# Probing ultralight scalar dark matter via microlensing in giant arcs

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# Dark matter substructure

*Two things we may agree upon …*

- (Unfortunately) all our evidence of dark matter is gravitational
- Many dark matter models feature extended substructure

Boson stars, Subhalos, Miniclusters, etc

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- (Unfortunately) all our evidence of dark matter is gravitational
- Many dark matter models feature extended substructure

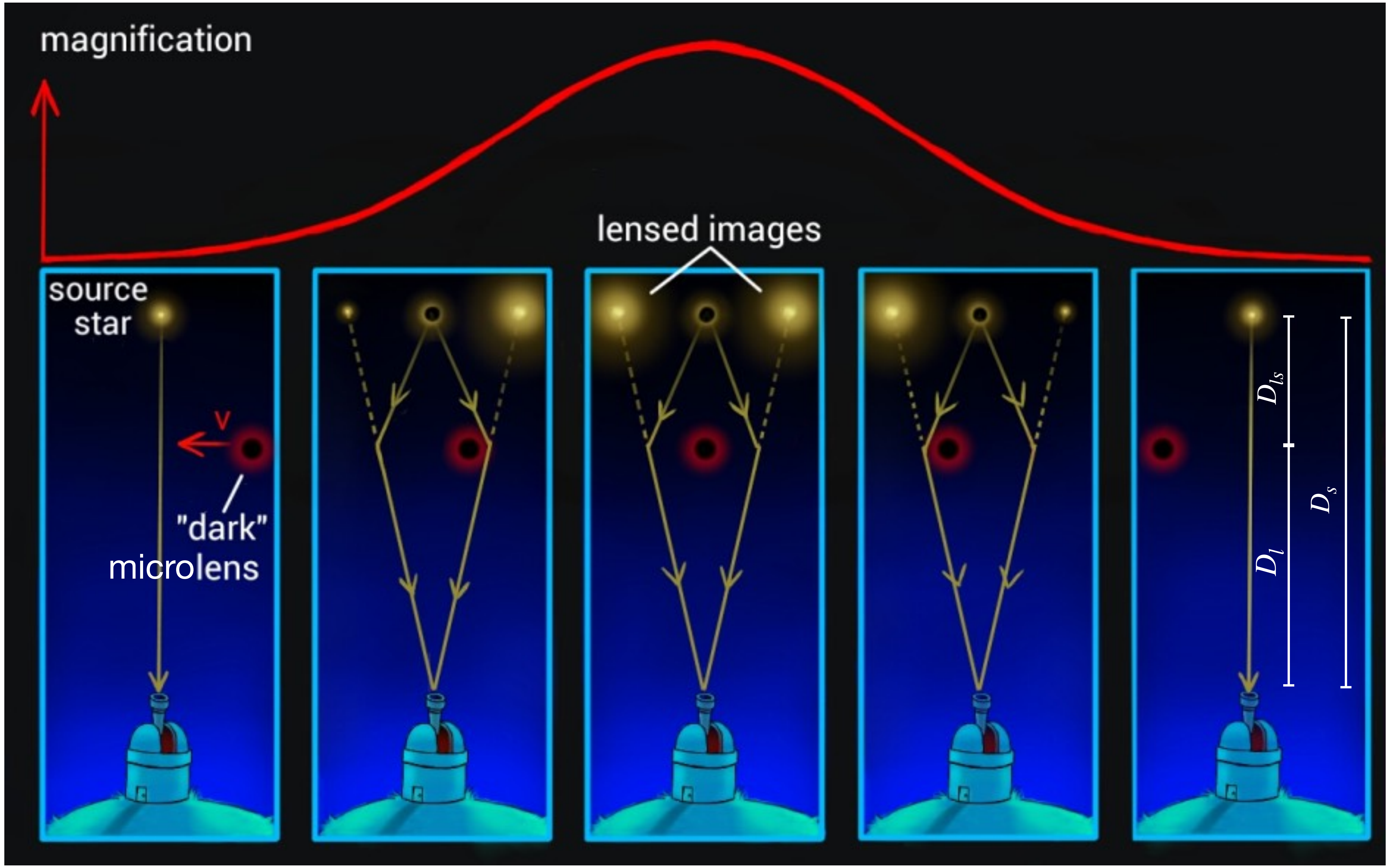
Boson stars, Subhalos, Miniclusters, etc

*What else can we learn from gravitational interactions?*

→ Microlensing in giant arcs surveys constrain extended structures
[Croon et al., arXiv:2511.20761v2]

→ Ultralight dark matter creates extended structures trough wave interference

# Gravitational microlensing




Adam Rogers, theamateurrealist.wordpress.com

Microlensing occurs when a massive object in front of a background source—like a star—**temporarily** magnifies its brightness.

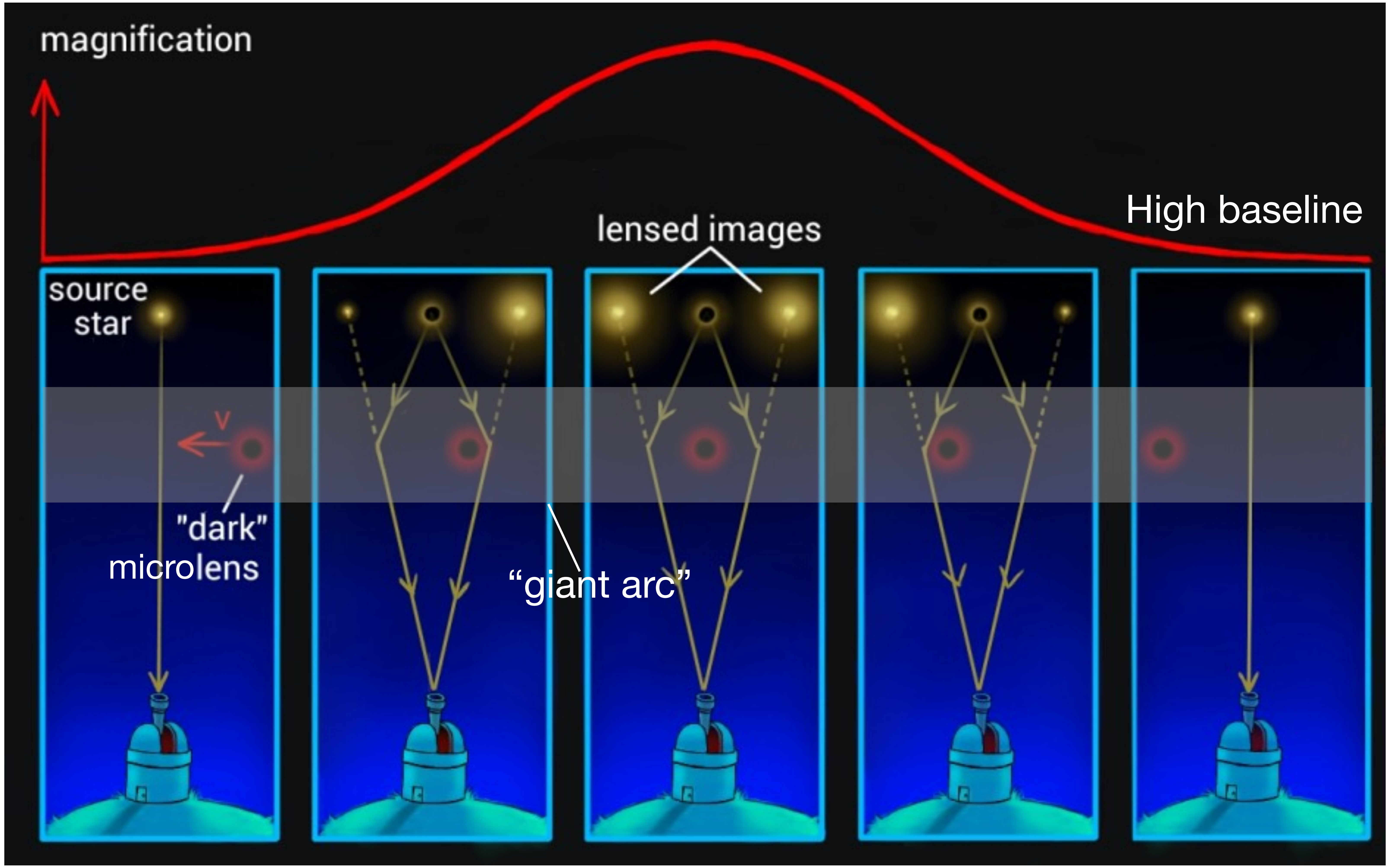
Microlensing is characterized by micro-critical curve:

- “Effective” size of a lens
- $\mu_{\text{micro}} \to \infty$.

For an isolated point-like lens This is given by “Einstein angle”

$$\theta_E = \left( \frac{4GM}{c^2} \frac{D_{ls}}{D_s D_l} \right)^{1/2}$$

# Gravitational microlensing in giant arcs (galaxy cluster)

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[Kelly et al., arXiv:1411.6009v3]

What happens if microlensing happens in giant arcs?

- Extreme magnification events
- Images are stretched immensely

Microlensing is enhanced!

# Part I: Microlensing of extended structures in giant arcs

# Micro-critical curves

- Microlensing is characterized by ***effective*** Einstein angle

Efficiency (finite-lens effects), $\epsilon \leq 1$

$$\bar{\theta}_{E,\mathrm{EDO}} \equiv \epsilon_{\mathrm{EDO}} \sqrt{\mu_t} \theta_E$$

