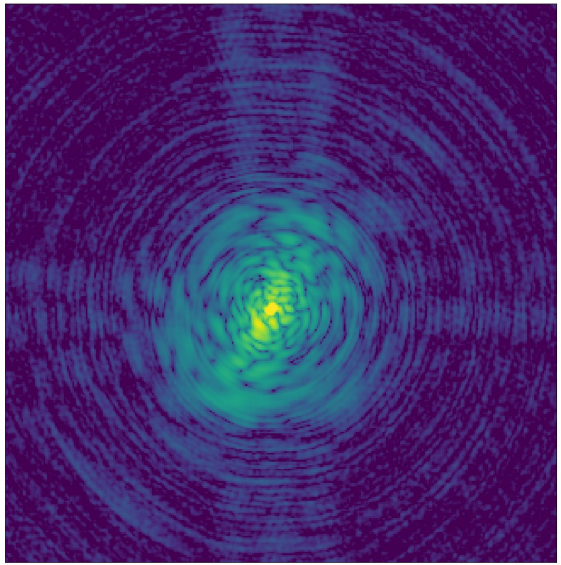
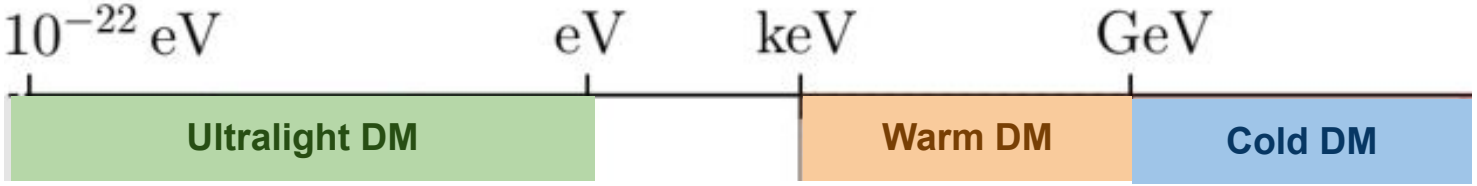
Revisiting the core-halo structure of FDM model

Jowett Chan, Masashi Chiba (Tohoku University),
Hayashi Kohei (Ichinoseki College)
Elisa Ferriera, Simon May (MPA)



Alternative Dark Matter Models

Motivation:
Reproducing CDM on large scale, solving challenges on small scale

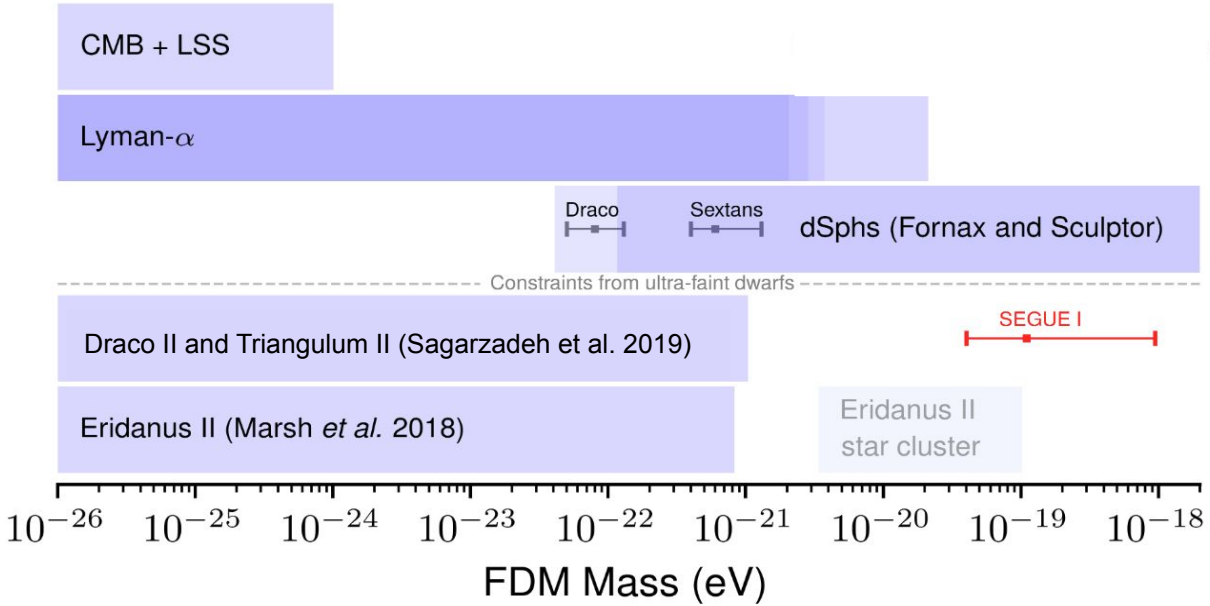


$$\lambda_{\mathrm{db}} = \frac{\hbar}{mv} \rightarrow \lambda_{\mathrm{db}} \sim 1 \text{ kpc} \quad m \sim 10^{-22}\,\mathrm{eV}$$

FDM might solve core-cusp problem and missing satellite

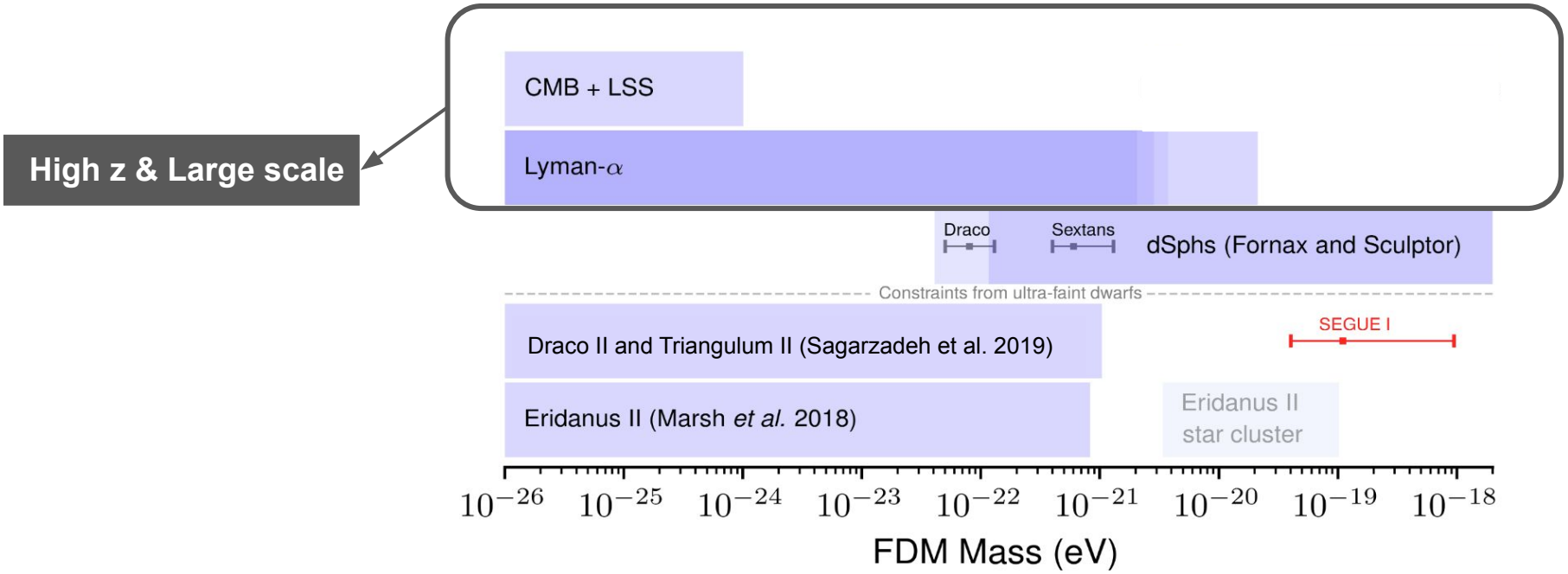
Current Constraints (Excluded Bound)

