Probing dark matter minihalos with extremely magnified extragalactic stars

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Dark Matter as a Portal to New Physics
Feb 2021

(QCD) Axion

The strong CP problem: no evidence for CP violation from QCD   ’t Hooft 1976

A famous solution: Peccei-Quinn symmetry breaking

Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978

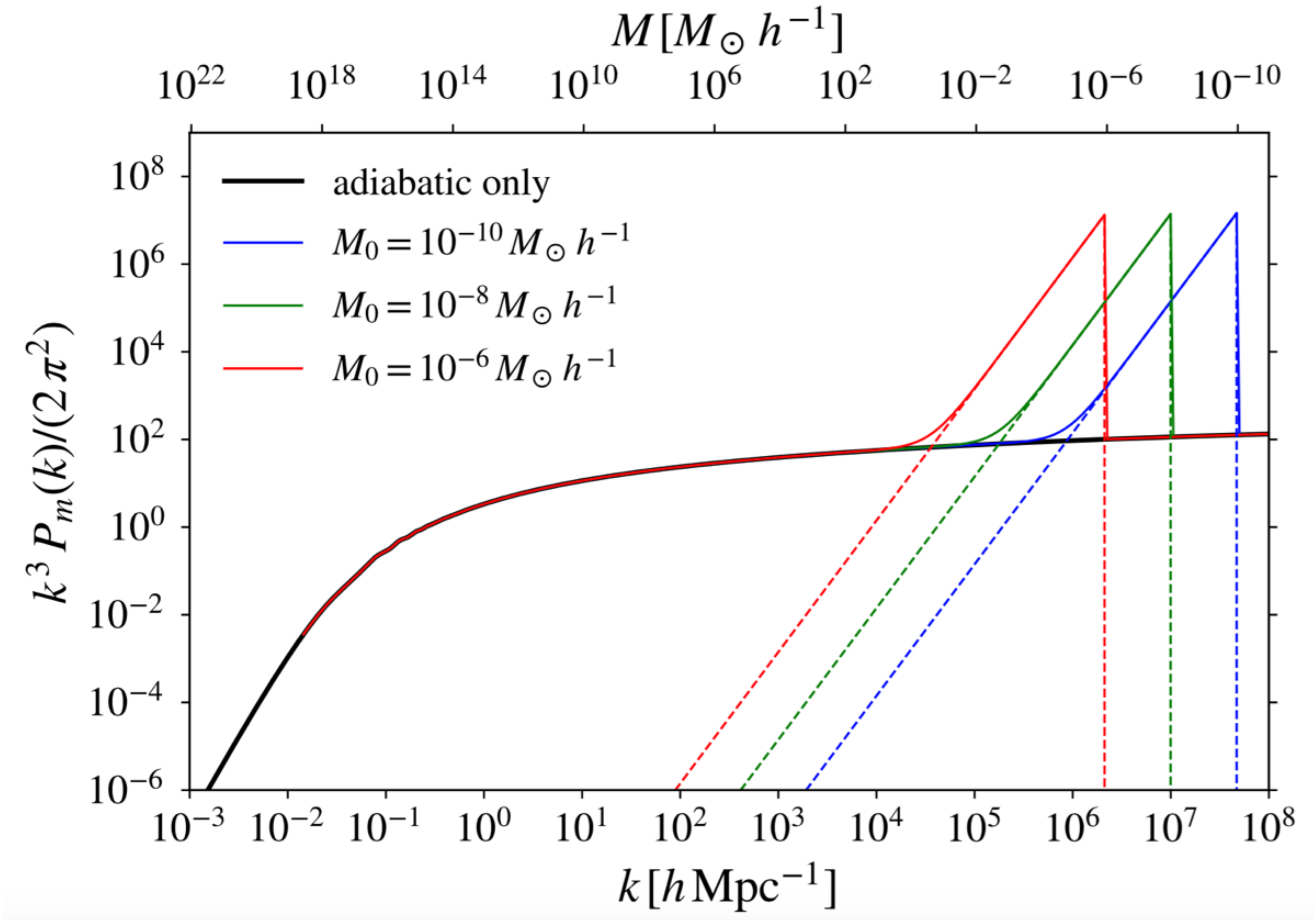
The **axion** particle:
A very light scalar particle;
Weakly interacting with standard model particles;
Dynamically drive CP violating term to zero

Bonus: axion particles can be the **Cold Dark Matter** (non-thermal relic) $10^{-11}\,\mathrm{eV} < m_a < 1\mathrm{eV}$

(Not “fuzzy” DM)

PQ symmetry breaking to incoherent horizon patches (topological defects) → non-negligible mass as the universe cools → start oscillation at $\mathbf{t_0}$; contribute to CDM

Axion Cosmology: Isocurvature Fluctuations



Initial density fluctuations:

Adiabatic modes from inflation

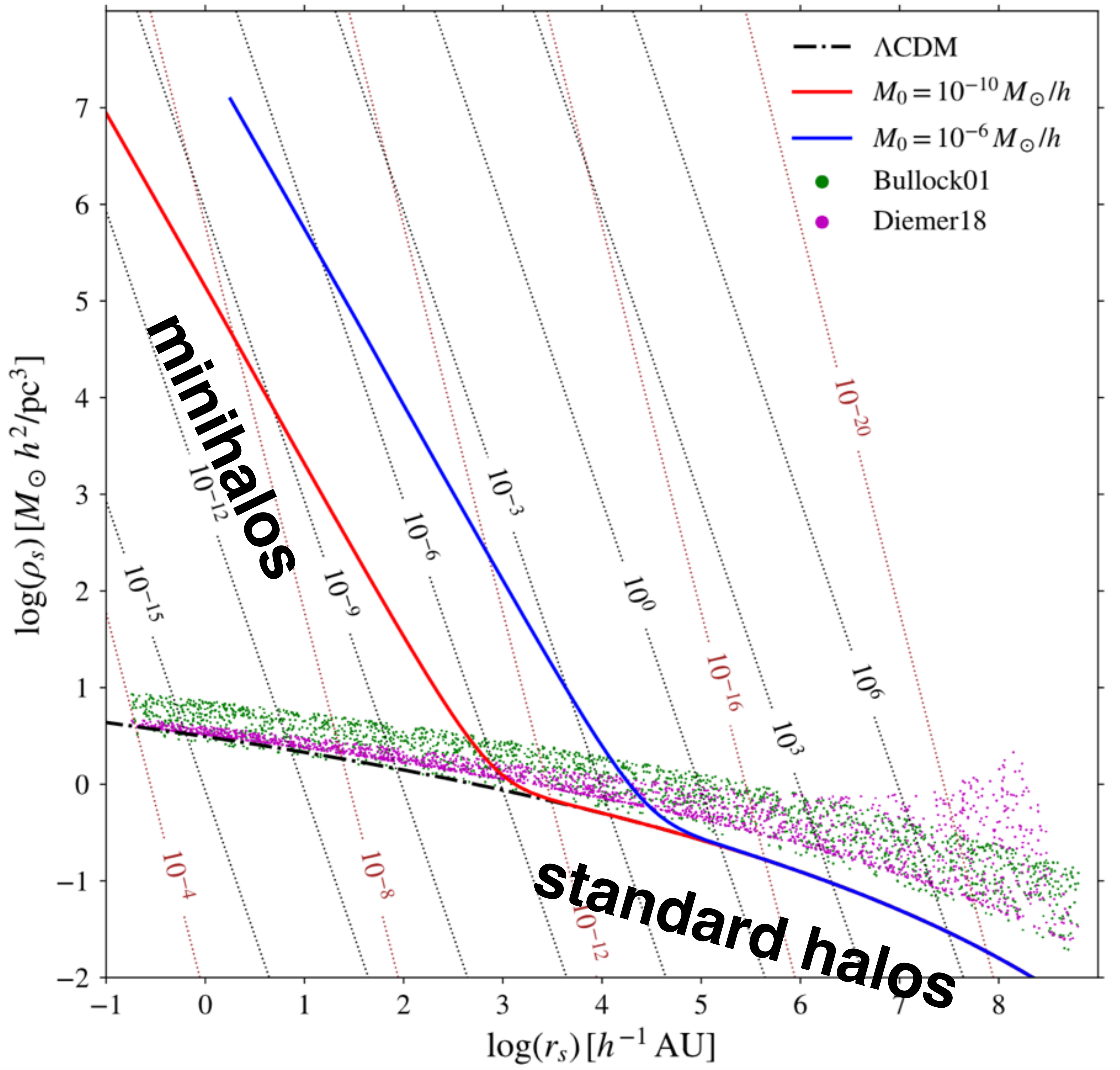
Isocurvature modes from topological defects

$$M_0 = \frac{4\pi}{3}\left(\frac{\pi}{k_0}\right)^3 \bar{\rho}_{m0}$$

(probable values as implied by calculation of $m_a(T)$)

Hogan & Rees 1988
Kolb & Tkachev 1994

Axion Cosmology: Minihalos



NFW density profile

Navarro, Frenk & White 96'; 97'

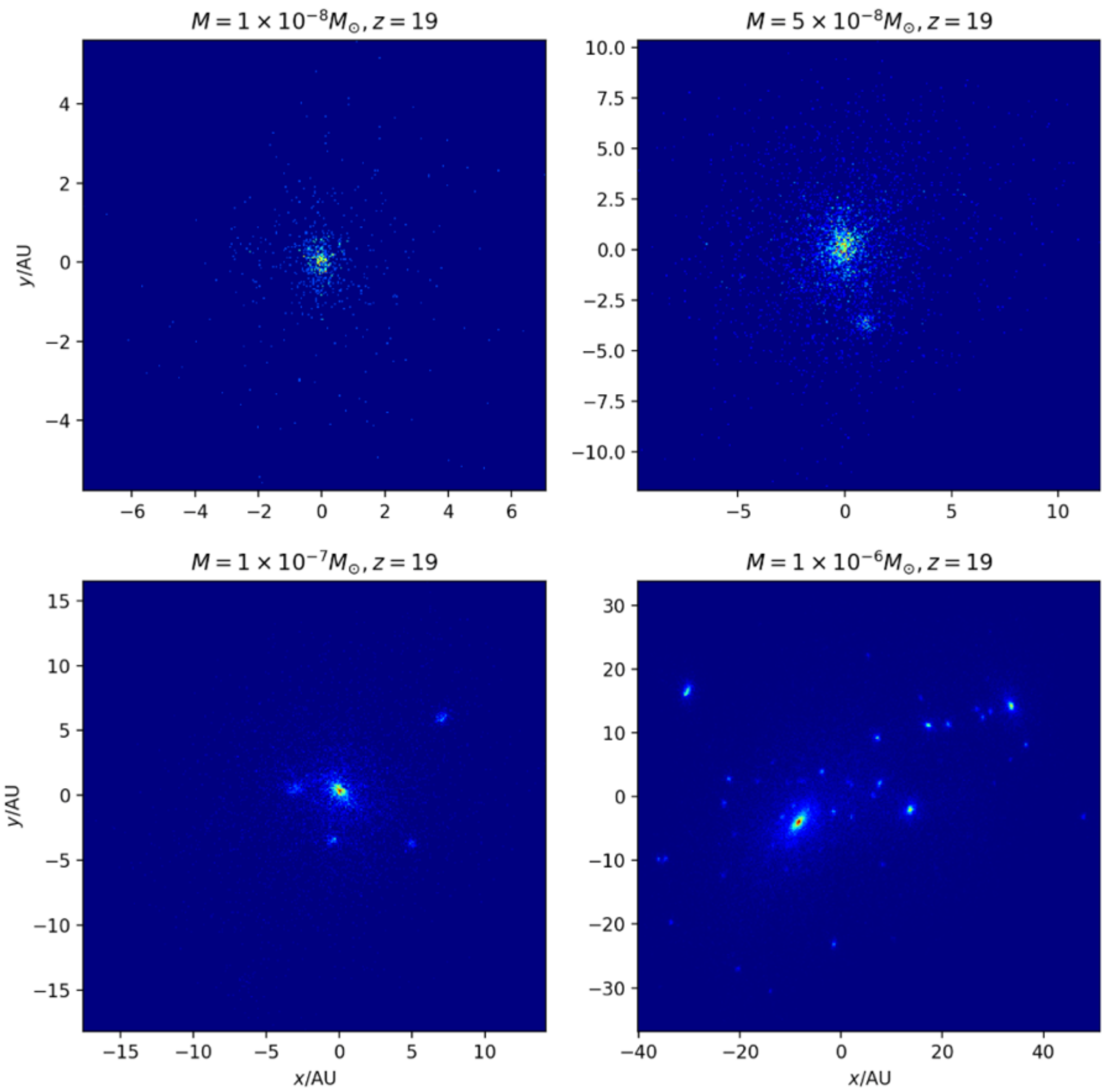
$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

Large halos same as in standard cosmology.

Small halos collapse earlier in axion cosmology (10 < z < 4000).

They are **denser and more compact** than in standard cosmology.

