Highly Magnified Extragalactic Stars

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Caustic and Critical Curve

Ray equation

$$\boldsymbol{y} = \boldsymbol{x} - \boldsymbol{\alpha}(\boldsymbol{x})$$

(Local) deformation of image

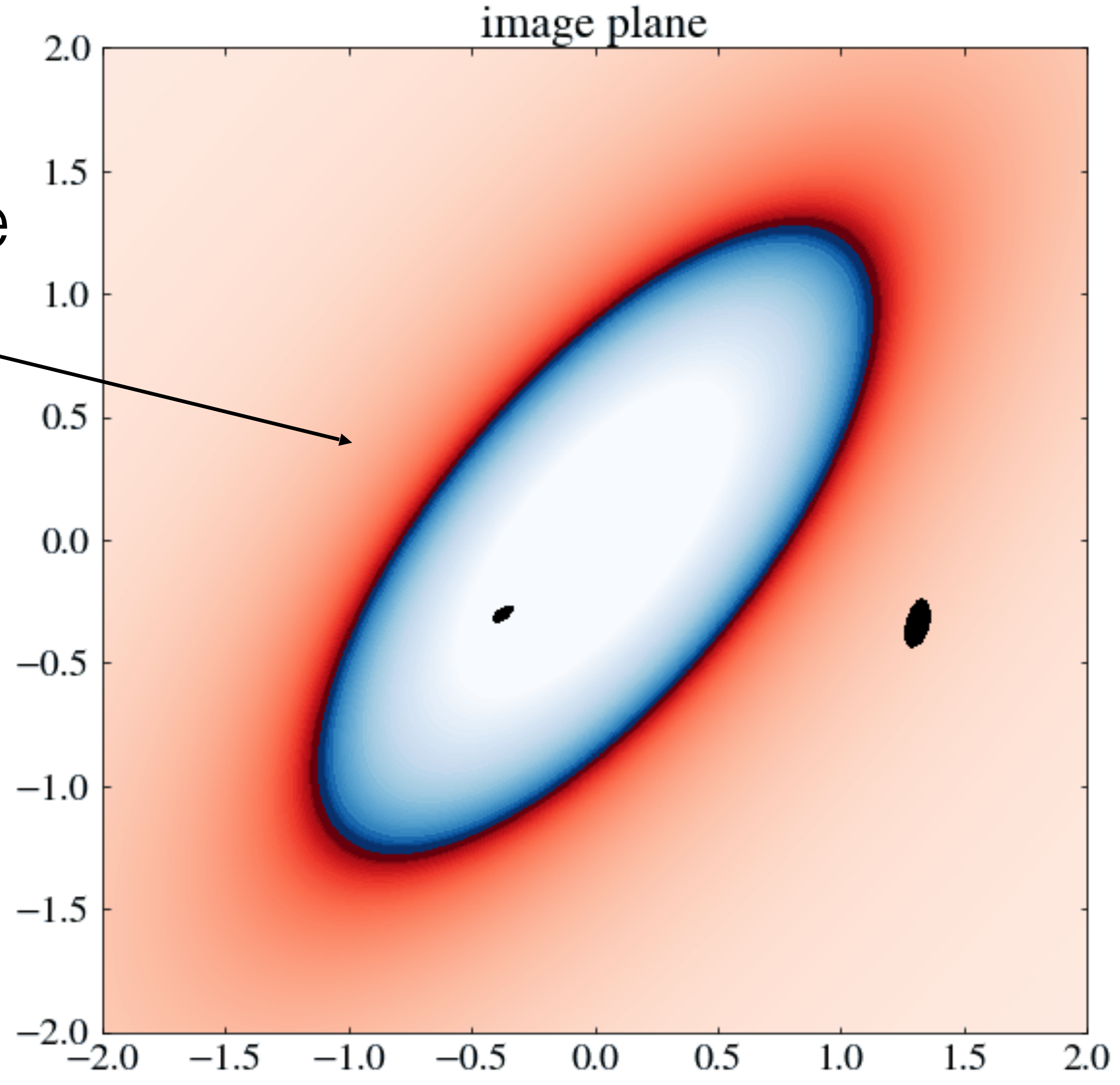
$$\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}} = \begin{bmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{bmatrix}$$

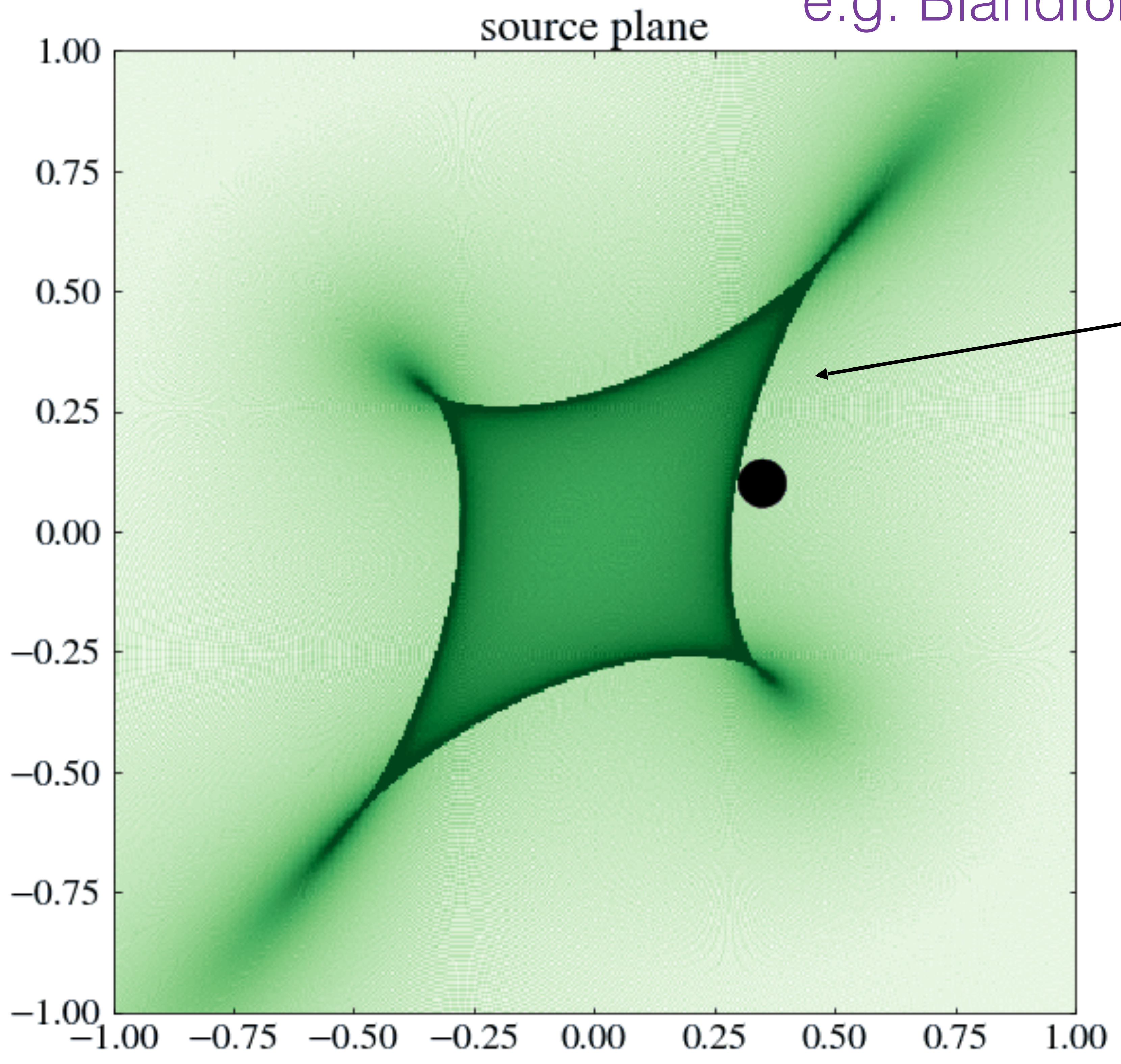
Red: positive magnification
Blue: negative magnification

Green: total (unsigned) magnification

e.g. Blandford & Narayan (1986)

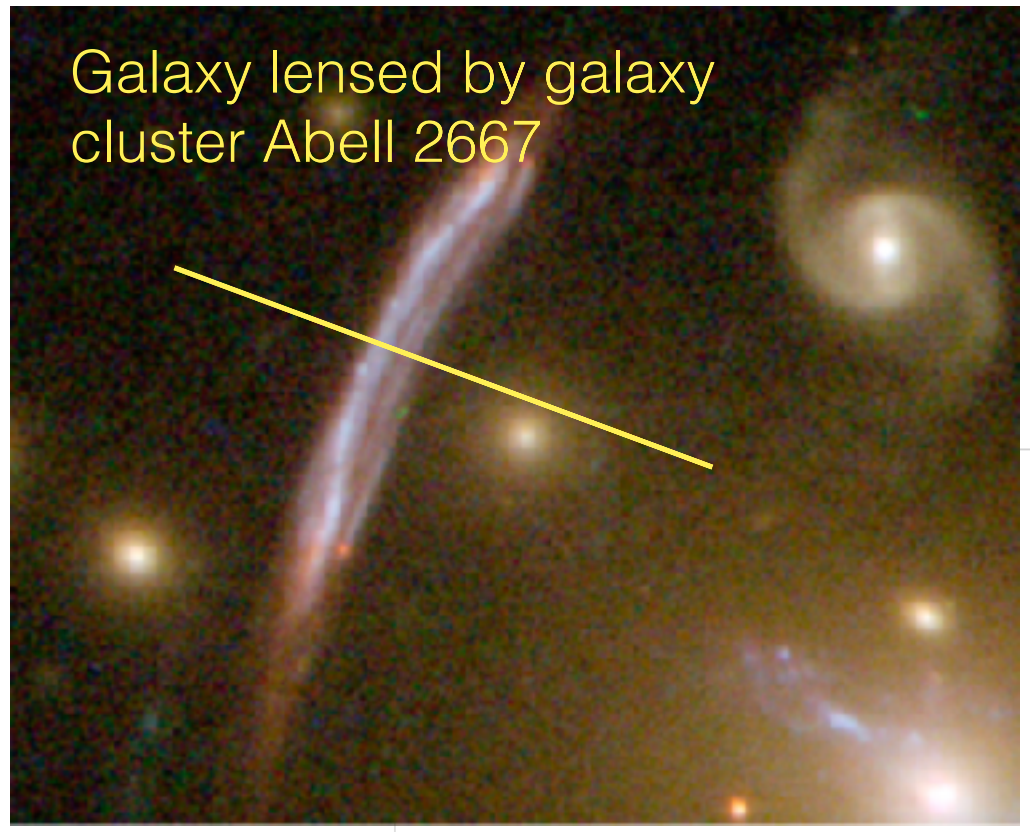
critical curve

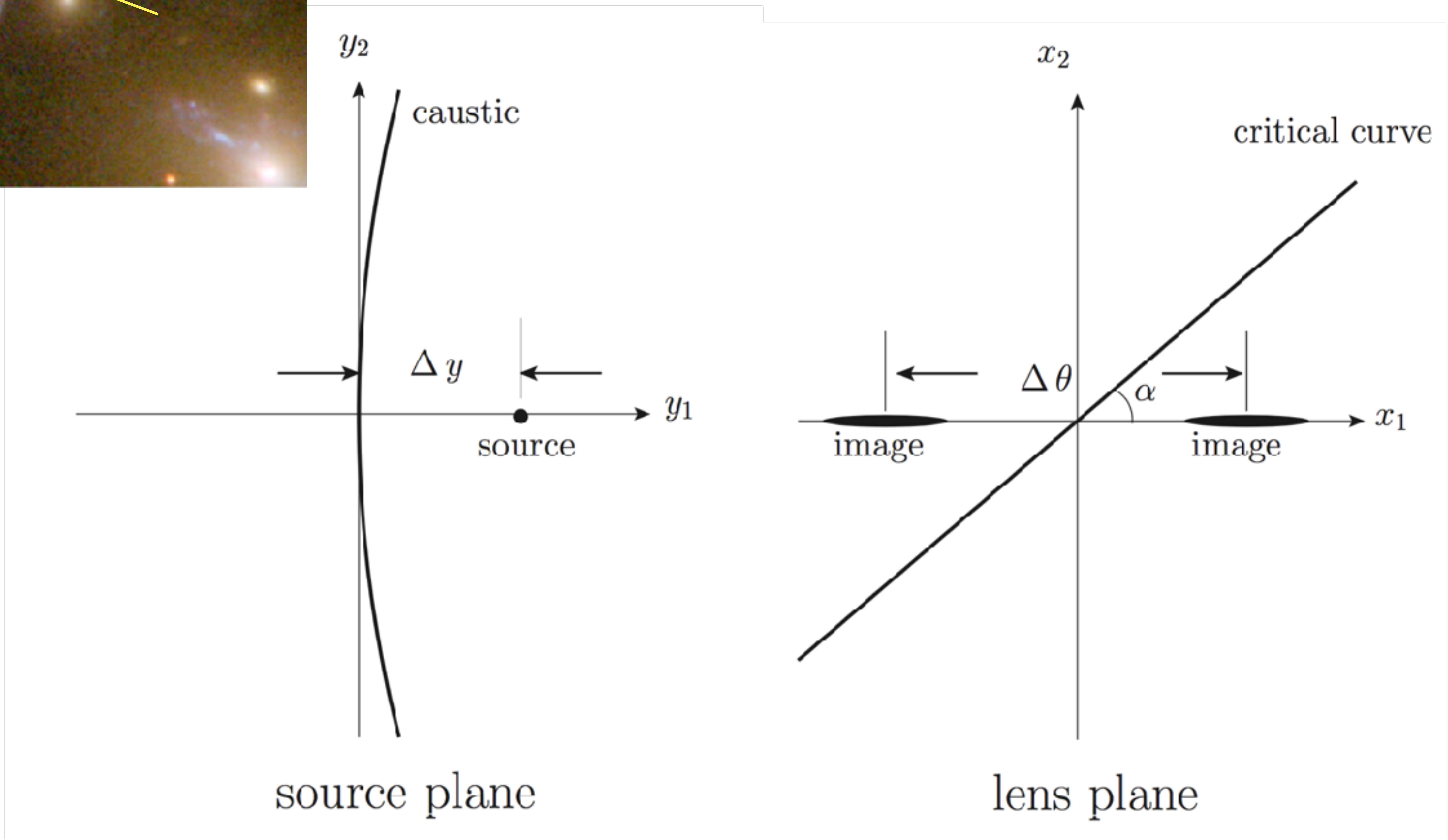




caustic

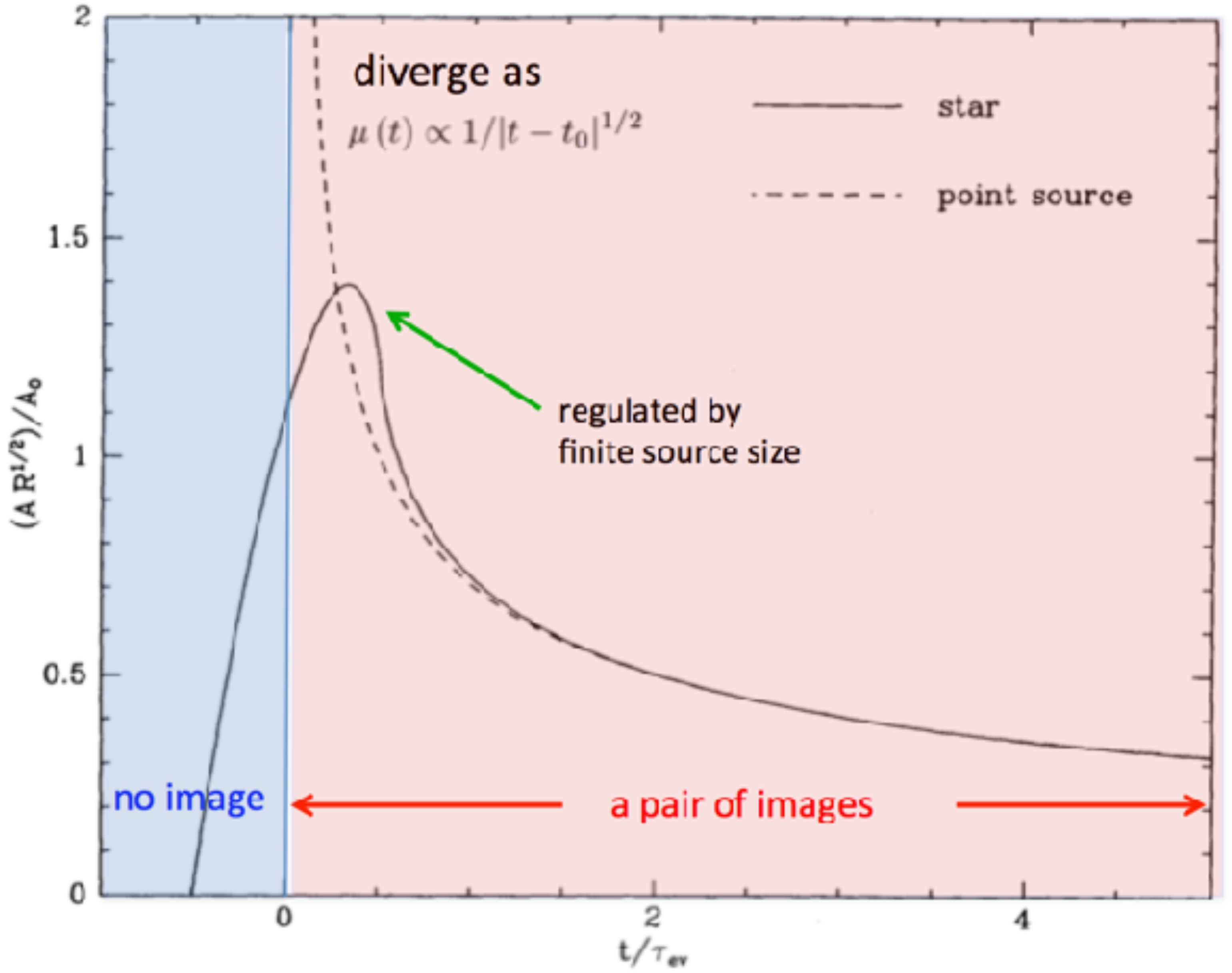
Magnified Stars Near Caustics





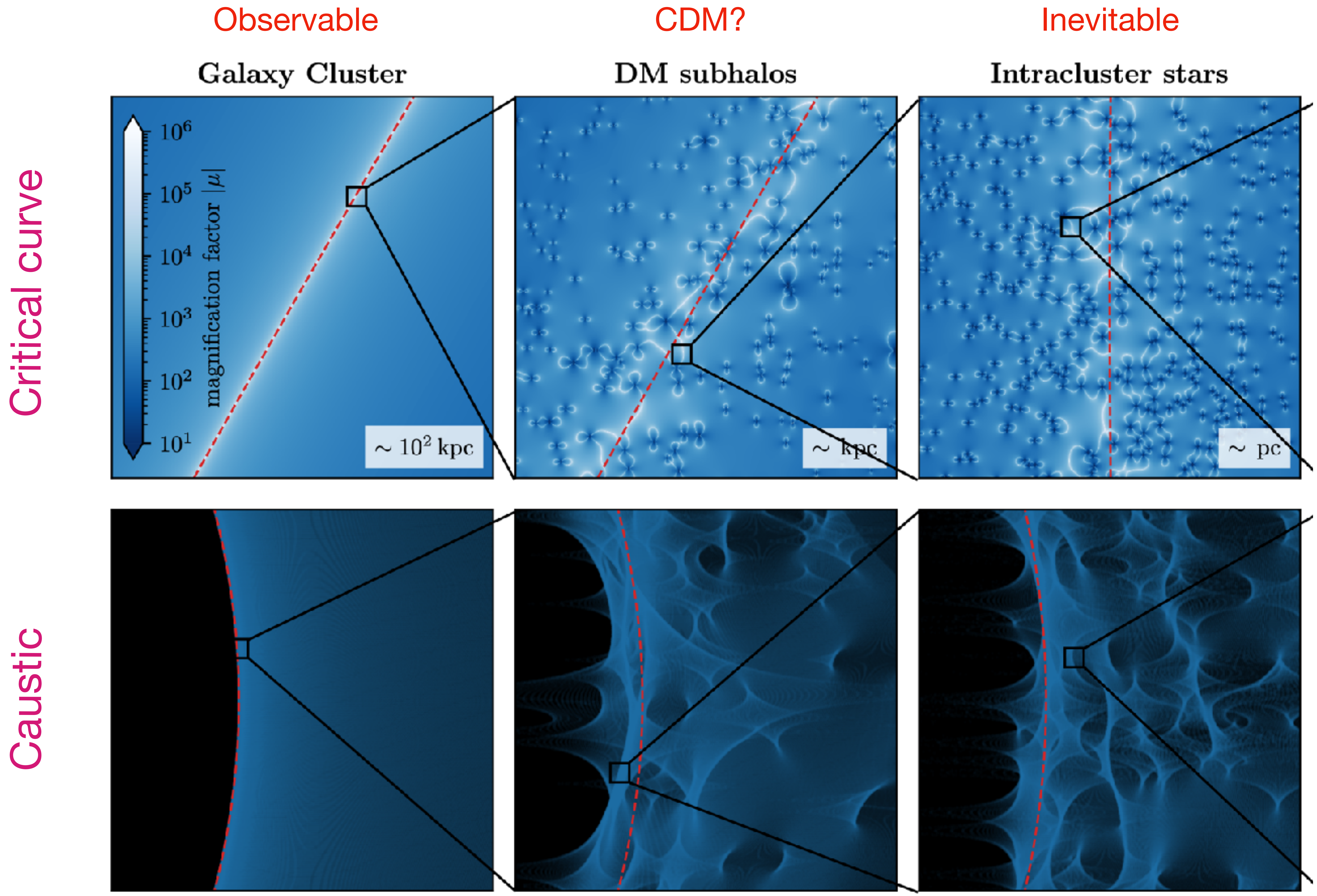
Jordi Miralda-Escudé

Miralda-Escudé (1991)



