2026年紫金山暗物质研讨会

Interpreting Positional Anomalies in HS 0810+2554 with Dark Matter Subhalos

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arXiv:2607.xxxxx

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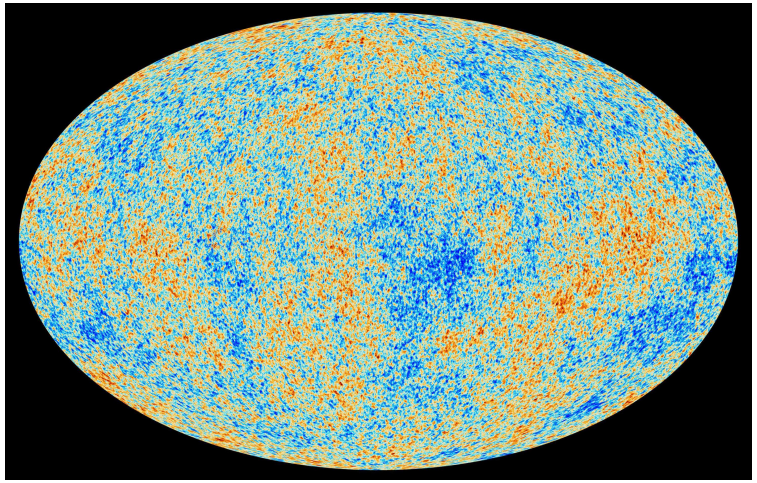
Outline

- Background introduction
- Positional anomalies in HS 0810+2554
- Interpretation with CDM subhalos
- Conclusion

Dark Matter in the Universe

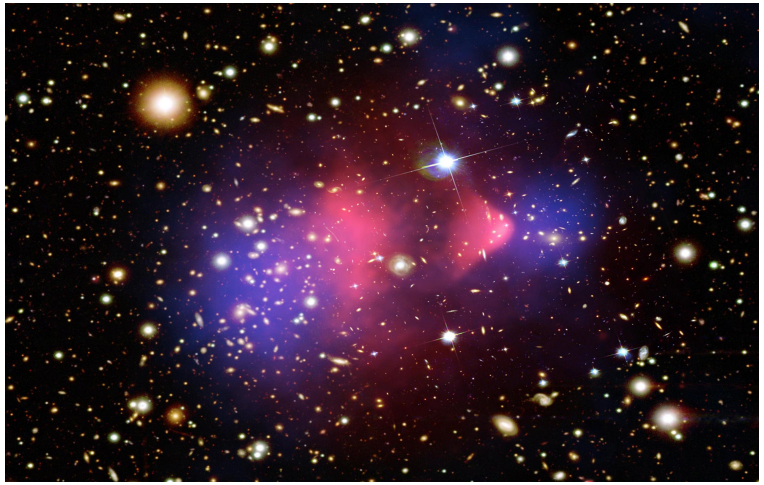
- Constitutes approximately 85% of the total matter
- Supported by multiple independent observations

Planck Collaboration 2018



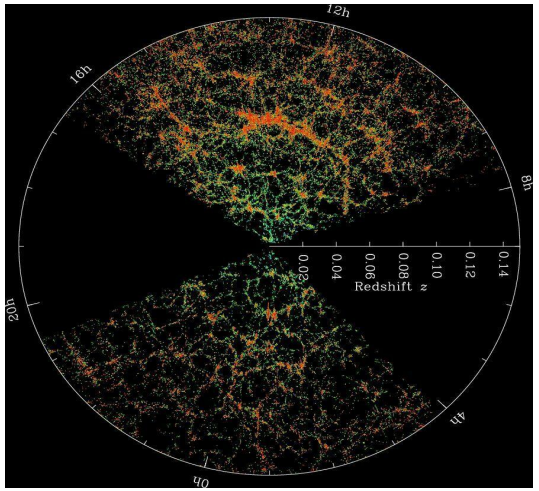
◆ Cosmic Microwave Background

Clowe et al. 2006 (Bullet Cluster)



