Caustic crossings as a dark matter probe

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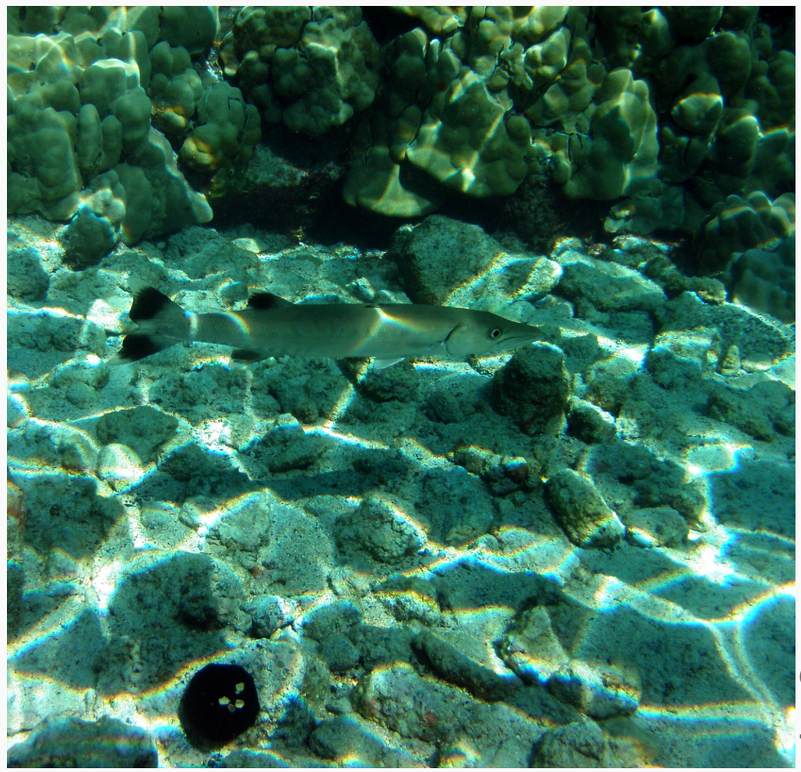
2022/3/30 dark matter symposium@Kavli IPMU

