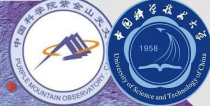


CDM

SIDM2v



Observational Clues to Beyond Collisionless Cold Dark Matter

Presenter: Si-yuan Hou (侯思媛)

arXiv 2502.14964

JCAP 08 (2025) 048

with Daneng Yang (杨大能)(PMO), Nan Li (李楠)(NAO),
Guoliang Li (李国亮)(PMO)

arXiv 2506.14898

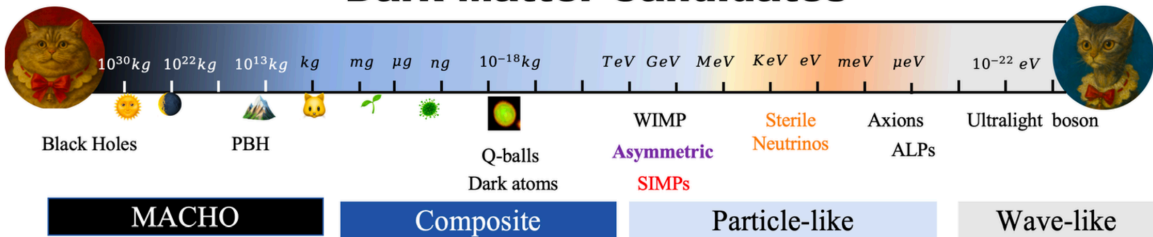
with Daneng Yang (杨大能), Yue-Lin Sming Tsai (蔡岳霖)(PMO), Yi-Zhong Fan (范一中)(PMO)

arXiv:25XX.XXXXX (Preliminary)

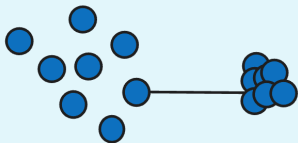
with Shucheng Xiang (项树诚)(PMO), Daneng Yang (杨大能), Nan Li (李楠), Guoliang Li (李国亮), Yiping Shu (舒轶平)(PMO), Yue-Lin Sming Tsai (蔡岳霖), Yi-Zhong Fan (范一中), Zizhao He (何紫朝)(PMO), Jiang Dong (董江)(BNU), Wenwen Zheng (郑雯雯)(PMO)

Dark matter Overview

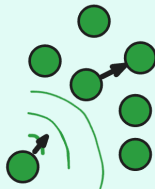
Dark Matter Candidates



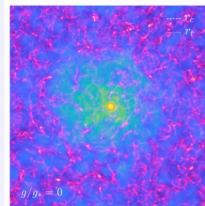
Cold DM



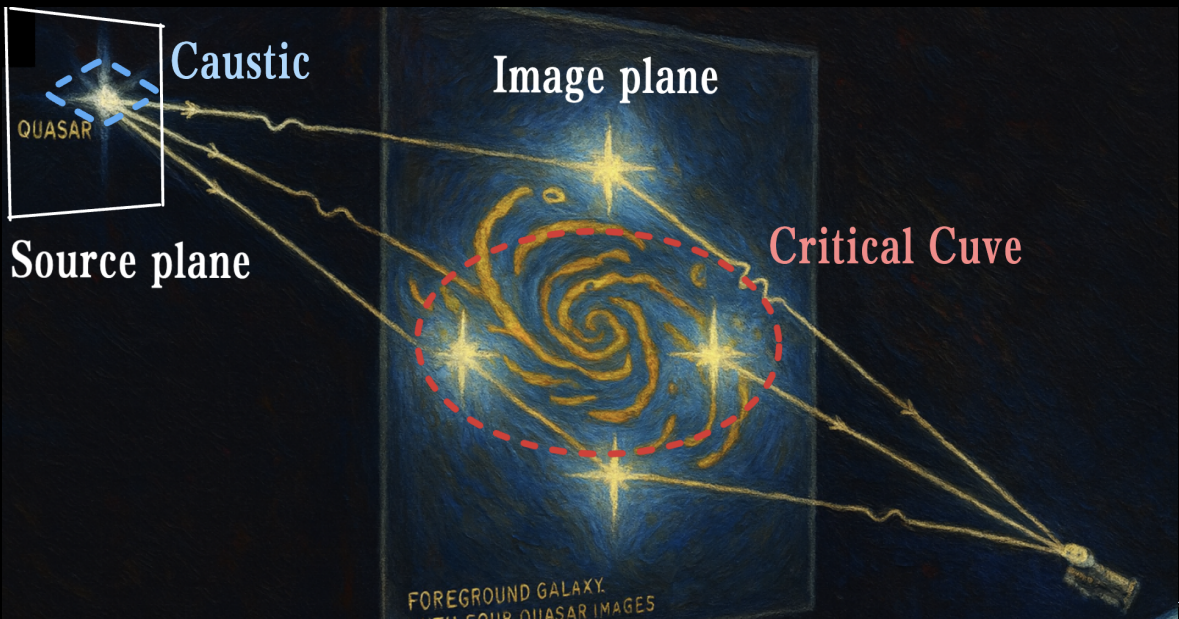
Self-Interacting DM



Fuzzy DM



Strong Gravitational Lensing

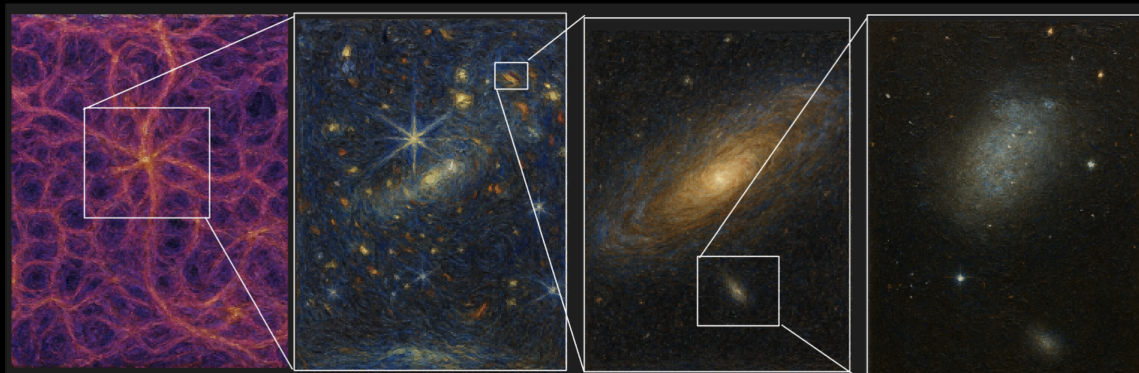


OUTLINE

1. Observational Clues from Small-scale Challenges

- 1 Observational Clues from Small-scale Challenges
- 2 Self-interacting Dark matter
- 3 Two-Component SIDM
- 4 Flux-ratio Anomalies (Preliminary)
- 5 Appendix

From Large-Scale to Small-Scale



Cosmic Web

Cluster Scale

Galactic Scale

Sub-galactic Scale

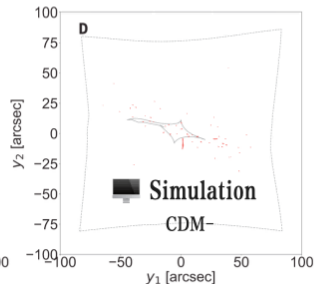
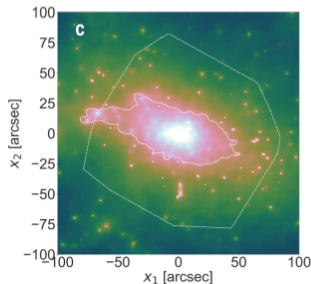
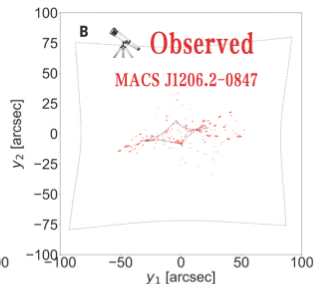
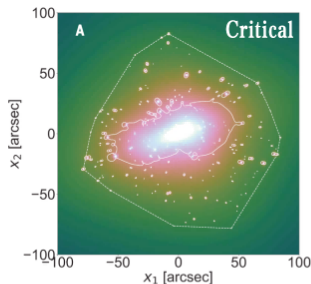
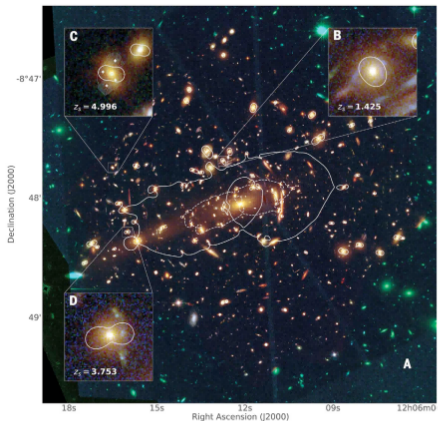


Cold Dark Matter Work → Small Scale Challenges



GGSL Probability Anomalies

MACS J1206.2-0847 ($z = 0.439$)



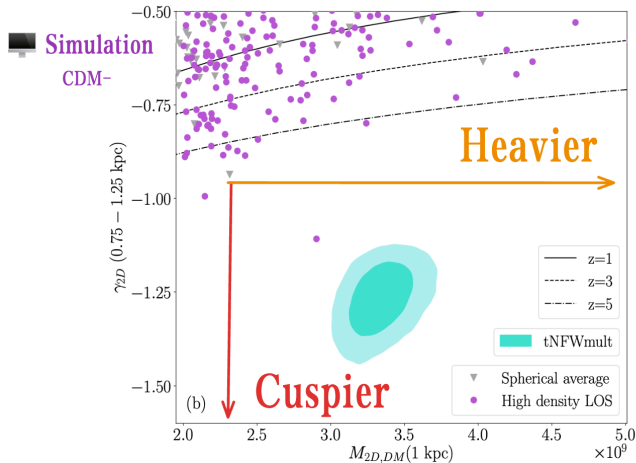
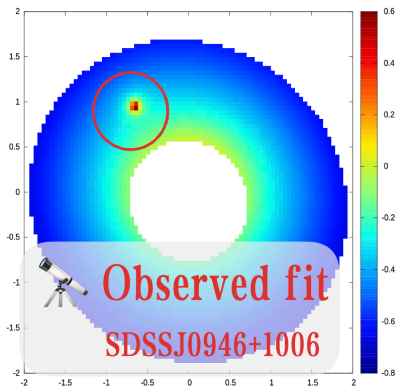
☹️ CDM Galaxy-Galaxy Strong Lensing (GGSL) probability is too small



