Dynamics of halos: Boundary, accretion and tidal stripping

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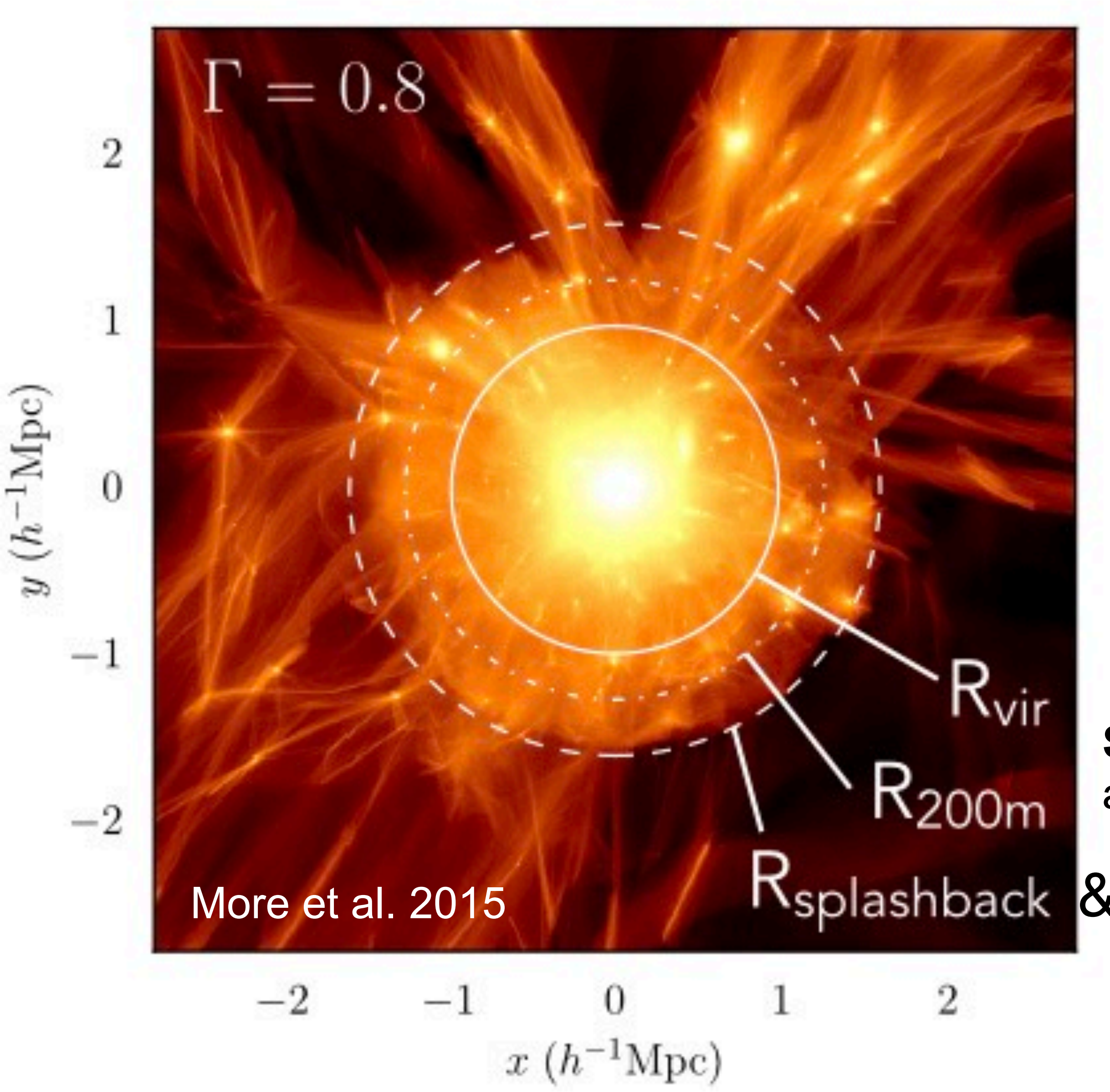
Avishai Dekel, Nir Mandelker (Hebrew U), Fangzhou Jiang (PKU), Jonathan Freundlich (Strasbourg)...

SJTU
May 25, 2025

Formation and dynamical evolution of halos



& $R_{depletion}$

Key dynamical drivers

❖ Accretion/mergers

❖ Tidal environment (esp. for satellites)

❖ Baryonic feedback (mostly for inner halo)

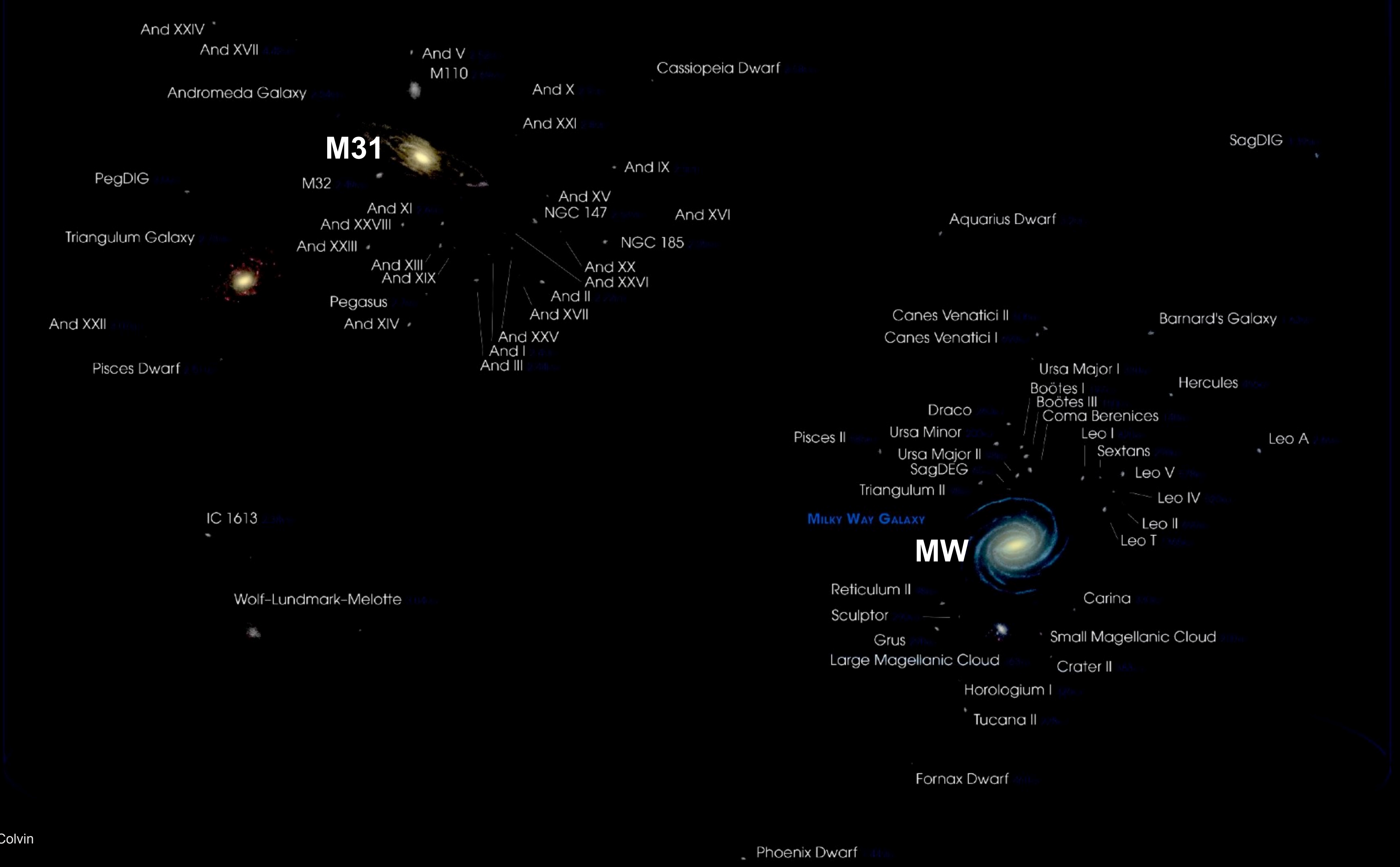
Topics I wish discuss

- **Measuring halo:** mass/boundary of MW
- **Assembly** of halo structure
- Modeling **dynamical evolution**