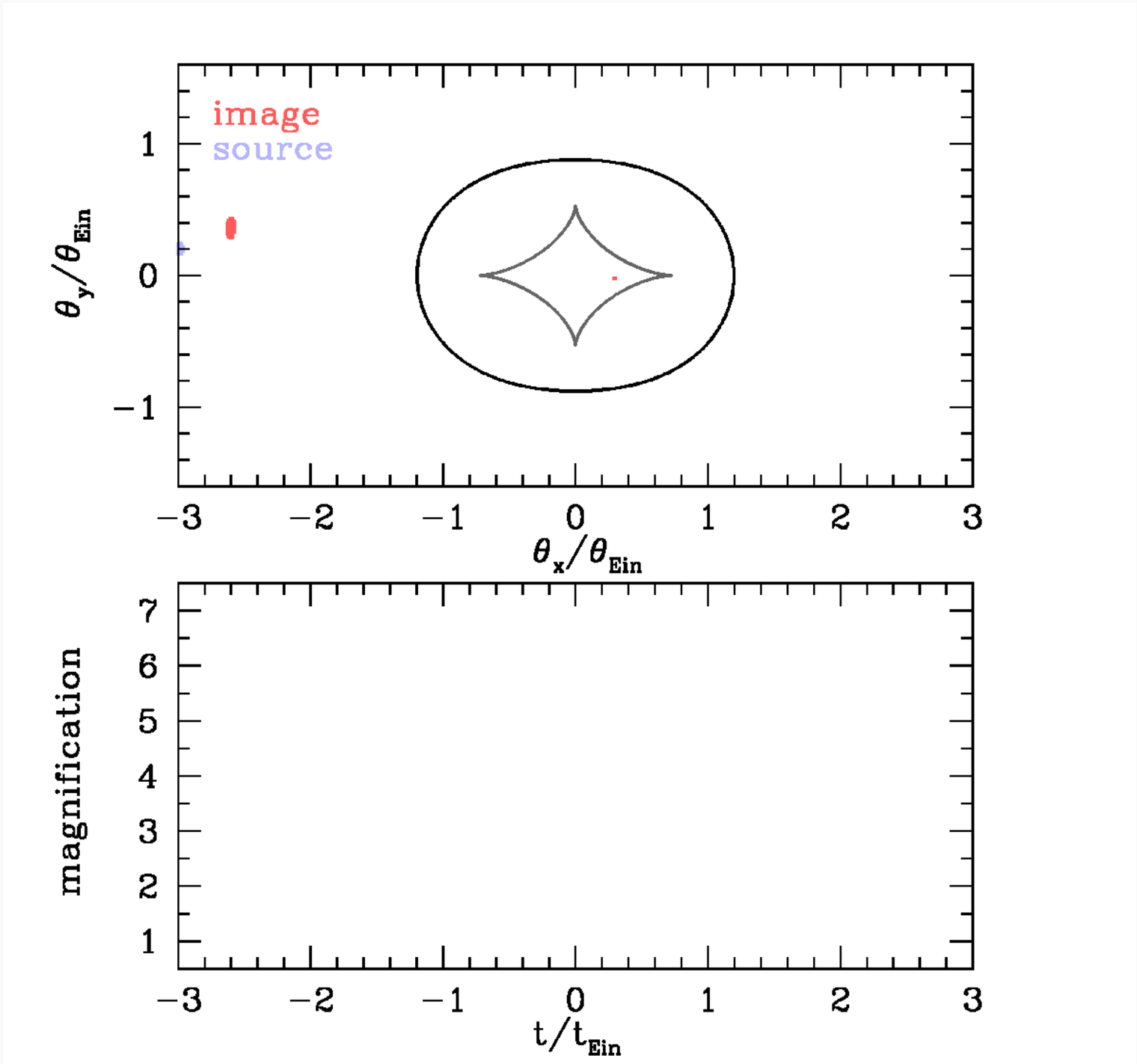
Caustic

- 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

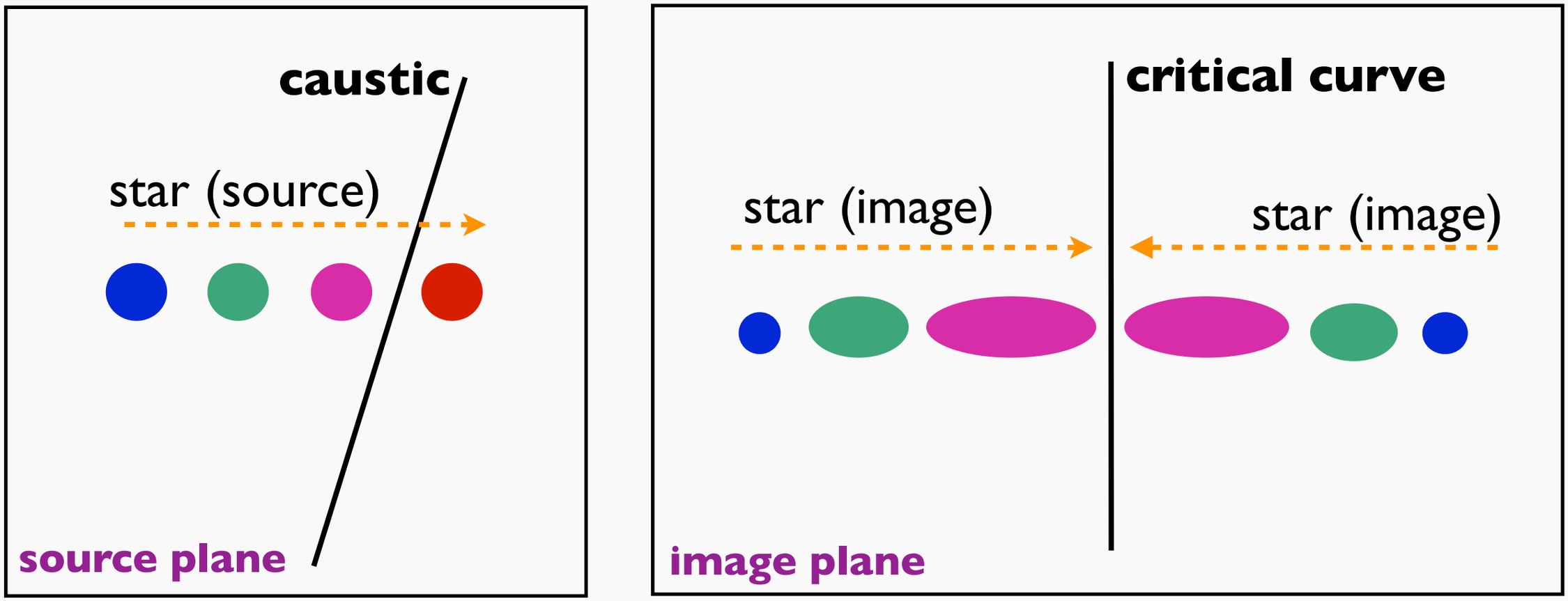


Brocken Inaglory

Caustic crossing