Axion Minihalos



Xiao, Williams & McQuinn 2101.04177

N-body simulation of axion minihalo formation and hierarchical assembly

From white-noise initial density fluctuations

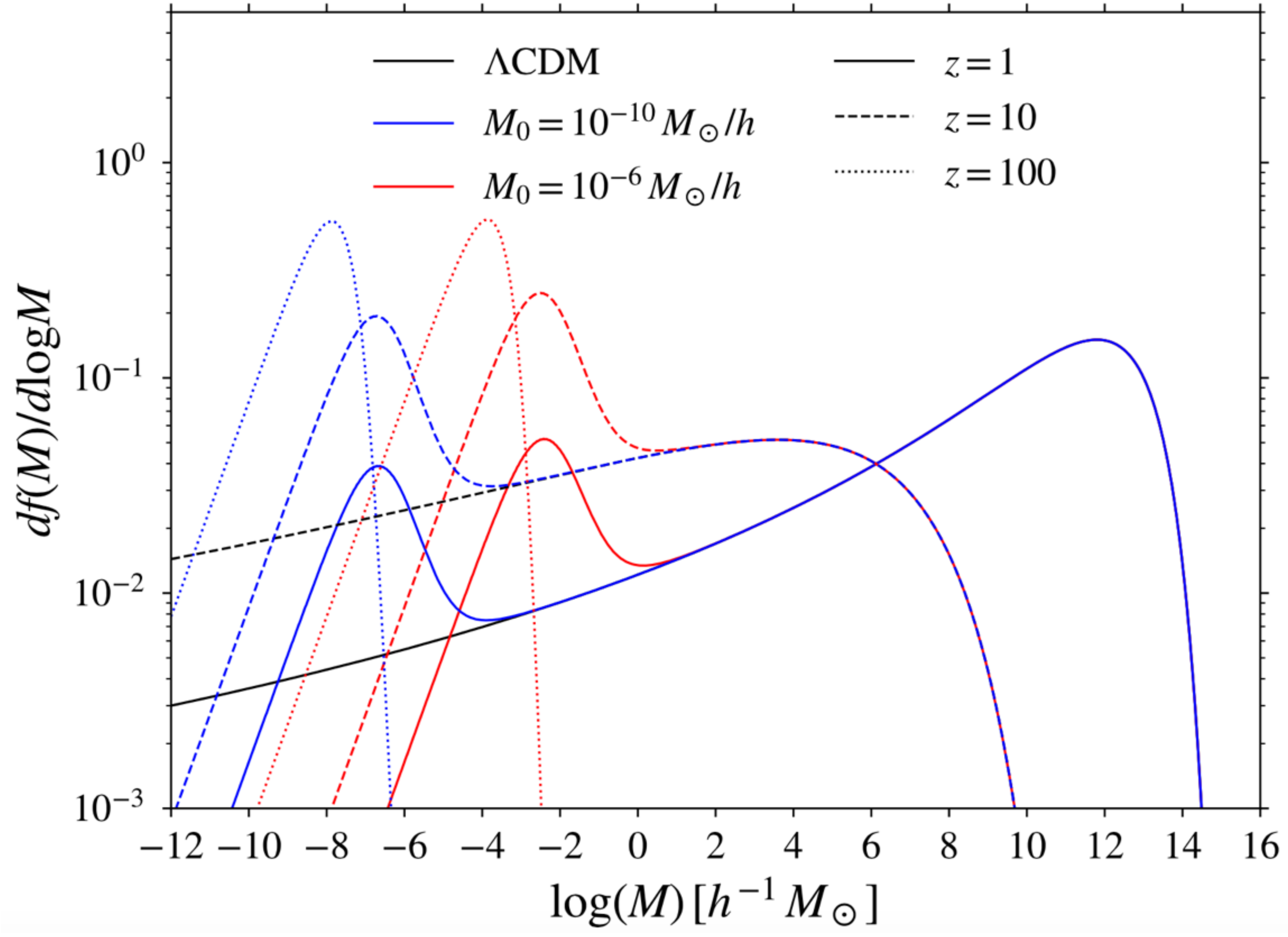
NFW profile is a very good fit

Minihalo concentration and scale radius

$$c(z) \equiv \frac{r_{\rm vir}}{r_s} = \frac{1.4 \times 10^4}{(1+z)\sqrt{M/(A_{\rm osc} M_0)}},$$

$$r_s(M) \approx 3.7 \times 10^{-3} h^{-1} {\rm pc} \left(\frac{A_{\rm osc} M_0}{10^{-11} M_\odot/h}\right)^{-1/2} \times \left(\frac{M}{10^{-6} M_\odot/h}\right)^{5/6},$$

Hierarchical Structure Assembly



Press-Schechter halo mass function

Press & Schechter 1974

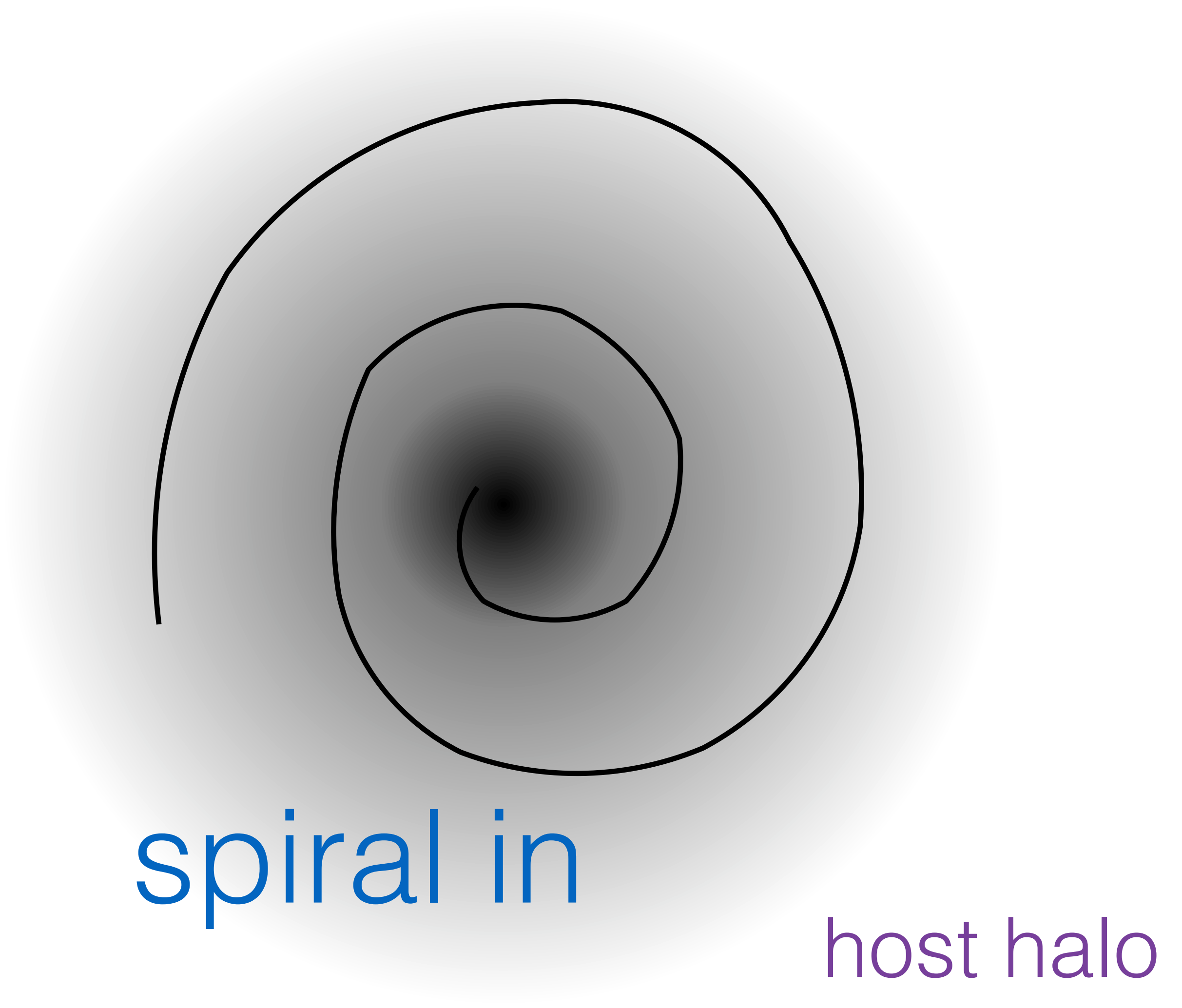
At z > 100:
DM locked into minihalos
Minihalos assemble from bottom up

At z <~ 10:
“Standard” CDM halos form
Many minihalo assimilated into standard halos

Even as late as z ~ 1:
Many field minihalos in isolation

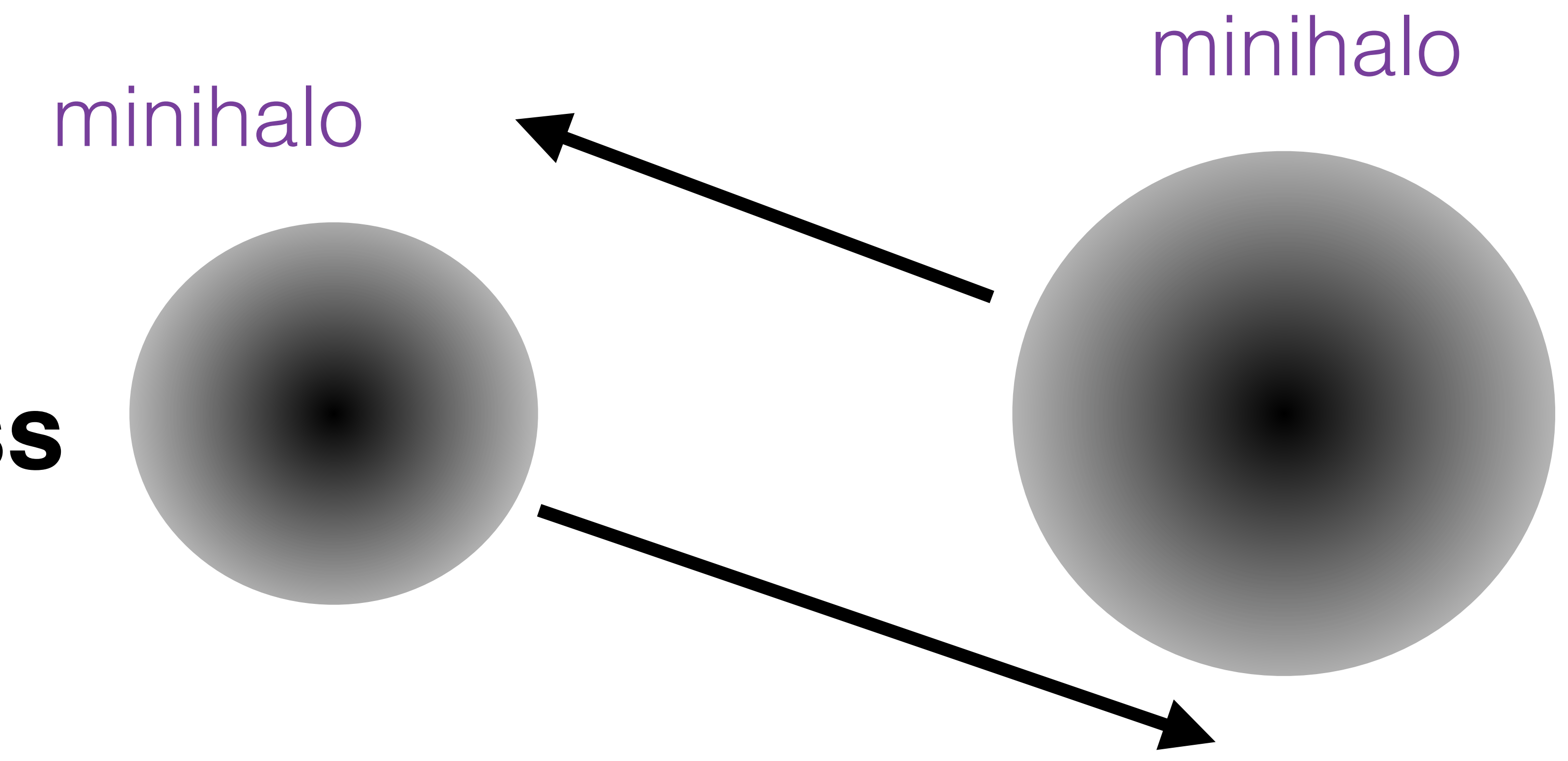
Collapse of cluster-sized halos:
Field minihalos fall into them

Surviving Dynamic Disruption



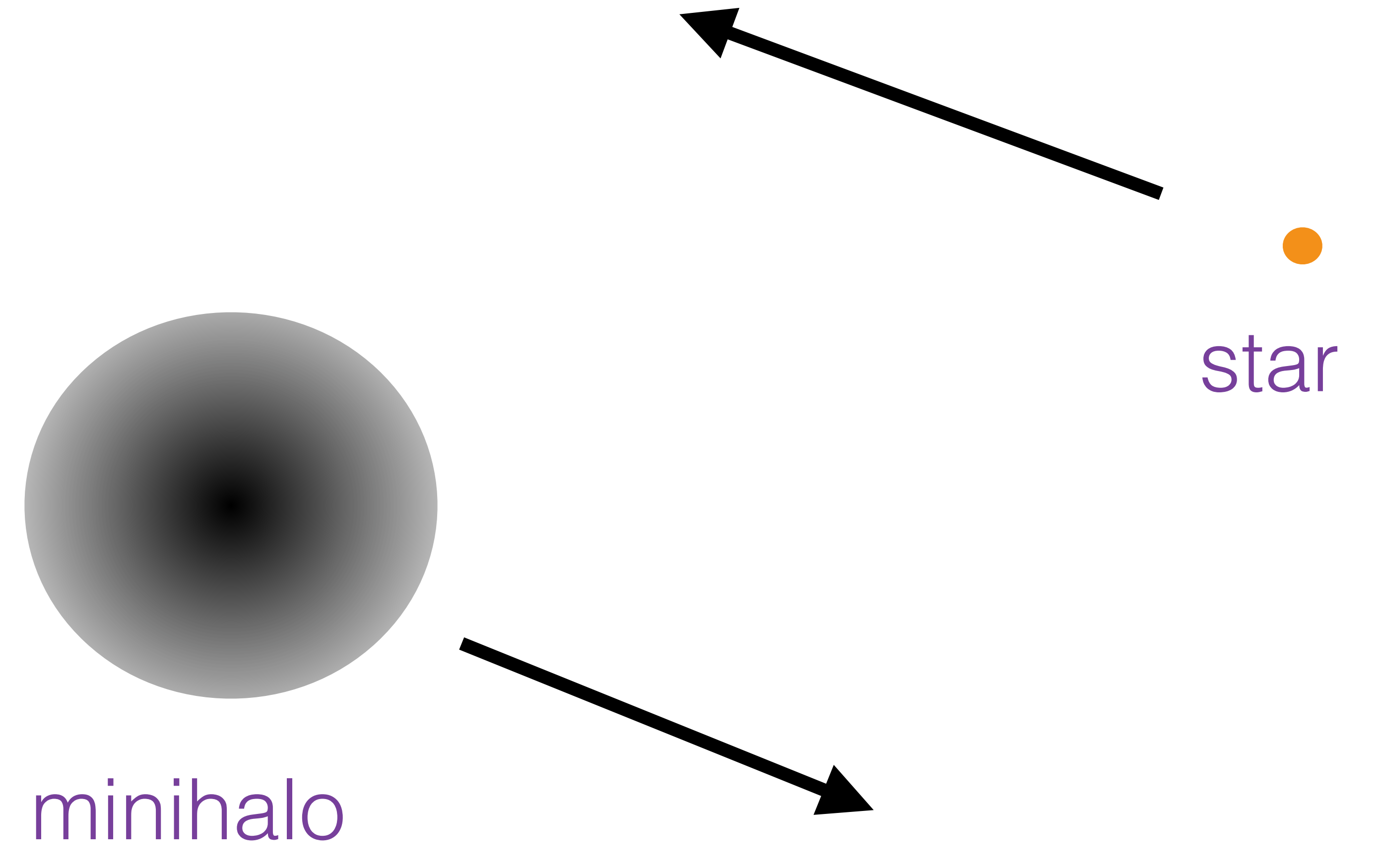
1. Spiral into central dense regions by dynamic friction

