Unscrambling Galaxy Cluster Fields in the JWST Era

Outline:

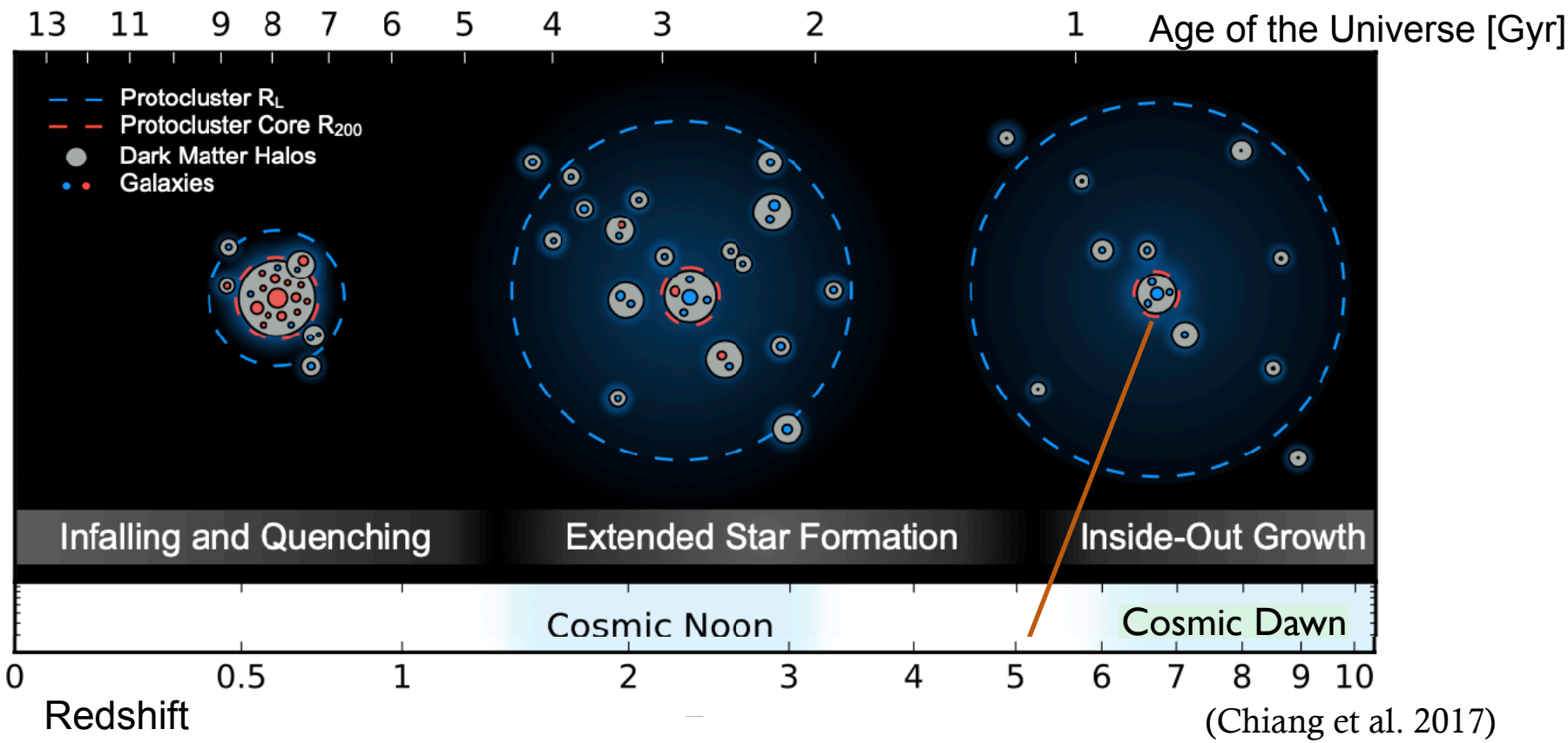
1. Cluster Lensing Motivation;
   PEARLS; Planck-selected clusters
2. One JWST **PEARLS** rebel:
   PLCK G165.7+67.0 (G165)
3. The JWST gift: SMACS 0723.3-7327 (SMACS 0723) and the future!

By Brenda Frye (UA), **Massimo Pascale (UCB), Nick Foo, Reagen Leimbach, Nikhil Garuda, Paulina Soto Robles (UA), Carlos Garcia** and D. Wang (U Mass. Amherst), K. Harrington (ESO), P. Kamiensky (ASU), L. Dai (UCB), L. Furtak & A. Zitrin (Ben Gurion), J. Diego (IFC, Spain), R. Windhorst (ASU) and the PEARLS Team

January 19, 2023

1. The Galaxy Clusters: motivation

- Inside-out: core dominates star forming activities by $z = 5$
- Extended SF: numerous halos reach 10^{12} Msun; galaxies maximize star formation rates (SFRs~1000 Msun yr^{-1}), and produce dust
- Late times: galaxy quenching lowers SFRs, flattens stellar mass



(Chiang et al. 2017)

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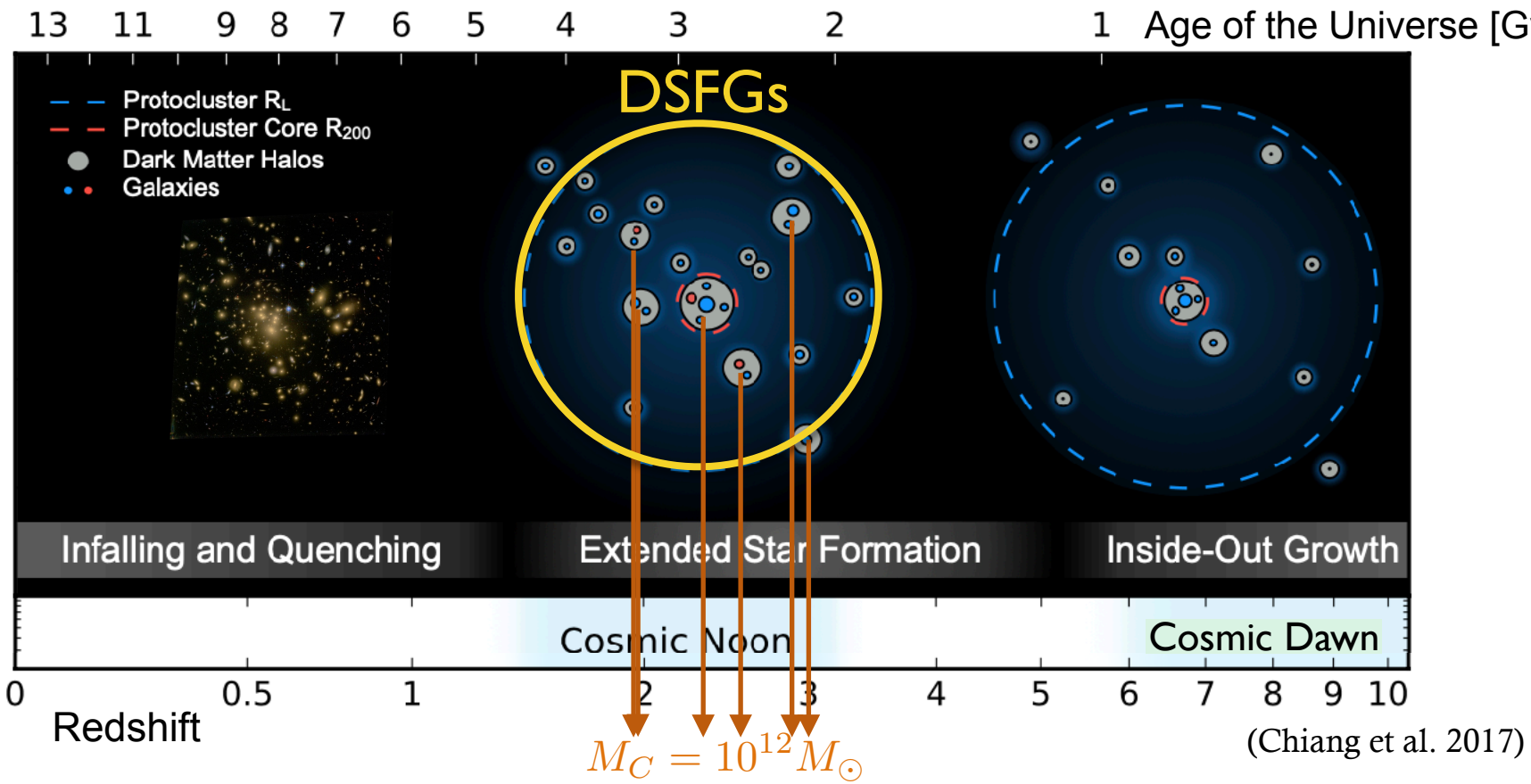


(Chiang et al. 2017)

Protoclusters deliver the highest active sites of star formation in universe up to Cosmic Noon

1. The Galaxy Clusters: the dark matter

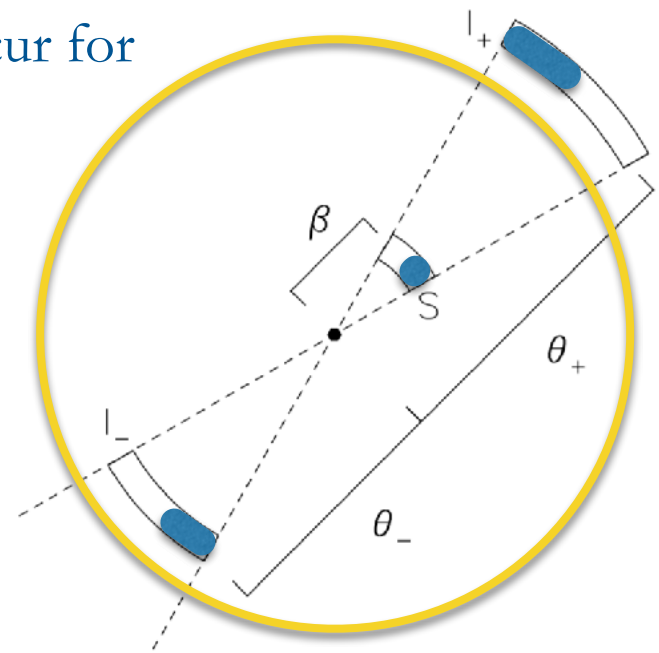
- The lens equation relates source, image and deflection angles relative to the optic axis: $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$

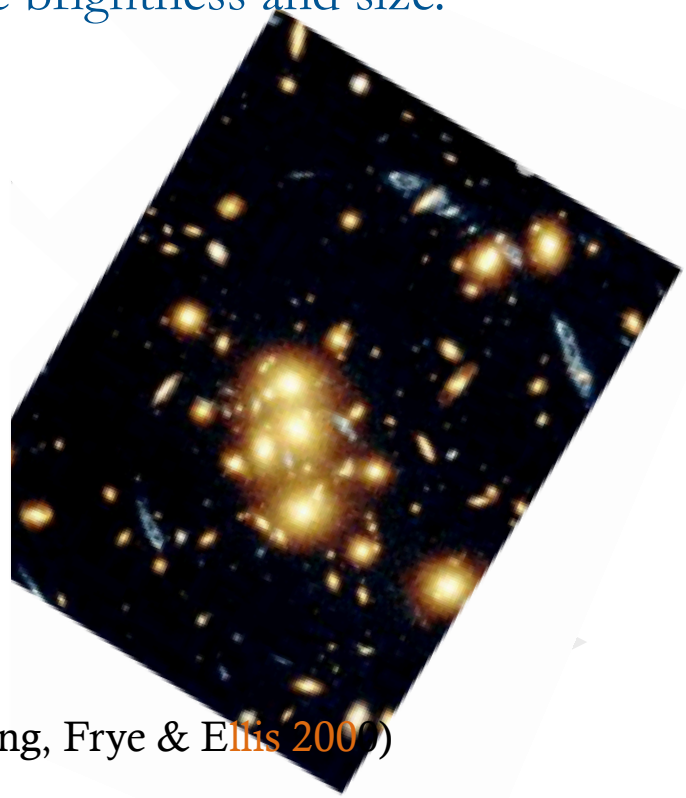
- For the point mass, $\alpha \sim 1/b$, and for the canonical singular isothermal sphere, the α = constant!

$$\alpha = 4\pi \frac{\sigma_v^2}{c^2} = 1.4 \left(\frac{\sigma_v}{220 kms^{-1}} \right)^2$$

- Magnification varies with radius: $\mu_{\pm} = \left(1 \mp \frac{\theta_E}{\theta_{\pm}}\right)^{-1}$, where θ_E is produced for a source on the optic axis. Lensing boosts image brightness and size.

- Multiple images occur for $\Sigma > \Sigma_{crit}$, $\beta < \theta_E$





(Broadhurst, Huang, Frye & Ellis 2000)

