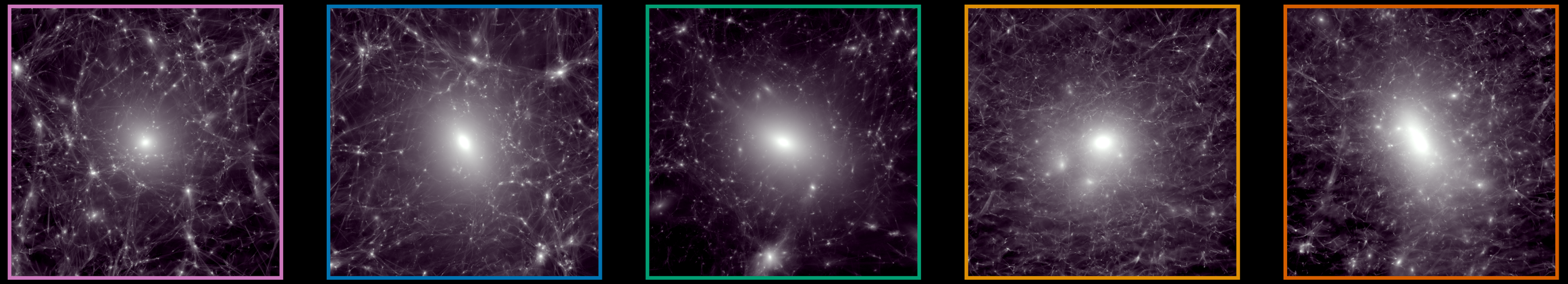
Cosmological Simulations with Novel Dark Matter Physics



Ethan Nadler

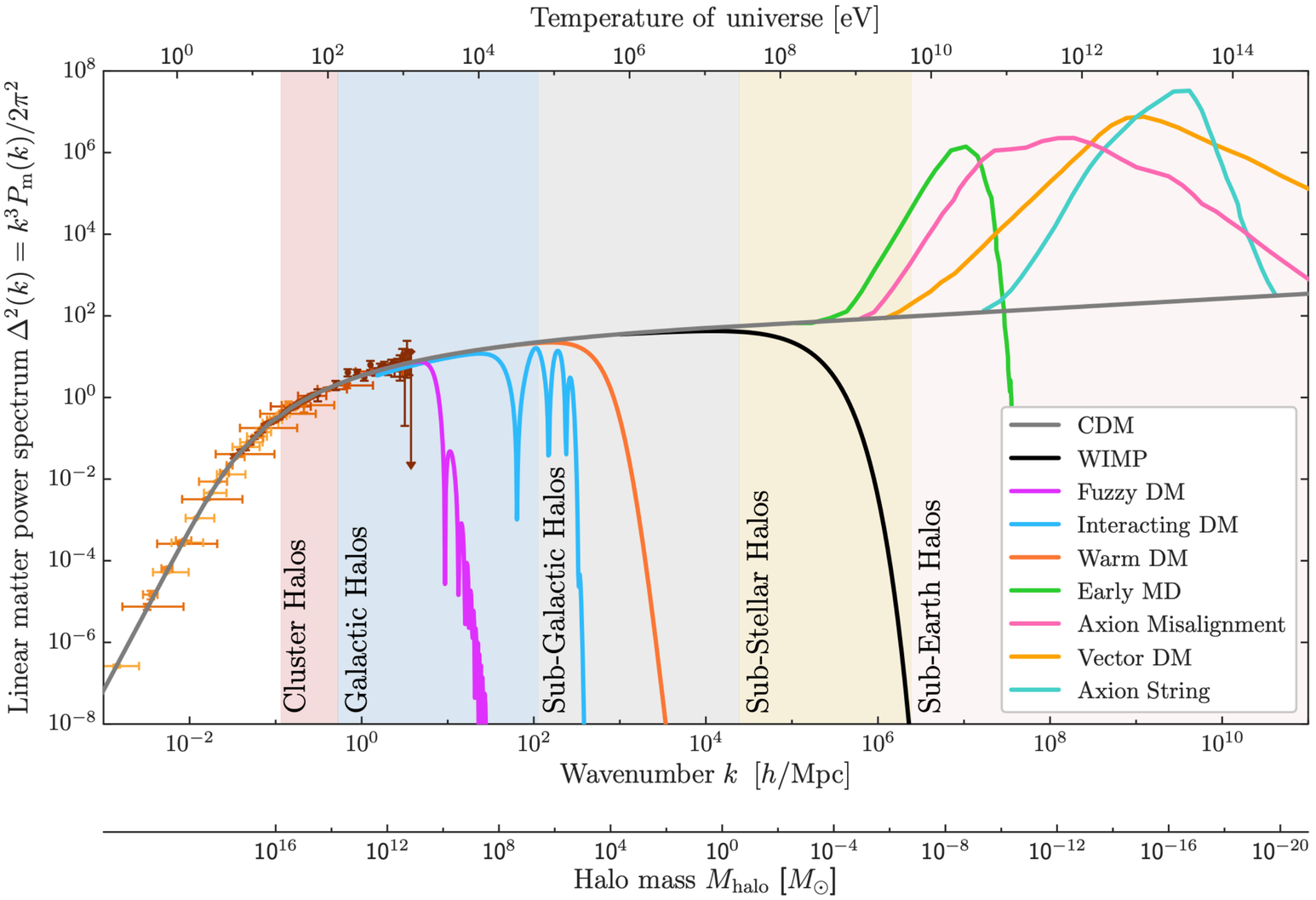
Carnegie Science

USC University of Southern California

UCLA Dark Matter 2023

3/30/2023

Dark Matter Physics on Small Scales

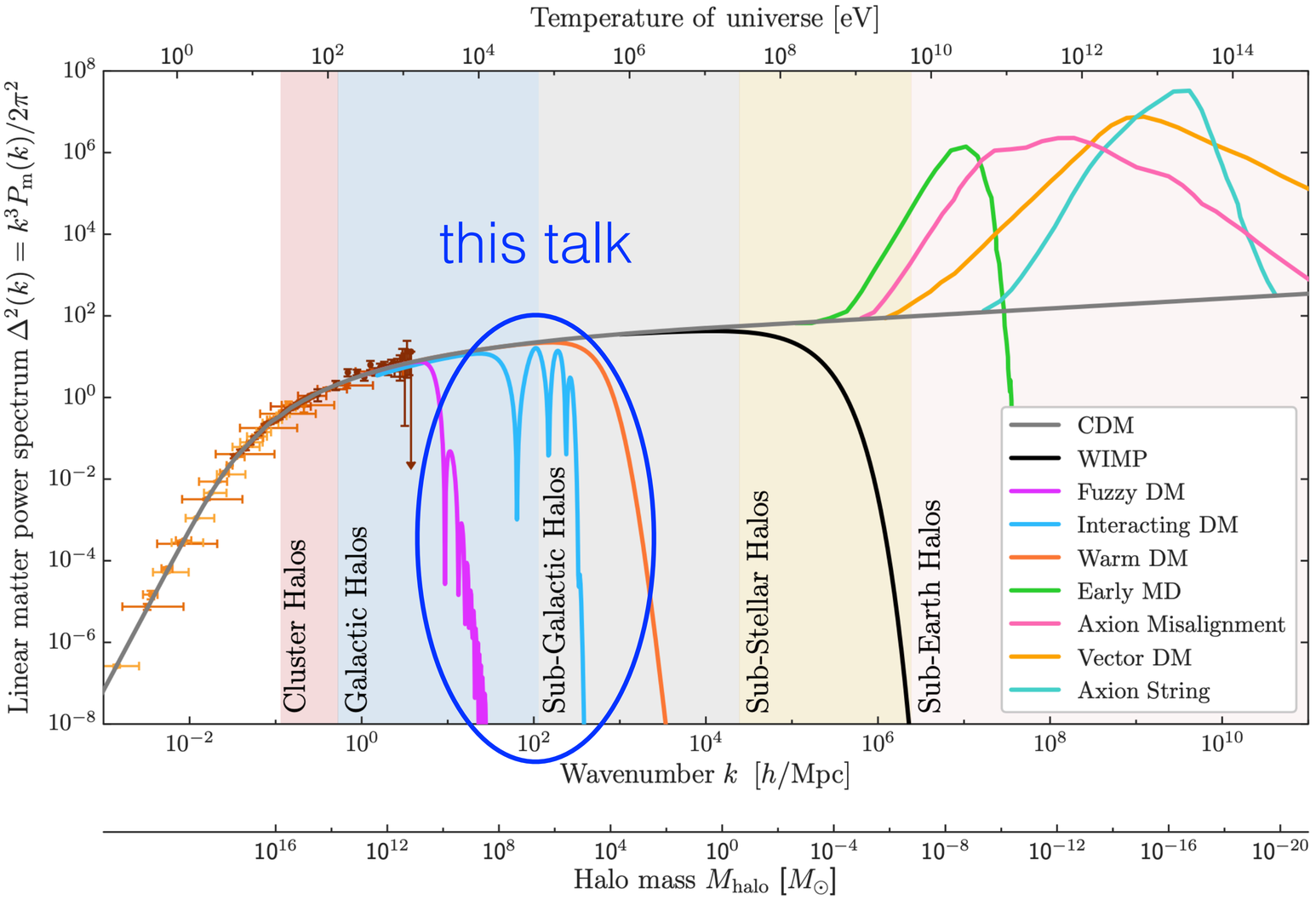


Snowmass Cosmic Frontier Report (2211.09978)

Dark matter physics affects structure formation throughout cosmic history:

- Clustering on scales smaller than ~1 Mpc is mostly unconstrained
- New DM physics affects abundance & density profiles of low-mass halos
- **Simulations are needed** to robustly explore DM physics near and below the galaxy formation threshold