Satellites: tracers of halo structure;
also interesting subjects themselves

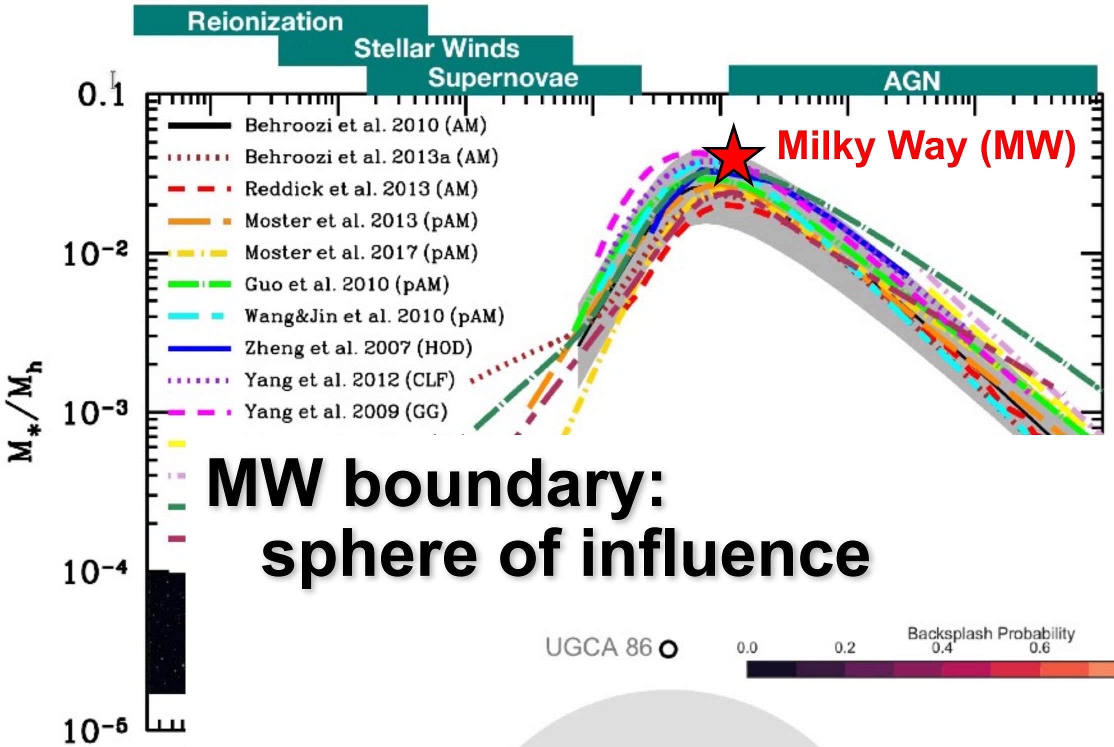
I. Measuring the Milky Way halo

LOCAL GROUP

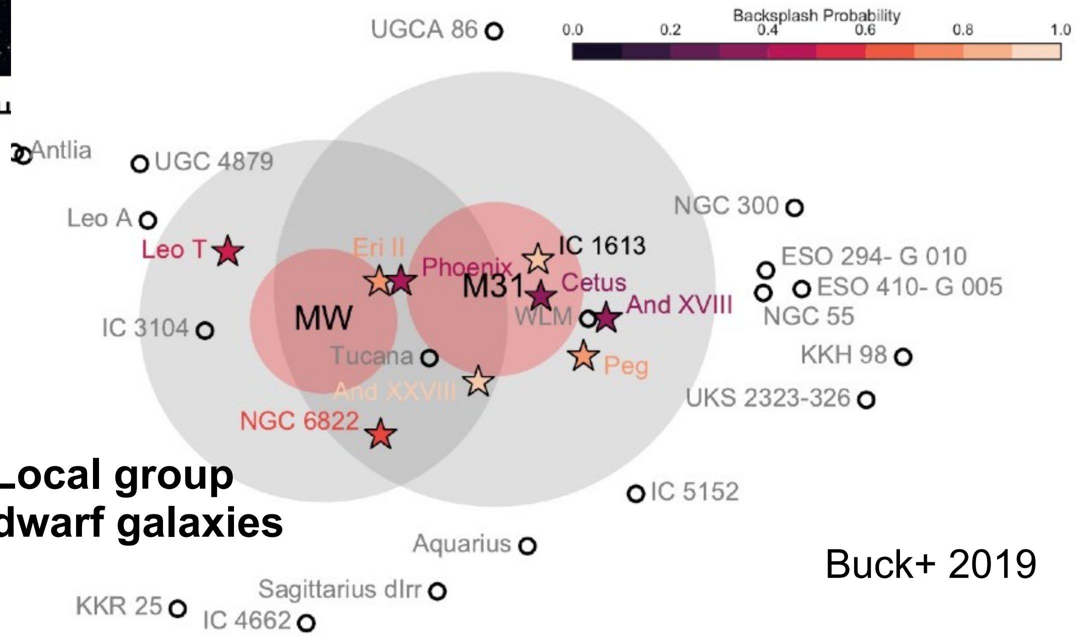


Credit: Andrew Z. Colvin

MW mass: placing the MW in context



MW boundary: sphere of influence

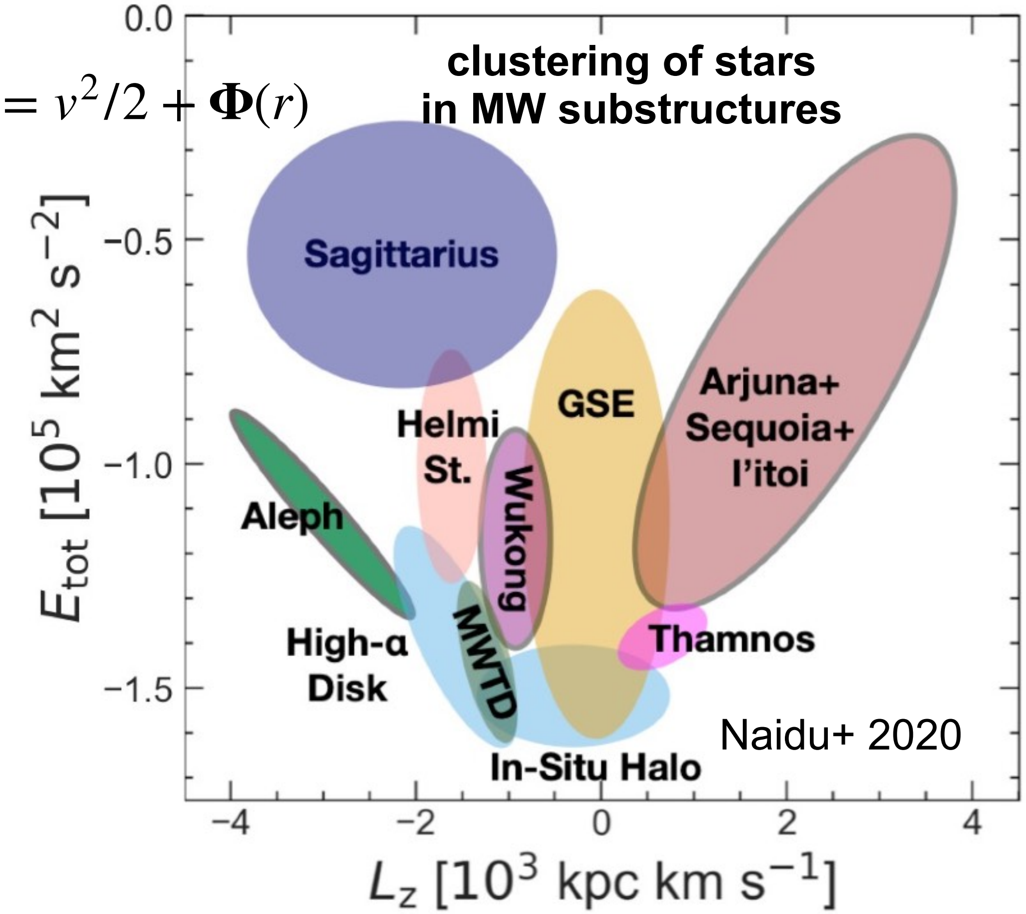


Local group dwarf galaxies

Buck+ 2019

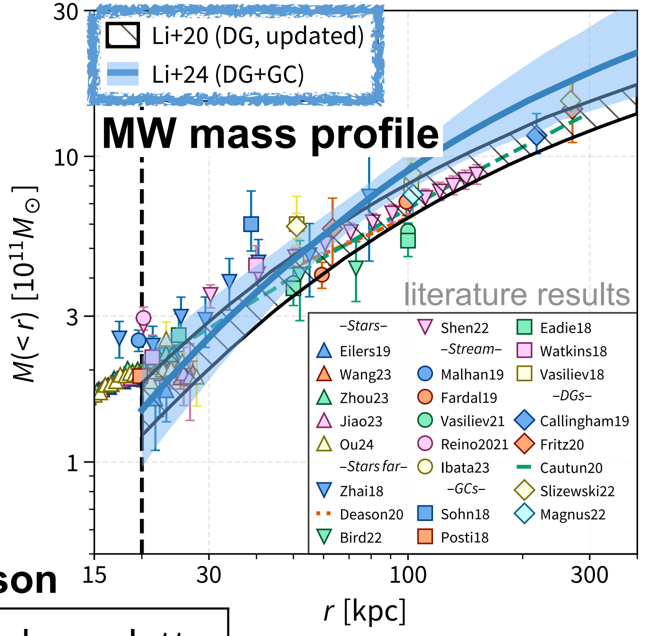
MW mass profile: understanding the MW structure

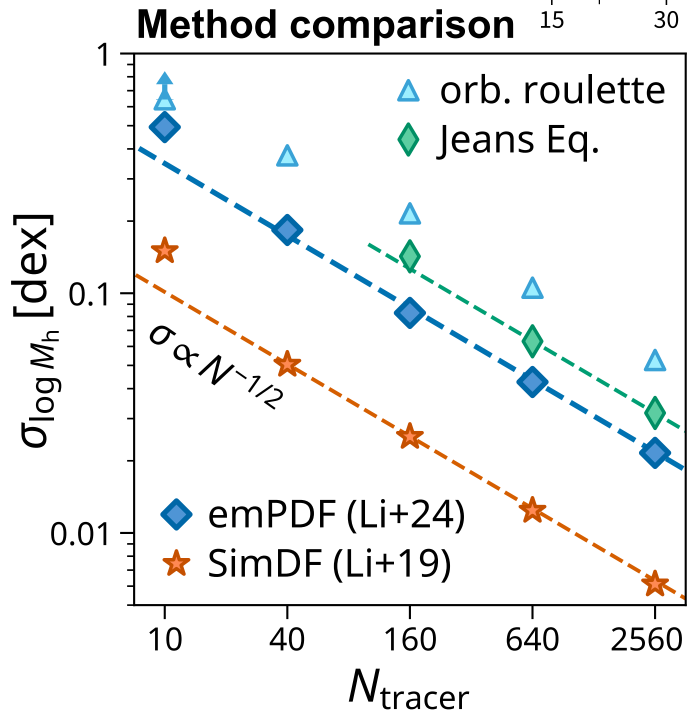
$$E = v^2/2 + \Phi(r)$$



Measure the Milky Way Mass/Boundary

- ❖ Difficult! --obs. error and incompleteness in MW outer halo
- ❖ Simulation-based model for motion of MW *satellite galaxies*
  - ✓ Realistic efficient model learnt from simulations **(Li+ 17,19;** initial orbits: **Li+20a)**
  - ✓ Robust estimates of MW mass profile >100kpc **(Li+ 20b)**
  - ✓ Reversely: observation as benchmark of simulations
- ❖ Data-driven model for MW *general tracers* **(Li+ 25)**
  - ✓ **Optimal efficiency** under minimum assumptions of oPDF **(Han+16)**
  - ✓ Being applied to halo stars
- ❖ Depletion radius of MW halo **(Li & Han 21)**





precision of halo mass estimate:

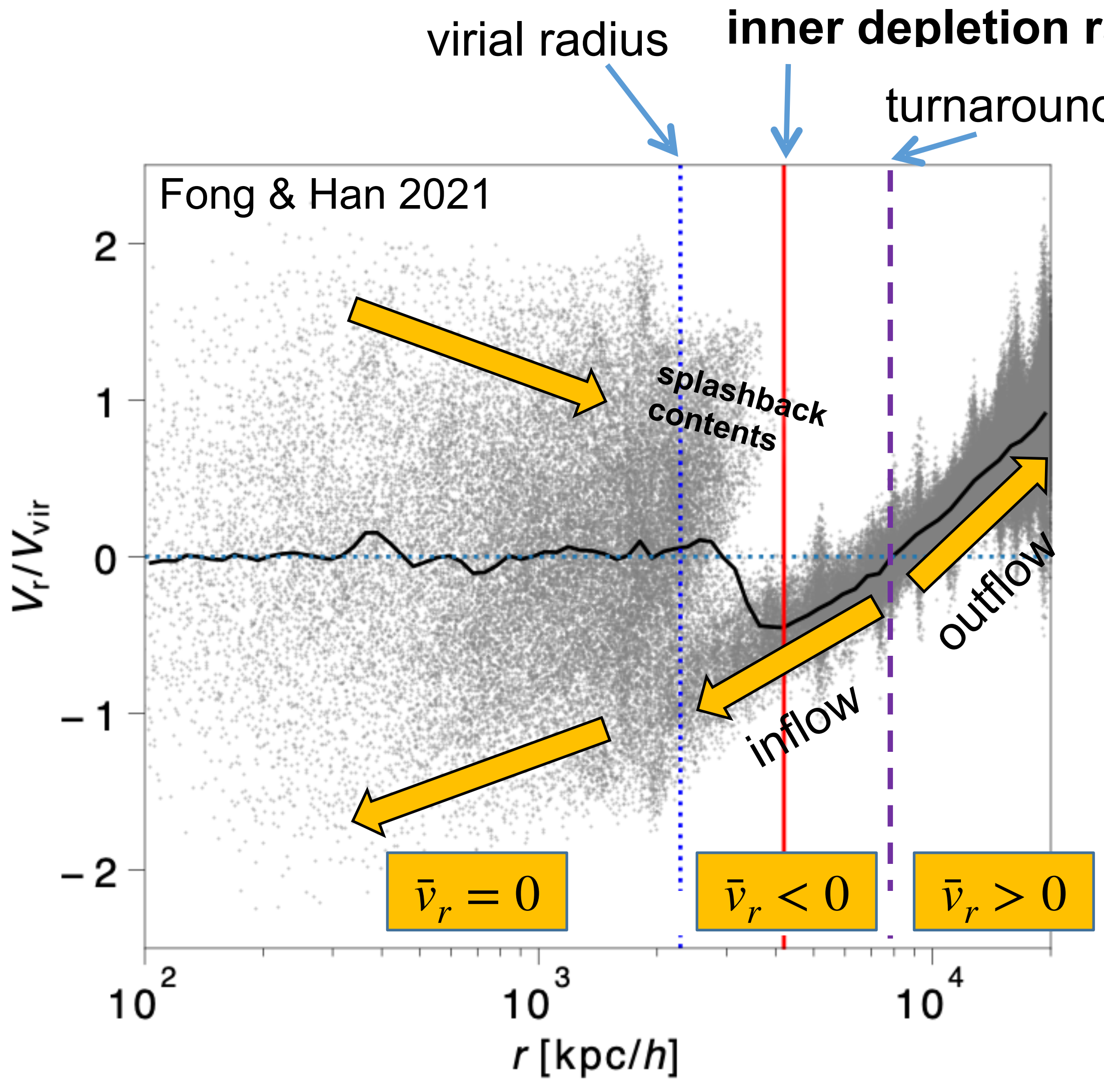
classic Jeans Eq.

