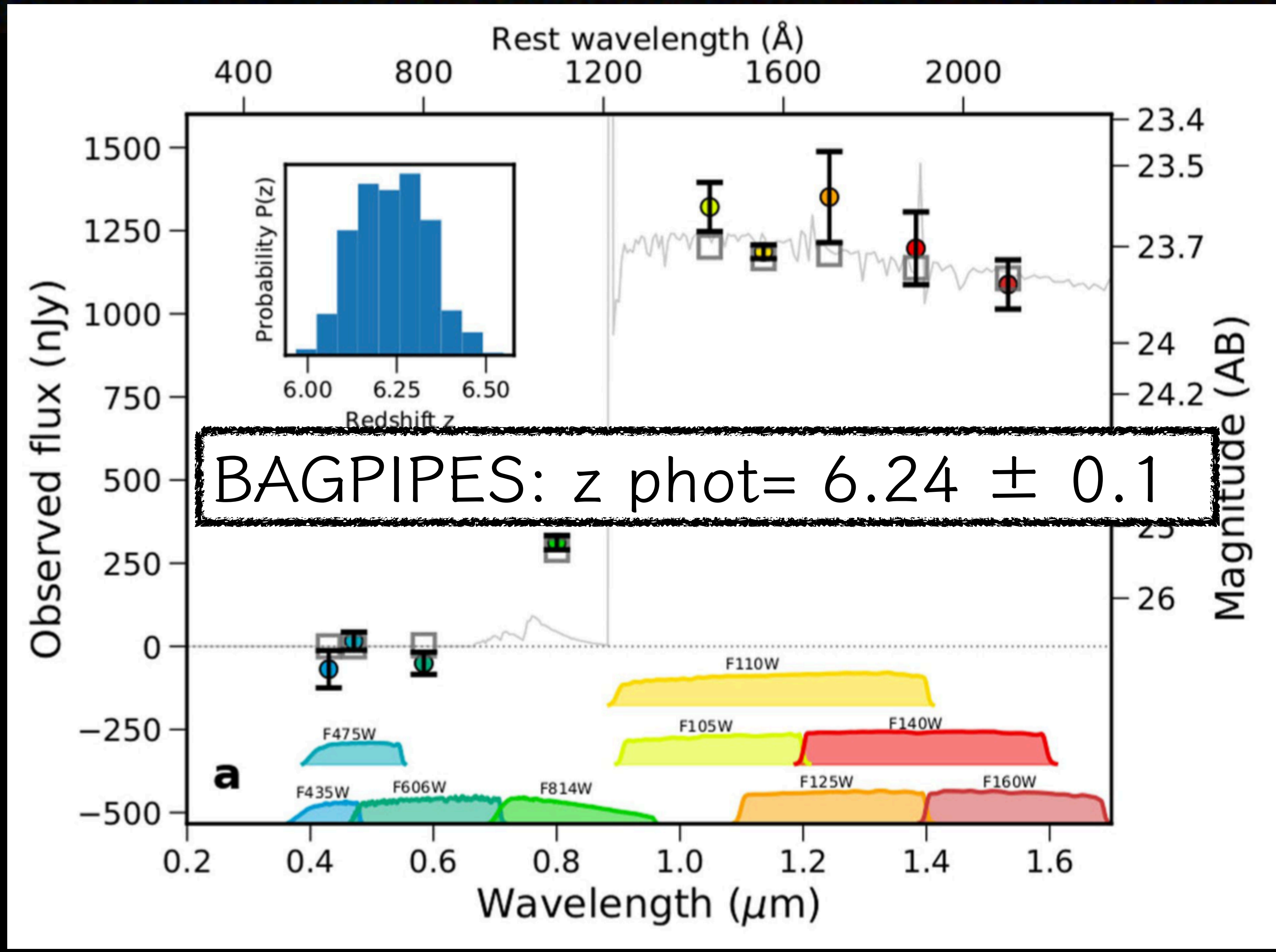
A $15''$-long lensed arc of a galaxy at photometric redshift $z_{\mathrm{phot}} = 6.2 \pm 0.1$

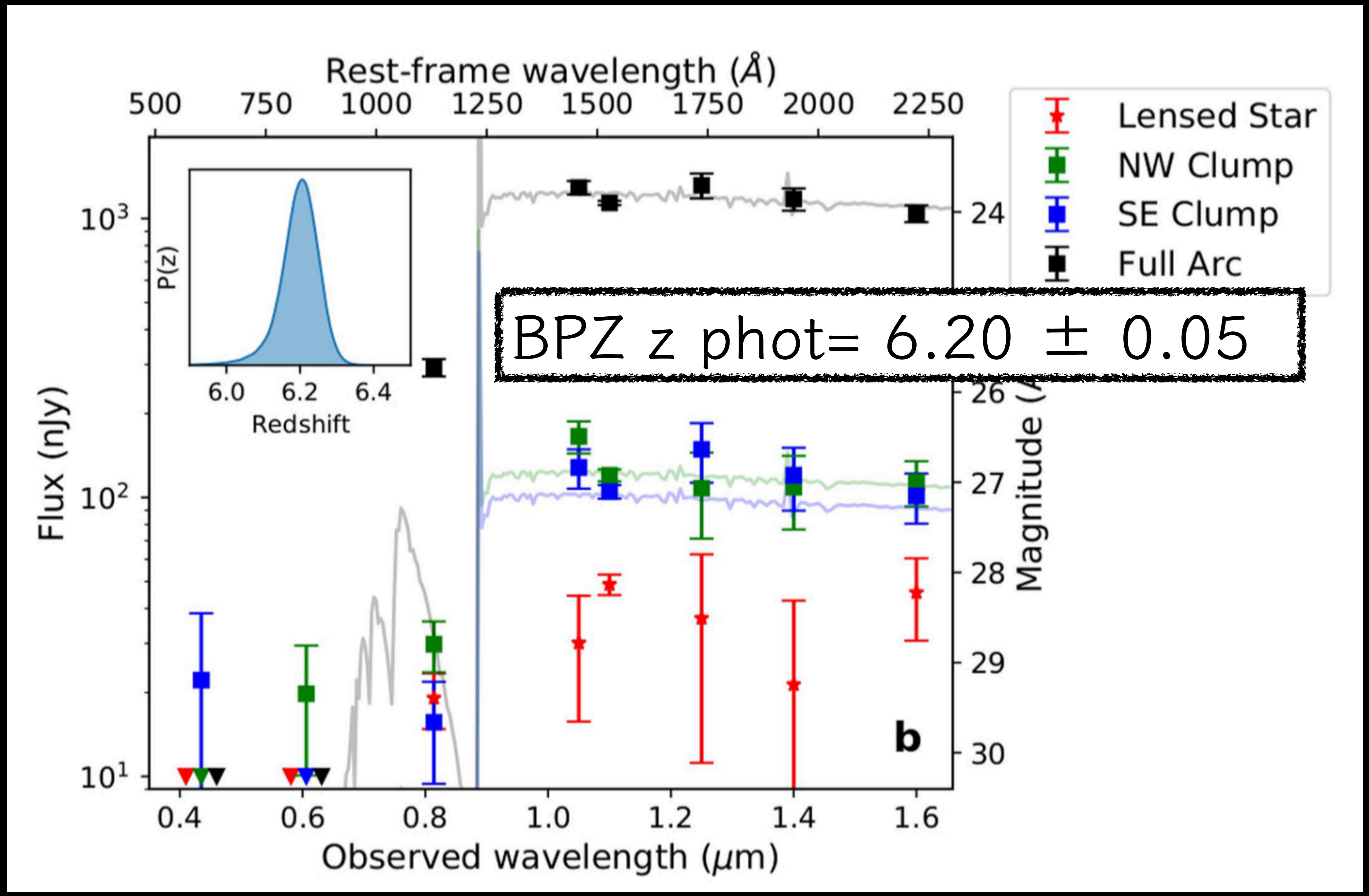
Earendel sitting atop the lensing critical curve





