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To be or not to be: (non-)universal features in dark matter halos

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Contents

(Non-)universal features of innermost structure of dark matter halos in cold and fuzzy (wave) dark matter models

Introduction & motivation

Cold dark matter: new universal radial structure of halos

Fuzzy dark matter: analytical insight into core-halo structure

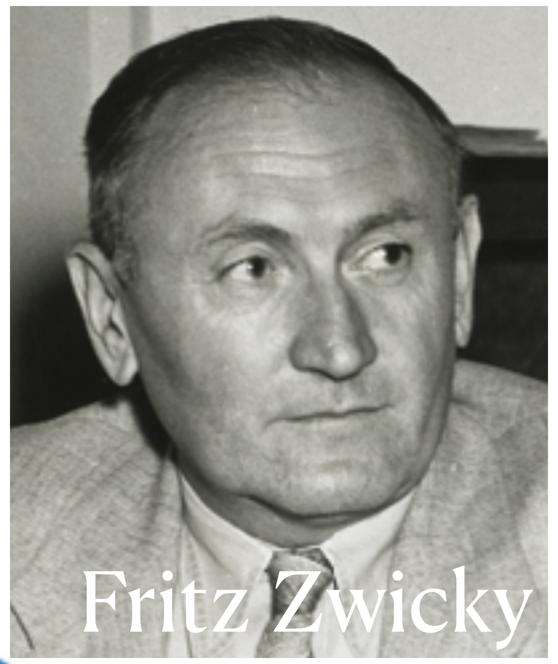
Summary

Based on

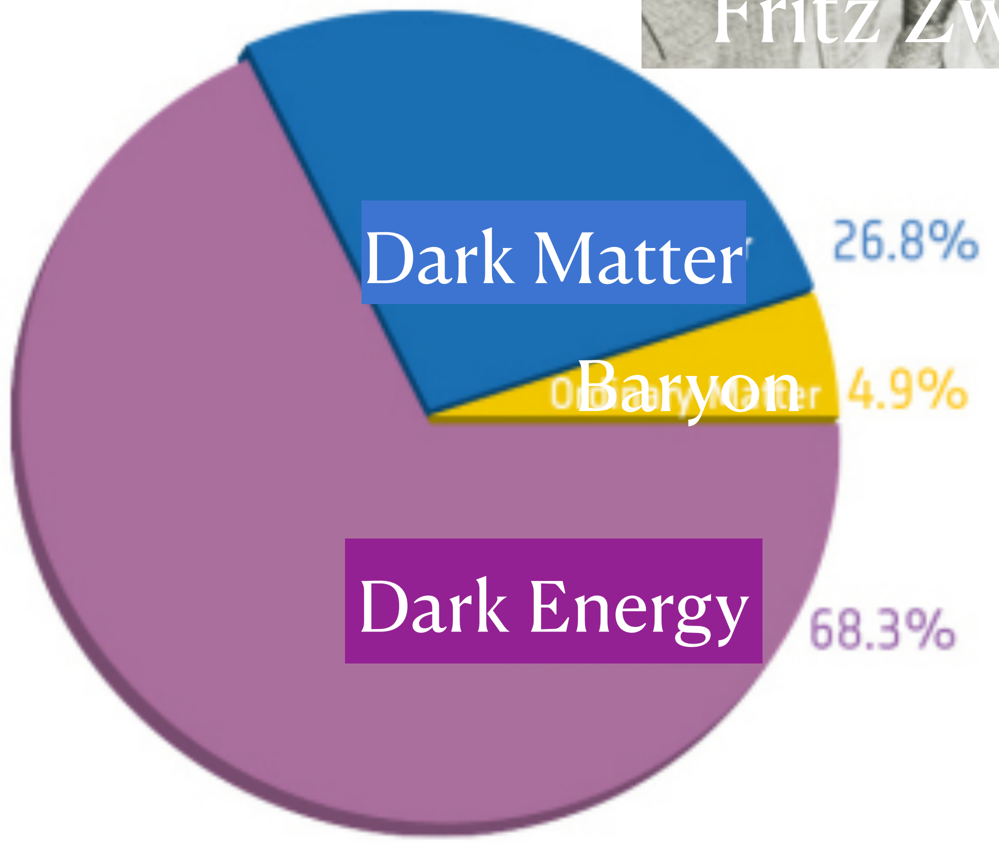
Y Enomoto, T. Nishimichi & AT, ApJL 950, L13 ('23), arXiv:2302.01531

AT & S. Saga, PRD 106, 103532 ('22), arXiv:2208.06562

Introduction: dark matter

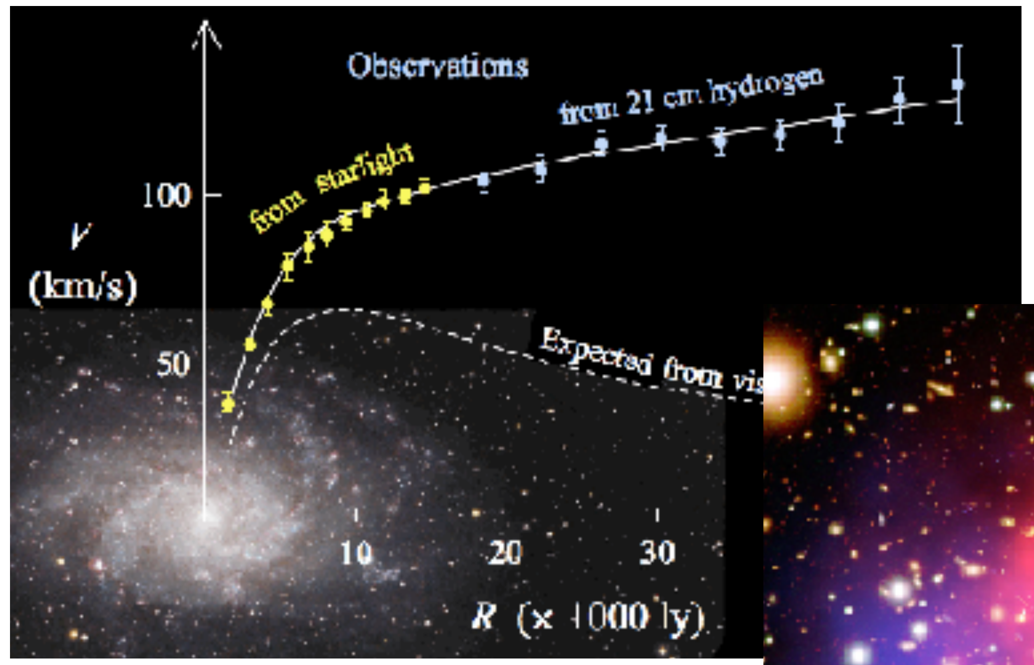


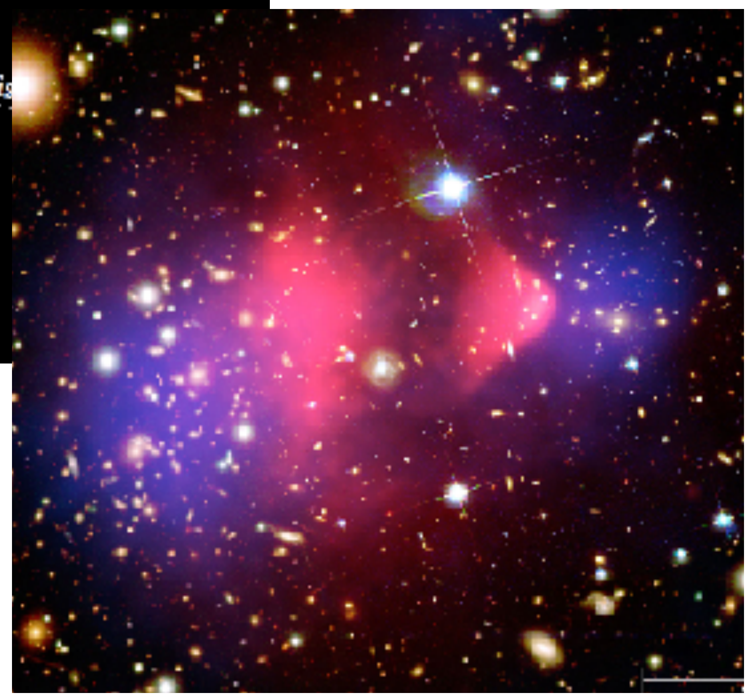
- Hypothetical matter component interacting only through gravity
- Accounting for ~30% of the energy content of the universe
- Many observational supports for the evidence of DM



flat rotation curves, gravitational lensing observations, CMB & large-scale structure, ...

While DM is indispensable for cosmic structure formation, its origin and nature is still mystery





Introduction: dark matter

Nevertheless,

Negligible thermal velocity

||

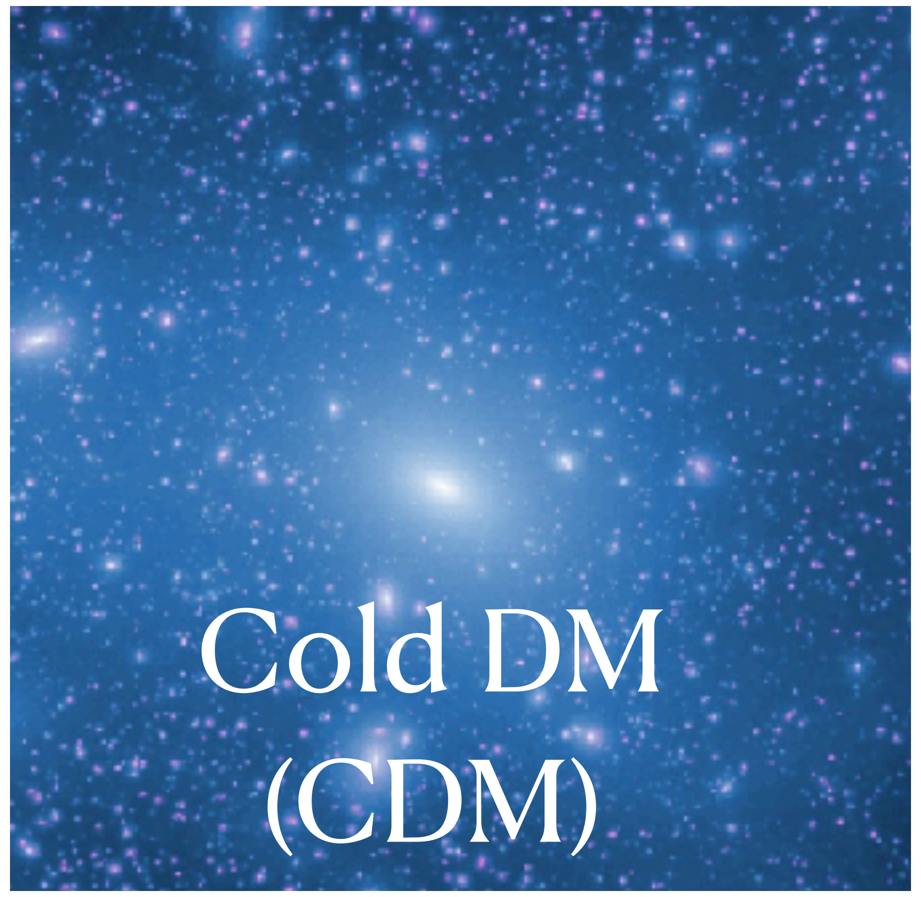
DM responsible for structure formation is thought to be ***non relativistic***

Peebles ('82, '84), Blumenthal et al. ('84), ...

