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Symposium on “What is dark matter ?”
@ Kavli IPMU

Center for Gravitational Physics and Quantum Information

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Innermost structure of dark matter halos

finding a clue of dark matter

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Introduction & motivation

Probing nature of dark matter from cosmic structure formation

Dark matter halos (DM halos) — self-gravitating bound objects

Its properties reflect nature of dark matter (DM)

substructure & ***inner structures*** sometimes exhibit ***universal features***

→ a unique channel to access nature of DM

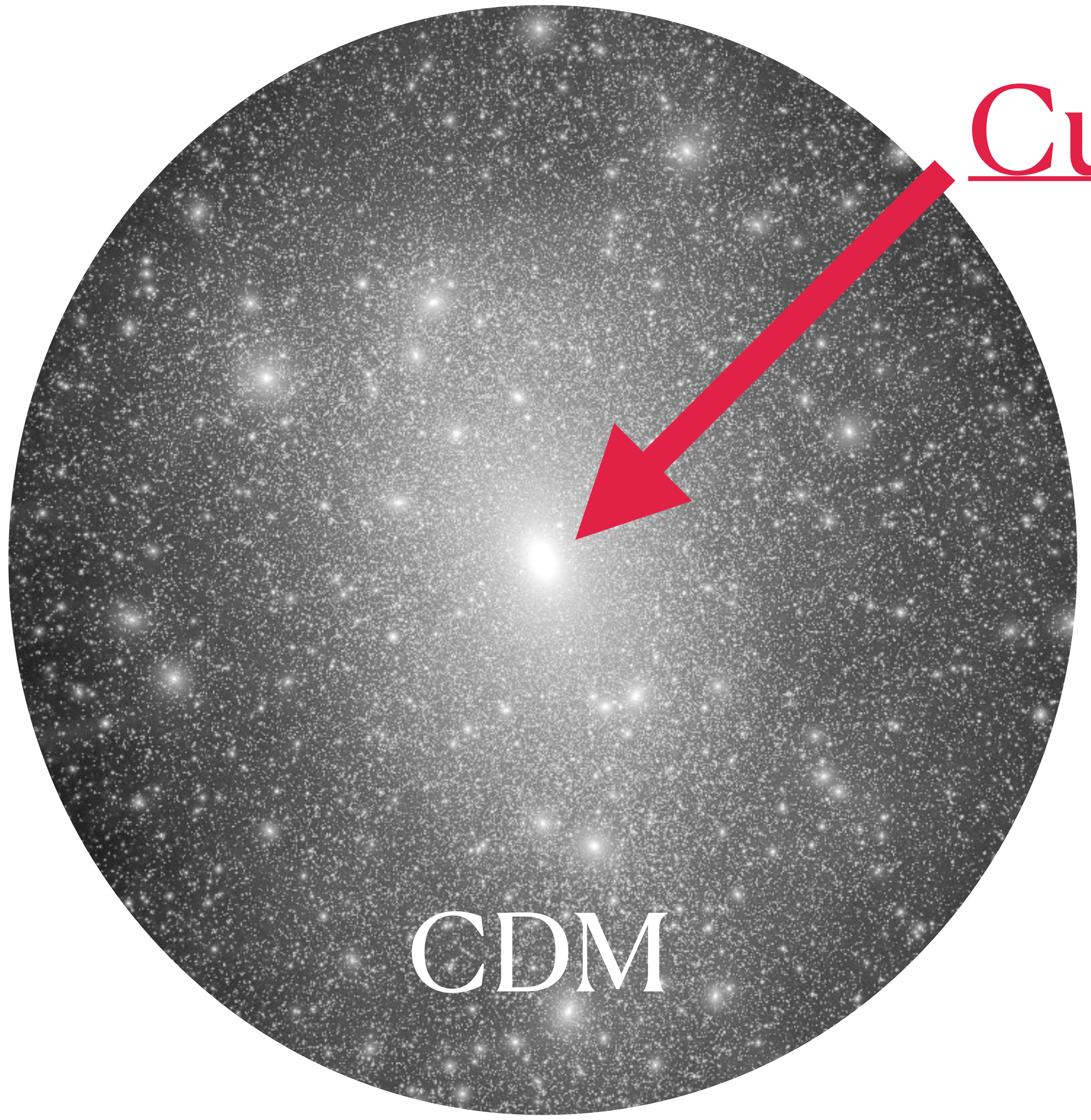
Here, we focus on "*universal*" properties in CDM & FDM

Enomoto, Nishimichi & AT, arXiv:2302.01531

AT & Saga, arXiv:2208.06562 (in PRD)

Cold dark matter (CDM) halo

Baseline DM in the concordant cosmological model (ΛCDM)



Cuspy structure

Studied extensively by N-body simulations

Radial density profile $\quad \rho(r) \overset{r \ll r_s}{\propto} r^{-\alpha} \quad (\alpha = 1 - 1.5)$

(Navarro, Frenk & White '96)

(c.f. prompt cusp of $\rho \propto r^{-3/2}$ of first halos)

(Ishiyama et al. '10; Delos & White'22)

Pseudo-phase space density $\quad Q(r) \equiv \rho(r)/\{\sigma_{\rm v}(r)\}^3$

(Taylor & Navarro '01)

$\propto r^{-\alpha_{\rm Q}} \quad (\alpha_{\rm Q} = 1.875)$

A more profound & universal property as a distinct feature of CDM ?