Camera	Filter	HST GO 14096 Exposure Time (s)	HST GO 15842 Exposure Time (s)	Depth 5σ (AB mag)	Sunrise Arc Flux (nJy)	Earendel Flux (nJy)
ACS	F435W	2072		27.2	-69 ± 56	-8 ± 12
ACS	F475W		3988	27.9	16 ± 27	9 ± 6
ACS	F606W	2072		27.6	-51 ± 33	-2 ± 7
ACS	F814W	2243	11083	28.0	312 ± 21	19 ± 4
WFC3/IR	F105W	1411		26.7	1321 ± 74	30 ± 14
WFC3/IR	F110W		5123	27.7	1187 ± 21	49 ± 4
WFC3/IR	F125W	711		26.0	1351 ± 137	37 ± 26
WFC3/IR	F140W	711		26.2	1197 ± 109	21 ± 21
WFC3/IR	F160W	1961		26.5	1088 ± 74	46 ± 15

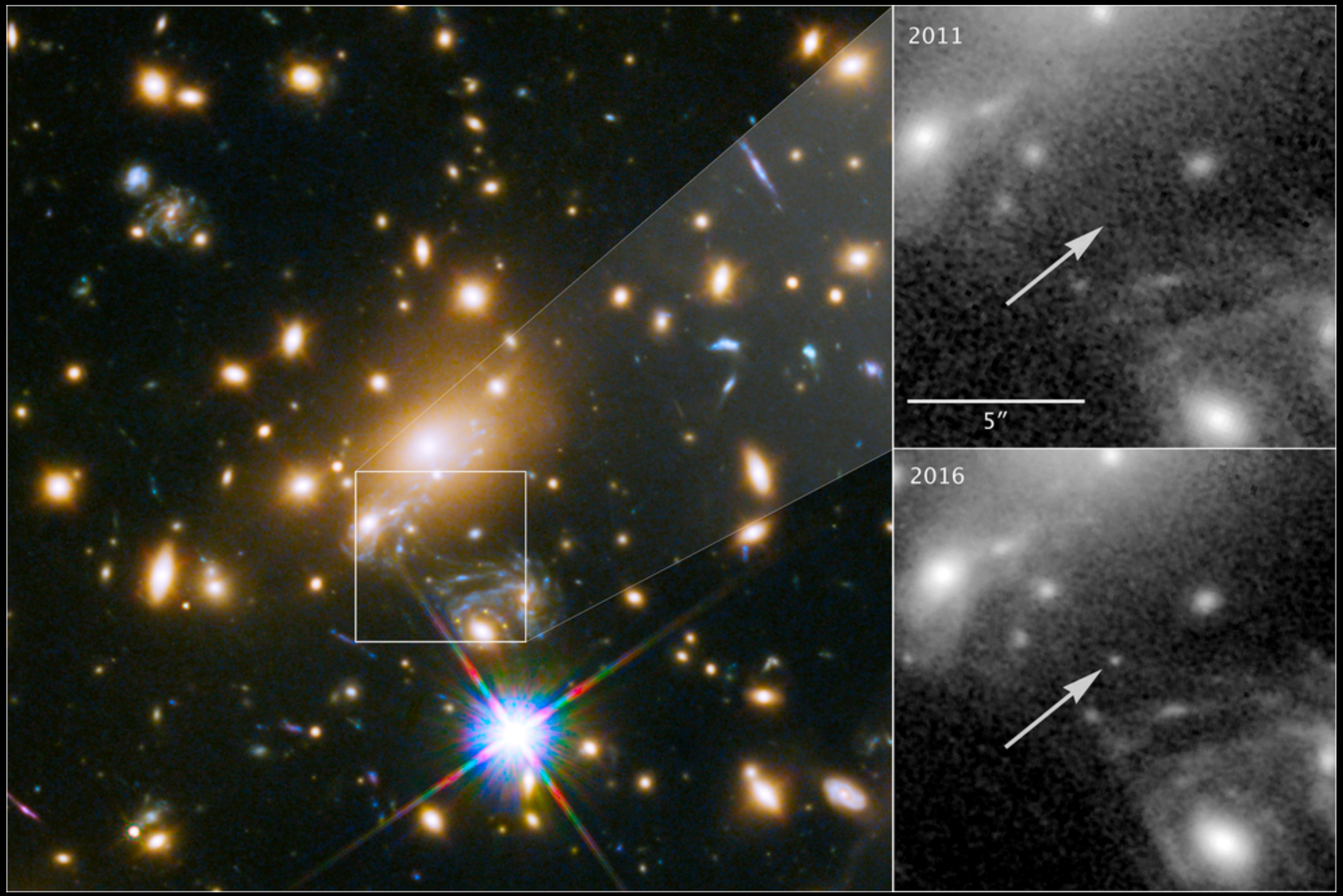




P. Kelly et al. 2018 (Nature Astronomy)

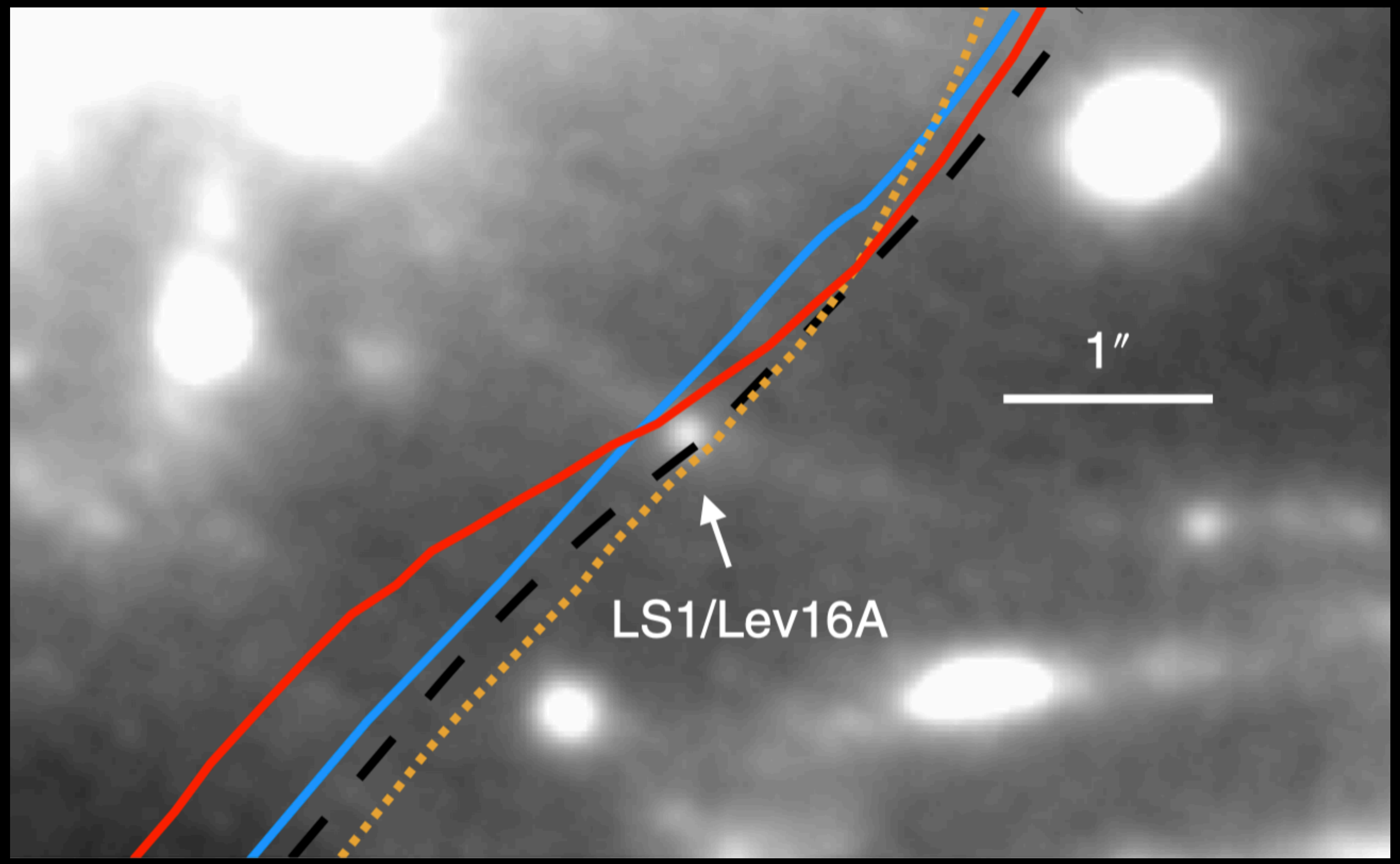
Previous record holder: Icarus

(MACS J1149+2223 Lensed Star 1)



