# Cosmological Simulations with Novel Dark Matter Physics

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PACIFIC 2024

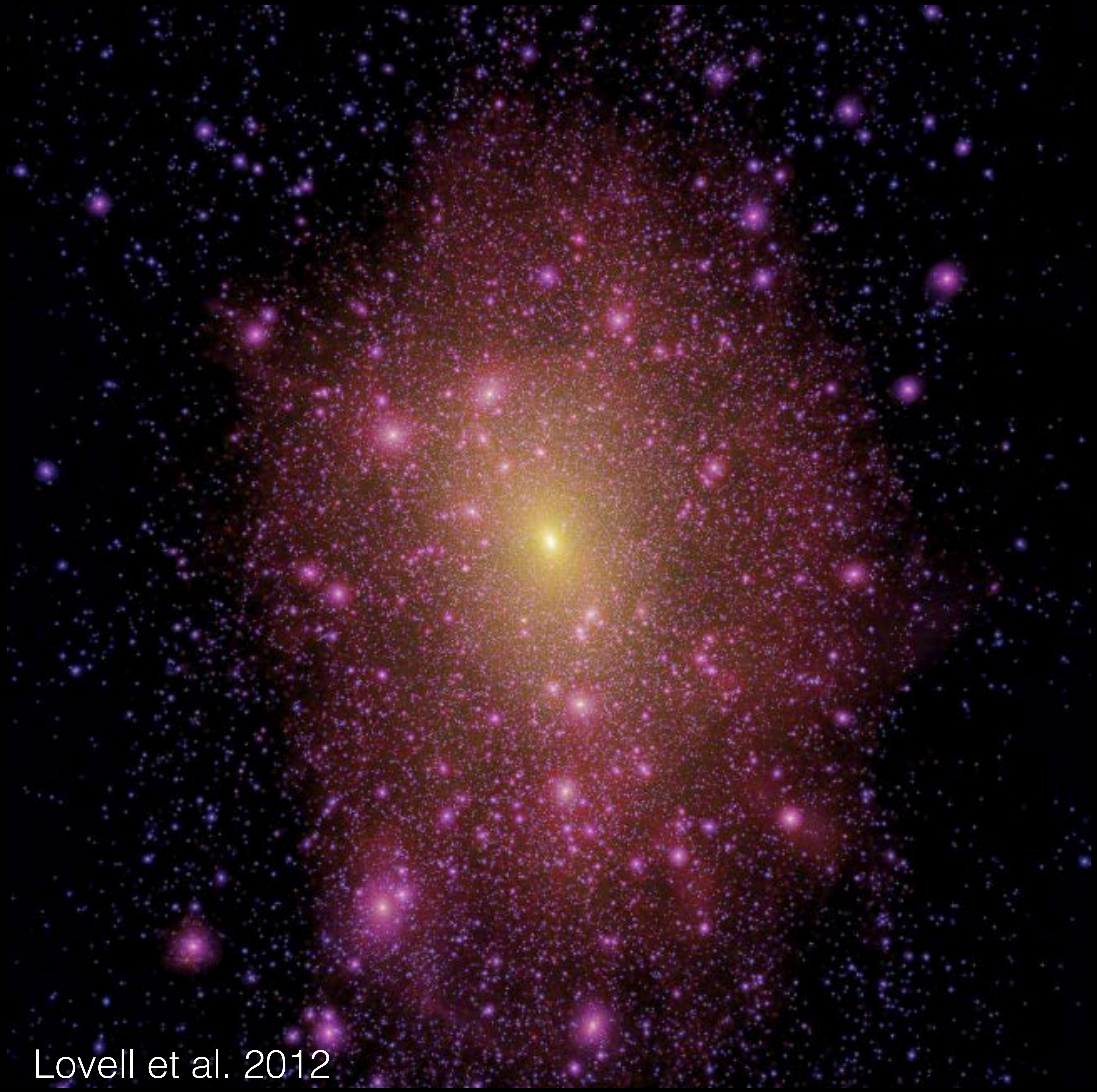
8/27/2024

Carnegie Science

USC University of Southern California

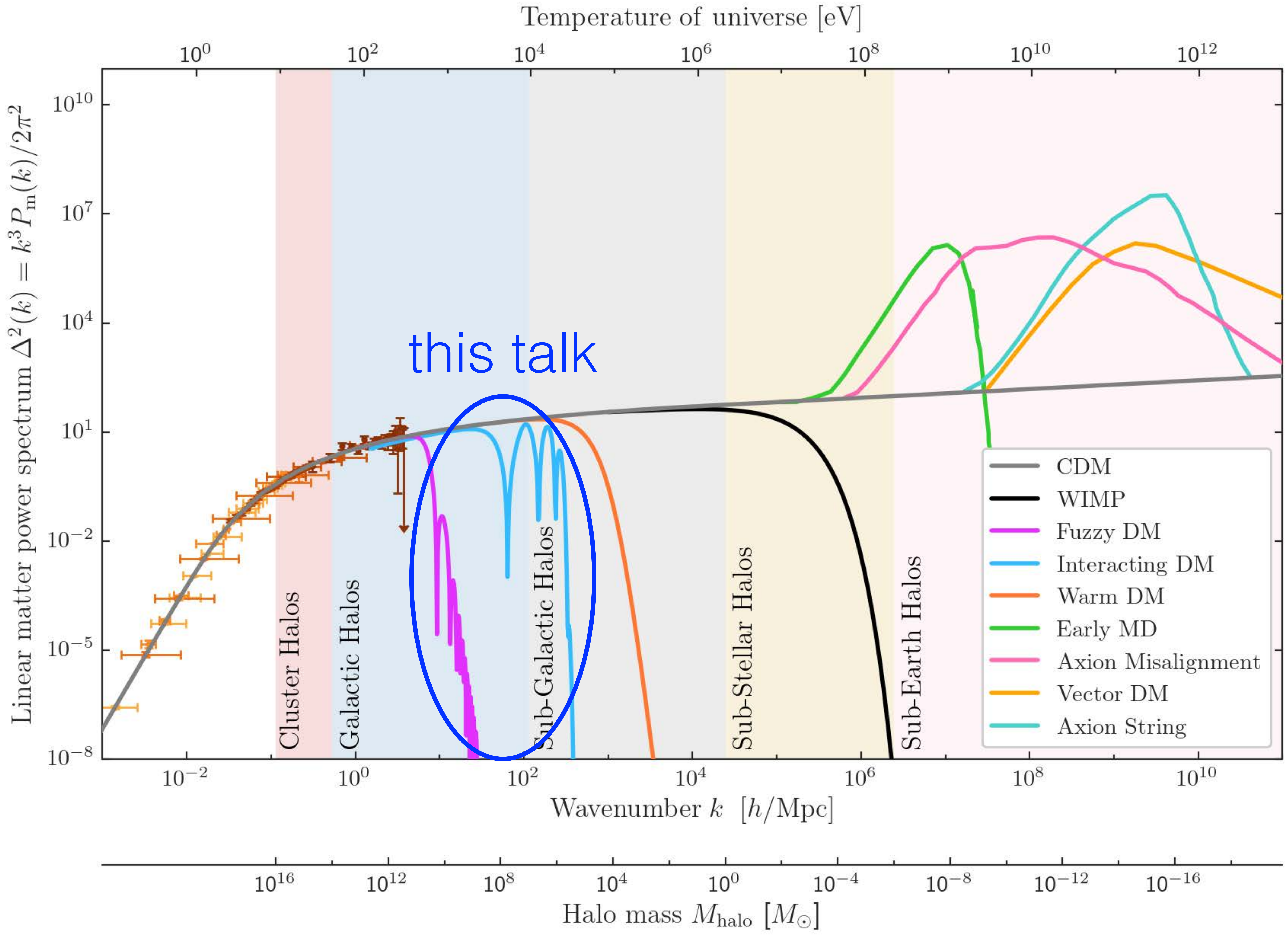
# Dark Matter Physics on Small Scales

Cold dark matter




New dark matter physics

# Dark Matter Physics on Small Scales




- Dark matter physics affects structure formation throughout cosmic history
- Matter clustering on sub-Mpc scales is mostly unconstrained
- **Simulations are needed** to explore a range of DM models on small scales


Snowmass Cosmic Probes of Dark Matter Report (2209.08215)

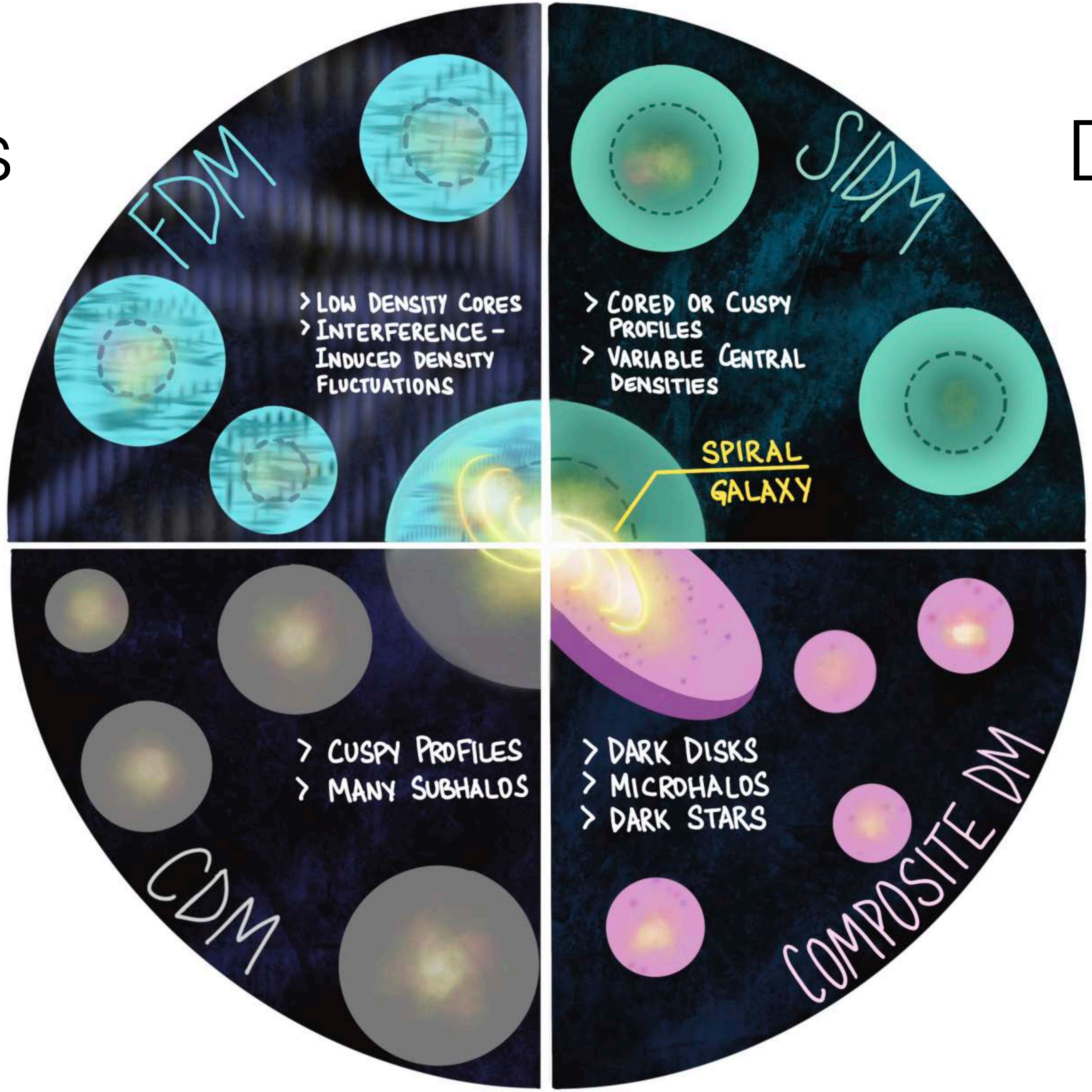
*Ab Initio*
DM Physics

alter initial conditions

production mechanism

Standard Model interactions

particle mass




*In Situ*
DM Physics

alter dynamics

self-interactions

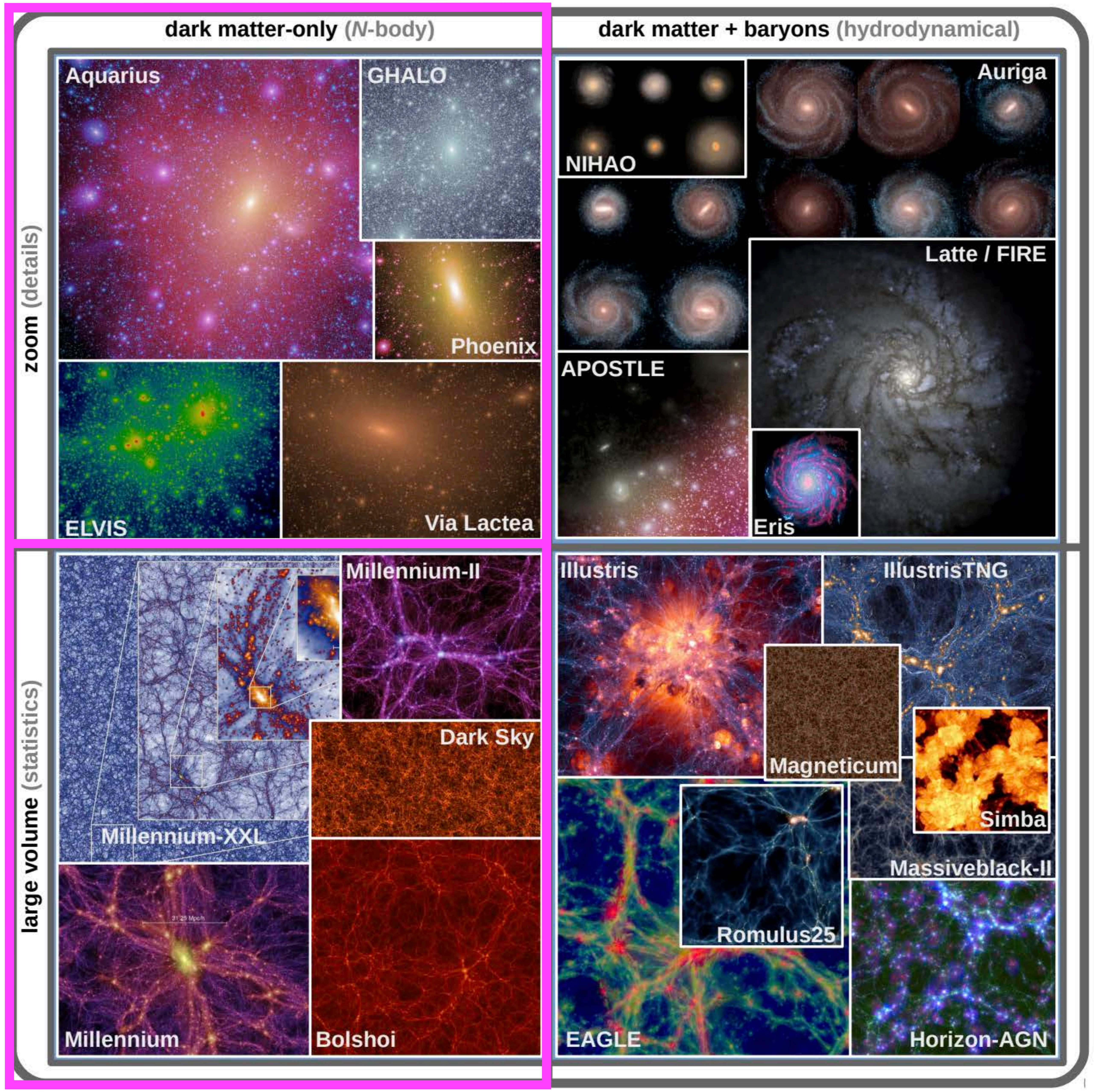
particle lifetime

particle mass

Bechtol et al. 2022 (2203.07354)

# The Landscape of Cosmological Simulations

- Cosmological simulations robustly predict nonlinear structure
- Dark matter only simulations enable DM parameter space exploration
- Zoom-in simulations resolve small scales in specific systems of interest (e.g. Milky Way, strong lenses)




