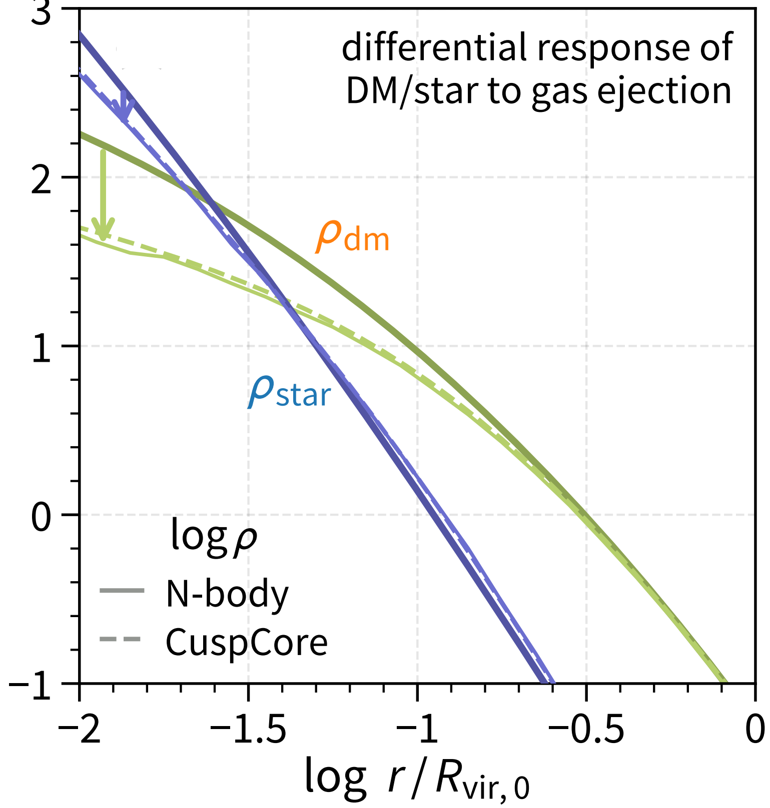
# Modeling the formation of dark-matter deficient galaxies

accurate analytical model
for structural evolution





**Zhaozhou Li** (李昭洲)

*Marie Skłodowska-Curie fellow

The Hebrew University of Jerusalem

Avishai Dekel (HUJI)

Nir Mandelker (HUJI)

Fangzhou Jiang (PKU)

Jonathan Freundlich (Strasbourg)

Thibaut L. François (Strasbourg)

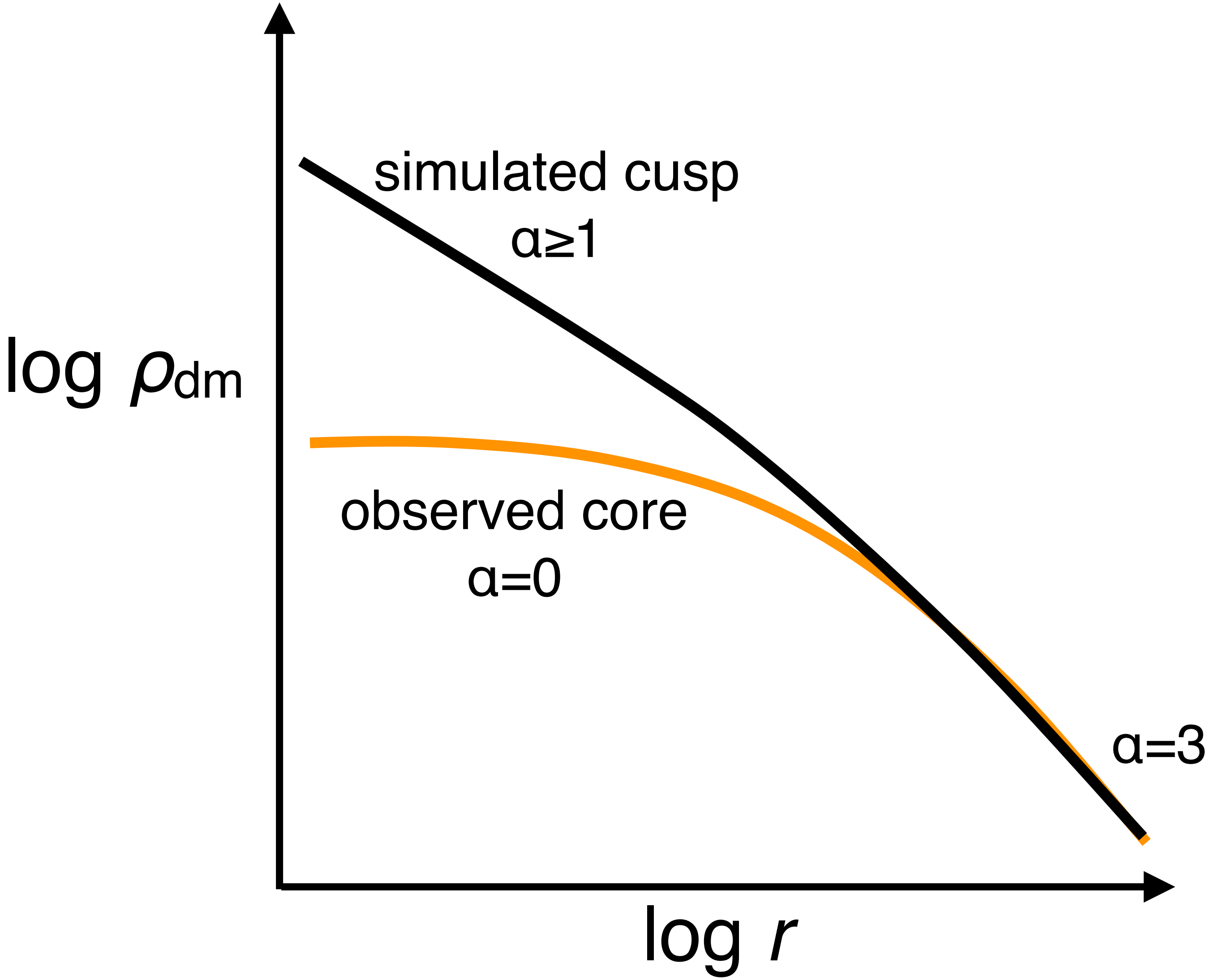
...


SJTU Collaboration Workshop
June 19, 2023

# Challenge to ΛCDM: diversity in galaxy structures

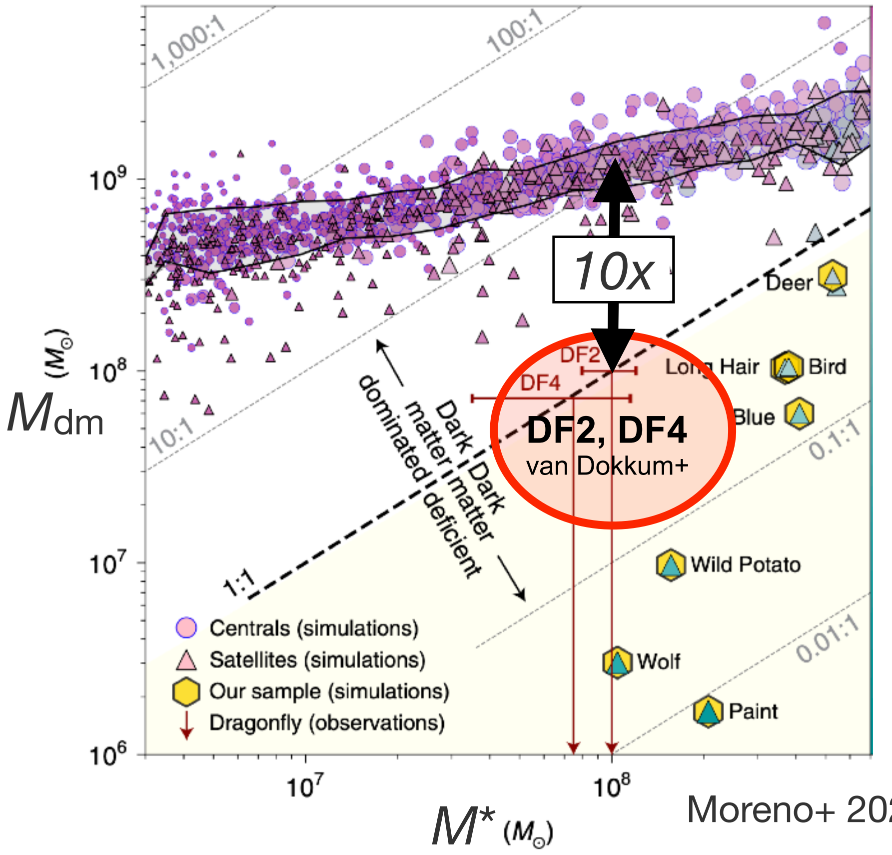
Diversity:
- Cusp or core?
- DM fraction?
- Galaxy size?

