## Caustic crossings as a new probe of dark matter

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024/10/15 Cosmic Indicators of Dark Matter@Tohoku



equation  $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$  $\ddot{\phantom{a}}$ • multiple solution of **image position <sup>θ</sup>** for lens ➞ **multiple images**

# Gravitational lensing by cluster



- massive concentration of dark matter
- useful site for studying dark matter



# Gravitational lensing by cluster



## Gravitational lensing by cluster



Abell 370, NASA/STScI

(Kawamata, <u>MO</u>+2016) 5

### Critical curve and caustic

lens equation: mapping btw source and image



**near critical curve/caustic → high magnification** 6

## 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





# Caustic crossing



# Caustic crossing



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

# Discovery of Icarus





Welch+ (incl. MO) Nature **603**(2022)815

# Discovery of Earendel



Welch+ (incl. MO) Nature **603**(2022)815

 $W_{\rm eff}$  is the final wave  $\sim$  F110W  $\sim$  F110W  $\sim$  F110W  $\sim$  F110W  $\sim$  F110W  $\sim$  F140W  $\sim$ 



# Discovery of Earendel



### Interpretation of caustic crossings

- caustic crossings look very simple, yet in fact they are not that simple because the mass distribution is not completely smooth
- non-smoothness due to stars responsible for **intra-cluster star** (**ICL**)
- tidal stripping of cluster member galaxies explains ICL







### 'Destruction' of critical curve  $\sum_{i=1}^n$ √ ∠ ∪estruction of critical cu



• destruction of critical curve due to overlapping Einstein ered the optical depth of the optical depth of the optical depth  $\epsilon$ radii of ICL stars

$$
\tau = \frac{\Sigma}{M} \pi \left( \sqrt{\mu_t} \theta_{\rm E} D_{ol} \right)^2 \left[ \tau z \right] \rightarrow \text{saturation}
$$

# Caustic crossing w/ ICL





Weisenbach, Anguita, Miralda-Escude, MO+ Space Sci. Rev. **220**(2024)57

# Simulation





Weisenbach, Anguita, Miralda-Escude, MO+ Space Sci. Rev. **220**(2024)57

# Caustic crossing lightcurves





#### Analytic model by the distance from the distance from the macro-critical curve or cause of the macro-critical curve or cause<br>All the macro-critical curve of the macro-critical curve or cause of the macro-critical curve of the macro-cri only a small fraction of the microlensies are in the microlensies are in the microlensies are in the microlens

tic, *e.g.*, Eq. (35), our model allows us to study how the • Assumption: caustic crossing proba  $\overline{\phantom{a}}$  as discussed in  $\overline{\phantom{a}}$ Proportional to humber of mueper micro-critic smaller than the size of the micro-critical curve, *i.e.*, the **• Assumpuo** proportional to number of independent factor is *represented* to the set of the high magnifical tensor is  $\mathbf{r}$  $\mathbf{H}$  and  $\mathbf{C}$  is the PDF by combining  $\mathbf{C}$ cal curves. The vertical curves of the vertical black dashed in the vertical black dashed in the vertical sett<br>The vertical black dashed line is the vertical black dashed in the vertical black dashed in the vertical black • Assumption: caustic crossing probability is proportional to number of independent  $P \leftarrow$  Ravlaigh dist smaller than the size of the micro-critical curve, *i.e.*, the micro-critical curves *N*★indep ← **Rayleigh dist.**

*dP*

$$
\frac{dP}{d\log_{10} r} \propto N_{\star}^{\text{indep}} \sqrt{\mu_{\text{av}}} r^{-2} S(r; r_{\text{max}})
$$

$$
\frac{S_{10}r}{\propto f_{\star}\kappa_{\rm tot}\exp(-f_{\star}\kappa_{\rm tot}\mu_{\rm av})\sqrt{\mu_{\rm av}r^{-2}}S(r;r_{\rm max})}
$$





