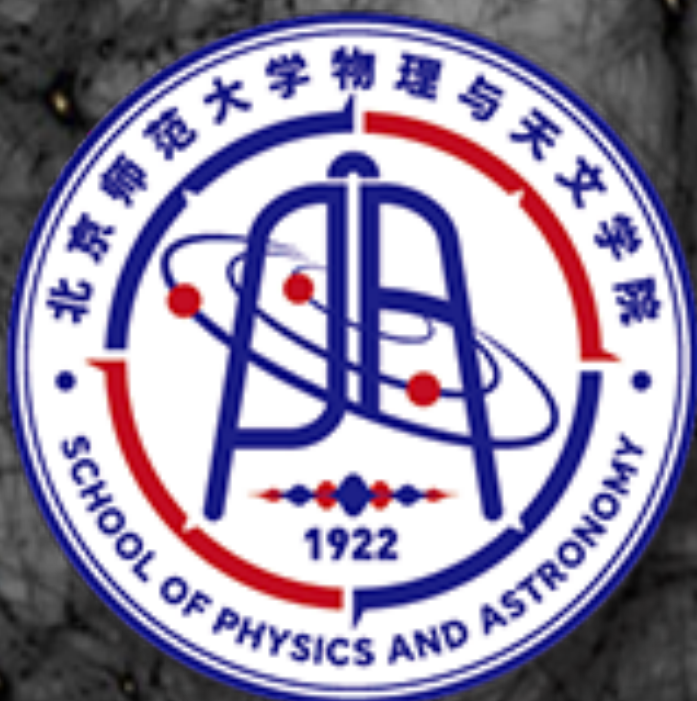


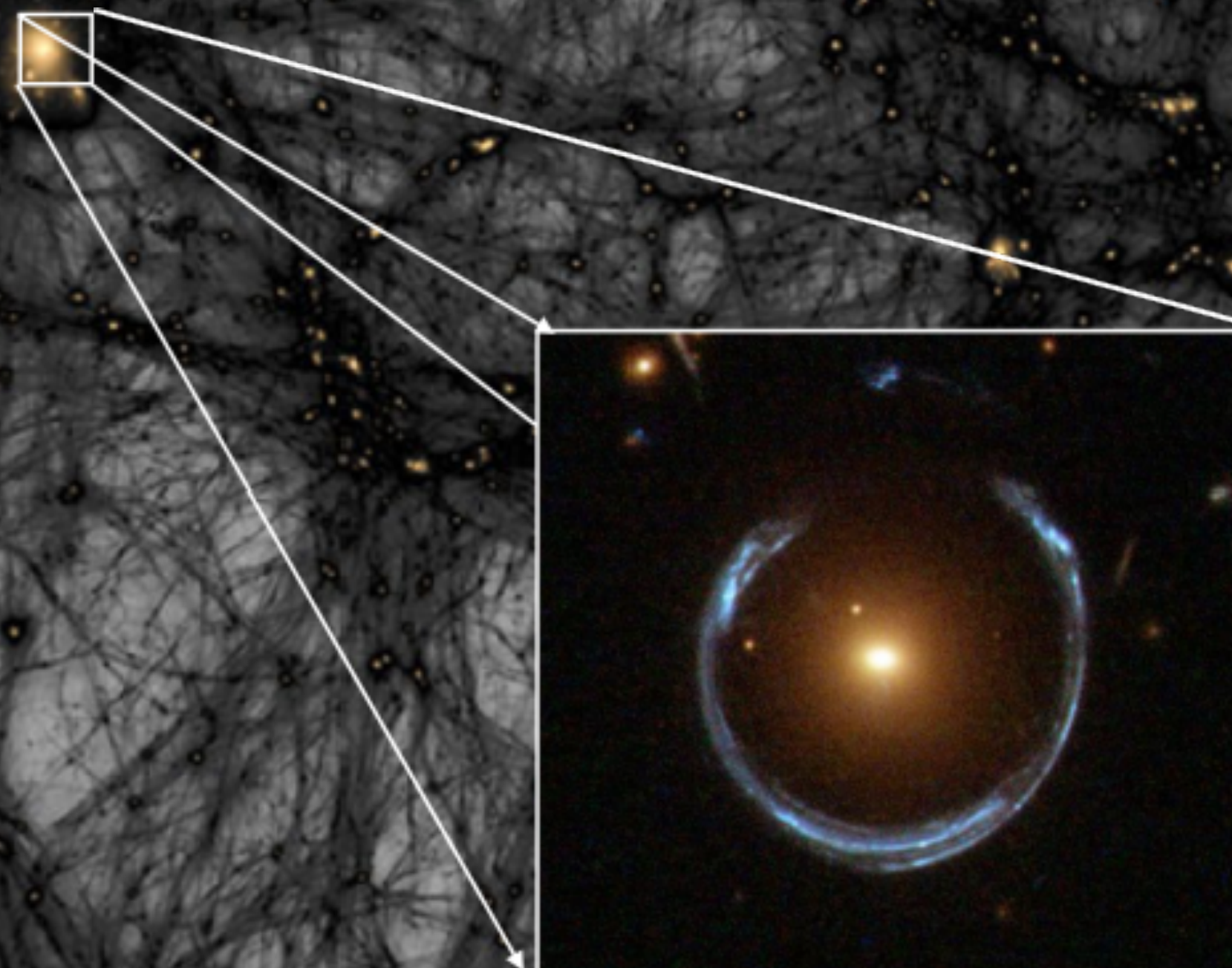
Exploring the identity of dark matter with galaxy strong lensing



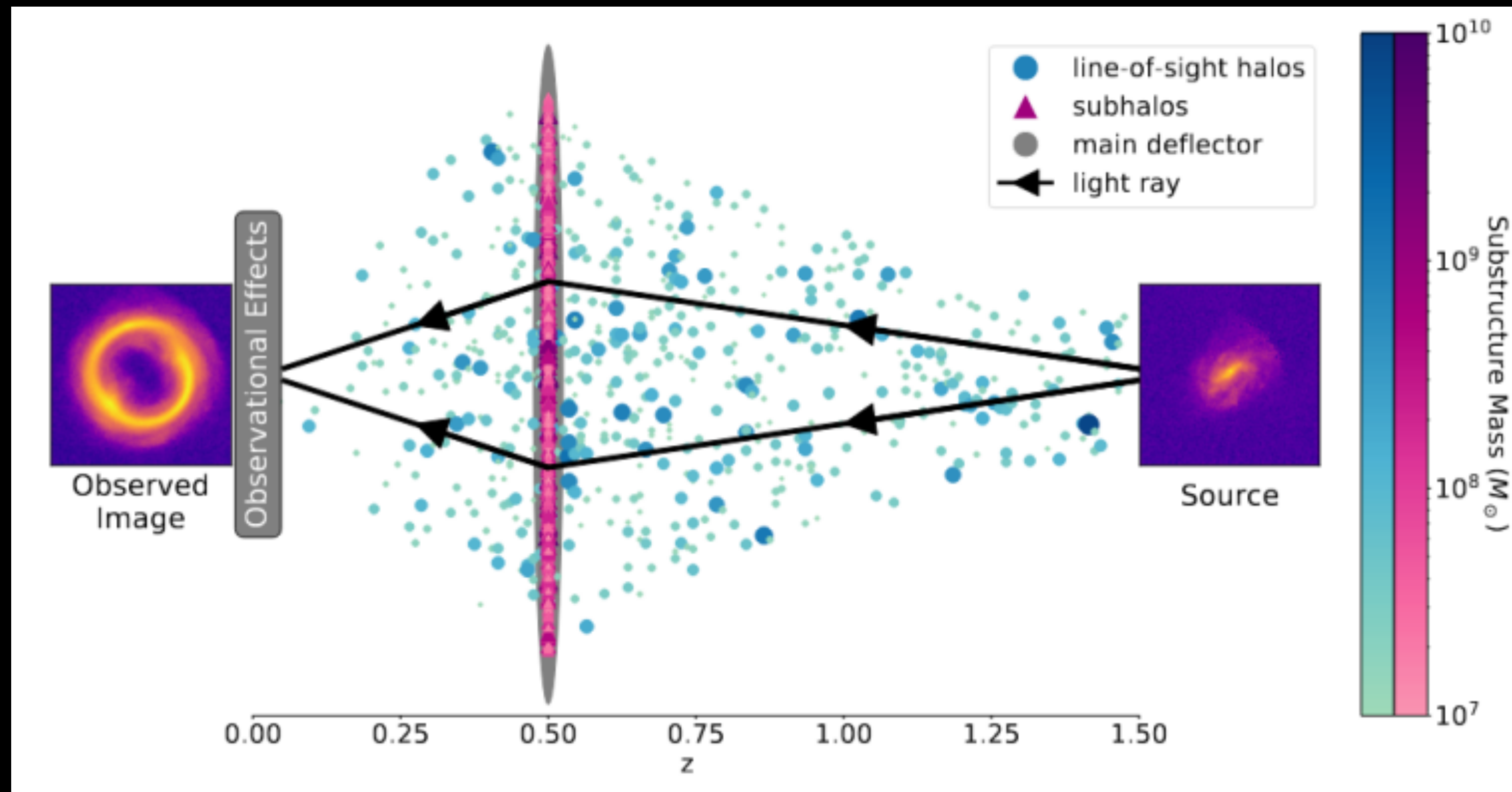
李然 Ran Li

Beijing Normal University

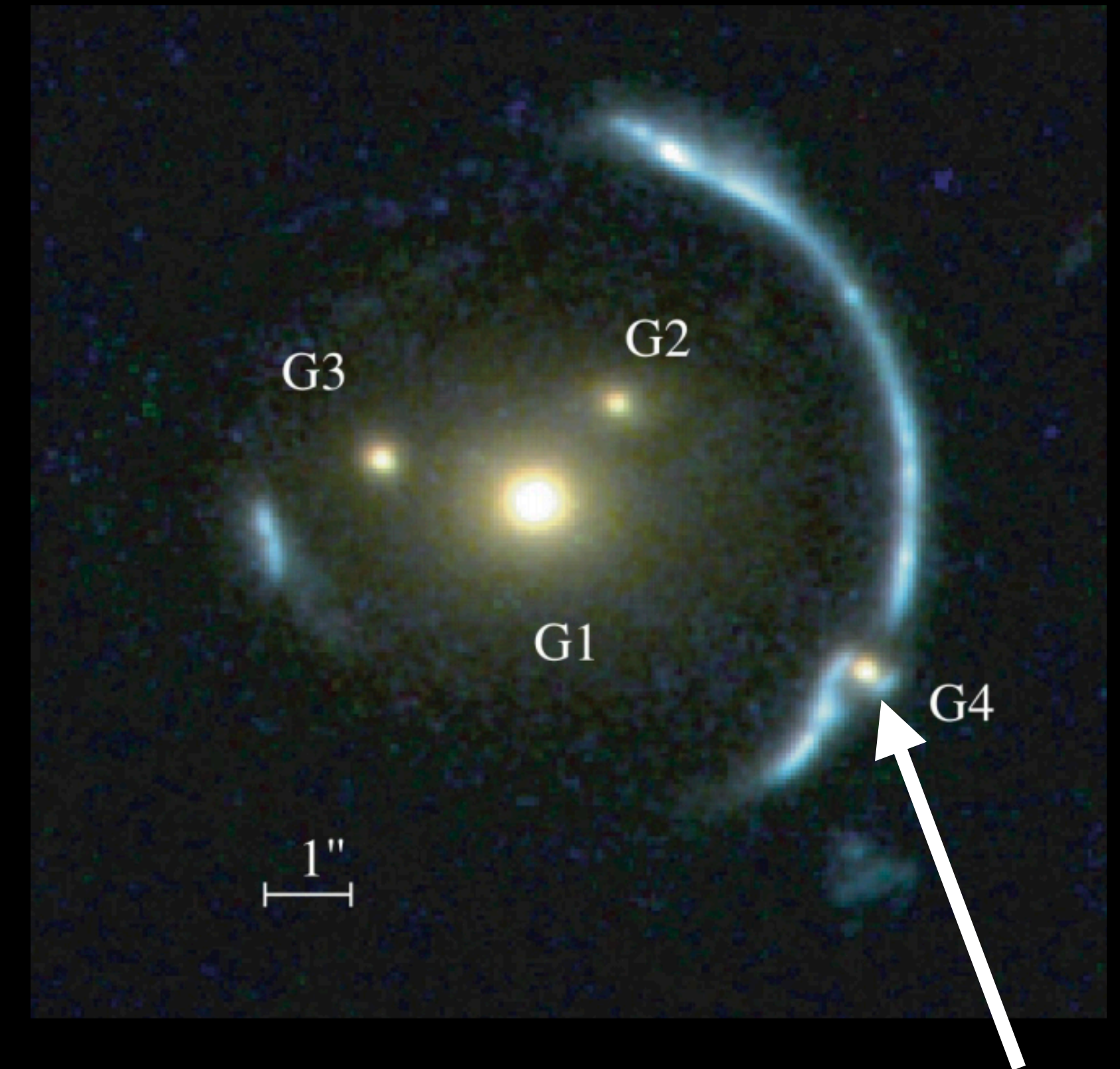
With: Xiaoyue Cao, Shubo Li, Qiuhan He, Kaihao Wang, James W. Nightingale, Samuel Lange, Kaihao Wang, Andrew Robertson, Aristeidis Amvrosiadis, Richard Massey, Shaun Cole, Carlos S. Frenk et al.



