

Identification and Morphologies of Galaxies with Old Stellar Populations at High Redshift

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How did the first massive galaxies form?

Theoretical modeling cannot yet answer this question, partly because global feedback from star formation and AGN winds is extremely complicated and difficult to model, both in semi-analytic and hydrodynamic approaches to galaxy formation.

“Ab initio calculations, beginning with inflationary fluctuations that evolve into mature galaxies, are currently a theorist’s dream and are likely to remain so.”

—J. Silk (2000) PASP, 112, 1003

Need observational evidence....

Two projects:

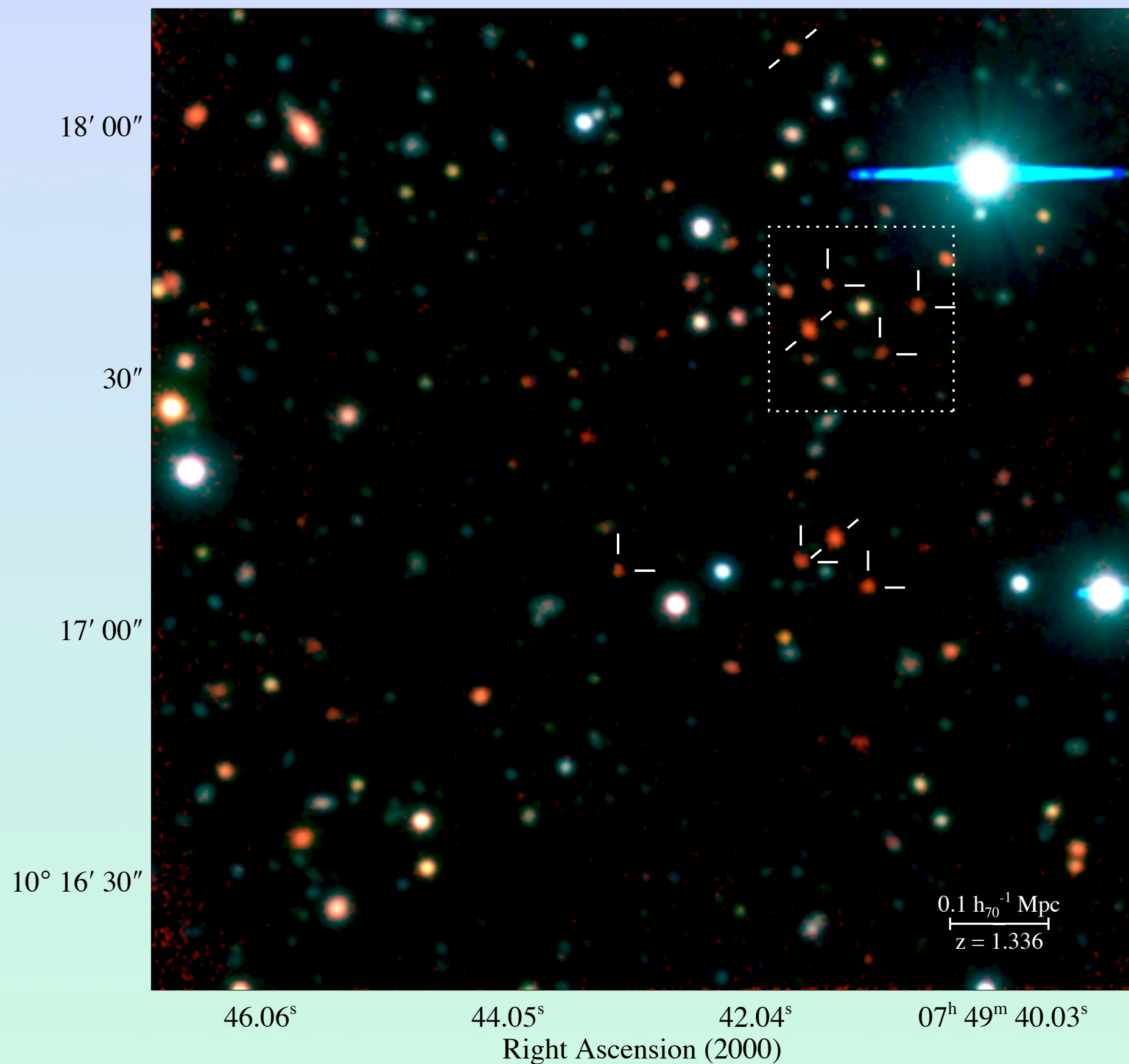
- ❖ Investigation of group of red galaxies found in the IfA Deep Survey with SuprimeCam.
- ❖ Morphologies of galaxies with old stellar populations found in radio-source fields at high redshift.

In both cases, morphologies of the galaxies can give constraints on formation scenarios.

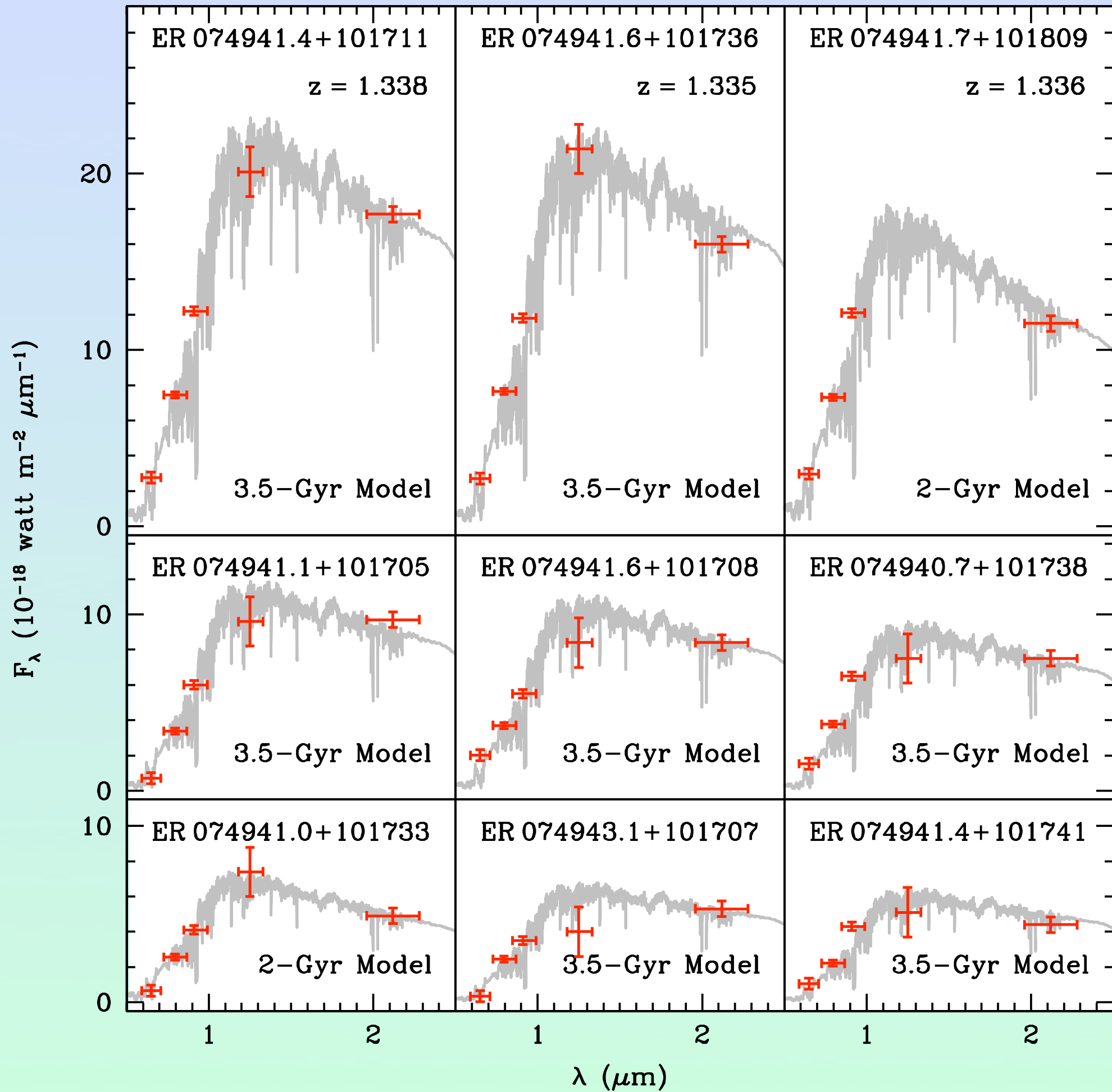
I. A group of galaxies with old stellar populations at $z = 1.34$

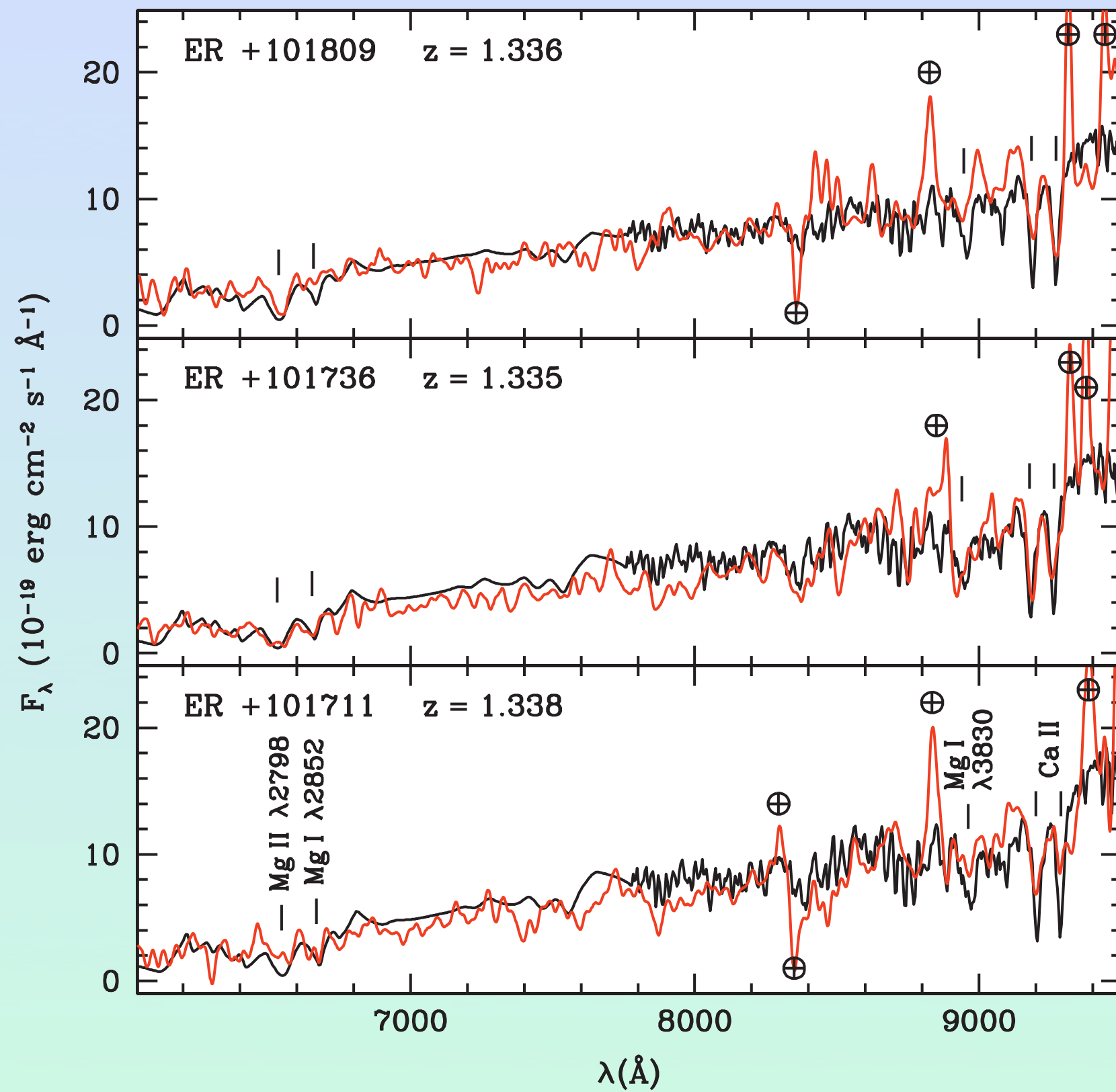
Fu, Stockton, & Liu (2005; ApJ, 632, 831)

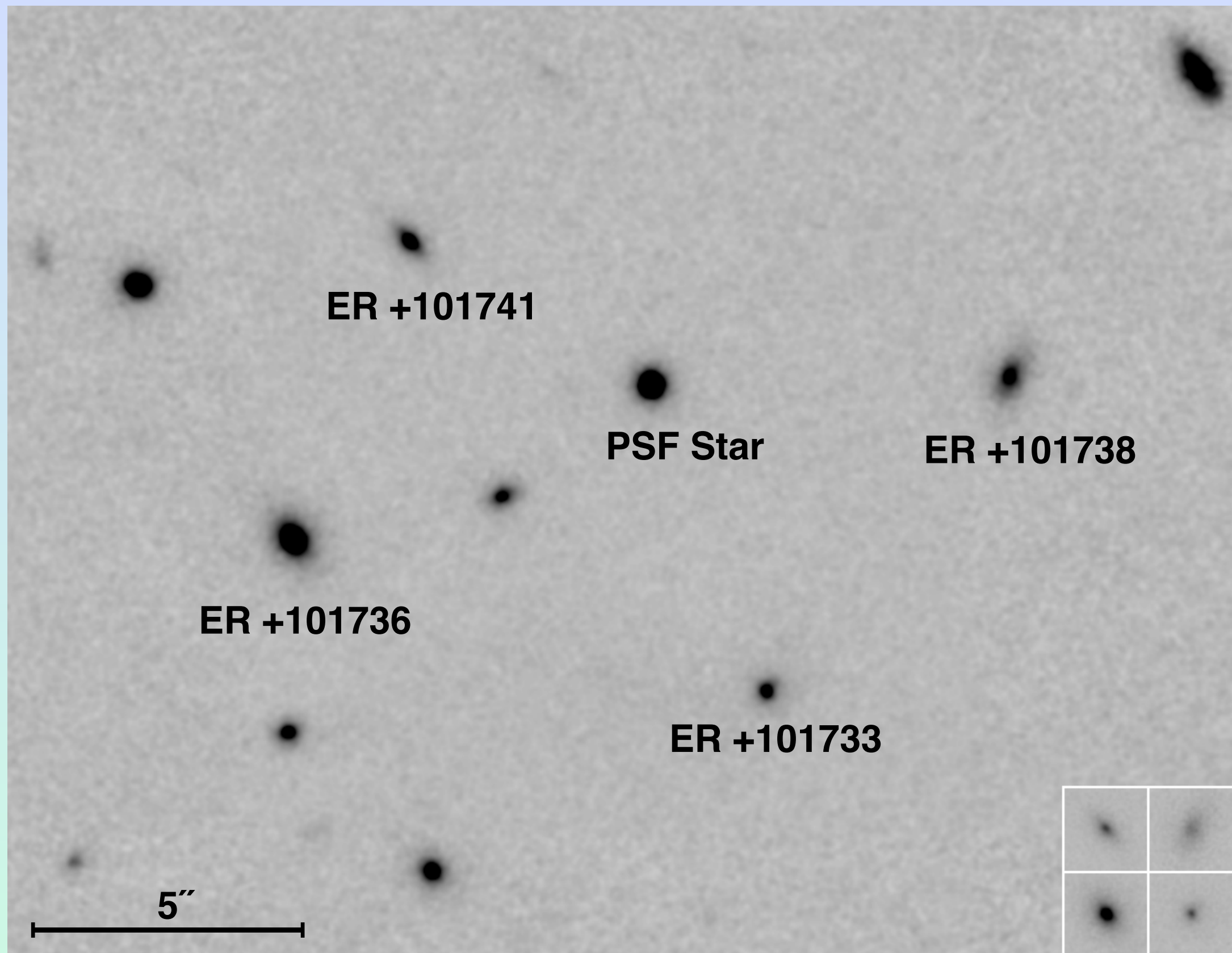
Declination (2000)



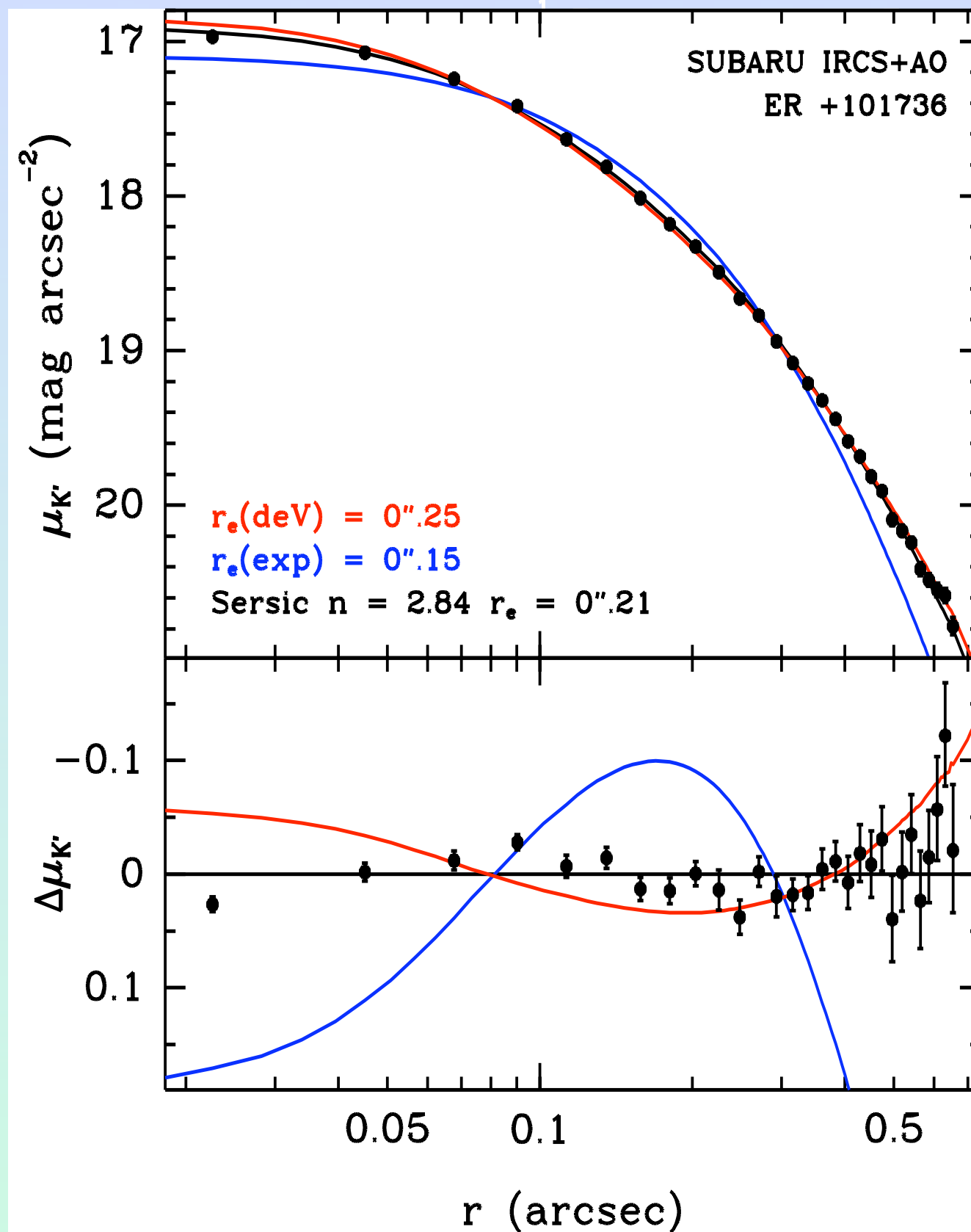
SuprimeCam R and I , CISCO K'







Subaru AO + IRCS K'



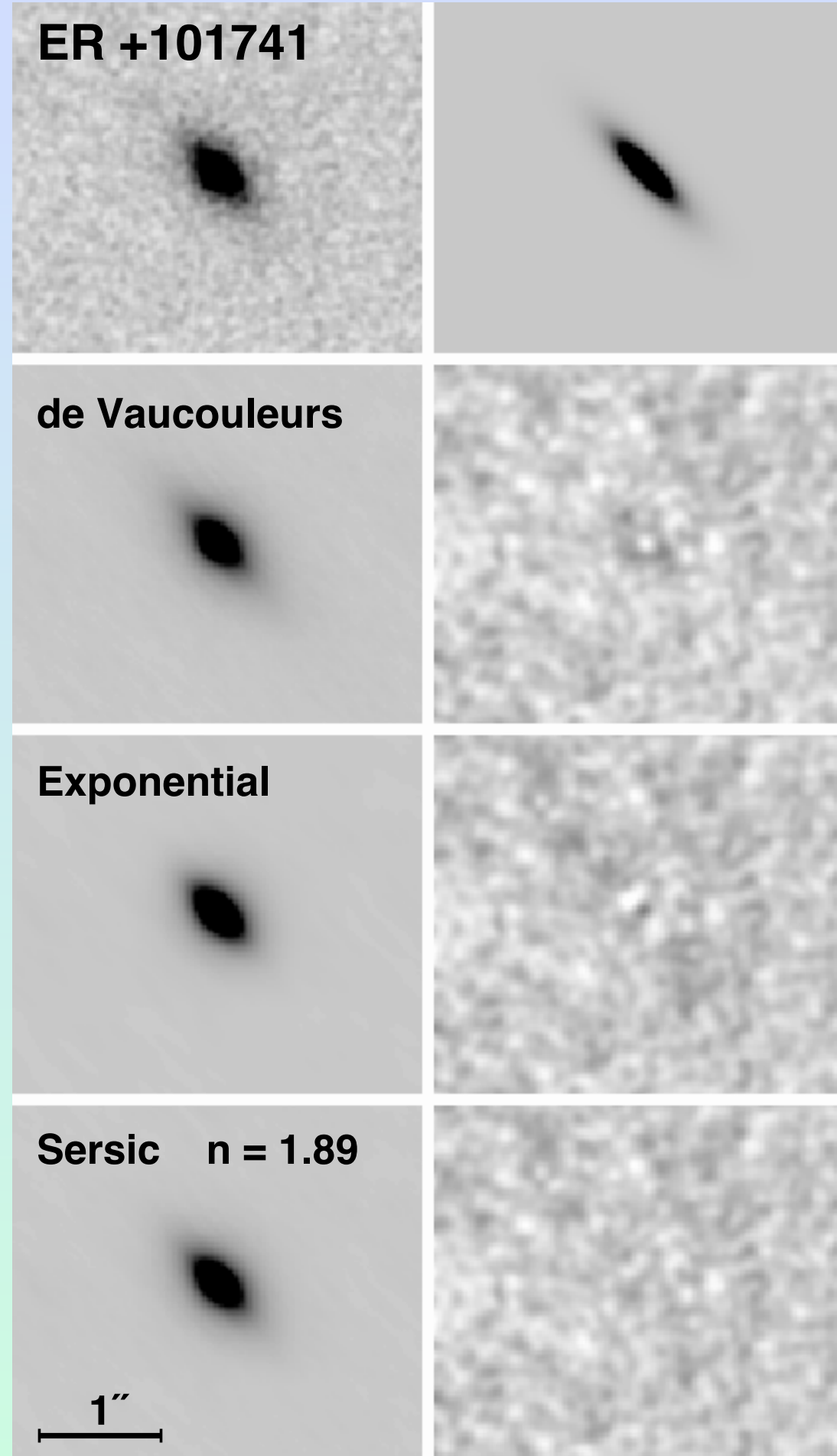
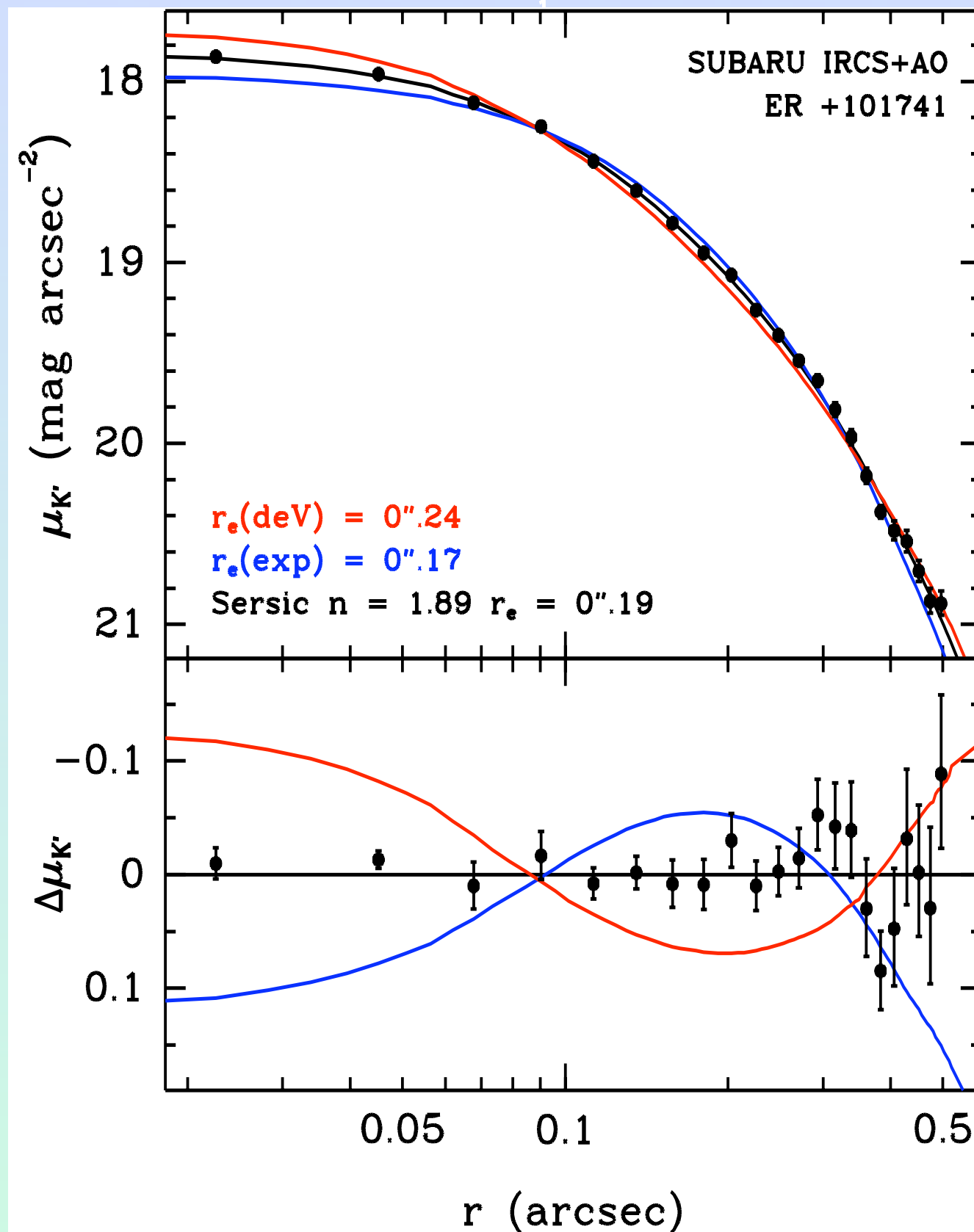
ER +101736

