What Can Dwarf Galaxies Reveal about the Nature of Dark Matter?

Ethan Nadler

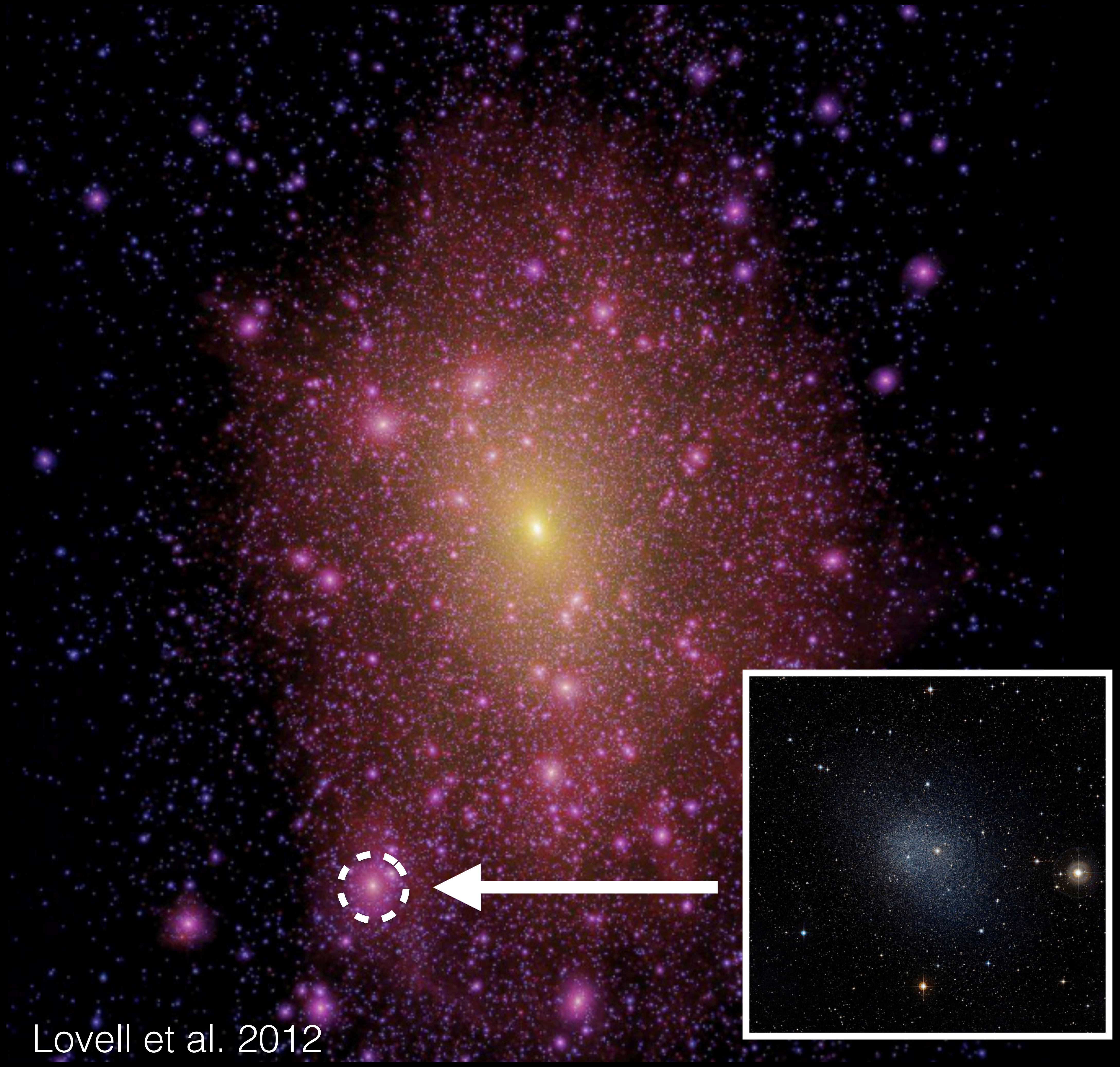
Dynamical Tracers of the Nature of Dark Matter

2/19/2025

UC San Diego

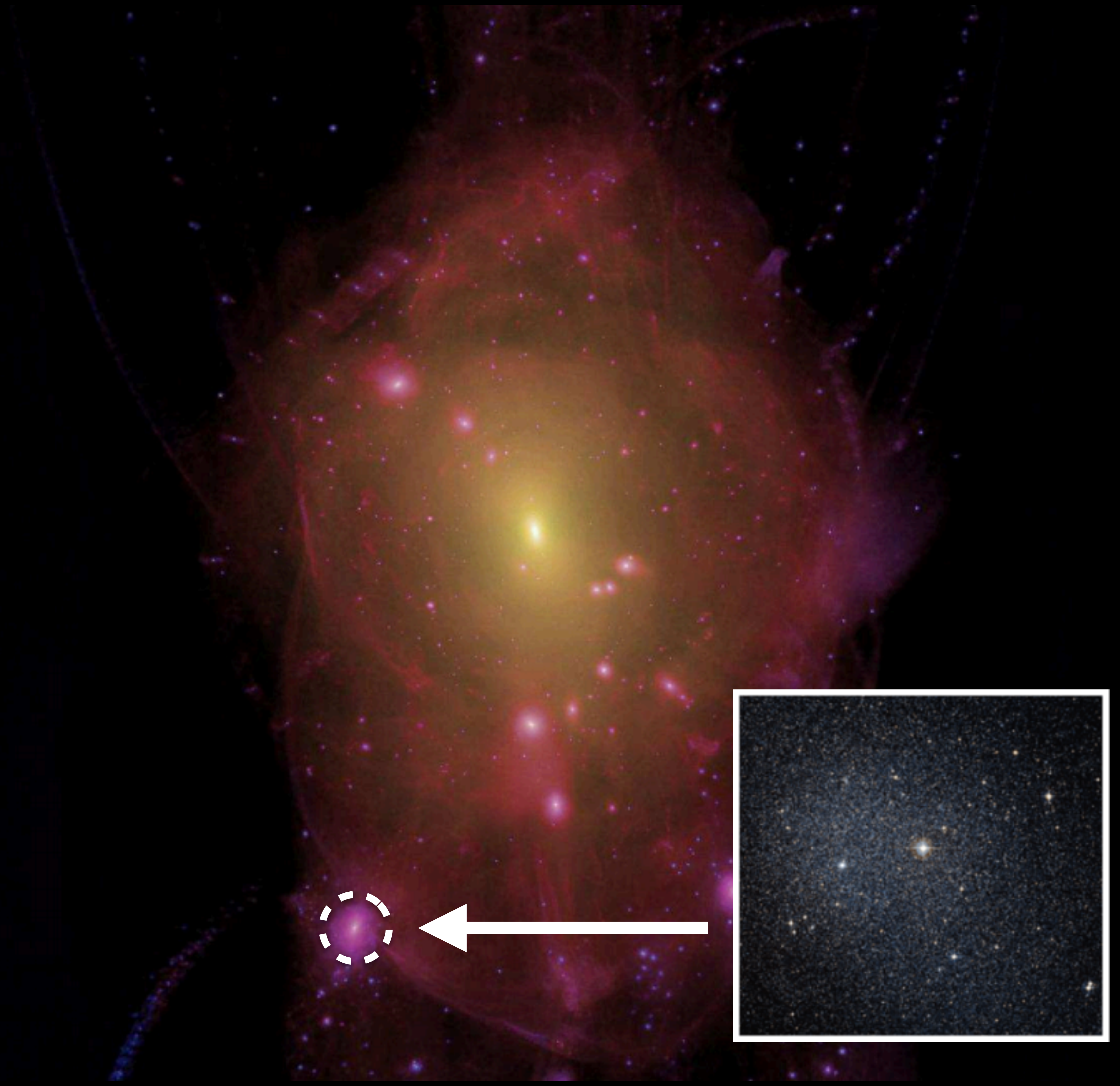
Dwarf Galaxies as Dark Matter Probes

Cold dark matter



Lovell et al. 2012

New dark matter physics



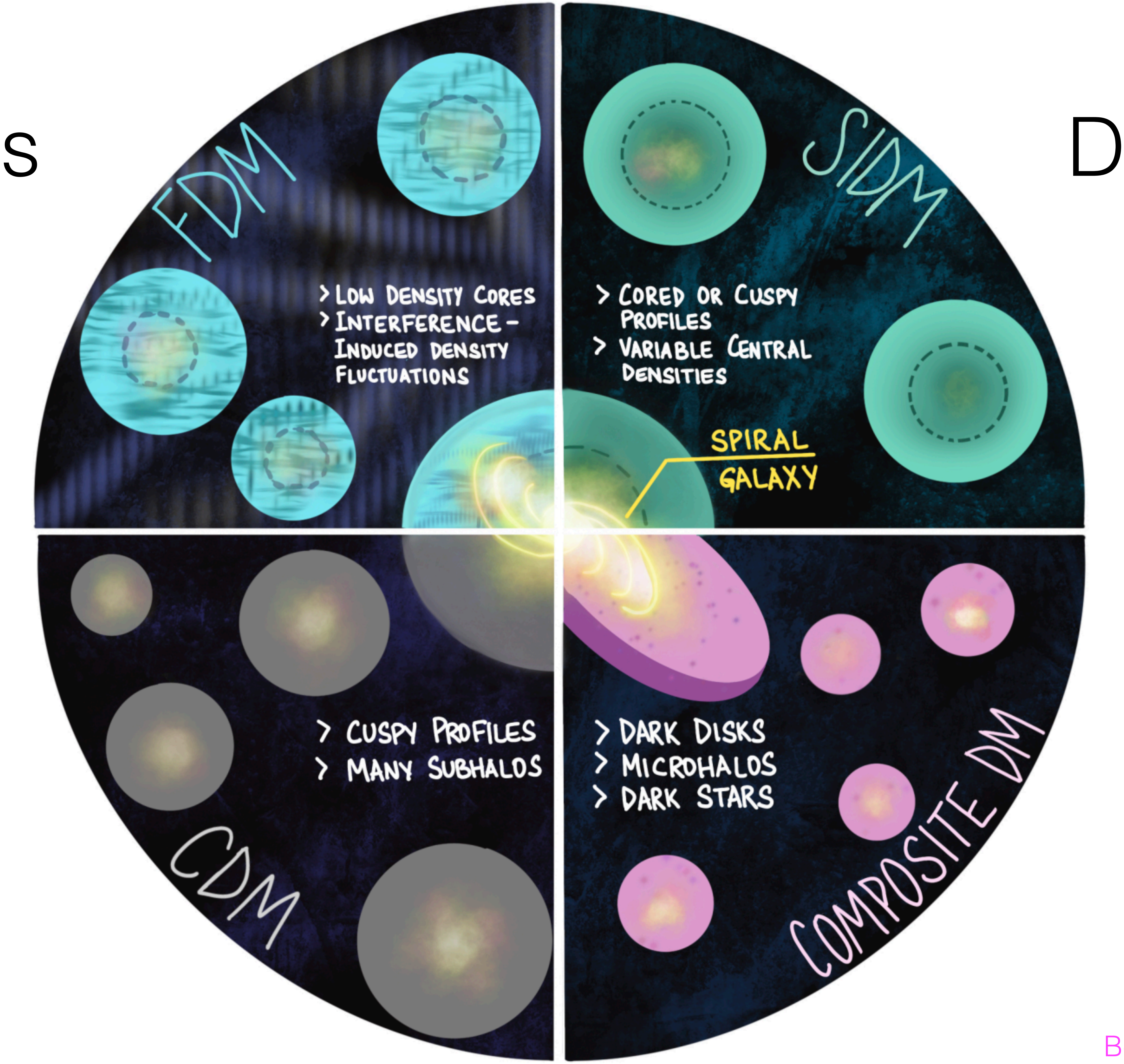
Ab Initio DM Physics

<u>alter initial conditions</u>

production mechanism

Standard Model interactions

particle mass



In Situ DM Physics

<u>alter dynamics</u>

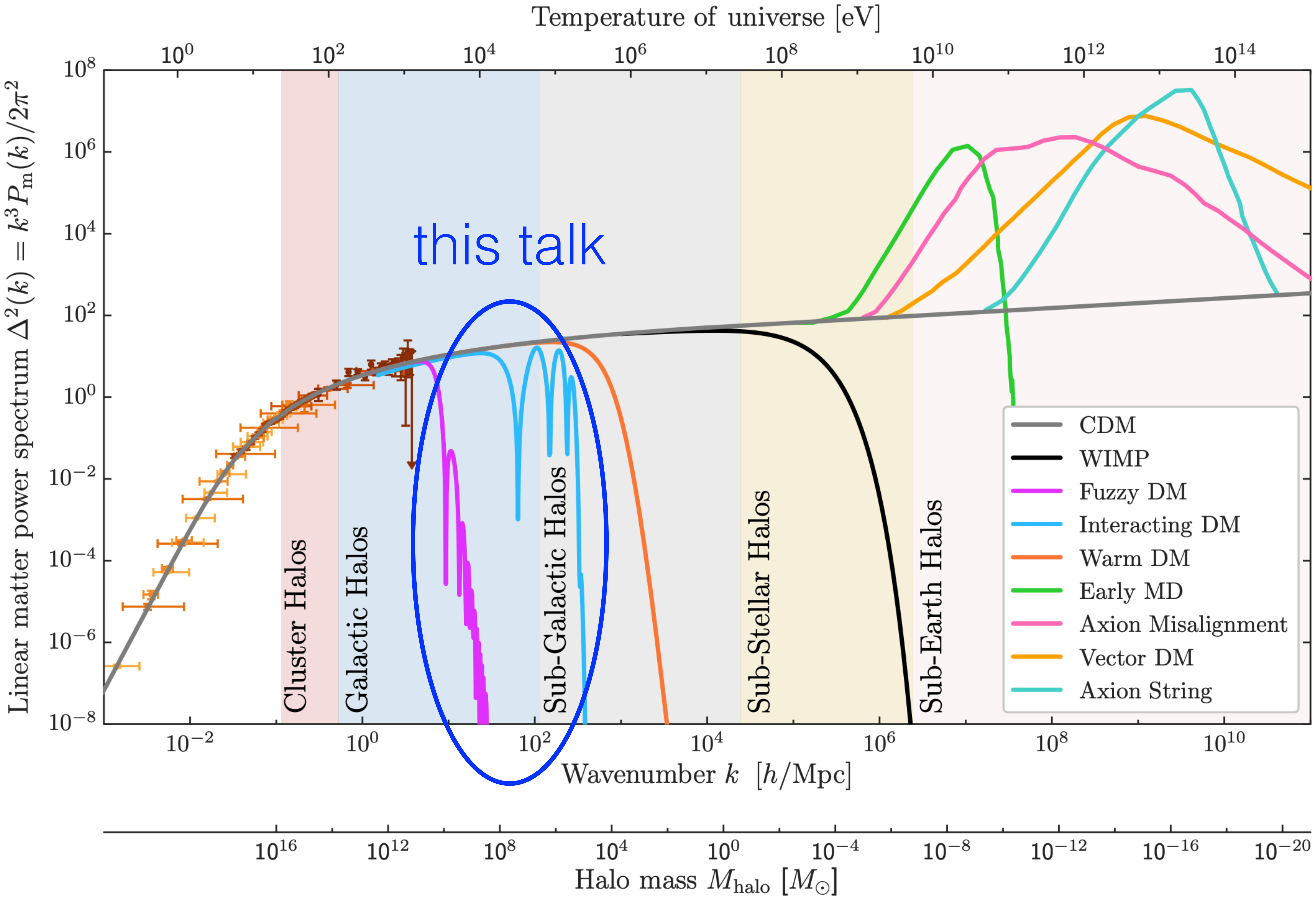
self-interactions

particle lifetime

particle mass

Bechtol et al. 2022 (2203.07354)

Ab Initio DM Physics on Dwarf Scales



this talk

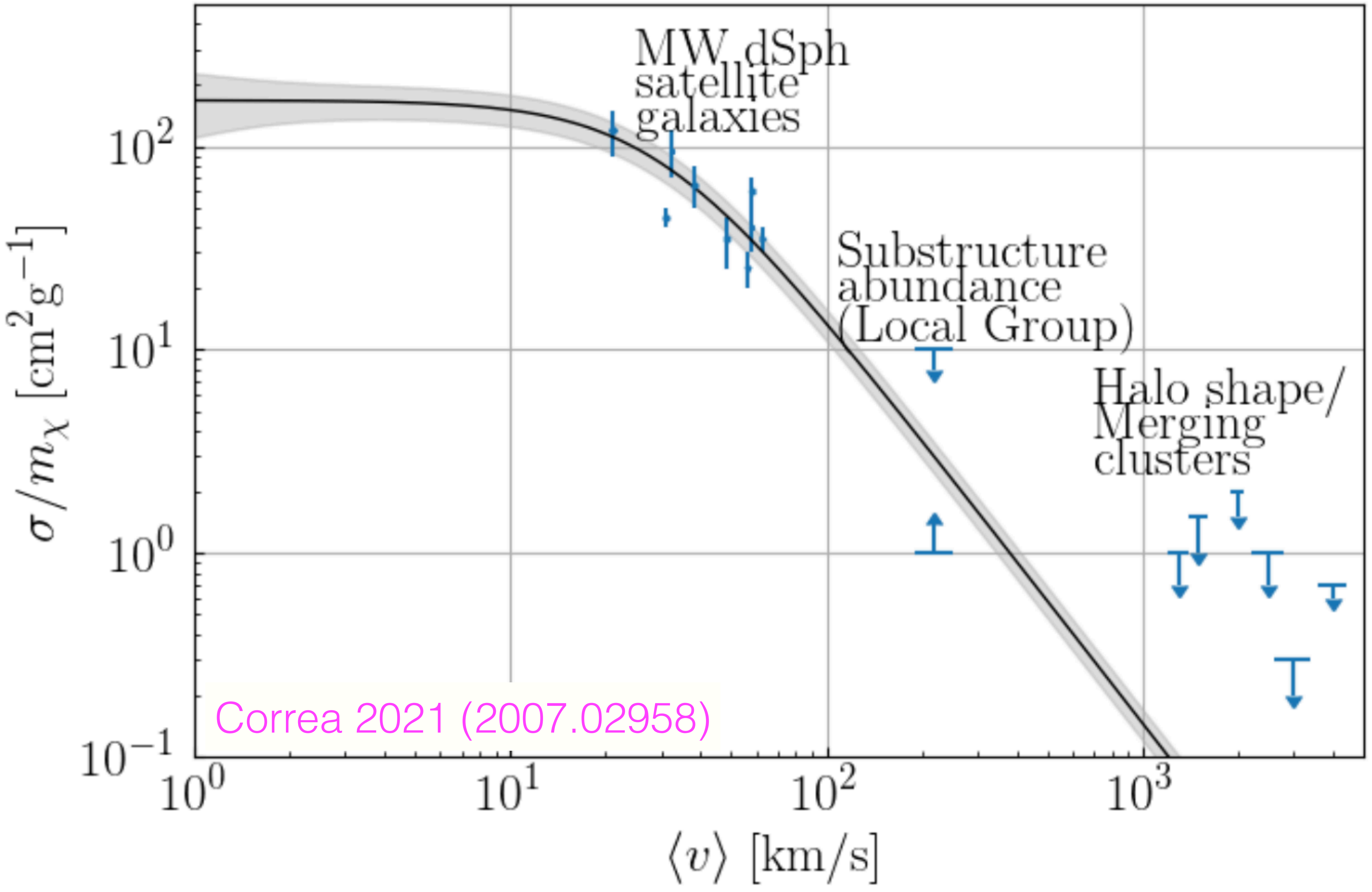
- Linear matter power spectrum *P(k)* sets initial conditions for structure formation
- *P(k)* suppression → fewer (sub)halos on corresponding mass scales; vice versa for enhancement
- Dwarfs probe small, unexplored scales:

$$M_{\rm halo} \sim 5 \times 10^9\ M_\odot \times \left(\frac{k}{10\ \mathrm{Mpc}^{-1}}\right)^{-3}$$

Snowmass Cosmic Probes of Dark Matter Report (2209.08215)

In Situ DM Physics on Dwarf Scales

Self-interacting DM: dwarfs probe low relative scattering velocities

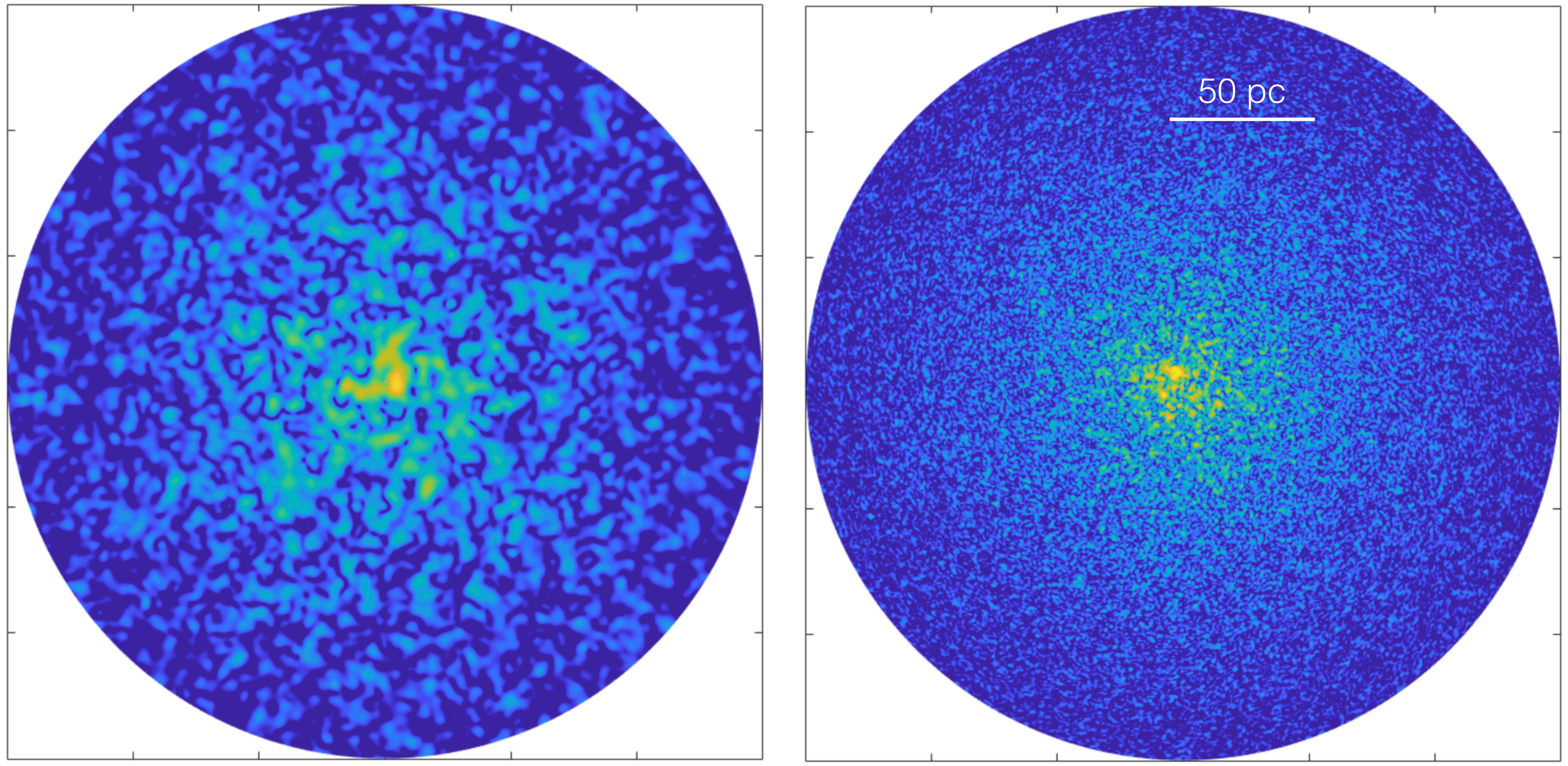


Correa 2021 (2007.02958)

$$R_{\rm scat} t_H \approx 1 \times \left(\frac{\rho_{\rm dm}}{0.1\ M_\odot\ {\rm pc}^{-3}}\right) \left(\frac{v_{\rm rel}}{50\ {\rm km\ s}^{-1}}\right) \left(\frac{\sigma/m}{1\ {\rm cm}^2\ {\rm g}^{-1}}\right)$$

Fuzzy DM: dwarfs probe small scales affected by wave interference

Dalal & Kravtsov 2022 (2203.05750)