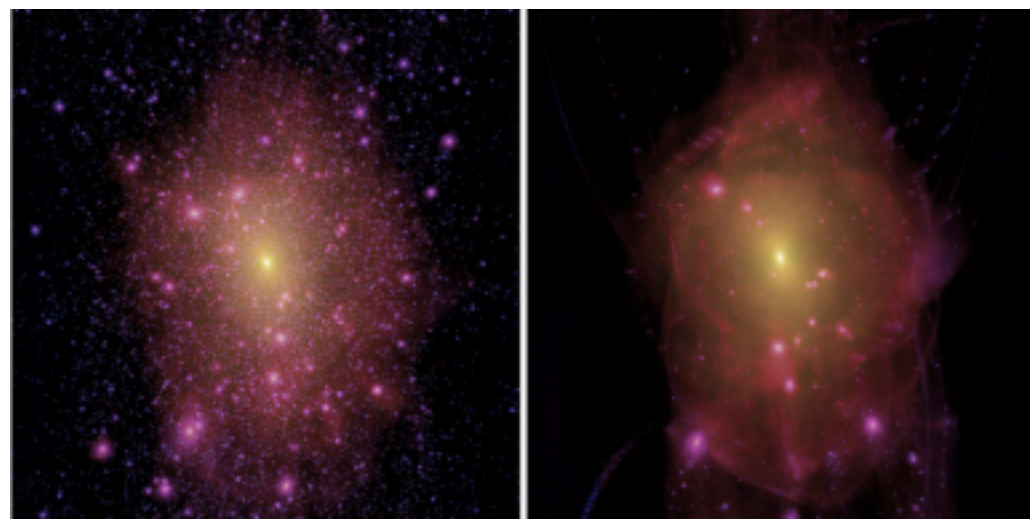
Detecting very low mass halo/subhalo



Wagner-Carena et al. 2023

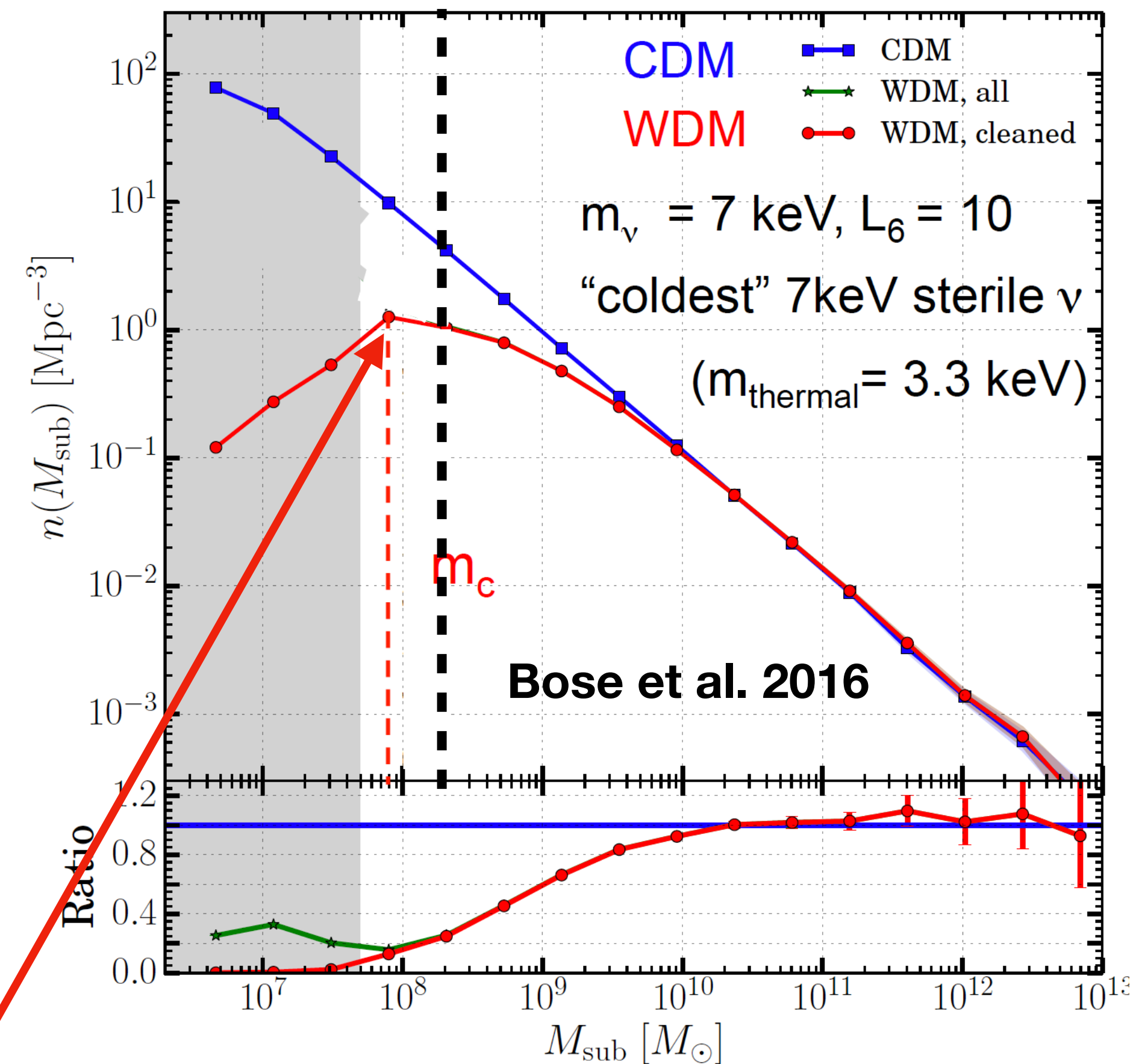


Substructure can perturb lensing image



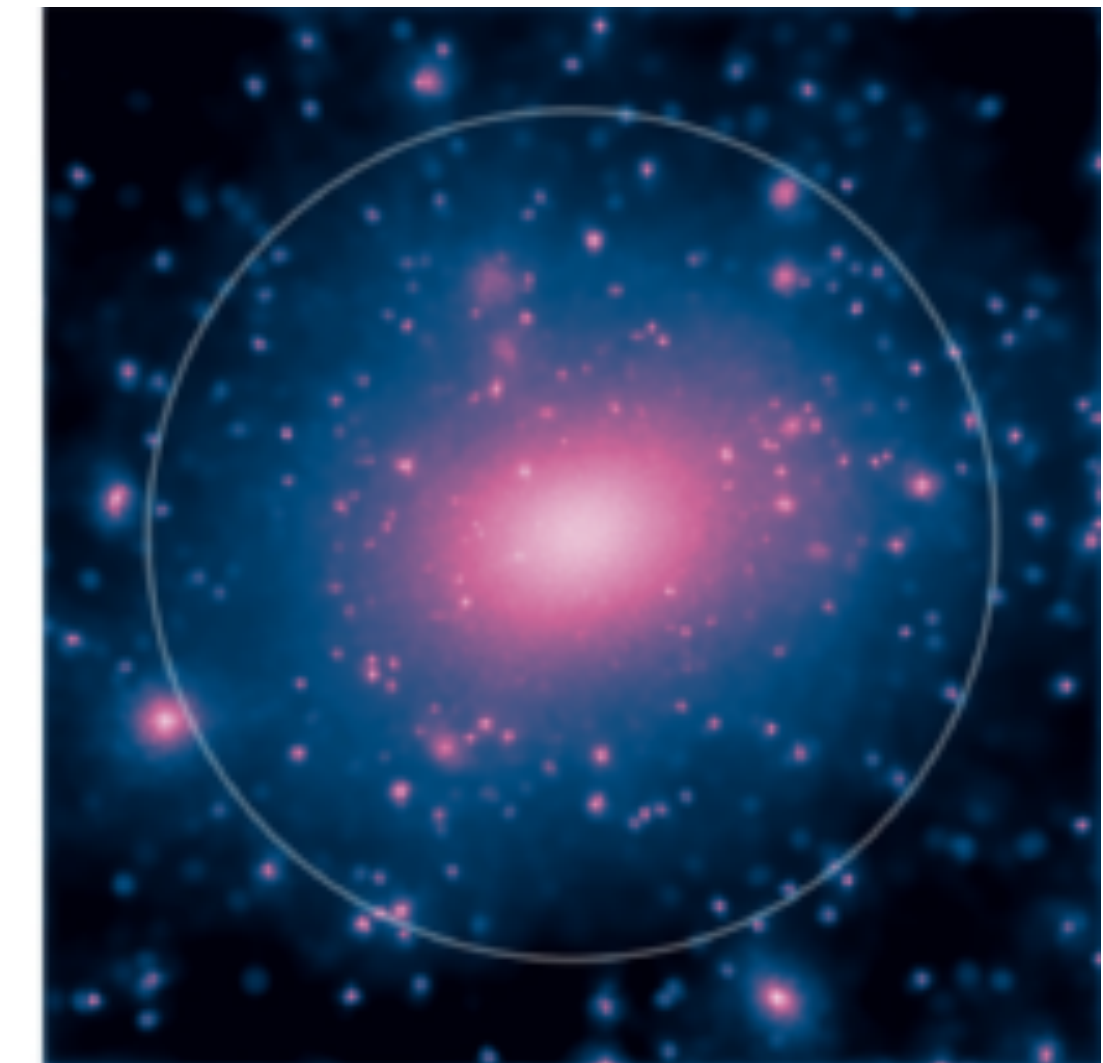
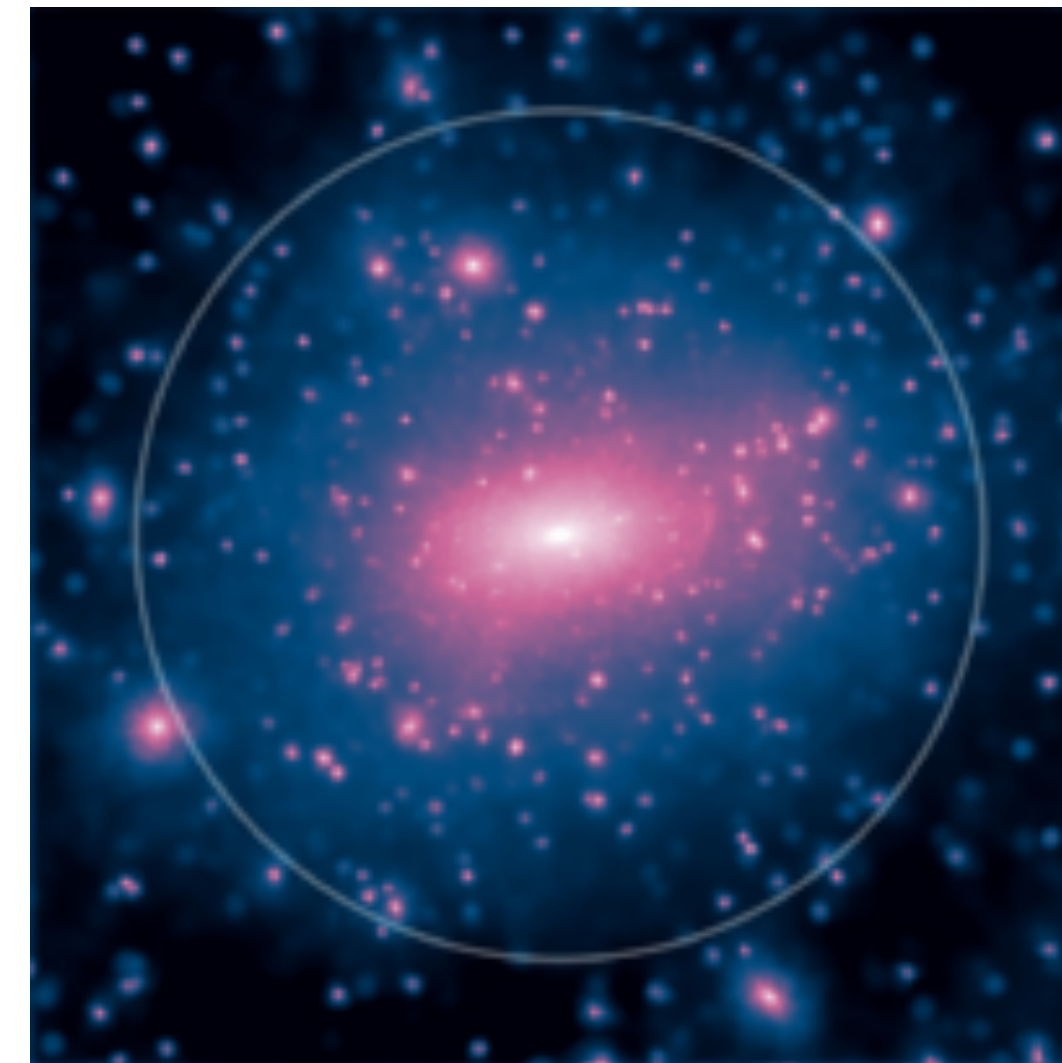
Warm or Cold?

Milky Way dwarf



Mass function Cut-off

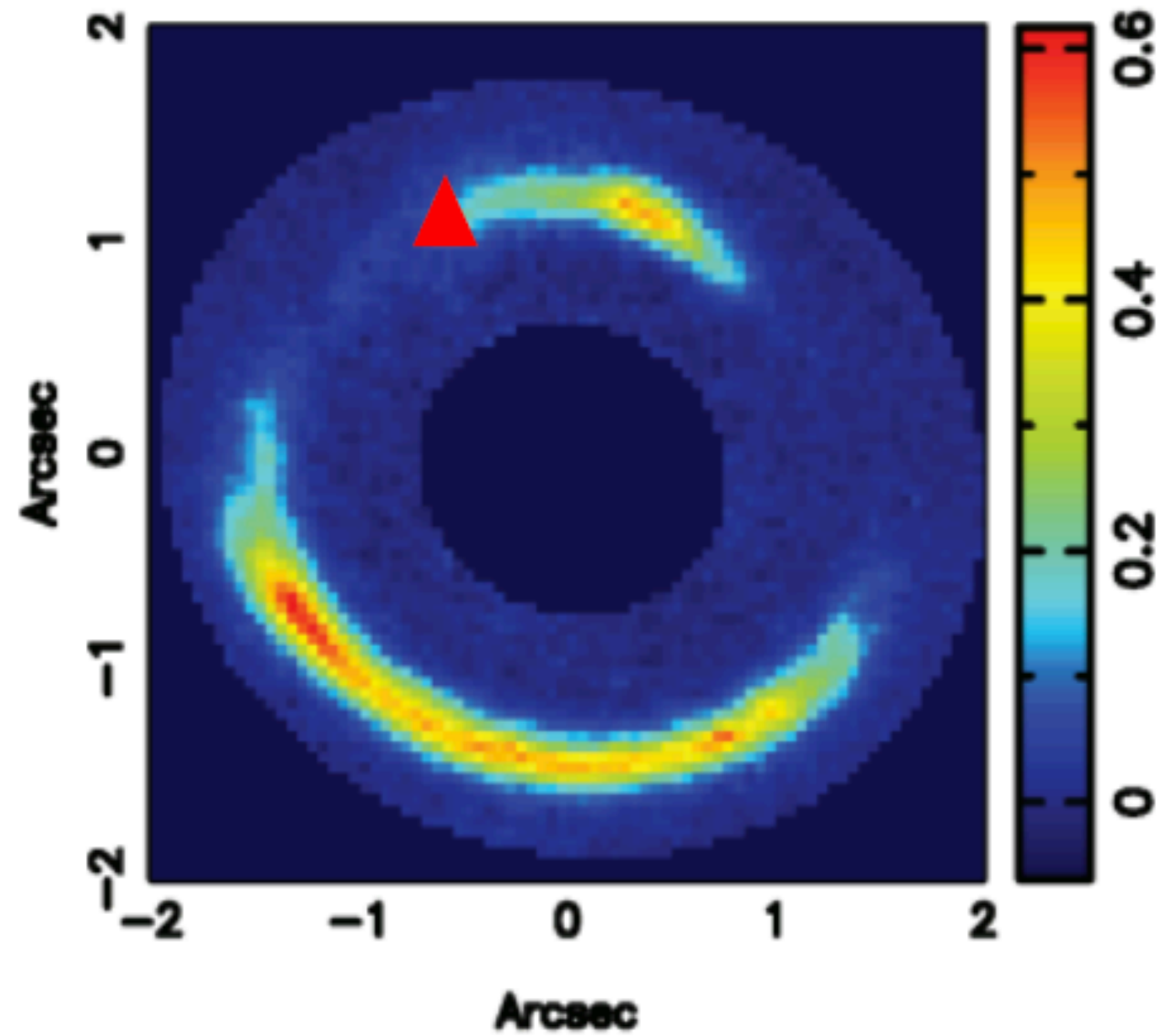
Self-interaction?



