A Unified Framework for Dwarf Galaxy Cores and Cluster Substructure Cusps via Self-Interacting Dark Matter with Mass Segregation

Based on
* arXiv:2506.14898 & 2504.02303
with Yue-Lin Sming Tsai， Yi-Zhong Fan, and Siyuan-Hou (PMO)
* JCAP08(2025)048, arXiv:2502.14964
with Siyuan-Hou, Guoliang Li (PMO), Nan Li (NAO)

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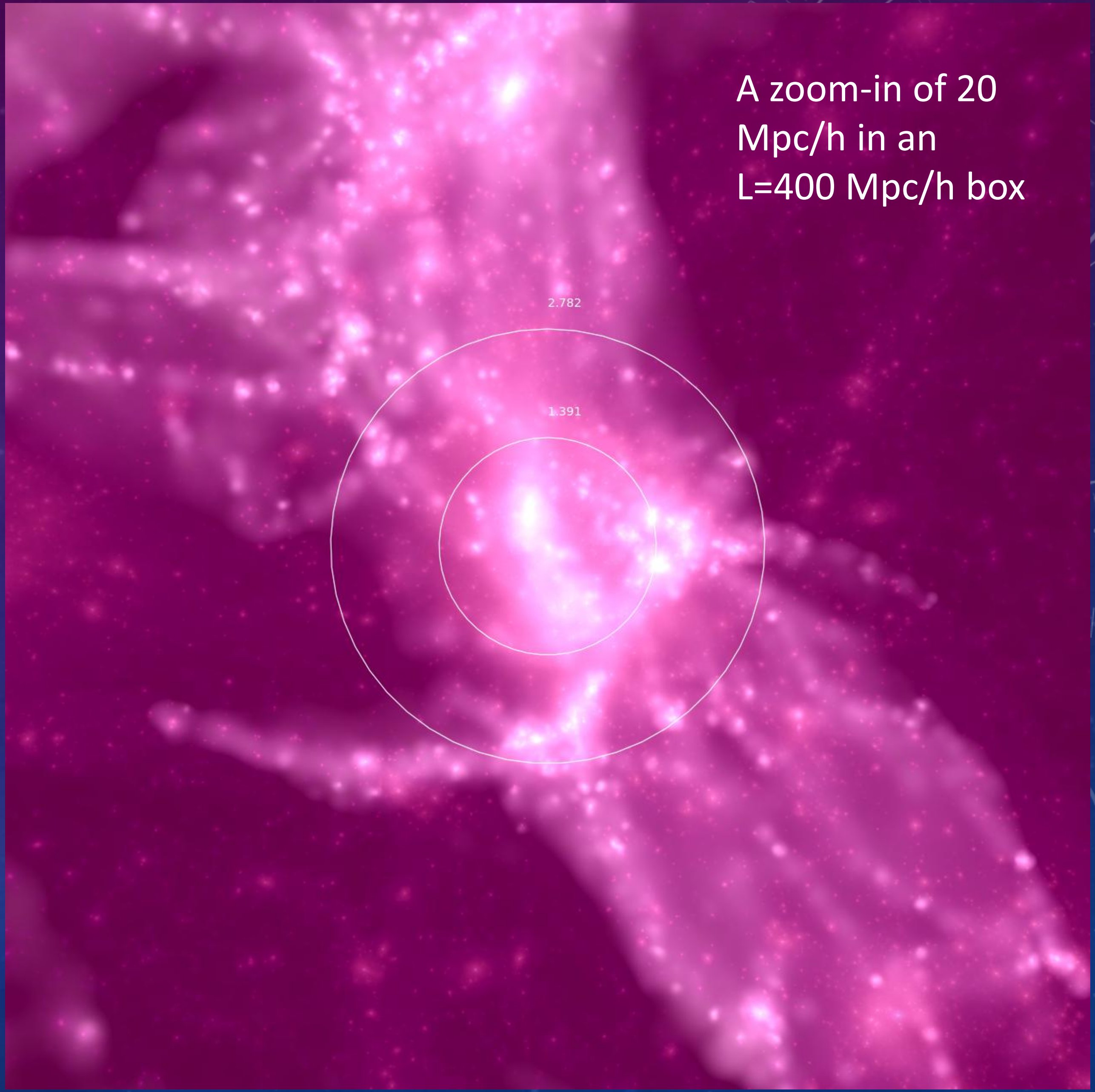
Purple Mountain Observatory, CAS

August 26, 2025
Xichang, Sichuan, China

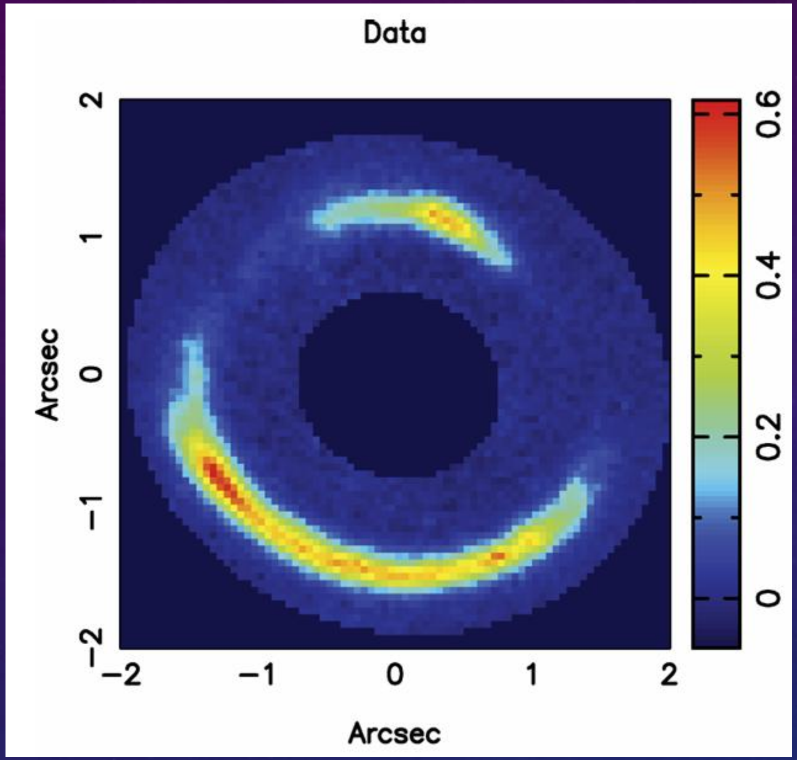
https://github.com/HouSiyuan2001/SIDM_Lensing_Model

Outline

- 3 Standing Small-Scale Challenges
- A 2 component Self-Interacting Dark Matter (SIDM) model with mass segregation
- Explaining observations
  - ✓ Dwarf clustering
  - ✓ Strong lensing perturbers
  - ✓ Excessive Galaxy-Galaxy Strong Lensing (GGSL) events

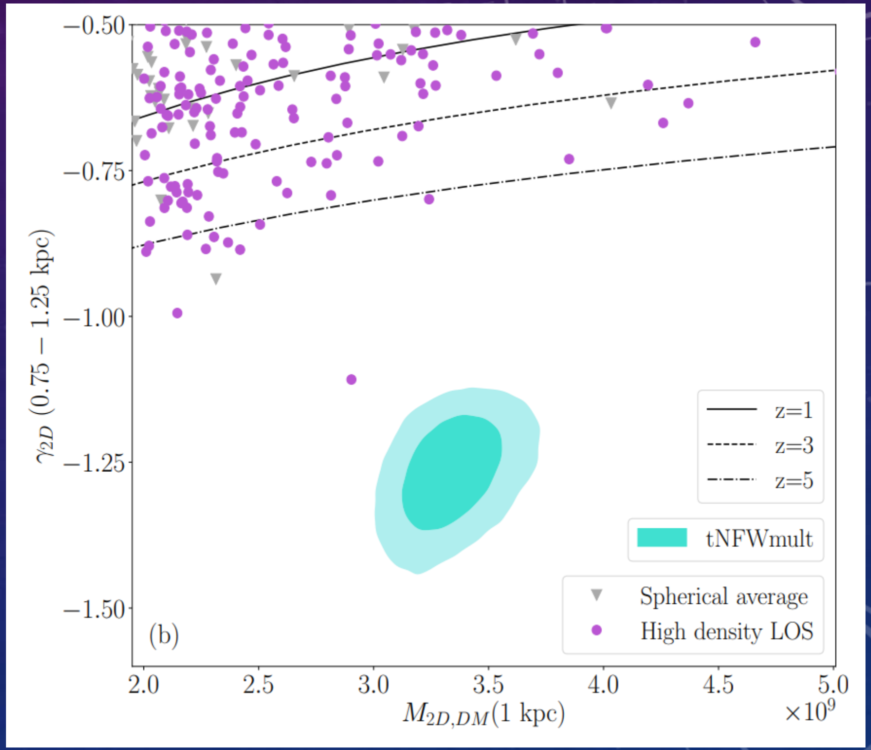


Persistent challenges from strong lensing observations
(1) strong lensing perturbers



Dark substructures found with J0946+1006 & B1938+666

Simona Vegetti et al. **MN 2009**
Simona Vegetti et al. **Nature 2012**
Daniel J. Ballard et al. MN2023
Ethan Nadler et al. ApJL 2023
Giulia Despali et al. 2024
Wolfgang J. R. Enzi et al. 2024
Shubo Li et al. 2025
M. Tajalli et al. 2025
… …



Mon. Not. R. Astron. Soc. **408,** 1969–1981 (2010) doi:10.1111/j.13

Detection of a dark substructure through gravitational imaging

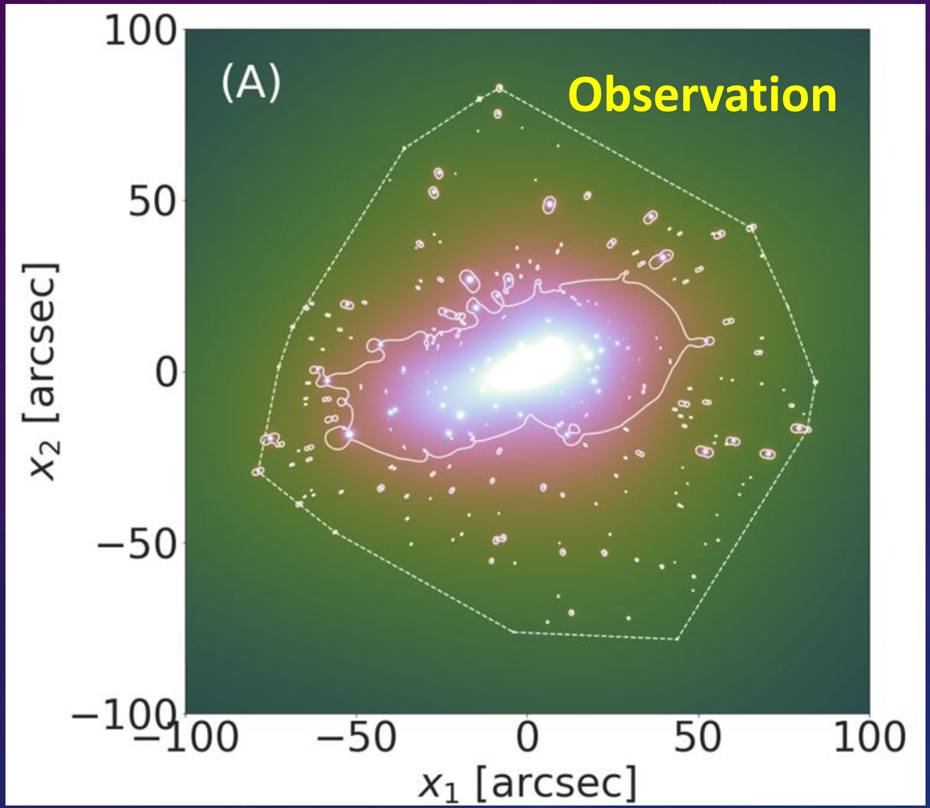
S. Vegetti,[1★] L. V. E. Koopmans,[1] A. Bolton,[2] T. Treu[3] and R. Gavazzi[4]

MNRAS **507,** 1662–1683 (2021) https://doi.org/10.1093/
Advance Access publication 2021 August 5

An unexpected high concentration for the dark substructure in the gravitational lens SDSSJ0946+1006

