Clues to the small-scale mass distribution of the dark matter probed by gravitational lensing.

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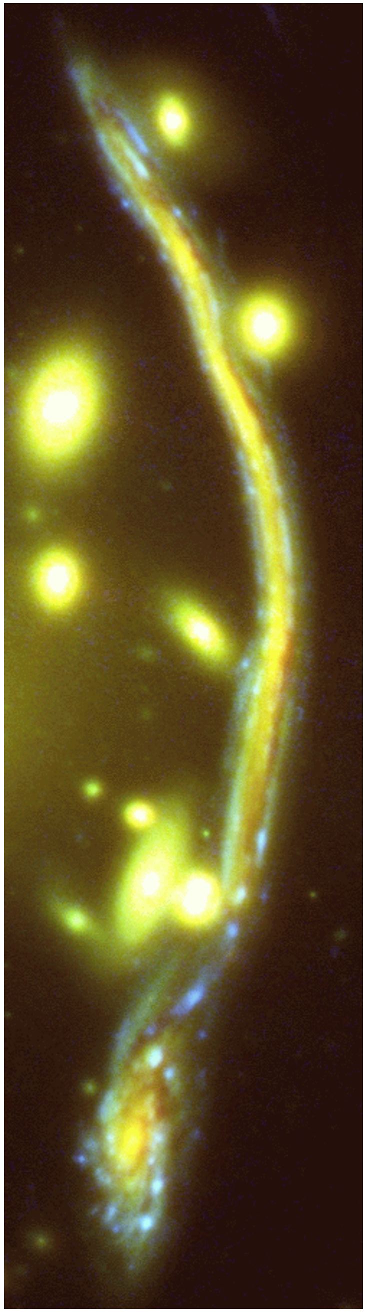
Fundamental question in cosmology:
What is the dark matter?

- The dark matter mass within some radius of many objects is measured in many astrophysical observations: galaxy rotation curves, dynamics of X-ray emitting gas in clusters, gravitational lensing in galaxies and clusters, large-scale structure flows.
- Probes of the small-scale clumpiness of dark matter: microlensing limits in the Milky Way and external galaxies, gravitational lensing effects of subhalos in galaxies (e.g. for flux ratios of multiple images of quasars), impact of subhalos in tidal streams… a rich observational phenomenology that opens the door to learn about the dark matter distribution.
- Many different theoretical predictions on dark matter granularity:
  - Primordial black holes.
  - Subhalos in standard CDM
  - Ultralight axions: dark matter may be a classical scalar wave.
  - QCD axion miniclusters: may collapse at high redshift from random isocurvature perturbations.
- This talk focuses on highly magnified stars by lensing clusters as probe of small-scale structure in the cluster dark matter mass.

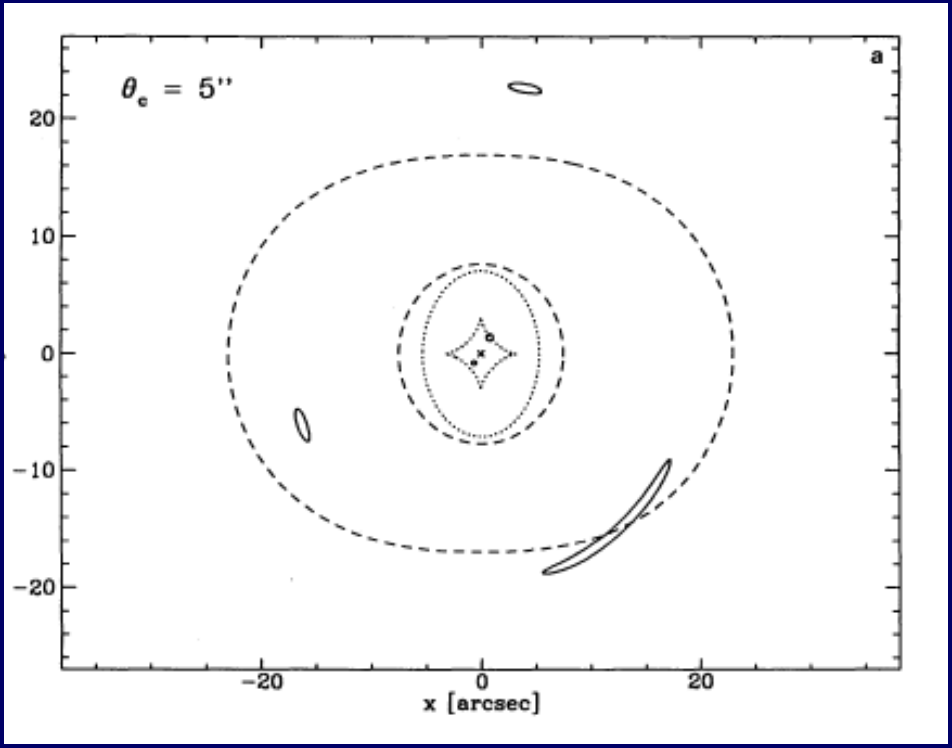
Gravitational lensing cluster Abell 370.



Cluster lens redshift z_l=0.37, source redshift z_s=0.72.

Strong lensing in clusters of galaxies: critical lines and caustics.

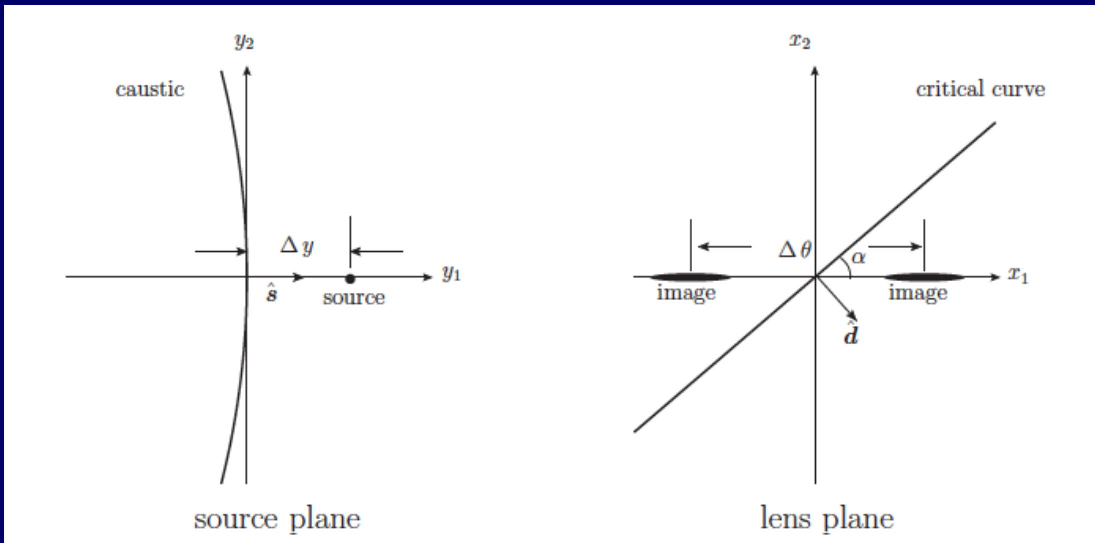
- When a source galaxy is located at a caustic, images merge on the corresponding critical line and the lensing magnification can formally go to infinity.
- What is the maximum magnification actually achieved? There are three limits:
  - Angular size of the source.
  - Diffraction
  - Microlensing in the cluster causing corrugation of the caustics.



