A Strongly Magnified Star and Parsec-Scale Star Clusters Observed in the First Billion Years

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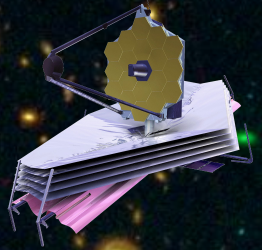
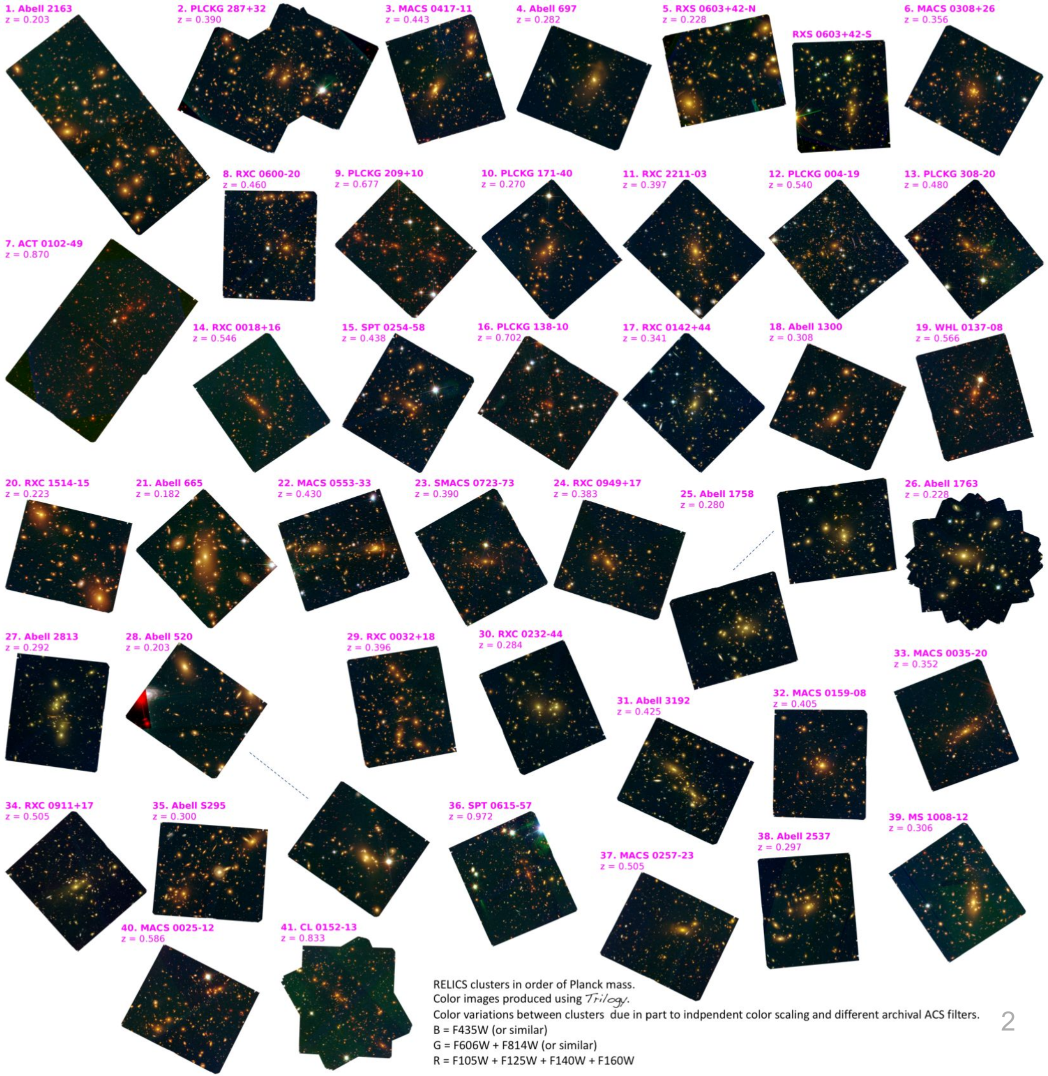


RELICS

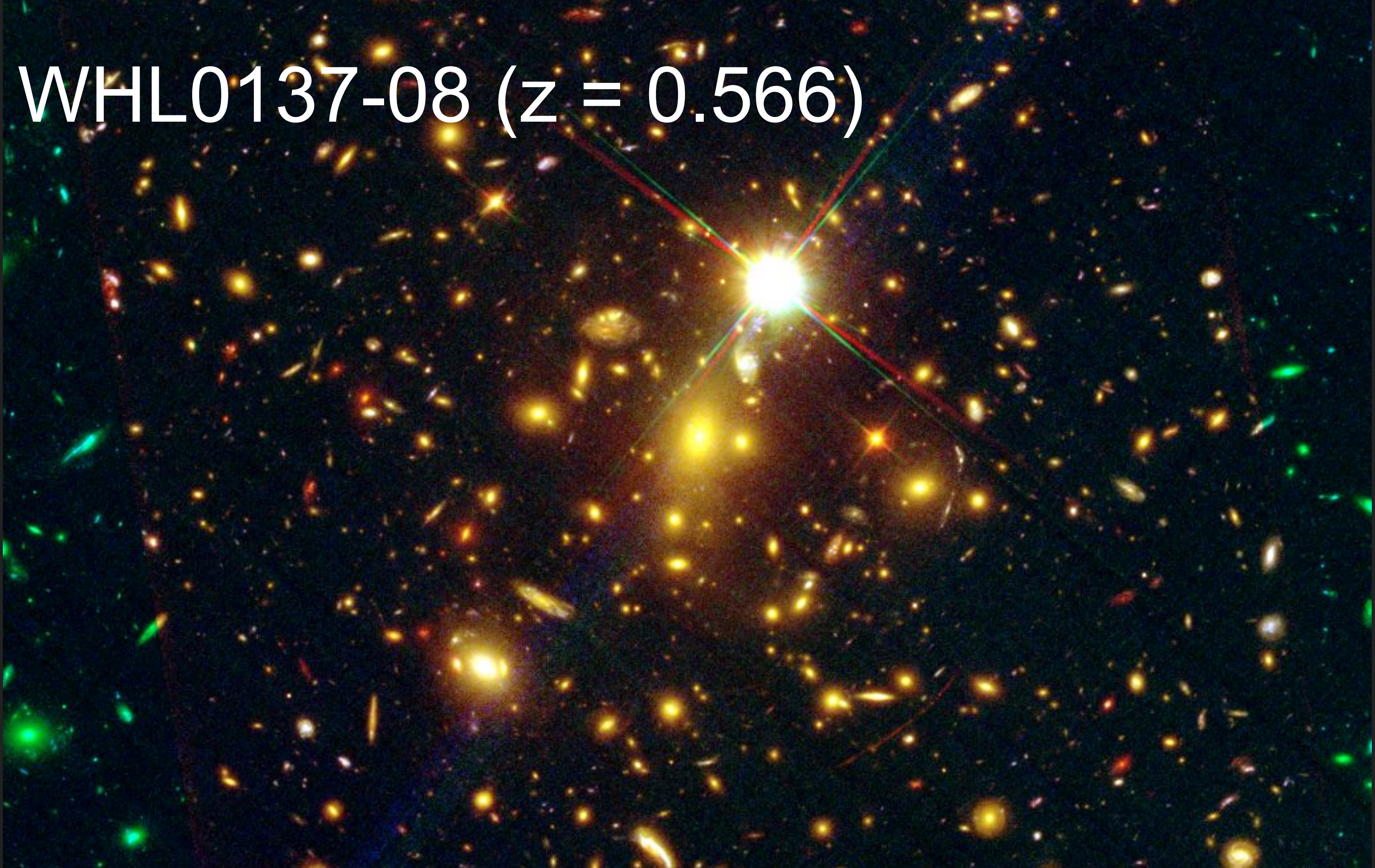
Reionization Lensing Cluster Survey

- 188 HST orbits (PI Coe)
- > 1000 Spitzer hours (PI Bradač)
- Observed 41 massive galaxy clusters
- Discovered over 300 z > 6 candidates, including some of the best and brightest known



RELICS clusters in order of Planck mass.
Color images produced using *Trilogy*.
Color variations between clusters due in part to indpendent color scaling and different archival ACS filters.
B = F435W (or similar)
G = F606W + F814W (or similar)
R = F105W + F125W + F140W + F160W

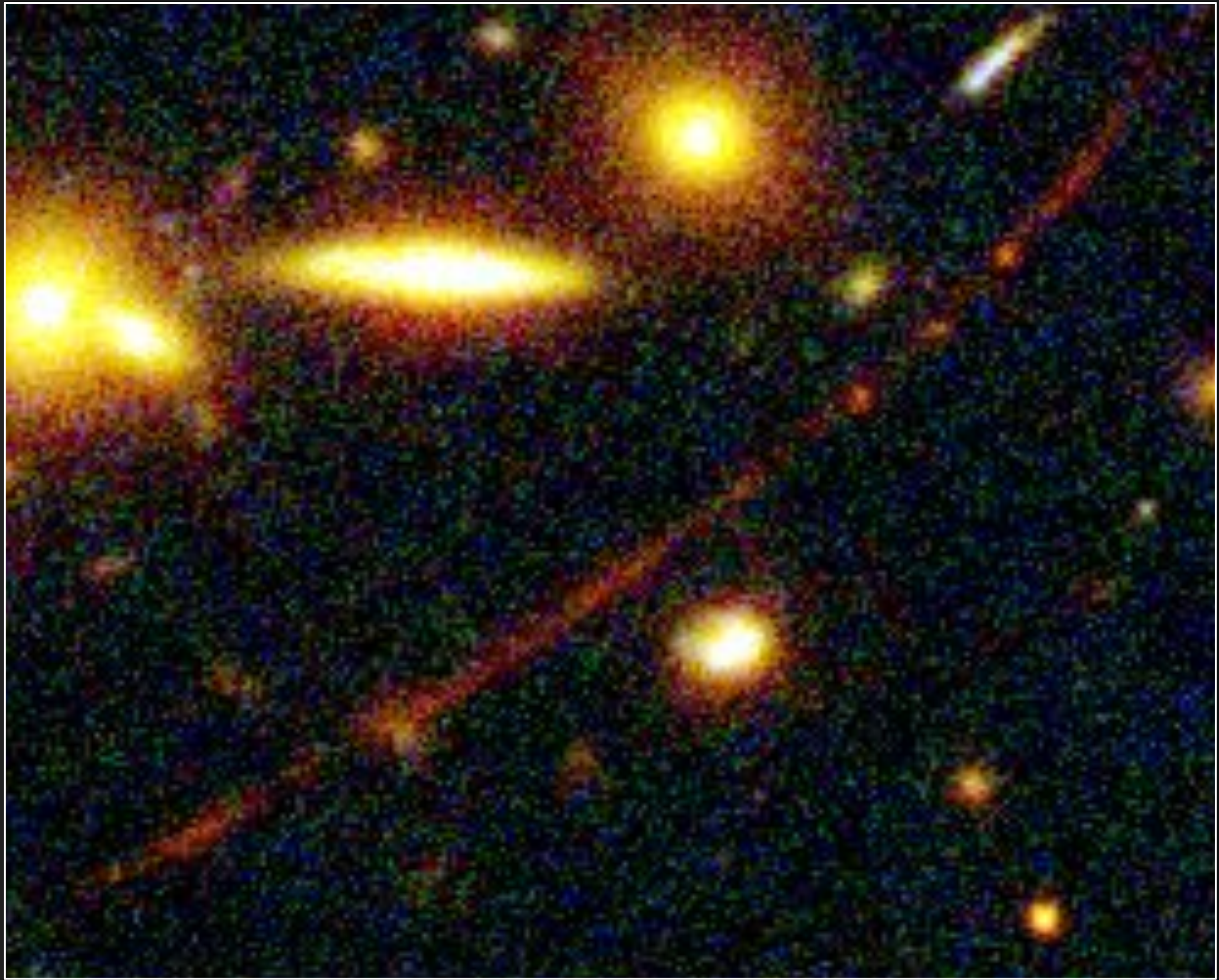
WHL0137-08 (z = 0.566)