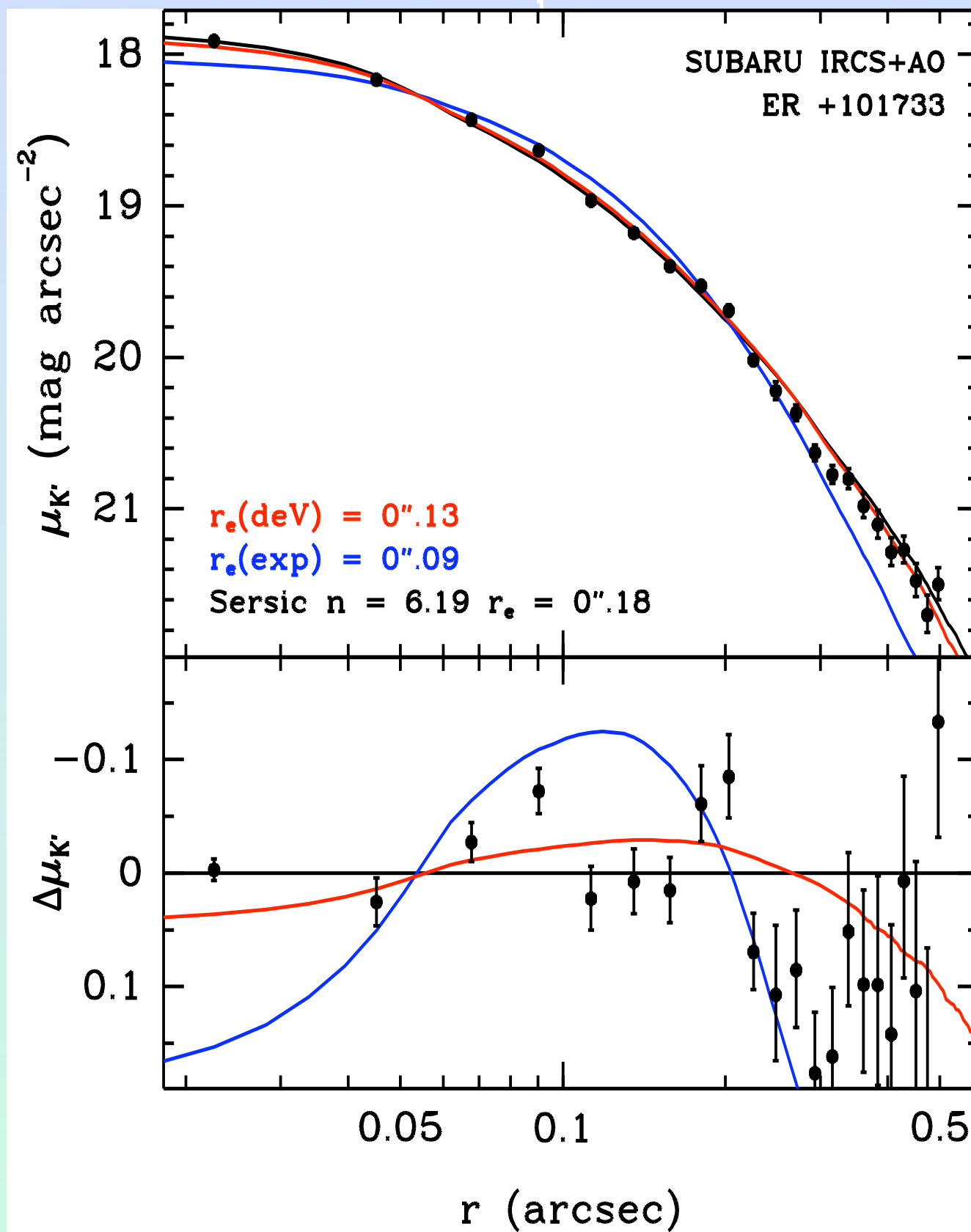
de Vaucouleurs

Exponential

Sersic $n = 2.84$

1''





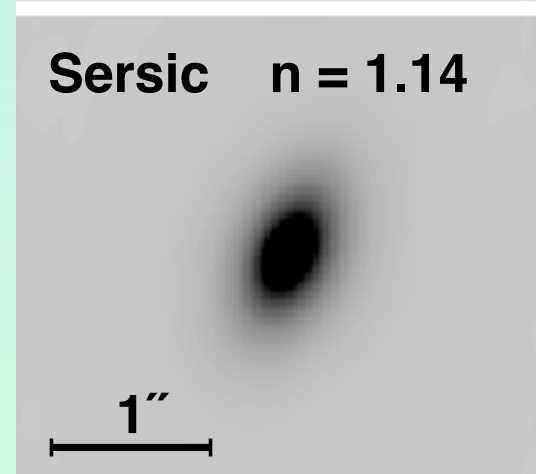
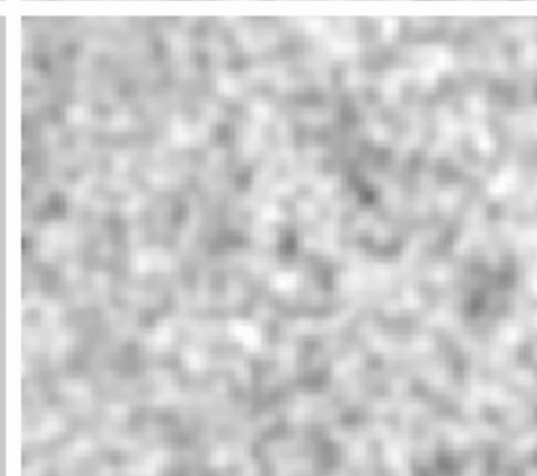
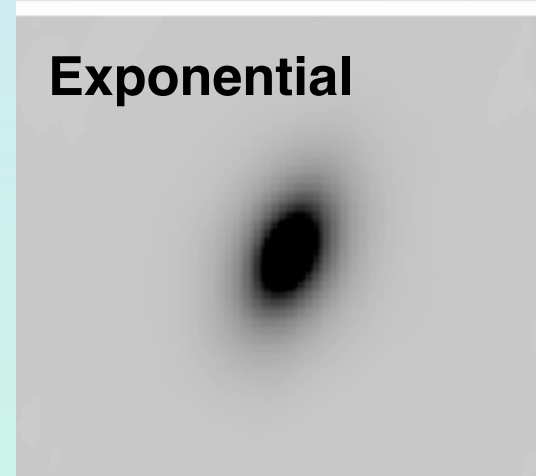
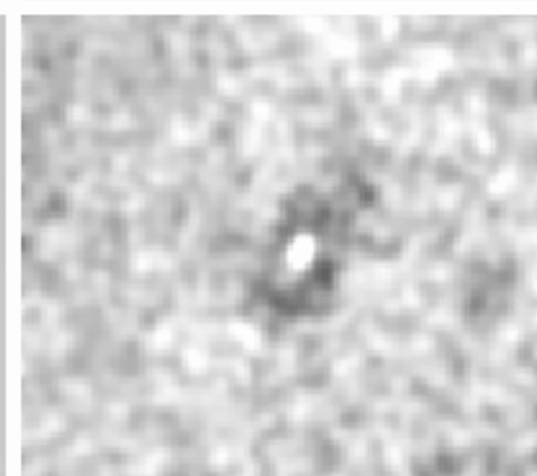
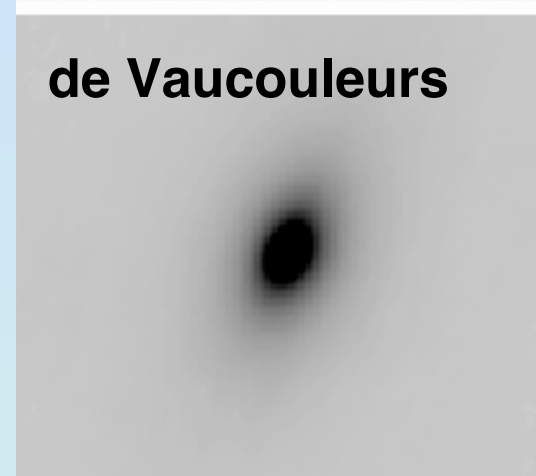
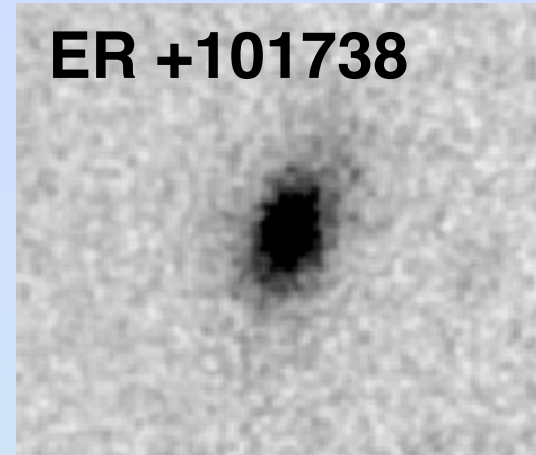
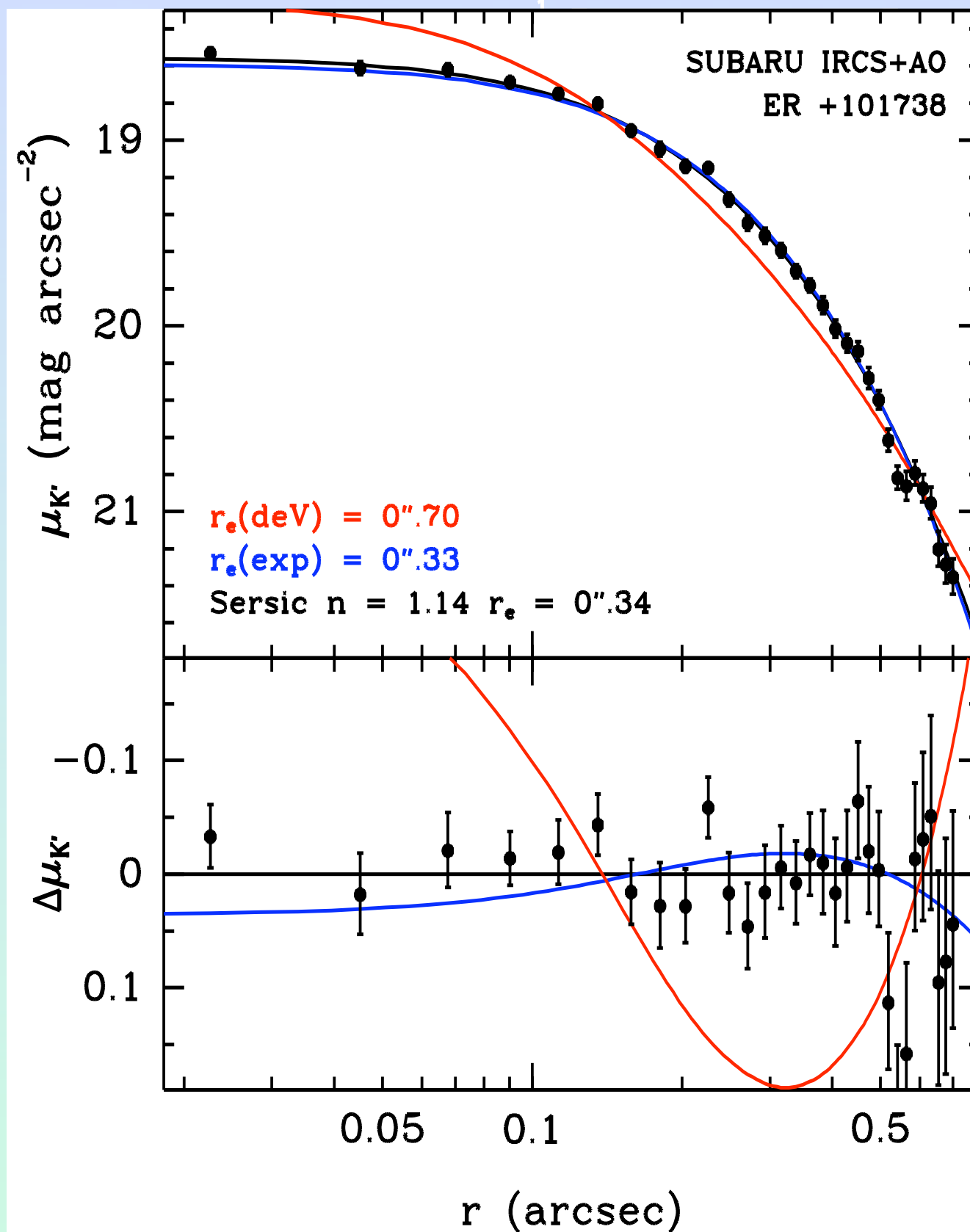
ER +101733

de Vaucouleurs

Exponential

Sersic $n = 6.19$

1''



Results:

- ❖ Galaxies in this group at $z = 1.34$ appear to be fully formed, with a high degree of symmetry.
- ❖ Three of the four galaxies for which we have AO imaging look very similar to types of galaxies with old stellar populations at the present epoch.
 - The two ellipticals lie fairly close to the Kormendy relation, taking into account passive evolution.
- ❖ The fourth galaxy appears to be a pure exponential disk of old stars, a type of galaxy that is rare or absent at the present epoch.

II. Galaxies with old stellar populations in fields of high-redshift radio sources.

Why radio sources?

- ❖ Radio sources track highly overdense regions.
- ❖ Radio sources with known redshifts allow redshift selection to optimize discrimination between galaxies with old stellar populations and other red galaxies.

Morphologies of these old galaxies can give constraints on formation scenarios.

Observations

First we must find suitable targets. Our criteria are quite stringent, so the objects are fairly rare.

1. Subaru CISCO for NIR imaging
2. Keck ESI or LRIS for optical imaging
3. Spitzer IRAC for highest- z objects

High-resolution imaging:

1. Subaru AO + IRCS
2. HST NICMOS
3. Keck AO (natural or laser guide star)

Object selection issues

We need to have a clean separation between truly “old” stellar populations and highly reddened objects.

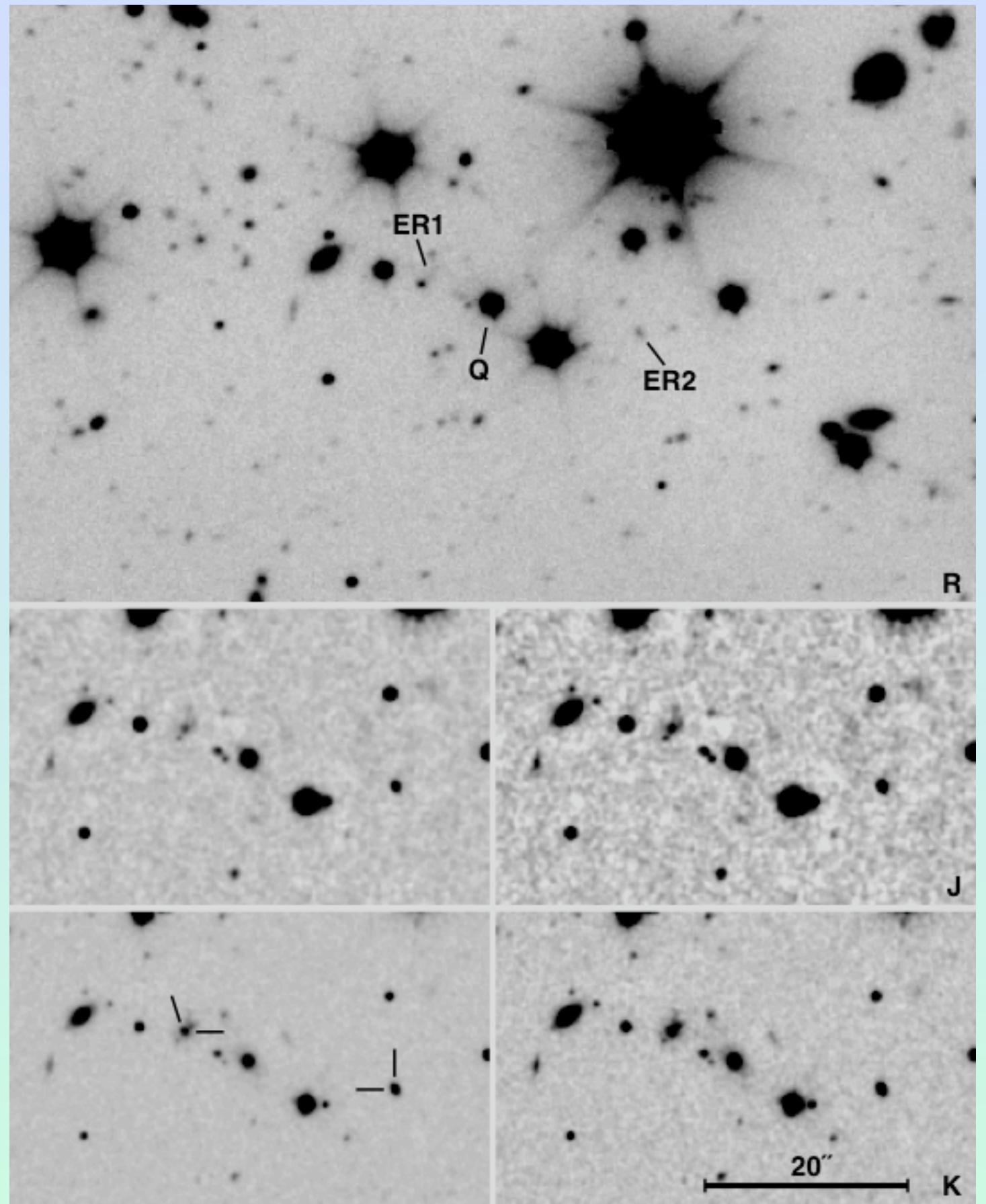
Choose objects in fields of radio sources with redshifts that allow standard filter bands to achieve the best discrimination.

Obtaining all of the necessary bands to sufficient depth requires large amounts of telescope time.

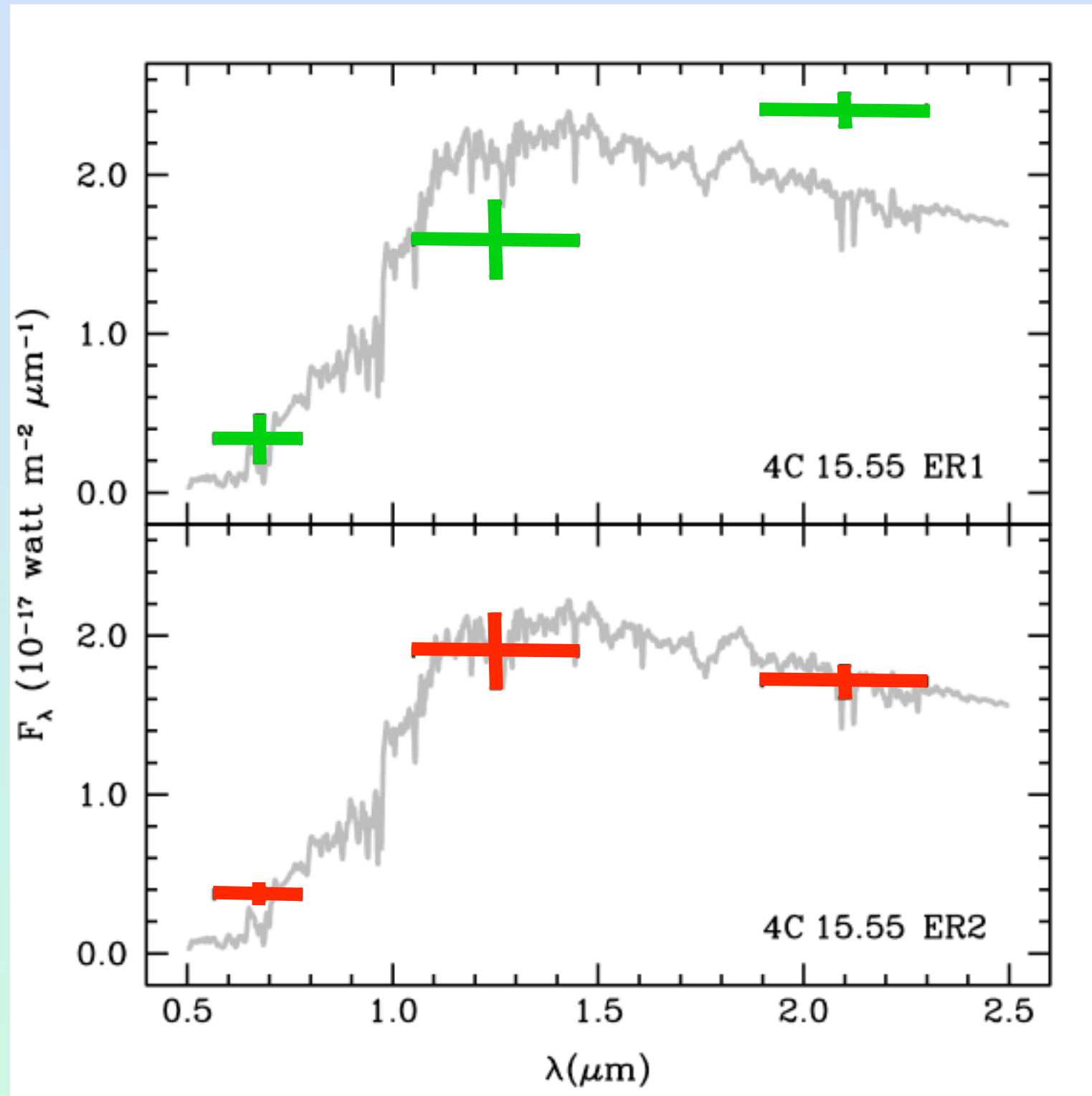
Use a photometric sieve approach.