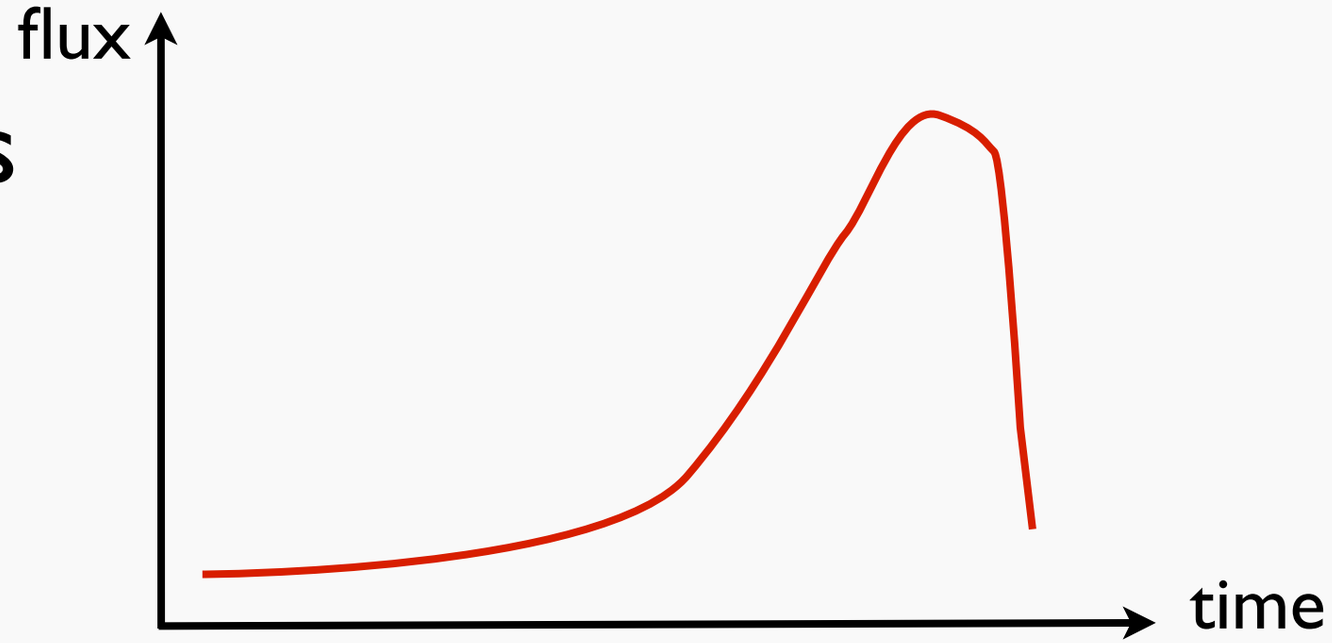


Caustic crossing

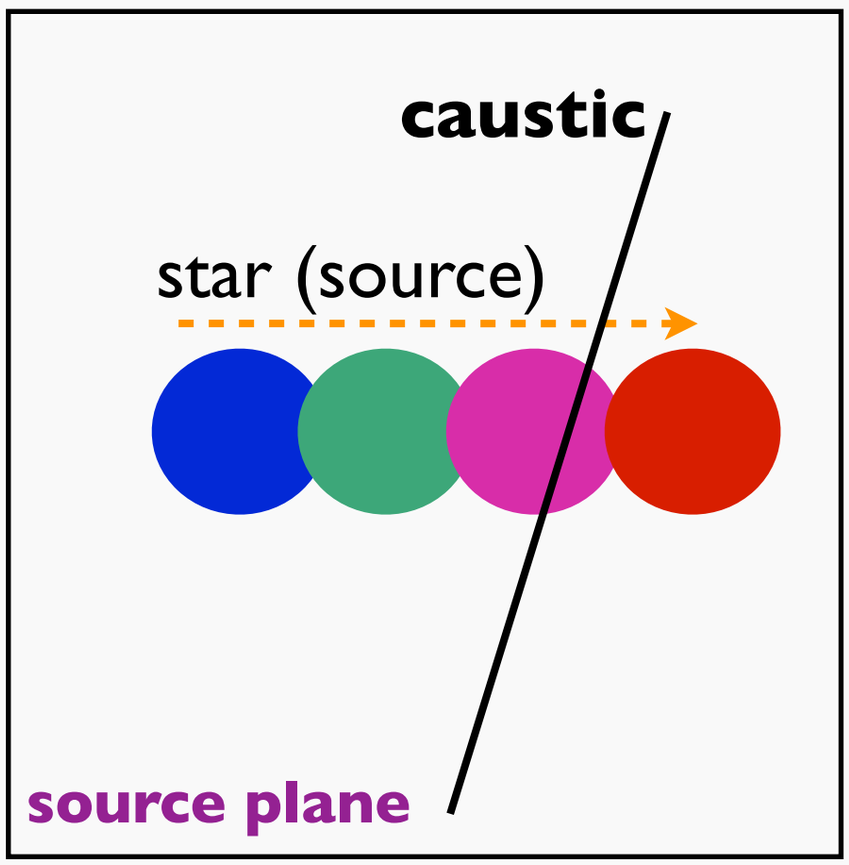


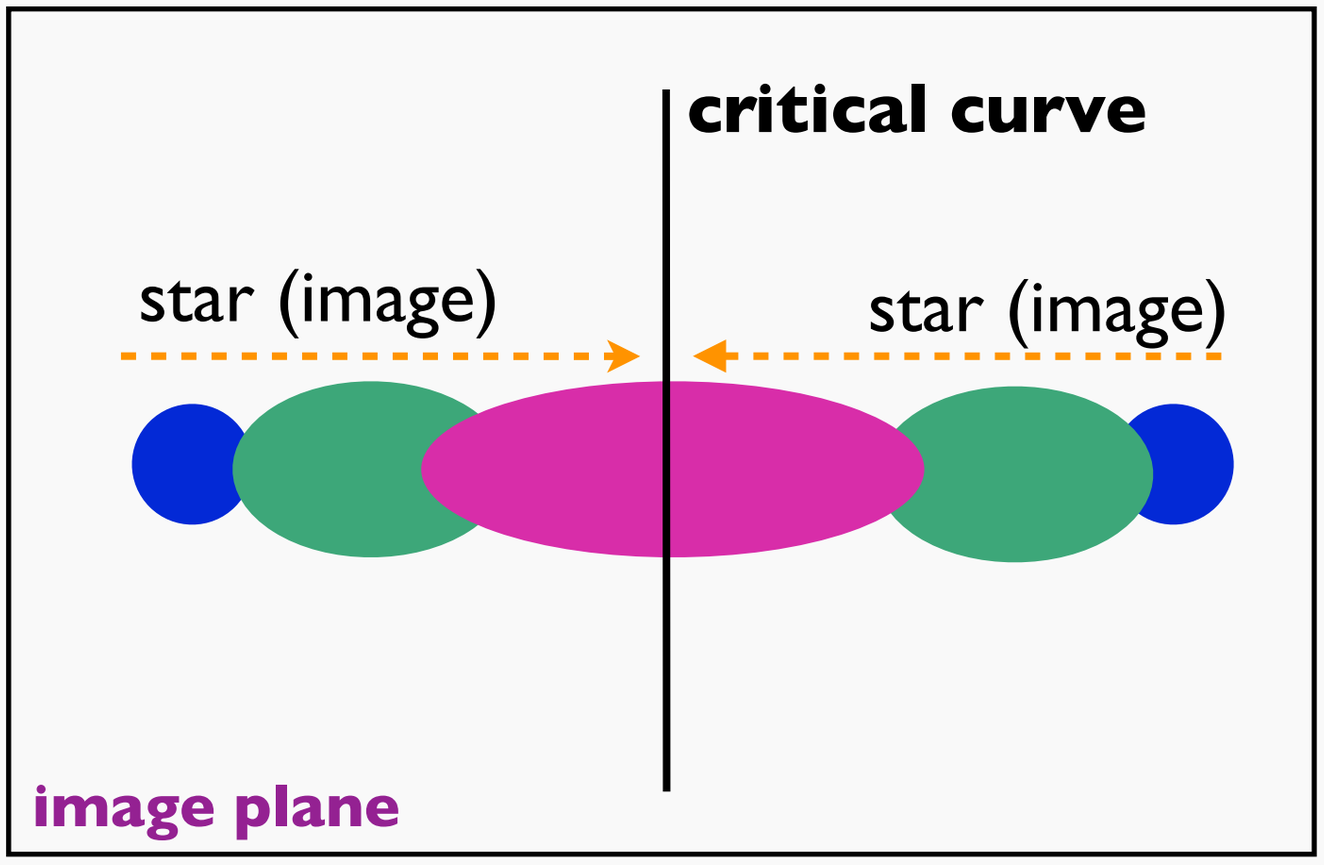
- two multiple images disappear

→ **asymmetric light curve**