Because minihalo have tiny masses, spiral-in timescales are **way too long**



2. Mutual High-speed encounters between minihalos:

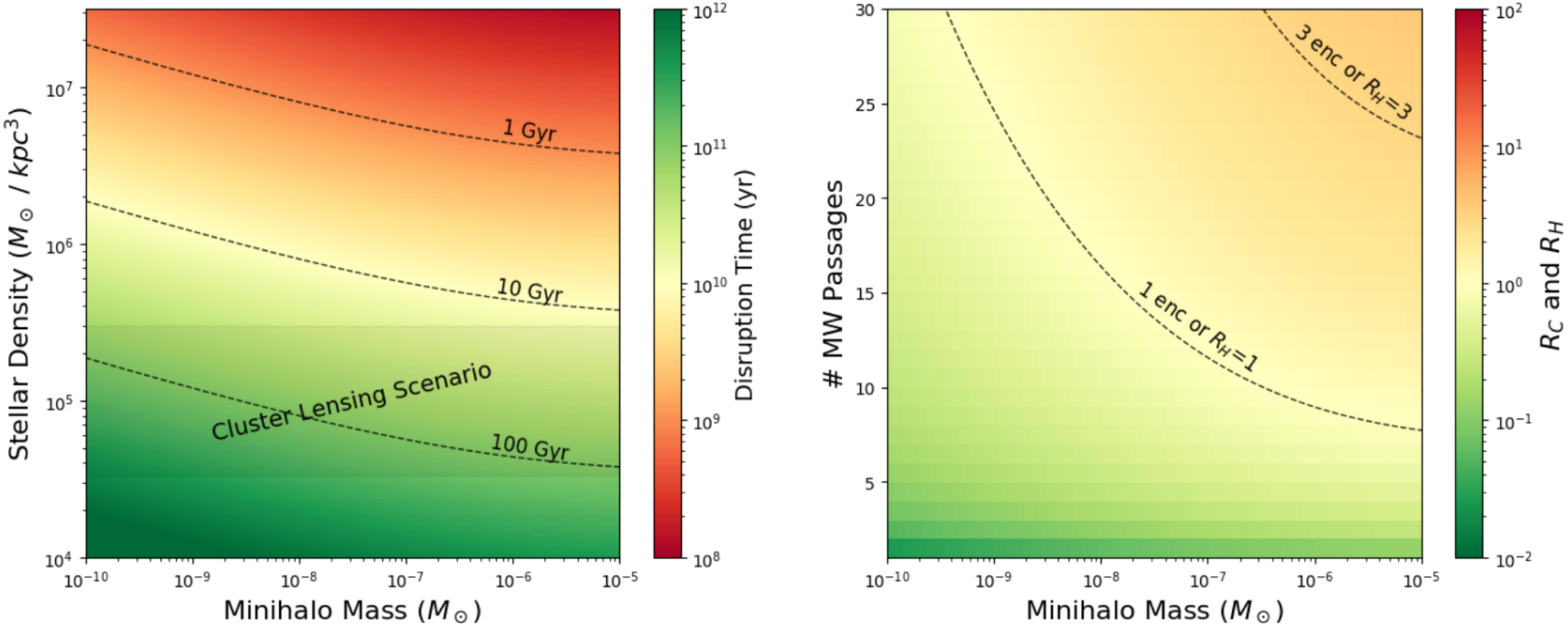
Repeated tidal heating due to **head-on collision between similar mass**
Timescale for disruption much longer than the age of the universe



3. High-speed encounters with passing stars

Single flyby disruption within some critical impact parameter
In the intracluster environment, timescale for disruption still a bit longer than the age of the universe

Dynamic disruption in MW and intracluster space



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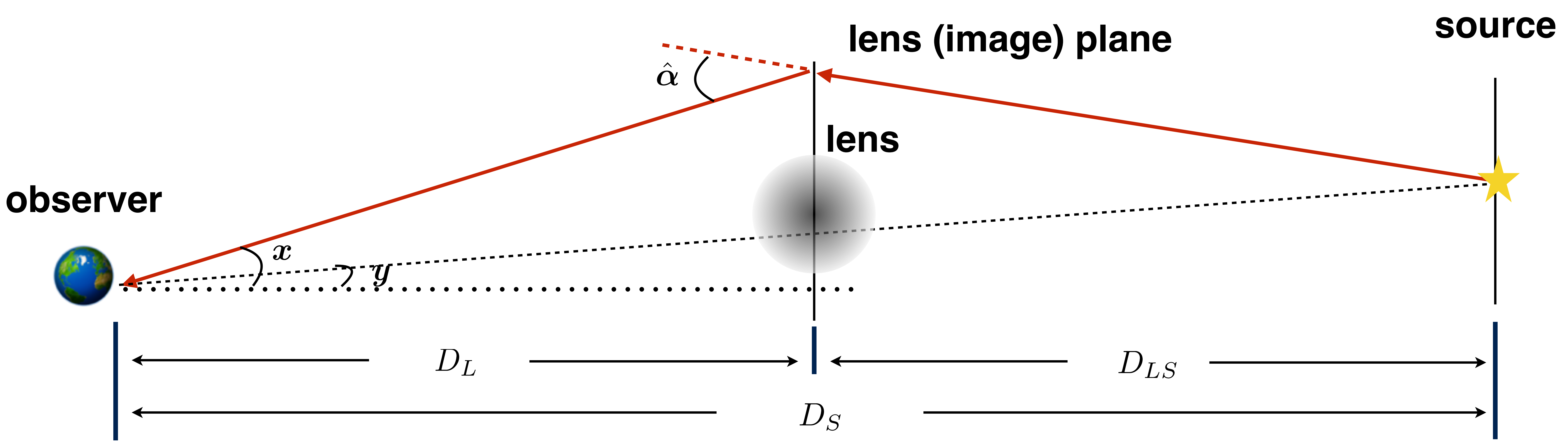
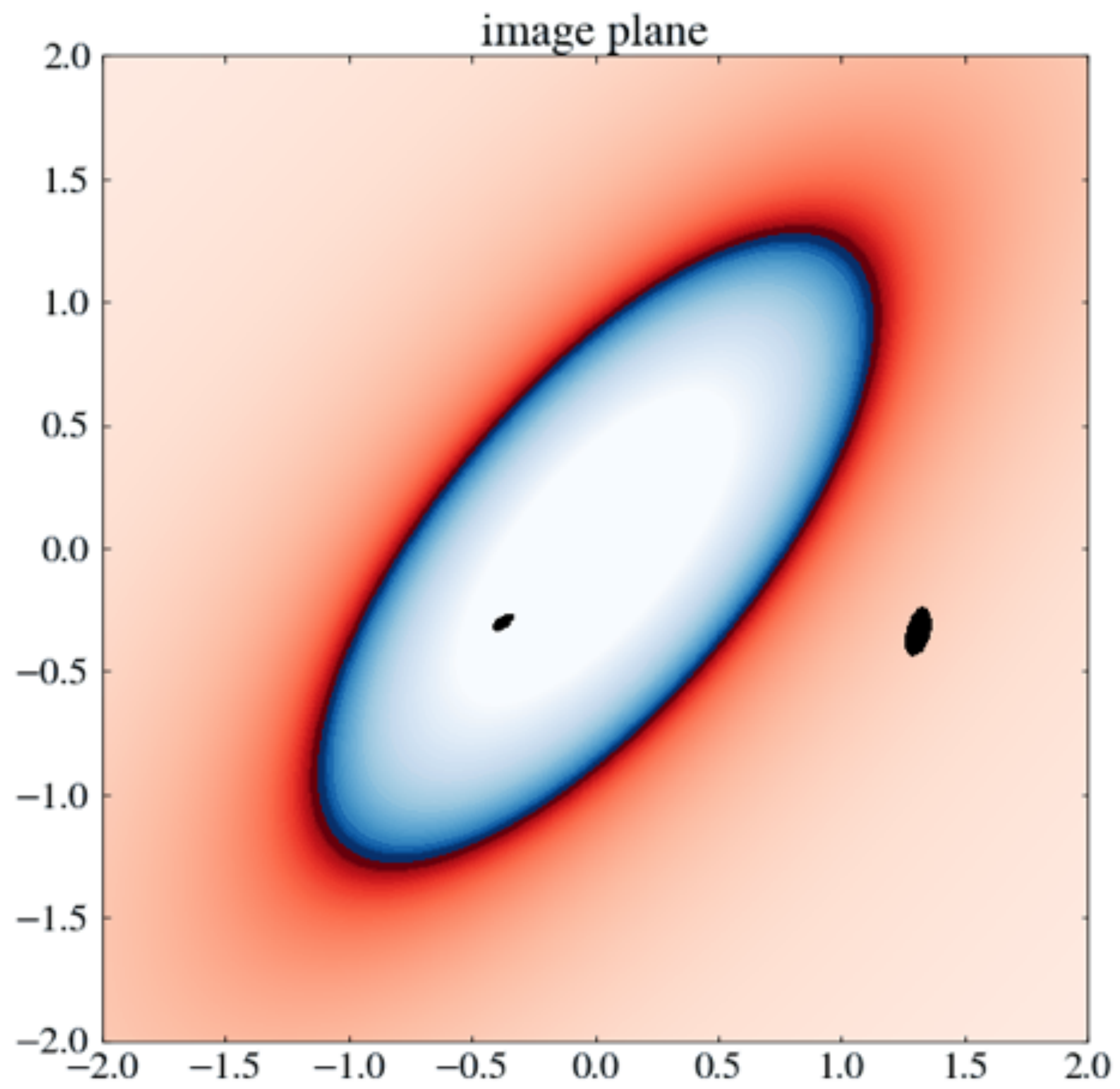
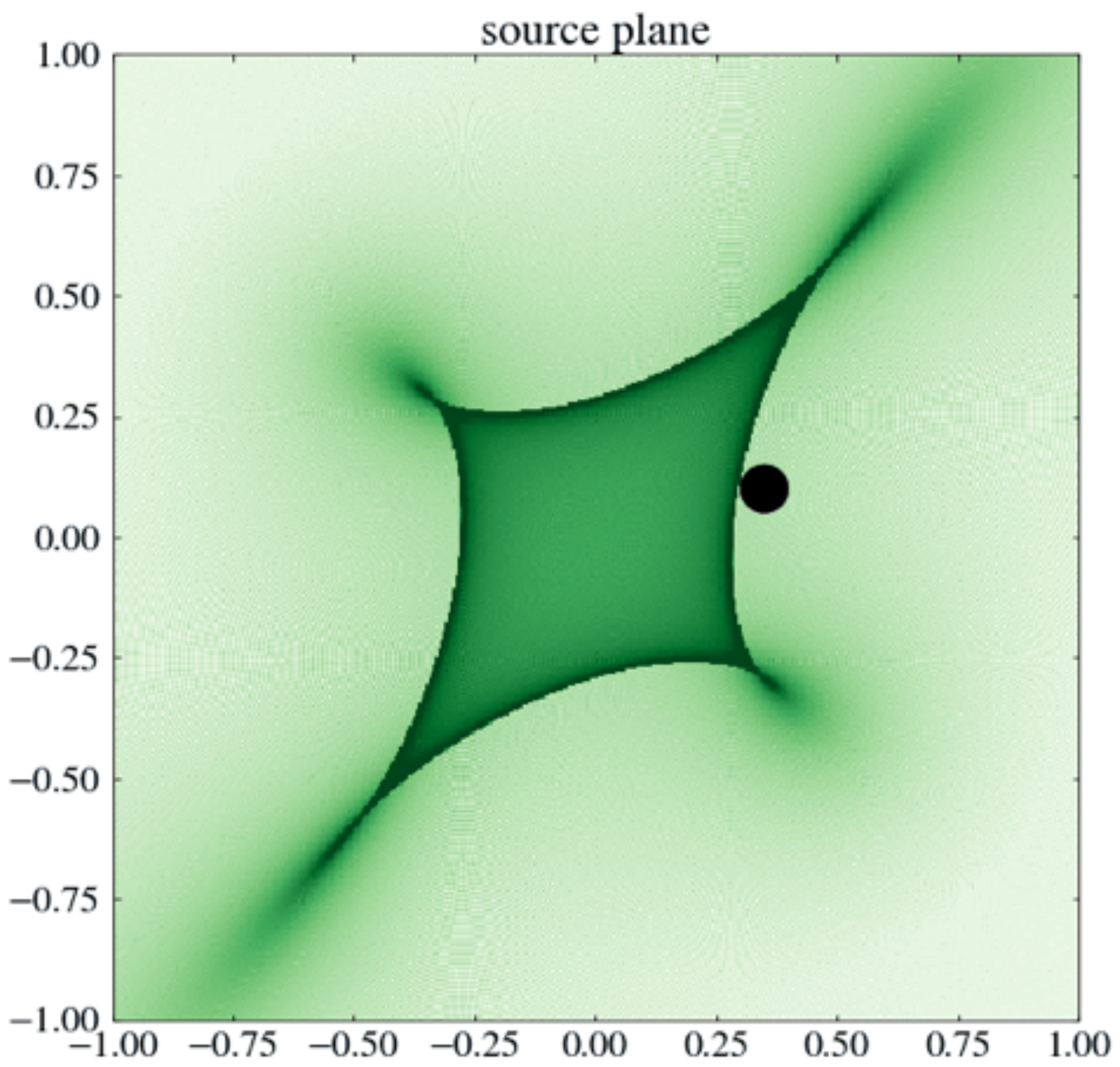
Geometric Description of Lensing







ray equation $$\boldsymbol{y} = \boldsymbol{x} - \frac{D_{LS}}{D_S}\hat{\boldsymbol{\alpha}}(\boldsymbol{x}) = \boldsymbol{x} - \boldsymbol{\alpha}(\boldsymbol{x})$$