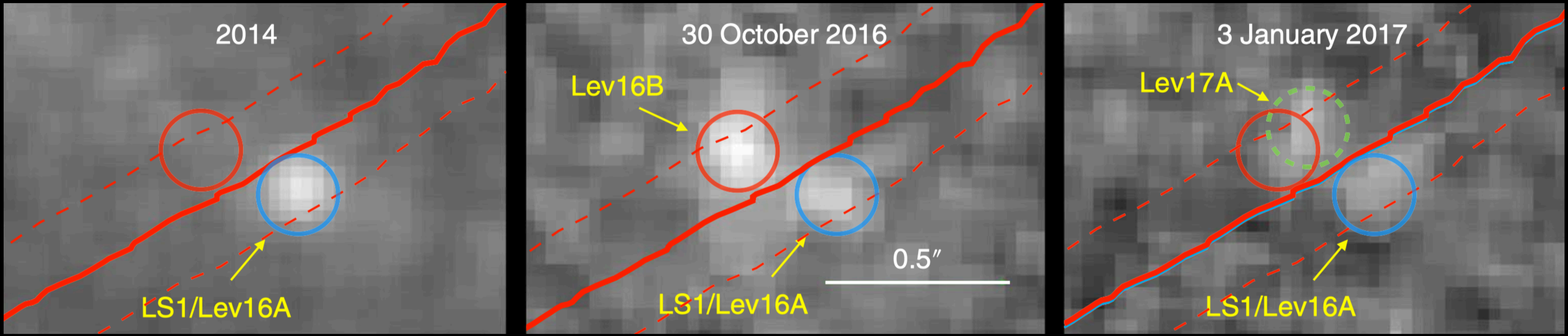
- A lensed blue supergiant at z = 1.49
- Foreground: MACS J1149 at z=0.54

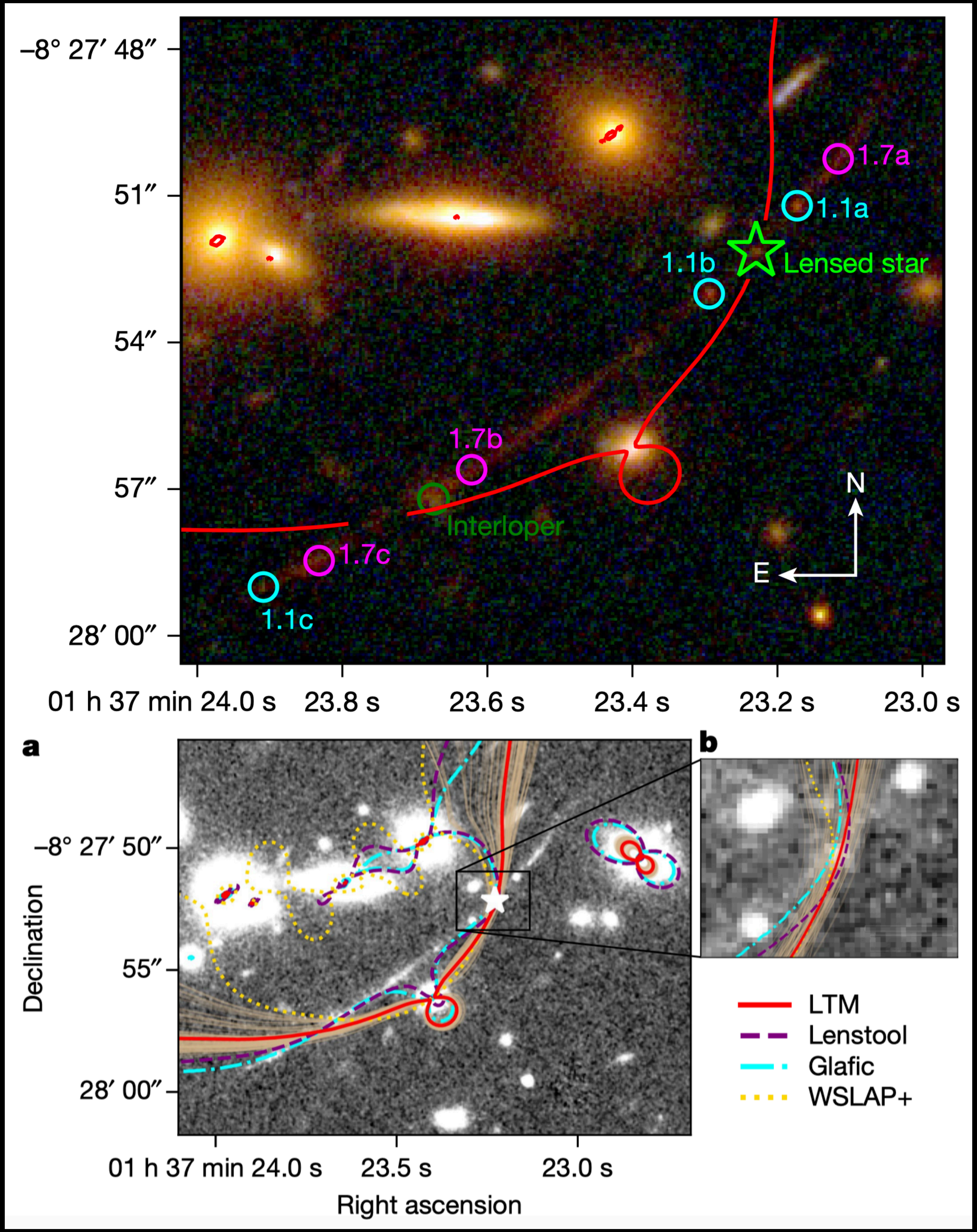
Icarus (MACS J1149+2223 Lensed Star 1)



- no farther than ~0.13″ from the critical curves of all publicly available high-resolution models ⇒ magnified by more than ×2,000

- unexpected new source ('Lev16B') on 30 October 2016 offset by 0.26″ from LS1
- Microlensing by an object with a mass of ≳3 M⊙



