

Self-interacting dark matter substructures: a tale of diversity and more

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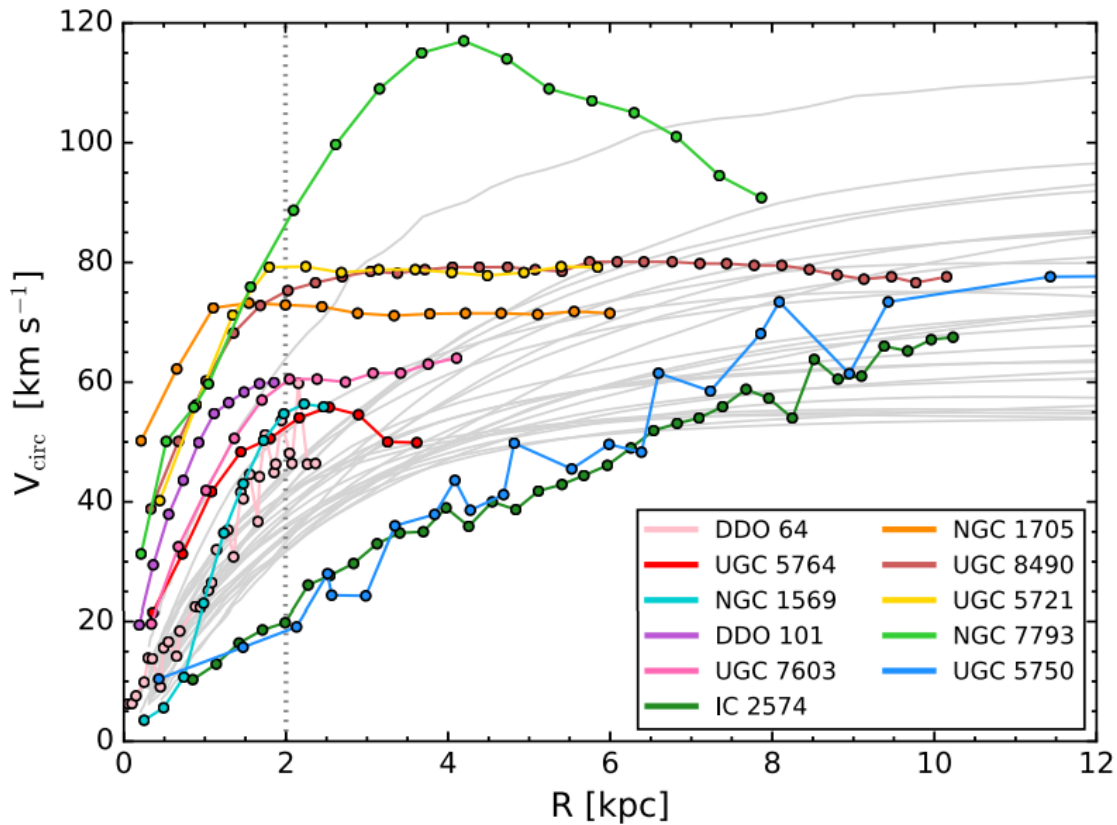
Oct 2024
TACOS at UT Austin

Background: diversity problem of dwarf galaxies

The observed dwarf galaxies display a larger scatter/diversity than cold dark matter (CDM) expectations: rotation curves, mass-size relation, etc.

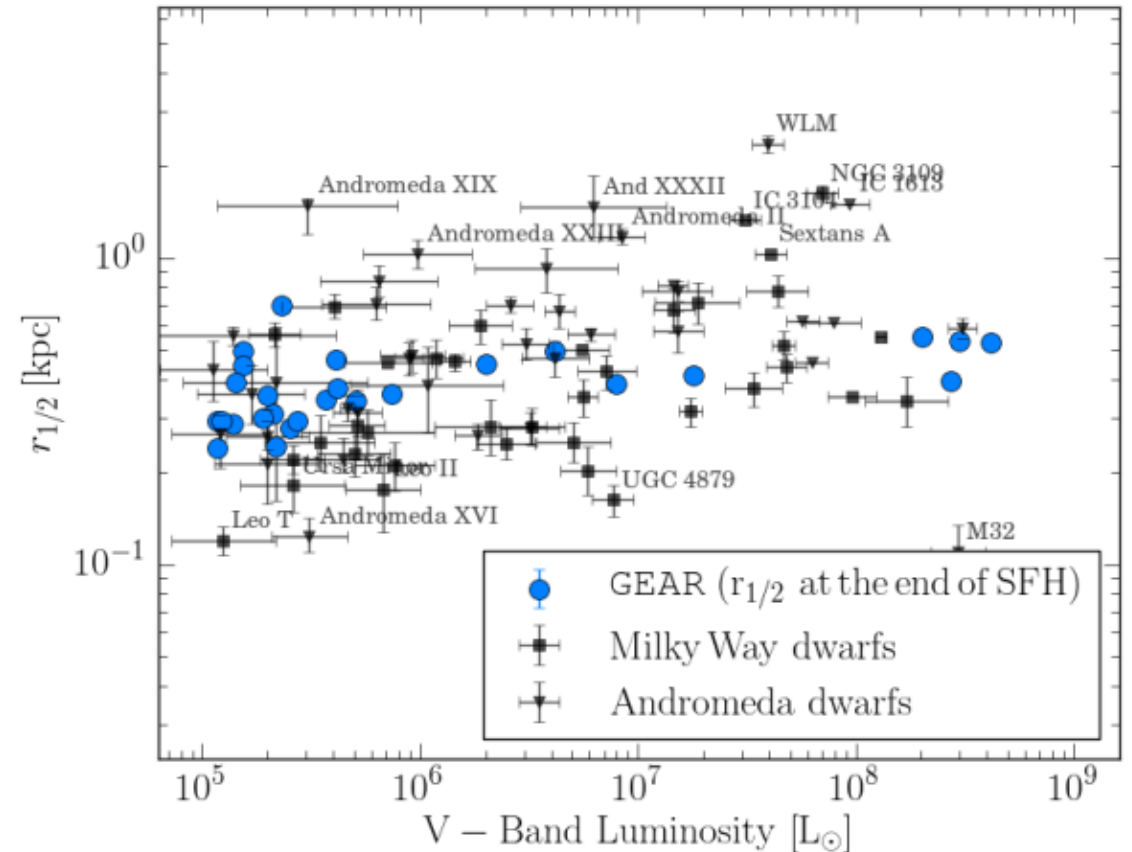
...suggests something funny is going on in the **inner mass distribution** of the DM halo

Diversity in rotation curves



Santos-Santos+ 1706.04202

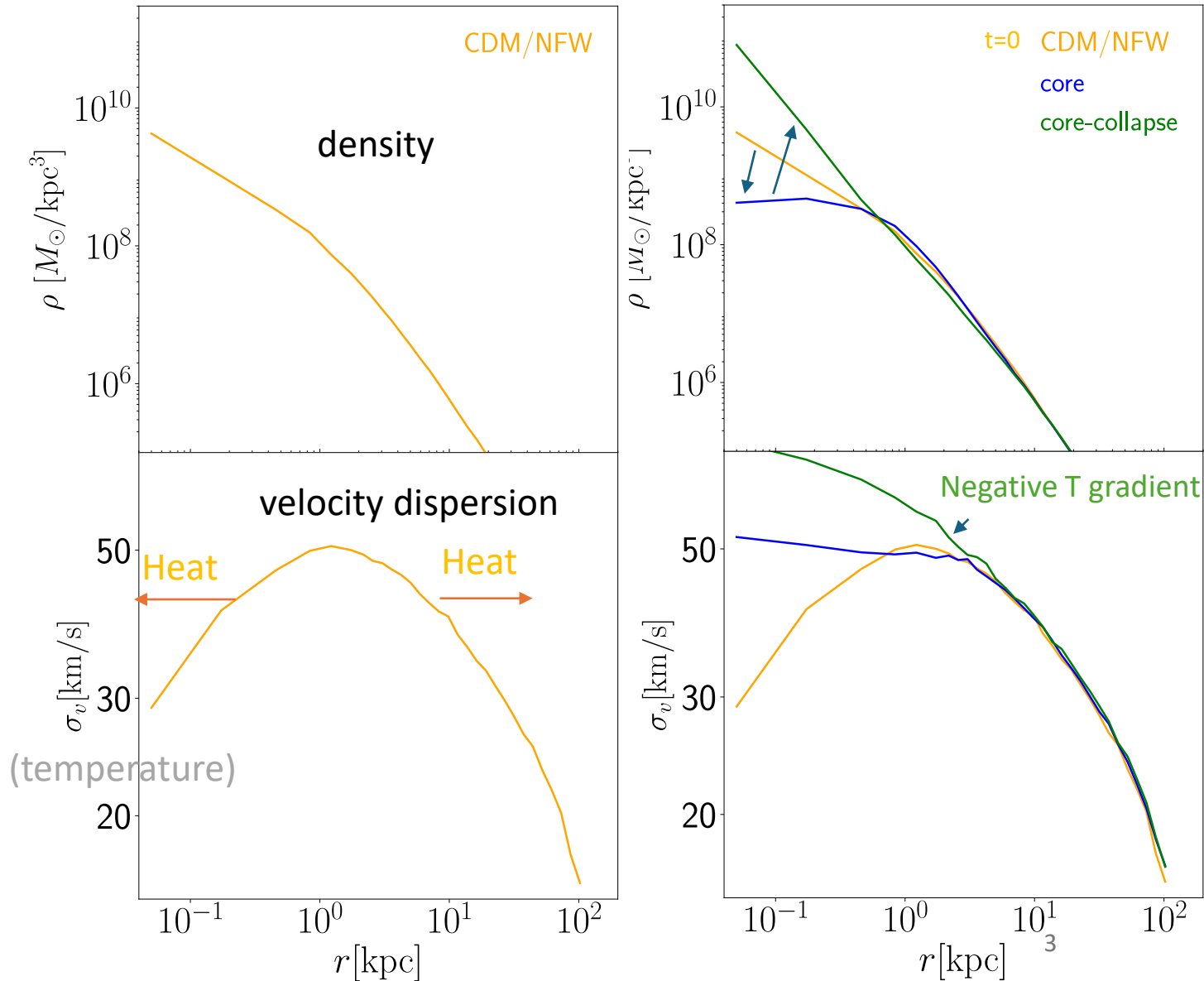
Diversity in stellar-mass vs. stellar-size plane