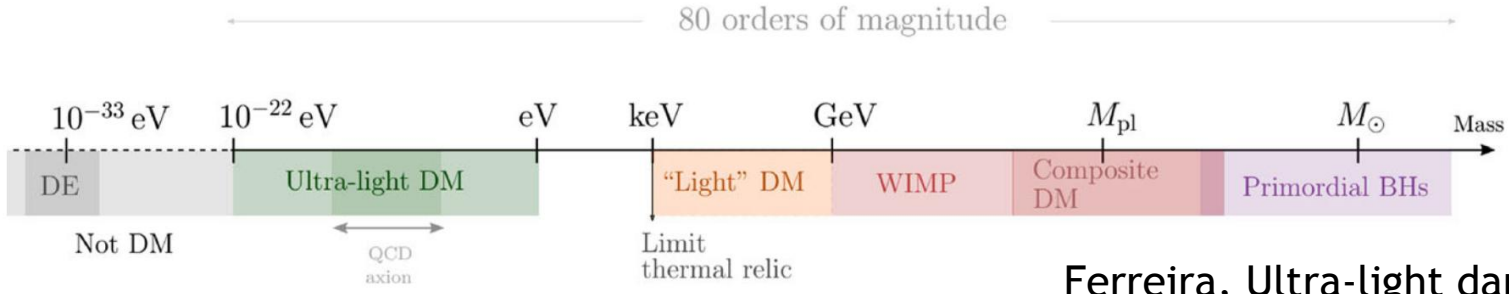
◆ Bullet Cluster

SDSS/BOSS

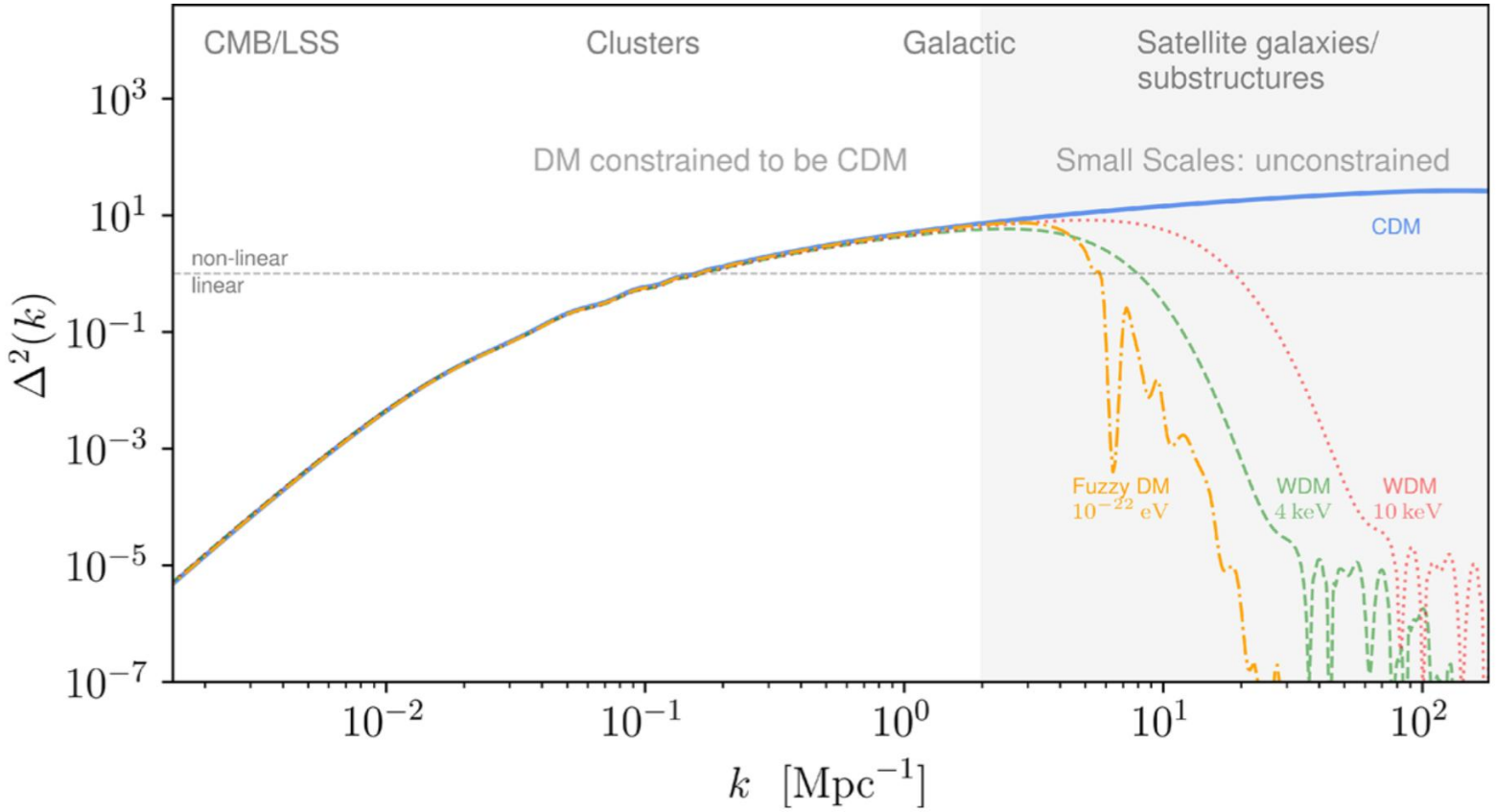


◆ Large-scale Structure

Dark Matter: theory vs observation



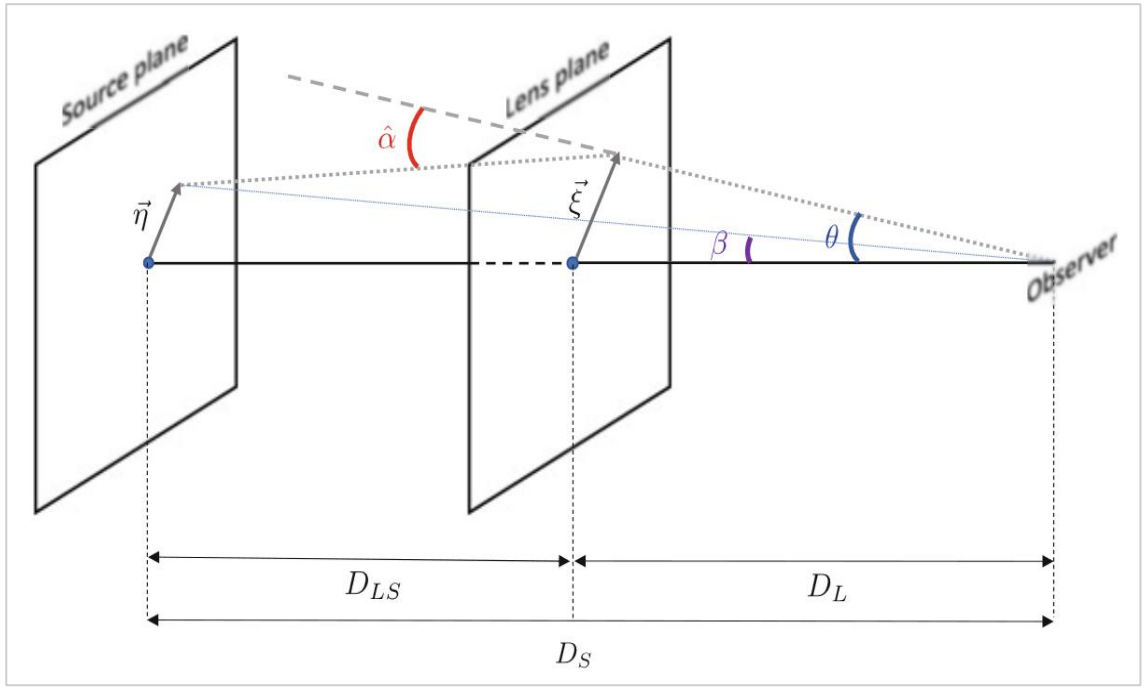
Ferreira, Ultra-light dark matter, 2021 A&AR



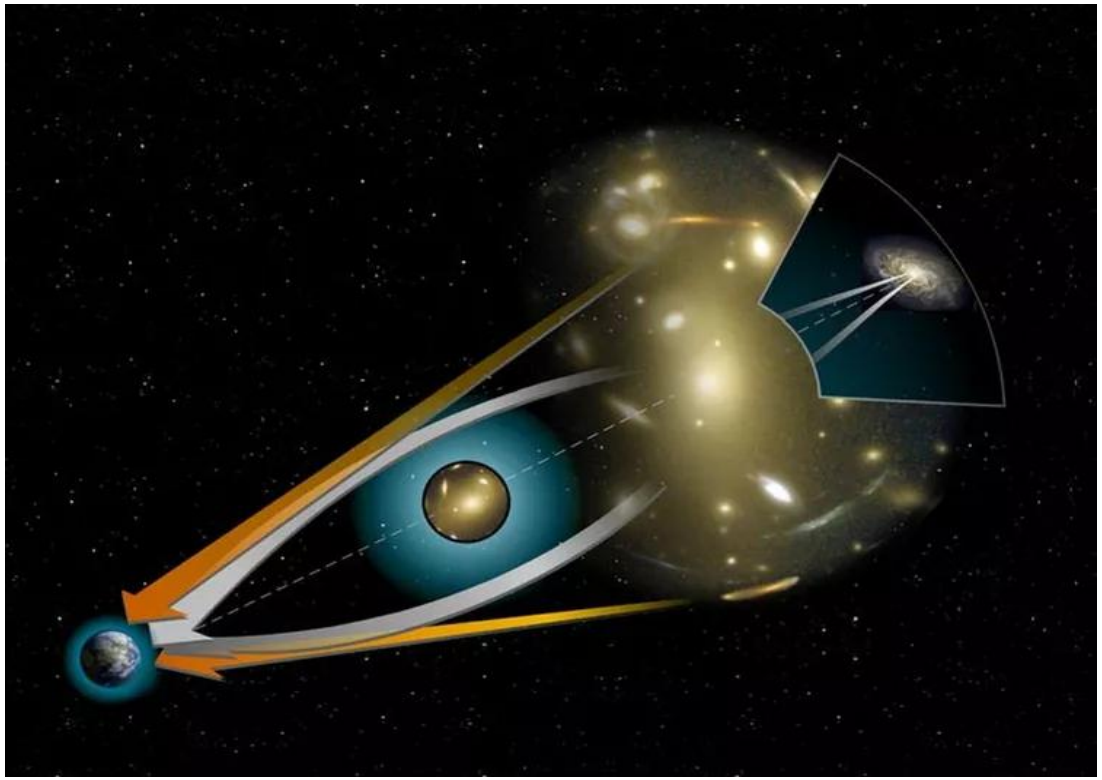
At relatively small scales, there is possible discrepancy between CDM prediction and observations, resulting in extensive discussion of alternatives of DM properties or baryonic effect

Strong lensing as a probe of dark matter

Lens Geometry



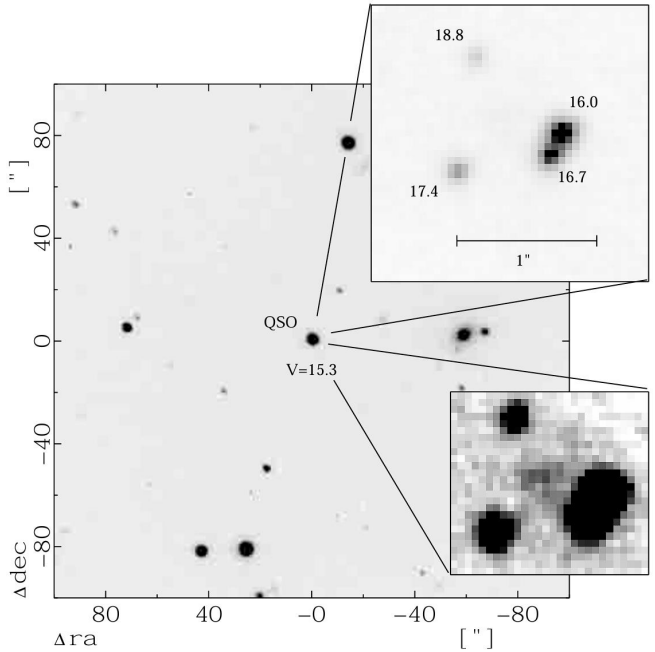
$$\beta = \theta - \alpha(\theta)$$



The **observed image configuration** is determined by the **lens mass distribution**

