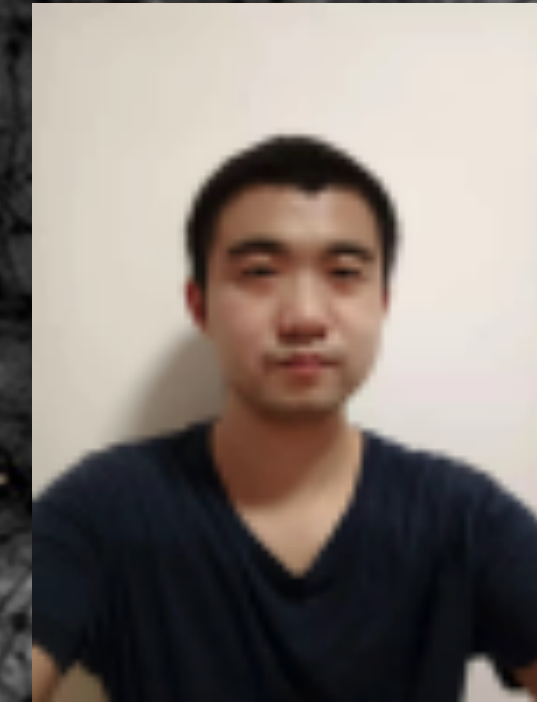


Little Dark Dot: 一场关于SIDM的四幕剧 和一点点CSST时代暗物质研究的展望

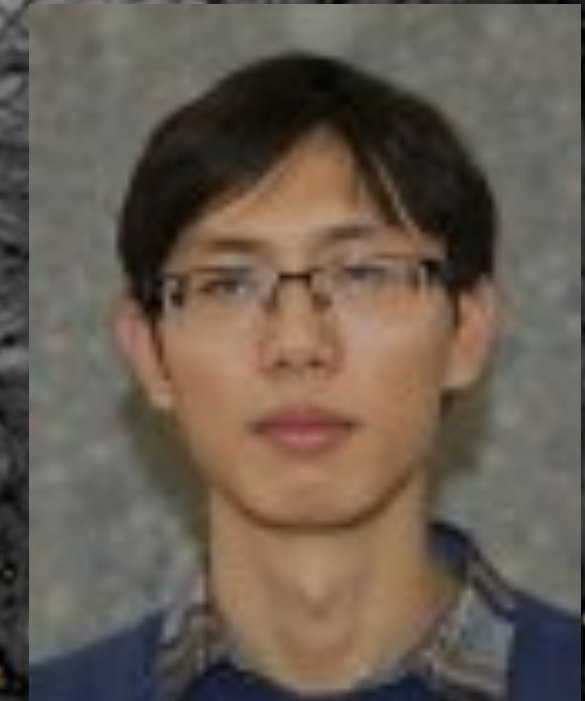
李然 Ran Li

Beijing Normal University

National Astronomical Observatories of China



曹潇月



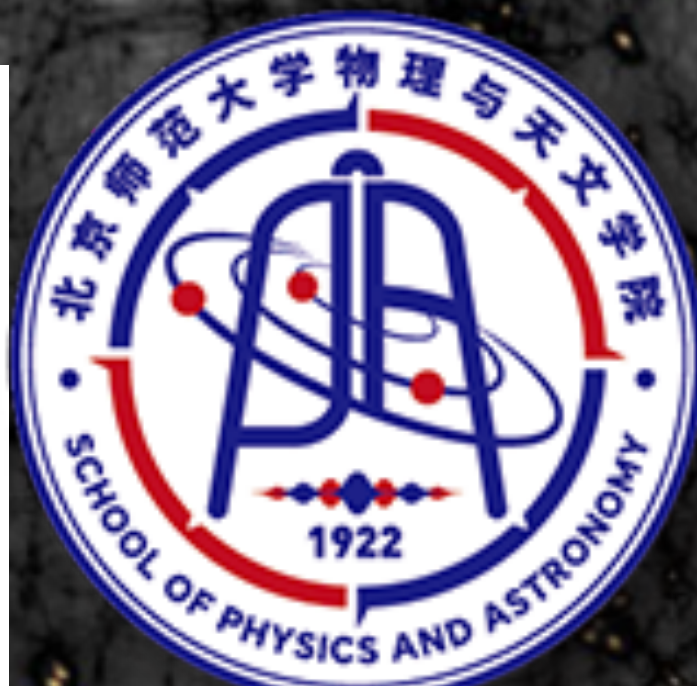
何秋翰



李树博

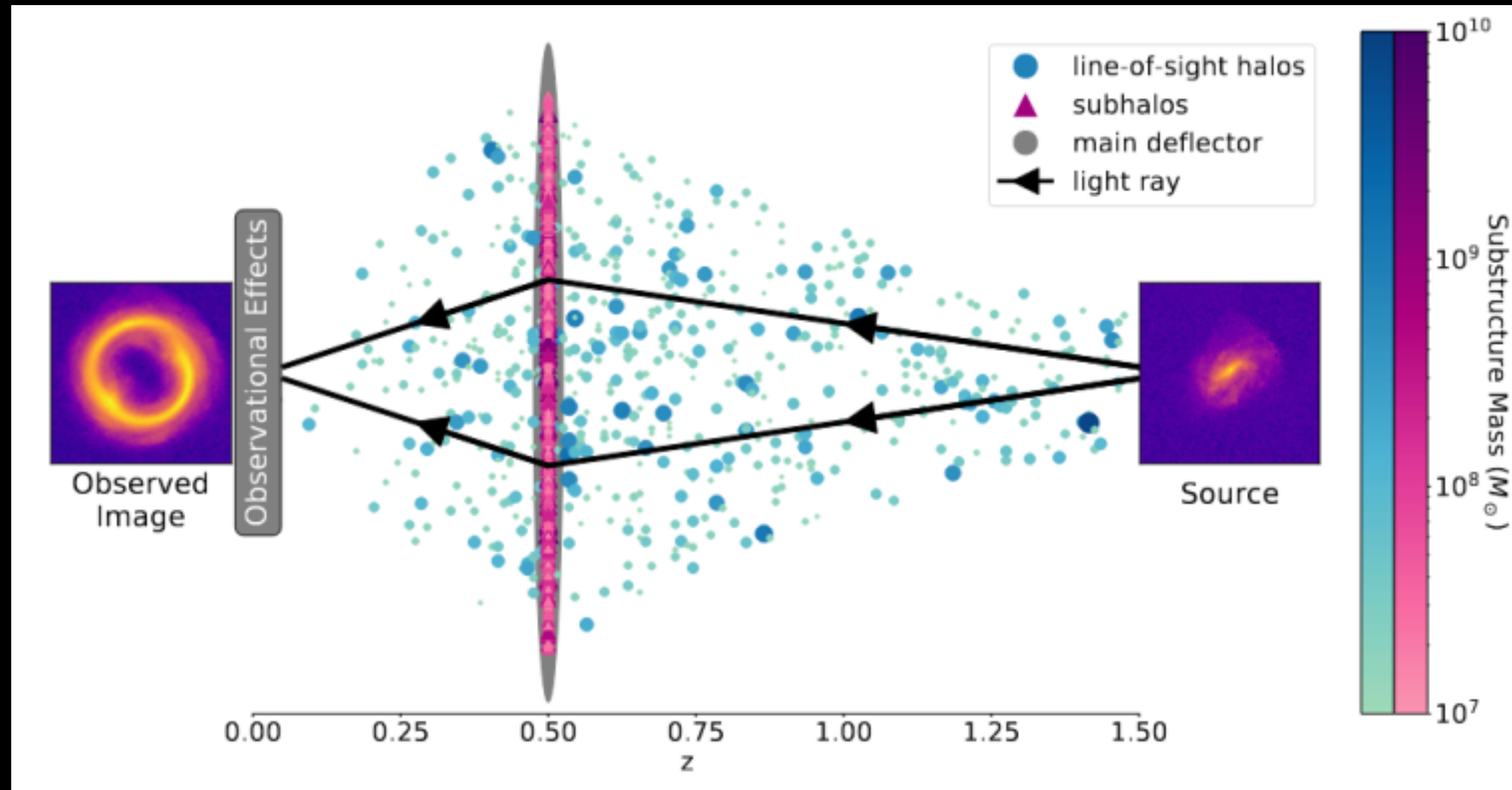


王凯浩

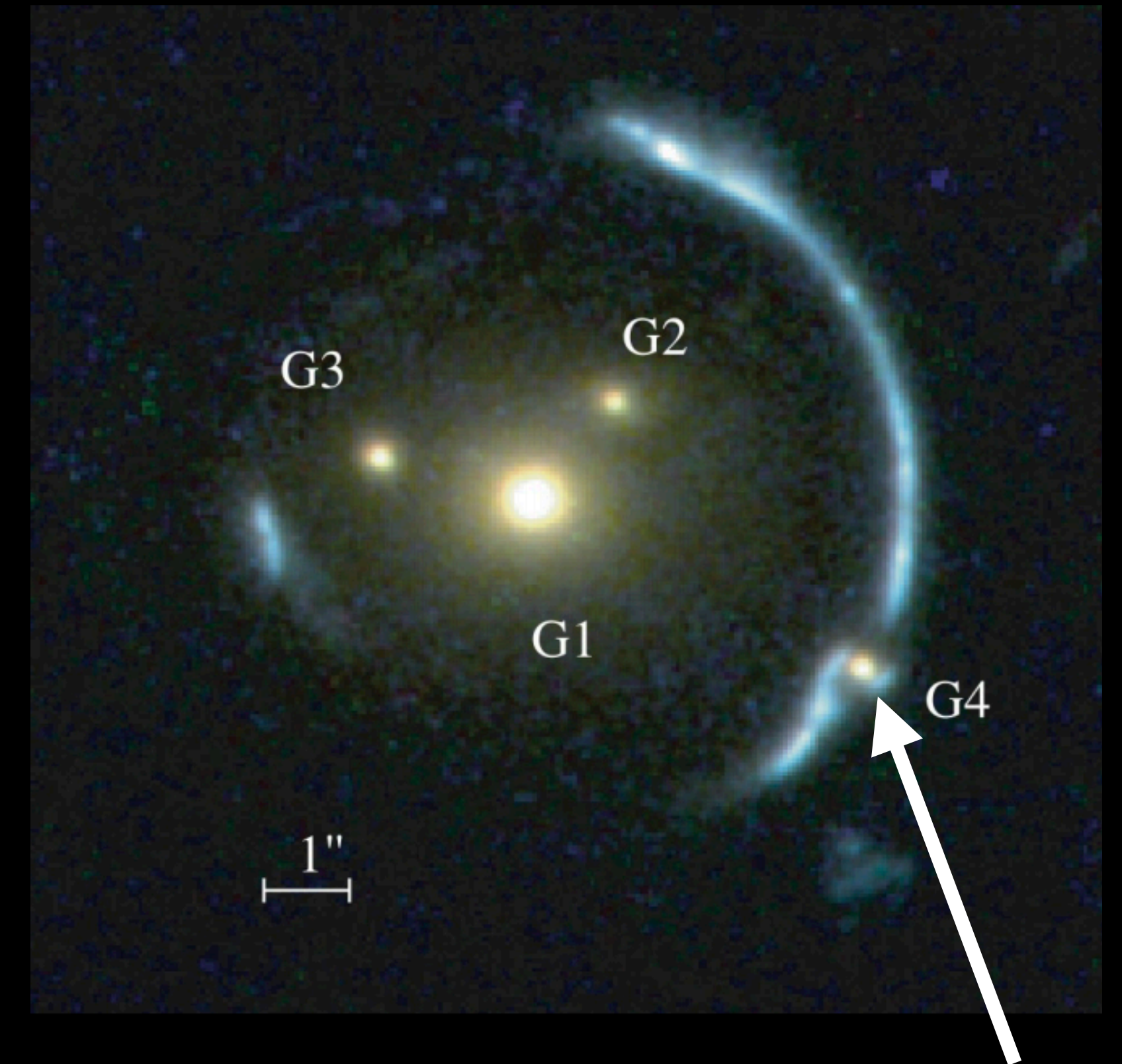


Cao XY, LR et al. arXiv: 2504.19177
Wang KH, Cao XY, LR et al. arXiv: 2501.16139
Li SHB, LR et al. arXiv: 2504.11800
He QH, LR et al. arXiv: 2506.07978

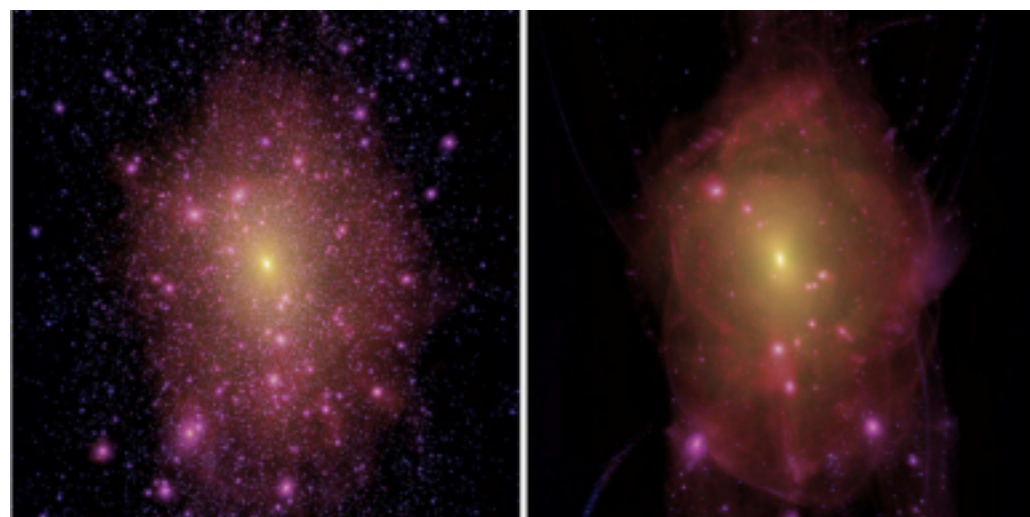
第一幕：遥远宇宙中的小暗晕



Wagner-Carena et al. 2023

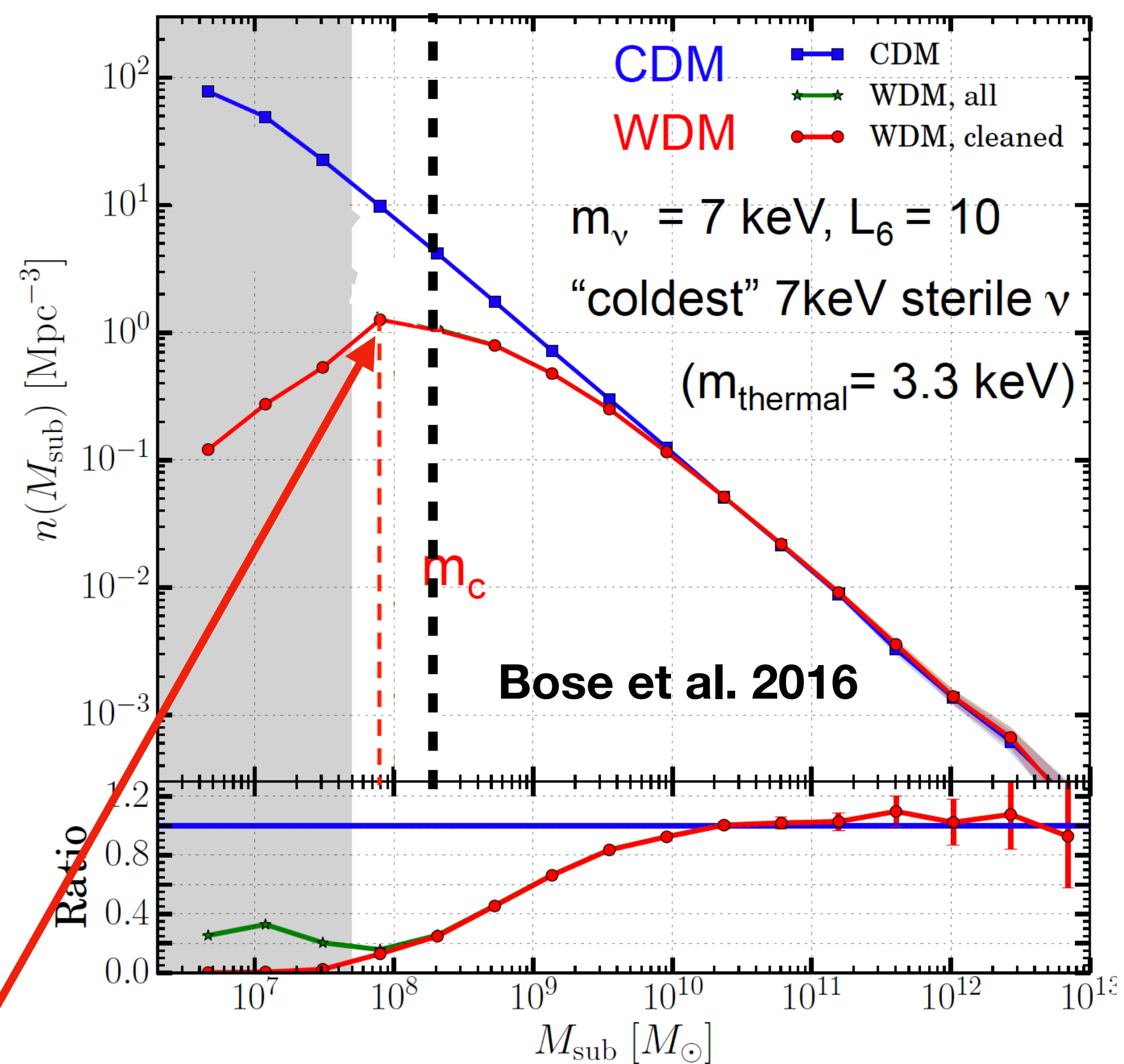


Substructure can perturb lensing image

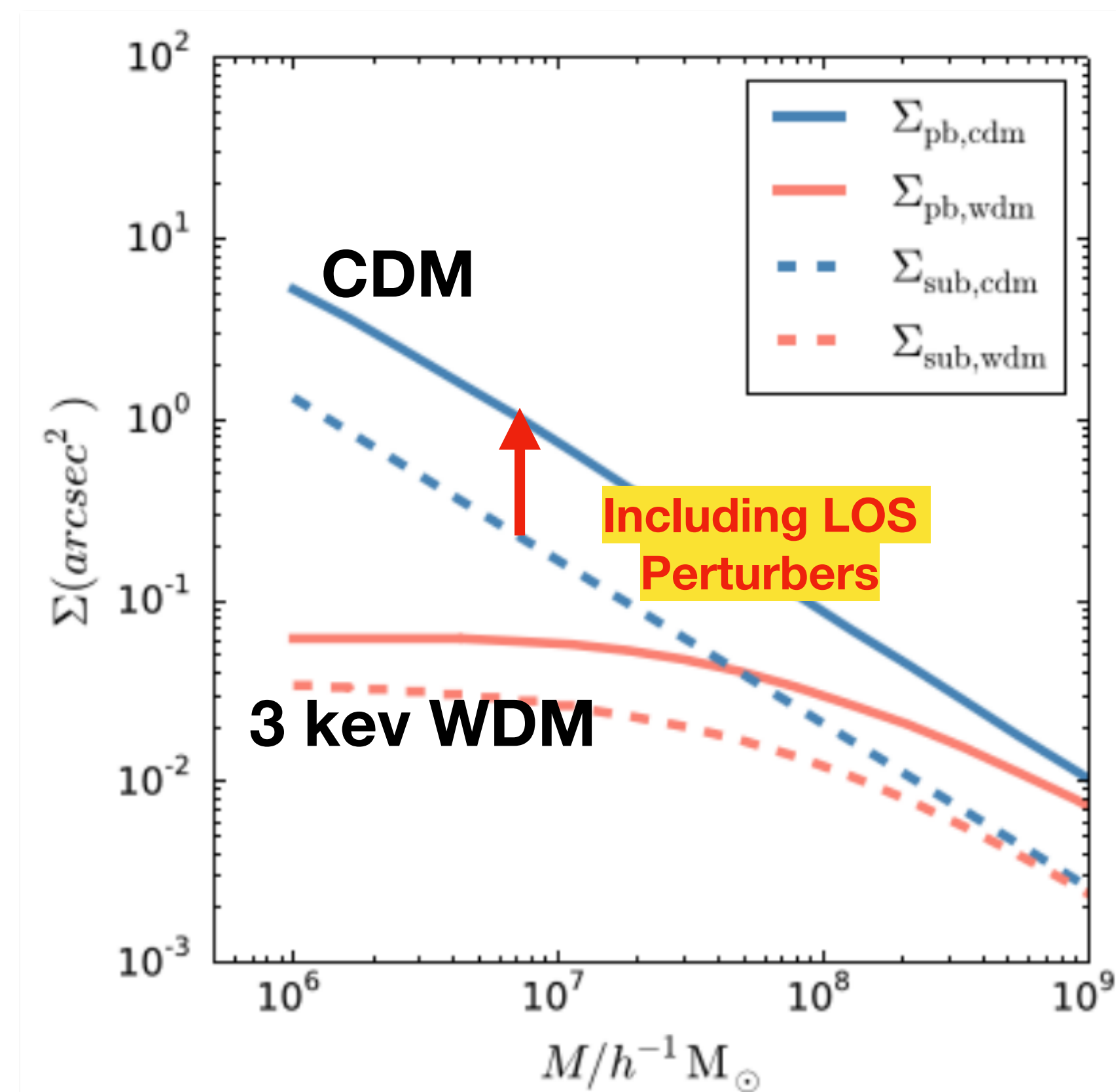


Warm or Cold?