JME 1993

$$A(x) \equiv \frac{\partial y(x)}{\partial x} = \begin{pmatrix} 1-\kappa(x)-\lambda(x) & -\eta(x) \\ -\eta(x) & 1-\kappa(x)+\lambda(x) \end{pmatrix}.$$

Lensing near a caustic



Venumadhav, Dai & JME 2017

Inverse magnification matrix:

$$\mathbf{A}(\mathrm{x}) \equiv \frac{\partial\, \mathrm{y}(\mathrm{x})}{\partial\, \mathrm{x}} = \begin{pmatrix} 1-\kappa(\mathrm{x})-\lambda(\mathrm{x}) & -\eta(\mathrm{x}) \\ -\eta(\mathrm{x}) & 1-\kappa(\mathrm{x})+\lambda(\mathrm{x}) \end{pmatrix}.$$

Image magnification:

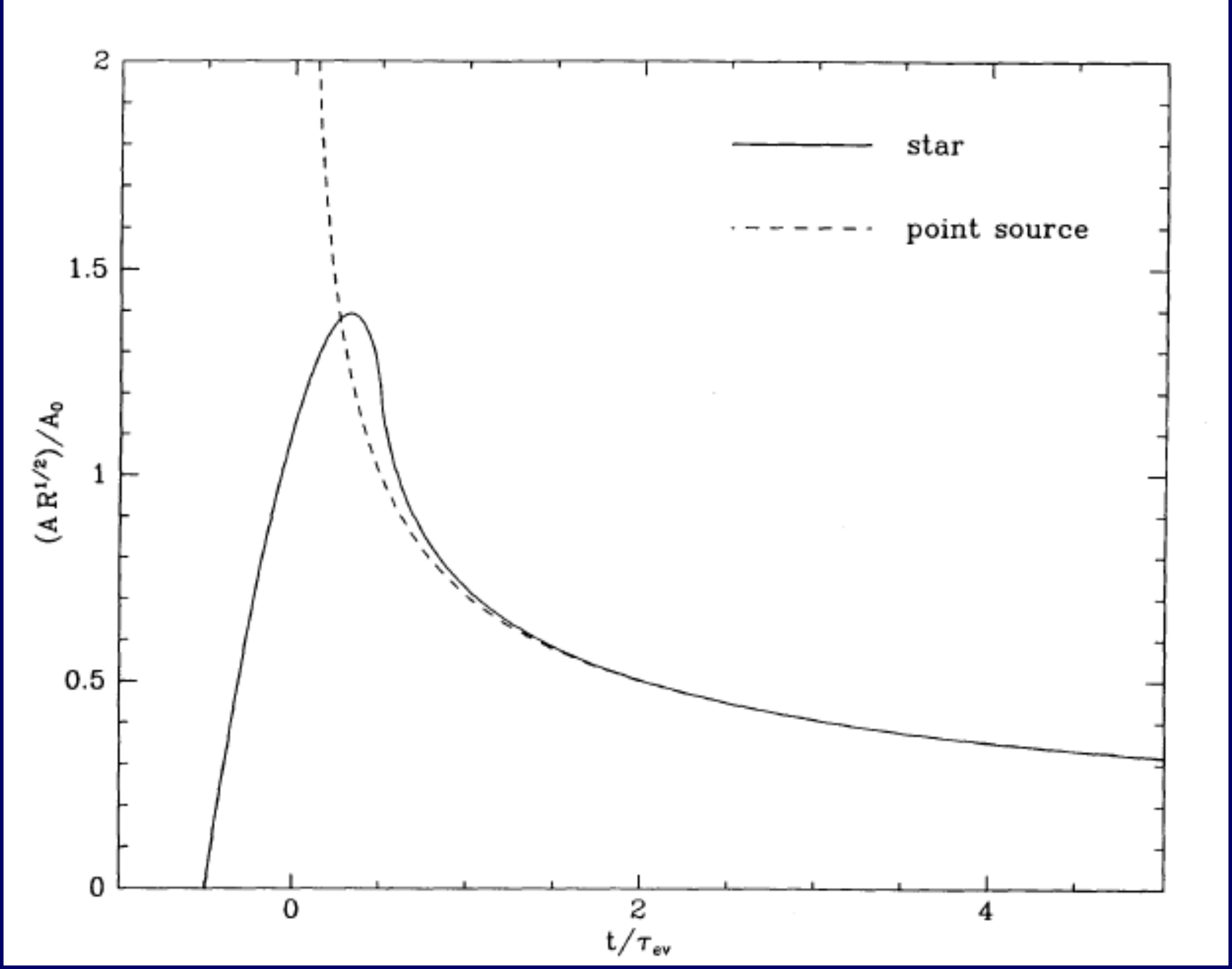
$$1/\mu(\mathrm{x}) = \det \mathbf{A}(\mathrm{x}) = 2\,(1-\kappa_0)\,(\mathbf{d}\cdot\mathrm{x})\,,$$
$$\mathbf{d} \equiv -(\boldsymbol{\nabla}\kappa)_0 - (\boldsymbol{\nabla}\lambda)_0\,,$$

Total magnification of two images of a point source, in the limit of being very close to a smooth caustic:

$$\mu_t(t) = \frac{1}{2|1-\kappa_0|}\left(\frac{2\,D_S}{d\,|\sin\alpha|\,v_t}\right)^{1/2}\frac{1}{|t-t_0|^{1/2}}$$
$$= 3.83\times 10^6\left(\frac{0.17}{|1-\kappa_0|}\right)\left(\frac{D_S}{1.7\,\mathrm{Gpc}}\right)^{1/2}\left(\frac{5\,\mathrm{arcmin}^{-1}}{d\,|\sin\alpha|}\right)^{1/2}\left(\frac{1000\,\mathrm{km\,s^{-1}}}{v_t}\right)^{1/2}\left(\frac{1\,\mathrm{hr}}{|t-t_0|}\right)^{1/2},$$

Lightcurve of a star crossing a caustic (uniform disk with no limb darkening)

There is a precise prediction of the lightcurve shape, which can be improved with limb-darkening models. This can be altered because of small-scale caustic corrugation and diffraction.



