SIDM (Sub)halos in Milky Way and Strong Lens Analogs

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Pollica SIDM 2023

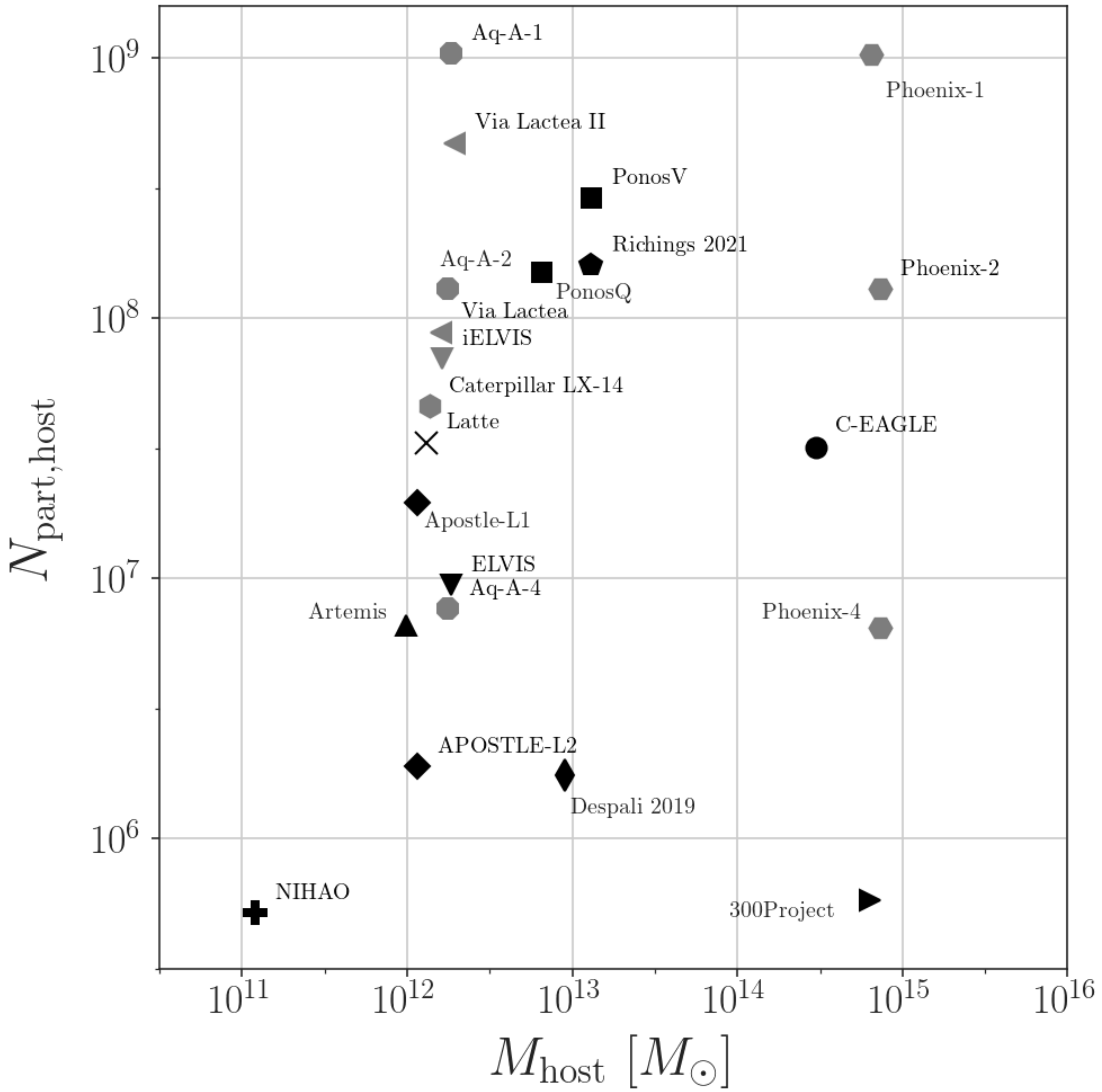
6/27/2023

Carnegie Science

USC University of Southern California

Landscape of Cosmological Zoom-in Simulations

- Zoom-in suites have largely focused on Milky Way and cluster-mass hosts
- Milky Way zoom-ins often do not match key constraints on the MW's formation history and satellite population
- Few zoom-ins target low or intermediate host masses, e.g. LMC and strong lens analogs (galaxy groups)

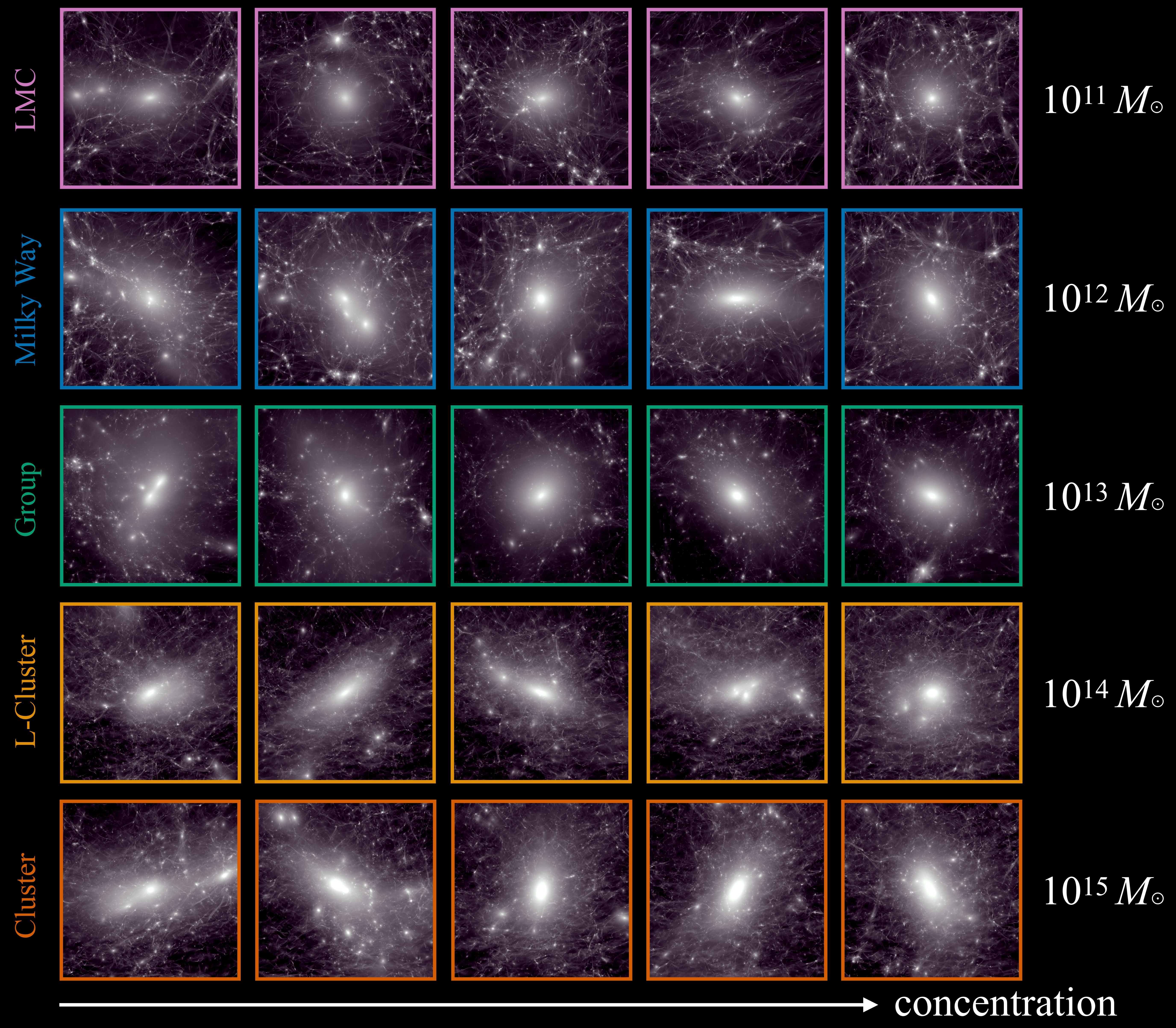


EN, Mansfield, Wang et al., 2209.02675

Symphony Zoom-in Simulations

- **262** high-resolution cosmological zoom-in simulations spanning 4 decades of host halo mass
- Includes the first large suites of **LMC** and **strong lens analog** host halos
- Run with a unified simulation and analysis code pipeline; all data is publicly available!

web.stanford.edu/group/gfc/symphony

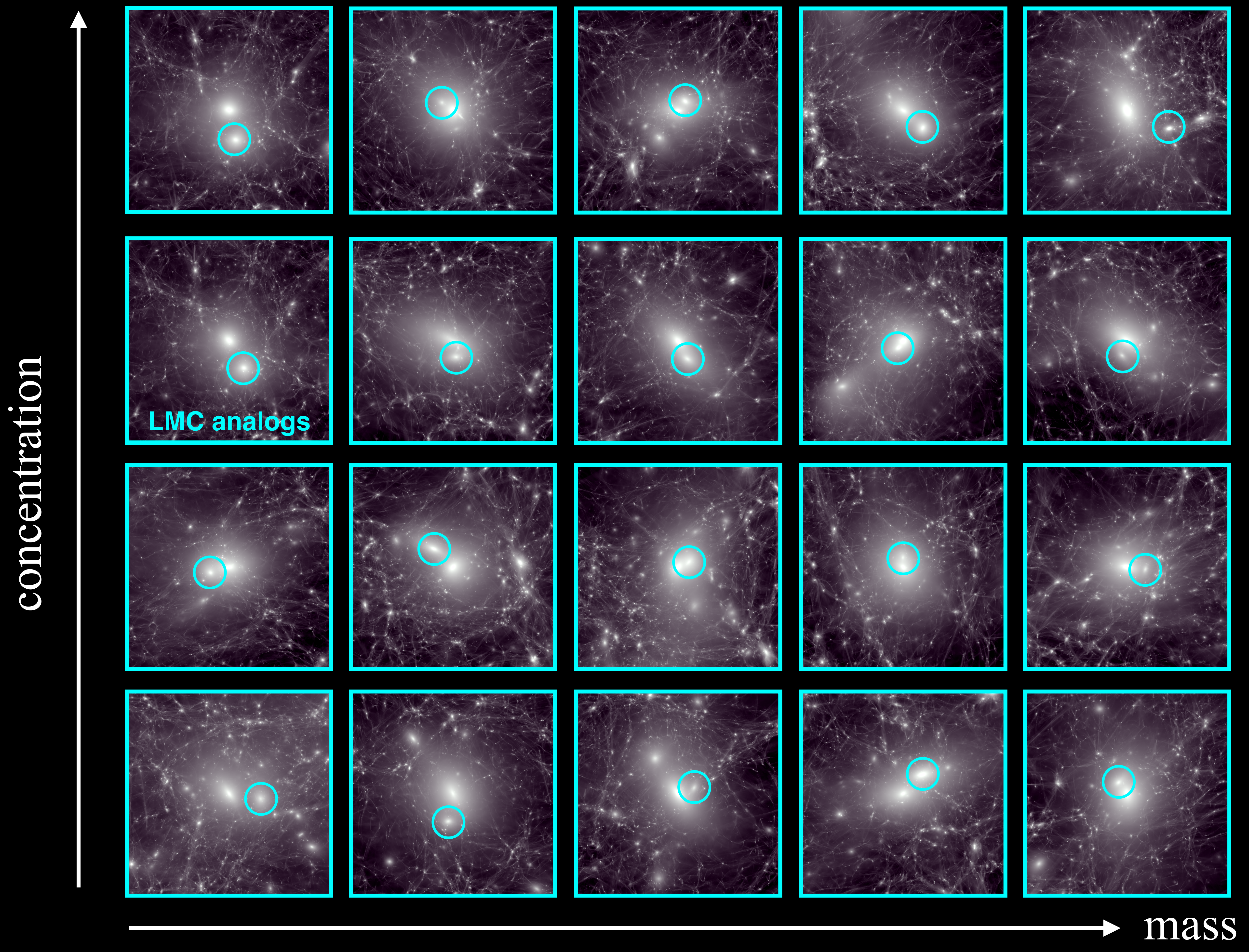


EN, Mansfield, Wang et al. (2209.02675)

Milky Way-est Zoom-in Simulations

- **20** high-resolution cosmological zoom-in simulations of Milky Way-like systems
- All realizations include **LMC** and ***Gaia*-Enceladus** analogs

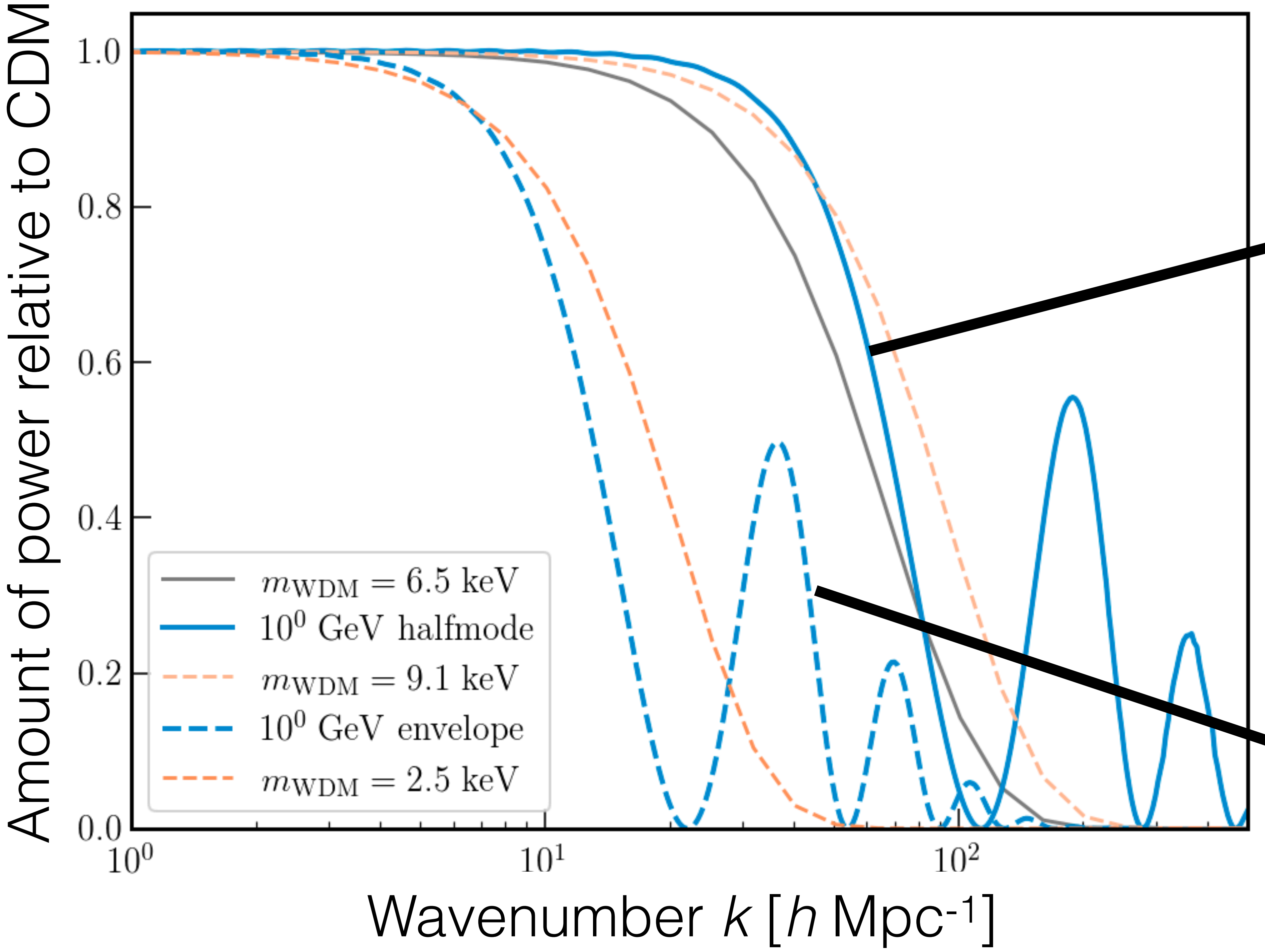
Deveshi Buch
(Stanford)

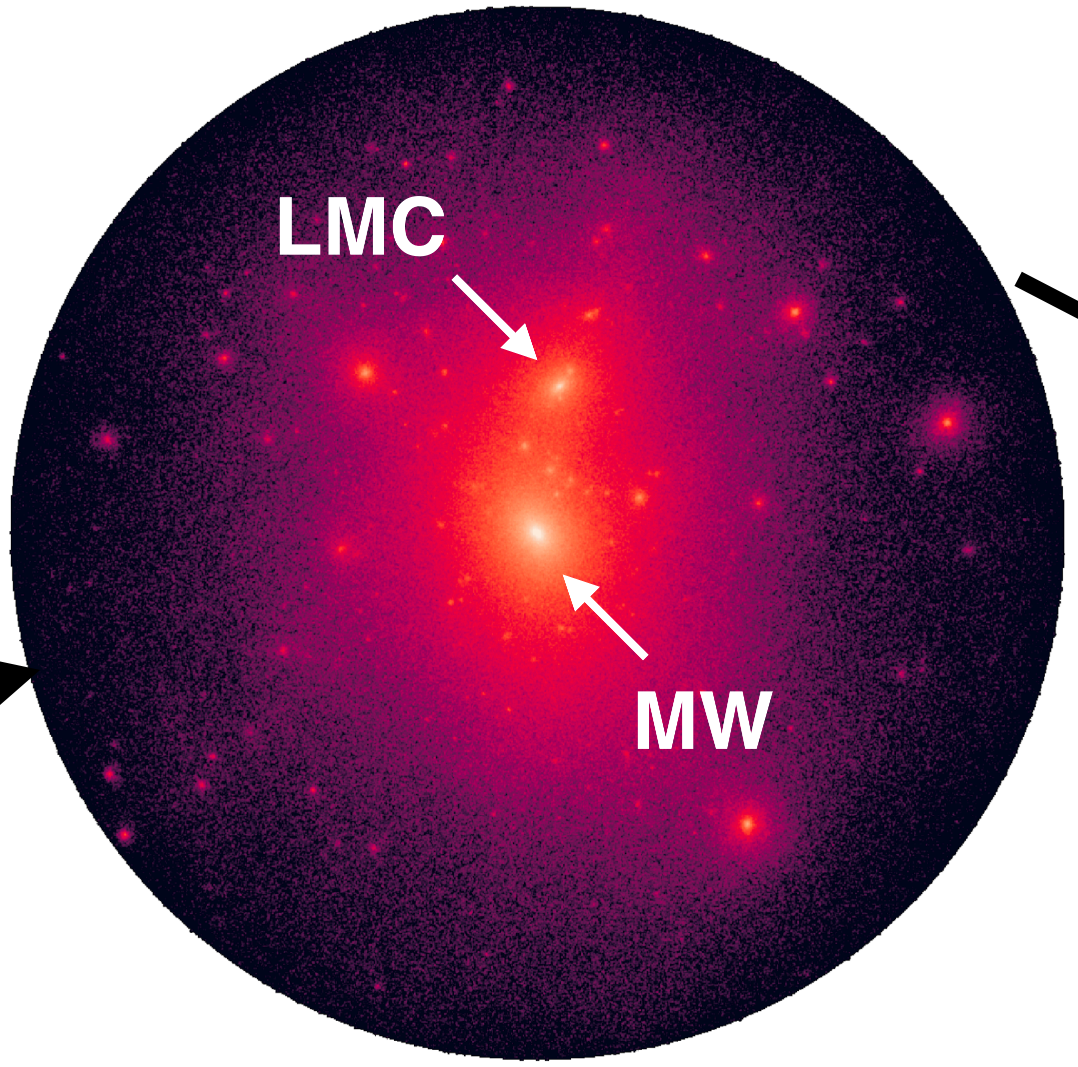


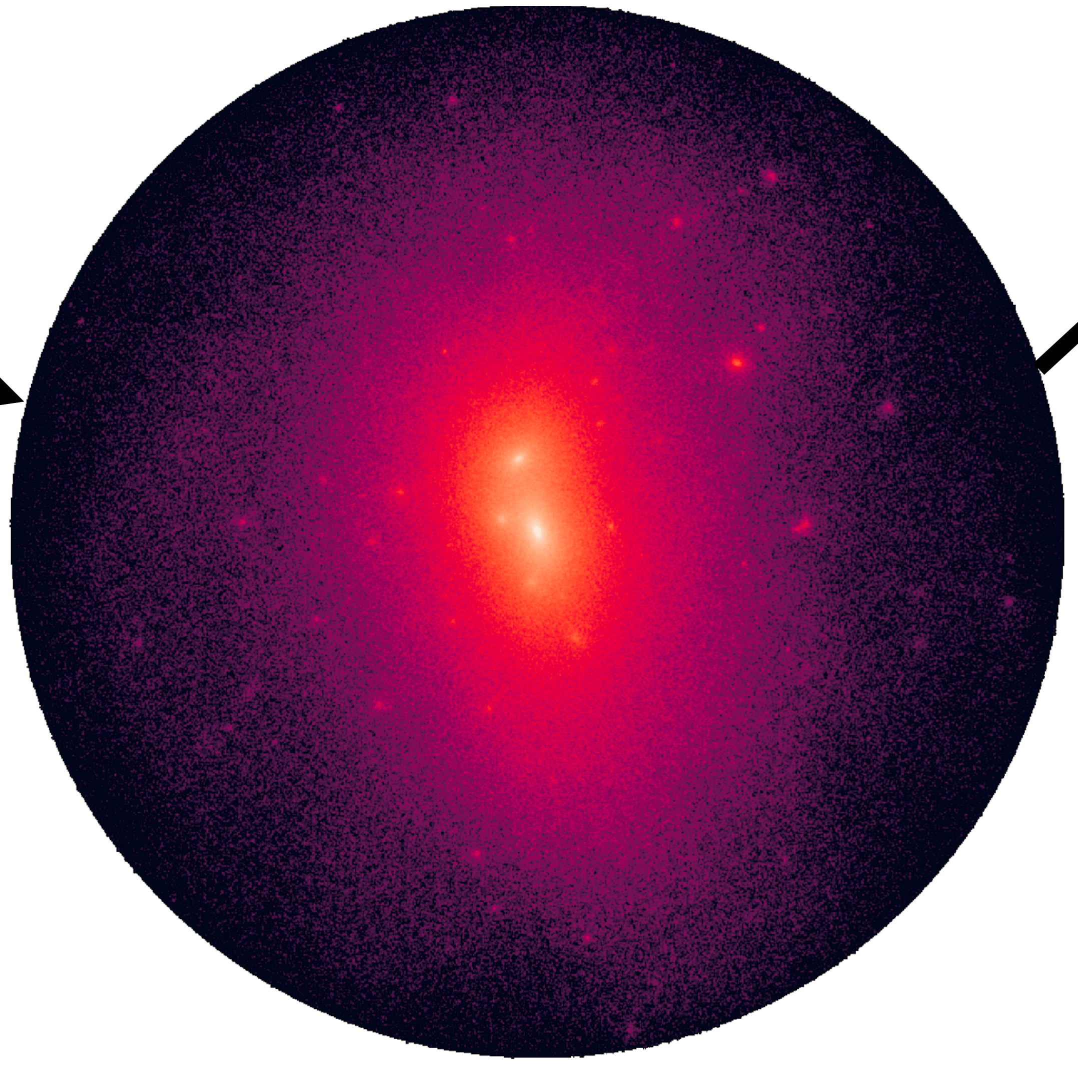
Buch & EN et al. in prep.