Dark Matter Physics on Small Scales



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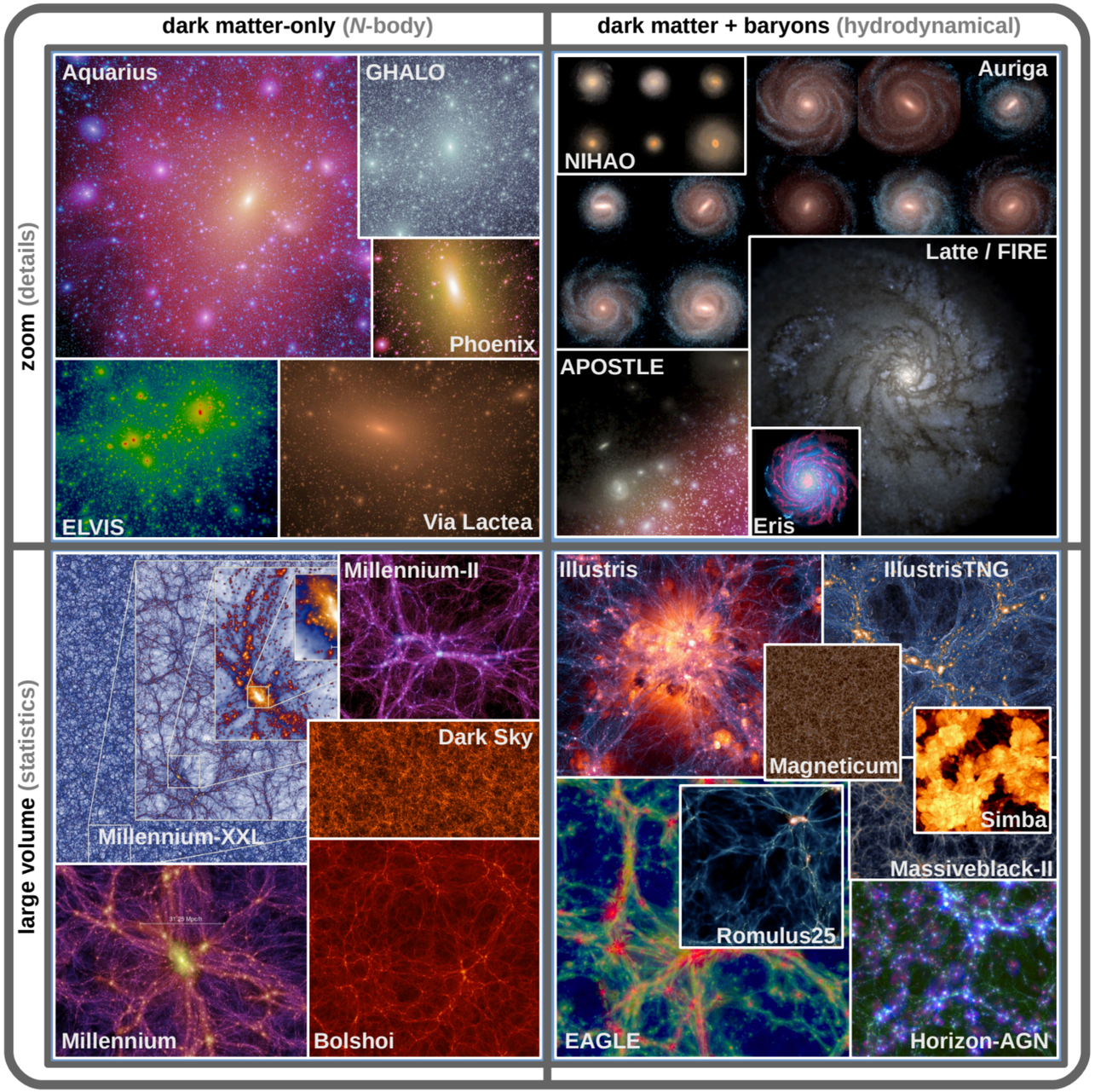
The Landscape of Cosmological Simulations

- Cosmological simulations are the **most accurate method** for modeling structure formation

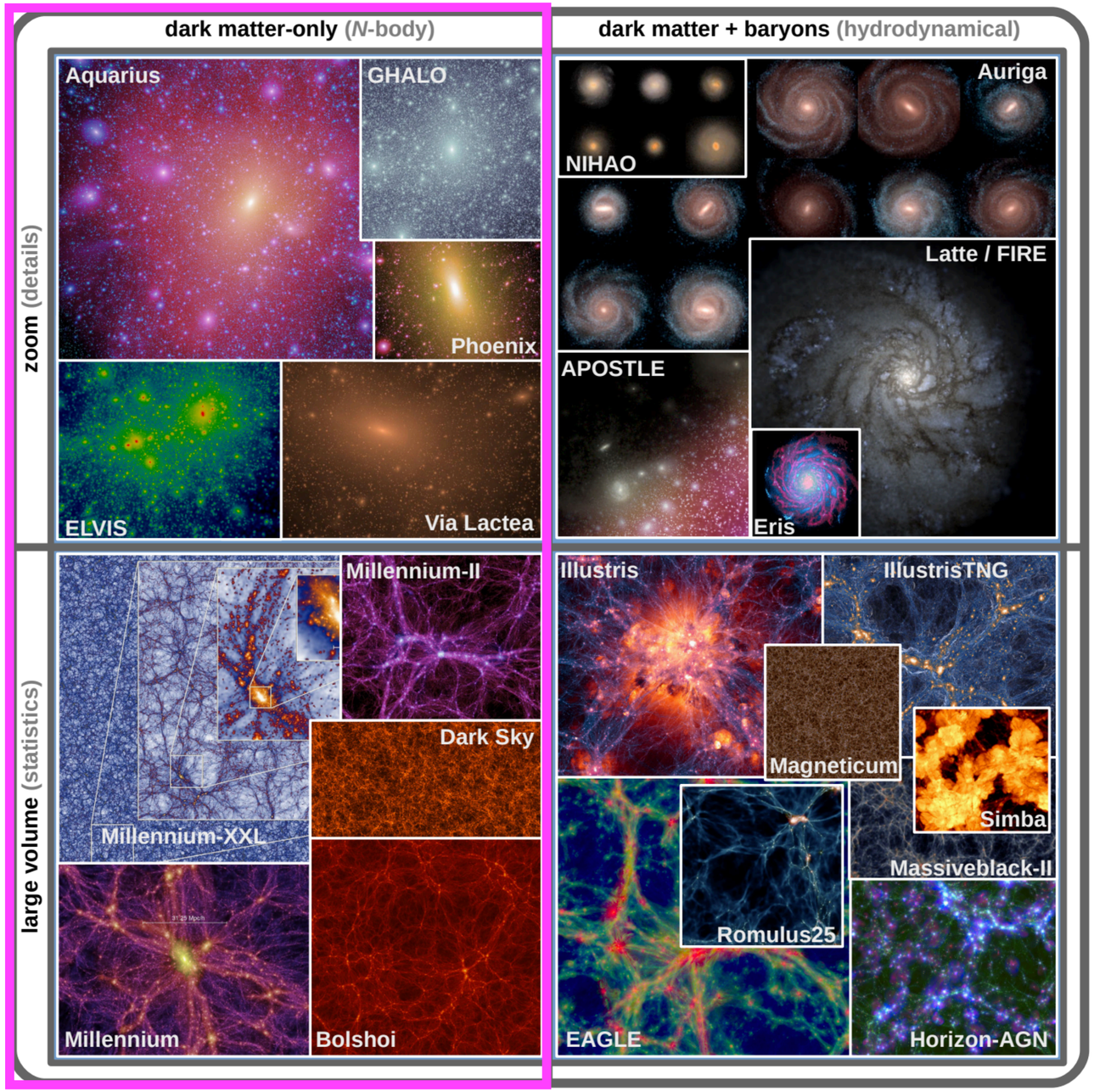


Vogelsberger et al. 2020

The Landscape of Cosmological Simulations

- Cosmological simulations are the **most accurate method** for modeling structure formation

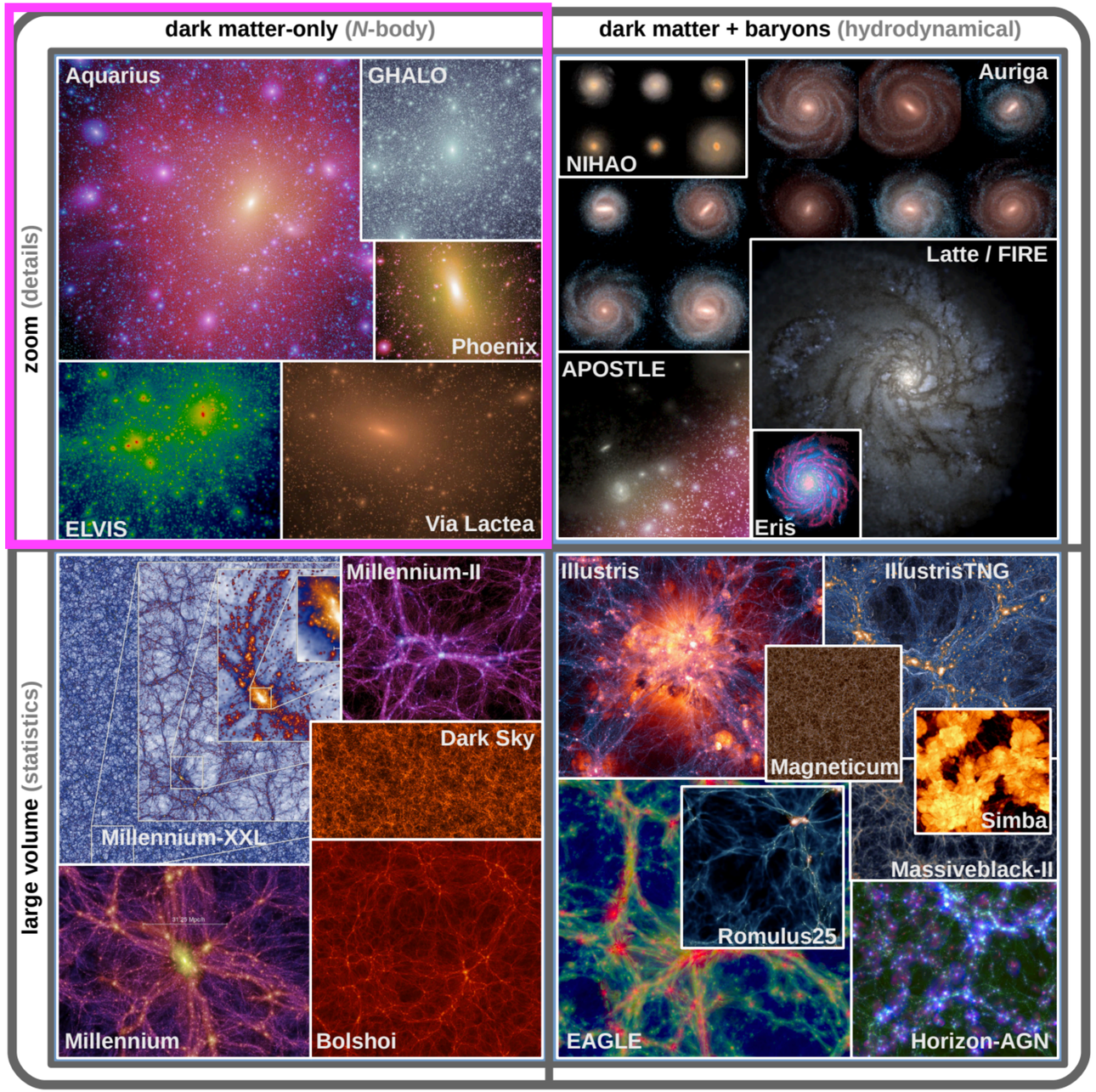
- Dark matter-only simulations provide a **robust template** for more complex modeling



Vogelsberger et al. 2020

The Landscape of Cosmological Simulations

- Cosmological simulations are the **most accurate method** for modeling structure formation
- Dark matter-only simulations provide a **robust template** for more complex modeling
- Zoom-in simulations focus on **small regions** of the universe at **high resolution**, allowing small-scale structure to be resolved