Vogelsberger et al. 2020

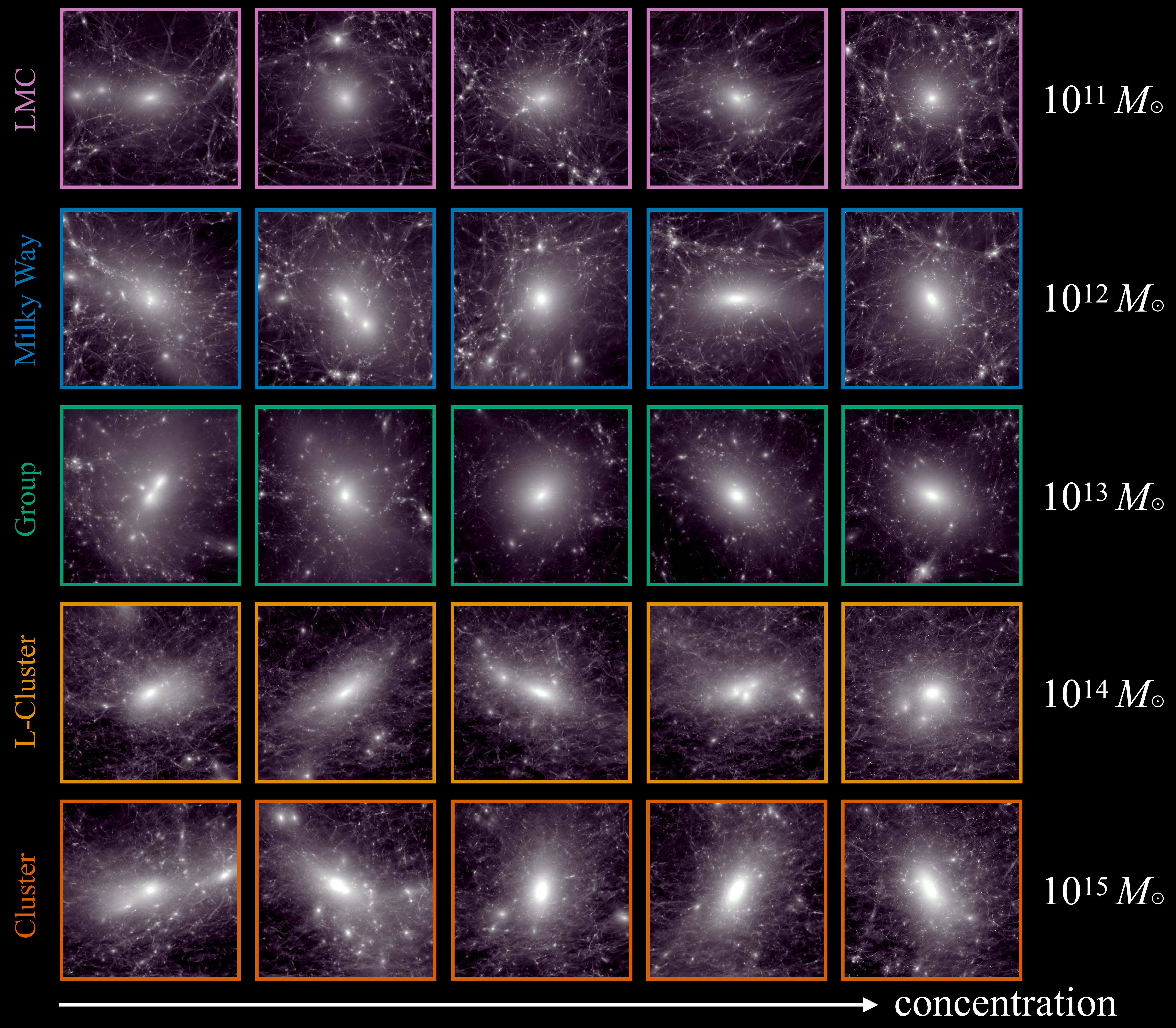
# Symphony Zoom-in Simulation Suites

- 262 cosmological CDM-only zoom-in simulations spanning four 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/gfcsims

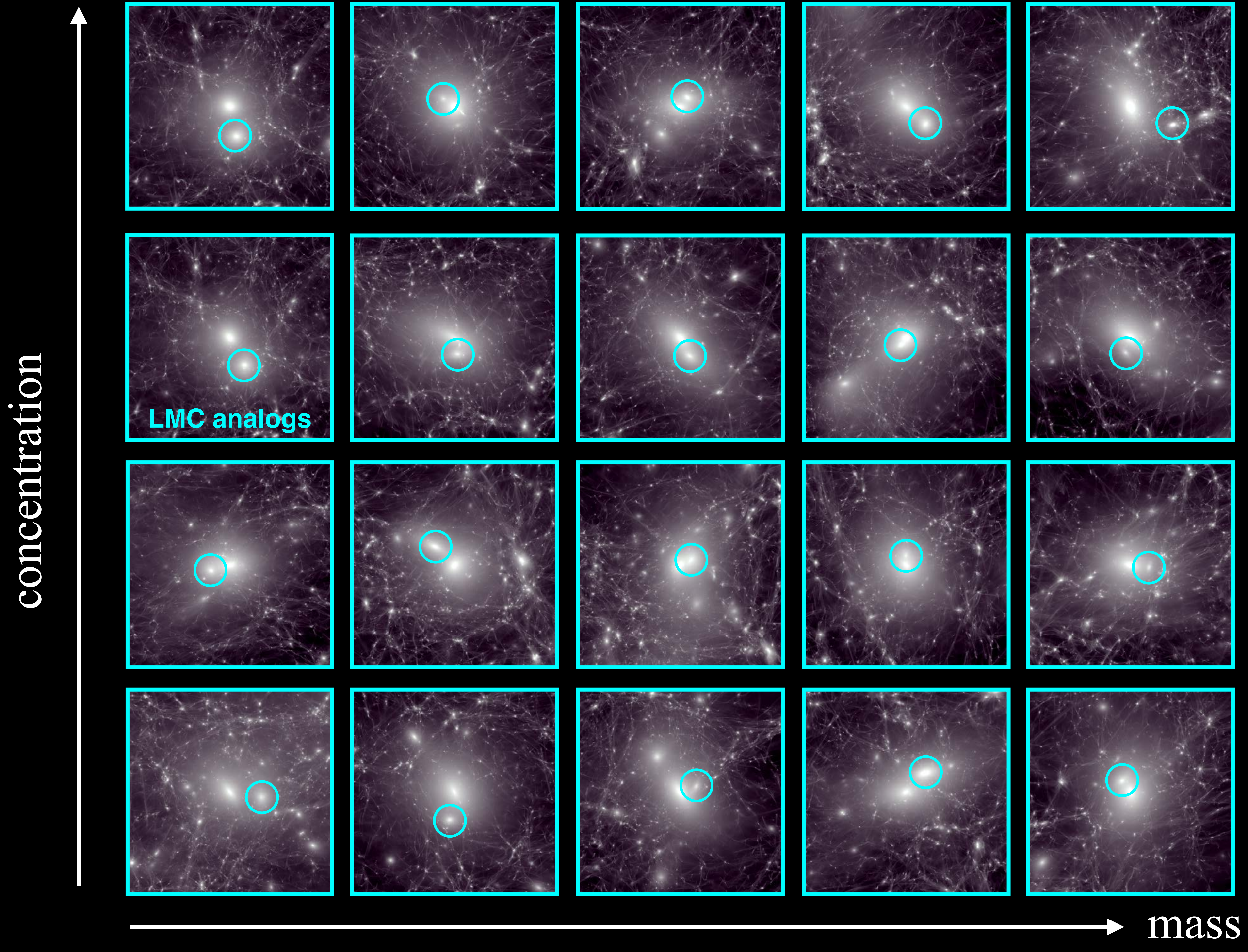



EN et al. 2023 (2209.02675)

# Milky Way-est Zoom-in Simulations

- 20 cosmological CDM-only zoom-in simulations of Milky Way-like systems
- All realizations include analogs of the **LMC** and **Gaia-Sausage-Enceladus**
- All data is publicly available: web.stanford.edu/group/gfc/gfcsims

Deveshi Buch
(Stanford)

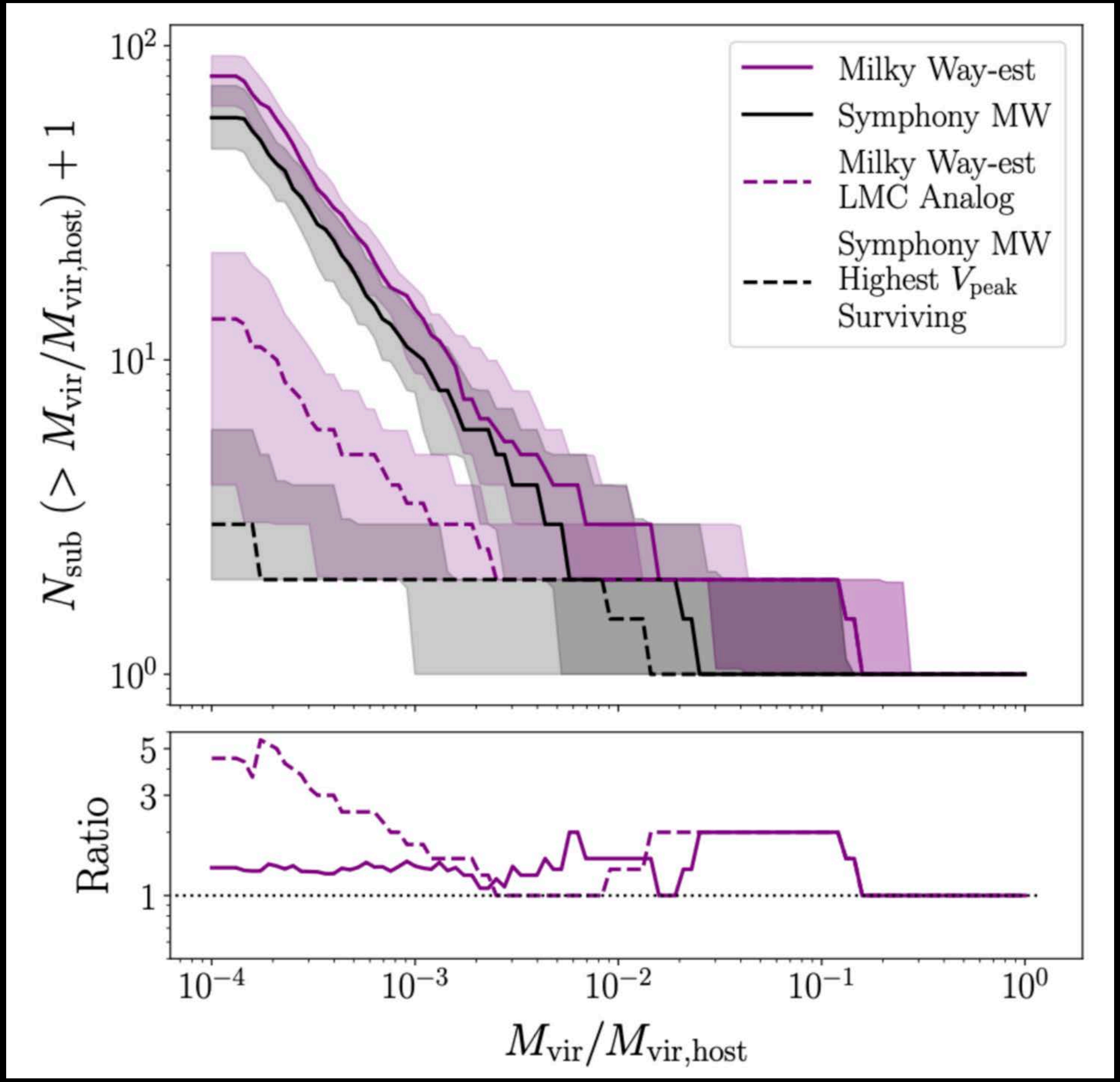


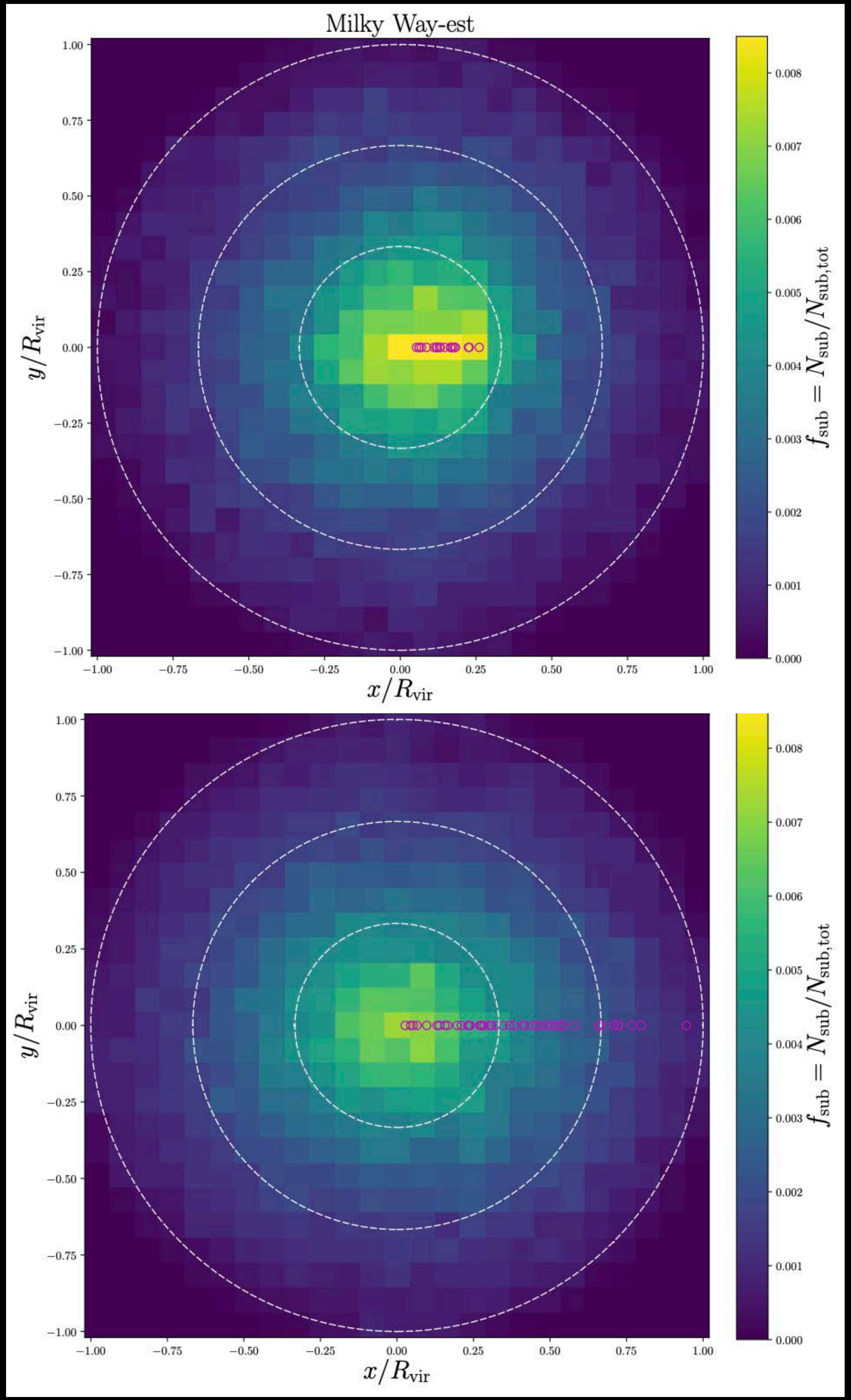

Buch & EN et al. 2024 (2404.08043)


Gaia-Sausage-Enceladus
Large Magellanic Cloud
Milky Way
Simulation: EN
Visualization: Ralf Kaehler

# Milky Way-est Zoom-in Simulations

- Milky Way-est subhalos are more **abundant**, **radially concentrated**, and **anisotropic** than average