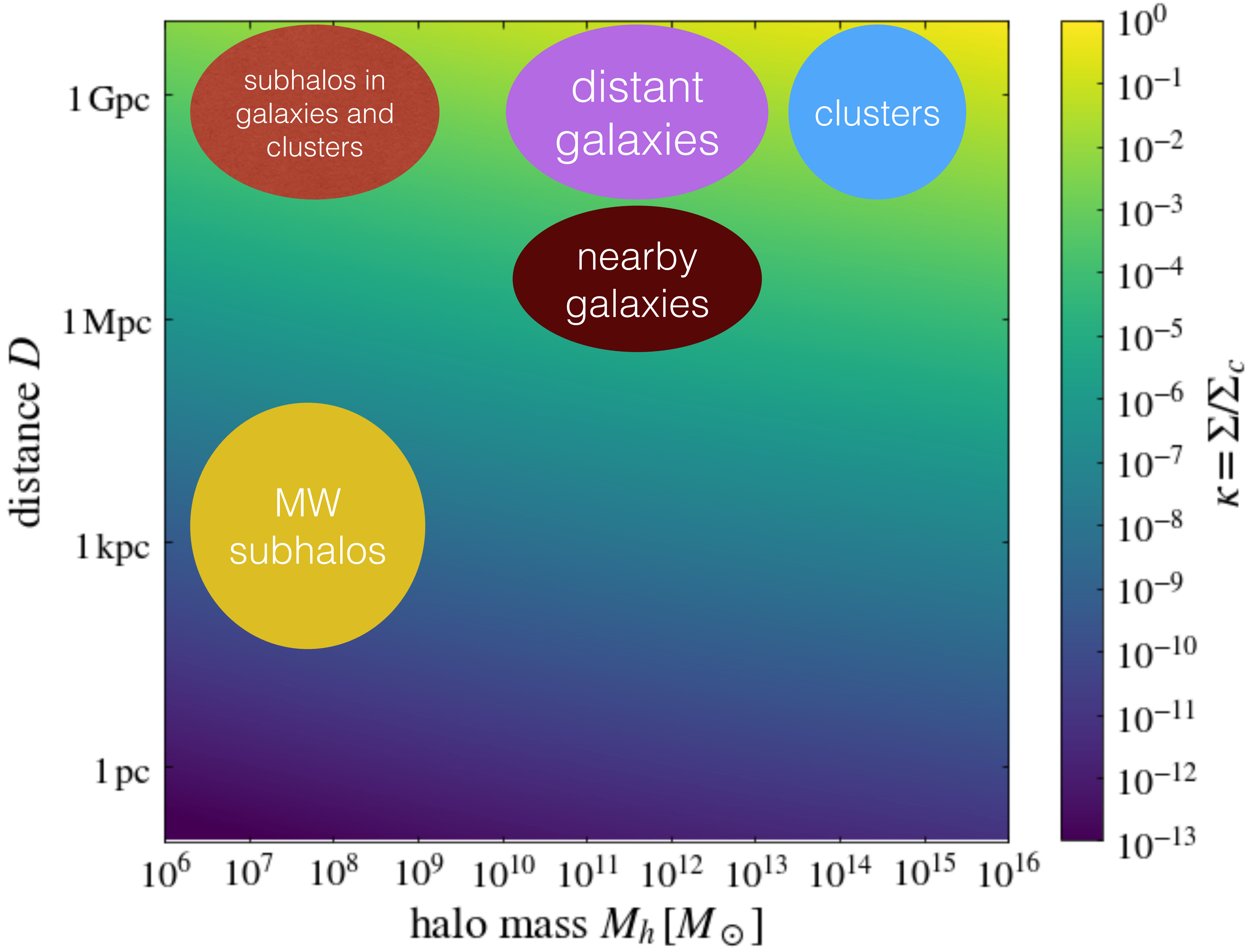
convergence and shear $$\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}} = \begin{bmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{bmatrix}$$

flux magnification $$\mu = 1/\left[(1-\kappa)^2 - (\gamma_1^2+\gamma_2^2)\right]$$

