Exciting transients at centers of clusters of galaxies

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Center for Frontier Science

2025/4/25 DM symposium@online

Summary of B03 papers

- 59 papers over 5 years
  - including 4 Nature, 1 Science, 3 Nature Astronomy
- book
- several press releases

support of 学術変革 is much appreciated!

MACS J1149+2223

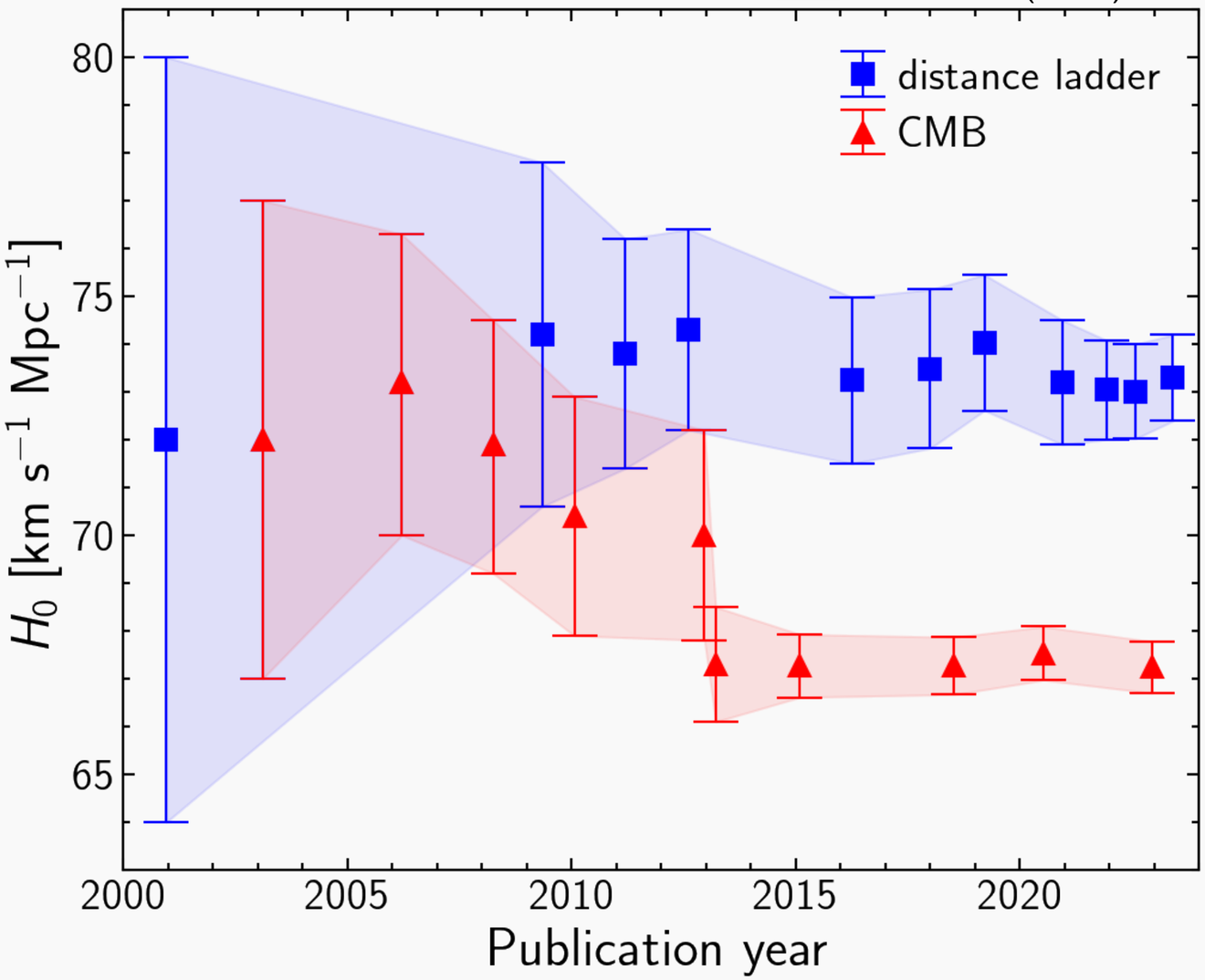
NASA/ESA/S. Rodeny et al.

caustic crossing
(highly magnified individual star)

gravitationally lensed supernova

Hubble tension

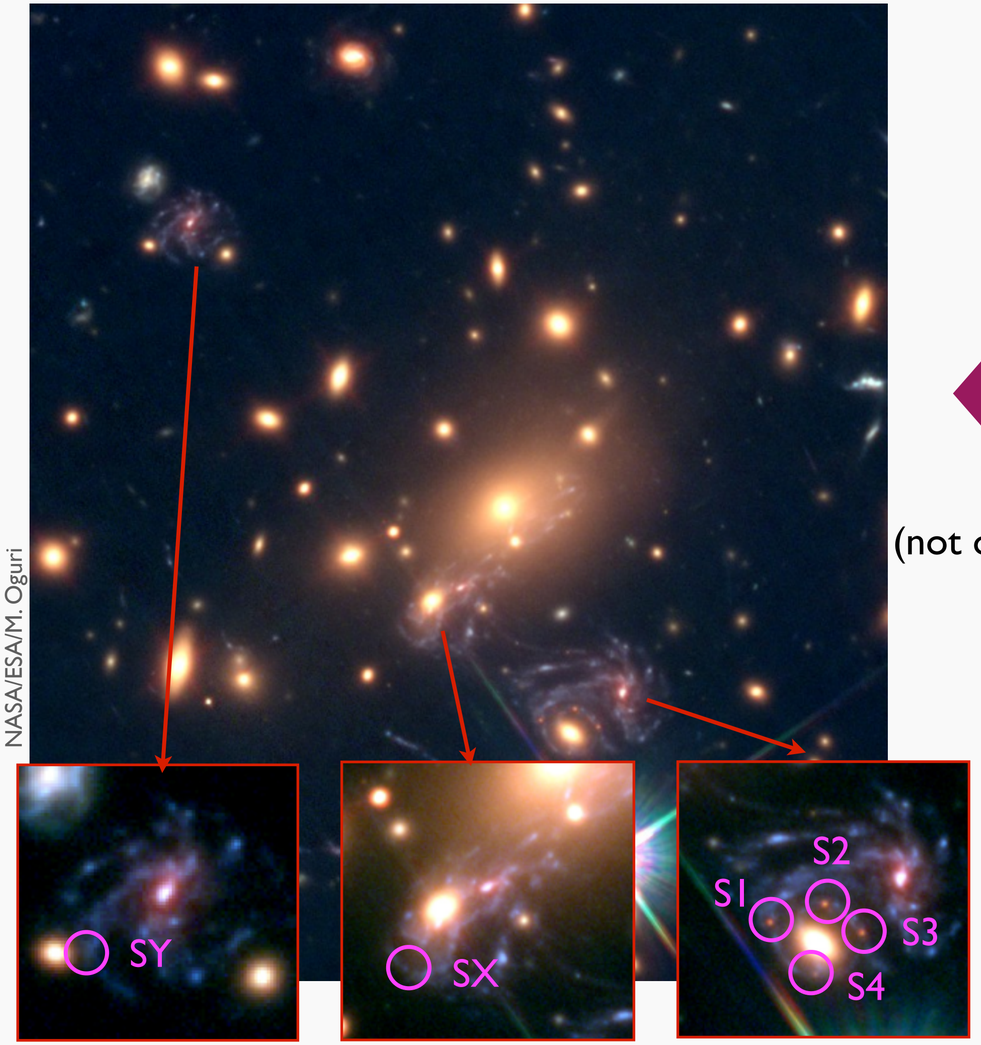
MO Butsuri **78**(2023)630

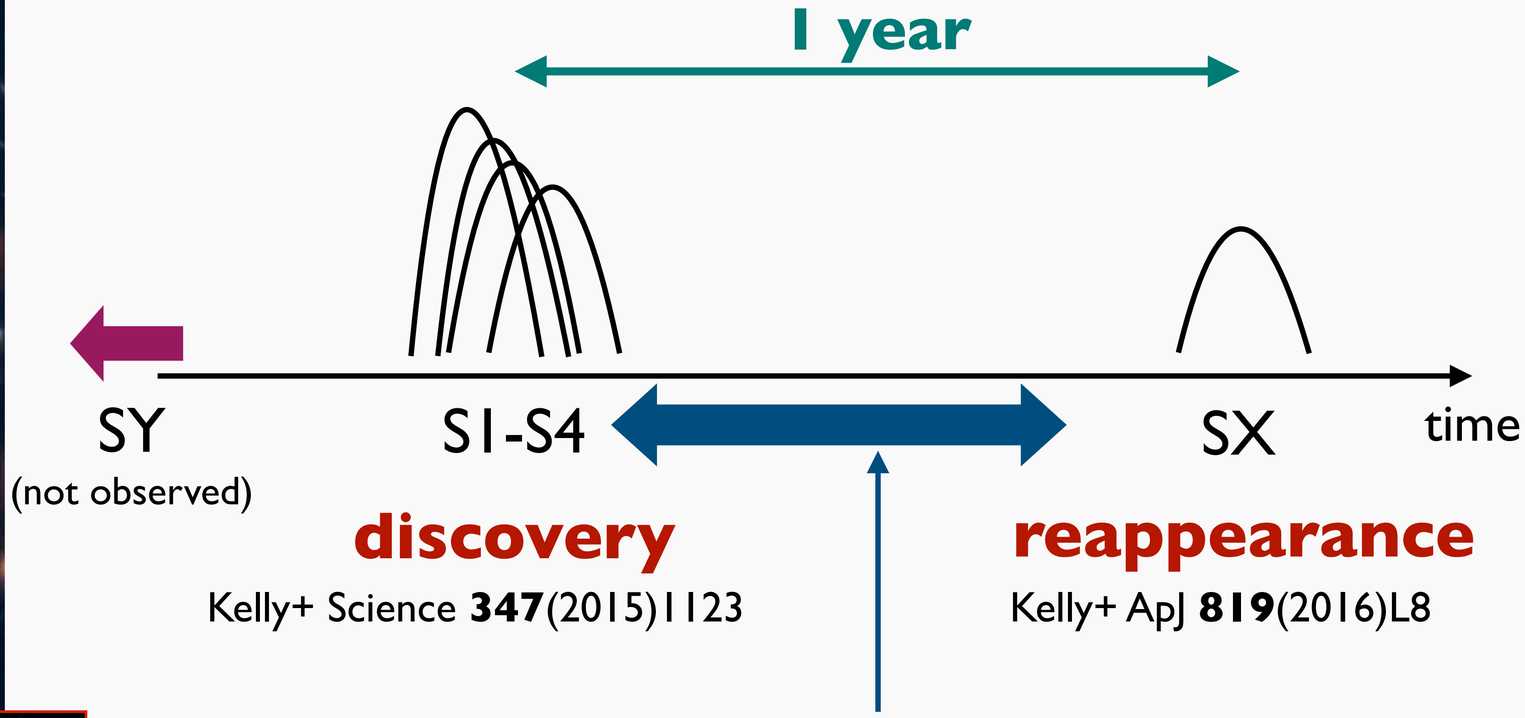


- its potential solution includes exotic dark matter models

(e.g., interacting dark matter, decaying dark matter, …)