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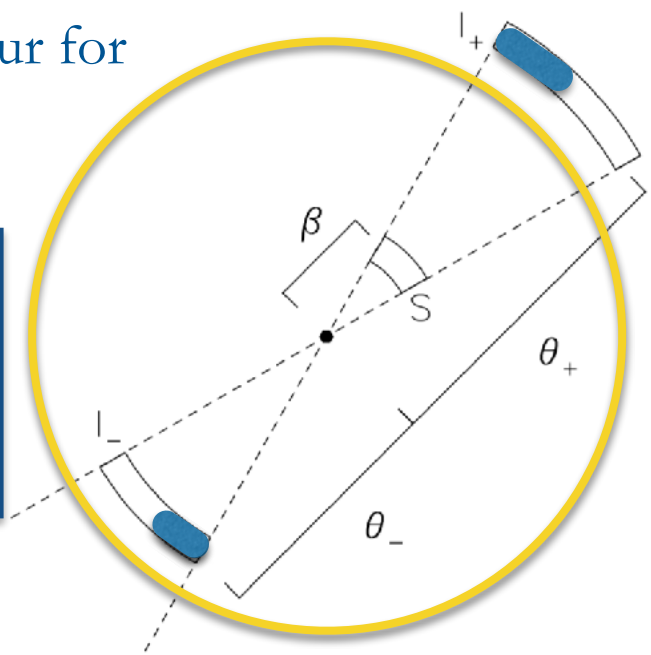
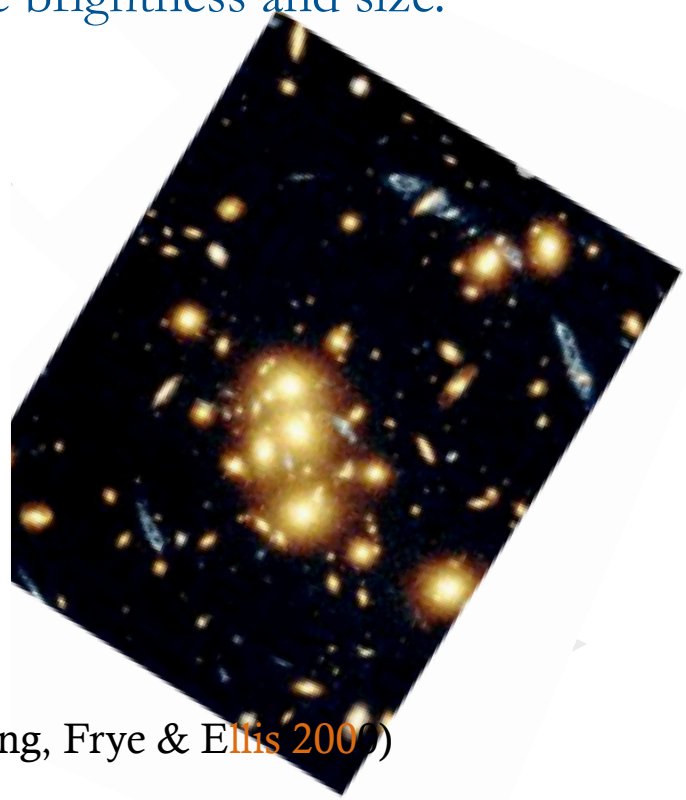
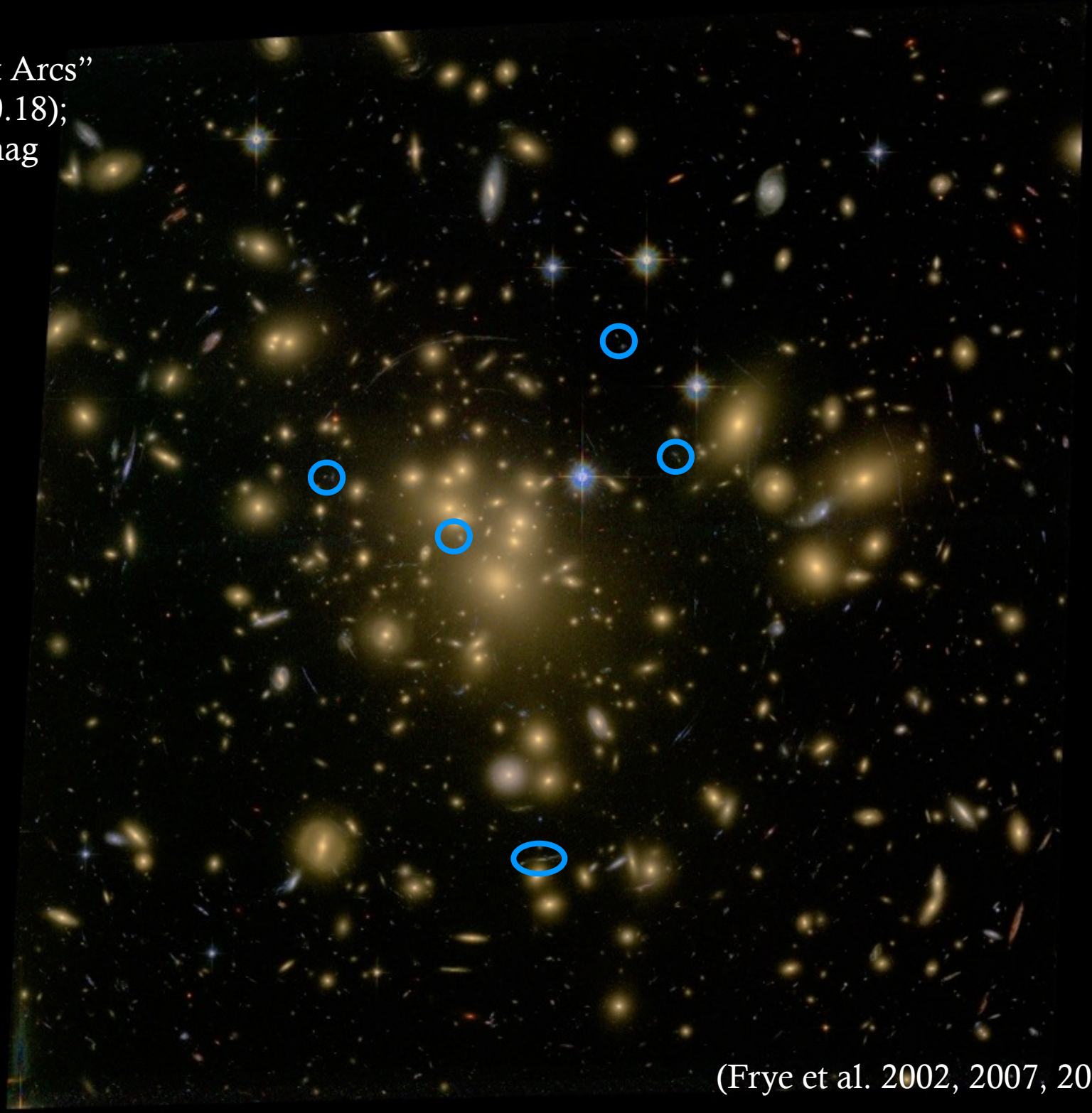
Multiply-imaged galaxies can be identified by color, lens-predicted location, and morphology





(Broadhurst, Huang, Frye & Ellis 2000)

The “Sextet Arcs”
A1689 (z=0.18);
m_{AB} ~ 27 mag



(Frye et al. 2002, 2007, 2008, 2012)

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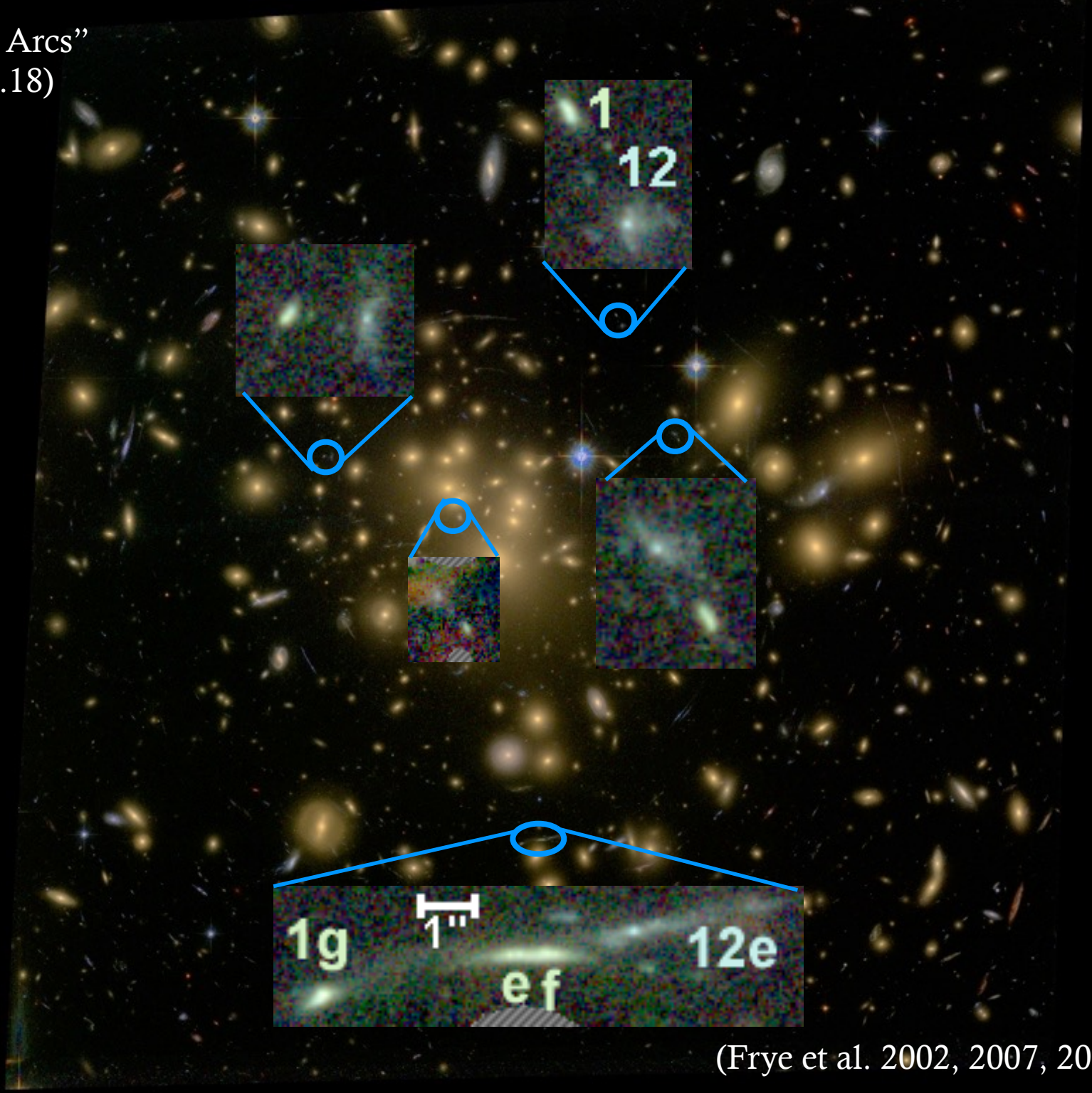

(Frye et al. 2002, 2007, 2008, 2012)

The JWST PEARLS Program

- Cluster lensing
  - HST surveys: ACS, CLASH, RELICS, HFFs
  - JWST plans lacked cluster coverage
- To meet JWST goals to understand mass assembly & discover first-light sources *requires* cluster component

- Instituted the fourth "pearl" in the **PEARLS** program, and recruited team
  - Two protoclusters:
  - Four well-studied clusters
  - Three rebels *by design*

All of them advance our understanding of dark matter, clusters, and distant universe by the lensing effect

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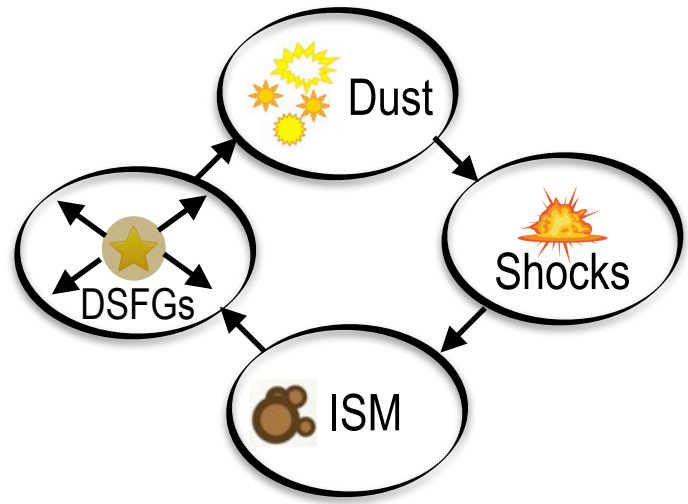
How to find an interesting cluster?

1. Motivation: Extending the Cluster Search Space, with JWST in mind



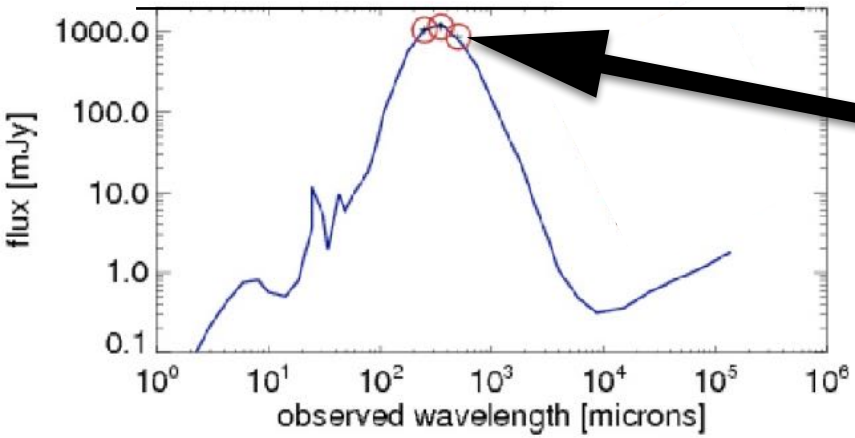
- Galaxy cluster searches
  - O/IR
  - X-rays
  - SZE
  - Is that all?

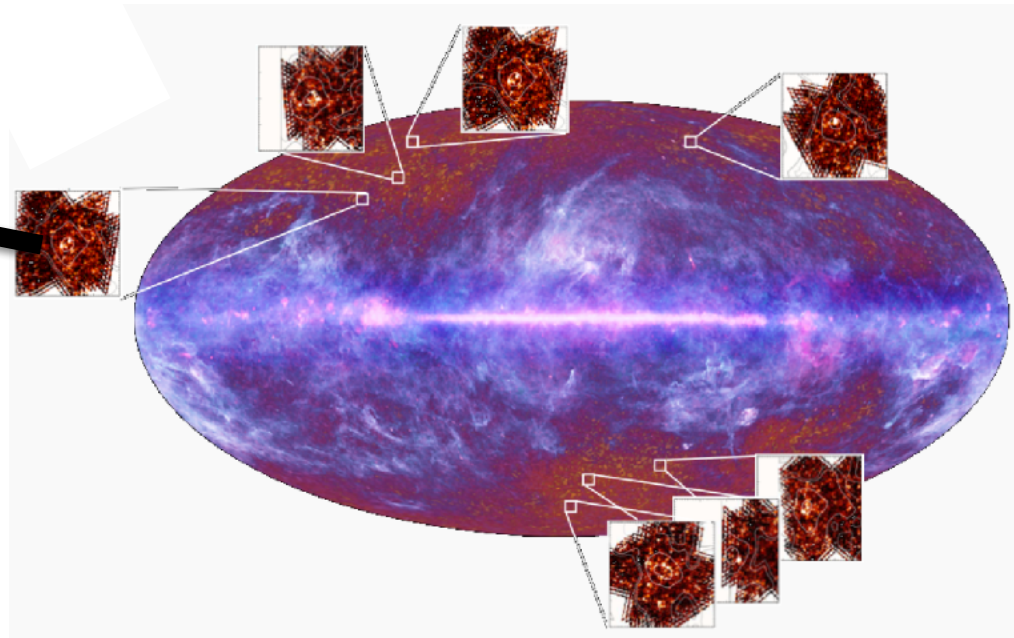
- Shake the pear tree:
  - Constrain dark matter properties
  - Understand how star-formation regulated at Cosmic Noon?

- Might clusters found by less conventional means contribute different cluster properties?
- One approach is to search for the over densities of DSFGs, which should coincide with protoclusters at Cosmic Noon!

1. Motivation: Extending the Cluster Search Space

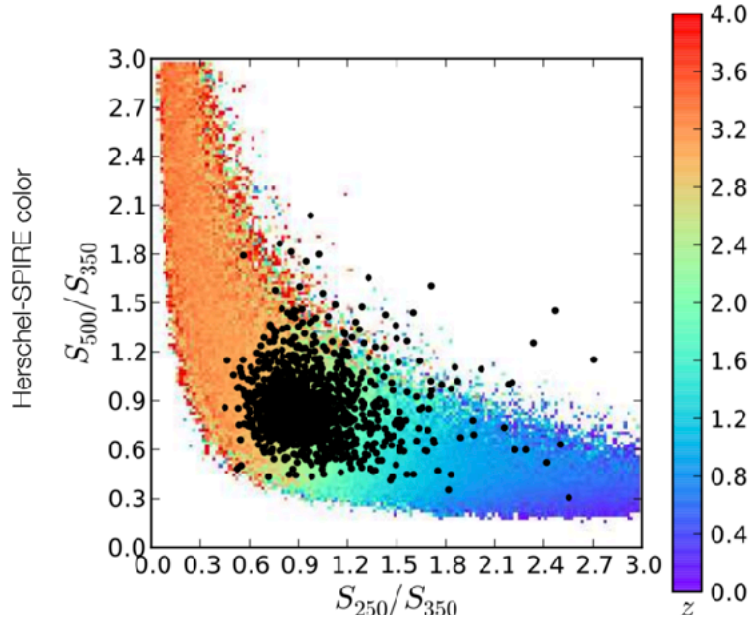
Planck!





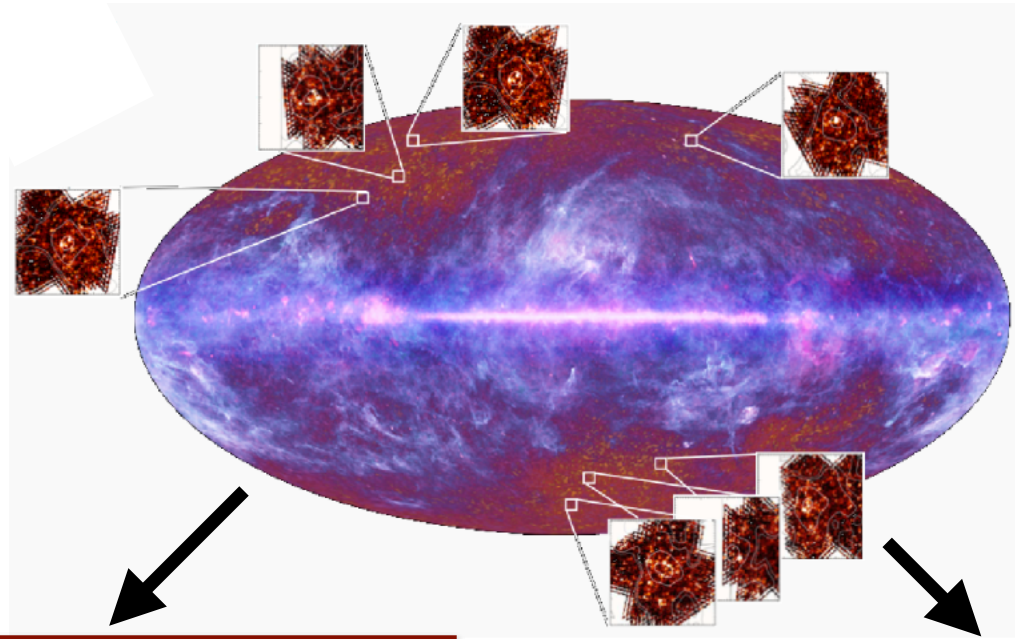
- new territory - CIB peaks ==> mass peaks
- all-sky survey relevant to find rare sources
- 2000 compact sources **FIR color-selected**
- follow-up 228 sources using *Herschel*

All sources are *new* - how did we do?