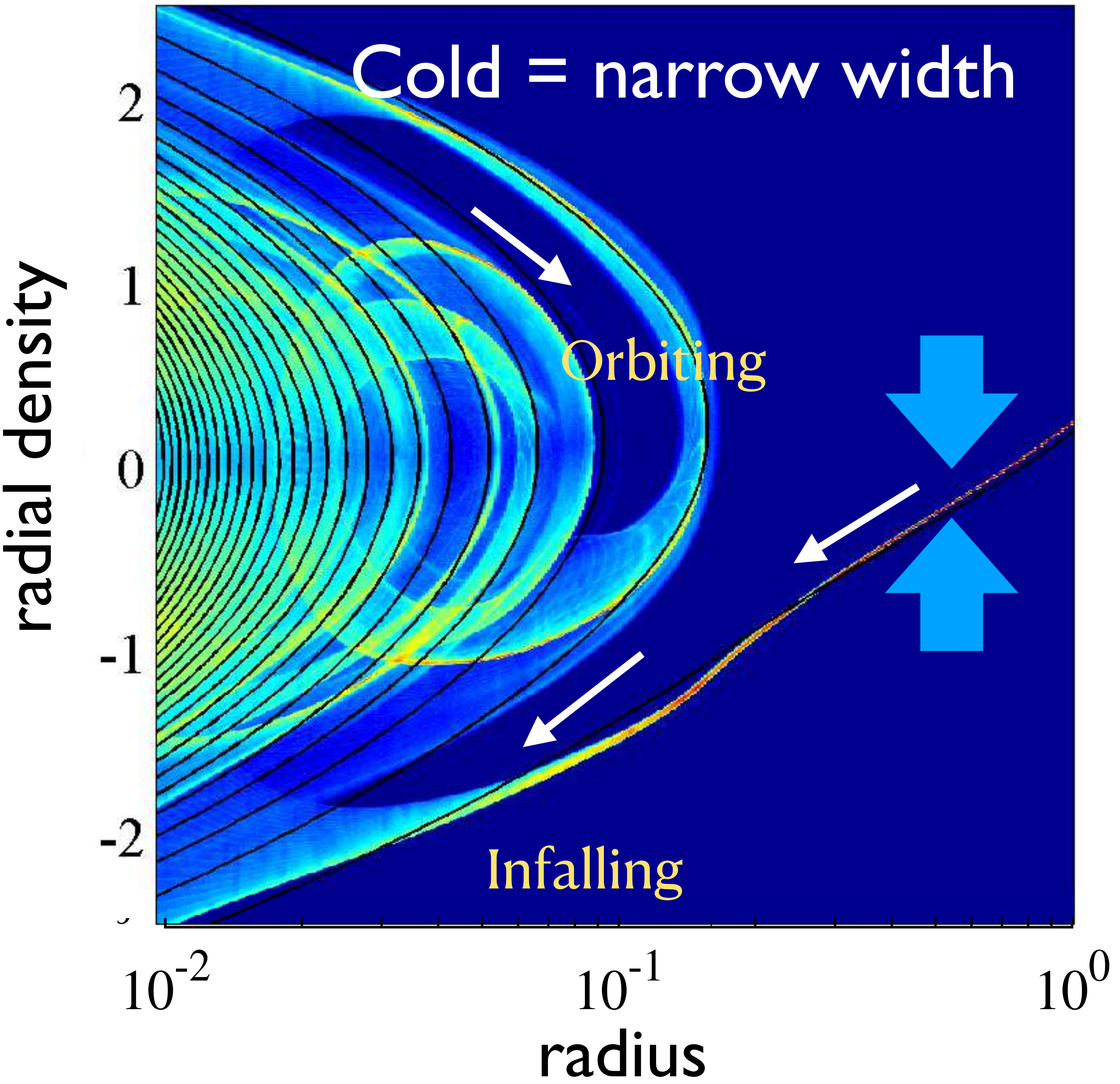
Multi-stream nature of CDM halos

<u>Cold nature of dark matter</u> provides a distinctive feature in CDM halos

Negligible velocity dispersion at an early time

Through accretion/merger processes

Adhikari, Dalal & Chamberlain ('14)



CDM halos exhibit

Onion-like structure

Multi-stream structures

with an <u>outer sharp boundary</u>

(=Splashback radius)

(e.g., Diemer & Kravtsov '14; Adhikari et al. '14)

Prediction of self-similar solutions

A fundamental universal feature may be hidden in phase space ?