K. Hayashi, E. Ferreira, J. Chan. 2021



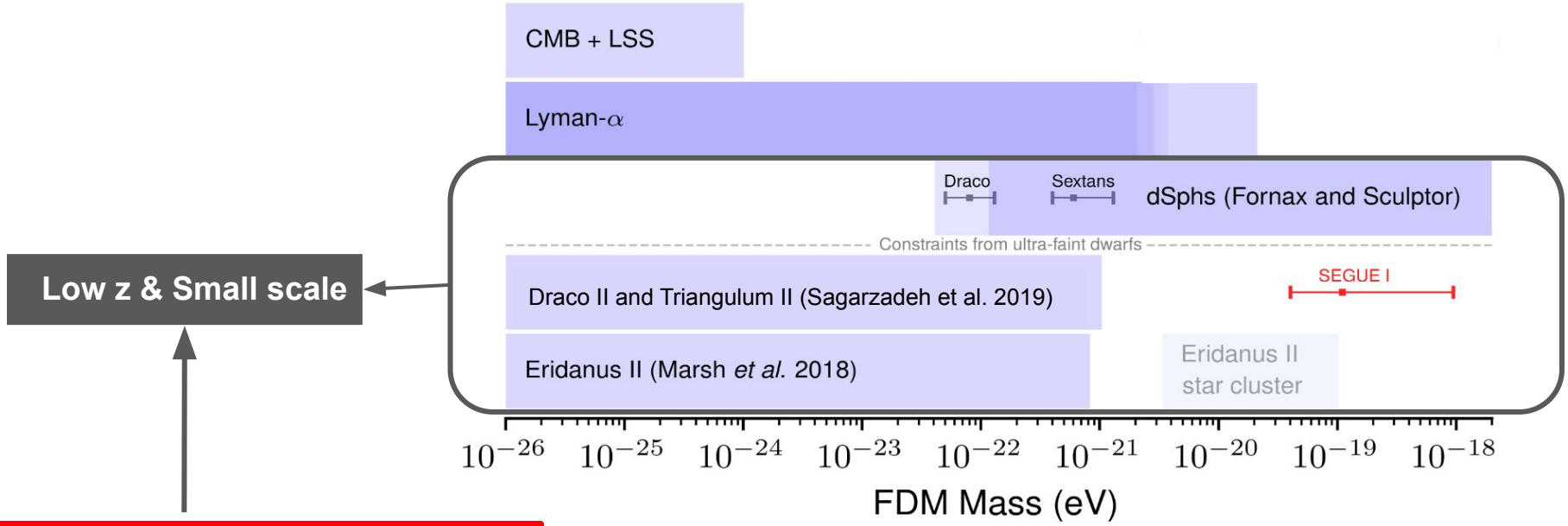
Current Constraints (Excluded Bound)

K. Hayashi, E. Ferreira, J. Chan. 2021



Current Constraints (Excluded Bound)

K. Hayashi, E. Ferreira, J. Chan. 2021



Low z & Small scale

Rely on core-halo structure !

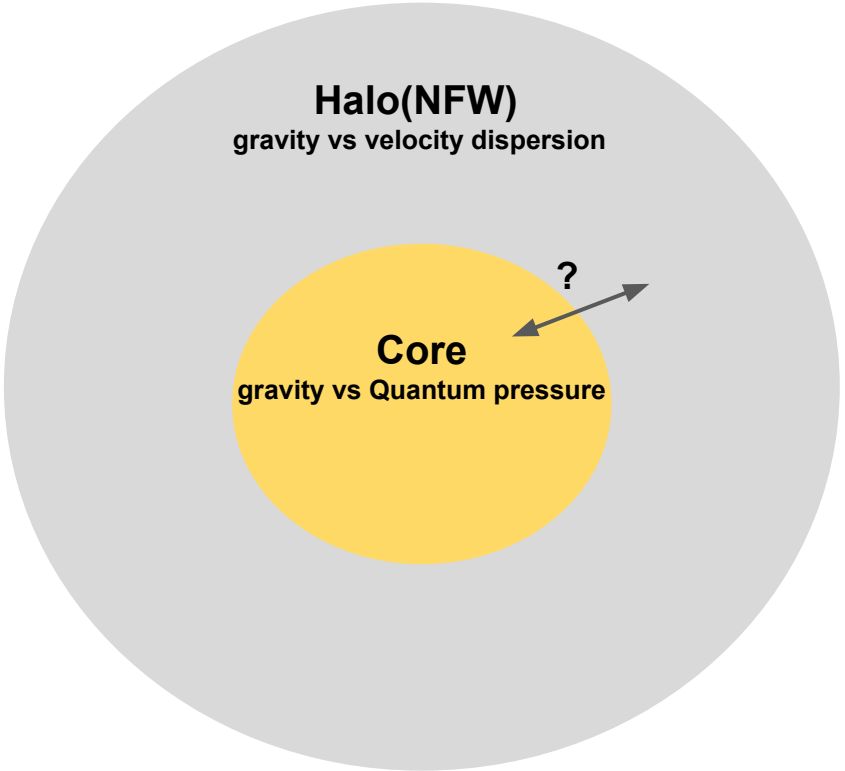
Core-Halo Structure

1) **Density Profile**

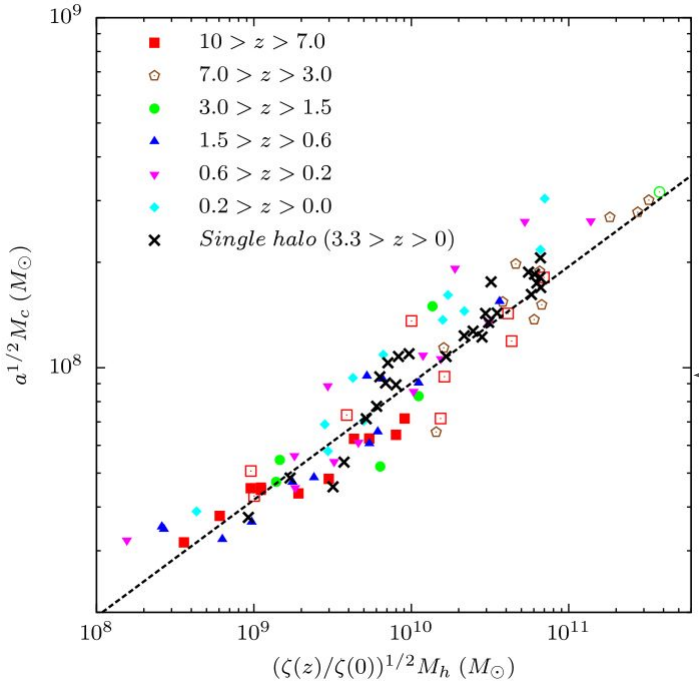
$$\rho = \rho_{\rm core} + \rho_{\rm NFW}$$

2) **Core-halo mass relation**

$$M_{\rm c} \propto M_{\rm h}^{\alpha}$$



Core-Halo Mass Relation



$$M_{\rm c} \propto M_{\rm h}^{\alpha}$$

	α
Mocz+17	0.556
Schive+14	0.333

Velmatt et al. 2018, Nori et al. 2020, Mina et al. 2020

No agreement has been made!

Main Motivation

Is there a universal scaling relation for the core-halo structure ?

Direct comparison with previous studies

Equation of Motion of FDM Model

Schrodinger-Poisson System

$$i\hbar\partial_t\psi = \left[-\frac{\hbar^2}{2ma^2}\nabla^2 + \frac{m\Phi}{a}\right]\psi$$

repulsive attractive

$$\nabla^2\Phi = 4\pi G m|\psi|^2$$

Operator Splitting Spectral Method

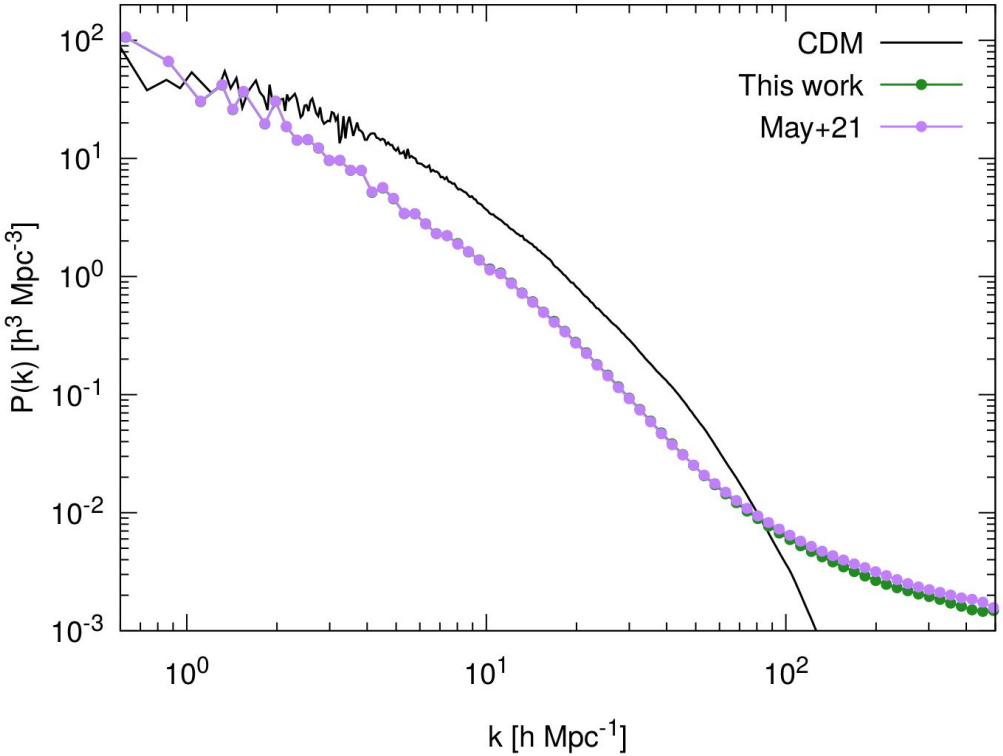
$$\psi^{n+1} \approx e^{i\Phi\Delta t/2}\mathcal{F}^{-1}[e^{ik^2\Delta t}\mathcal{F}[e^{i\Phi\Delta t/2}\psi^n]]$$