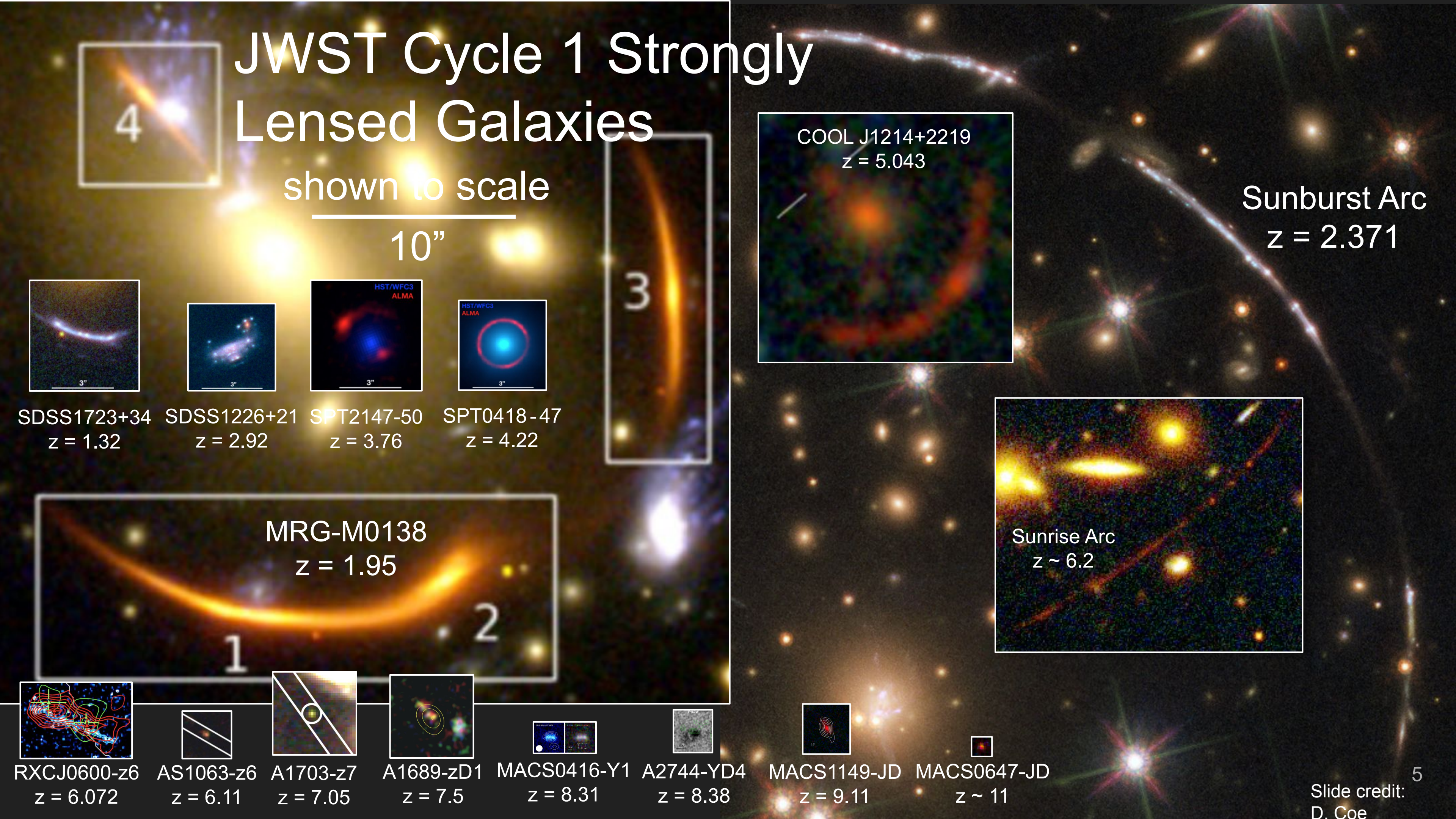


Sunrise Arc

$z_{phot} = 6.2$

Longest z > 6 lensed arc at ~15 arcsec



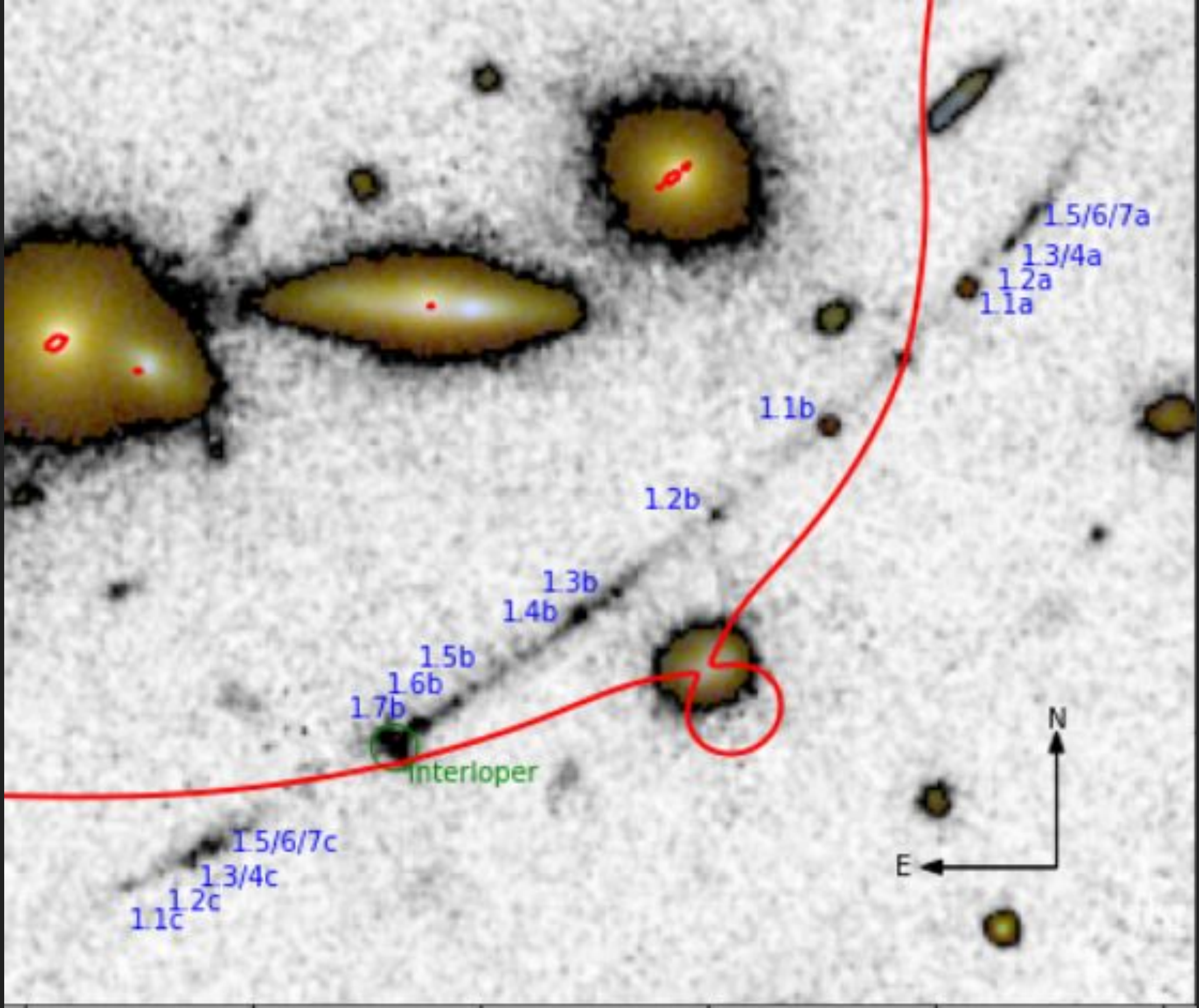


JWST Cycle 1 Strongly Lensed Galaxies
shown to scale
10”
4
3
SDSS1723+34
z = 1.32
SDSS1226+21
z = 2.92
HST/WFC3
ALMA
SPT2147-50
z = 3.76
HST/WFC3
ALMA
SPT0418-47
z = 4.22
MRG-M0138
z = 1.95
1
2
COOL J1214+2219
z = 5.043
Sunburst Arc
z = 2.371
Sunrise Arc
z ~ 6.2
RXCJ0600-z6
z = 6.072
AS1063-z6
z = 6.11
A1703-z7
z = 7.05
A1689-zD1
z = 7.5
MACS0416-Y1
z = 8.31
A2744-YD4
z = 8.38
MACS1149-JD
z = 9.11
MACS0647-JD
z ~ 11
Slide credit: D. Coe

A Closer Look

Critical curve at
z = 6.2

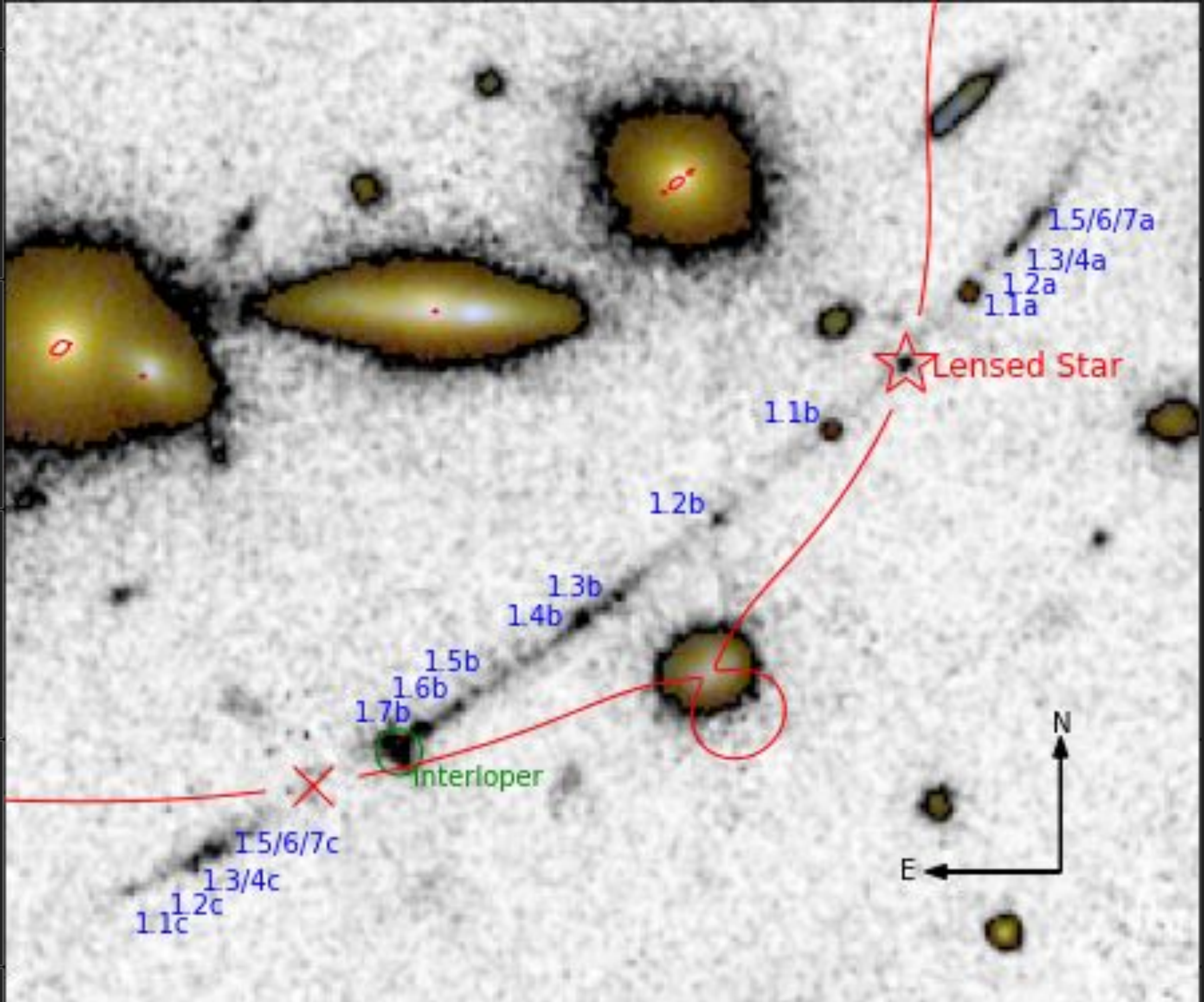
Magnification increases closer to the critical curve. Typical lensed galaxies are magnified by $\mu < 10$.
The Sunrise Arc has a total magnification of $\mu = 300$



A Closer Look

Critical curve at z = 6.2

Lensed star WHL0137-LS, nicknamed Earendel (Old English “morning star”). The star is magnified by μ > 1000