Tracing multi-stream flow with particles

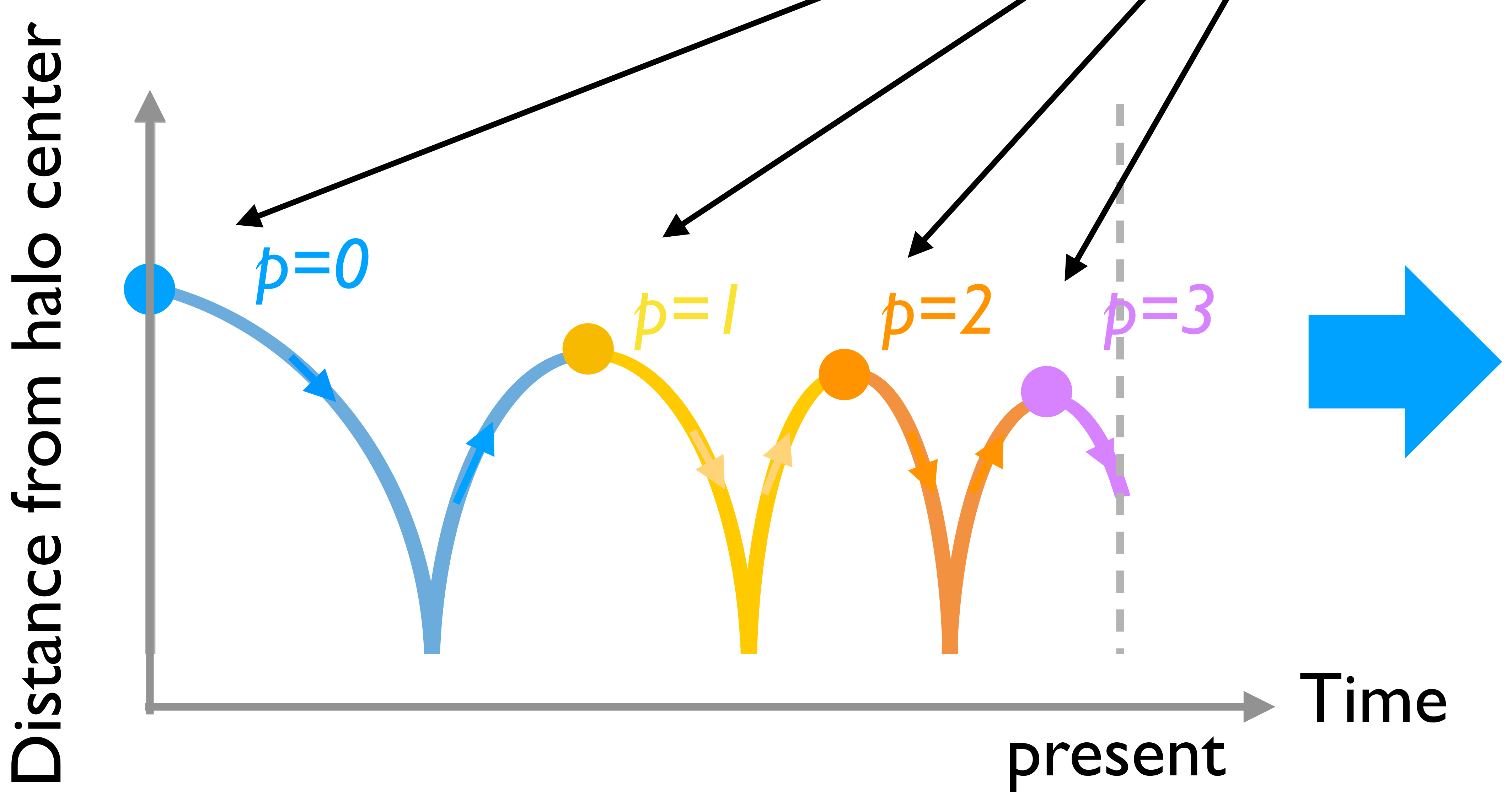
ΛCDM, $L_{\rm box} = 41\,h^{-1}$Mpc & $N_{\rm dm} = 500^3$

