Extremely Magnified Extragalactic Stars and Small-scale Dark Matter Structures

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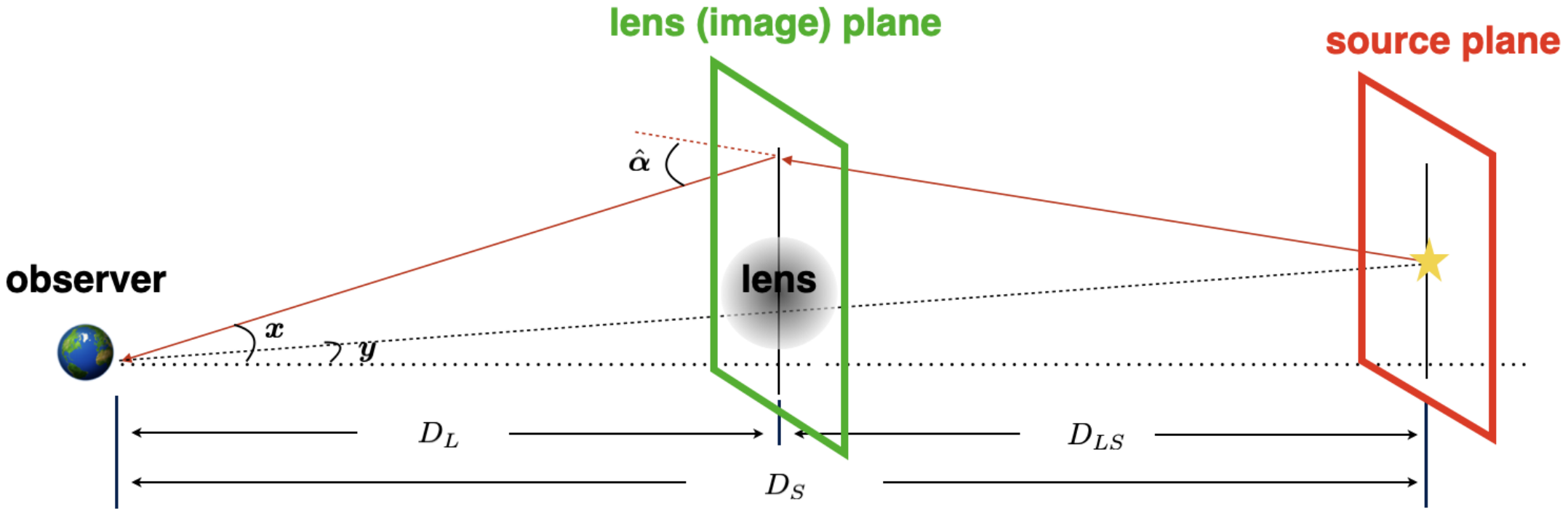
Fudan University

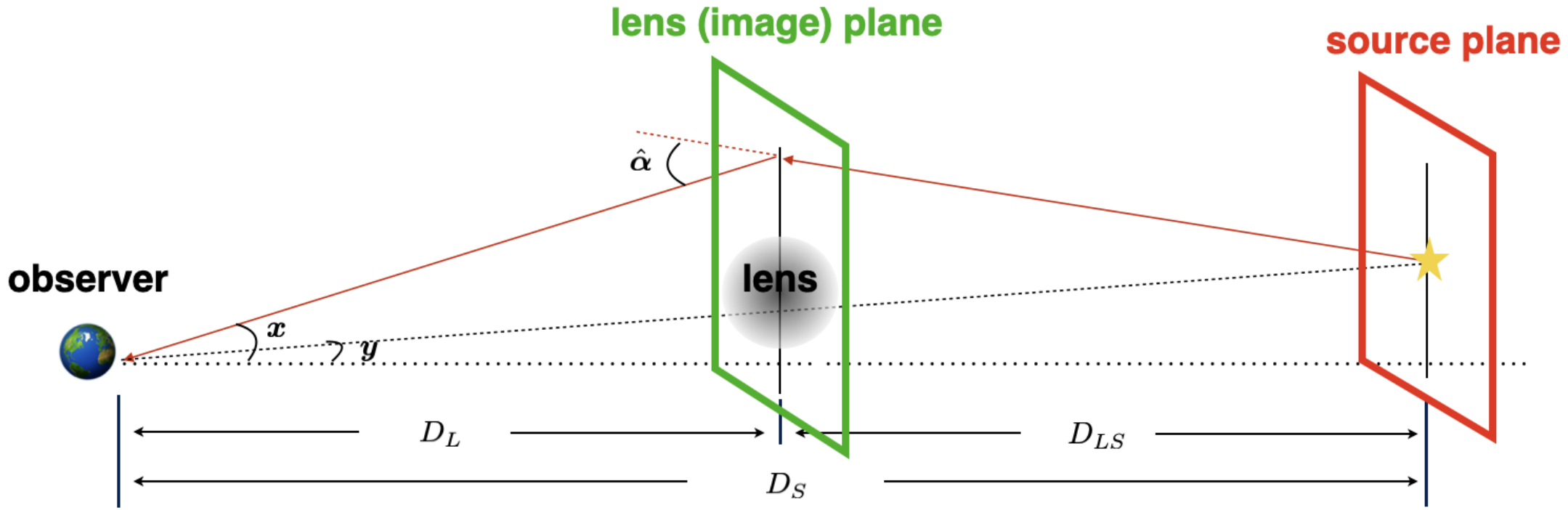
Seminar @ CAS
Nov 2026

Geometric optics description of lensing



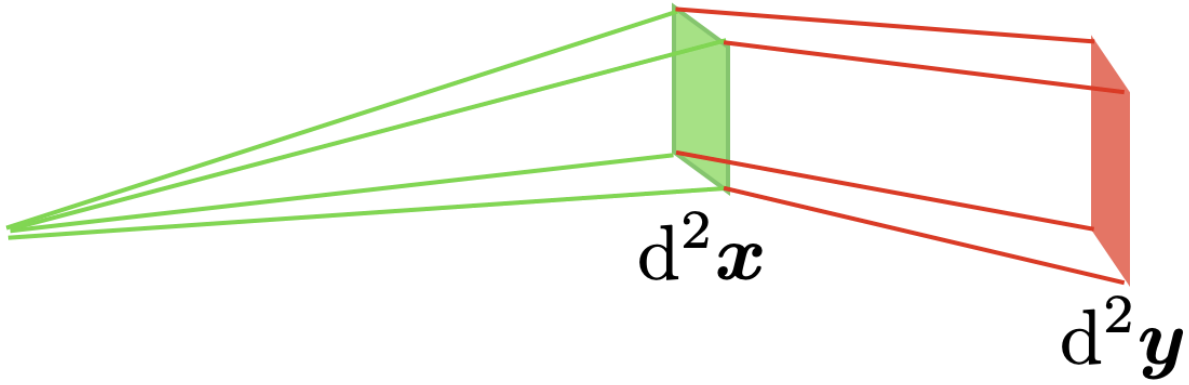
Ray equation $\boldsymbol{y = x - \alpha(x)}$

Geometric optics description of lensing



Ray bundle deformation

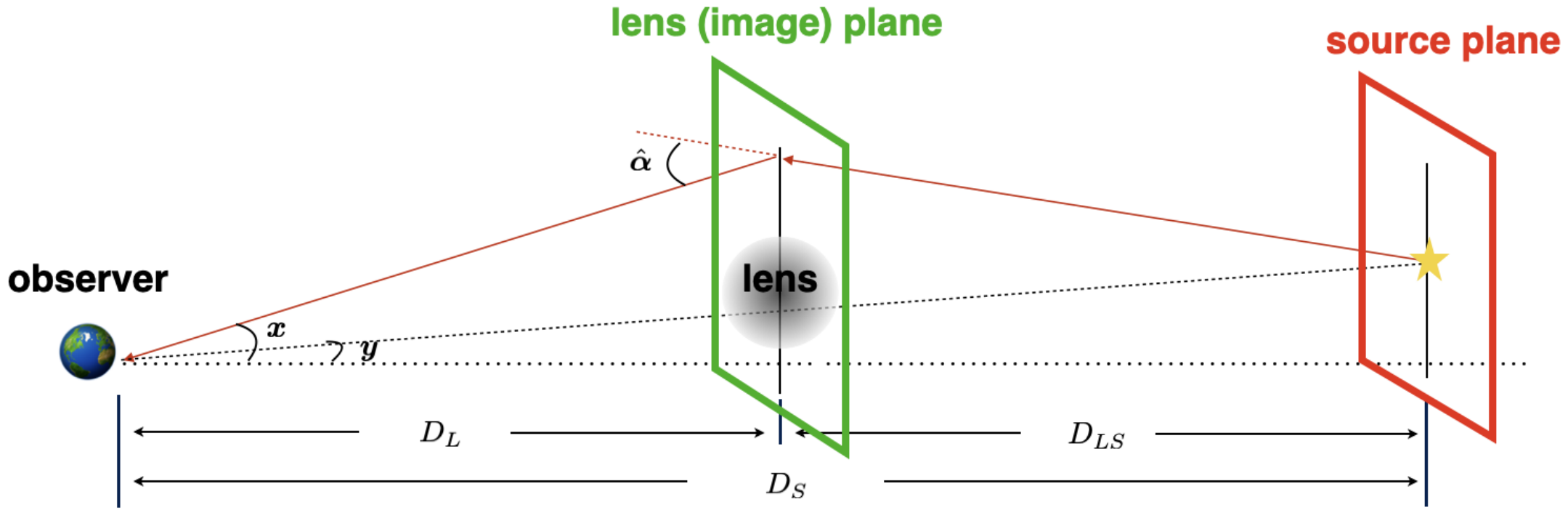
$$\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}} = \begin{bmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{bmatrix}$$



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

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

Geometric optics description of lensing

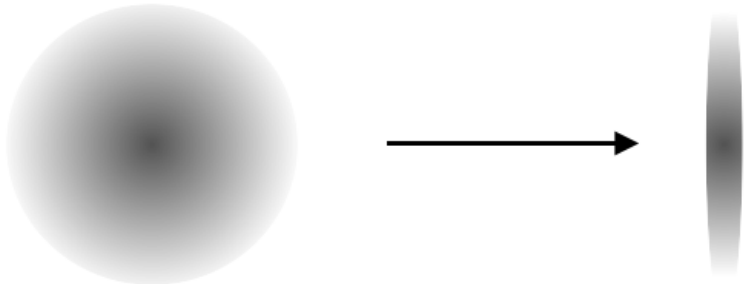


convergence

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

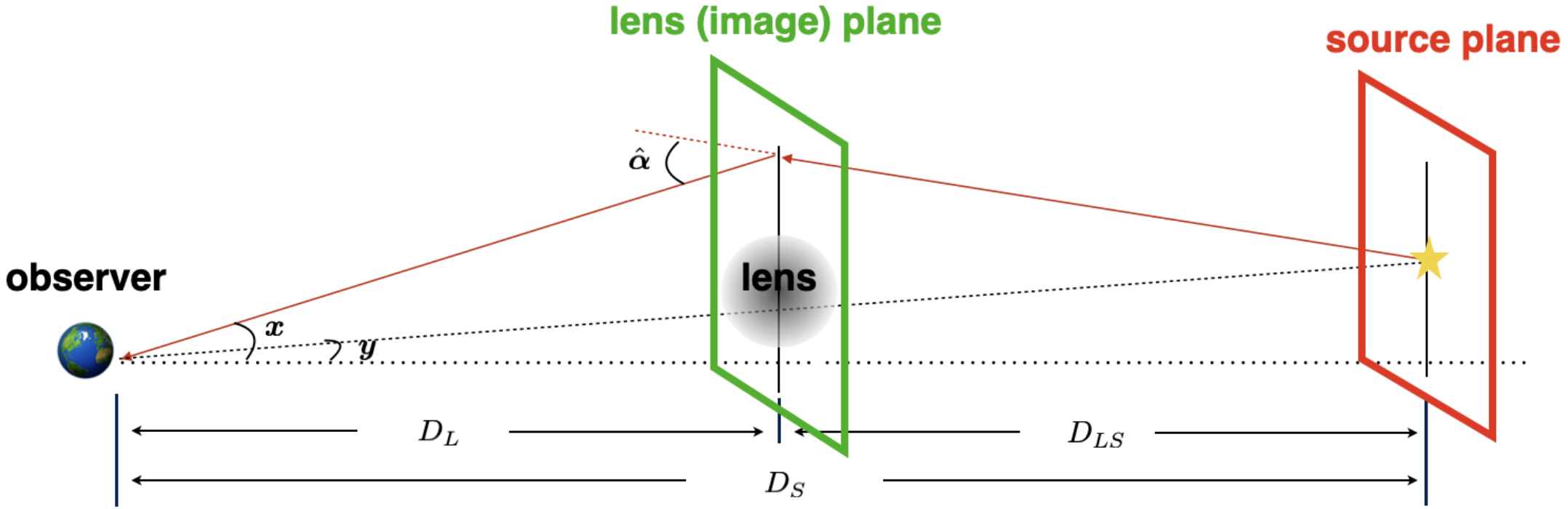
Critical surface density

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



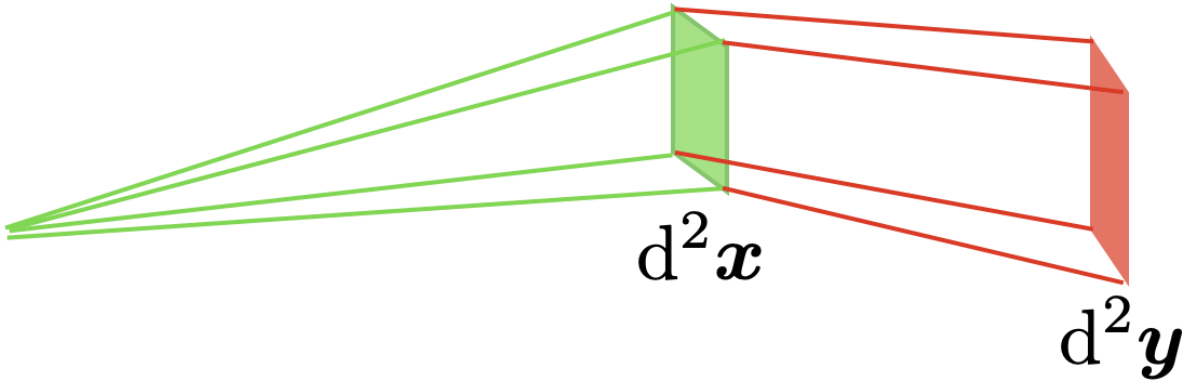
Lens surface mass density matters

Geometric optics description of lensing



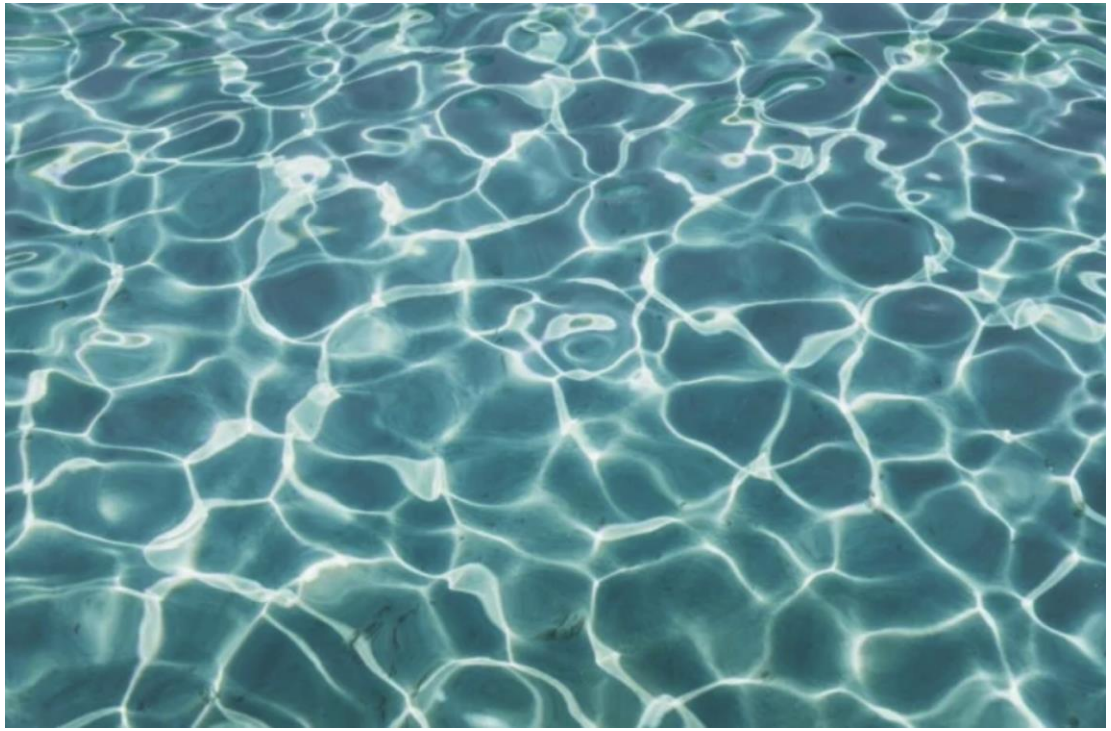
(signed) magnification factor for flux

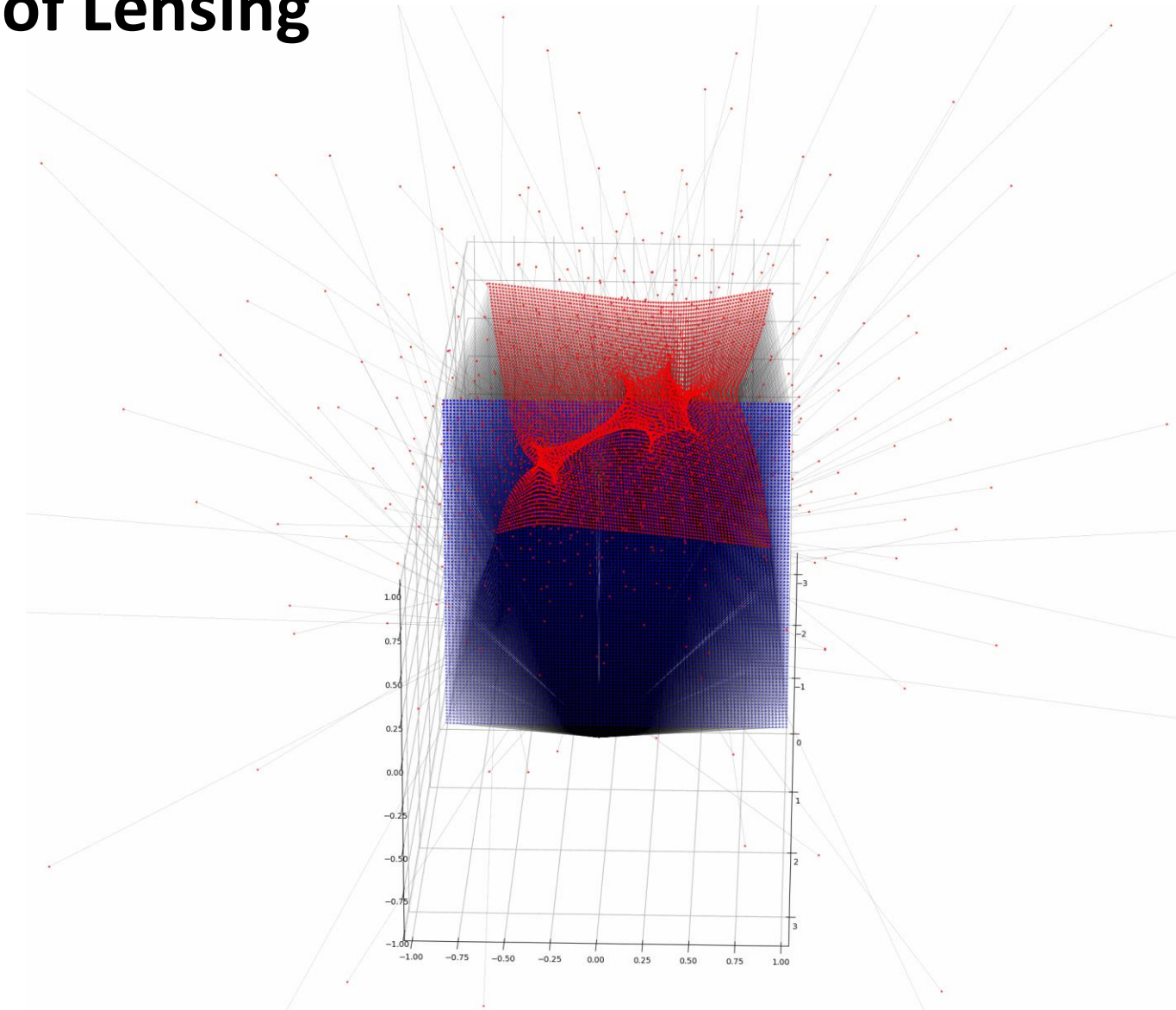
$$\mu = \frac{\mathrm{d}^2\boldsymbol{x}}{\mathrm{d}^2\boldsymbol{y}} = \frac{1}{(1-\kappa)^2 - (\gamma_1^2 + \gamma_2^2)}$$