Beyond-CDM Zoom-in Simulations

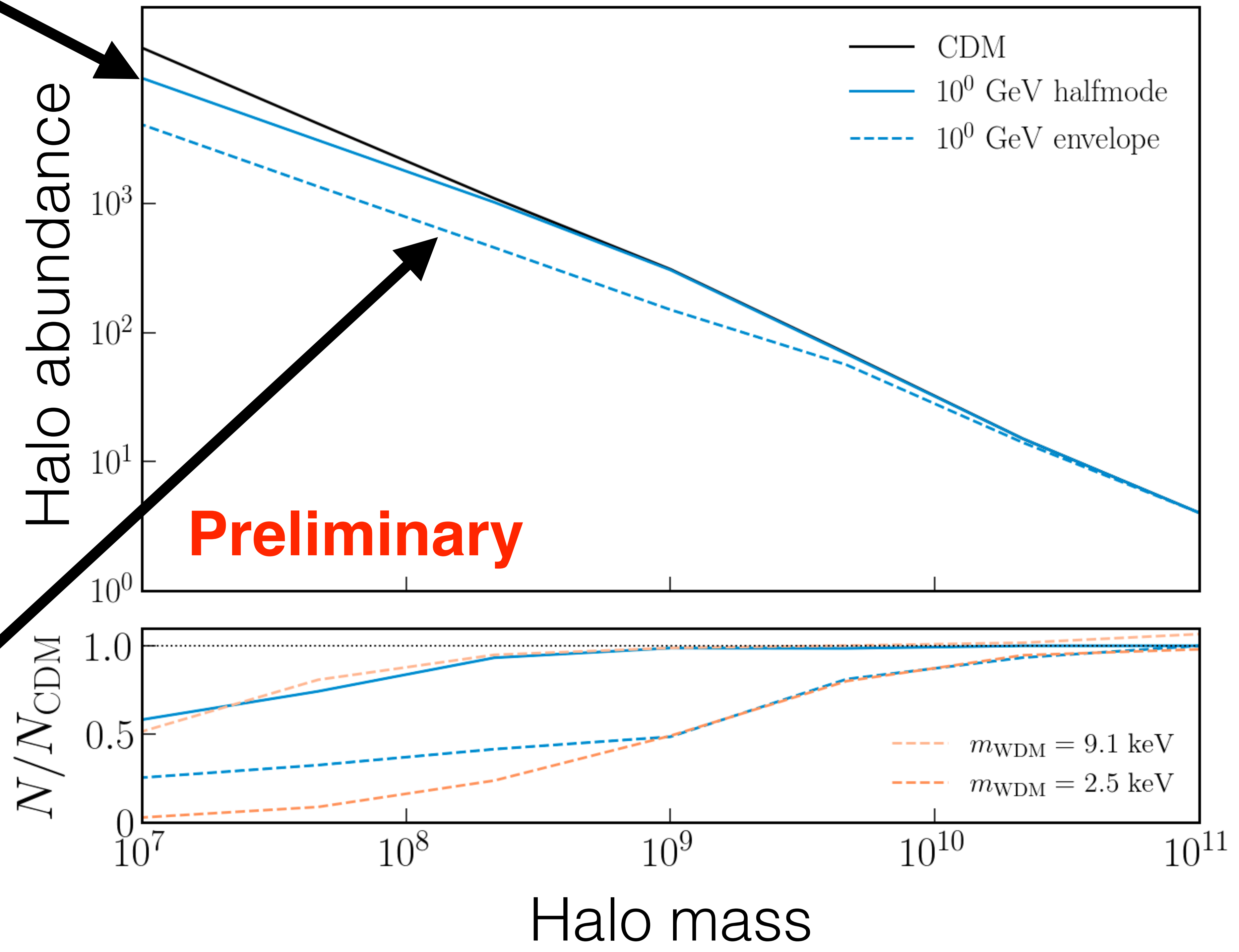
Initial conditions from linear theory







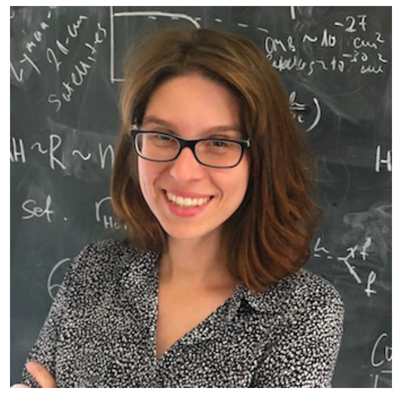
Halo and subhalo populations



100+ high-resolution cosmological zoom-ins of MW-like systems: ICs for **warm**, **interacting**, **fuzzy** dark matter

Rui An (USC)

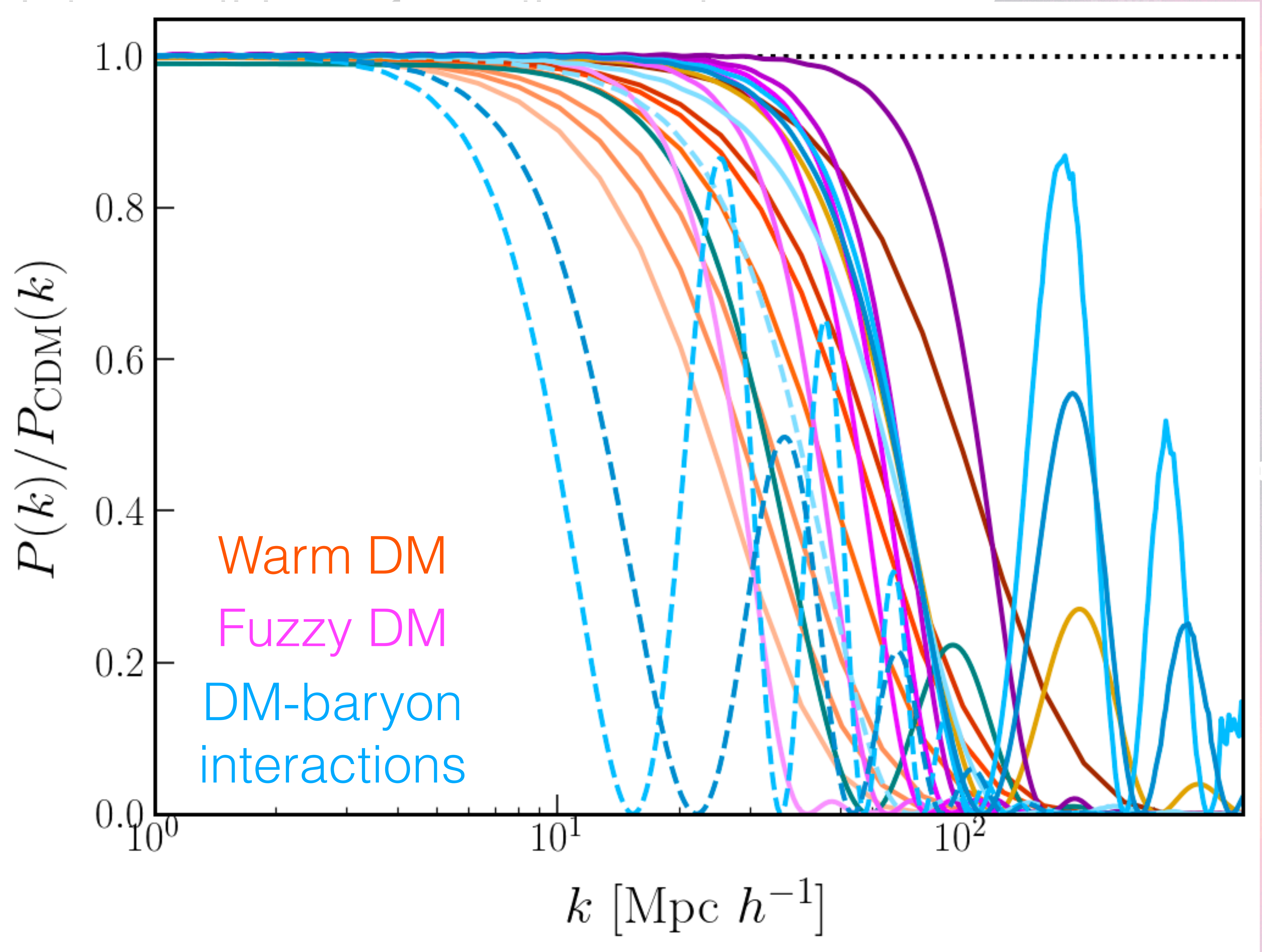
Andrew Benson (Carnegie)

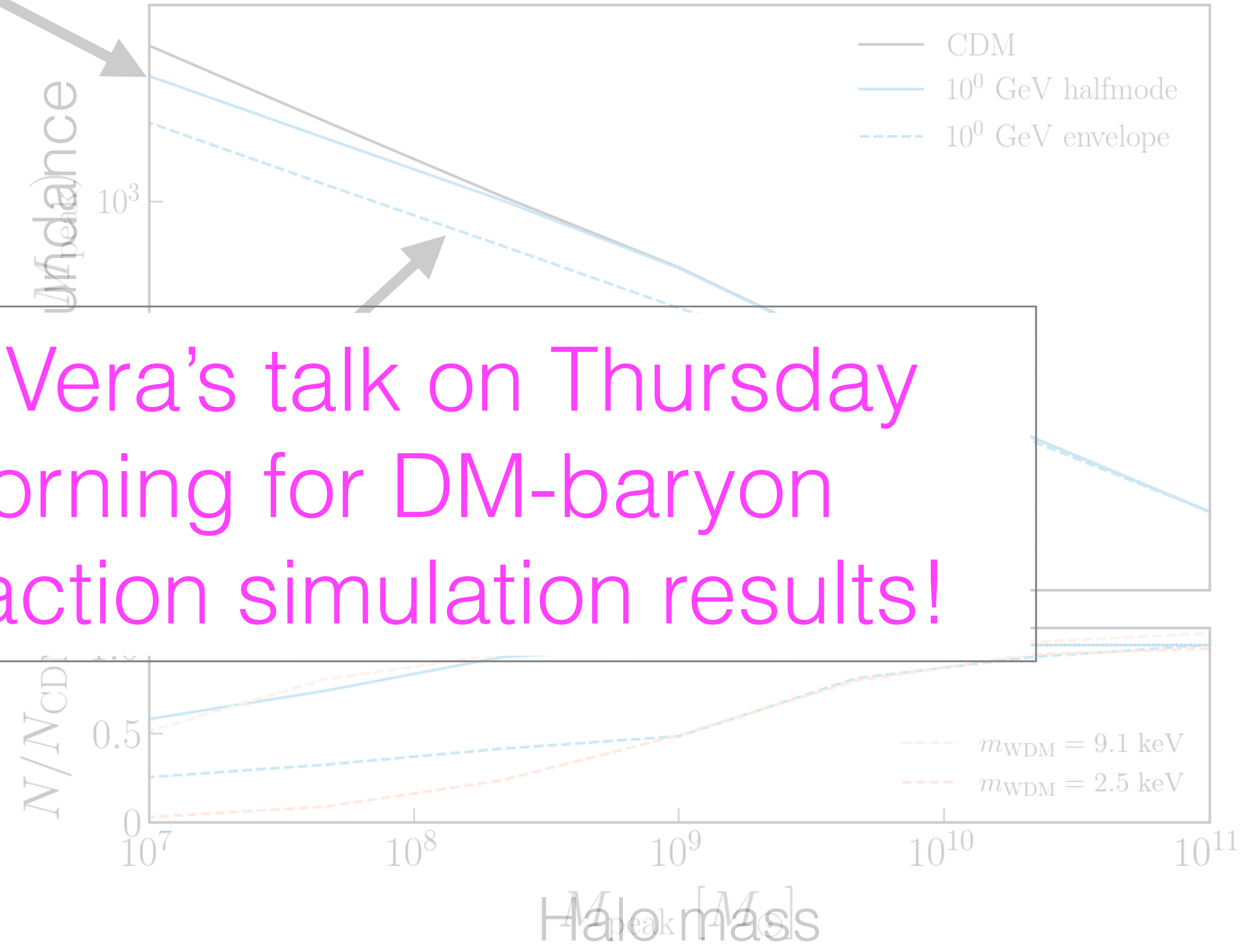


Vera Gluscevic (USC)

EN et al. in prep.

Beyond-CDM Zoom-in Simulations





See Vera's talk on Thursday morning for DM-baryon interaction simulation results!

100+ cosmological simulations of MW-like systems with initial conditions for warm, interacting, fuzzy dark matter

Rui An (USC)

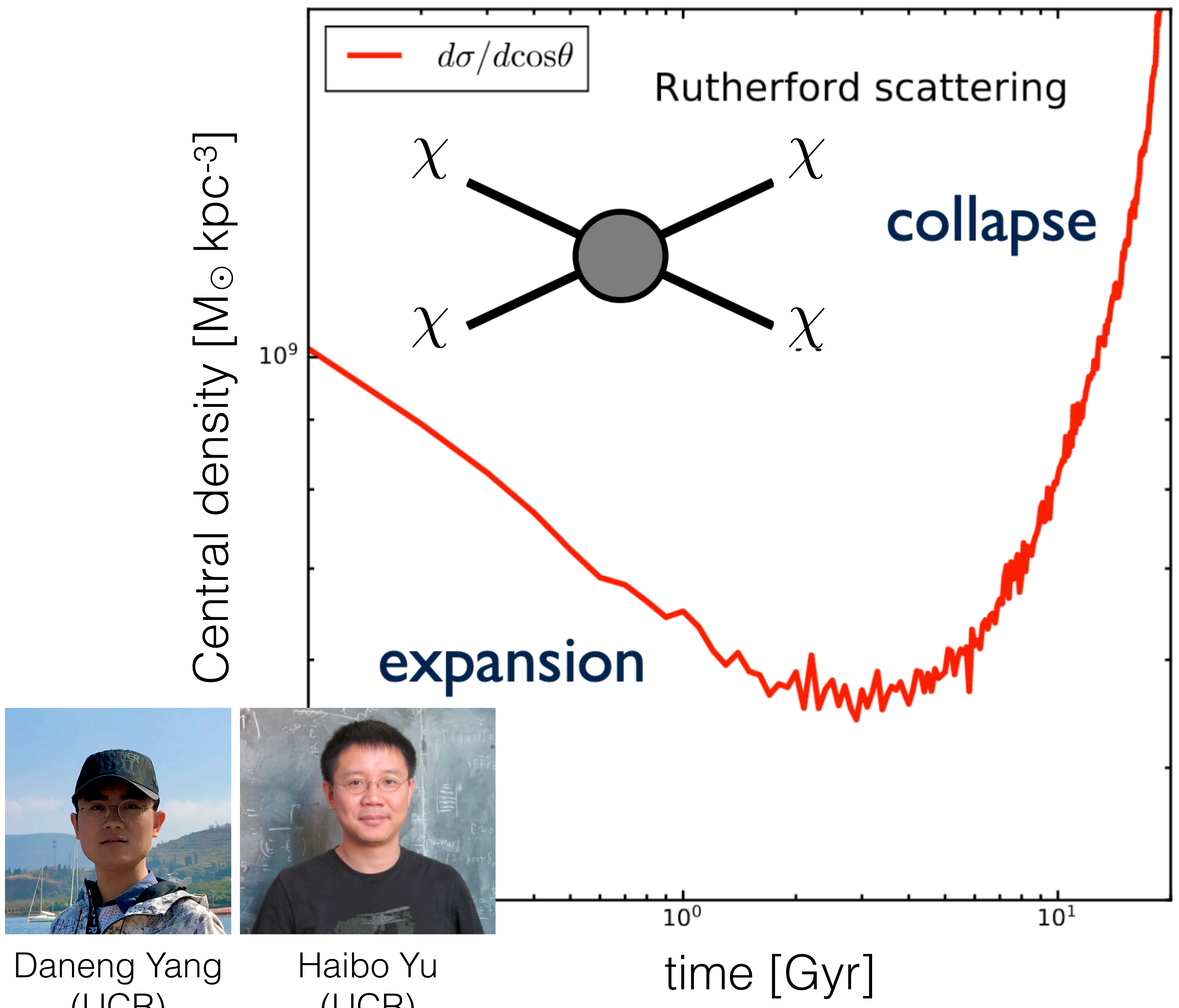
Andrew Benson (Carnegie)

Vera Gluscevic (USC)

EN et al. in prep.