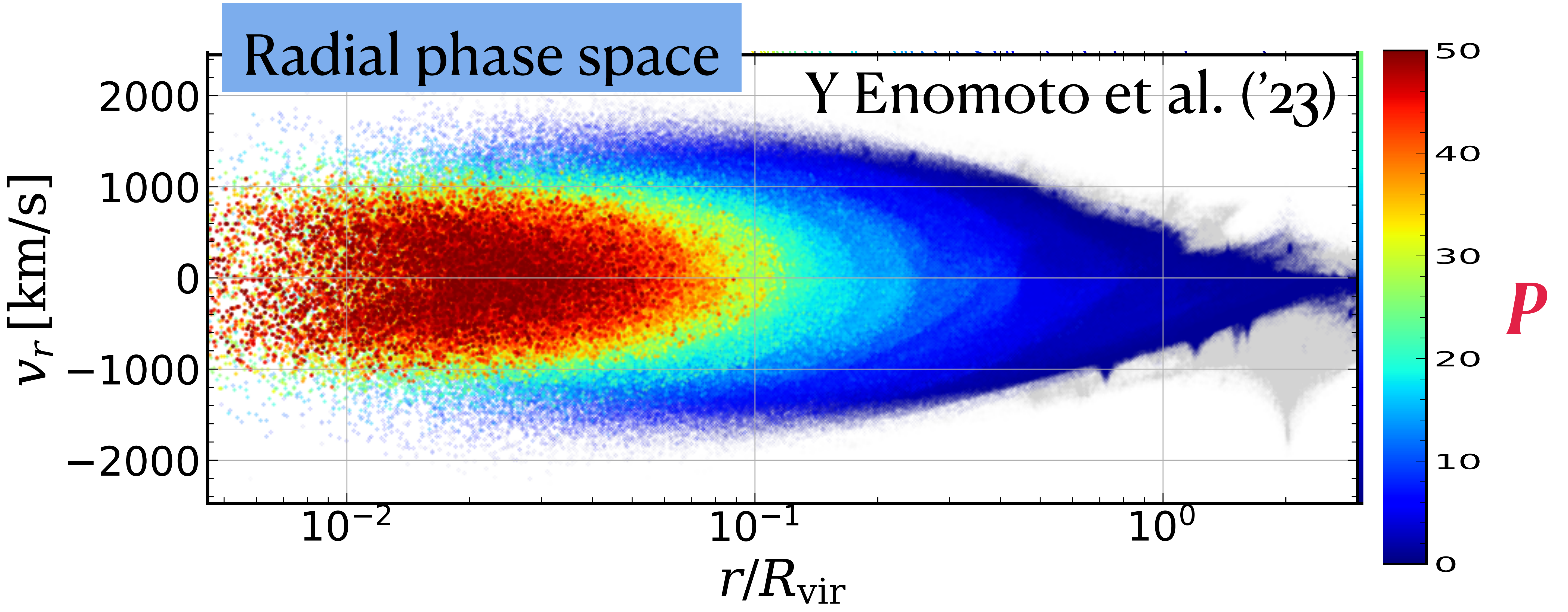
Using ***1,001*** snapshot data of cosmological *N*-body simulations over z=0~5

Keep track of apocenter passage(s) for particle trajectories (Sugiura et al. '20)

and count the number of apocenter passages, ***p***, for each particle See also Diemer ('17)

Tiling phase-space streams with ***p*** up to p~50 !!



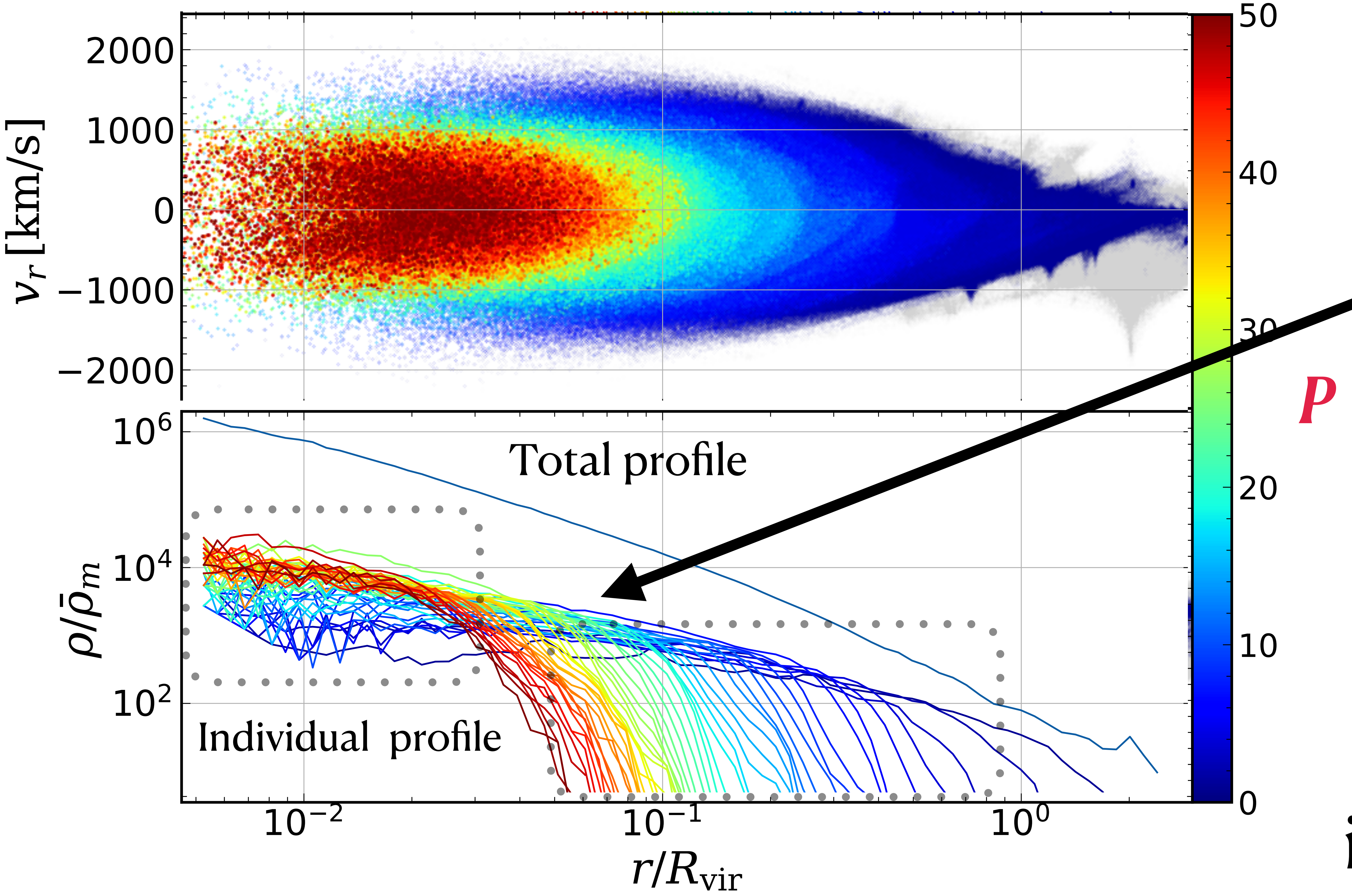


Multi-stream radial profiles

Enomoto, Nishimichi & AT ('23)