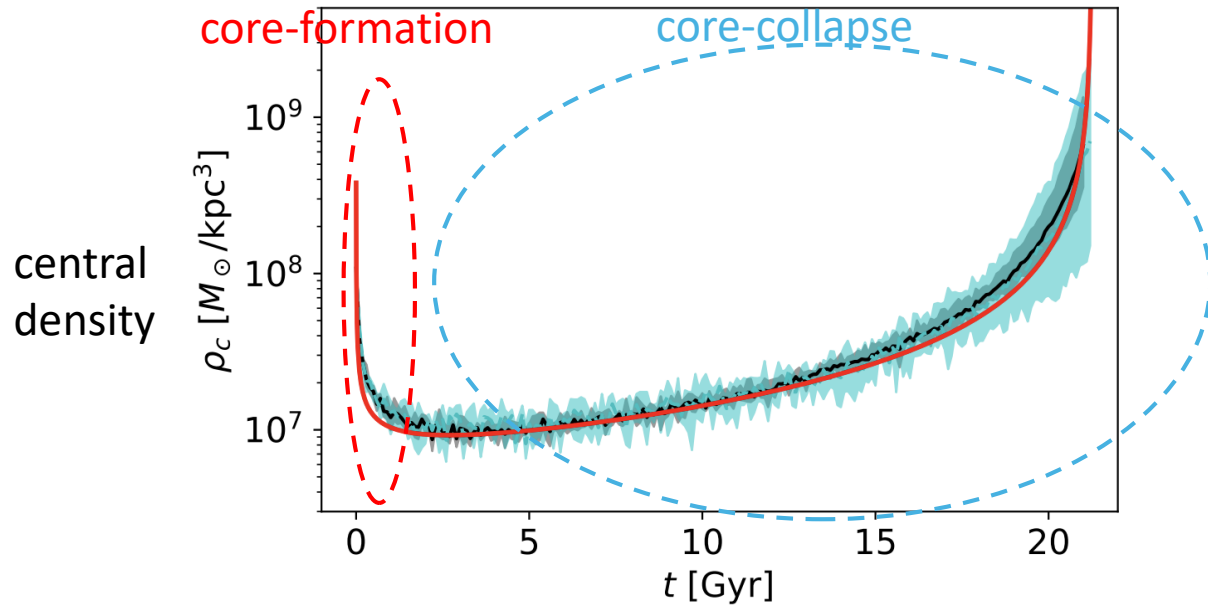
Revaz & Jablonka
1801.06222

SIDM halos: core-formation then core-collapse

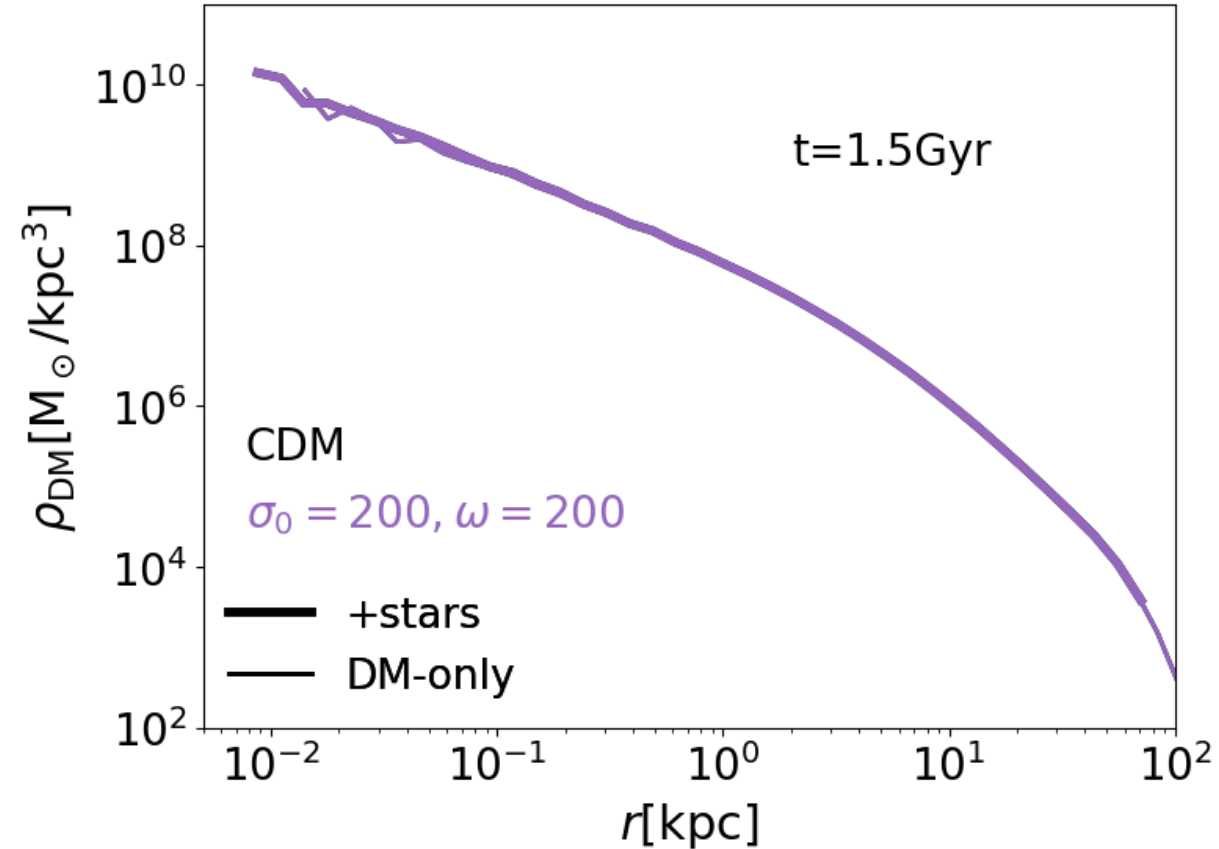
- DM Self-interaction in form of particle scatterings, “collisional”
- Heat transfer among halo shells
- Unique 2-phase evolution
 - ☐ Heat inflow: CDM → core
 - ☐ Heat outflow: core → core-collapse
- Core-collapse:
 - Takes long-time to happen
 - But a runaway process
 - Negative heat capacity of self-gravitating system: globular clusters



SIDM halos: core-formation to core-collapse



- A natural large diversity in inner mass distribution
- ...when observed at different stages from core-formation to core-collapse
- Orbital effects further enhance the diversity (next slide)



Main features of core-collapse happening:
(in the center) **denser, hotter, steeper density slope**

DM-only: individual SIDM subhalo

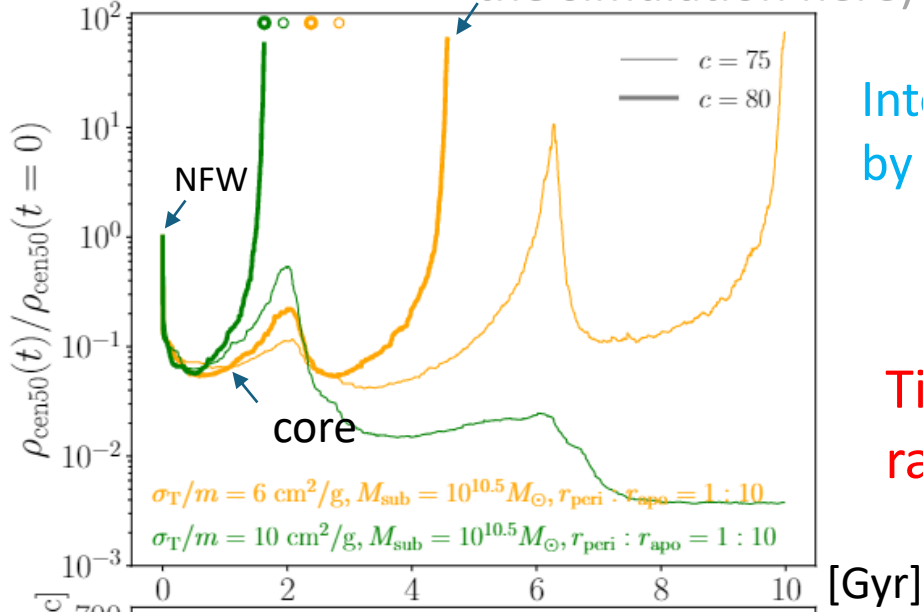
Zeng+ 2110.00259

Getting more complicated and fun with orbits!