Universal behavior of a point source near a caustic

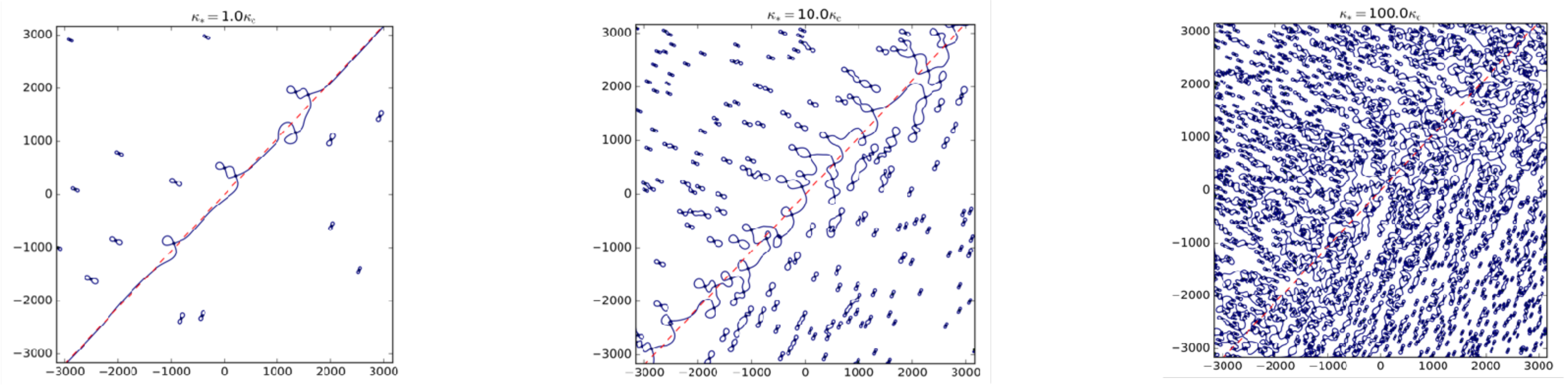
Hierarchy of caustic structures



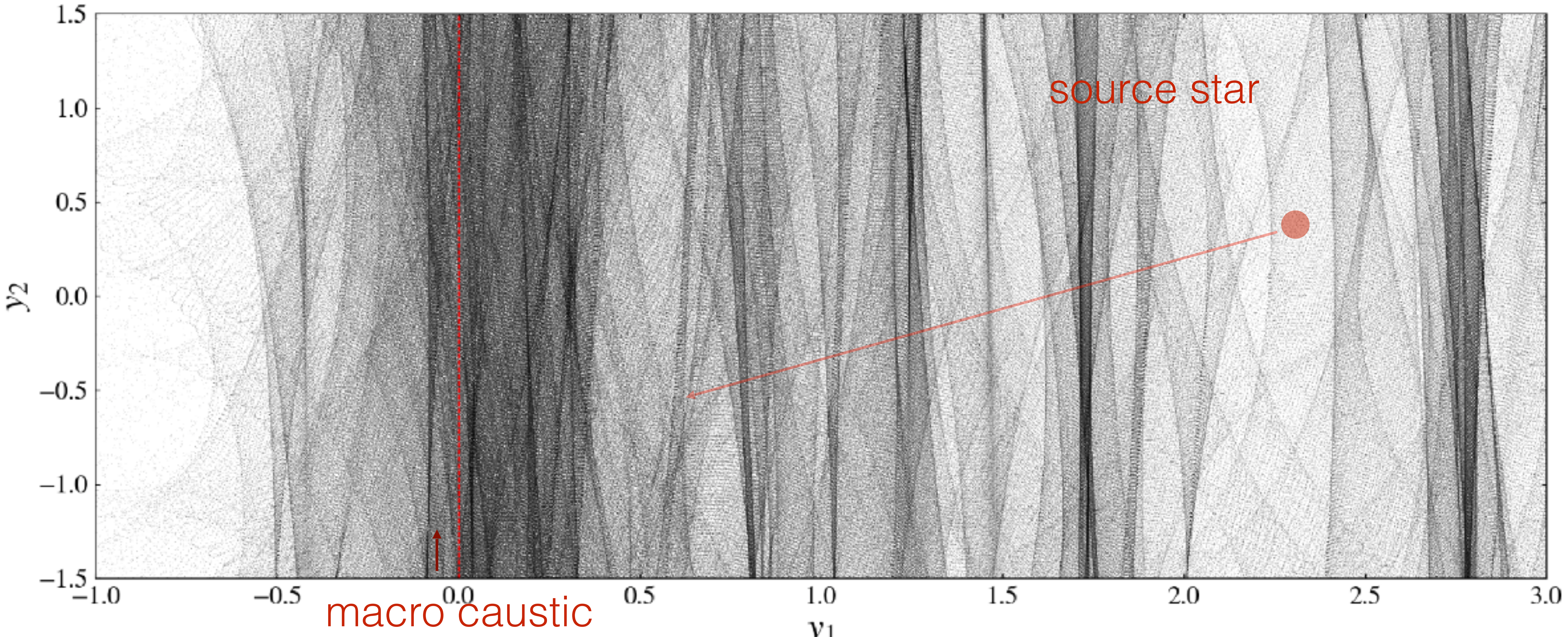
Micro caustic network induced by intracluster stars

Venumadhav, LD & Miralda-Escudé 2017; Diego++ 2017; Oguri++ 2018; Diego 2019

Little “hourglasses” much larger than Einstein length

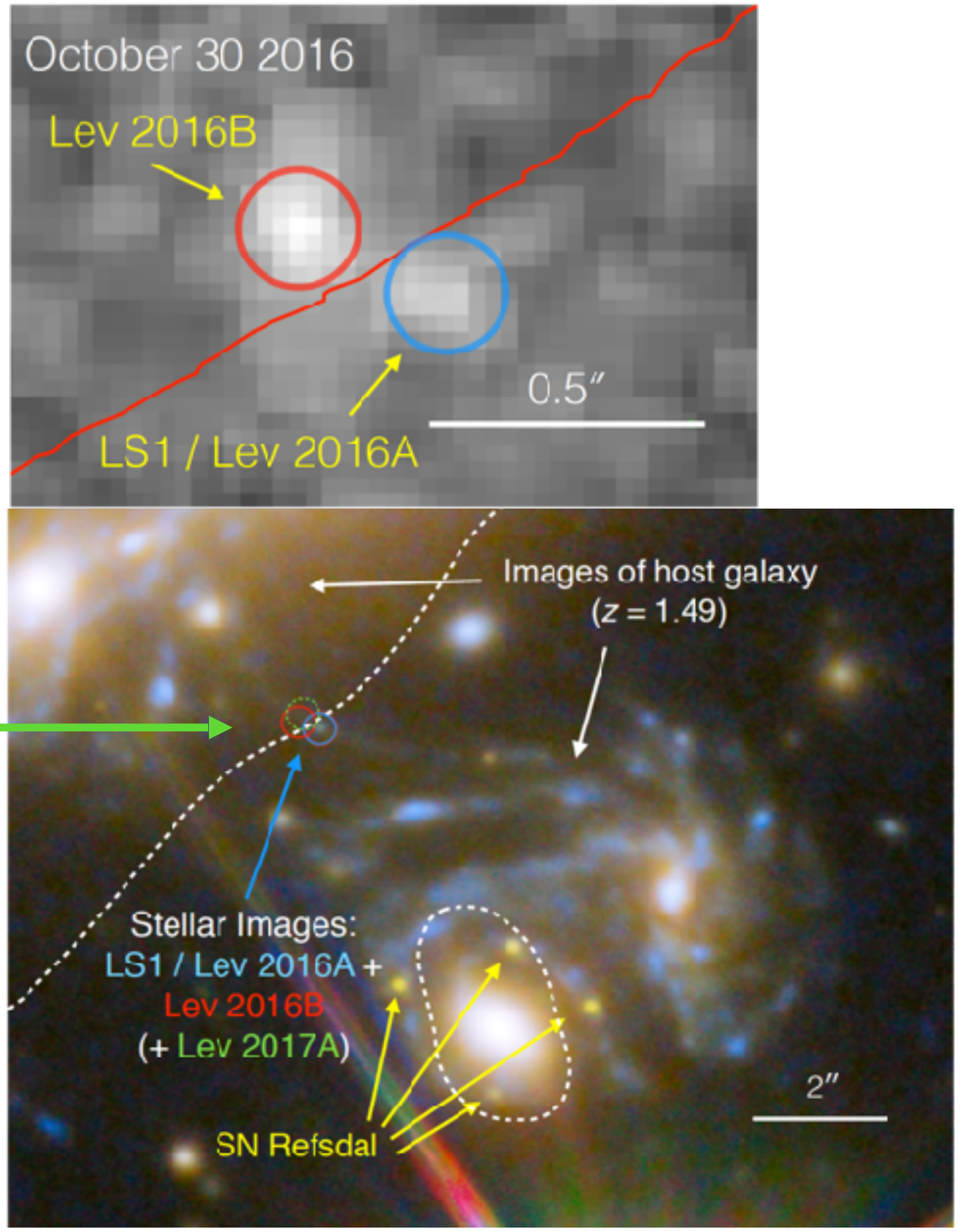


Intracluster stars make up ~ 0.1%—1% of the surface masss density



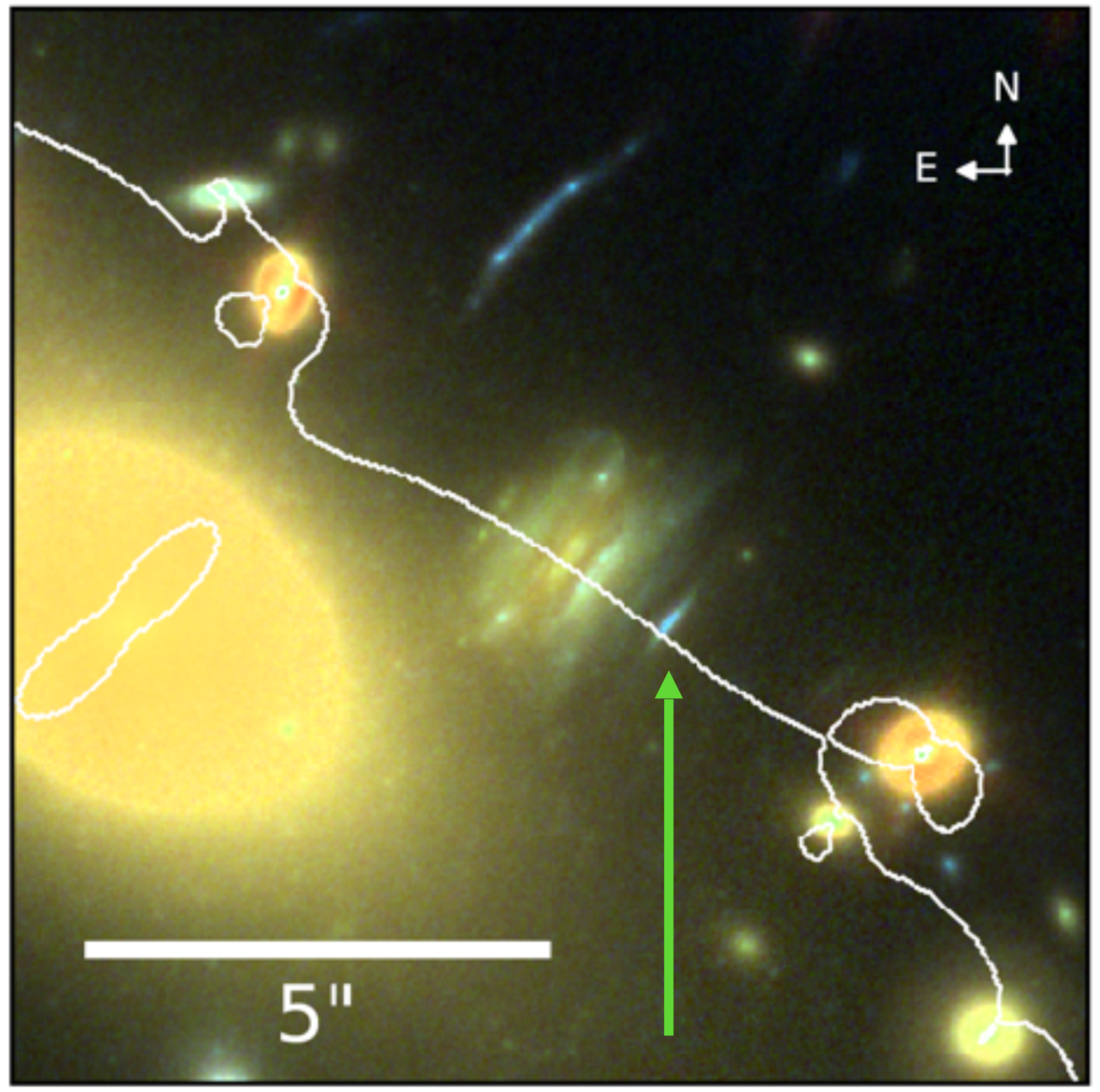
Observation with Space Telescopes

Kelly++ (2017)



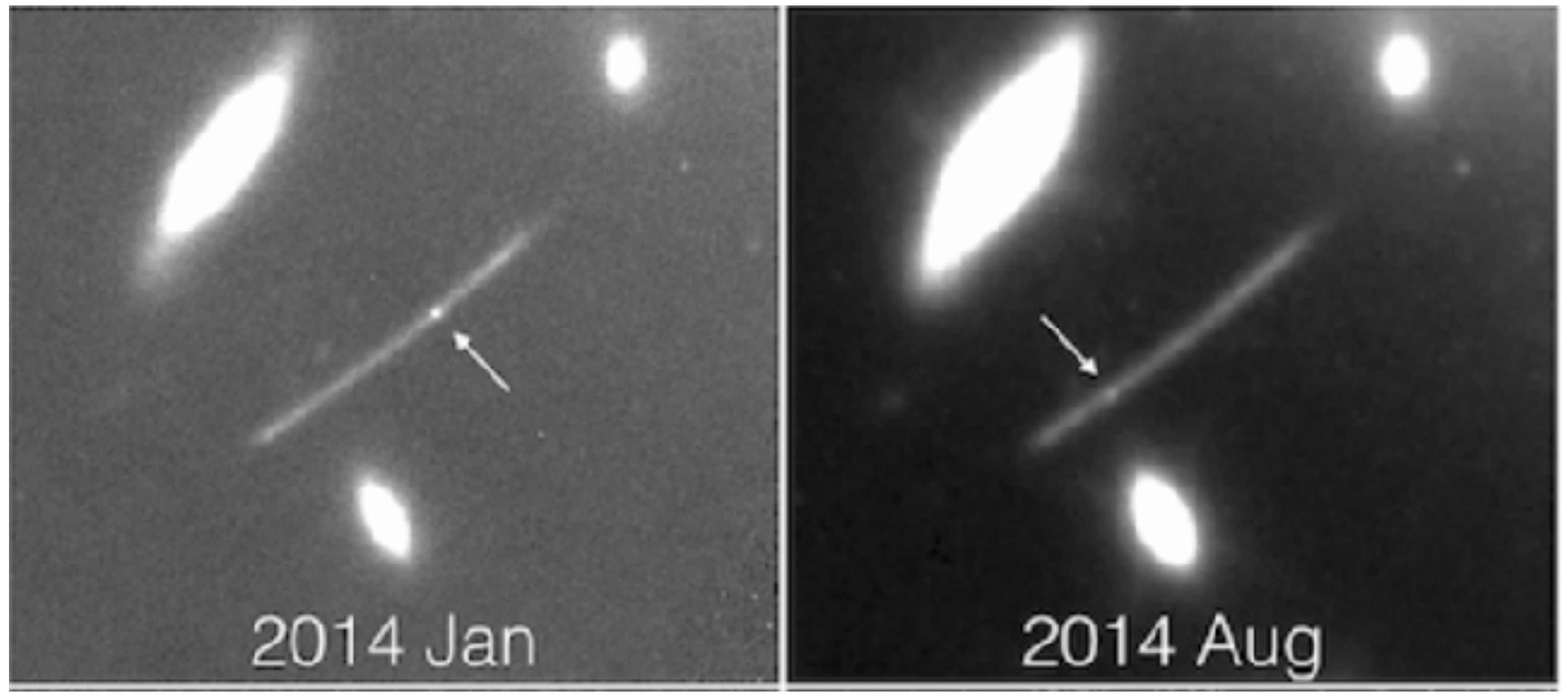
Blue supergiant T=11000-14000 K
Luminosity ~ 10^6 Lsun

Chen++ (2019)
Kaurov, LD, Venumadhav, Miralda-Escudé & Frye (2019)



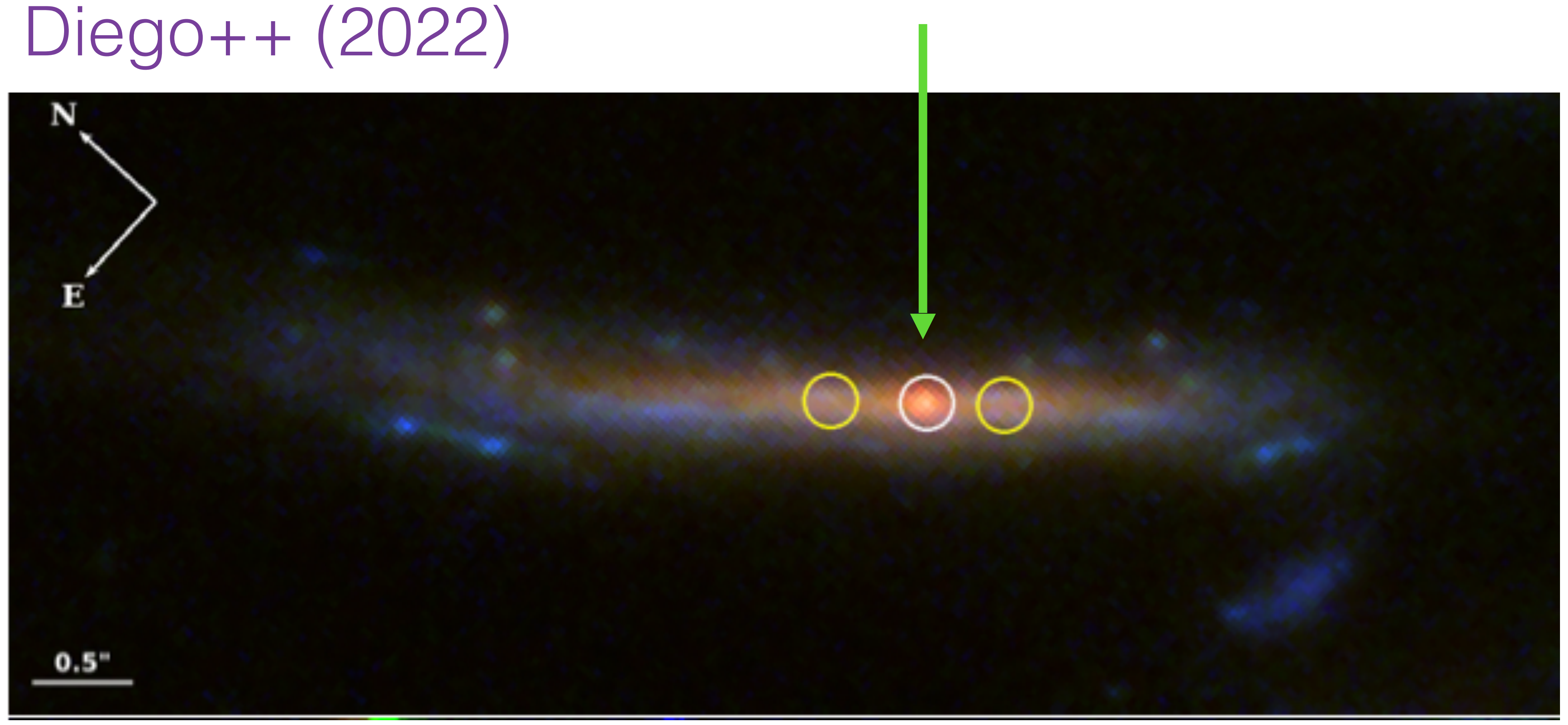
“Warhol”