Brinckmann et al. 2018

HST Imaging

Data SLAC 0946+1006

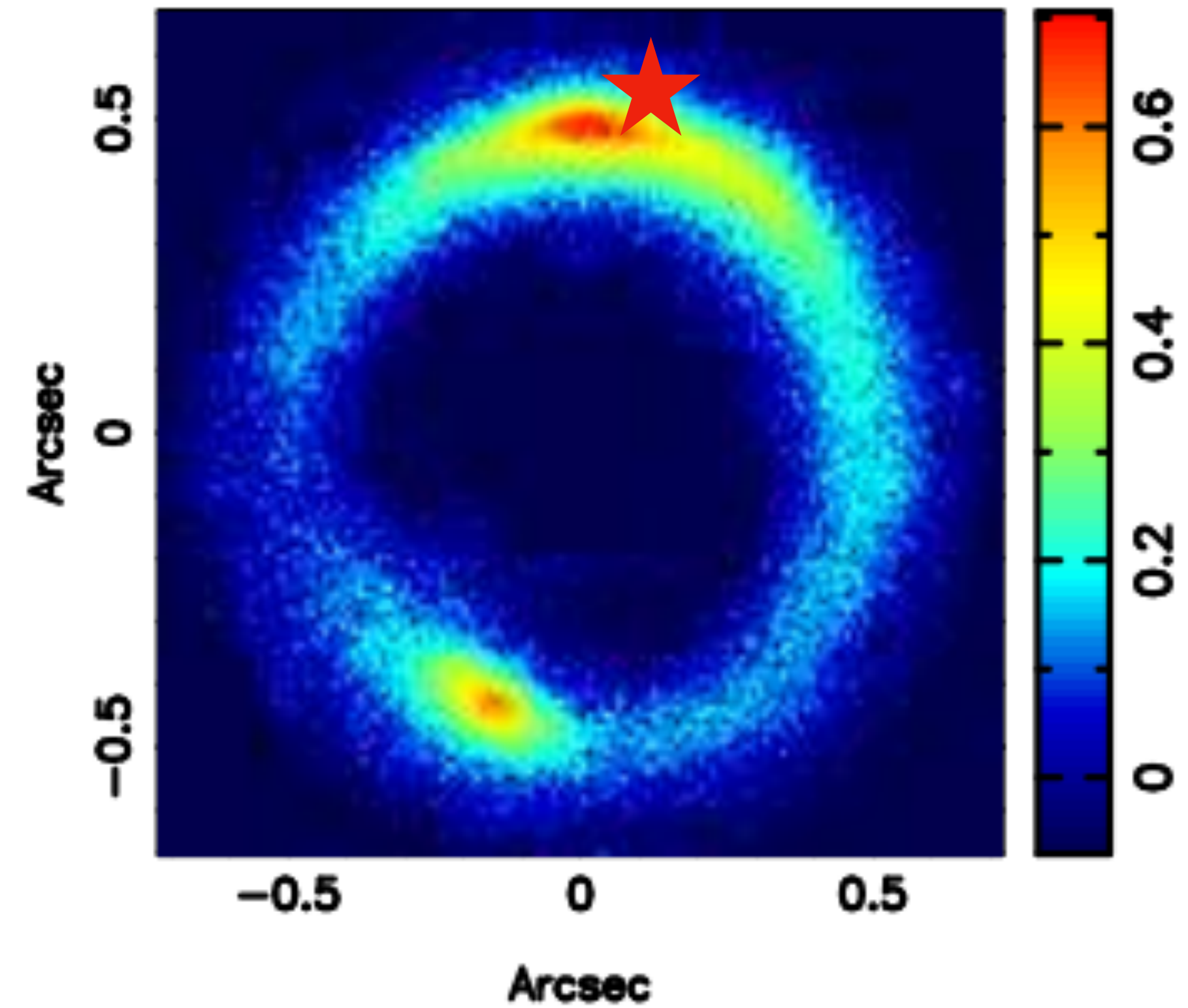


$$M_{\text{sub}} > 10^{10} M_{\odot}$$

Vegetti et al. 2010

Keck AO Imaging

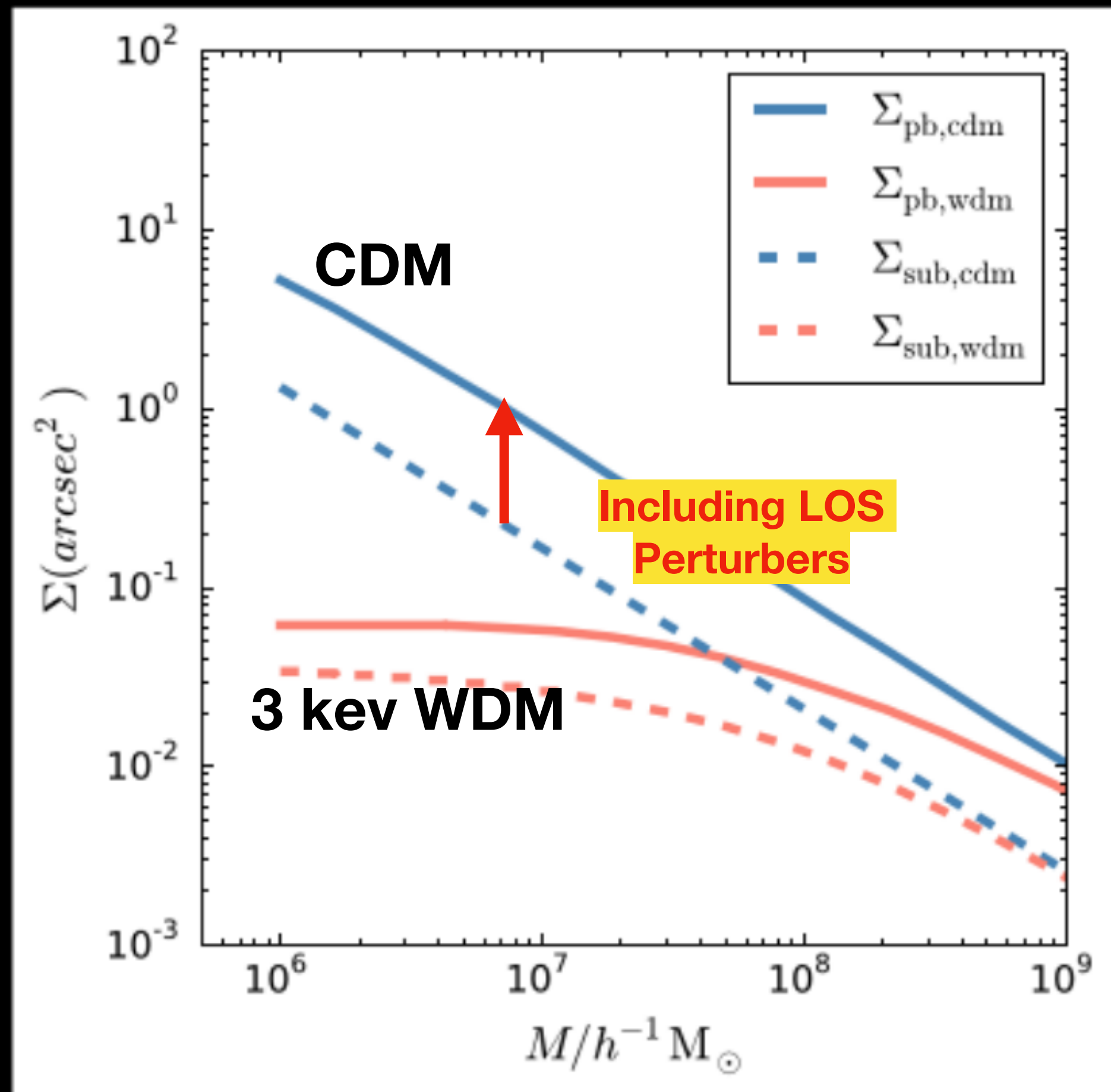
Data B1938+666



$$M_{\text{sub}} > 10^8 M_{\odot}, 12\sigma$$

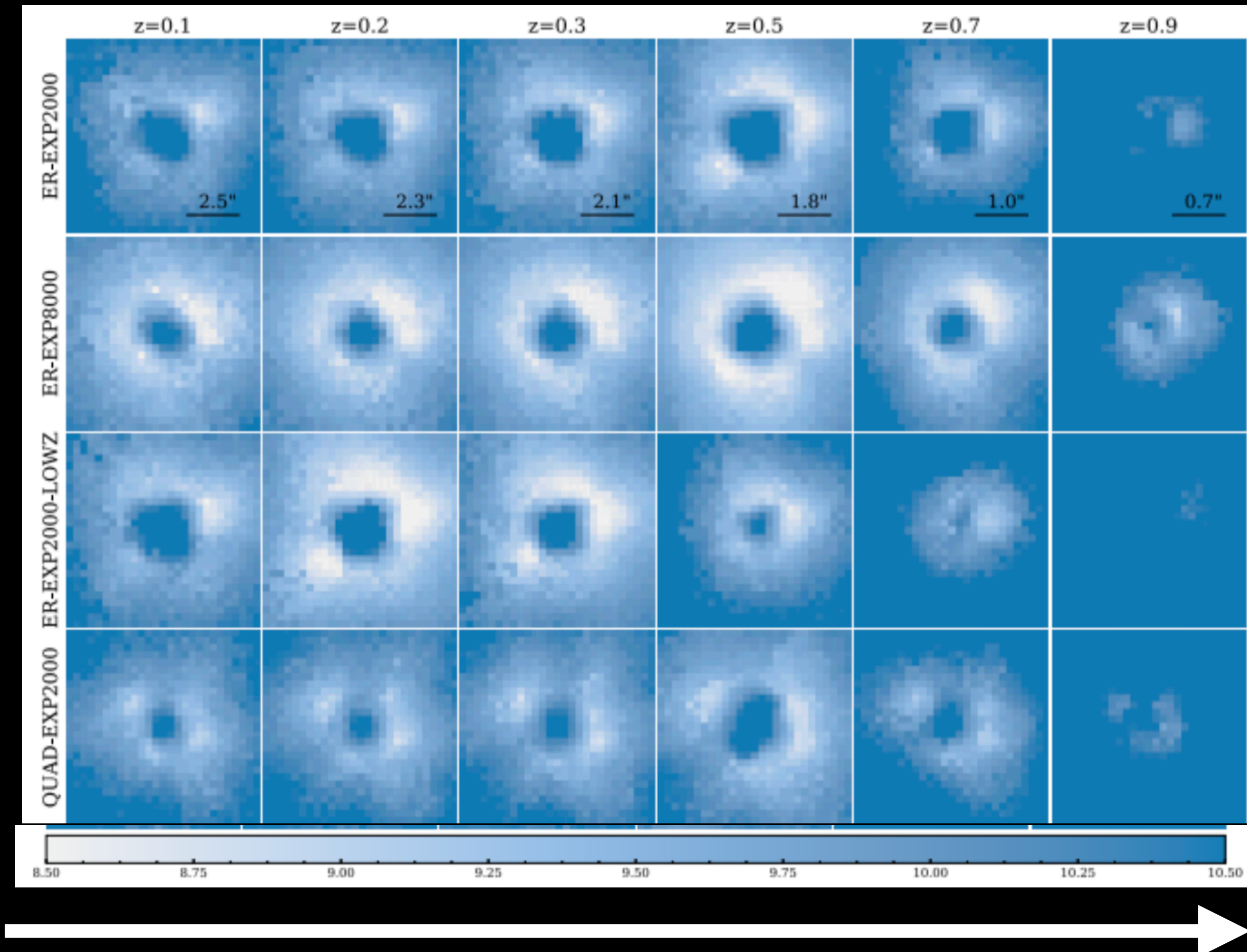
Vegetti et al. 2012

Theoretical Prediction for Perturber Abundance



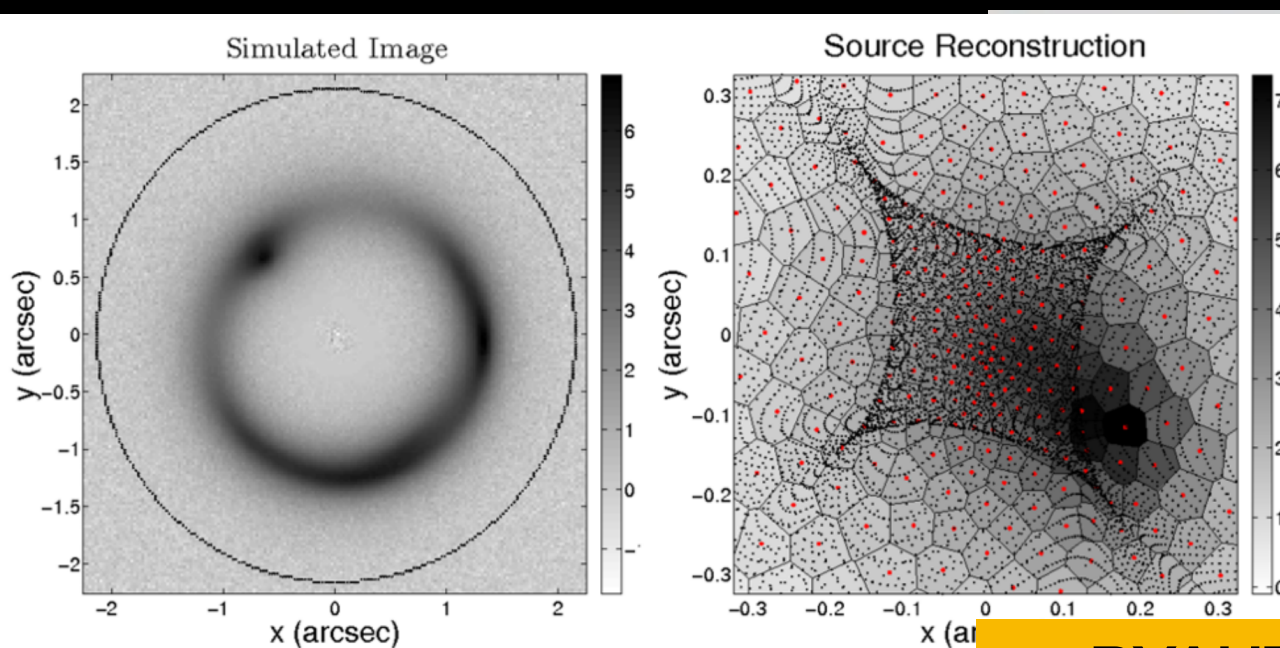
Ran Li et al. 2016,2017

Line-of-sight halo sensitivity

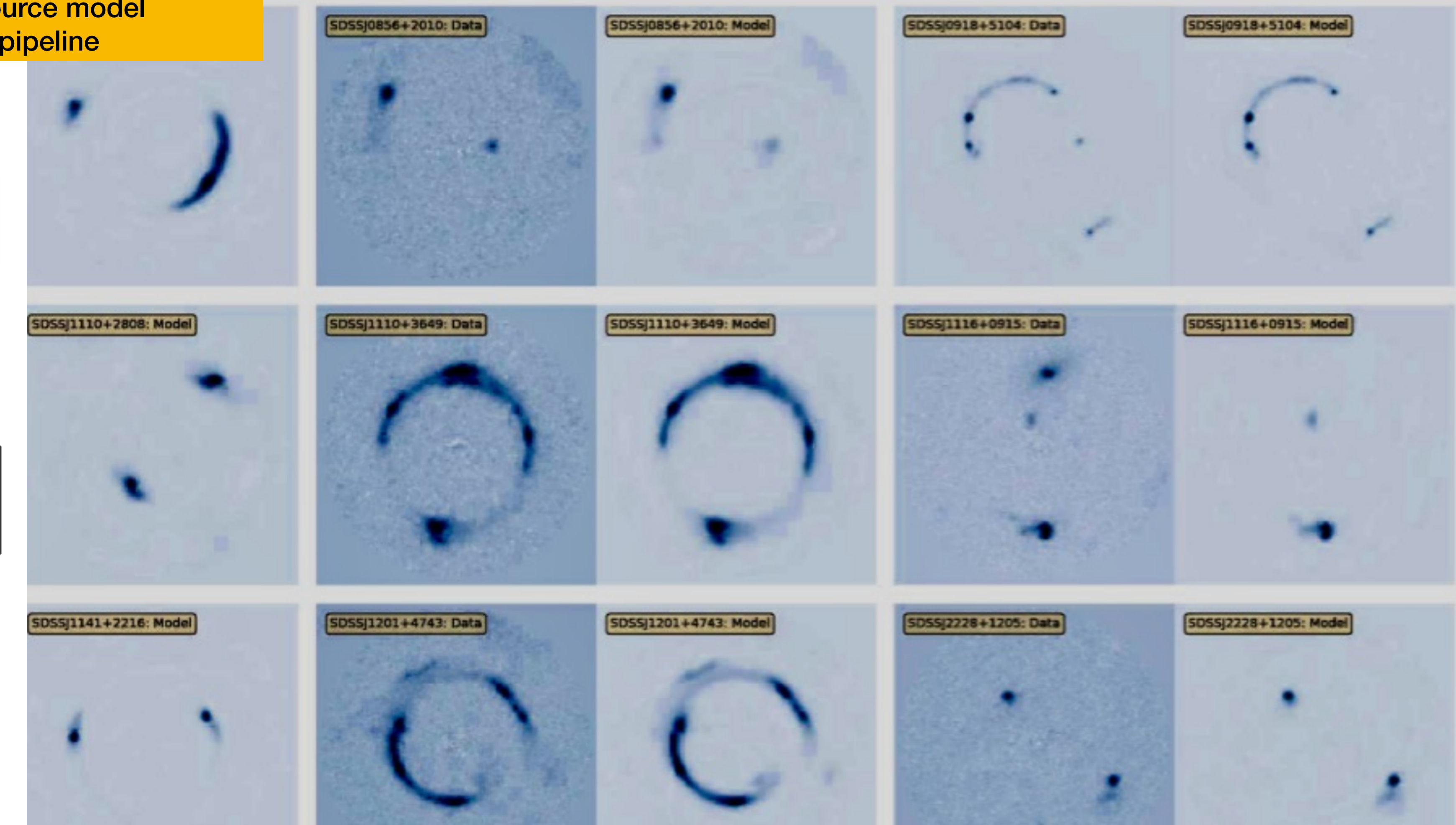
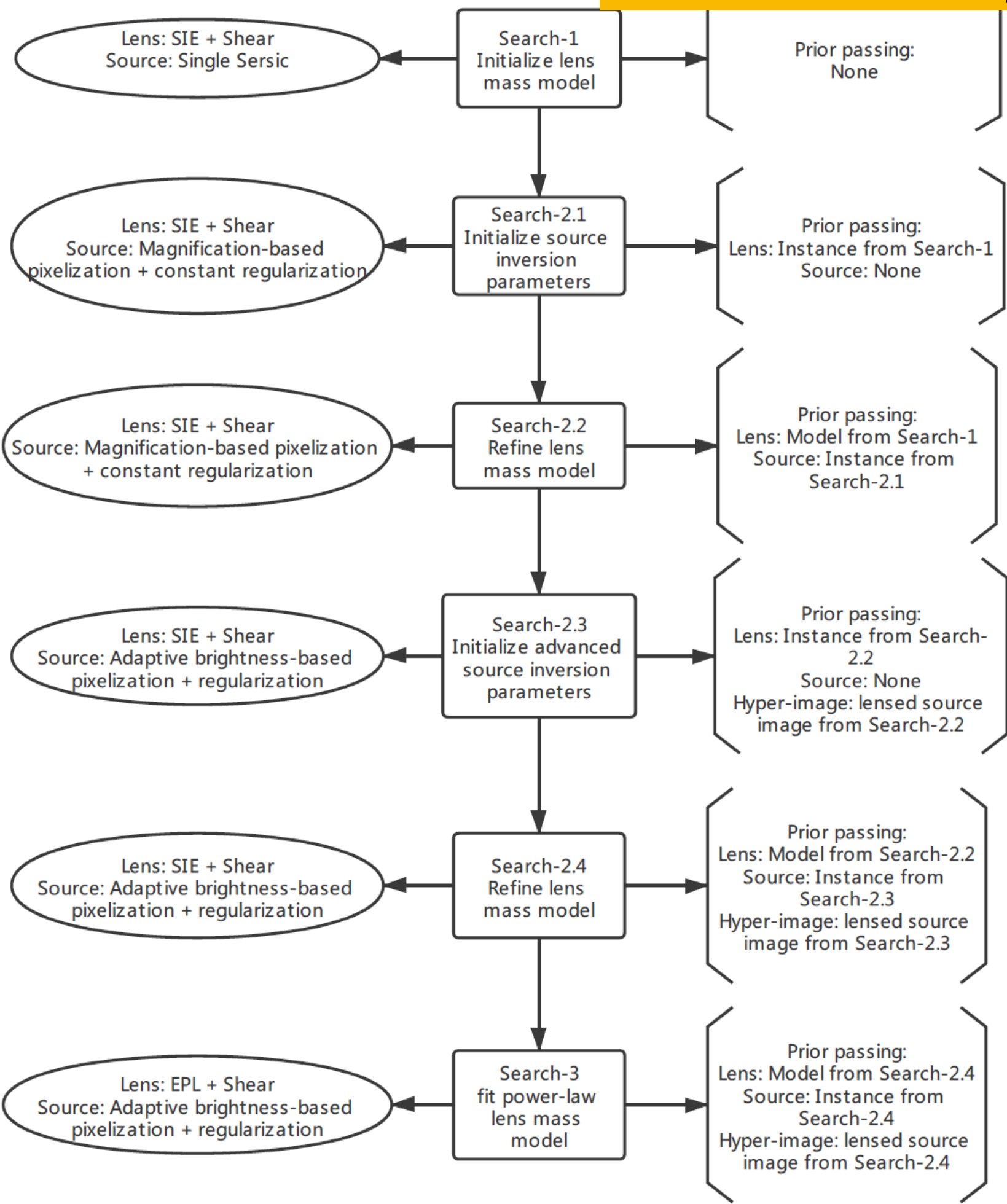


Redshift

QH He et al. 2022

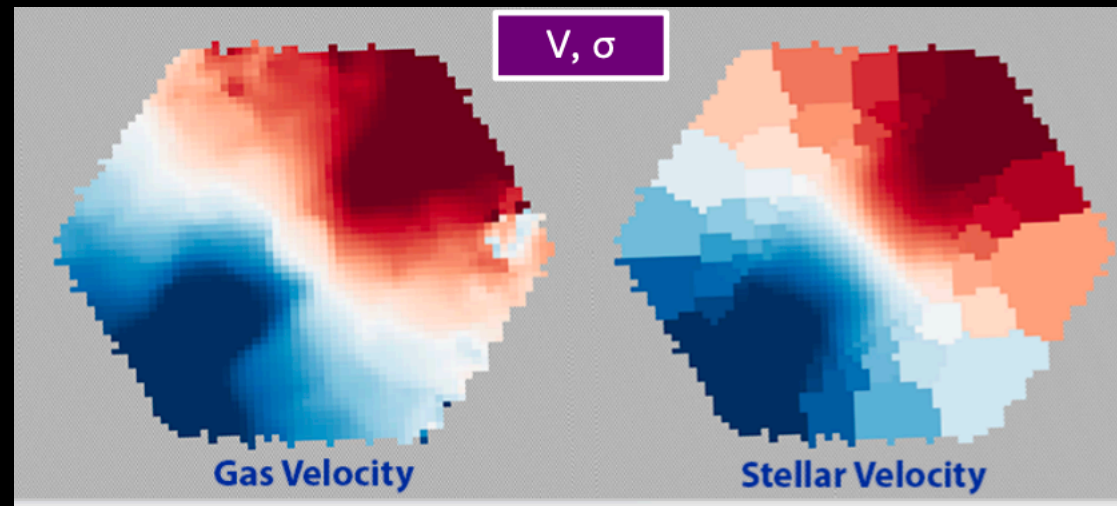
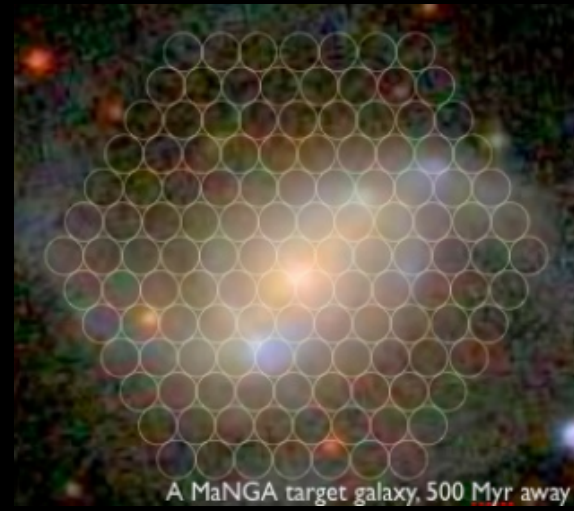


