Caustic crossings as a new probe of dark matter

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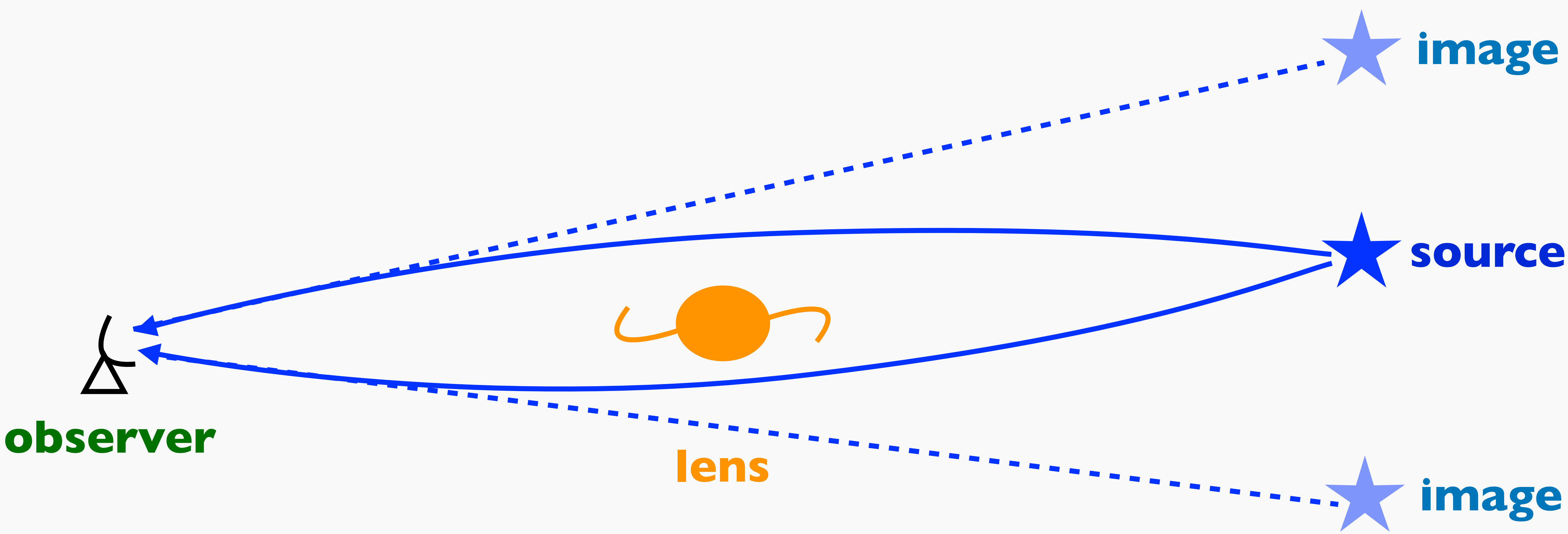
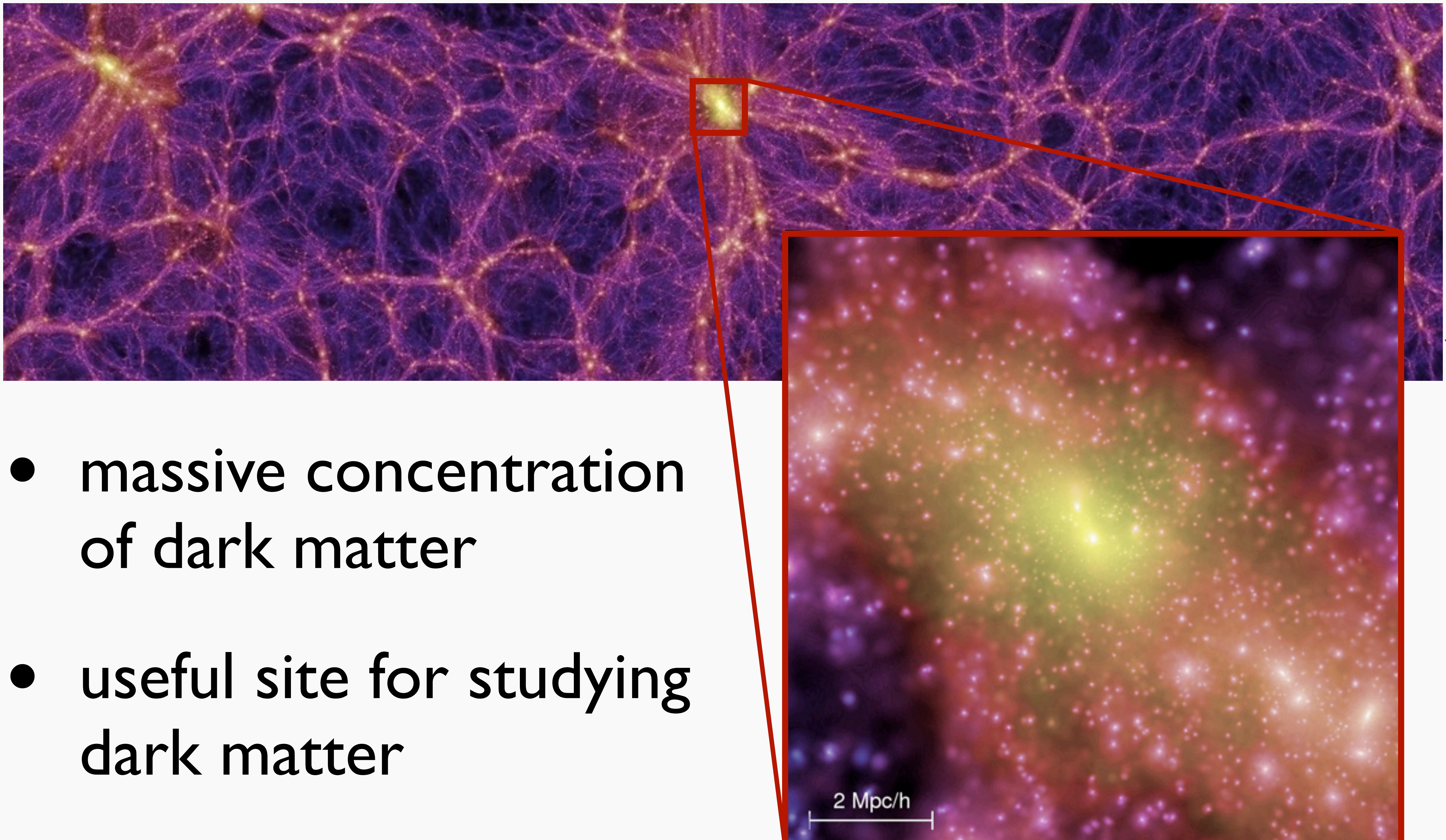
Strong gravitational lensing



- multiple solution of **image position $\vec{\theta}$** for lens equation $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$