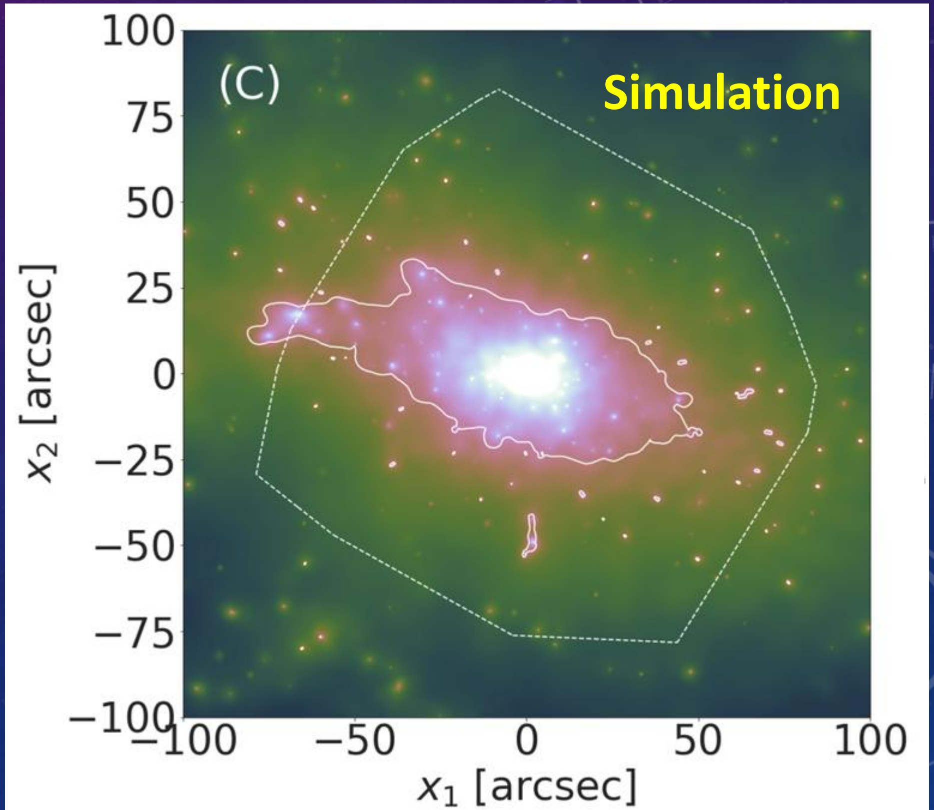
Quinn Minor,[1,2★] Sophia Gad-Nasr,[3] Manoj Kaplinghat[3] and Simona Vegetti[4]

Persistent challenges from strong lensing observations (2) excessive small-scale lenses



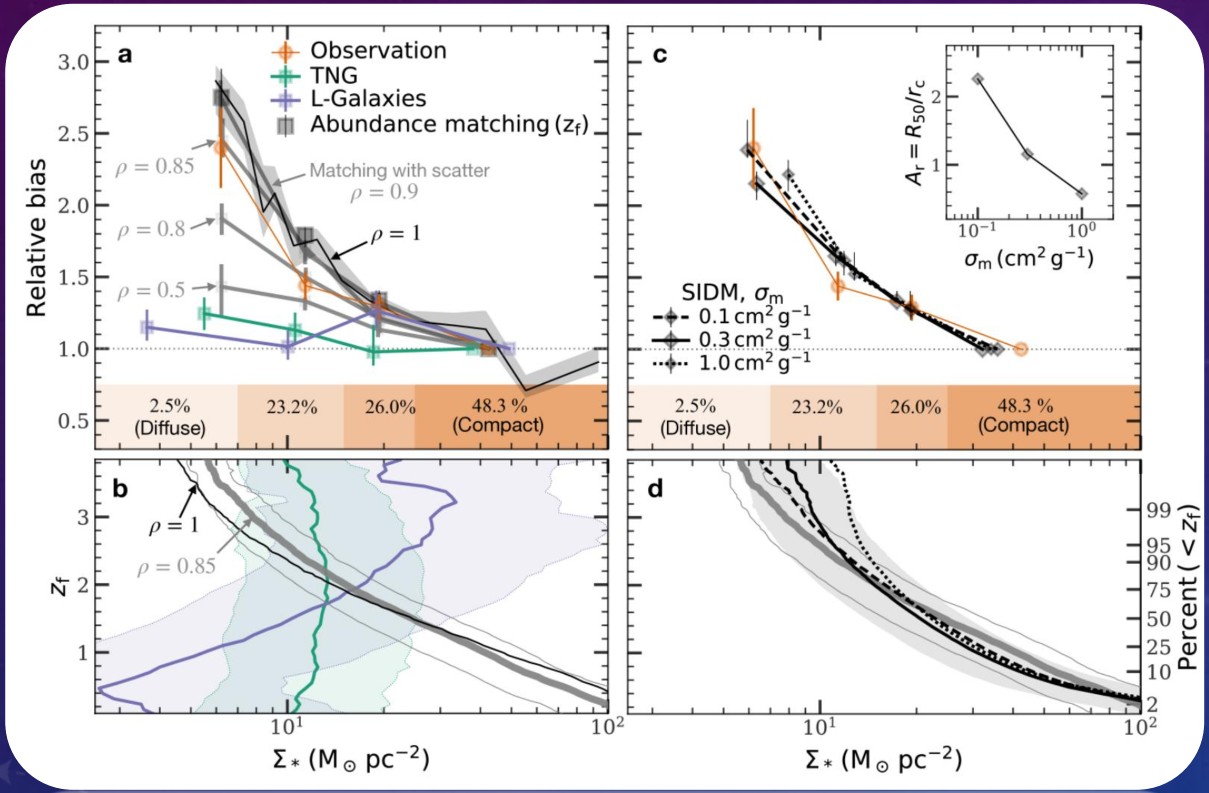
Meneghetti+2009.04471 (*Science*)
The efficiency of small scale lenses from Galaxy-Galaxy Strong Lensing (GGSL) analysis is **one order of magnitude higher** in observation

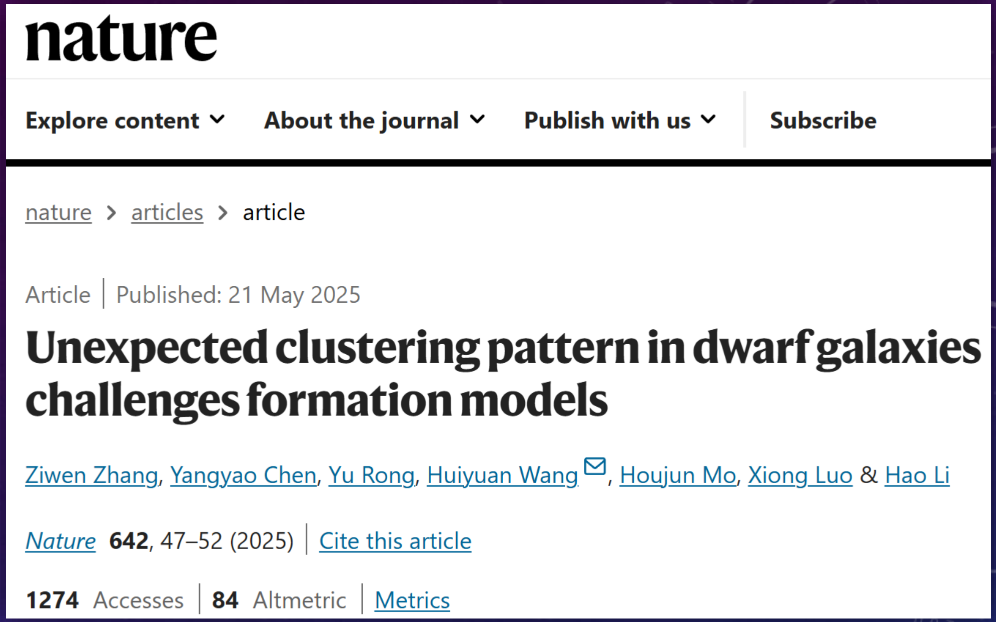
Ragagnin+22 A&A
Tokayer+24
Angora+23 (A&A)
Meneghetti+22,23 A&A



2023 update, A&A 678, L2 (2023) Letter: **A persistent excess** of galaxy-galaxy strong lensing observed in galaxy clusters

A new challenge from the clustering of dwarf galaxies





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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

- ◆Decreasing surface density
- ◆Hydro baryonic simulation gives inverted feature
- ◆Self-Interacting Dark Matter (SIDM), with

  σ/m=0.3 cm^2/g (SIDM03)

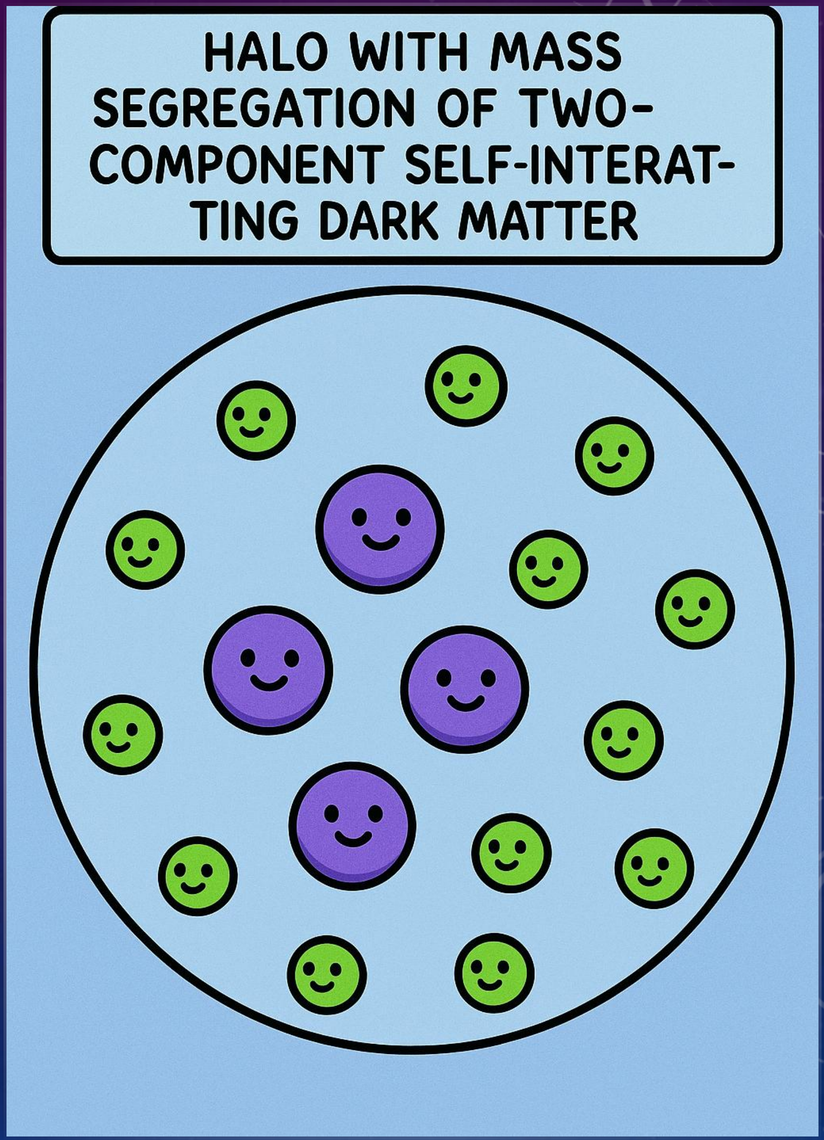
  can explain the observation

THEY CAN BE EXPLAINED SIMULTANEOUSLY

Self-Interacting Dark Matter with Mass Segregation

arXiv: 2506.14898

Daneng Yang, Yi-Zhong Fan, Siyuan Hou, and Yue-Lin Sming Tsai



WHY MASS SEGREGATION?