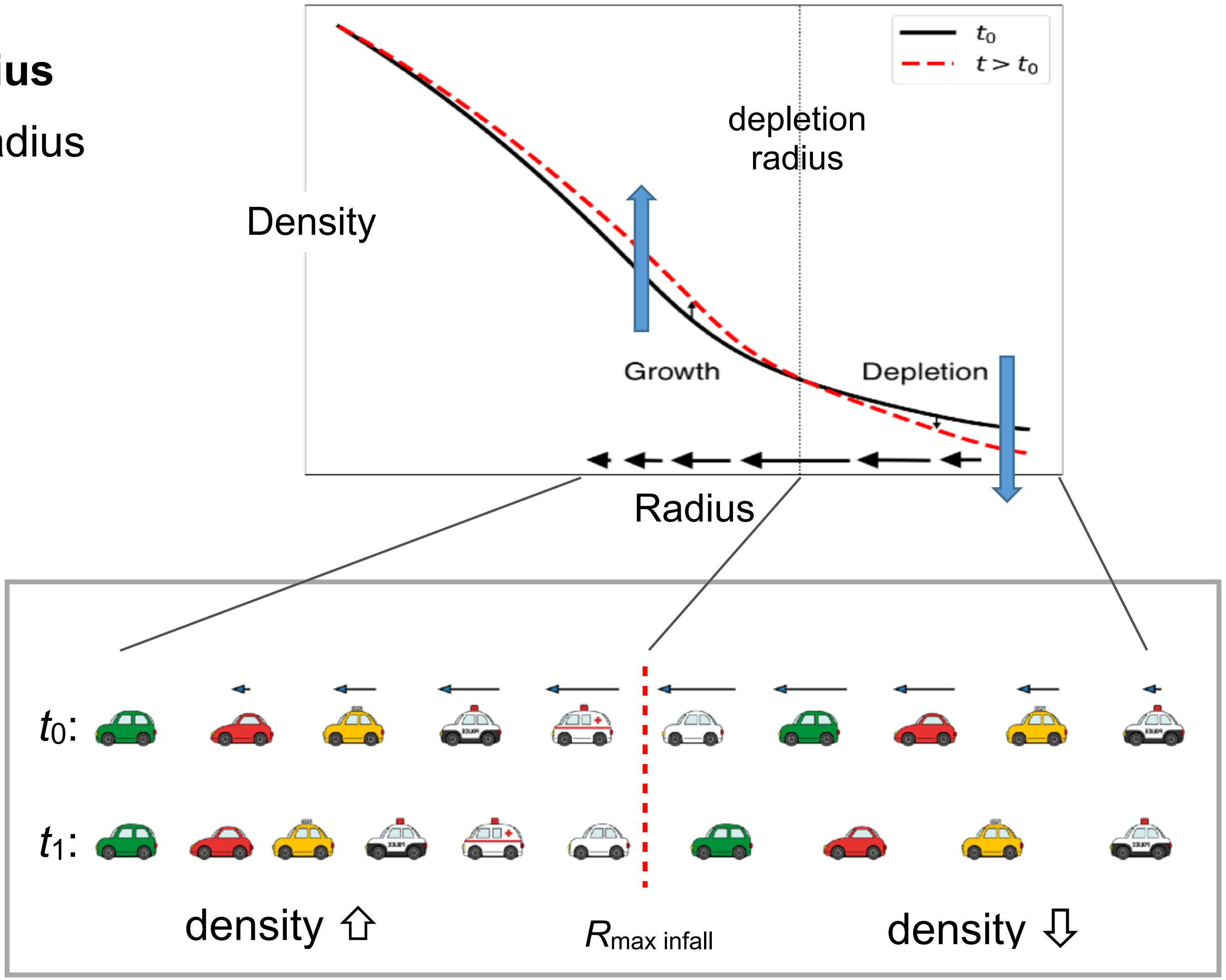
1.5x improv **(Li+25)**

5x improv. **(Li+19)**

Depletion radius as a natural halo boundary

Fong & Han 2021
Gao, Han+ 2023
Zhou, Han+ 2023, 24



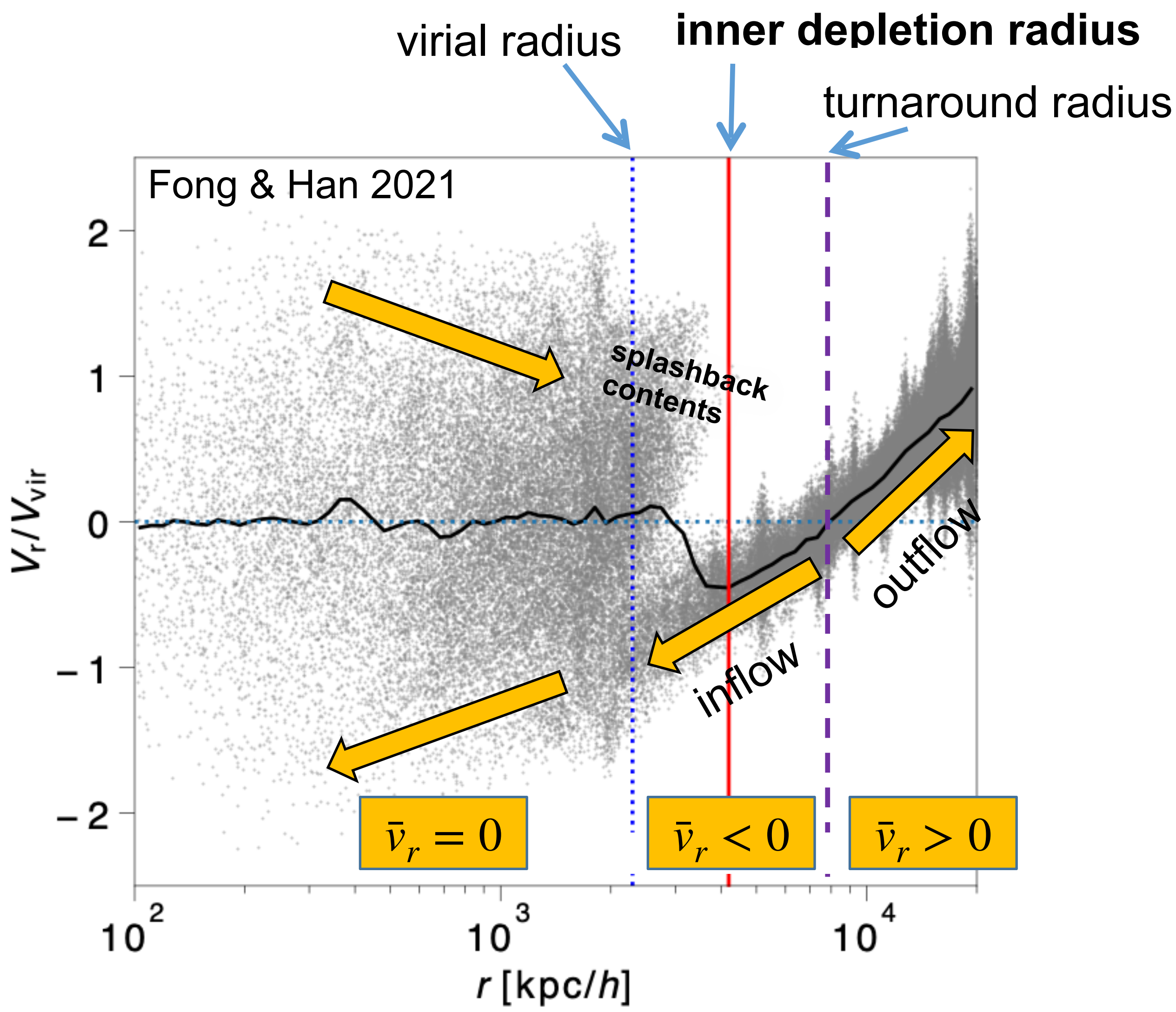


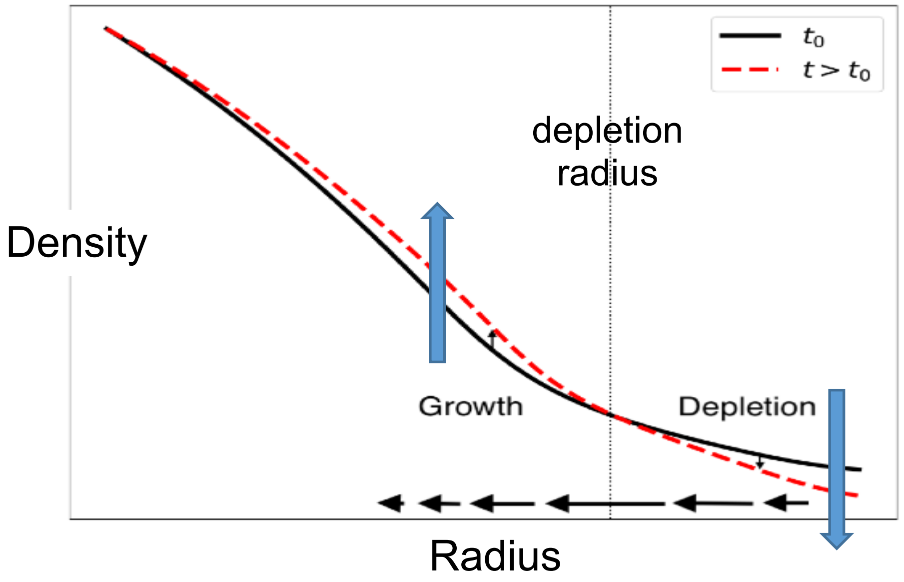
depletion radius separates growing halo from environ.

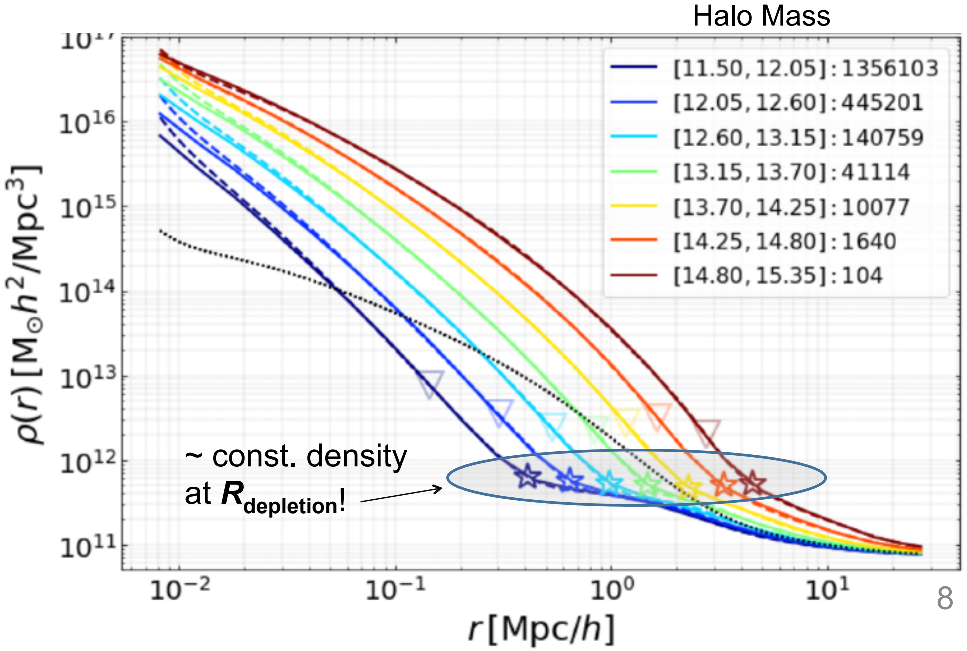
See Jiaxin, Jiale, Yifeng's talks

Depletion radius as a natural halo boundary

Fong & Han 2021
Gao, Han+ 2023
Zhou, Han+ 2023, 24



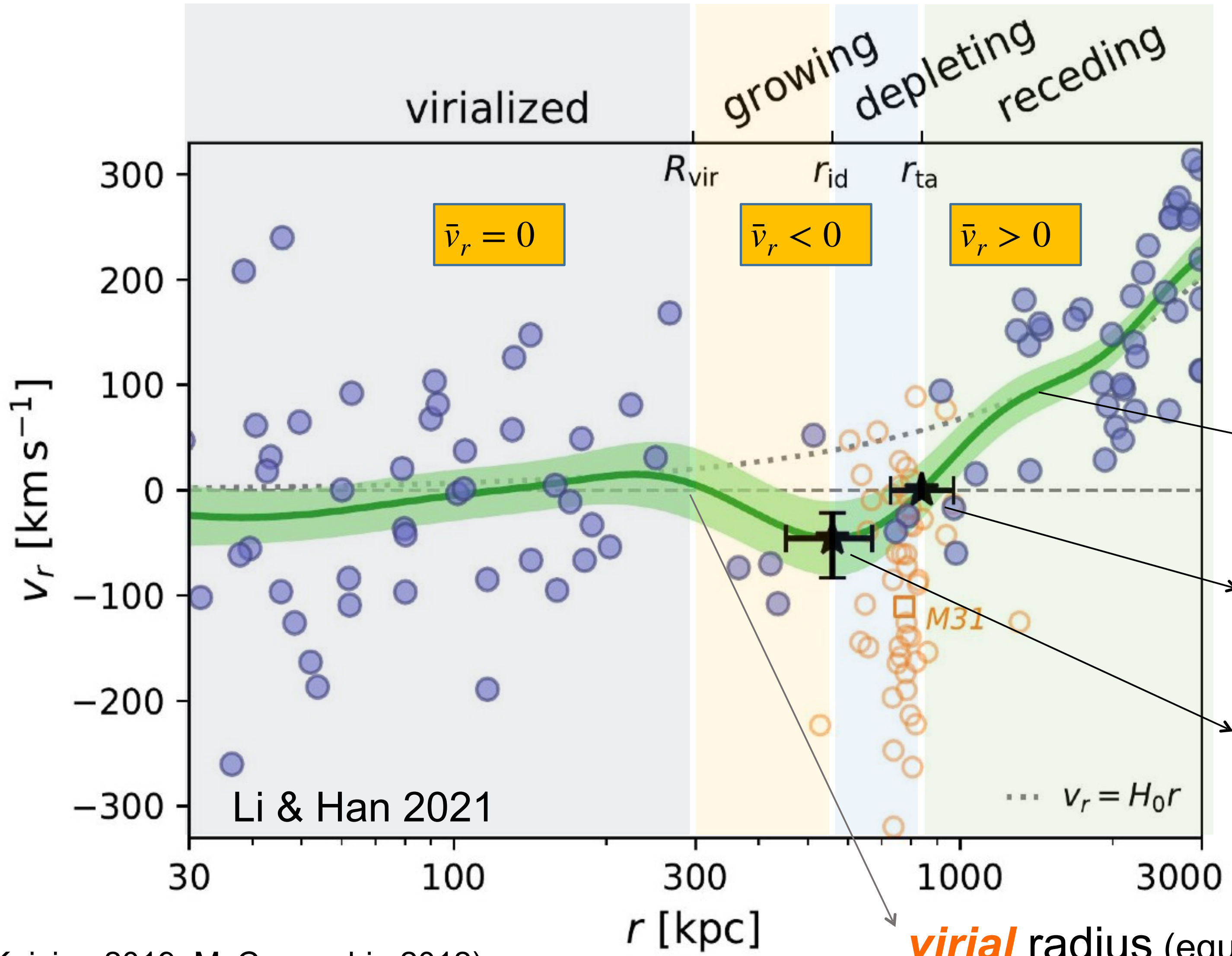


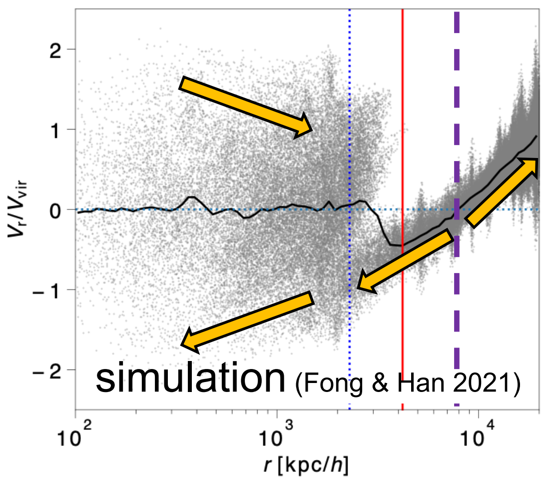


See Jiaxin, Jiale, Yifeng's talks

Regional map around the Milky Way (MW)

from nearby dwarf galaxies within 3Mpc





velocity away from MW

$\bar{v}_r$ from Gaussian process

turnaround radius
r_{ta} = 839 ± 121kpc

inner depletion radius
r_{id} = 559 ± 107kpc

[Li & Han 2021]

virial radius (equilibrium dyn)
r_{vir} = 297 ± 16kpc [Li+ 2020]