Simulating Strong Dark Matter Self-interactions

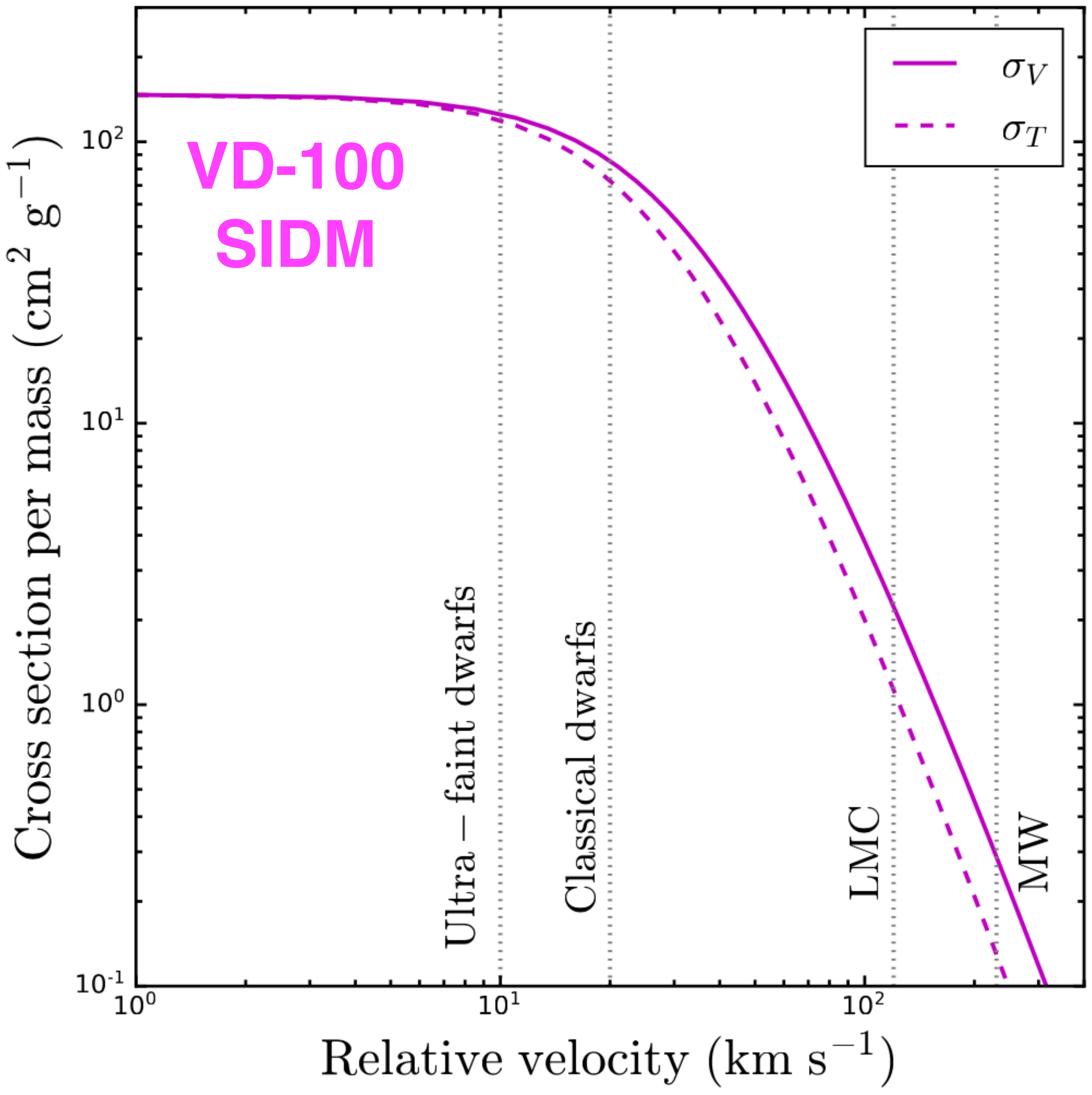
Yang & Yu 2022 (2205.03392)



Daneng Yang (UCR)

Haibo Yu (UCR)

Yang, EN, Yu 2023 (2211.13768)

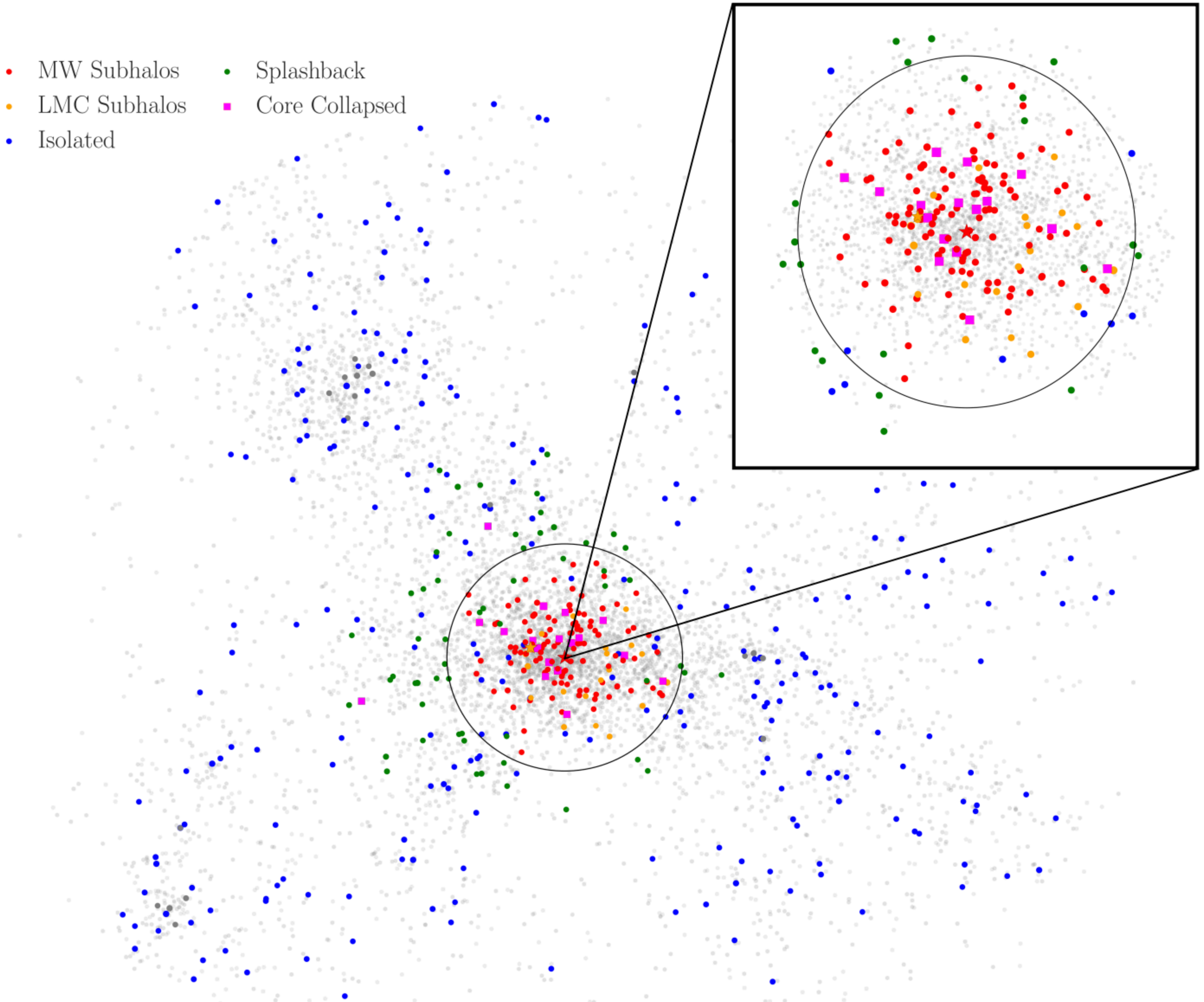


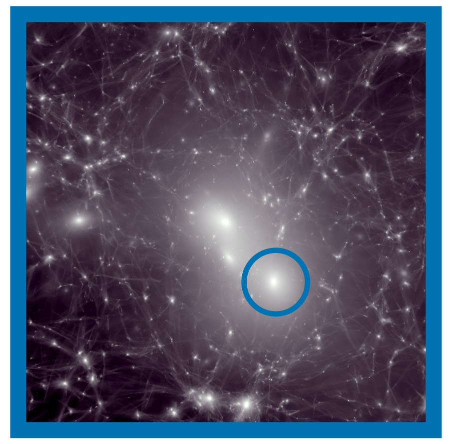
Strong, velocity-dependent self-interactions → core-collapse in small halos / core-formation in large halos

VD-100 SIDM

Milky Way Simulation

- High-resolution Milky Way (+LMC) zoom-in with strong, velocity-dependent DM self-interactions
- Self-consistent analysis of halos in all environments: isolated halos, subhalos, splashback halos,
- Core collapse in ~10% of isolated halos, **~20% of subhalos** down to $10^8\ M_\odot$

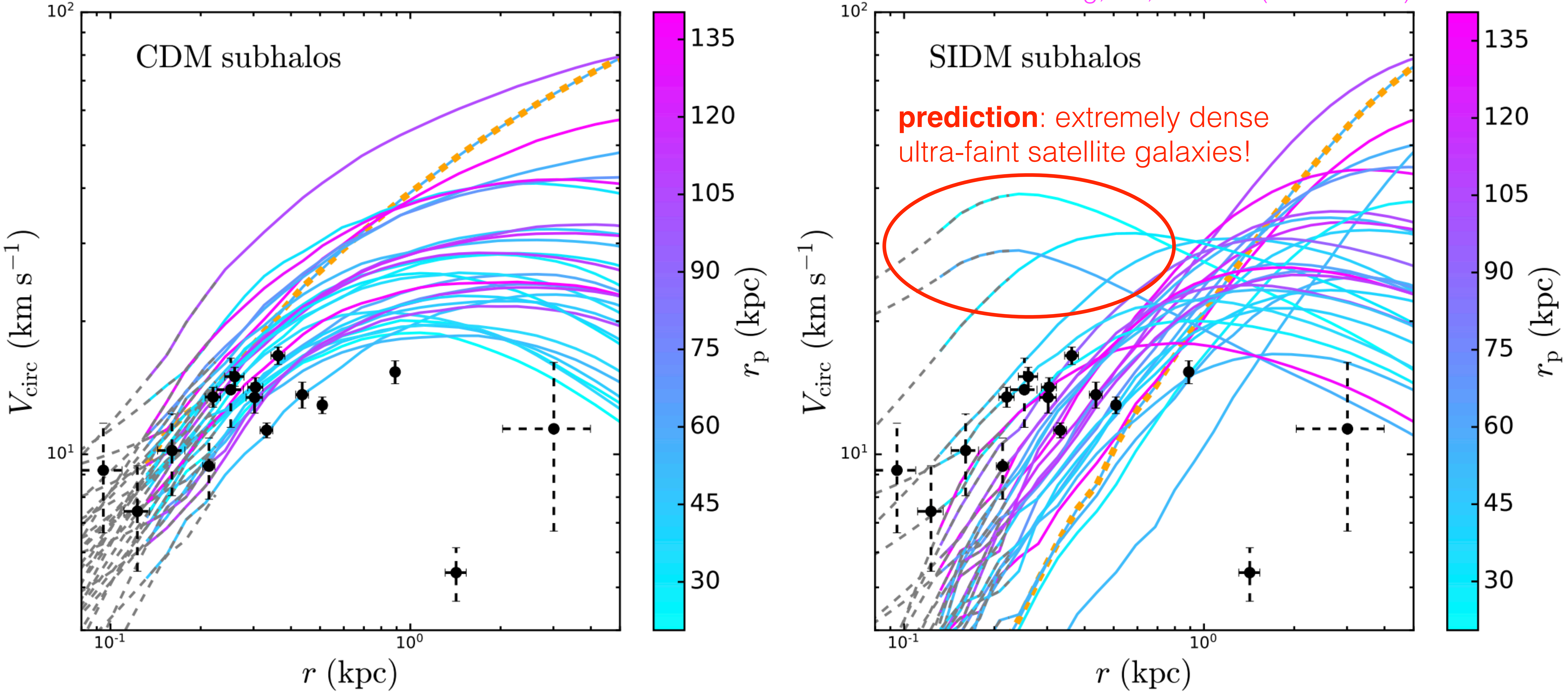




Yang, EN, Yu 2023 (2211.13768)

VD-100 SIDM Milky Way Simulation

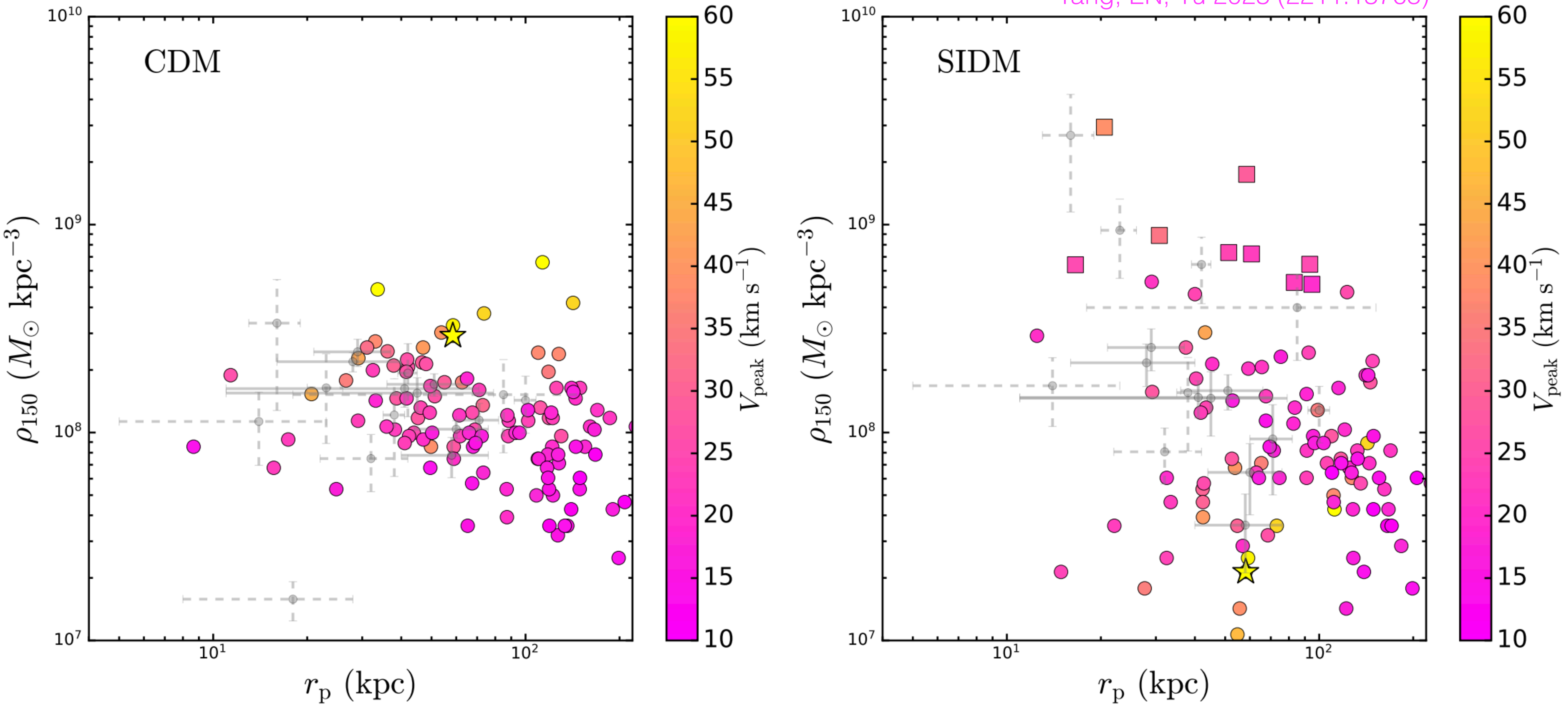
Yang, EN, Yu 2023 (2211.13768)



VD-100 diversifies subhalo profiles, alleviating “too big to fail” problem for brightest MW satellites

VD-100 SIDM Milky Way Simulation

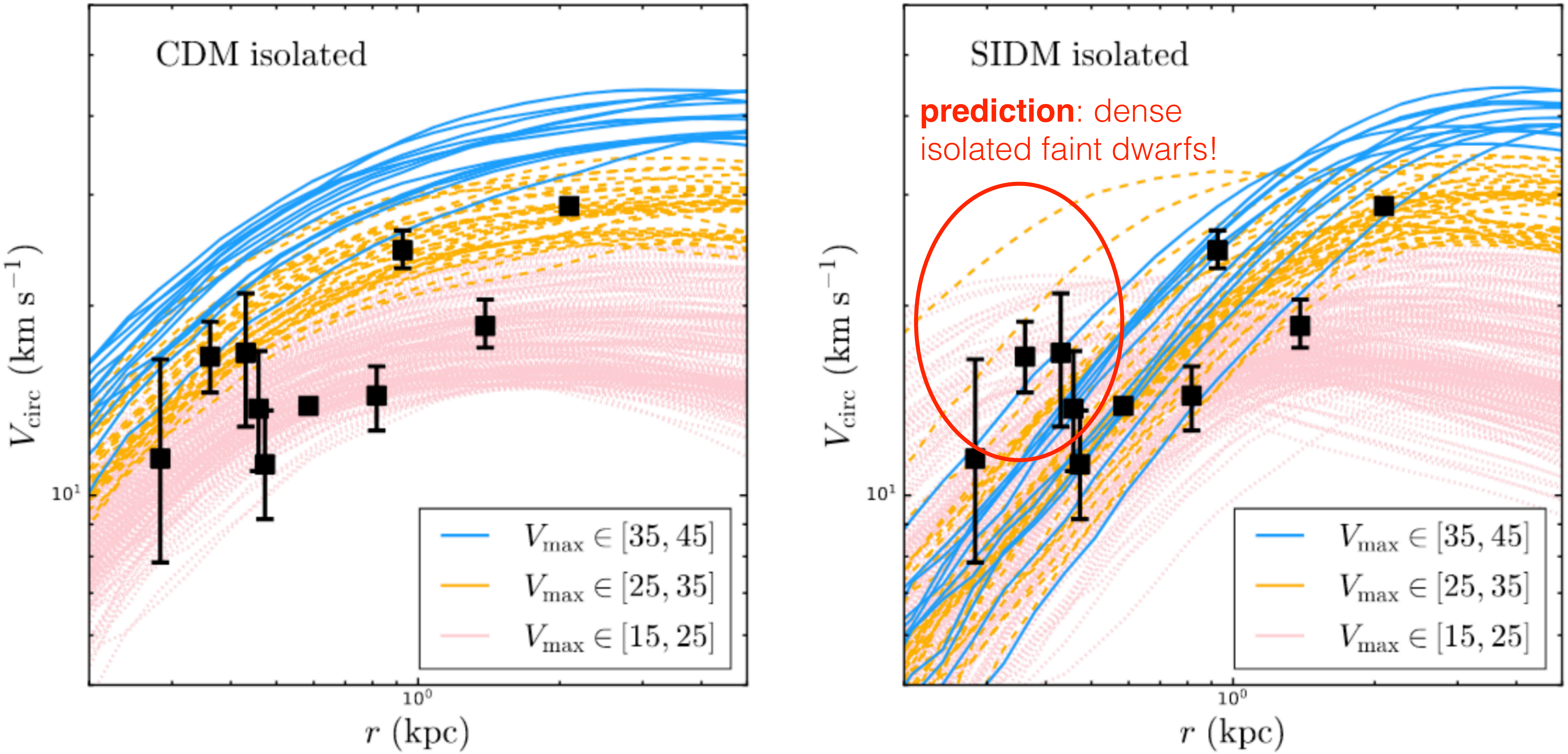
Yang, EN, Yu 2023 (2211.13768)



VD-100 diversifies central density-pericenter relation; velocity-independent SIDM <u>erases</u> anti-correlation

VD-100 SIDM Milky Way Simulation

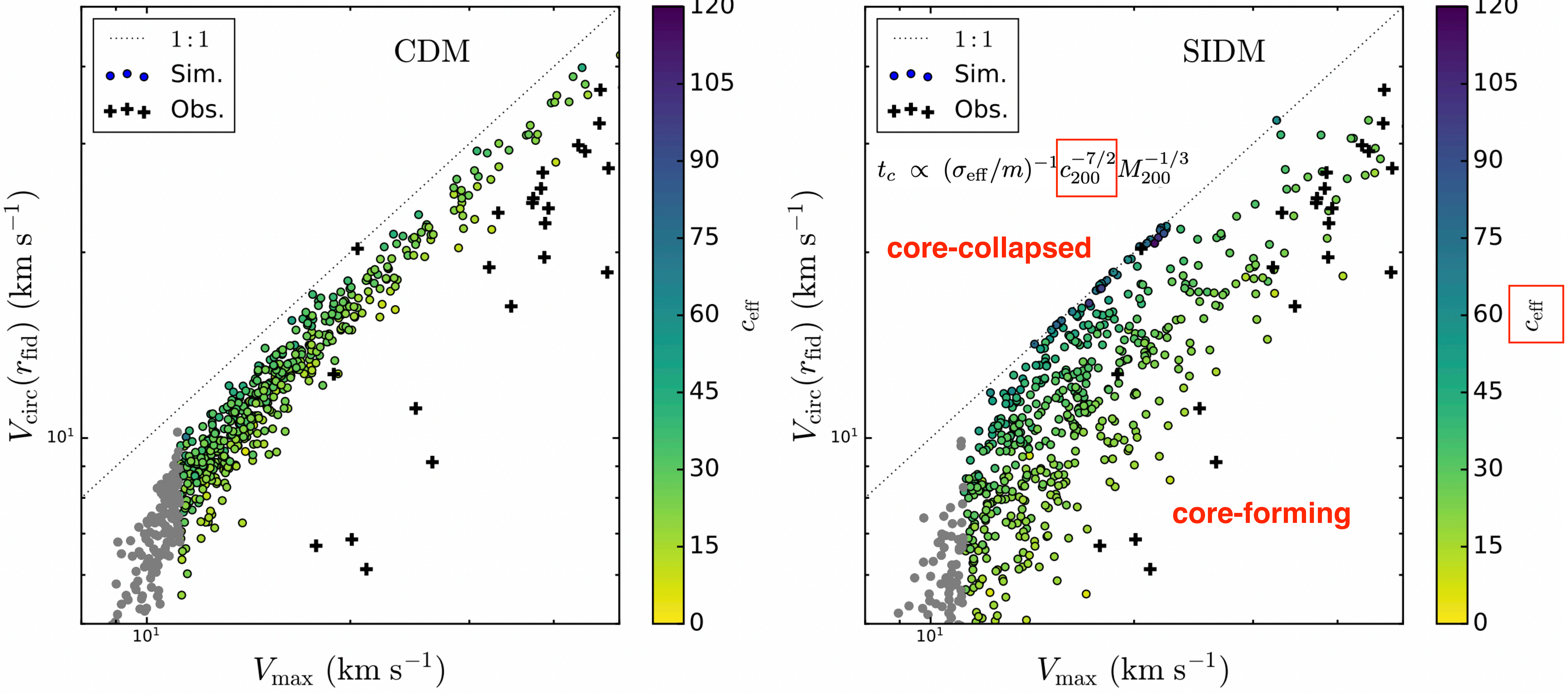
Yang, EN, Yu 2023 (2211.13768)



VD100 diversifies isolated halo profiles, alleviating “too big to fail” problem in the local field