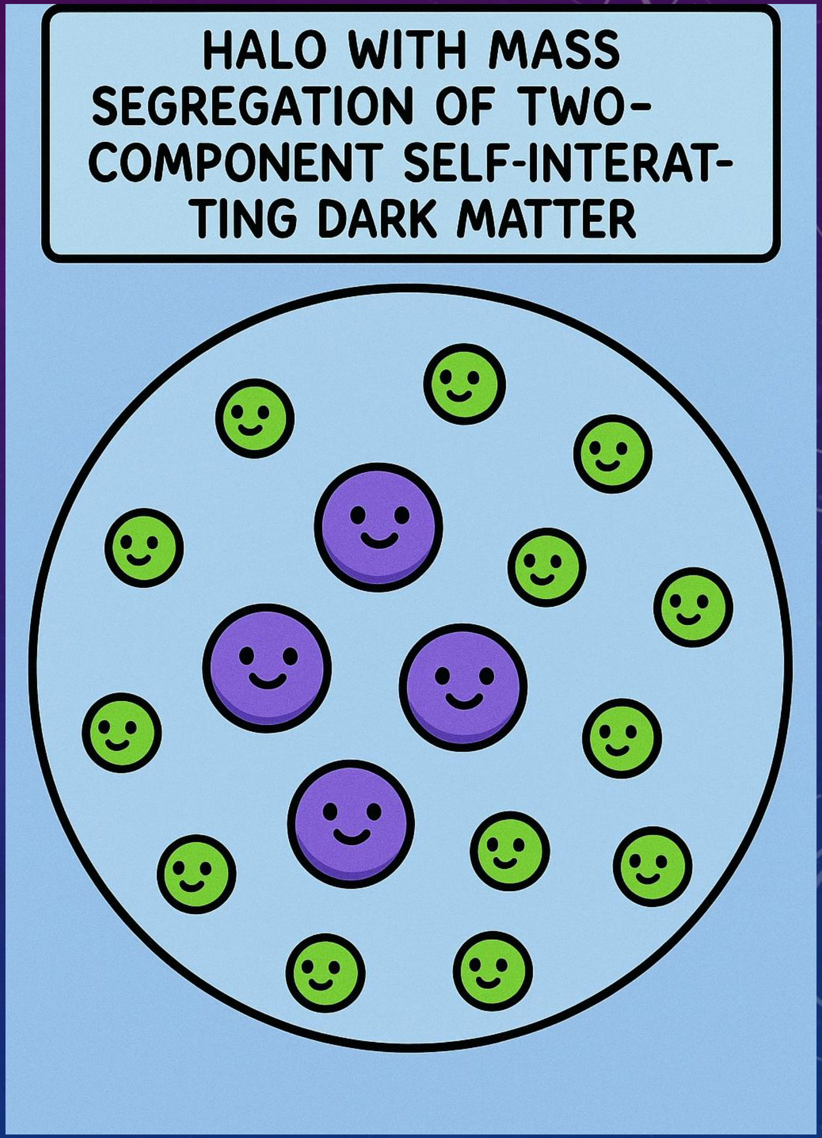
Collisions (SIDM) lead to energy equilibration:

$$m_1 v_1^2 \sim m_2 v_2^2$$

$m_1 > m_2$ implies $v_1 < v_2$

Massive particles will sink inside, elevating central halo mass

Core collapse: more dense
Mass segregation: more dense
& more massive



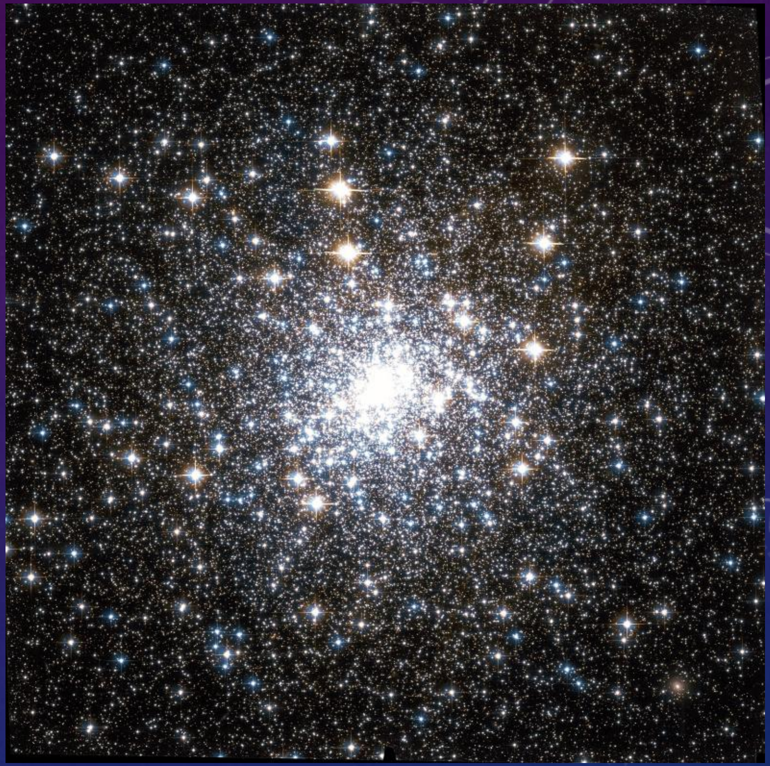
SIDM with mass segregation

Mass segregation is effective in star clusters

But inefficient in dark matter halos

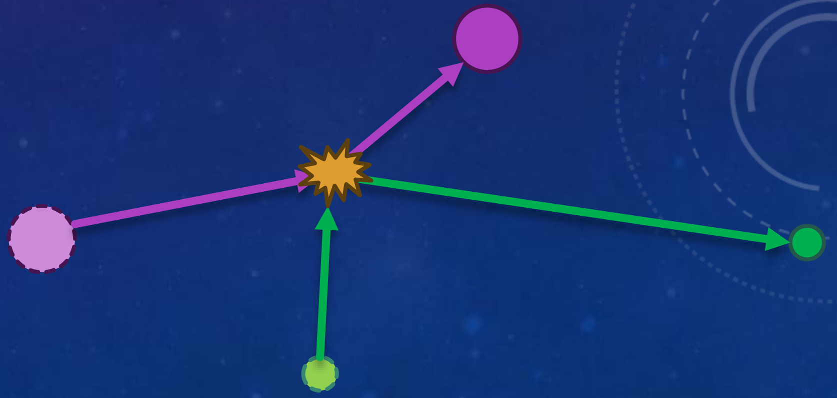
$$t_{\rm relax} = \frac{N}{8 \ln N} \times t_{\rm cross}$$

$$t_{\rm m_1} = \frac{m_2}{m_1} \times t_{\rm relax}$$

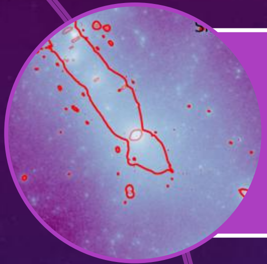


Cross-species scatterings (SIDMx) makes mass segregation efficient

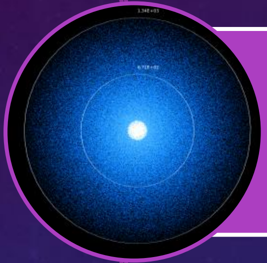
$$t_r \sim 1/(n\sigma v)$$



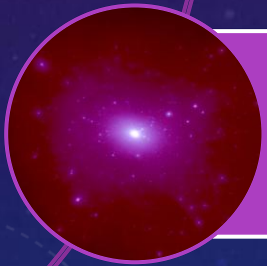
We propose a v-dependent 2-comp model with **three crucial features**



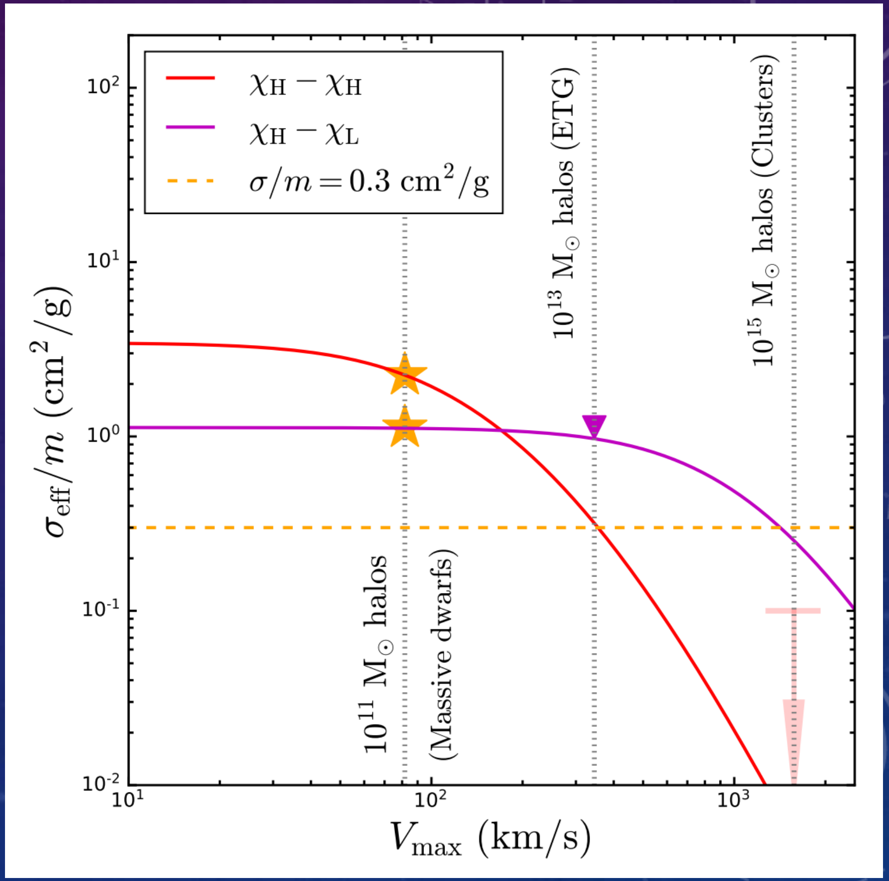
Enhancing inner halo masses: mass segregation



Compact halos become more compact: boosted evolution



Diffuse halos develop cores: weak mass segregation effect



SIDM among the same types: red

SIDM across two components

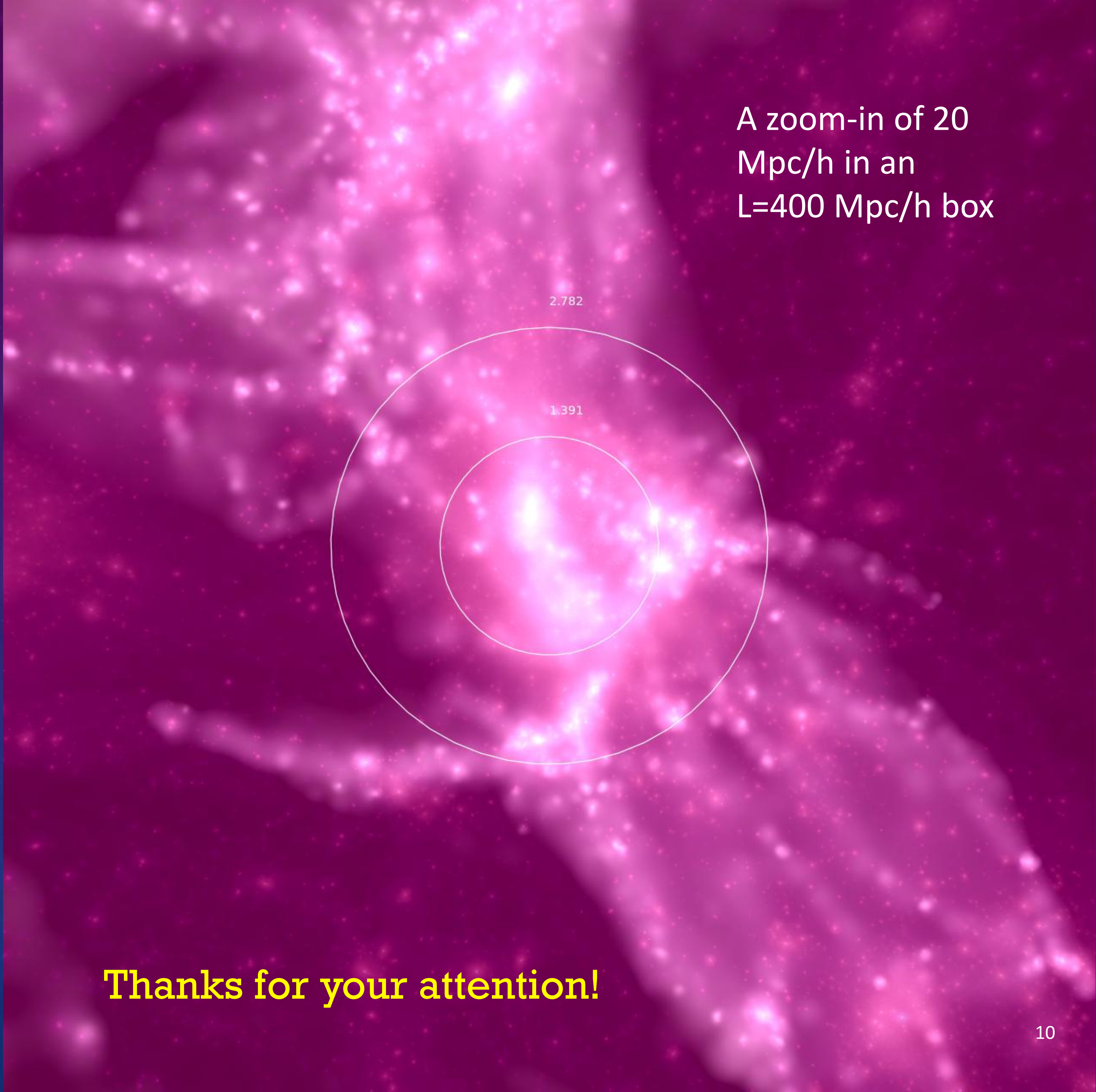
Cosmological zoom-in & controlled simulations

Cosmological simulations

- Zoom-in one cluster with substructures
- Mh~1e15 Msun/h in a 400 Mpc/h box, mpart=1e8 Msun

Controlled simulations

- Dwarf scale
  - -1,0,+1 σ M11
  - +2.5 σ concentrations M10-M11
- Cluster scale: cosmological analog



A zoom-in of 20 Mpc/h in an L=400 Mpc/h box

Thanks for your attention!

