中国科学院紫金山天文台
Purple Mountain Observatory,Chinese Academy of Sciences
中国科学技术大学
University of Science and Technology of China

强透镜JVAS B1938+666系统中的暗物质子晕：暗物质的自相互作用或波动性

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6. National Astronomical Observatories, ***CAS***.

山东青岛 5月10号, 2025

Small-scale Problem of LCDM

James S. Bullock and Michael Boylan-Kolchin, ARA&A, 2017

THREE CHALLENGES TO BASIC ΛCDM PREDICTIONS

There are three classic problems associated with the small-scale predictions for DM in the ΛCDM framework. Other anomalies exist, including some that we discuss in this review, but these three are important because (*a*) they concern basic predictions about DM that are fundamental to the hierarchical nature of the theory and (*b*) they have received significant attention in the literature.

Missing Satellites and Dwarfs

The observed stellar mass functions of field galaxies and satellite galaxies in the Local Group are much flatter at low masses than predicted DM halo mass functions; $dn/dM_\star \propto M_\star^{\alpha_g}$ with $\alpha_g \simeq -1.5$ (versus $\alpha \simeq -1.9$ for DM). The issue is most acute for Galactic satellites, where completeness issues are less of a concern. There are only ~50 known galaxies with $M_\star > 300\ M_\odot$ within 300 kpc of the MW compared with as many as ~1,000 dark subhalos (with $M_{sub} > 10^7\ M_\odot$) that could conceivably host galaxies. One solution to this problem is to posit that galaxy formation becomes increasingly inefficient as the halo mass drops. The smallest DM halos have simply failed to form stars altogether. See **Figures 3–8**.

Low-Density Cores Versus High-Density Cusps

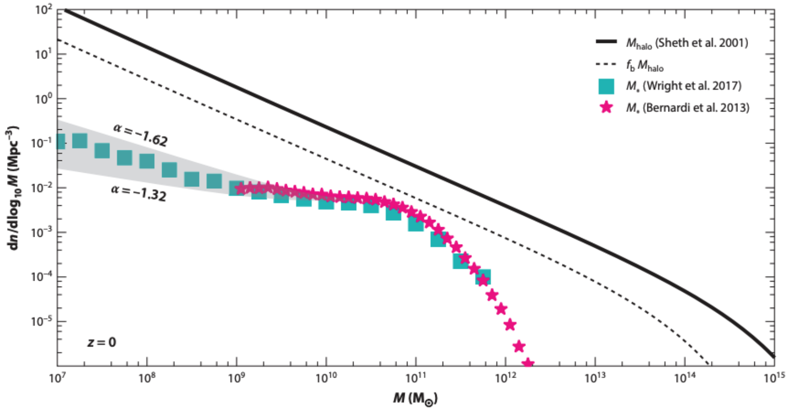
The central regions of DM-dominated galaxies as inferred from rotation curves tend to be both less dense (in normalization) and less cuspy (in inferred density profile slope) than predicted for standard ΛCDM halos (such as those plotted in **Figure 4**). An important question is whether baryonic feedback alters the structure of DM halos. See **Figure 9**.

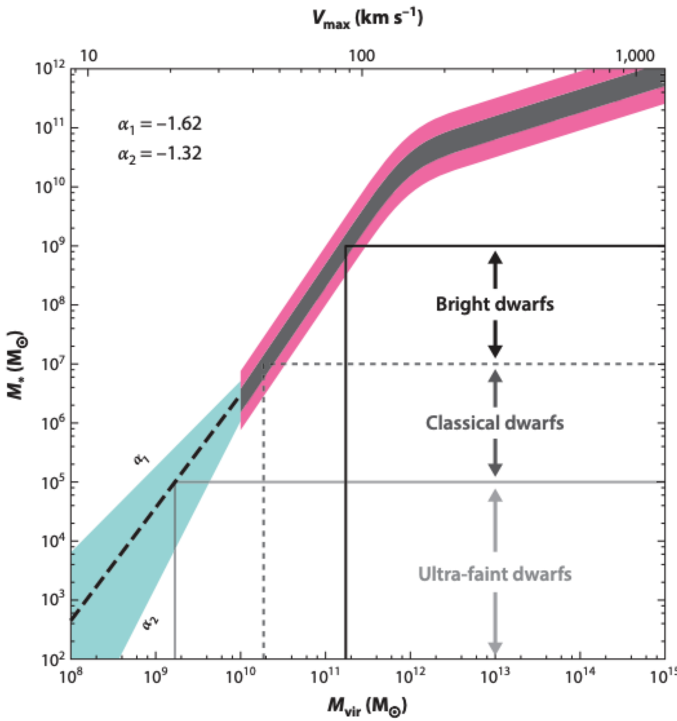
Too-Big-to-Fail

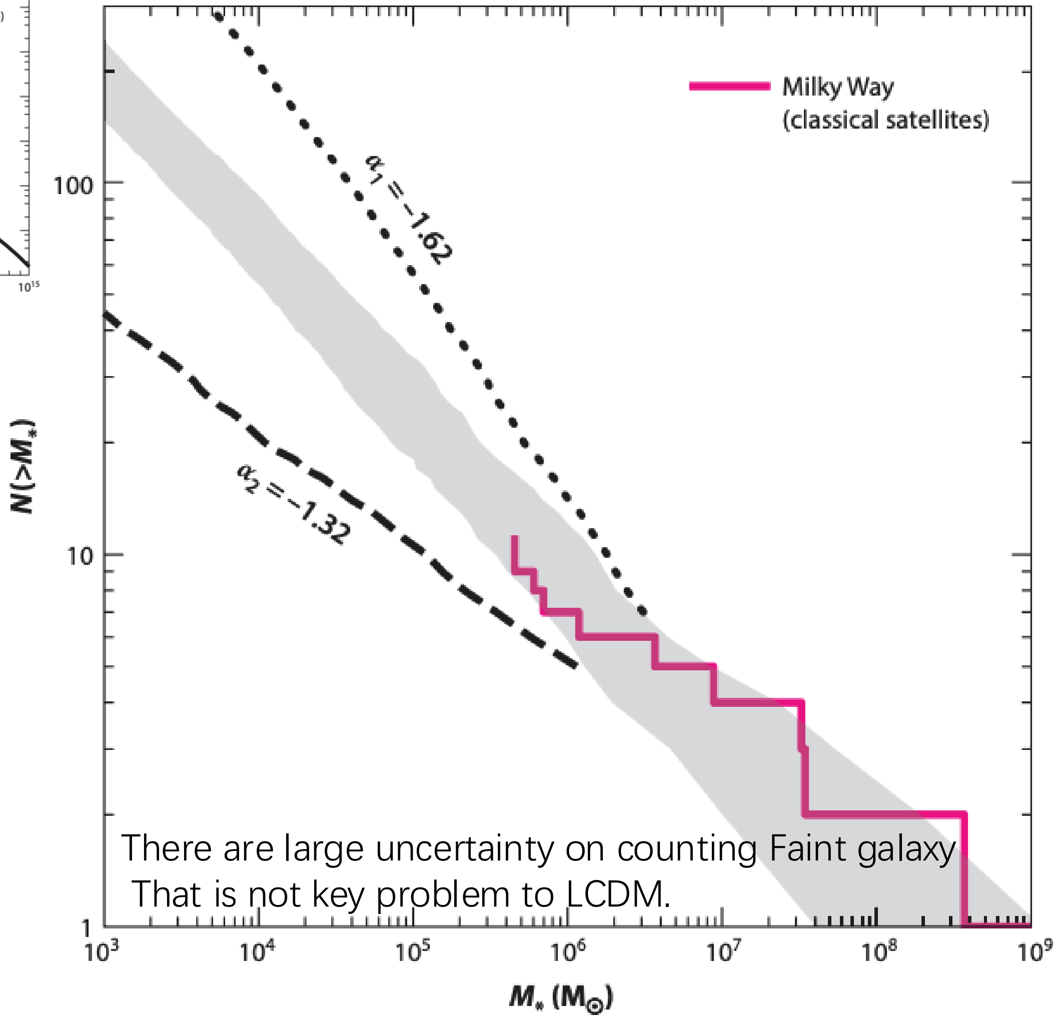
The local Universe contains too few galaxies with central densities indicative of $M_{vir} \simeq 10^{10}\ M_\odot$ halos. Halos of this mass are generally believed to be too massive to have failed to form stars, so the fact that they are missing is hard to understand. The stellar mass associated with this halo mass scale ($M_\star \simeq 10^6\ M_\odot$, **Figure 6**) may be too small for baryonic processes to alter their halo structure (see **Figure 13**). See **Figure 10**.

Small-scale Problem of LCDM

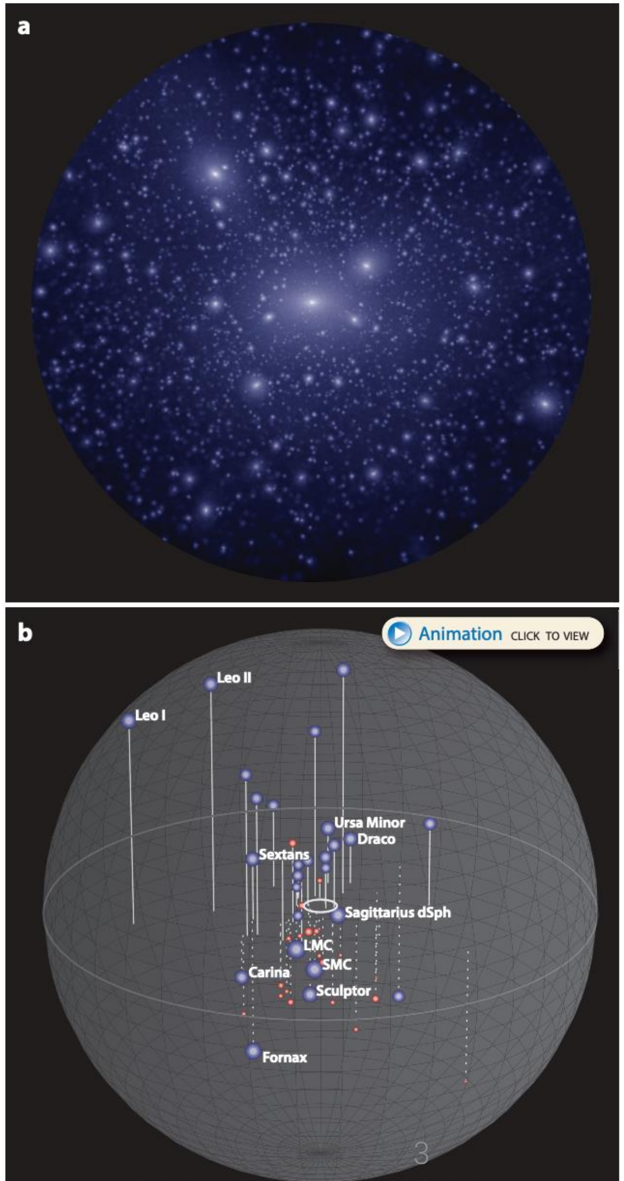
1. Missing Satellites and Dwarfs







There are large uncertainty on counting Faint galaxy
That is not key problem to LCDM.

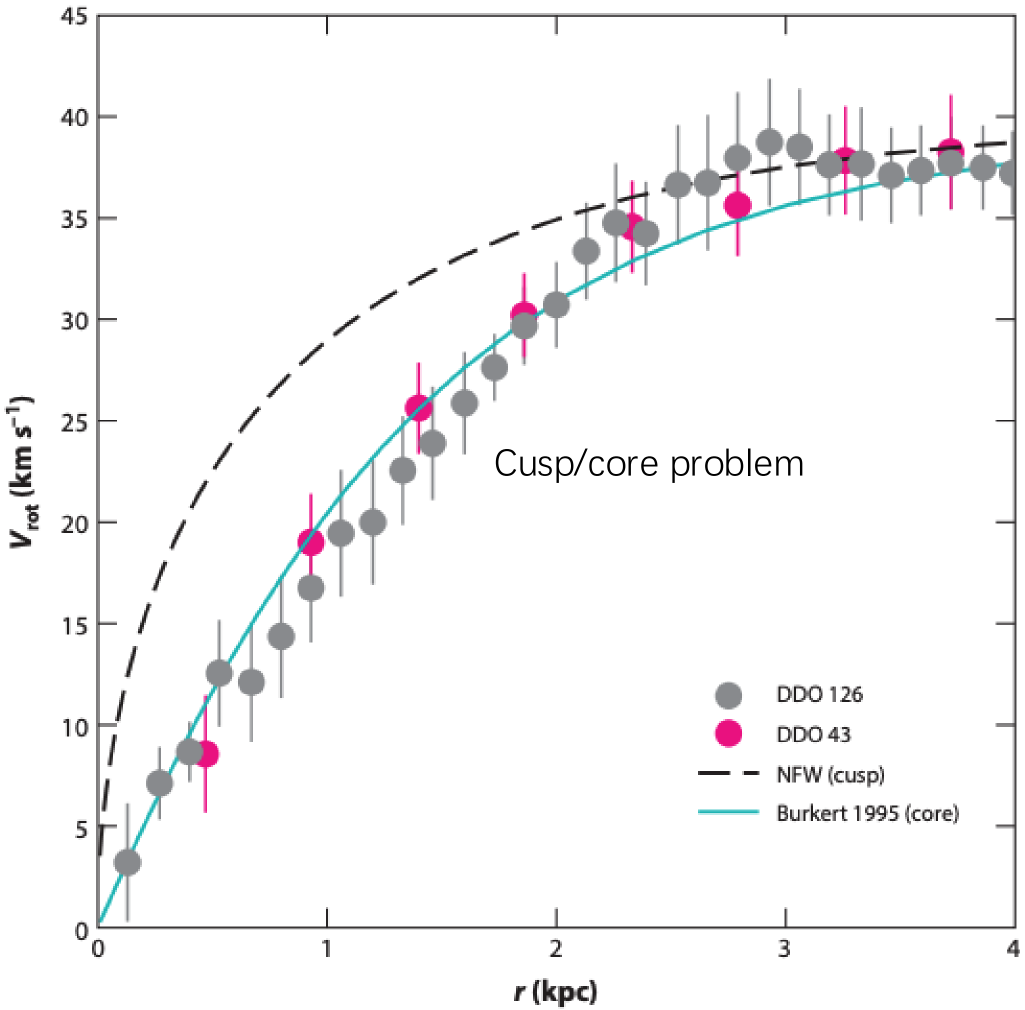


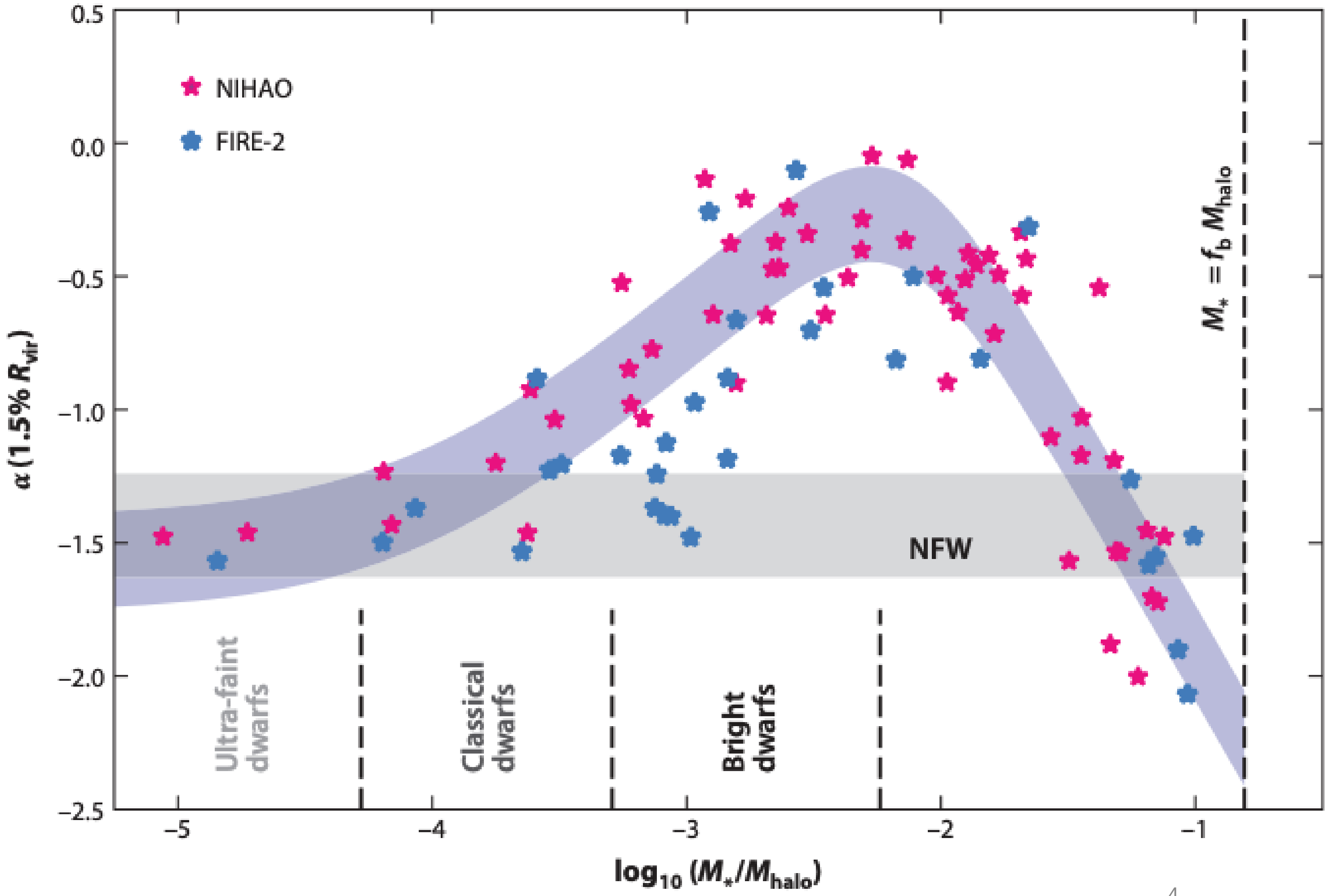
Pawlowski/Bullock/Boylan-Kolchin

James S. Bullock and Michael Boylan-Kolchin, ARA&A, 2017

Small-scale Problem of LCDM

2. Low-Density Cores v.s. High-Density Cusps





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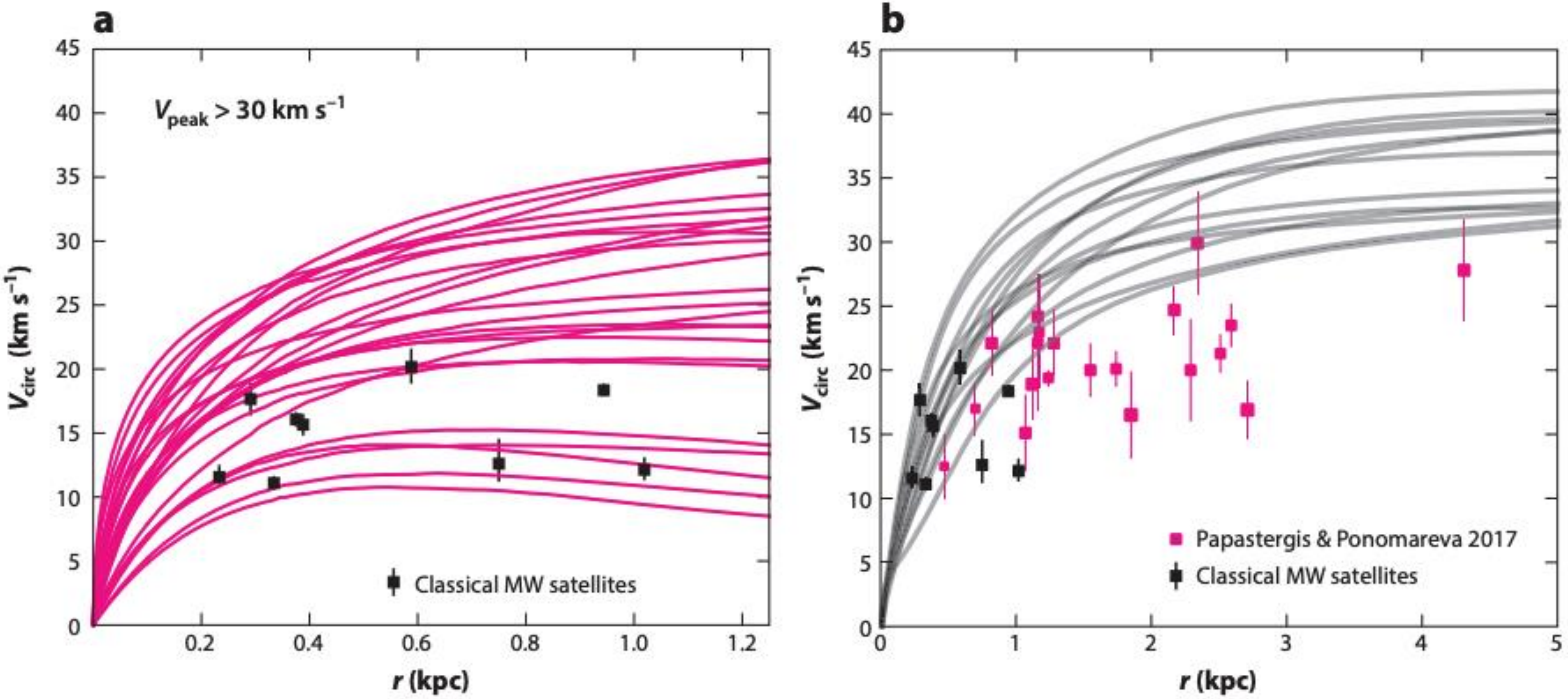
Small-scale Problem of LCDM