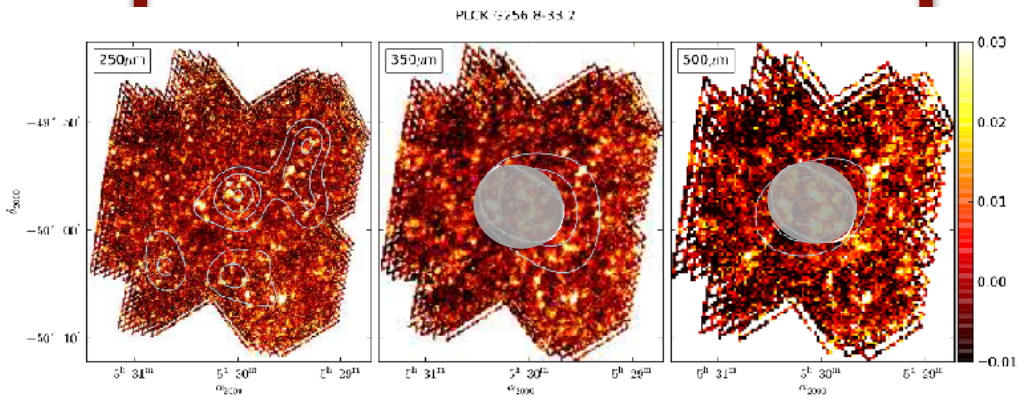


(Planck Collaboration XXVII 2015)

Two Sources and Two Directions

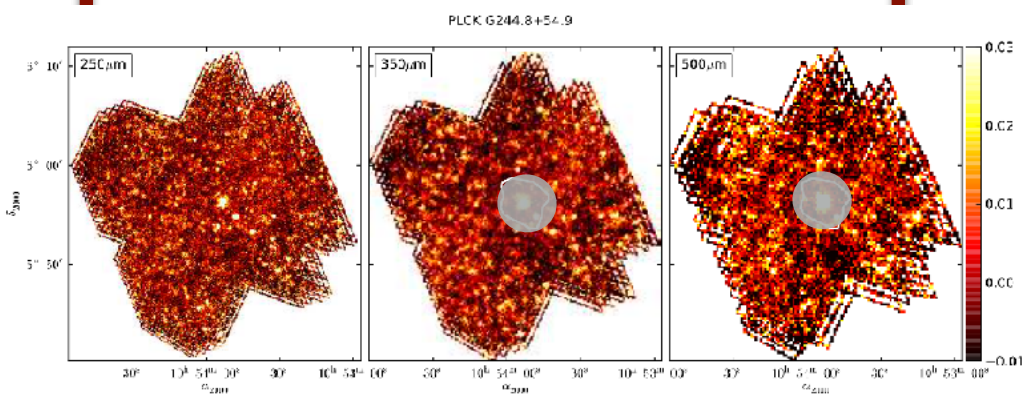


- Detect *protoclusters*



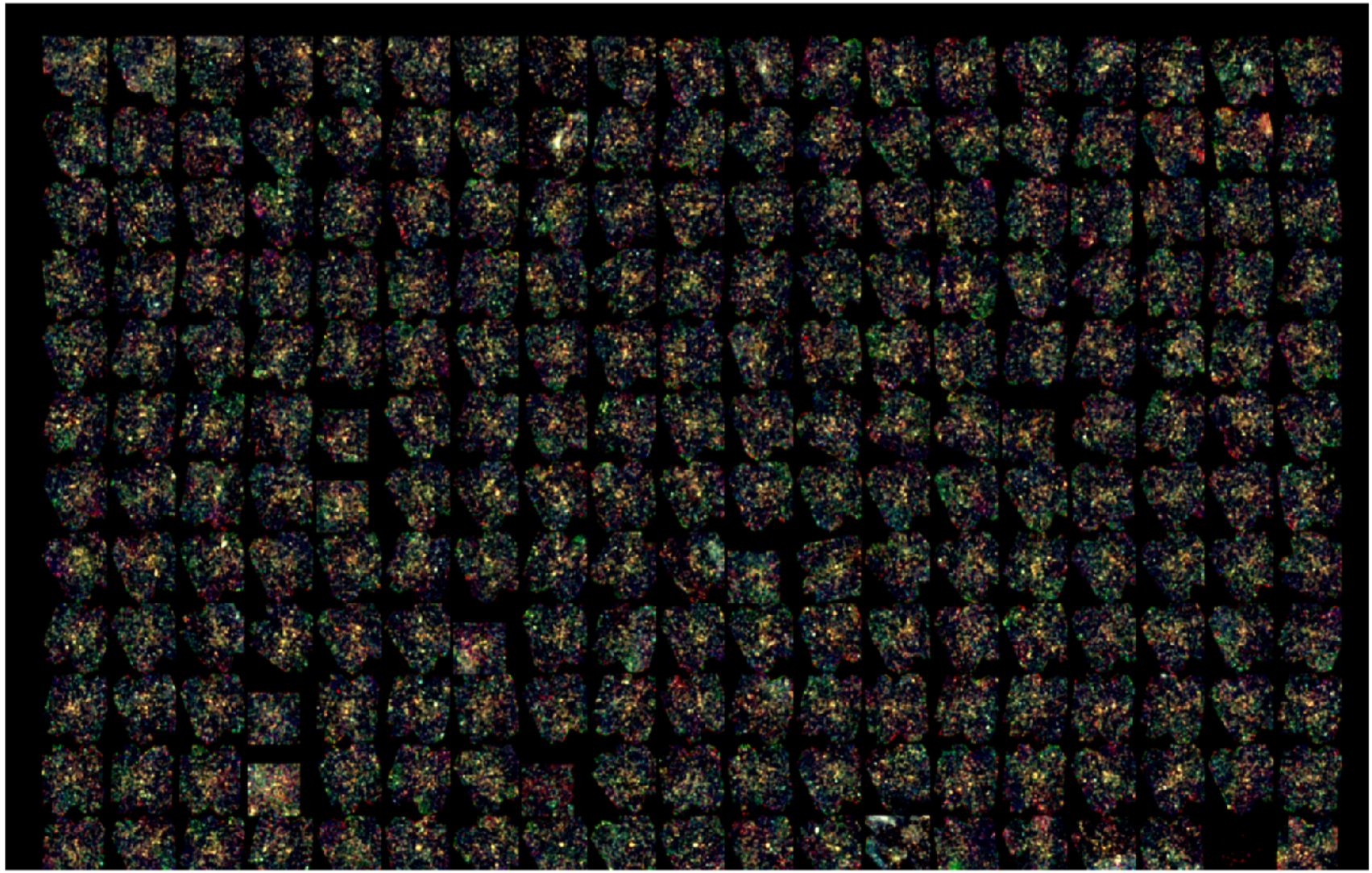
- Sources are in the field

- Detect *giant arcs*



- Sources located behind lenses

"Astronomers Find Hundreds of Baby Galaxy Clusters" (Wired Magazine, 2015)



Homogeneously-selected sample of proto-cluster candidates!

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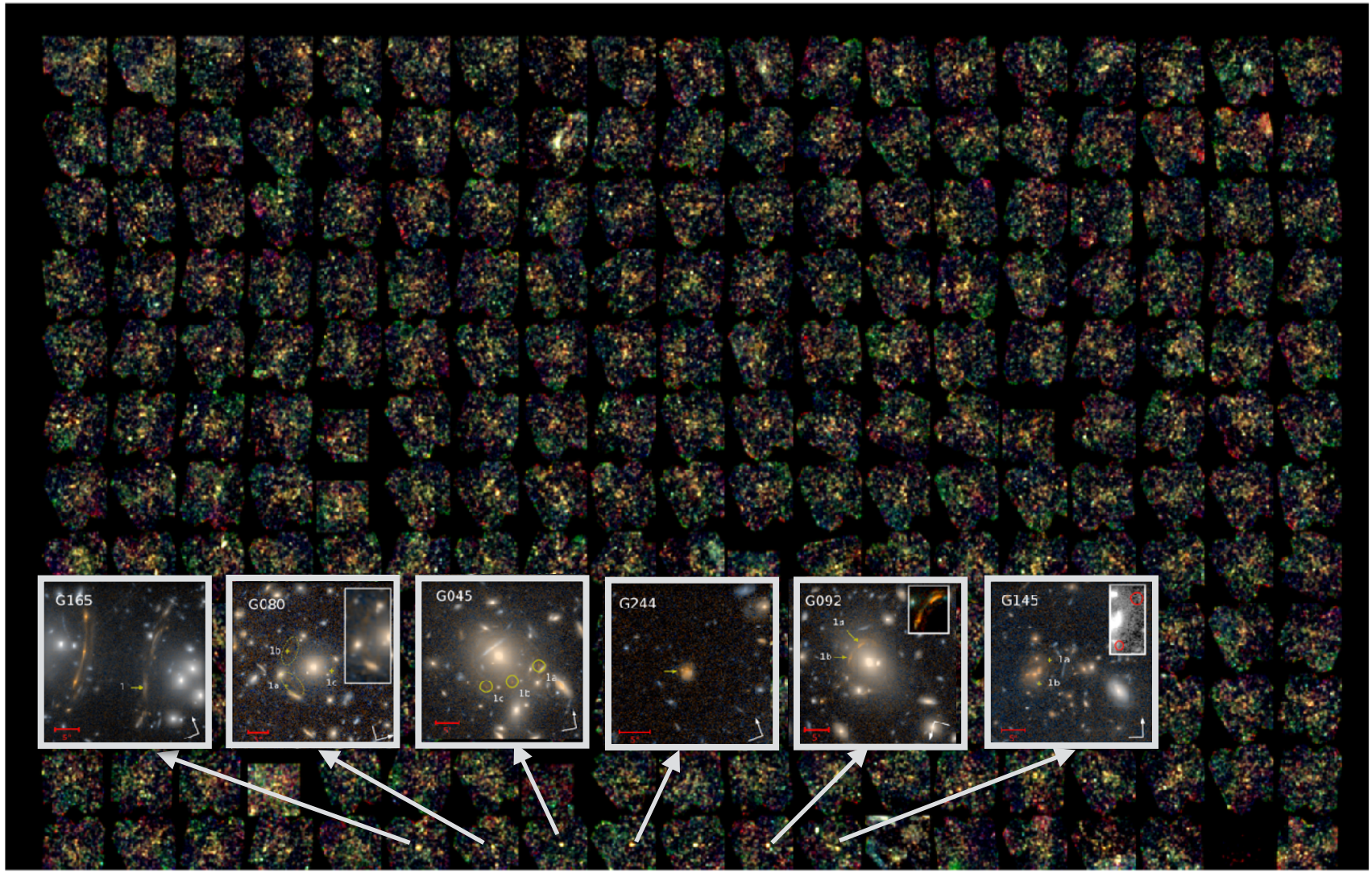
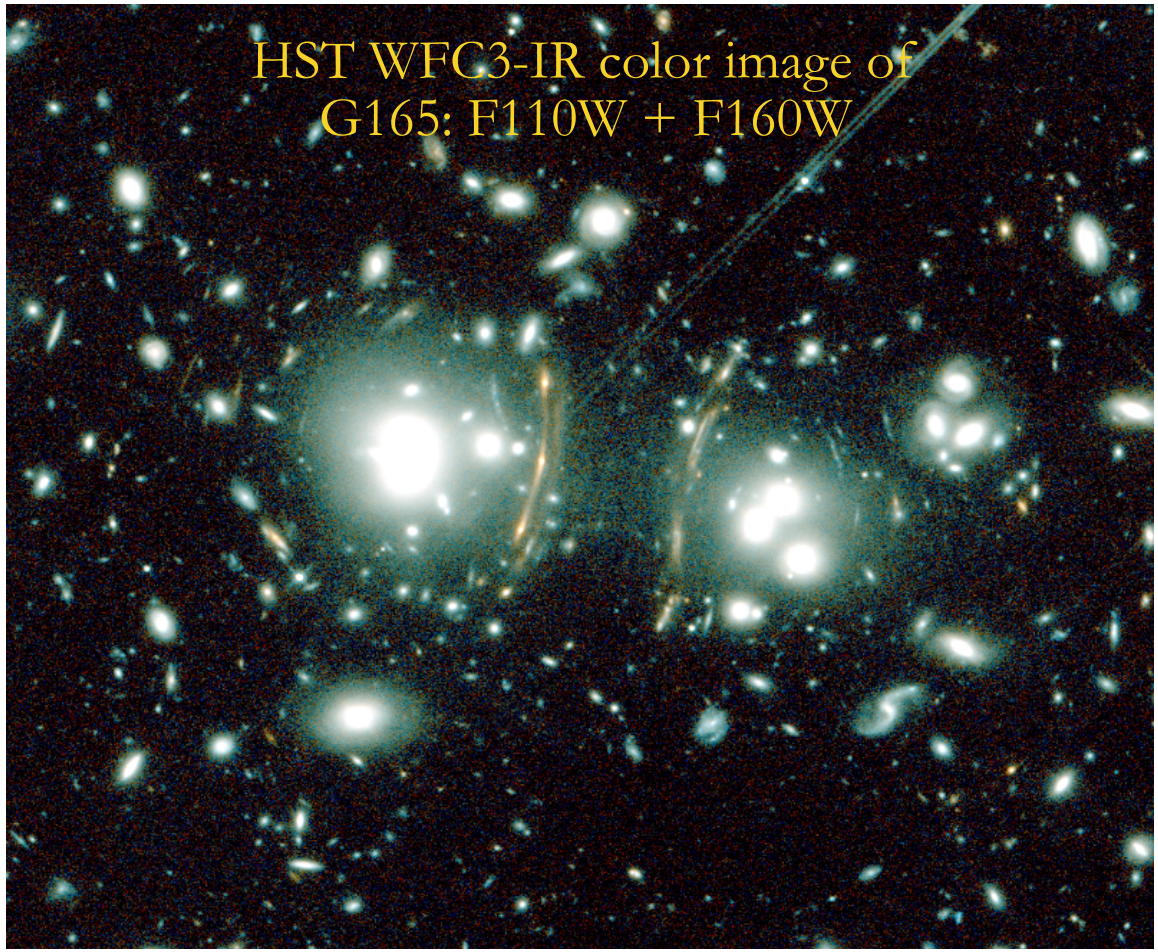


Homogeneously-selected sample of proto-cluster candidates, and lenses.

(Wired Magazine, 2015; Planck Collab. XXVII 2015; Canameras+15; Harrington+16)

2. PLCK G165.7+67.0 (G165)



Where is the Planck lensed source that is one of the brightest beacons in the sub-millimeter sky?