$m_{\rm FDM} = 2 \times 10^{-19}$ eV

$m_{\rm FDM} = 8 \times 10^{-19}$ eV

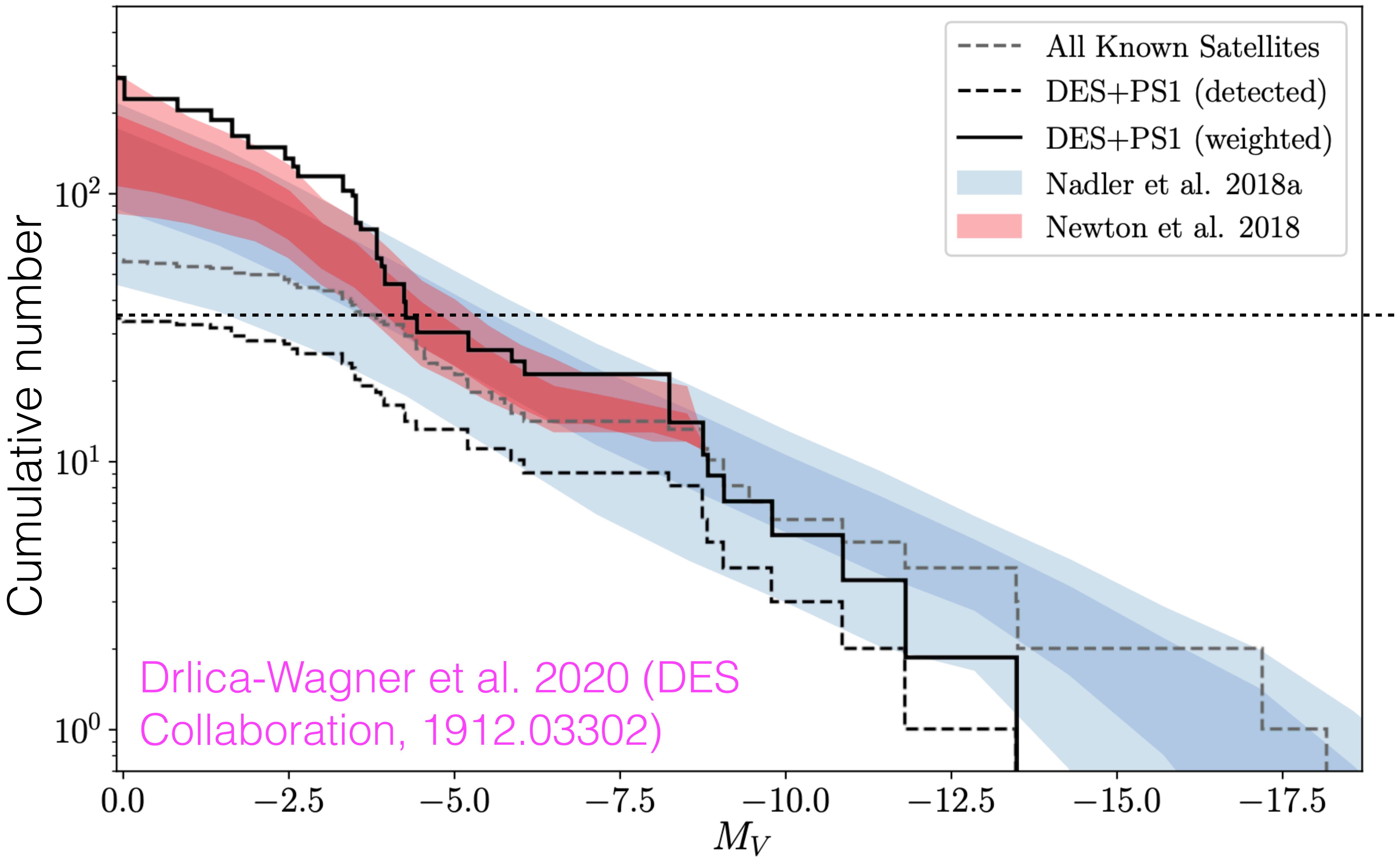
$$\lambda_{\rm dB} \approx 1\ {\rm kpc} \times \left(\frac{m_{\rm FDM}}{10^{-22}\ {\rm eV}}\right)^{-1} \left(\frac{v}{10\ {\rm km\ s}^{-1}}\right)^{-1}$$

Probe 1: Dwarf Luminosity Function

- Counting argument: subhalos with peak masses below ~$10^9\ M_\odot$ host faint Milky Way satellites

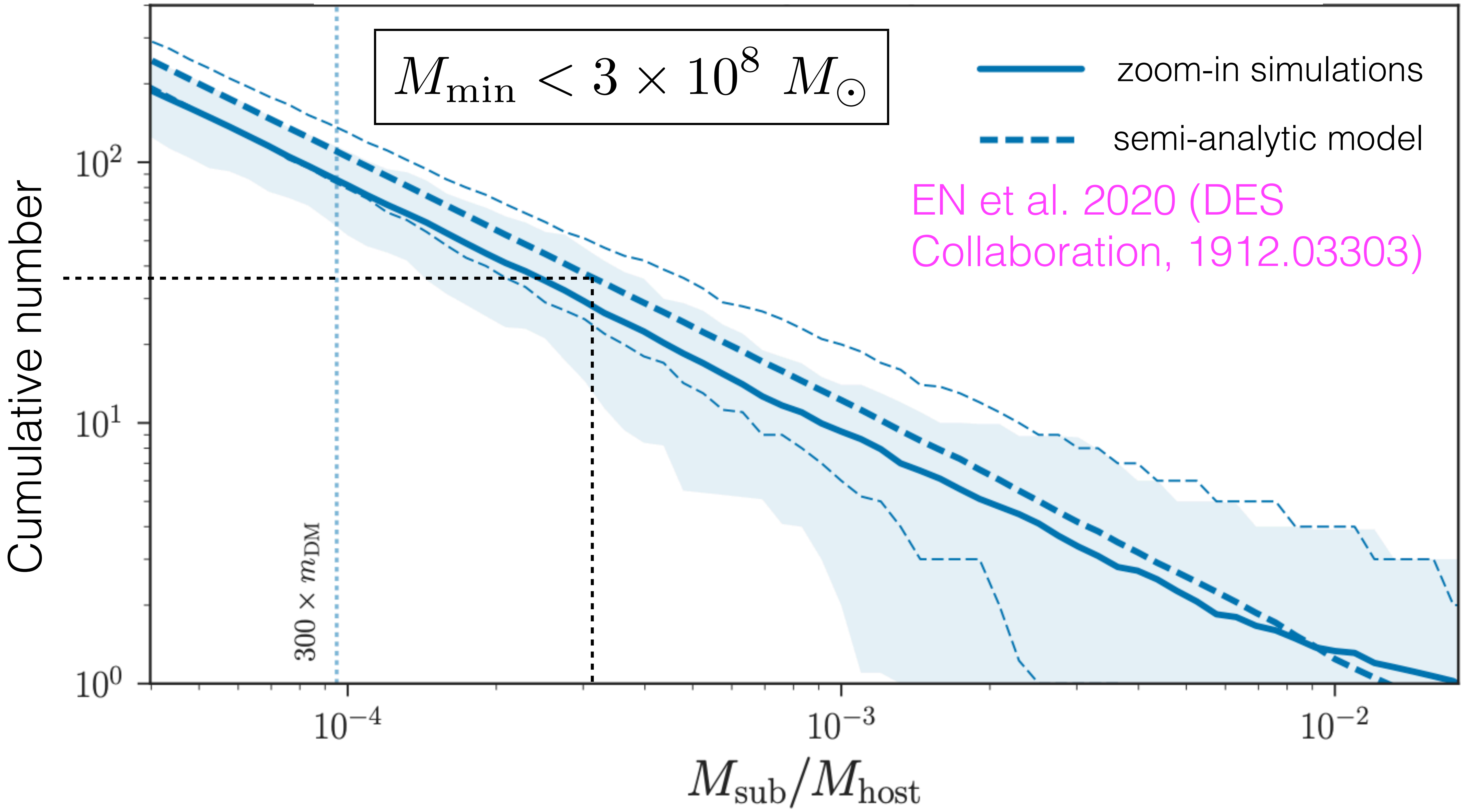
- Incompleteness, inefficient galaxy formation, scatter in the faint-end galaxy-halo connection, and disruption by the Milky Way push this limit to **~$10^8\ M_\odot$**

Milky Way satellite luminosity function



Drlica-Wagner et al. 2020 (DES Collaboration, 1912.03302)

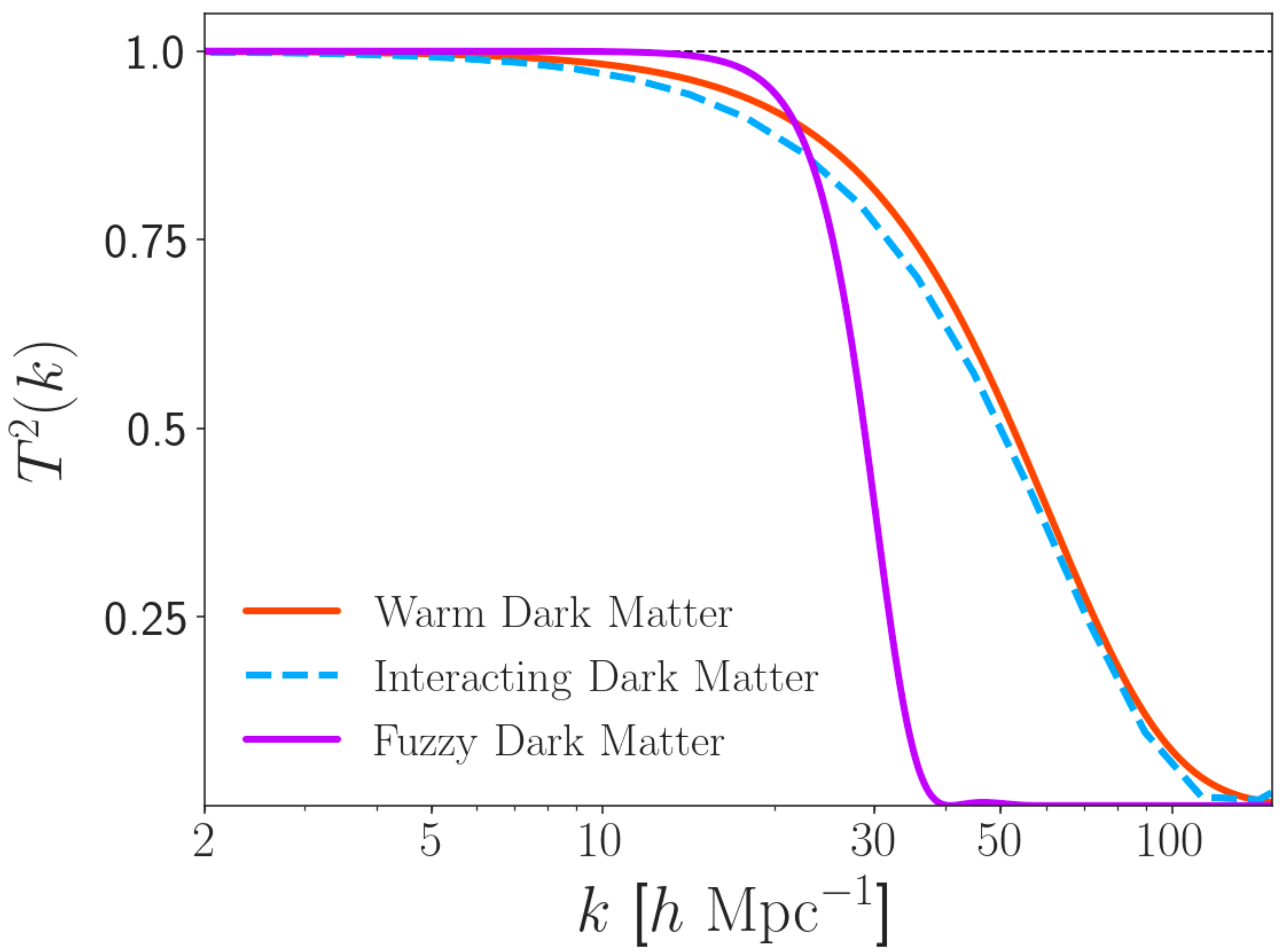
Milky Way subhalo mass function (CDM)



EN et al. 2020 (DES Collaboration, 1912.03303)

Luminosity Function: Bounds on *Ab Initio* DM Physics

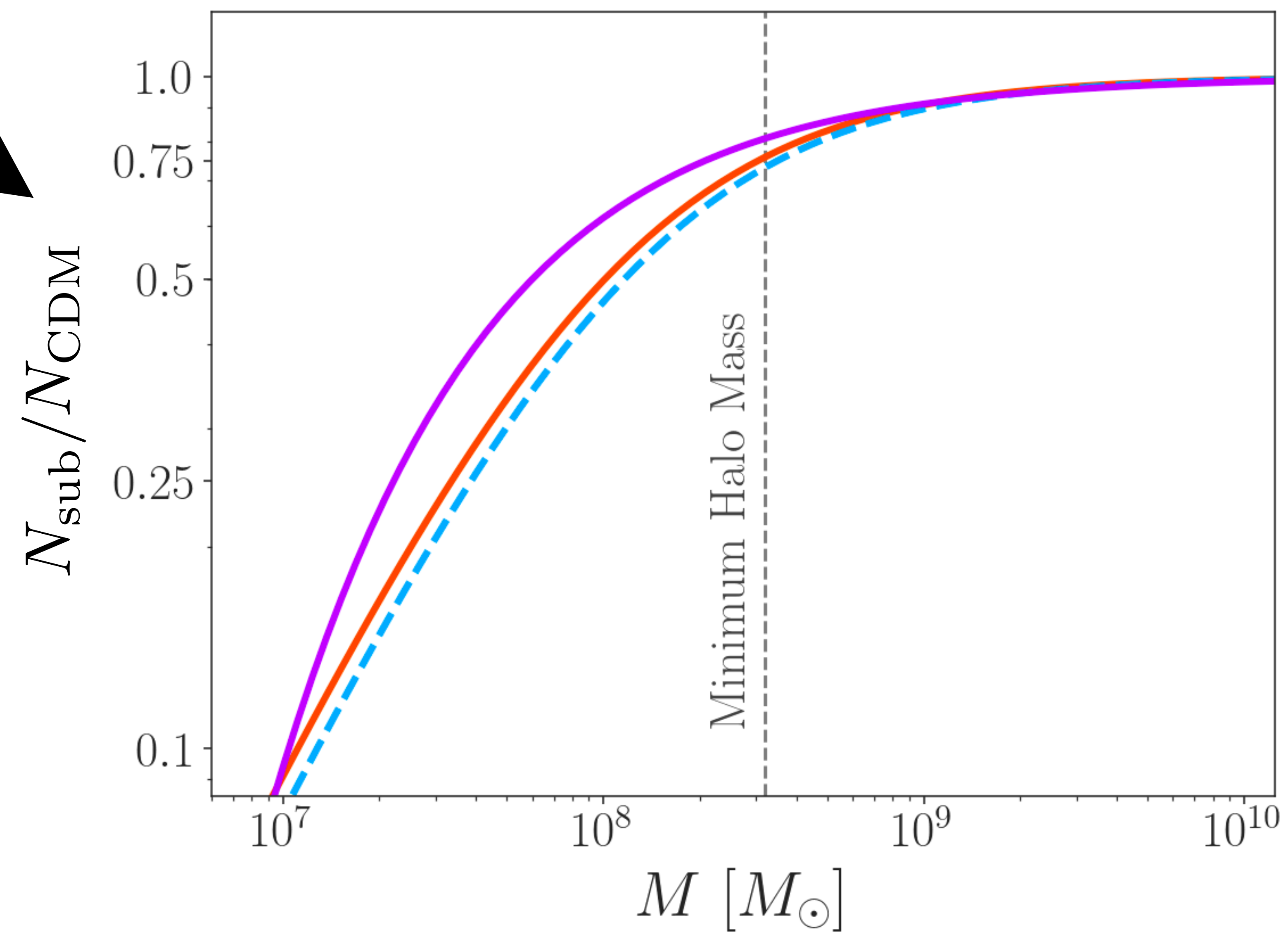
Transfer function



$$T^2(k) = P(k)/P_{\mathrm{CDM}}(k)$$

$$T^2(k = k_{\mathrm{hm}}) = 0.25$$

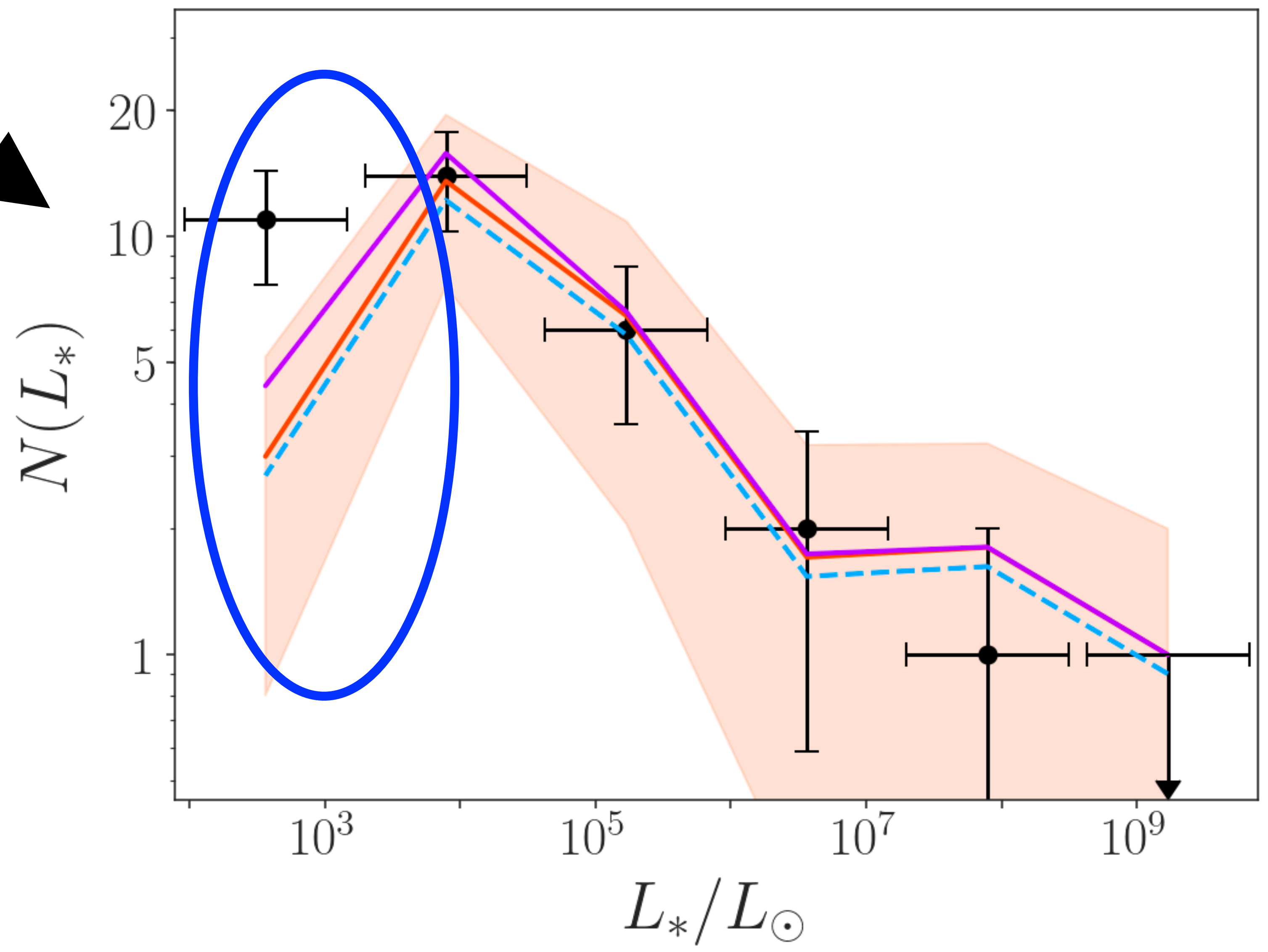
Subhalo mass function suppression



$$\boxed{m_{\mathrm{WDM}} > 6.5\ \mathrm{keV}}$$

$$k_{\mathrm{hm}} > 50\ \mathrm{Mpc}^{-1}$$

Satellite luminosity function



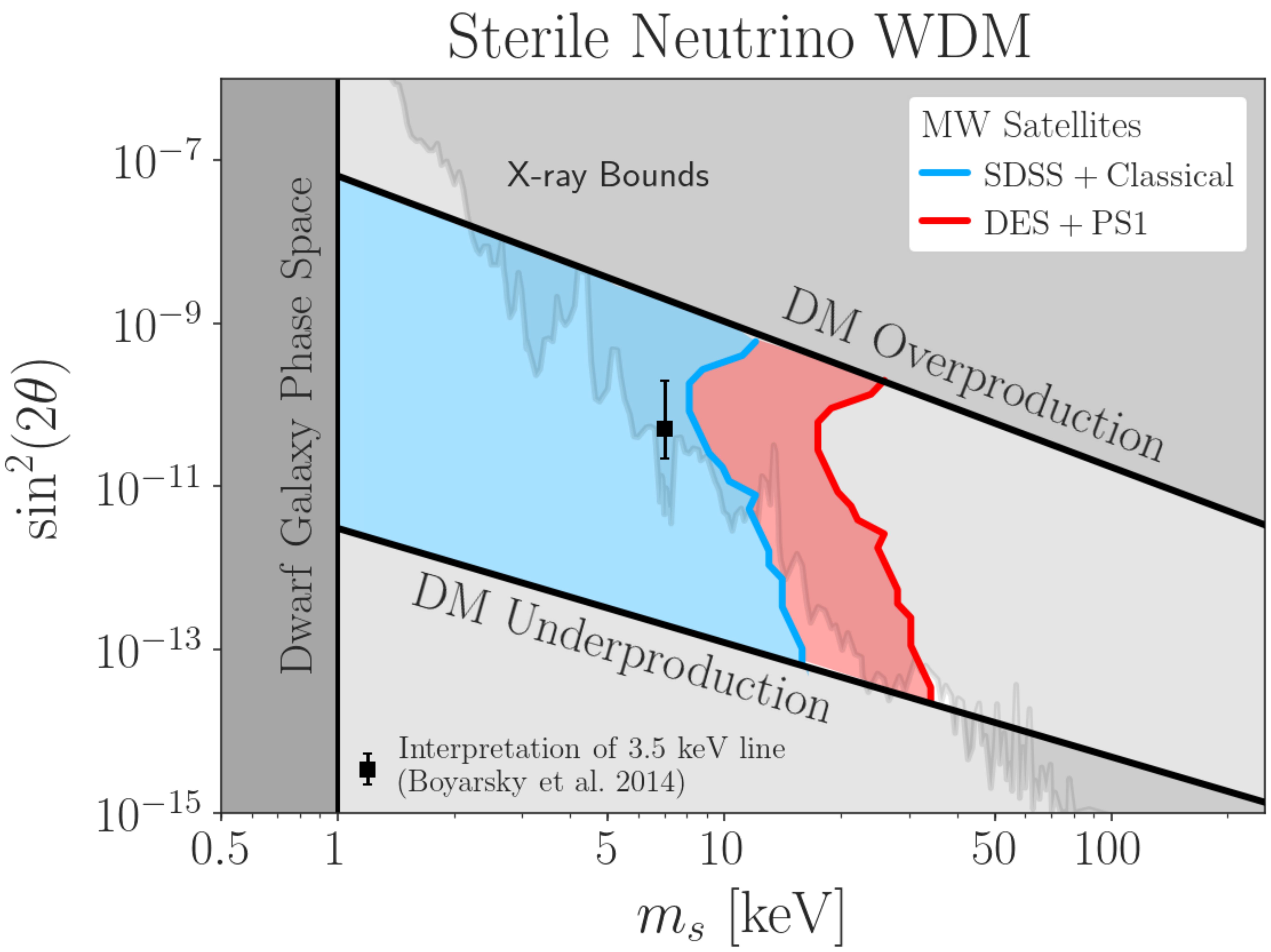
Milky Way satellite abundances complement Lyman-α forest, strong lensing, stellar stream, and high-*z* UVLF

EN et al. 2021 (DES Collaboration, 2008.00022)

Luminosity Function: Sterile Neutrino DM Limits

- Sterile neutrino DM is tightly constrained by Milky Way satellite counts, regardless of specific production mechanism
- $m_{\mathrm{WDM}} > 6.5$ keV $\implies$ interpretation of 3.5 keV line as 100% sterile neutrino DM annihilation is ruled out at high confidence
- In general: DM free-streaming must not erase $M_{\mathrm{peak}} \sim 10^8\ M_\odot$ halos:

$$\lambda_{\mathrm{fs}} \sim \int_{t_i}^{t_{\mathrm{eq}}} \frac{\langle v(t) \rangle \ \mathrm{d}t}{a(t)} \lesssim 10 \ \mathrm{kpc}$$



EN et al. 2021 (DES Collaboration, 2008.00022)