Meneghetti+ (Science 2020, 2022)

arXiv:2009.04471

Unexpected Dense Dark Substructure



Minor+ (2020)

arXiv:2011.10627

Enzi+(2024)

arXiv:2411.08565

Shubo Li+ (2025)

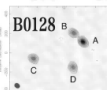
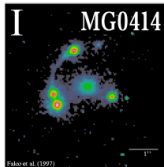
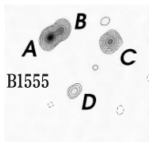
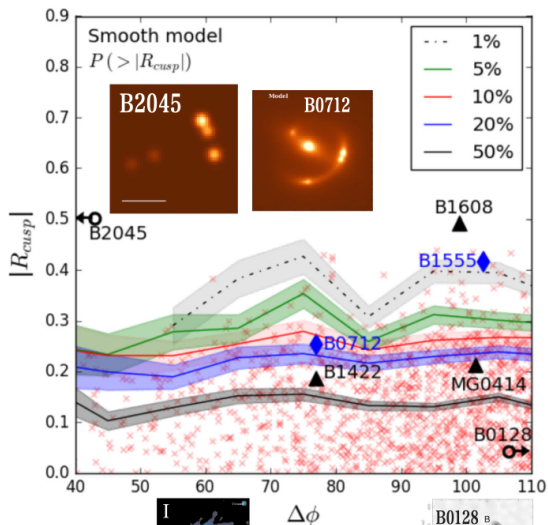
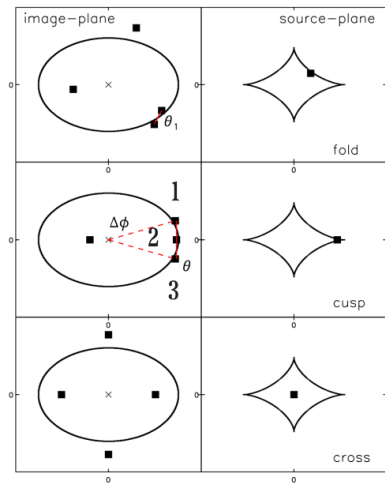
arXiv:2504.11800

...

☹️ The lensing perturber shows unexpectedly **high central density**

Flux-ratio Anomalies

$$R_{\text{cusp}} = \frac{\mu_1 + \mu_2 + \mu_3}{|\mu_1| + |\mu_2| + |\mu_3|}$$



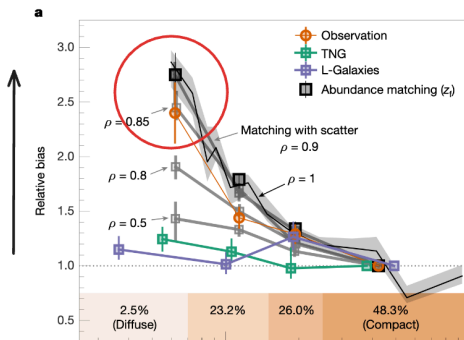
Dandan Xu+ (2015, 2018)

arXiv:1410.3282

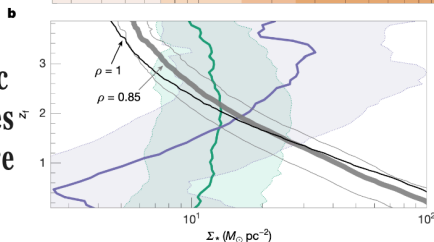
arXiv:1707.07680

A new challenge from the clustering of dwarf galaxies

Stronger
Spatial
Clustering



Hydro baryonic
simulation gives
inverted feature



nature

Explore content ▾ About the journal ▾ Publish with us ▾ Subscribe

[nature](#) > [articles](#) > article

Article | Published: 21 May 2025

Unexpected clustering pattern in dwarf galaxies challenges formation models

Ziwen Zhang, Yangyao Chen, Yu Rong, Huiyuan Wang , Houjun Mo, Xiong Luo & Hao Li

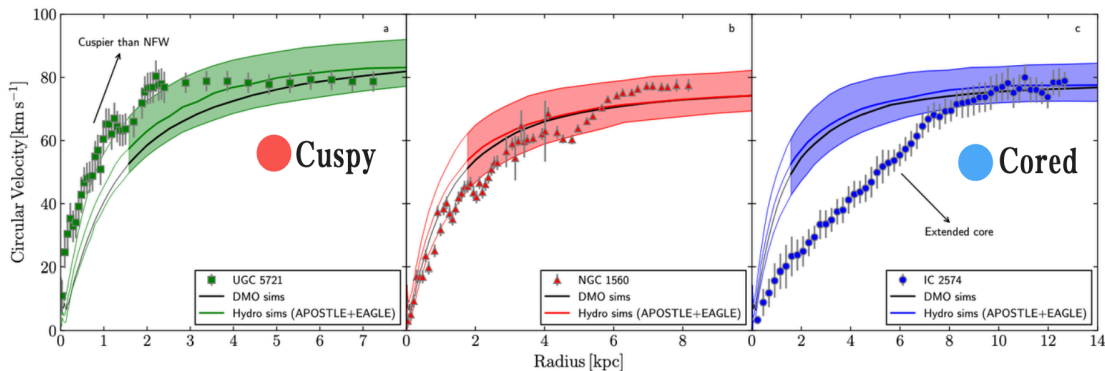
[Nature](#) 642, 47–52 (2025) | [Cite this article](#)

1274 Accesses | 84 Altmetric | [Metrics](#)

 Self-Interacting Dark Matter (SIDM), can explain the observation

$$\sigma = 0.3 \text{cm}^2/g$$

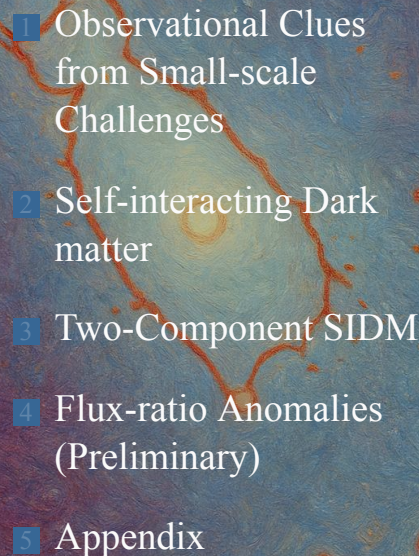
Observed Diversity of Local Volume Dwarf Galaxy Rotation Curves



CDM fails to reproduce the observed diversity of rotation curves.

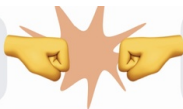
[Oman+\(MNRAS\) \(2015\)](#) [arXiv:1504.01437](#)

2. Self-interacting Dark matter

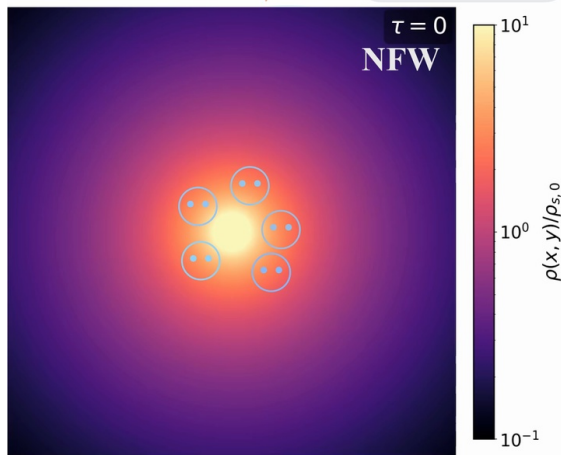
- 
- 1 Observational Clues from Small-scale Challenges
 - 2 Self-interacting Dark matter
 - 3 Two-Component SIDM
 - 4 Flux-ratio Anomalies (Preliminary)
 - 5 Appendix

SIDM halos: Gravothermal Evolution

Free path
 $\lambda = 1/(n\sigma)$



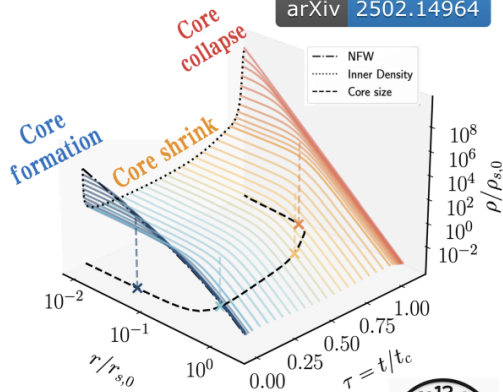
Scale height
 $H = \sqrt{v^2/4\pi G\rho}$



Essig+ (PRL, 2019) arXiv:1809.01144
Outmezguine+ (2022) arXiv:2204.06568

Yang+ (2023) arXiv:2305.16176
Zhong+ (2023) arXiv:2306.08028

arXiv 2502.14964

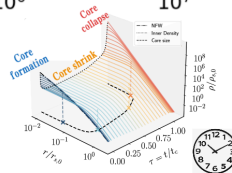
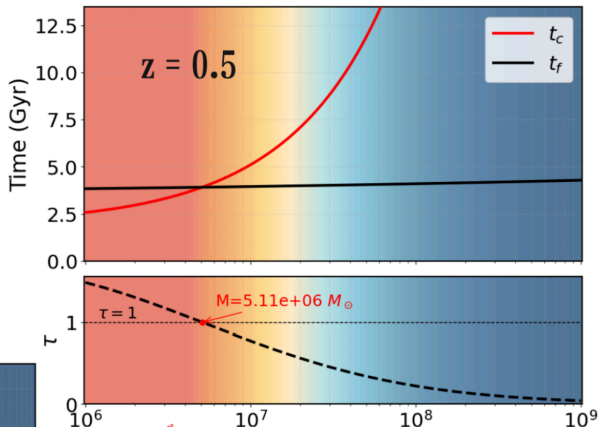
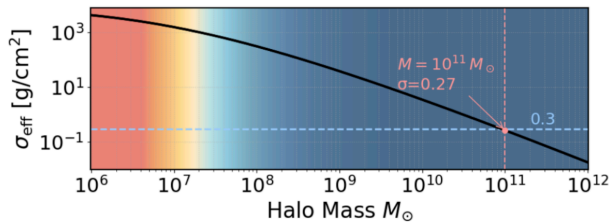
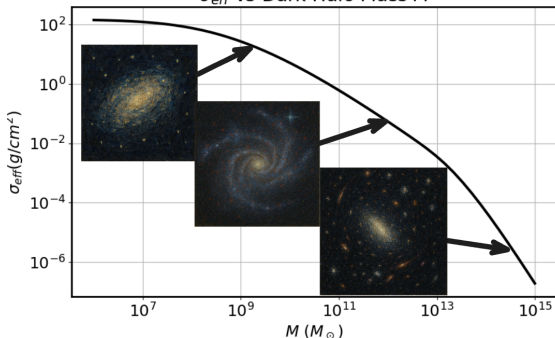