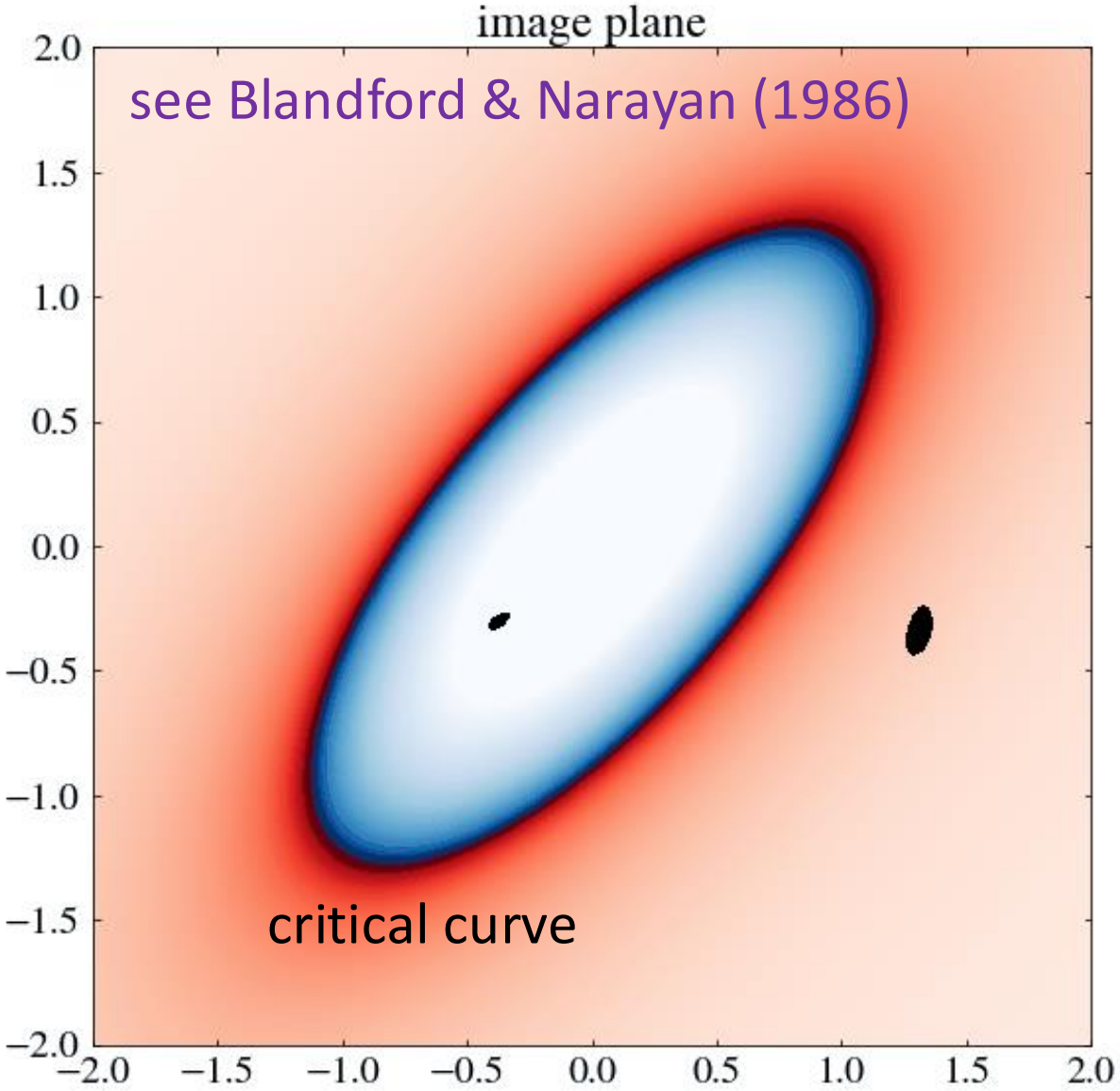
Caustics of Lensing

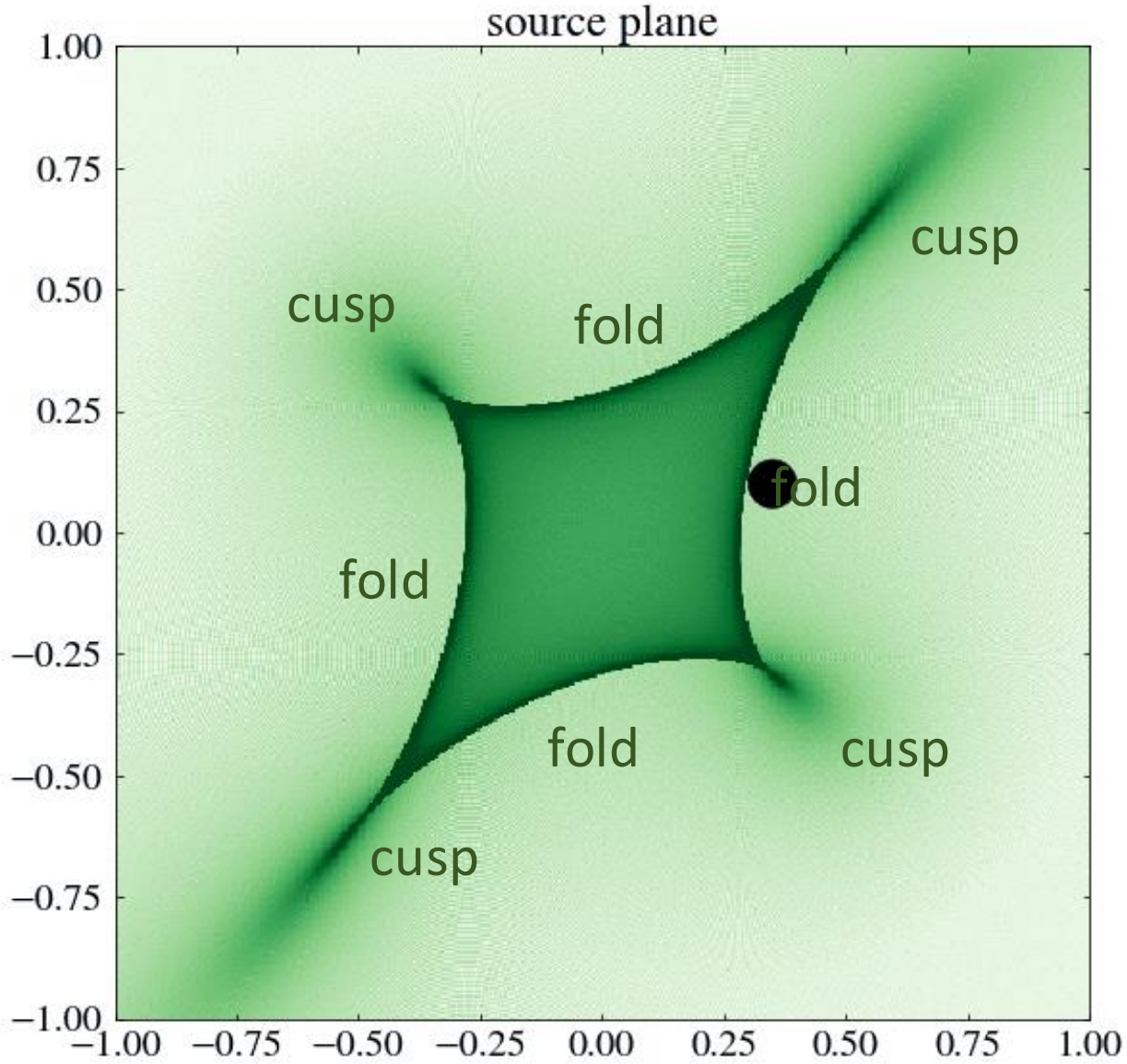
The Sun illuminating the bottom of a swimming pool



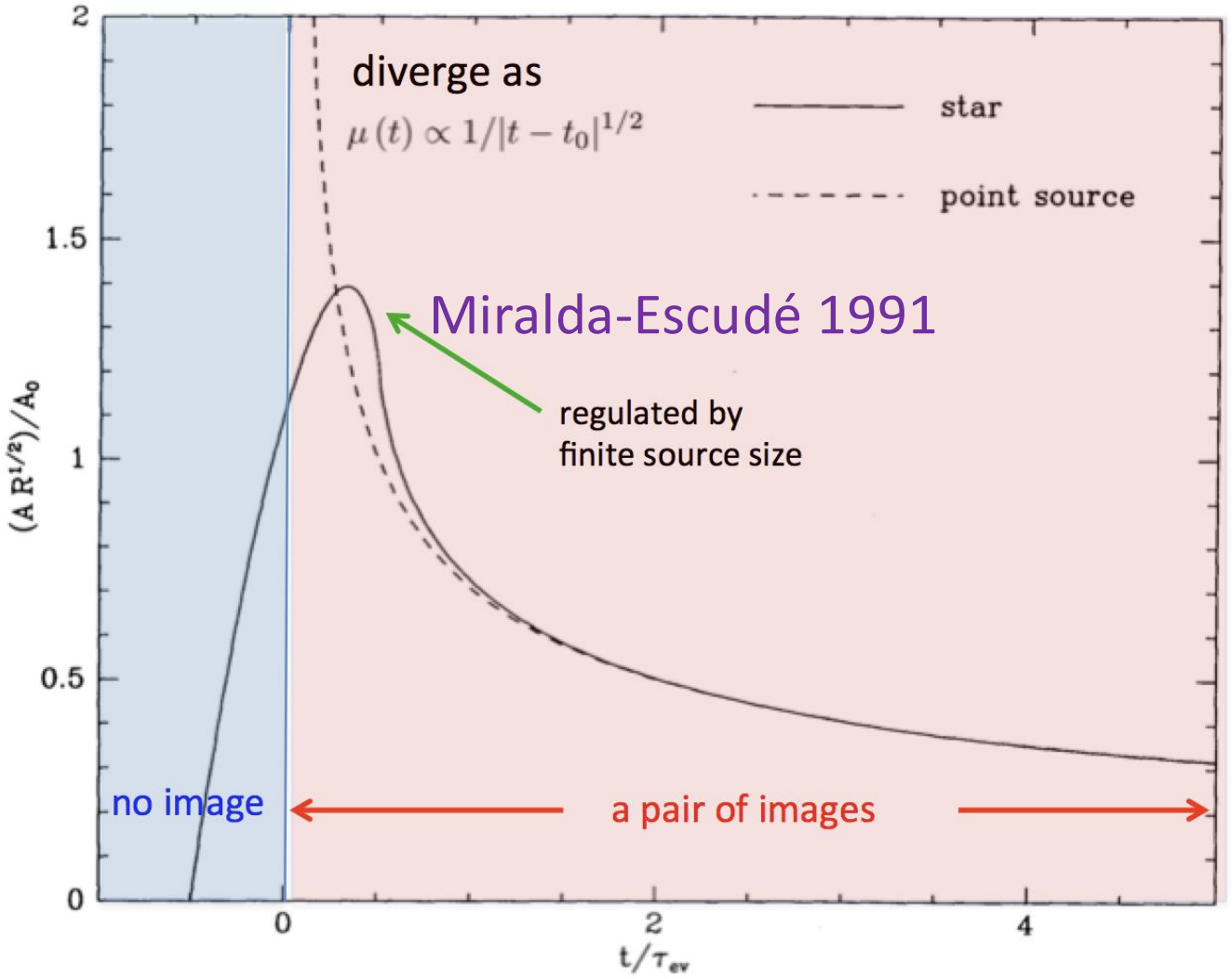


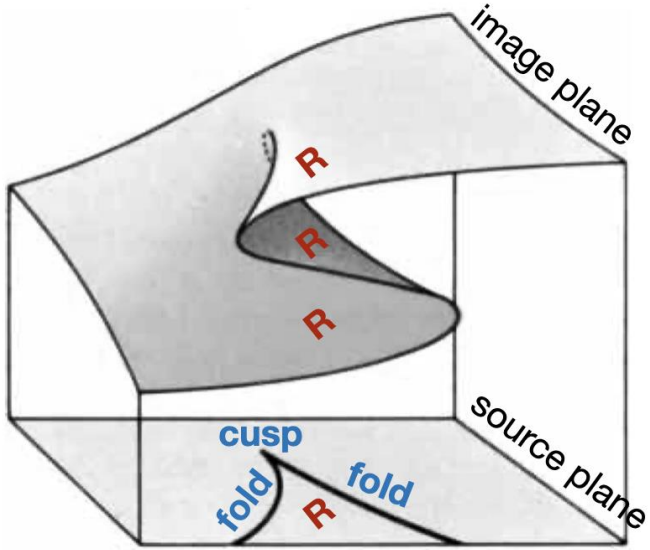
Caustics (焦散线) and Critical Curves （临界曲线）