Vogelsberger et al. 2020

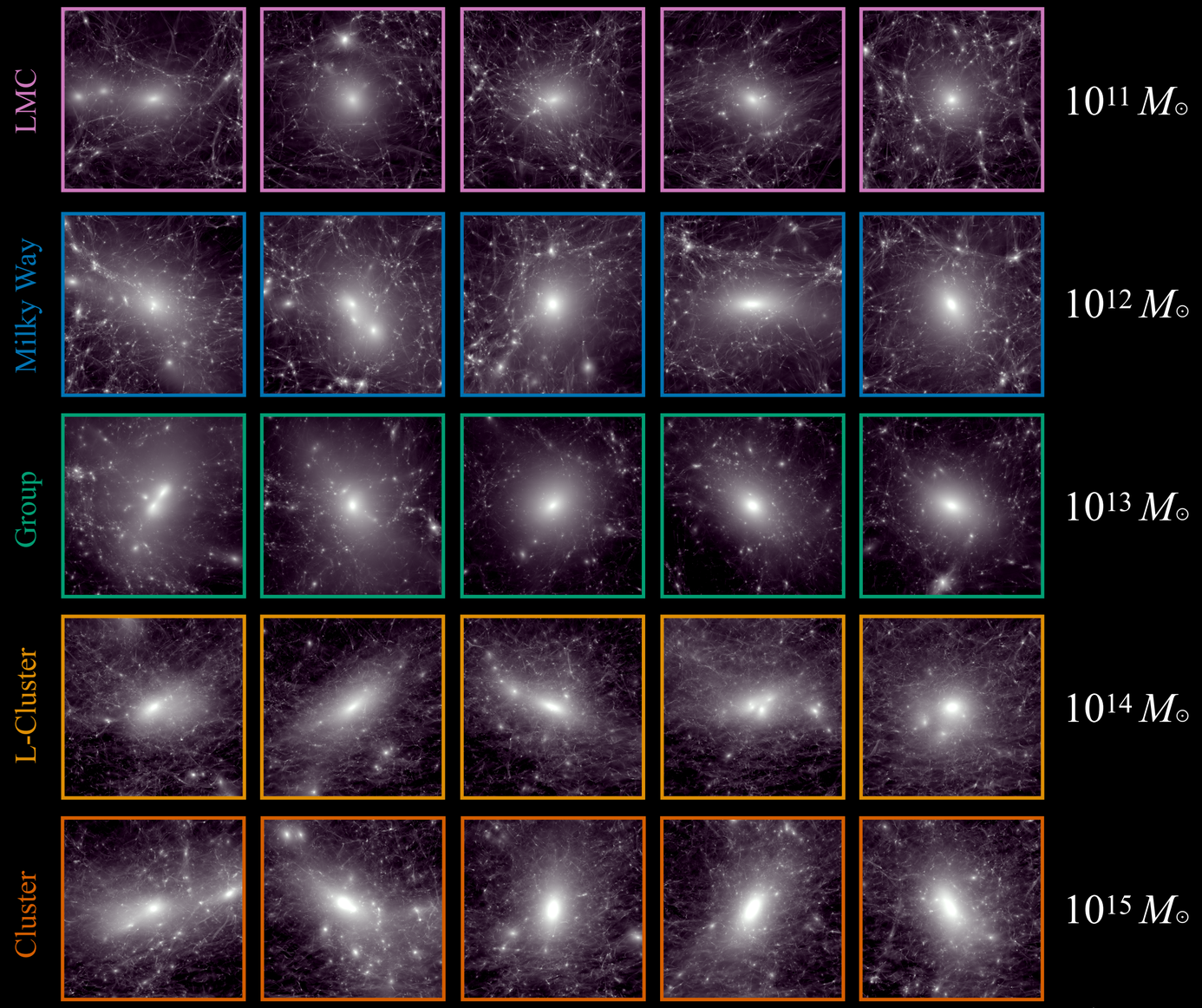
Symphony Zoom-in Simulations

- **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



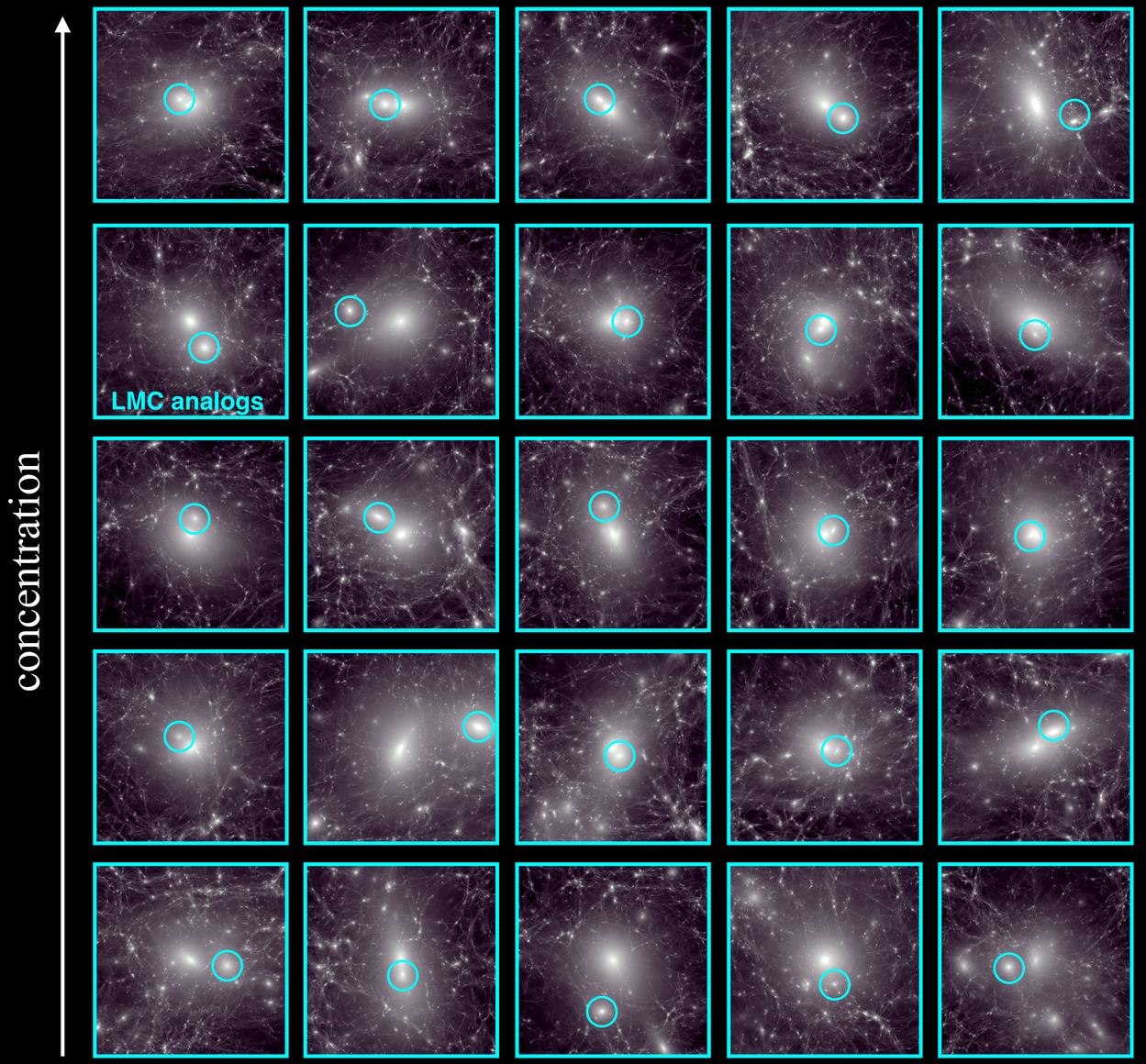
EN, Mansfield, Wang et al. (2209.02675)

Milky Way-est Zoom-in Simulations

- **25** high-resolution cosmological zoom-in simulations of **Milky Way-like systems**

- All realizations include **LMC analogs** on first infall and analogs of the ***Gaia*-Enceladus** merger

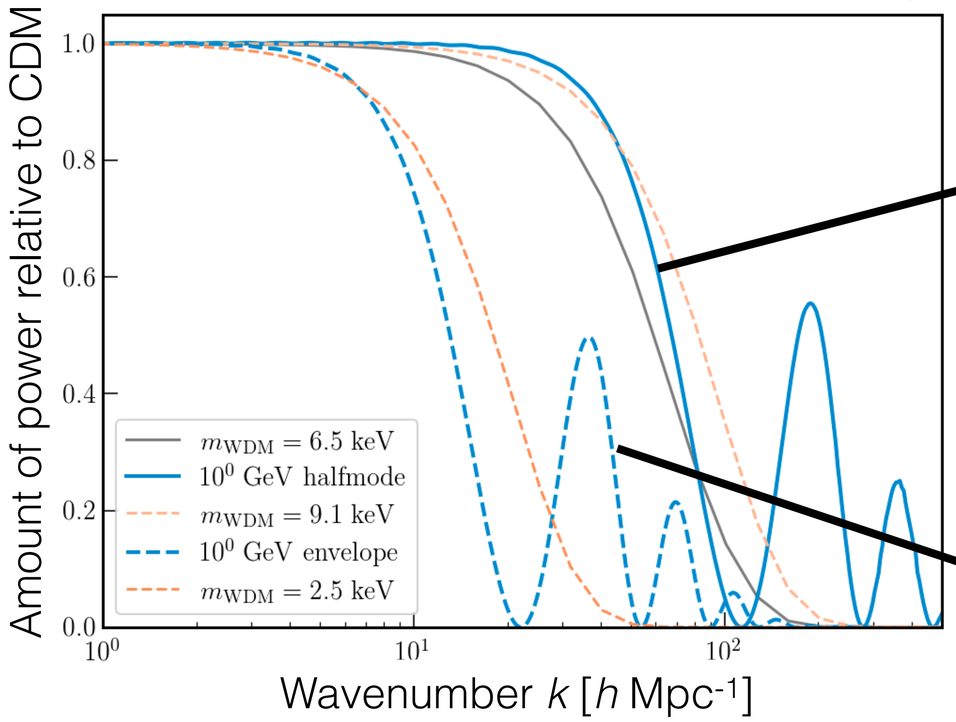
Deveshi Buch
(Stanford)

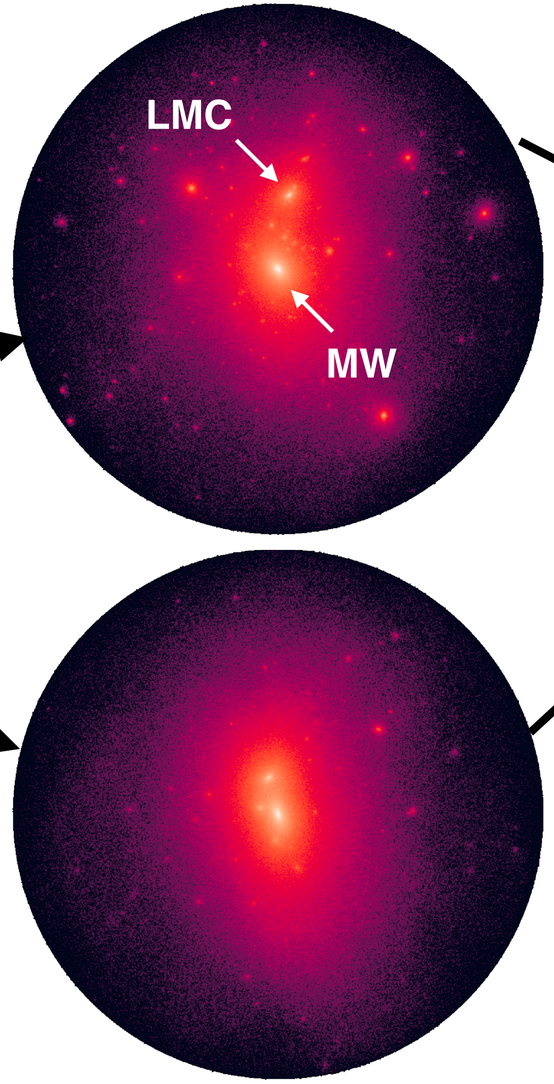


Buch & EN et al. in prep.