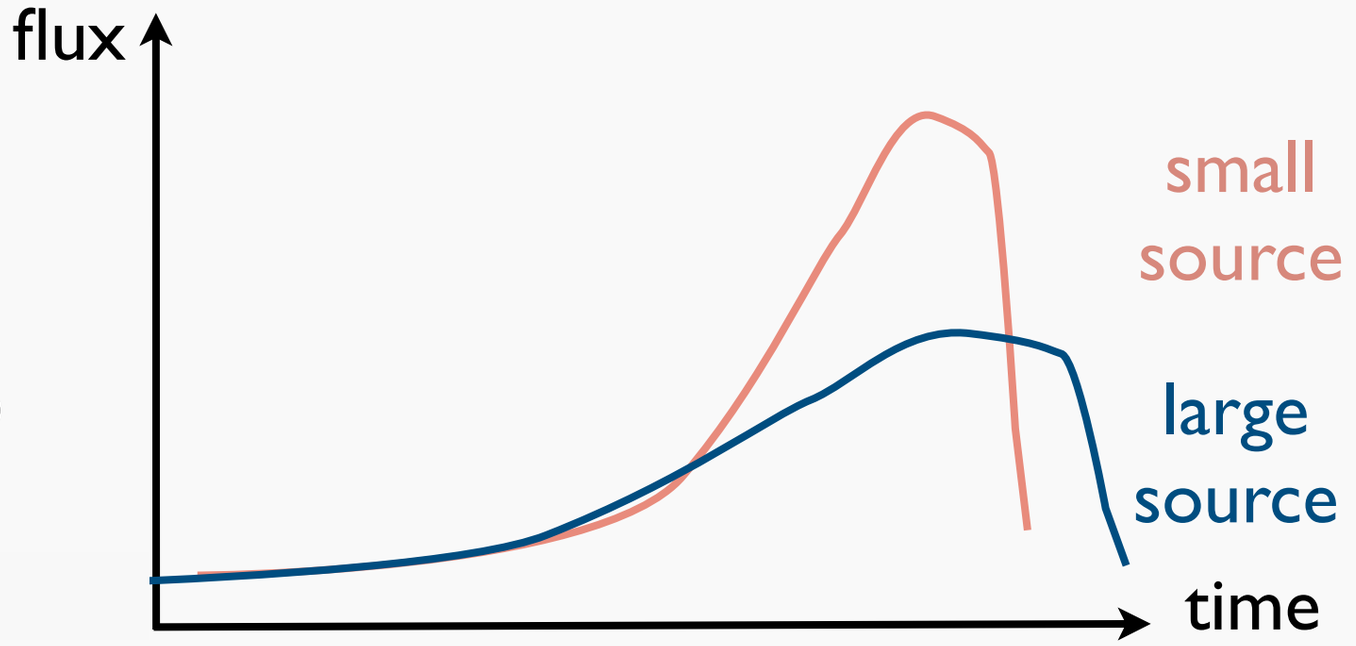


Caustic crossing





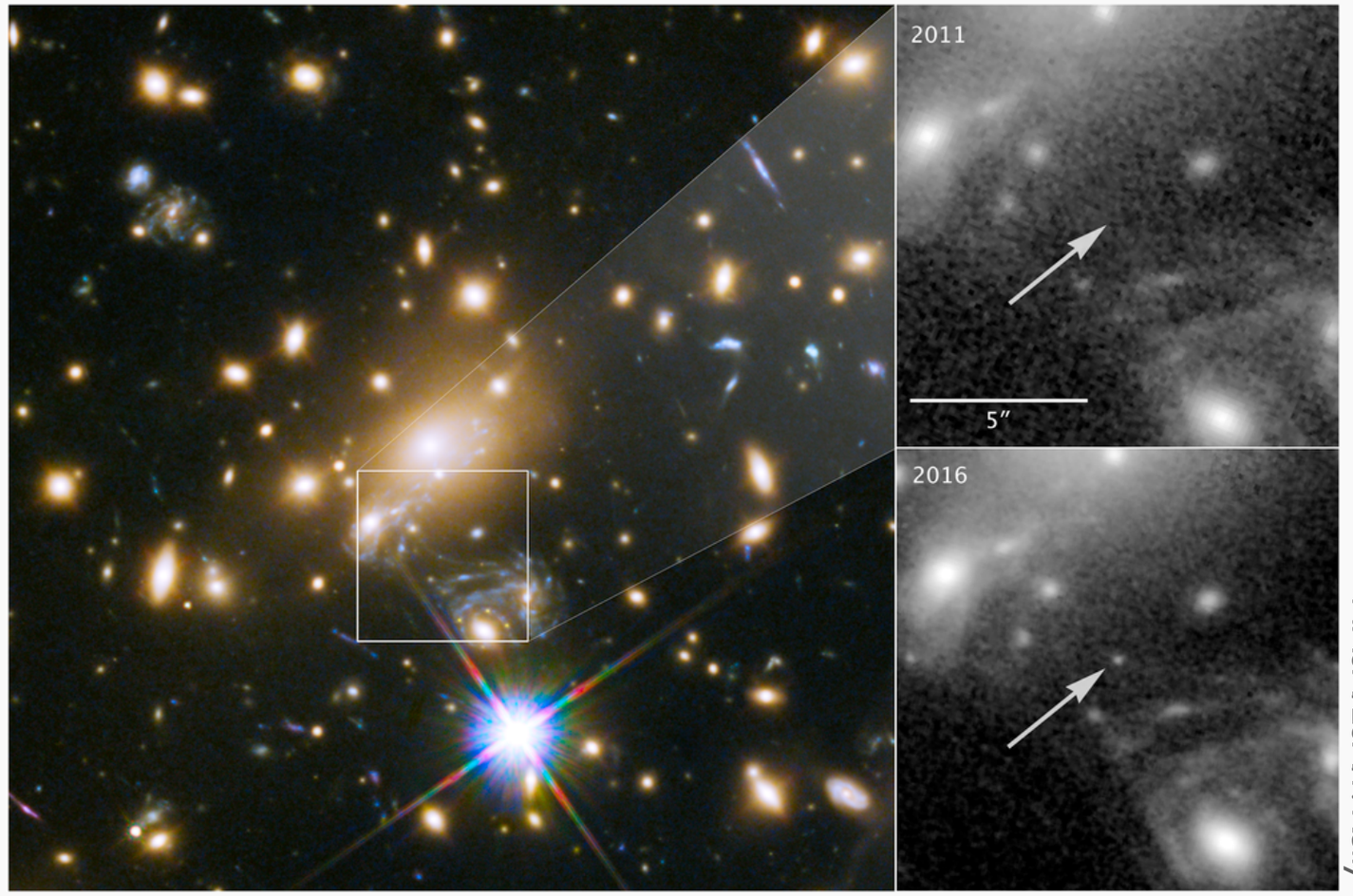
- maximum mag. and width of the light curve is sensitive to source size