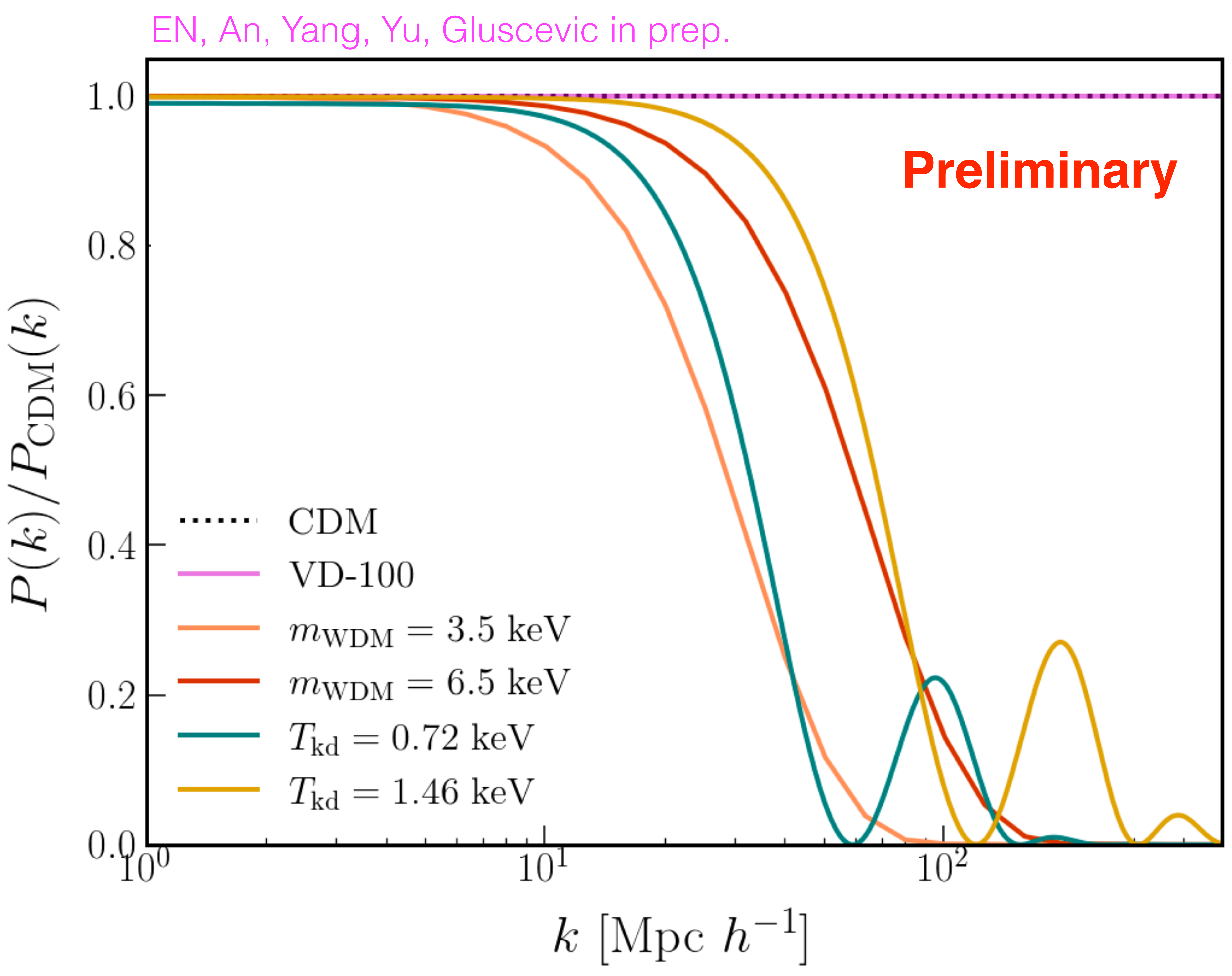
VD-100 SIDM Milky Way Simulation

Yang, EN, Yu 2023 (2211.13768)



VD-100 qualitatively reproduces observed rotation curve diversity due to core formation + collapse

Combining *P(k)* Suppression with Strong SIDM



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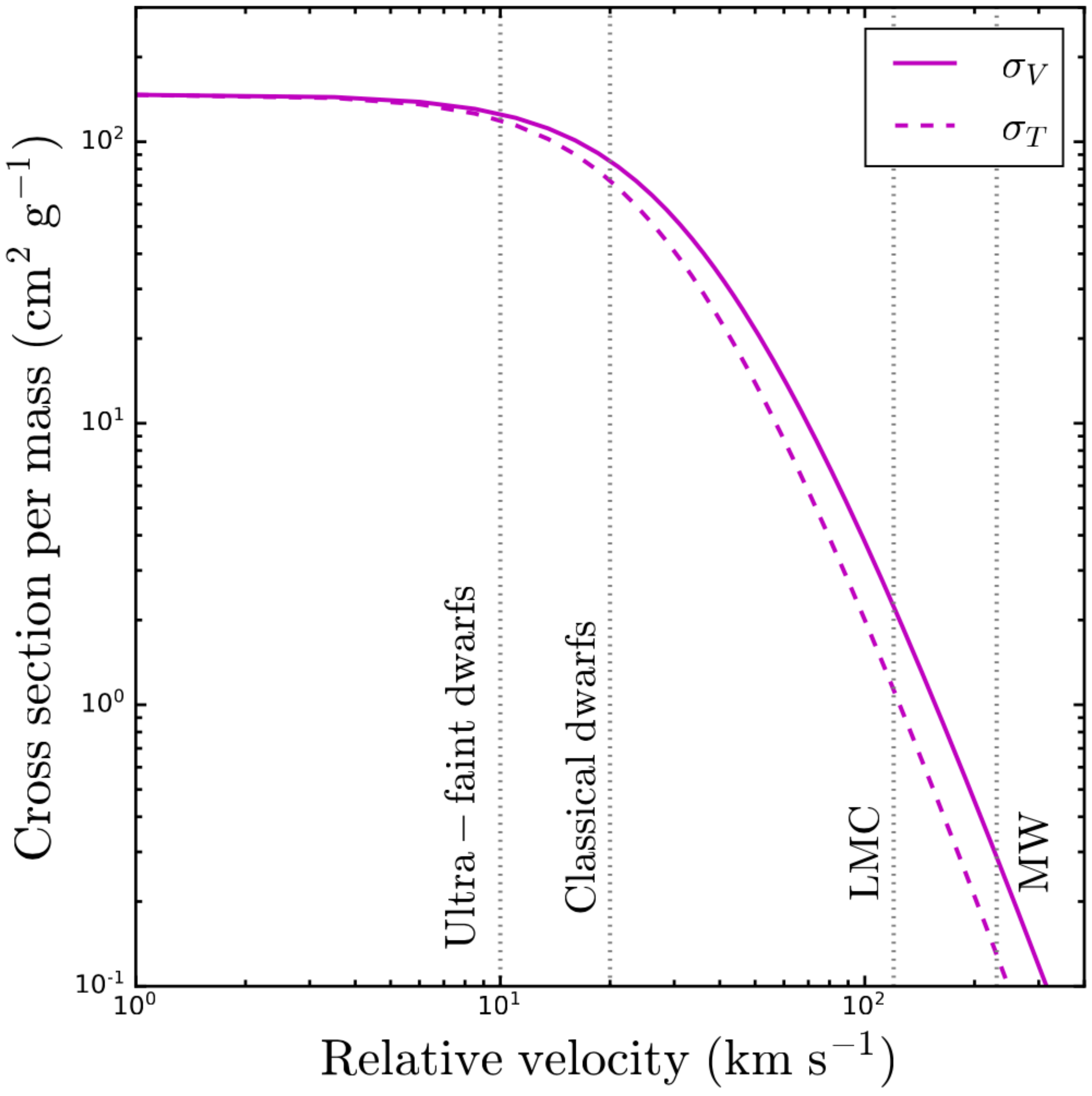
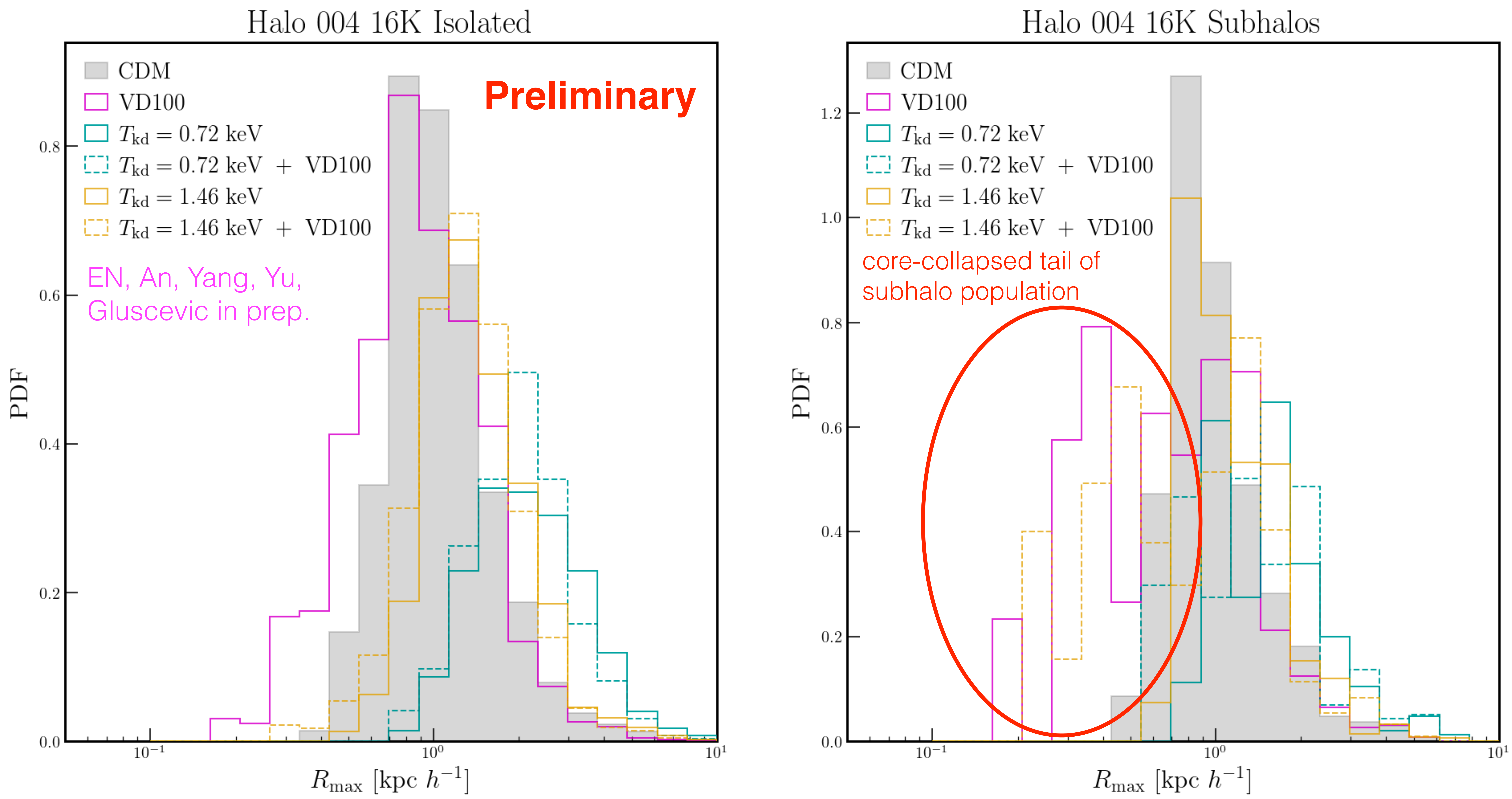


Combine VD-100 with self-consistent initial conditions; benchmark vs. *P(k)* or SIDM-only models

Combining *P(k)* Suppression with Strong SIDM

Halo mass function suppression mainly set by *P(k)*; self-interactions slightly enhance subhalo disruption

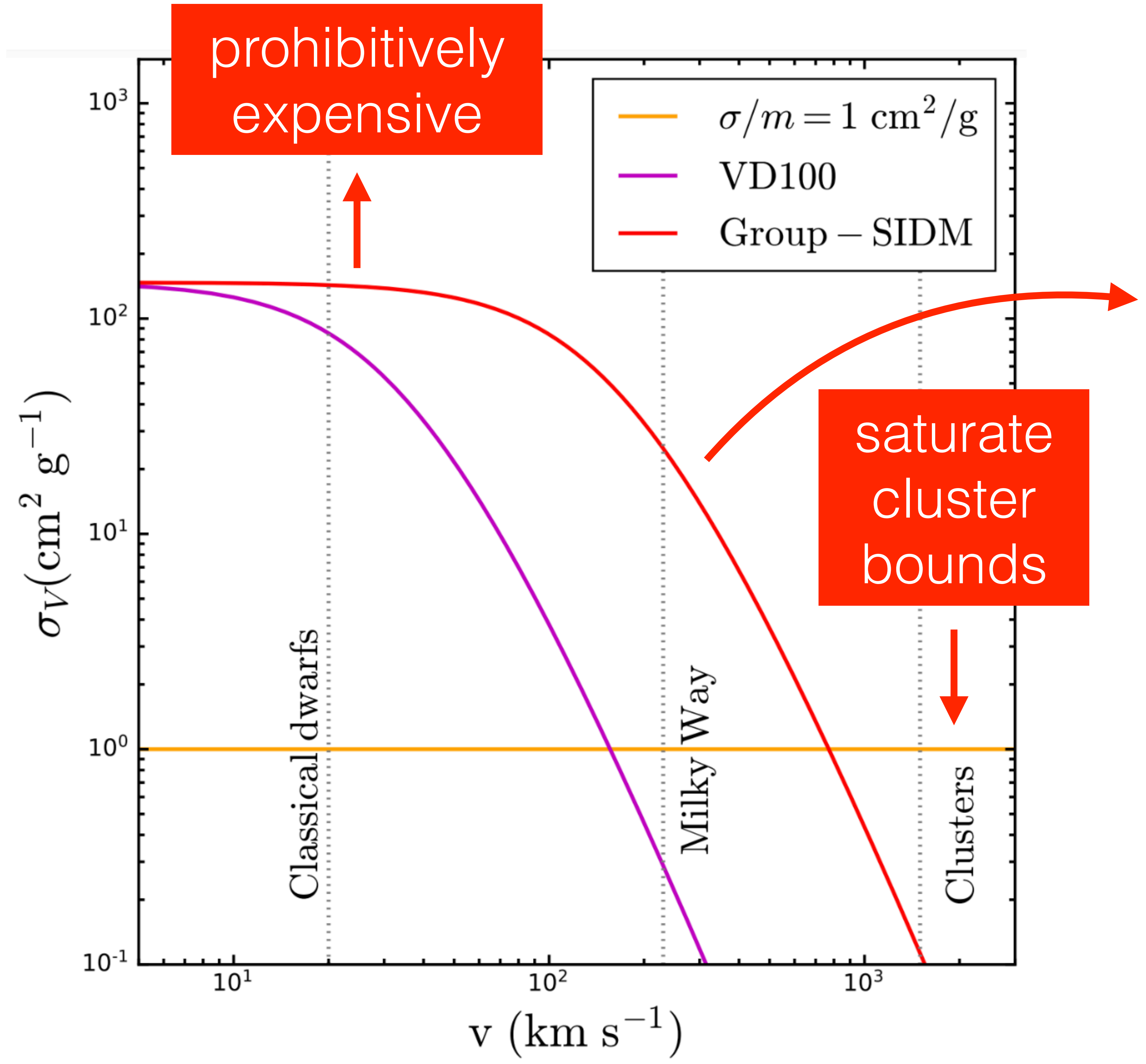
Combining *P(k)* Suppression with Strong SIDM

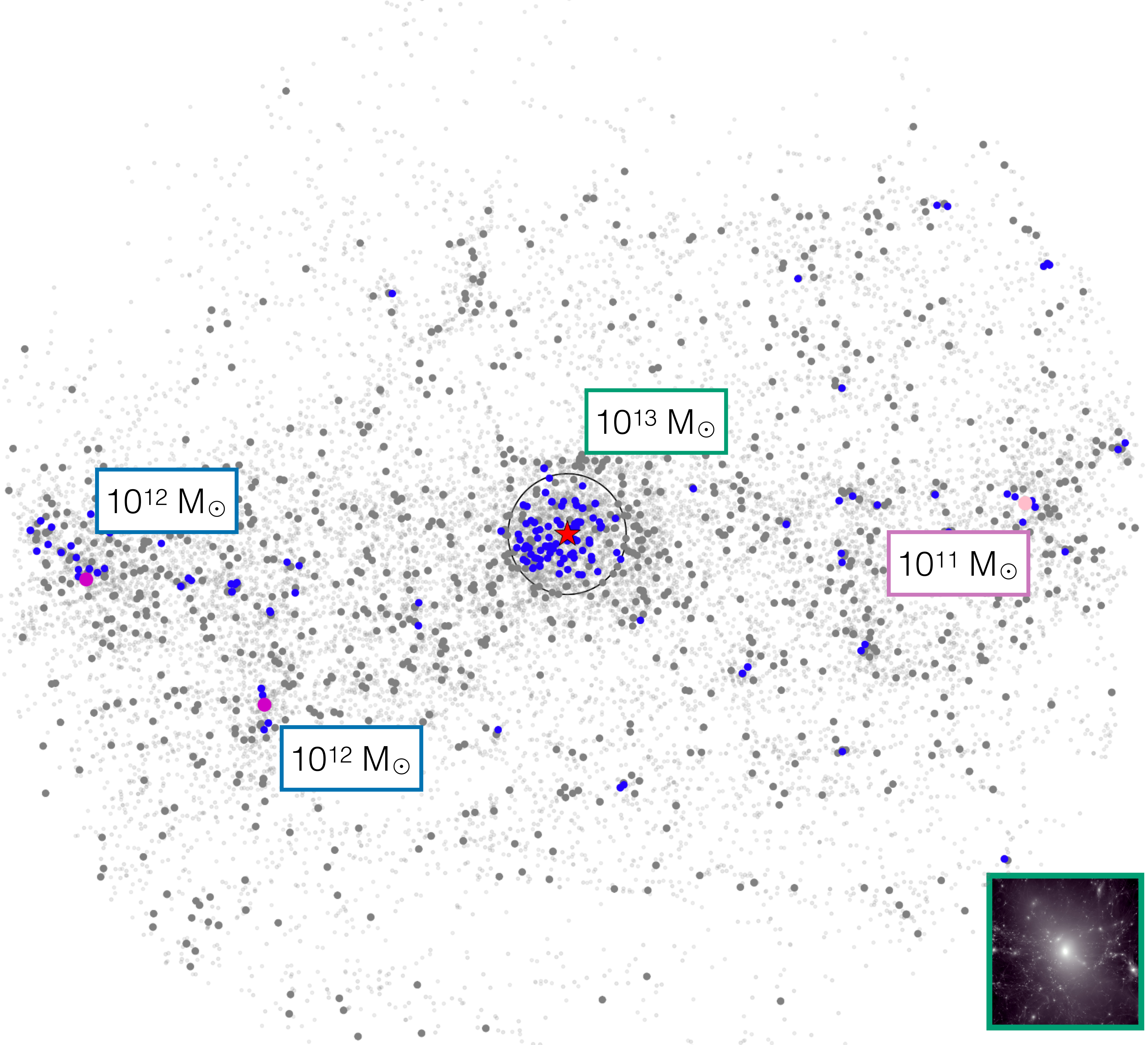


At current WDM limits, suppressed formation/growth of low-mass halos largely erases core collapse

Group-SIDM Strong Lens Analog Simulation

- First group-scale simulation with strong DM self-interactions

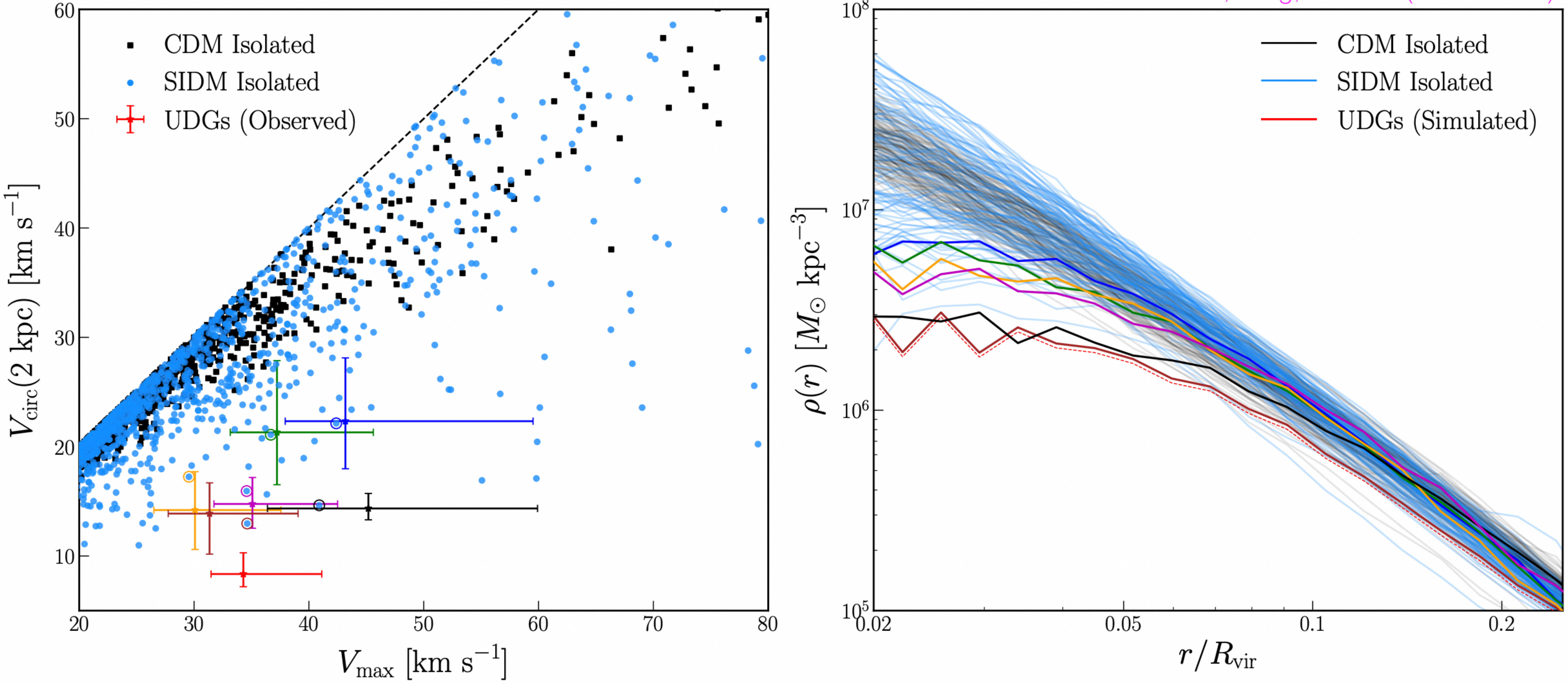




EN, Yang, Yu 2023 (2306.01830)