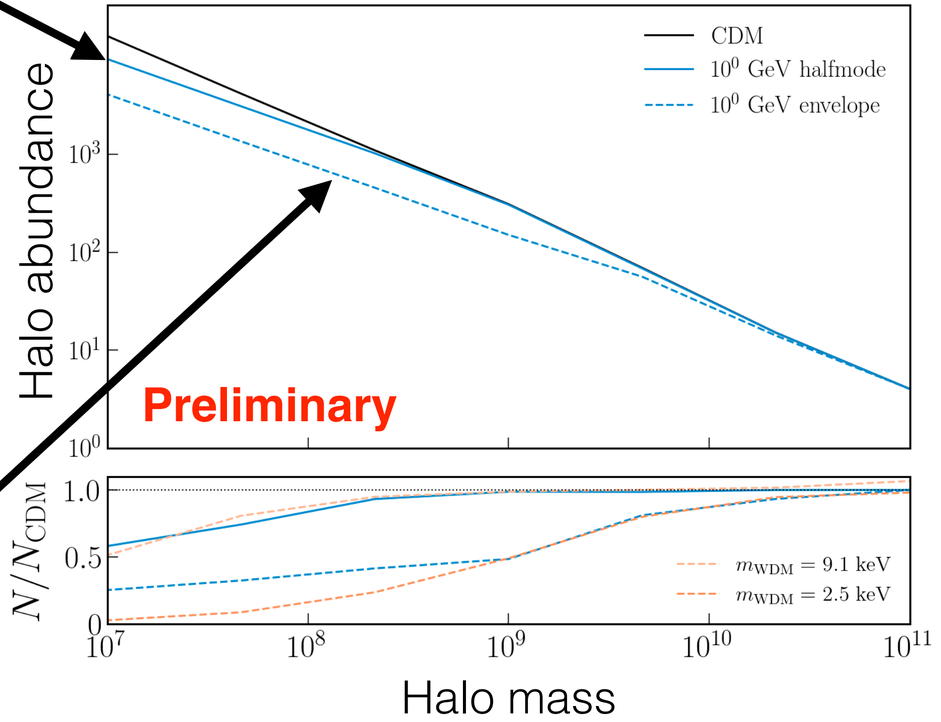
Beyond-CDM Zoom-in Simulations

Initial conditions from linear theory





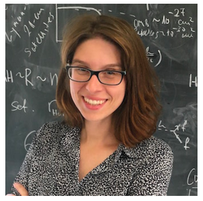
Halo and subhalo populations



72 cosmological simulations of Milky Way-like systems with initial conditions for warm, interacting, fuzzy dark matter


Rui An
(USC)


Andrew Benson
(Carnegie)

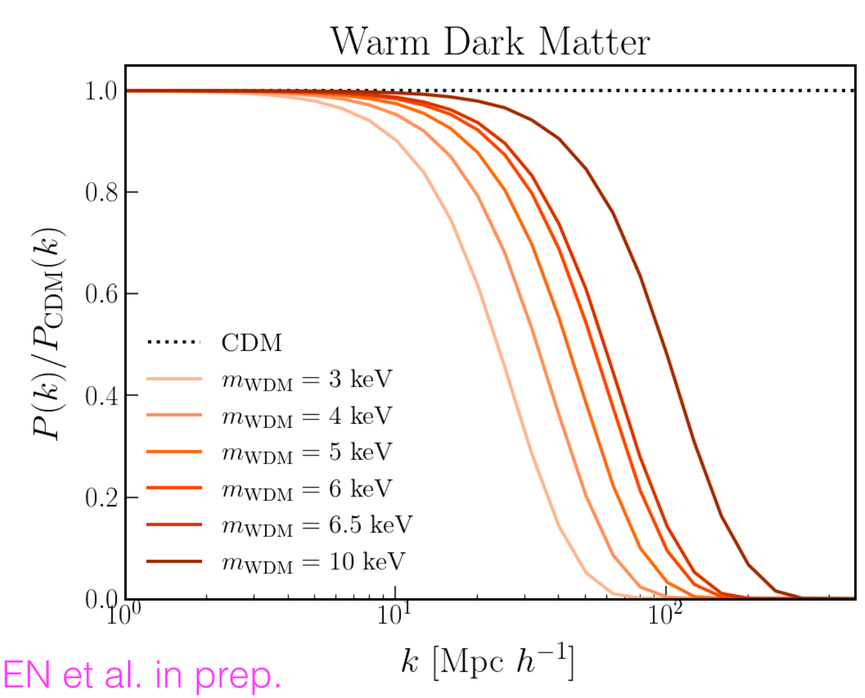

Vera Gluscevic
(USC)

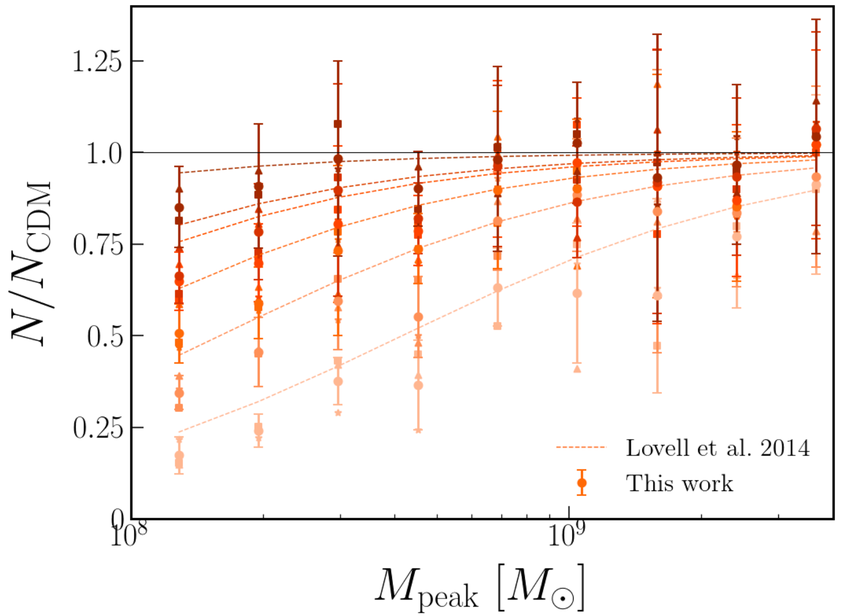
EN et al. in prep.