3rd 2nd 1st

Timestep critierion

$$\Delta t \sim \Delta x^2$$

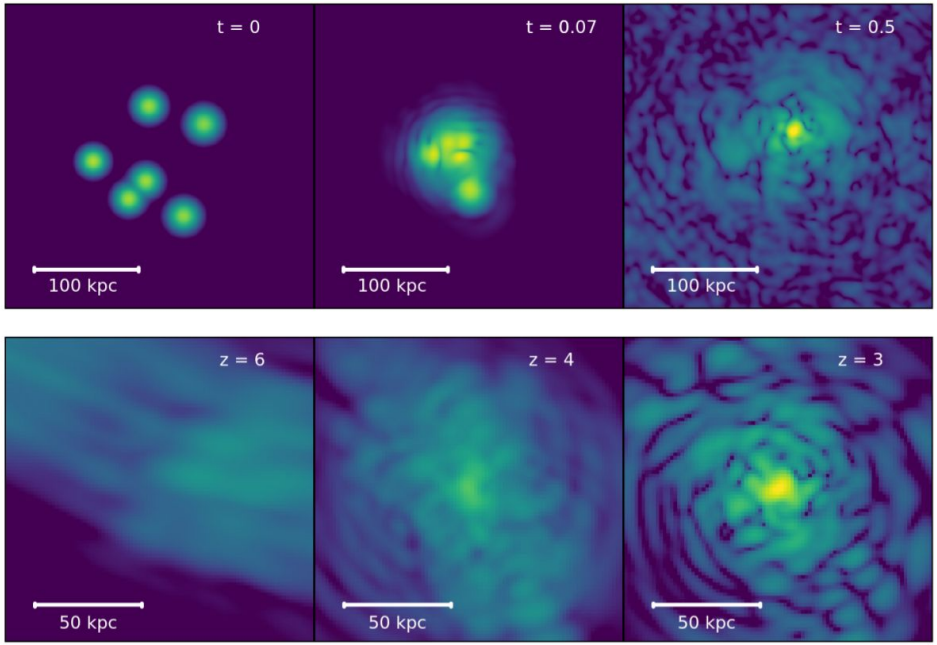
FDM Code Comparison



Simulation Set Up

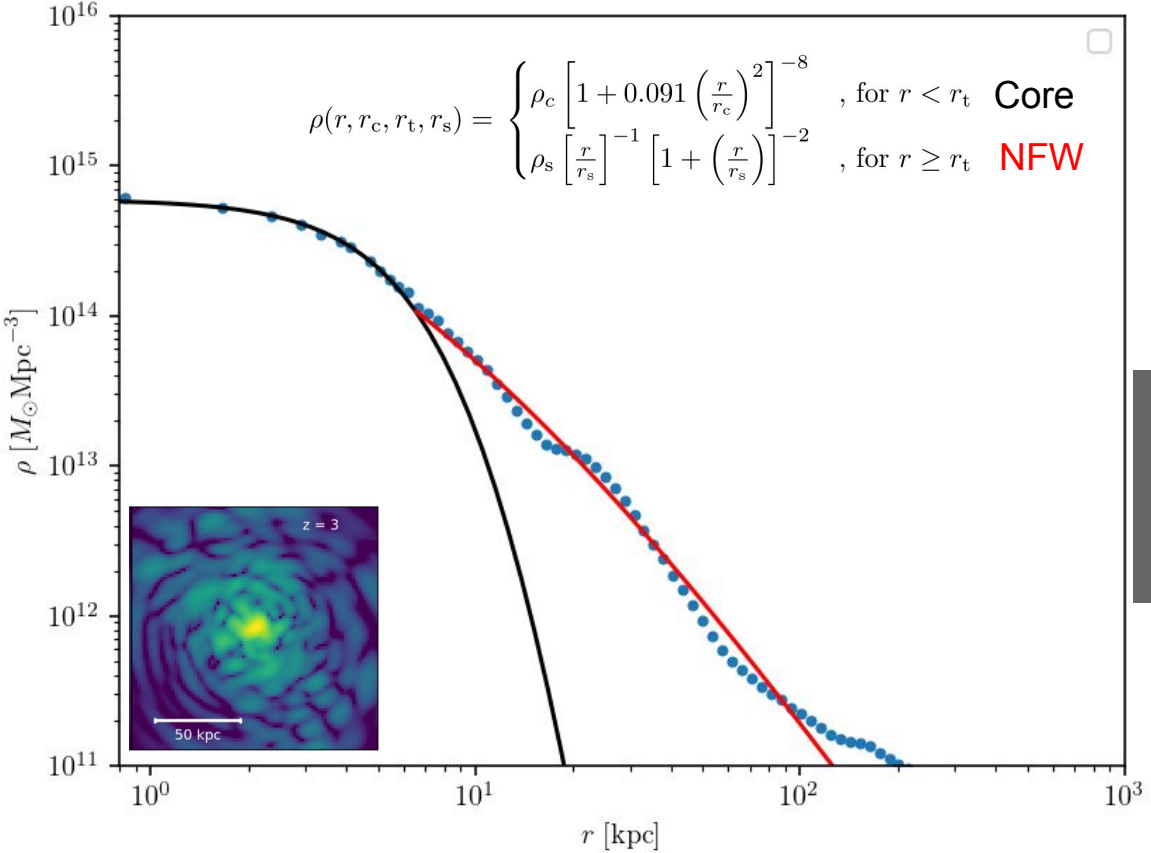
	(This Work)	(May+21)
	Soliton merger	Large-box cosmological
L	0.3 Mpc	10 Mpc/h
N^3	512^3	8640^3
mc^2	10^{-22} eV	7×10^{-23} eV
$z_{\rm f}$	3	3
Δx	0.644 kpc	1.547 kpc

Formation of FDM Halo



- Co-evolution of core and halo
- Interference pattern
- Core size decreases as halo mass increases