Supernova Refsdal



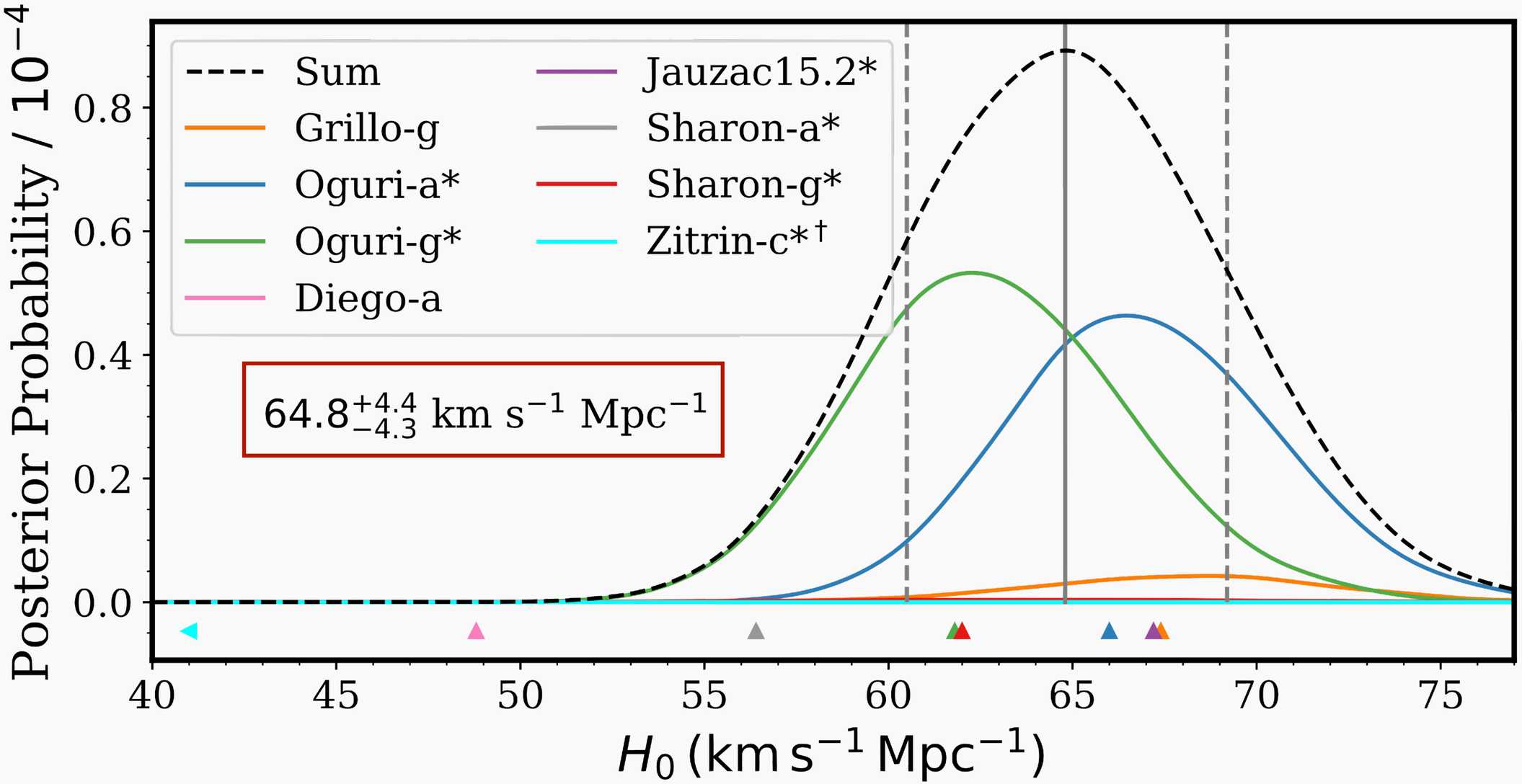


predictions of reappearance timing

MO 2015; Sharon & Johnson 2015; Diego+2016; Jauzac+2016; Treu+2016; …

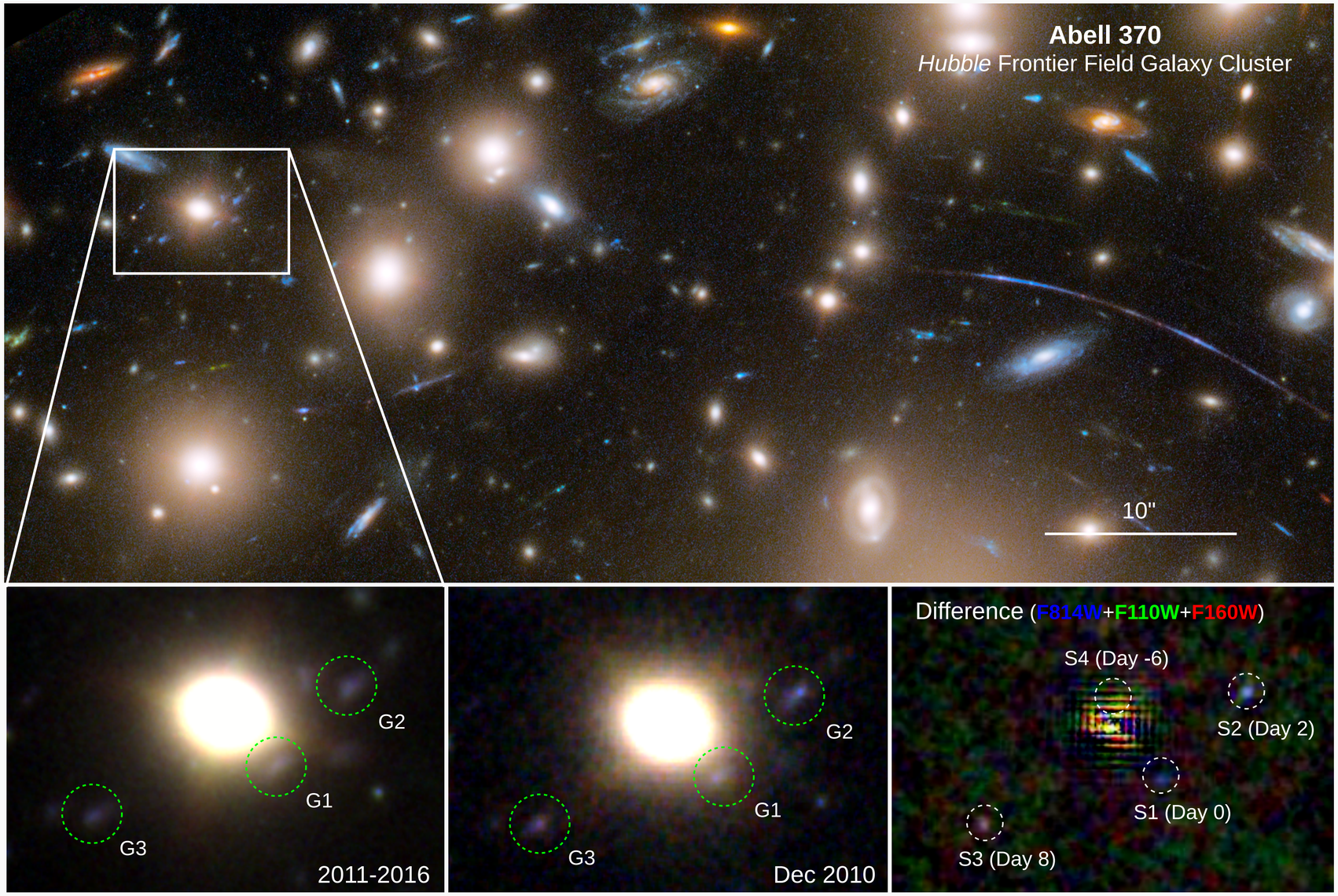
Kelly, Rodney, Treu, MO+ Science **380**(2023)abh1322

Hubble constant with Refsdal

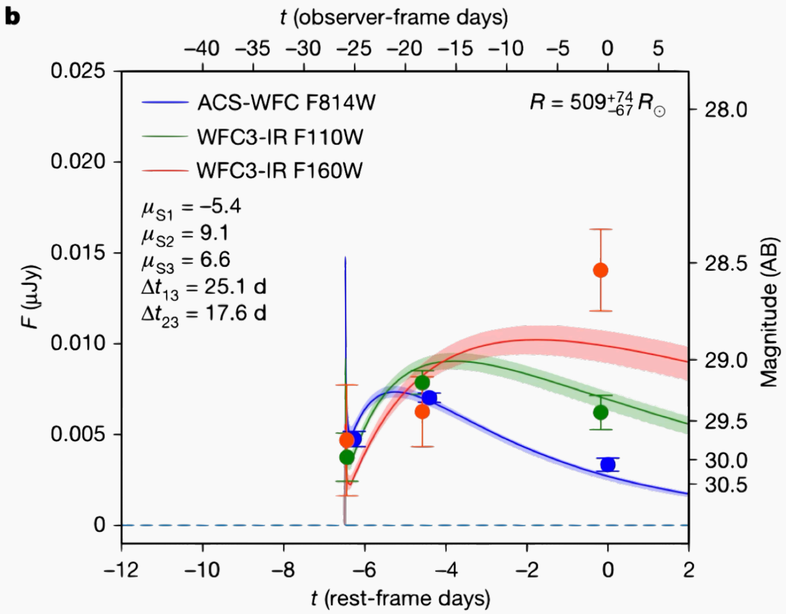


Chen, Kelly, MO+ Nature **611**(2022)256

More and more lensed supernovae!