$$t_c \sim 1/(\sigma v n)$$



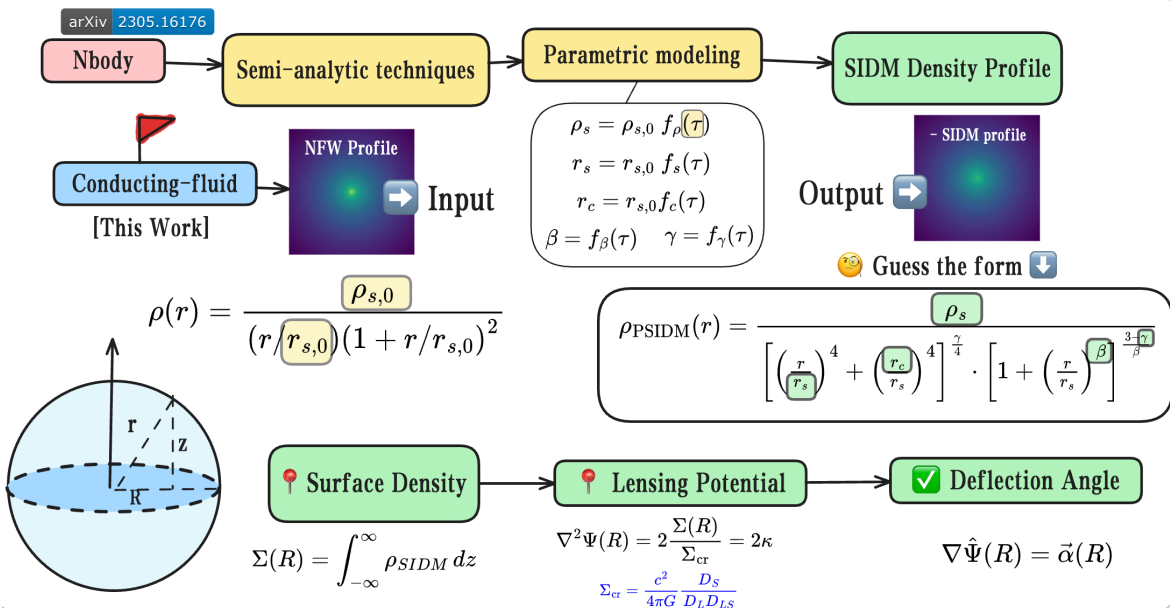
Velocity-dependent Cross Section

Cross section σ_{eff} vs Dark Halo Mass M



$$t_c \sim 1/(\sigma v n)$$

Efficiency parametric SIDM Model



A Parametric Model for SIDM Lensing

$$\Psi(R) = \frac{2}{\Sigma_{\text{cr}}} \int_0^R s \Sigma(s) \ln \left(\frac{R}{s} \right) ds$$

$$\hat{\Psi} \equiv \frac{\Psi \Sigma_{\text{cr}}}{\rho_{s,0} r_{s,0}^3}, \quad \hat{\Sigma} \equiv \frac{\Sigma}{\rho_{s,0} r_{s,0}^2}$$

$$\hat{\Psi}(\hat{R}) = 2 \int_0^{\hat{R}} s \hat{\Sigma}(s) \ln \left(\frac{\hat{R}}{s} \right) ds$$



Guess the form



$$\hat{\Psi}(\hat{R}) = a \ln \left(1 + b\hat{R} + c\hat{R}^2 \right)^c - \ln \left(p\hat{R} + 1 \right)^s$$

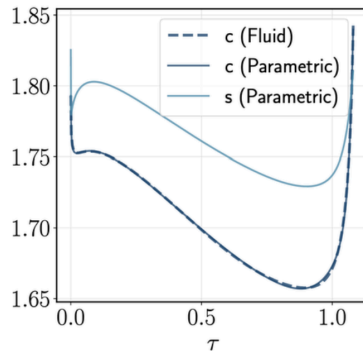
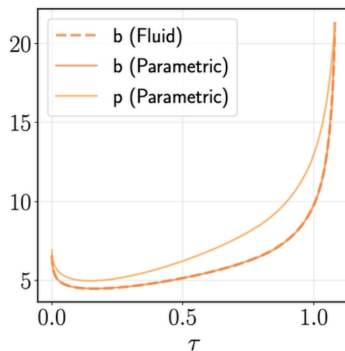
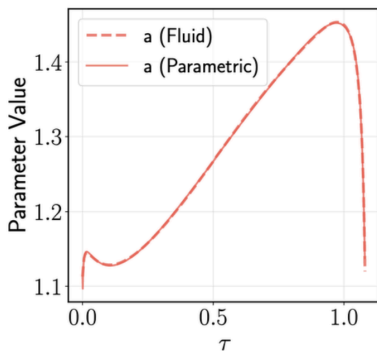


 Figure 3. The lensing model parameters a , b , c , p , and s as functions of τ

Accruacy of the Model

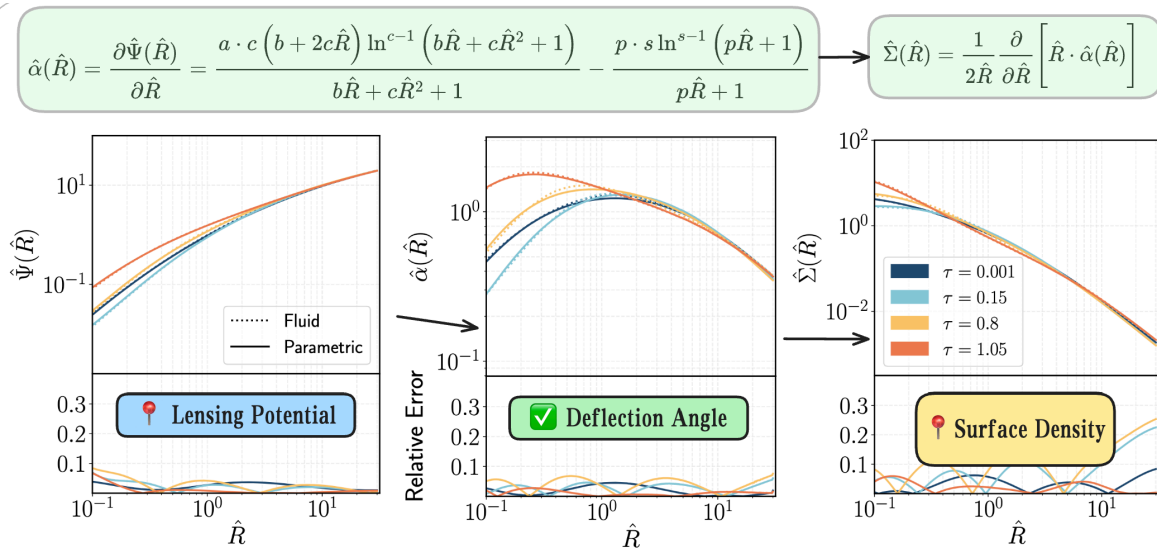
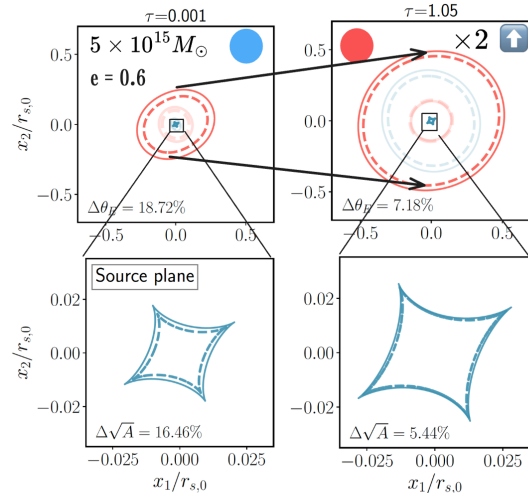


Figure 4. Comparison of simulated (dotted) and model-predicted (solid).