  → **multiple images**

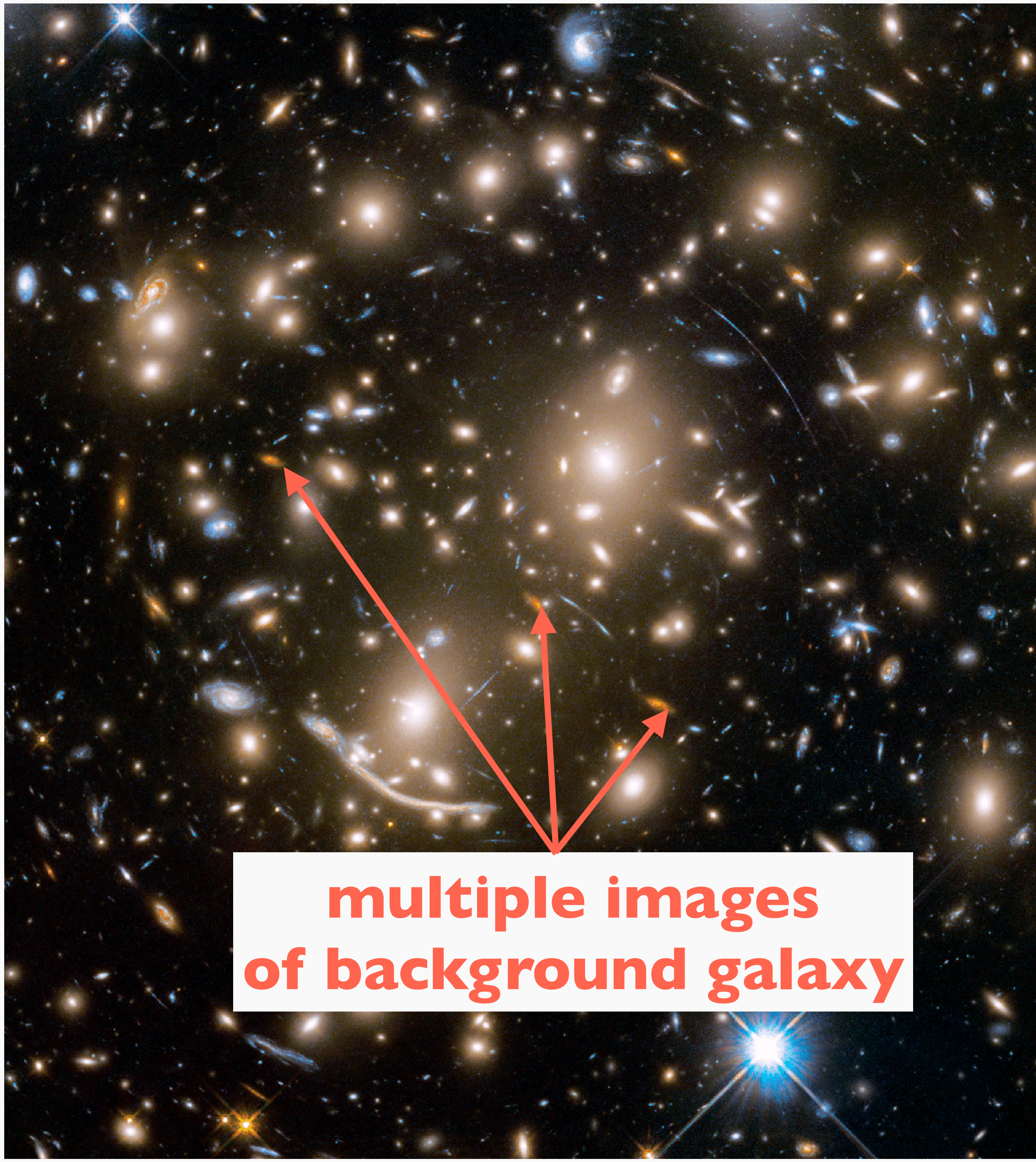
Gravitational lensing by cluster



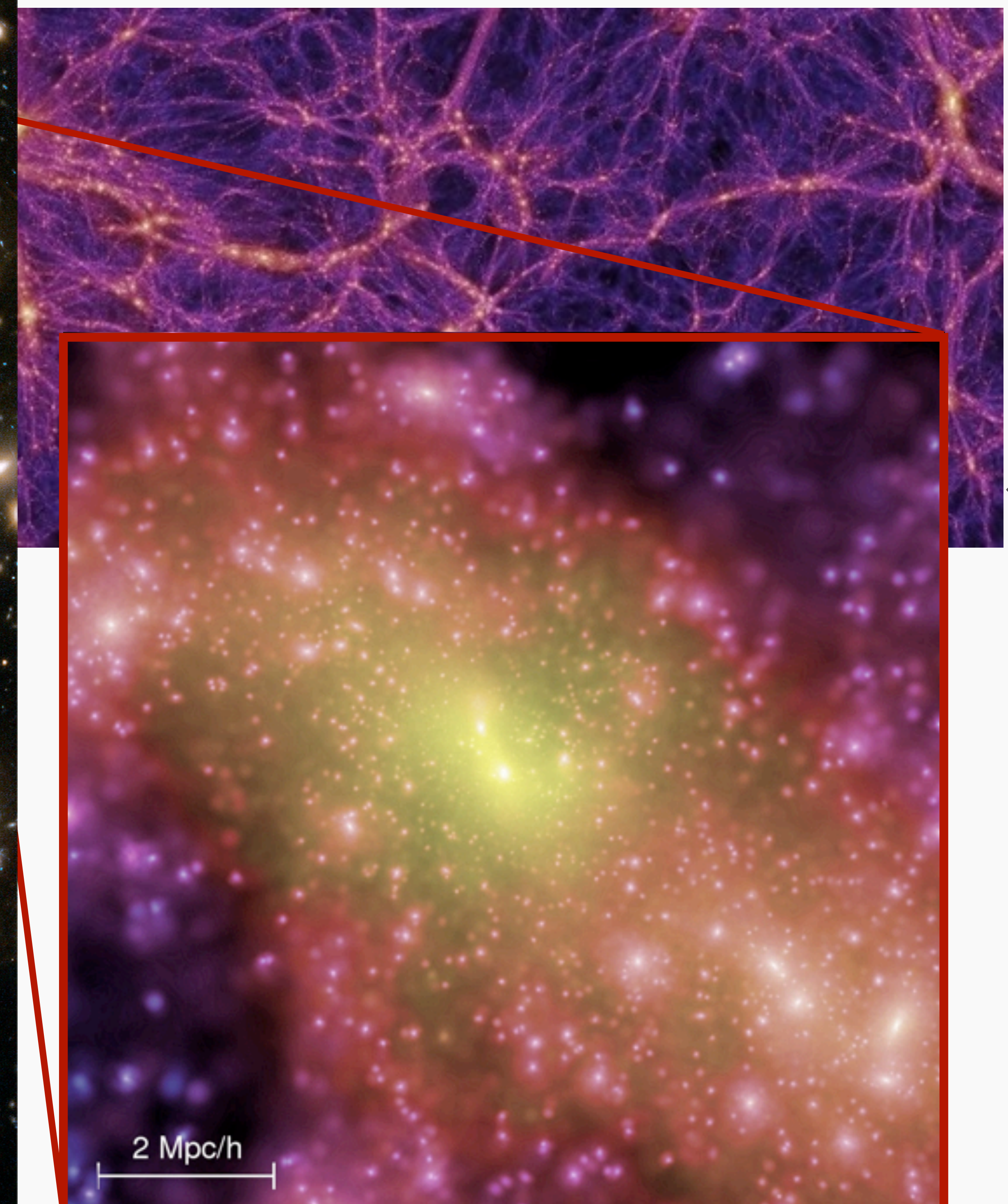
Millennium Simulation Project

- massive concentration of dark matter
- useful site for studying dark matter

Gravitational lensing by cluster

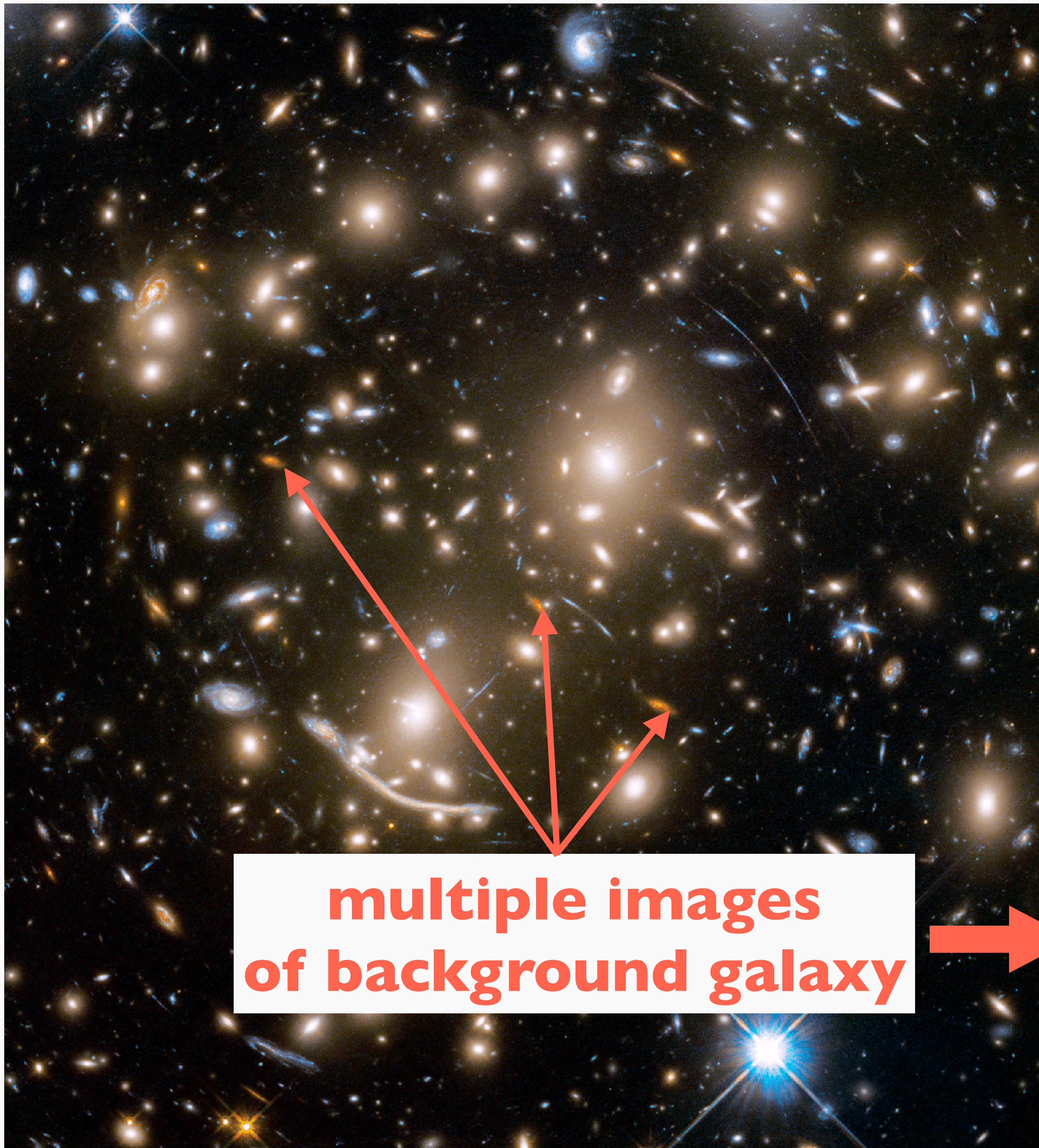


Abell 370, NASA/STScI

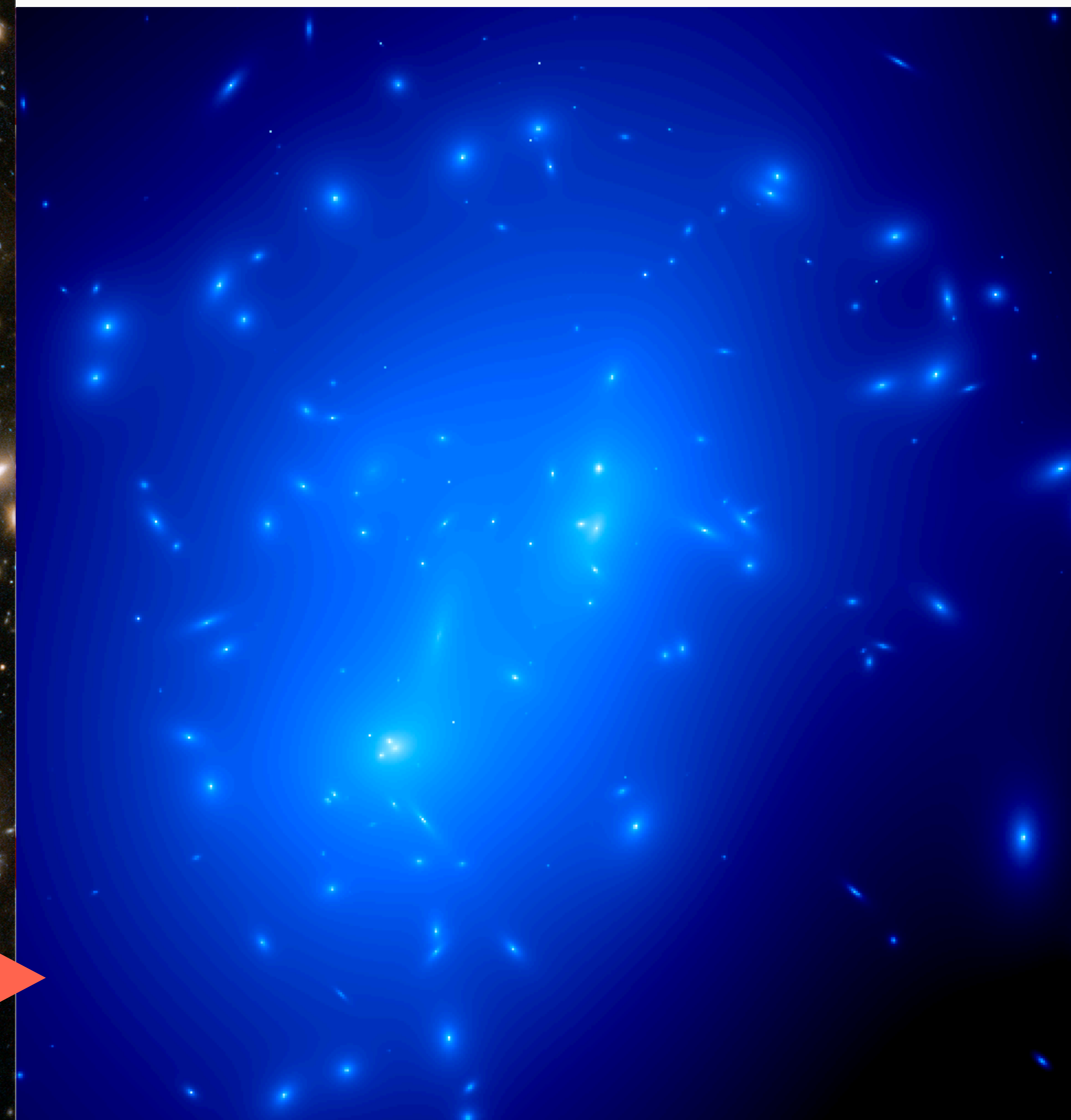


Millennium Simulation Project

Gravitational lensing by cluster



Abell 370, NASA/STScI



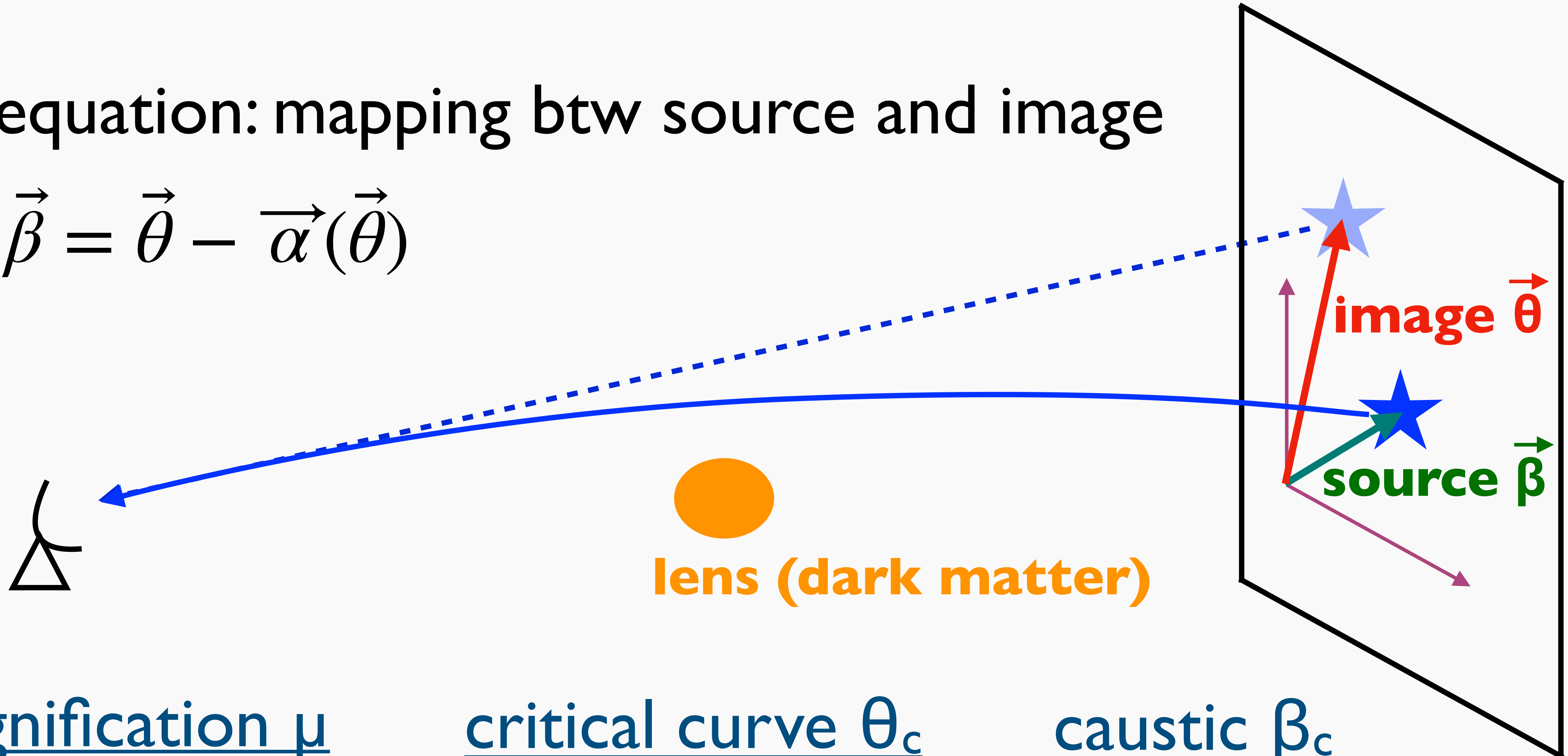
reconstructed matter distribution

(Kawamata, MO+2016)

Critical curve and caustic

lens equation: mapping btw source and image

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$



magnification μ

$$\mu = \left[\det \left(\frac{\partial \vec{\beta}}{\partial \vec{\theta}} \right) \right]^{-1}$$

critical curve θ_c

$$\det \left(\frac{\partial \vec{\beta}}{\partial \vec{\theta}} \right) \Bigg|_{\vec{\theta}=\vec{\theta}_c} = 0$$

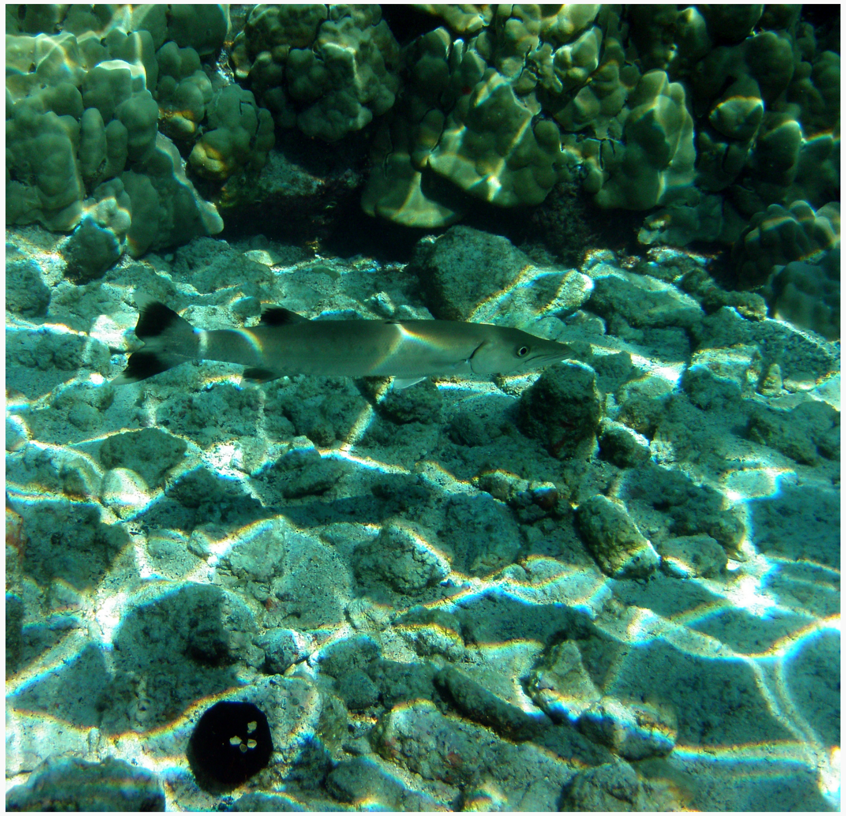
caustic β_c

$$\vec{\beta}_c = \vec{\beta}(\vec{\theta}_c)$$

near critical curve/caustic → high magnification

Caustic

- concentration of reflected or refracted light
- in gravitational lensing, it is where
  - magnification of a point source formally diverges
  - a pair of multiple images appear/disappear



Brocken Inaglory

Caustic crossing

critical curve
(image plane)

caustic
(source plane)

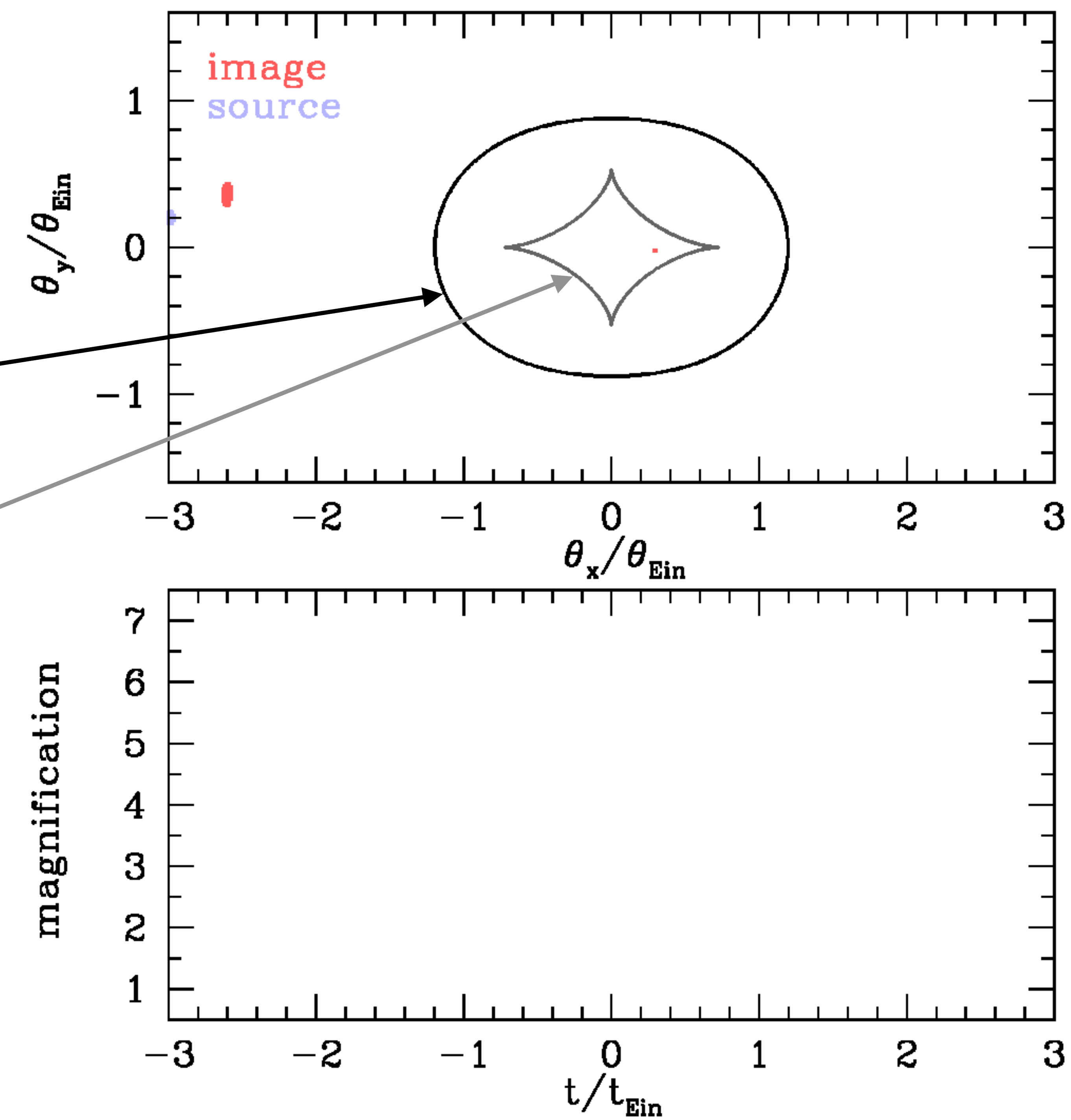
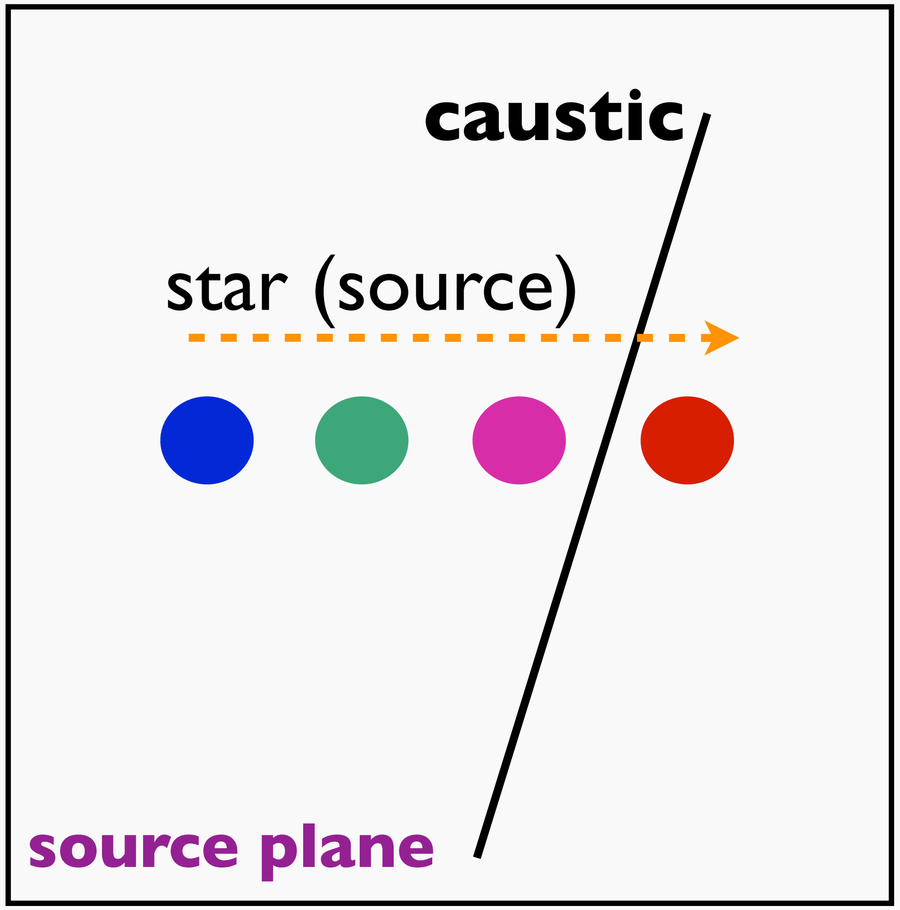
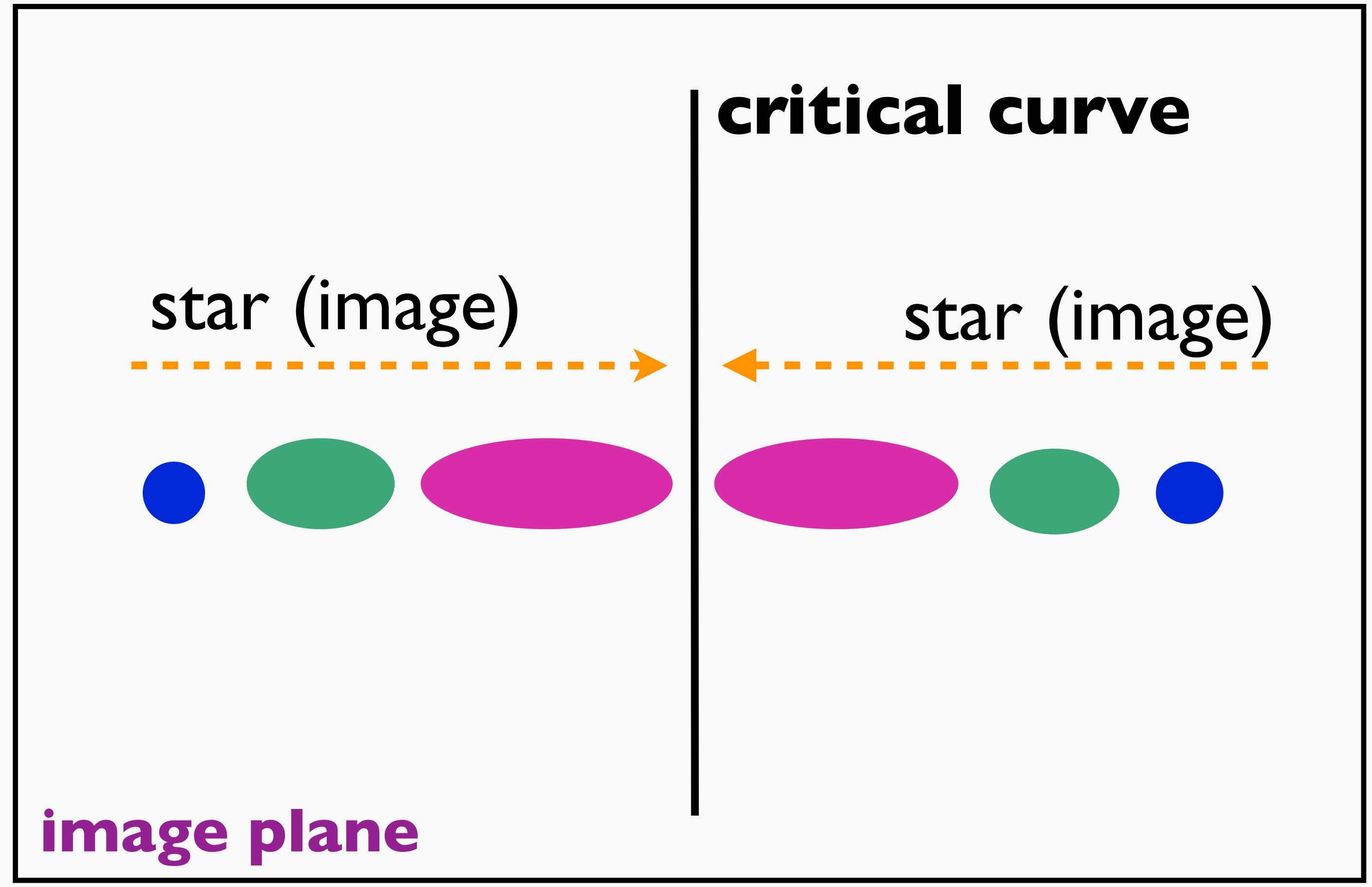