Milky Way dwarf



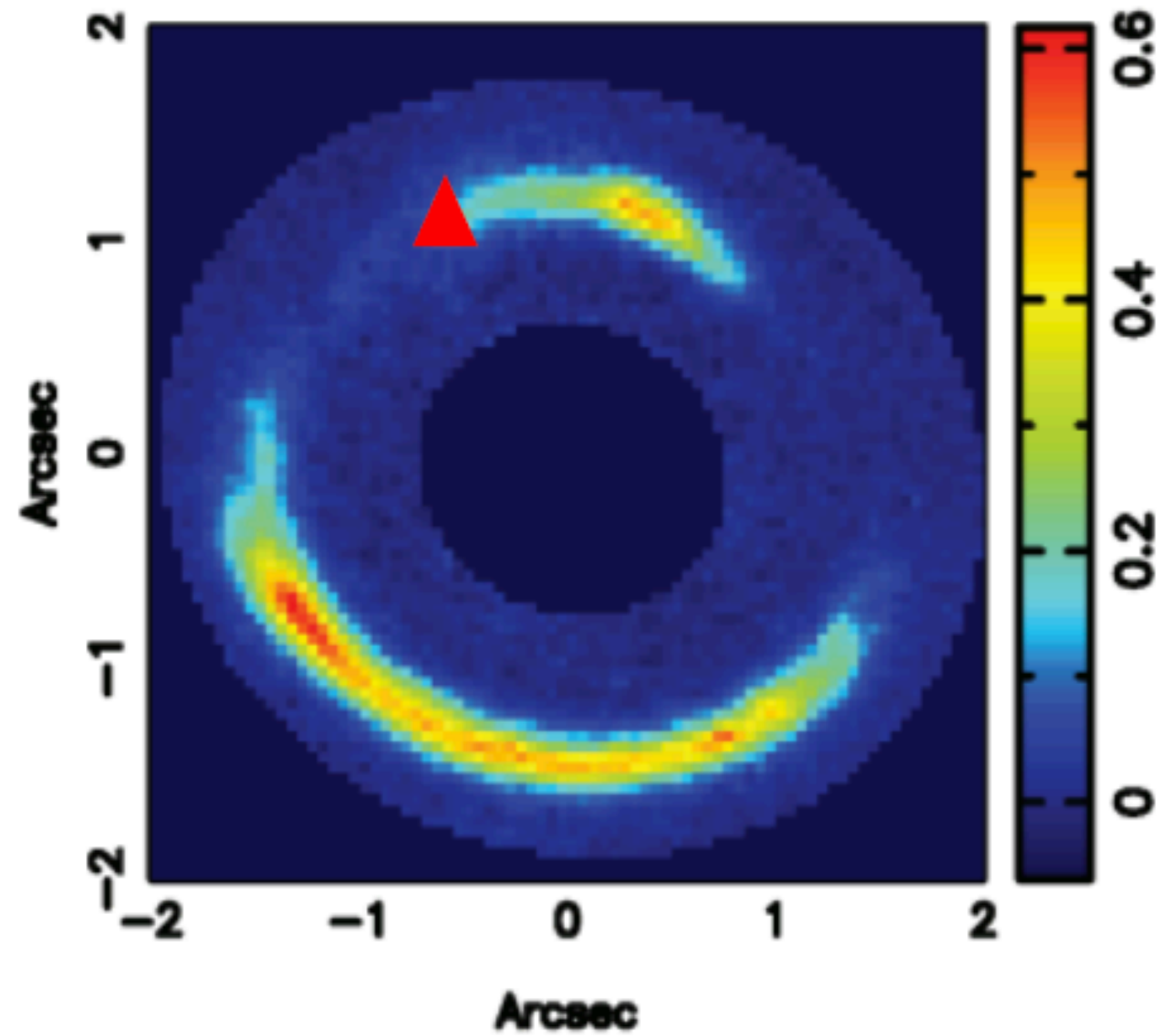
Mass function Cut-off



Ran Li et al. 2016,2017

HST Imaging

Data SLAC 0946+1006

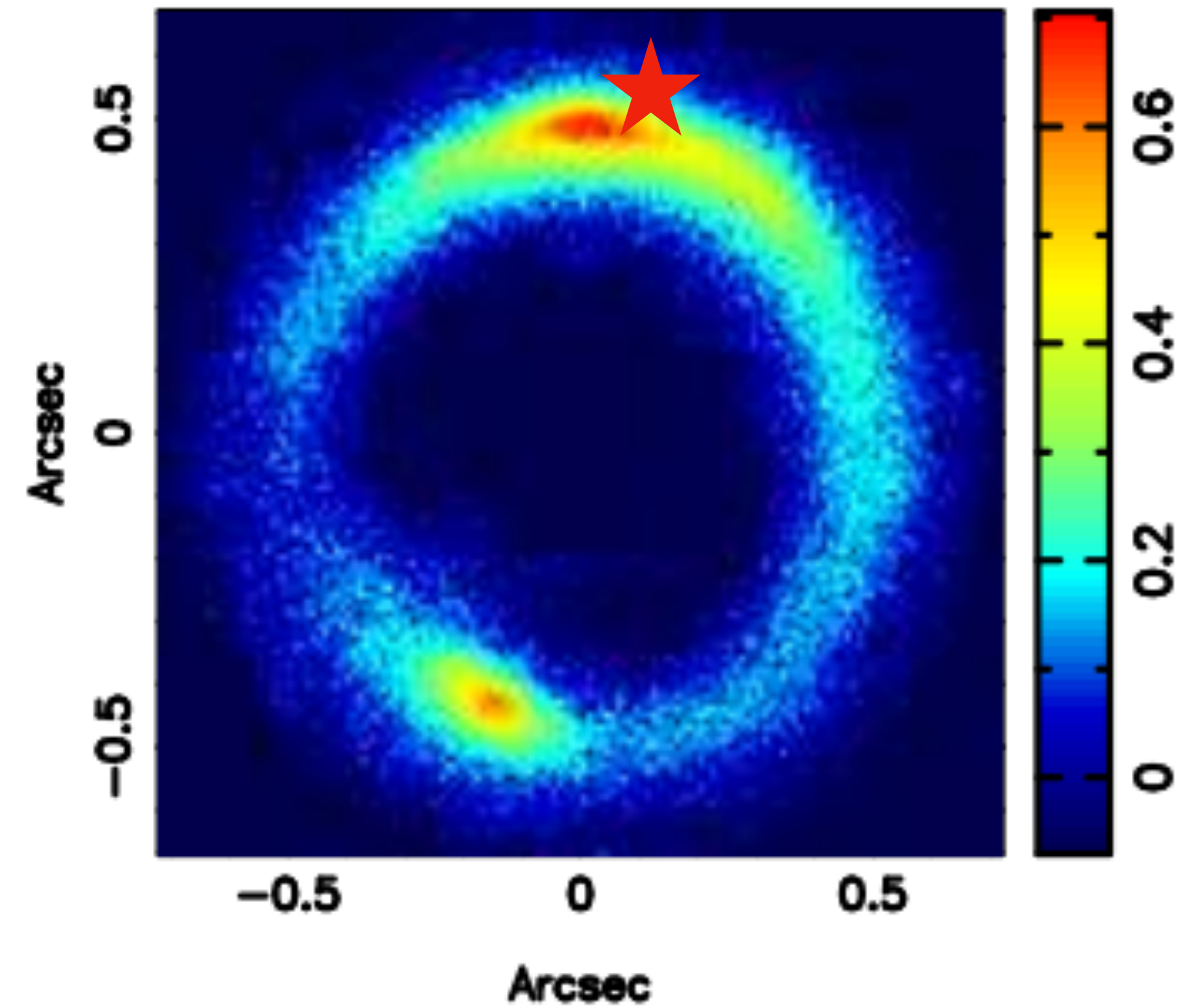


$$M_{\text{sub}} > 10^{10} M_{\odot}$$

Vegetti et al. 2010

Keck AO Imaging

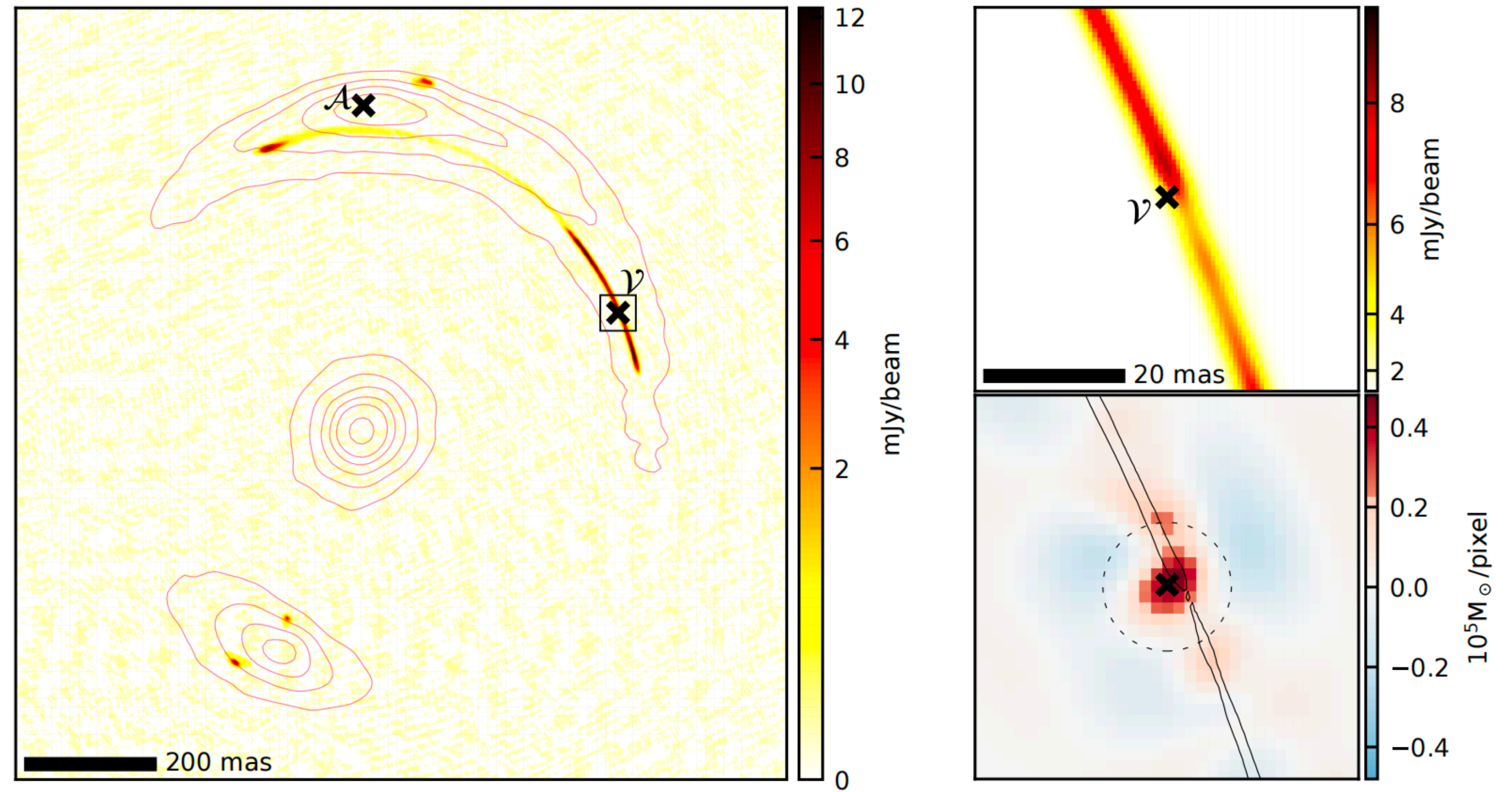
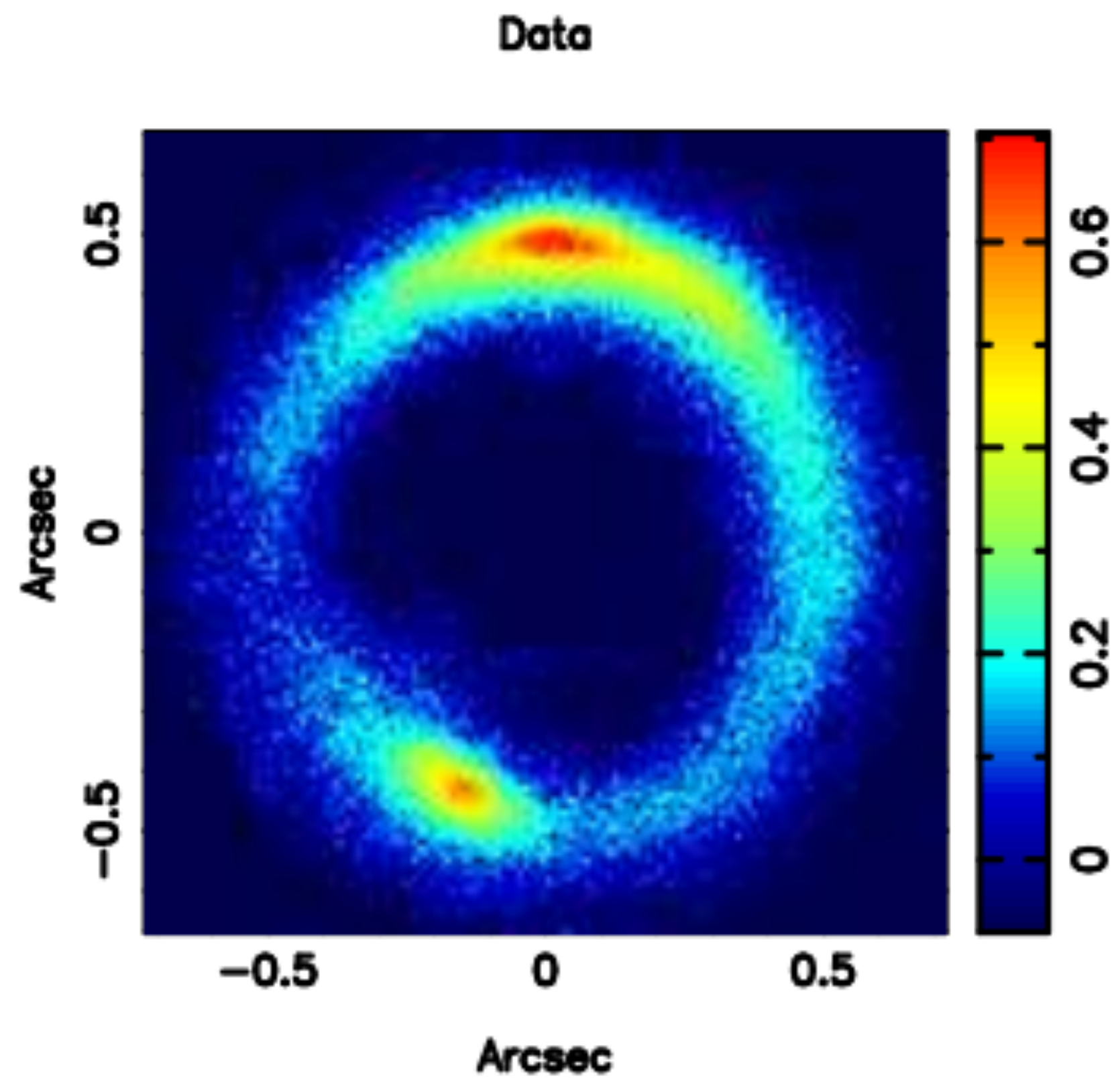
Data B1938+666



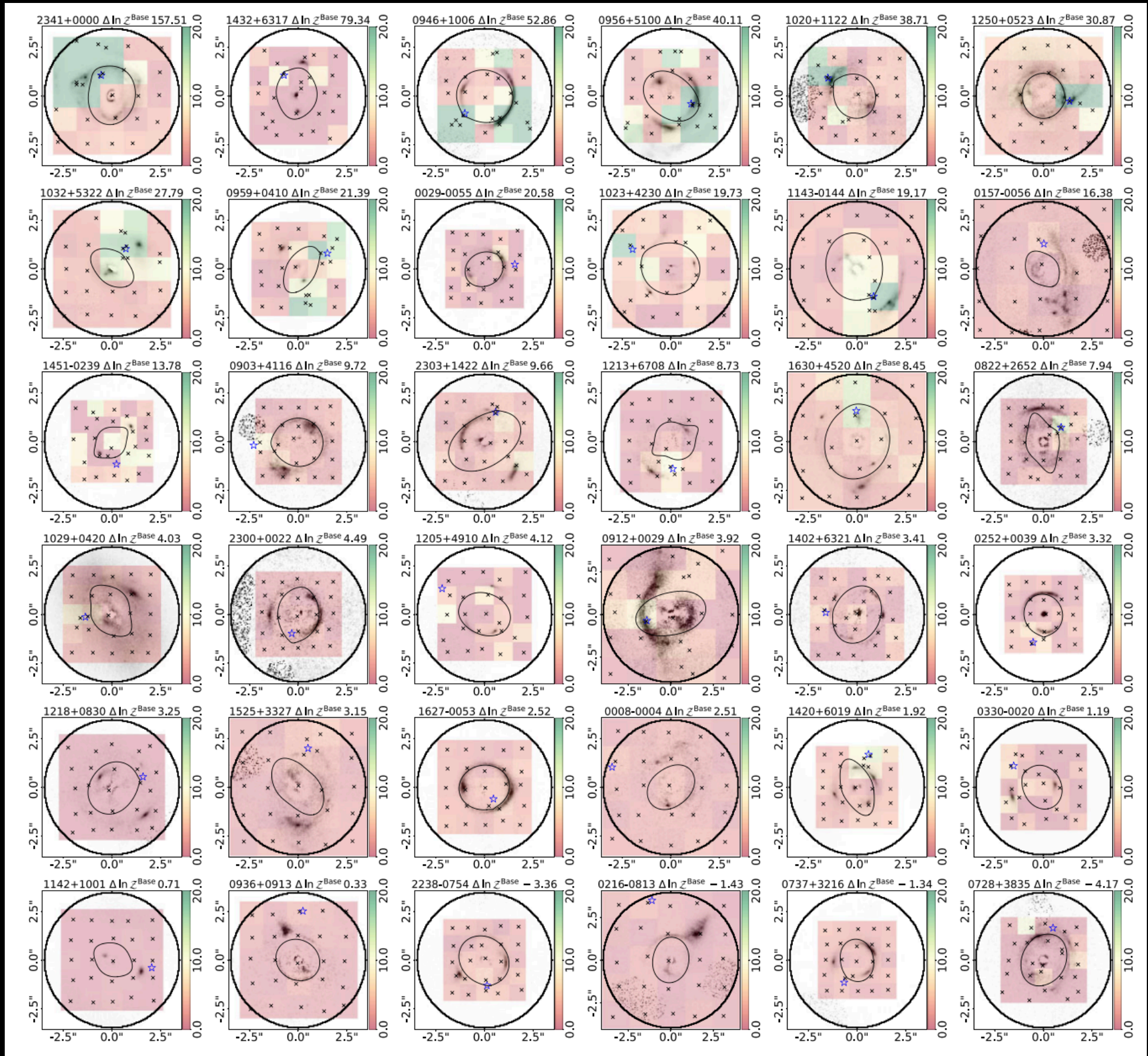
$$M_{\text{sub}} > 10^8 M_{\odot}, 12\sigma$$

Vegetti et al. 2012

VLBI imaging second perturber with $m=1.13 \times 10^6 \text{ Mo}$, by Vegetti et al. 2025 Nature, 2510.0738