SIDM Strong-Lensing – Isolated Halo



arXiv 2502.14964

Tangential Caustics

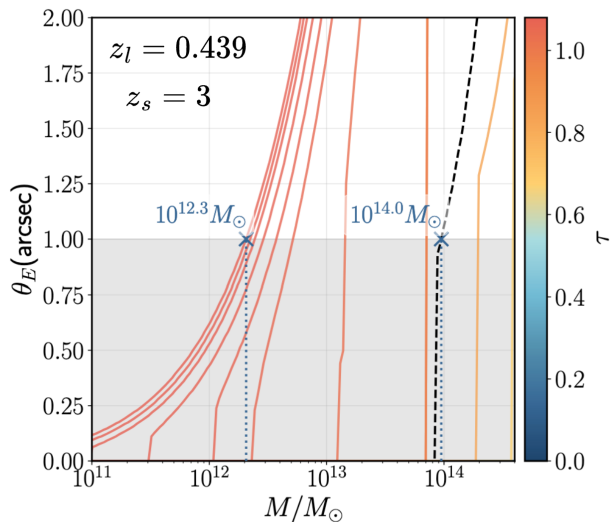
Radial Caustics

Tangential Critical

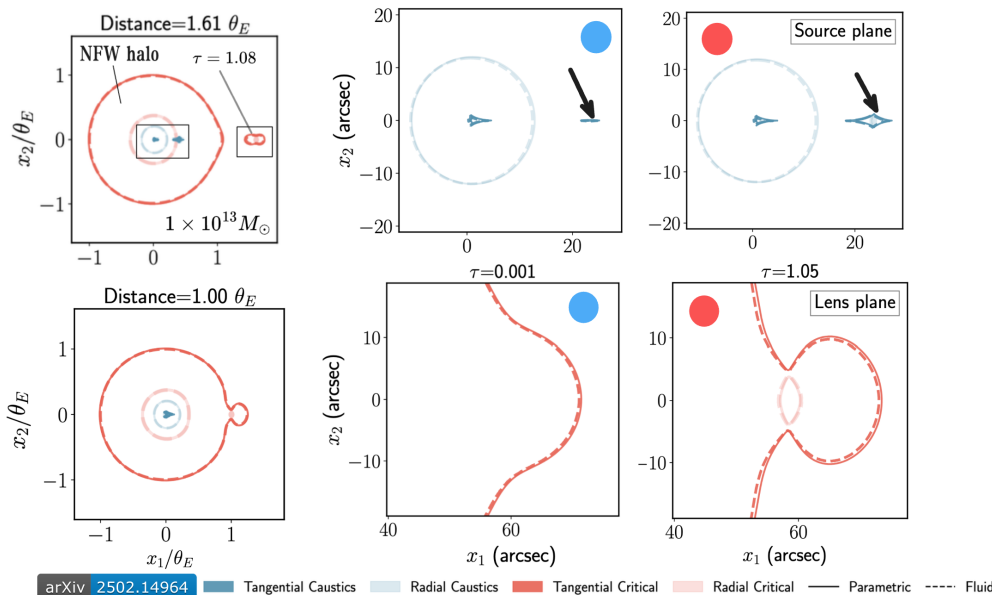
Radial Critical

Parametric

Fluid



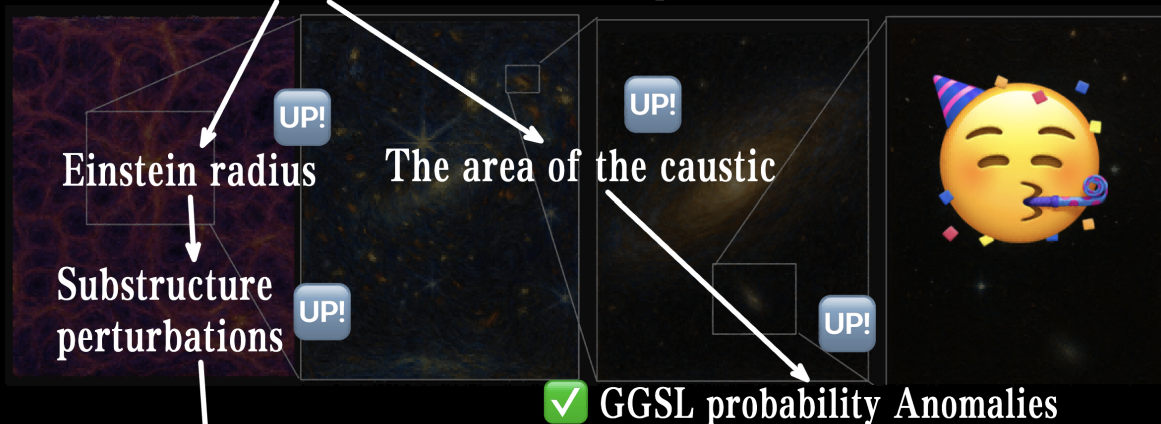
SIDM Strong-Lensing – Host halo + Subhalo



arXiv 2502.14964

SIDM core collapse

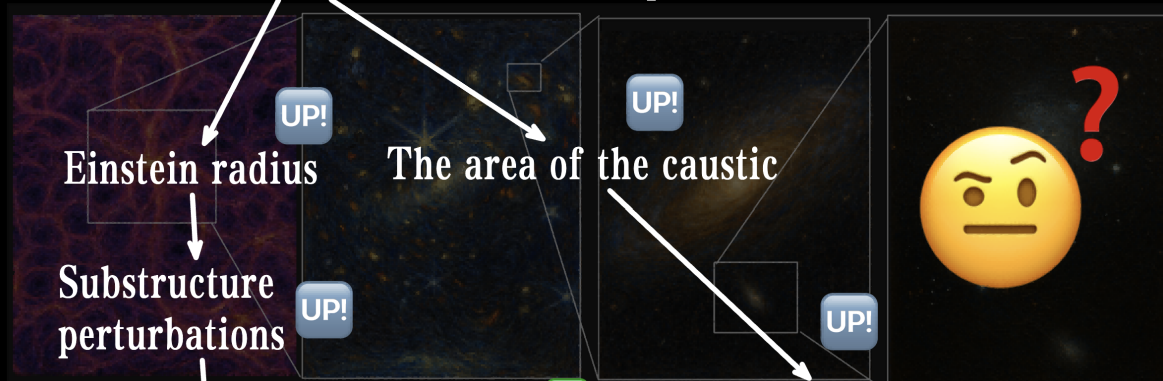
denser halos → ✓ Unexpected Dense Dark Substructure



✓ Flux-ratio Anomalies

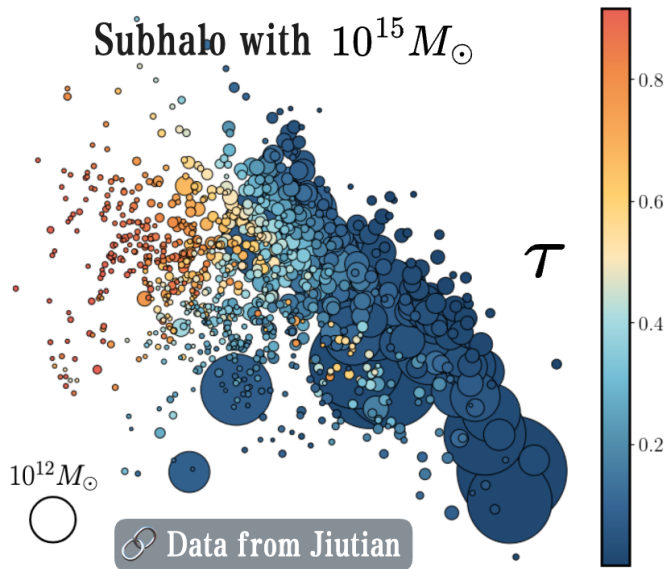
SIDM core collapse

denser halos → ✓ Unexpected Dense Dark Substructure

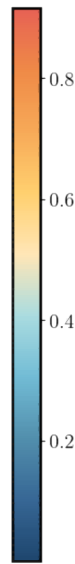
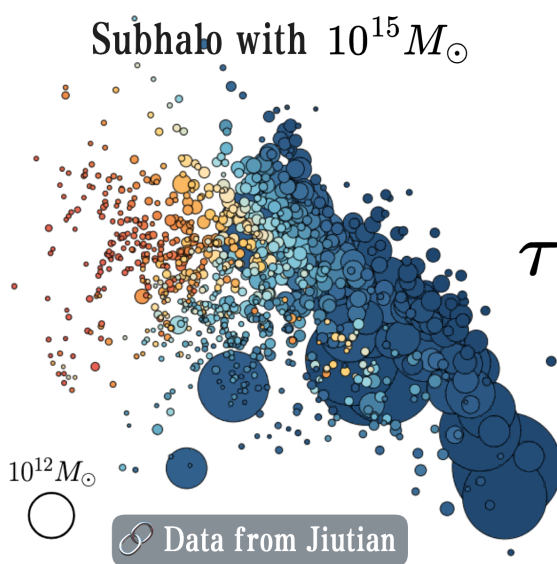


✓ Flux-ratio Anomalies

Galaxies in Clusters Undergoing Core Formation



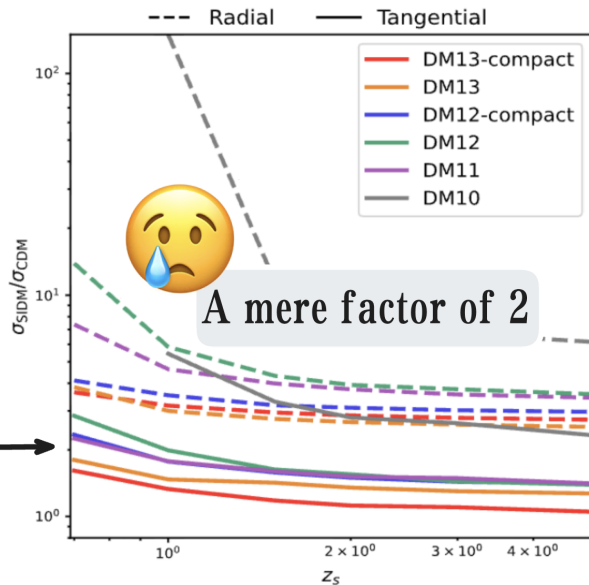
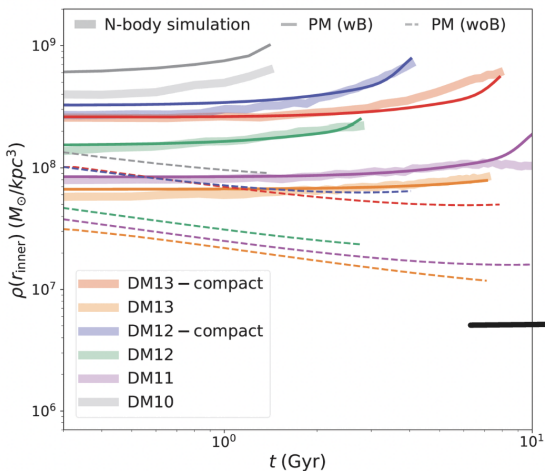
Galaxies in Clusters Undergoing Core Formation



Limited Impact of Baryons on GGSL Probability in SIDM Models

Meiwen Yang + arXiv:25XX.XXXXX

Preliminary



3. Two-Component SIDM

- 
- 1 Observational Clues from Small-scale Challenges
 - 2 Self-interacting Dark matter
 - 3 Two-Component SIDM
 - 4 Flux-ratio Anomalies (Preliminary)
 - 5 Appendix

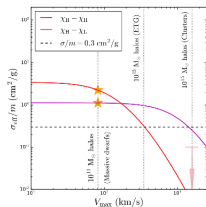
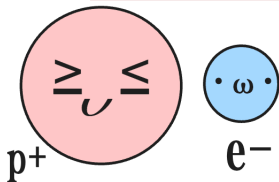
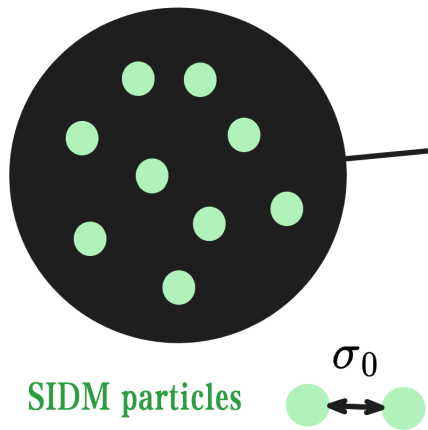
Two-Component SIDM