3. Too-Big-to-Fail

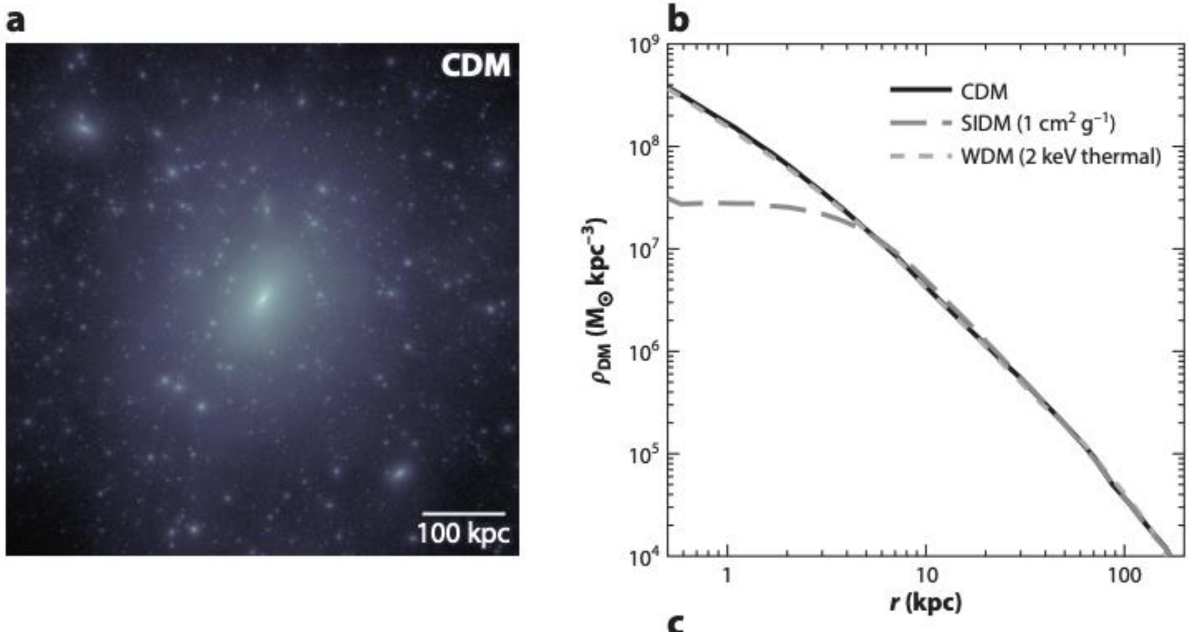


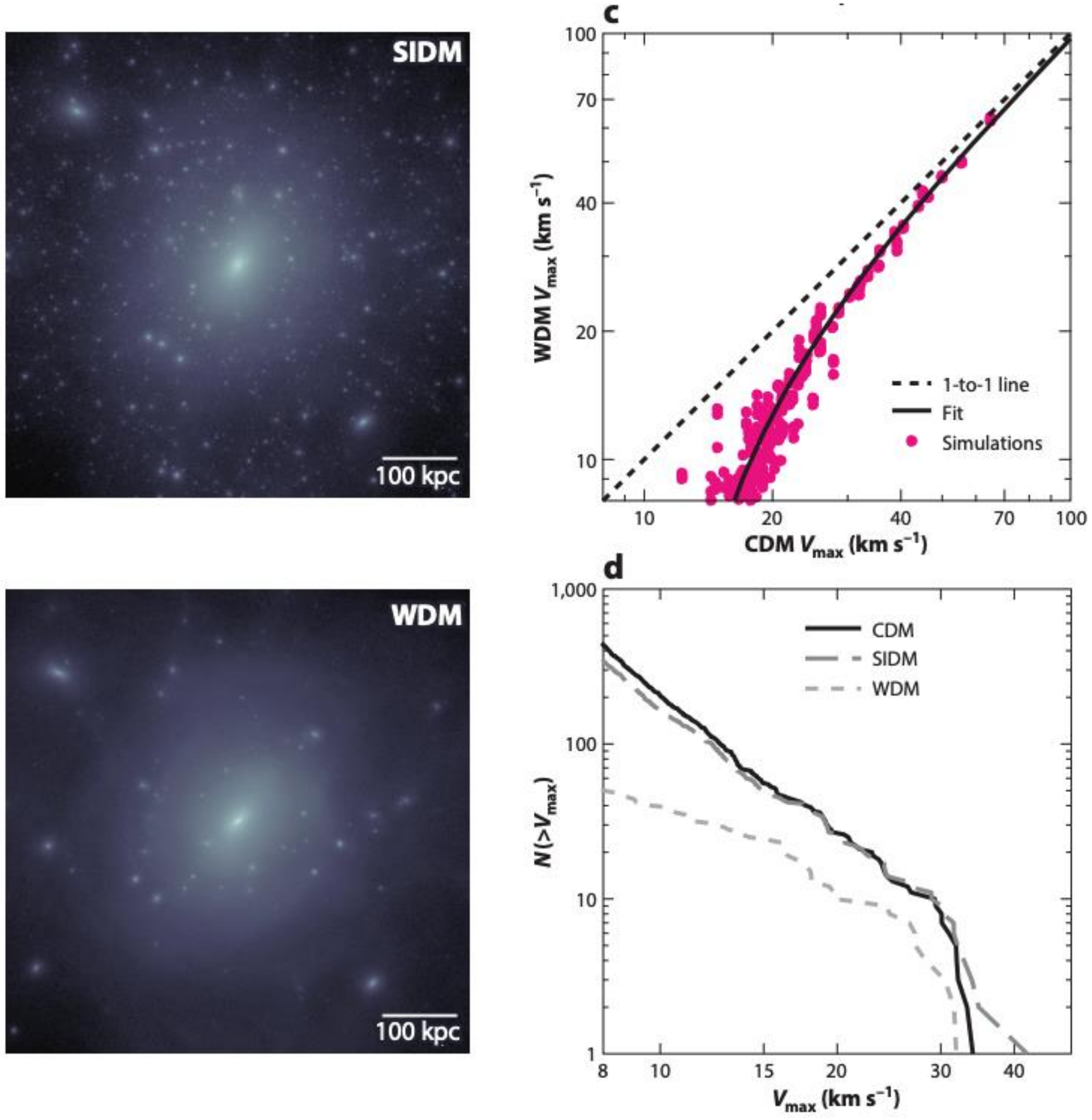
James S. Bullock and Michael Boylan-Kolchin, ARA&A, 2017

Core formation can be a solution of this problem

Small-scale Problem of LCDM

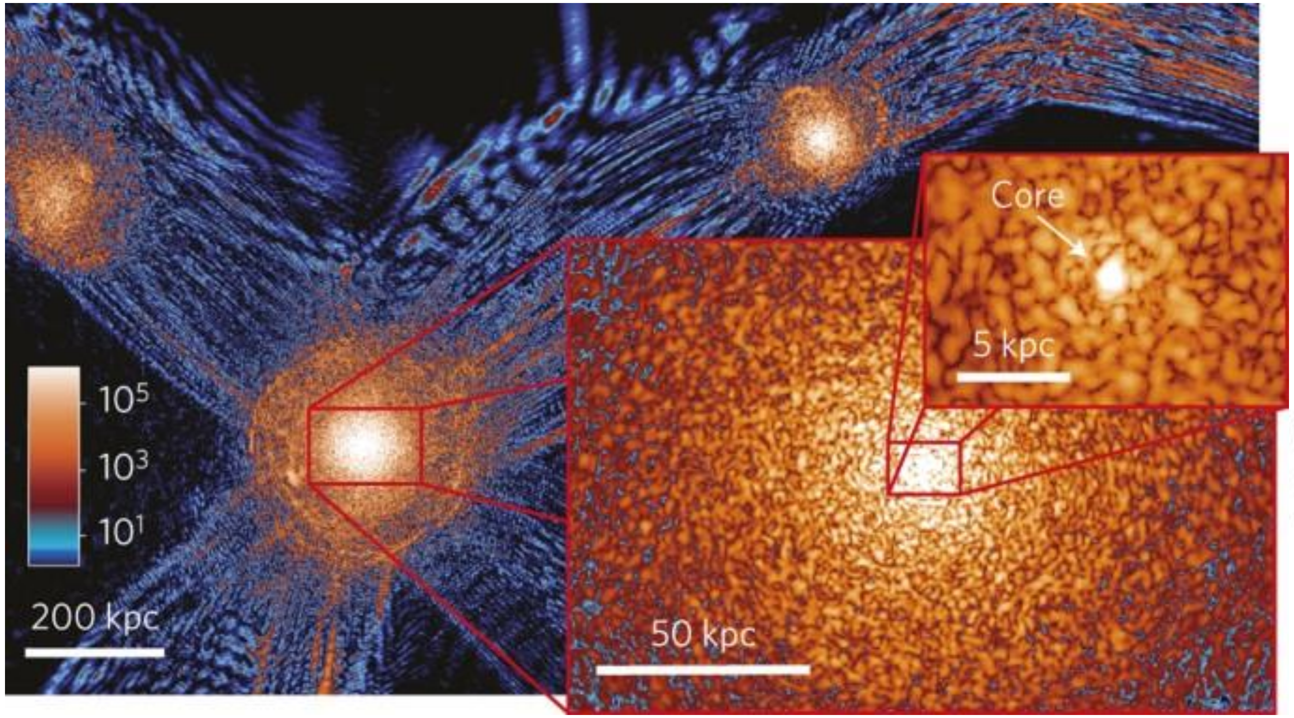
Other solution: Modifying nonlinear predictions
WDM/SIDM/FDM

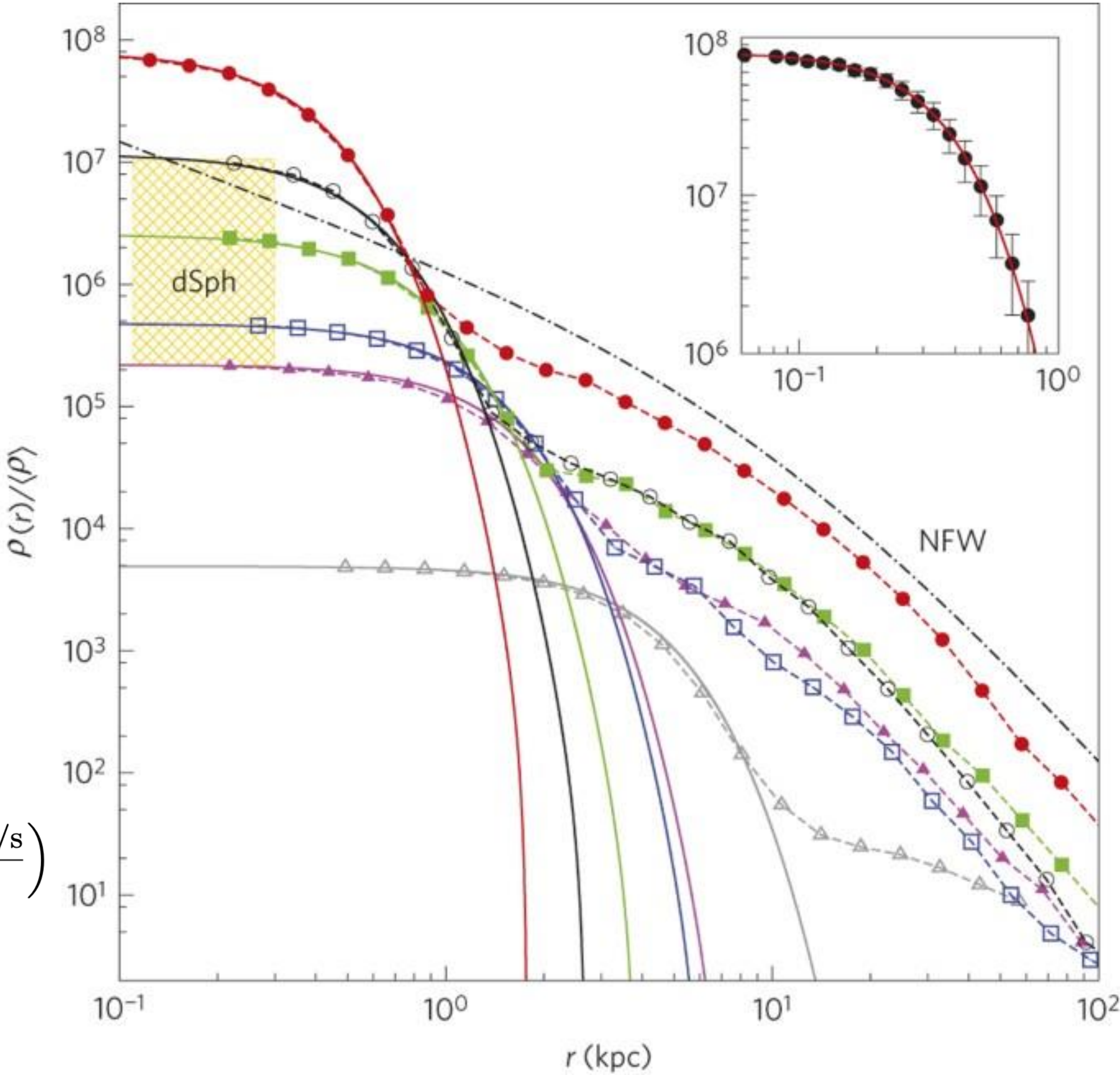




James S. Bullock and Michael Boylan-Kolchin, ARA&A, 2017

A solution of small-scale problem : FDM

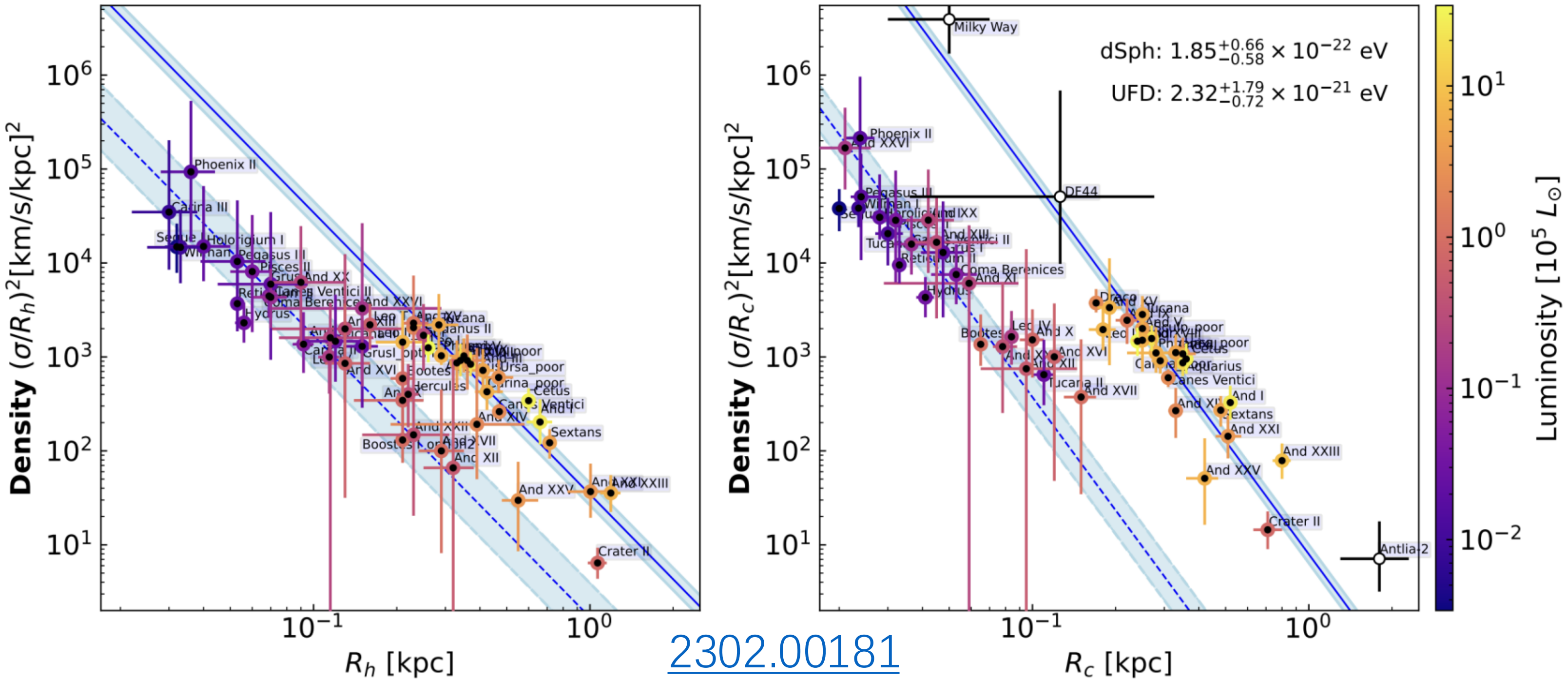




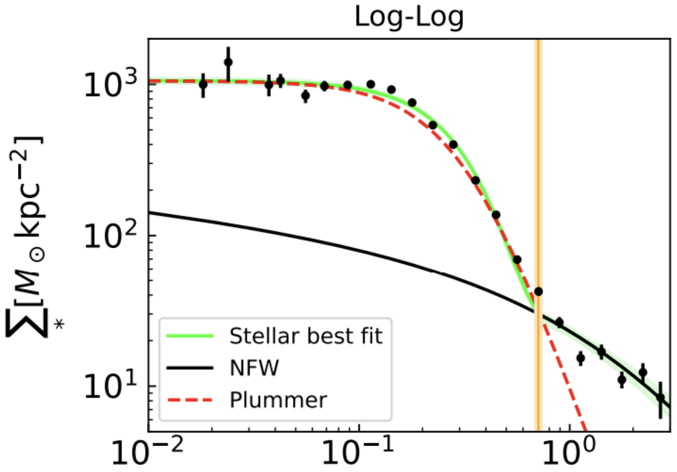
$$\lambda_{\rm dB} \equiv \frac{2\pi}{mv} = 0.48\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{250\,{\rm km/s}}{v}\right) = 1.49\,{\rm km}\left(\frac{10^{-6}\,{\rm eV}}{m}\right)\left(\frac{250\,{\rm km/s}}{v}\right)$$

His-Yu Schive et al. 2014, Nat. Phy.

FDM – dwarf galaxies



[2302.00181](https://arxiv.org/abs/2302.00181)



FDM to dwarf galaxies

Profile of FDM

$$\rho_c(x) = \frac{1.9 \times 10^7 \left(\frac{m_\psi}{10^{-22}\mathrm{eV}}\right)^{-2} \left(\frac{x_c}{\mathrm{kpc}}\right)^{-4}}{a\left[1 + 9.1 \times 10^{-2}\left(\frac{x}{x_c}\right)^2\right]^8} M_\odot \,\mathrm{kpc}^{-3}. \quad (1)$$

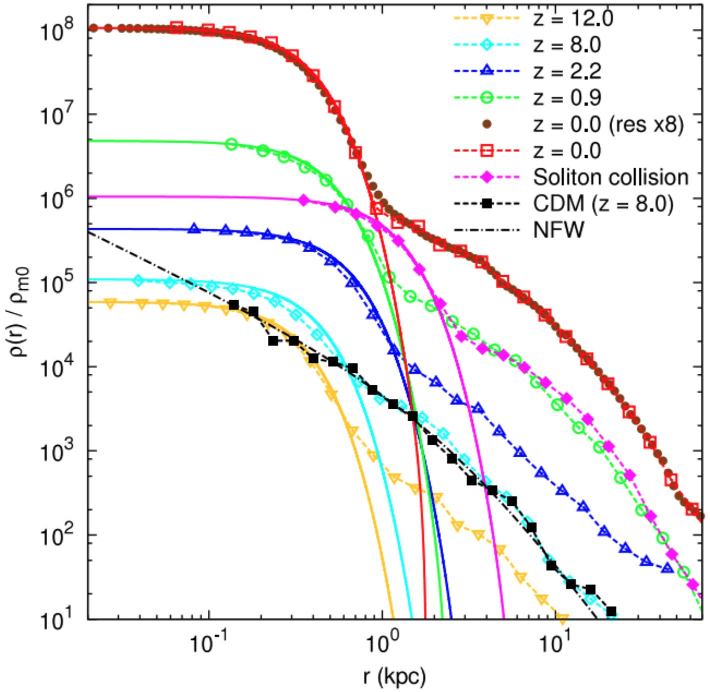
$$x_c = r_c/a, \quad (2)$$

1407.7762.pdf

$$r_c = \frac{1.6a^{1/2}}{\left(\frac{m_\psi}{10^{-22}\,\mathrm{eV}}\right)\left(\frac{\zeta(z)}{\zeta(0)}\right)^{1/6}\left(\frac{M_h}{10^9\,\mathrm{M}_\odot}\right)^{1/3}}\,\mathrm{kpc}, \quad (3)$$

Only two free-parameters: M_h m_ψ

$$\zeta(z) = \frac{18\pi^2 + 82\left(\Omega_m(z) - 1\right) - 39\left(\Omega_m(z) - 1\right)^2}{\Omega_m(z)}. \quad (4)$$