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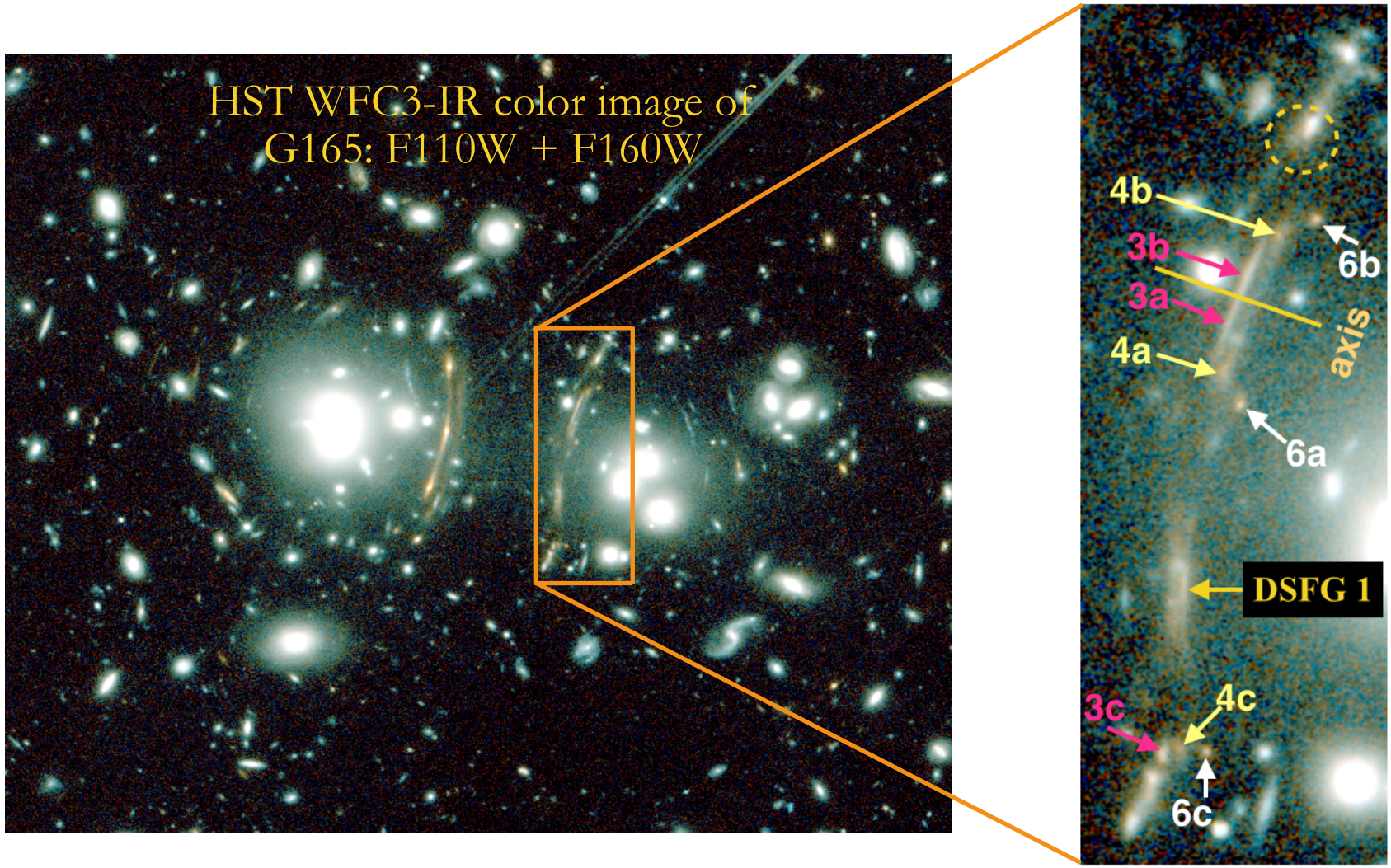

Using two-band HST imaging, we can identify the single galaxies behind the lens that appear in more than one location in the image plane! But this is not enough to detect all arclet families

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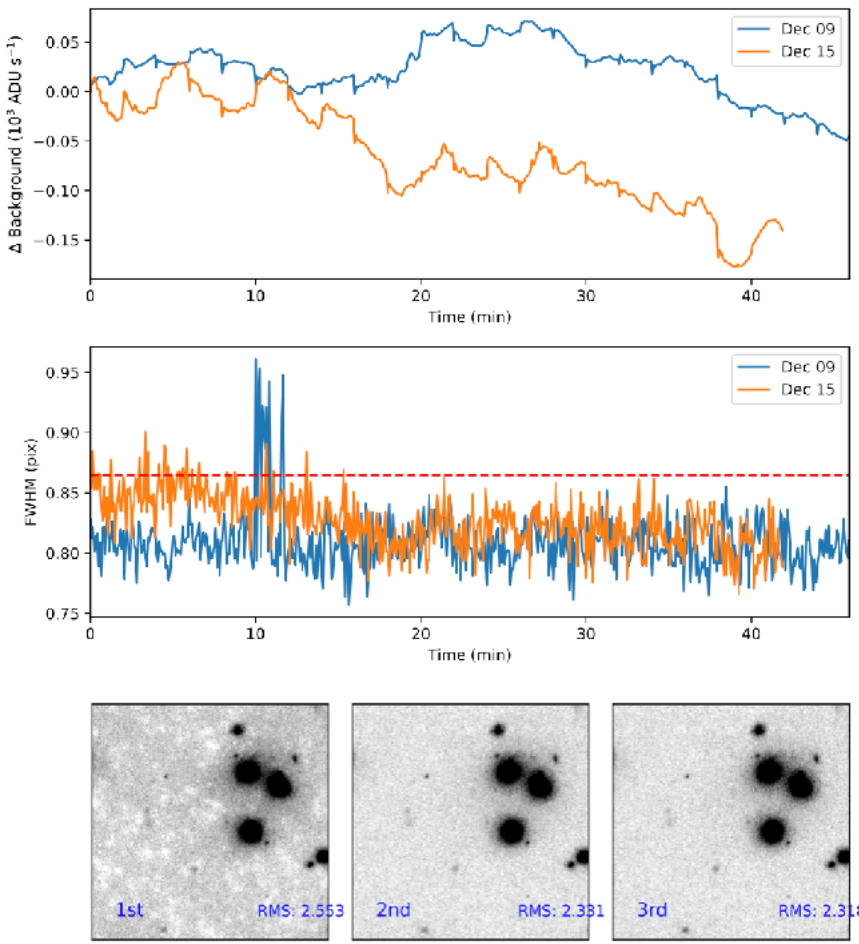

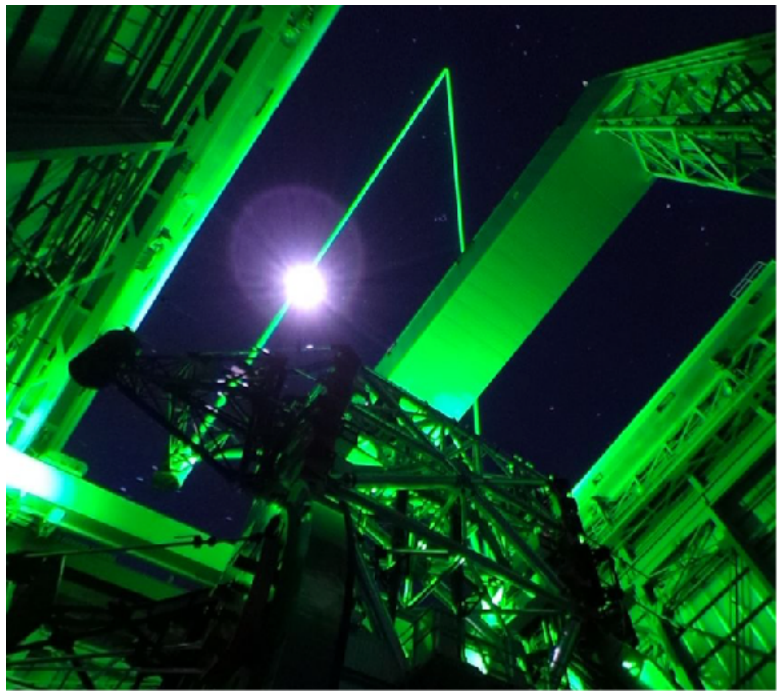

High spatial resolution NIR imaging over "large" fields is now possible from the ground using multi-laser AO-guided imaging. We acquired K-band imaging using LBT LUCI + ARGOS (PI: Frye+19b, Rabien+19)

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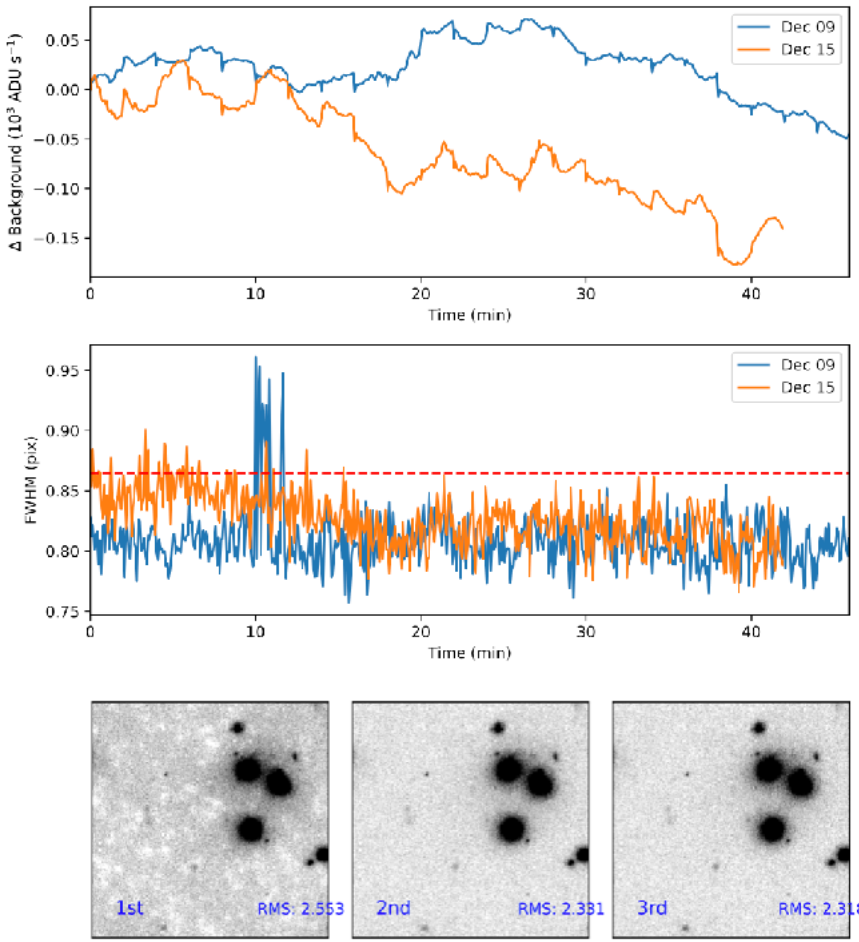

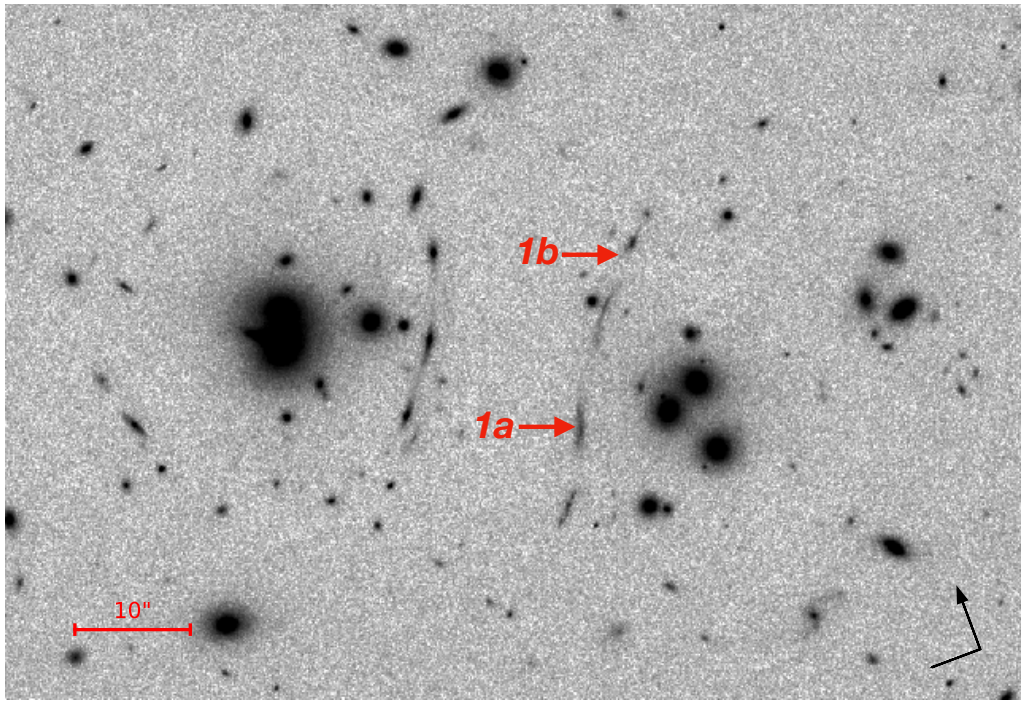

(Frye et al. 2019a; Rabien et al. 2019)

In this breakthrough ground-based NIR image, dozens of arcs are detected. Our high-resolution image (FWHM = 0.29 arcsec), enables rare side-by-side comparisons with our HST data set