Group-SIDM Strong Lens Analog Simulation

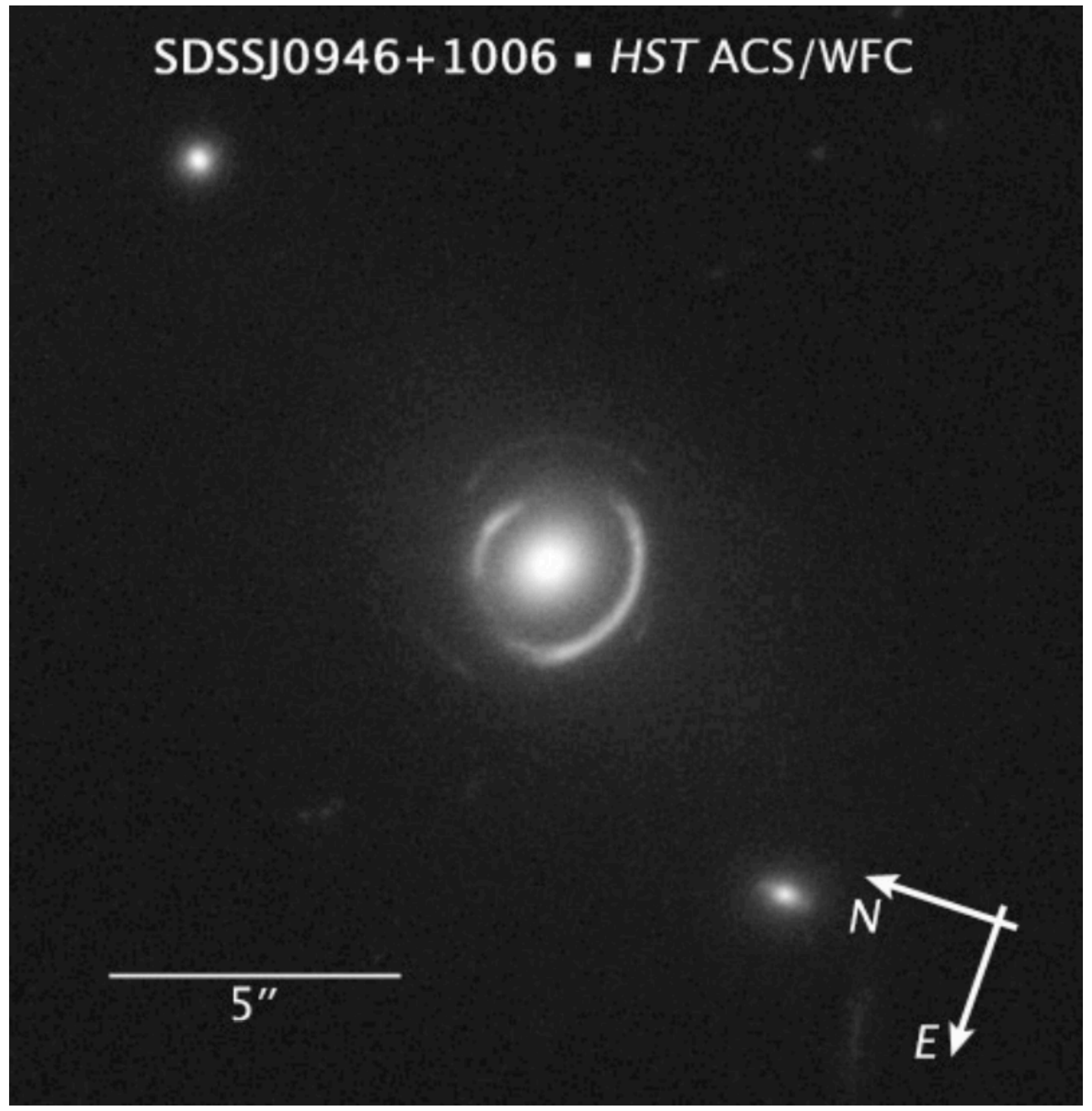
EN, Yang, Yu 2023 (2306.01830)



~50% of isolated Group-SIDM halos have kpc-scale cores: **analogs of observed ultra-diffuse galaxies**

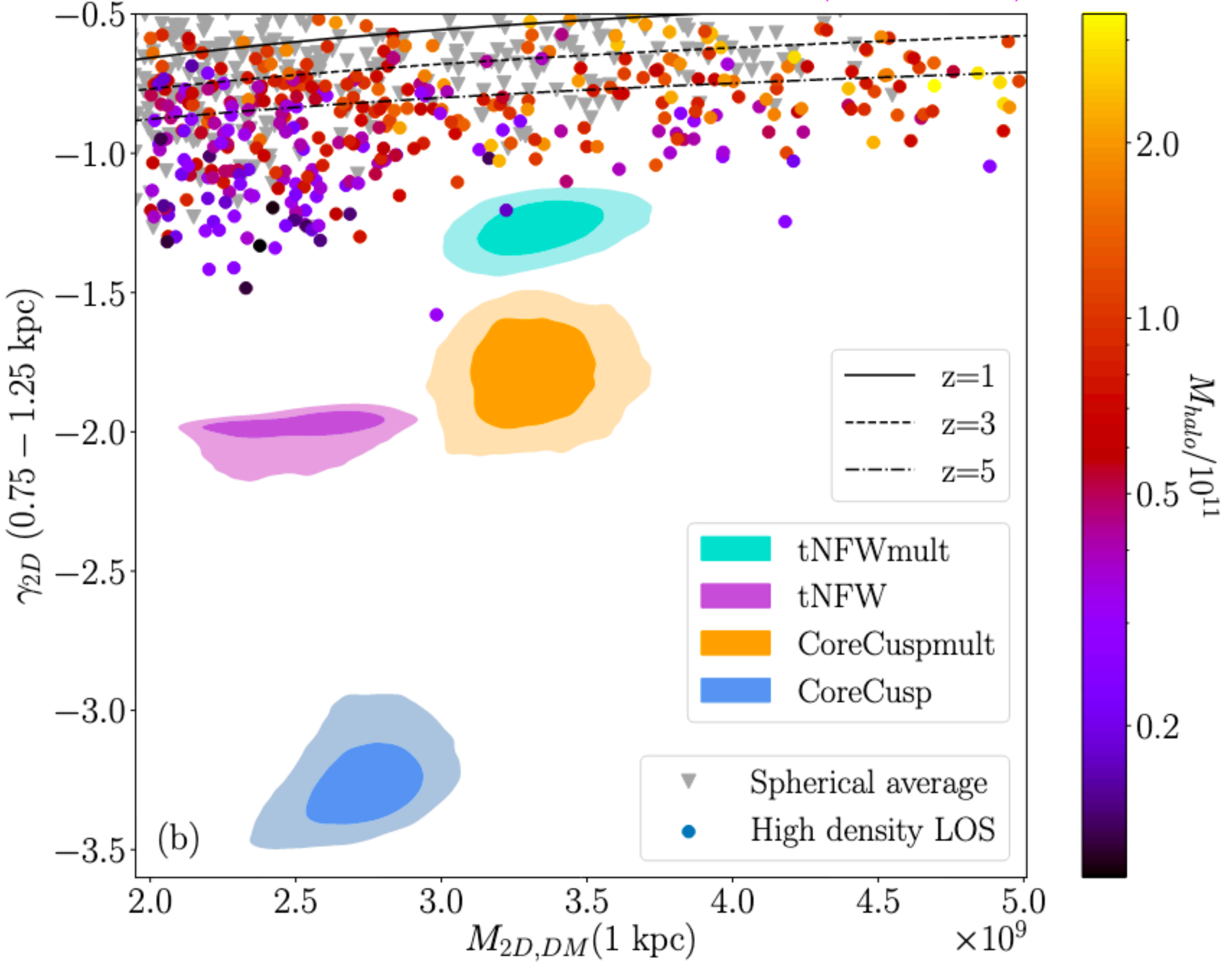
Group-SIDM Strong Lens Analog Simulation

- A strong lensing perturber with no detectable luminous component has an extremely steep central density profile
- Simulations rarely produce such dense (sub)structure, even with baryons



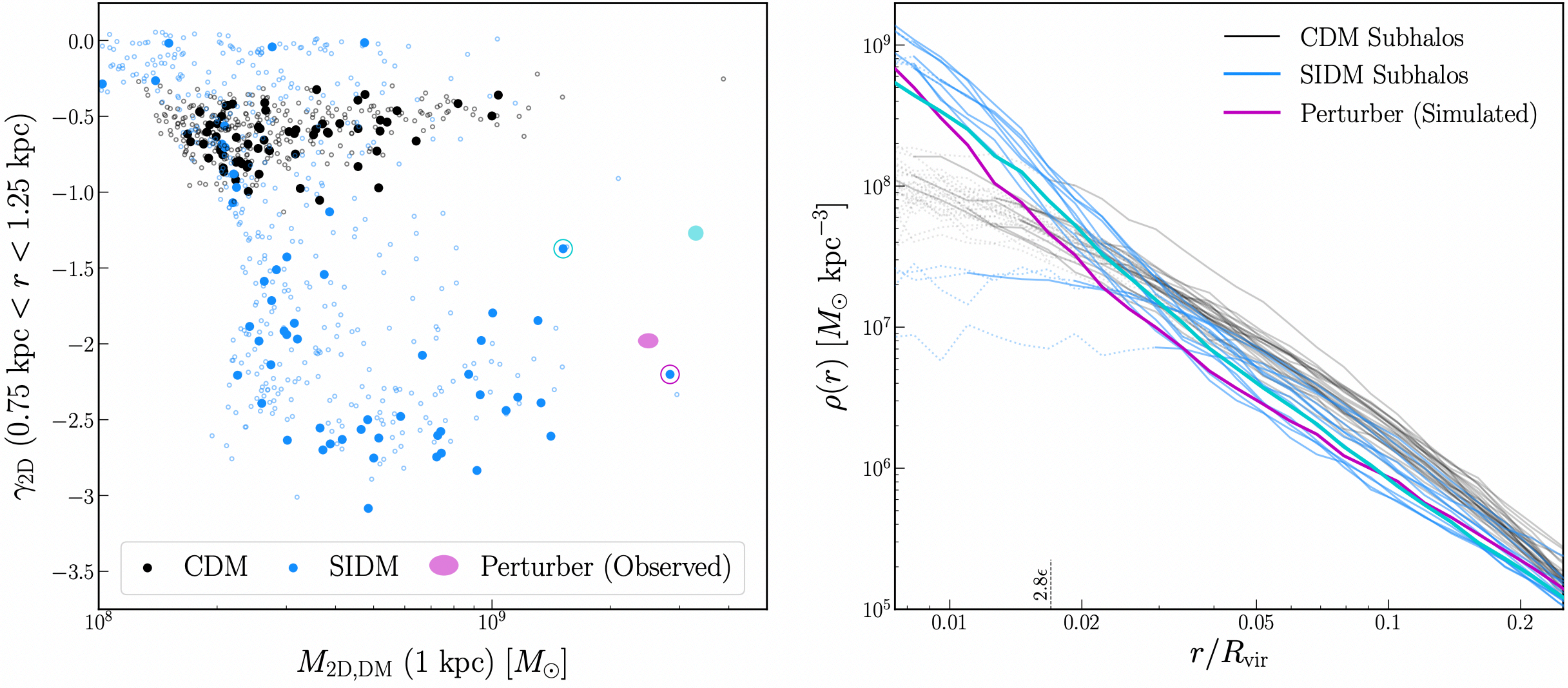
Vegetti et al. 2010 (0910.0760)

Minor et al. 2020 (2011.10627)



Group-SIDM Strong Lens Analog Simulation

EN, Yang, Yu 2023 (2306.01830)

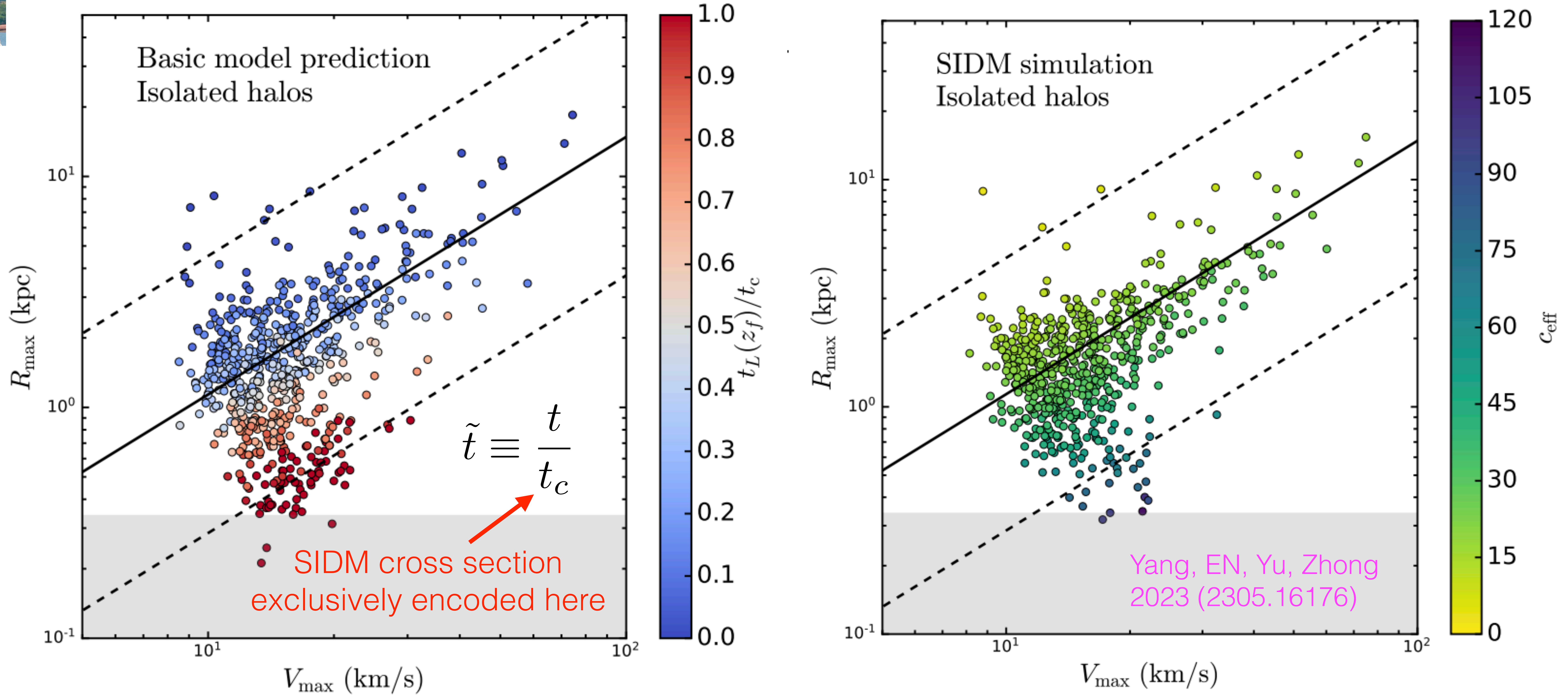


Nearly all surviving Group-SIDM subhalos core collapse: **analogs of observed strong lensing perturber**

A Parametric Model for SIDM Effects

Daneng Yang (UCR)

$$\frac{V_{\max}}{V_{\max,0}} = 1 + 0.1777\tilde{t} - 4.399\tilde{t}^3 + 16.66\tilde{t}^4 - 18.87\tilde{t}^5 + 9.077\tilde{t}^7 - 2.436\tilde{t}^9$$

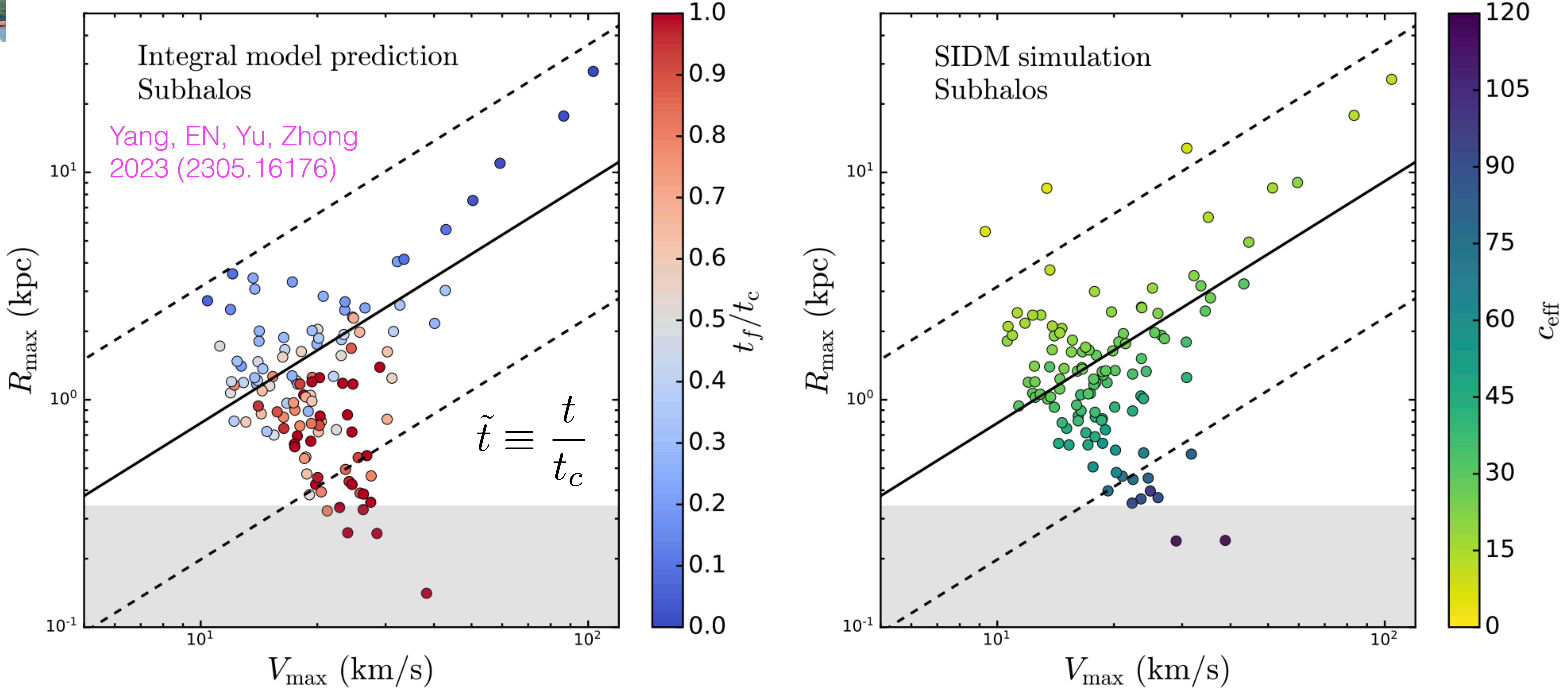


Basic model: initial CDM halo properties → SIDM halo evolution;
Calibrated to controlled simulations, agrees with isolated halos from cosmological SIDM simulations

A Parametric Model for SIDM Effects

Daneng Yang (UCR)

$$V_{\max}(t) = V_{\max,\mathrm{CDM}}(t_f) + \int_{t_f}^{t} dt' \frac{dV_{\max,\mathrm{CDM}}(t')}{dt'} + \int_{t_f}^{t} \frac{dt'}{t_c(t')} \frac{dV_{\max,\mathrm{Model}}(\tilde{t}')}{d\tilde{t}'}$$



Integral model: CDM halo evolution → SIDM halo evolution;
Agrees with isolated halos and subhalos from cosmological SIDM simulations

- **Symphony**: 262 zoom-ins, including **LMC** and **strong lens analogs**;
- **Milky Way-est**: 20 zoom-ins of **Milky Way-like systems** with LMC & GE analogs
- **Beyond-CDM**: 100+ zoom-ins with **warm**, **fuzzy**, **interacting** DM initial conditions