Early growth of DM fluctuations before recombination → baryon catchup

Hierarchical clustering of structure formation

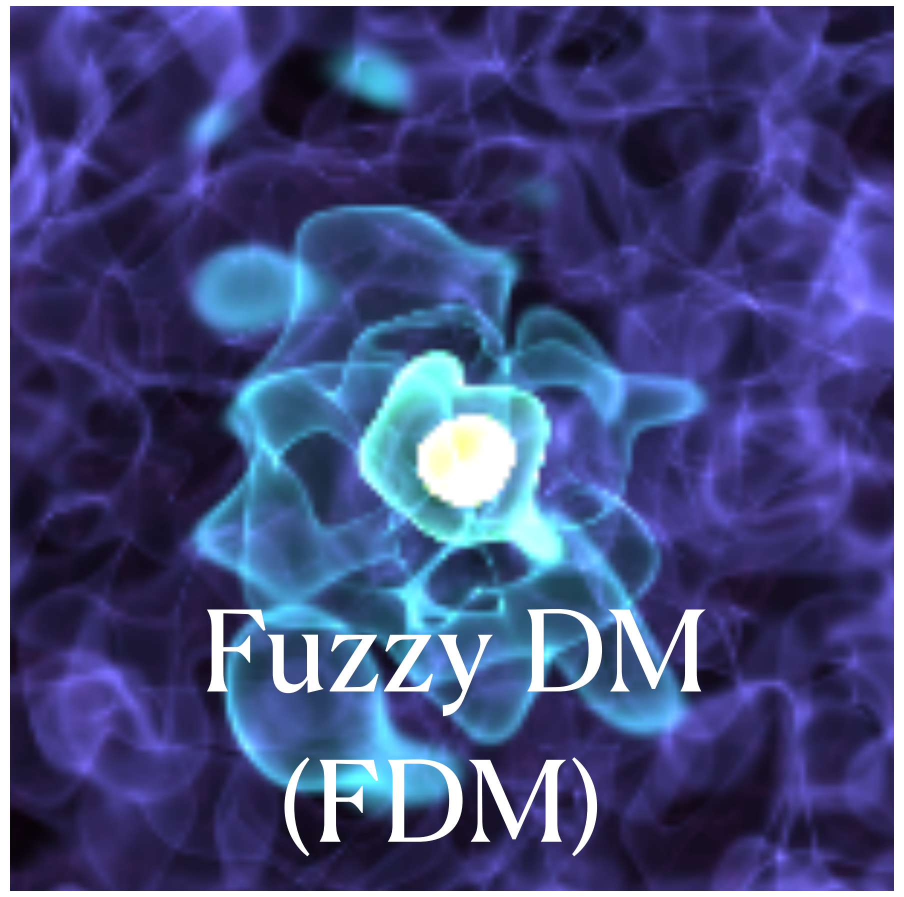
Still, there are several types of DM having such a property:



$m_{\rm DM} \sim 100\,{\rm GeV}$

$m_{\rm DM} \sim \mathcal{O}(10)\,{\rm KeV}$

$\sigma/m_{\rm DM} \sim \mathcal{O}(1)\,{\rm cm}^2/{\rm g}$



$m_{\rm DM} \sim \mathcal{O}(10^{-22})\,{\rm eV}$

Introduction: dark matter

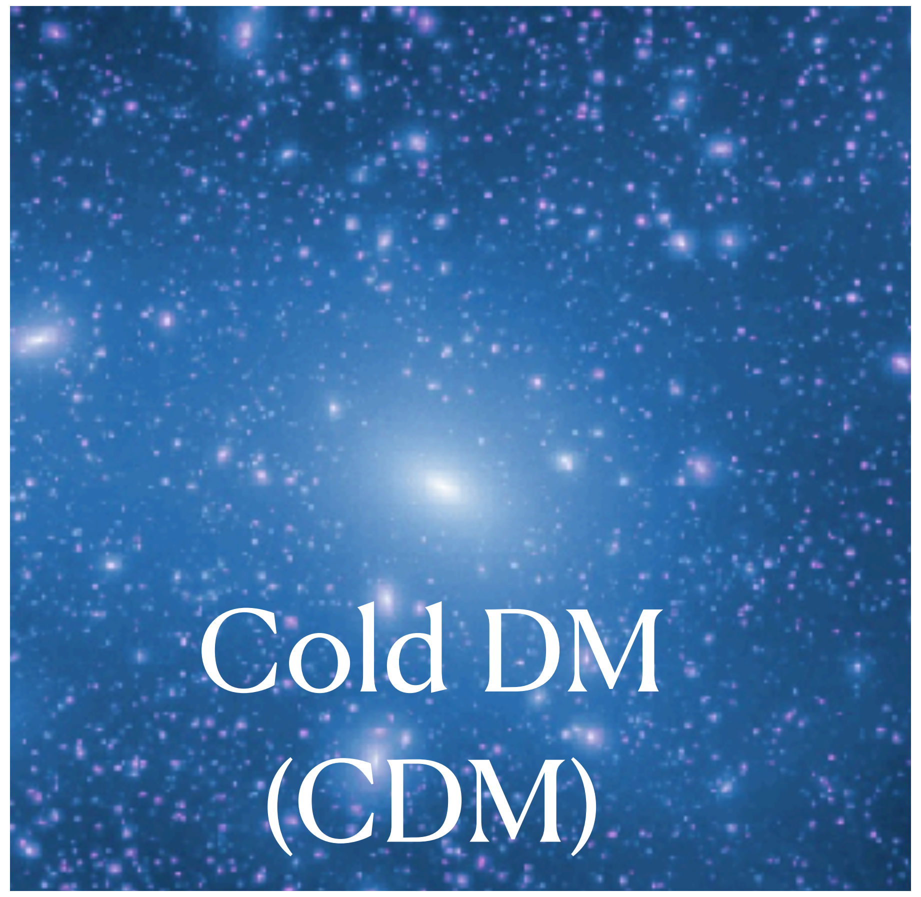
Question How well one can observationally discriminate between DM models ?

Key DM halos — self-gravitating bound objects

Its structural properties reflect nature of DM

In particular, ***inner structures*** sometimes exhibit ***universal features***

→ a unique channel to access nature of DM



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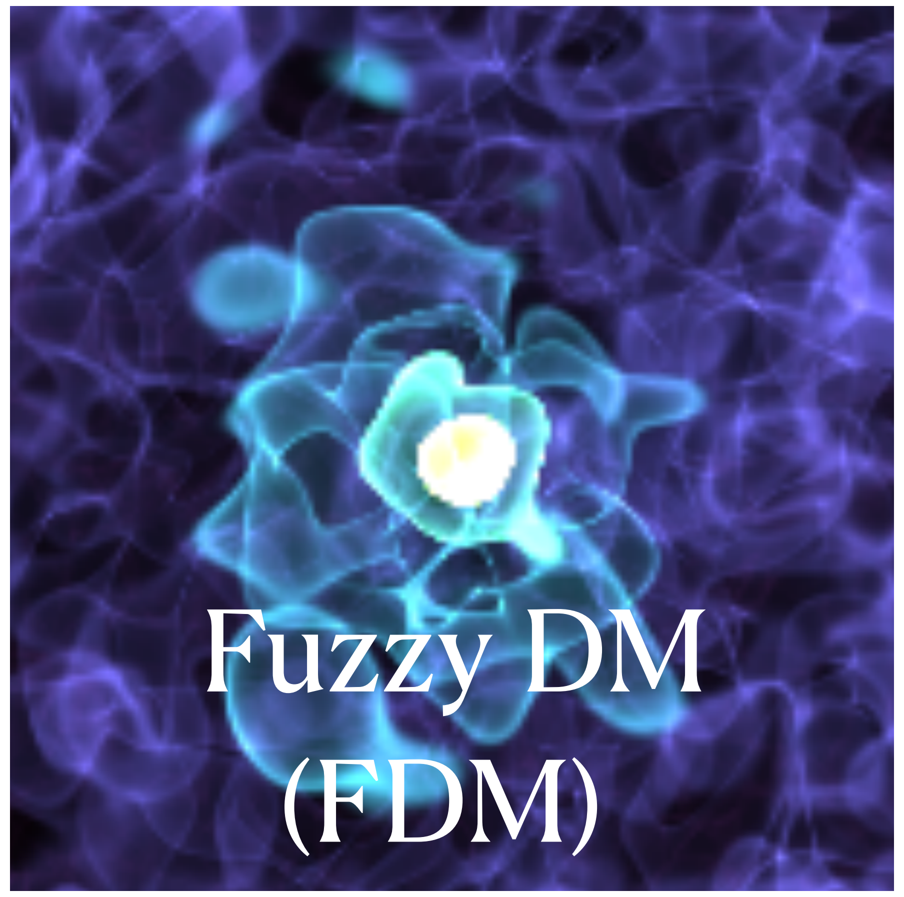


$m_{DM} \sim \mathcal{O}(10^{-22})\,\mathrm{eV}$

Rest of talk

Finding and clarifying universal features are very important toward observational probe of DM

$m_{\rm DM} \sim 100\,{\rm GeV}$

Based on numerical simulations,

New universal feature in multi-stream structures of DM halos

Y Enomoto, T. Nishimichi & AT, ApJL 950, L13 ('23), arXiv:2302.01531

$m_{\rm DM} \sim \mathcal{O}(10^{-22})$ eV

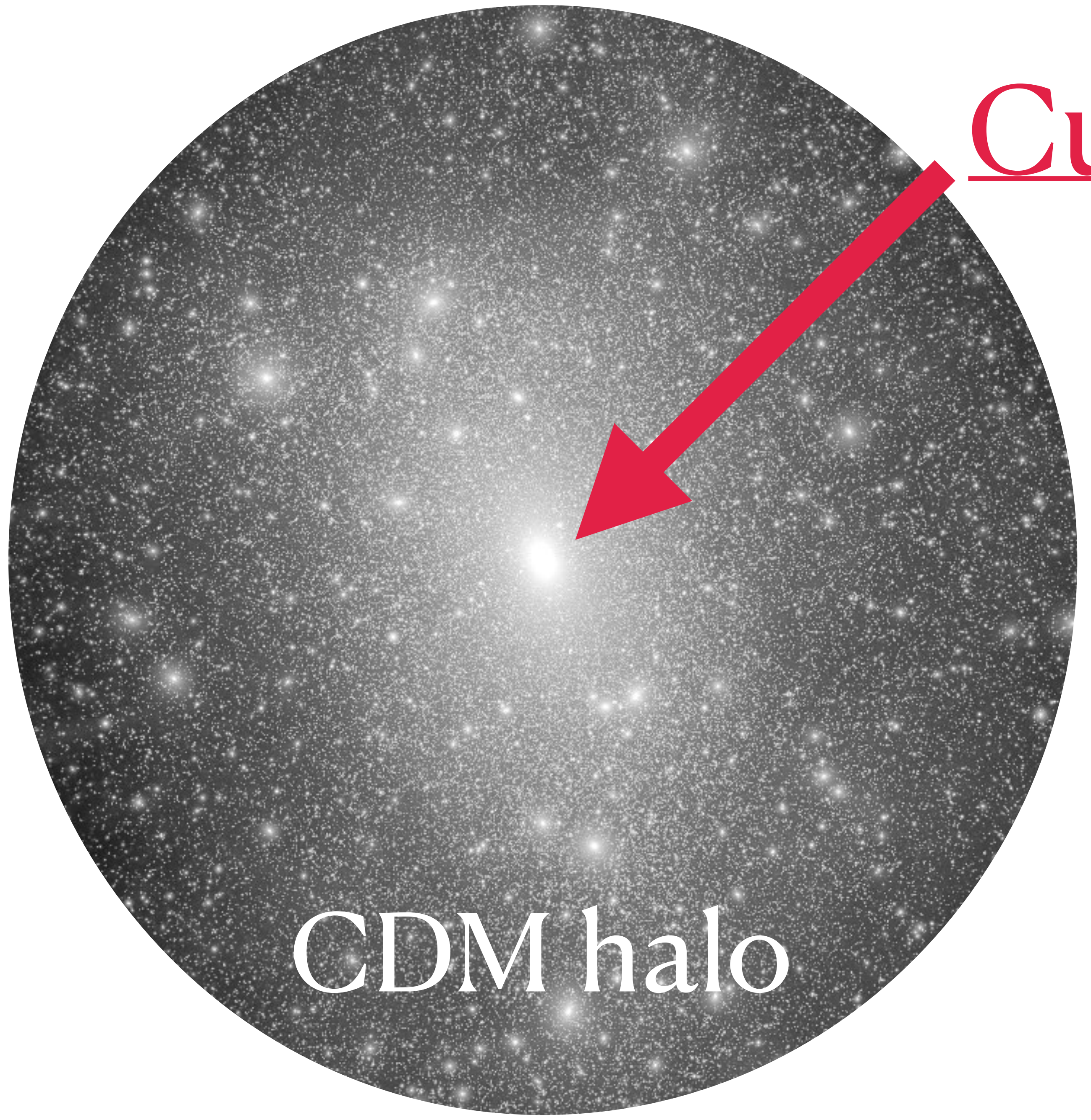
Based on analytical treatment,

Cosmological dependence of core-halo structures

AT & S. Saga, PRD 106, 103532 ('22), arXiv:2208.06562

Cold dark matter (CDM) halo

Baseline DM in the concordant cosmological model (ΛCDM)



