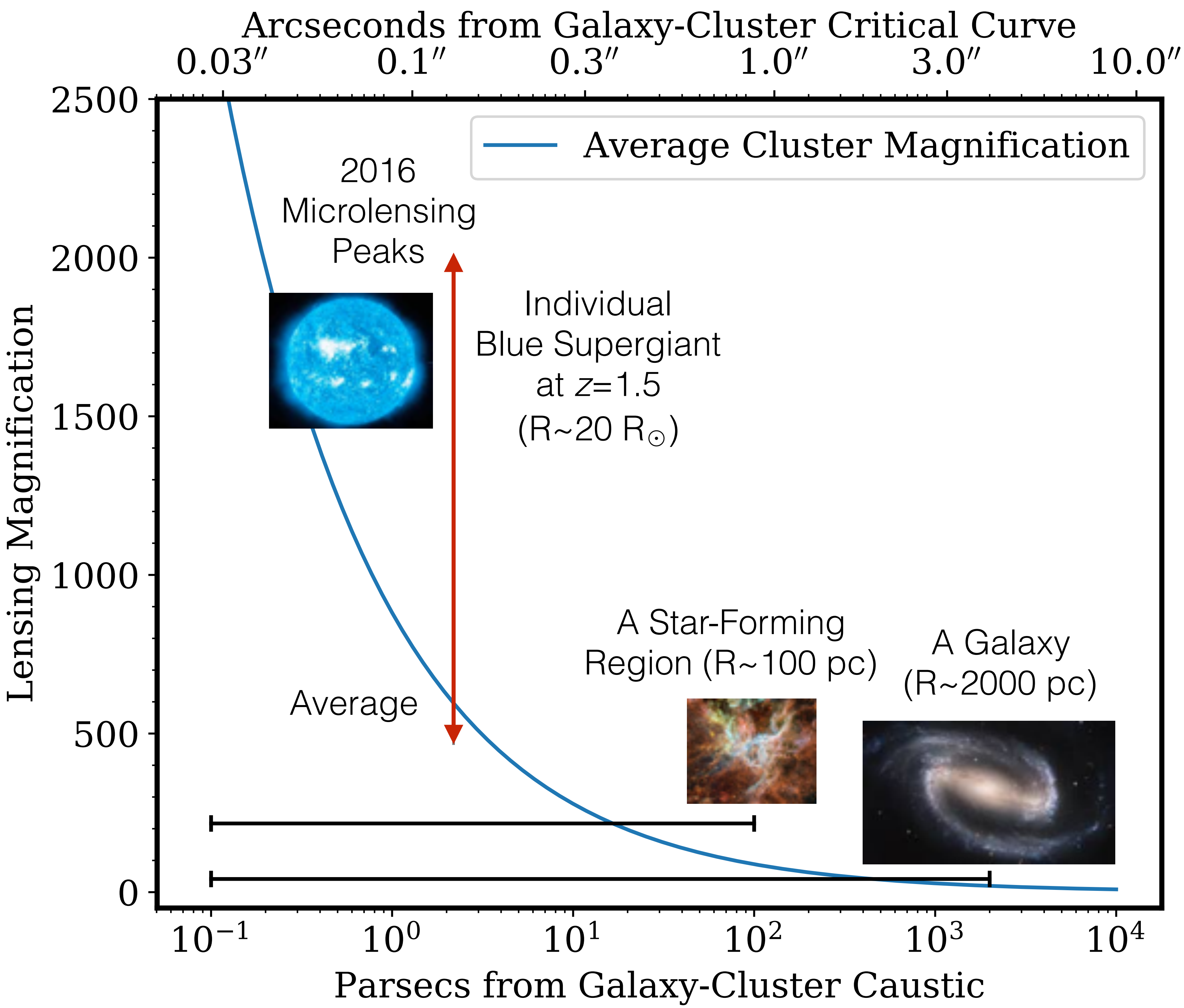
# Caustic-Crossing Events + Highly Magnified Stars

Patrick Kelly
University of Minnesota

**Blue supergiant star "Icarus"**

**Blue supergiant star "Warhol"**

# Small Source Size —> Possibility of Extreme Magnification



# What happens when a star crosses a caustic?

Typical transverse velocity of ~1000 km / s

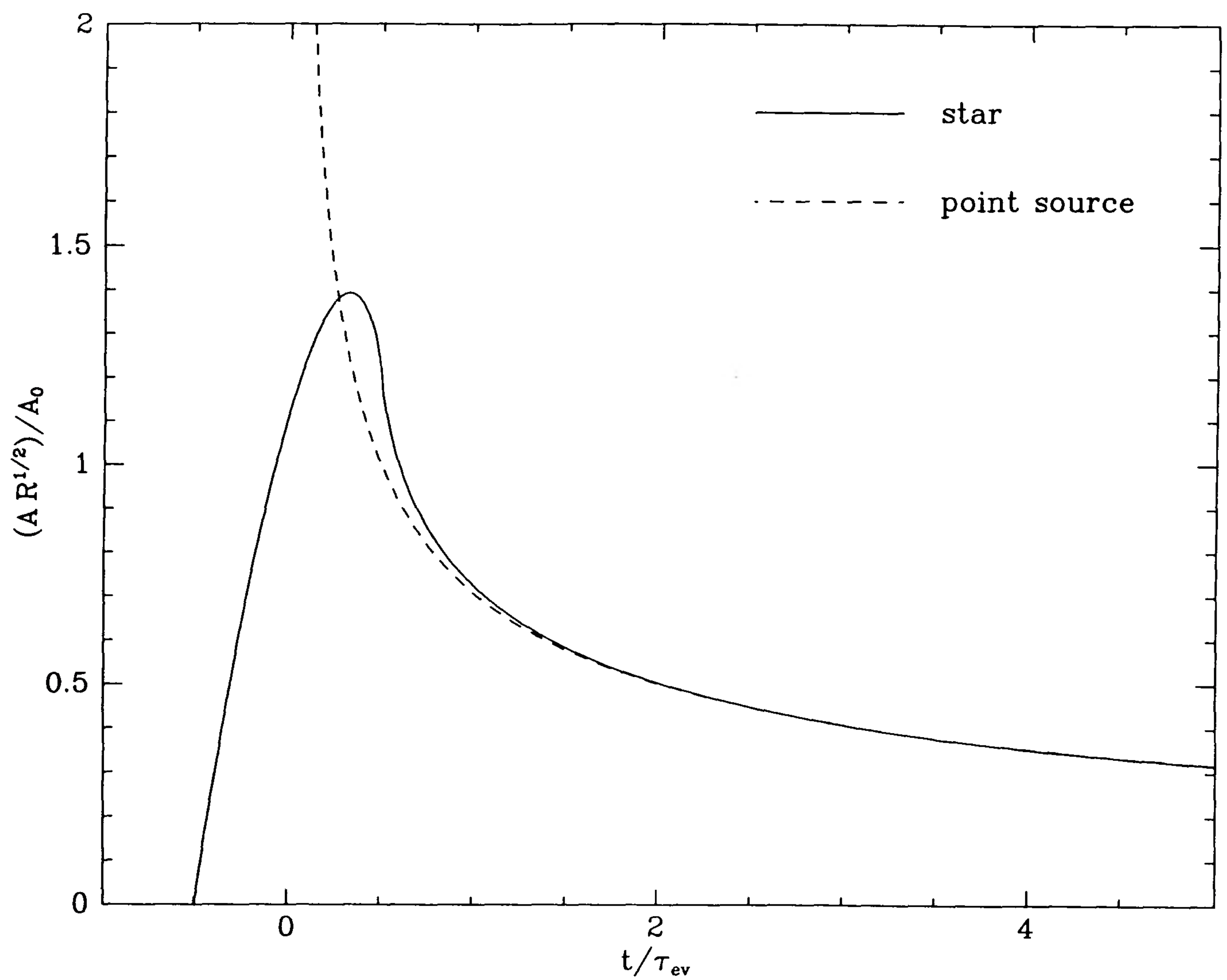
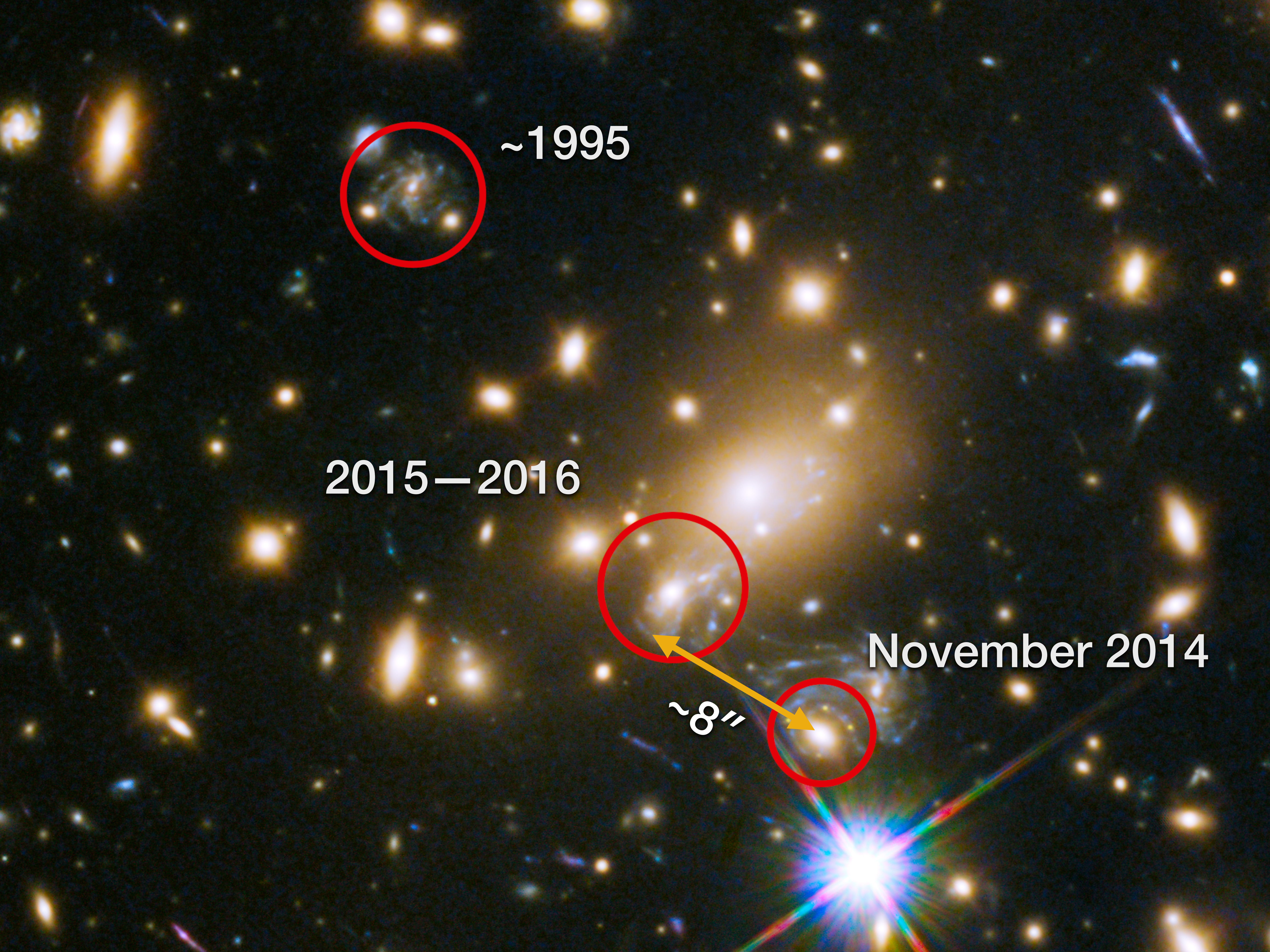


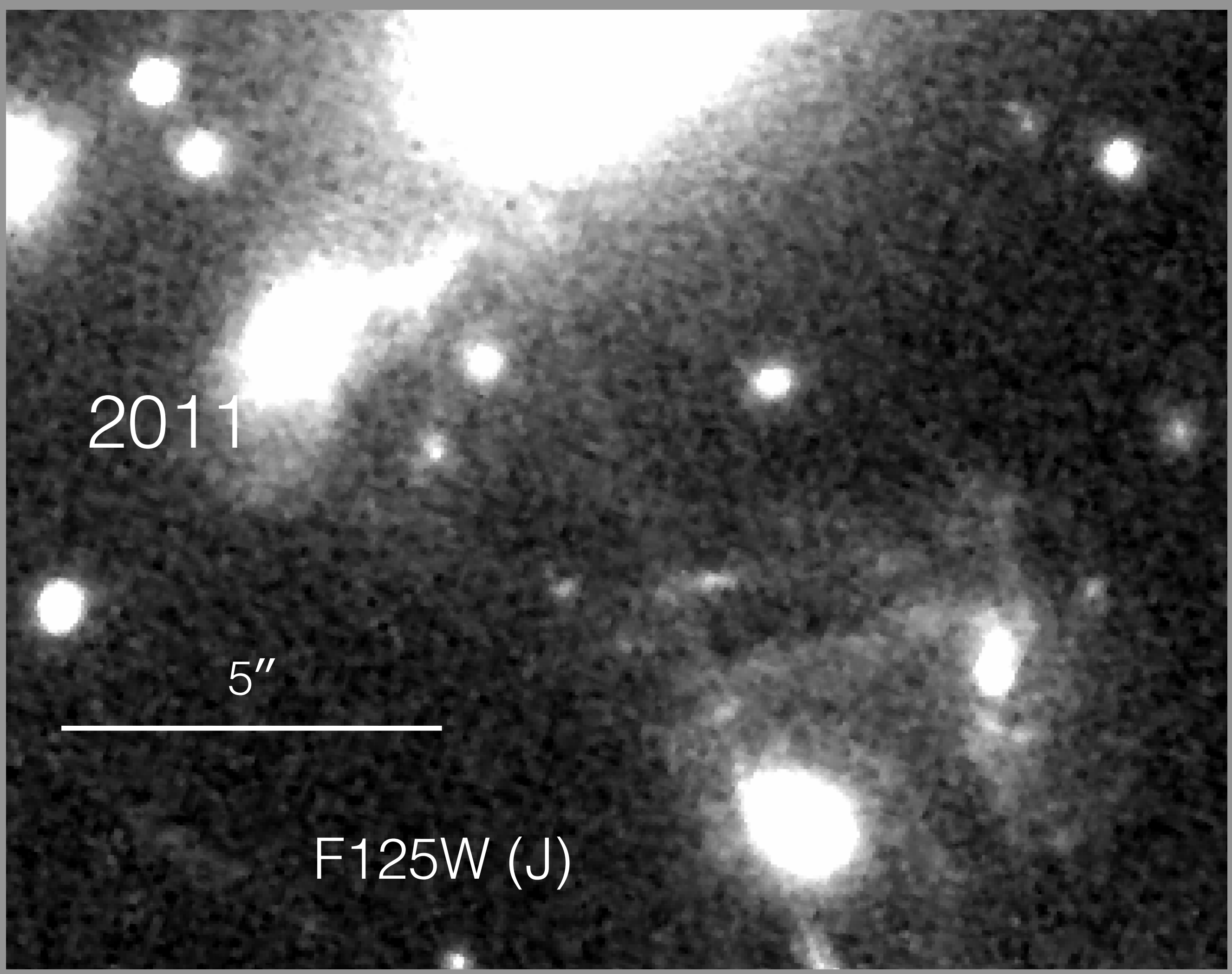

FIG. 2.—Magnification of a star with uniform surface brightness as a function of the time since the center of the star crossed the caustic. Magnification of a point source at the center of the star is also shown. Characteristic time $\tau_{ev}$ is given in eq. (12). In 50% of the cases this curve should occur in the reverse order in time.

Miralda-Escude 91


~1995
2015—2016
November 2014
~8″

# Event Close to Critical Curve

Discovered in late April 2016 "RefsdalRedux" program to search for SN reappearance



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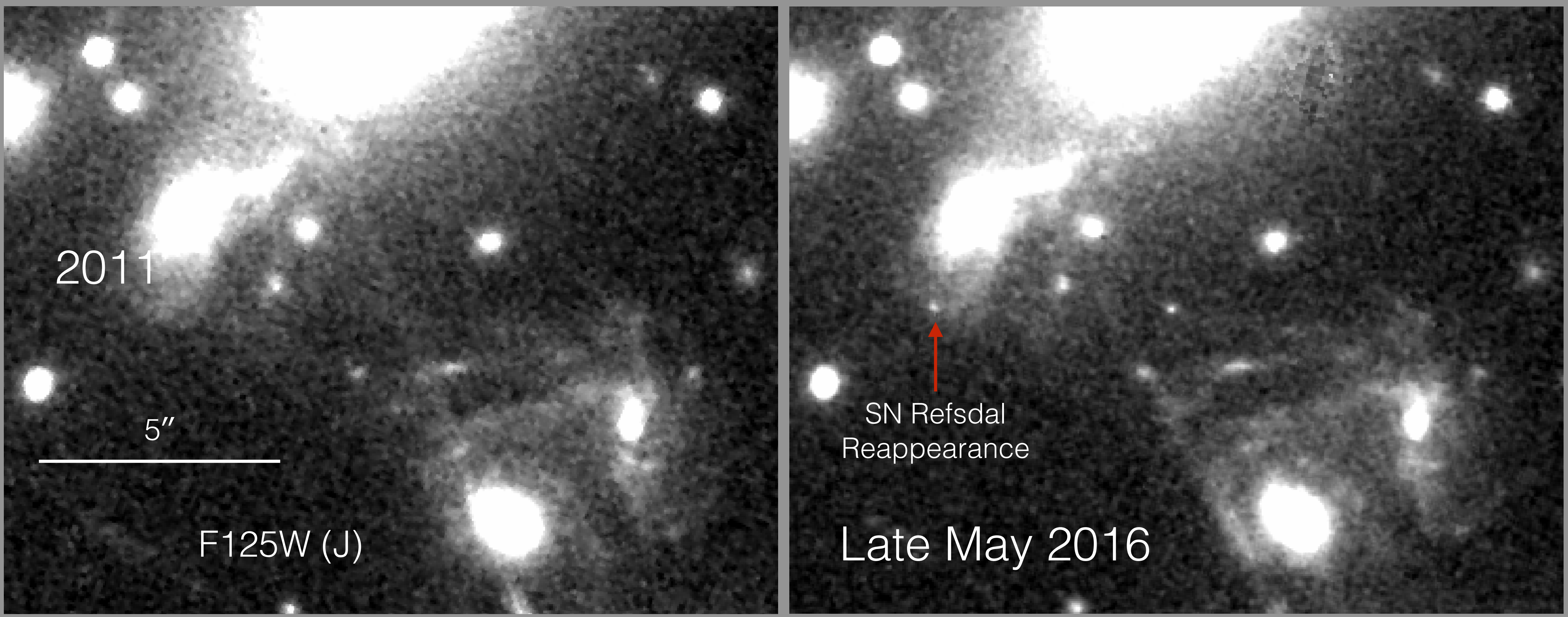

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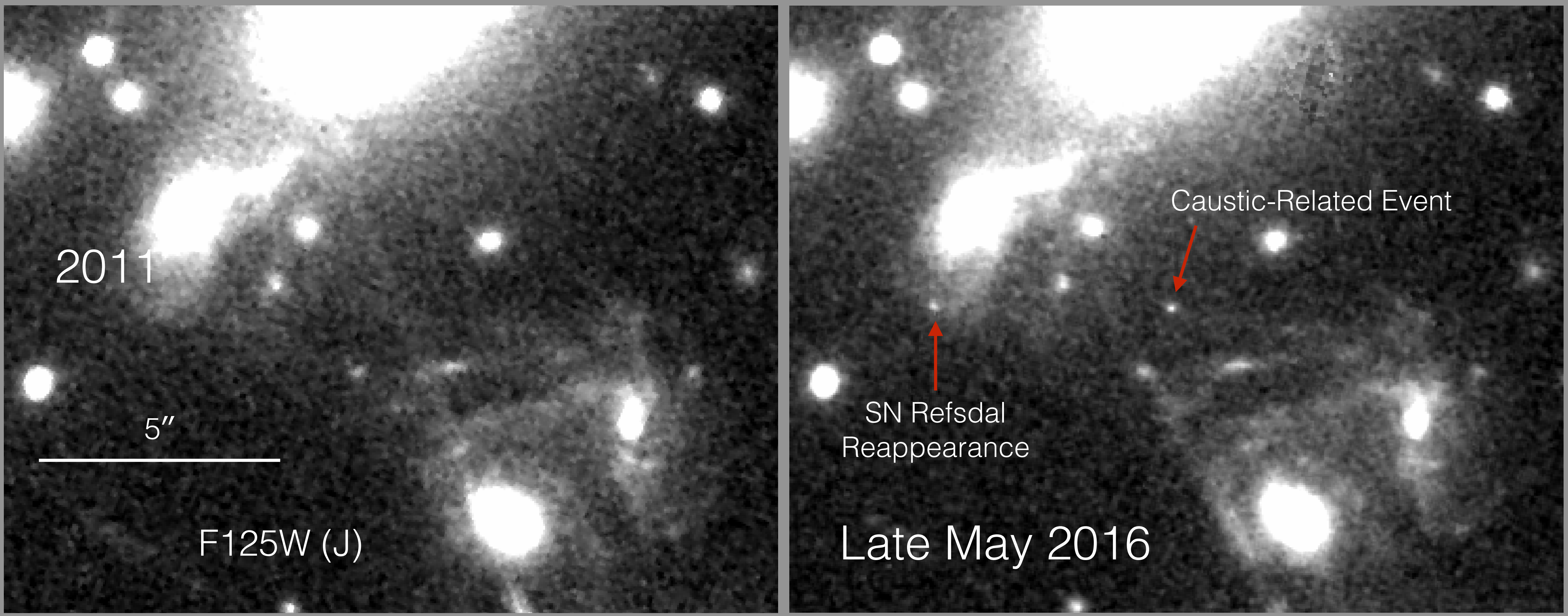