Asymmetric Dark Matter

review: [arXiv:1305.4939](https://arxiv.org/abs/1305.4939)

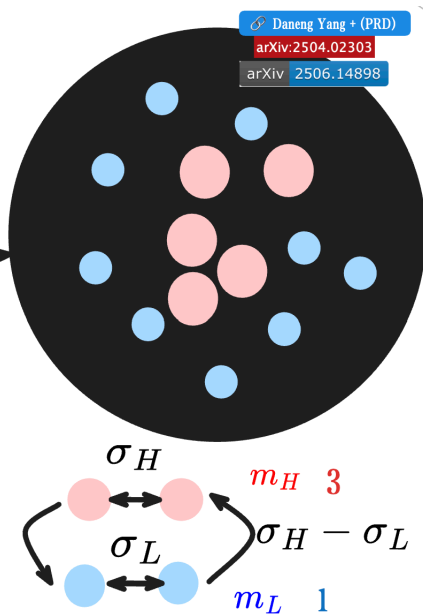
Baryogenesis

Darkogenesis



SIDM particles 1

SIDM particles 2

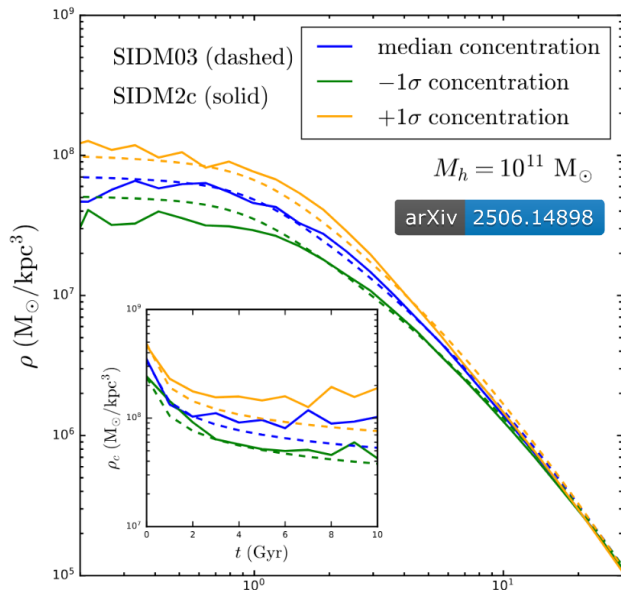


[Daneng Yang + \(PRD\)](#)

[arXiv:2504.02303](#)

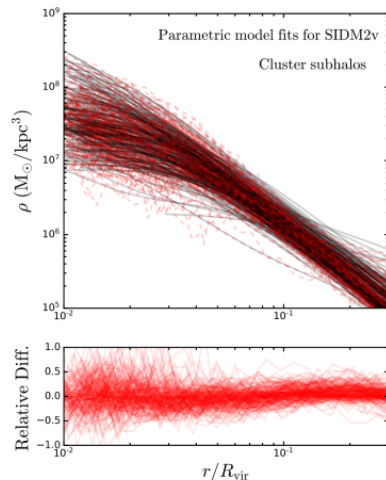
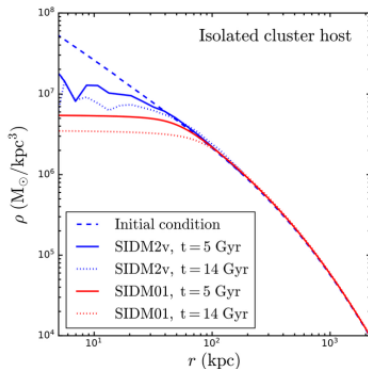
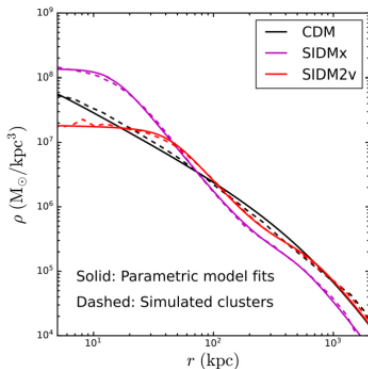
[arXiv:2506.14898](#)

Halos with Mass Segregation



PSIDM Fits Two-Component SIDM for Fast Lensing

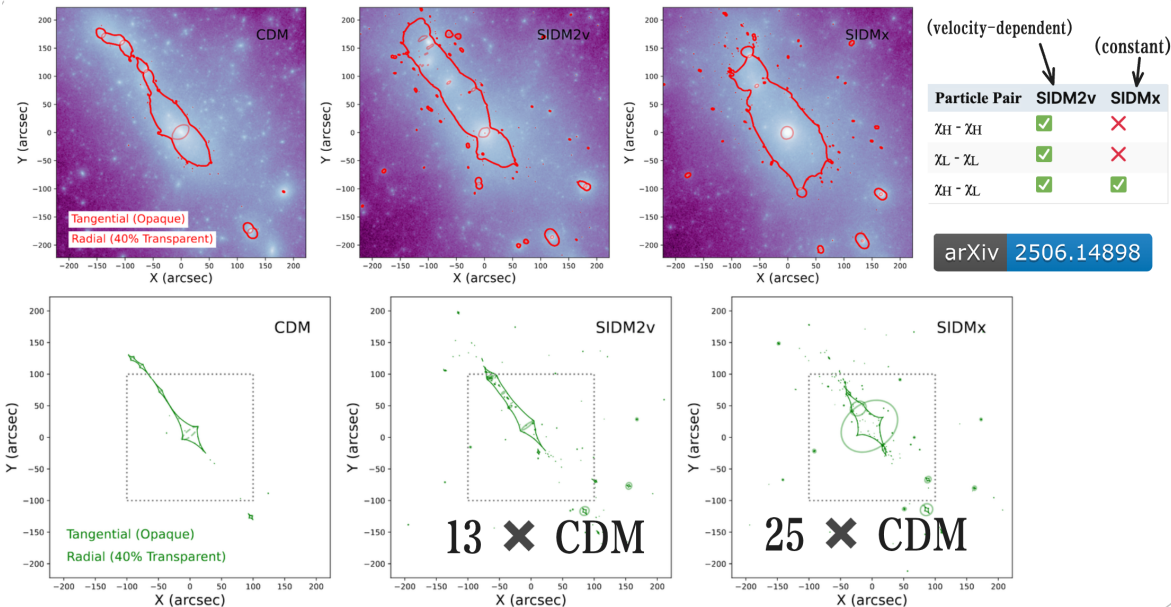
arXiv 2506.14898



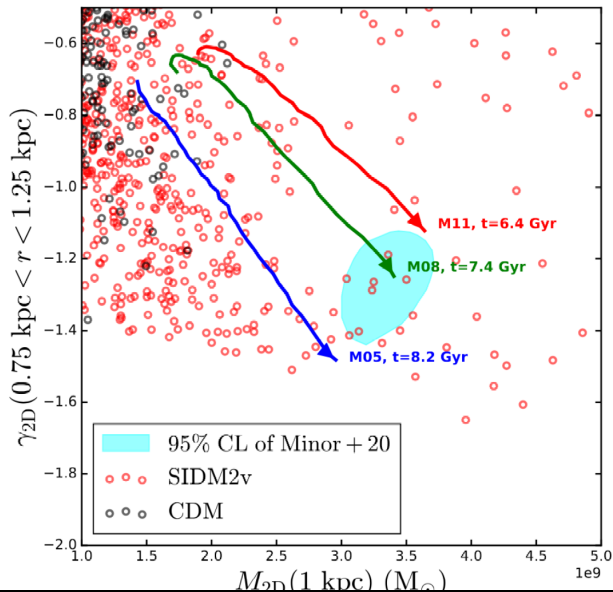
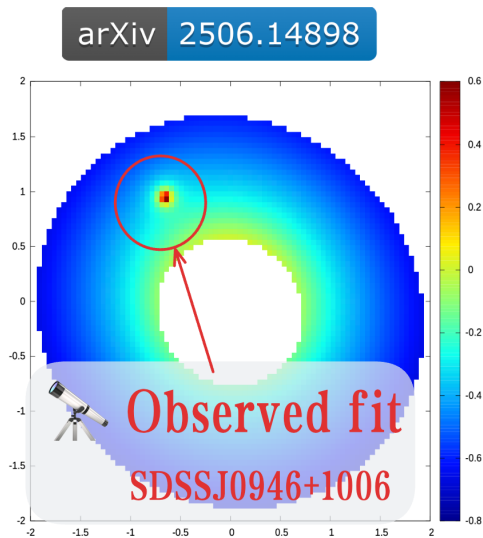
✓ Accurate fits across CDM, SIDMx, and SIDM2v halos.

✓ Robust results for a large population of cluster subhalos

Enhanced GGSL Probability!



High-Concentration Subhalos Naturally Arise!