PYAUTOLENS by Nightingale et al.
Pixellized source model
Iterative pipeline

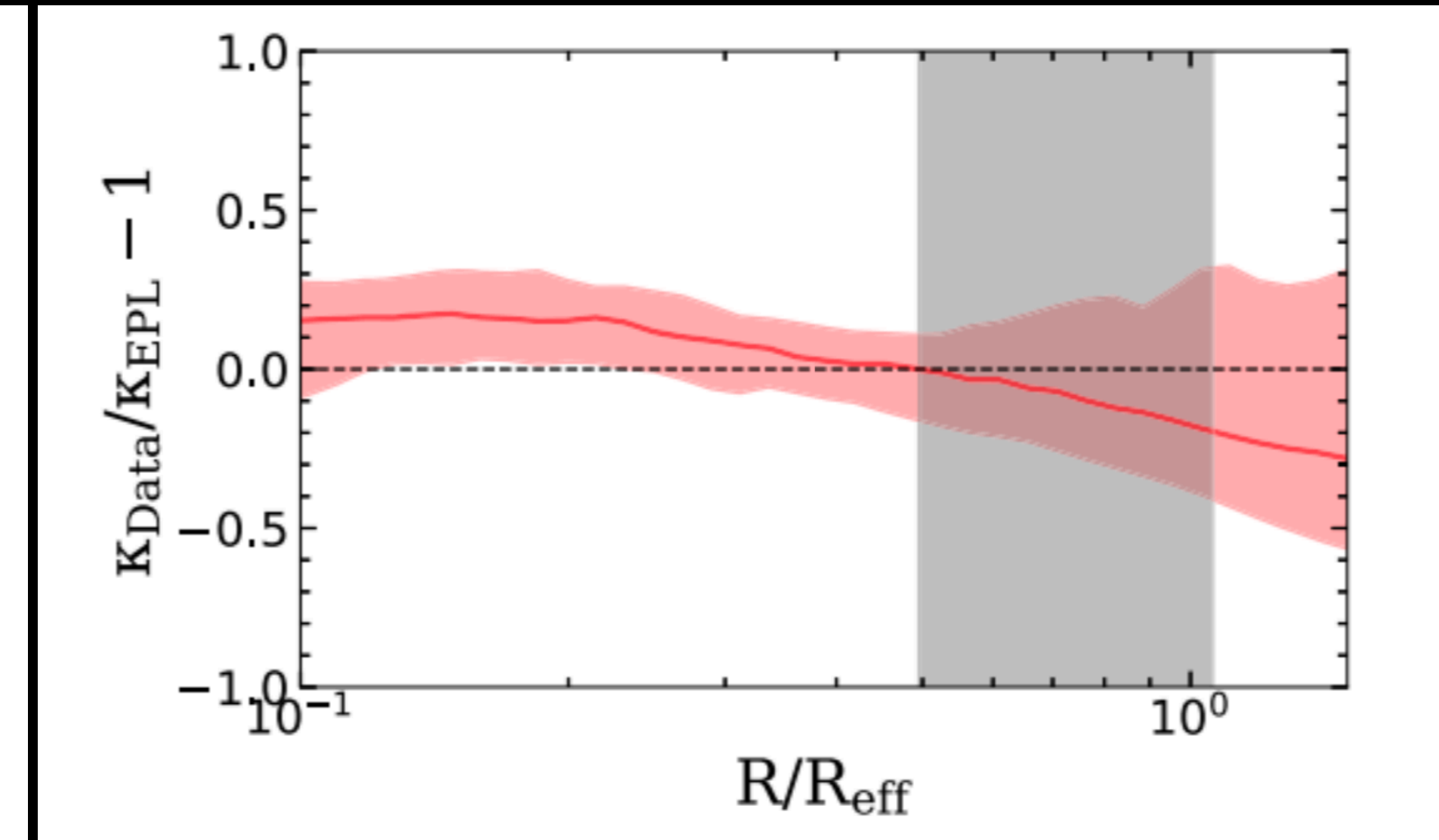
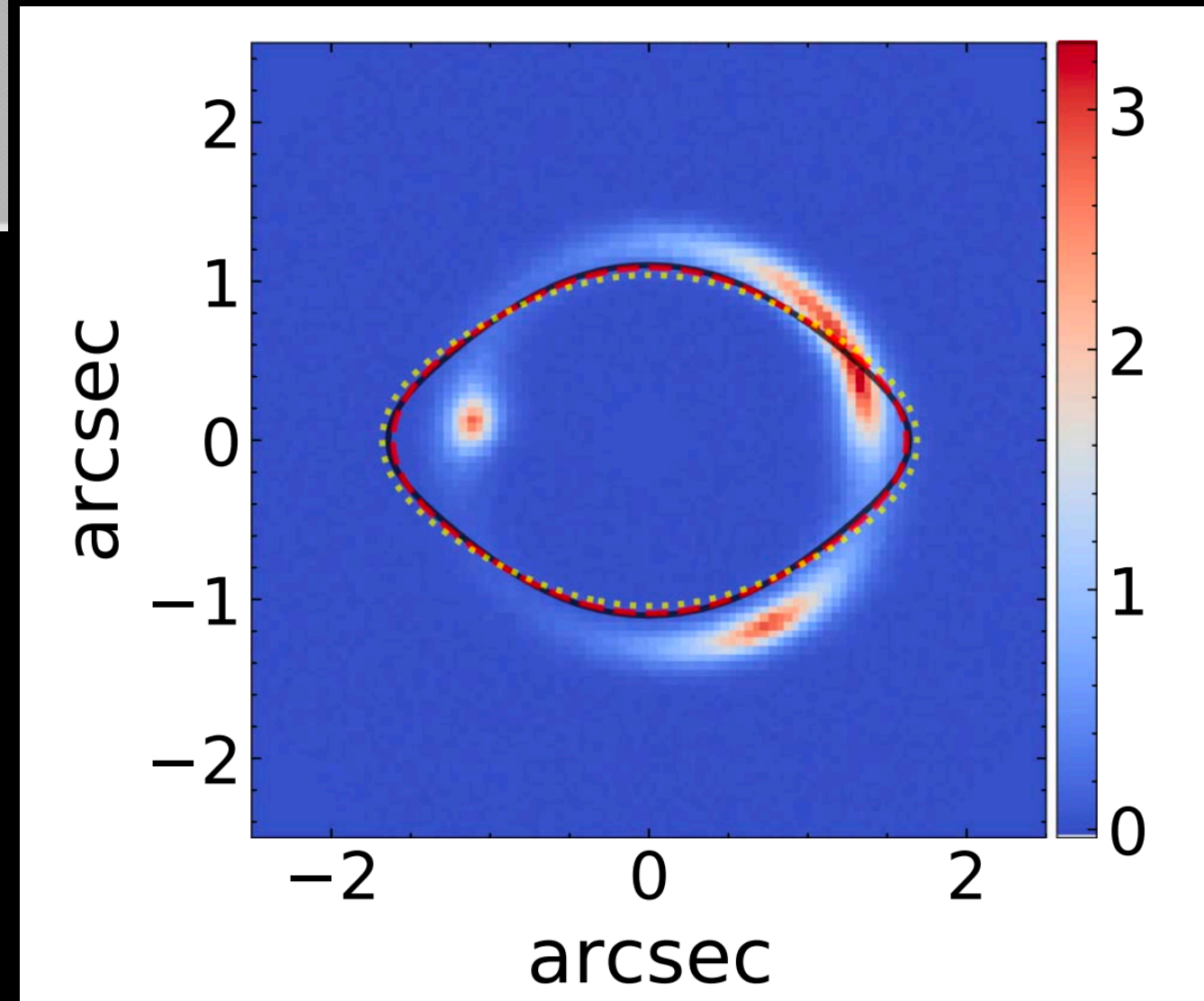


Model of lenses with Hubble Imaging from Xiaoyue Cao

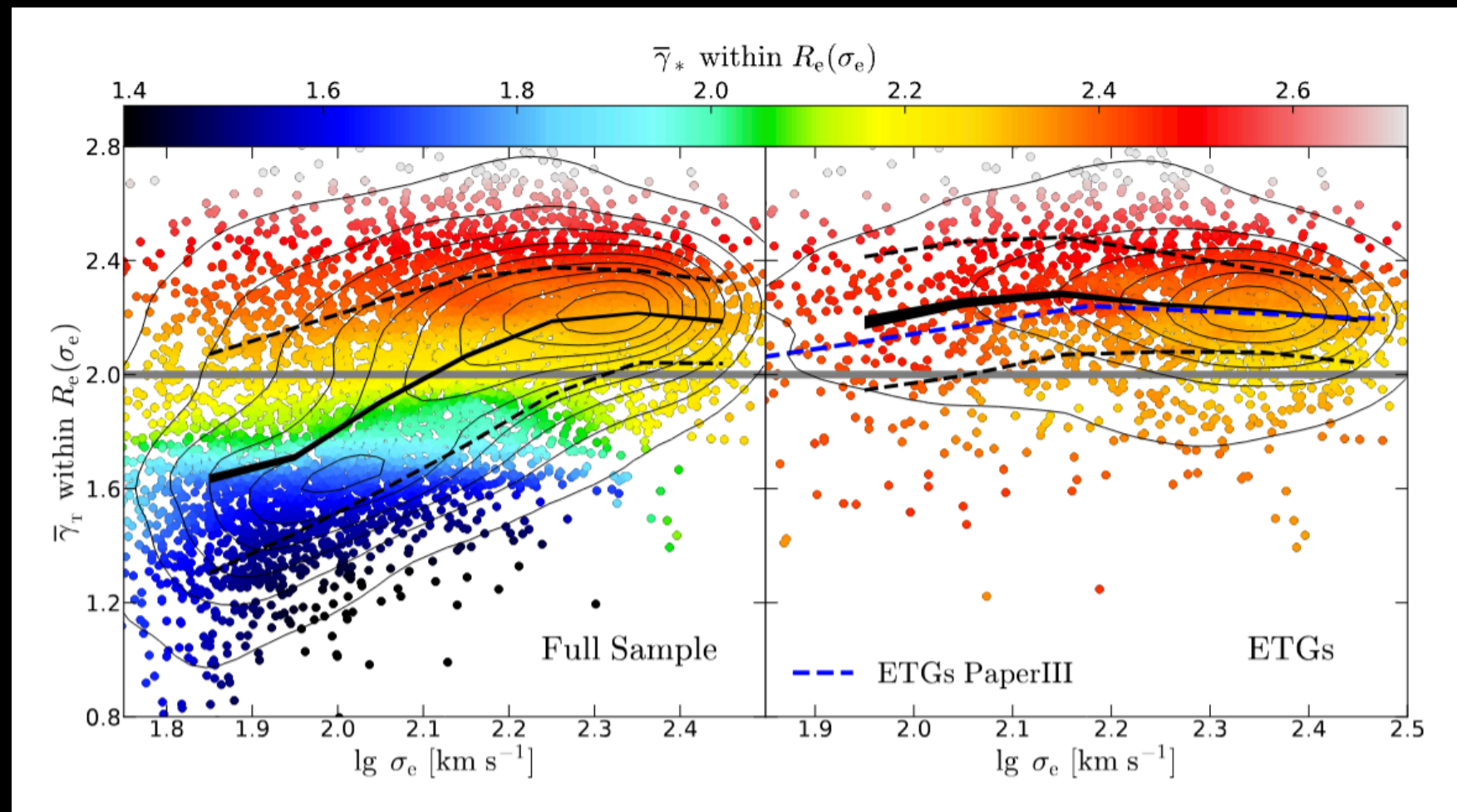
MaNGA DYNPOP
 Zhu K., et al. 2023a,b
 Lu et al. 2023
 SHB LI et al. 2024



Building Mock Lenses using mass distribution derived from IFU stellar kinematics



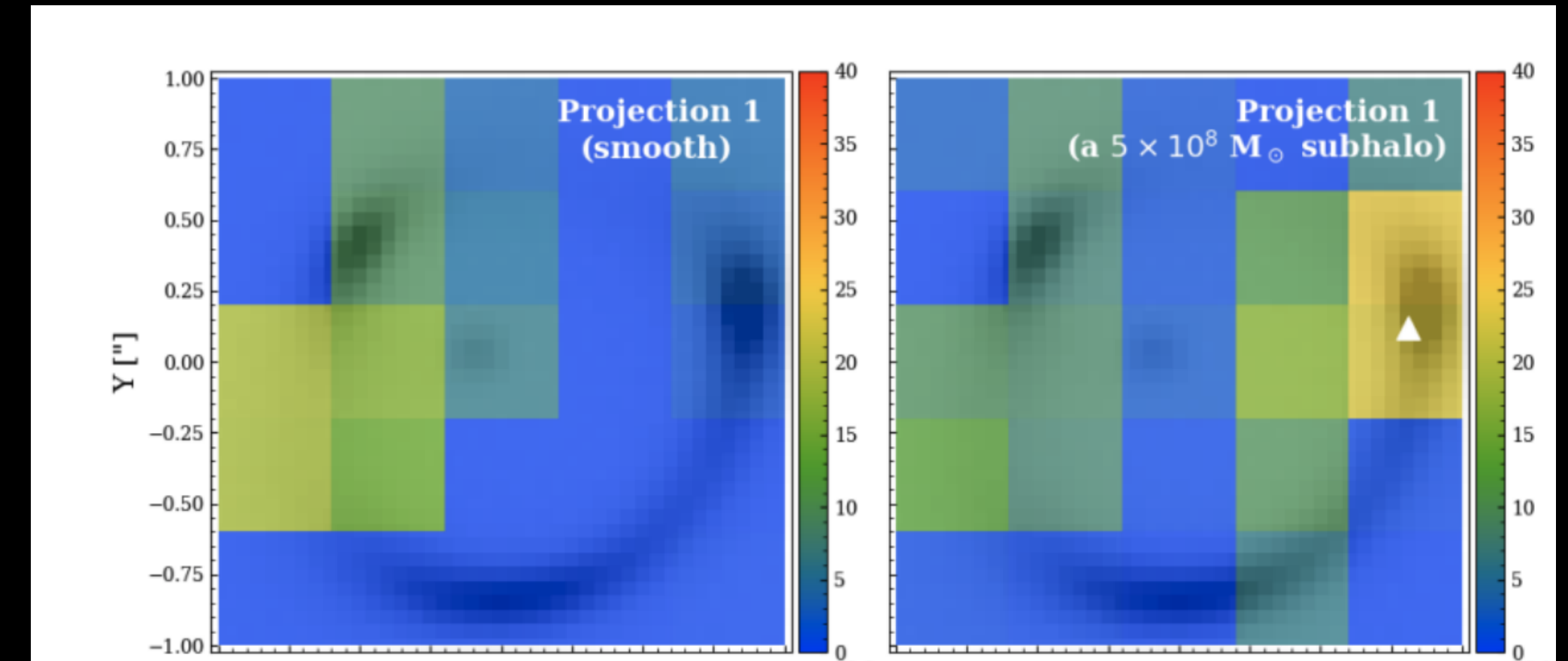
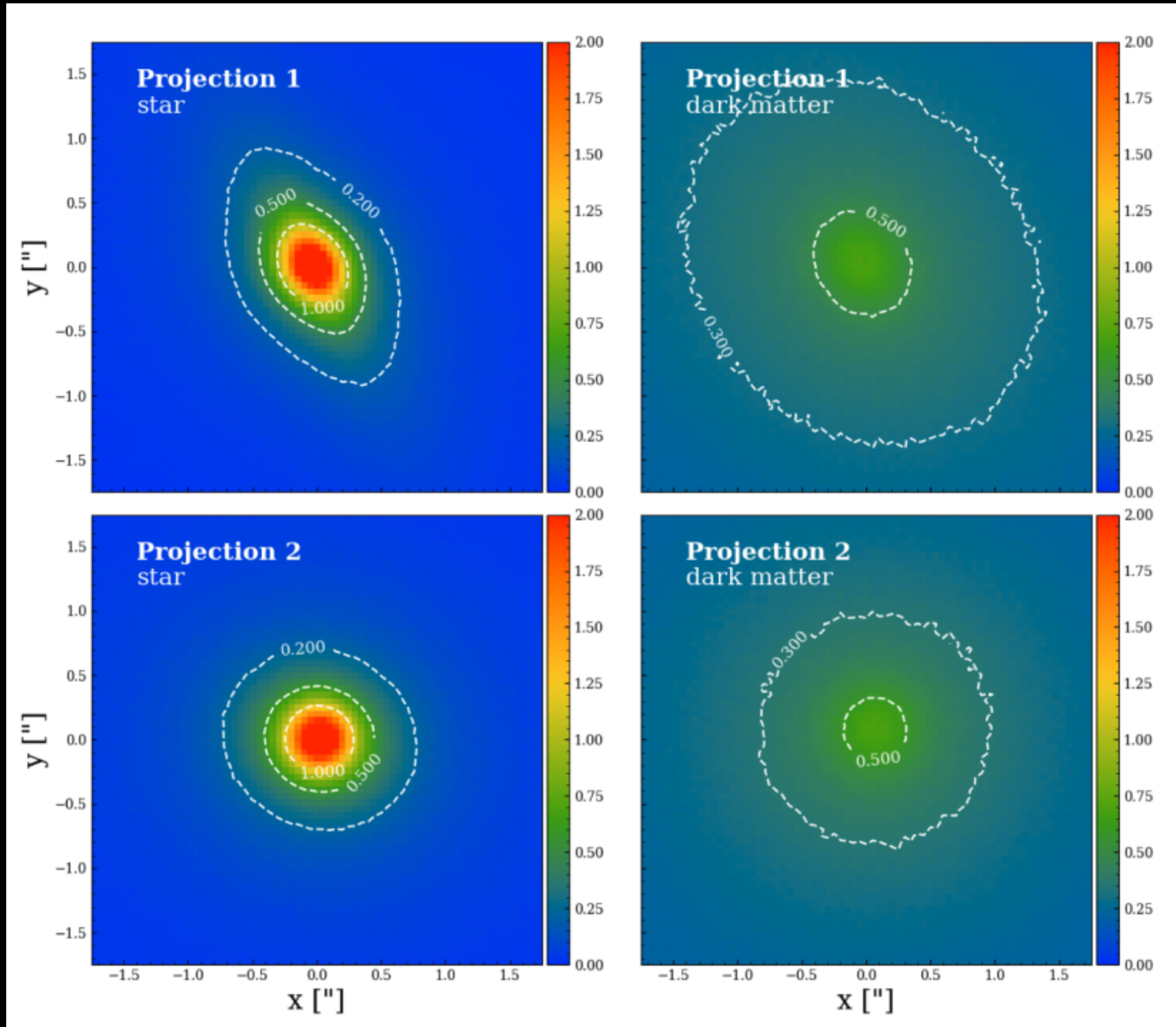
XY Cao, Ran Li et al. 2022
 arxiv:2110.14554