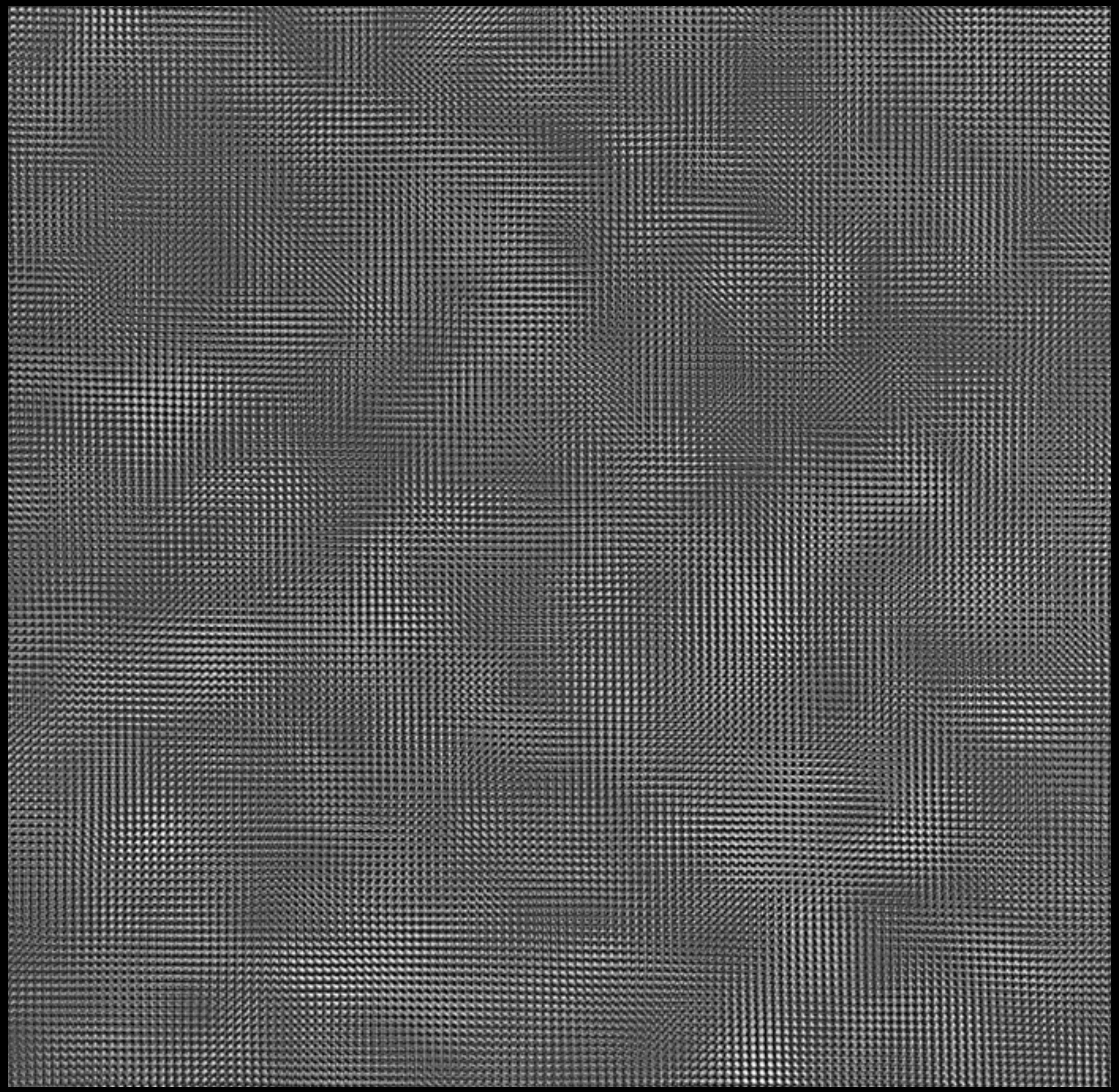

Milky Way-est

Symphony MW

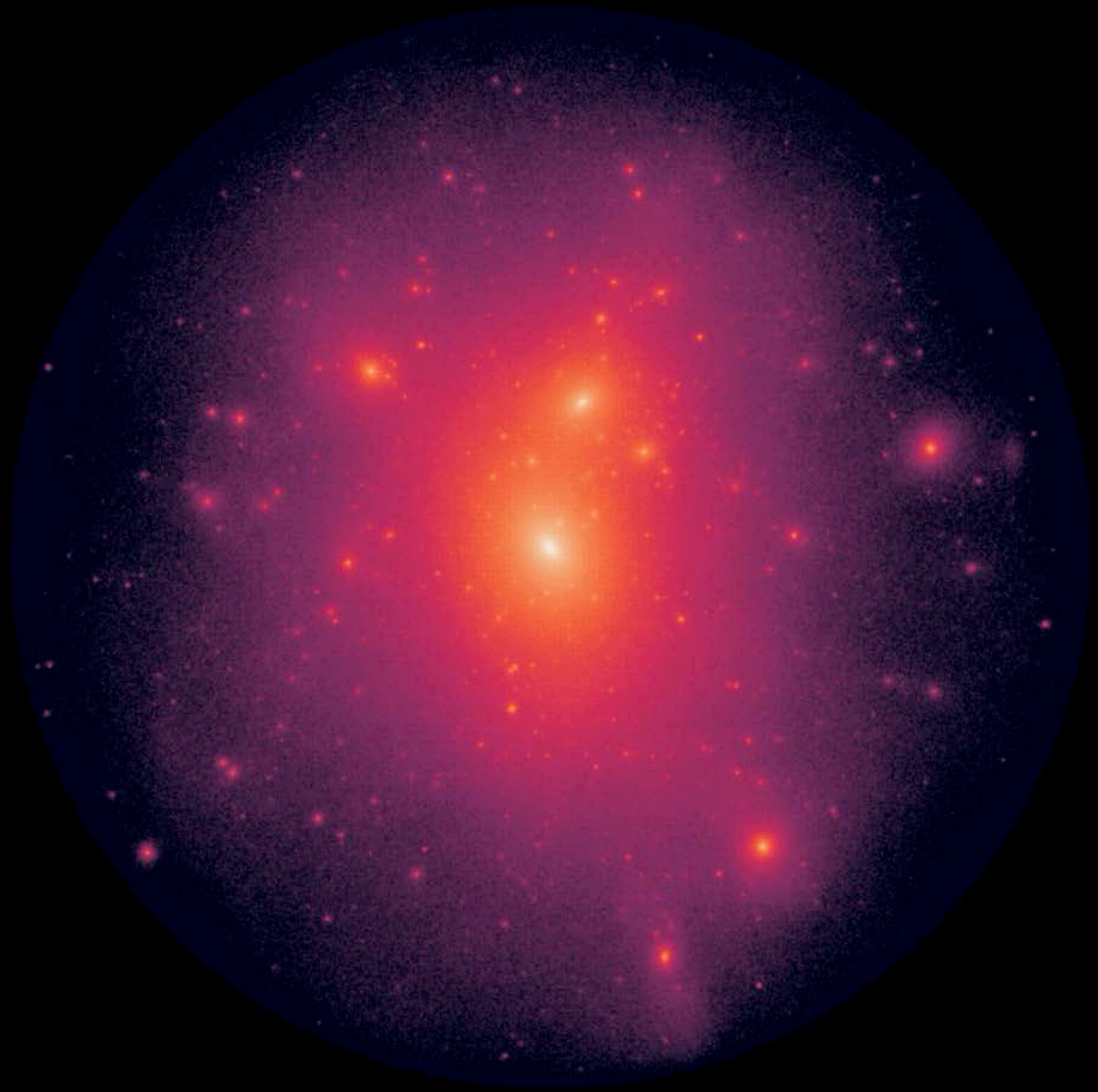
Buch & EN et al. 2024 (2404.08043)

# Simulating Initial Conditions Beyond CDM

*Ab Initio*



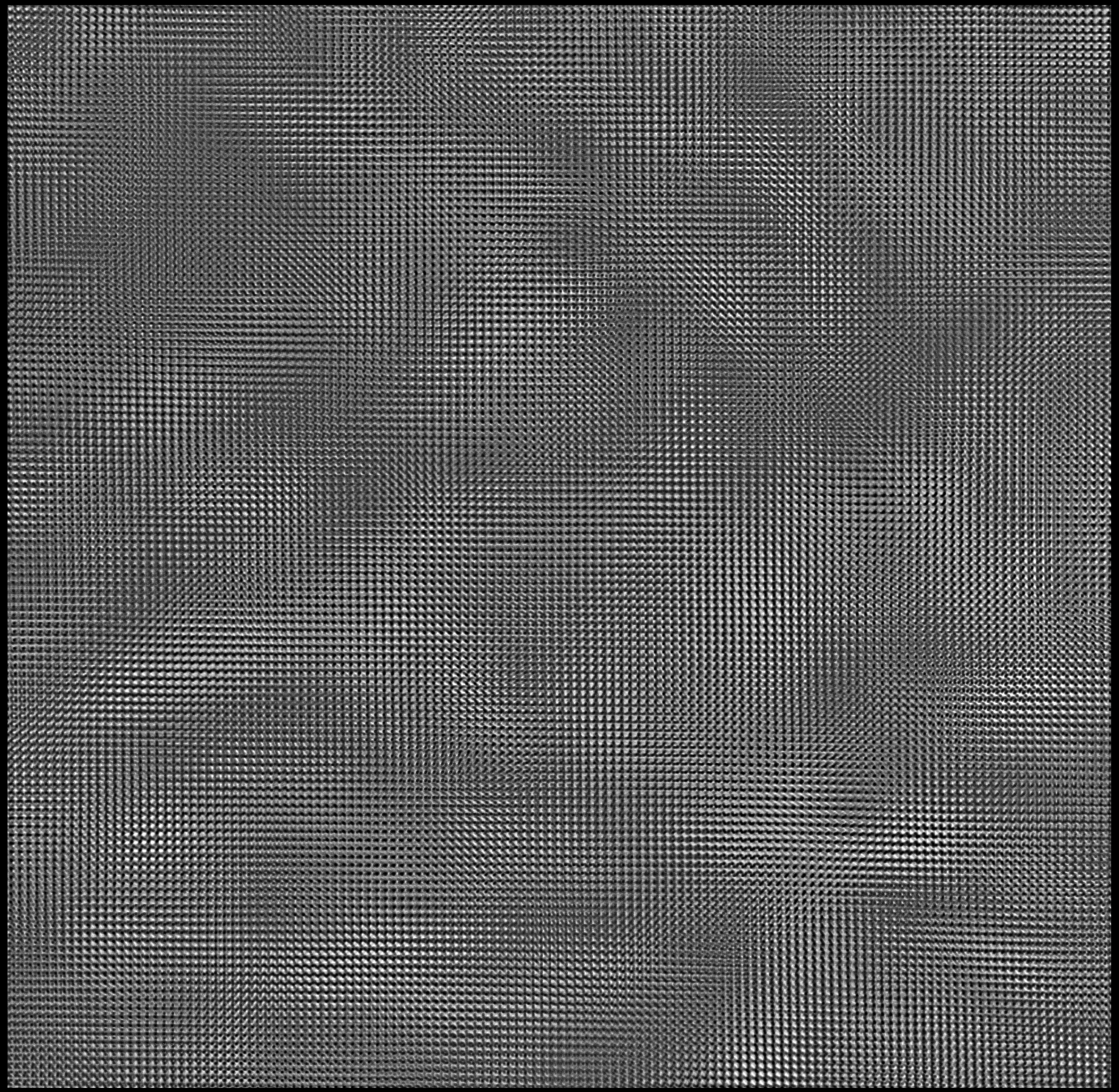
300,000 years after Big Bang



Today

# Simulating Initial Conditions Beyond CDM

*Ab Initio*



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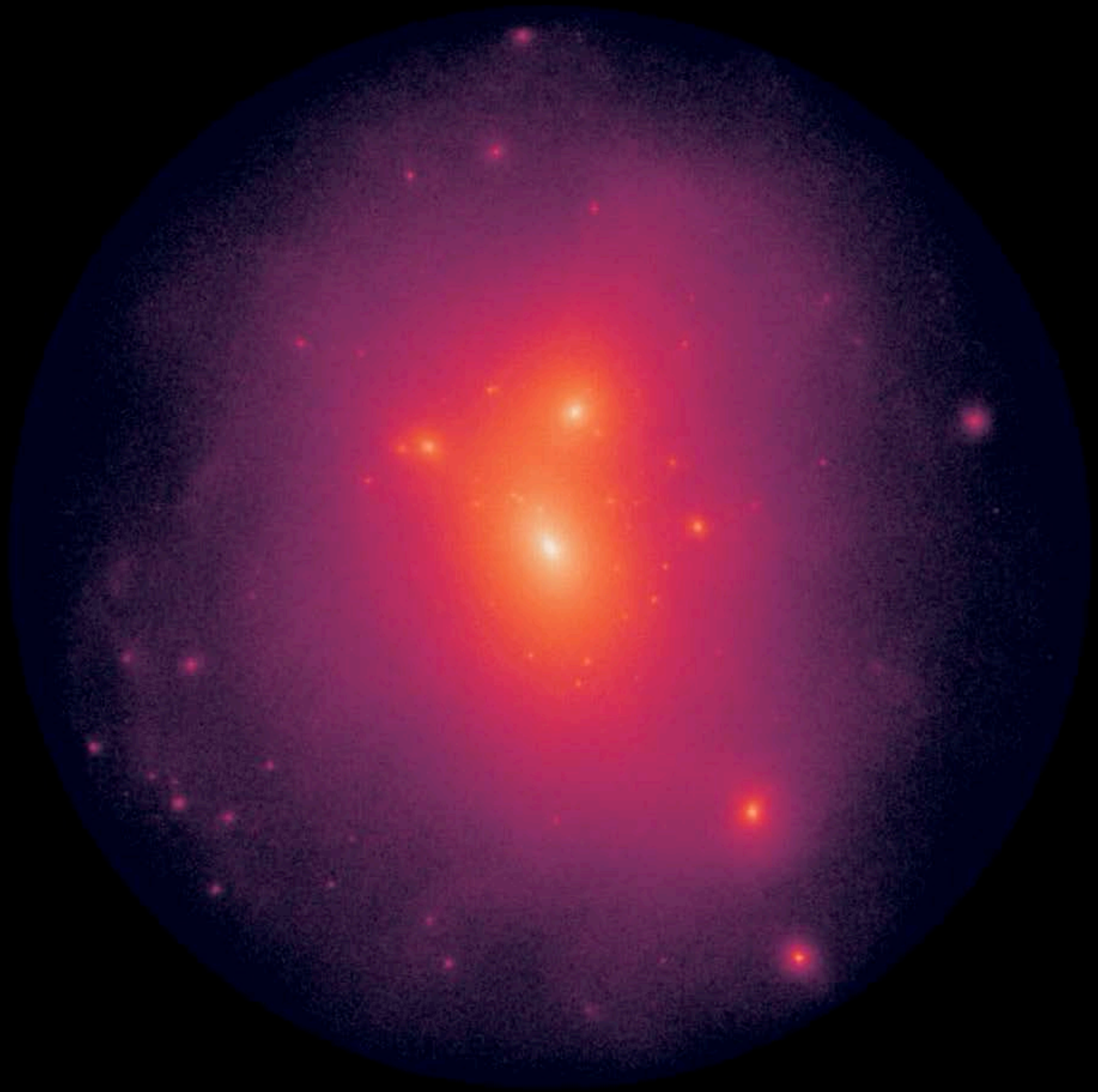
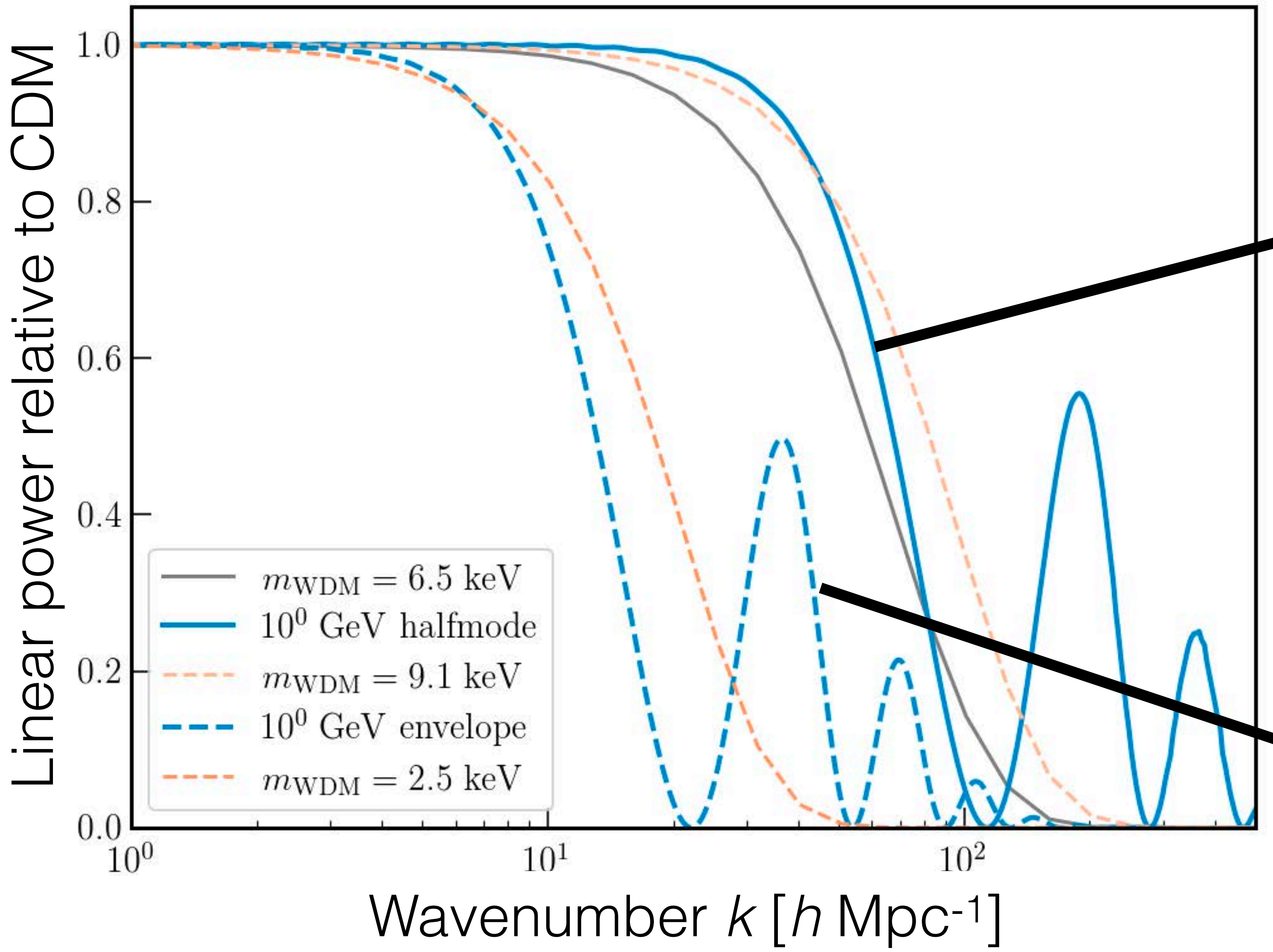
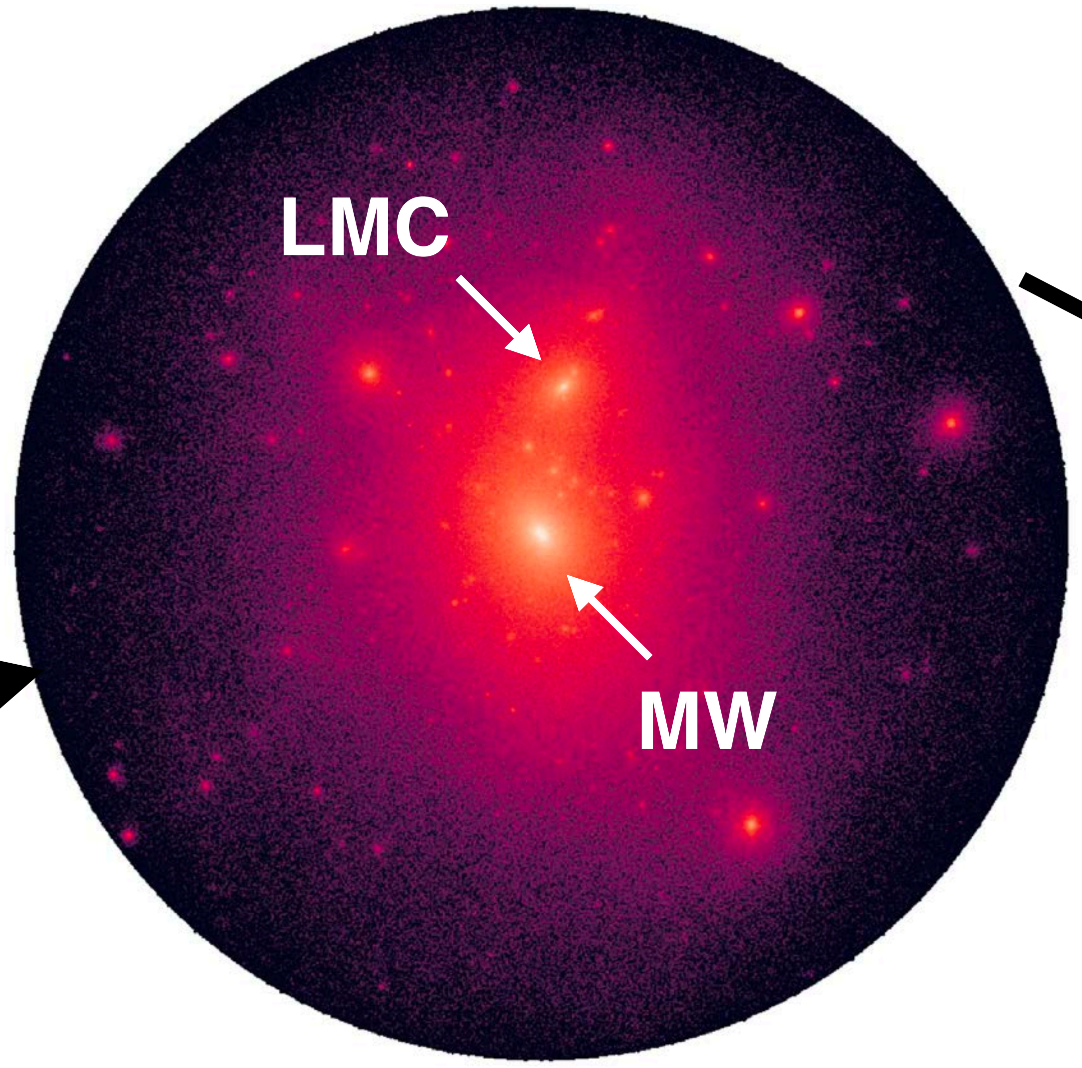