Profile of FDM

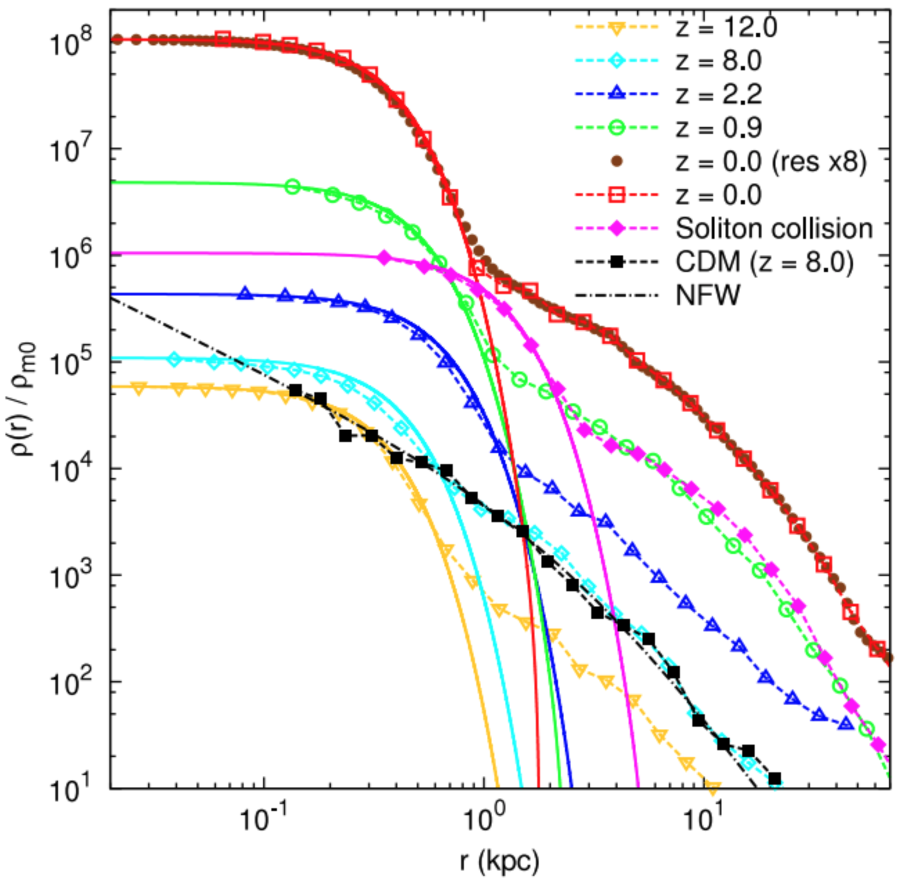
1407.7762.pdf

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}, \qquad (5)$$

$$\rho_0 = \rho_c(r_s). \qquad (6)$$

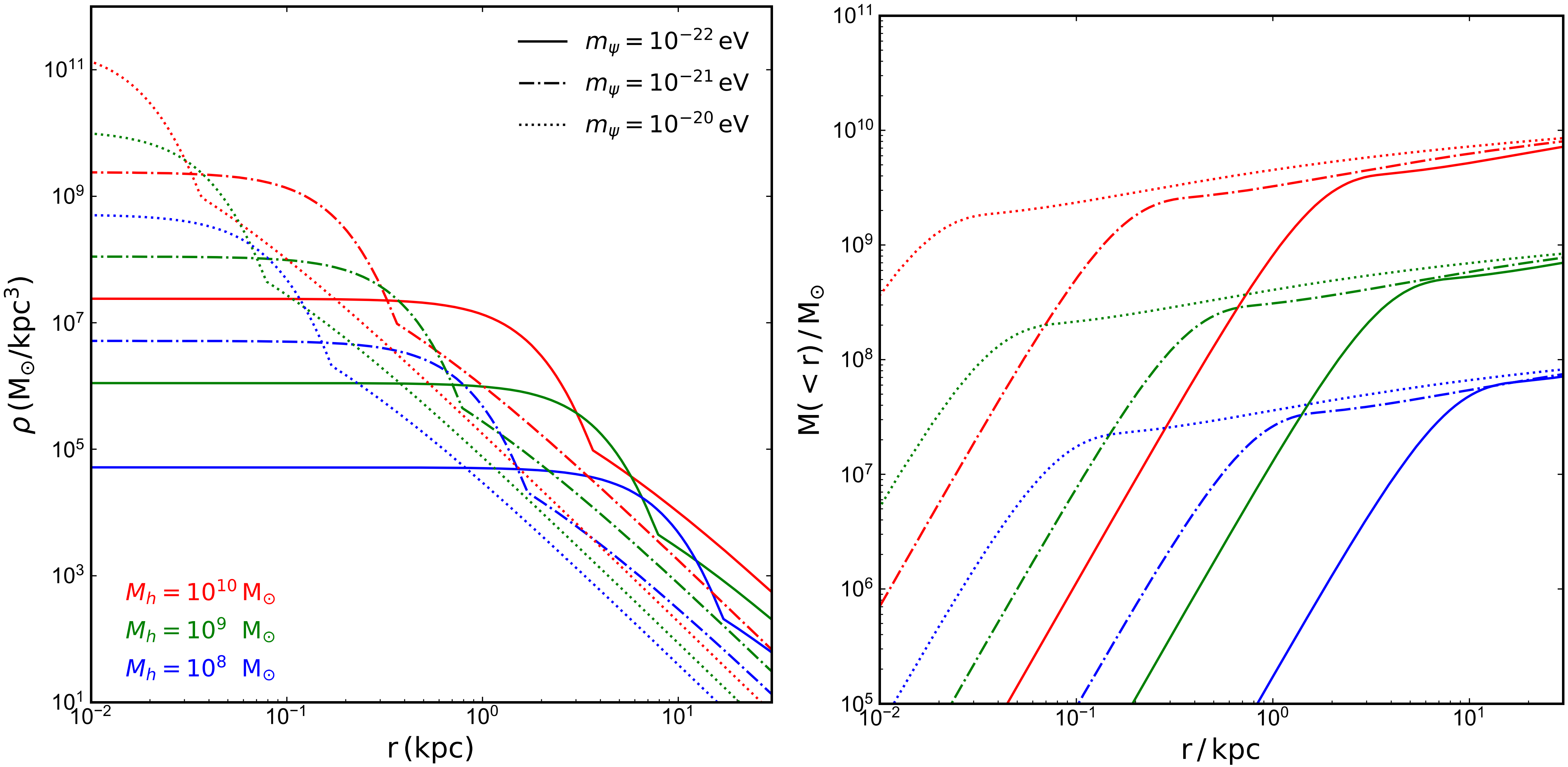
$$\rho(r) = \begin{cases} \rho_c(r), & r \leqslant r_s \\ \rho_{\rm NFW}(r), & r > r_s \end{cases} \qquad (7)$$

$$m(r) = \int_0^r 4\pi r^2 \rho(r)\, dr \qquad (8)$$



r_s/r_c is in the range of 2.7 ~ 3.5 usually

Profile of FDM



This work

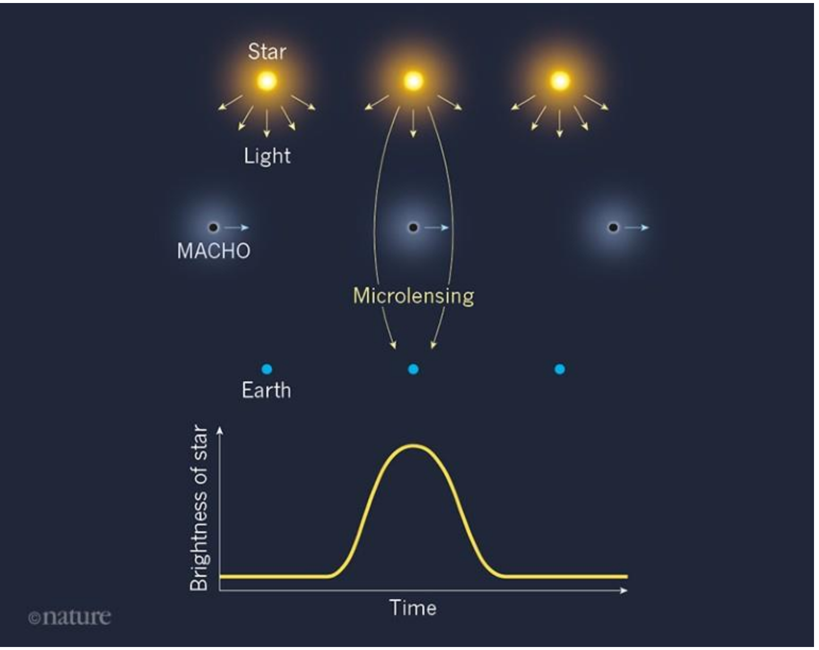
Much lighter halo, Much larger core!

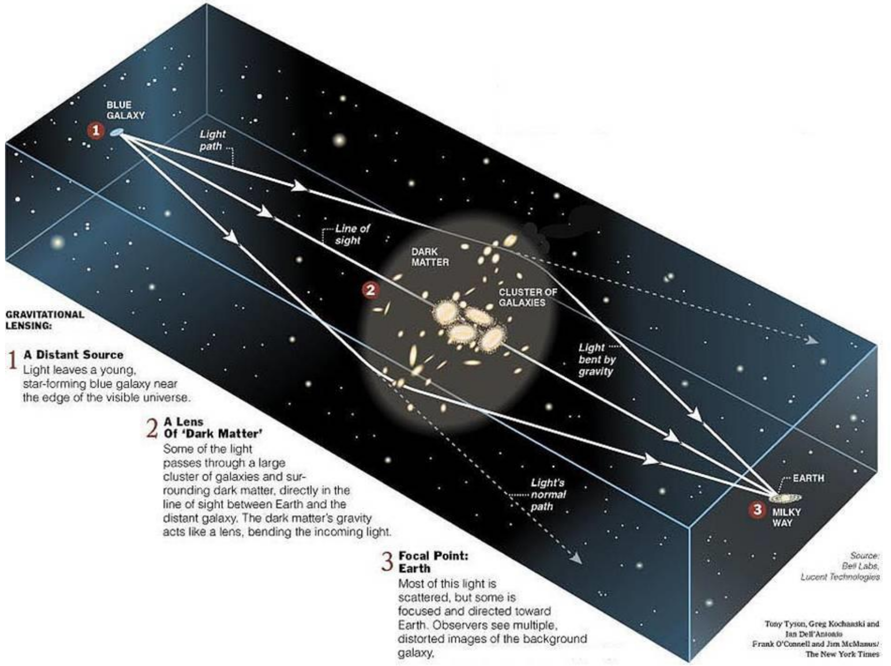
Lensing: a good probe of density profile

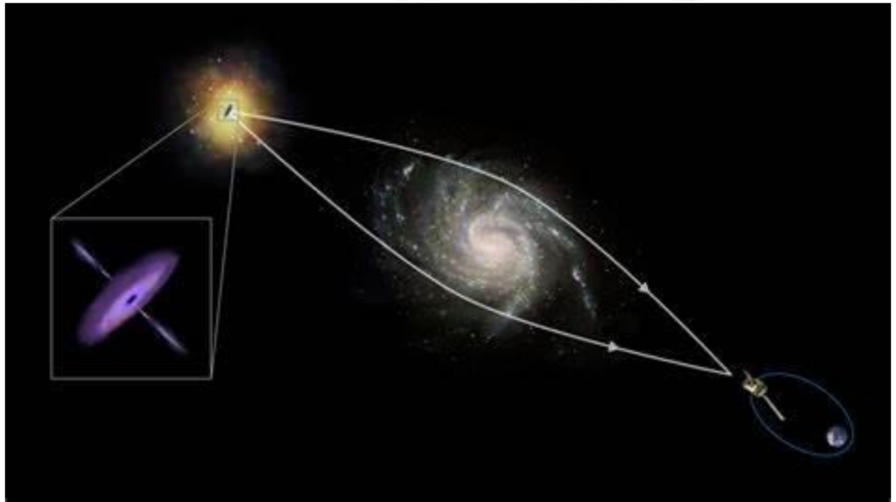
high-mass inner: Strong-lensing

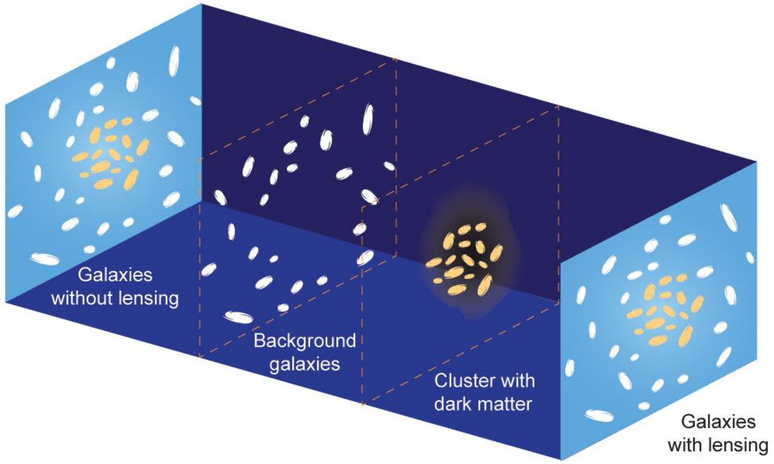
low-mass: Micro-lensing

high-mass skirt: weak-lensing









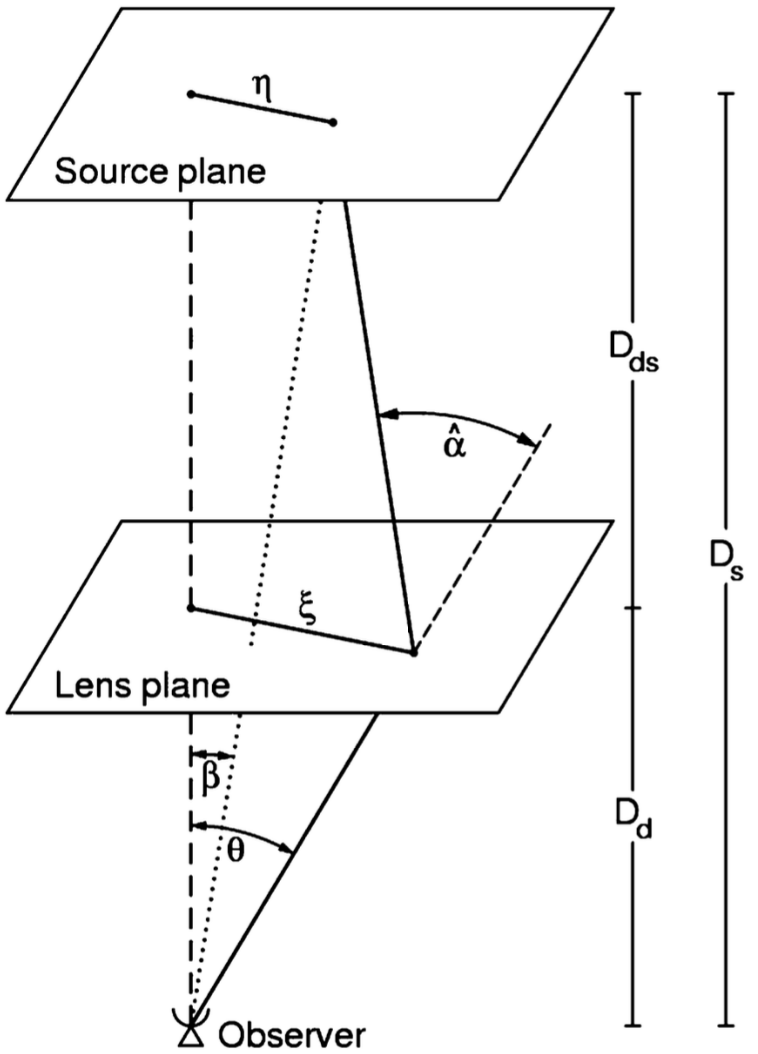
https://www.nature.com/articles/d41586-018-07006-8

Gravitational Strong Lensing

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \frac{D_{\rm ds}}{D_{\rm s}} \hat{\boldsymbol{\alpha}}(\boldsymbol{\theta})$$

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \frac{4G}{c^2} \frac{D_{\rm ds}}{D_{\rm d} D_{\rm s}} \sum_i M_i \frac{\boldsymbol{\theta} - \boldsymbol{\theta}_i}{|\boldsymbol{\theta} - \boldsymbol{\theta}_i|^2},$$

$$\theta_{\rm E} = \frac{4GM}{c^2 \xi} \frac{D_{\rm ds}}{D_{\rm s}}$$

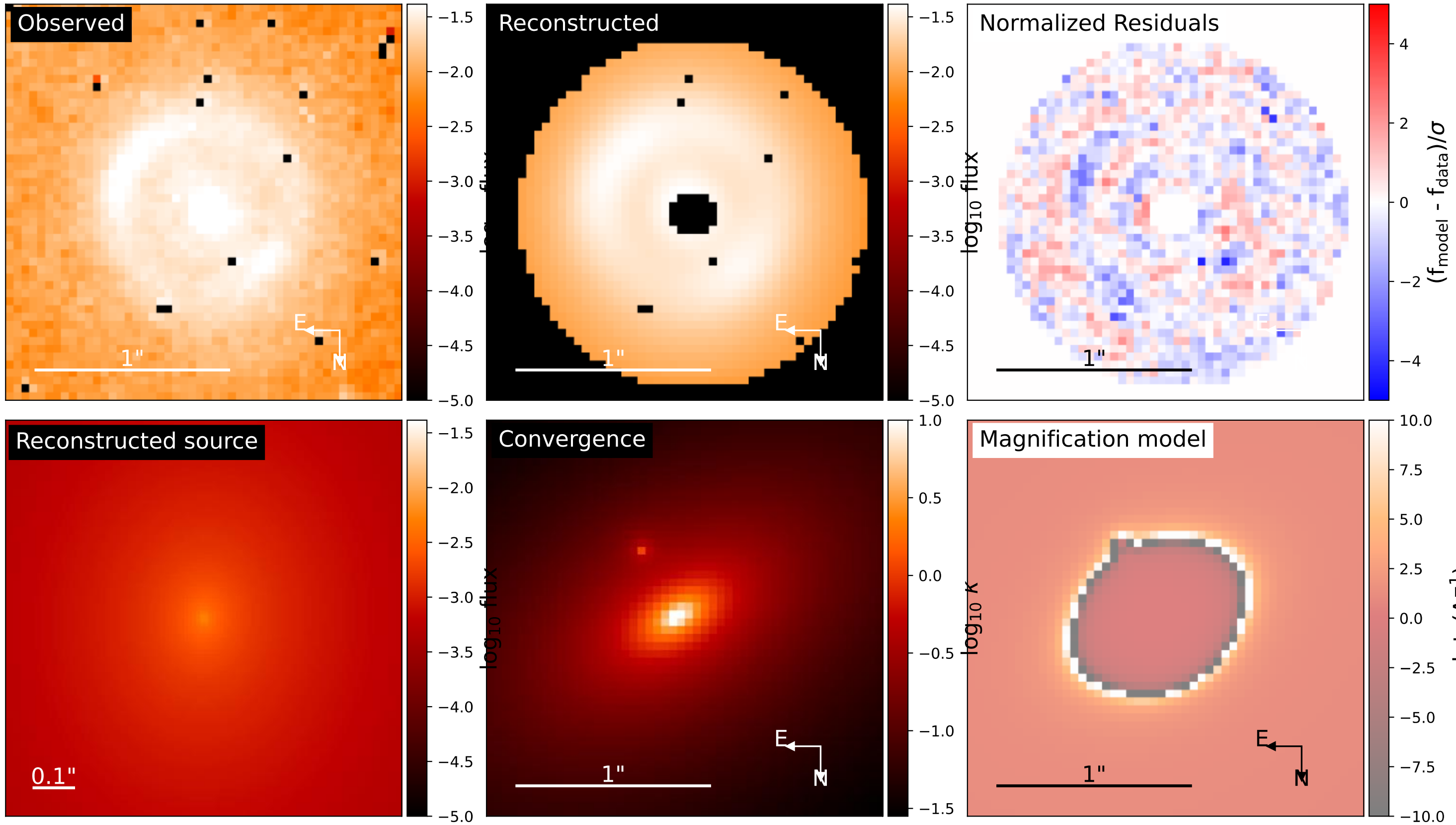


Saha et al. Space Science Reviews (2024) 220:12

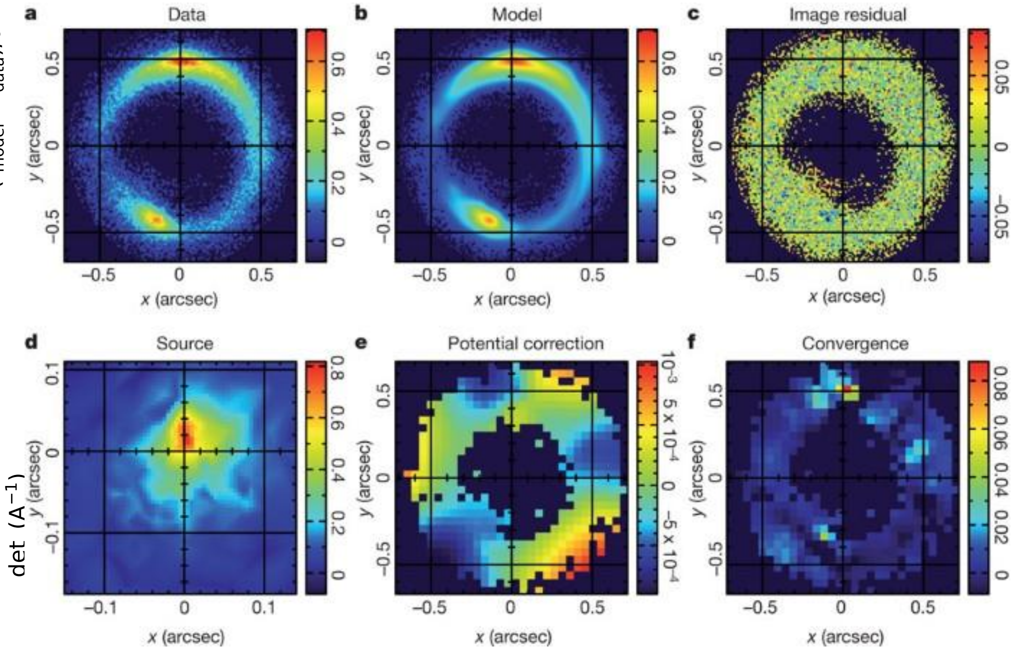
Main halo+ subhalo: HST data

HST B1938+666 Main halo+sub halo (EPL+Shear+NFW)