(Review: Sales+ 2022)



# Puzzle: DM-deficient galaxies in observation

**Ultra-diffuse dwarf galaxies**




Moreno+ 2022

✤ **SN-driven outflows + Tidal evolution**
(Pontzen+12, Di Cintio+17, Ogiya+18, 22, Jiang+19, Liao+19, Carleton+19, Moreno+22)

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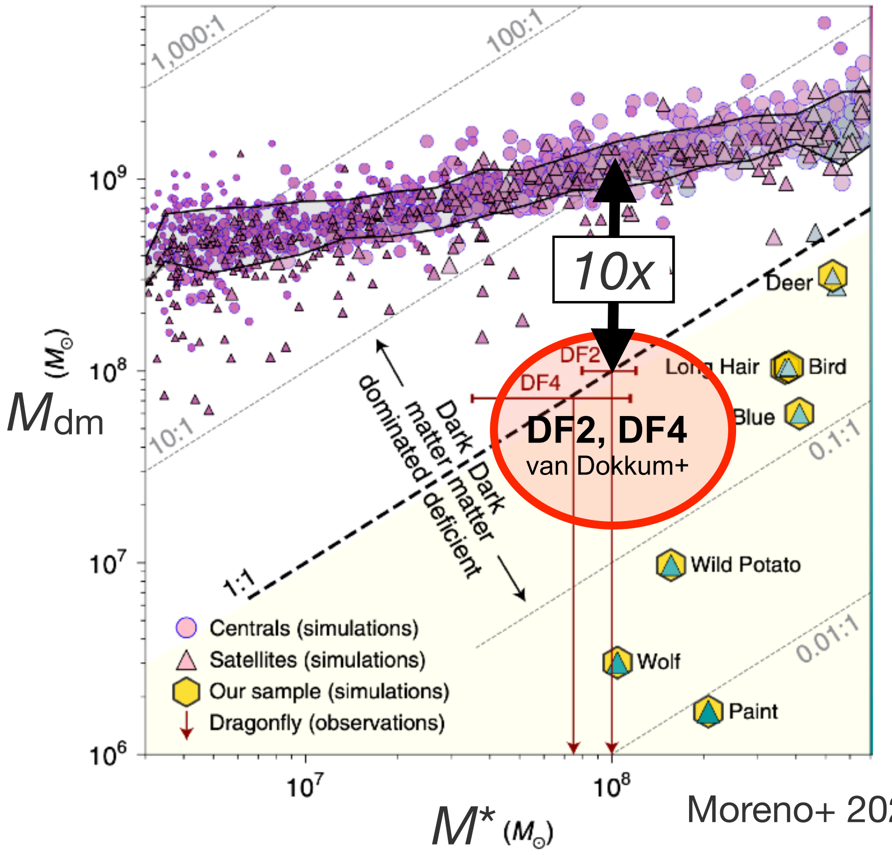


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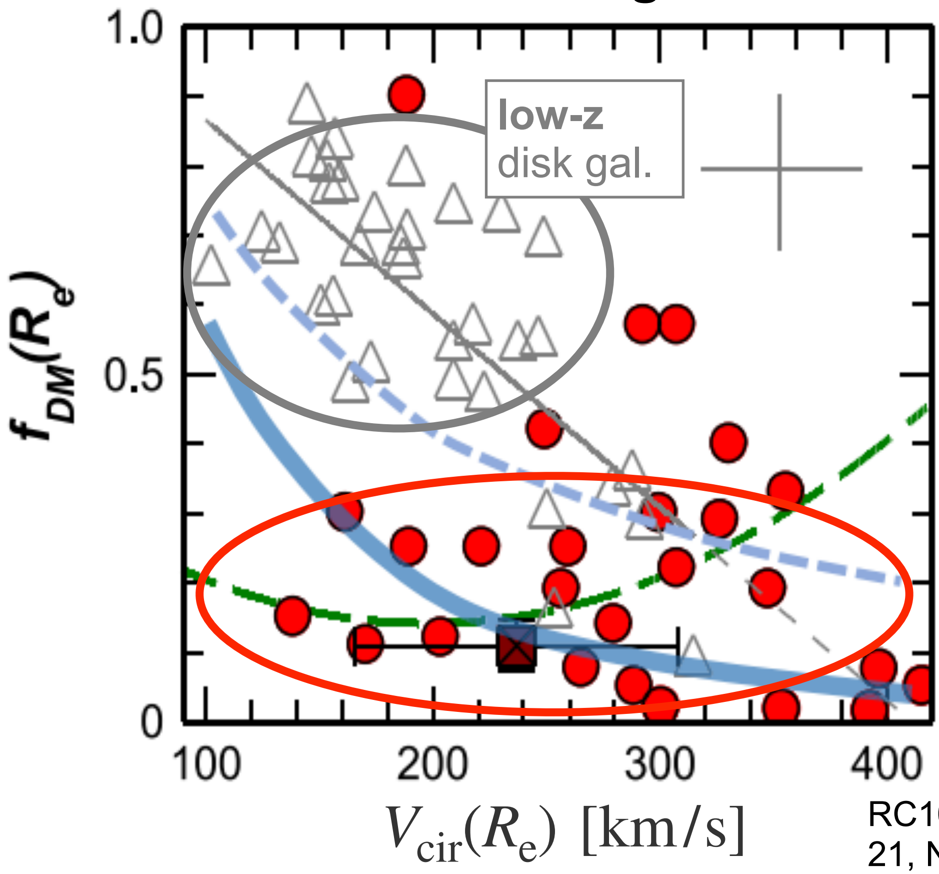
**Cores in massive galaxies at $z \sim 2$**




high-z disk gal.
$f_{DM} < 0.3$
core ~10kpc
$M_{vir} \sim 10^{12.5} M_\odot$

RC100: Genzel+ 20, Price+ 21, Nestor Shachar+ 22

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- Not reproduced in current hydro sims (resolution, subgrid model?)
  **Analytical models** can help!