Central density

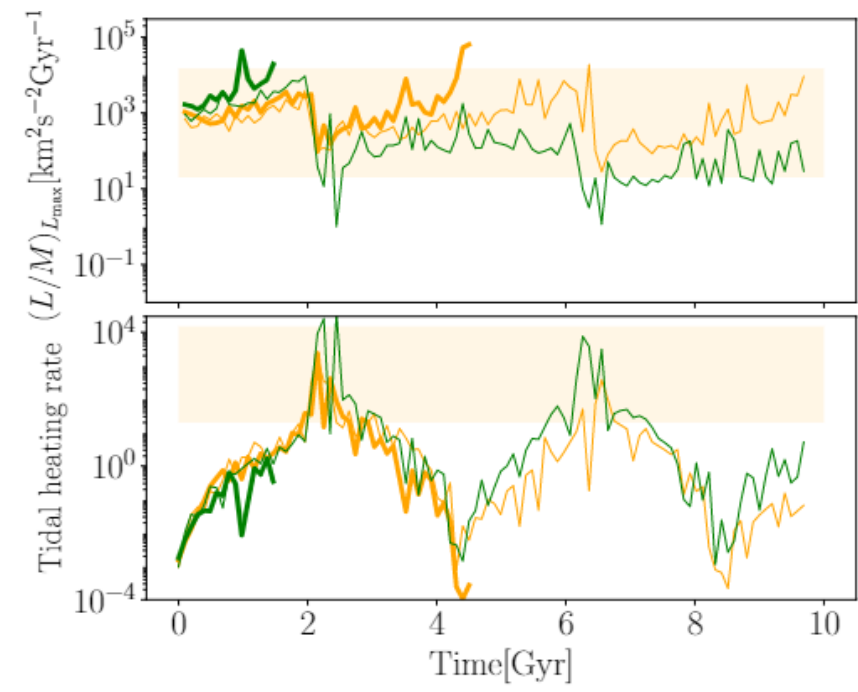
Tracer of core to core-collapse

Core-collapse (terminate the simulation here)



Internal cooling by heat outflow

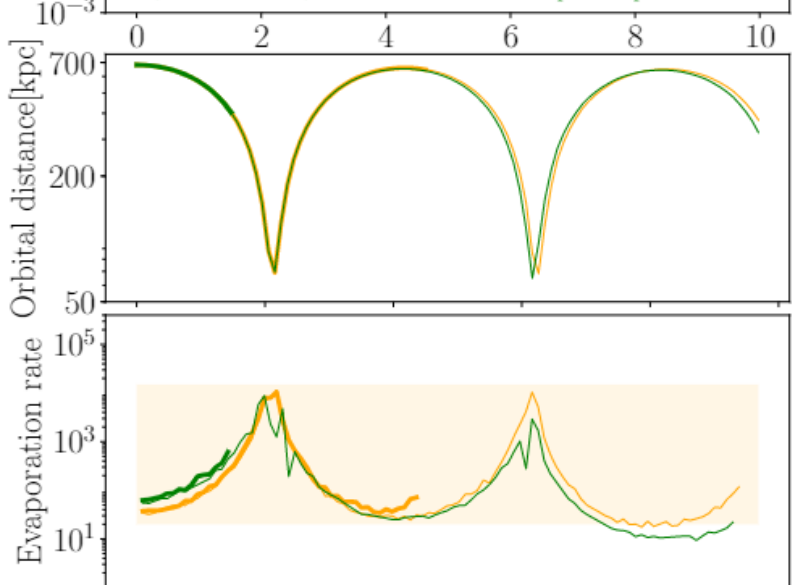
Tidal heating rate



Orbital distance

Evaporation heating event rate:

$$\propto v_{\text{orbit}} \frac{\sigma}{m} \rho_{\text{host}}$$



- Subhalo central density grows only if **cooling** > **heating**
- Evaporation heating can be strong enough to disrupt pre-core-collapse
- Core-collapse or not is **highly sensitive** to subhalo parameters
- **Diversity of subhalo central density!**

We've talked about:

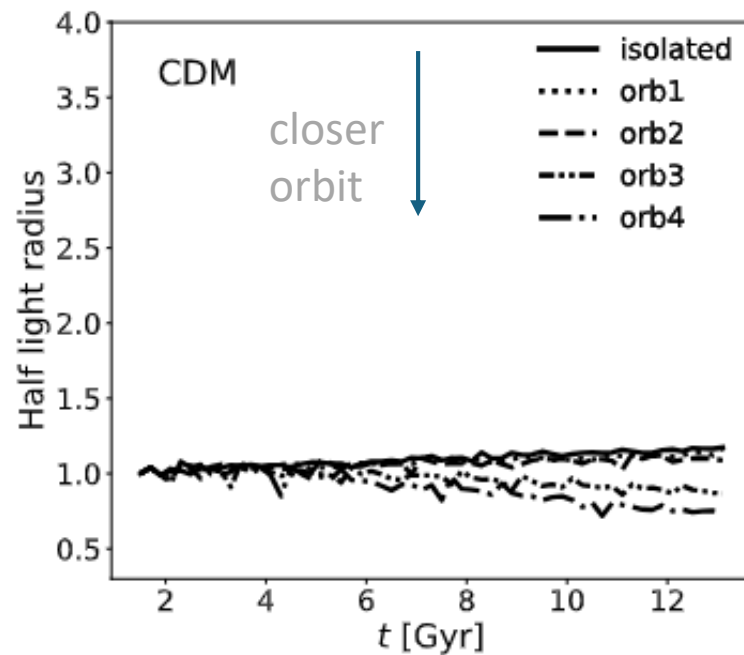
- the diversity in dark matter components of SIDM

To what extent is this diversity propagated to stellar components?

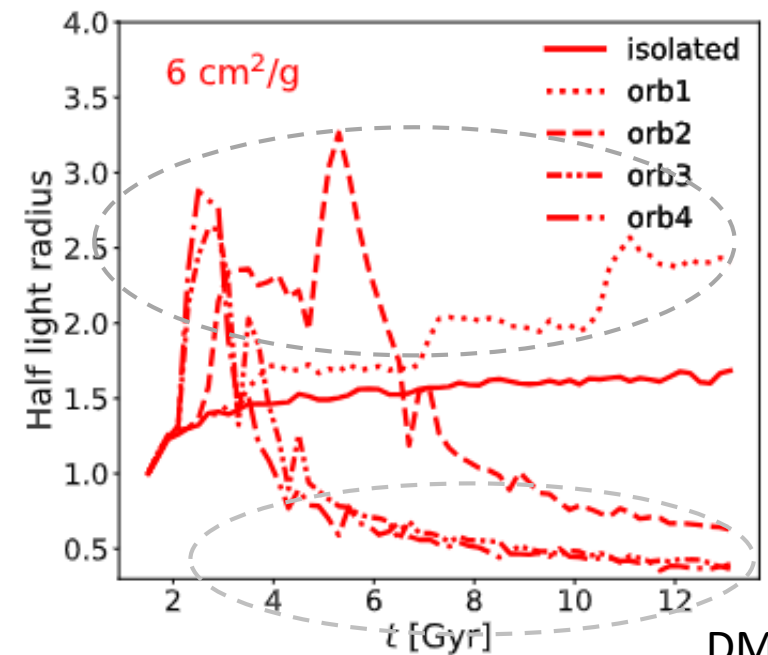
- Simulation with two species of particles
- Dark matter (gravity+self-interaction) Zeng+ 2411.xxxxx
- Stars (gravity)
- Use one SIDM dwarf (satellite) galaxy as a demonstrative case study

Time evolution of dwarf galaxy's size

- r_{half} increases:
 - Core-formation ($\sim \times 1.5$)
 - Evaporation ($\sim \times 3$ at max)
- r_{half} decreases:
 - Core-collapse ($< \times 0.5$)
 - (most cases) Late time accelerating size-reduction
 - Tidal stripping on stars
 - Forming DM-free galaxies
 - (only for cuspy stellar profiles in I.C.)



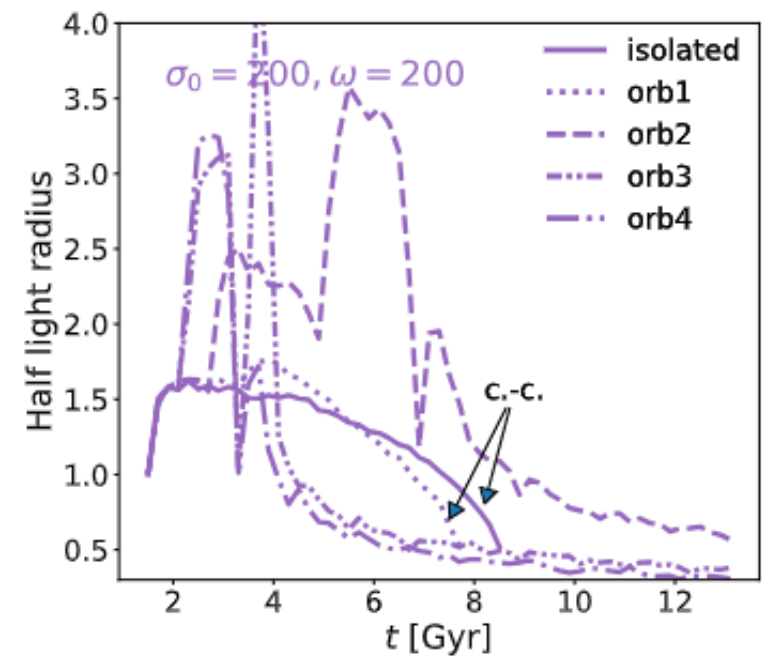
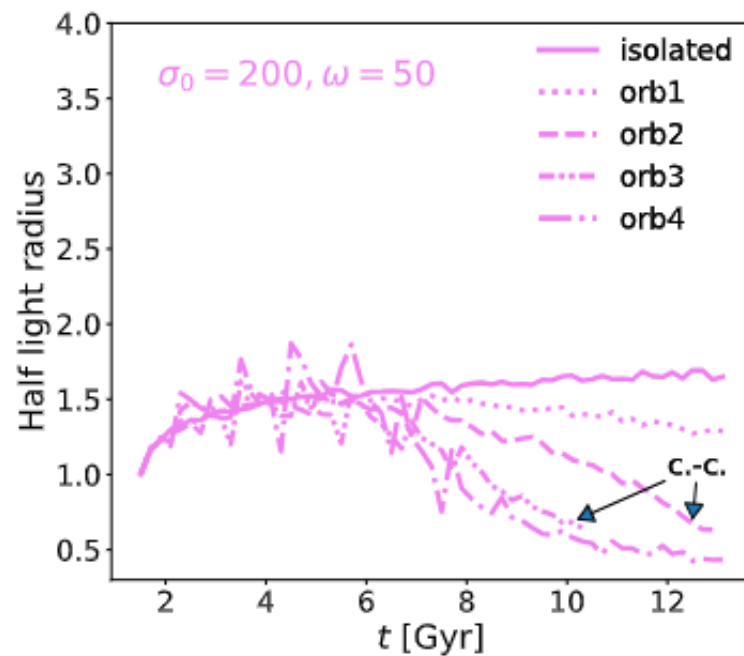
(a)