Problem Detecting Extended Lenses

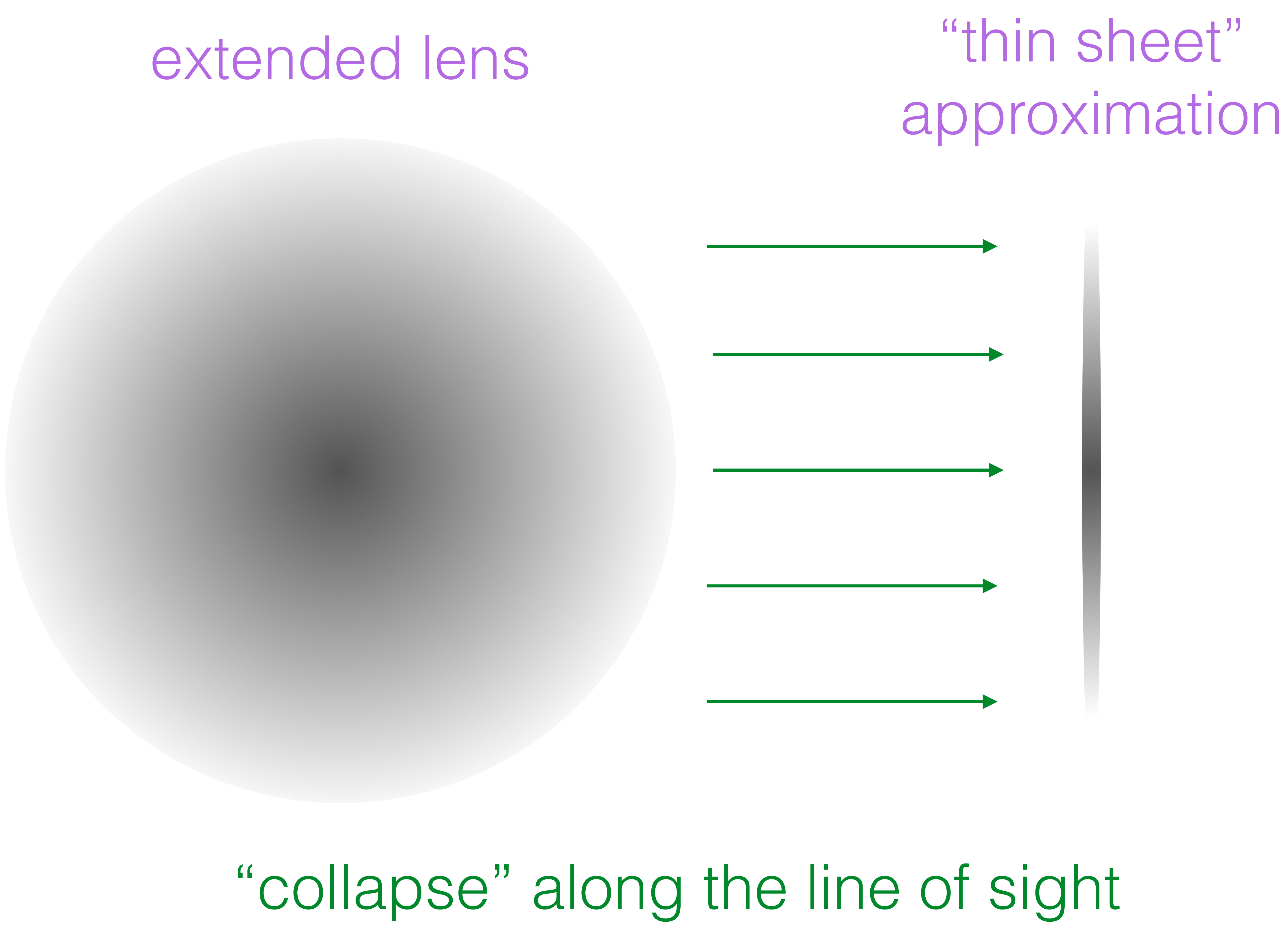
Lensing convergence

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

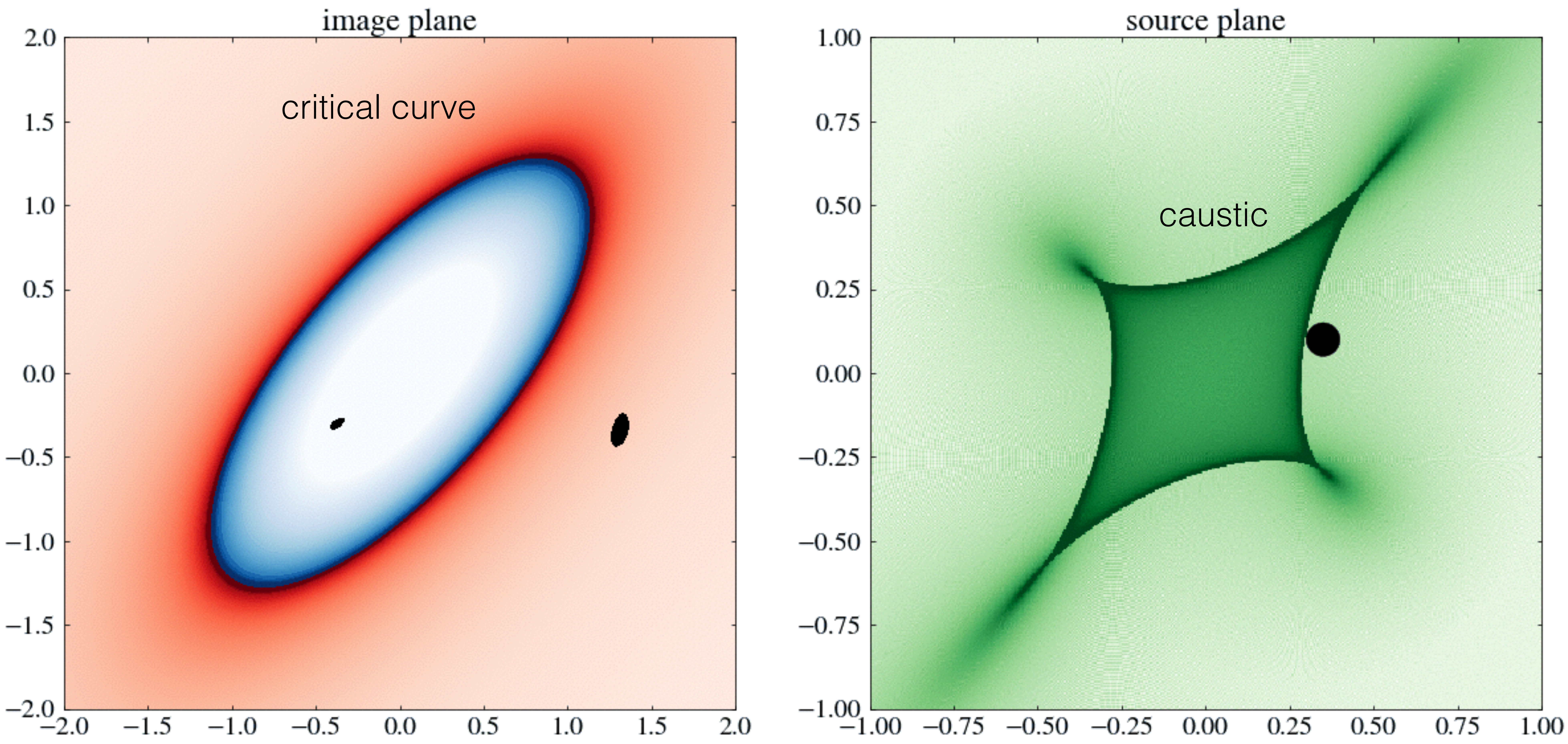


Critical lens surface density

$$\Sigma_c \sim \frac{1}{4\pi\, G\, D}$$

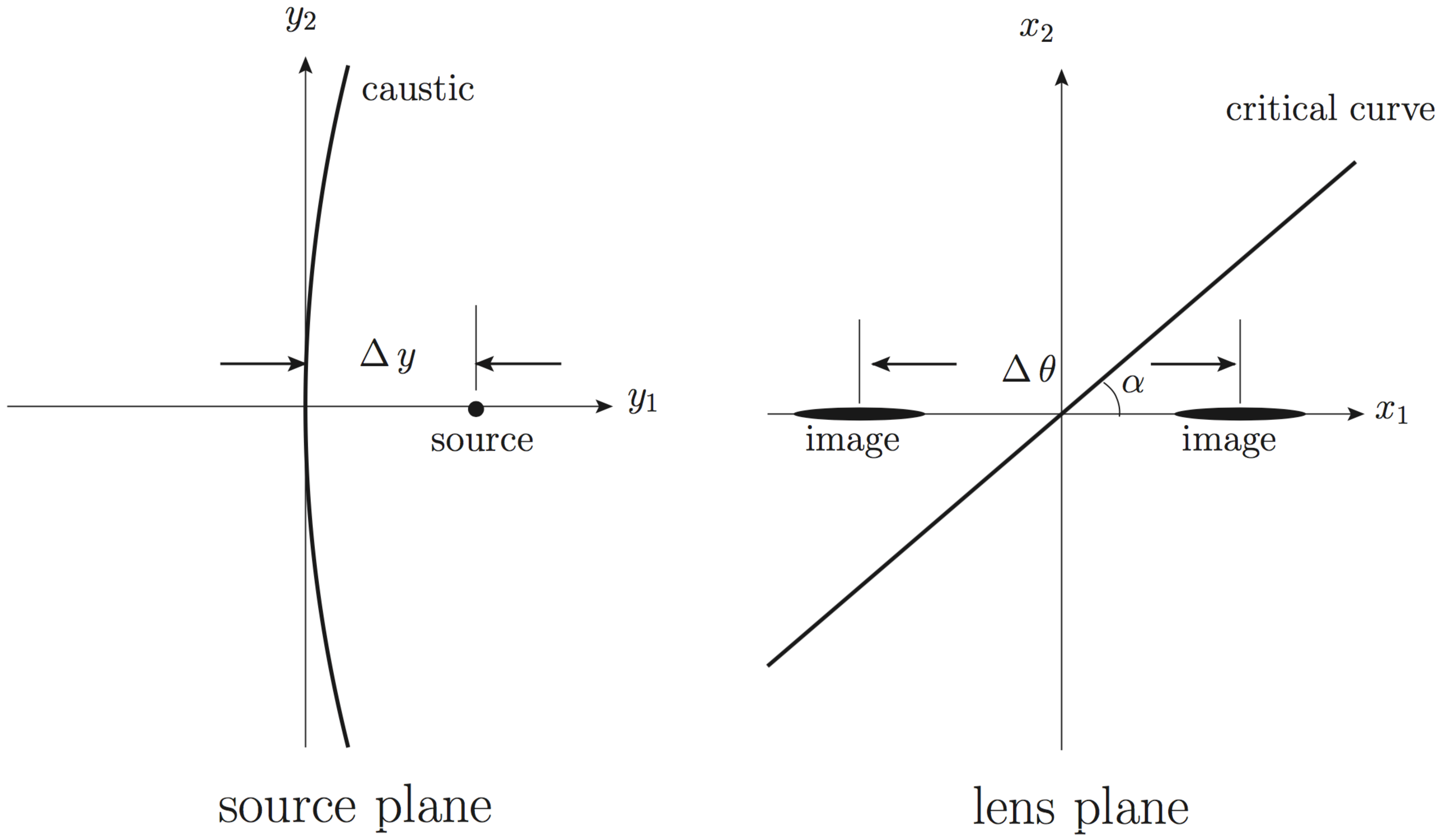


Caustic and Critical Curve



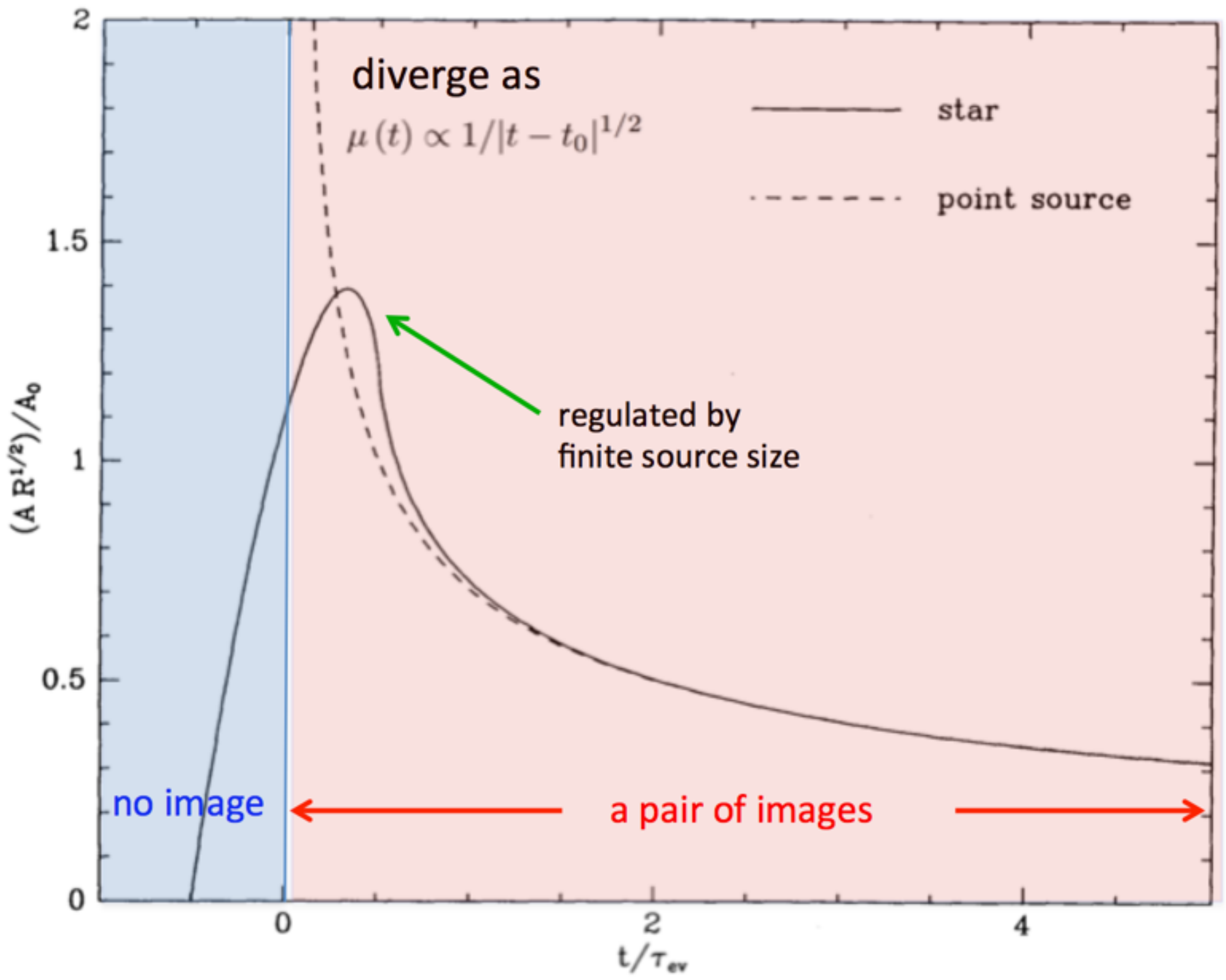
Discontinuous change in the number and configuration of images.
Exhibit **universal behaviors** governed by Catastrophe Theory

Caustic Transit of Compact Sources



$$\mu \sim \theta_C / \Delta\theta$$

Miralda-Escudé 91'



$$\Delta\theta \sim 10 - 100\,\mathrm{mas}$$

$$\theta_C \sim 10''$$

$$\mu \sim \frac{\theta_C}{\Delta\theta} \sim \mathrm{few} \times 10^{2-3}$$

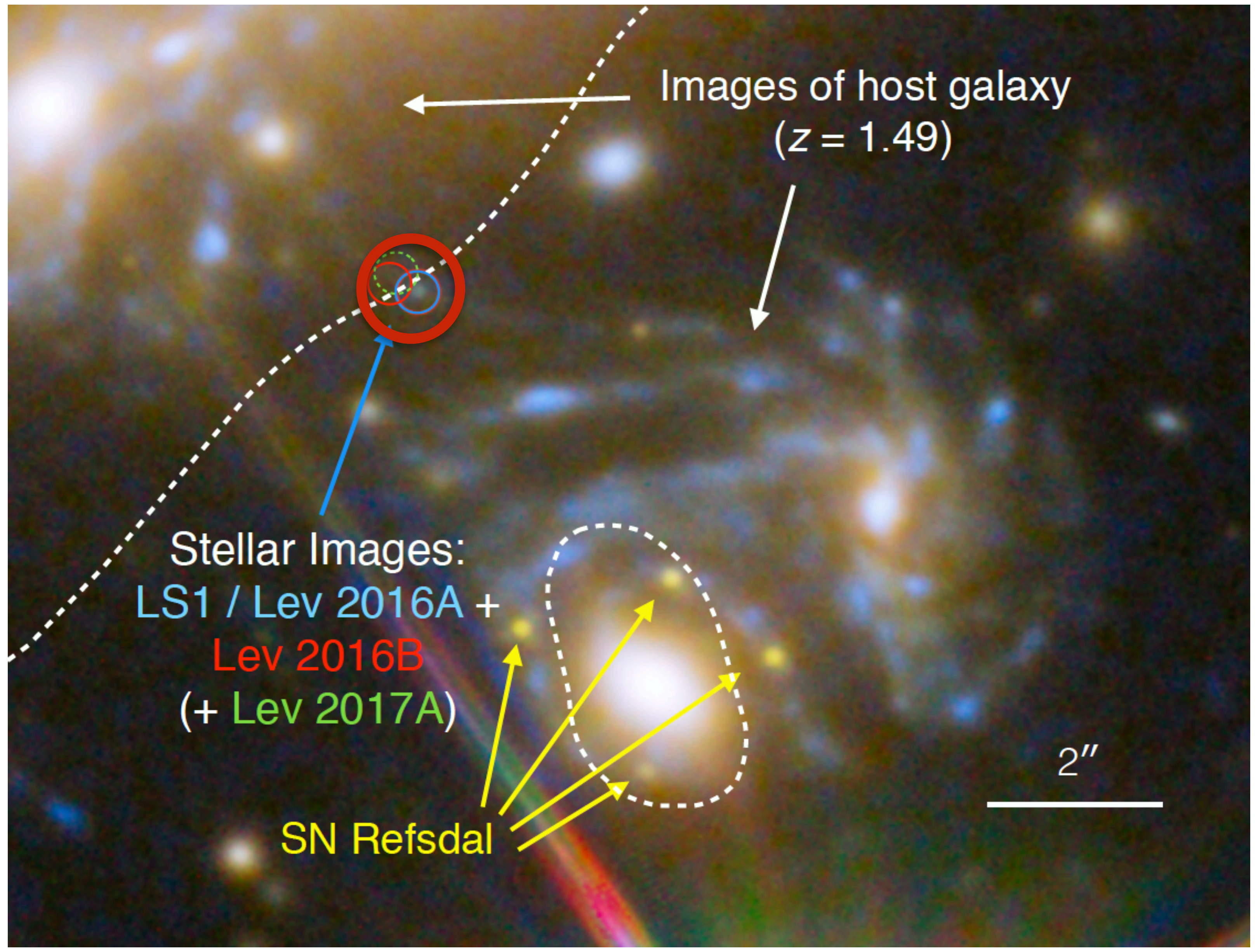
finite source size $\mu_{\rm pk} \propto R_S^{1/2}$

wave diffraction $\mu_{\rm pk} \propto \lambda^{-1/3}$

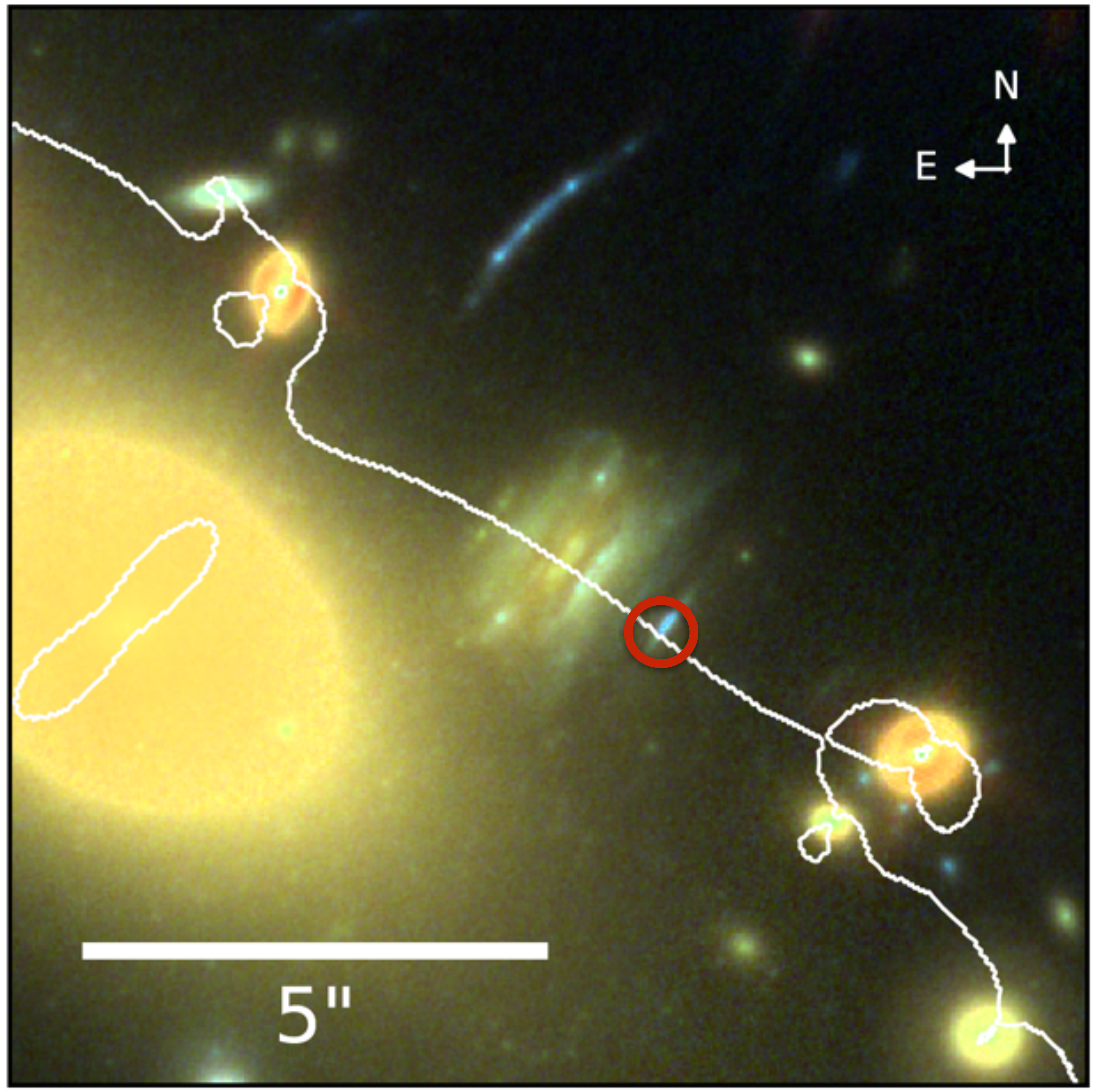
Extremely Magnified Stars

Miralda-Escudé 1991

Kelley++ 2017 MACS J1149 LS1



Chen++ 2019
Kaurov++ 2019 MACS J0416



Supergiant stars residing in z ~ 1 lensed arcs

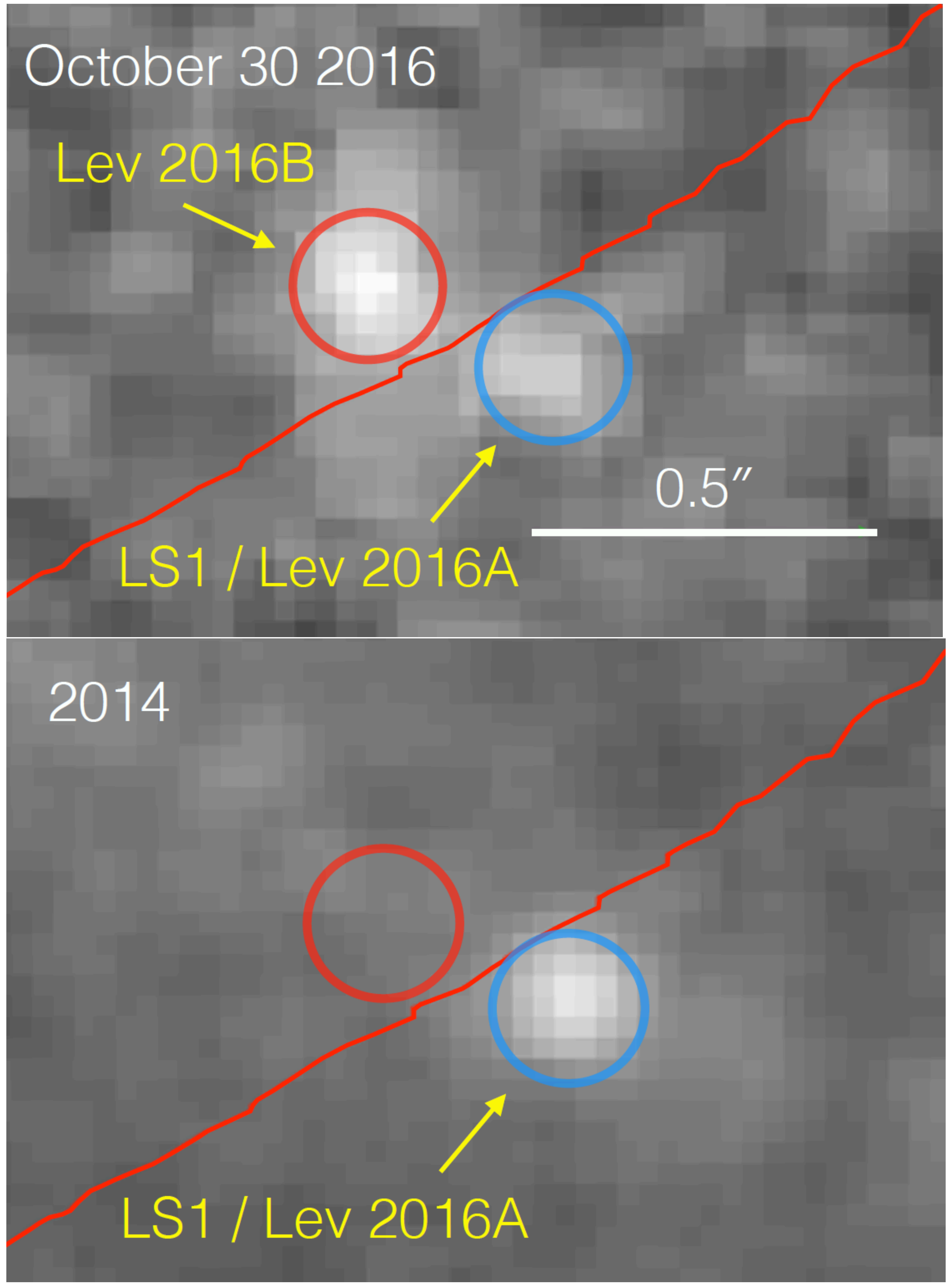
Persistently magnified by O(100) fold. Reach AB mag = 28 — 29