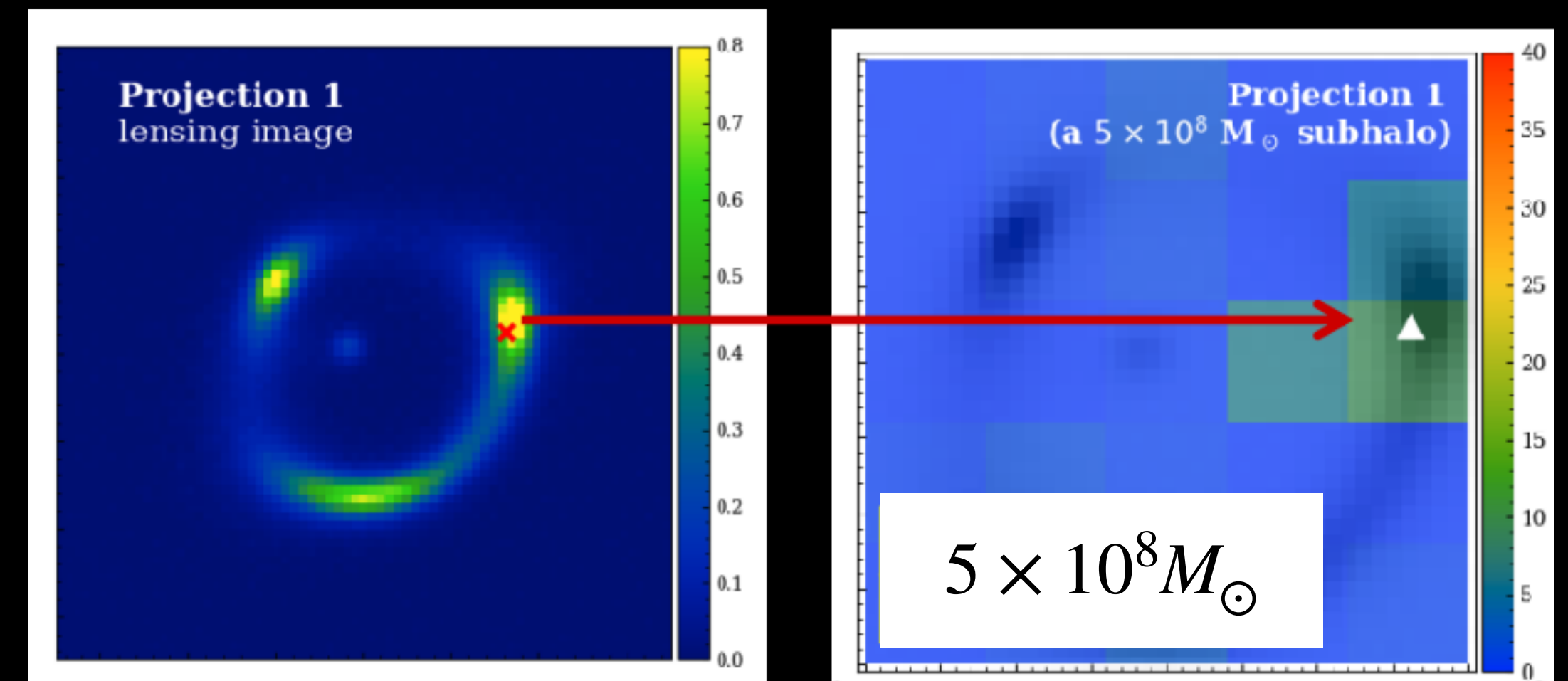
Systematics: Marco model mismatch

Cosmological simulation test

Using elliptical power-law macro model
many false detection



stellar+dark halo macro model,
true location recovered

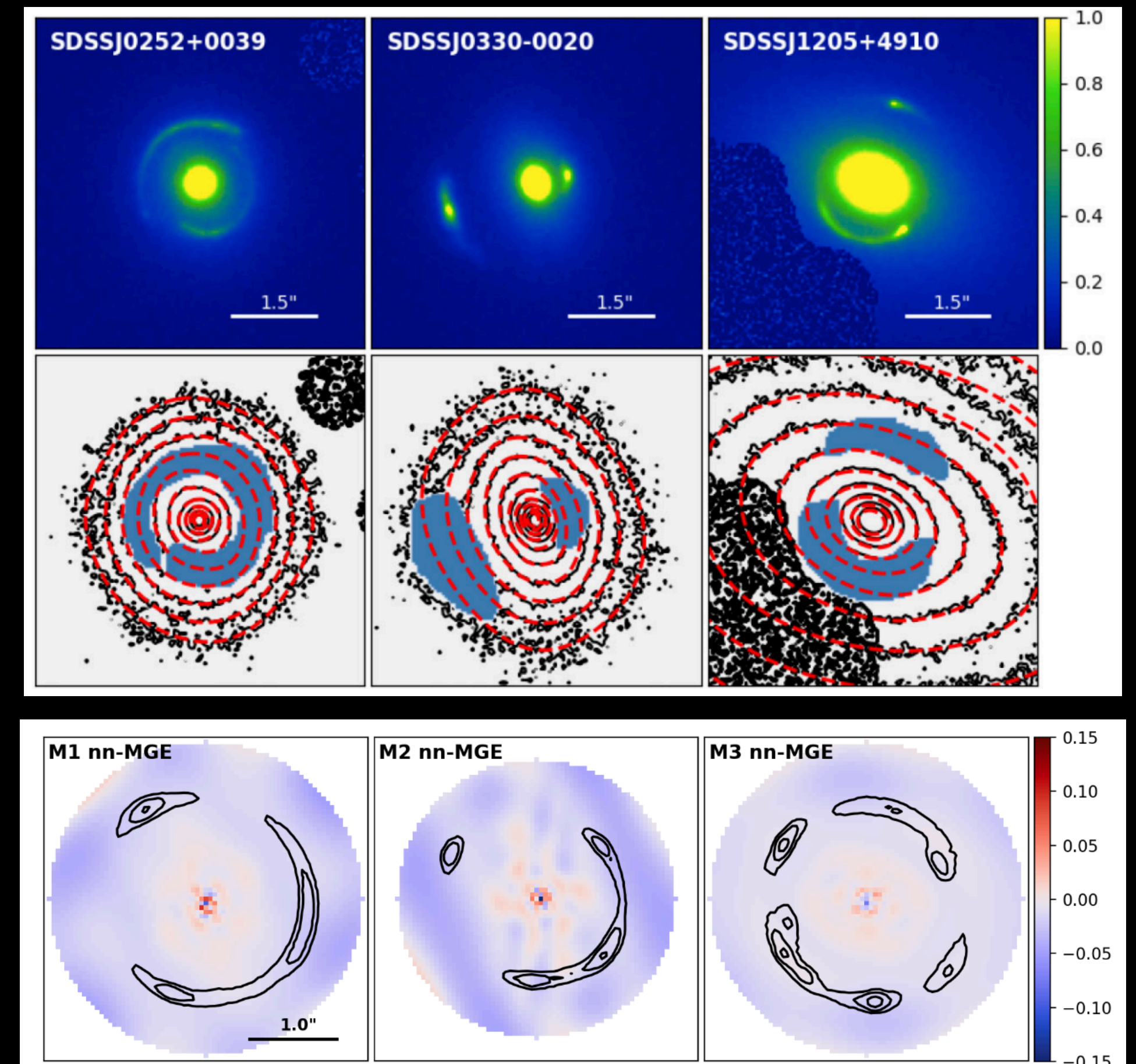


Lens Light Complexity

He et al. 2024

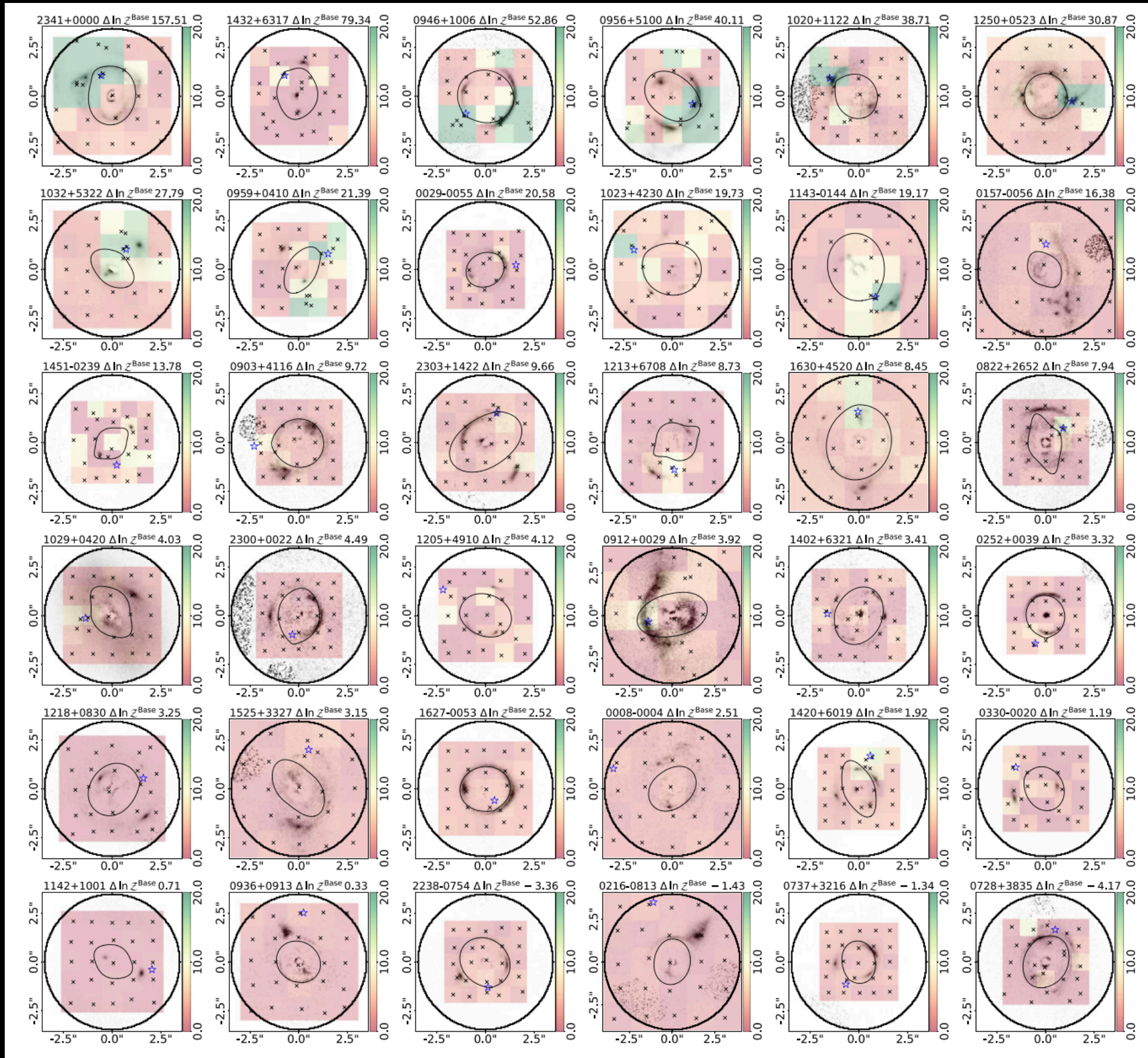


A early type galaxy in HSC deep imaging



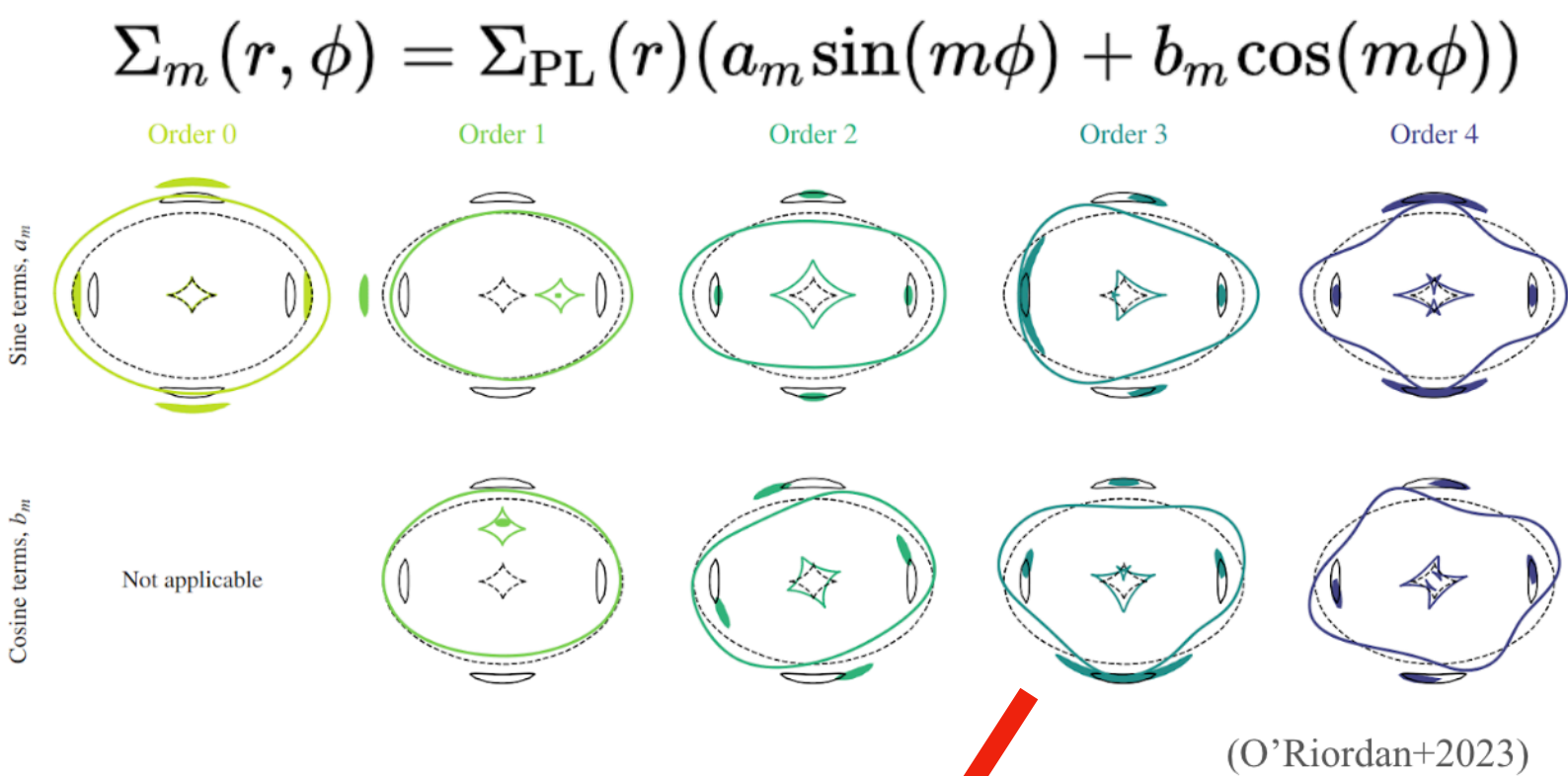
Differences between the best-fitting MGE lens light model and the input

Candidates From Hubble Imaging



54 lenses from SLACS and Bells sample

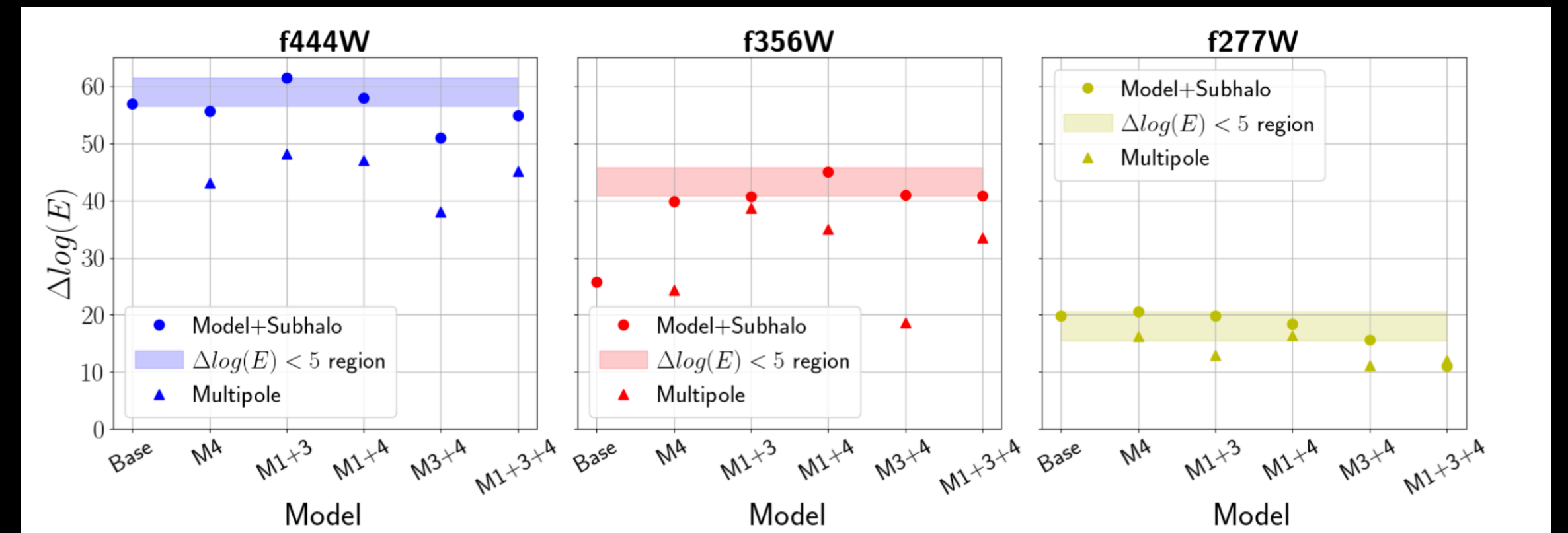
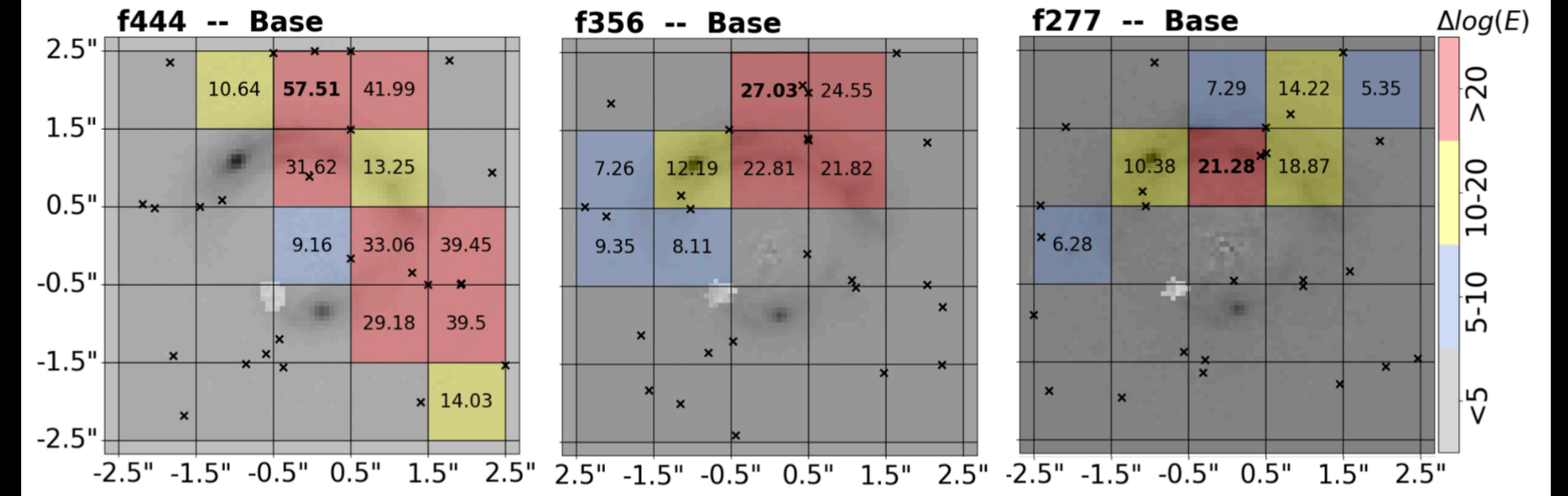
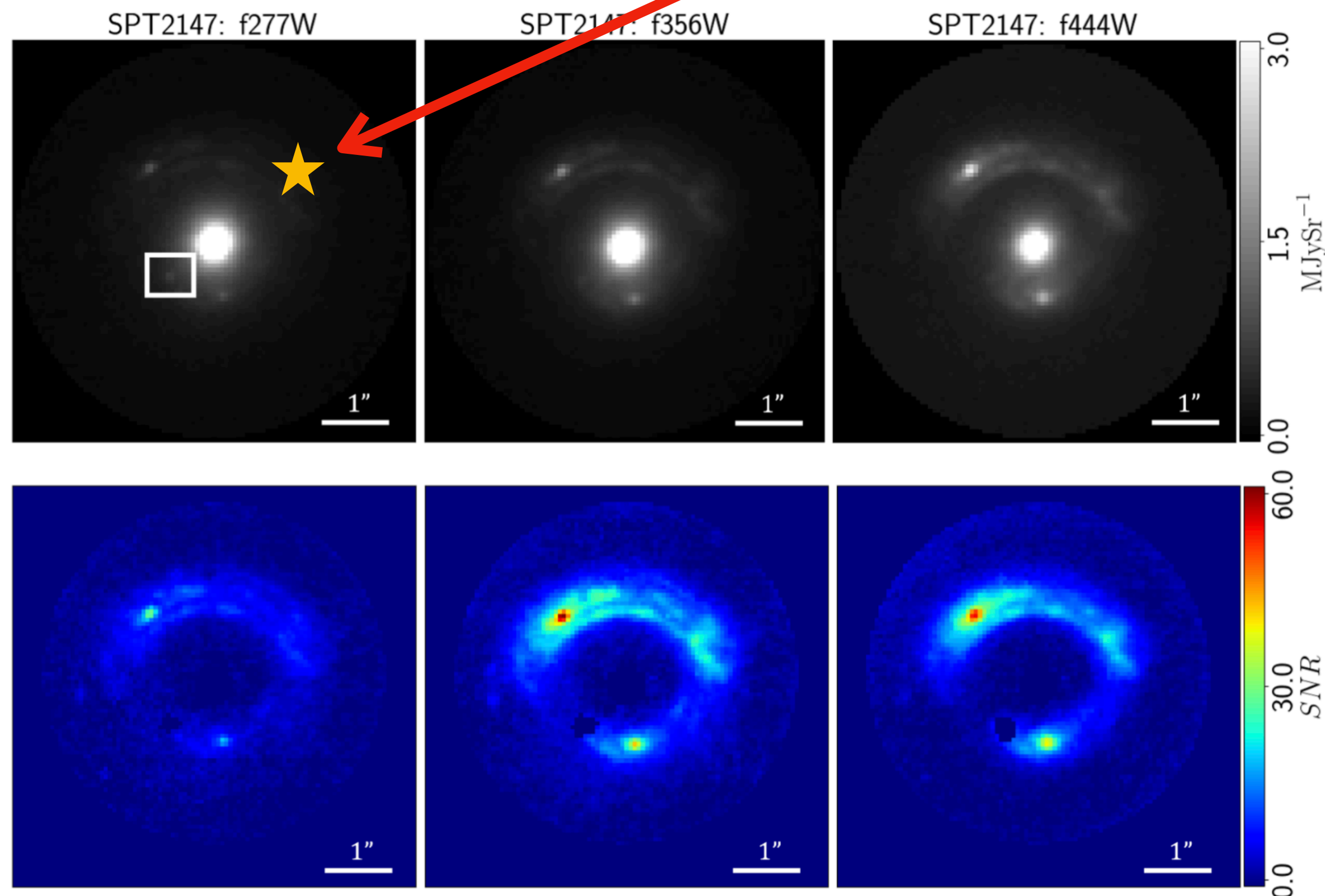
Multipoles:



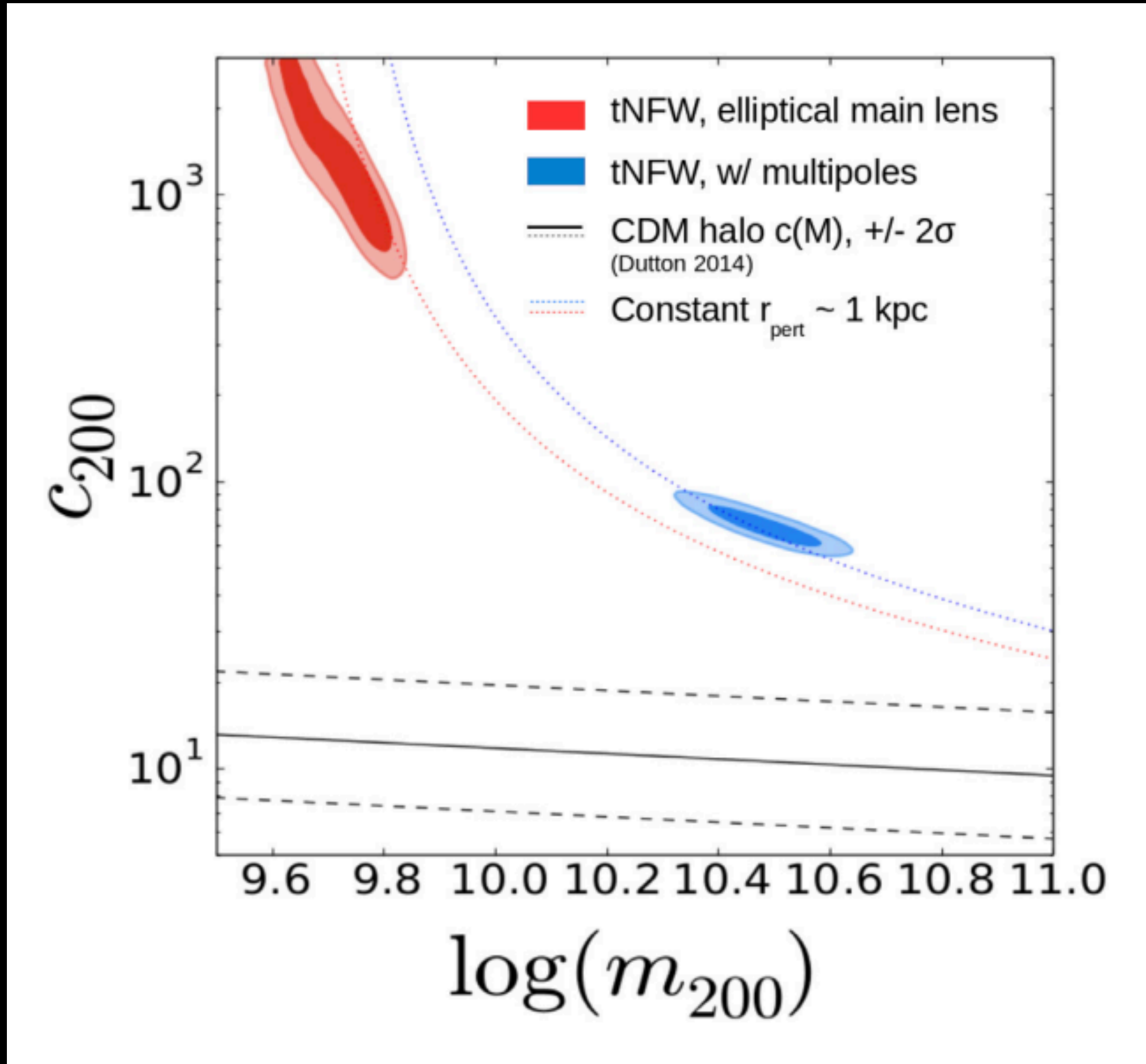
Lens name	BPL	PL with multipoles	Decomposed
SLACS0946 + 1006	$8.62^{+2.15}_{-2.54}$	$10.37^{+0.80}_{-0.51}$	$10.37^{+0.80}_{-0.51}$
SLACS0029-0055	$10.03^{+0.03}_{-0.03}$		$10.03^{+0.03}_{-0.03}$
SLACS1029 + 0420			$9.05^{+2.57}_{-3.04}$
BELLS1226 + 5457	$11.67^{+0.18}_{-0.37}$	$11.48^{+0.16}_{-0.35}$	$10.96^{+0.27}_{-0.15}$
BELLS1201 + 4743	$11.23^{+0.12}_{-0.20}$		

New candidate from JWST

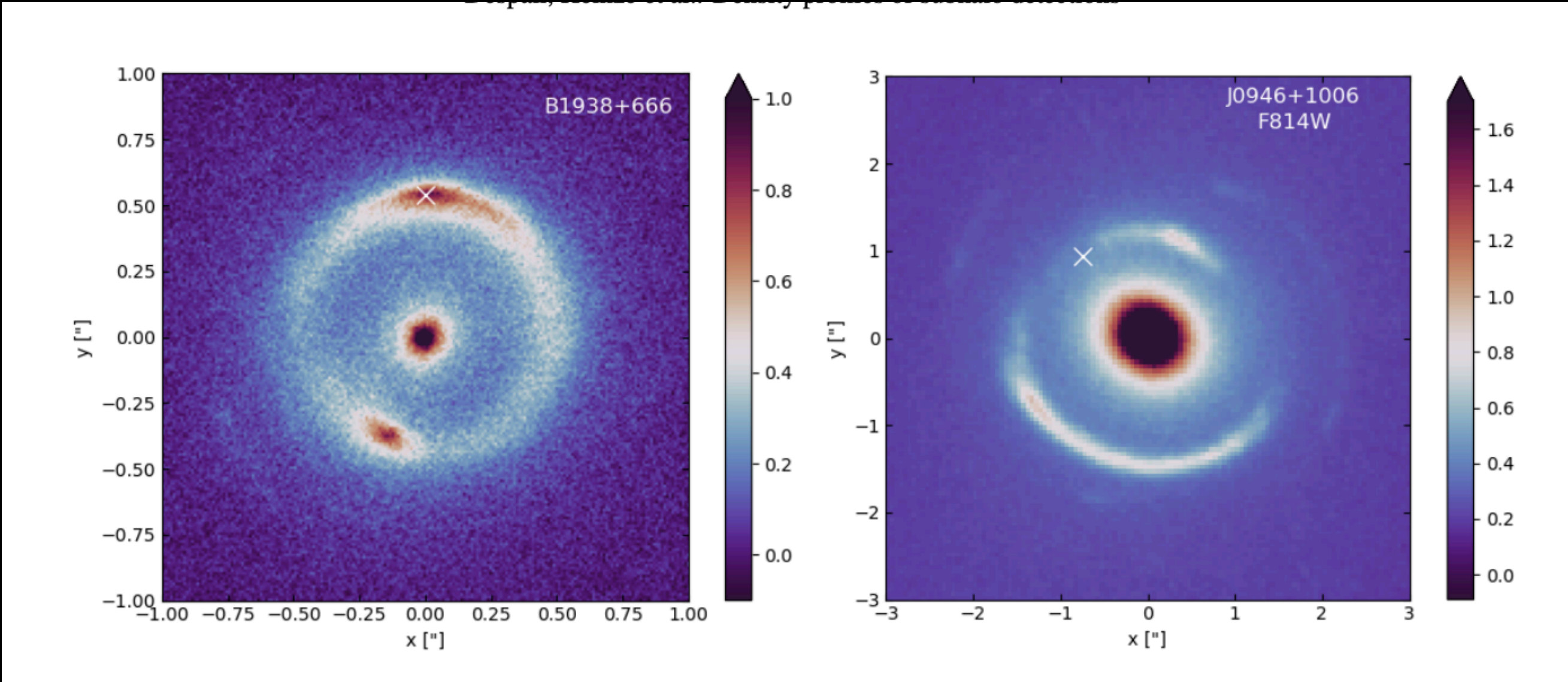
A probable candidate dark perturber, $M_{200}/M_{\odot} = 10.87^{+0.54}_{-0.71}$



Steep profile: CDM halo outlier or a challenge?



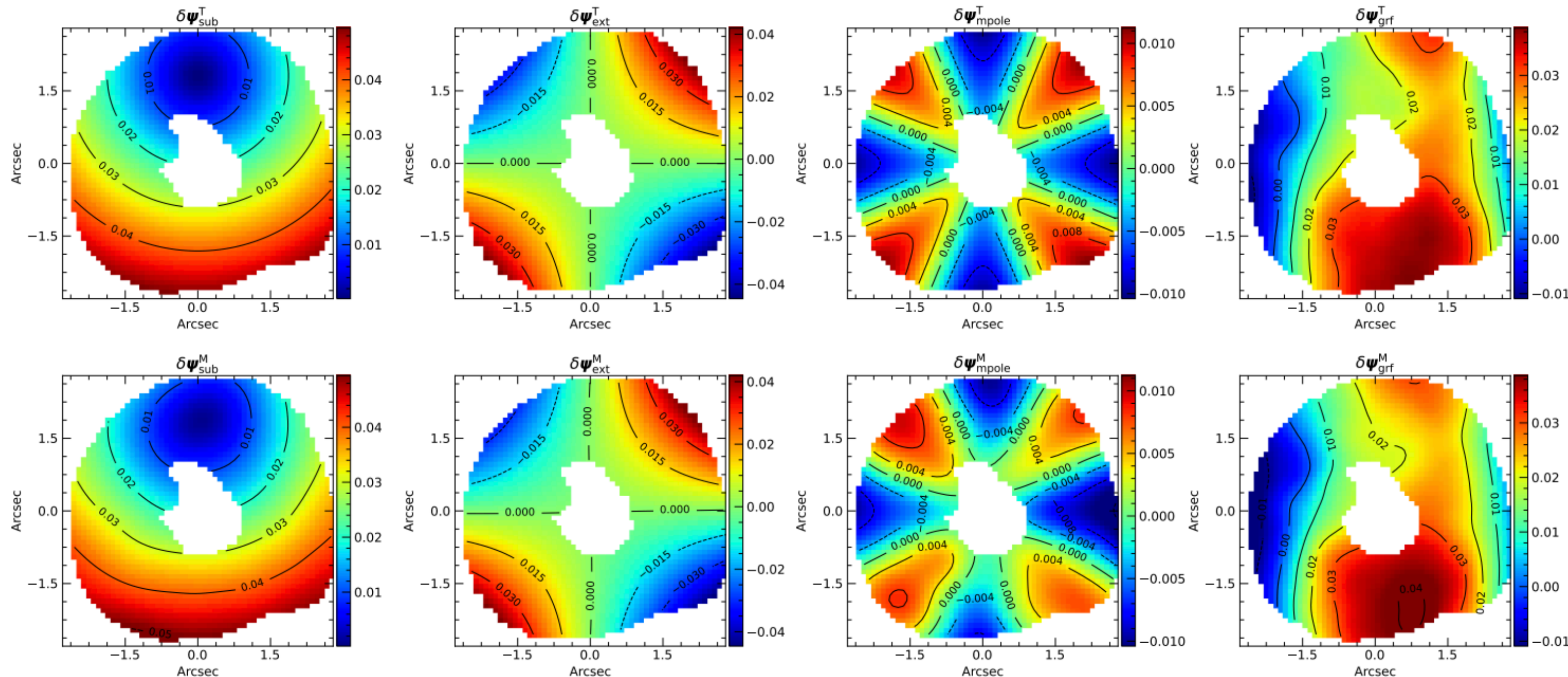
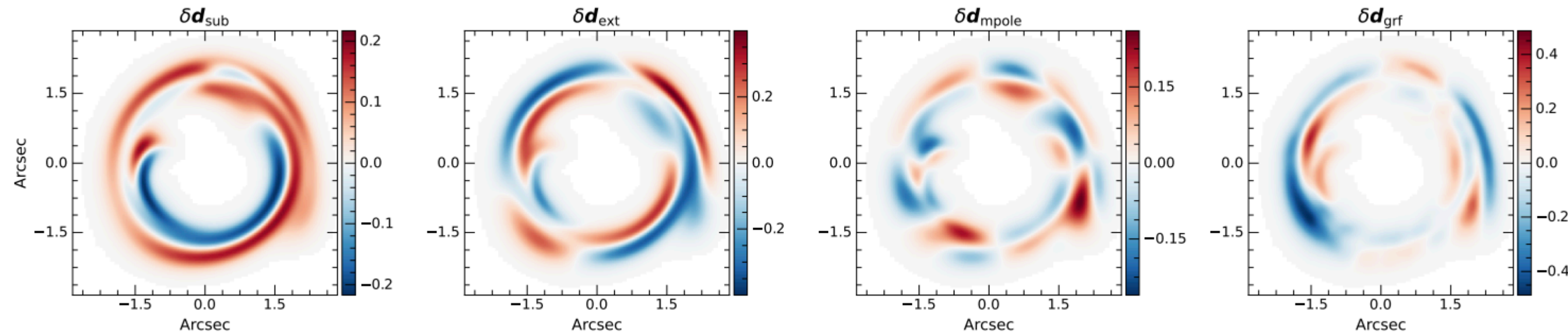
Minor et al. 2021



Lens	Instrument	Band	$M_{\text{sub}} [10^9 M_{\odot}]$	c_{sub}	Profile	Ref.
B1938+666	Keck/NIRC2+HST	K'+NICMOS	0.19 ± 0.01	-	PJ	V12
	Keck/NIRC2	K'	-	-	-	L12
	HST/NICMOS	F160W	-	-	-	K98
	HST/NICMOS	F160W	1	~ 60 ($\gamma_{\text{sub}} = 1.96 \pm 0.12$)	tNFW	S22
J0946+1006	HST/ACS	F814W	-	-	-	G08
			3.51 ± 0.15	-	PJ	V10
			$5.01^{+1.4}_{-1}$, $30.2^{+9.8}_{-17.2}$	1560^{+1440}_{-859} , $70.6^{+17.8}_{-11.9}$	tNFW	M21
	+MUSE +HST/WFC3,WFC2 MUSE	+F336W +F(160,606,438)W	8^{+87}_{-59} , 812^{+164}_{-583}	251^{+543}_{-125}	NFW	N24
			$1.58^{+2.4}_{-0.33}$	-	tNFW	B24
			-	-	-	S12
			-	-	-	C20