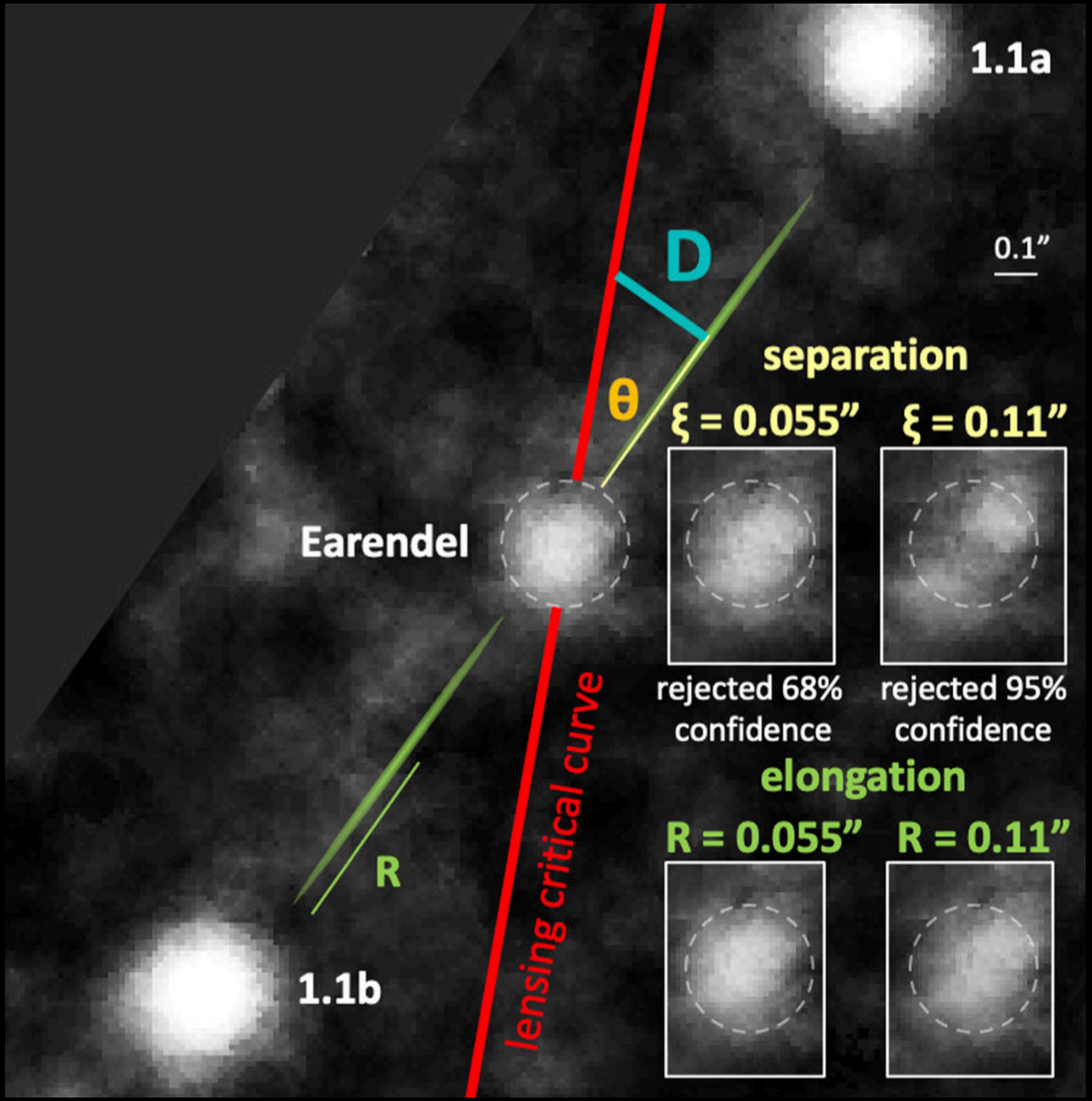


Earendel (WHL0137-LS)

- the source is within 0.1″ in approximately 80% of models, and the maximum distance reaches 0.4″

- ☐ If Earendel were farther from the critical curve, there would be two multiple images
- ☐ A single image observed: its two images are spatially unresolved? or microlensing is suppressing the flux of one image?
- ☐ The latter ✕ : optically thick microlensing network for the foreground cluster 😖 microlensing cannot hide one of the images

Earendel (WHL0137-LS)



Q1: How do you know that is a star?

size constraints

① the observed lensed radius along the arc R

✓ the image of Earendel is unresolved: consistent with and not measurably wider than the PSF

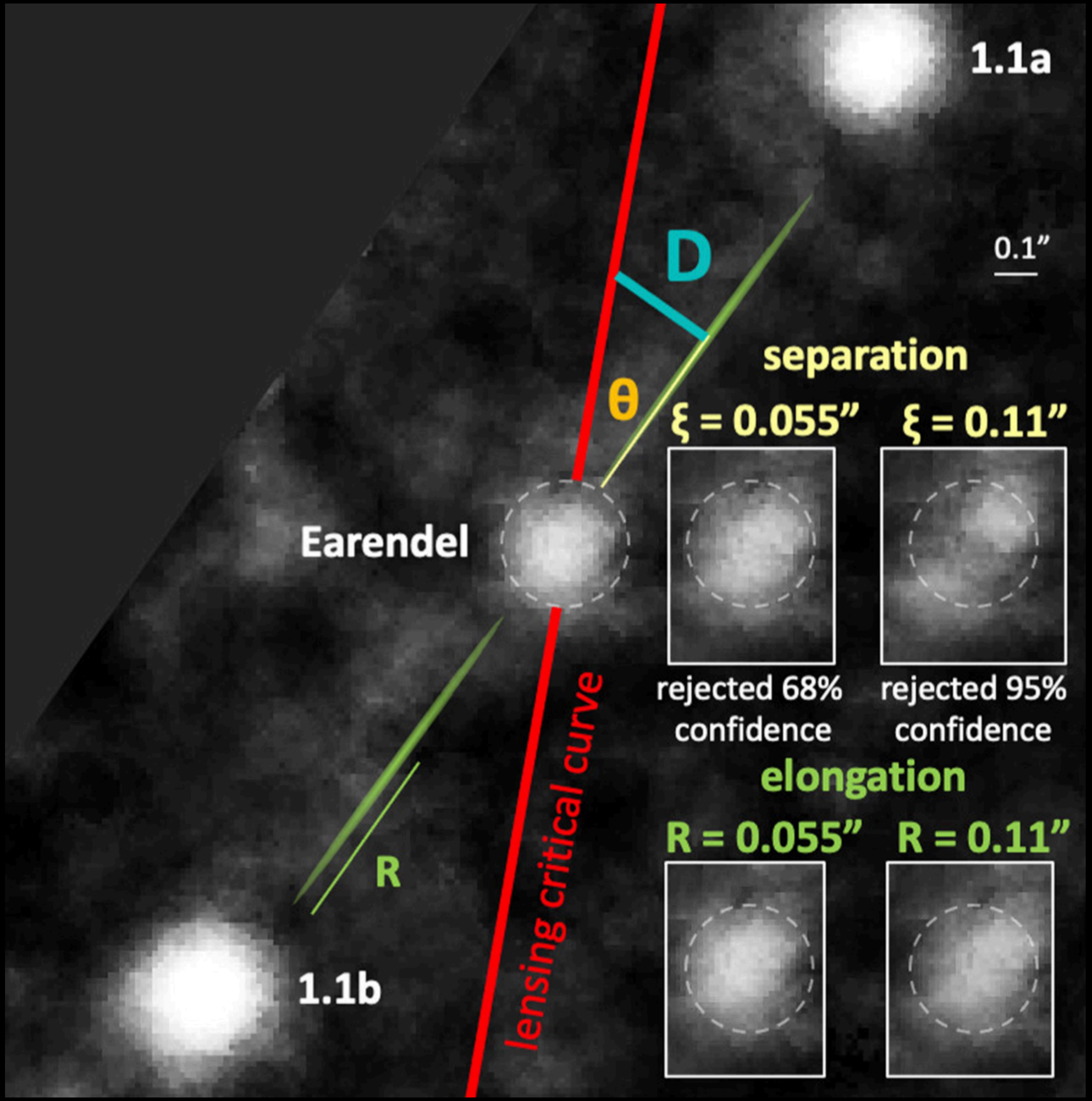
> model the source as a Gaussian light profile
> stretch this Gaussian along the arc for a given model magnification $\mu = \mu_{||}\,\mu_{\perp}$ and axis ratio $\mu_{||}/\mu_{\perp}$

(almost stretched almost entirely tangentially along the arc)

> a 1D Gaussian with a width σ of $\gtrsim 0.055''$ would begin to appear spatially resolved

$$R < 0.055''$$

Earendel (WHL0137-LS)



Q1: How do you know that is a star?

size constraints

② the distance from the critical curve D

> Separation between two lensed point sources 2ξ : spatially resolved when separated by a distance $2\xi \approx 0.11''$, with $\xi \approx 0.055''$