Elongated macro image pair; separated by telescope

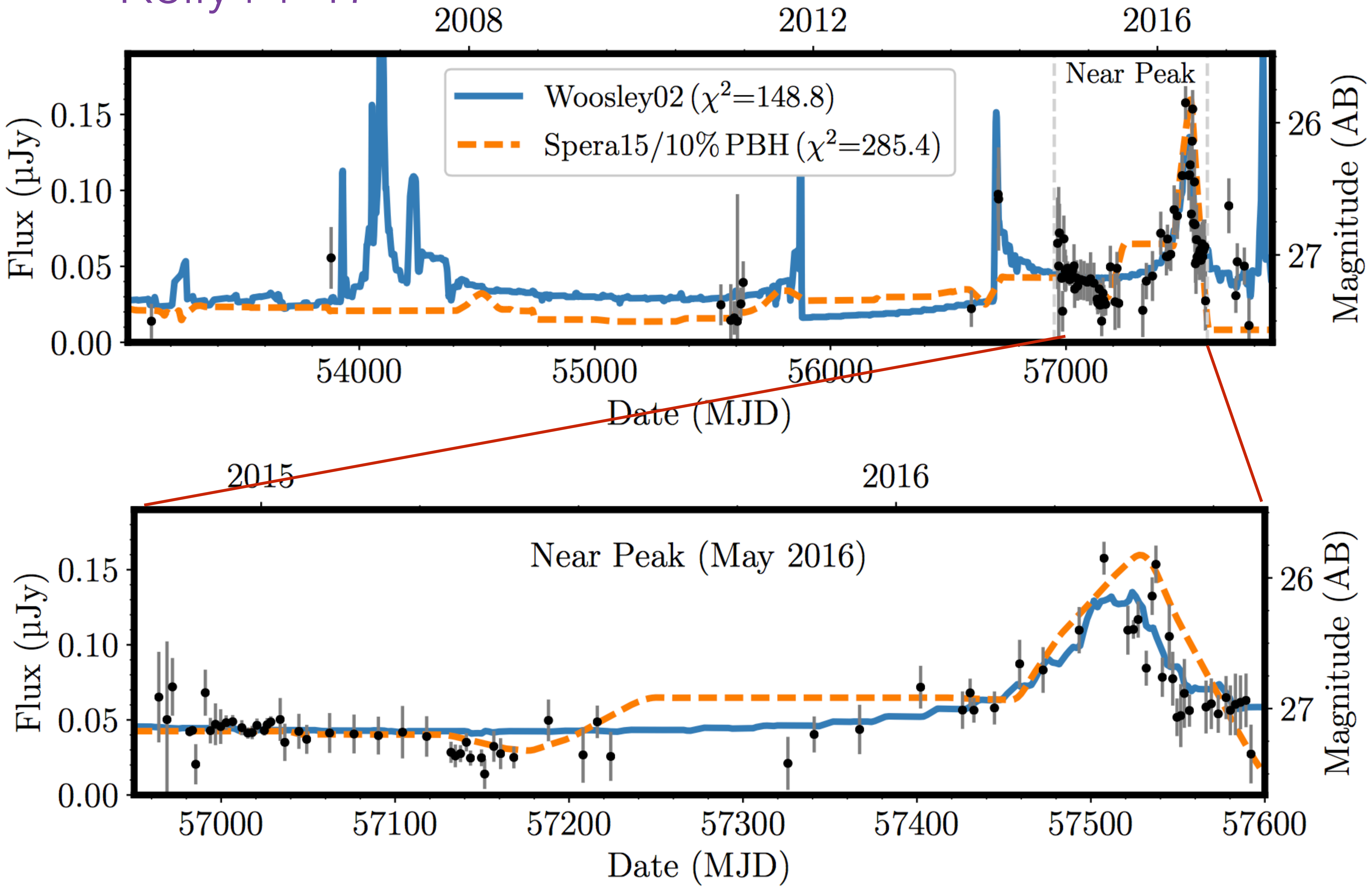
Phenomenology very sensitive to lumpiness in the lens

Dai++ 2018

Caustic Transient Variability



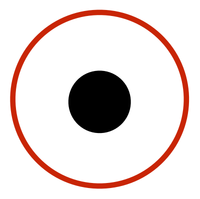
Kelly++ 17'



A pair of images resolved.
Source intermittently brightens

"Microlensing" Near Critical Curve

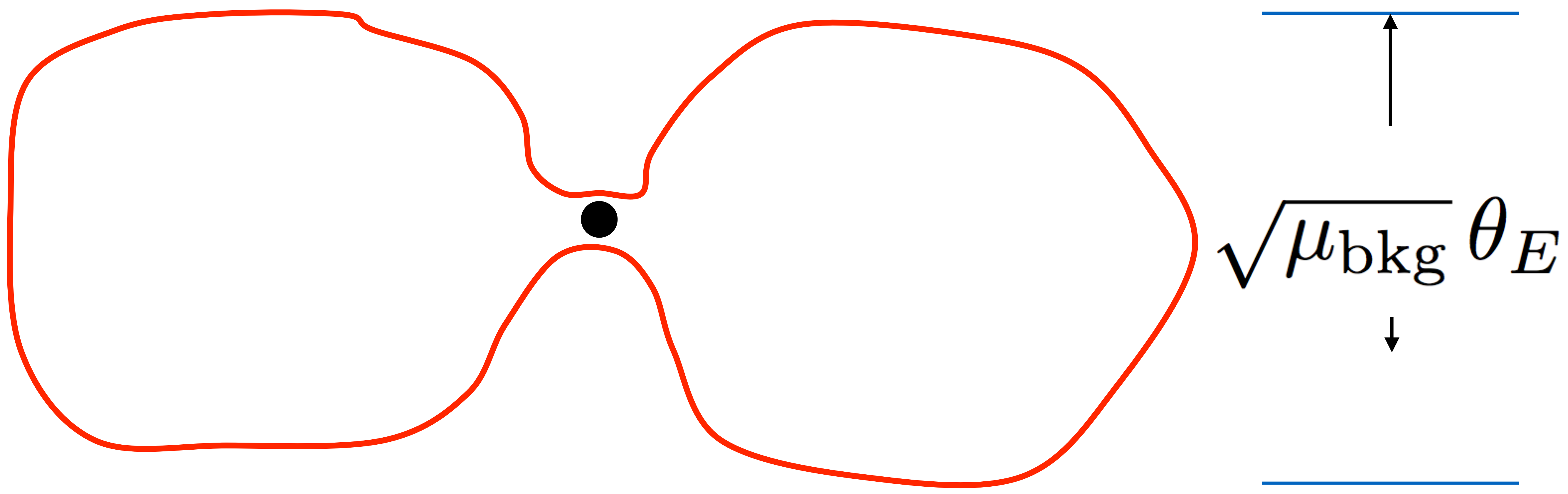
An isolated microlens



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

Covering factor of "Einstein disks" is minuscule for isolated micro-lenses

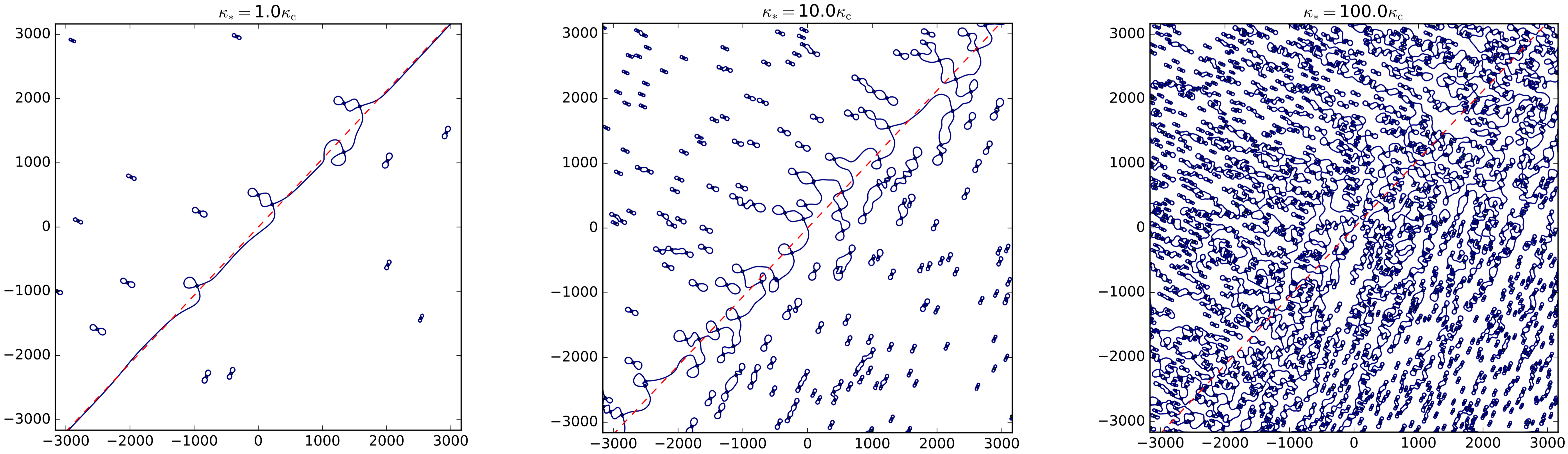
An microlens (in projection) near the critical curve



Microlensing cross section enhanced by a huge factor $\sim 10^{2\text{-}3}$

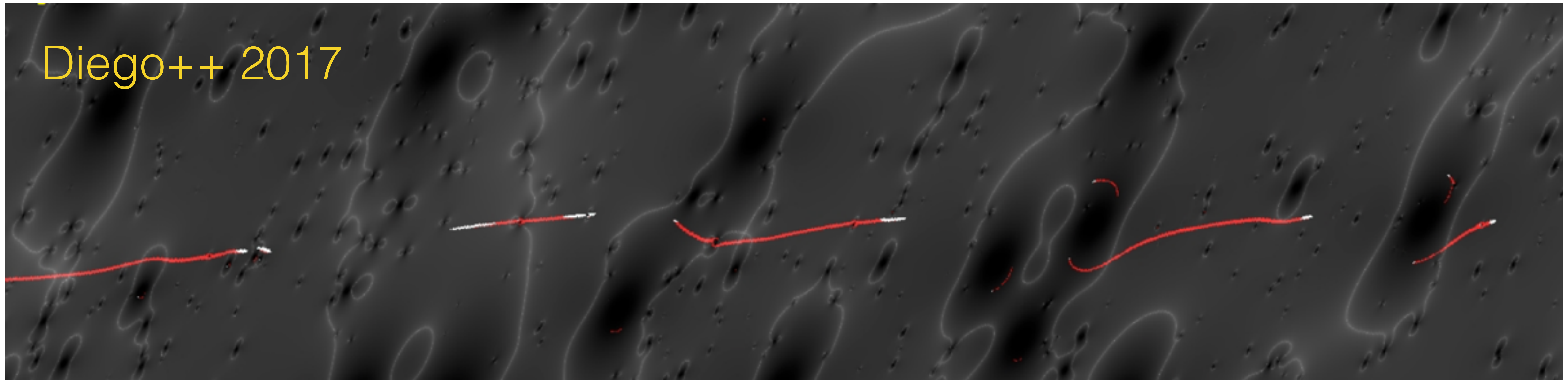
Effects of Many Micro-lenses

Venumadhav, LD & Miralda-Escudé 17'
Diego++ 17'
Oguri++ 18'



occasionally perturbed | completely disrupted | corrugated network

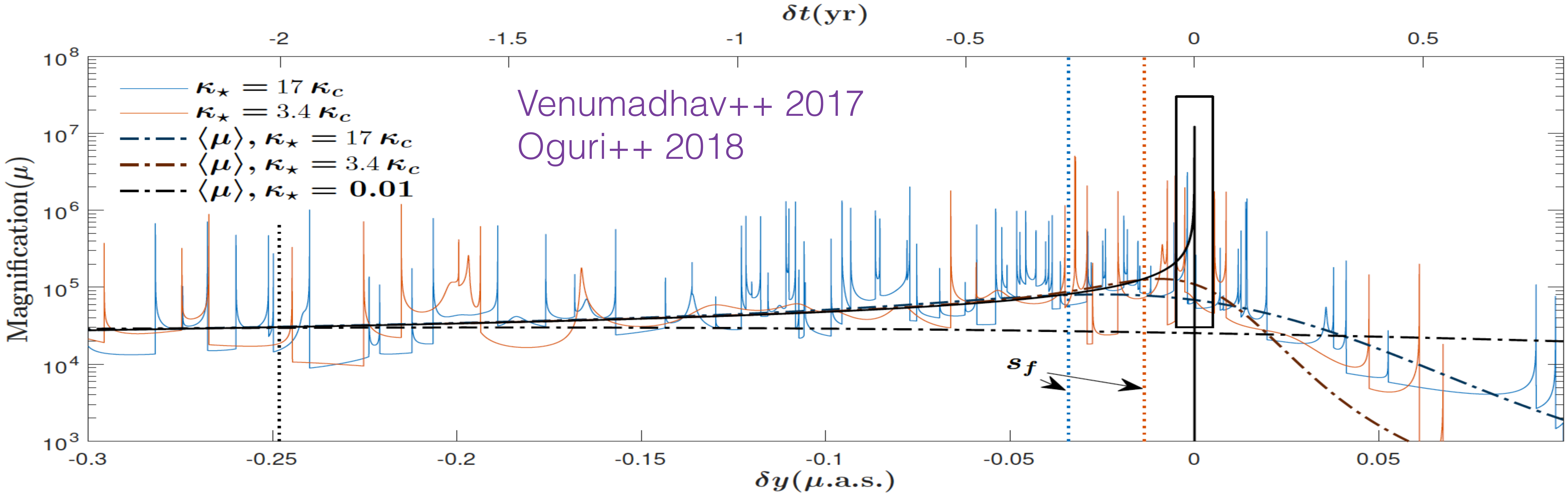
Intermittent Microlensing by Intracluster Stars