A Lensed Star Crossing a Fold Caustic



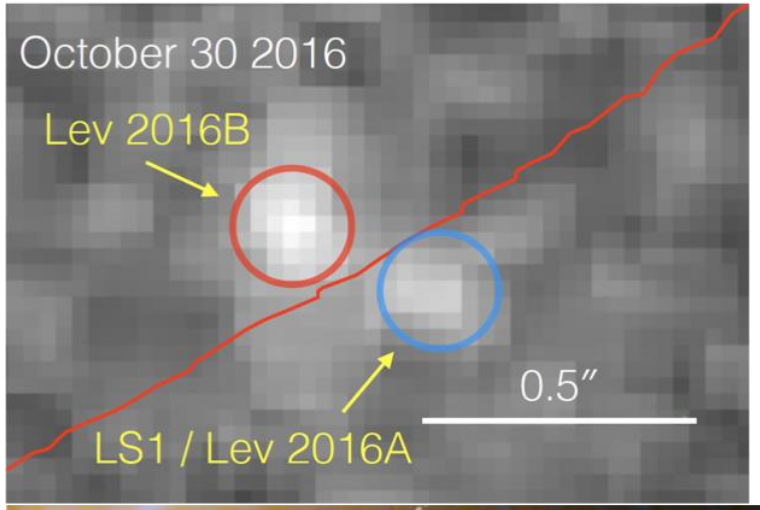


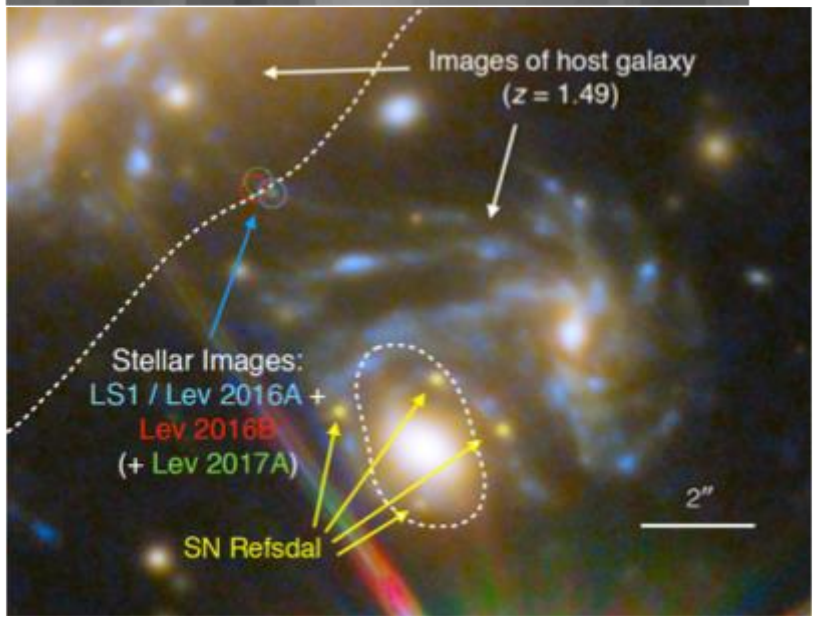


Jordi Miralda-Escudé

Highly Magnified Stars Seen by Space Telescopes

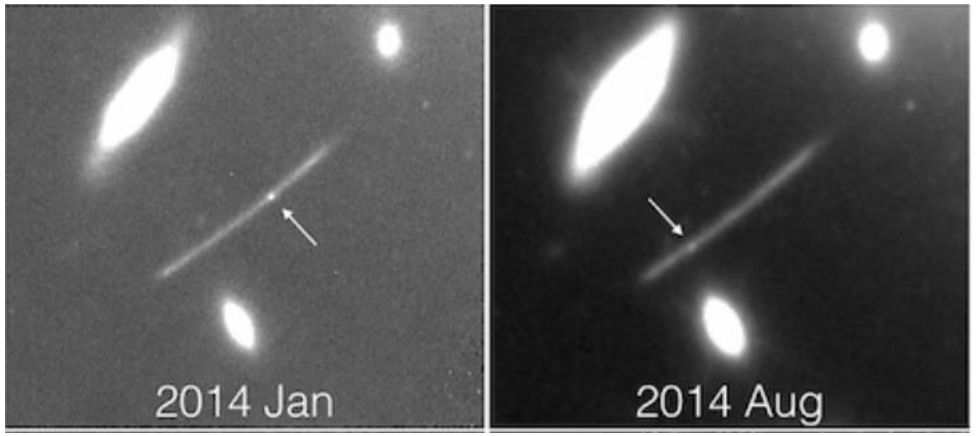
Kelly et al 2017 Icarus z=1.49





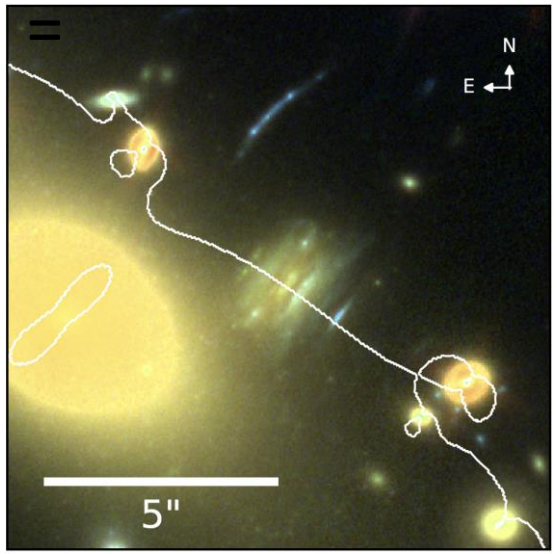
Spock Arc “Christmas tree” z = 1.00

Rodney et al 2018



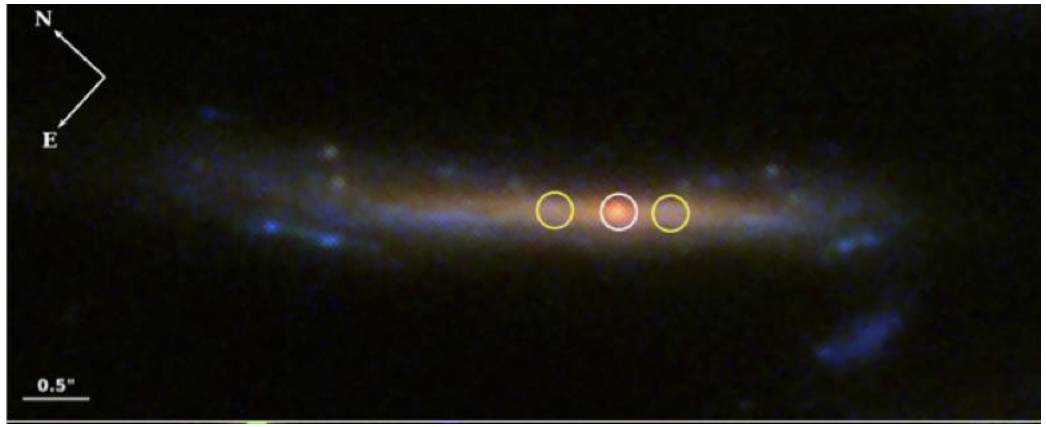
Warhol Arc z = 0.94

Chen et al 2019;
Kaurov et al 2019

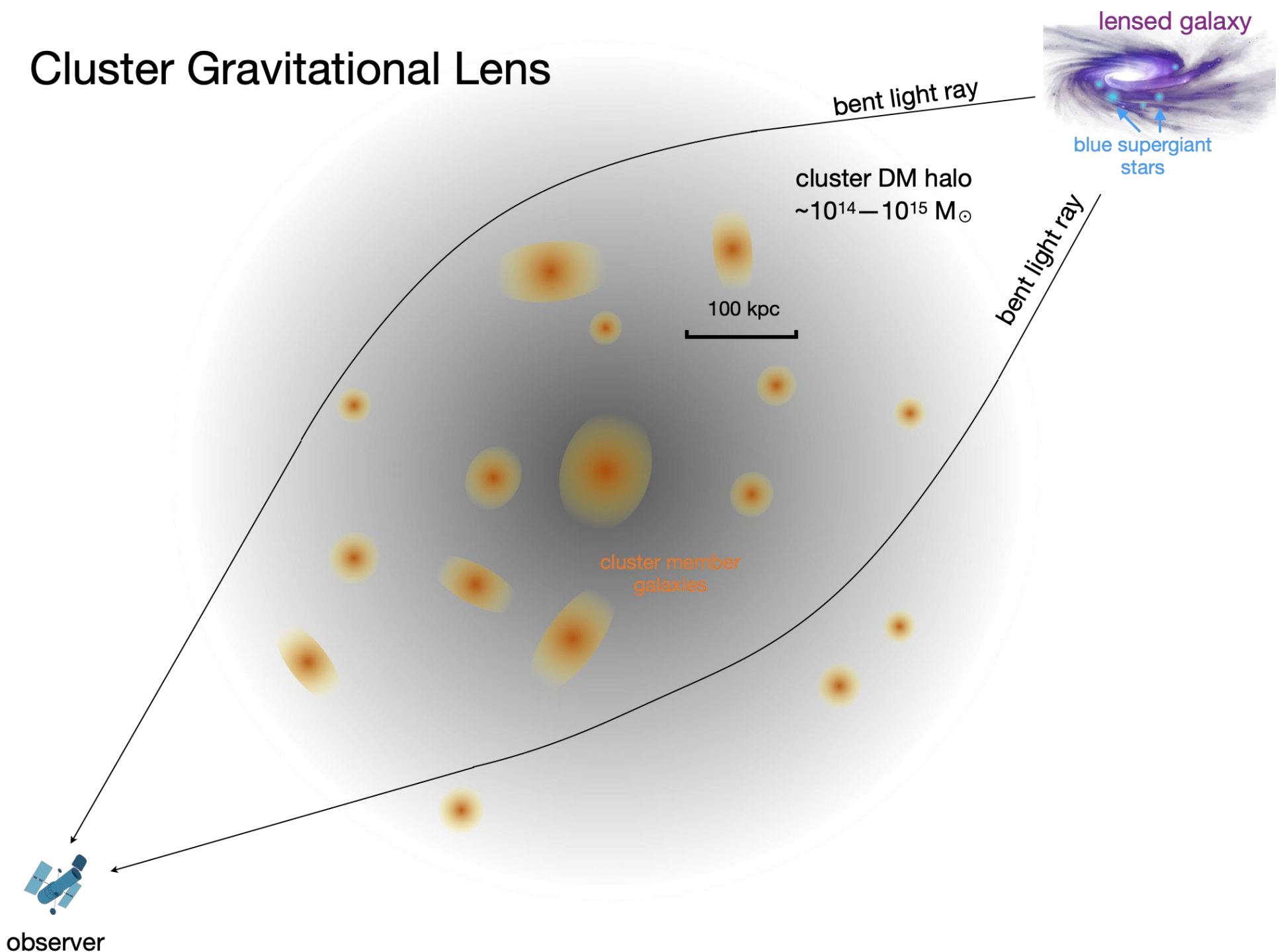


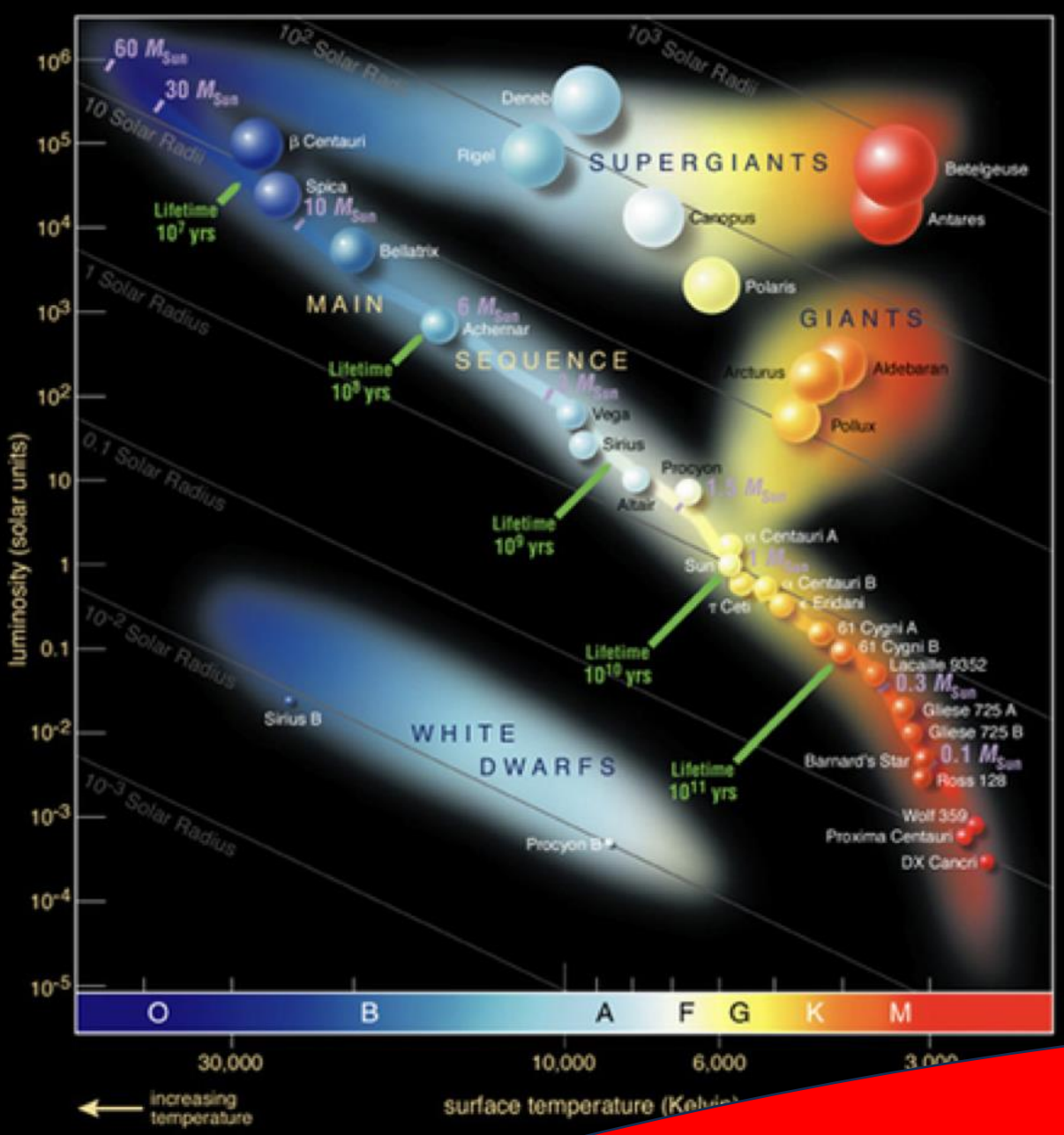
Quyllur, z=2.19

Diego et al 2022



Cluster Gravitational Lens





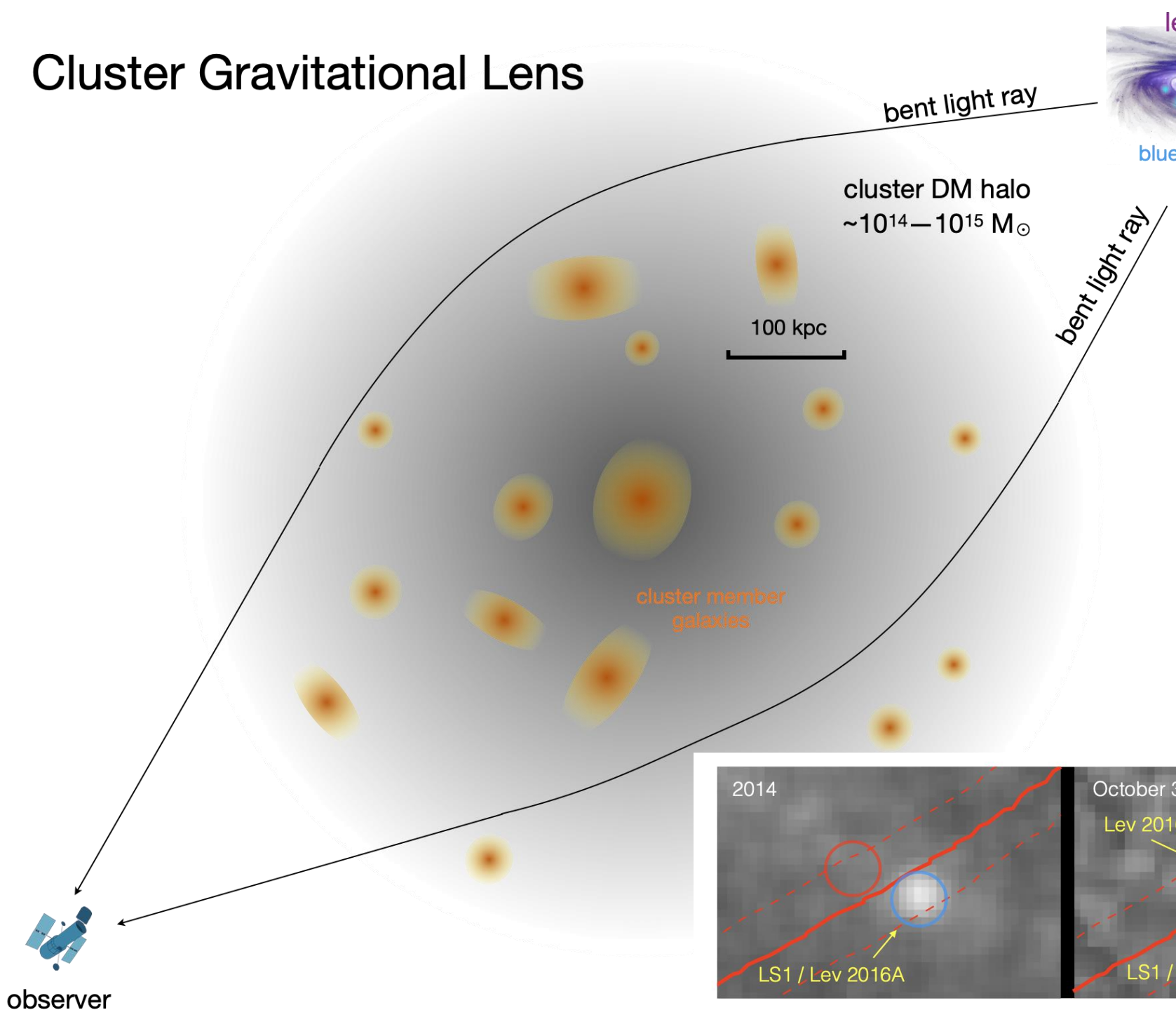
O star ~ a few – 10 $R_\odot$

The Sun

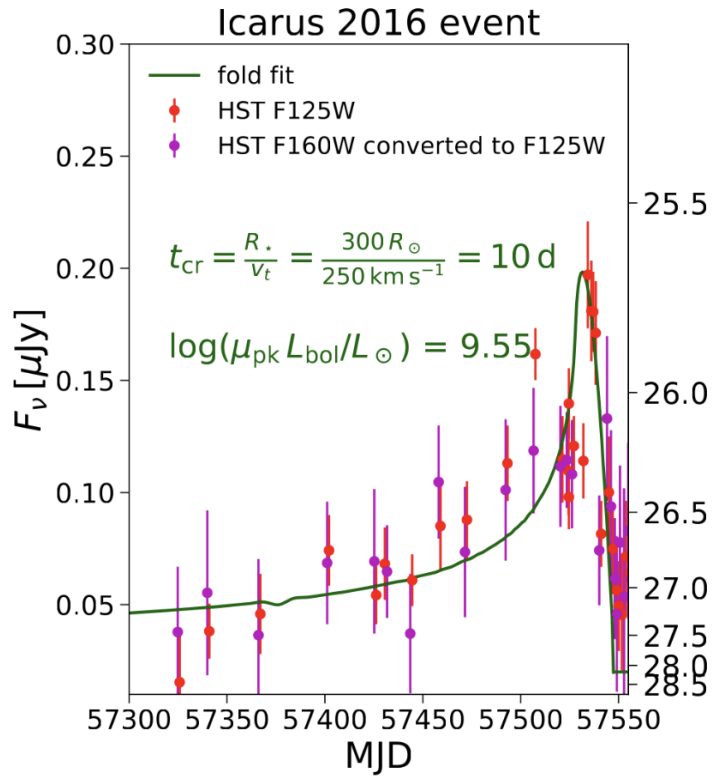
Blue supergiant ~ 100--300 $R_\odot$

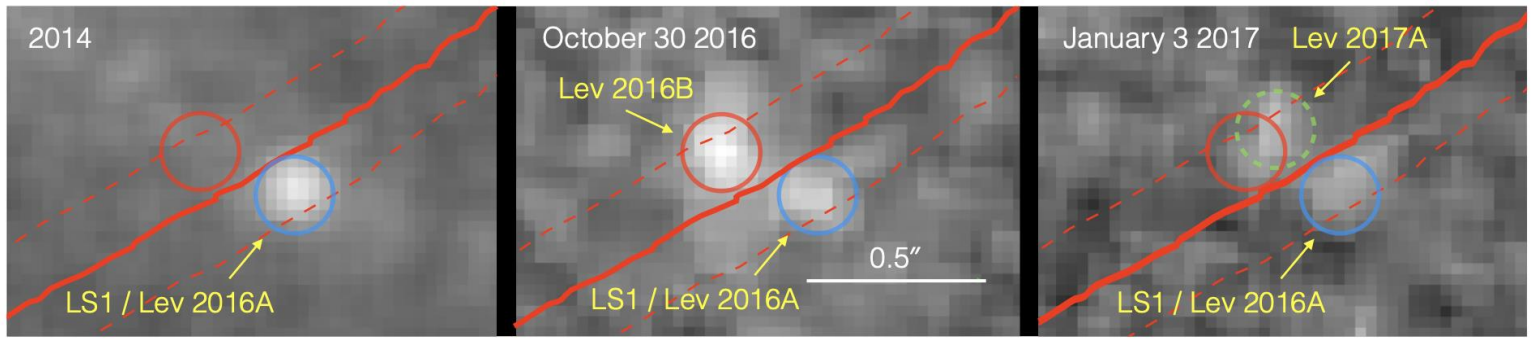
Red supergiant ~ 500--1500 $R_\odot$

Cluster Gravitational Lens

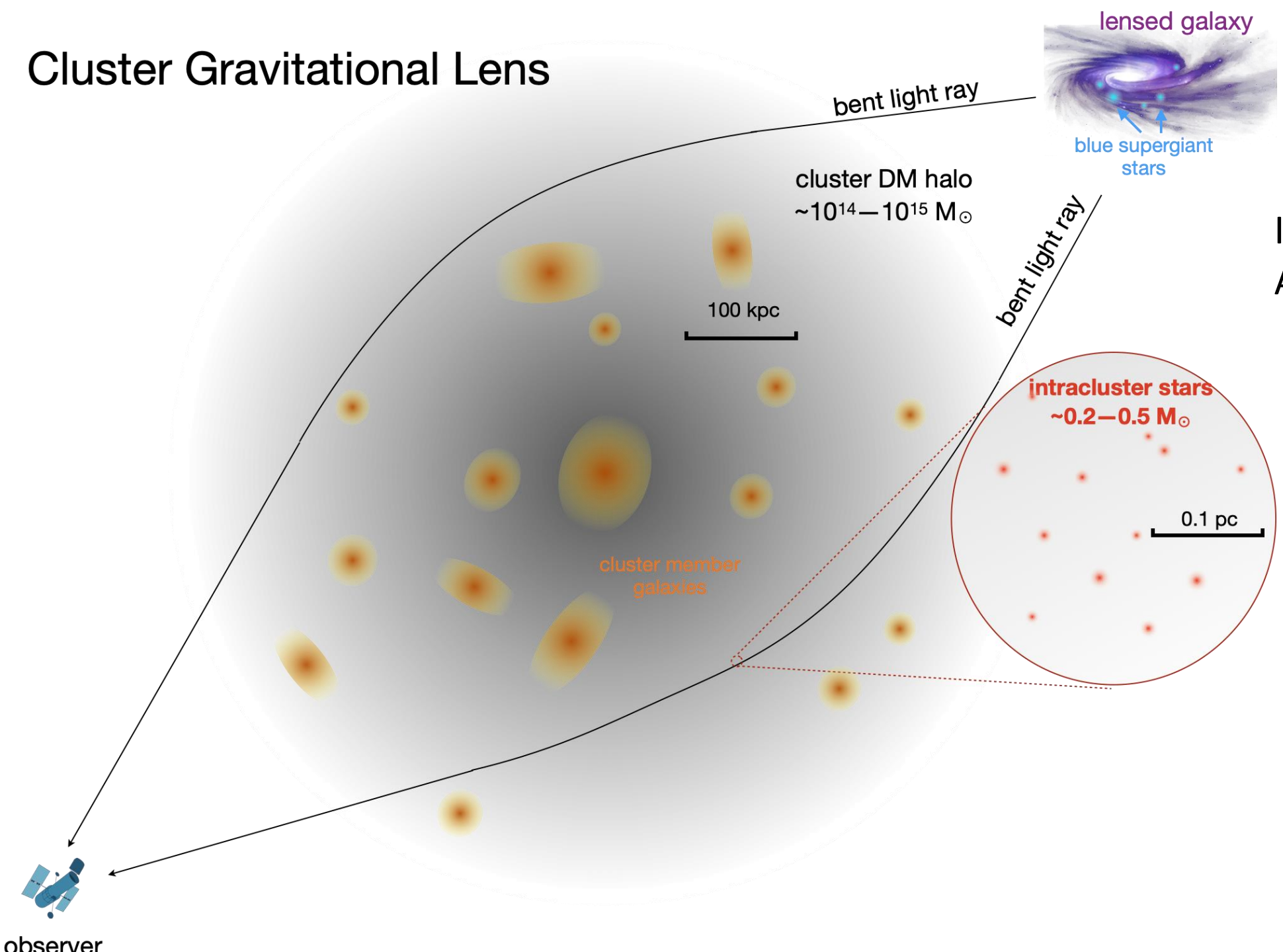


How come is variability so fast?





Cluster Gravitational Lens

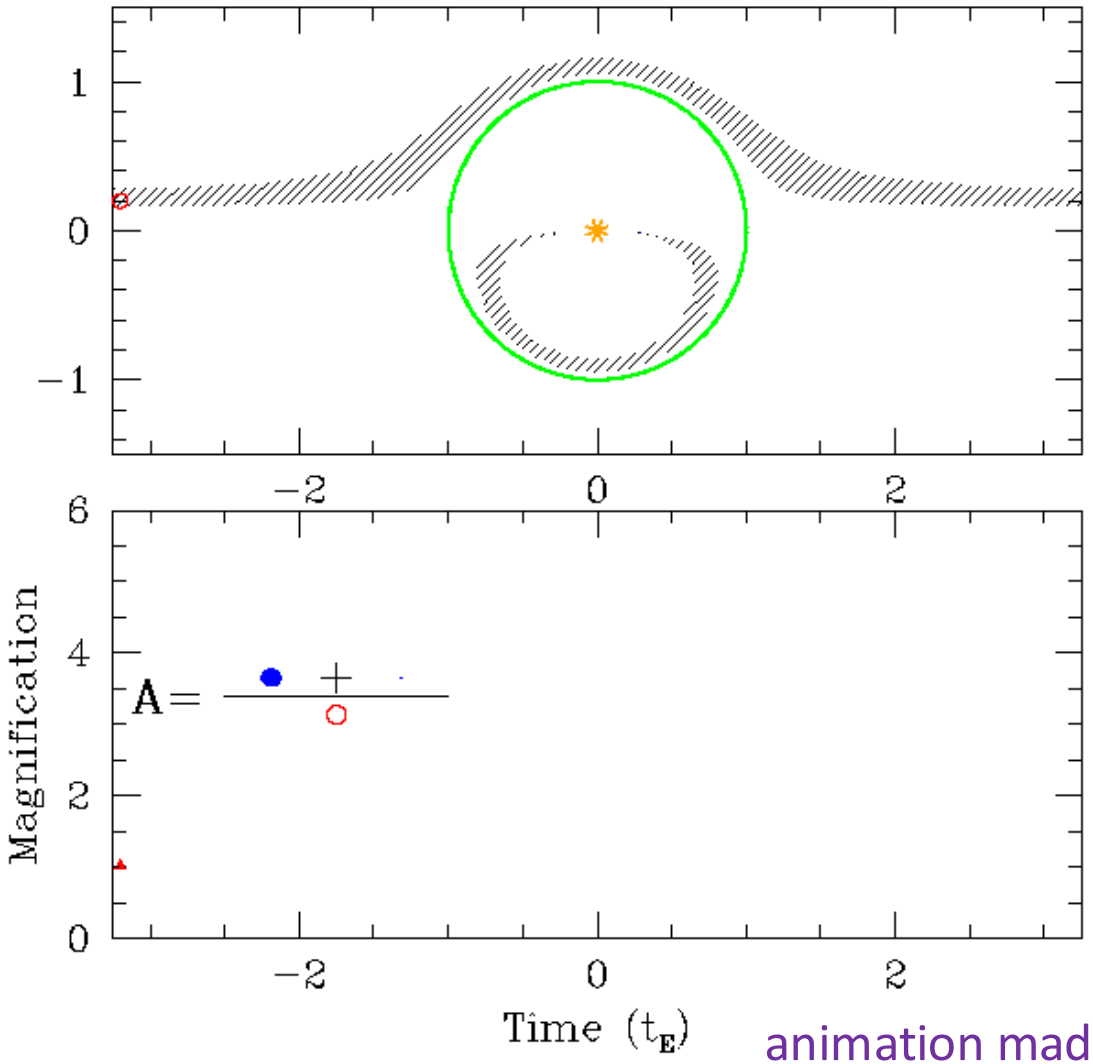


Intracluster light in Abell S1063



Micro-lensing By Point Mass

Galactic microlensing event



animation made by S. Gaudi

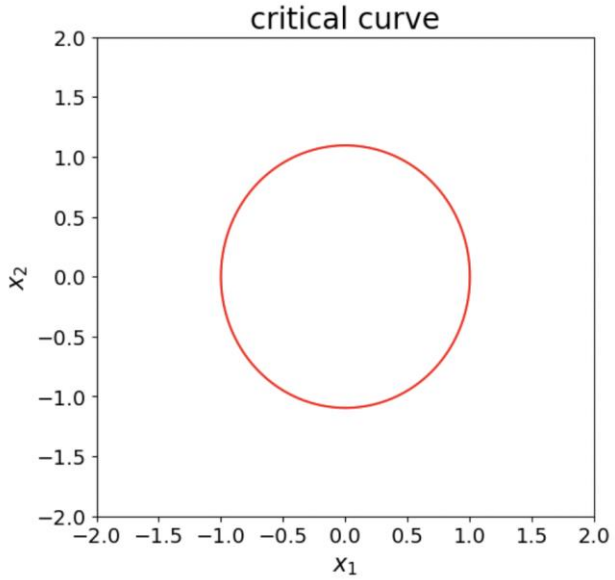
Einstein angle

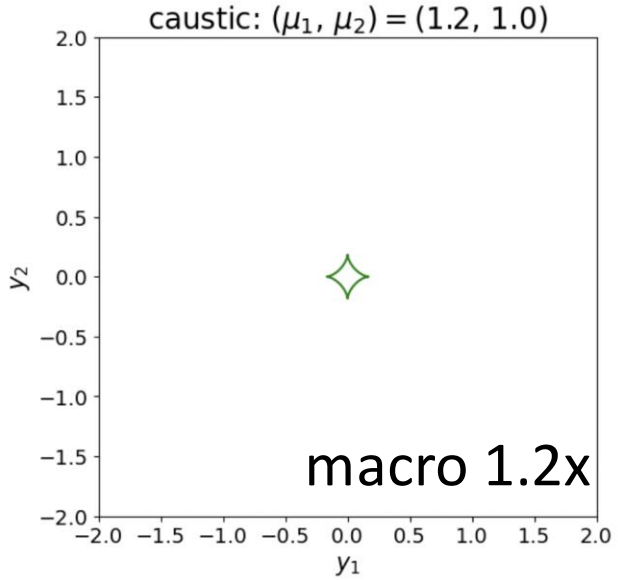
$$\theta_E = \left[\frac{4\,G\,M_\star}{c^2} \, \frac{D_{LS}}{D_L\,D_S} \right]^{\frac{1}{2}}$$

Einstein length

$$r_E = D_L\,\theta_E = \left[\frac{M_\star}{\pi\,\Sigma_{\rm crit}} \right]^{\frac{1}{2}}$$