Density profile of FDM halo

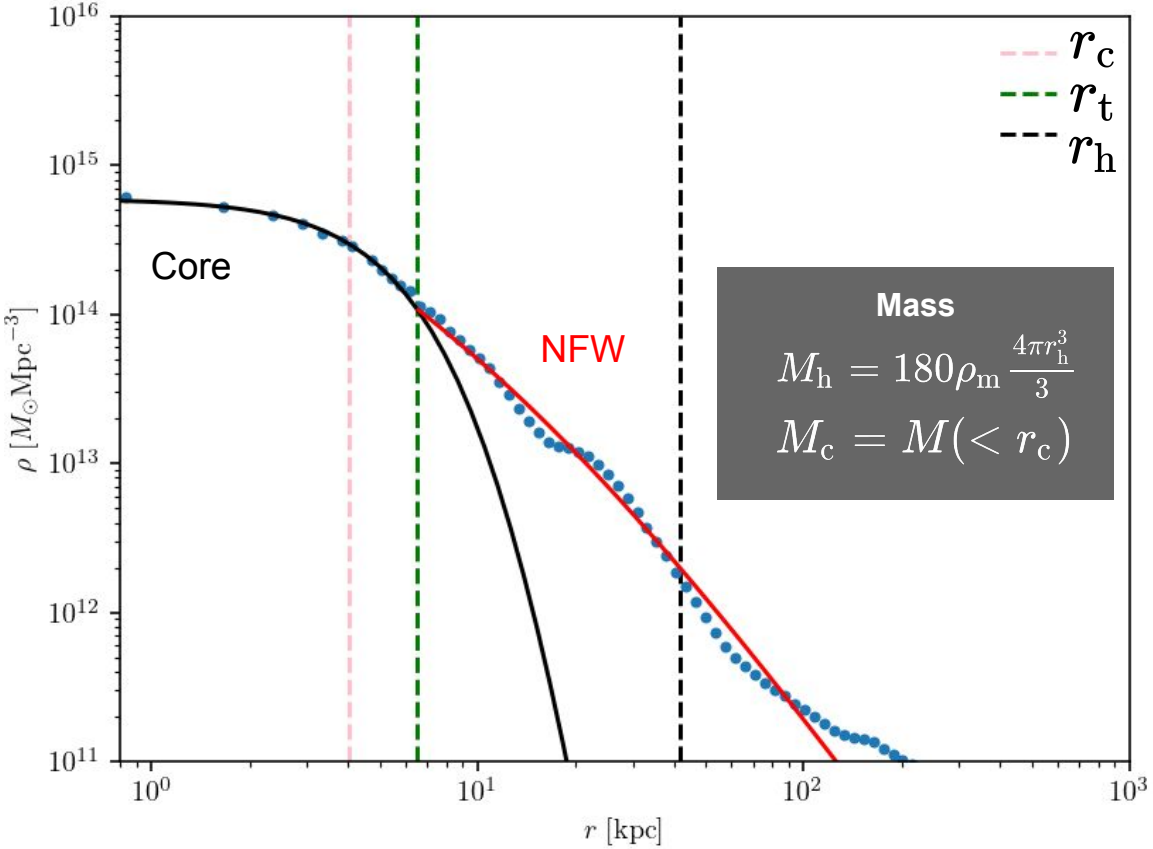


Mass

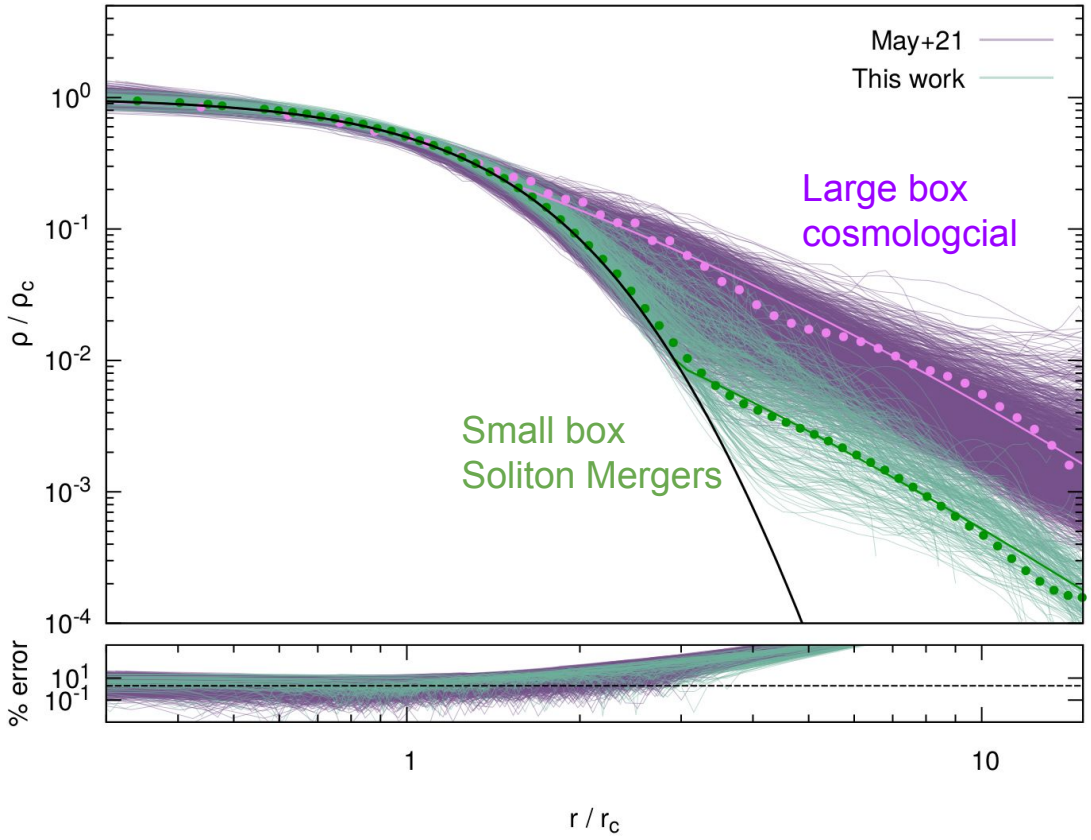
$$M_\mathrm{h} = 180\rho_\mathrm{m}\frac{4\pi r_\mathrm{h}^3}{3}$$

$$M_\mathrm{c} = M(<r_\mathrm{c})$$

Density profile of FDM halo



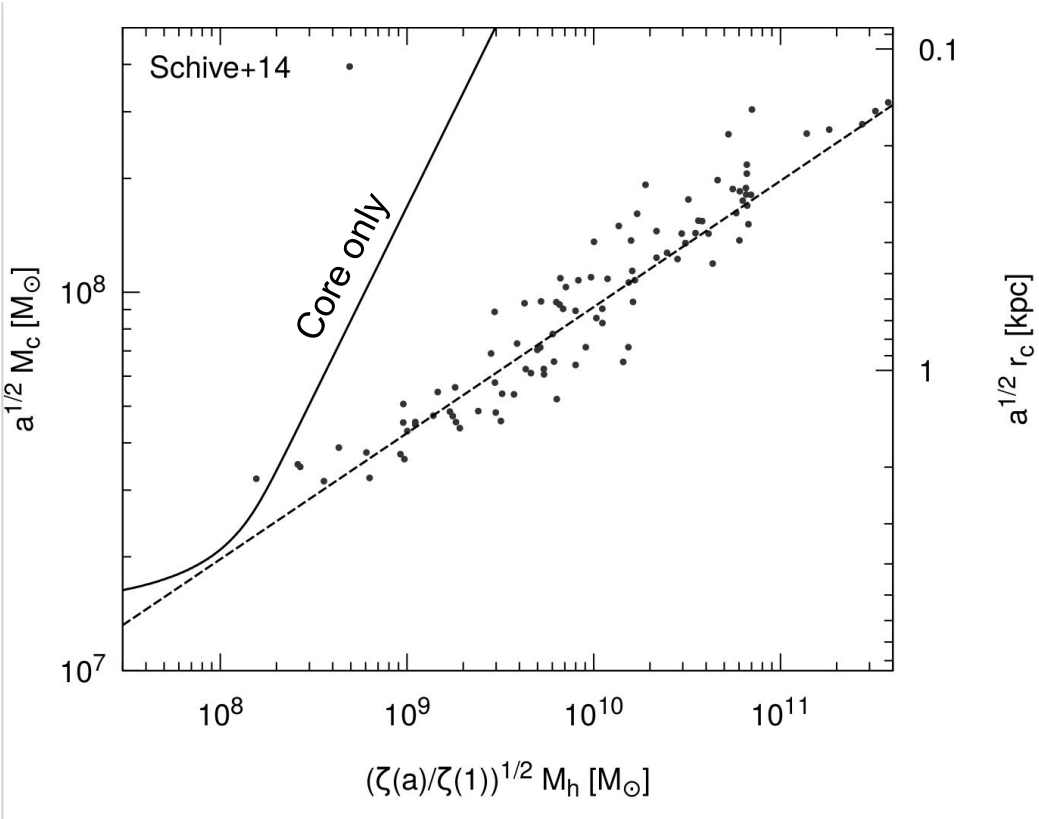
Density Profiles of FDM Halo



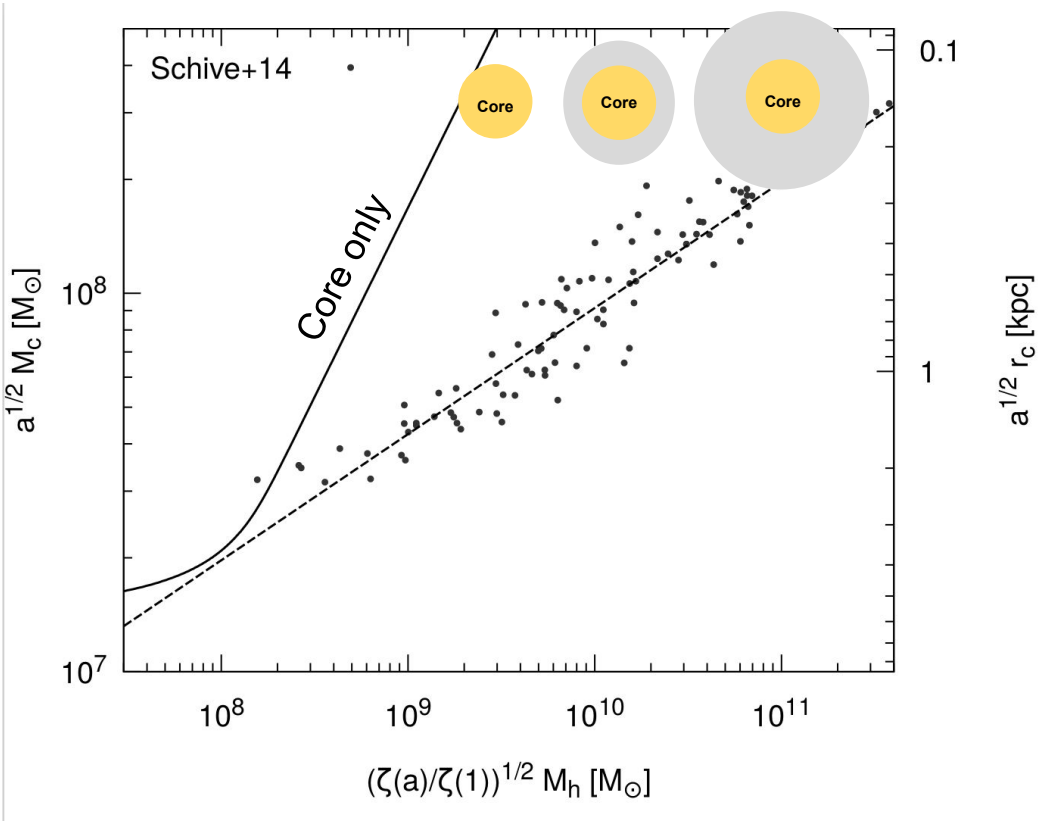
- Core+NFW profile fits well
- Small oscillation in the NFW region
- Most have $r_{\rm t} \leq 3r_{\rm c}$

(Closer to smooth and continuous transition)