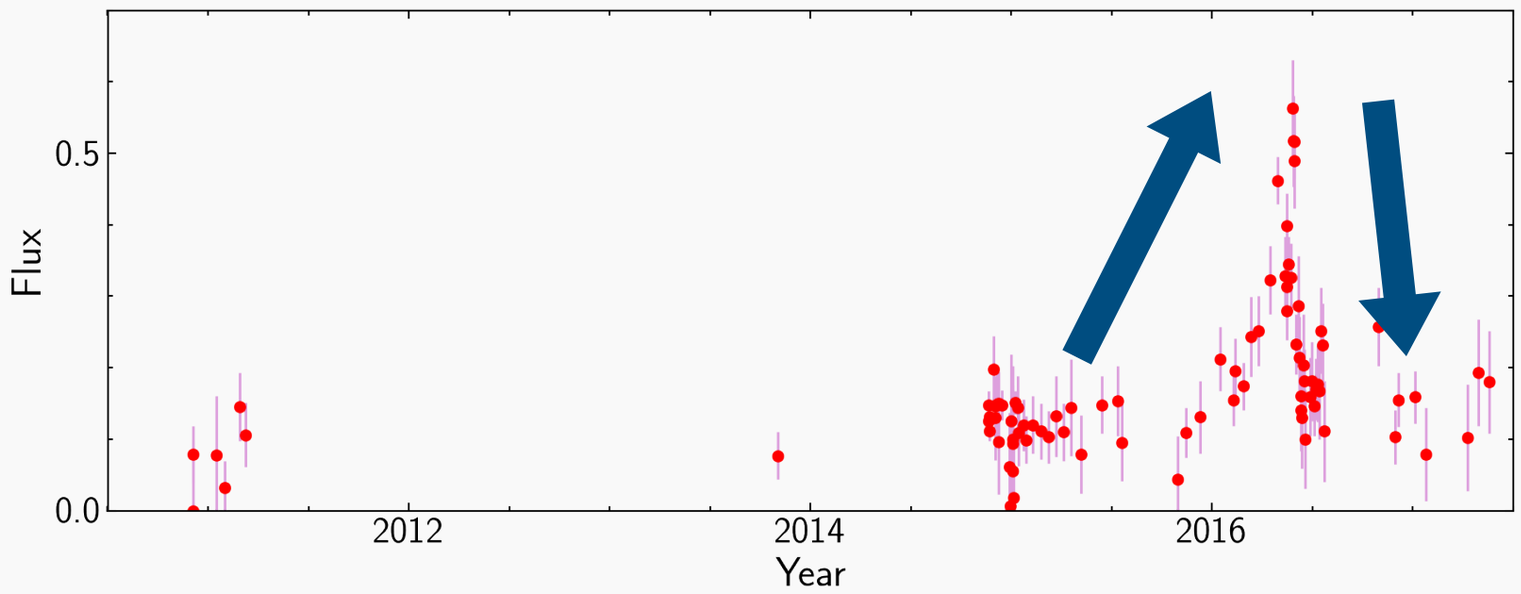


Kelly+ (incl. MO) Nat. Ast. **2**(2018)334

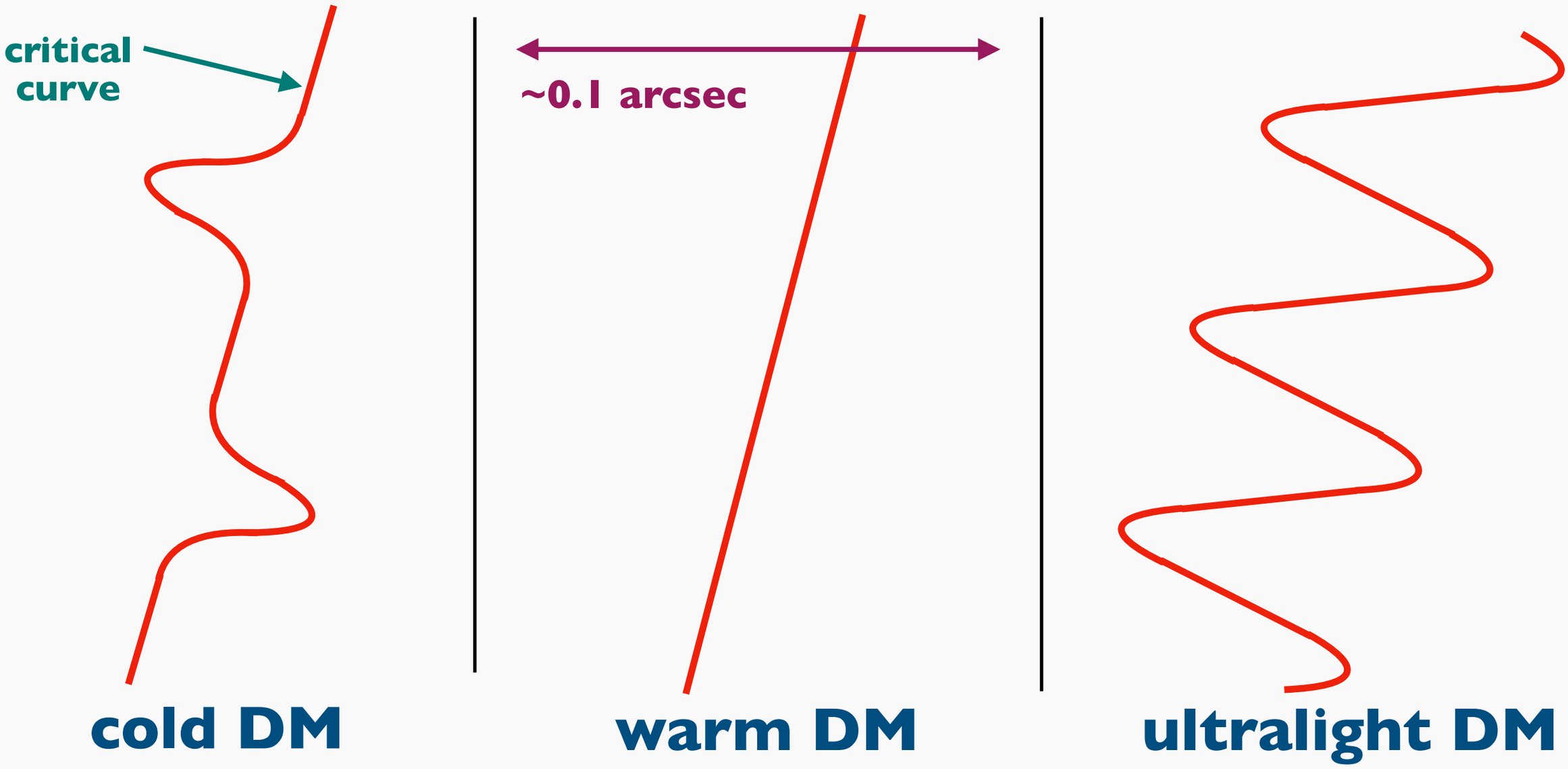
Farthest star ever seen

- single star at redshift 1.5
- caustic crossing led to maximum magnification > 2000





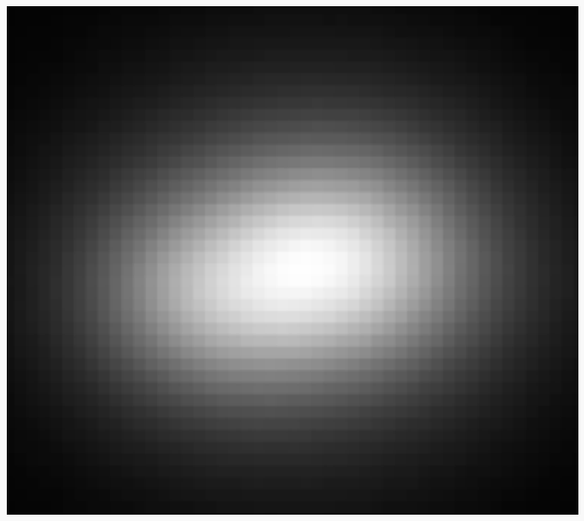
Why is it important for DM?



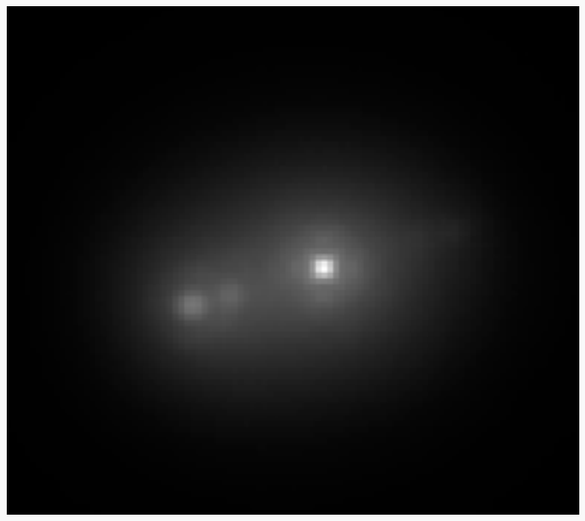
- observing many caustic crossing events tells us the small-scale structure of critical curve!