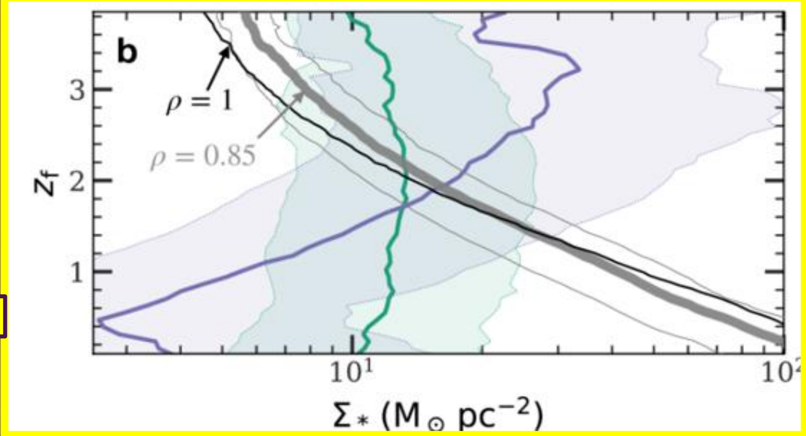
Cored dwarf hosts

Dashed lines: 1 component SIDM03

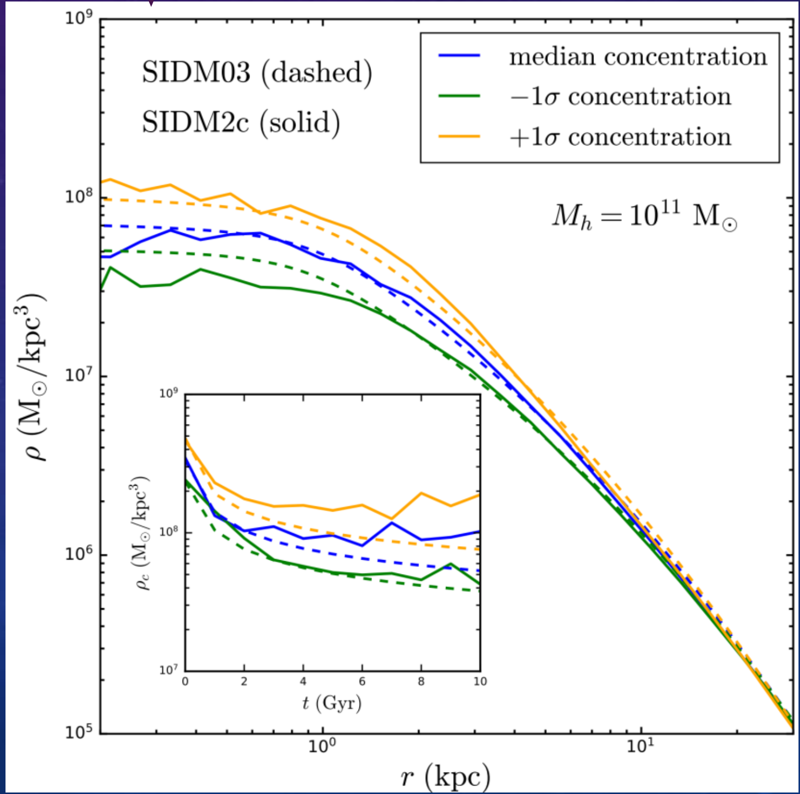
Following Zhang et al. *Nature* (2025)

$\sigma/m \sim 0.3\ \mathrm{cm}^2/\mathrm{g}$

We need a time dependent decreasing surface density in dwarfs



Test against Massive dwarfs of Median, +1 sigma, -1 sigma concentration



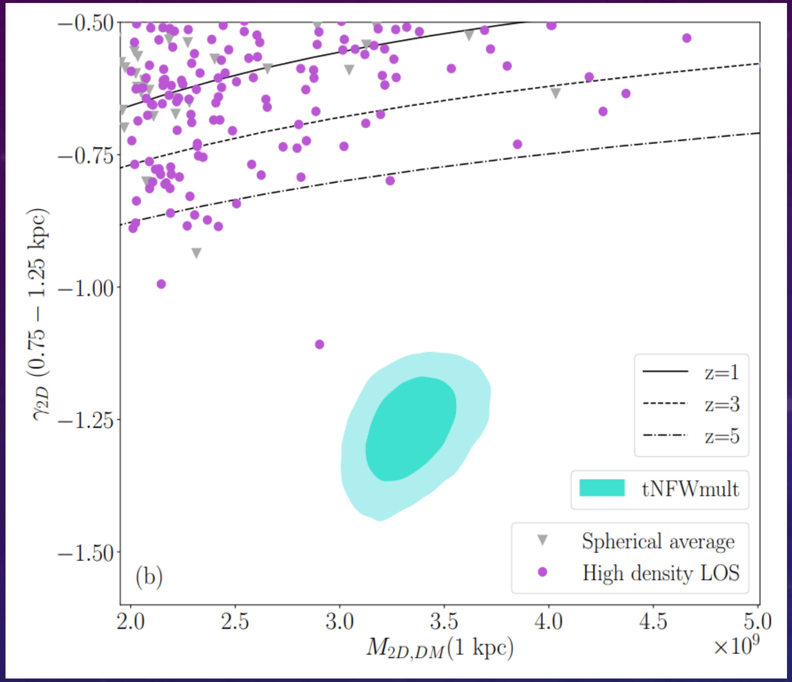
Flat halos evolve similar to 1 component SIDM halos

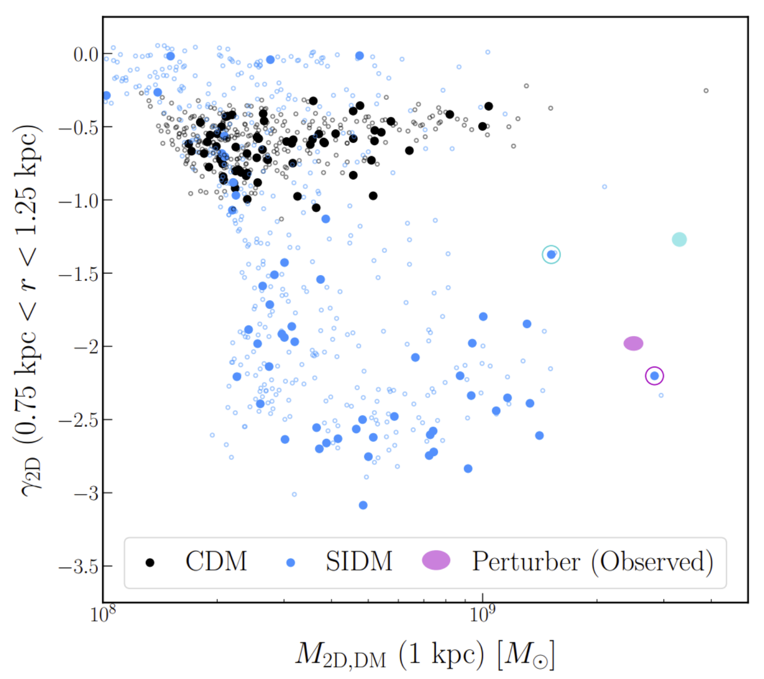
Hint: dense halos become denser

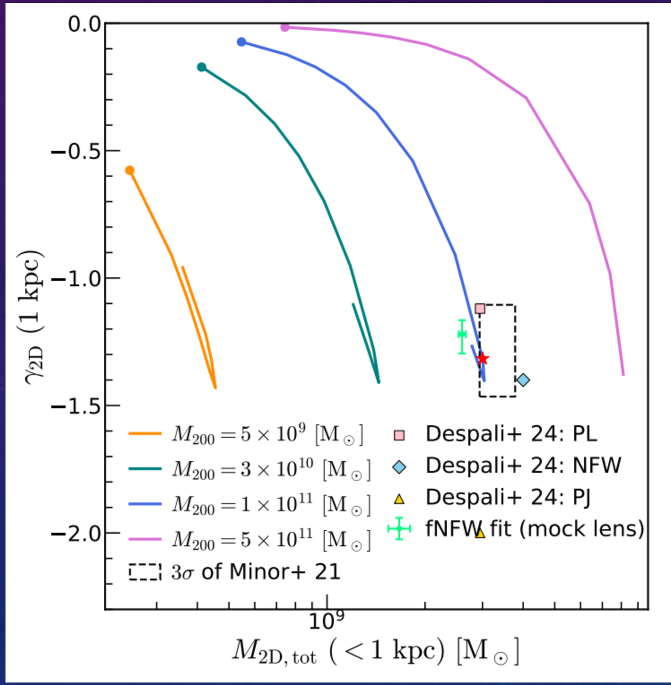
Solid lines: SIDM2c with two component

Produce roughly identical results

Strong lensing perturbers could be core-collapsed SIDM subhalos







Minor et al. 2011.10627
The dark substructure has
unexpected high concentration

Nadler, Yang, Yu, ApJL 2023
Strong SIDM with
$\sigma/m > 100\ cm^2/g$ in group
substructures

S. Li & R. Li+2504.11800
Little dark dots
$\sigma/m > 138\ cm^2/g$
Why M11 does not host a
visible galaxy?

SIDM + mass segregation

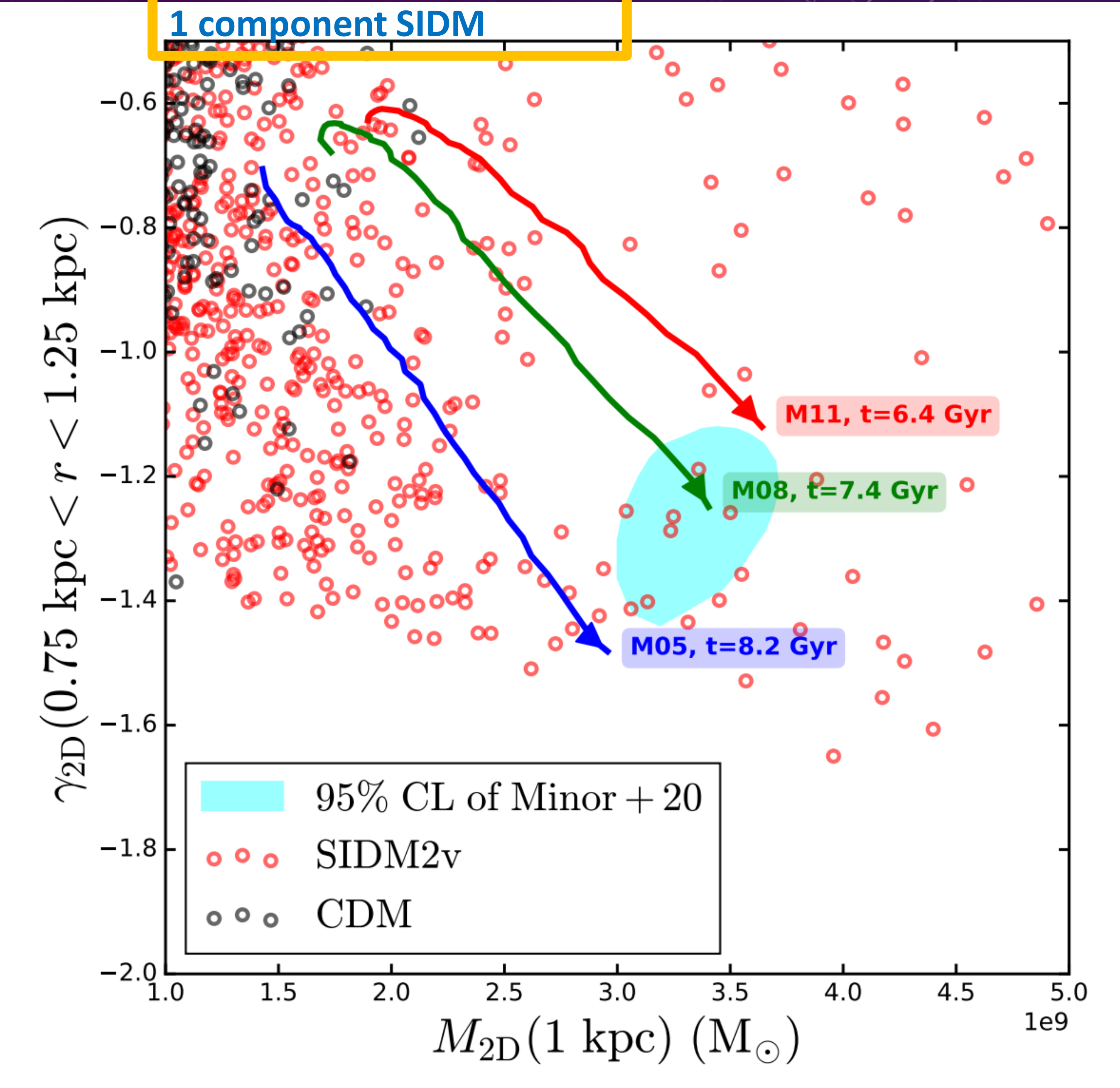
Controlled simulations with +2.5 sigma concentration:
M05 (5e10 Msun), M08 (8e10 Msun), M11 (1e11 Msun)