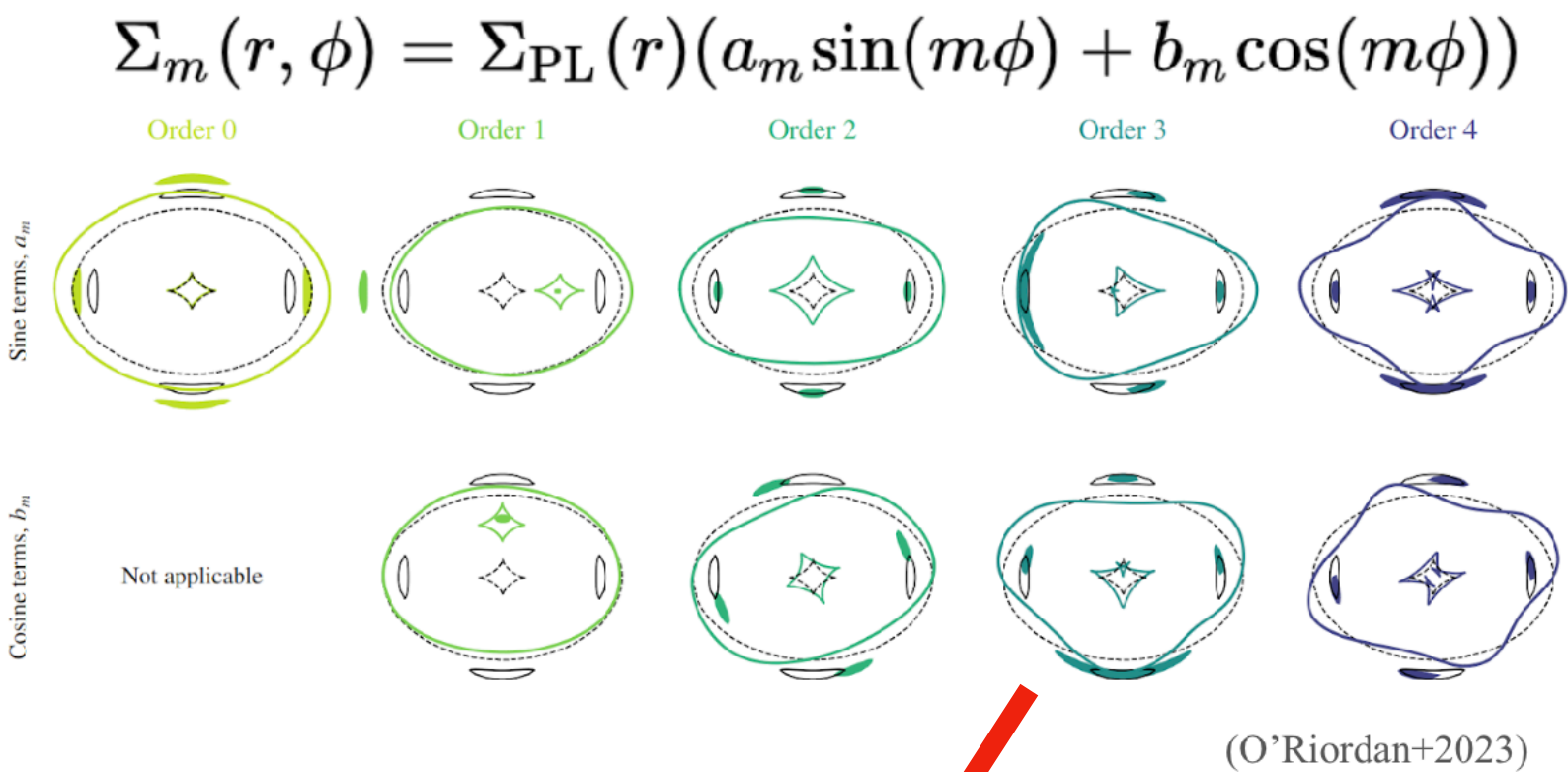


Candidates From Hubble Imaging



54 lenses from SLACS and Bells sample

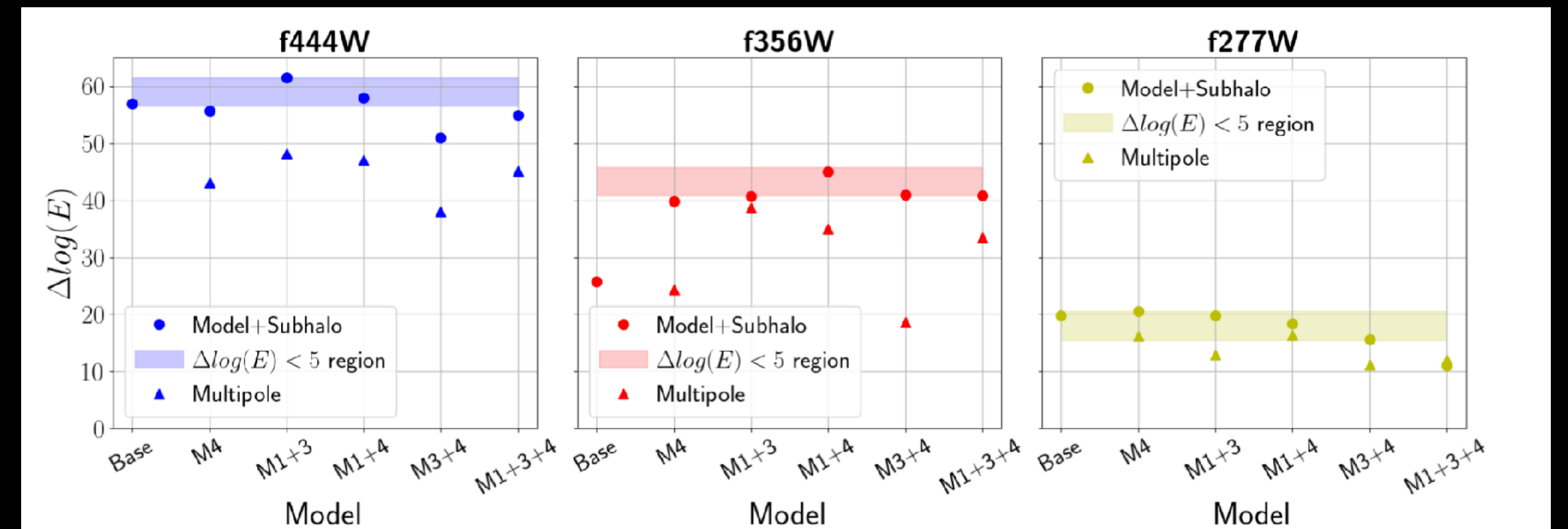
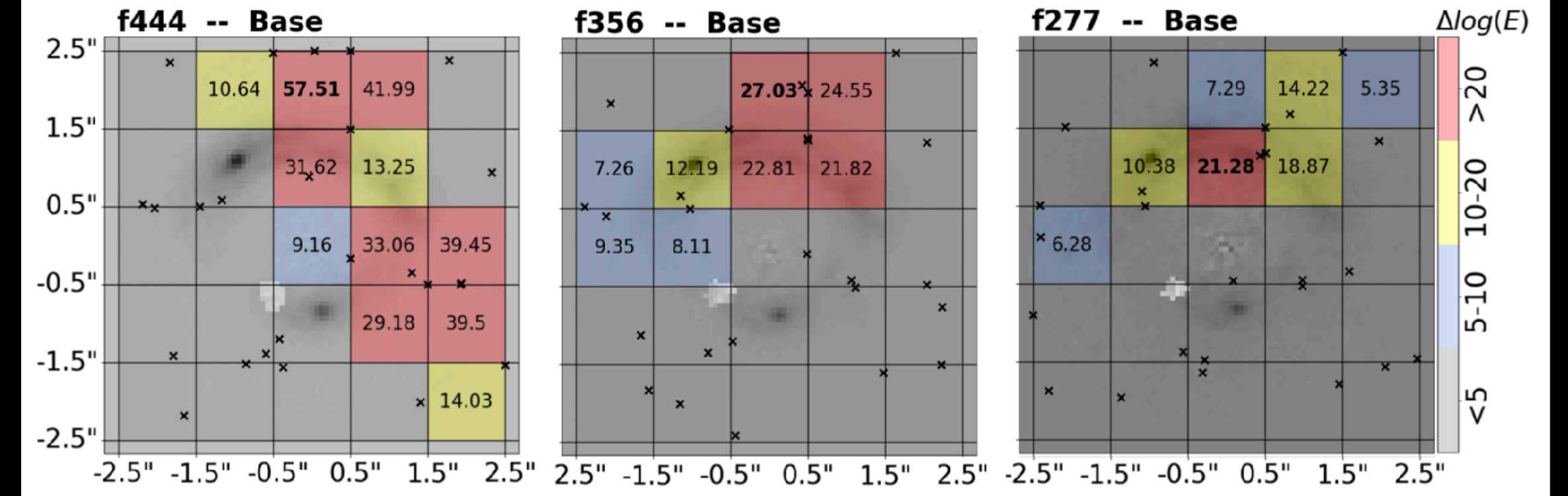
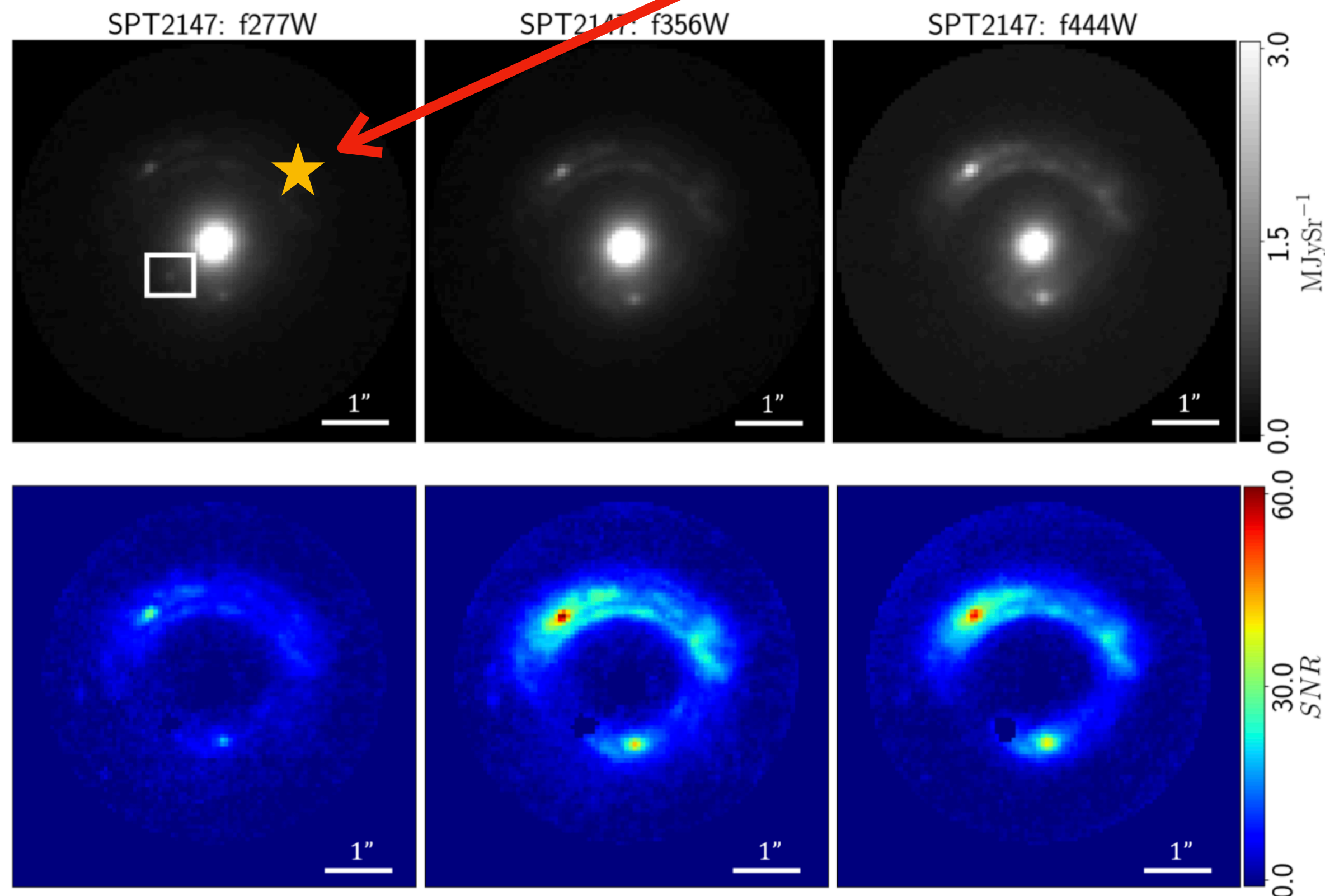
Multipoles:



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	$11.23^{+0.12}_{-0.20}$		

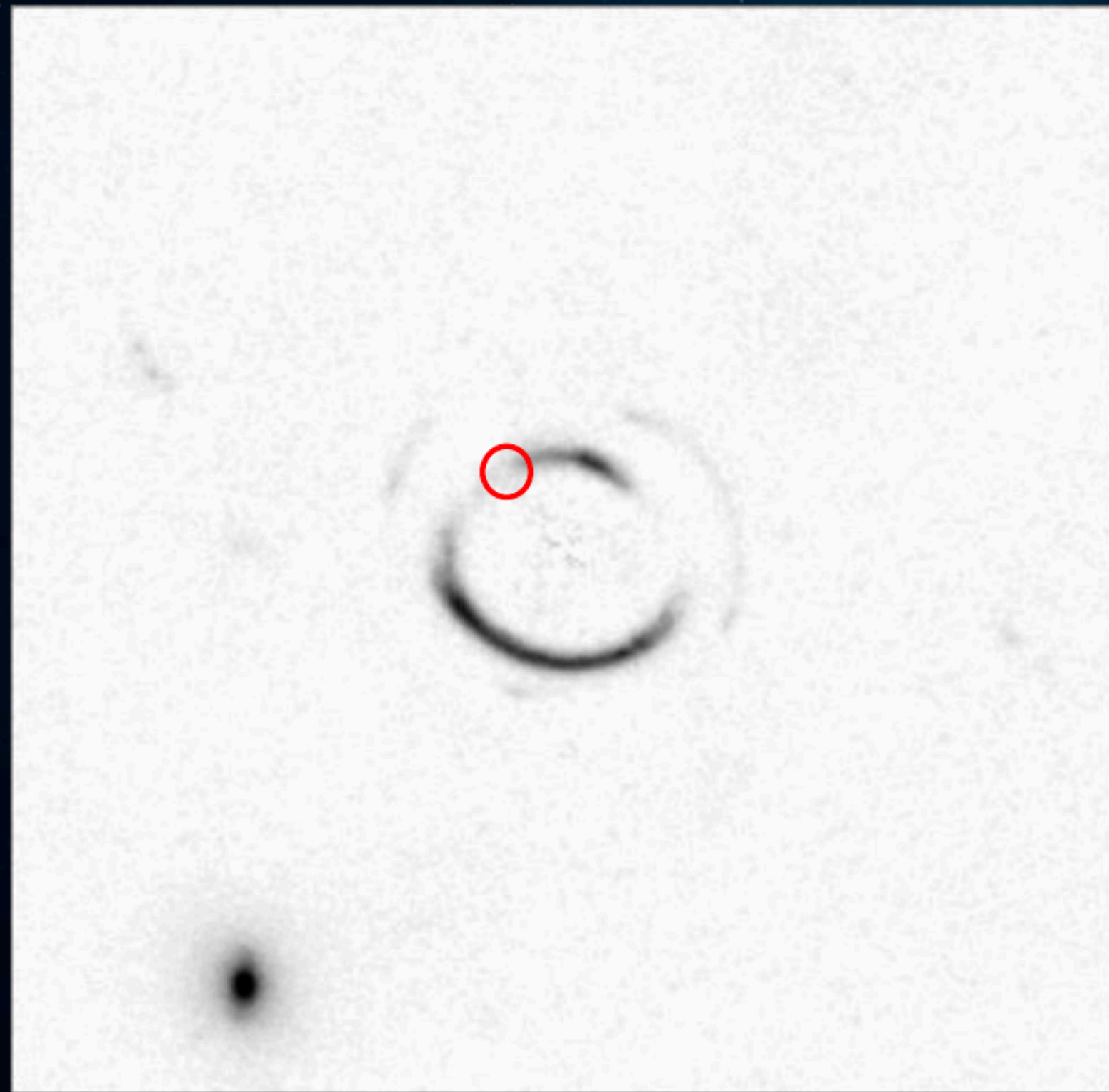
New candidate from JWST

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

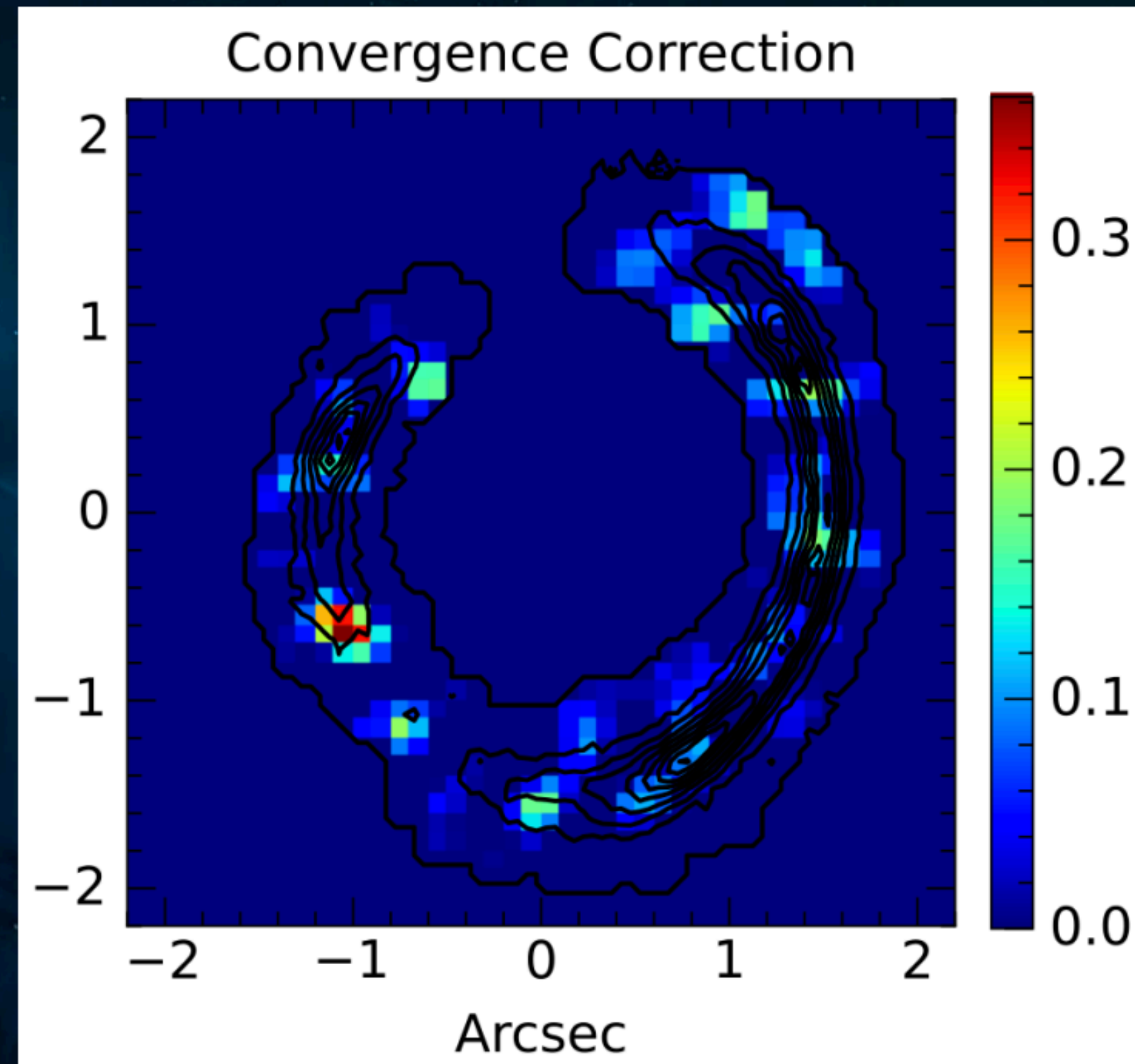


试金石样本

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



HST ACS F814W image *S. Vegetti et al. 2010*



free-form modelling *X. Cao et al. 2025*

Detection confirmed by:

Simona Vegetti et al. 2010

Quinn Minor et al. 2021

James Nightingale et al. 2024

Daniel Ballard et al. 2024

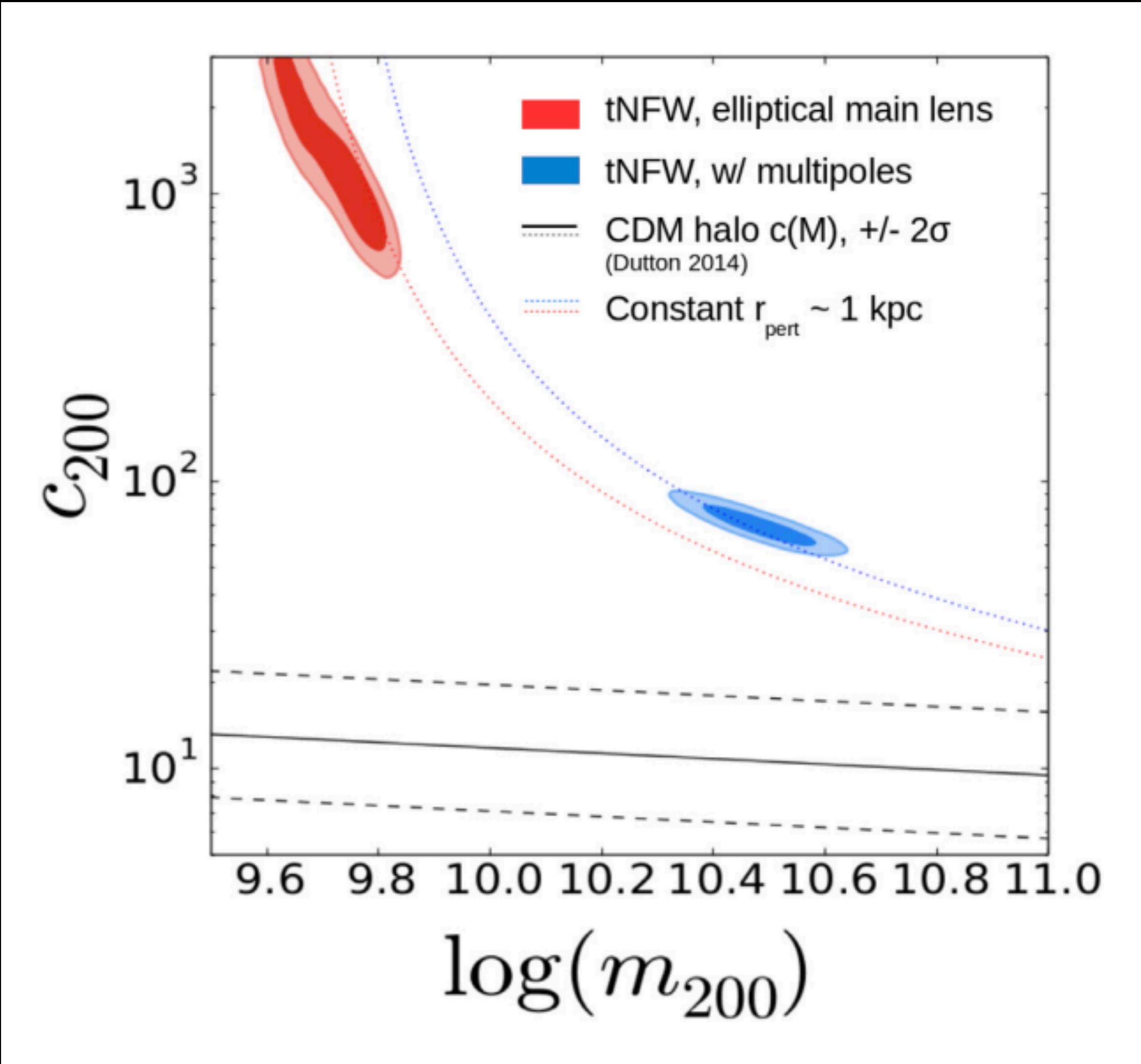
Quinn Minor 2024

Giulia Despali et al. 2024

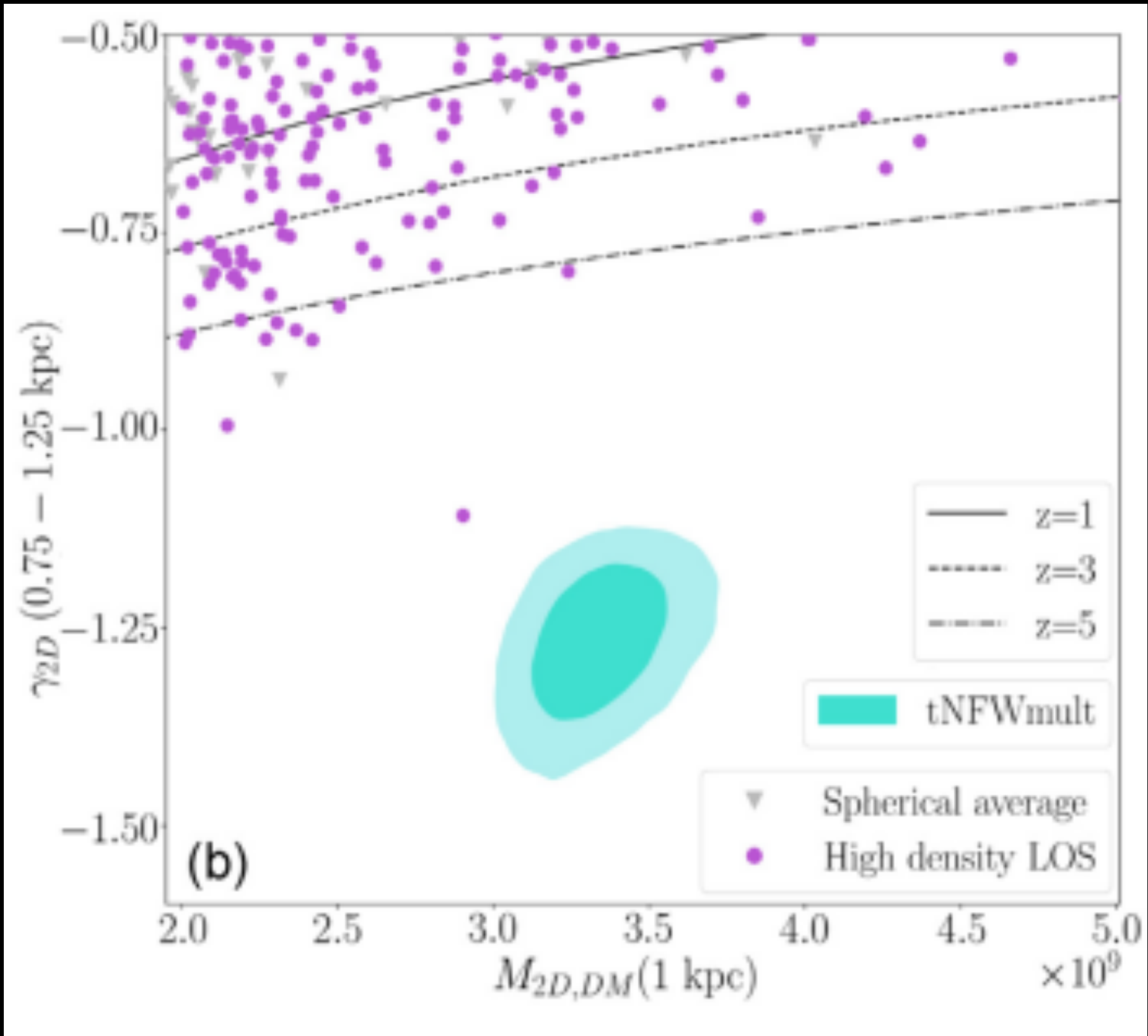
Wolfgang Eniz et al. 2024

Xiaoyue Cao et al. 2025

第二幕：暗物质的“大”危机？



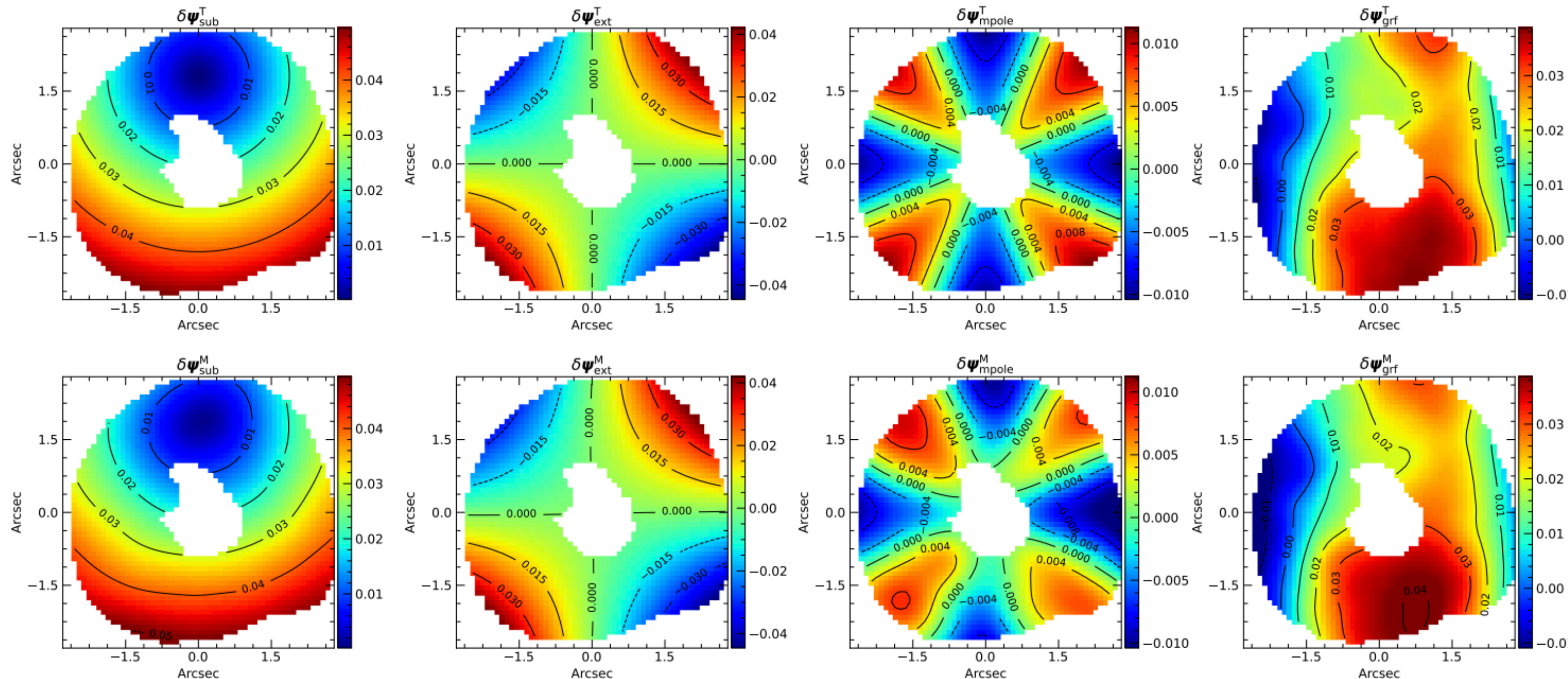
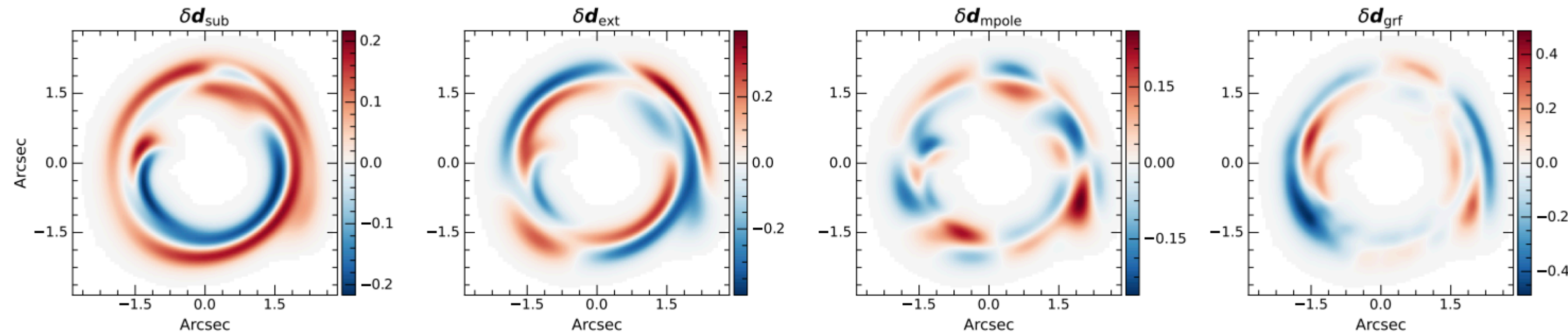
Minor et al. 2021



Despali et al. 2024

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
			8^{+87}_{-59} , 812^{+164}_{-583}	Ludlow et al. (2016)	NFW	N24
			$1.58^{+2.4}_{-0.33}$	251^{+543}_{-125}	tNFW	B24
	+MUSE	+F336W	-	-	-	S12
	+HST/WFC3,WFC2	+F(160,606,438)W	-	-	-	C20
	MUSE		-	-	-	

