Title: Stars under Einsteinâ€™s microscope: strong gravitational lensing near caustics

Speakers: Liang Dai

Series: Colloquium

Date: March 27, 2024 - 2:00 PM

URL: https://pirsa.org/24030119

Abstract: Rich clusters of galaxies are the largest gravitational magnifiers in the Universe. One of the most interesting gravitational lensing phenomena arises when background galaxies overlap with the lensing caustics cast by the cluster lens, such that a portion of it is tremendously magnified by hundreds to even thousands fold. As a result, Nature's most luminous classes of stars have been individually or collectively detected by space telescopes from cosmological distances. Quantitatively studying their behavior will enable us to probe an impressive hierarchy of fine mass structures inside the lens: from star-free sub-galactic cold dark matter halos, to intracluster stars, and to even minuscule dark matter clumps predicted in many of the particle physics models of the dark matter. I will talk about what we have theoretically understood about the extremely magnified stars, what latest observational advances there are, and what unique constraints on dark matter micro-structures can be derived.

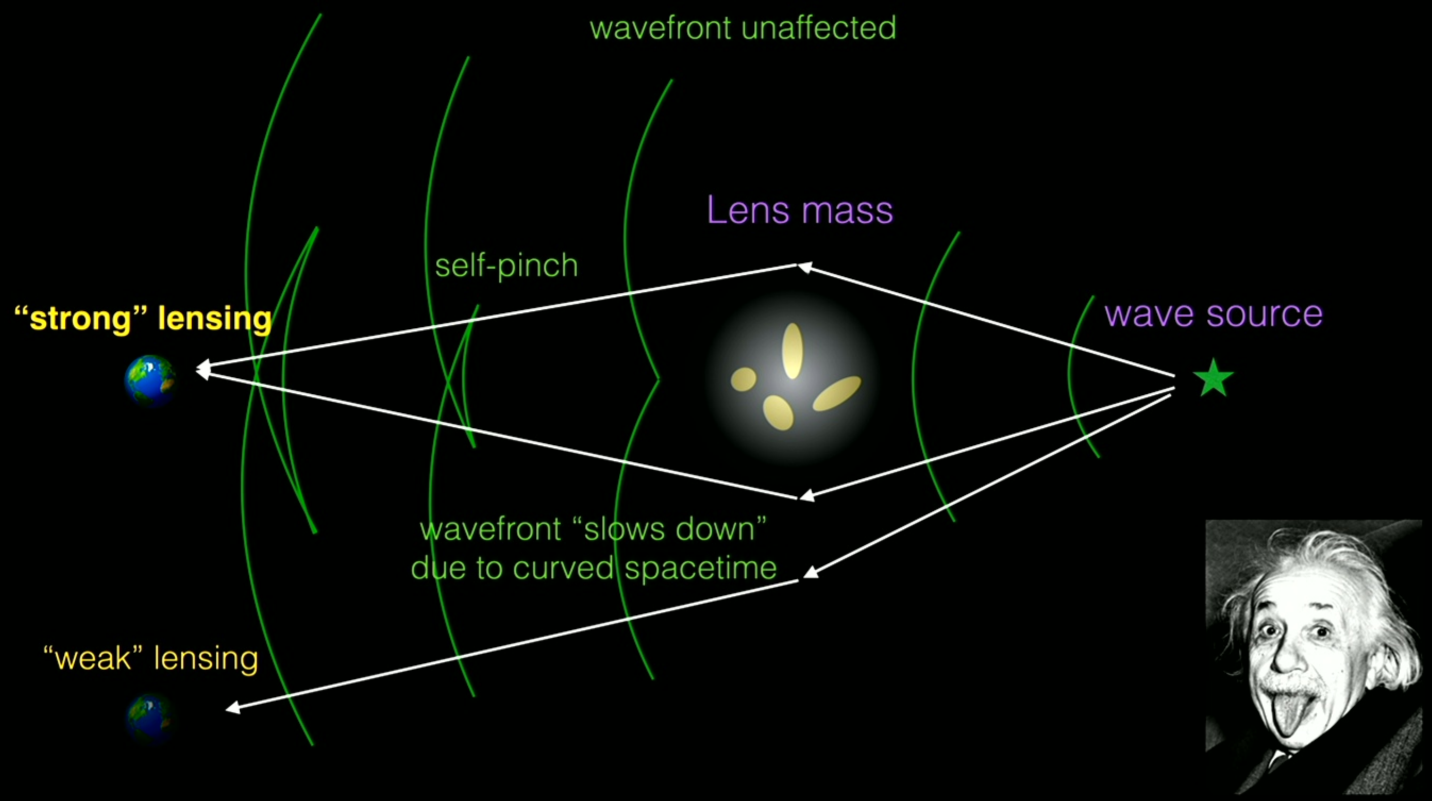
Zoom link

Stars Under Einstein's Microscope: Strong Gravitational Lensing Near Caustics

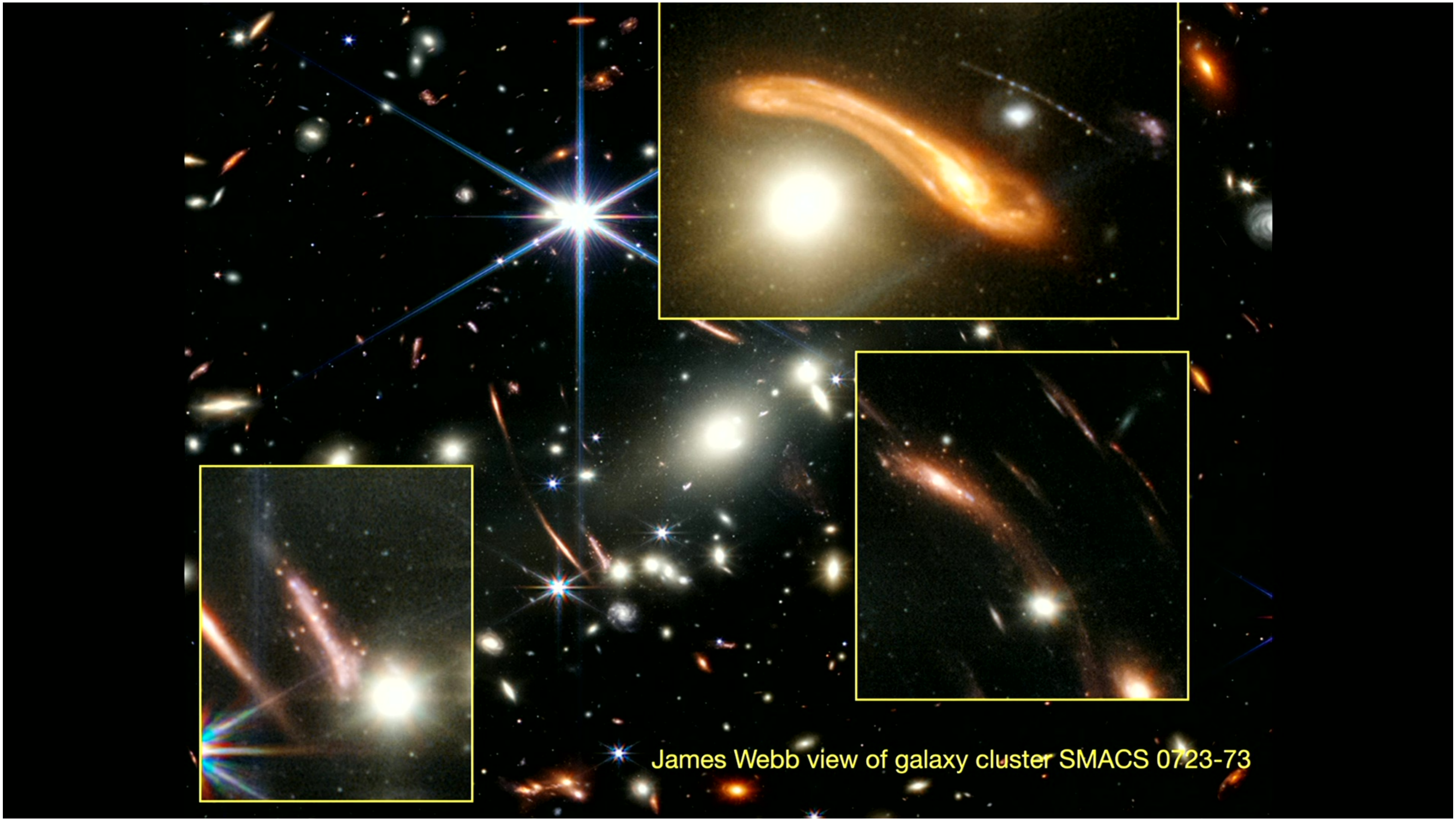
Liang Dai (UCB)

Perimeter Institute Colloquium
March 2024

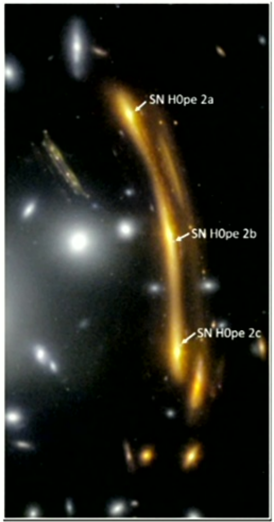
Gravitational Lensing




James Webb view of galaxy cluster SMACS 0723-73


James Webb view of galaxy cluster SMACS 0723-73

Rich Science of Cluster Lensing Fields



Measure **cosmic expansion** by timing strongly lensed SNe

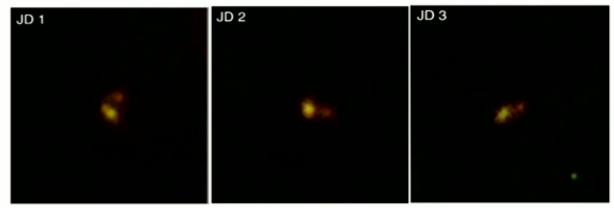
e.g. Frye++ (2023)

Type Ia SN H0pe (standard candel) at z=1.78
3 lensed images

Detect and resolve ancient galaxies at **Cosmic Dawn** (z>8)

A primordial galaxy at z=11;
Two components ~ 70 pc and ~ 20 pc

e.g. Hsiao++ (2023)



Reveal **extreme star formation** at Cosmic Noon (z~2–4)

Chemical enrichment from stellar winds and SNe

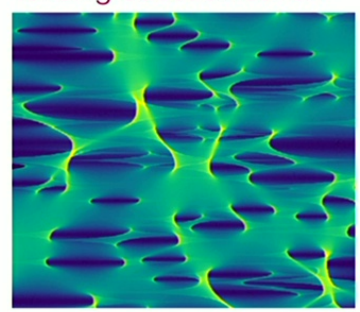
Gas condensation and retention and formation of "2nd gen." stars?

Pascale, LD, McKee & Tsang (2023)
Pascale, LD & McKee (in prep)

Extragalactic **extremely magnified stars**

- Study individual massive stars in young universe
- Probe dark matter substructures

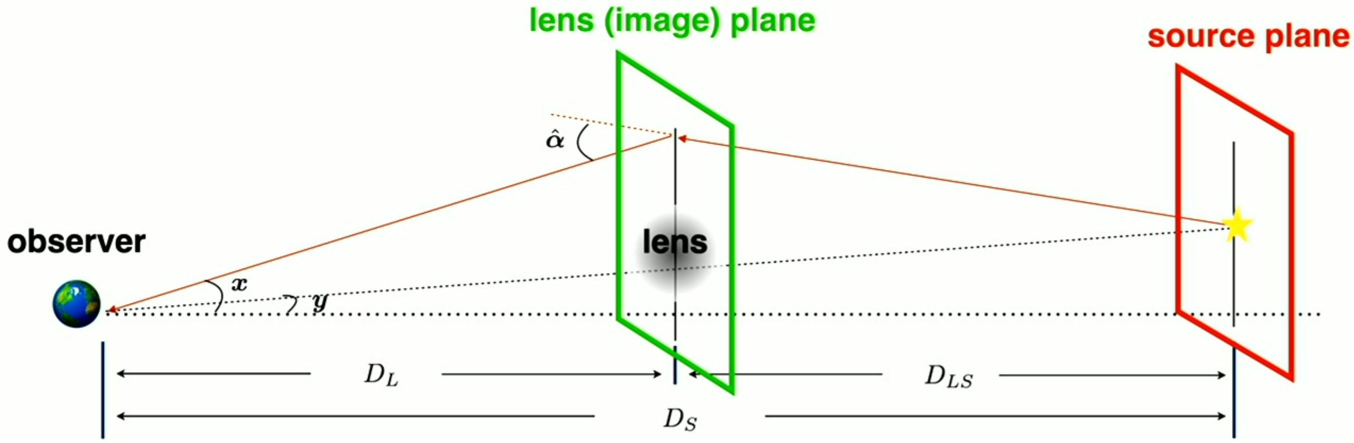
lensing caustic network



Outline

- Introduction: geometric lensing, caustic and critical curves
- Highly magnified stars seen in galaxy cluster lensing
- Microlensing effects of intracluster stars
- Effects of sub-galactic dark matter subhalos
- Effects of dark matter micro-structures (?)

Geometrical Lensing



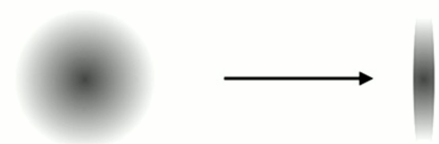
Ray equation $\boldsymbol{y} = \boldsymbol{x} - \boldsymbol{\alpha}(\boldsymbol{x})$

Ray bundle deformation

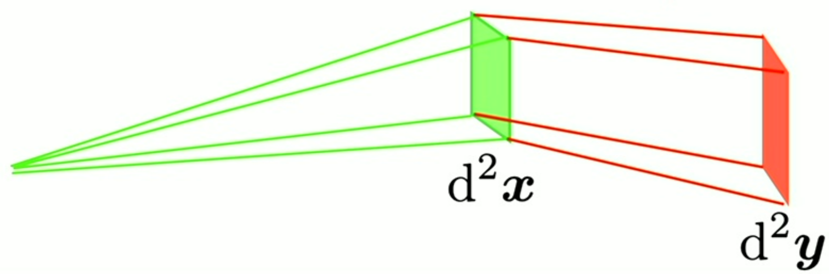
$$\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}} = \begin{bmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{bmatrix}$$