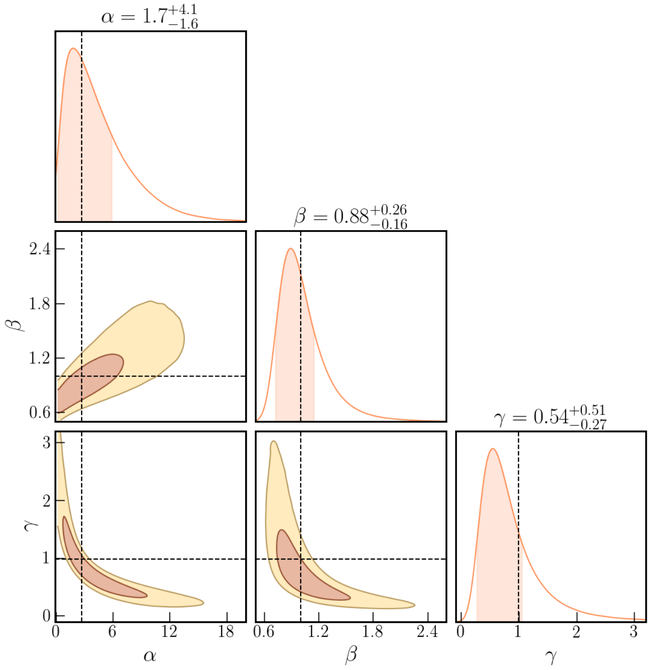
Beyond-CDM Zoom-in Simulations

- 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

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



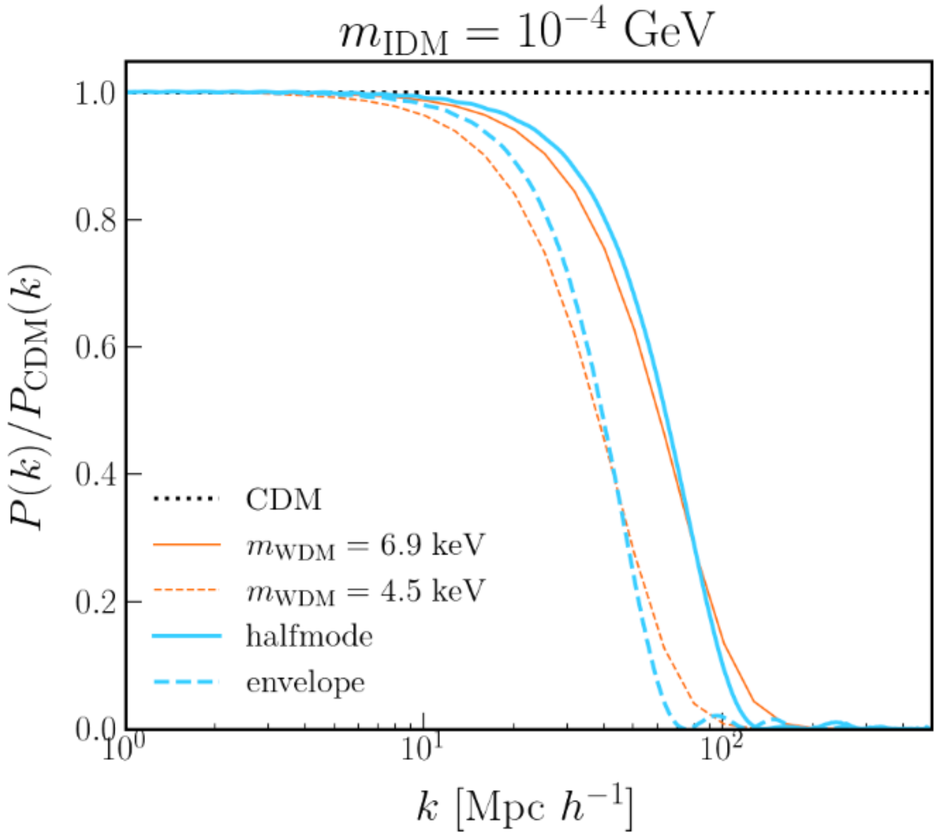


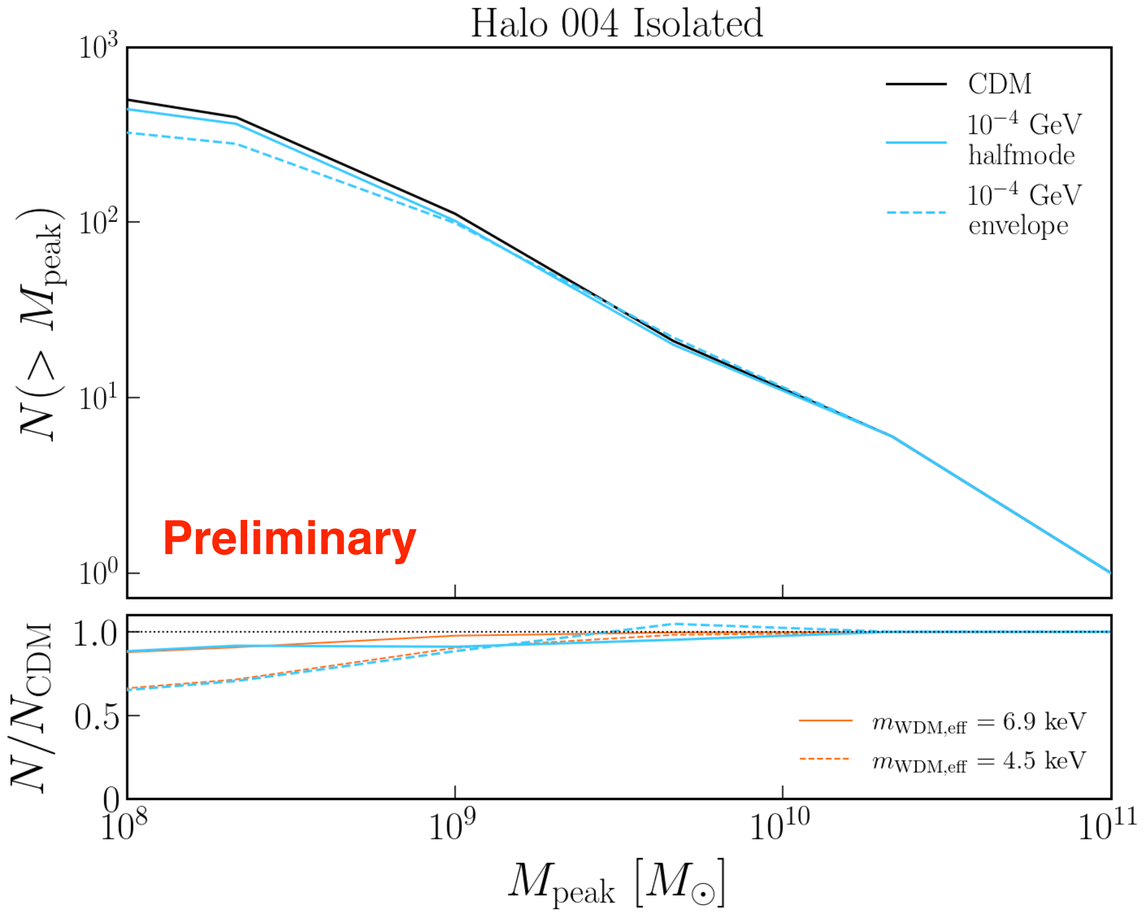


EN et al. in prep.

Beyond-CDM Zoom-in Simulations

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

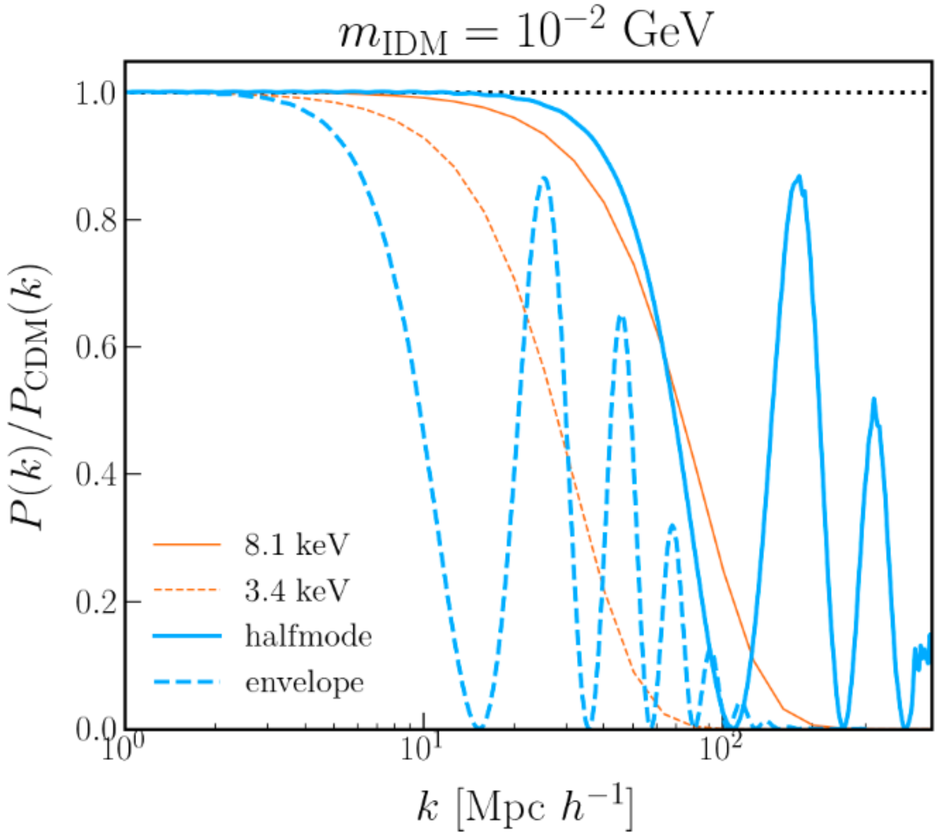


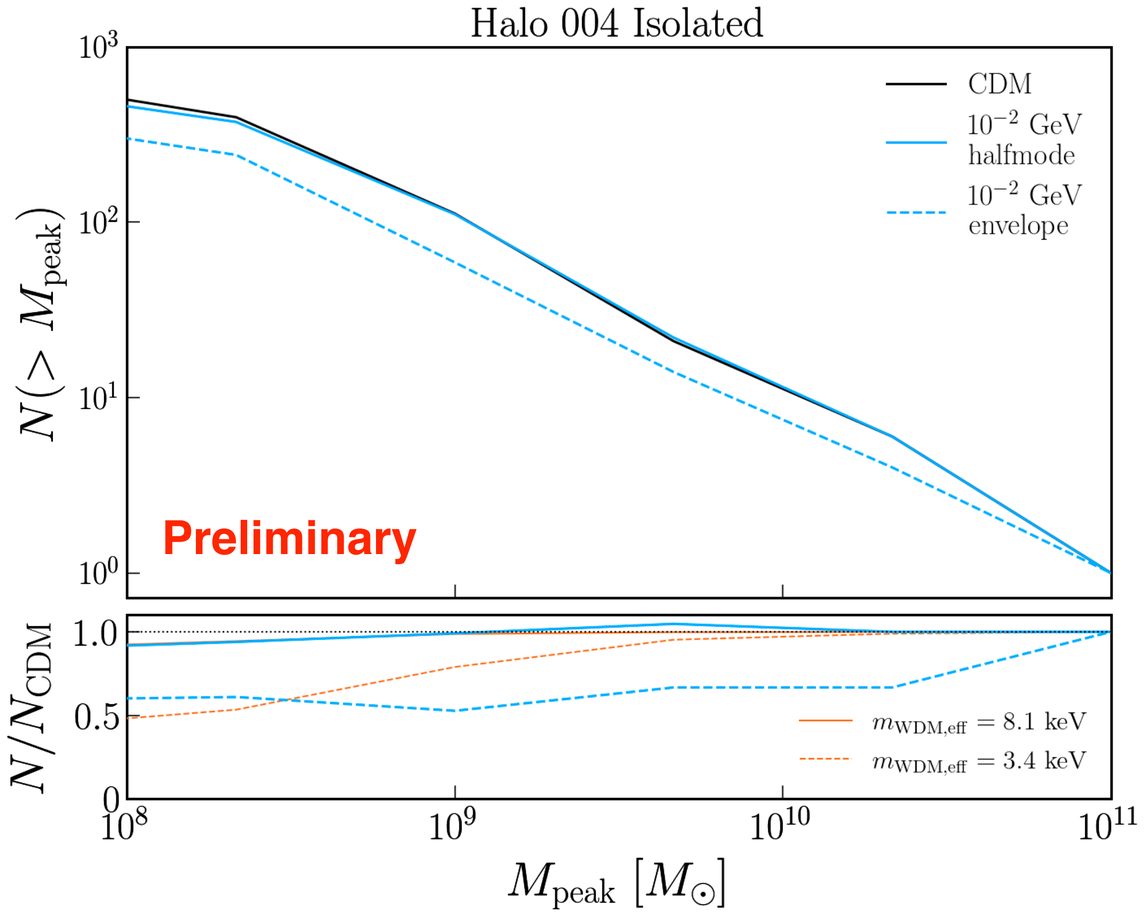


EN et al. in prep.

Beyond-CDM Zoom-in Simulations

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

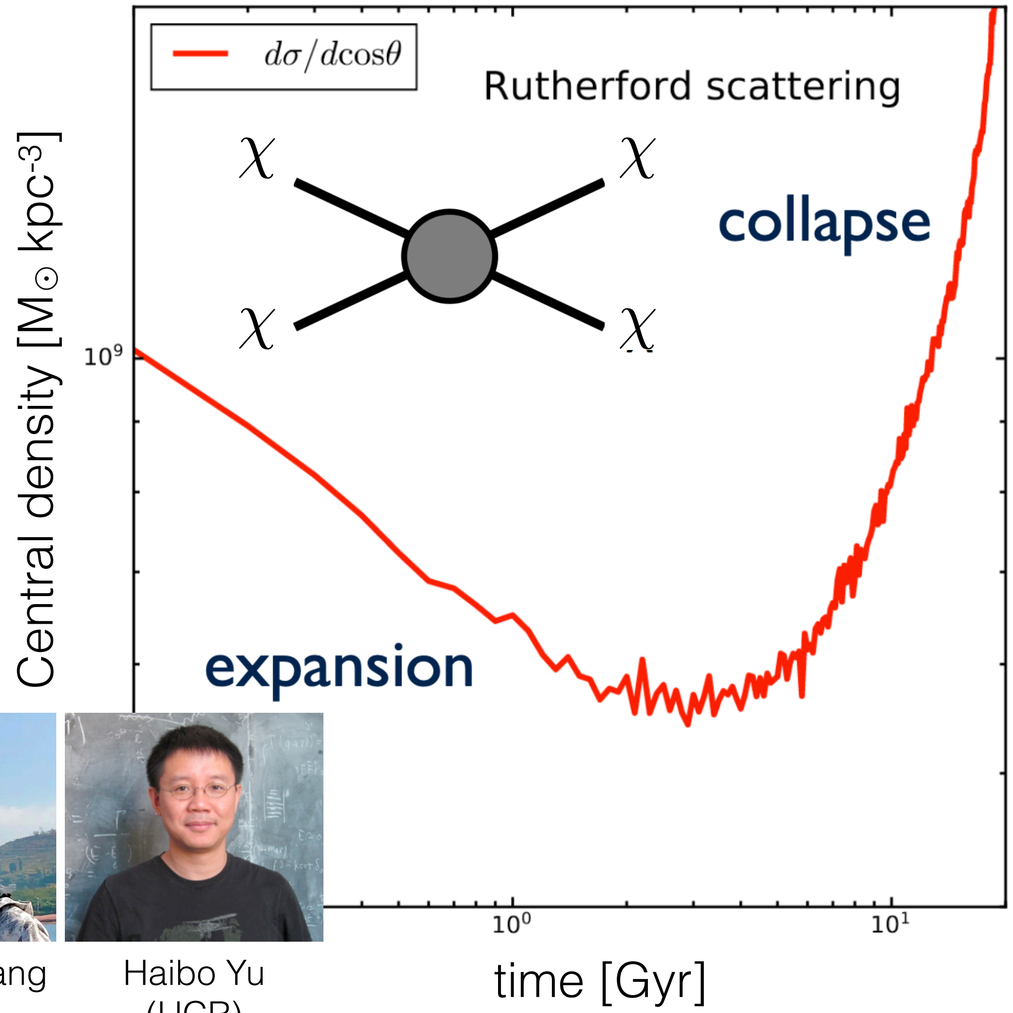




EN et al. in prep.