Rodney++ (2018)



“Christmas Tree”

Diego++ (2022)

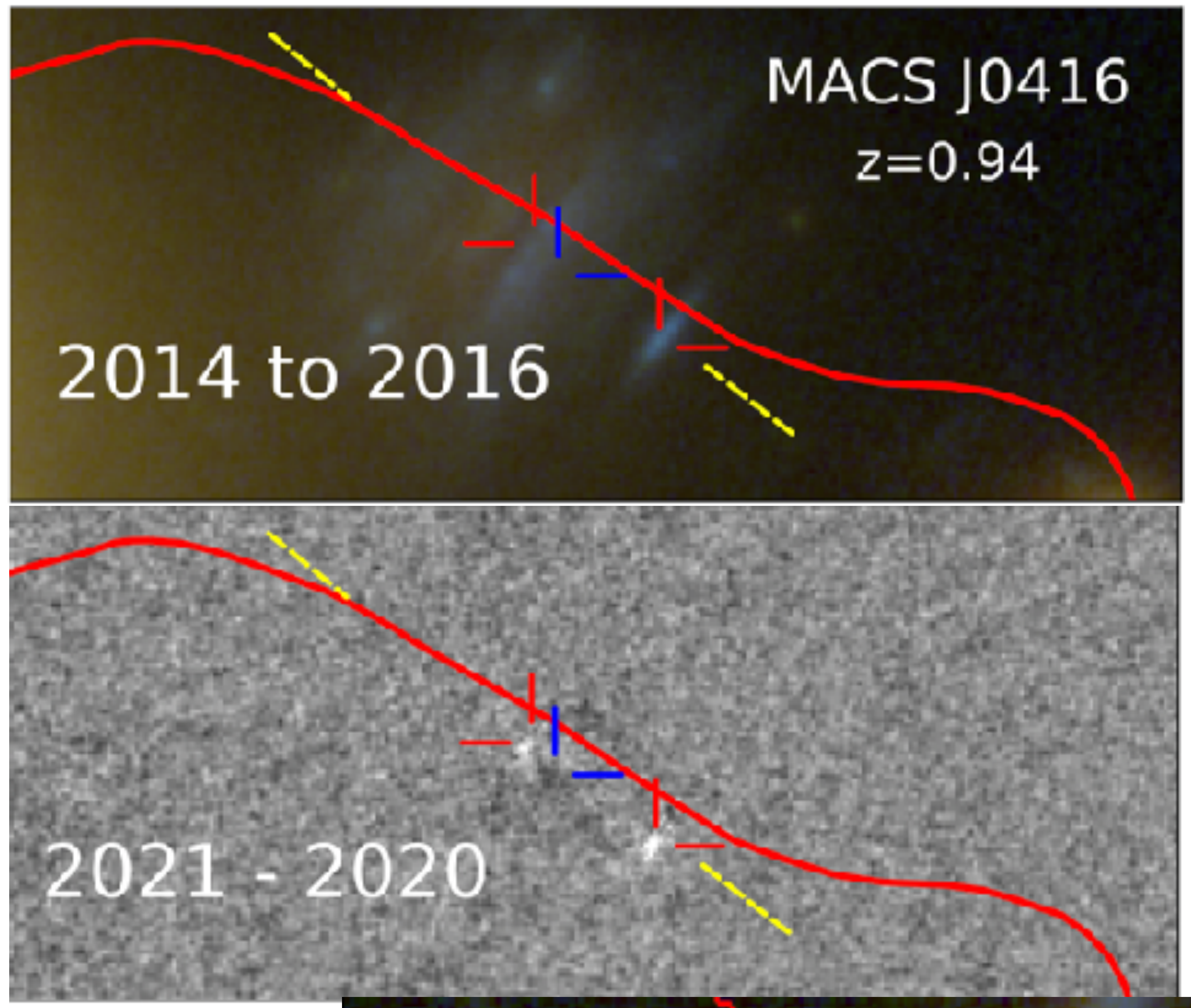


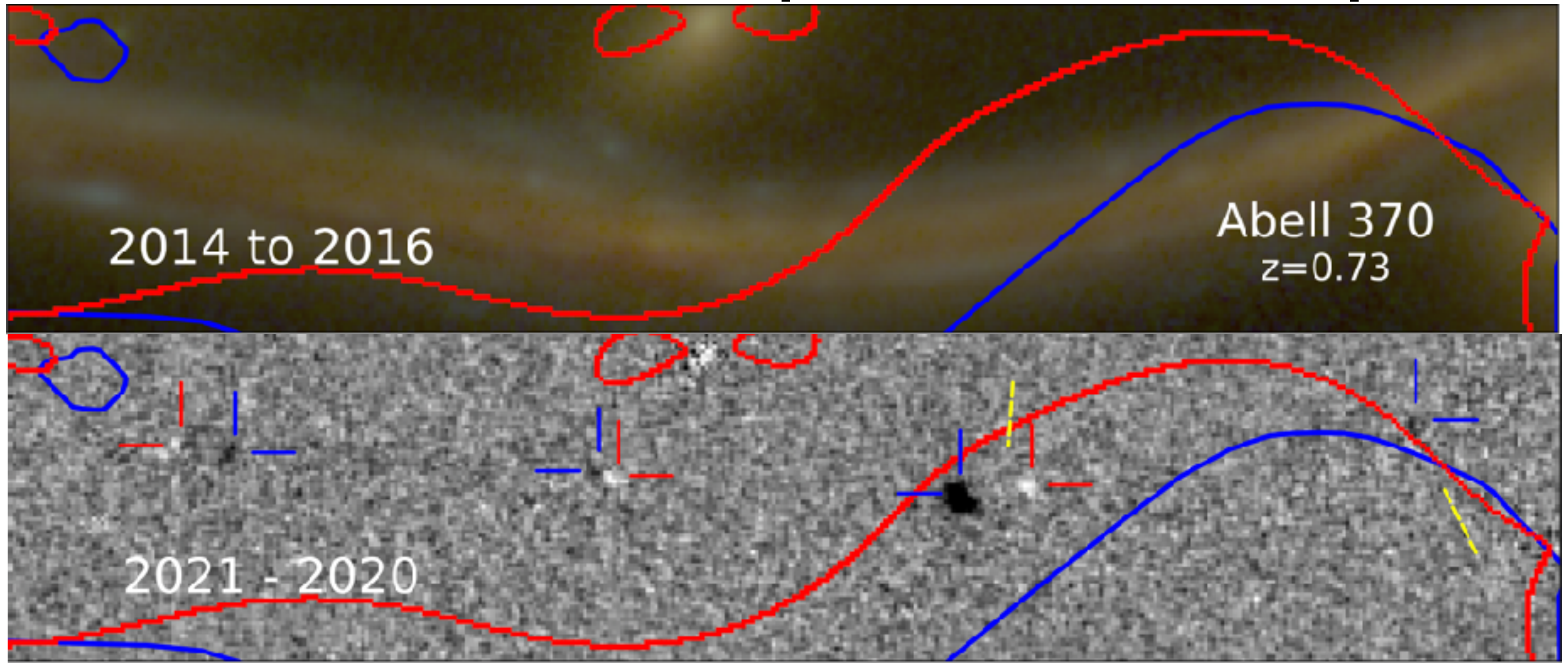
JWST observed highly magnified a red supergiant?

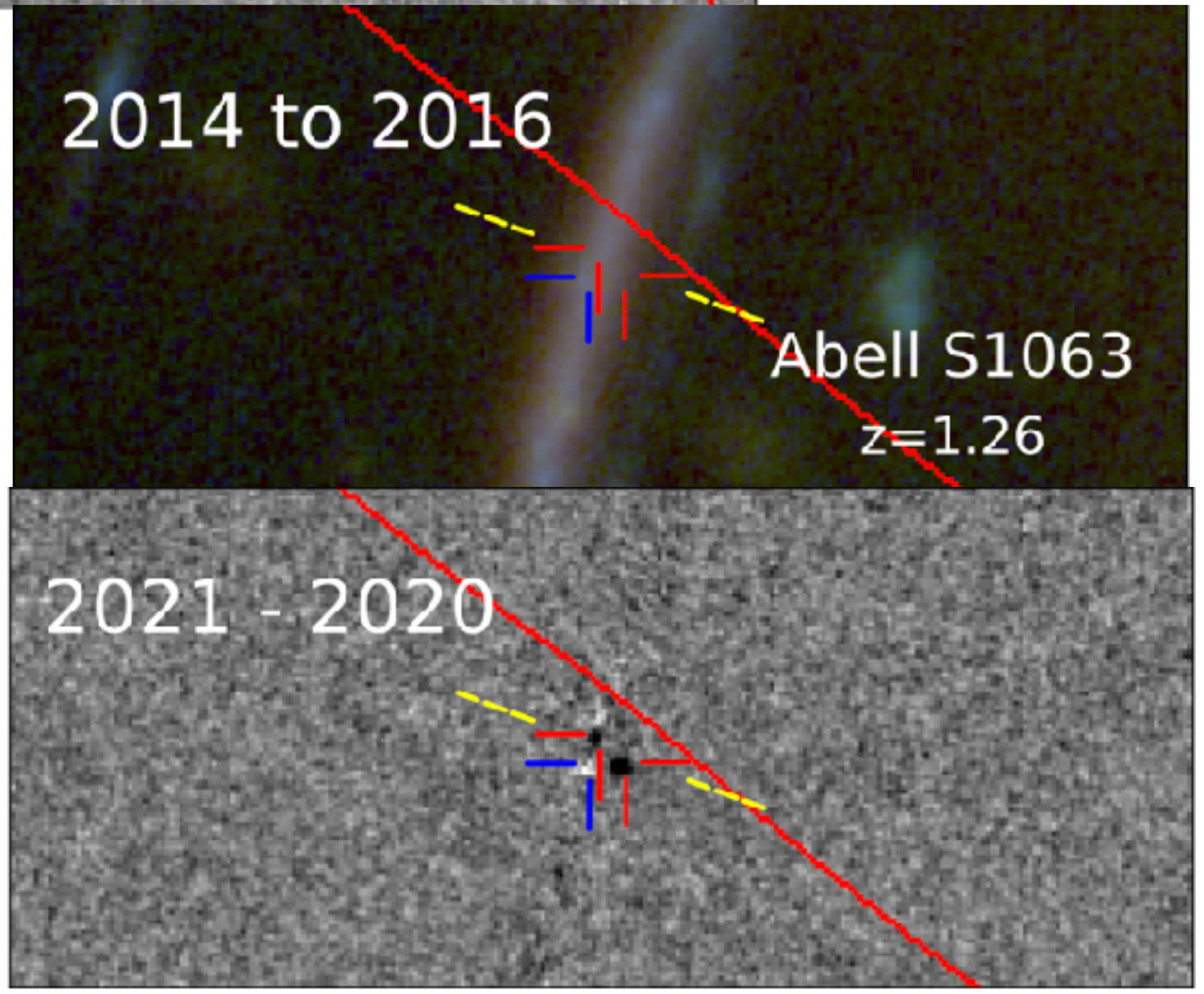
Observation with Space Telescopes

Flashlight program (PI: P. Kelly)

~30 mag per epoch at 5σ
image difference technique

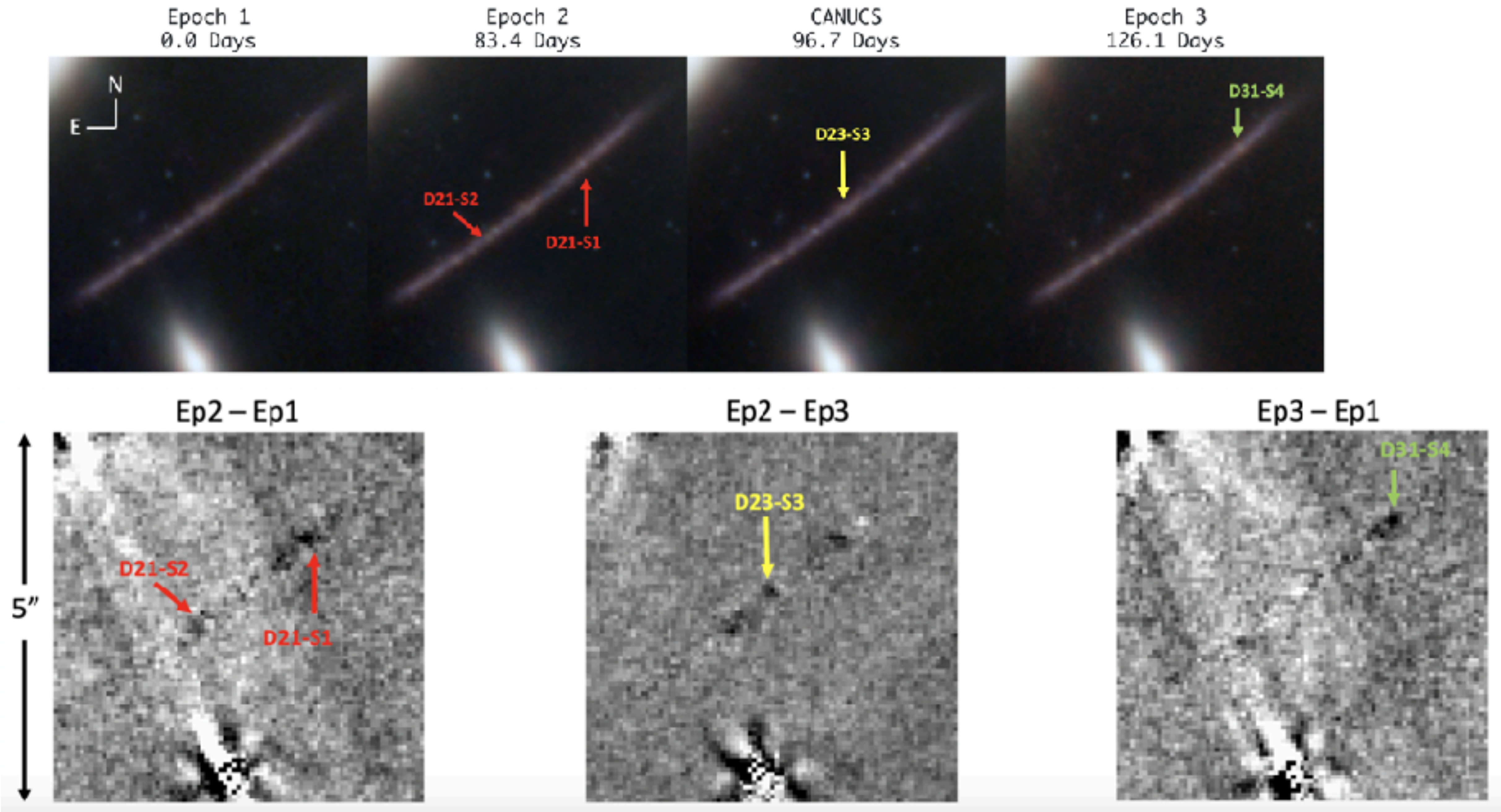






Kelly++ (2022)