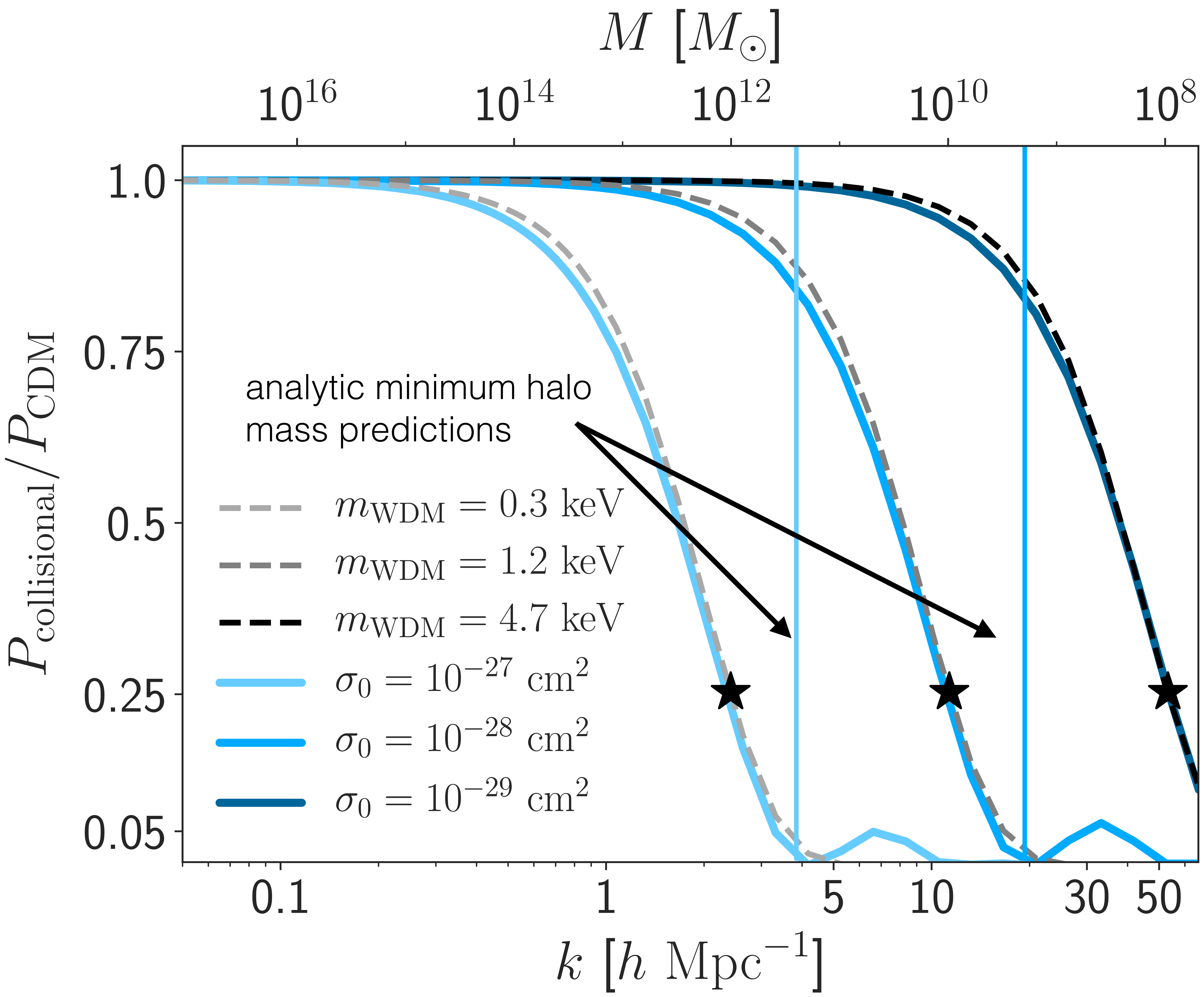
Luminosity Function: DM–Baryon Interaction Limits

- Non-gravitational DM–baryon scattering suppresses small-scale structure
- Momentum transfer is efficient in early universe, affecting linear *P(k)*; late-time *in situ* scattering is rare
- Mass function cutoff is set by the size of the cosmological horizon when

$$R_\chi \sim aH$$

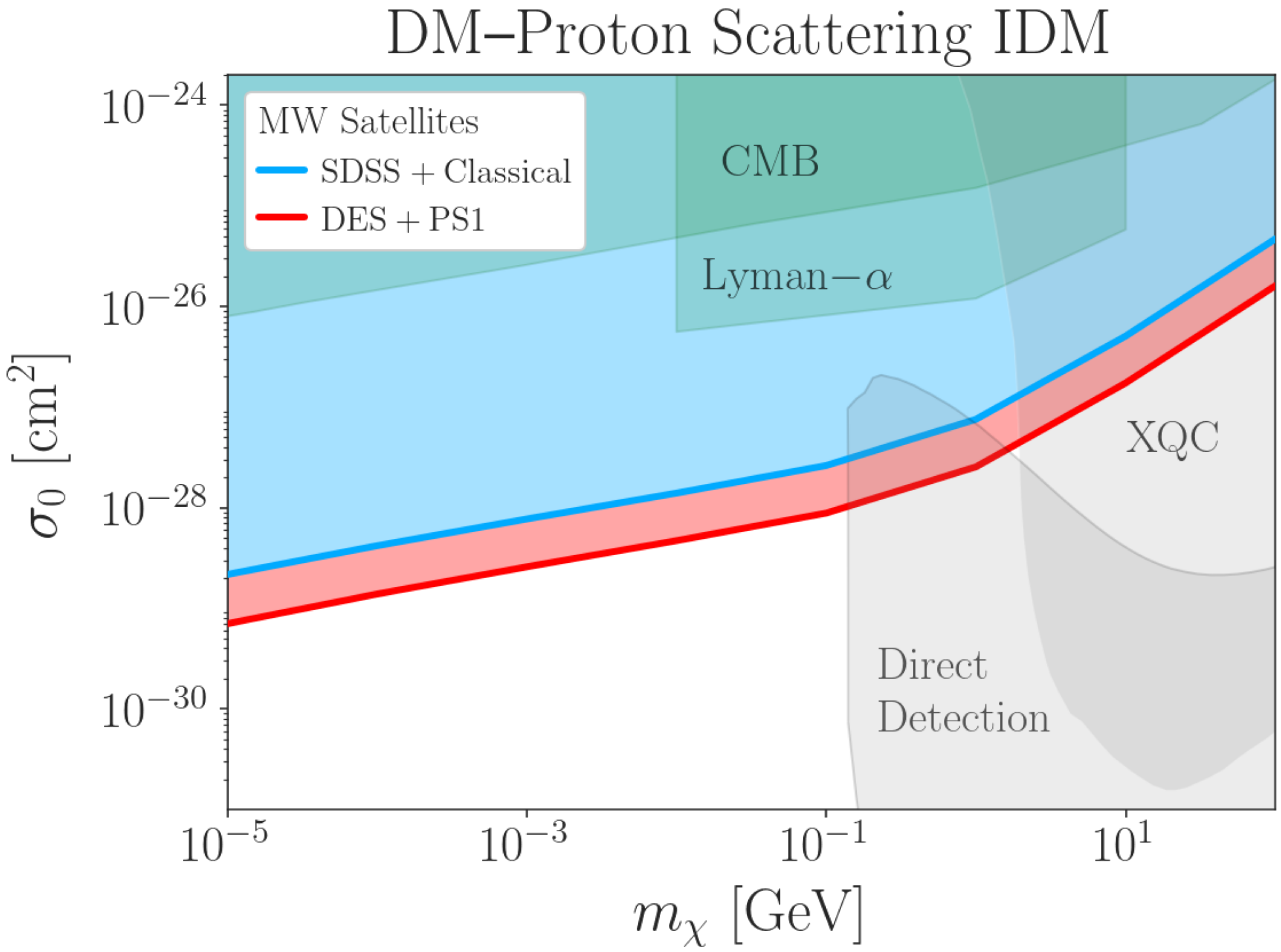
Momentum transfer rate

Hubble rate



EN, Gluscevic, Boddy, Wechsler 2019 (1904.10000)

Luminosity Function: DM–Baryon Interaction Limits



- Milky Way satellite luminosity function improves DM–proton scattering limits by ~3 orders of magnitude

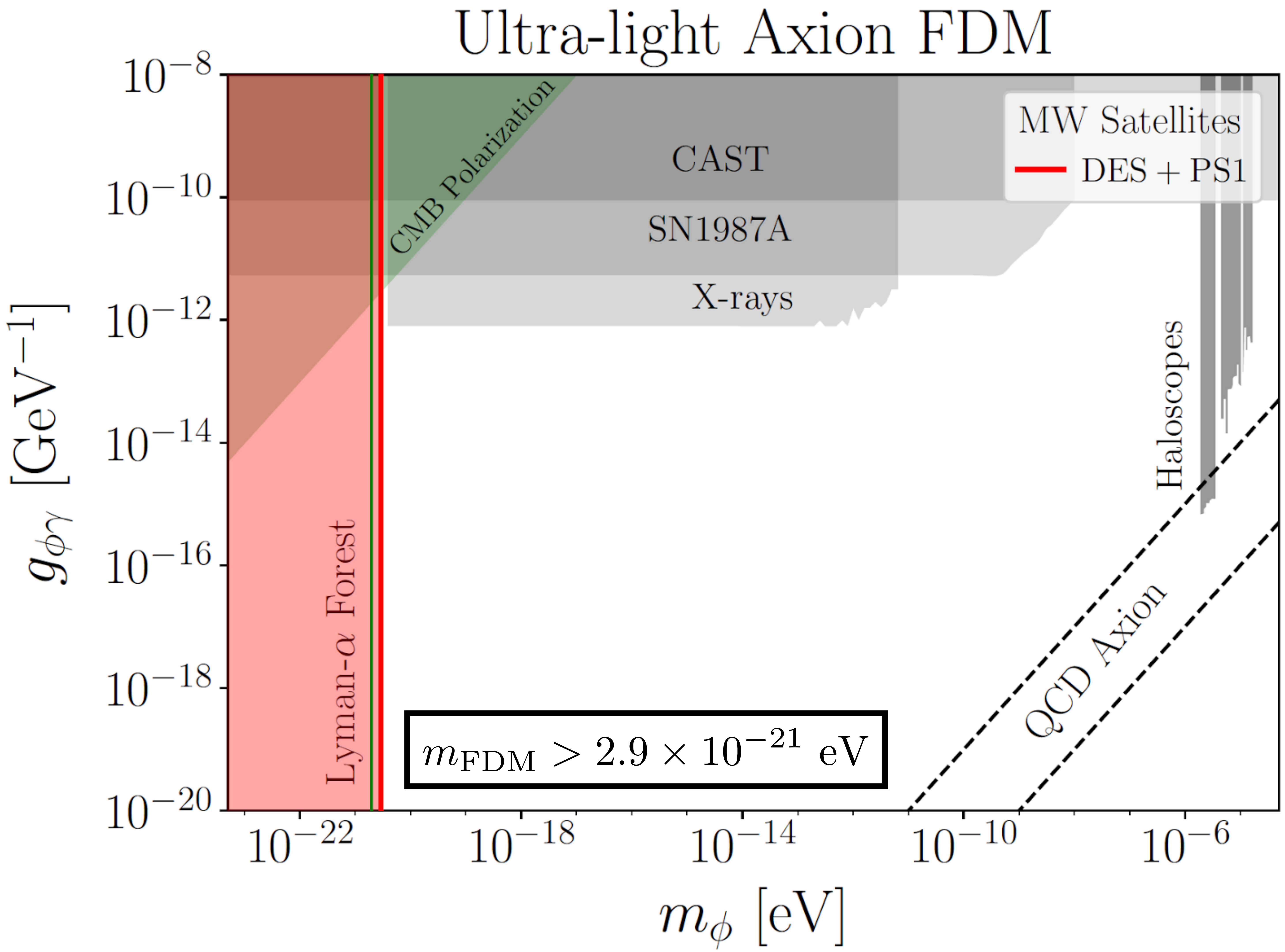
- Similar gains for DM–electron/radiation scattering, velocity-dependent models

- In general: collisional damping due to DM–SM interactions must not erase $M_{\rm peak} \sim 10^8\ M_\odot$ halos:

$$\lambda_{\rm dec} \sim R_H(n_t \sigma_{\chi t} v_{\rm rel} < aH) \lesssim 100 \text{ kpc}$$

EN et al. 2021 (2008.00022); also see Maamari et al. 2021 (2010.02936), Nguyen et al. 2021 (2107.12830), Crumrine et al. 2024 (2406.19458)

Luminosity Function: Fuzzy DM Limits



EN et al. 2021 (DES Collaboration, 2008.00022)

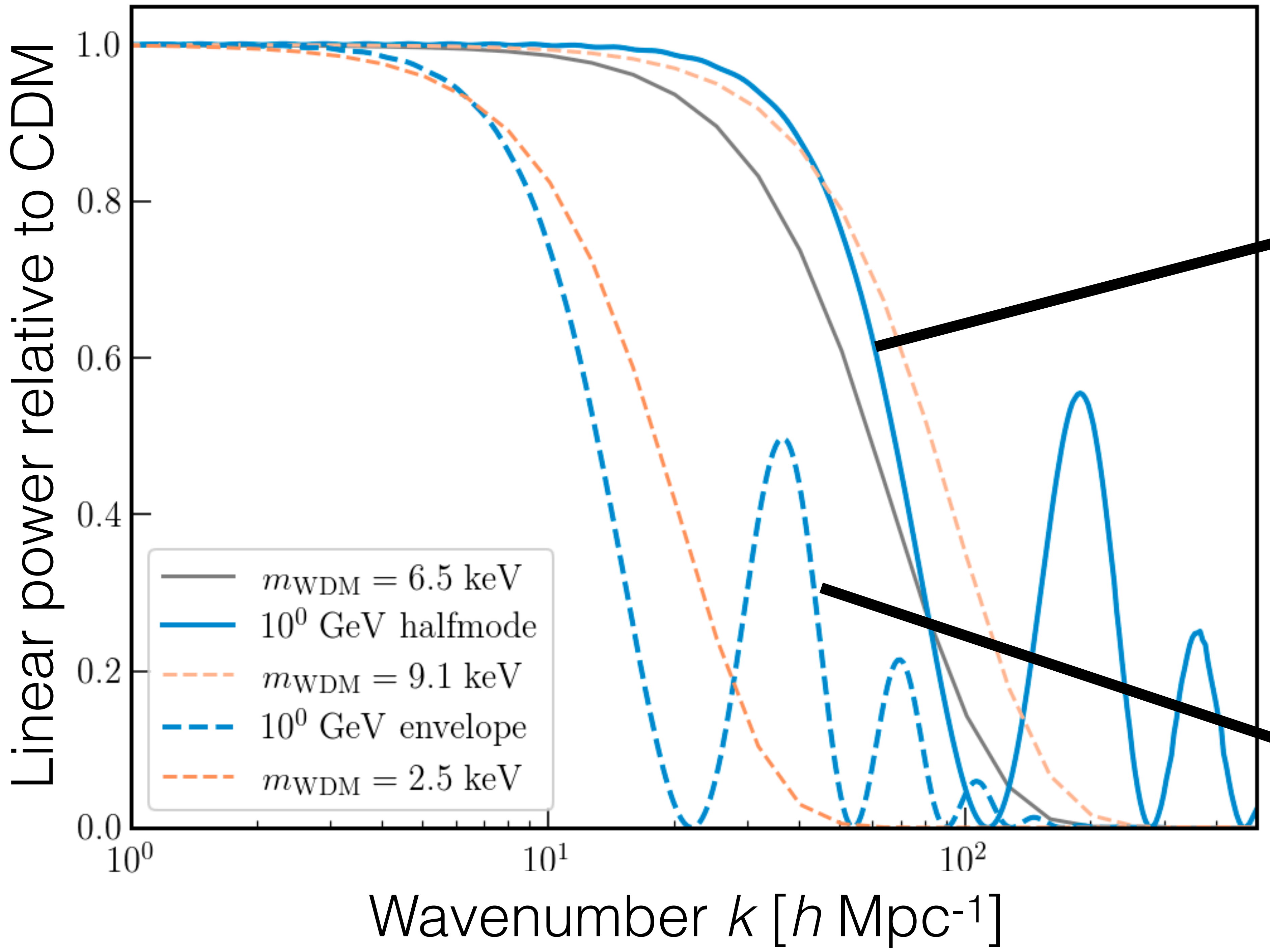
- Milky Way satellite abundances rule out DM masses below ~10^{-21} eV
- This limit strongly disfavors ultra-light DM models that produce large cores in dwarf galaxies
- In general: Jeans length associated with DM wave interference must not erase $M_{\mathrm{peak}} \sim 10^8\ M_\odot$ halos:

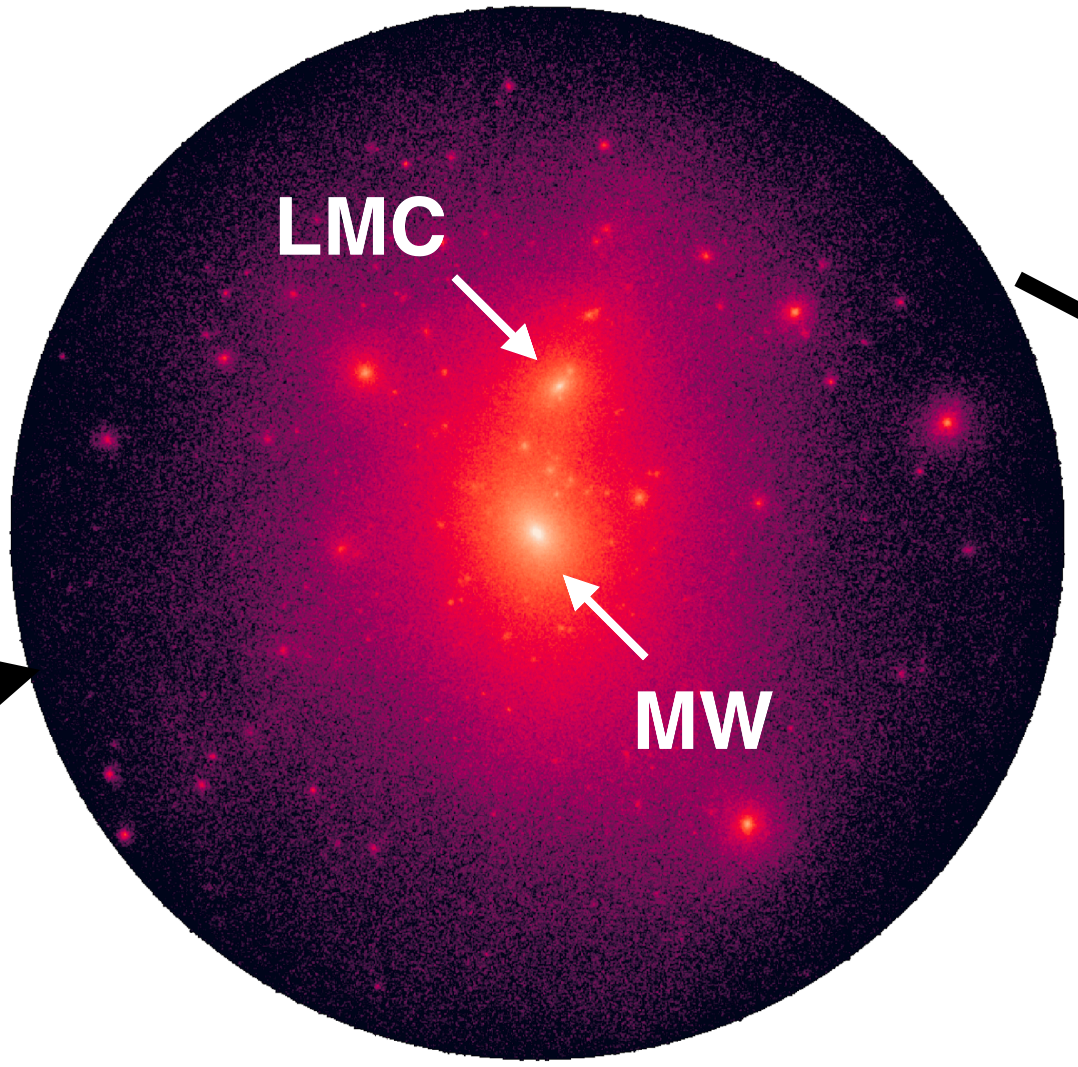
$$\lambda_J \approx 0.7\ \mathrm{Mpc} \times \left(\frac{m_{\mathrm{FDM}}}{10^{-22}\ \mathrm{eV}}\right)^{-1/2} \lesssim 100\ \mathrm{kpc}$$

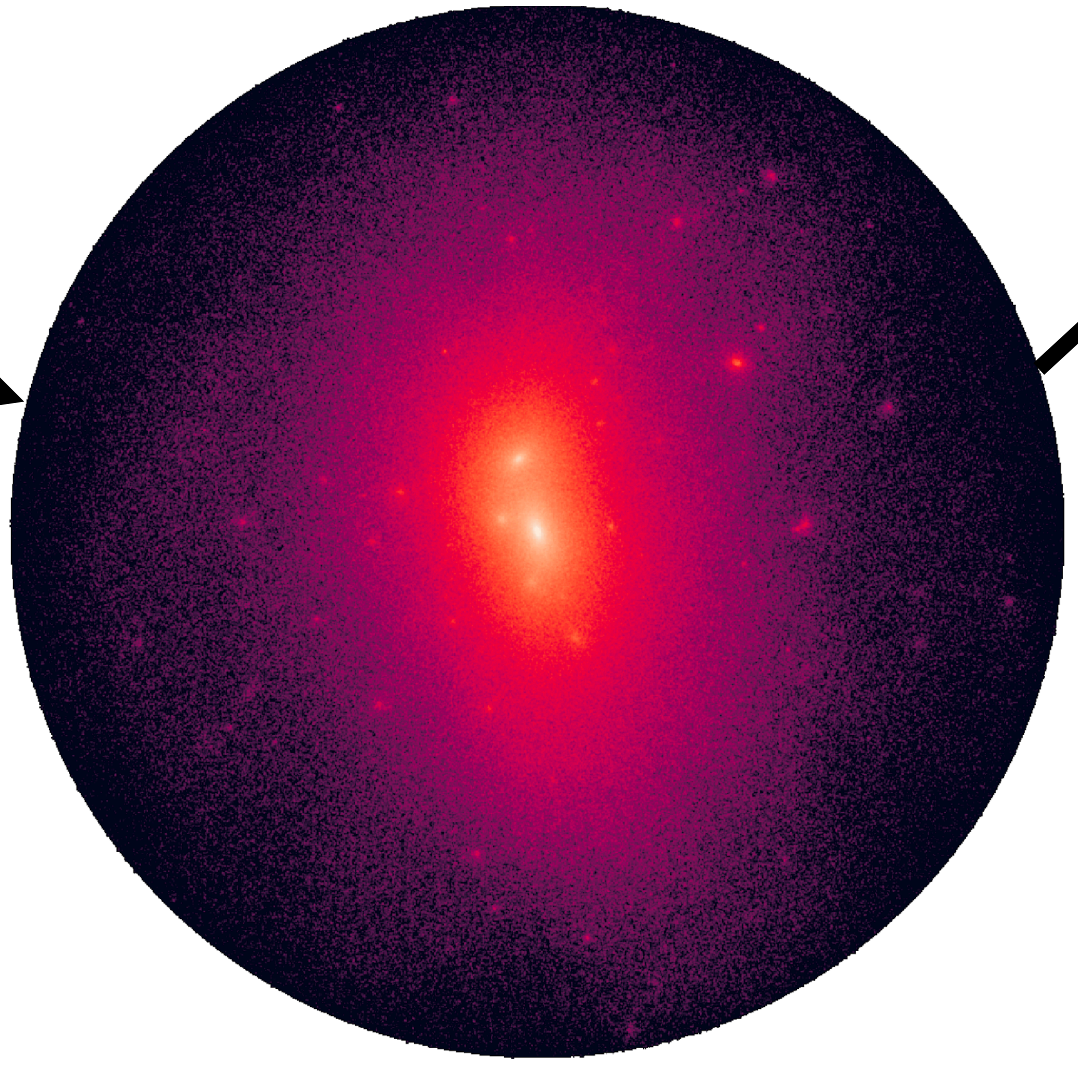
> *"If you want a large core you won't get the galaxy, if you get the galaxy it won't have a large core"*
> *— Macciò et al. 2012 (1202.1282)*