Strong lensing system HS 0810+2554

1997 — Discovery of HS 0810+2554 in the Hamburg Survey



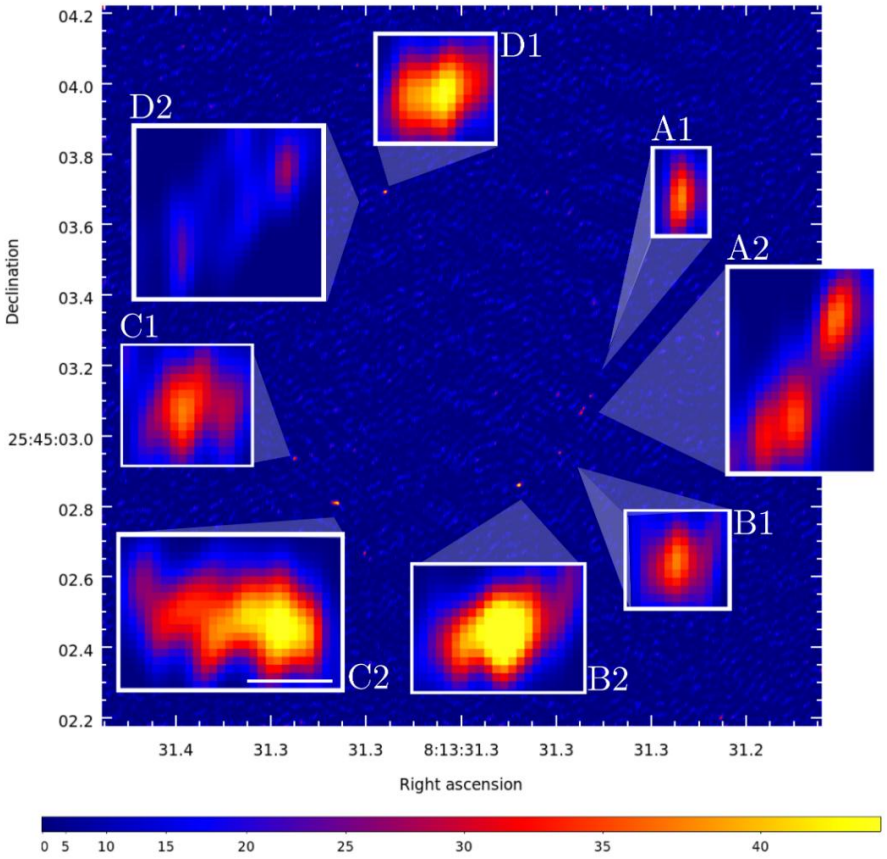
Reimers et al. (1997)

- Quad-image lens
- $z_l = 0.89$, $z_s = 1.51$
- Image separation 0.54”

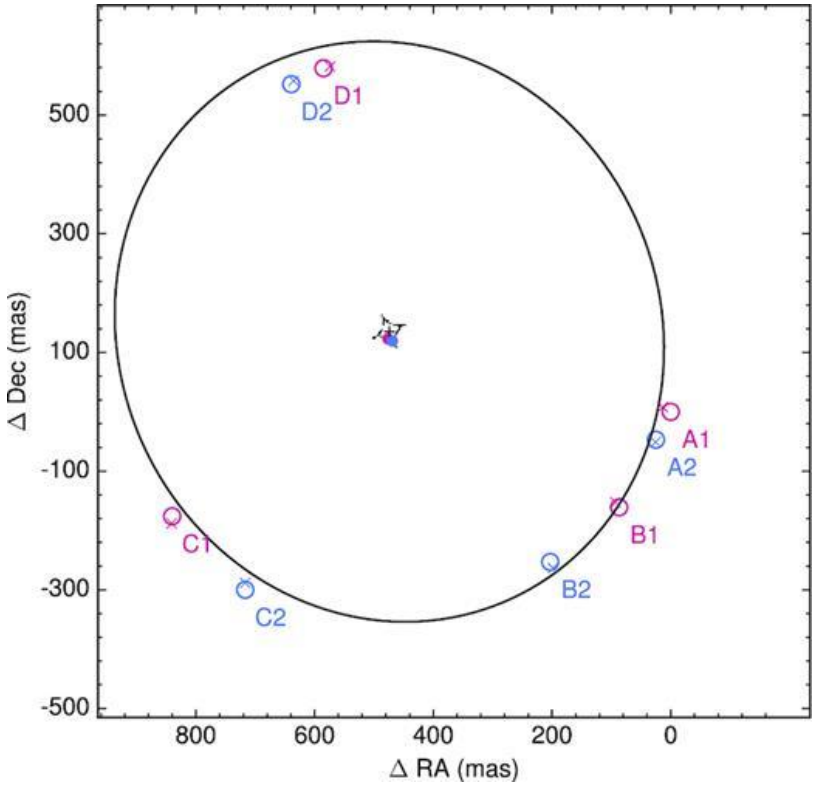
This optical observation can be explained with a smooth lens (Jackson et al., 2015)

Improved observation by radio VLBI

Hartley et al. (2019) MNRAS



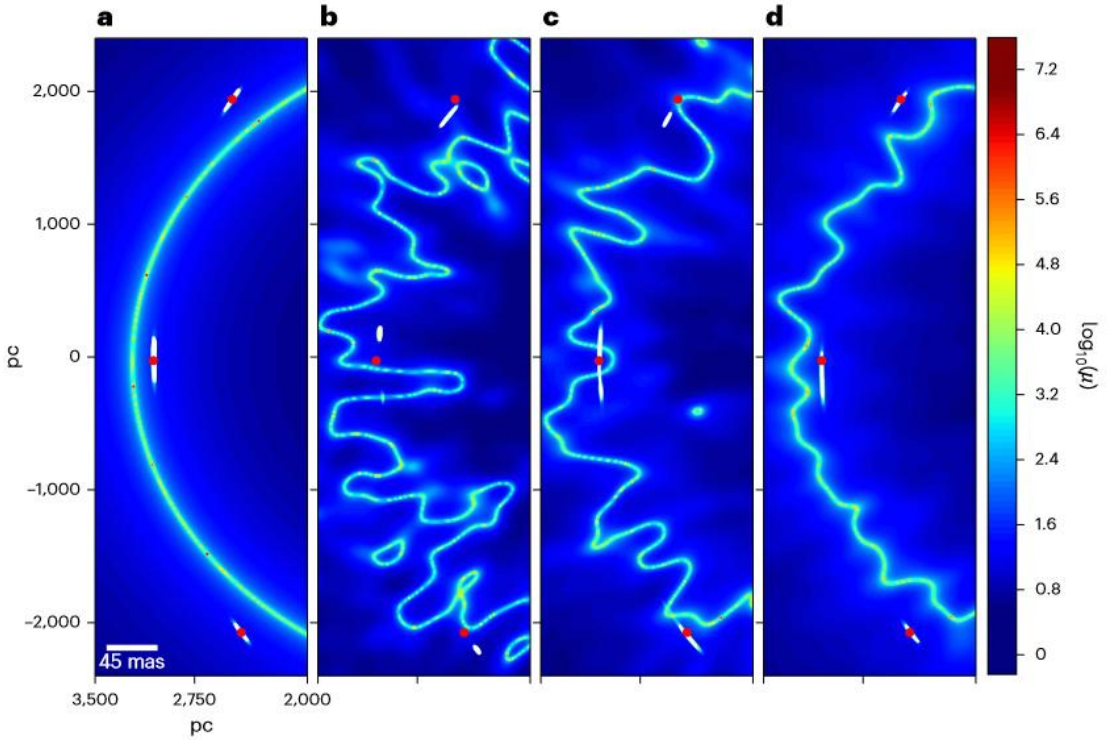
VLBI resolved two compact radio components