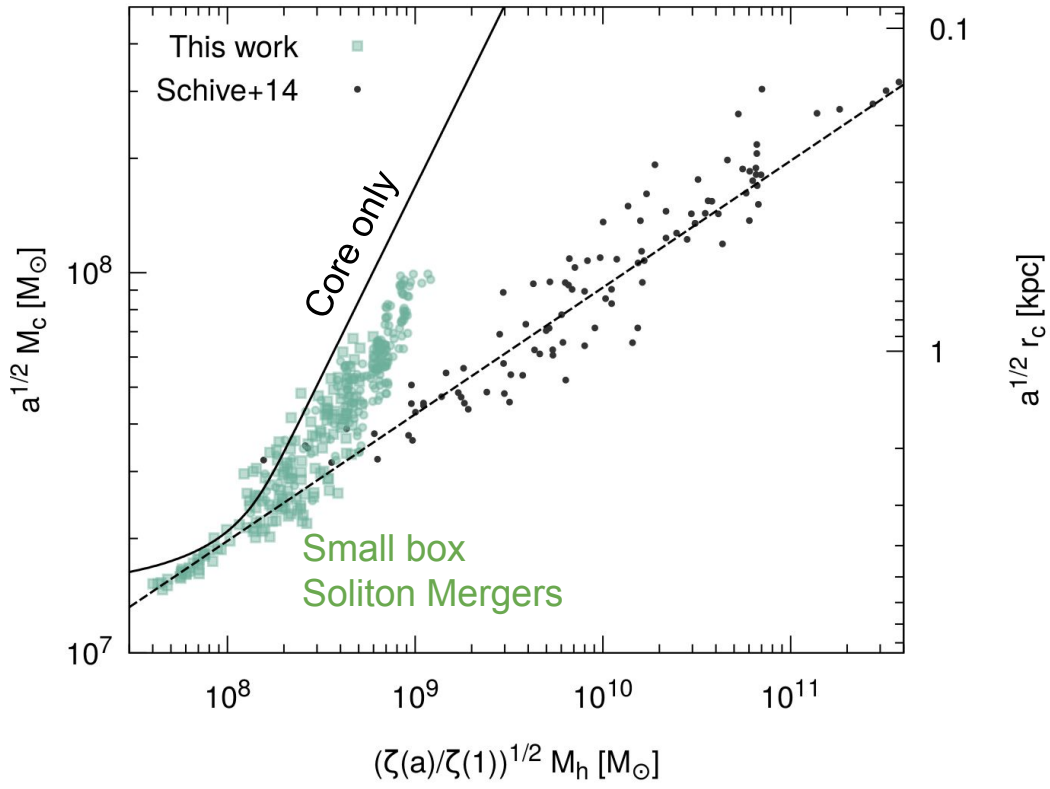
Core-Halo Mass Relation



Core-Halo Mass Relation



Core-Halo Mass Relation (This work)

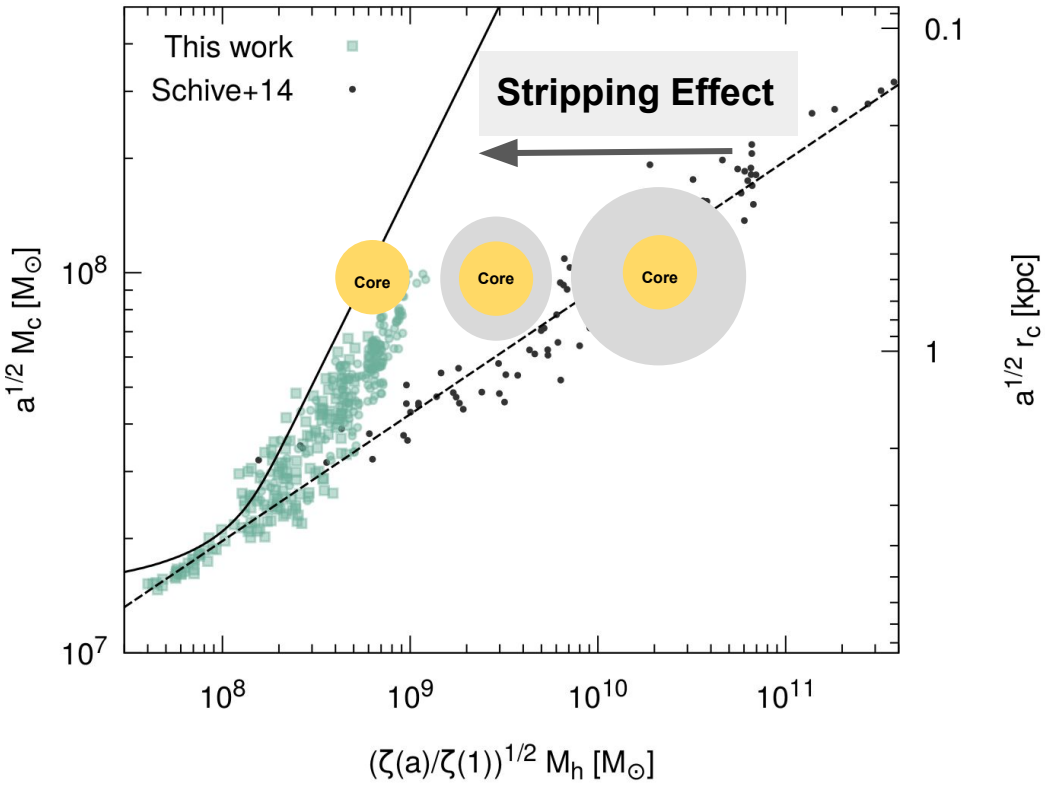


Variety of slopes

	α	Boxsize
This work	~ 0.9	335 kpc
Mocz+17	0.556	1765 kpc
Schive+14	0.333	$\geq$ 2000 kpc

- **Stable core-halo structure can exist in different environment**

Core-Halo Mass Relation (This work)

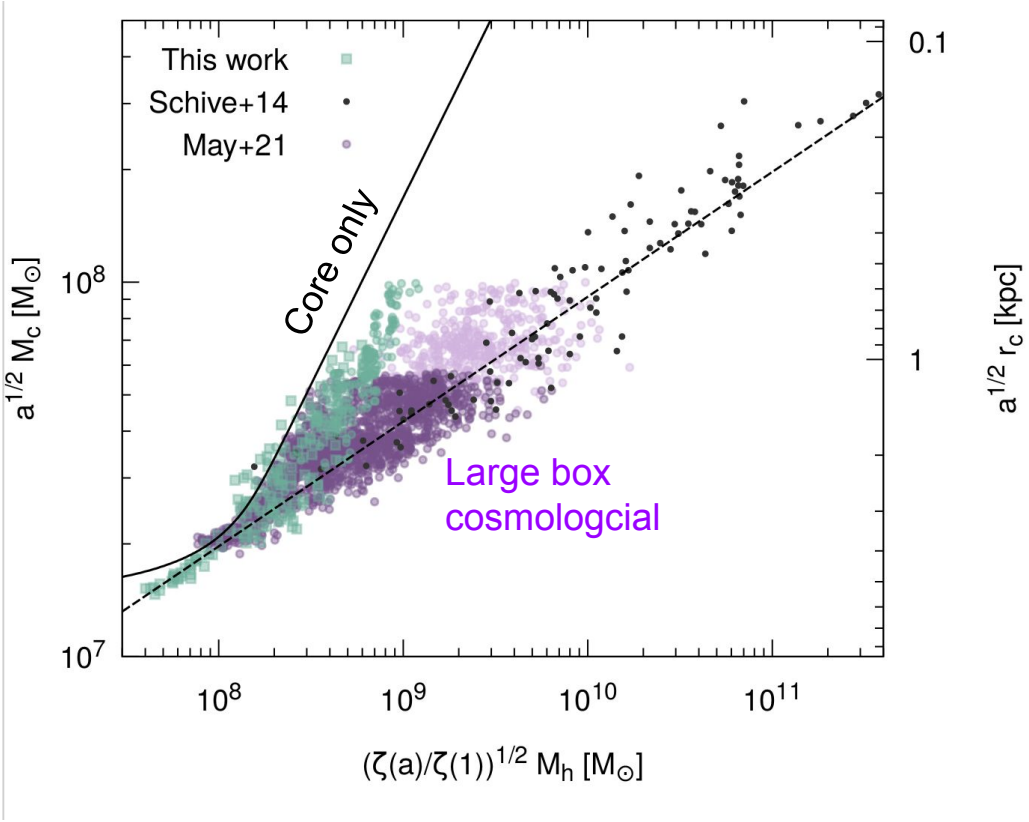


Variety of slopes

	α	Boxsize
This work	~ 0.9	335 kpc
Mocz+17	0.556	1765 kpc
Schive+14	0.333	$\geq$ 2000 kpc