early supernova light curve reconstructed with gravitational lens time delay



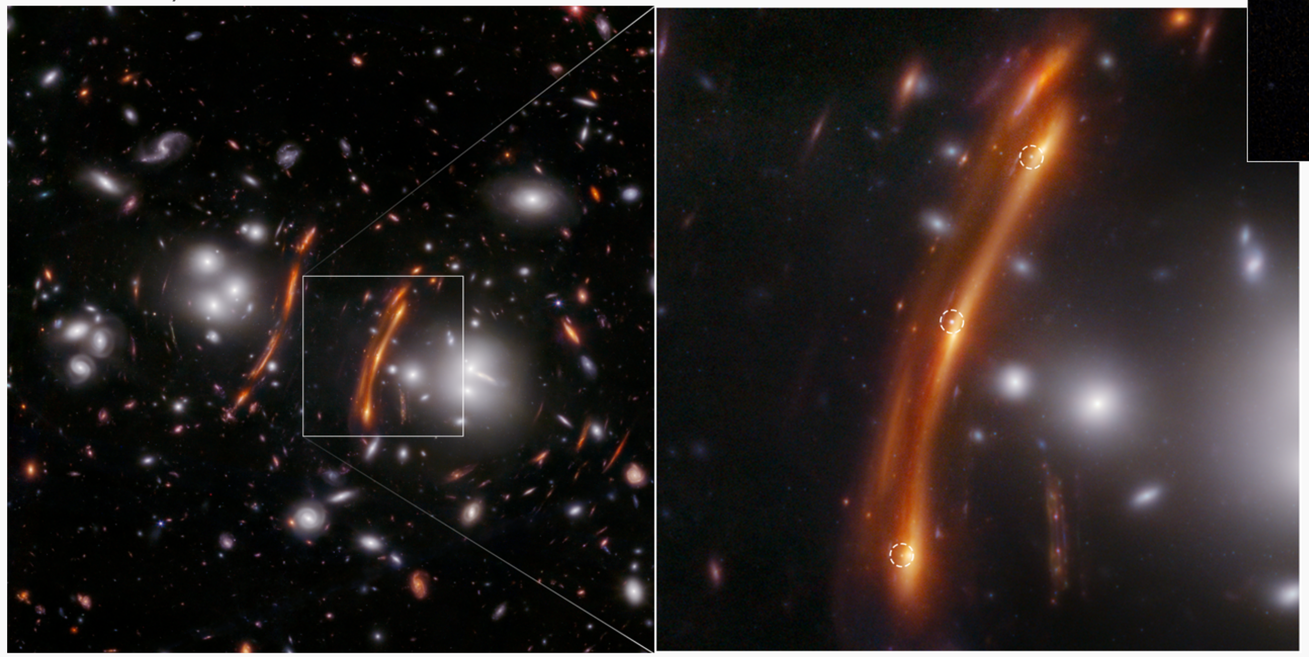
More and more lensed supernovae!

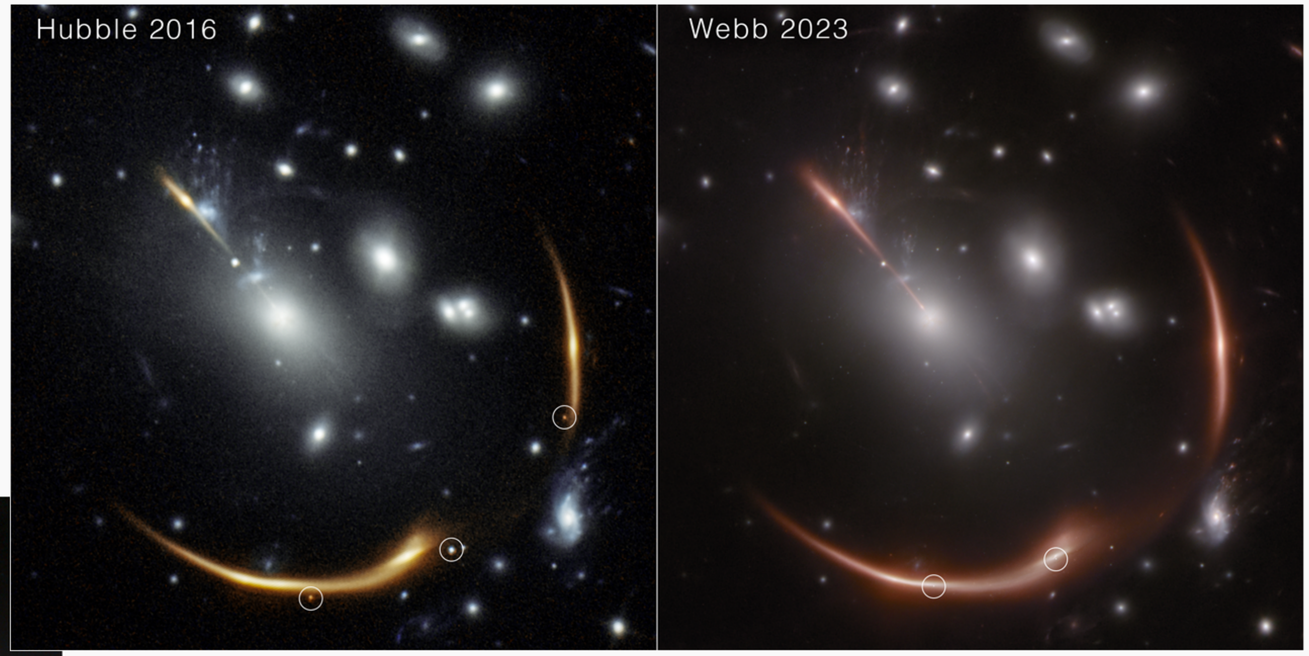
Supernova H0pe (Type Ia, z=1.78)

$H_0=75.7^{+8.1}_{-5.5}$ km/s/Mpc

Pascale+ (incl. MO) ApJ **979**(2025)13

NASA/ESA/B. Frye et al.





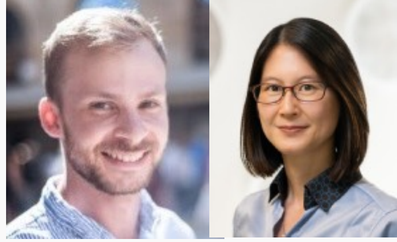
NASA/ESA/J. Pierel et al.

Supernova Requiem & Encore (Type Ia, z=1.95)

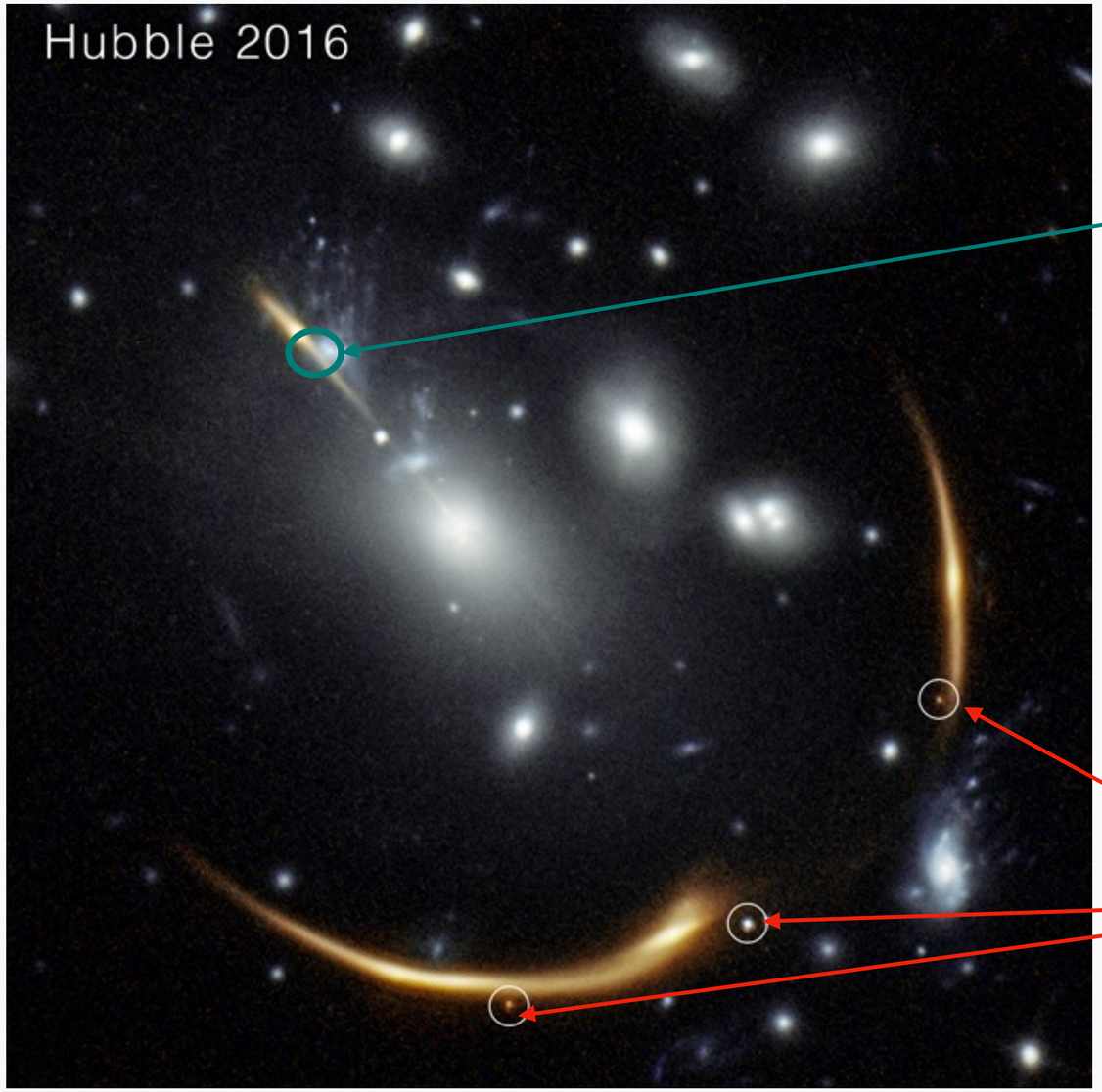
H_0=???

work in progress

work in progress



Reappearance of Requiem



NASA/ESA/J. Pierel et al.