4C 15.55 Field

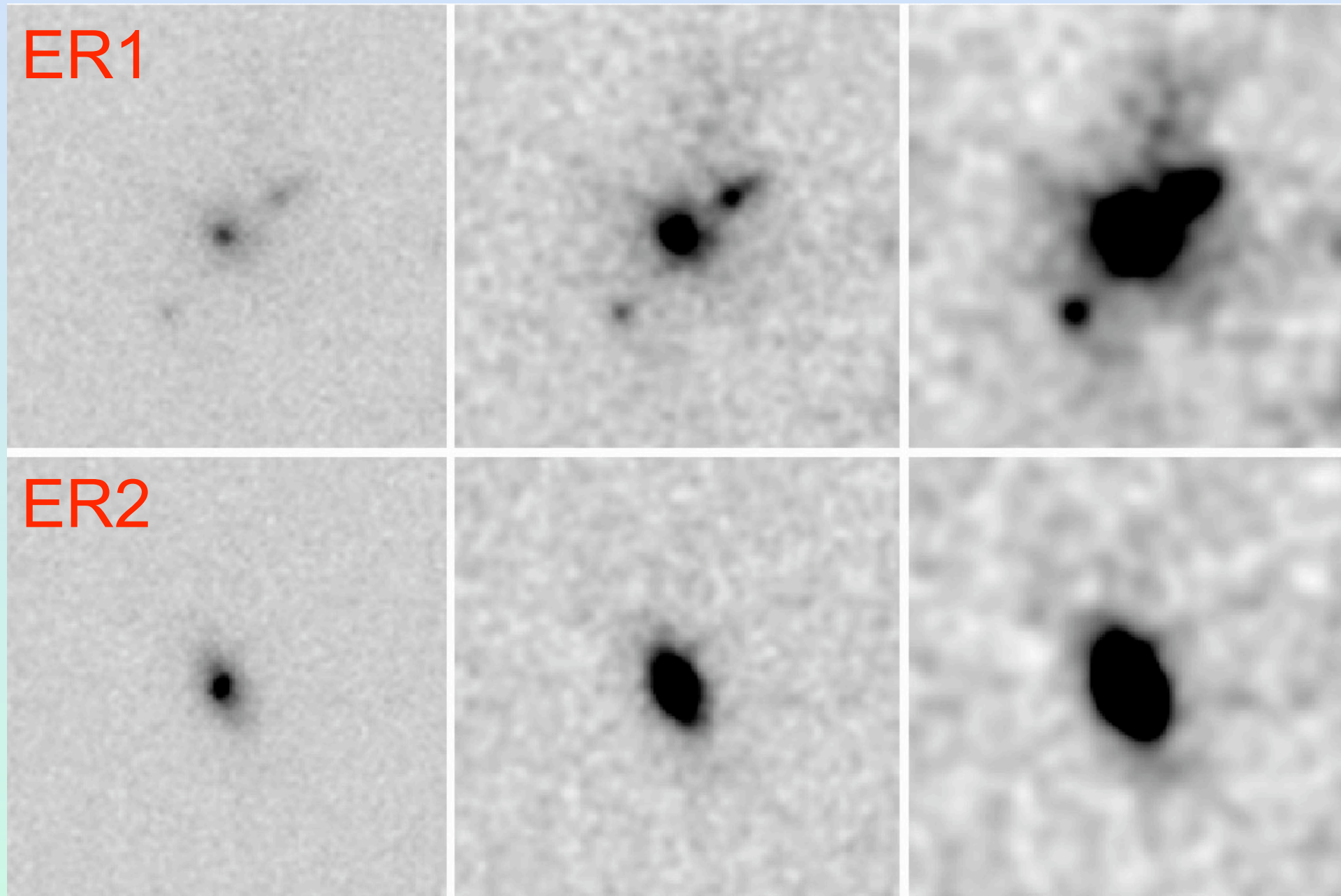
- $z_Q = 1.406$
- ER1 is a starburst
- ER2 has an old stellar population



4C 15.55 ER2



4C 15.55 EROs

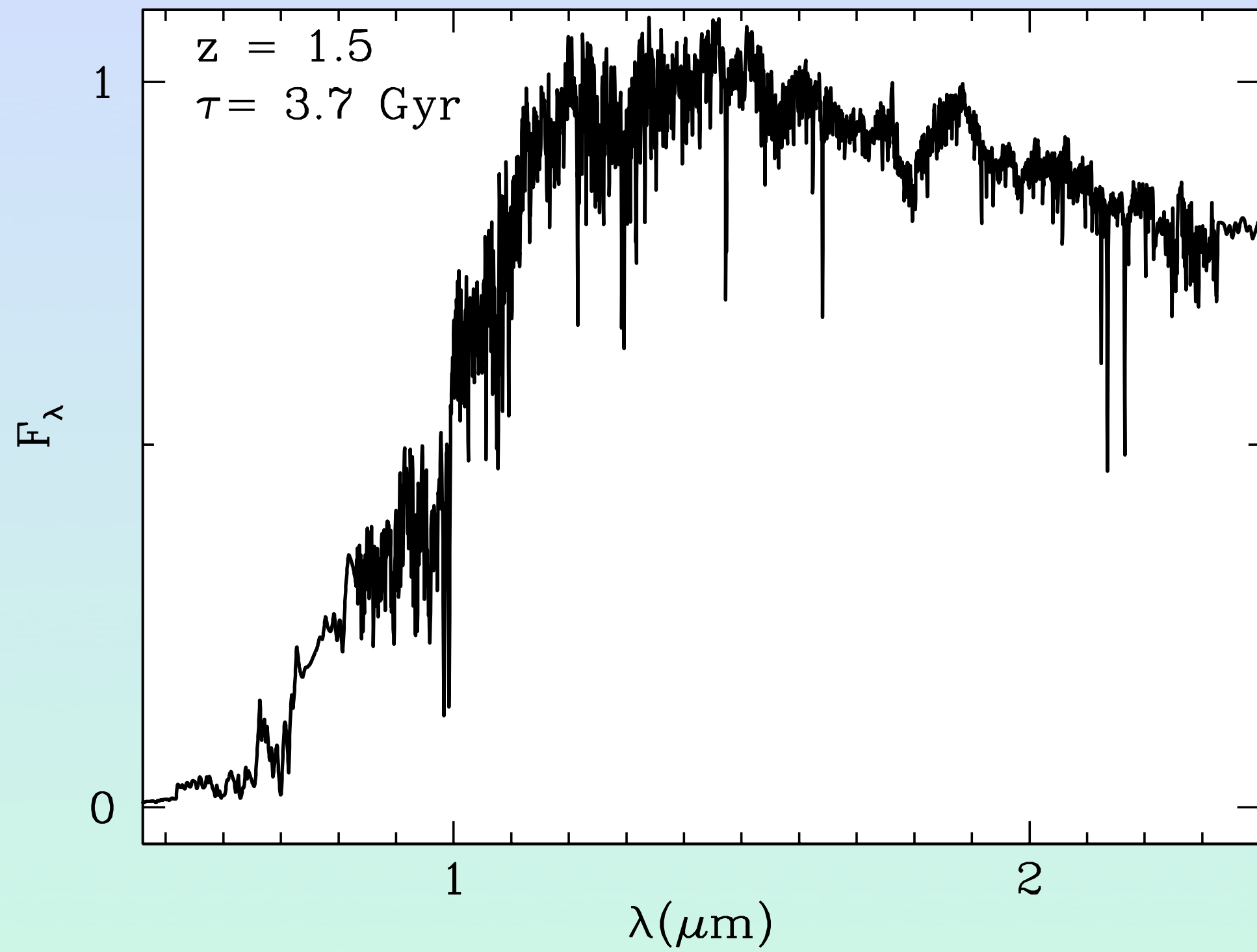


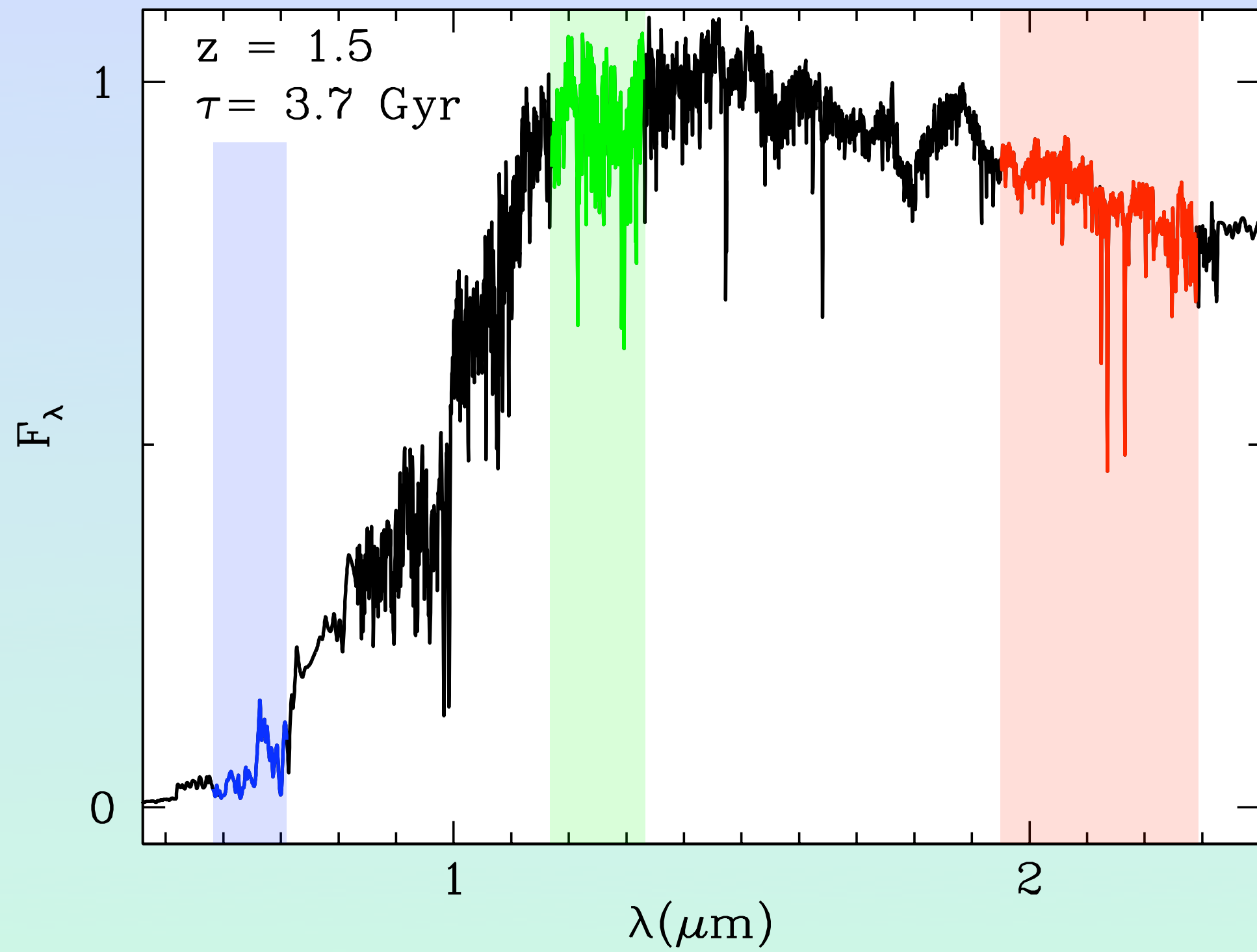
Subaru AO + IRCS

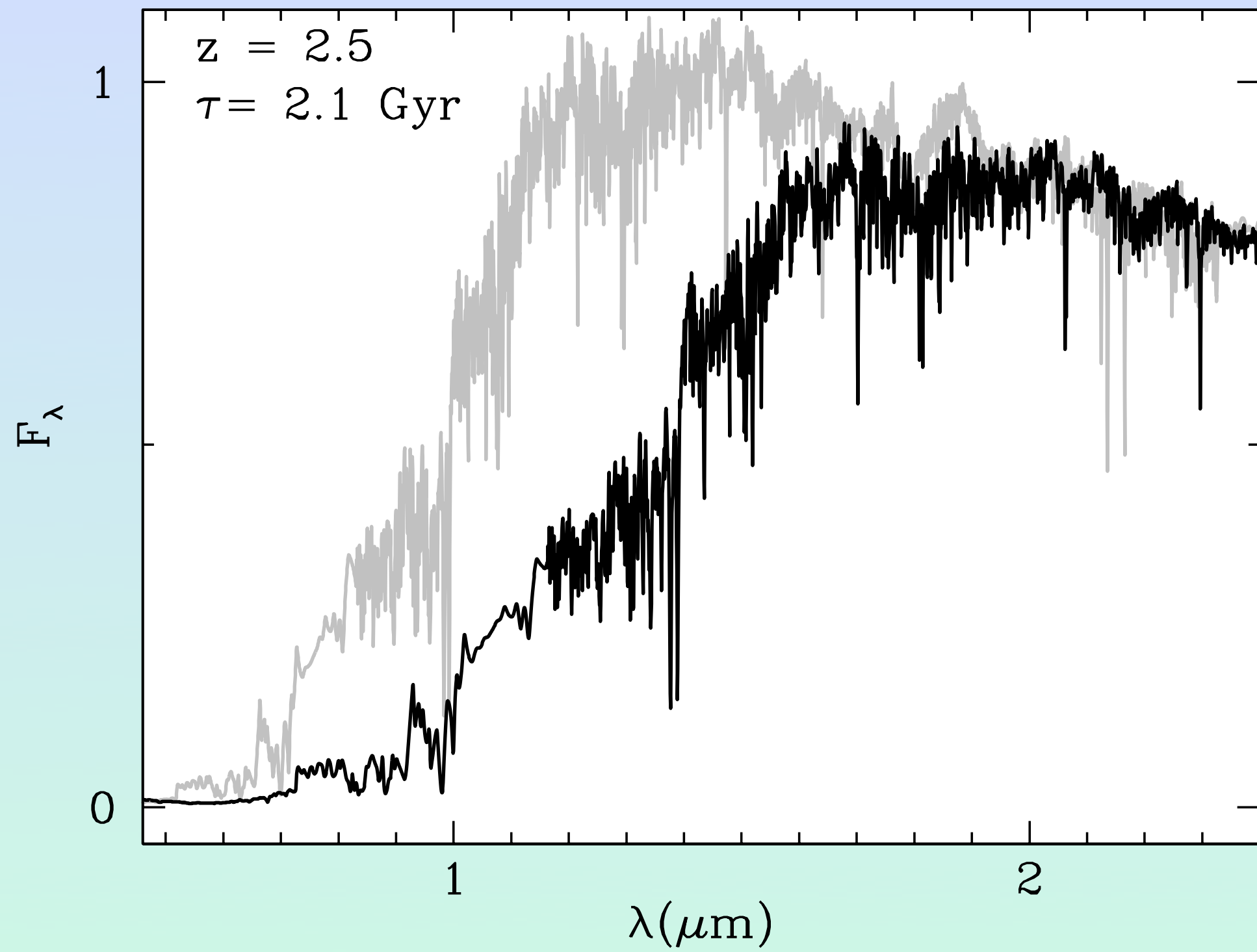
Defining a reference galaxy

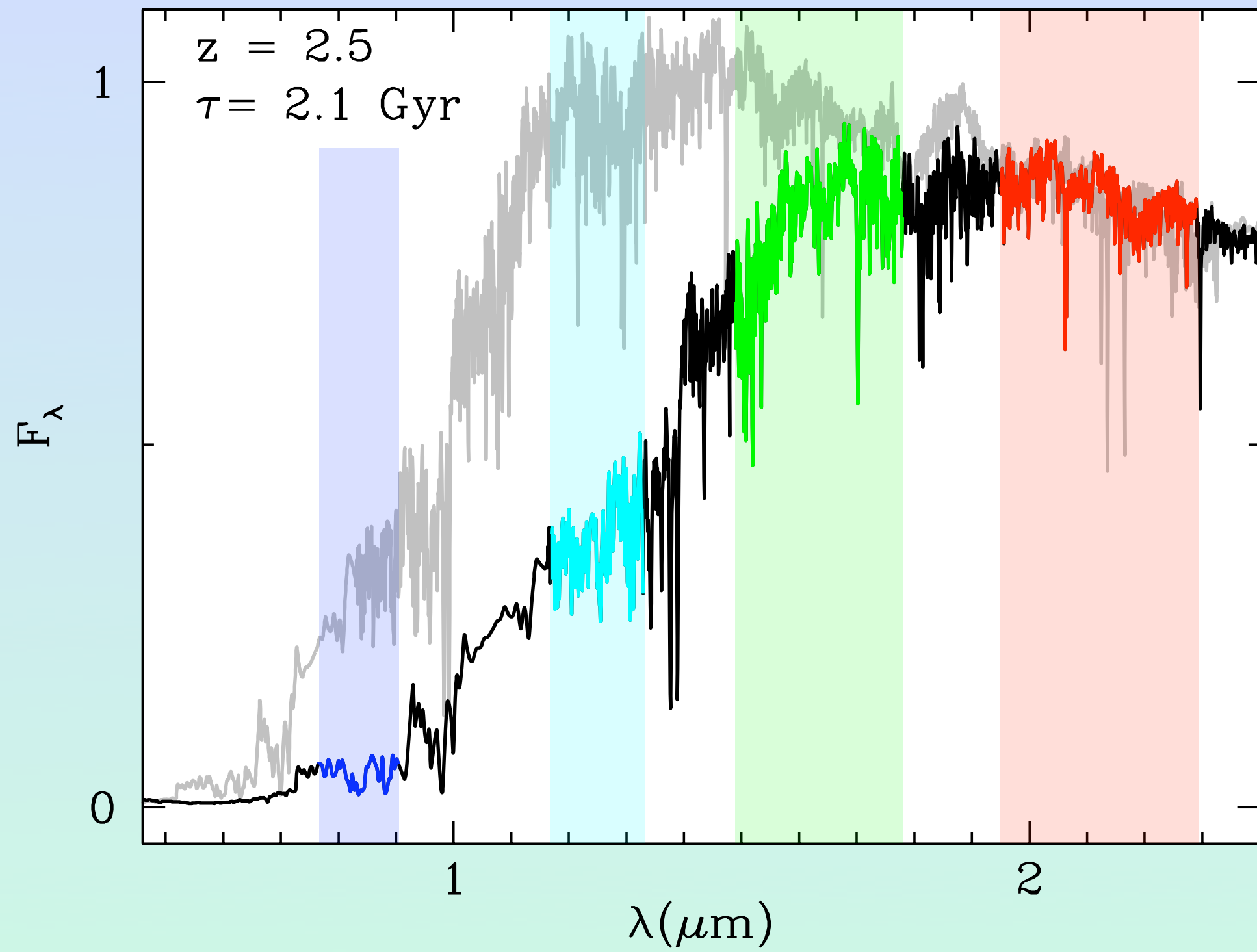
In order to evaluate photometric detection schemes, we define a strawman reference galaxy:

- ❖ All stars form 500 Myr after the Big Bang (corresponds to $z = 9.5$).
- ❖ Luminosity set to give $K' = 2L^*$ at $z = 0$ (passive evolution).
- ❖ We use Bruzual-Charlot (2003) models to give the SED at any given redshift.