Yan++ (2023); JWST imaging

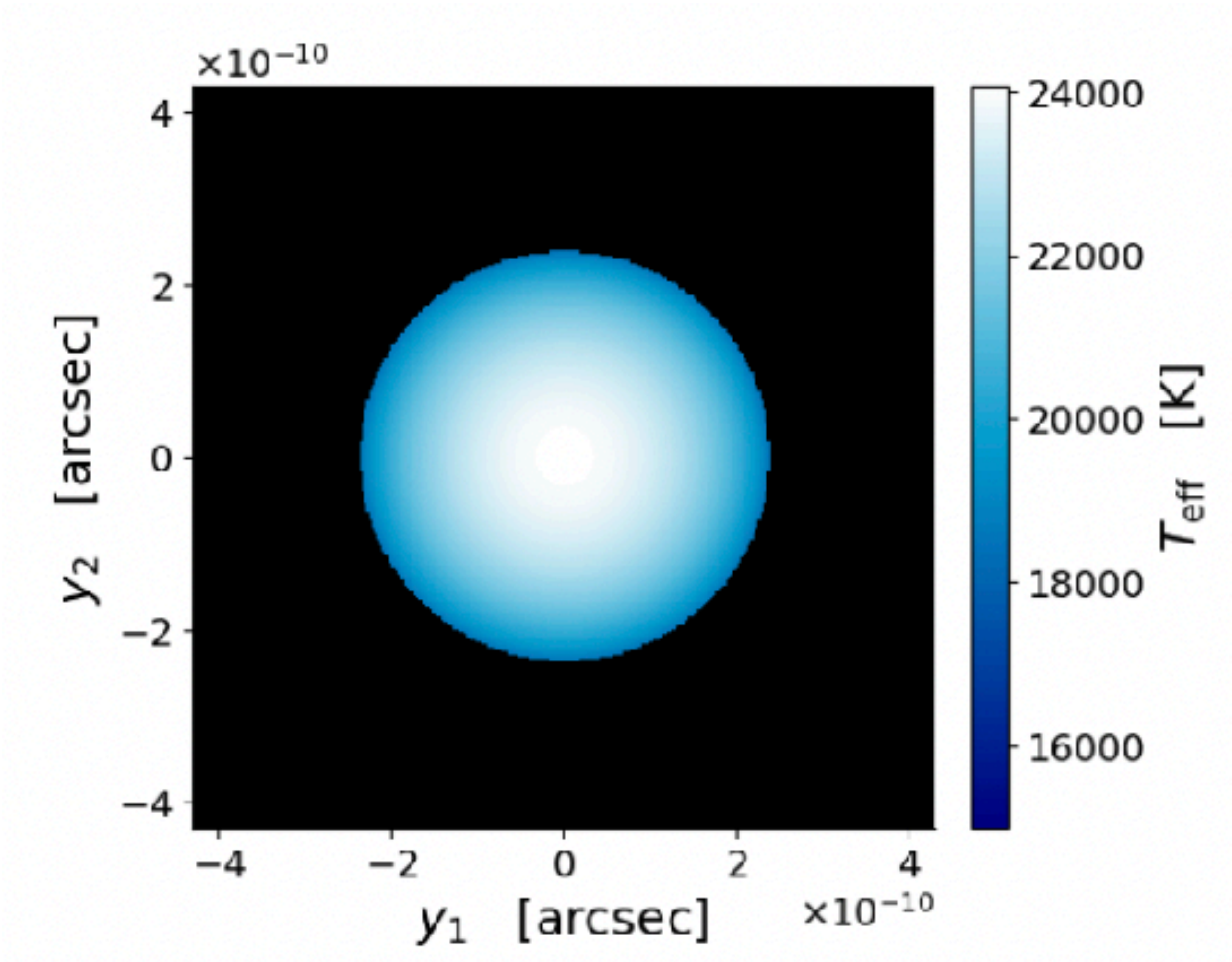


Measuring Star Properties During Micro Caustic Crossing

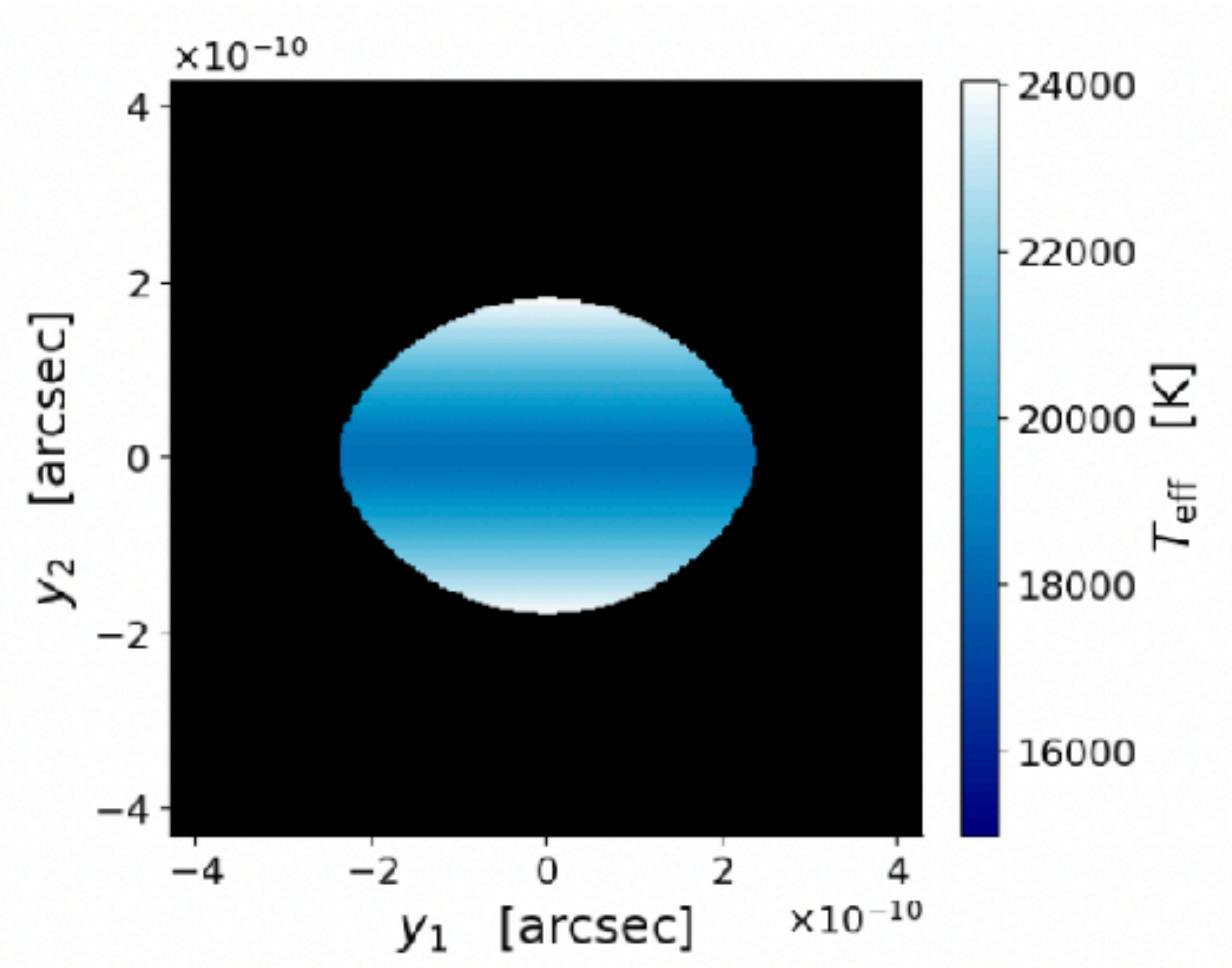
Xu Han

Effect of surface rotation:
[1] flattened shape
[2] gravity darkening

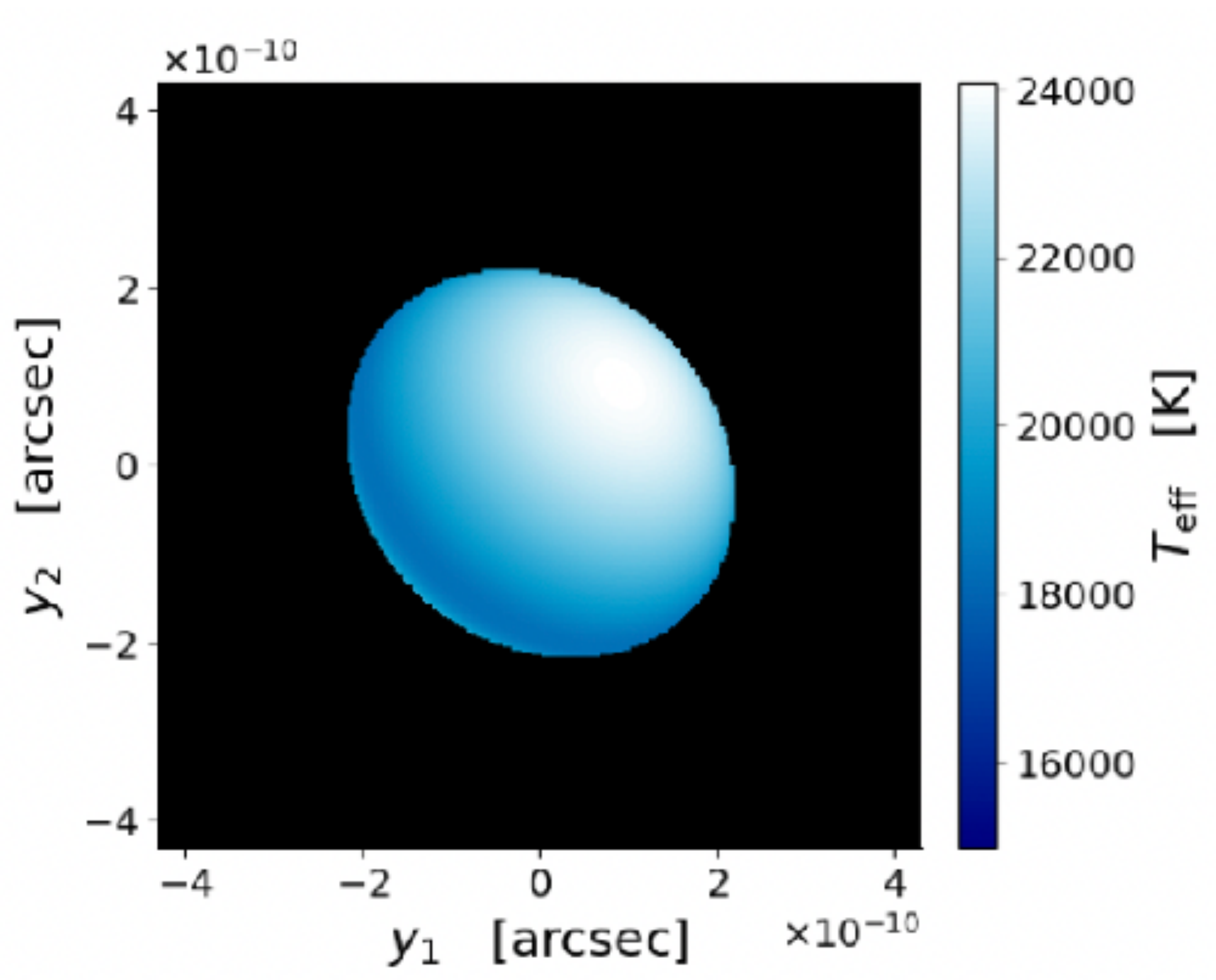
Rapidly rotating star $\omega = 0.8$



Pole view



Equatorial view



Inclined

Ray-tracing Example of A Star Crossing a Caustic

Rapidly rotating star $\omega = 0.8$

Viewed at an inclined angle

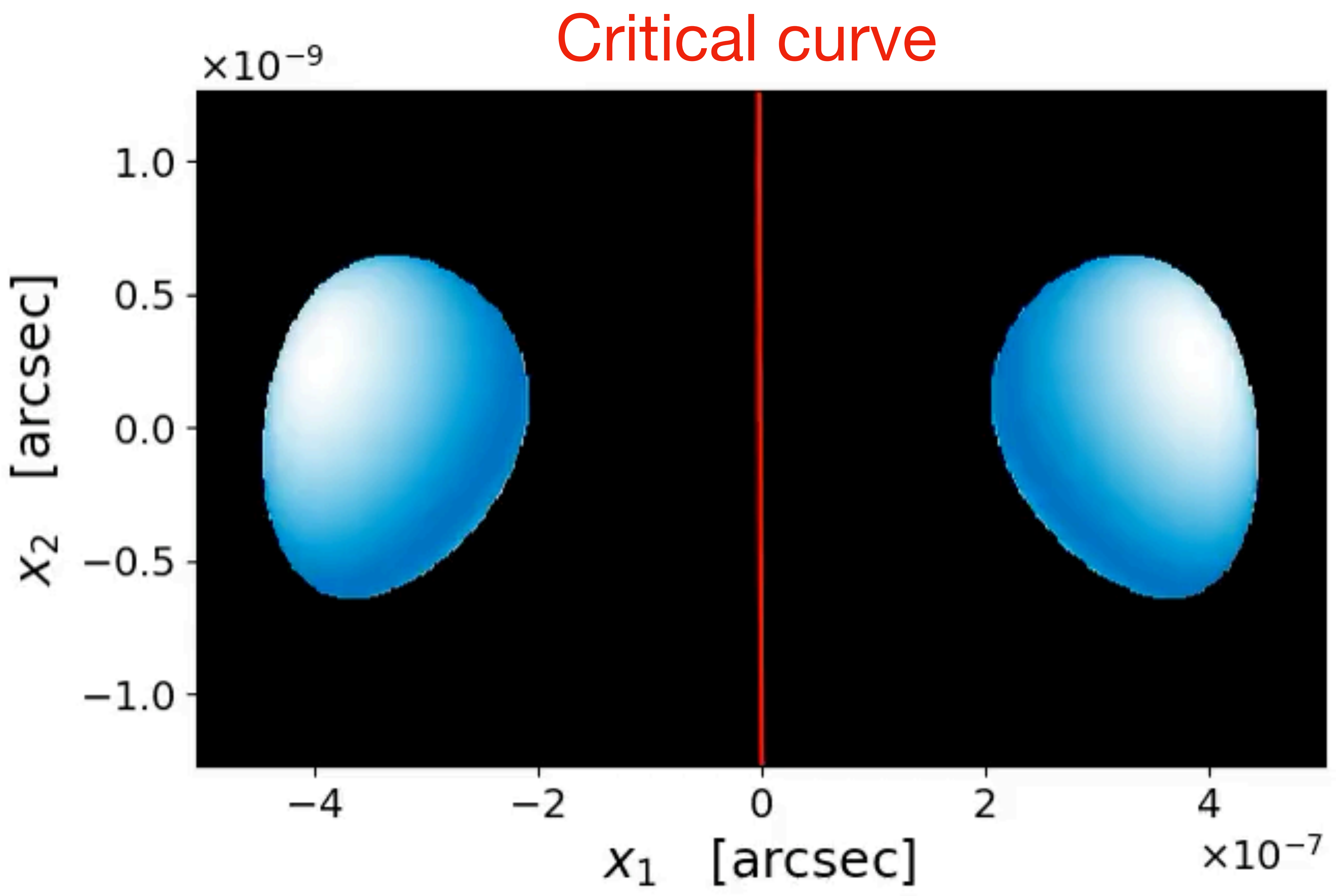
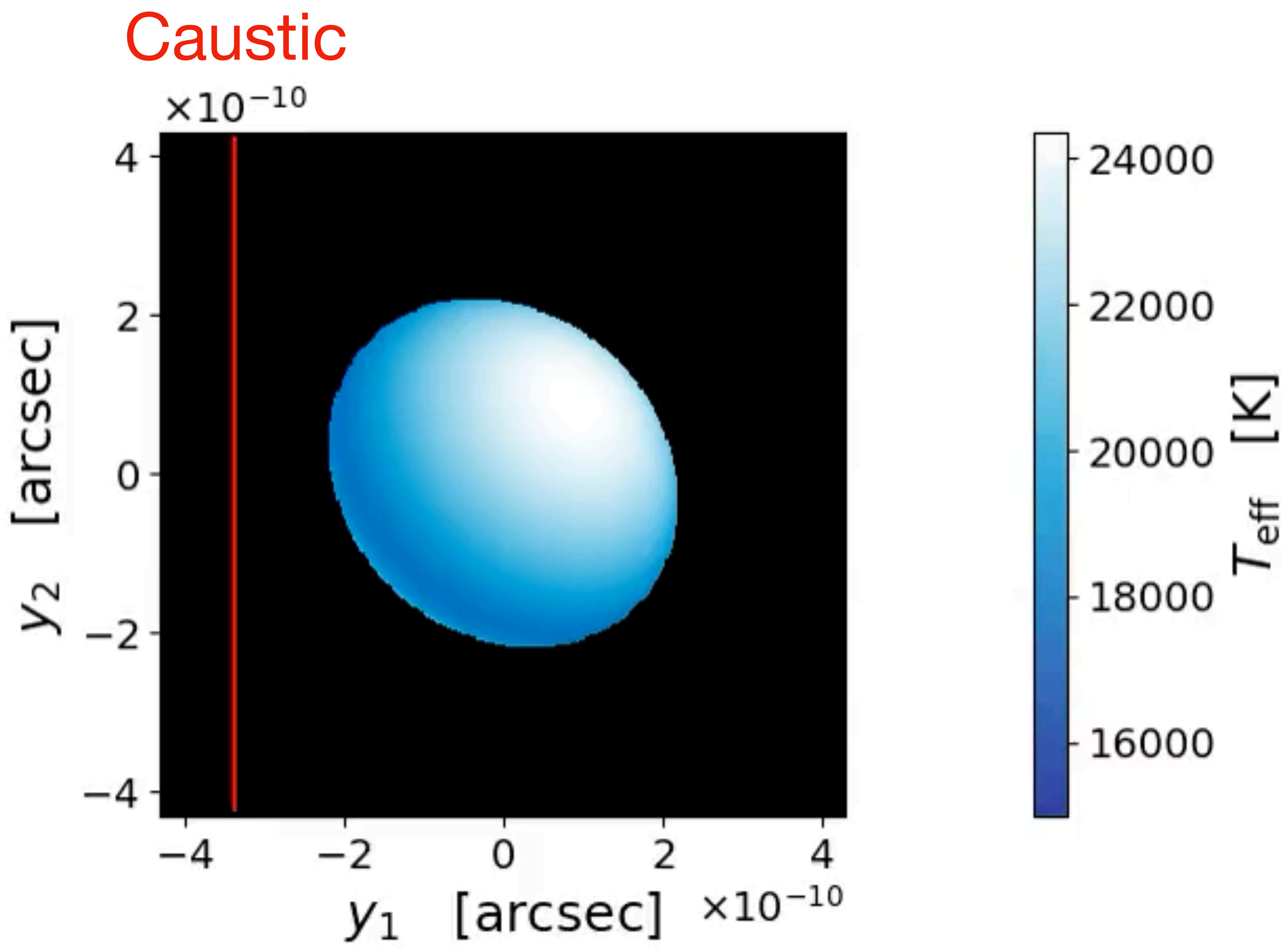