Requiem reappearance in 2026-2027 predicted by the latest mass models

→ <3% measurement of H_0

3 supernova image observed in 2016 Rodney+ Nature Astronomy **5**(2021)1118

Caustic crossing

critical curve
(image plane)

caustic
(source plane)

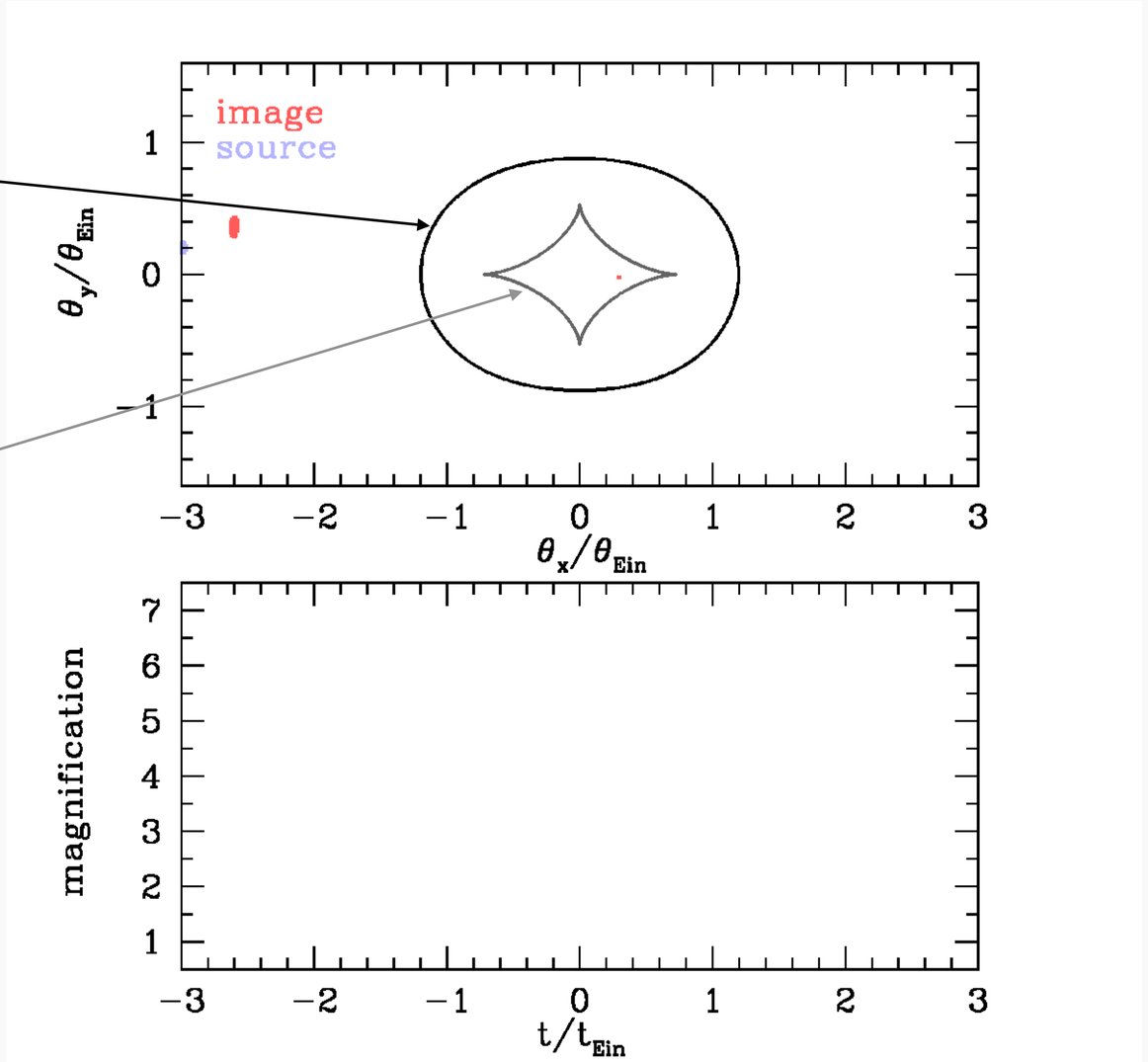


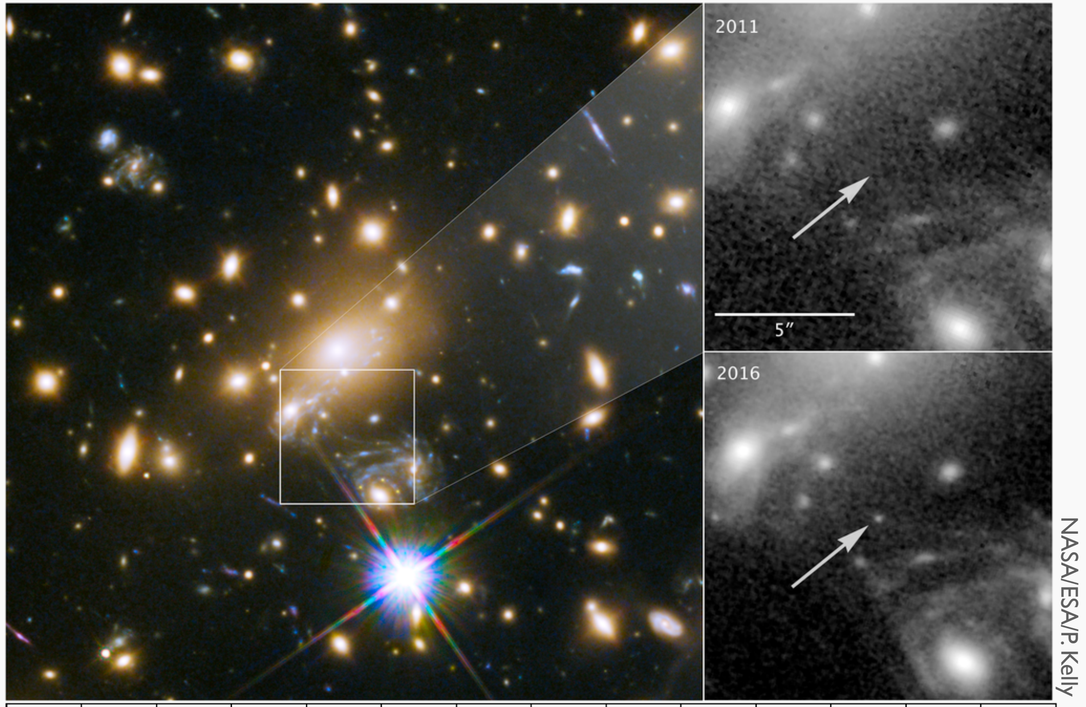
image
(observed)

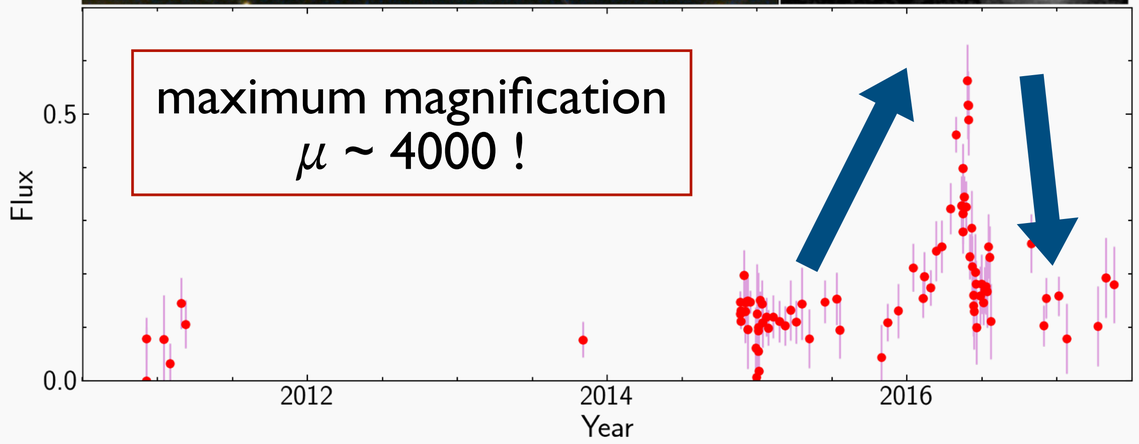
source
(not observed)

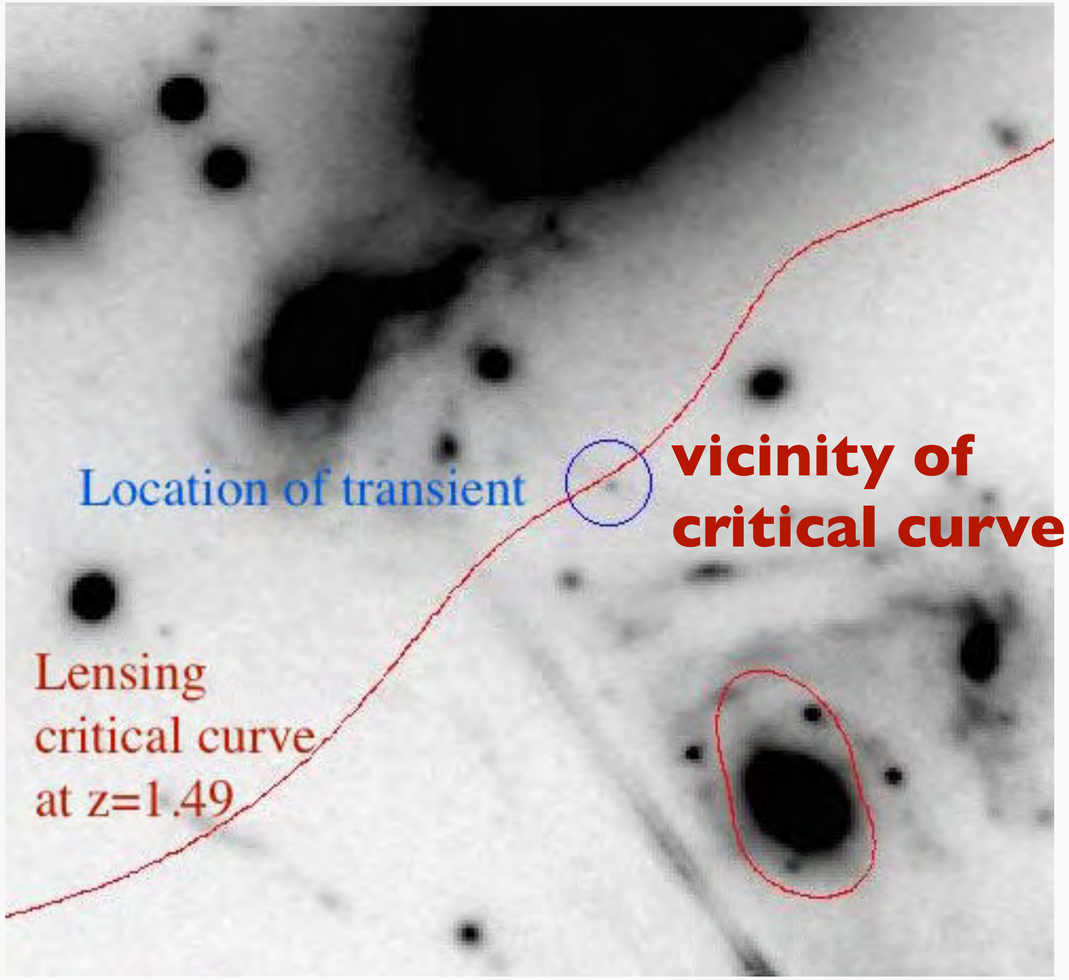
very high magnification when source crosses caustic