κ **convergence**

$\gamma_1,\ \gamma_2$ **shear**



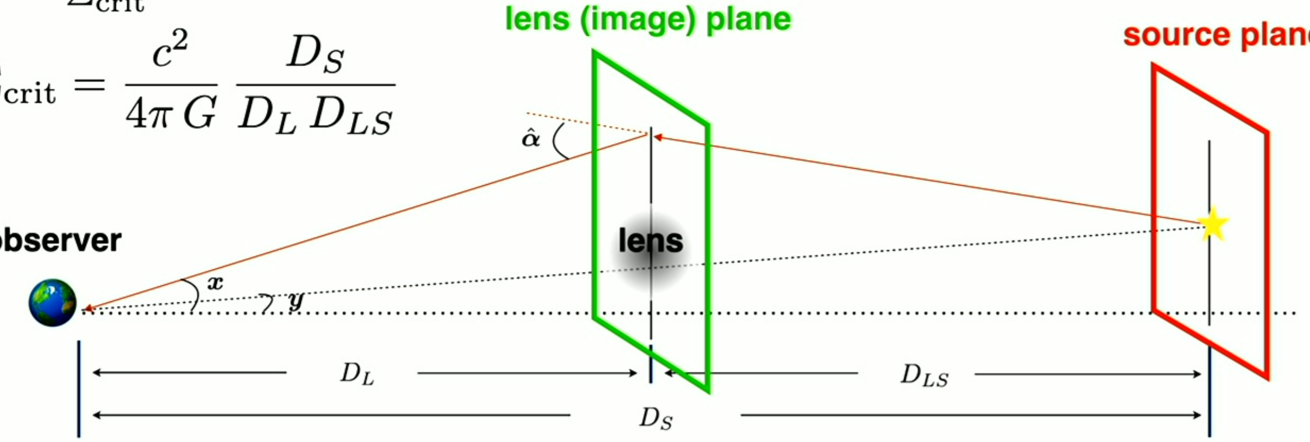
Lens surface mass density matters



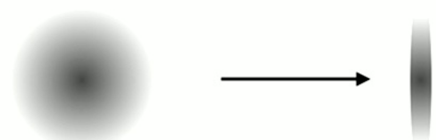
Geometrical Lensing

$$\kappa = \frac{\Sigma}{\Sigma_{\rm crit}}$$

$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_S}{D_L\,D_{LS}}$$



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



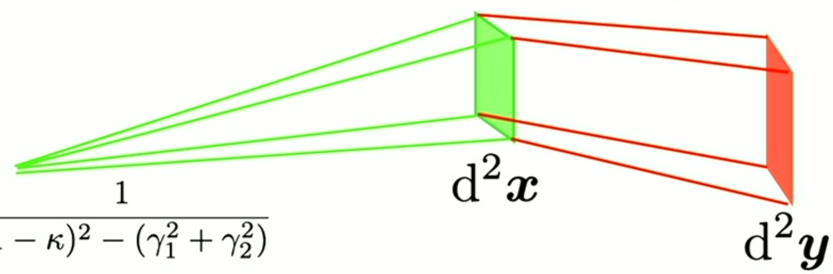
Ray bundle deformation

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

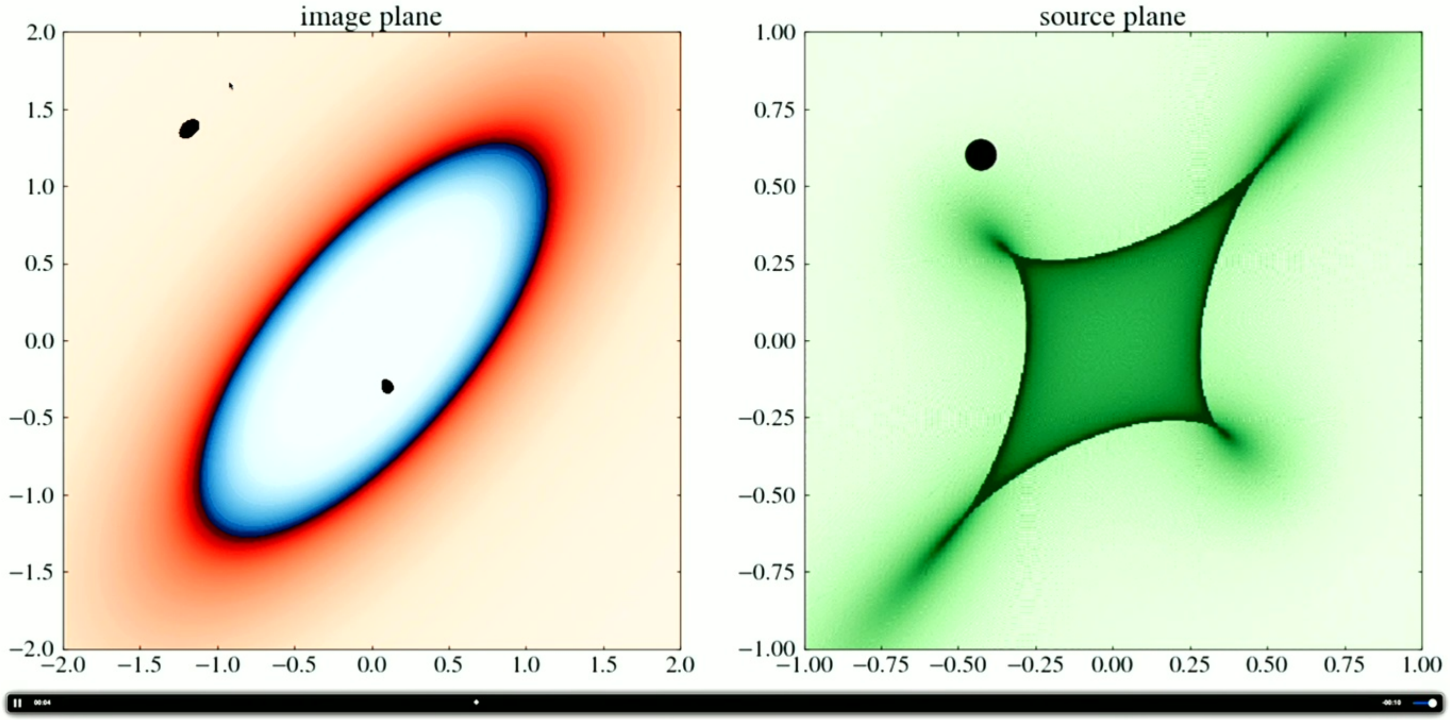
Lens surface mass density matters

$\kappa(\boldsymbol{x})$ **convergence**

$\gamma_1(\boldsymbol{x}),\ \gamma_2(\boldsymbol{x})$ **shear**



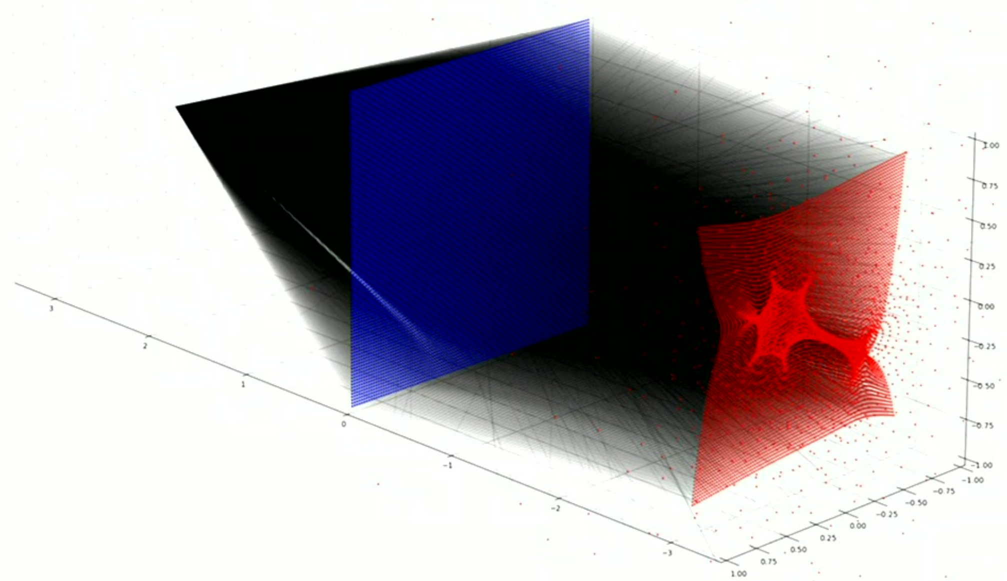
magnification factor $\mu = \frac{d^2\boldsymbol{x}}{d^2\boldsymbol{y}} = \frac{1}{(1-\kappa)^2 - (\gamma_1^2+\gamma_2^2)}$



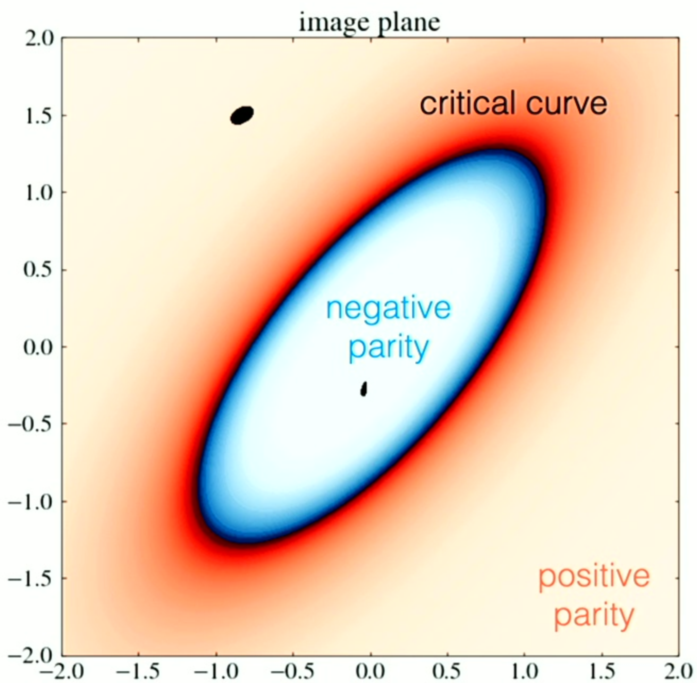
- Surface brightness conserved
- (De-)magnified source looks (smaller) bigger and (fainter) brighter
- Multiple images can form

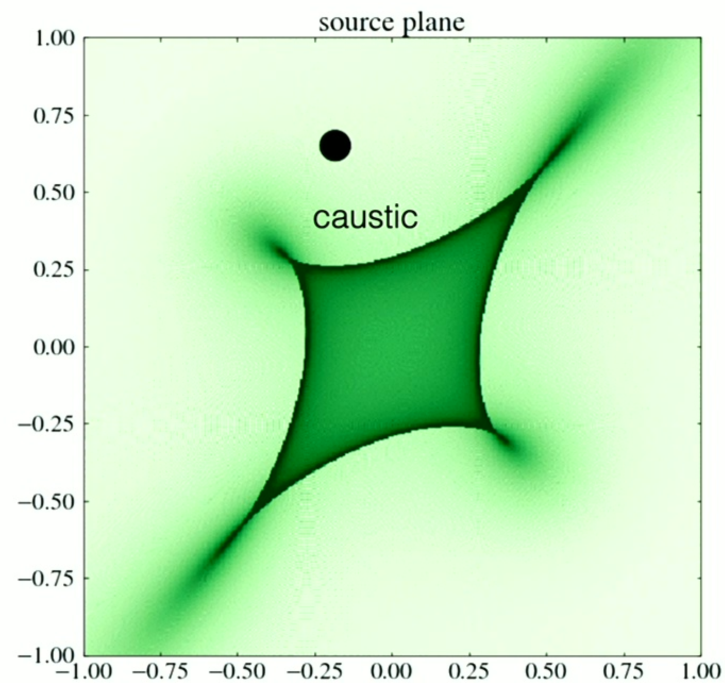
Caustics in a swimming pool

Caustic



Caustic and Critical Curve

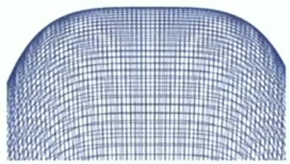




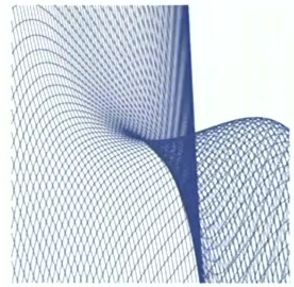
see Blandford & Narayan (1986)

Caustics in Catastrophe Theory

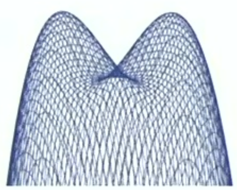
Catastrophe theory deals with **discontinuous transitions** between the states of a system given **smooth variation** of the underlying parameters.



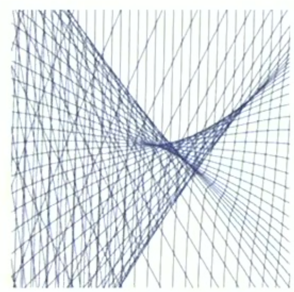
fold



cusp

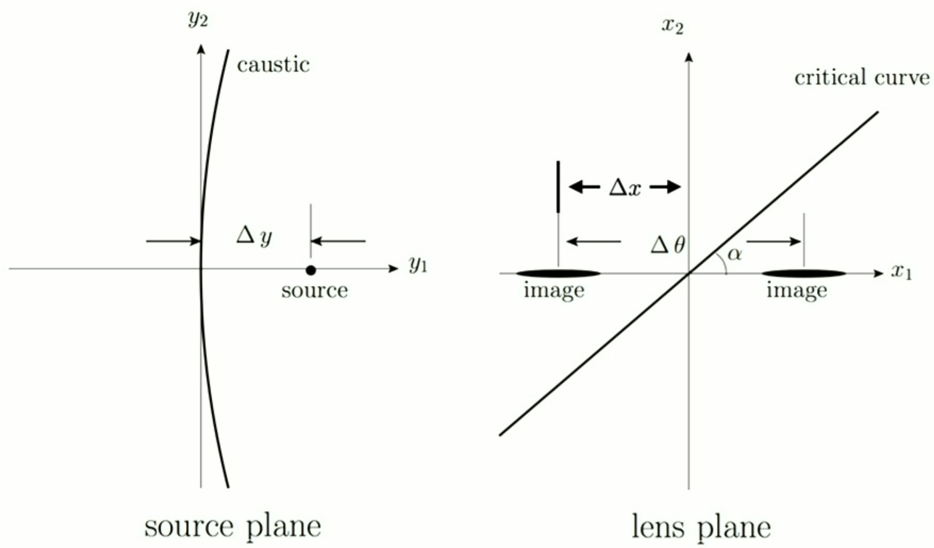


swallowtail



butterfly

Lensing near fold caustic



Perpendicular magnification (moderate)

$$\mu_\perp \sim [2\,(1-\kappa_0)]^{-1}$$

Parallel magnification

$$\mu_\parallel = 1/(d\,\sin\alpha\,\Delta x)$$

Total magnification

$$\mu = \mu_\parallel\,\mu_\perp$$

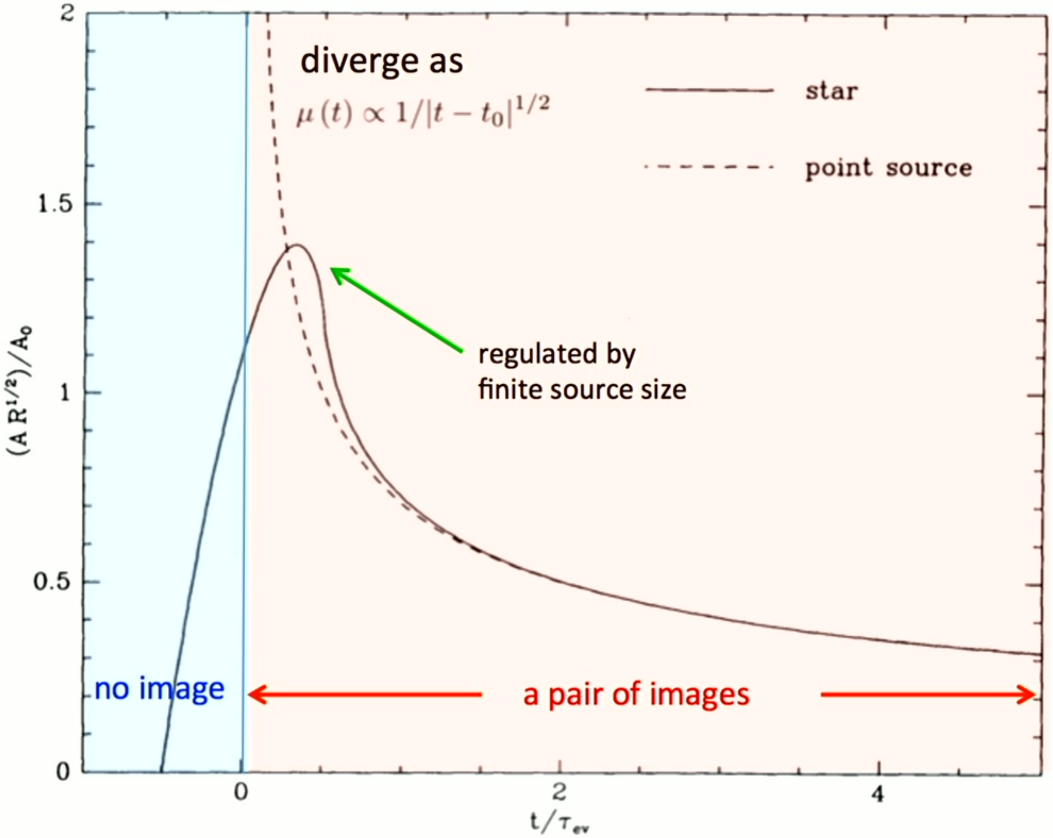
3 parameters:

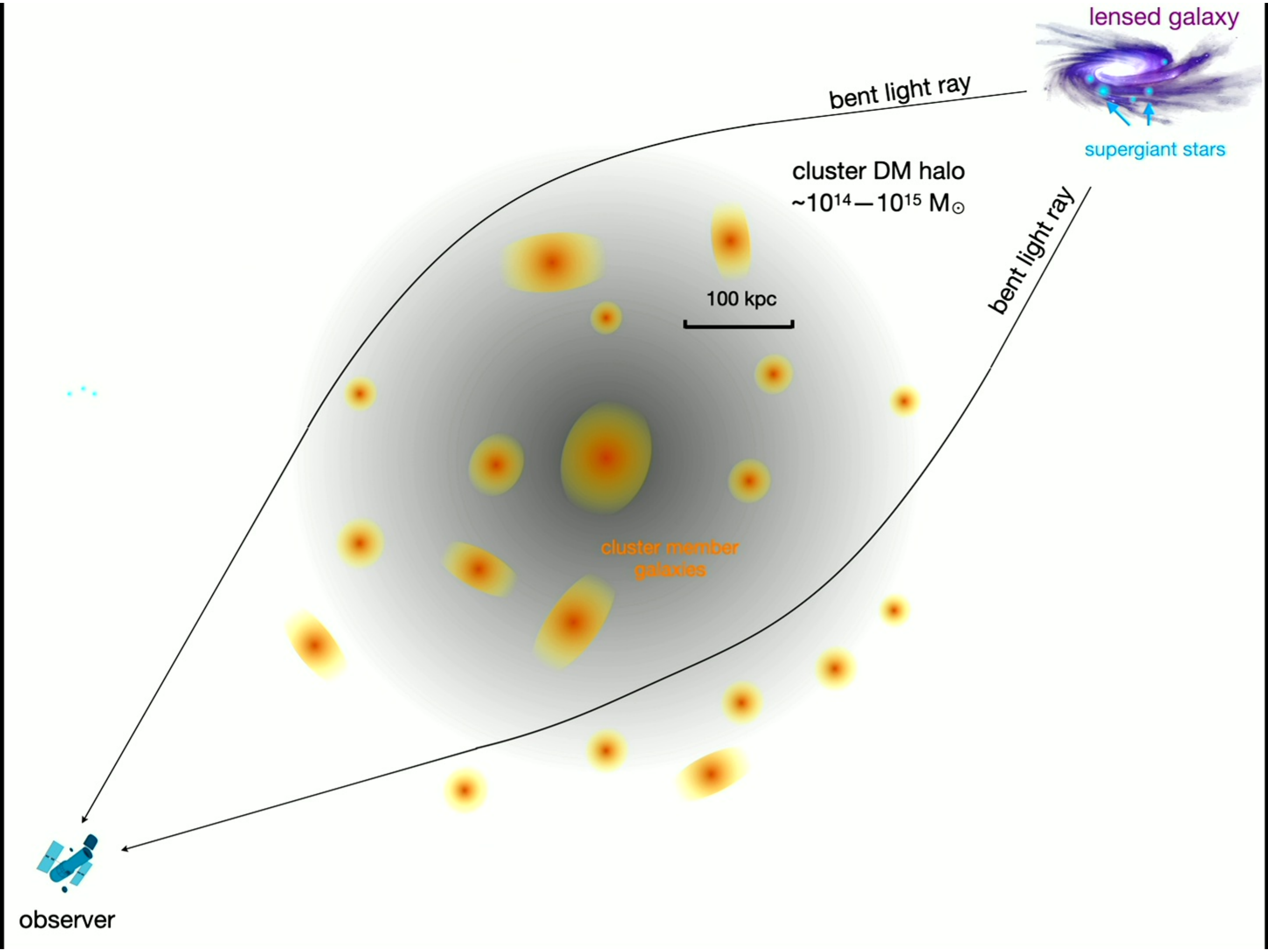
(1) local convergence κ_0
(2) 2nd derivative of deflection d
(3) angle α

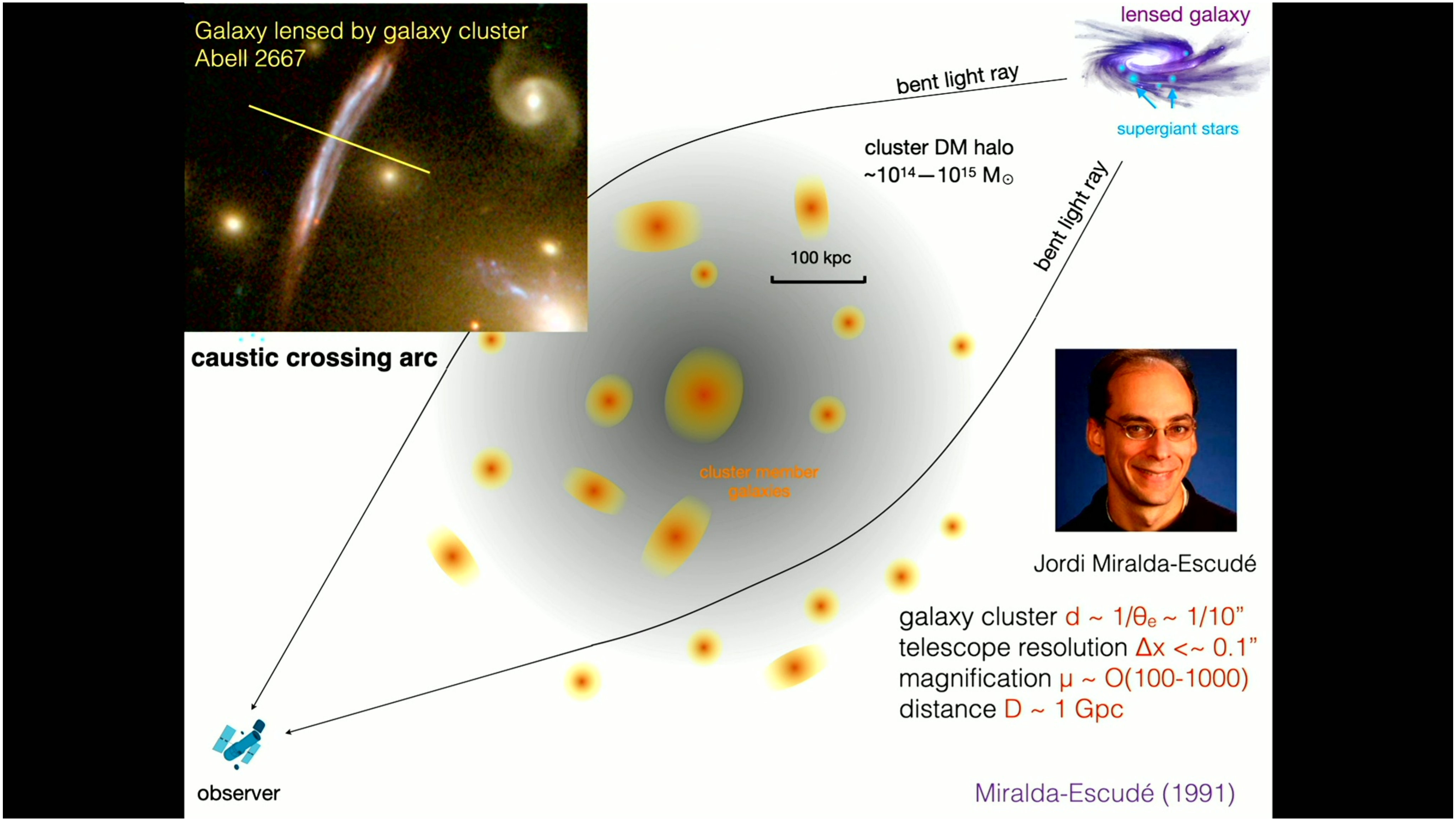
source plane region

$$\Delta y = \frac{1}{2}\,(d\,\sin\alpha)\,(\Delta x)^2 = \frac{\mu_\parallel^2}{2\,d\,\sin\alpha}$$

Source passing a fold

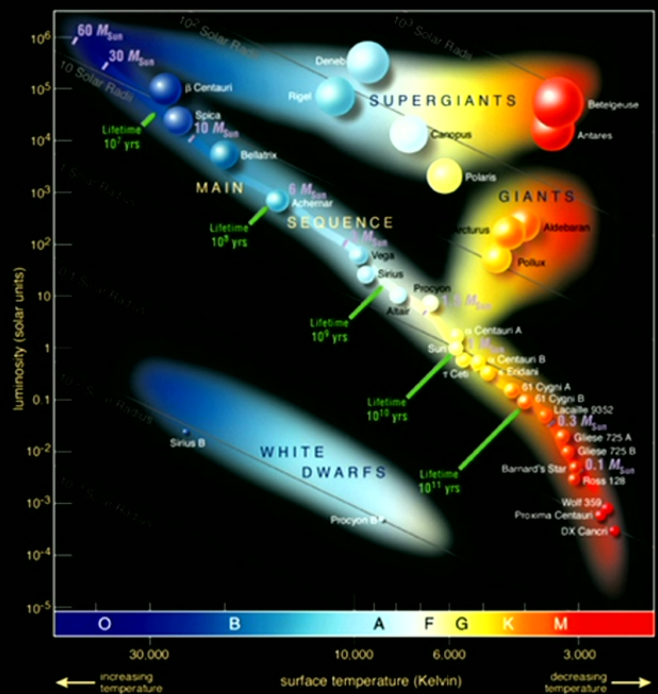



lensed galaxy
bent light ray
supergiant stars
cluster DM halo
~10¹⁴—10¹⁵ M☉
bent light ray
100 kpc
cluster member
galaxies
observer

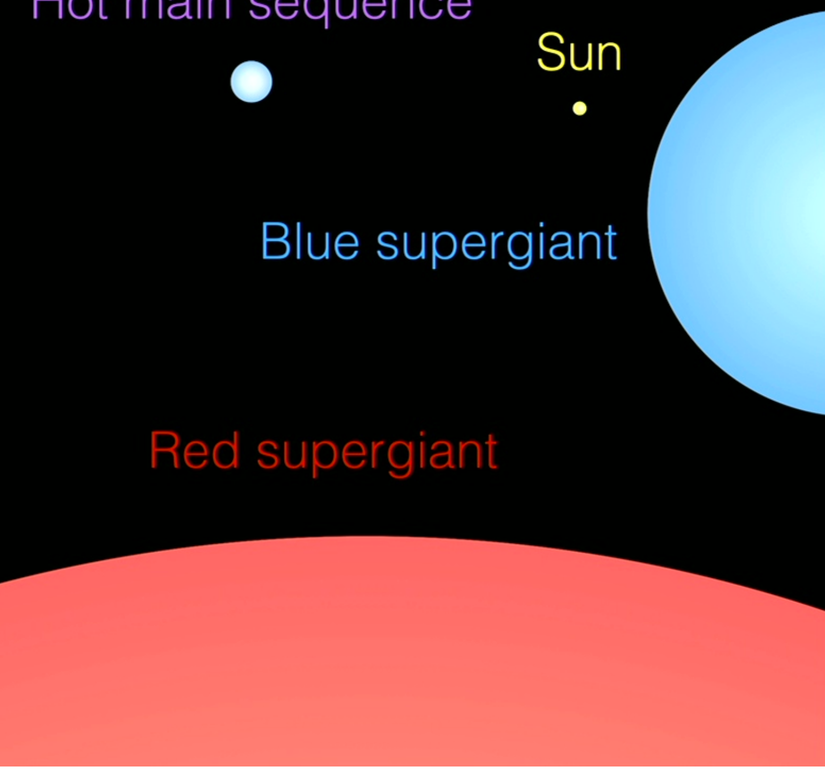


Galaxy lensed by galaxy cluster Abell 2667
caustic crossing arc
lensed galaxy
supergiant stars
bent light ray
bent light ray
cluster DM halo
~10¹⁴—10¹⁵ M☉
100 kpc
cluster member galaxies
Jordi Miralda-Escudé
galaxy cluster d ~ 1/θe ~ 1/10”
telescope resolution Δx <~ 0.1”
magnification μ ~ O(100-1000)
distance D ~ 1 Gpc
observer
Miralda-Escudé (1991)

What individual stars are sufficiently bright?

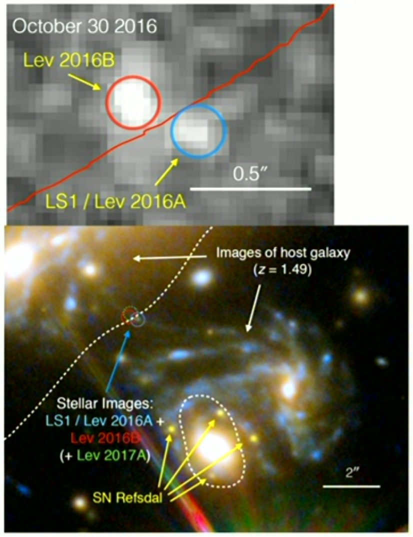


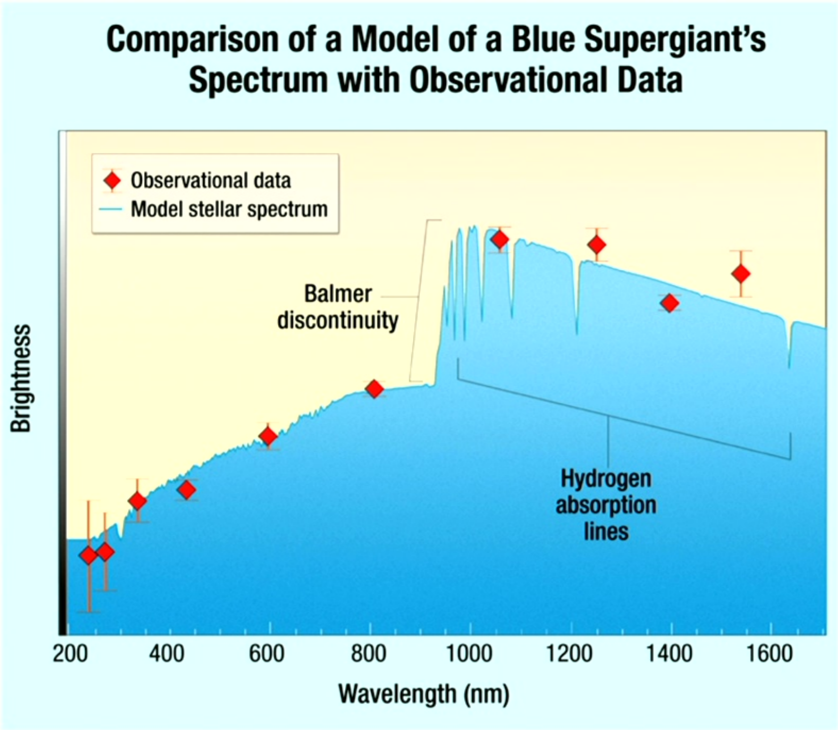
Need stars whose (bolometric) luminosity is ~$10^{5\text{-}6}$ Lsun



First discovery of highly magnified star

Kelly++ (2017)



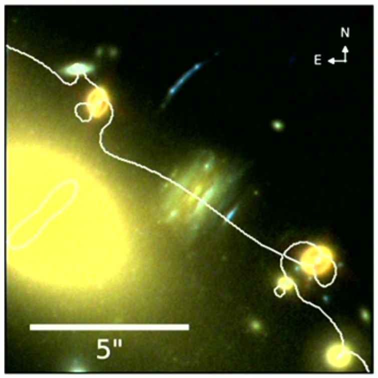


Blue supergiant
R ~ 100 R_sun
T = 11000 — 14000 K

More detections of highly magnified star

Chen++ (2019)

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



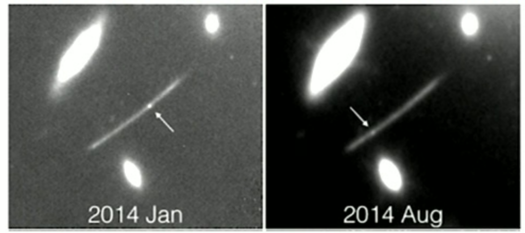
“Warhol”

lone image of Earendel
a star at z=6?