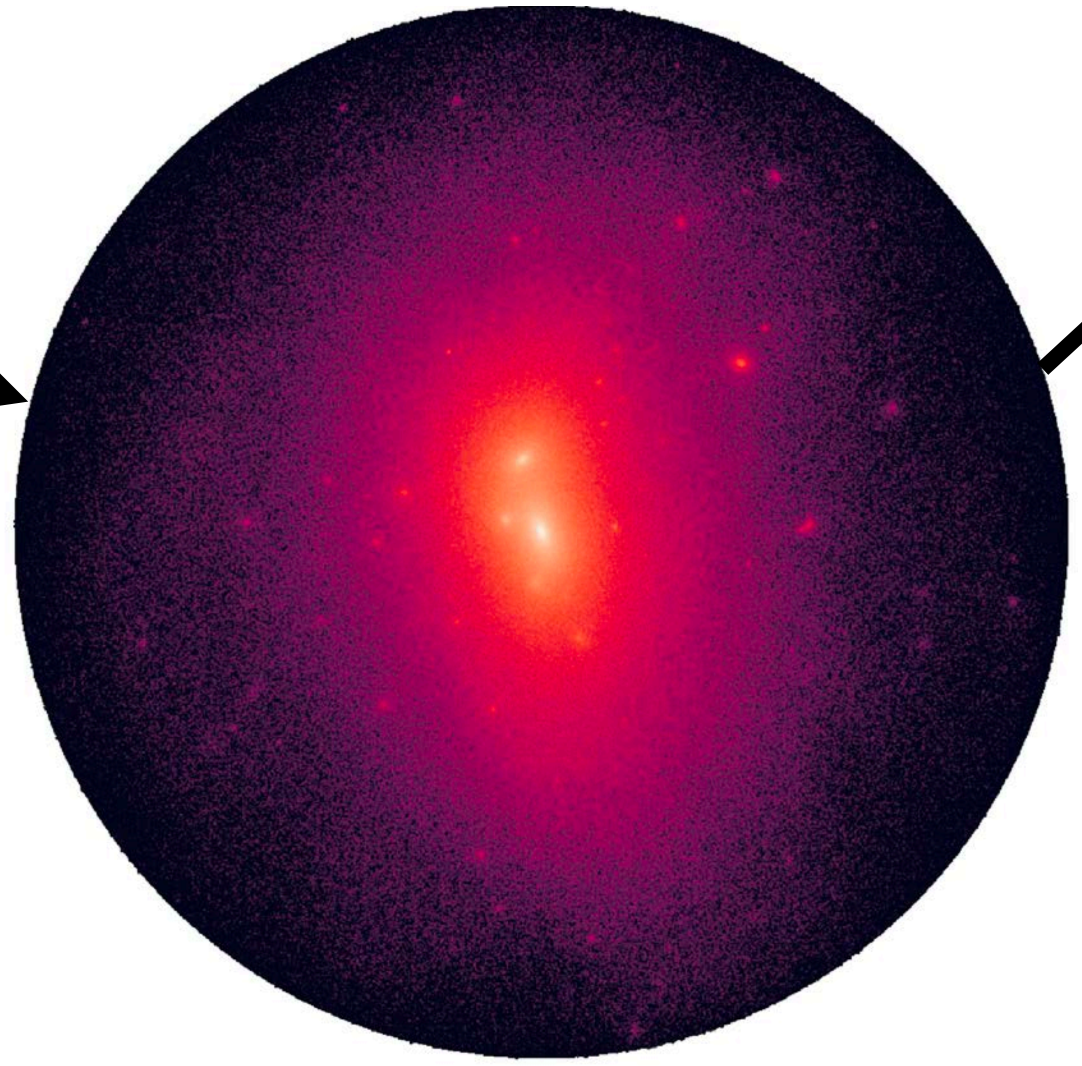
Today

# COZMIC Zoom-in Simulations

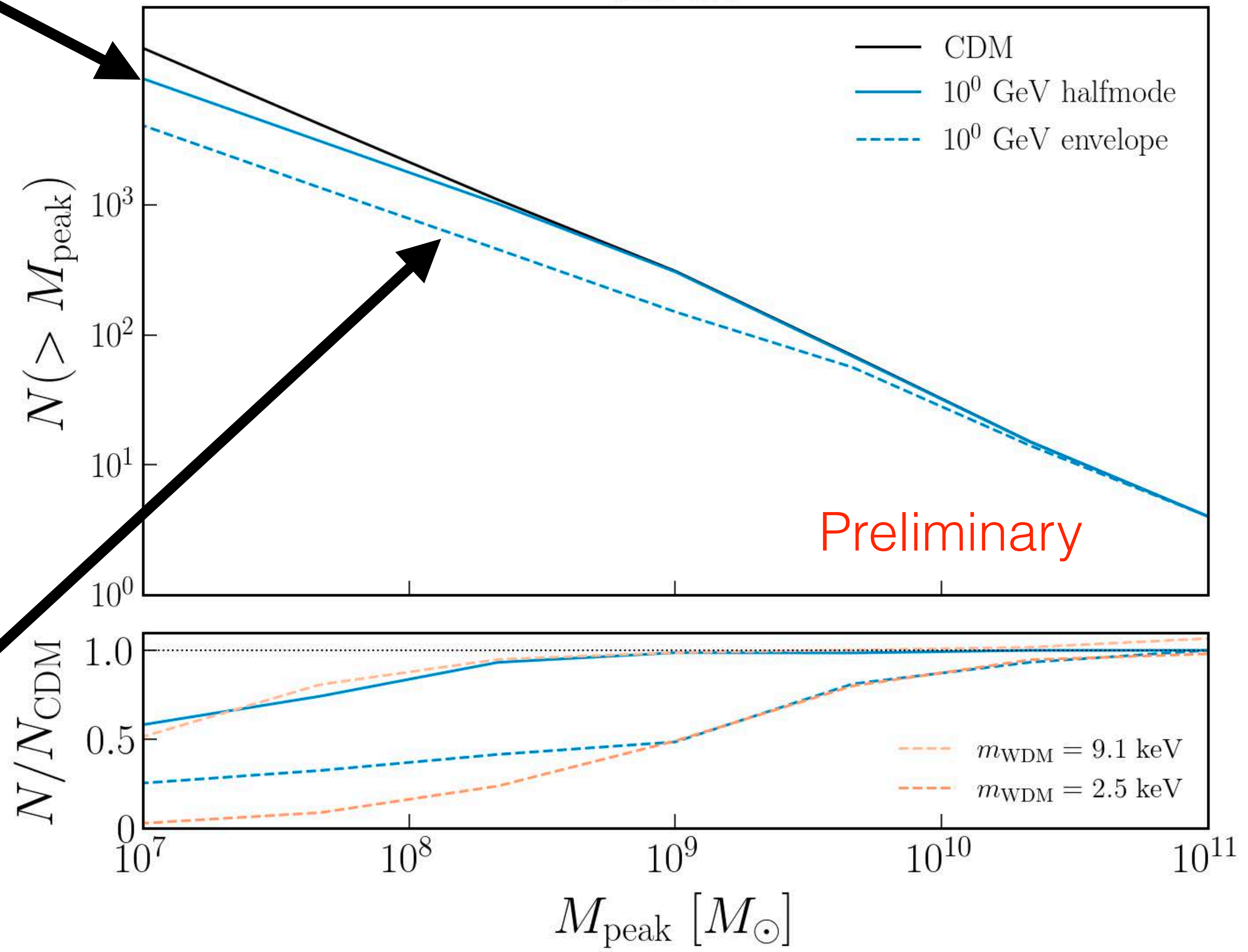
## Initial conditions from linear theory



## Halo and subhalo populations




**100+** cosmological simulations of Milky Way analogs with initial conditions for **warm**, **fuzzy**, **interacting** DM

Rui An
(USC)

Andrew Benson
(Carnegie)

Vera Gluscevic
(USC)

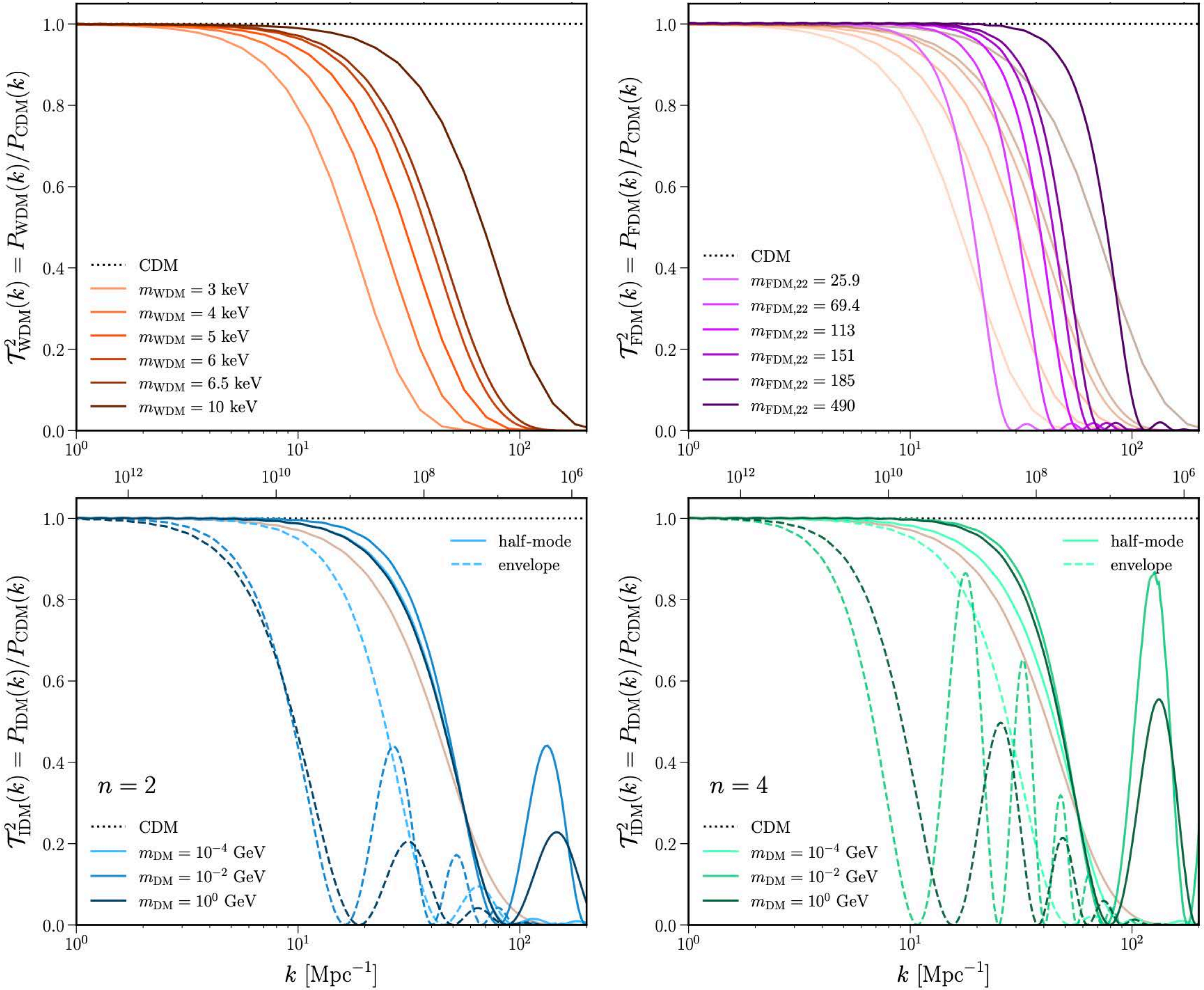
EN et al., in prep.

Warm Dark Matter

Fuzzy Dark Matter

Interacting Dark Matter ($n = 2$)

Interacting Dark Matter ($n = 4$)




EN et al., in prep.

Warm Dark Matter

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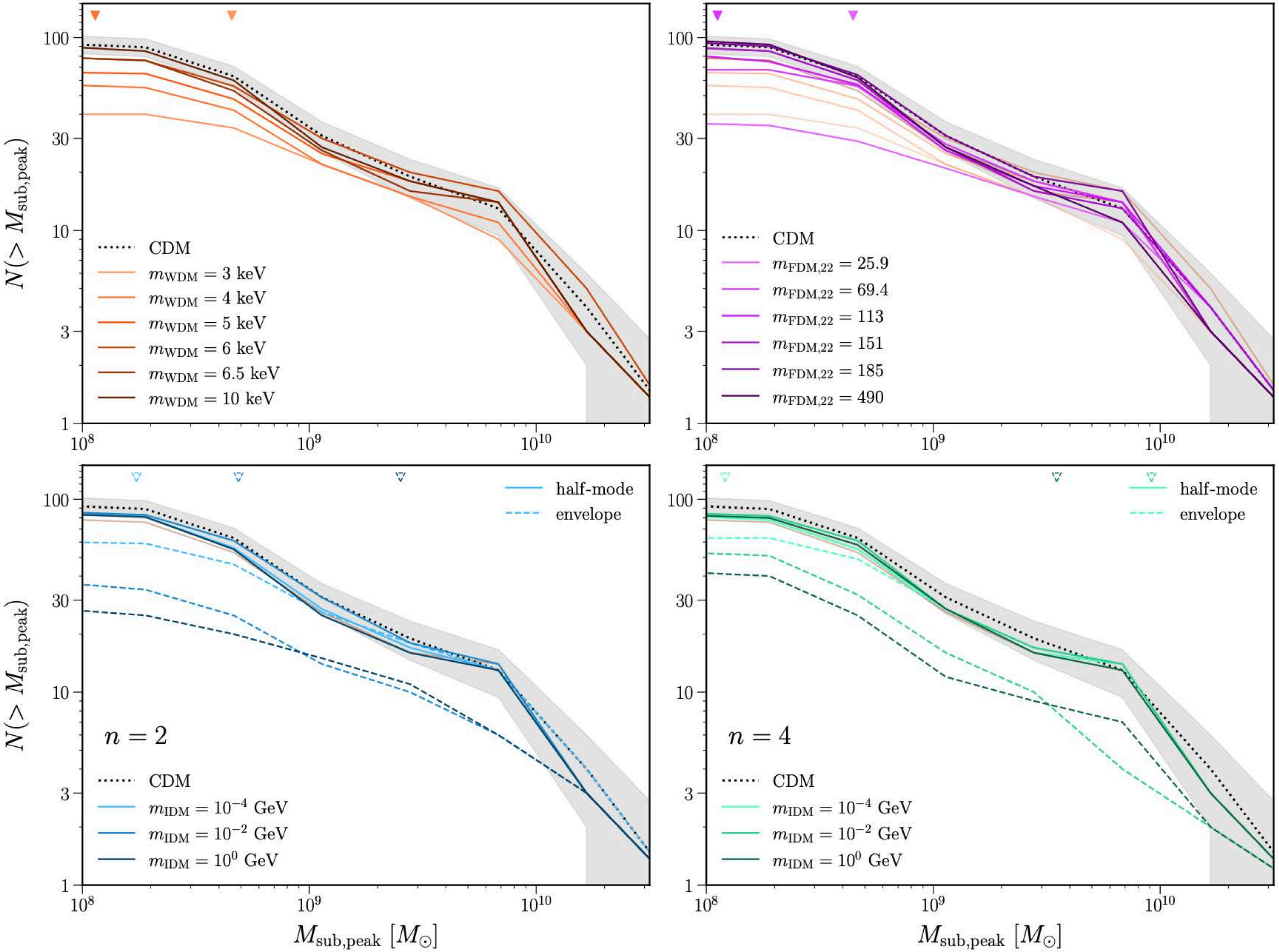
Interacting Dark Matter ($n = 2$)