Signatures of Strong Dark Matter Self-interactions

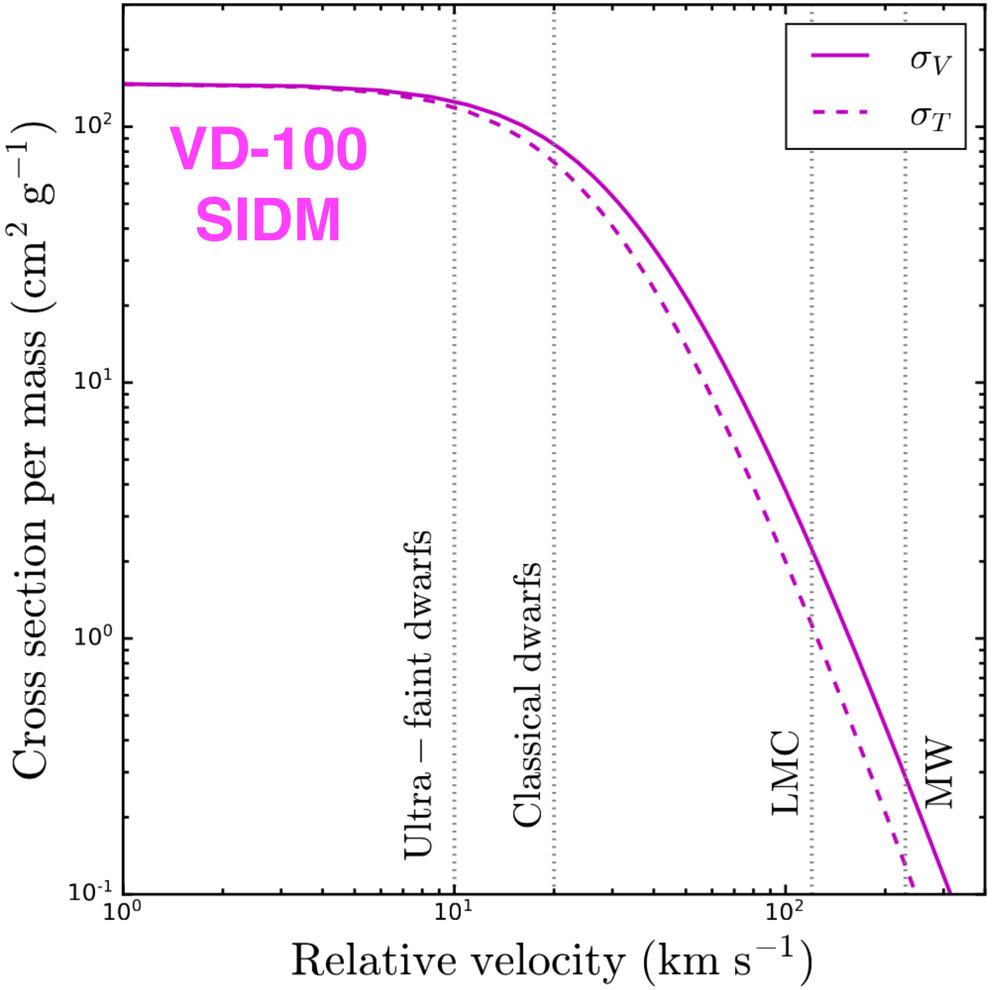
Yang & Yu 2022 (2205.03392)



Daneng Yang (UCR)

Haibo Yu (UCR)

Yang, EN, Yu 2023 (2211.13768)



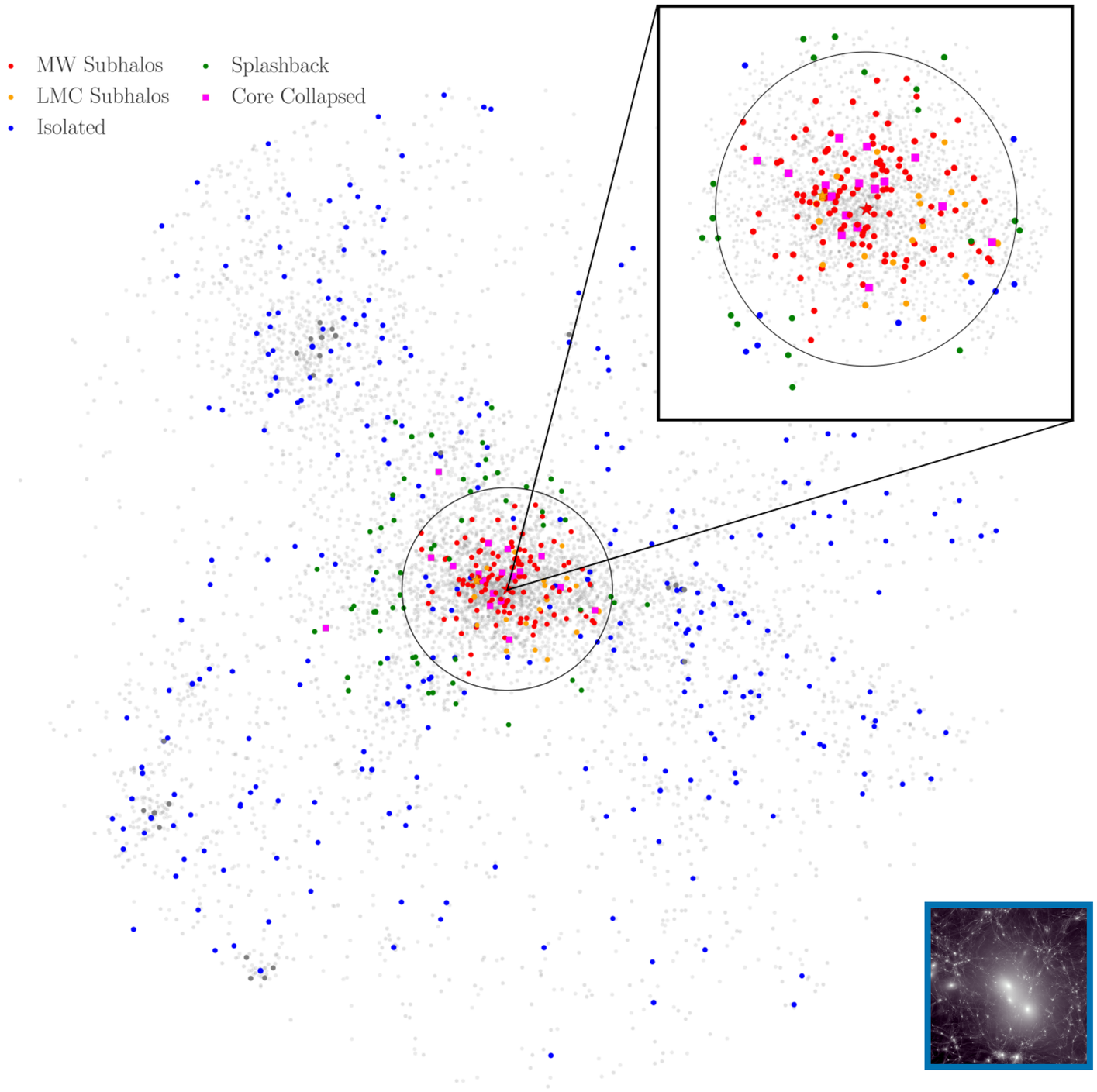
Strong, velocity-dependent self-interactions → **core-collapse** in small halos & core-formation in large halos

VD-100 SIDM
Milky Way Simulation

- Extremely high-resolution MW zoom-in with **strong**, **velocity-dependent self-interactions**

- Self-consistent analysis of halos in **all environments** throughout high-resolution volume

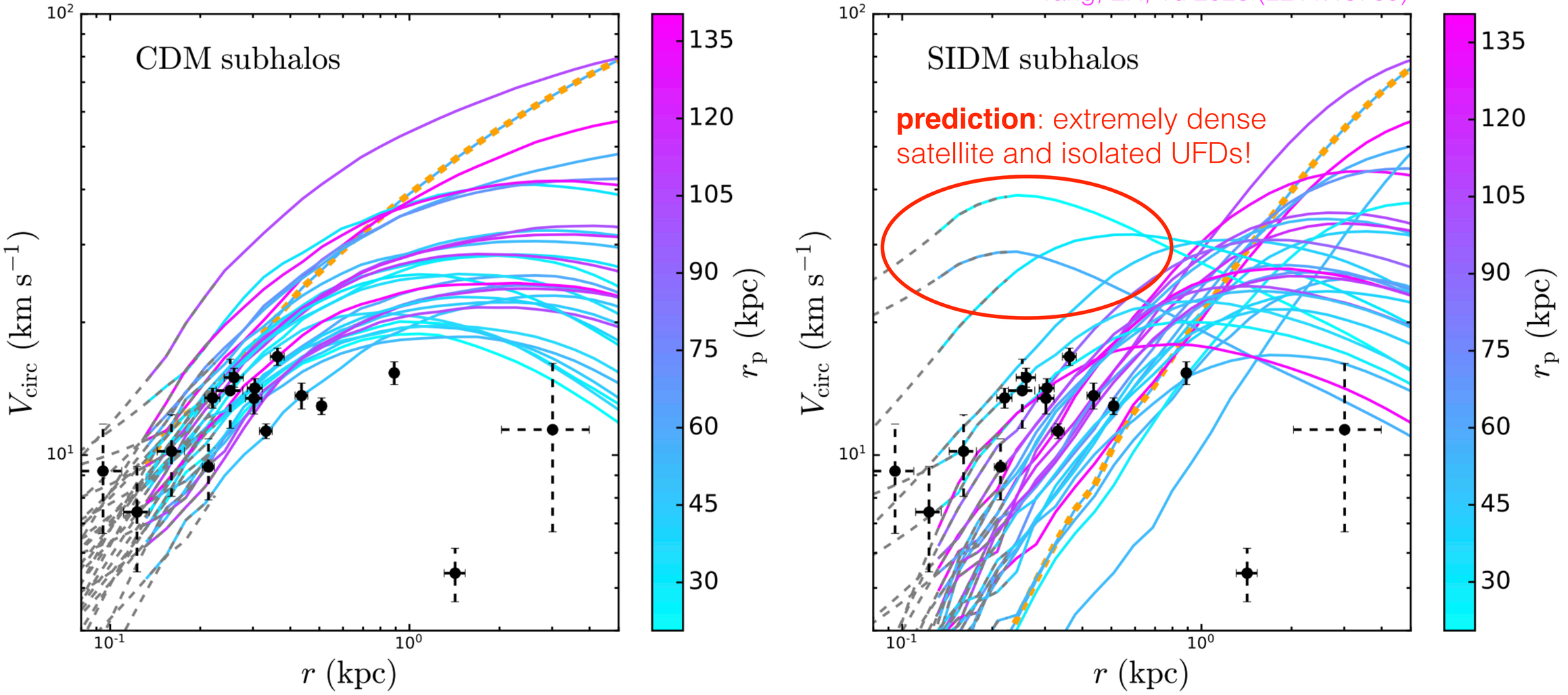
- **Deep core-collapse** in ~10% of isolated halos, ~20% of subhalos down to 10^8 $M_\odot$