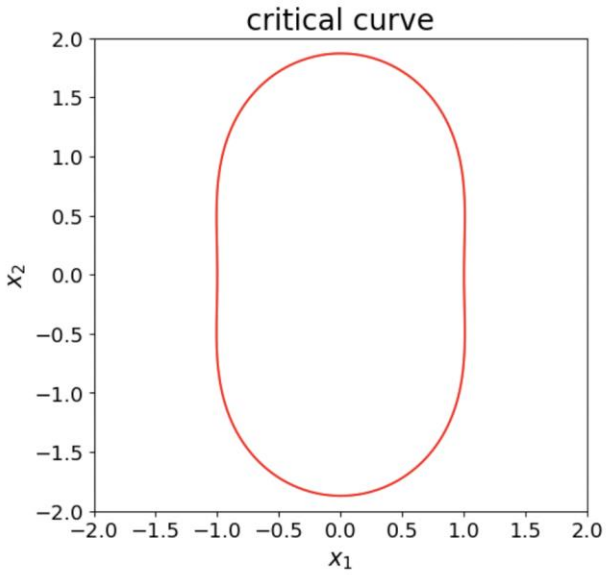
Micro-lens Embedded in Macro-lens

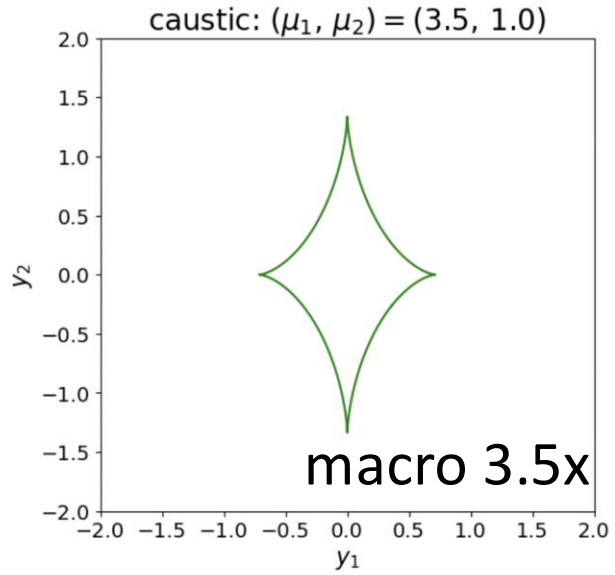


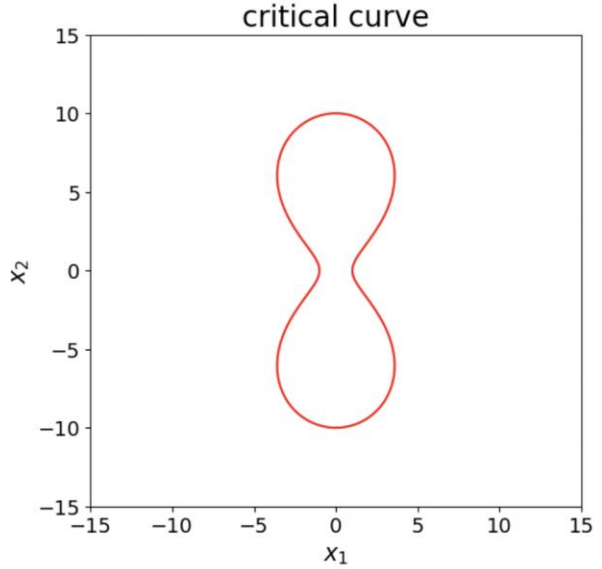


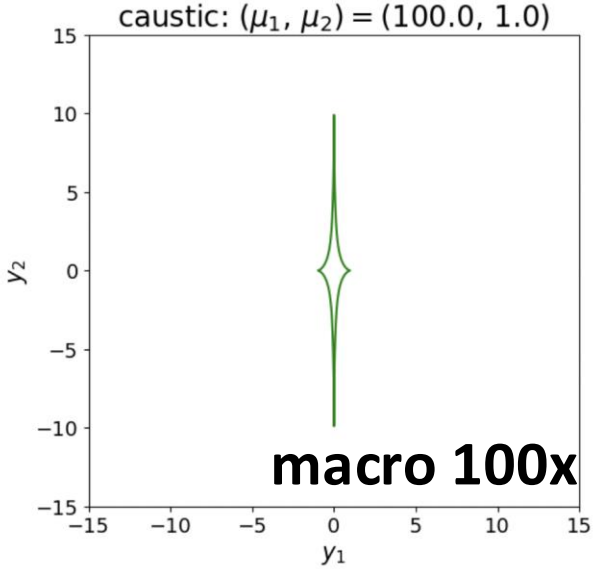
Einstein angular scale

$$\theta_E = \left[\frac{4GM_\star}{c^2} \frac{D_{LS}}{D_L D_S} \right]^{\frac{1}{2}}$$



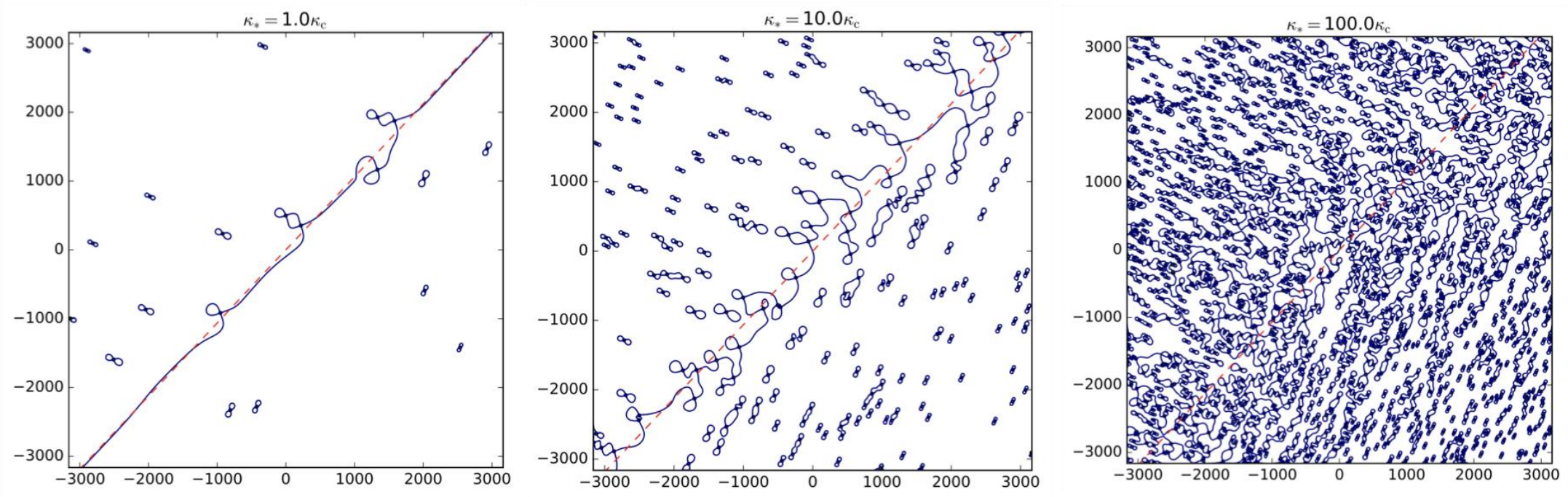






Intracluster Microlensing Inevitable

e.g. Venumadhav, Dai & Miralda-Escudé 17
Diego et al 18; Oguri et al 18; Dai & Pascale 21



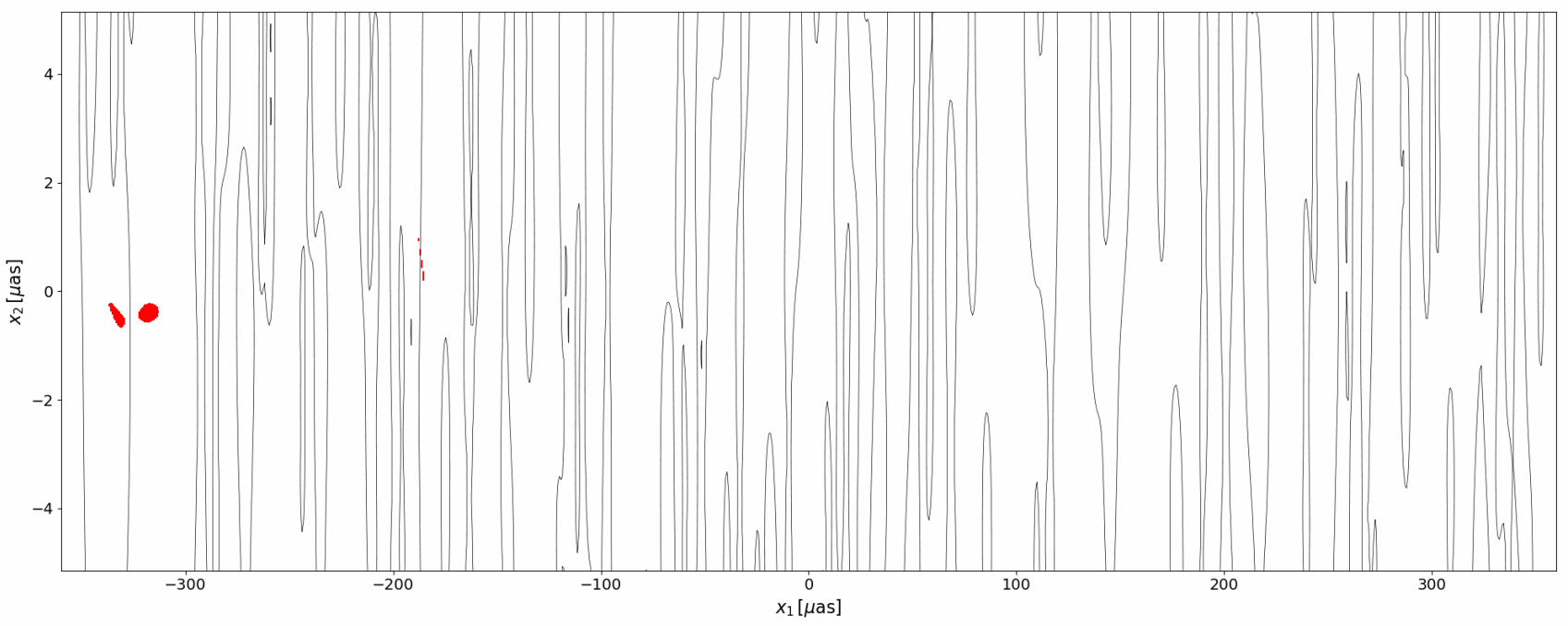
Occasionally perturbed Everywhere disrupted interconnected network

Critical value $\kappa_\star \sim (\theta_\star\, d)^{2/3} \sim \left(\frac{\theta_\star}{\theta_{\rm cl}}\right)^{2/3} \sim \left(\frac{1\,\mu{\rm as}}{10\,{\rm as}}\right)^{2/3} \sim 10^{-5}$

Typical intracluster light $\kappa_\star \sim 10^{-3} - 10^{-2}$ super critical !

If telescope could resolve micro-arc seconds…

(NOTE: source size greatly exaggerated for visibility)



If telescope could resolve micro-arc seconds…

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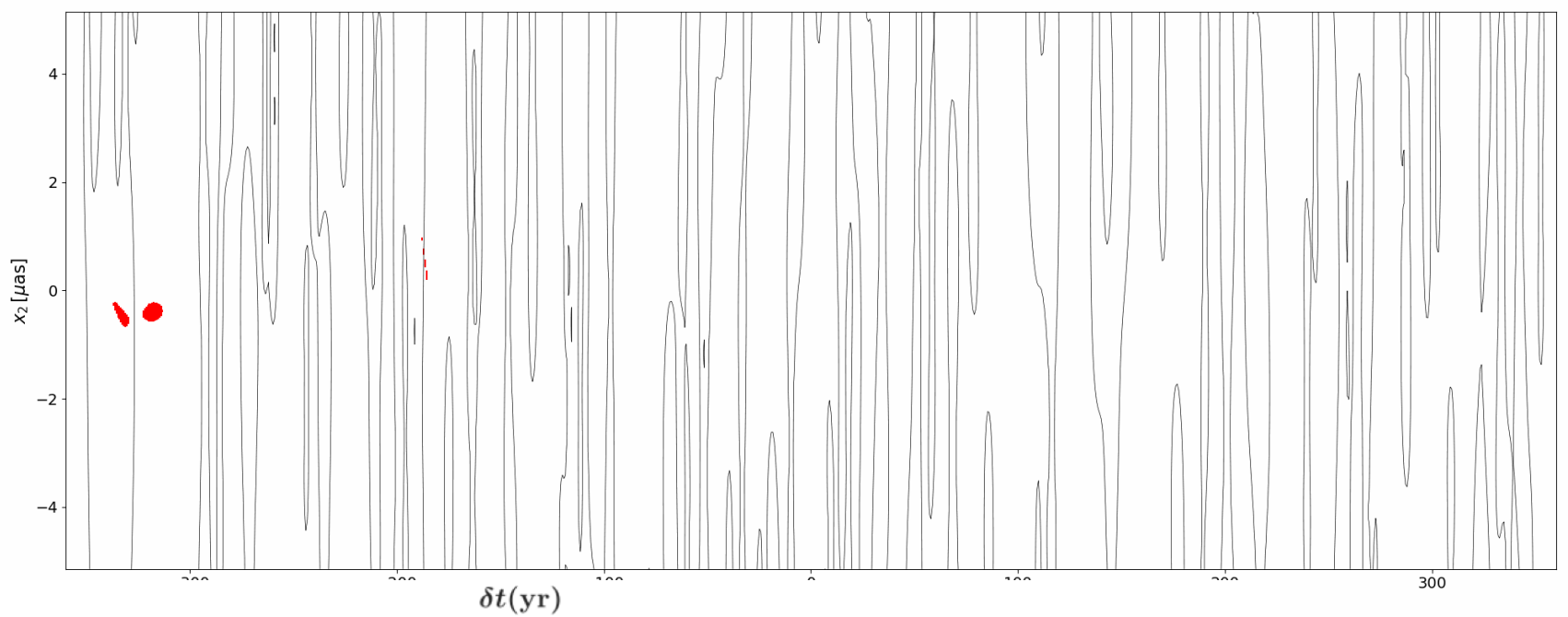
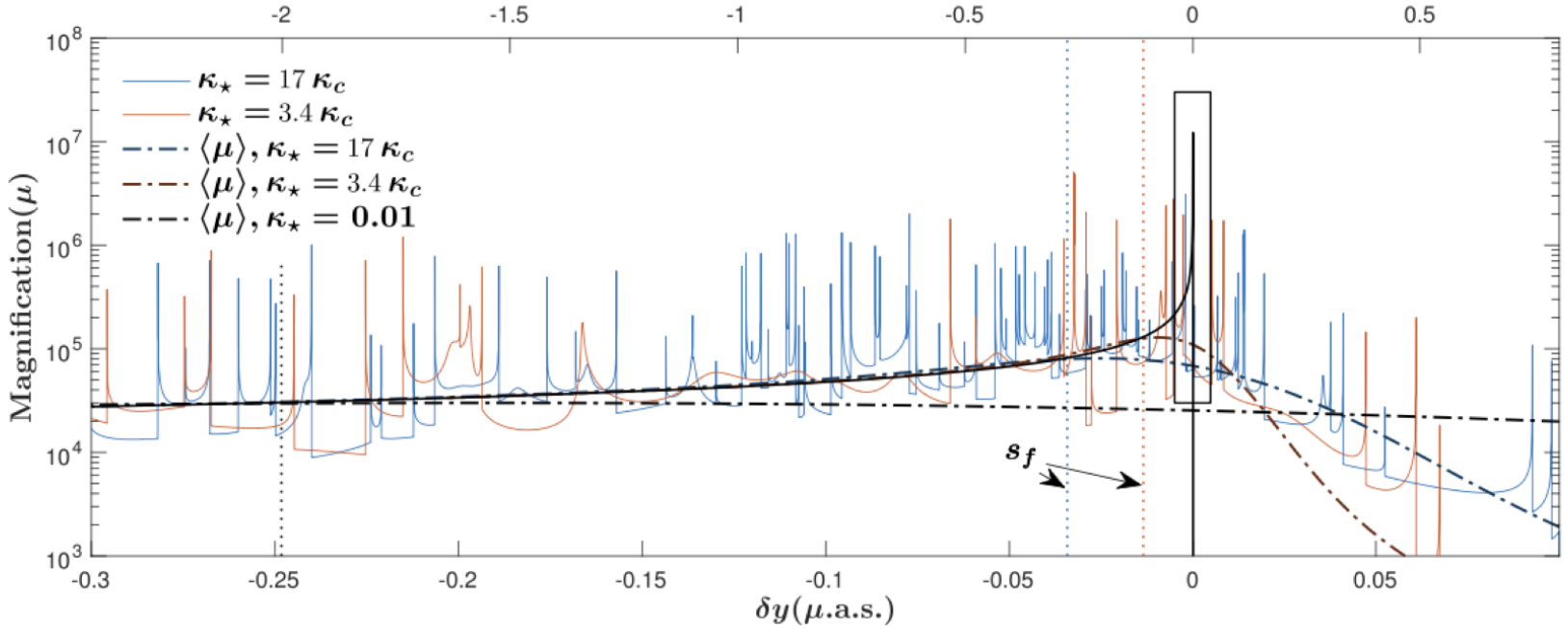
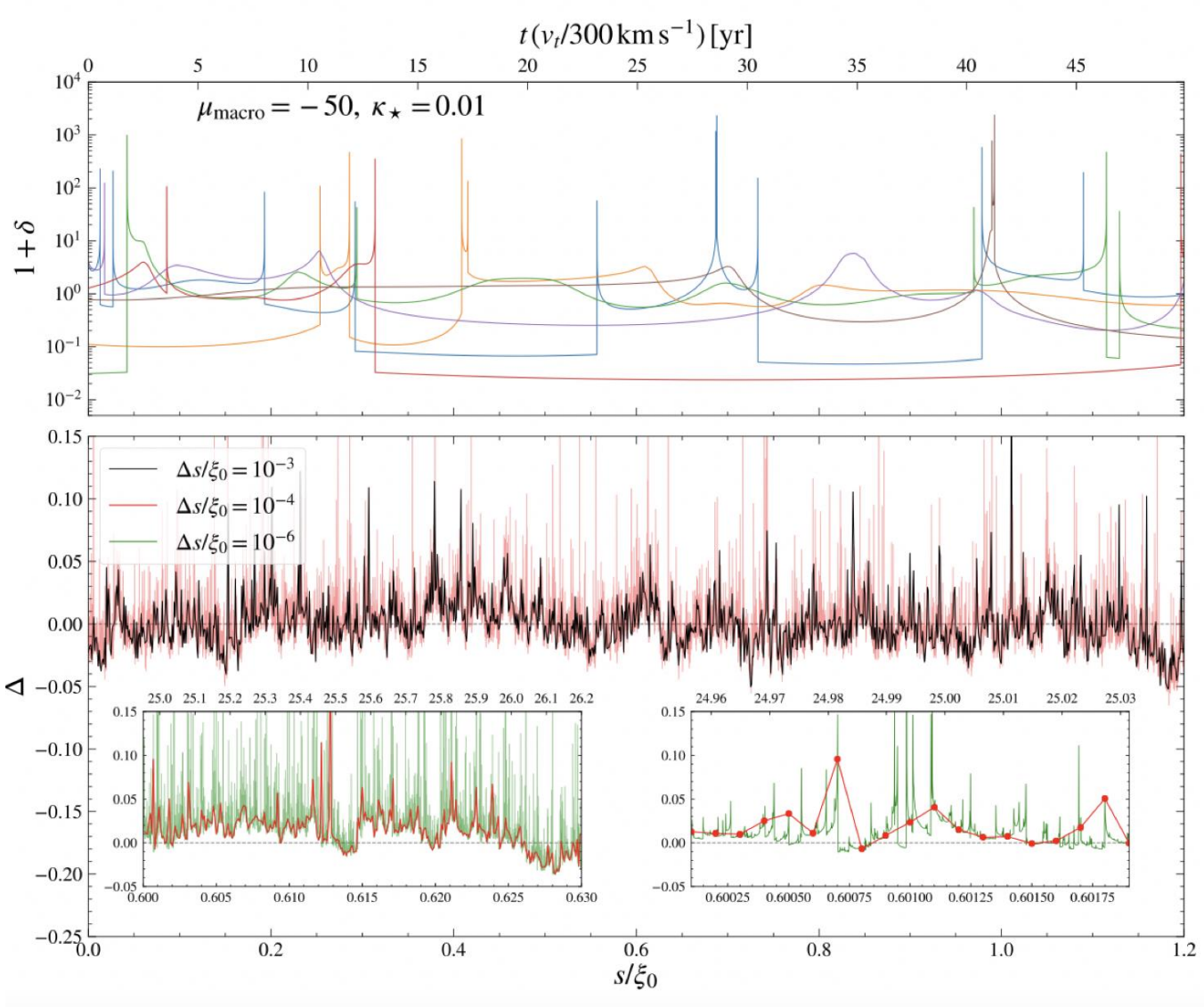




Once any single lensed star is discovered, its microlensing induced variability can be followed-up (essentially) **forever**!

Lensed Star or Lensed Cluster of Stars?



Large photometric variability is the “golden standard” !