$\Delta\chi^2 = -46$



This work, Lenstronomy



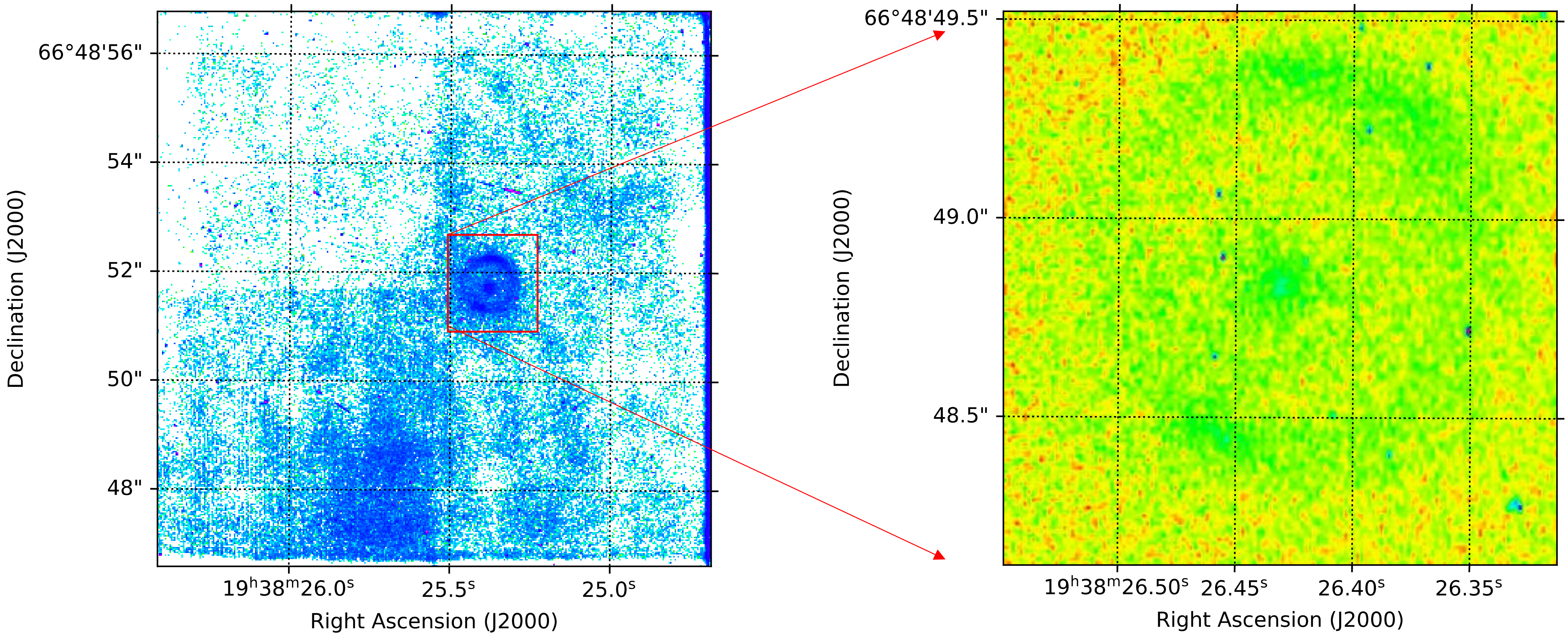
S. Vegetti et al. NATURE Letter, 2012

bad pixels + low exposure pixels are masked

Keck Data

Keck II K band B1938+666 system: reproduction——reduction\selection

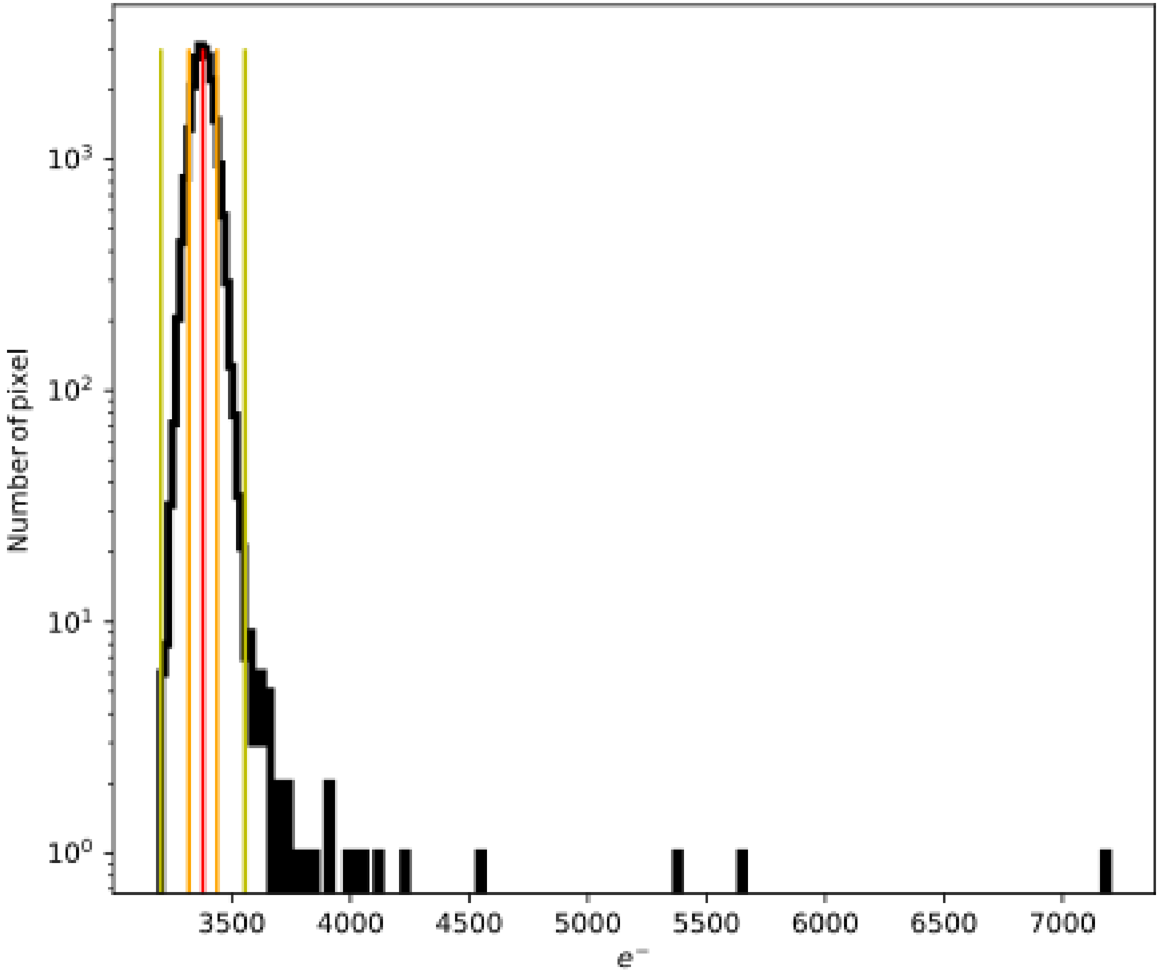
K band 93 frames, CCD gap、low-SNR 27frames, selected high-SNR 66 frames / exposure=180 s