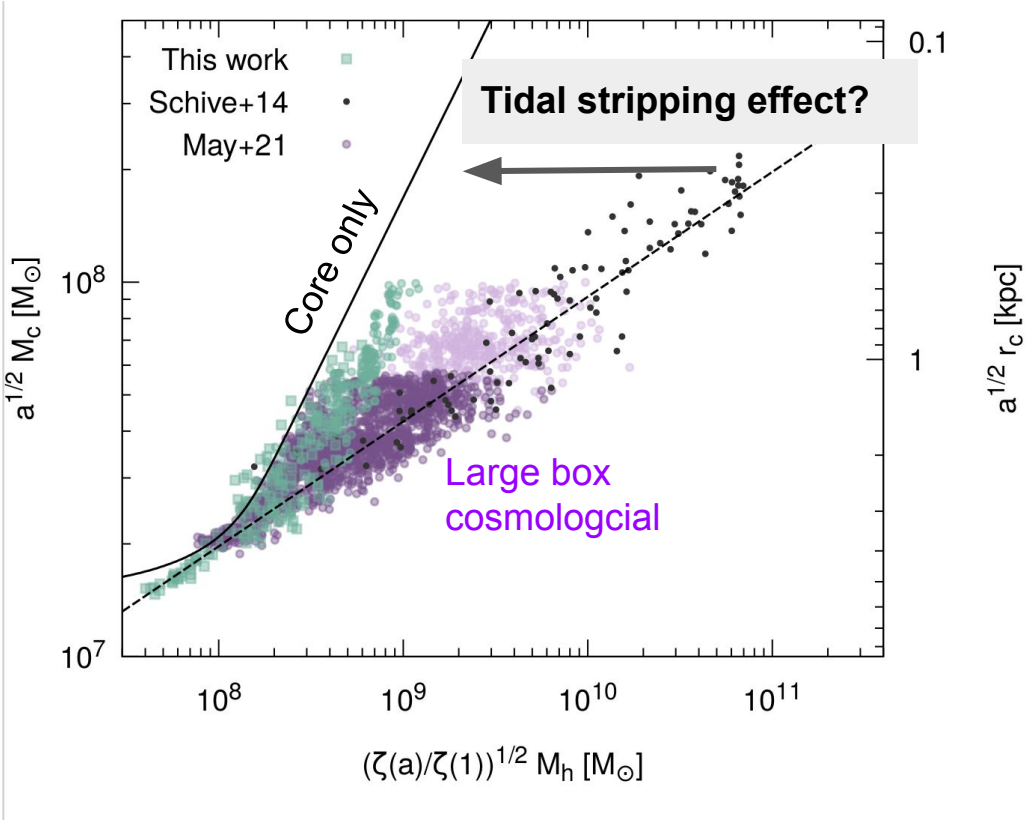
- **Stable core-halo structure can exist in different environment And configuration**

Core-Halo Mass Relation (May+21)



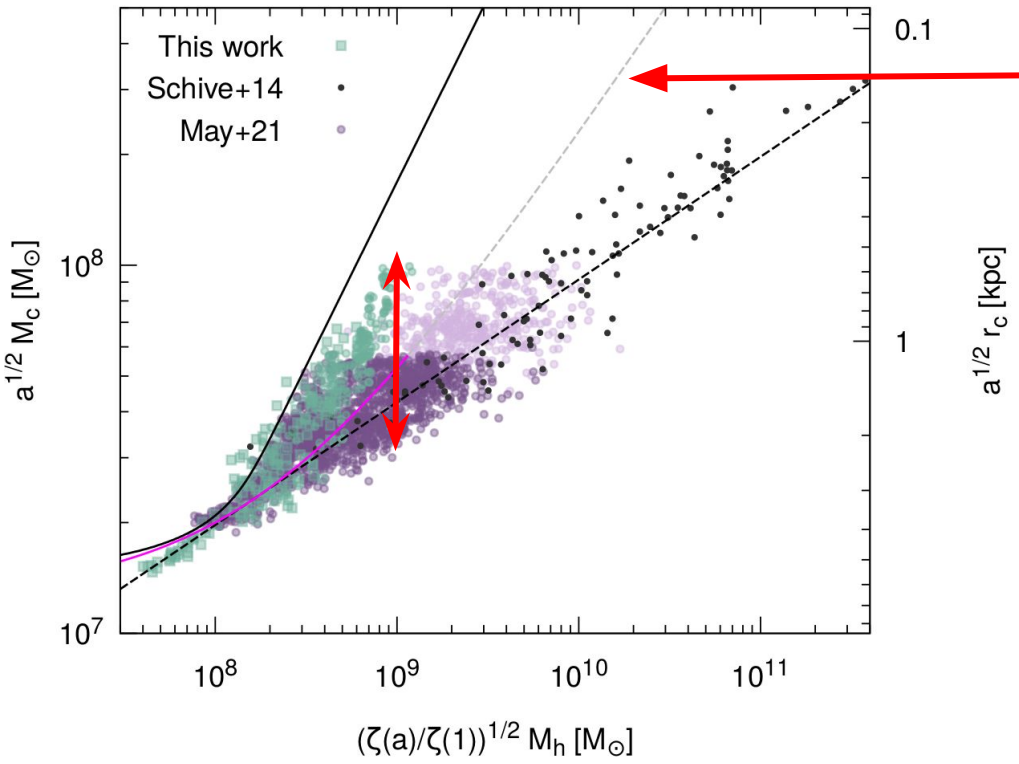
- A large dispersion
- Diversity of core-halo structure
- Previous studies only describe part of the core-halo population

Origin of the dispersion



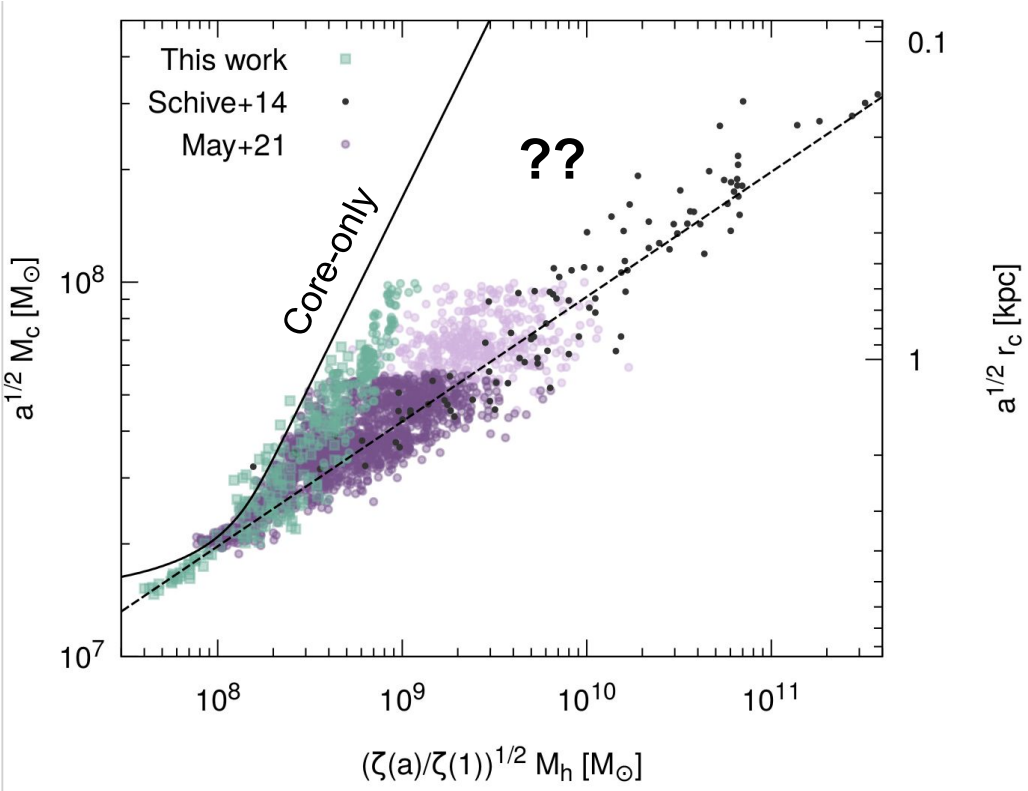
- Yavetz+21 - merger history
  Nori+21 - relaxation state

Observational Consequences



- New Empirical Equation (in prep)
- Any “one-to-one” core-halo relation will suffer from an additional ~ 50% error

Core-Halo Mass Relation



- **Suggestions for future simulations**

Summary (The End)

- We revisit the core-halo structure in the FDM model, using samples obtained from soliton mergers and large-box cosmological simulations.