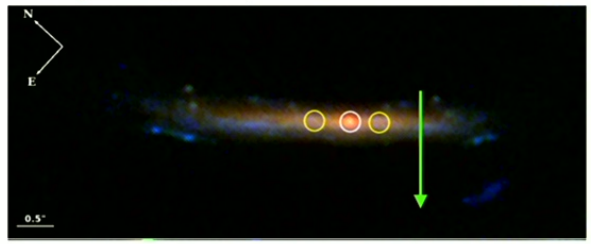
Welch++ (2022a)

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

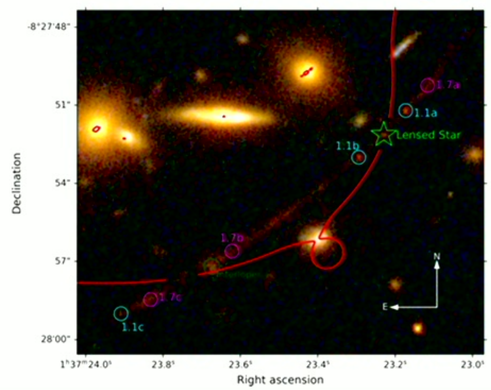
Rodney++ (2018) “Christmas Tree”

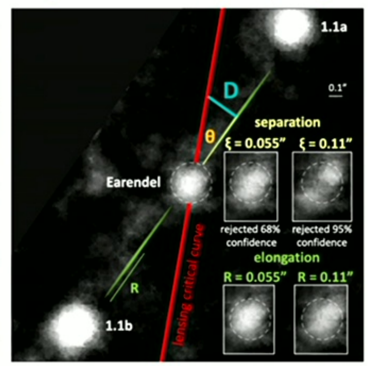


Diego++ (2022)



JWST observed the first highly magnified a red supergiant?



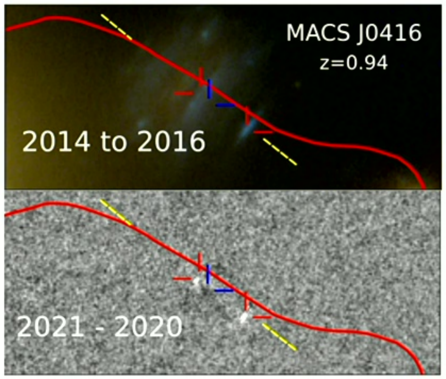


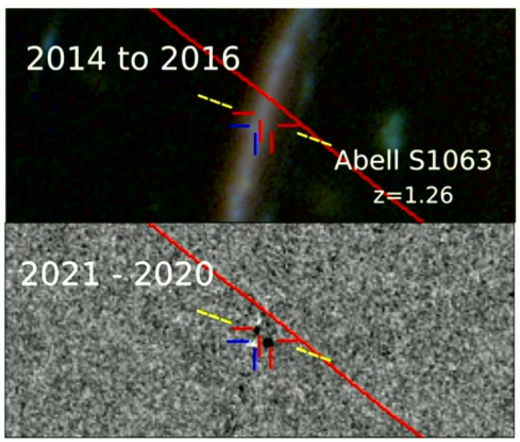
Flashlight program (PI: P. Kelly)

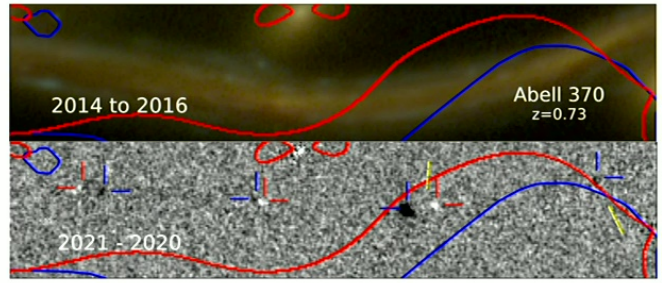
Kelly++ (2022)

~30 mag per epoch at 5σ

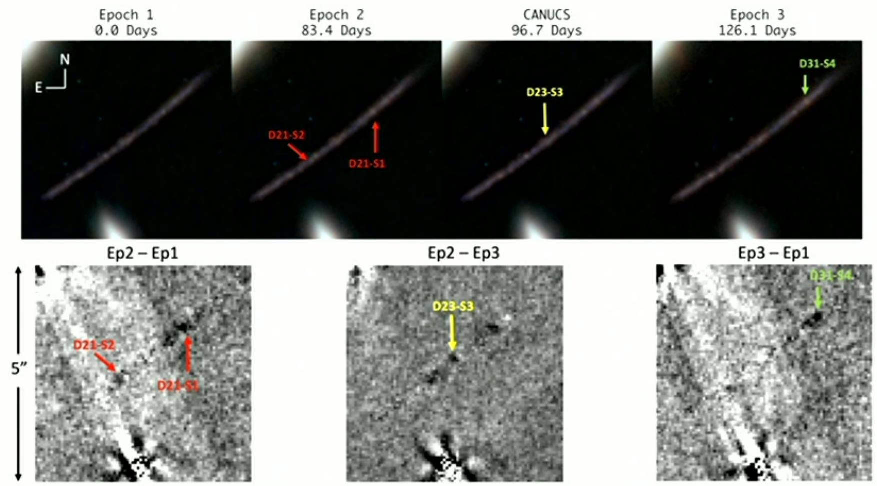
image difference technique

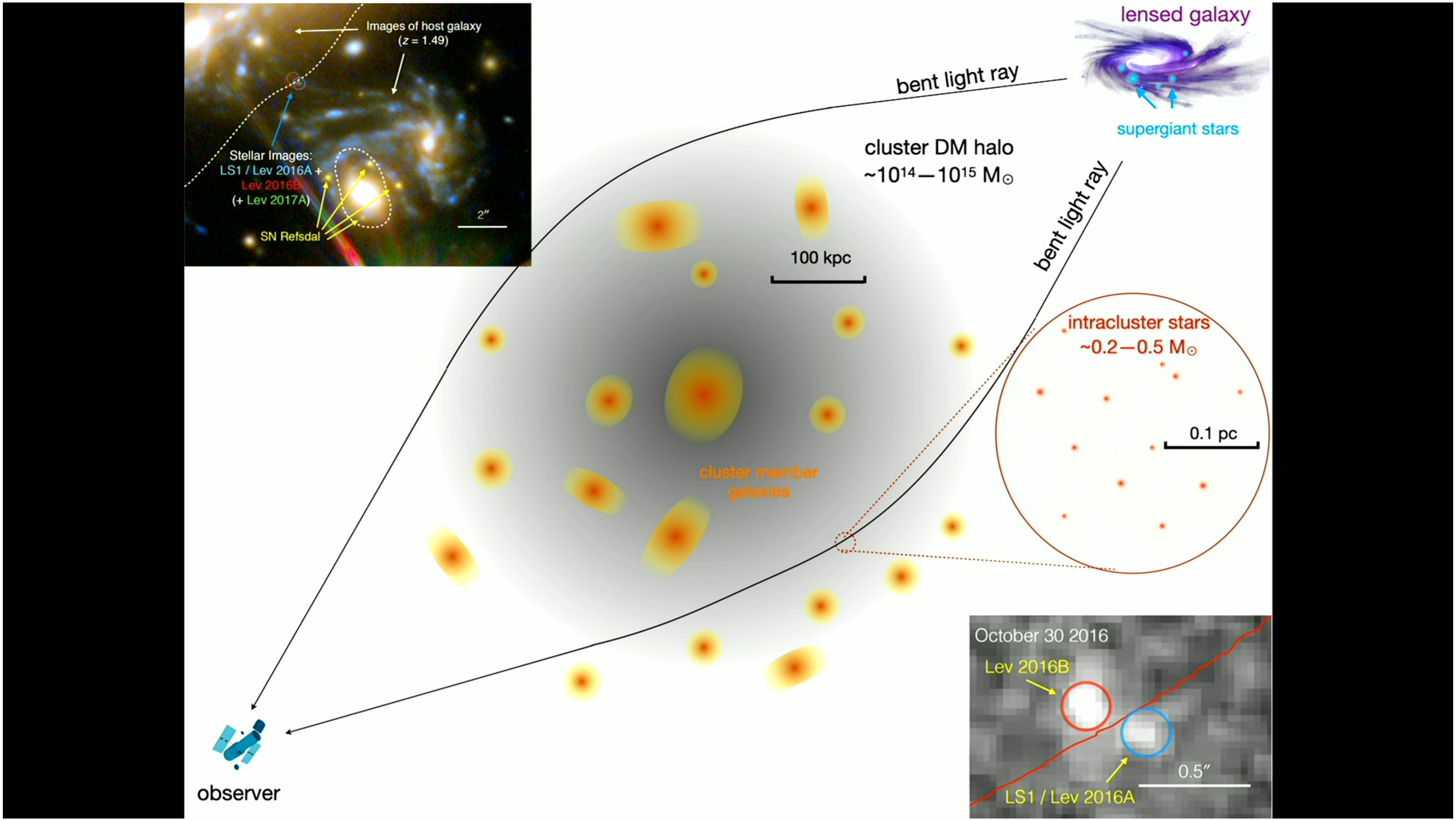






Yan++ (2023); JWST imaging

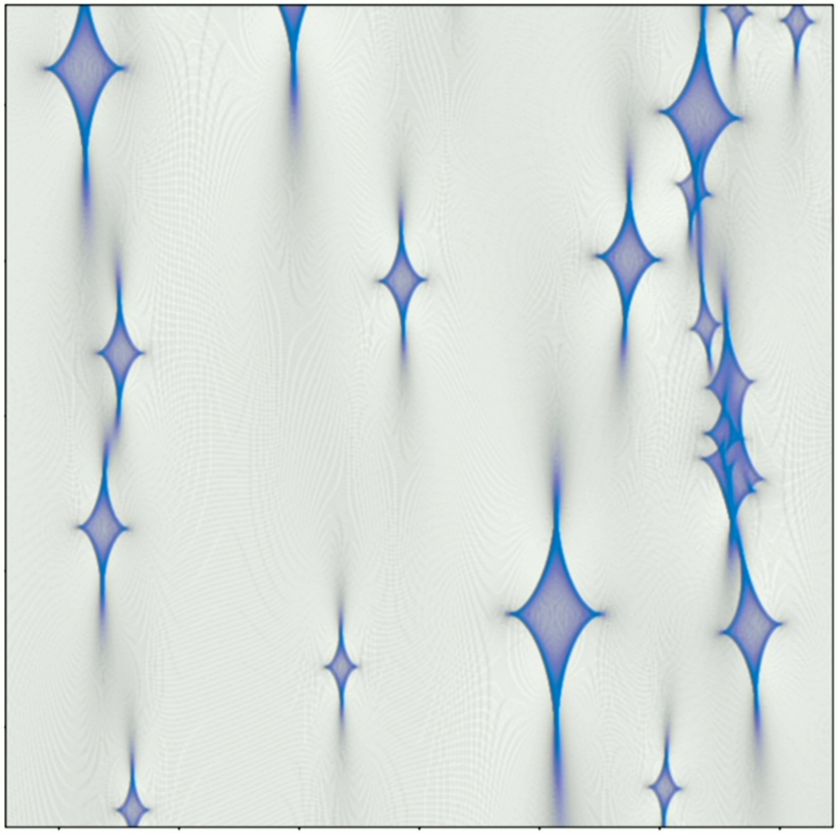




Images of host galaxy
(z = 1.49)
Stellar Images:
LS1 / Lev 2016A +
Lev 2016B
(+ Lev 2017A)
SN Refsdal
2″
lensed galaxy
supergiant stars
bent light ray
cluster DM halo
~10¹⁴—10¹⁵ M☉
bent light ray
100 kpc
intracluster stars
~0.2—0.5 M☉
0.1 pc
cluster member galaxies
October 30 2016
Lev 2016B
0.5″
LS1 / Lev 2016A
observer

Point-like microlenses

$\mu_B = 3,\ \kappa_\star = 0.03$ "optically thin"



Typical size of "diamond": Einstein radius

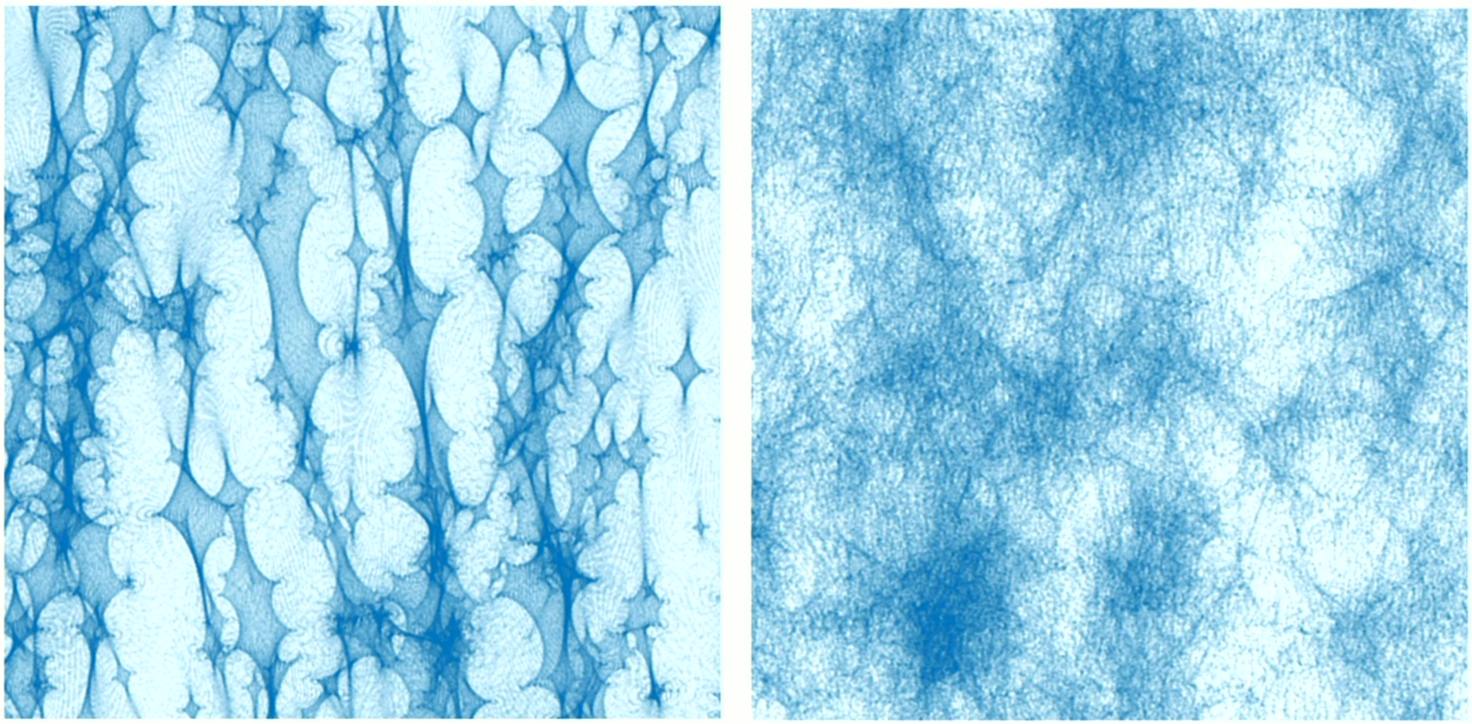
$$\theta_E = \left[\frac{4\,G\,M}{c^2}\,\frac{D_{LS}}{D_L\,D_S}\right]^{1/2} \sim 10^{-6}\,\mathrm{arcsec}$$

Abundance of microlenses quantified by the **course-grained convergence**

$$\kappa_\star = \frac{\Sigma_\star}{\Sigma_{\mathrm{crit}}}$$

More microlenses

$\mu_B = 3,\ \kappa_\star = 0.3$ "optically marginal" $\mu_B = 3,\ \kappa_\star = 2.0$ "optically thick"