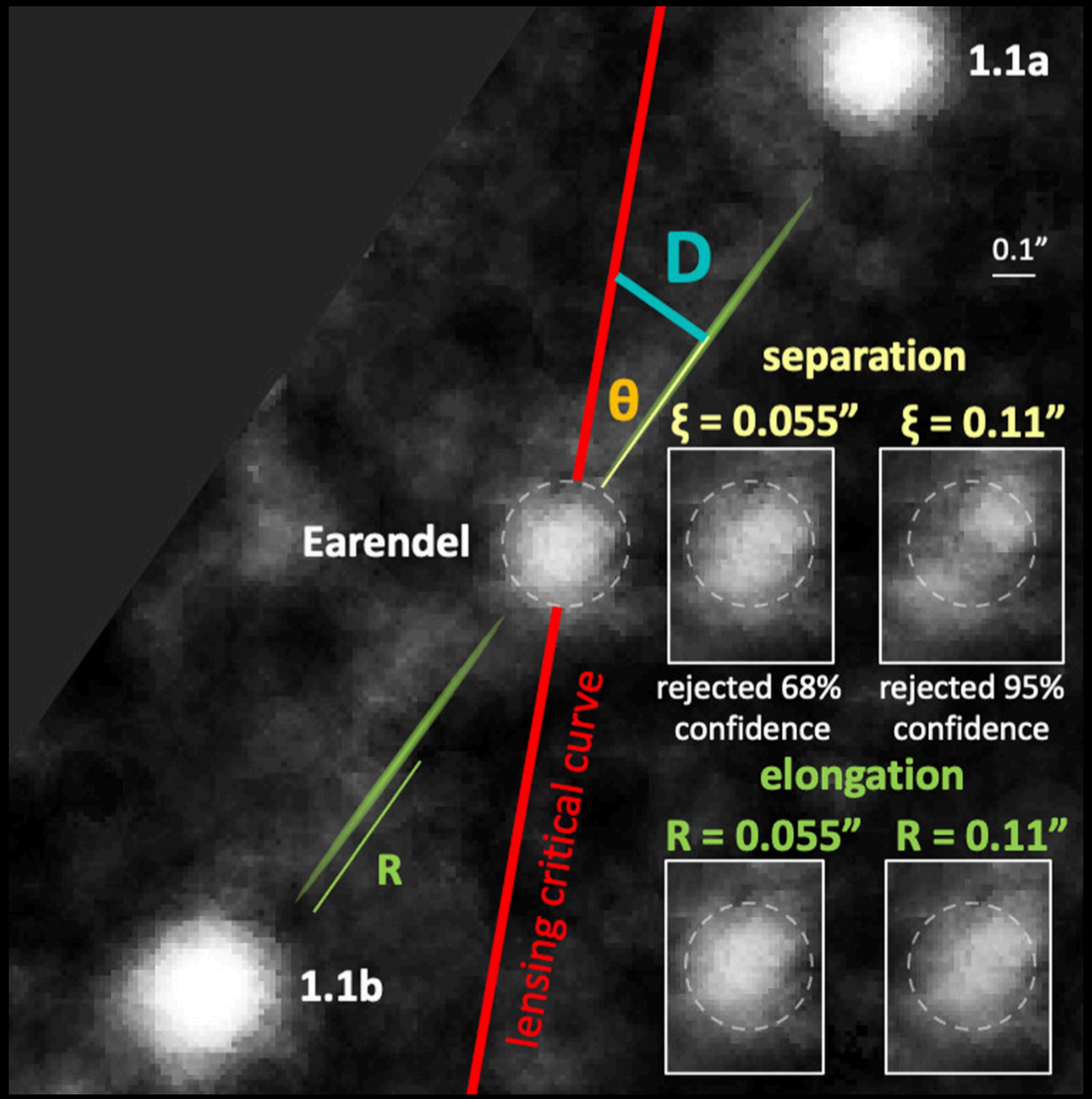
$$2\xi < 0.11''$$

> The lensing critical curve intersects the arc at an angle θ that varies between 22° and 41° , depending on the lens model.

$$D = \xi \sin\theta \, . \; D < 0.055'' \times \sin\theta$$

varies from $D < 0.02''$ to $D < 0.036''$

Earendel (WHL0137-LS)



Q1: How do you know that is a star?

size constraints

$D < 0.02''$ to $D < 0.036''$

$R < 0.055''$

$\mu = \mu_0 / D$

$R = \mu_{||} r = \mu_0 r / D \mu_{\perp}$

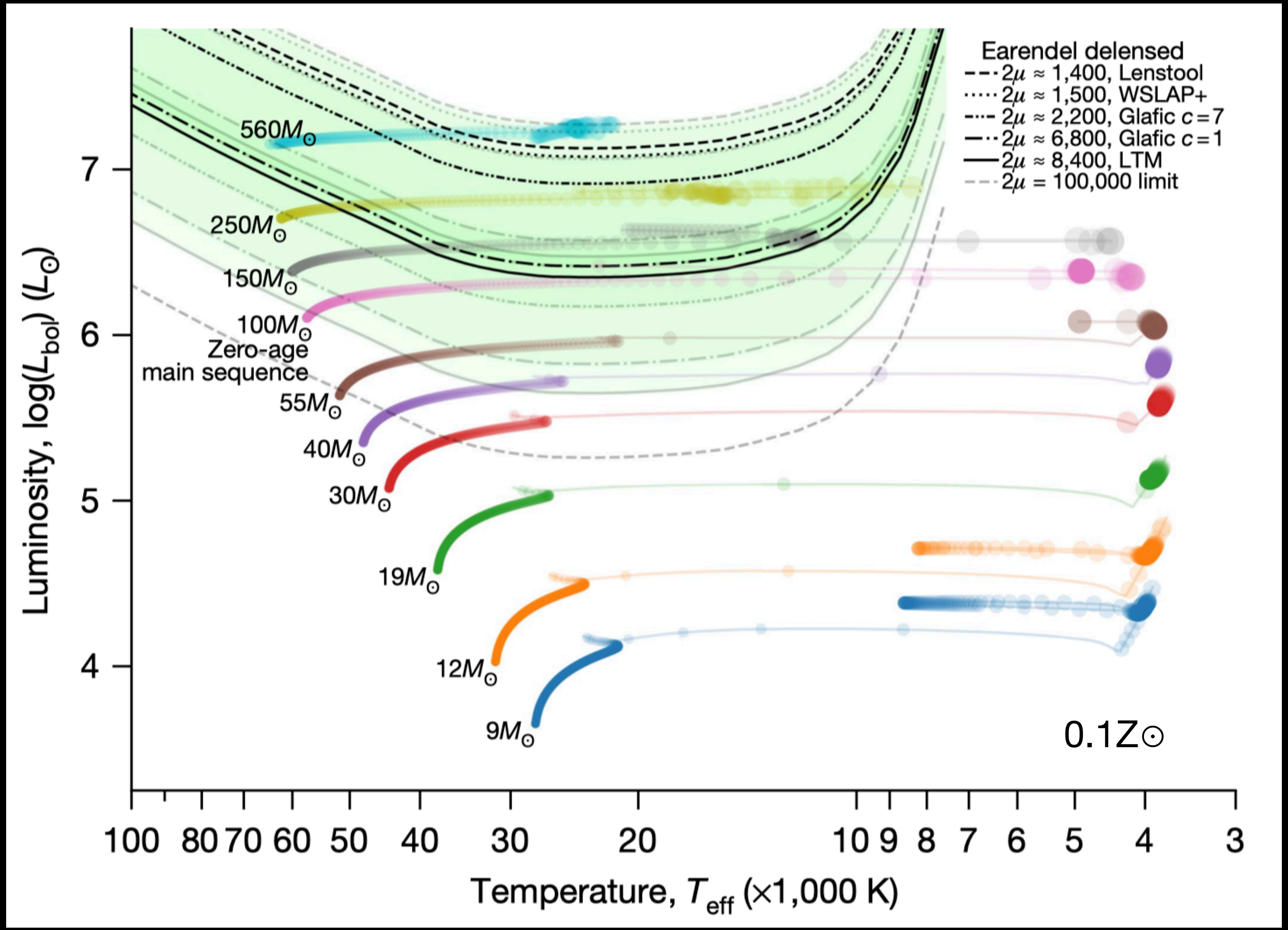
Earendel's intrinsic delensed radius is

$r <$ 0.09–0.36 pc

Lens model	μ_0	D_{crit} (″)	Magnification, 2μ	Flux (nJy)	AB magnitude	M_{UV}	Axis ratio	Radius (pc)
LTM	113	0.027	$8,400^{+33,600}_{-2,400}$	6^{+2}_{-5}	$37.0^{+1.7}_{-0.4}$	$-9.8^{+1.7}_{-0.4}$	1,500	<0.09
Glafic (c=1)	69	0.020	$6,800^{+27,100}_{-2,000}$	7^{+3}_{-6}	$36.8^{+1.7}_{-0.4}$	$-10.0^{+1.7}_{-0.4}$	760	<0.14
Glafic (c=7)	23	0.020	$2,200^{+9,000}_{-600}$	22^{+9}_{-18}	$35.6^{+1.7}_{-0.4}$	$-11.2^{+1.7}_{-0.4}$	930	<0.21
WSLAP	28	0.036	$1,500^{+6,100}_{-500}$	32^{+13}_{-26}	$35.1^{+1.8}_{-0.3}$	$-11.7^{+1.8}_{-0.3}$	580	<0.33
Lenstool	18	0.026	$1,400^{+5,500}_{-400}$	36^{+14}_{-29}	$35.0^{+1.8}_{-0.3}$	$-11.8^{+1.8}_{-0.3}$	560	<0.36

Earendel (WHL0137-LS)

Q2: Properties if it is a star?