Radial density profile of each stream classified with p commonly exhibits a *double power-law feature* (for $p > 1$)

# of apocenter passages



✓ Inner: shallow cusp

$$\rho_{\rm stream}(r) \propto r^{-\alpha},\ (\alpha < -2)$$

✓ Outer: sharp cutoff

$$\rho_{\rm stream}(r) \propto r^{-\beta},\ (\beta > -7)$$

These features remain true irrespective halo masses (→next slide)

Stacked multi-stream radial profiles

Enomoto, Nishimichi & AT ('23)

Universal fitting form

$$\rho_{\rm stream}(r;p) = \frac{A(p)}{x\,(1+x^7)}\,; \quad x \equiv \frac{r}{S(p)}$$

With $A(p)$ & $S(p)$ described by a simple fitting form

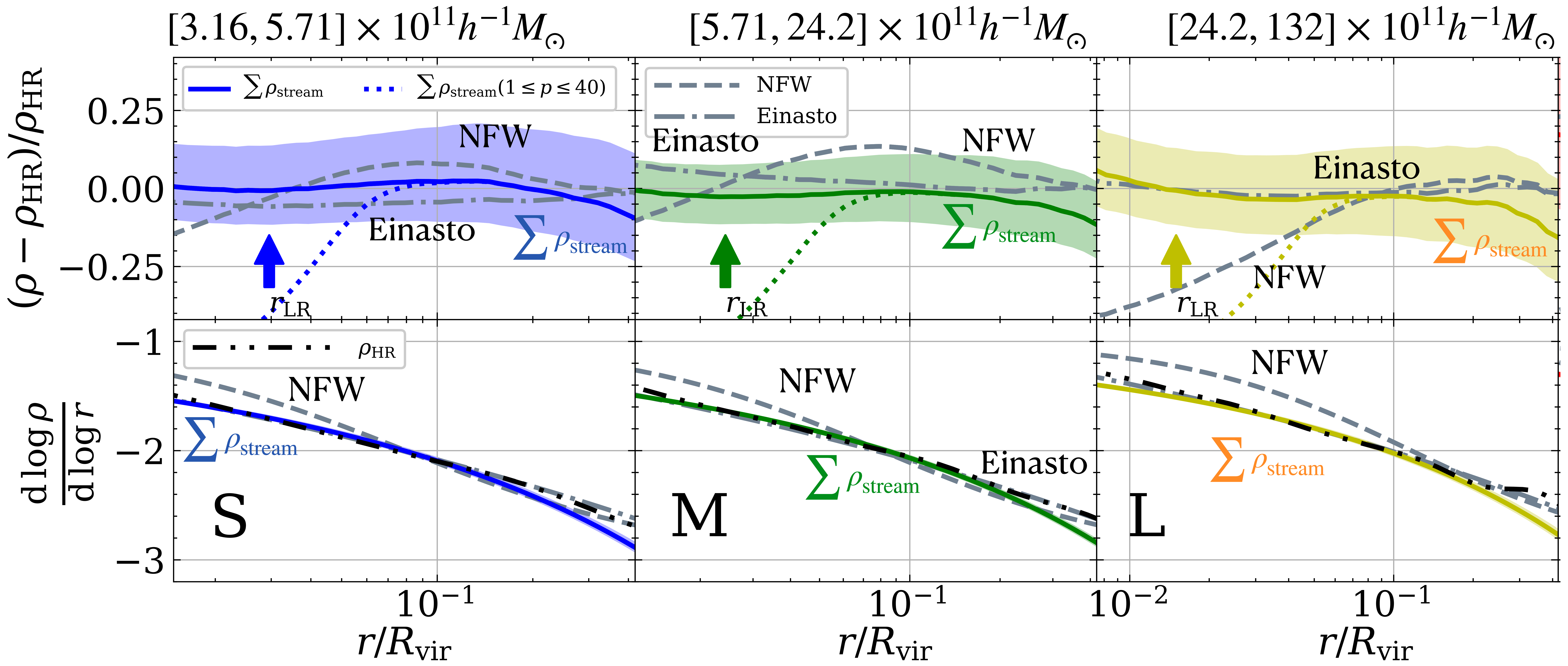
$M_{10} \equiv M_{\rm vir}/(10^{10} h^{-1} M_\odot)$

$$\log_{10}\{A(p)/\bar{\rho}_{\rm m}\} = 4.89 - 0.119\log_{10}(M_{10}) + \{-3.89 + 0.243\log_{10}(M_{10})\}\,p^{-9/40}$$

$$\log_{10}\{S(p)/R_{\rm vir}\} = 2.46 - 0.0474\log_{10}(M_{10}) + \{-2.29 - 0.0639\log_{10}(M_{10})\}\,p^{1/8}$$