Reveal the perturber morphology from free-form reconstruction



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

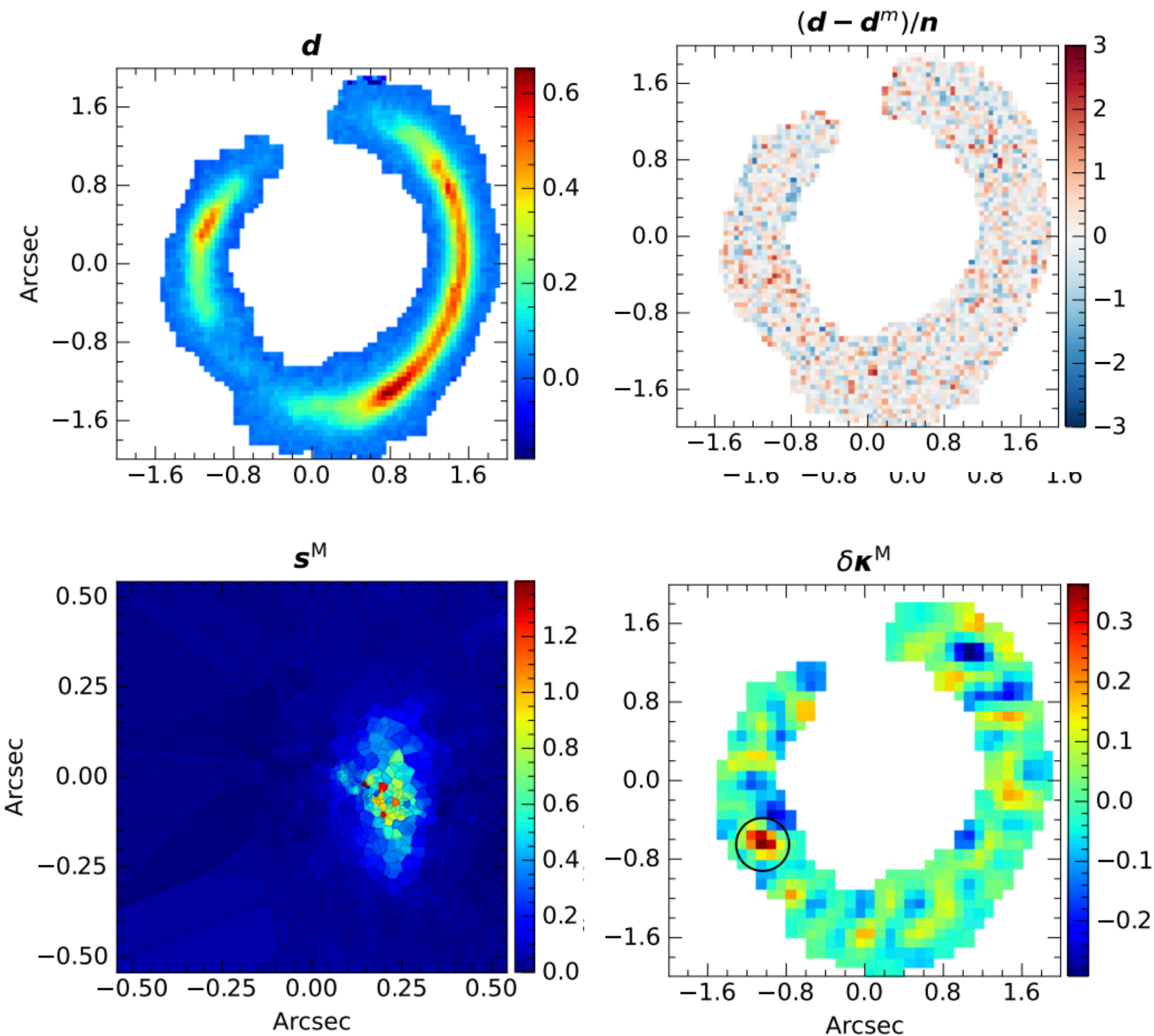
Source light gradient

Potential gradient

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

Reveal the perturber from potential correction

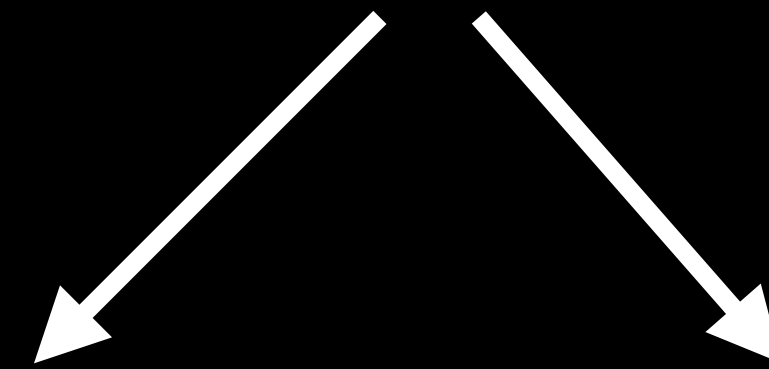
SLACS 0946+1006



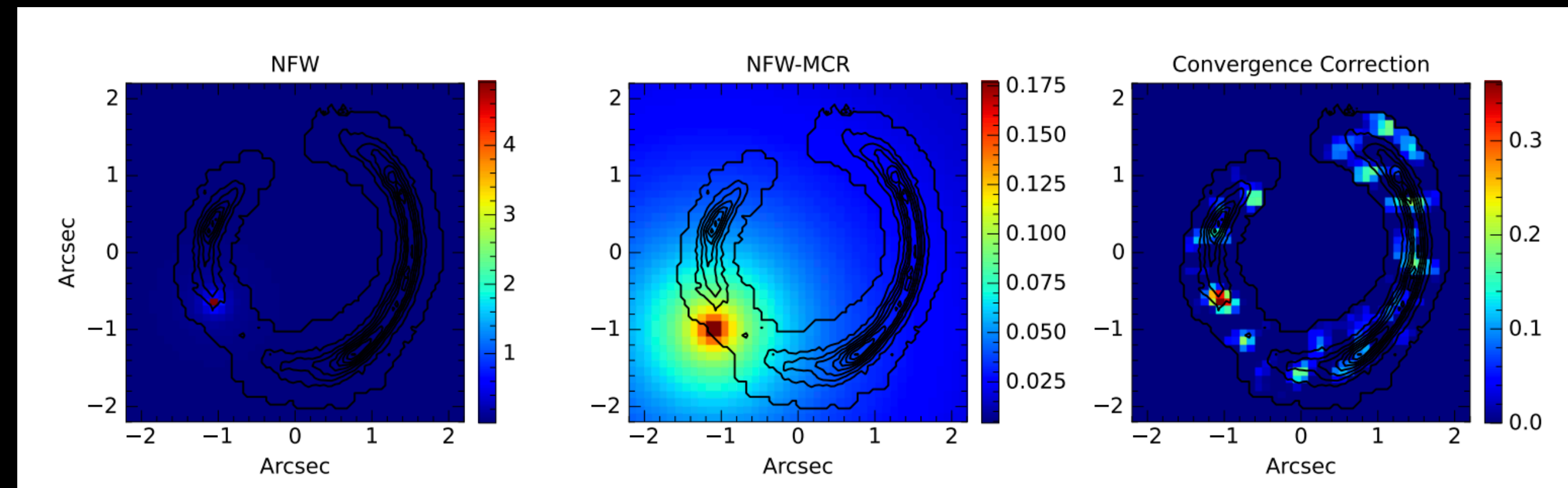
Parametric Model

Left: fix mass-concentration relation

Right: free concentration parameter



Free Form Reconstruction

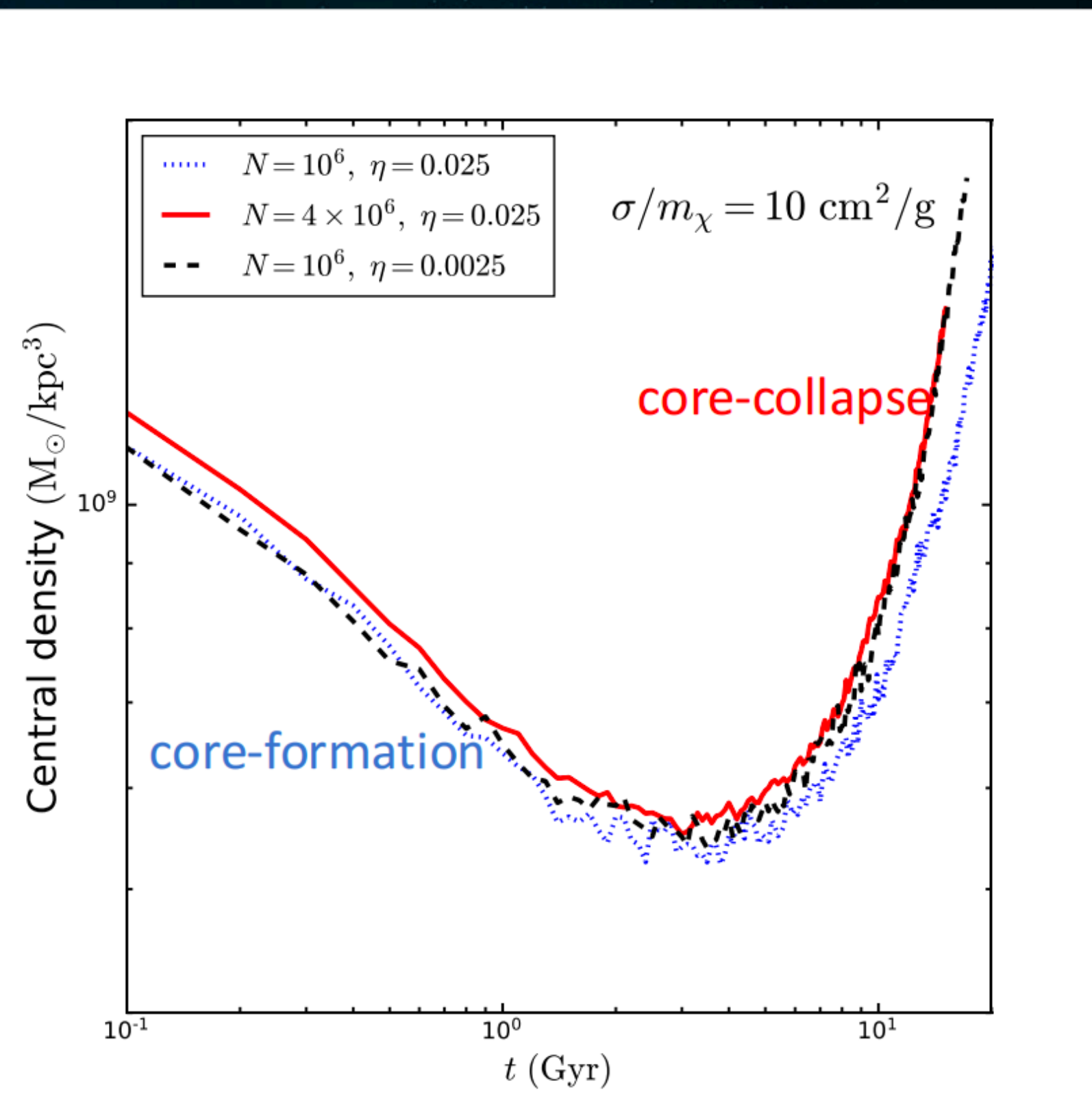


XY Cao, Ran Li et al. submitted, 2025

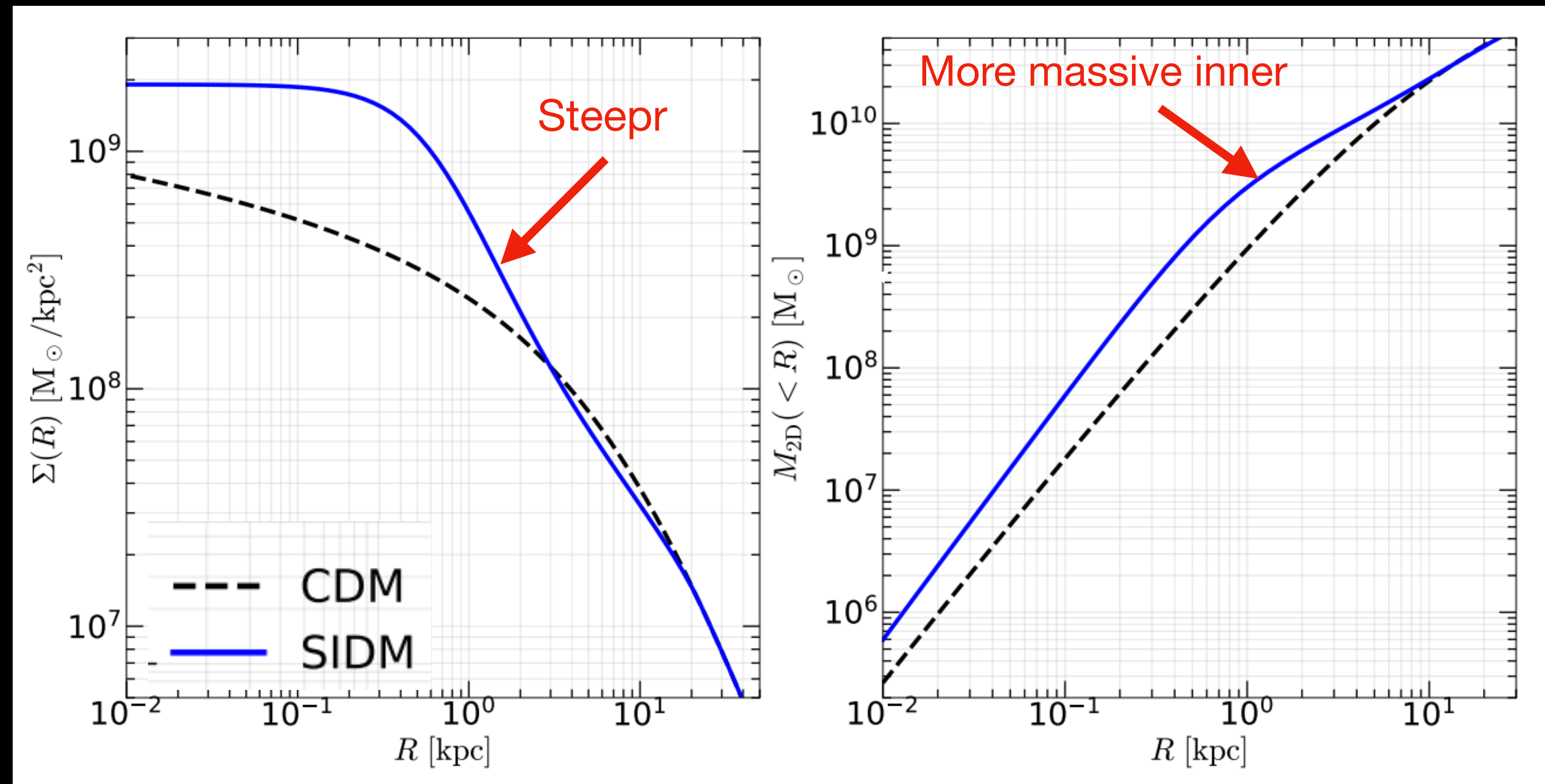
arxiv: 2504.19177

第三幕：SIDM预言的核心坍缩 (Core-collapse) 暗晕？

gravothermal evolution of SIDM core



Daneng Yang & Hai-Bo Yu, 2022



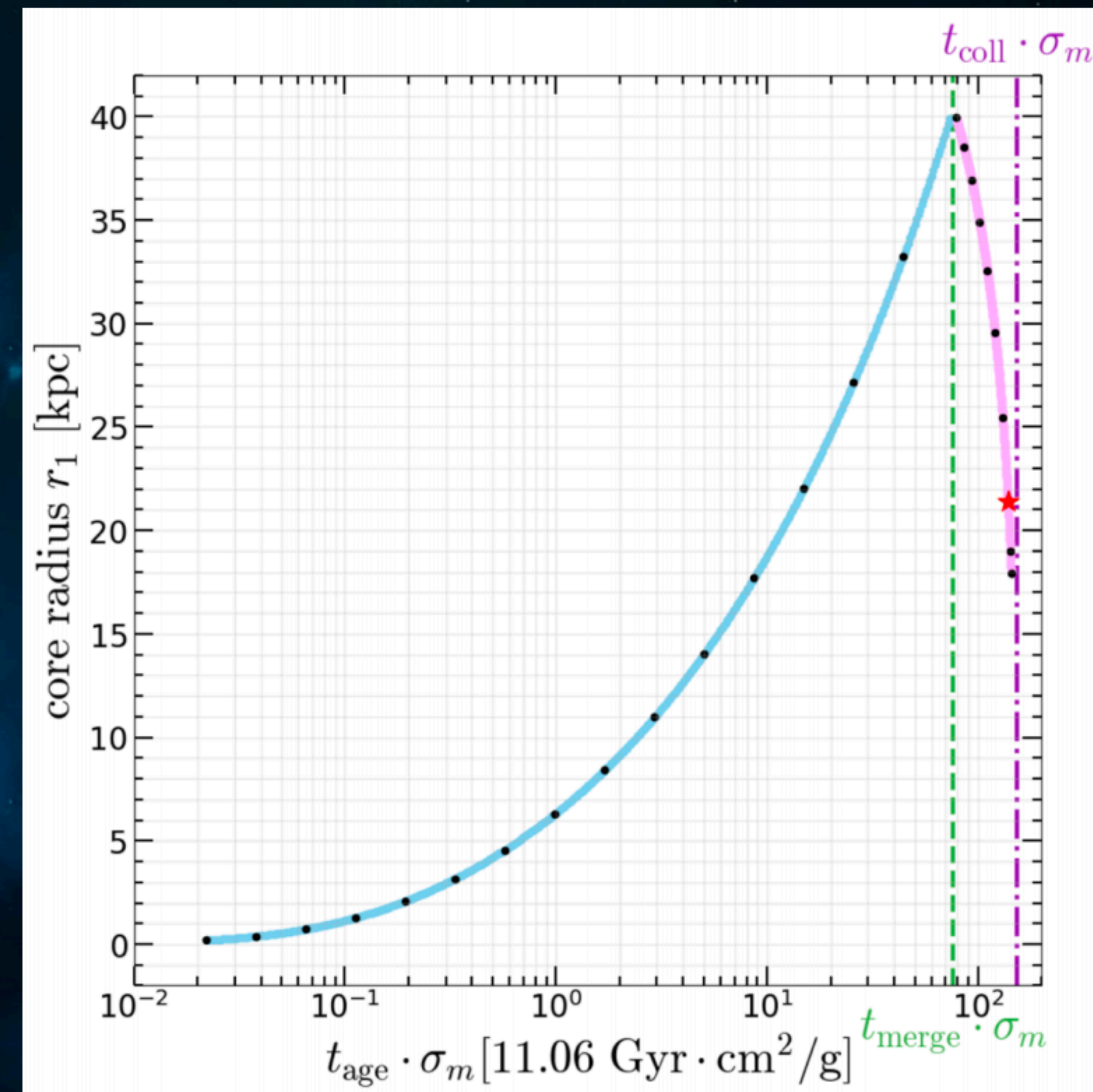
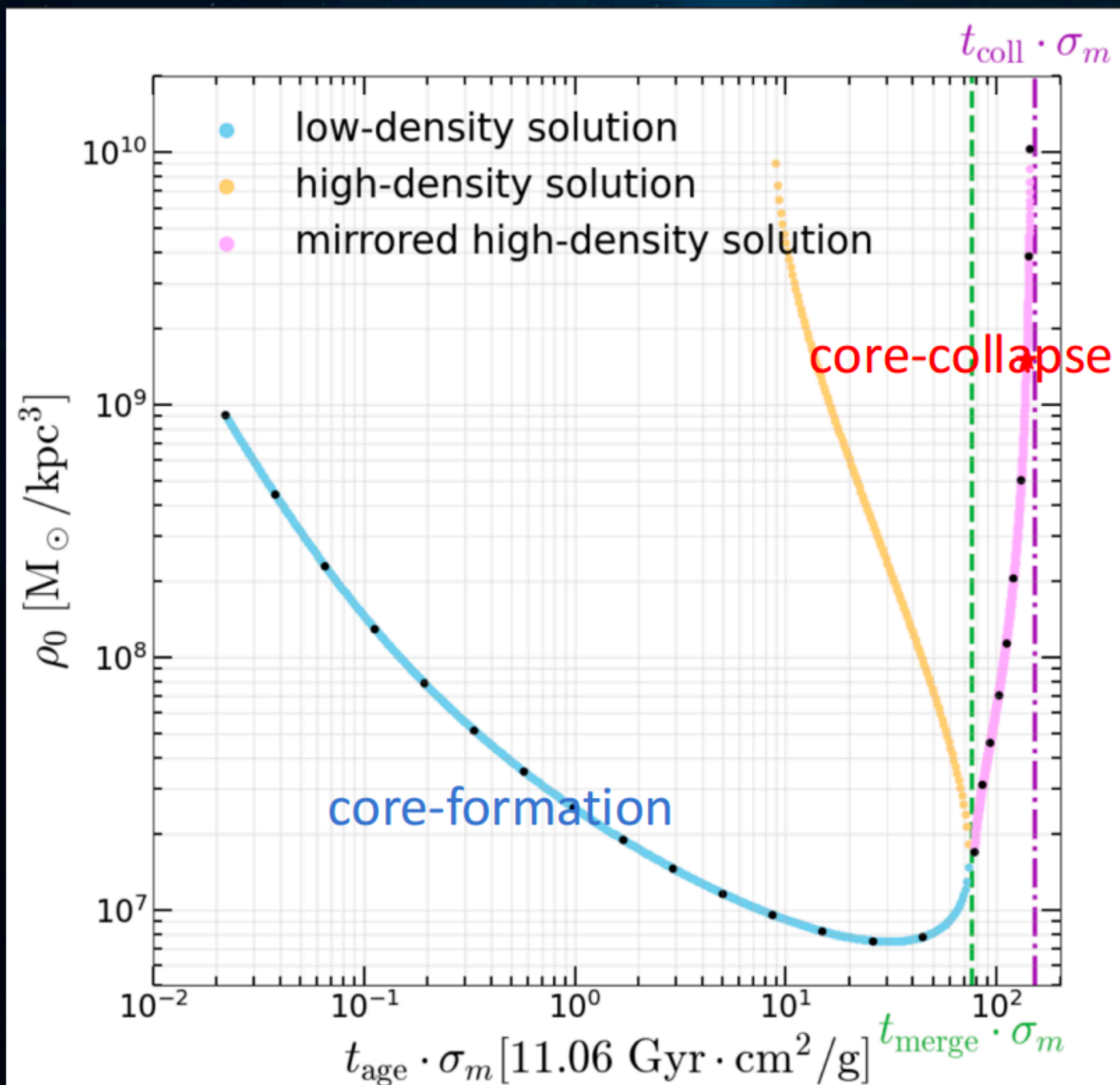
SHB Li, Ran Li + 2025, submitted, arxiv:
2504.11800

$$\frac{1}{t_{age}} = \sigma_m \langle v_{pair}(r_1) \rangle \rho_{CDM}(r_1)$$

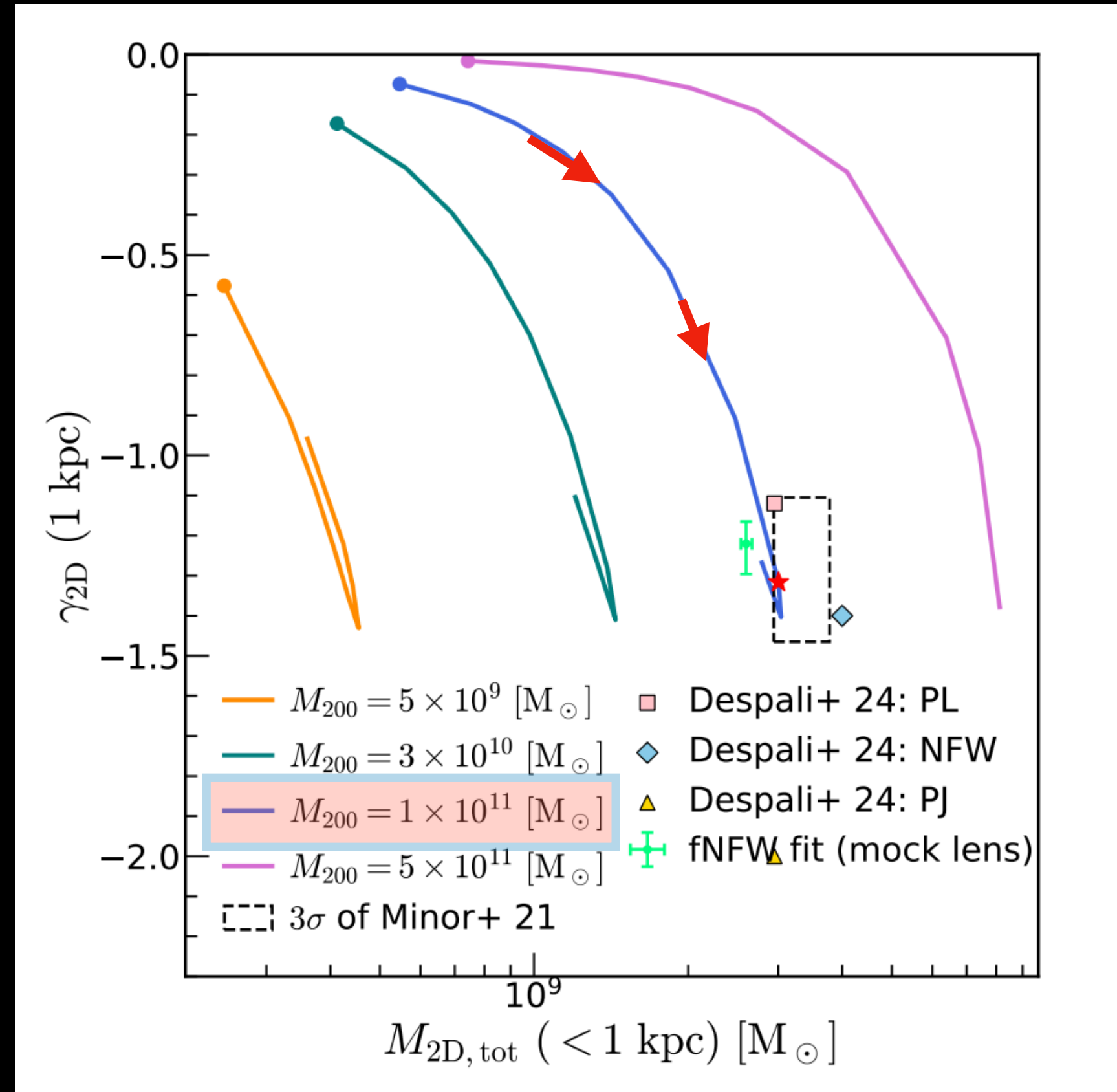
central density ρ_0

stitching radius r_1

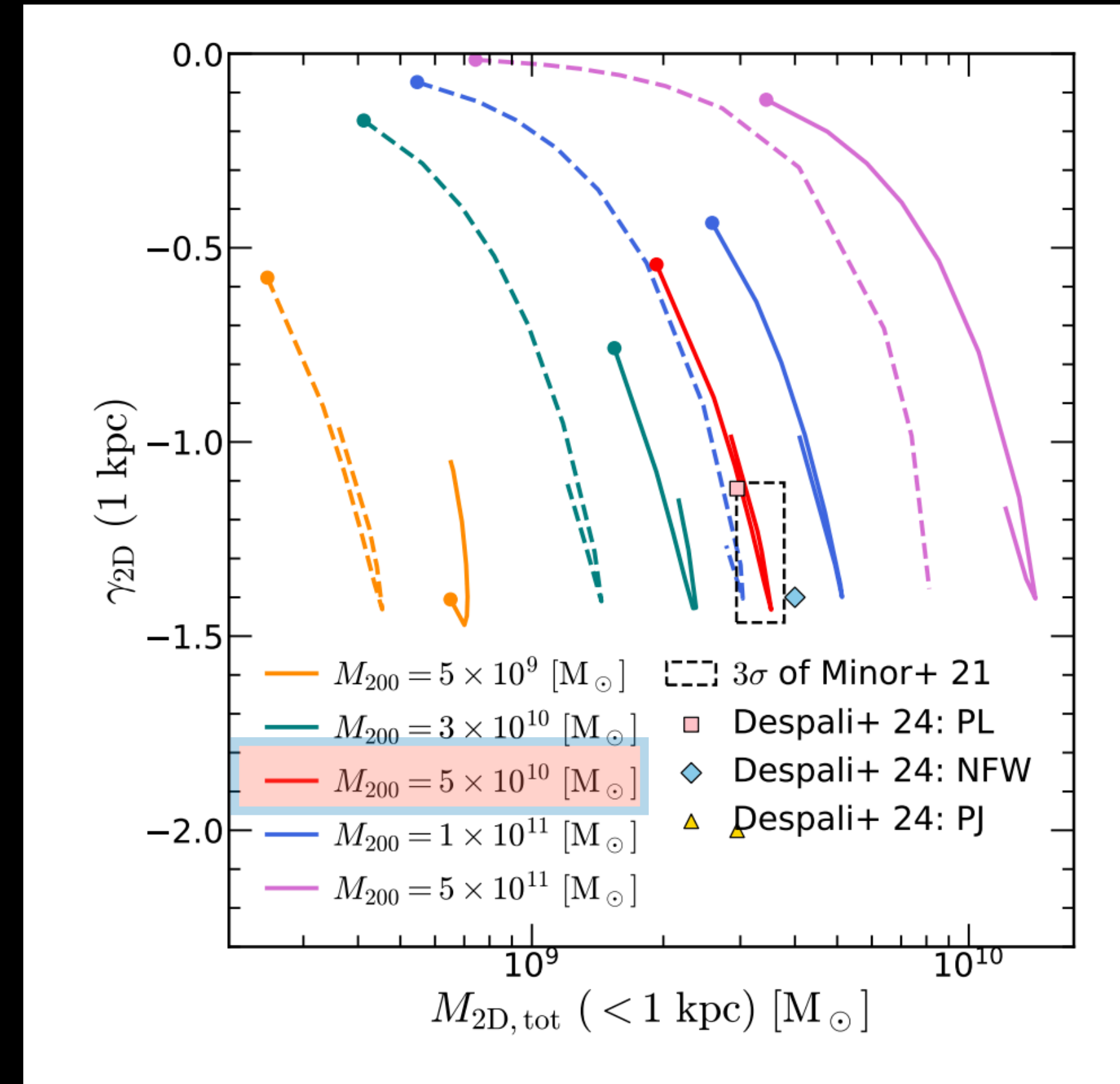
$t_{age} \cdot \sigma_m$



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



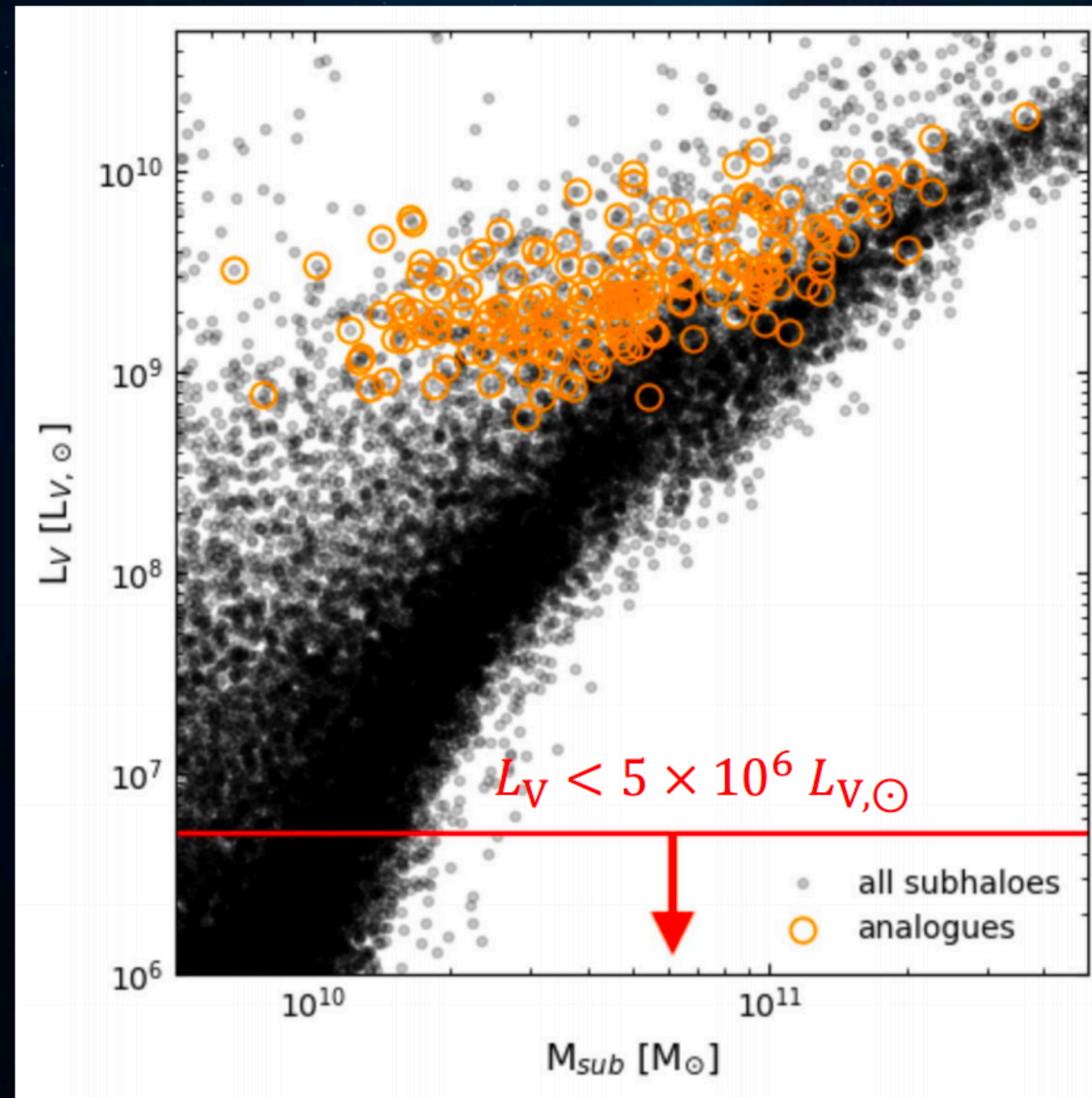
High initial halo concentration
reduces the required mass of halo