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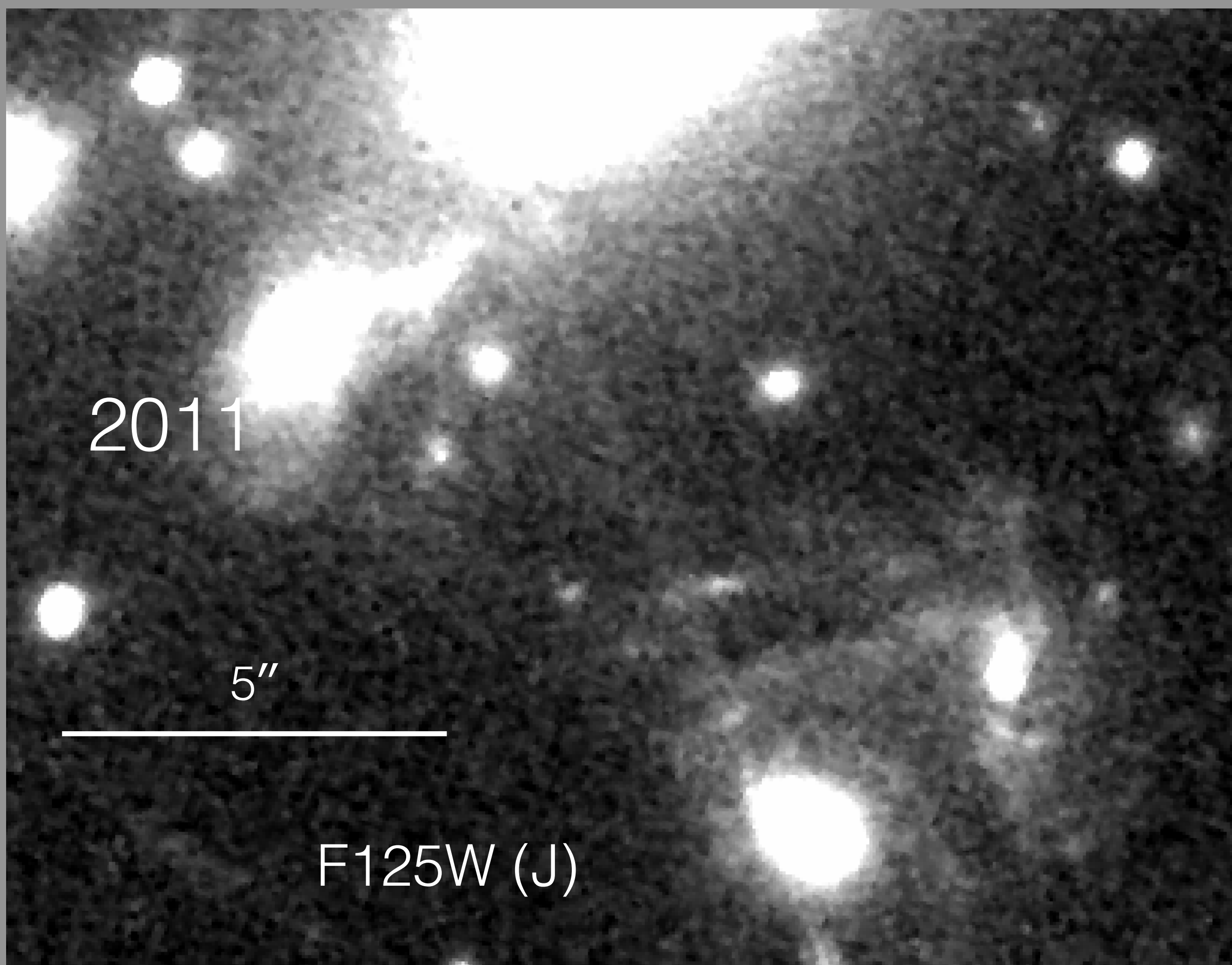
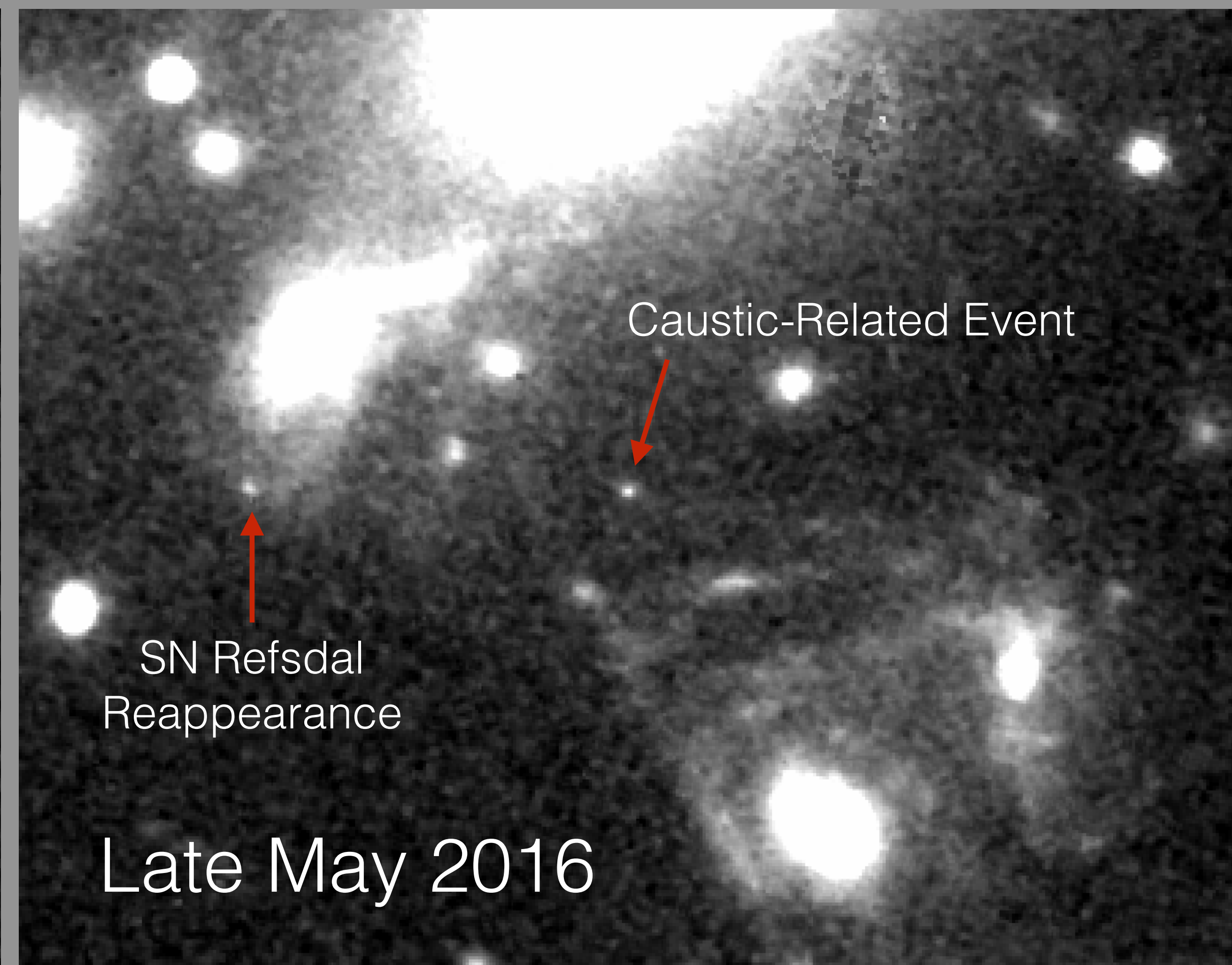
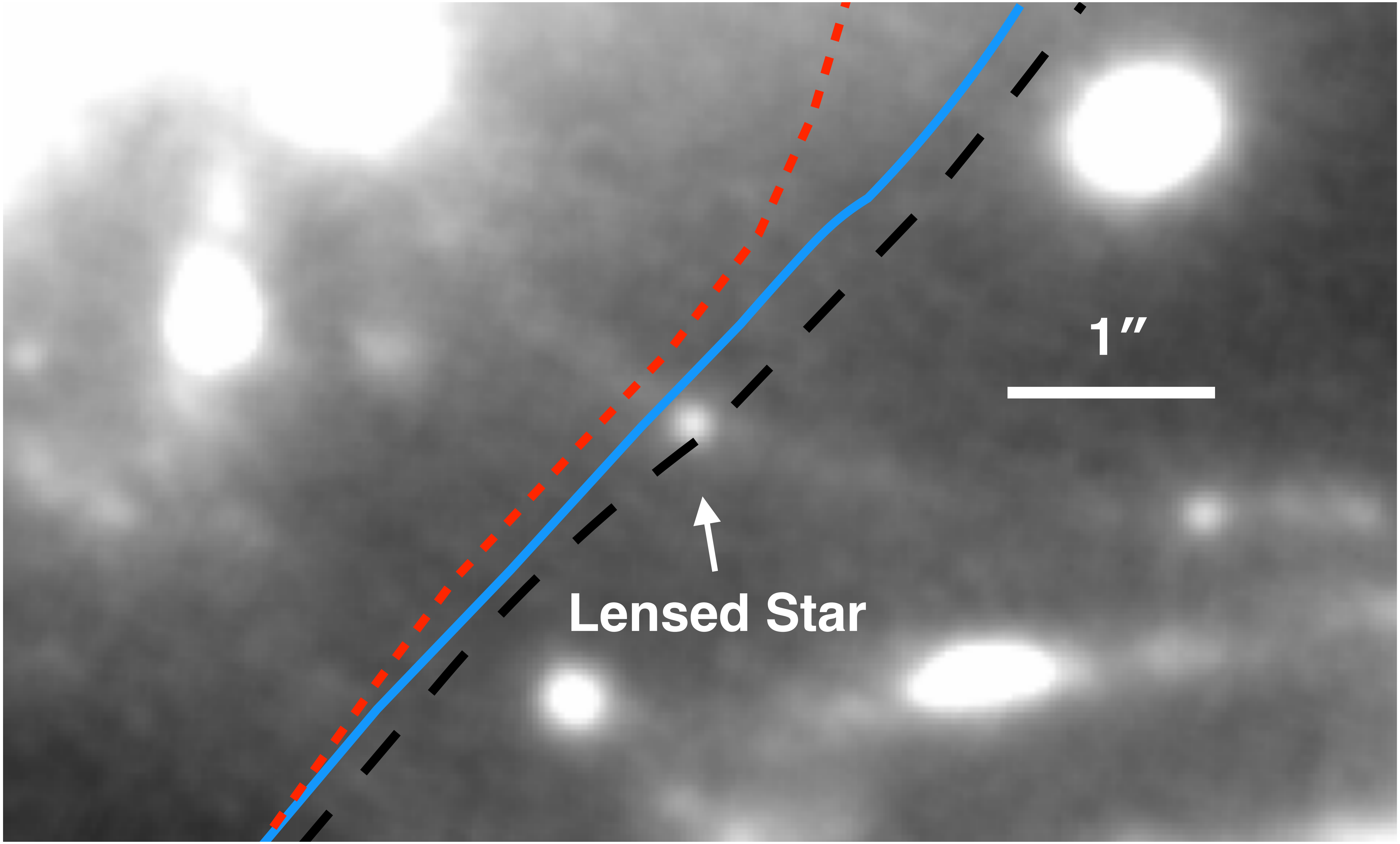


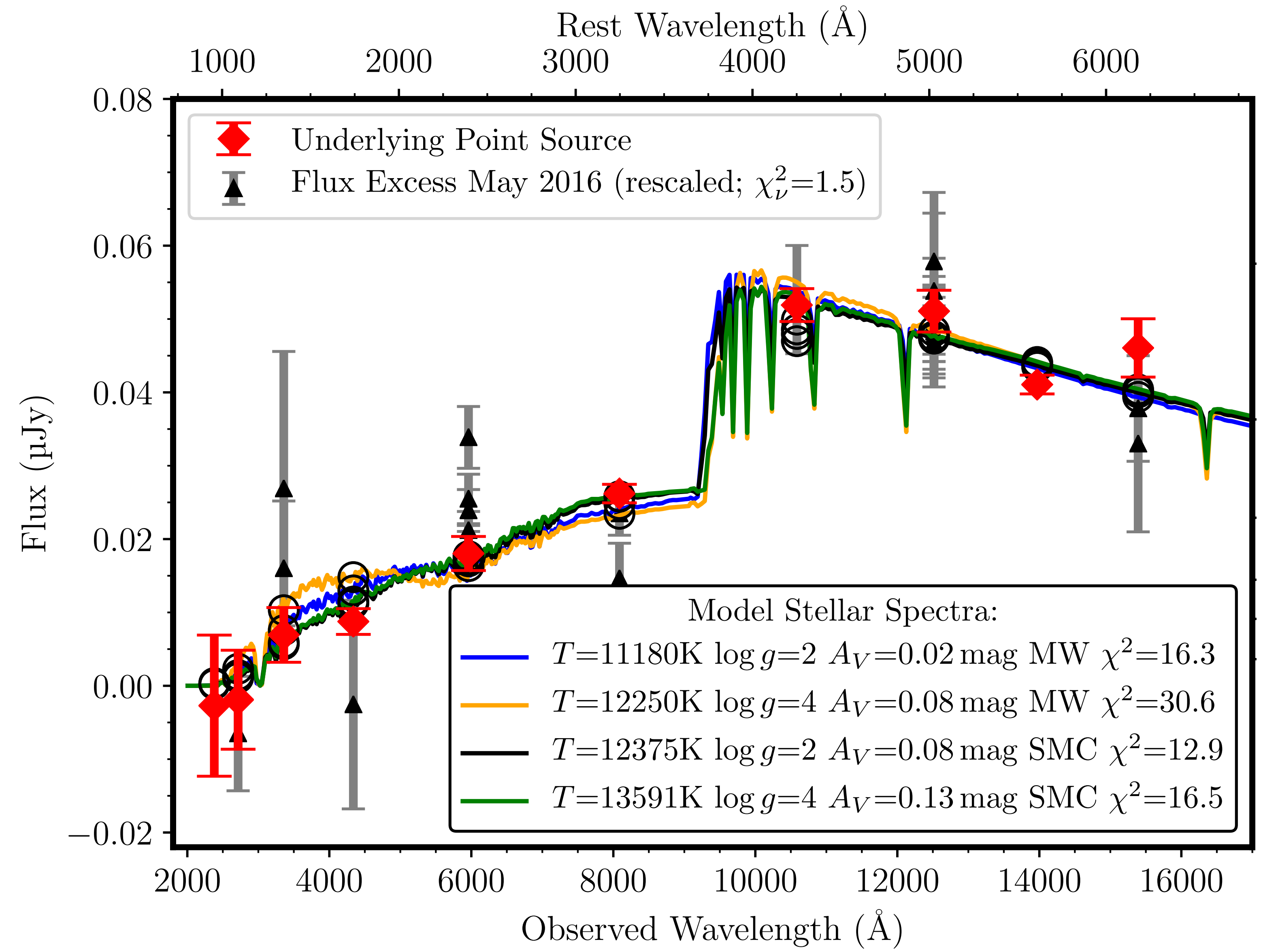

Follow-up GO-14199, 14528, and14872 (PI: Kelly), and 14208 (PI: Rodney)

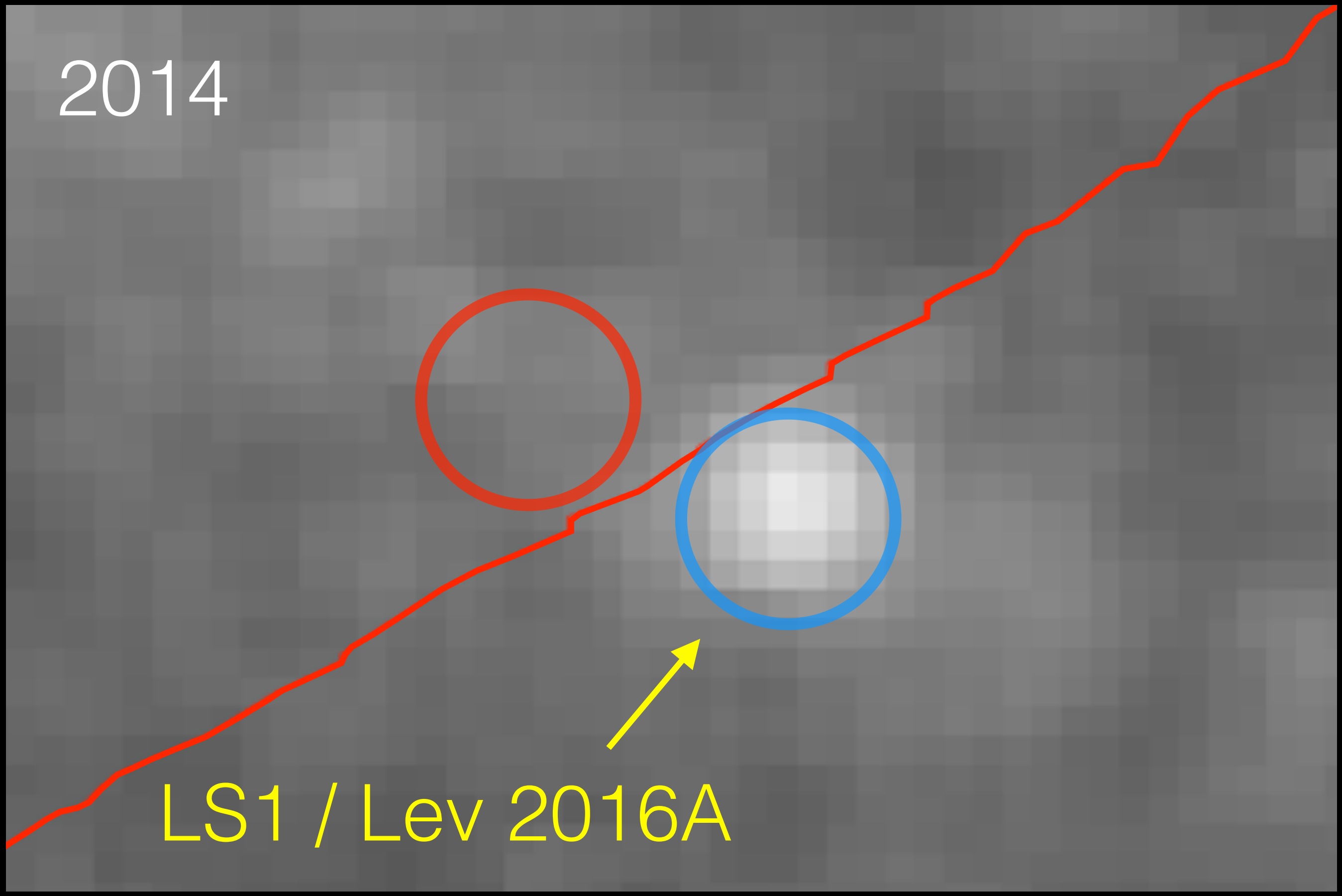


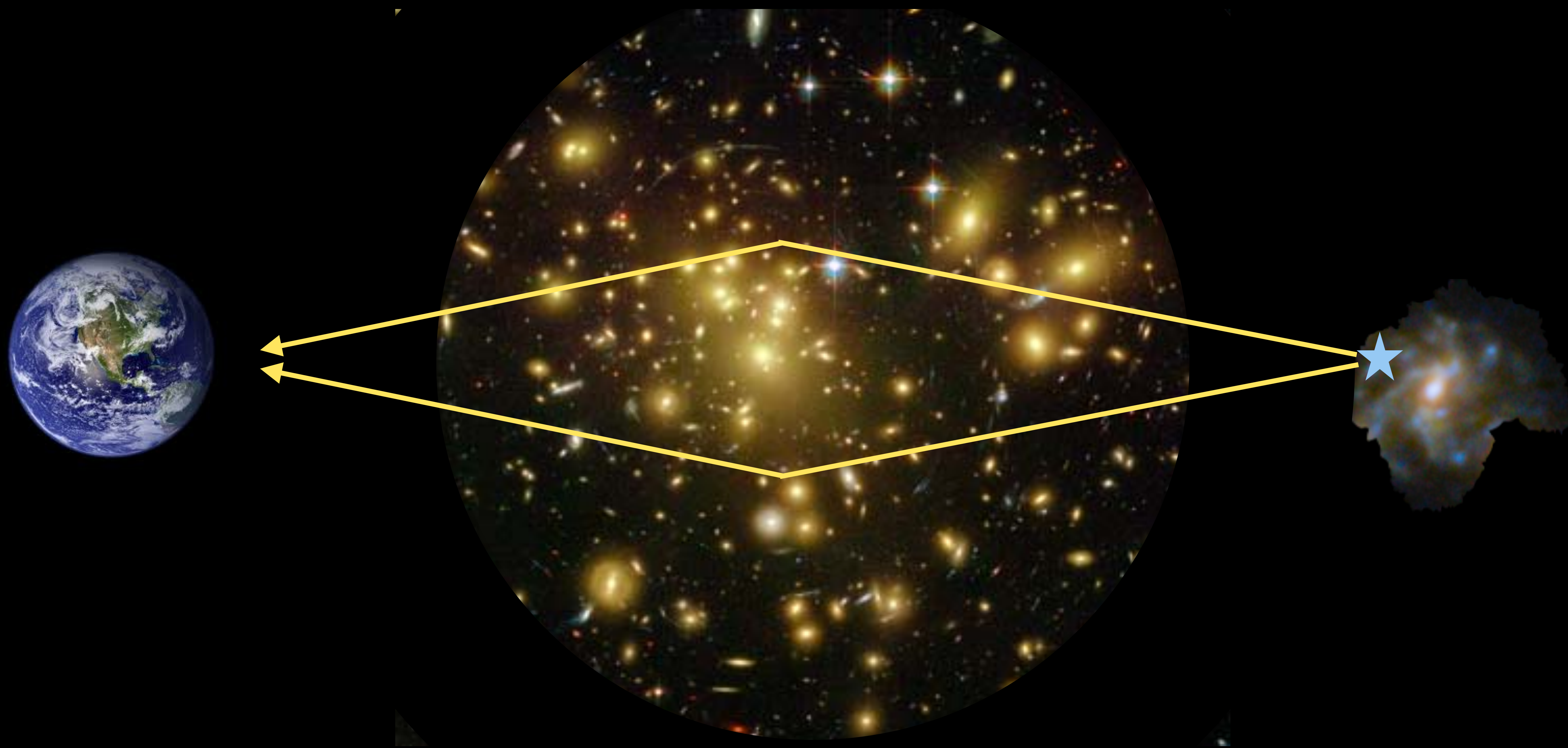

Zitrin et al. (dashed red), Oguri et al. GLAFIC (solid blue), and Keeton et al. (dashed black)