Kelly+ (incl. MO) Nature Astronomy **2**(2018)334

Discovery of Icarus

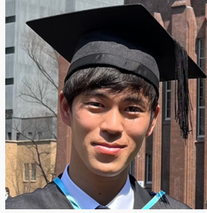






- single star (blue supergiant) at z=1.5

Kawai & MO arXiv:2411.13816



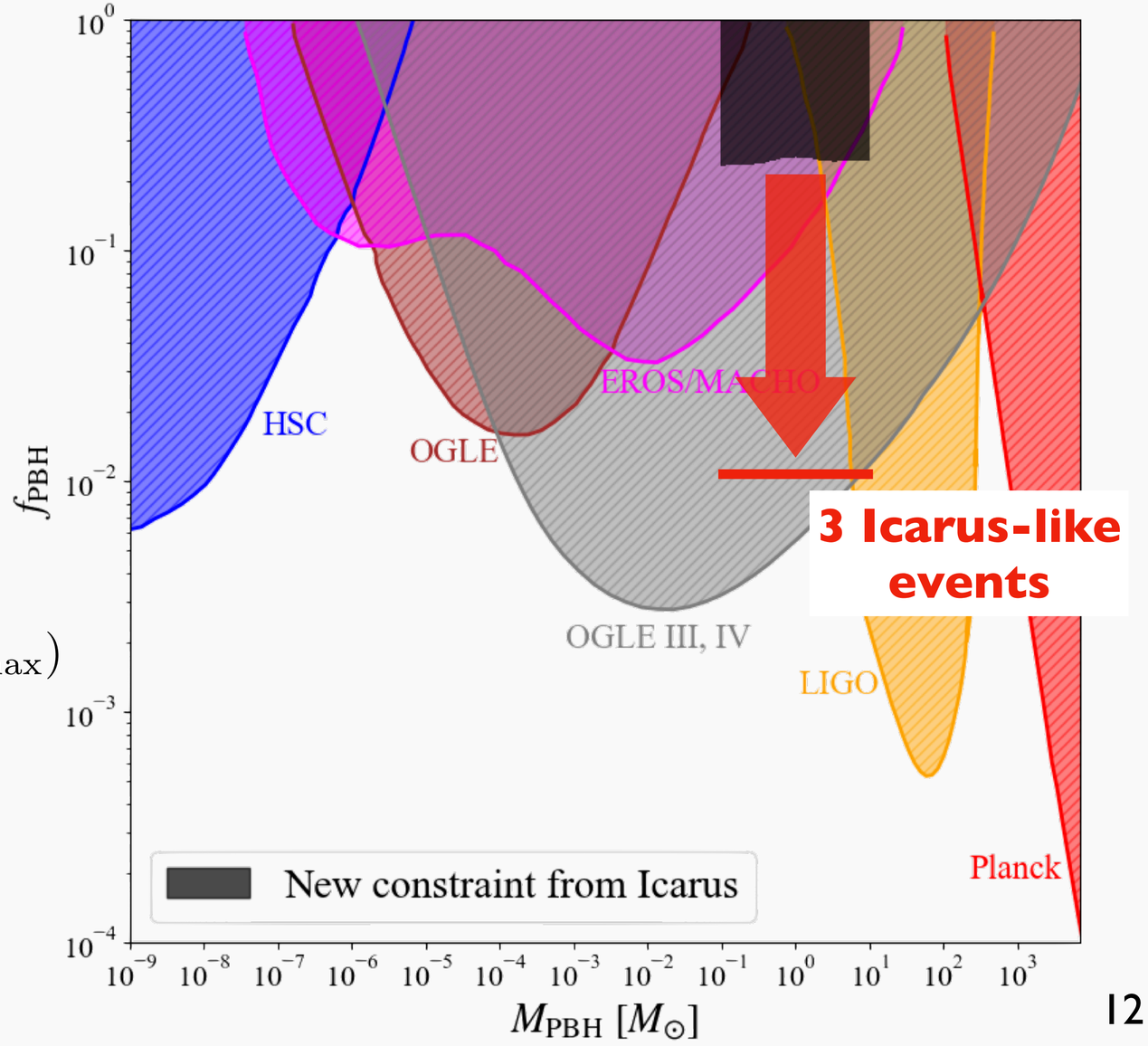
Constraint on Primordial Black Holes

- new analytic model assuming probability is proportional to number of independent micro-critical curves $N_\star^{\rm indep}$