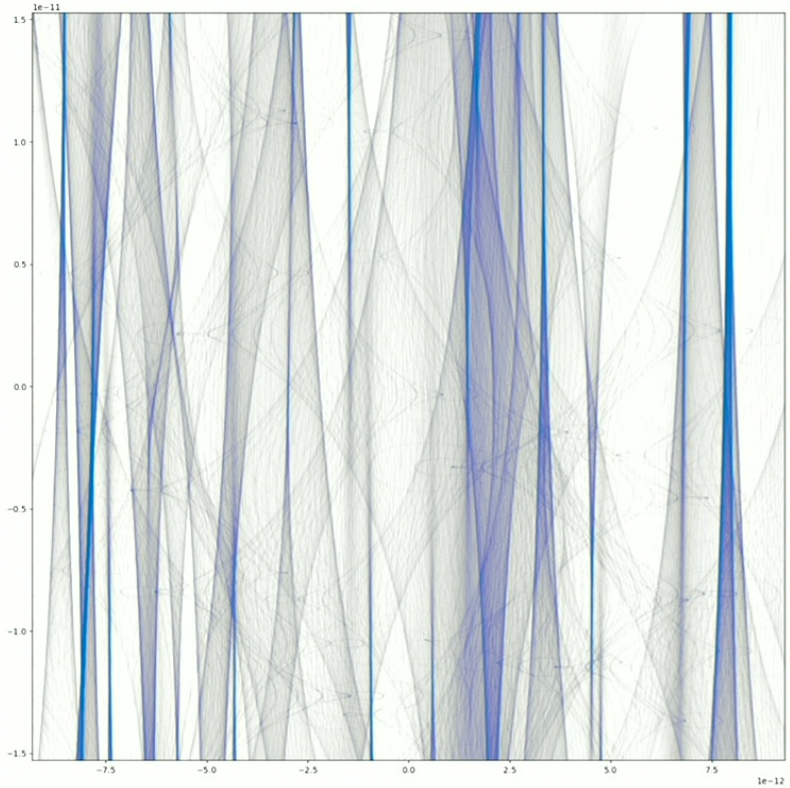
Microlenses with large macro magnification

Intracluster star abundance at the location of the caustic crossing arc

"Optically" thick!

$$\kappa_\star \sim 0.001 - 0.01$$

$$\mu_B = 200,\ \kappa_\star = 0.01$$



Optically thin:

$$\kappa_\star < 1/\mu_B$$

Optically marginal:

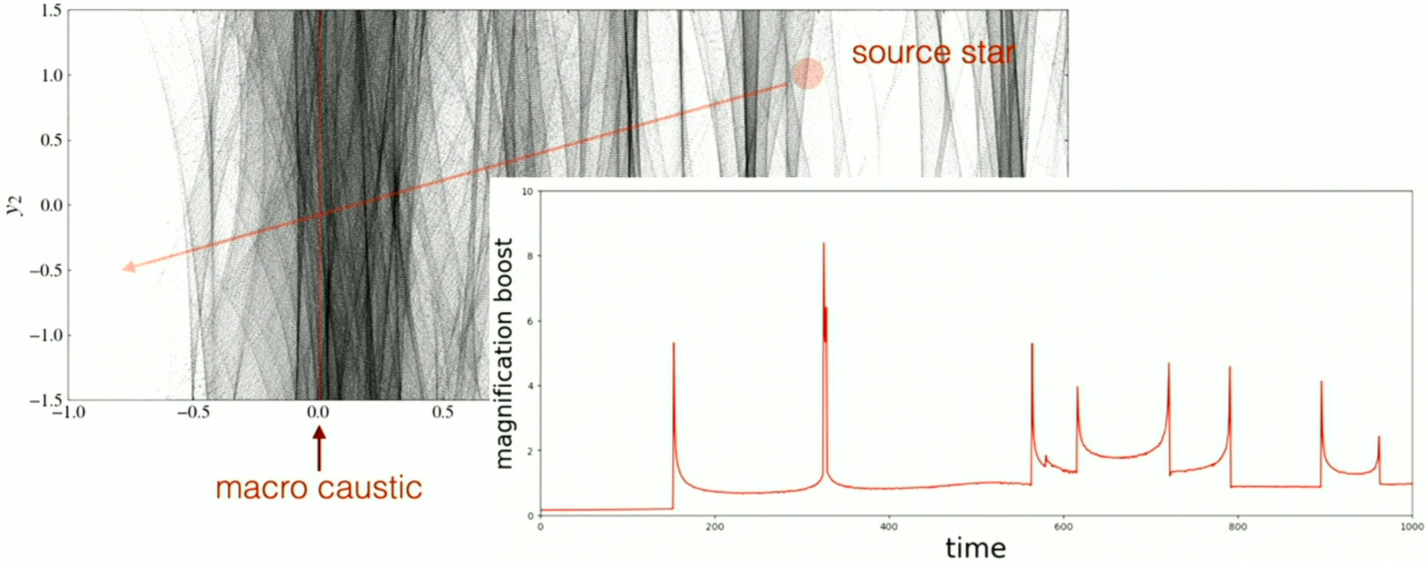
$$\kappa_\star \simeq 1/\mu_B$$

Optically thick:

$$\kappa_\star > 1/\mu_B$$

Observational Consequences of Microlensing

Source star traversing the micro-caustic network on the source plane

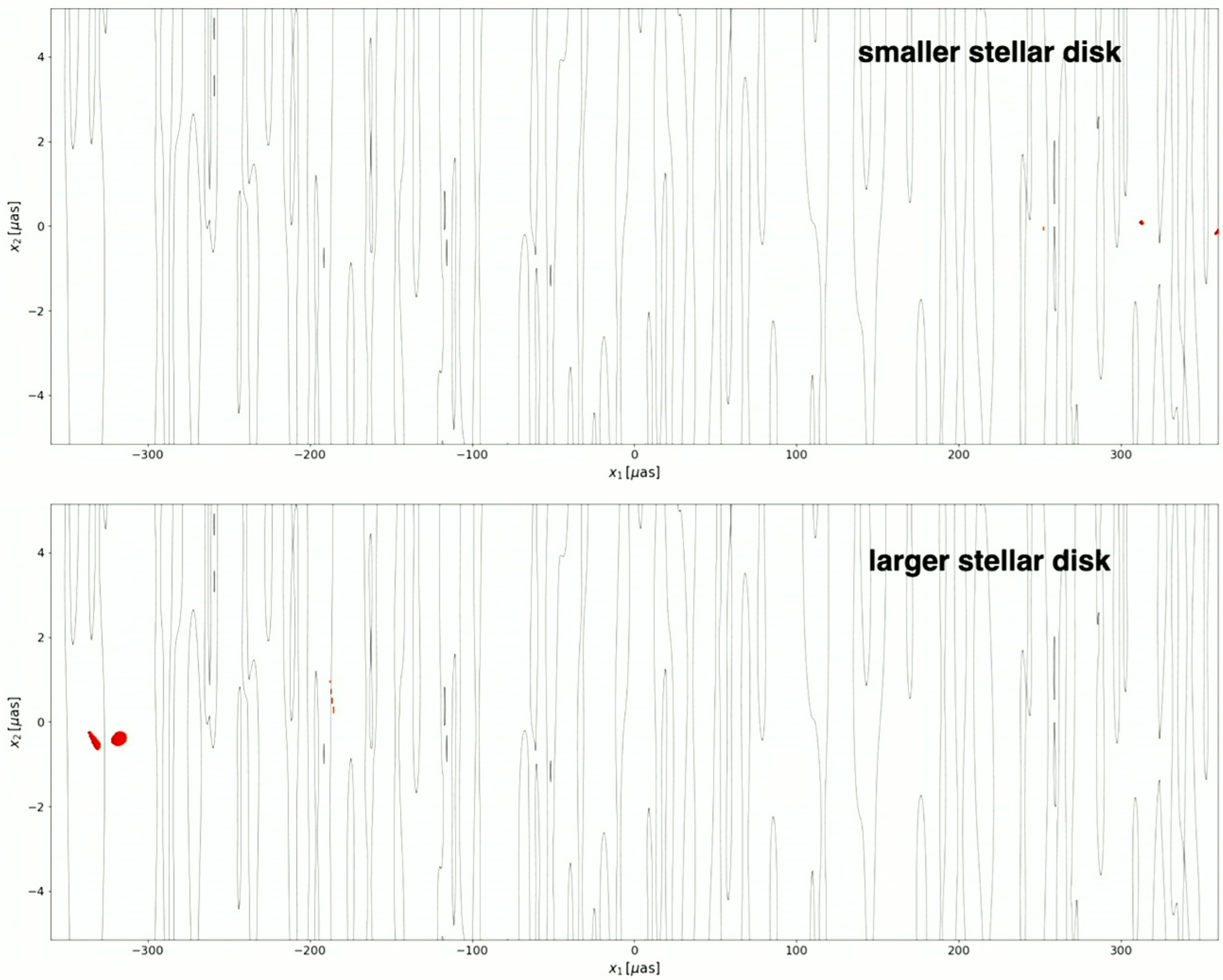


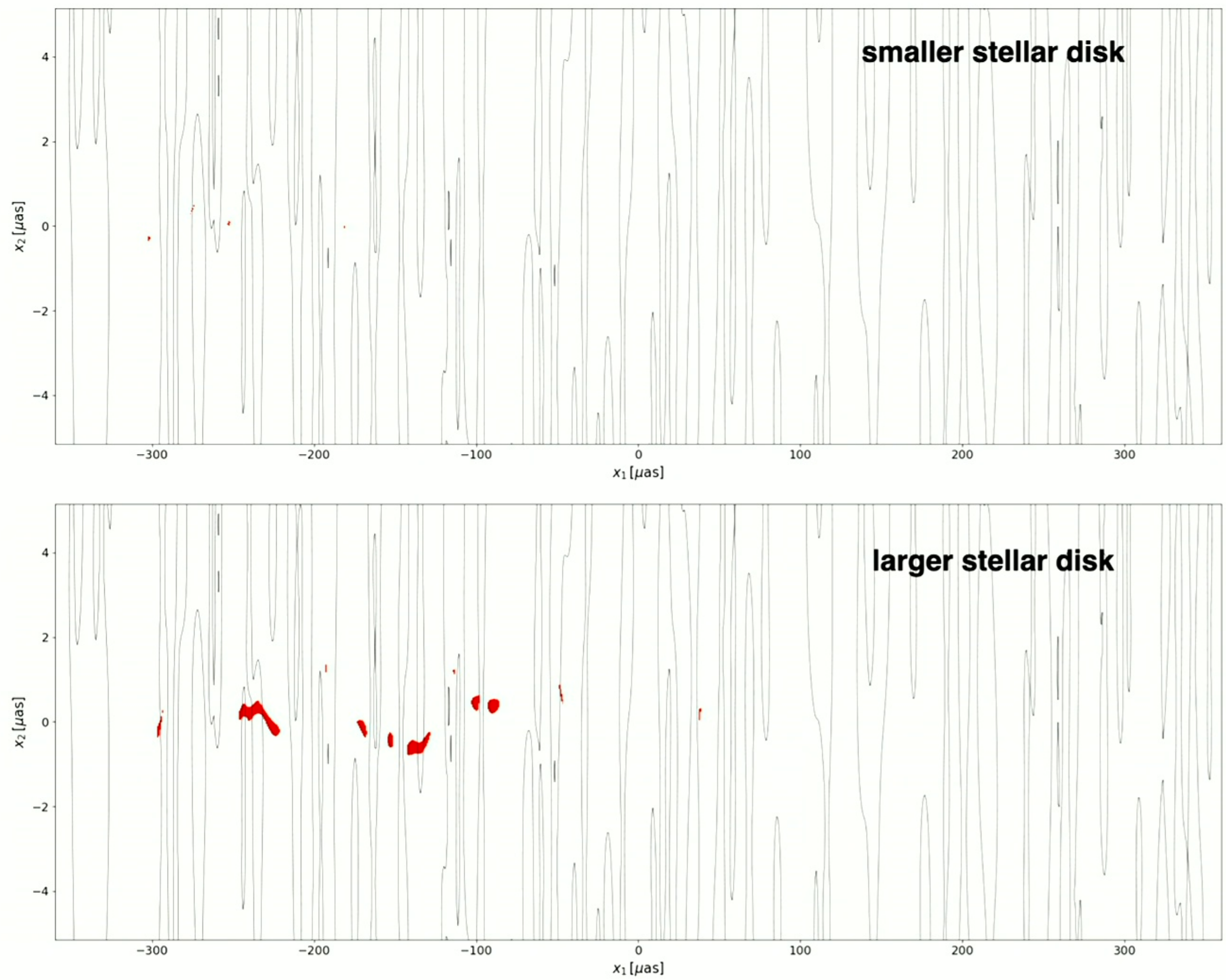
Crossing of micro caustics: $\mu_{\rm peak} \sim 10^4\,(R/10\,R_\odot)^{-1/2}$

Occurrence of peak events: **~1—100 per year**

Timescale for transiting the network: **~10^4 years**

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


smaller stellar disk
larger stellar disk
$x_2\,[\mu as]$
$x_1\,[\mu as]$
−300
−200
−100
0
100
200
300
4
2
0
−2
−4



smaller stellar disk
larger stellar disk
$x_2\,[\mu as]$
$x_1\,[\mu as]$

Study stellar properties during micro-caustic crossing

Han & LD (2024)

Xu Han

Critical curve

Caustic

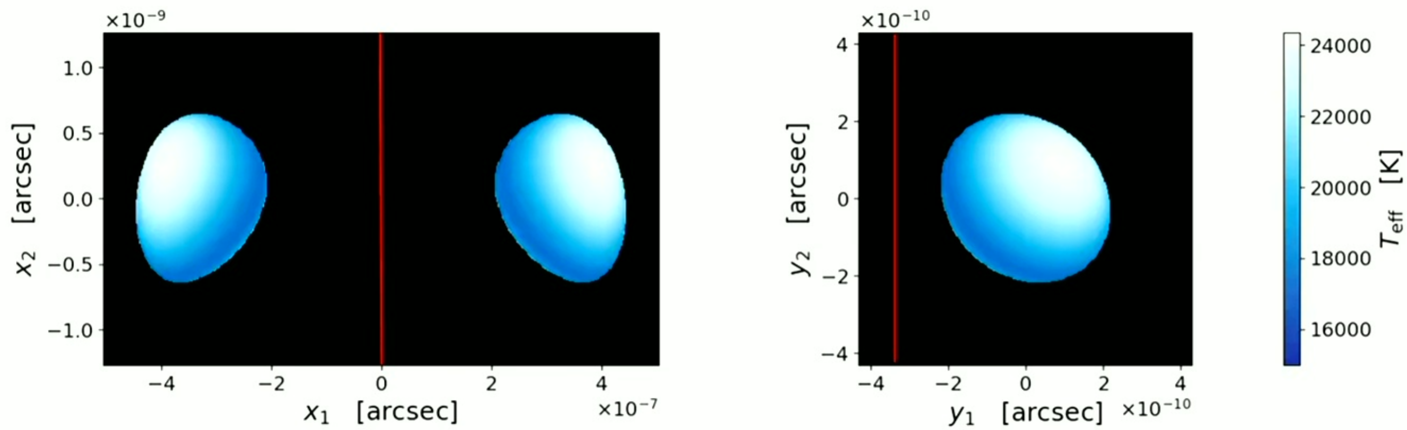
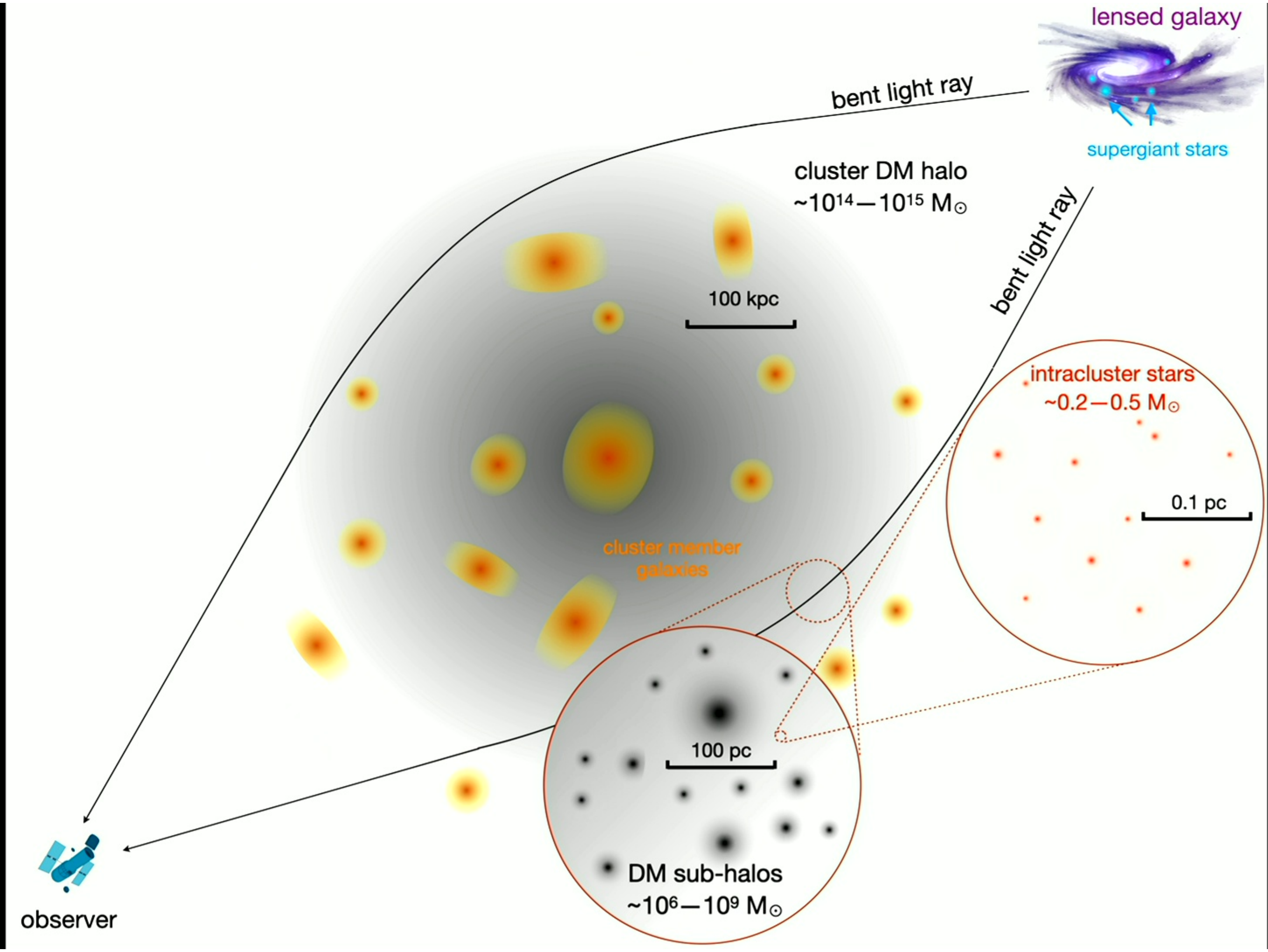