Previous Lensed Star Discoveries

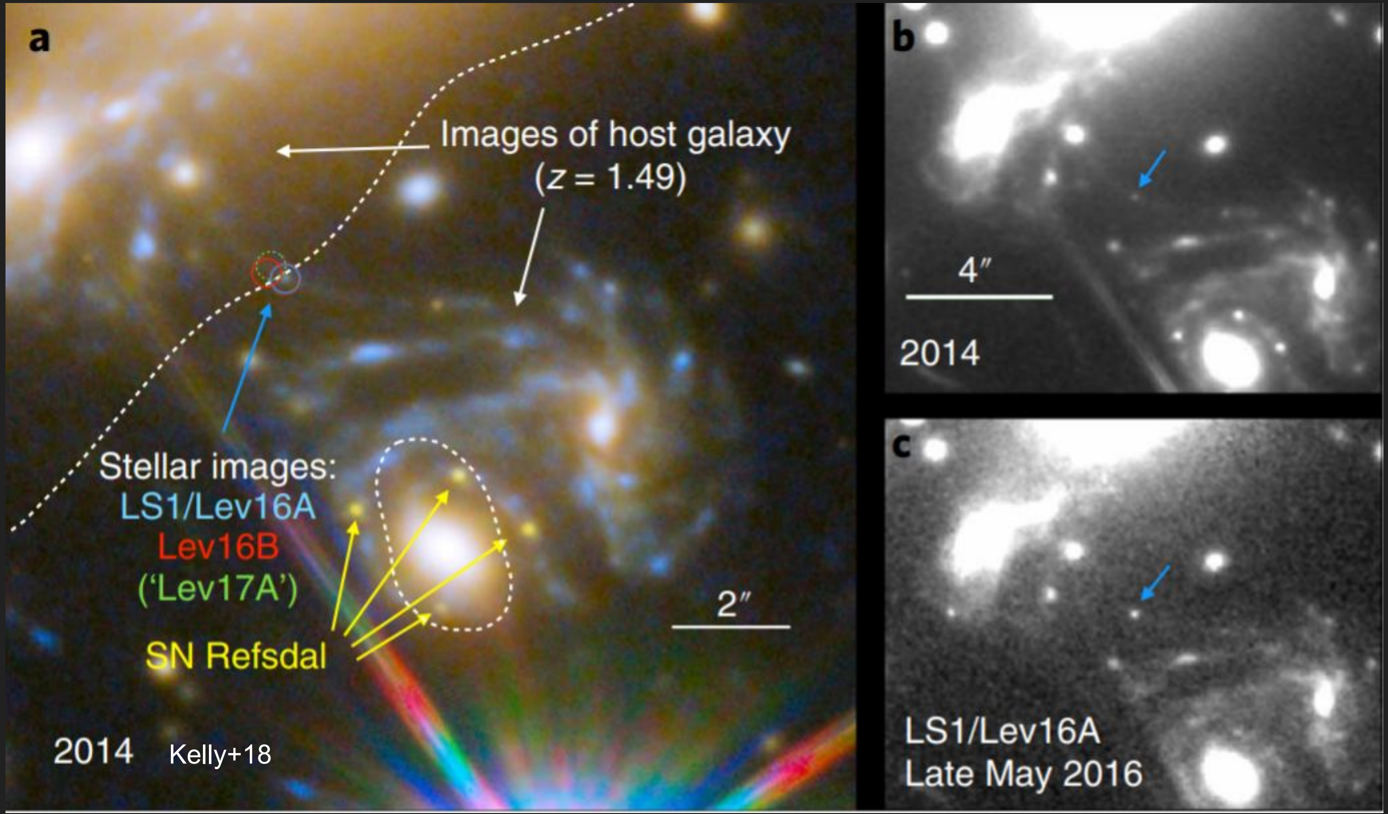
Kelly+18 - “Icarus” z = 1.5

Rodney+18 - “Spock” z = 1.0

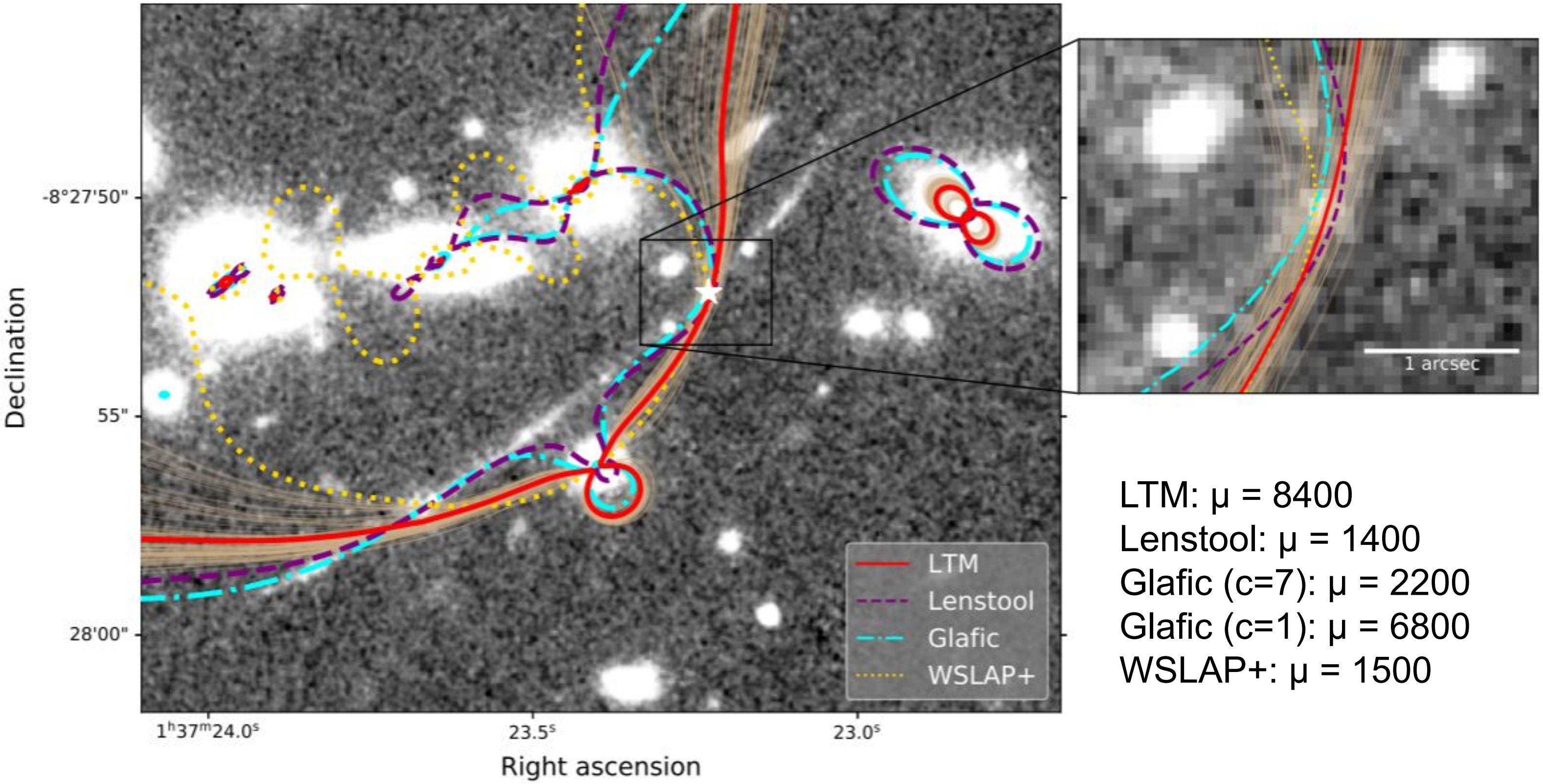
Chen+18 - “Warhol” z = 0.94

Kaurov+18 - z = 0.94

All discovered as transients



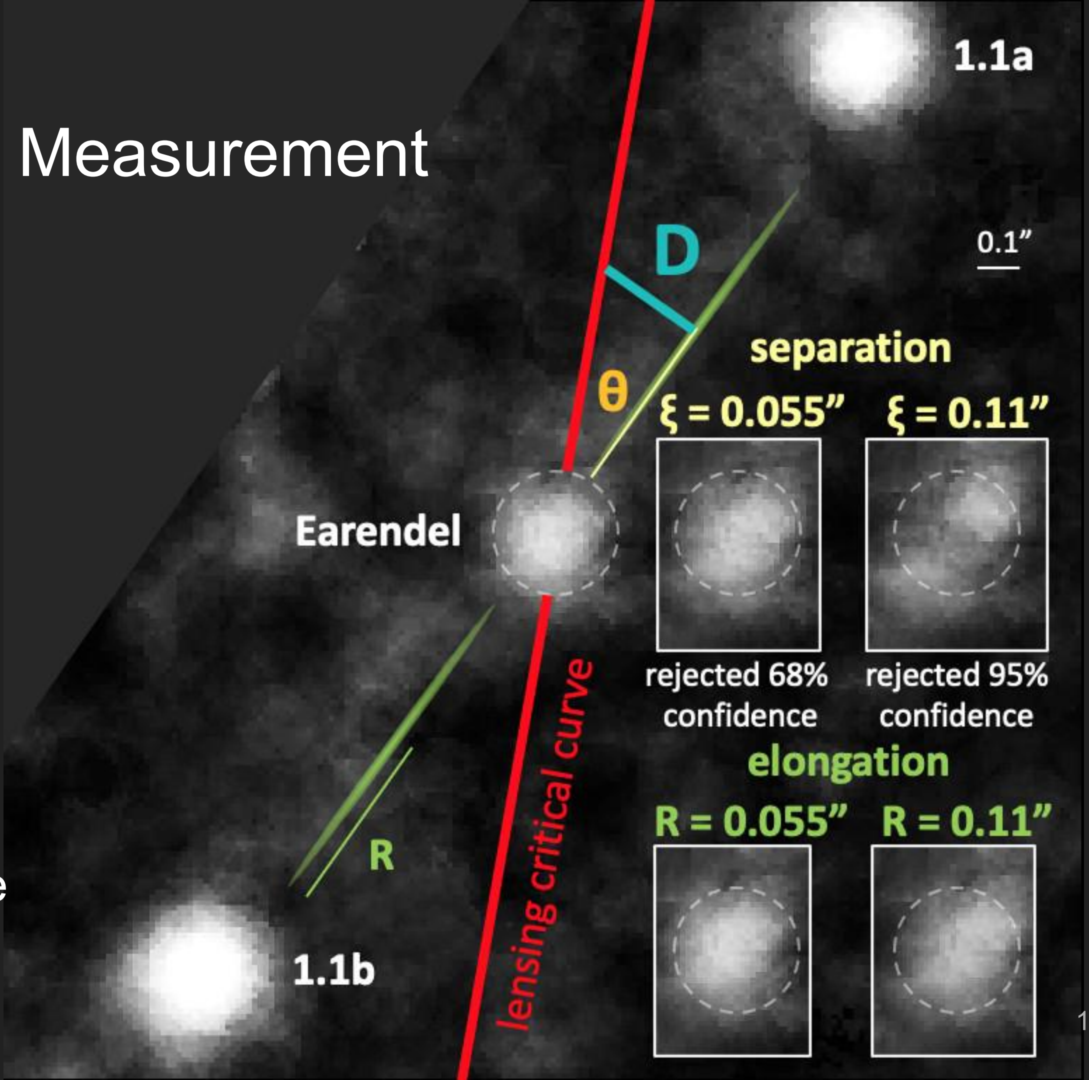
Comparison with Multiple Lens Models



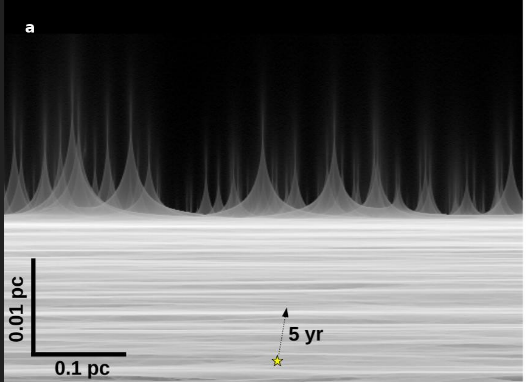
LTM: μ = 8400
Lenstool: μ = 1400
Glafic (c=7): μ = 2200
Glafic (c=1): μ = 6800
WSLAP+: μ = 1500

Radius & Magnification Measurement

- 10x supersampled image
- Highly sheared Gaussian inconsistent with a point source
  - R = 0.055”
  - r_{source} < 0.09-0.36 pc
  - Smaller than any known star clusters (Portegies-Zwart+10)
- How far apart two point sources remain unresolved (ξ = 0.055”)
- ξ → Distance from crit. curve → min. magnification



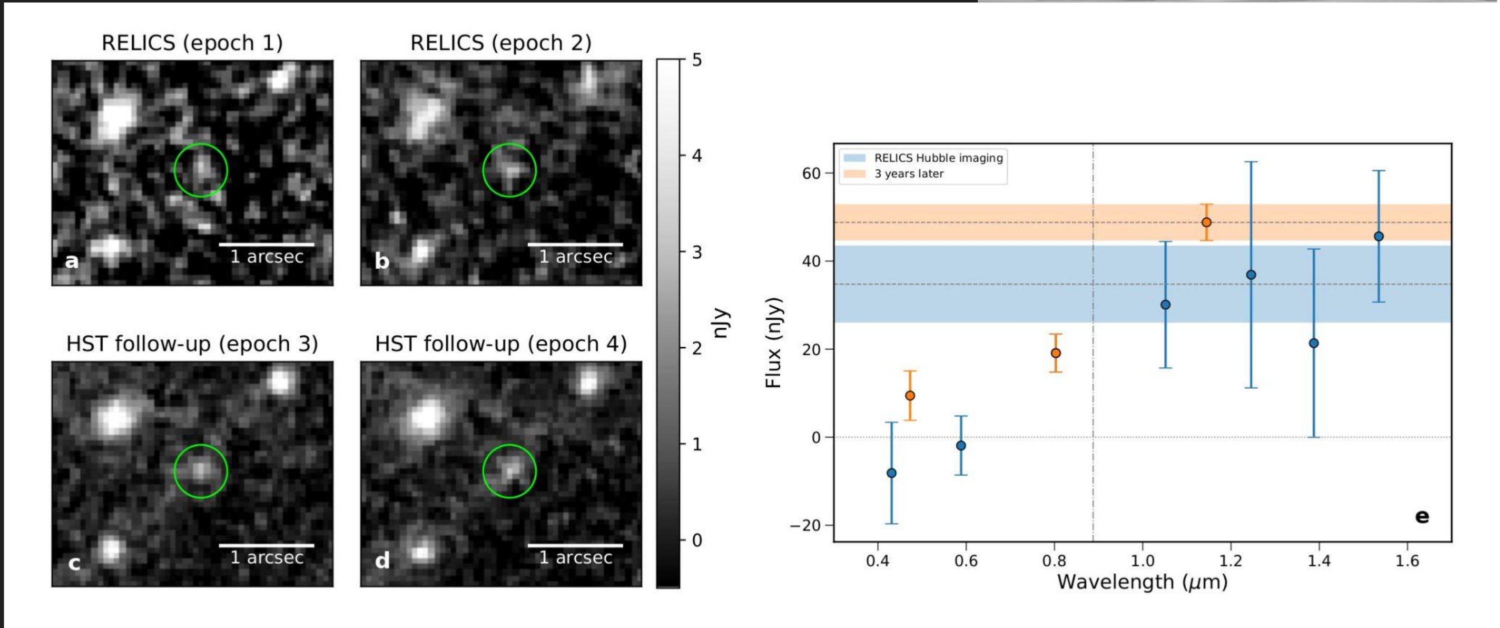
Microlensing - A Stable Lensed Star



"Optically thick" microlens network predicted in simulations

~1.4x variation between RELICS and follow-up imaging
Consistent with expectations from simulations