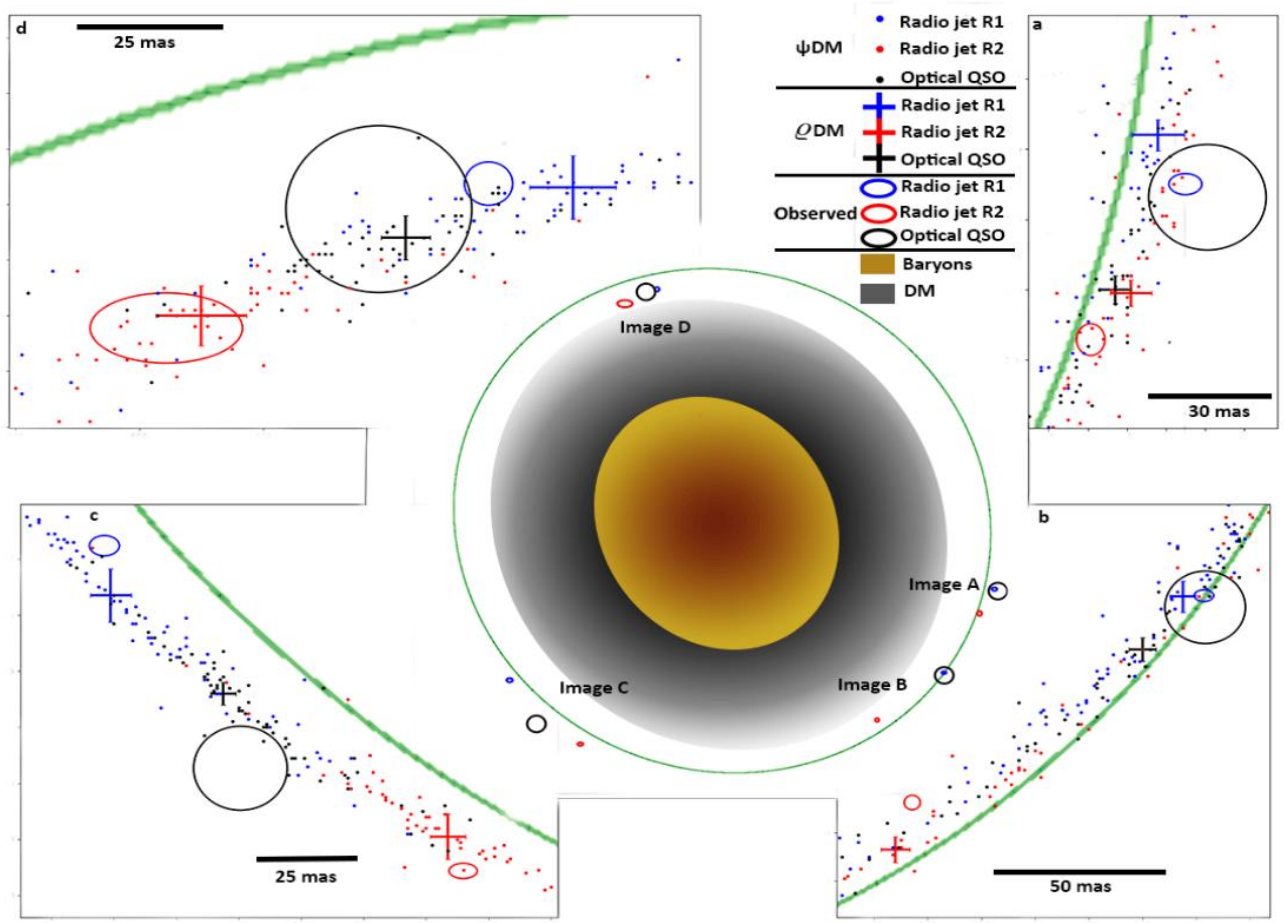
Best-fit CDM model

Smooth lens models alone can no longer explain the VLBI image positions

Fuzzy dark matter as a solution of HS 0810+2554



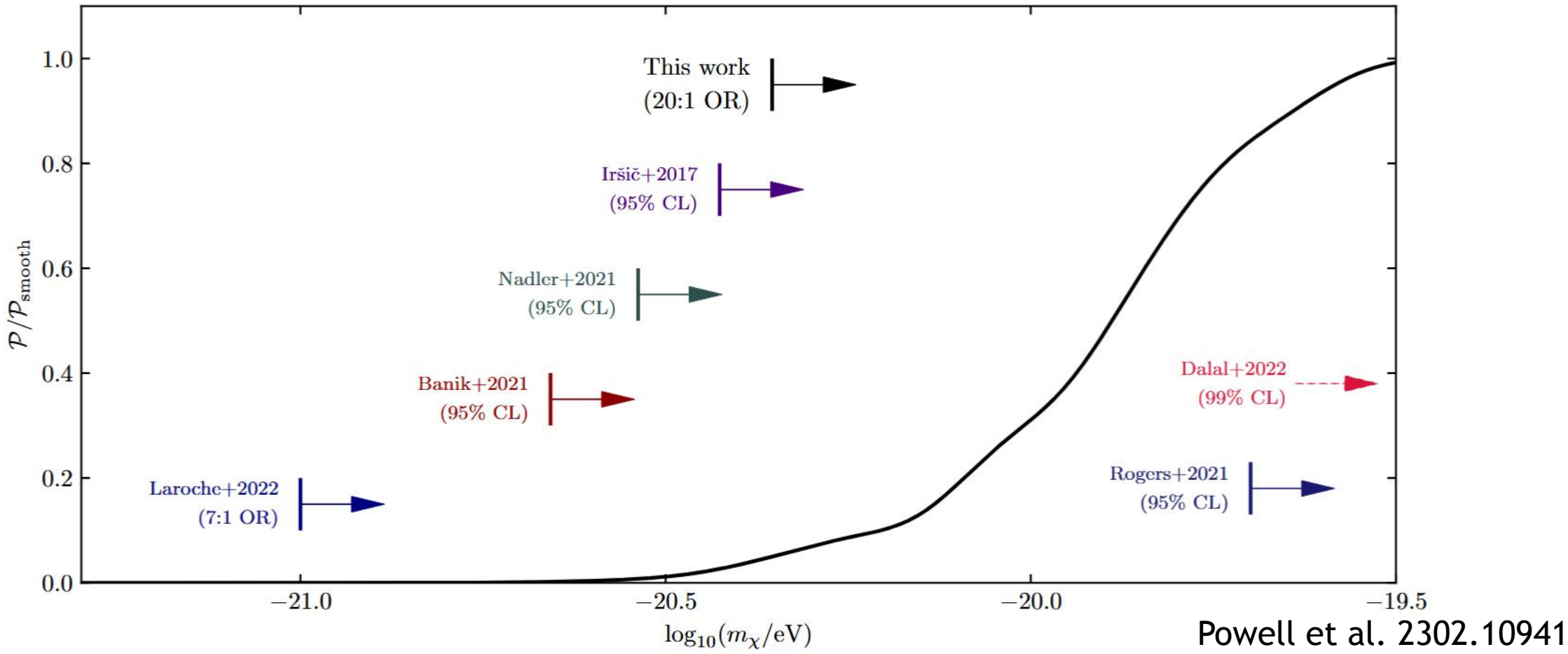
Lensing magnification of CDM versus FDM halos



FDM fits HS 0810+2554 perfectly, but CDM fails

Amruth et al. (2023) Nature Astronomy

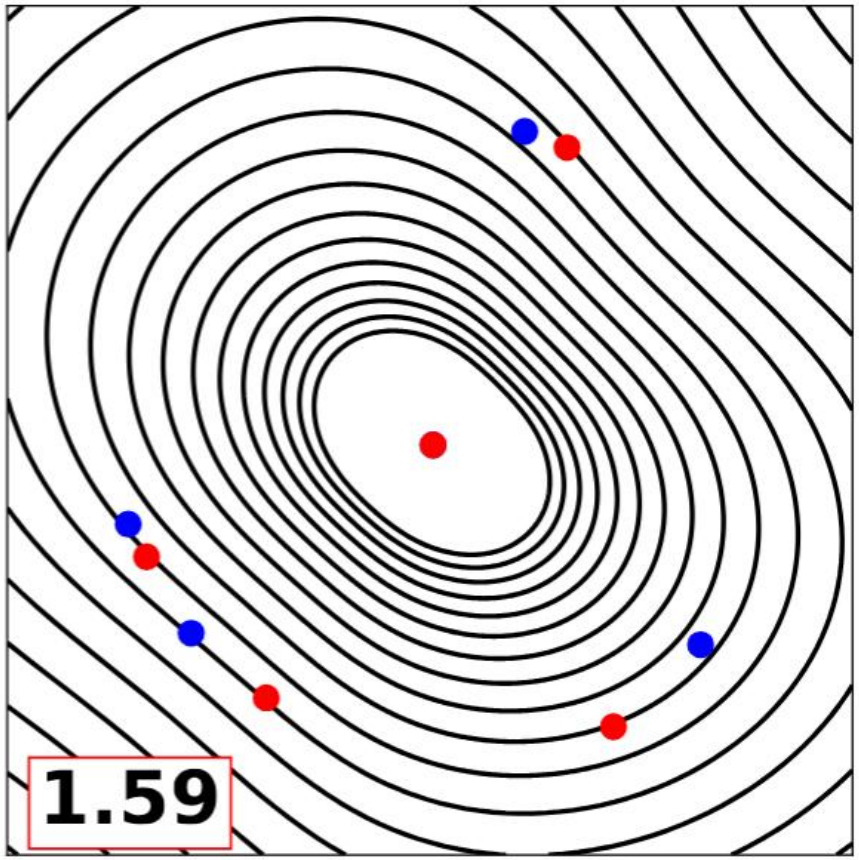
However, fuzzy dark matter is strongly constrained



Powell et al. 2302.10941

The preferred FDM mass (~10^{-22} eV) is in conflict with observation constraints