JME 1991

Can we see individual stars at cosmological redshifts?

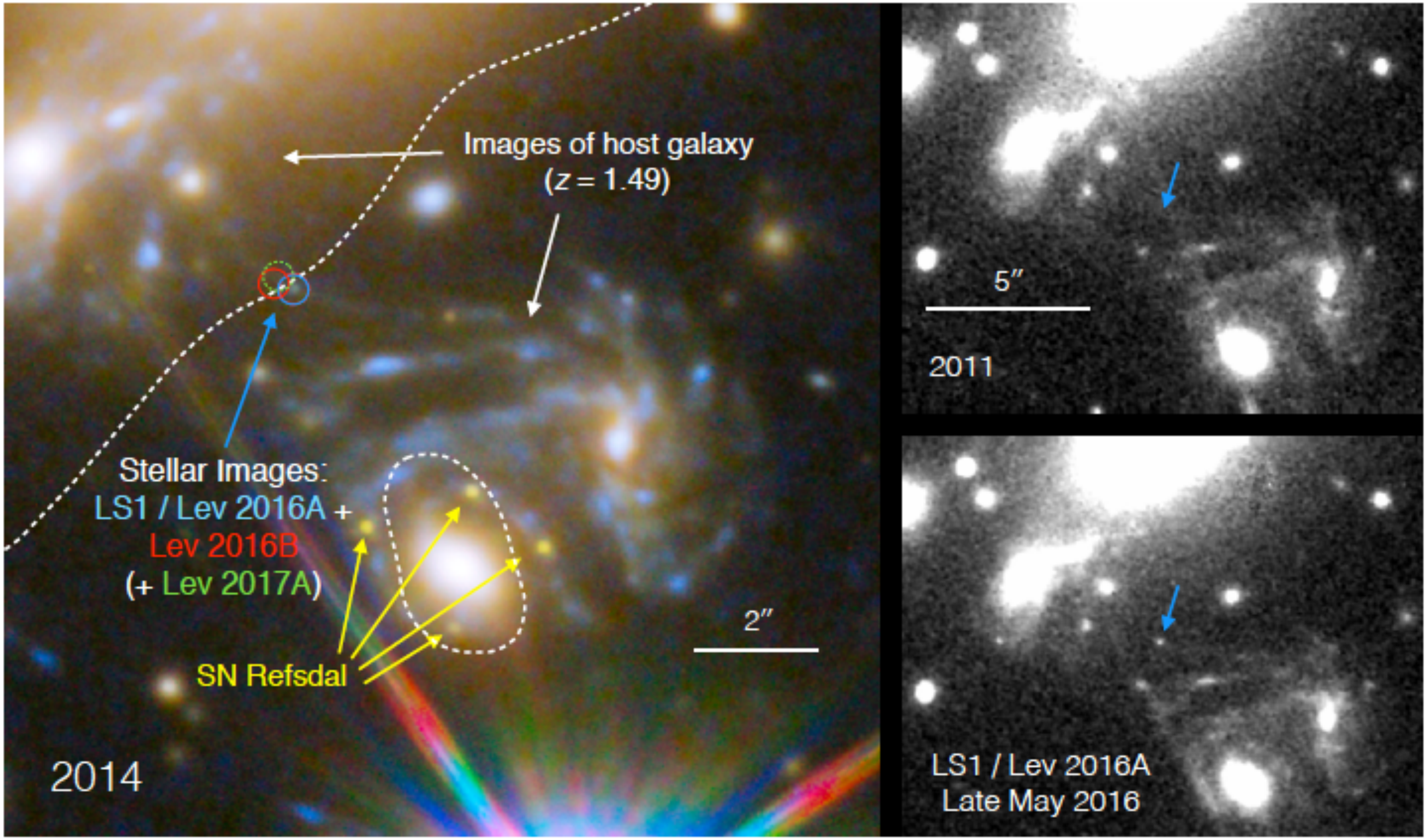
- Maximum lensing magnification achieved by a star when crossing a smooth

$$\mu_{\rm t,max} = \frac{1.4}{|1-\kappa_0|}\left(\frac{D_S}{2\,R\,d\,|\sin\alpha|}\right)^{1/2} \simeq 4\times10^6\left(\frac{0.17}{|1-\kappa_0|}\right)\left(\frac{D_S}{1.7\,{\rm Gpc}}\right)^{1/2}\left(\frac{5\,{\rm arcmin}^{-1}}{d\,|\sin\alpha|}\right)^{1/2}\left(\frac{10\,R_\odot}{R}\right)^{1/2}$$

d sinα is the eigenvalue gradient, R is the star radius.