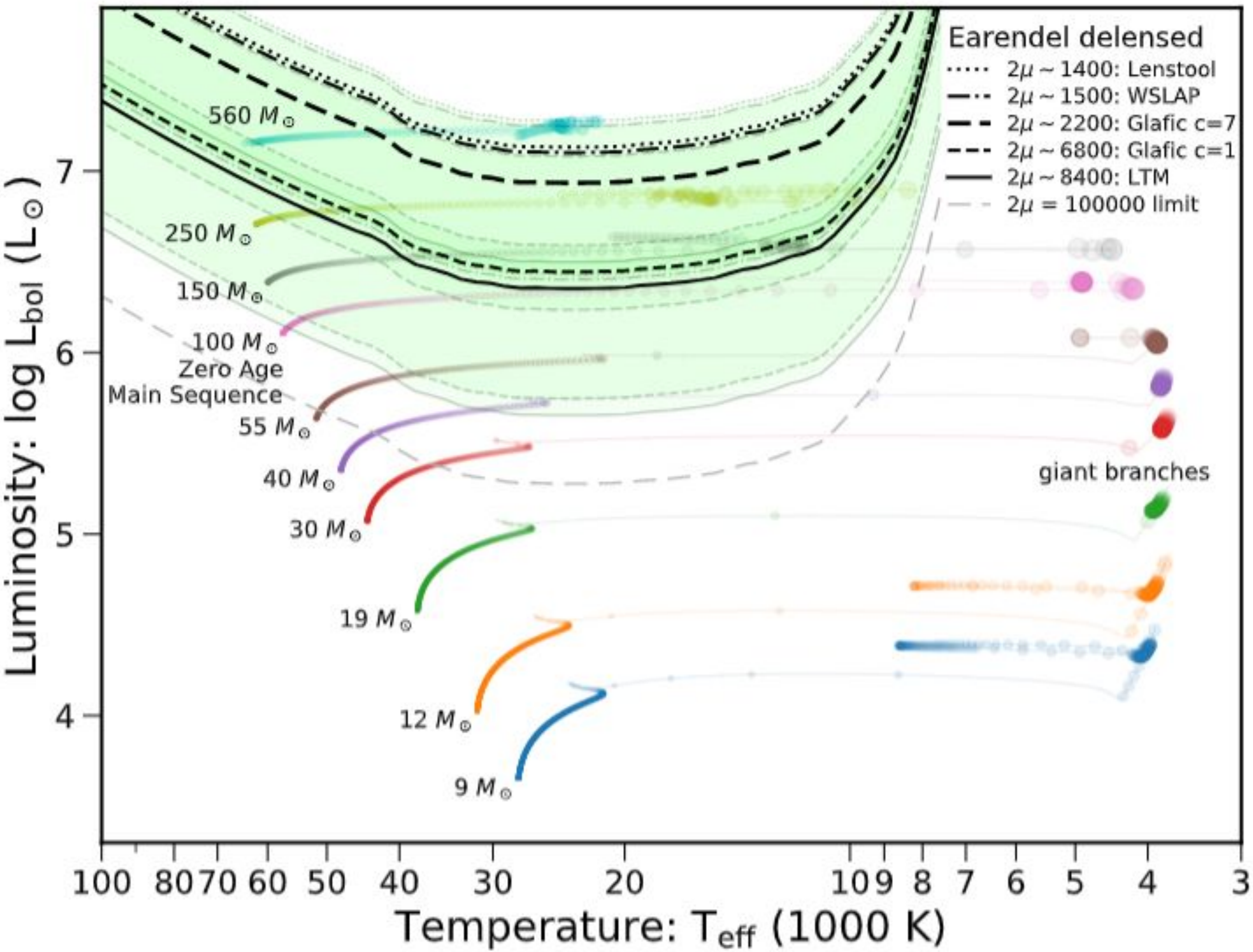
Further follow-up ongoing with HST



Stellar properties

$M \gtrsim 50\ M_\odot$

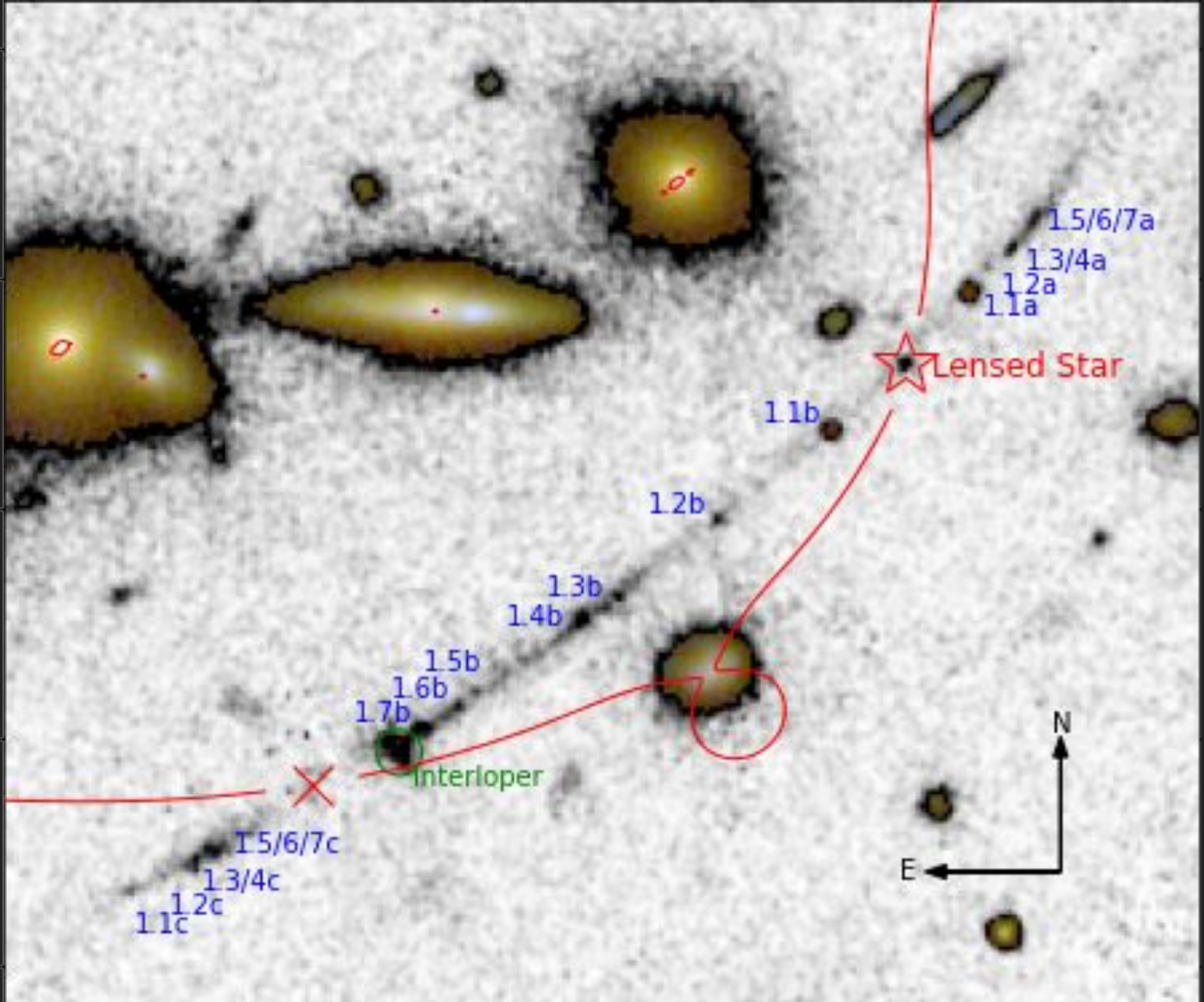
Tighter constraints forthcoming from JWST



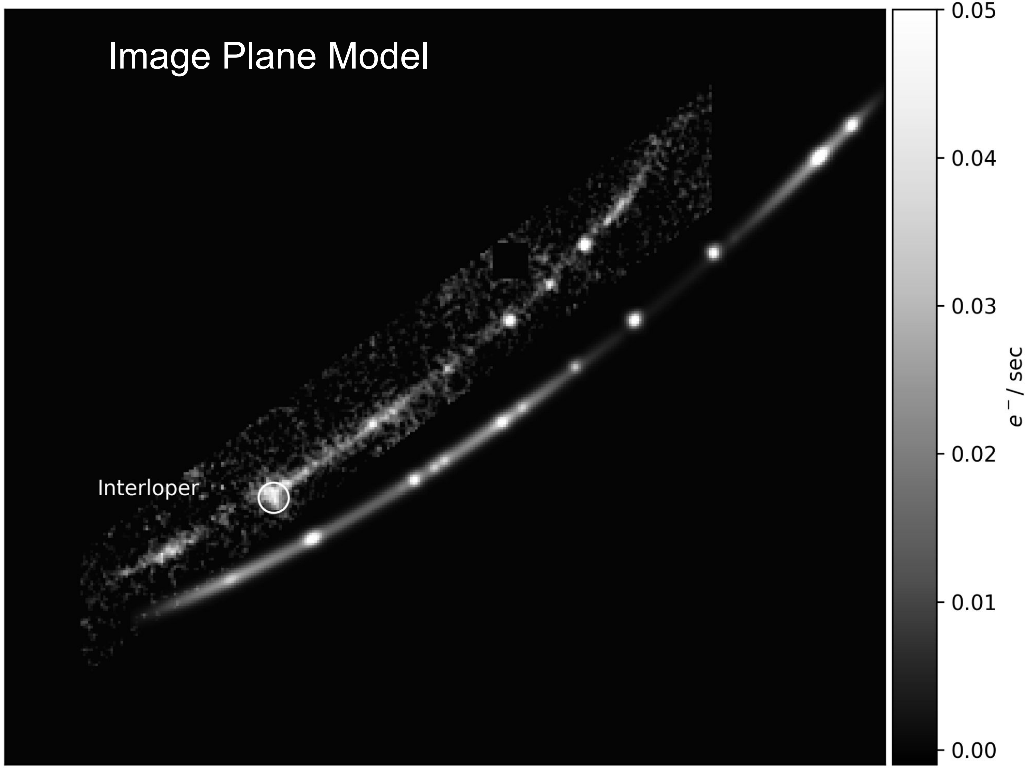
A Closer Look

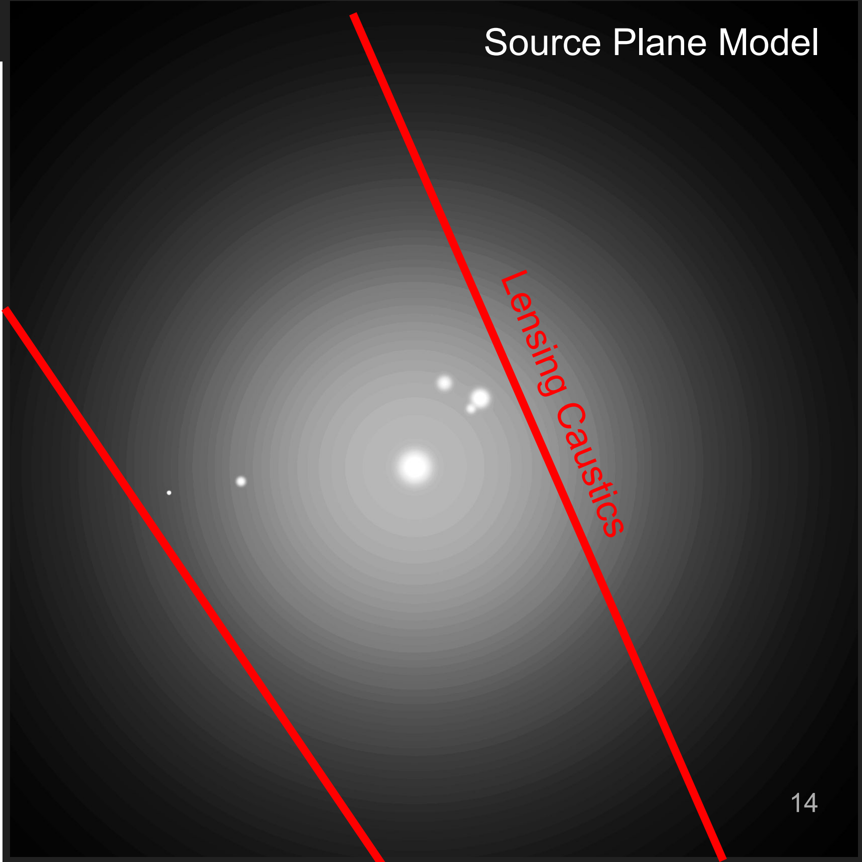
Critical curve at z = 6.2

Lensed star WHL0137-LS, nicknamed Earendel (Old English “morning star”). The star is magnified by μ > 1000