frequent microlensing peaks ~ few times per yr

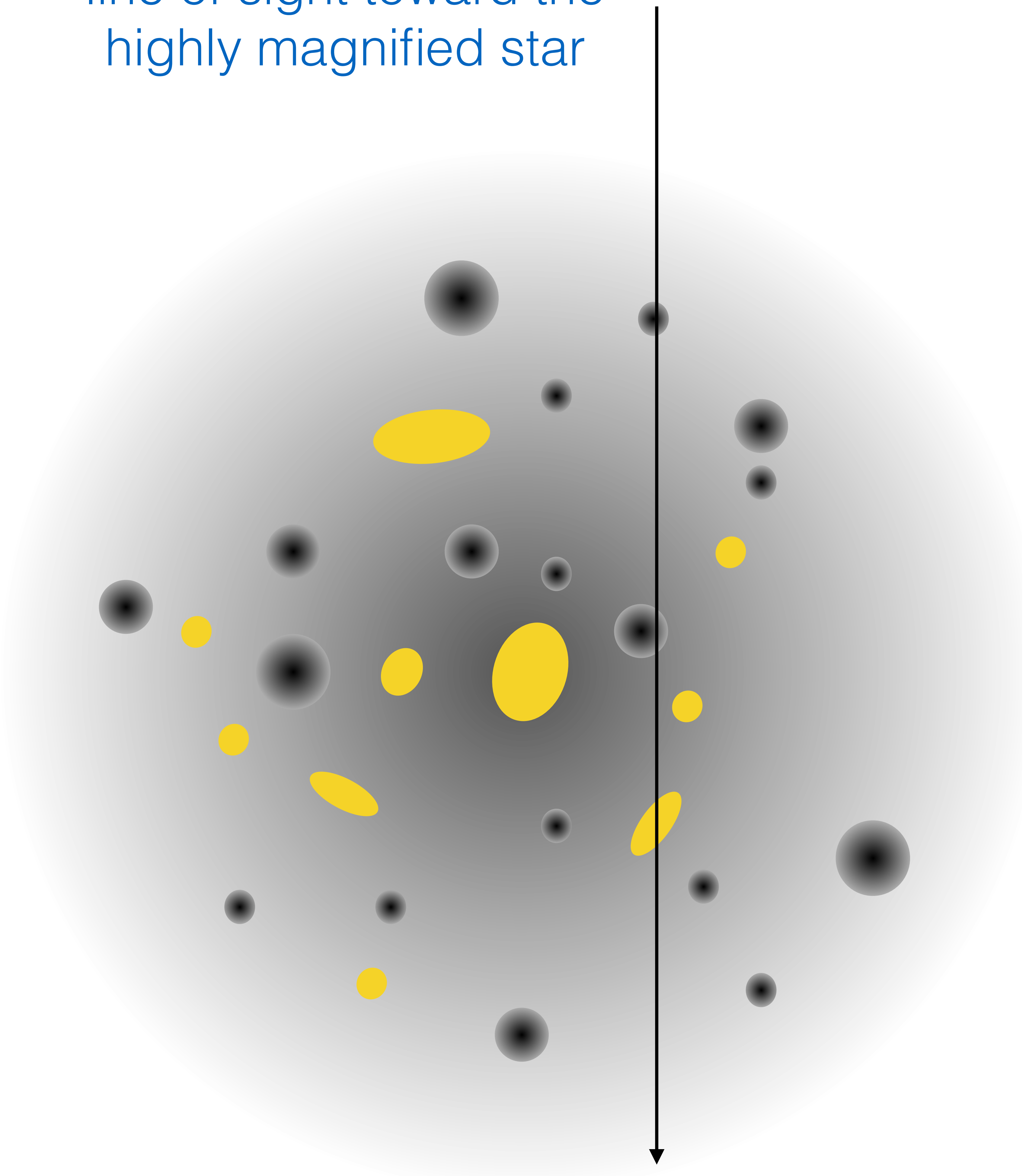
$$\mu_{\rm peak} \sim 10^4 \, (R/10\, R_\odot)^{-1/2}$$

cross corrugated network for **~ 10⁴ yrs** !!



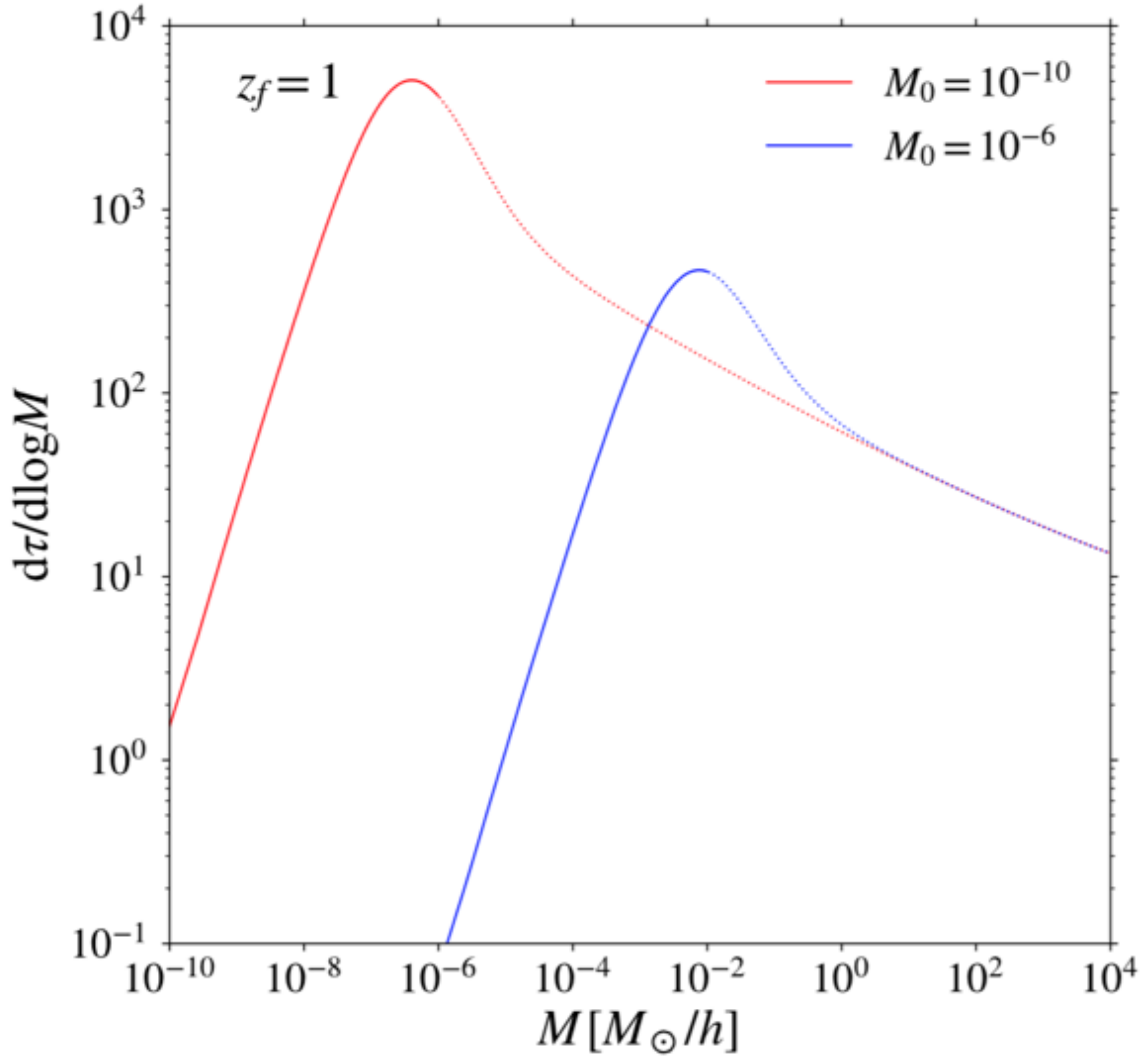
Many Minihalos Stacked Along LoS

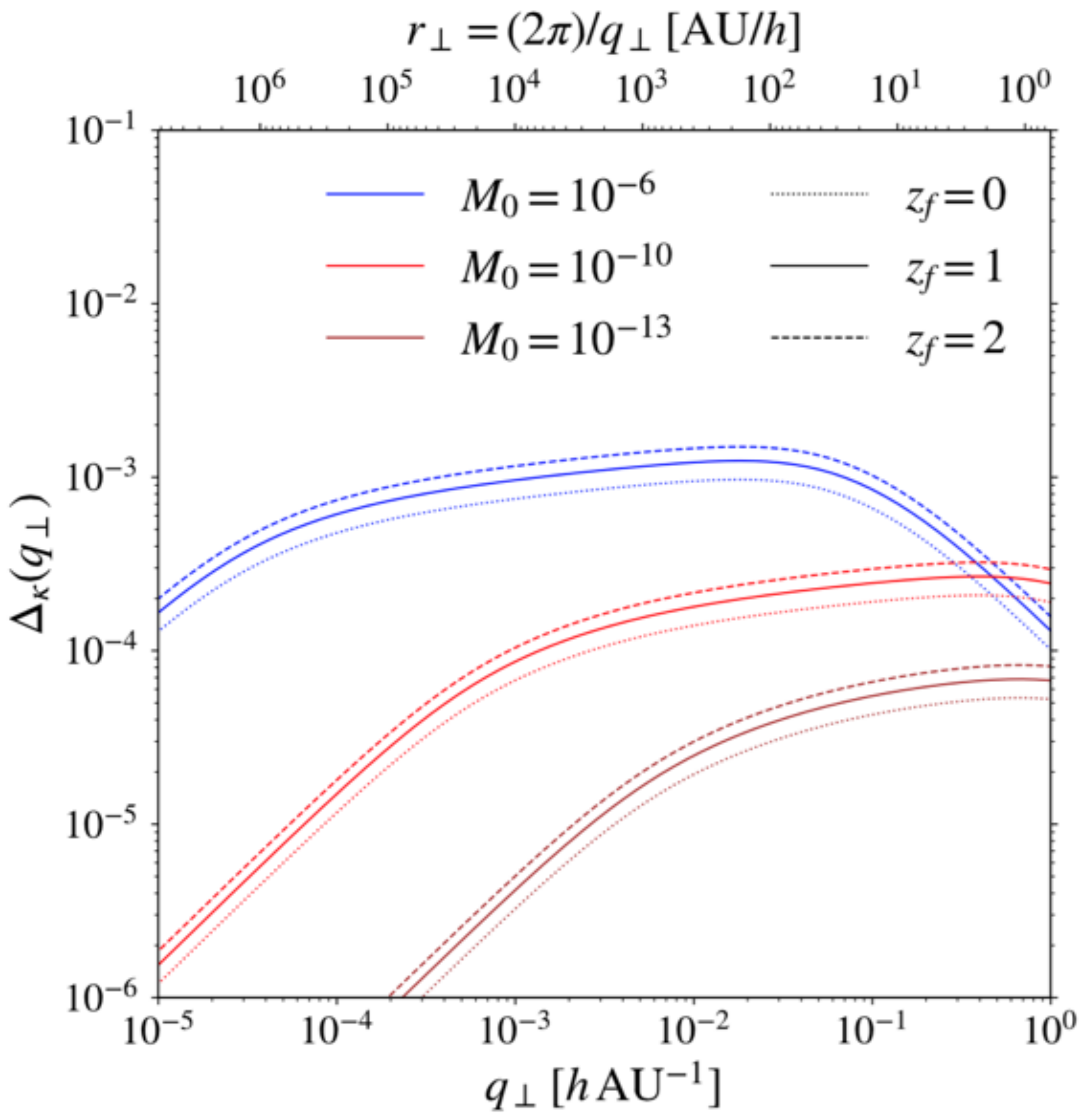
line of sight toward the
highly magnified star



galaxy cluster

(minihalos too small and too
numerous to be shown here)