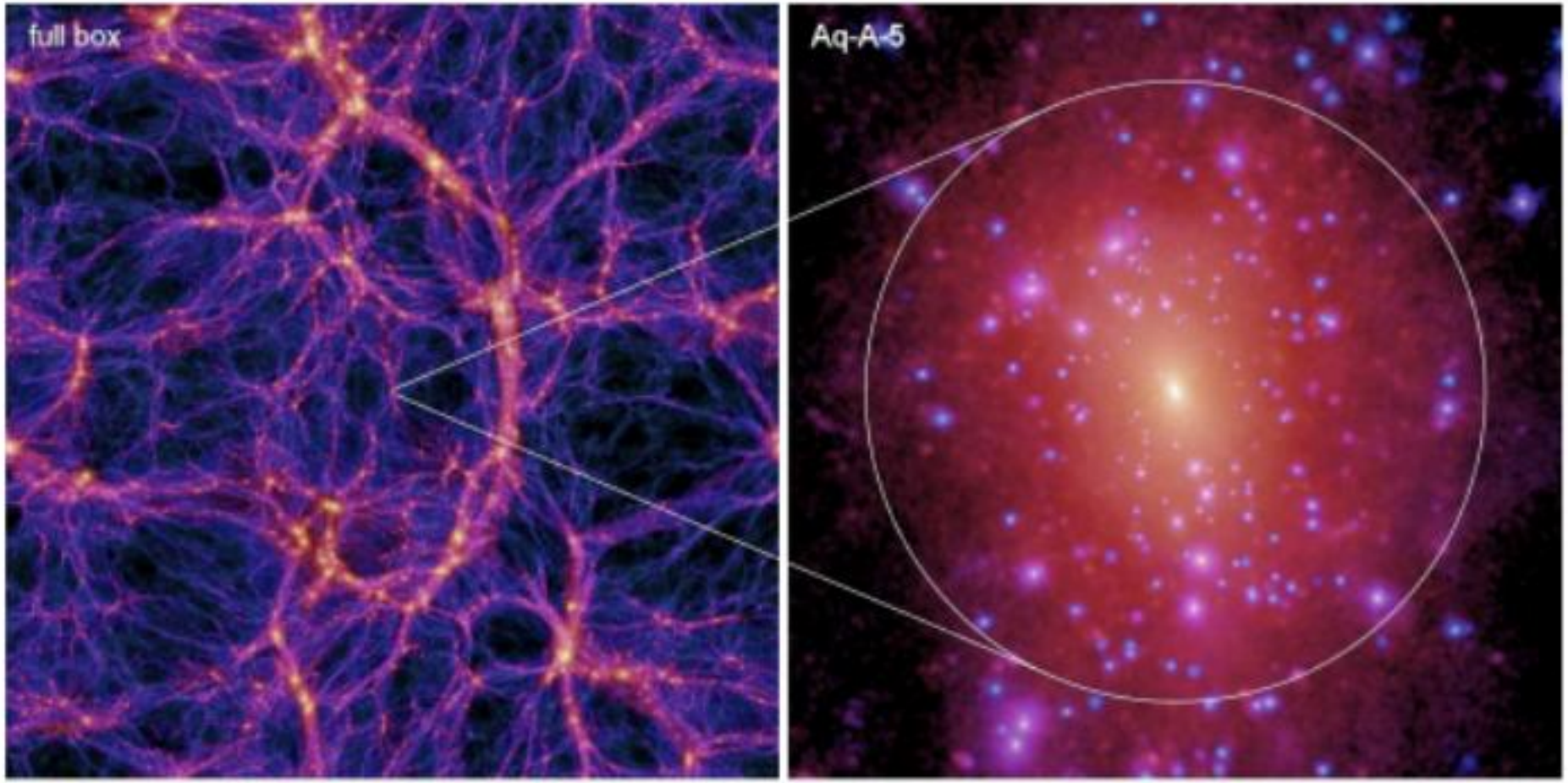
Alternative solution: high-order mass model



- Standard CDM with higher-order angular perturbations
- Best-fit χ=1.59
- Significantly improved compared with smooth halo model (χ~7-10)

Miller et al. (2025)

Subhalos expected in the CDM scenario

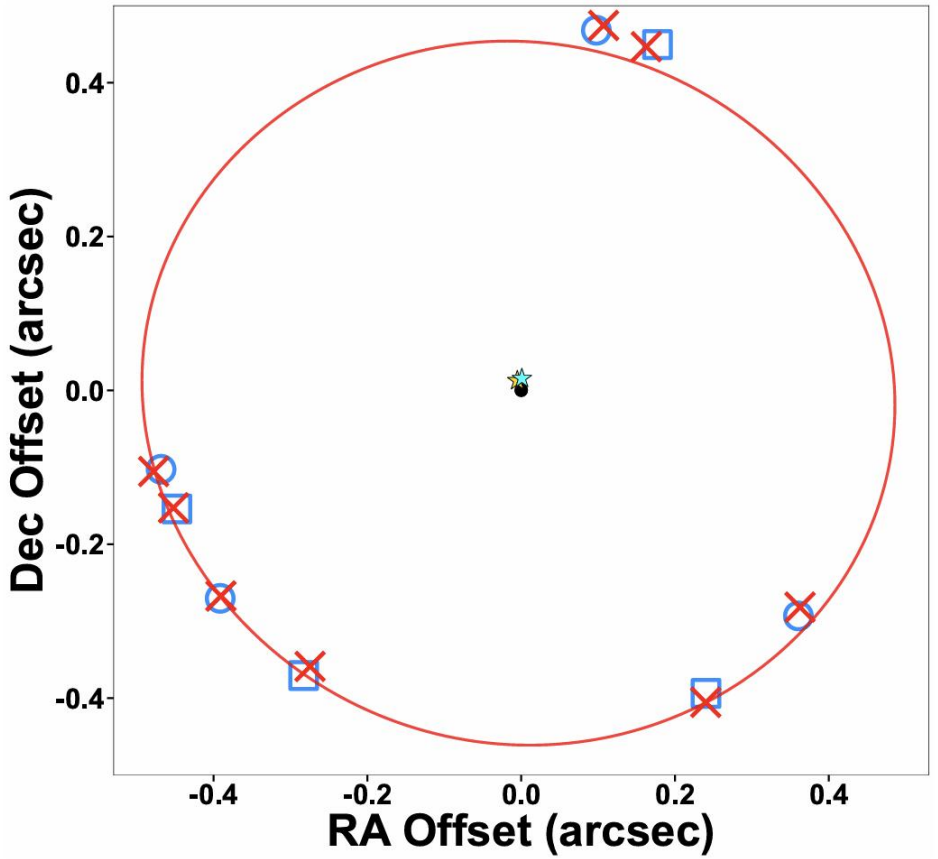


Springel et al. 2008, Aquarius simulation

Step 1: smooth halo fitting

Parameter	Prior Range	Best-fit Value
θ_E	$\mathcal{U}(0,1)$	0.4742
γ	$\mathcal{U}(1.5,2.5)$	2.3009
$x_{\rm lens}$	$\mathcal{U}(-1,1)$	0.0780
$y_{\rm lens}$	$\mathcal{U}(-1,1)$	0.1056
e_1	$\mathcal{U}(-0.5,0.5)$	0.0832
e_2	$\mathcal{U}(-0.5,0.5)$	-0.0161
γ_1	$\mathcal{U}(-0.1,0.1)$	0.0276
γ_2	$\mathcal{U}(-0.1,0.1)$	0.0074
β_{x1}	$\mathcal{U}(-1,1)$	0.0728
β_{y1}	$\mathcal{U}(-1,1)$	0.1181
$\theta_{\rm rel}$	$\mathcal{U}(0,2\pi)$	0.4367