Interacting Dark Matter ($n = 4$)



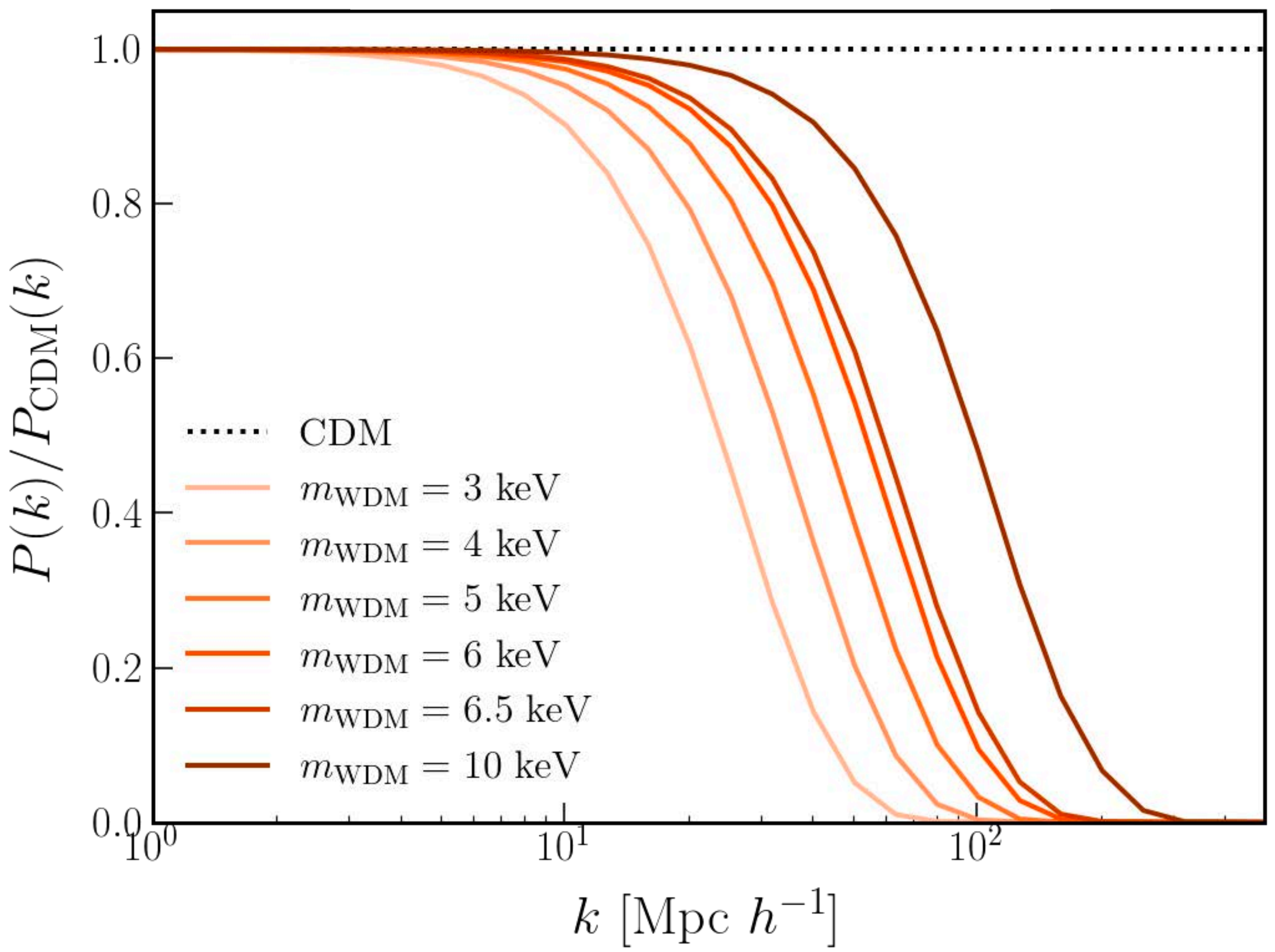

EN et al., in prep.

# COZMIC I: Warm Dark Matter

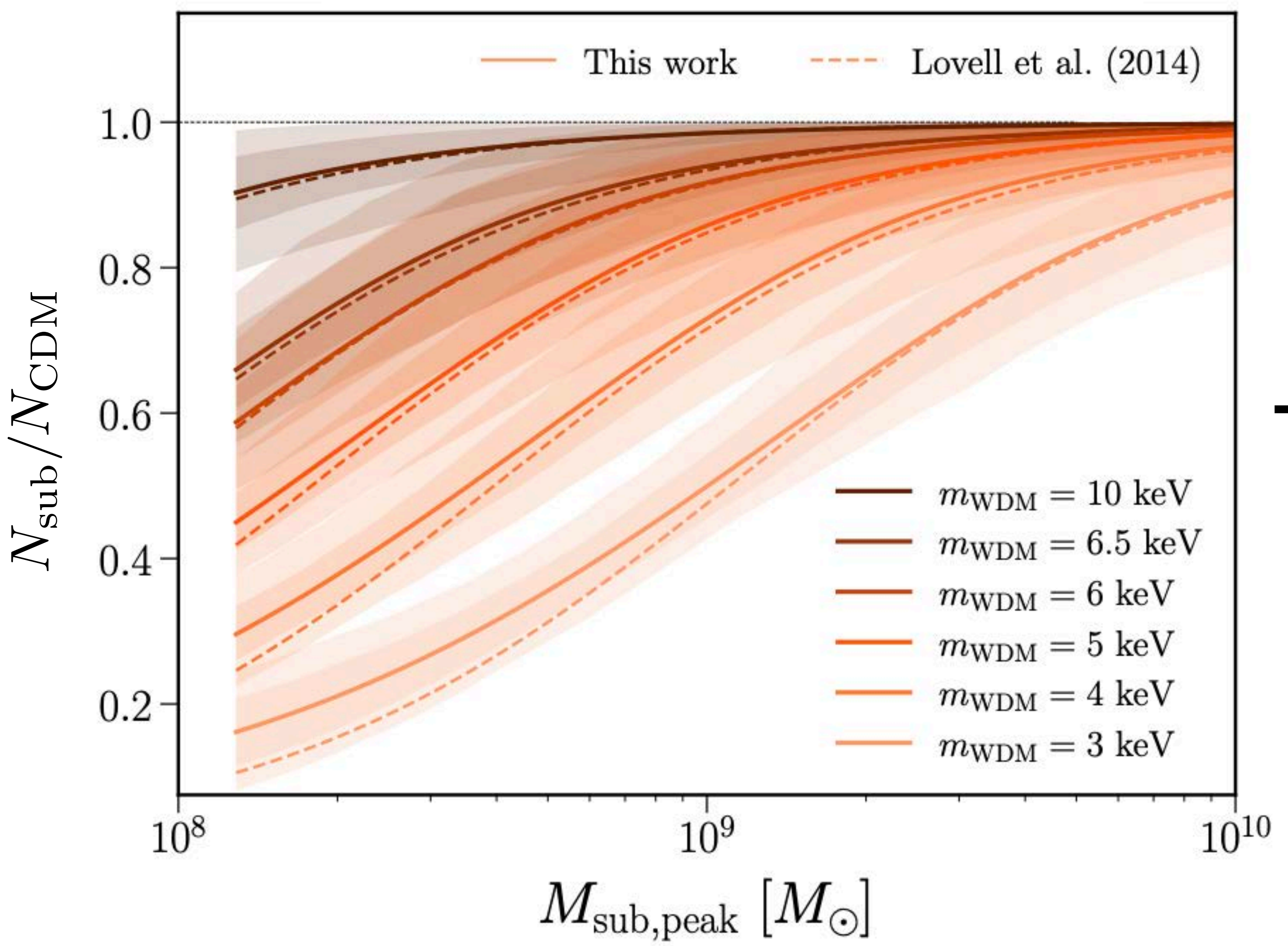
- Recalibrate WDM subhalo mass function suppression, including treatment of statistical uncertainties and halo-to-halo scatter; integrated with `CLASS`
- Subhalo mass function suppression is well constrained
- Extremely small contamination from spurious halos

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

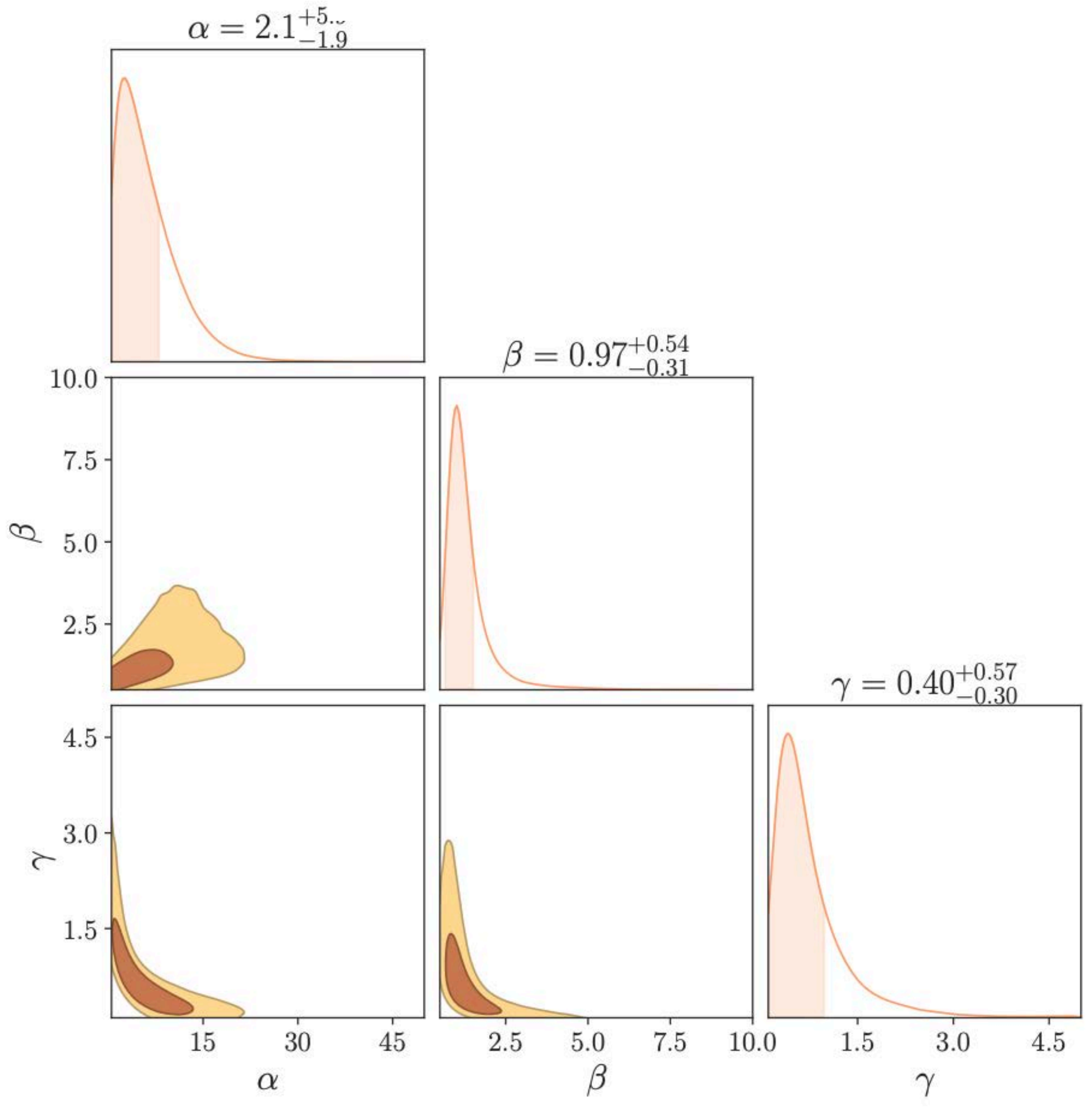
**Initial conditions**




**Subhalo populations**




**SHMF fit**

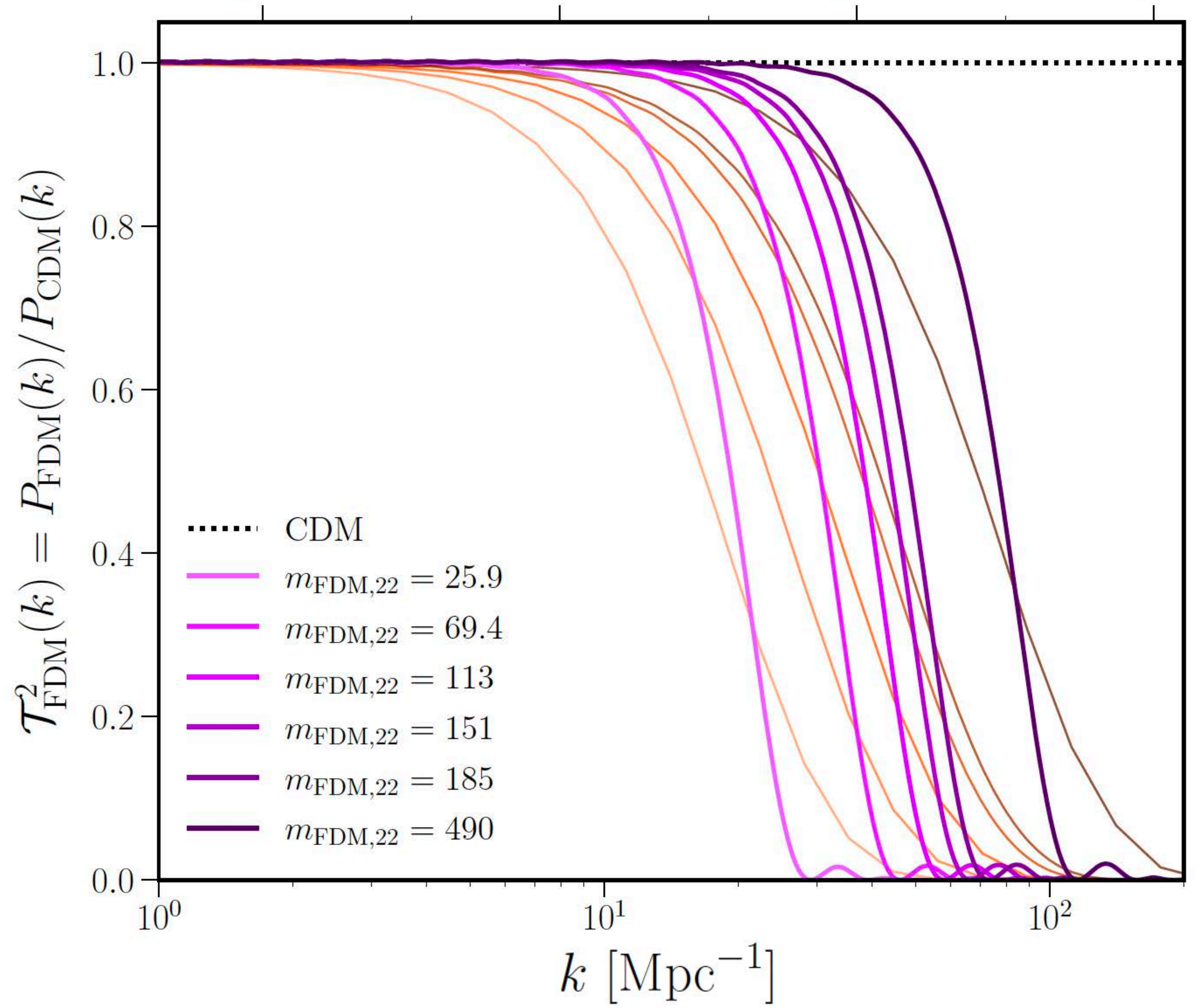



EN et al., in prep.