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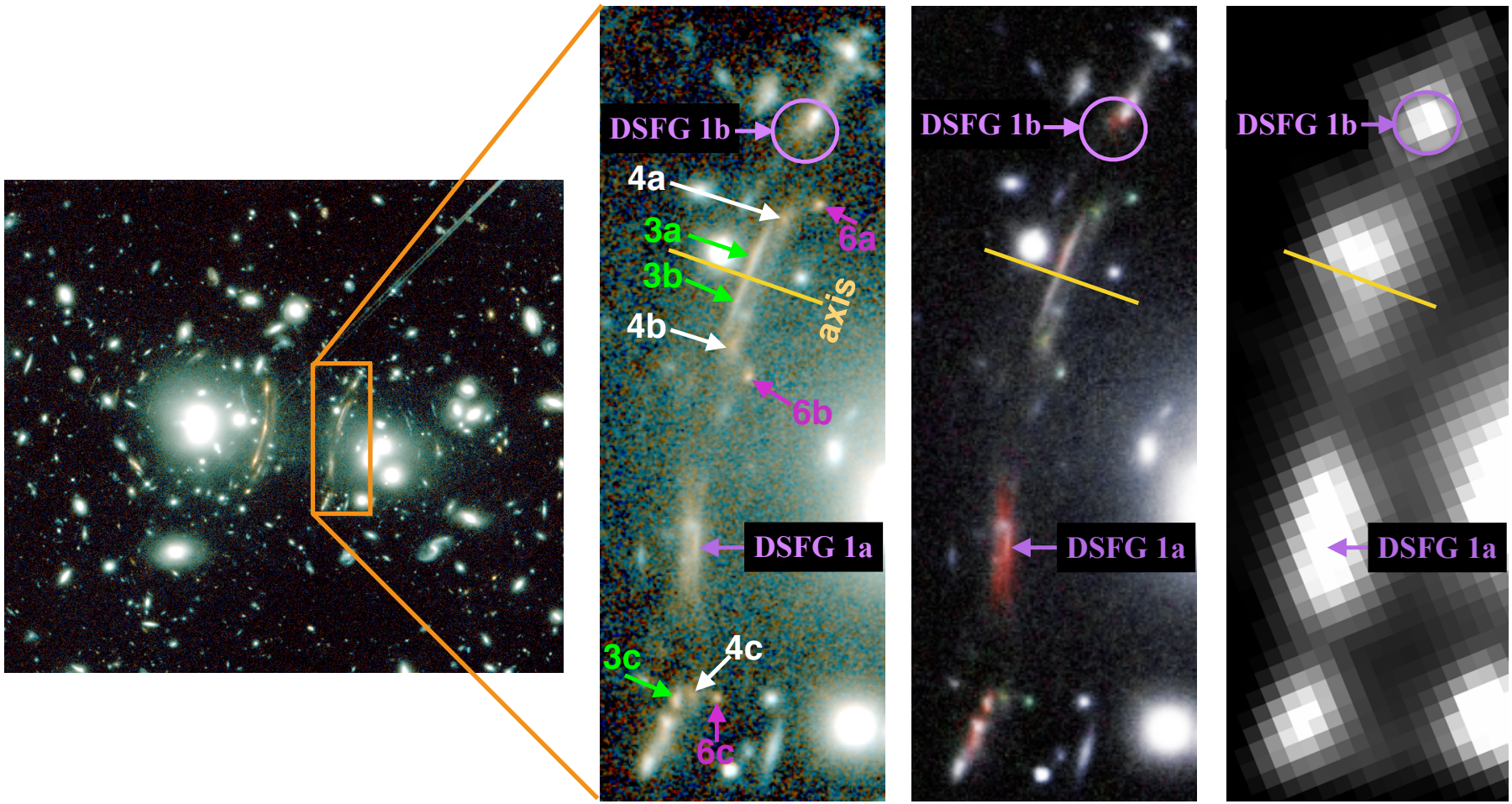
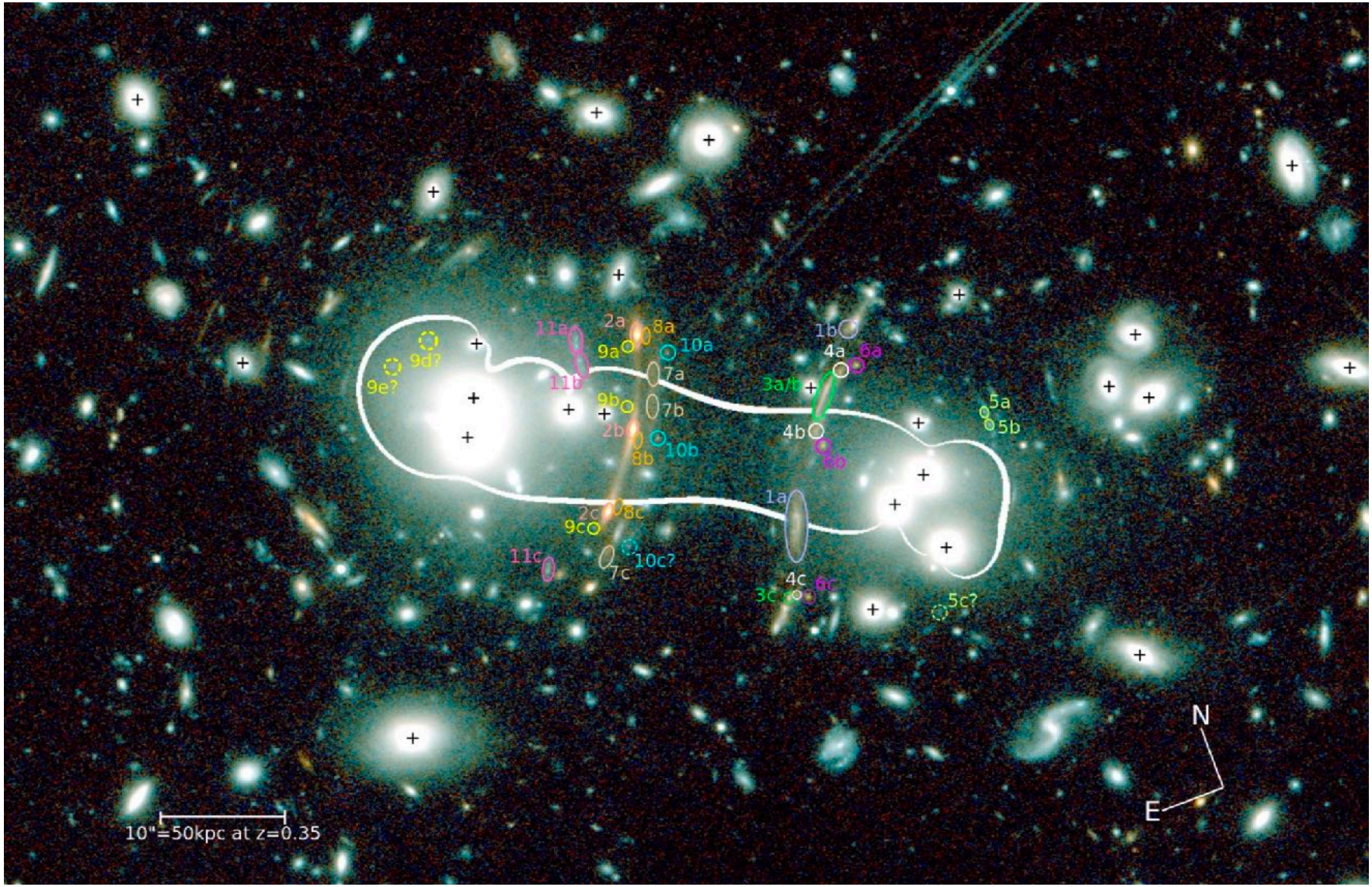


The counter-part of the DSFG is detected only in our *K*-band and Spitzer data sets. This is impactful as it is the only arclet family with a measured redshift. The imaging can also constrain the redshifts

2. G165 with critical curve and arclet families overlaid



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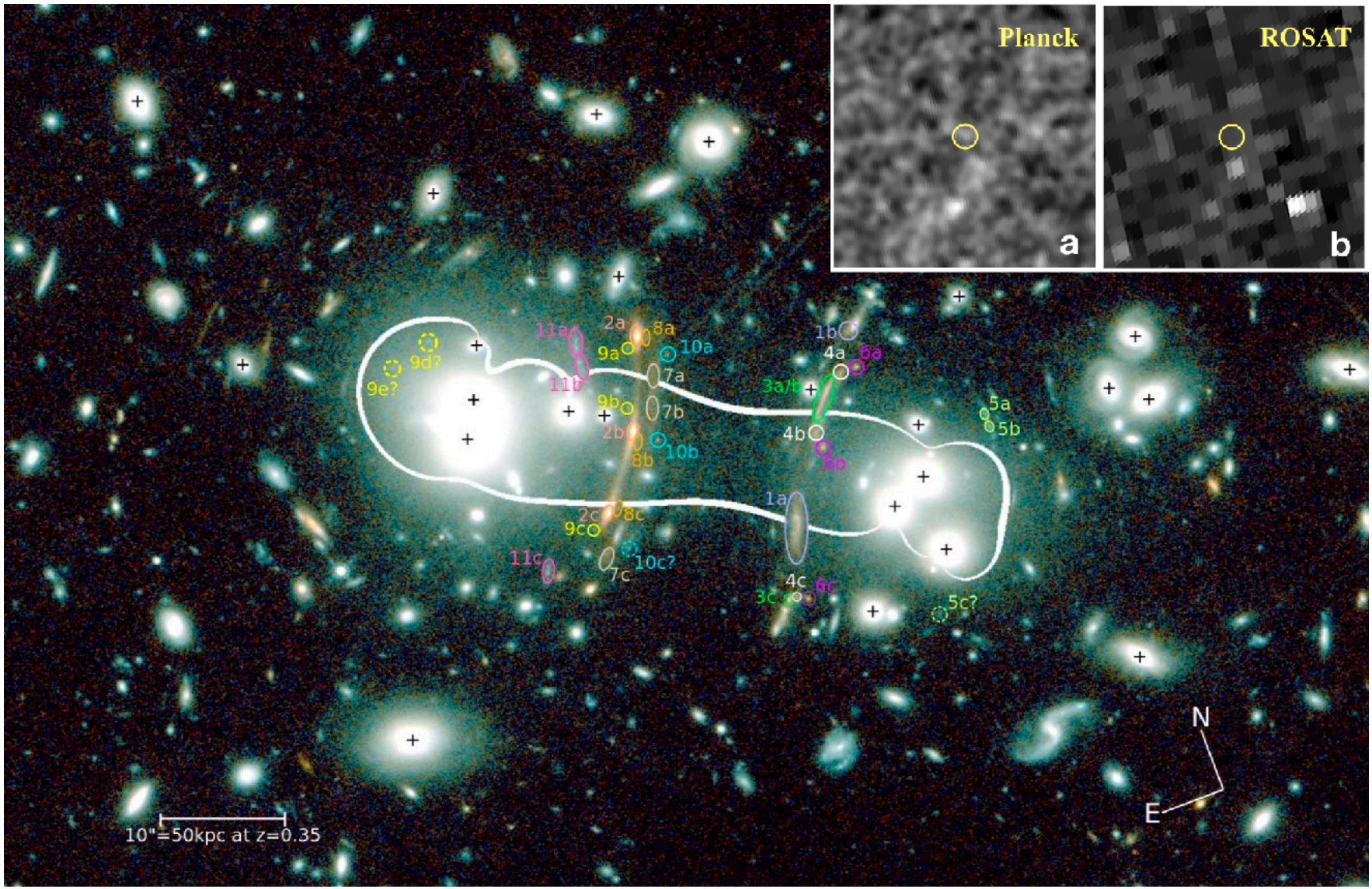
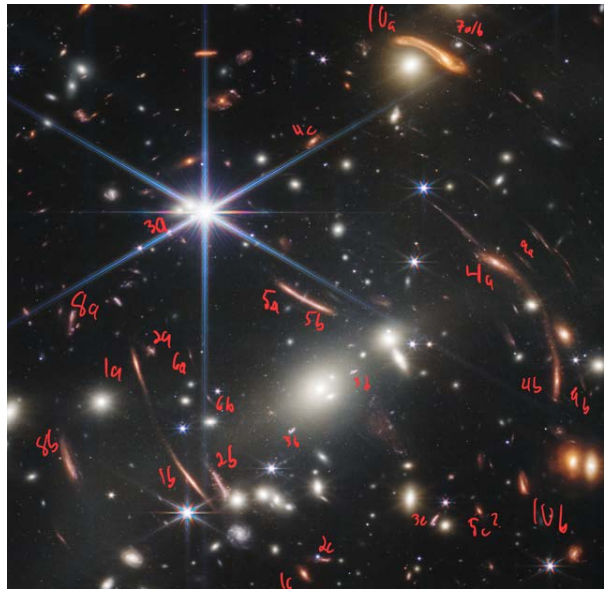
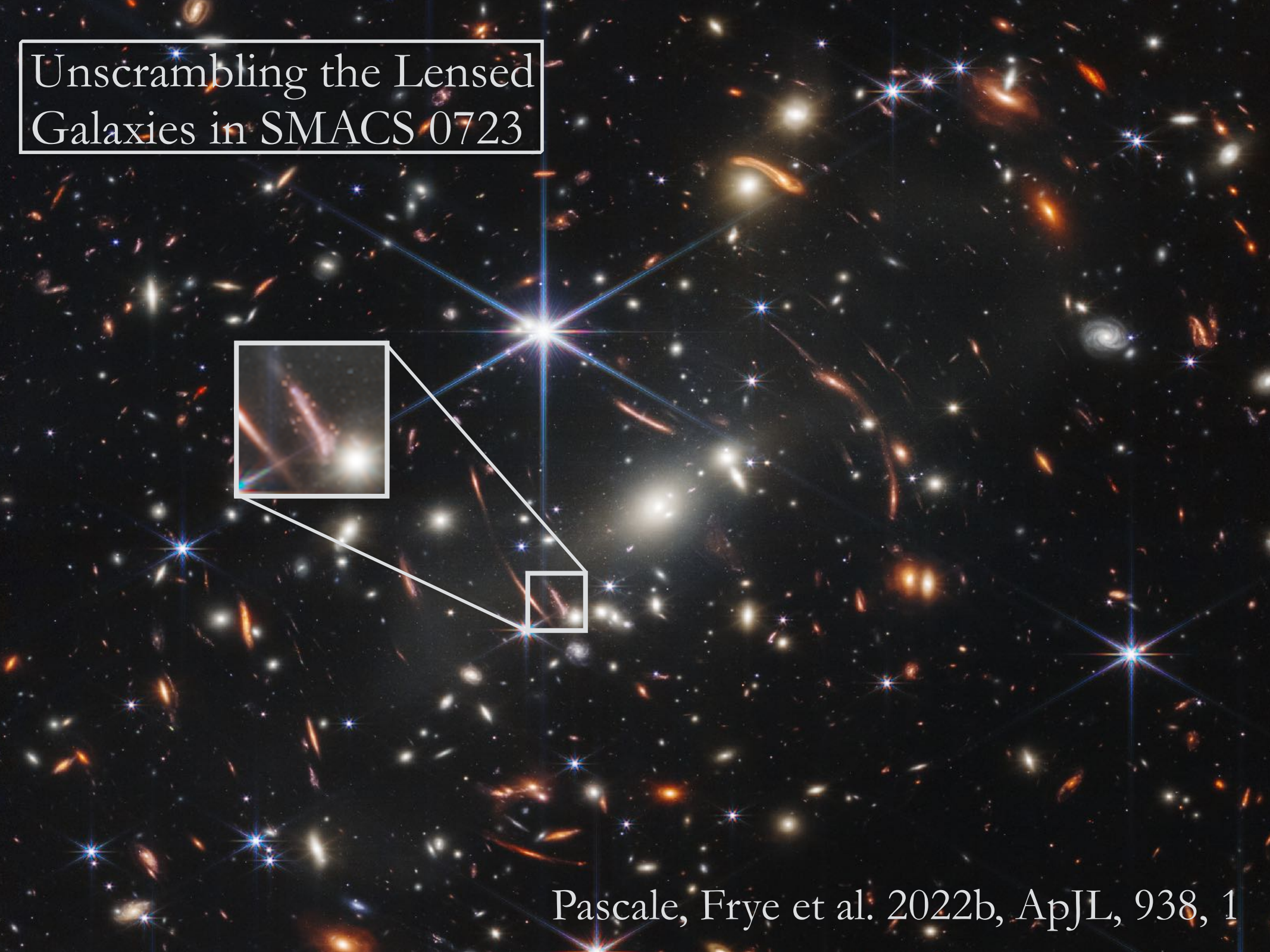


(Pascale et al. 2022a)

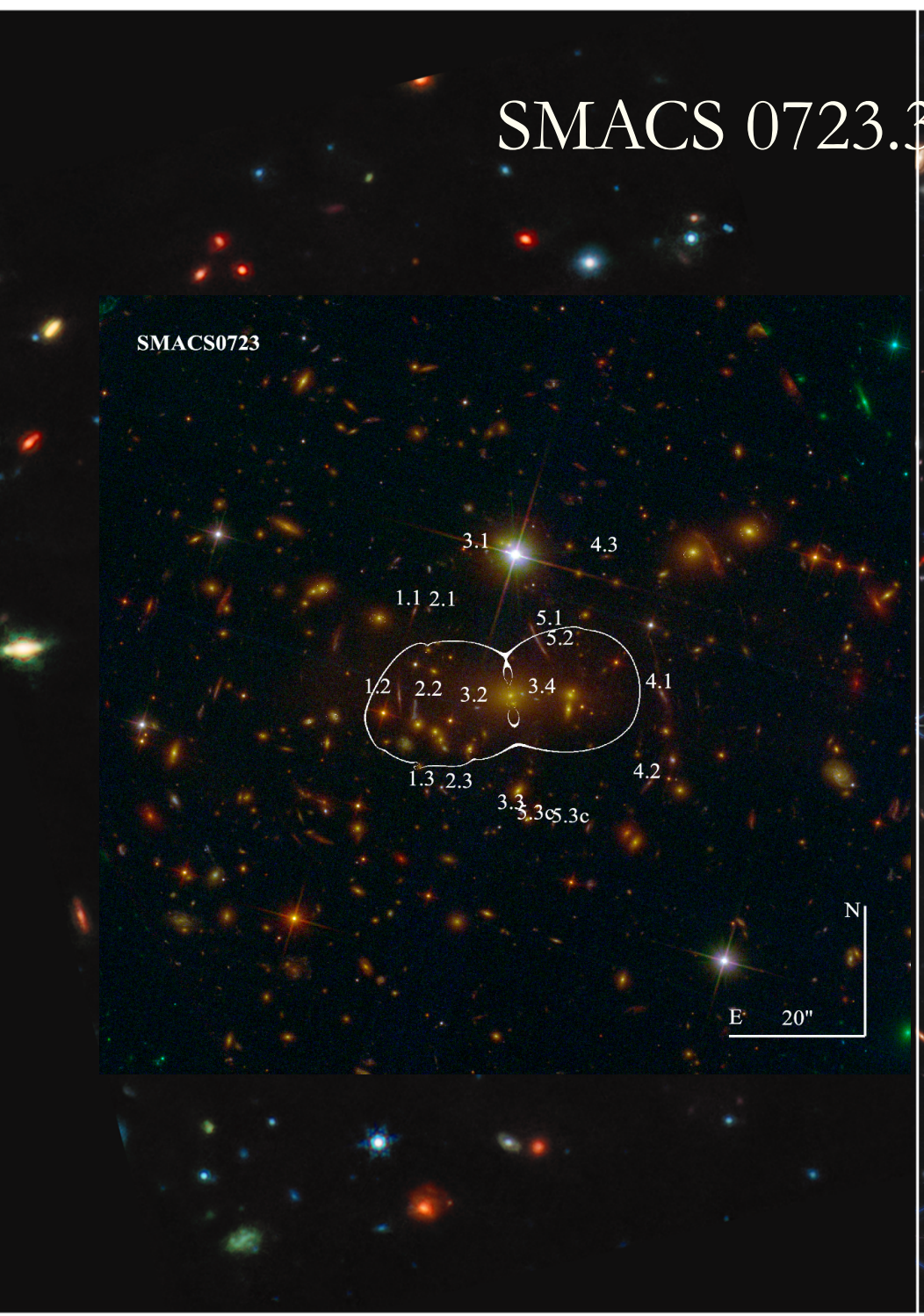
SMACS 0723.3-7327 (SMACS)