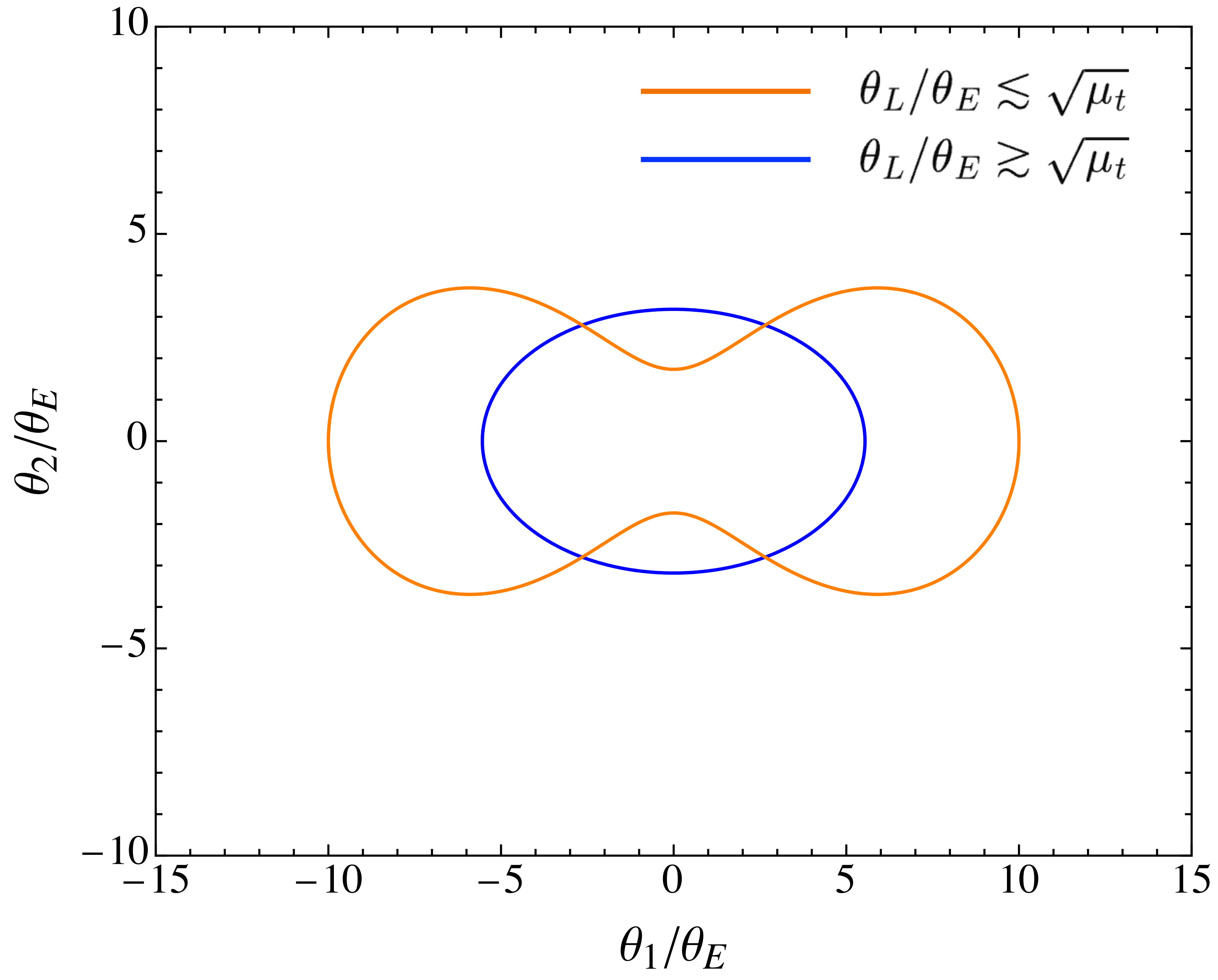
Macro-magnification from giant arc, $\mu_t \gg 1$

- Maximum magnification

$$\mu \propto \mu_t \mu_{\mathrm{micro}}$$

E.g: Parabolic sphere

$$\rho(\theta) = \rho_0 \left(1 - \frac{\theta^2}{\theta_L^2}\right) \Theta(\theta_L - \theta)$$



# Saturation

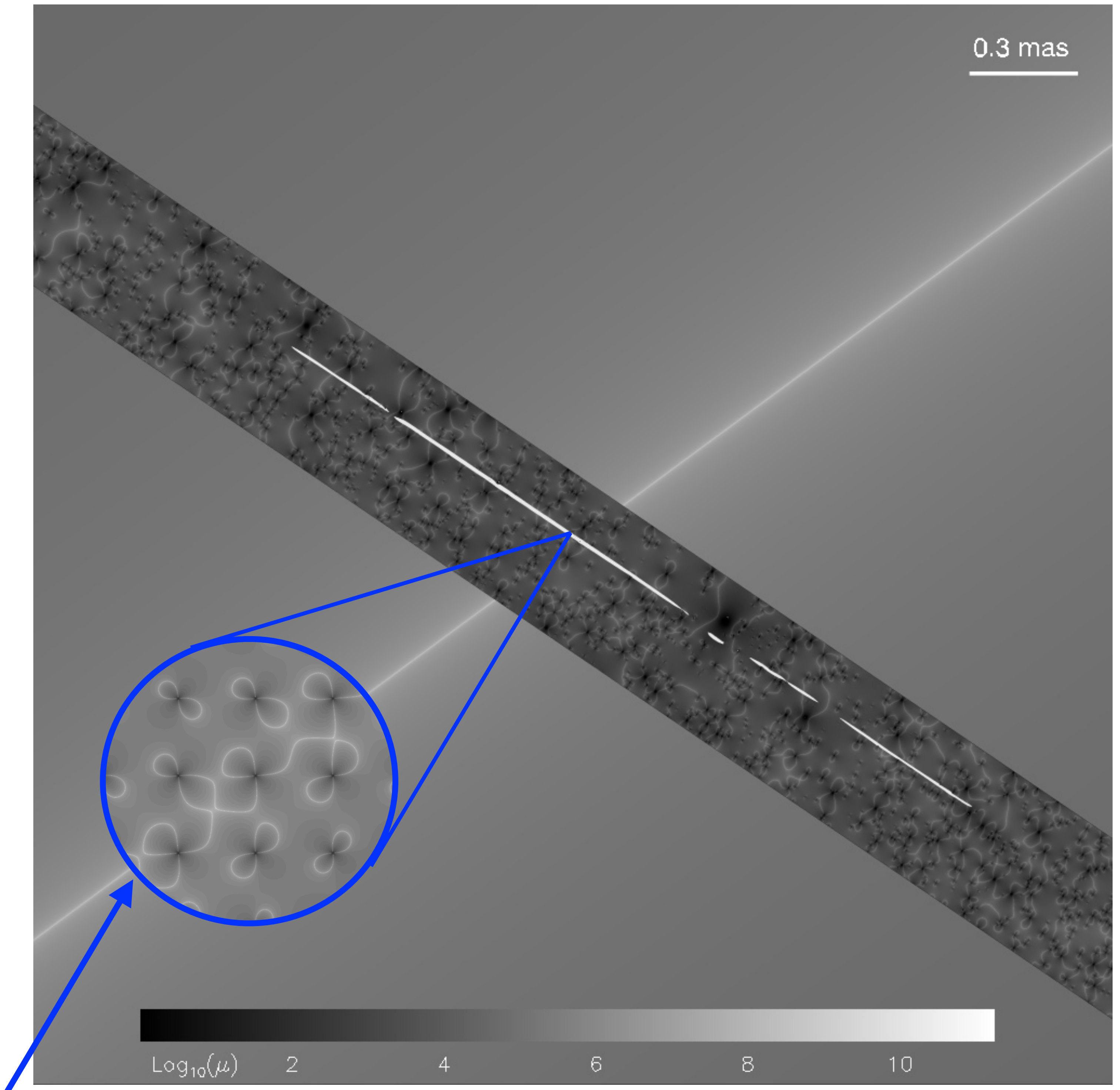
- Microlenses disrupt macro-CC and $\mu_t$ is "capped" when microlenses overlap: $\tau \approx 1$ (saturation)

$$\tau = \mu_t \kappa_{\rm tot} f_{\rm co} \epsilon_{\rm EDO}^2$$

Mass fraction of monochromatic compact objects

$$\mu_{t,\rm sat} \approx \kappa_{\rm tot}^{-1} f_{\rm co}^{-1} \epsilon_{\rm EDO}^{-2}$$

- Larger fractions of dark objects "kills" the macro-magnification → Fainter events.

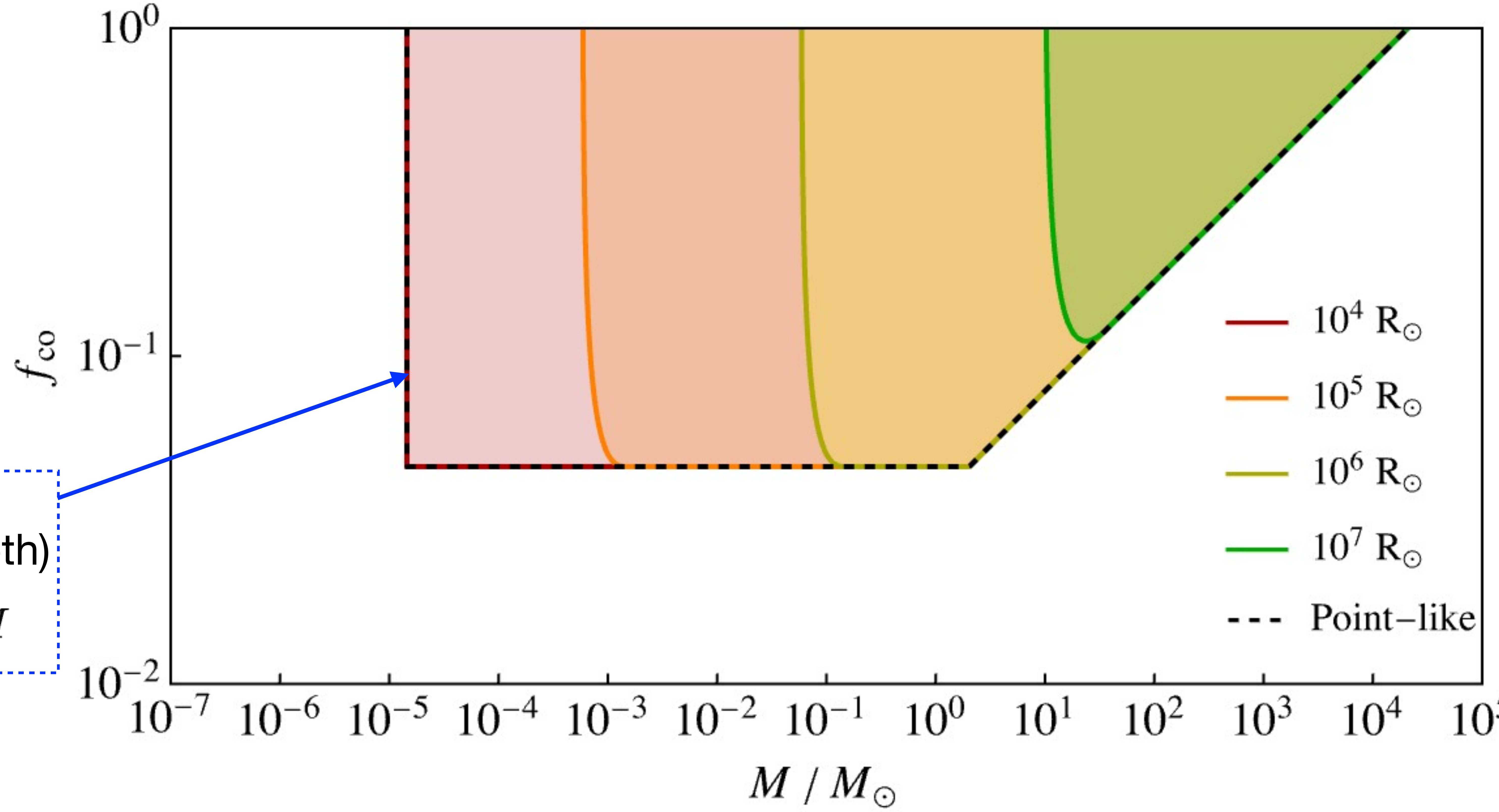



[Diego et al., arXiv:1706.10281]