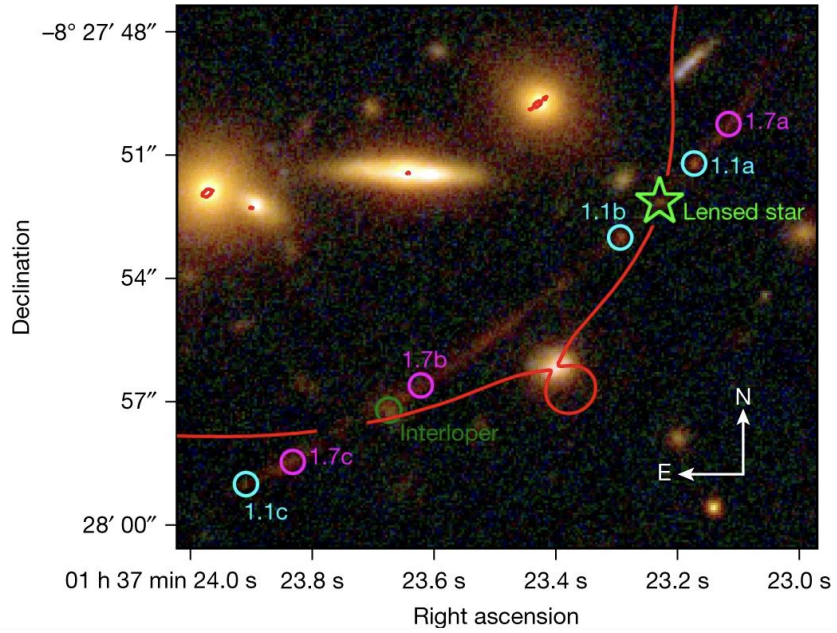
Single or binary stars:
Infrequency but large fractional flux change

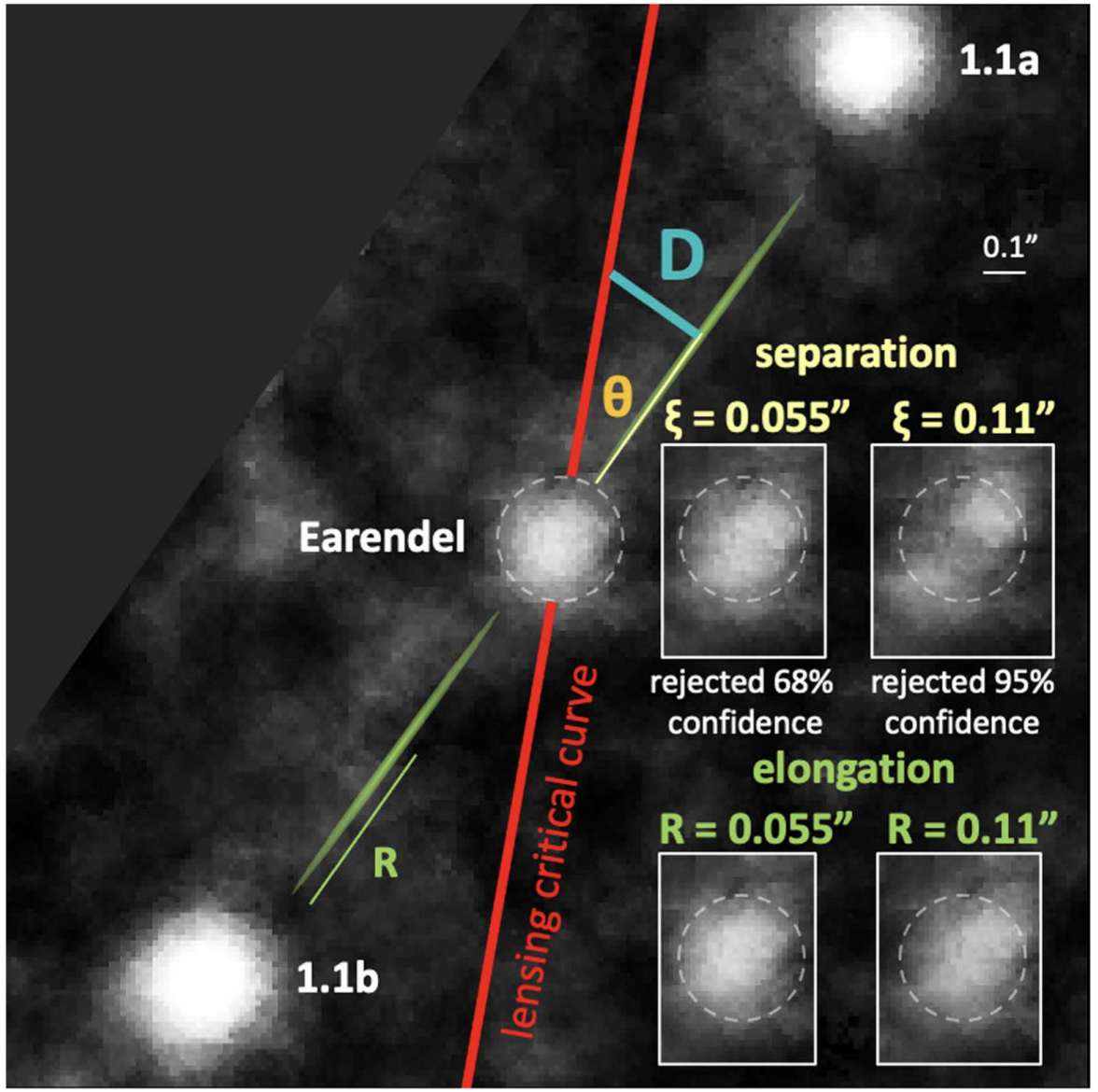
Large cluster of stars
frequent but small fractional flux change

Dai 2021

Earendel: a lensed star at z = 6 ?!

Welch et al 2022a,b





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Article | Published: 30 March 2022

A highly magnified star at redshift 6.2

Brian Welch ✉, Dan Coe, Jose M. Diego, Adi Zitrin, Erik Zackrisson, Paola Dimauro, Yolanda Jiménez-Teja, Patrick Kelly, Guillaume Mahler, Masamune Oguri, F. X. Timmes, Rogier Windhorst, Michael Florian, S. E. de Mink, Roberto J. Avila, Jay Anderson, Larry Bradley, Keren Sharon, Anton Vikaeus, Stephan McCandliss, Maruša Bradač, Jane Rigby, Brenda Frye, Sune Toft, … Tom Broadhurst

+ Show authors

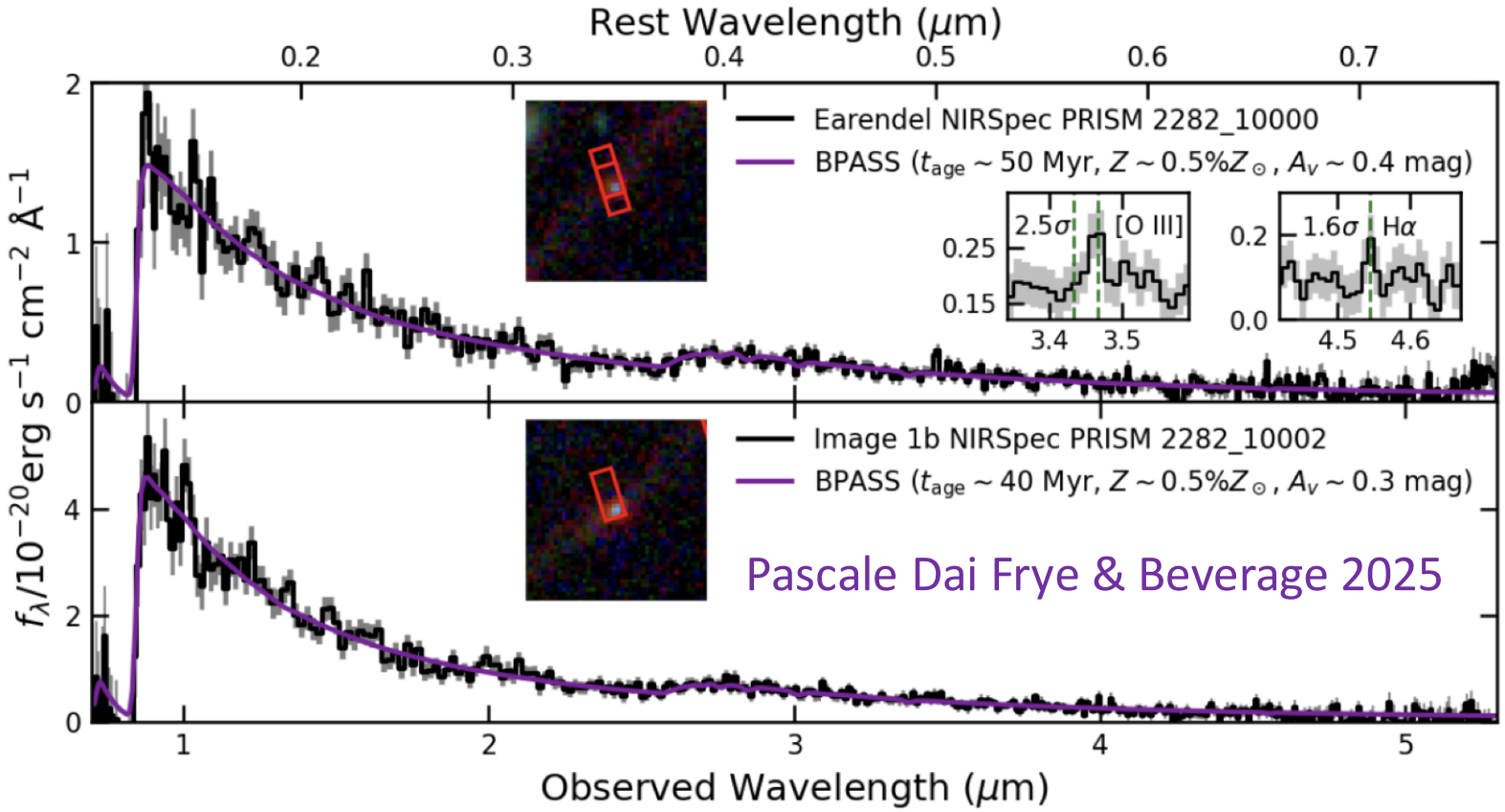
Suspicions:

[1] No microlensing induced variability

[2] Require a Very Massive Star magnified by >8000 x

[3] Spectral fit to one or two stars not well

SED fits intermediate age (20—100 Myr), metal poor (< 10% $Z_\odot$) **globular cluster progenitor**



Pascale Dai Frye & Beverage 2025



Massimo Pascale

now Hubble Fellow@UCLA



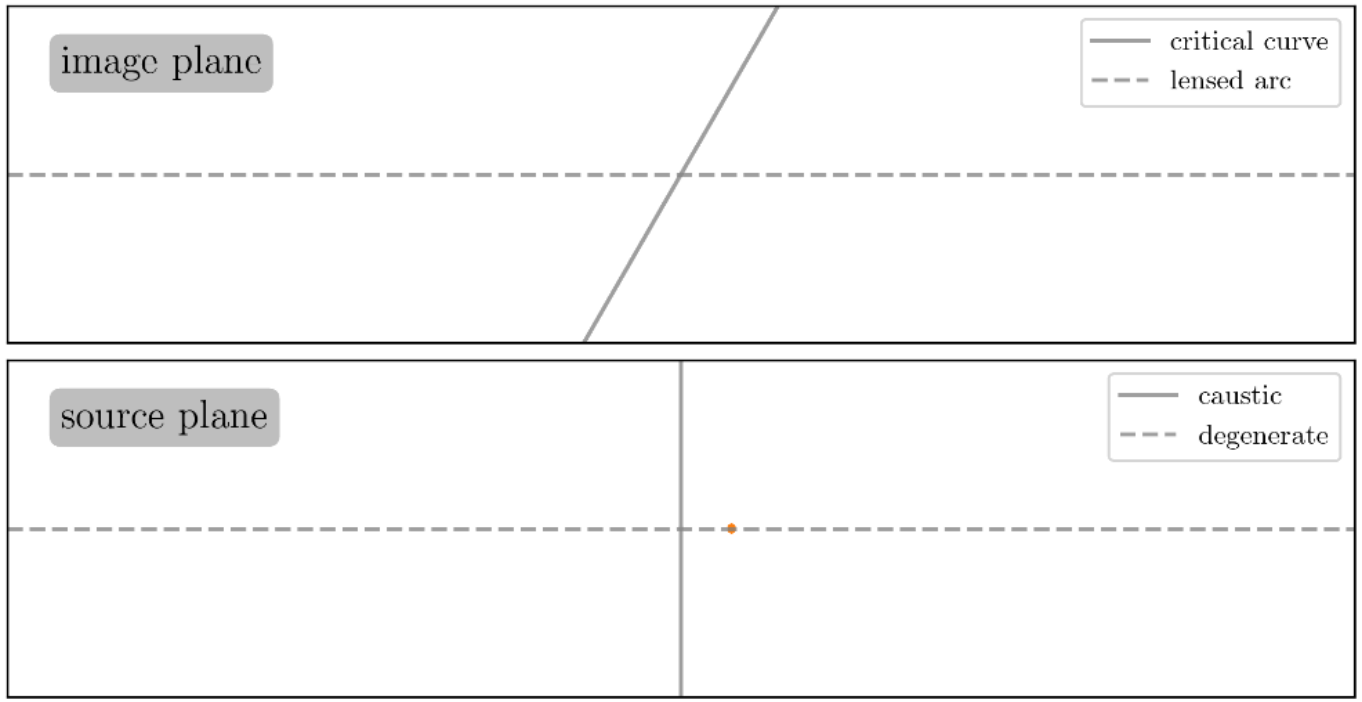
How Large is Earendel?

$$r \lesssim 0.17\,\mathrm{pc} \left(\frac{\mathcal{R}}{0.055''}\right)^2 \left(\frac{D_\mathrm{S}}{1182\,\mathrm{Mpc}}\right) \left(\frac{\left|\boldsymbol{d}^\mathbf{0} \cdot \boldsymbol{e}^\mathbf{0}_\parallel\right|}{(1/50'') \cdot \cos(\pi/3)}\right)$$

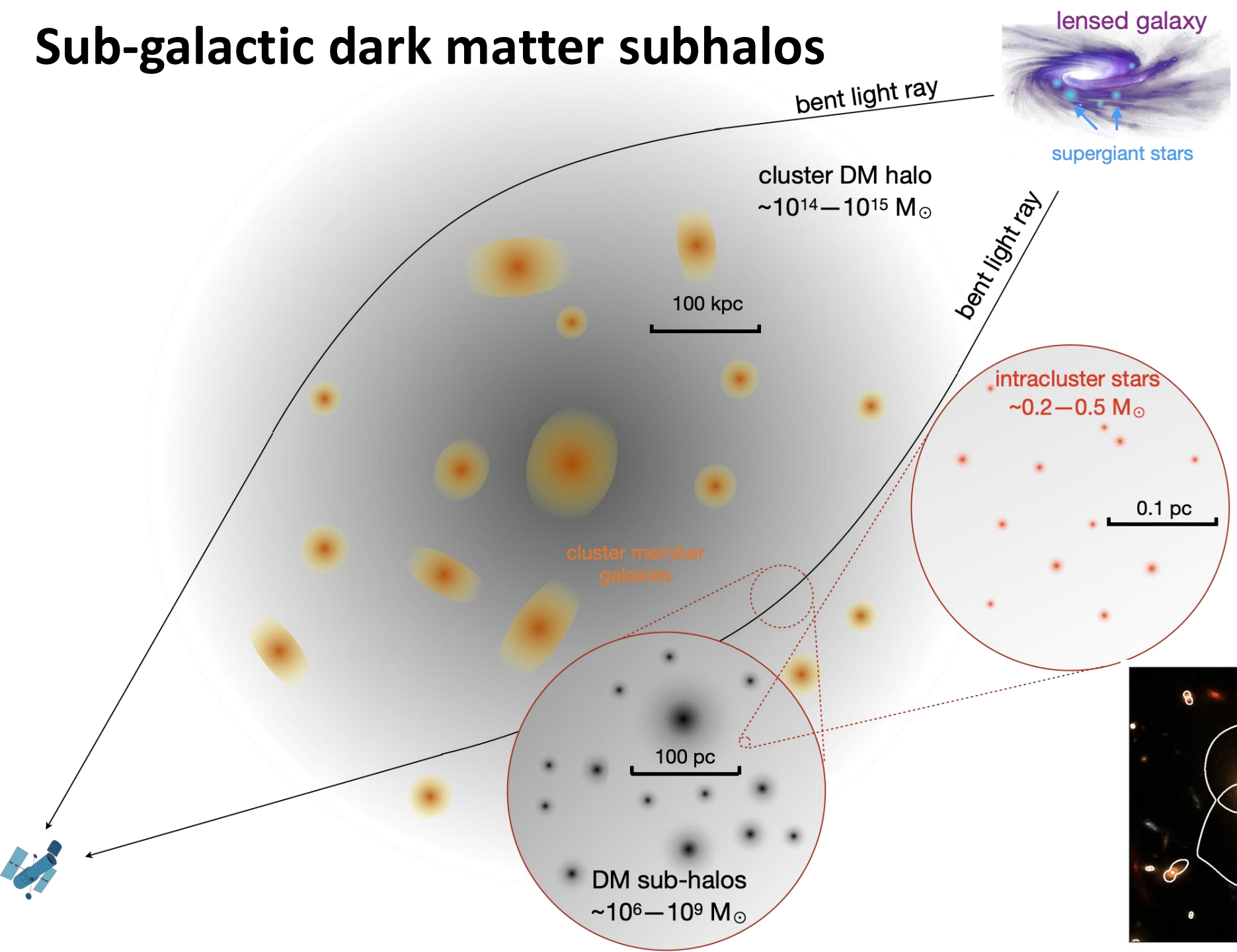
telescope

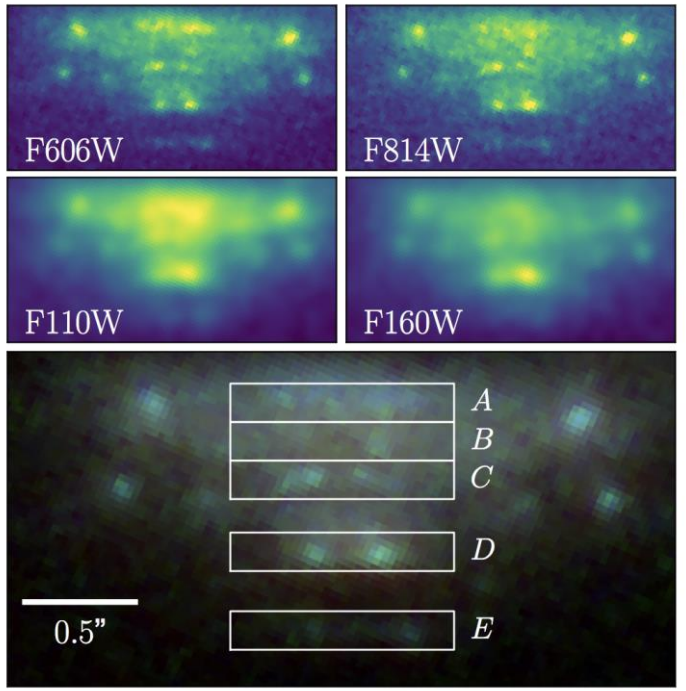
distance to Earendel

galaxy cluster lens model (caustic "strength")



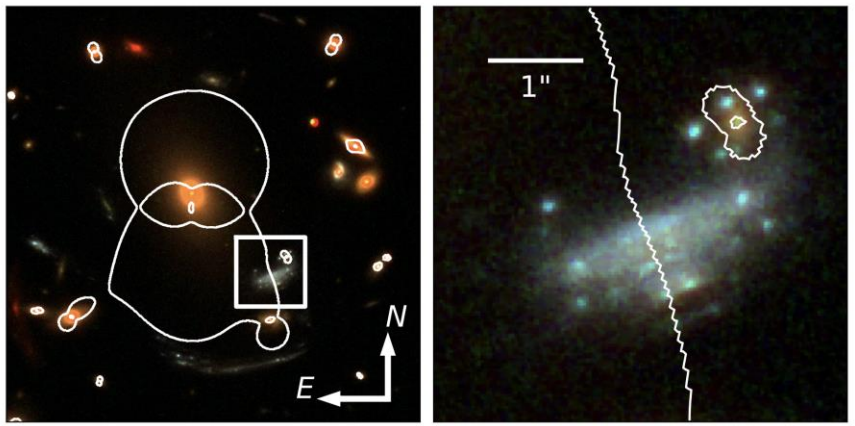
Sub-galactic dark matter subhalos

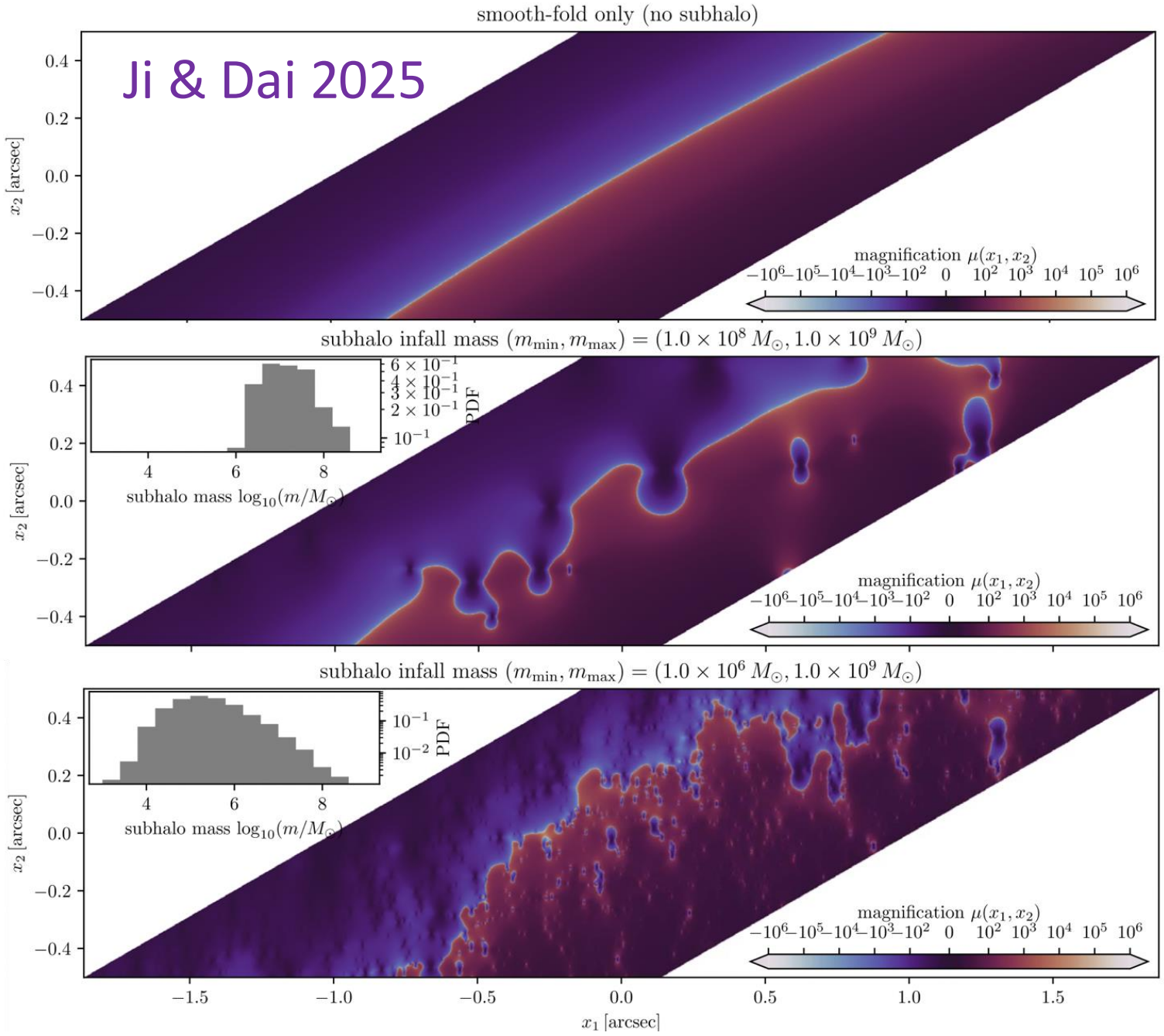




Dai et al 2020

Flux asymmetries





$$r \lesssim 0.17\,\mathrm{pc} \left(\frac{\mathcal{R}}{0.055''}\right)^2 \left(\frac{D_S}{1182\,\mathrm{Mpc}}\right) \left(\frac{\left|\boldsymbol{d}^0 \cdot \boldsymbol{e}_\parallel^0\right|}{(1/50'') \cdot \cos(\pi/3)}\right)$$