Hold on to your seats…


Unscrambling the Lensed Galaxies in SMACS 0723
Pascale, Frye et al. 2022b, ApJL, 938, 1

SMACS 0723.3-7327 (SMACS)



ESAWebb July 12, 2022

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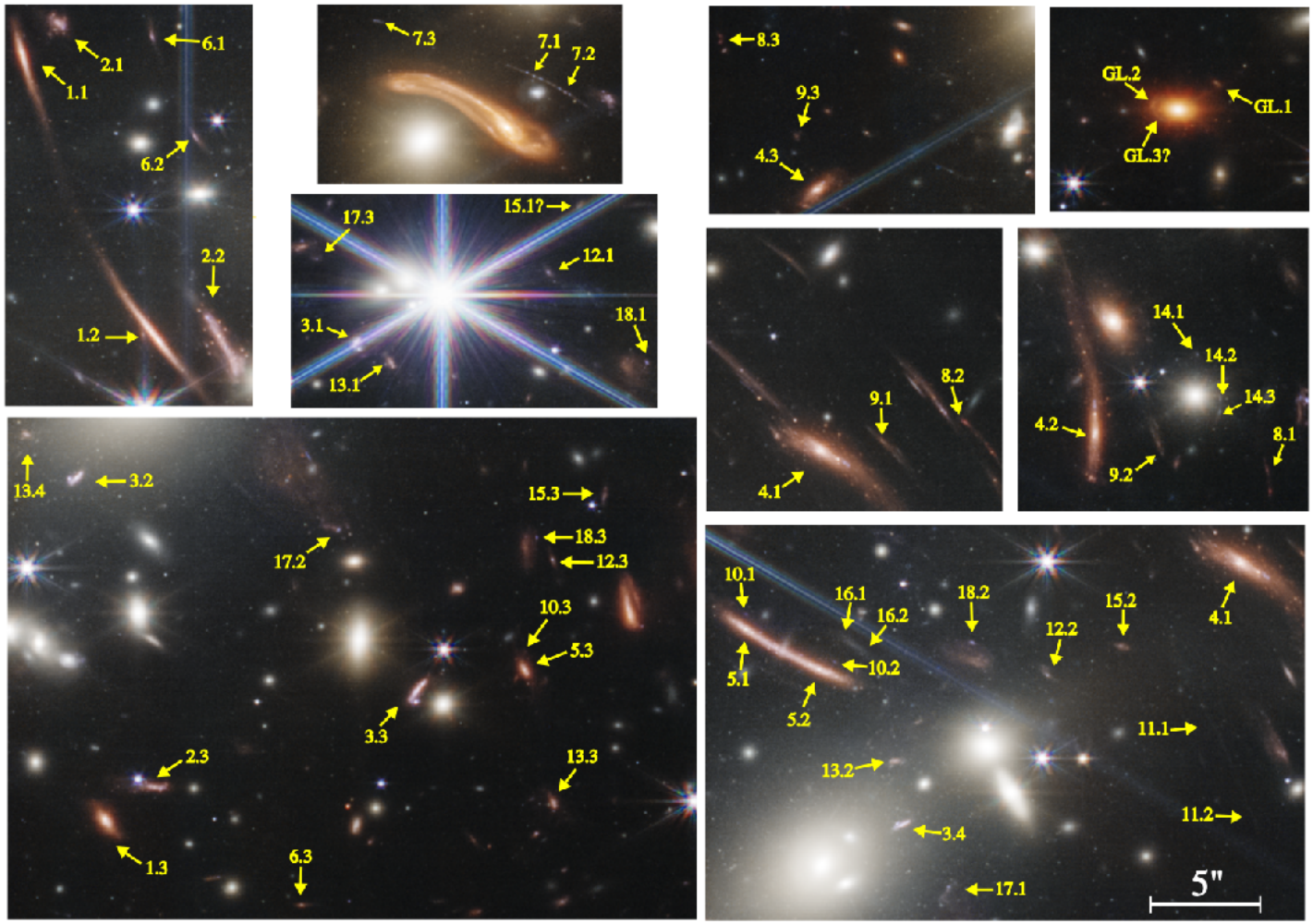

- Image sets found by eye and vetted by the lens model
- ID 14 new sets of multiply-imaged galaxies (42 images)

- Overall 4x improvement in lensing constraints!

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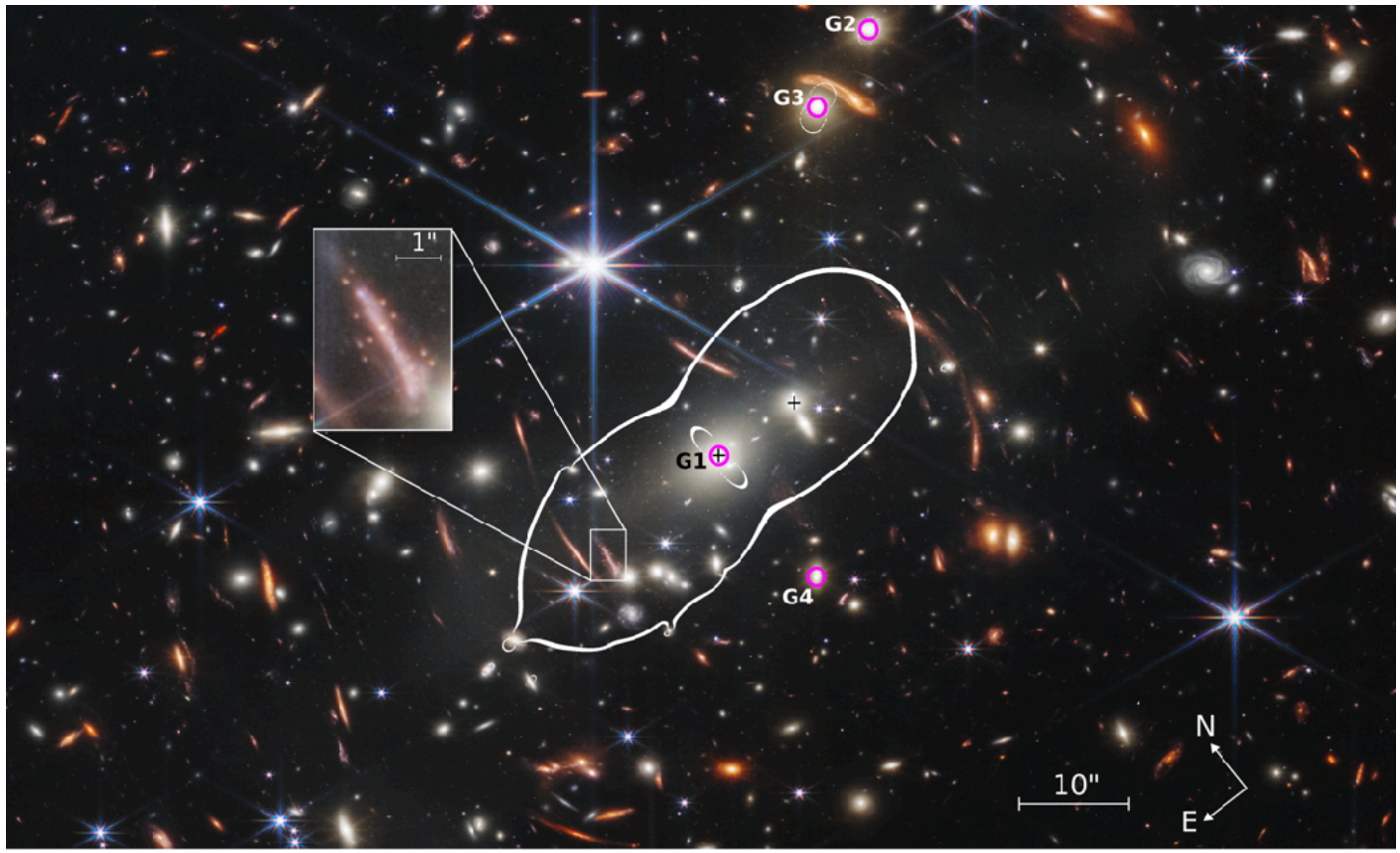
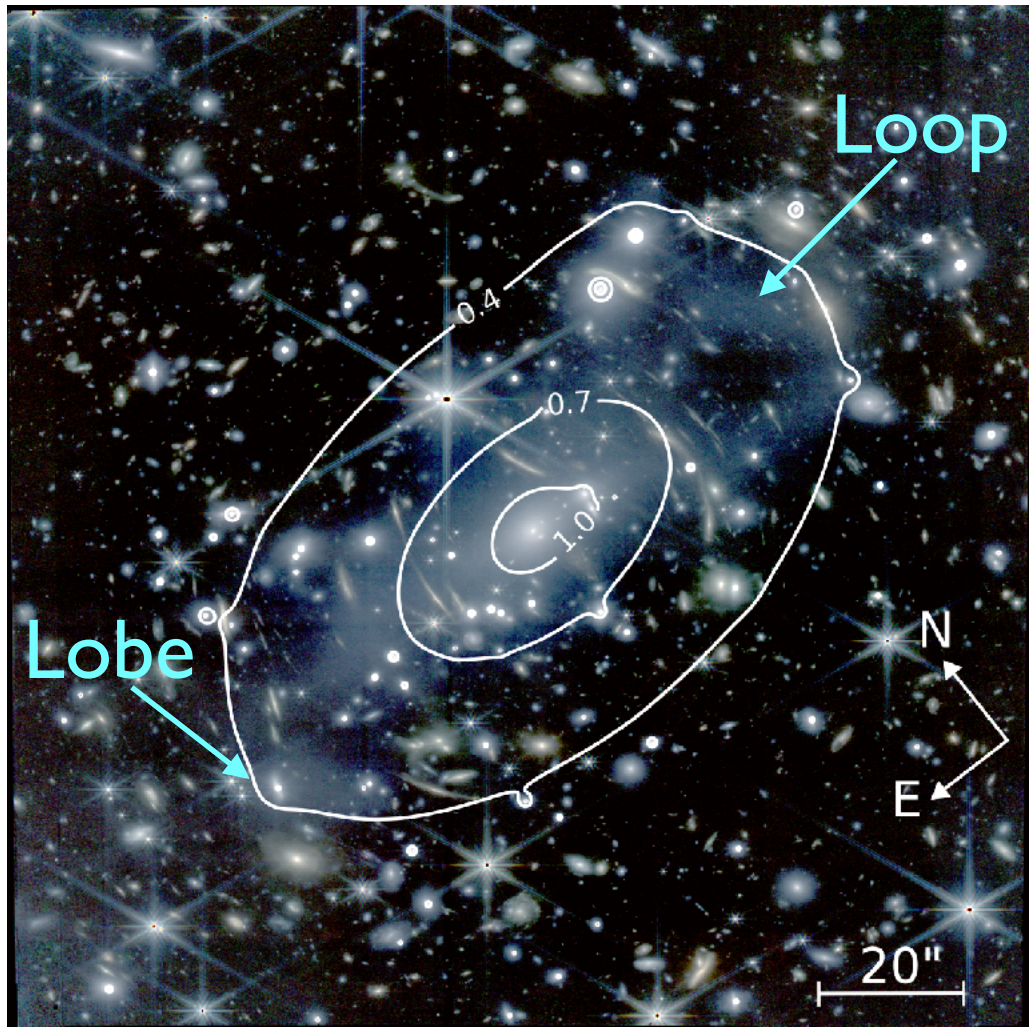


- Parametric lens model (Zitrin+22)
- Reproduces image positions to <0.5”
- M~6x10^{13} Msun
- Mass generally agrees with HST model, but is more elongated than Golubchik+22

3. SMACS 0723.3-7327 (SMACS)

- Intracluster light (ICL) generally traces the mass as predicted by the lens model. Does it trace the DM?
- Loop- and a lobe-like structures appear
- Is this cluster suffering a major disturbance?