Macro-magnification is redistributed into a network of micro-images

# DM Constraints

- Icarus event: First ever star observed at cosmological distances ($z = 1.49$)




Finite-source effects
(Microlenses ~ smooth)

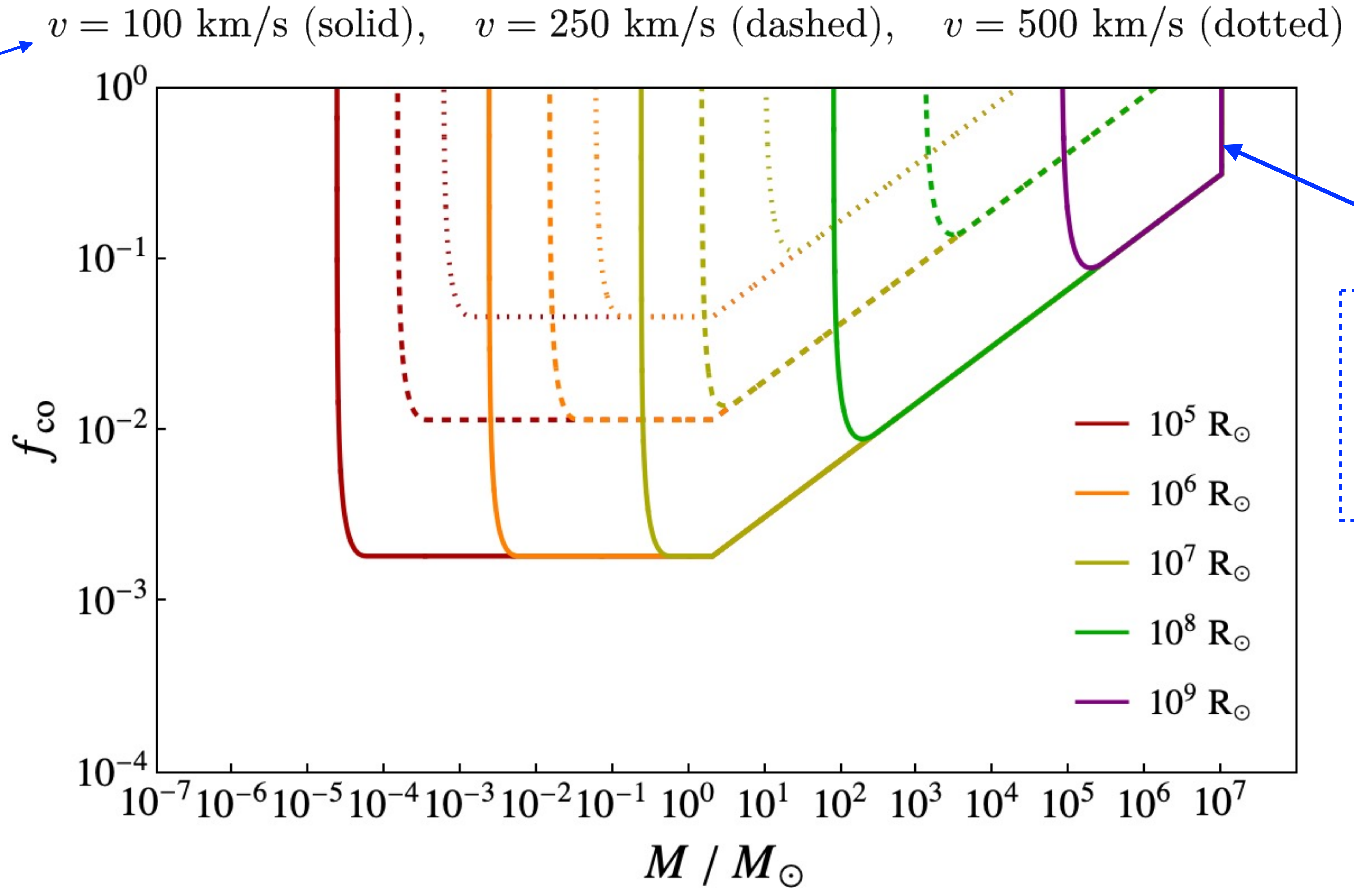
$1.5 \times 10^{-5} M_\odot \lesssim M$

Massive lens → More deflection → More magnification → More fraction allowed

# DM Constraints

- Icarus event: First ever observed star at cosmological distances ($z = 1.49$)

Bulk velocity of cluster




Micro-CC merge with giant arc (assumptions break down)

$$M \lesssim 5.1 \times 10^7 M_\odot$$

Higher bulk velocity → Larger source → More magnification → More fraction allowed

# Part II: Ultralight scalar dark matter

# Density perturbations

- Ultralight dark scalar matter behaves as classical waves

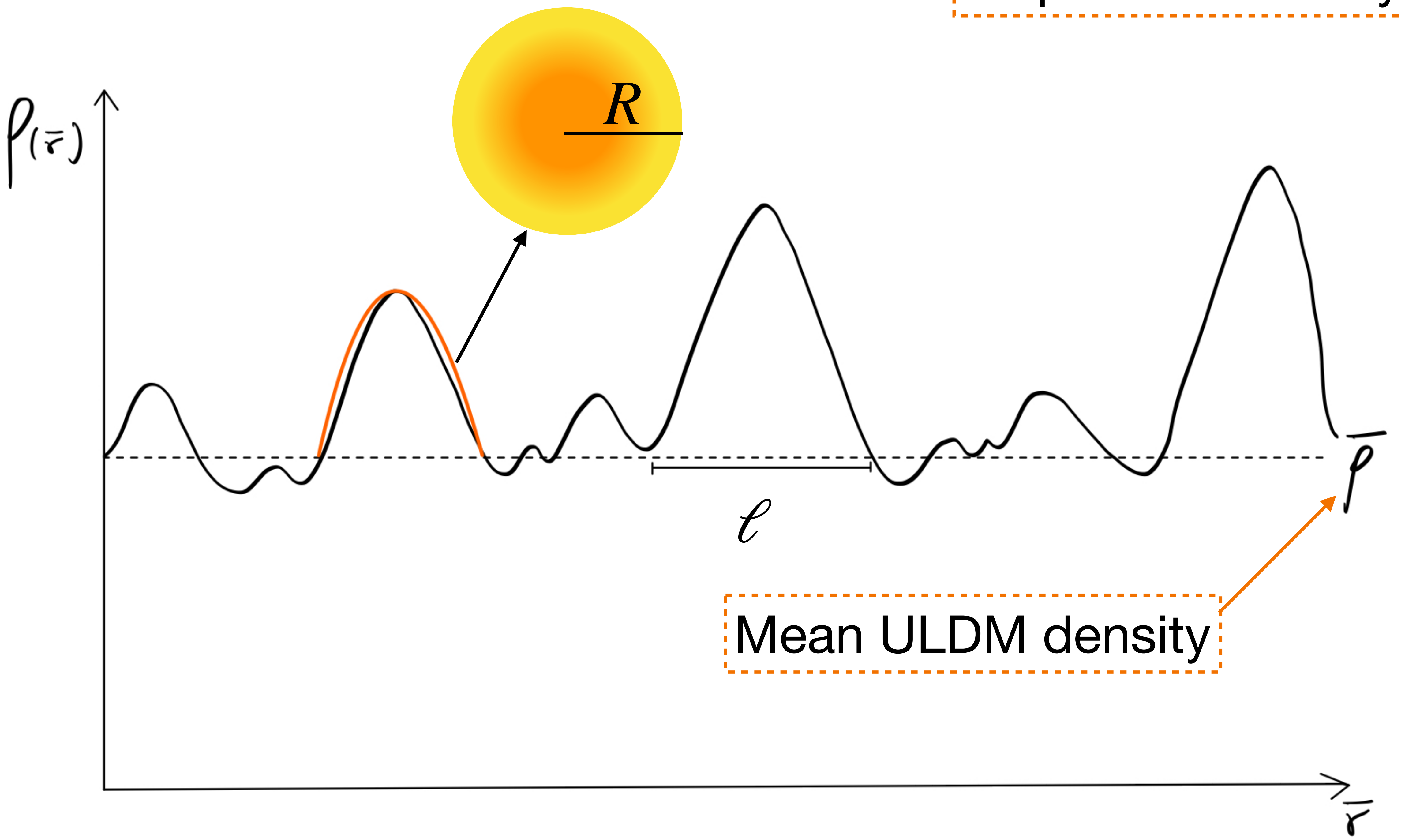
$$\ell \equiv \frac{1}{mv} \approx 5.3 \times 10^9 R_\odot \left(\frac{10^{-22}\ \mathrm{eV}}{m}\right)\left(\frac{1000\ \mathrm{km/s}}{v}\right)$$

Dispersion velocity

- Constructive interference creates massive extended objects

$$\delta\rho \propto \left(1 - \frac{r^2}{R^2}\right)\Theta(R - r)$$

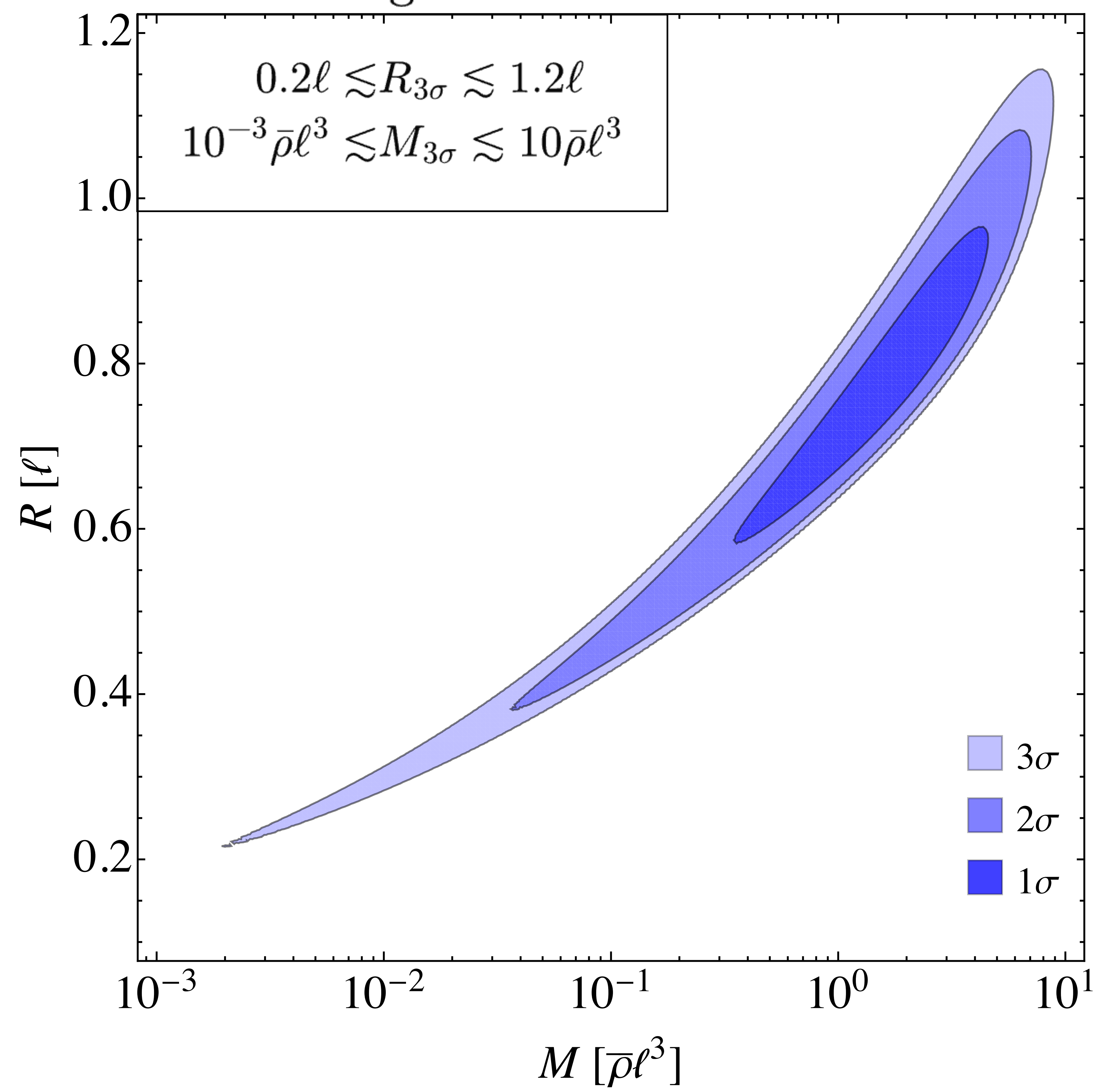
Parabolic sphere!