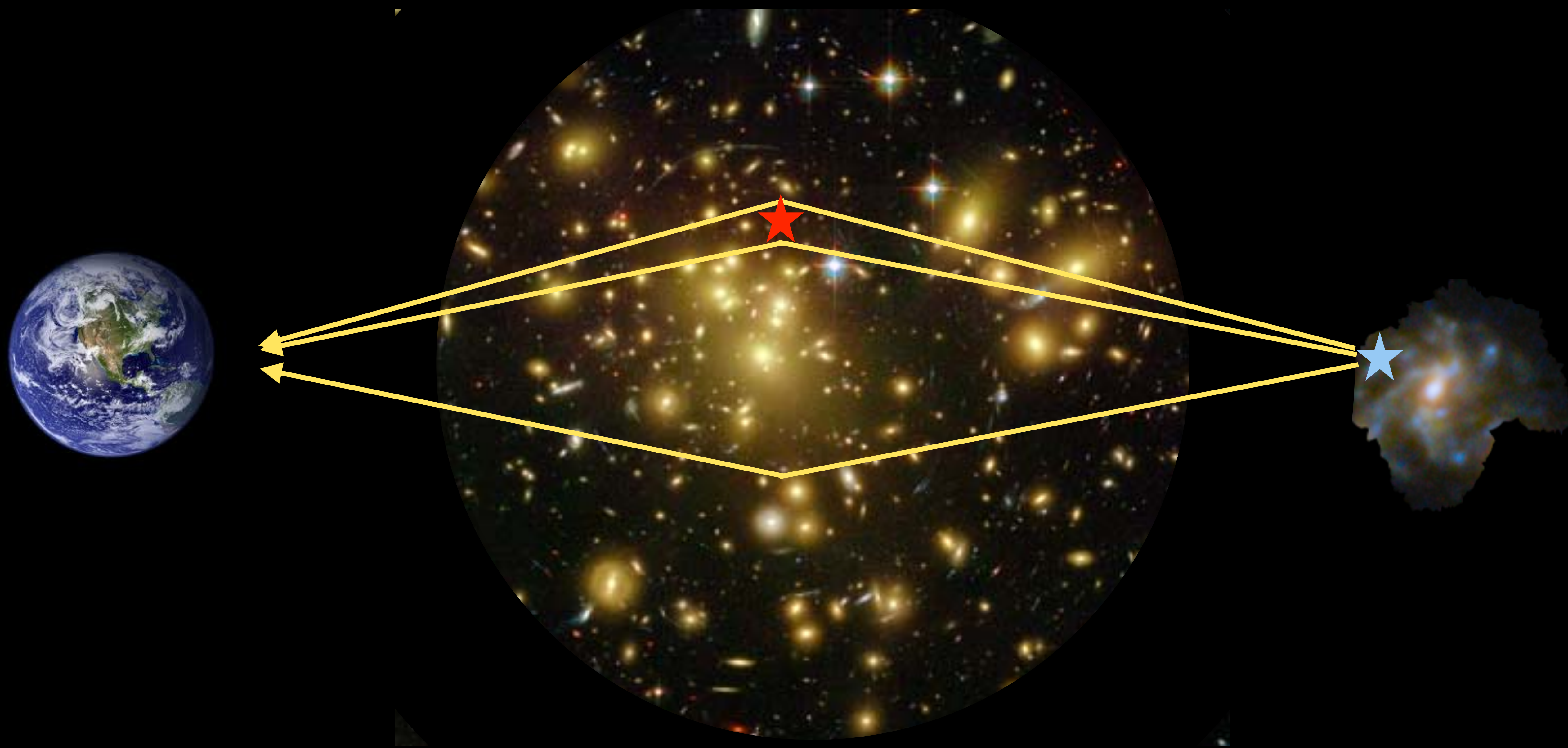
# Mid-to-Late B-type Star

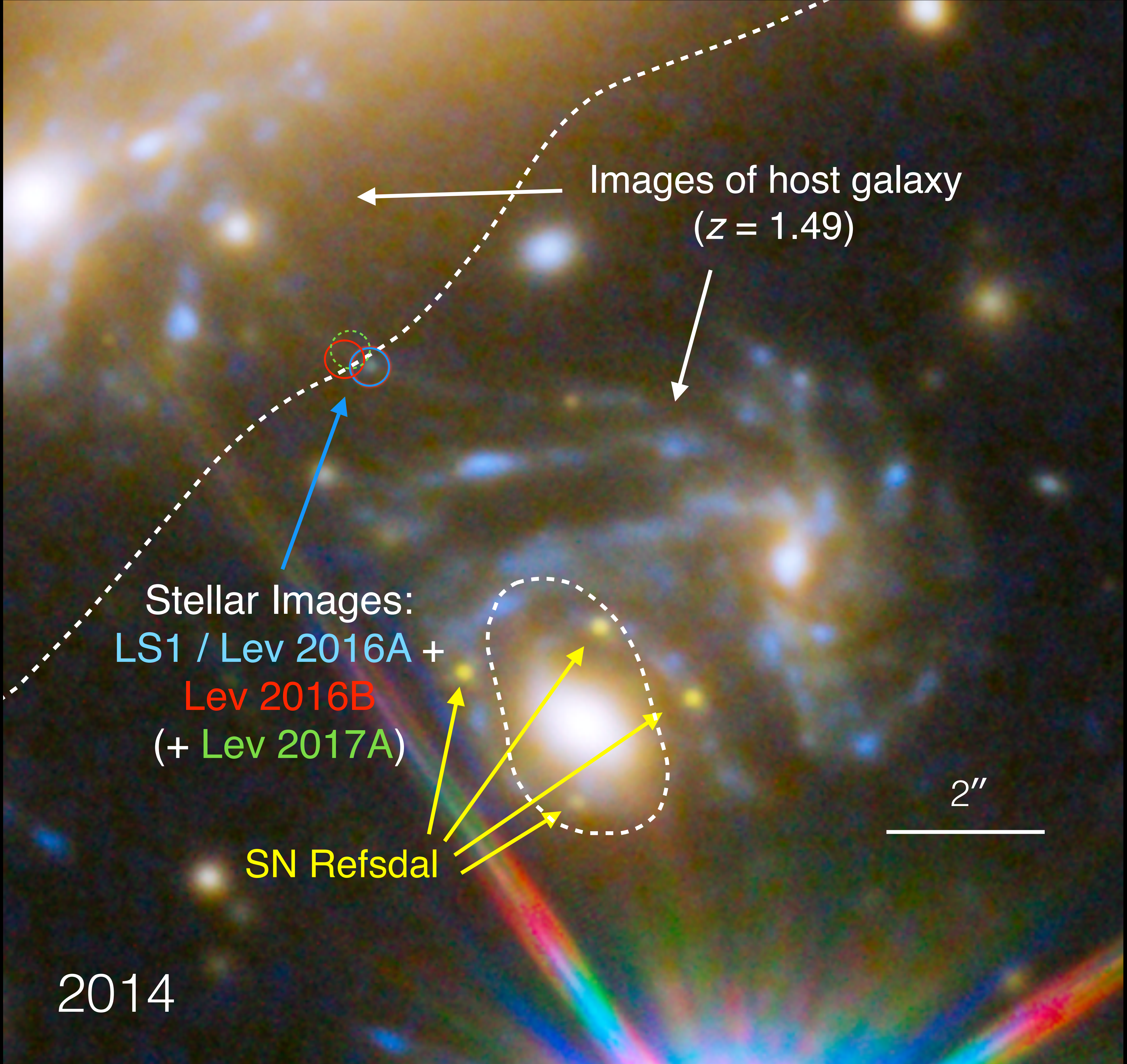
- No change in SED
- Magnified by ~2000x near peak
- Hotter than H-rich transients
- Light curve unlike stellar explosions
- Blue super (hyper?) giant similar to Refsdal progenitor

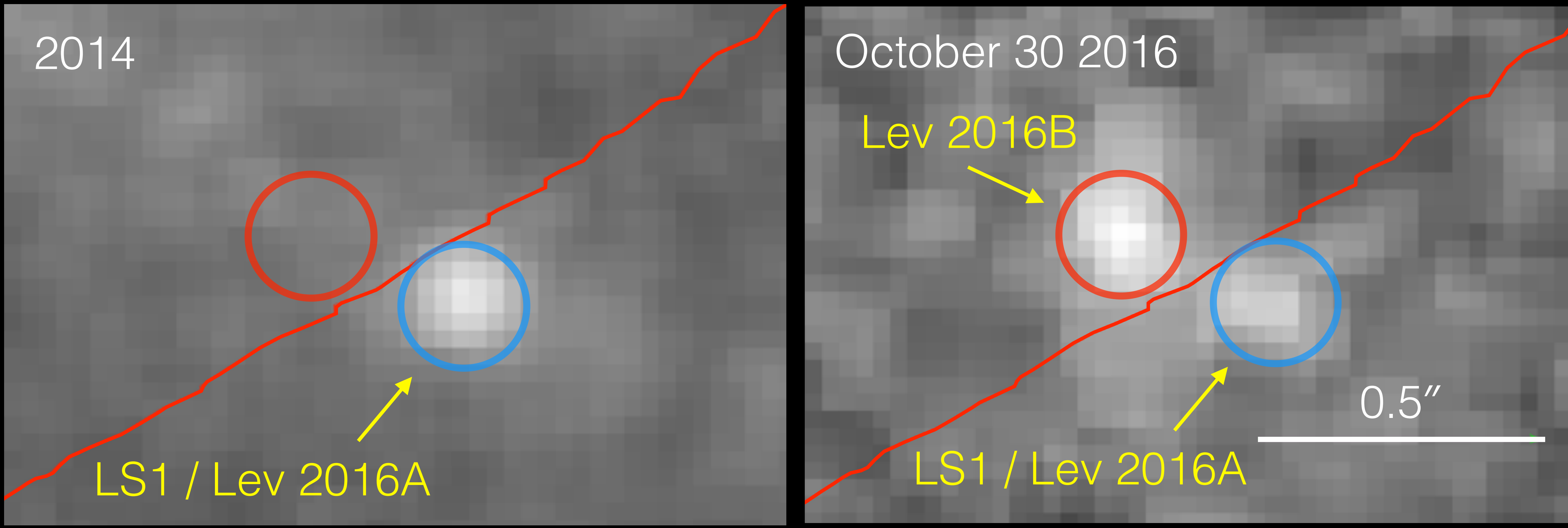



2014
LS1 / Lev 2016A

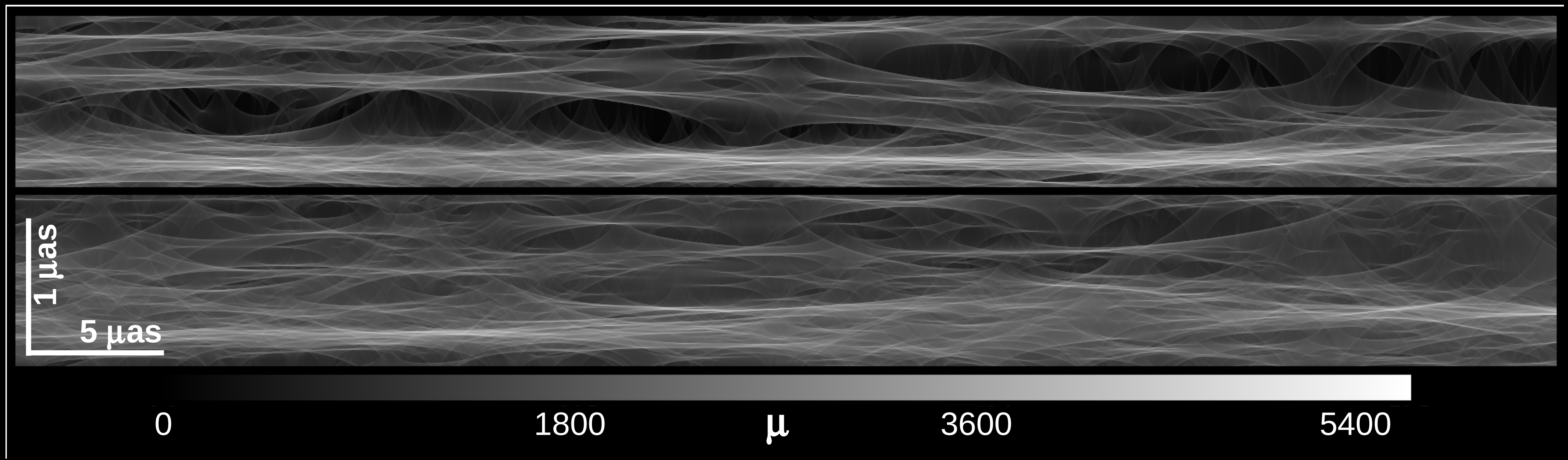


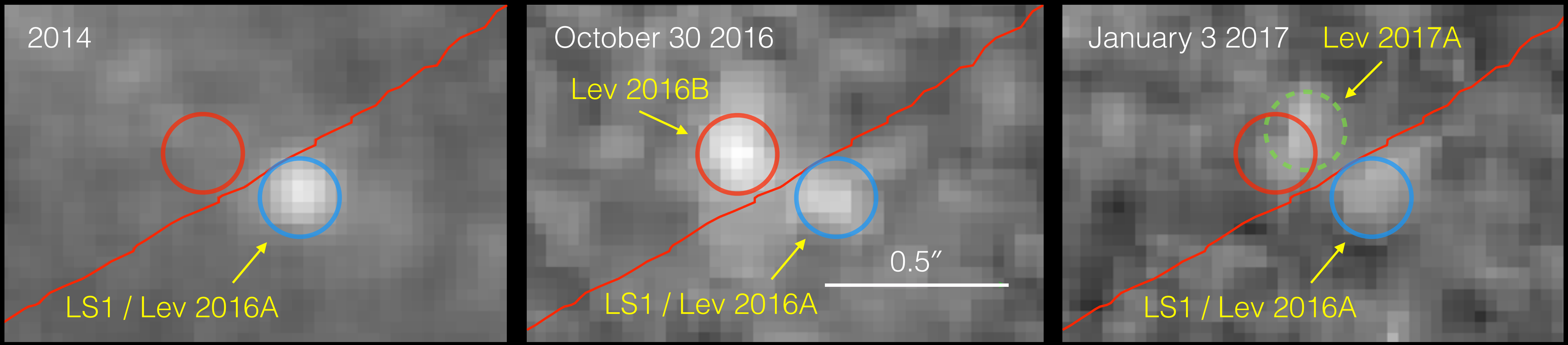



Images of host galaxy
(z = 1.49)
Stellar Images:
LS1 / Lev 2016A +
Lev 2016B
(+ Lev 2017A)
SN Refsdal
2″
2014



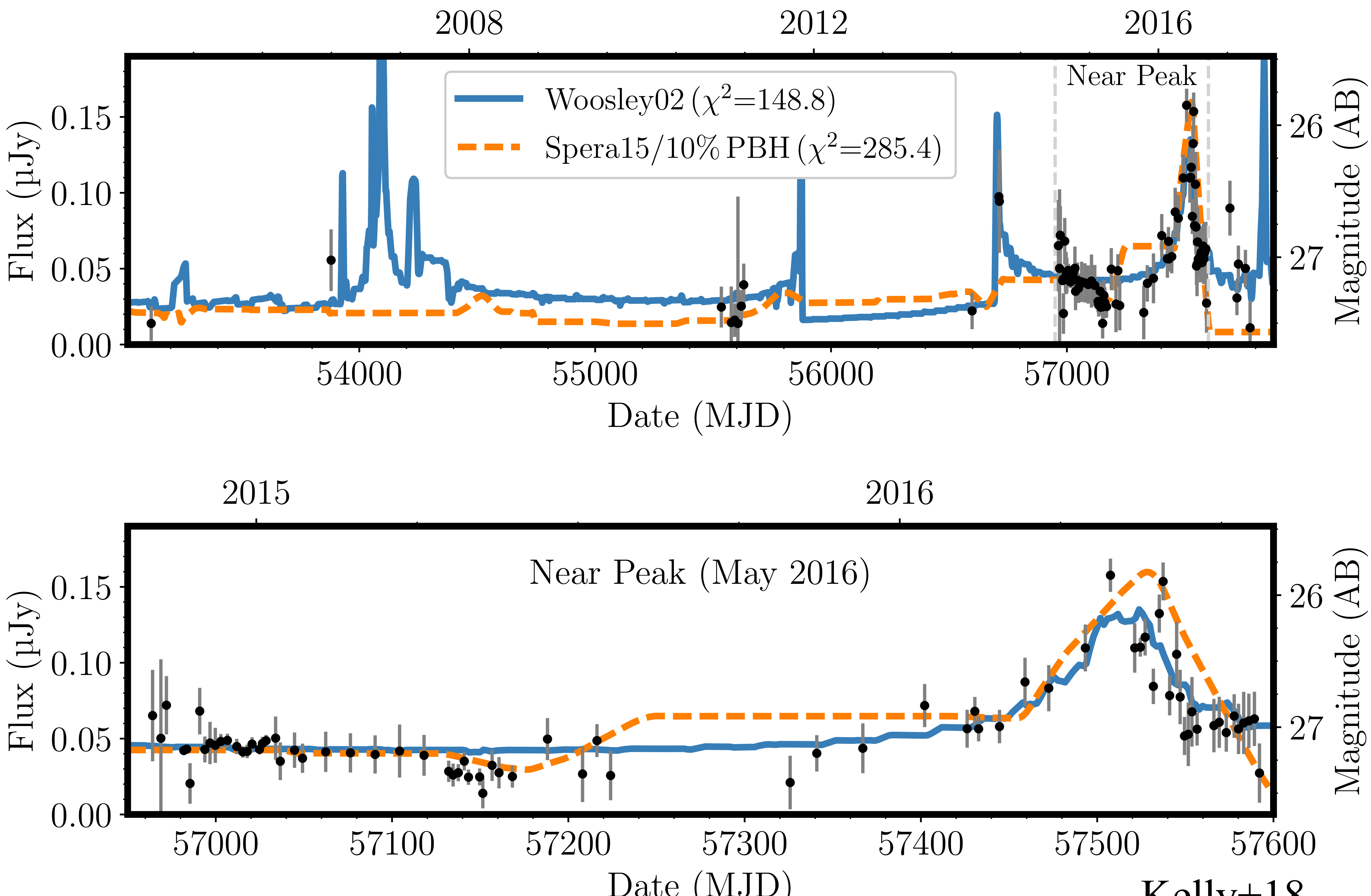

Colors of LS1 / Lev 16A and Lev 16B are consistent with each other —> simulations show parity should yield differing behavior






Found even a third possible microlensing event

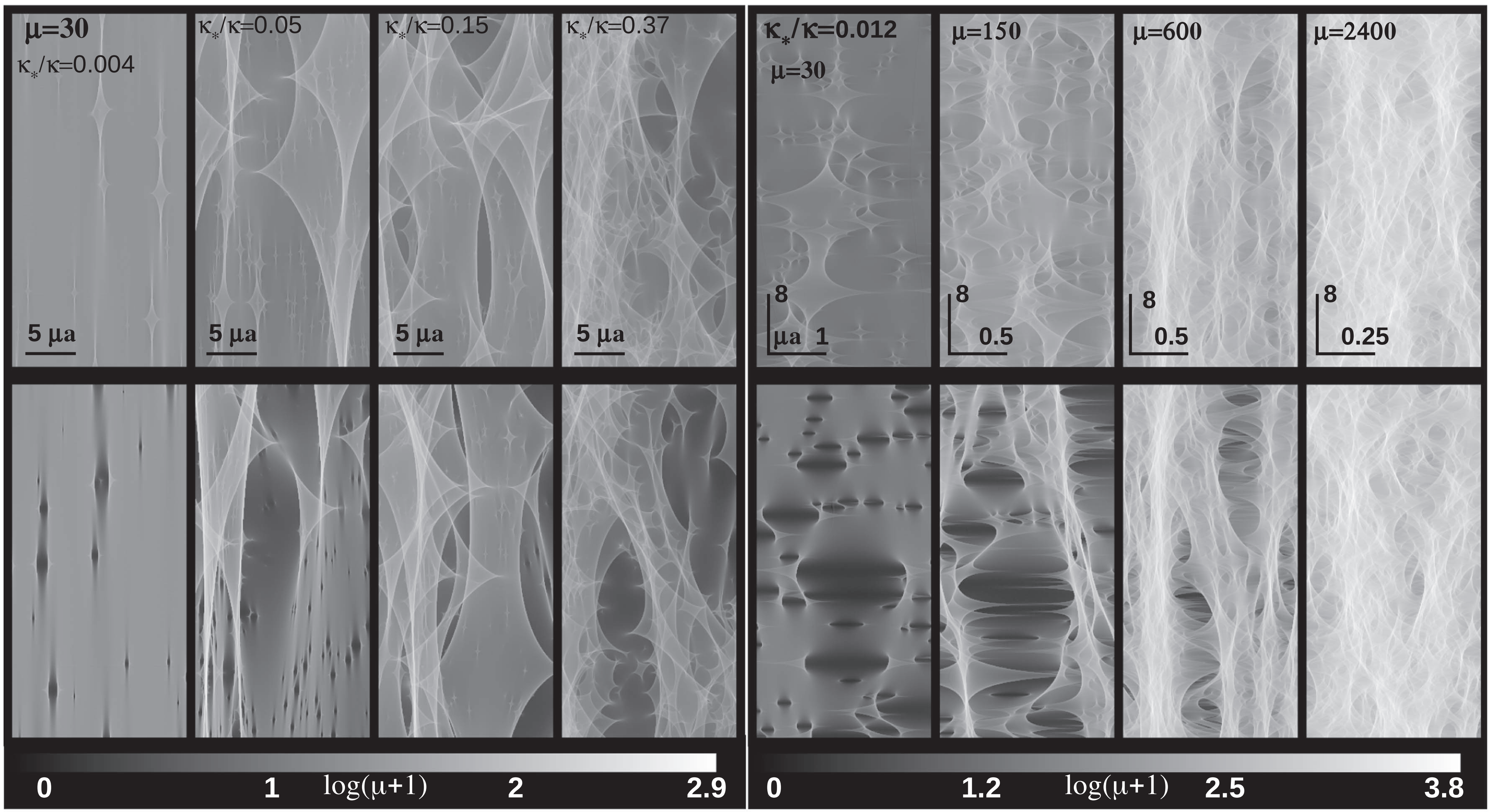
# Icarus' light curve matches simulation of microlensing