Image Plane



Source Plane

Simulated Multi-filter Lightcurves

Lightcurves near peak magnification

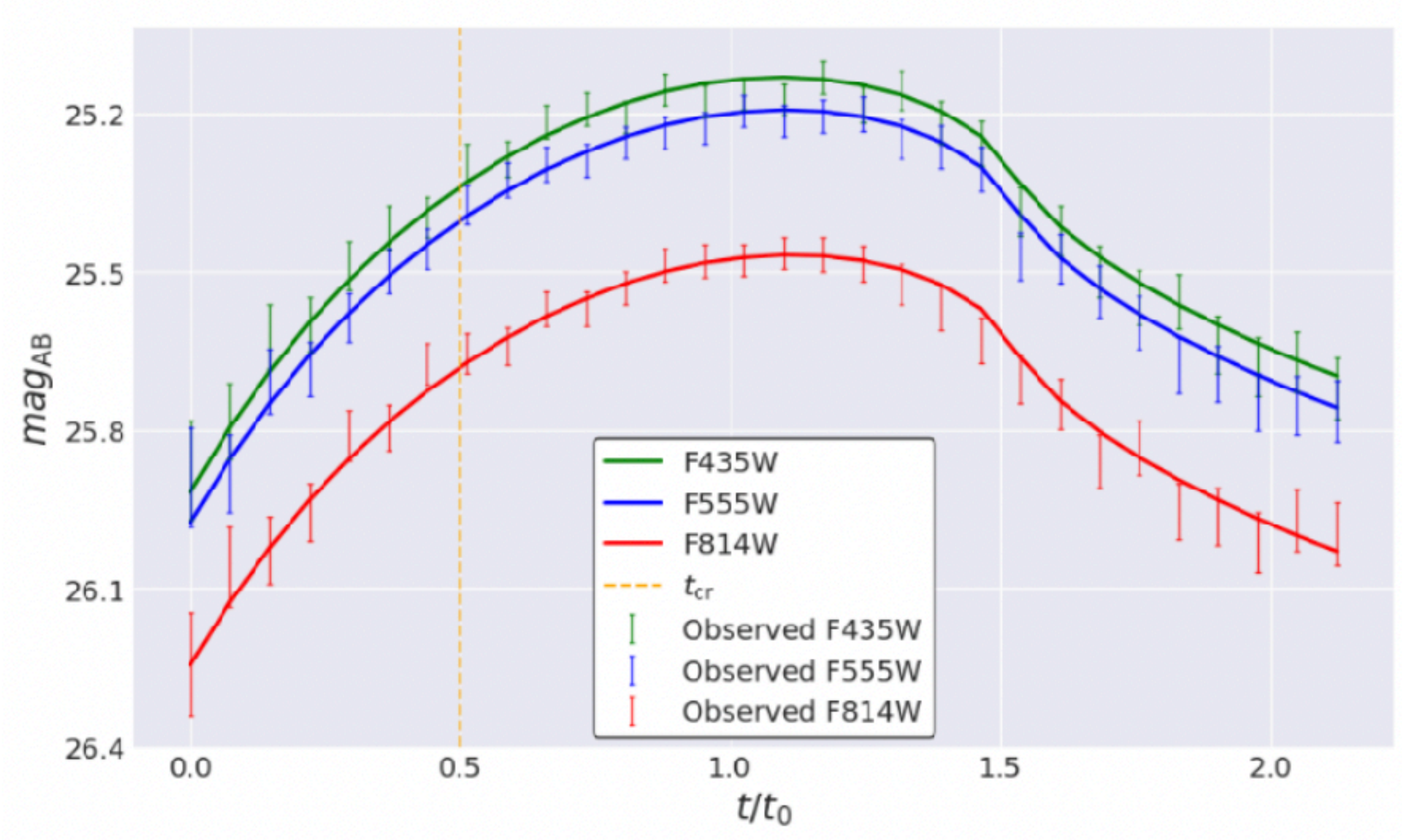
3 HST filters: ~435nm, ~555nm, ~814nm

~ 1hr per filter, 29 mag @ 1σ

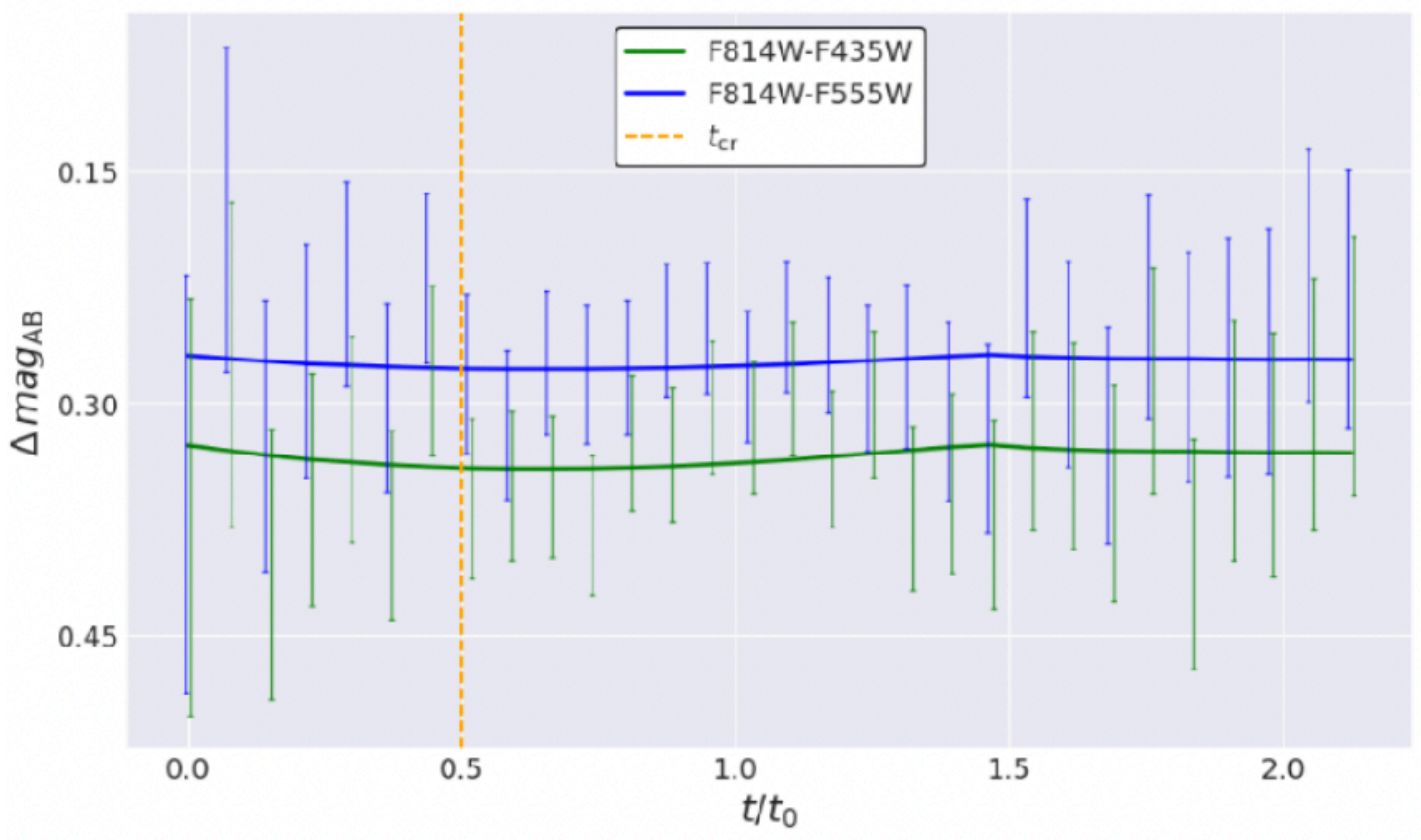
Fast rotating star $\omega = 0.4$

$T_{\rm eff} \simeq 20000\,{\rm K}$

$L_{\rm bol} = 10^6\,L_\odot$ $R = 83\,R_\odot$



Lightcurves near peak magnification

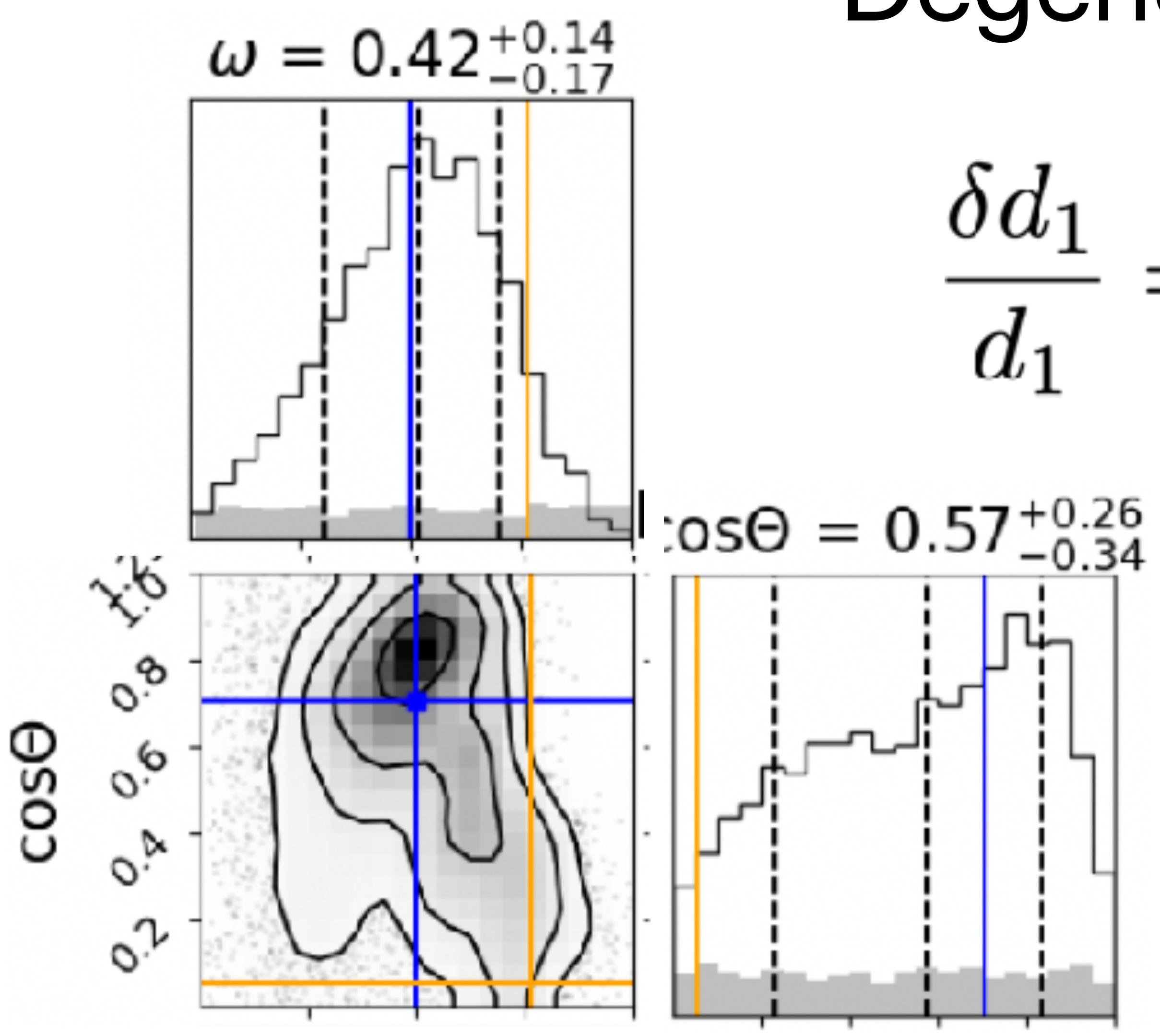


No significant color variation

Parameter Inference Test (Single Star)

Han & LD 2312.04774

Surface rotation (relative to breakup)	$\omega = \Omega/\Omega_{cr}$
Equatorial radius	R_e
Bolometric luminosity	L_{bol}
Stellar mass	M
Inclination	Θ
Position angle	Φ
Micro Caustic Strength	$\mathbf{d} = (d_1, d_2)$
Effective velocity	v_t
Epoch of Caustic Crossing	t_{cr}



Degeneracy between R_e, L_{bol}, d_1, v_t

$$\frac{\delta d_1}{d_1} = 3\,\frac{\delta R_e}{R_e} = \frac{3}{2}\,\frac{\delta L_{\rm bol}}{L_{\rm bol}} = 3\,\frac{\delta v_t}{v_t}$$

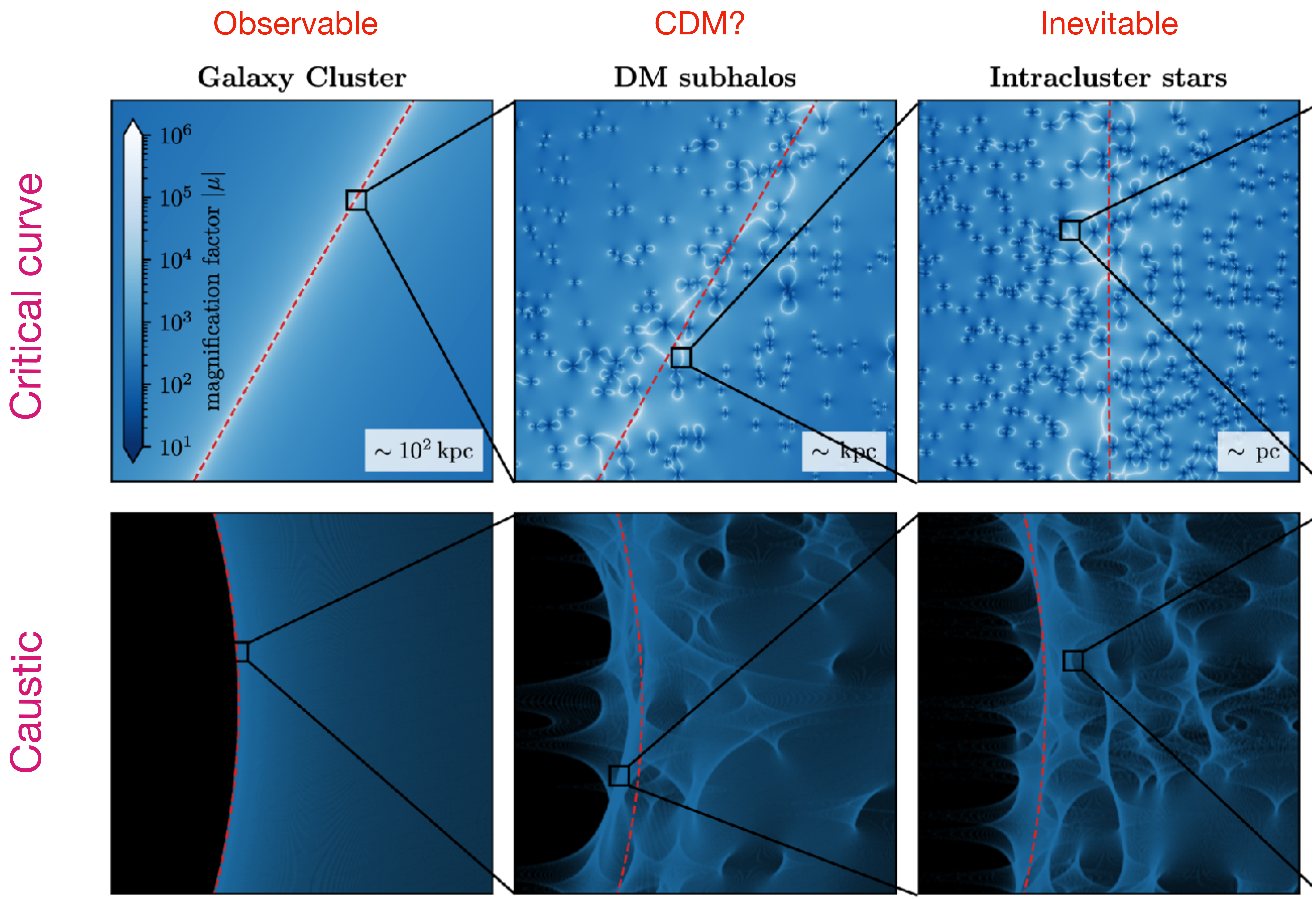
Limitation: unknown micro caustic strength d_1

Future extension:
[1] limb darkening
[2] dust reddening
[3] additional micro-images

Possible improvement:
jointly analyzing multiple micro caustic crossings for the same source star

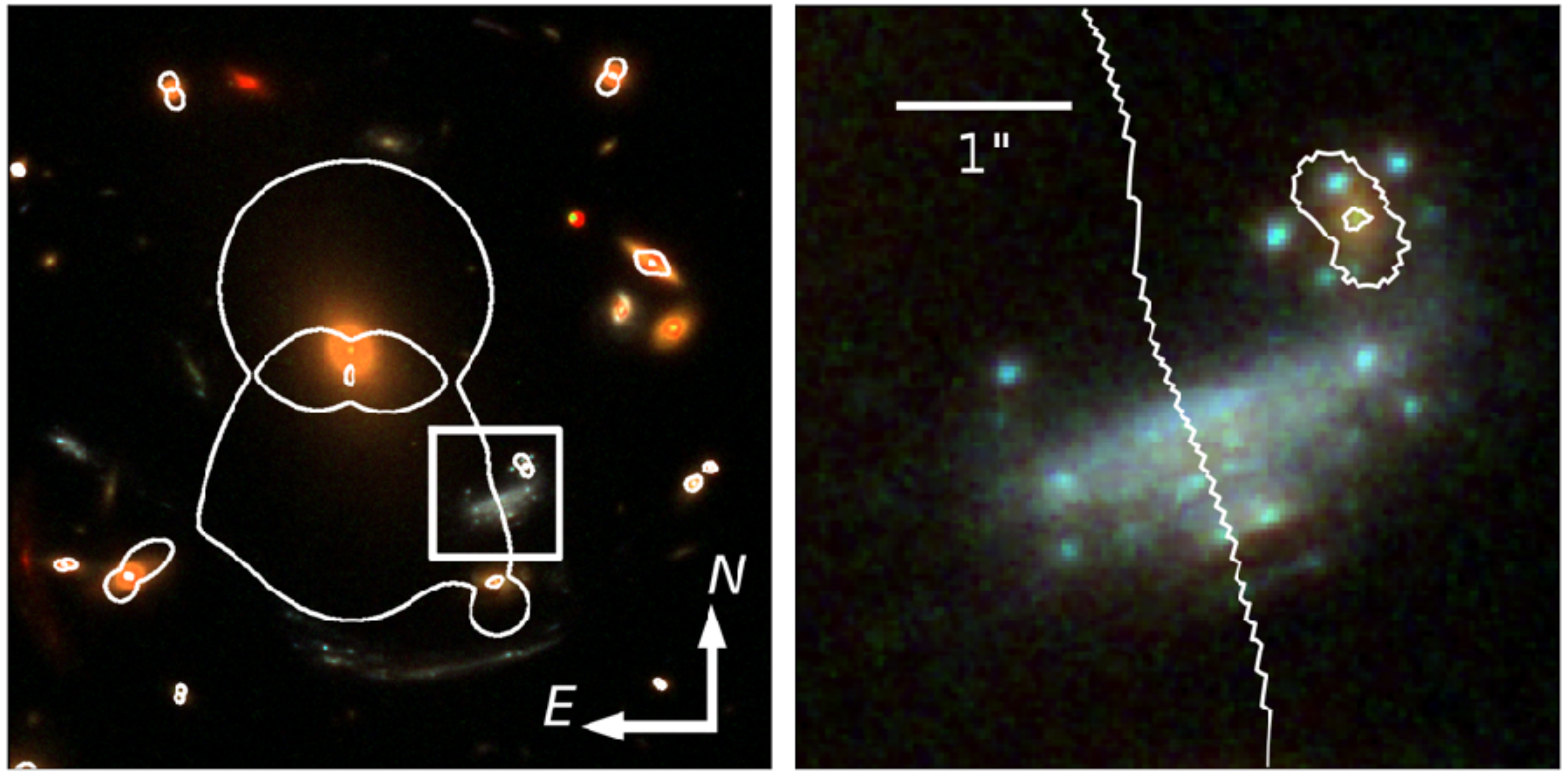
Potential use:
[1] survey (very) massive stars in z~1—2 galaxies
[2] associate caustic-crossing events with source stars for dark matter probes

Hierarchy of caustic structures



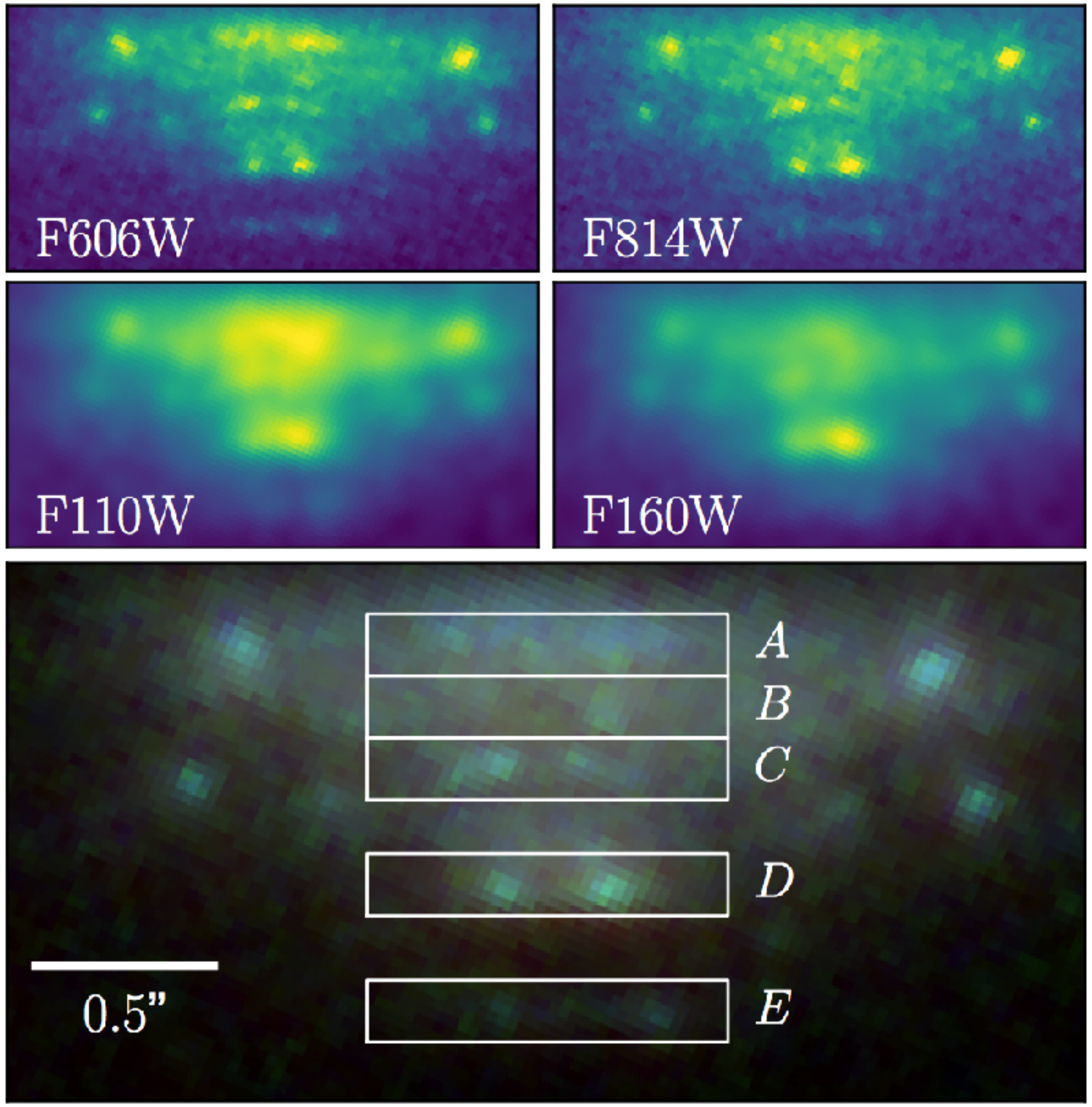
Flux asymmetry induced by sub-galactic CDM halos

LD, Kaurov, Sharon++ (2020)



Evidence for a population of 10^6-10^8 solar mass dark matter halos

Images from Hubble



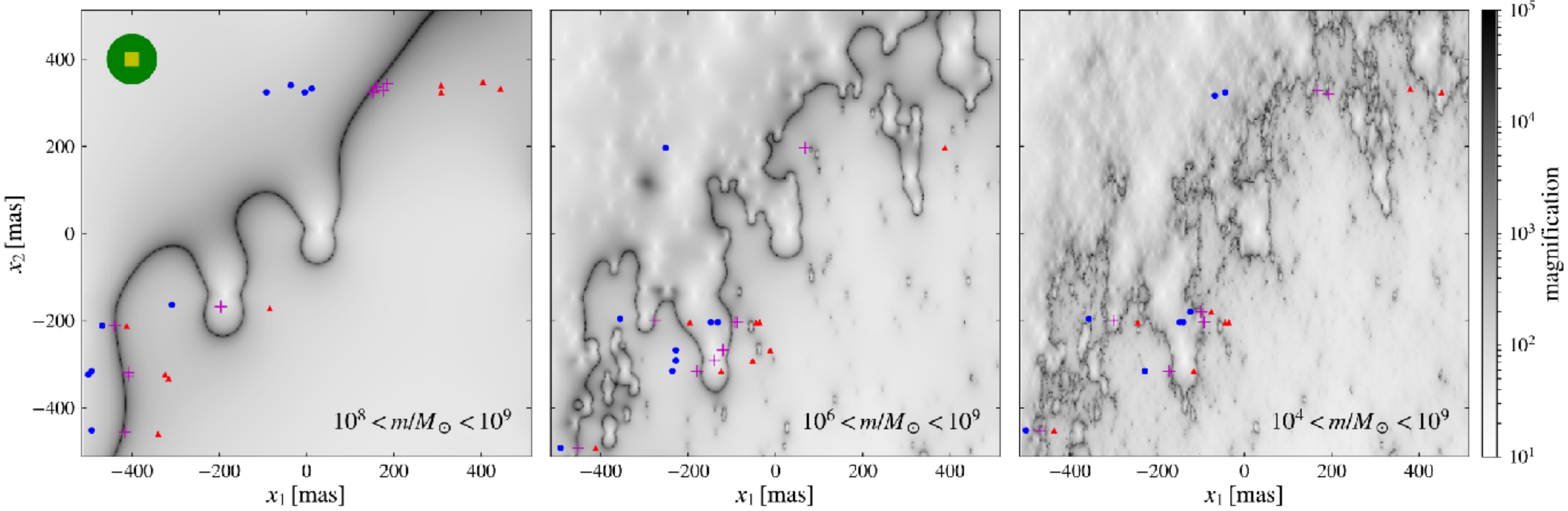
Astrometric signals of sub-galactic CDM halos

Considered a giant arc like the one in Abell 370

JWST PSF (~1.5 μm)

NIRCam pixel (32 mas)

LD, Venumadhav, Kaurov & Miralda-Escudé (2018)