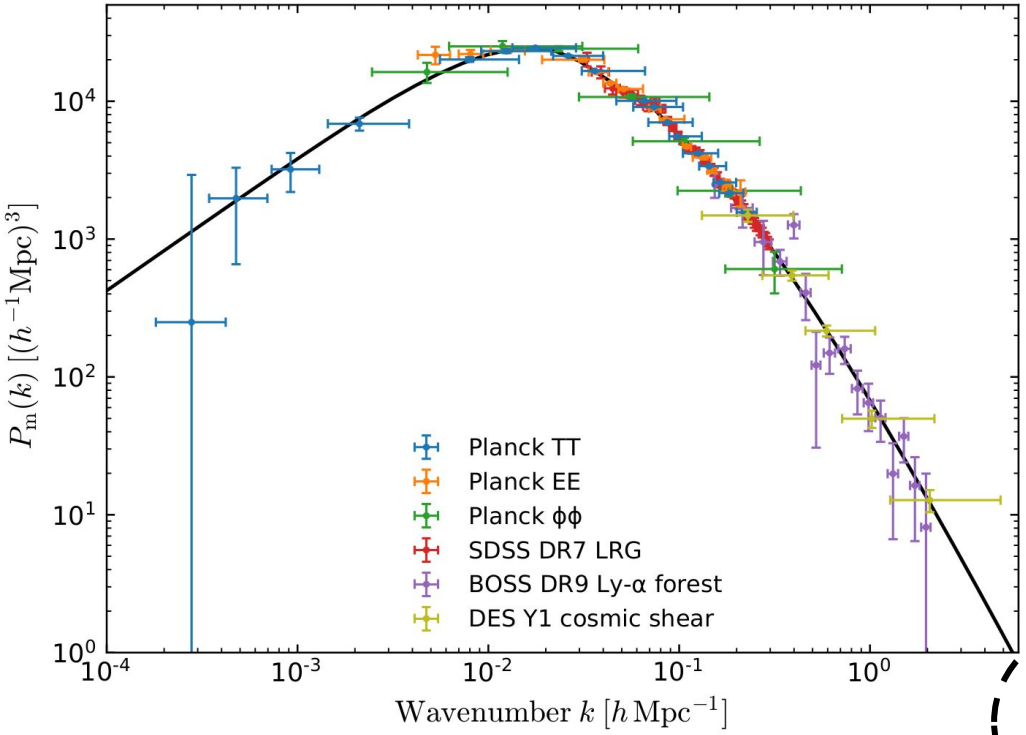
- We found a diversity in the stable core-halo structure, that can explain the variety of core-halo relation obtained by different groups.

- Any observational constraints that adopt a core-halo relation will suffer from an additional ~50% error, due to the dispersion.

- The dispersion may be related to tidal stripping effect, which needs further investigation.

Success and Challenges of LCDM Model

ESA and Planck Collaboration



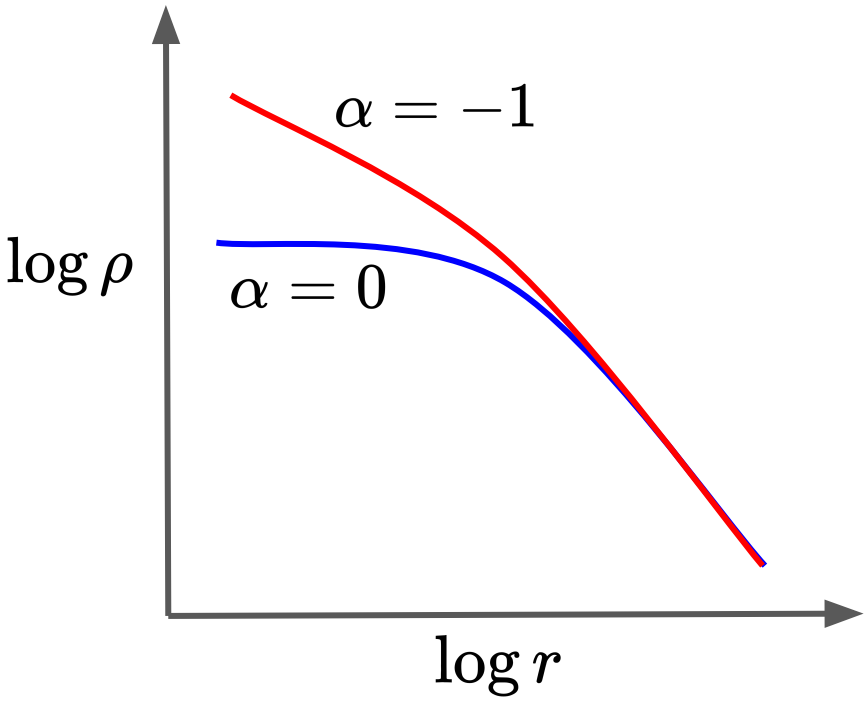
Small Scale Challenges:

Missing Satellites
Core-Cusp Problem
Too Big to Fail

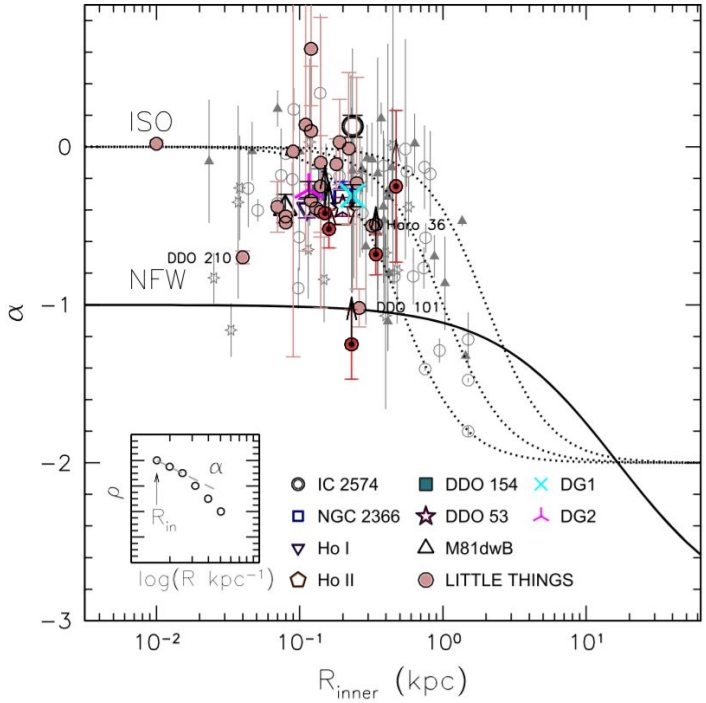
Misdetection of WIMP

?

Core- Cusp Problem

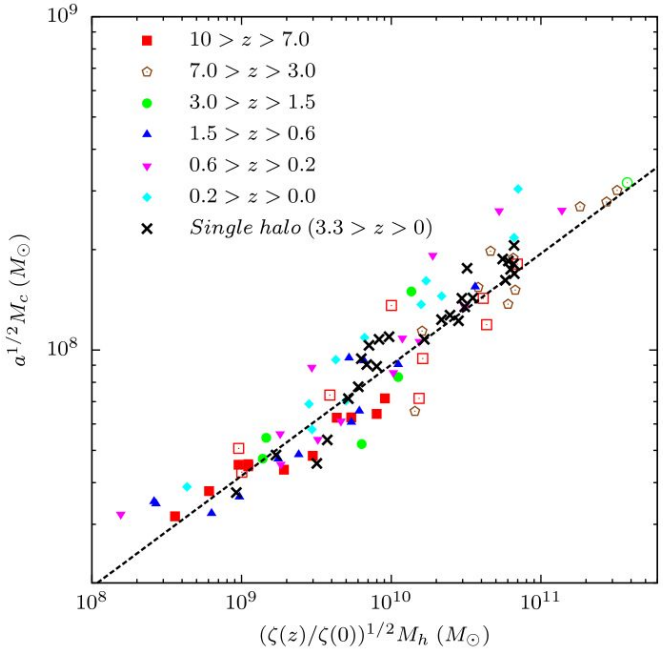


Density Profile (core vs NFW)



Little Things (Oh et al. 2015)