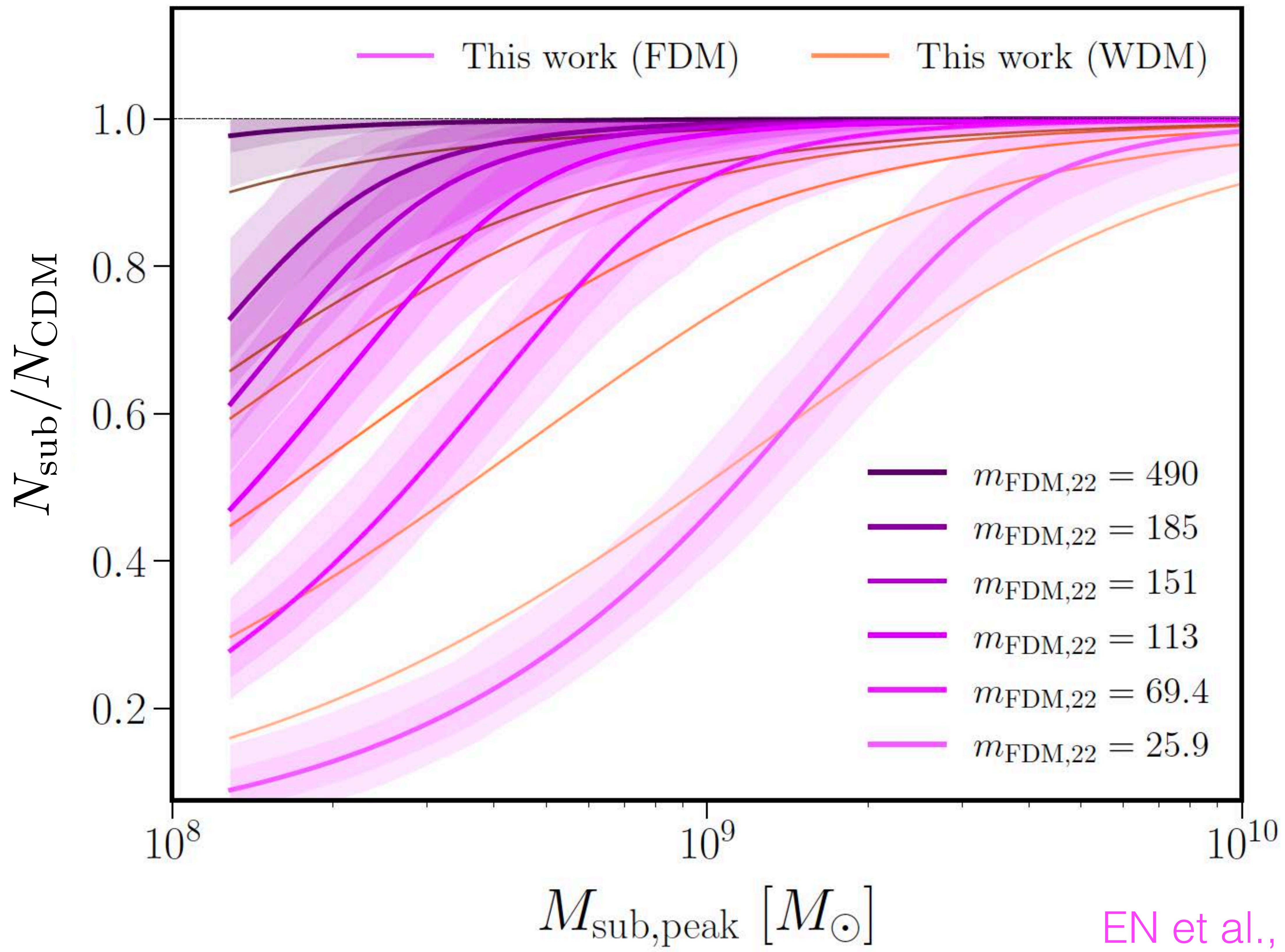
# COZMIC I: Fuzzy Dark Matter

- Fuzzy dark matter subhalo mass function cuts off more sharply than WDM due to *P(k)* shape
- New calibration improves Milky Way satellite bound by order of magnitude: $\boxed{m_{\rm FDM} > 1.4 \times 10^{-20}\ \mathrm{eV}}$

Linear matter power spectrum suppression




Subhalo mass function suppression

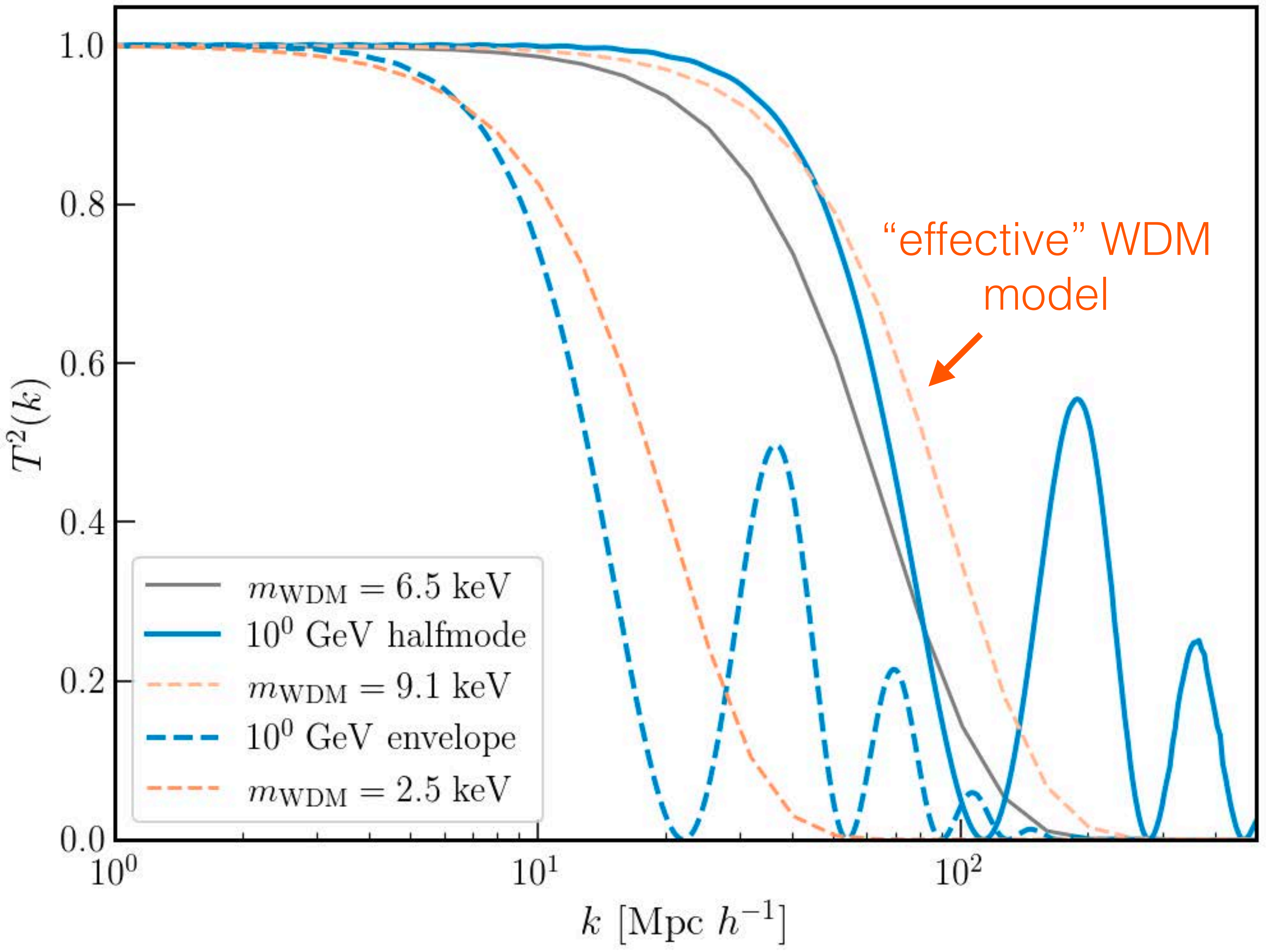


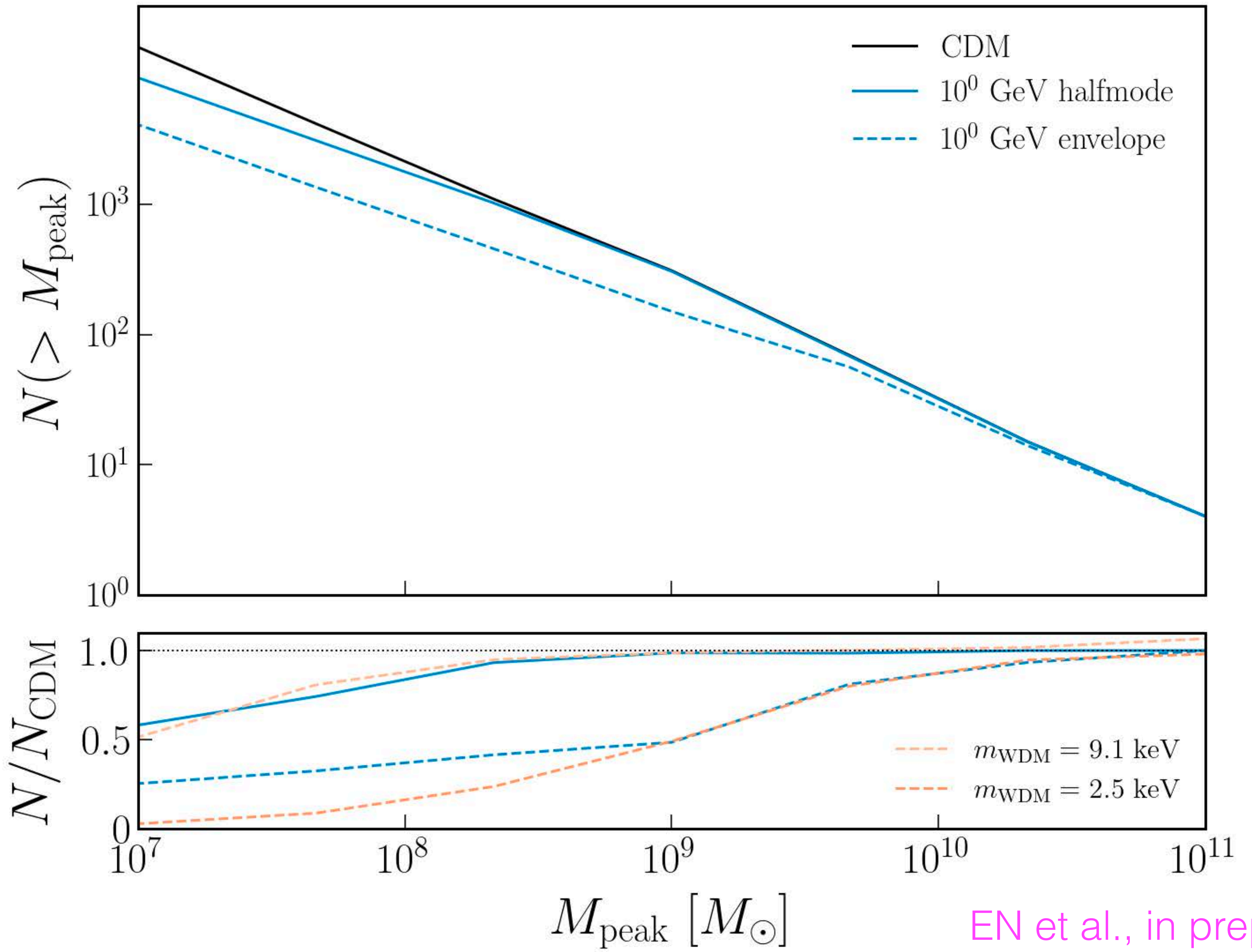

EN et al., in prep.

# COZMIC I: Interacting Dark Matter

- Interacting dark matter models with prominent dark acoustic oscillations are "colder" than WDM models with the same initial *P(k)* cutoff

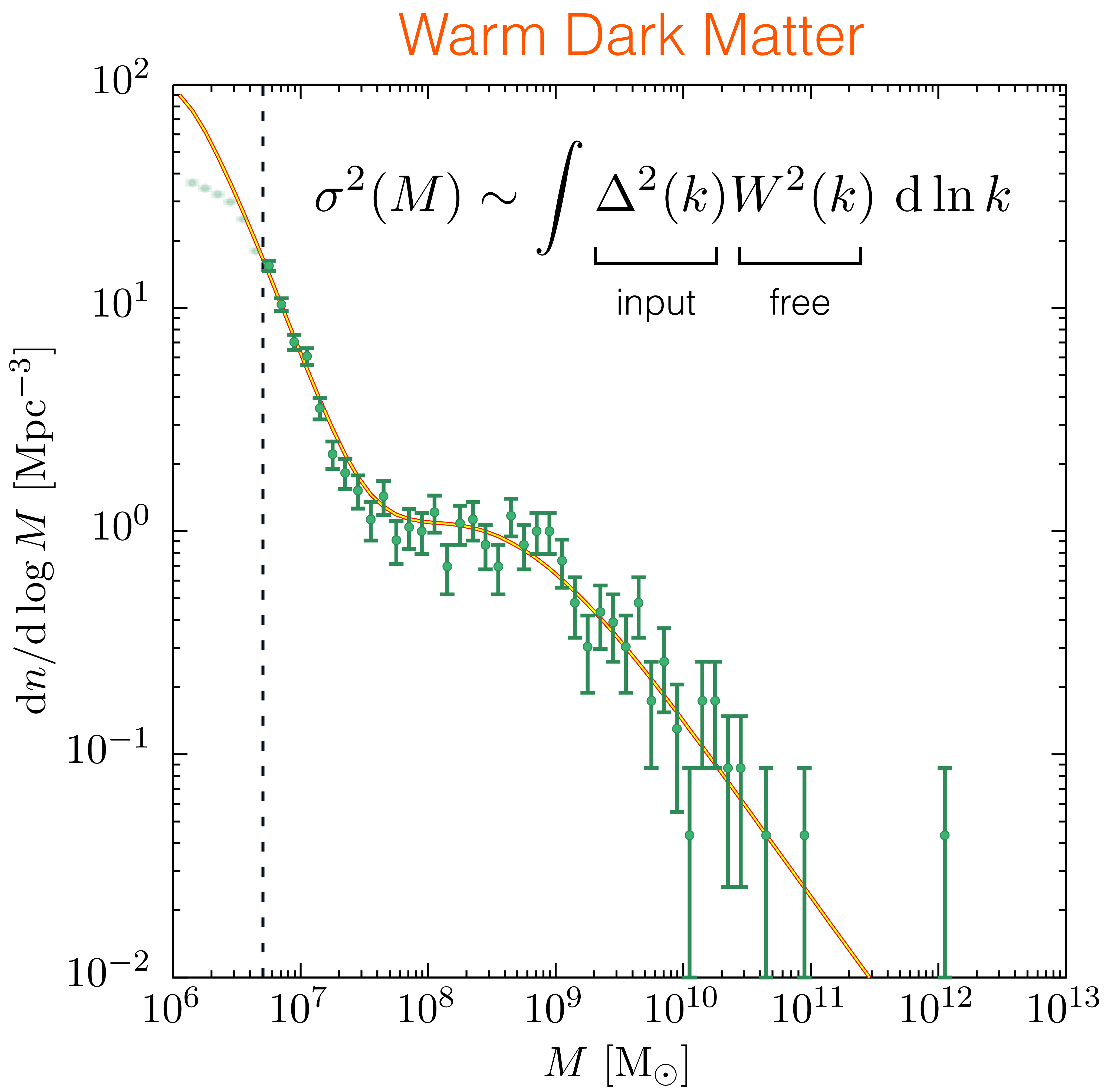
- Accurate SHMF predictions improve interaction cross section bounds by orders of magnitude

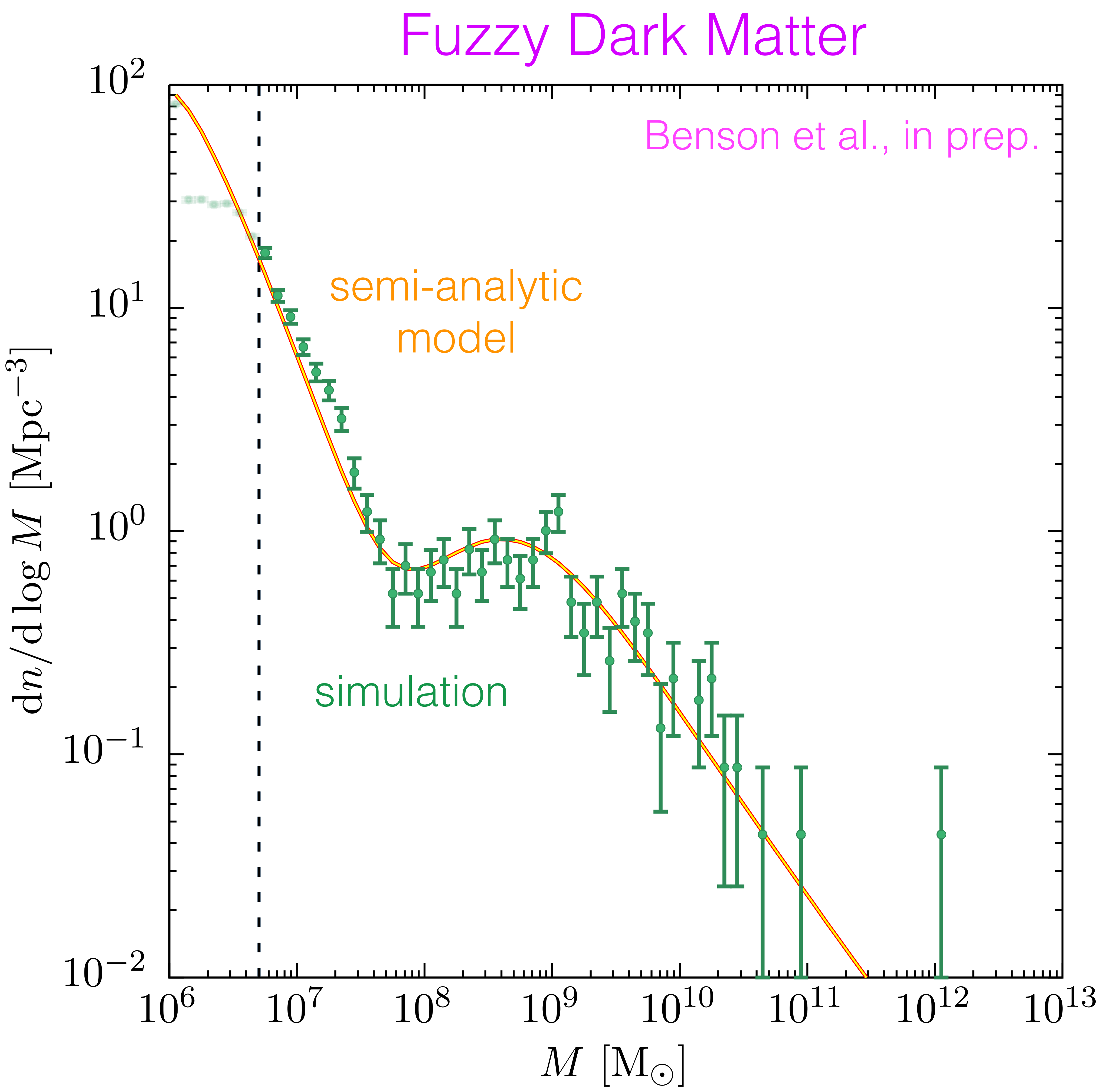



EN et al., in prep.