7 Star-forming Clumps out to ~500 pc





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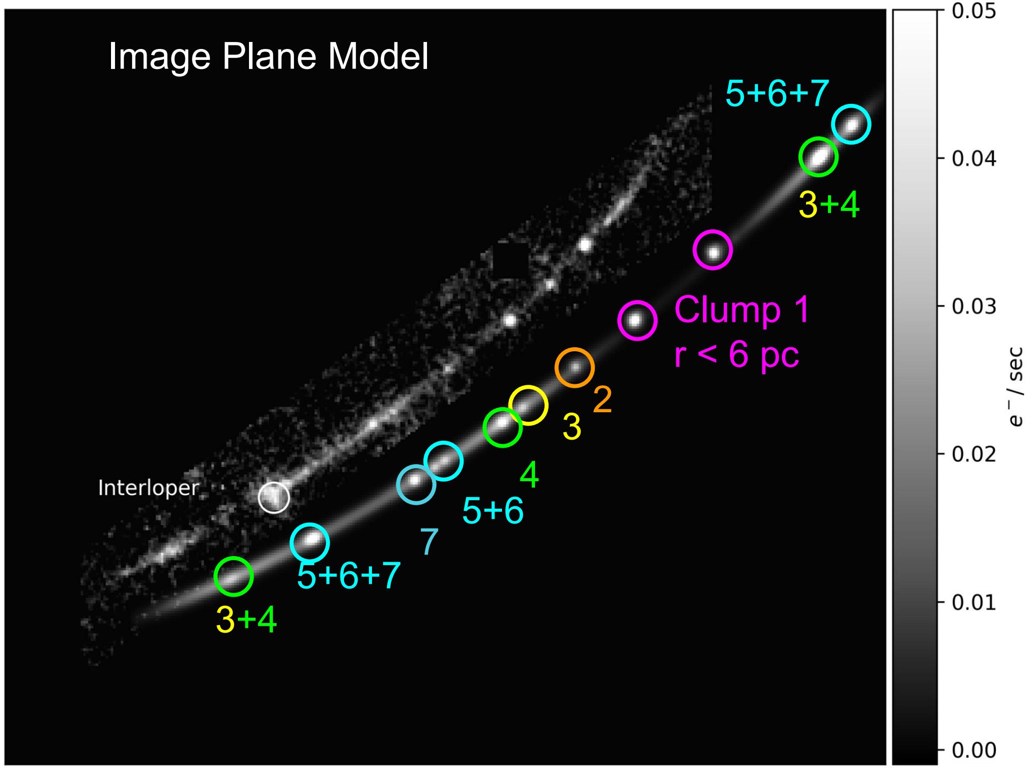
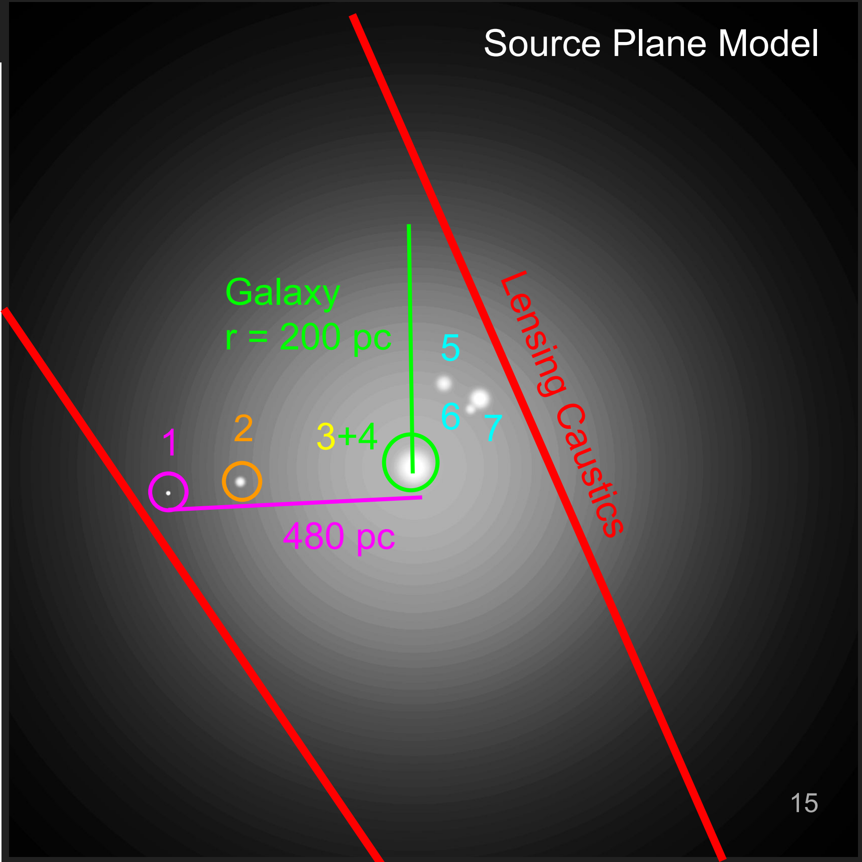
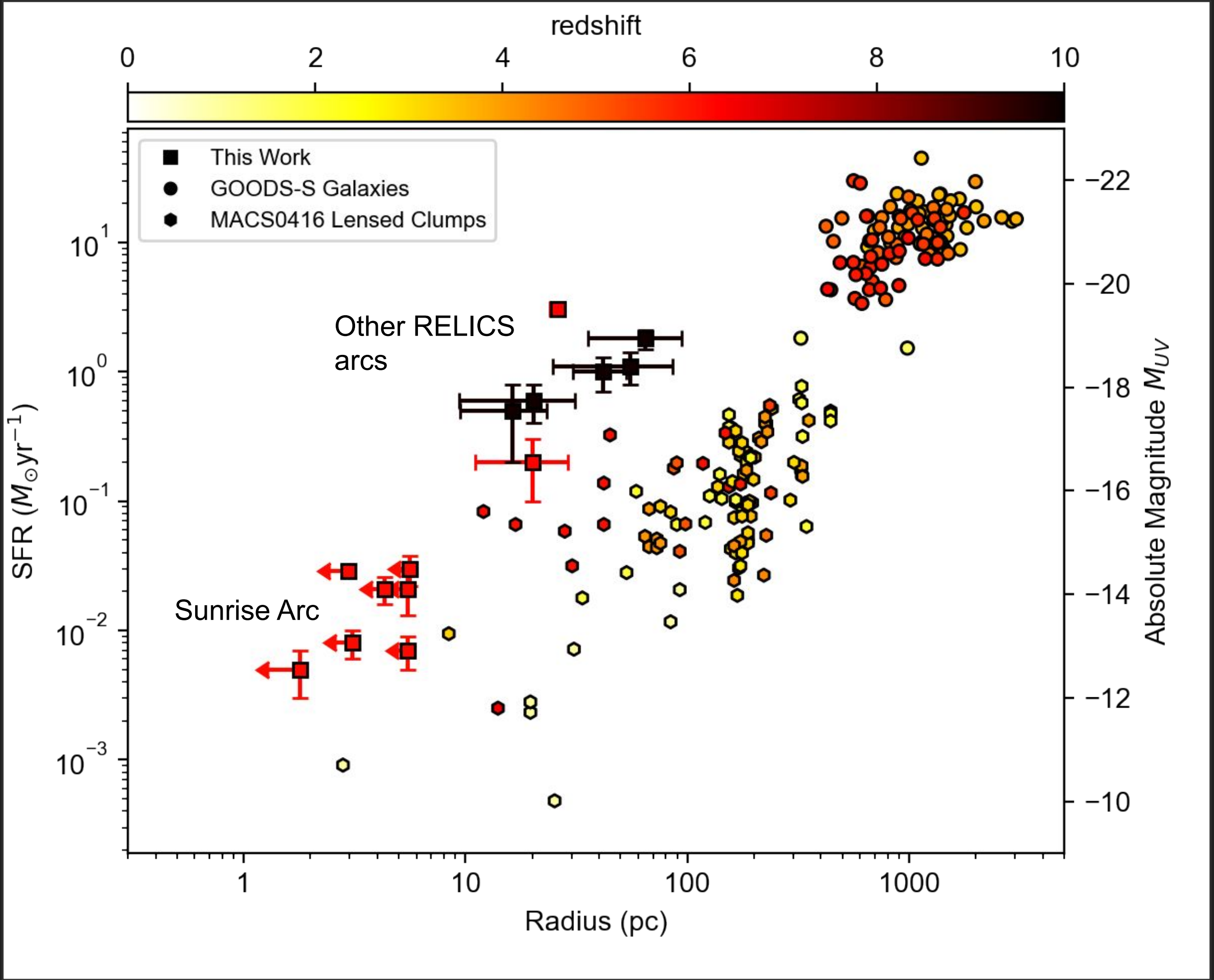




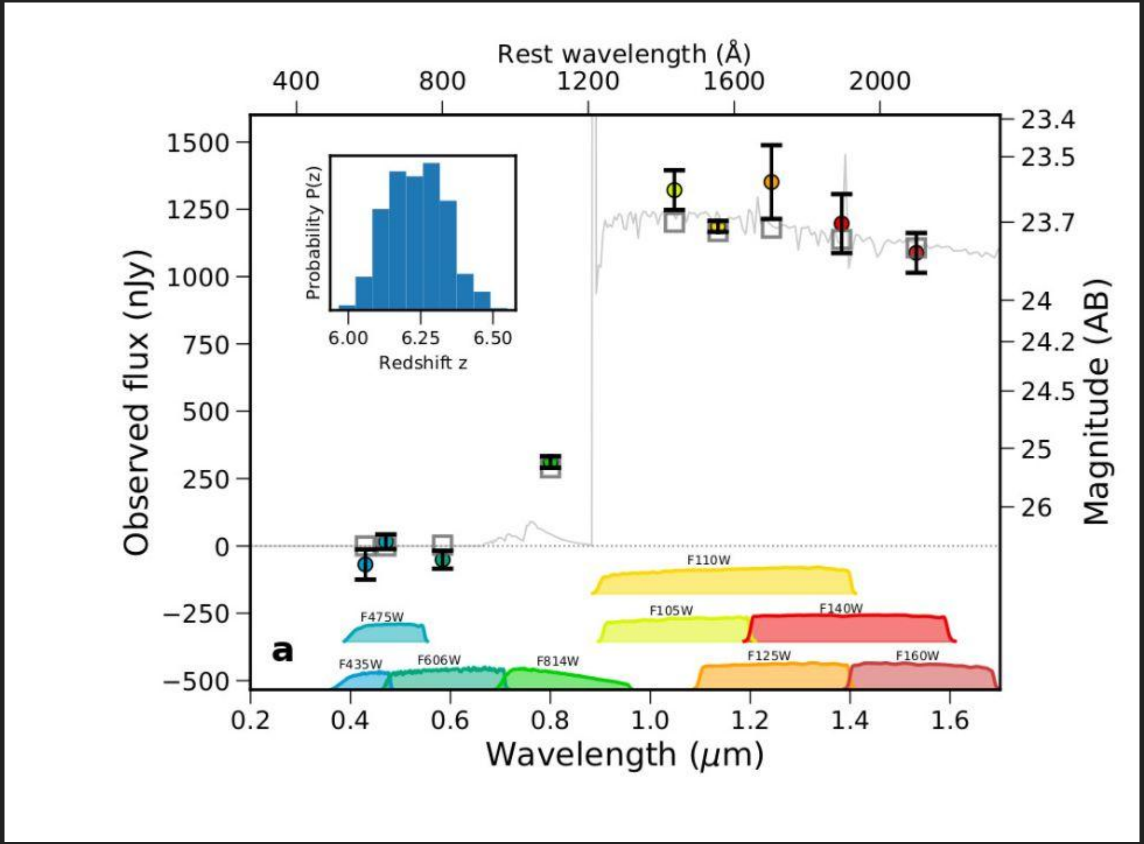
Parsec-scale Clumps at z~6

With radii < 10 pc, the Sunrise Arc hosts the smallest star clusters known at z > 6



SED Fitting

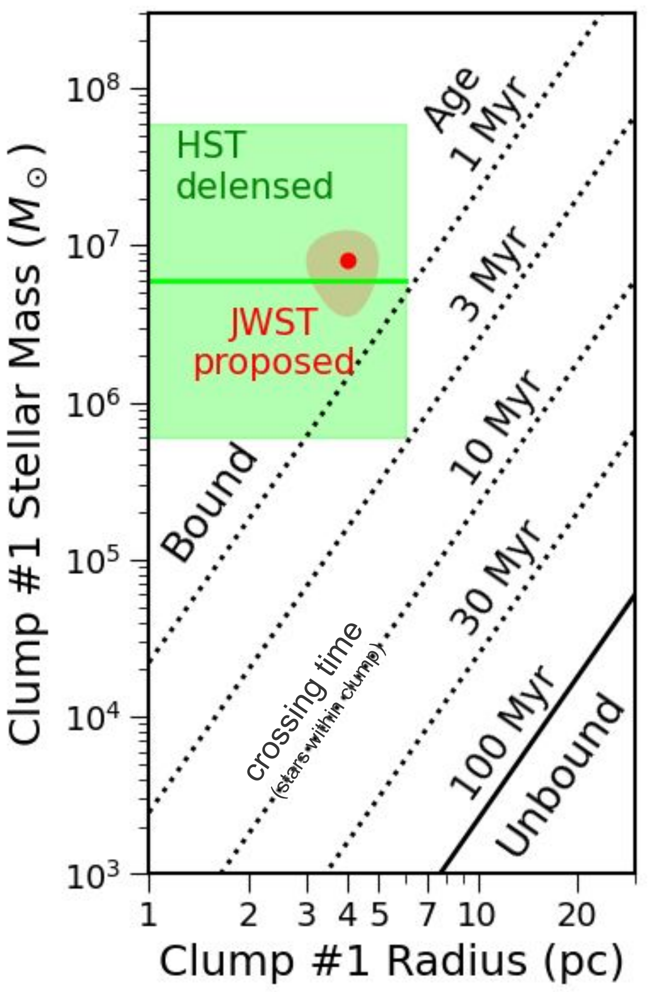
- Fit to full Sunrise Arc using BAGPIPES
- Only HST data available, too faint for reliable Spitzer fluxes
- Good constraints on SFR, M*
- Scale properties down to individual clusters, as they are too faint to fit individually



Bound star clusters?

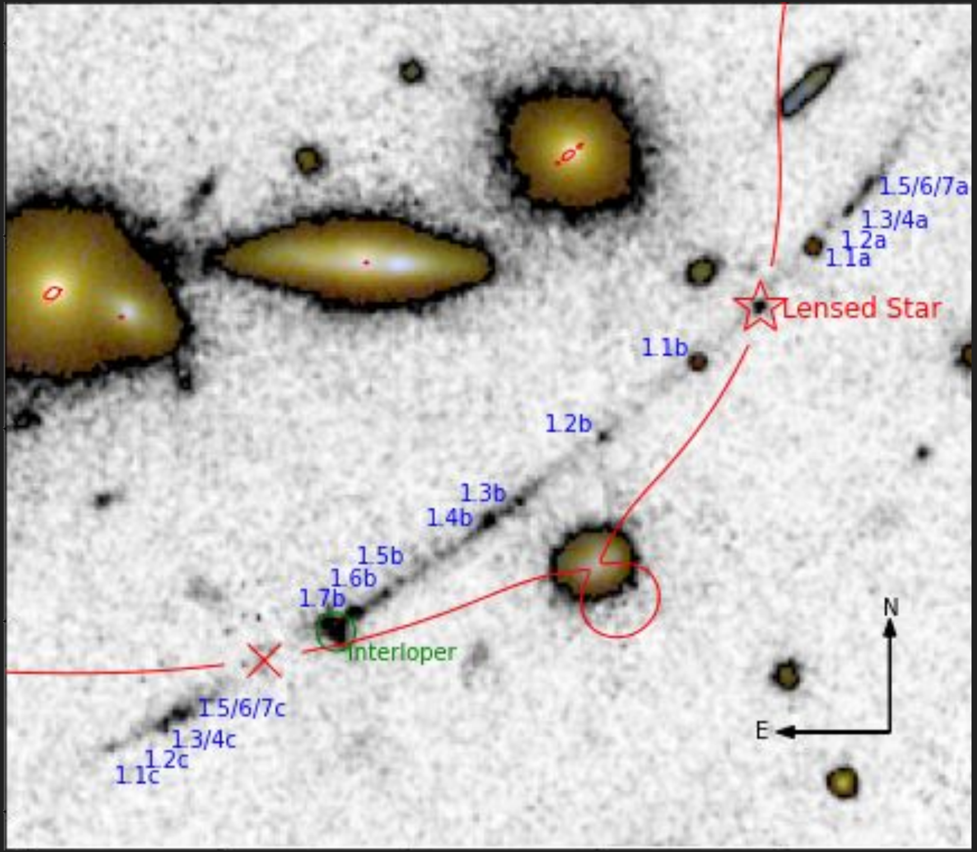
- Each star cluster in the Sunrise Arc has crossing time < 1 Myr
- Ages are poorly constrained from SED fitting, given only HST near-IR data
    - Best-fit ages are ~ few hundred Myr
- High Σ_{SFR} (750 $M_{\odot}$ yr^{-1} kpc^{-2}) could imply stellar feedback will disrupt clusters
- Better constraints to come from JWST