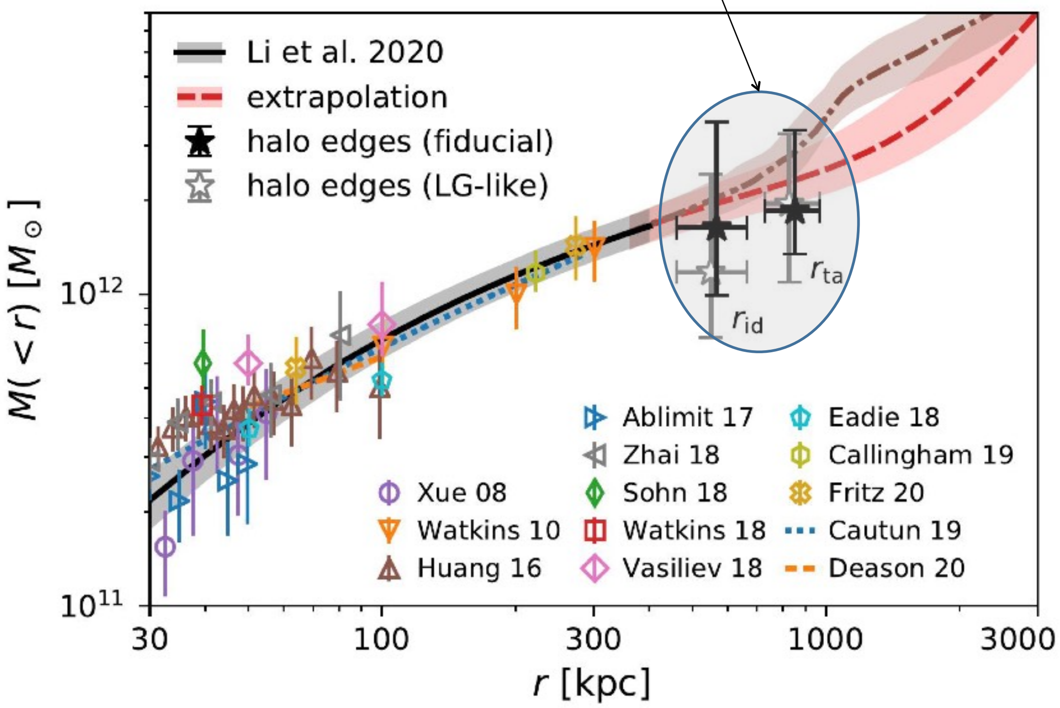
(data: Karachentsev & Kaisina 2019; McConnachie 2012)
See also Deason+20 for $R_{sp, MW}$

Milky Way mass beyond virial radius

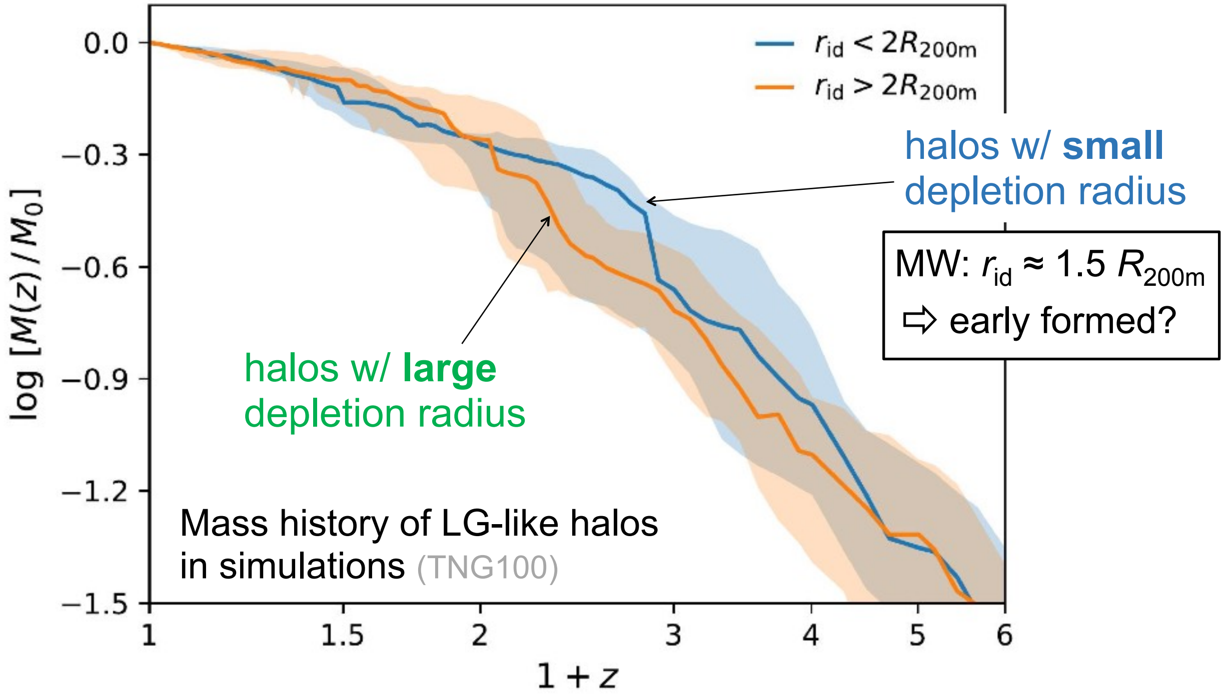
Simulations: $\bar{\rho}(<r_{\rm id}) \simeq 60\rho_m;\ \bar{\rho}(<r_{\rm ta}) \simeq 20\rho_m$

See Jiale's talks for updates

⇨ MW mass estimates beyond R_{vir}



Early formed halos have smaller depletion radius?

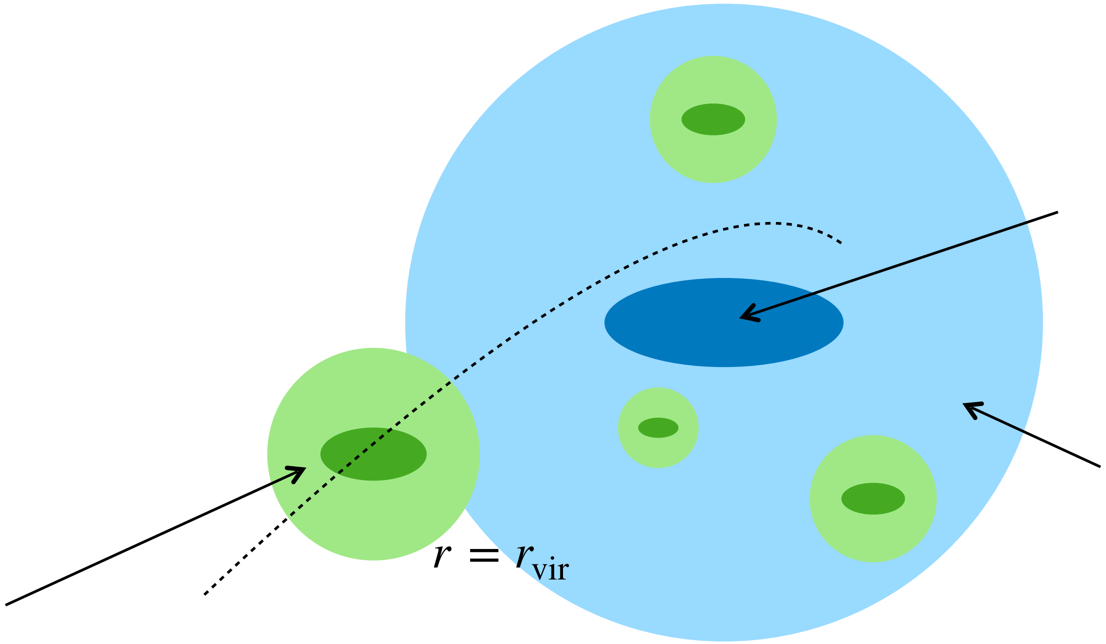


Li & Han 2021

II. Assembly of halo structure

Subhalo infall orbits: initial condition for central/satellite evolution

⇨ **Crucial for (semi)analytical models** (e.g. Yang+ 2011, Jiang+ 2020)

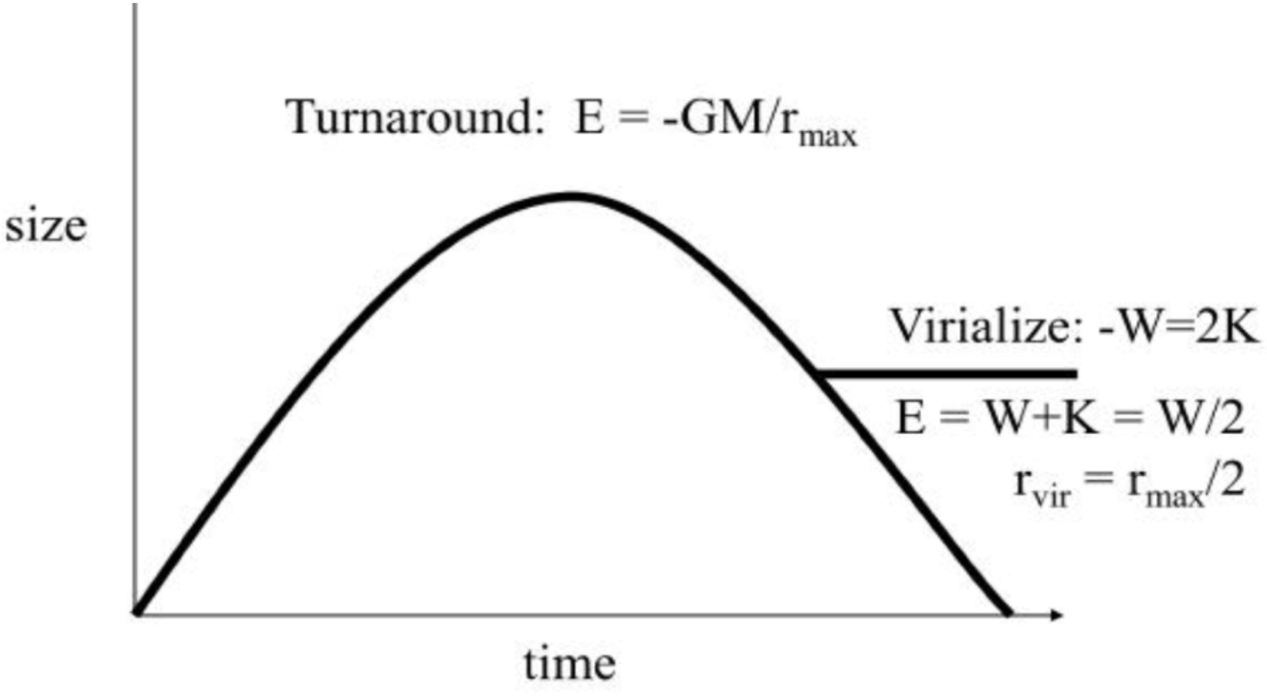


Central galaxy
- morphology transformation
- formation of stellar halo

Host halo
- assembly of dynamical structure

Satellite halo/galaxy
- dynamical friction
- tidal heating and stripping, disruption...