Yang, EN, Yu 2023 (2211.13768)

VD-100 SIDM Milky Way Simulation

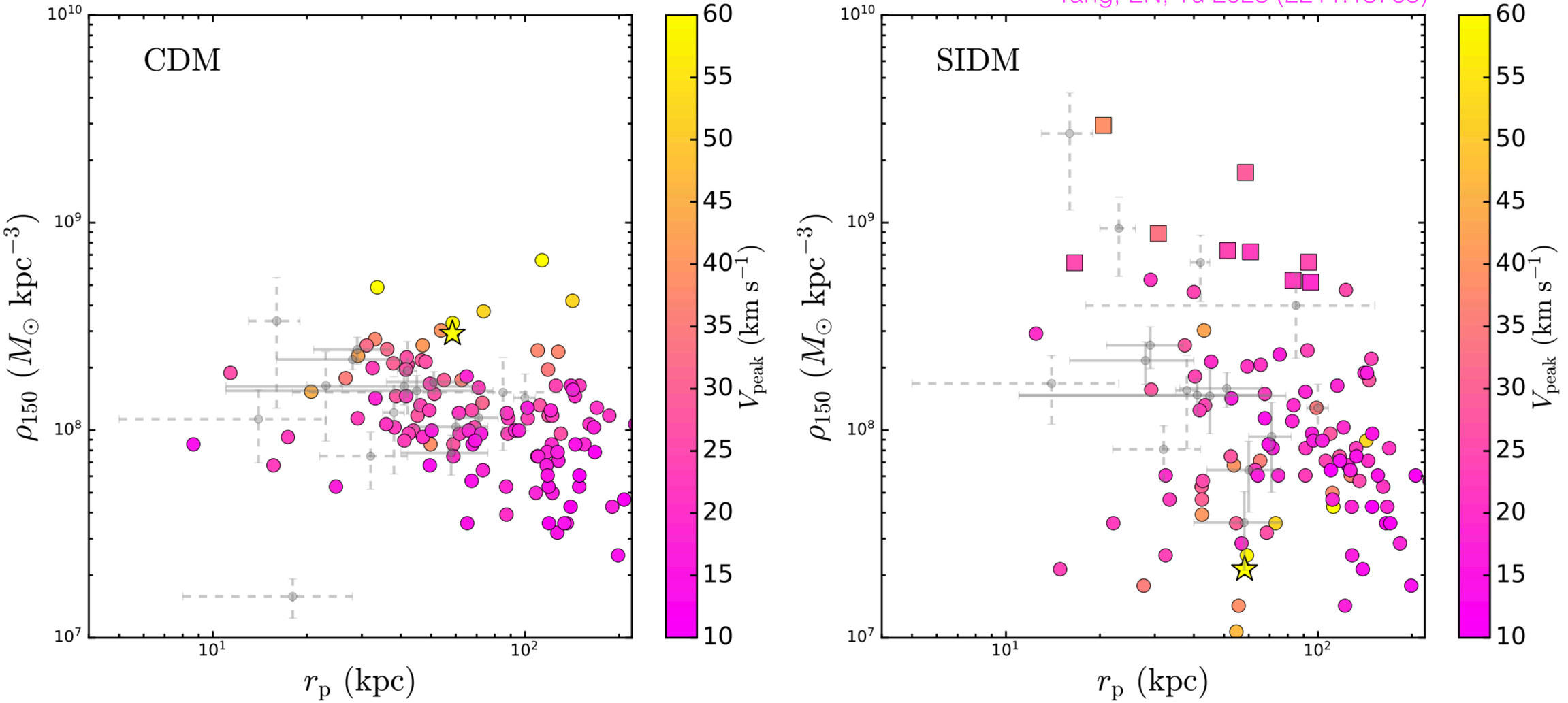
Yang, EN, Yu 2023 (2211.13768)



VD-100 subhalos are **more diverse** than in CDM, alleviating too big to fail problem for brightest systems

VD-100 SIDM Milky Way Simulation

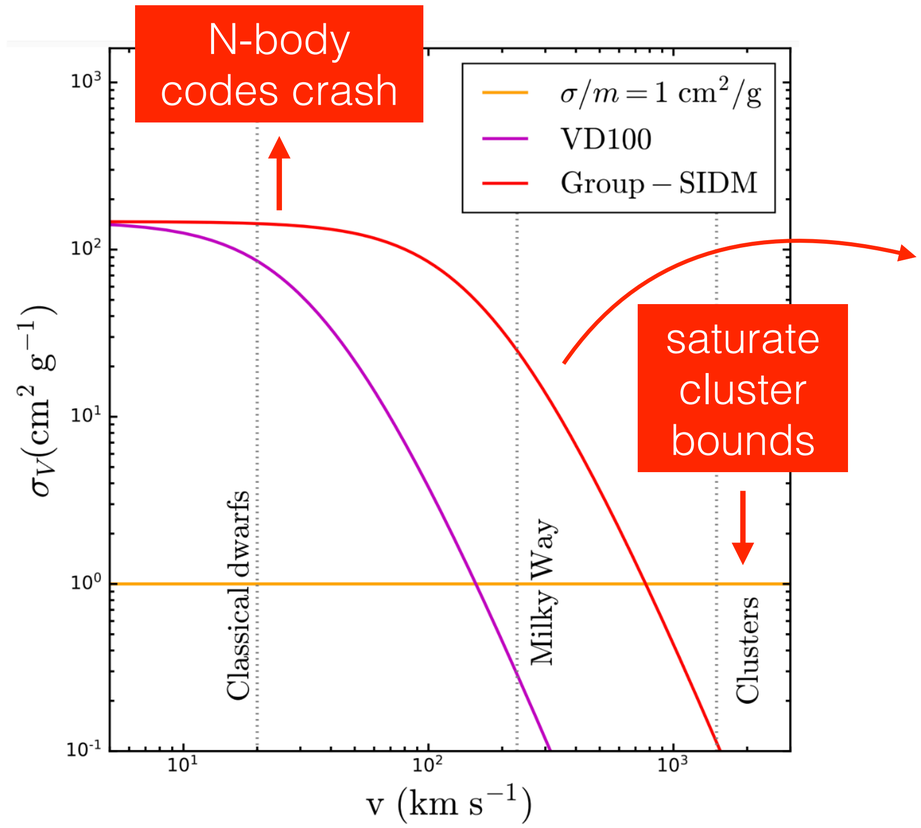
Yang, EN, Yu 2023 (2211.13768)

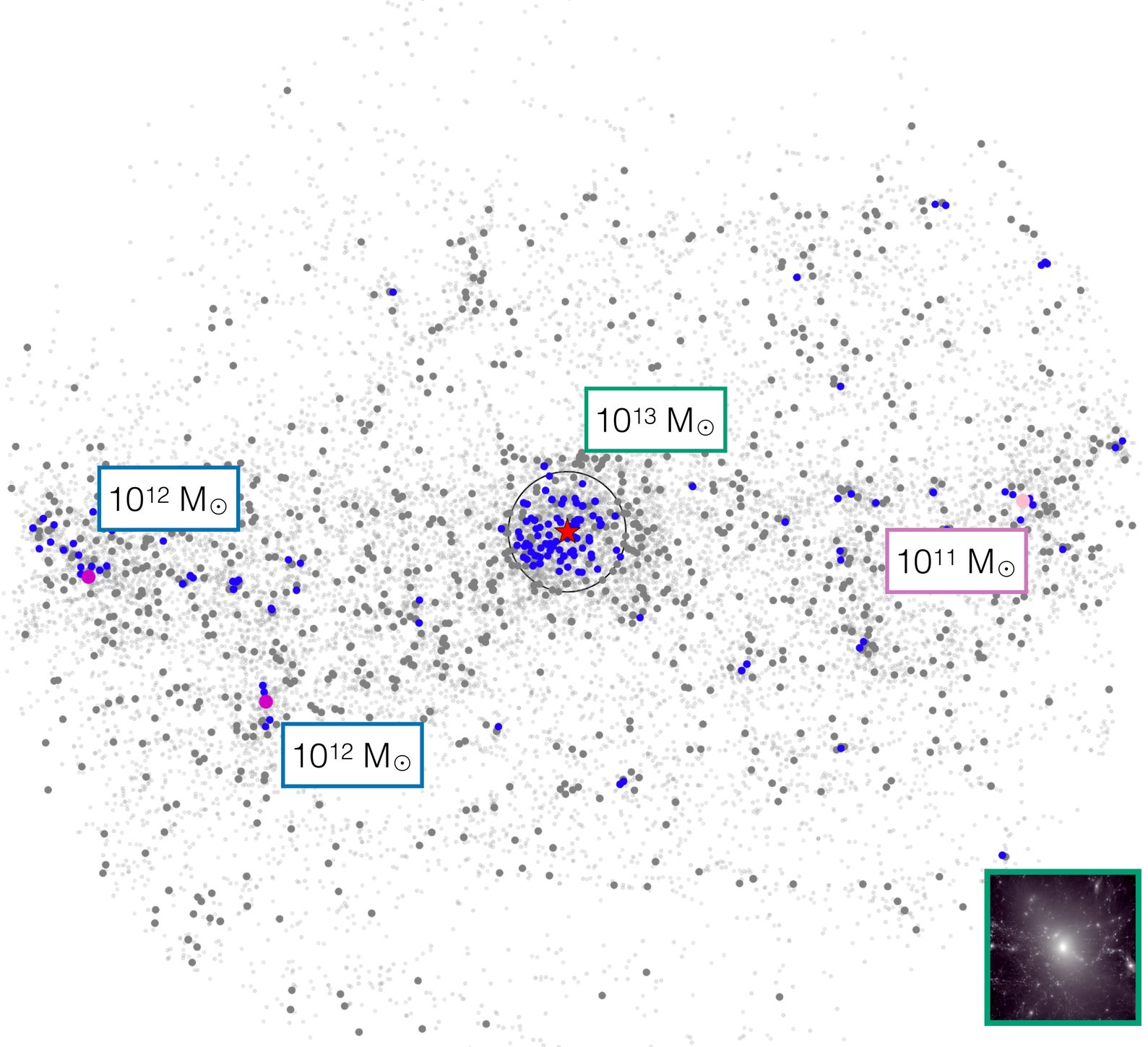


VD-100 diversifies central density-pericenter relation; velocity-independent interactions erase anti-correlation