Connection with CMOS

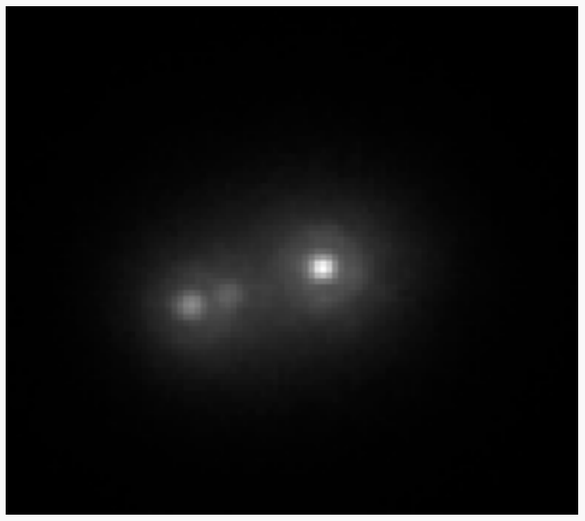
- lucky imaging with CMOS can significantly improve the sensitivity for point sources
- search/monitor caustic crossings without relying on space telescopes



all images combined



50% best images combined



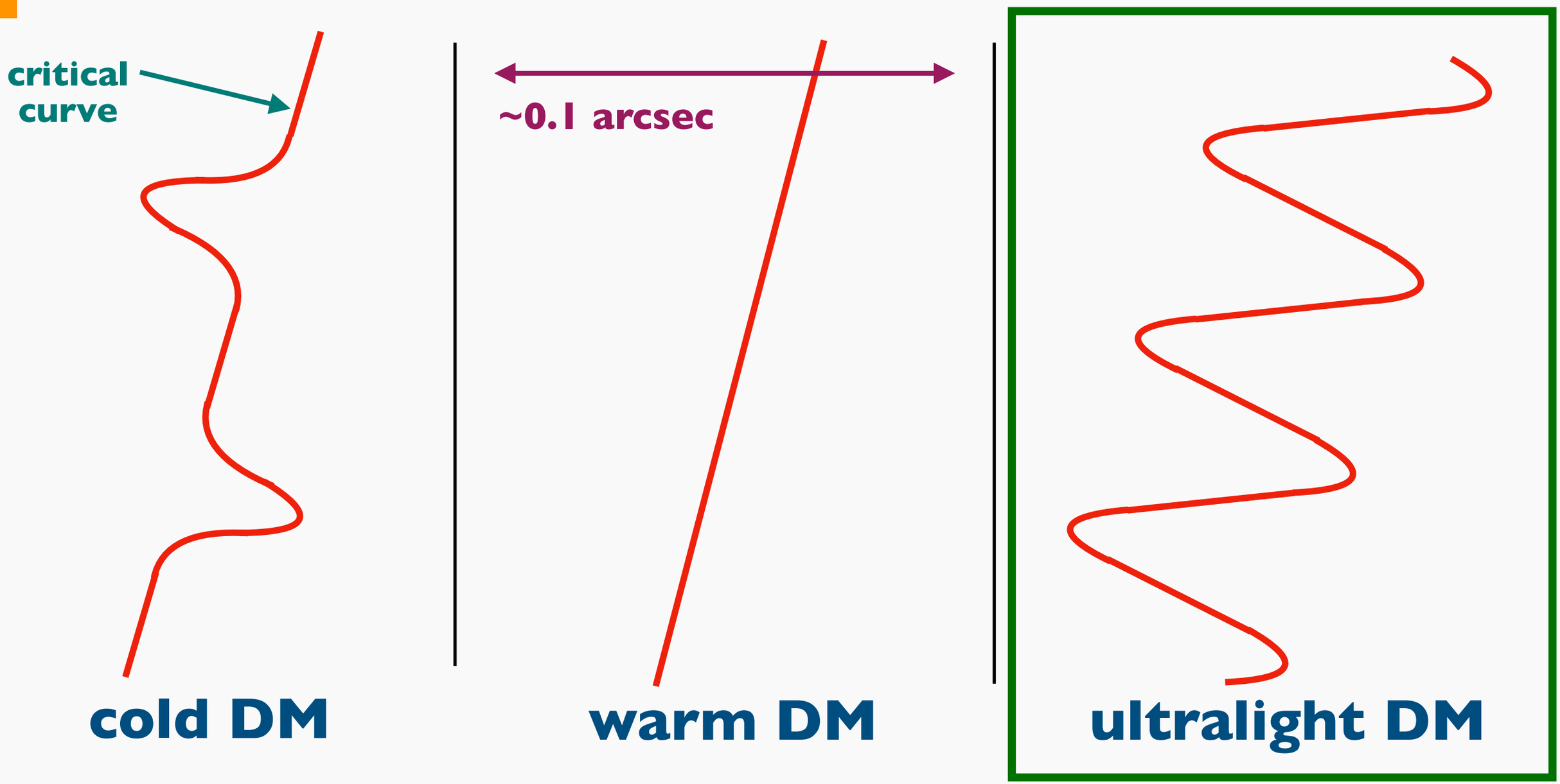
1% best images combined

Wikipedia

Recent progress

- theory
  – power spectrum in fuzzy dark matter
  (– short review article on caustic crossings)
- observations
  – record breaking discovery
  – ongoing search with HST

Why is it important for DM?