Despali et al. 2024

Reveal the perturber morphology from free-form reconstruction



$$\delta d = -BC_f D_s(s_{MP}) D_\psi \delta \psi$$

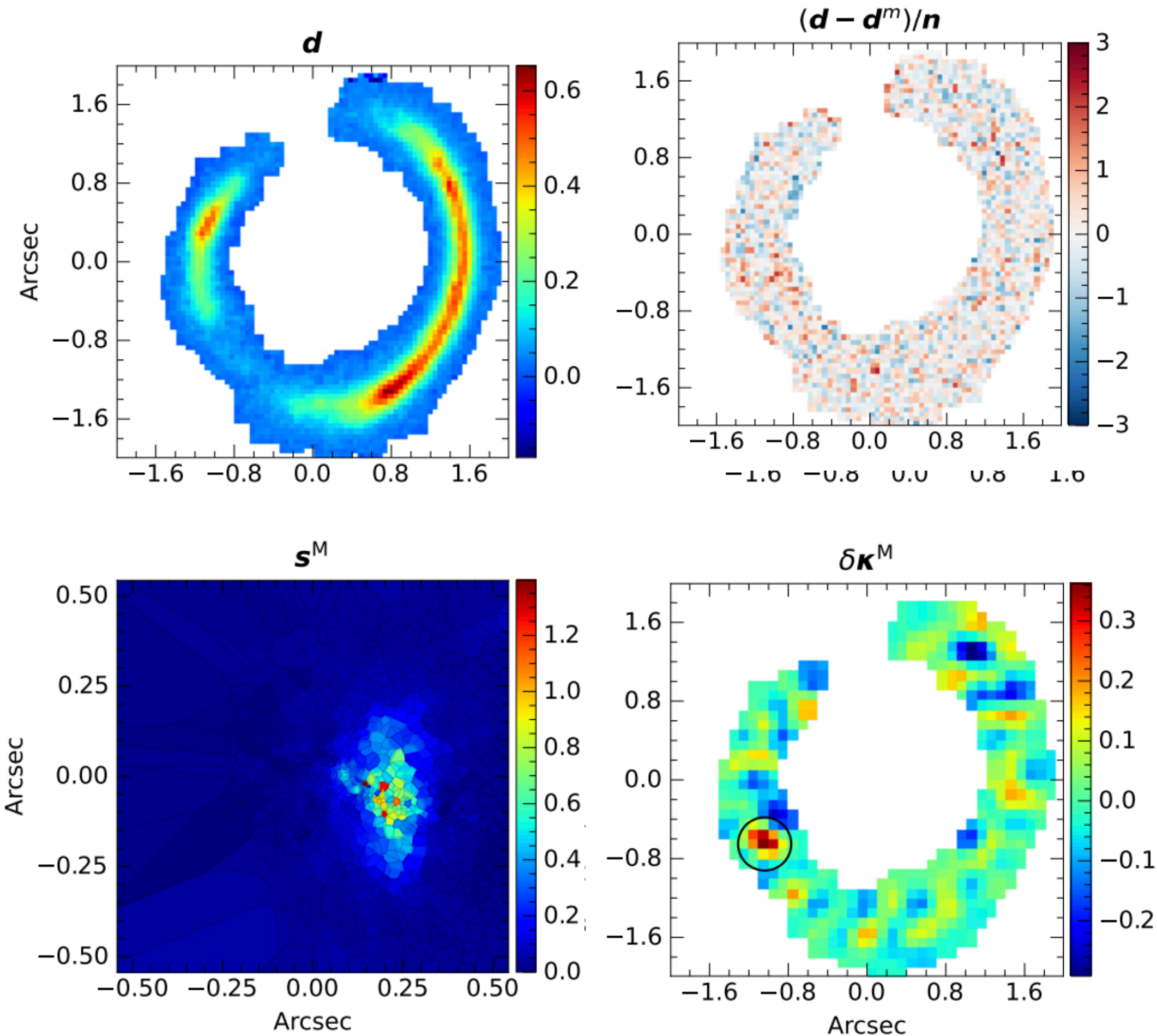
Source light gradient

Potential gradient

XY Cao, Ran Li et al. submitted, 2025
<https://arxiv.org/pdf/2504.19177>

Reveal the perturber from potential correction

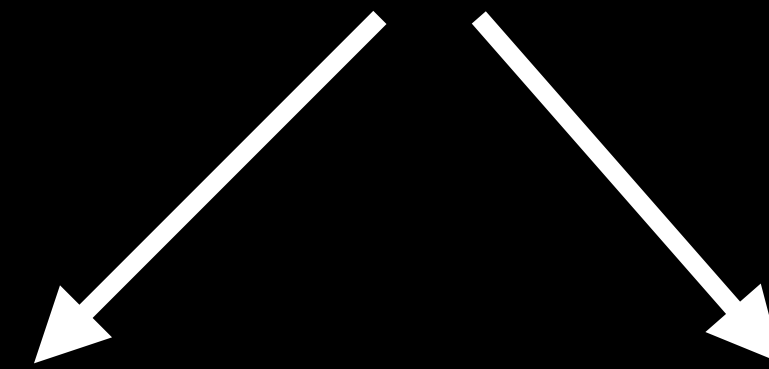
SLACS 0946+1006



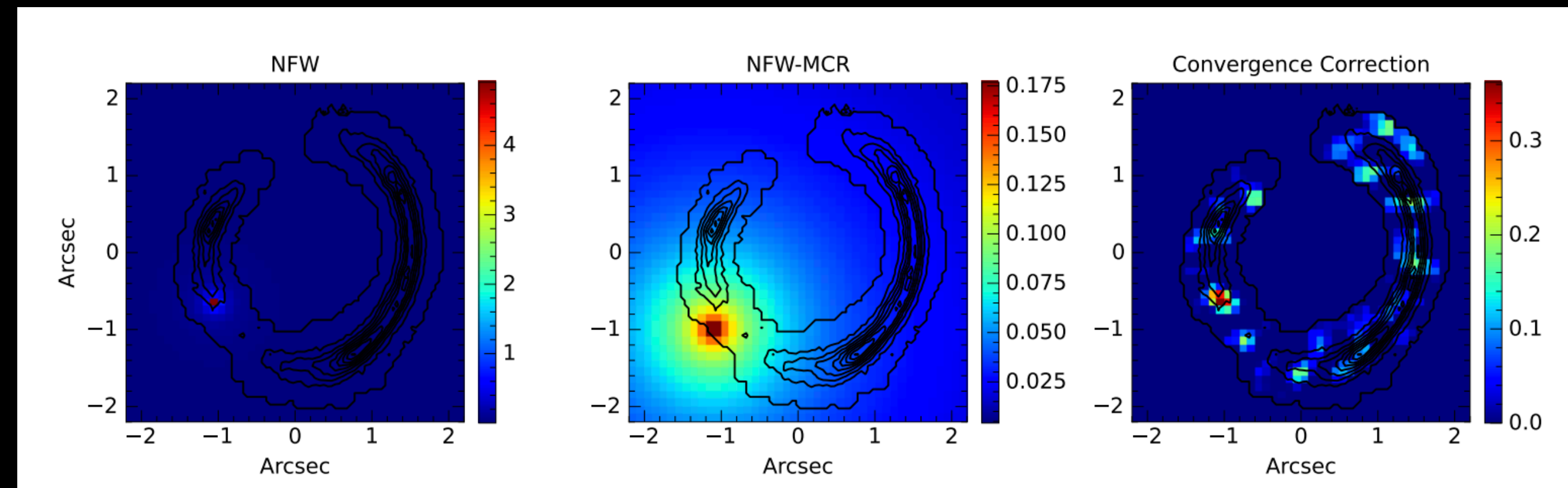
Parametric Model

Left: fix mass-concentration relation

Right: free concentration parameter



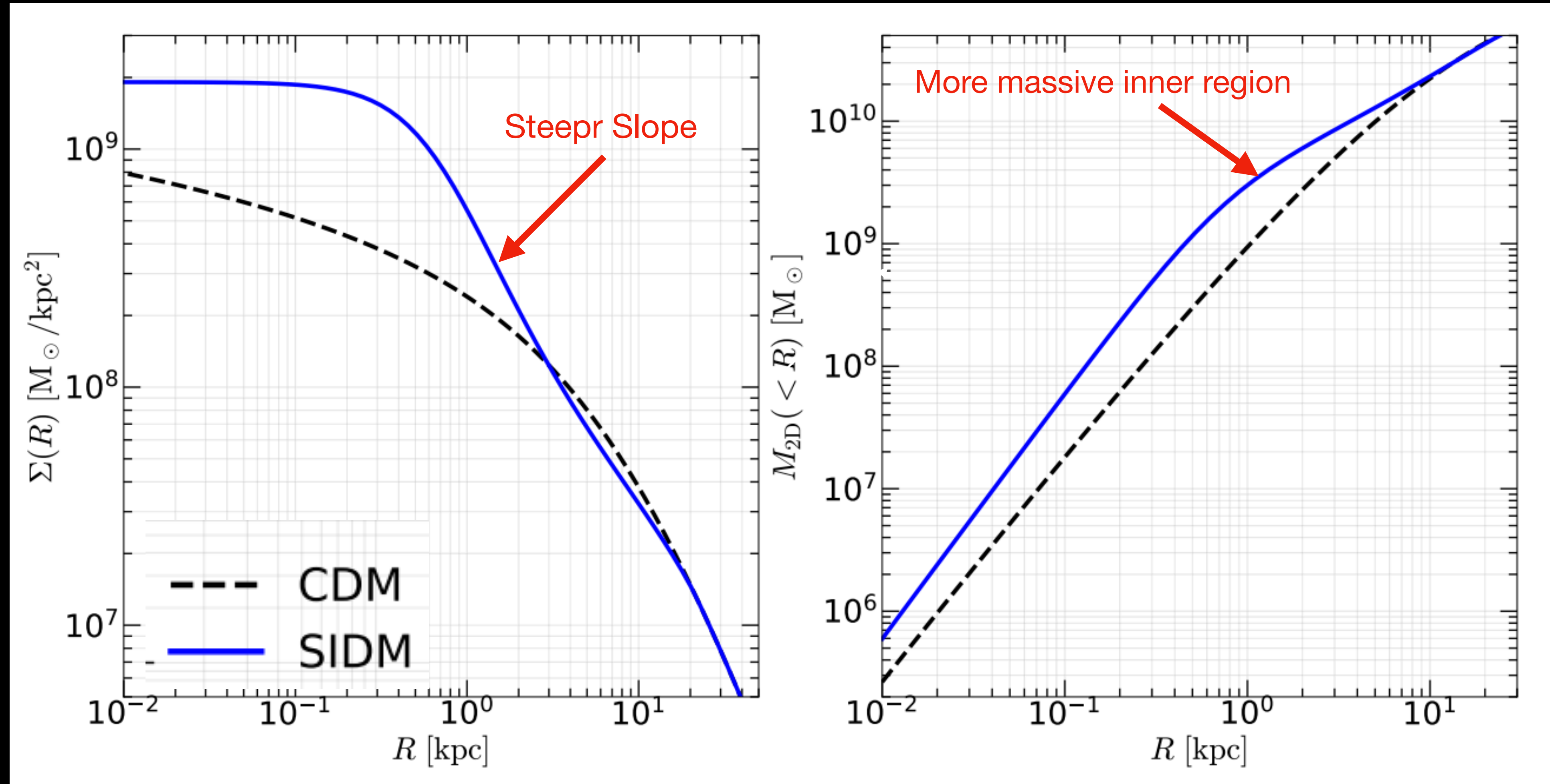
Free Form Reconstruction



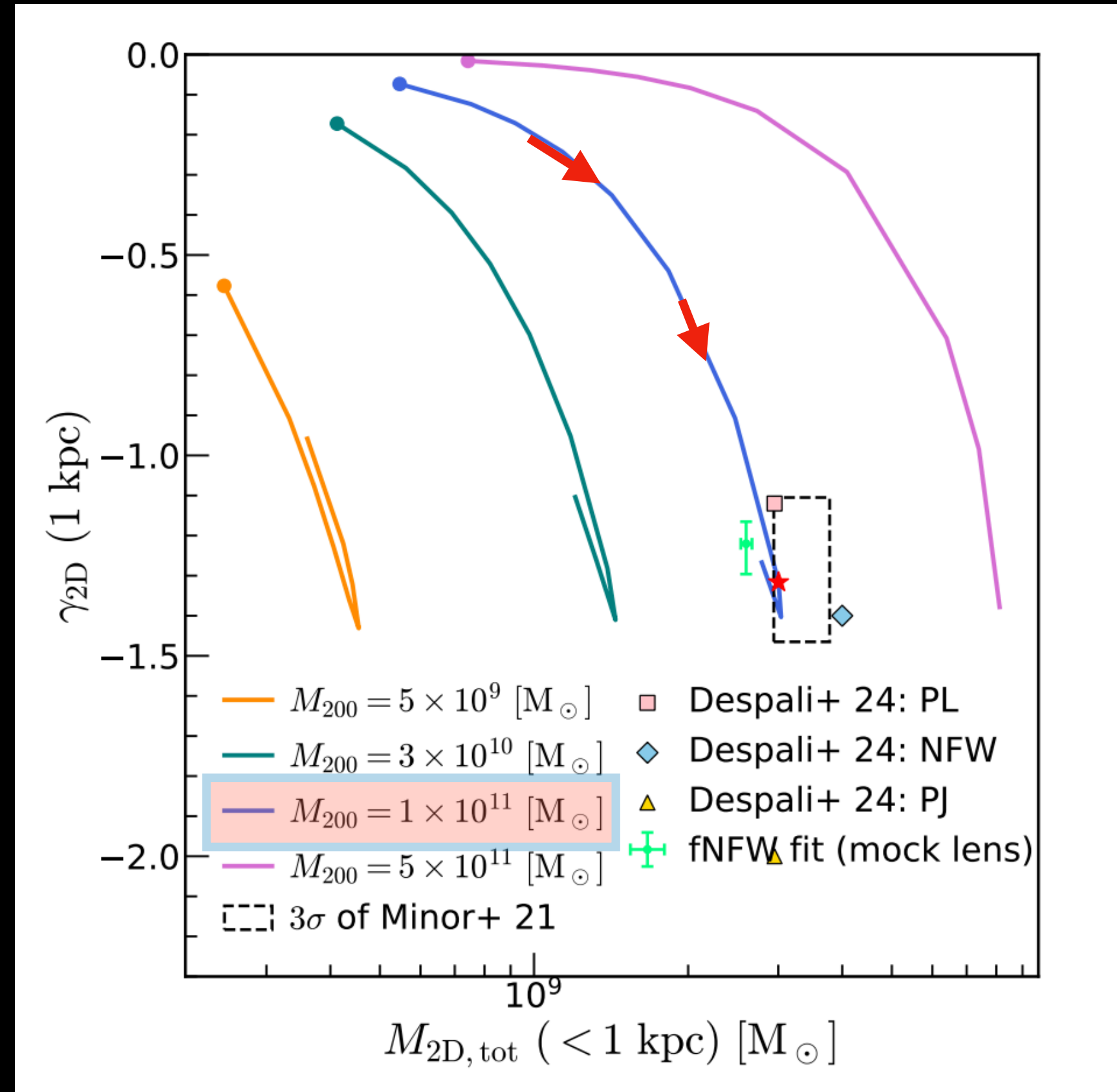
XY Cao, Ran Li et al. submitted, 2025

arxiv: 2504.19177

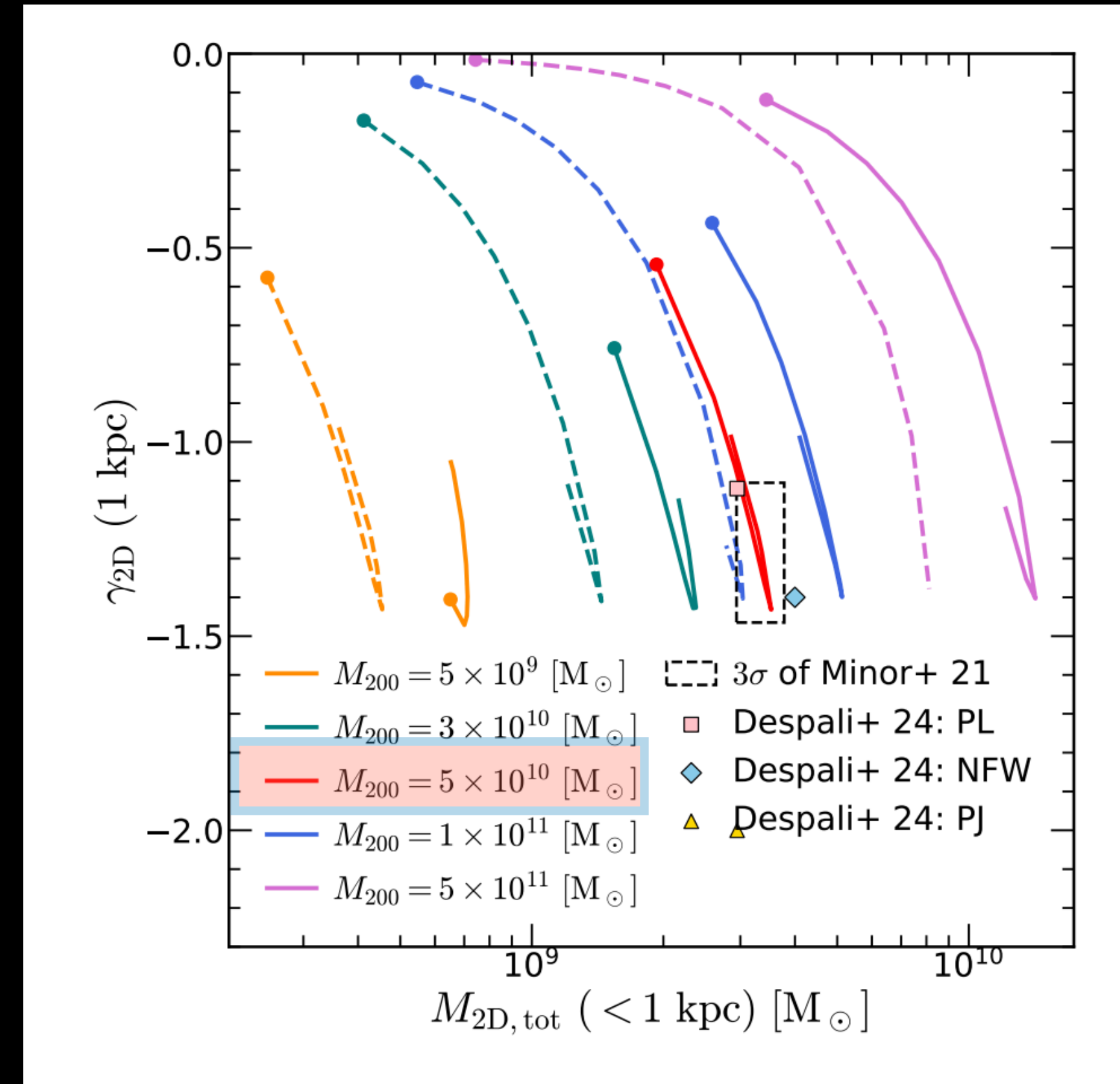
Could core-collapse halo in a SIDM model explain the perturber?