(b)

Evaporation induced size boost

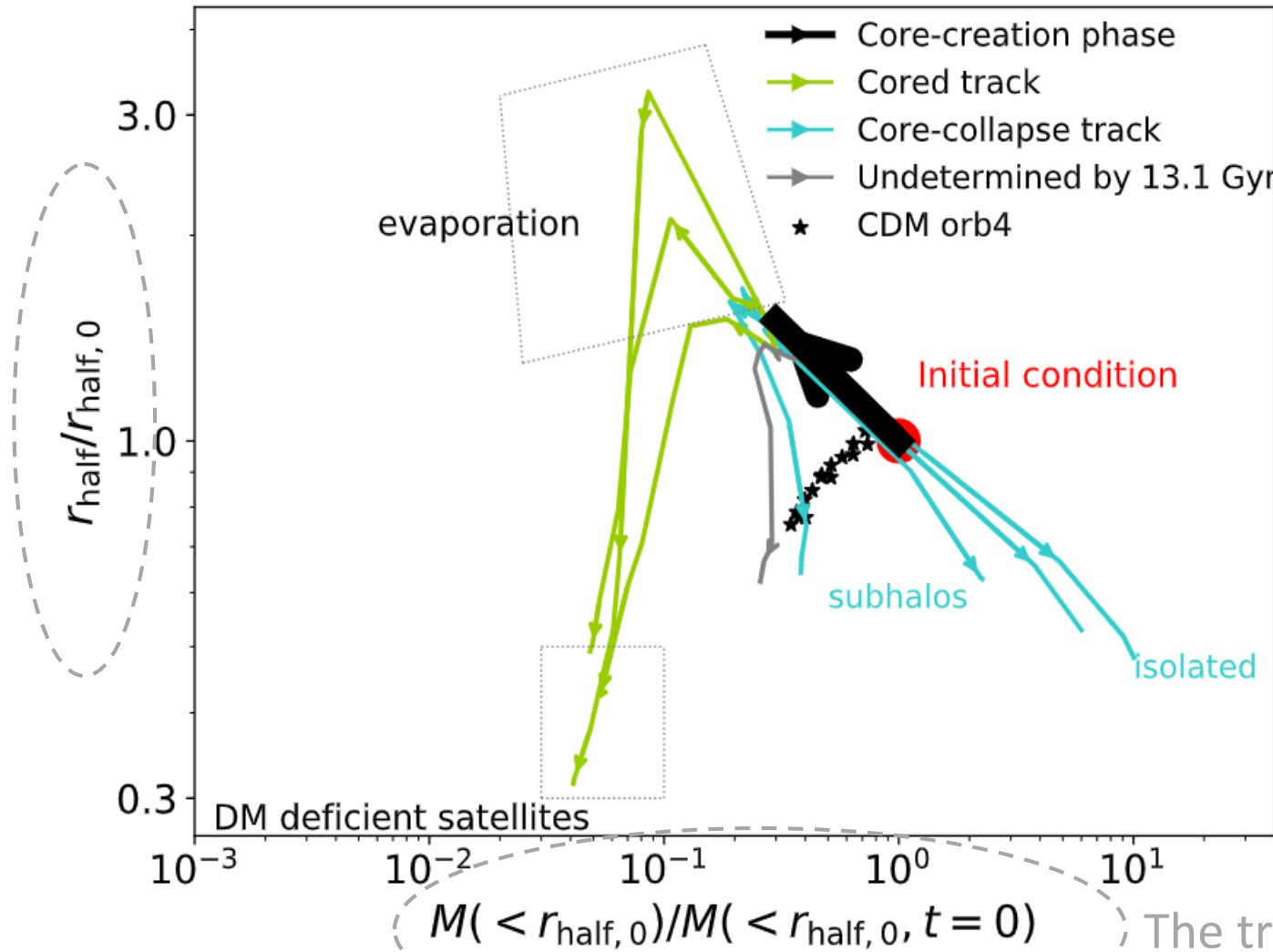
DM-free galaxy



Tidal evolution tracks of stellar size

Diversity & universality

Observable –
but demands
higher
resolution to
simulate



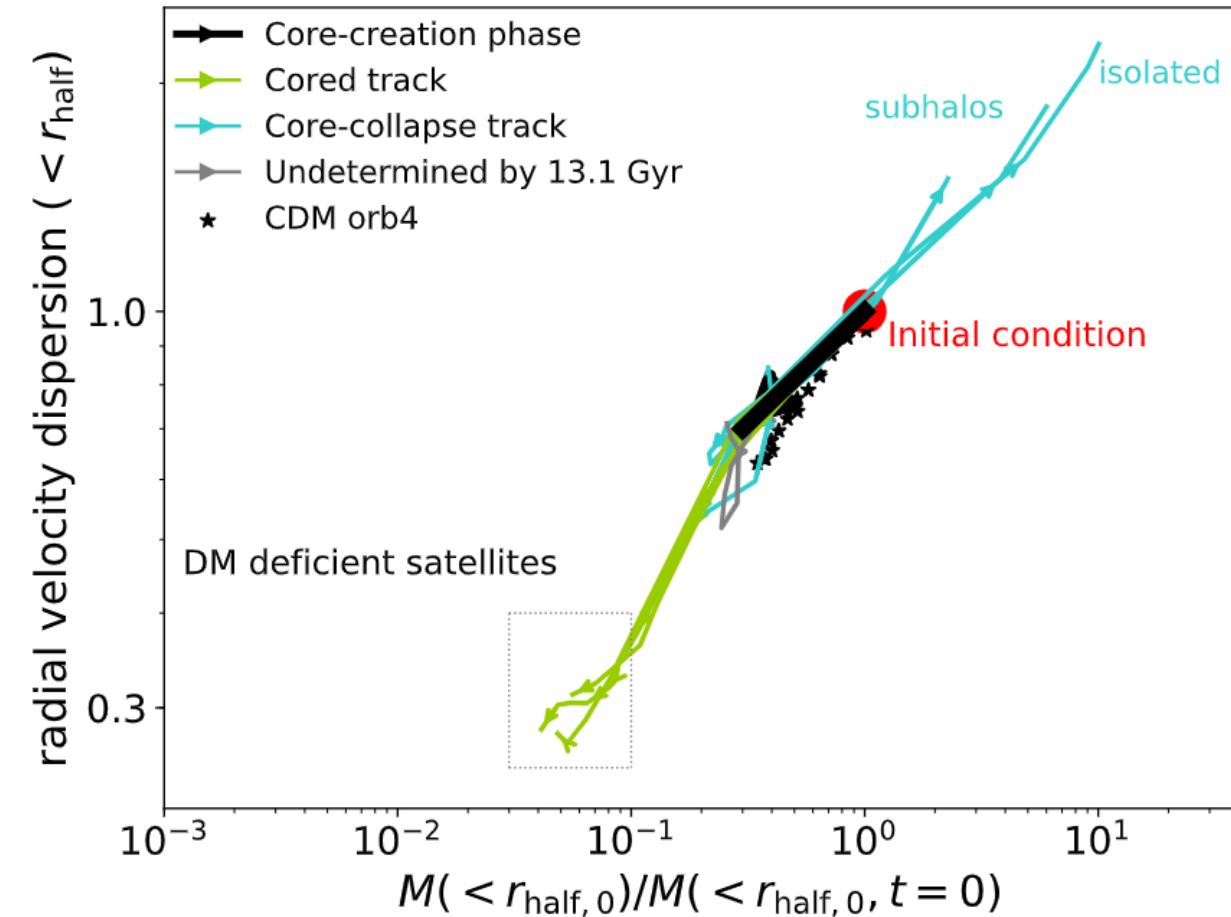
- Diversity: much larger span than CDM
- Universality: the evolution tracks are highly explainable, and potentially parameterizable
- Fitting “tidal tracks” → a cost-efficient approach for future large-scale sims