. fraction **f**★ **: ICL fraction** 

onvergence  $\mathcal{U}$ av $\mathcal{U}$ **tot : convergence**  $\mathbf{r} = \mu / \mu_{\mathbf{av}}$ 



**defining the smooth background as a curve of the smooth background as a smooth background as a smooth background as**  $\int d^4x \, d^4x \, d^4x$  **parameter dependent**  $\frac{10^{-5}}{2}$   $\frac{2}{\pi}$   $\frac{1}{\pi}$  in ray-tracing sim is  $\frac{1}{10^{-3} \cdot 10^{-2} \cdot 10^{-1} \cdot 10^{0}}$   $\frac{1}{10^{1}}$  well reproduced! *d* log<sup>10</sup> *r r* (68) *,* parameter dependence  $r = \mu / \mu_{av}$ *<sup>P</sup>* PS(*r>r*th) = <sup>Z</sup> <sup>1</sup> well reproduced!

# Probing DM with caustic crossings

- caustic crossing probability is sensitive to mass fraction *f*★ of compact objects
	- → **primordial black holes** (PBH)
- caustic corssings appear near critical curves of clusters, which are sensitive to small-scale dark matter distribution
	- → **warm dark matter** (WDM)  **fuzzy dark matter** (FDM)

Kawai & MO, arXiv:2411.13816

# Constraint on PBH



• constraints from event rate (w/o ICL)



Kawai & MO, arXiv:2411.13816 the total black dotted line indicates the position of the macro-critical curve, and the vertical black dashed  $\nu$ line marks the location of Icarus. Left: variation in the maximum source radius, reflecting the maximum source r<br>The maximum source radius, reflecting the different performance radius, reflecting the different performance

# **Constraint on PBH**



### Critical curve and dark matter





### Critical curve and dark matter  $\bigcap_{\alpha:\alpha:\alpha\in\mathbb{Z}}$ LD, Venumadhav, Kaurov & Miralda-Escudé 18'



### Critical curve and caustic crossings



25

Abe, Kawai, <u>MO</u> PRD **109**(2024)083517 Abe, Kawai, <u>MO</u> PRD **109**(2024)083517



#### Critical curve fluctuations **Designed** (x) 5 ⇥ <sup>10</sup><sup>6</sup> <sup>10</sup><sup>11</sup> <sup>0</sup>*.*<sup>112</sup> *<sup>±</sup>* <sup>0</sup>*.*044 0*.*186 6*.*0<sup>00</sup> ⇥ <sup>6</sup>*.*000, 10 realizations (xii) 5 ⇥ <sup>10</sup><sup>6</sup> <sup>10</sup><sup>12</sup> <sup>0</sup>*.*<sup>129</sup> *<sup>±</sup>* <sup>0</sup>*.*041 0*.*291 6*.*0<sup>00</sup> ⇥ <sup>6</sup>*.*000, 10 realizations (xi) 5 ⇥ <sup>10</sup><sup>6</sup> <sup>5</sup> ⇥ <sup>10</sup><sup>11</sup> <sup>0</sup>*.*<sup>122</sup> *<sup>±</sup>* <sup>0</sup>*.*0529 0*.*256 6*.*0<sup>00</sup> ⇥ <sup>6</sup>*.*000, 10 realizations **Exitical curv**  $U_{\text{S}}$   $\blacksquare$



(ix) 5 ⇥ <sup>10</sup><sup>6</sup> <sup>6</sup> ⇥ <sup>10</sup><sup>10</sup> <sup>0</sup>*.*<sup>122</sup> *<sup>±</sup>* <sup>0</sup>*.*044 0*.*170 6*.*0<sup>00</sup> ⇥ <sup>6</sup>*.*000, 10 realizations

(x) 5 ⇥ <sup>10</sup><sup>6</sup> <sup>10</sup><sup>11</sup> <sup>0</sup>*.*<sup>112</sup> *<sup>±</sup>* <sup>0</sup>*.*044 0*.*186 6*.*0<sup>00</sup> ⇥ <sup>6</sup>*.*000, 10 realizations