Core-Halo Mass Relation



Schive et al. 2014

$$M_c \propto M_h^{1/3}$$

Mocz et al. 2017

$$M_c \propto M_h^{5/9}$$

Velocity dispersion tracing

$$\sigma_c \sim \sigma_h$$

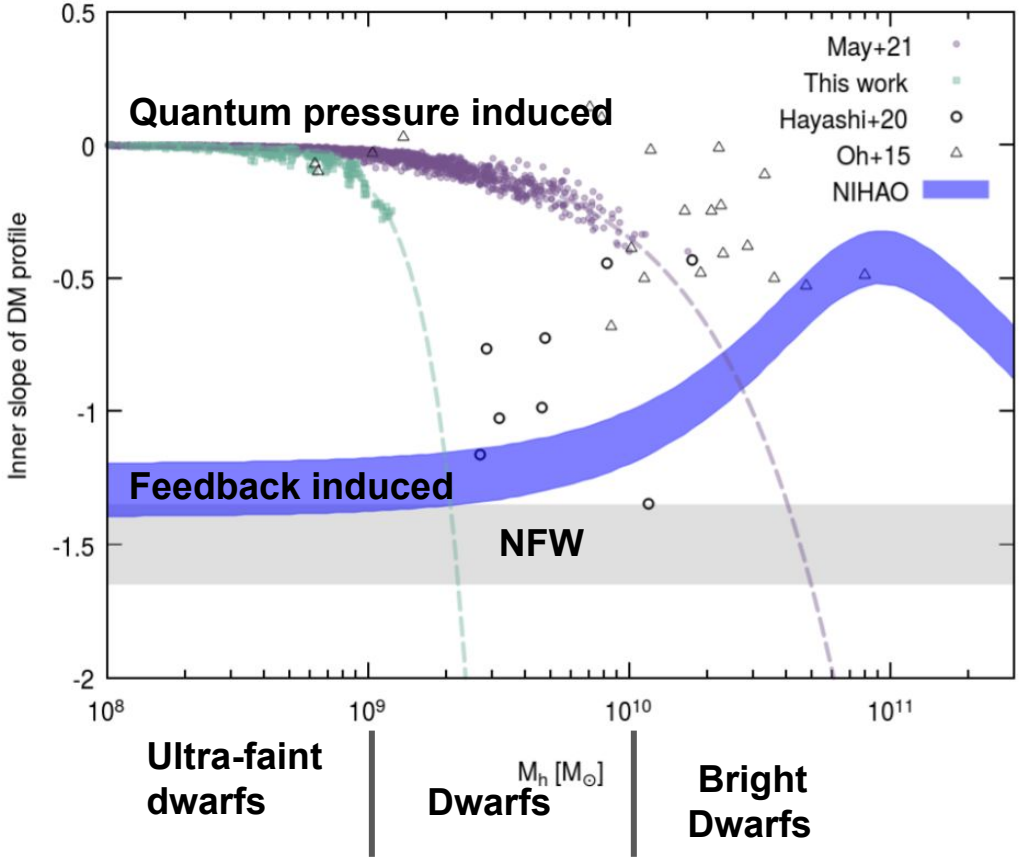
Energy tracing

$$M_c\sigma_c^2 \sim M_h\sigma_h^2$$

Velmatt et al. 2018, Nori et al. 2020, Mina et al. 2020

No agreement has been made!

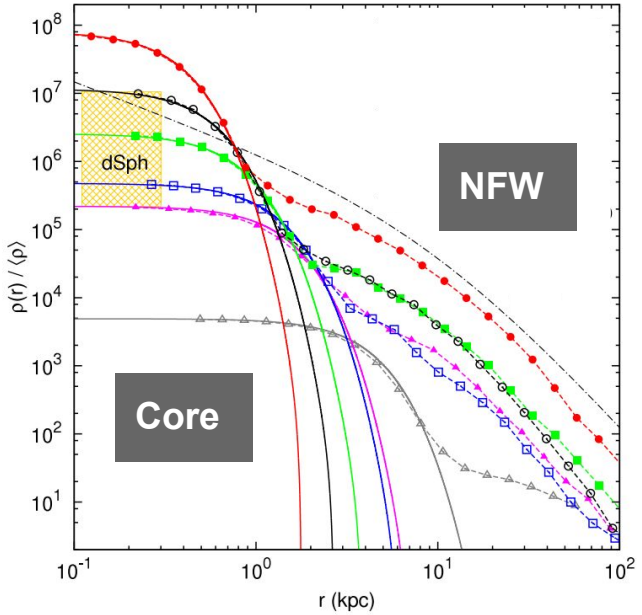
Inner slope-halo mass relation



- Ultra-faint dwarf is essential
- Diversity of core-halo structure may be able to explain diversity of inner slope

Density Profile of FDM halo

Schive et al. 2014

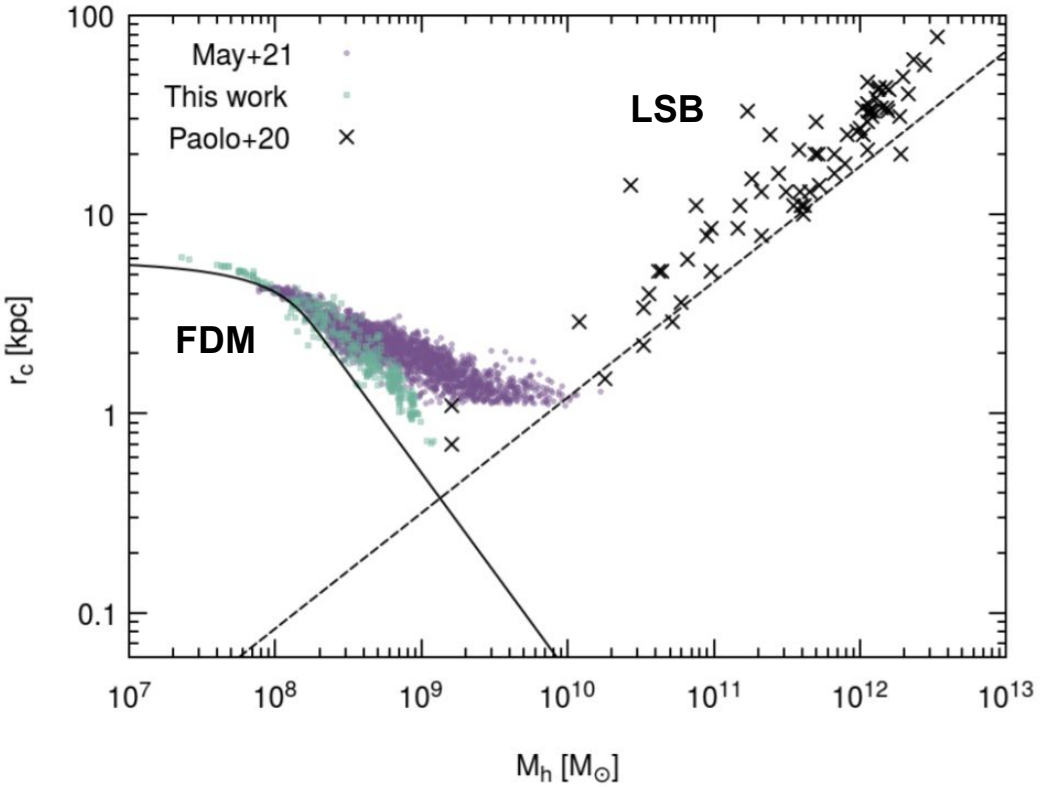


Core density profile

$$\rho_{\rm soliton}(r) = \frac{1.9\times10^{12} M_\odot\ {\rm pc}^{-3}}{[1+0.091(r/r_c)^2]^8}\left(\frac{m_\psi}{10^{-22}{\rm eV}}\right)^{-2}\left(\frac{r_c}{\rm pc}\right)^{-4}$$

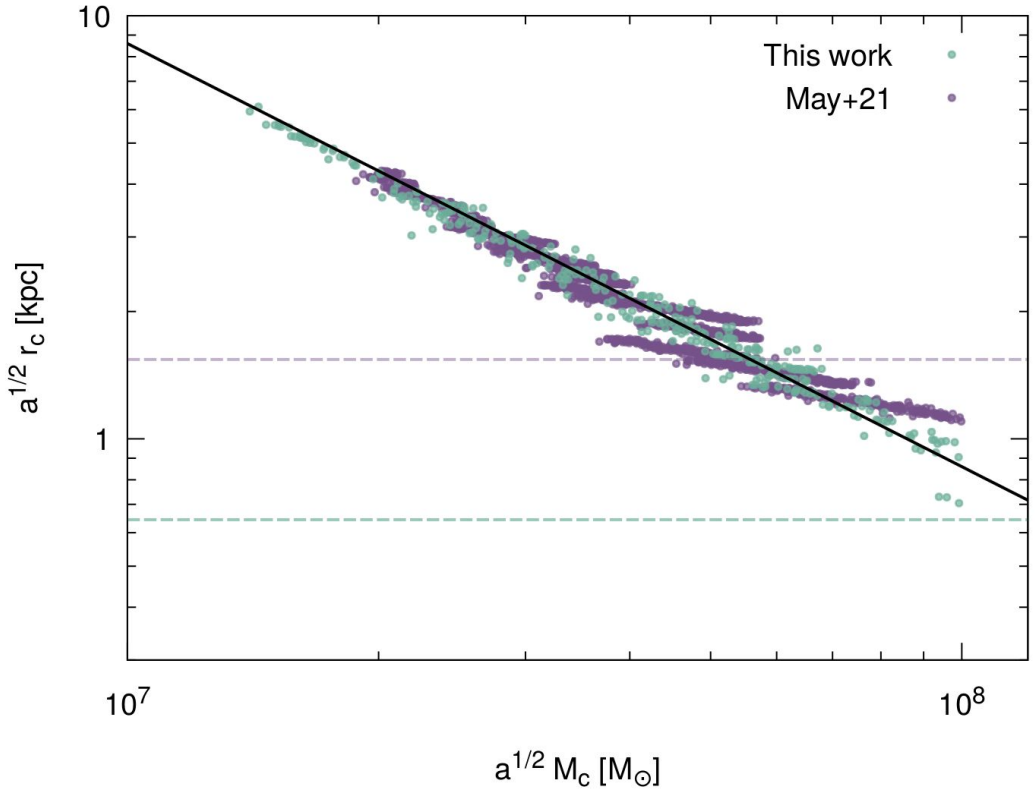
? $M_{\rm h}$

Core radius-halo mass relation



- Challenge to FDM model?
- Only baryonic effect may help solving the issue

Spatial Resolution



$$M_c = \frac{5.5 \times 10^9}{(mc^2/10^{-23}\,\mathrm{eV})^2 (r_c/\mathrm{kpc})} \mathrm{M}_\odot \,.$$

- **The relation becomes more dispersed and discretized.**