SIDM strength $\lesssim 1\ \mathrm{cm^2/g}$

No candidate in CDM

7 candidates in SIDM2v, mass in (1-10) x 1e10 Msun

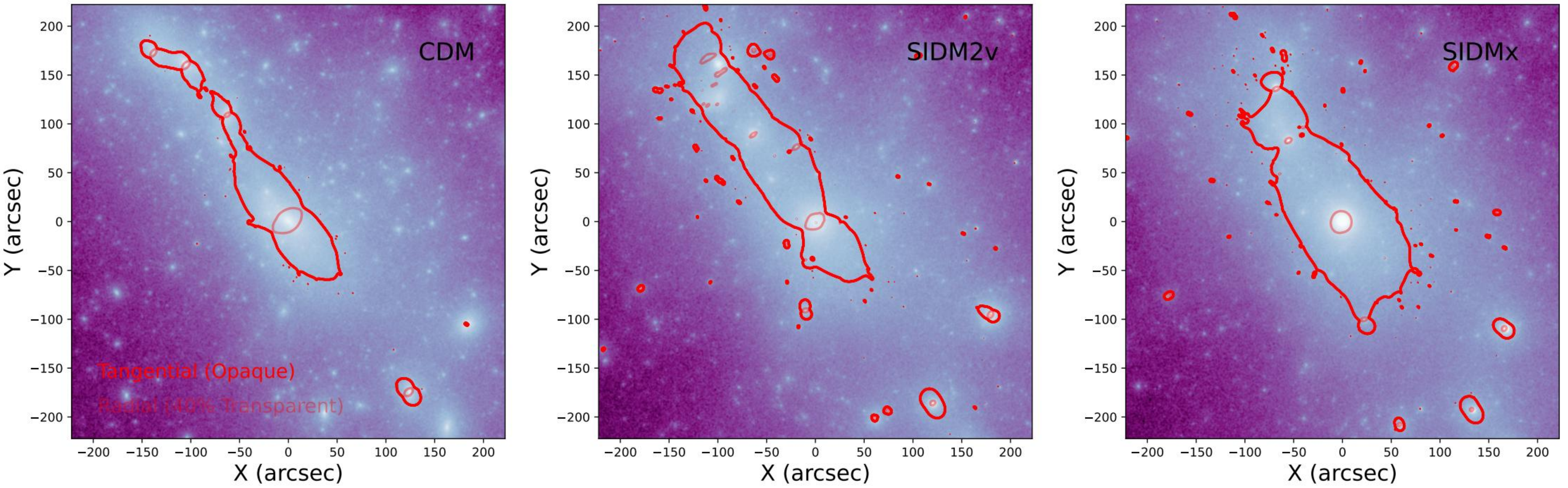
Would be here if consider
1 component SIDM



Gravitational lensing by cluster substructures

Number of small scale lenses, effective radii>0.5’’

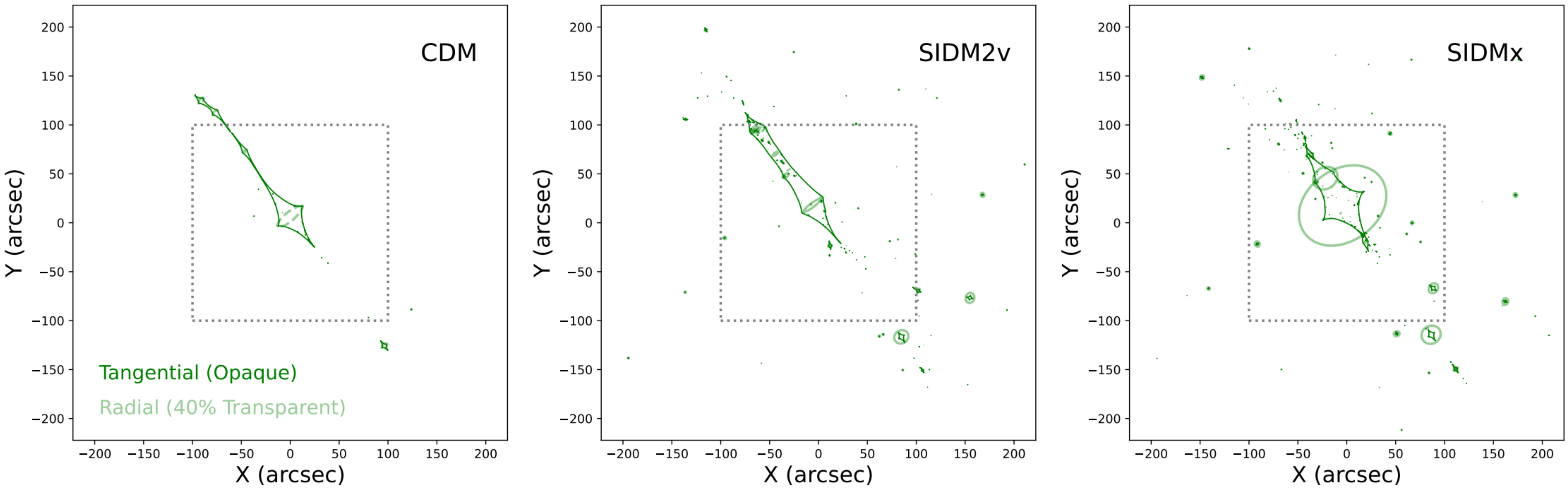
5 (CDM) **30 (SIDM2v,fiducial)** **37 (SIDMx)**



Gravitational lensing by cluster substructures

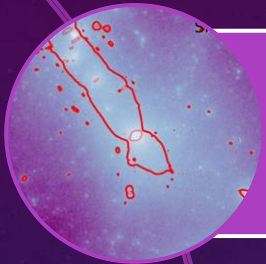
GGSL cross section of secondary caustics, excluding the ones that may dominate over 90%

0.515 (CDM) 6.76 (SIDM2v,fiducial) 12.8 (SIDMx)

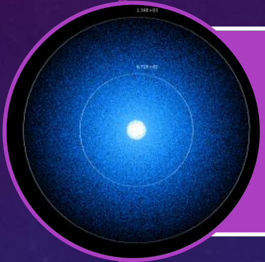


13x CDM

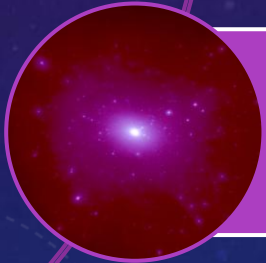
Natural solutions to the three key observations



Enhancing inner halo masses: mass segregation



Compact halos become more compact: boosted evolution



Diffuse halos develop cores: weak mass segregation effect

GGSL excess

- ✓ x10 GGSL cross section
- ✓ x6 number of lenses

Lensing Perturber

- ✓ A small cross section can work
- ✓ Predict more candidates to search

Dwarf Clustering

- ✓ Time dependent core formation close to SIDM03

FURTHER EVIDENCE?

Analytic models facilitates obtaining predictions

Hou, Yang, Li, Li JCAP 08 (2025) 048

- A family of central density profiles ranging r^{0} to $\mathrm{r}^{-2.5}$ with analytic lensing predictions
- Lensing for complex density fields via superposing models (not limited to SIDM)

- High redshift galaxies
- **Low mass subhalos from lensing**
- **Little red dots**
- Diverse rotation curves
- ?
- **Bullet cluster anomaly**
- **Core collapse seeded black holes**
- ?

Thanks for your attention!

Back up

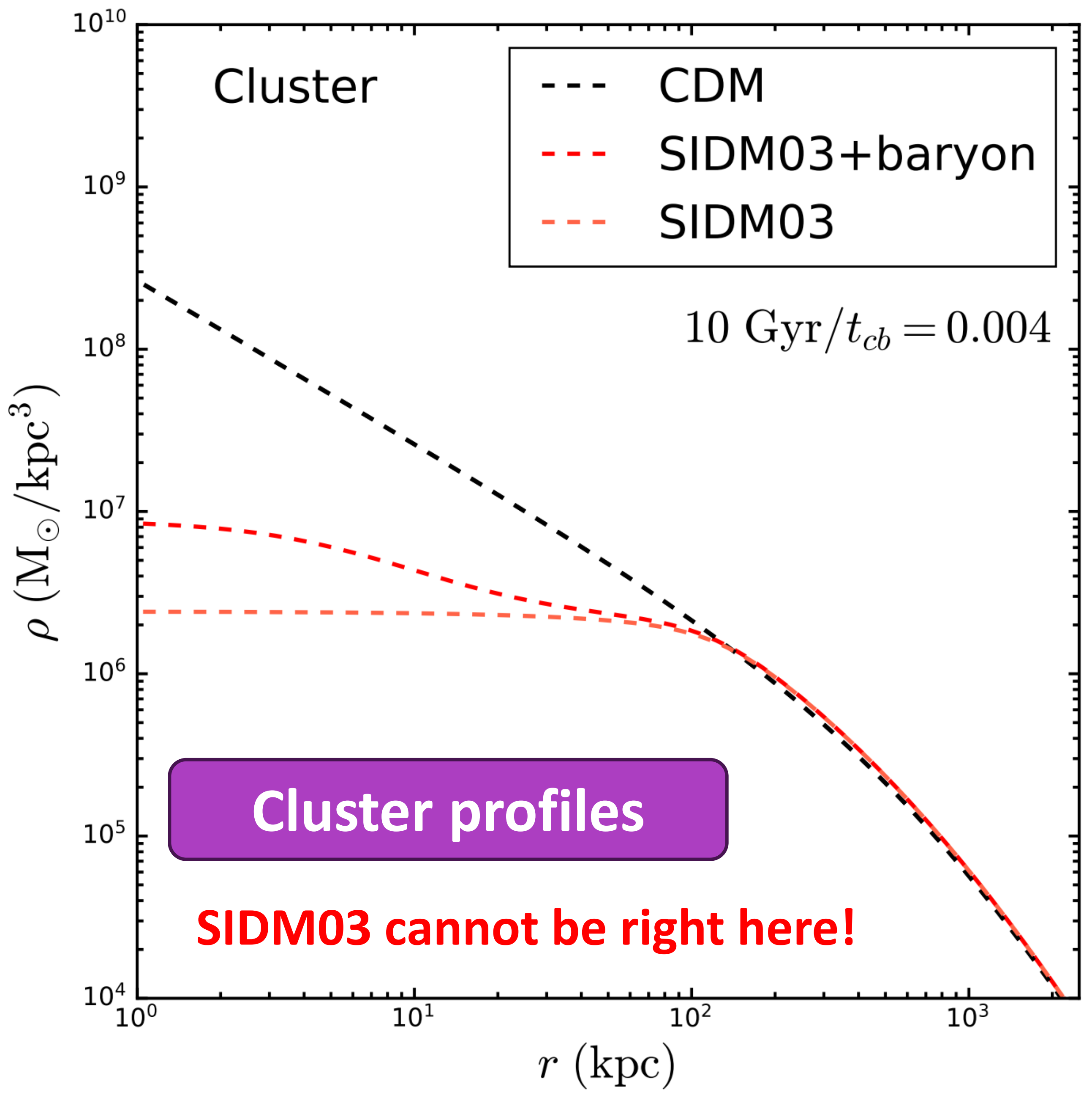
Zhang et al. *Nature* (2025) predicts SIDM
$\sigma/m \sim 0.3\ cm^2/g$ in dwarf halos
What if it applies to **cluster halos**?