Traditional

✓ Core-Cusp Problem

✓ Too-Big-to-Fail Problem

✓ Missing Satellites

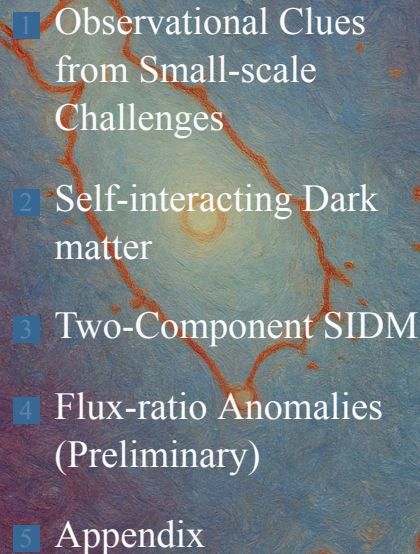
arXiv 2502.14964

arXiv 2506.14898

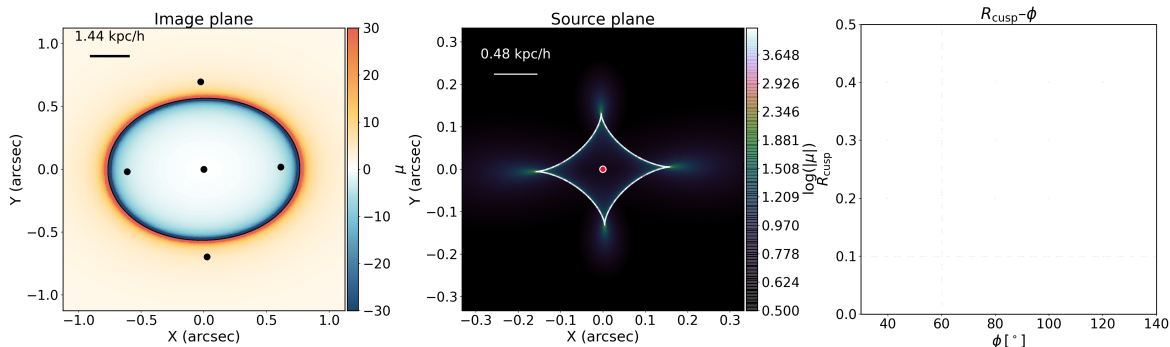
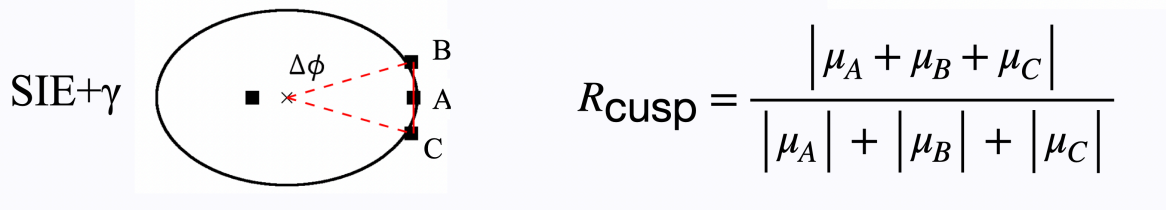


New	Λ CDM	1C-SIDM	2C-SIDM
Galaxy-Galaxy Strong Lensing	✗	✗	✓
Strong-Lensing Perturbers	✗	✓ (partial)	✓
Lensed Quasar Flux-Ratio Anomalies	✗	✗	🤔 📌 Todo
Dwarf Galaxy Clustering	✗	✓	✓
Rotation Curve Diversity	✗	✓	✓

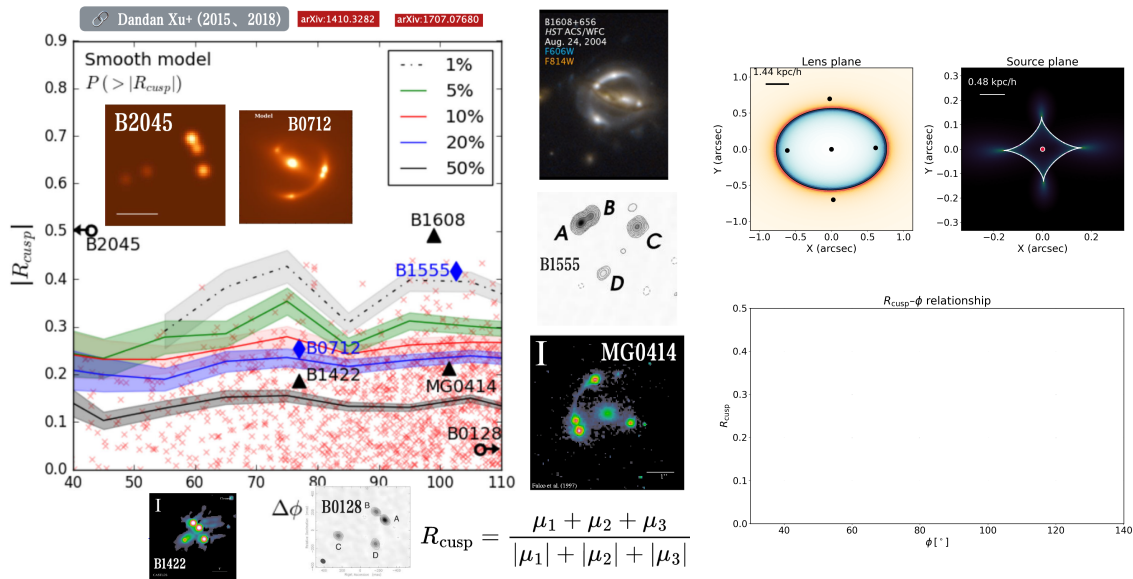
4. Flux-ratio Anomalies (Preliminary)

- 
- The background of the slide is a deep blue, textured image resembling a galaxy cluster or a cosmic web. A prominent, irregular, reddish-brown filamentary structure winds across the frame, starting from the top left, looping around a central bright yellowish-white region, and extending towards the bottom right. The texture is painterly, with visible brushstrokes or pixelated patterns. The text is overlaid on this background, with each item in the list preceded by a small blue square containing a white number.
- 1 Observational Clues from Small-scale Challenges
 - 2 Self-interacting Dark matter
 - 3 Two-Component SIDM
 - 4 Flux-ratio Anomalies (Preliminary)
 - 5 Appendix

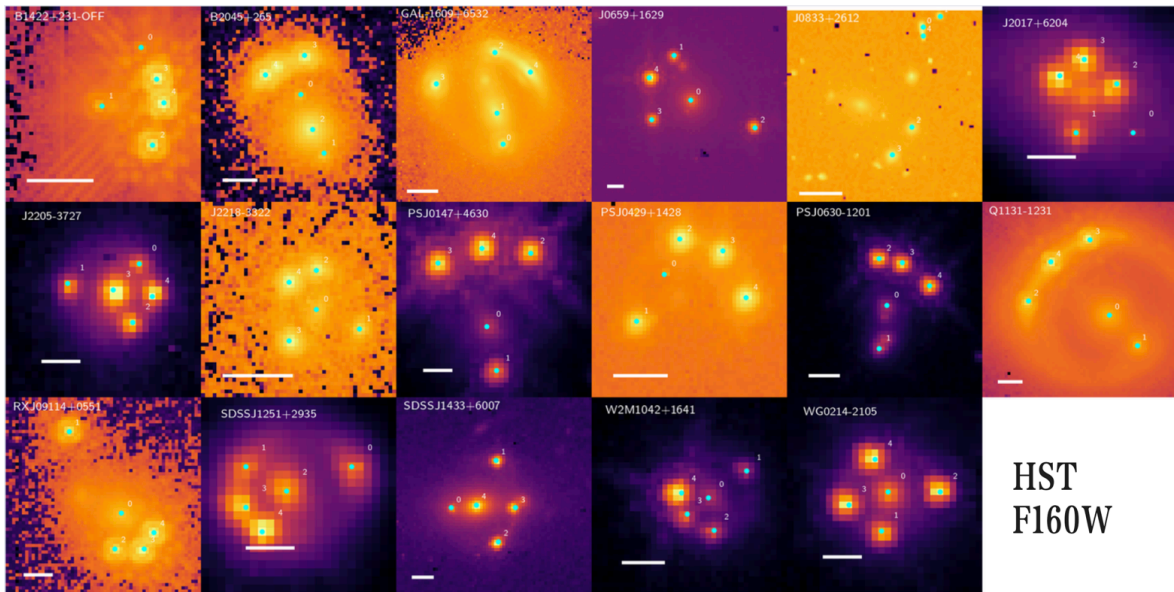
Rcusp-phi Relationship



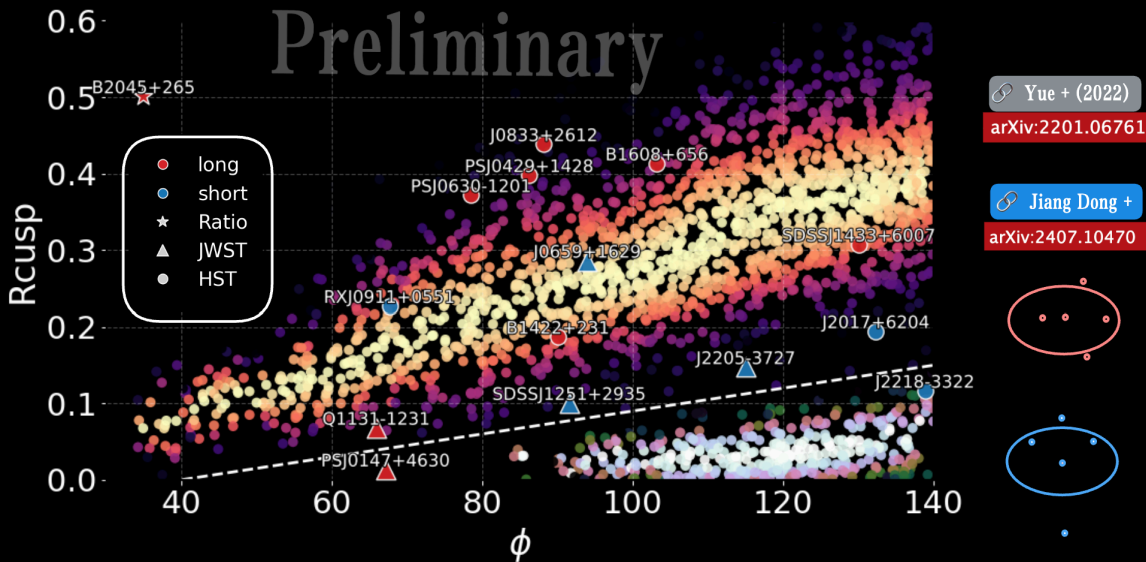
Flux-ratio Anomalies



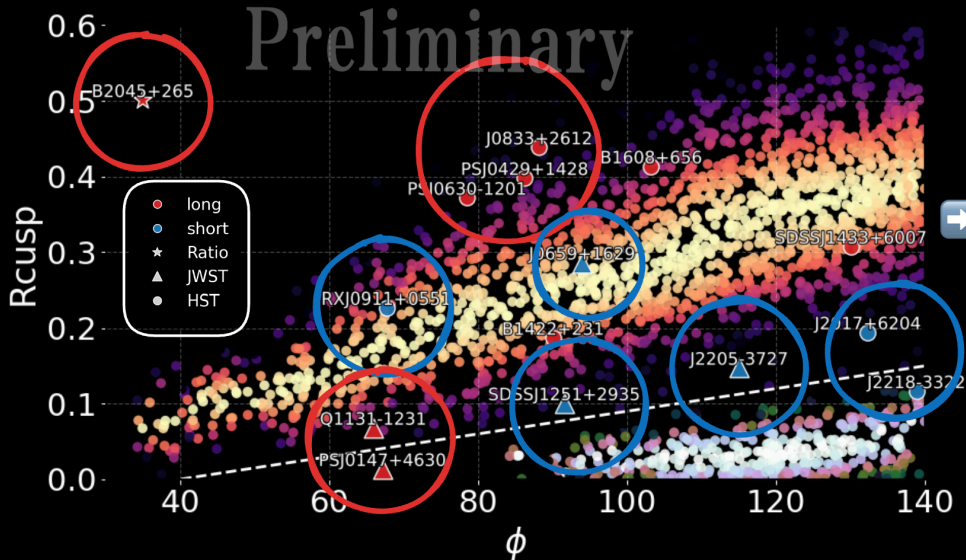
All Known Cusp System Images



Rcusp- ϕ Relationship: Observations vs. SIE Mock



Rcusp- ϕ Relationship: Observations vs. SIE Mock



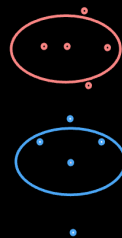
Yue + (2022)