Cuspy structure

Studied extensively by N-body simulations

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

(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 $Q(r) \equiv \rho(r)/\{\sigma_{\rm v}(r)\}^3$

(Taylor & Navarro '01)

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

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

Multi-stream nature of CDM halos

Cold nature of dark matter provides a distinctive feature in CDM halos

Negligible velocity dispersion at an early time

Through accretion/merger processes

CDM halos exhibit

Onion-like structure

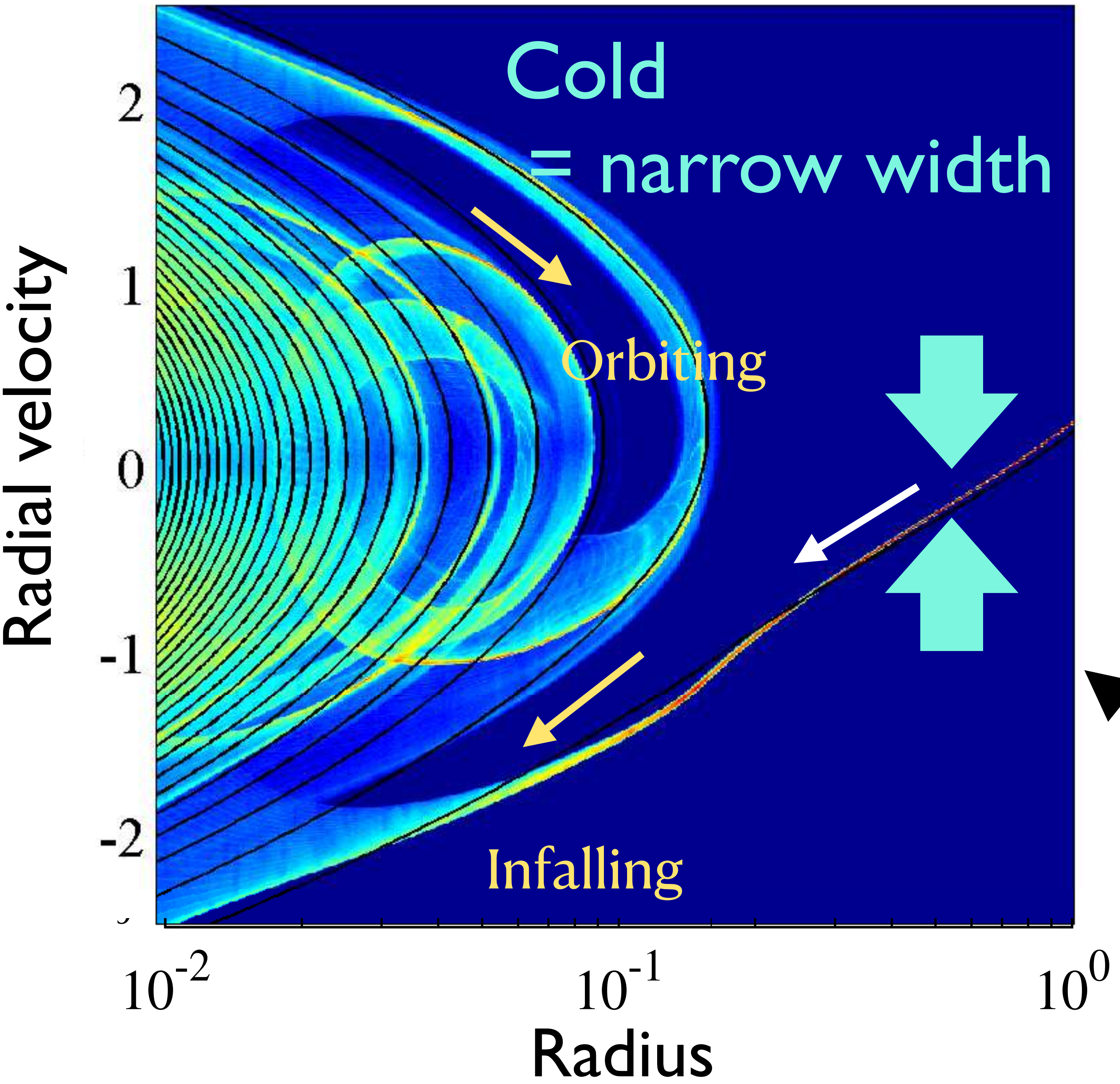
Multi-stream structures

with an outer sharp boundary

(=Splashback radius)

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

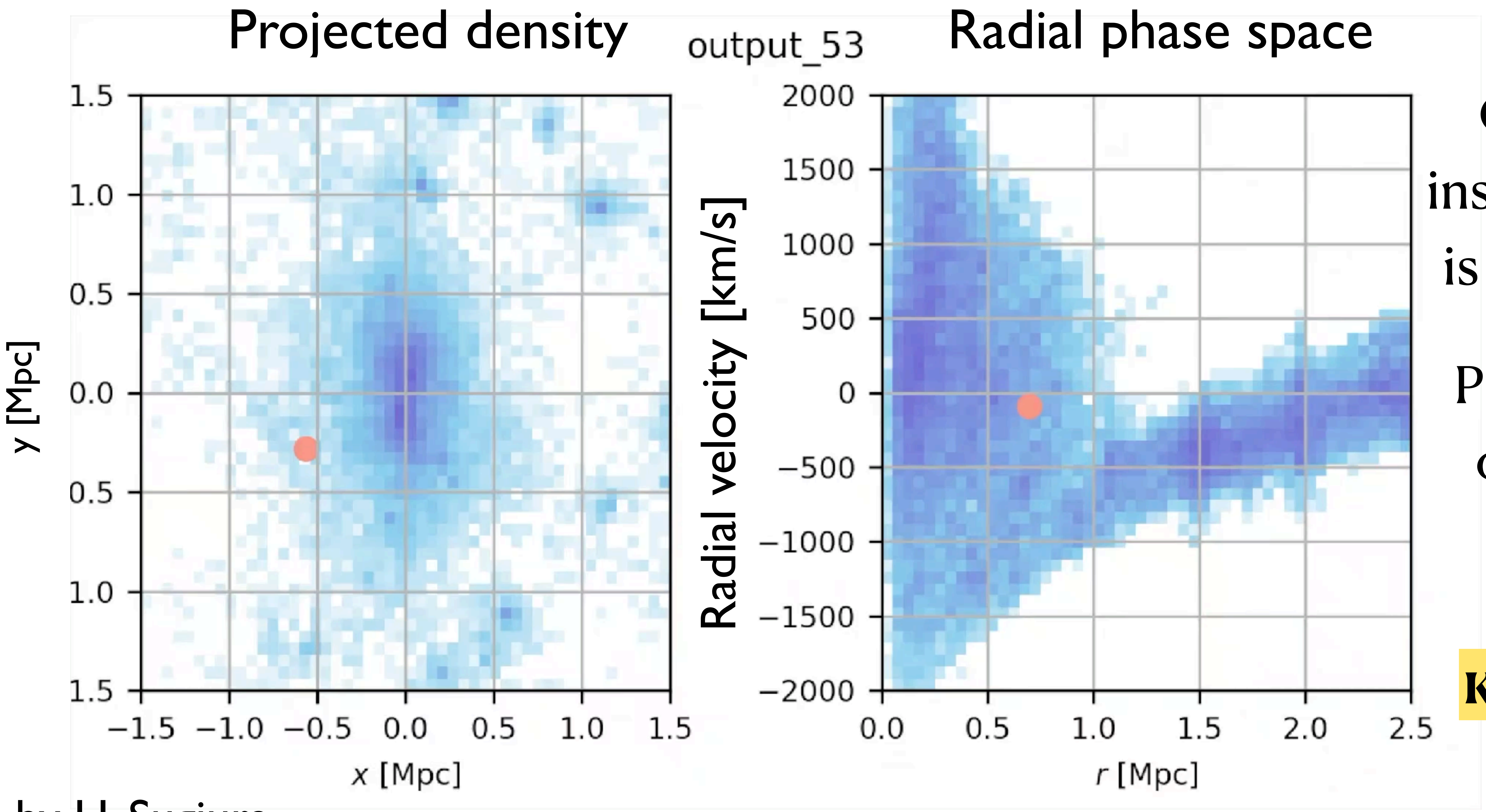
Adhikari, Dalal & Chamberlain ('14)



Prediction of self-similar solutions

Q Is there fundamental universal feature hidden in phase space ?

Characterizing multi-stream flow in simulations



Only one snapshot is insufficient to reveal what is happening inside halo

Provided the animation, one can deduce multi-stream flow

Key trajectories o f dark matter particles

by H. Sugiura

Tracing multi-stream flow with particles

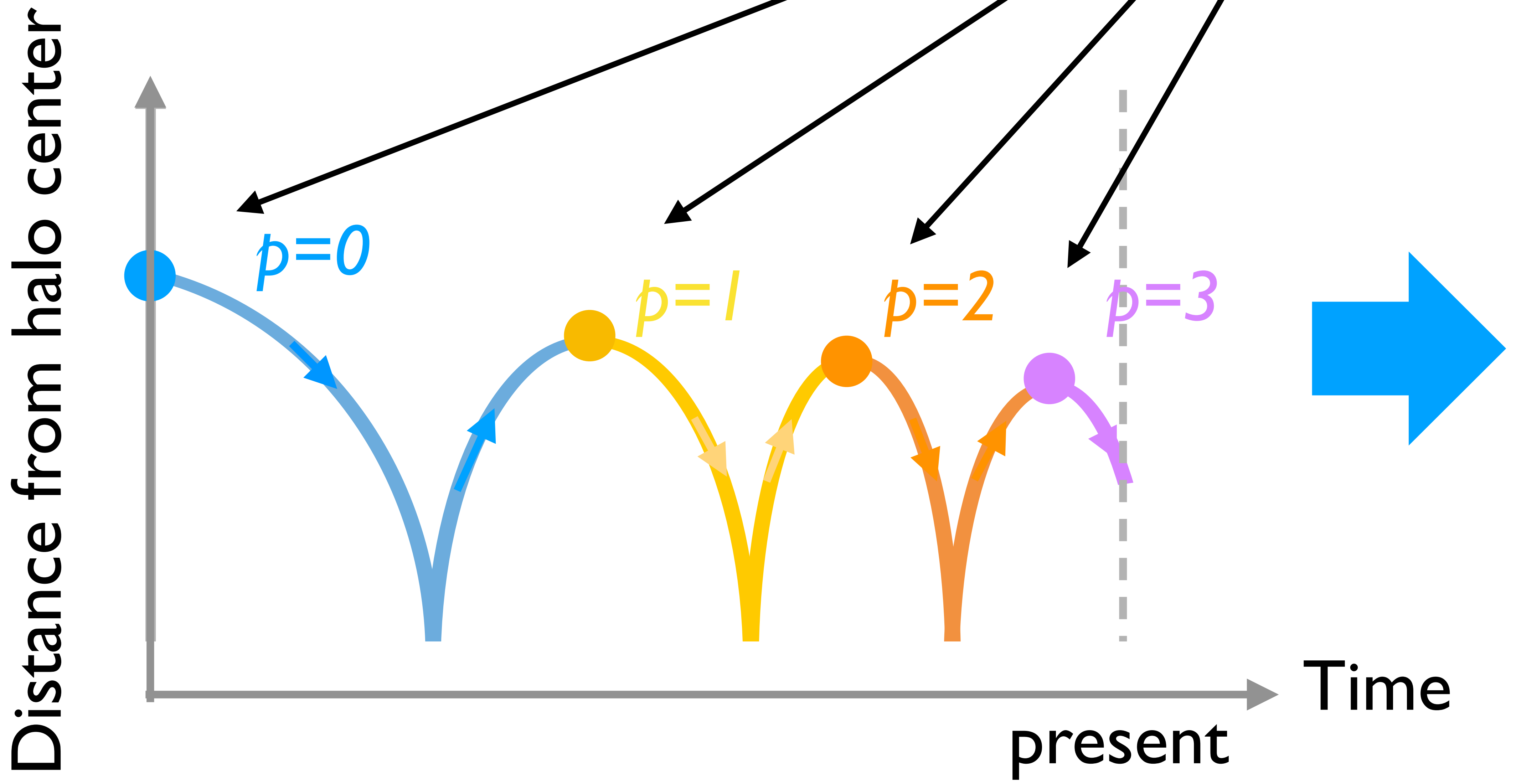
ΛCDM, $L_{\rm box} = 41\,h^{-1}$Mpc & $N_{\rm dm} = 500^3$