SIDM effect, measured in terms of the gravothermal phase scales as ~ $\sigma/m * \rho_s^{3/2} r_s$
More effective in massive halos

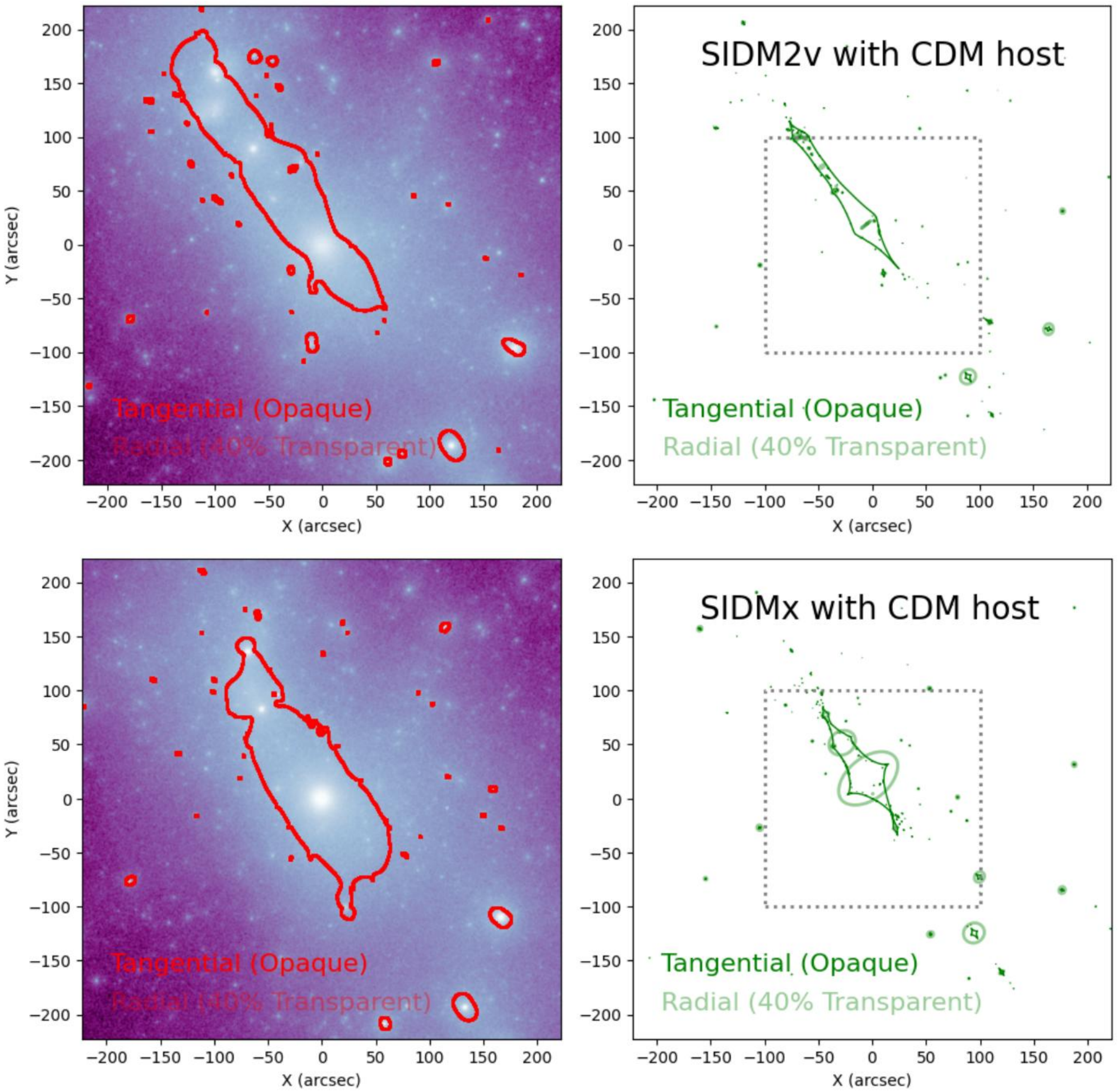
A cluster halo as little stellar mass,

~ 0.05% halo mass:

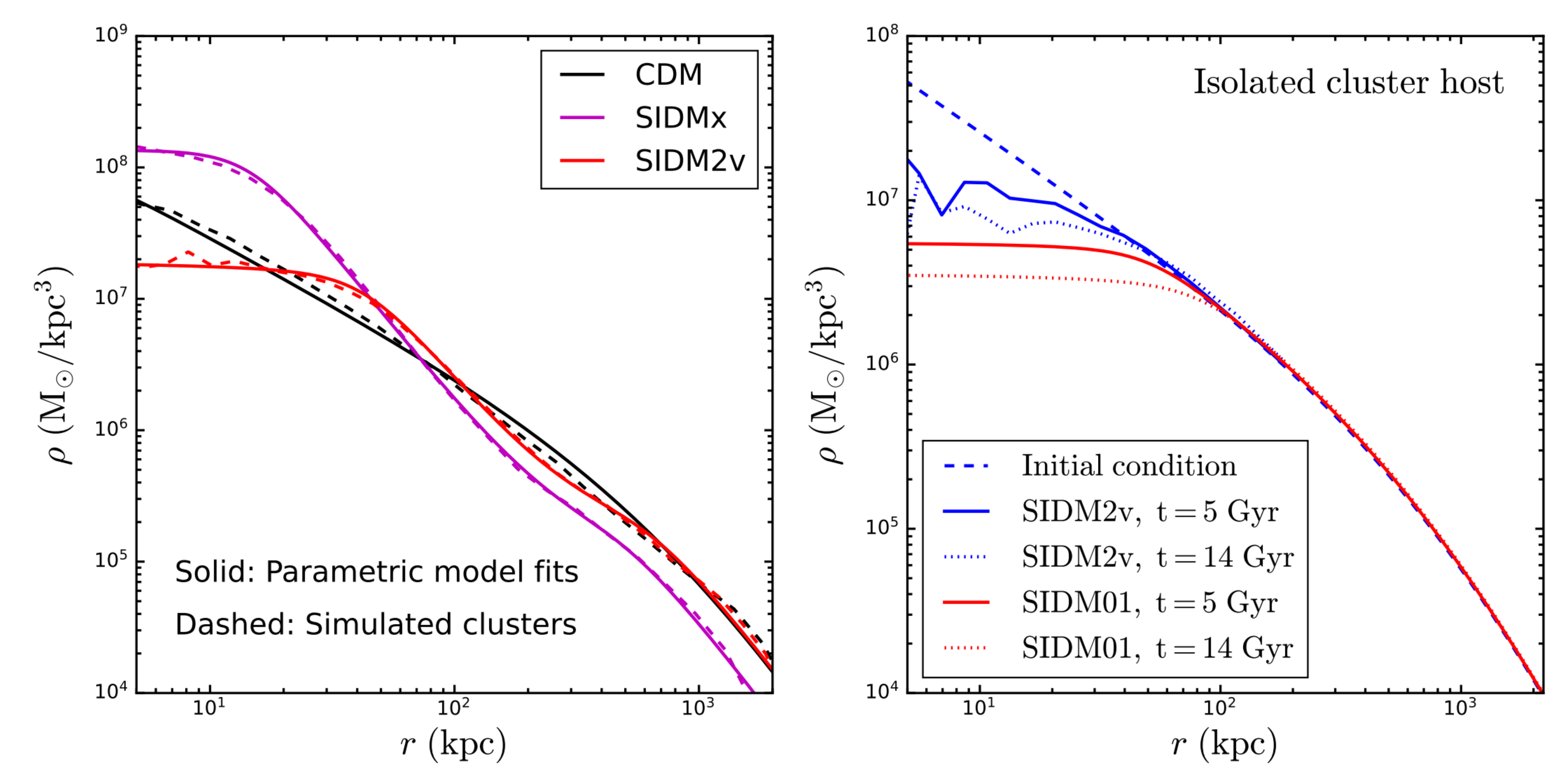
small contraction effect



Model the host halo using the CDM one



Host clusters are safe from the SIDM01 constraint



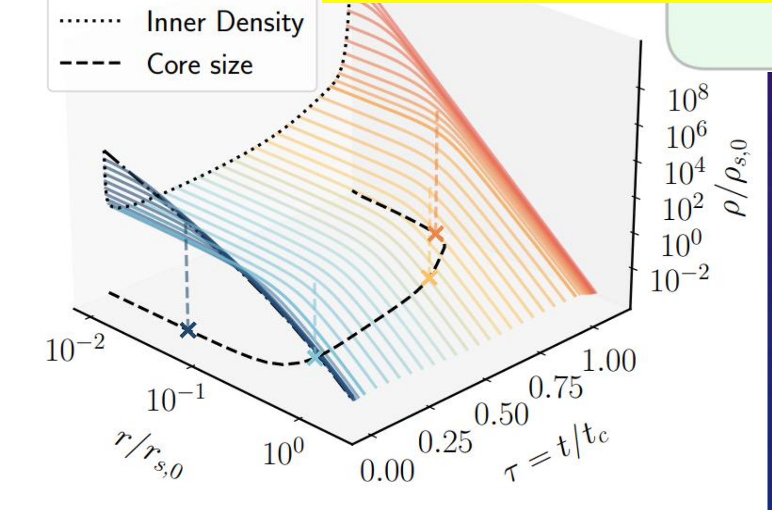
README · GPL-3.0 license

A Universal Analytic Model for Gravitational Lensing by Self-Interacting Dark Matter Halos

arXiv 2502.14964

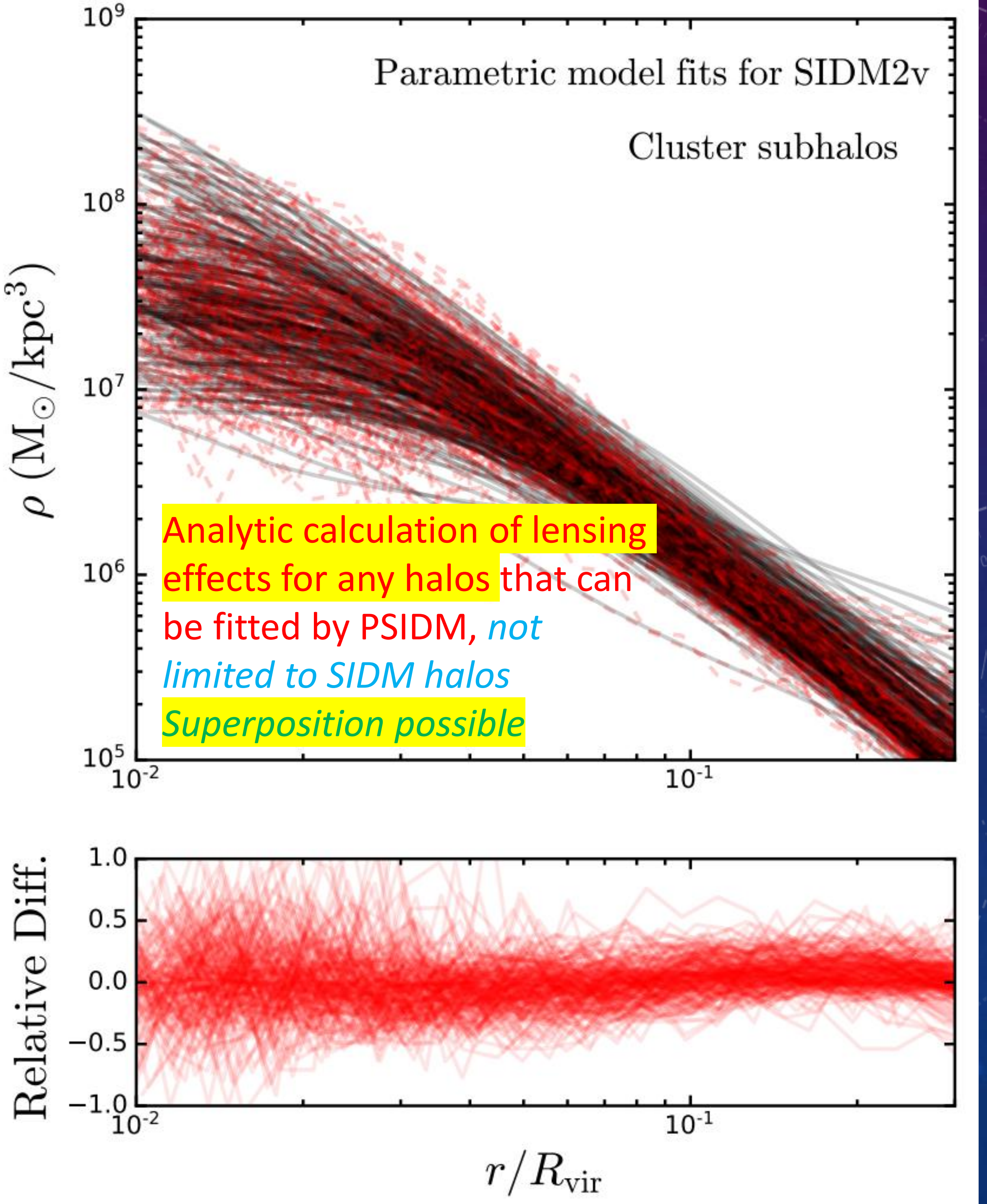
This code implements a **parametric model for gravitational lensing** by self-interacting dark matter (SIDM) halos. It extends the parametric framework introduced in arXiv:2305.16176 (JCAP), enabling more comprehensive lensing studies. The code allows for the analytic calculation of the lensing potential, deflection angle, and convergence (κ). It includes example scripts to compute critical curves and caustics for SIDM halos, both in isolation and within a main halo, and track their evolution through the gravothermal phase. For broader applicability, we also provide efficient

$$\rho_{PSIDM}(r, \rho_{s,0}, r_{s,0}, \tau) = \frac{\rho_s}{\left[\left(\frac{r}{r_s}\right)^4 + \left(\frac{r_c}{r_s}\right)^4\right]^{\frac{\gamma}{4}} \cdot \left[1 + \left(\frac{r}{r_s}\right)^{\beta}\right]^{\frac{3-\gamma}{\beta}}}$$



$$\rho_s = \rho_{s,0}\, f_\rho(\tau)$$
$$r_s = r_{s,0}\, f_s(\tau)$$
$$r_c = r_{s,0} f_c(\tau)$$
$$\beta = f_\beta(\tau) \qquad \gamma = f_\gamma(\tau)$$

arXiv:2502.14964 & arXiv:2305.16176
https://github.com/HouSiyuan2001/SIDM_Lensing_Model