arXiv:2201.06761

Jiang Dong +

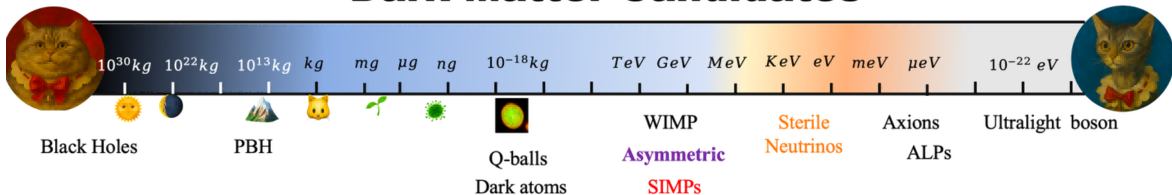
arXiv:2407.10470

➔ **Adding
Substructure!**



Flux-Ratio Anomalies Explained by Fuzzy Dark Matter (FDM)

Dark Matter Candidates

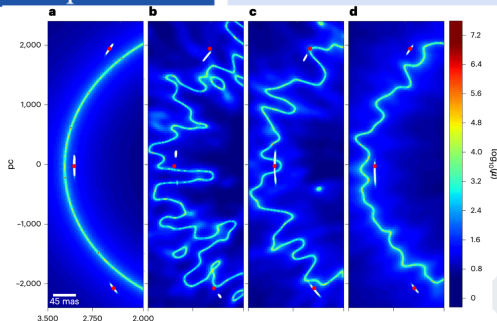
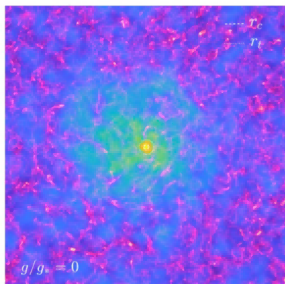


MACHO

Composite

Particle-like

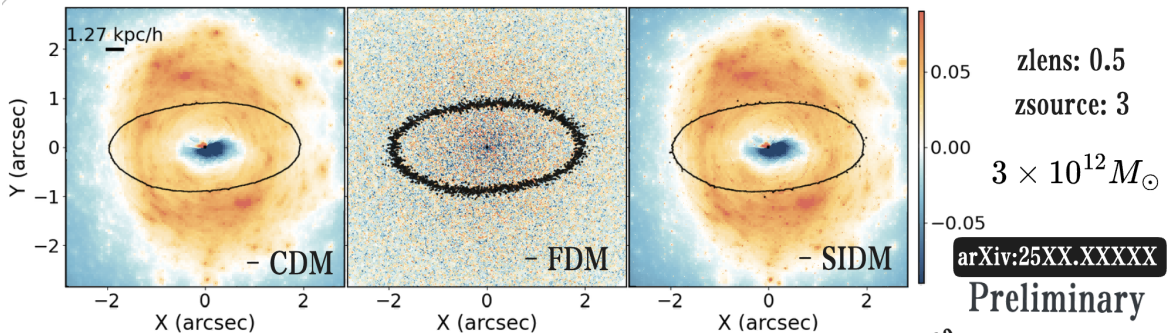
Wave-like



arXiv:2304.09895

Jeremy+ (Nature Astronomy)

Substructure Implementation Method



$$\kappa_{\text{sub}}(\text{eff}) = \kappa_{\text{eff}} - \kappa_{\text{macro}} - \langle \kappa_{\text{sub}} \rangle$$

30,000 halos

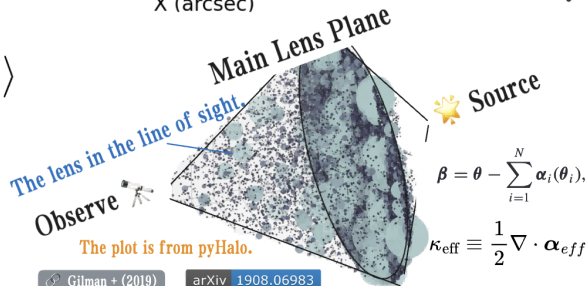
+ high-resolution ray tracing

Numerical: 🐌 1 week

This work: 🚀 10 min

Nan Li + (2020)

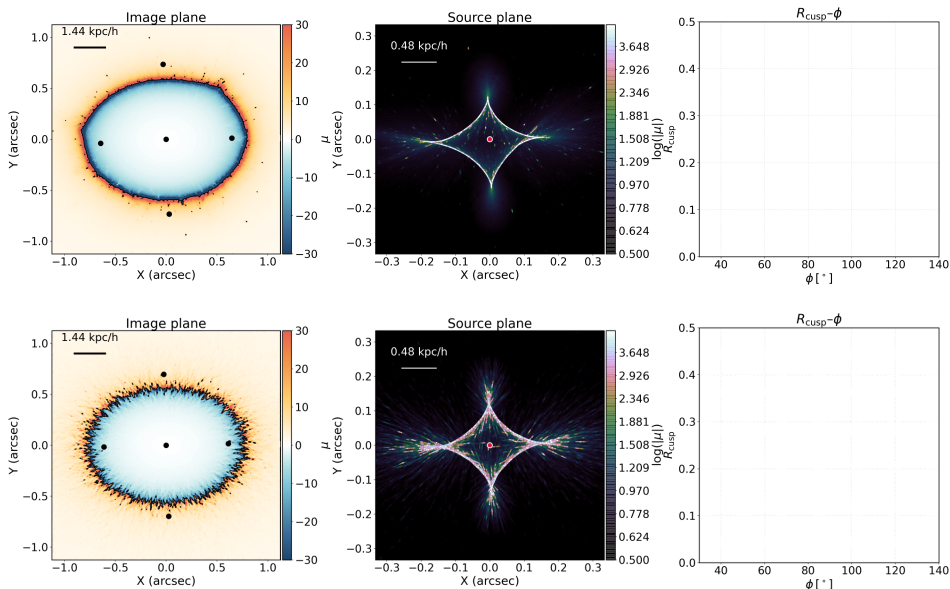
arXiv 2006.08540



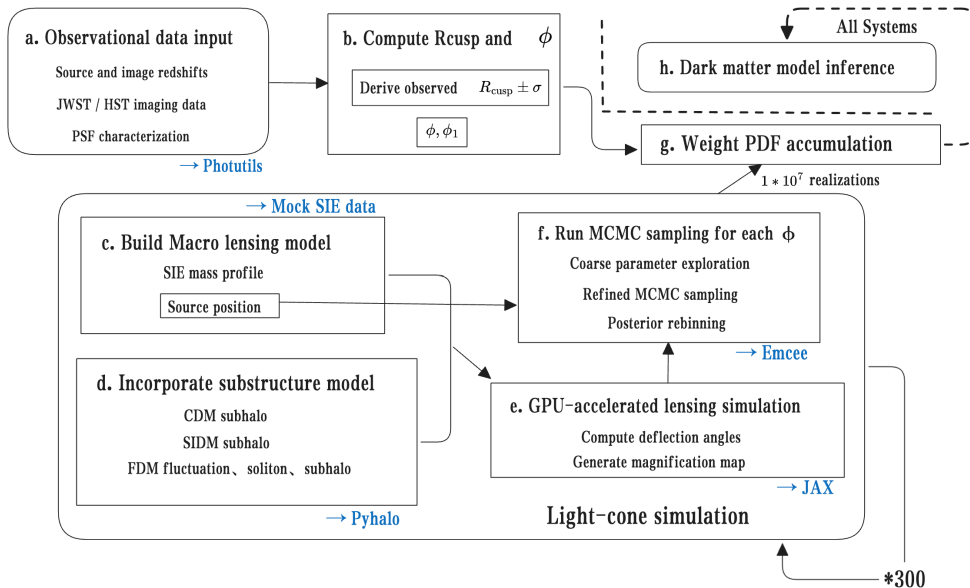
Gilman + (2019)

arXiv 1908.06983

The impact of dark matter substructures on the $R_{\text{cusp}} - \phi$ relationship



Overview of Methods for Probing Dark Matter Properties



CSST's Eye on DM

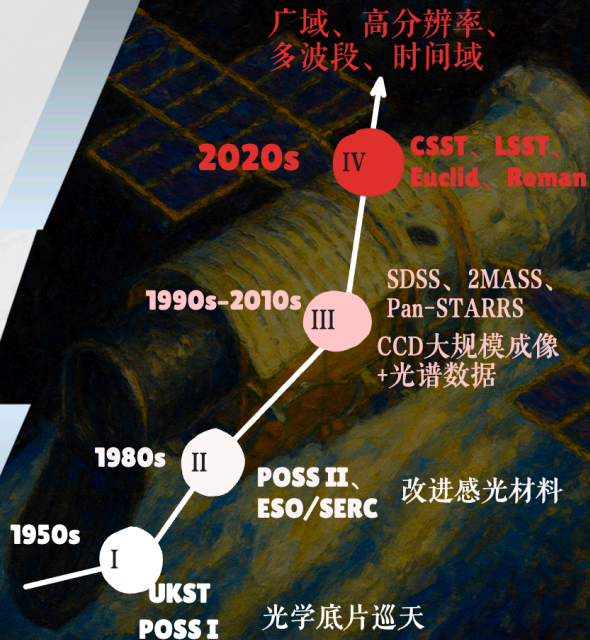
 Wide Surveys $\approx 17,500 \text{ deg}^2$
(~40% of the sky)