COZMIC Zoom-in Simulations

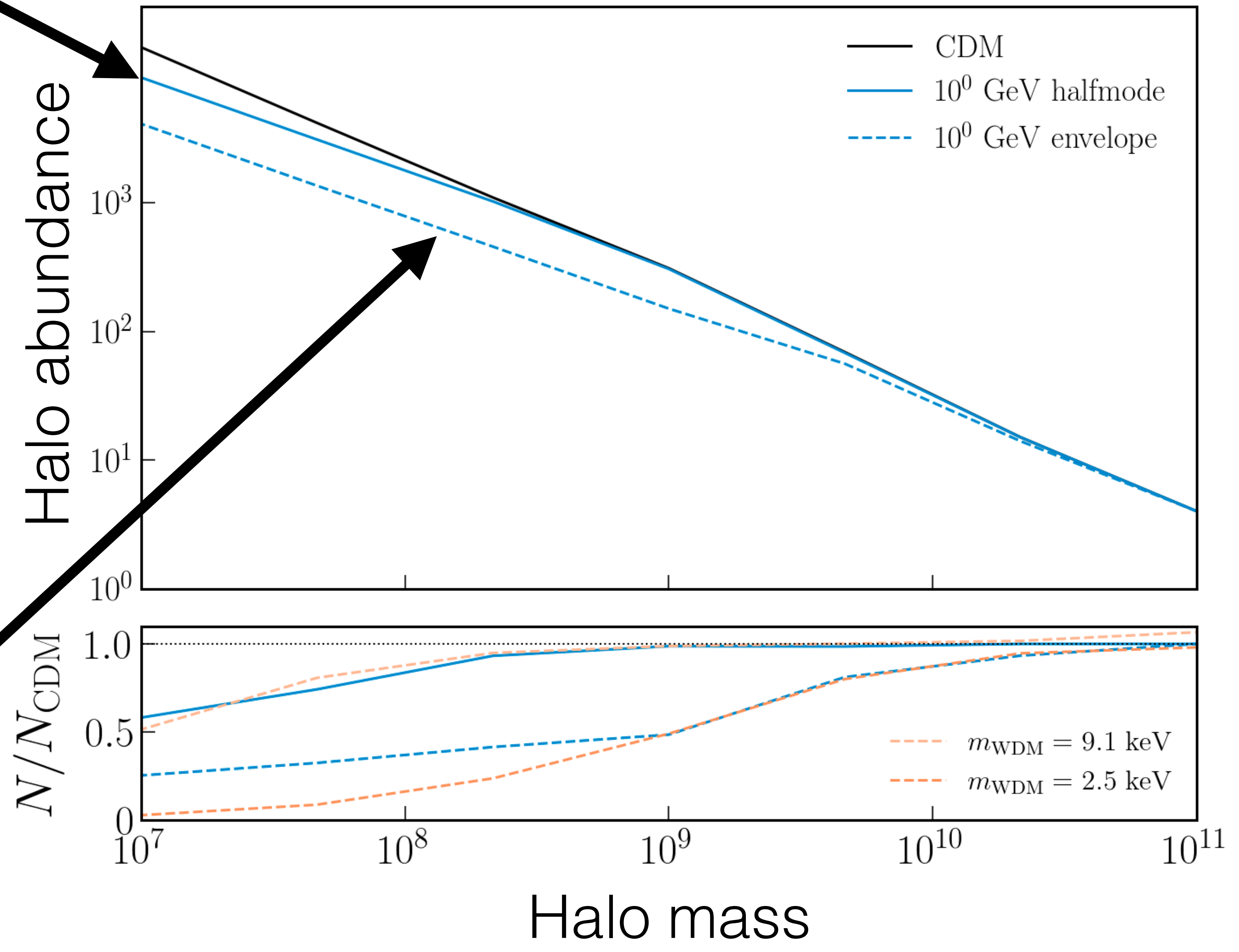
Initial conditions from linear theory







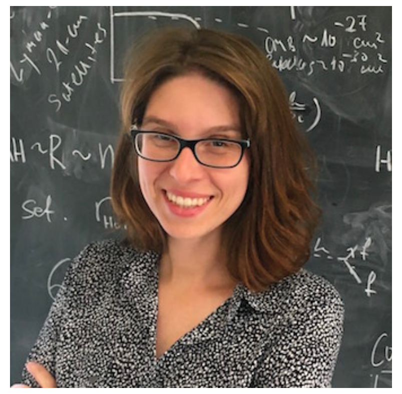
Halo and subhalo populations



100+ cosmological DM-only zoom-in simulations with initial conditions for warm, fuzzy, interacting DM

Rui An
(USC)

Andrew Benson
(Carnegie)



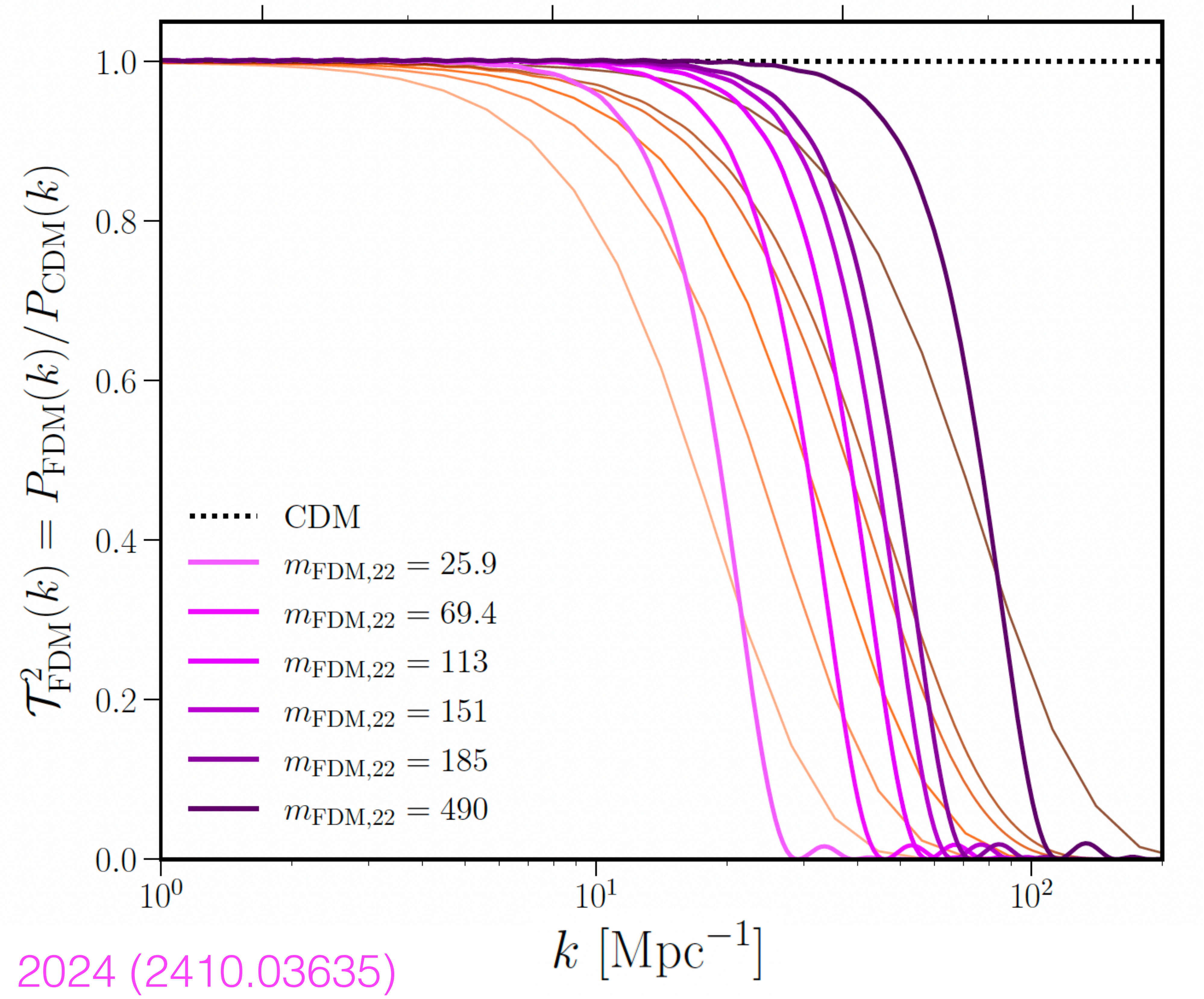
Vera Gluscevic
(USC)

EN et al. 2024 (2410.03635), An & EN et al. 2024 (2411.03431), EN et al. 2024 (2412.13065)

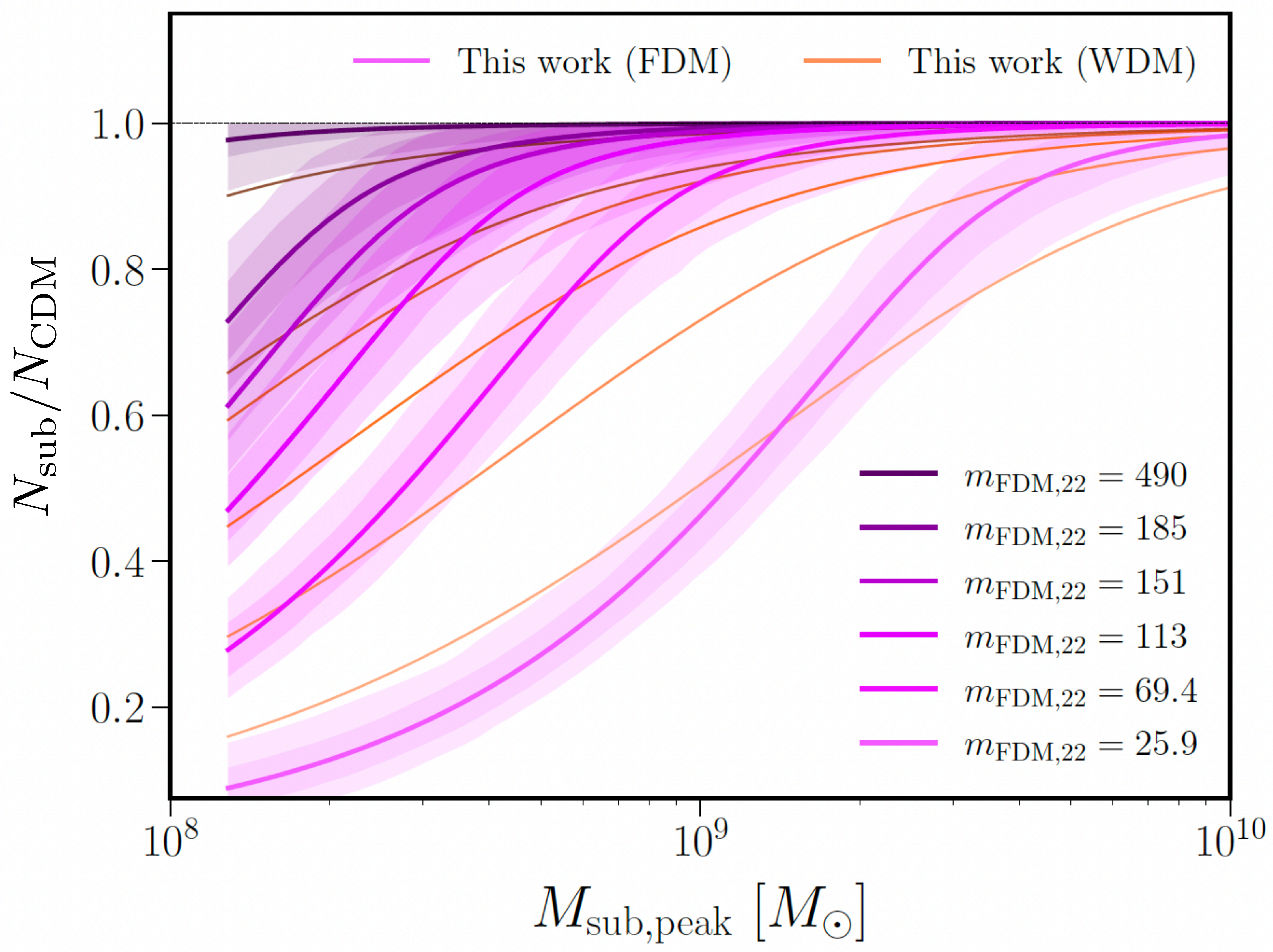
COZMIC I: Fuzzy Dark Matter

- Fuzzy dark matter SHMF cuts off more sharply than WDM: imprint of *P(k)* on subhalo population
- New SHMF model significantly improves limit from Milky Way satellite counts: $\boxed{m_{\rm FDM} > 1.4 \times 10^{-20}\ {\rm eV}}$

Linear matter power spectrum suppression

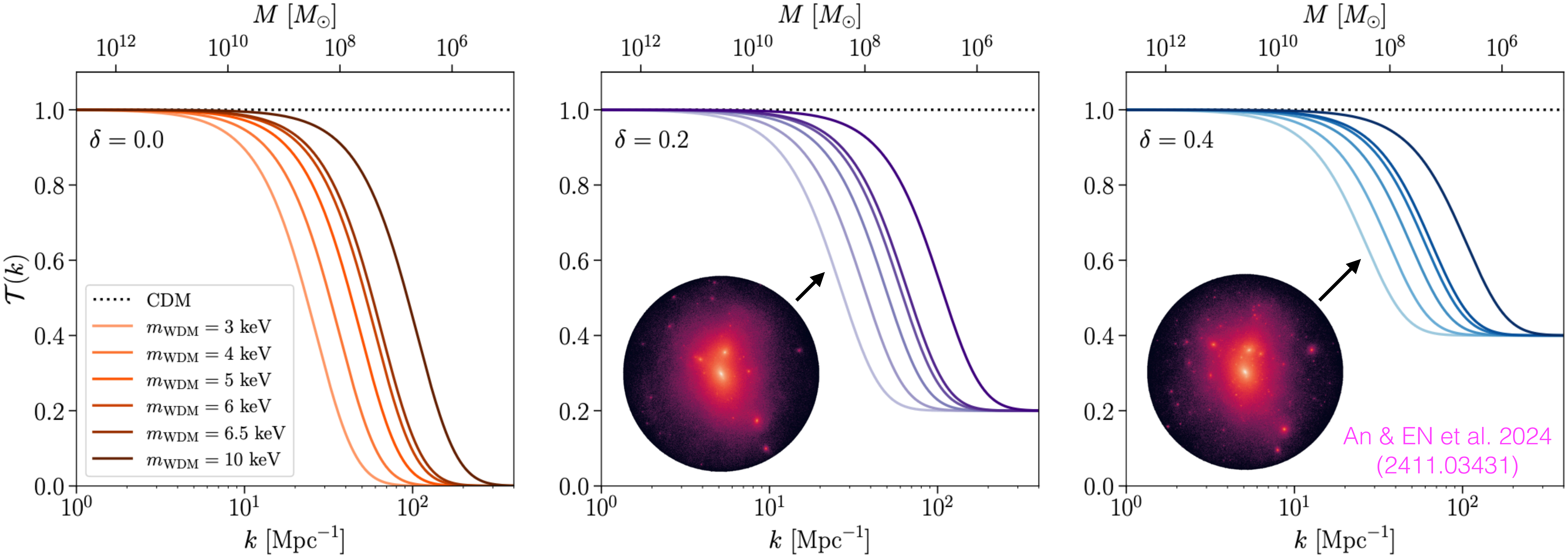


Subhalo mass function suppression



EN et al. 2024 (2410.03635)

COZMIC II: Mixed Dark Matter

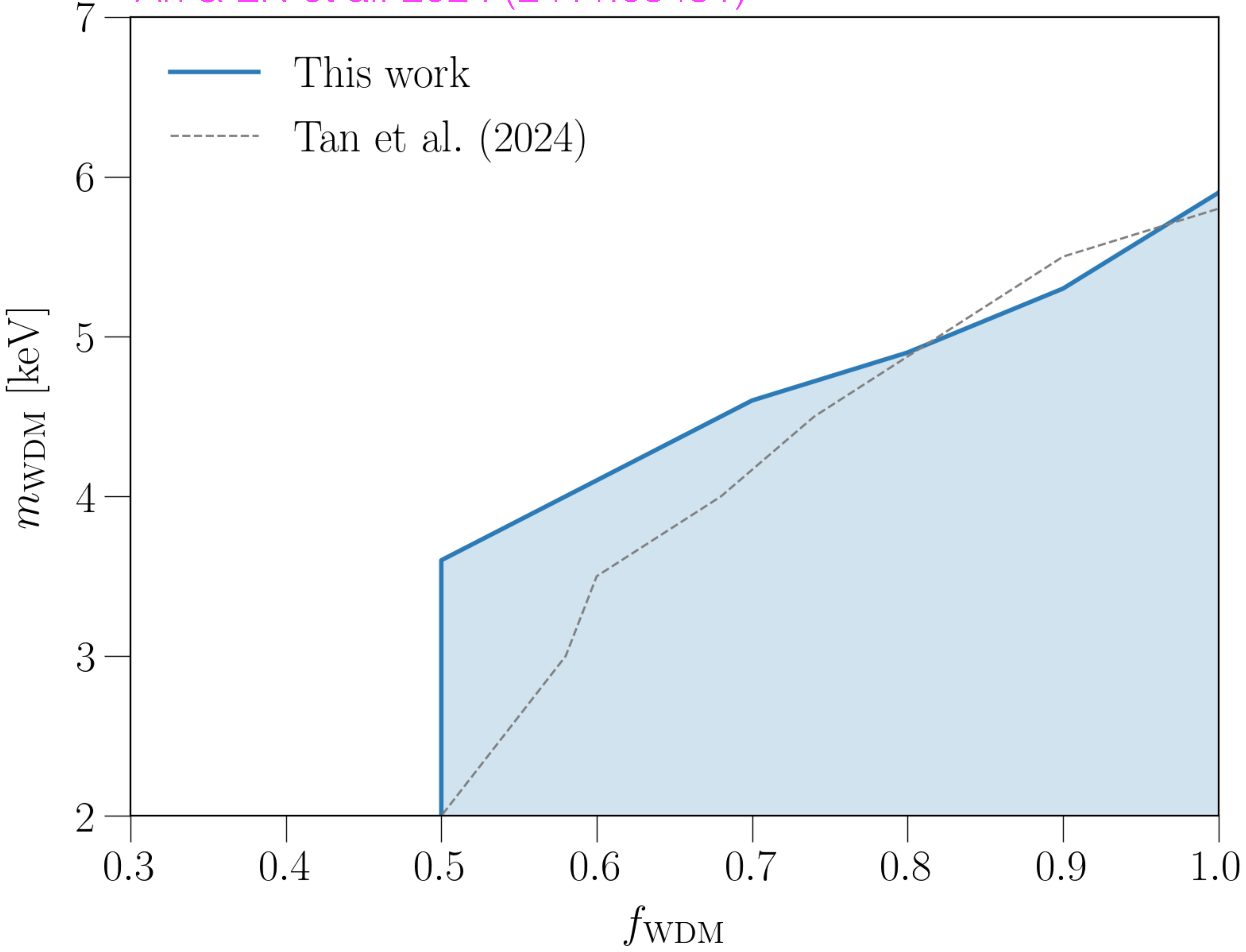


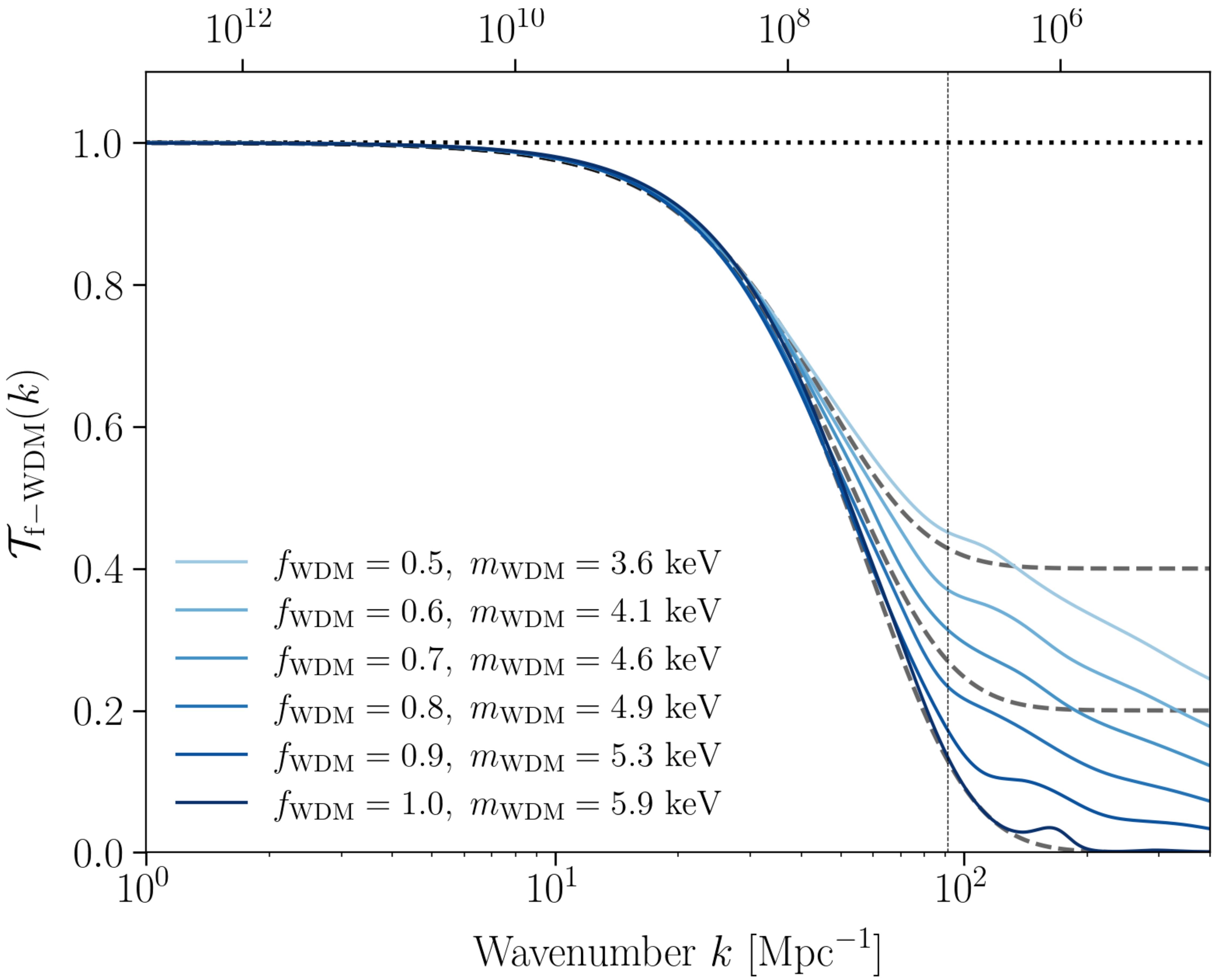
An & EN et al. 2024 (2411.03431)

- 24 zoom-in simulations of a Milky Way analog with initial fractional conditions for mixed dark matter models
- Mixed dark matter transfer functions modeled with suppression scale and constant-amplitude plateau

COZMIC II: Mixed Dark Matter

An & EN et al. 2024 (2411.03431)



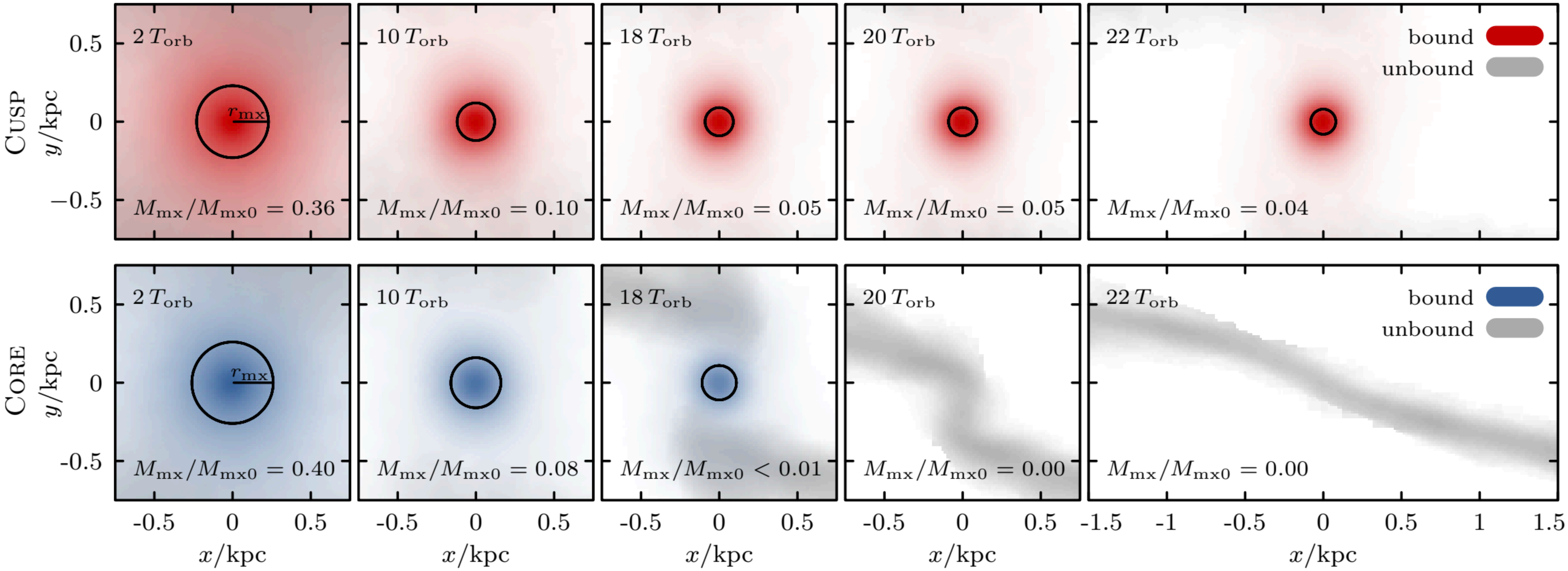


- Milky Way satellite abundances constrain mixed WDM/CDM models with a ≳ 50% WDM component
- SHMF models yield new limits on transfer function, relevant for many fractional non-CDM scenarios