A delensed flux 1–50 pJy (AB mag 38.7–34.6) in the F110W filter (0.9–1.4 μm), corresponding to an absolute UV (1,600 Å) magnitude −8 > M AB> −12

- calculate the intrinsic stellar luminosity, assuming blackbody spectra for hot stars with effective temperatures T eff< 40,000 K

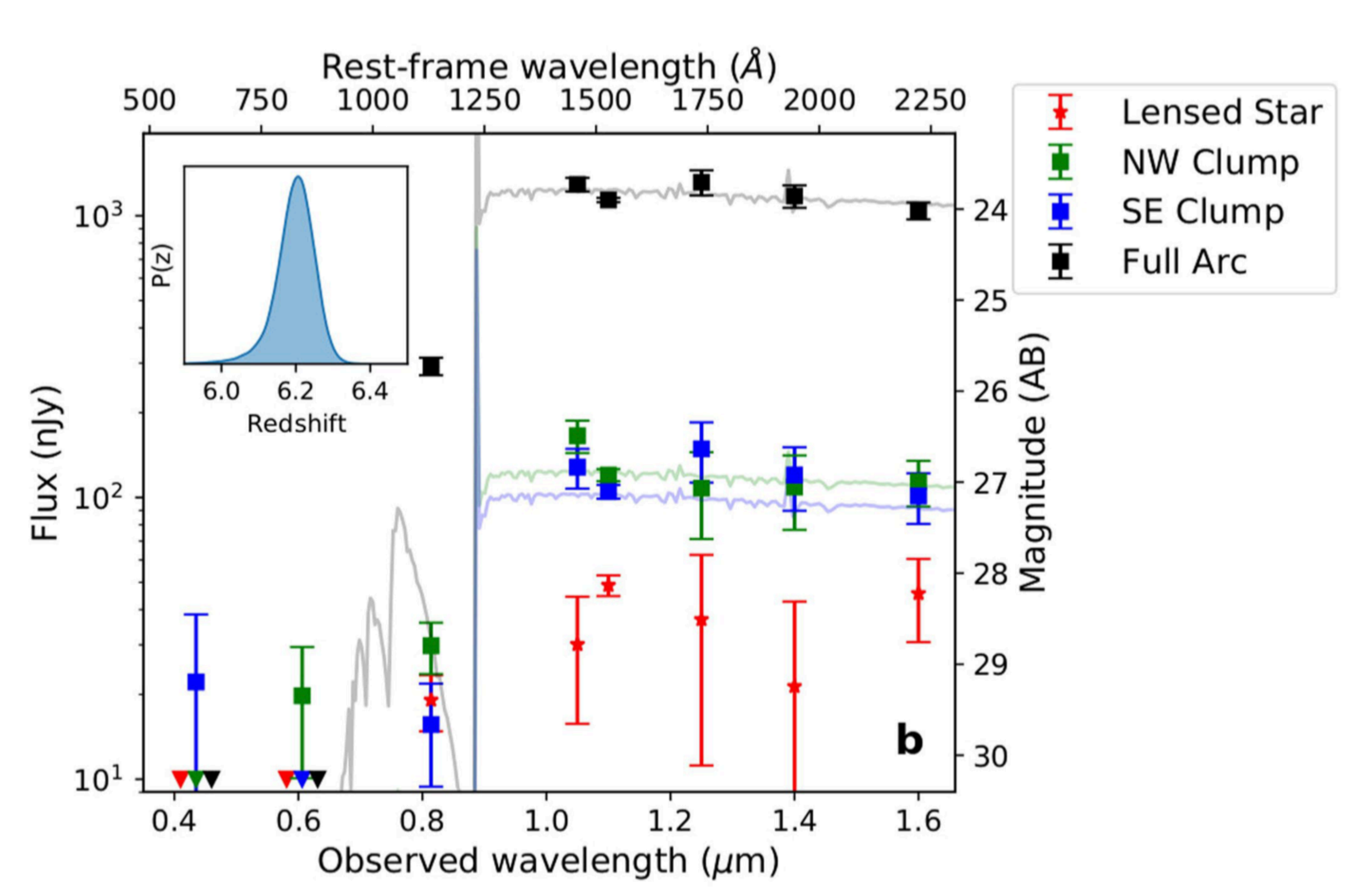
- constrain Earendel's luminosity as a function of temperature in the Hertzsprung–Russell (H–R) diagram

a single massive star with initial mass of approximately (40–500) M⊙

a massive O-type star T~60,000 K and mass >100M⊙

or an evolved O-, B- or A-type star with mass >40M⊙ and T~8,000-60,000 K

Earendel (WHL0137-LS)



Q3: Alternative possibilities?