Kelly+18

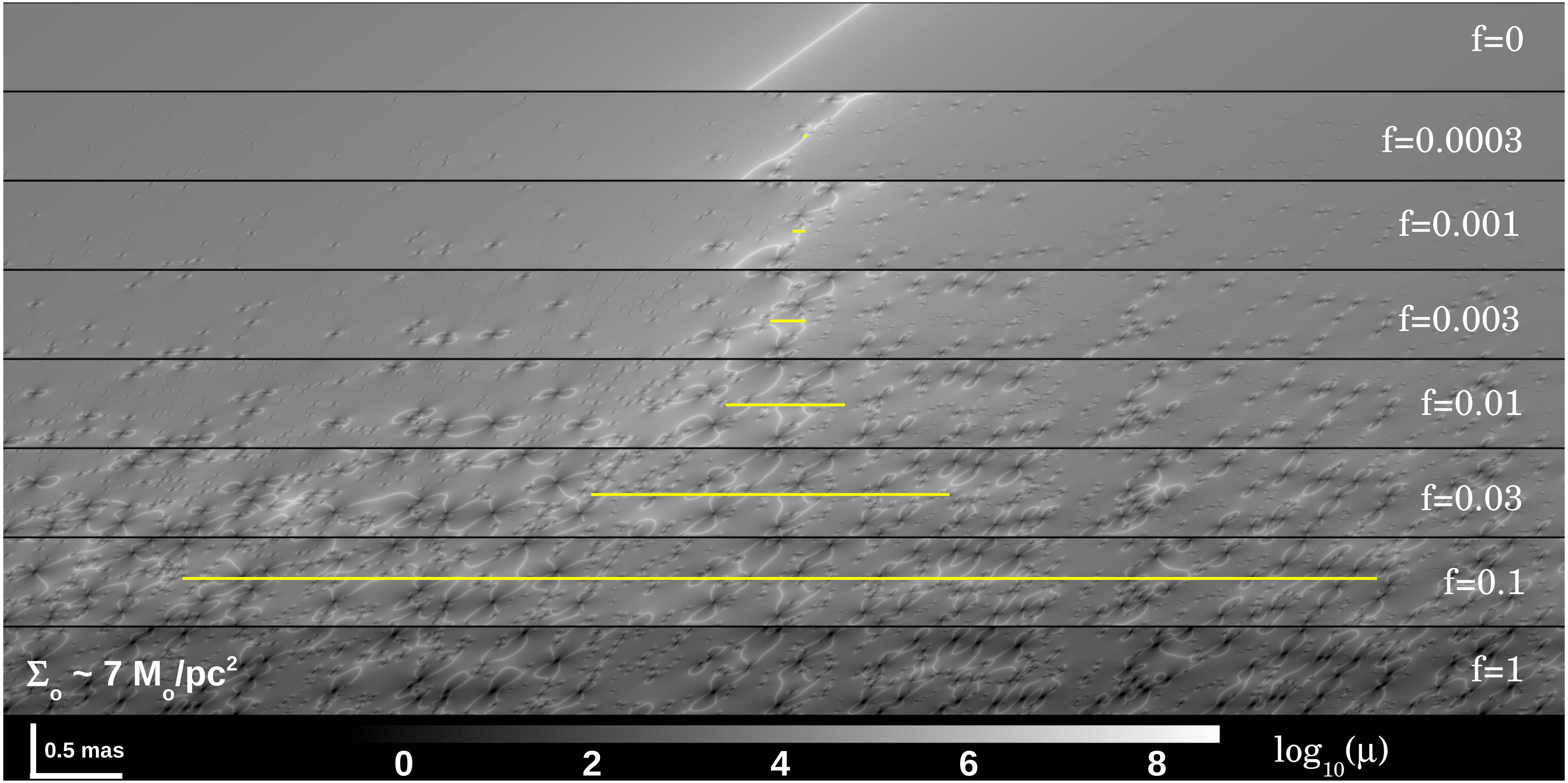
# Stars+Remnants+Dark Matter

The potential of a galaxy cluster acts to exaggerate the Einstein radii of objects in its intracluster medium by factors of up to ~ 100 near its critical curves (Diego et al., 2018; Venumadhav et al., 2017)



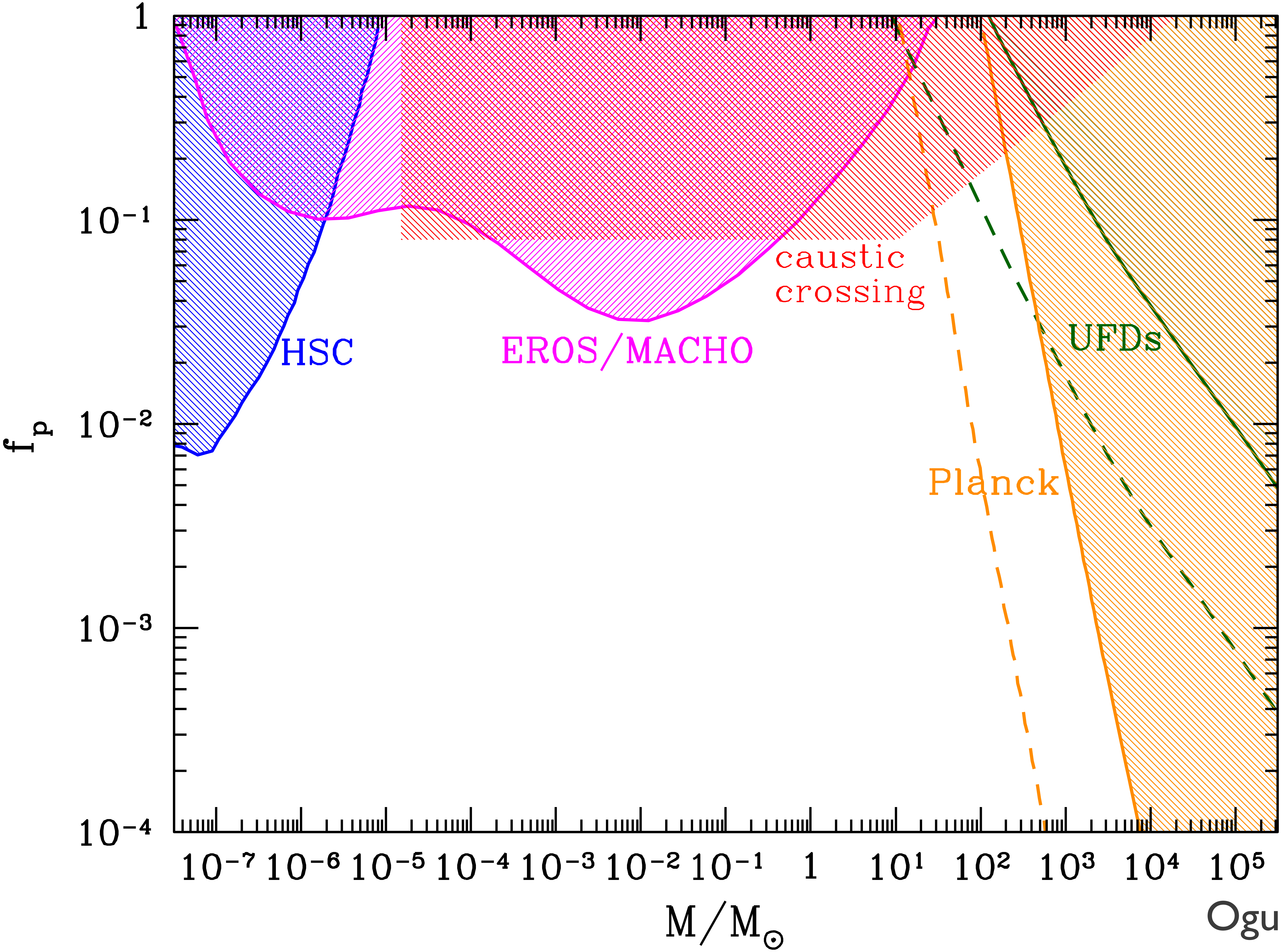

Diego+18

# Adding Microlenses

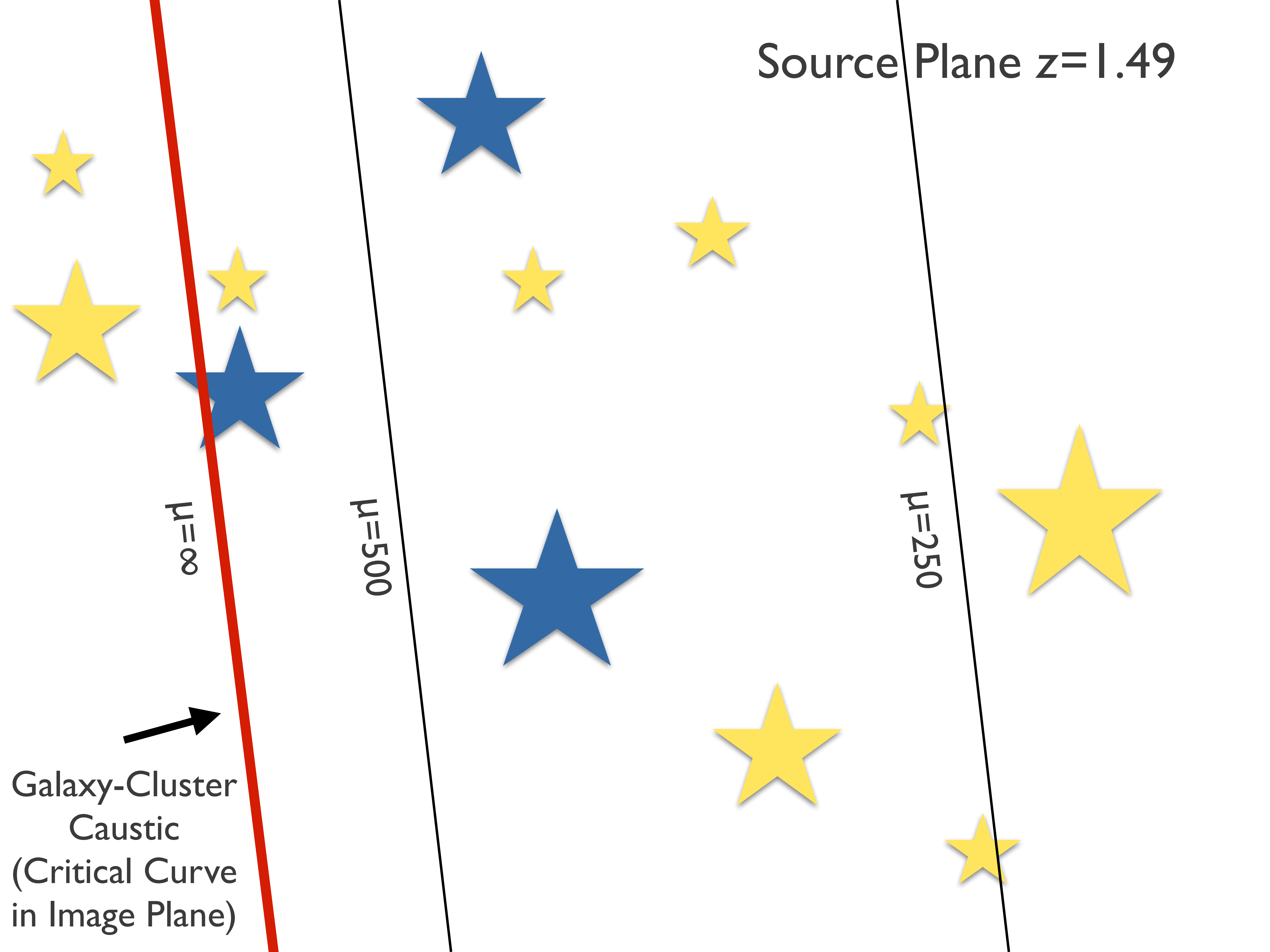



Diego+18

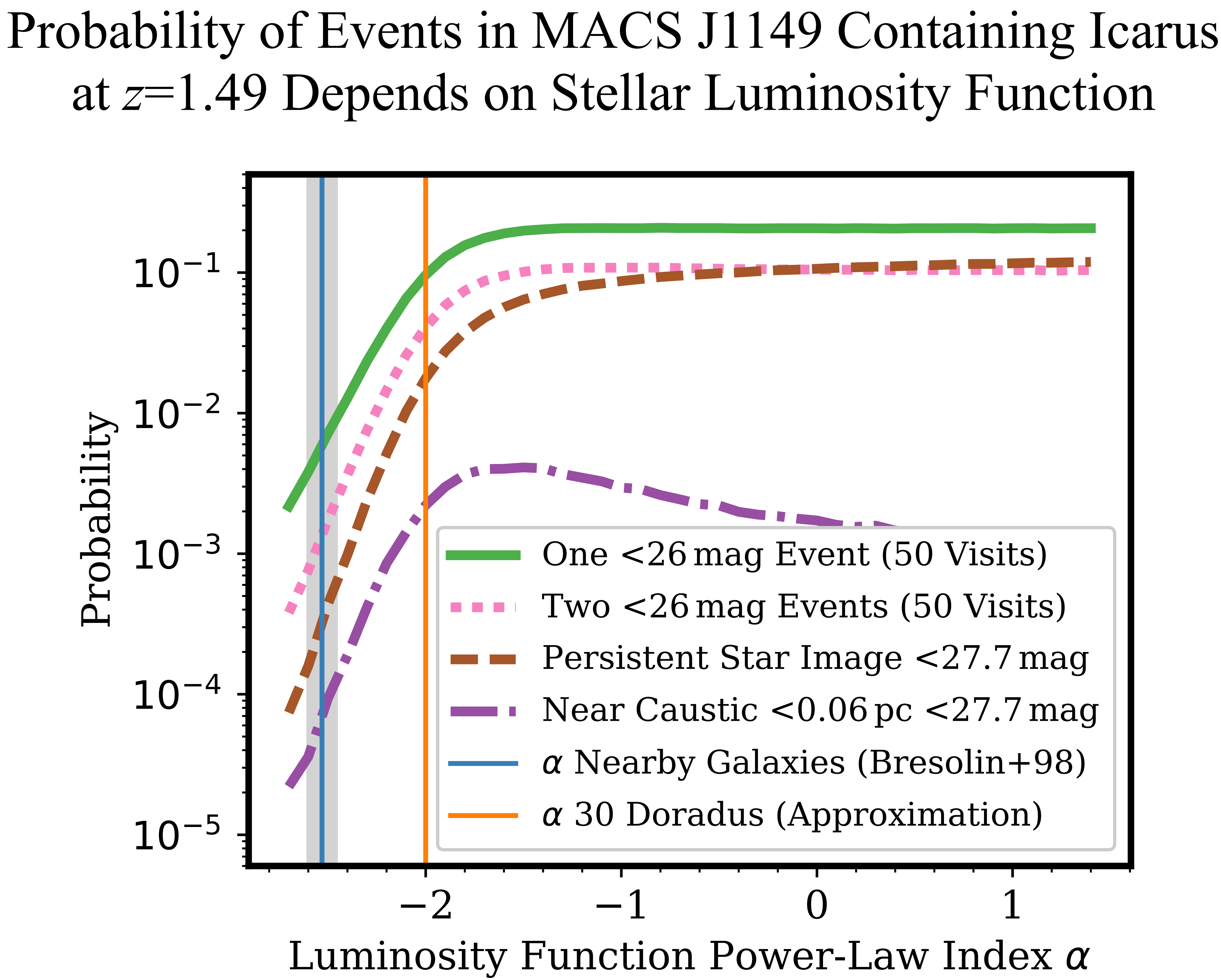
# Constraints on Abundance of Primordial Black Holes from Icarus




Oguri+18

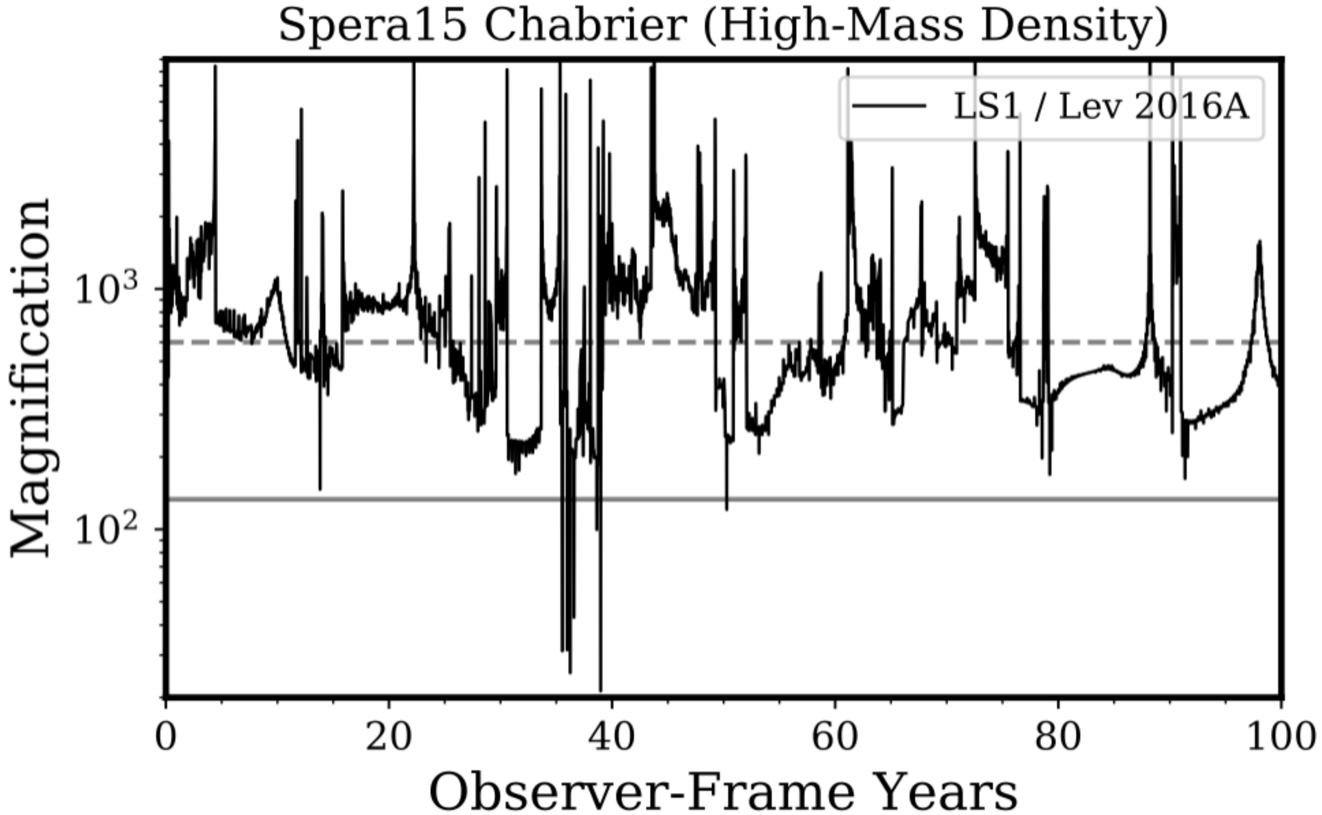


Source Plane z=1.49
μ=∞
μ=500
μ=250
Galaxy-Cluster Caustic (Critical Curve in Image Plane)