Luminosity Function: Bounds on *In Situ* DM Physics

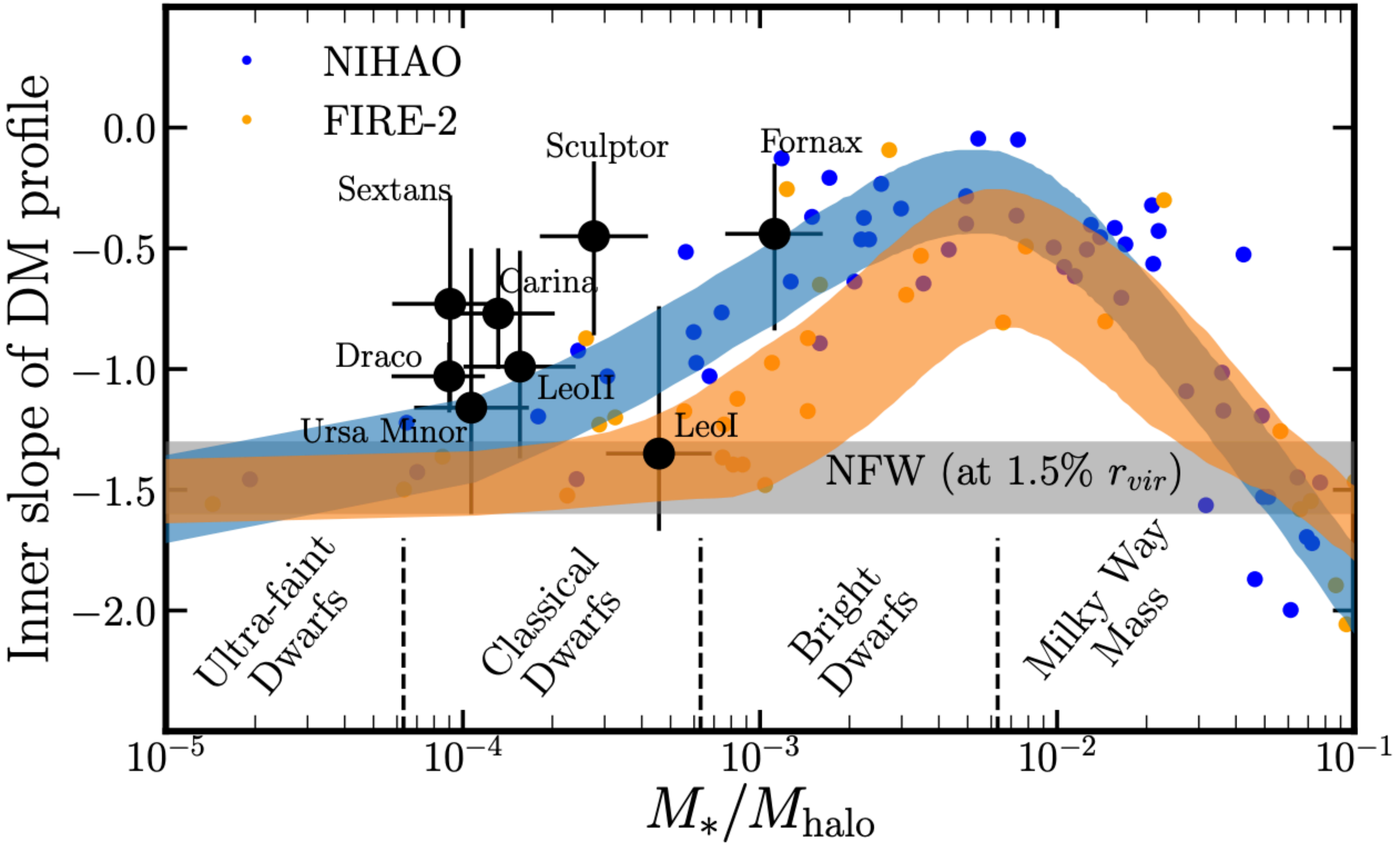
- DM self-interactions, decays, and other coring mechanisms can lead to subhalo disruption
- <u>Future work</u>: Combine *stellar* disruption modeling and cosmological merger trees to derive limits

Errani et al. 2022 (2210.01131)

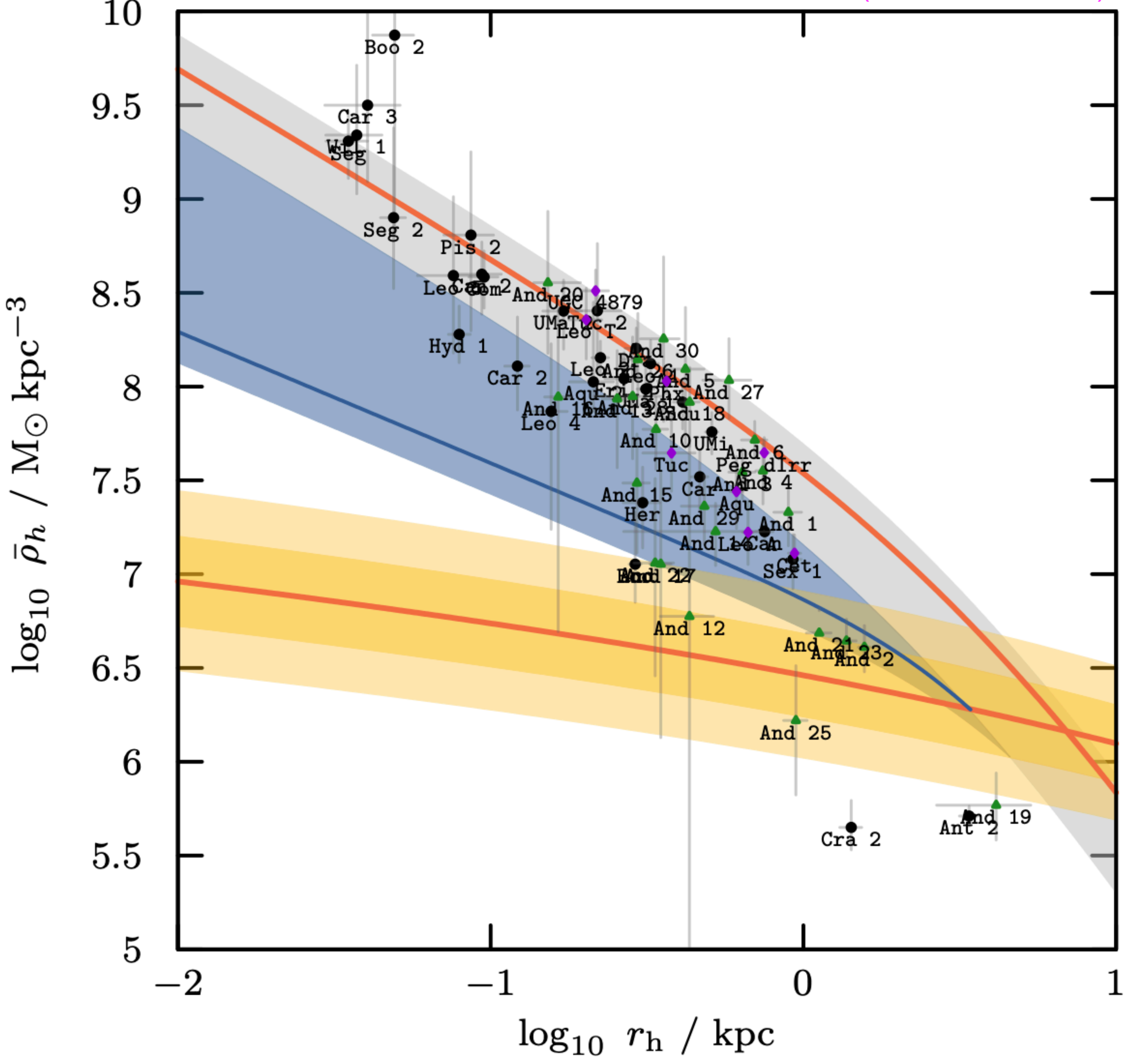


Probe 2: Dwarf Profiles

Hayashi et al. 2020 (2007.13780)



Errani et al. 2022 (2111.05866)

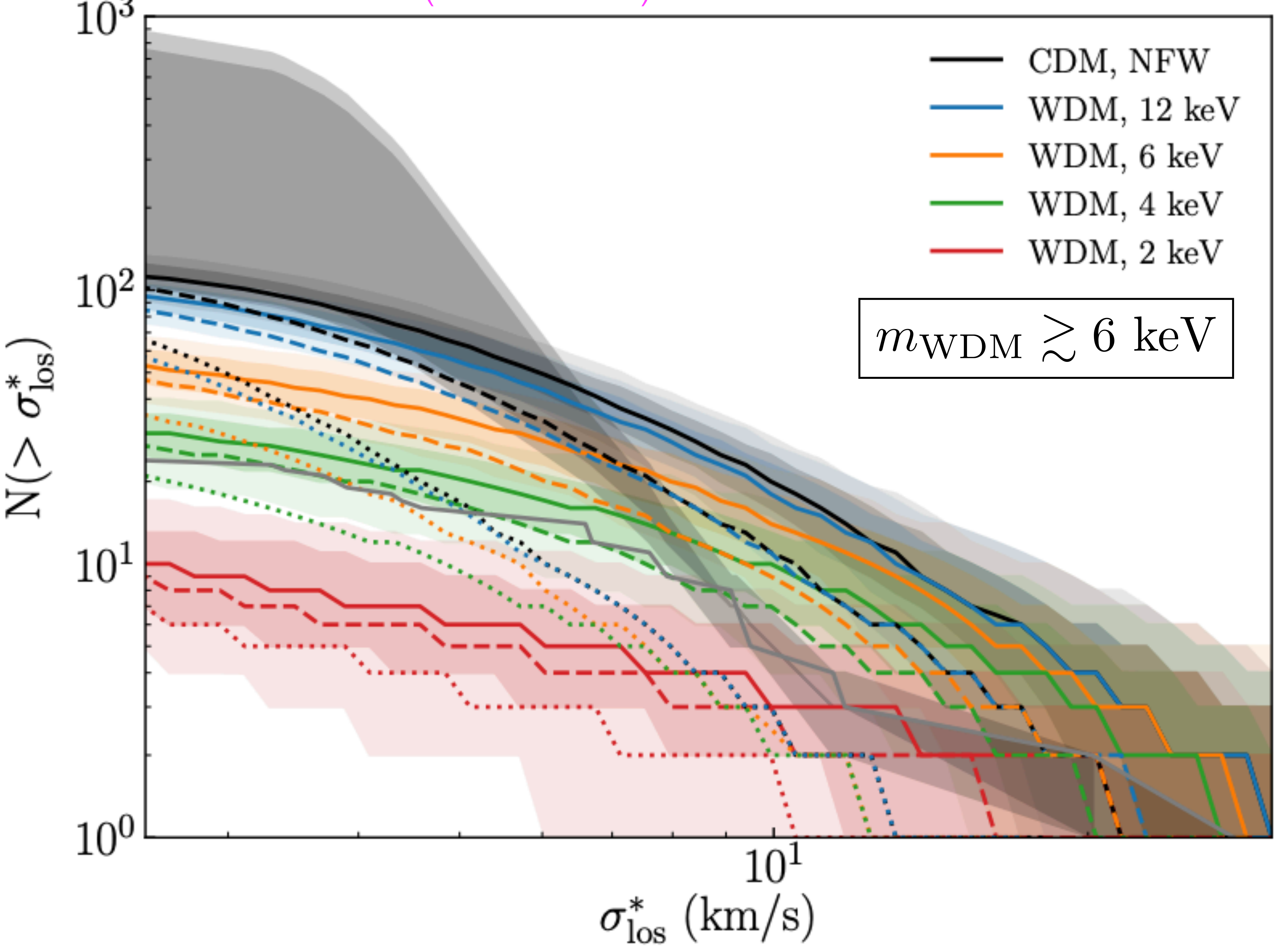


Measurements of faint dwarfs' inner density profile slopes probe physics beyond CDM

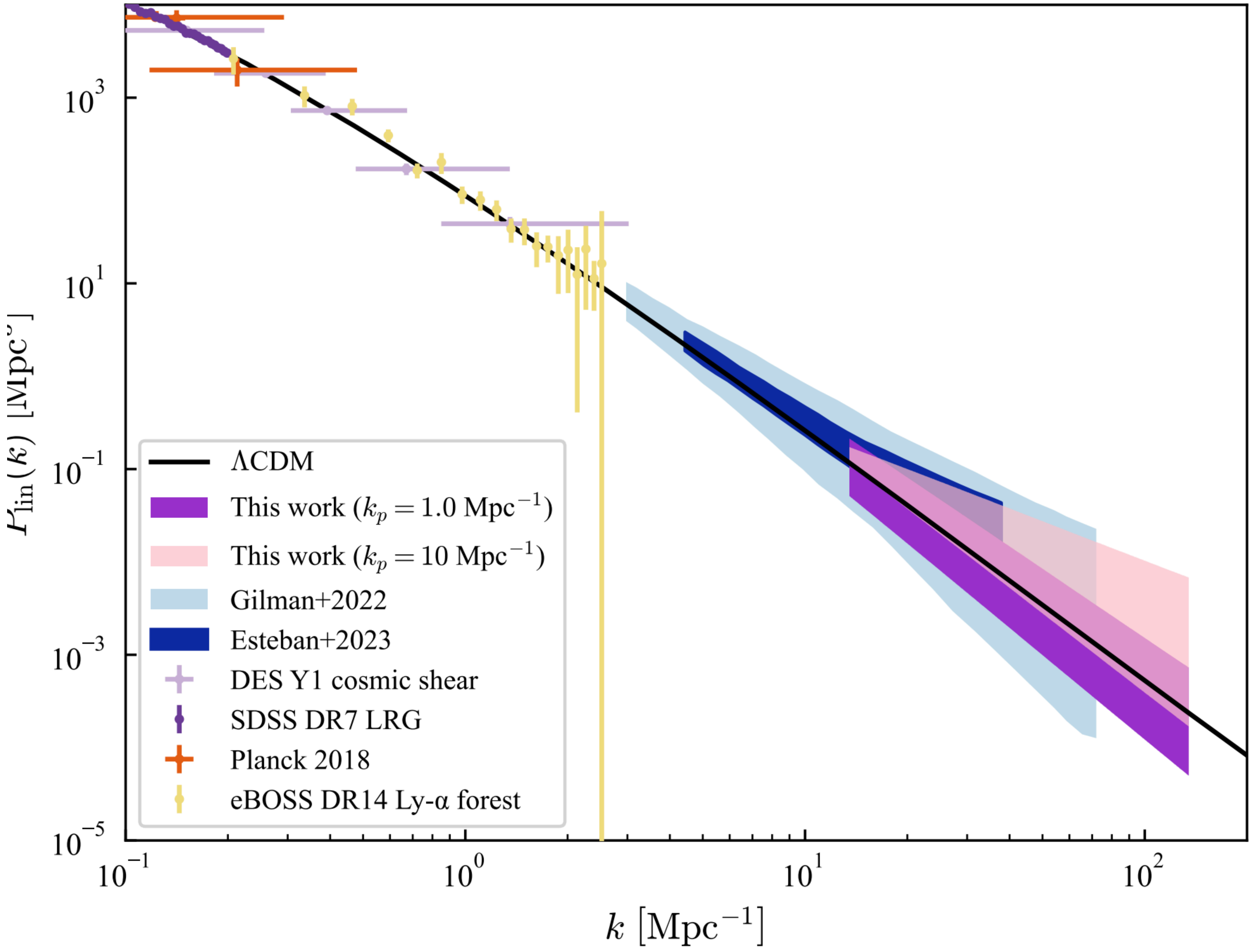
For many systems, we only have a velocity dispersion measurement in the inner regions

Dwarf Profiles: Bounds on *Ab Initio* DM Physics

Kim et al. 2021 (2106.09050)



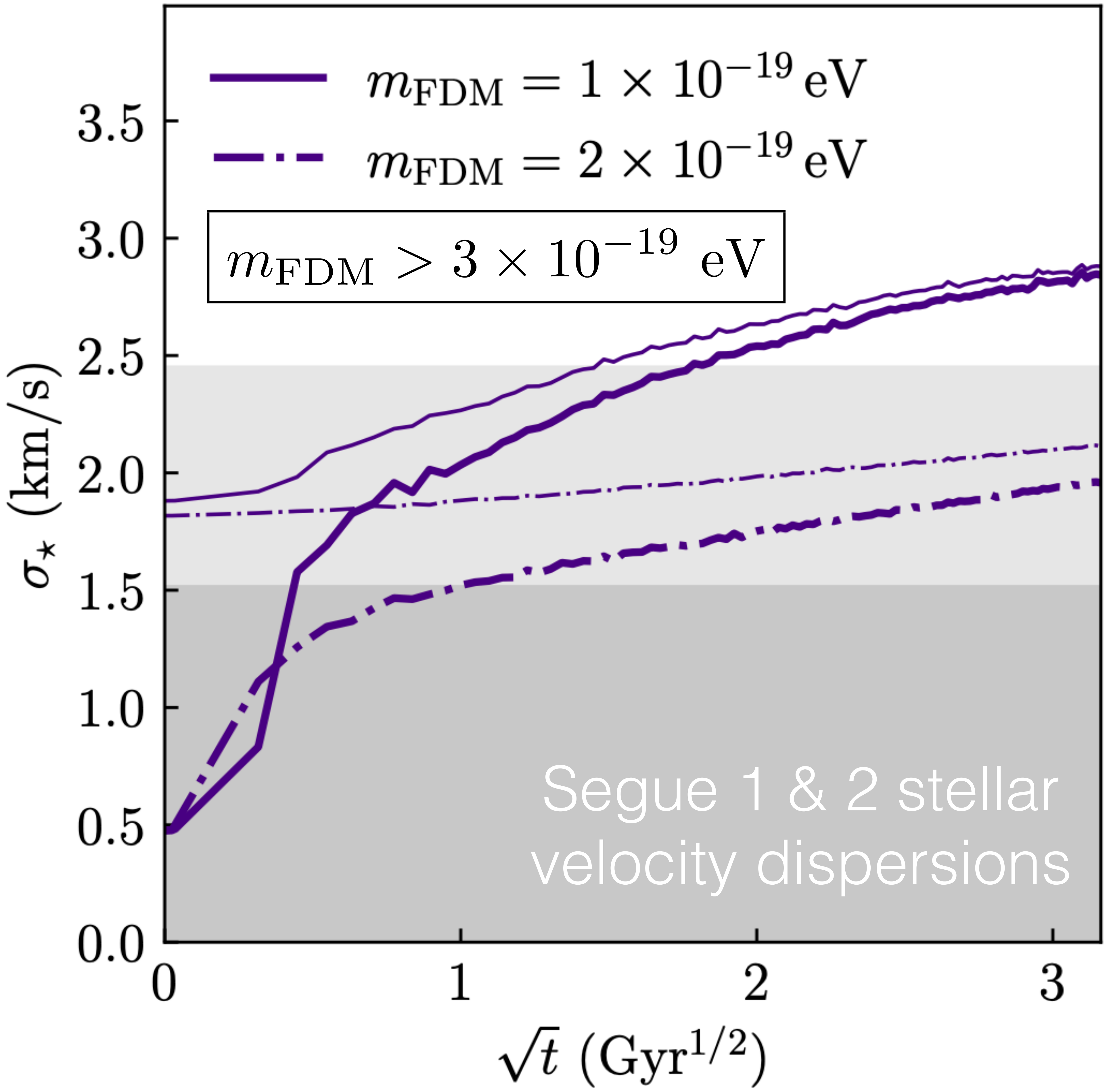
Dekker & Kravtsov 2024 (2407.04198)

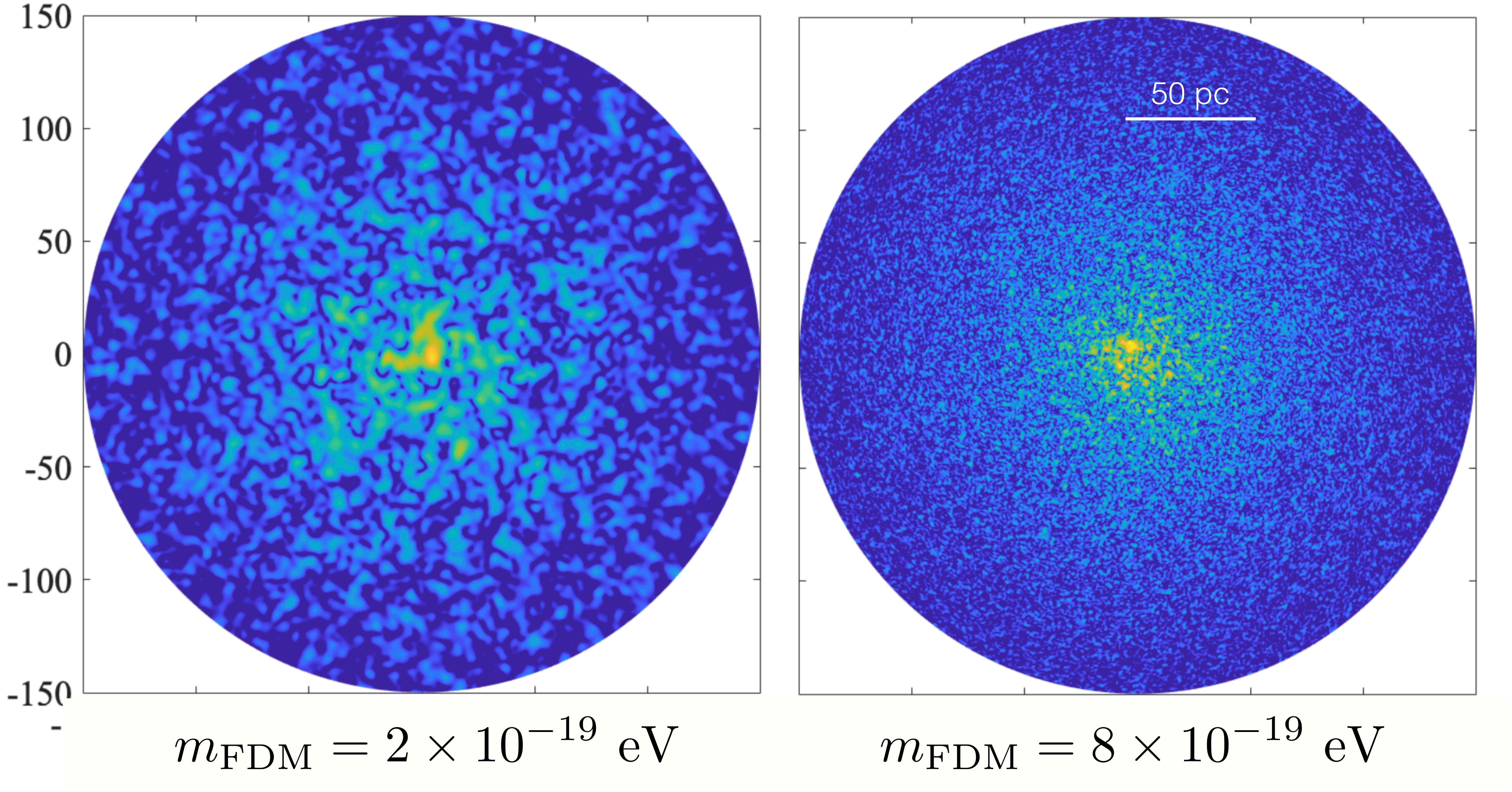


- Changes to *P(k)* affect halo formation times/concentrations, systematically altering velocity dispersions
- This mechanism can be used to constrain both suppressed and enhanced linear matter power spectra

Dwarf Profiles: Bounds on Fuzzy DM

Dalal & Kravtsov 2022 (2203.05750)