① not associated with the Arc, and thus not a lensed star at $z \approx 6$

e.g. local dwarfs aligning with both the arc and critical curve by chance

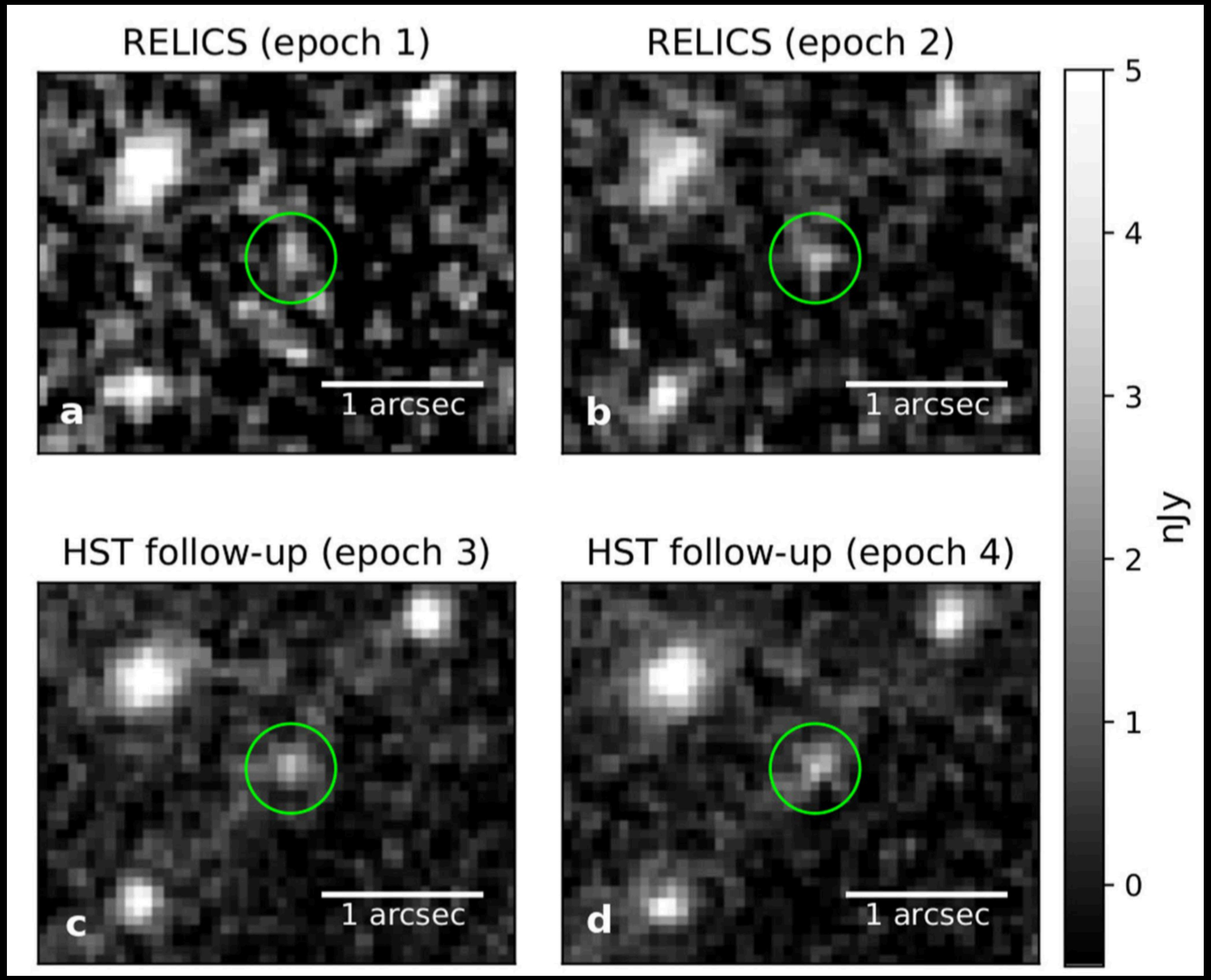
Current photometry data cannot

＊ Existing HST photometry cannot conclusively rule out a brown dwarf.

＊ SED fitting of Earendel alone to brown dwarf spectra ~ a 3,000-K local star

Upcoming JWST photometry and spectroscopy!

Earendel (WHL0137-LS)



Q3: Alternative possibilities?

① *not associated with the Arc, and thus not a lensed star at z ≈ 6*

e.g. local dwarfs aligning with both the arc and critical curve by chance

Proper motion

> *Might be expected*

> *No evidence of proper motion over the 3.5-year observation window*

chance alignment probability

> *~1.2 M-type dwarfs per arcmin2 out to magnitude 24 in multiple fields observed with HST*

> *Rescaling to 27th magnitude → ~100 such stars per arcmin2*

> *the solid angle surrounding the critical curve crossings in the Arc (constrained to within 0.1″) → the probability ~ the order of 0.01%*

Earendel (WHL0137-LS)

Q3: Alternative possibilities?

② an accreting stellar-mass black hole

e.g. black hole were persistently fed by a lower-mass star overfilling its Roche lobe

strong X-ray emission?

XMM-Newton: no clear signal near this position

Cons:

> 6″ spatial resolution of XMM-Newton would dilute the signal

> Expect deeper, higher-resolution X-ray images with the Chandra X-ray Observatory (resolution ~0.5″) or the upcoming Athena mission

Earendel (WHL0137-LS)

Q3: Alternative possibilities?

③ a population III star with zero metallicity

Low probability

SED fitting of the Arc: a stellar mass of $M_* \approx 3 \times 10^7 M_\odot$, expecting a metallicity of ~ $0.01Z_\odot$-$0.1Z_\odot$

⇒ some enrichment has taken place!

Not ruled out

Trenti, M. Et al. 2009: predict pockets of zero-metallicity gas may still exist at $z \approx 6$, particularly near the outskirts of galaxies ⇒ where population III stars can form

Vanzella, E. et al. 2020: Candidate population III stellar complex at $z = 6.629$ in the MUSE Deep Lensed Field

Earendel (WHL0137-LS)

Q3: Alternative possibilities?