 Discover $\sim 10^5$ – 10^6 new strong lens systems

 0.15" resolution:
sensitive to substructures

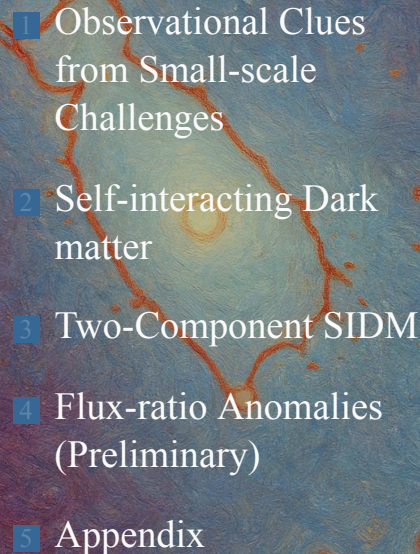
 Multiband Imaging:
NUV–NIR coverage

**Thank you for
Listening !**



OUTLINE

5. Appendix

- 
- The background of the slide is a deep blue, textured image resembling a galaxy cluster or a cosmic web. A prominent, irregular, reddish-brown filamentary structure winds across the frame, starting from the top left, looping around a central bright yellowish-white region, and extending towards the bottom right. The texture is painterly, with visible brushstrokes or pixelated patterns. The text is overlaid on this background, with each item in the list preceded by a small blue square containing a white number.
- 1 Observational Clues from Small-scale Challenges
 - 2 Self-interacting Dark matter
 - 3 Two-Component SIDM
 - 4 Flux-ratio Anomalies (Preliminary)
 - 5 Appendix

Why SIDM Exhibits Evolutionary Universality

Heat conduction breaks time reversal invariance

Arrow of time dependent on SIDM (the collision term)



$$\begin{aligned} \frac{\partial}{\partial r} M &= 4\pi r^2 \rho, \\ \text{Dynamic pressure } \frac{\partial}{\partial r} (\rho \nu^2) &= -\frac{GM\rho}{r^2}, \\ \frac{\partial}{\partial r} \left(r^2 \kappa m \frac{\partial \nu^2}{\partial r} \right) &= r^2 \rho \nu^2 \frac{D}{Dt} \ln \frac{\nu^3}{\rho} \end{aligned}$$

- Mass distribution

- Equilibrium condition

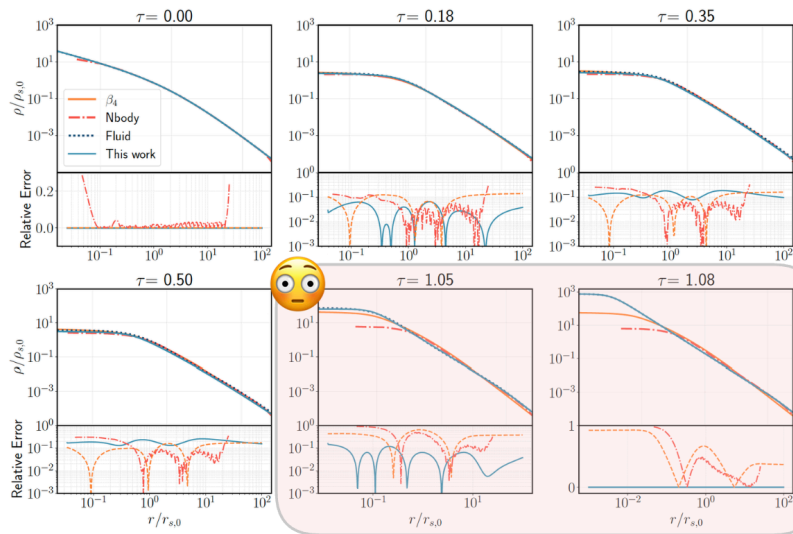
- Energy transport

$$\kappa_{LMFP} \propto \frac{\sigma}{m} \frac{\rho \nu^3}{mG}$$

SIDM effect can be absorb into t

$$\frac{\partial}{\partial r} \left(\frac{r^2 \rho_{DM} \nu_{tot}^3}{G} \frac{\partial \nu_{tot}^2}{\partial r} \right) \propto r^2 \rho_{tot} \nu_{tot}^2 \frac{D}{D(t\sigma/m)} \ln \frac{\nu_{tot}^3}{\rho_{tot}}$$

Why a Fluid Is Needed

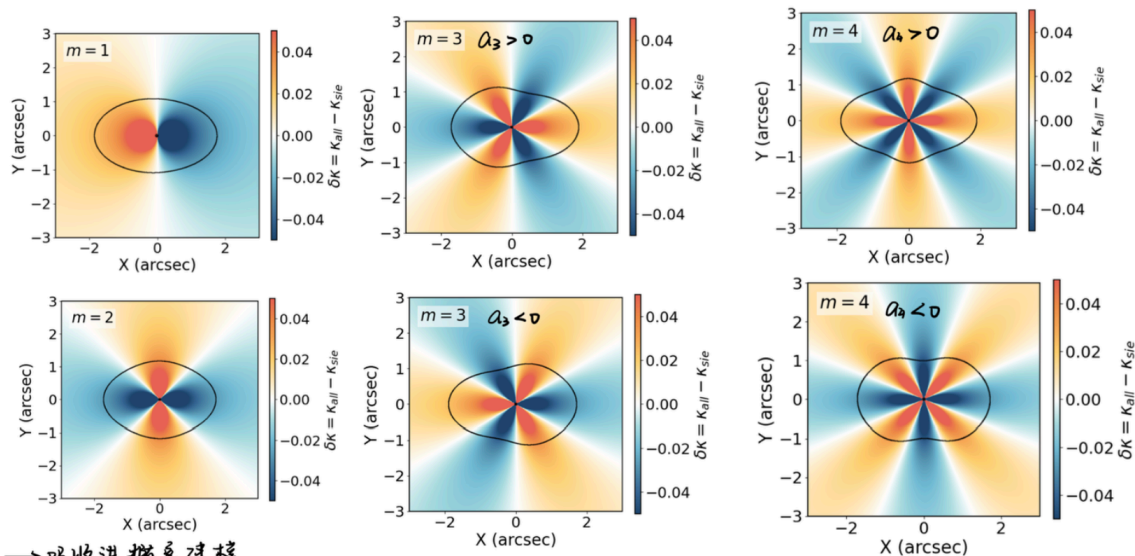


✗ N-body simulations cannot achieve sufficient accuracy during the core collapse phase

✓ Fluid simulations are needed.

Comparison of SIDM halo density profiles from simulations and model predictions at representative τ values.

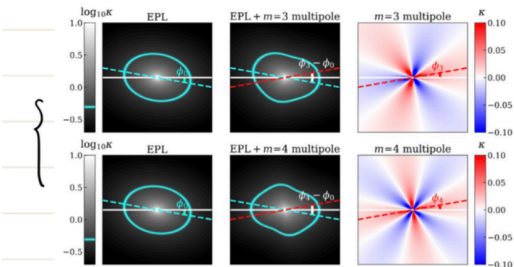
Introduction to Multipole Components



→ 吸收进椭圆建模
(shear)

恒星盘, 并合, 或相互作用

Distribution Characteristics of Multipole Parameters



$\phi_3 - \phi_0$
↑
无强相关

a_3/a
↑
在0附近对称分布
宽度随 ϕ 变化

arXiv:2404.17124

$$\alpha = \frac{\phi_3}{\sqrt{2}}$$

$\phi_4 - \phi_0$
↑
 a_4 更大更趋于0

a_4/a
↑
更椭圆时更大(且偏向正值)
disky

变量 ξ : $(\xi, \frac{a_3}{a}, \phi_3 - \phi_0, \frac{a_4}{a}, \phi_4 - \phi_0)$

$P(\xi)$ | $P(\frac{a_3}{a} | \xi)$
高斯分布

$$\mu = 0, \sigma(\xi)$$

$$[-0.08, 0.08]$$

$P(\phi_3 - \phi_0 | \frac{a_3}{a})$
均匀分布

$$[-\frac{\pi}{6}, \frac{\pi}{6}]$$

$P(\frac{a_4}{a} | \xi)$
skew - 正态

参数 $\alpha(\xi), \beta(\xi), w(\xi)$

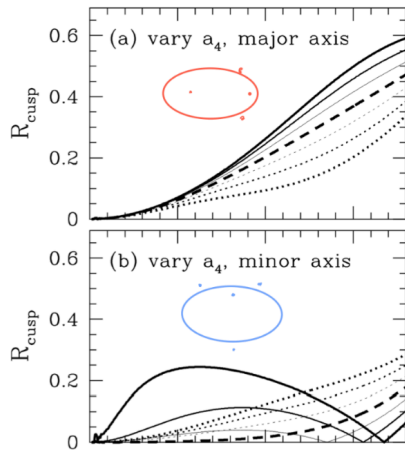
$$[-0.05, 0.14]$$

$P(\phi_4 - \phi_0 | \frac{a_4}{a})$
对称广义高斯

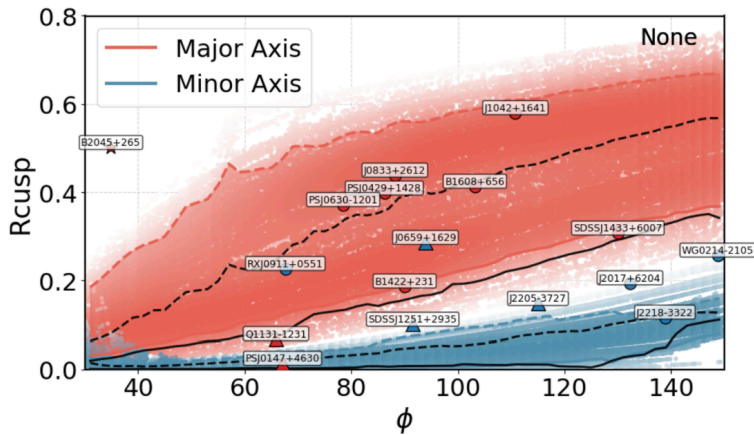
$$\mu = 0, \alpha(\frac{a_4}{a}), \beta(\frac{a_4}{a})$$

$$[-\frac{\pi}{8}, \frac{\pi}{8}]$$

Impact of Multipole Perturbations on the R_{cusp} ϕ Relationship



arxiv.0210318



Dark Matter Constraints After Introducing Multipole Perturbations