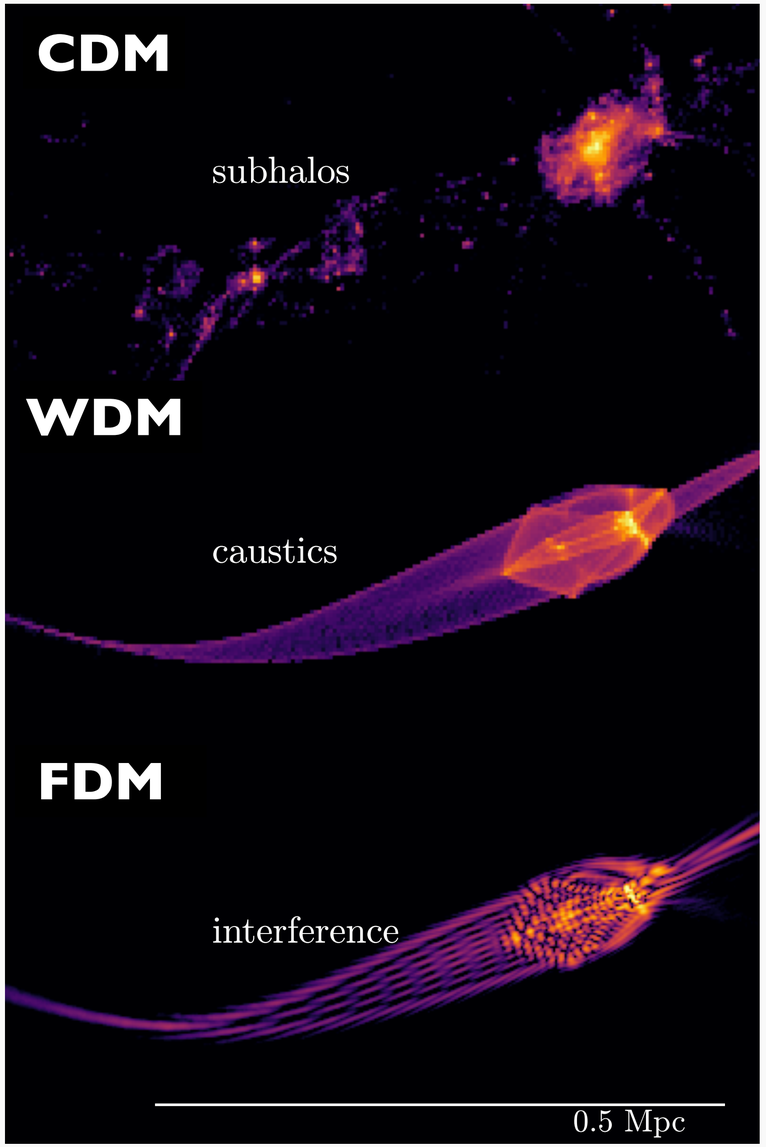
  Kawai & MO PRD **110**(2024)083514

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

- constraints get much tighter with a few more Icarus-like events



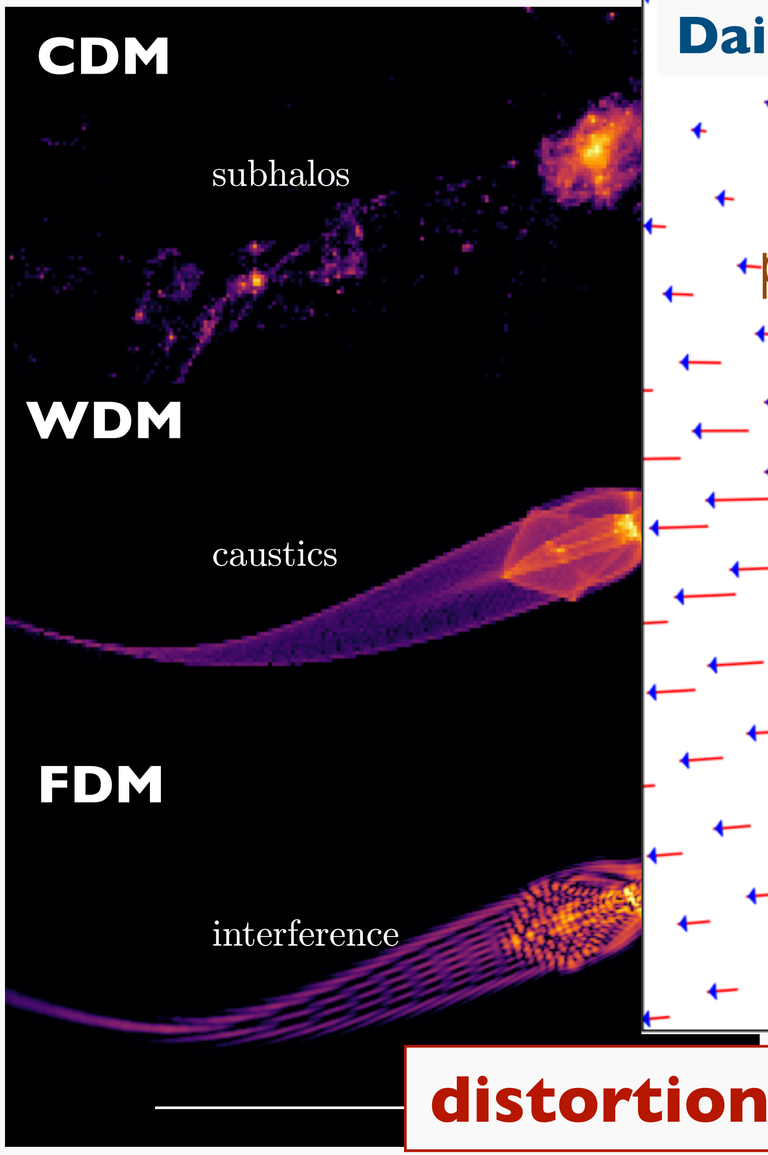
Critical curve and dark matter



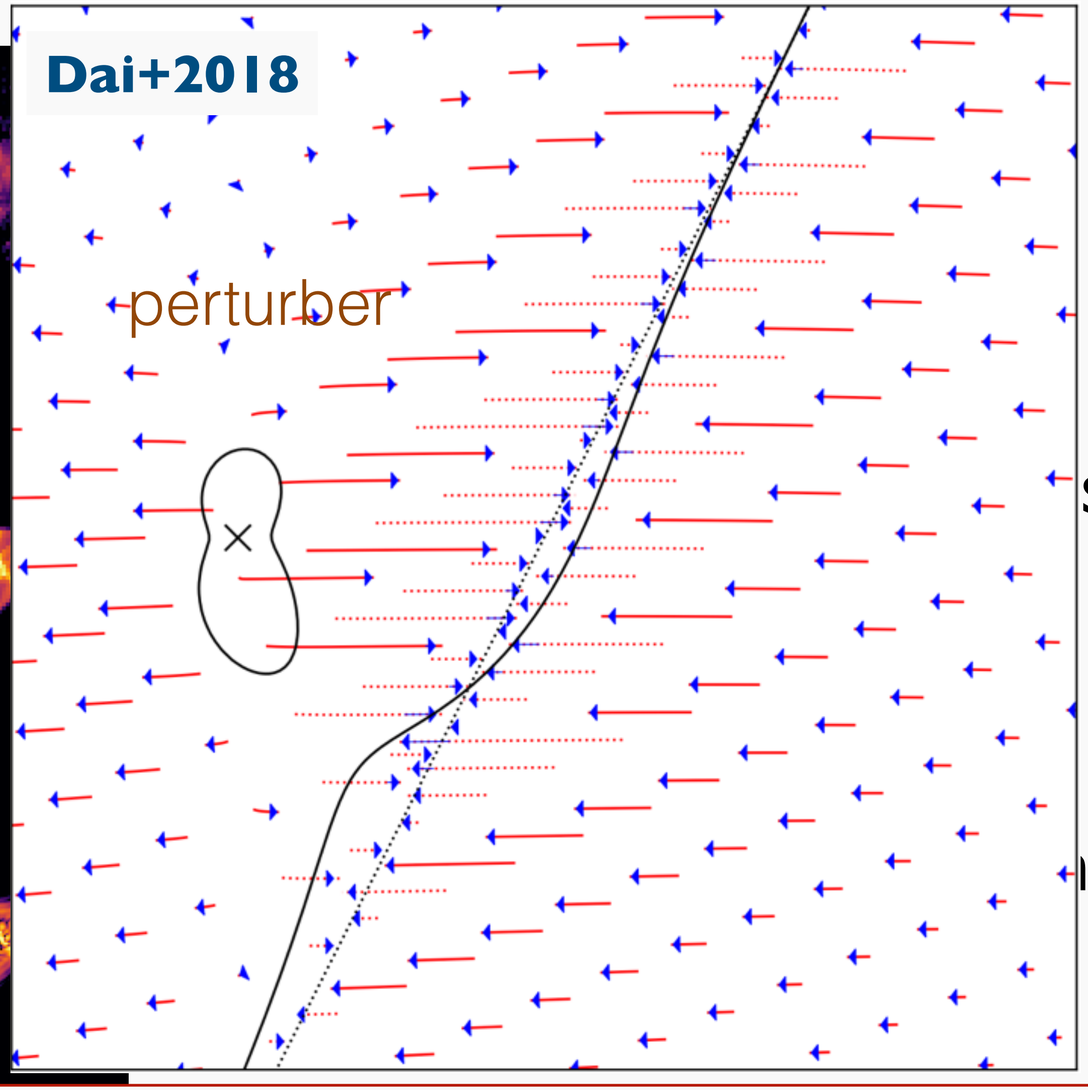
Mocz+2020

- CDM: many small clumps
- WDM: smooth, no clumps
- FDM: clumps due to quantum interference

Critical curve and dark matter



Mocz+2020



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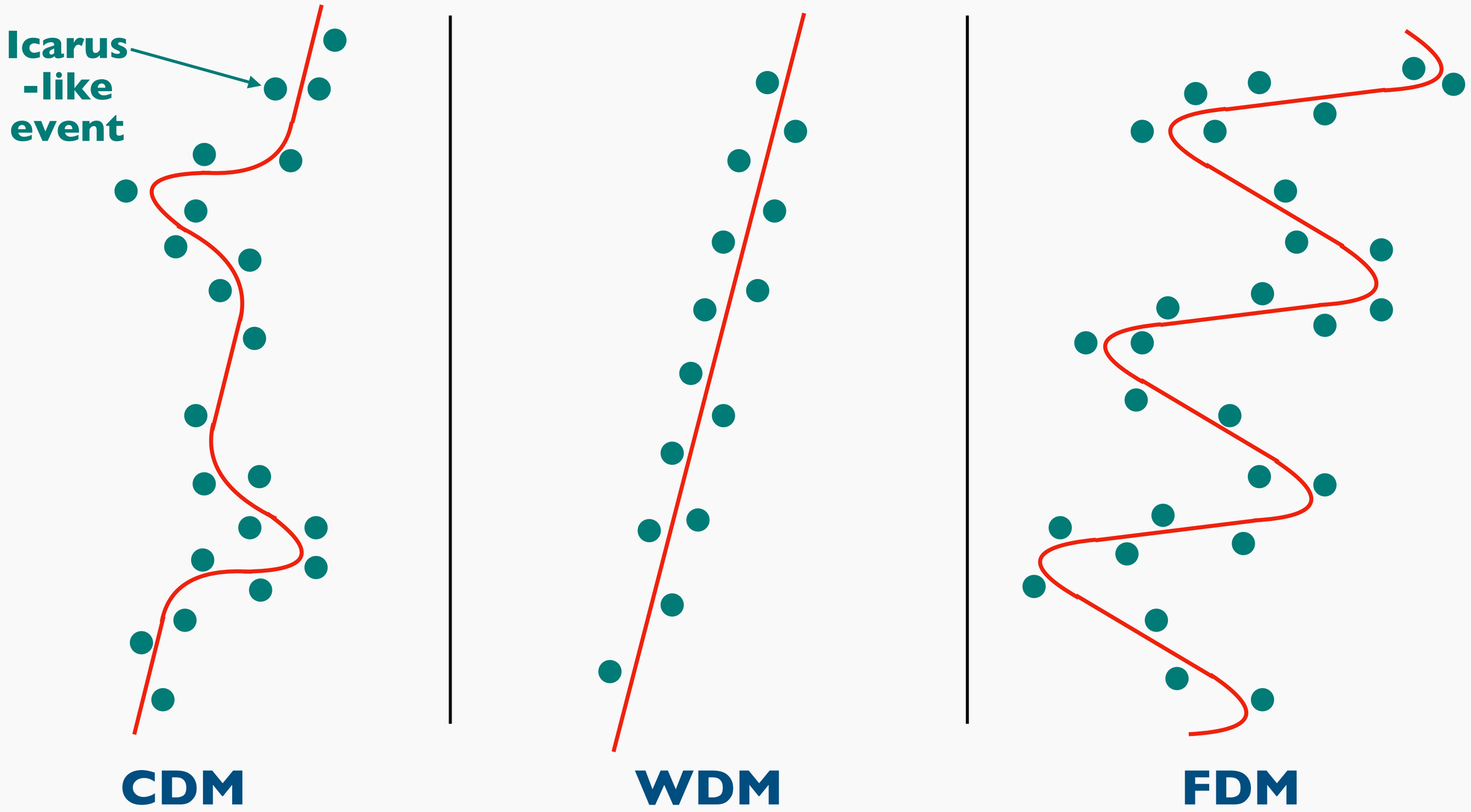
tum interference

distortion of critical curve by small clumps

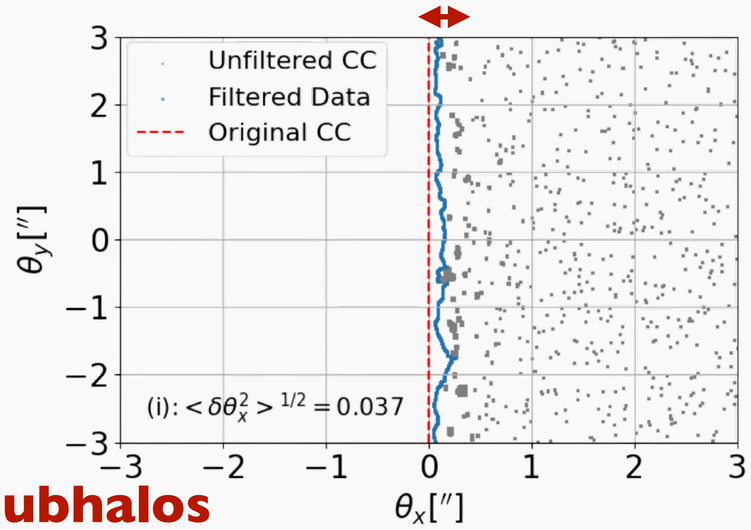
Critical curve and caustic crossings



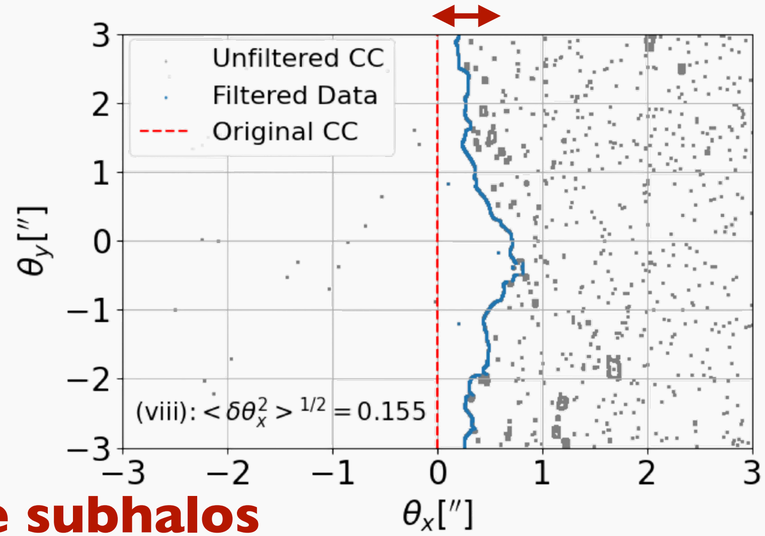
- can measure critical curve shape with many caustic crossings