Total profiles from multi-stream profiles

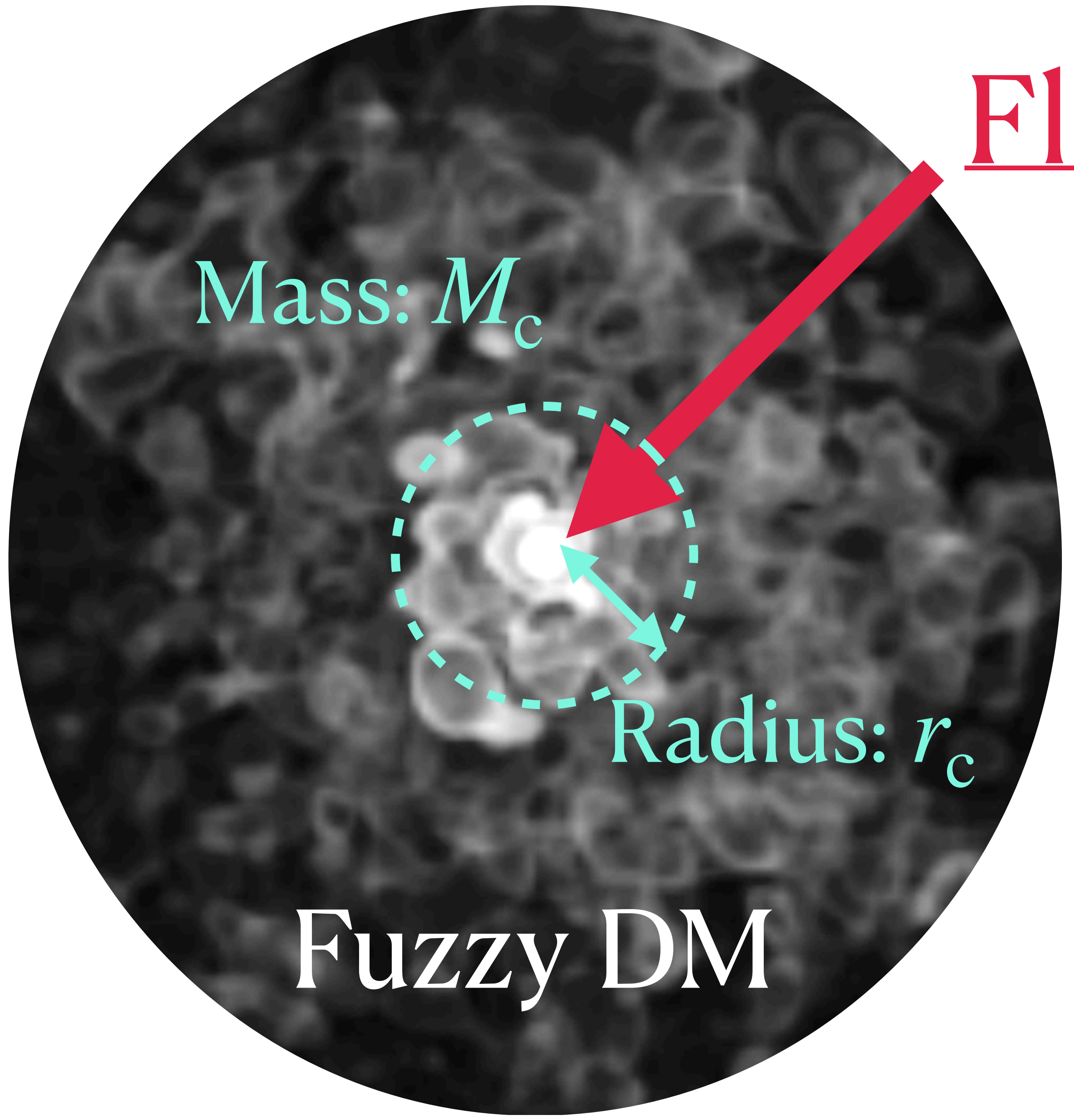
Enomoto, Nishimichi & AT ('23)



Sum of double power-law profiles accurately describes high-resolution (HR) results

Fuzzy dark matter (FDM) halo

Alternative DM candidate having a ultralight mass ($\sim 10^{-22}$ eV)



Flat dense core = *soliton*

found by numerical simulations of Schrödinger-Poisson (S-P) equation

Core-halo relations Schive et al. ('14)

$r_c \propto m_\phi^{-1} M_h^{-1/3}$ $M_c \propto m_\phi^{-1} M_h^{1/3}$

M_h : Halo mass

m_ϕ :Mass of FDM

$\longrightarrow$ unique feature to constrain mass of fuzzy DM

(e.g., Safarzadeh & Spergel '20; Hayashi & Obata '20)

However,

some contradiction as well as a diversity of their relations reported

(Schwabe et al. '16, Du et al. '17, Mocz et al. '17, Nori & Baldi '21, Mina et al. '22, Chan et al. '22)