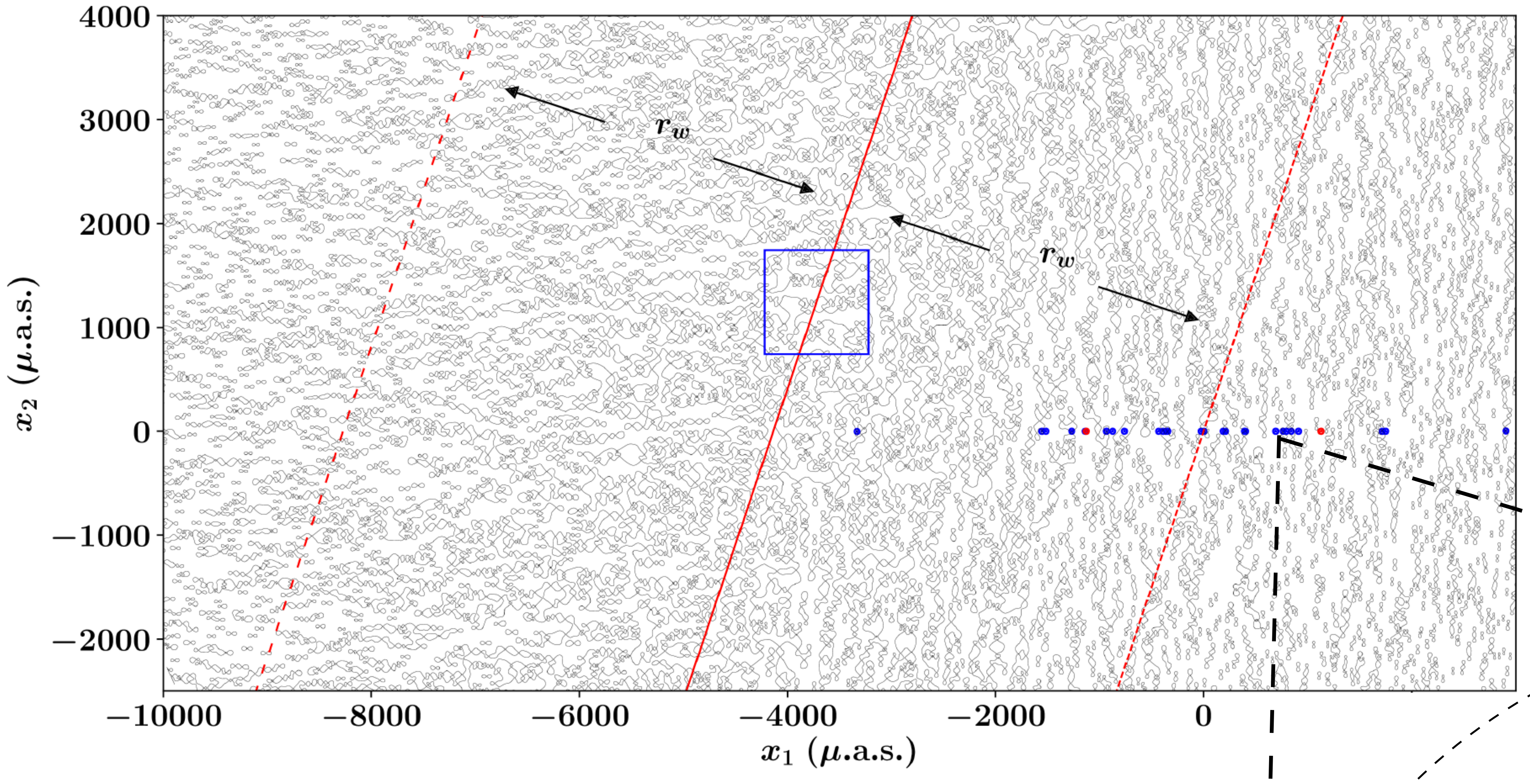


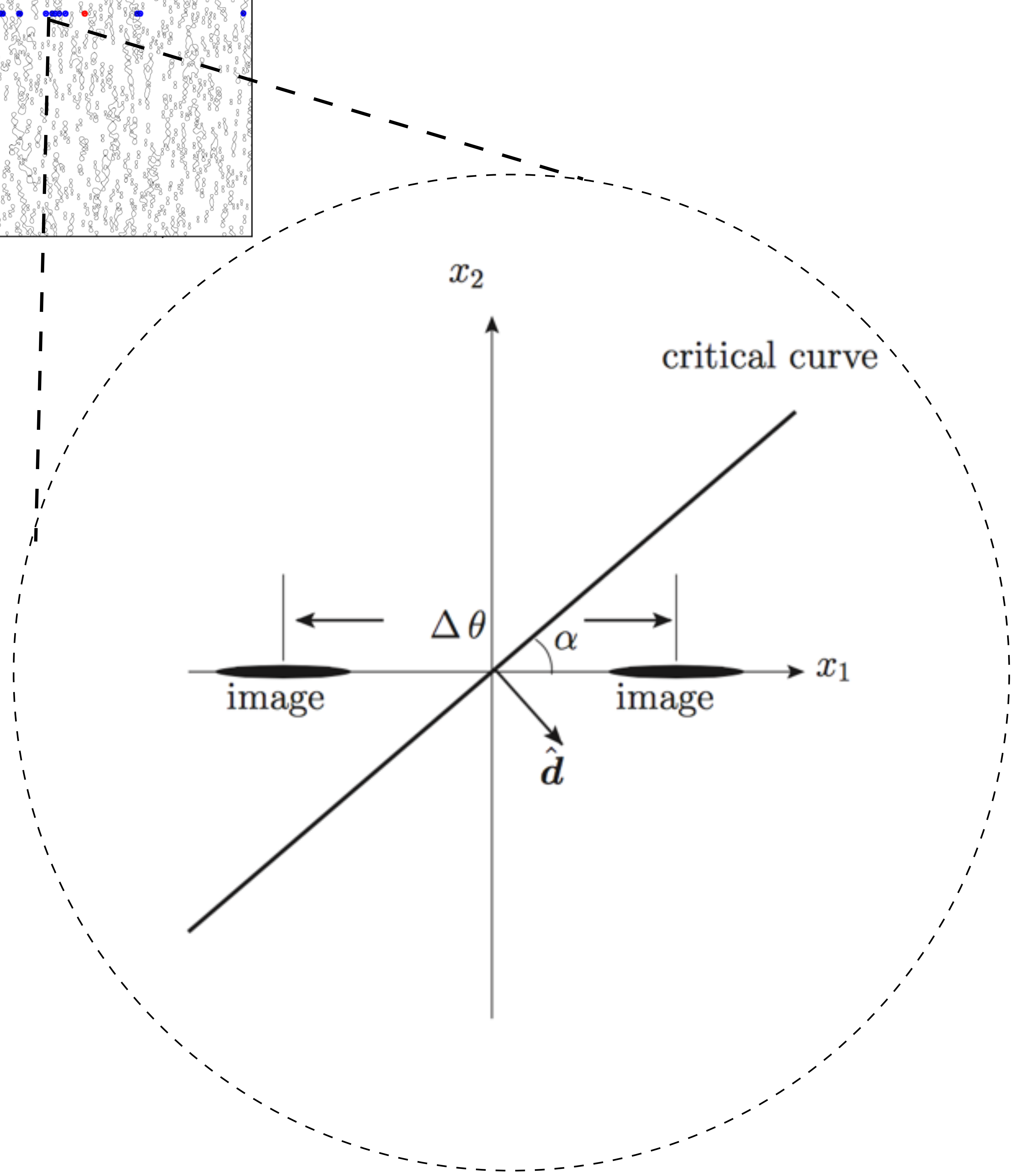


volume occupation factor << 1
area covering factor >> 1

(Gaussianized) surface density fluctuations
~ 10^{-4}—10^{-3} on scales **~10^{2}—10^{4} AU**

Minuscule Fluctuations Can Matter ?!

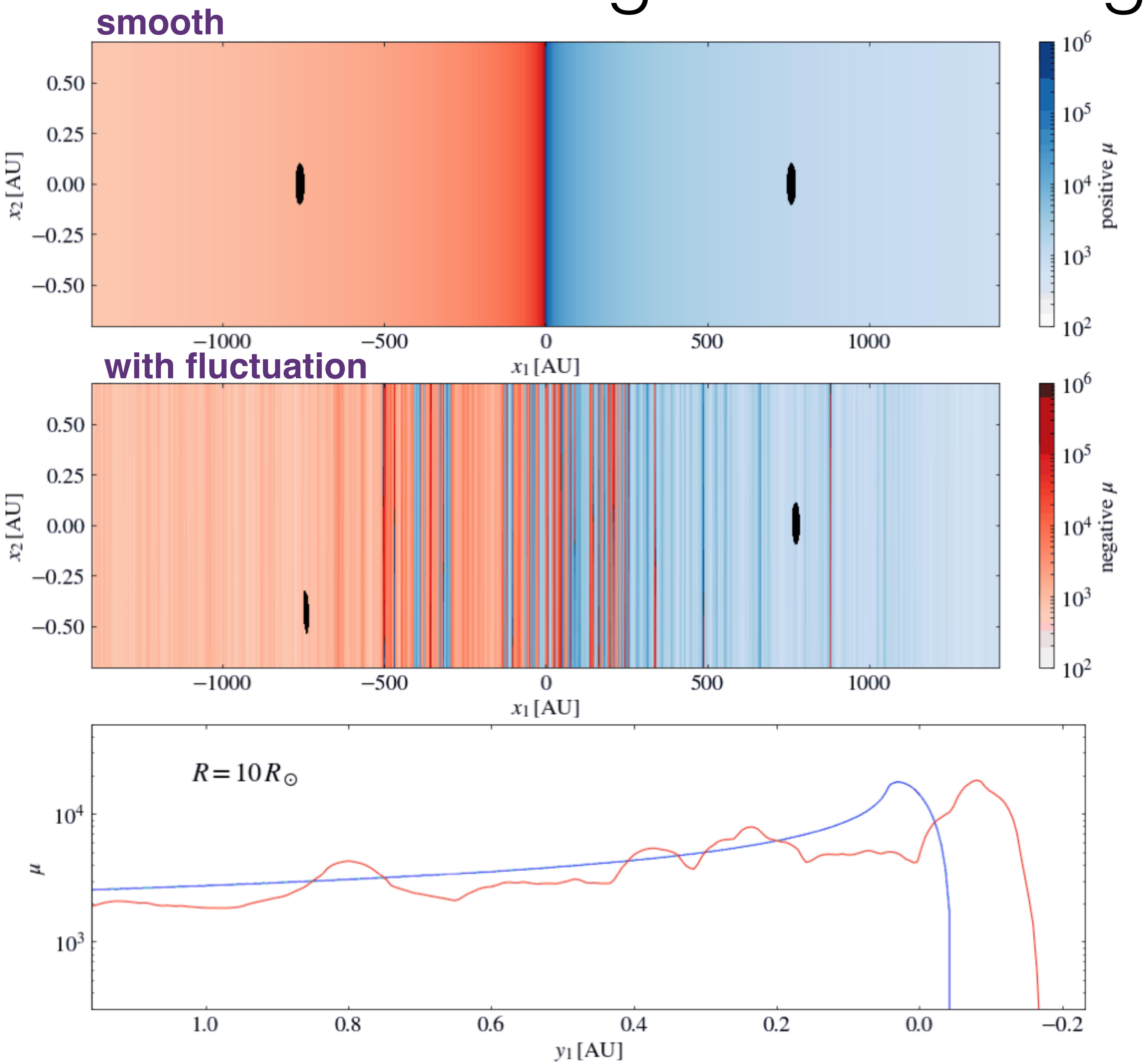




Around the times of microlensing peaks, two micro images are magnified up to ~ 10^3—10^4

If surface density varies on scales close to the size of the (elongated) micro images, fractional changes on the order of **the inverse magnification** alter the flux by **order unity**!

Light Curve Irregularities



An example of a microlensing peaking event

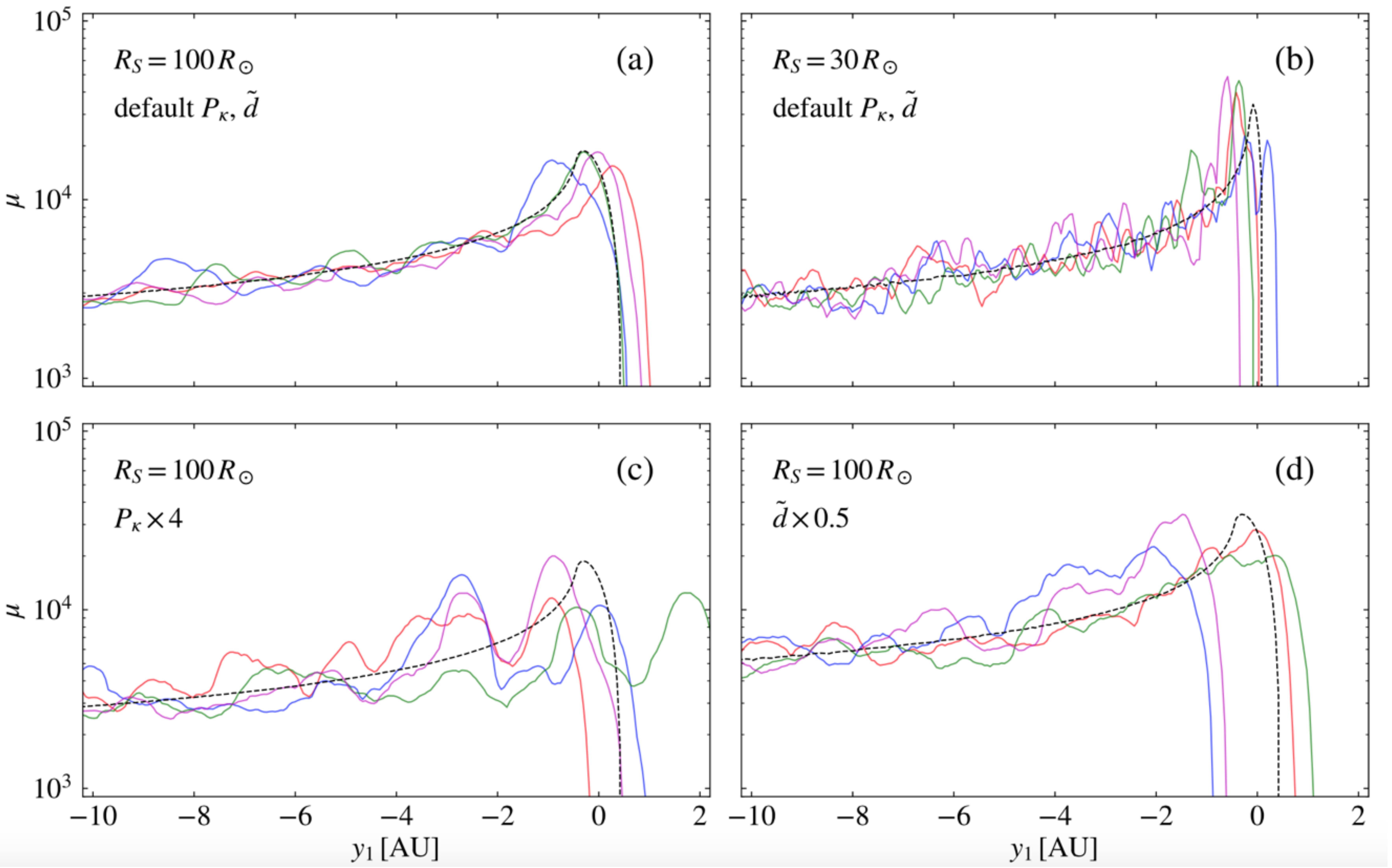
Parameters inferred for **MACS J1149 LS1**

time to traverse 1 AU = $6\,\mathrm{d}\left(\frac{v_t}{300\,\mathrm{km/sec}}\right)$

Conclusion:

We should follow up microlensing peak events with dedicated observations !

Light Curve Irregularities



Dependence on:
stellar size, convergence fluctuation,
and peak magnification.

Summary

- The axion particle is viable candidate for CDM. Additional gravitationally bound structures can form on very small scales if Peccei-Quinn phase transition occurs after inflation. However, gravitational lensing detection of individual mini-halos seems infeasible.

- High abundance of mini halos are expected in intracluster space and are expected to survive the dynamic environment there. They collectively produce subtle surface density fluctuations on minuscule scales.

- Highly magnified extragalactic stars have been observed near the lensing caustic behind galaxy cluster lenses. They undergo frequency microlensing events due to intracluster stars.

- Order unity irregularities in the light curve can be produced by the minihalo population, whenever a caustic crossing star is temporarily magnified by a tremendous factor ($\sim 10^4$)