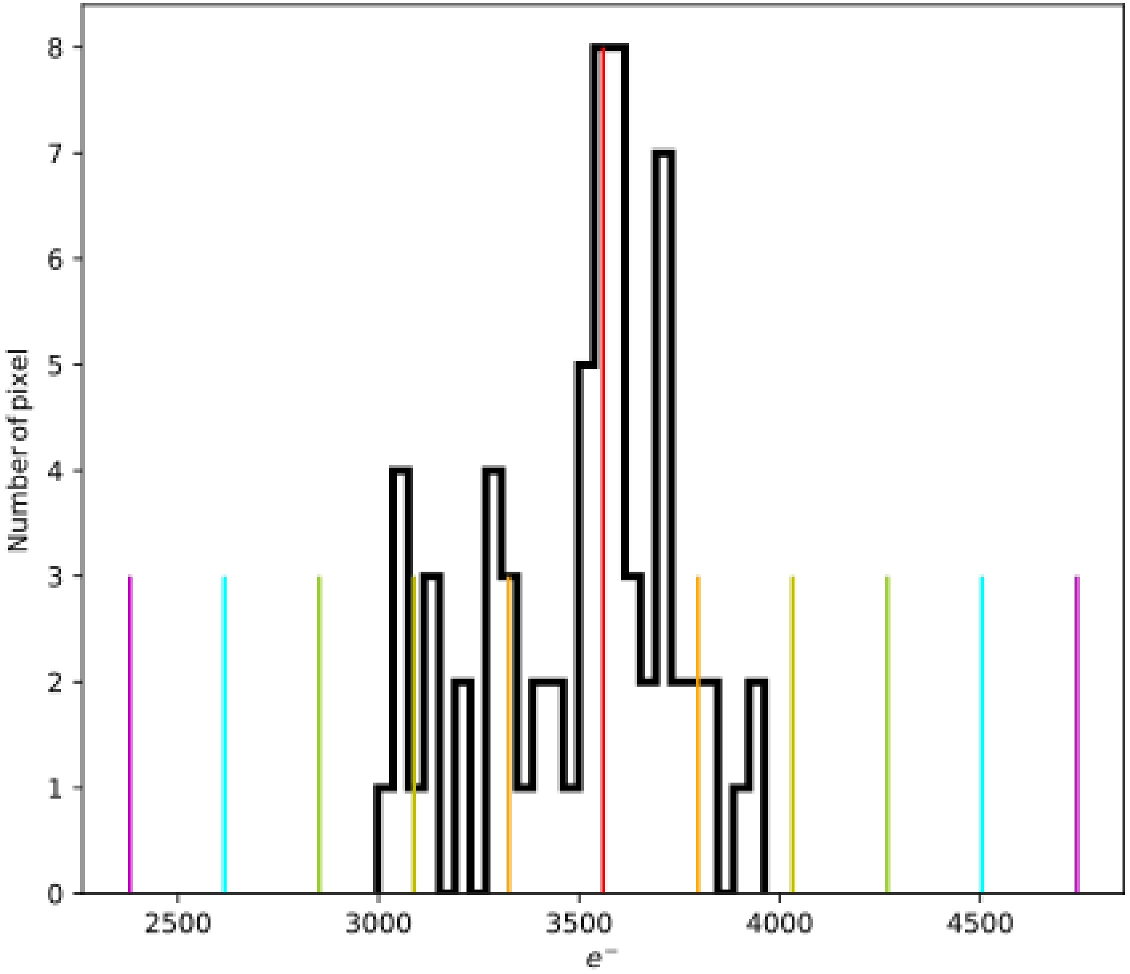
This work

Keck Data: 3-sigma clip of bad pixels

e− Distribution in one frame

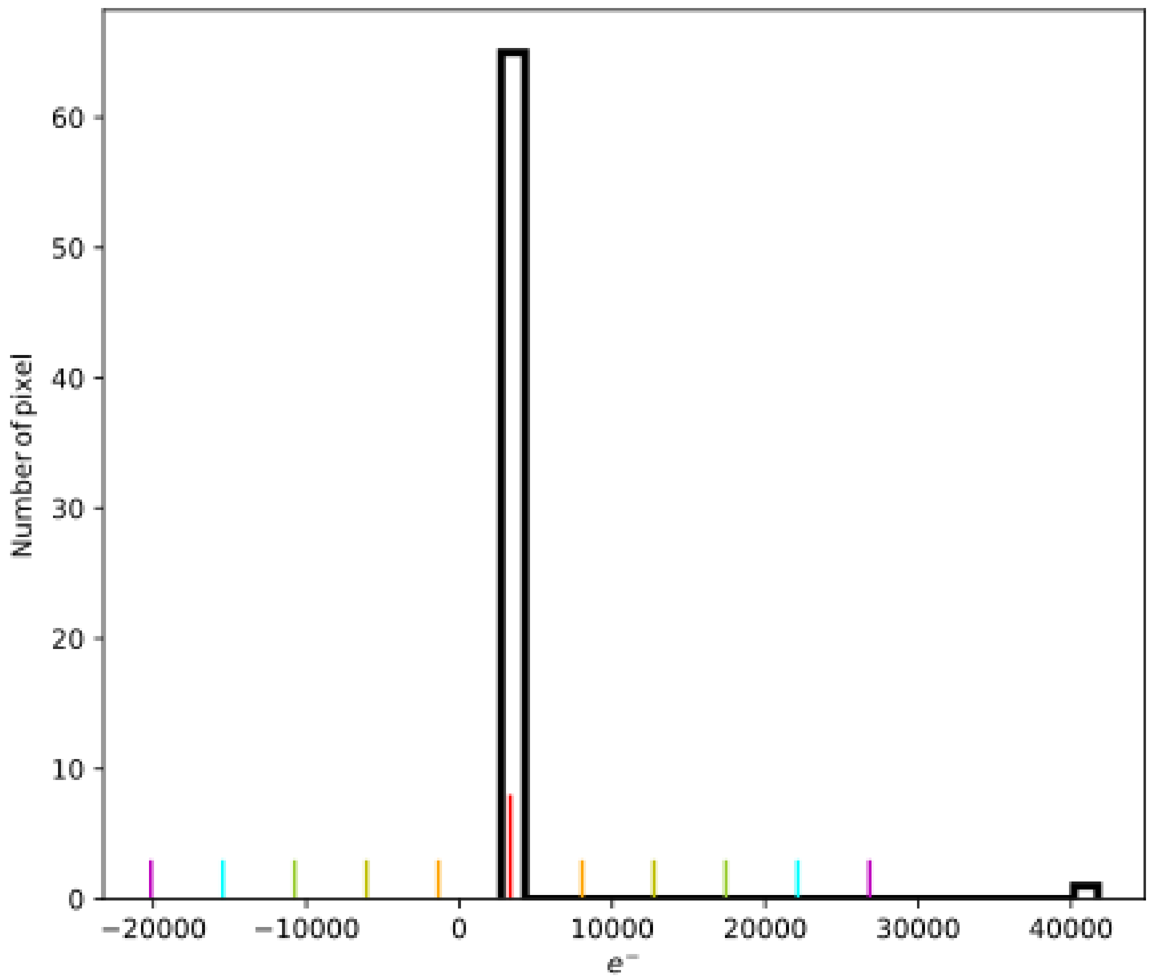


e− Distribution in one column

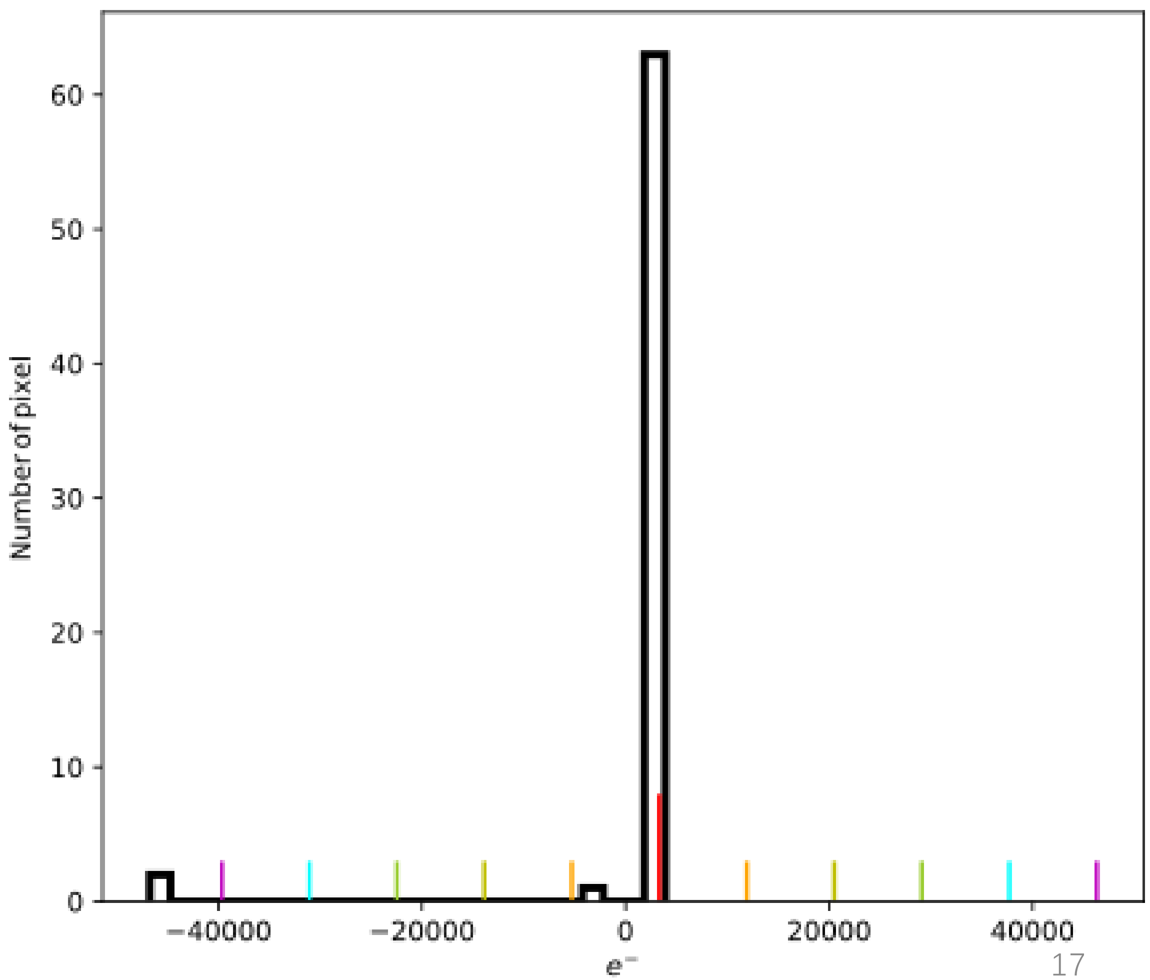


Keck Data : 3-sigma clip of bad pixels

e− Distribution in one bad column

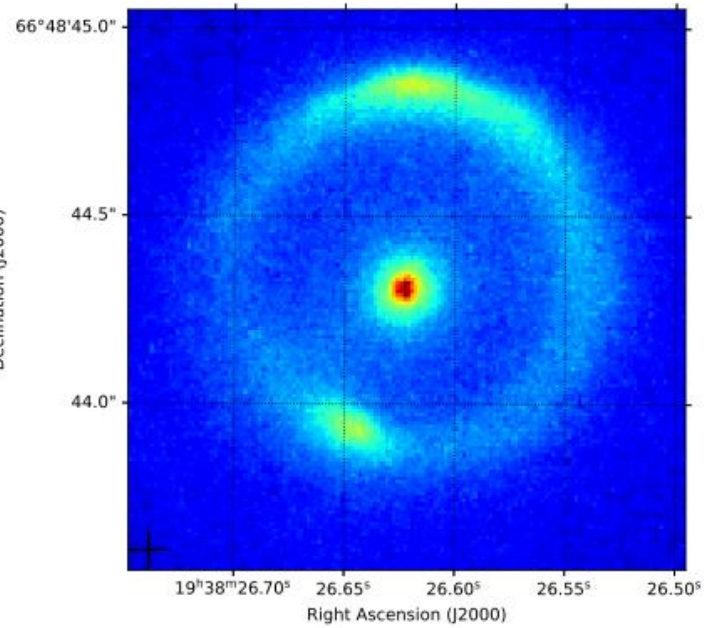


e− Distribution in one bad column

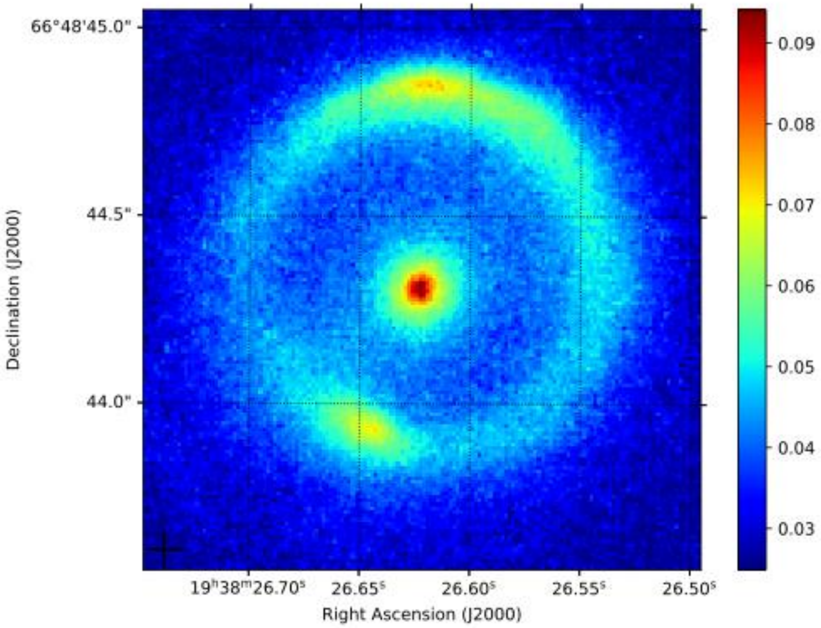


Keck data: Flux & SNR

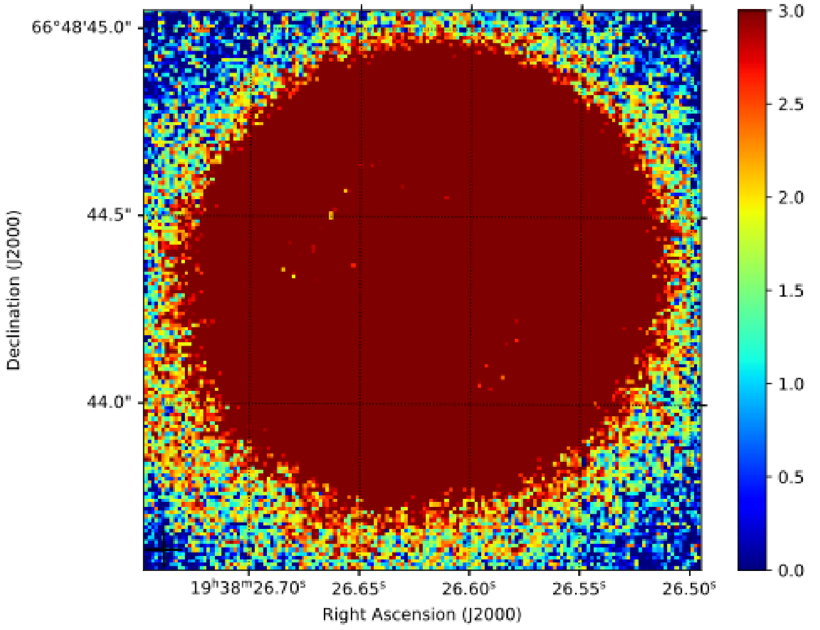
Flux: e^{-}/s



Noise: e^{-}/s



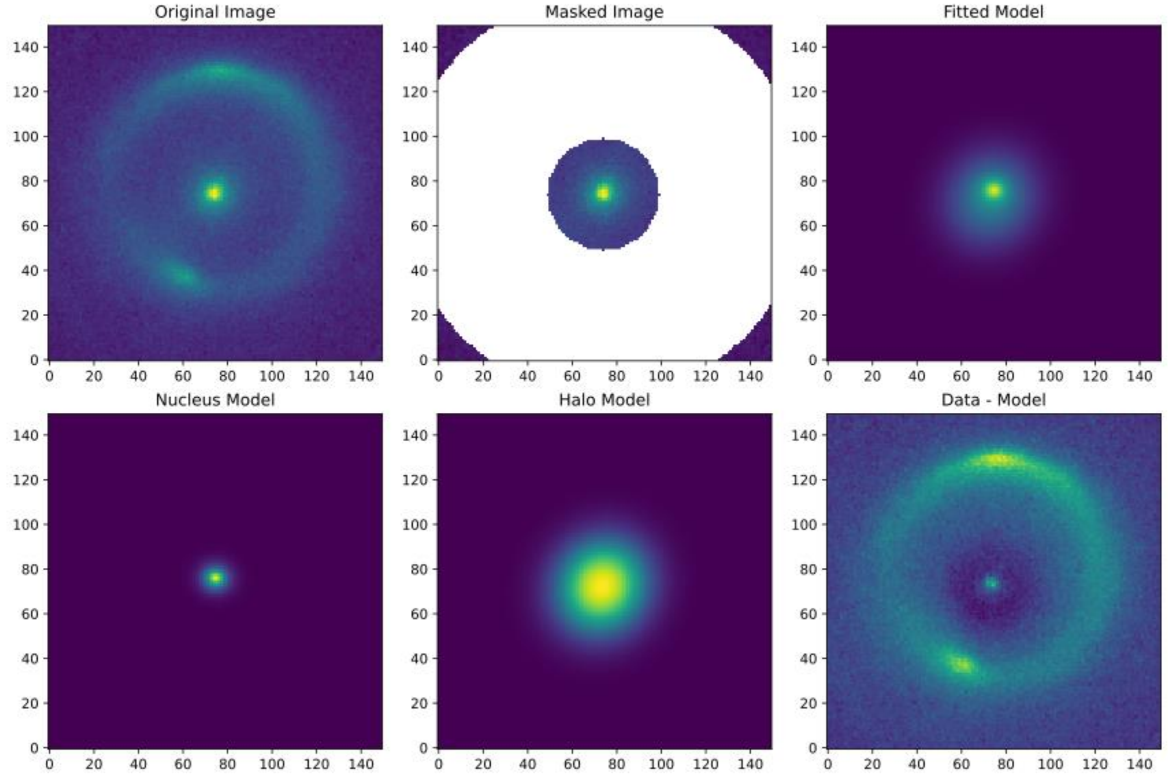
SNR: normalized color map up to 3



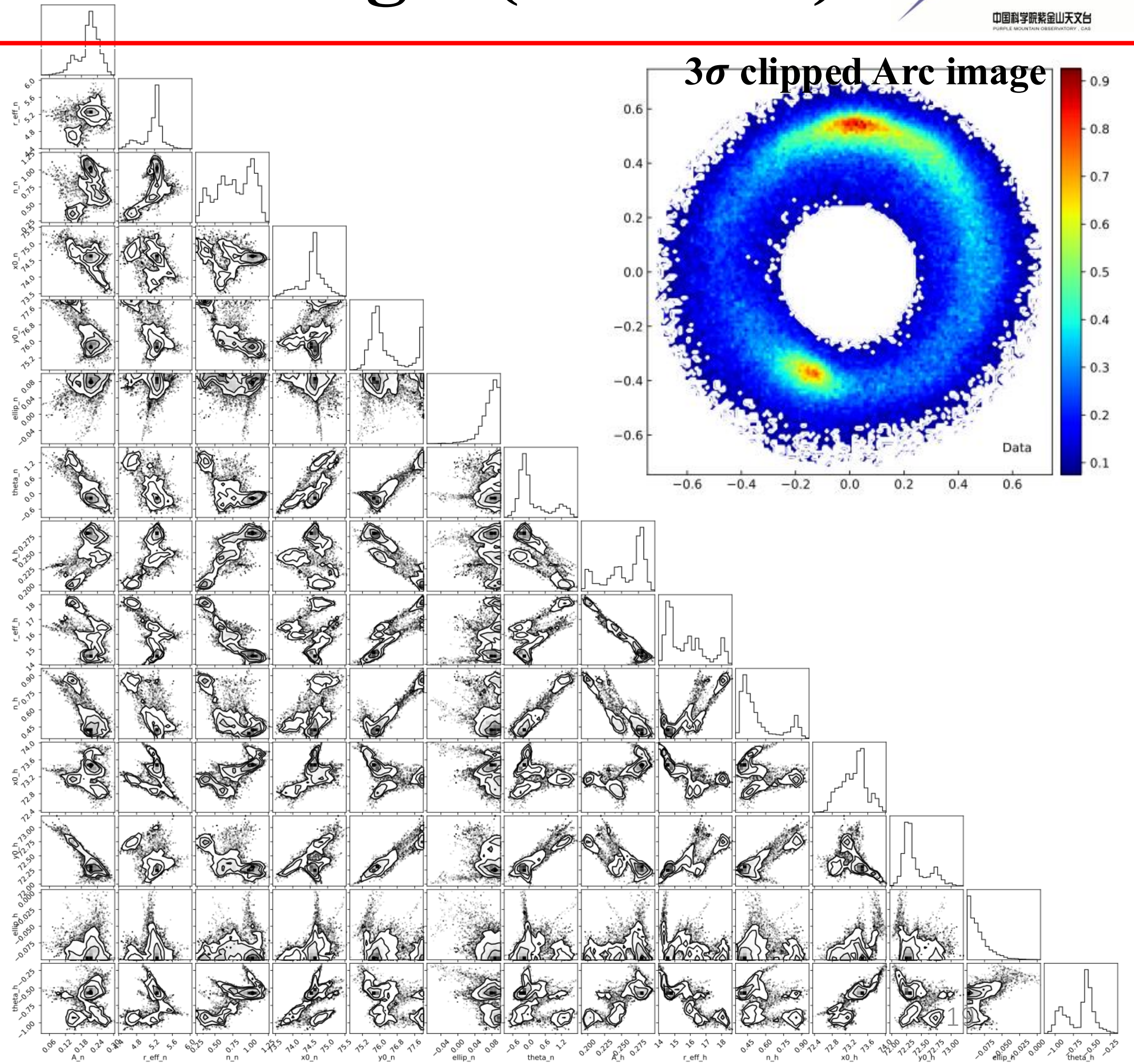
This work

Keck data: subtract Lens Light(2 Sersic)

2 Sersic: stellar nucleus & halo models



3σ clipped Arc image



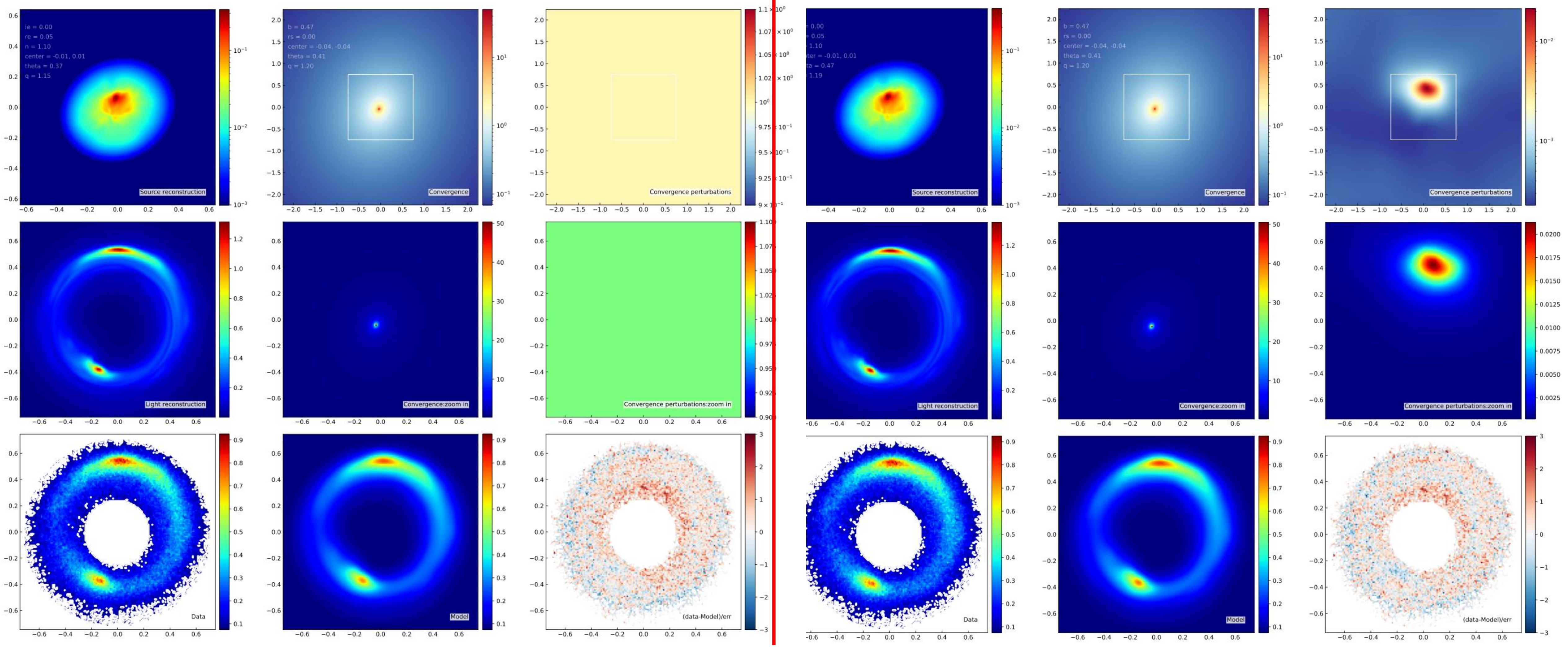
Posterior of 2 Sersic models →

This work

B1938 Arc fitting with LensCharm

Best-fit host halo

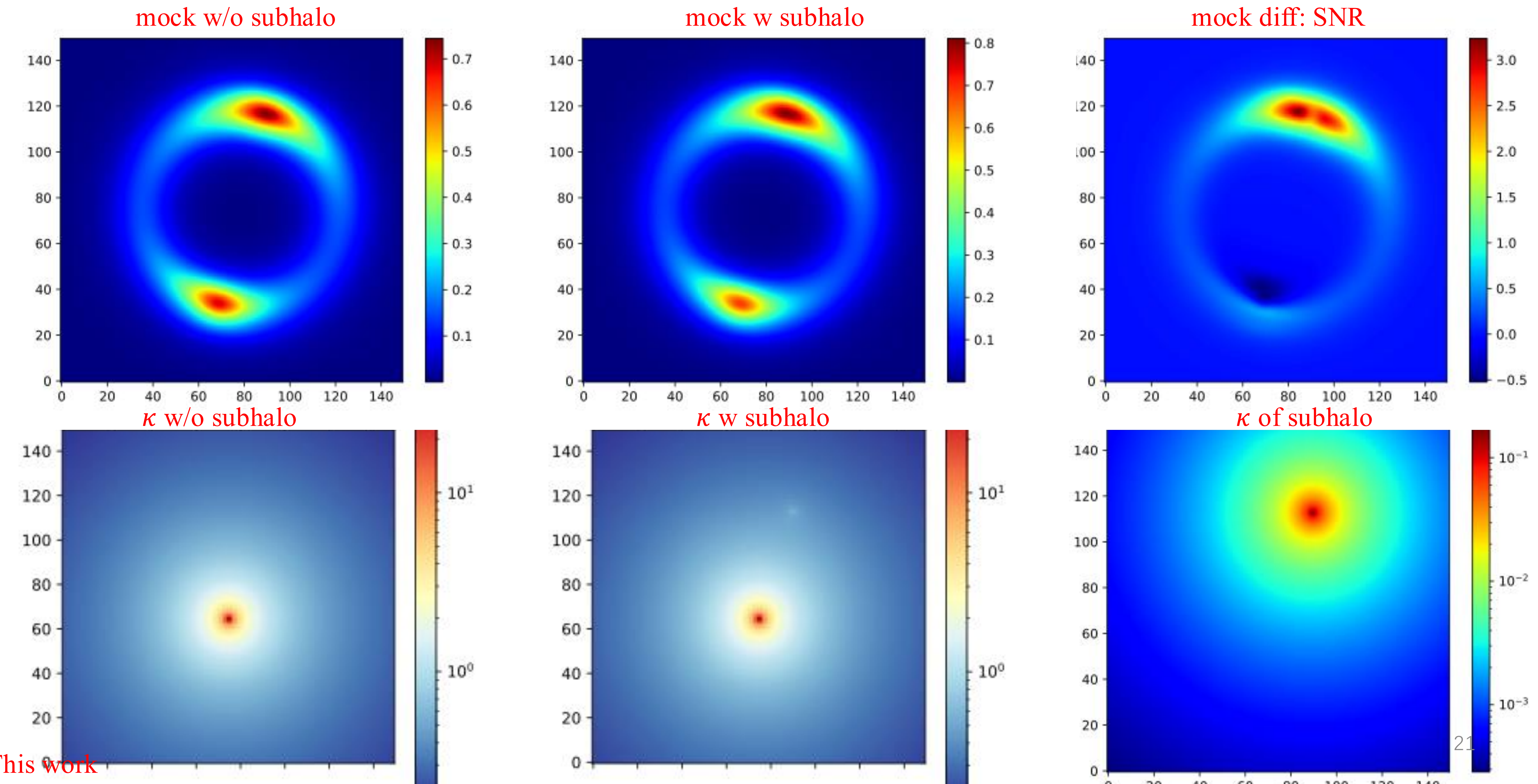
Best-fit host+sub halos



This work

$$\Delta\, BIC = BIC_{main+sub\ halo} - BIC_{main\ halo\ only} = -129.1\ (10\ \sigma\ in\ Gaussian)$$