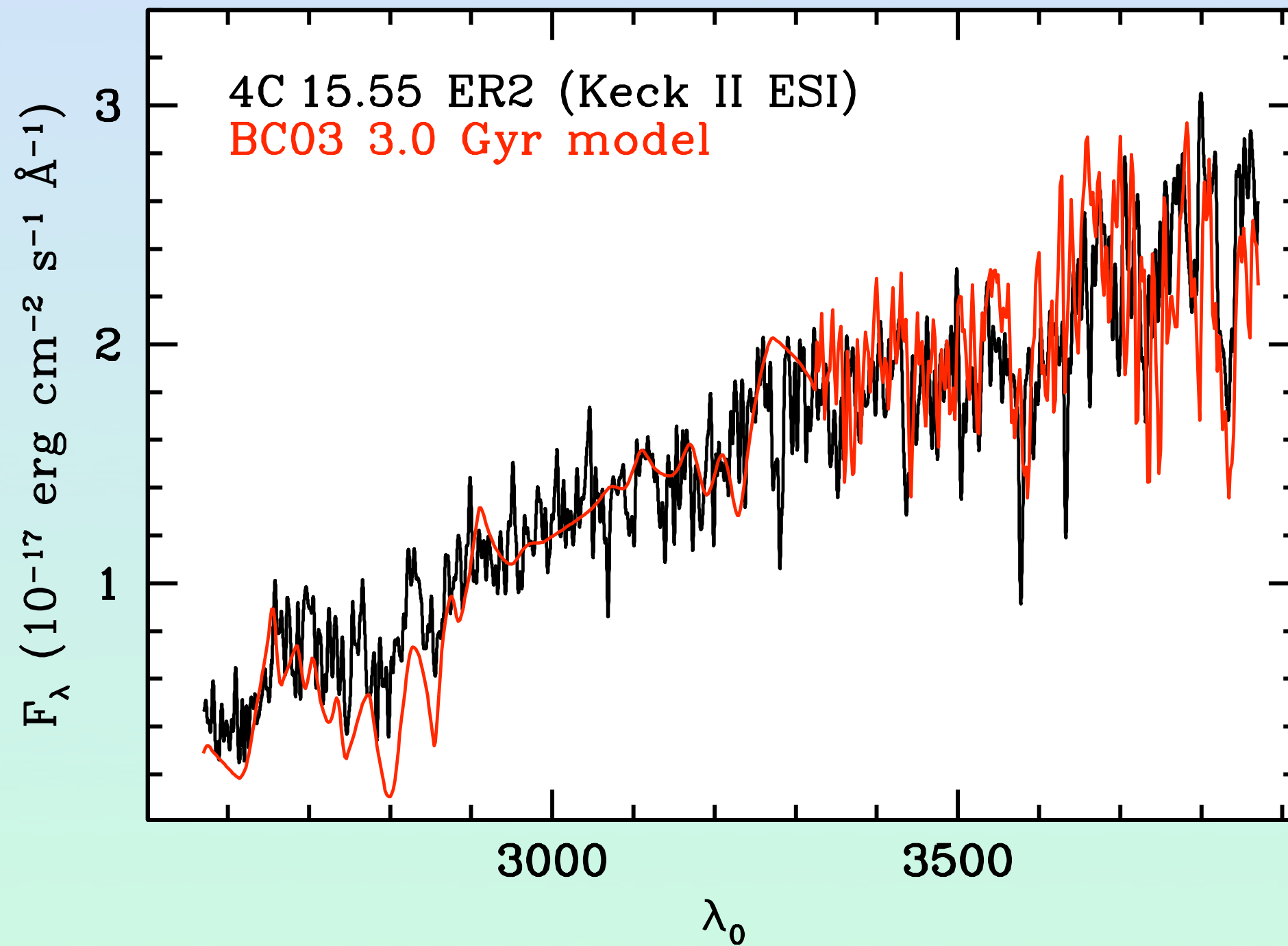




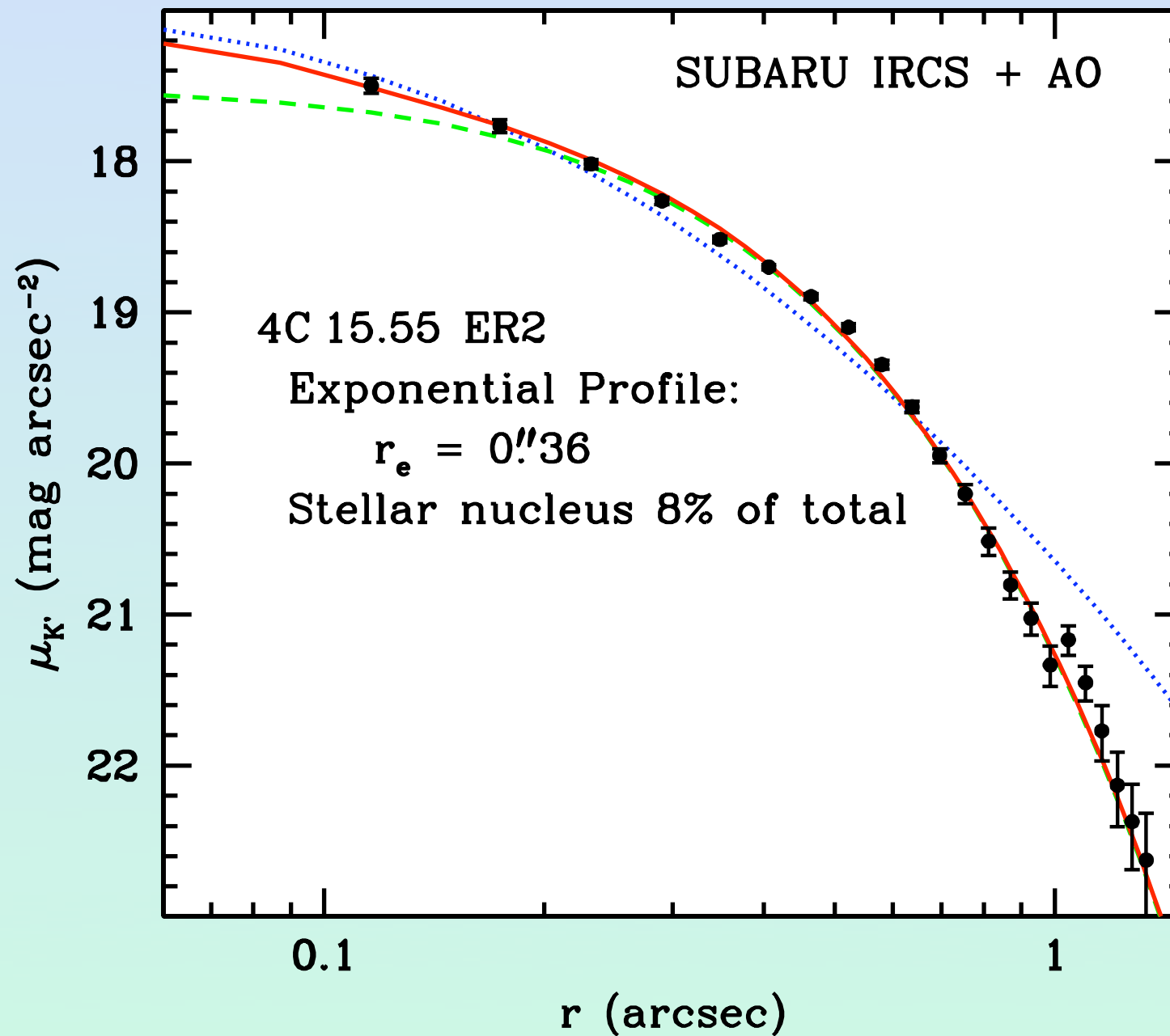




4C 15.55 ER2

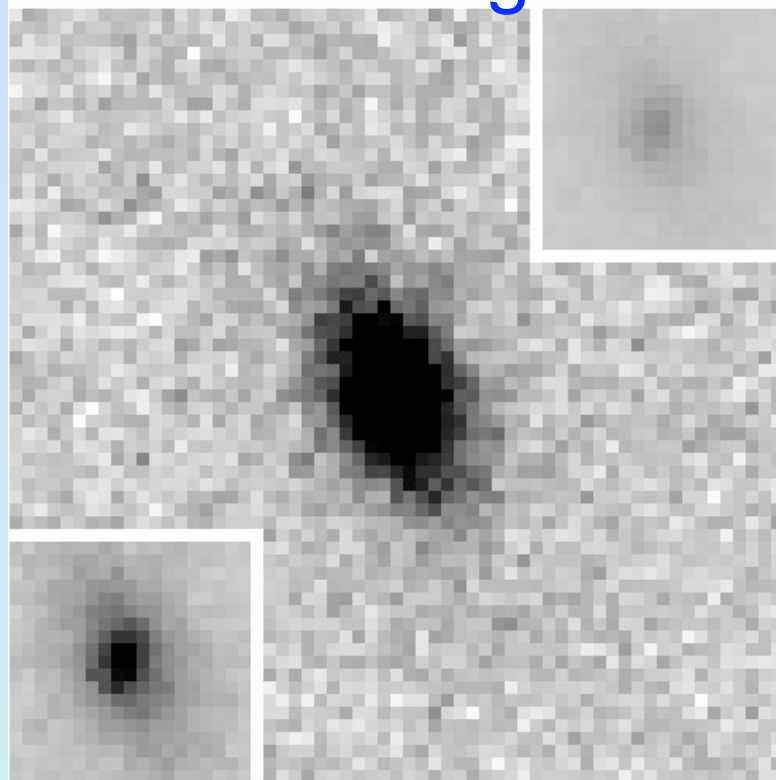


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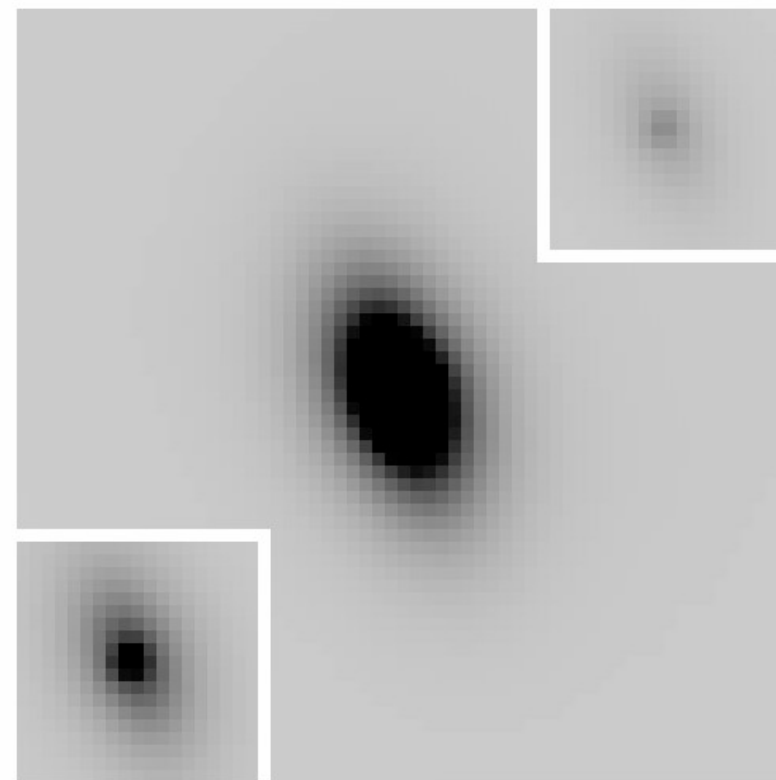


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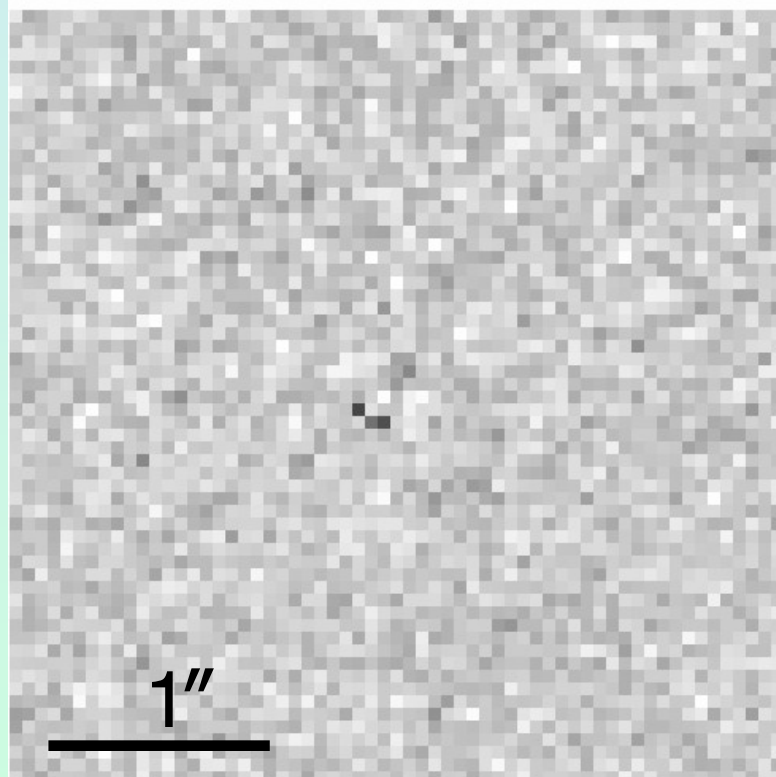
AO Image



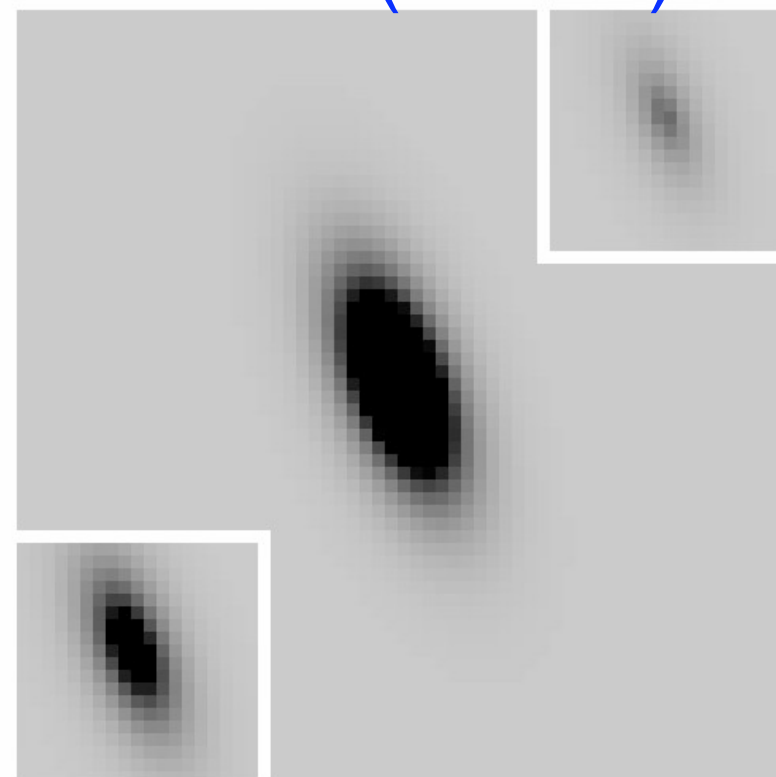
Model with PSF



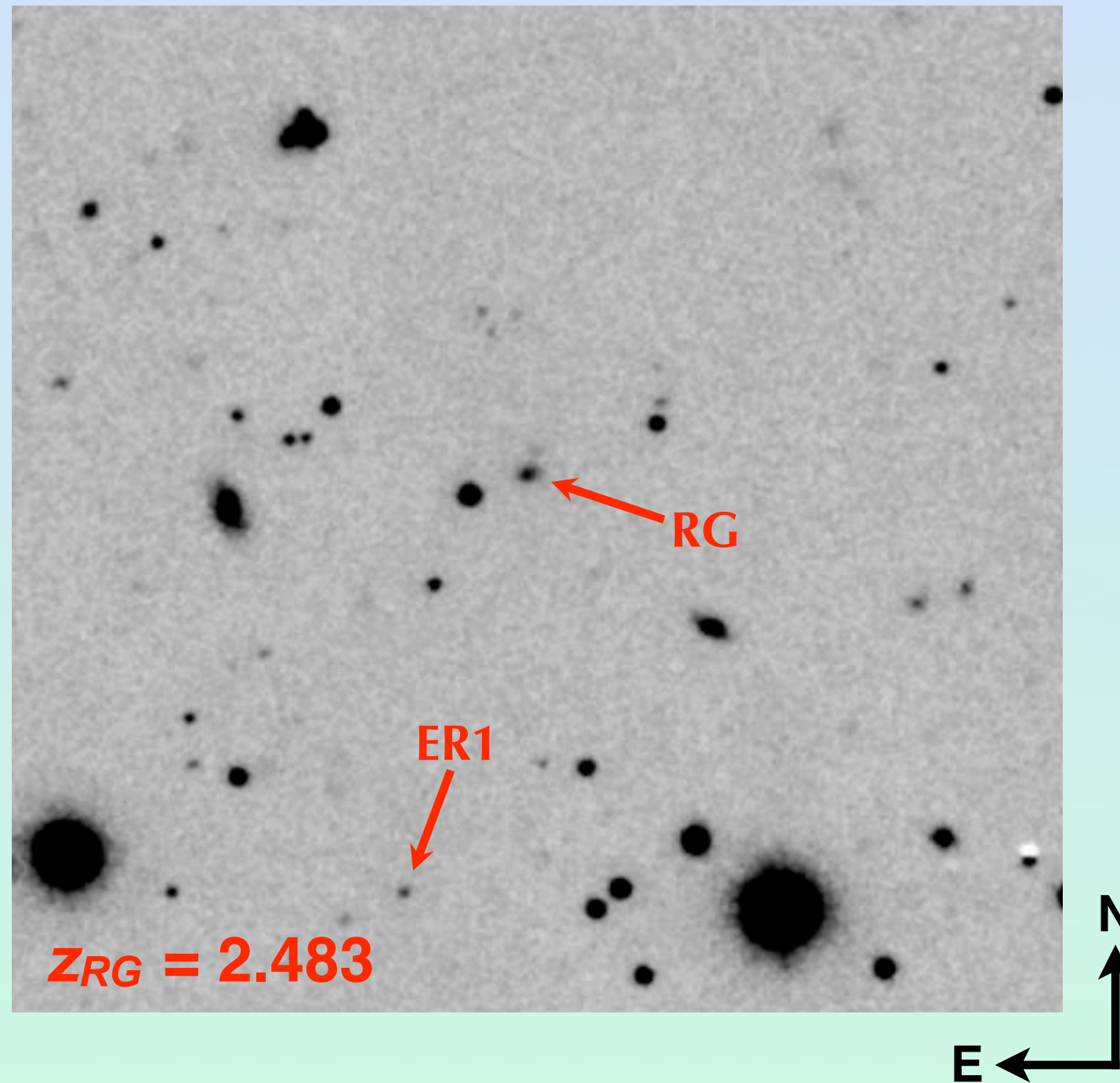
Residual



Model (no star)

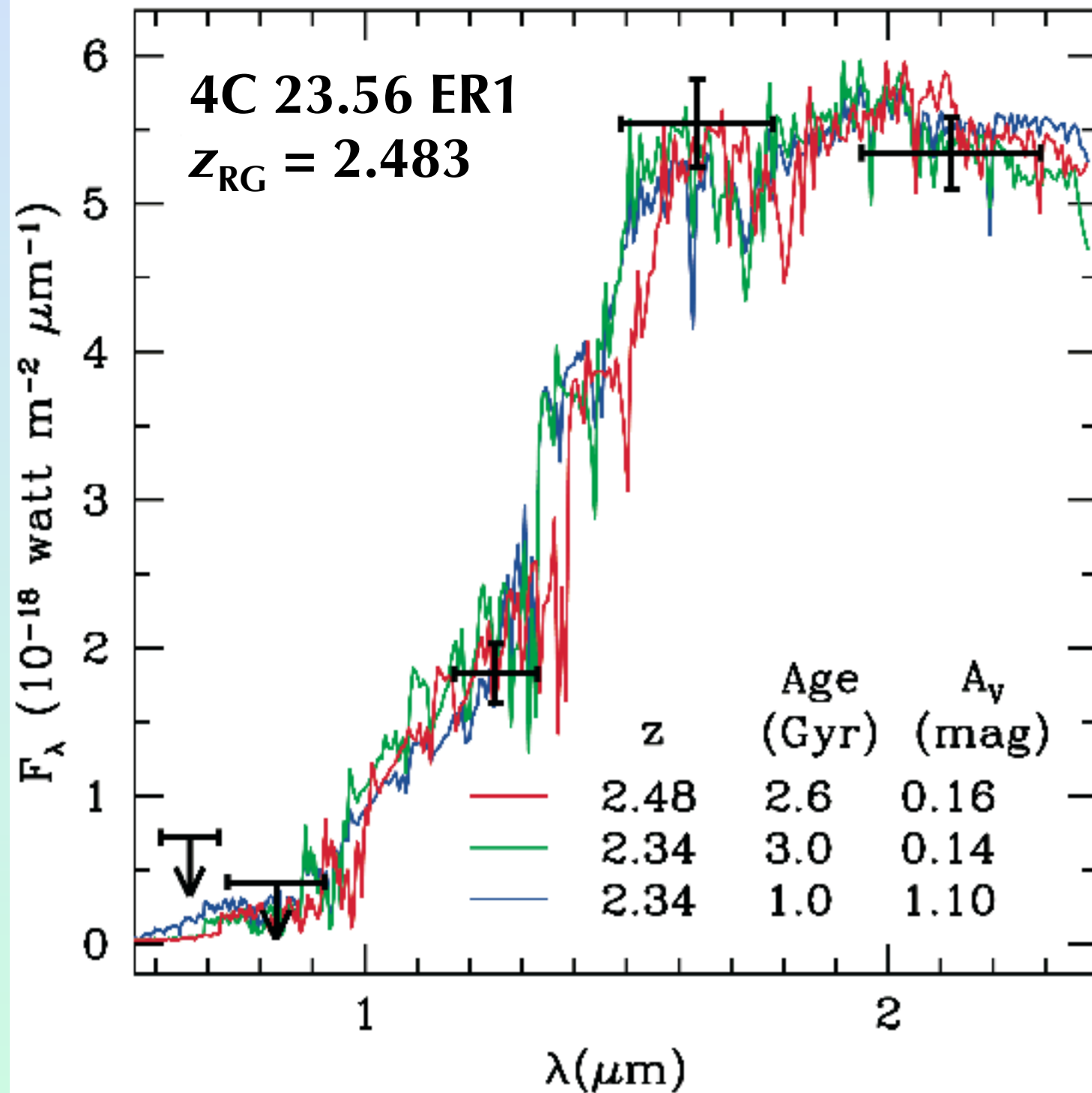


4C 23.56 ER1

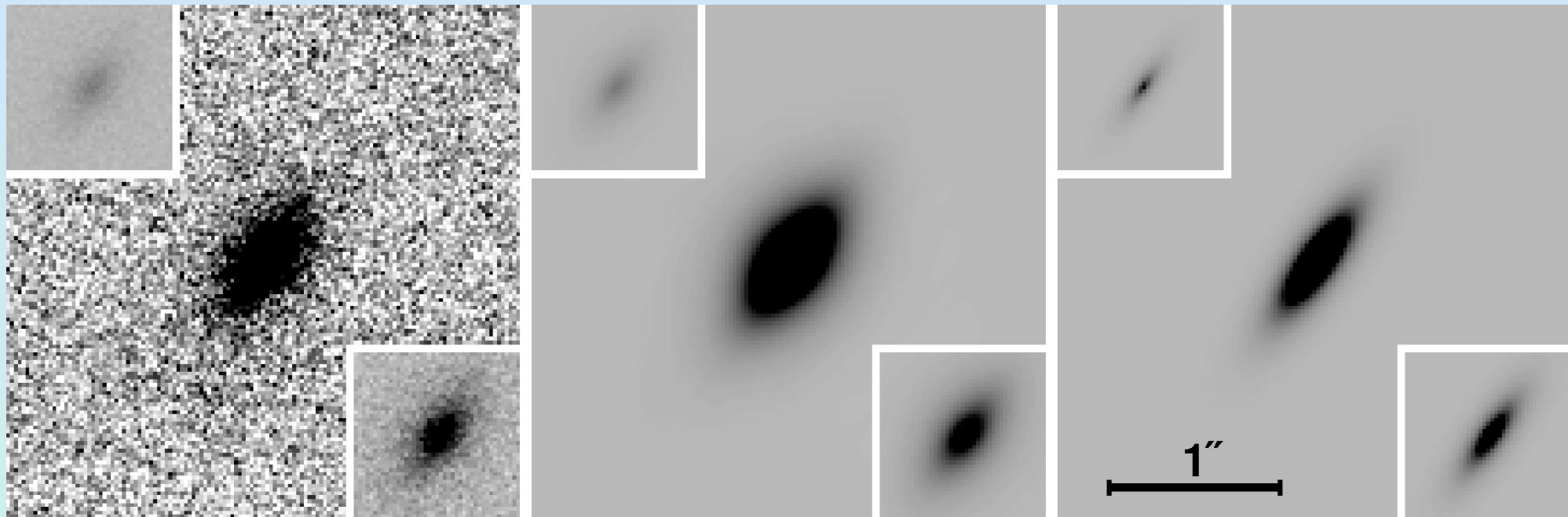


(Stockton, Canalizo, & Maihara (2004), ApJ, 605, 37)