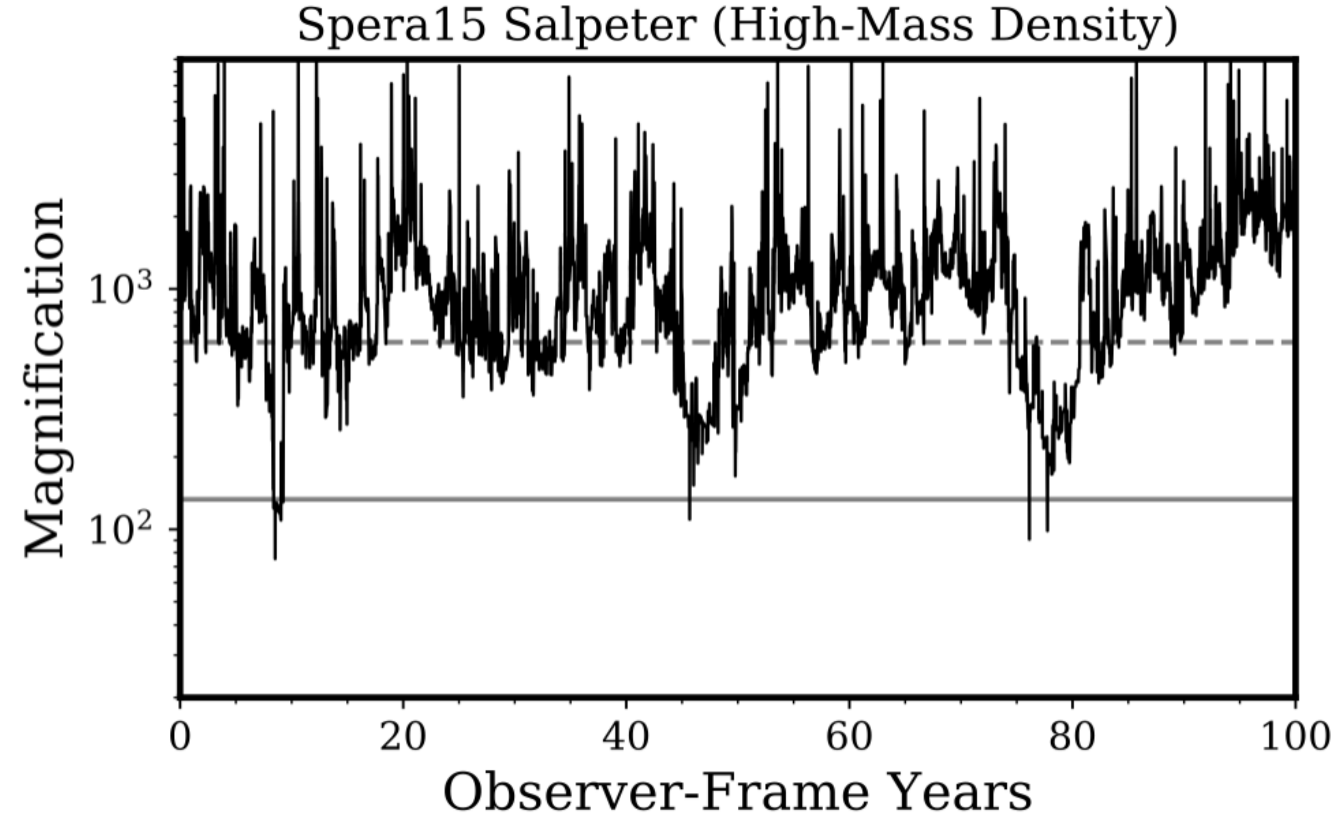


Probability of Events in MACS J1149 Containing Icarus
at z=1.49 Depends on Stellar Luminosity Function
Probability
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
−2
−1
0
1
Luminosity Function Power-Law Index α
One <26 mag Event (50 Visits)
Two <26 mag Events (50 Visits)
Persistent Star Image <27.7 mag
Near Caustic <0.06 pc <27.7 mag
α Nearby Galaxies (Bresolin+98)
α 30 Doradus (Approximation)

# For bottom-heavy IMF, much higher frequency of microlensing peaks




Chabrier — Milky-Way like

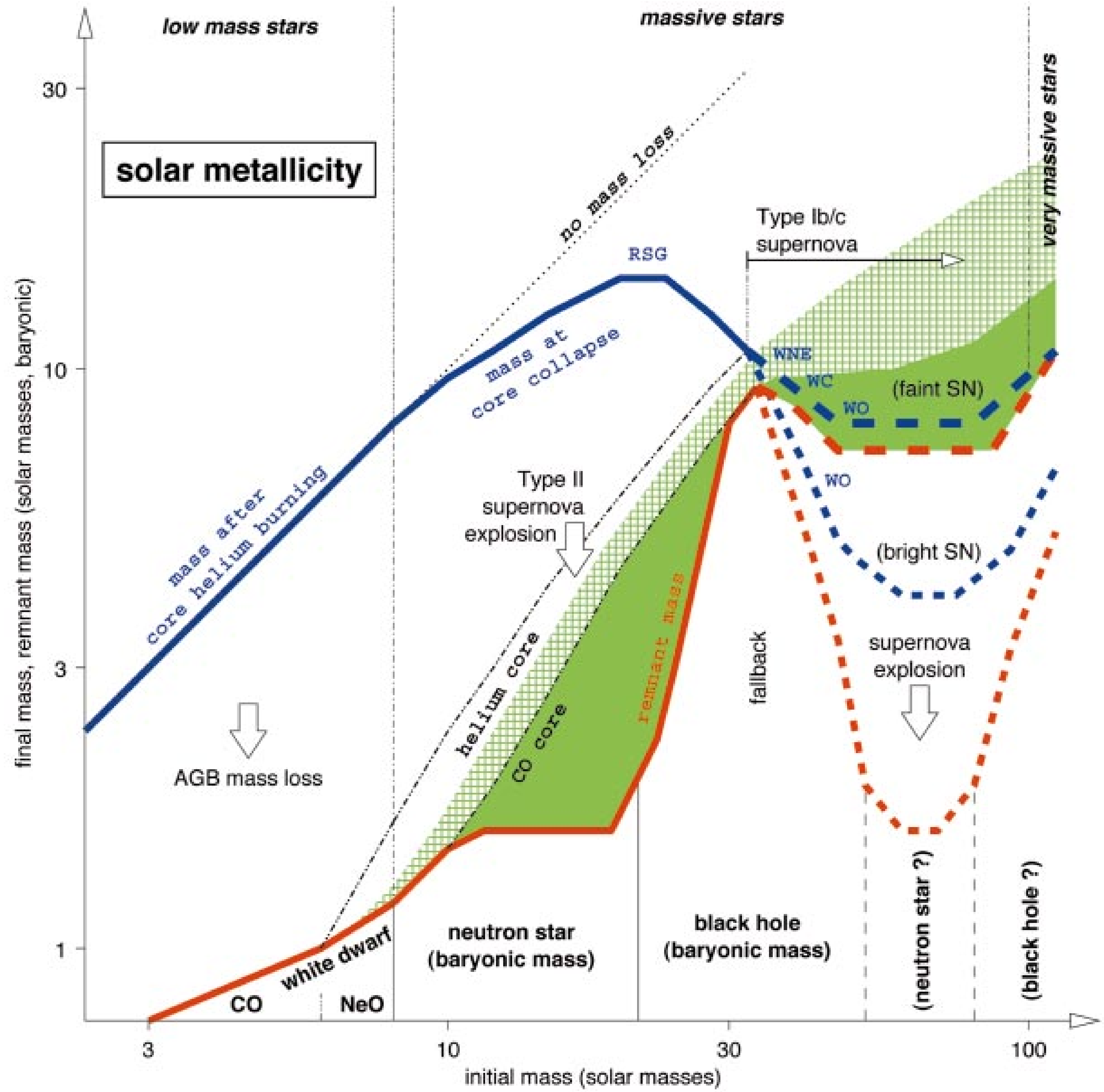



Salpeter — “bottom heavy”

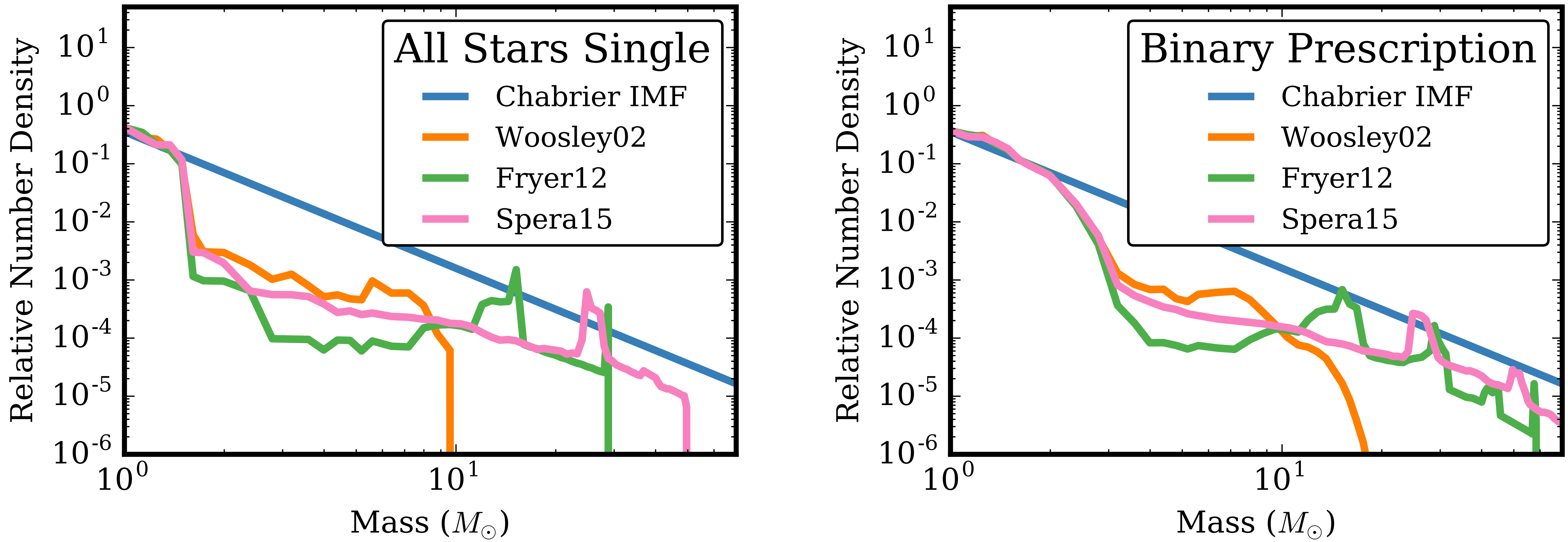
LS1 light curve probes the stars making up the intracluster medium, which may have been stripped from cluster members

# Outcomes of massive stellar evolution

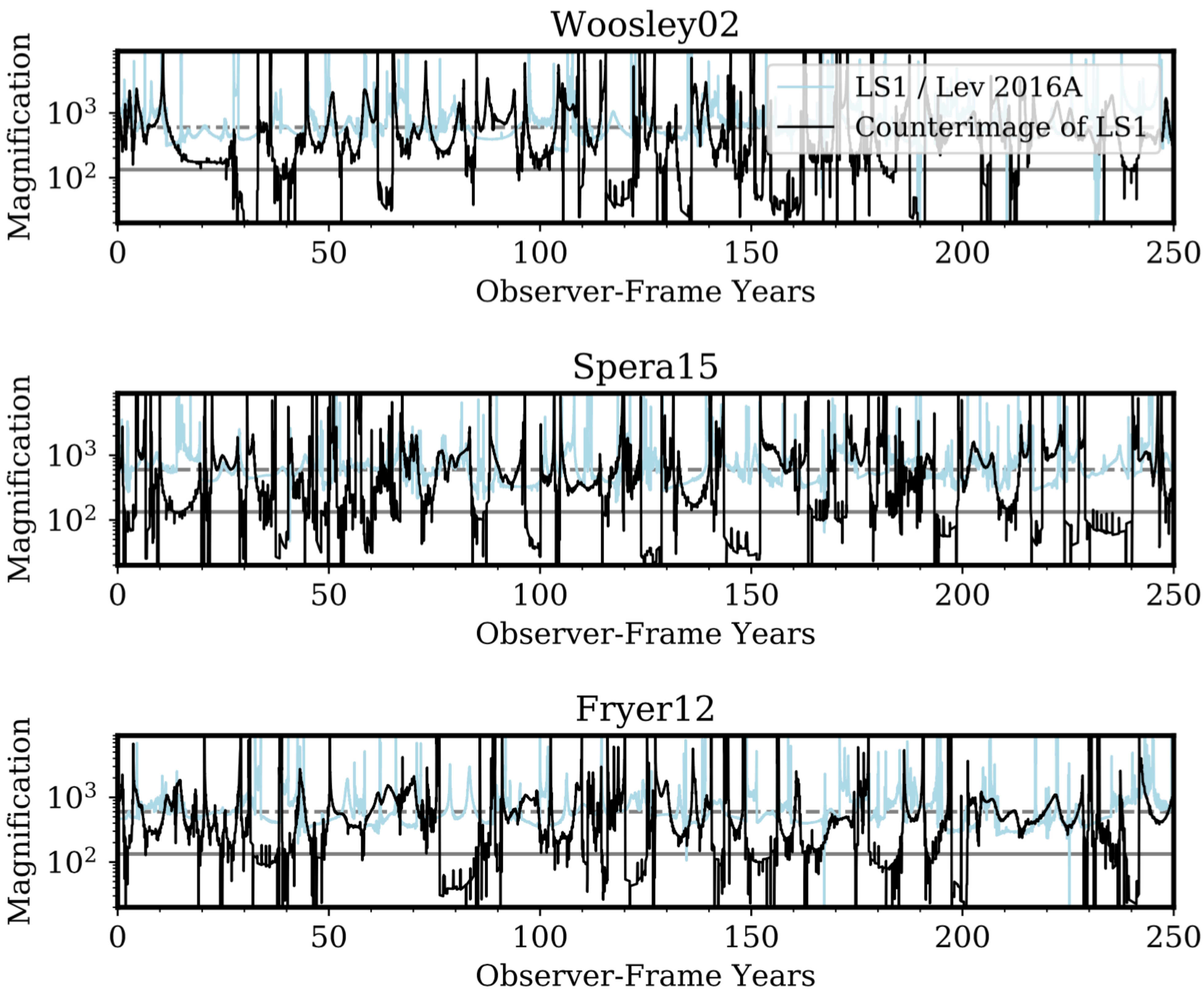
- Intracluster stellar population formed at high redshift
- Remnant population (NS + BH) mass function
  - Mass loss rate
  - Which SN explosions are successful? Neutrino mechanism



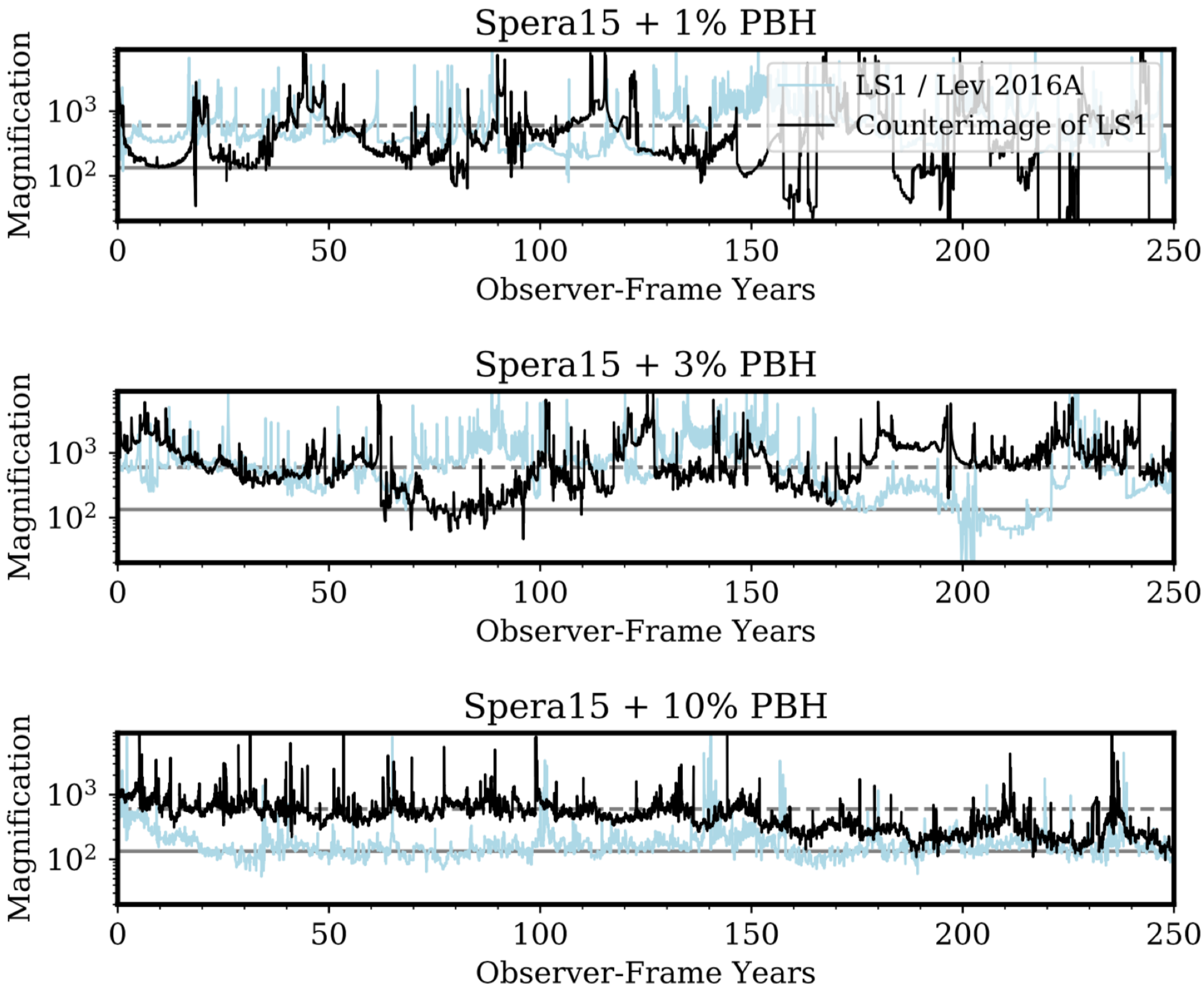
# Mass Functions for Different Models of Massive Stellar Evolution



# Massive Stellar Evolution Models



# Primordial Black Hole Abundance

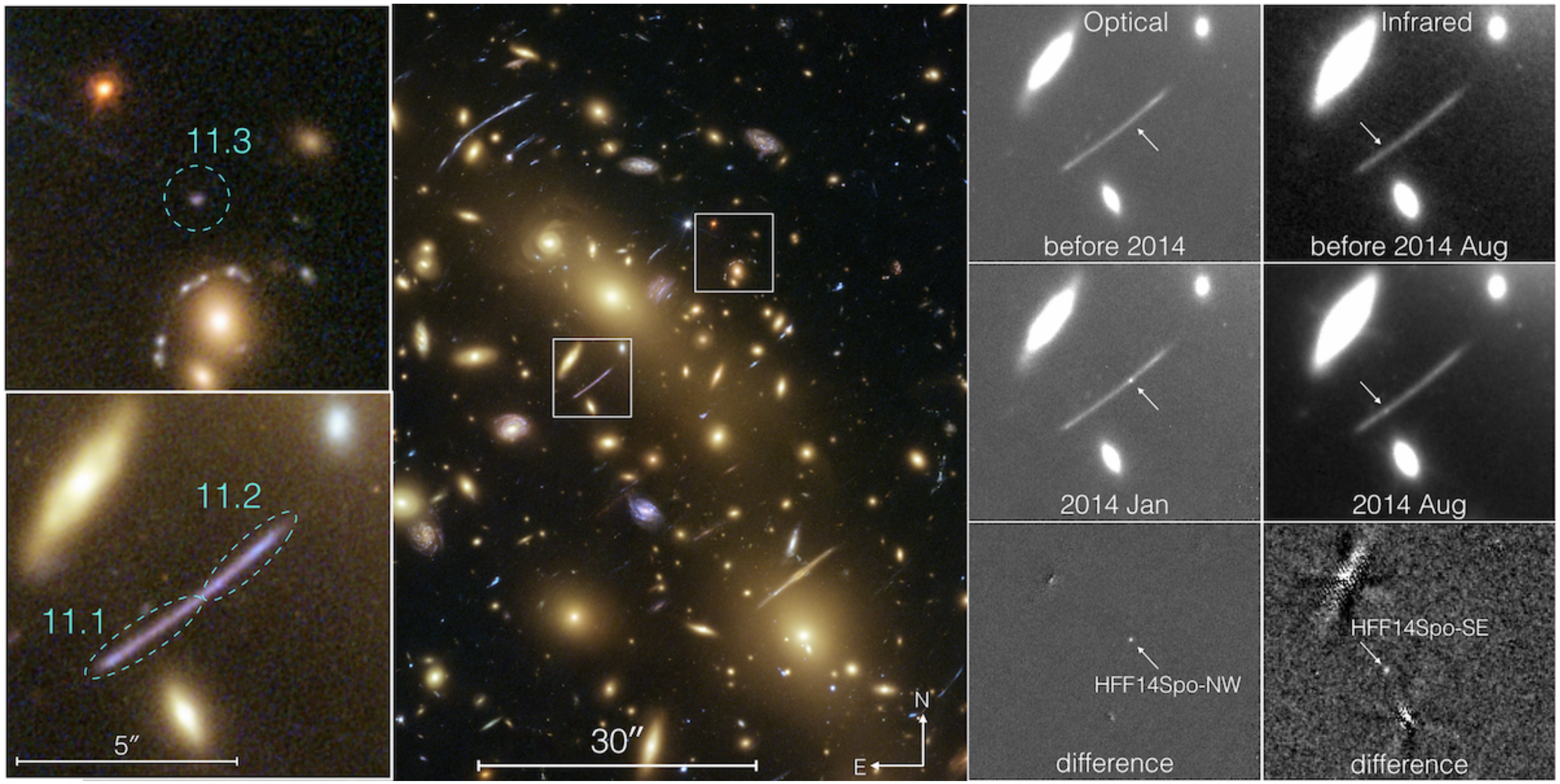


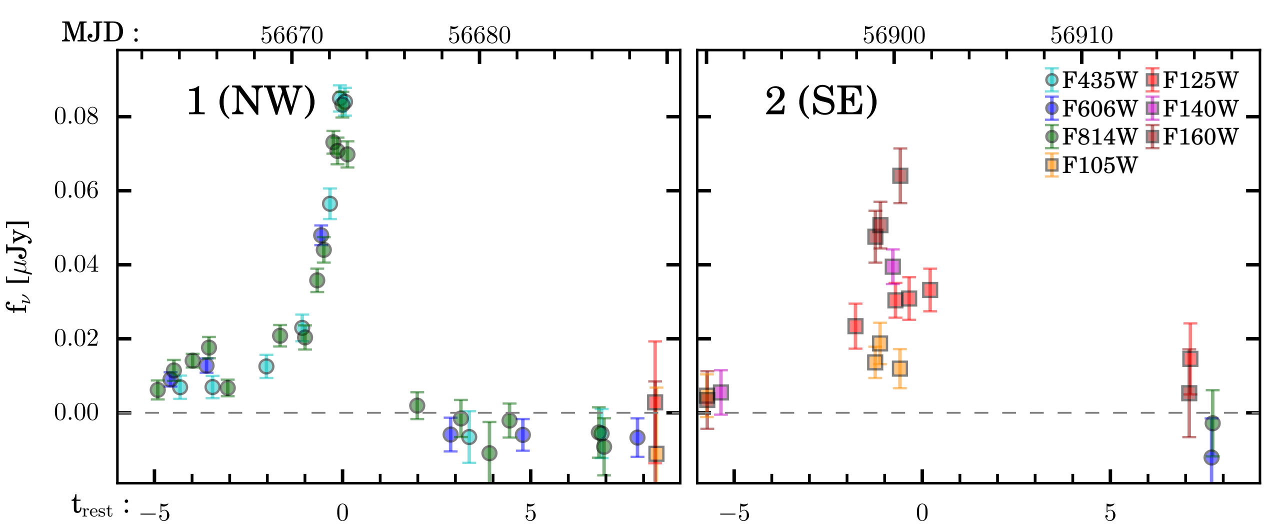
# Evidence for Theories of the Stellar Initial-Final Mass Function

| | $-7.50 > M_V > -9.50$ 150 Best Matches (406 yr) | | | | | | $-7.50 > M_V > -8.50$ 150 Best Matches (406 yr) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\langle\chi^2\rangle$ | $\Sigma$ | Model | PBH | T | IMF | $\langle\chi^2\rangle$ | $\Sigma$ | Model | PBH | T | IMF |
| | Low Stellar-Mass Density | | | | | | | | | | | |
| **Best** | 356.0 | L | Fryer12 | | B | Cha | 416.3 | L | Fryer12 | | B | Cha |
| | 366.5 | L | Woosley02 | | B | Cha | 462.1 | L | Spera15 | | S | Cha |
| | 372.4 | L | Spera15 | | B | Cha | 464.0 | L | Woosley02 | | S | Cha |
| | 383.6 | L | Woosley02 | | S | Cha | 488.9 | L | Spera15 | 3% | S | Cha |
| | 392.4 | L | Spera15 | | S | Cha | 516.5 | L | Woosley02 | | B | Cha |
| | 403.0 | L | Fryer12 | | S | Cha | 534.0 | L | Spera15 | | B | Cha |
| | 406.8 | L | Spera15 | 1% | S | Cha | 560.6 | L | Fryer12 | | S | Cha |
| **Worst** | 462.4 | L | Spera15 | 3% | S | Cha | 567.2 | L | Spera15 | 1% | S | Cha |
| | High Stellar-Mass Density | | | | | | | | | | | |
| **Best** | 347.4 | H | Spera15 | | B | Sal | 412.1 | H | Spera15 | | B | Sal |
| **Worst** | 367.8 | H | Spera15 | | B | Cha | 508.3 | H | Spera15 | | B | Cha |