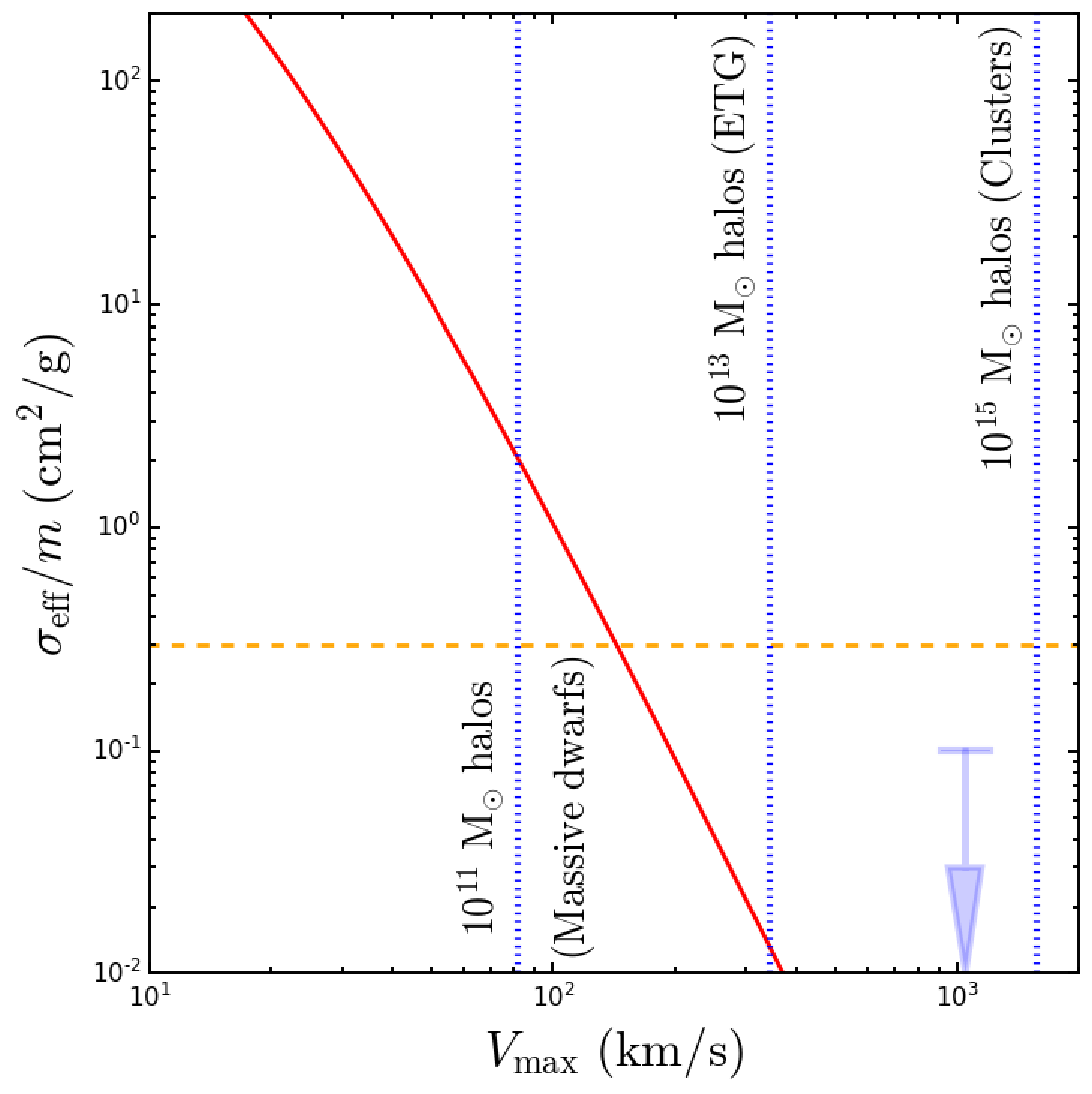
A v-dependent SIDM1c is insufficient

S.Li+2504.11800, core collapsed SIDM halo could address the "little dark dot" in 1e11 Msun halos with $\sigma/m>138\ \mathrm{cm}^2/\mathrm{g}$

Jiang+2503.23710, core collapsed SIDM in 1e9 Msun halos can seed "little red dots", with $\sigma/m \sim 10\ \mathrm{cm}^2/\mathrm{g}$

A *velocity dependent model* could help with "little red dots" & clusters, but…

- No core collapse in massive dwarfs (M11)
- No core collapse in 1e13 Msun ETGs

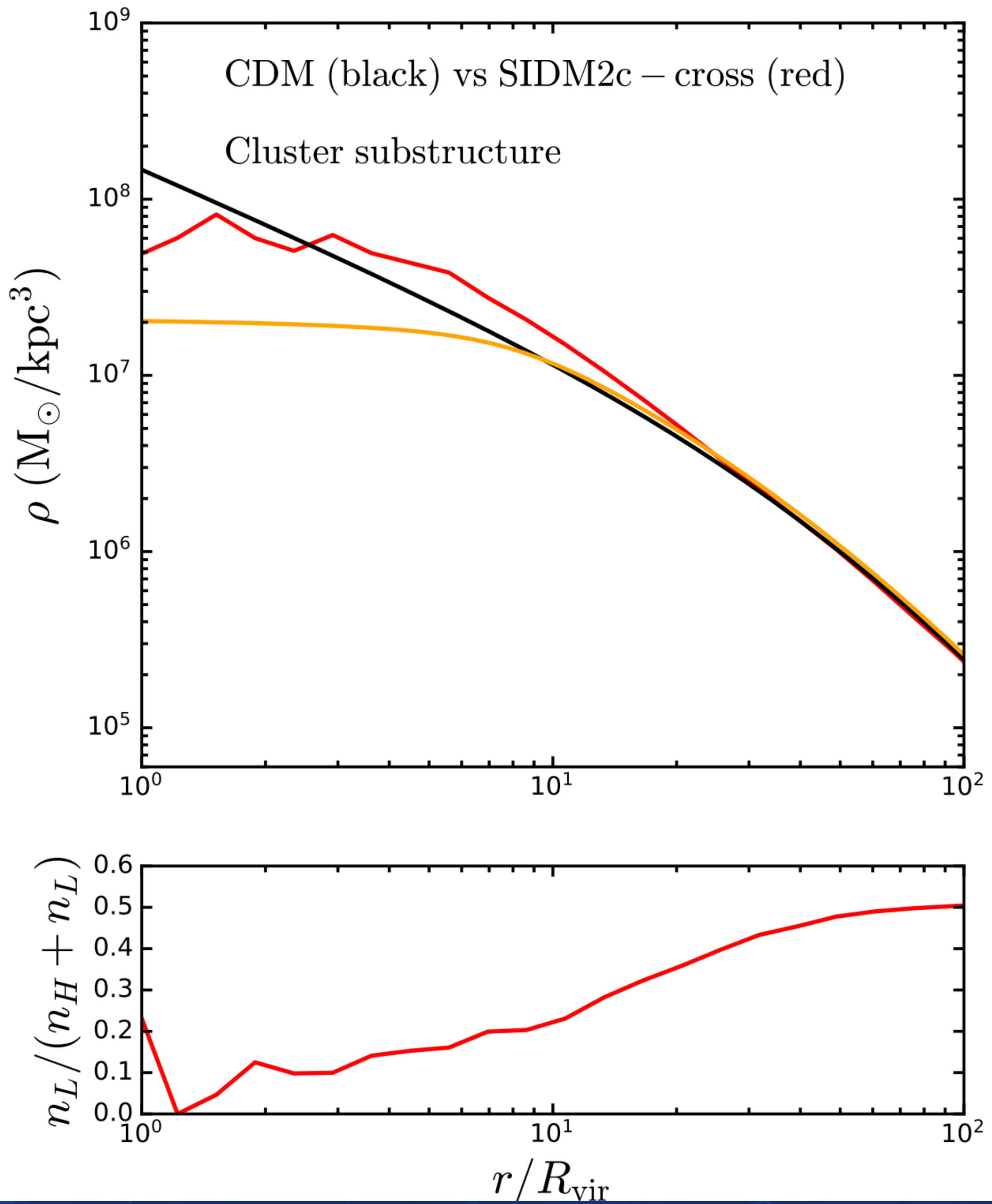


MASS SEGREGATION IN SIDM

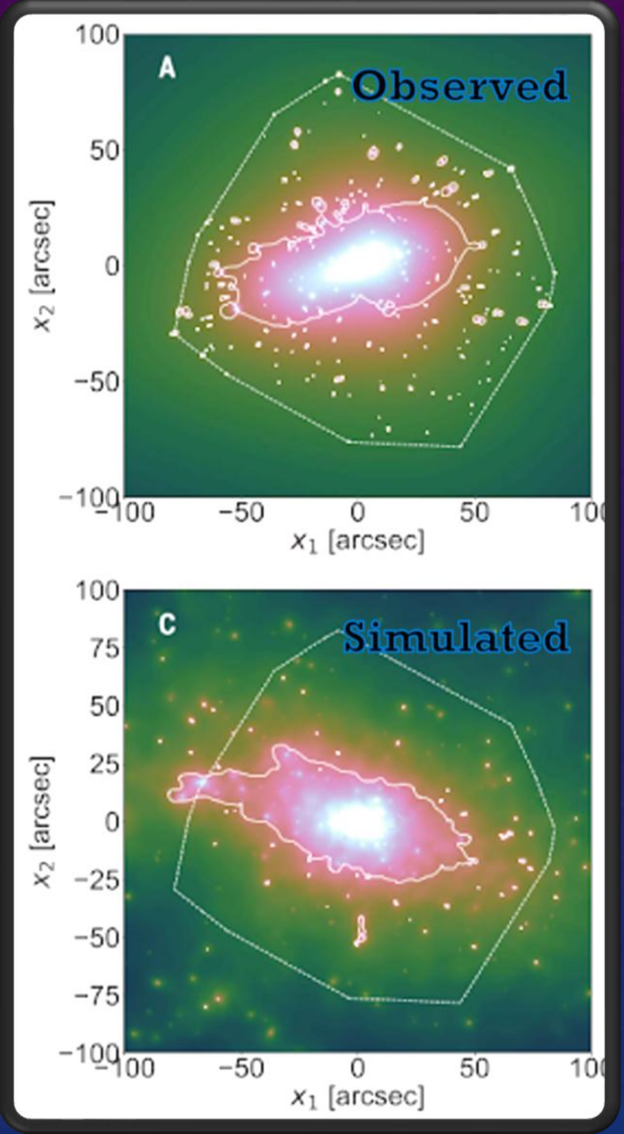
Efficient in SIDM, because $t_r \sim 1/(n\sigma v)$

Core collapse: more dense
Mass segregation: more dense
& **more massive**

SIDM03 in orange
SIDM2c in red, constant cross sections picked s.t. they leads to similar dwarf scale effects



Further GGSL related discussion

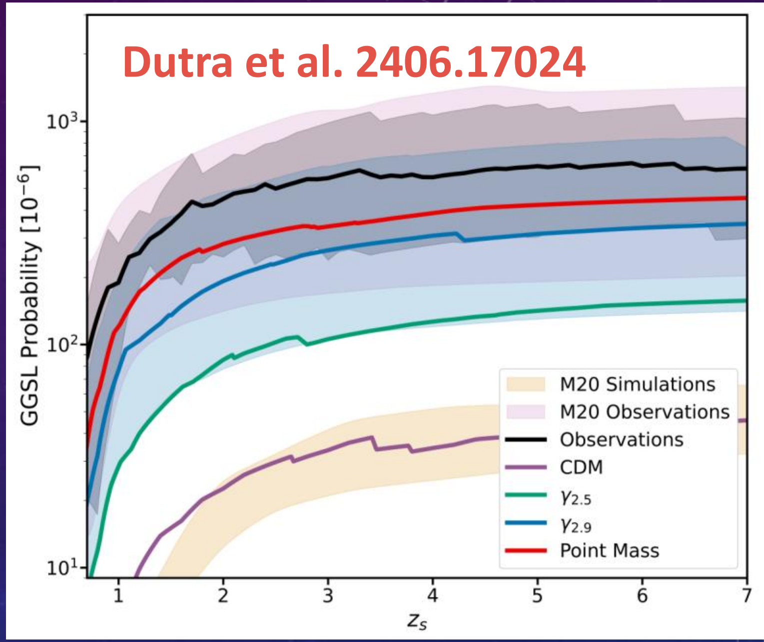


Meneghetti+2009.04471 (*Science*)
on Galaxy-Galaxy strong lensing (GGSL)

Baryonic solutions?
Y. Bahé, Jan 2021
& A. Robertson, Jan 2021
Results driven by 1 or 2 massive substructures

Novel dark matter solutions?