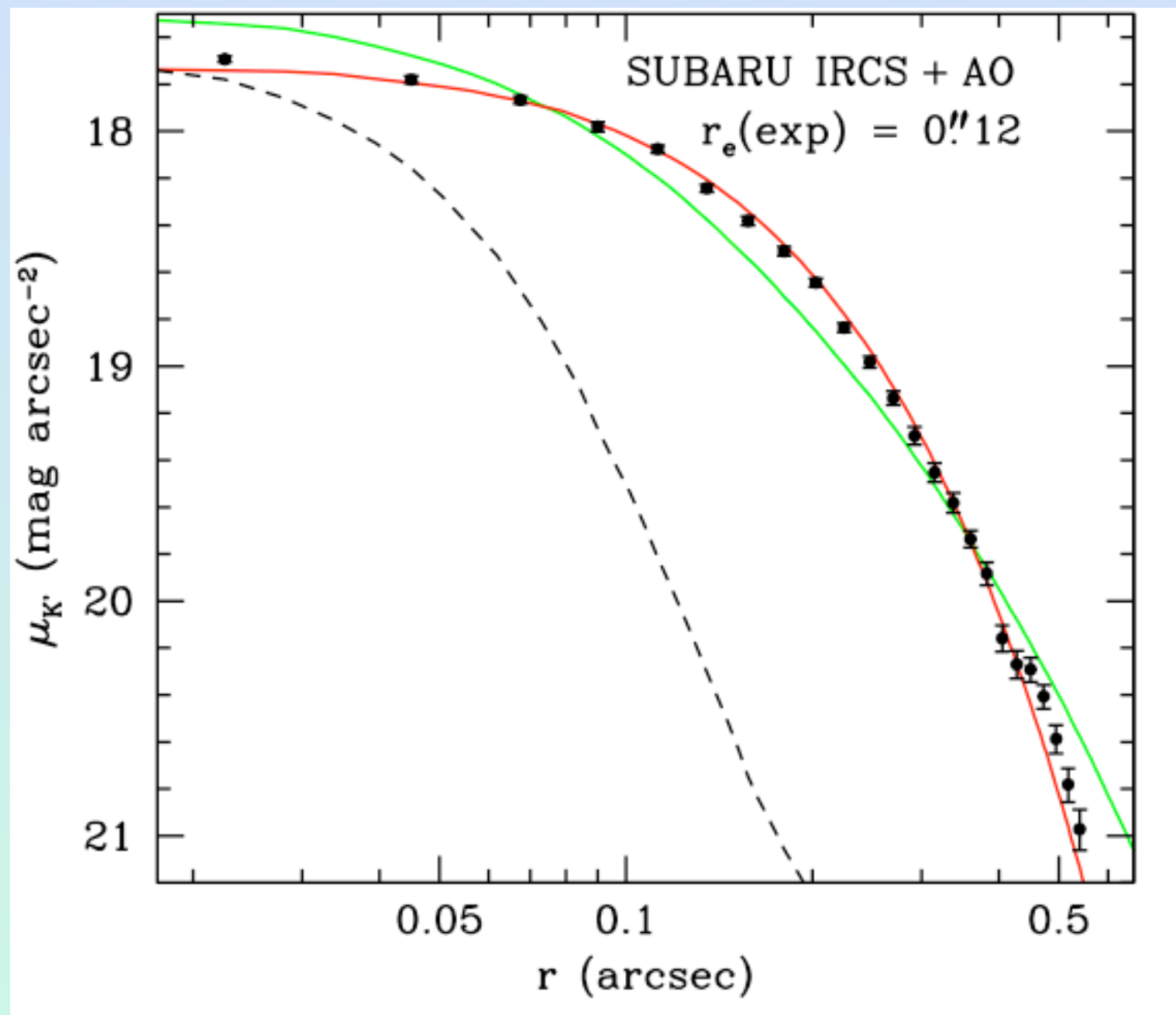
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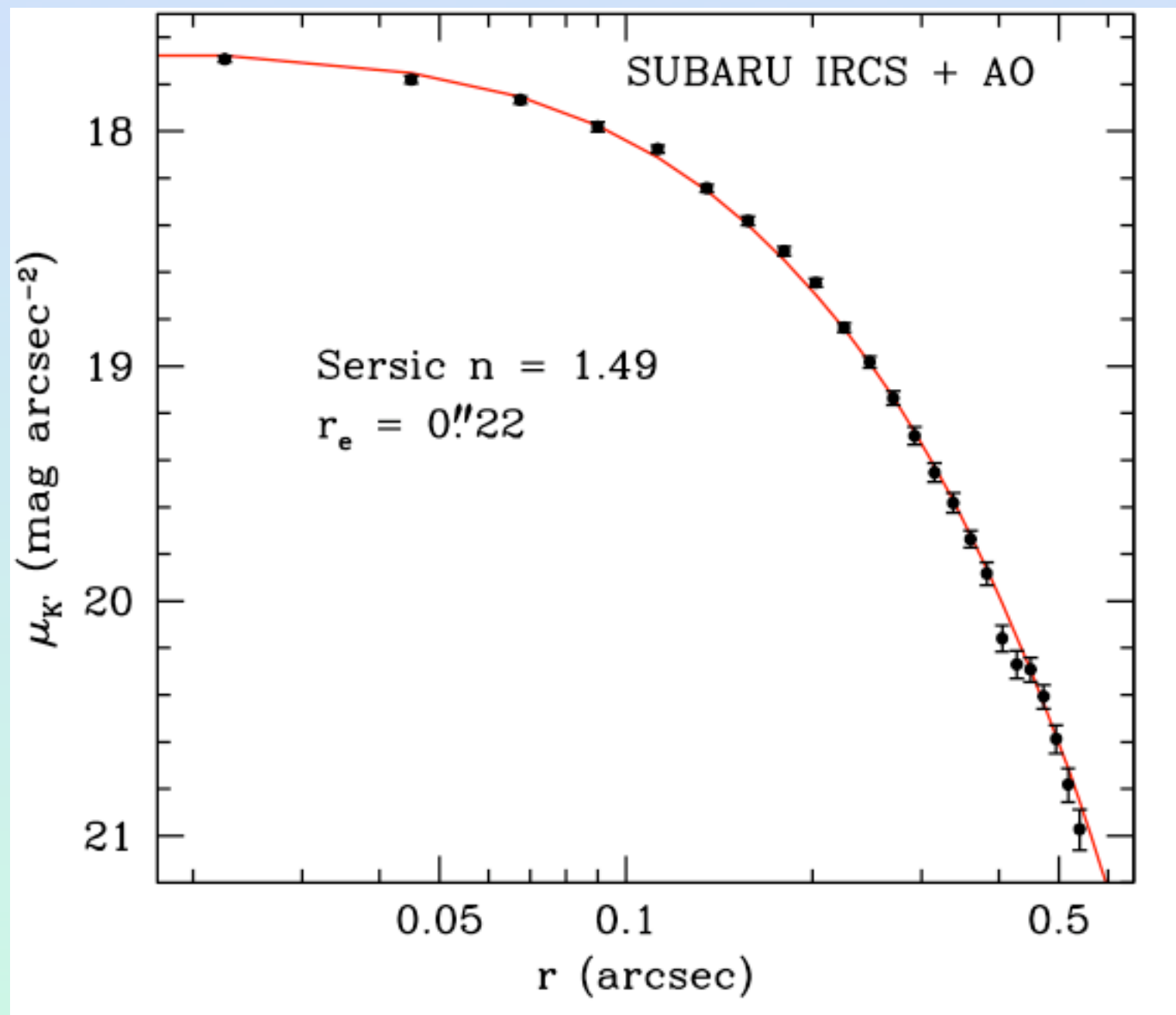
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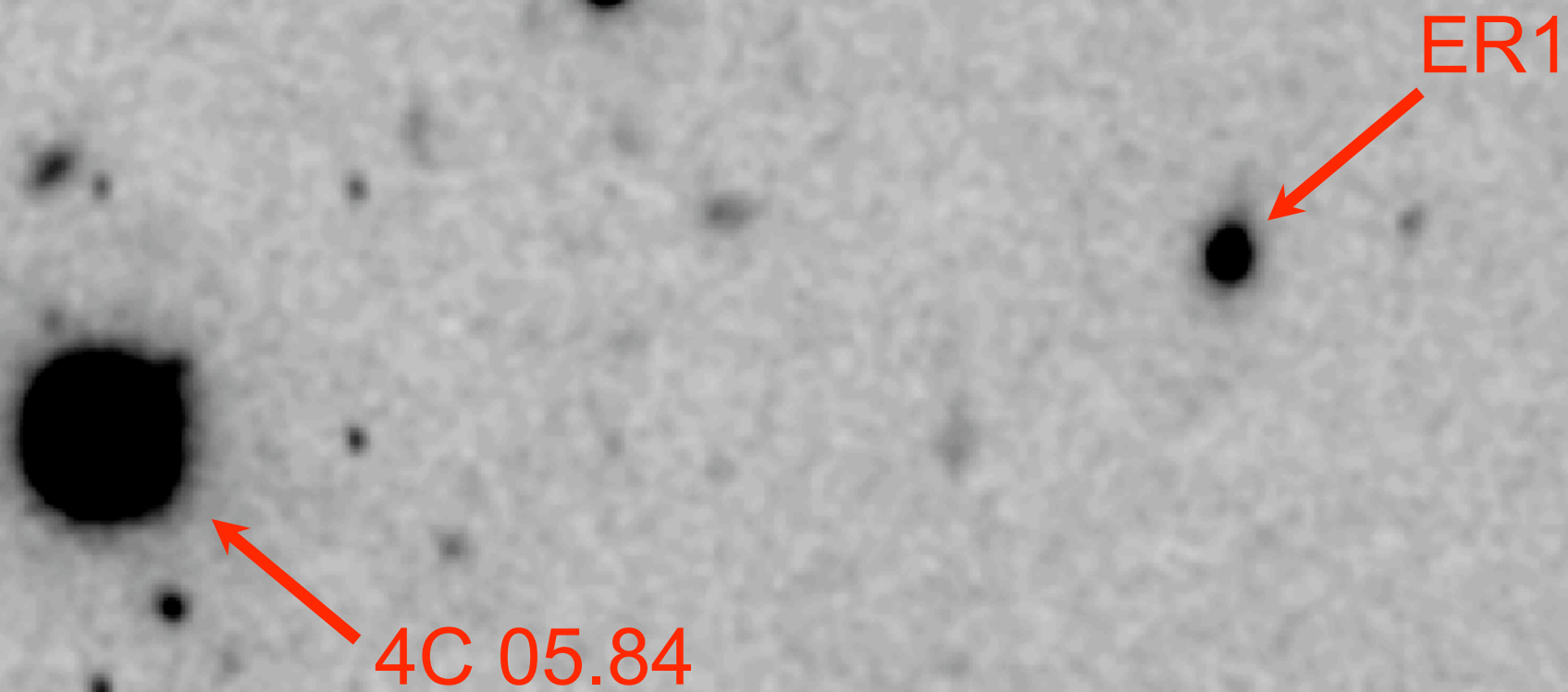
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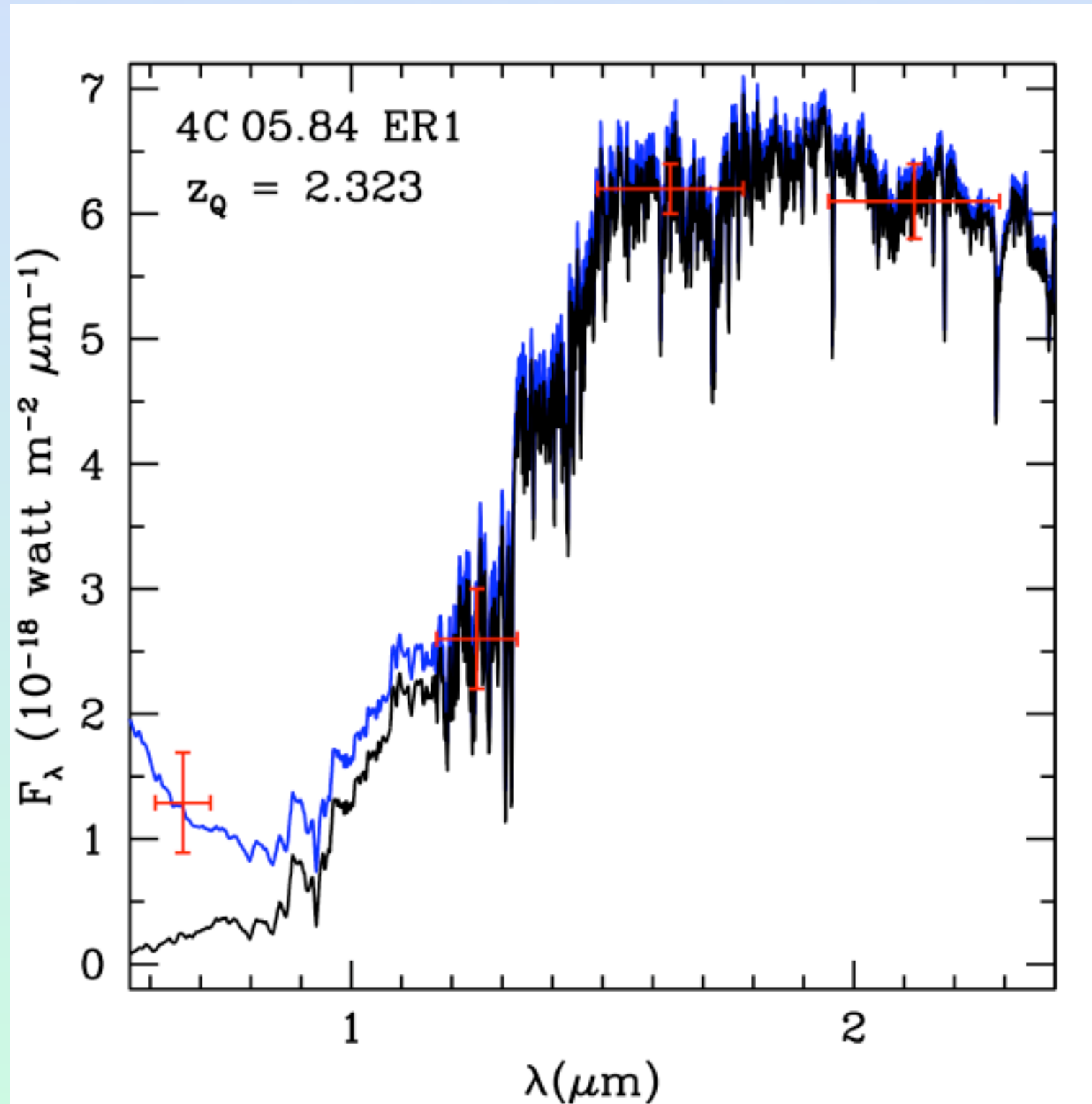
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4C 05.84 ER1

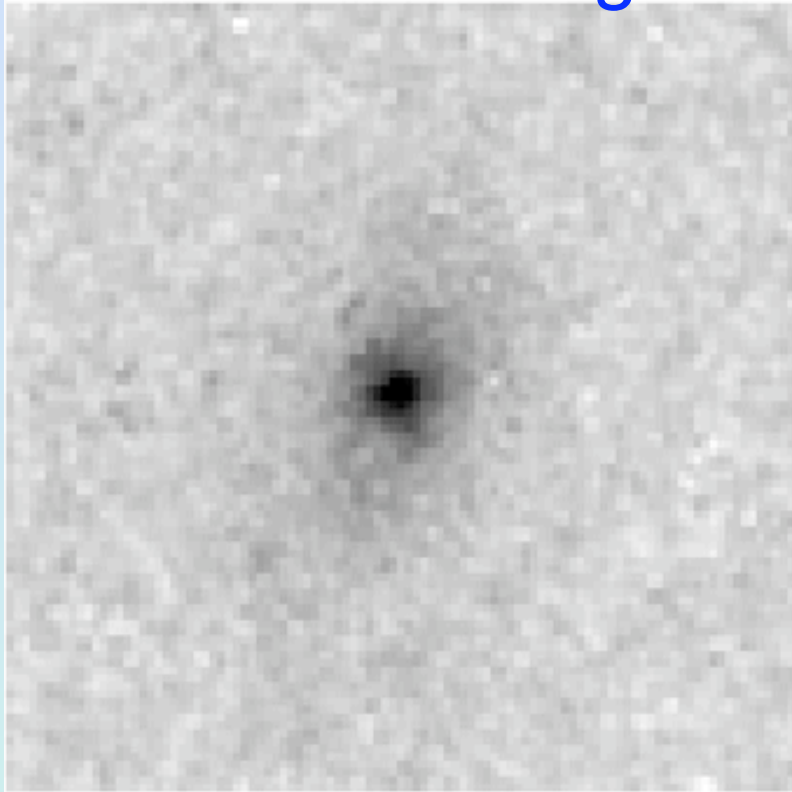


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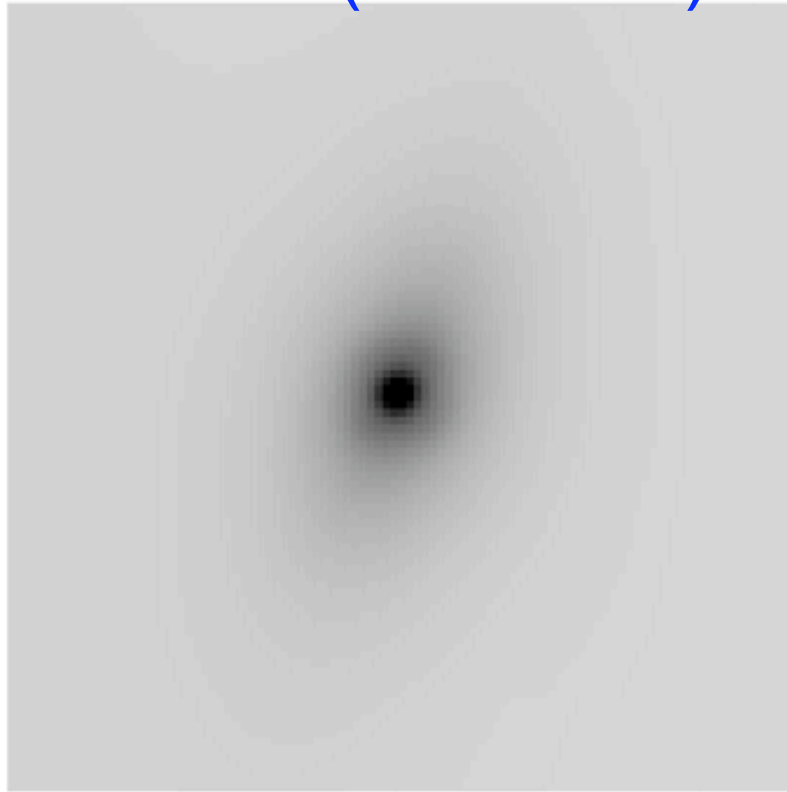


4C 05.84 ER1

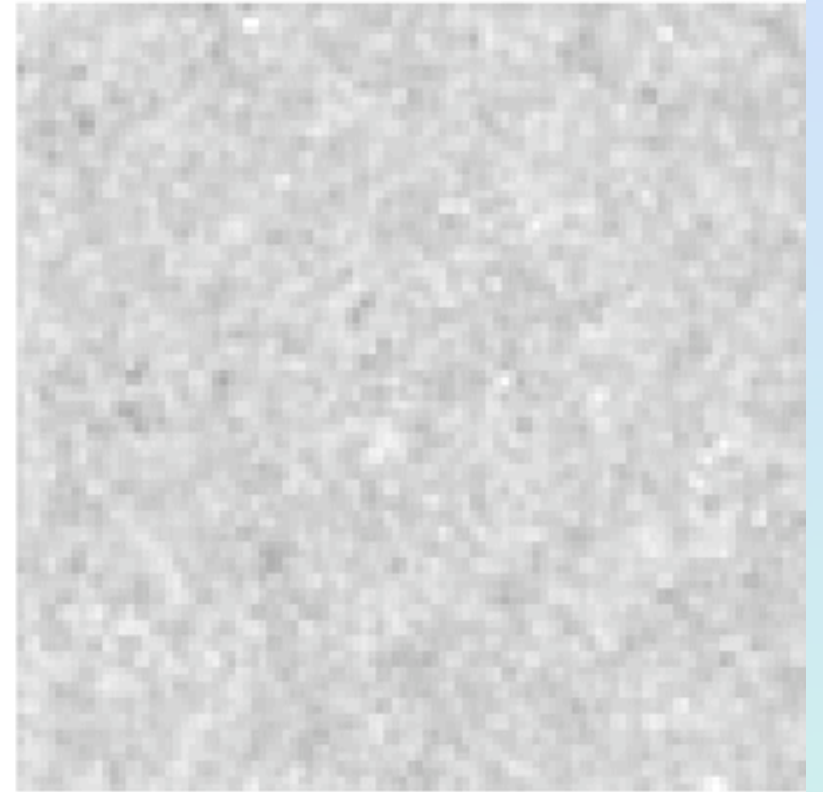
NICMOS Image



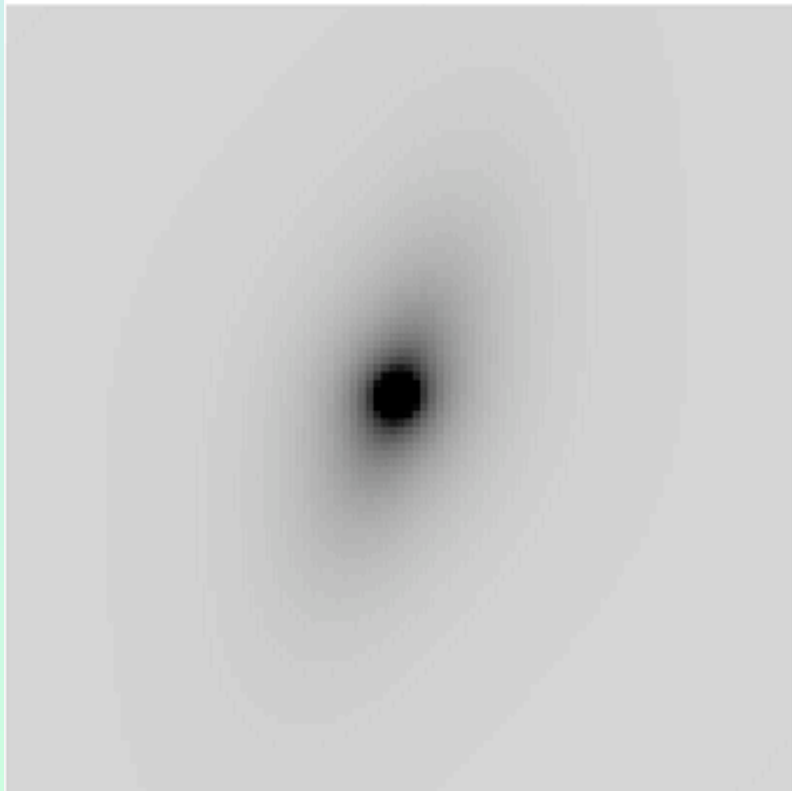
Model (with PSF)