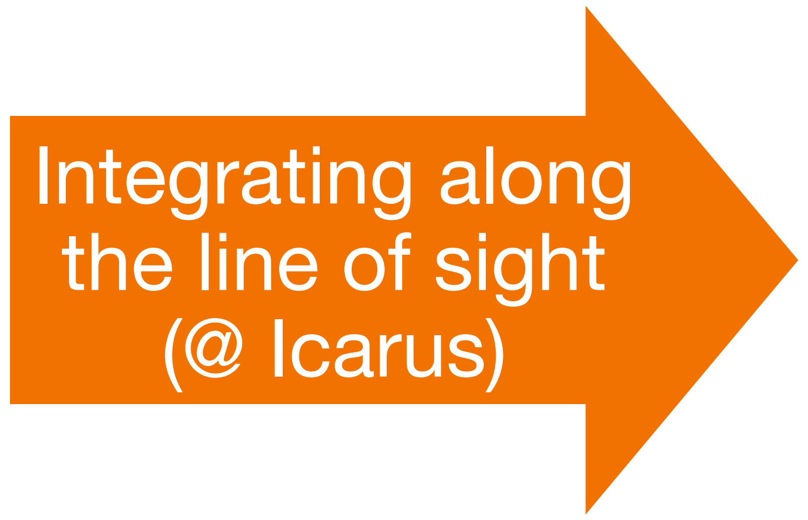


# Mass/radii extended function

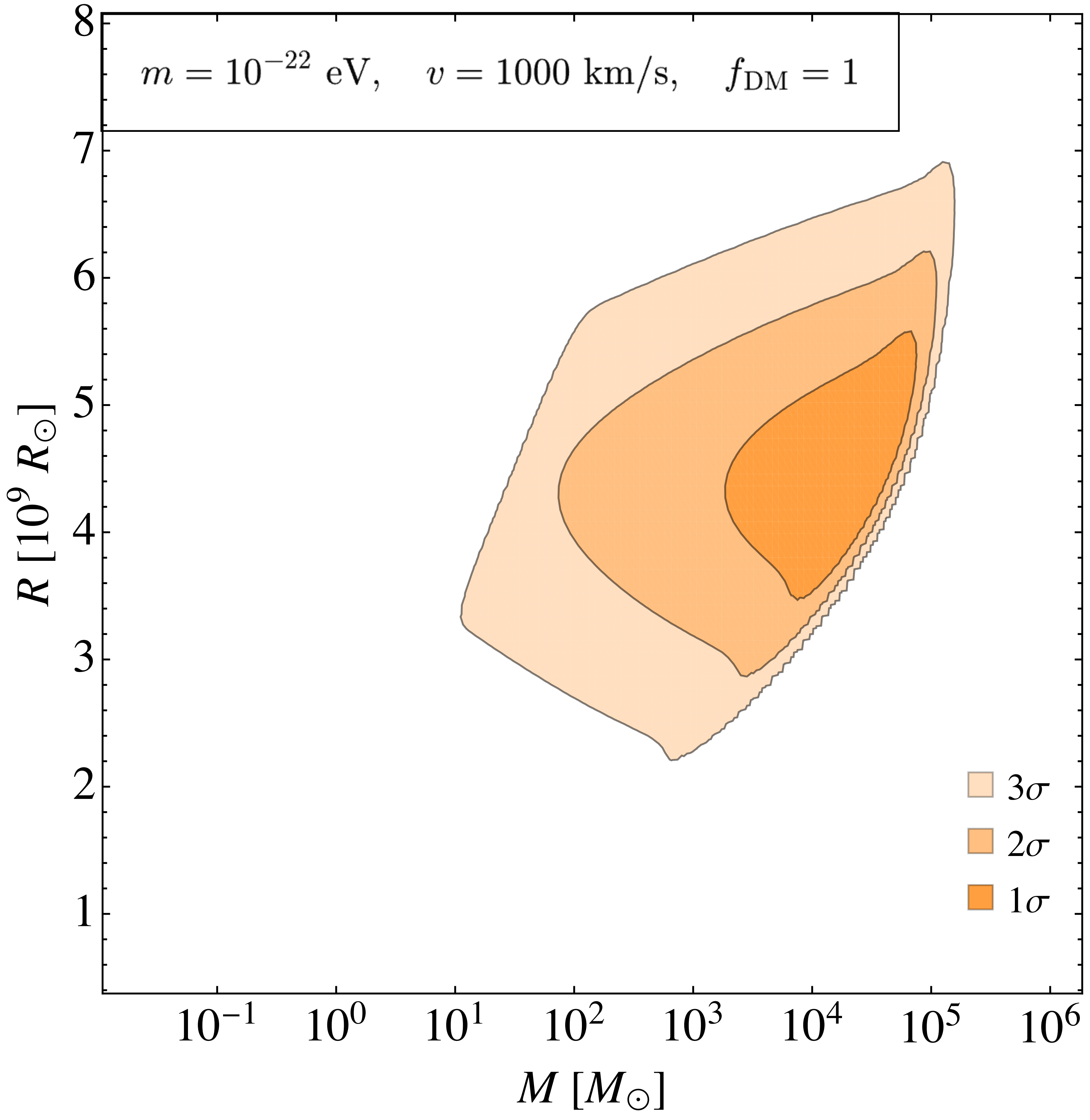
- Gaussian density fluctuation → Large/small structure suppression

$$\frac{d^2 n_{3D}}{d\log M\, dR} \equiv n(M, R, \ell, \bar{\rho})$$




$$\frac{d f_{\rm DO}}{d\log M\, dR} = \frac{M}{\Sigma_{\rm tot}} \frac{d^2 n_{2D}}{d\log M\, dR}$$



# Saturation

- Optical depth for an extended mass/radii function

$$\frac{d\tau}{d\log M\, dR} = \mu_t\, \kappa_{\rm tot}\, \frac{df_{\rm DO}}{d\log M\, dR}\, \epsilon^2_{\rm EDO}(M,R)$$

Each object has its own efficiency.

- At saturation $\tau = 1$,

$$\mu_{t,\rm sat} = \frac{\kappa_{\rm tot}^{-1}}{\int dR \int d\log M \frac{df_{\rm DO}}{d\log M\, dR}\epsilon^2_{\rm EDO}(M,R)}$$

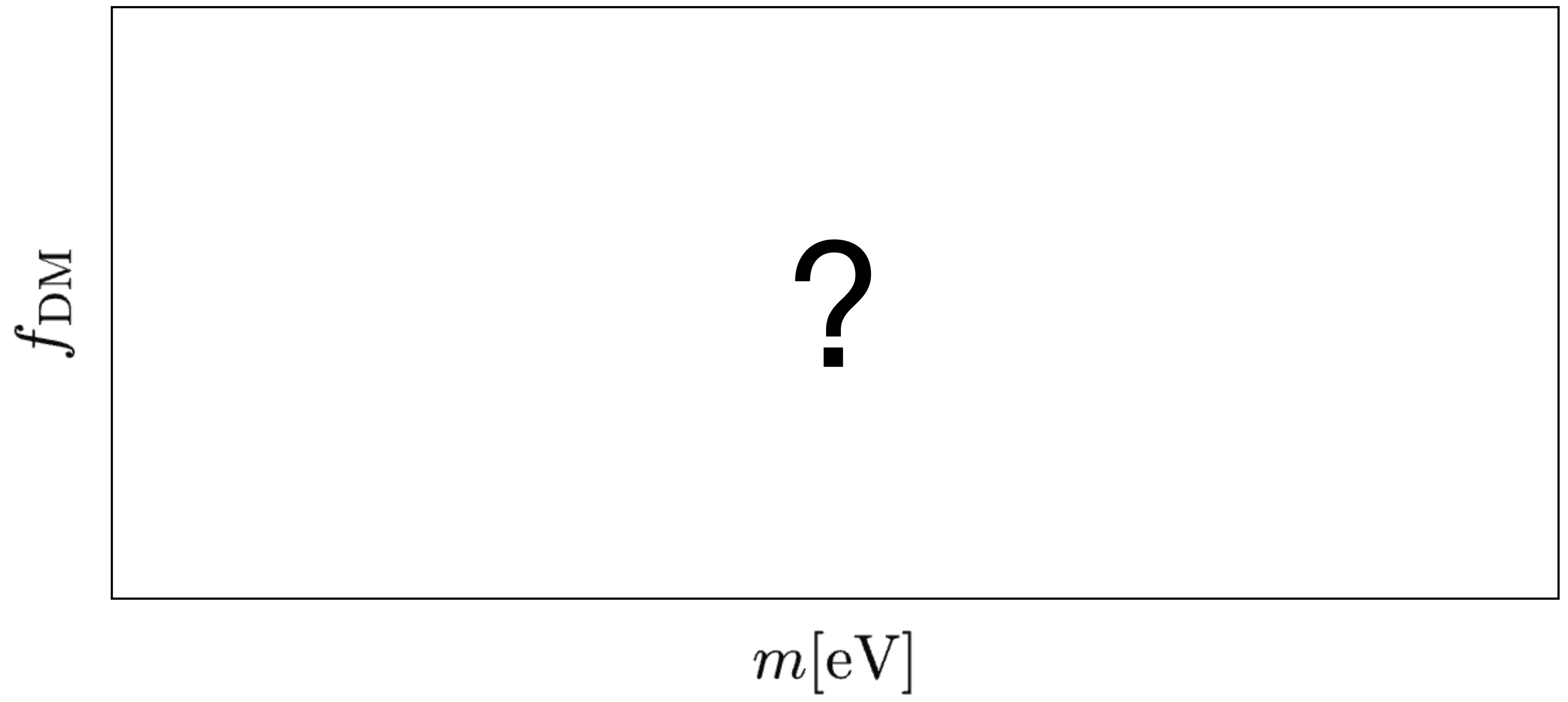
- *Next step:* We feed $\mu_{t,\rm sat}$ into the Icarus observation to see whether or not the model is constrained by the Icarus event (in progress).