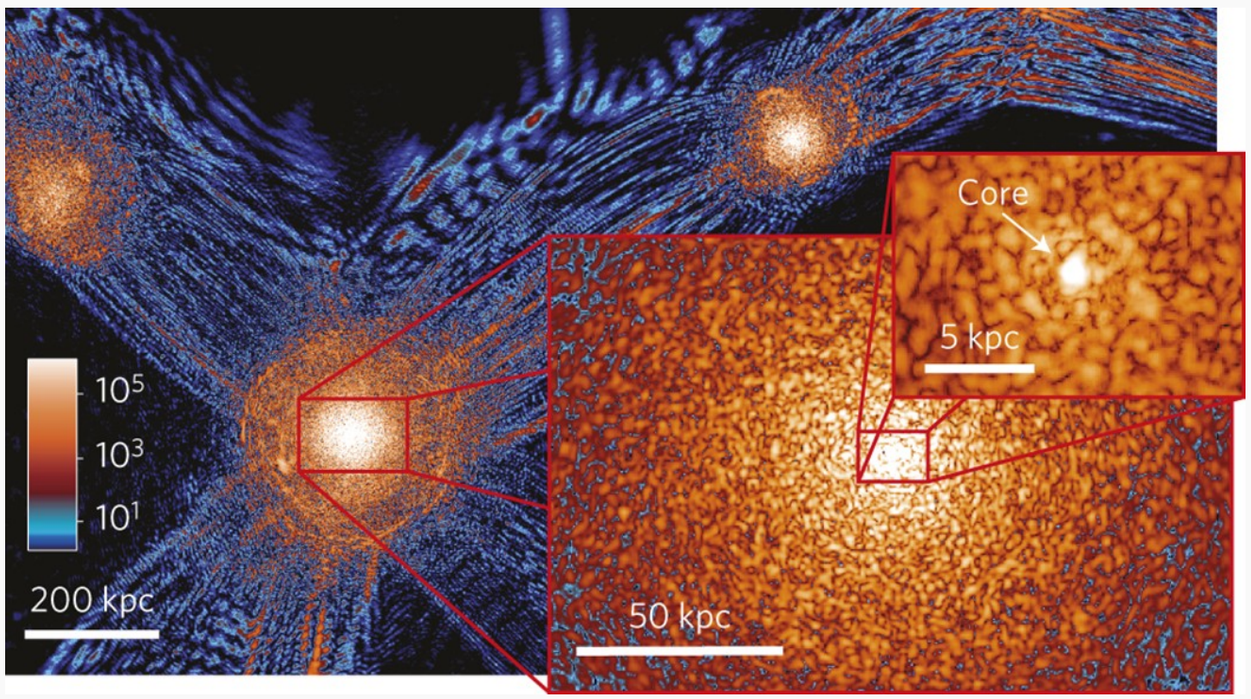
- observing many caustic crossing events tells us the small-scale structure of critical curve!

Fuzzy (ultralight) dark matter

- 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 ~ $\lambda_{\rm dB}$

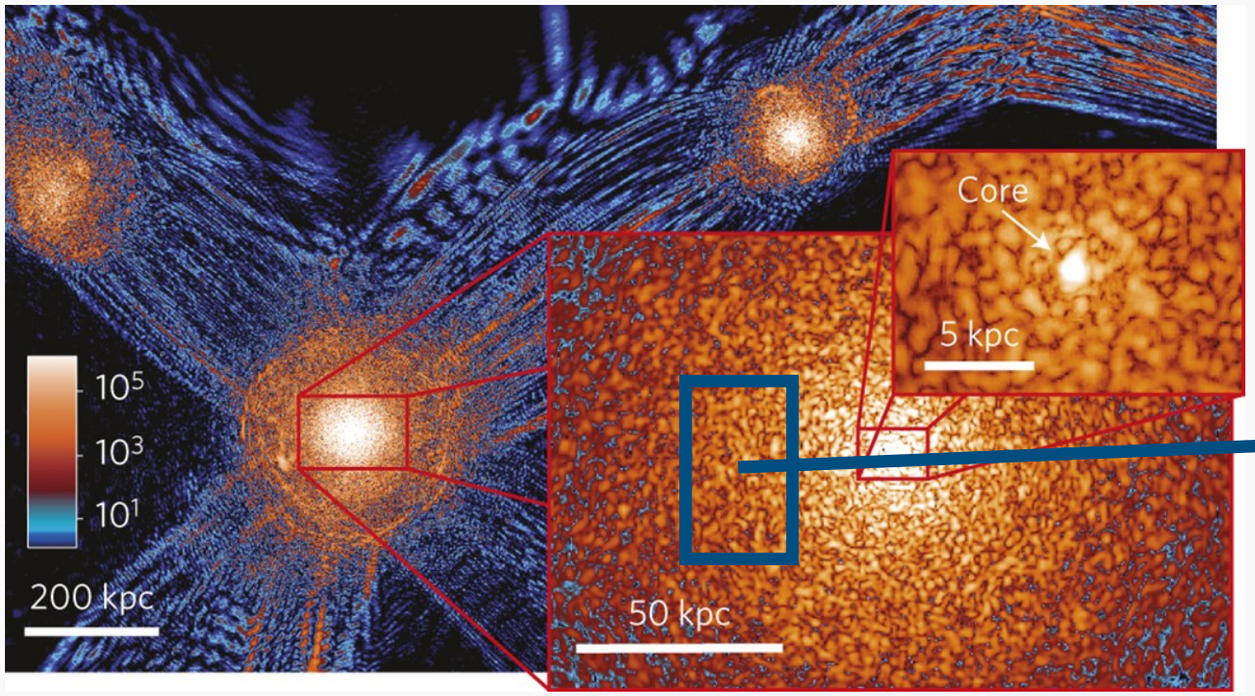


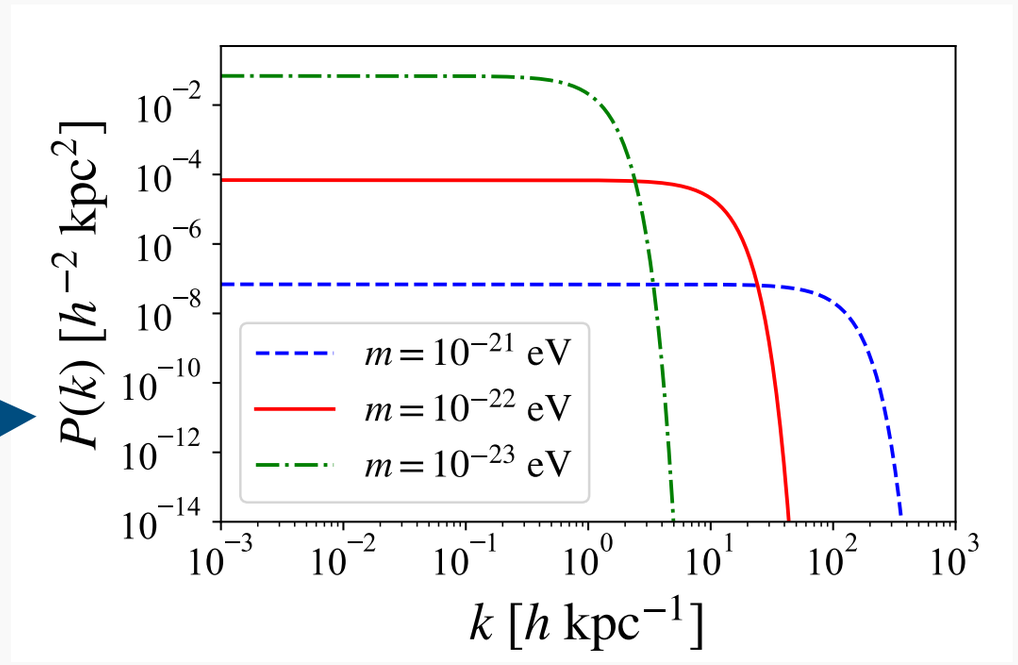
simulation (Schive+2014)