Age > crossing time = Bound cluster



Looking to the Future with JWST

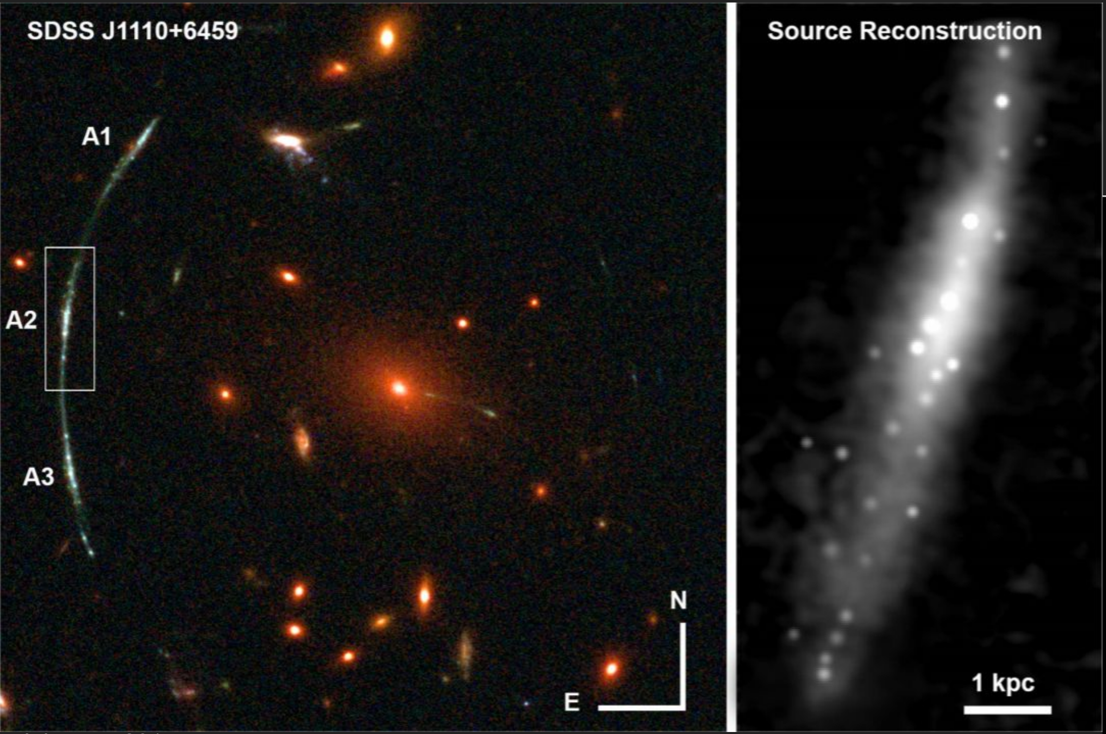
- Upcoming JWST GO 2282 (PI Coe)
- NIRCam - tighter size constraints
- NIRSpec
  - Spec-z
  - SFR ($H\alpha$),
  - Metallicity
  - Ionization parameter
  - Escape fraction
  - Stellar spectrum for Earendel
- More possibilities for future cycles!



Conclusions

- Lensing offers a more detailed look into hi-z galaxies, down to parsec scales
- Helps constrain star/galaxy formation, reionization
- JWST spectroscopy of strongly lensed galaxies will be awesome

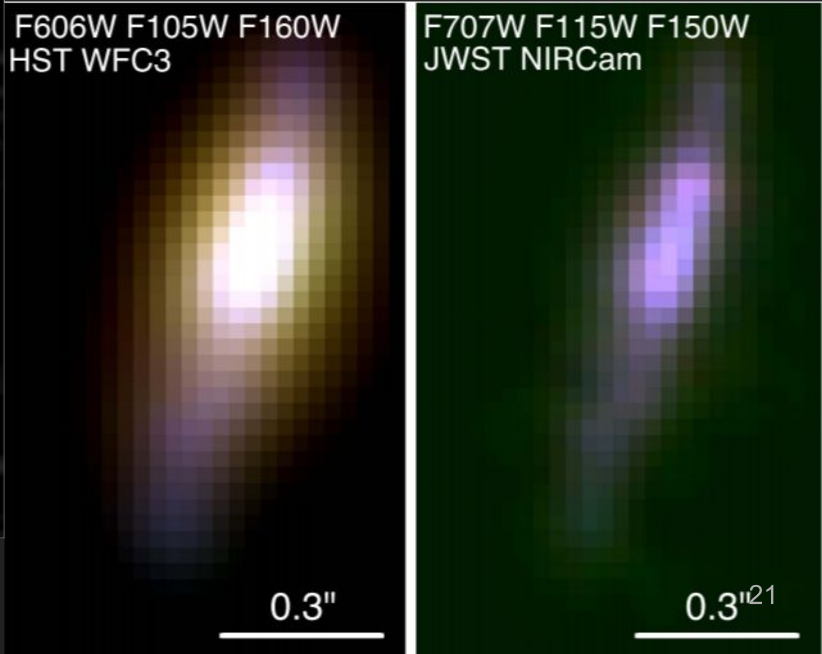
Lensing Magnifies the Distant Universe



Johnson+2017

Rigby+2017

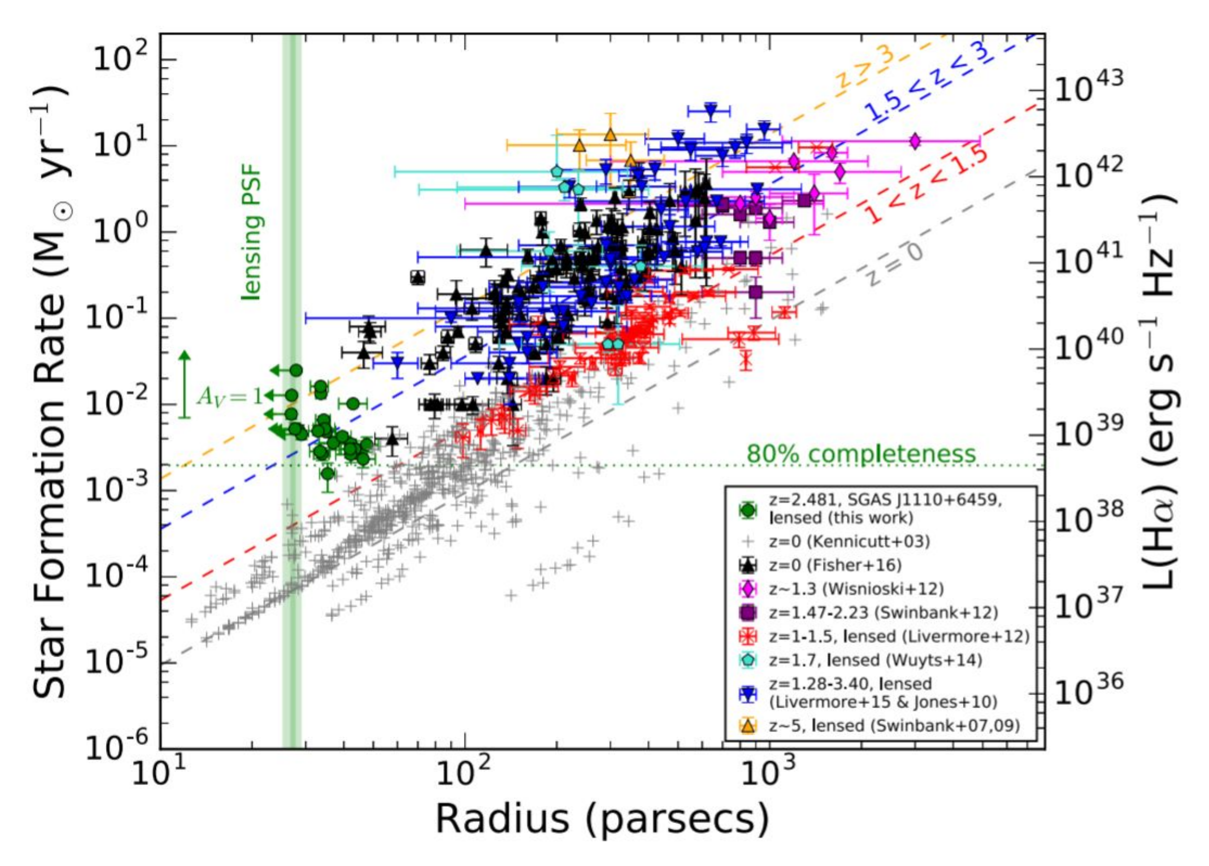
Probe physical scales down to tens of parsecs (or lower!)
Comparable to local star forming regions



“Turtles all the way down”

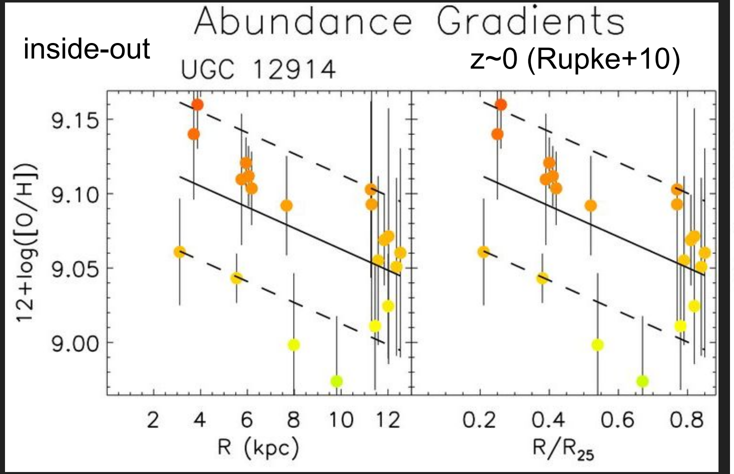
- Galaxies are clumpier at higher redshift
- Most star formation occurs in clumps
- Lensed galaxies reveal smallest star forming clumps
- Star formation in clumps evolves with redshift (out to z ~ 3)

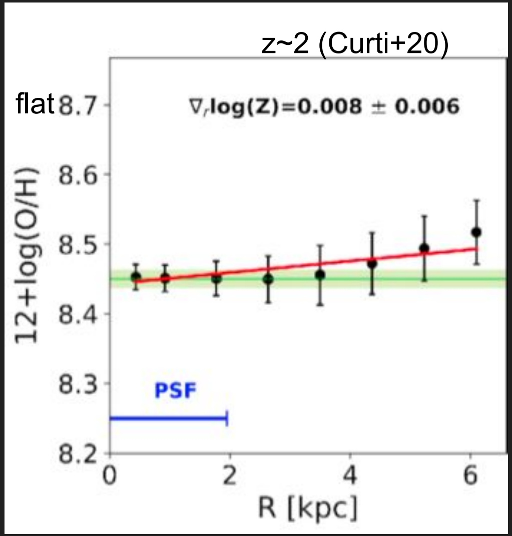
Johnson+17

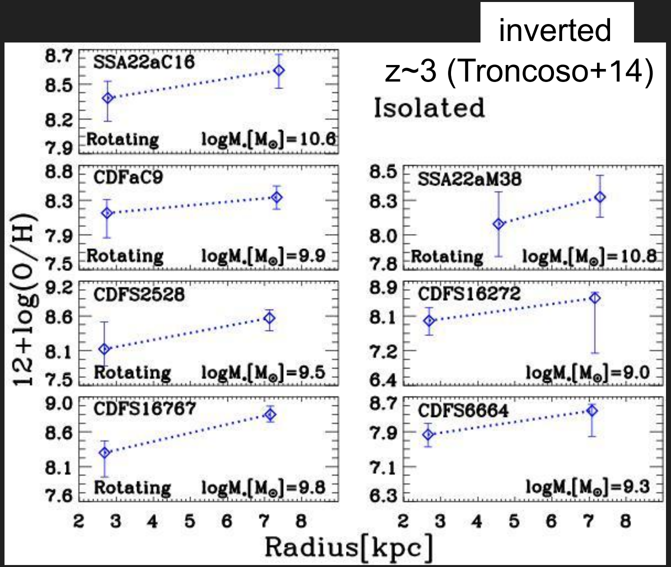


Galaxy clump analyses constrain galaxy formation models

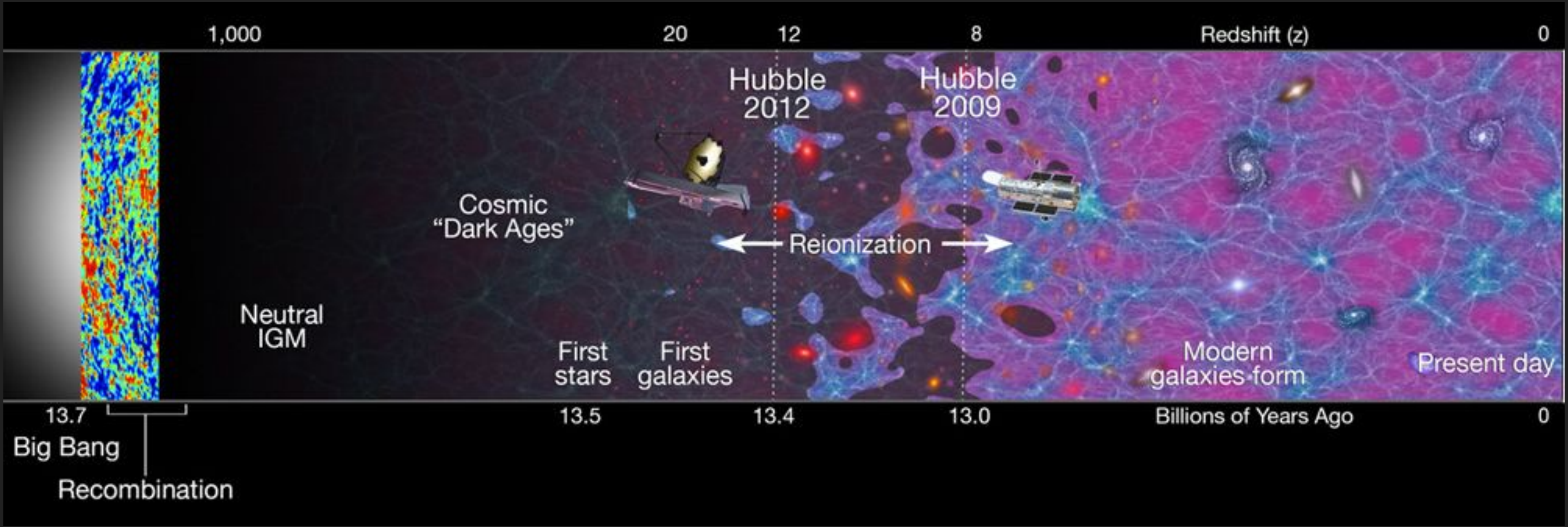
- Inside-out growth: more massive, older, higher metallicity clumps in core? Inverted metallicity gradients in high-z galaxies?