image
(observed)

source
(not observed)

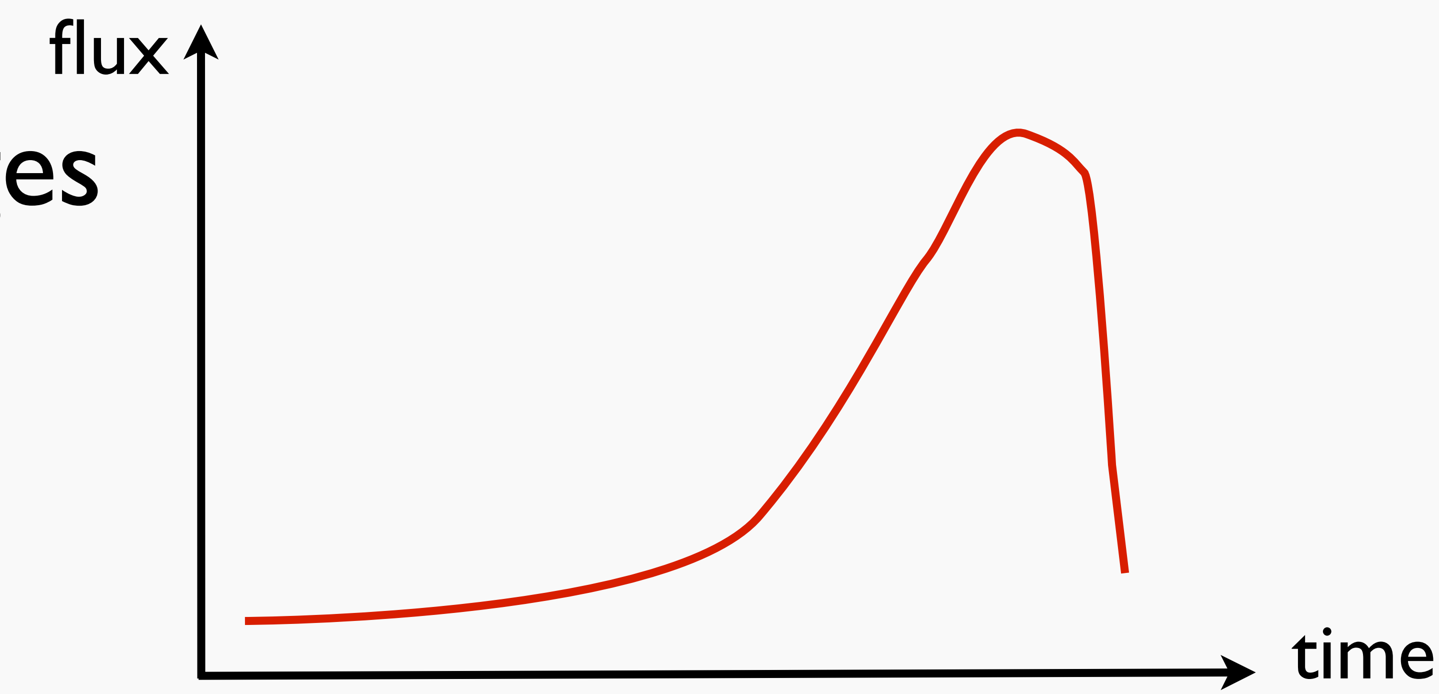
Caustic crossing



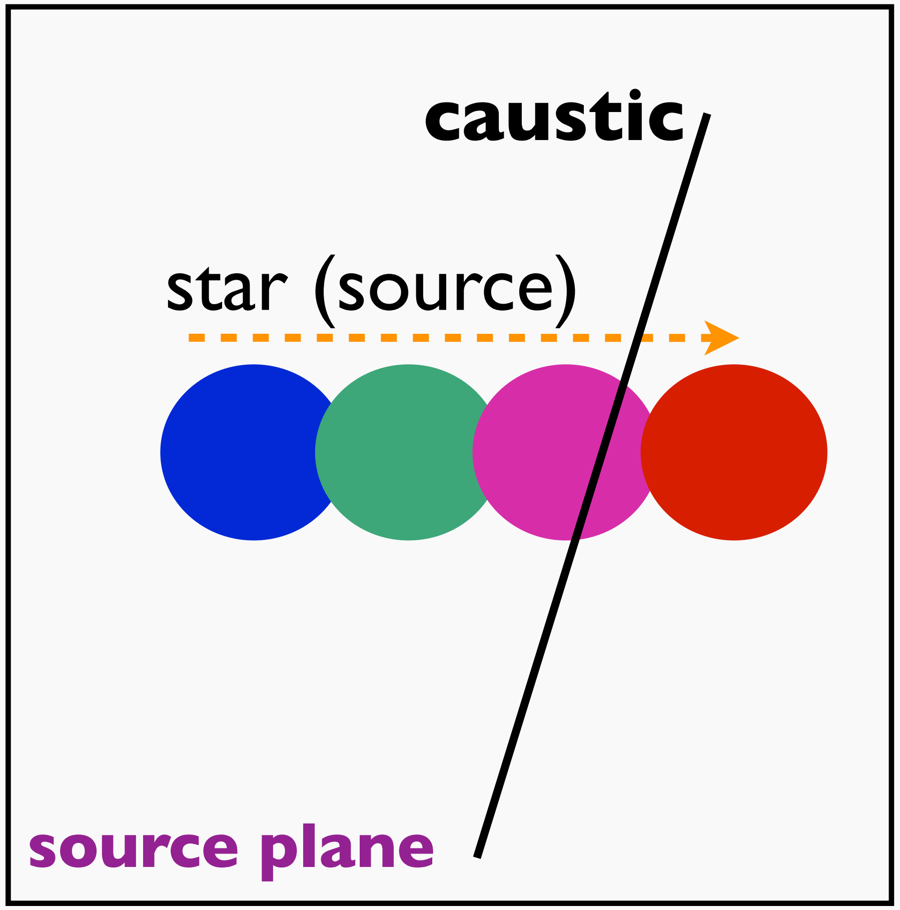


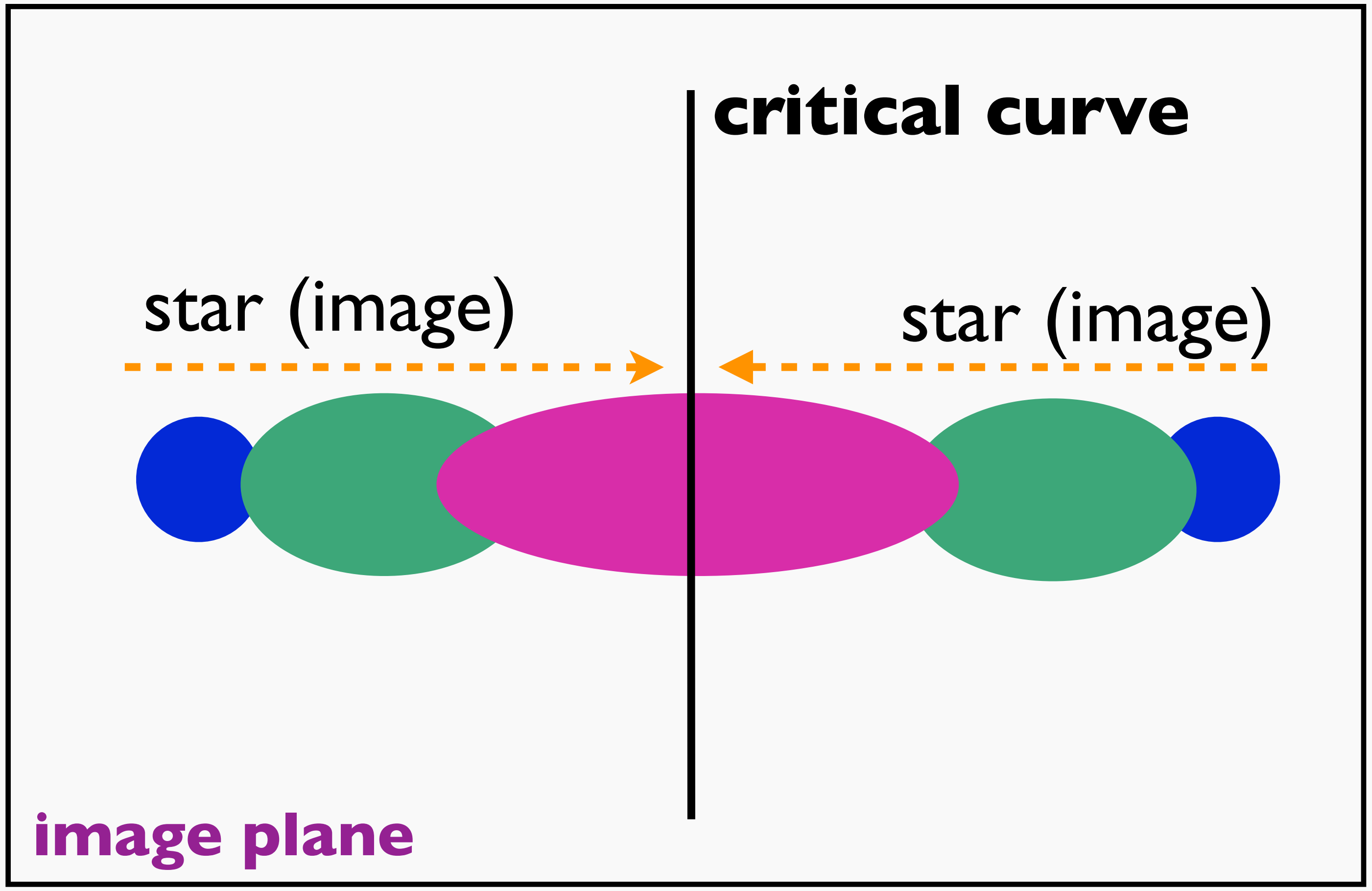
- two multiple images disappear

→ **asymmetric light curve**

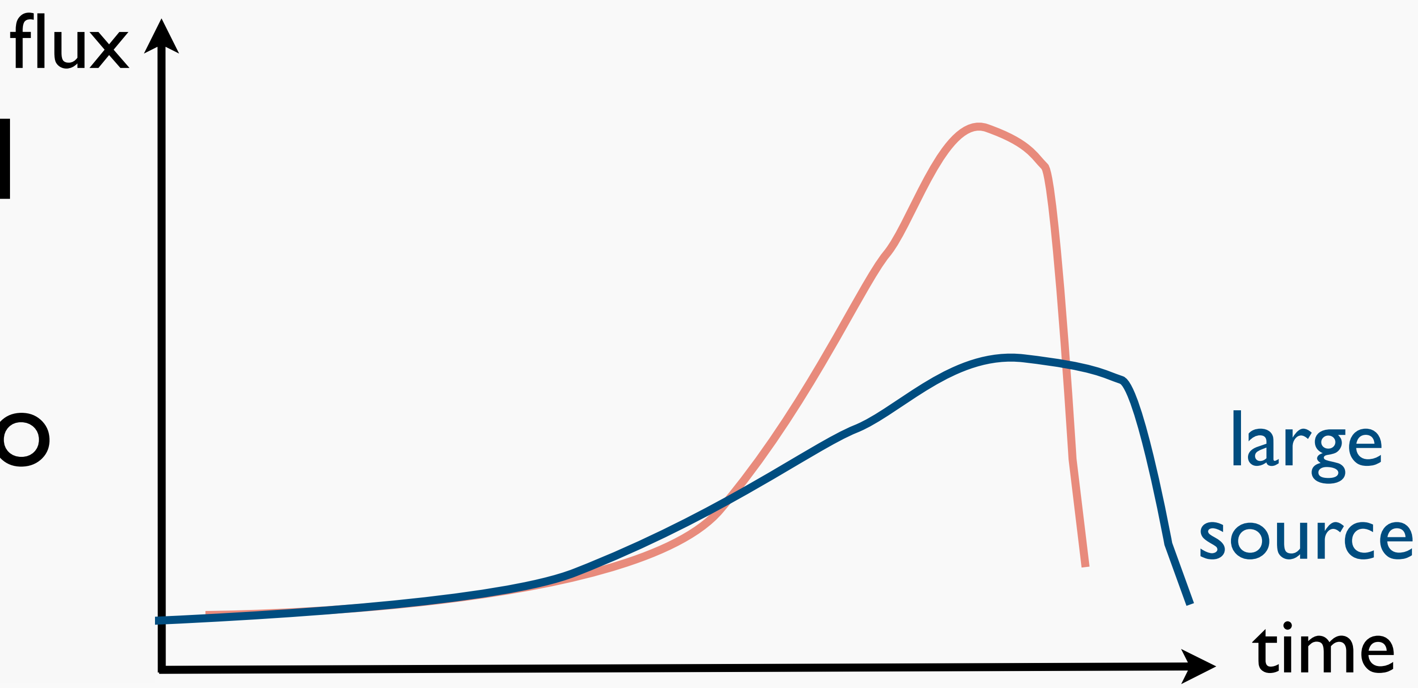


Caustic crossing



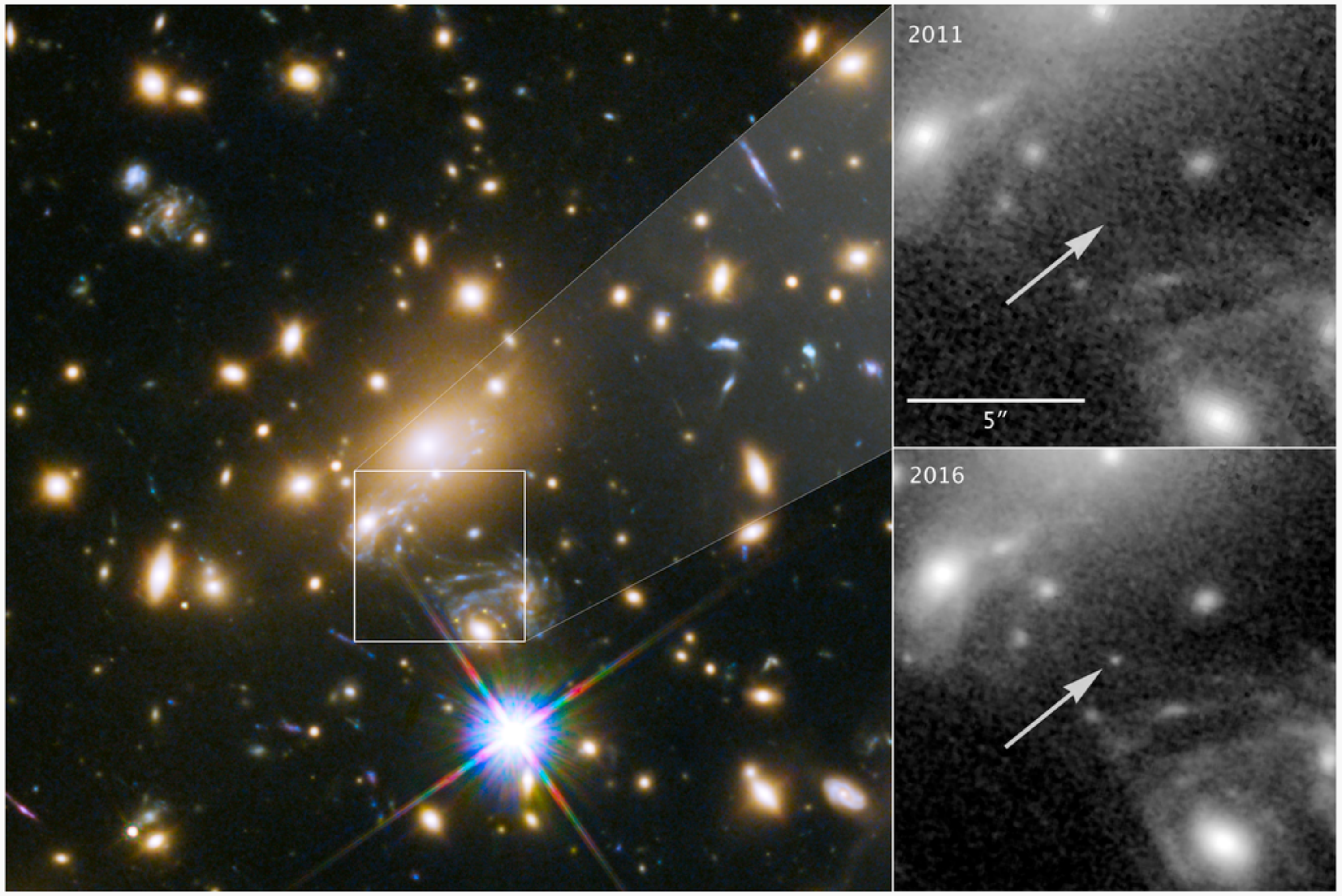


- maximum mag. and width of the light curve is sensitive to source size

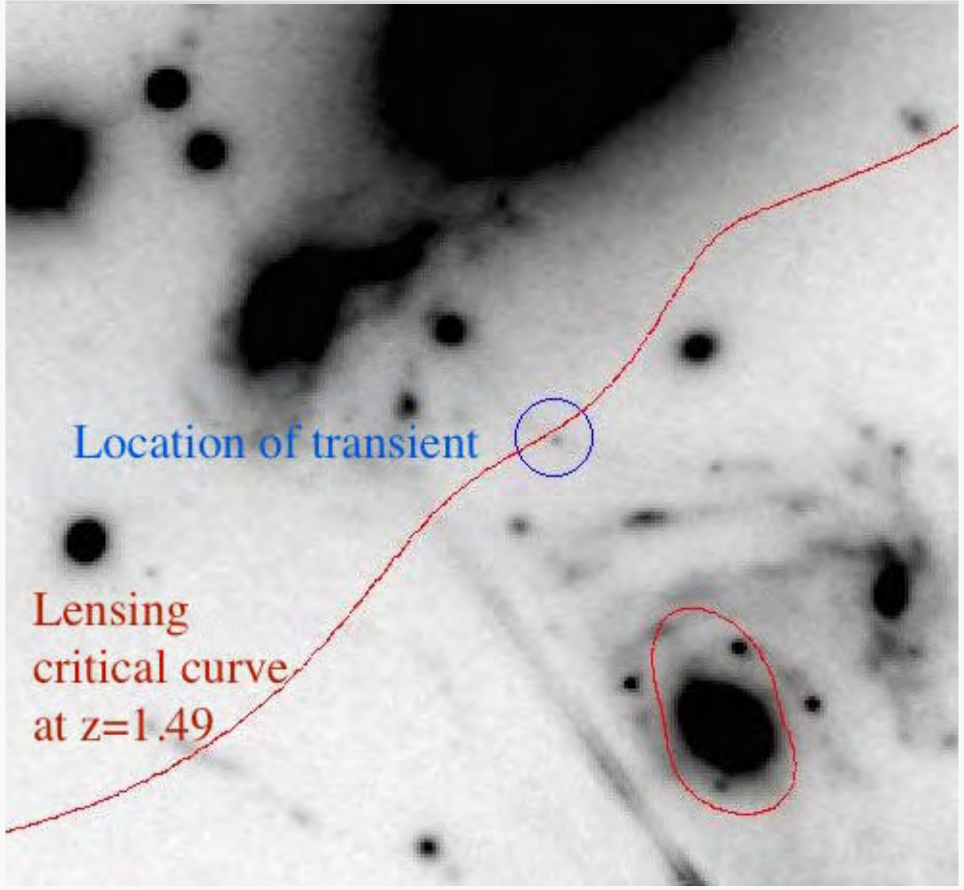