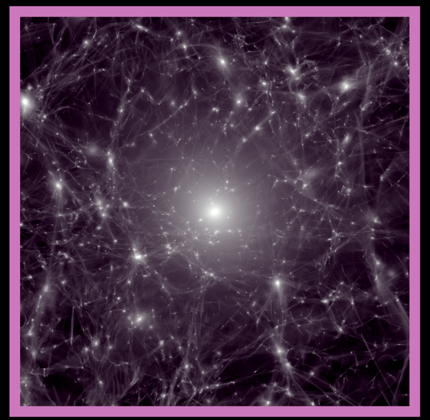
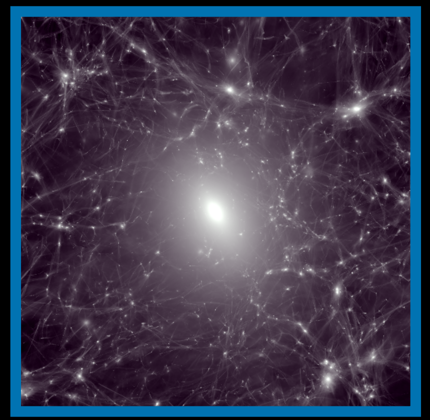
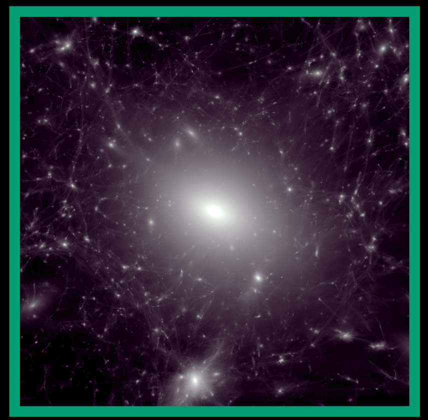
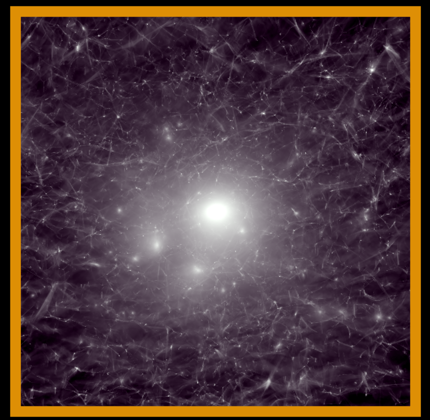
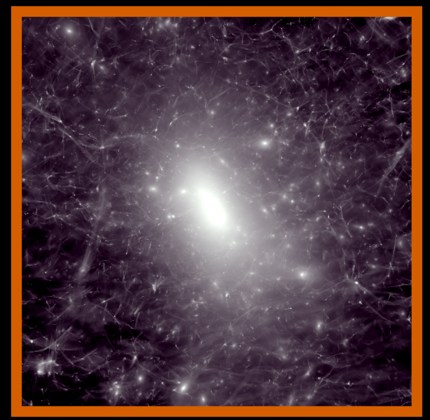
- **VD-100 Milky Way Simulation**: strong, velocity-dependent SIDM yields **diverse halo populations** within and surrounding the Milky Way; **~20% of subhalos core collapse**

- ***P(k)* Suppression + Strong SIDM**: self-consistent initial conditions in strong SIDM scenario **largely erase core collapse** for *P(k)* suppression at current WDM limits

- **Group-SIDM Simulation**: extreme self-interactions produce analogs of observed **UDGs** and **strong-lensing perturbers**; nearly all surviving subhalos core collapse

- **Parametric Model for SIDM Effects**: agrees with isolated halo and subhalo populations from cosmological SIDM simulations, enabling rapid predictions in SIDM parameter space

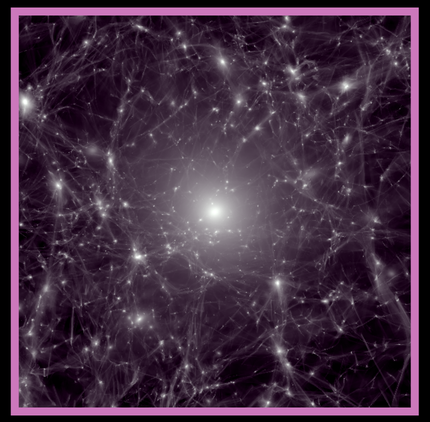
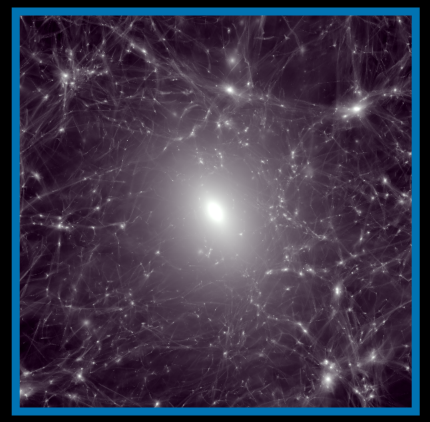
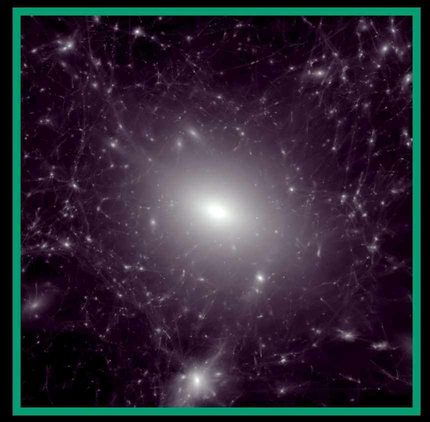
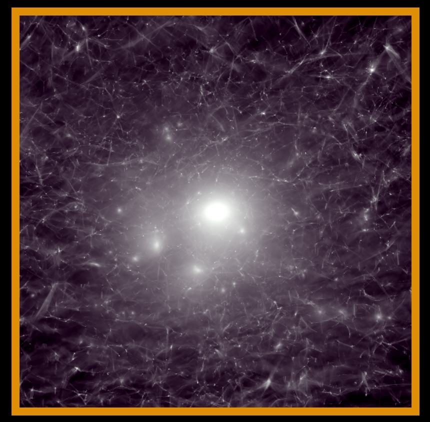
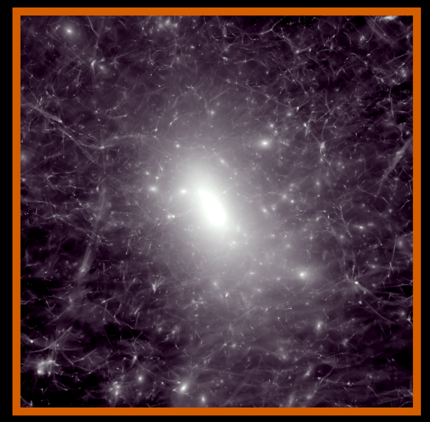
CARNEGIE SCIENCE

USC University of Southern California

Thanks!

Rui An, Andrew Benson, Deveshi Buch, Xiaolong Du,
Vera Gluscevic, Phil Mansfield, Yao-Yuan Mao, Yunchong Wang,
Risa Wechsler, Daneng Yang, Haibo Yu, Yiming Zhong

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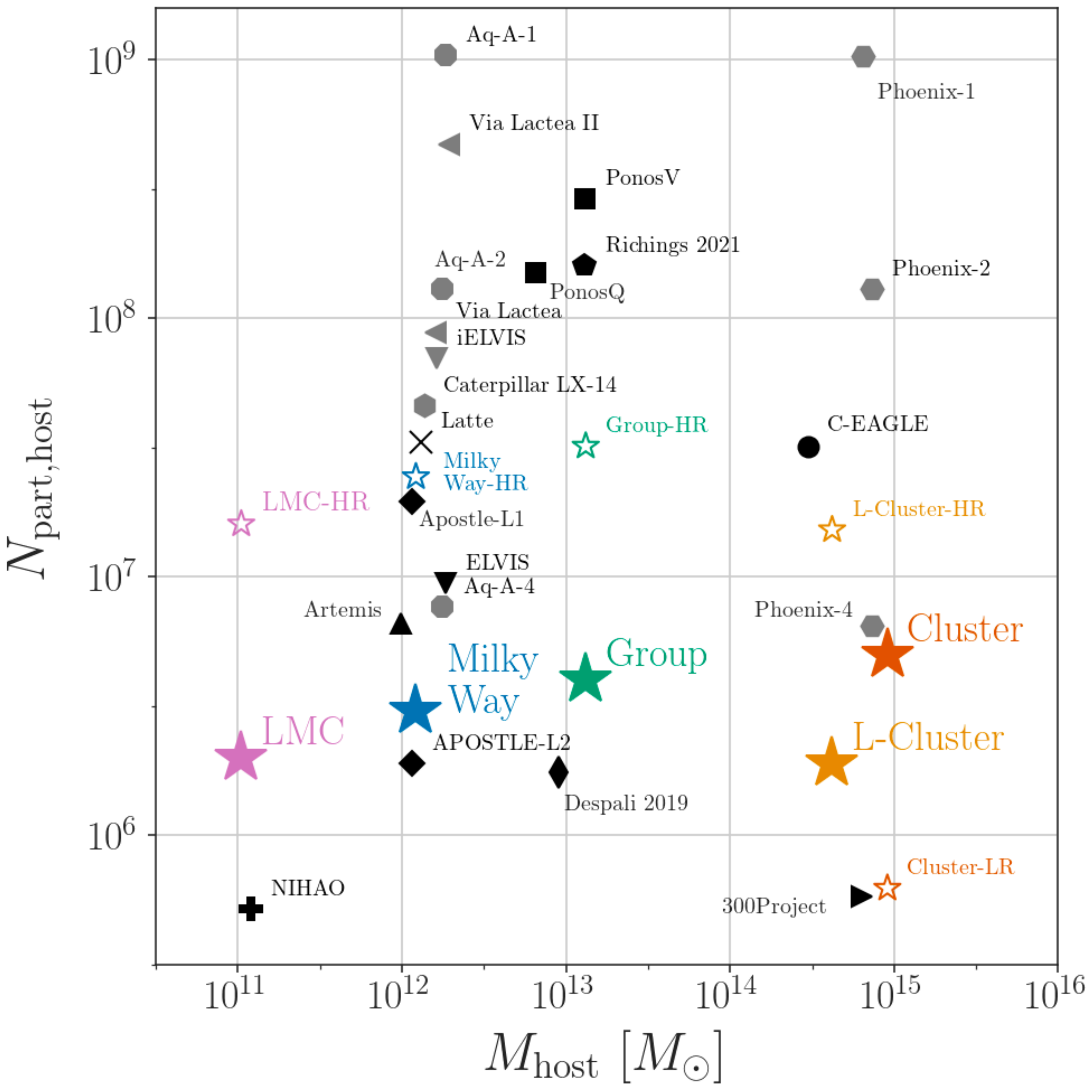
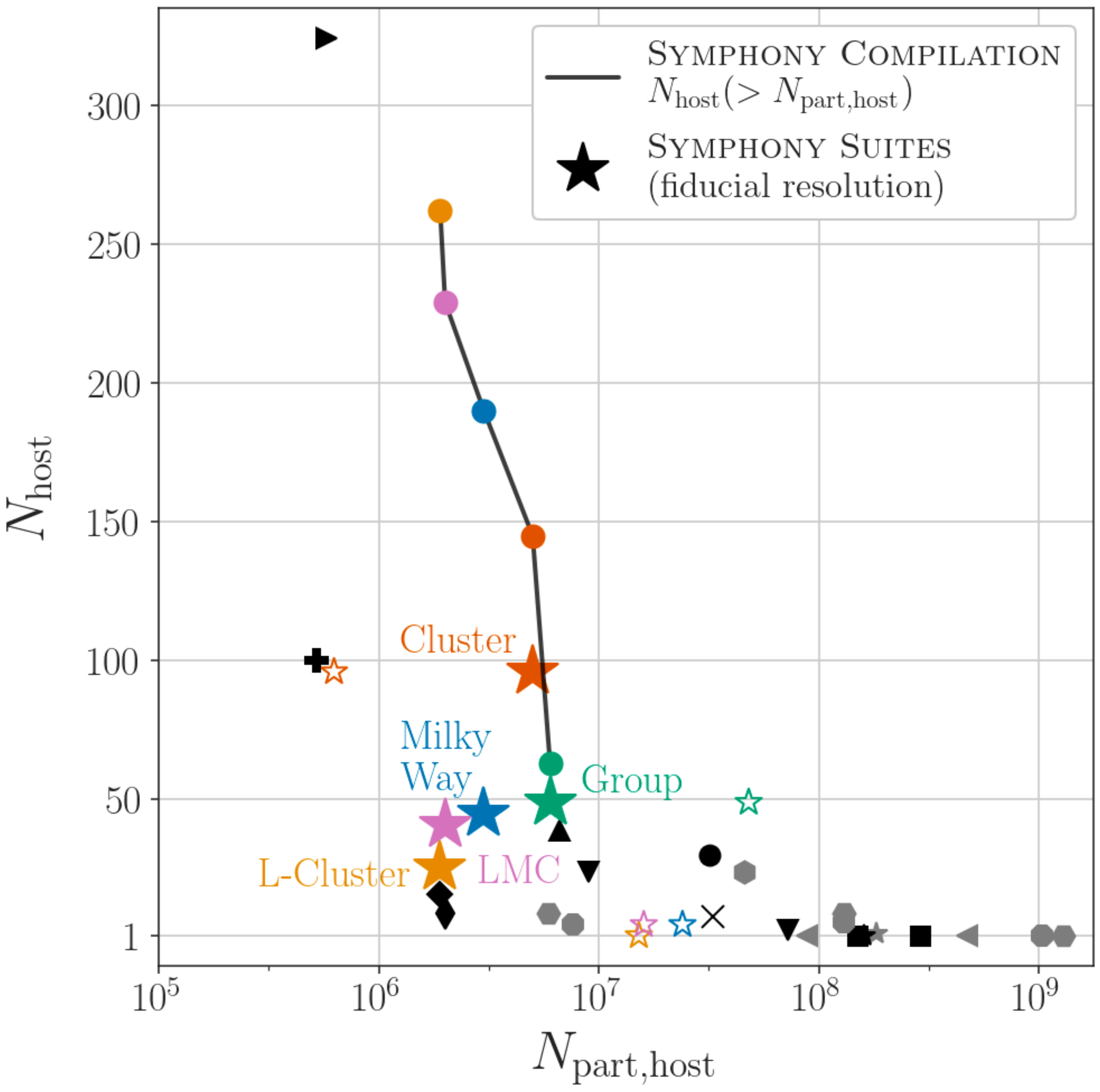
Symphony Zoom-in Simulations





EN, Mansfield, Wang et al., 2209.02675

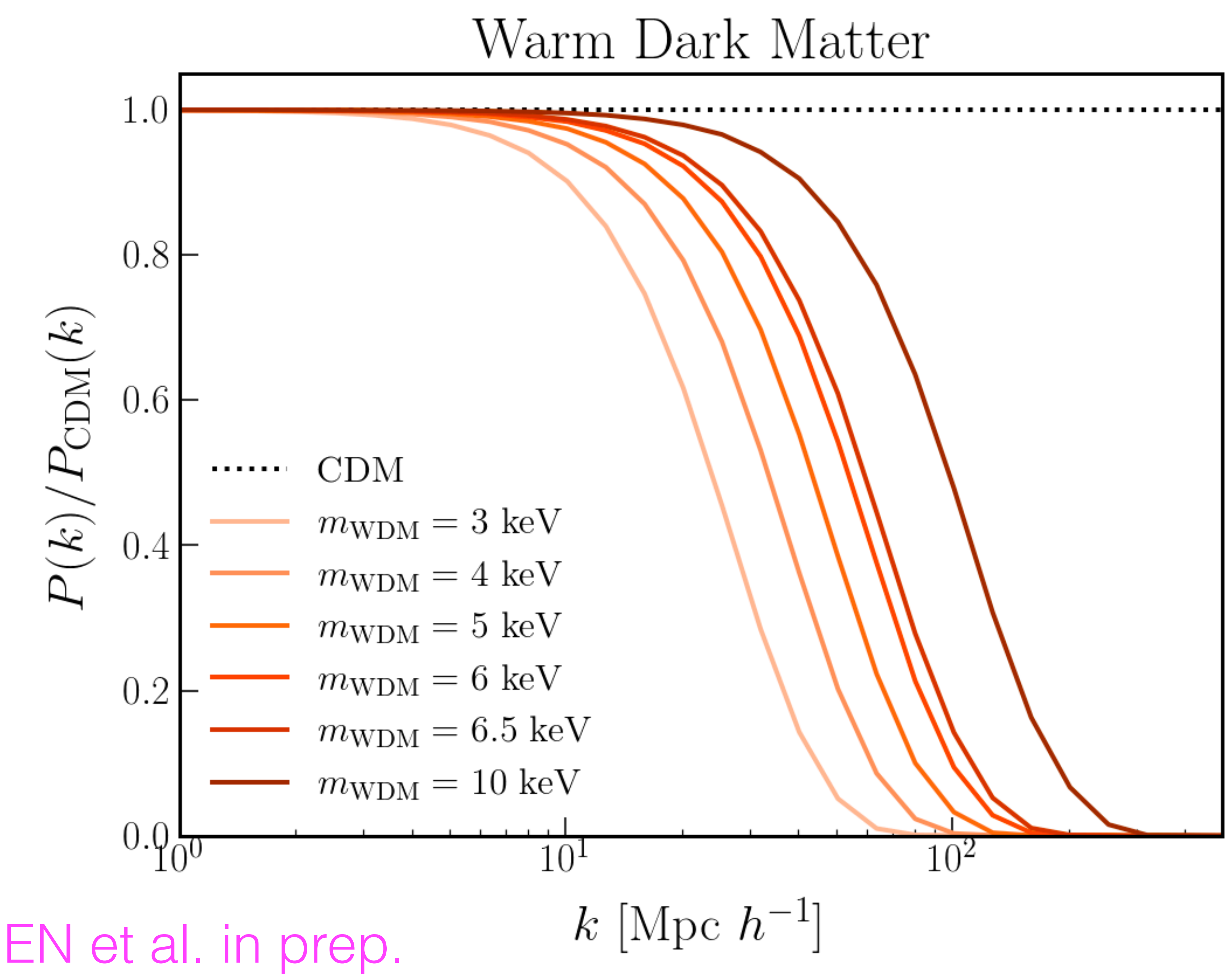
Beyond-CDM Zoom-in Simulations

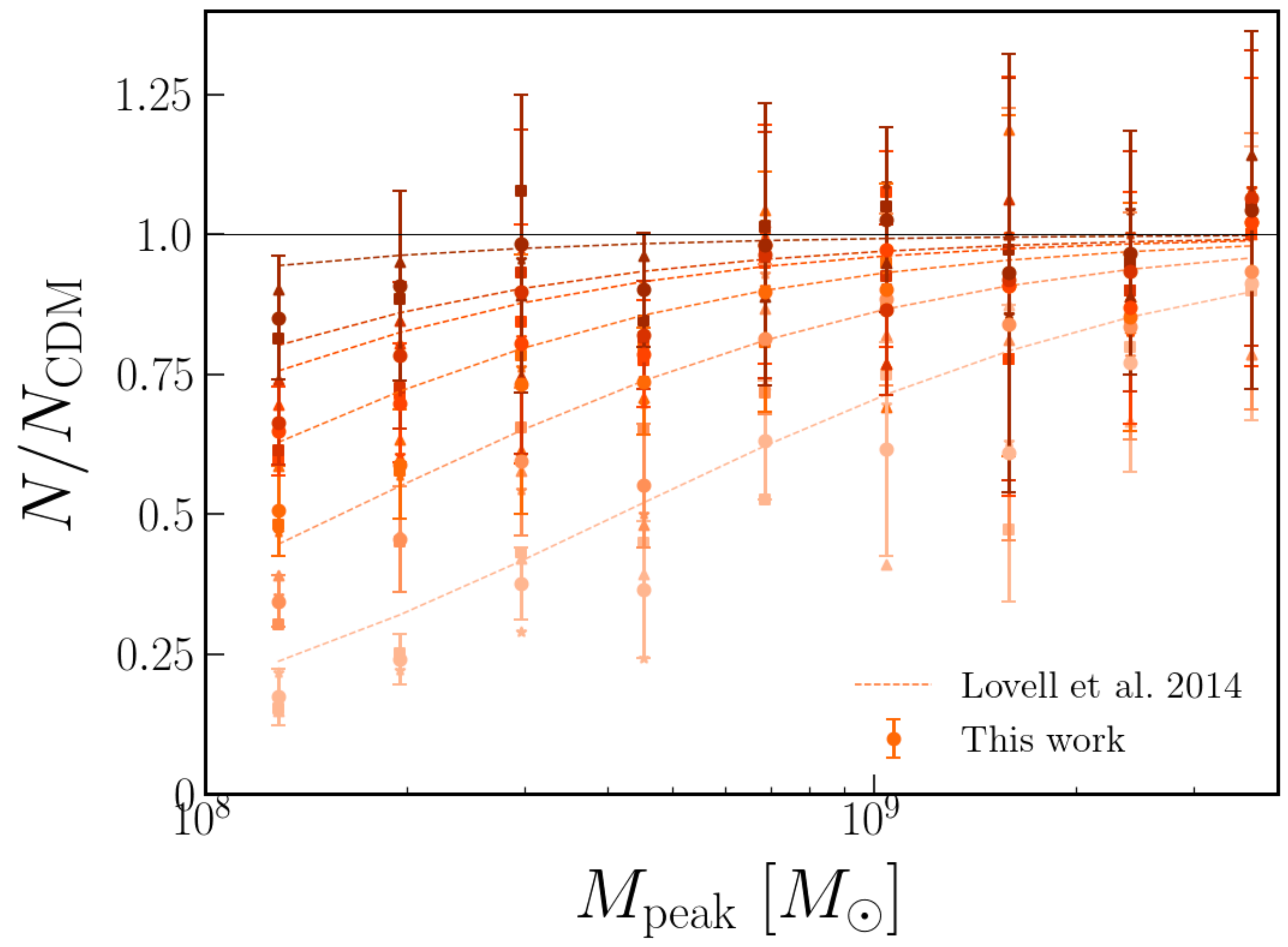
- Recalibrate WDM halo mass function suppression: full treatment of statistical uncertainties, halo-to-halo scatter, fit degeneracies; integrated with **CLASS**