③ a population III star with zero metallicity

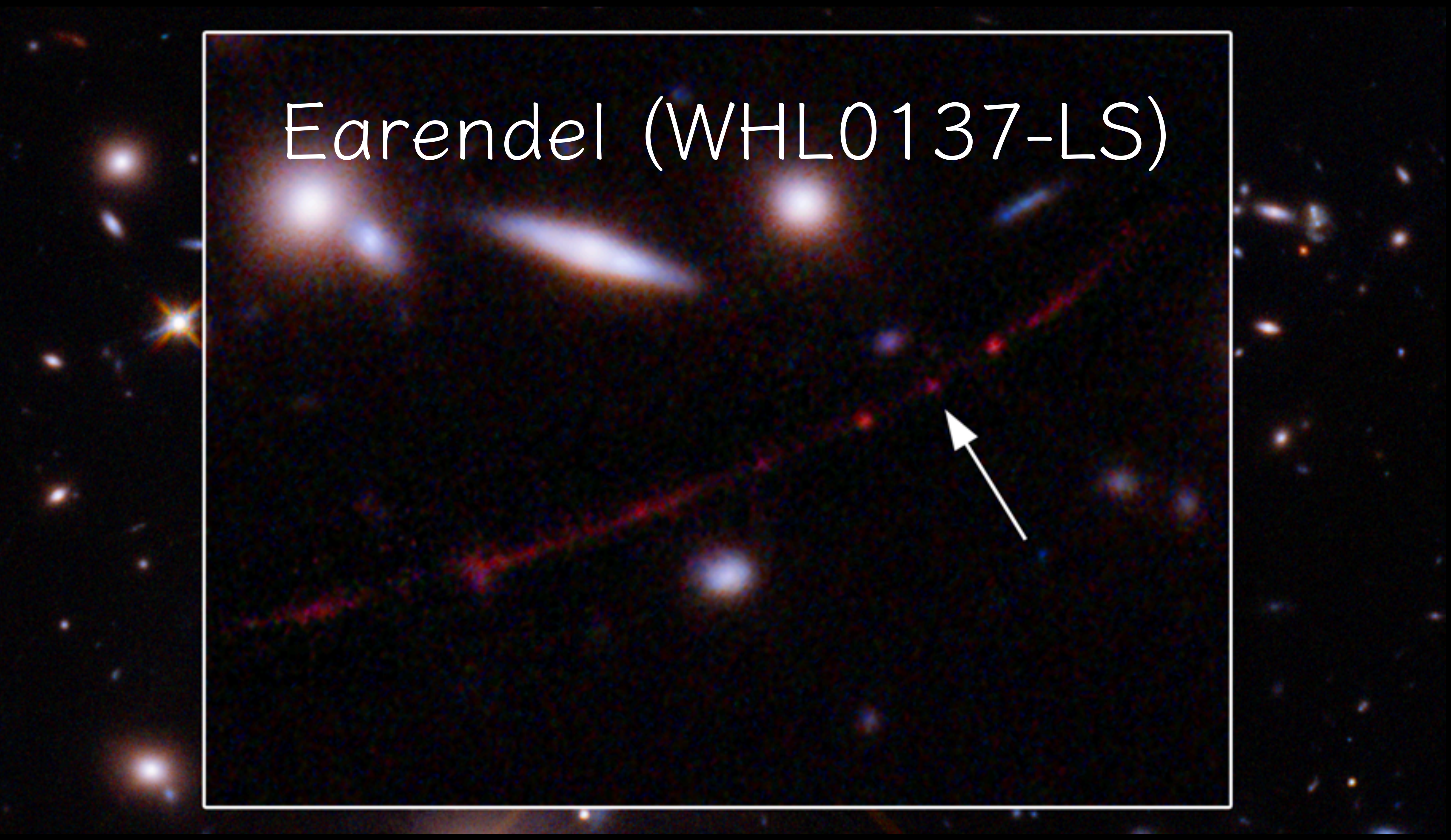
If so

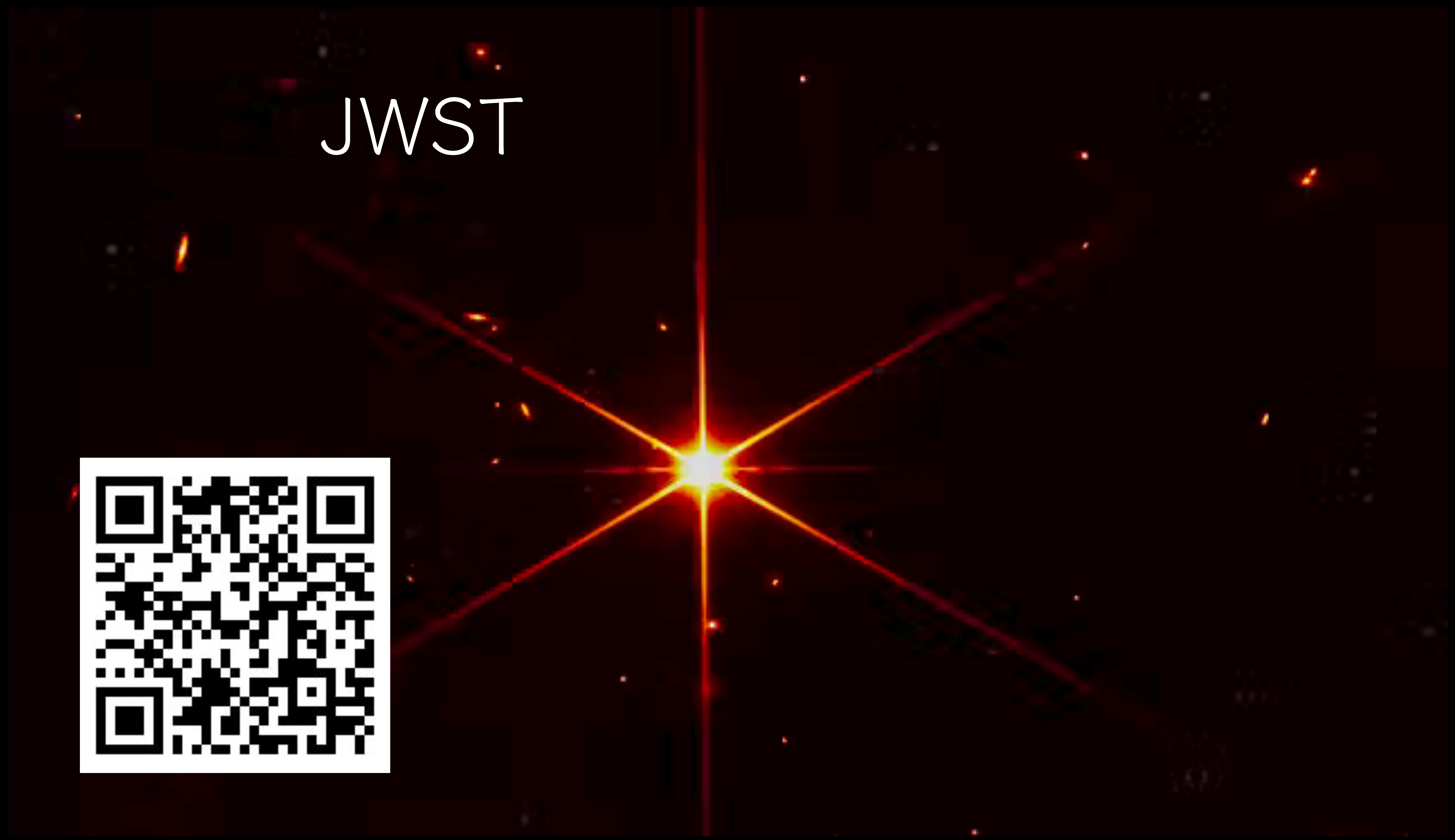
Breaking Breaking new!

the first such star observed / important confirmation that such stars formed,

possible progenitor for massive binary black hole merger

Spectroscopic follow-up will be required to assess the possibility of Earendel being a population III star



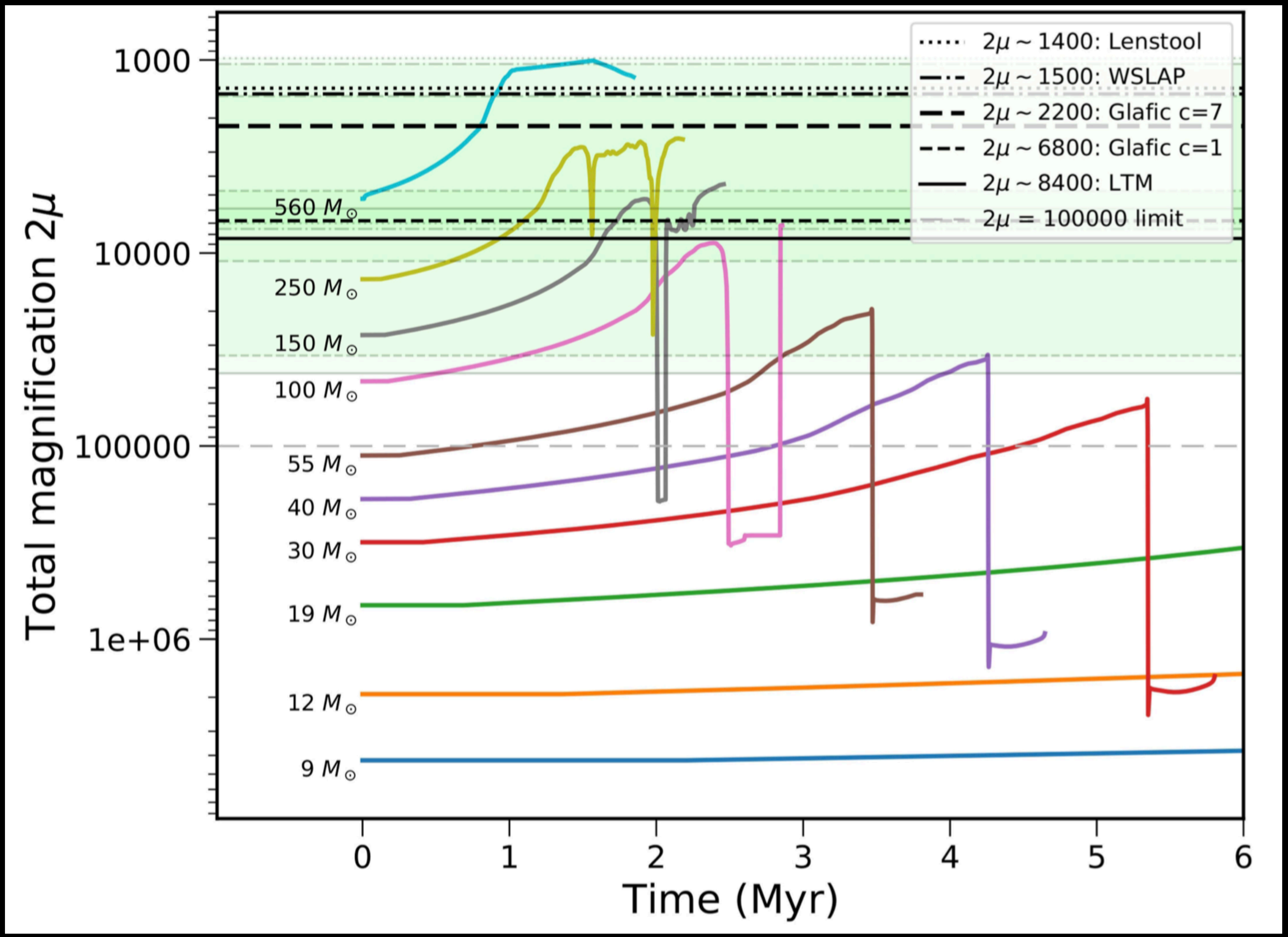


Summary / take home message

- A highly magnified star at redshift 6.2
  - $r < 0.09–0.36$ pc
- magnified by a factor of thousands by the foreground galaxy cluster lens
  - sitting atop the lensing critical curve
- mass of approximately $(40–500)M_\odot$
  - $M \sim 50\text{-}100\ M_\odot$ and $T > 20{,}000$ K are most probable
- Future spectroscopic observations with JWST
  - spectral type, temperature and mass of the star

Earendel (WHL0137-LS)

Q2: Properties if it is a star?



total magnification required to lens stars to Earendel's apparent magnitude as a function of time on stellar evolution tracks

- very massive stars of ≳100$M_\odot$ spend the greatest time (~2 Myr) with a luminosity matching Earendel within the uncertainties.
- ~55$M_\odot$ would only match the luminosity constraint for ~0.5 Myr ⇒ decrease the detection probability by ~1/4 / roughly four times as numerous as 100$M_\odot$ stars
- More massive stars are less numerous / a less massive star would not be bright enough

masses of roughly (50–100) $M_\odot$ are most likely if Earendel is a single star.