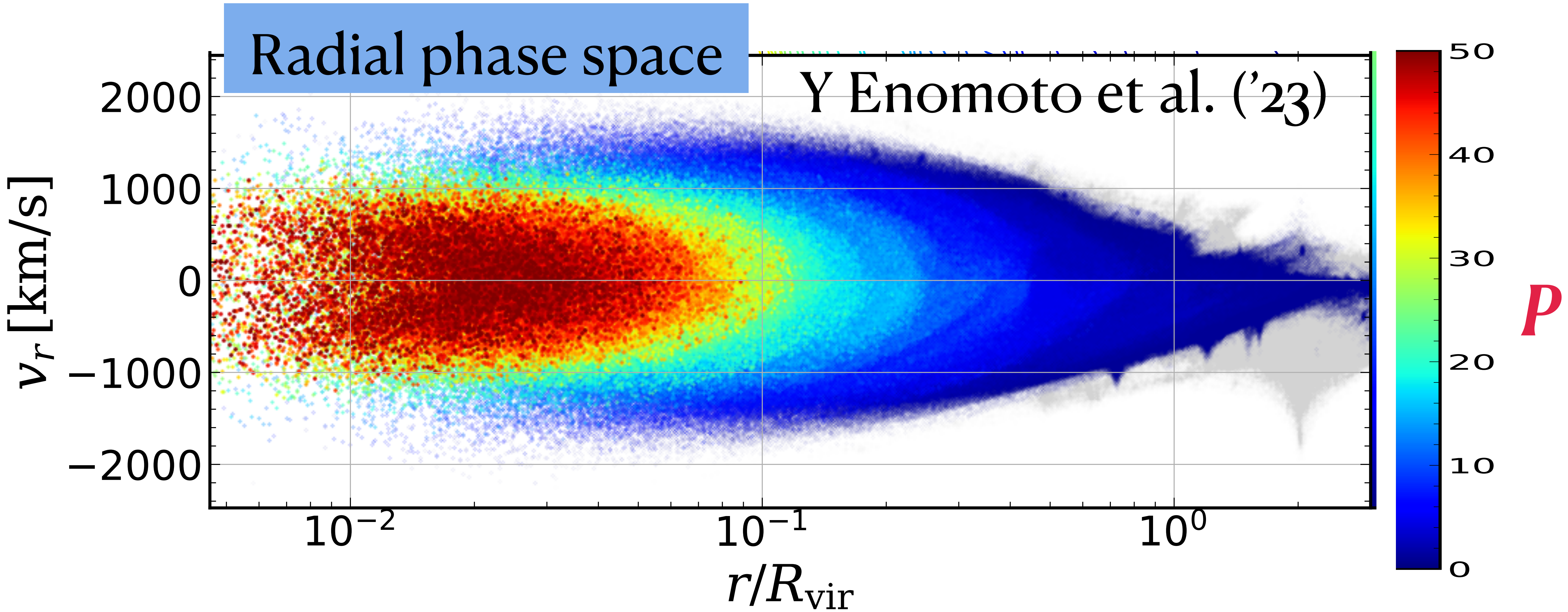
Using ***1,001*** snapshot data of cosmological *N*-body simulations over z=0~5

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 !!



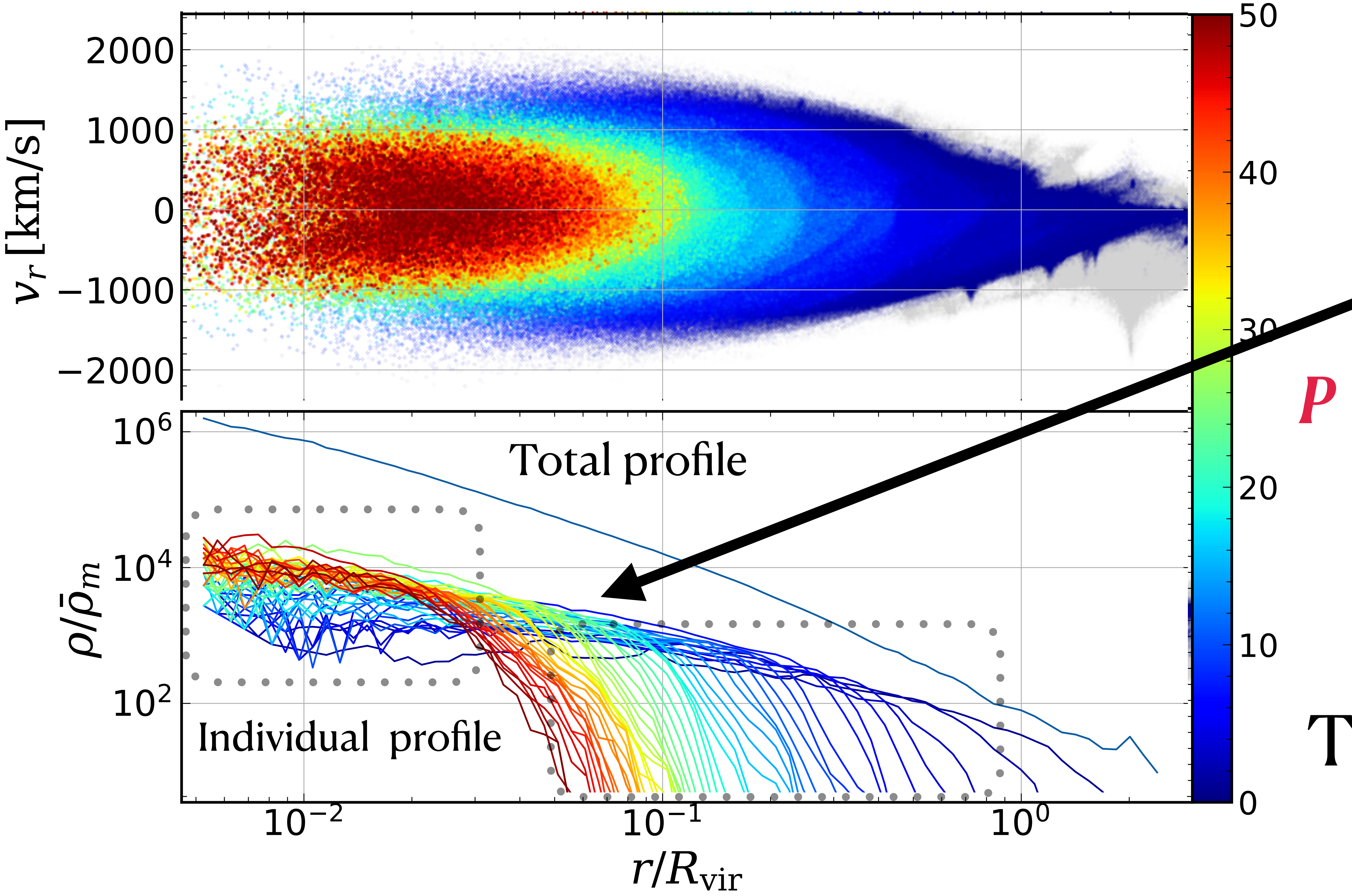


Multi-stream radial profiles

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 of halo masses (→next slide)

Stacked multi-stream radial profiles

Enomoto, Nishimichi & AT ('23)

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

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

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

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

Total profiles from multi-stream profiles

Enomoto, Nishimichi & AT ('23)

ΛCDM, $L_{\rm box} = 41\,h^{-1}$Mpc & $N_{\rm dm} = 2{,}000^3$

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

Comparison with self-similar solutions

Enomoto, Nishimichi & AT ('23, in prep.)

Self-similar solutions of collisionless shell (spherical)

(Filmore & Goldreich '84; Bertschinger '85; Sikivie et al. '97; Nusser '01)

Parameters: $(\epsilon,\ L)$

initial slope & angular momentum

None of the solutions consistently reproduce N-body results !! (In contrast to previous claim)

(Spherically symmetric)

(particularly for the inner slope of $\rho \propto r^{-1}$)

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Self-similar solutions of collisionless shell (spherical)

(Filmore & Goldreich '84; Bertschinger '85; Sikivie et al. '97; Nusser '01)

Parameters: $(\epsilon,\ L)$

initial slope & angular momentum

A more comprehensive theoretical study is necessary to understand the universal features, taking presumably angular momentum distribution into account

None of the solutions consistently reproduce N-body results !!

Spherically symmetric

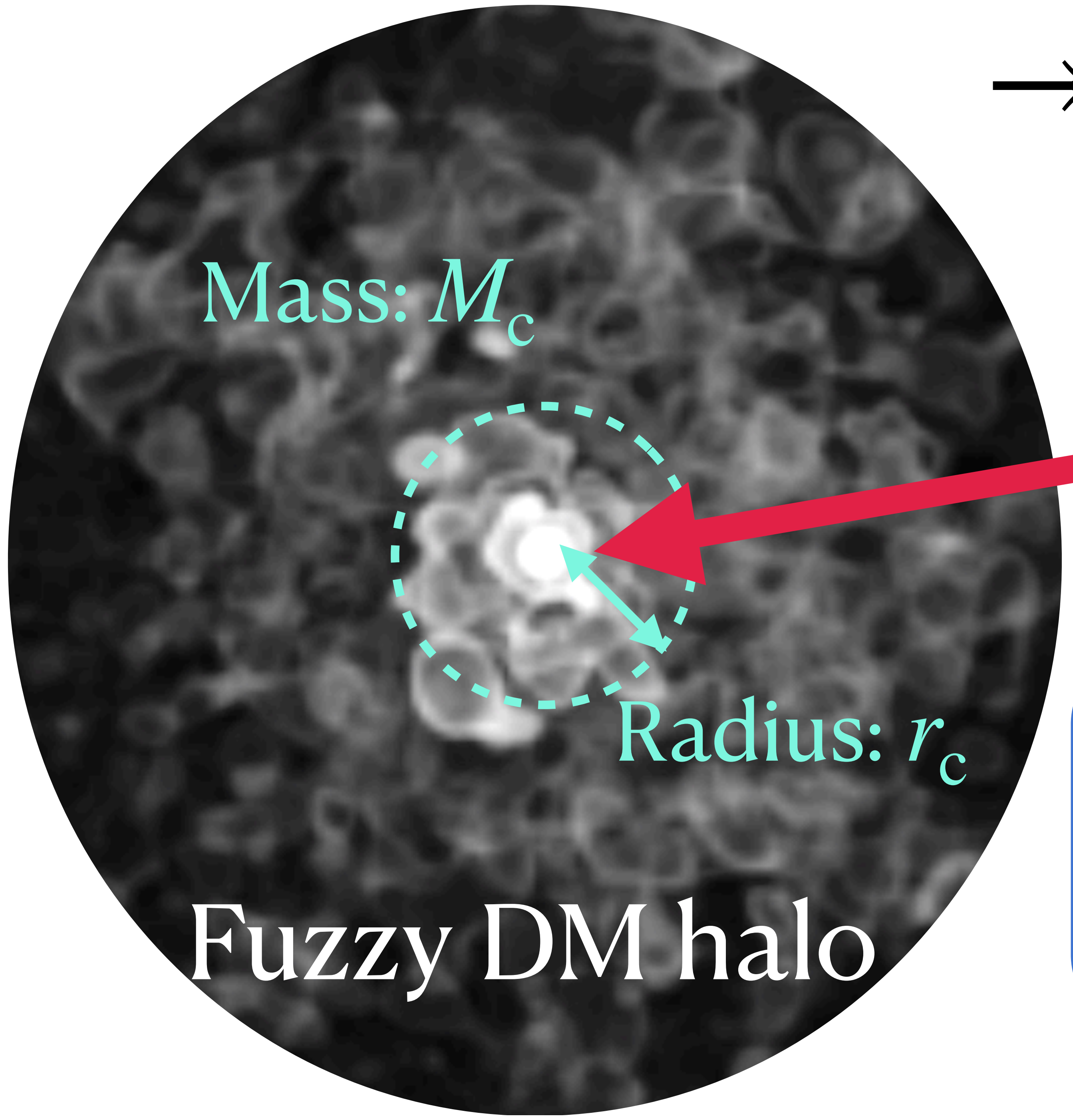
(particularly for the inner slope of $\rho \propto r^{-1}$)