Image plane

Source plane

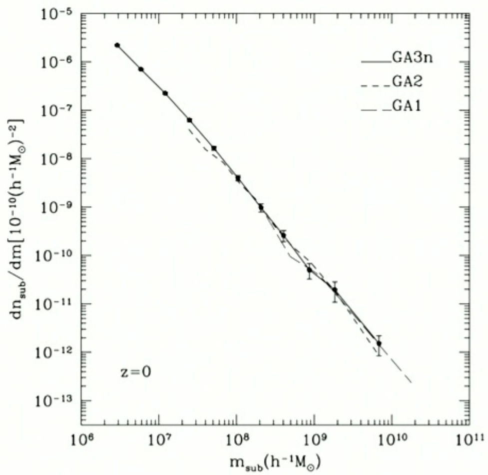
Can measure **individual** massive star properties in **high-redshift galaxies**:
(dimensionless) stellar rotation, luminosity, radius

$$\omega = \Omega/\Omega_{cr}$$


lensed galaxy
bent light ray
supergiant stars
cluster DM halo
~10¹⁴—10¹⁵ M⊙
bent light ray
100 kpc
intracluster stars
~0.2—0.5 M⊙
0.1 pc
cluster member
galaxies
100 pc
DM sub-halos
~10⁶—10⁹ M⊙
observer

Subhalos inside halo

Gao, White, Jenkins, Stoehr & Springel (2004)



Up to **~10%** of dark matter in a galaxy cluster halo is locked up in **subhalos**

"Halos inside halos"

Subhalo mass function:
10x more subhalos when subhalo mass decreases by 10x

Subhalos <10^9 solar masses are essentially devoid of stars

Bullock & Boylan-Kolchin (2017)

Cold Dark Matter

Warm Dark Matter

Hezaveh++ (2016)

Imprint of a 10^9 solar mass subhalo in an Einstein ring seen in sub-mm

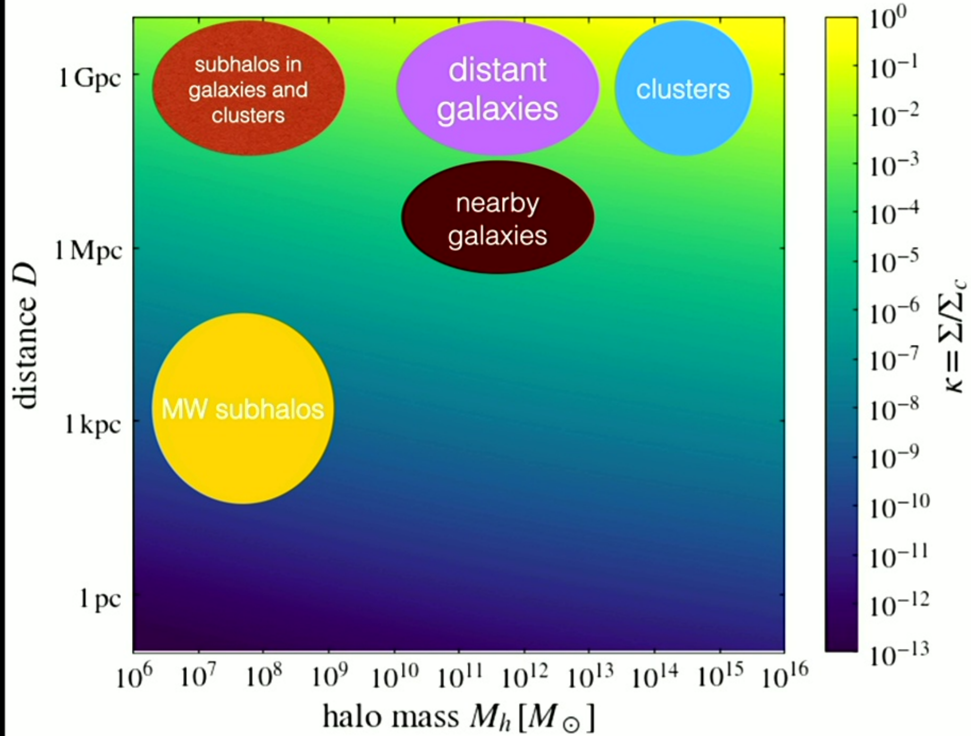
Subhalos are inefficient lenses

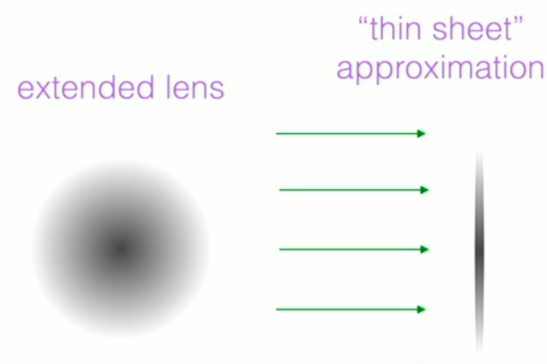
Lensing convergence

$$\kappa = \Sigma/\Sigma_c$$

Critical lens surface density

$$\Sigma_c \sim \frac{c^2}{4\pi G D} \sim 10^9 \frac{M_\odot}{\mathrm{kpc}^2} \left(\frac{D}{\mathrm{Gpc}}\right)^{-1}$$





To have strong lensing
We normally need κ ~ O(1)

Solution: exploit large "background" magnification

Ray-bundle deformation matrix

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

Flux magnification $$\mu = \frac{1}{\det \frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}}}$$

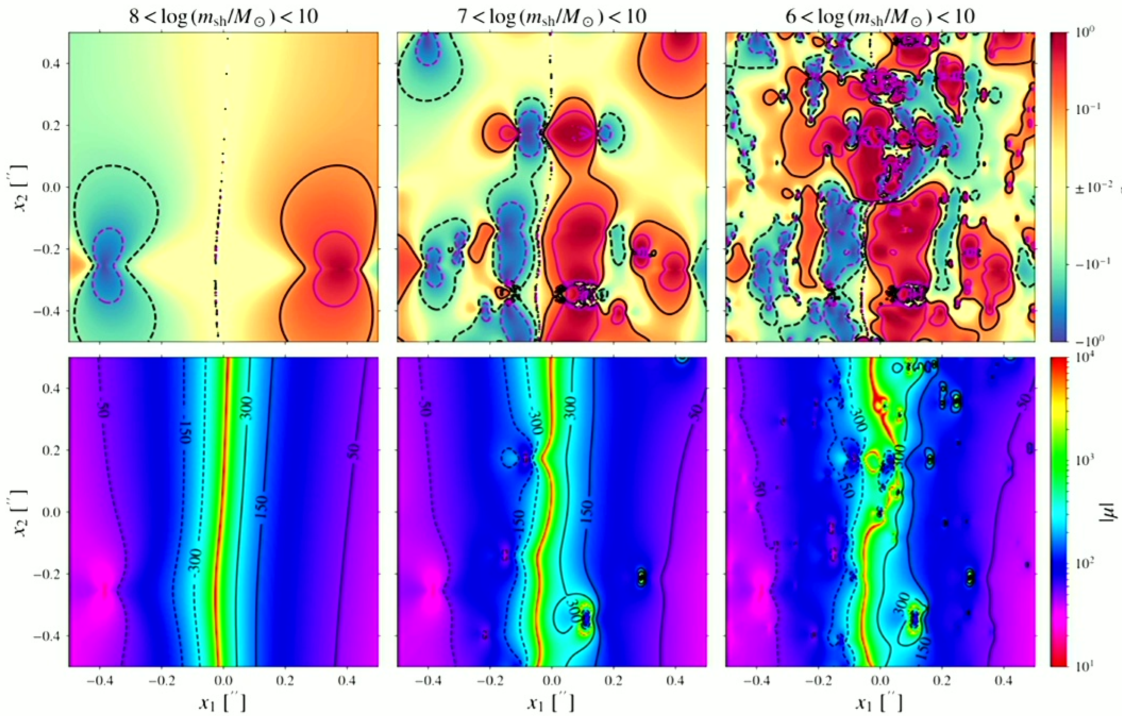
$$\kappa = \kappa_{\rm macro} + \kappa_{\rm sub}$$

$$\gamma_1 = \gamma_{1,\rm macro} + \gamma_{1,\rm sub}$$

$$\gamma_2 = \gamma_{2,\rm macro} + \gamma_{2,\rm sub}$$

Evidence for Sub-galactic CDM Subhalos

LD, Kaurov, Sharon++ (2020)

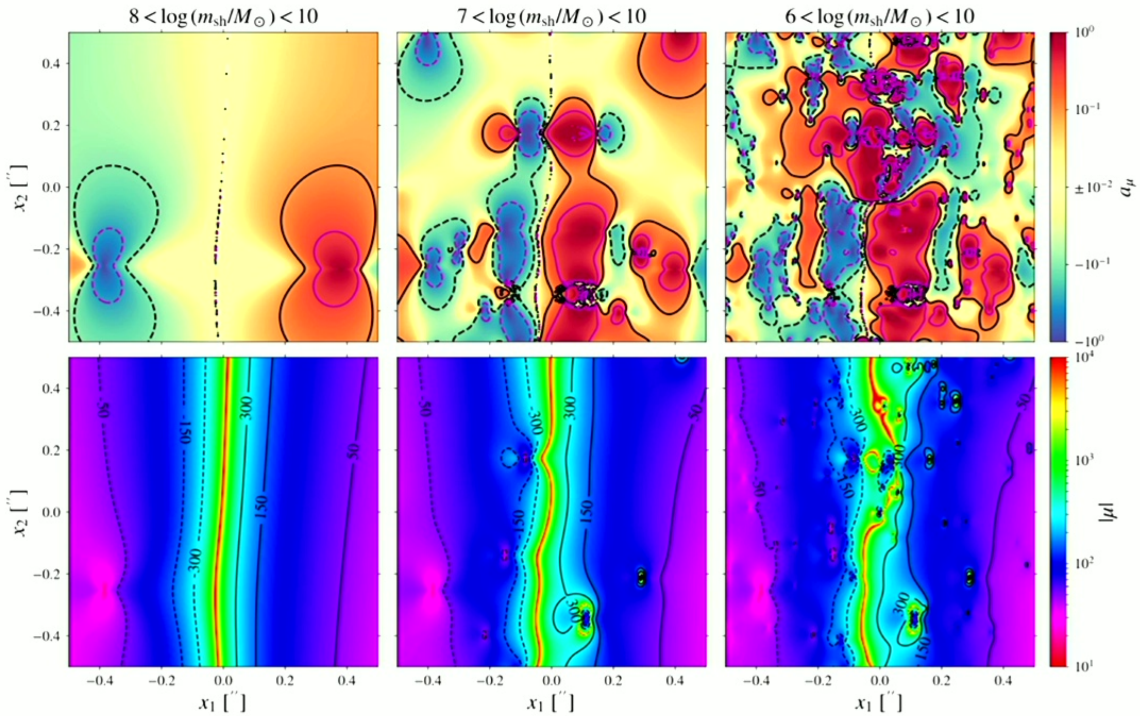


Difficult to explain using time-varying microlensing effects.

Evidence for a population of 10^6-10^8 solar mass dark matter halos (which are expected to be "galaxy-free")

Evidence for Sub-galactic CDM Subhalos

LD, Kaurov, Sharon++ (2020)

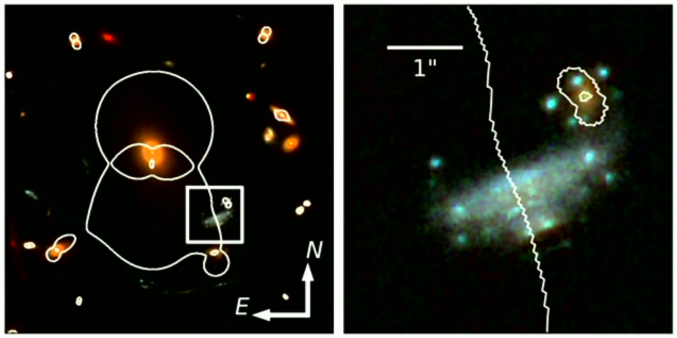


Difficult to explain using time-varying microlensing effects.

Evidence for a population of 10^6-10^8 solar mass dark matter halos (which are expected to be “galaxy-free”)

Flux asymmetry

LD, Kaurov, Sharon++ (2020)



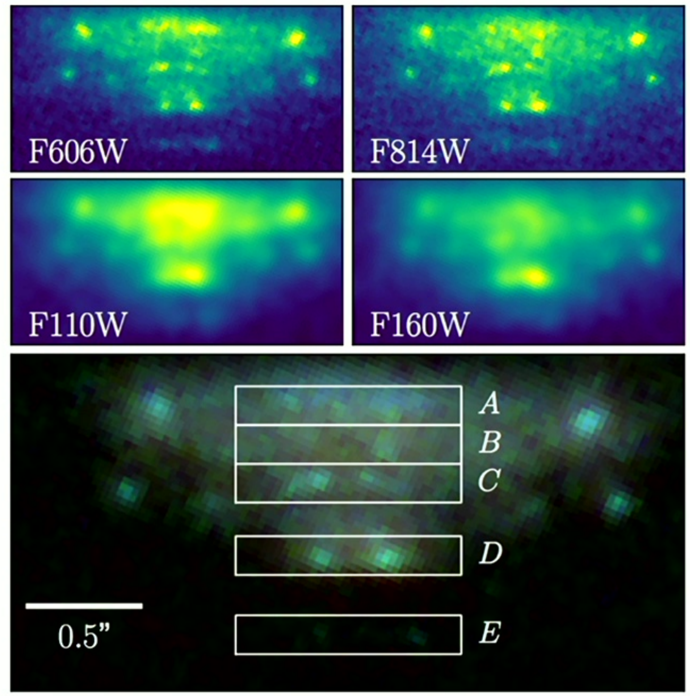
Lensed galaxy at z = 2.9

Multiple clumps of stars near the caustic.

Lensed image pairs straddle the model critical curve.