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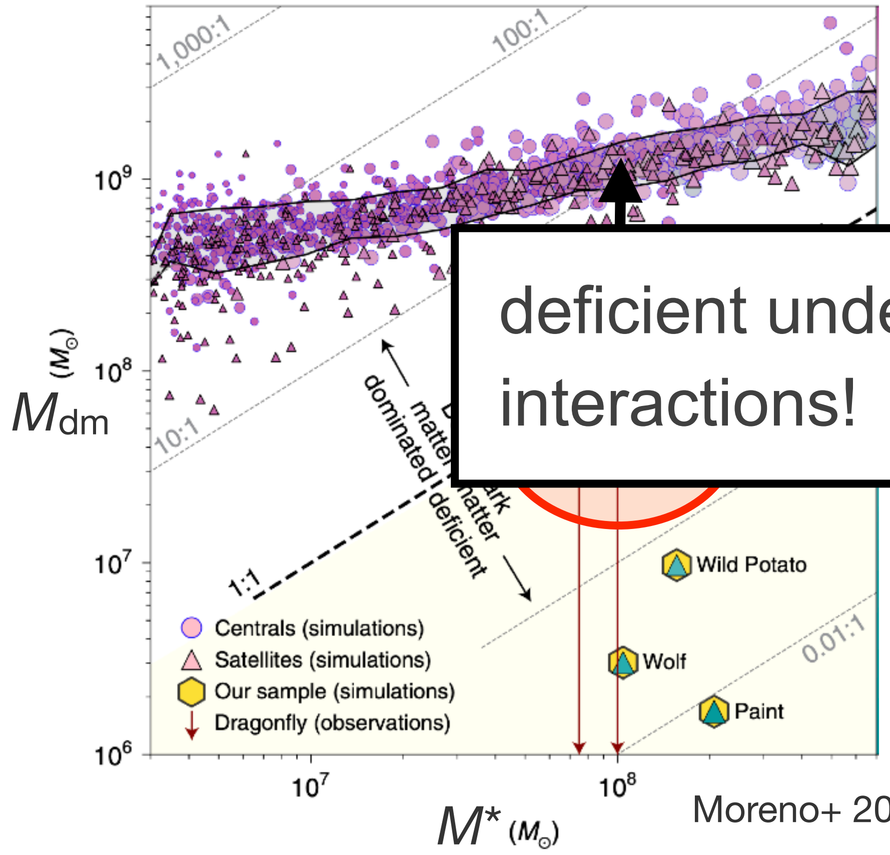


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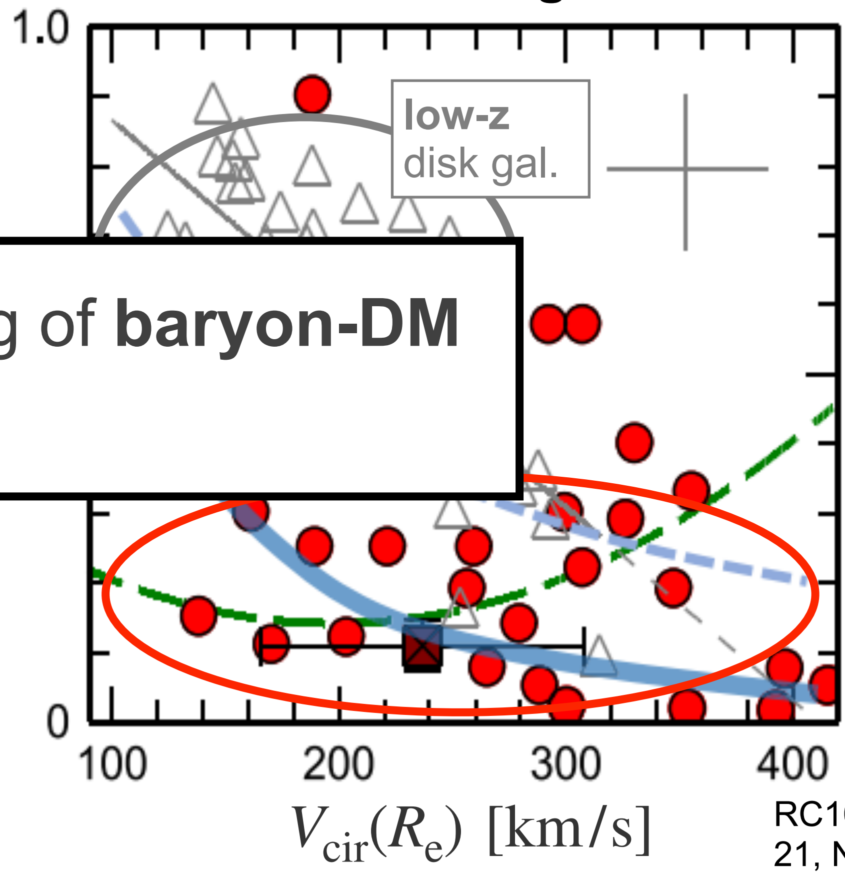


deficient understanding of **baryon-DM** interactions!

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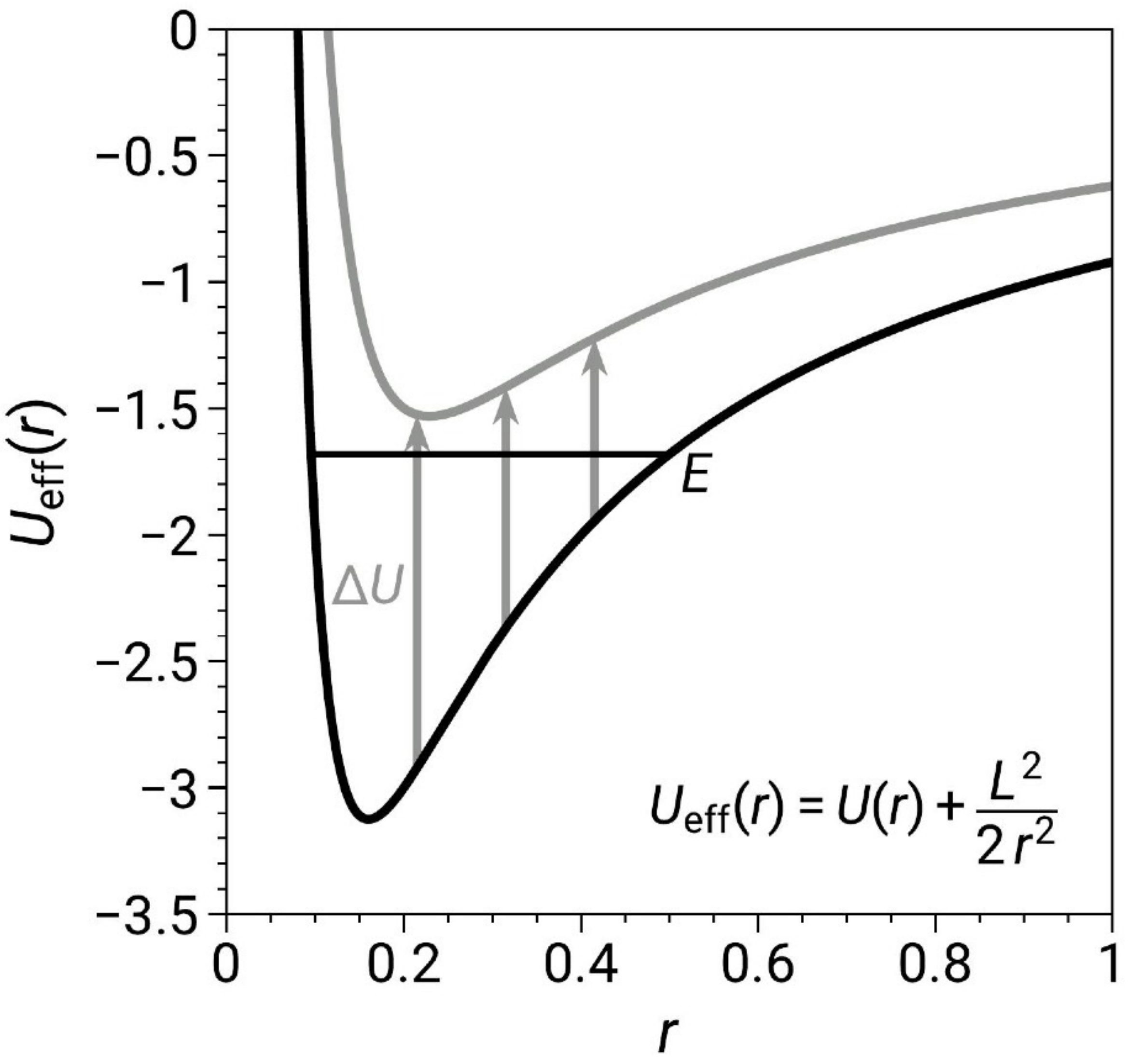