To explain SDSS 0946, requires
a SIDM halo with total mass of 10^{11} Mo



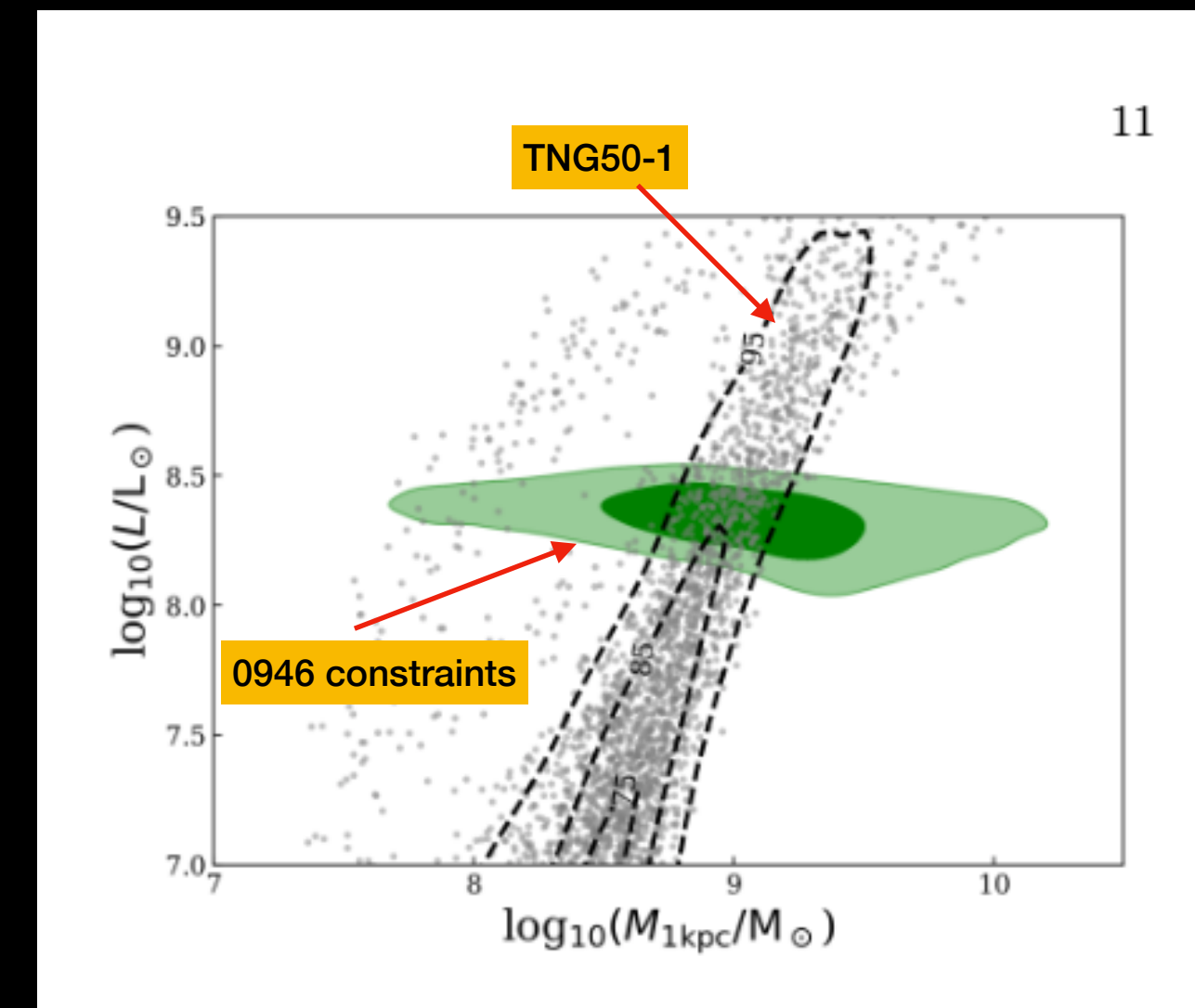
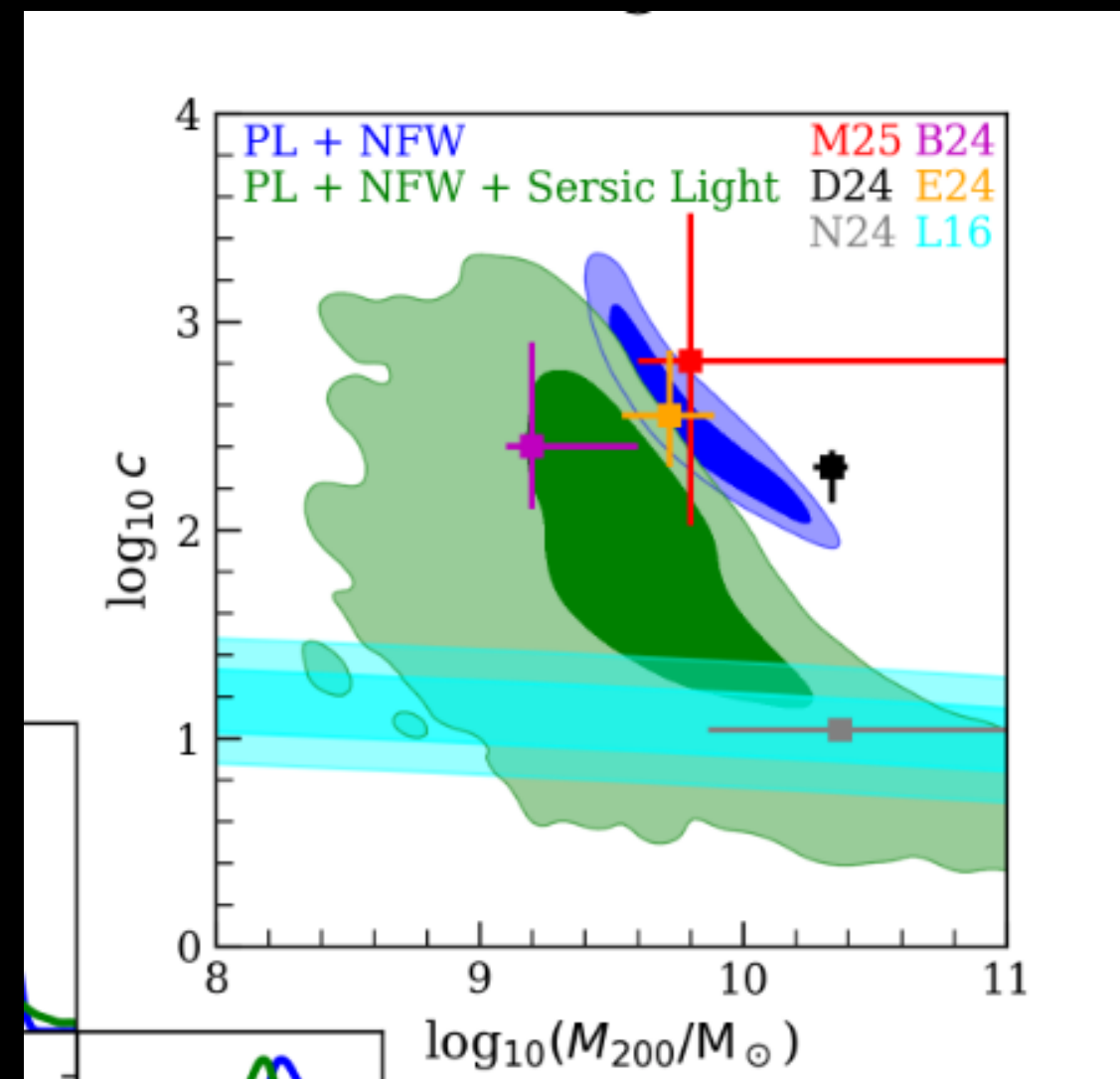
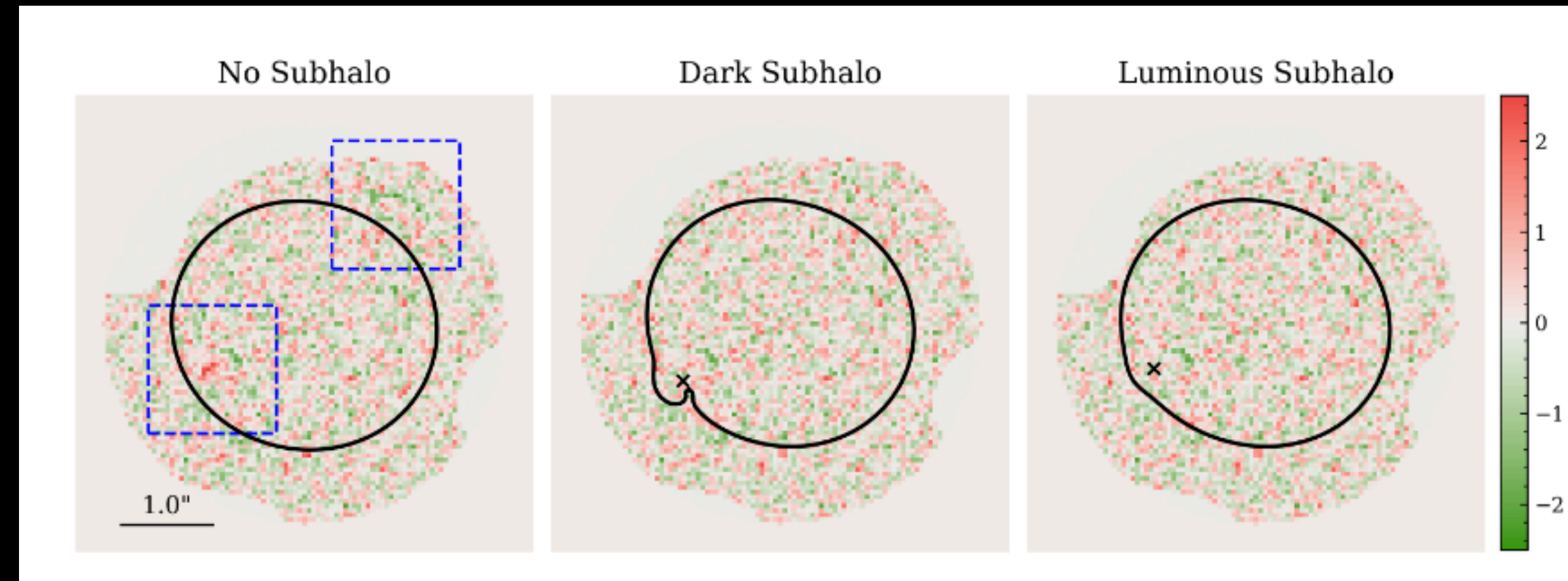
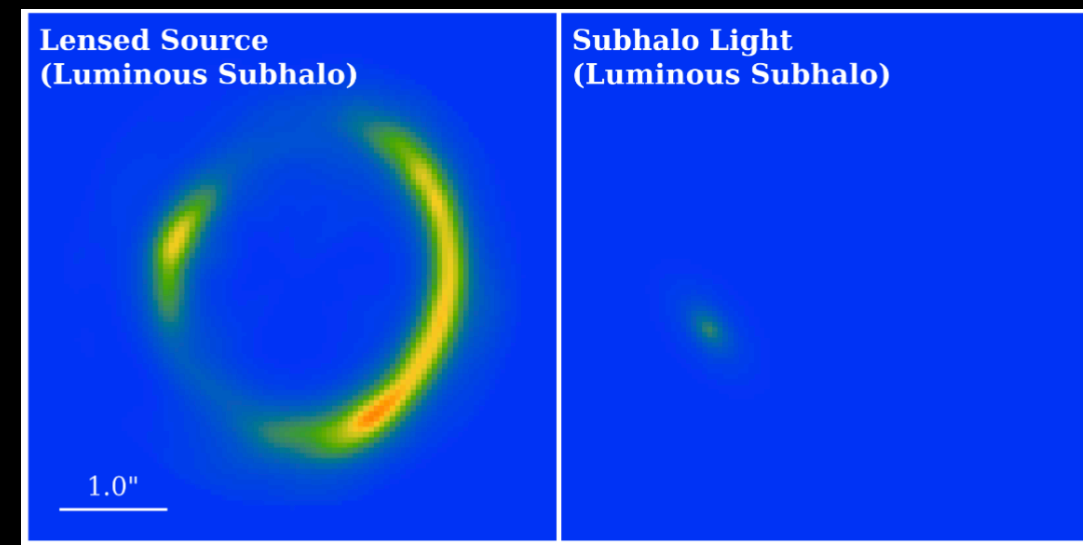
High initial halo concentration
reduces the required mass of halo



SHB Li, Ran Li + 2025, submitted, arxiv: 2504.11800 (details in Shubo Li's talk)

Why don't we see the galaxy within the perturber?

The normalized residuals



Ongoing and Upcoming Space Optical Surveys



Euclid Telescope and Q1 Lenses



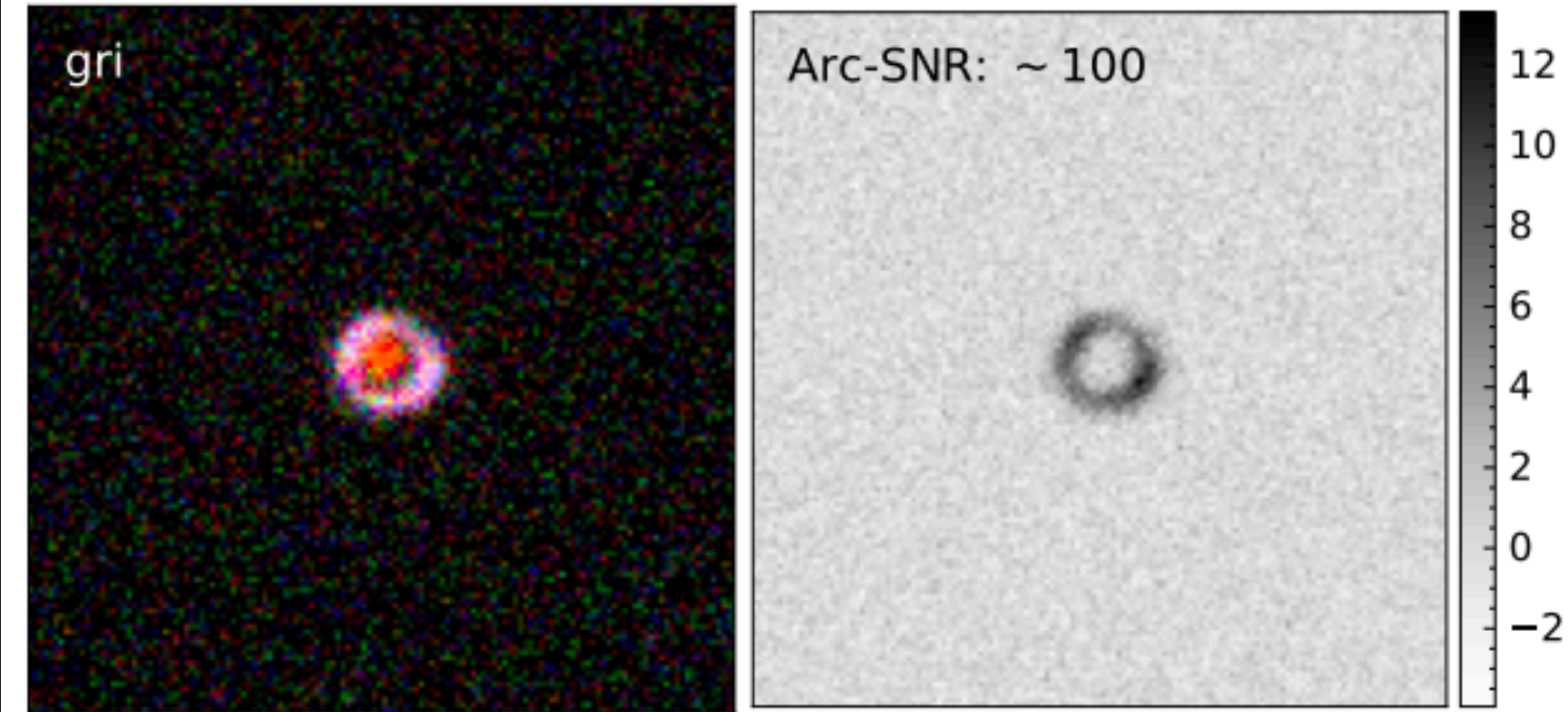
China Space Station Telescope (CSST, “巡天”)

Multi-band imaging covering 17500°

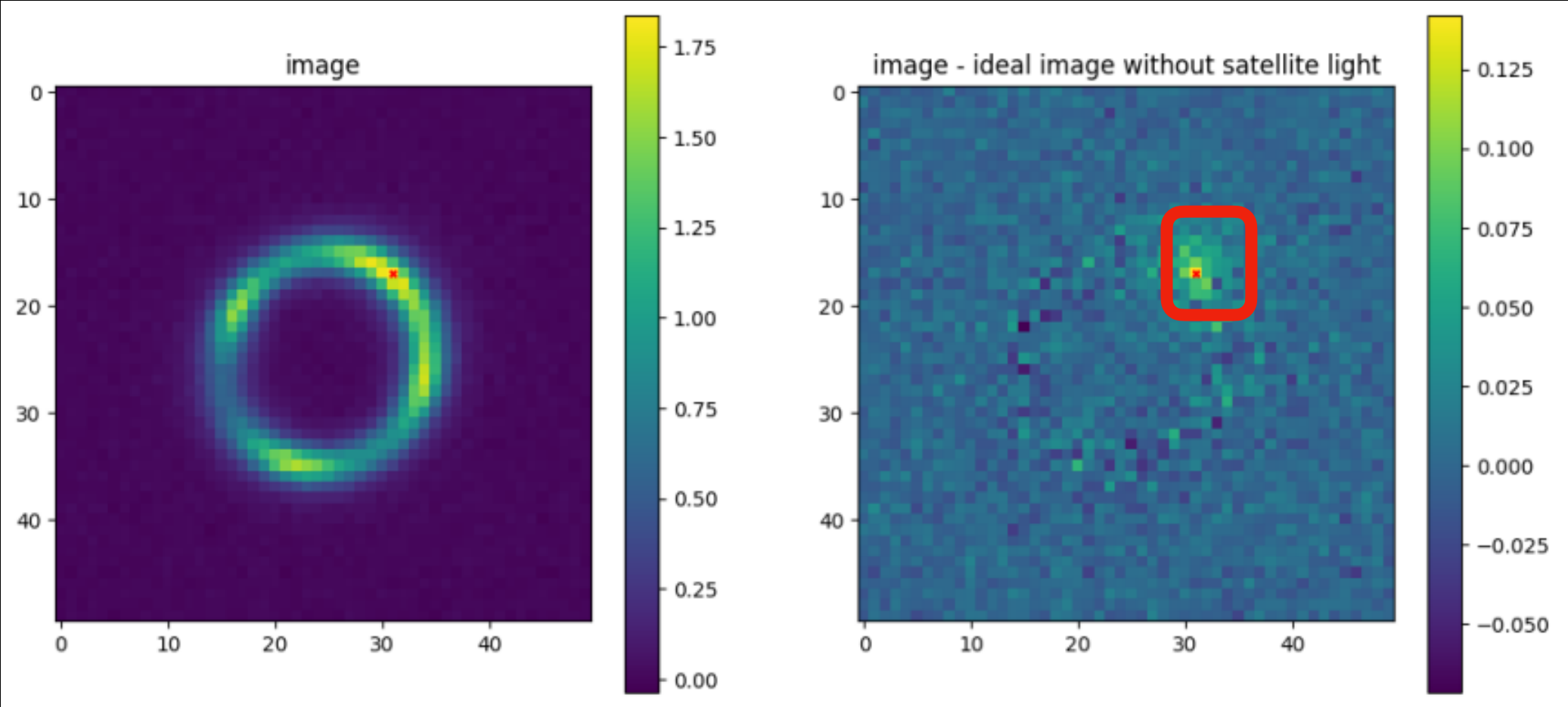
(avg. 25.5 mag) $R_{ee80} < 0.15''$

Launch ~2027

	WF	DF	UDF
stack	161000	17800	830
single	76300	11900	720
combine	162000	18100	840
$\text{SNR}_{\text{arc}} > 100$	4000	1010	200
$z_l > 1$	30600	4200	200
$M_{\text{ein}} < 10^{11} M_{\odot}$	61500	6900	310



$z_{\text{lens}}=0.2$ Mag~24.62, KH Wang et al. 2025 in prep



~5000 with S/N>100

Ground Base Limit

Summary

- Galaxy strong lensing is a promising tool to probing small dark matter halo/subhalo directly in distant universe
- Counting and detailed modeling of dark perturbers form crucial test for CDM structure formation theory.
- Galaxy lens modelling technique develops significantly in the past 10 years.
- New generation of space telescopes will be game changer for the field