Group-SIDM Strong Lens Analog Simulation

- **First** group-scale simulation with core-collapse (see Haibo Yu's talk)

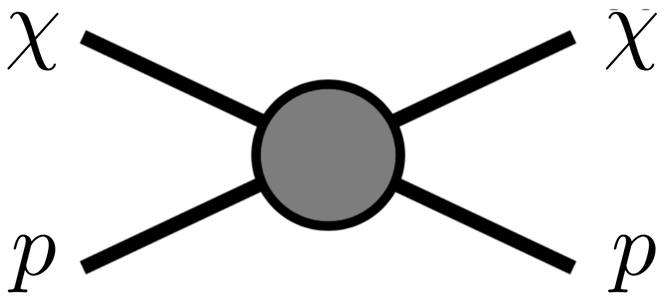




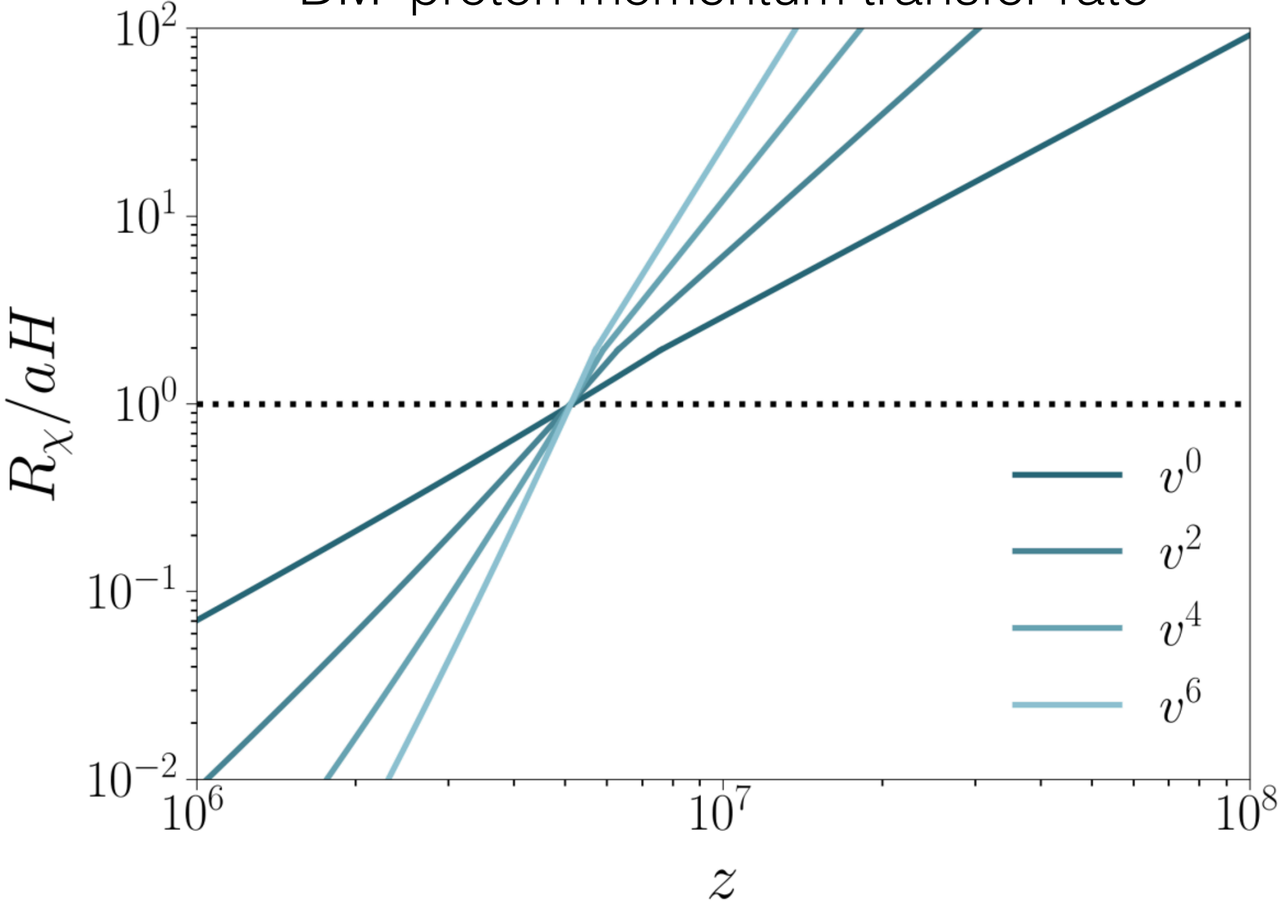
EN, Yang, Yu in prep.

Simulating Dark Matter–Baryon Interactions

- Late-time dark matter–baryon scattering is constrained to be **rare**
- Idea: simulate DM–baryon scattering with an N-body algorithm, analogous to SIDM; **first implementation of this physics!**
- Unlike SIDM, these interactions couple DM to a hot, collisional species



DM–proton momentum transfer rate

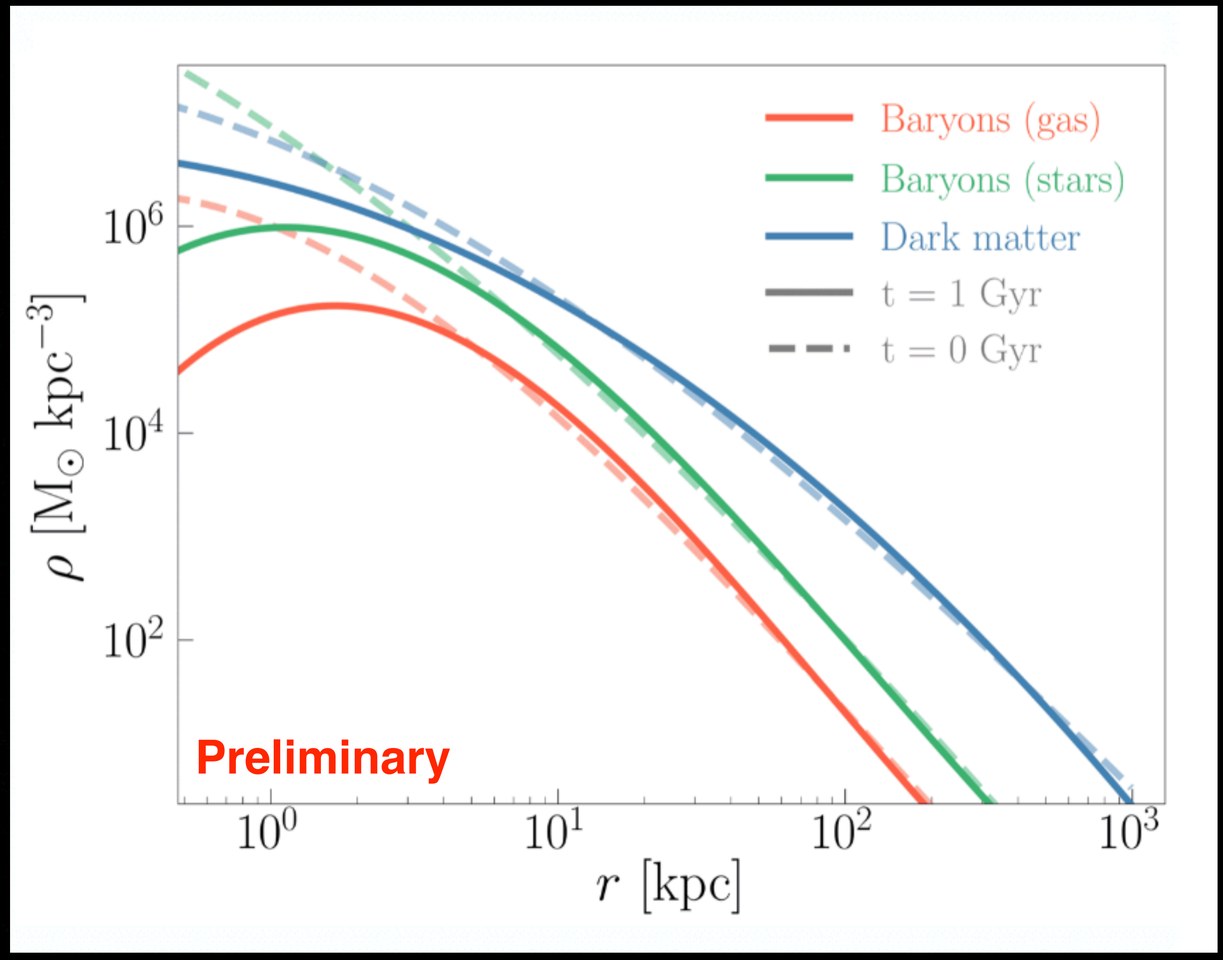


Maamari, Gluscevic, Boddy, EN et al. 2021 (2010.02936)

Simulating Dark Matter–Baryon Interactions

Karime Maamari
(USC)

Maamari, EN, Gluscevic in prep.



Dark matter–baryon interactions thermalize DM in inner regions, phenomenologically similar to SIDM

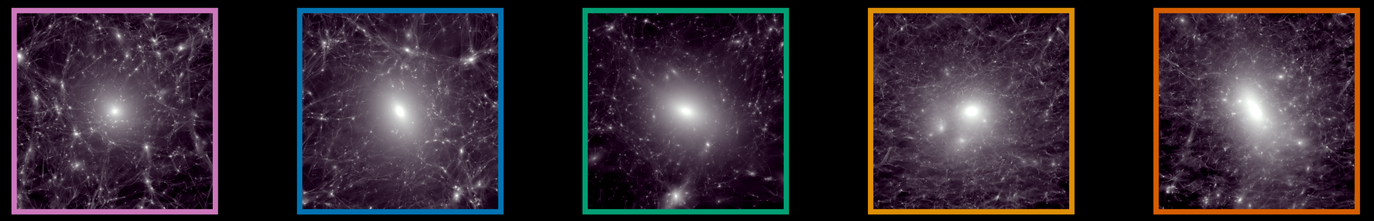
- Symphony: **262** high-resolution cosmological zoom-in simulations, spanning four decades of host halo mass, including the first suites of **LMC** and **strong lens analog** hosts

- Milky Way-est: **25** high-resolution cosmological zoom-in simulations of **Milky Way-like systems**, including realistic **LMC** and ***Gaia*-Enceladus analogs**

- Beyond-CDM: **72** high-resolution cosmological zoom-in simulations of Milky Way systems with initial conditions appropriate for **warm**, **interacting**, **fuzzy** DM

- VD-100 SIDM: extremely high-resolution Milky Way-like system with **strong**, **velocity-dependent self-interactions** yields **diverse halo populations**

- Simulating dark matter–baryon interactions: **first implementation** of this physics, with hints of SIDM-like signatures



Carnegie Science

USC University of Southern California