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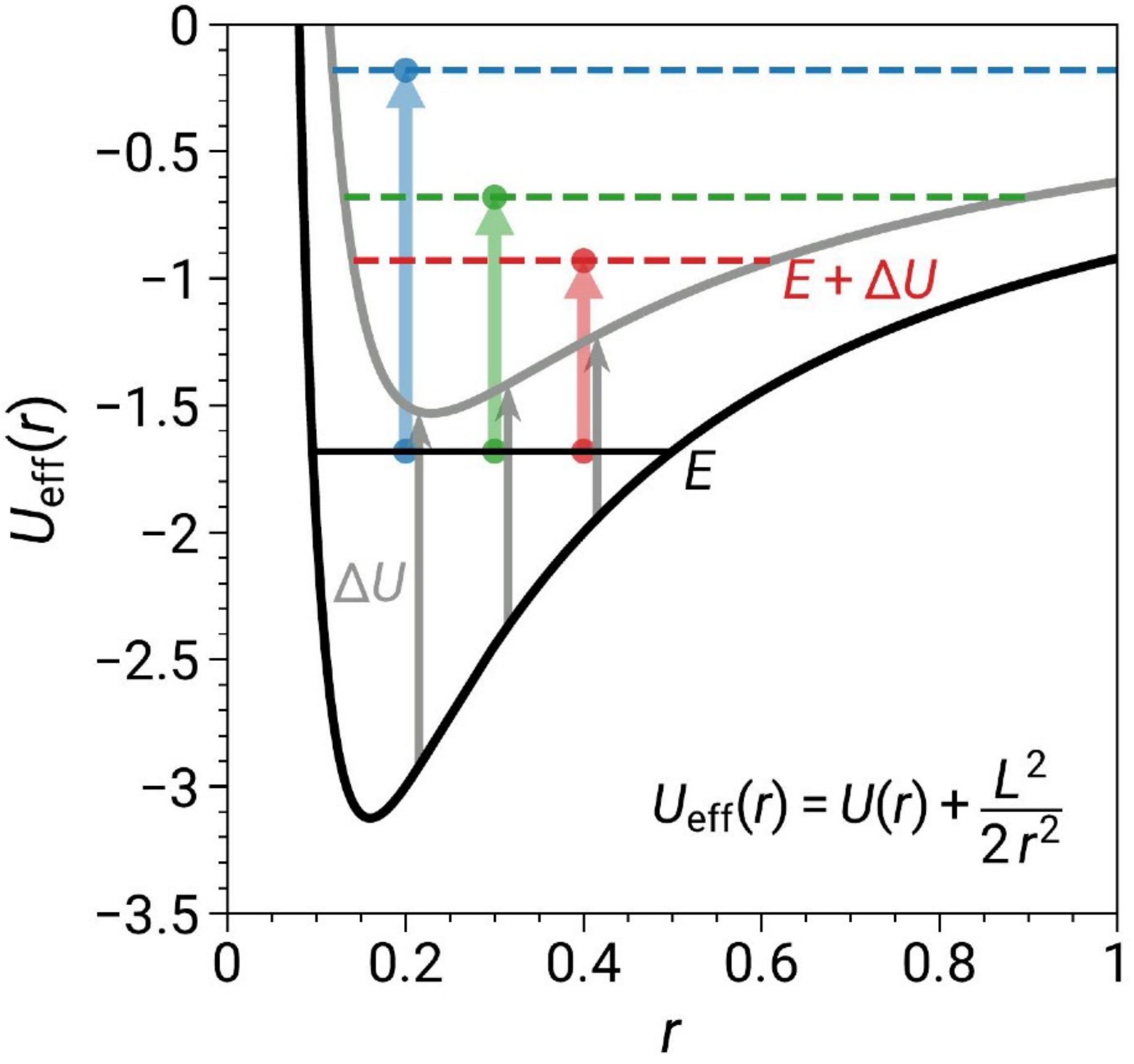


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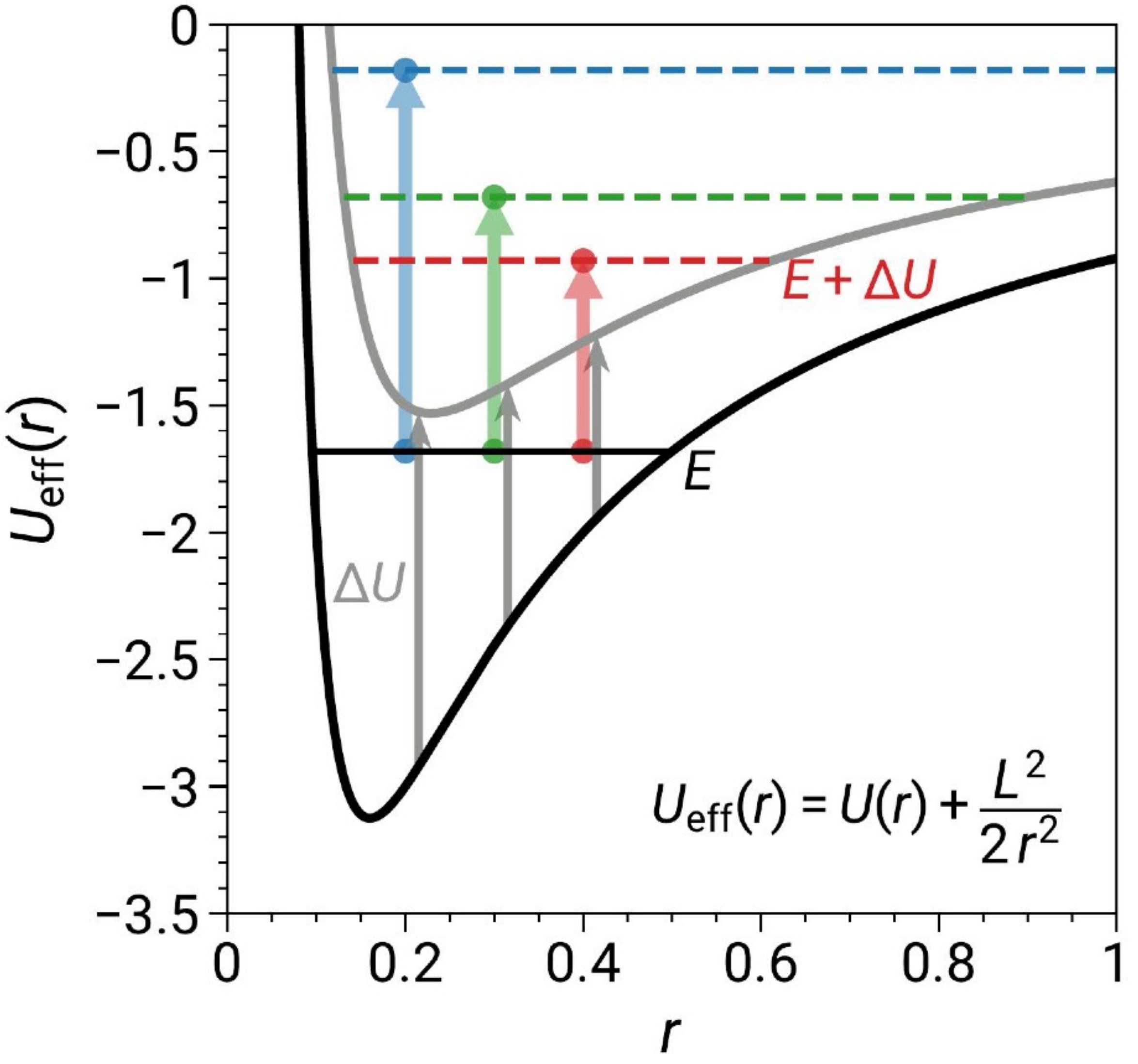