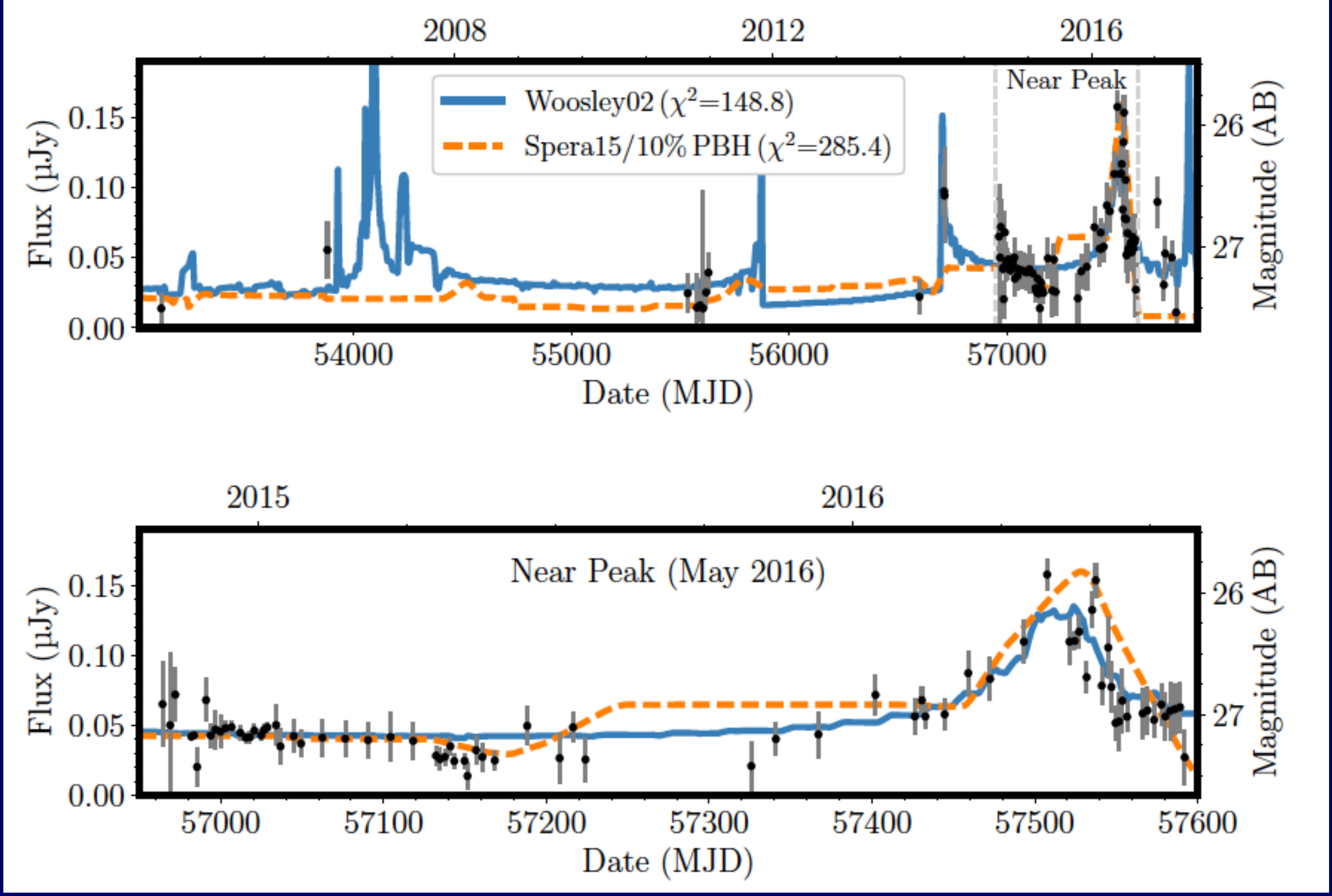
- With magnification of a million we can see stars of 500 $L_\odot$ at z=1 at magnitude 28. But this magnification is reached for only a few days, and the rate of crossings is ~ 1 per 30 years in a typical galaxy crossed by a caustic at ~ 1000 km/s.
- More luminous stars can be seen for much longer. A star of 50000 $L_\odot$ crosses only once every ~10000 years, but it is visible for ~ 100 years above magnitude 28. However, it is difficult to identify if it does not vary.
- Here is where microlensing can actually help: introducing variability to see the most luminous stars when crossing micro-caustics.

A caustic-crossing star has been detected with HST by Kelly et al. (2017) in MACS J1149