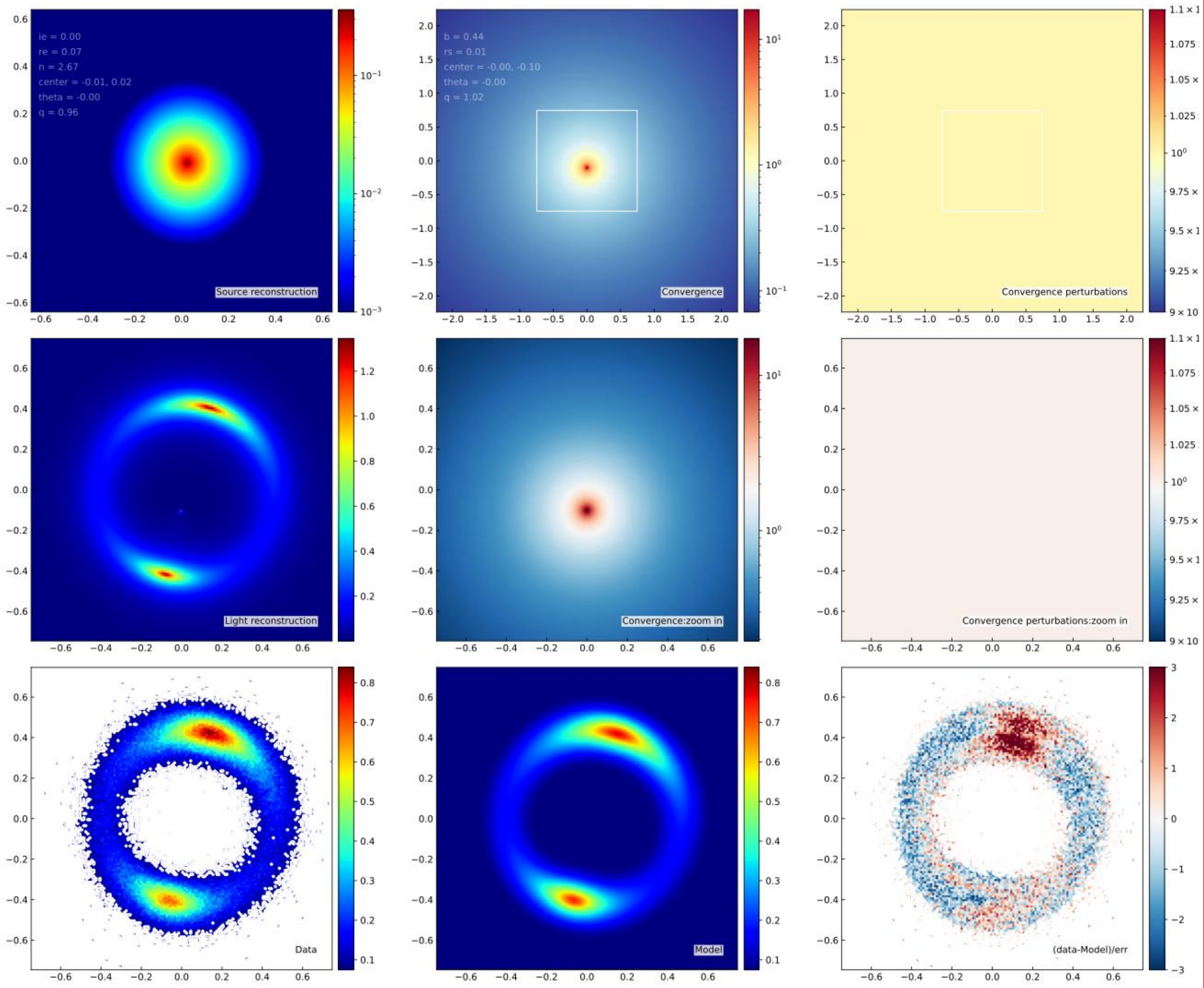
LensCharm SysError: mock subhalo



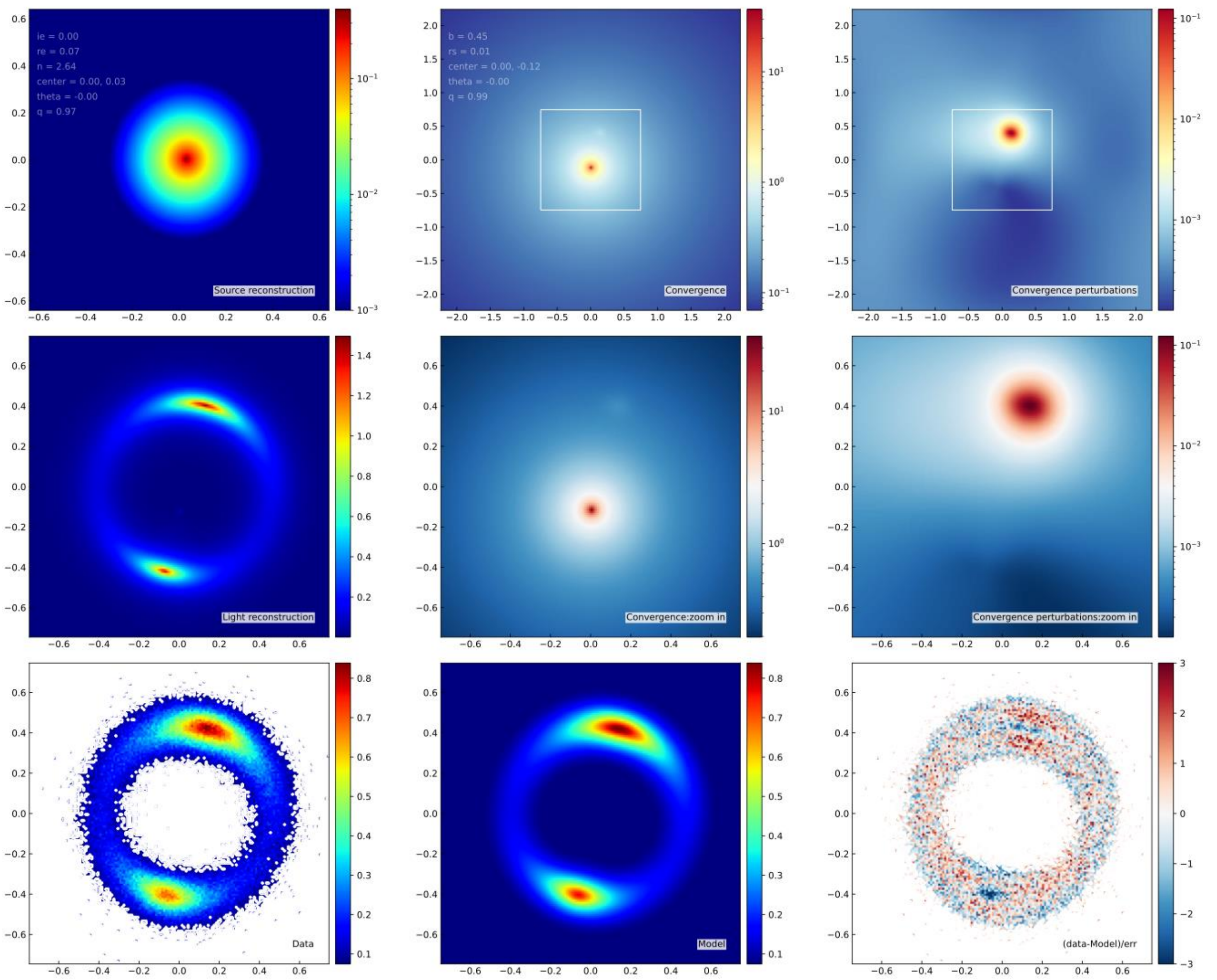
This work

LensCharm SysError: mock subhalo fitting

Best-fit w/o subhalo



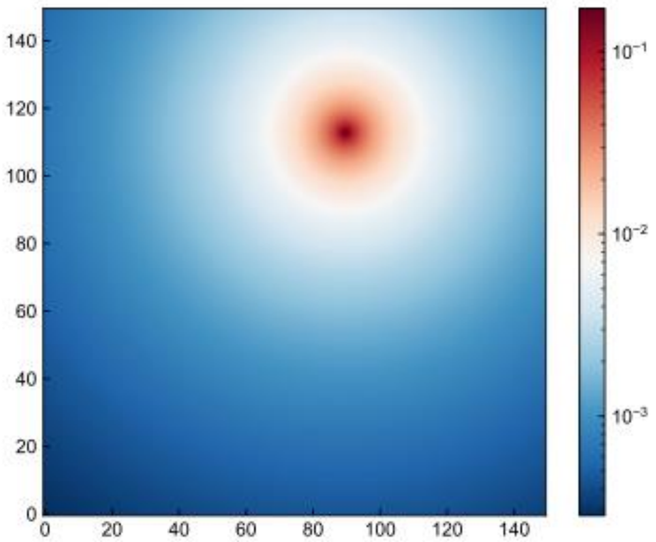
Best-fit w subhalo



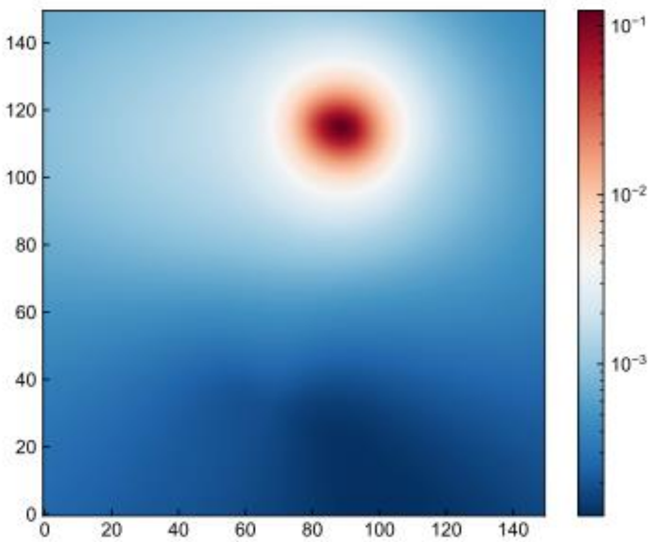
This work

SysError of Arc fitting with LensCharm

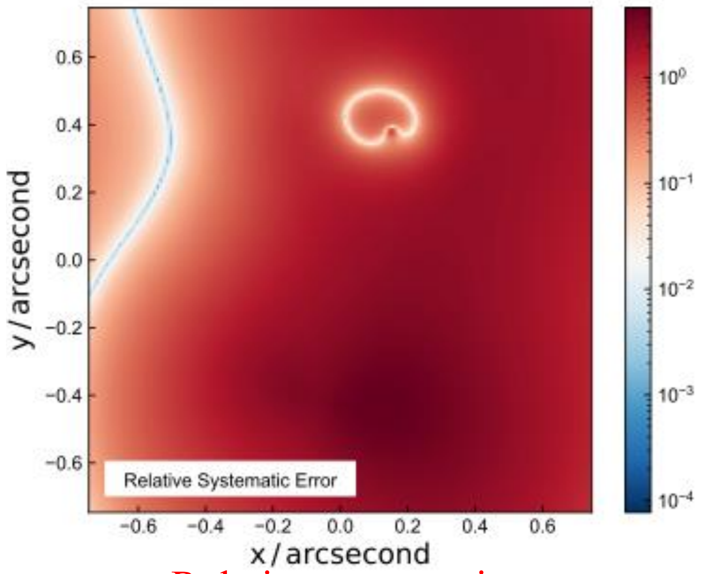
mock subhalo κ



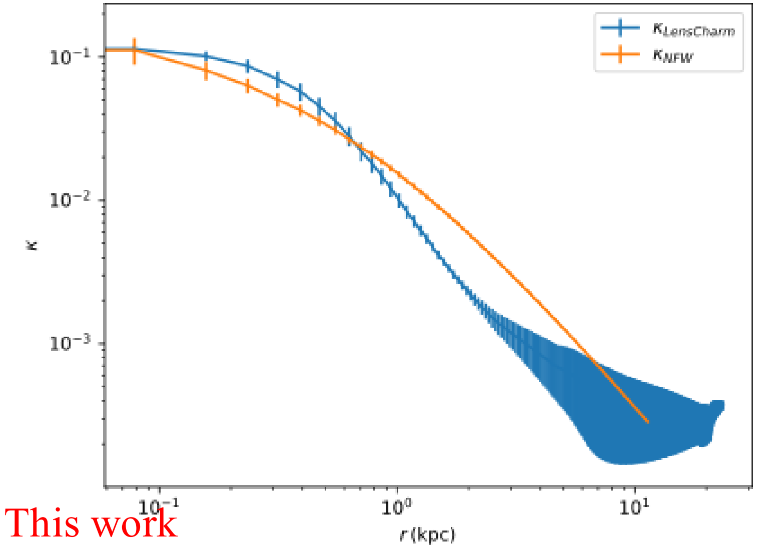
Best-fit subhalo κ



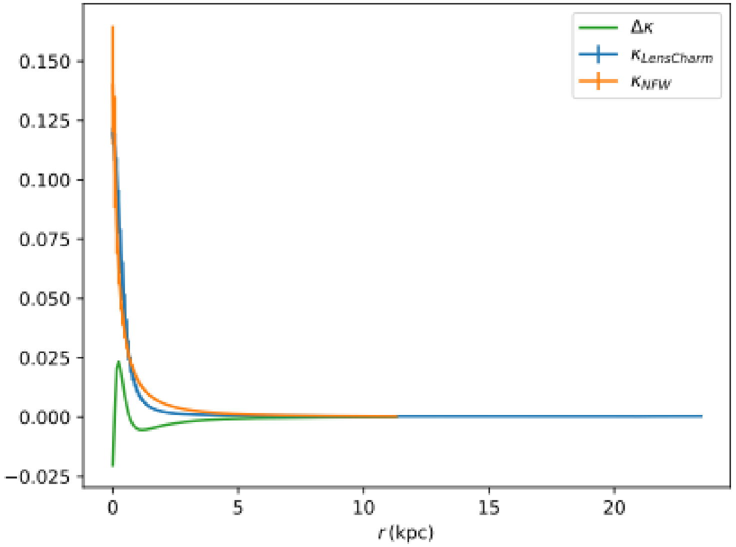
relative systematic error map



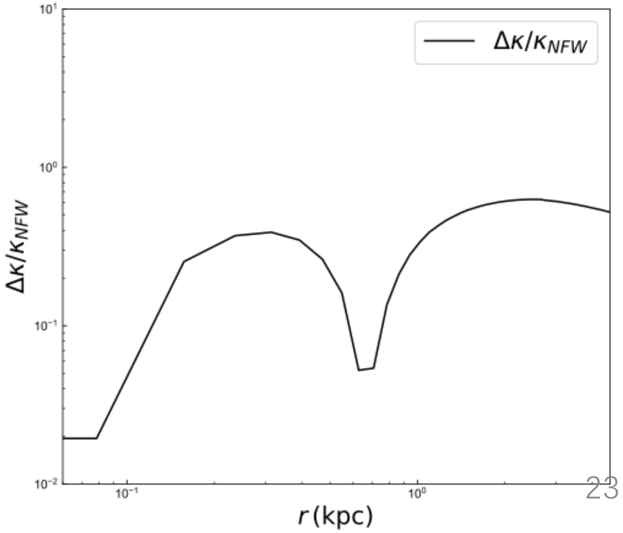
κ_{NFW} vs $\kappa_{LensCharm}$



κ_{NFW} vs $\kappa_{LensCharm}$ vs $\Delta\kappa$



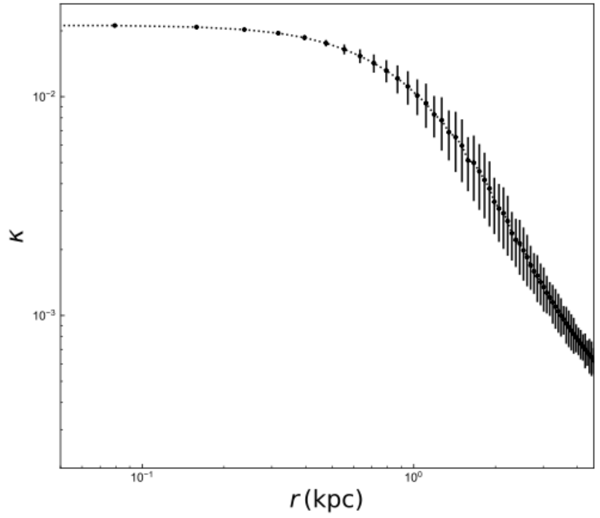
Relative systematic error



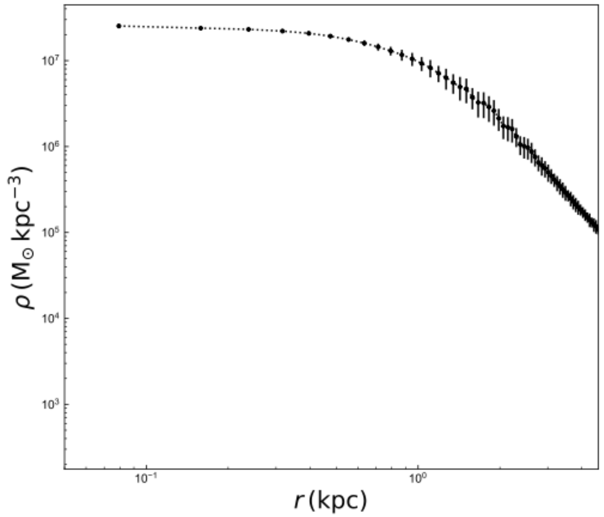
This work

B1938+666 result with sysErr

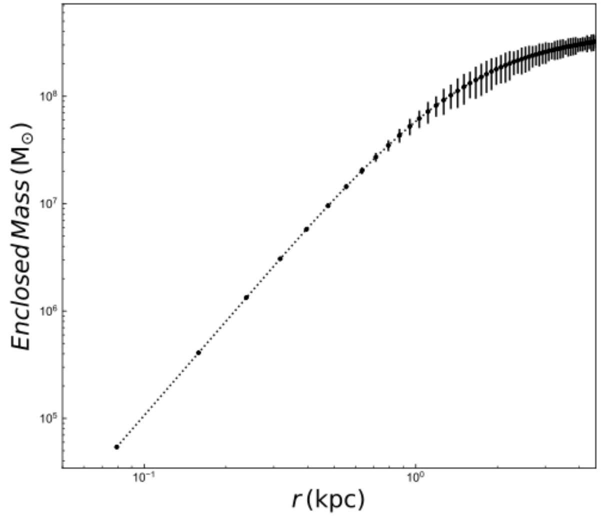
κ : statistical error only



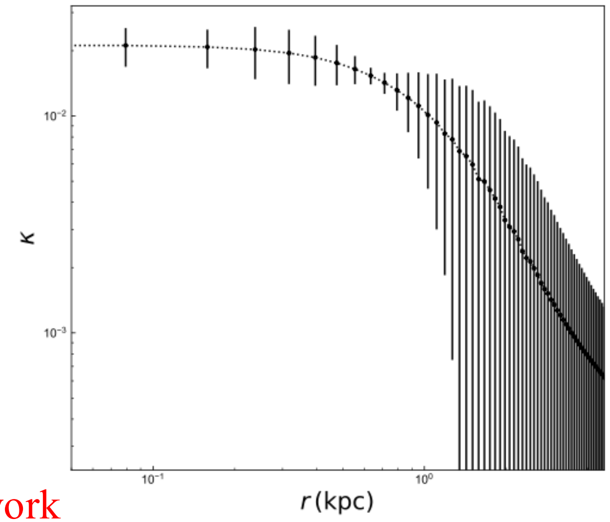
ρ: statistical error only



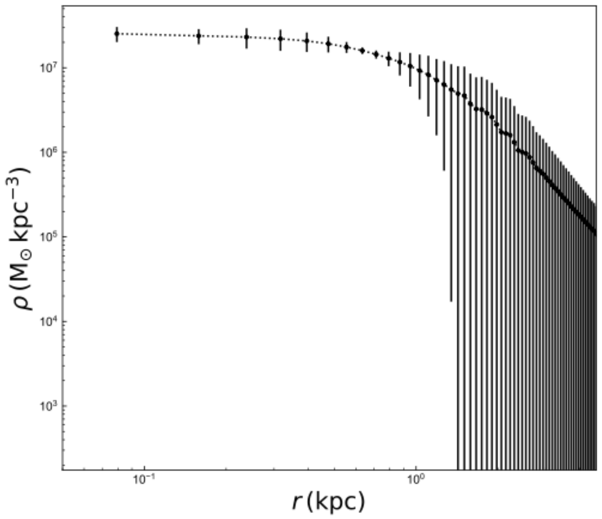
Enclosed mass: statistical error only



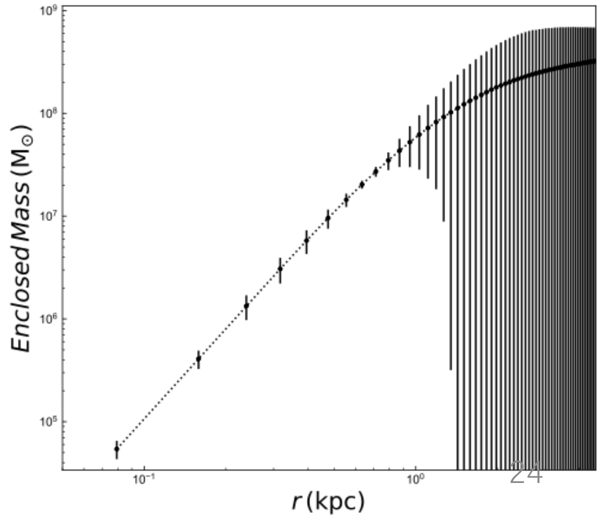
κ : total error included



ρ: total error included



Enclosed mass: total error included

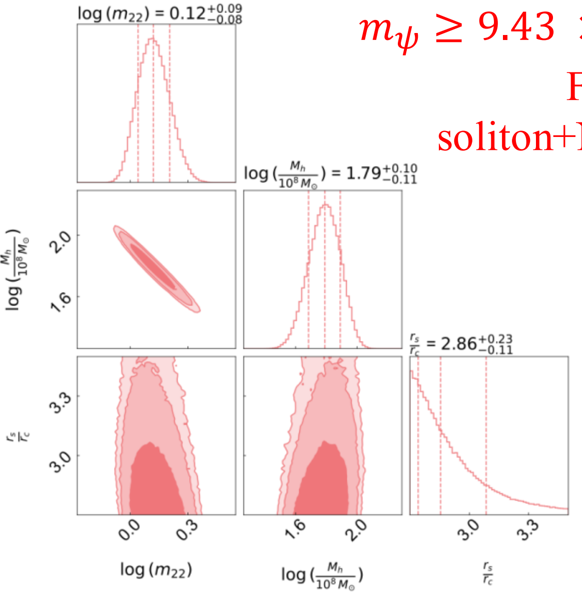


This work

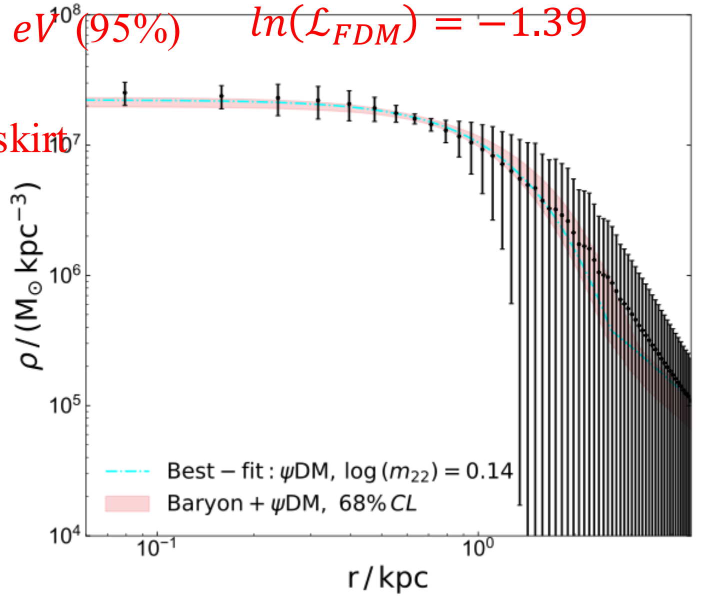
$\rho_{B1938+666}$ to Dark Matter Halo Models

$m_\psi \geq 9.43 \times 10^{-23}\ eV$ (95%)

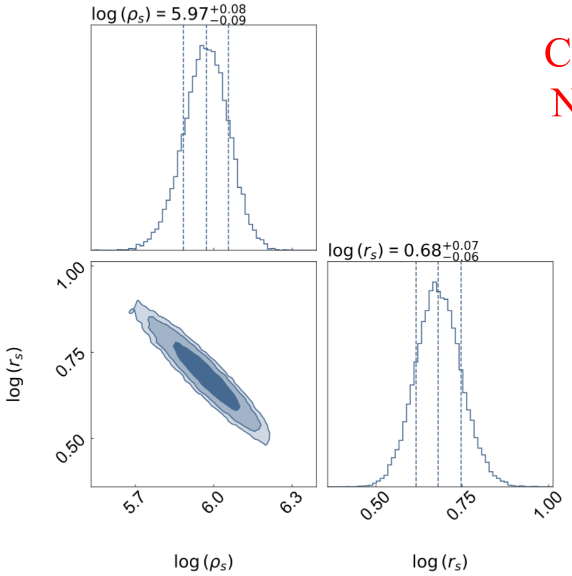
FDM: soliton+NFWoutskirt



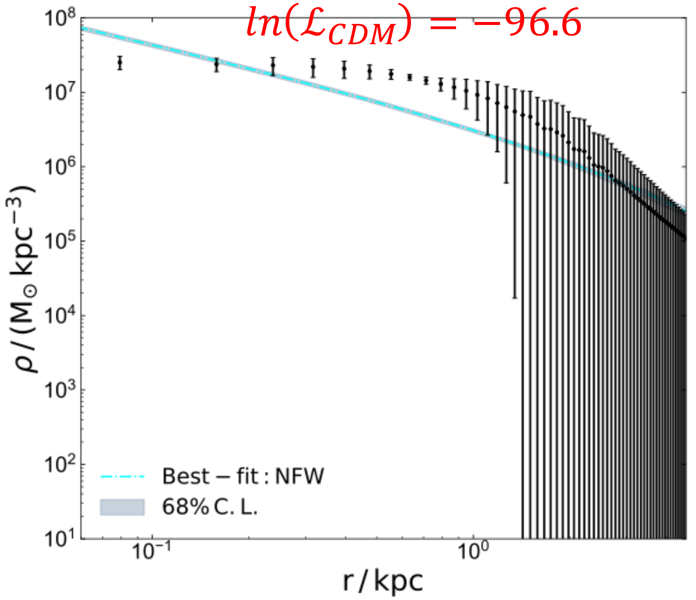
$ln(\mathcal{L}_{FDM}) = -1.39$



CDM: NFW



$ln(\mathcal{L}_{CDM}) = -96.6$



$$BIC = k\ln(n) - 2\ln(L) = k\ln(n) + \chi^2$$

$$\ln(BF_{AB}) = BIC_B - BIC_A$$

Byes Factor	Evidence that model A is better than B
1~3	primary
3~10	median
10~30	significant
30~100	very significant
>100	extreme significant

$\ln(BF) = BIC_{\mathrm{NFW}} - BIC_{\mathrm{FDM}} = 186.3$ (~14 σ)

$\Delta\, 2\ln\mathcal{L} = -2\ln\mathcal{L}_{FDM} - (-2\ln\mathcal{L}_{NFW}) = -190.4$