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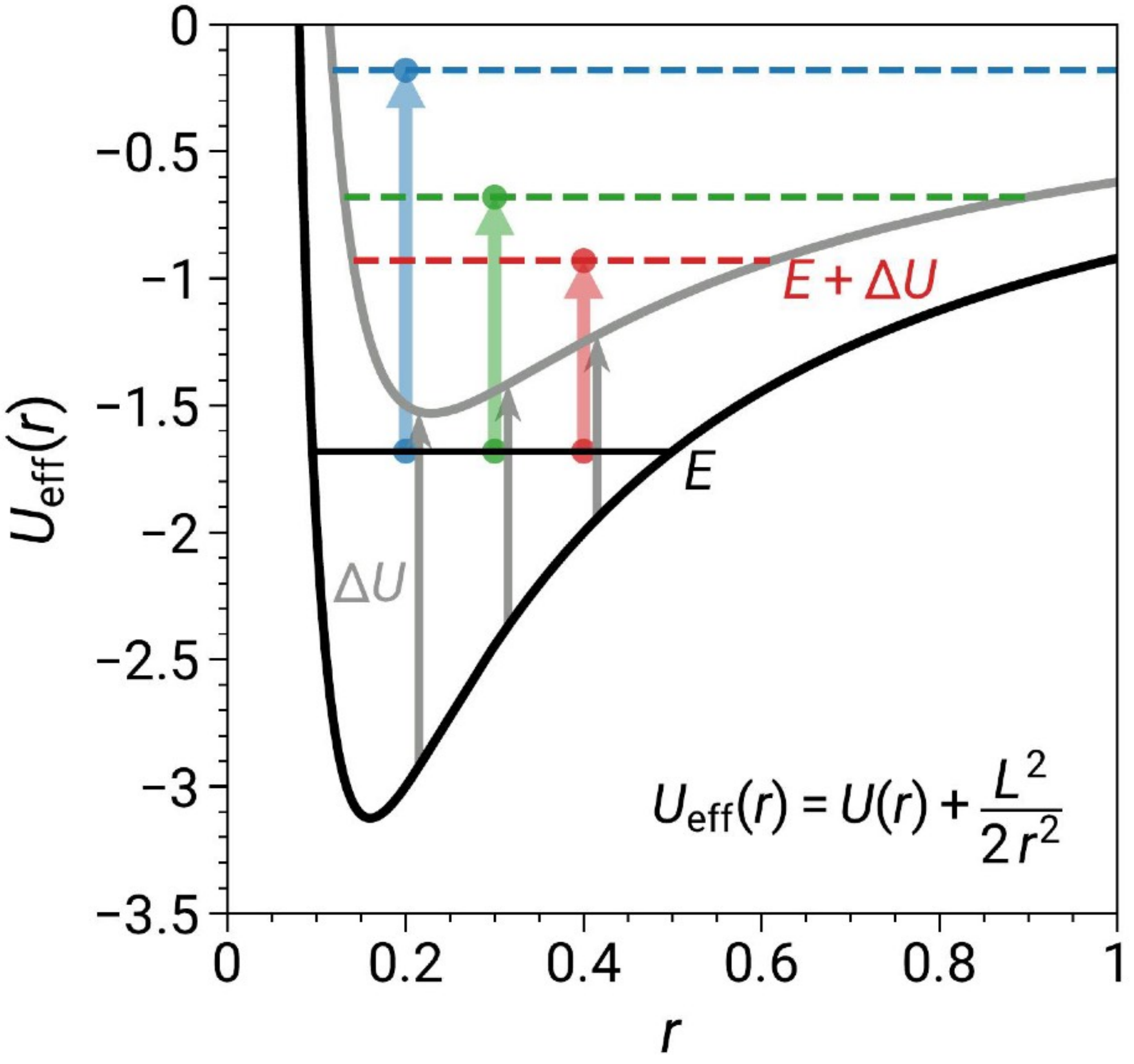


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$E' = E + \Delta U(\mathrm{r})$ for particles at $r$

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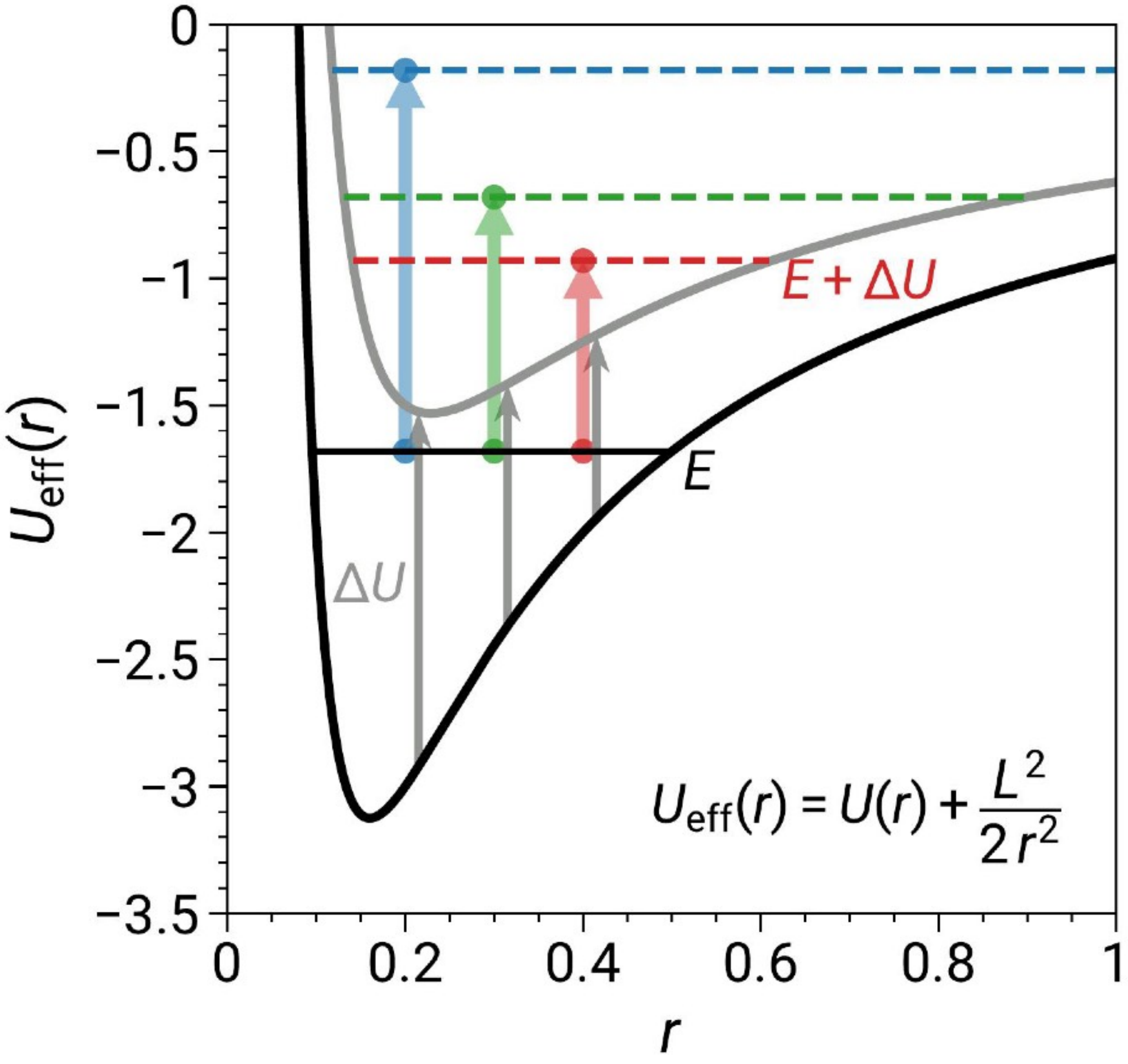