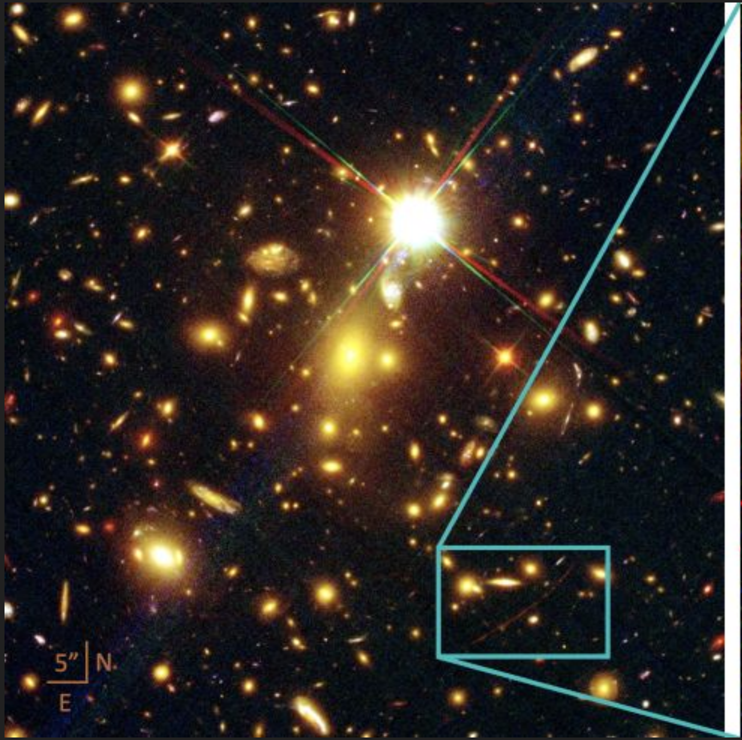


Reionization!

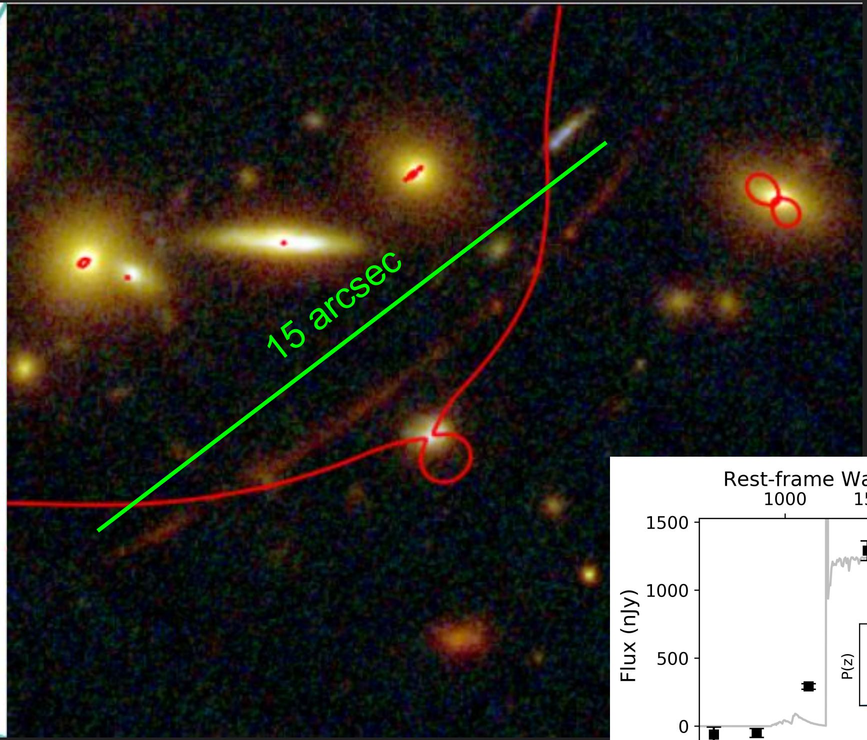


Detailed hi-z galaxy studies can give us insight into ionizing photon escape

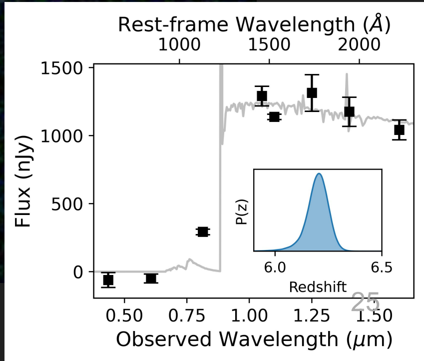
The Sunrise Arc: The most highly magnified z > 6 galaxy



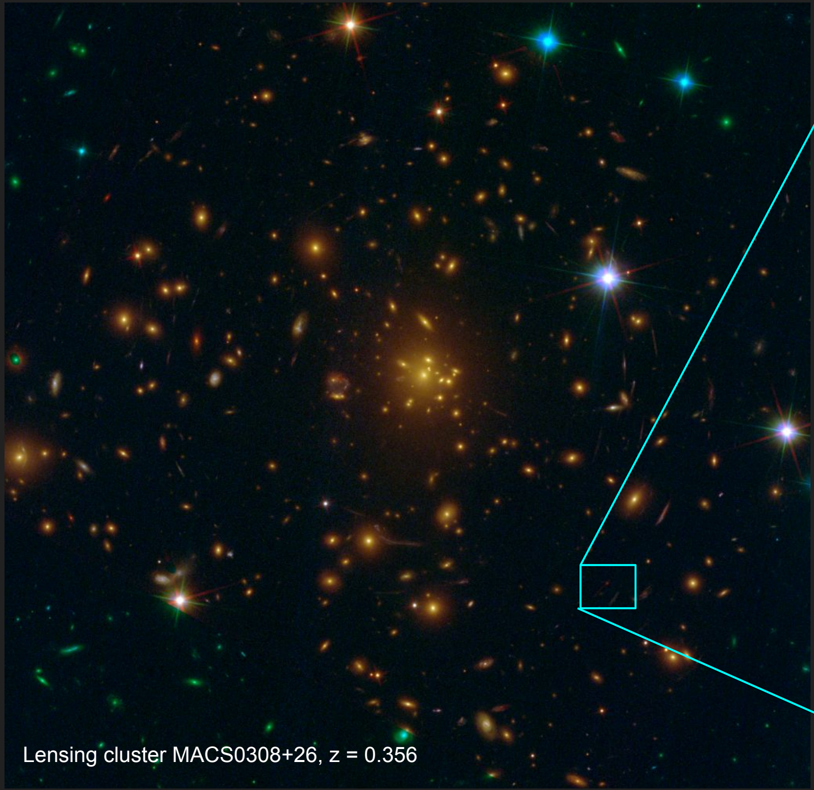
Lensing cluster WHL0137-08, z = 0.566



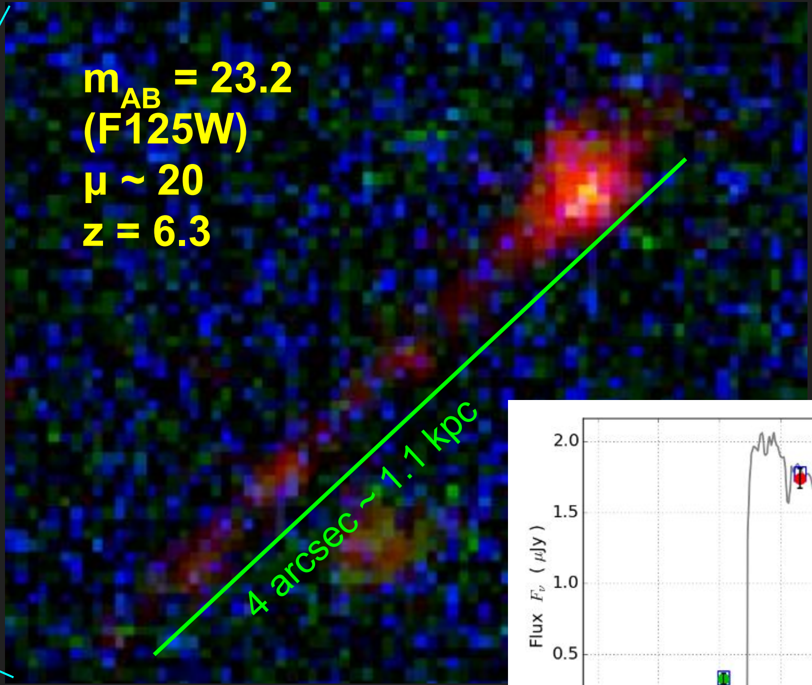
HST Follow-up: GO 15842 (PI Coe)