Several image pairs show asymmetric fluxes ~ 60%

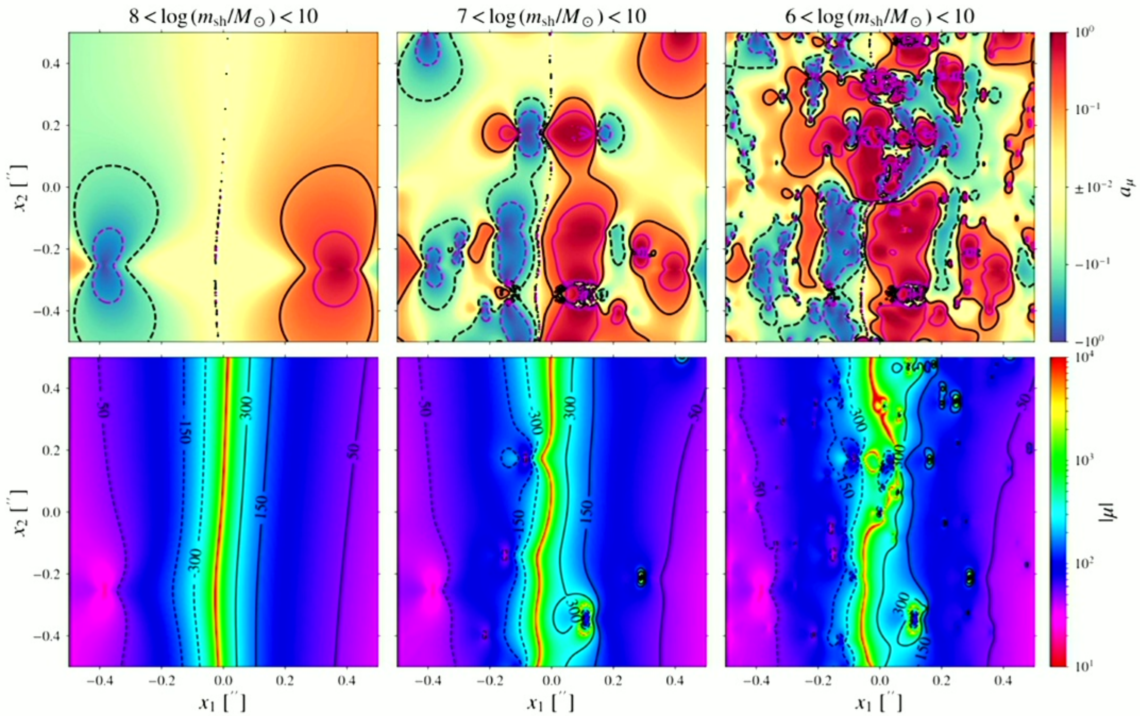
Images from Hubble



Evidence for a population of 10^6-10^8 solar mass (invisible) DM sub-halos

Evidence for Sub-galactic CDM Subhalos

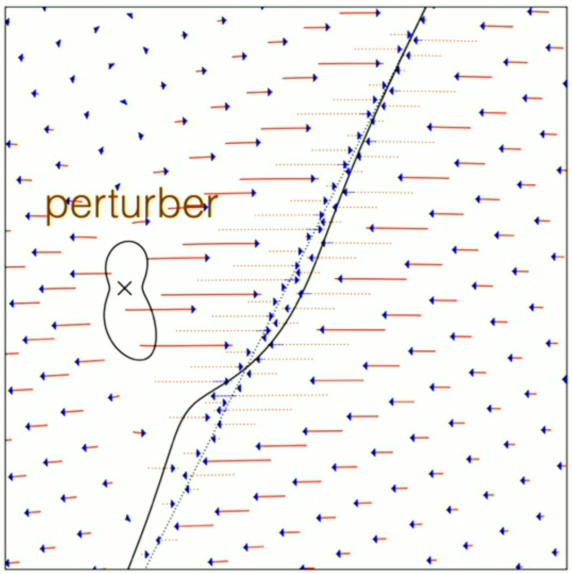
LD, Kaurov, Sharon++ (2020)



Difficult to explain using time-varying microlensing effects.

Evidence for a population of 10^6-10^8 solar mass dark matter halos (which are expected to be "galaxy-free")

Astrometric signatures



Enhanced perturbation on magnification

$$\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}} = \boxed{\boldsymbol{I} - \frac{\partial \boldsymbol{\alpha}_B}{\partial \boldsymbol{x}}} - \frac{\partial \boldsymbol{\alpha}_s}{\partial \boldsymbol{x}}$$

nearly singular matrix

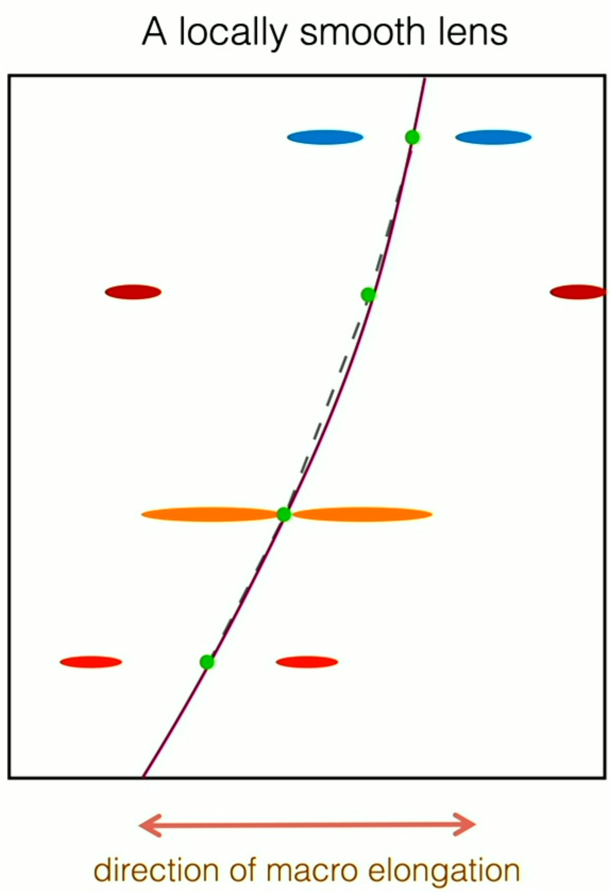
Enhanced perturbation on image position

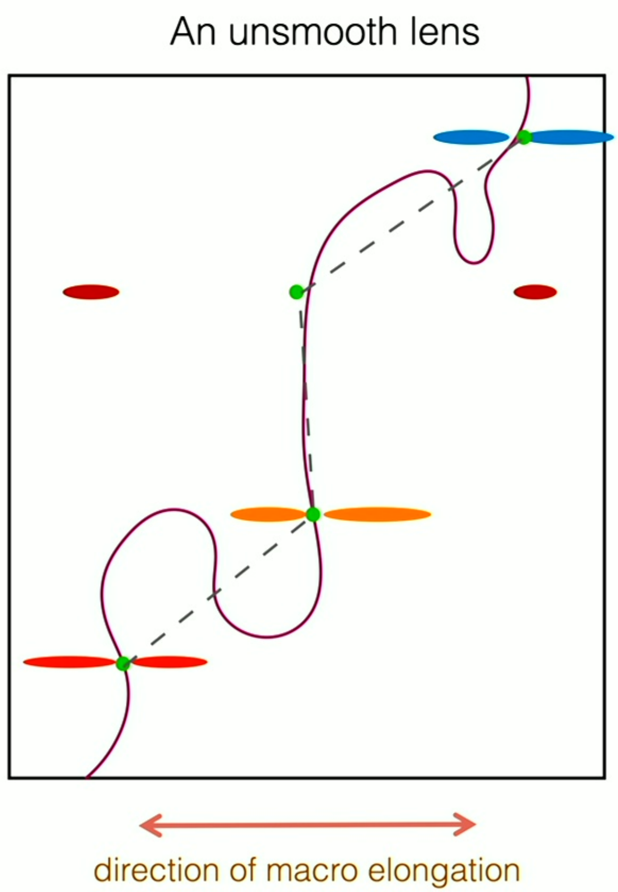
$$\delta \boldsymbol{x} = \left[\boldsymbol{I} - \frac{\partial \boldsymbol{\alpha}_B}{\partial \boldsymbol{x}} \right]^{-1} \boldsymbol{\alpha}_s$$

Shift of image position

Ray deflection from perturber

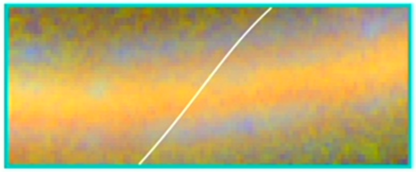
Lensed image pairs in the critical curve vicinity





Astrometric Signals of Perturbed Critical Curve

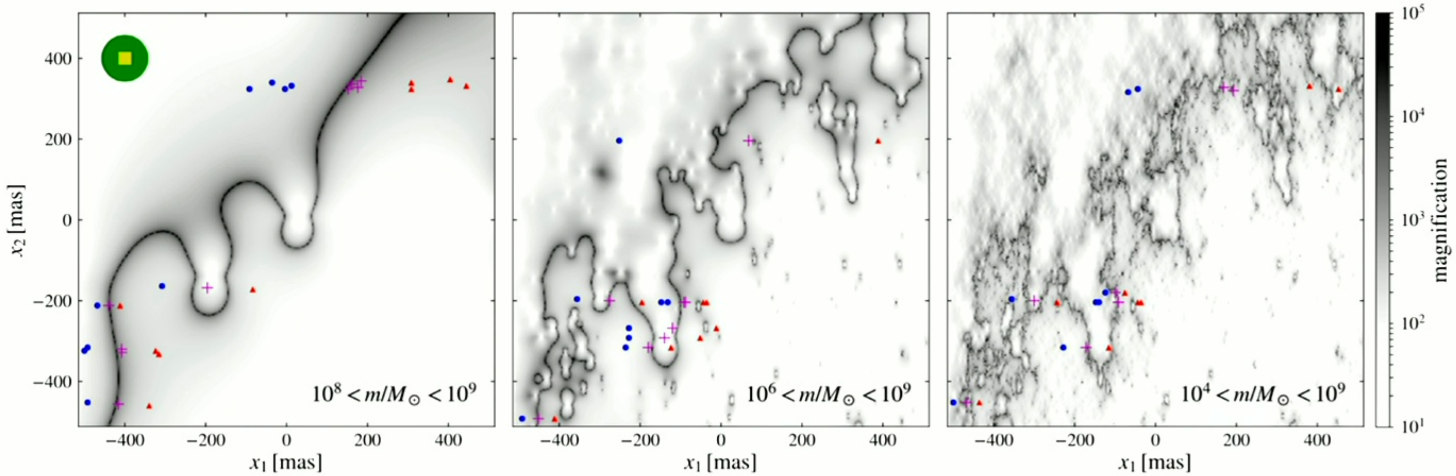
Considered a giant arc like the one in Abell 370



JWST PSF (~1.5 μm)

NIRCam pixel (32 mas)

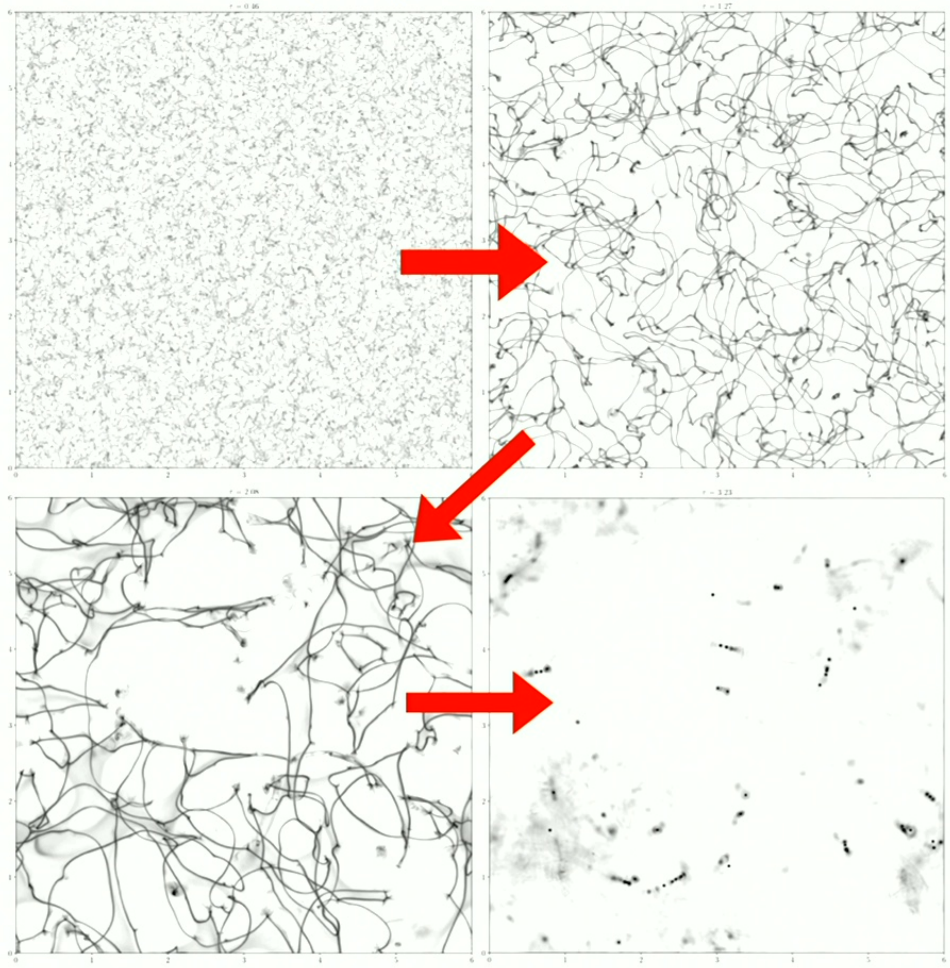
LD, Venumadhav, Kaurov & Miralda-Escudé (2018)

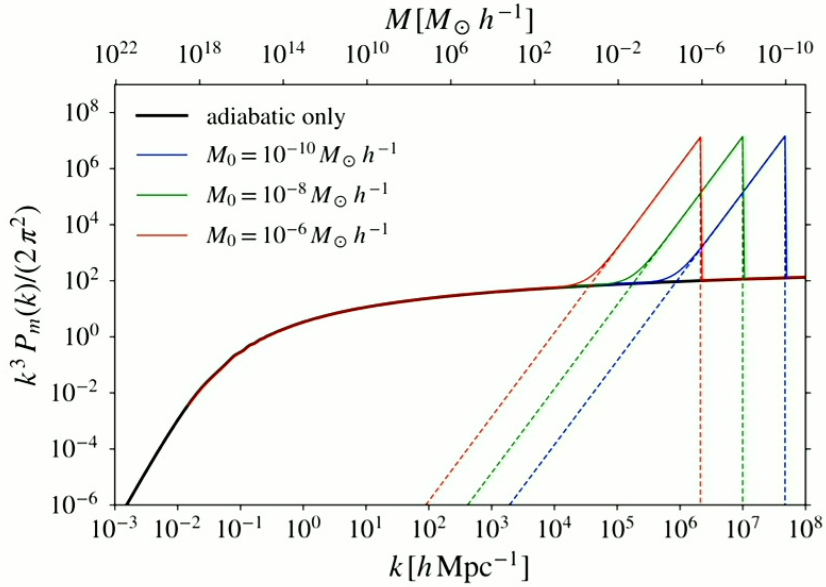


Midpoints of image pairs should not lie along a nearly straight line.
Sensitive to the population of subhalos in the mass range 10^6–10^8 solar masses

In new JWST images a few dozen highly magnified stars have been uncovered.
Stay tuned!