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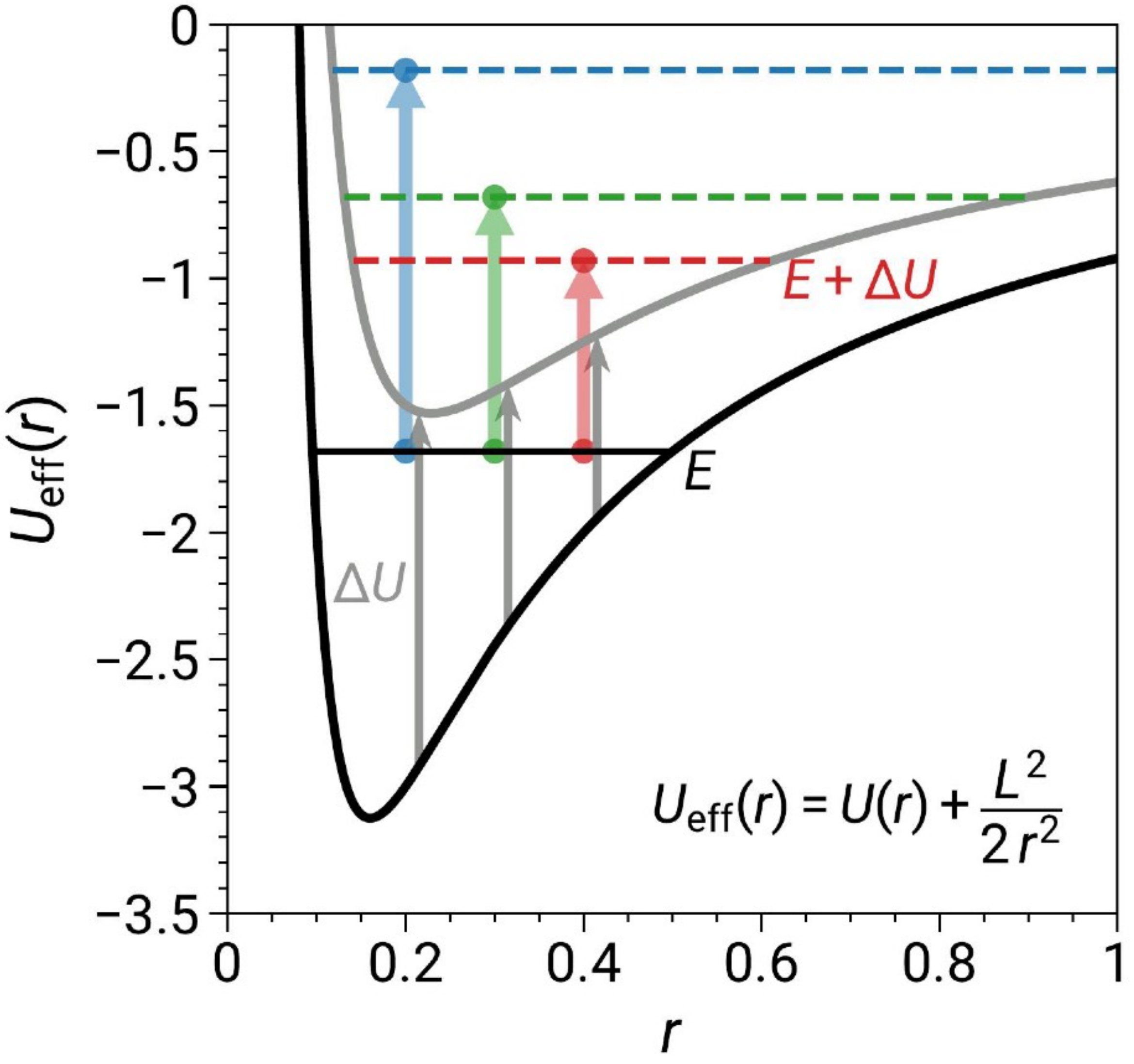


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❖ **CuspCore2 model**: evolve the distribution function $f(E)$ iteratively (Li, Dekel+ 2023)

# CuspCore2: accurate model for structural evolution

NEW!

① **Initial equilibrium**

distribution function: $f_0(E) = \dfrac{d^6 M}{d^3\mathbf{x}\, d^3\mathbf{v}}$

(Eddington inversion)

Li+ 2023a (arXiv:2206.07069)
Li+ 2023b,c, in prep

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## ③ Violent relaxation (no free params)

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

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Equilibrium density in the transient $\Phi_k$

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

Evolve $\Phi$ towards the equilibrium

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

loop until convergence

$k \mathrel{+}= 1$

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

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Marie Curie fellowship

Score 99/100: “very ambitious, clear and has the potential to significantly advance the state of the art”

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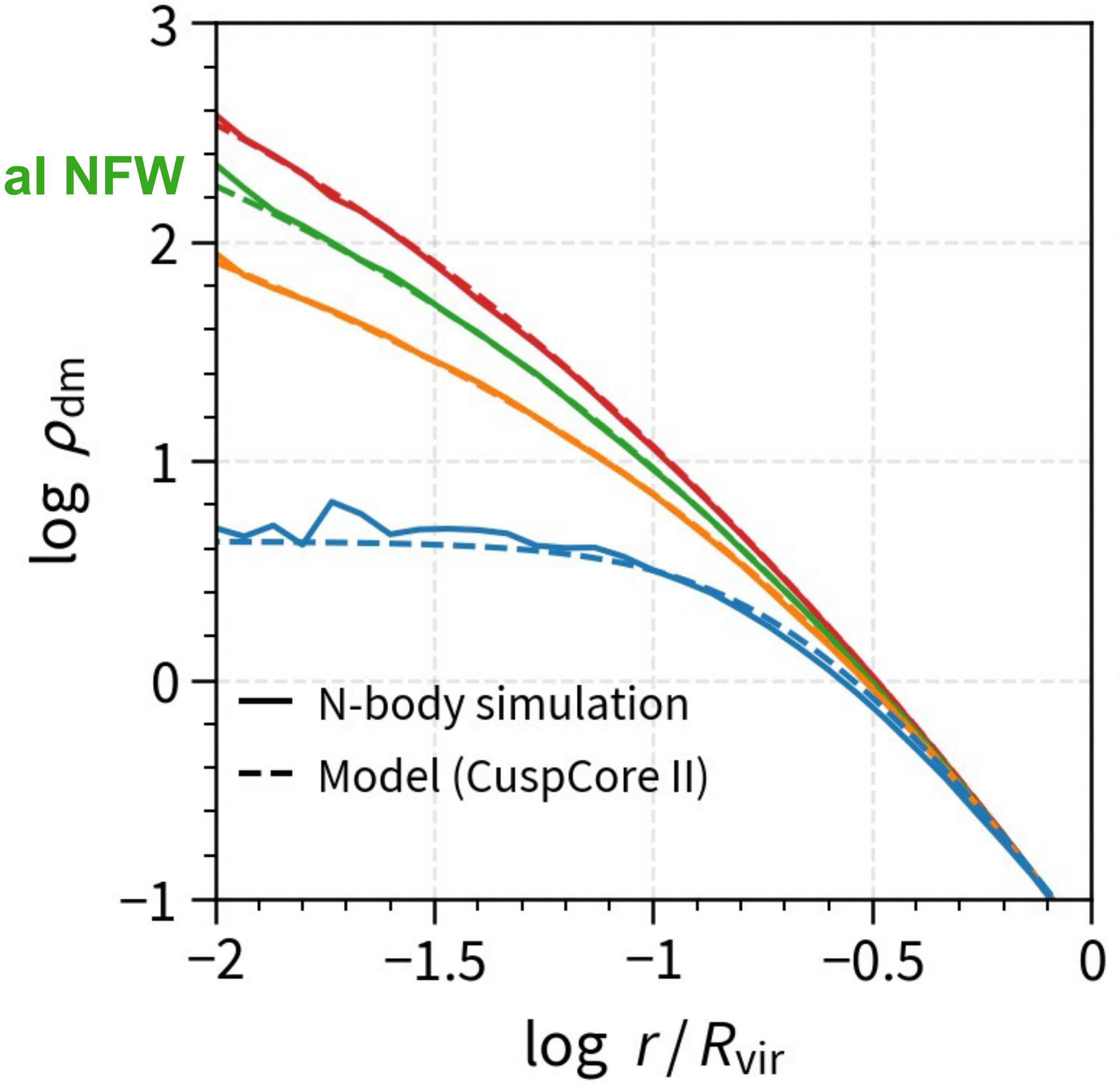
Li+ 2023b,c, in prep