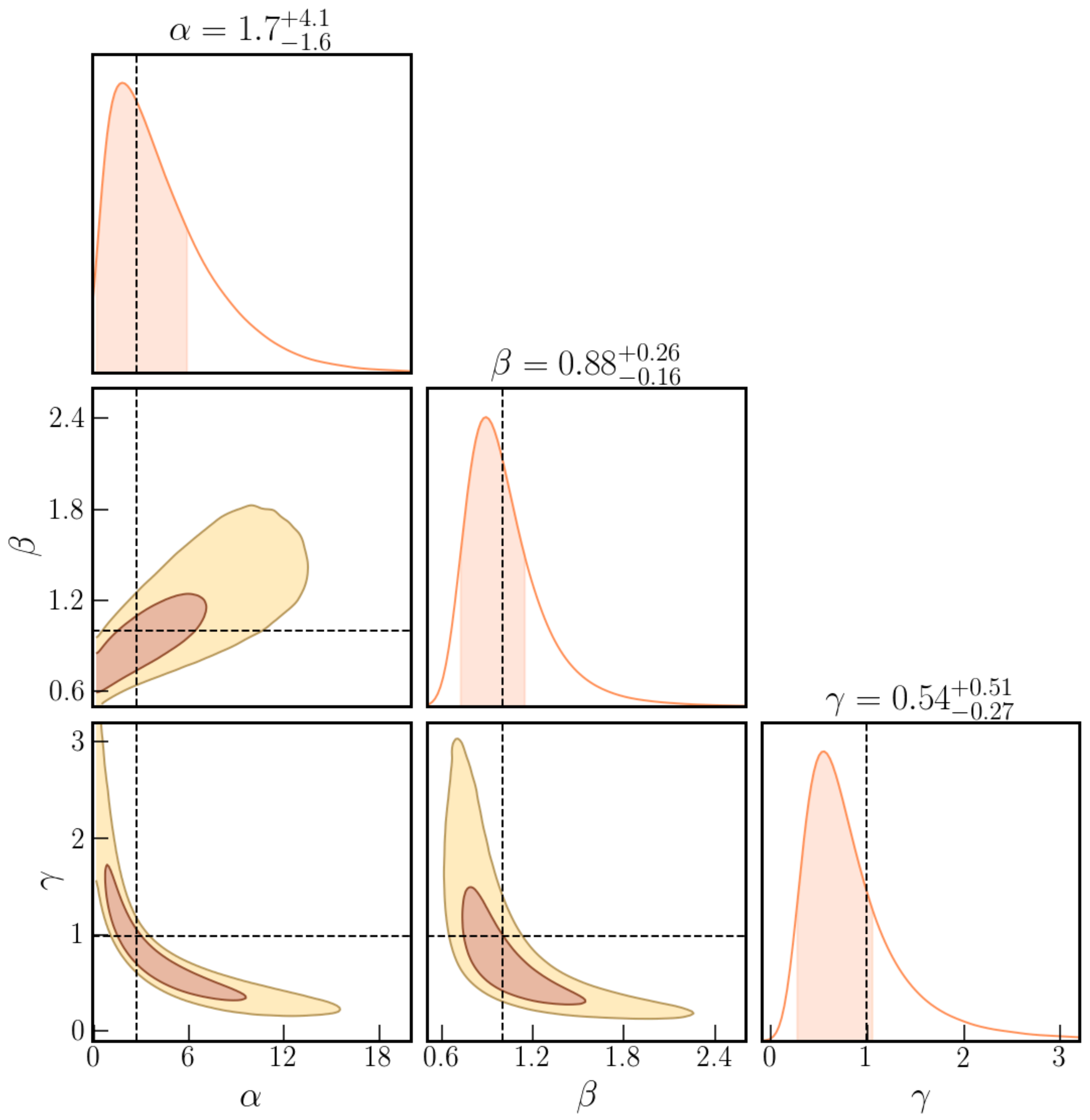
- Halo mass function suppression slightly enhanced relative to previous fits

- Extremely small contamination from artificial halos

$$\frac{(\mathrm{d}n/\mathrm{d}M)_{\mathrm{WDM}}}{(\mathrm{d}n/\mathrm{d}M)_{\mathrm{CDM}}} = \left[1 + \left(\frac{\alpha M_{\mathrm{hm}}(m_{\mathrm{WDM}})}{M}\right)^{\beta}\right]^{-\gamma}$$



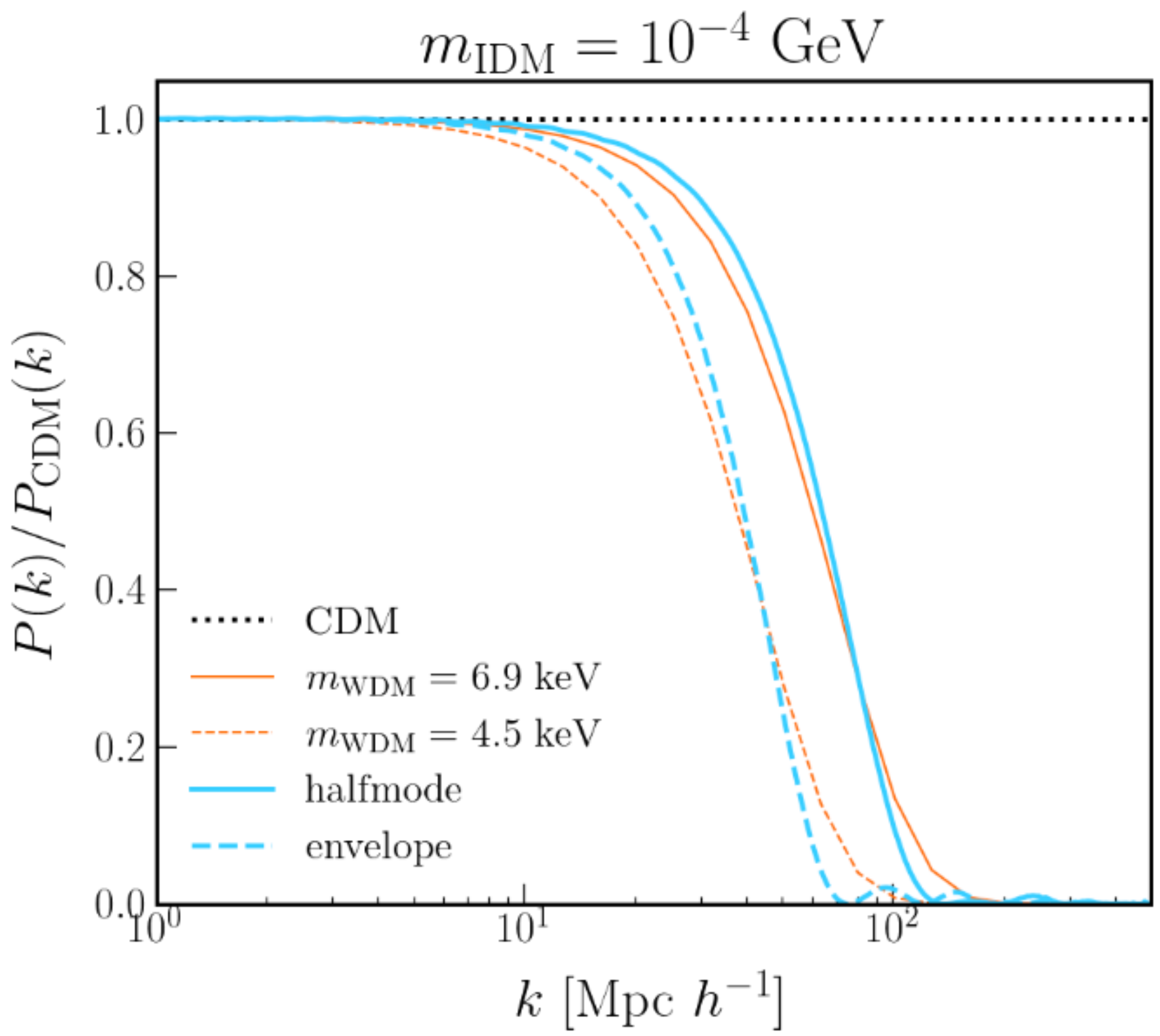


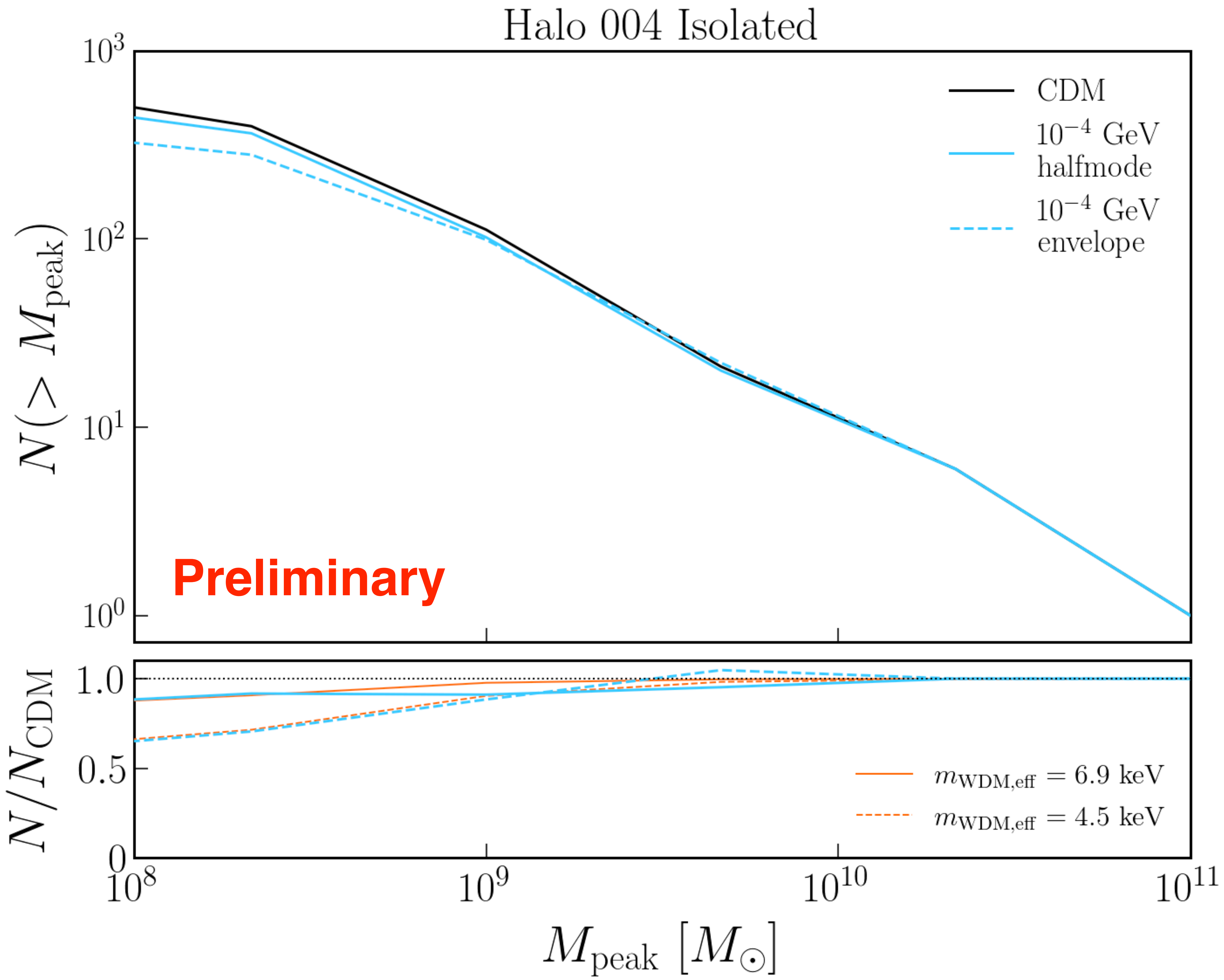


EN et al. in prep.

Beyond-CDM Zoom-in Simulations

- Interacting dark matter models with small dark acoustic oscillations map to effective WDM models:

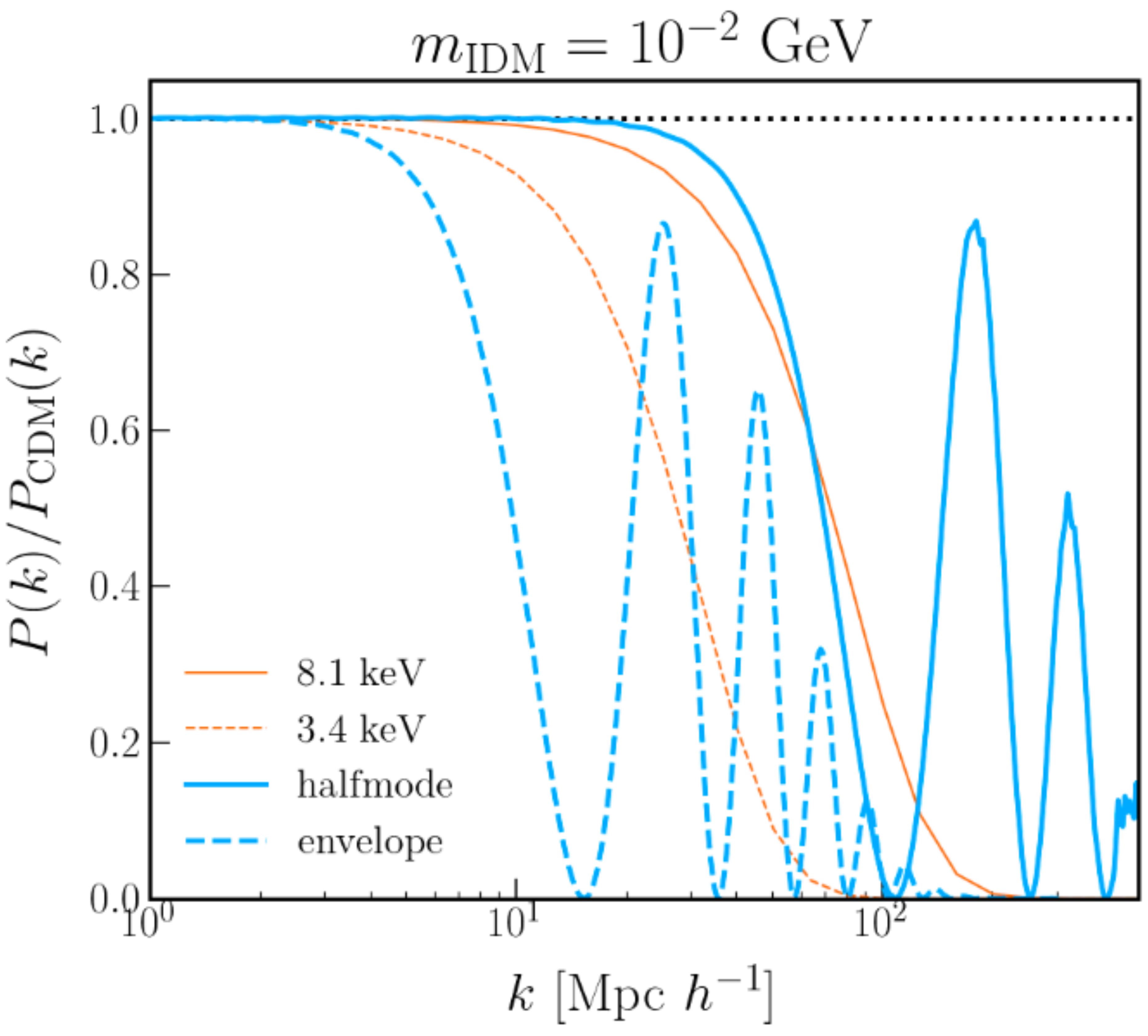


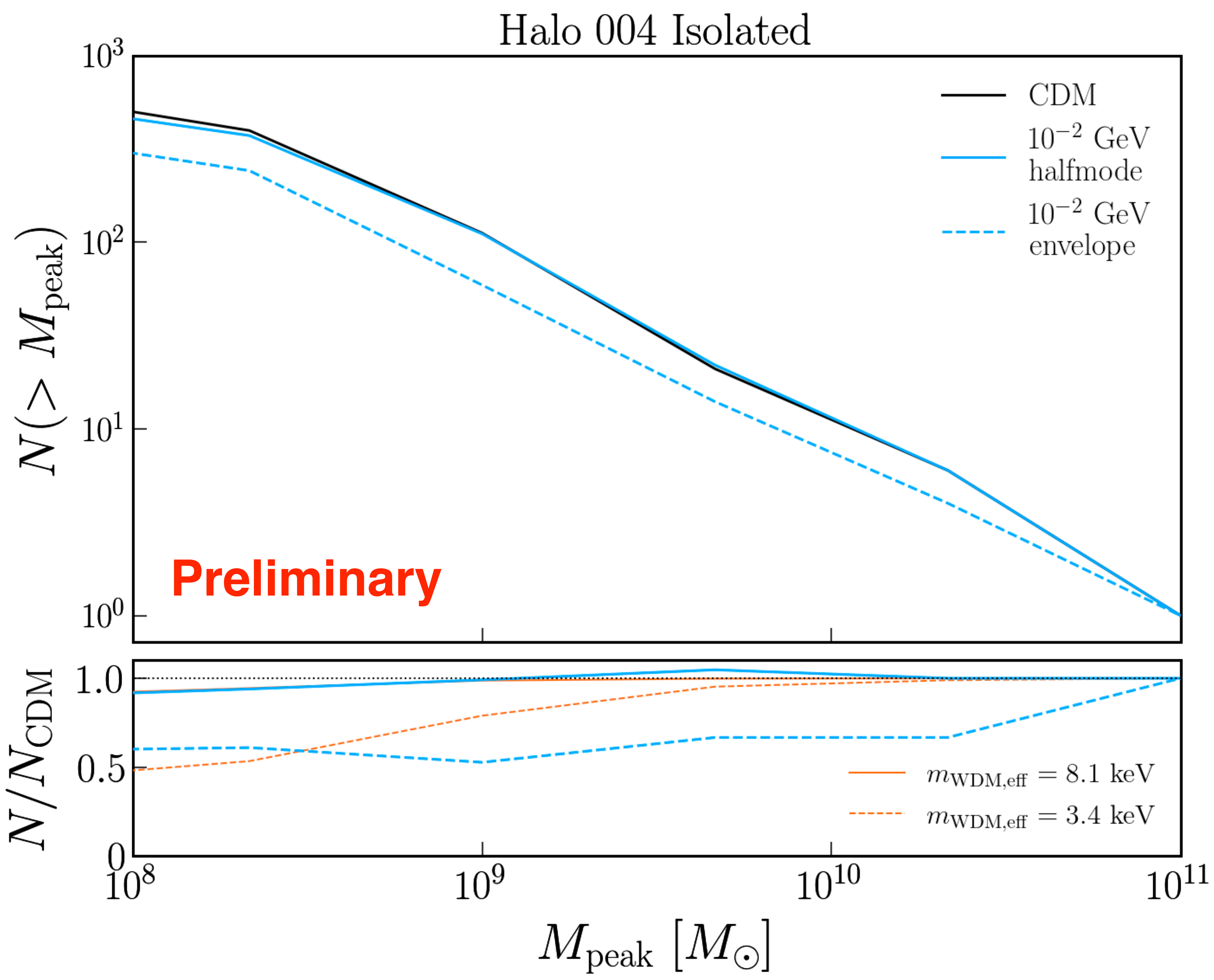


EN et al. in prep.

Beyond-CDM Zoom-in Simulations

- Interacting dark matter models with large dark acoustic oscillations are "colder" than WDM models with the same initial cutoff:



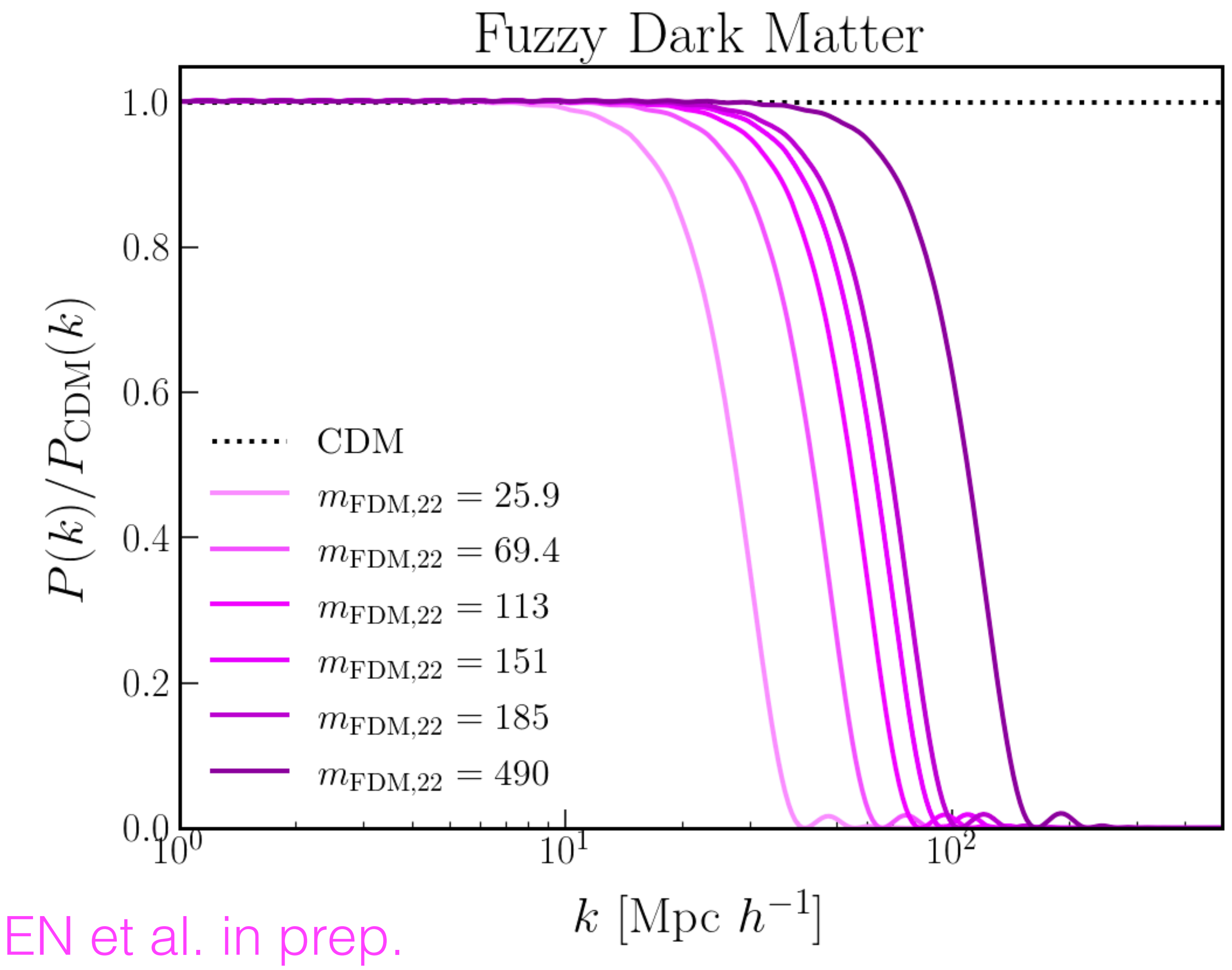


EN et al. in prep.