# Takeaways

- Microlensing in giant arcs represents a compelling laboratory to constrain extended dark matter structures.

- Icarus was just the beginning. New observations (Earandel, Spock, Godzilla, etc.) will potentially put sharper constraints on a variety of extended DM.

- Ultralight scalar dark matter wave interference naturally generates extended massive substructure.



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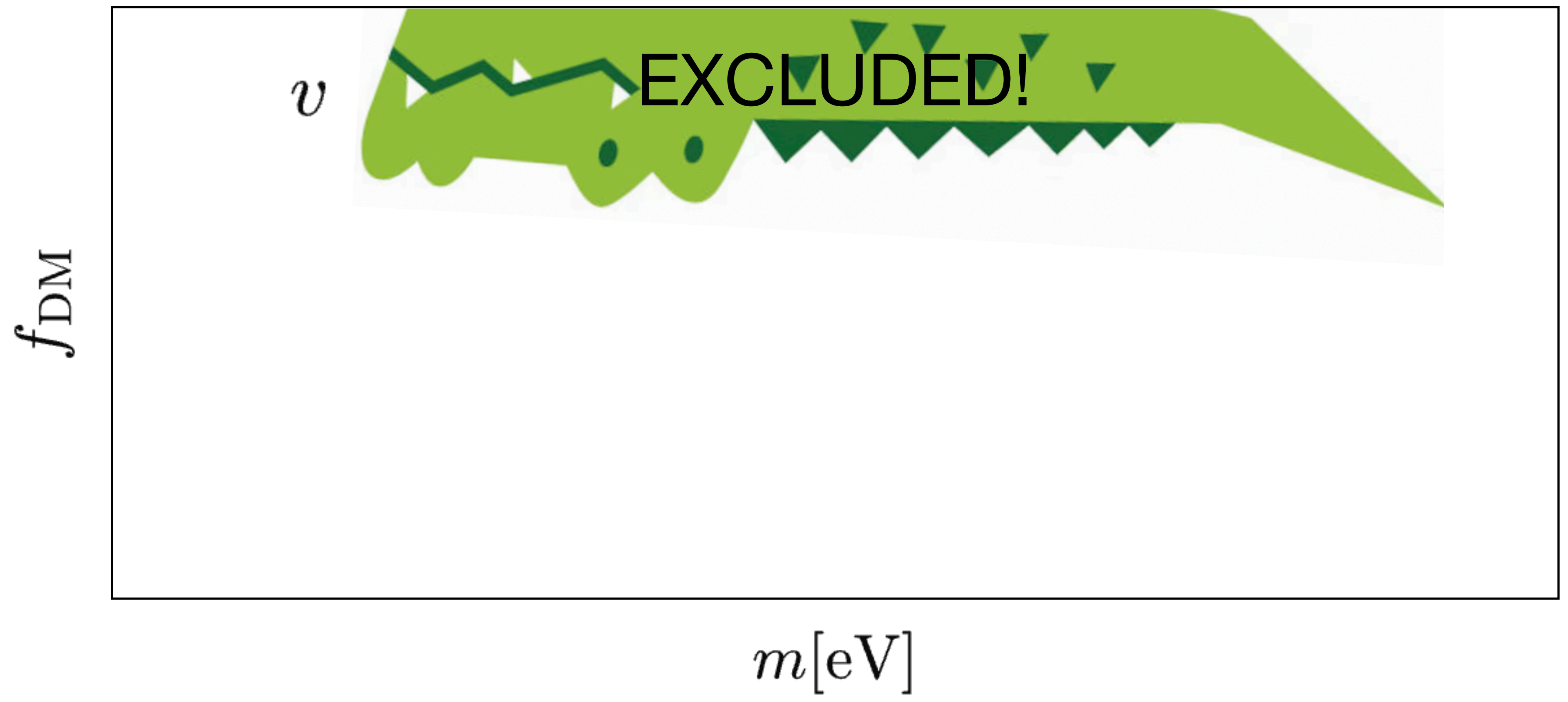
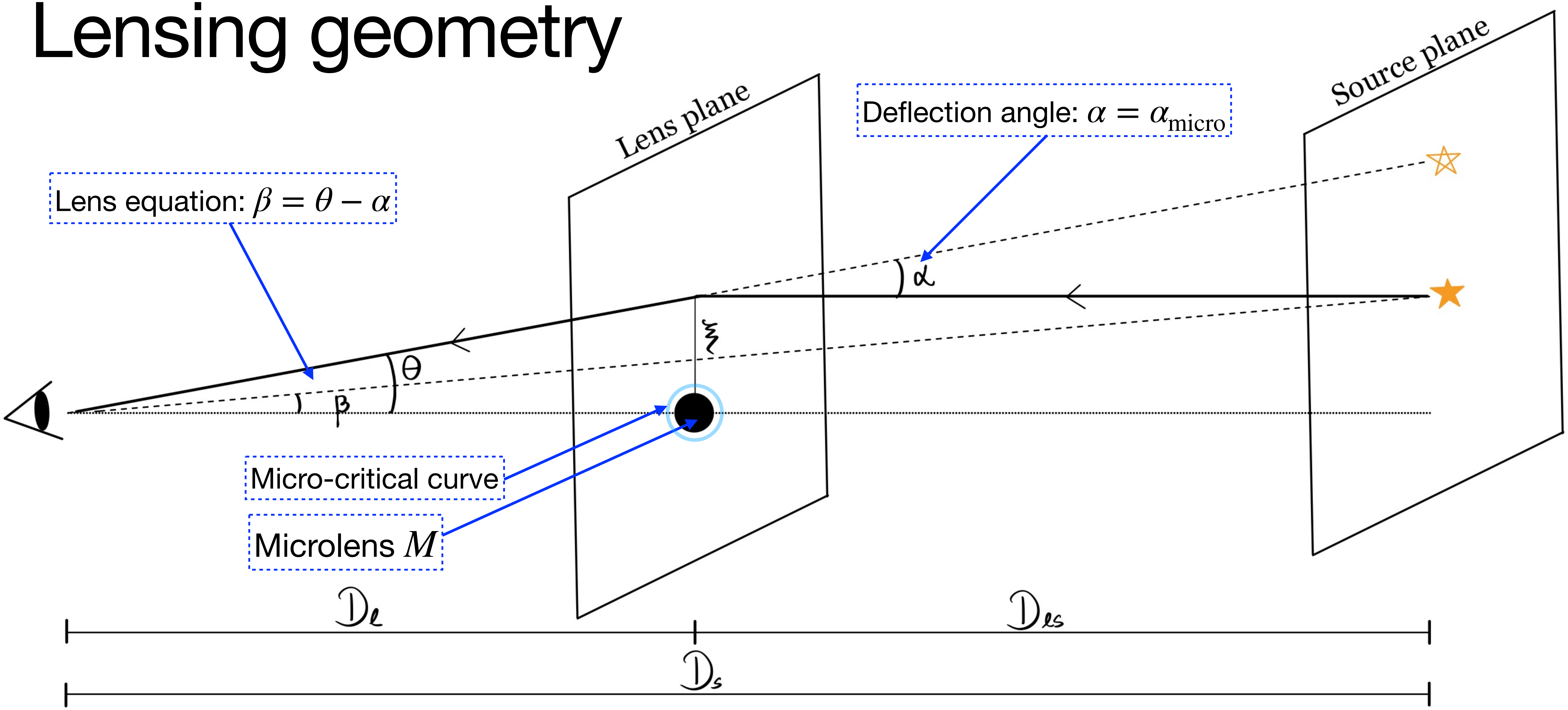



Thank you!