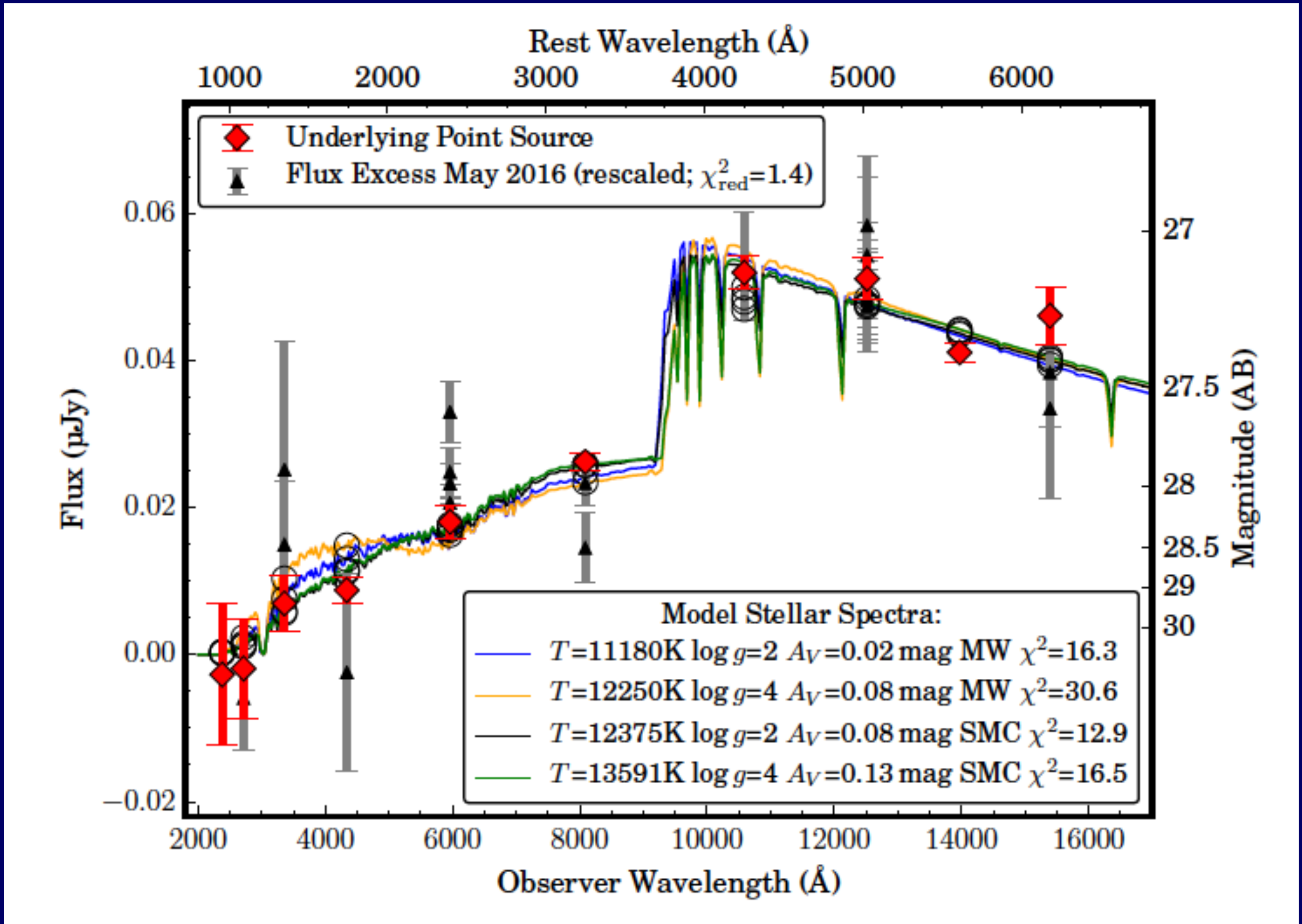
Kelly et al. 2017

Lightcurve of magnified star



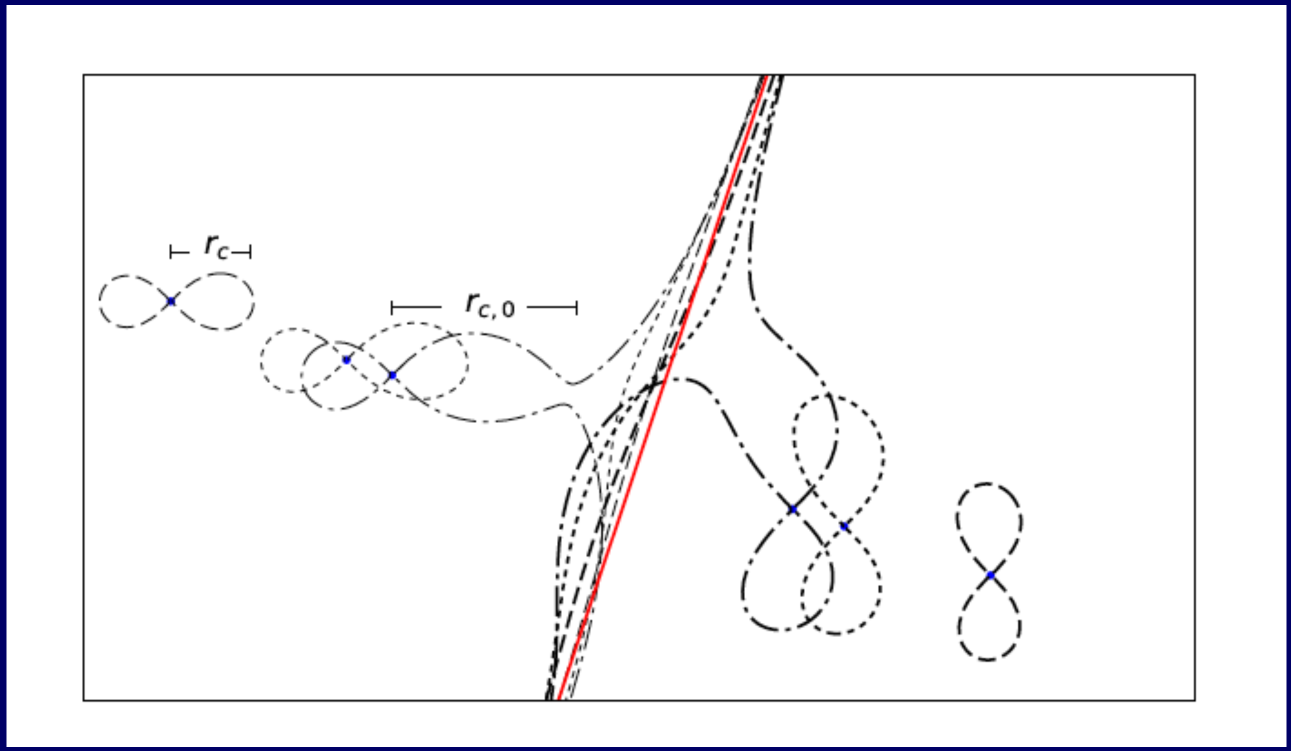
Kelly et al. 2017

Spectrum of the magnified star



Kelly et al. 2017: spectrum of the star in 2011-2015 and the excess flux in 2016 is consistent with a star at T ~ 12000 K.

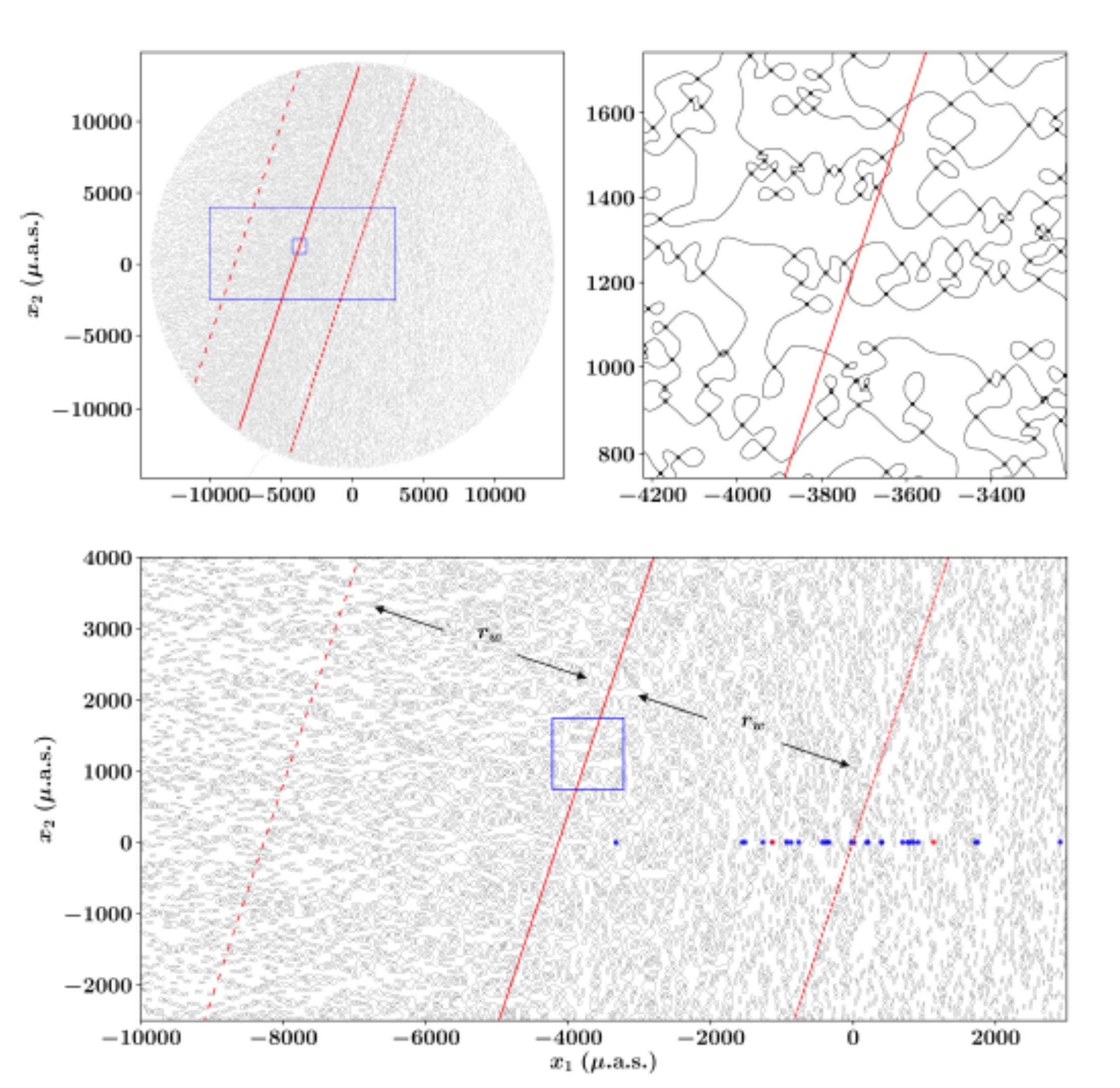
Effects of microlensing: single point mass (Venumadhav et al. 2017).