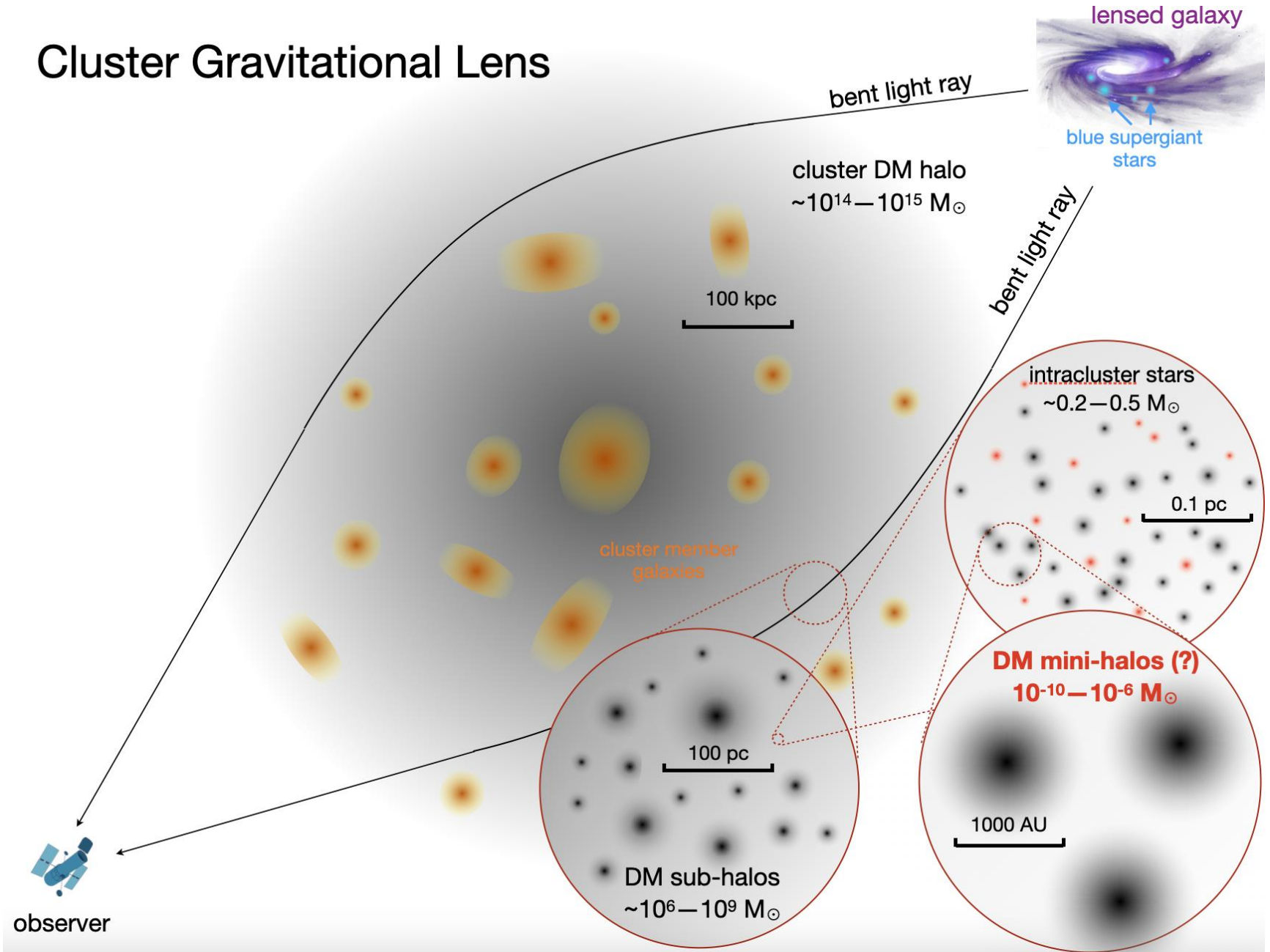
10^6--10^8 $M_\odot$ CDM subhalos weaken the caustic

Earendel's true size can be as large as ~ 1—3 pc

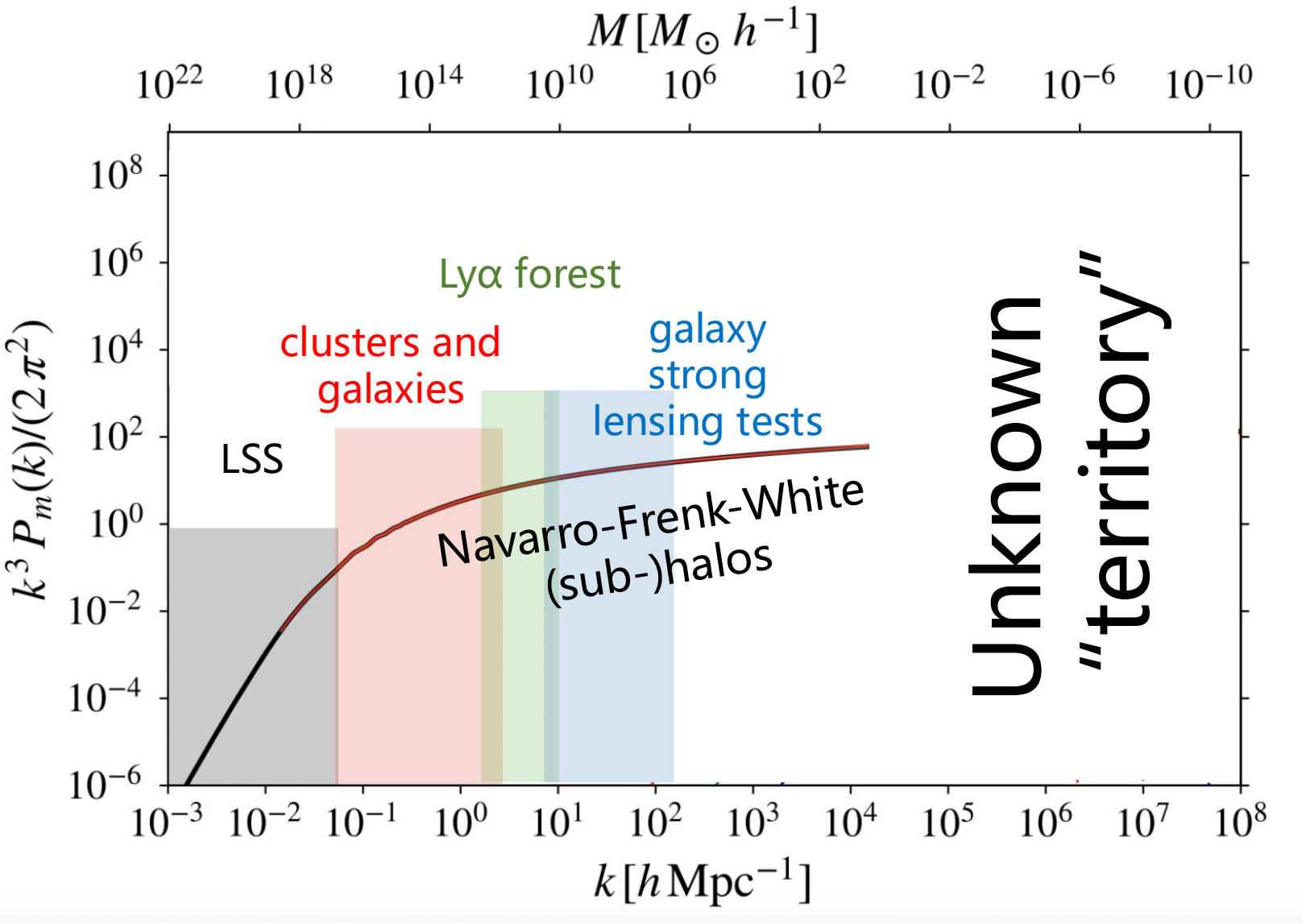


Lingyuan Ji

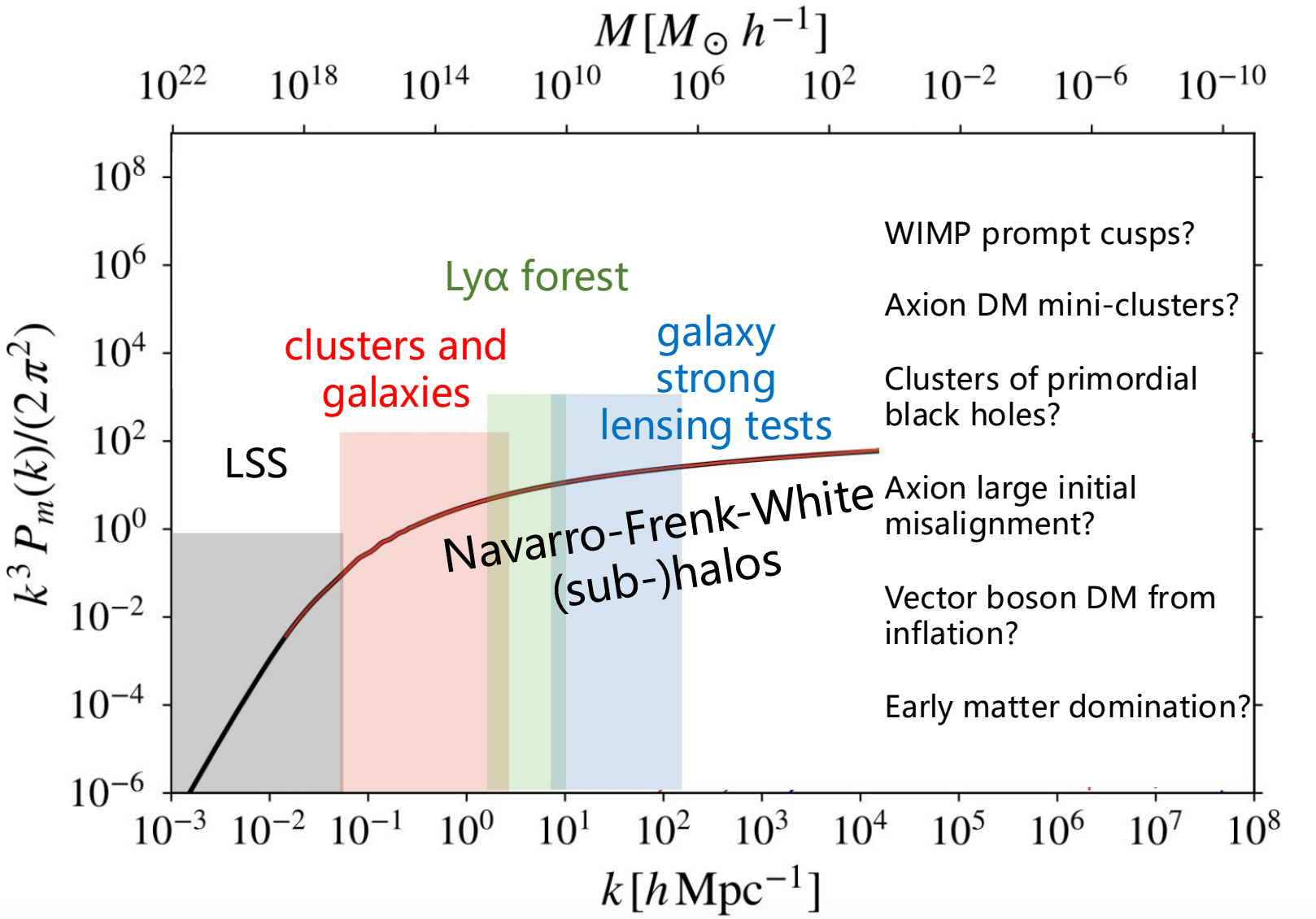
Additional clumpy dark matter structures on tiny scales?



Structure formation from initial density



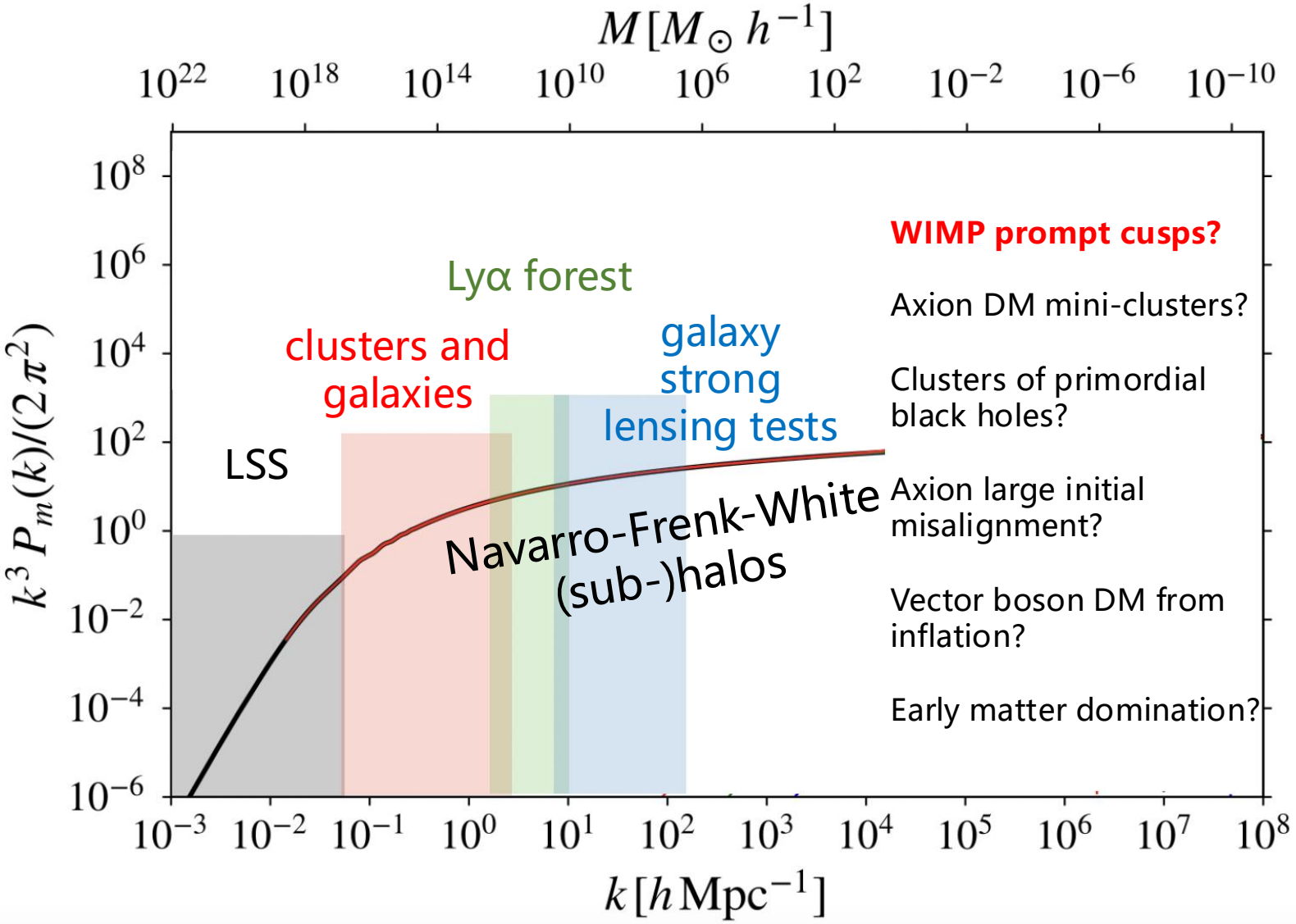
Structure formation from initial density



Mini-halo properties:

1. (sub-)planetary masses
2. Solar-system sizes
3. Survive dynamic disruption in intergalactic or intracluster space

Structure formation from initial density



WIMP prompt cusps?

Axion DM mini-clusters?

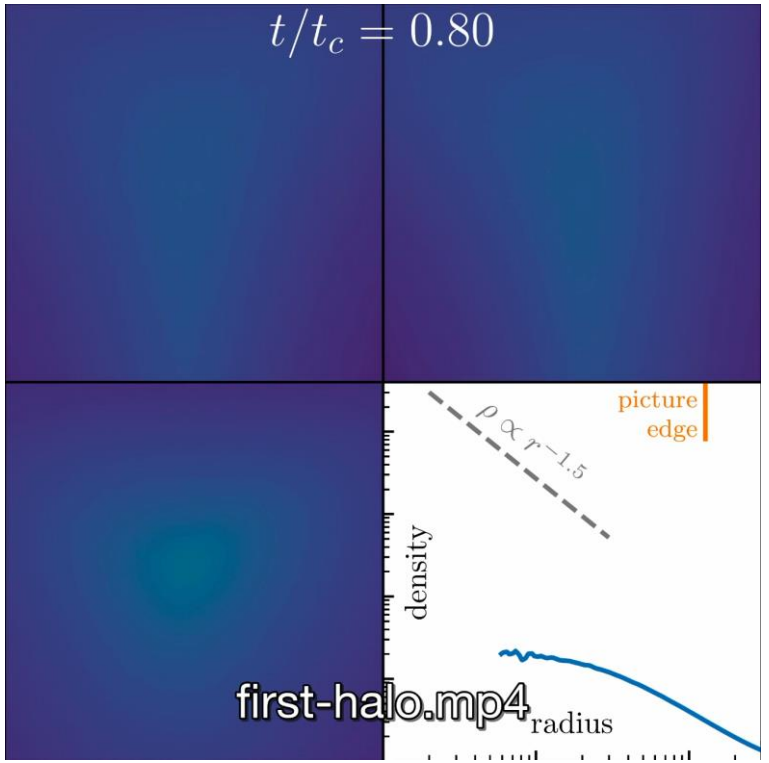
Clusters of primordial black holes?

Axion large initial misalignment?

Vector boson DM from inflation?

Early matter domination?

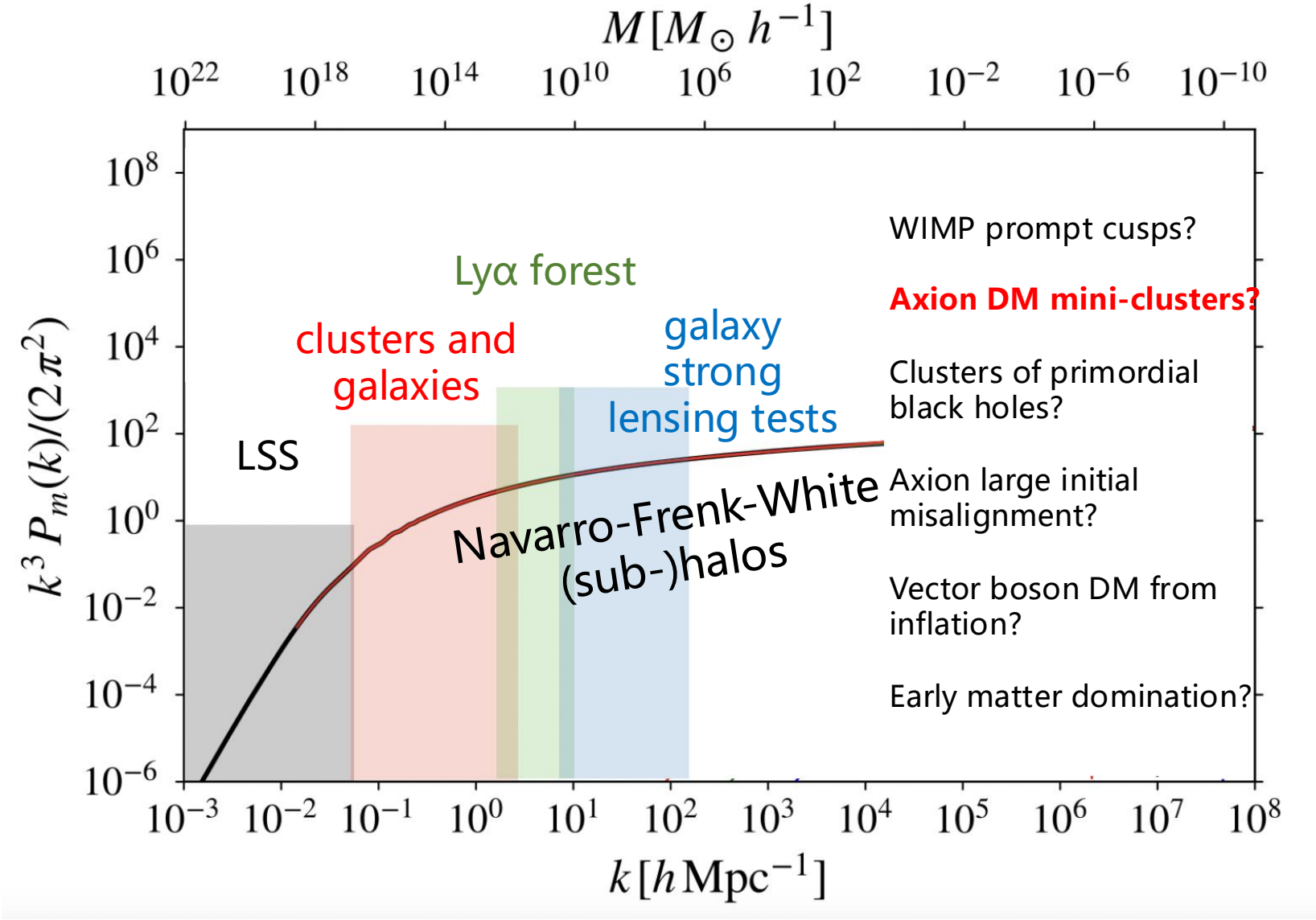
Prompt cusp formation on free-streaming scale



animation credits: M. Sten Delos

e.g. Delos, Bruff & Erickcek 19
Delos & White 22

Structure formation from initial density



WIMP prompt cusps?