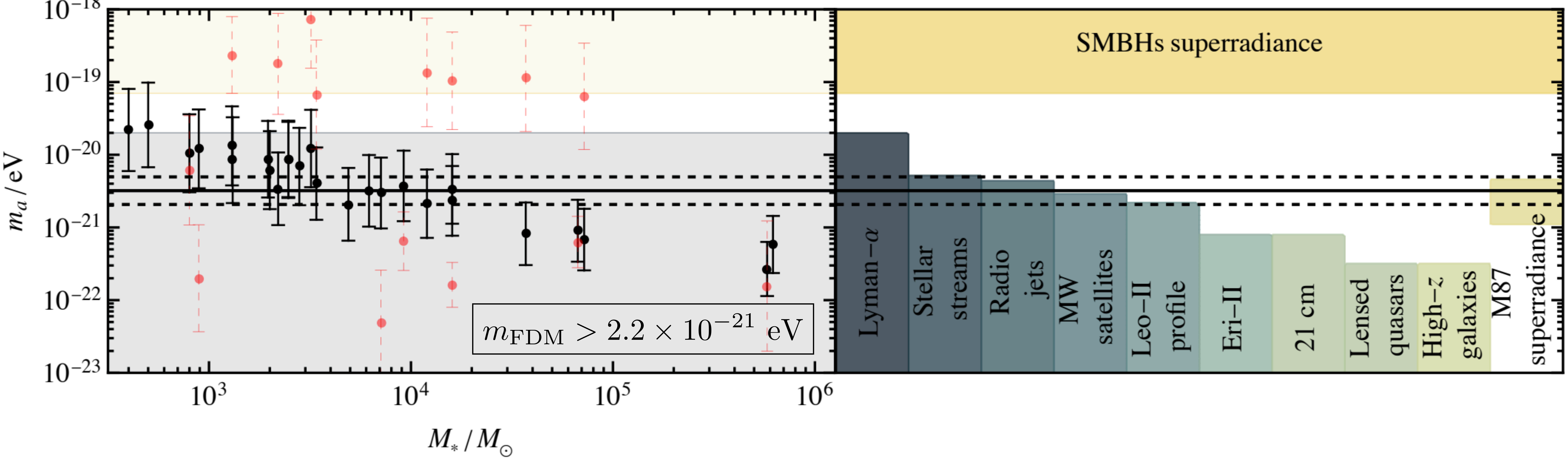
$m_{\rm FDM} = 2 \times 10^{-19}$ eV

$m_{\rm FDM} = 8 \times 10^{-19}$ eV

- Fluctuations in fuzzy DM field heat stars in ultra-faint dwarf galaxies, increasing velocity dispersion
- Fuzzy DM bound from Segue 1 & 2 velocity dispersions + sizes is among the strongest in the literature

Dwarf Profiles: Bounds on Fuzzy DM

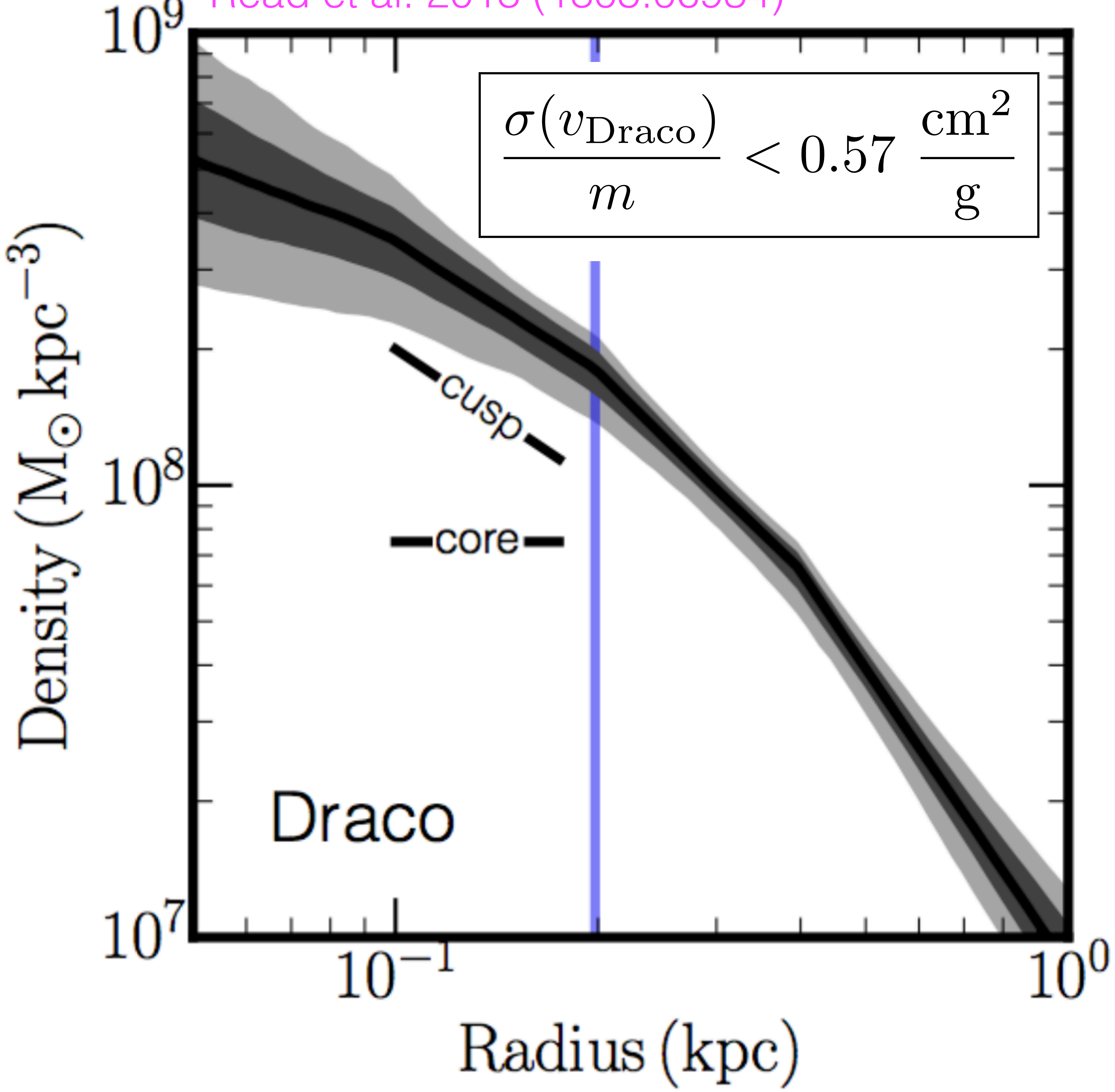
Benito et al. 2025 (2502.12030); also see Hayashi et al. 2021 (2102.05300), Zimmerman et al. 2024 (2405.20374)



- Fuzzy DM predicts larger cores in smaller dwarfs, inconsistent with observed dwarfs' core size scaling
- UFD profiles place strong constraints on the fuzzy DM mass, comparable to structure formation limits

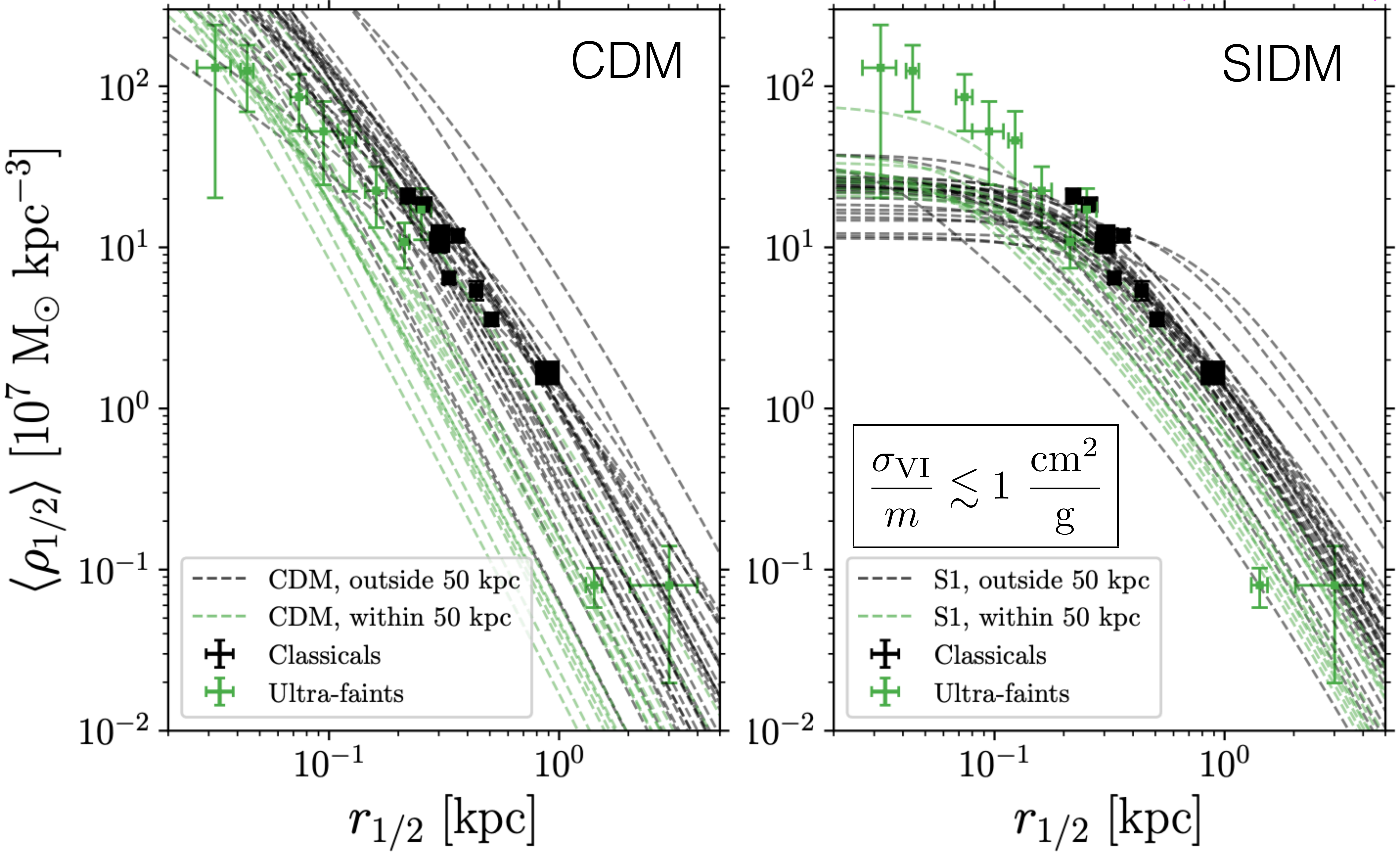
Dwarf Profiles: Bounds on SIDM

Read et al. 2018 (1805.06934)



Cuspy profiles of bright, quiescent dwarfs limit SIDM cross section at specific velocities

Silverman et al. 2022 (2203.10104)



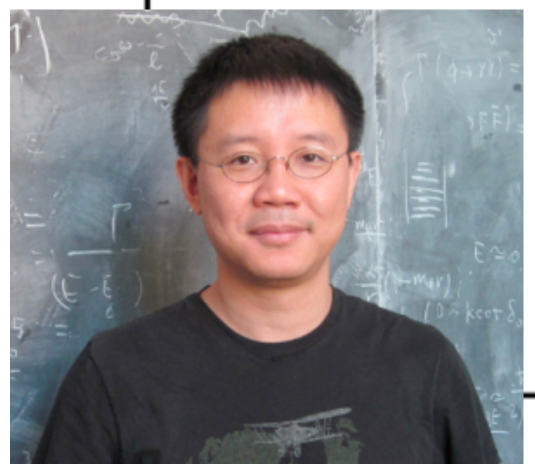
Population analysis limits velocity-independent SIDM cross section over dwarf velocity range

Dwarf Profiles: Strong, Velocity-dependent SIDM

Yang & Yu 2022 (2205.03392)

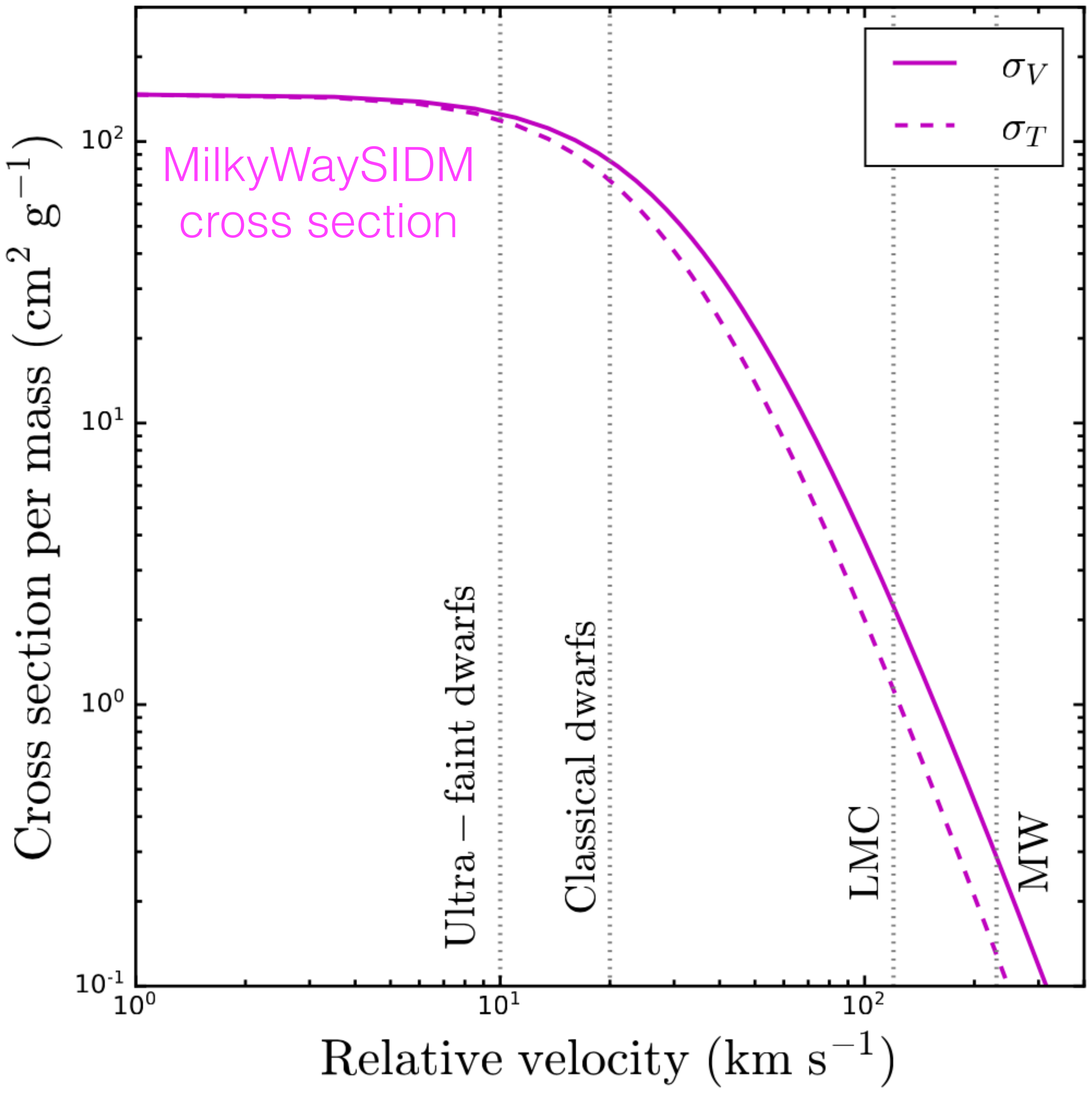
Also see Correa 2021 (2007.02958), Turner et al. 2021 (2010.02924)

Daneng Yang
(UCR)



Haibo Yu
(UCR)

Yang, EN, Yu 2023 (2211.13768)

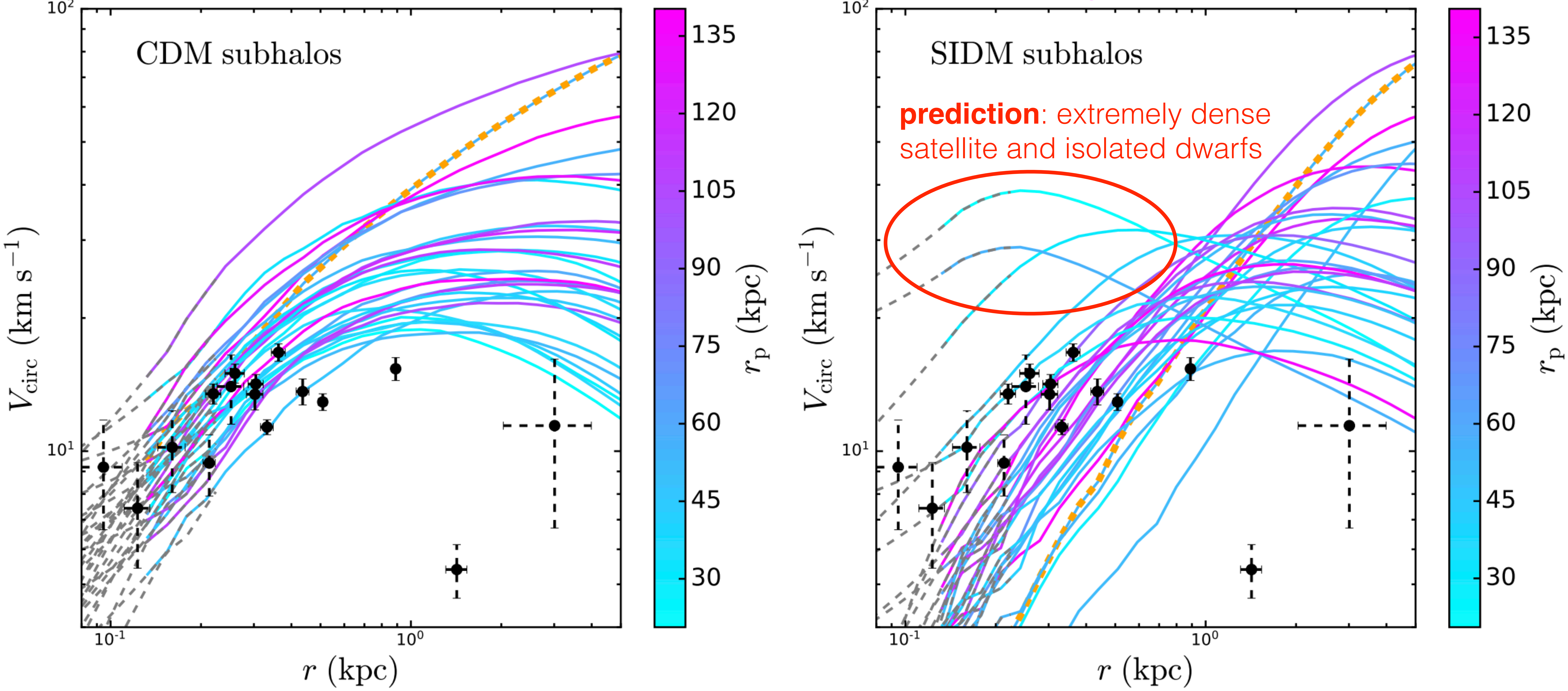


MilkyWaySIDM cross section

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

Dwarf Profiles: Strong, Velocity-dependent SIDM

Yang, EN, Yu 2023 (2211.13768)

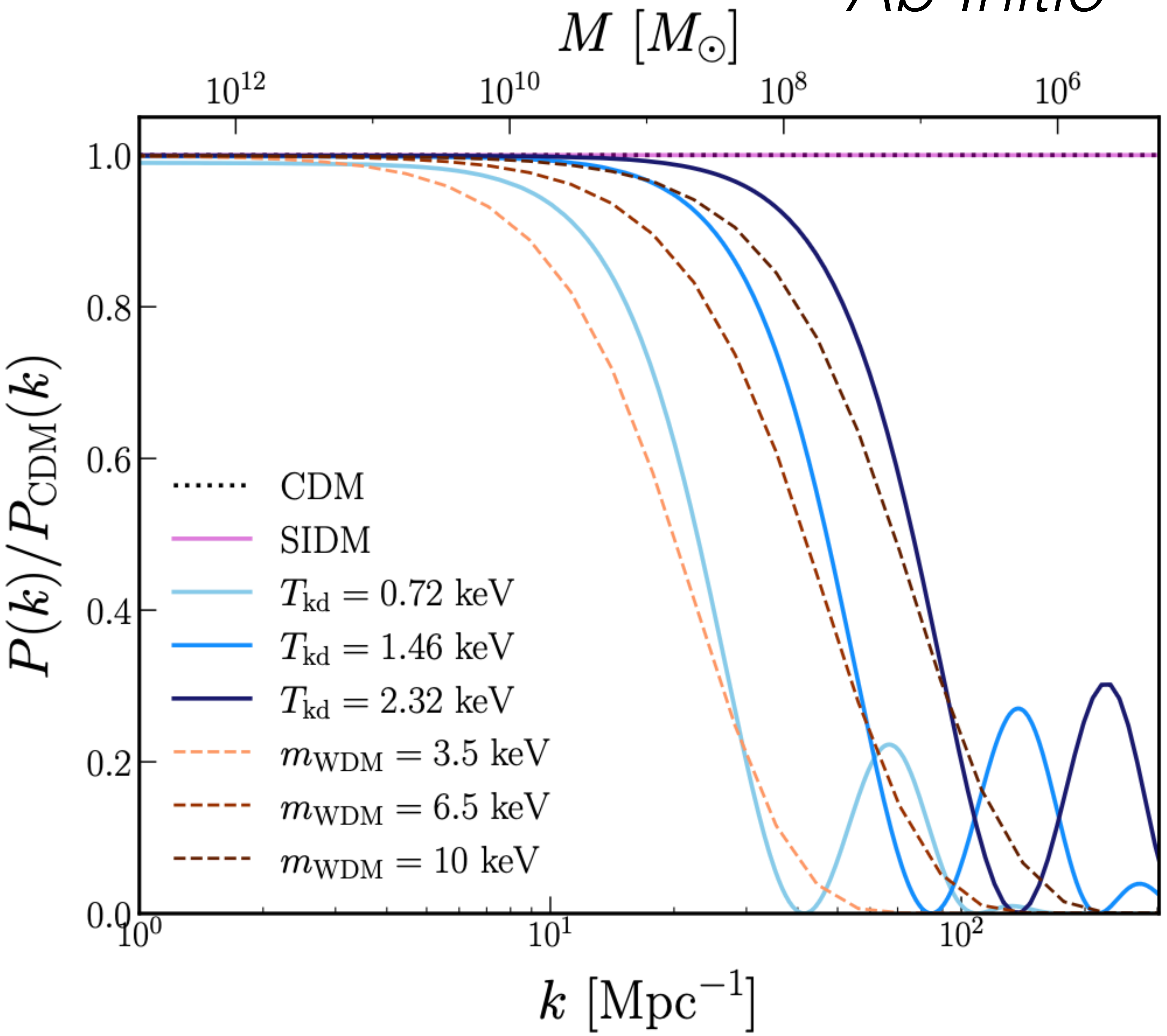


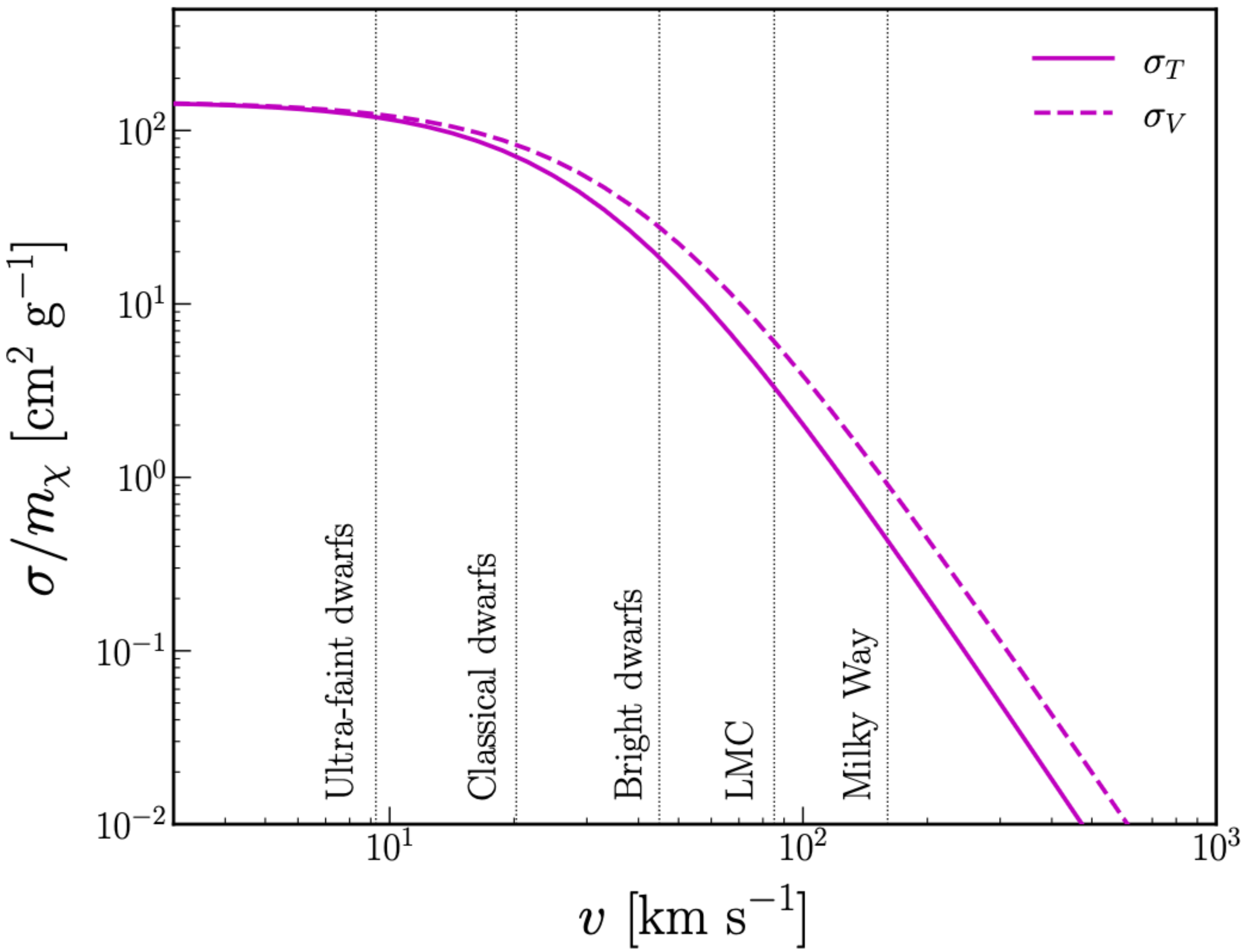
prediction: extremely dense satellite and isolated dwarfs