- Critical lines when a single point mass is added to the smooth mass distribution.
- There is a critical density of microlenses when critical lines start merging,

$$\kappa_c \simeq \left(\frac{\theta_\star}{r_{c,0}}\right)^2 = (\theta_\star\, d)^{2/3} \simeq 1.9 \times 10^{-5} \left(\frac{\theta_\star}{\mu\mathrm{as}}\right)^{2/3} (d \cdot 12\,\mathrm{arcsec})^{2/3} \ll 1.$$

- We expect to have microlenses at least owing to intracluster light, which inevitably forms from tidal disruption of galaxies moving in the cluster potential.
- The region of corrugated micro-critical lines has a width proportional to the convergence of microlenses. κ_*. The microlensing variations probe very sensitively the granularity of dark matter.
- Width of critical line network $\sim \kappa_*$
- Width of caustic network $\sim \kappa_*^2$
- Width of highest micro-caustic density $\sim \kappa_*^{1/2}$

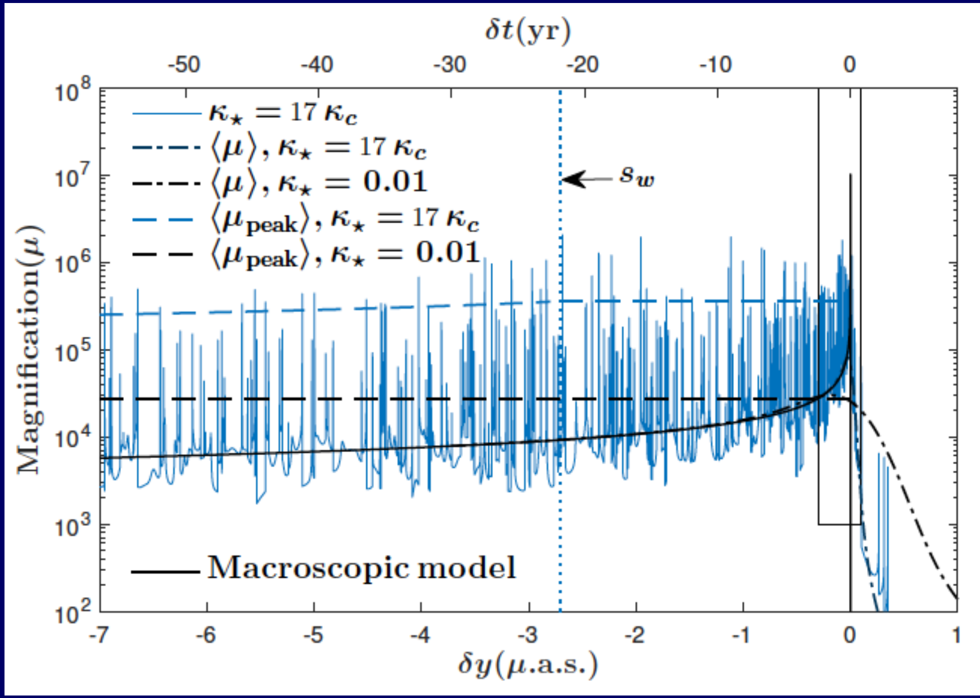


Venumadhav, Liang and JME 2017

Effects of microlensing by intracluster stars: lower magnifications, but many more events.

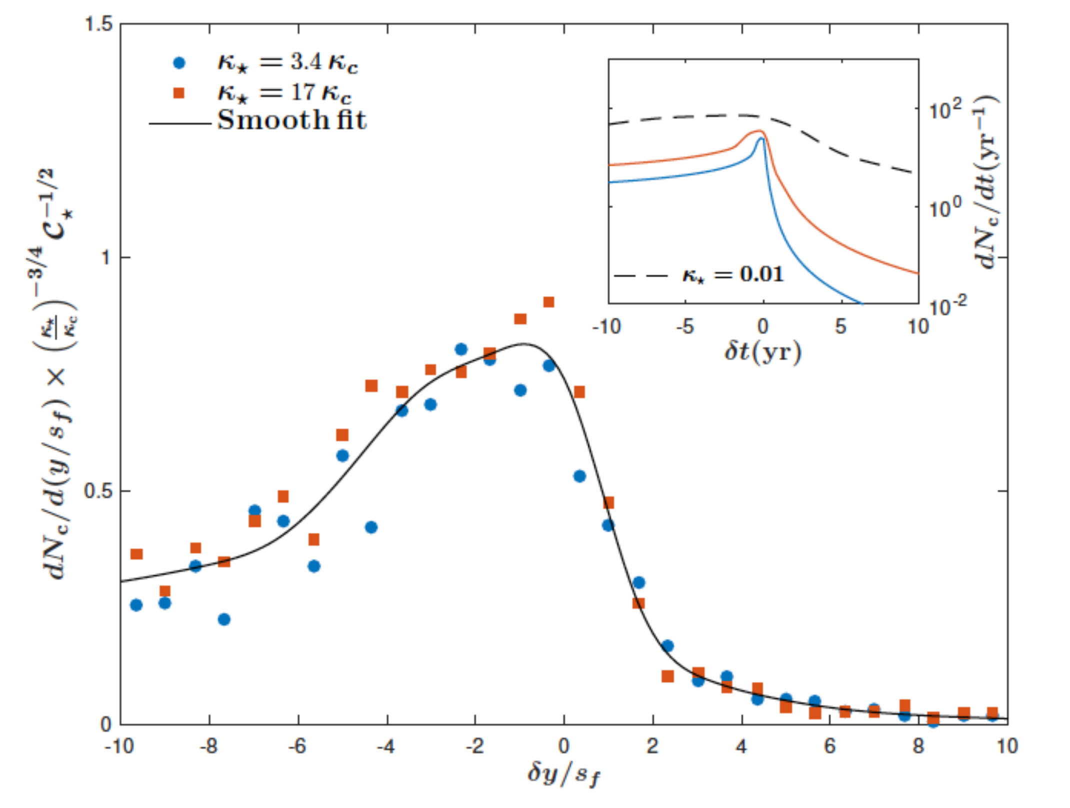
$$\mu_{\rm peak} \simeq \frac{1}{|1-\kappa_0|}\left(\frac{D_S}{Rd}\right)^{1/2}\left(\frac{\kappa_c}{\kappa_\star}\right)^{3/4} \simeq \frac{1}{|1-\kappa_0|}\left(\frac{D_S\theta_\star}{R}\right)^{1/2}(\kappa_\star)^{-3/4} .$$

- A star with L ~ 50000 $L_\odot$ at z=1, magnification 10000, has magnitude 28, for ~ 100 years.
- But microlensing causes further variation on short timescales, reducing the maximum magnification but producing more frequent detectable variations, depending on the microlens surface density.