# Halo response to gas inflow/outflow

initial NFW




within ~10% vs N-body

Li, Dekel+ 2023a

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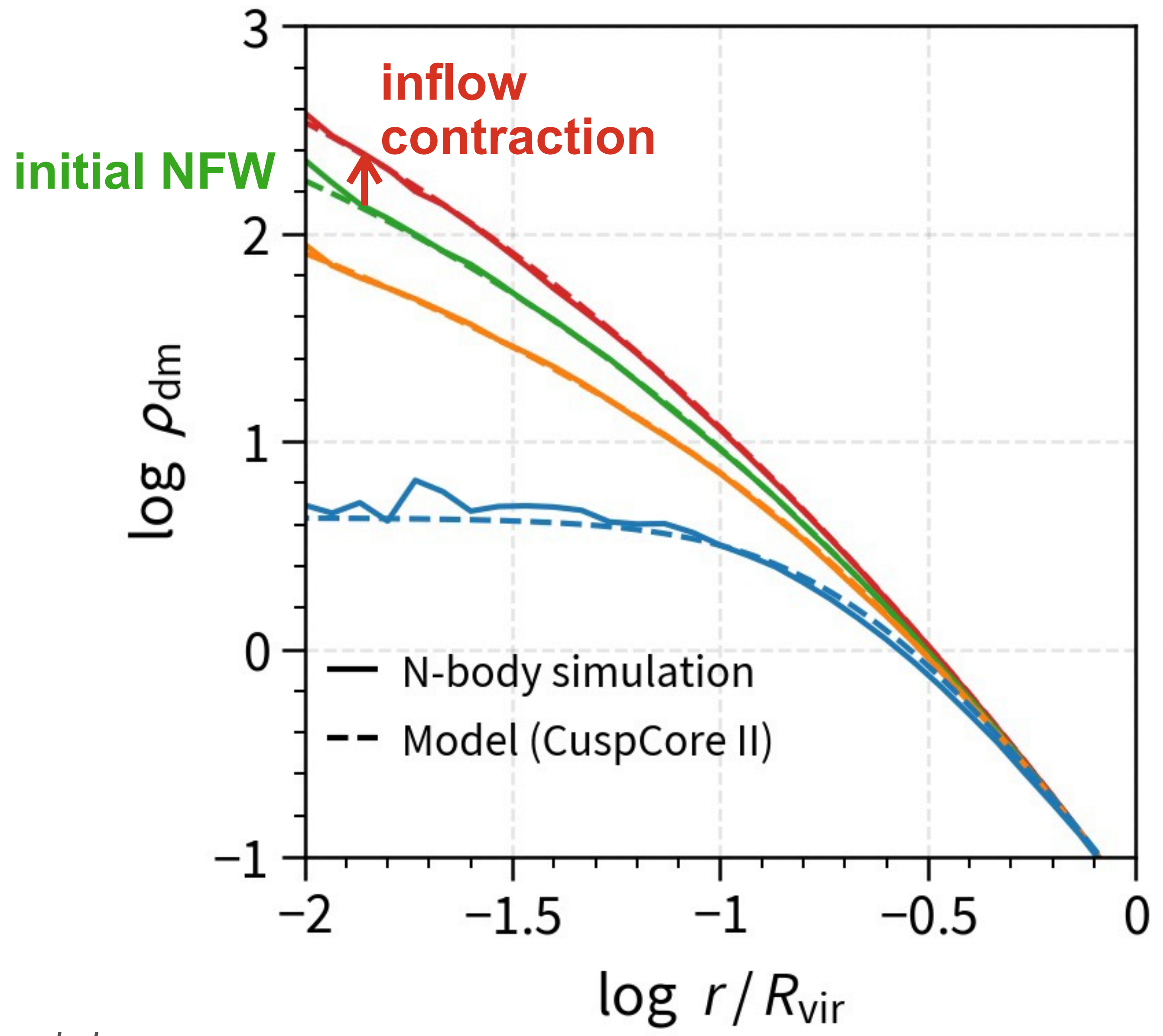


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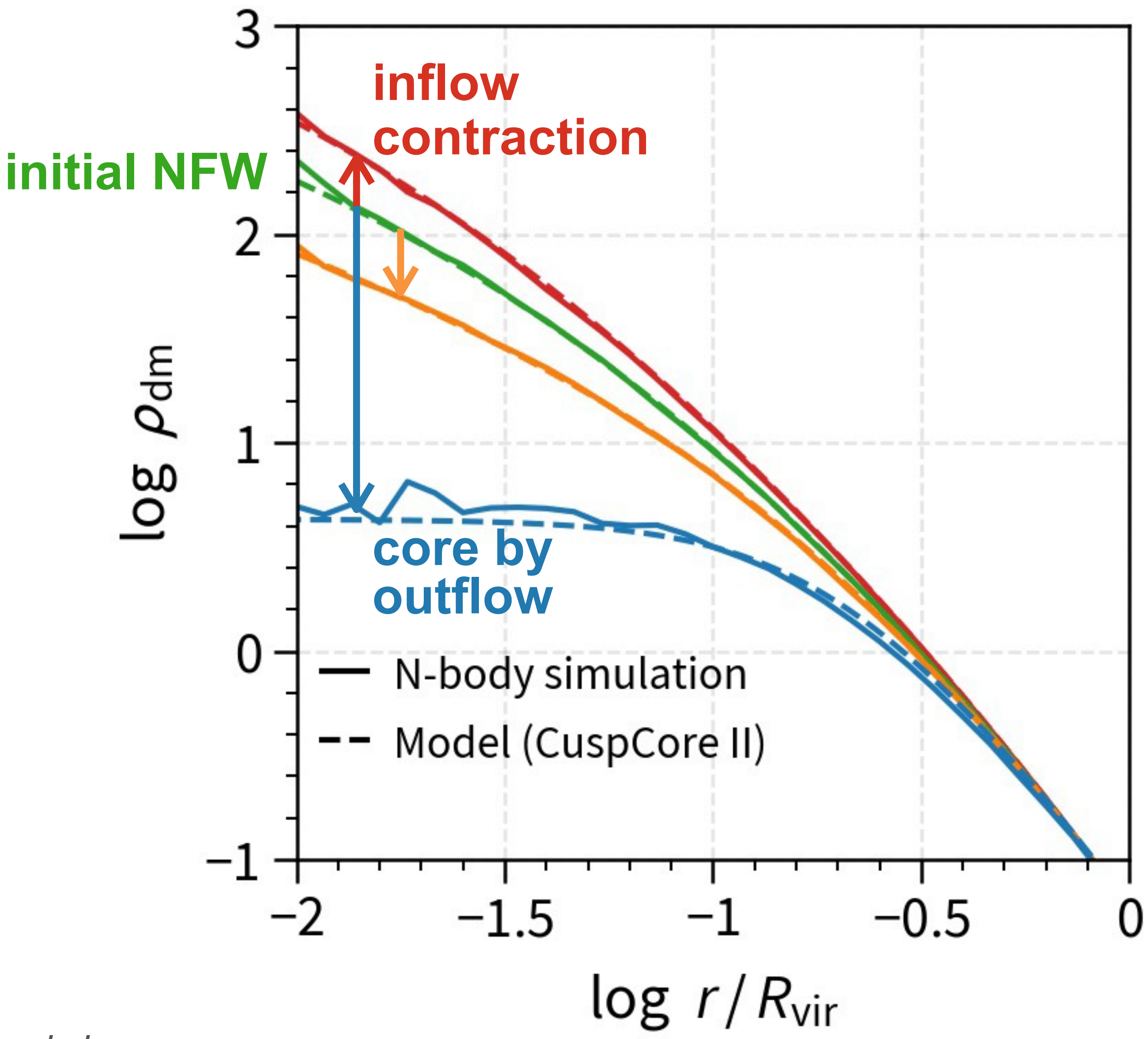