Beyond-CDM Zoom-in Simulations

- Recalibrate FDM halo mass function suppression: full treatment of statistical uncertainties, halo-to-halo scatter, fit degeneracies; integrated with **`axionCAMB`**
- Halo mass function suppression slightly reduced relative to previous fits (Schrödinger-Poisson dynamics are not modeled)
- Extremely small contamination from artificial halos

$$\frac{(\mathrm{d}n/\mathrm{d}M)_{\mathrm{FDM}}}{(\mathrm{d}n/\mathrm{d}M)_{\mathrm{CDM}}} = \left[1 + \left(\frac{\alpha M_0(m_{\mathrm{FDM}})}{M}\right)^{\beta}\right]^{-\gamma}$$



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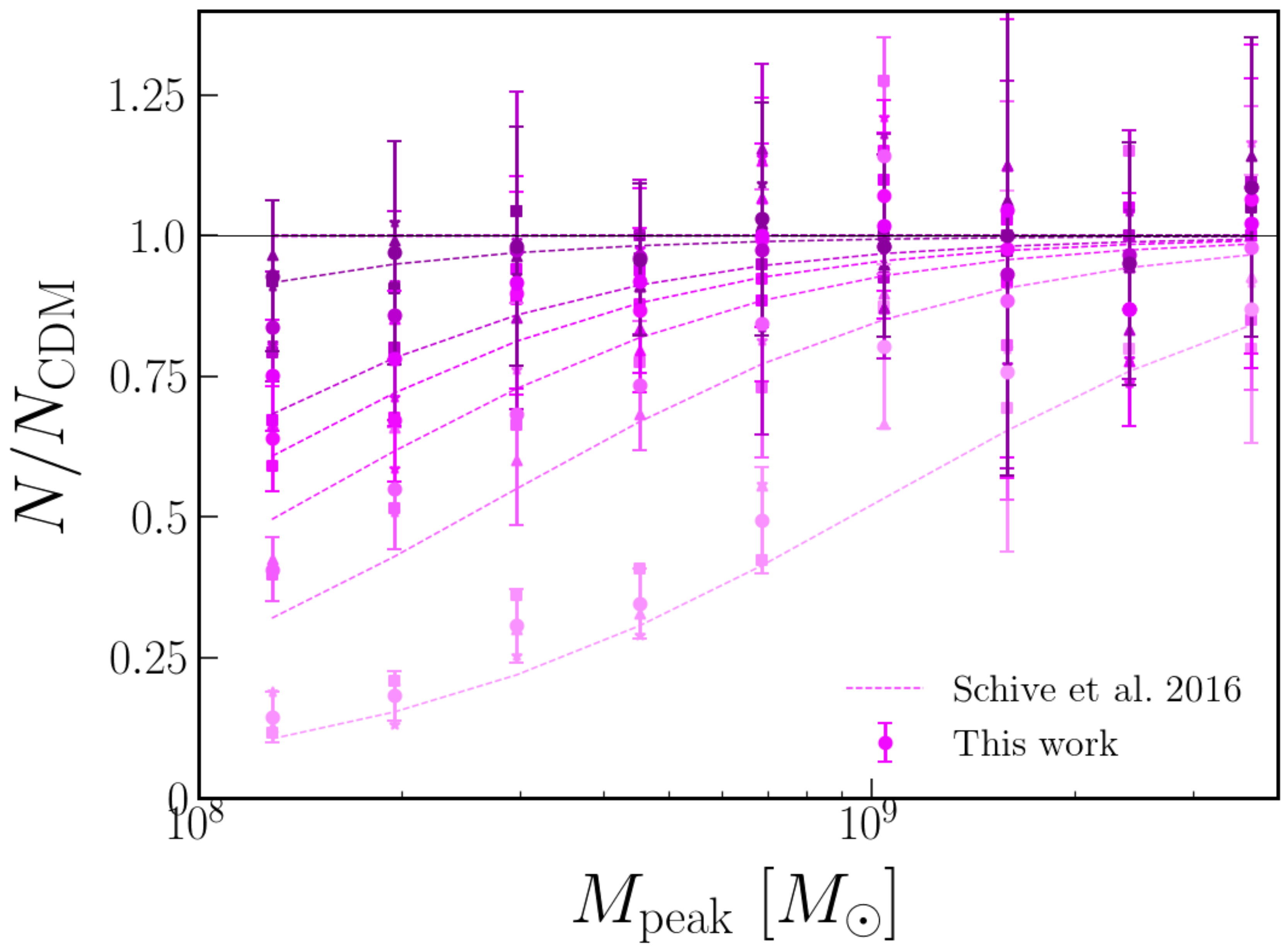

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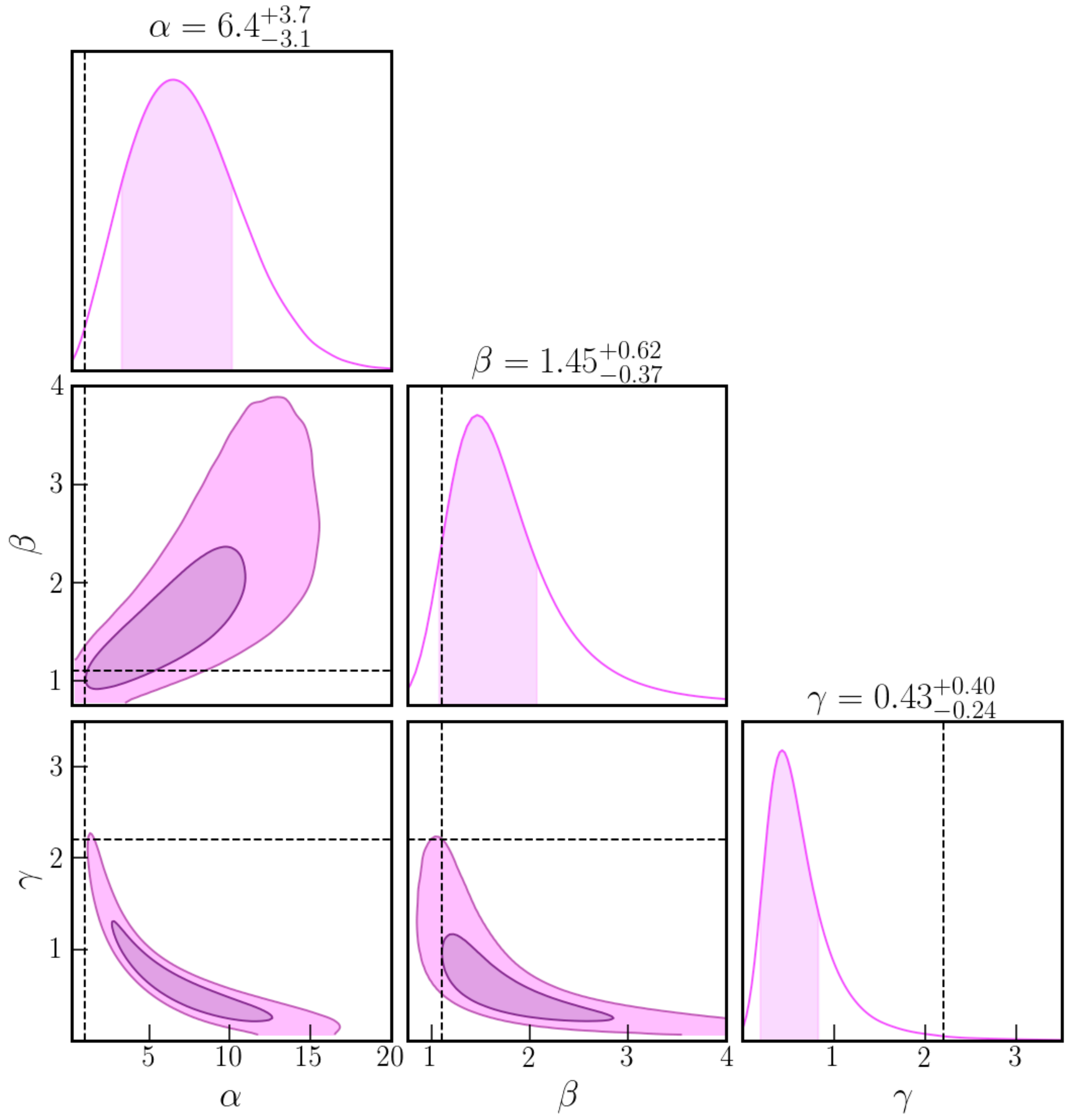
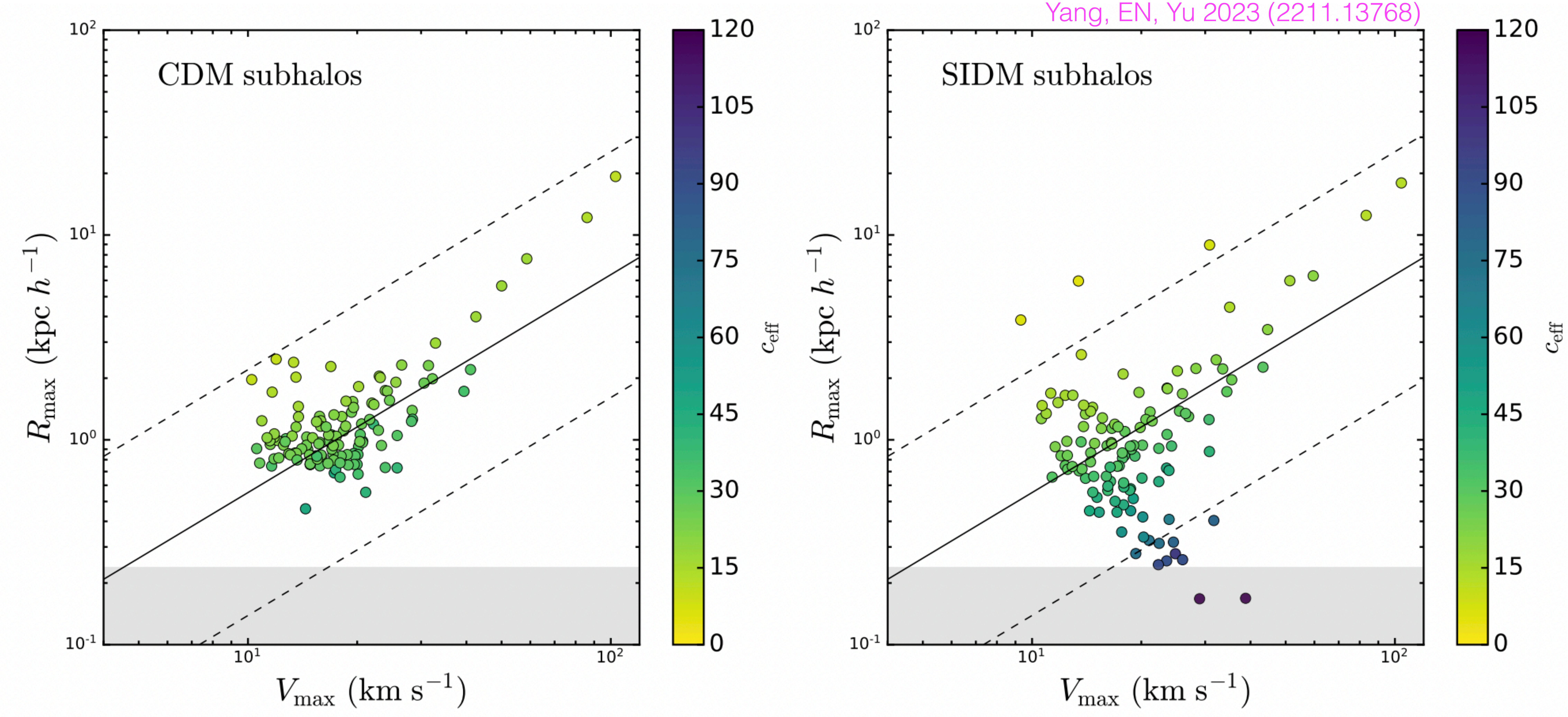


EN et al. in prep.

VD-100 SIDM Milky Way Simulation

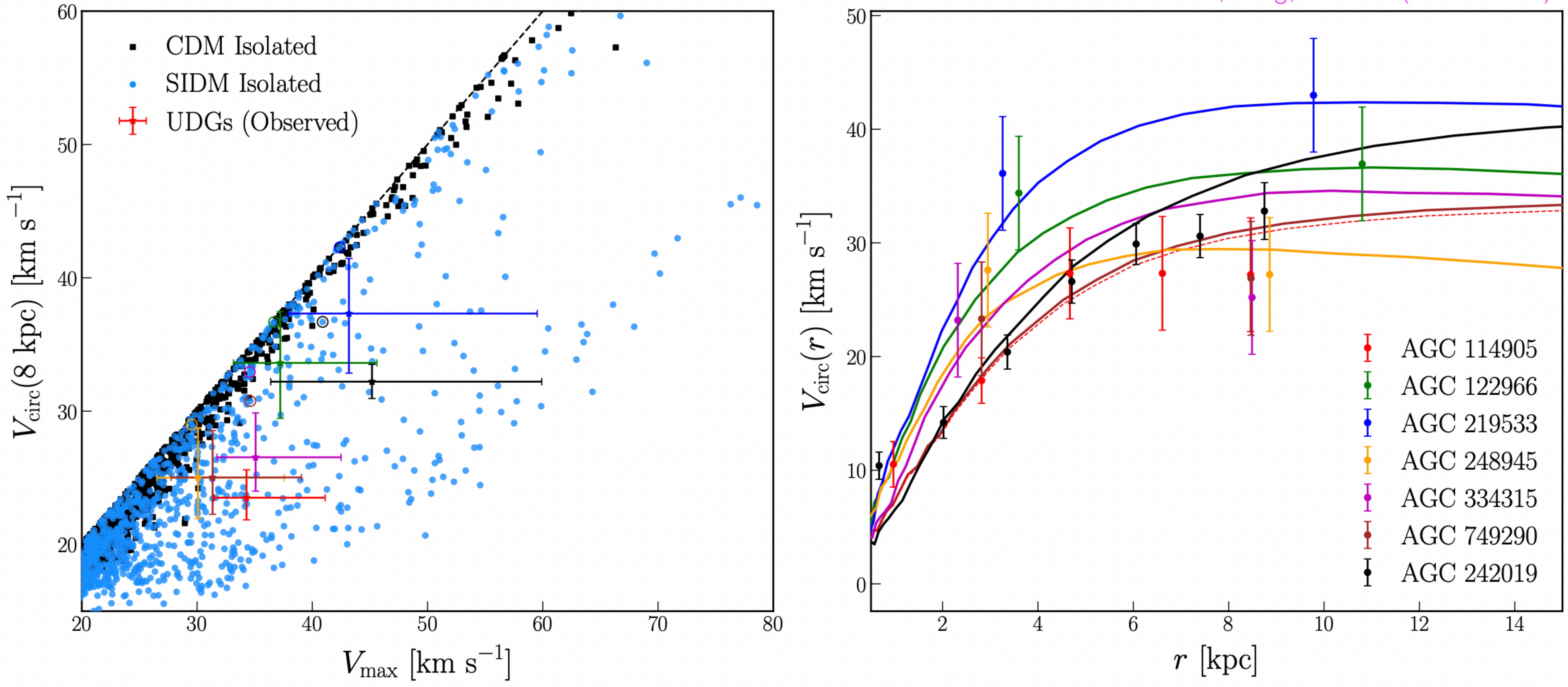
Yang, EN, Yu 2023 (2211.13768)



Core-collapsed (sub)halos are extreme outliers in R_{max}-V_{max} plane; consistent with analytic t_c predictions

Group-SIDM Strong Lens Analog Simulation

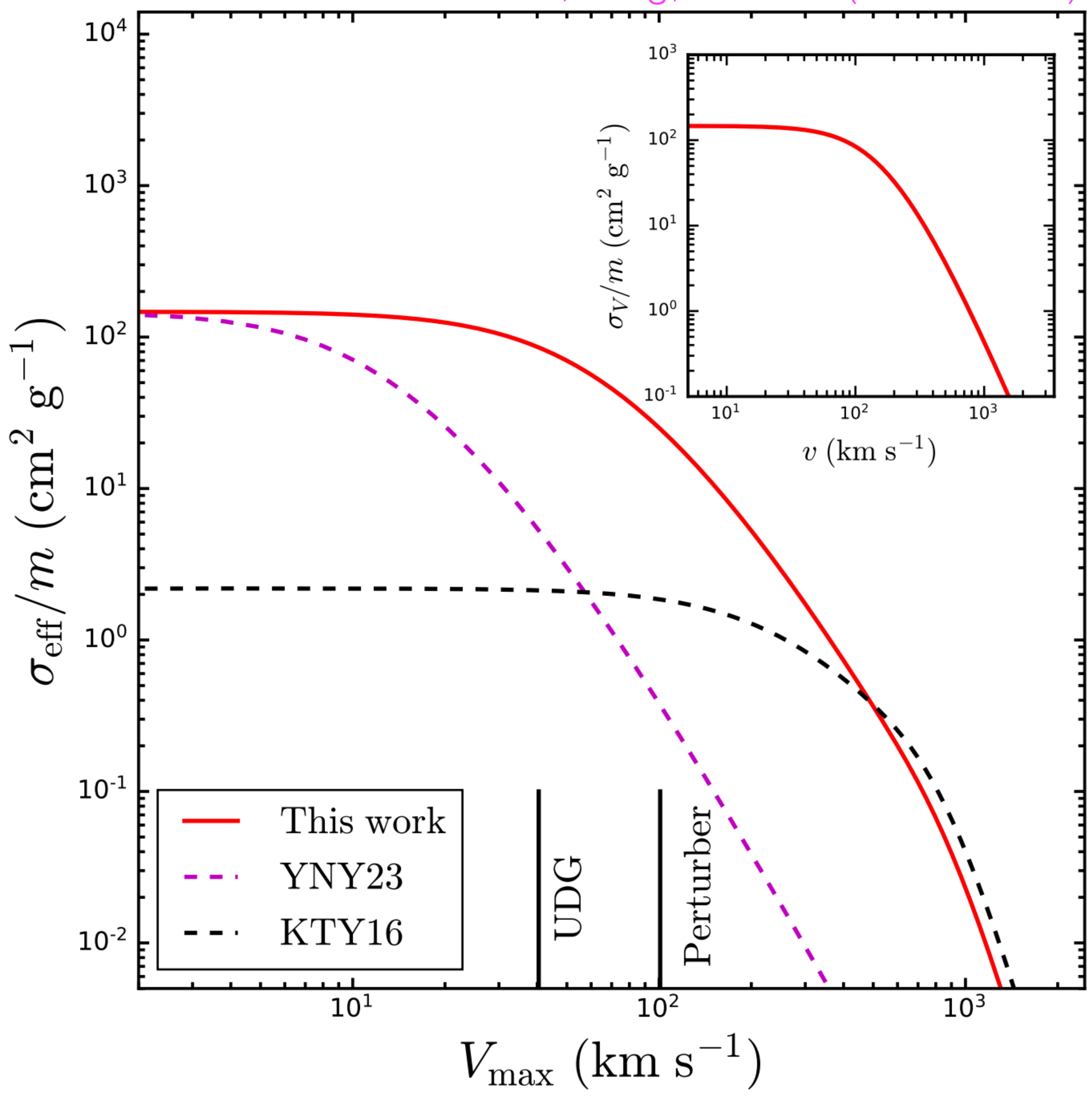
EN, Yang, Yu 2023 (2306.01830)



Group-SIDM model reproduces entire rotation curves of observed UDGs reasonably well

Group-SIDM Strong Lens Analog Simulation

EN, Yang, Yu 2023 (2306.01830)



Group-SIDM effective cross section compared to velocity scales of UDGs and strong-lensing perturber