MilkyWaySIDM predicts diverse subhalo profiles; mass, concentration, orbit influence gravothermal evolution

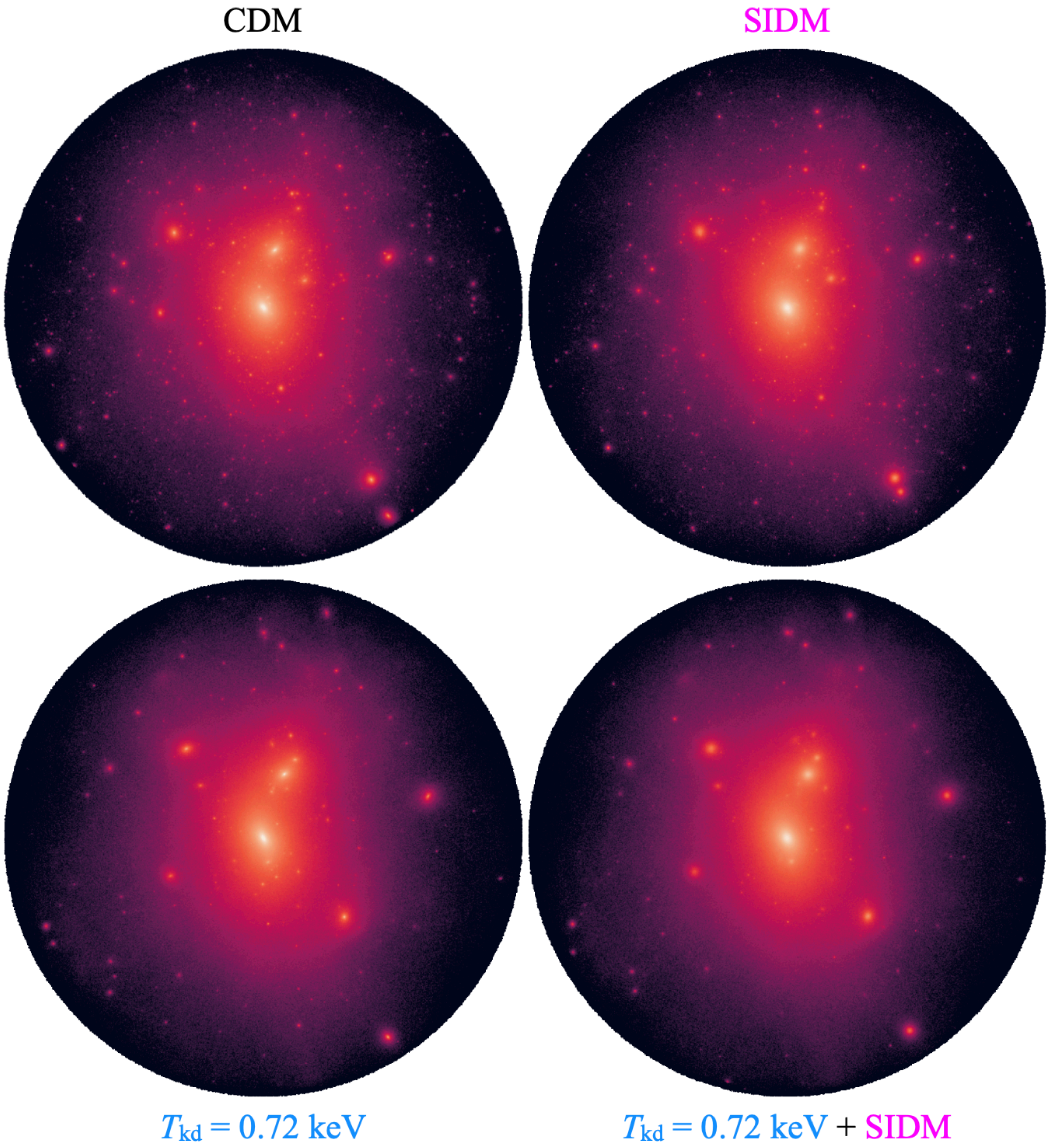
COZMIC III: SIDM with Consistent Initial Conditions

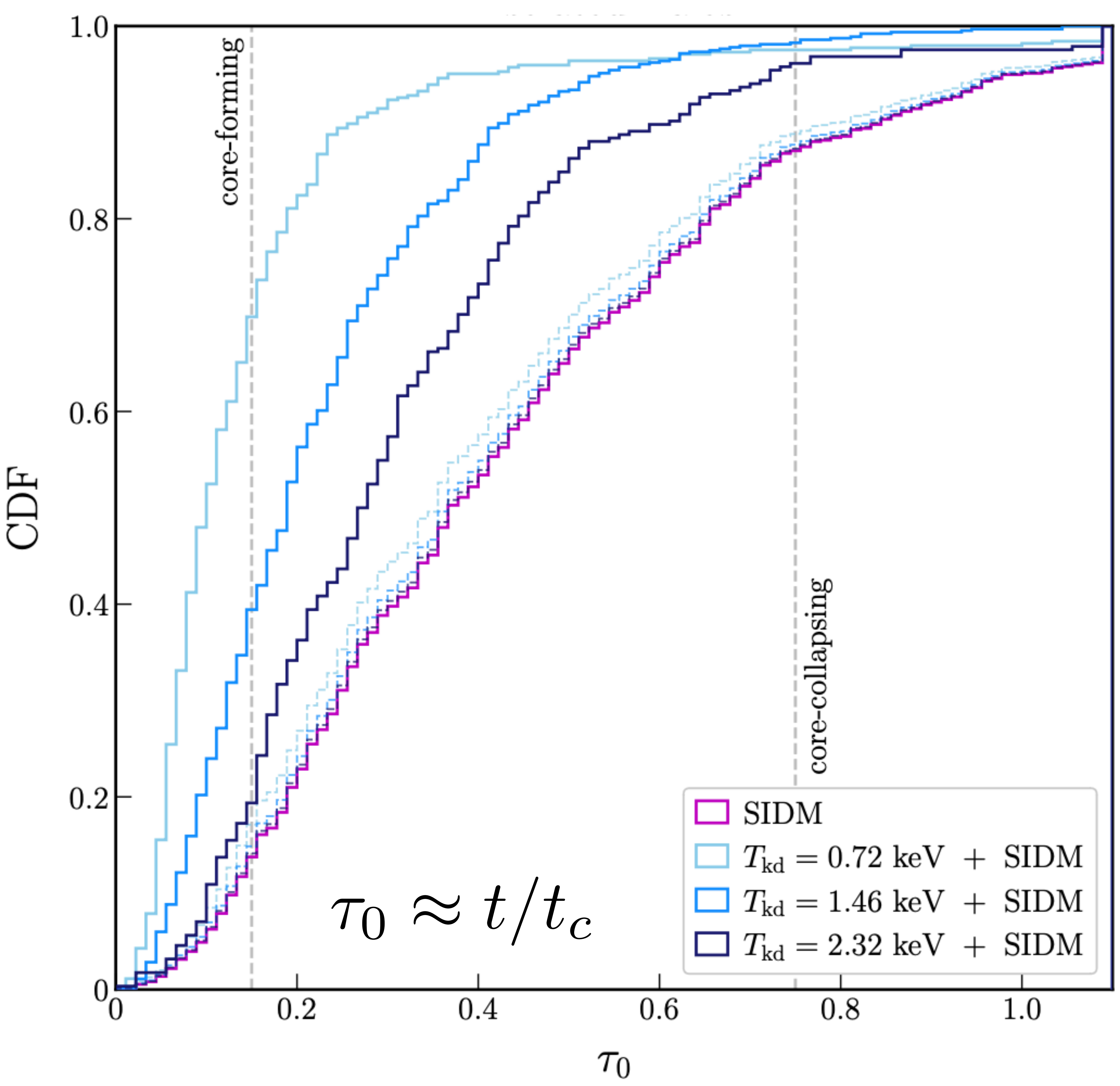
Ab Initio 🤝 *In Situ*




EN et al. 2024 (2412.13065)

8 Milky Way zoom-ins with initial conditions determined by velocity-dependent SIDM interaction mediator



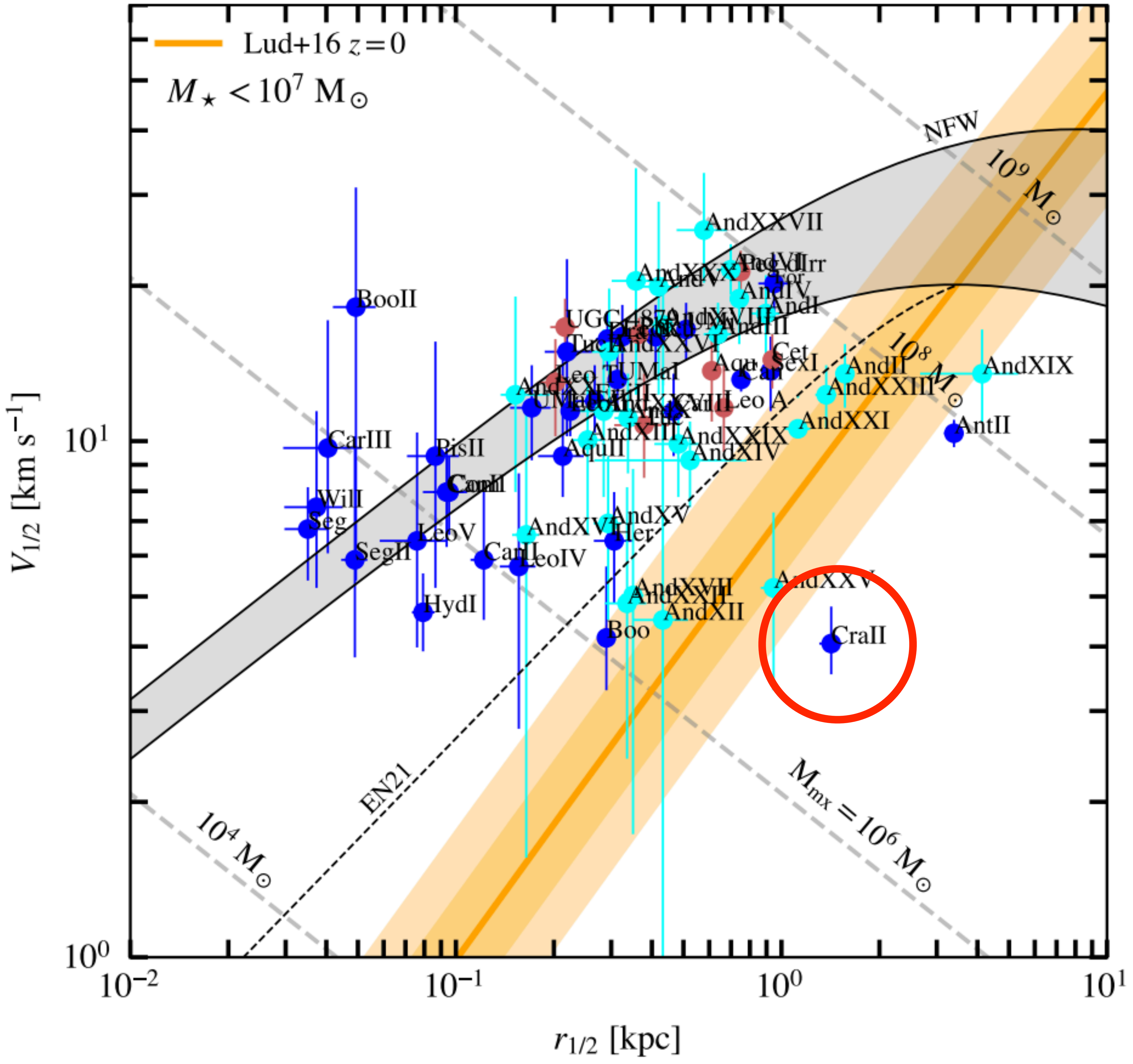


- ***P(k)* suppression reduces core-collapse**
- Two effects: delayed growth and erasure of low-mass halos

EN et al. 2024 (2412.13065)

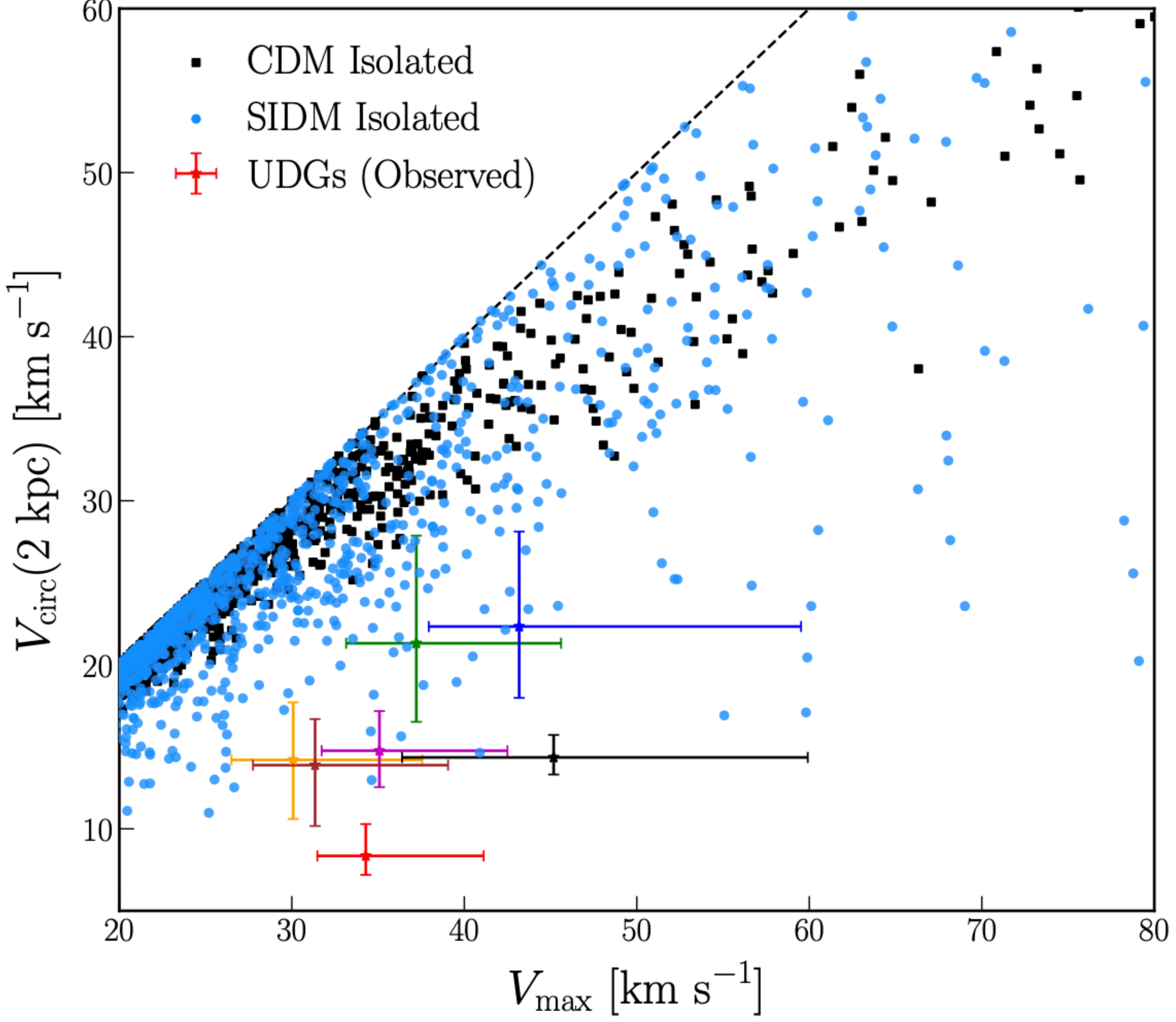
Dwarf Profiles: Puzzles in Existing Data

Borukhovetskaya et al. 2022 (2112.01540)



Crater II size and kinematics are difficult to explain through tidal stripping in CDM

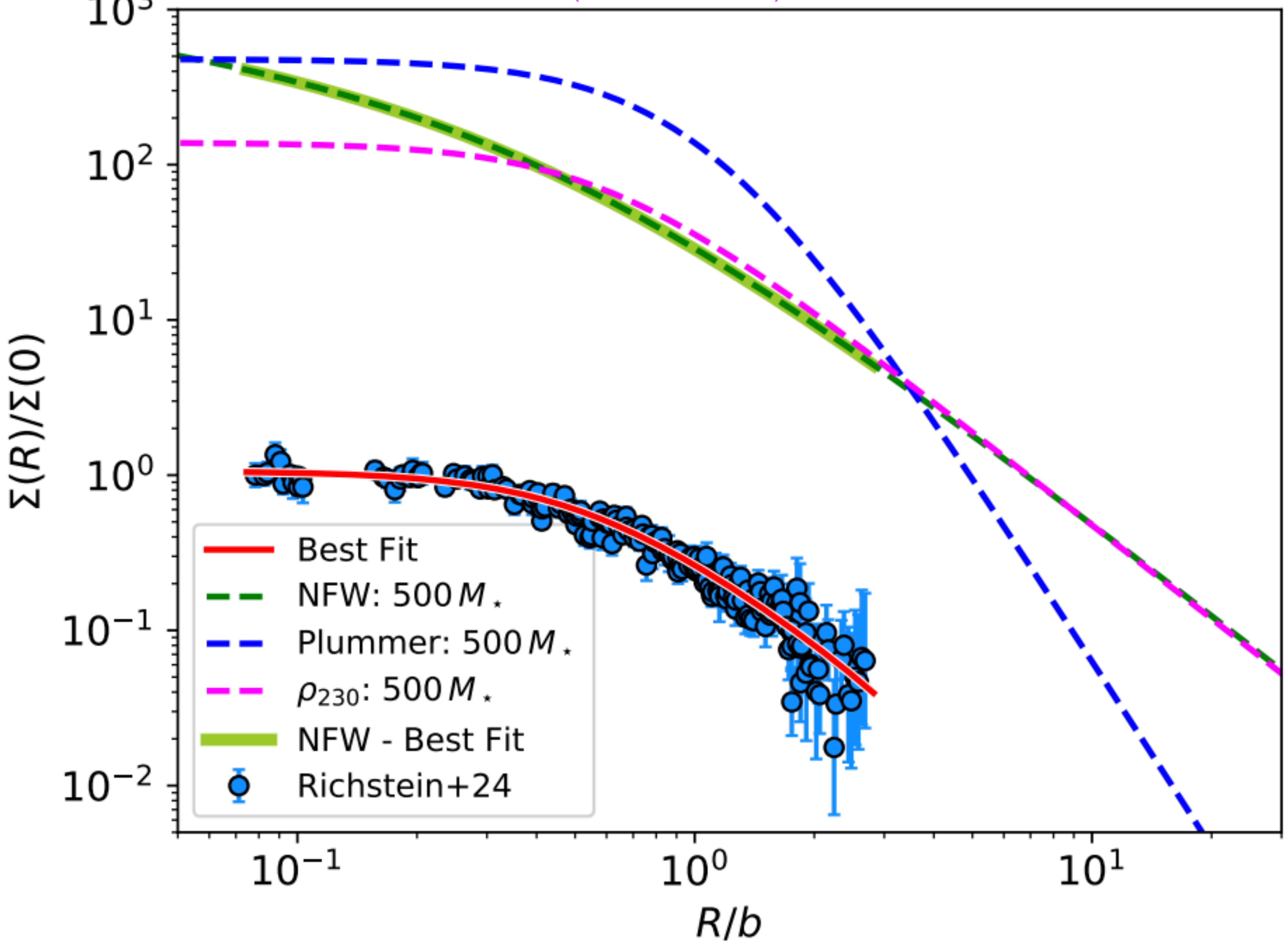
EN, Yang, Yu 2023 (2306.01830)

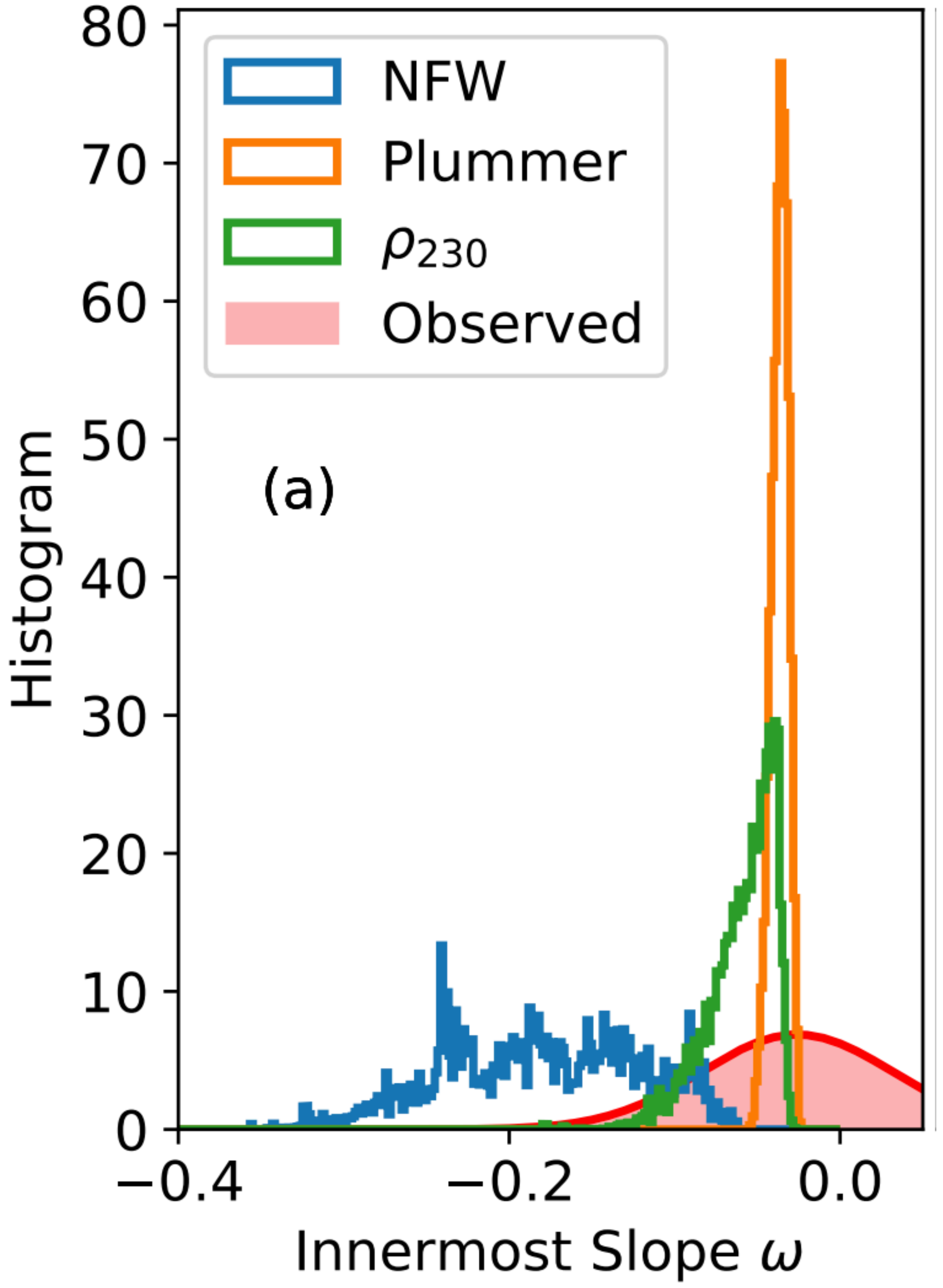


Isolated gas-rich ultra-diffuse dwarfs are rare in CDM; can be produced in SIDM

Dwarf Profiles: Puzzles in Existing Data

Sánchez Almeida 2024 (2407.16755)