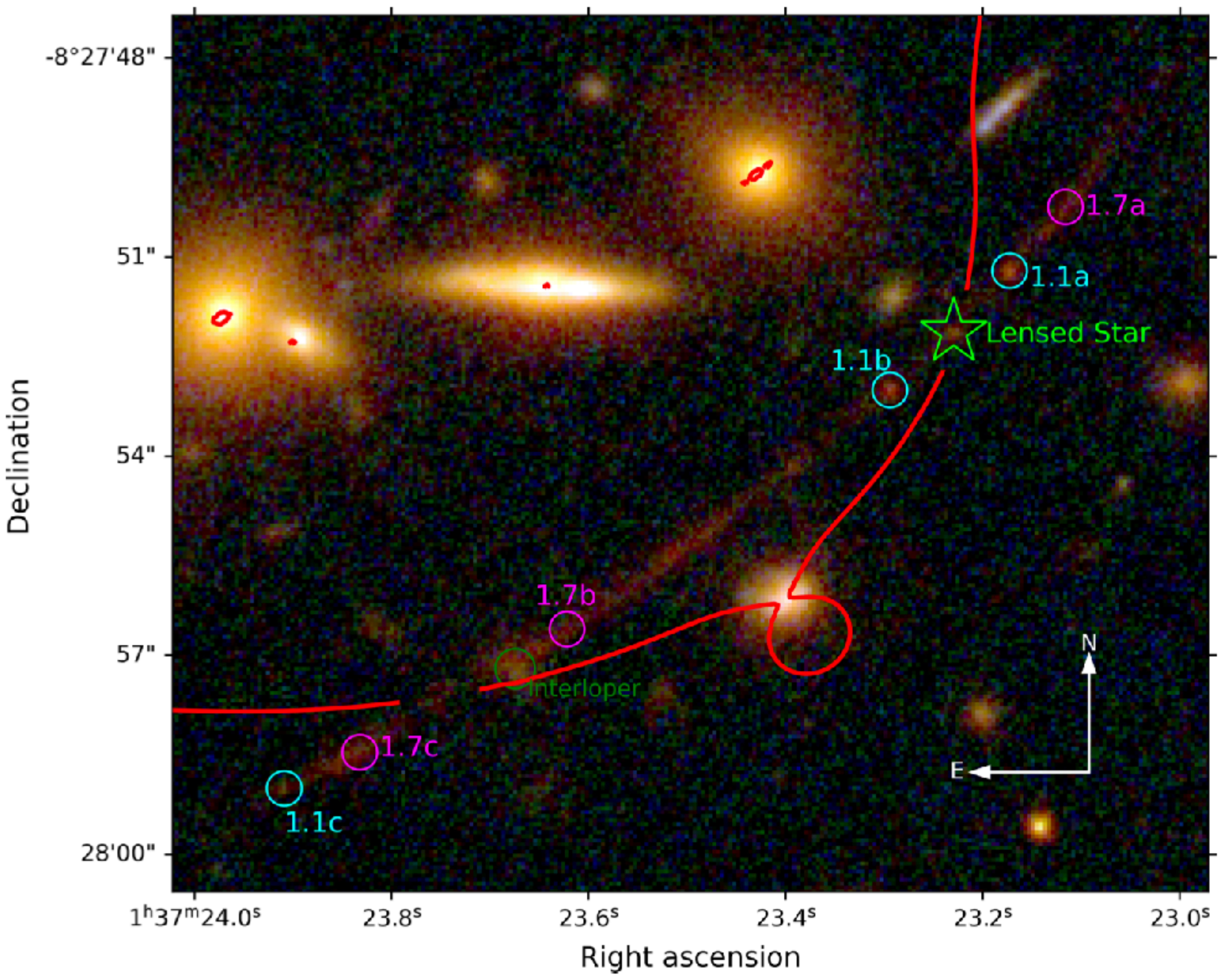
See also:
Williams++ (2023)
Abe, Kawai & Oguri (2023)

Midpoints of image pairs should not lie along a nearly straight line.

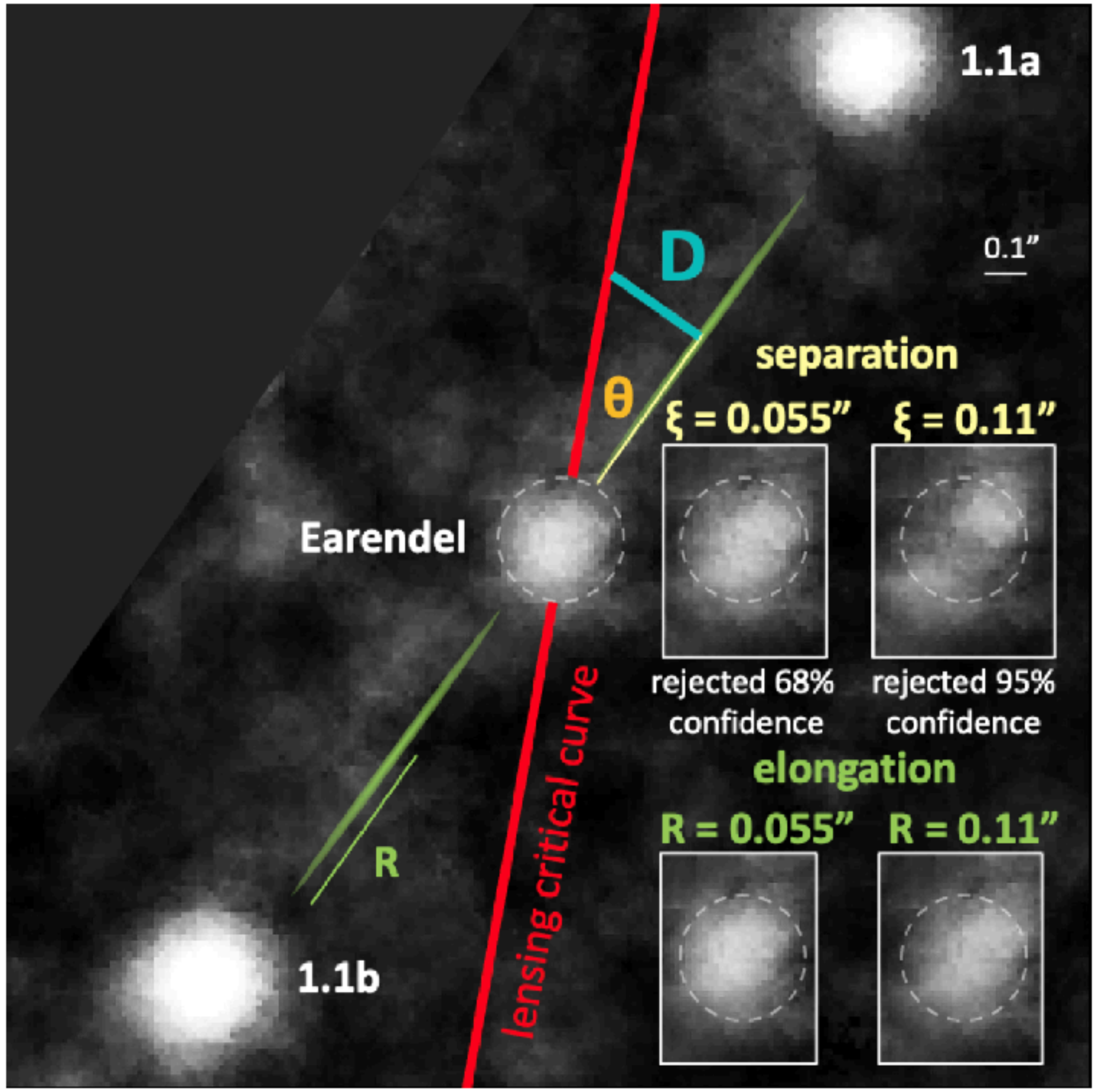
Sensitive to the population of subhalos in the mass range 10^6–10^8 solar masses

Earendel: highly magnified individual star at z=6?

Lensed galaxy: z~6 from IGM absorption bluebird of Lyα

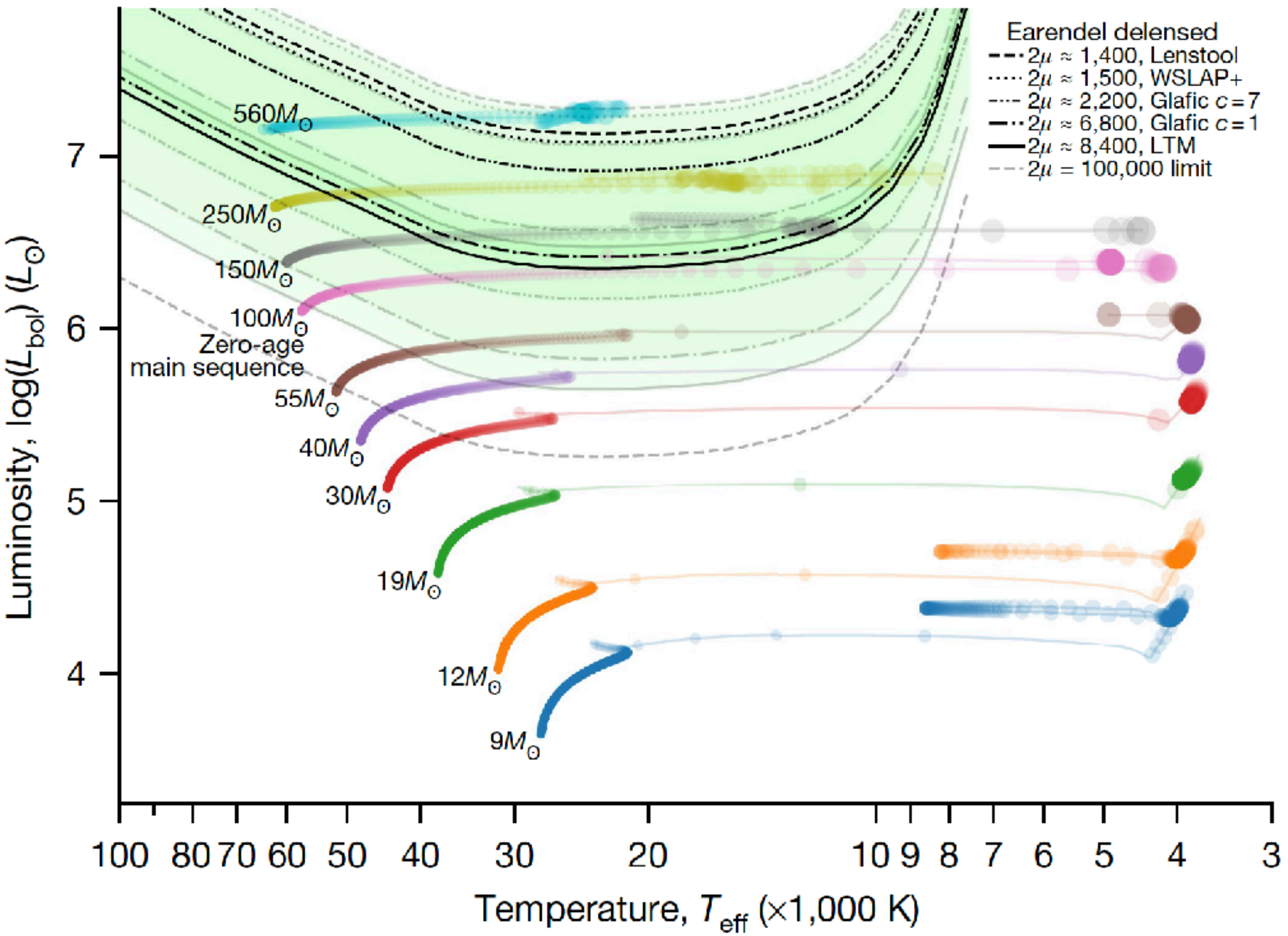


lone image of Earendel



Earendel: highly magnified individual star at z=6?

Welch++ (2022a)



Maybe a M ~ 100 Msun evolved (T_{eff} = 15000 K) low-Z blue supergiant that is magnified by ~ 8000 fold

Source size constraint < 0.1—0.3 pc

$$r_S \lesssim \mathcal{R}^2 D_S \left| \mathbf{d^0} \cdot \mathbf{e}^{\mathbf{0}}_{\parallel} \right|$$

0.055”

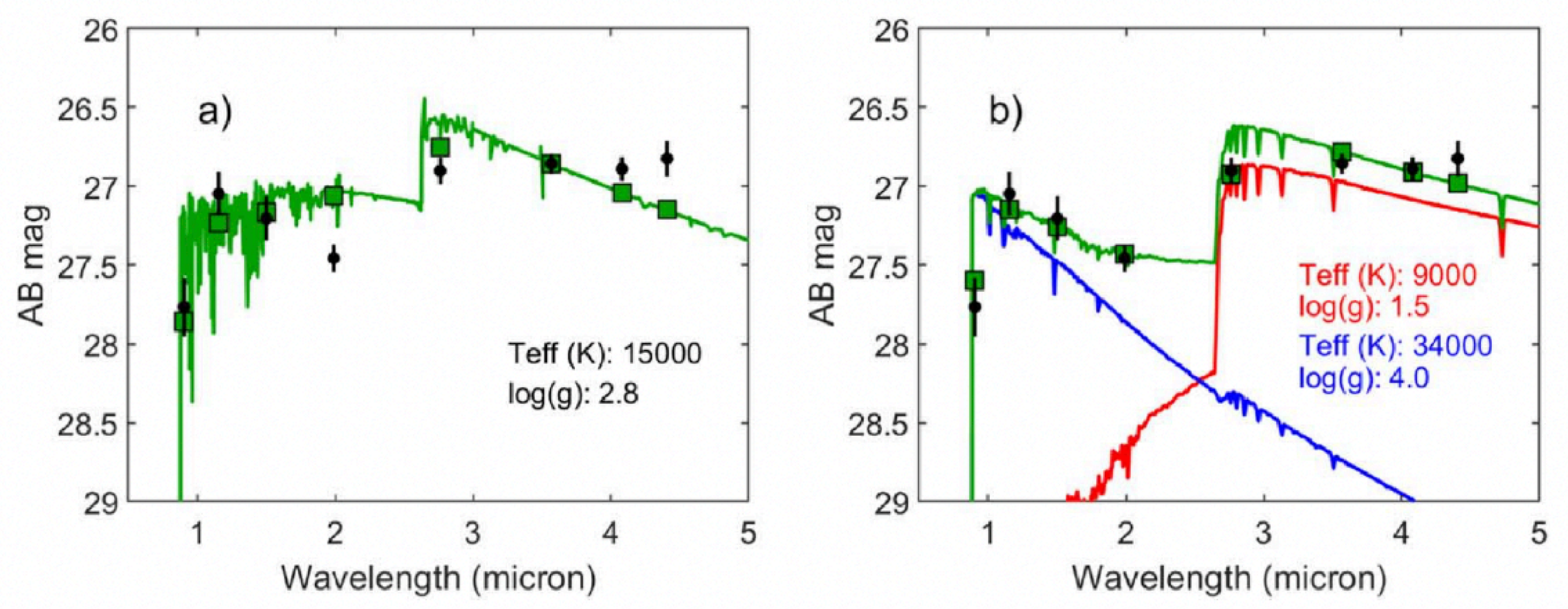
caustic strength (Inverse angle)

Thought to be too stringent to be a star group/cluster

Possible issues with single star interpretation

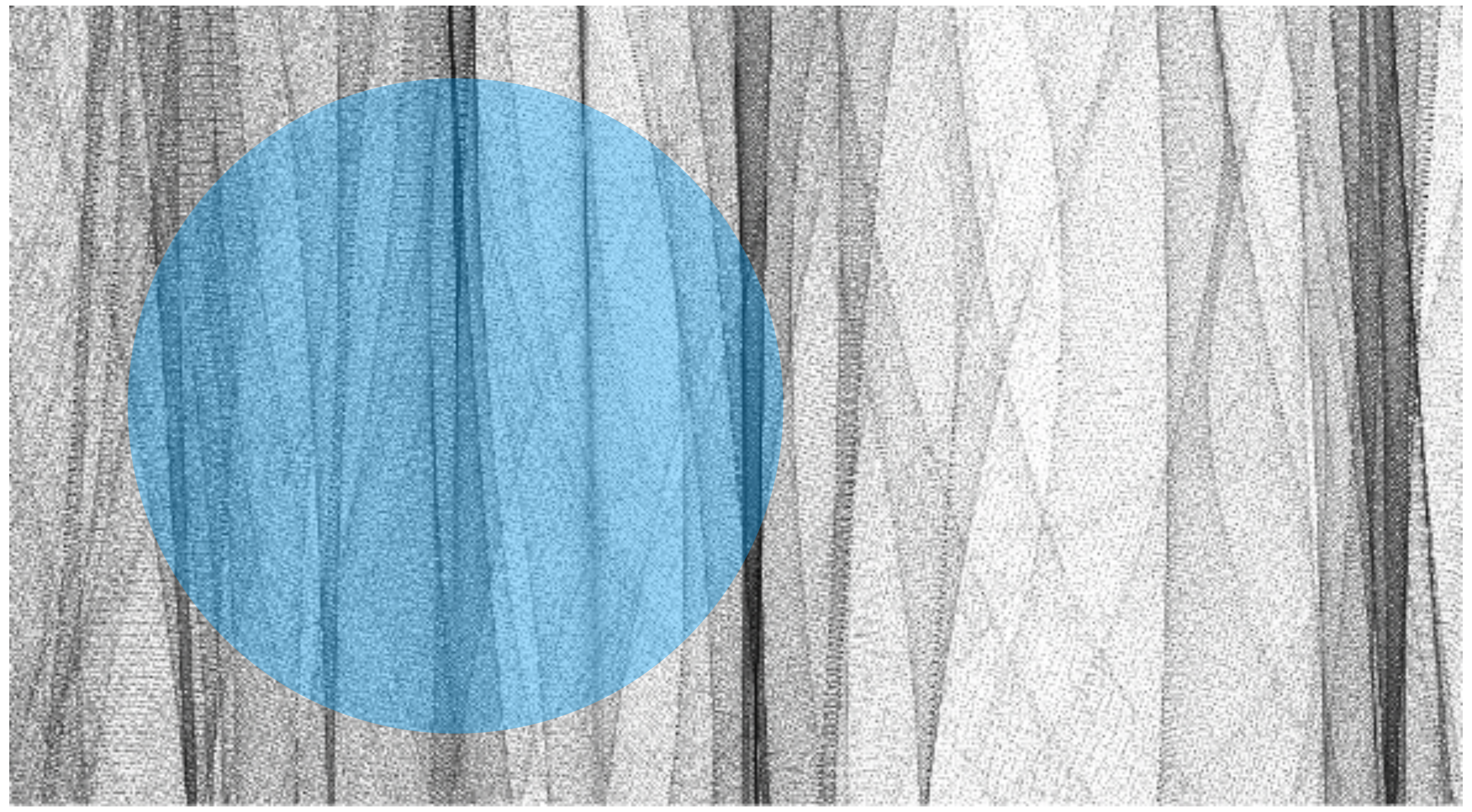
Welch++ (2022b)

JWST/NIRCam SED somewhat intriguing



Single star does not decently fit JWST/NIRCam photometry
A hot-cool binary stellar system can fit the data better

source size compared to caustic density



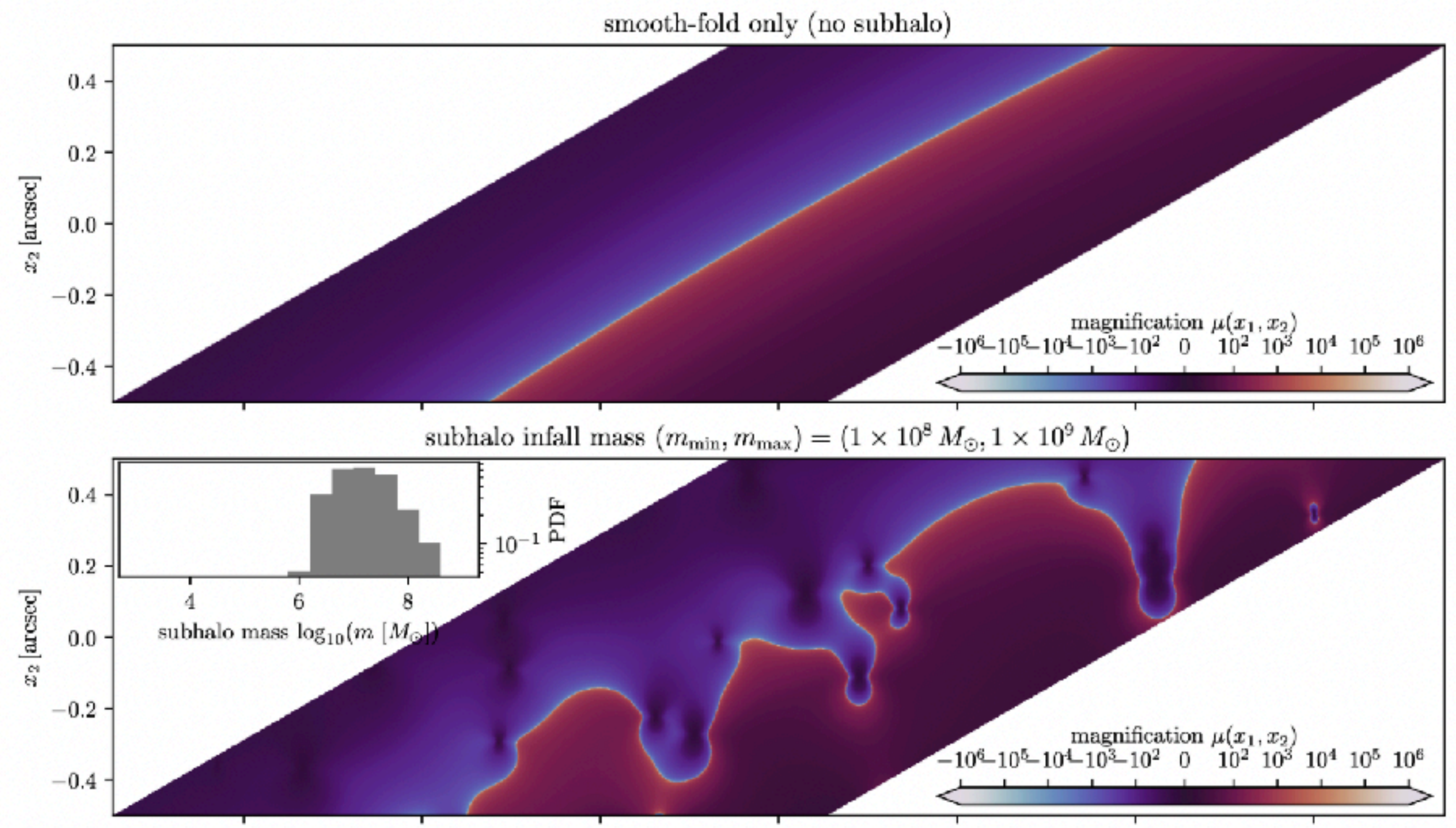
Non-detection of flux variability
Where is microlensing?