Idealized scheme: spherical collapse



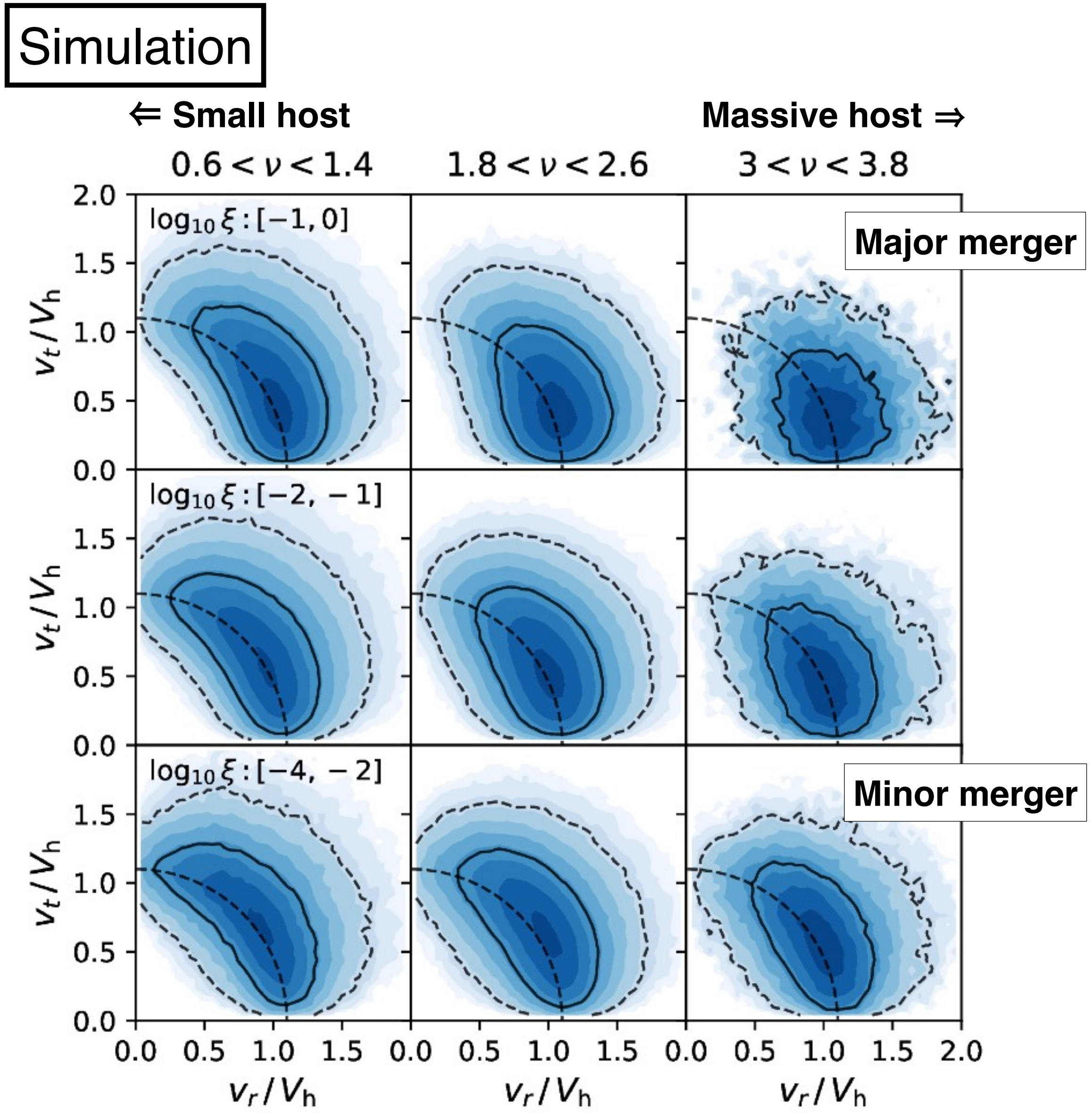
Naive expectation for radial accretion

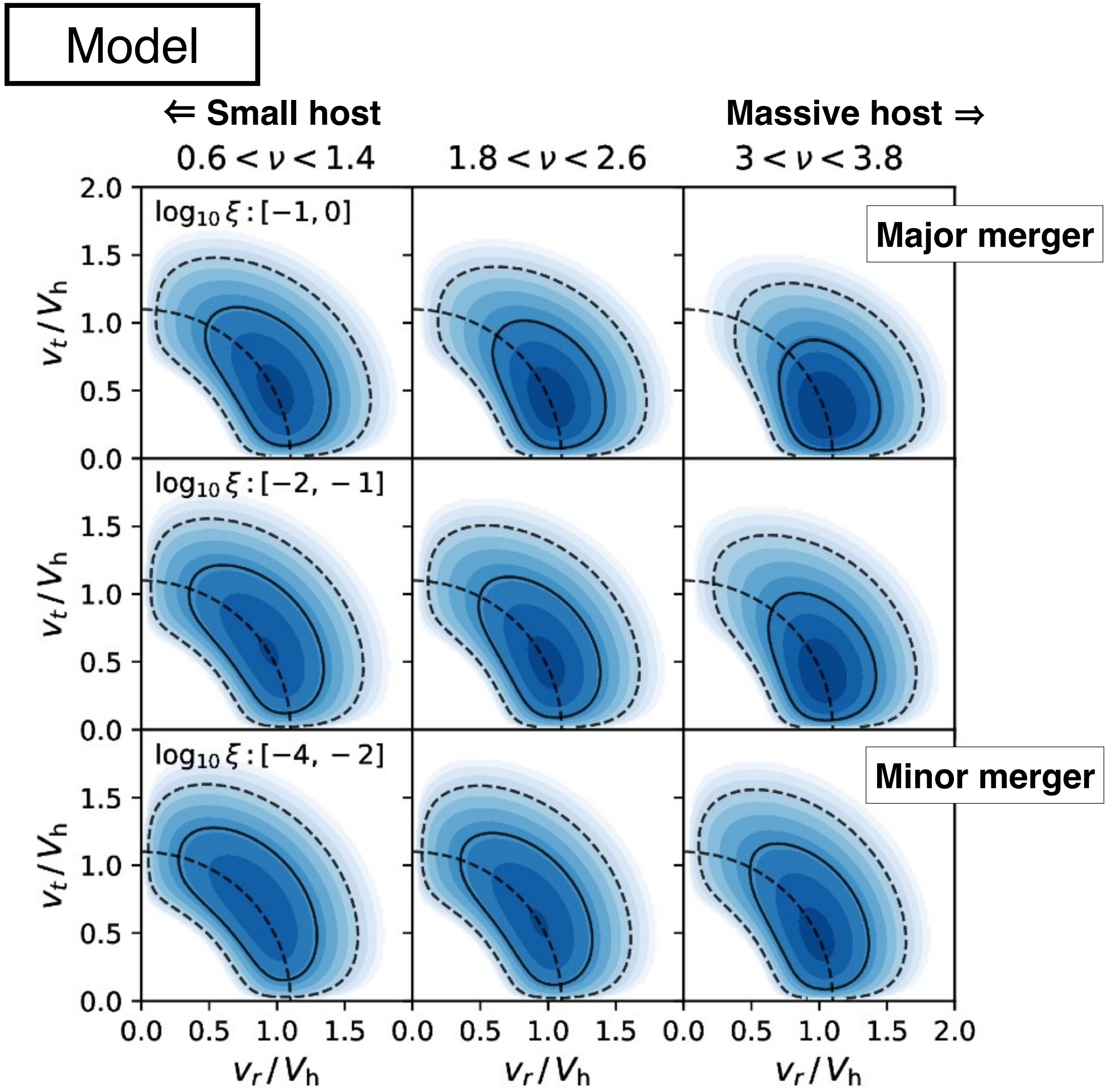
$$-\frac{GM_h}{R_{ta}} = -\frac{GM_h}{R_h} + \frac{1}{2}v^2 \Rightarrow \quad v_{infall}(r_{vir}) \simeq v_{vir} \equiv \sqrt{GM_{vir}/r_{vir}}$$

Real world: highly nonlinear ⇨ We need simulations!

Unified model of initial subhalo orbits validated for z<6

Li et al. 2020b



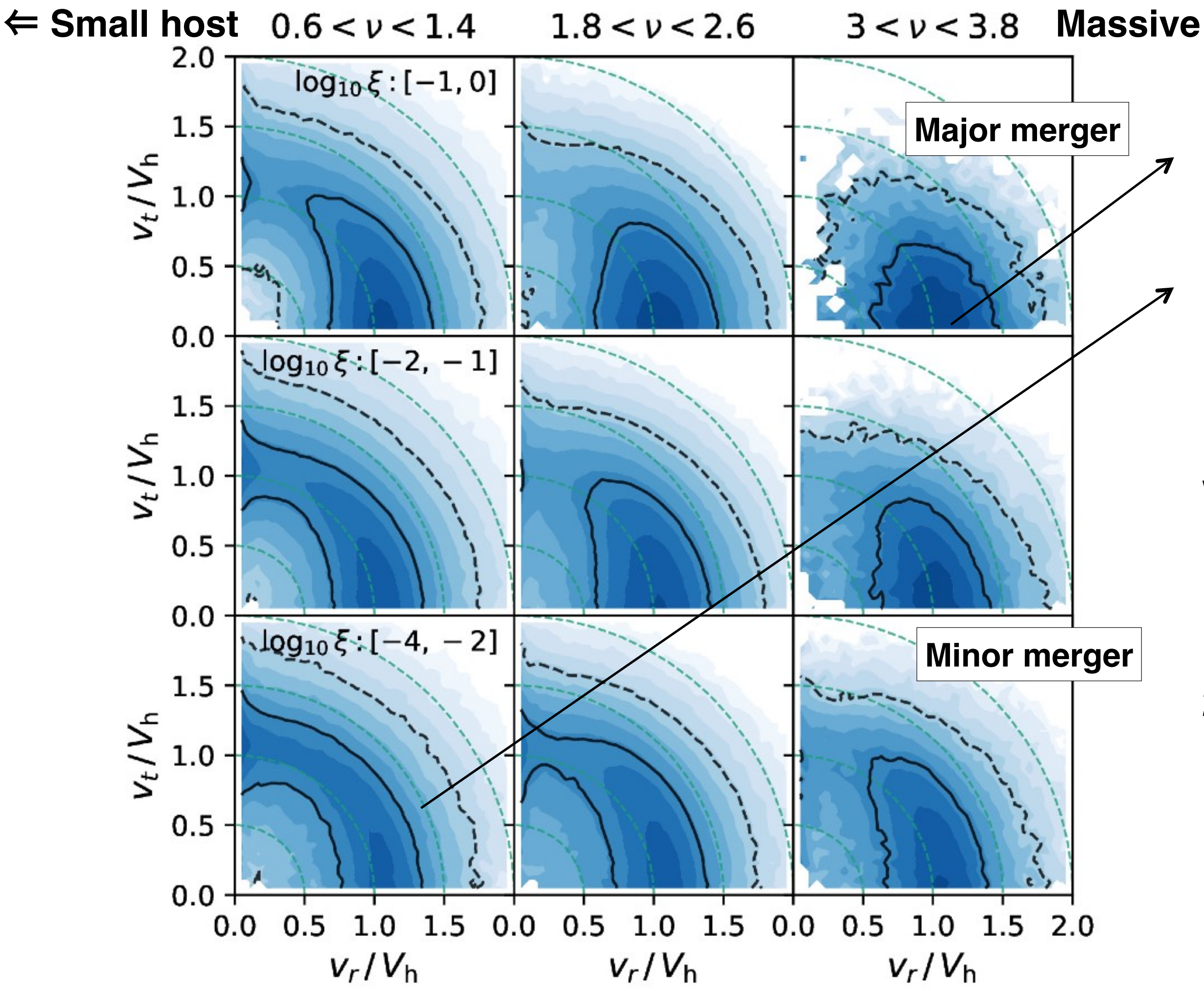


cf. Wang05, Benson05, Wetzel11, Jiang14, Shi15

Initial subhalo orbits in phase space

$$\frac{d^6N}{d^3xd^3v} = f(v_r, v_t, r = r_{\rm vir})$$

Slice of the velocity ellipsoid at $r = r_{\rm vir}$



Radial infall of $v_{\rm vir}$ for massive halos (as expected by spherical collapse!)

Isotropic accretion for small halos

Why?

1. Larger halos are more resistant to environmental perturbations

2. The environment affects more on infall angle rather than velocity

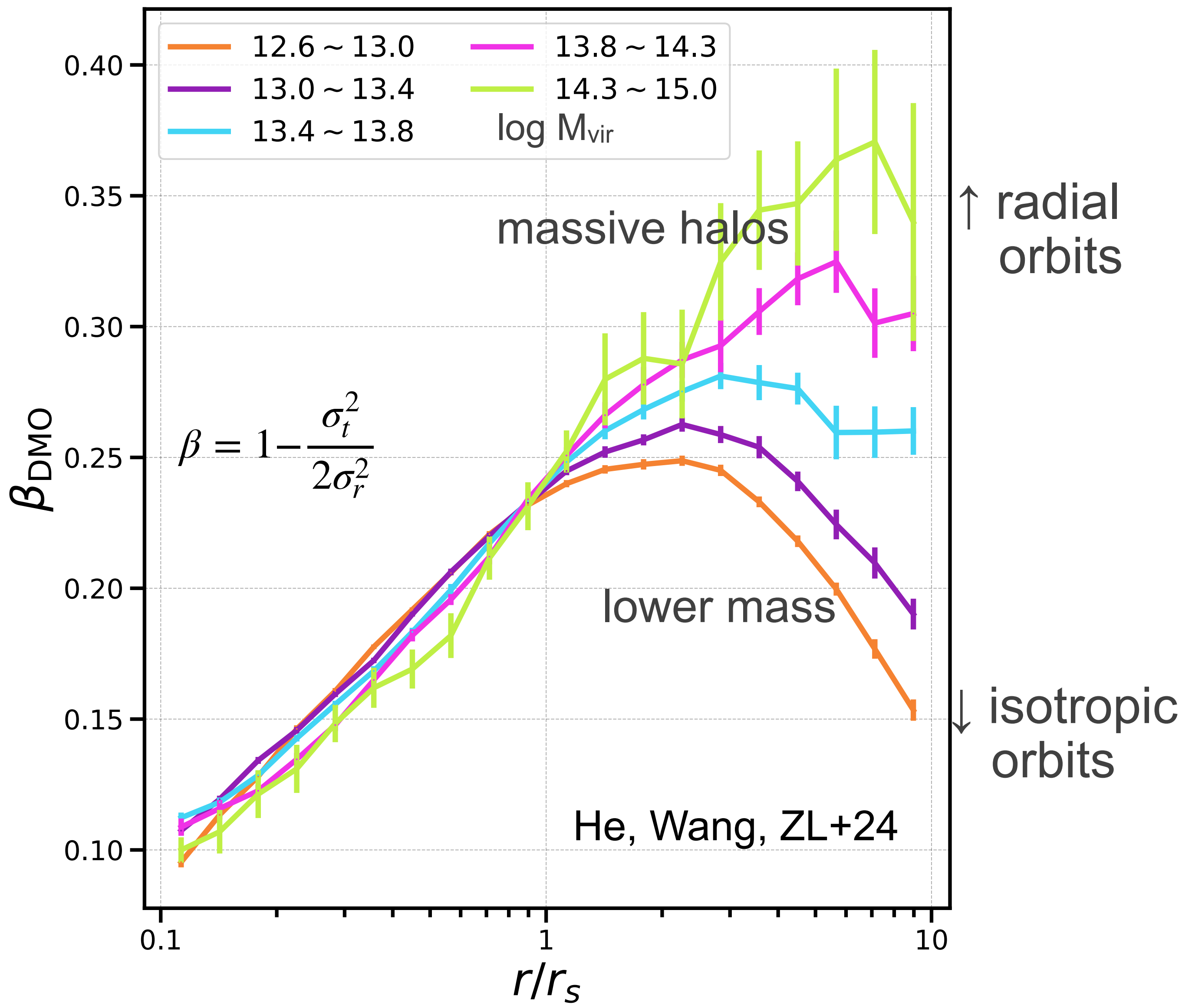
Li et al. 2020b

Build-up of anisotropic halos

- Outer halo:
  massive halos have more radial accretion pattern
  ⇒ Higher velocity anisotropy expected

- Inner halo: universal
  not well understood yet
  orbital evolution during fast growth phase?