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

Analytic model of power spectrum

simulation (Schive+2014)





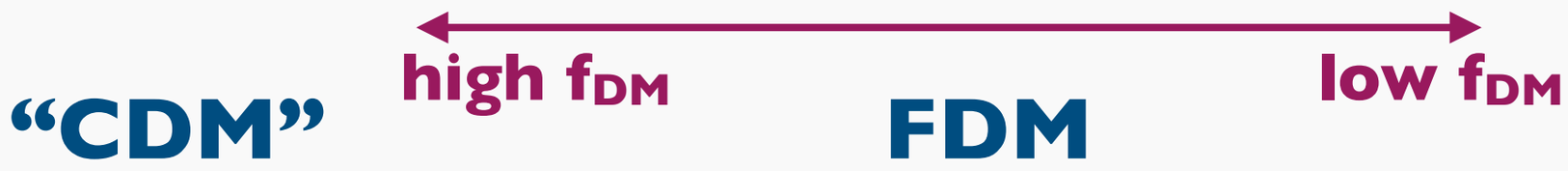
- derive P(k) assuming superposition of Gaussian clumps

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

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

Amruth, Broadhurst, Lim, MO+ submitted

Modulation of critical curve

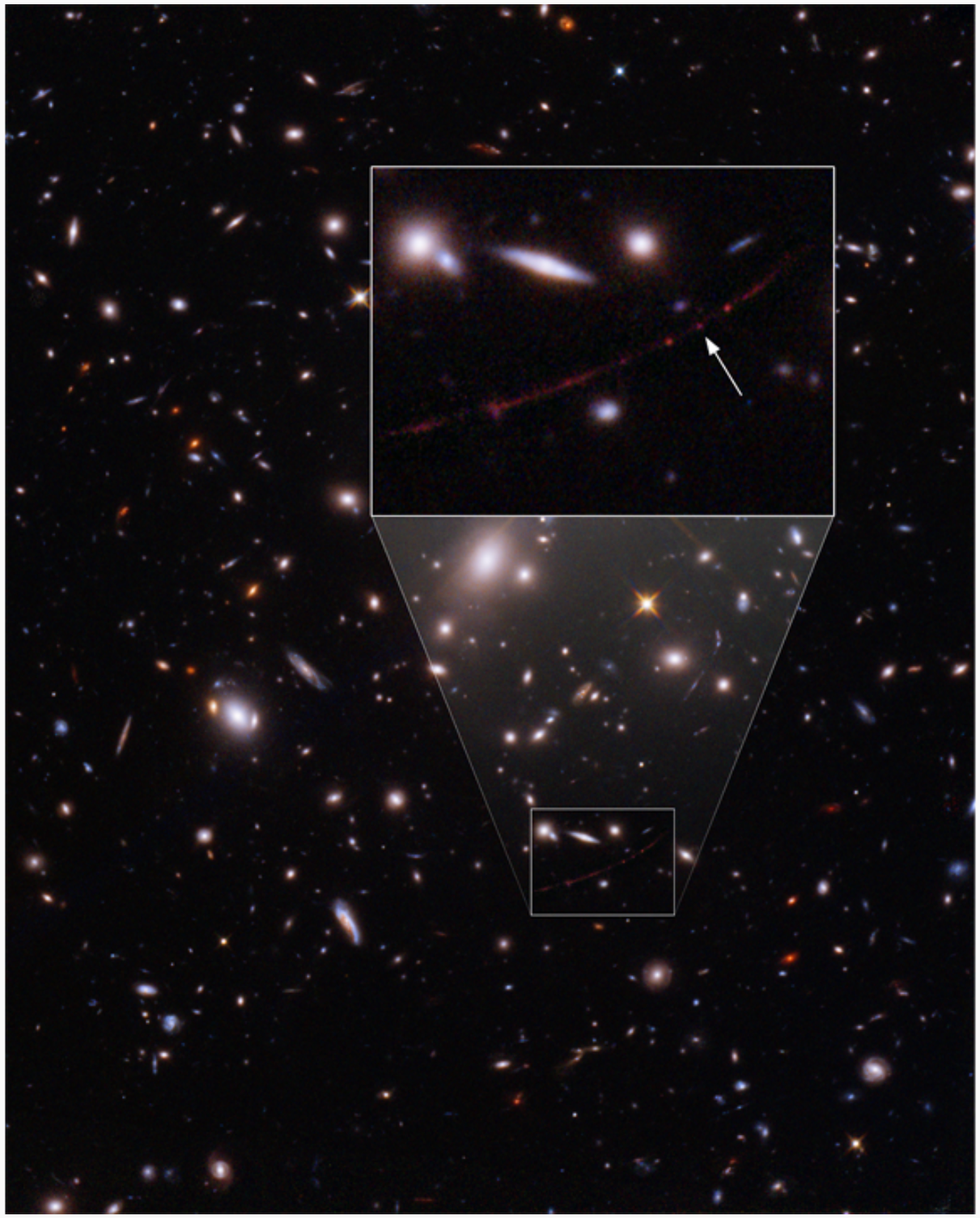


Observations

- Icarus Kelly+ (incl. MO) Nat. Ast. **2**(2018)334
- Spock Rodney,+ (incl. MO) Nat. Ast. **2**(2018)324
- Warhol Chen, Kelly, Diego, MO+ ApJ **881**(2019)8
- Godzilla Diego+ arXiv:2203.08158
- Earendel
- more events from *flashlights*

Welch+ (incl. MO) to appear in Nature

Discovery of Earendel



NASA/ESA/B. Welch

- single star at redshift of 6.2 (record breaking)
- follow-up with JWST planned

Flashlights

- large HST program to find many caustic crossings
[PI: P. Kelly]

Flashlights: Many Extremely Magnified Individual Stars as Probes of Dark Matter and Stellar Populations to Redshift z~2

Scientific Category: Cosmology
Scientific Keywords: Clusters Of Galaxies, Gravitational Lensing, Intracluster Medium, Reionization
Alternate Category: Stellar Populations
Instruments: ACS, WFC3
Exclusive Access Period: 0 months

Proposal Size: Large JWST Initiative Yes UV Initiative: Yes

Fundamental Physics: Yes

Orbit Request	Prime	Parallel
Cycle 27	96	96
Cycle 28	96	96
Total	192	192

Many events being discovered…

[preliminary!]

Summary

- caustic crossings in clusters offer a unique probe of small-scale dark matter distribution
- one of important targets for CMOS observations (lucky imaging)
- an analytic model of small-scale power spectrum in fuzzy dark matter is presented
- caustic crossing single start at z=6.2 discovered, and more discoveries to come