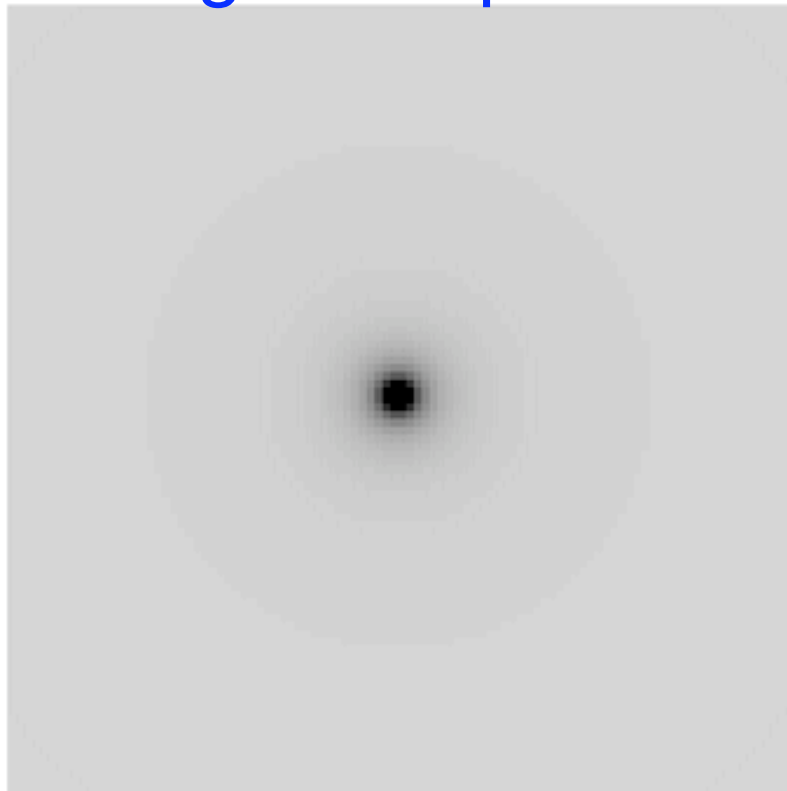
Residual



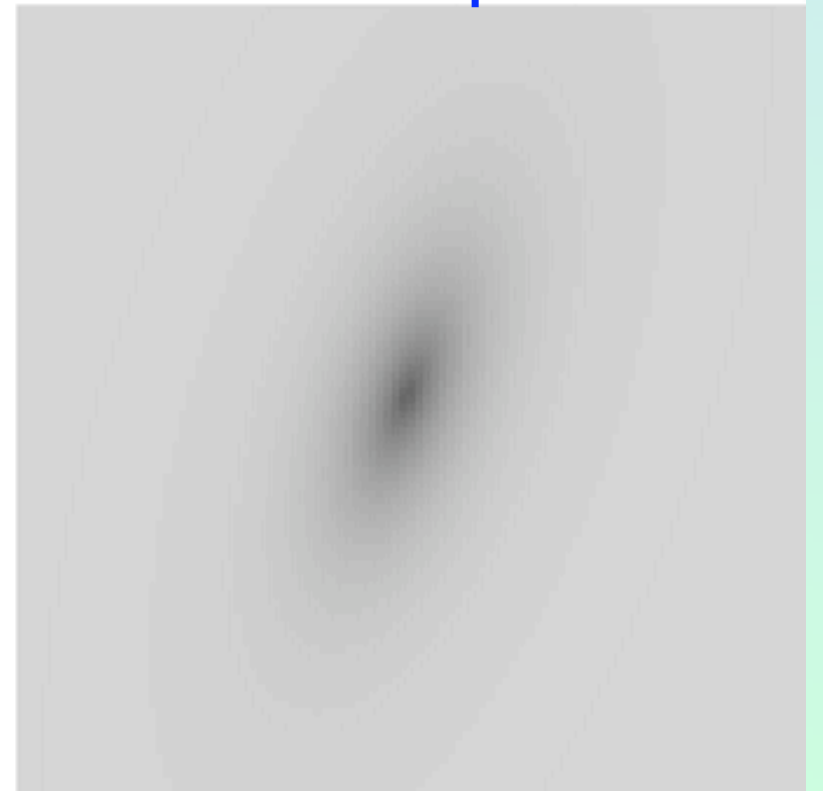
Model



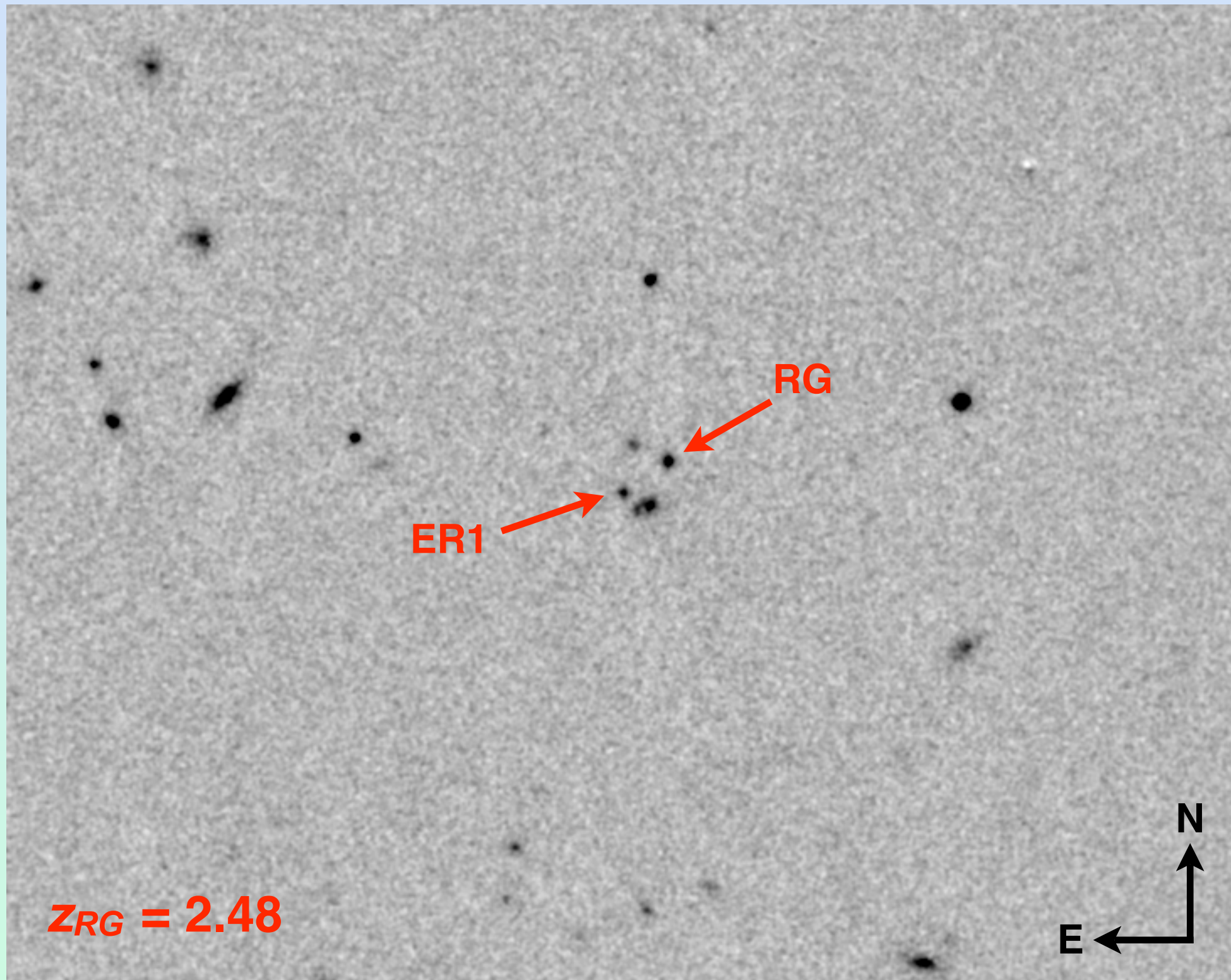
Bulge Component



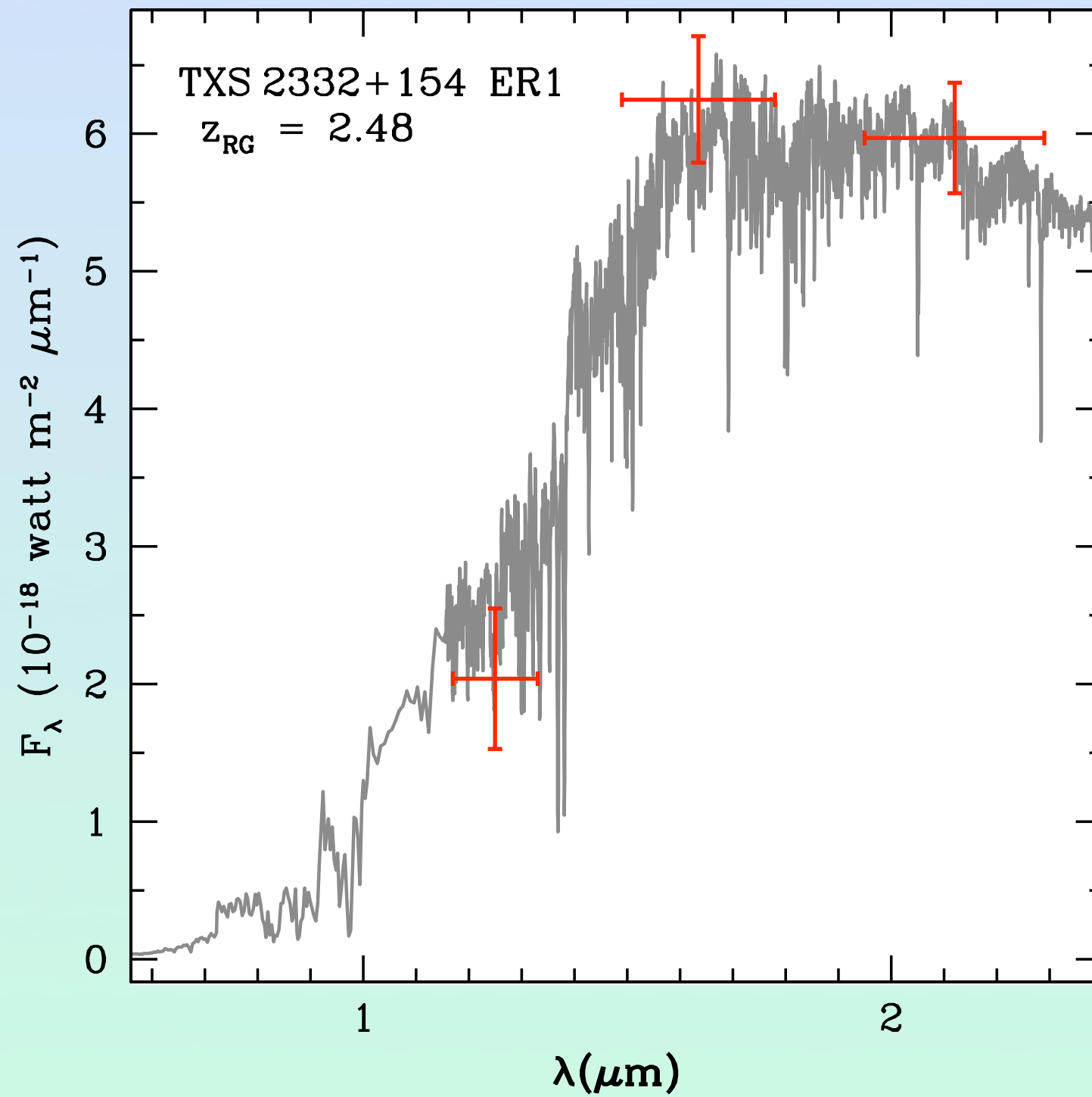
Disk Component



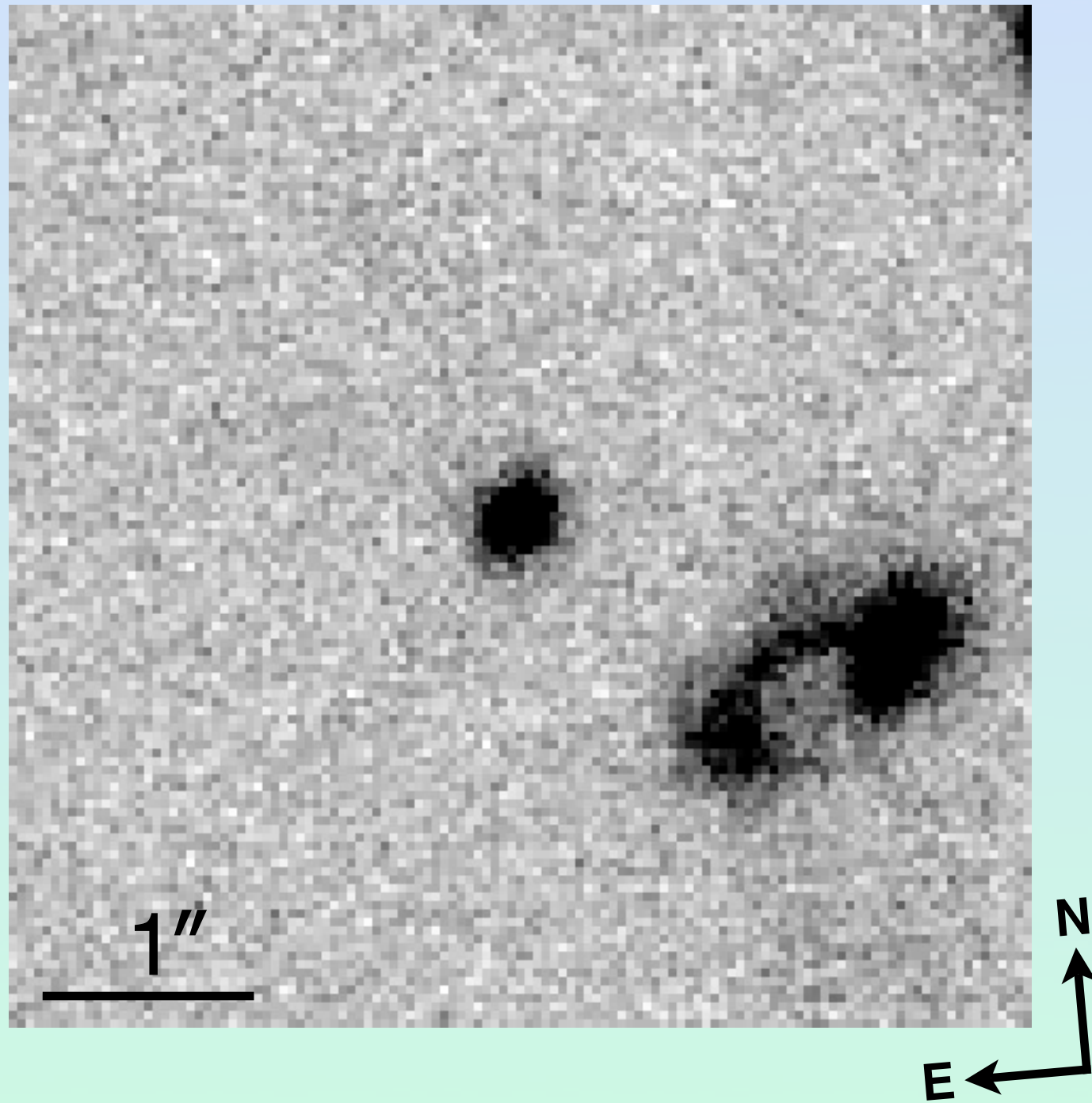
TXS 2332+154 ER1



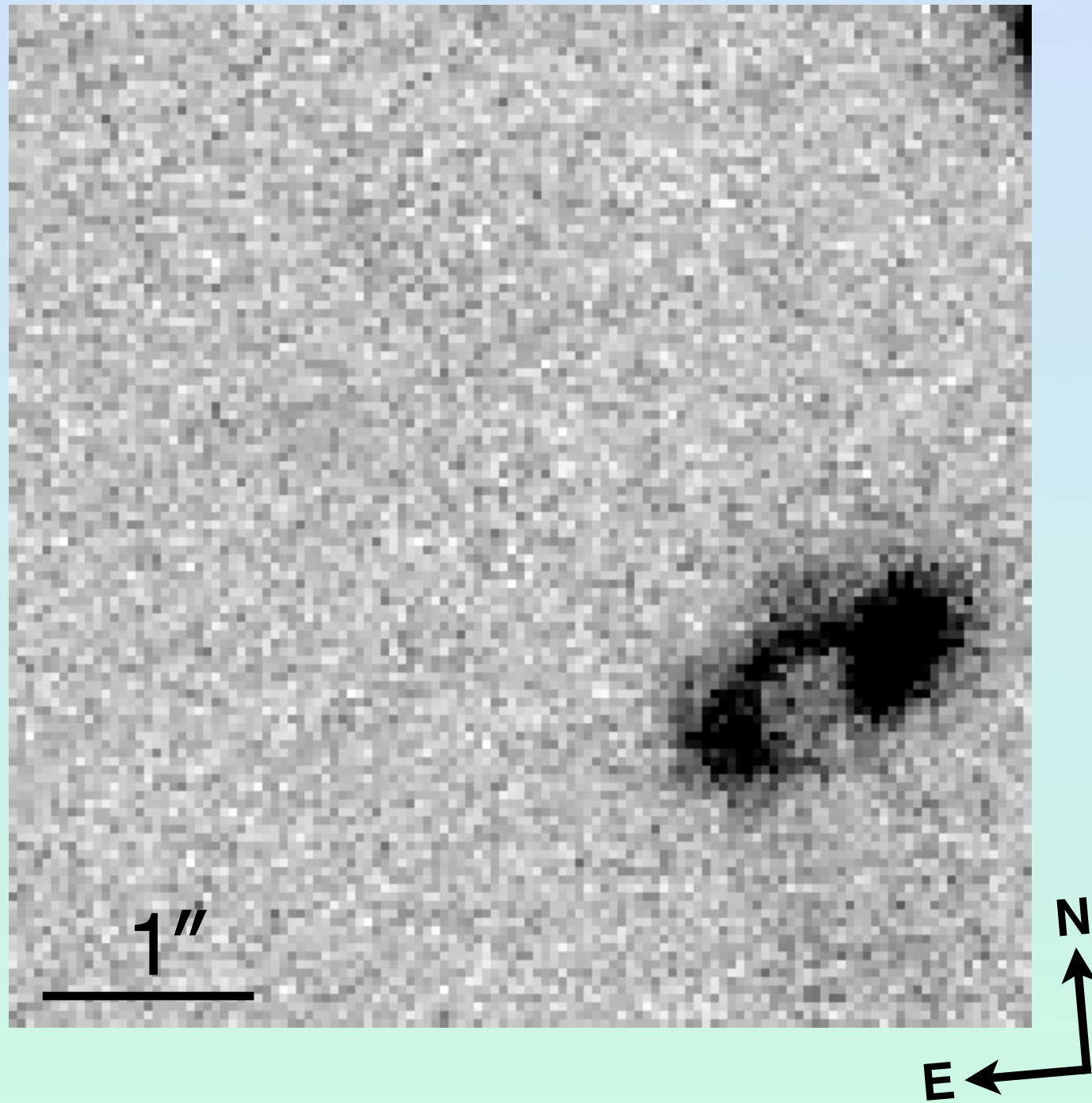
TXS 2332+154 ER1



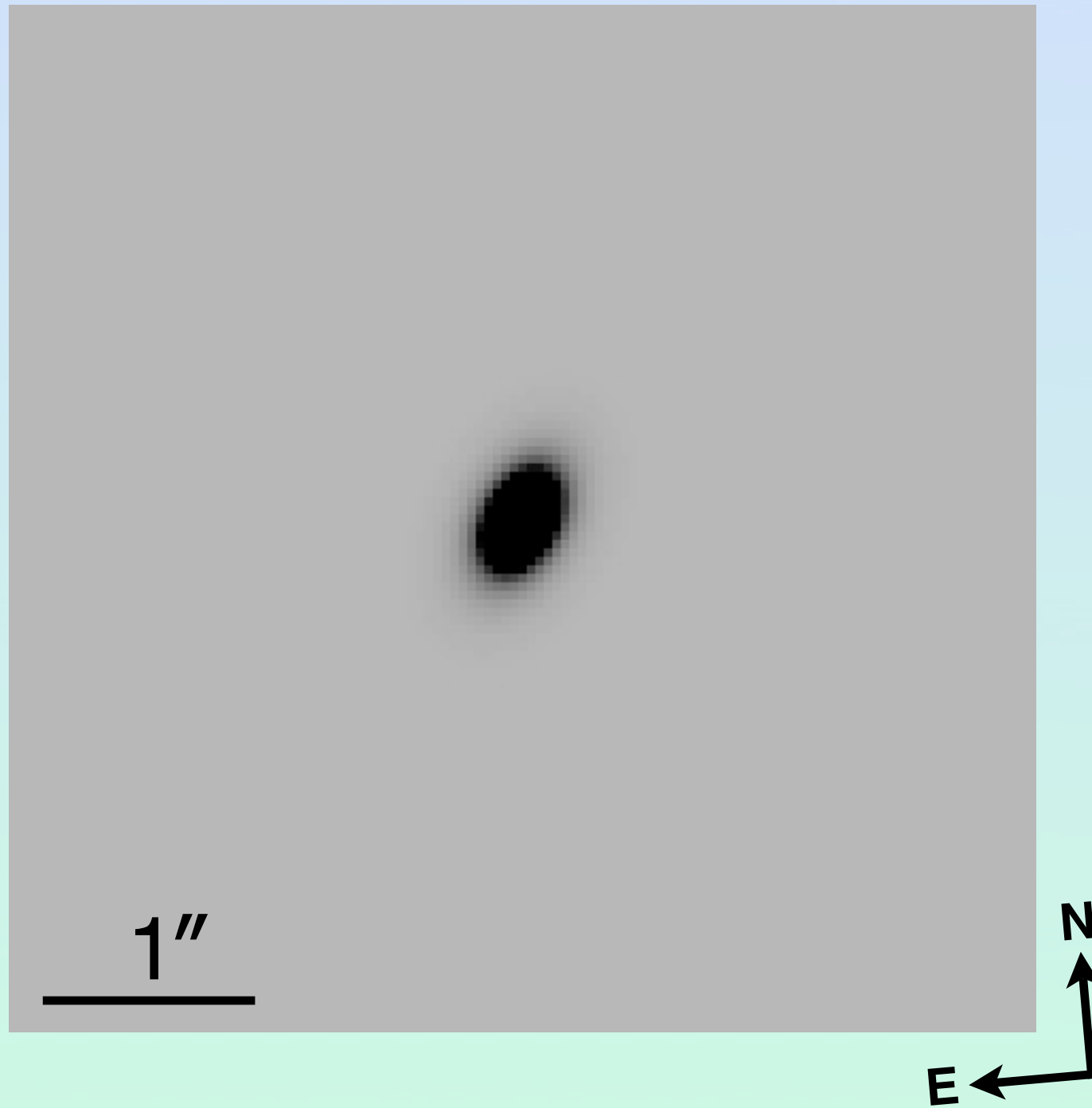
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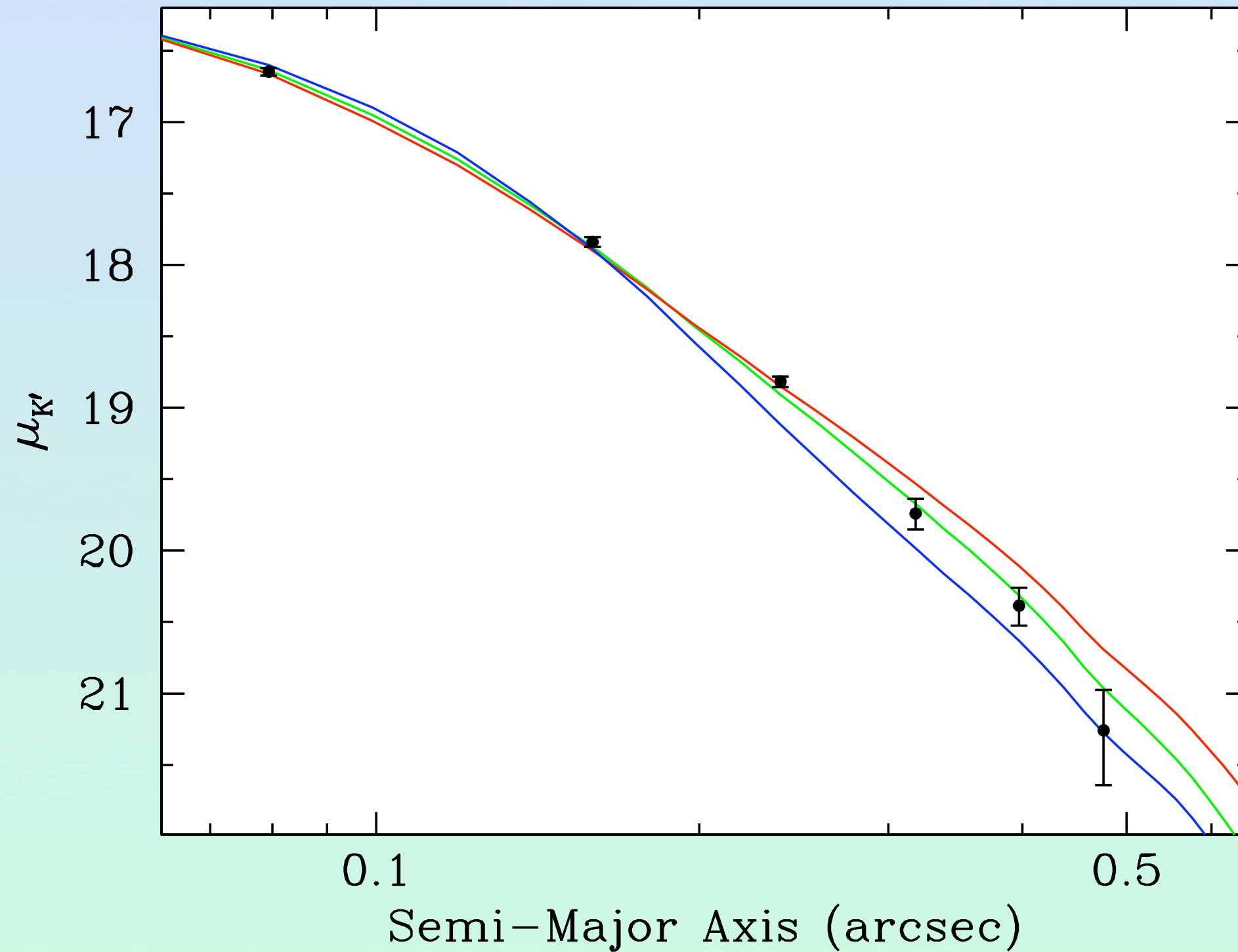
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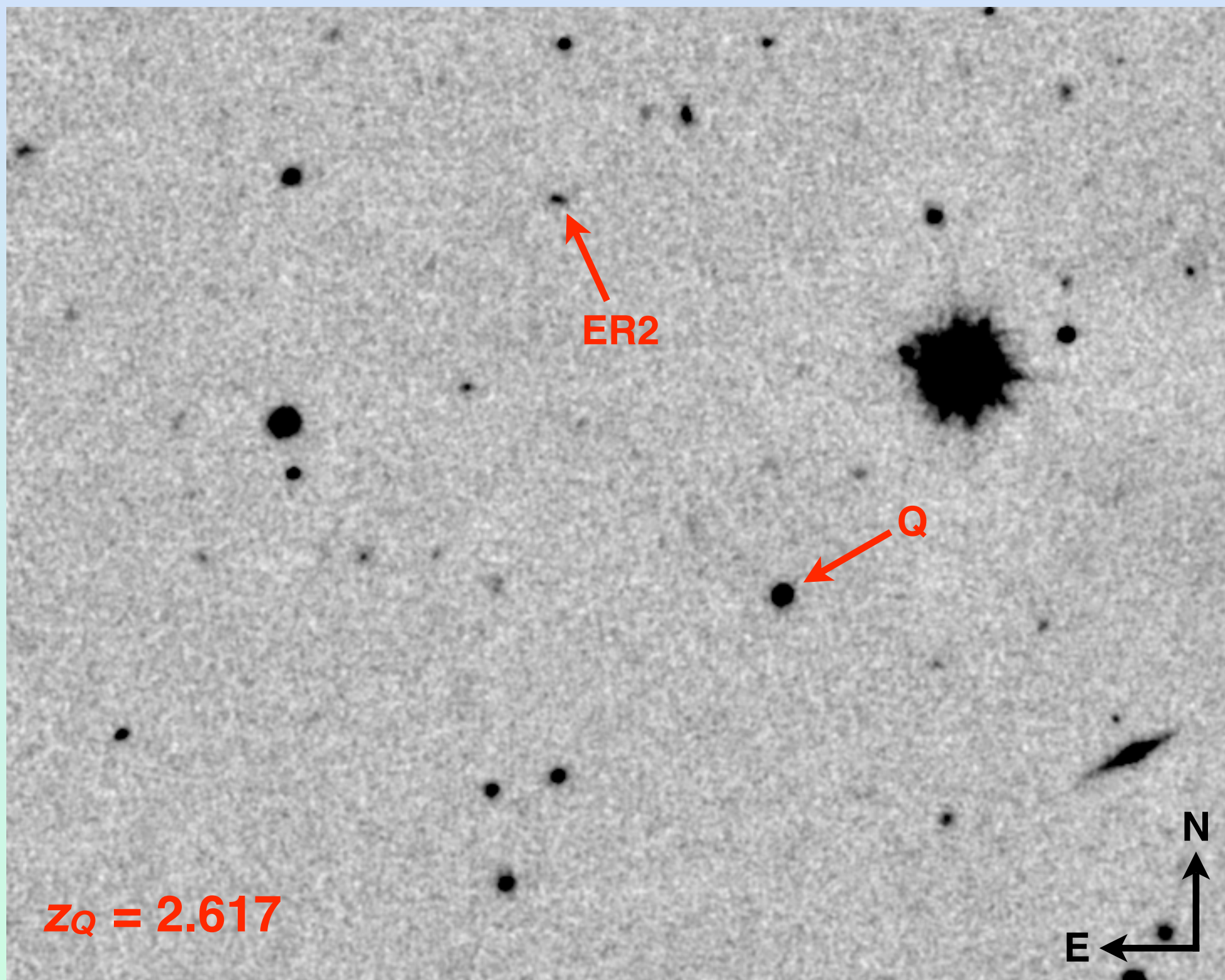
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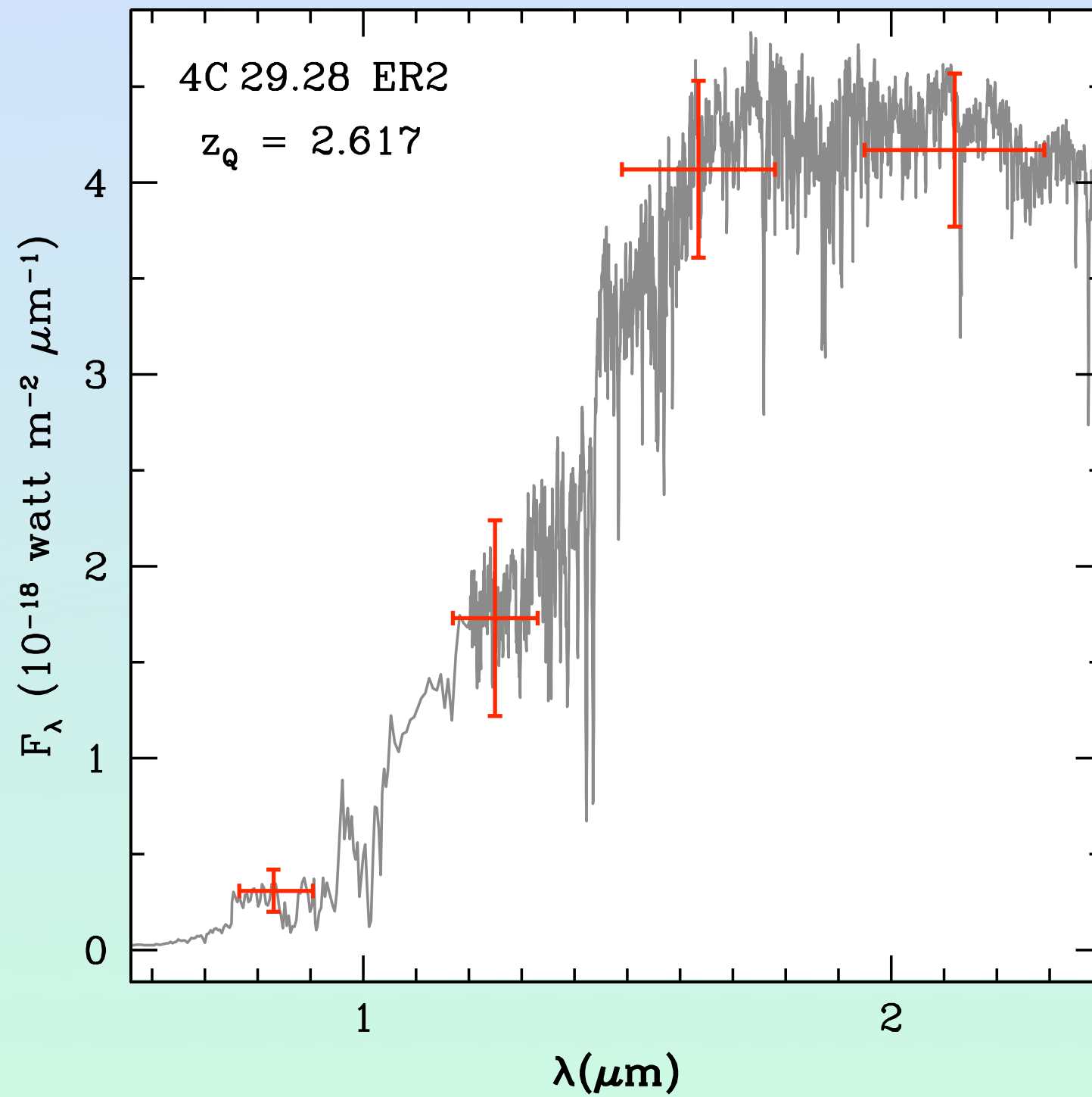
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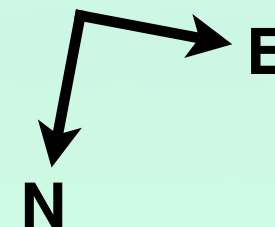
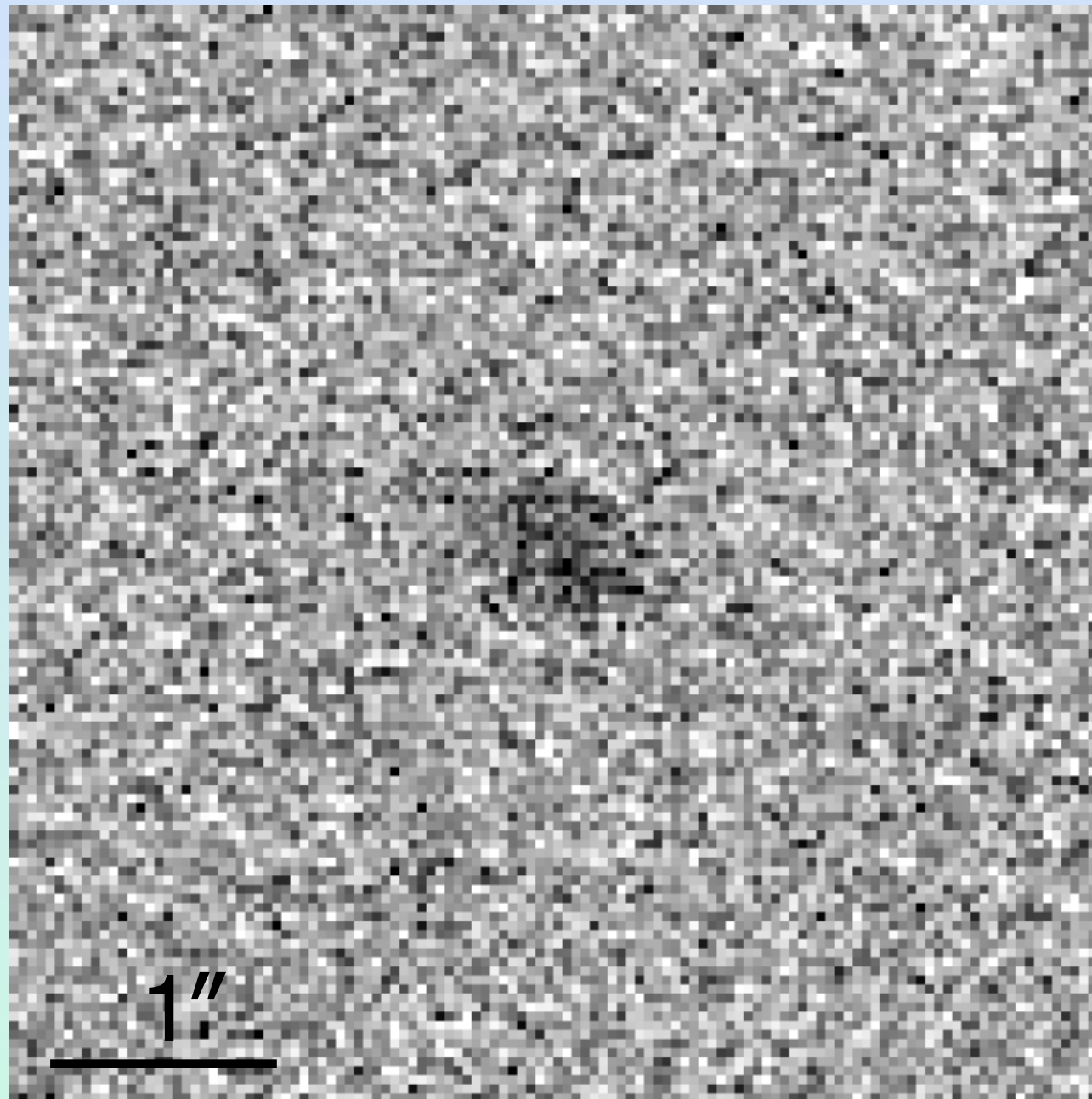
4C 29.28 ER2