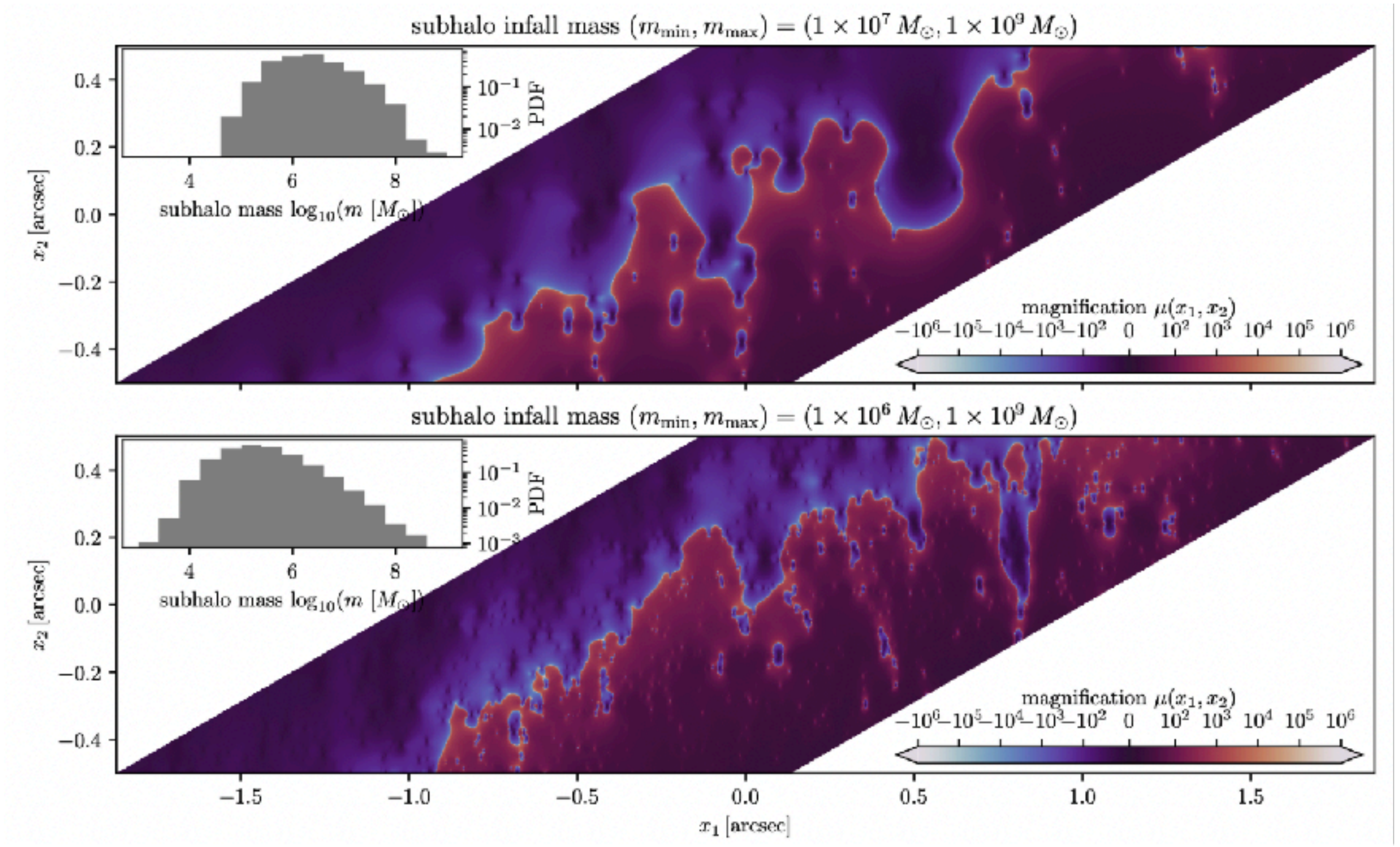
The effect of sub-galactic CDM subhalos

Ji & LD in prep

Lingyuan Ji (BCCP)

Macro caustic not expected to be smooth, but corrugated with fine structures





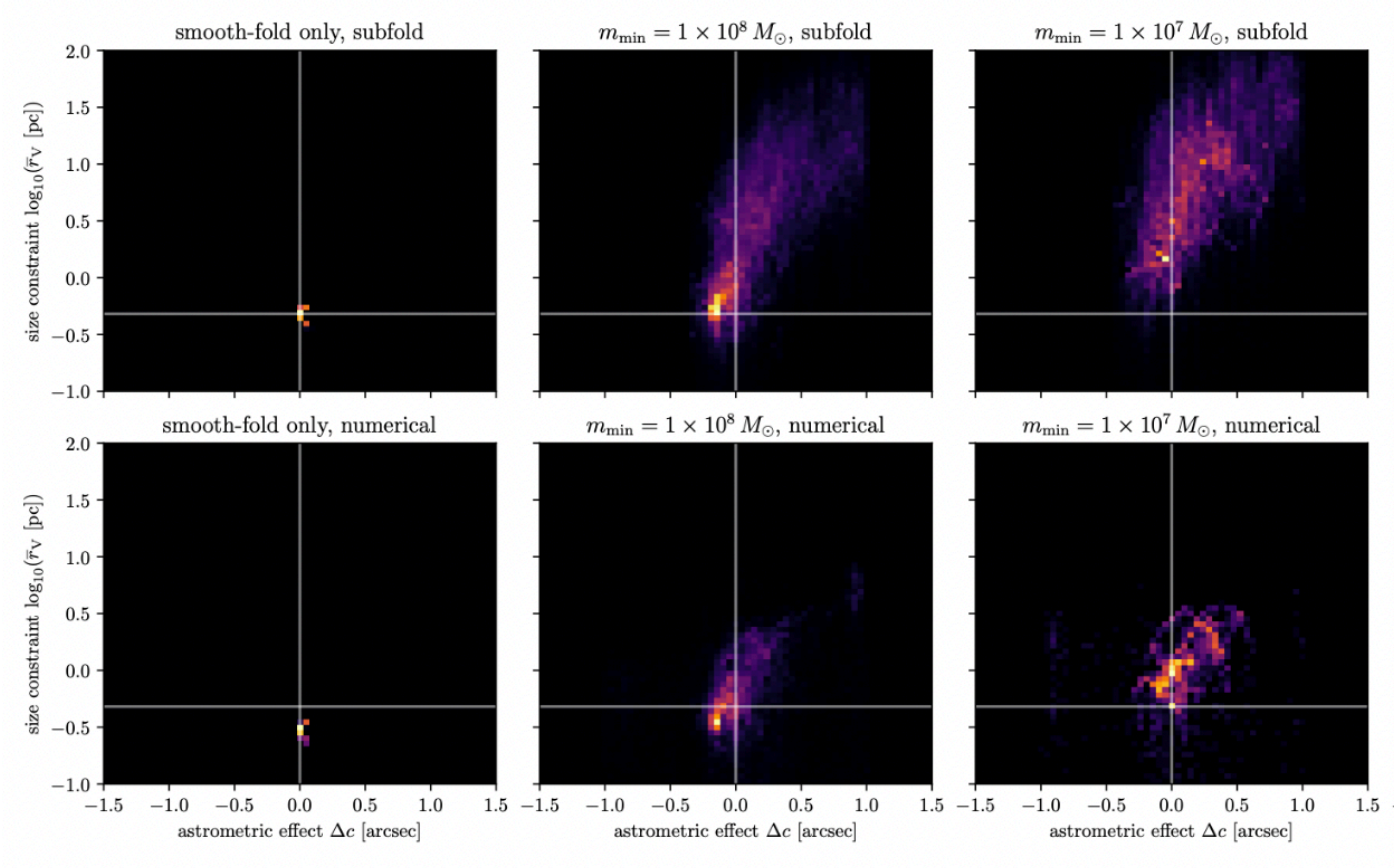
Source size constraint?

$$r_{\rm S} \lesssim \mathcal{R}^2 D_{\rm S} \left| \boldsymbol{d}^{\boldsymbol{0}} \cdot \boldsymbol{e}^{\boldsymbol{0}}_{\parallel} \right|$$

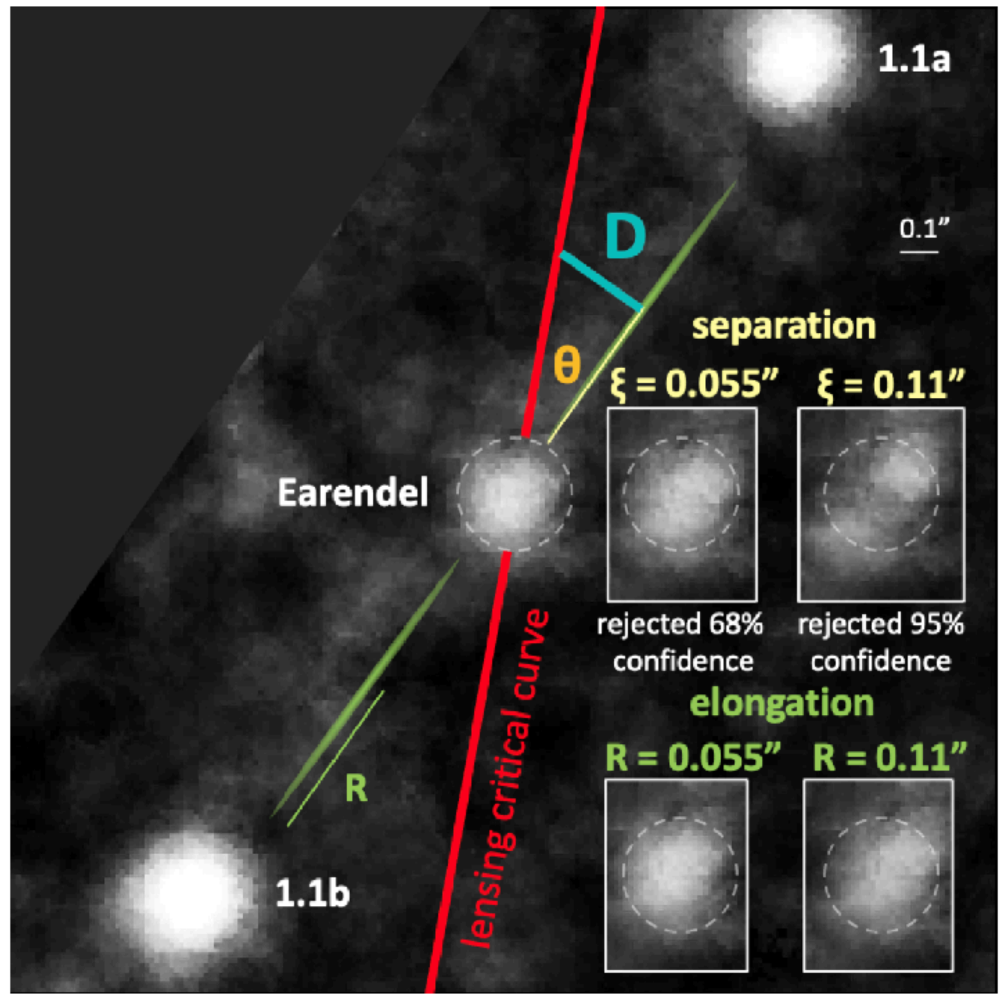
caustic strength weakens by nearby perturbing subhalos
(Inverse angle increases)

Effect of subhalos: size constraint and astrometric shift

size constraint



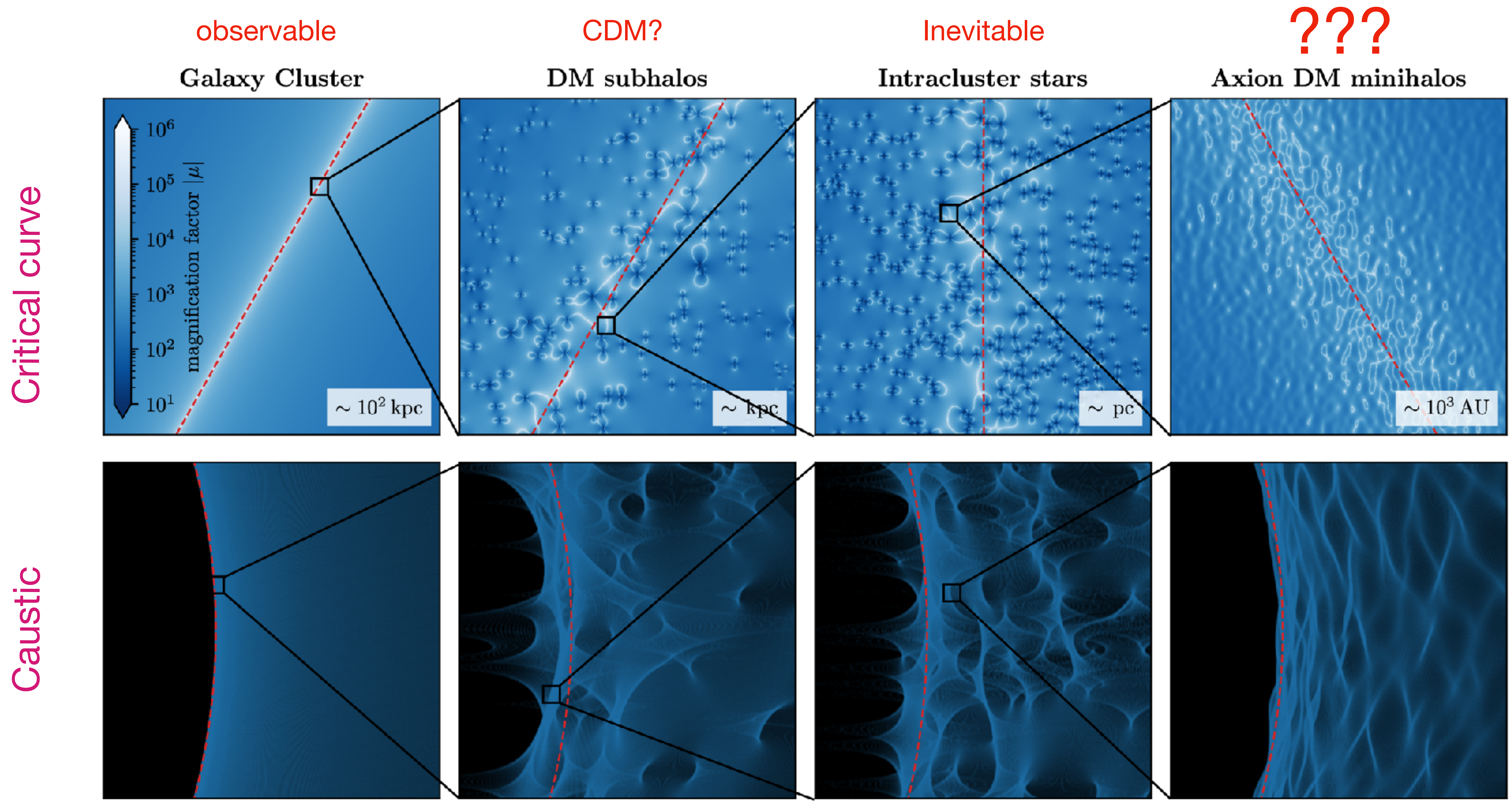
Astrometric departure from "midpoint"



Source size constraint loses by (3—10) x: < 0.3—3 pc

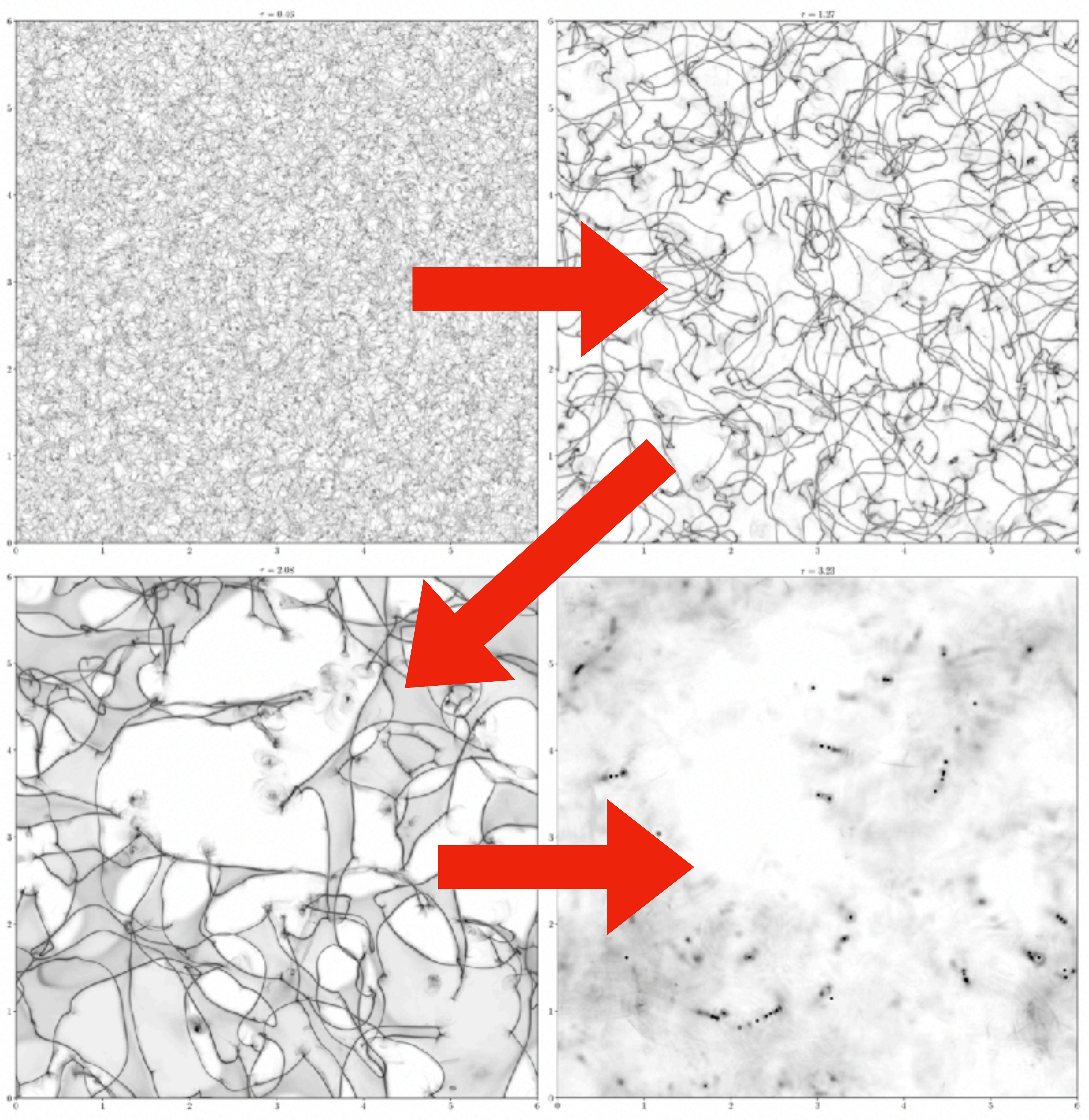
Compact star cluster remains a possibility