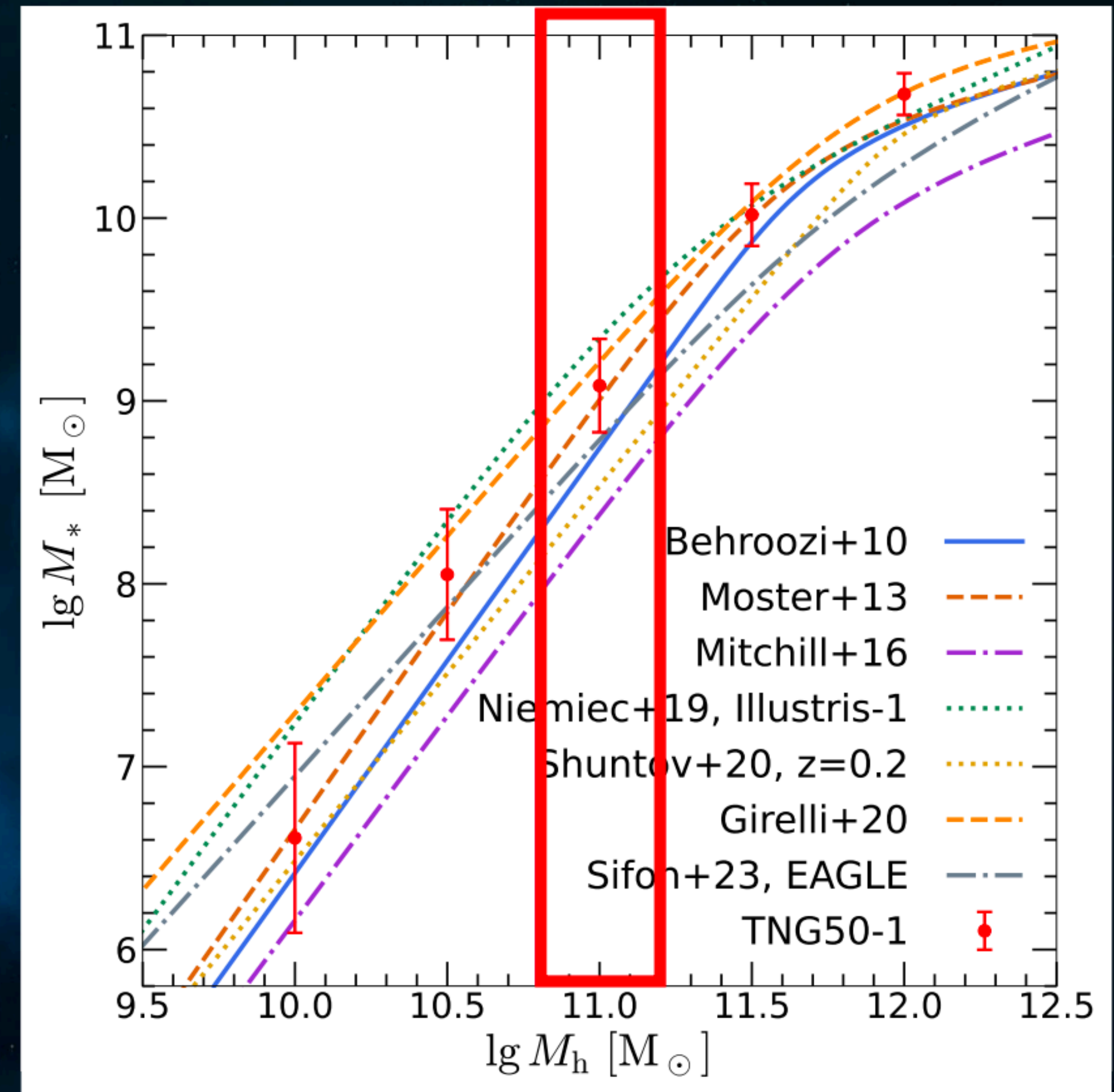
SHB Li, Ran Li + 2025, submitted, arxiv: 2504.11800 (details in Shubo Li's talk)

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

analogues in TNG50

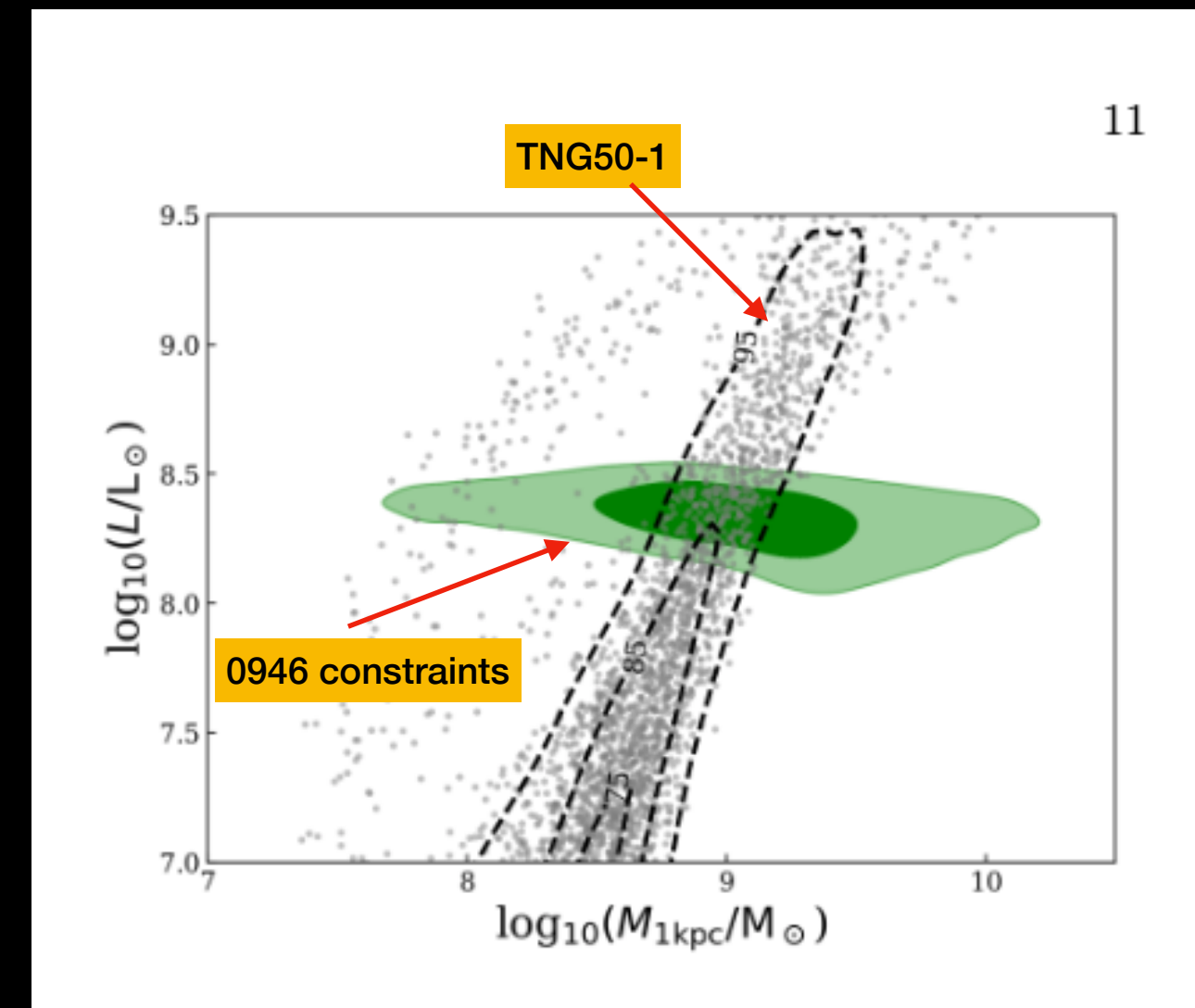
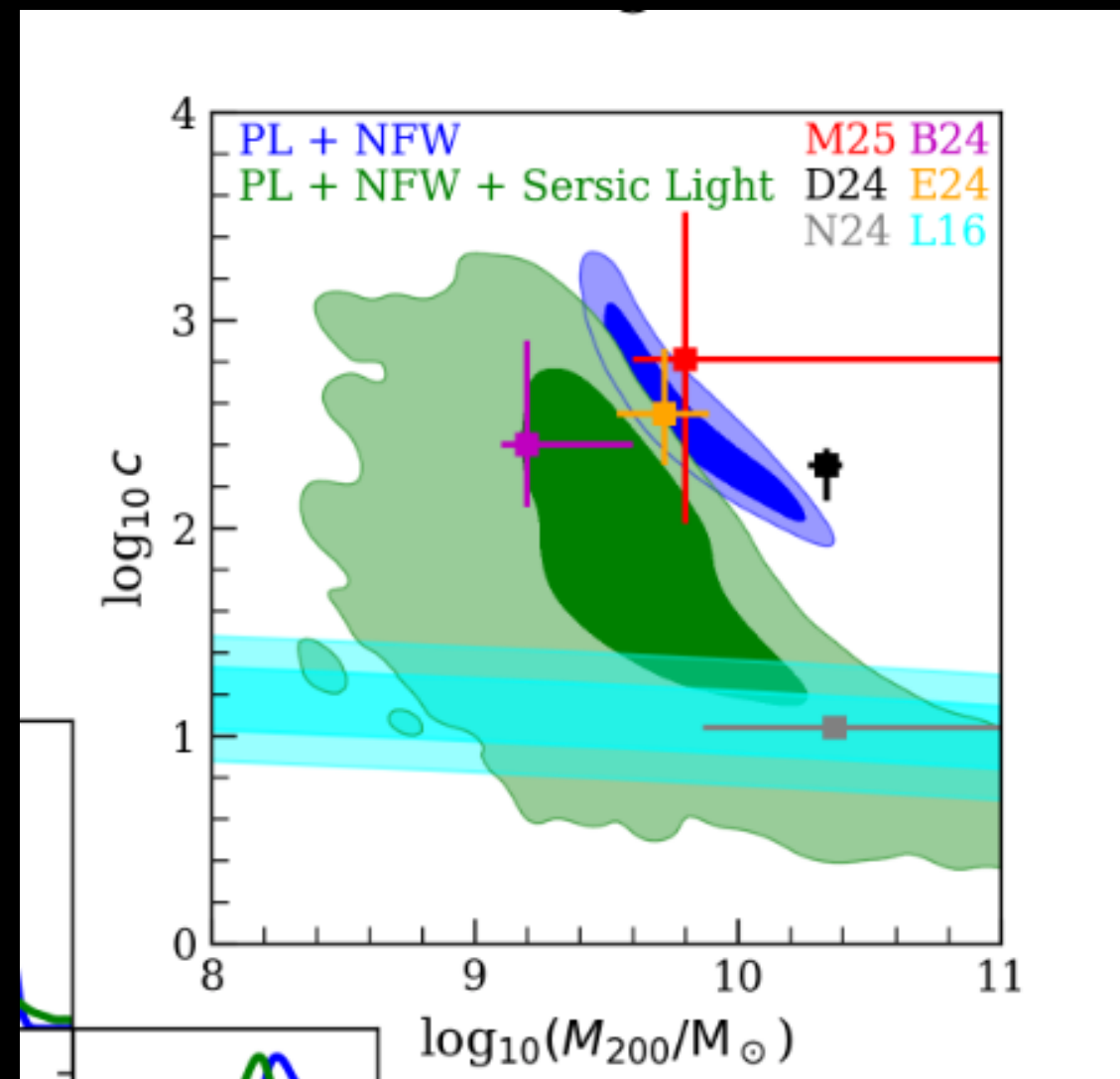
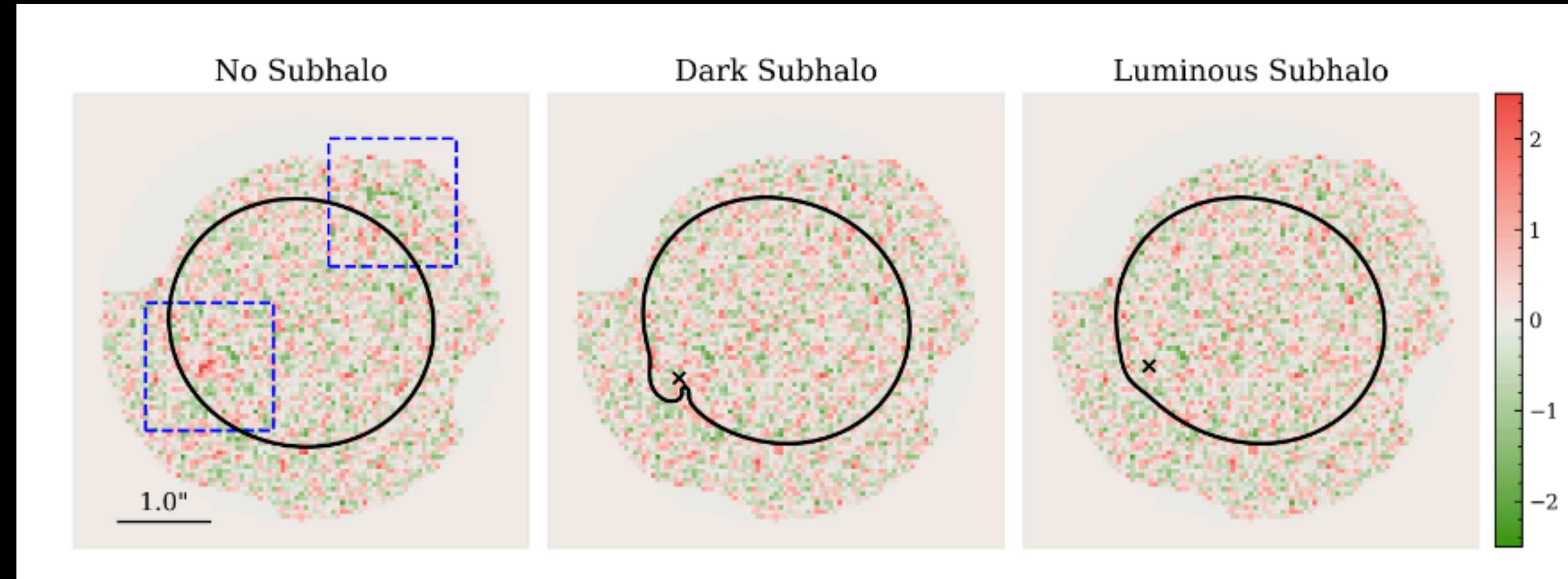
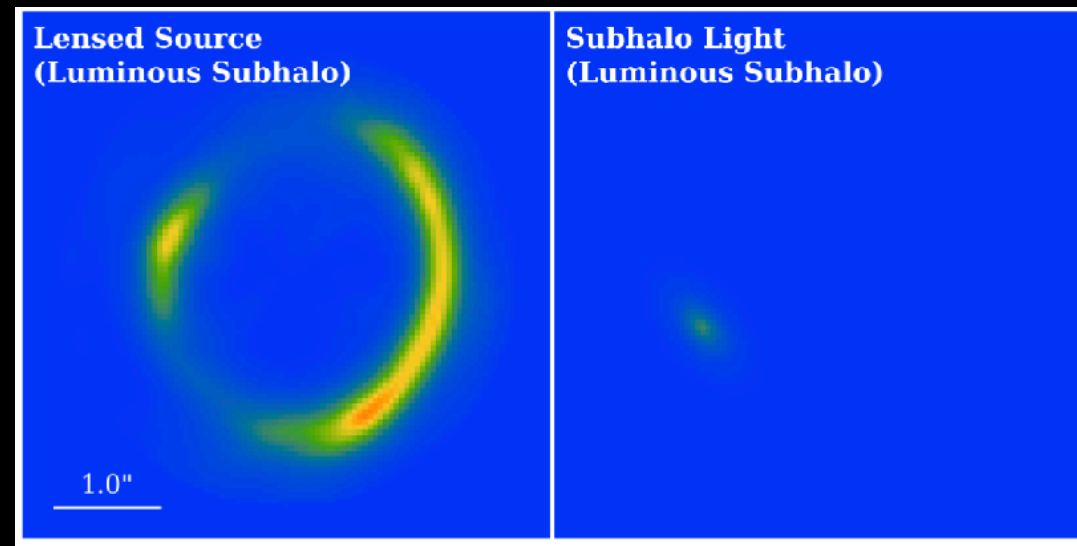


stellar-halo mass relation



第四幕：峰回路转， not so dark, not so dense?

The normalized residuals



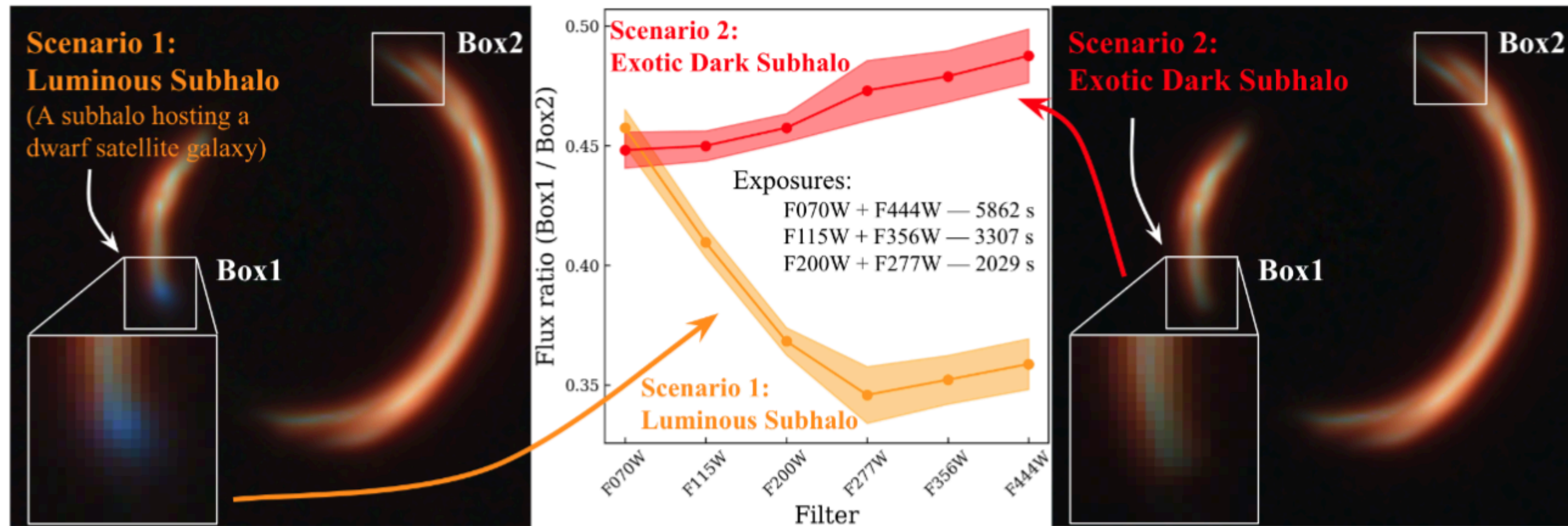
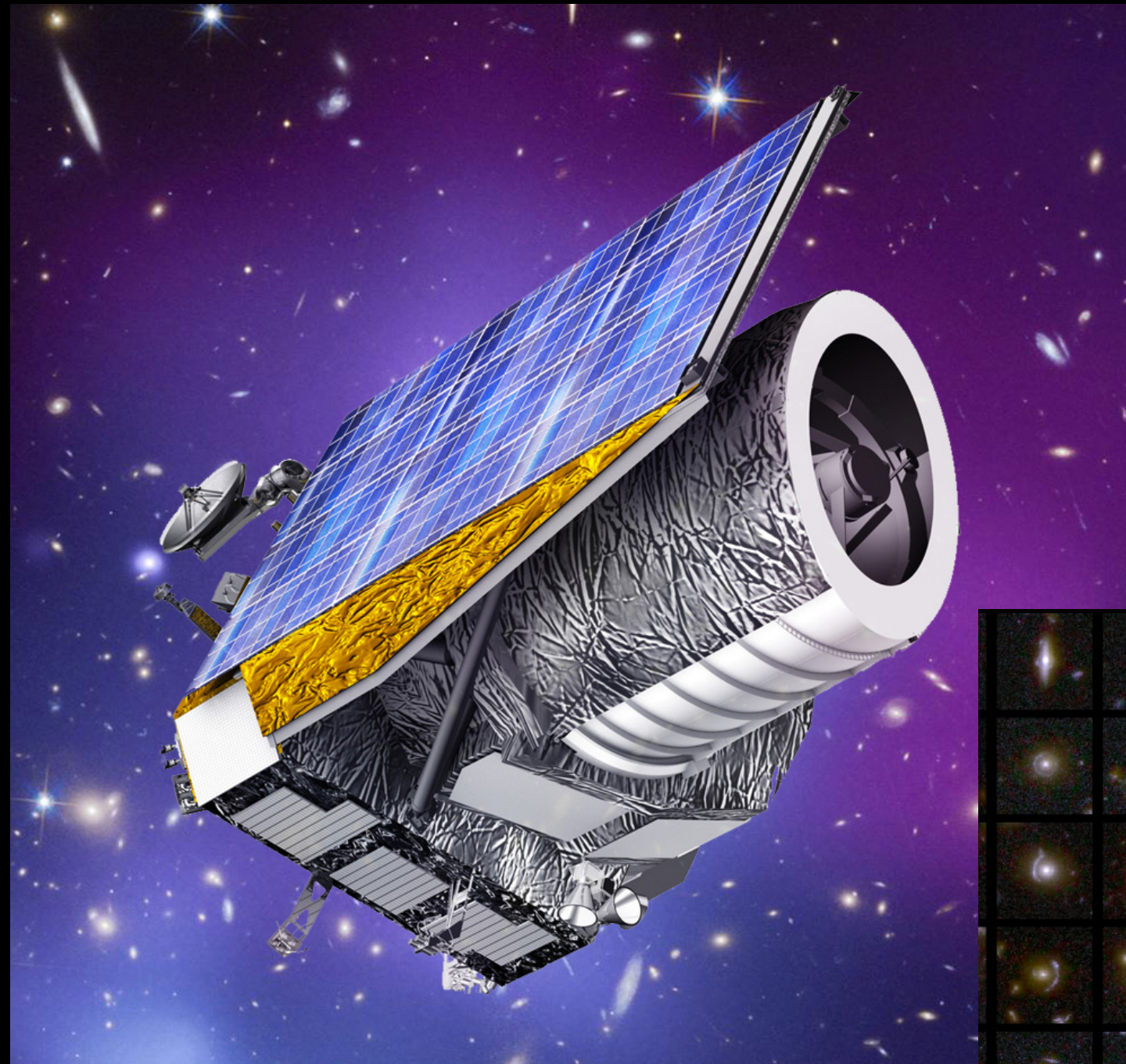