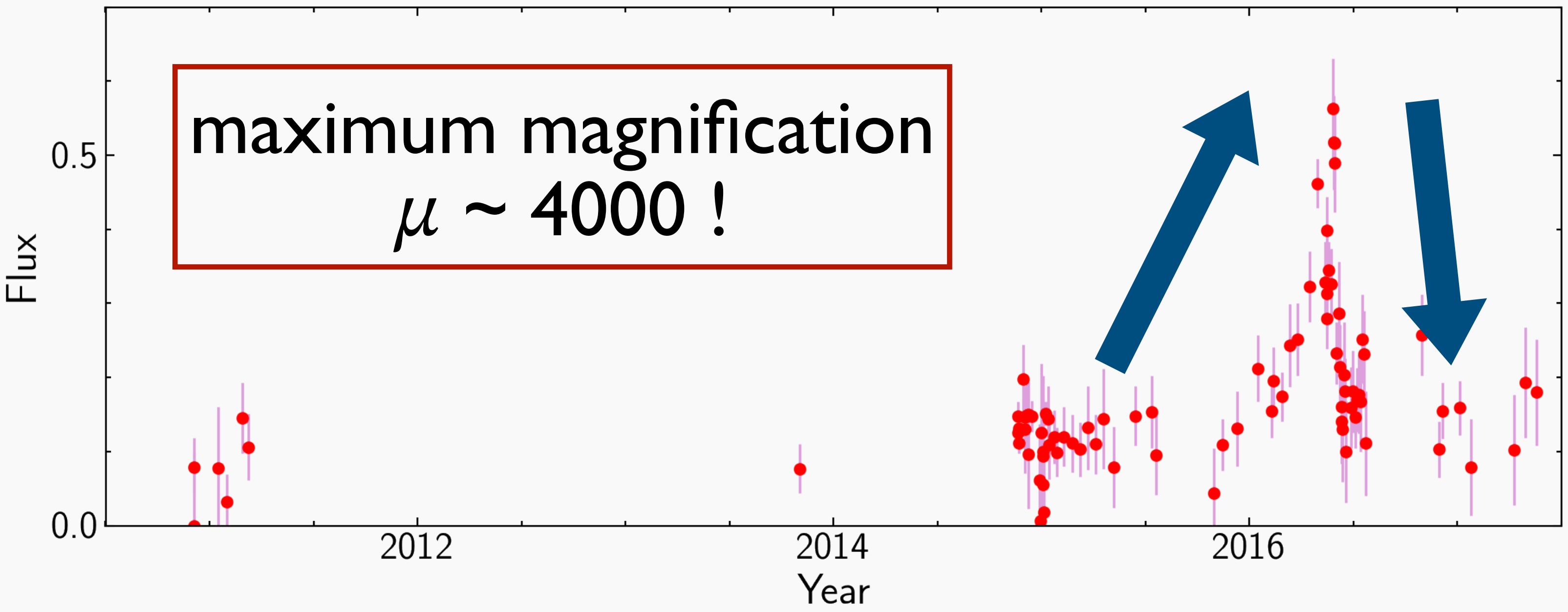
Kelly+ (incl. MO) Nat. Ast. **2**(2018)334

Discovery of Icarus



NASA/ESA/P. Kelly

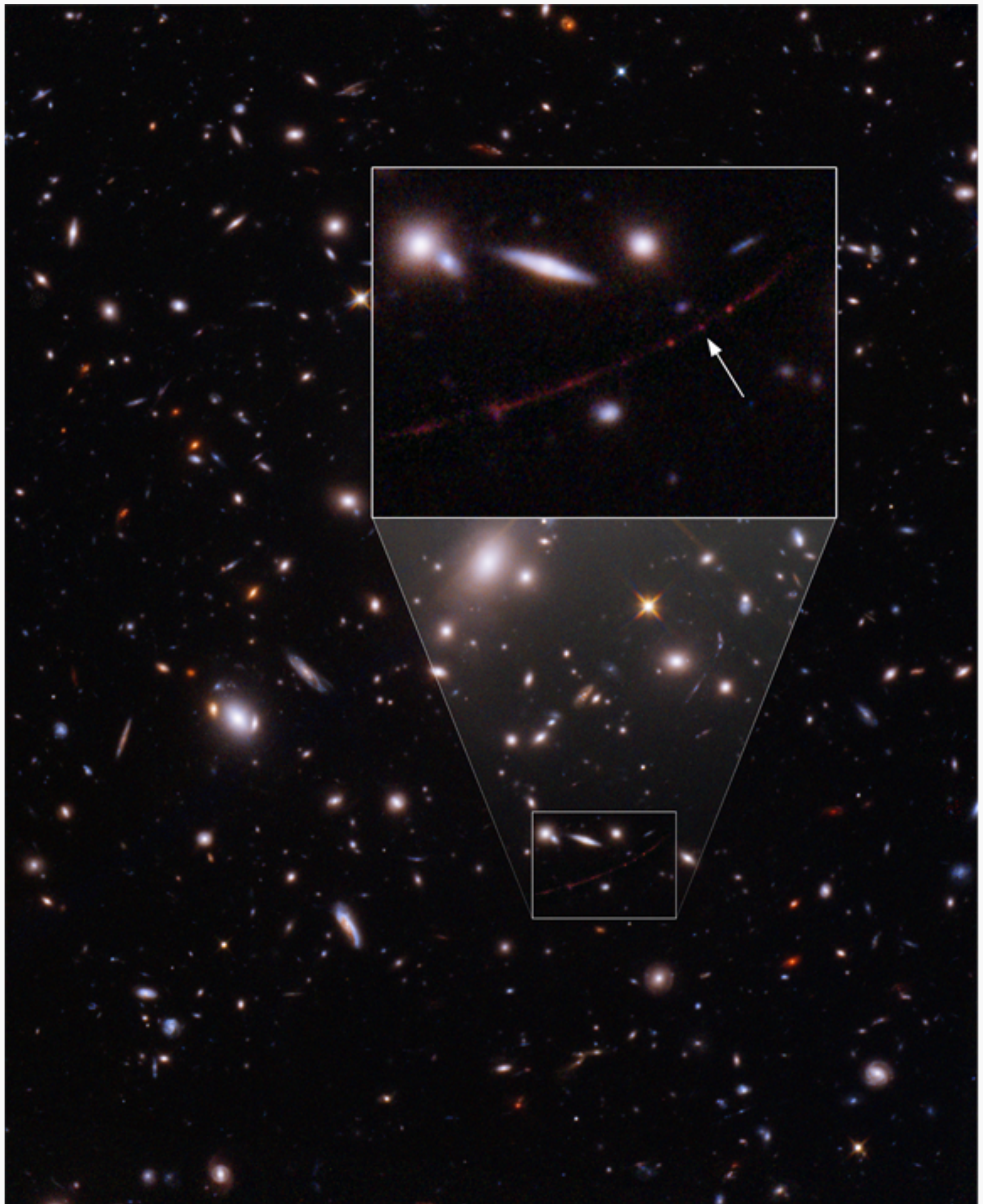




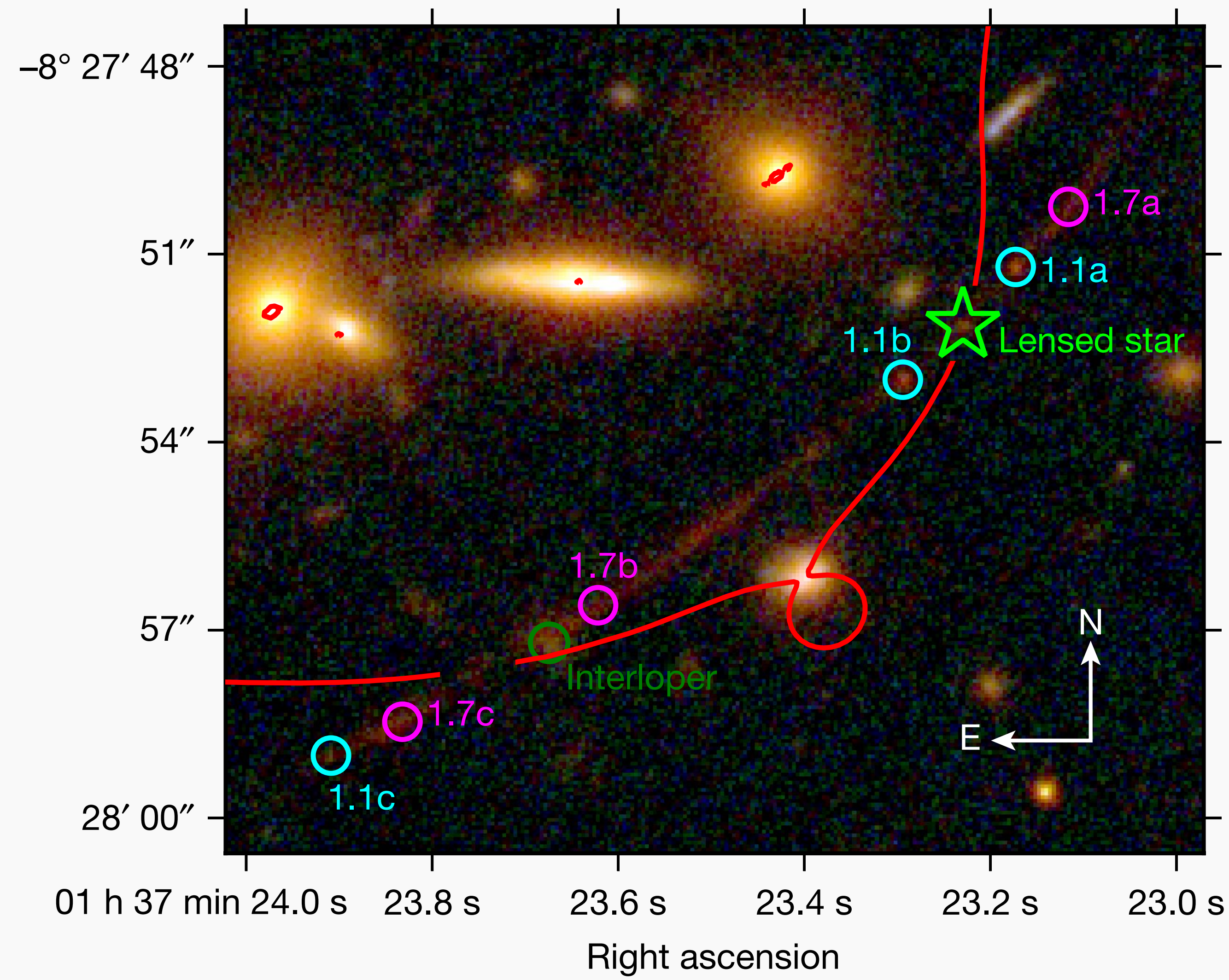
- single star (blue supergiant) at z=1.5

Welch+ (incl. MO) Nature **603**(2022)815

Discovery of Earendel



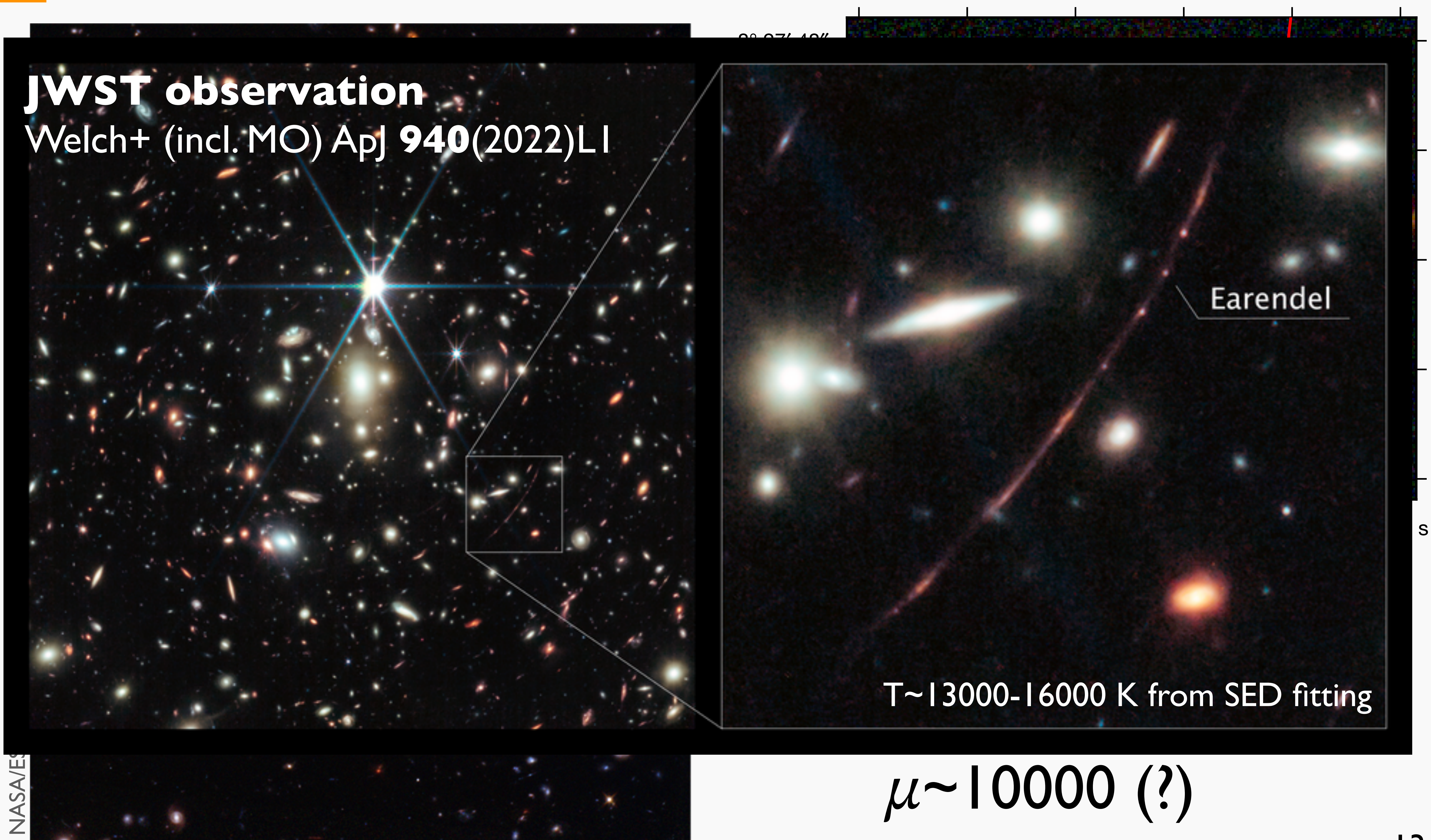
NASA/ESA?CSA/D. Coe et al.
NASA/ESA/B.Welch



- single star at z=6.2
- magnification μ~10000 (?)