 $\blacksquare$ E-mail : Phone : that connects P(k) of critical 04/2020 - 03/2022 : • derive **an analytic formula** curve fluctuations with P(k) an vernaced actoris with r (15)<br>of DM small-scale density fluctuations!  $\frac{1}{2}$  $\frac{1}{1}$   $\frac{1}{2}$   $\frac{1}{3}$  inucluations:

**critical curve fluctuations**

$$
P_{\delta\theta_x} = \frac{3}{2\epsilon^2} P_{\delta\kappa} \qquad \epsilon \sim 1/\theta_{\text{Ein}}
$$

$$
\sim 1/\theta_{\text{Ein}}
$$

**DM small-scale density fluctuations**

 $\overline{\phantom{a}}$  $\alpha$  *k*  $\alpha$  mple cimulat 3 • formula validated with ith in the set of the s<br>Experiment of the set simple simulations

# P(k) of CDM and WDM

• can be calculated with halo-model approach (e.g, Hezaveh+2016)

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

subhalo mass function Fourier transform of NFW profile



# P(k) of FDM?

• wave effect below de Broglie wavelength

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

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



simulation (Schive+2014)

Kawai, MO+ ApJ **925**(2022)61 awai, <u>MO</u>+ ApJ 925(2022)61 rai, <u>MO</u>+ ApJ **925**(2022)61



#### Analytic model of P(k) in FDM  $396$  tum clumps along the line of sight increases. The largest increases  $\mathcal{L}_{\mathcal{A}}$  $\Delta$  palotic pacel of sight results in the line of sight results in the line of sight results in the sight result of  $\Delta$ ANG SMALLER AMPLITUDE SPECIFIE  $\sqrt{1}$  ,  $\cdot$  from the sub-galactic matter  $\mathbb{R}$ power spectrum. Two parameters *M*s*/M*<sup>h</sup> and *m* are fixed as *M*s*/M*<sup>h</sup> = 0*.*01 and *m* = 10<sup>22</sup>eV, respectively. The position *x* is set to one-tenth of the virial radius of each halo, which *R* vir where G is the gravitational constant, Mtot is the total mass that