LS1 light curve probes the stars making up the intracluster medium, which may have been stripped from cluster members

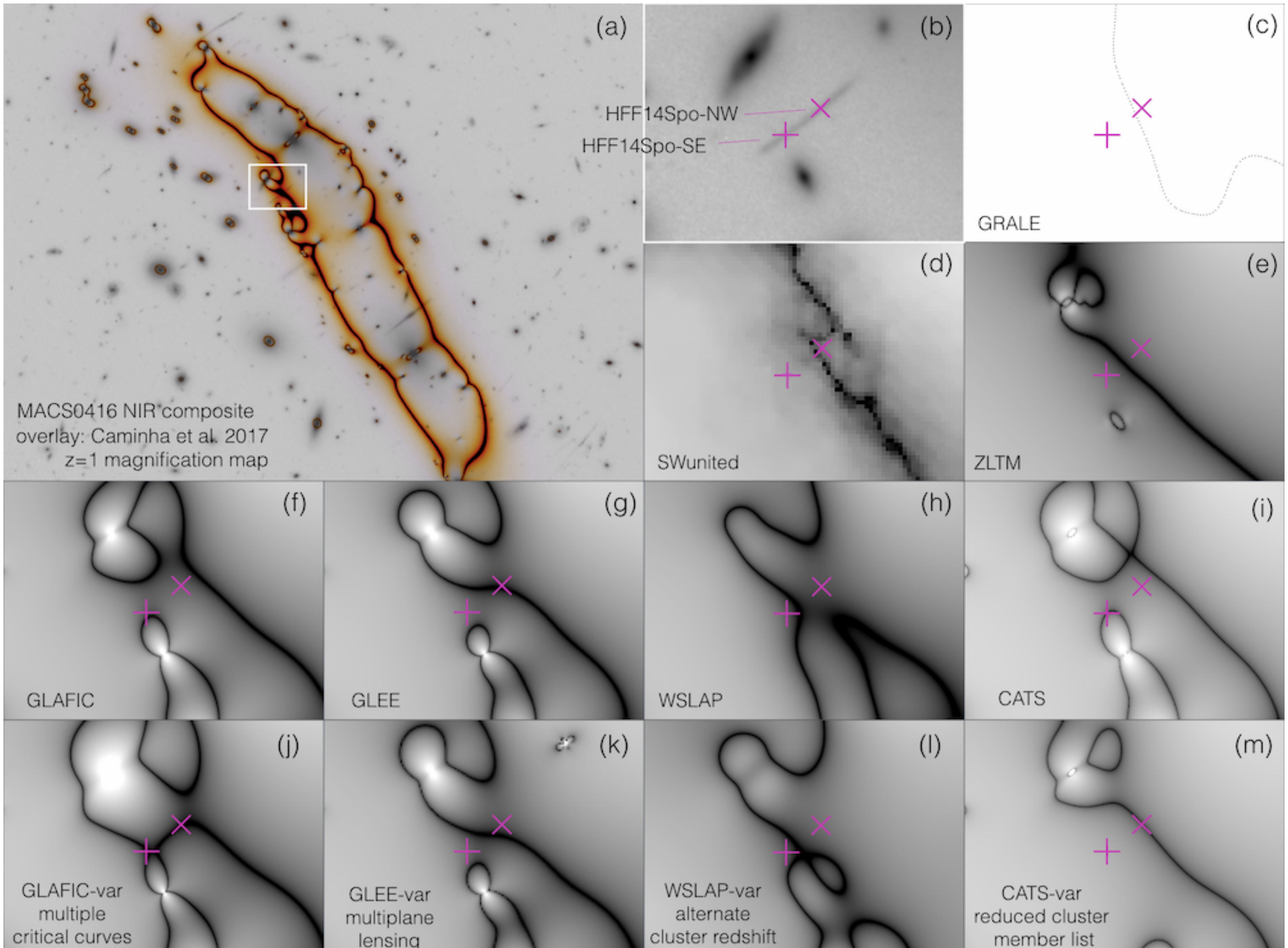
# Spock Events in MACS J0416




Rodney+18

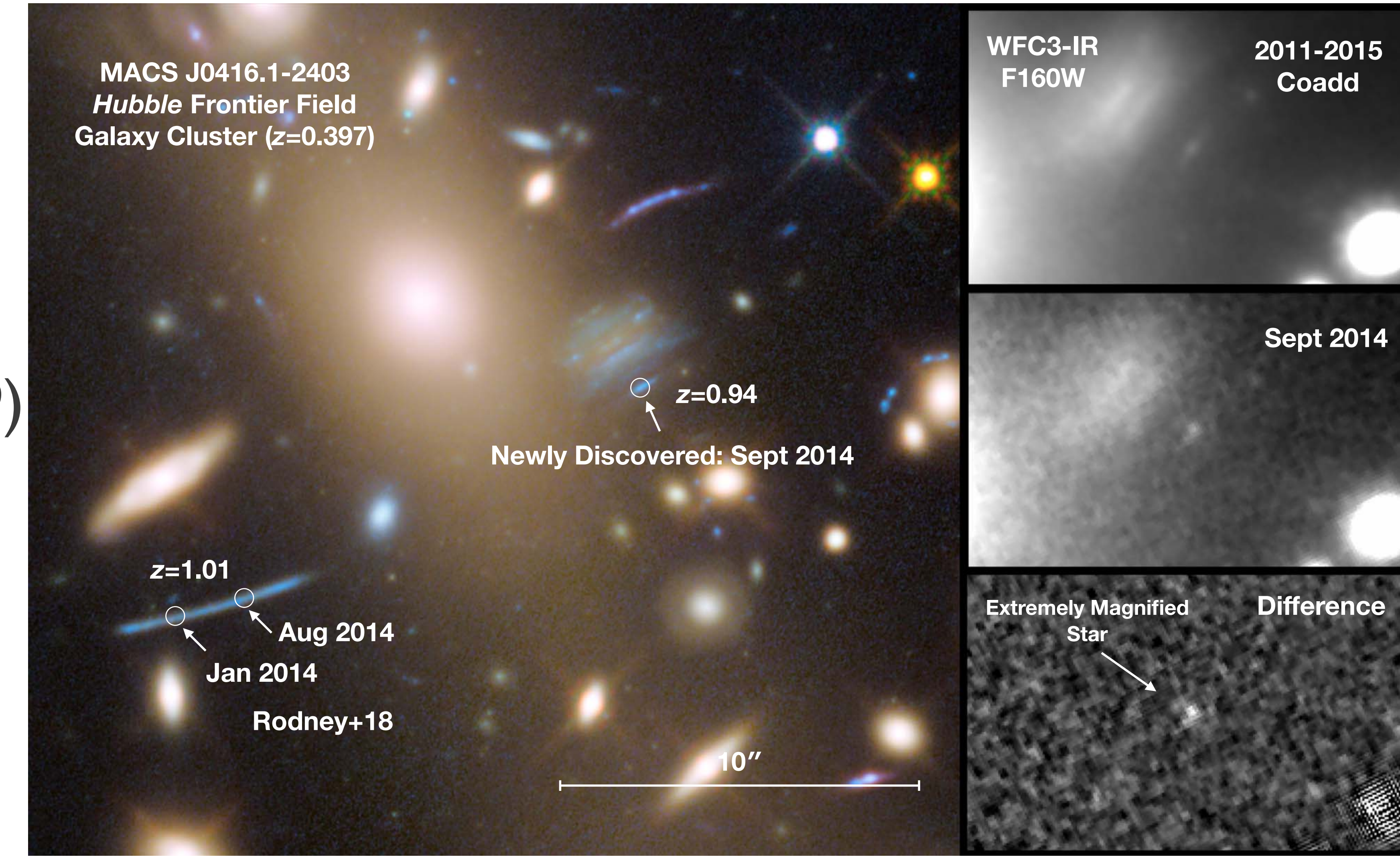
# Complexity of Critical Curve

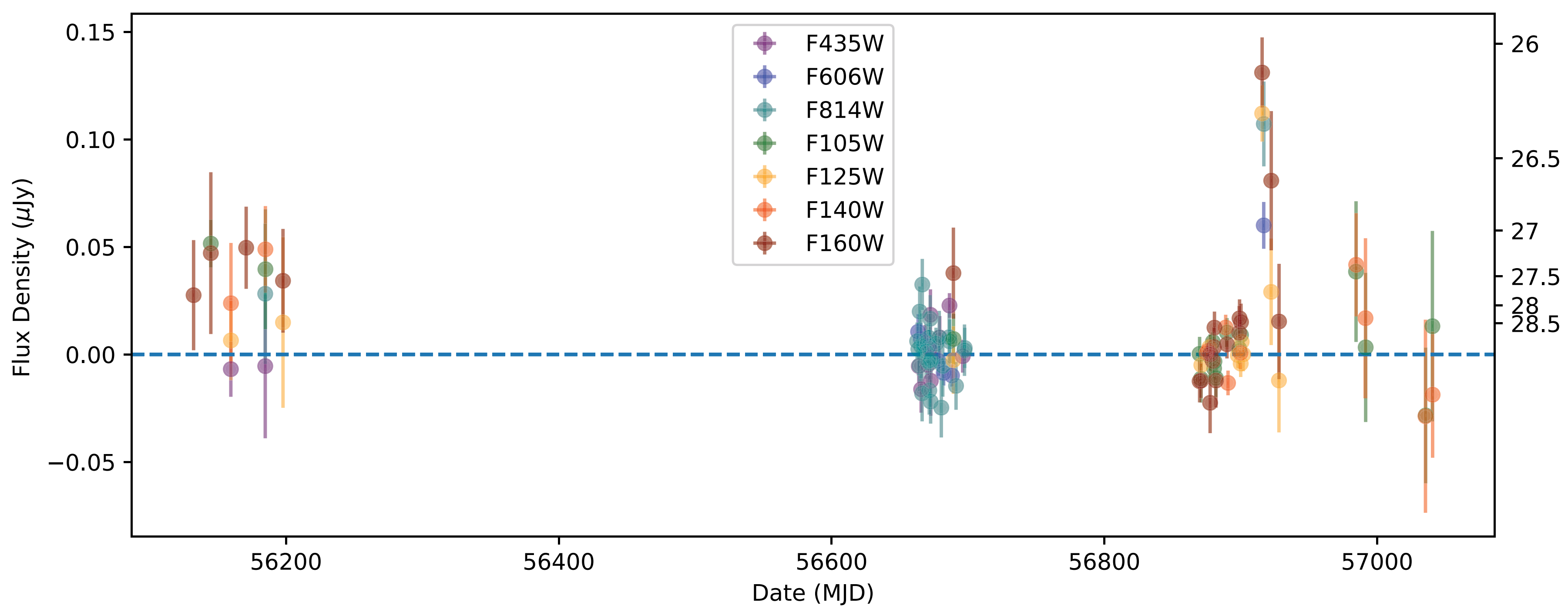


# Warhol: An Newly Discovered Highly Magnified Star

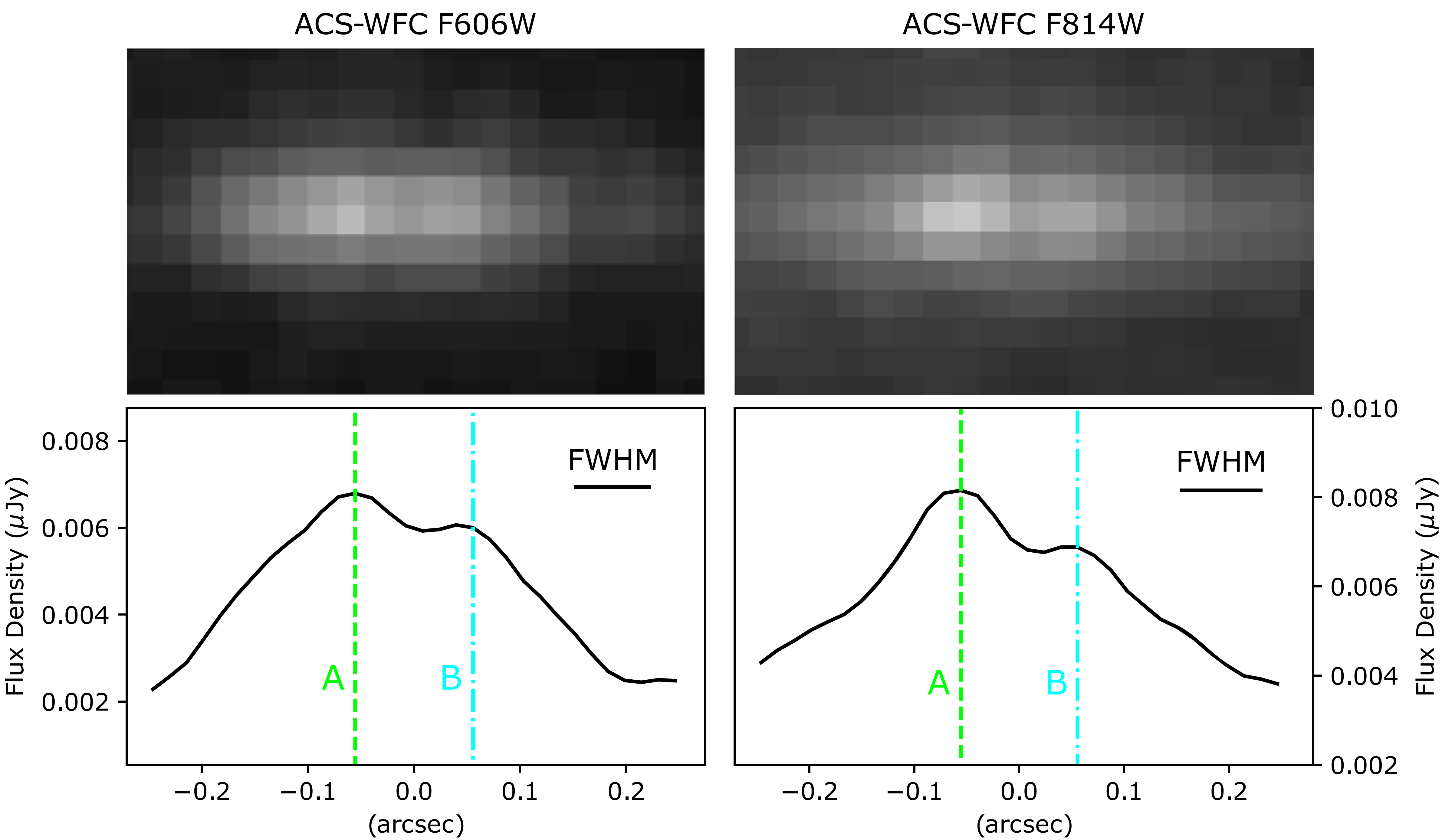
Wenlei Chen, P. Kelly, .. (2019)
&
Kaurov et al. (2019)

Redshift z=0.94



# Two Images of Star Always Seen

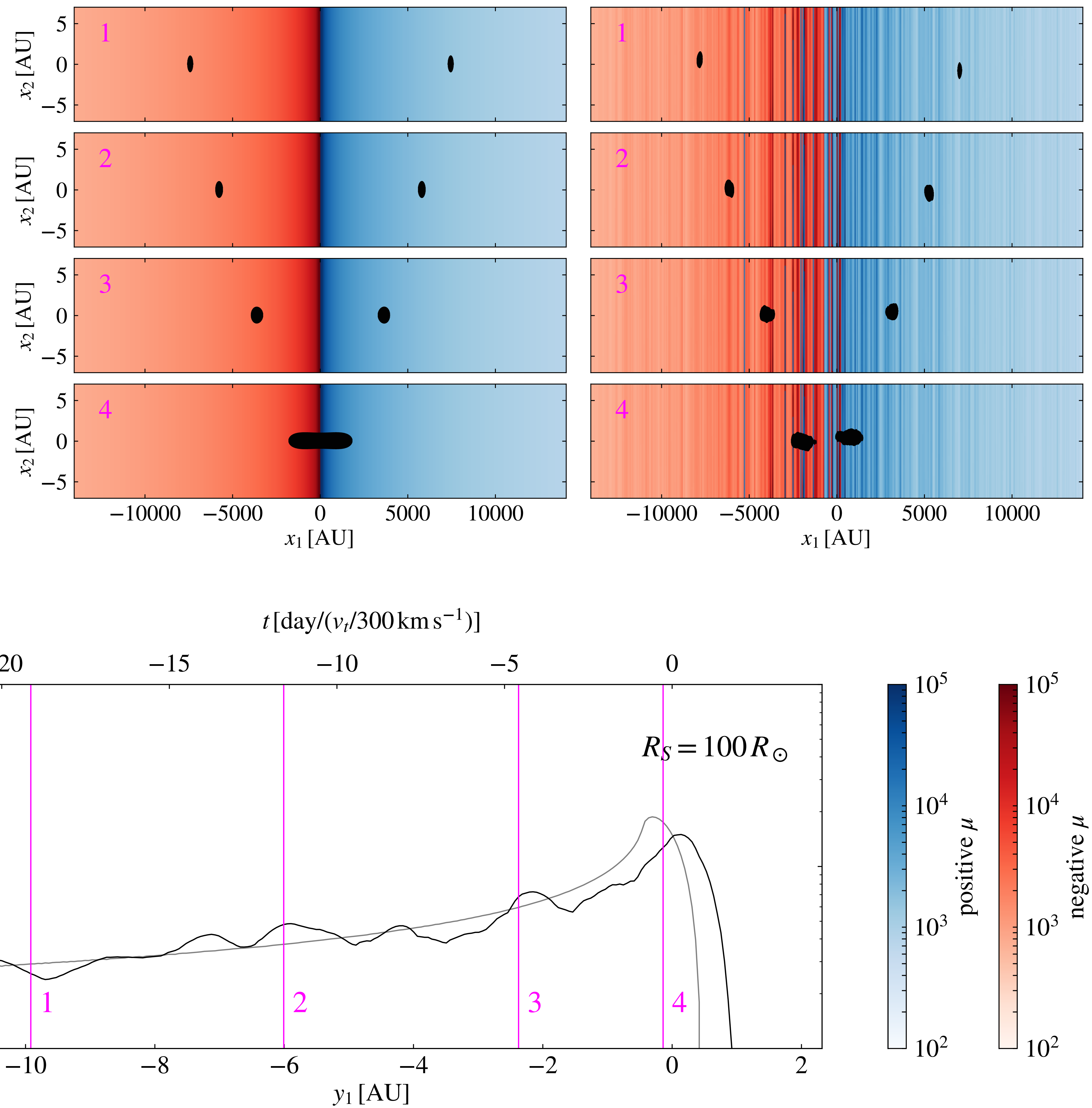


# Published Detections of Caustic-Crossing Events to Date

| Name | Redshift | Peak AB Magnitude | Reference |
|---|---|---|---|
| Icarus | 1.49 | F125W $\approx$ 25.5 | Kelly et al. 2018 |
| Iapyx | 1.49 | F125W $\approx$ 25.5 | Kelly et al. 2018 |
| Spock SE | 1.04 | F125W $\approx$ 27.6 | Rodney et al. 2018 |
| Spock NW | 1.04 | F814W $\approx$ 26.6 | Rodney et al. 2018 |
| Warhol | 0.94 | F125W $\approx$ 26.3 | Chen et al. 2019; Kaurov et al. 2019 |