# Backup slides

# Lensing geometry



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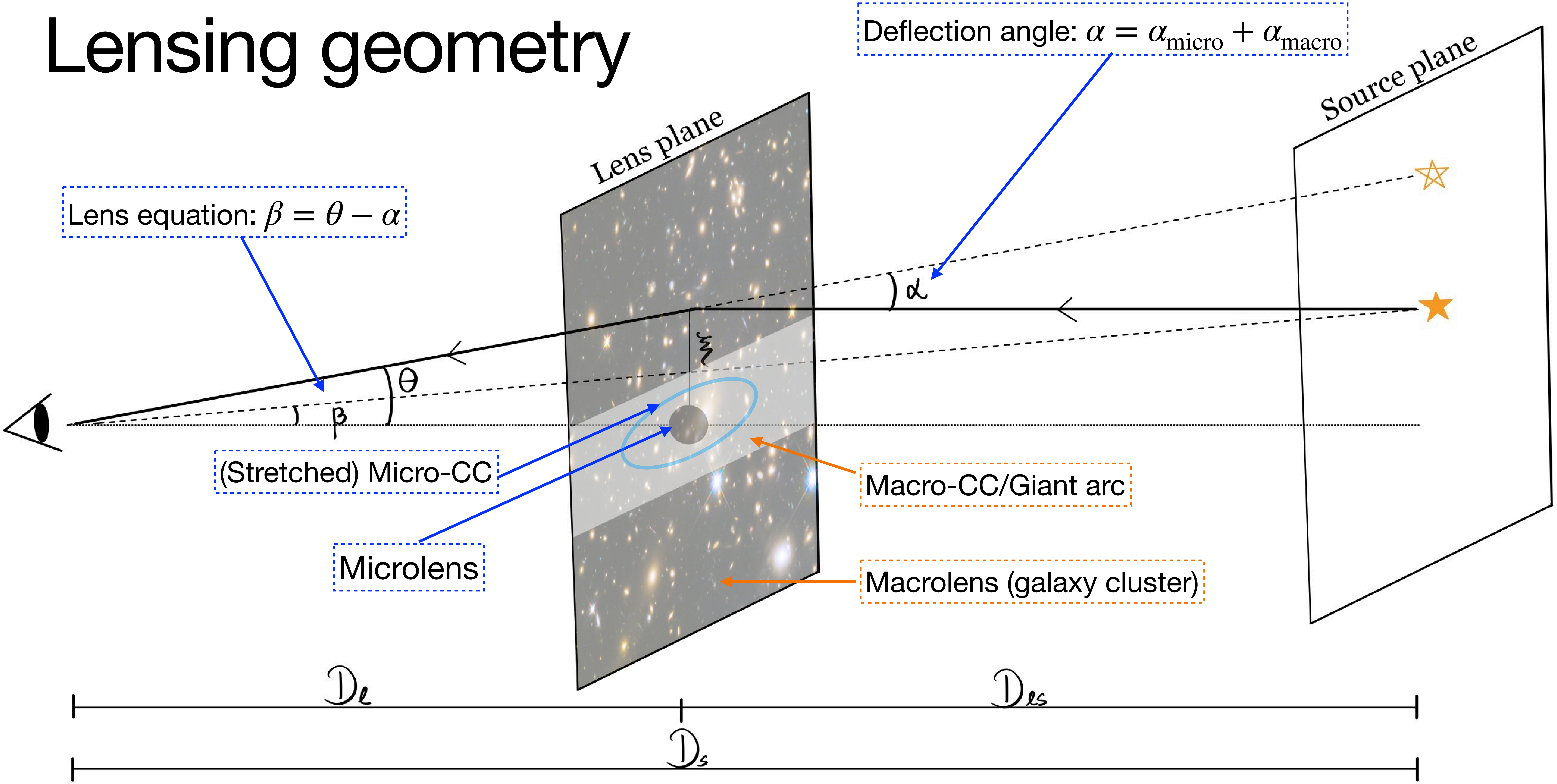
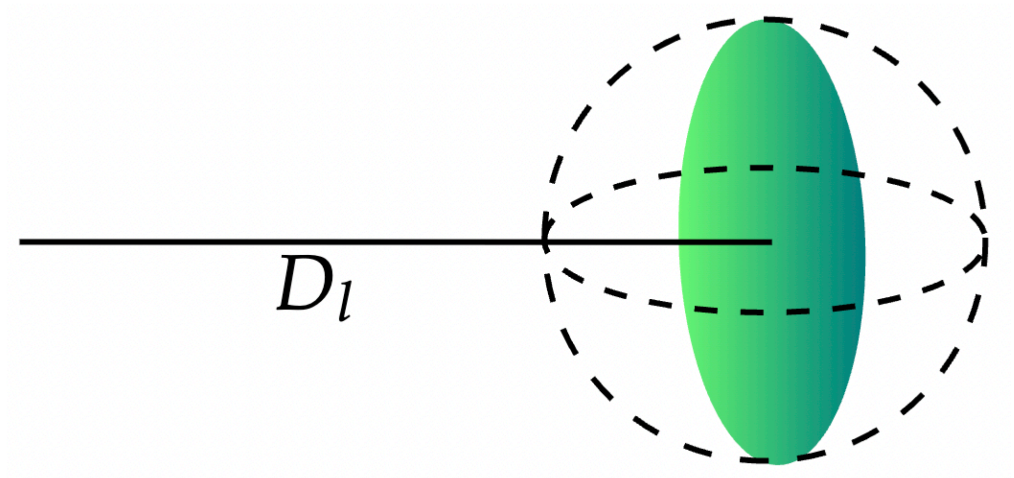


# The lensing equation (“Chang-Refsdal lens”)

- Chang-Refsdal lens: Two length-scale problem, macrolens acts as a perturber
- The source position $\beta$ and image position $\theta$ are related by

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}_{\mathrm{micro}} - \vec{\alpha}_{\mathrm{macro}}$$

$$\vec{\alpha}_{\mathrm{micro}} = \frac{\theta_E^2}{\theta^2}\frac{M(\theta)}{M}\vec{\theta}, \quad \theta_E = \left(\frac{4GM}{c^2}\frac{D_{ls}}{D_s D_l}\right)^{1/2}$$




“Einstein angle”

$$\vec{\alpha}_{\mathrm{macro}} = \begin{pmatrix} \bar{\kappa} - \bar{\gamma} & 0 \\ 0 & \bar{\kappa} + \bar{\gamma} \end{pmatrix} \vec{\theta}$$

Macrolens convergence and shear
(stretching of images!)

# The lensing equation (“Chang-Refsdal lens”)

- After some redefinitions: $y = \beta/\theta_E$, $x = \theta/\theta_E$, $m(x) = M(x\theta_E)/M$

$$\mu_r = (1 - \bar{\kappa} + \bar{\gamma})^{-1}$$
$$\mu_t = (1 - \bar{\kappa} - \bar{\gamma})^{-1}$$

Radial and tangential macro-magnification.
Near a tangential macro-CC: $\mu_t \gg \mu_r$

$$y_1 = \frac{x_1}{\mu_r} - \frac{m(x)}{x^2} x_1$$
$$y_2 = \frac{x_2}{\mu_t} - \frac{m(x)}{x^2} x_2$$

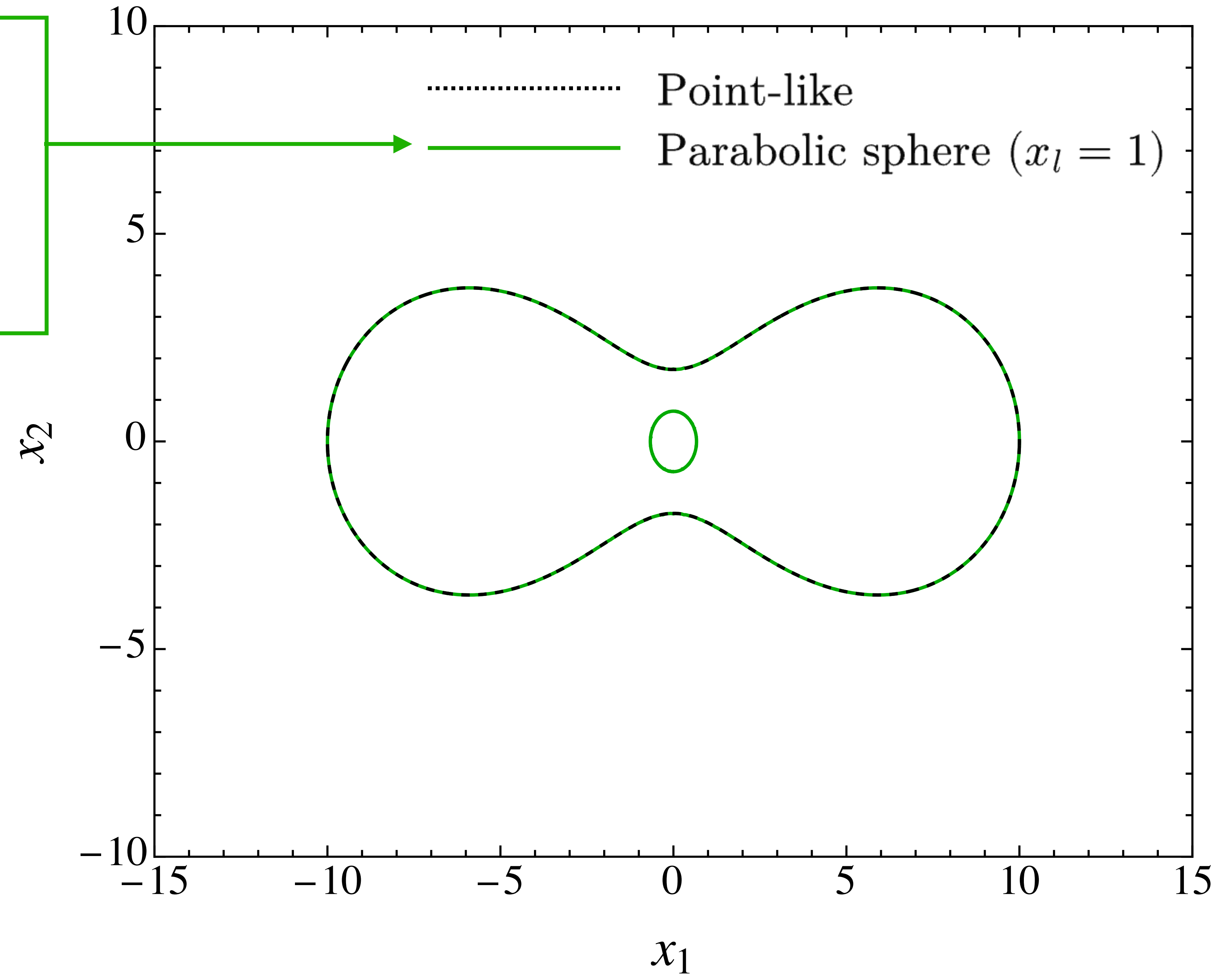
- The magnification of the micro+macrolens system is

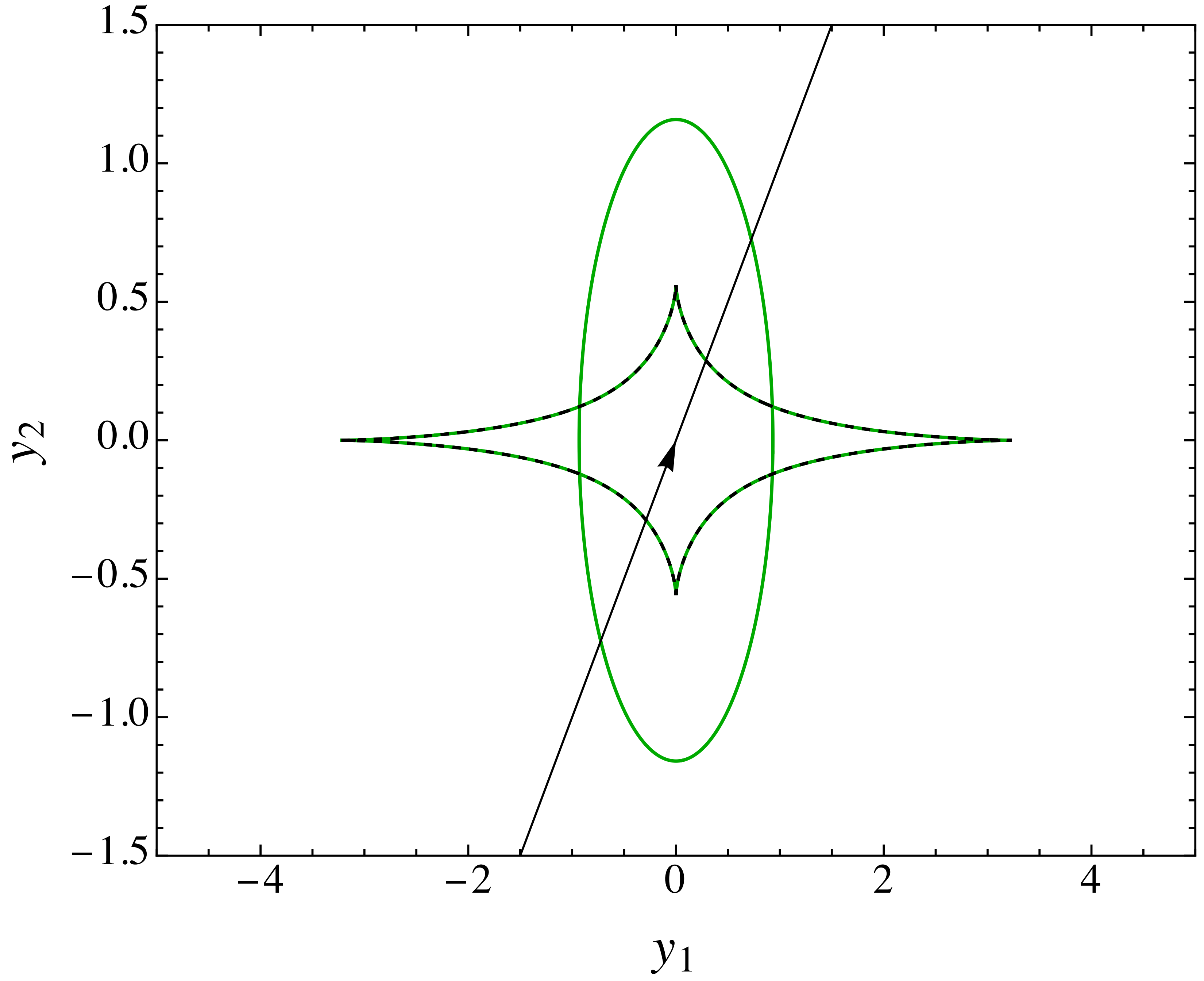
$$\mu^{-1} = (\mu_r \mu_t)^{-1} - \frac{m^2(x)}{x^4} - (\mu_r^{-1} + \mu_t^{-1}) \frac{m'(x)}{2x} + \frac{m(x)m'(x)}{x^3}$$
$$-(\mu_r^{-1} - \mu_t^{-1}) \left( \frac{m(x)}{x^2} - \frac{m'(x)}{2x} \right) \cos(2\phi)$$