Vaquero, Redondo & Stadler (2019)

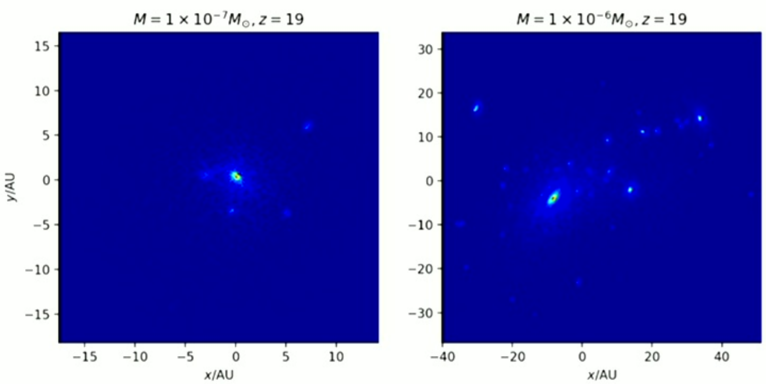




Hogan & Rees 1988
Kolb & Tkachev 1994

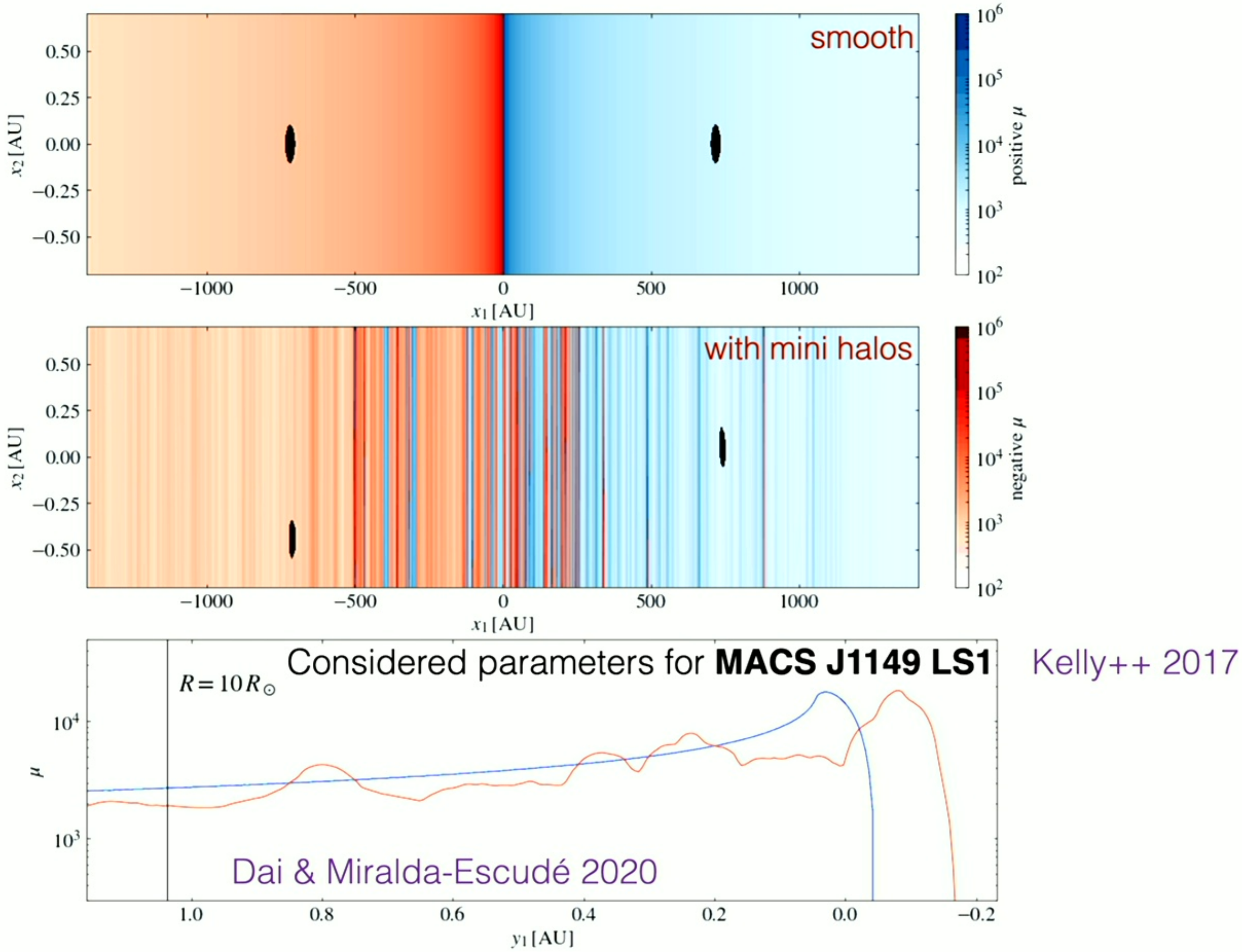
LD & Miralda-Escudé (2020)

Axion minihalos: collapse after z=3400, solar system sized, asteroid to planet masses



Xiao, Williams & McQuinn (2021)

Irregular variability during micro caustic-crossing



Ongoing Theoretical Efforts

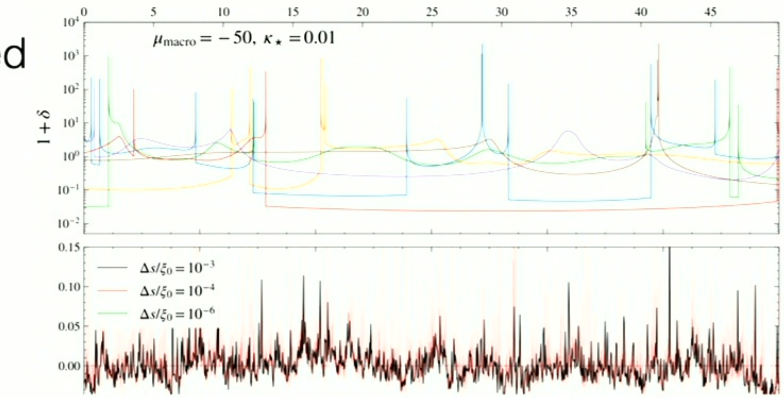
- Accurate and efficient model for light curve **statistics**.

magnification variance, PDF, temporal two-point correlation

e.g. Dai & Pascale 2021
e.g. Palencia++ 2023

- Theory of variability from blended source stars.

star clusters e.g. Dai 2021
pixel variability e.g. Tuntsov++ 2004



- Constraining DM micro-structures using latest data (esp. JWST)

Early universe scenarios: axion large-misalignment, axion minihalos, vector boson DM, early matter domination, primordial kination era

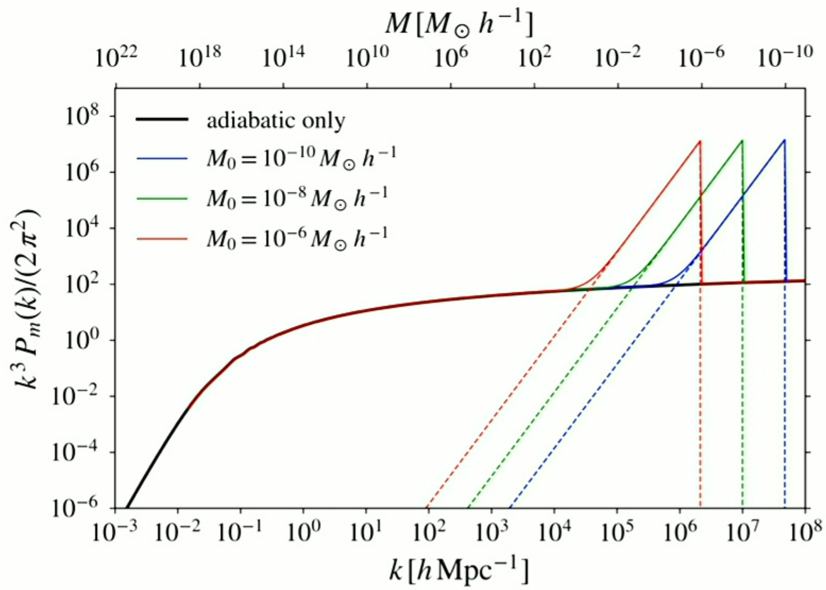
e.g. Arvanitaki++ 2019; Redmond, Trezza & Erieckcek 2018;
Graham, Marden & Rajendran 2016;
Erieckcet & Sigurdson 2011; Fan, Oszey & Watson 2014

Summary

- **Individual massive stars** can be detected from cosmological distances thanks to extreme magnification near cluster lensing caustics

- The cluster lensing caustic has rich layers of fine structures: smaller caustics cast by **sub-galactic dark matter halos**, yet smaller caustics cast by **intracluster stars**, and maybe minuscule caustics cast by **dark matter micro-halos**.

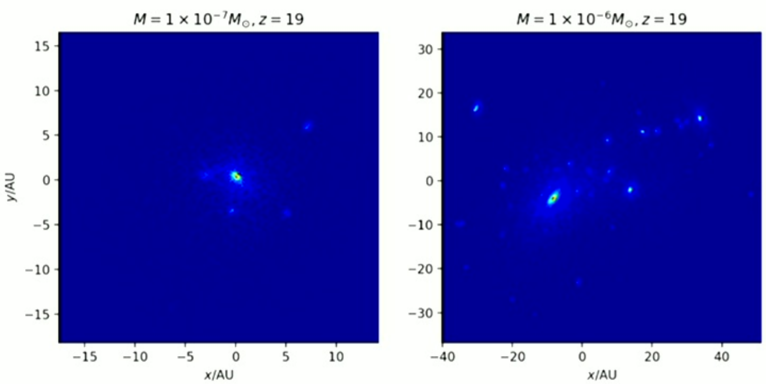
- In the era of James Webb, data is already pouring in. To quantitatively infer the small-scale structure of dark matter, much theory and modeling efforts are needed.



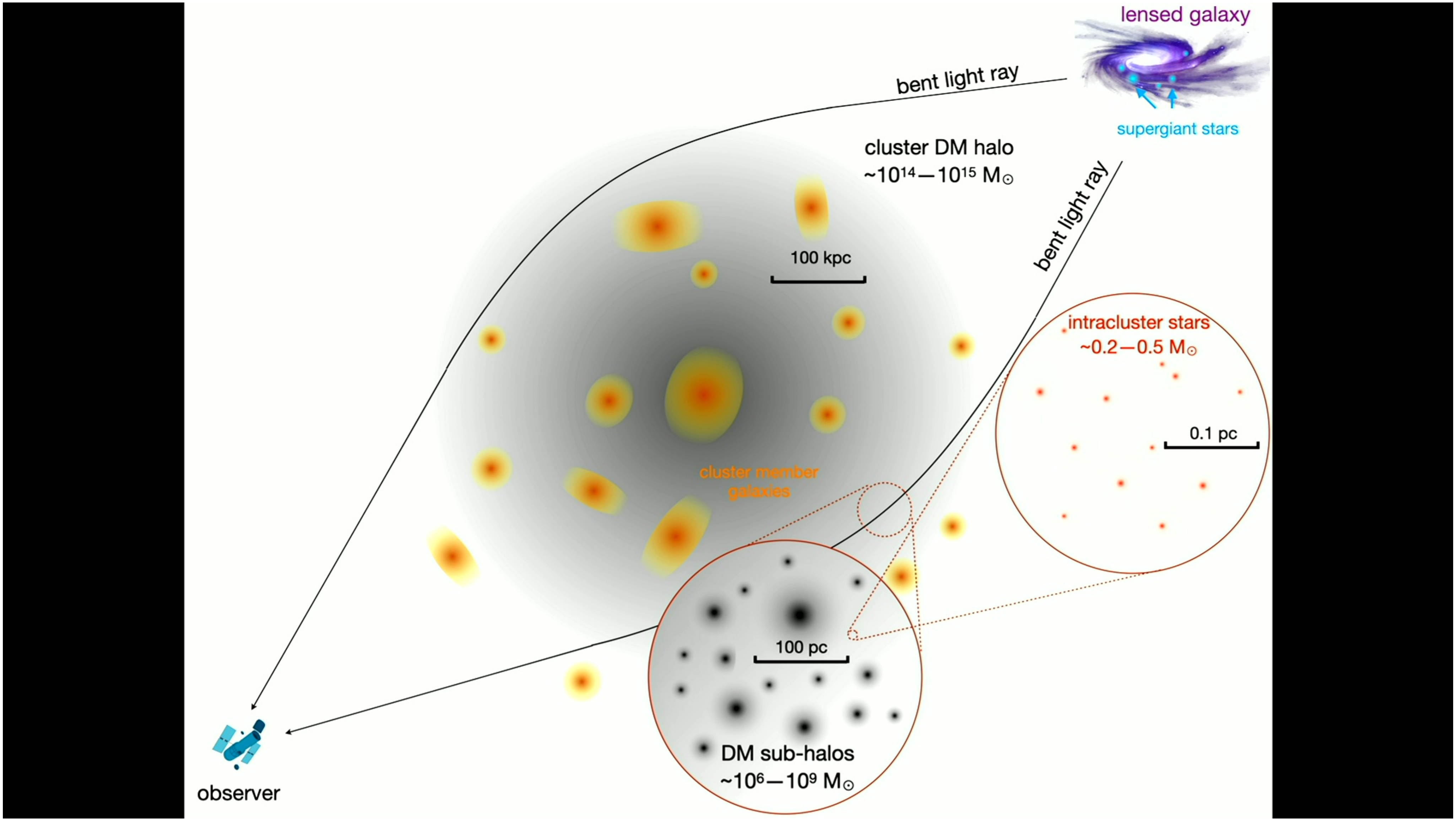
Hogan & Rees 1988
Kolb & Tkachev 1994

LD & Miralda-Escudé (2020)

Axion minihalos: collapse after z=3400, solar system sized, asteroid to planet masses



Xiao, Williams & McQuinn (2021)


lensed galaxy
bent light ray
supergiant stars
cluster DM halo
~10¹⁴—10¹⁵ M⊙
bent light ray
100 kpc
intracluster stars
~0.2—0.5 M⊙
0.1 pc
cluster member galaxies
100 pc
DM sub-halos
~10⁶—10⁹ M⊙
observer

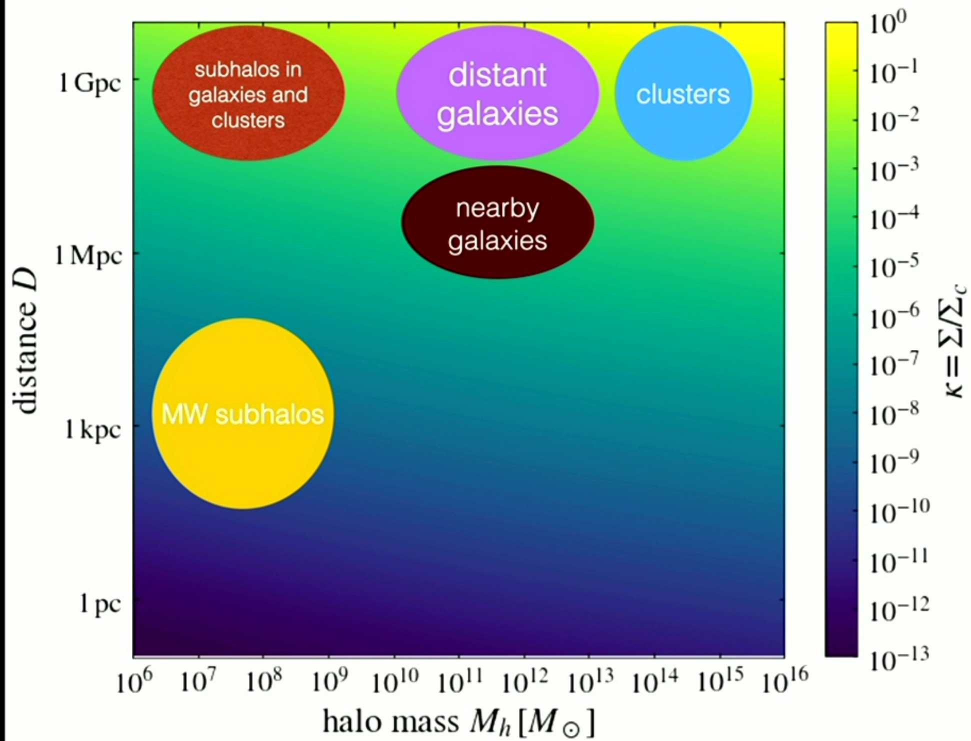
Subhalos are inefficient lenses

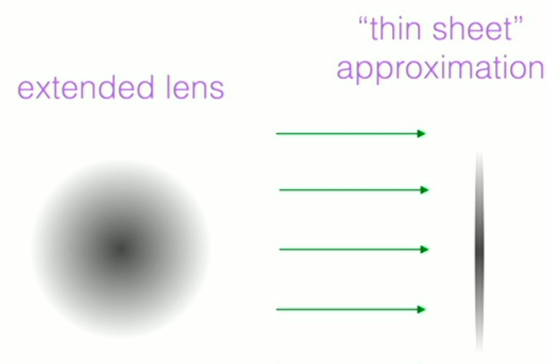
Lensing convergence

$$\kappa = \Sigma/\Sigma_c$$

Critical lens surface density

$$\Sigma_c \sim \frac{c^2}{4\pi G D} \sim 10^9 \frac{M_\odot}{\text{kpc}^2} \left(\frac{D}{\text{Gpc}}\right)^{-1}$$





To have strong lensing
We normally need κ ~ O(1)