Liang Dai &
Jordi Miralda-Escude
2020

Means to Detect
Presence of Axion
Mini-Halos
at Maximum



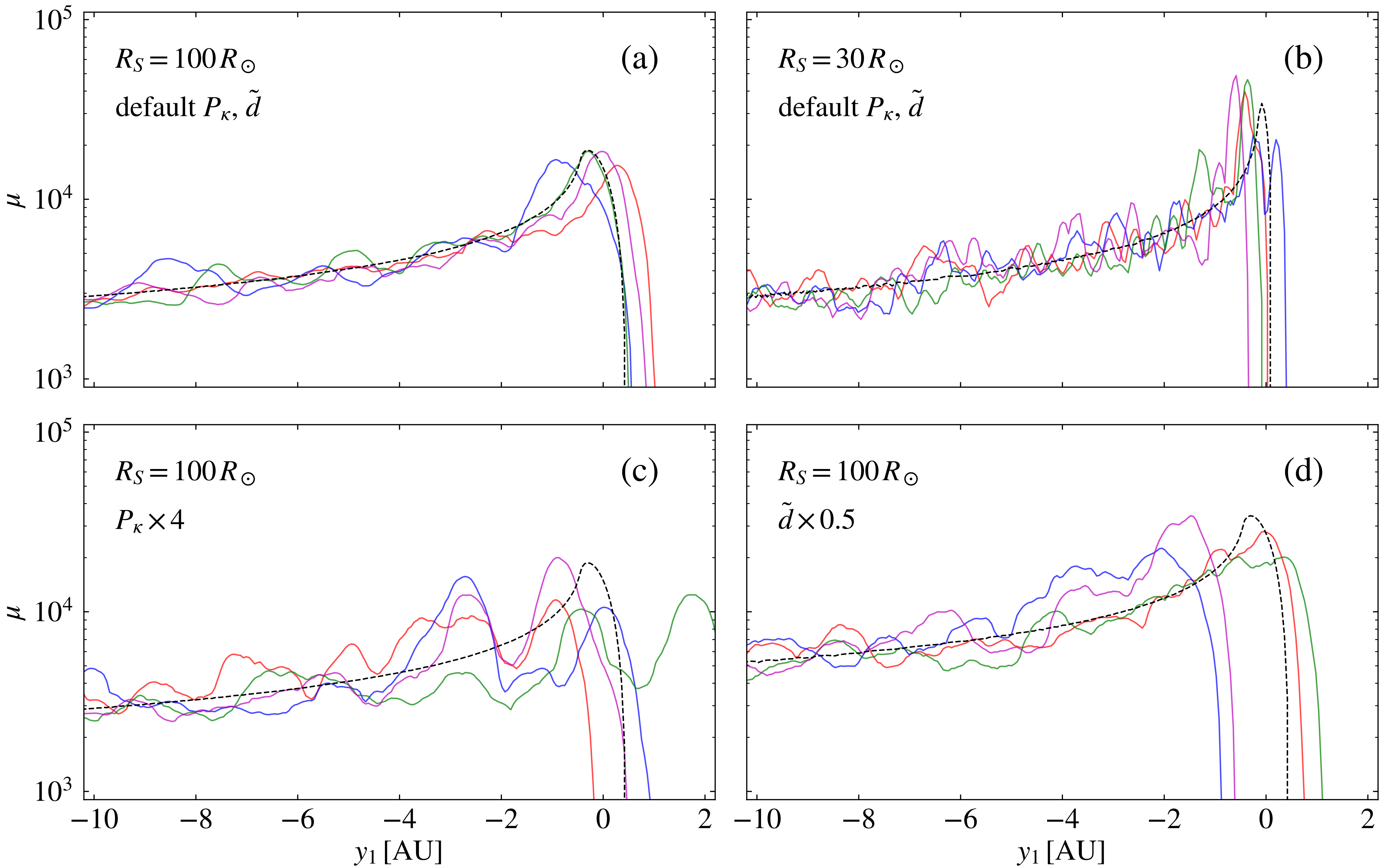
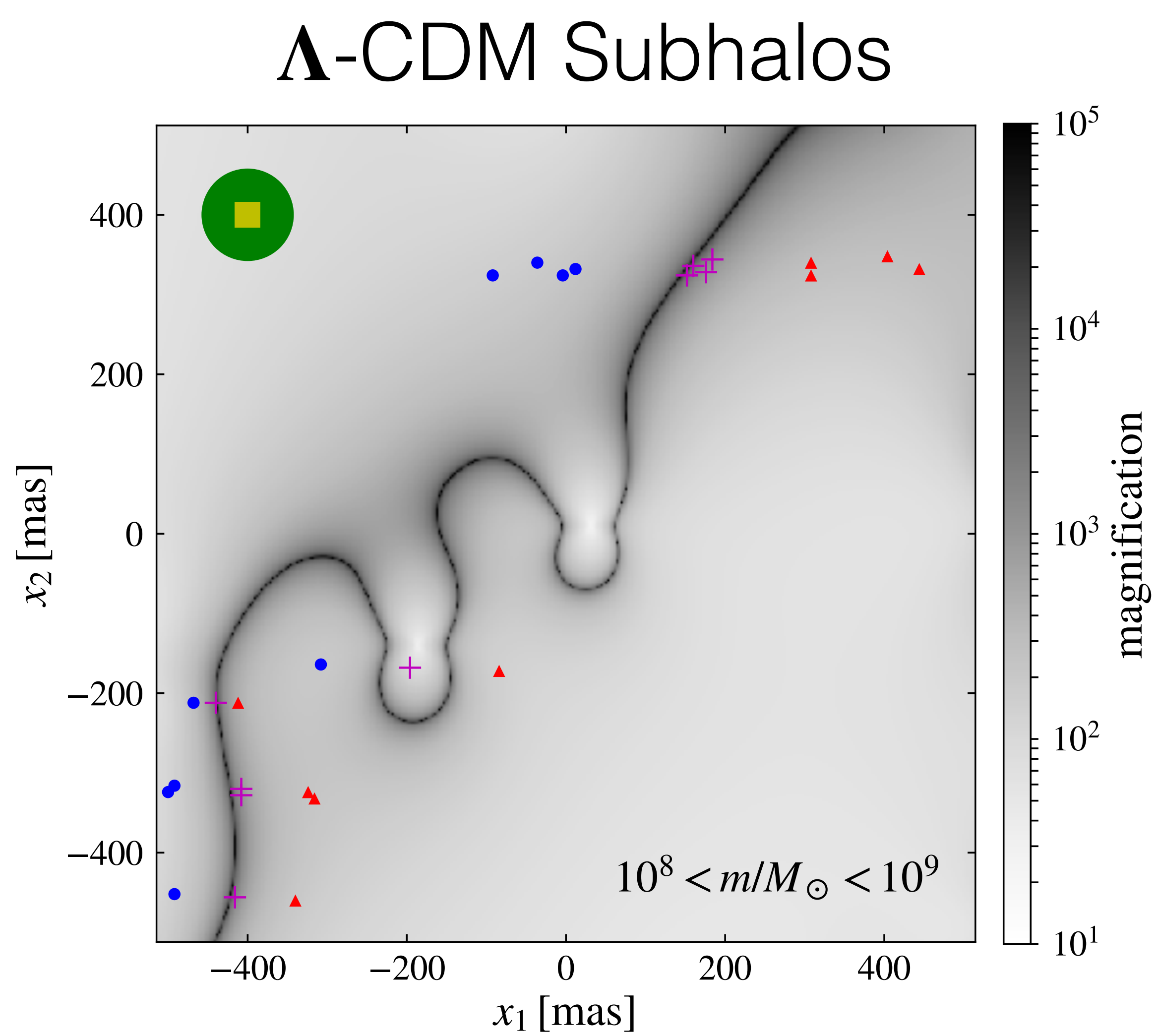
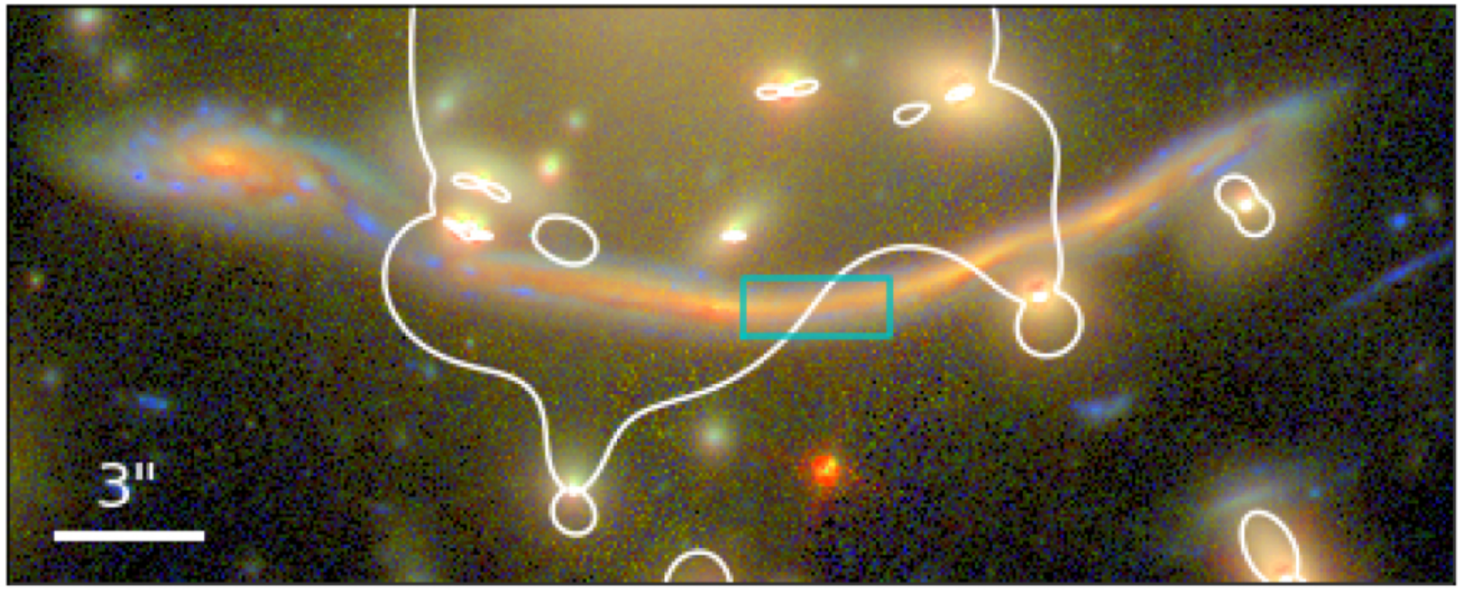


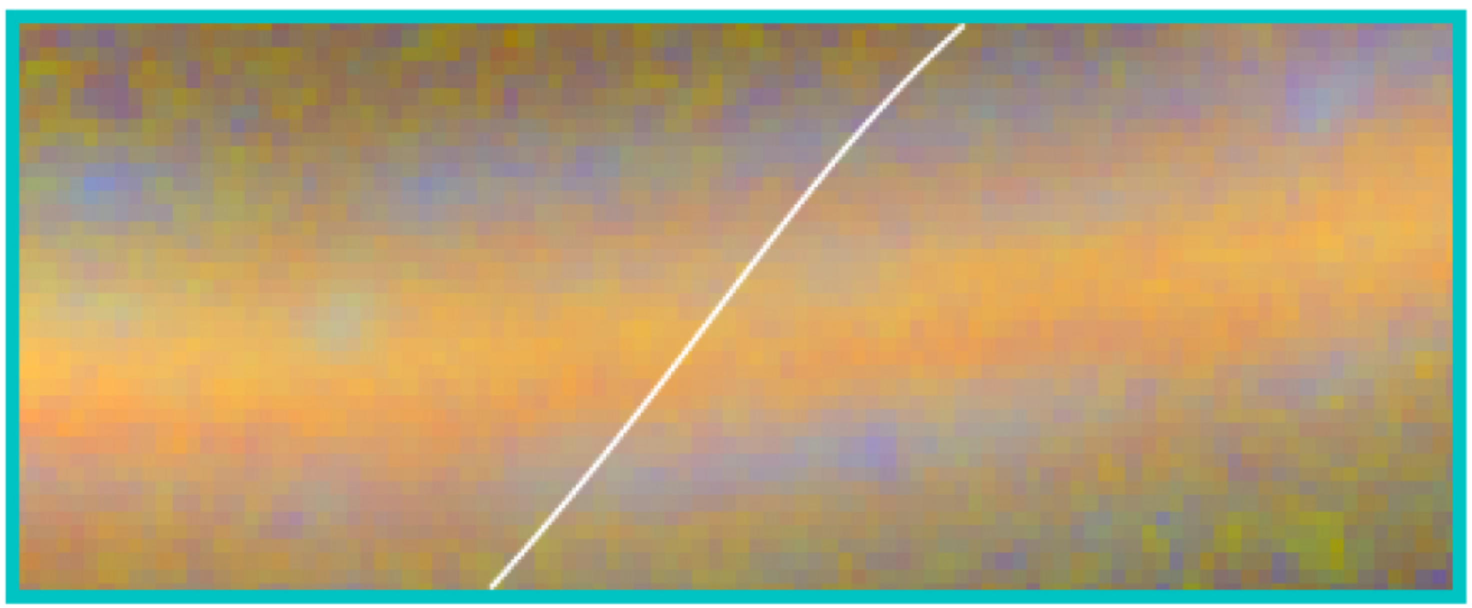

**Figure 7.** Perturbed light curves (colored curves) compared to smooth light curve (dashed black curve) around the time of a microlensing peak event. Each panel shows four random realizations of convergence fluctuations (one color for each). (a) Default case as in Figure 6. (b) A more compact source star with $R_S = 30\,R_\odot$. (c) Power spectrum $P_\kappa$ enhanced by a factor of four. (d) $\tilde{d} = |\tilde{\boldsymbol{d}}|$ decreased by a factor of two.

# Use Pairs of Images to Constrain Location of the Critical Curve

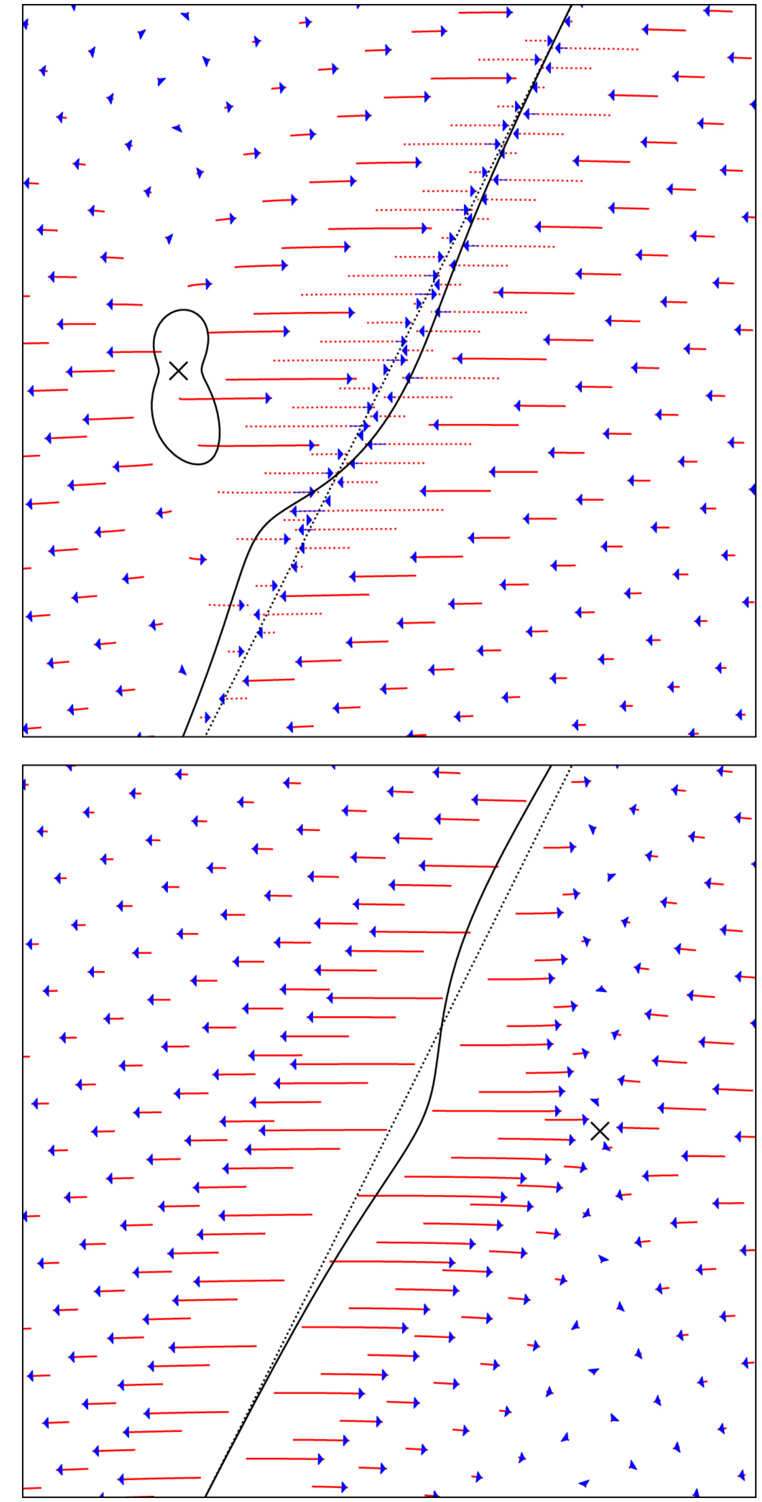



"Astrometric distortions" carry imprint of poorly understood dark matter halo mass function (Dai+18). Could also identify ultra-light bosons as DM.



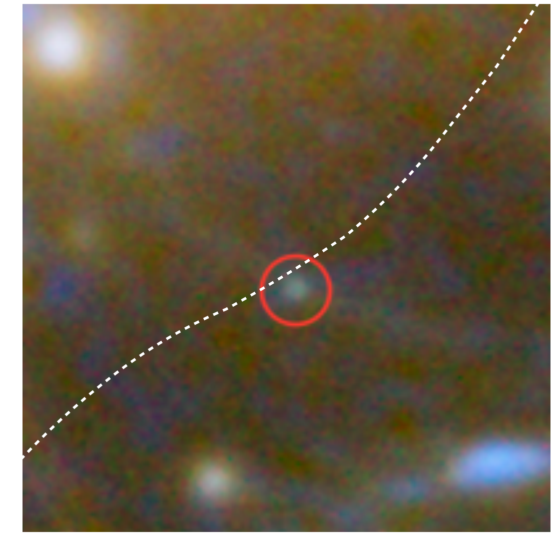
Famous arc in Abell 370 (Dai+18)



Distortion due to subhalo

“Subhalos of masses in the range of $10^6$–$10^8$ $M_\odot$ with the abundance predicted in the cold dark matter theory should typically imprint astrometric distortions at the level of 20–80 mas.”

# How Can We Find More Magnified Stars?



Near the critical curve (of a fold caustic), the average magnification $\bar{\mu}$ goes as,

$$\bar{\mu} \propto 1/\sqrt{R}$$

where $R$ is the separation of the star from the critical curve in the source plane. In consequence, the area with magnification exceeding $\mu$ is

$$A(> \mu) \propto 1/\mu^2$$

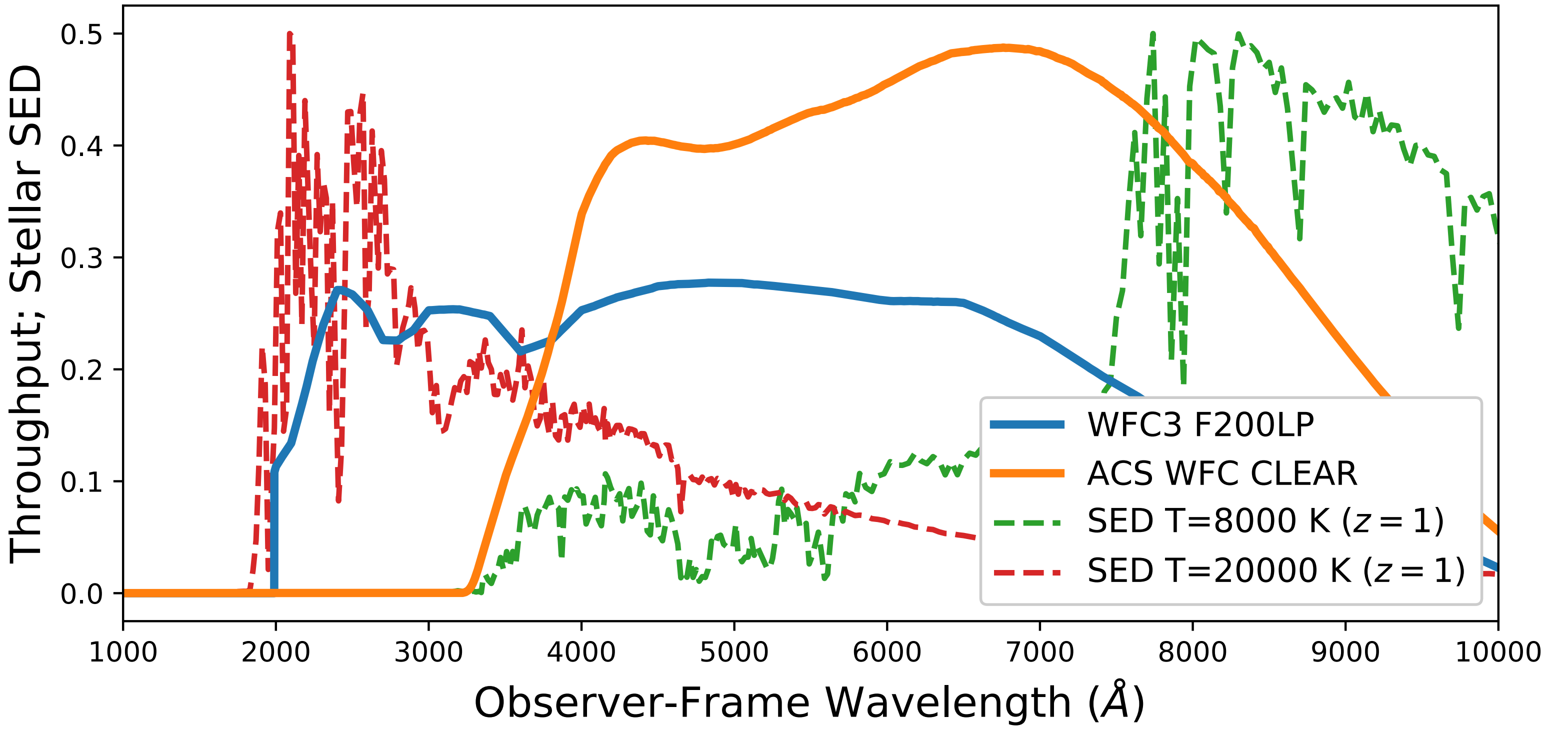
So, more or less, improving sensitivity by factor of say five, would yield ~25x more highly magnified stars.