# Micro-critical curves and caustics

- New micro-critical curves/caustics structures

$$\rho(r) = \rho_0 \left(1 - \frac{r^2}{r_l^2}\right) \Theta(r_l - r)$$



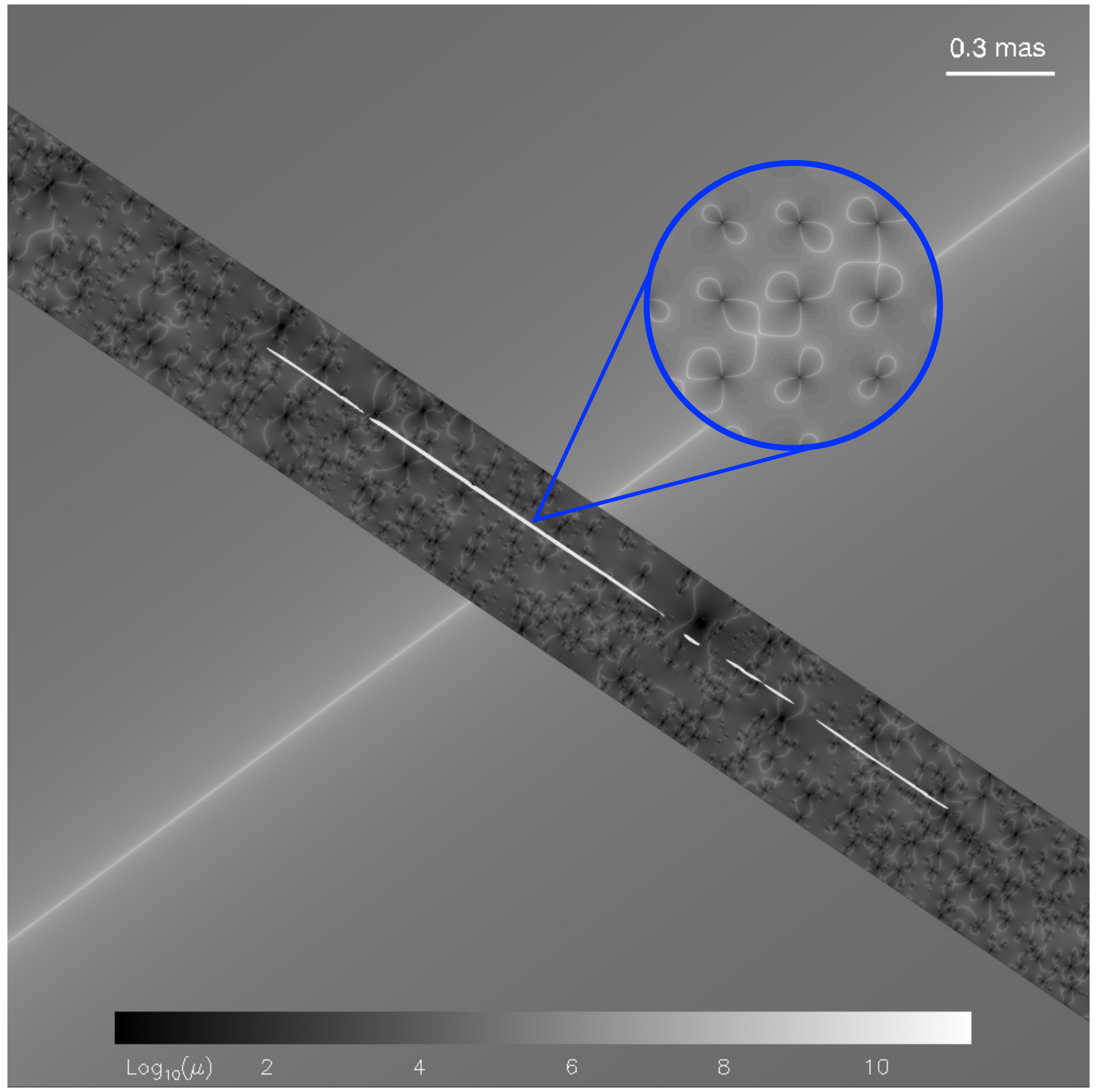

- Microlensing is now characterized by *effective* Einstein angle

$$\bar{\theta}_{E,\mathrm{EDO}} \equiv \epsilon_{\mathrm{EDO}} \sqrt{\mu_t}\, \theta_E$$

Efficiency (finite-lens effects), $\epsilon \leq 1$

Macro-CC stretching

# Saturation




- Normally one expects that as the image of a lensed source approaches the macro-CC it gets brighter $\mu_t \rightarrow \infty$

- Microlenses disrupt macro-CC and $\mu_t$ is "capped" when microlenses overlap: $\tau \approx 1$ (saturation)

$$\tau = \mu_t \kappa_{\rm tot} f_{\rm co} \epsilon_{\rm EDO}^2$$

$$\mu_{t,\rm sat} \approx \kappa_{\rm tot}^{-1} f_{\rm co}^{-1} \epsilon_{\rm EDO}^{-2}$$