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

Calculating critical curve fluctuations



less subhalos



more subhalos

- derive **an analytic formula** that connects power spectrum of critical curve fluctuations with that of DM small-scale density fluctuations

critical curve fluctuations

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

$$\epsilon \sim \frac{1}{\theta_{\rm Ein}}$$

DM small-scale density fluctuations

- formula validated with simple simulations

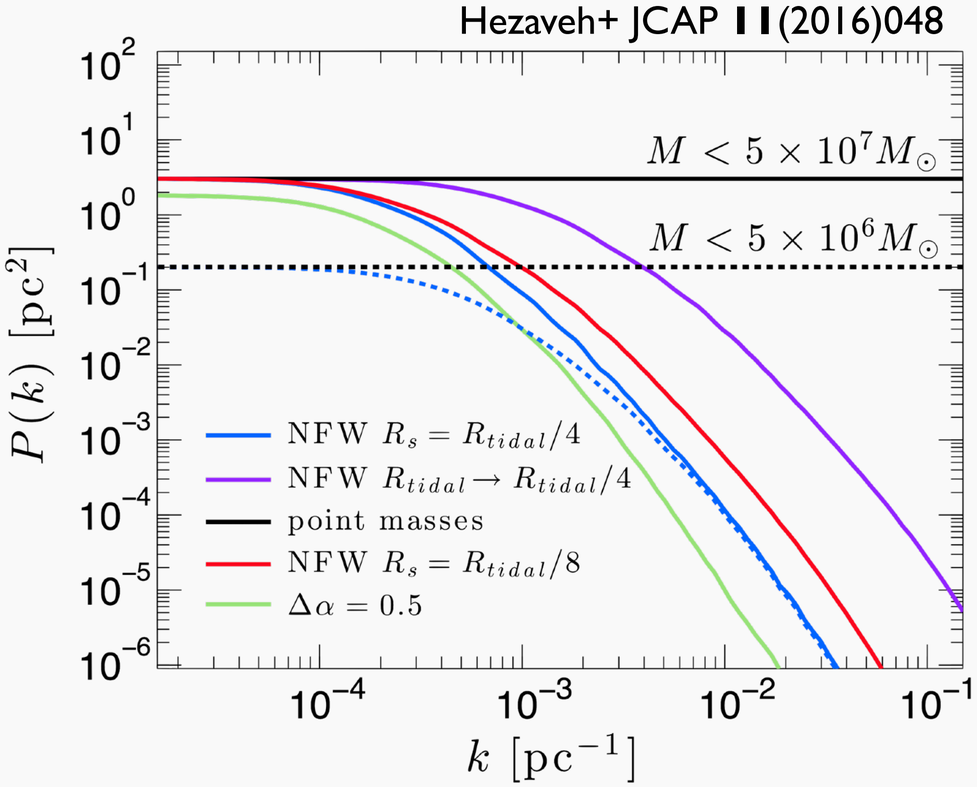
P(k) of CDM and WDM

- can be calculated with halo-model approach

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

subhalo mass function

Fourier transform of NFW profile

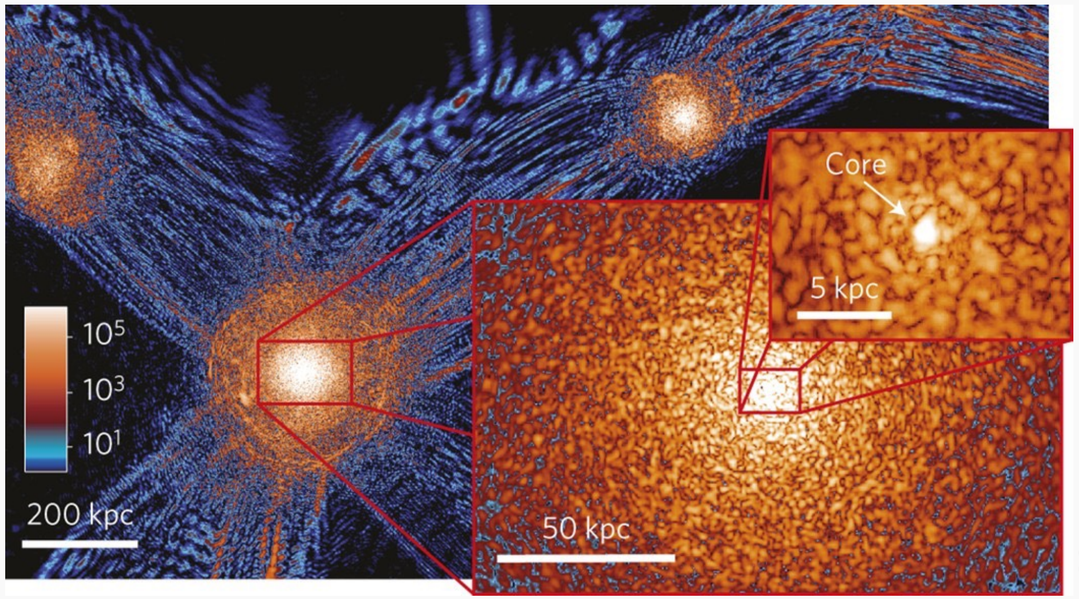


P(k) of FDM?

- wave effect below de Broglie wavelength

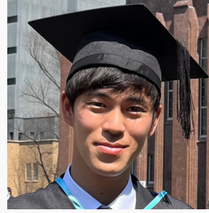
$$\lambda_{\rm dB} = \frac{h}{mv} = 180\,{\rm pc}\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^{-1}\left(\frac{v}{1000\,{\rm km/s}}\right)^{-1}$$