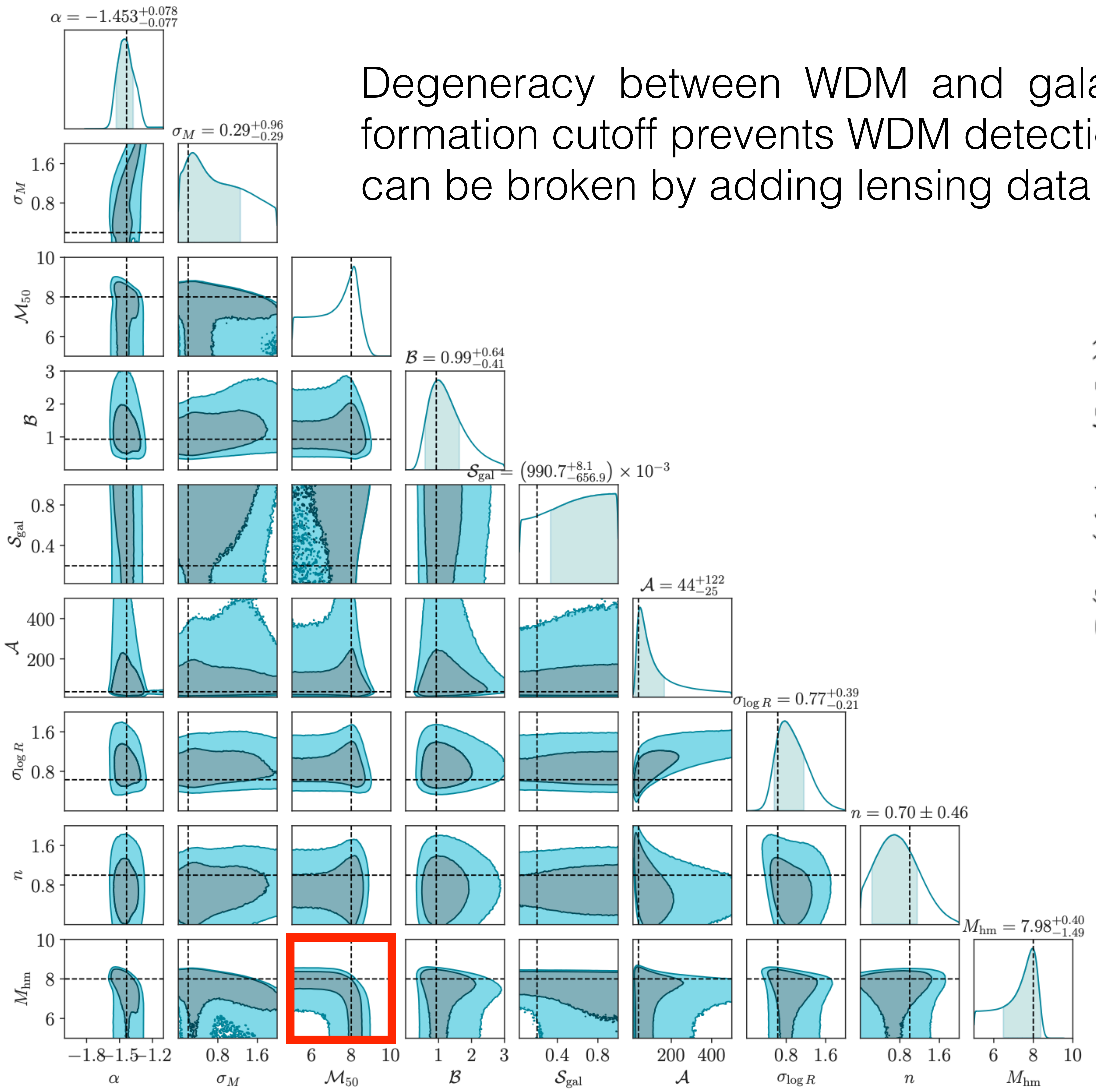


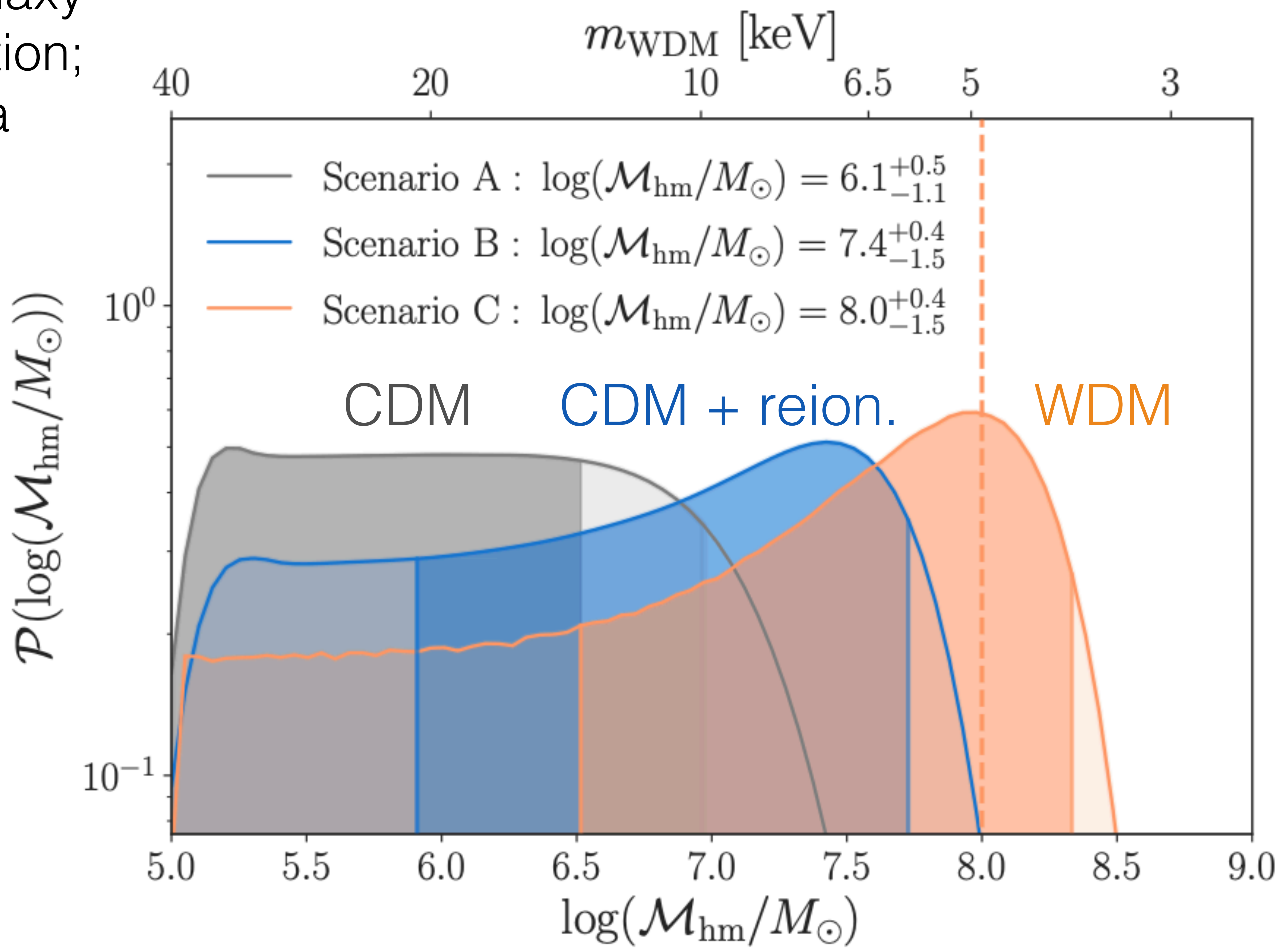


- Several UFDs have universal stellar surface density profiles that suggest cored inner dark matter profiles
- Too faint to be cored by feedback; DM profile inferred by Eddington inversion with no velocity anisotropy

Looking Forward: Warm Dark Matter Forecsasts

Degeneracy between WDM and galaxy formation cutoff prevents WDM detection; can be broken by adding lensing data

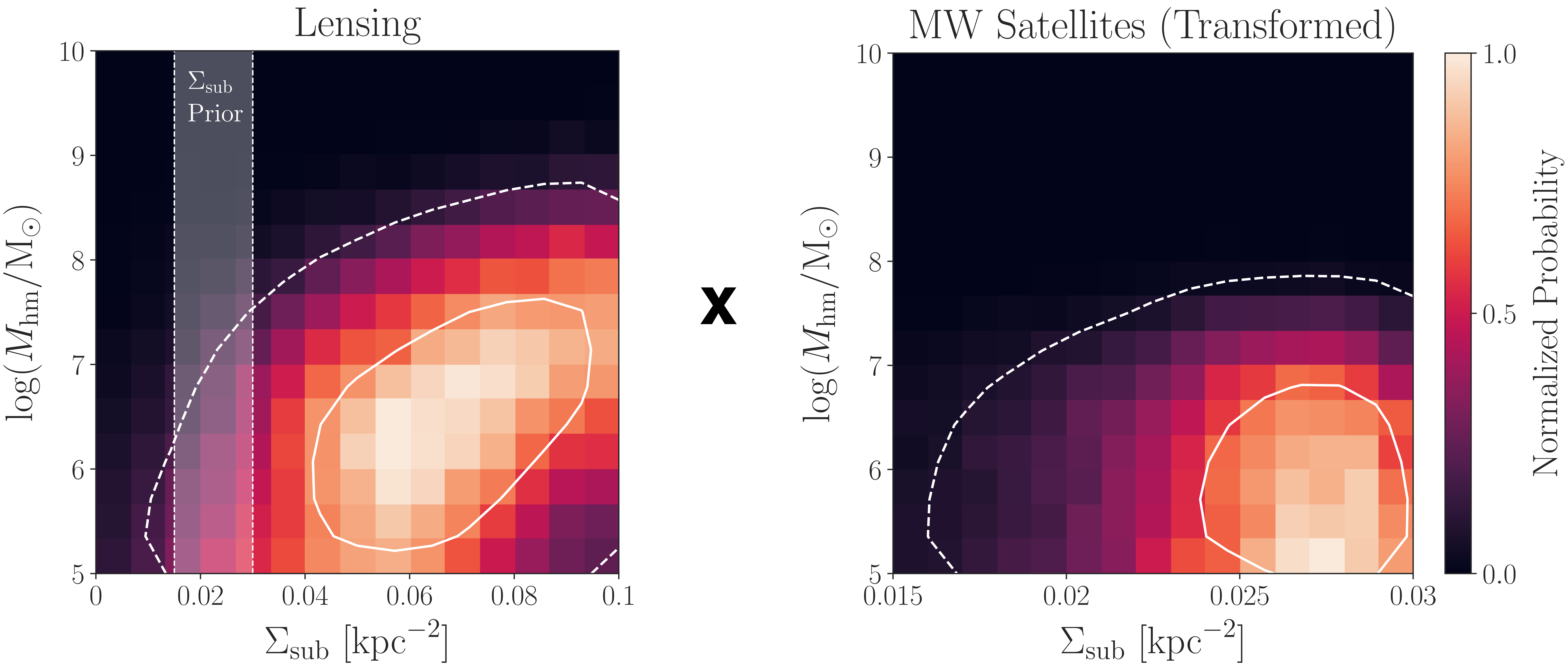




Two complete satellite populations probe ~**20 keV** WDM, or *P(k)* suppression of ~10% at *k* ~ 50 Mpc^{-1}

EN et al. 2024 (2401.10318)

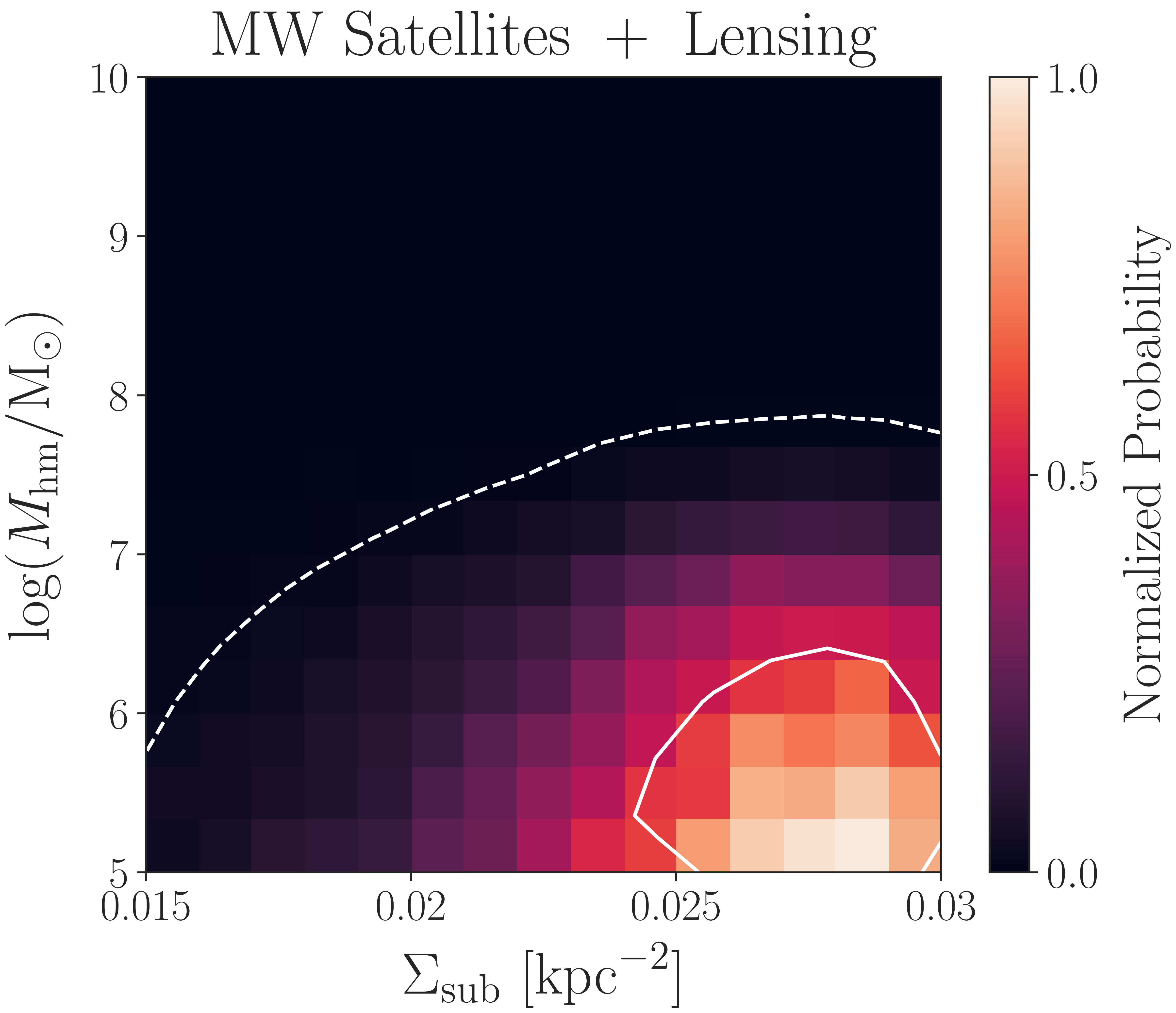
Looking Forward: Probe Combination



EN, et al. 2021 (2101.07810); also see Enzi et al. 2021 (2010.13802)

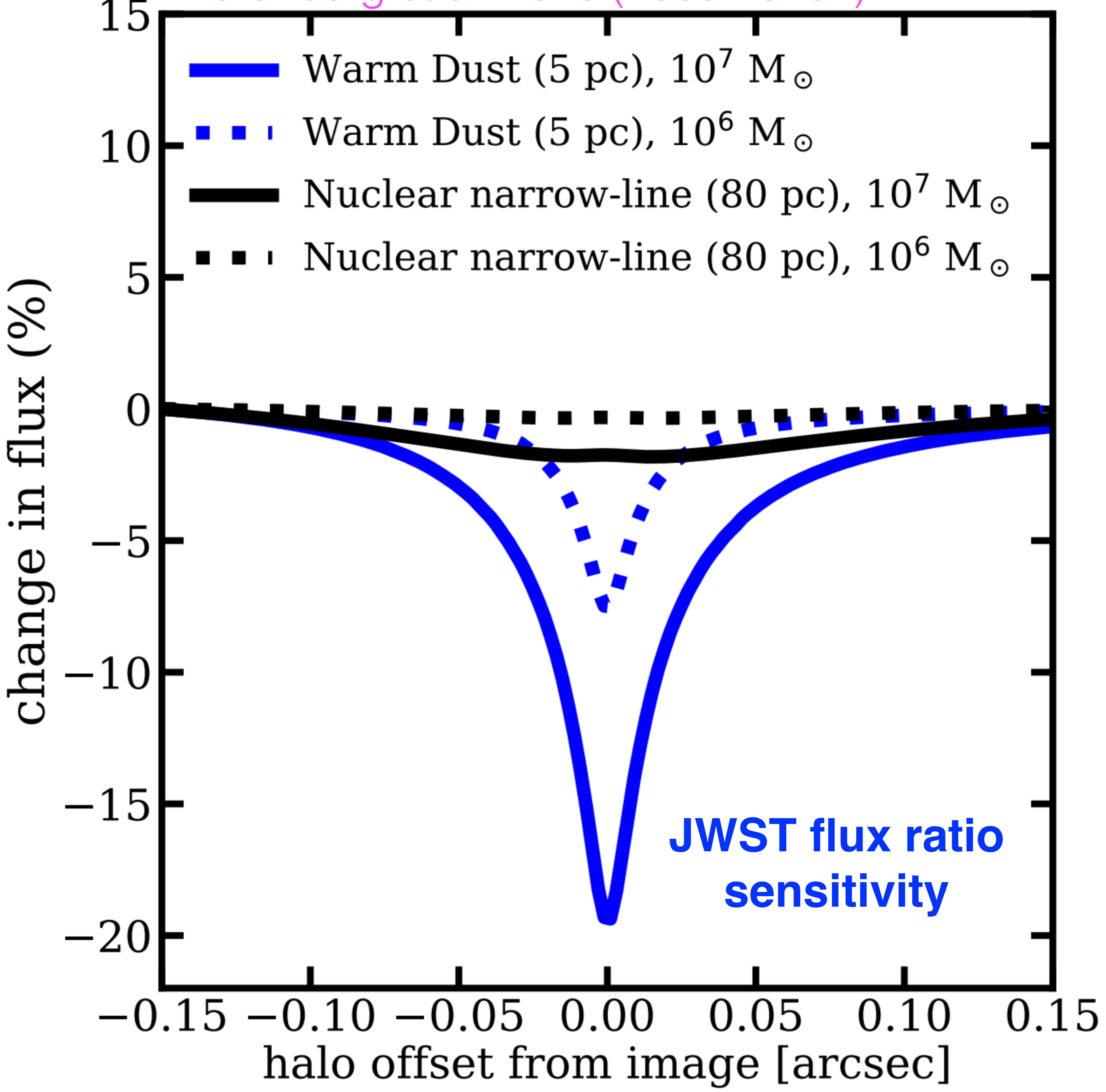
Looking Forward: Probe Combination

- Combining flux ratios and Milky Way satellite galaxies yields **$m_{\mathrm{WDM}} > 9.7$ keV** (95% CL)
- Joint analysis places strongest constraint on linear matter power spectrum cutoff to date
- Unified inference framework will be needed to infer the existence of galaxy-free halos



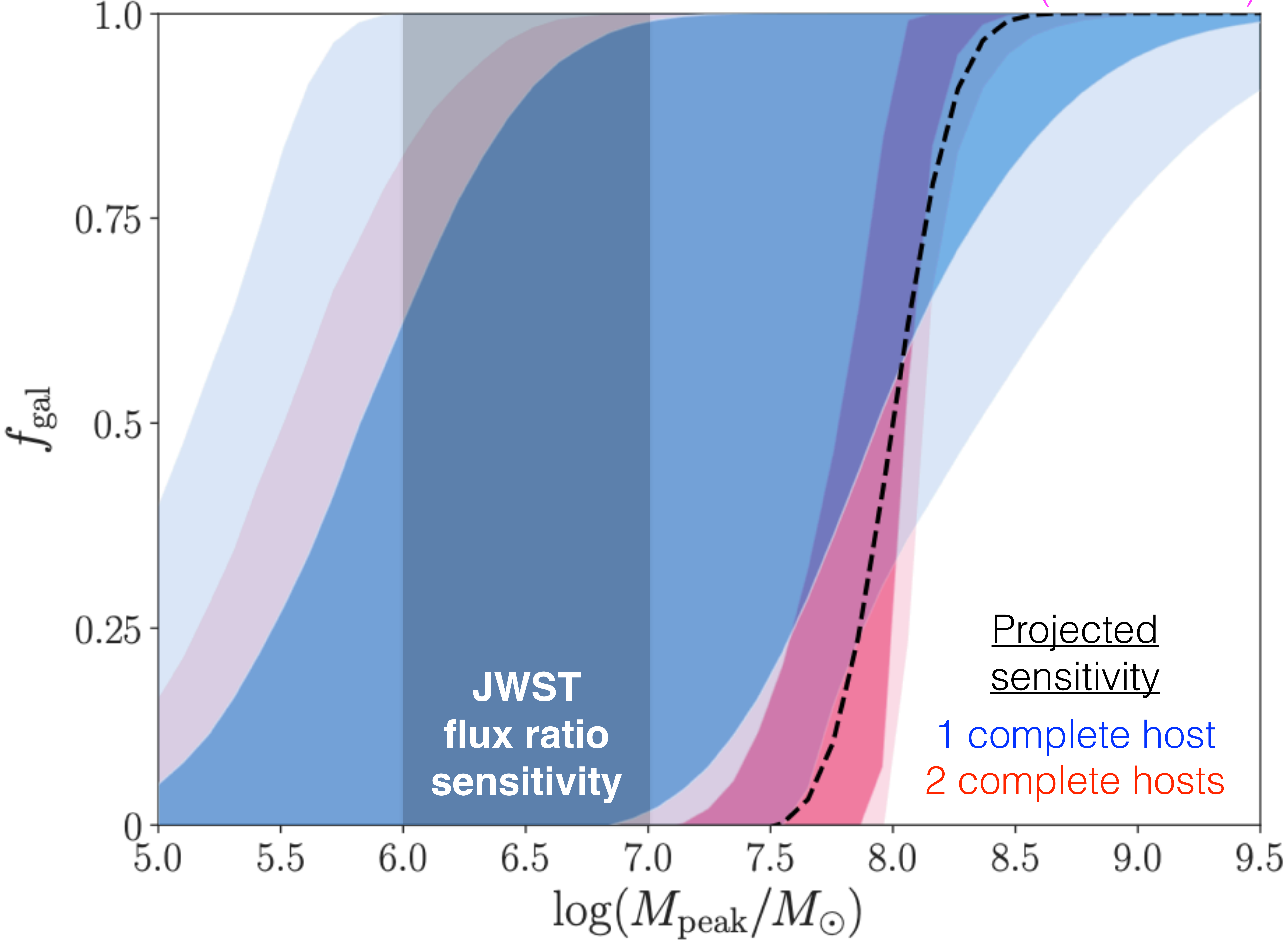
EN, et al. 2021 (2101.07810); also see Enzi et al. 2021 (2010.13802)

Looking Forward: Probe Combination



Nierenberg et al. 2023 (2309.10101)

JWST flux ratio sensitivity



EN et al. 2024 (2401.10318)

JWST flux ratio sensitivity

Projected sensitivity

1 complete host

2 complete hosts

- Strong lensing is becoming sensitive to (sub)halos well below the galaxy formation threshold
- Combining upcoming lensing and dwarf data will probe dark halos, testing DM in a new regime

- Dwarf galaxies are a critical test of dark matter physics
- Key areas for modeling work:
  - Luminosity function constraints on *in situ* DM physics
  - Dwarf profile constraints on velocity-dependent SIDM
  - Joint analysis of satellite and isolated dwarfs within and beyond Milky Way
- Moving from *constraints* to *discovery* will require combining dwarf galaxy data with complementary small-scale probes (Lyman-α, strong lensing, streams, high-z UVLF, 21-cm)

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