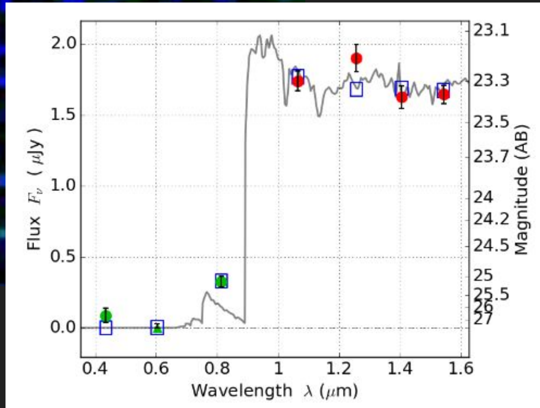
The Brightest Lensed z~6 Galaxy



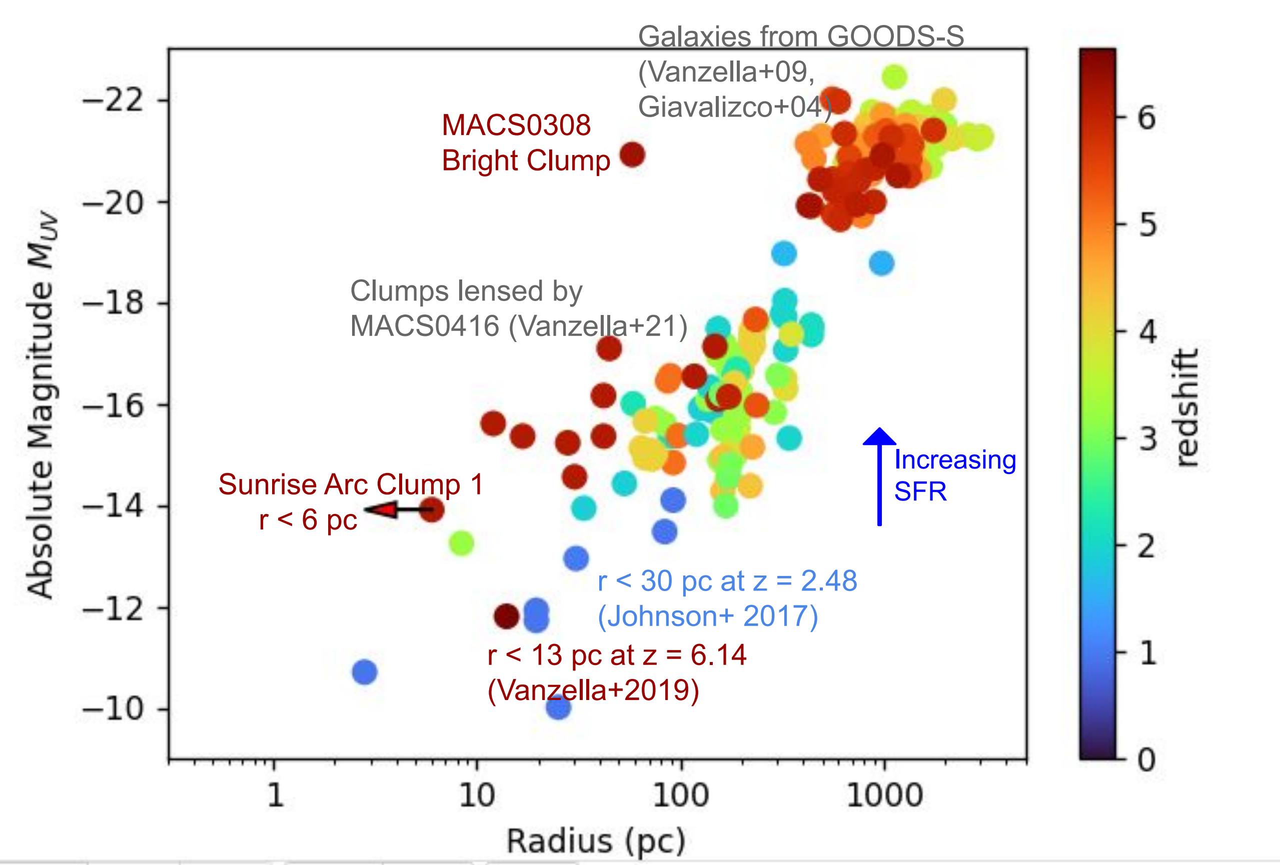
Lensing cluster MACS0308+26, z = 0.356



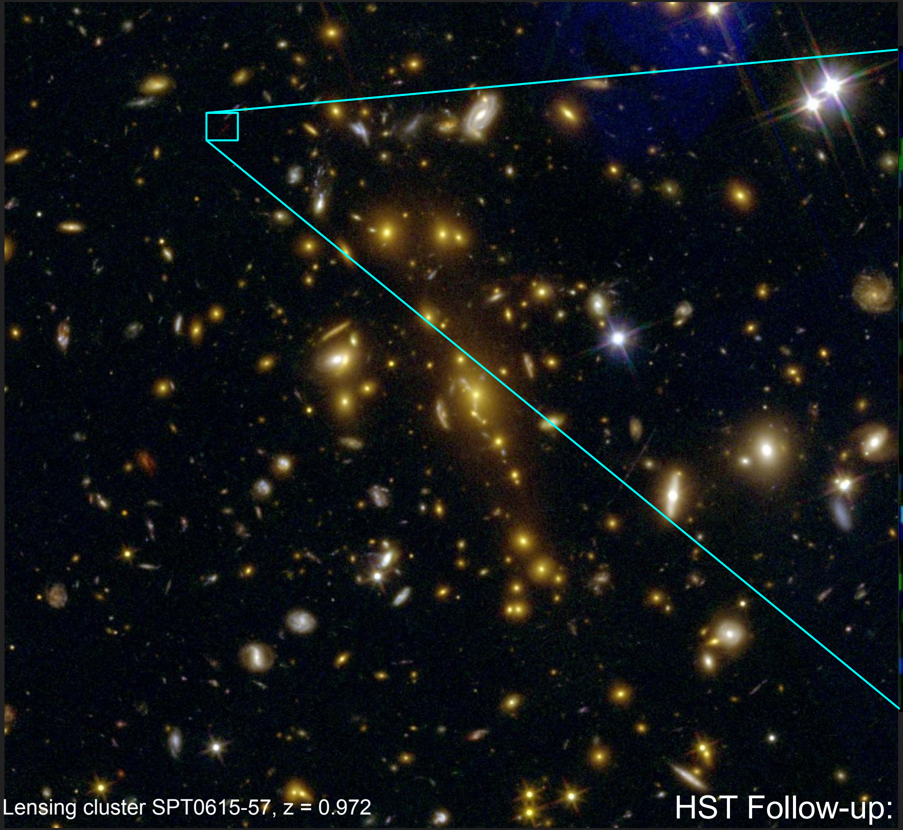
Acebron+2018



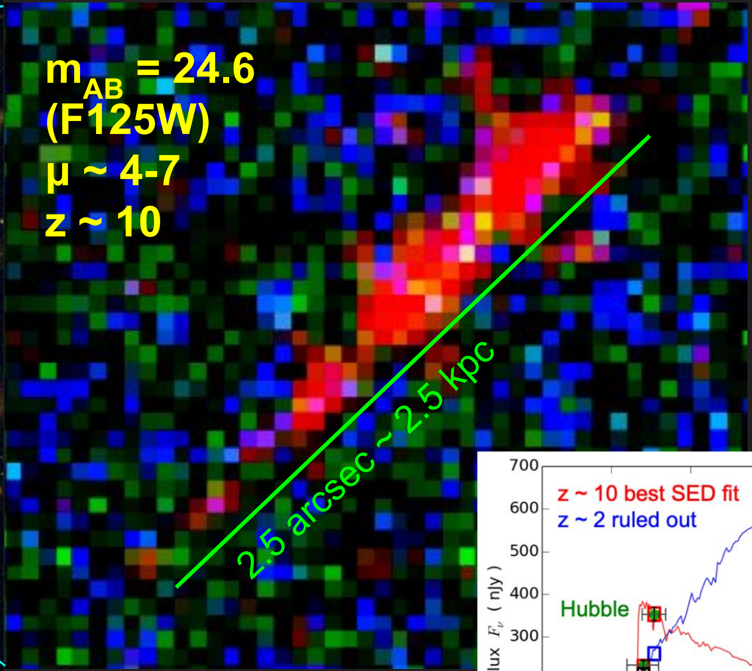
Parsec-scale Clumps at z~6



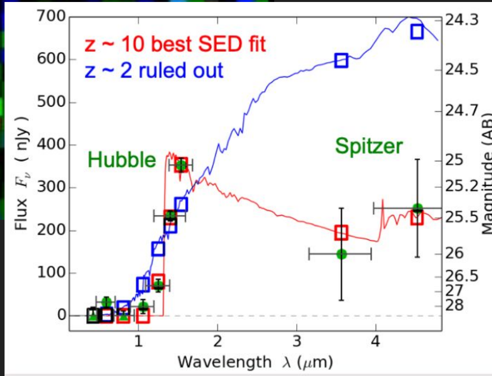
The Only Lensed Arc at z~10



Lensing cluster SPT0615-57, z = 0.972

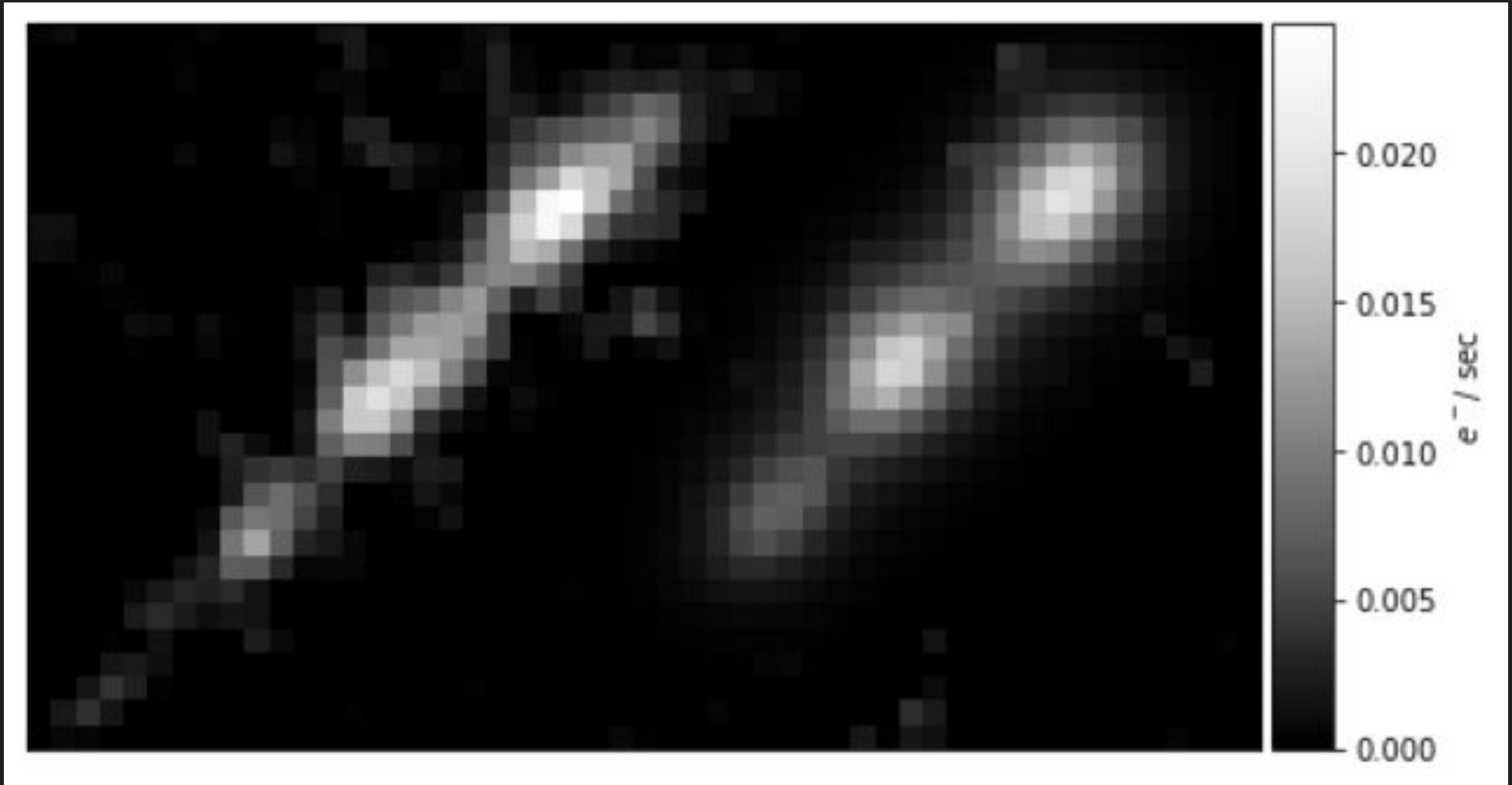


Salmon+ 2018, Strait+2020
Paterno-Mahler+2018

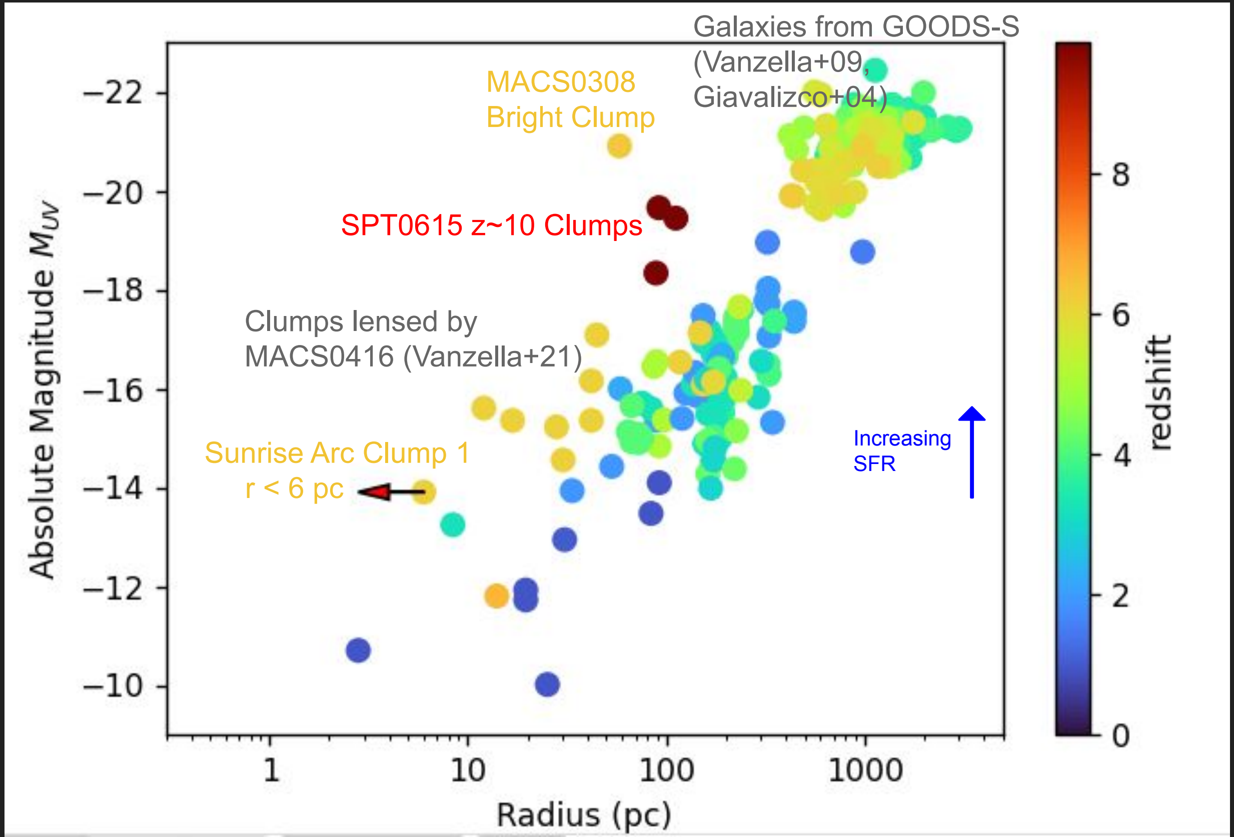


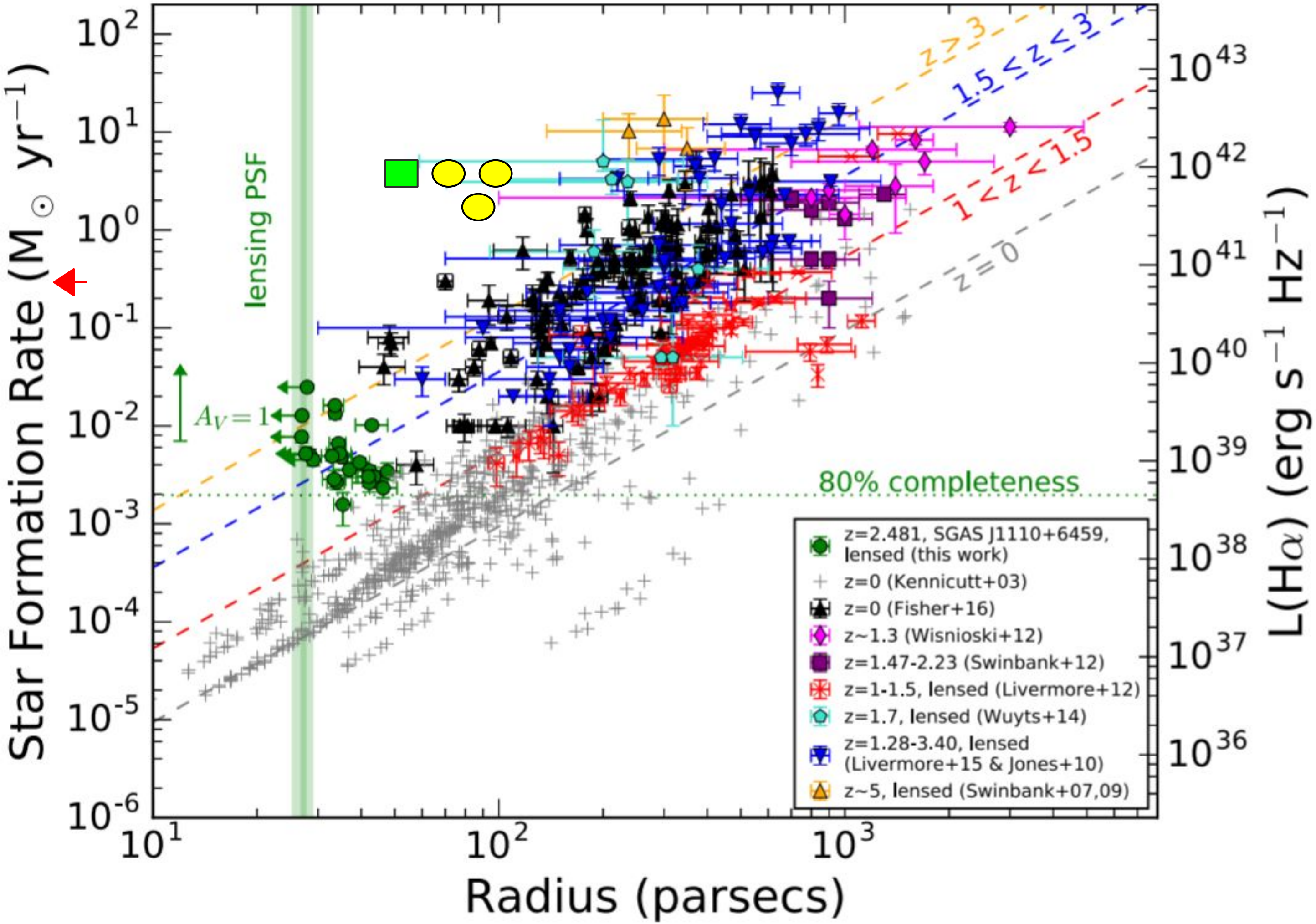
HST Follow-up: GO 15920 (PI Salmon)

Lensed arc at z~10



Parsec-scale Clumps at z~6





= WHL0137-08 (Sunrise Arc, z~6)

= MACS0308+26 (Bright arc, z~6)

= SPT0615-57 (Most distant, z~10)