Venumadhav, Liang and JME 2017

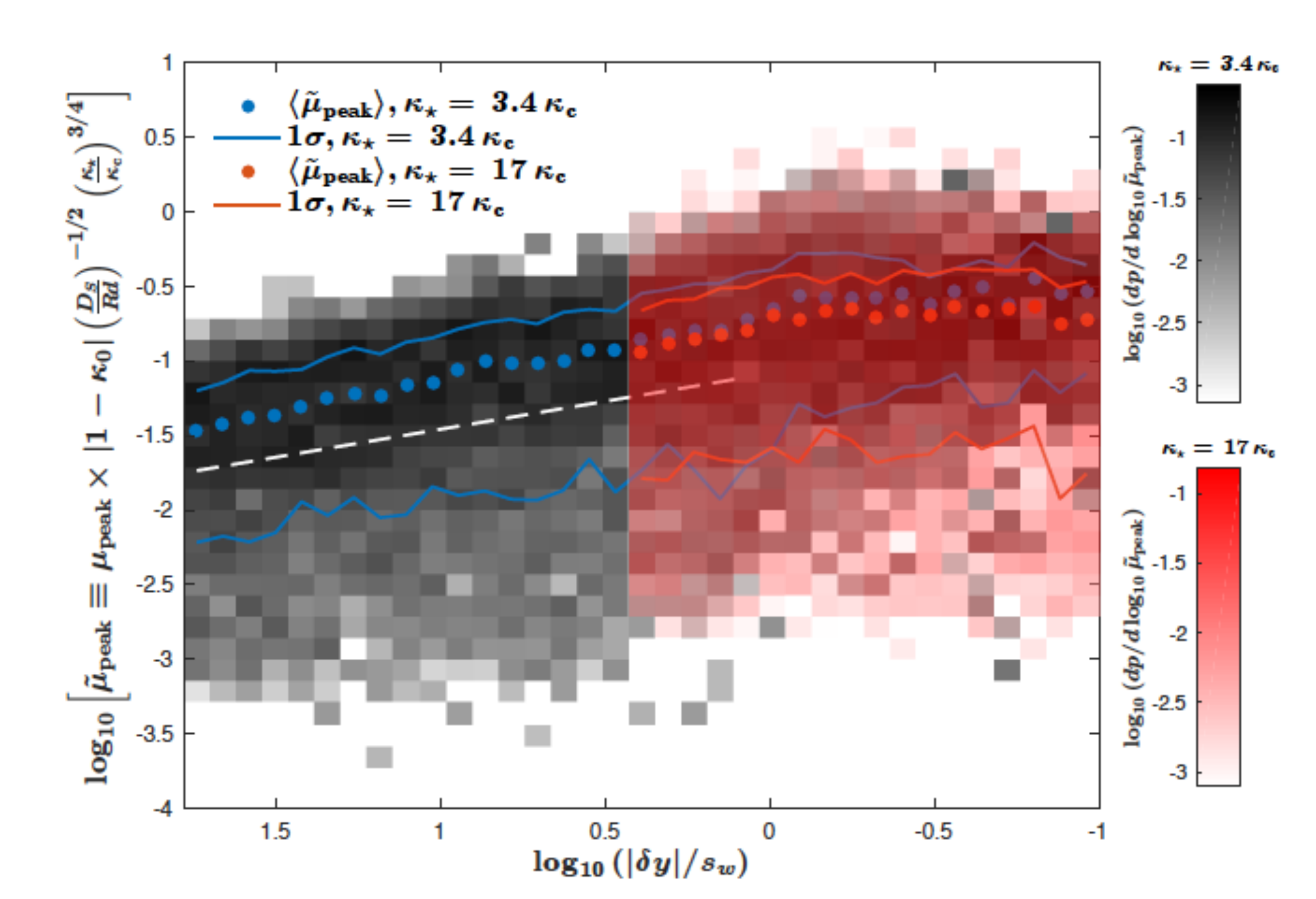
Density of caustic crossings



- The highest density of caustic crossings has a width scaling as the square root of the microlens surface density. The region of highest peak magnifications in the source plane scales as the square of the microlens surface density. For $\kappa_* >> \kappa_c$, most visible events are far from the region of highest micro-caustic density.

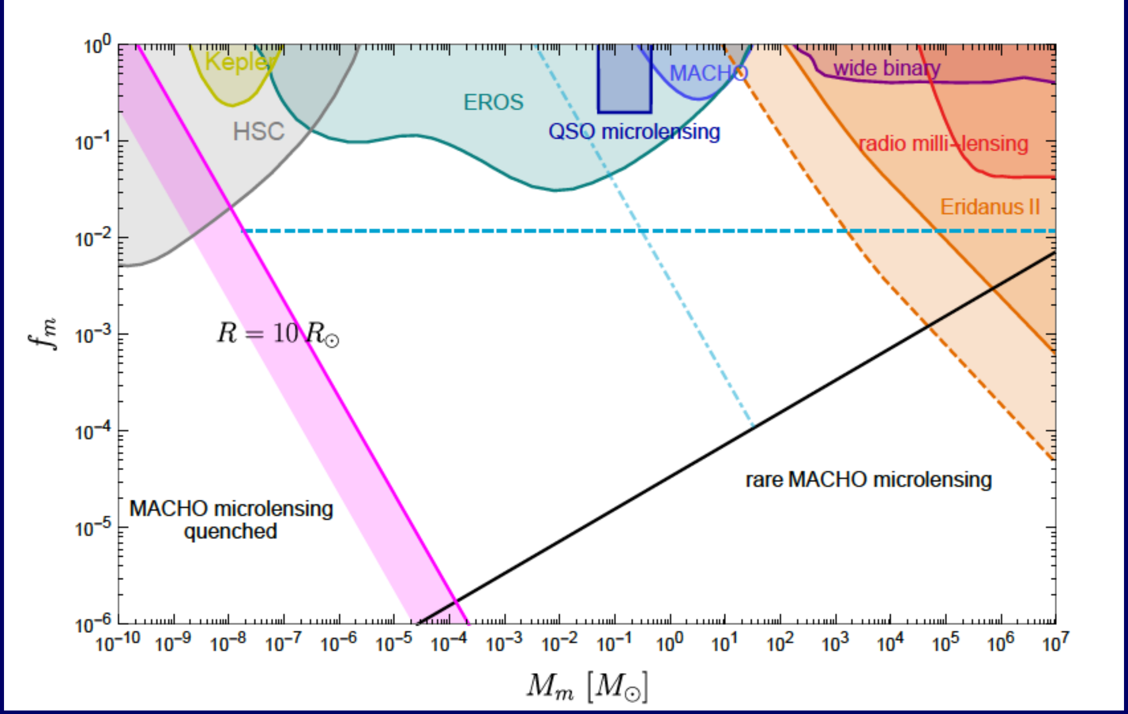
Peak magnification probability distribution