$$M(< r_{\text{half},0}) / M(< r_{\text{half},0}, t=0)$$

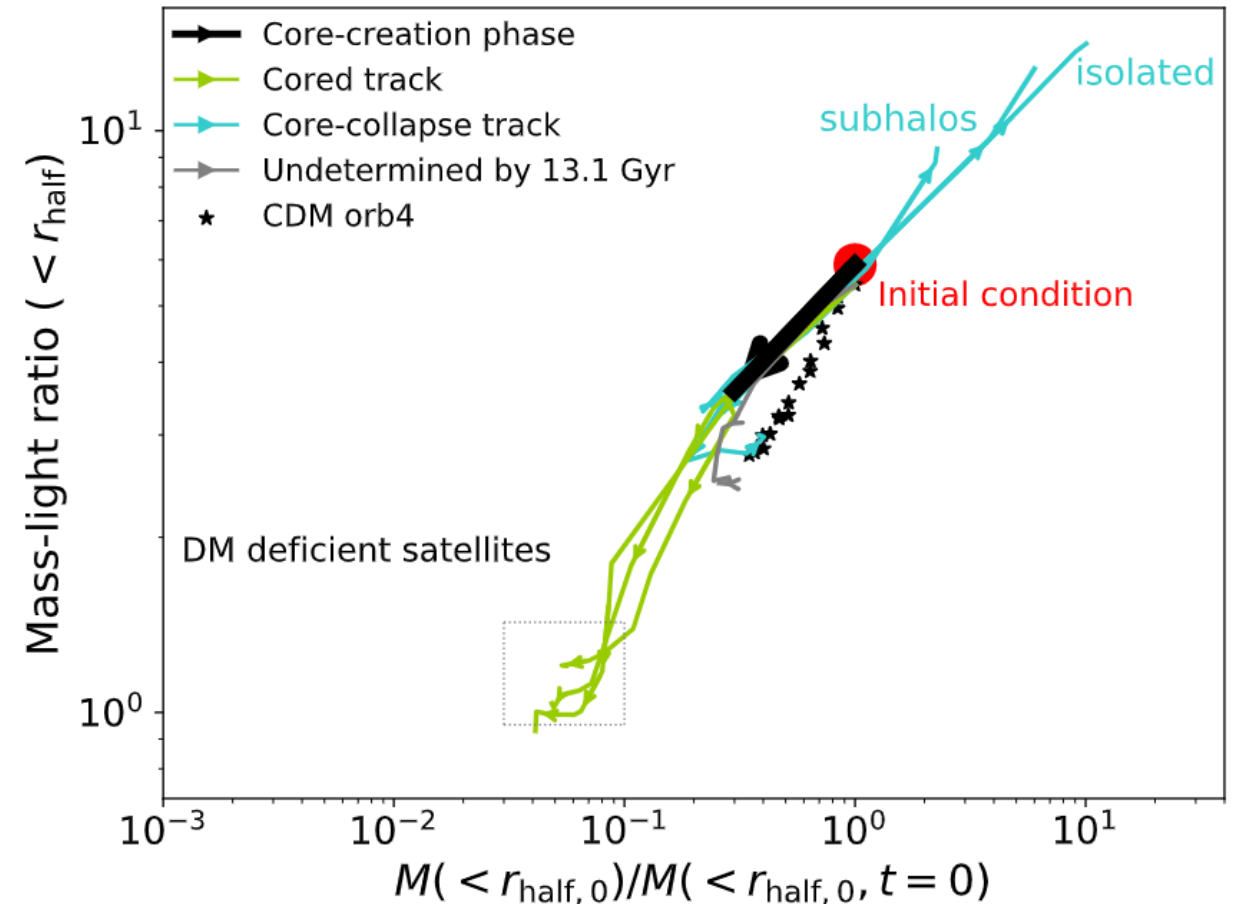
The tracer that demands lower resolution

Tidal evolution track of stellar size

Radial velocity dispersion

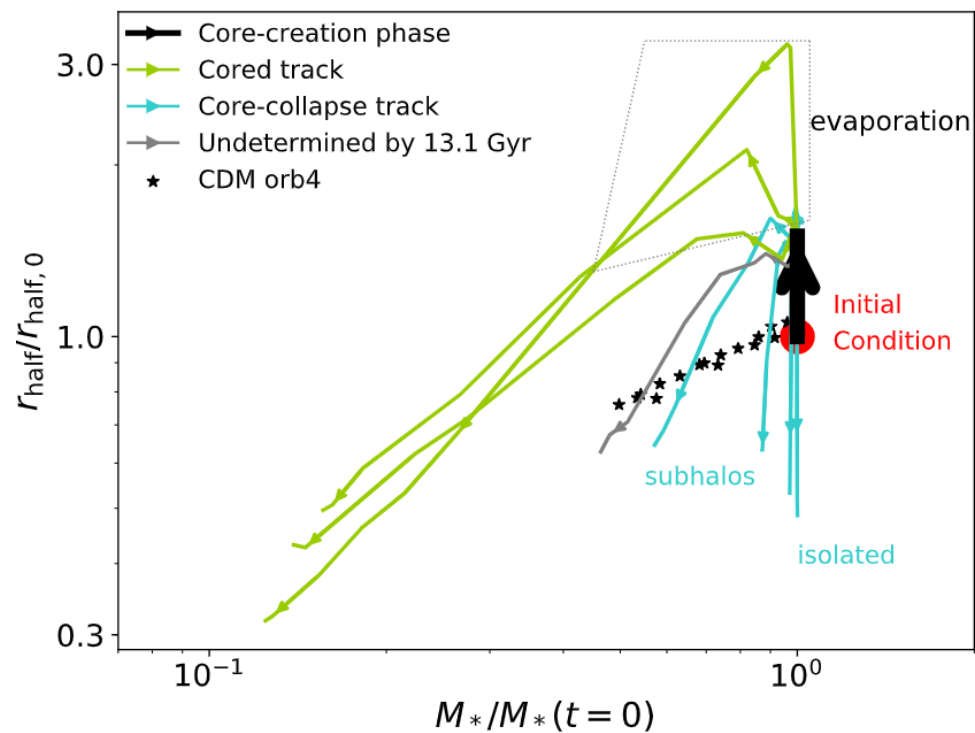


Mass-light ratio



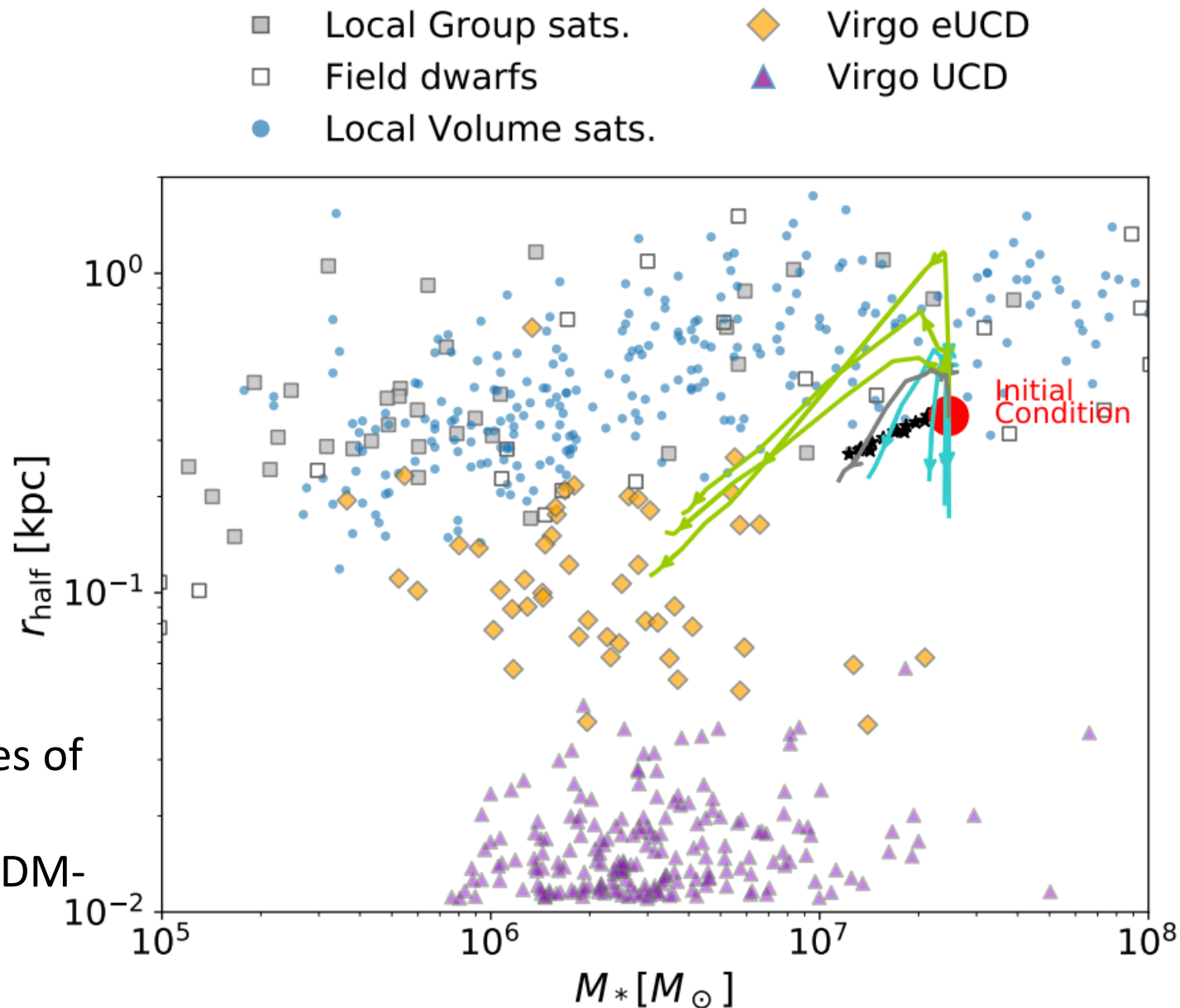
diversity (large spanned range)
& universality (similar, explainable trends)

SIDM dwarfs in stellar mass-size plane



Can SIDM accommodate all the extremes of dwarf galaxies?