- Enhanced structure formation?
- Dissipative SIDM?
- SIDM? (Yang&Yu 2021)
- *SIDM with mass segregation*



Denser halo distribution is favored…
Inner density slope as dense as -2.5 can marginally match the observation

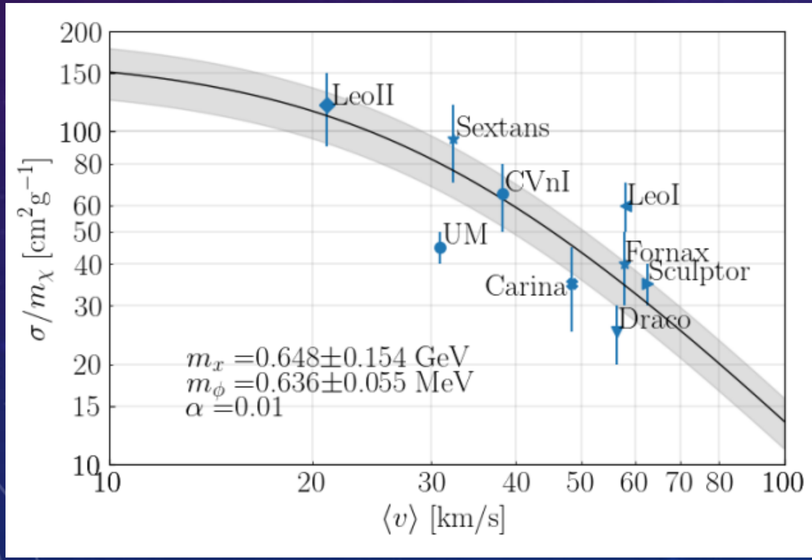
Yang & Yu 21: SIDM core collapse boost Radial GGSL, i.e., do not significantly affect 4-image events…

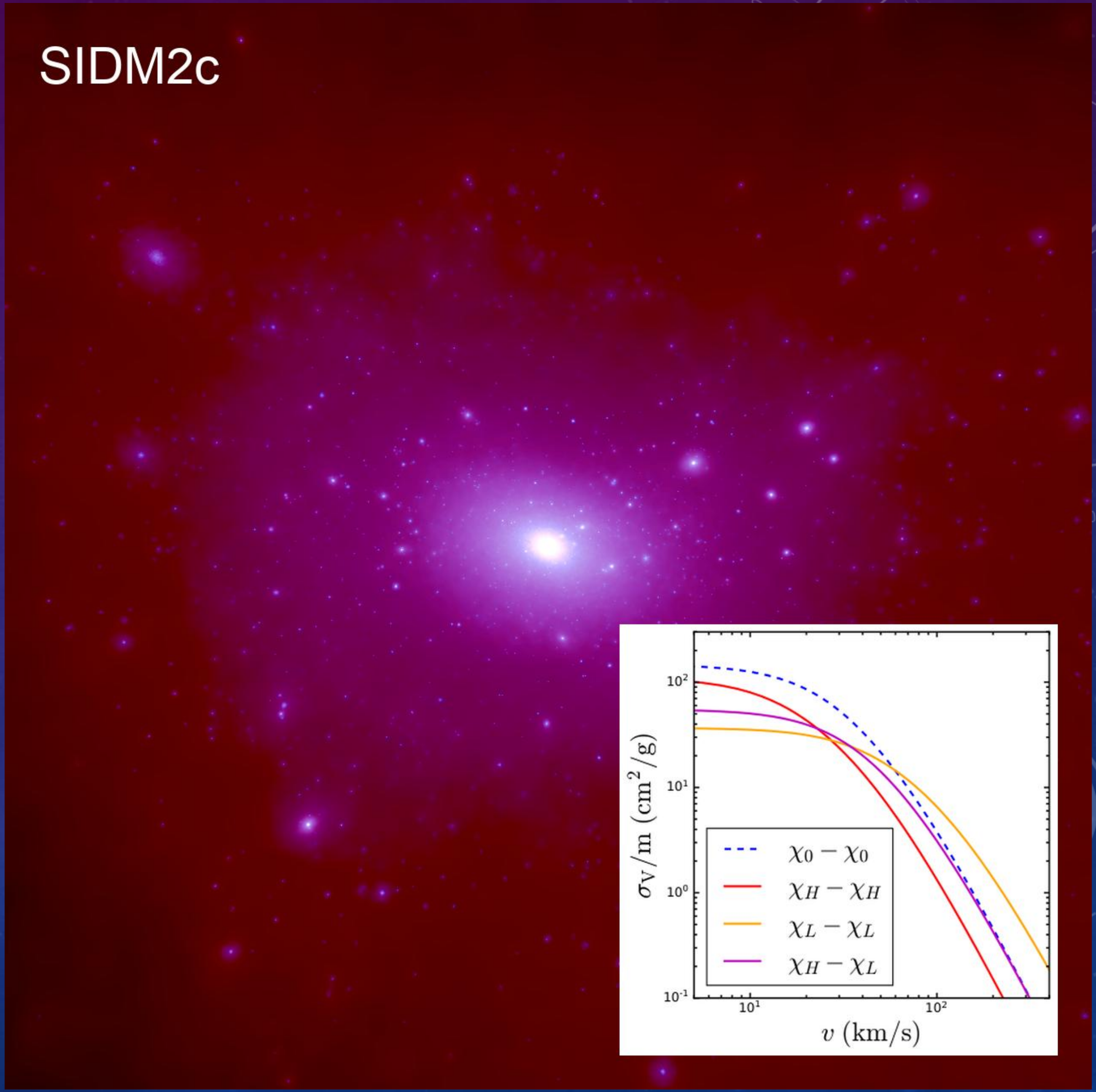
Our first paper on SIDM with mass segregation:

arXiv:2504.02303 with Yue-Lin Sming Tsai , Yi-Zhong Fan (PMO)

Strong SIDM with mass segregation in a Milky-Way like system

Correa 2020, MNRAS

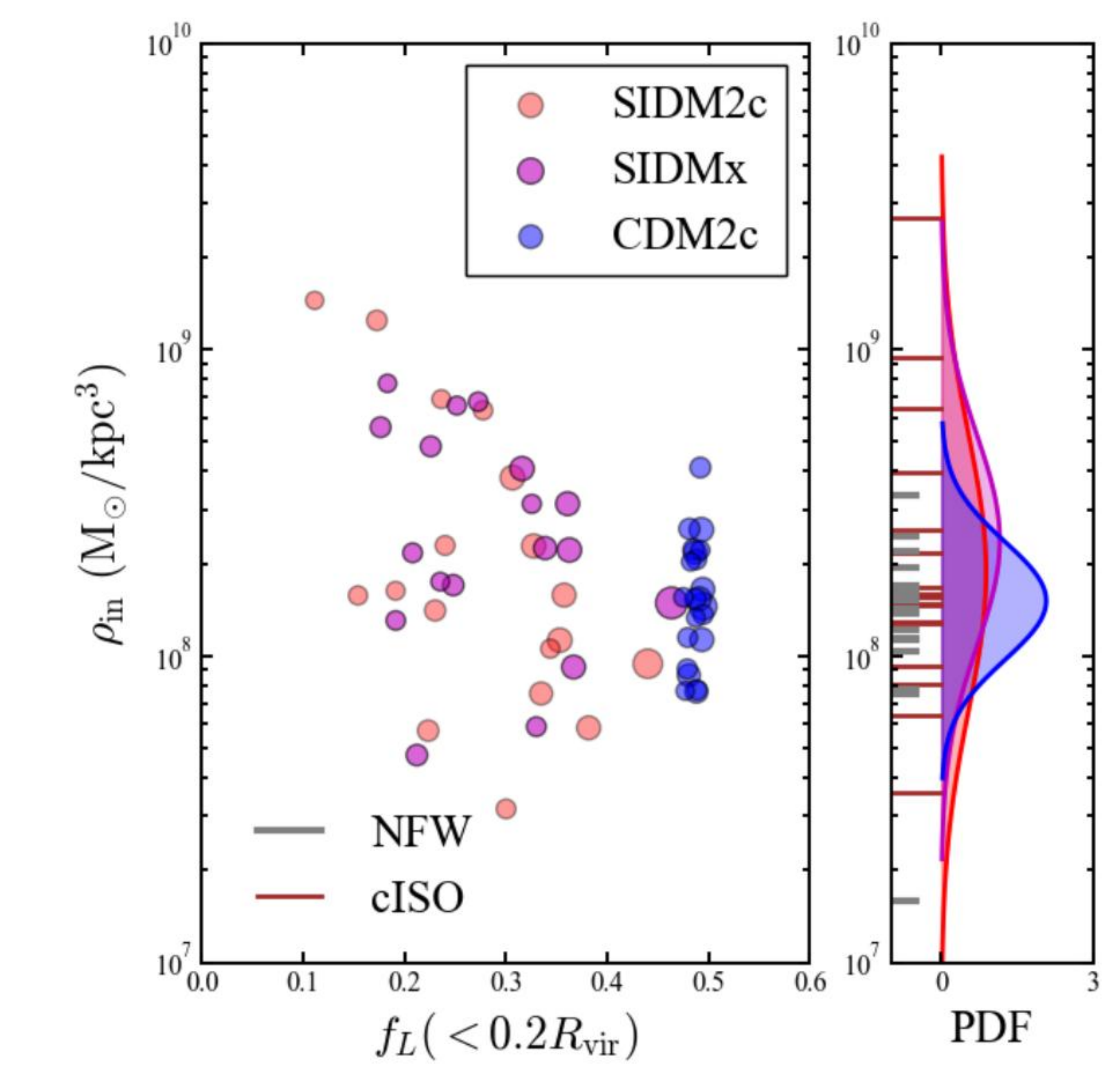




arXiv:2504.02303 with Yue-Lin Sming Tsai， Yi-Zhong Fan (PMO)

Mass segregation contributes a new d.o.f. in reshaping the diversity…

- Stronger segregation -> higher inner densities
- SIDM of the inner heavy component has gravothermal evolution (core & cusp)



Scatterings	Mass relation	$\frac{\sigma_0}{m}$ relation	w (km/s) relation
$\chi_0 - \chi_0$	$m_0 = \frac{2}{3} m_H$	$\frac{\sigma_M}{m_0} = 147.1\ \frac{\mathrm{cm}^2}{\mathrm{g}}$	$w_M = 24.33\ \frac{\mathrm{km}}{\mathrm{s}}$
$\chi_H - \chi_H$	$m_H = \frac{3}{2} m_0$	$\frac{\sigma_H}{m_H} = \frac{3}{2} \frac{\sigma_M}{m_0}$	$w_1 = \frac{2}{3} w_M$
$\chi_L - \chi_L$	$m_L = \frac{1}{3} m_H$	$\frac{\sigma_L}{m_L} = \frac{1}{3} \frac{\sigma_H}{m_H}$	$w_2 = 3 w_1$
$\chi_H - \chi_H$	$m_H = 3 m_L$	$\frac{\sigma_x}{m_H} = \frac{1}{4} \frac{\sigma_H}{m_H}$	$w_x = 2 w_1$

TABLE II. SIDM model parameters for different scattering processes in a dark QED theory with fixed m_V and α_D. The mass assignments ensure the total particle number remains the same in all simulations.