Analytical approach to core-halo structure

- Self-gravity of soliton ignored
- Soliton formed in the (smooth) NFW potential

Solving S-P equation analytically under the assumptions

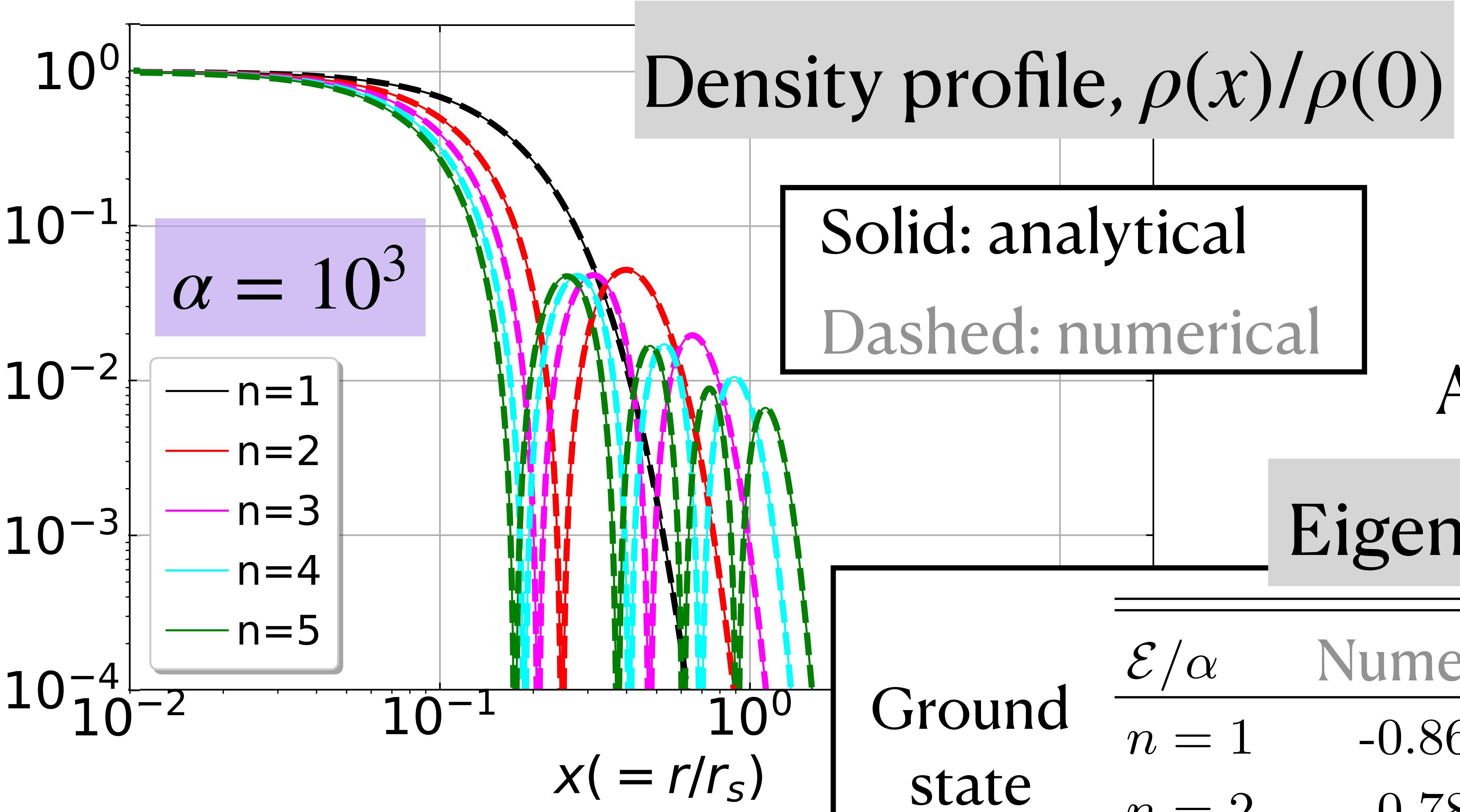
→ approximate but *super-accurate* analytical solutions for soliton eigenstates

<u>(New) core-halo relation</u>

$$r_\mathrm{c} \propto m_\phi^{-1} M_\mathrm{h}^{-1/3} \left\{ \frac{g(c_\mathrm{vir})}{1+\mathscr{E}_{1,0}/\alpha} \right\}^{1/2}$$

$$M_\mathrm{c} \propto m_\phi^{-1} M_\mathrm{h}^{1/3} \left\{ \frac{g(c_\mathrm{vir})}{1+\mathscr{E}_{1,0}/\alpha} \right\}^{-1/2}$$

A factor dependent on the halo concentration (c_vir) & soliton eigenstate ($\mathscr{E}_{1,0}/\alpha$)



AT & Saga ('22)