- ultra-diffuse, ultra-compact, DM-free, DM-dominant



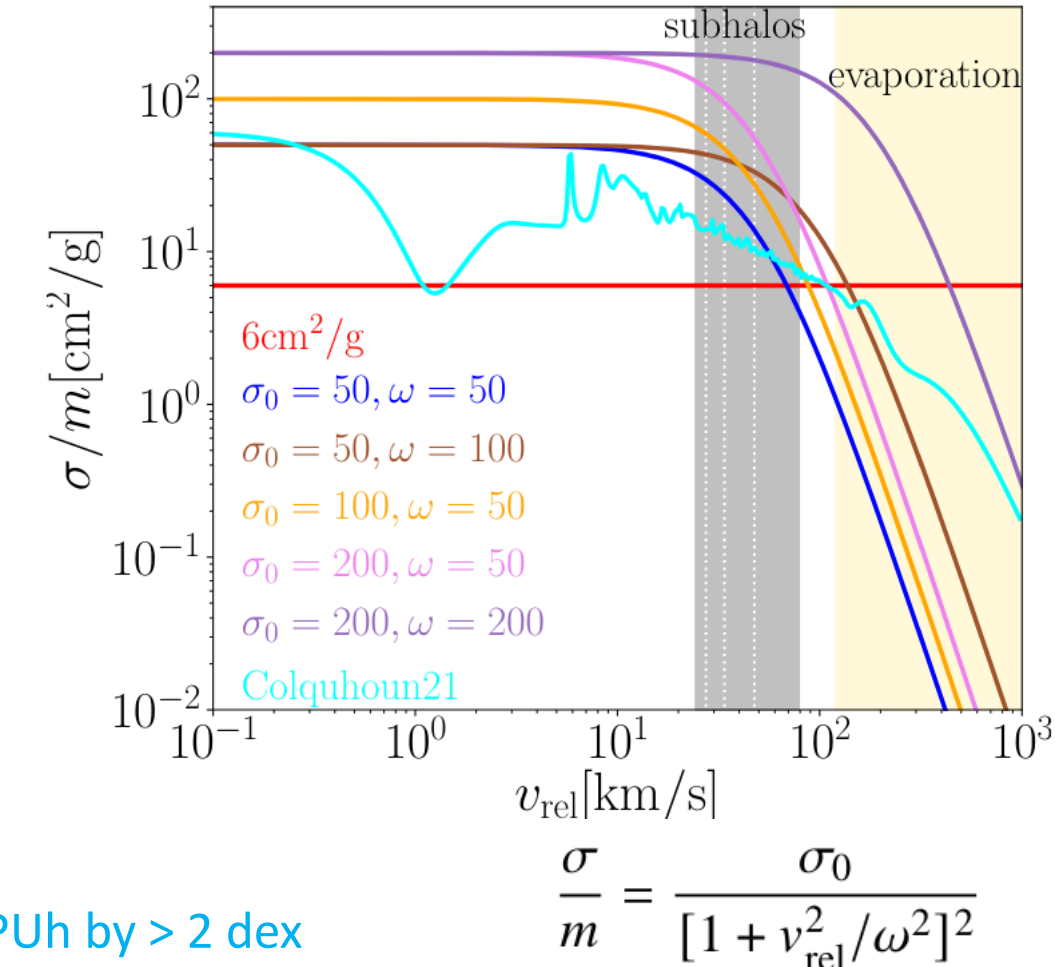
Take away

- SIDM halos have unique core to core-collapse evolution
- This brings natural diversity in halos' inner density/mass
- Even larger diversity if orbiting host halos

- Not only in DM components, this diversity is also propagated (in part) to stellar components
- → future: look into whether/what SIDM models can explain the diversity problem in statistics

Method: controlled simulation + hybrid method

- The system: an isolated host + its subhalo(s)
- **We focus on the low-mass subhalos**
- Very expensive if simulation particles for both host and subhalos
 - Host mass $> 10^3$ subhalo mass
 - Core-collapse requires orders of magnitude more CPUh
- Thus we do **analytic host + particle subhalo -- hybrid**
 - Host: analytic mass & velocity distribution
 - Capture the host-subhalo interaction
 - Tidal force --- already mature
 - **Evaporation**: self-interaction of host-sub particle pair
 - Semi-analytically calculated



Reduces CPUh by > 2 dex

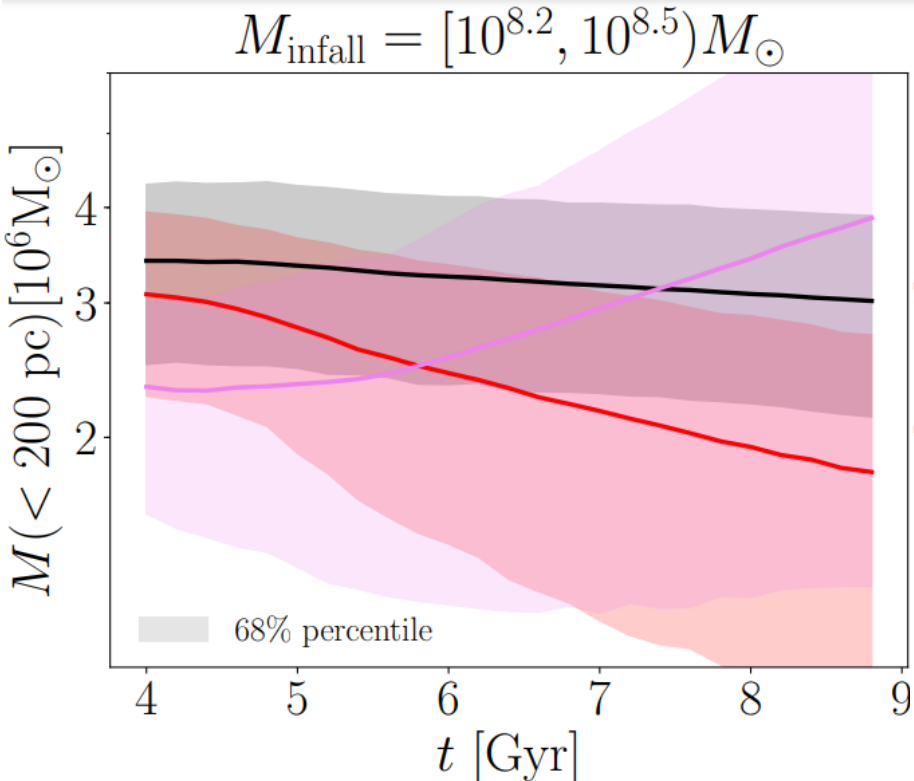
For each subhalo particle: $P_h = \delta_t \frac{\sigma_{\text{T}}}{m} \rho_h |\mathbf{v}_h - \mathbf{v}_s|$

a population of subhalos

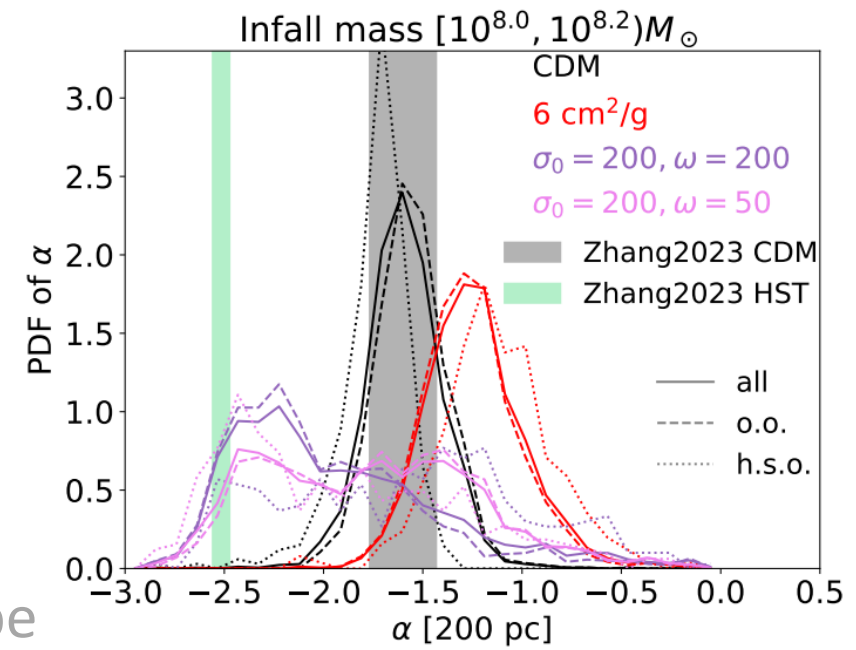
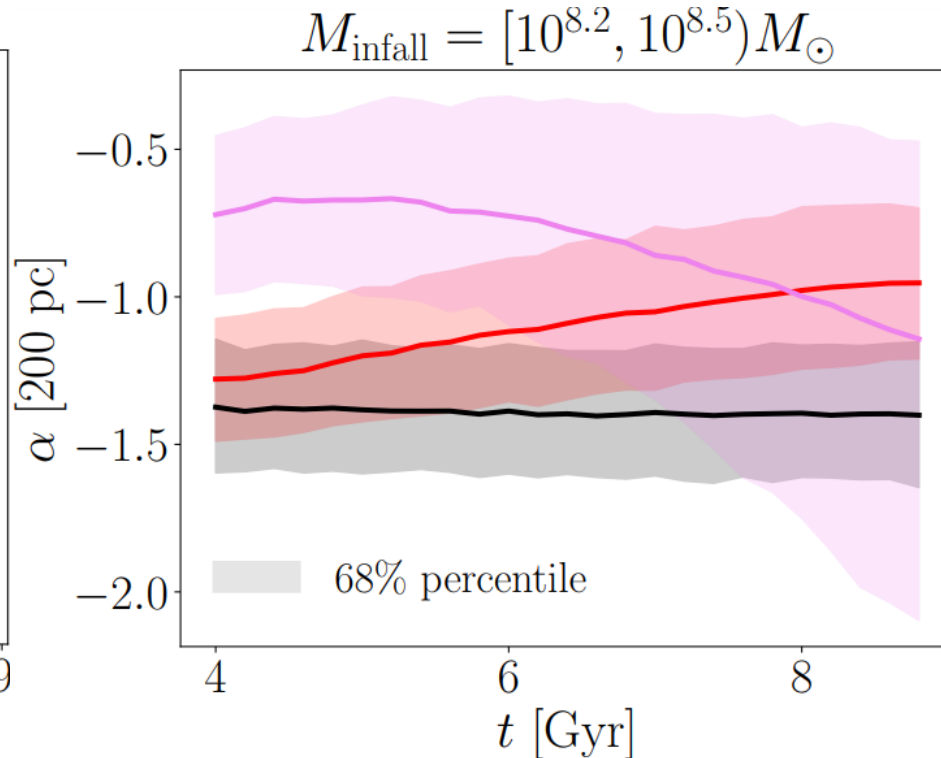
Zeng+ 2310.09910