P-value: 2.6e-43

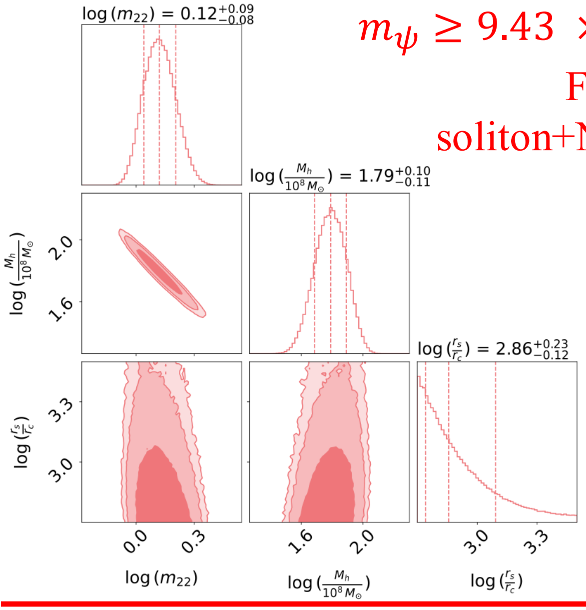
NFW is tension with data in: 13.75 (sigma)

This work

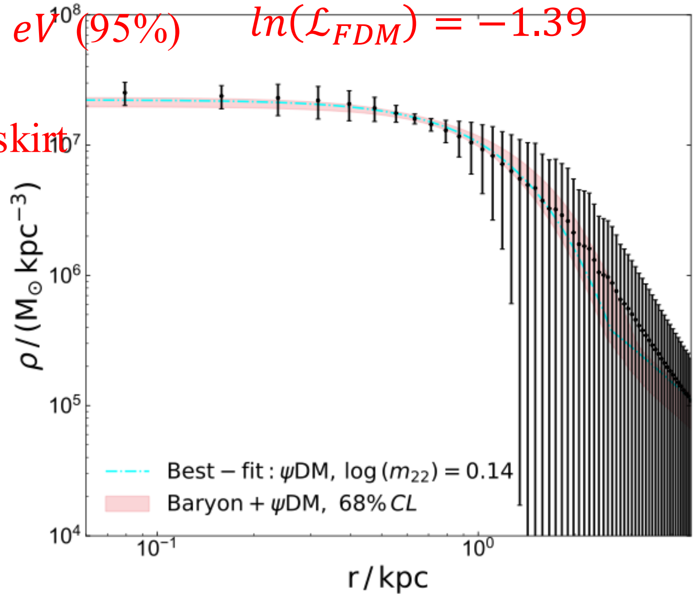
$\rho_{B1938+666}$ to Dark Matter Halo Models

$m_\psi \geq 9.43 \times 10^{-23}\ eV\ (95\%)$

FDM:
soliton+NFWoutskirt



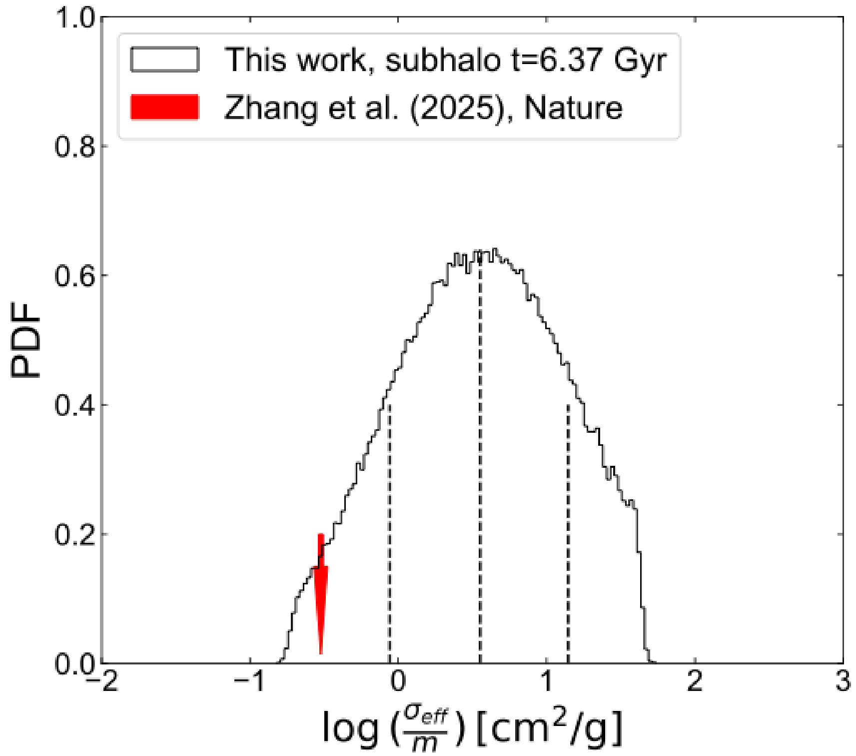
$ln(\mathcal{L}_{FDM}) = -1.39$



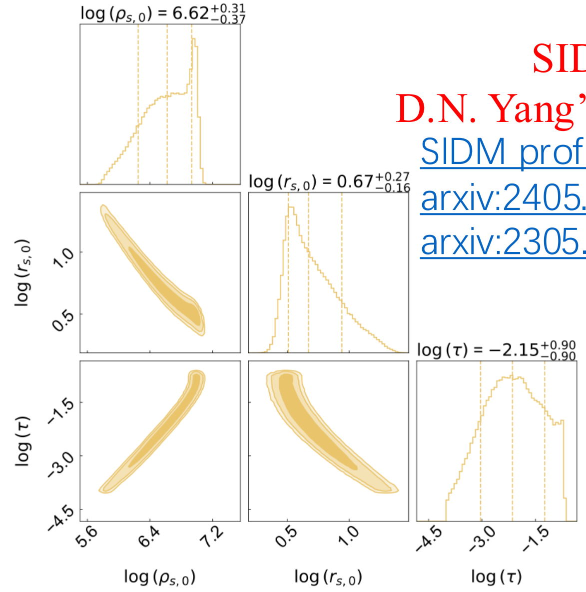
$\ln(BF) = BIC_{\mathrm{SIDM}} - BIC_{\mathrm{FDM}} = -2.67$

$\Delta\, 2\ln\mathcal{L} = -2\ln\mathcal{L}_{FDM} - (-2\ln\mathcal{L}_{SIDM}) = 2.67$

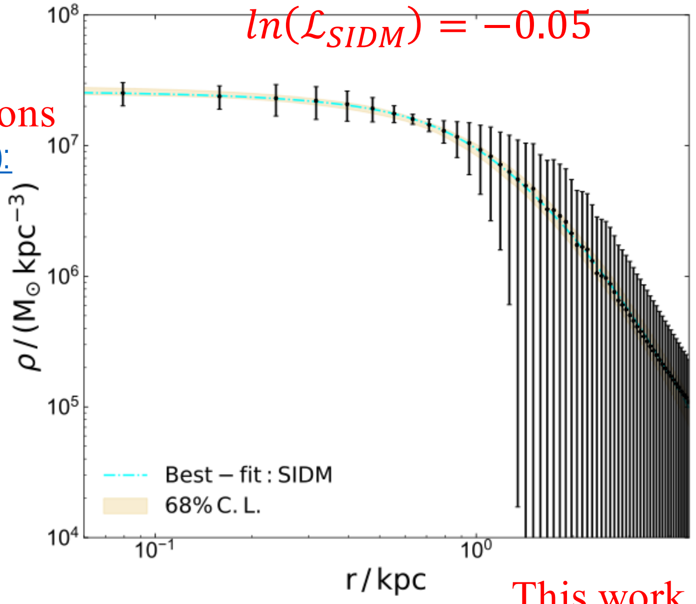
$BF = 14.44$



SIDM:
D.N. Yang's Equations
SIDM profile (Yang):
arxiv:2405.03787
arxiv:2305.16176



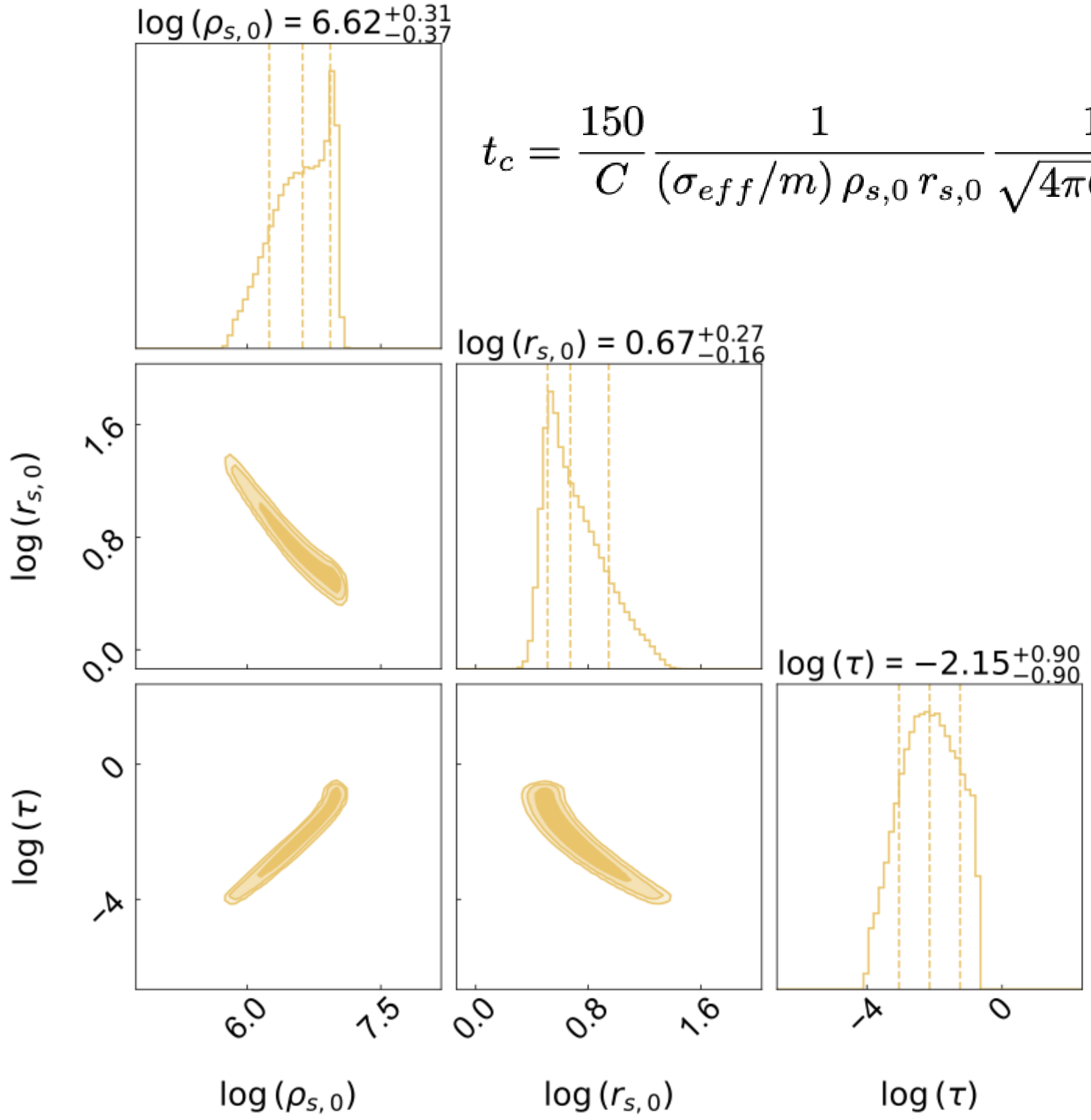
$ln(\mathcal{L}_{SIDM}) = -0.05$



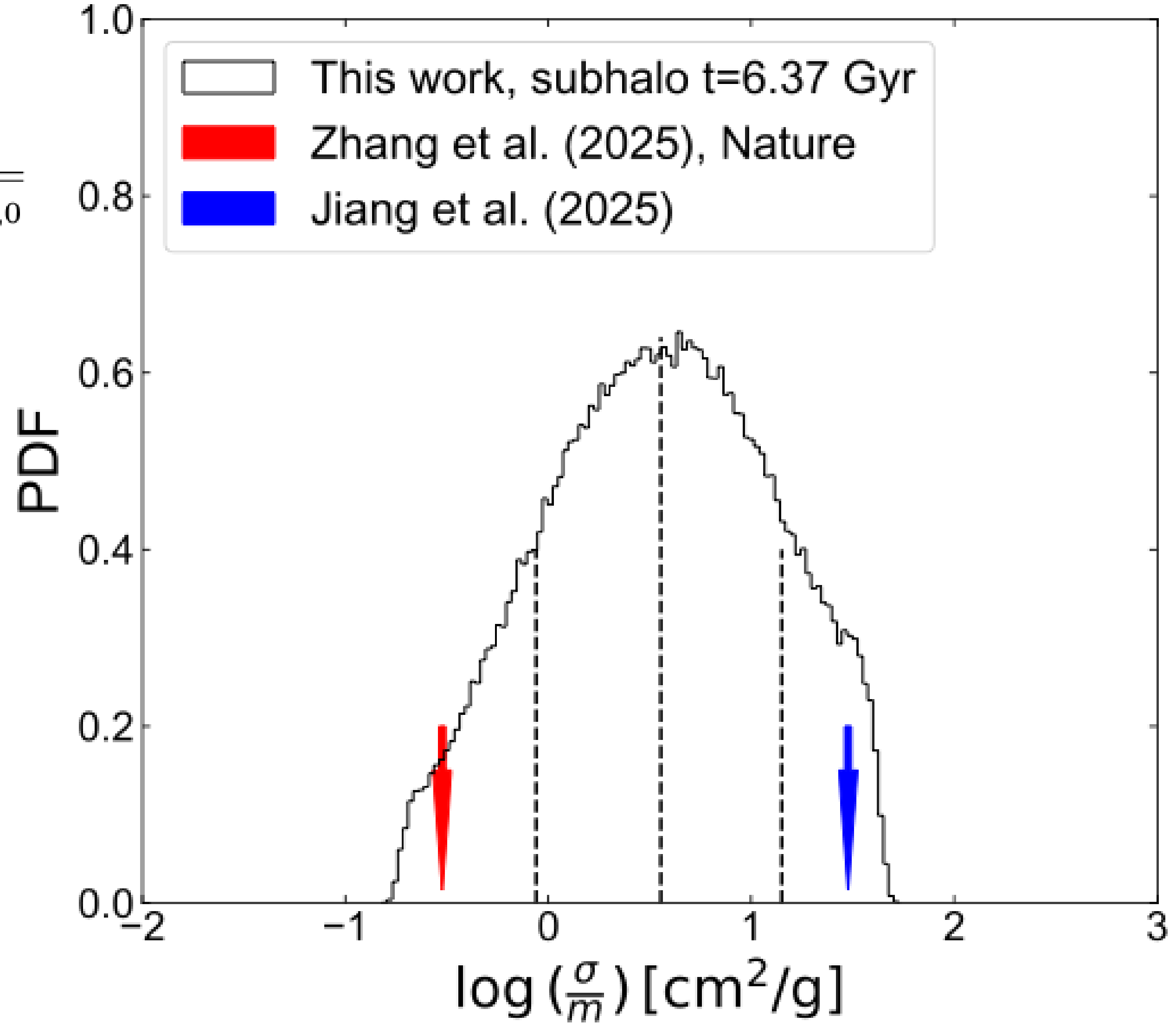
This work

Jiang: arxiv:2503.23710
Zhang: arxiv:2504.03305

SIDM: cross-section



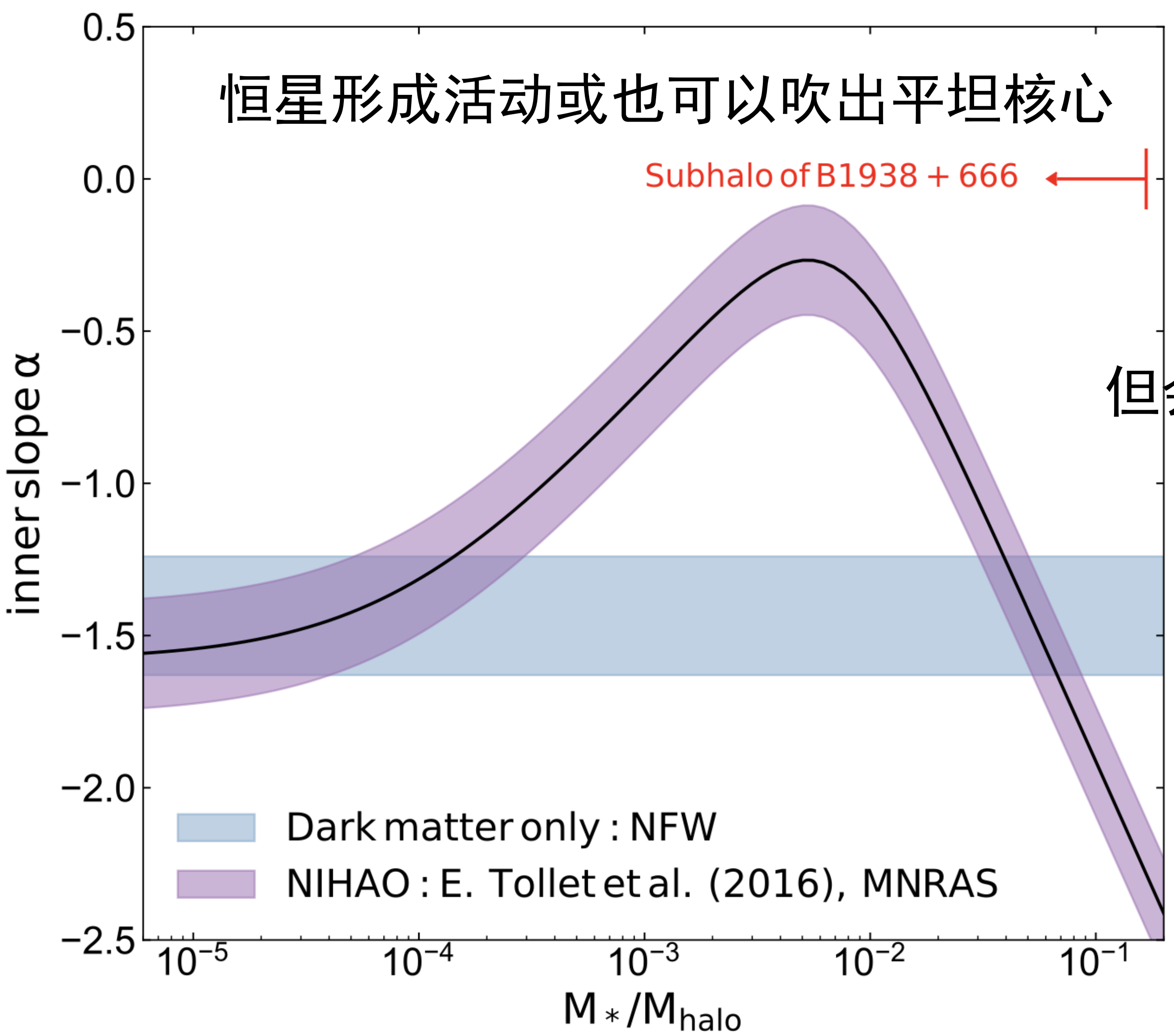
$$t_c = \frac{150}{C} \frac{1}{(\sigma_{eff}/m)\, \rho_{s,0}\, r_{s,0}} \frac{1}{\sqrt{4\pi G \rho_{s,0}}}$$



Jiang: arxiv:2503.23710

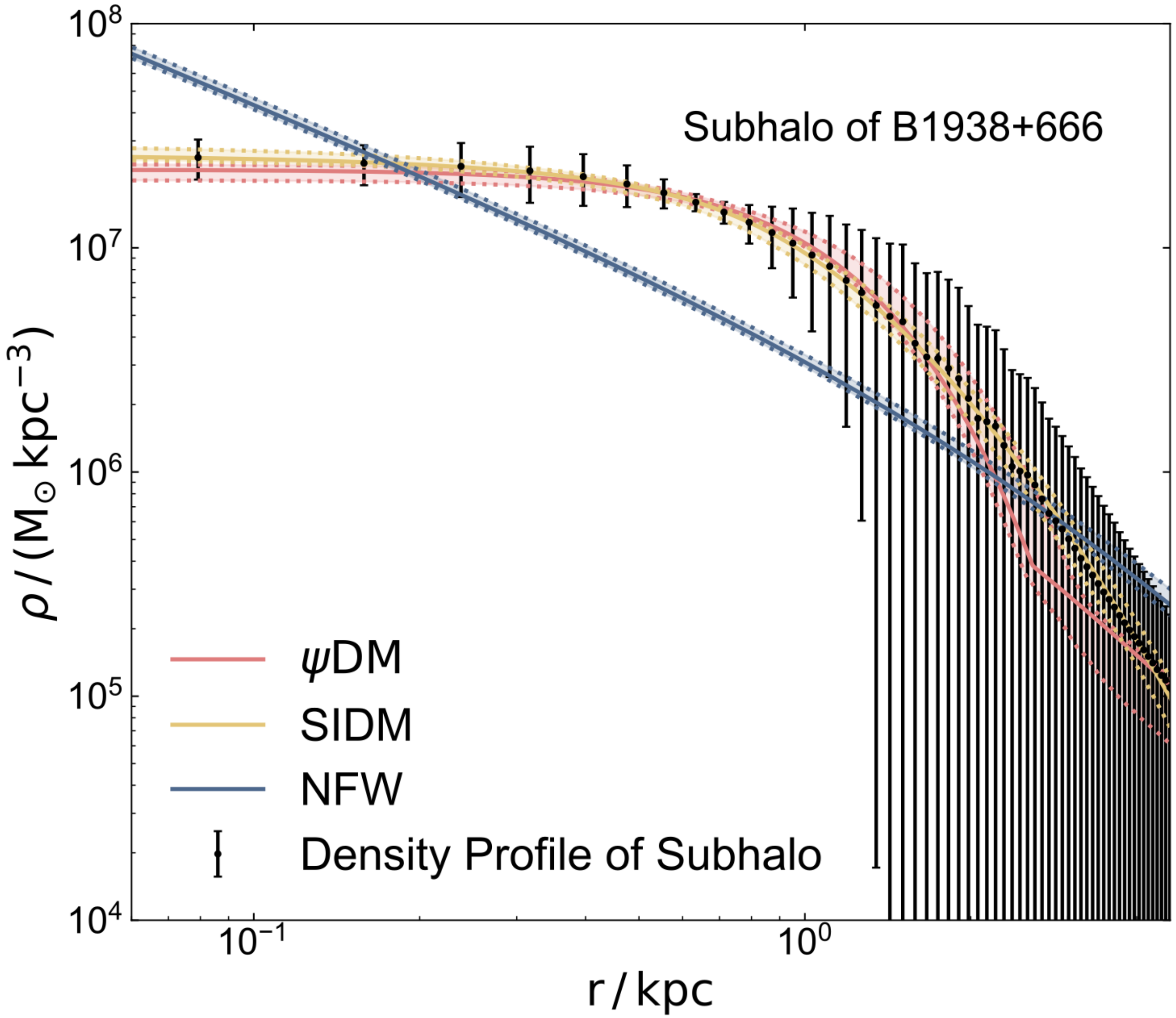
Zhang: arxiv:2504.03305

DM core: stellar feedback?