In contrast to previous claim

Fuzzy dark matter (FDM) halo

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

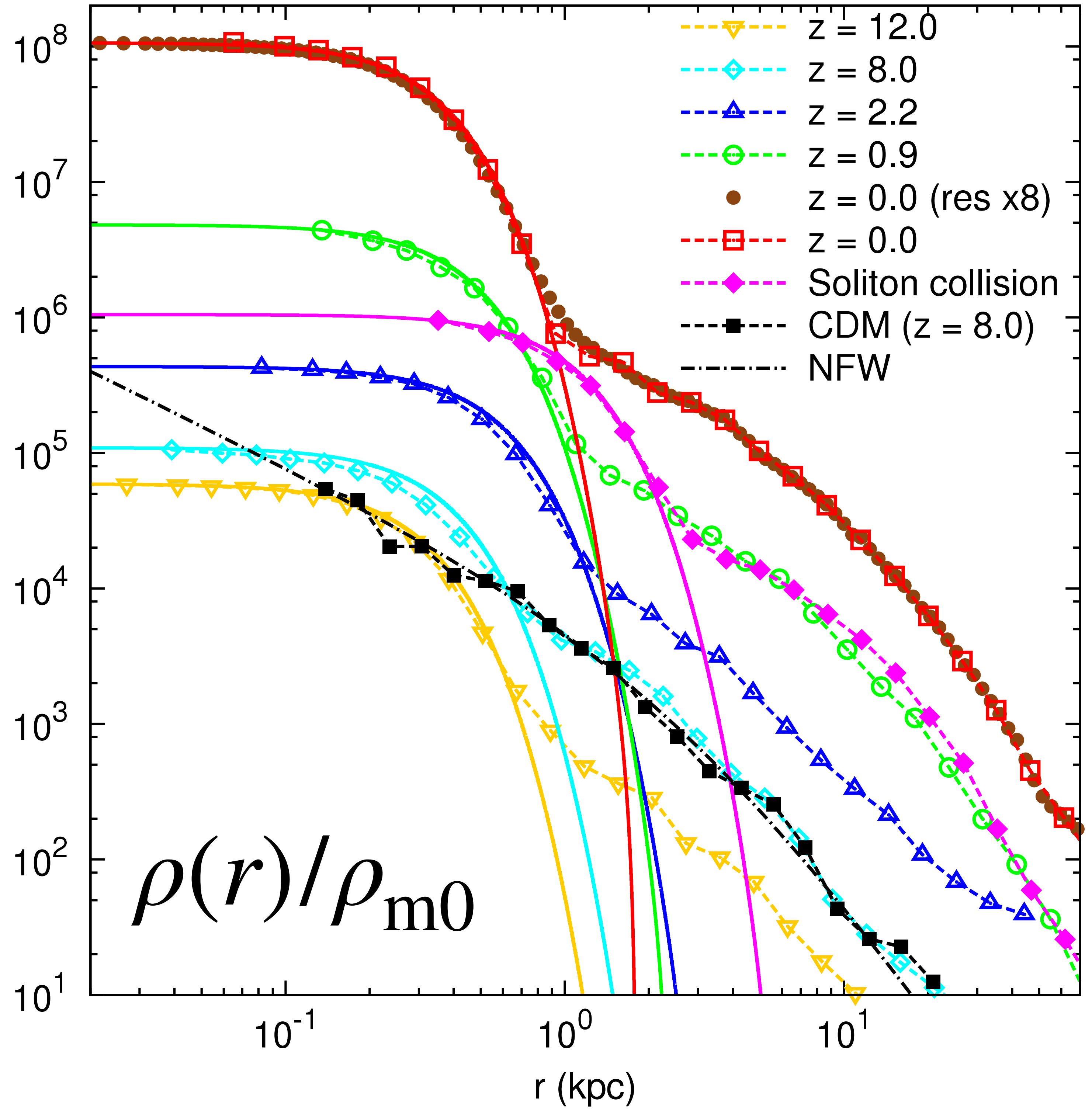
→ very long de Broglie wavelength ($\lambda_{\rm dB} \sim 0.5$kpc)



Flat dense core = ***soliton***

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

Schive et al. ('14)



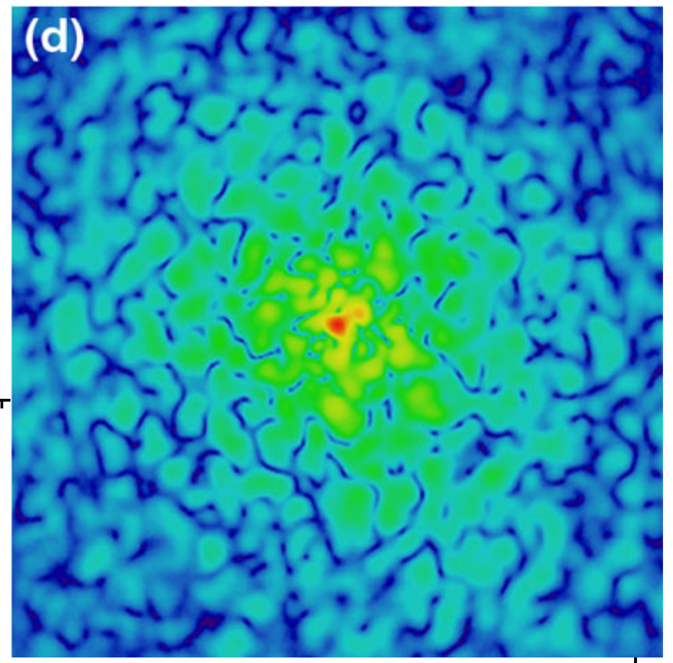
Intriguingly,

Properties of soliton core seem to be tightly related to those of overall halo (r_c & M_c)

(→ next)

Core-halo relations

Soliton core size (r_c) & mass (M_c) are correlated with halo mass (M_h),
following a *power-law* form

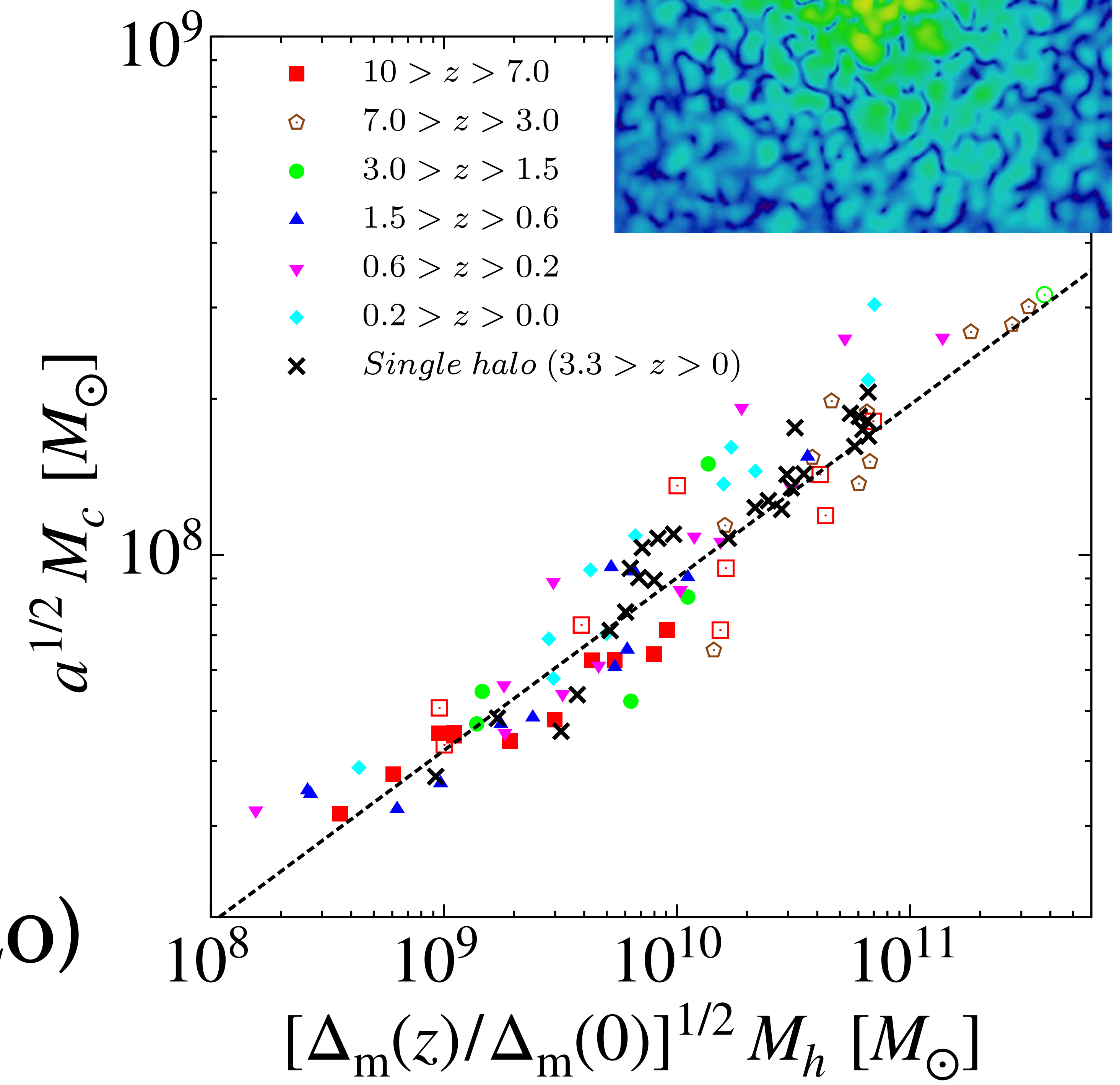


Core-halo relations (Schive et al. '14)

$$r_c \propto m_{\rm DM}^{-1} M_h^{-1/3}, \quad M_c \propto m_{\rm DM} M_h^{1/3}$$

M_h : Halo mass

$m_{\rm DM}$:Mass of FDM



→ Used for observational constraints on DM mass

(e.g., Schive et al. '14, Safarzadeh & Spergel '20; Hayashi & Obata '20)

c.f. Latest numerical works:

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

Q Can we better understand analytically the core-halo relations ?

Analytic description of soliton core

AT & Saga ('22)

Schrödinger-Poisson equations (Non-relativistic scalar field EOM coupled with gravity)

Assumptions

- Self-gravity of soliton ignored
- Soliton formed in (smooth) NFW halo $\rho_{\rm NFW}(r) = \dfrac{\rho_s}{(r/r_s)(1+r/r_s)^2}$

Linear eigenvalue problem $\phi \simeq \dfrac{1}{(2m_{\rm DM})^{1/2} a^{3/2}} (u_{\ell m}/x)\, e^{-i m_{\rm DM} \tau}$

$$\left[-\frac{d^2}{dx^2} - \alpha \frac{\log(1+x)}{x} + \frac{\ell(\ell+1)}{x^2} \right] u_{n\ell}(x) = \mathcal{E}_{n\ell}\, u_{n\ell}(x) \qquad \rho_{\rm soliton}(x) \propto \left| \frac{u_{n\ell}(x)}{x} \right|$$

Energy eigenvalue (dimensionless)

where we define $x \equiv \dfrac{r}{r_s}$, $\alpha \equiv 8\pi G m_{\rm DM}^2 \rho_s r_s^4\, a \sim \left(r_s/\lambda_{\rm dB} \right)^2 \gg 1$

Making use of $\alpha \gg 1$,one can obtain accurate approximate solutions (→next)

Super

(with technique beyond WKB approx.)