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



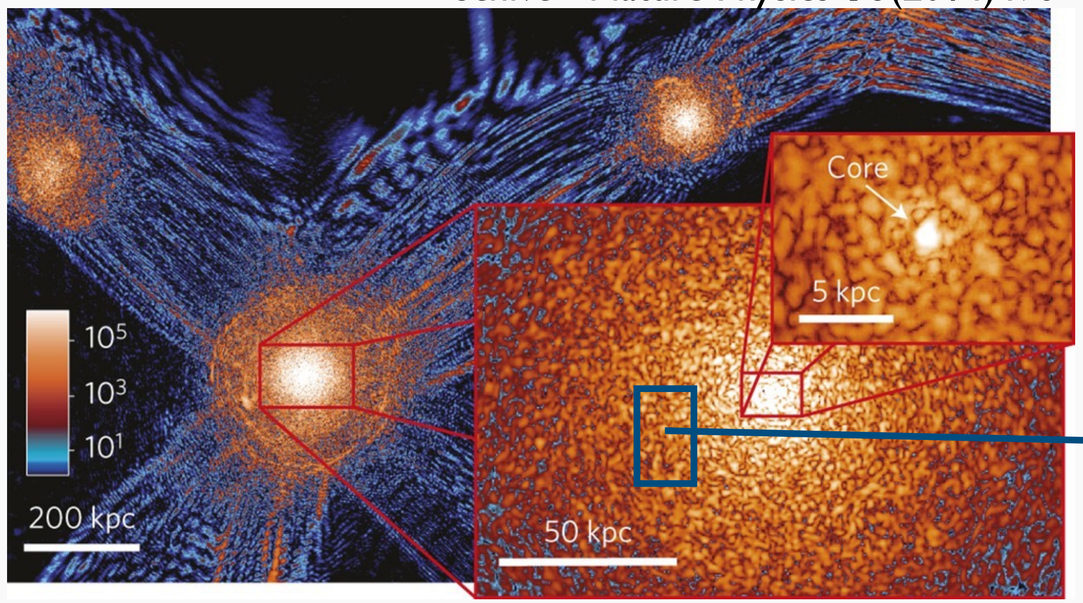
Schive+ Nature Physics **10**(2014)496

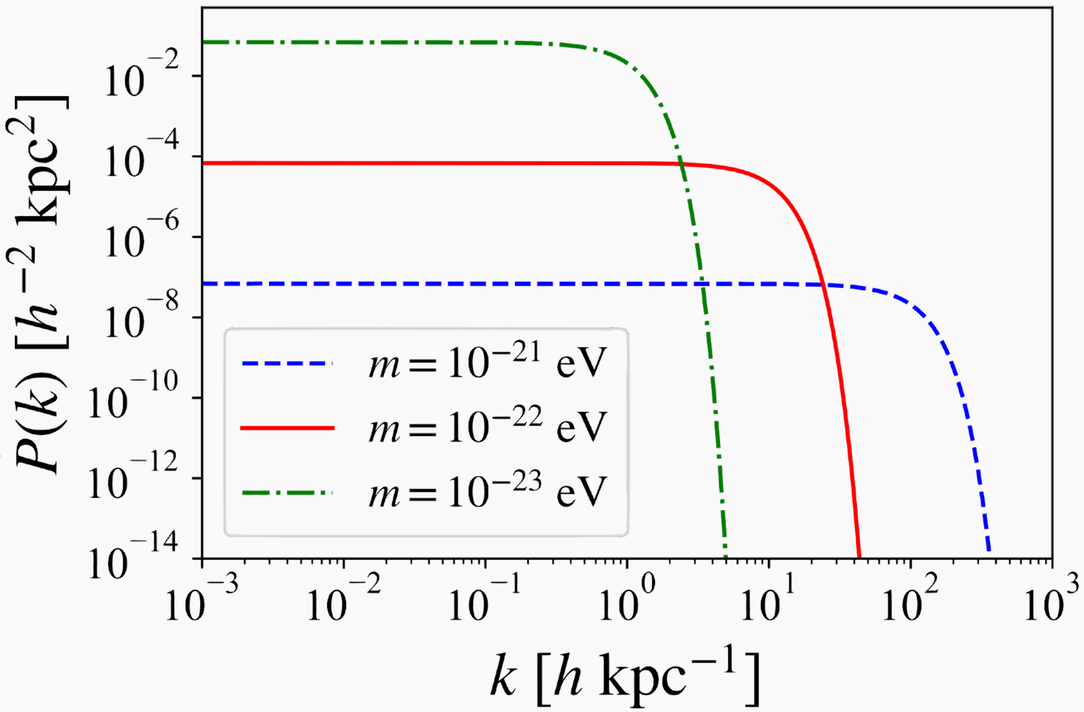
Kawai, MO+ ApJ **925**(2022)61



Analytic model of P(k) in FDM

Schive+ Nature Physics **10**(2014)496



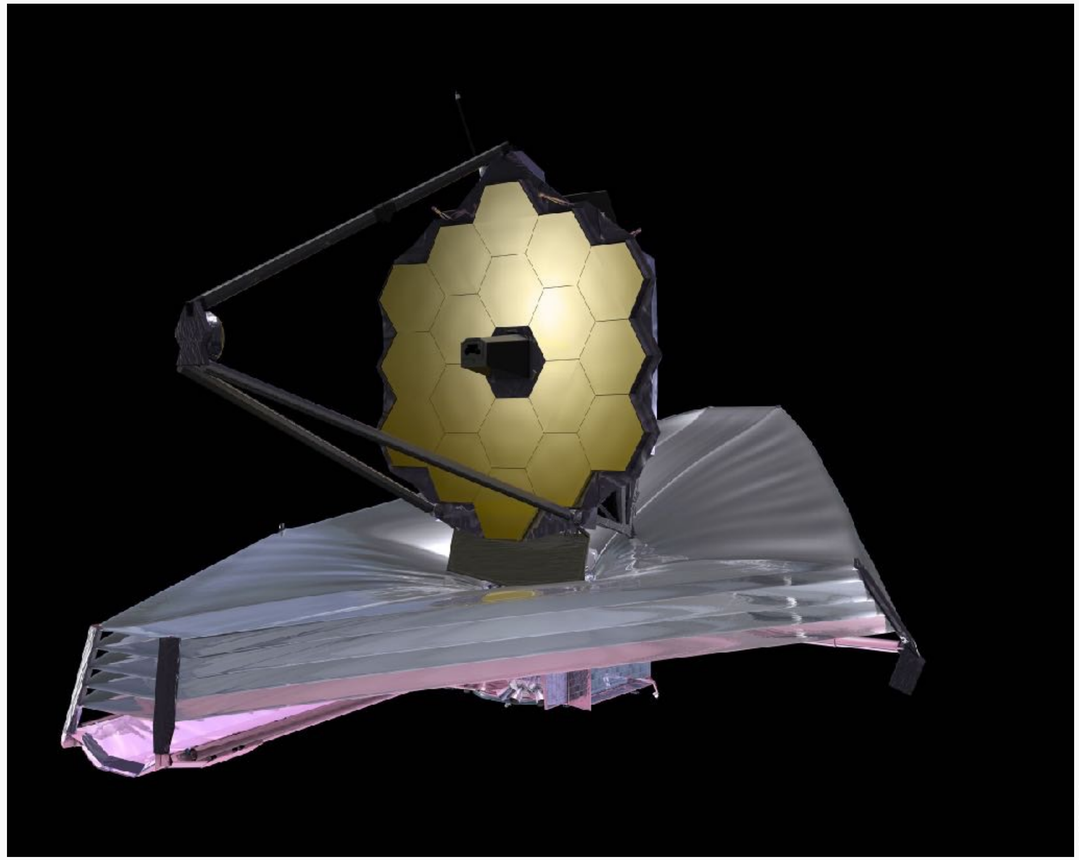


- derive P(k) assuming superposition of Gaussian clumps

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

Progress with JWST

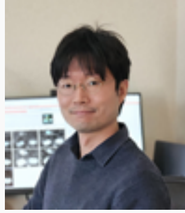
NASA



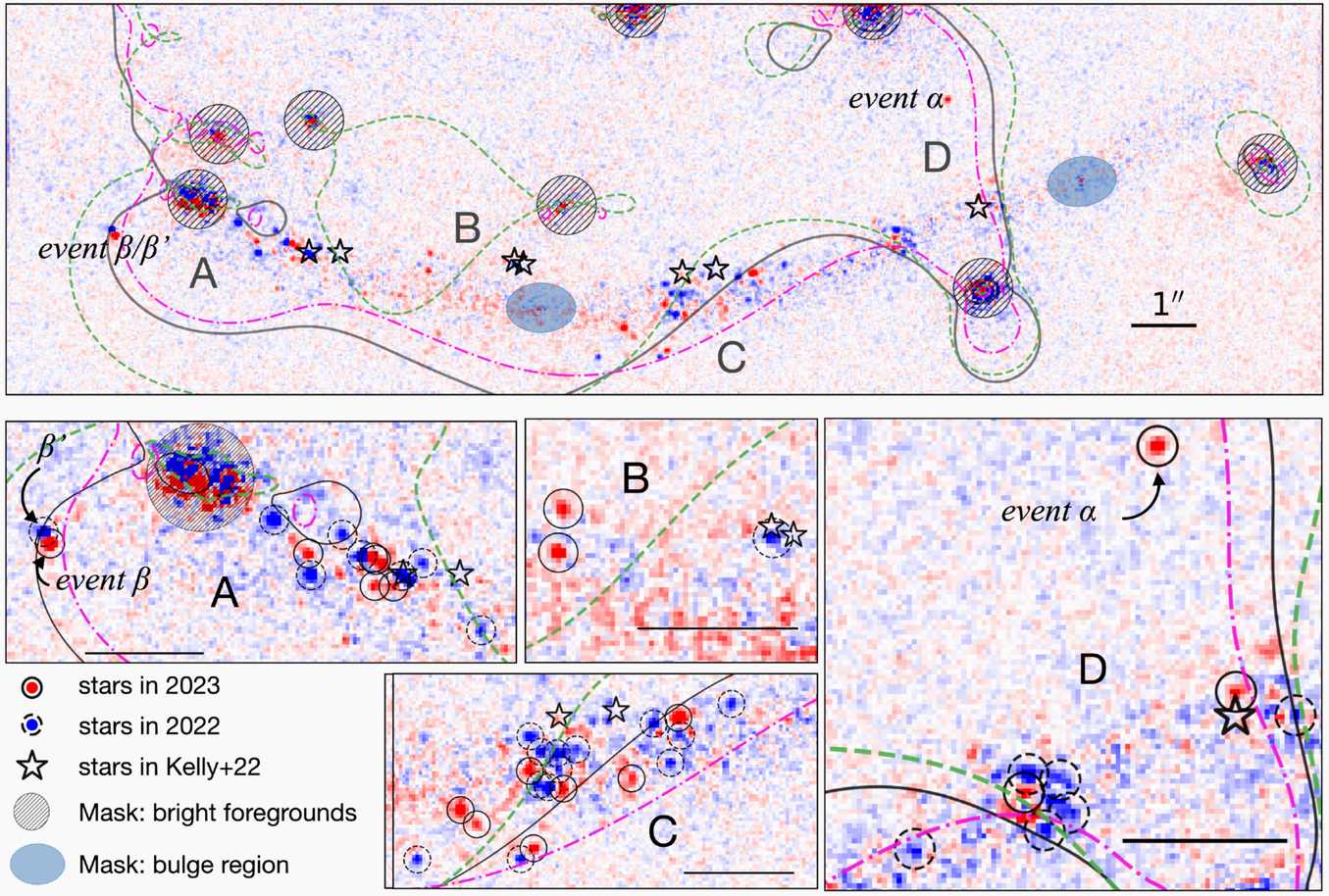
NASA

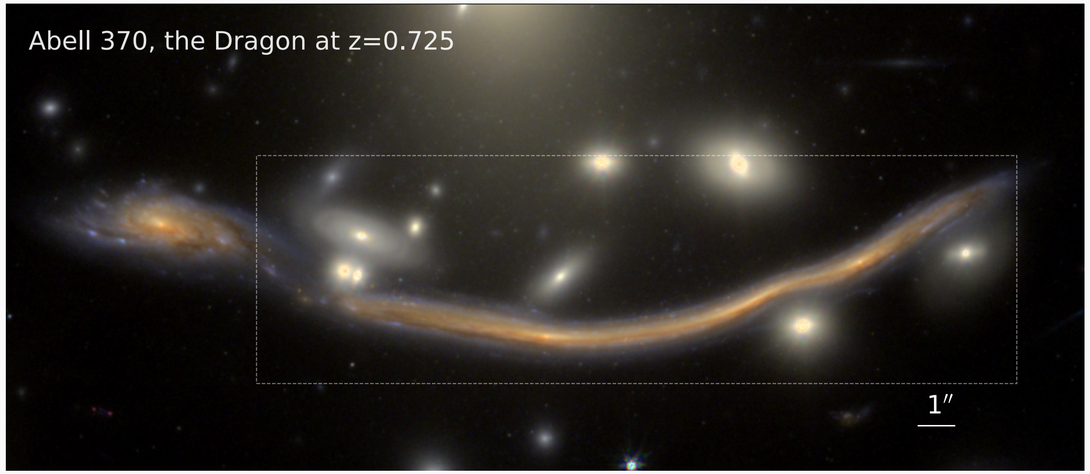
- more caustic crossings needed to study DM
- **JWST** is the solution

Fudamoto, Sun, Diego, Dai, MO+ Nature Astronomy **9**(2025)428



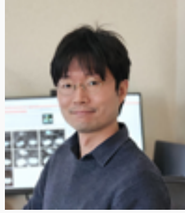
>40 caustic crossings in Dragon Arc





- Dragon Arc at z=0.725 behind Abell 370
- **>40 lensed stars** discovered from 2 epoch JWST obs. of Dragon

Fudamoto, Sun, Diego, Dai, MO+ Nature Astronomy **9**(2025)428



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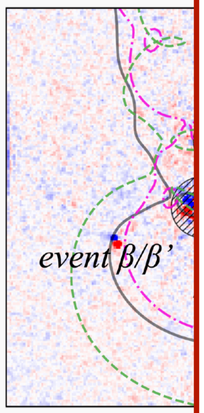

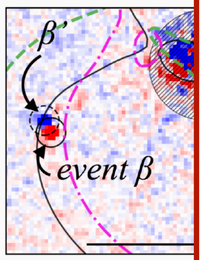

stars in 20
stars in 20
stars in Ke
Mask: brig
Mask: bul

GO 7345

Fri Apr 11 09:48:18 EDT 2025

Principal Investigator: Yoshinobu Fudamoto
PI Institution: Chiba University
Investigators (XML)

Title: The Dragon survey: A Direct Probe of the Early Stellar Luminosity Function and Dark Matter through Multi-cycle Multi-cadence Microlensing at z=0.73
Cycle: 4
External Allocation: 36.0 hours
Exclusive Access Period: 12 months

Program Status: Implementation

Program Coordinator: Christian Soto Contact

NIRCAM Reviewer: Adam Riess Contact

JWST proposal accepted (cycle 4, 5, 6)

>200 caustic crossings to come!

Abell

d from

Summary

- exciting discoveries and science from time-domain observations of centers of massive clusters of galaxies
- discoveries of gravitationally lensed supernovae leading to competitive constraints on H_0 from time delays
- statistical studies of caustic crossings revealing small-scale dark matter distribution
- cluster centers are promising targets for future CMOS observations!