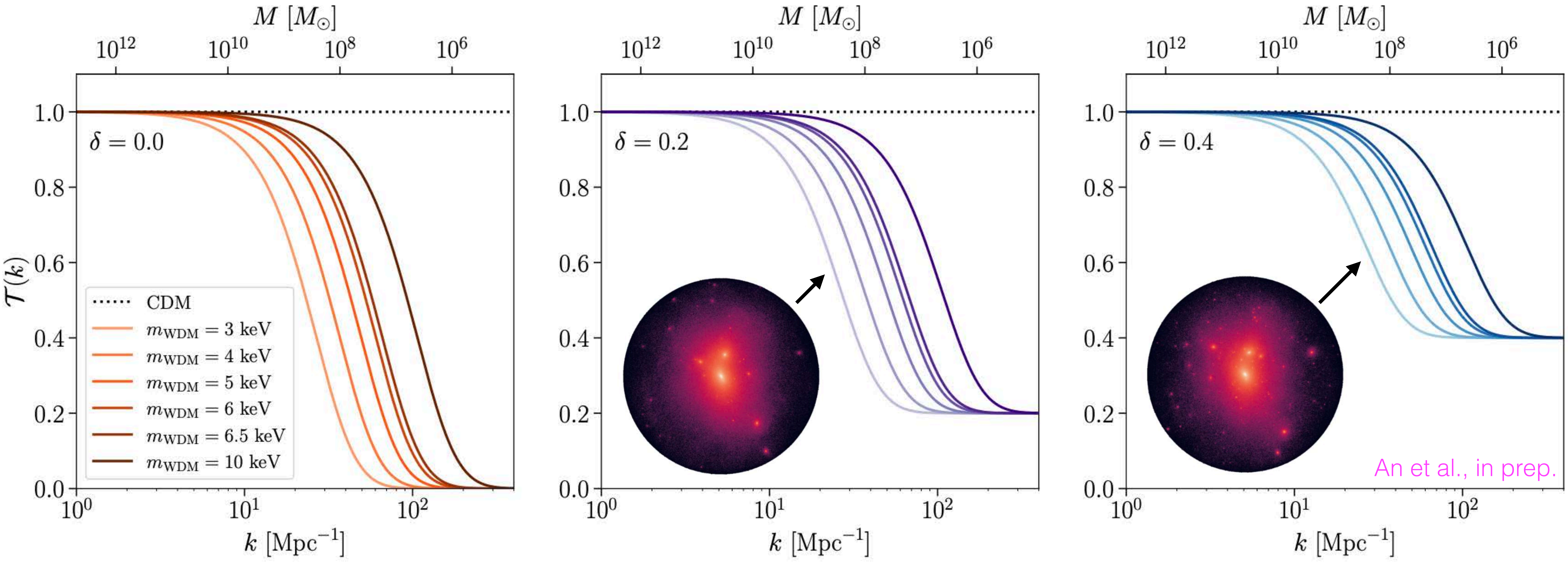
# COZMIC I: Semi-analytic Model Calibration




- Calibrate extended Press-Schechter smooth-*k* window function to COZMIC I simulations
- Yields universal semi-analytic model for (sub)halo mass function; accurate to within ~10%

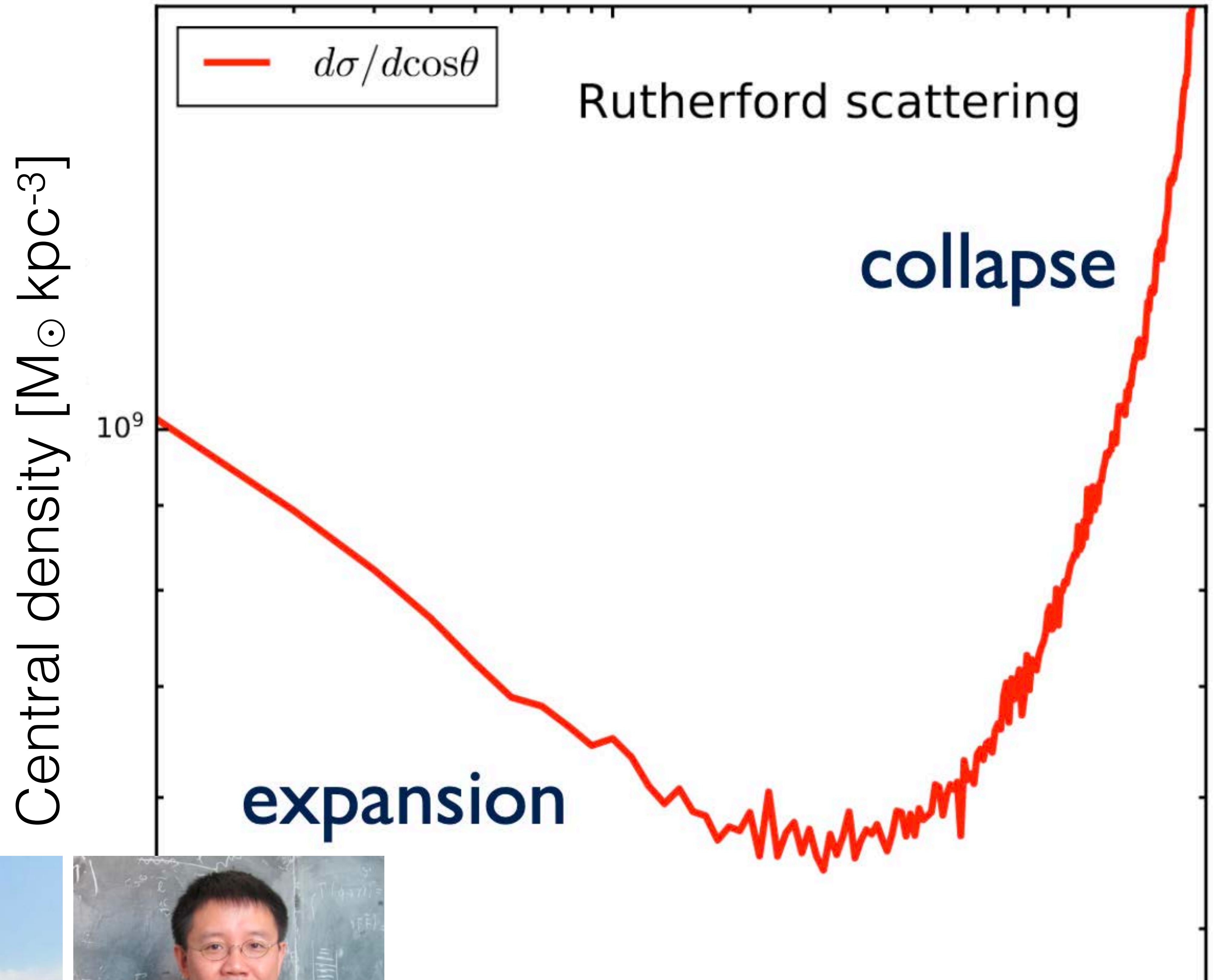
# COZMIC II: Mixed Dark Matter



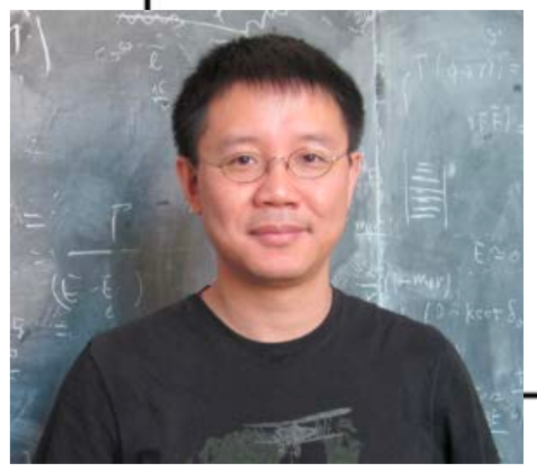

- Parameterize mixed dark matter models by transfer function cutoff scale and plateau height
- Subhalo mass function suppression is reduced as plateau height increases, at fixed cutoff scale
- Simulations enable **new bounds** on ≳ 50% non-CDM components from Milky Way satellite counts

# Simulating Strong Dark Matter Self-interactions

Yang & Yu 2022 (2205.03392)

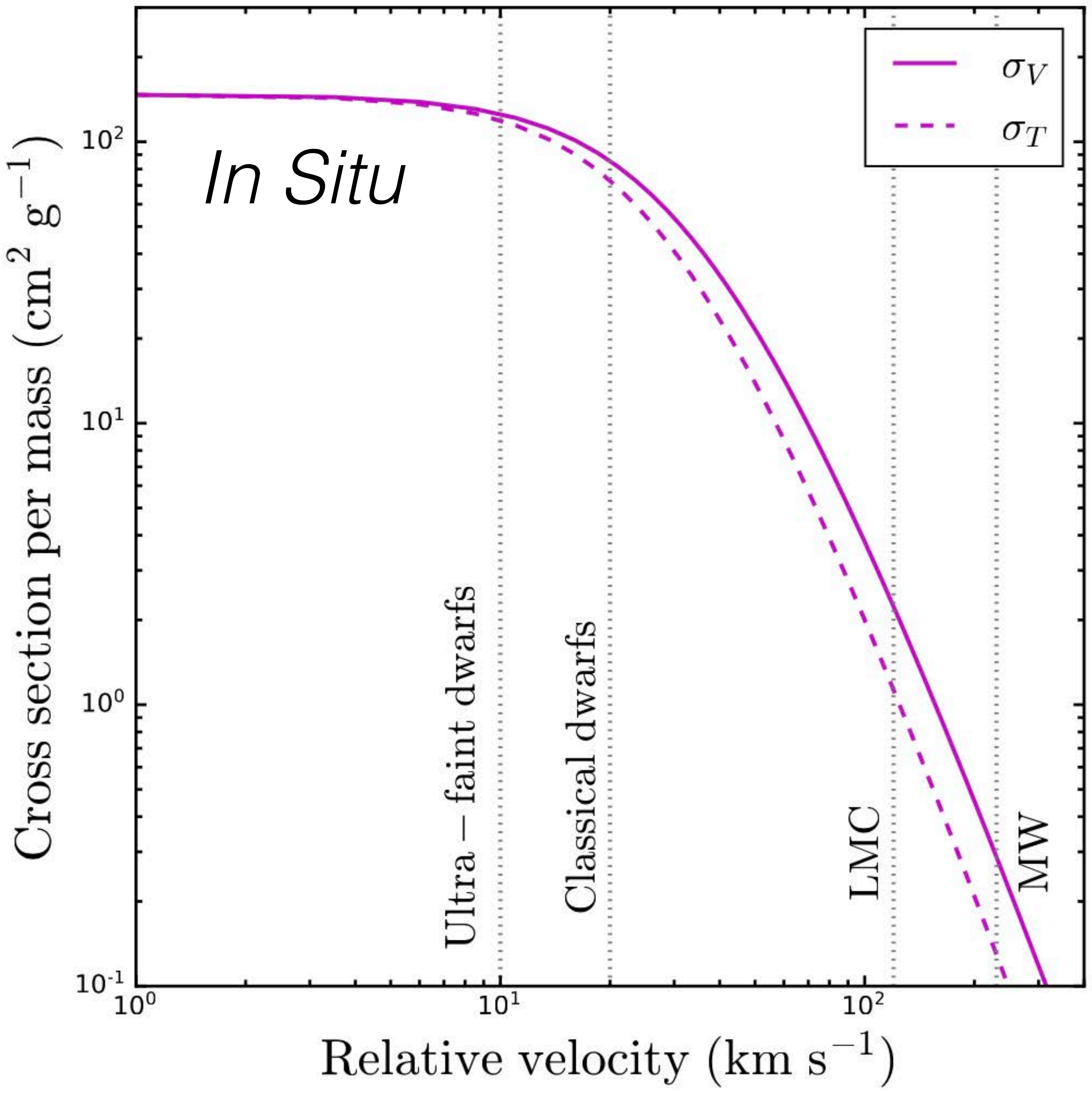



Daneng Yang
(UCR)



Haibo Yu
(UCR)

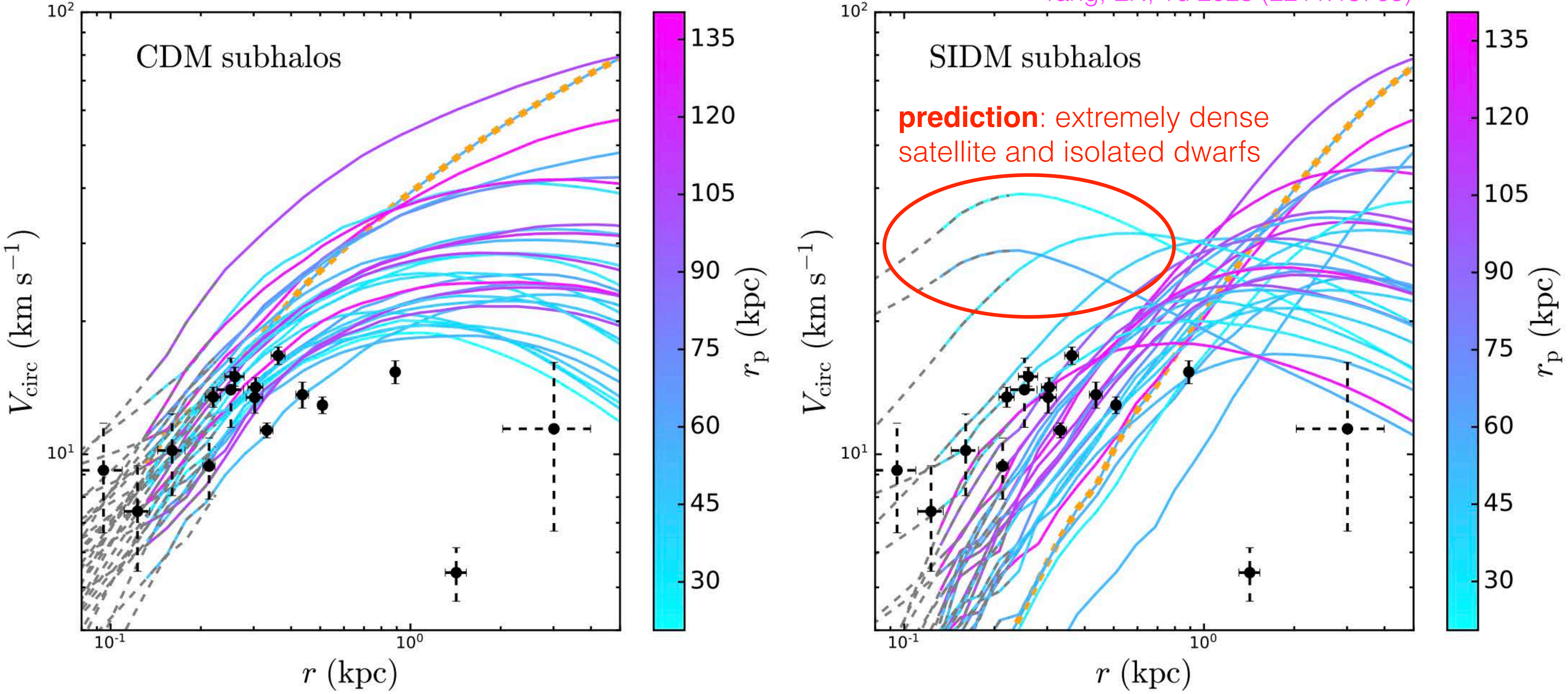
Yang, EN, Yu 2023 (2211.13768)




Strong, velocity-dependent self-interactions → **core-collapse** in low-mass and/or highly concentrated halos