Welch+ (incl. MO) Nature **603**(2022)815

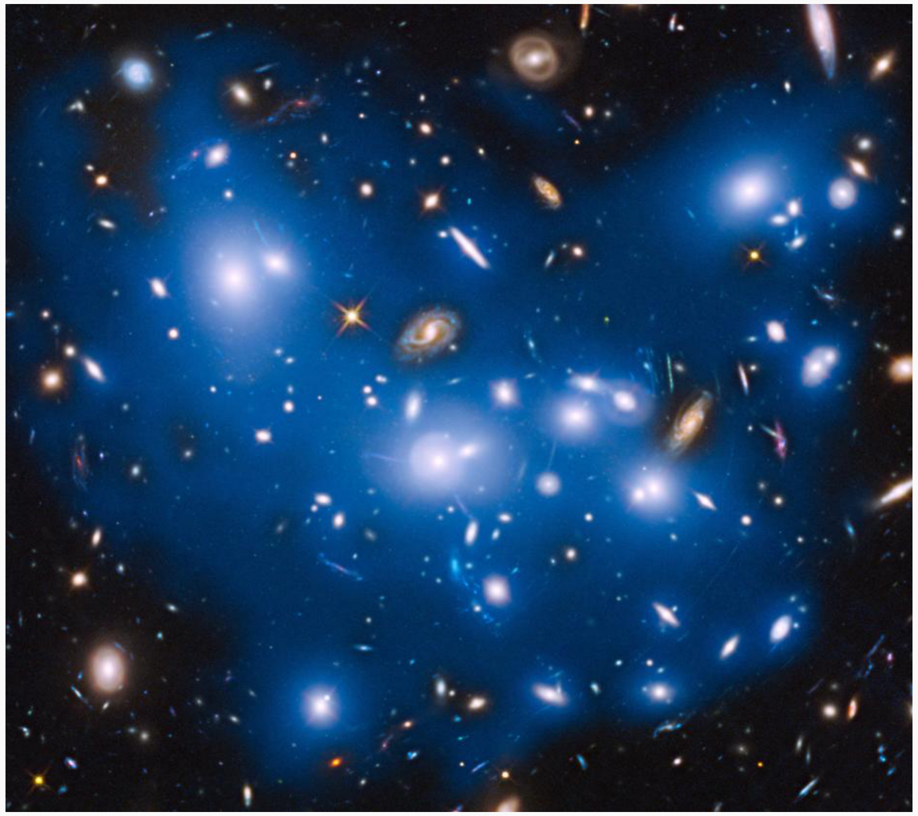
Discovery of Earendel



μ~10000 (?)

Interpretation of caustic crossings

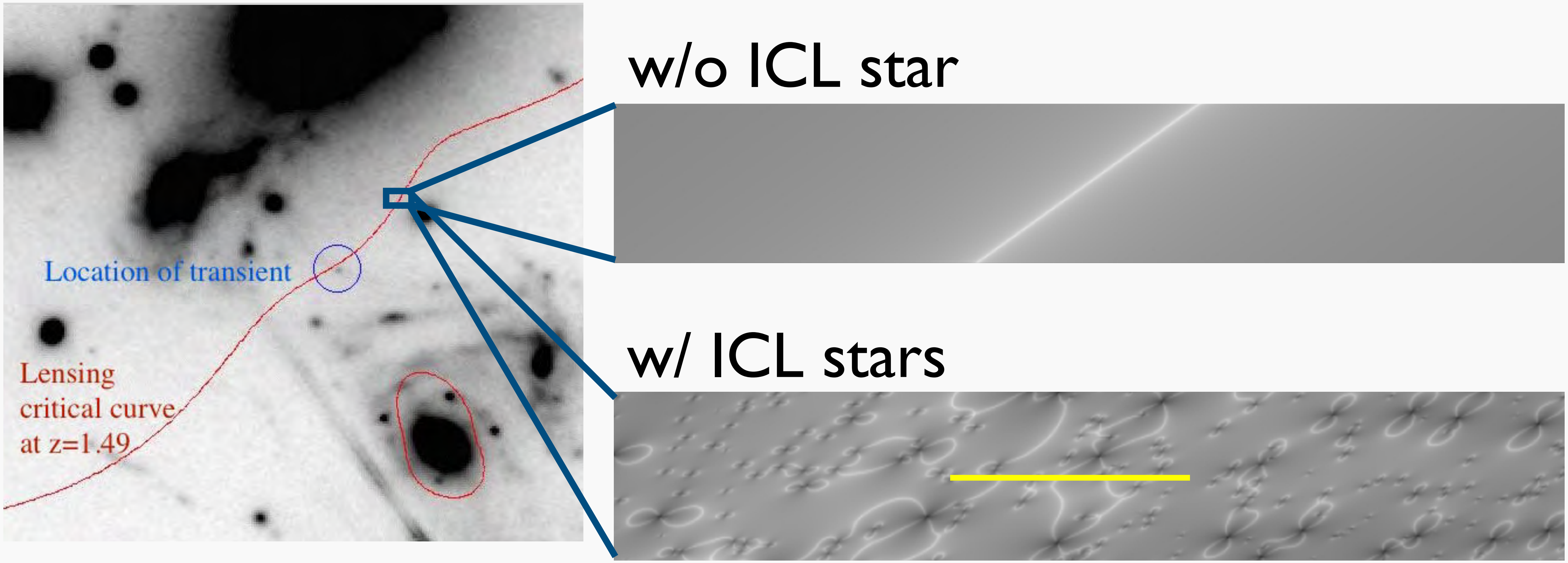
- caustic crossings look very simple, yet in fact they are not that simple because the mass distribution is not completely smooth
- non-smoothness due to stars responsible for **intra-cluster star** (**ICL**)
- tidal stripping of cluster member galaxies explains ICL



NASA/ESA/IAC/HFF team, STScI

MO, Diego, Kaiser+ PRD **97**(2018)023518
Diego+ (incl. MO) ApJ **857**(2018)25

'Destruction' of critical curve

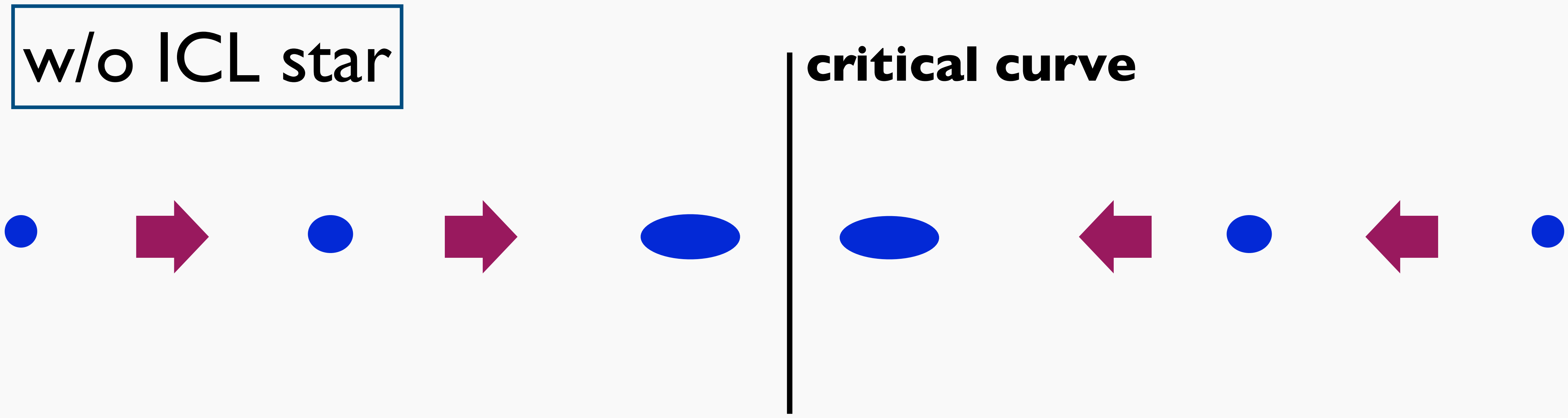


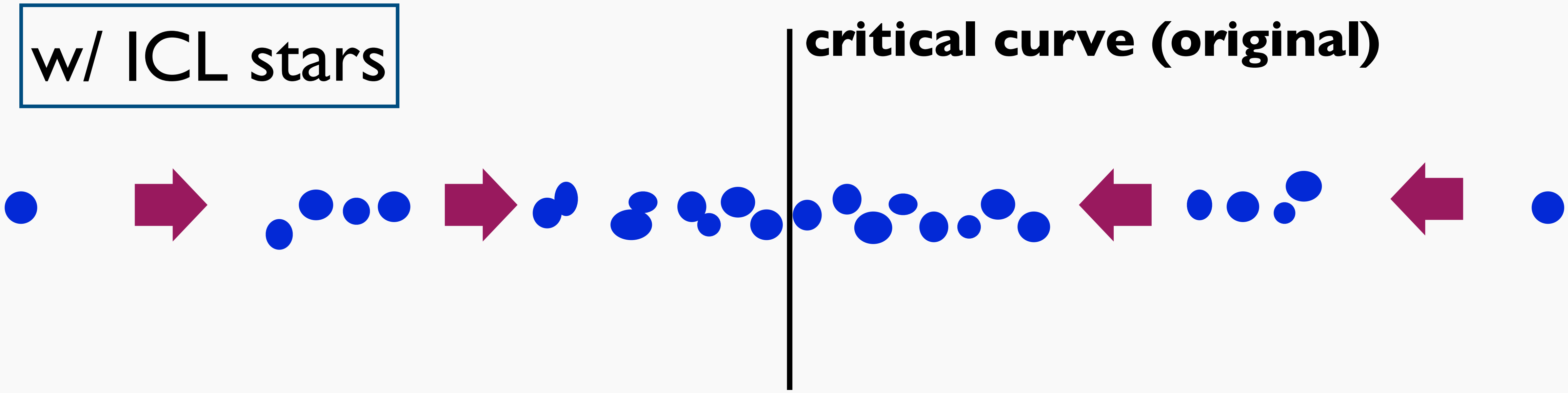
- destruction of critical curve due to overlapping Einstein radii of ICL stars

$$\tau = \frac{\Sigma}{M}\pi\left(\sqrt{\mu_{\rm t}}\theta_{\rm E}D_{ol}\right)^2$$

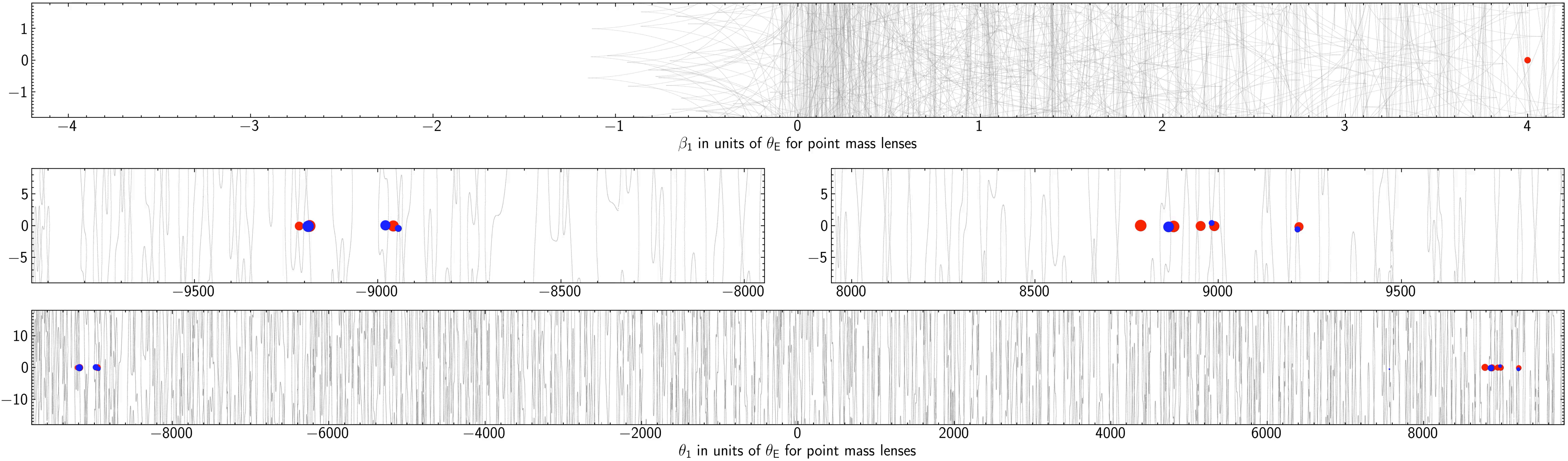
τ≳1 → saturation

Caustic crossing w/ ICL

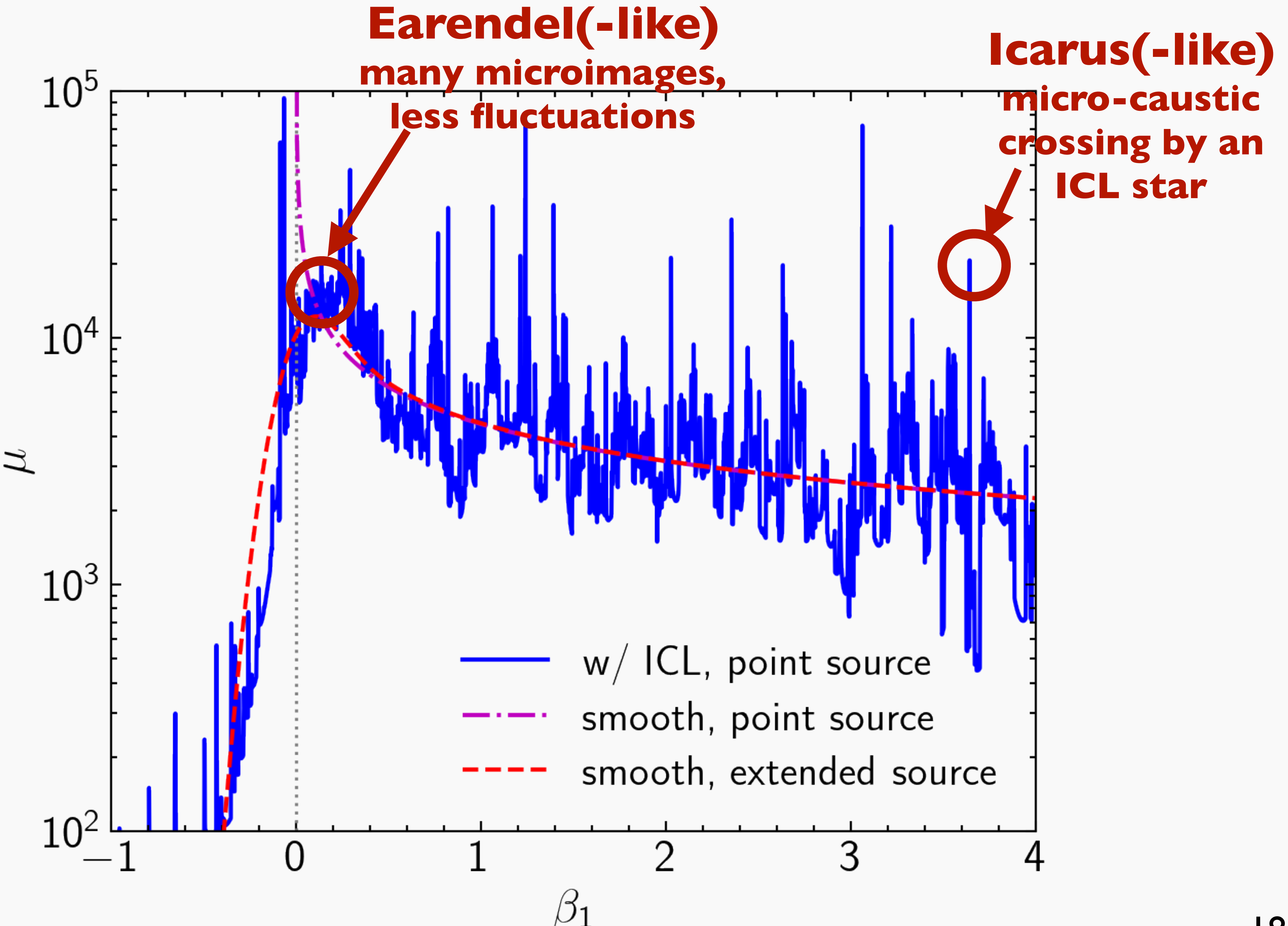


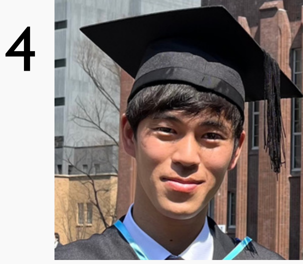


Simulation


β_1 in units of θ_E for point mass lenses
θ_1 in units of θ_E for point mass lenses

Caustic crossing lightcurves

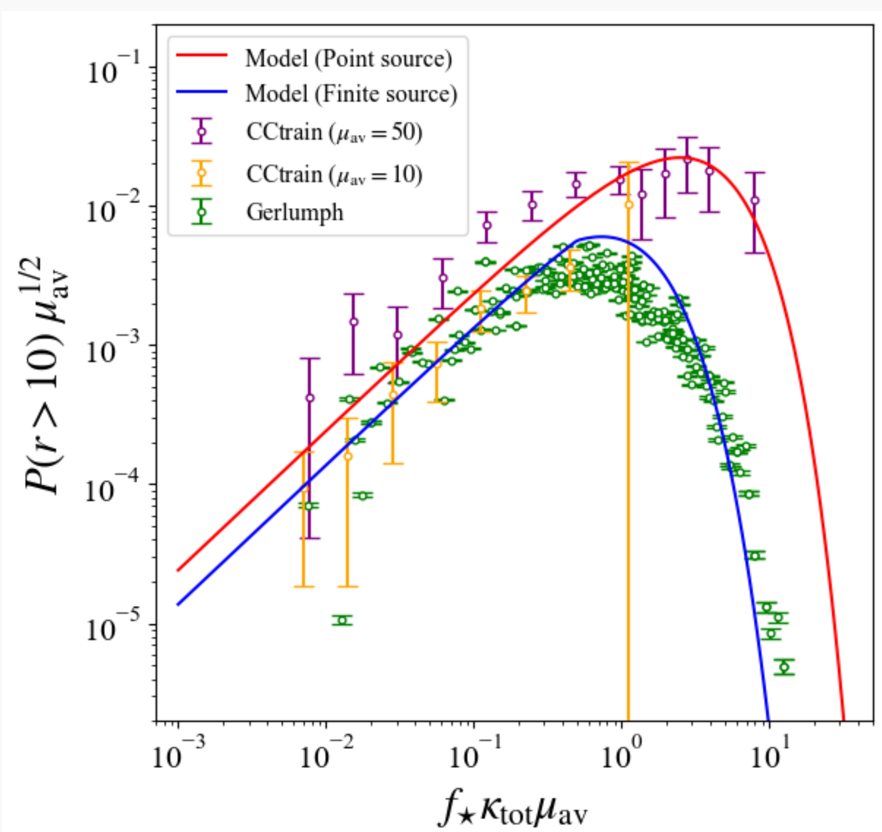




Analytic model

- Assumption: caustic crossing probability is proportional to number of independent micro-critical curves $N_\star^{\rm indep}$ ← **Rayleigh dist.**

$$\frac{dP}{d\log_{10} r} \propto N_\star^{\rm indep} \sqrt{\mu_{\rm av}}\, r^{-2} S(r; r_{\rm max})$$
$$\propto f_\star \kappa_{\rm tot} \exp(-f_\star \kappa_{\rm tot} \mu_{\rm av}) \sqrt{\mu_{\rm av}}\, r^{-2} S(r; r_{\rm max})$$



parameter dependence in ray-tracing sim is well reproduced!