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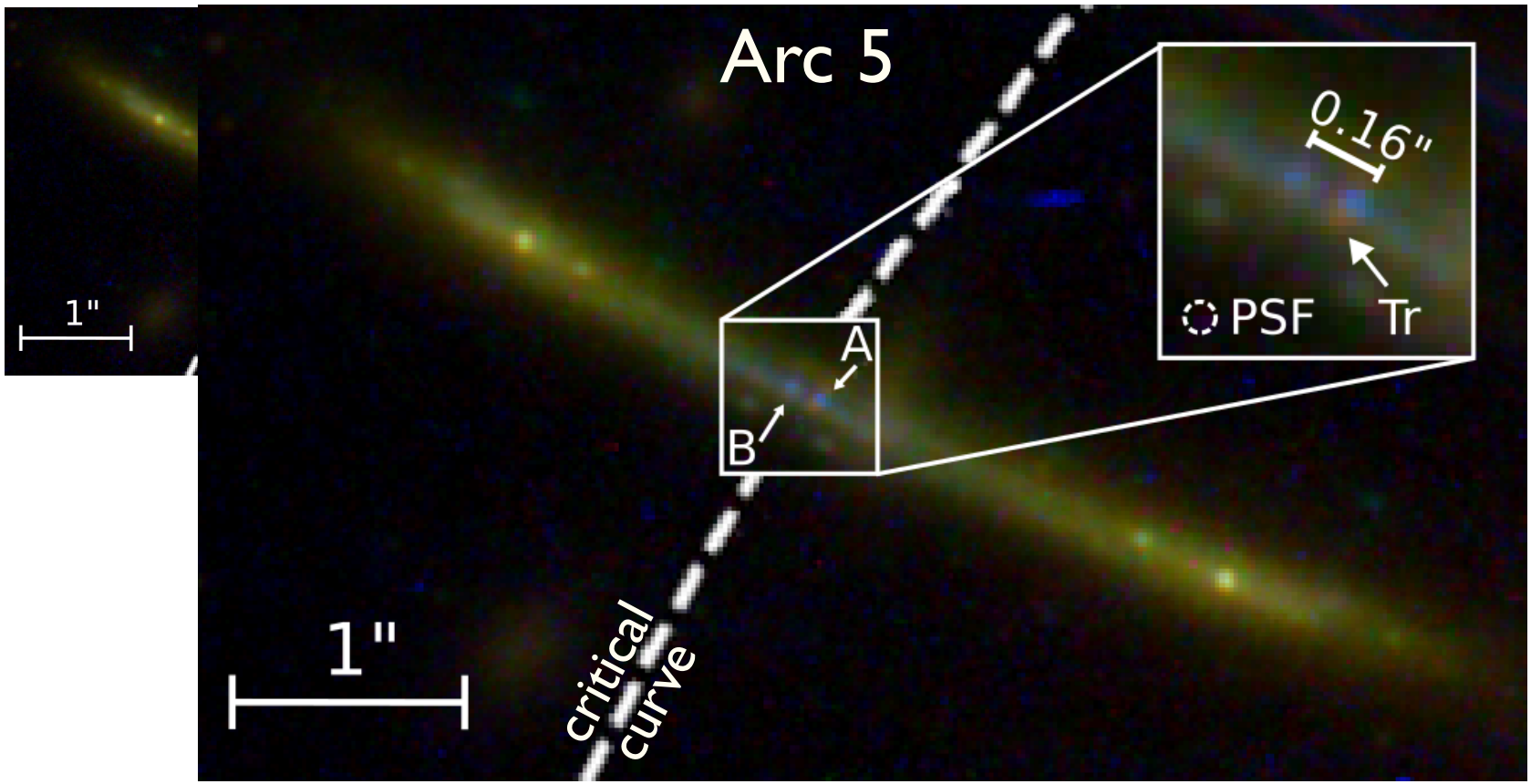
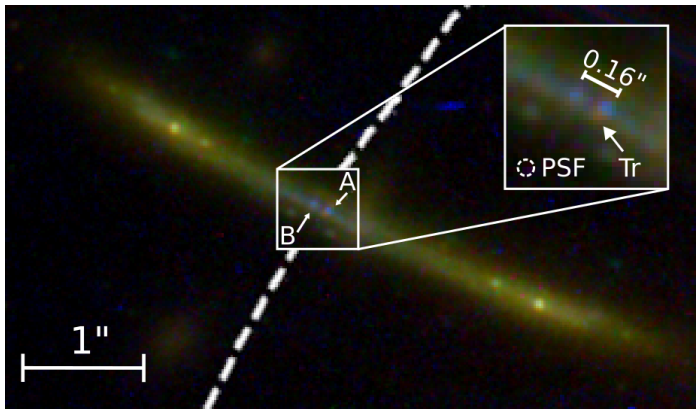
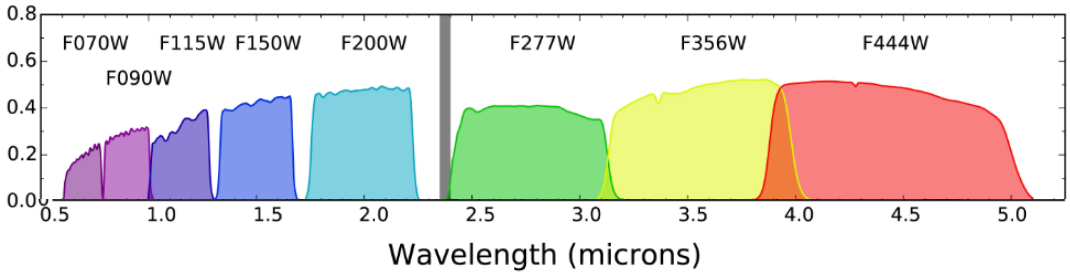


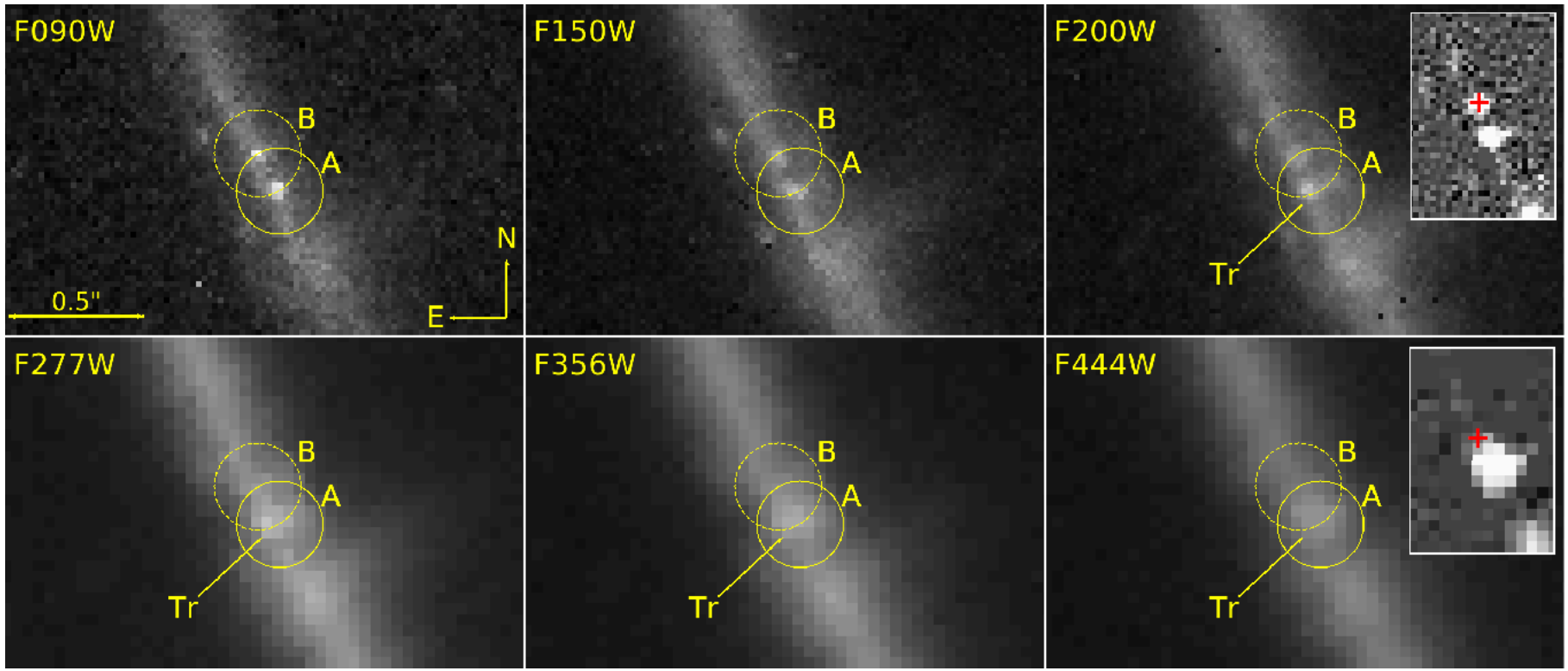
- Arc 5 is a caustic-crossing arc
- Lensed images symmetric about the critical curve
- Knots A & B highly magnified (factor of hundreds)
- The offset redder knot, Tr, without obvious counterpart
- Could this be a microlensing event?

3. SMACS 0723.3-7327 (SMACS)





(Pascale, Frye, et al. 2022b)



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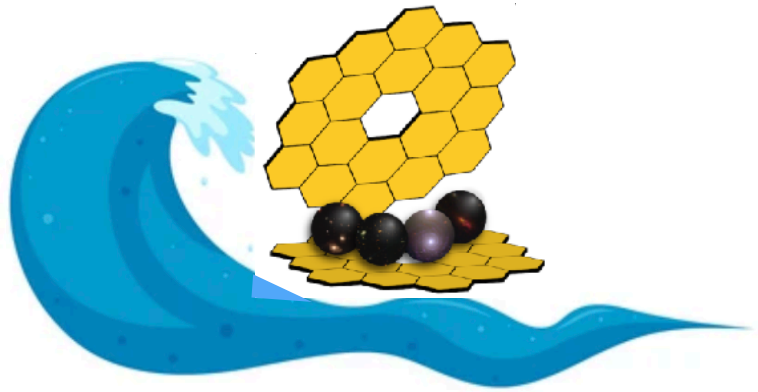
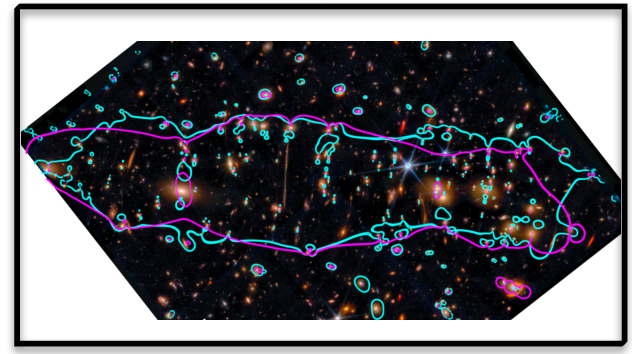
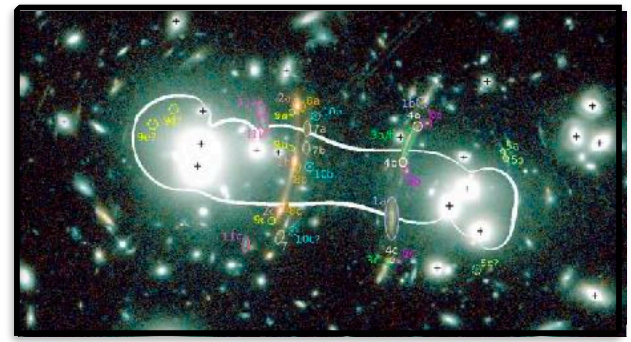


- **Summary**:
  - Protoclusters detected by Planck by *color*
  - Lensed galaxies are individually detected by Planck
  - JWST IDs new image multiplicities, uncovers unseen ICL/DM substructure
  - **PEARLS-Clusters** is one route to:
    - Discover first-light sources
    - Constrain DM properties
    - Study stars, subhalos by caustic transients

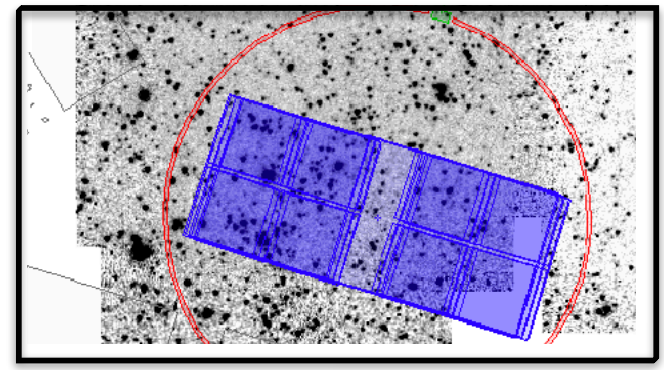
- **Clusters: look out for 2023!**
  - Abell 2744
  - ✓ MACS J0416
  - MACS J1149
  - ✓ ***El Gordo***
  - PLCK G191
  - TN J1338-1942
  - PLCK G165.7+67.0
  - CLIO
  - ✓ RMJ 1212



(El Gordo; Diego+22, Frye+23 in prep!)

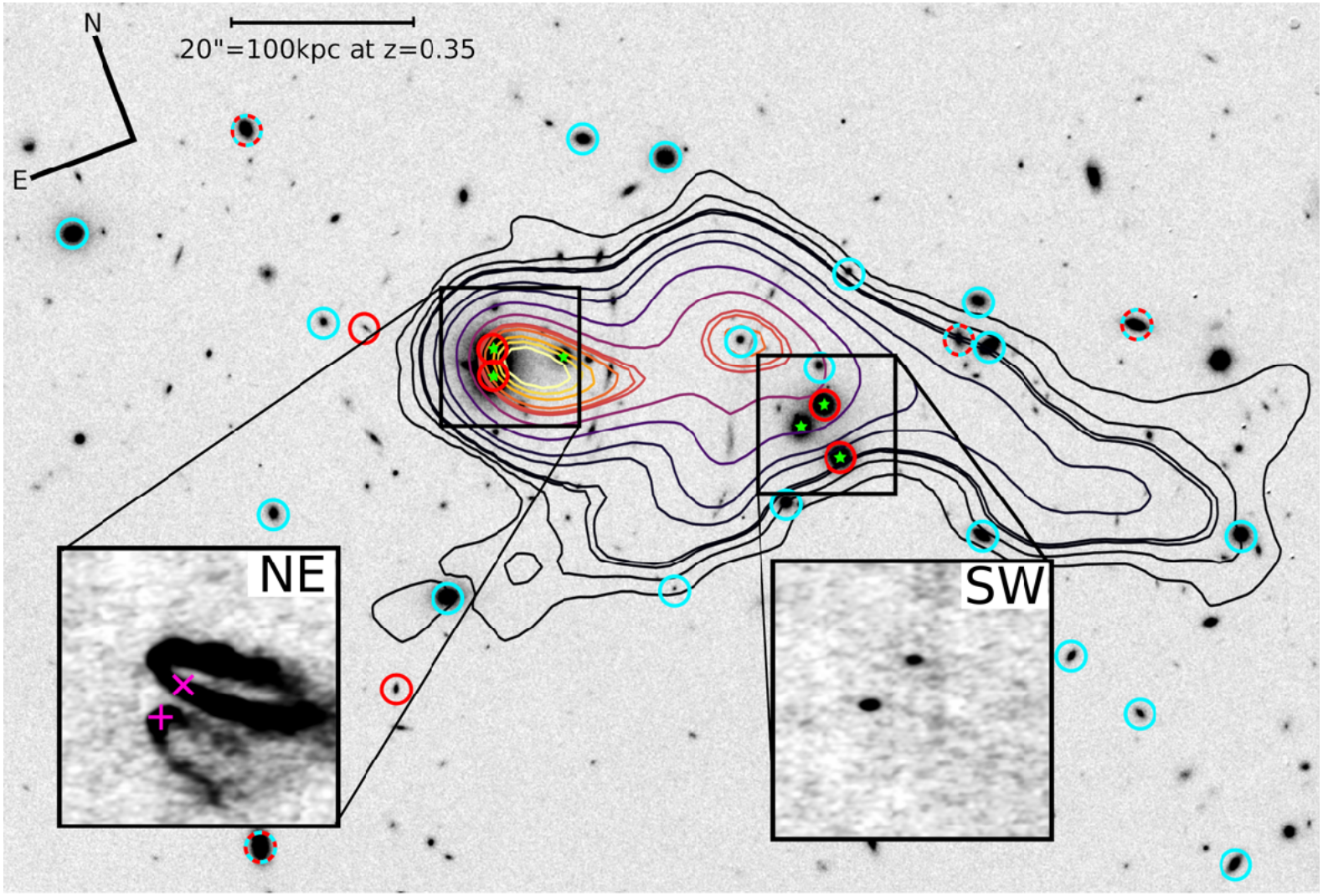


(G165; Frye+19a, Pascale+22a)



(G191; Polletta+22)

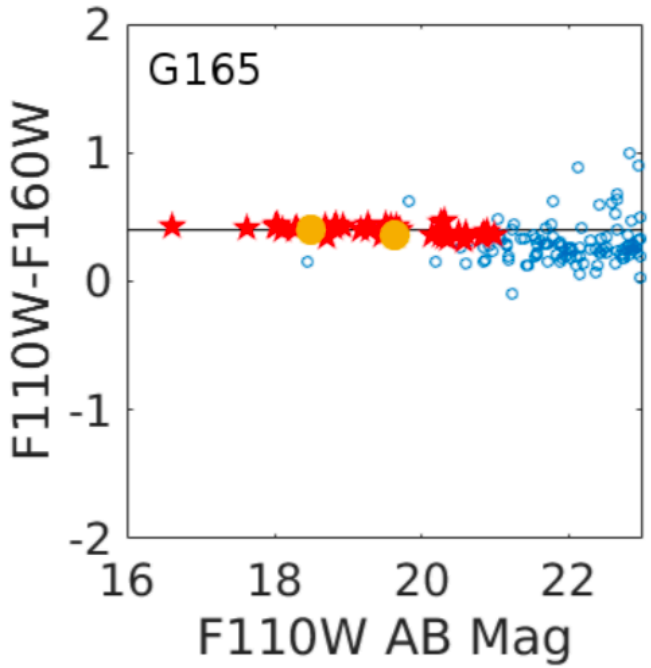
2. G165 (LOFAR + VLA)

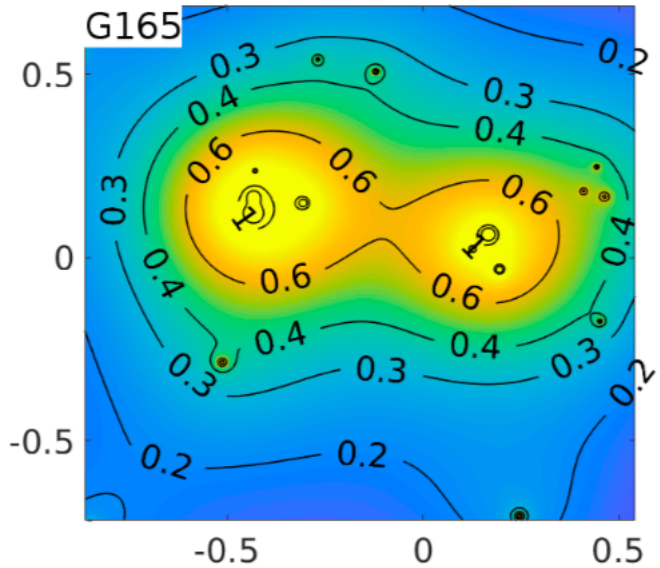


- VLA data uncover head-tail radio sources, which together with spectroscopy suggest face-on orientation, but this doesn't explain the non-standard X-ray properties. Stay tuned for JWST and XMM!