Figure 3: Combined ‘JWST-colour’ images for the luminous (**left**) and exotic dark (**right**) subhalo scenarios. **Middle** panel shows the wavelength-dependent flux ratio measured within the two white $0.5'' \times 0.5''$ boxes. These boxes trace roughly to the same region of the source while the bottom-left one contains the subhalo.

bottom-left box is centred on the subhalo position, while the top-right box roughly samples

3小时JWST观测会最终告诉我们答案

Ongoing and Upcoming Space Optical Surveys



Euclid Telescope and Q1 Lenses



China Space Station Telescope (CSST, “巡天”)

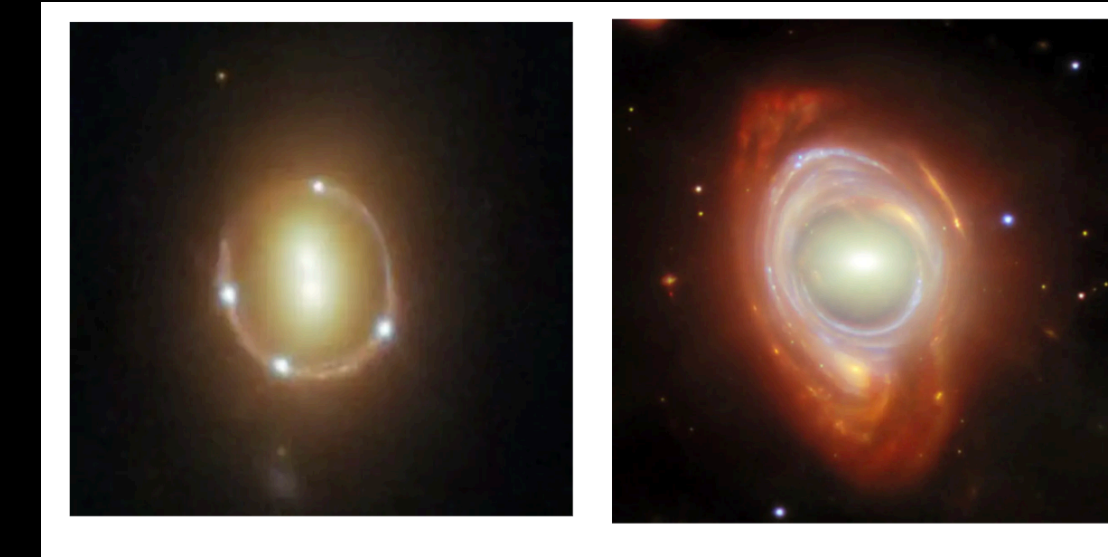
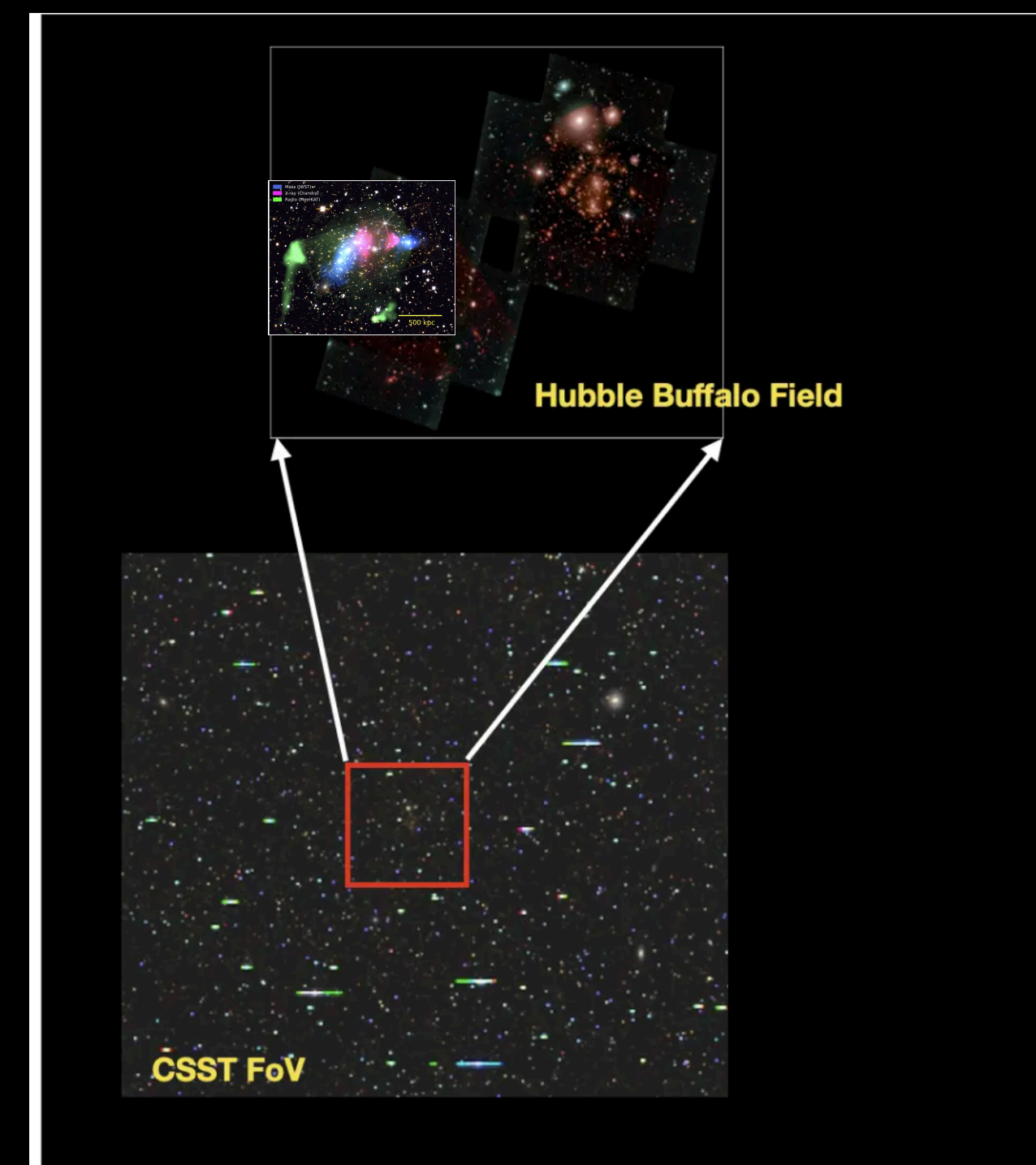
Multi-band imaging covering 17500°

(avg. 25.5 mag) $R_{e80} < 0.15''$

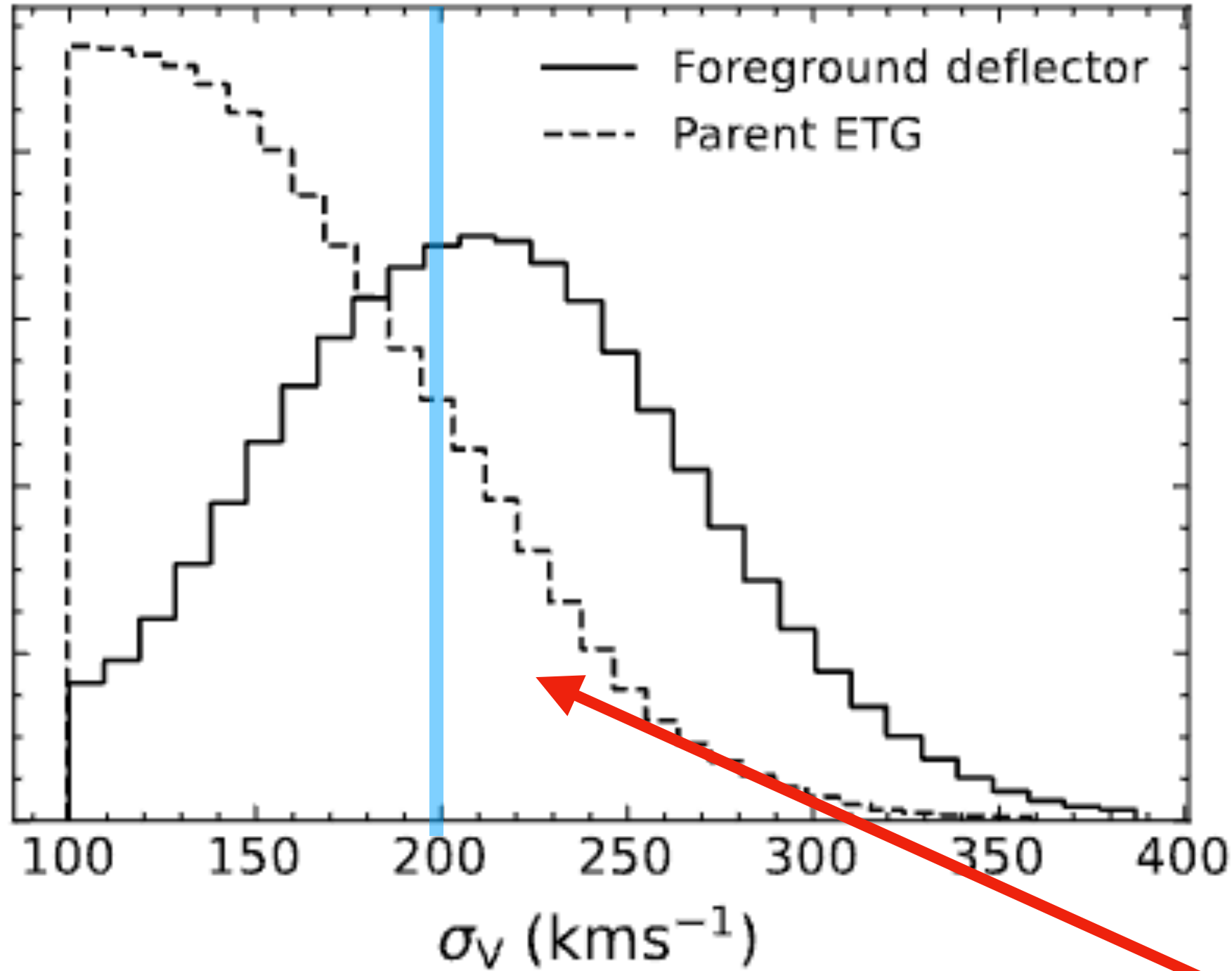
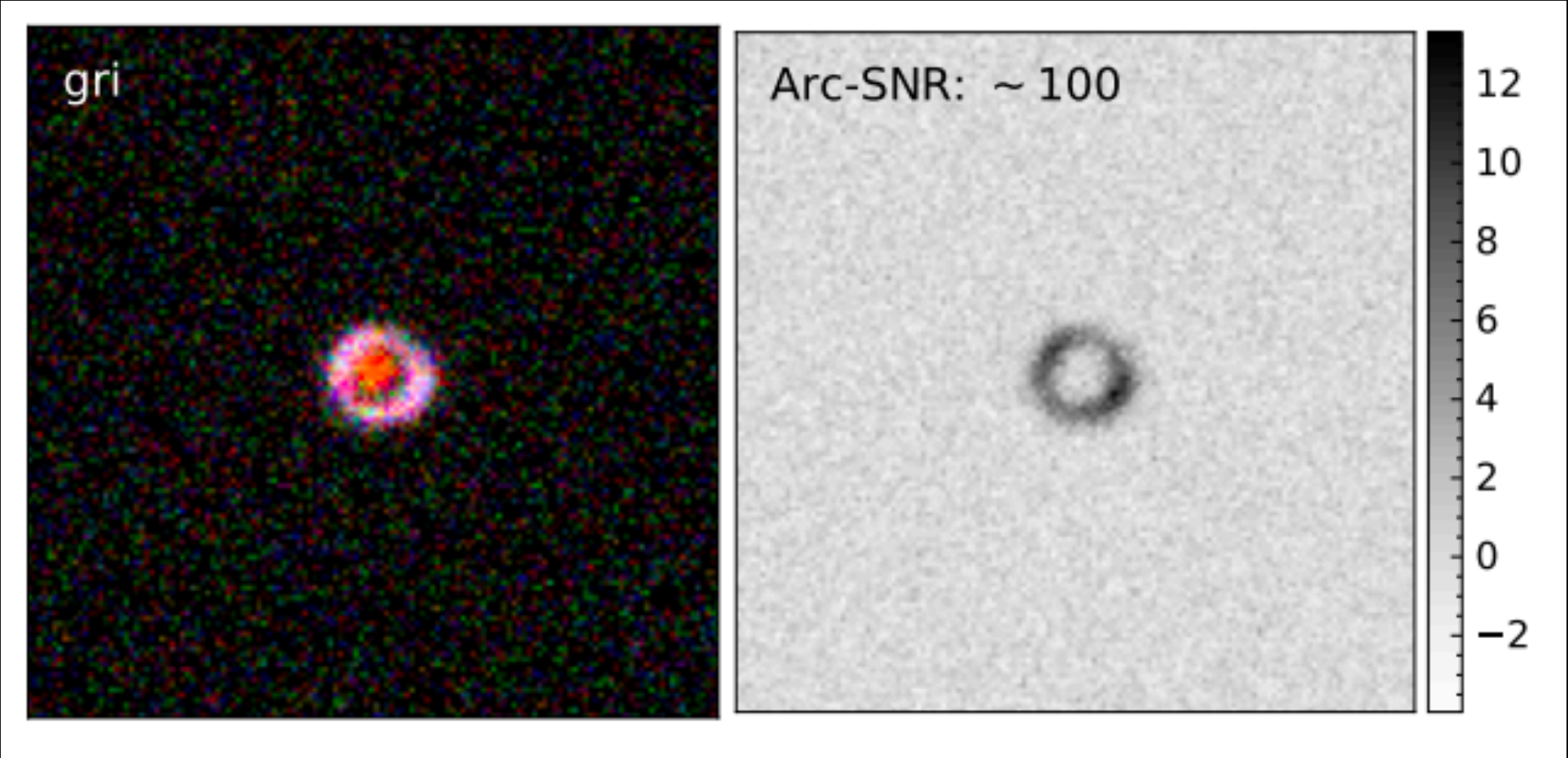
Launch ~2027

Dark Matter@CSST

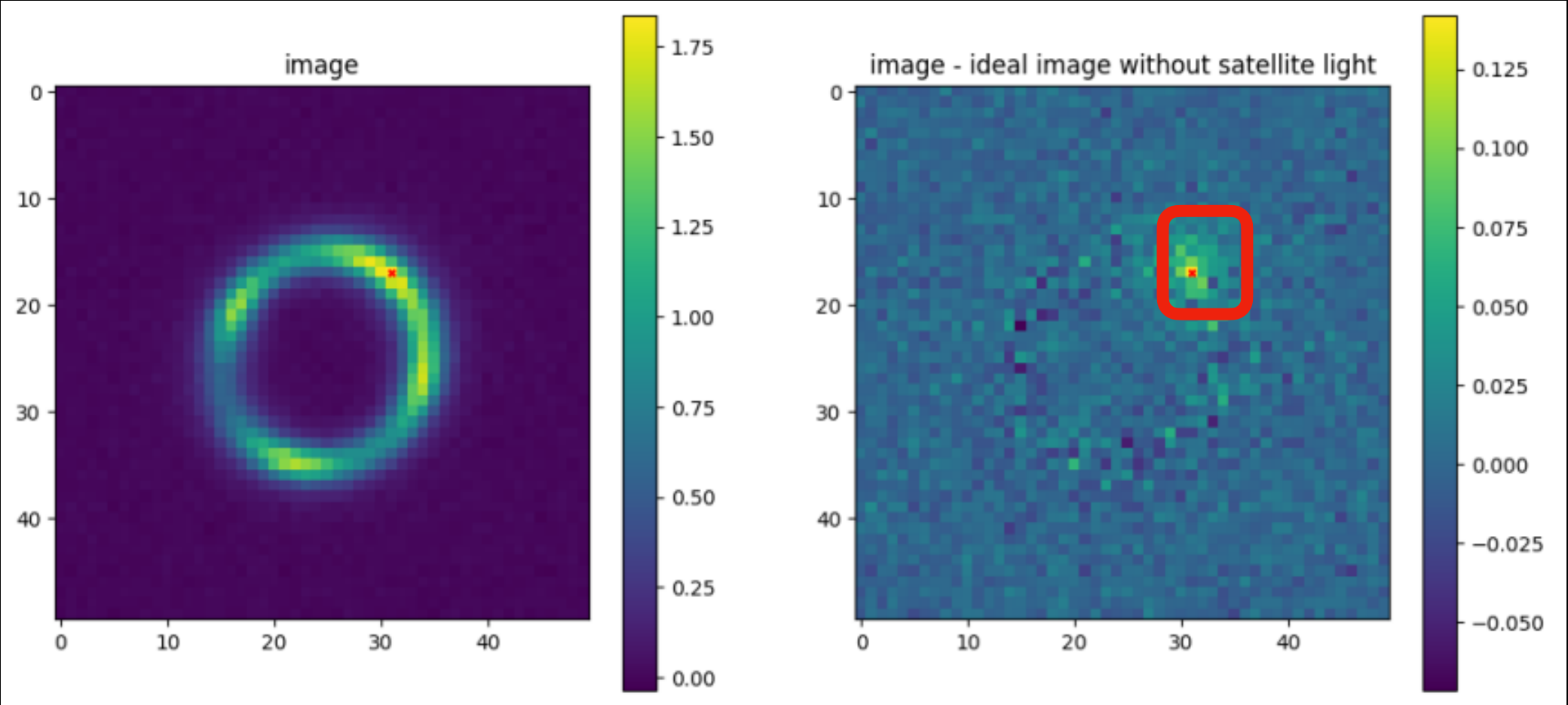
- ~100000 galaxy-galaxy lensing, with 5000 with $S/N > 100$
- Many hundreds of galaxy lensing cluster
- Weak lensing map of all sky, up to redshift $z \sim 1.5$
- Galaxy-galaxy lensing from dwarf galaxies to clusters
- Complete sample of high-res imaging of nearby universe