$$\chi^2 = 60.38$$



$\theta_E = 0.4742''$, $M_{\rm host} = 1.785 \times 10^{12} M_\odot$

Consistent with previous work

Step 2: smooth halo + 1 subhalo

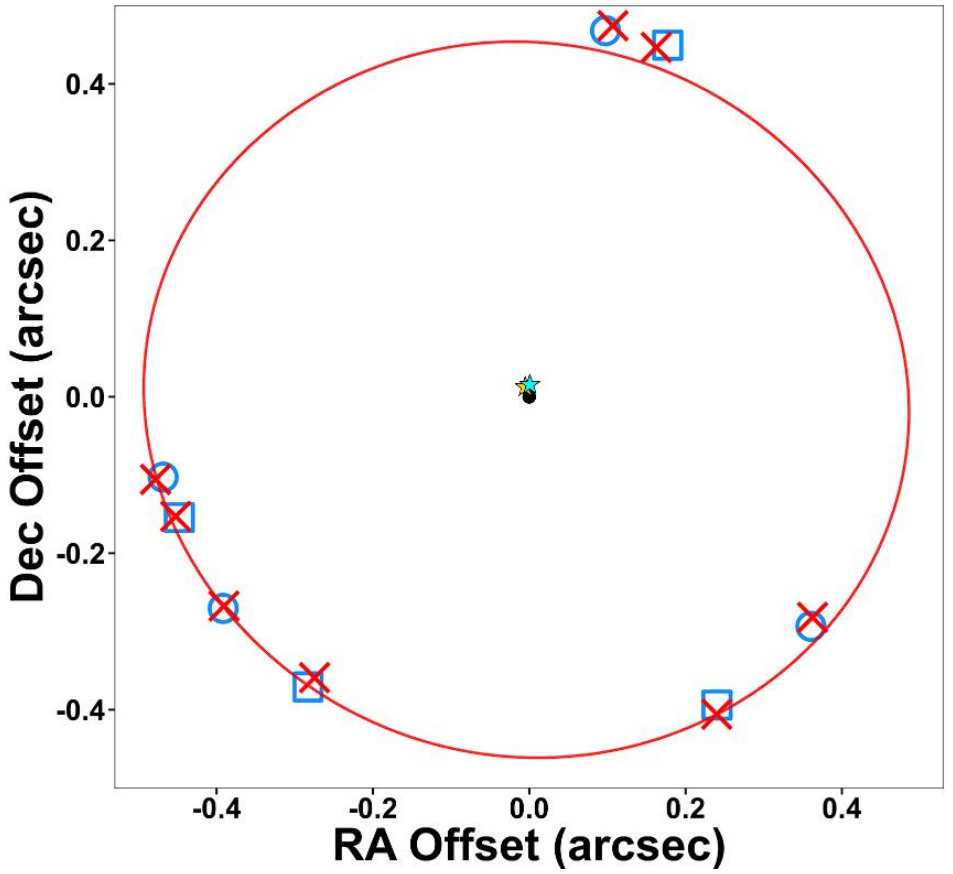
Adding an NFW subhalo with free mass and location

$$\rho(r) = \frac{\rho_s}{(r/r_s)\,(1+r/r_s)^2}$$

$$M_{\rm sub} = 1.26 \times 10^{10}\ M_\odot$$

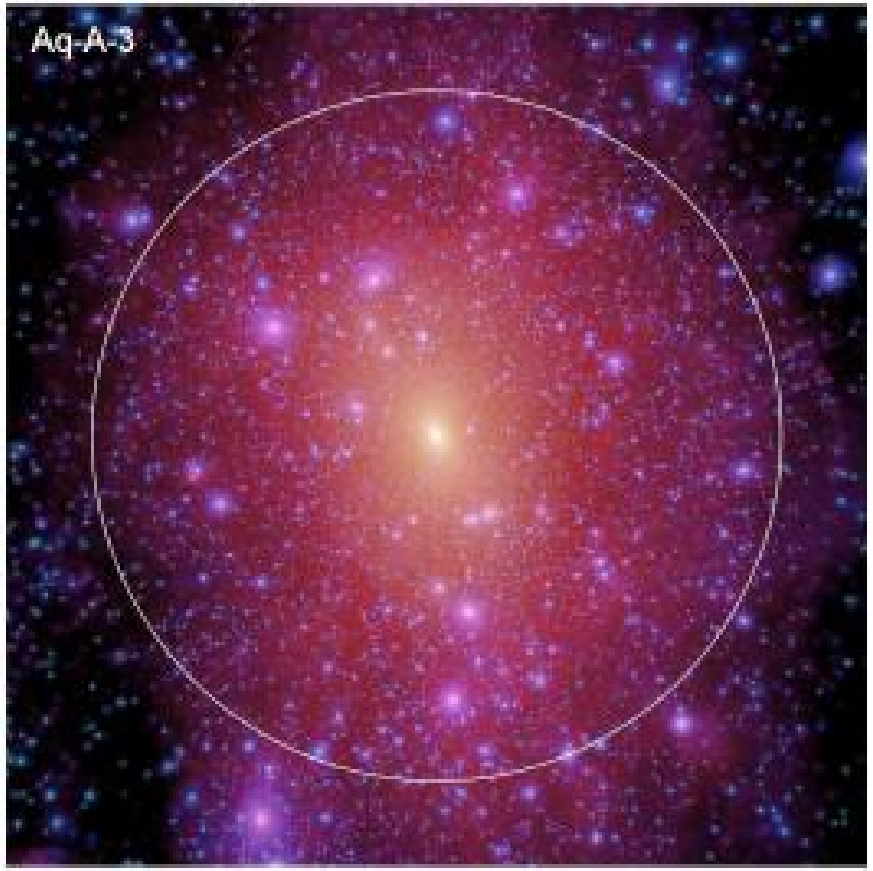
$$(x_{\rm sub}, y_{\rm sub}) = (0.185'', -0.311'')$$

$\chi^2 = 60.38 \rightarrow \chi^2 = 30.58$

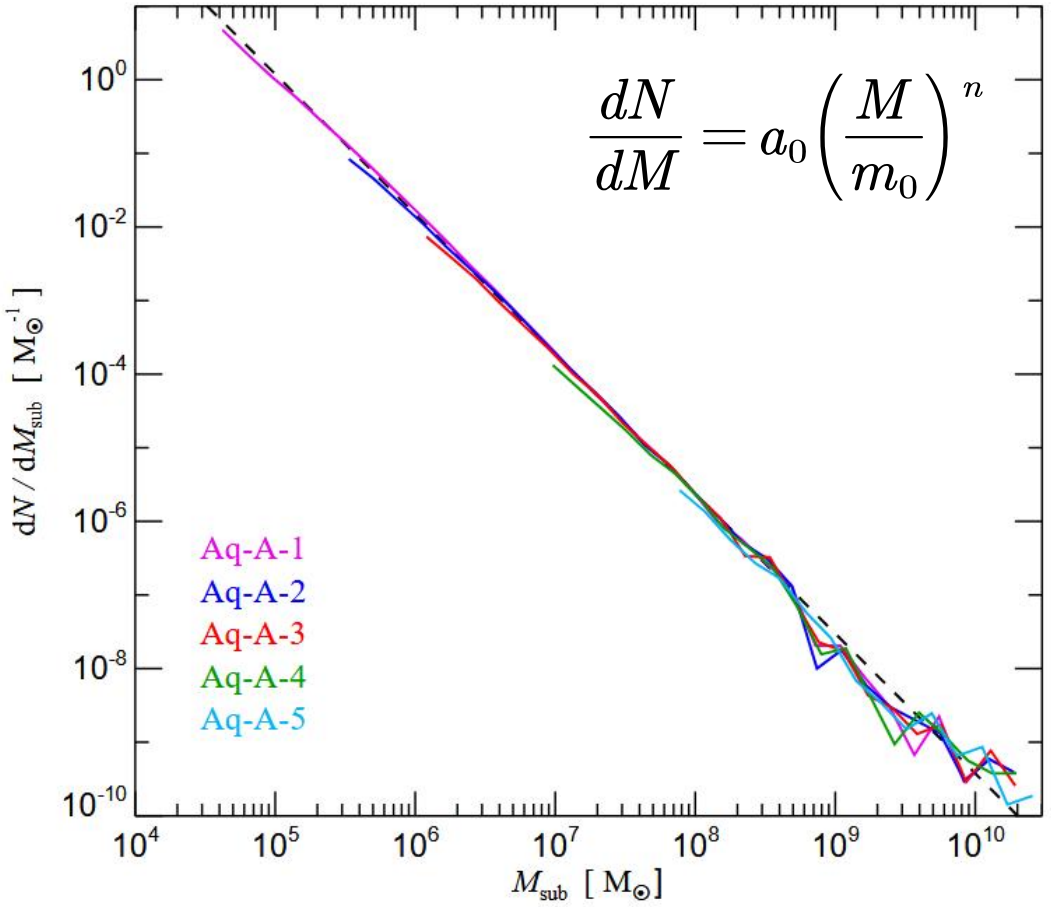


A single subhalo improves the fit, but cannot fully explain the observed anomalies