Axion DM mini-clusters?

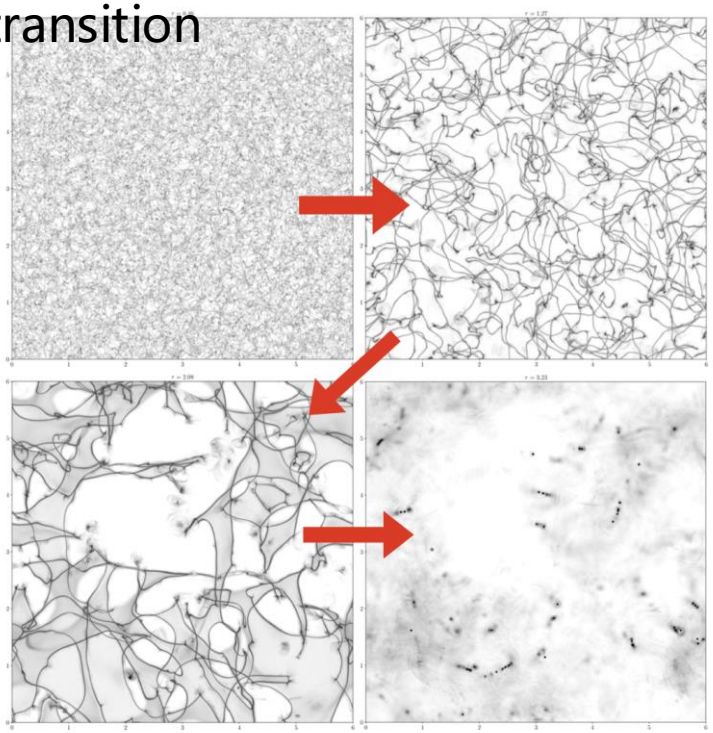
Clusters of primordial black holes?

Axion large initial misalignment?

Vector boson DM from inflation?

Early matter domination?

Axion mini-cluster collapse from **isocurvature fluctuations** following Peccei-Quinn phase transition



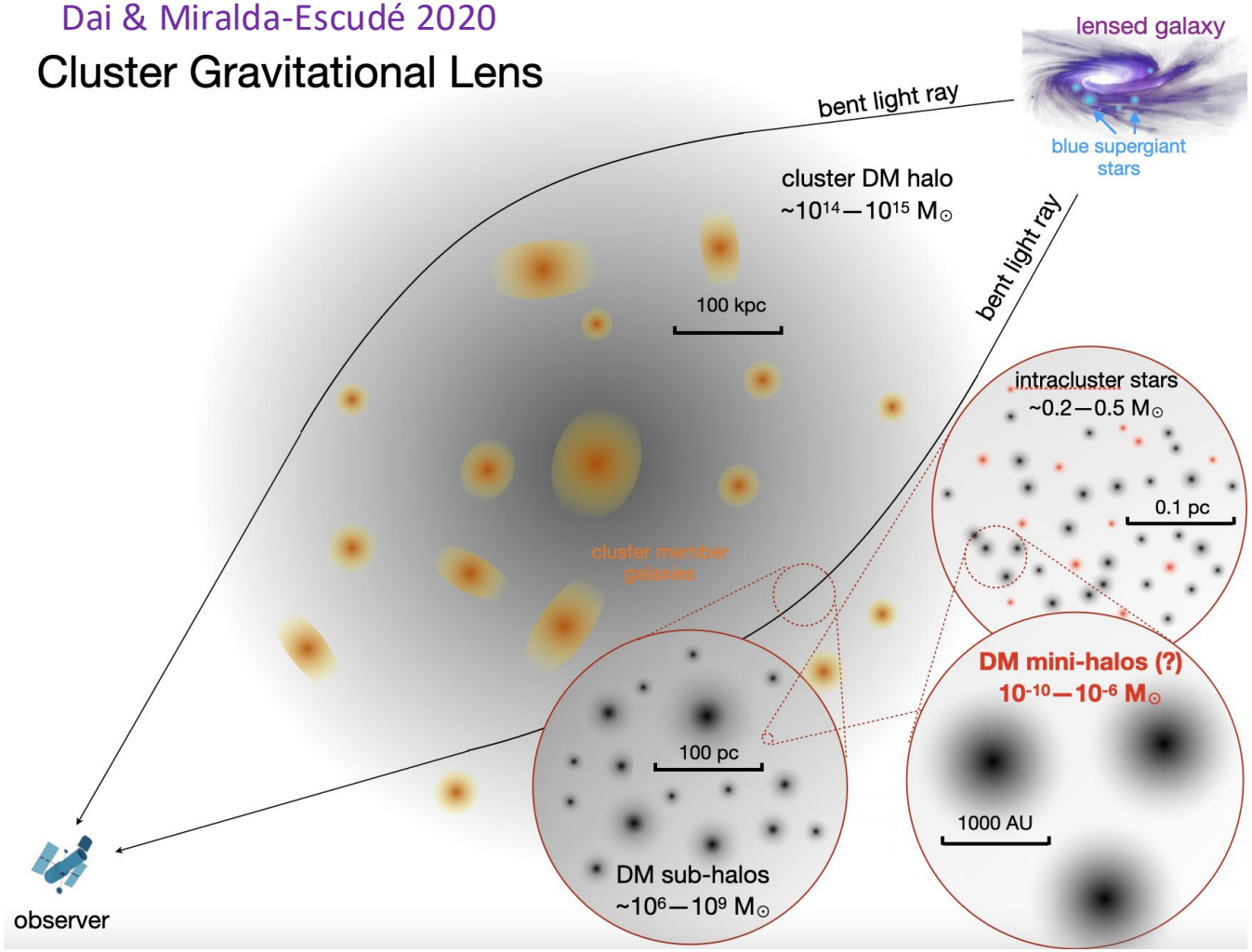
Hogan & Rees 88
Kolb & Tkachev 94
Vaquero, Redondo & Stadler 19
Xiao, Williams & McQuinn 21

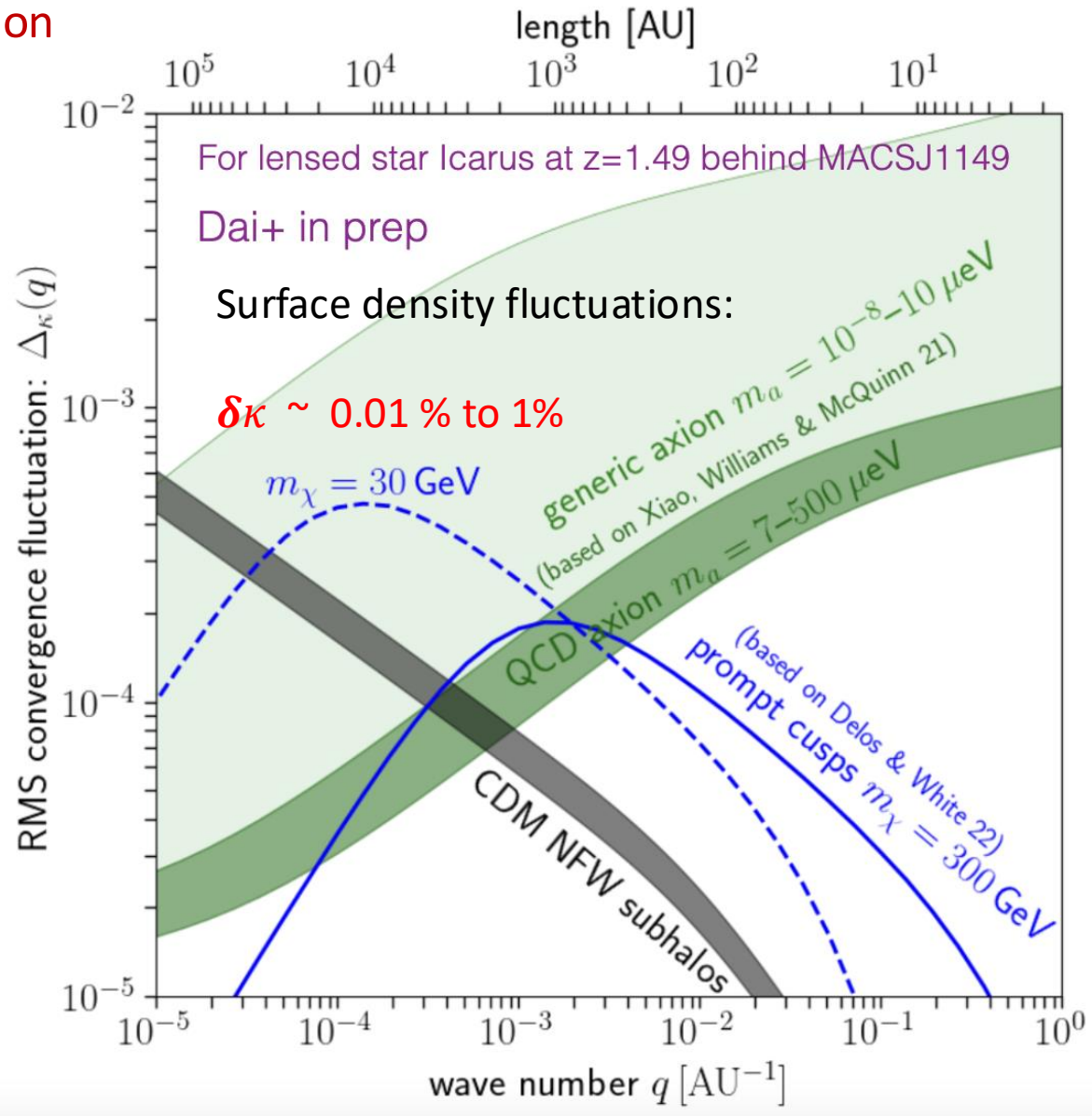
Collective observable effect of mini-halos

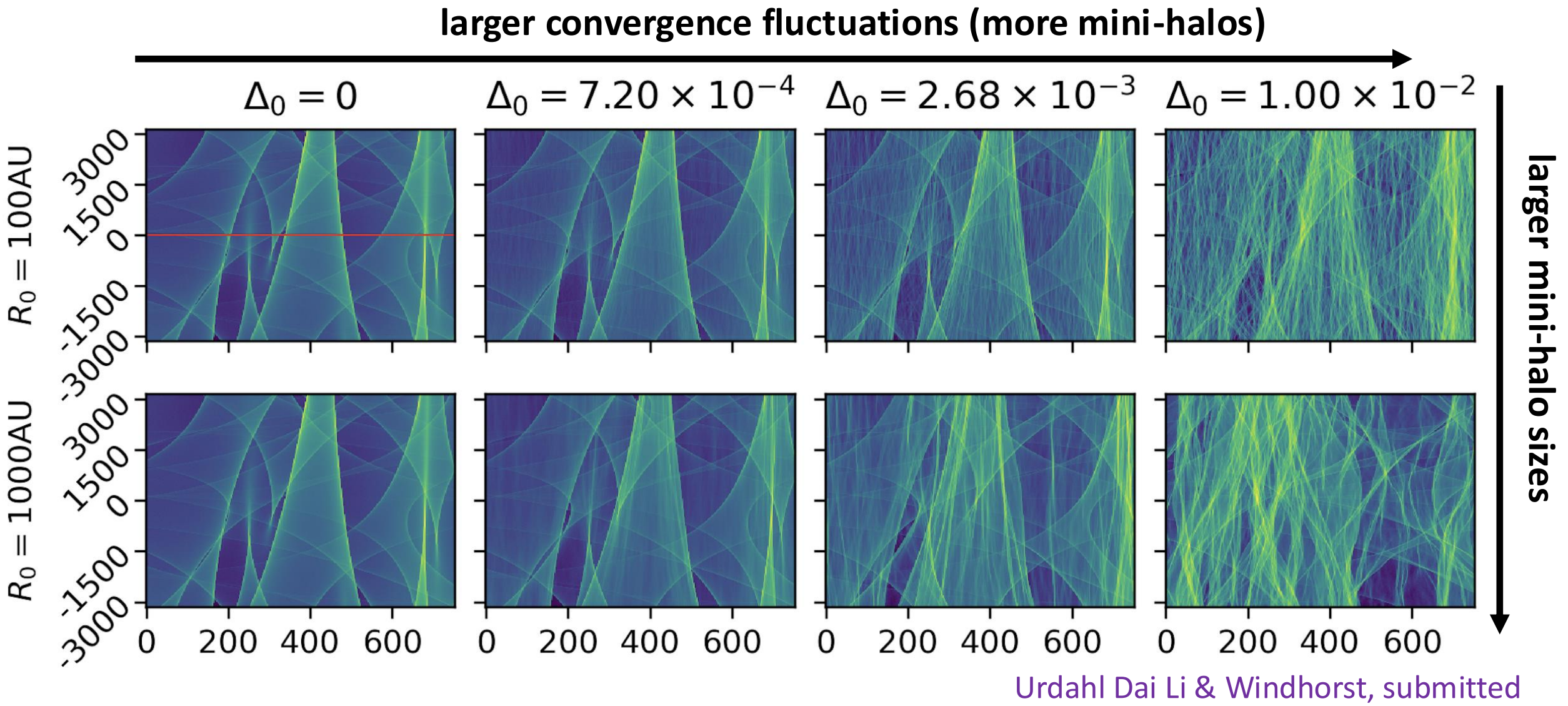
Mini-halos: a huge number along the LoS overlap in projection

PBHs: many along the LoS

Dai & Miralda-Escudé 2020





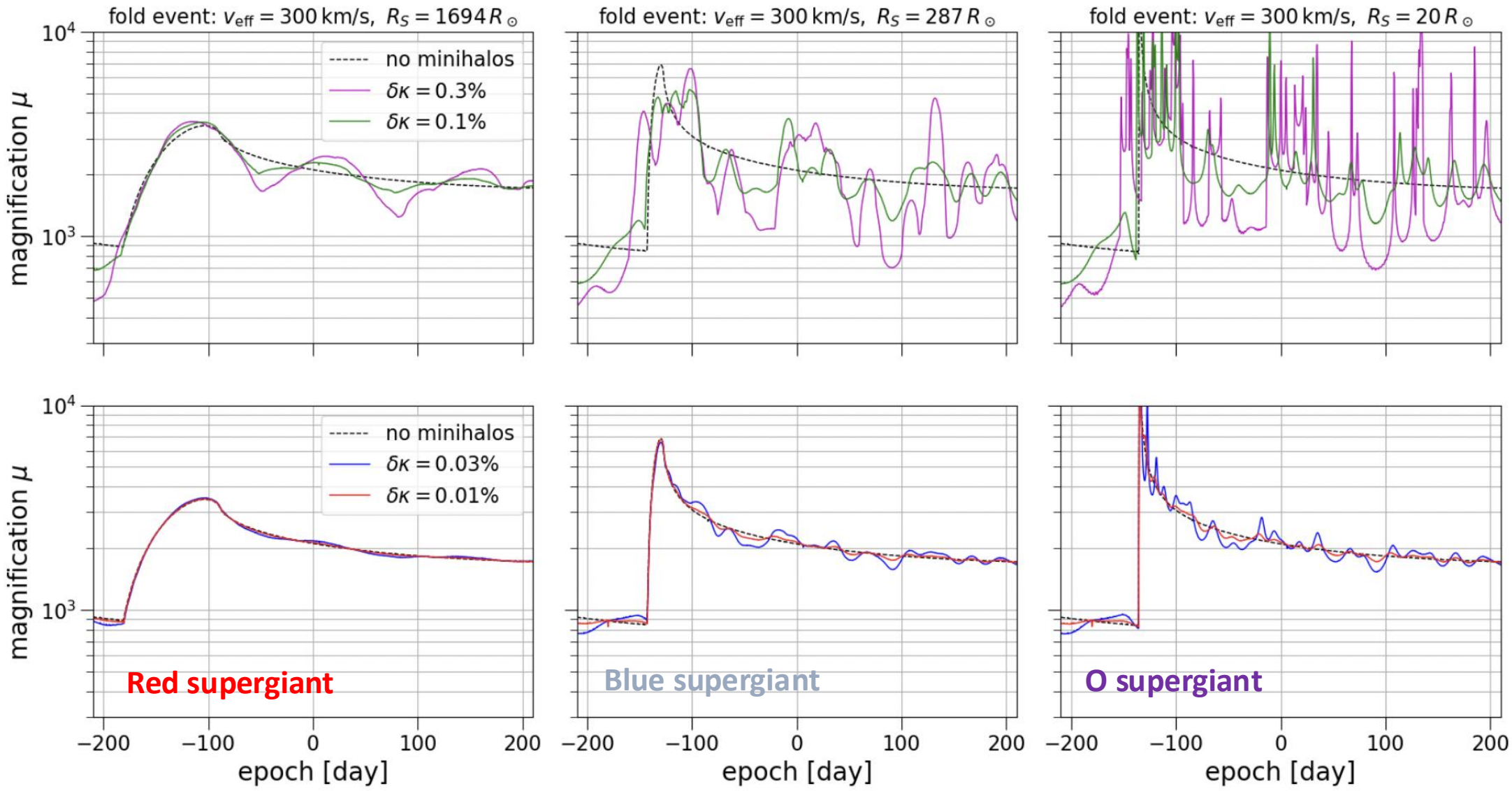


Urdahl Dai Li & Windhorst, submitted

Δ_0 Characteristic amplitude of convergence fluctuation **~ 0.01% --- 1%**

R_0 Characteristic length scale of convergence fluctuation **~ 10^2 --- 10^4 AU**

Smaller Stars Are Better DM Probes

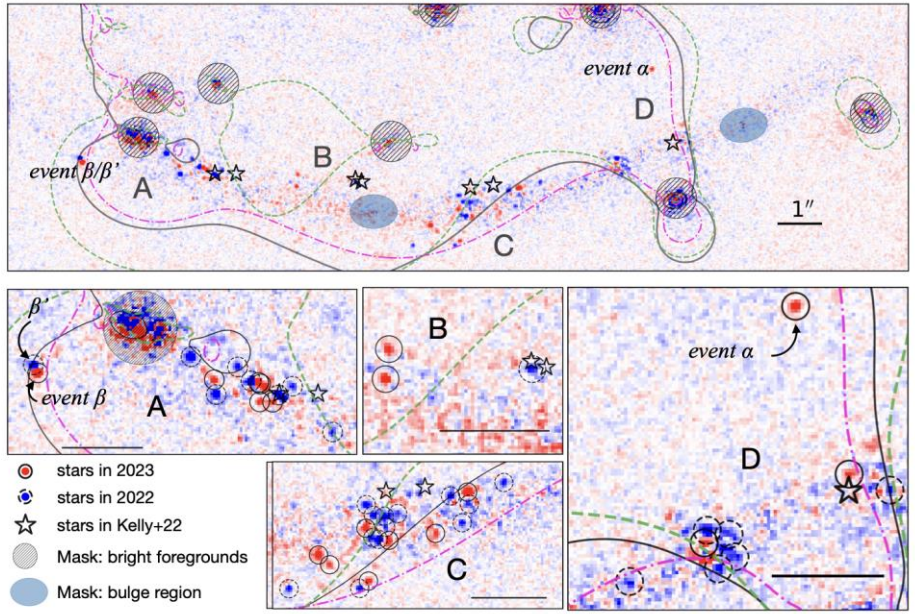


Assume the host of Icarus: $z_s = 1.49$

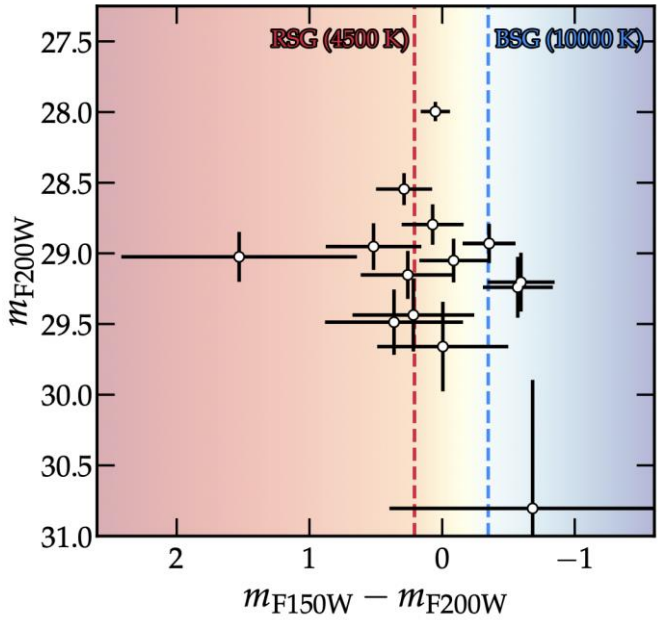
Do we have to use lensed extragalactic stars?

	typical magnification	critical surface density	image size	source crossing time	caustic crossings
Lensed extragalactic stars	**A few x 100 to a few x 1000**	**~ 1000 $M_\odot pc^{-2}$**	**~ 100–1000 AU**	**~ day to weeks**	**common**
Lensed QSOs	several to a few dozen	**~ 1000 $M_\odot pc^{-2}$**	~ 10000 AU	~ decade	rare
Lensed SNe	several to a few dozen	**~ 1000 $M_\odot pc^{-2}$**	~ 10000 AU	~ decade	rare
Galactic/local group microlensing	up to ~ 100	~ 10^6—10^8 $M_\odot pc^{-2}$	**~ 0.1–10 AU**	**~ hours**	rare