$\mu_{\rm av}$: mean magnif.

S : finite source size effect

$f_\star$: ICL fraction

$\kappa_{\rm tot}$: convergence

$r = \mu / \mu_{\rm av}$

Probing DM with caustic crossings

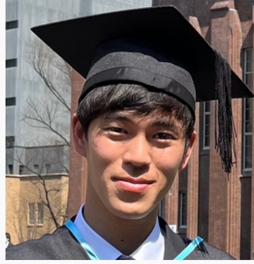
- caustic crossing probability is sensitive to mass fraction $f_\star$ of compact objects

→ **primordial black holes** (PBH)

- caustic corssings appear near critical curves of clusters, which are sensitive to small-scale dark matter distribution

→ **warm dark matter** (WDM)
fuzzy dark matter (FDM)

Kawai & MO, in prep.



Constraint on PBH

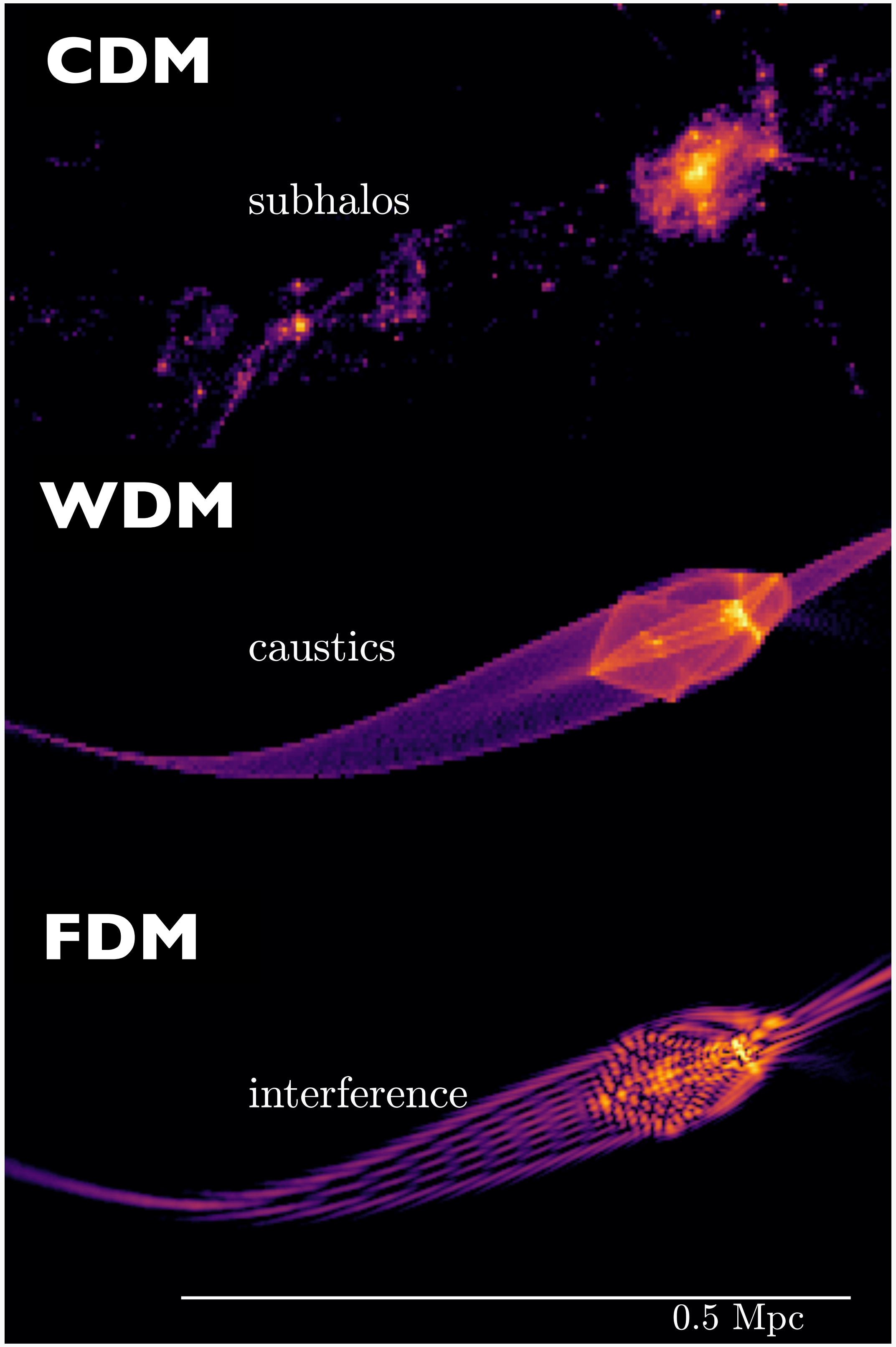
- constraints from event rate (w/o ICL)