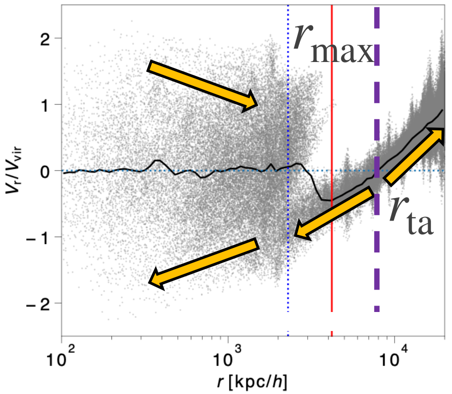
velocity anisotropy of DM particles in TNG



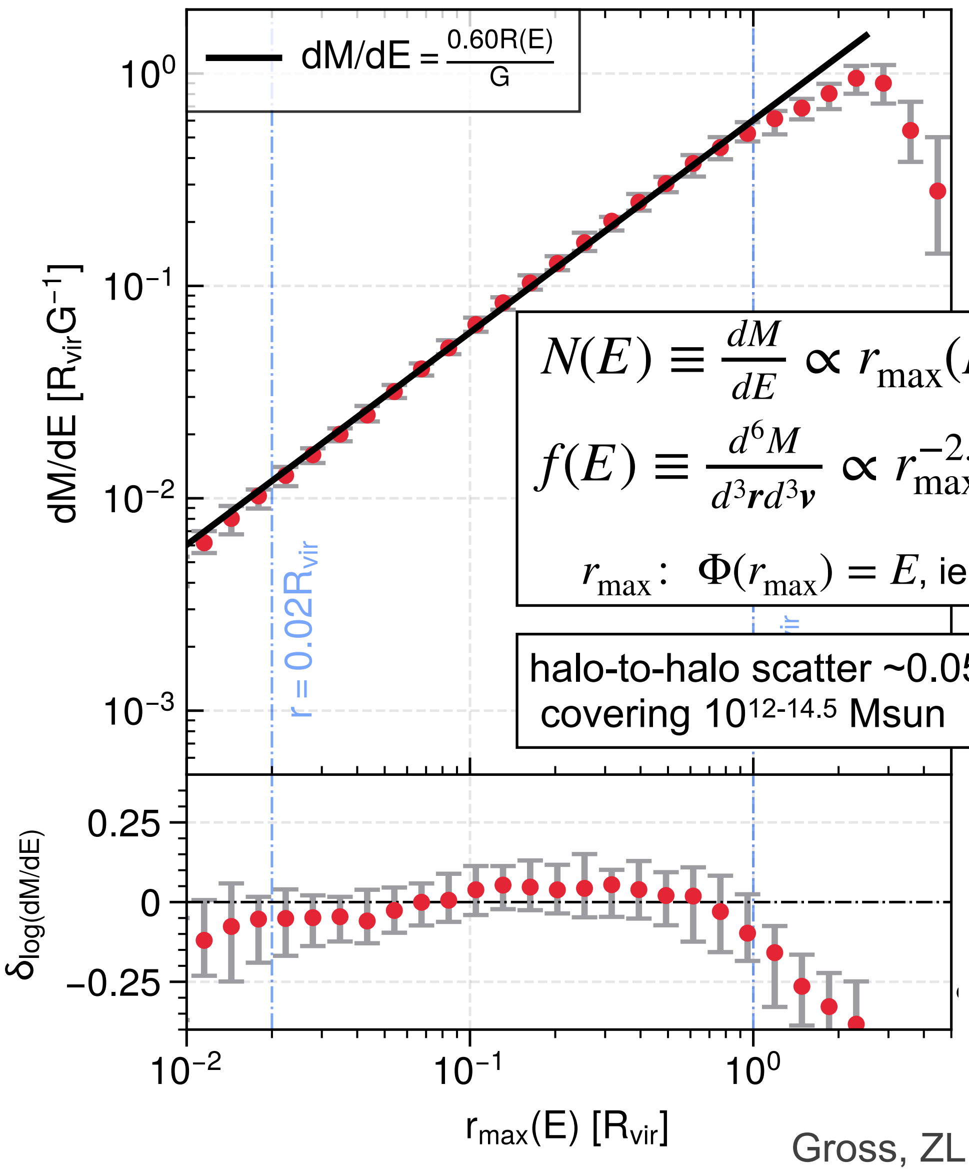
similar trend for orbits of stars and satellites in TNG

also cf. Lemze+ 2012, Shi+ 2015

Build-up of halo phase-space distribution



New scaling relations in halo phase space



$$N(E) \equiv \frac{dM}{dE} \propto r_{\max}(E)$$

$$f(E) \equiv \frac{d^6 M}{d^3\boldsymbol{r} d^3\boldsymbol{v}} \propto r_{\max}^{-2.08}(E)$$

$r_{\max}$: $\Phi(r_{\max}) = E$, ie. r_{apo}

halo-to-halo scatter ~0.05 dex covering $10^{12-14.5}$ Msun

Gross, ZL, and Qian 2025

A simple model:
assuming rank of energy preserved

- mass: $M_0(< E) = M_{ta}$
- radius: $r_{\max}(E) \leftrightarrow E \leftrightarrow r_{ta}$

⇨ Energy distribution

$$\frac{dM_0}{dE} = \frac{dM_{ta}}{d\ln r_{ta}} \frac{d\ln r_{ta}}{d\ln r_{\max}(E)} \frac{d\ln r_{\max}(E)}{dE} \equiv \kappa \frac{r_{\max}(E)}{G}$$

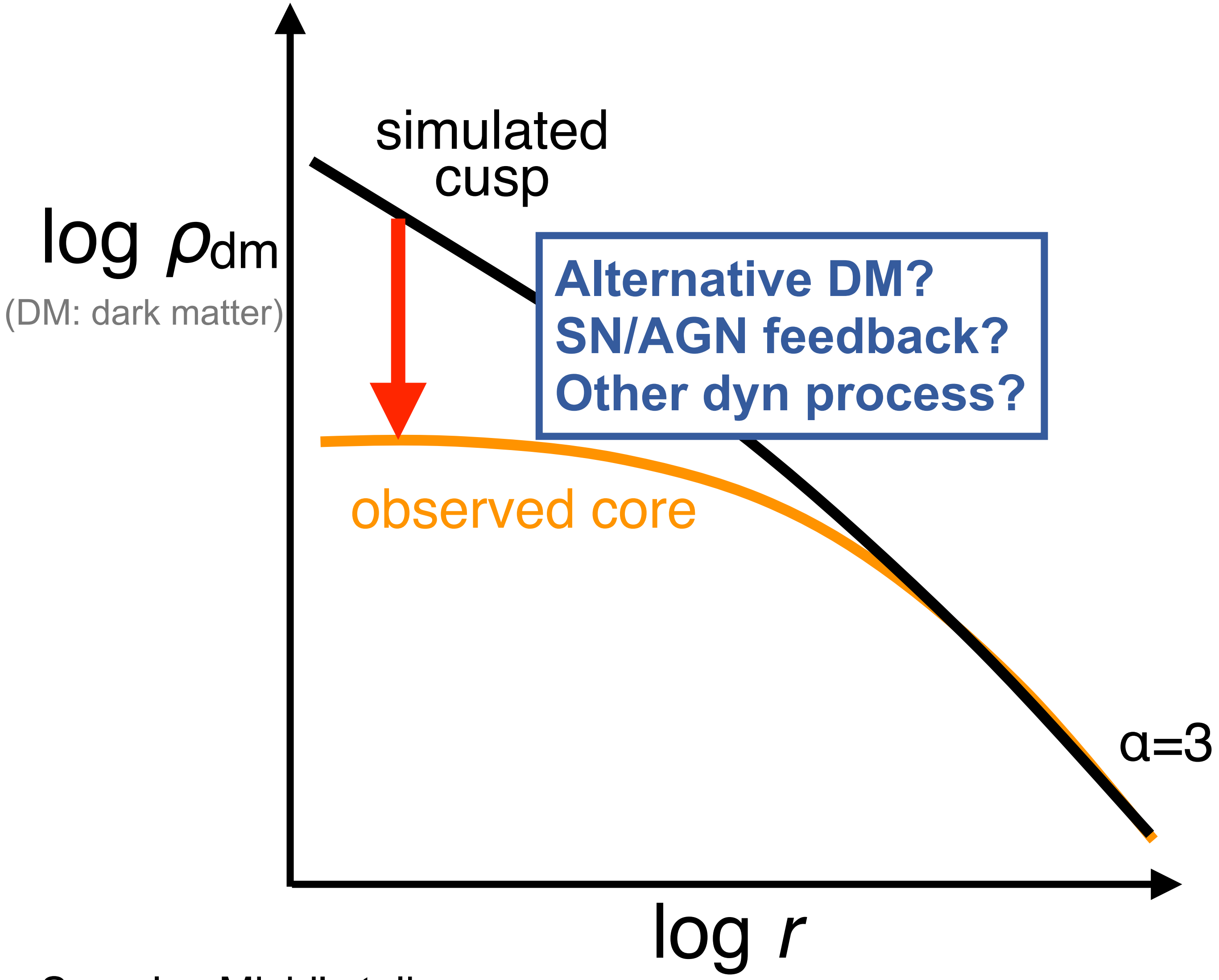
$$\kappa \equiv \frac{d\ln M_{ta}}{d\ln r_{ta}} \times \frac{M_{ta}}{M_0(r_{\max})} \times \frac{d\ln r_{ta}}{d\ln r_{\max}} \sim \text{const. } 0.6$$

initial condition | shell crossing | radius contraction due to shell crossing

III. Modeling dynamical evolution of halo structure

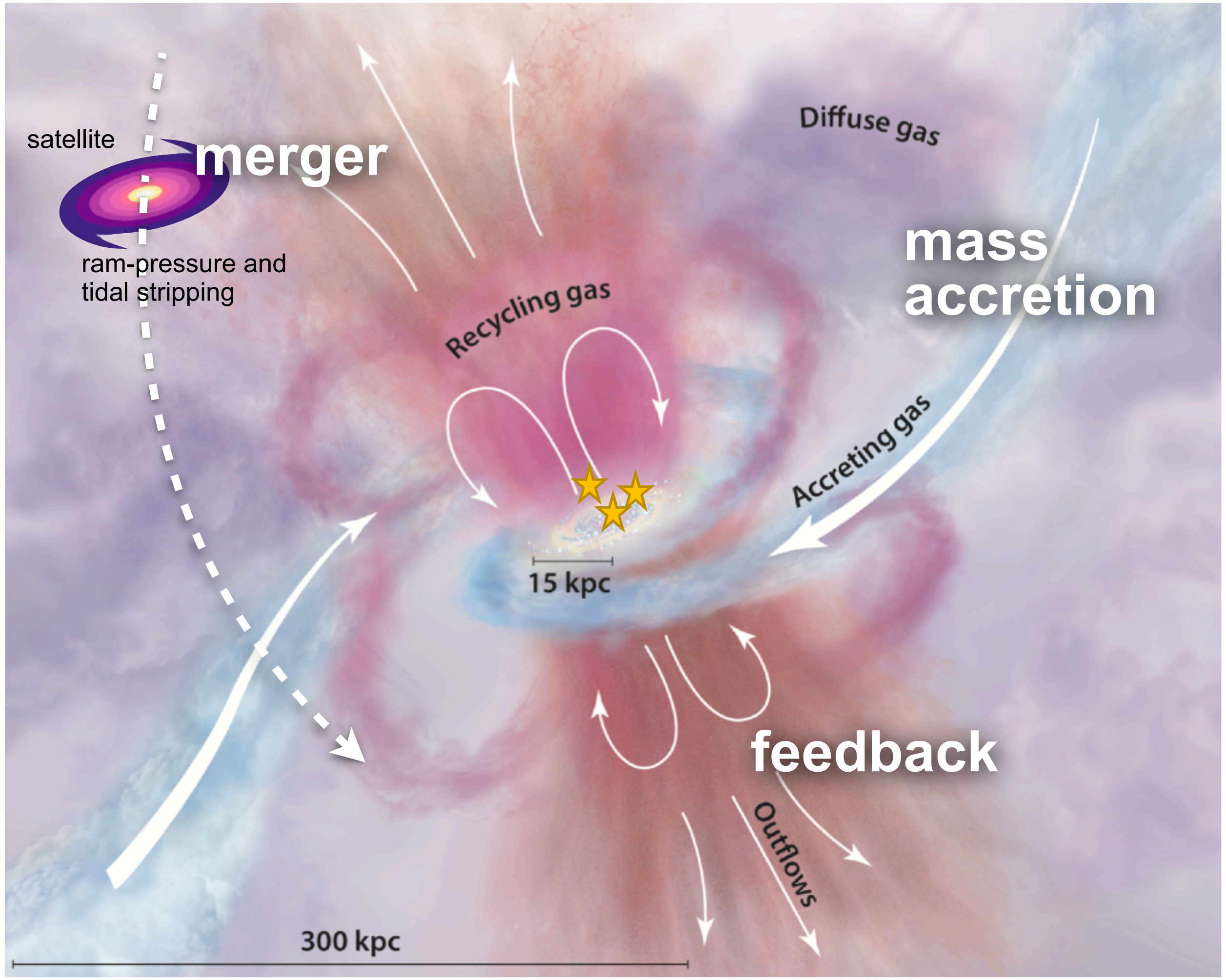
Galaxy/halo structural diversities: Potential challenge to ΛCDM

- ❖ Structural diversity
  - ▸ DM cusp vs core
  - ▸ DM fraction (deficiency crisis!)
  - ▸ Galaxy size: diffuse/compact
- ❖ Not fully reproduced by modern simulations (resolution? subgrid model? ...)
  (Review: Sales+ 2022)



See also Michi's talk

Modeling the Galaxy/Halo Structural Evolution?



Tumlinson+ 2017

⇨ Why difficult:

- ❖ So many distinct dynamical processes
- ❖ **Violent Relaxation: 50-year challenge** (since Lynden-Bell 1967!)

★ Breakthrough: **CuspCore2 model**
unified framework: **accretion, outflow, dyn heating, tidal stripping, etc**
accurate, cheap, and flexible

CuspCore2: accurate model for general dyn. evolution

NEW!

① Initial equilibrium

distribution function: $f_0(E) = \frac{d^6M}{d^3\boldsymbol{x}d^3\boldsymbol{v}}$

(Eddington inversion)

② Perturbed system

- **mass change** $\Delta E = \Delta\Phi(r)$
- **heating** $\Delta E = \Delta K(r)$

accretion, gas outflow, dyn heating, tidal stripping ...