Mass fraction of compact objects

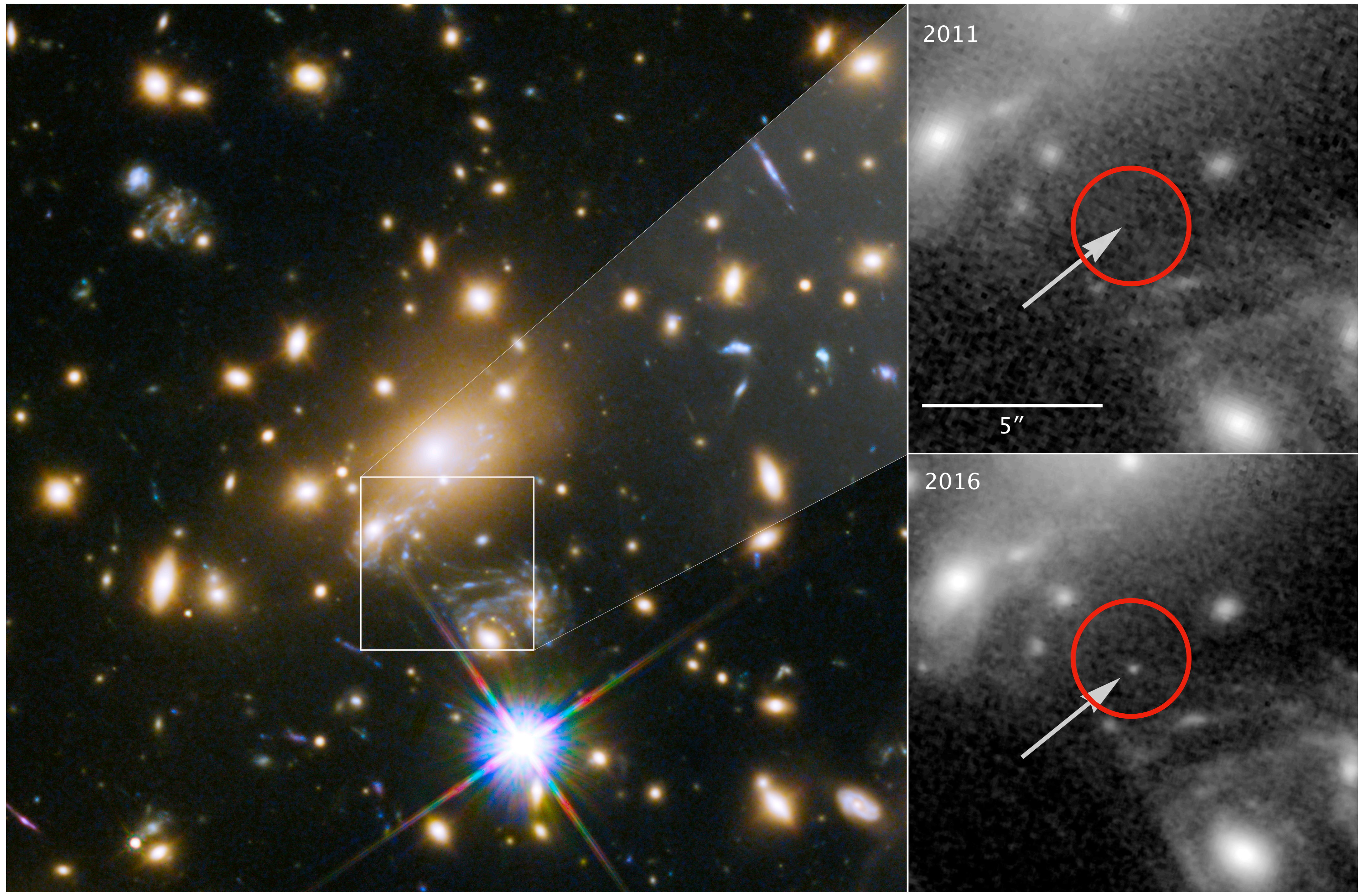
- Saturation validity

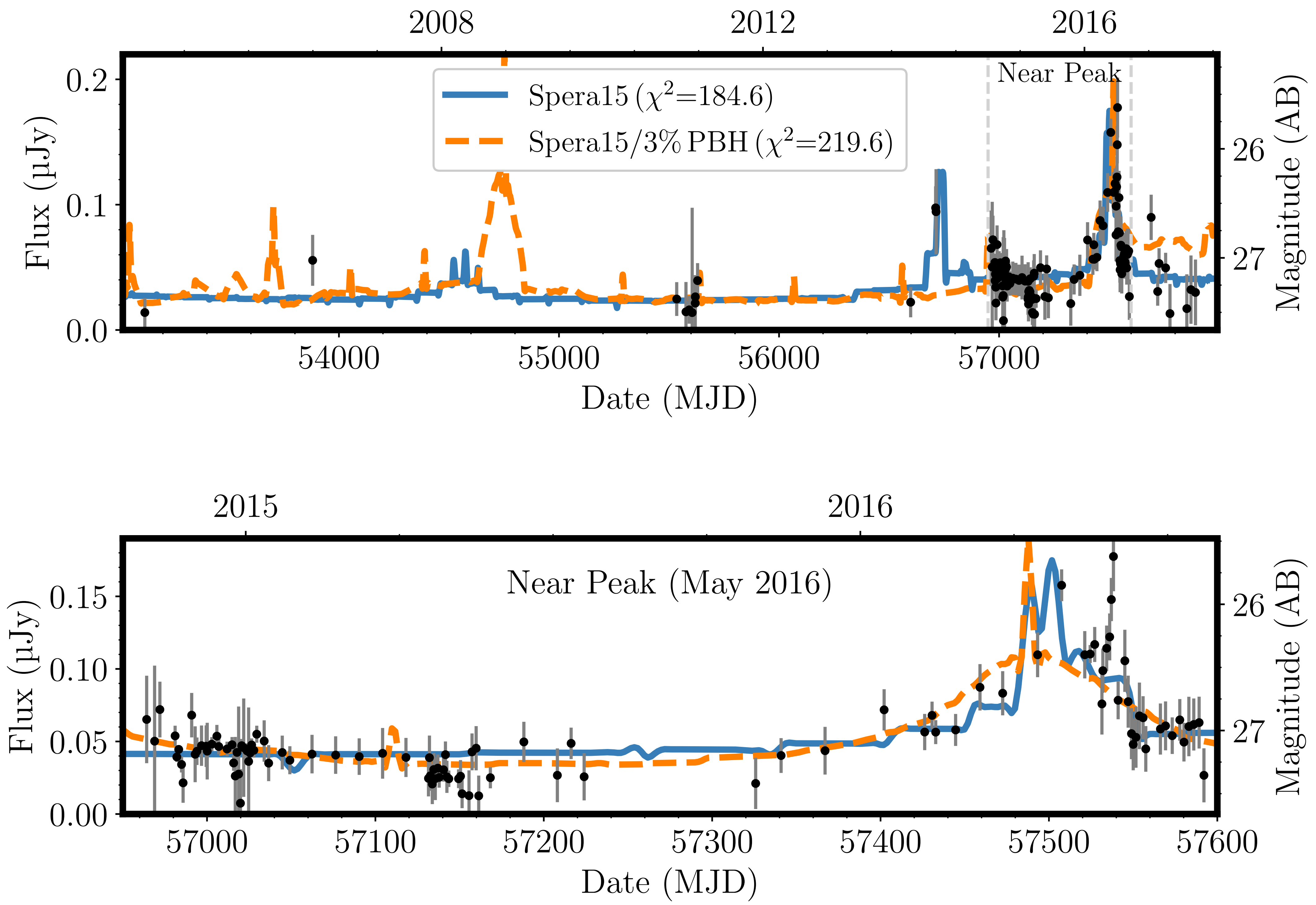
Finite-source effects

Micro-CC merge with macro-CC

$$1.5 \times 10^{-7} \mu_{t,\rm obs} M_\odot \left(\frac{v}{500\ \rm km/s}\right)^2 \lesssim M \lesssim 5.1 \times 10^9 \mu_{t,\rm obs}^{-1} M_\odot \left(\frac{\theta_h}{0.13''}\right)^2$$

# Icarus event

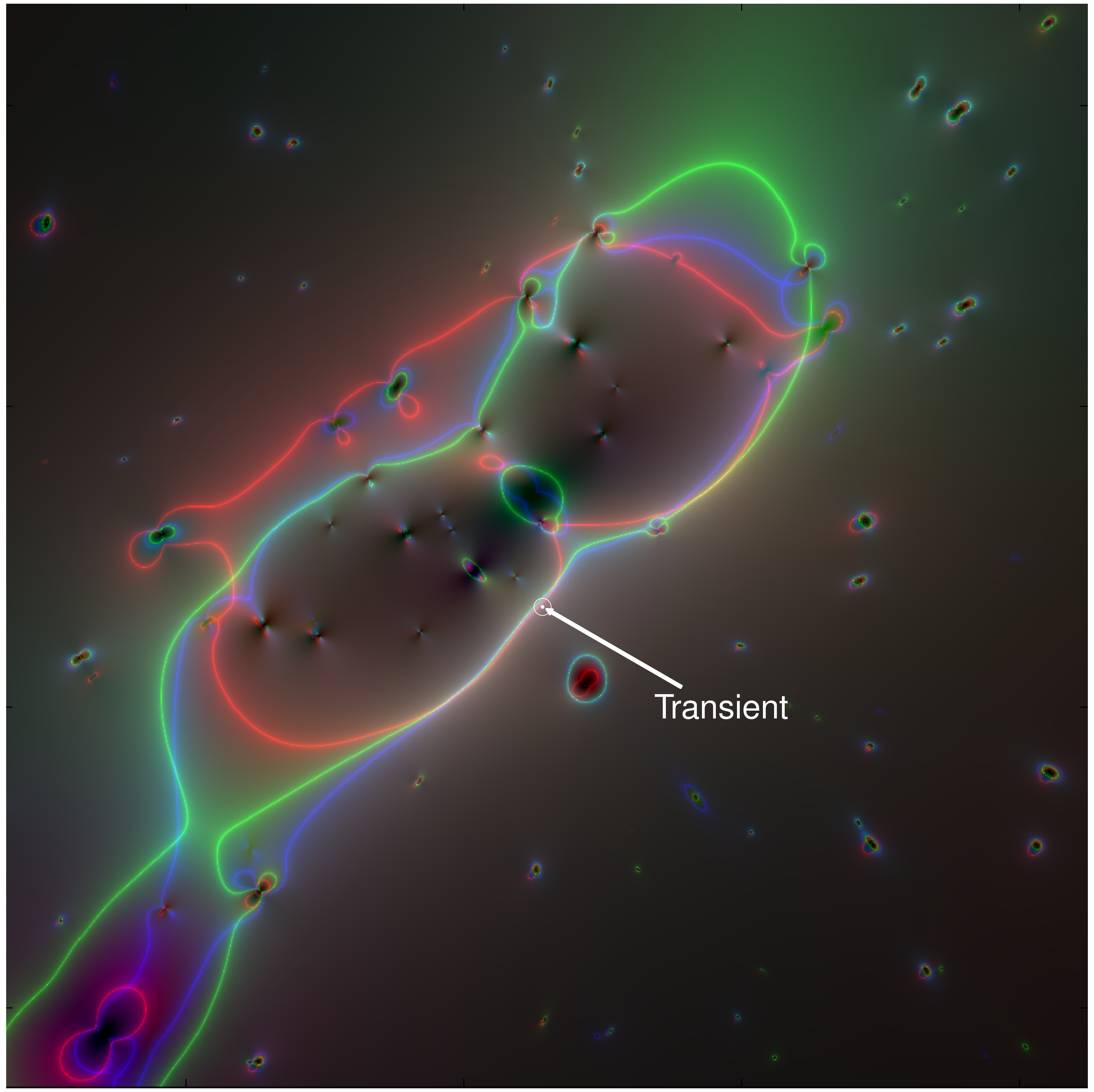



$$m_{\rm peak,min} \approx 25.1 - 0.625 \log_{10}\left(\frac{M_{\rm peak}}{M_\odot}\right) - 1.875 \log_{10}\left(\frac{\mu_{t,\rm sat}}{100}\right) - 3.75 \log_{10}\left(\frac{v}{500\ \rm km/s}\right) < 26$$

# DM Constraints

- Icarus event: First ever star observed at cosmological distances $(z = 1.49)$




[Venumadhav, Dai, Miralda-Escude, arXiv:1707.00003]

→ Microlens embedded in giant arc

→ Observation matches intracluster star population

$$f_{\rm ICL} \approx 0.007$$

without causing saturation

→ High fractions of DM are incompatible with observation

# ULDM Model

- Ultralight scalar dark matter (non-relativistic)

Classical scalar field → $$a(t,\mathbf{x}) = a_0(\mathbf{x})\cos(mt + \alpha(t,\mathbf{x}))$$

Energy density → $$\rho(t,\mathbf{x}) \equiv T_{00} = \frac{1}{2}\left(\dot{a}(t,\mathbf{x})^2 + (\nabla a(t,\mathbf{x}))^2 + m^2 a(t,\mathbf{x})^2\right)$$

- Density two-point function (slow mode)

Two-point function → $$\langle \rho(\mathbf{x})\rho(\mathbf{x}')\rangle = \bar{\rho}^2 e^{-|\mathbf{\Delta x}|^2/\ell^2}$$

Power spectrum → $$P(k) = \pi^{3/2}\bar{\rho}^2\ell^3 e^{-k^2/\ell^2}$$

# ULDM Model

- BBKS formalism: Power spectrum → Peaks $(\nu)$ and curvature $(x)$ distribution

$\propto \delta\rho$ $\qquad$ $\propto \nabla^2(\delta\rho)$

- Parabolic sphere: $\nu(M,R) = \frac{15}{8\pi\sigma}\frac{M}{R^3}, \quad x(M,R) = \frac{45}{4\pi\sigma_{(2)}}\frac{M}{R^5}, \quad \sigma^2 = \bar{\rho}^2$

Curvature probability

$$\frac{d^2 n_{3D}}{dM dR} = \frac{1}{(2\pi)^2 R_*^3}\frac{5\sigma_{(2)}^2}{48\pi\sigma^3}\frac{x^3}{\nu^2}\frac{f(x)}{\sqrt{2\pi(1-\gamma^2)}}\exp\left\{-\frac{1}{2}\left(\nu^2 + \frac{(x-\gamma\nu)^2}{1-\gamma^2}\right)\right\}$$

# Surface mass fraction

- Lens-plane-projected surface number density

$$\frac{d^2 n_{2D}}{d\log M dR} = \int_{-\infty}^{+\infty} \frac{d^2 n_{3D}}{d\log M dR} dz$$

$$\bar{\rho} = f_{\rm DM}\rho_{\rm DM}$$

- Surface mass fraction

$$\frac{d f_{\rm DO}}{d\log M\, dR} = \frac{M}{\Sigma_{\rm tot}} \frac{d^2 n_{2D}}{d\log M\, dR}$$

- At Icarus position