# Simulating Strong Dark Matter Self-interactions

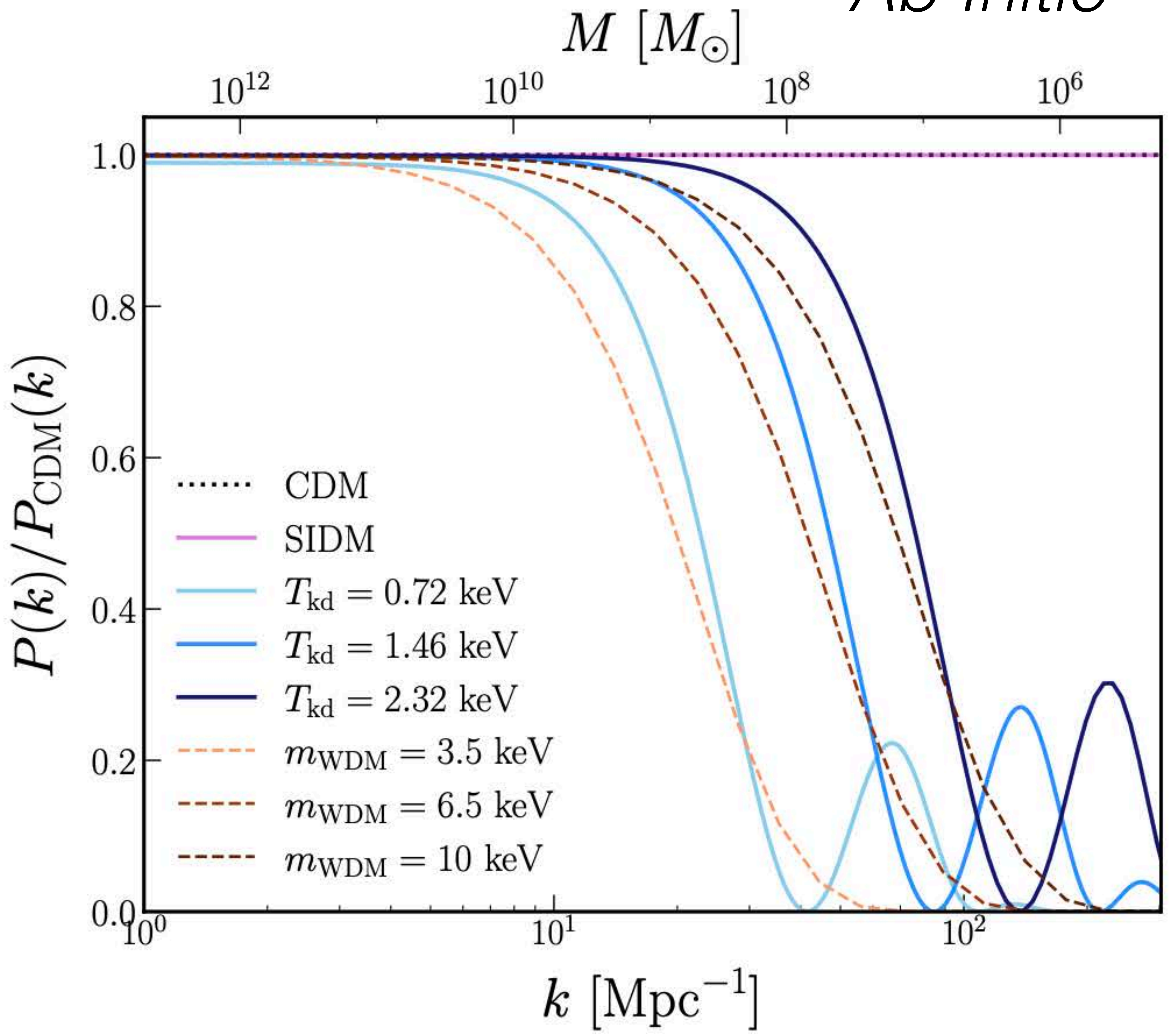
Yang, EN, Yu 2023 (2211.13768)



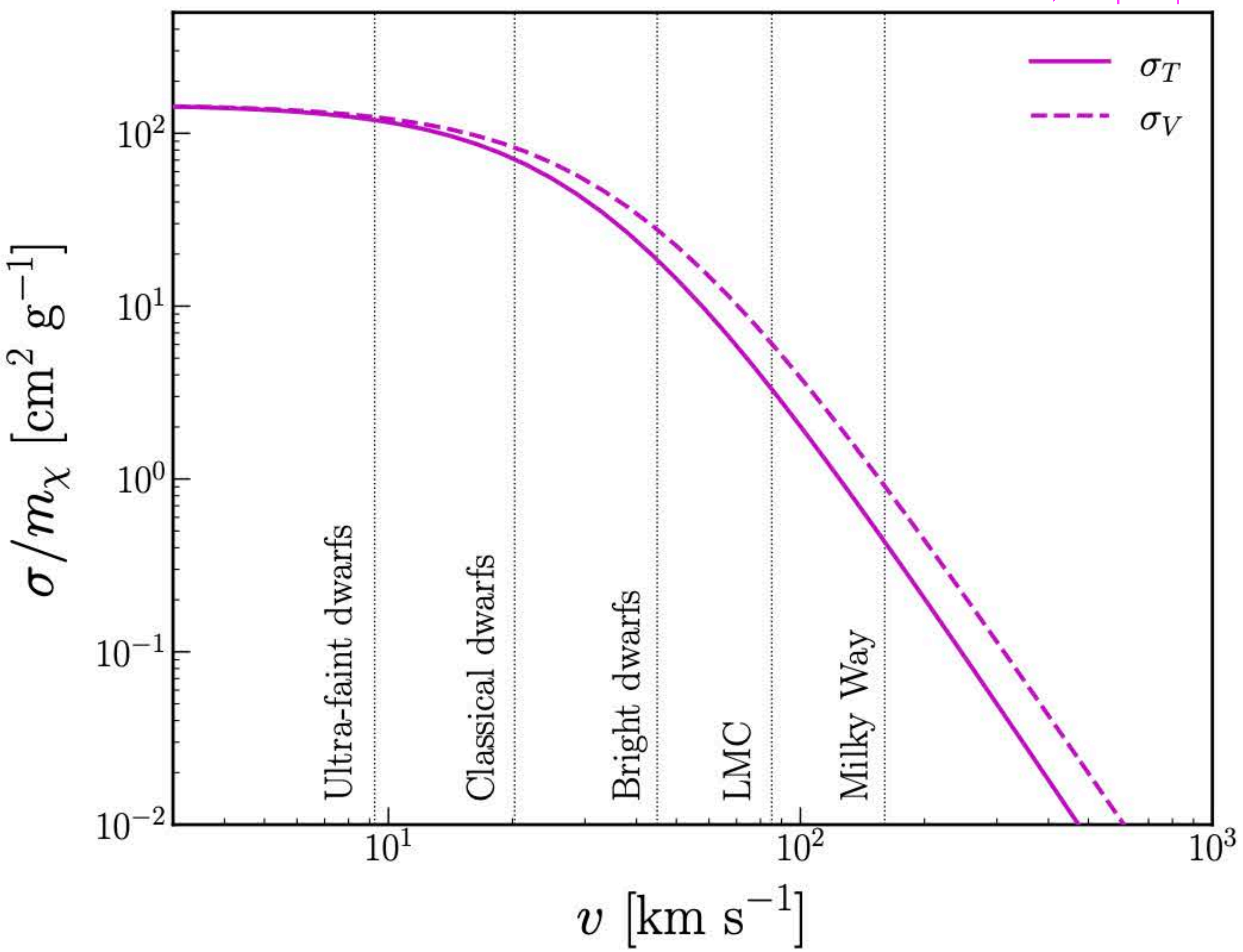

Strong, velocity-dependent SIDM diversifies subhalo profiles; mass/concentration/orbit influence evolution

# COZMIC III: Warm + Self-interacting Dark Matter

*Ab Initio* 🤝 *In Situ*




EN et al., in prep.

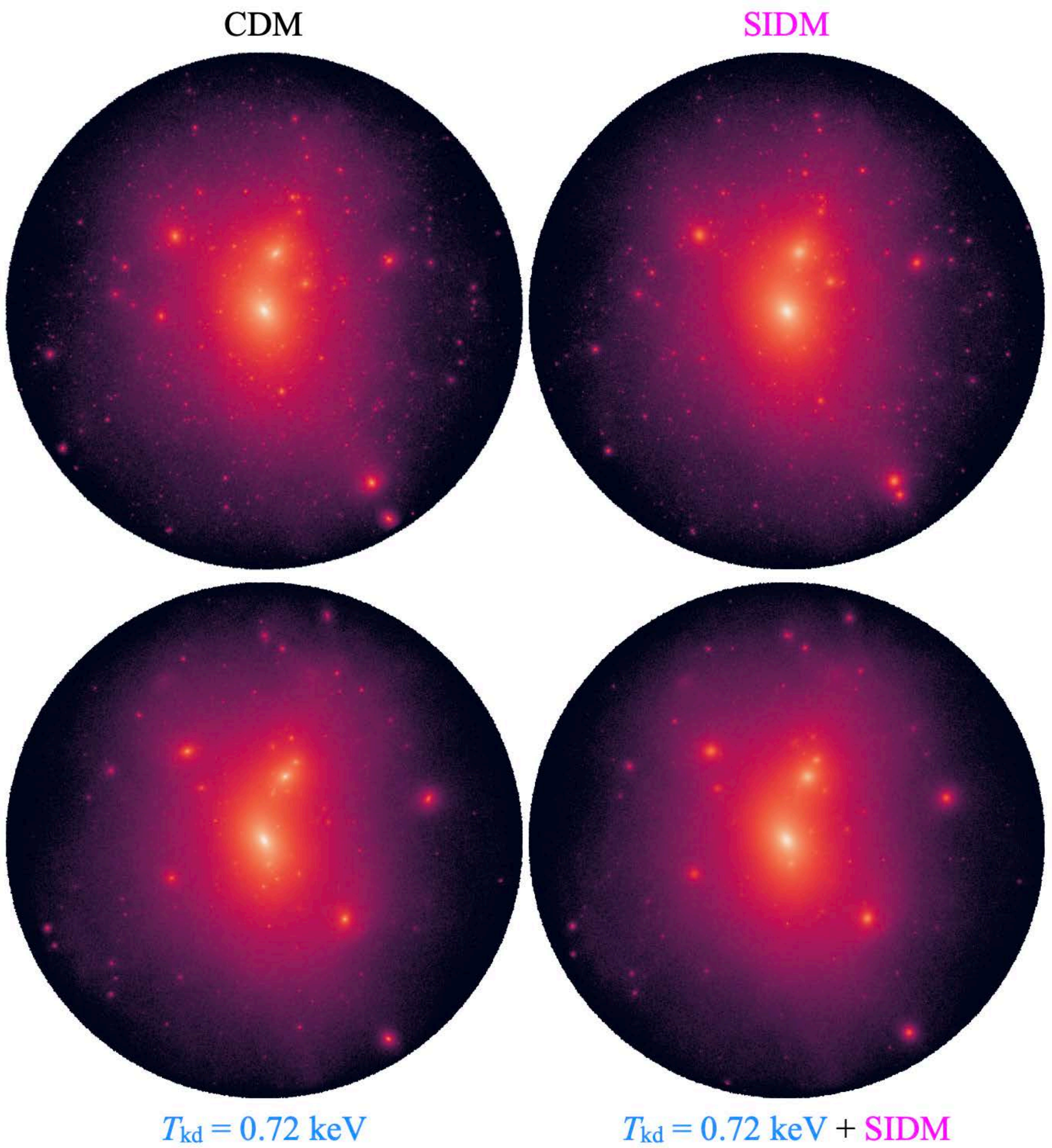


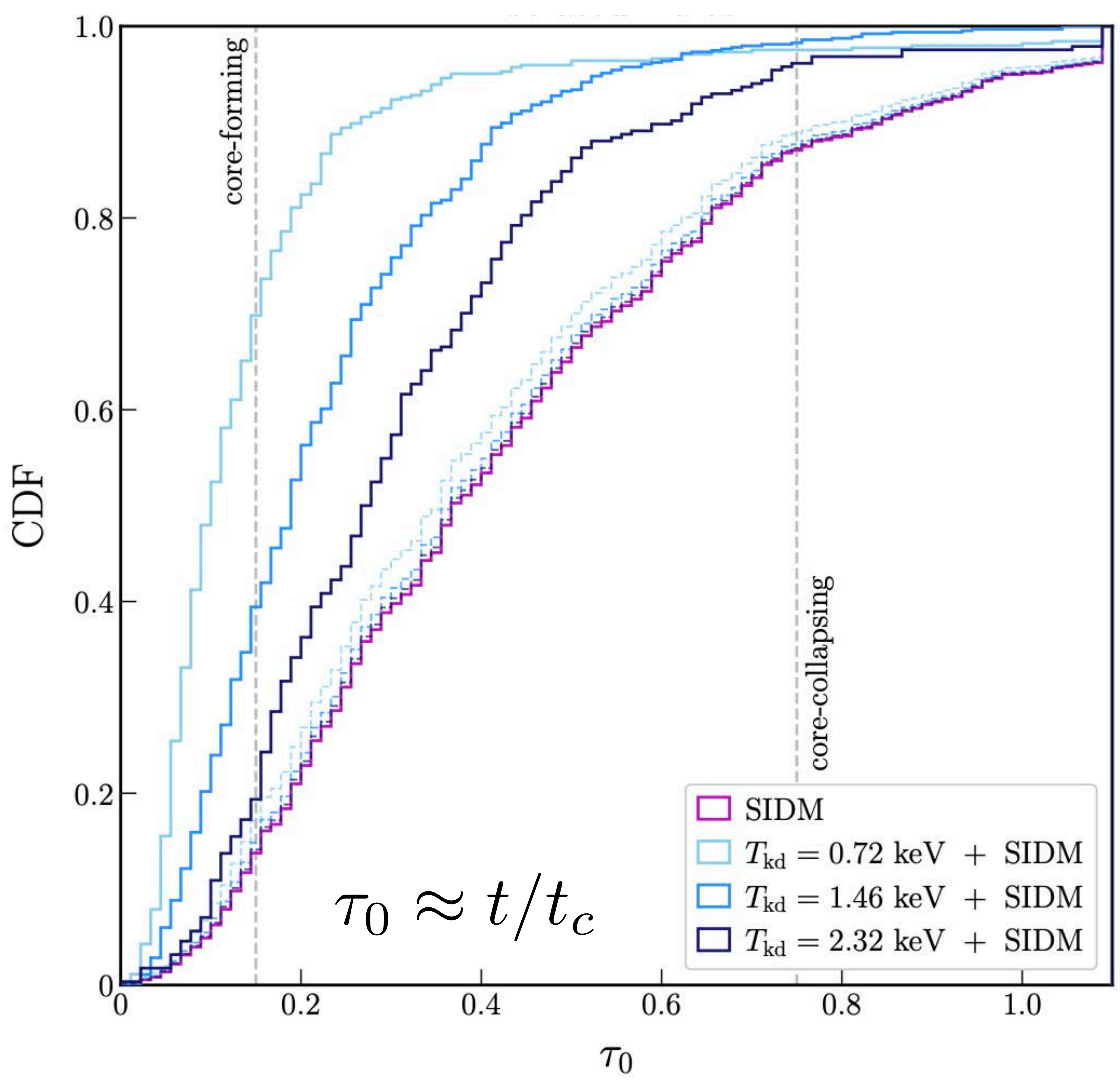

First simulations of core-collapsing SIDM with initial conditions determined by light mediator model

# COZMIC III: Warm + Self-interacting Dark Matter

EN et al., in prep.


Halo and subhalo mass function suppression mainly set by *P(k)*; SIDM slightly enhances subhalo disruption



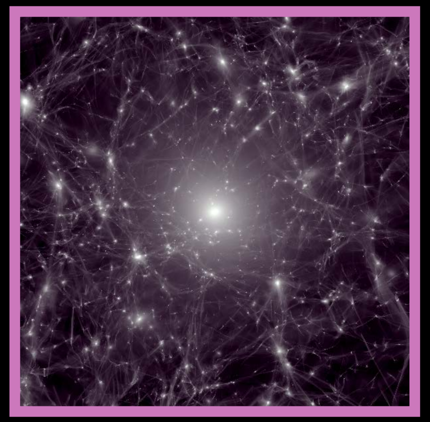
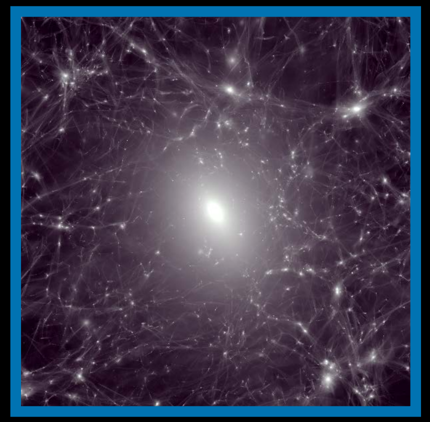



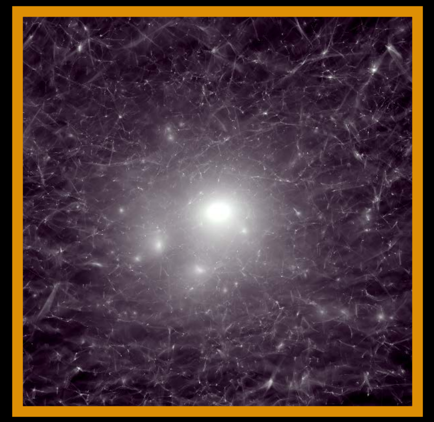
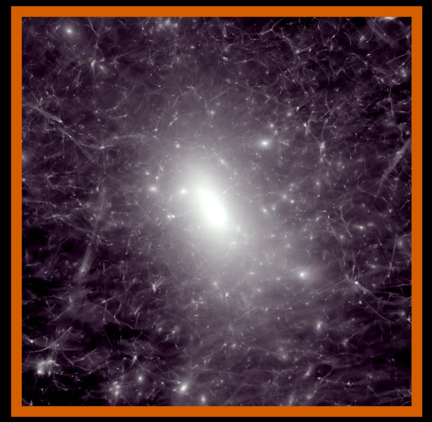

- ***P(k)* suppression reduces core-collapse**
- Effect is more severe for warmer models
- Further diversifies SIDM profile predictions

EN et al., in prep.

- Symphony: 262 cosmological zoom-in simulations spanning four decades of host mass
- Milky Way-est: Subhalos in Milky Way analogs are more abundant, radially concentrated, and anisotropically distributed than average
- COZMIC I: Shape of *P(k)* suppression is imprinted on (sub)halo mass function; improves fuzzy and interacting dark matter bounds by orders of magnitude
- COZMIC II: Subhalo mass function is suppressed in mixed dark matter models; ~50% non-CDM components can be constrained by Milky Way satellites
- COZMIC III: Core collapse in strong, velocity-dependent SIDM is counteracted by *P(k)* suppression in light mediator models

CARNEGIE SCIENCE

USC University of Southern California