 $394$  the line of sight. As the total halo mass becomes larger, a

 $395$  the virial radius becomes larger and the number of  $q$ 



dorivo P(L) accuming  $\mathbf{C}$  and  $\mathbf{C}$  is much smaller than  $\mathbf{C}$   $F(k) =$  $\mathbf{a}$ 30 pci position of al. 2020  $\overline{C}$ Gaussian clumps  $r_h(x) =$ <sup>423</sup> matter power spectrum, which we discuss in Sec. 3.  $\sum_{k=1}^{\infty} (k)$   $\frac{\sqrt{2}}{4\pi}$   $\frac{3}{3}$   $\frac{1}{2}$   $\frac{2}{k^2}$  $\frac{\Delta_h(\lambda)}{\lambda}$  **h**  $\frac{\Delta_h(\lambda)}{\lambda}$  **d**  $\frac{\Delta_h(\lambda)}{\lambda}$  **d**  $\frac{\Delta_h(\lambda)}{\lambda}$  **d**  $\frac{\Delta_h(\lambda)}{\lambda}$  $\Gamma_{i}(r) \perp \Gamma_{i}(r)$  $\left(\int d\tau a(r)\right)^2$ <sup>436</sup> in Sec. 3.2, and the future prospect in Sec. 3.3.  $\int_{\mathcal{I}} d\mathbf{z} \rho_{\mathbf{k}}^2(r)$   $\int_{\mathcal{I}} d\mathbf{z} \rho_{\mathbf{k}}^2(r)$  $\mathcal{L}(k) = \left( \frac{\sum_{\mathbf{h}}(x)}{\sum_{\mathbf{h}}(x) + \sum_{\mathbf{h}}(x)} \right)$  $(x) + \Sigma_{b}(x)$  ) 3r<sub>h</sub> $(x)$  $P(k) = \left(\frac{\Sigma_{h}(x)}{\sum_{k=1}^{n} \Sigma_{k}^{k}}\right)^{2} \frac{4\pi\lambda_{c}^{3}}{2\pi\lambda_{c}^{3}} \exp\left(-\frac{\lambda_{c}^{2}k^{2}}{4}\right)^{3}$  $x) + \Sigma_{\rm b}(x)$  ) 3r<sub>h</sub>(x)  $4\pi\lambda_c^3$   $\left(\lambda_c^2k\right)$  $\frac{\hbar(x)}{\hbar}$   $\left(\frac{4\pi\lambda_c}{3r_h(x)}\exp\left(-\frac{\lambda_c k^2}{4}\right)\right)$  $h(x) + \Delta_b$ 2 c 3 h  $\pi \lambda_c^3$  **a**  $\left(\lambda_c^2 k^2\right)$  $\equiv$  $\sum$  $\Sigma_{h}(x) + \Sigma$  $\left( \frac{\Delta_h(x)}{\sum_{(x)} |\sum_{(x)}^n} \right) \frac{4\pi \Delta_c}{2\pi (x)} \exp \left( -\frac{\Delta_c \Delta_c}{4} \right)$  $\overline{\mathcal{L}}$ ⎞  $\overline{\phantom{a}}$  $\mathsf I$  $\overline{\mathcal{L}}$ ⎞  $\overline{U}$ • derive P(k) assuming superposition of  $\frac{\sum_{h} (x)}{\sum_{h} (x) + \sum_{h} (x)}$  $\left( \frac{\Sigma_{h}(x)}{2} \right)^{2} 4\pi \lambda_{c}^{3} \exp \left( -\frac{\lambda_{c}^{2} k^{2}}{2} \right)$  $\sqrt{\sum_{k}}$  $\frac{\sum_{\mathbf{h}}(x)}{\sum_{\mathbf{h}}(x)}$   $\frac{4\pi\lambda_c^3}{\exp{\left(-\frac{\lambda_c^2k^2}{k}\right)}}$  $\sum$  $2-h(x)$  $f(x) = \frac{\sum_{h}^{2}(x)}{\sum_{r}^{2}(x)} = \frac{\left(\int_{Z} dz \rho_{h}(r)\right)^{2}}{\int_{Z}^{2}(x)}$  $(r)$  $(r)$  $(r)$  $r_h(x) = \frac{\sum_h^2(x)}{r_h(x)} = \frac{\left(\int_Z dz \rho_h(r)\right)}{r_h(x)}$  $dz$   $\rho_{\rm h}^2(r)$  $dz$   $\rho$ <sub>h</sub> $(r$  $dz \rho_{\rm h}^2(r)$ *Z Z Z* h h 2 h 2 h 2  $\int_Z dz \rho_h^2(r) \qquad \int_Z dz \rho_h^2$  $\int$  $\rho_h^2(r)$   $\int$  $\rho$  $\rho$  $\frac{1}{1}$  $\sum$  $\frac{1}{1}$ 

# Progress with JWST



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

Fudamoto, Sun, Diego, Dai, MO+ arXiv:2404.08045



# >40 lensed stars in "Dragon"



- Dragon Arc at z=0.725 behind Abell 370
- **>40 lensed stars** discovered from 2 epoch JWST obs. of Dragon!
- DM can be constrained in several ways

Broadhurst+ (incl. MO) arXiv:2405.19422



# Constraint from skewness



Broadhurst+ (incl. MO) arXiv:2405.19422



### Constraint from skewness **6 Broadhurst Exercise**



# Summary

- caustic crossings are new phenomena reported for the first time in 2018
- highly magnified (~thousands) individual stars
- interpretation rather complicated, but their basic properties now understood thanks to the progress of theoretical studies
- they offer a new route to probe the nature of dark matter
	- sensitive to the PBH abundance
	- probe DM small scale density fluctuations