Eigenvalues, $\mathscr{E}_{n0}/\alpha$

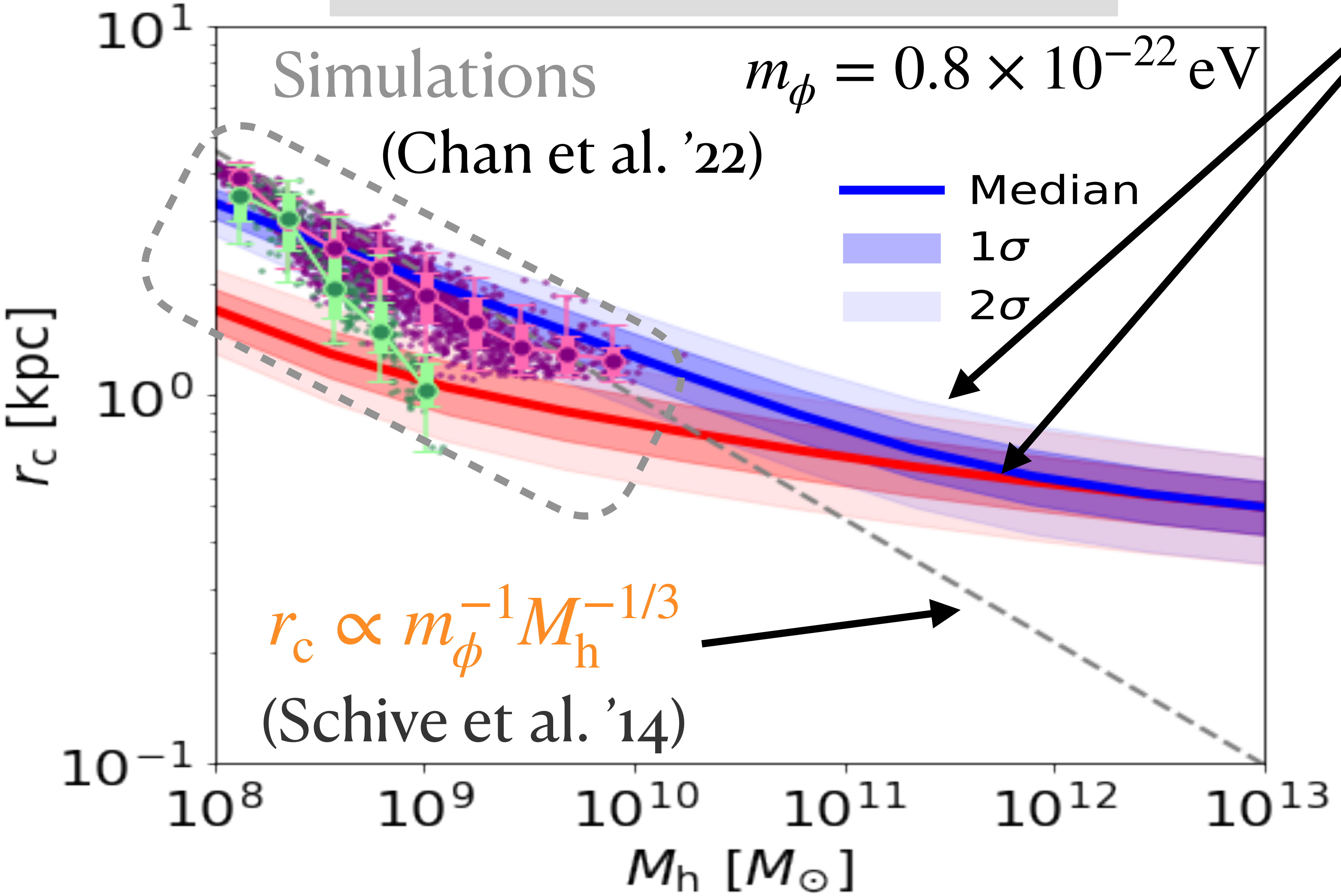
	$\mathcal{E}/\alpha$	Numerical	Analytical
Ground state	$n=1$	-0.86680	-0.86687
Excited states	$n=2$	-0.78318	-0.78323
	$n=3$	-0.72307	-0.72311
	$n=4$	-0.67531	-0.67535
	$n=5$	-0.63553	-0.63557

Analytical approach to core-halo structure

AT & Saga ('22)

A missing factor largely changes core-halo relations, showing extra cosmological dependence

Core radius vs halo mass



Present work

adopting the concentration-mass relation $c_{vir}(M_h)$ of FDM/CDM models

- Non power-law behaviors
- Non-negligible amount of scatter

c.f.) recent claim by Zagorac et al. ('23)

"There is no universal core-halo relationship"

Summary

To be or not to be... (non-)universal features of innermost structure of dark matter halos based on analytical & numerical study

Cold dark matter (CDM)

Enomoto, Nishimichi & AT, arXiv:2302.01531

A new remarkable feature found in multi-stream structures

Radial multi-stream profiles

$$\rho_{\rm stream}(r;p) = \frac{A(p)}{x\,(1+x^7)}\,; \quad x \equiv \frac{r}{S(p)}$$

With $A(p)$ & $S(p)$ described by a simple fitting form

Fuzzy dark matter (FDM)

AT & Saga, arXiv:2208.06562 (in PRD)

A missing factor in core-halo relations found analytically

Non power-law feature of core-halo relation dependent on cosmology (concentration-halo mass relation)

→ no universal relation ?