Critical curve and dark matter

- many small clumps

- smooth, no clumps

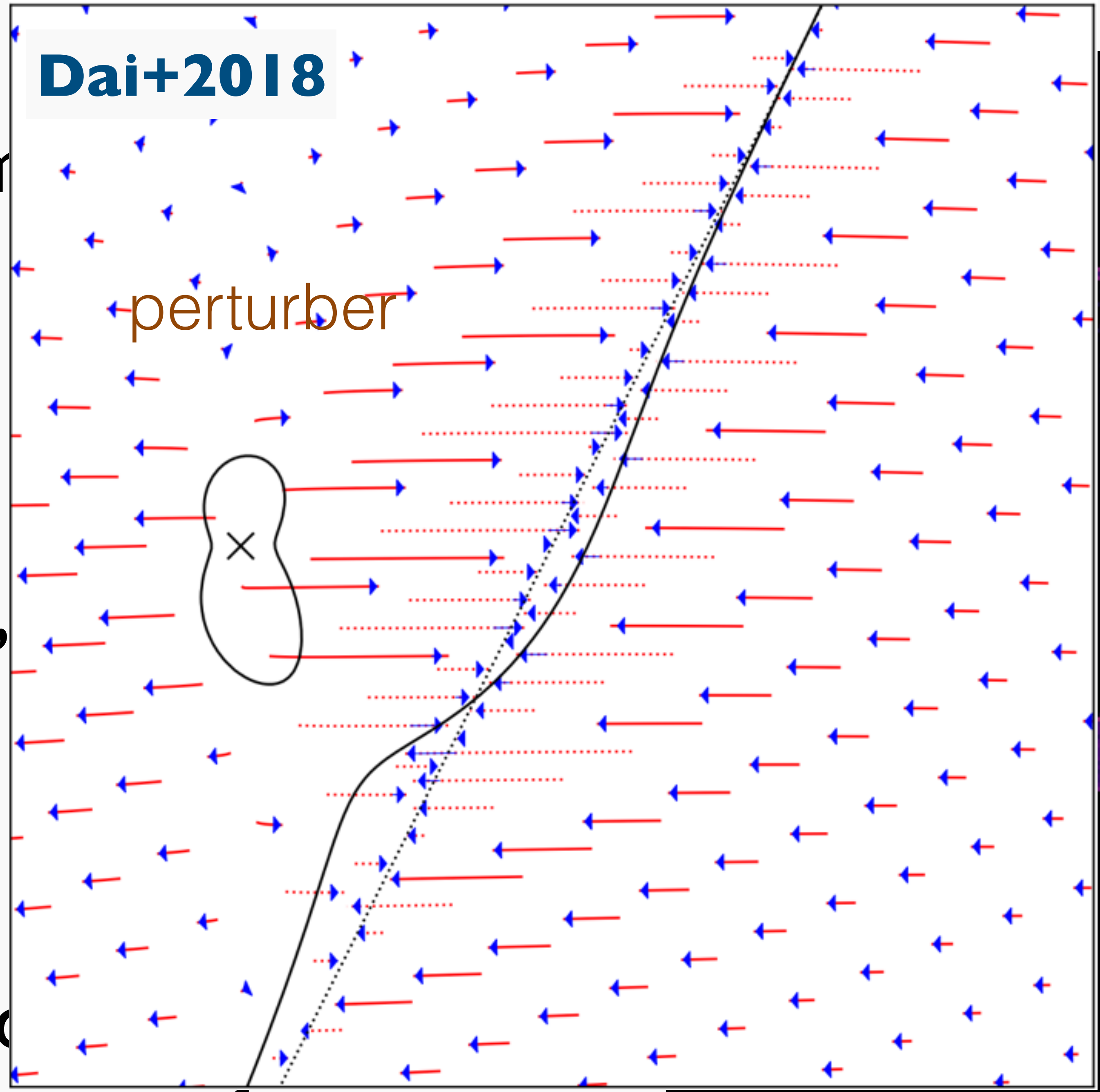
- clumps due to quantum interference

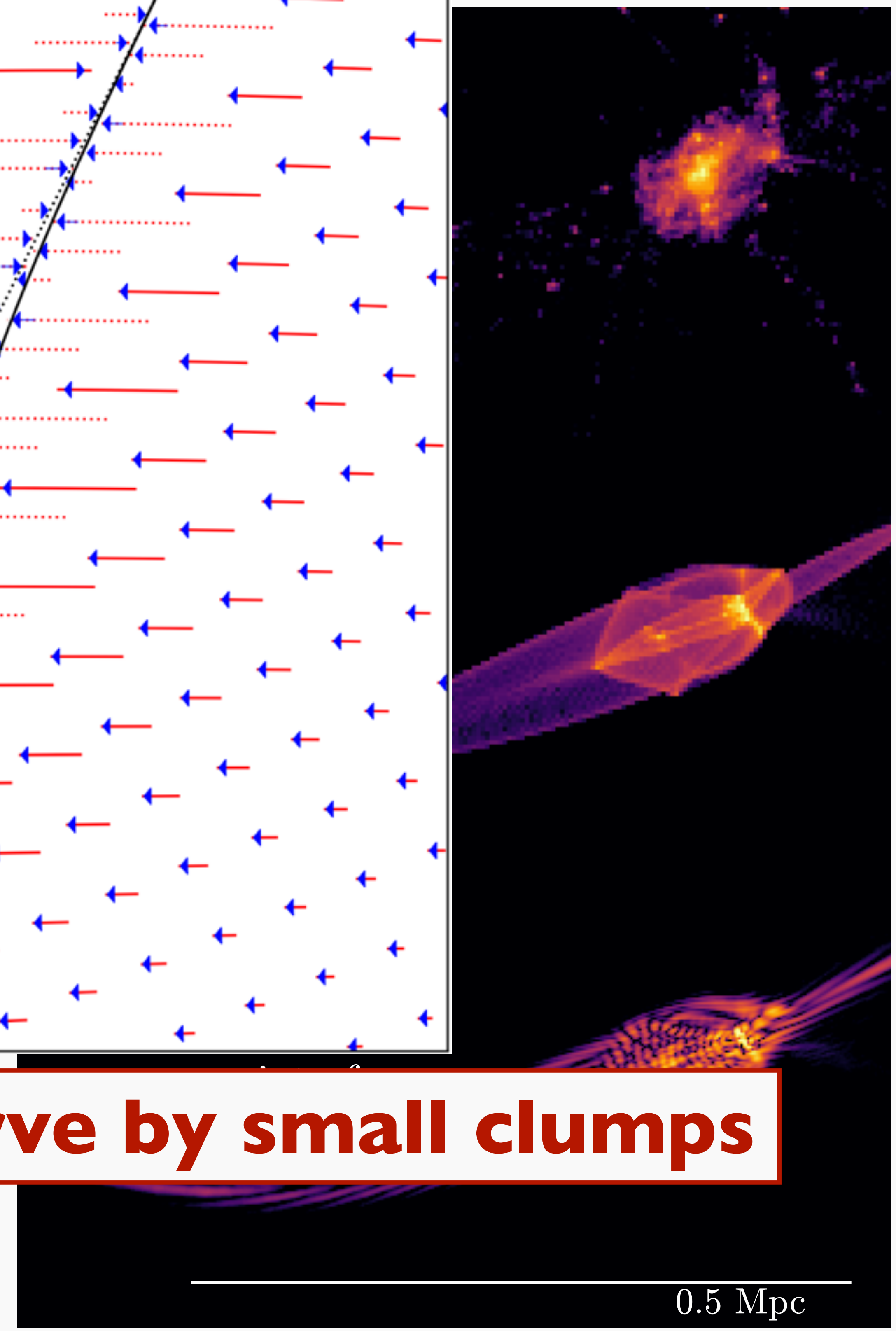


Mocz+2020

Critical curve and dark matter

- many sm
- smooth,
- clumps c

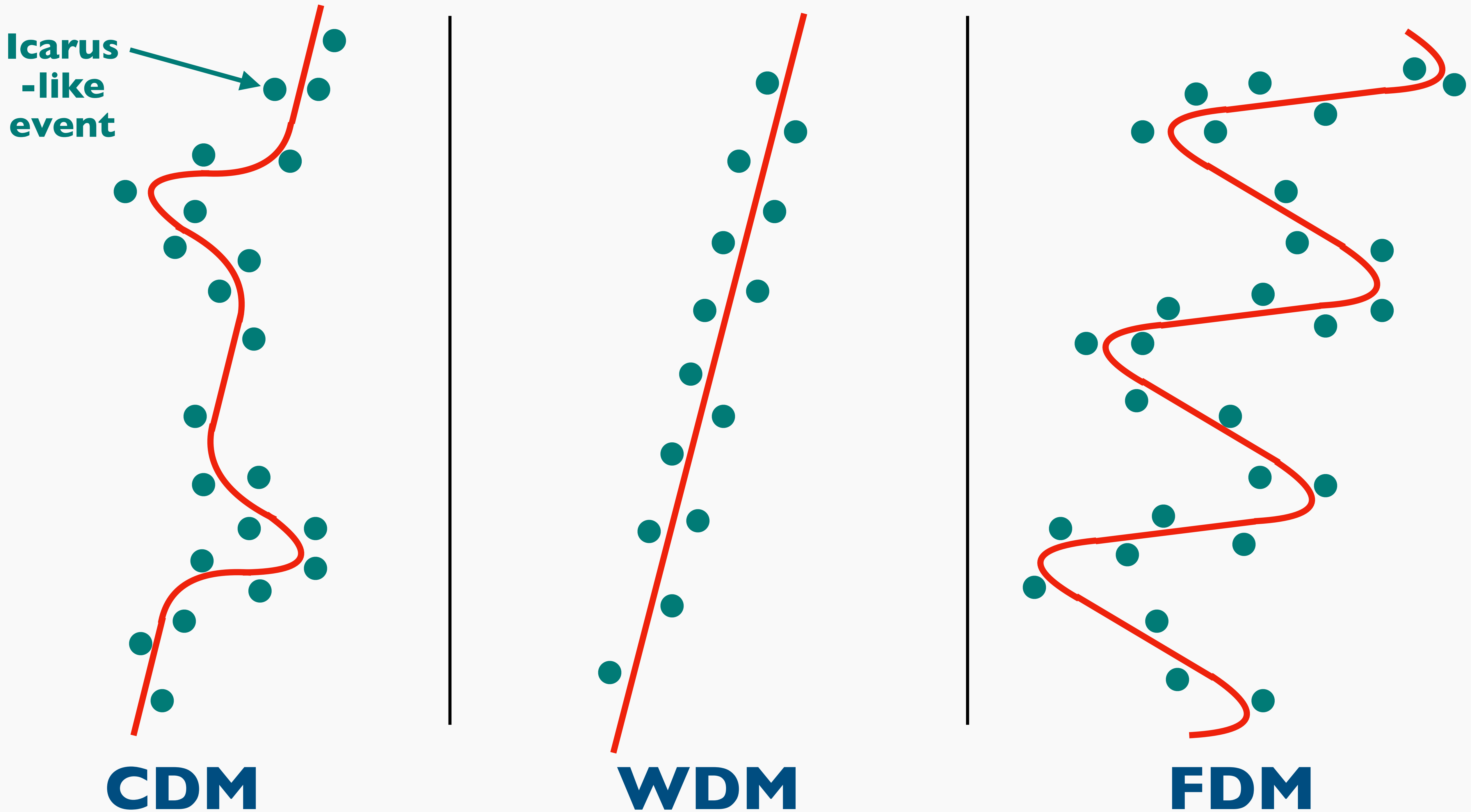




Mocz+2020

distortion of critical curve by small clumps

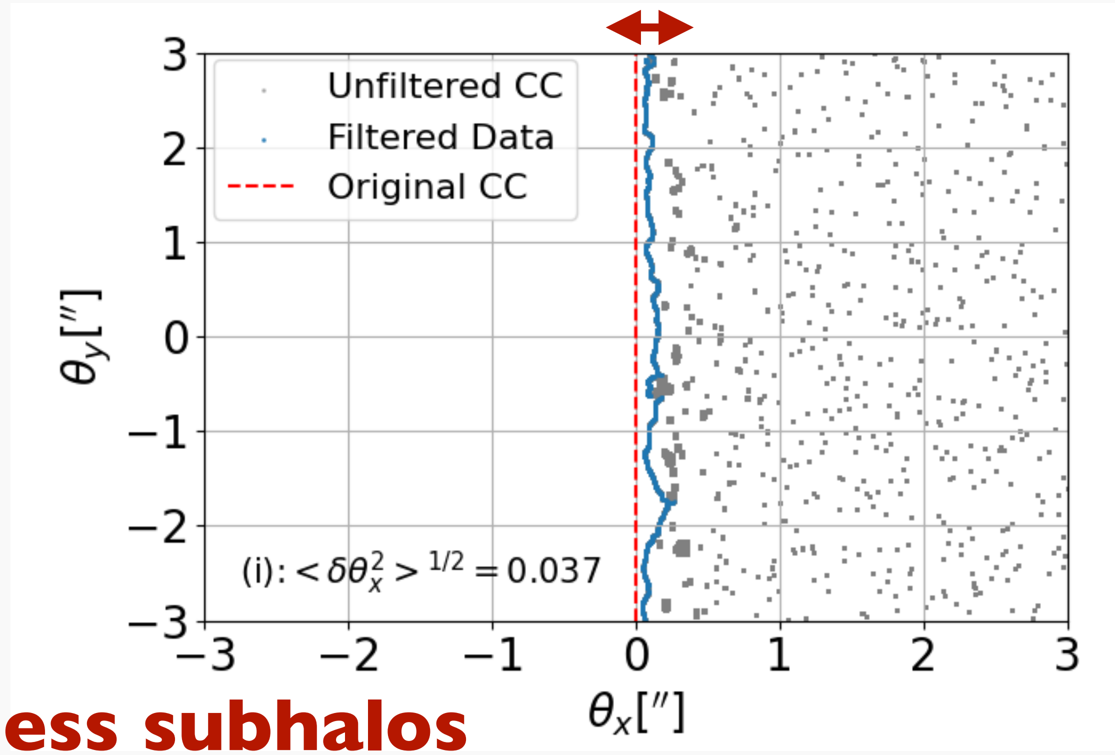
Critical curve and caustic crossings



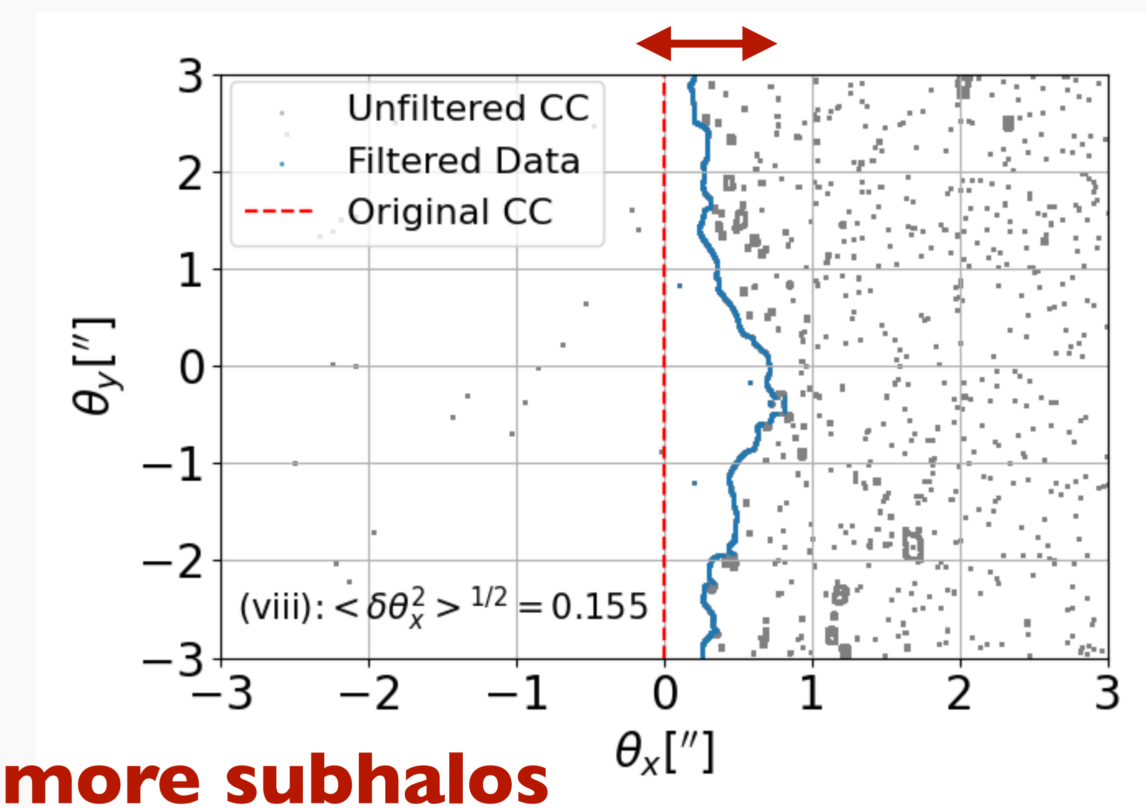
- can measure critical curve shape with many caustic crossing

Abe, Kawai, MO PRD **109**(2024)083517

Critical curve fluctuations



less subhalos



more subhalos

- derive **an analytic formula** that connects P(k) of critical curve fluctuations with P(k) of DM small-scale density fluctuations!

critical curve fluctuations

$$P_{\delta\theta_x} = \frac{3}{2\epsilon^2} P_{\delta\kappa}$$

$\epsilon \sim 1/\theta_{\mathrm{Ein}}$

DM small-scale density fluctuations

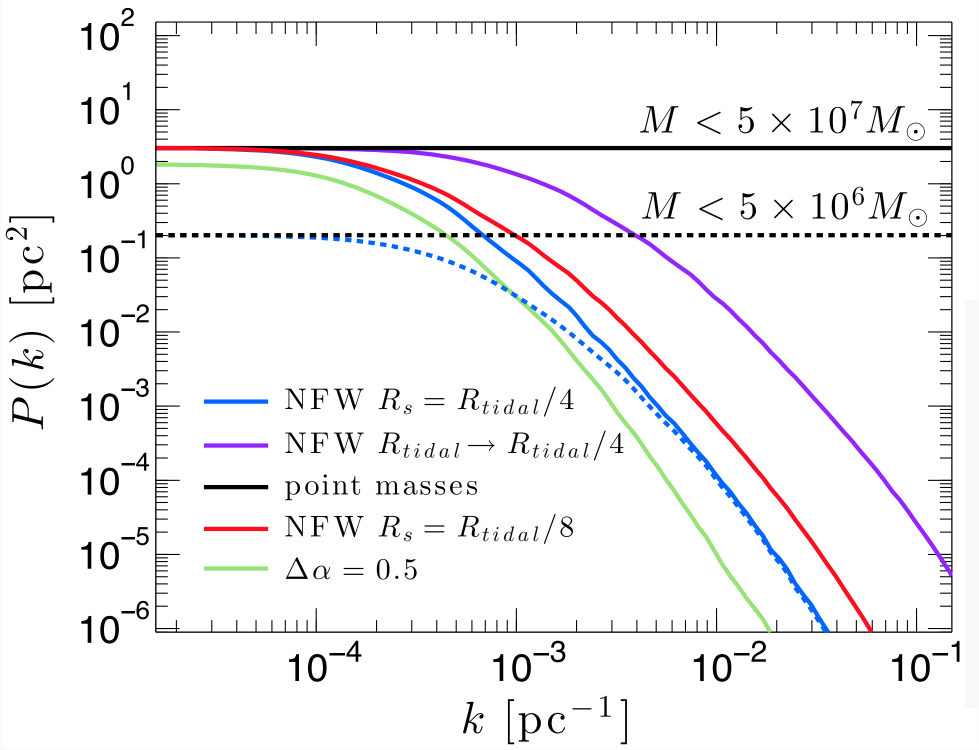
- formula validated with simple simulations

P(k) of CDM and WDM

- can be calculated with halo-model approach
  (e.g, Hezaveh+2016)

$$P(k) = \int dM \frac{dn}{dM} \left| \tilde{u}(k) \right|^2$$

subhalo mass function **Fourier transform of NFW profile**



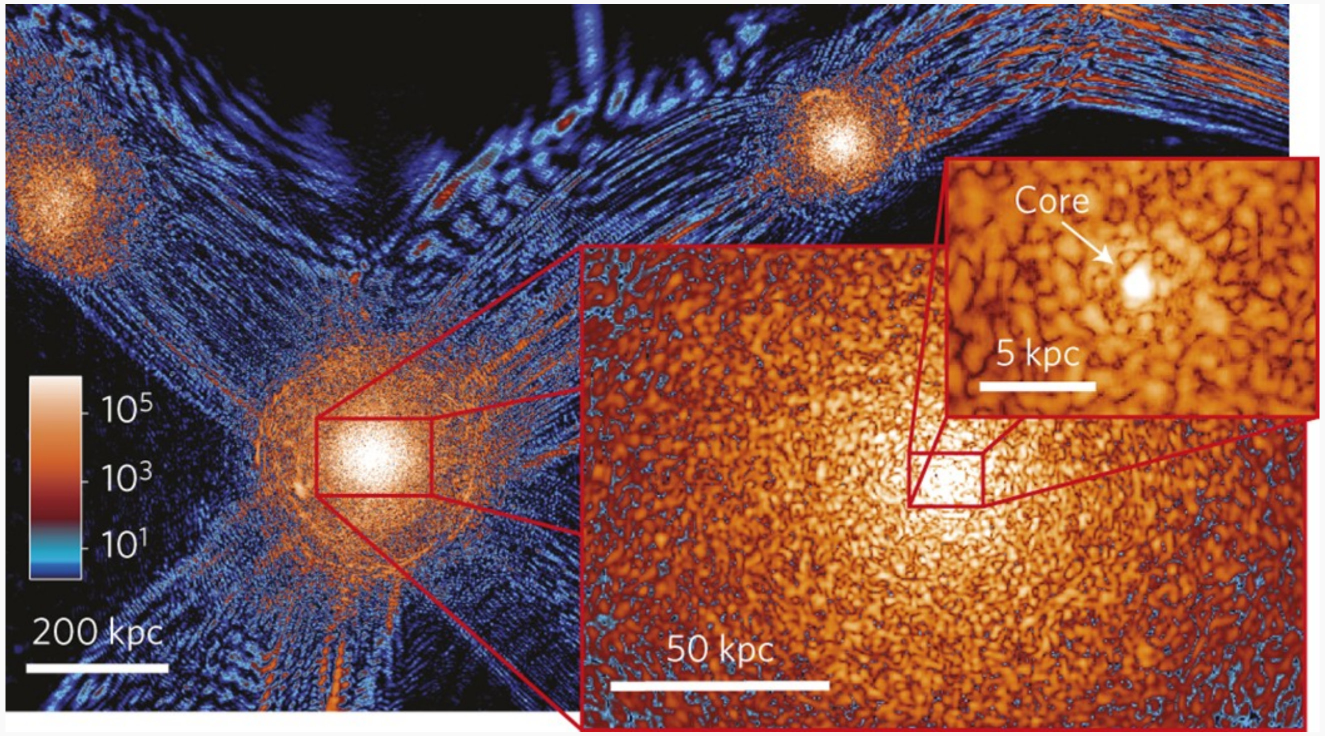
Hezaveh+2016

P(k) of FDM?

- wave effect below de Broglie wavelength

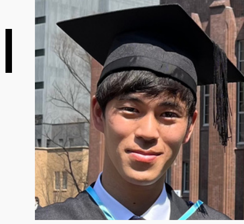
$$\lambda_{\rm dB} = \frac{h}{mv} = 180\,{\rm pc}\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^{-1}\left(\frac{v}{1000\,{\rm km/s}}\right)^{-1}$$

- dark matter halo consists of quantum clumps with their size ~ $\lambda_{\rm dB}$



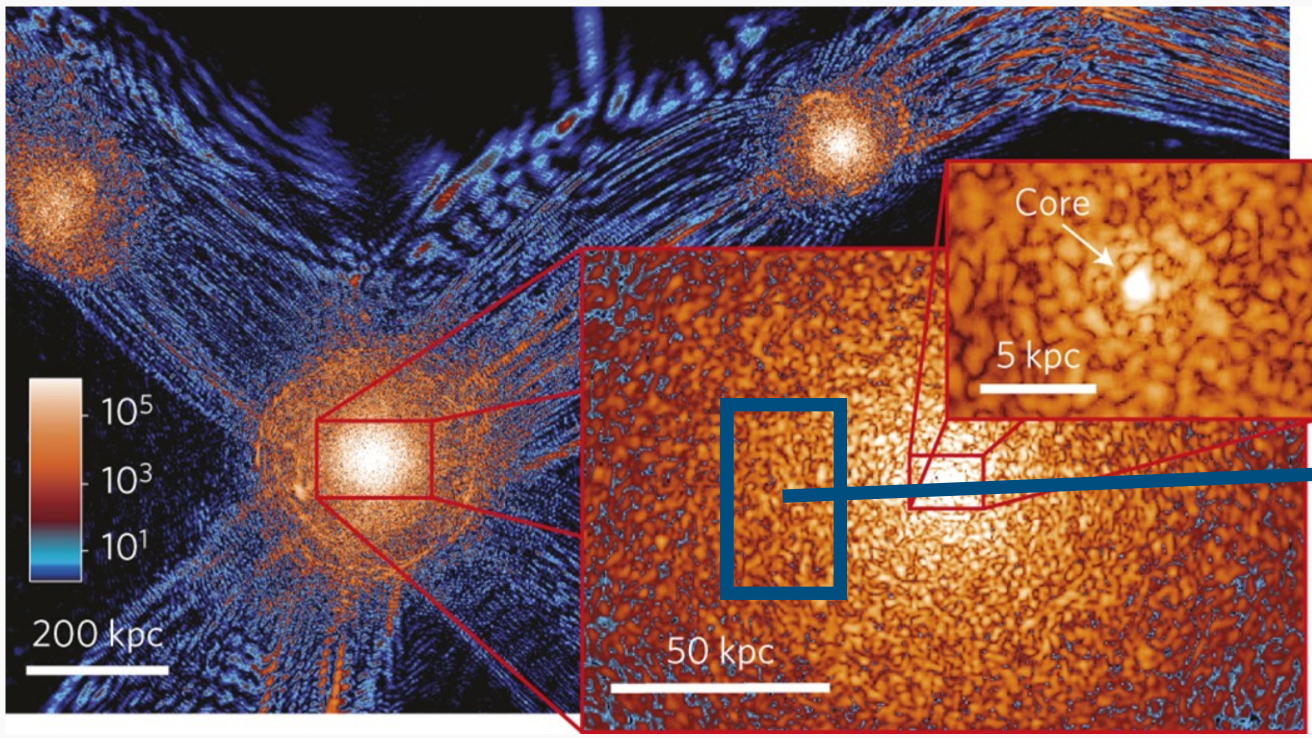
simulation (Schive+2014)

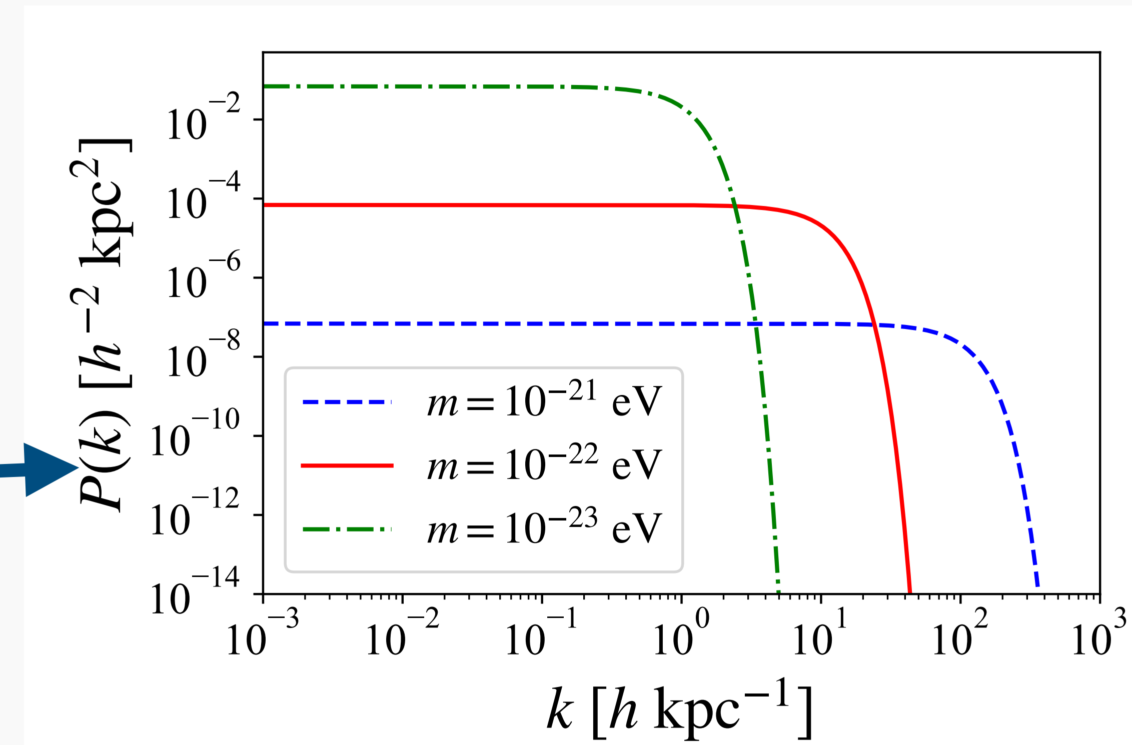
Kawai, MO+ ApJ **925**(2022)61



Analytic model of P(k) in FDM

simulation (Schive+2014)