Analytic description of soliton core

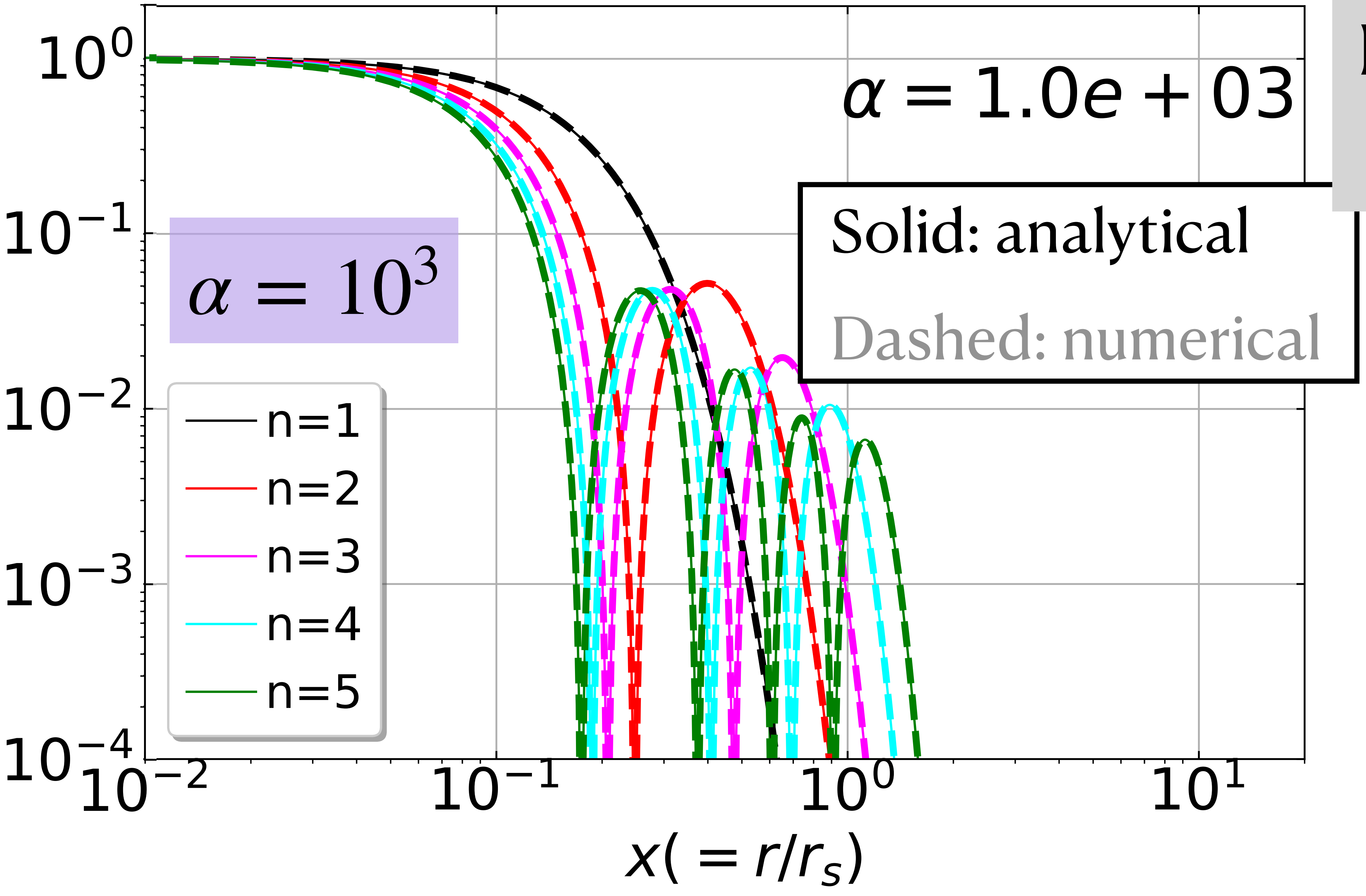
AT & Saga ('22)

Performance of approximate solutions ($\ell = 0$)

Eigenfunctions (u_{n0}) expressed analytically in terms of Airy function

Density profile
$\rho(x)/\rho(0)$

$\rho(x) \propto |u_{n0}(x)/x|^2$



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

In particular,

Ground-sate solution (n=1) reproduces the fitting formula of $\rho_{\rm soliton}(r)$ (Schive et al. '14)

Asymptotic behaviors of the n=1 solution gives analytical core-halo relations (→next)

Analytic description of soliton core

Analytical core-halo relations (AT & Saga '22)

Concentration parameter: $c_{\rm vir} \equiv r_{\rm vir}/r_{\rm s}$

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

Eigenvalues

$$g(c_{\rm vir}) \equiv \frac{\ln(1+c_{\rm vir})}{c_{\rm vir}} - \frac{1}{1+c_{\rm vir}}$$

- They look similar to the original expressions, but involve <u>additional factors</u> !
- Energy eigenvalue, $\mathscr{E}_{1,0}/\alpha$, is given as a function of parameter α, which depends on $c_{\rm vir}$

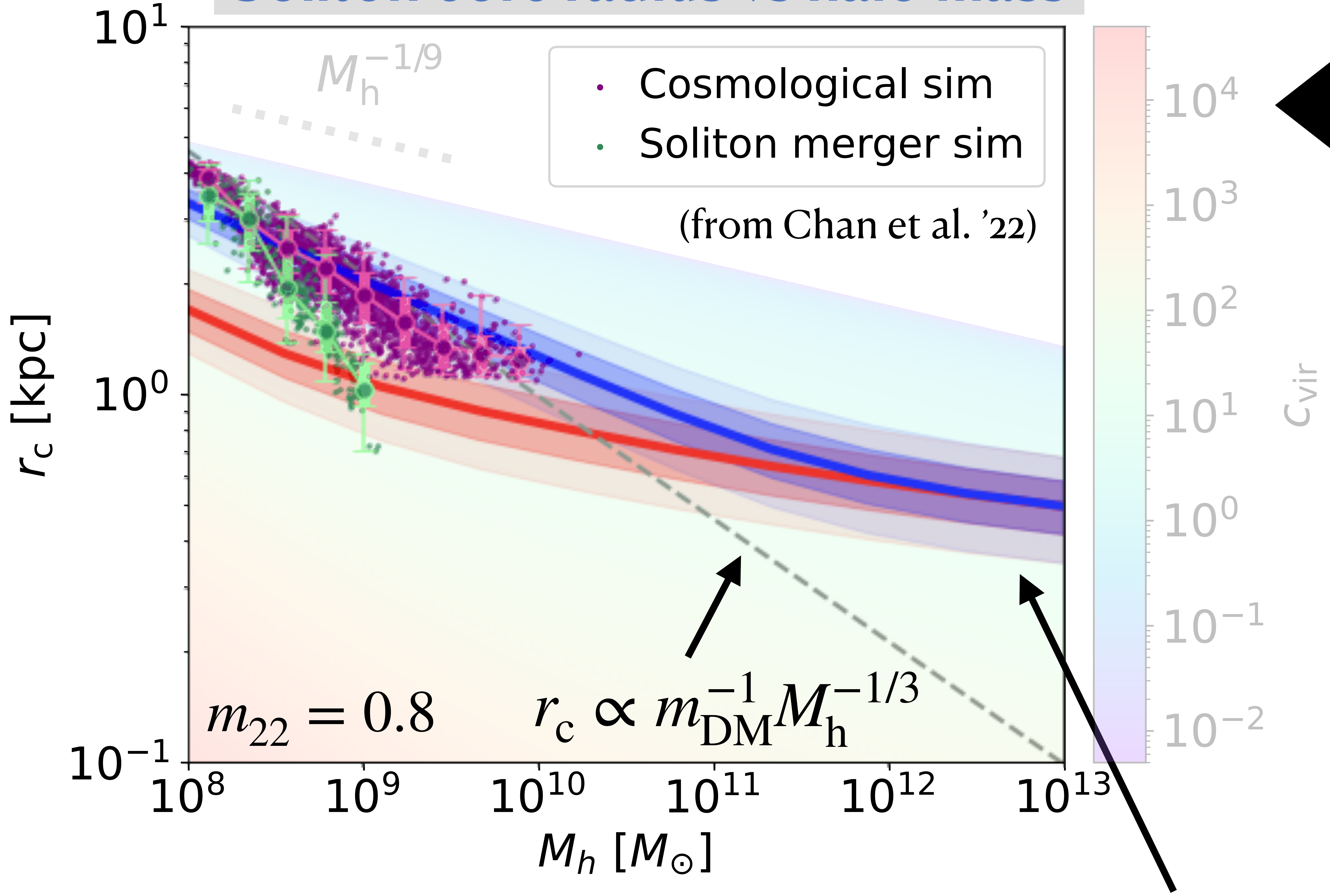
Through the concentraion-mass relation, $c_{\rm vir}(M_{\rm h})$,

predicted core-halo relations show a *non-trivial* dependence on halo mass (→next)

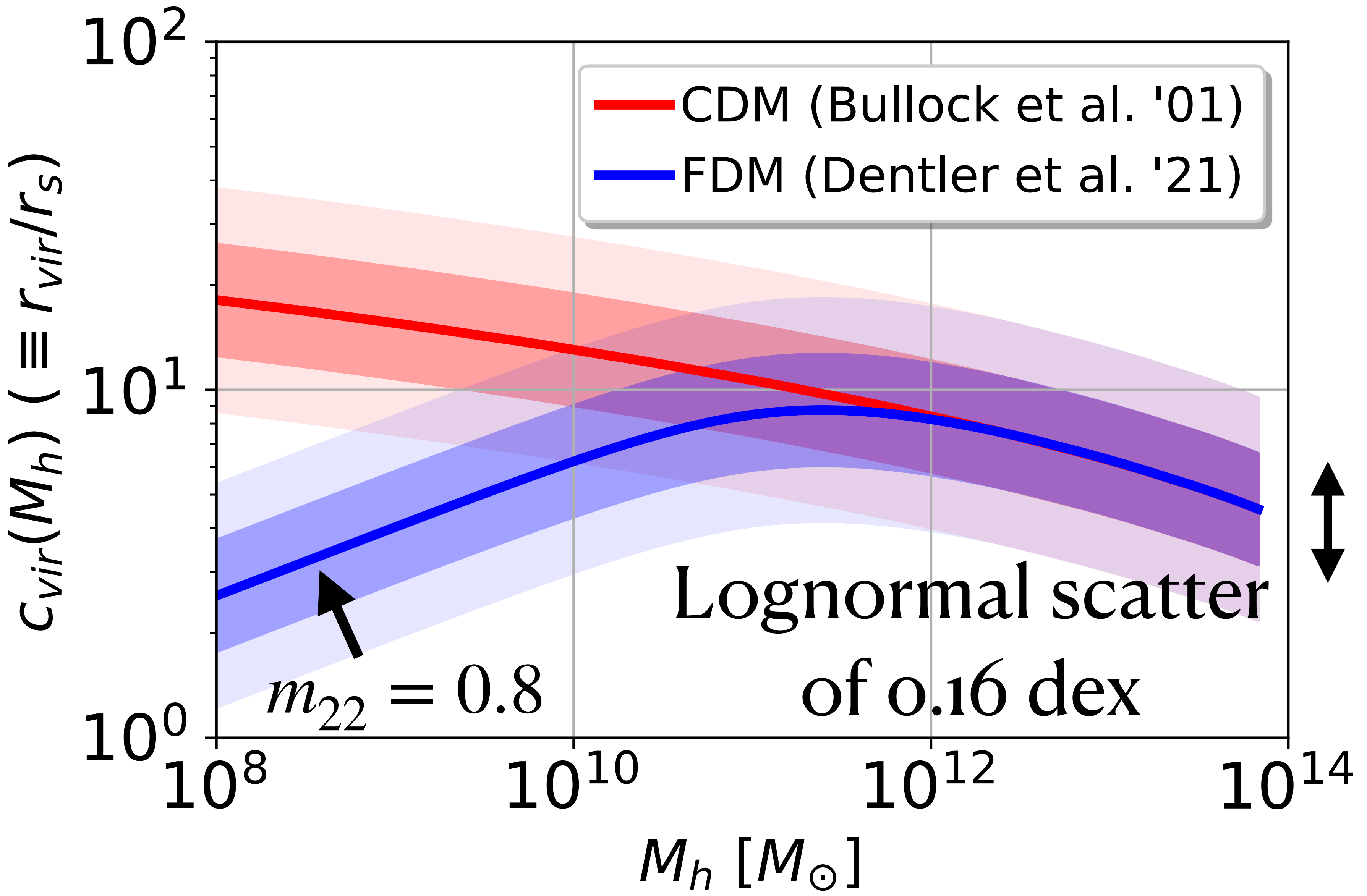
Predicted core-halo relations

AT & Saga ('22)