# Flashlights Multi-Year Program with the *Hubble Space Telescope*

Should detect many highly magnified stars to look-back times of ~10 Gyrs

The deepest observations ever taken of galaxy-cluster fields by a significant factor (~5) — strategy is to take very deep observation in as short a period as possible

A total of 192 *HST* orbits — a “Large” program



# Flashlights Multi-Year Program with the *Hubble Space Telescope*

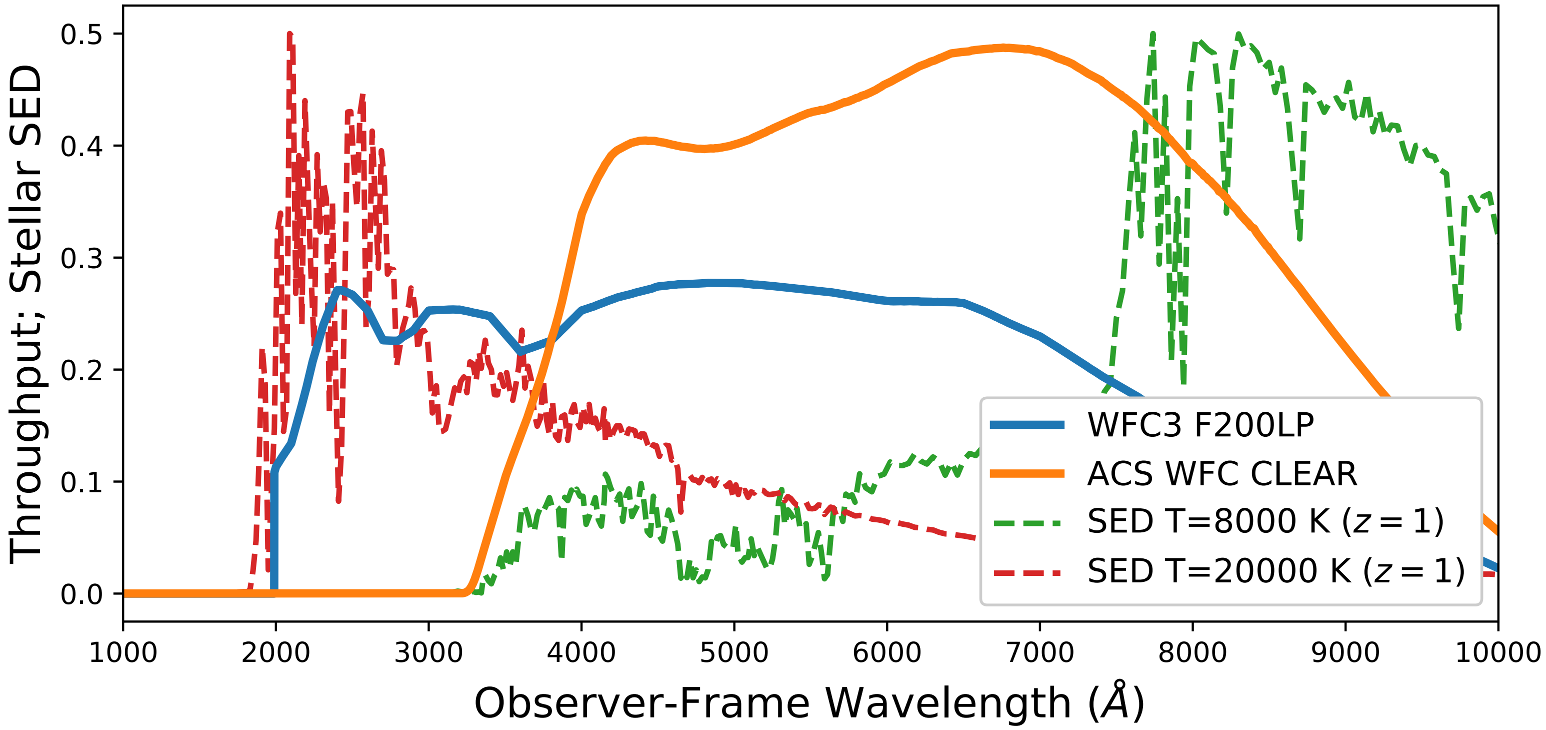
~5-sigma limiting magnitude of ~31 AB from long-pass filters

Expect dozens of microlensing events to three-sigma with dependence on abundance of primoridal black holes at 1-2% level

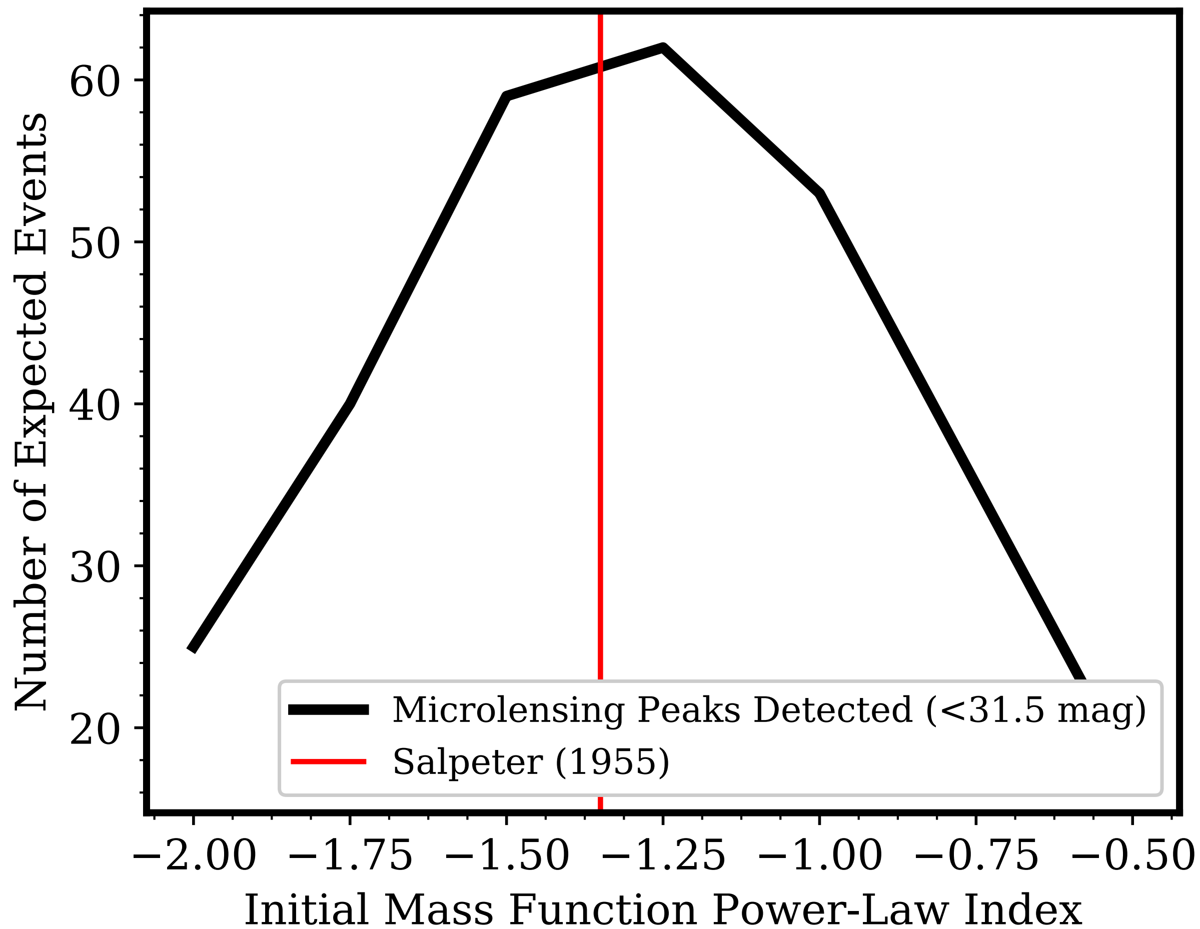
Identify pairs of highly magnified stars to constrain critical curve locations

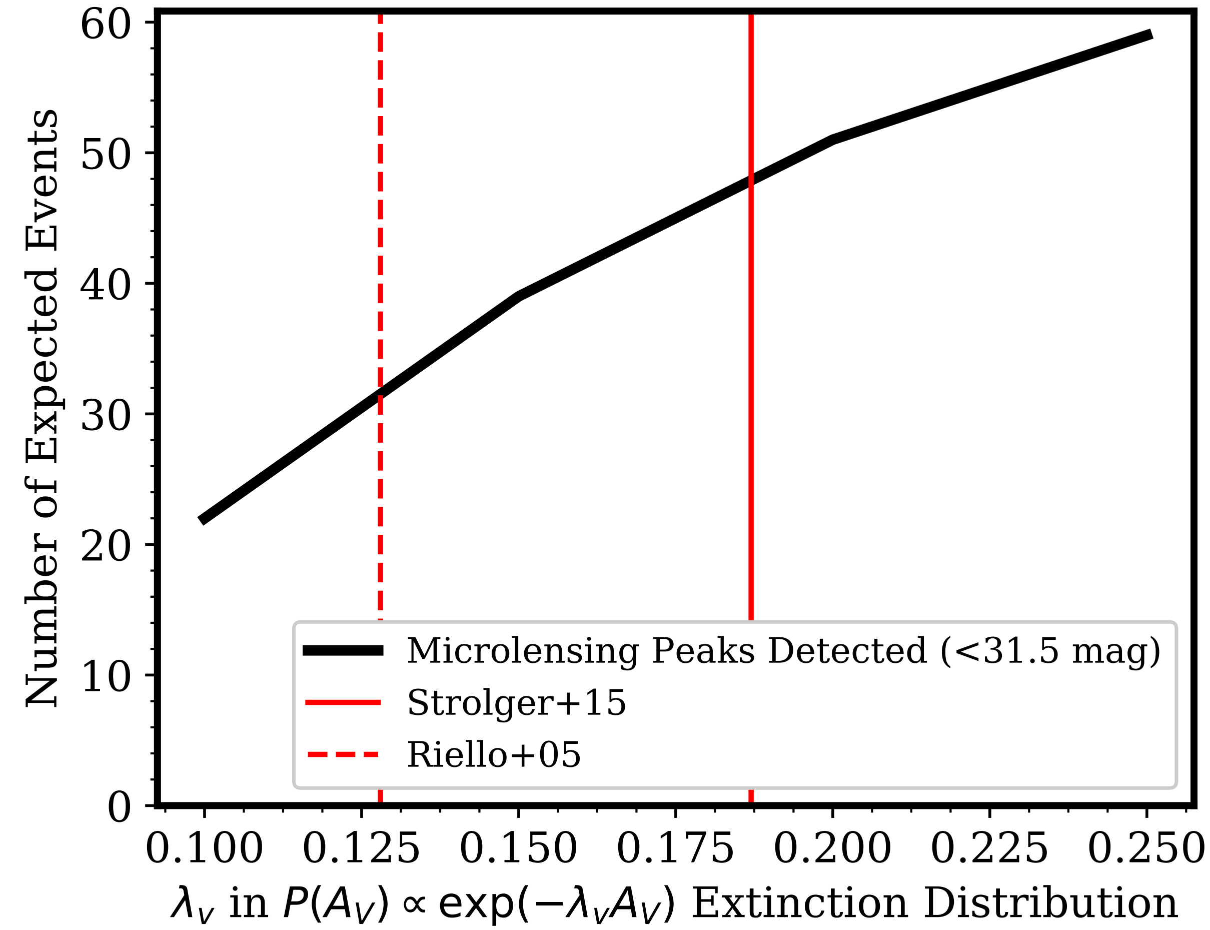
Identify the signature of ultra-light dark matter

UV sensitivity to hot, OB stars

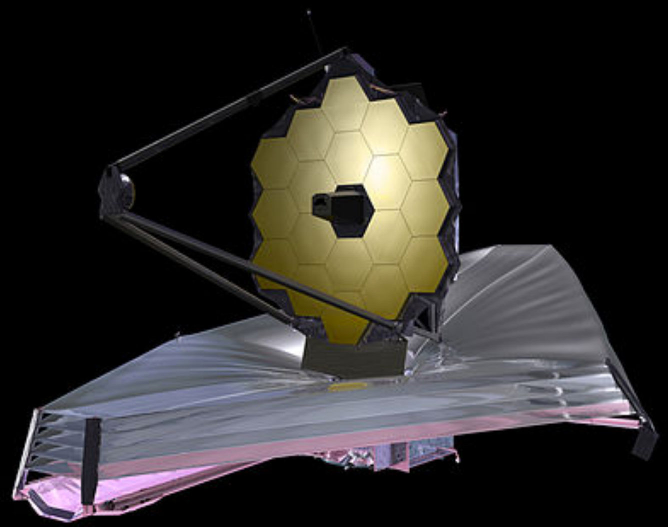


# Flashlights Rate of Events Sensitive to the Initial Mass Function of Stars



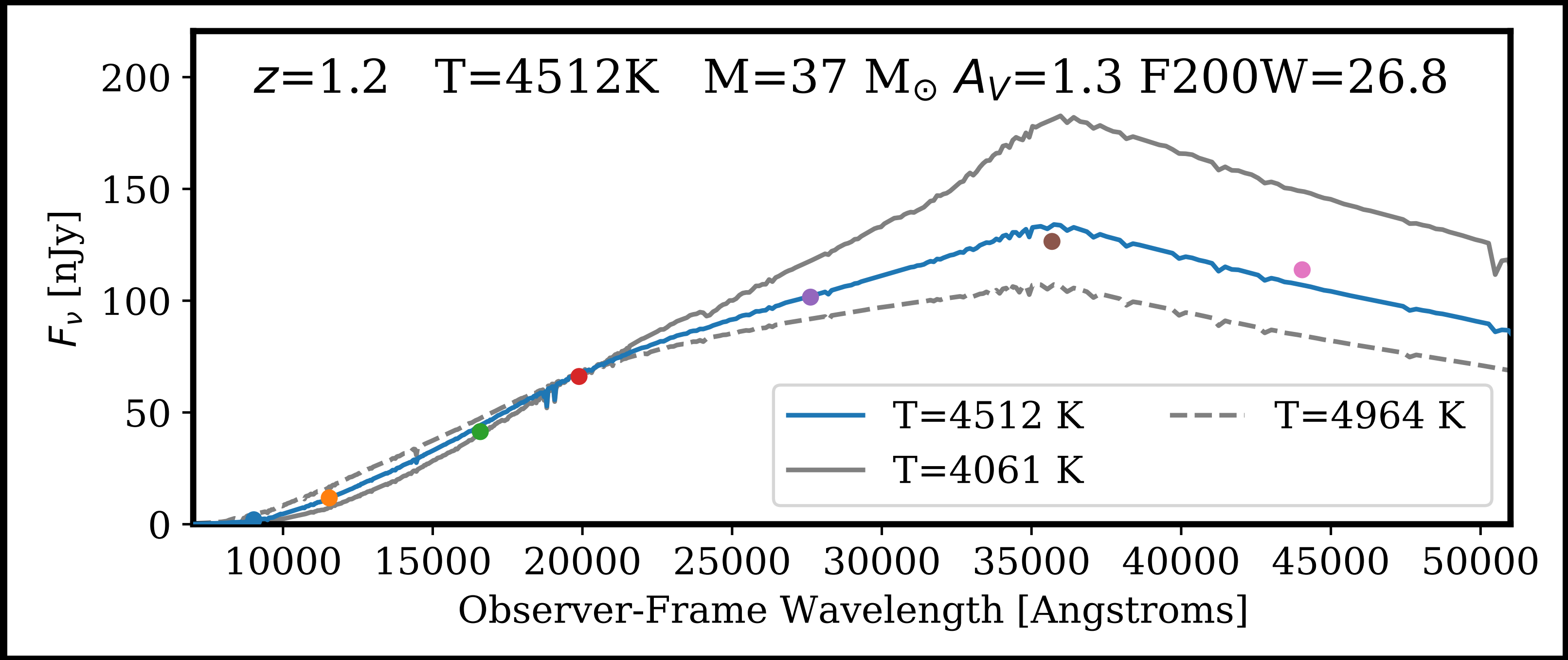
# James Webb Space Telescope (*JWST*)



6.5 m
0.6-28 μm
Launch in October — fingers crossed!

Sensitivity to red supergiants

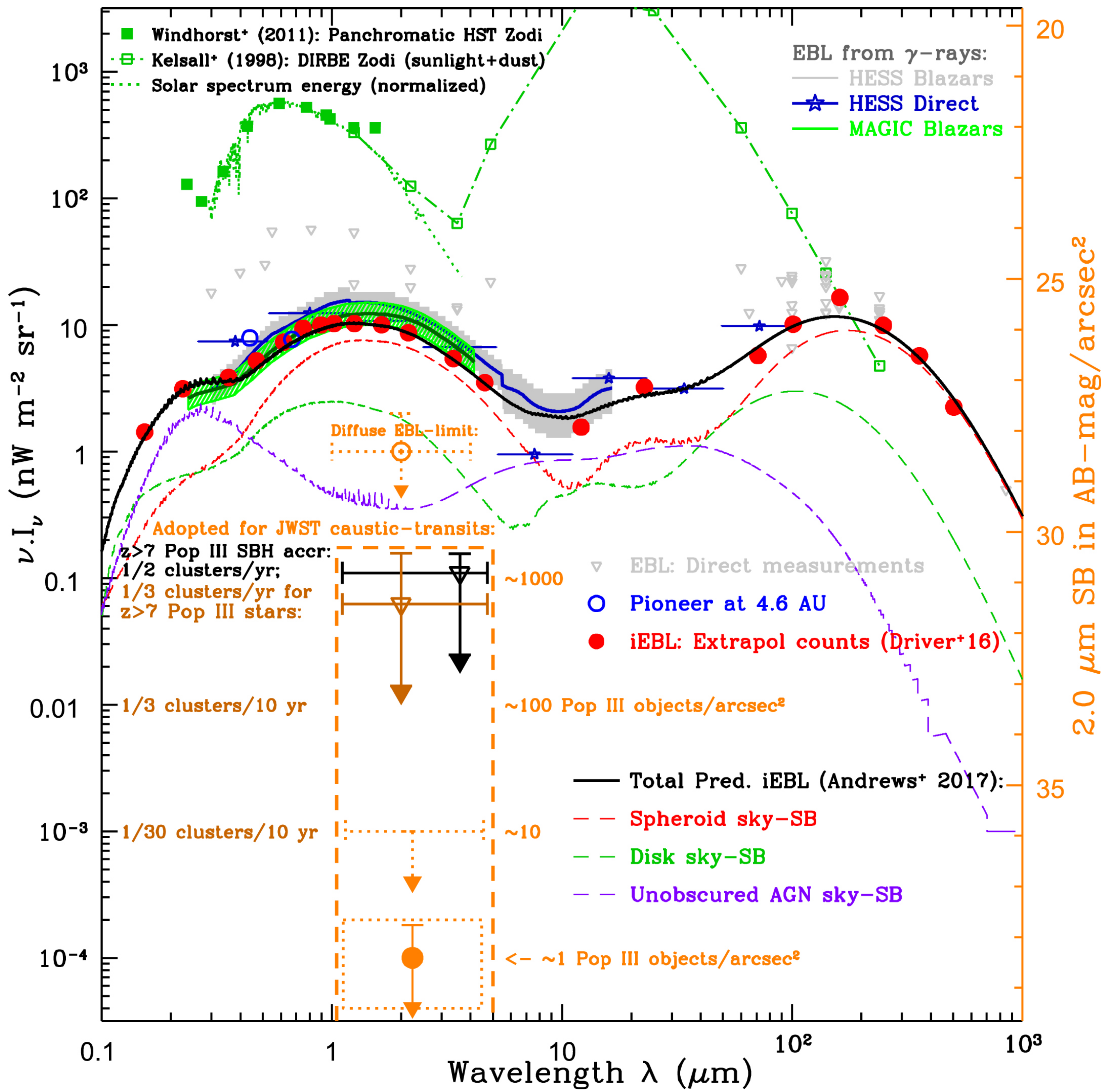
Complements *HST*'s blue sensitivity



# Pop III stars + BH accretion disks

Pop III may contribute significantly to near-IR EBL

Monitor 3-30 clusters for a decade to 29 AB to detect caustic crossing




Windhorst+18

# Caustic-Crossing Events + Highly Magnified Stars

- A handful of events have been discovered using *HST*
- Deeper observations with *HST* + *JWST* should yield much larger samples of dozens + begin to realize promise
  - Nature of dark matter — PBH's, axions, subhalos
  - Properties of intracluster stars — IMF, massive stellar evolution
  - Properties of high-redshift stars — IMF, stellar luminosity function