但会留下强烈反馈的证据?

暗物质子晕的密度轮廓



将随文发布密度轮廓数据

Radius (kpc)	$\rho/10^6$ $(\mathrm{M_\odot/kpc^3})$	$\sigma_\rho/10^6$ $(\mathrm{M_\odot/kpc^3})$	$M(<r)/10^8$ $(\mathrm{M_\odot})$	$\sigma_{M(<r)}/10^8$ $(\mathrm{M_\odot})$
0.079	25.285	5.123	0.001	0.0001
0.158	23.843	4.831	0.004	0.001
0.238	23.098	6.244	0.013	0.004
0.317	22.061	6.187	0.031	0.009
0.396	20.776	5.392	0.058	0.015
0.475	19.257	4.064	0.096	0.02
0.555	17.595	2.607	0.144	0.021

总结 & 展望

Conclusion

1 非参数化测量了暗物质子晕的密度

2 首次在高红移观测到对应近邻宇宙矮星系的core

3 有望未来大量应用

4 或暗示DM有波动性或自相互作用，或子晕中有很强的恒星反馈

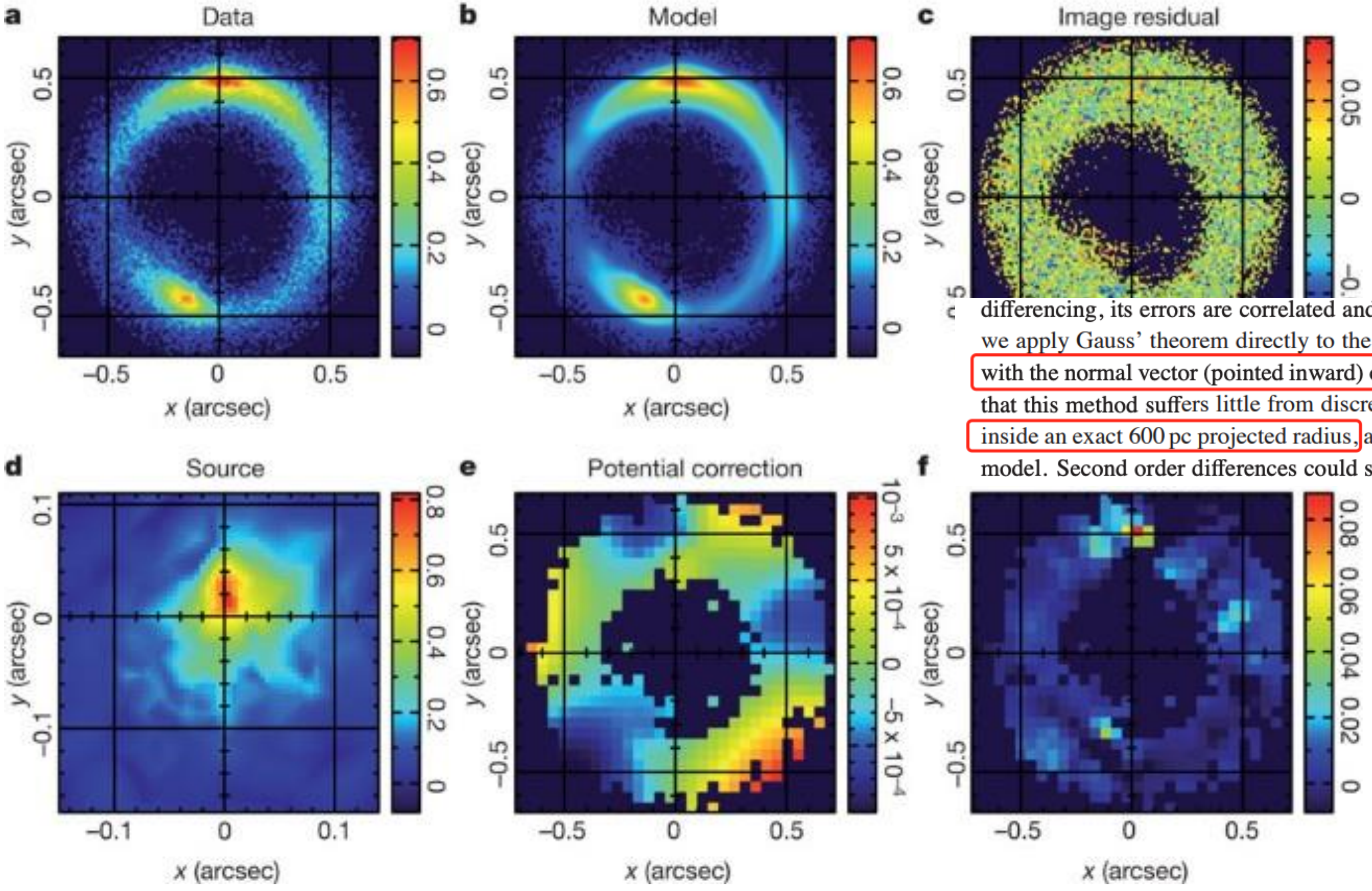
Outlook

1 JWST/Euclid/CSST 期待强引力透镜搜寻子晕大样本
2 对B1938+666的ELT/JWST补充研究的必要性
3 小尺度危机与SIDM、baryonic feedback等

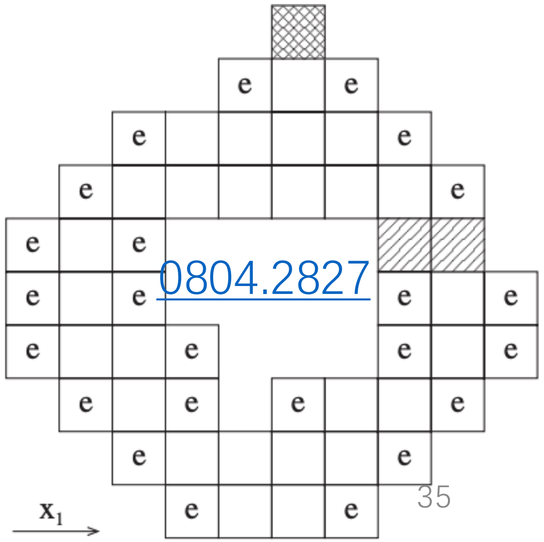
Presenter : Lei Lei[1,2] (雷磊) PhD candidate，leilei@pmo.ac.cn

Data

Subhalo inner mass r<0.6 kpc



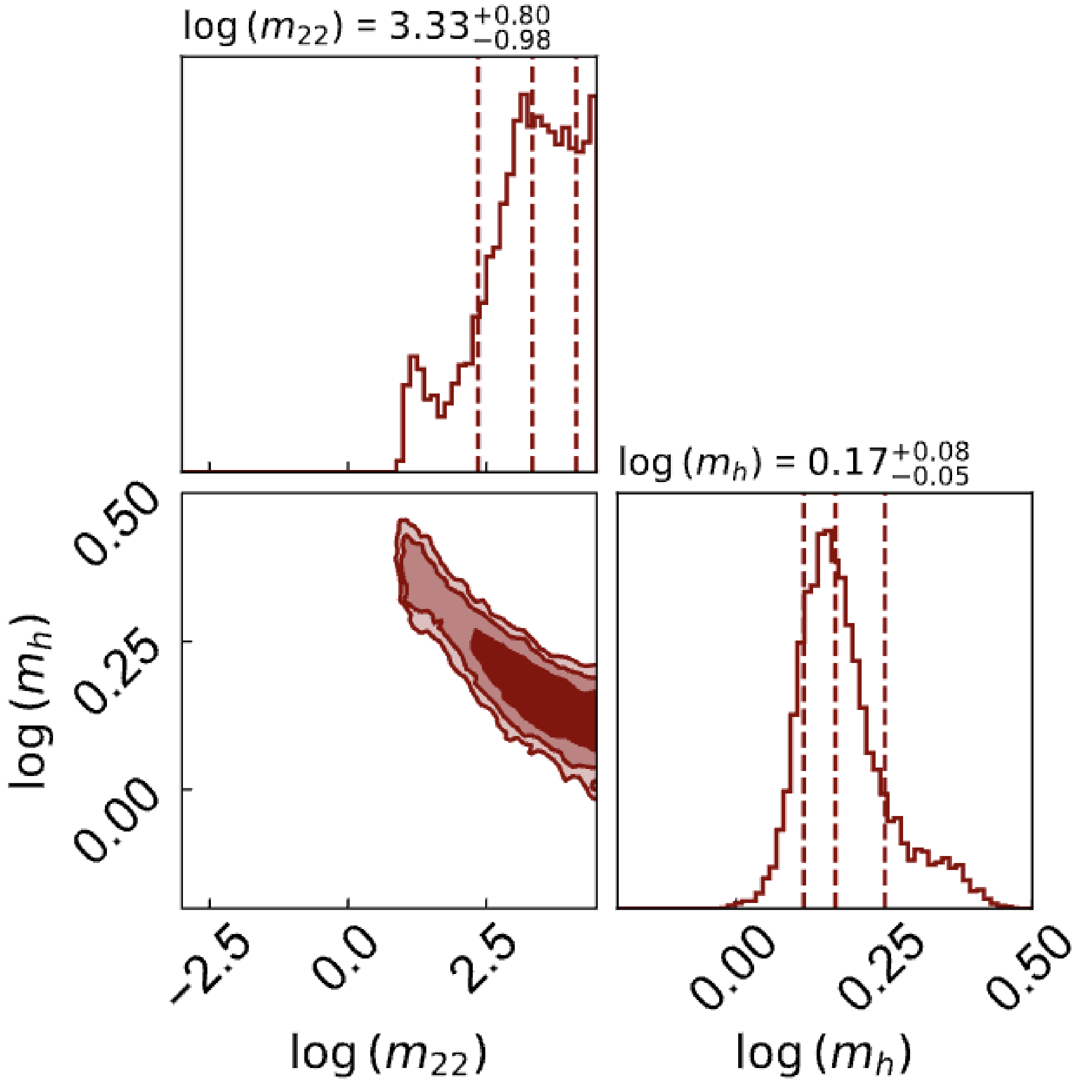
differencing, its errors are correlated and harder to estimate. To reduce the effect of finite differencing, we apply Gauss' theorem directly to the potential correction grid, by integrating the in-product of $\nabla\delta\psi$ with the normal vector (pointed inward) of a circular curve centred on the convergence peak. Tests show that this method suffers little from discretisation of the grid. This way, we find a mass of $1.7 \times 10^8 M_\odot$ inside an exact 600 pc projected radius, again in good agreement with the direct method and the analytic model. Second order differences could still be due to the choice of the substructure density profile, but

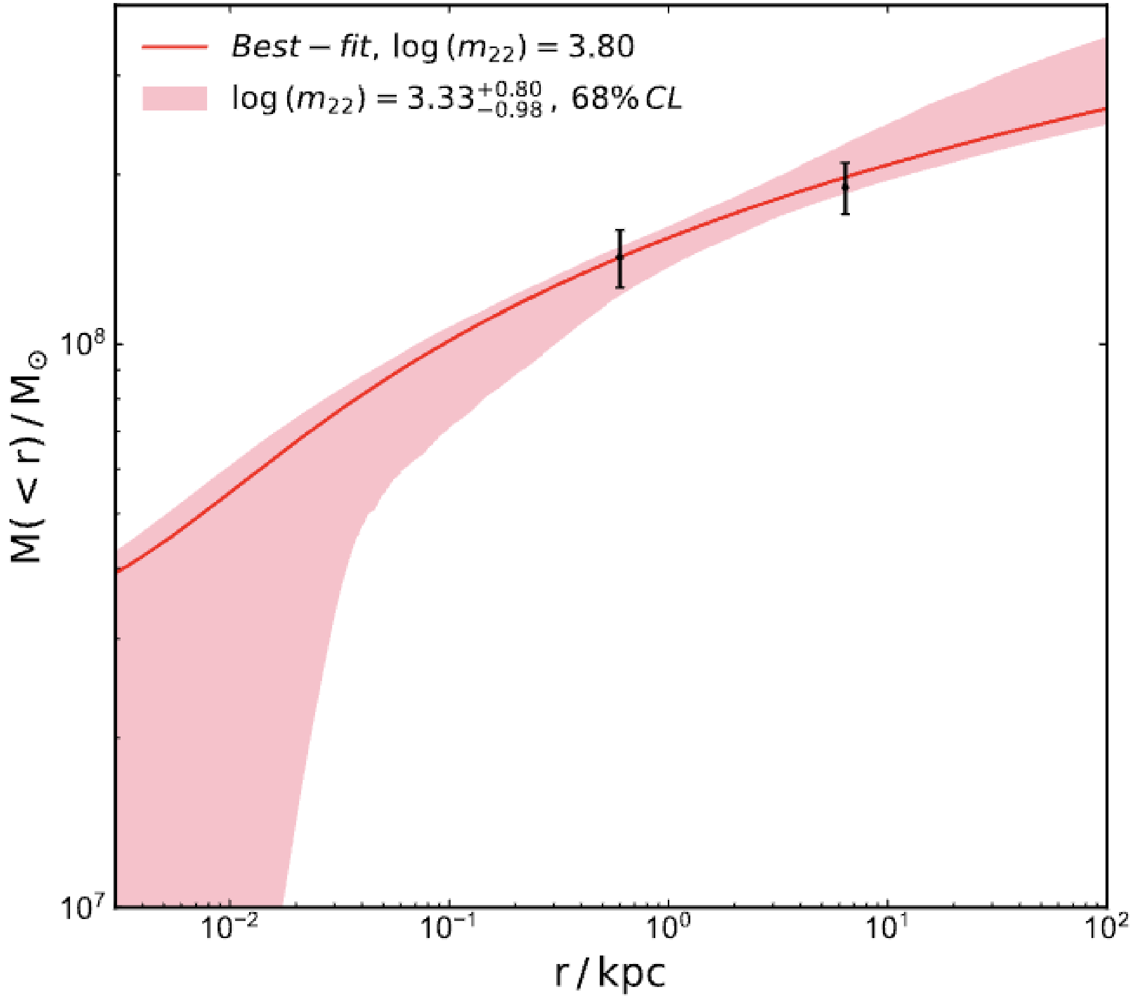


0804.2827

S. Vegetti et al. NATURE Letter, 2012

Analysis & Result



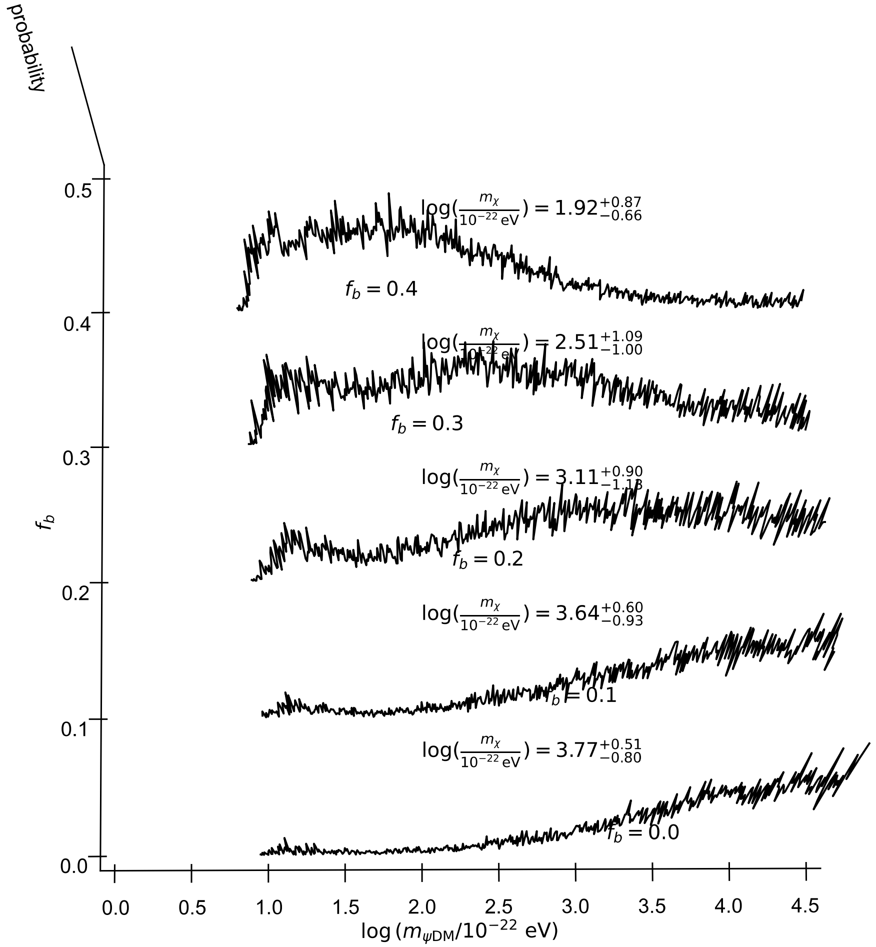


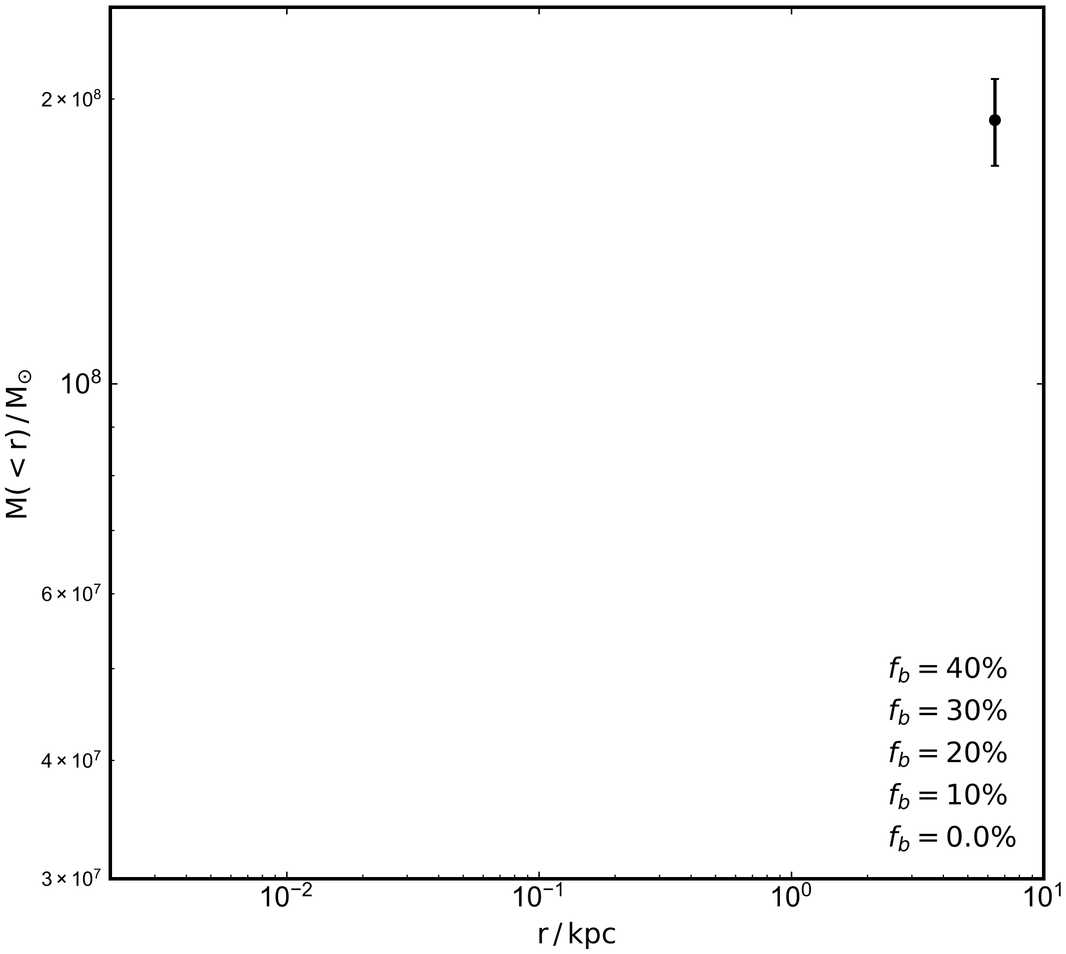
This work

$$m_\psi > 1.5 \times 10^{-21}\,\text{eV at 95\% }(2\sigma)\text{ CL.} \qquad (11)$$

Discussion

Baryon fraction





This work m_FDM > 1E-21 eV, in different baryon fraction conditions