Detecting Many Lensed Stars With Few Imaging Visits



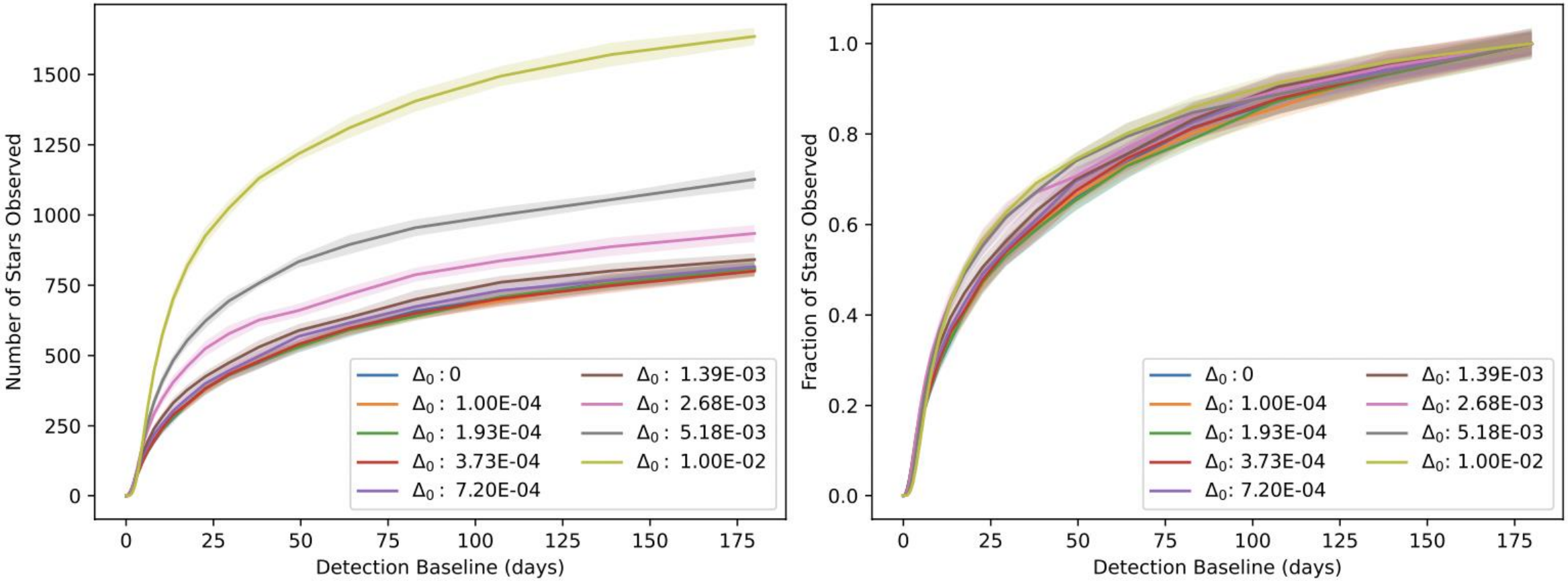
Fudamoto et al 2025
40+ events reported



Palencia et al 2026
100+ events reported

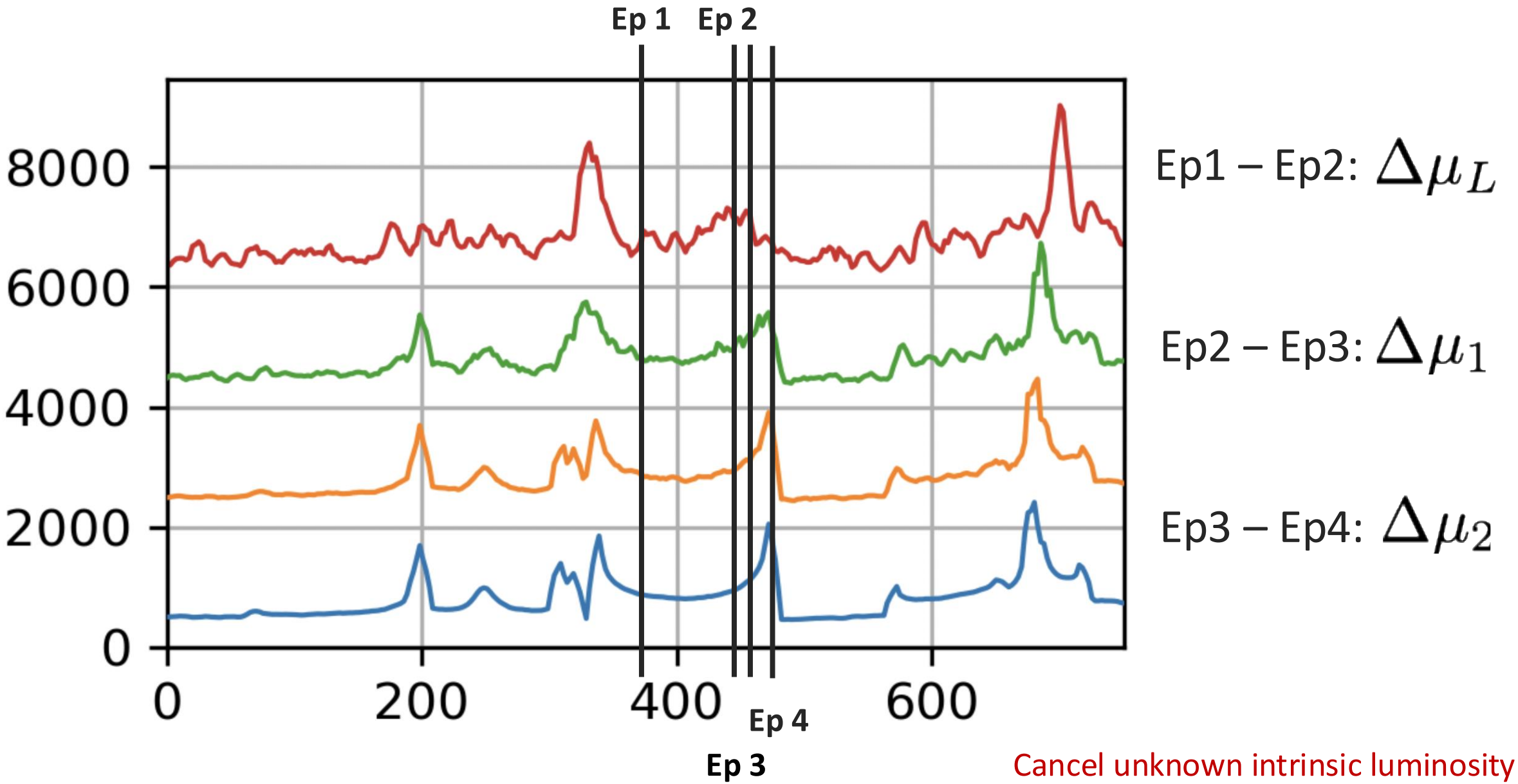


Simple statistics do NOT reveal DM mini-halos



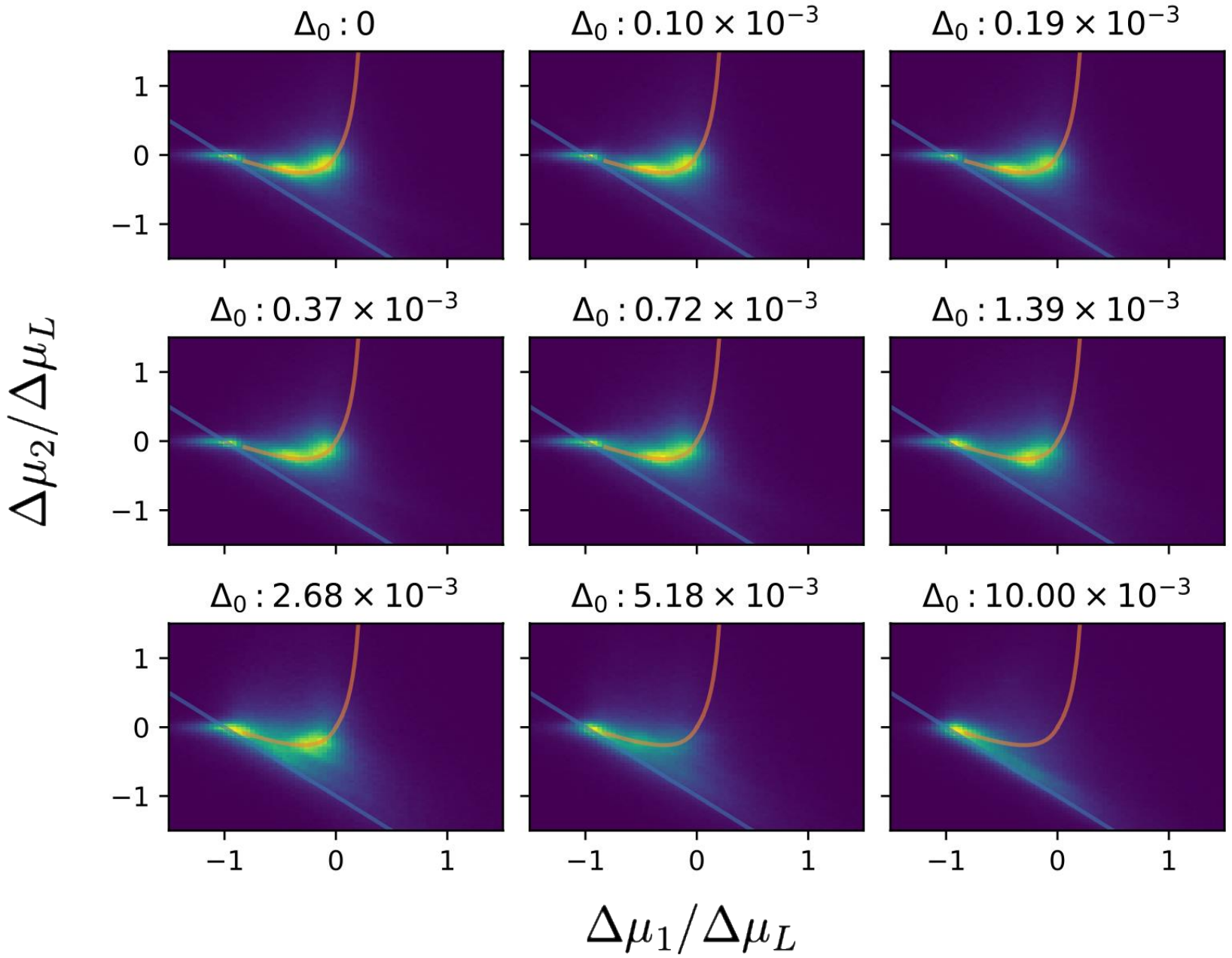
Normalized dependence of detection rate on image-difference time baseline

Ratios of Magnification Factor Changes

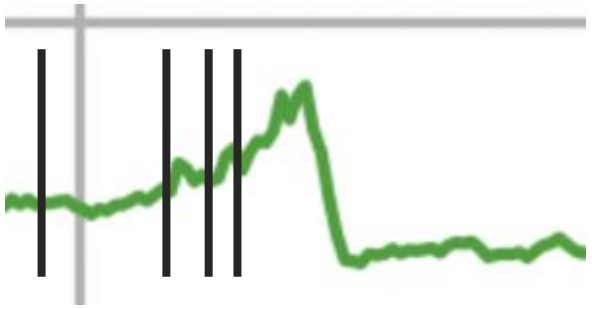


Cancel unknown intrinsic luminosity!

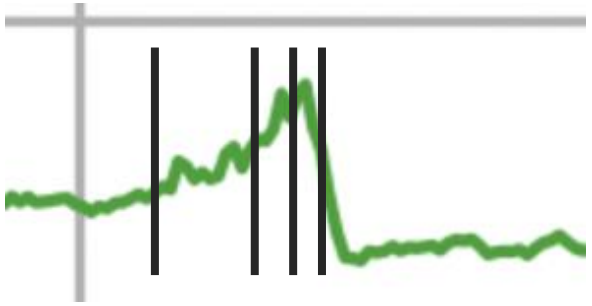
Distribution of Magnification Change Ratios



ORANGE:



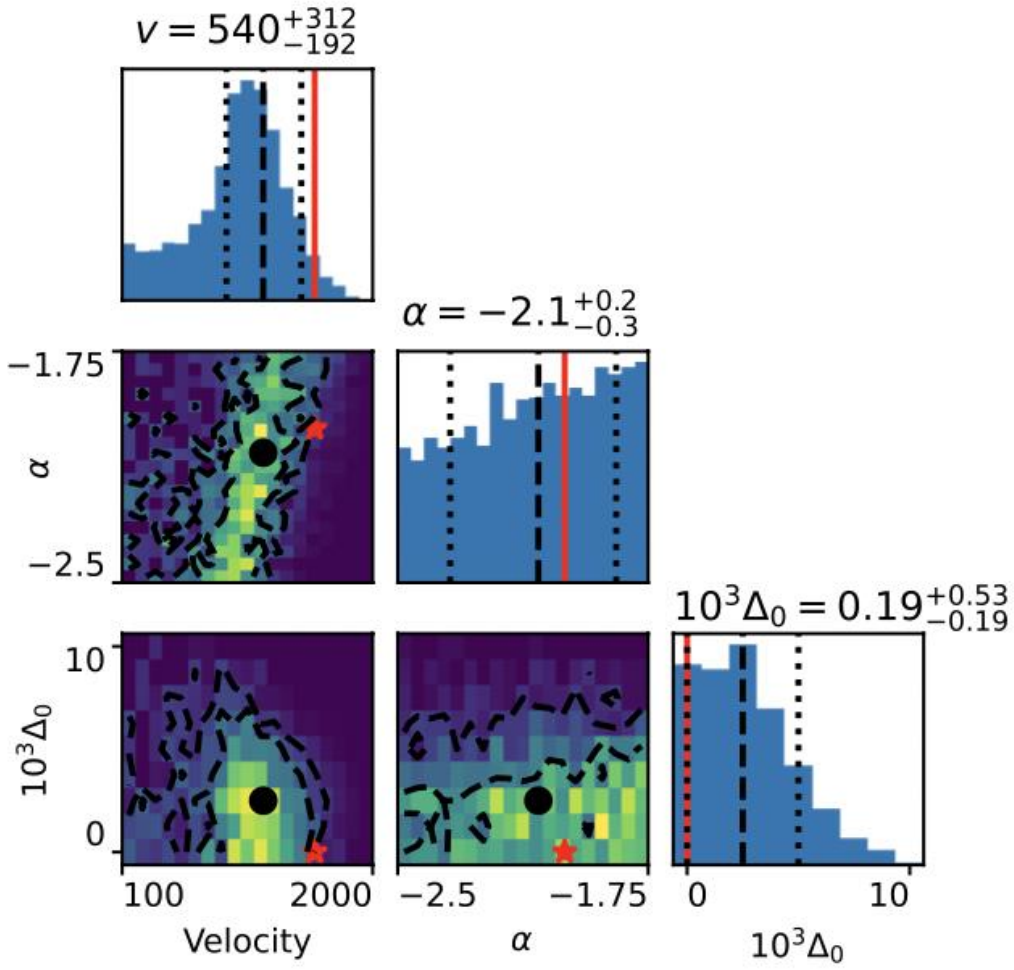
BLUE:

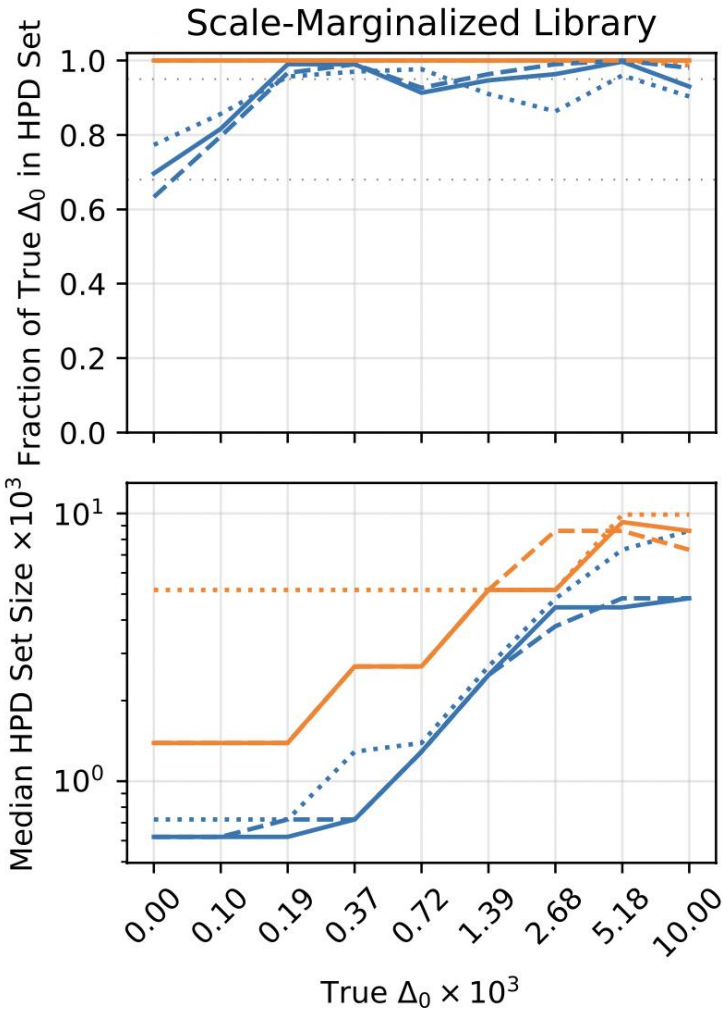


Approximate Bayesian Computation (ABC) based on forward modeling

Urdahl Dai Li & Windhorst, submitted

Δ_0: RMS small-scale convergence fluctuation
α: logarithmic slope of RSG luminosity function
v: bulk relative velocity between lens and host galaxy







William Urdahl

Expected Science Reach

Modest goal with low-cadence data

high-cadence monitoring of curated lensed stars: small hot stars and cusp events

Positive results

Variability incompatible with microlensing by *only* intracluster stars:

A smoking gun of **New Physics** beyond perfect CDM

Negative results

Variability consistent with microlensing by *only* intracluster stars

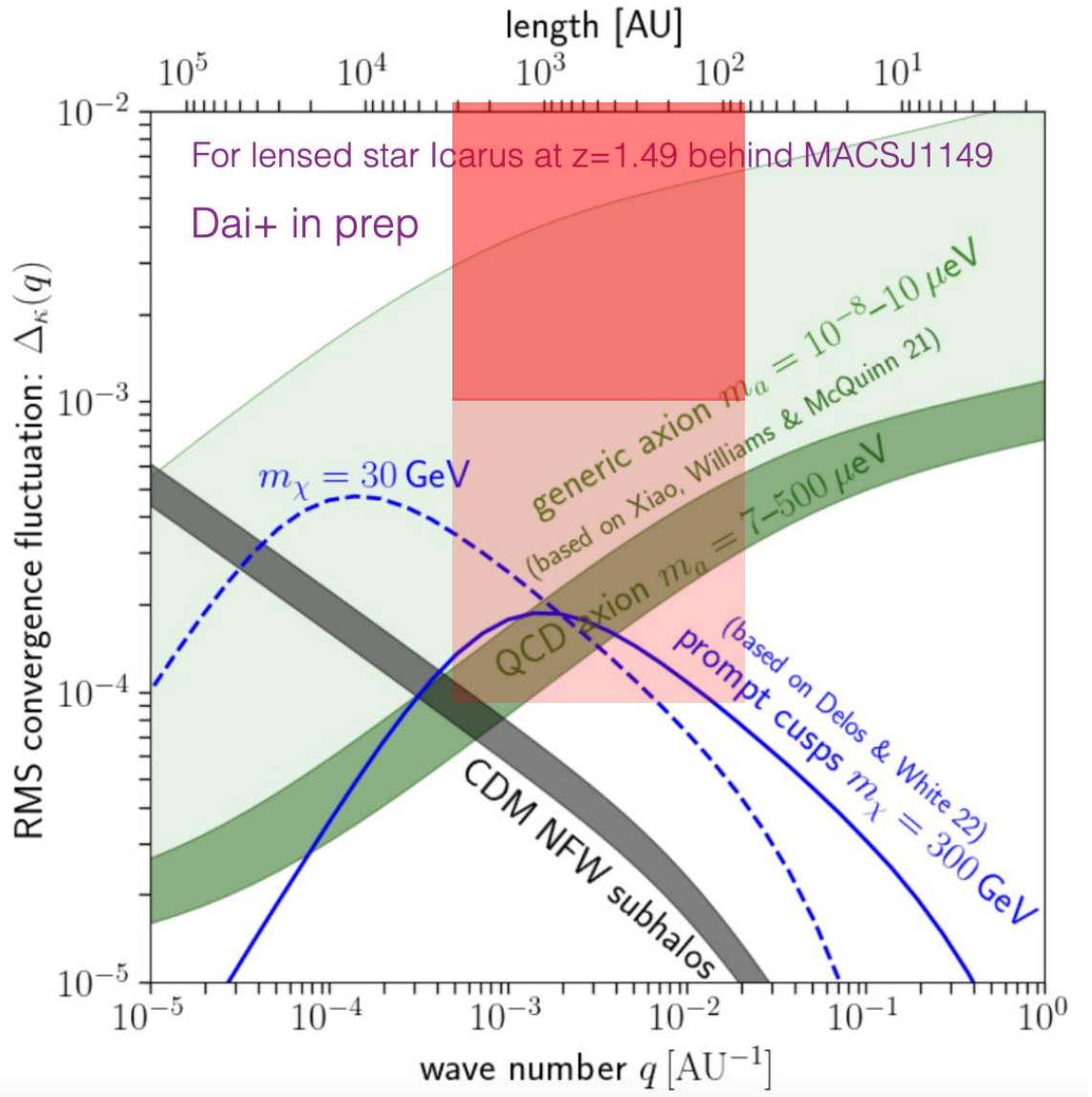
Model-independent limits $\delta\kappa$ <0.01—0.1% on 10^2—10^4 AU

Thermal relic freeze-out: constrain WIMP particle mass 10—1000 GeV

Post-inflation Peccei-Quinn: 11 orders of magnitude in axion particle mass including QCD axion DM

Constrain general scenario of **enhanced micro-halo formation**

e.g. Blinov Dolan Draper & Shelton 2021; Croon et al 2026



Take-home messages

1. Optical-NIR telescopes in space (such as HST, JWST and in the future CSST) can detect extremely magnified (~ 100—10000x) extragalactic stars as microlensing transients.

2. Microlensing-induced light variability of extremely magnified stars is sensitive to > 0.01% -- 0.1% convergence fluctuations in the lens on solar system scales ~ 100 -- 10000 AU, uniquely and model-independently probing a population of dark matter micro-halos that might have formed in the early universe.

3. If (for now) we don't have the luxury to monitor a curated sample of lensed stars at high cadence and with accuracy photometry, we may alternatively image a large sample of lensed stars at several epochs and perform statistical tests to tell apart stellar microlensing and random convergence fluctuations.