③ Violent relaxation (no free params)

New distribution for $E \to E + \Delta E(r)$

$$f_k(E) = \frac{\int f_{k-1}(E - \Delta E(r))\sqrt{E - \Delta E(r) - \Phi_{k-1}(r)}\,r^2 dr}{\int \sqrt{E - \Phi_k(r)}\,r^2 dr}$$

Equilibrium density in the transient Φ_k

$$f_k(E) \Rightarrow \rho'(r) \Rightarrow \Phi'(r)$$

Evolve Φ towards the equilibrium

$$\Phi_{k+1} = \mu\Phi' + (1-\mu)\Phi_k$$

loop until convergence

$k \mathrel{+}= 1$

$\Delta E = \Phi_k - \Phi_{k-1}$

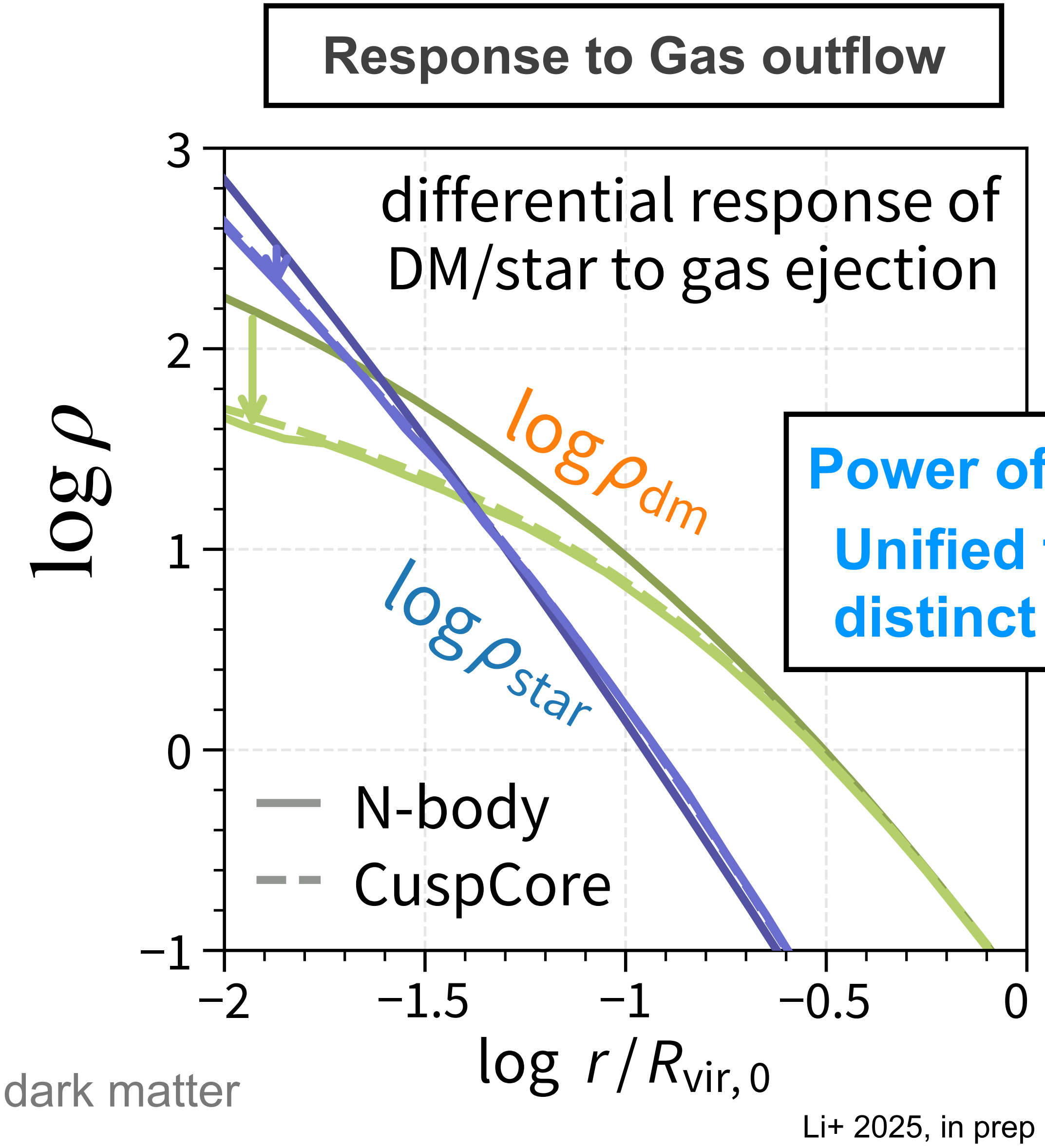
④ New equilibrium (with mass redistributed)

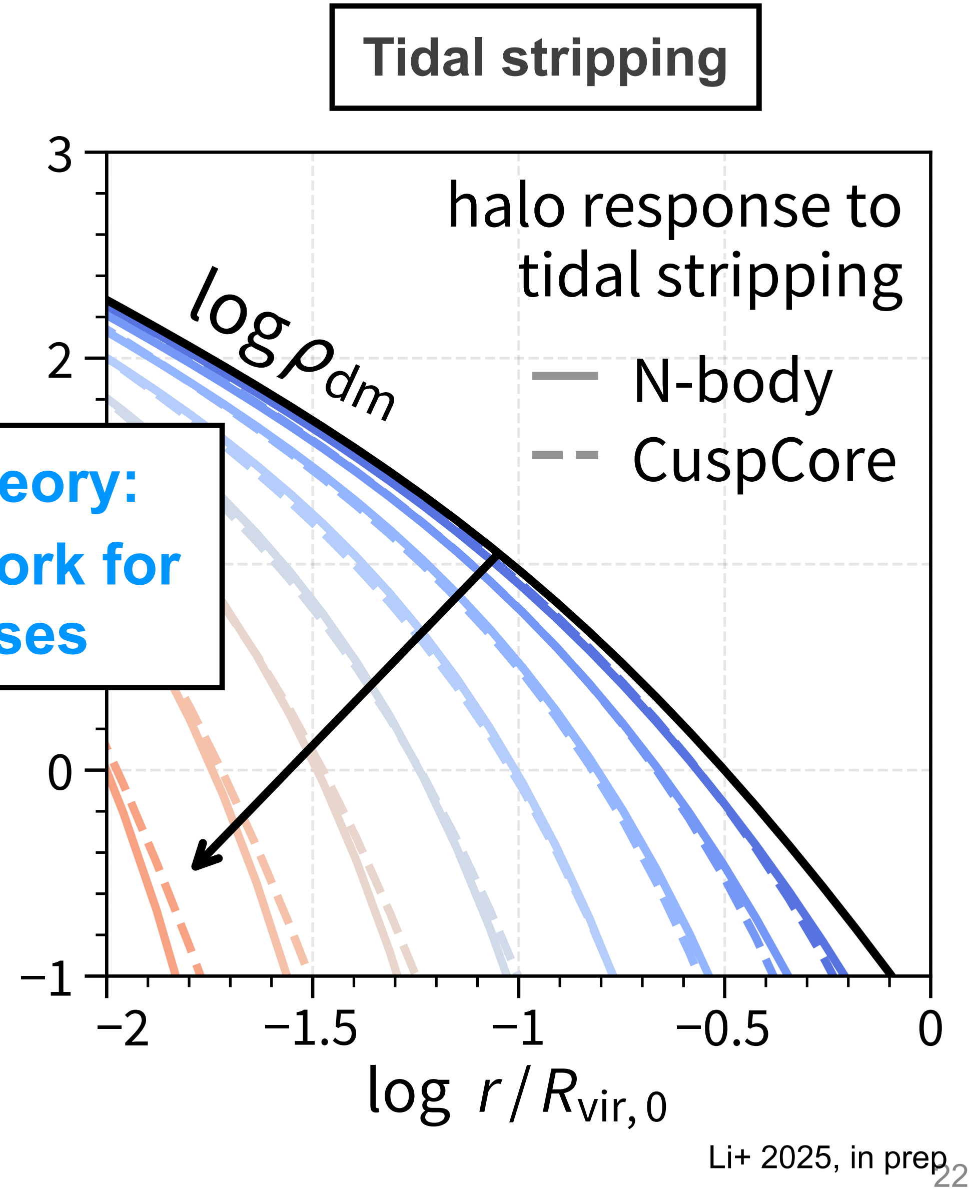
limited to spherical systems so far...

Li+ 2023 (arXiv:2206.07069)

Li+ 2025, in prep

Model vs simulation: accurate but better generalizability





Power of new theory:

Unified framework for distinct processes

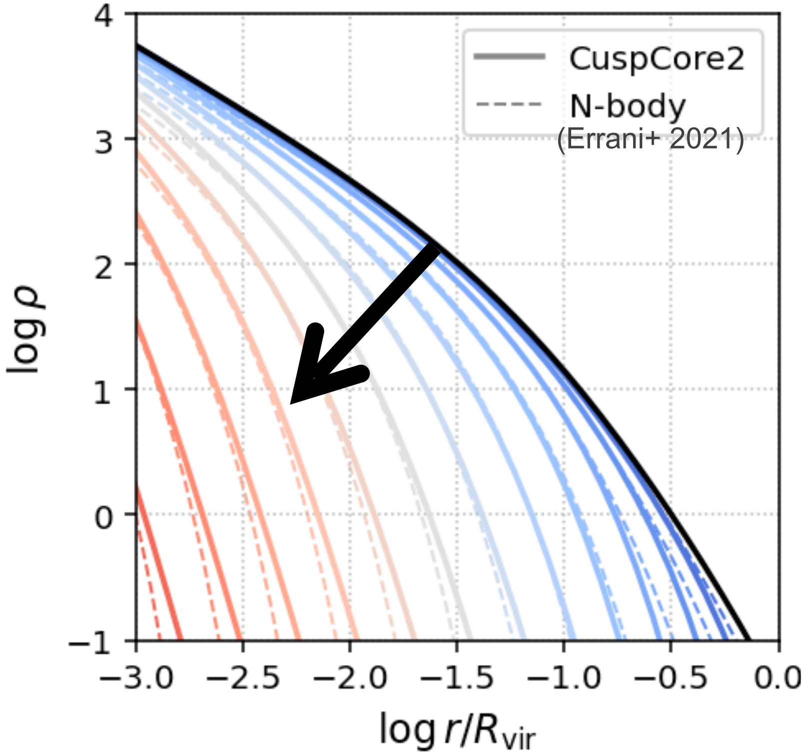
DM: dark matter

Application 1: Tidal stripping of satellite galaxies

Li+ 2024c, in prep

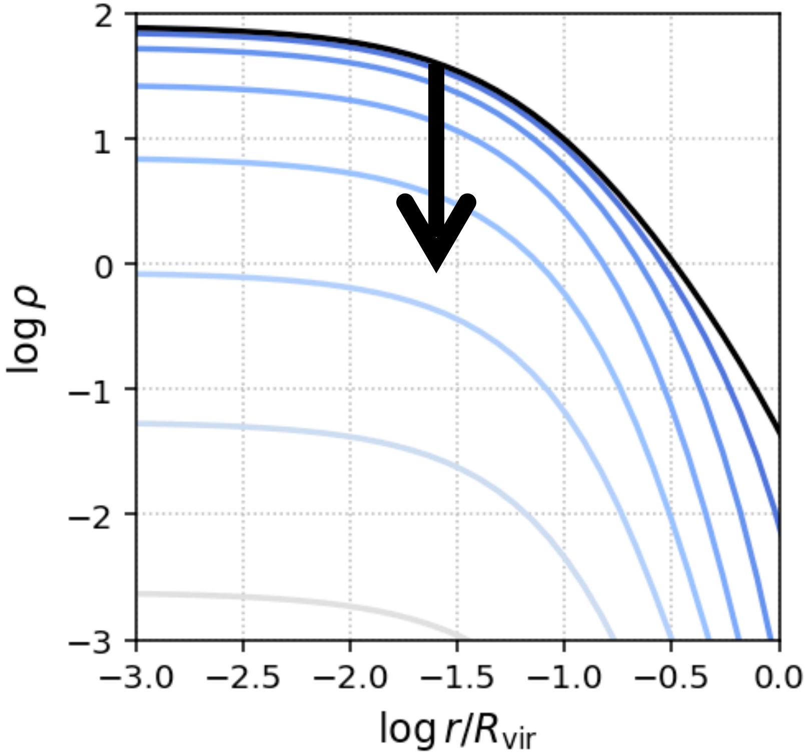
Truncation in energy (Errani+ 2021, Amorisco 2021)
+ re-virialization via CuspCore2 model