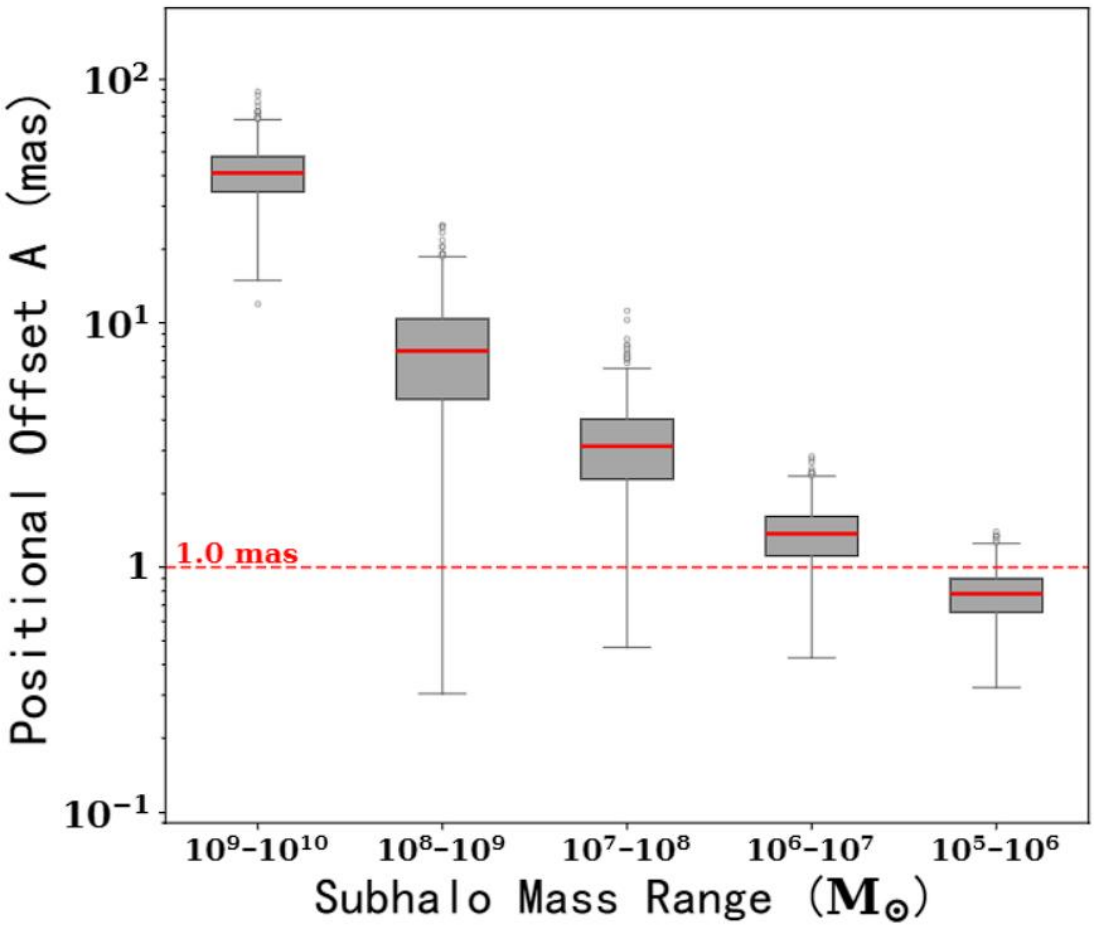
Step 3: smooth halo + subhalo population

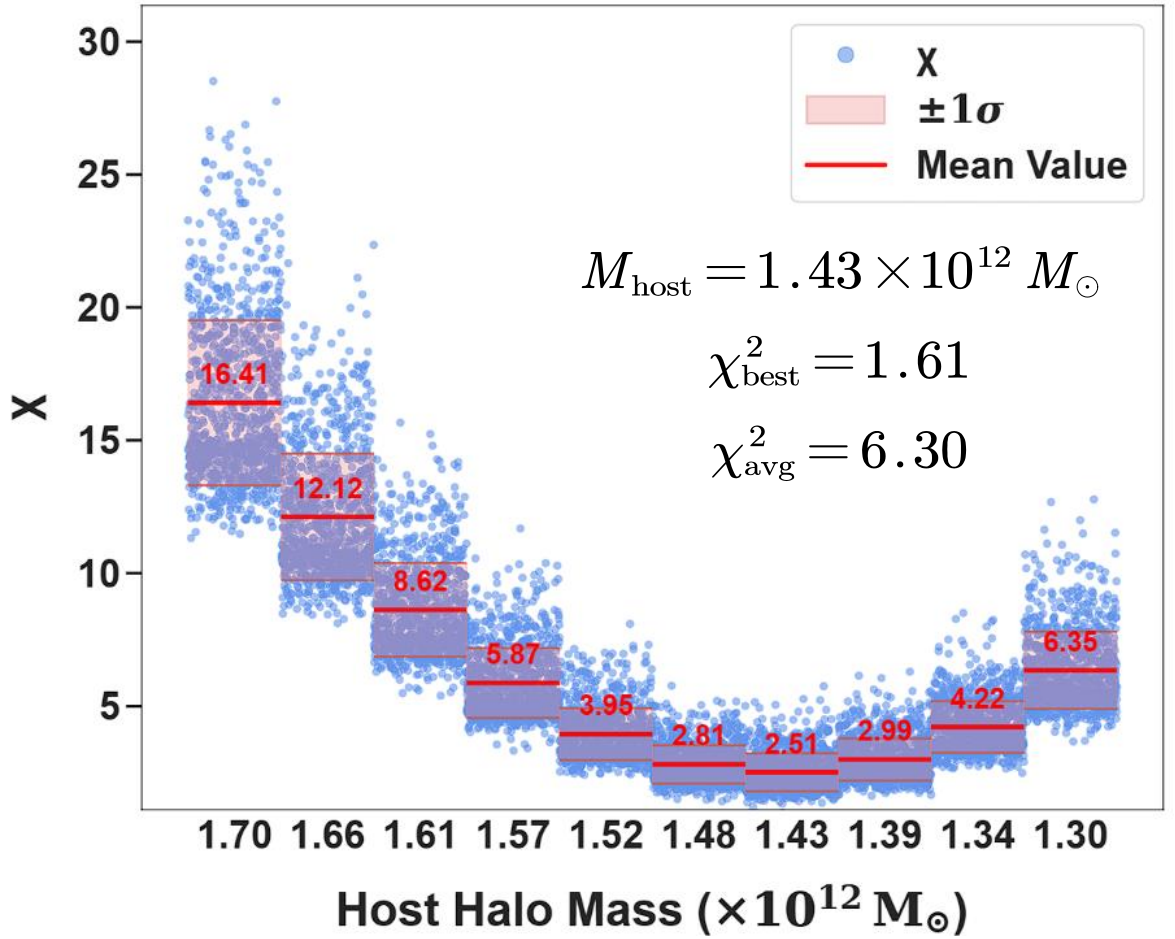


$$\rho(r) = \rho_{-2} \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right)\right]$$



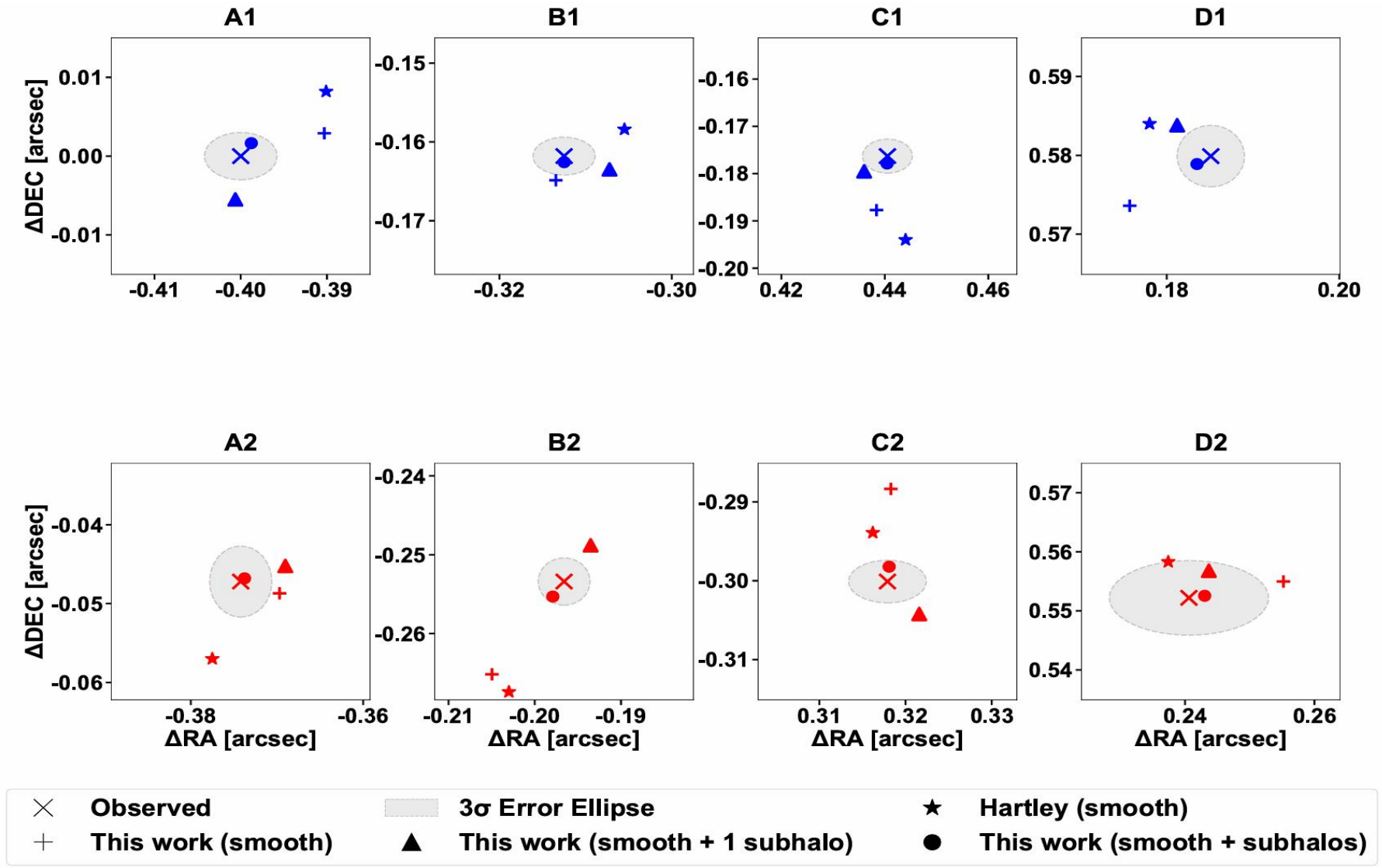
Step 3: smooth halo + subhalo population