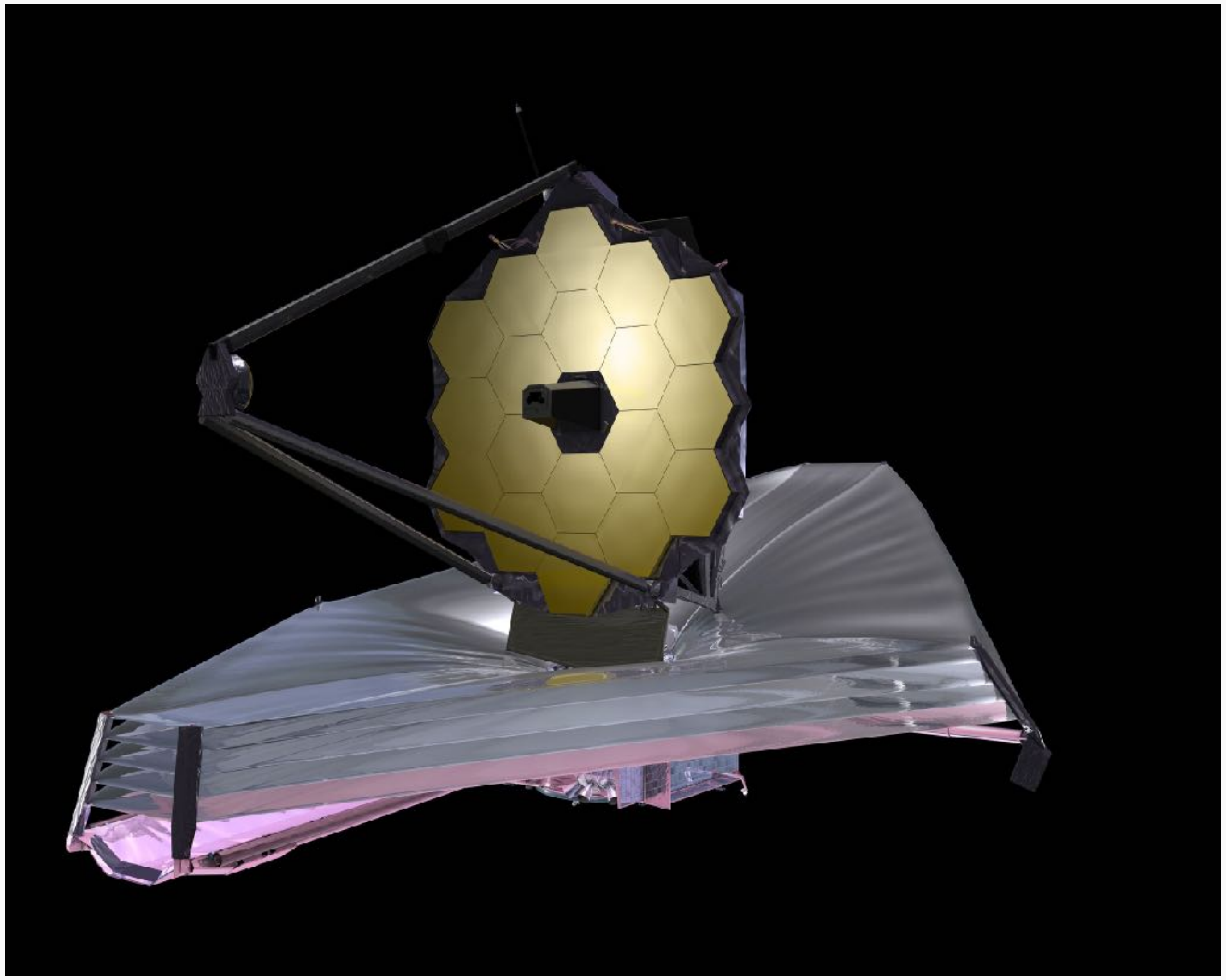
- derive P(k) assuming superposition of Gaussian clumps

$$P(k) = \left(\frac{\Sigma_\mathrm{h}(x)}{\Sigma_\mathrm{h}(x) + \Sigma_\mathrm{b}(x)} \right)^2 \frac{4\pi\lambda_\mathrm{c}^3}{3 r_\mathrm{h}(x)} \exp\left(-\frac{\lambda_\mathrm{c}^2 k^2}{4} \right)$$

$$r_\mathrm{h}(x) = \frac{\Sigma_\mathrm{h}^2(x)}{\int_Z dz\ \rho_\mathrm{h}^2(r)} = \frac{\left(\int_Z dz\ \rho_\mathrm{h}(r)\right)^2}{\int_Z dz\ \rho_\mathrm{h}^2(r)}$$

Progress with JWST

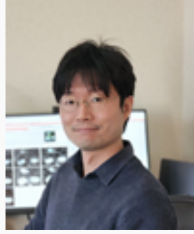
NASA



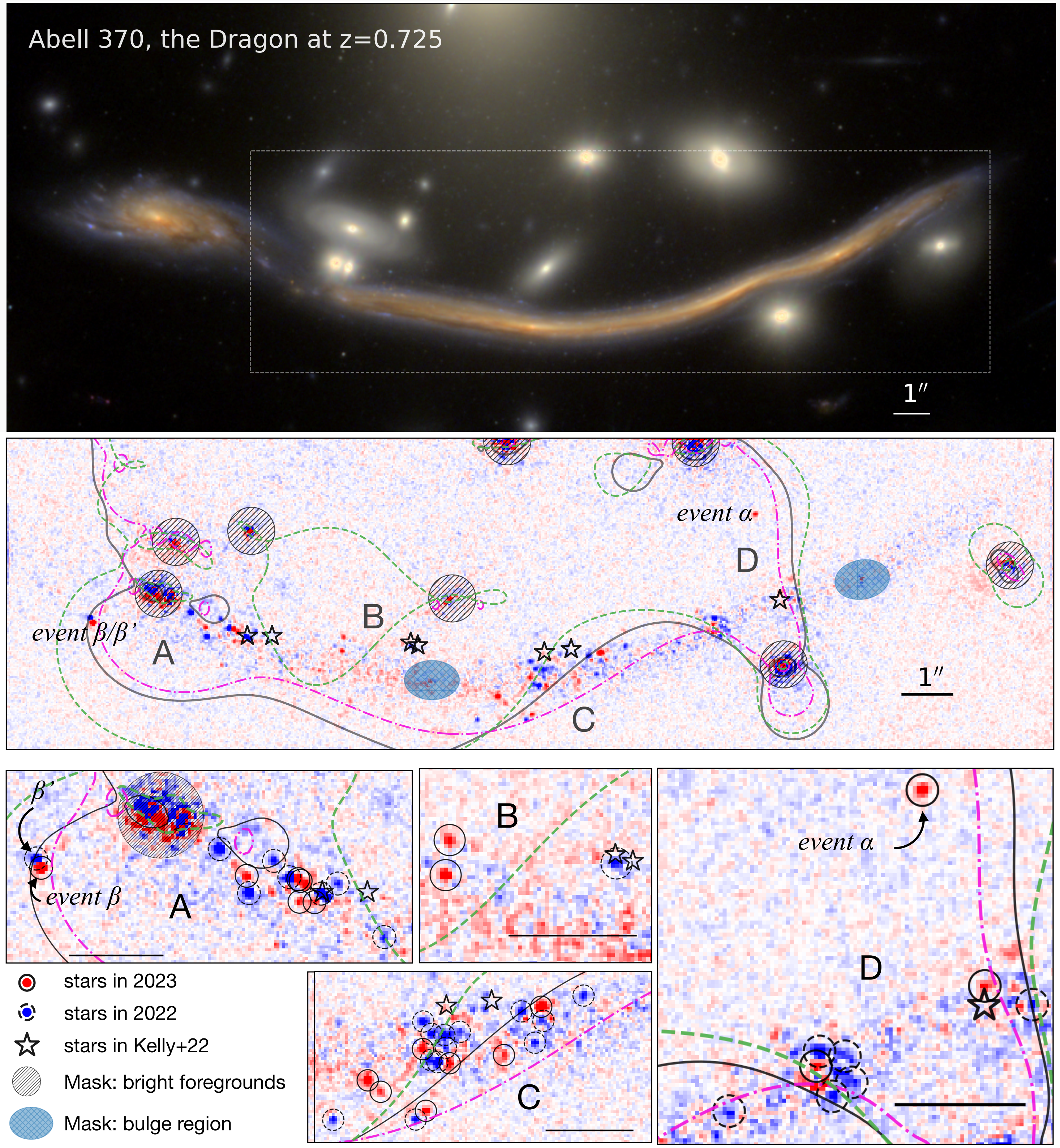
NASA

- more caustic crossings needed to study DM
- **JWST** is the solution!

Fudamoto, Sun, Diego, Dai, MO+ arXiv:2404.08045



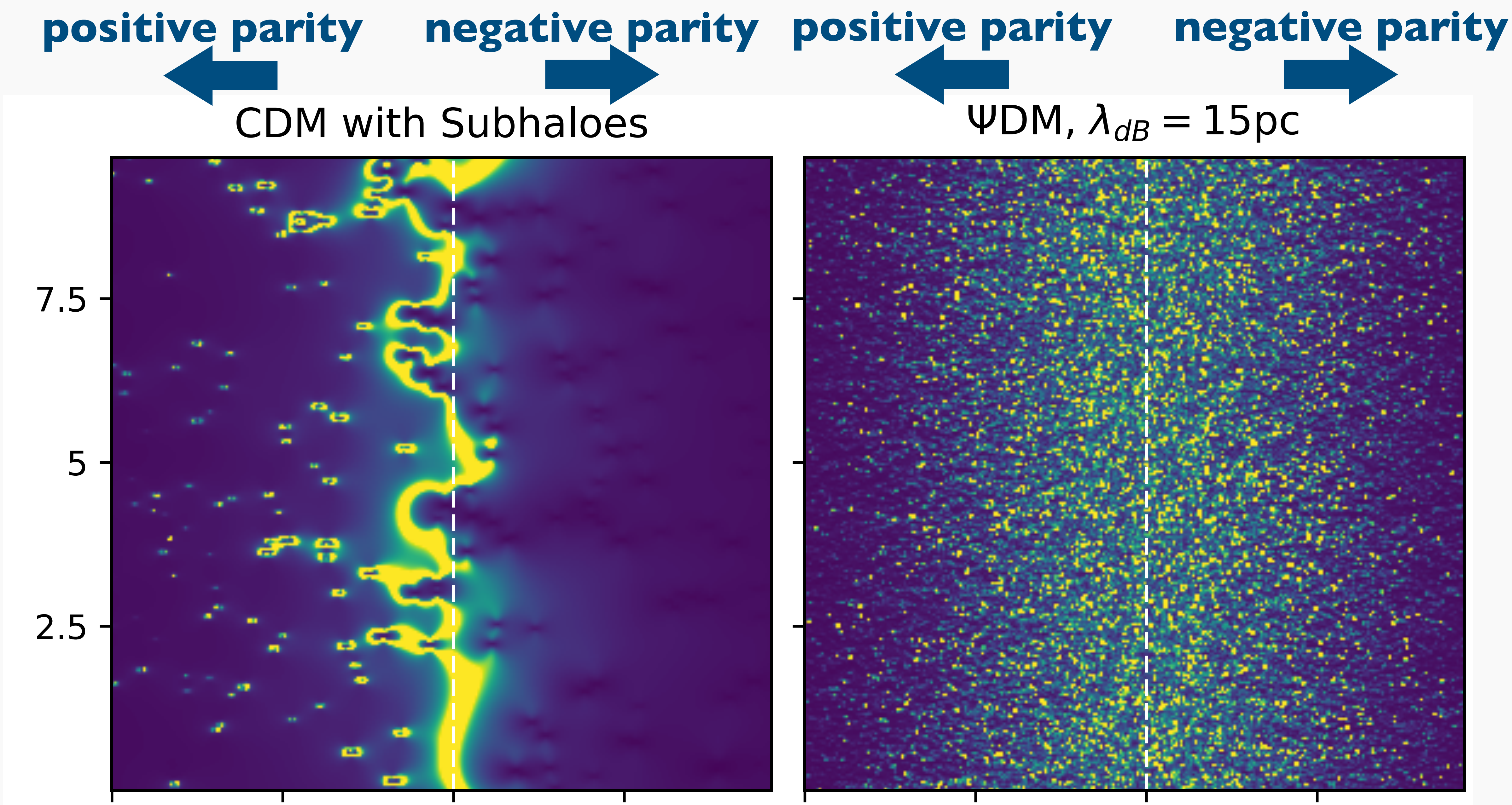
>40 lensed stars in “Dragon”



- Dragon Arc at z=0.725 behind Abell 370
- **>40 lensed stars** discovered from 2 epoch JWST obs. of Dragon!
- DM can be constrained in several ways

Broadhurst+ (incl. MO) arXiv:2405.19422

Constraint from skewness

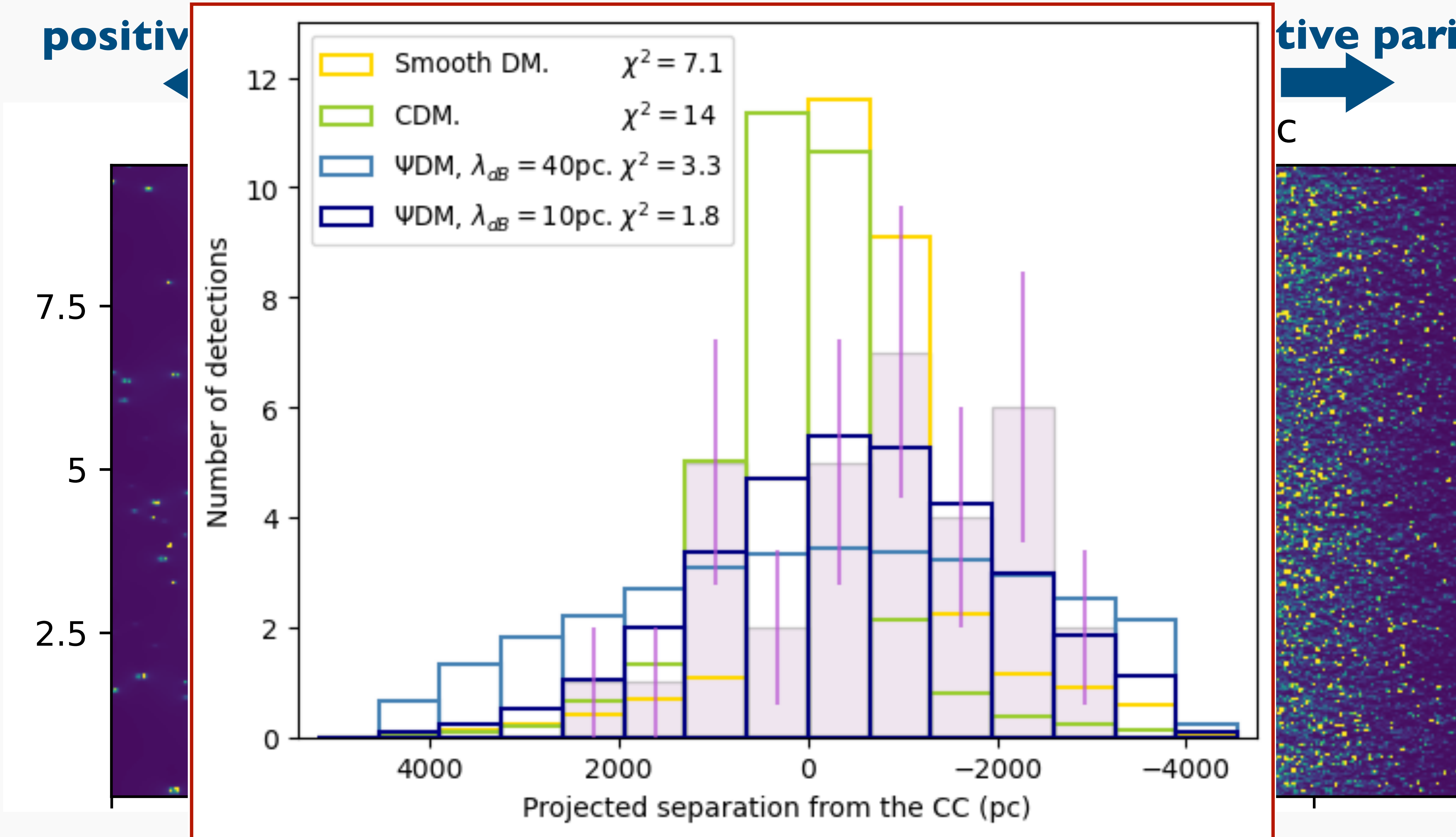


effect of clumps is asymmetric

effect of clumps is symmetric

Broadhurst+ (incl. MO) arXiv:2405.19422

Constraint from skewness



Dragon Arc observation favors FDM (?)

Summary

- caustic crossings are new phenomena reported for the first time in 2018
- highly magnified (~thousands) individual stars
- interpretation rather complicated, but their basic properties now understood thanks to the progress of theoretical studies
- they offer a new route to probe the nature of dark matter
  - sensitive to the PBH abundance
  - probe DM small scale density fluctuations