NFW subhalo



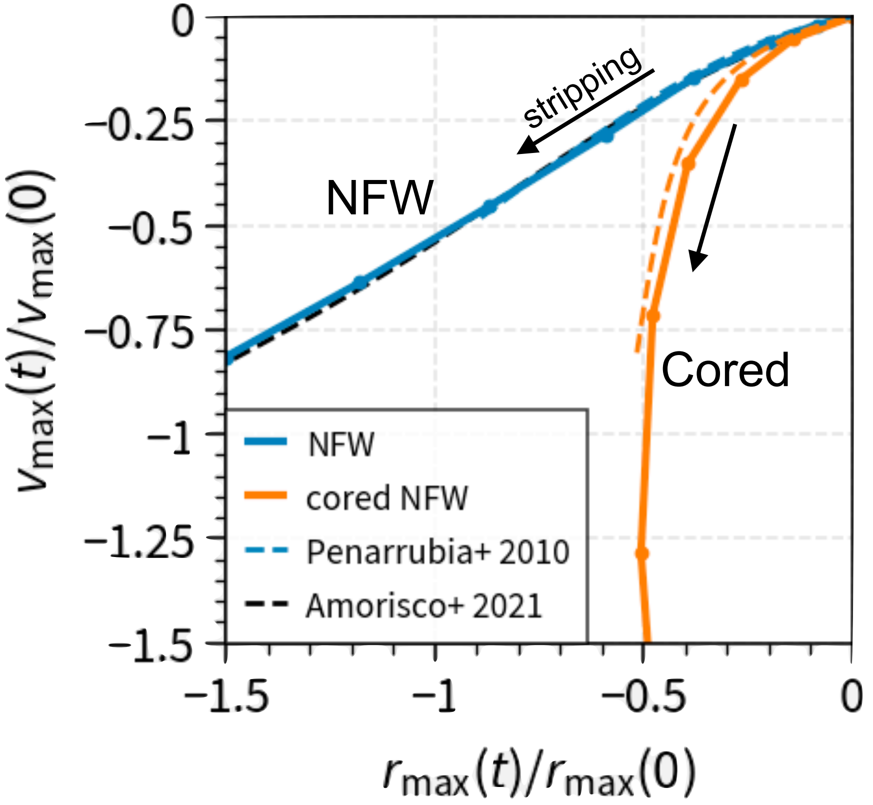
central cusps can survive

Cored subhalo



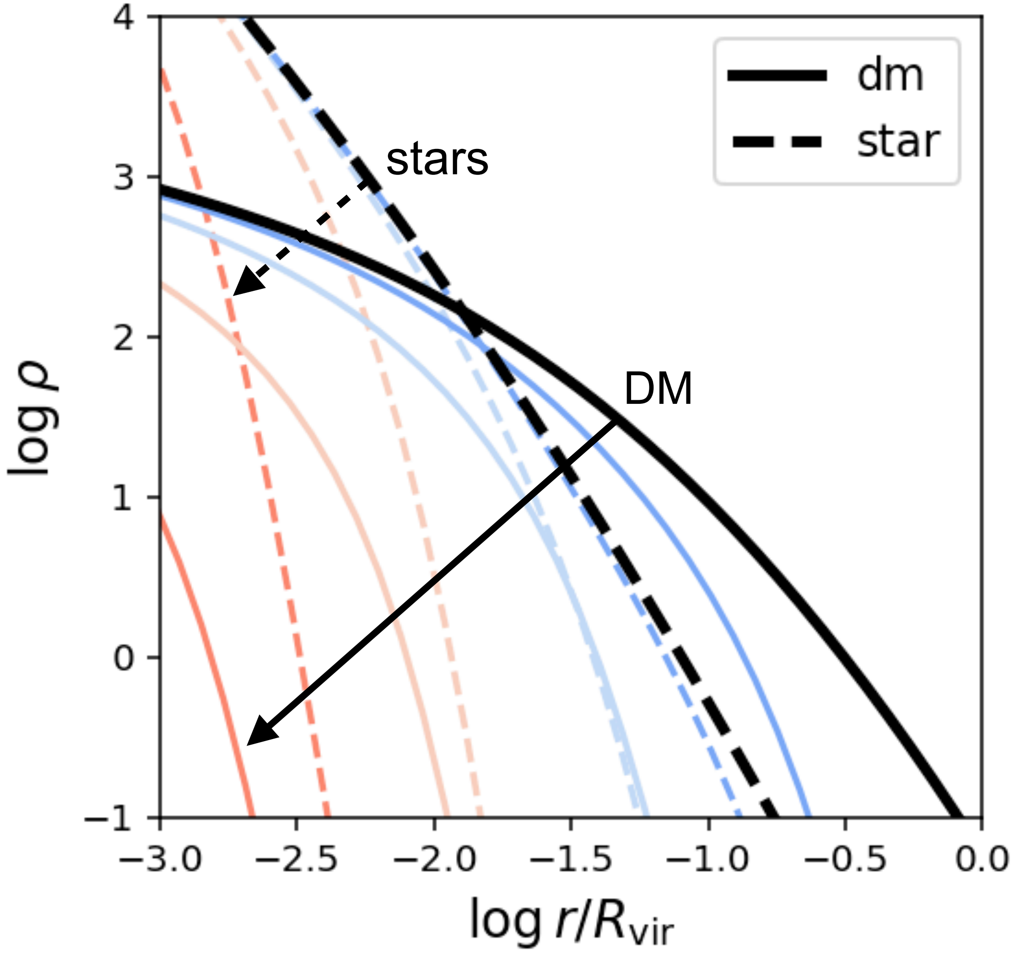
cores will undergo
run-away mass loss

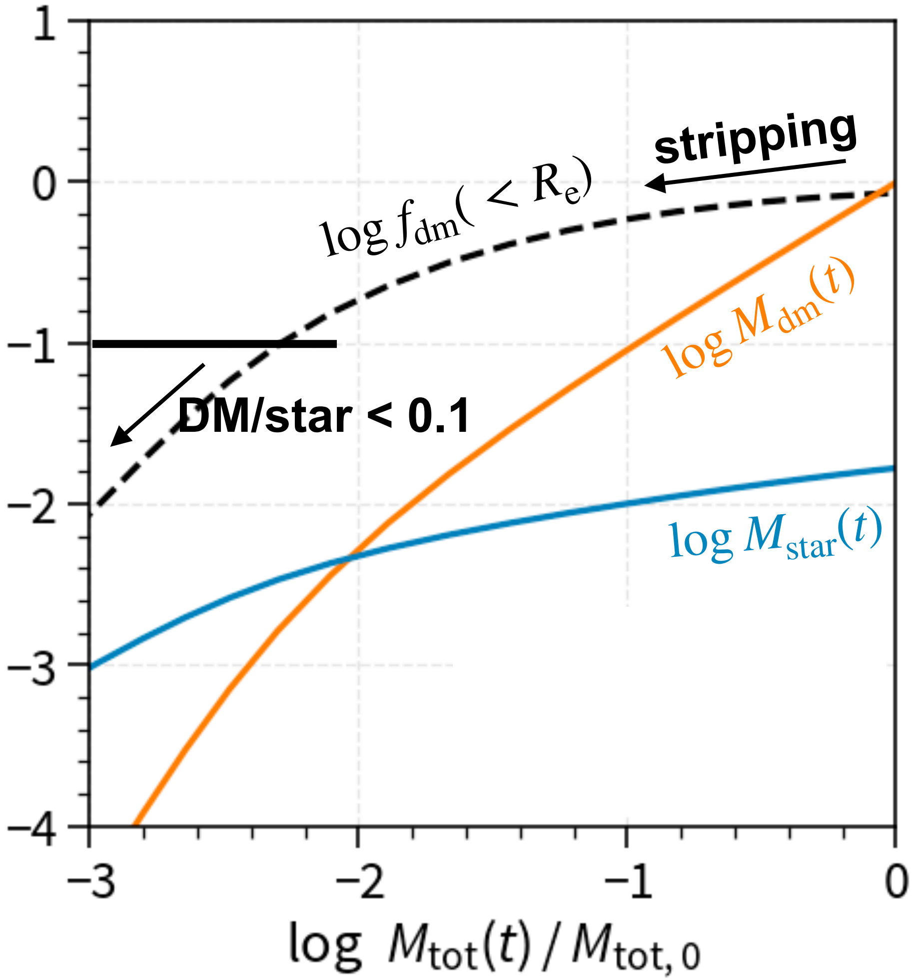
tidal track: $v_{max}(t)$ vs $r_{max}(t)$



Application 1: DM-deficient Satellite Galaxies

DM get stripped faster than stars → reduced DM frac





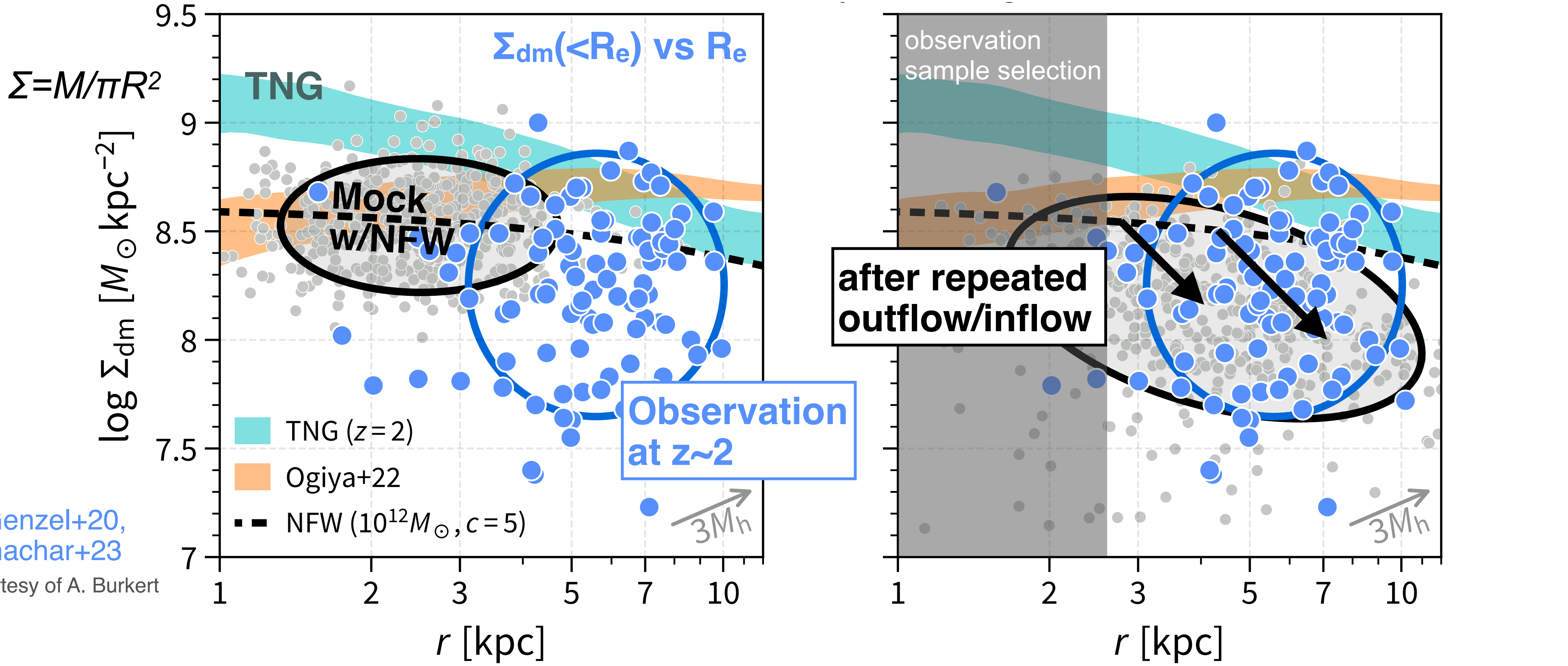
To explore: initial profiles and orbits ⇔ structure diversity

(dep. on SN feedback) (ultra compact/diffuse)

Li+ 2025, in prep

Application 2: DM-deficient/Ultra-diffuse Field Galaxies

Multi-episode gas outflows → galaxy size ↑ and DM density ↓



RC100: Genzel+20, Nestor Shachar+23

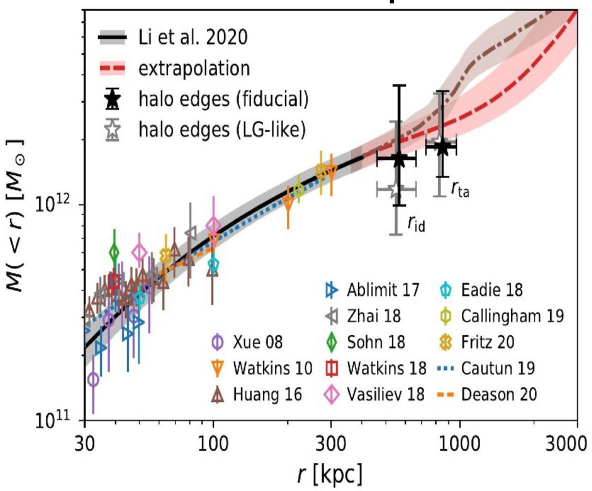
TNG: by courtesy of A. Burkert

Li+ 2025, in prep

Dynamics of halo structures

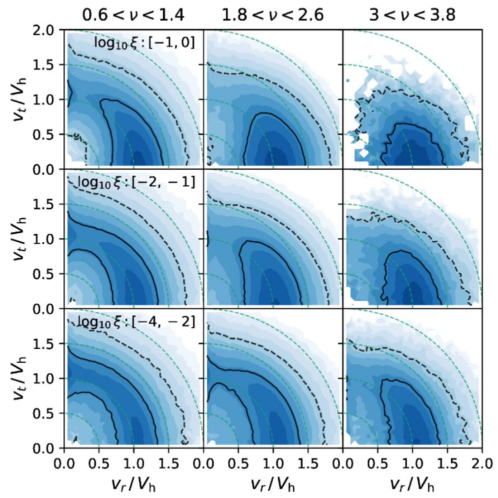
- ❖ **Measuring mass and boundary** from satellite kinematics: example of Milky Way halo
  - ✦ depletion radius: measurable, separate growing halo from environ.

MW mass profile



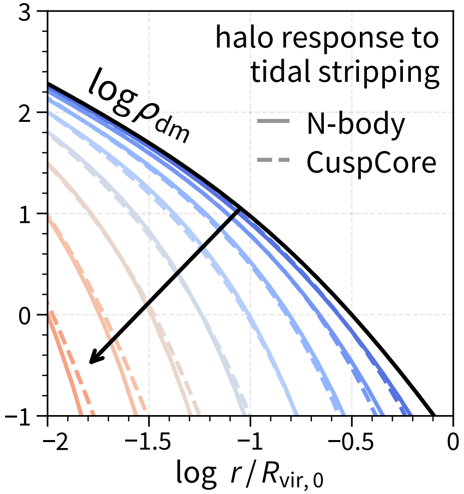
- ❖ Initial accretion orbits: insights into **halo structure build-up**
  - ✦ massive halos have more radial accretion and vel. anisotropy
  - ✦ simple model for halo phase-space distribution

initial subhalo orbits



- ❖ Unified model for **structural evolution** w/ **outflows**, dynamical **heating**, and **tidal stripping**
  - ✦ formation of DM-deficient galaxies: differential response of DM/stars

tidal stripping



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