Main features of core-collapse happening:
 (near the center) **denser, hotter, steeper density slope**

Subhalos' inner mass



Subhalos' inner slope

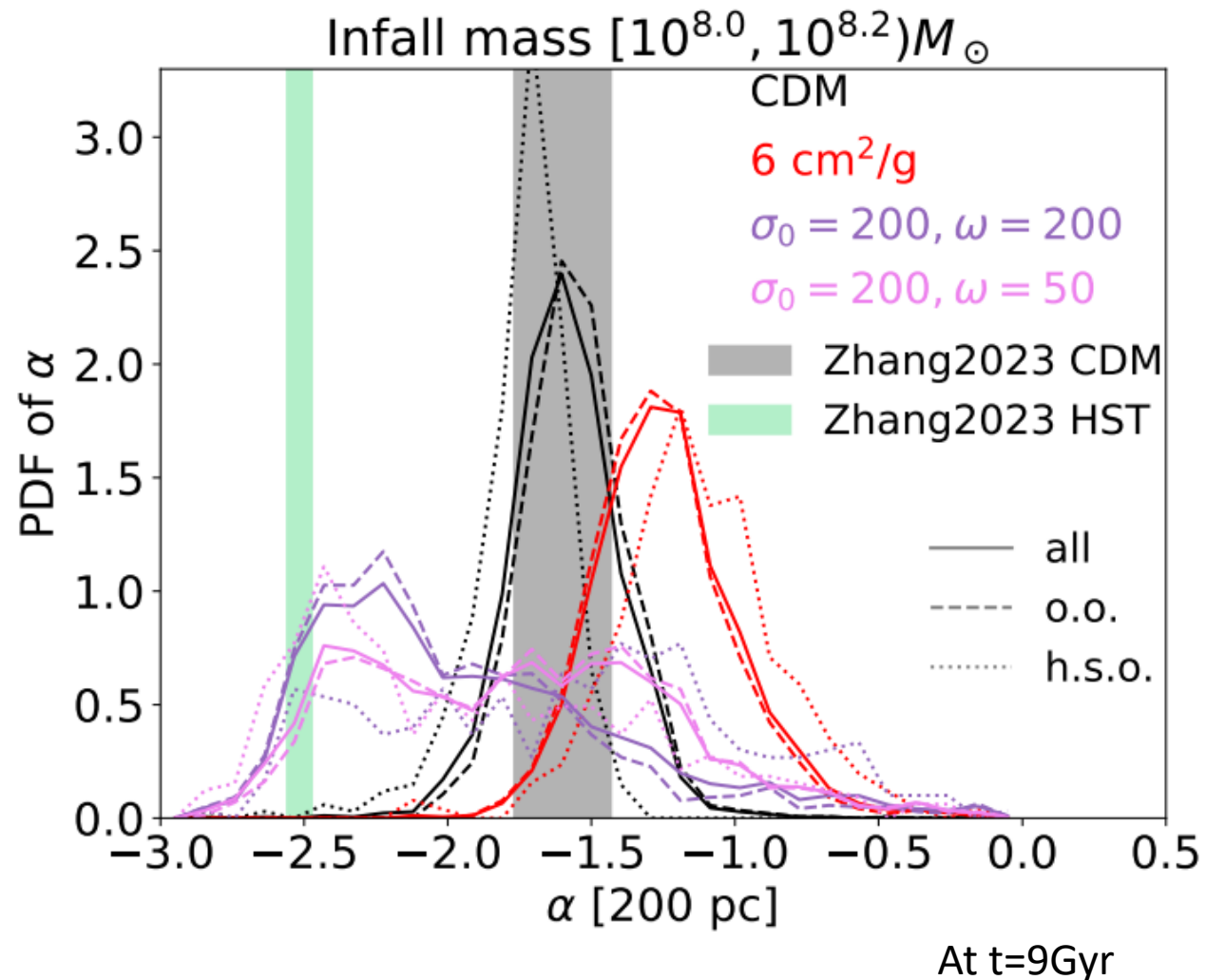


CDM

6 cm^2/g
 Cored subhalos,
 evaporation

$\sigma_0 = 200, \omega = 50$
 (a velocity dependent
 SIDM model)
 10-20% subhalos core-
 collapsed

Population of subhalos



SIDM core-collapse in subhalos can explain ultra-steep inner slope in subhalos found by lensing with Hubble Space Telescope (13 images)

Zhang+ 2308.09739

How do stars respond to SIDM core to core-collapse and orbital effects?

‘Inner’ defined at the initial $r_{half,0}$ in this work

(Qualitatively)	Inner DM mass	Inner stellar mass	Stellar r_{half}
Core-creation	--	-	+
Core-collapse	++	+	-
Tidal stripping	--	-	-
Evaporation	---	-then--	++ then --

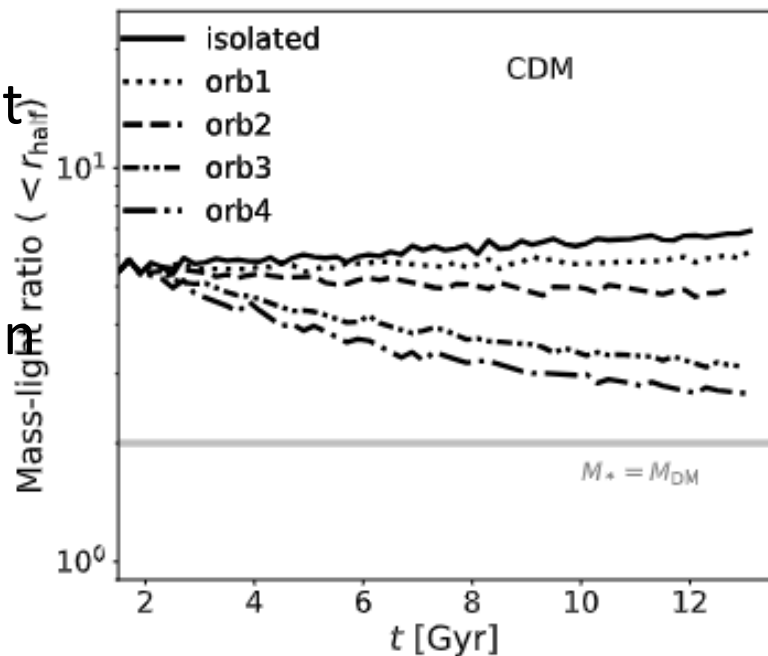
Time evolution: mass-light ratio

- Defined by total mass/stellar mass within r_{half}

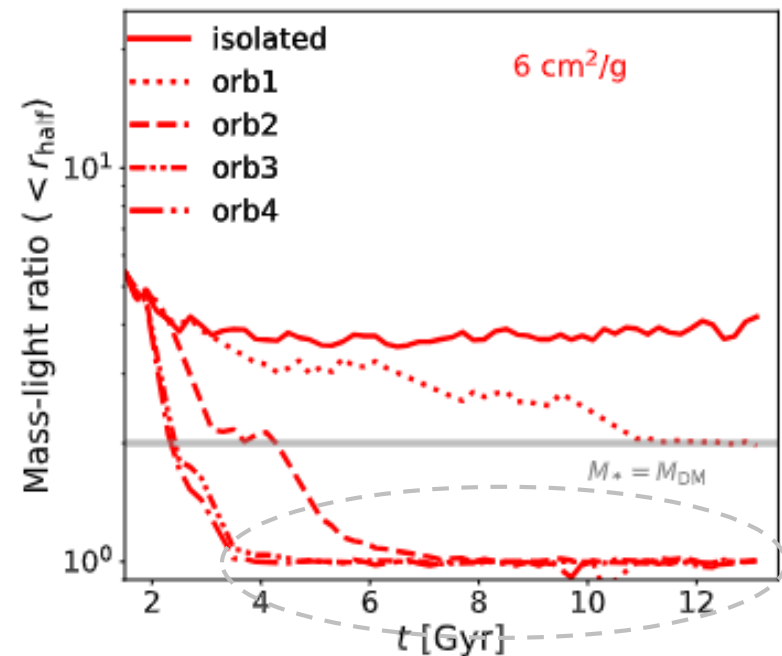
- If not core-collapse: monotonically decreasing (more baryon-dominated)