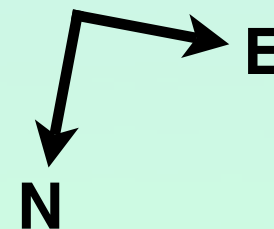
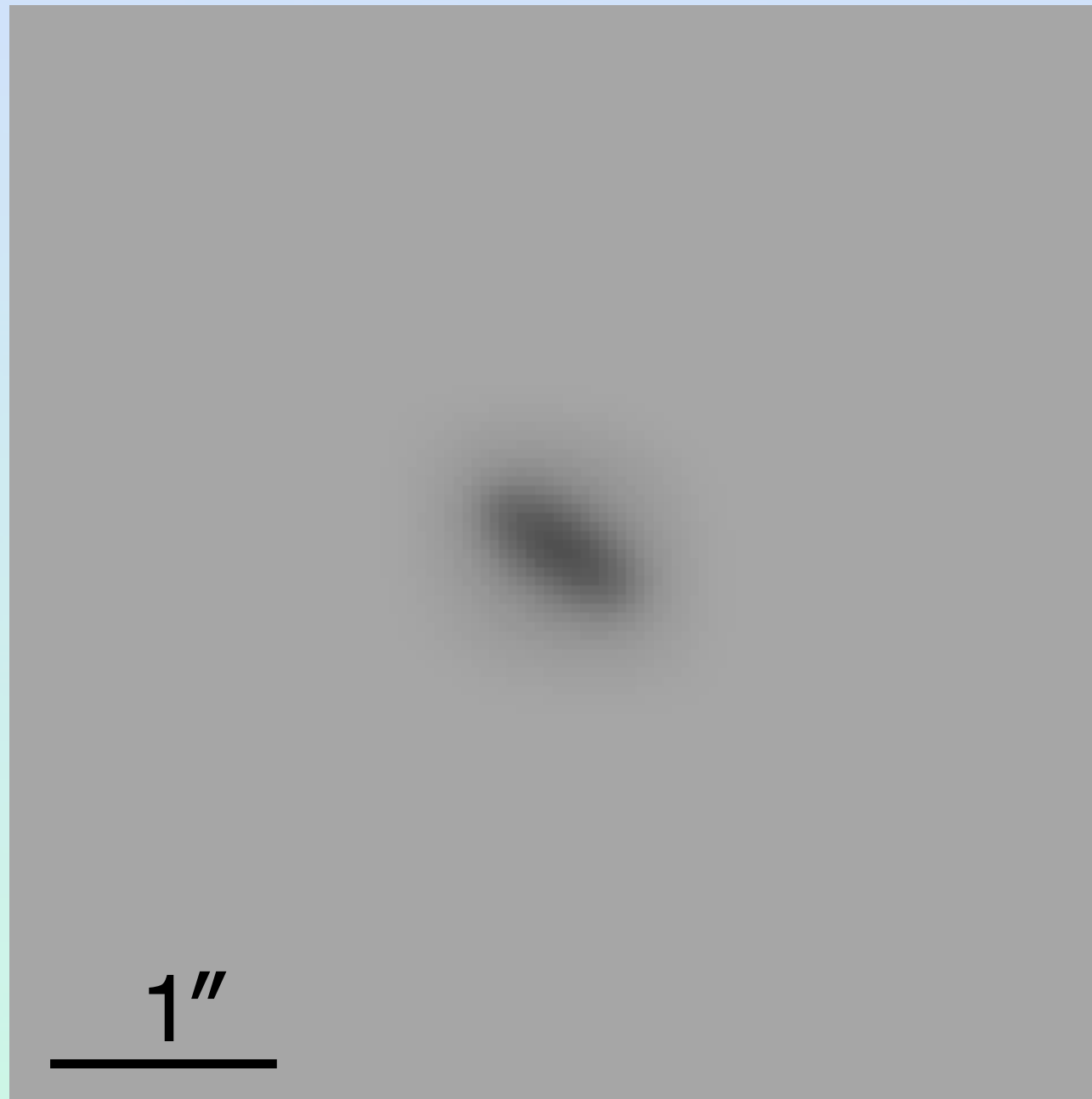
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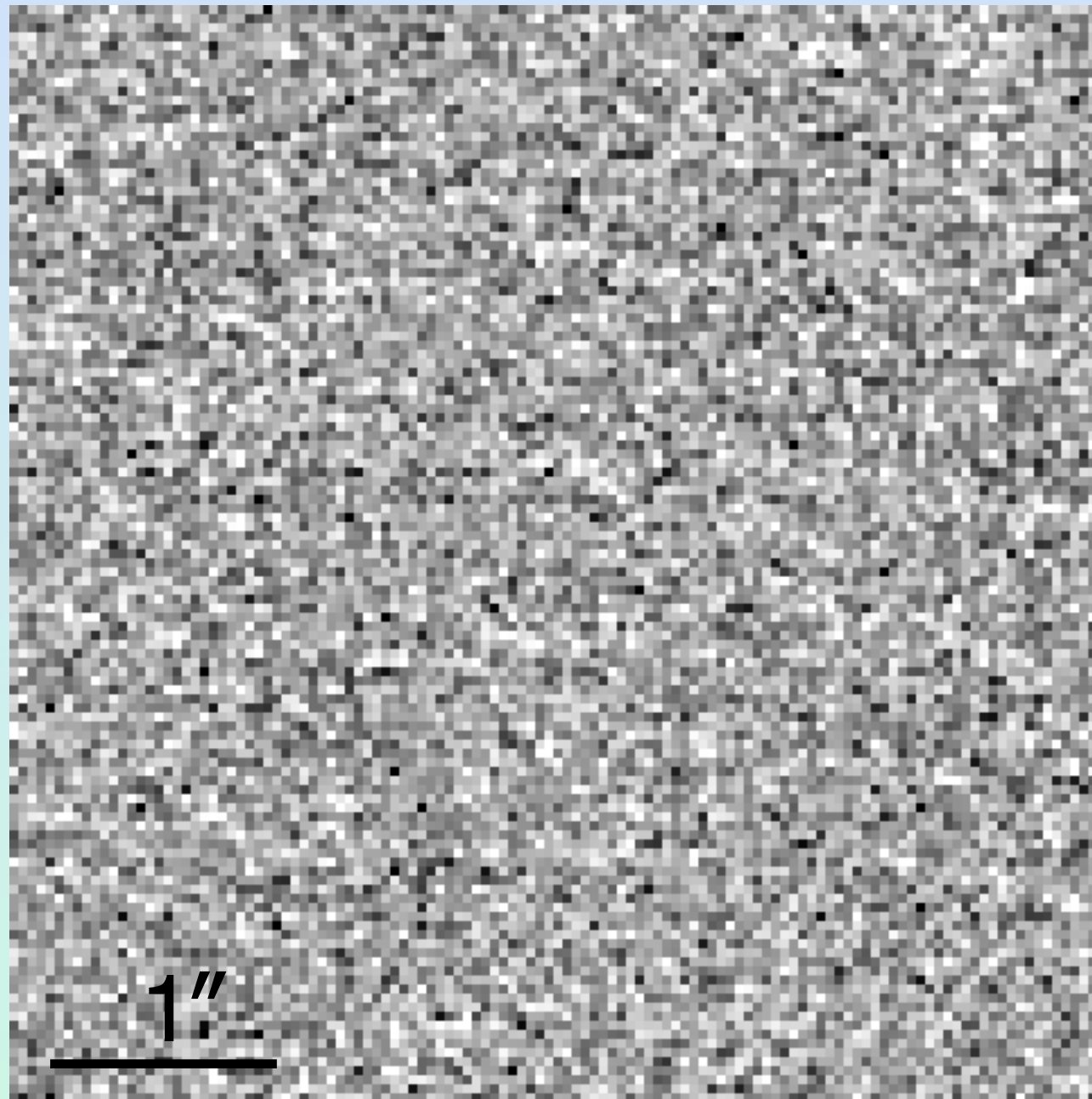
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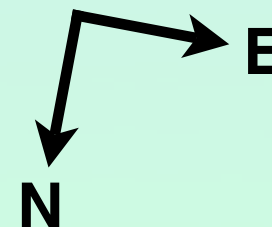
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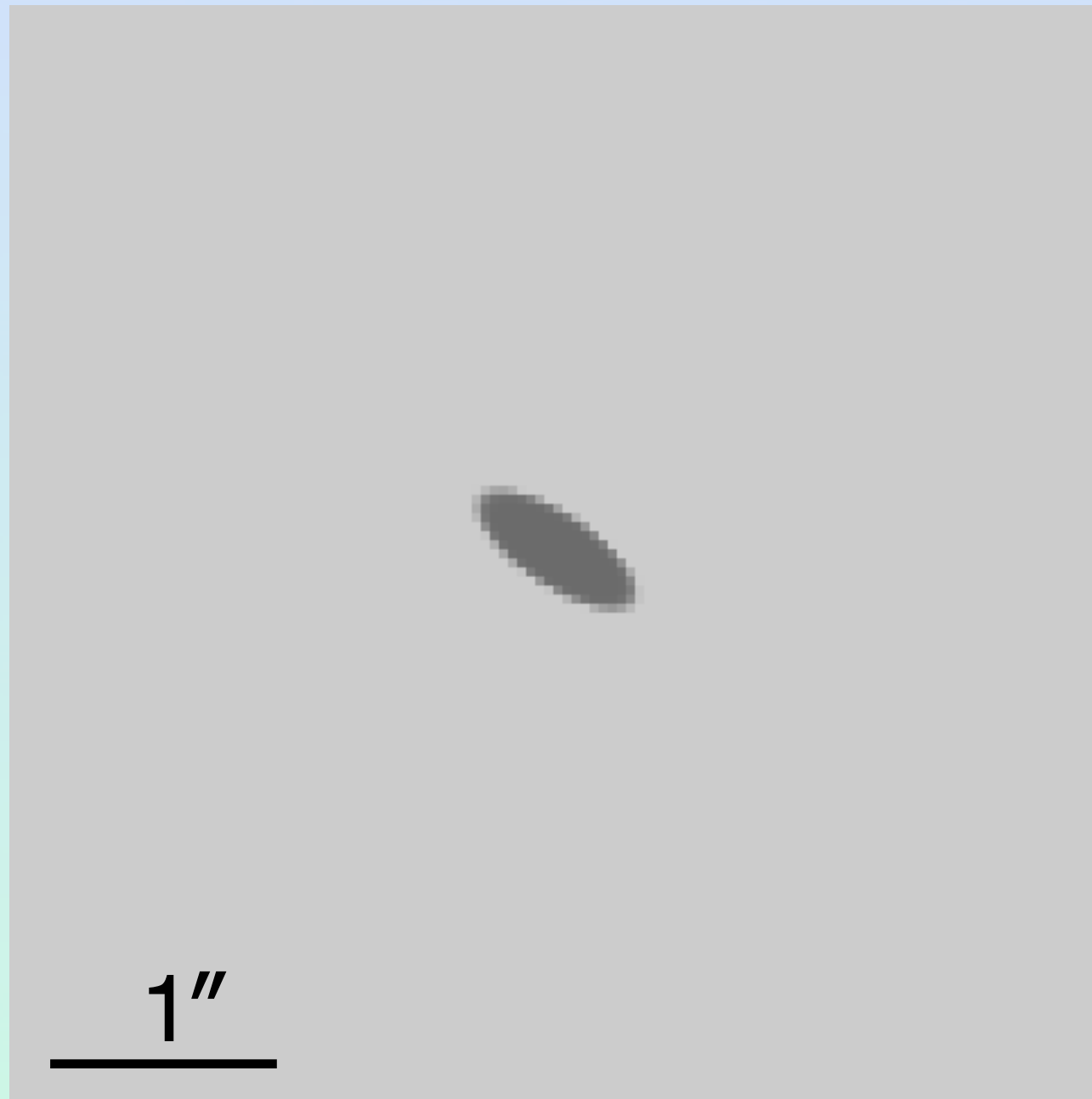
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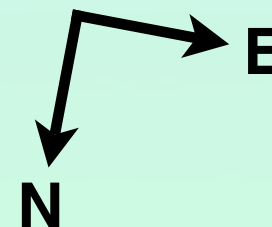
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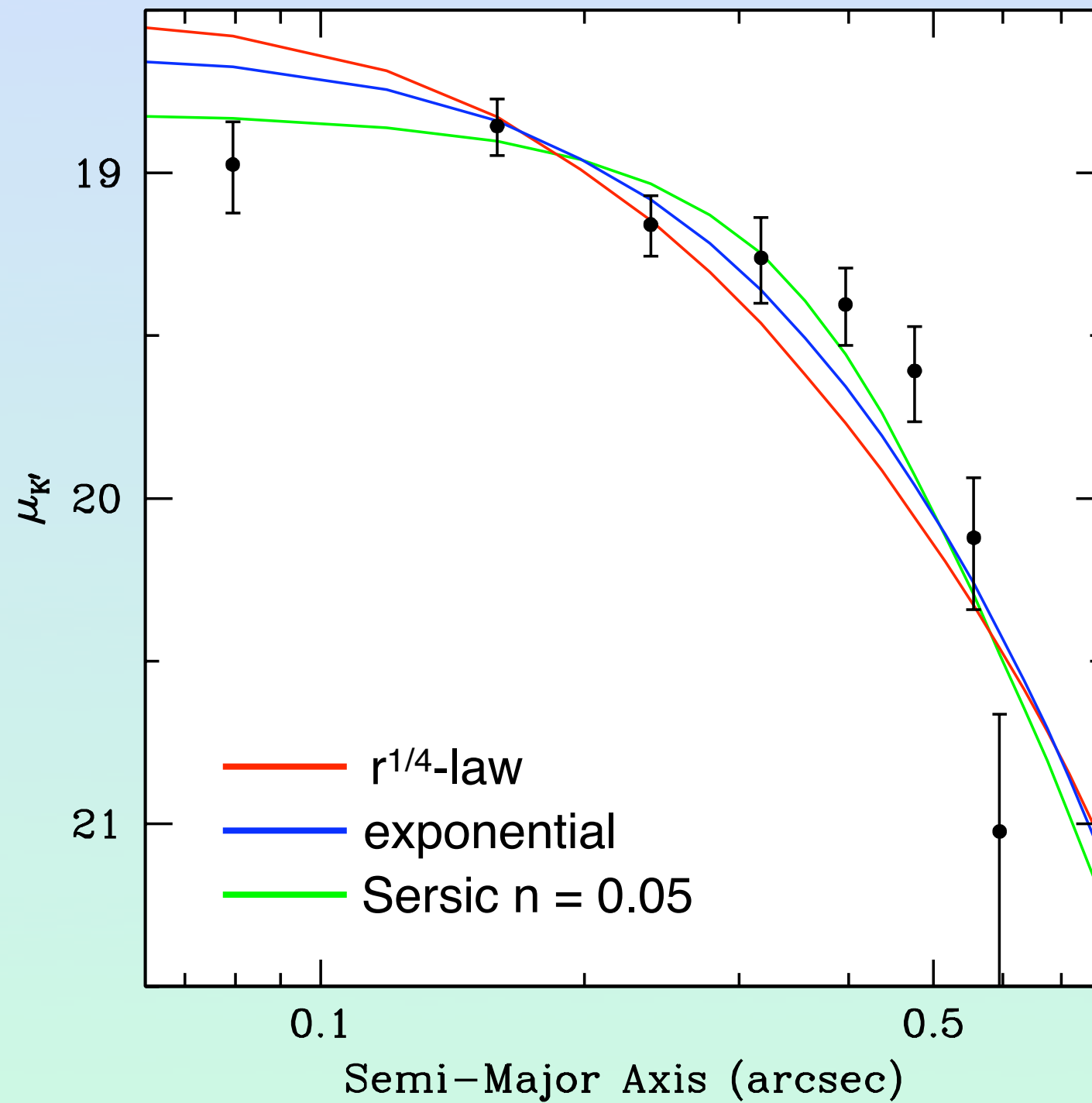
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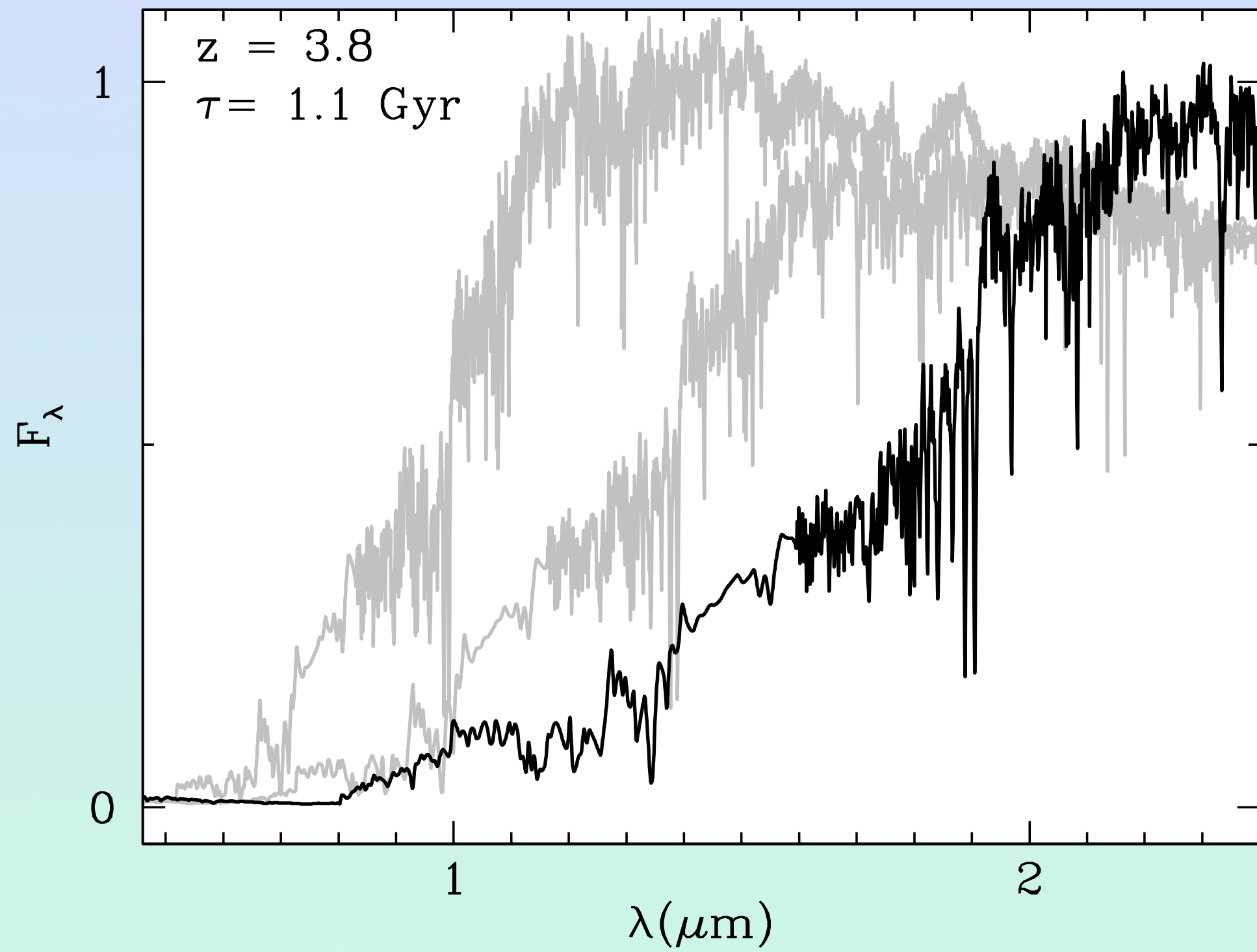