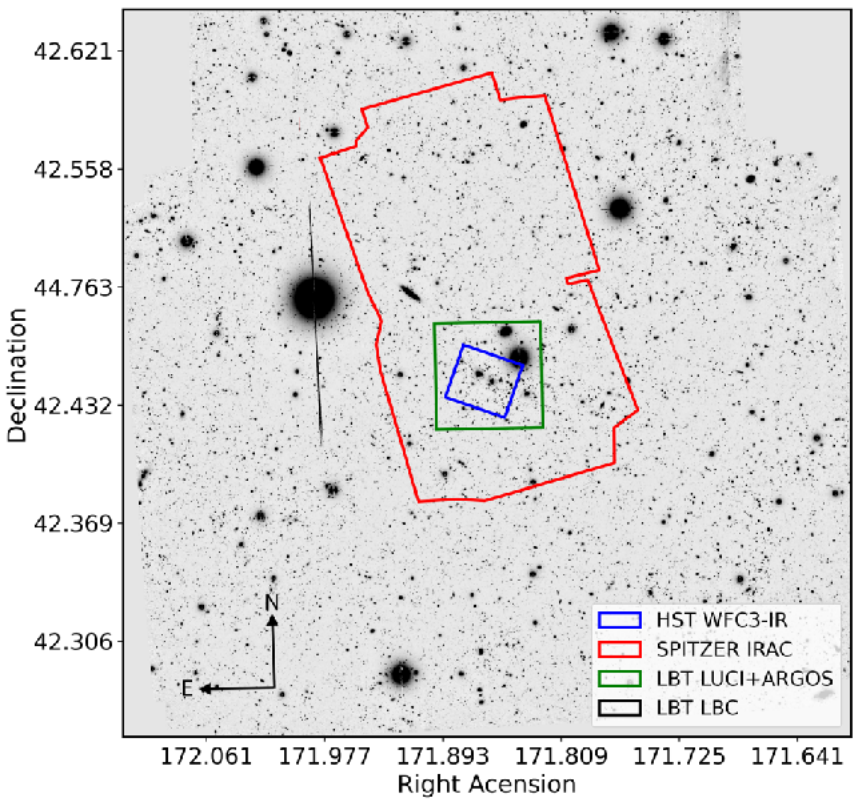
3. The Lens Models

- Construct lens models using light traces mass (LTM) method (Zitrin et al. 2009, 2015)
- Cluster members identified by color
- Arclet families discovered by color, morphology and model-predicted location
- Lens IDs and redshift, and the arc IDs and redshifts (where available) provide inputs to the strong lensing models
- Bimodal mass is recovered by the model

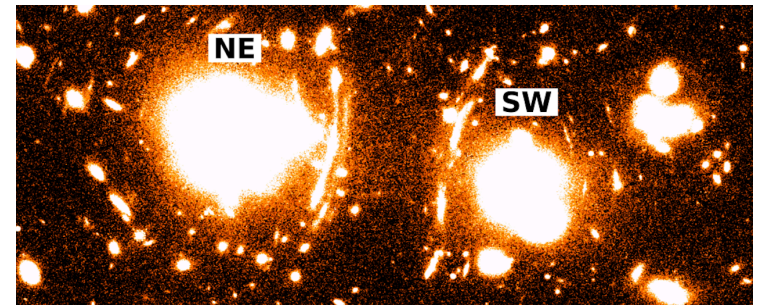




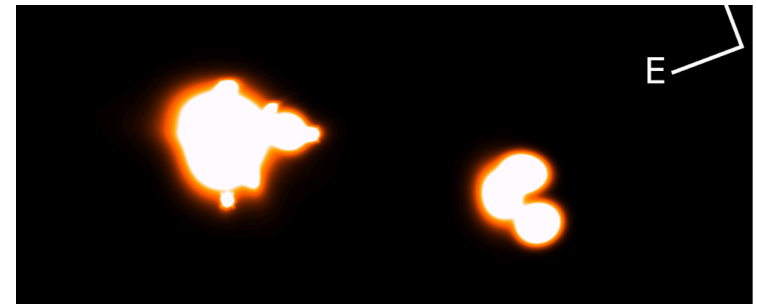
- 7 bands: how to do multi band photometry with wide variations in image characteristics and PSFs?



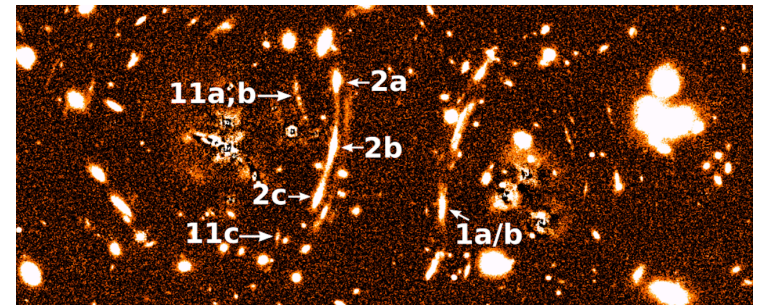
- Reference frame preparation:



G165 F160W

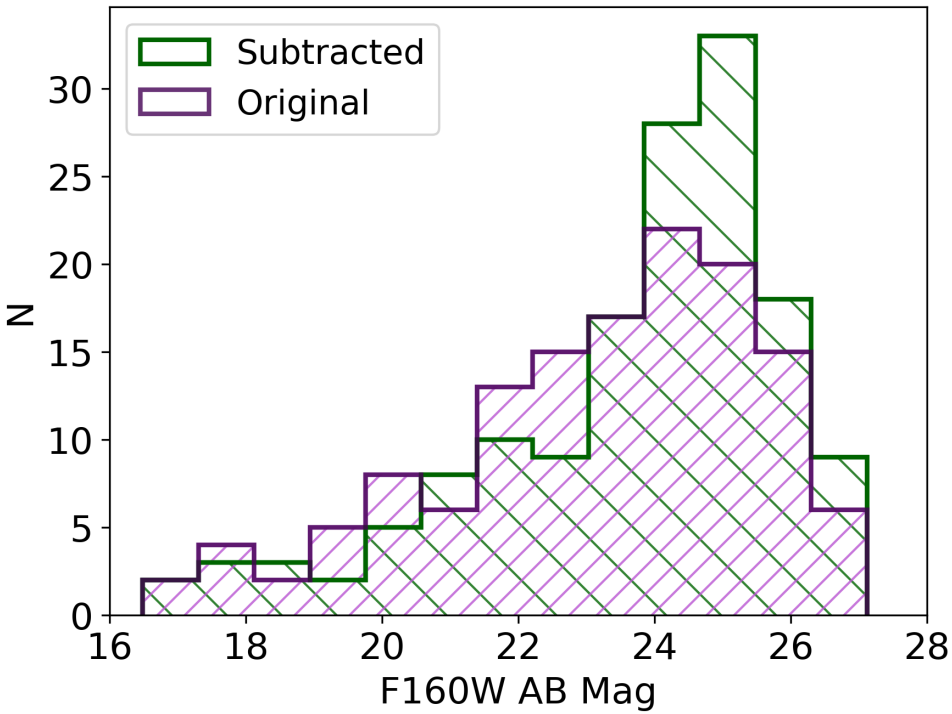


Model of cluster light



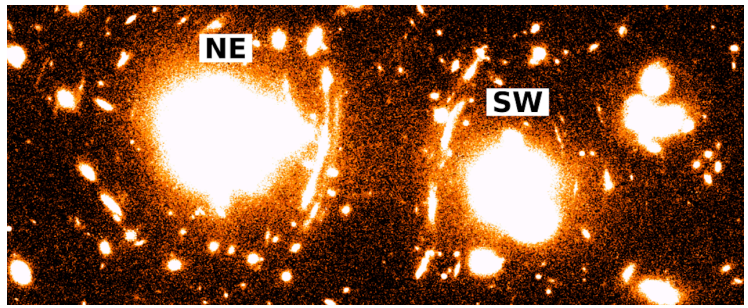
G165 F16W (subtracted)

- 7 bands: how to do multi band photometry with wide variations in image characteristics and PSFs?

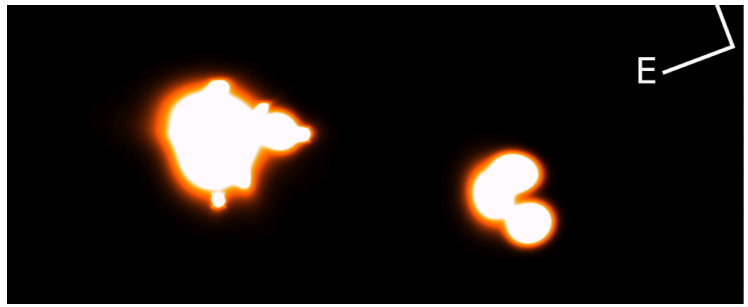


- Subtracted image yields higher yields, especially for fainter sources, thereby effectively pushing detections to fainter limiting magnitudes.

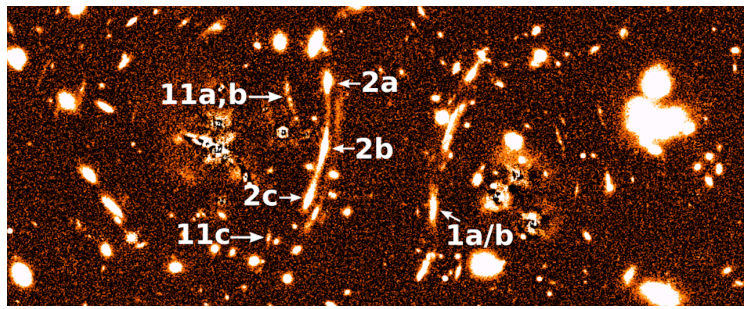
- Reference frame preparation:



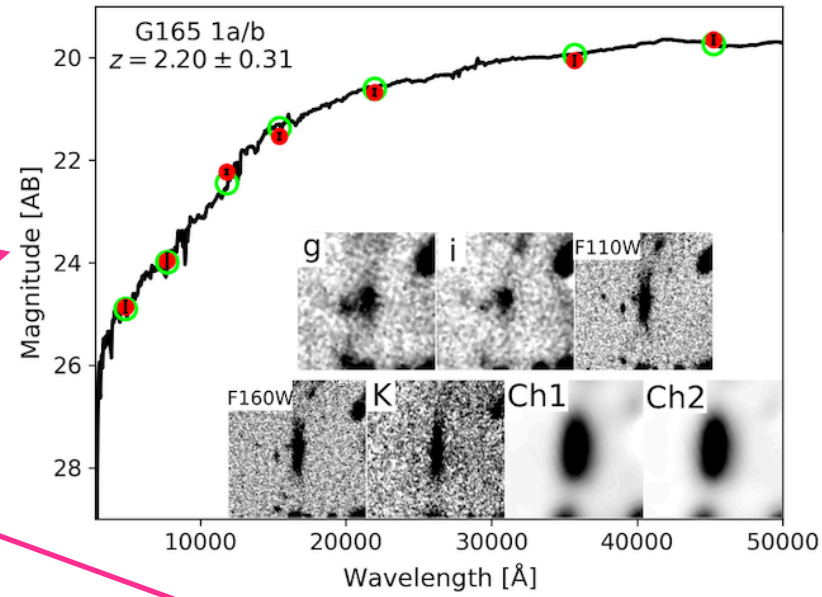
G165 F160W

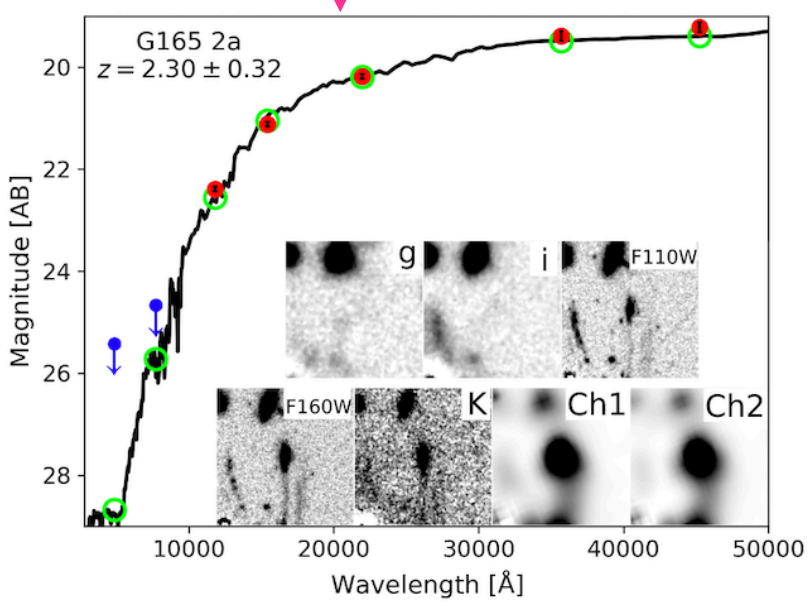


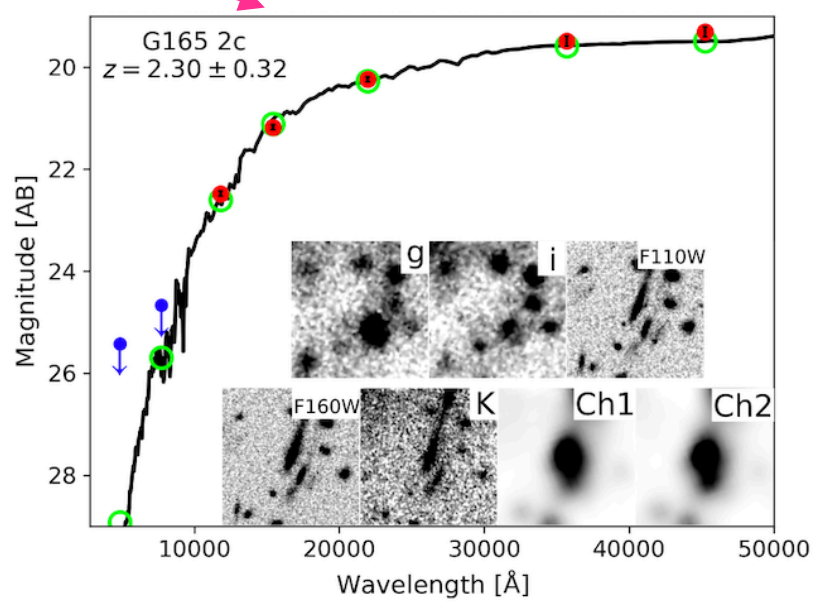
Model of cluster light



G165 F16W (subtracted)


G165 1a/b
$z = 2.20 \pm 0.31$
Magnitude [AB]
Wavelength [Å]
g
i
F110W
F160W
K
Ch1
Ch2


G165 2a
$z = 2.30 \pm 0.32$
Magnitude [AB]
Wavelength [Å]
g
i
F110W
F160W
K
Ch1
Ch2


G165 2c
$z = 2.30 \pm 0.32$
Magnitude [AB]
Wavelength [Å]
g
i
F110W
F160W
K
Ch1
Ch2