Hierarchy of caustic structures

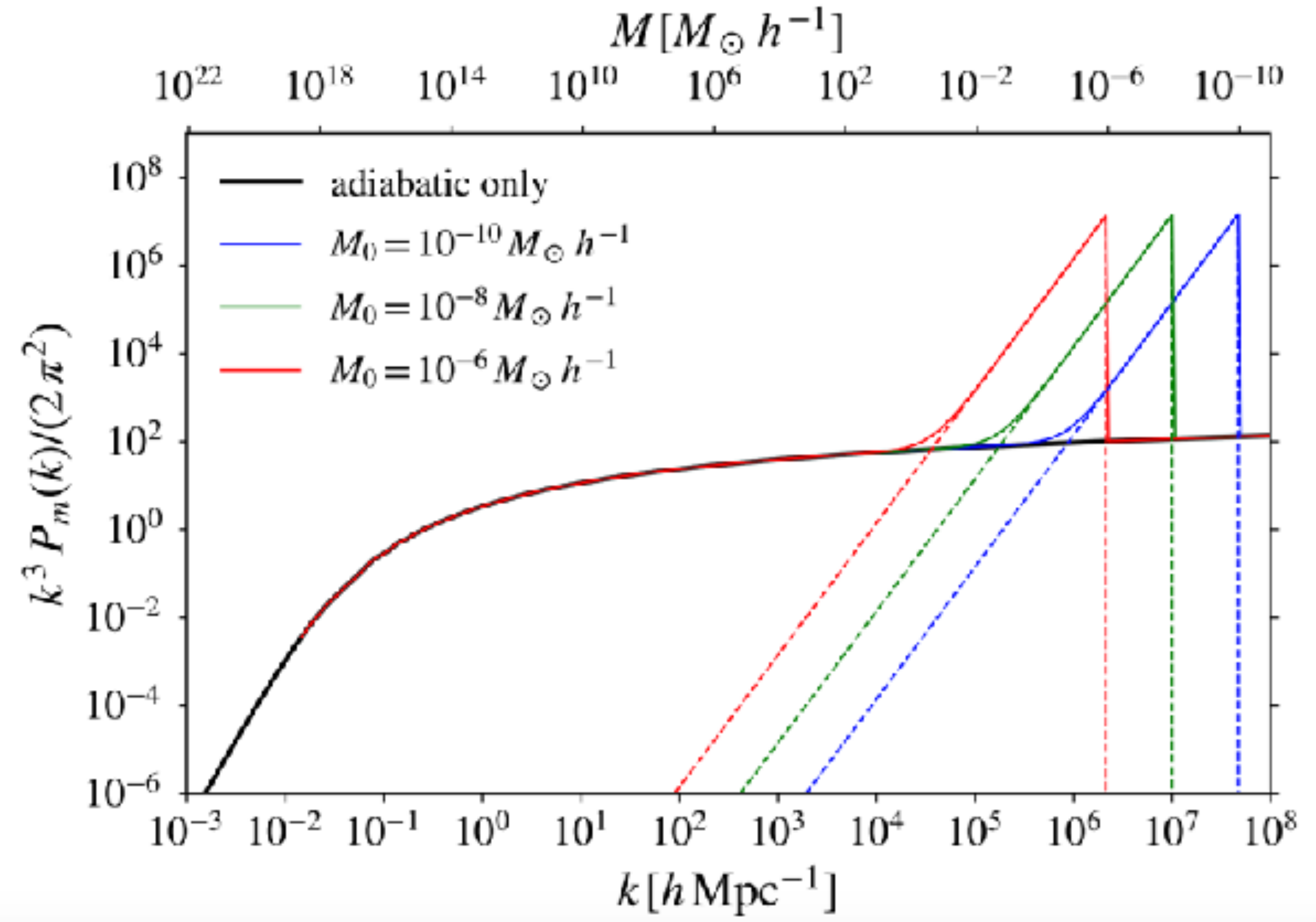


QCD axion DM: Peccei-Quinn phase transition after inflation

Vaquero, Redondo & Stadler (2019)



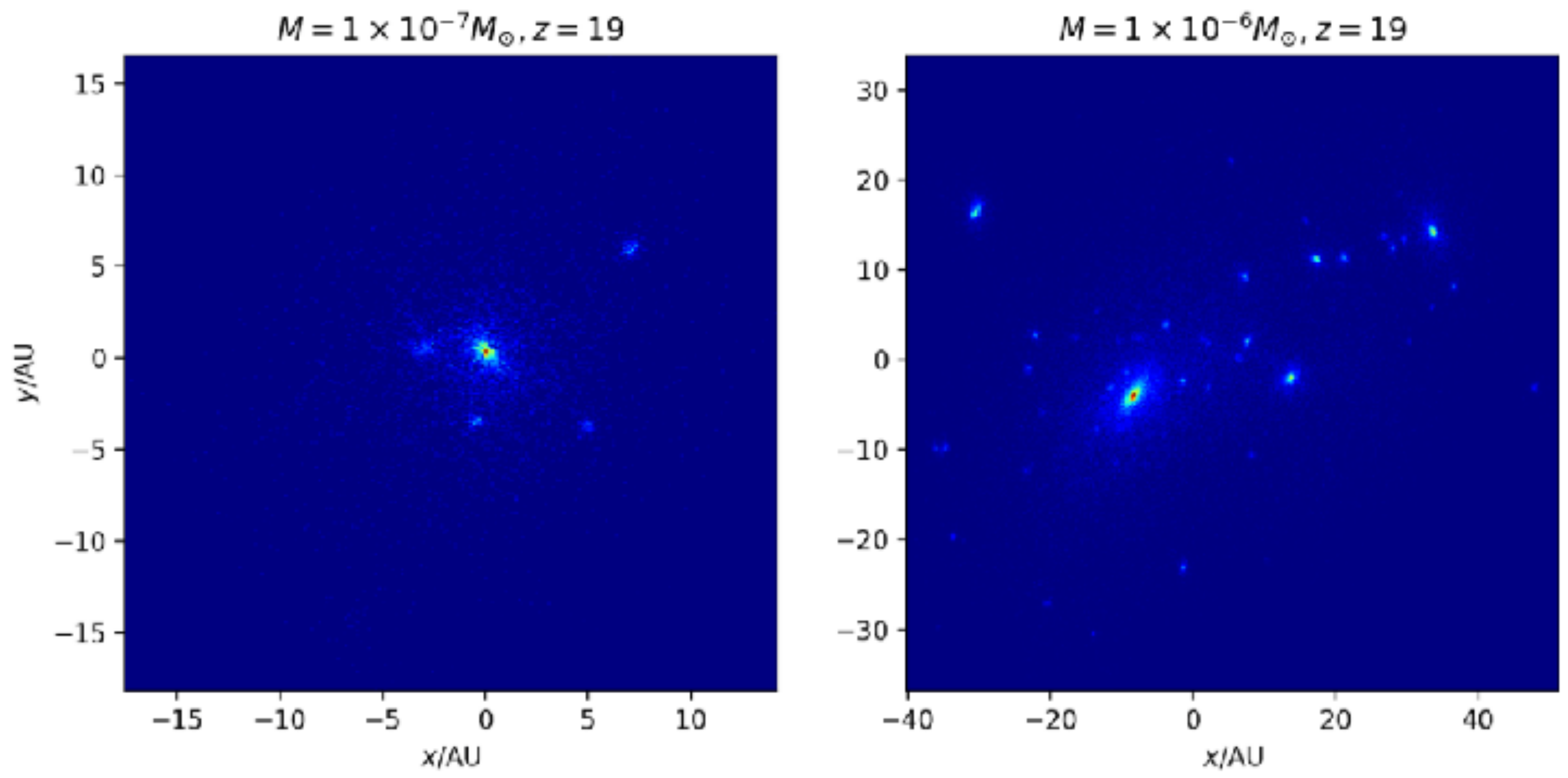
Isocurvature initial density fluctuations



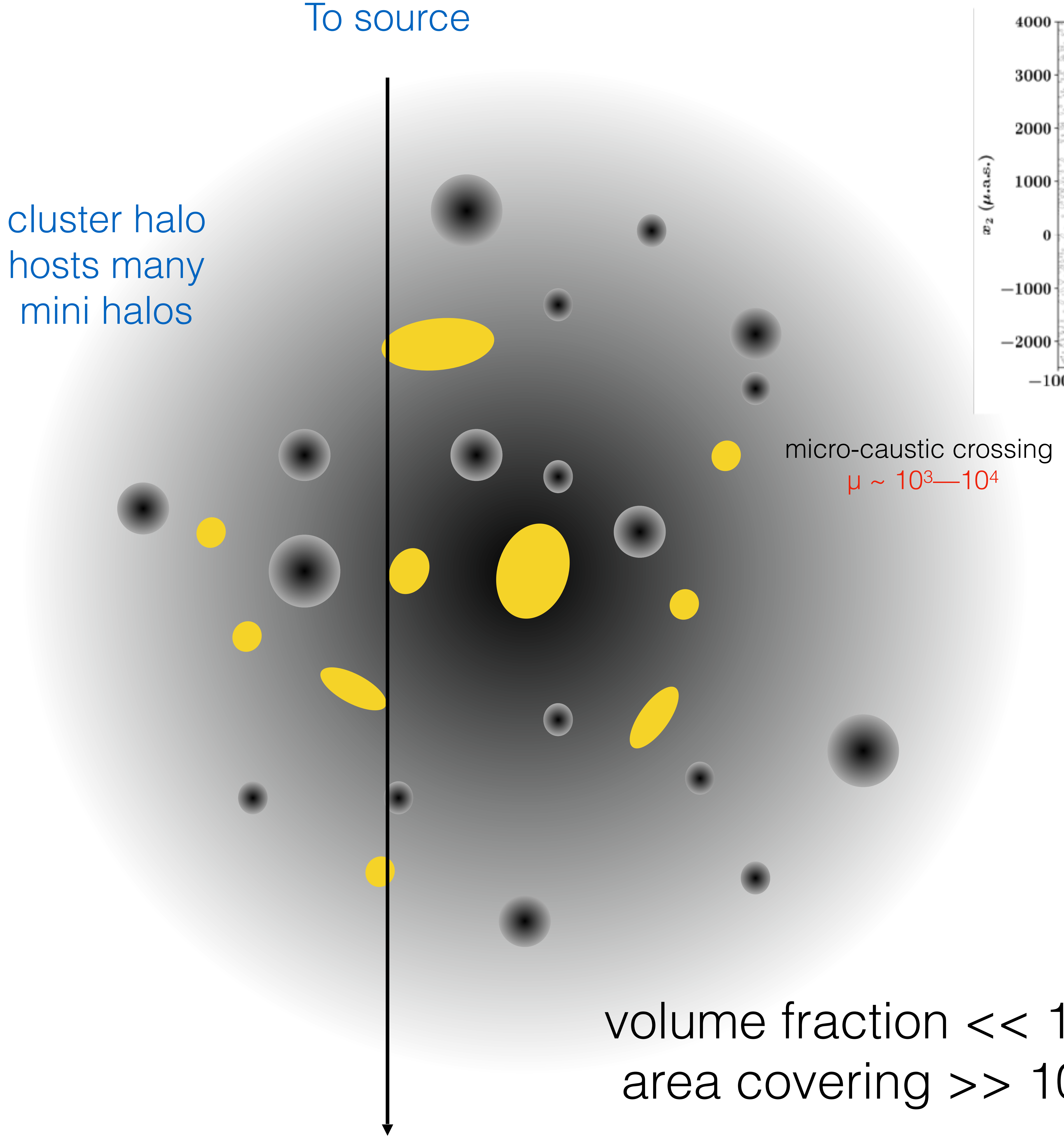
Hogan & Rees 1988
Kolb & Tkachev 1994

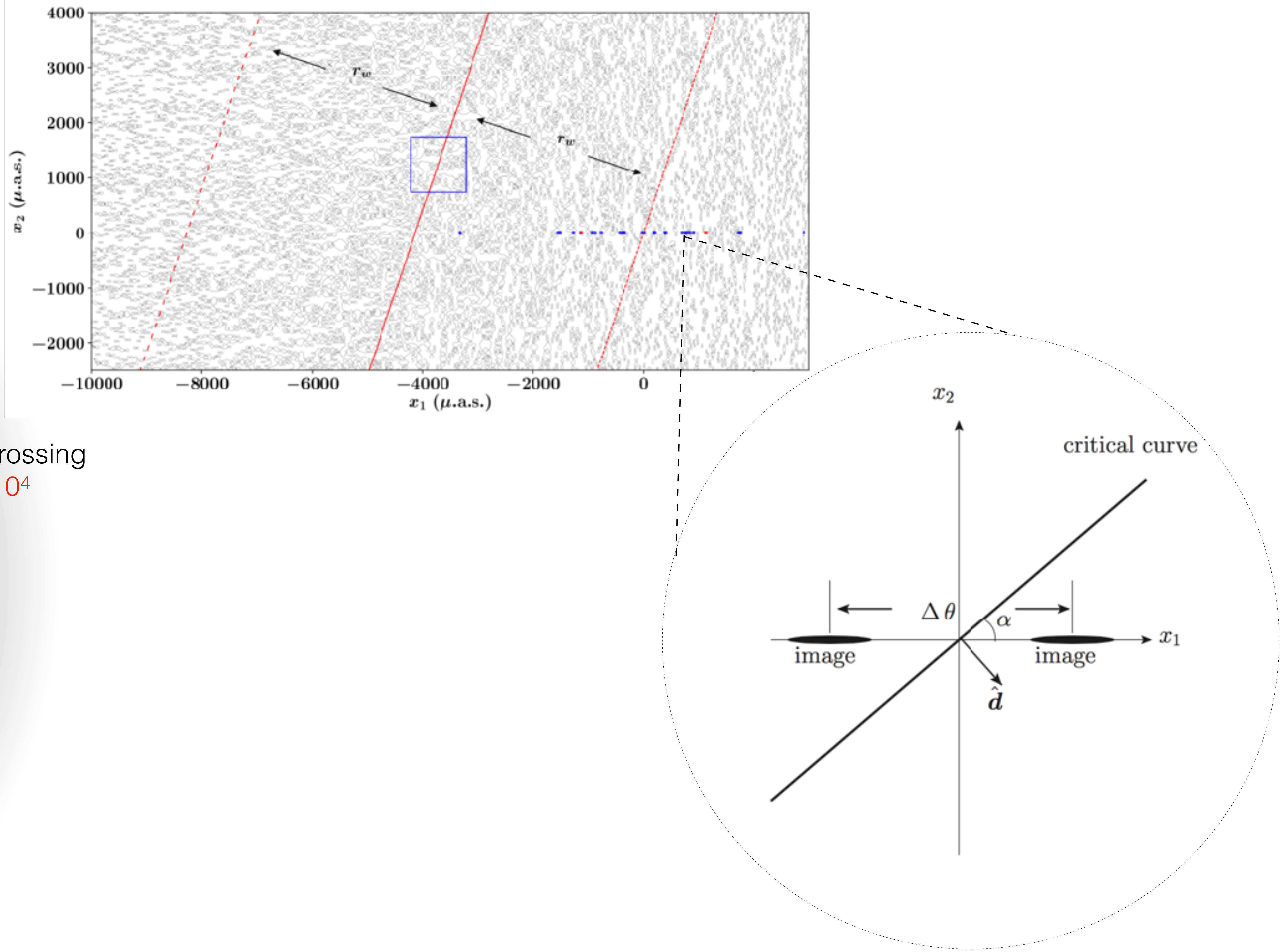
LD & Miralda-Escudé (2020)

Axion minihalos: collapse after z=3400, solar system sized, asteroid to planet masses Xiao, Williams & McQuinn (2021)



Collective lensing effect of many minihalos (in projection)



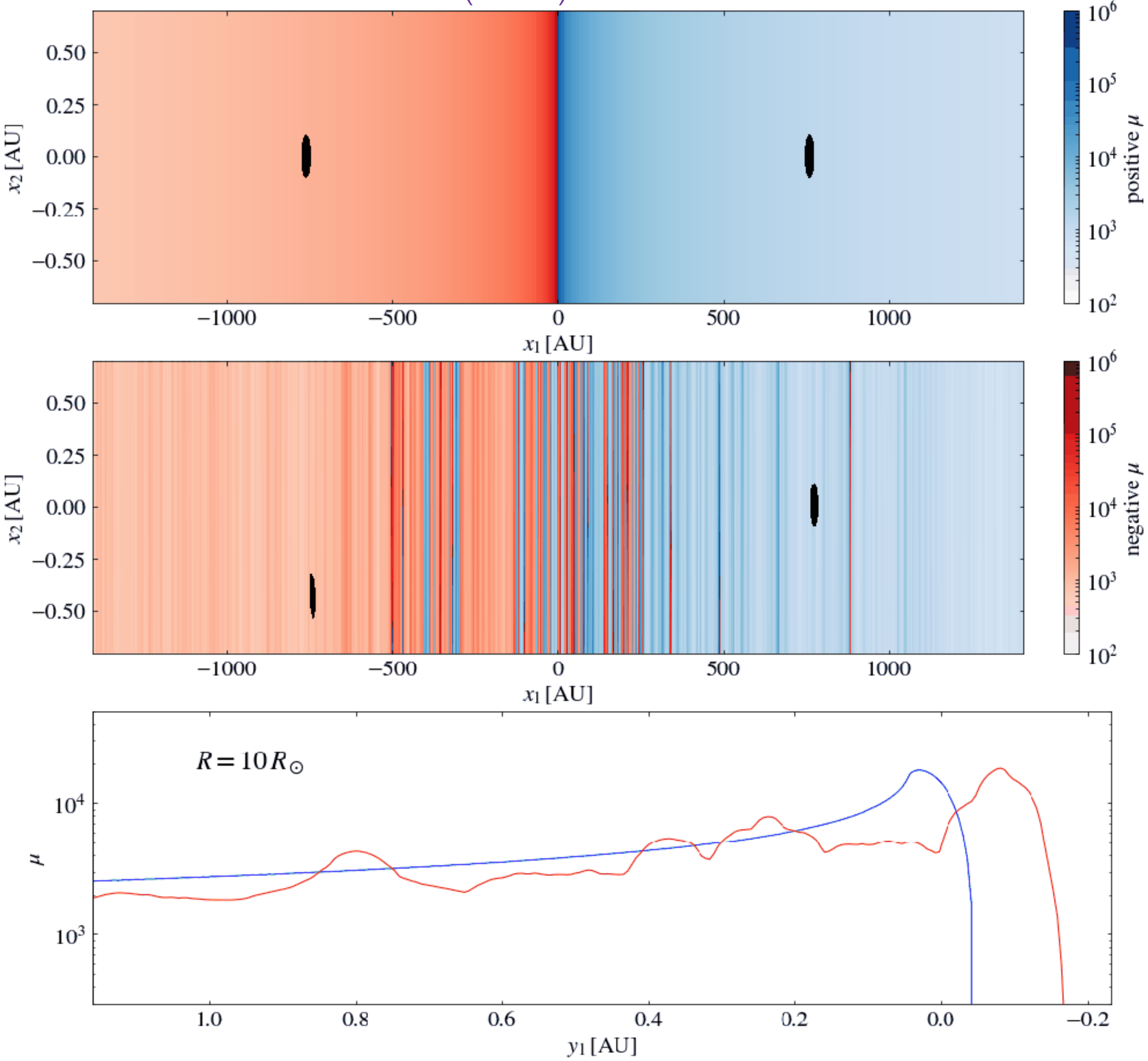


volume fraction << 100%
area covering >> 100%

Lens surface density unsmooth:
Fractional fluctuation: 0.01—0.1%
Projected scale: 100—10000 AU

Signature: Irregular Lightcurve Variability

LD & Miralda-Escudé (2020)



Without small-scale surface density fluctuations

With small-scale surface density fluctuations (axion mini halos)

Summary

Highly magnified extragalactic stars arise in caustic crossing lensed galaxies. They are often very massive stars and have been individually detected by space telescopes through deep imaging. The number of detections rapidly grows toward a magnitude limit ~ 29-30

Highly magnified stars repeatedly cross micro caustics cast by intracluster stars. This renders each one of them a recurrent transient. Micro caustic crossings can enable measurement of stellar properties including surface rotation.

Highly magnified stars can be used to probe a population of sub-galactic dark matter halos (10^6–10^8 Msun) predicted in the CDM theory.

High cadence deep lightcurve measurements can uniquely enable us to discover or constrain tiny dark matter clumpy structures on minuscule length scales, with important candidates being the minihalos made of the QCD axion.