- Core-collapse: increases again

- DM-free objects form easily with evaporation

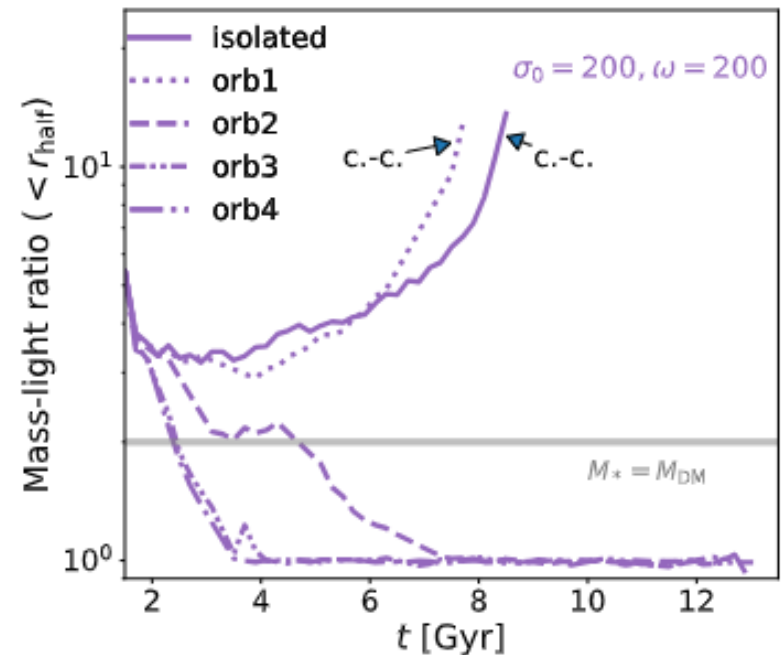
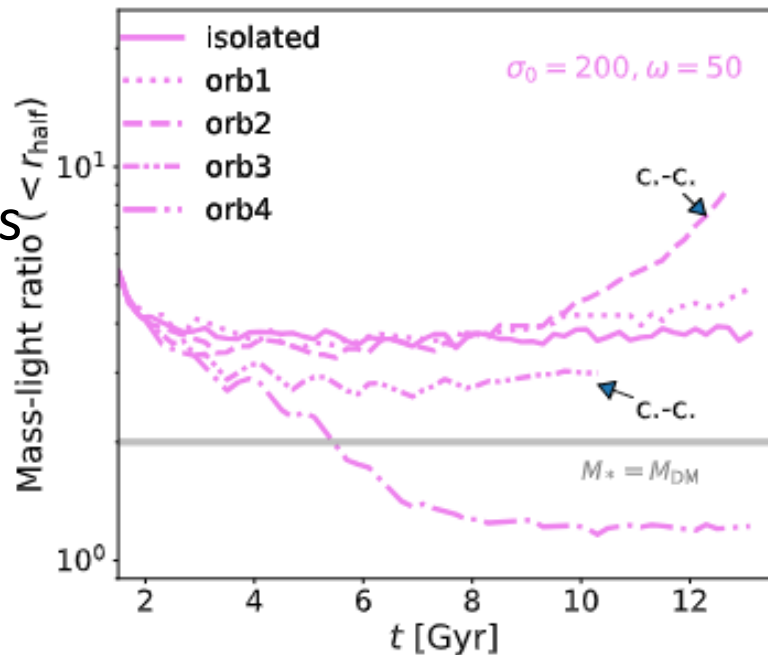


(a)



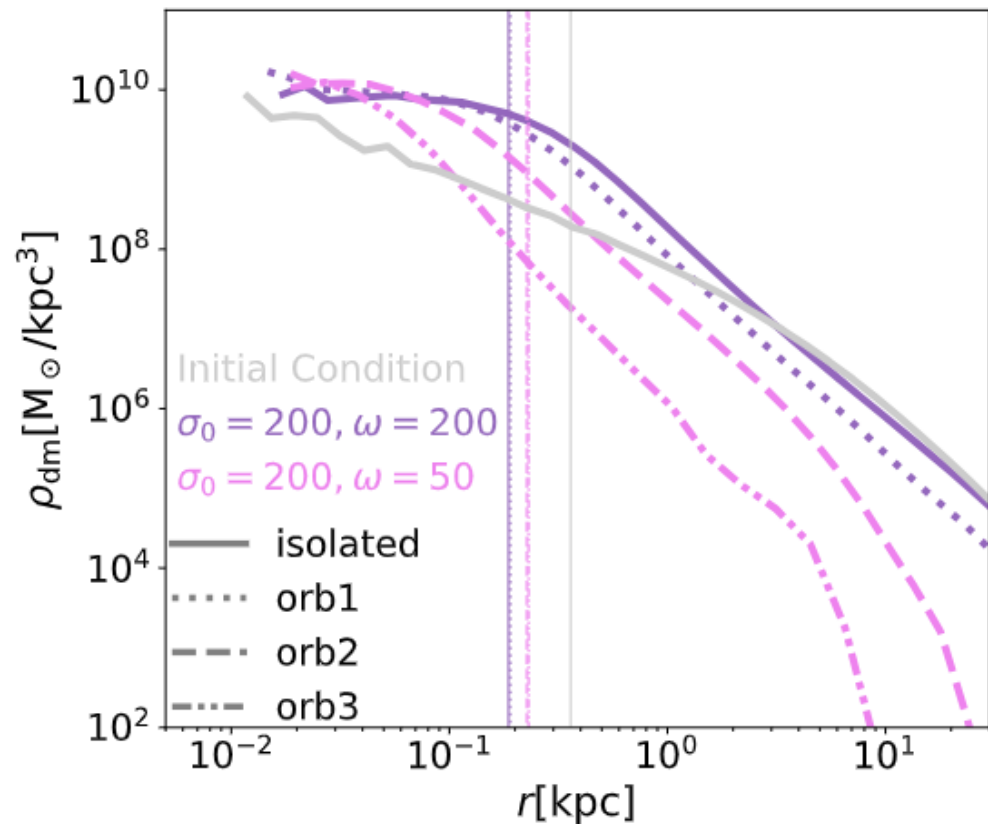
(b)

DM-free galaxy

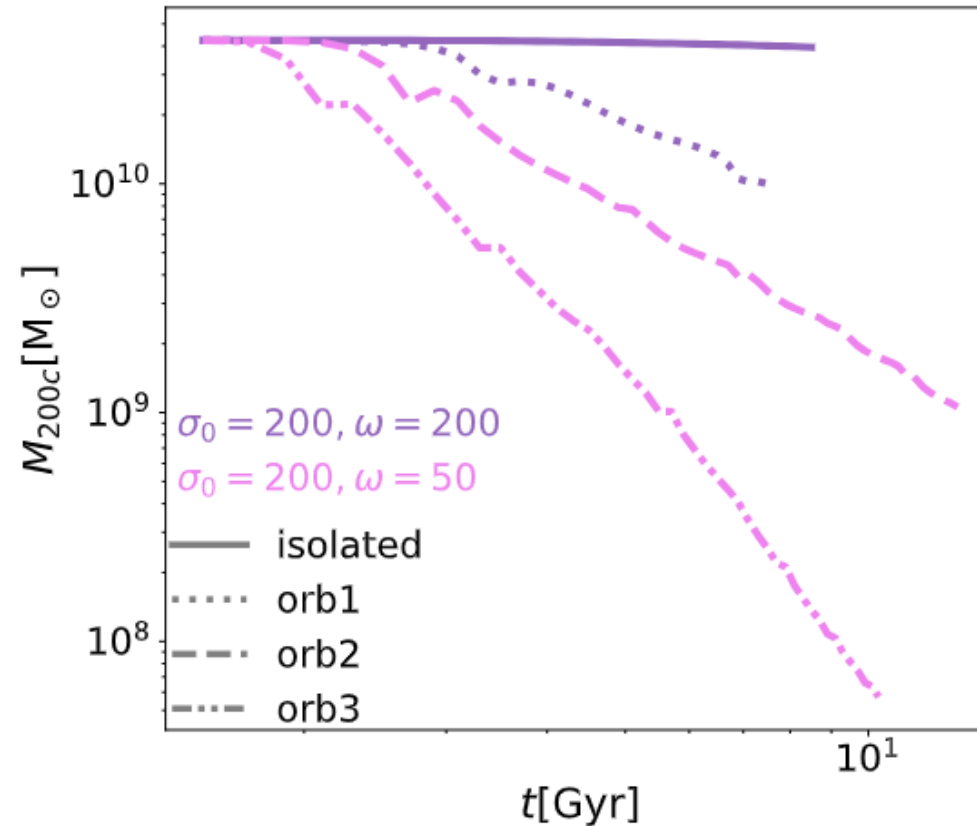


The core-collapsing cases: what happened to the exception?

DM density at core-collapse



Total mass loss history



- Stellar properties can probe core-collapse only when $r_{\text{half}} \lesssim r_{\text{c.c.}}$.
- But $r_{\text{c.c.}}$ keeps shrinking as it proceeds..
- ...eventually r_{half} and $r_{\text{c.c.}}$ decouples for every case?

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