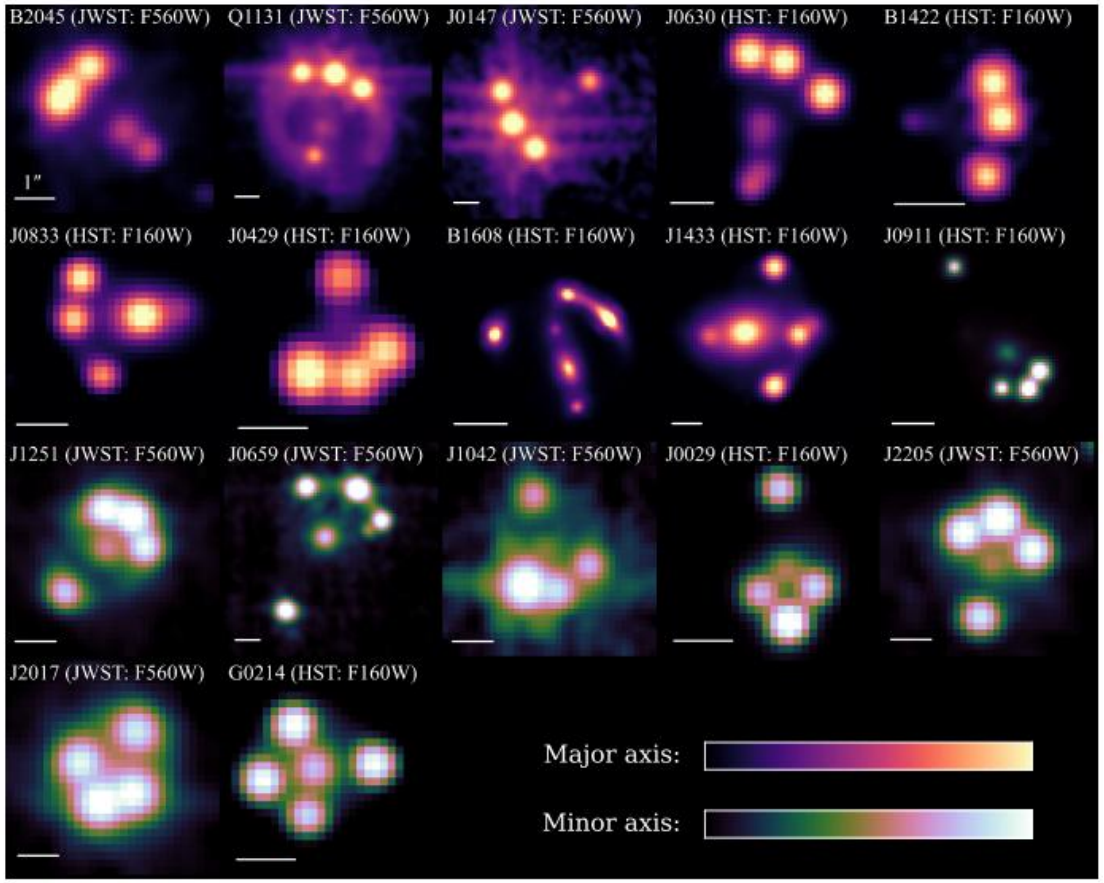


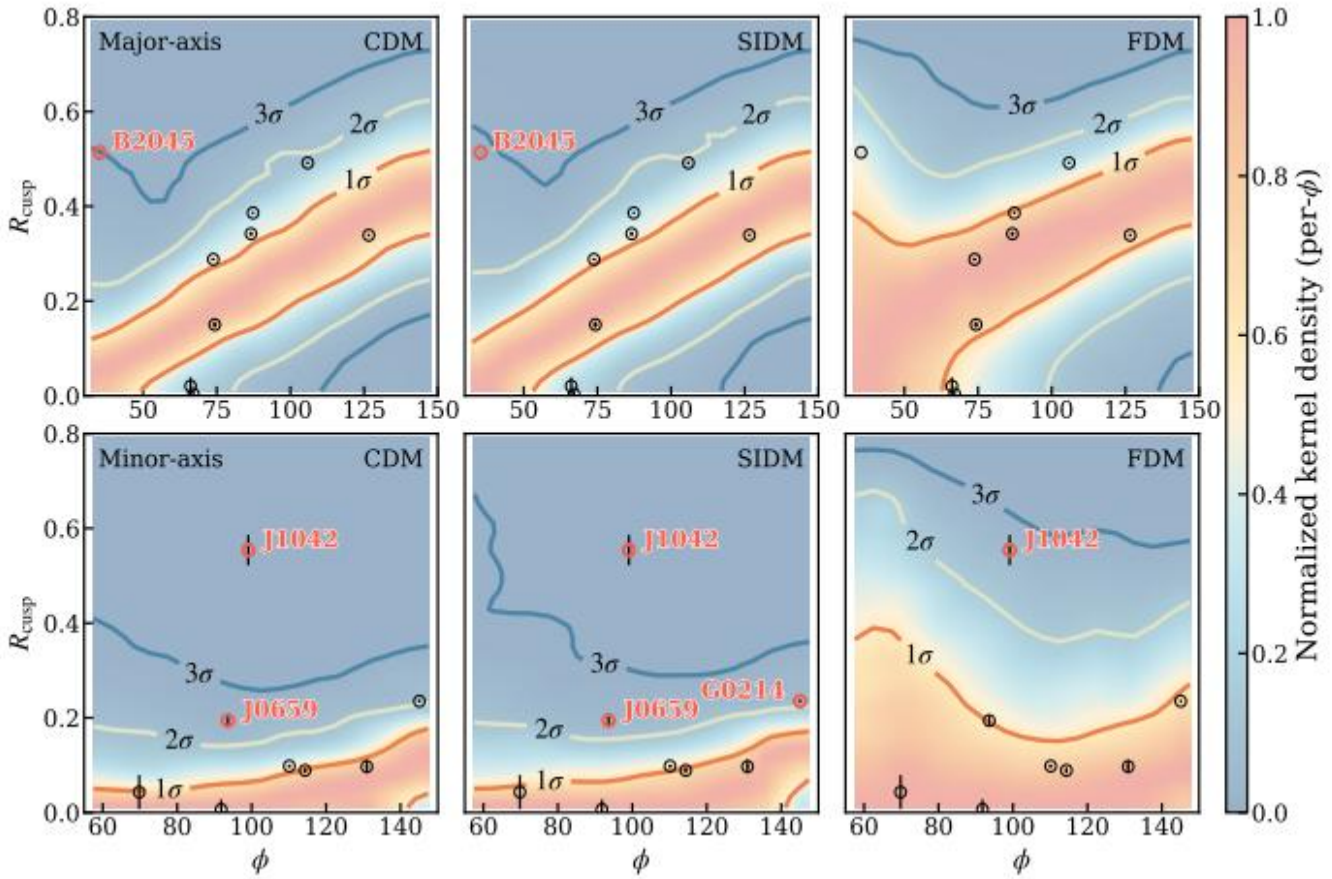
Positional offset from different mass ranges of subhalos

Step 3: smooth halo + subhalo population



More strong lensing systems





Hou et al., arXiv:2601.16818

Conclusion

- Strong gravitational lensing is a powerful tool to probe dark matter distribution and properties
- The positional anomalies in HS 0810+2554 show deviation from expectation of a smooth CDM halo, triggerring discussion on fuzzy dark matter or high-order mass distribution
- Including the CDM subhalos can naturally explain the positional anomalies

Thank you!