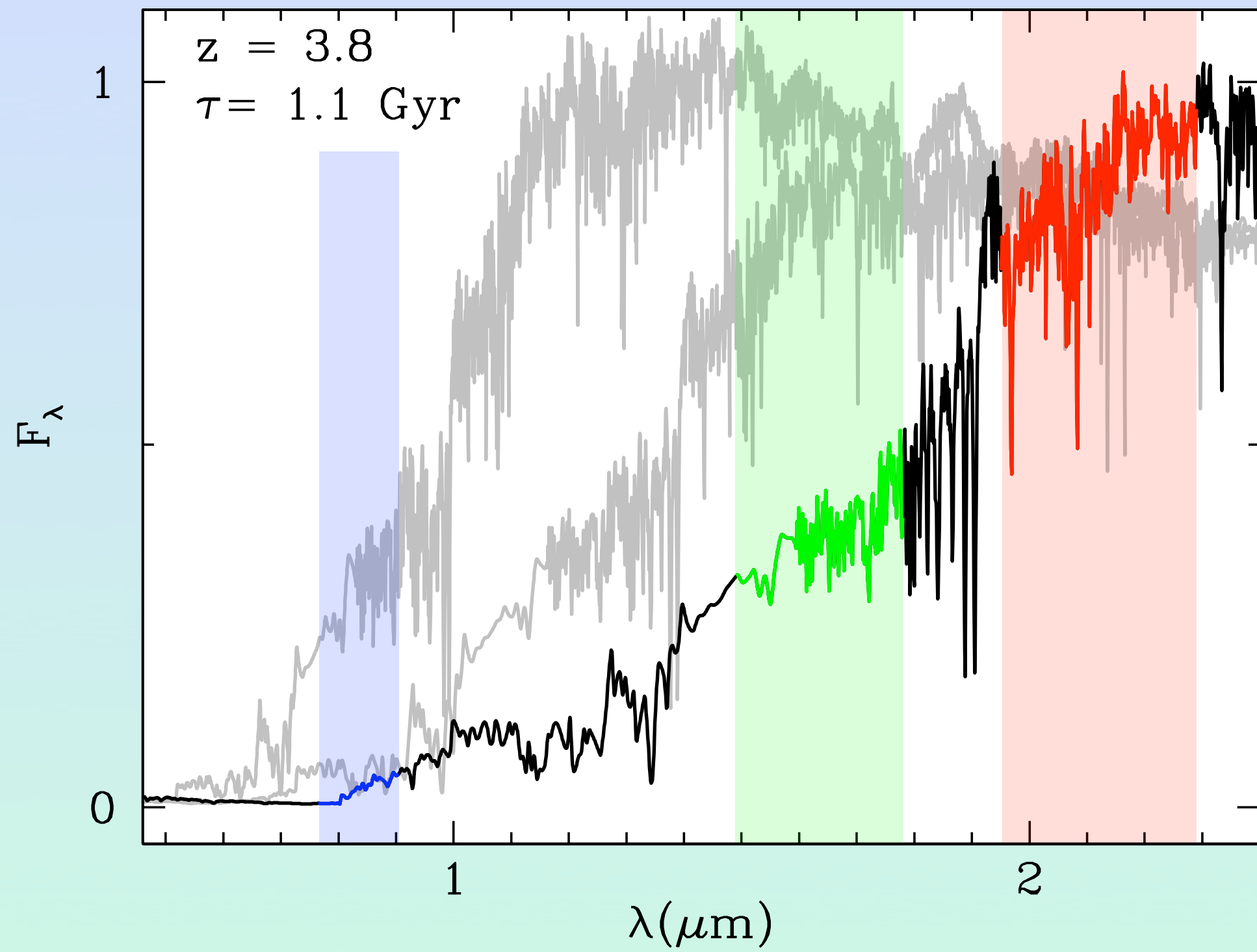
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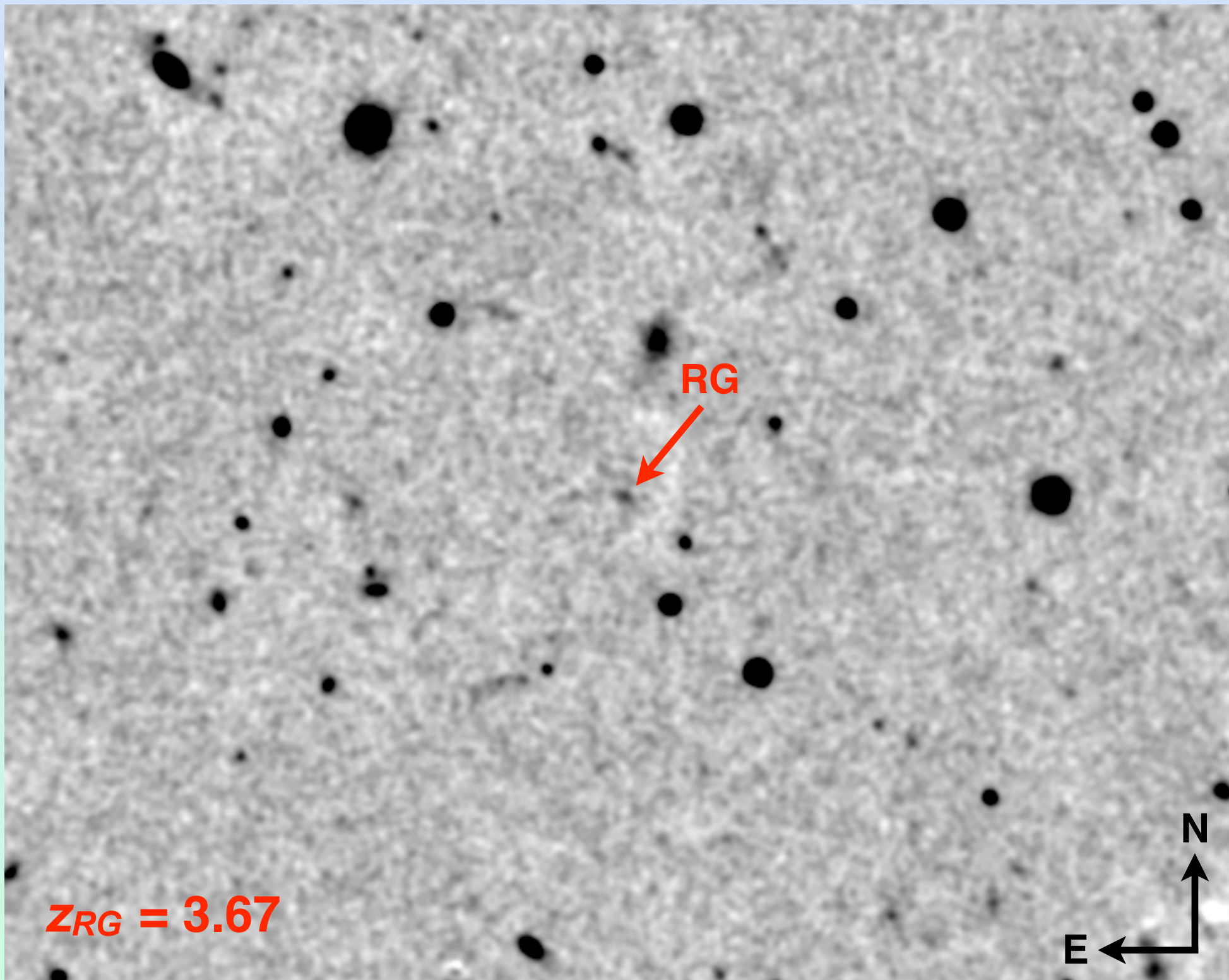
4C 29.28 ER2



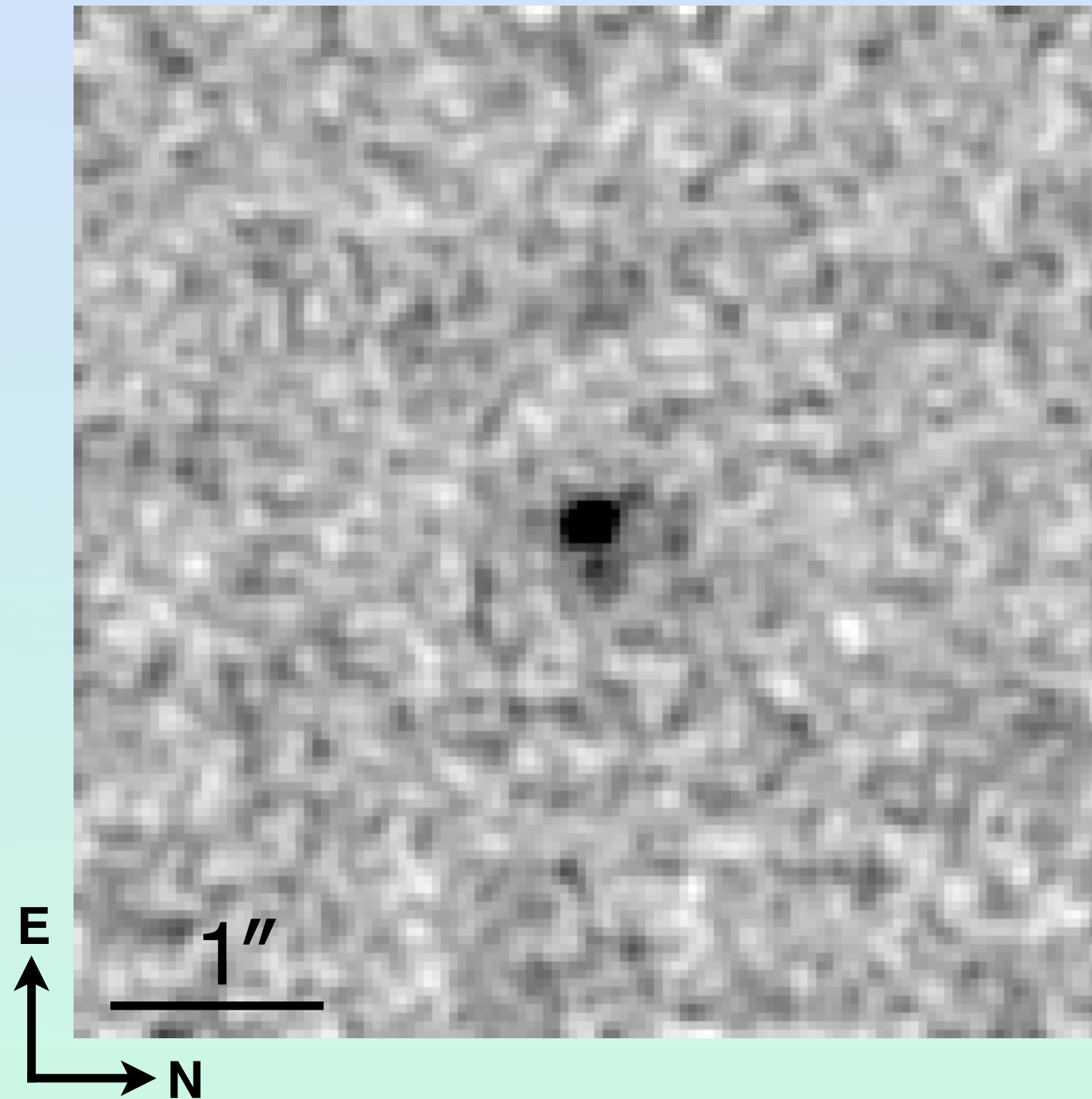




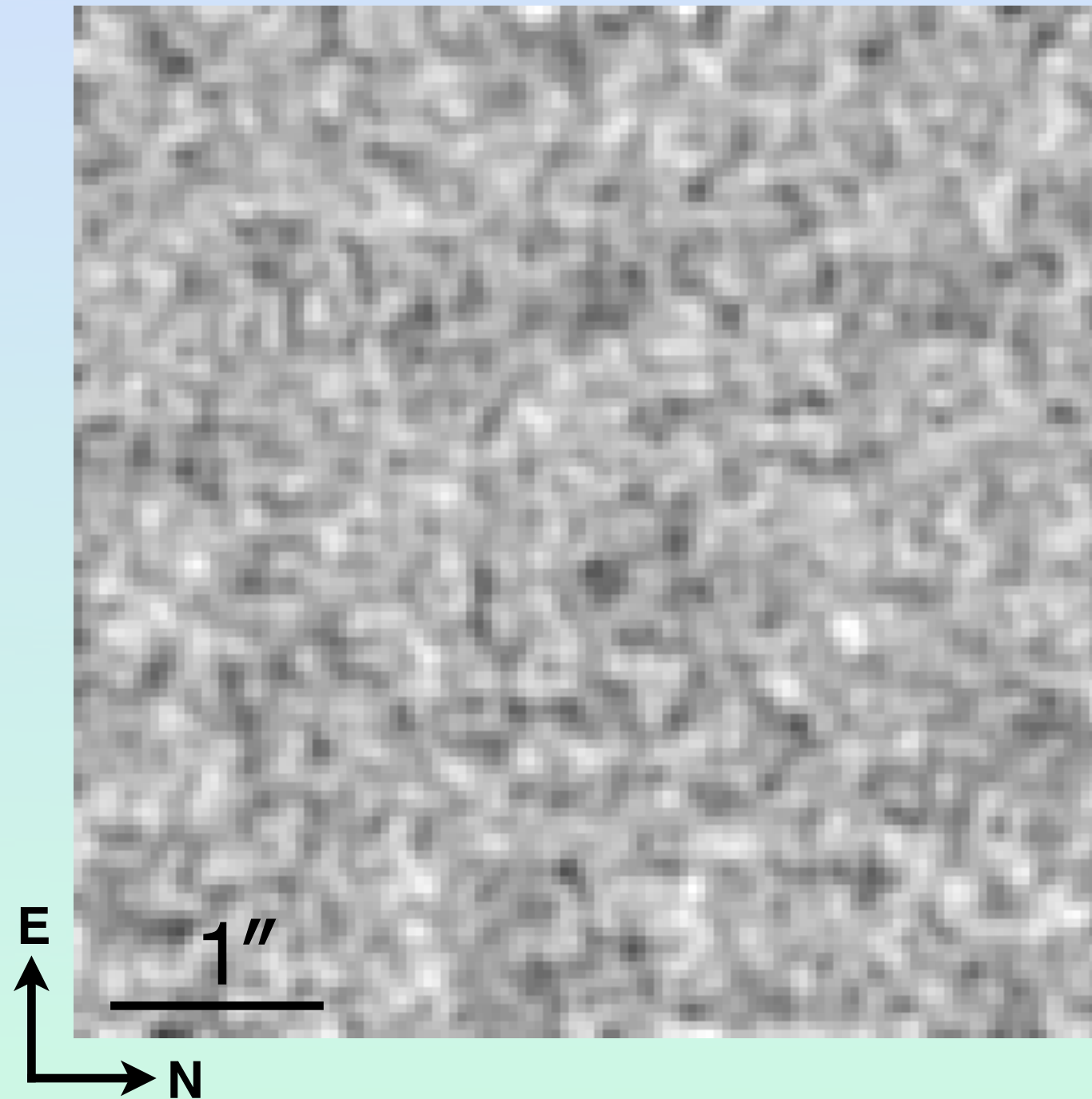
B3 0032+154



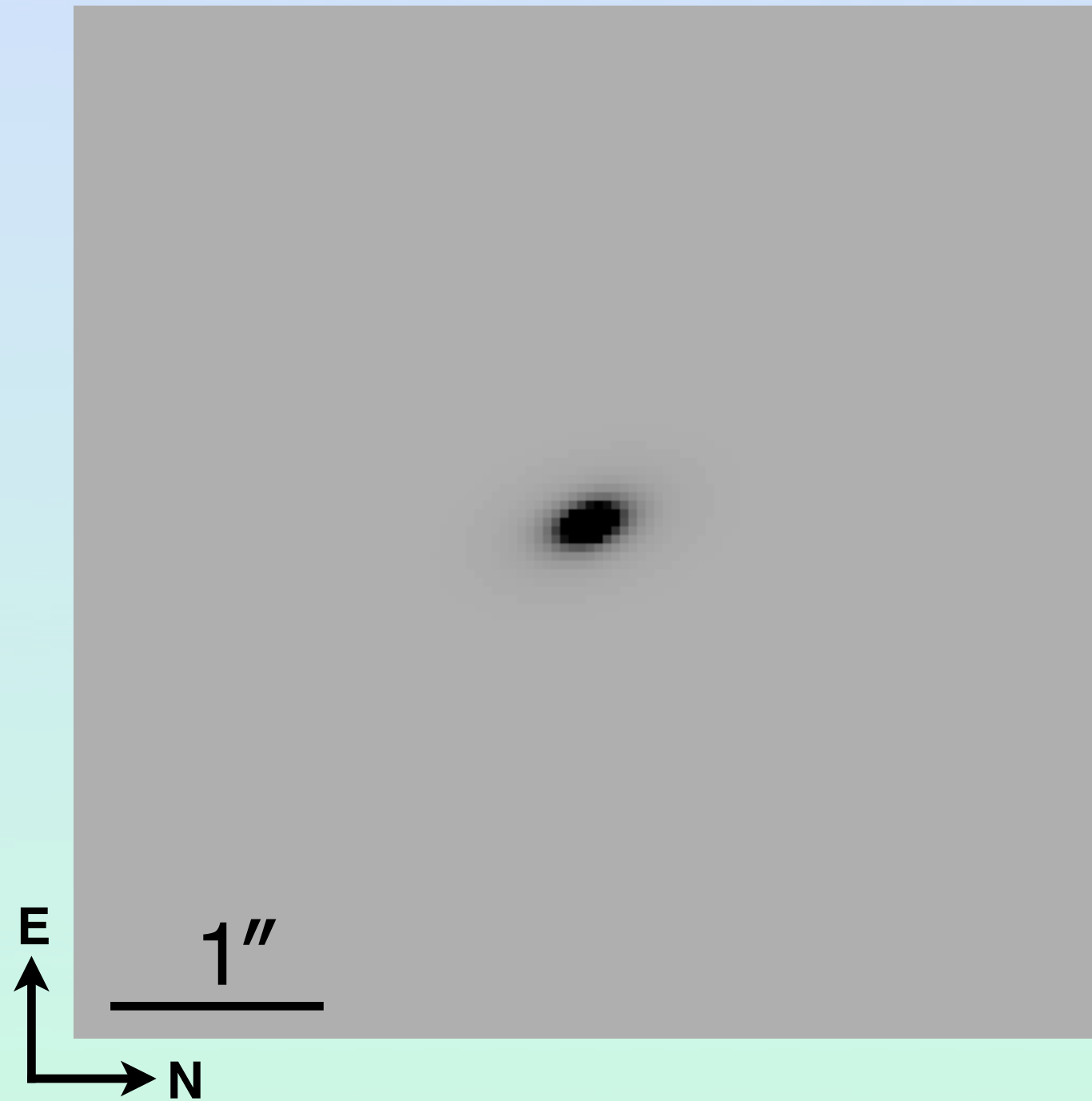
B3 0032+154



B3 0032+154



B3 0032+154



Summary

Galaxy	z	r_e (kpc)	Sersic n	Morphology
4C 15.55 ER2	1.41	3.0	1.92	Exp + point source (8%)
4C 05.84 ER1	2.32	9.4	2.56	Exp (63%) + bulge (37%)
4C 23.56 ER1	2.48	1.8	1.49	Exponential
TXS 2332 ER1	2.48	0.6	2.30	(Exponential)
4C 29.28 ER1	2.62	2.4	0.05	Uncertain
B3 0032+154	3.67	0.7	2.38	(Exponential)

Formation of massive galaxies

- ▶ The apparent prevalence of disks (or at least of exponential light distributions) means that it is unlikely that most of these galaxies have suffered major mergers in their lifetimes.
- ▶ This means that at least some massive ($\sim 2 \times 10^{11} M_{\odot}$) galaxies almost certainly formed monolithically early on.
- ▶ The masses and conservative limits on the ages imply average star formation rates of at least a few hundred M_{\odot} per year, sustained for a few 10^8 years.
- ▶ This raises the question: How can one arrange such a sustained starburst to end up with what appears (in at least some cases) to be a well relaxed disk?