The average peak magnification is flat within the width s_w , but falls as $|\delta y|^{-3/8}$ at larger separations.



Because $\mu_{peak} \sim M_*^{1/4}\, \kappa_*^{-3/4}$, if there is too much surface density in microlenses the high magnifications are disfavored.

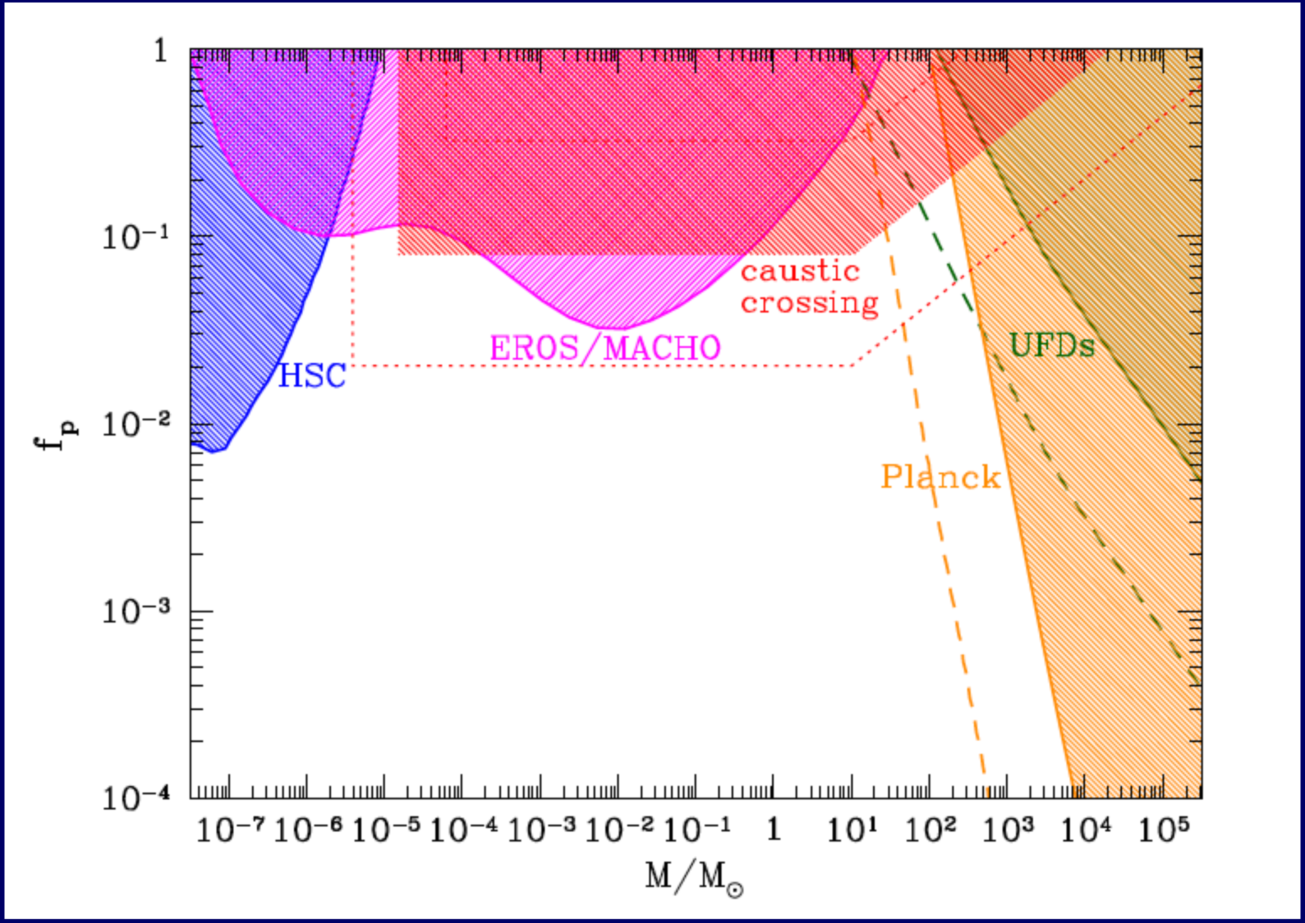
Constraints on dark matter: primordial black holes.



- A high fraction of primordial black holes compared to intracluster stars widens the microcaustic network too much and lowers the peak magnifications.
- Black holes can be detected down to the smallest scales in which micr-caustics are resolved by stellar radii. They need to be distinguished from intracluster stars.
- Scalar wave dark matter could also be detected from the wavy pattern it would cause on the critical line network, but again it must be distinguished from dark matter subhalos.

Oguri et al. 2018: limits on abundance of primordial black holes.

- They use an observed caustic crossing duration and star temperature to derive star radius and luminosity, and maximum magnification.
- However, the proximity of the observed event to the model critical line, and the expected stellar luminosity functions, are also important constraints.



Conclusions

- Individual stars at $z \sim 1$ highly magnified in cluster caustics can be detected with our most sensitive telescopes (HST and JWST, and large ground-based telescopes). One of these stars has been detected in MACS J1149 by Kelly et al. (2017).
- A tiny surface density of point masses is enough to break the smooth cluster caustic into a corrugated network of micro-caustics. The photometric variations and distribution around the critical lines of the highly magnified star images are a powerful probe to any granularity in the dark matter and the intracluster stars acting as microlenses.
- As we are able to observe fainter point sources, the number of detectable lensed stars rises very rapidly. Observing in the near-infrared is also advantageous to detect many more luminous stars in typical star-forming galaxies at $z \sim 1$. The launch of JWST promises to bring much progress to use this new probe of the nature of the dark matter.