Soliton core radius vs halo mass



Incorporating a model of $c_{vir}(M_h)$ into the analytical results

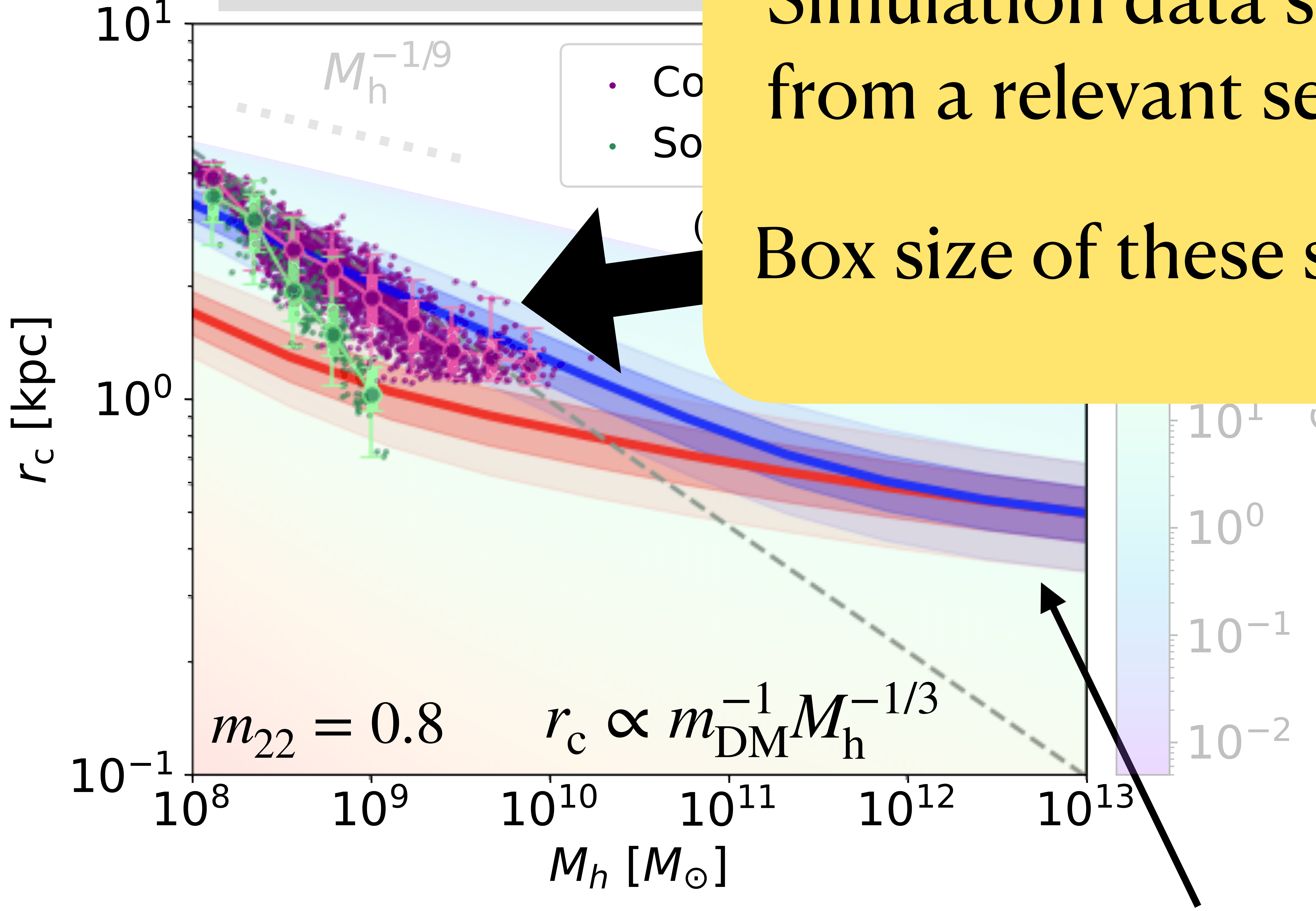


Predictions exhibit ***non power-law behaviors*** with ***a large scatter*** (consistent with simulations ?)

Predicted core-halo relations

AT & Saga ('22)

Soliton core radiu

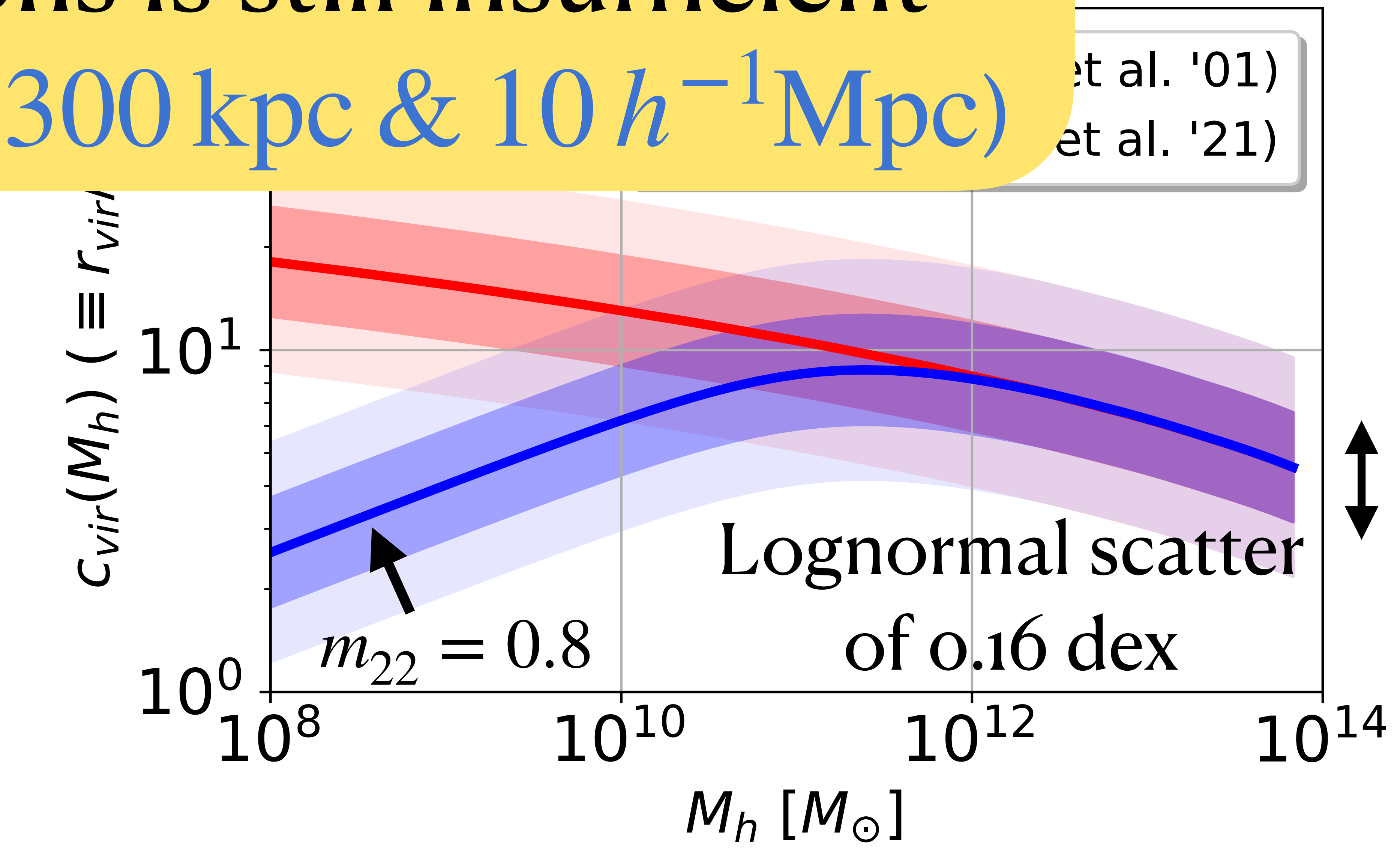


Simulation data shown here are not obtained from a relevant setup with small-scale cutoff

Box size of these simulations is still insufficient ($L_{box} = 300\,\mathrm{kpc}\ \&\ 10\,h^{-1}\mathrm{Mpc}$)

$c_{vir}(M_h)$

ults



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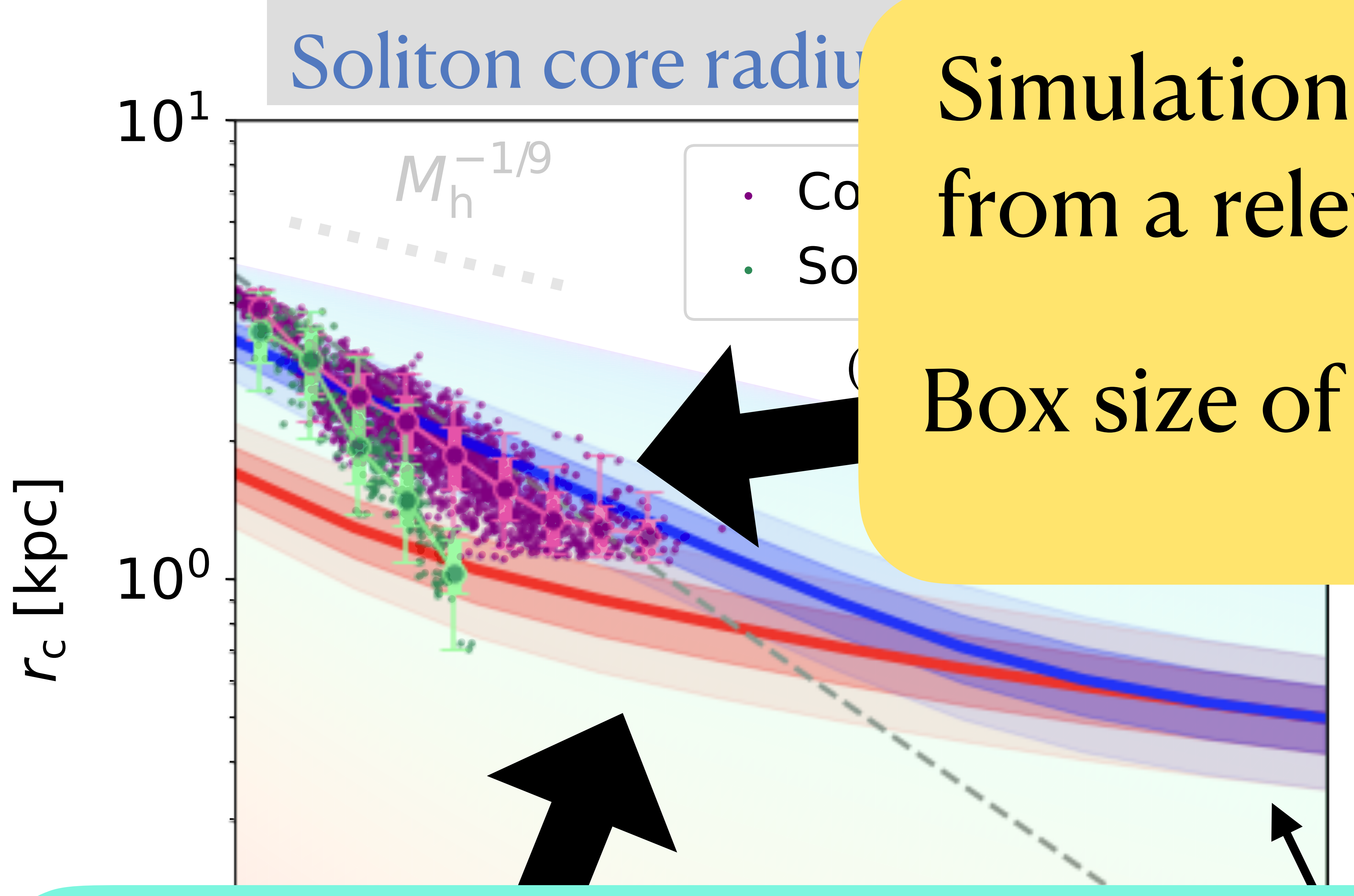