	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



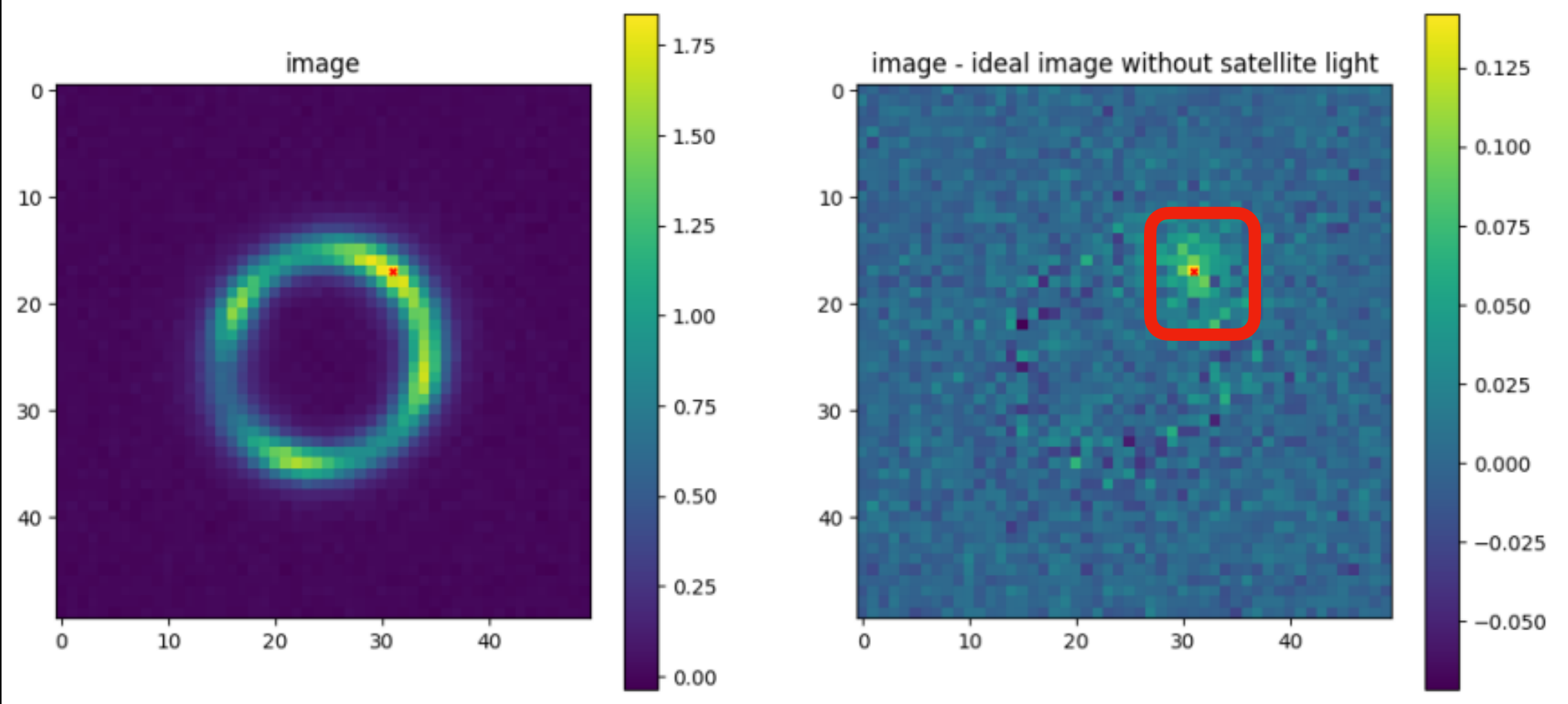
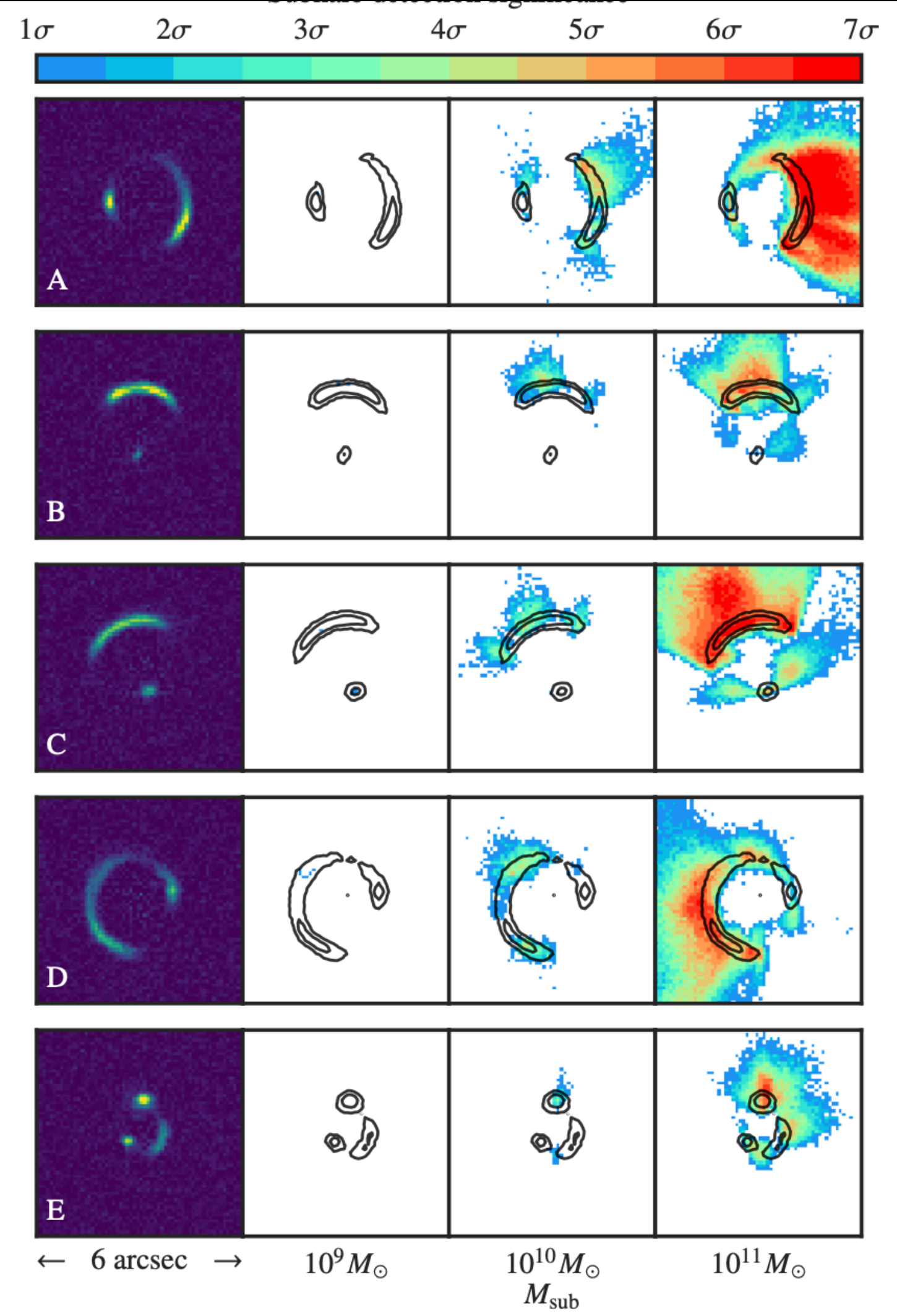
$z_{\text{lens}}=0.2$ Mag~24.62, KH Wang et al. 2025



~5000 with S/N>100

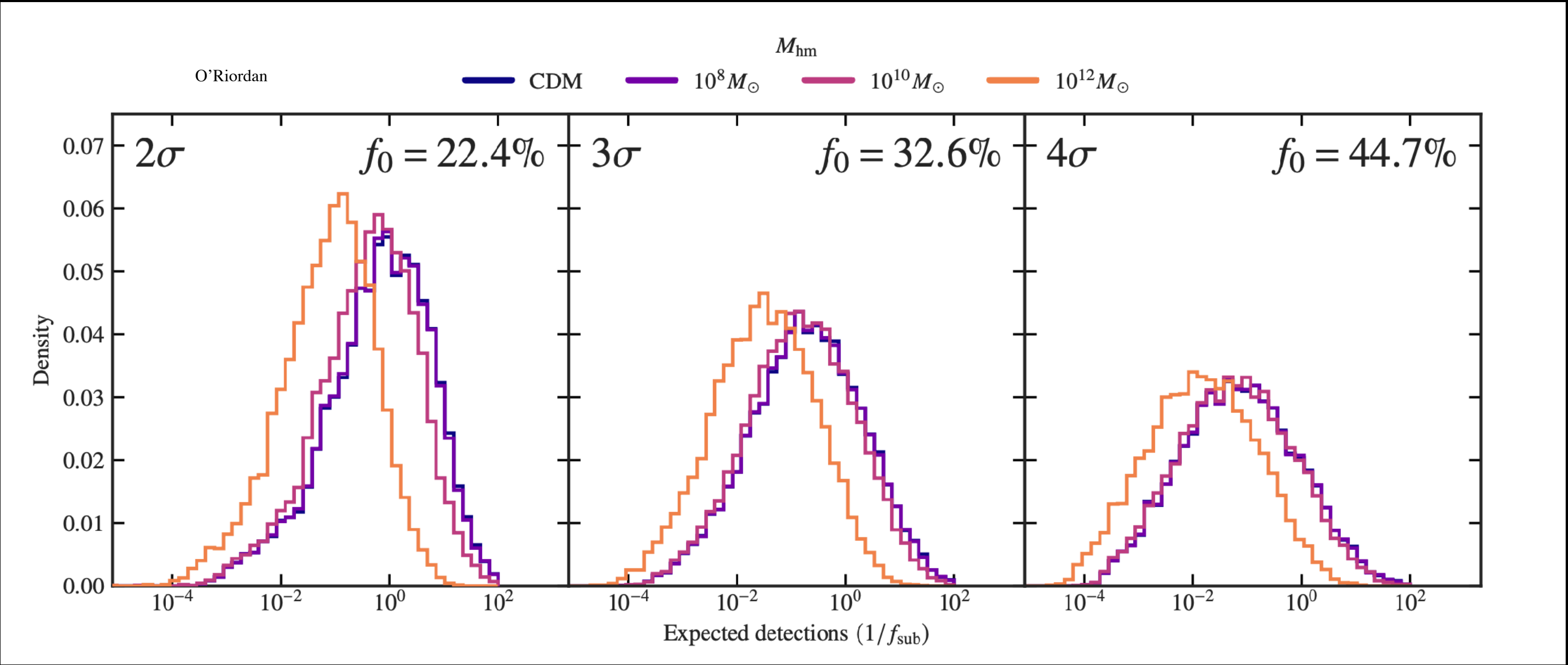
Ground Base Limit

Euclid prediction



$z=0.2$
Mag~24.62

Wang Kaihao et al. in prep



Expect ~ 2500 new subhalo detections
Most $>10^{10} M_\odot$

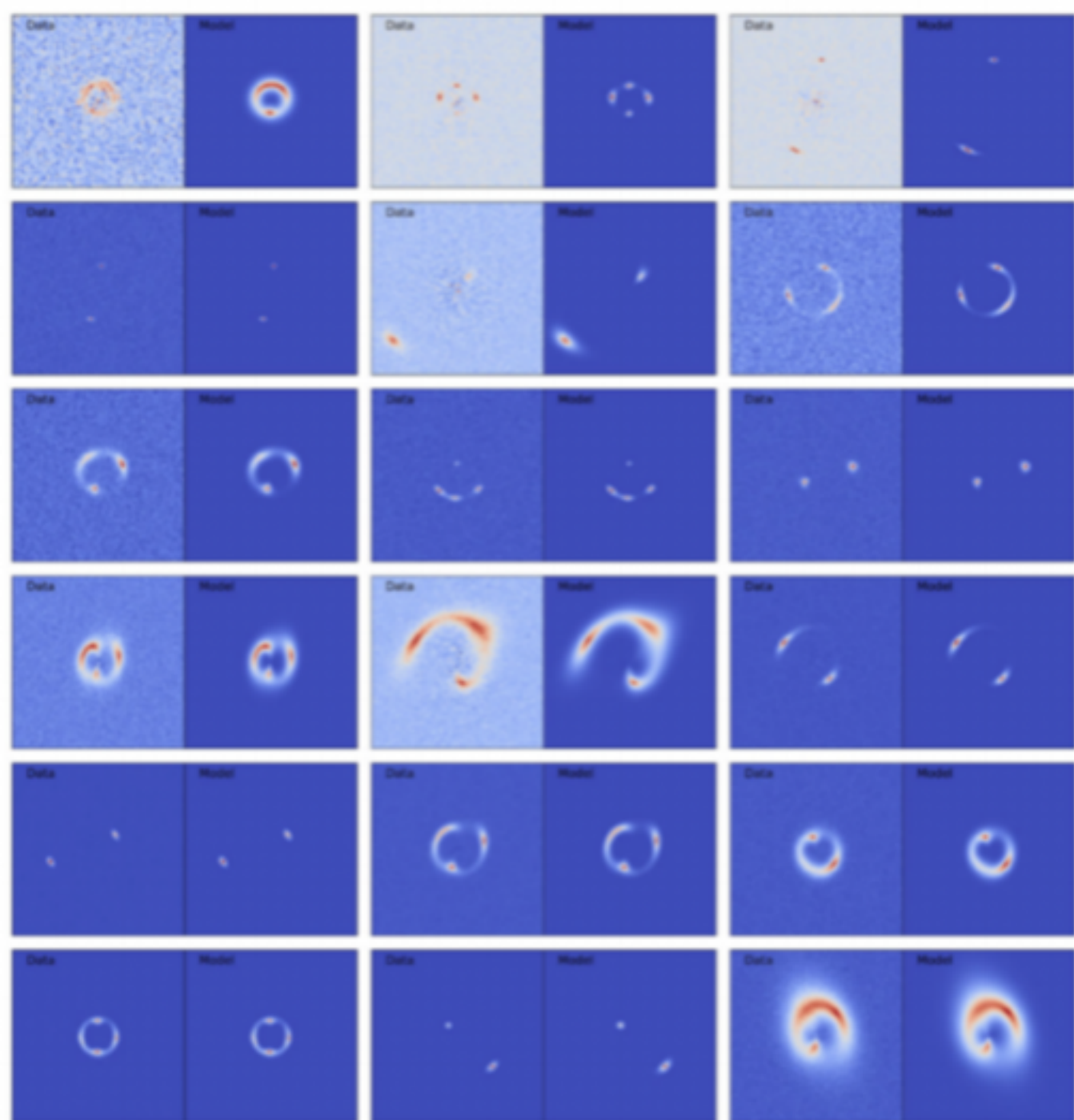
自动化高效分析管线：一个例子

TinyLensGpu Cao XY, Li Ran et al. 2025, MNRAS, 540, 312

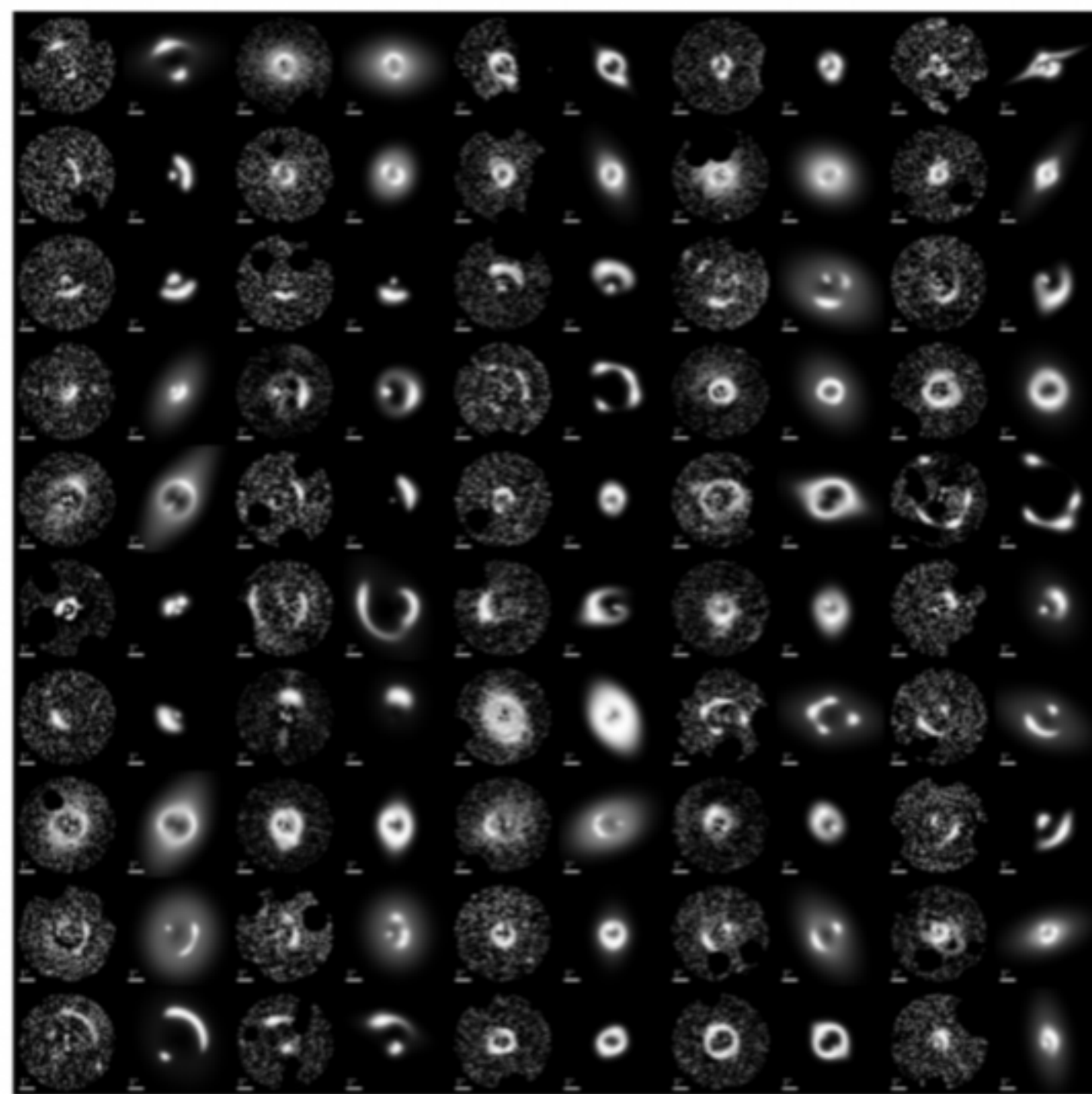


曹潇月

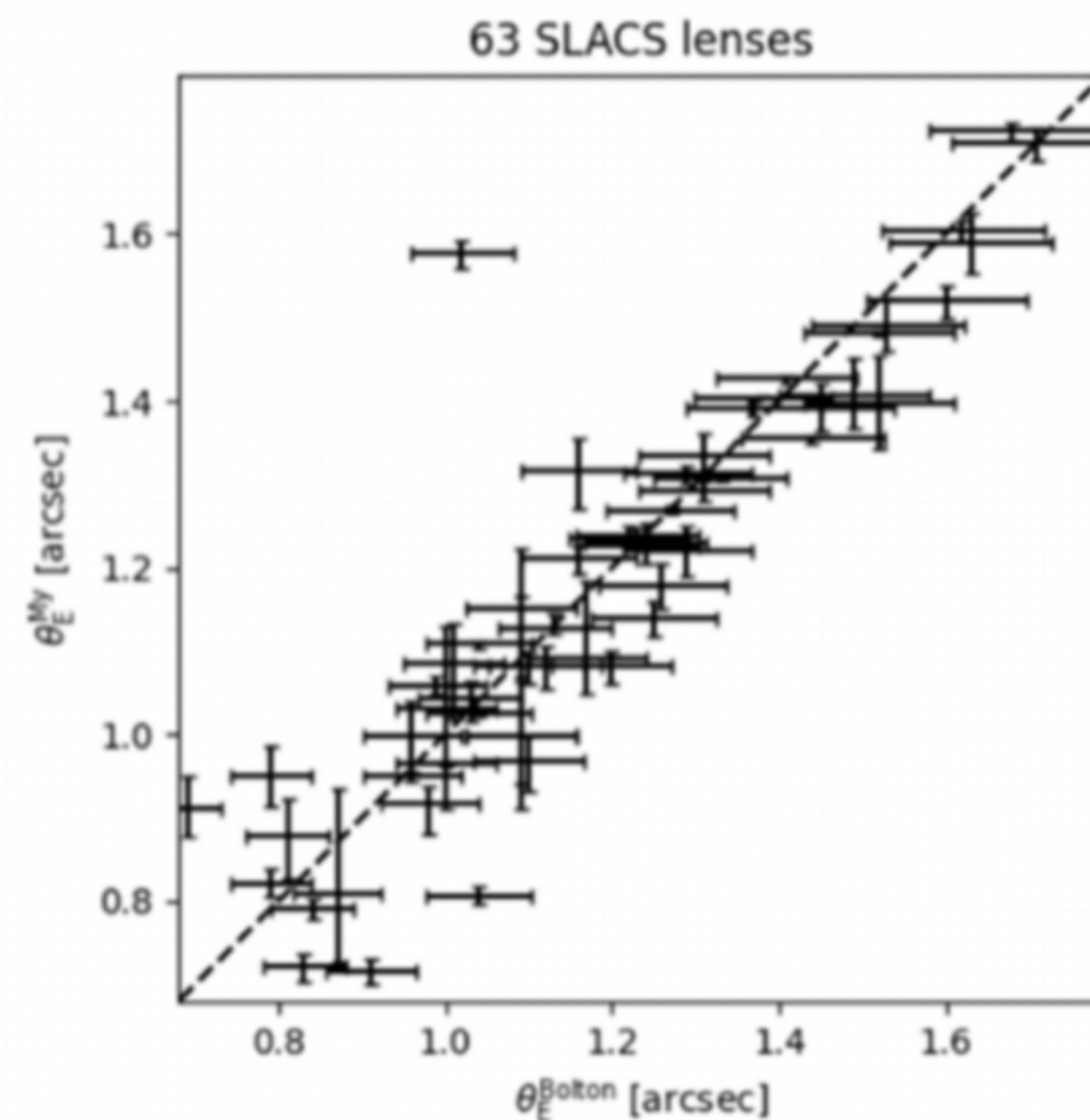
CSST mock



Euclid Q1
真实数据建模



Hubble 望远镜
真实数据建和Hubble SLAC team 结果比较



全自动化精确建模，建模一个仿真CSST强引力透镜体系的速度相比经典建模程序快了~100倍，对10K+ Lens建模的计算资源问题完全解决

Summary

- 星系强透镜建模技巧在过去10年发展完善，借助空间分辨率数据可以探测到低至 10^{10} 太阳质量暗晕，还可以测量其结构
- 致密的perturber的性质 (m_{2d} - γ_{2d}) 依赖于其未塌缩的起始状态，这给了我们利用低质量暗晕的致密度可以作为SIDM的一个有力限制
- SLAC0946是引力透镜建模的试金石，多个研究组利用这一系统互相校验了分析方法。0946的dark perturber是否真的致密，有望在不久的将来通过JWST follow-up解决
- 这个问题有望在CSST/Euclid+JWST/ELT时代得到极大推进