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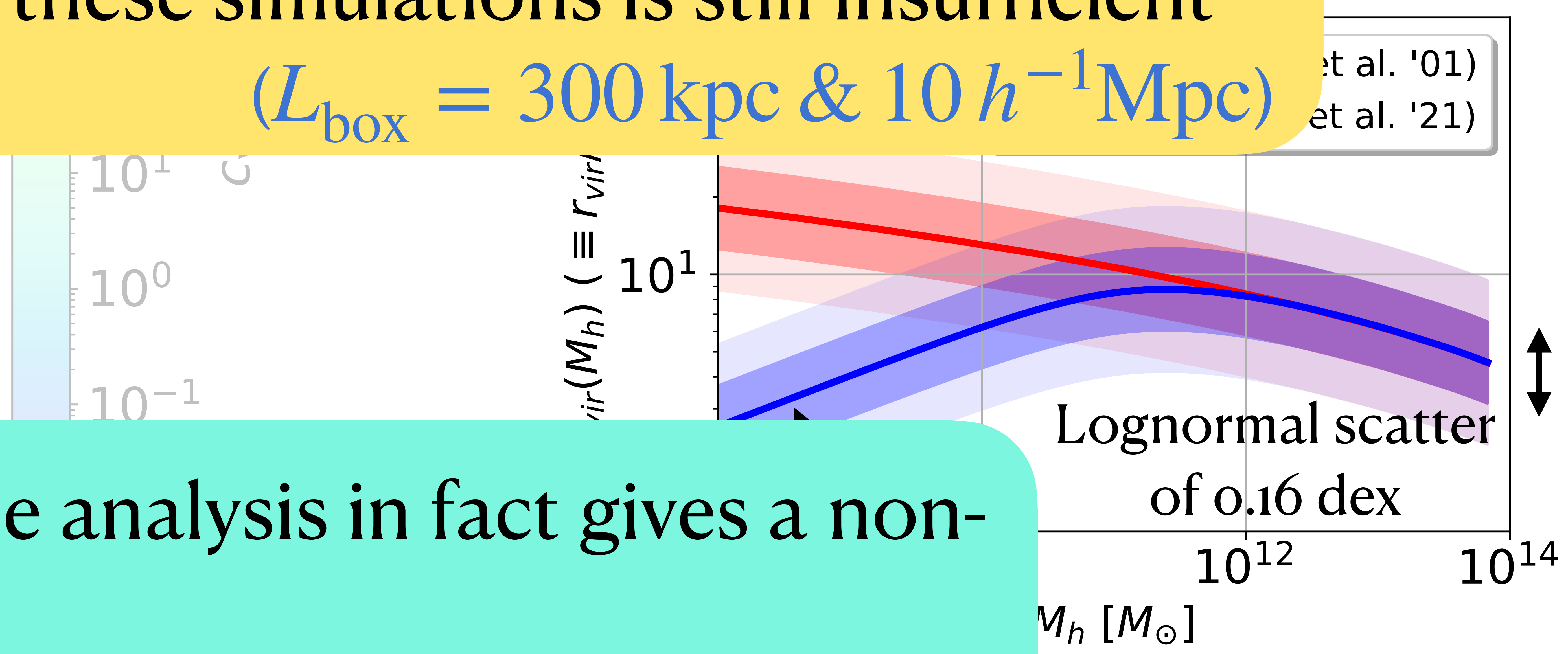


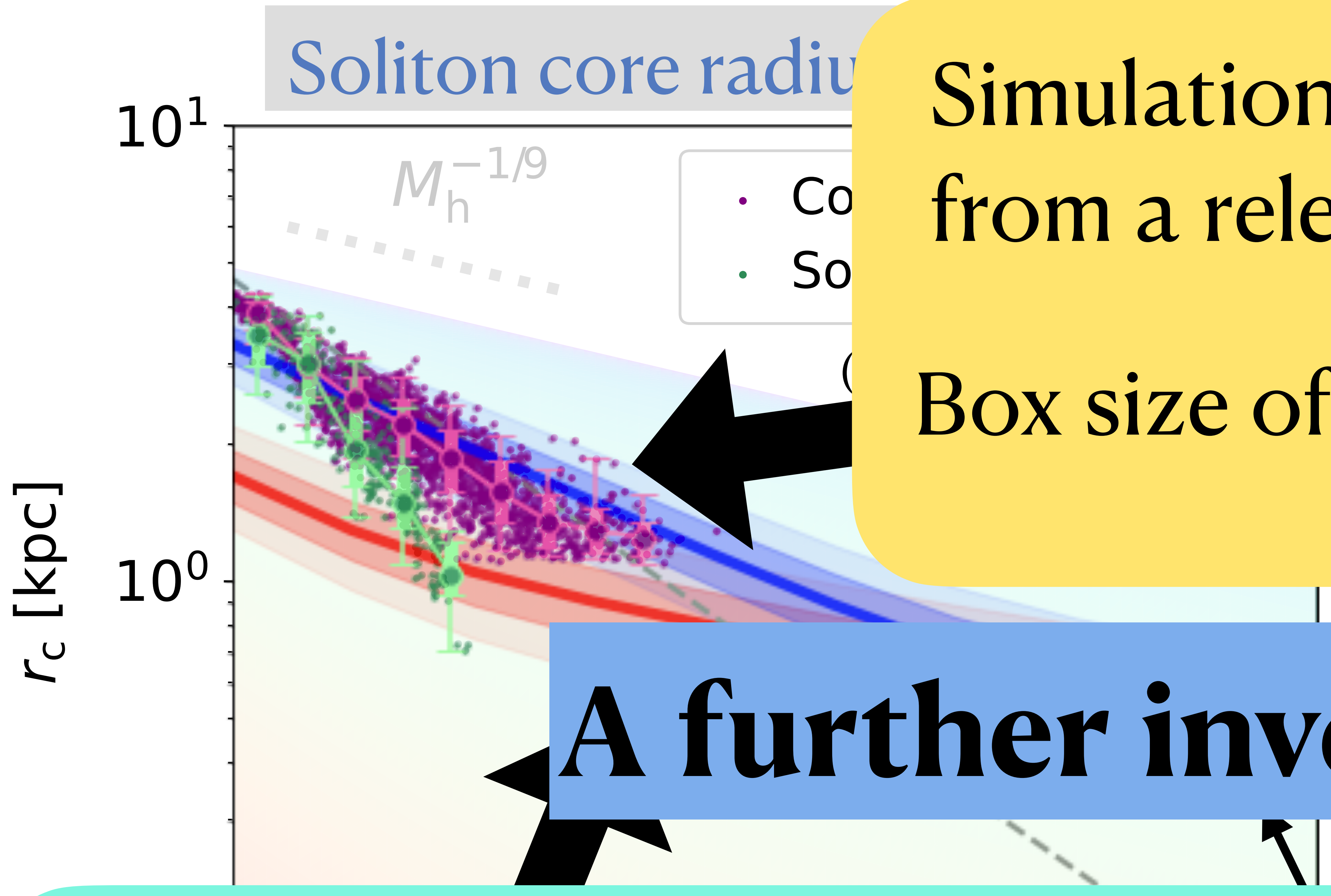
Soliton's self-gravity ignored in the analysis in fact gives a non-negligible impact

(but our perturbative estimation suggests only ~**20% change**)

aw behaviors with *a large scatter* (consistent with simulations ?)

Predicted core-halo relations

AT & Saga ('22)



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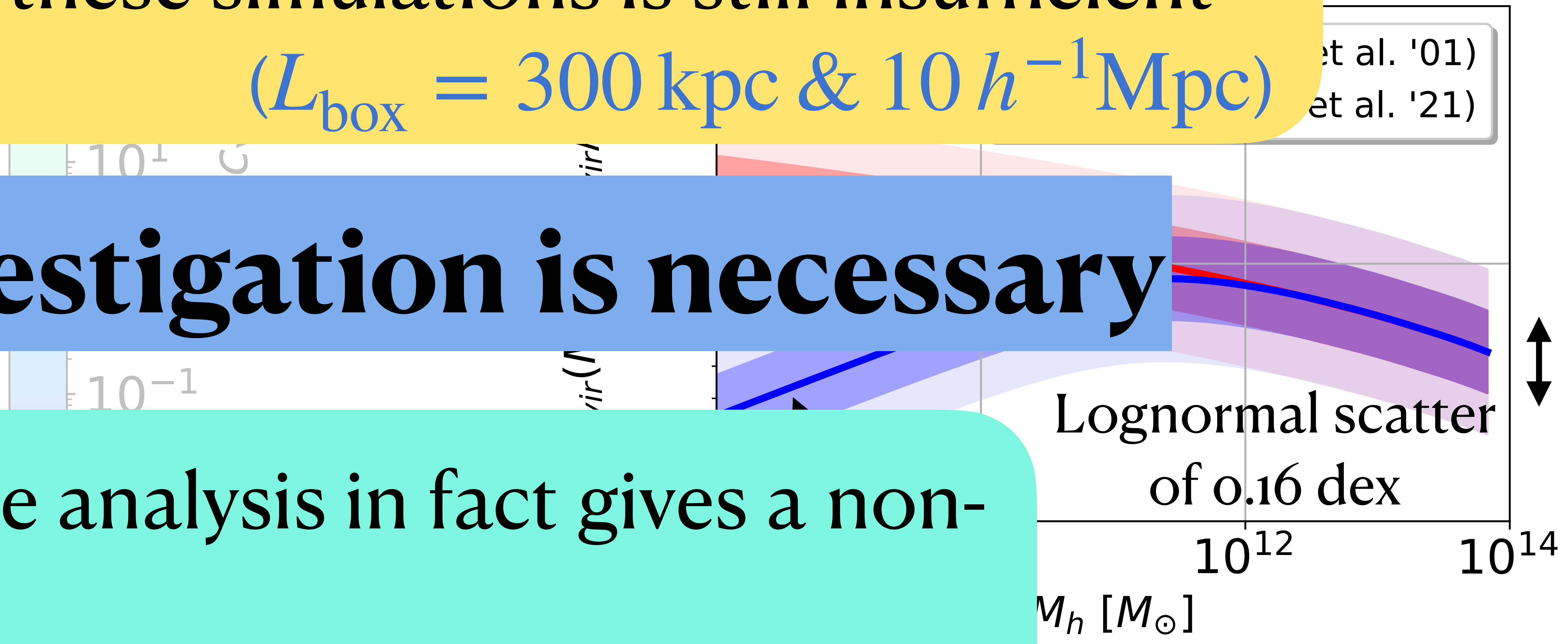
Box size of these simulations is still insufficient

$(L_{\rm box} = 300\,{\rm kpc}\ \&\ 10\,h^{-1}{\rm Mpc})$

$c_{\rm vir}(M_{\rm h})$

ults



A further investigation is necessary

Soliton's self-gravity ignored in the analysis in fact gives a non-negligible impact

(but our perturbative estimation suggests only ~**20% change**)

aw behaviors with *a large scatter* (consistent with simulations ?)

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)

Y Enomoto, T. Nishimichi & AT, ApJL 950, L13 ('23), arXiv:2302.01531

A new universal feature found in multi-stream structures

(self-similar solutions fail to explain)

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 & S. Saga, PRD 106, 103532 ('22), arXiv:2208.06562

A missing factor in core-halo relations found analytically

→ non power-law core-halo relation with a large scatter

Understanding (non-)universal features in DM halos largely impacts cosmology