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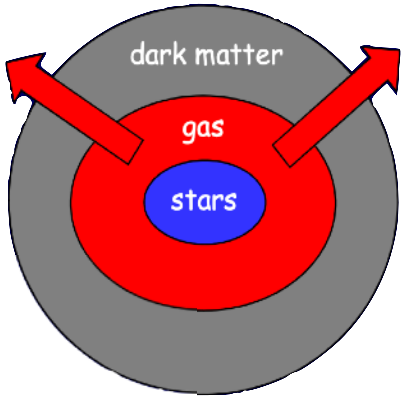
# Differential response of stars and DM to gas outflow

Li+ 2023b, in prep




- DM deficiency:
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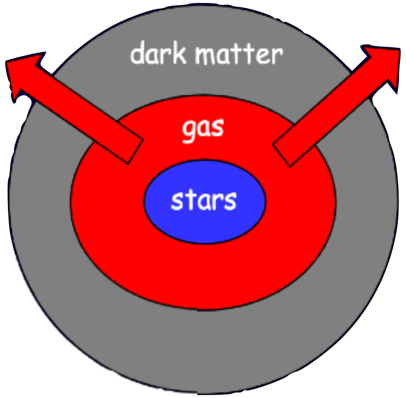


- DM deficiency:
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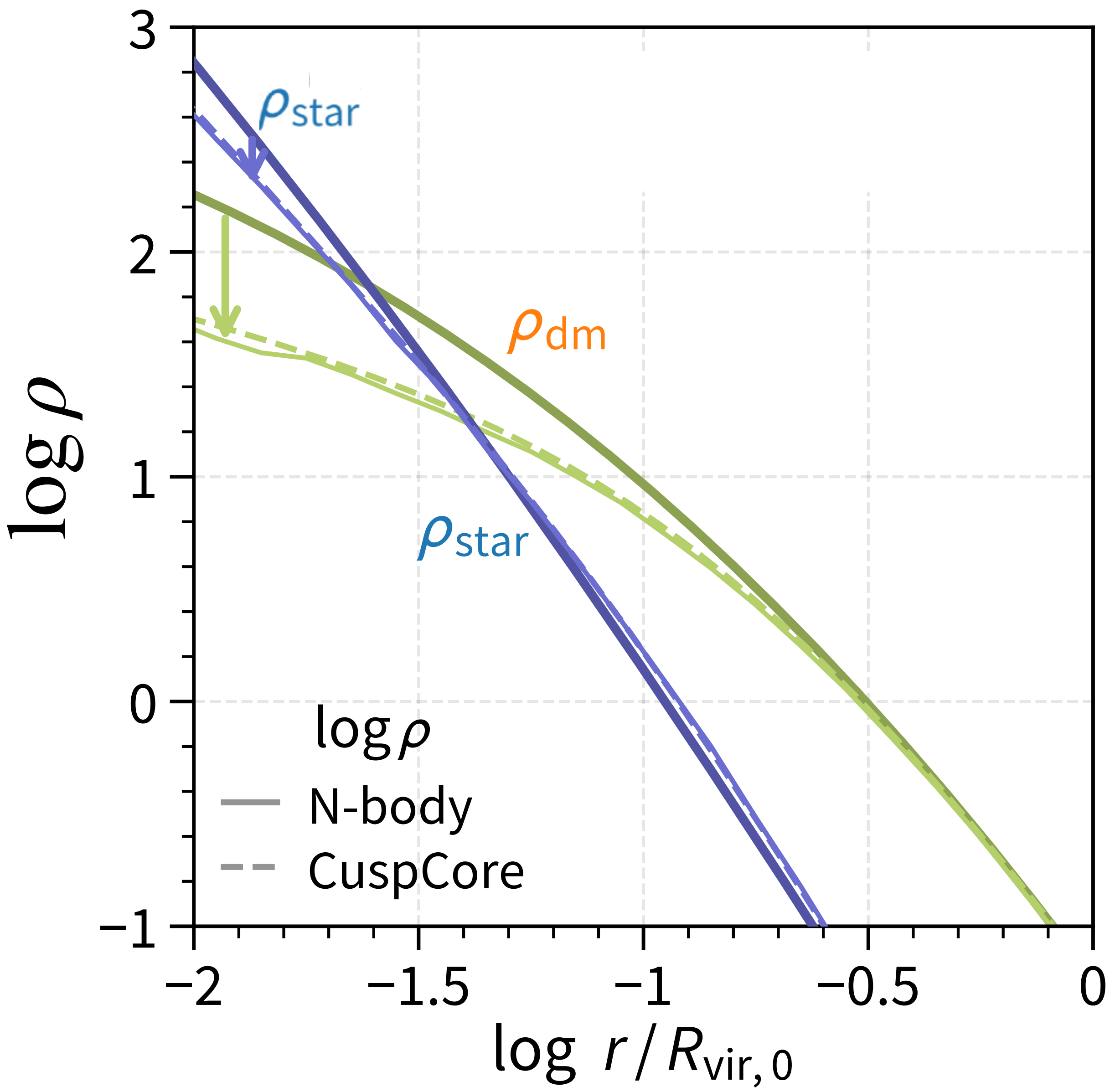
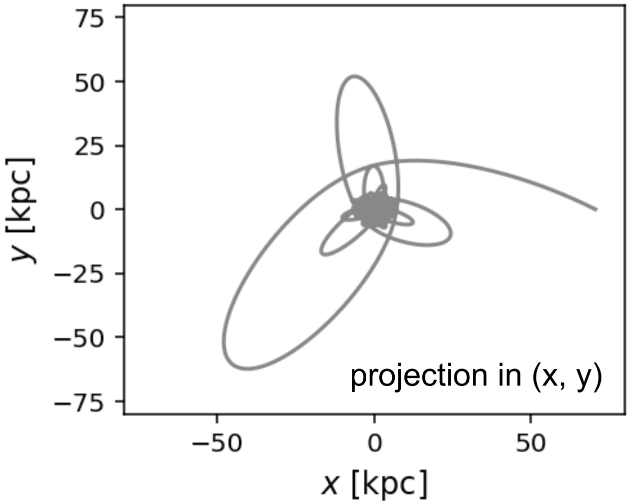
- The "hot", extended DM is more responsive to outflow and heating!



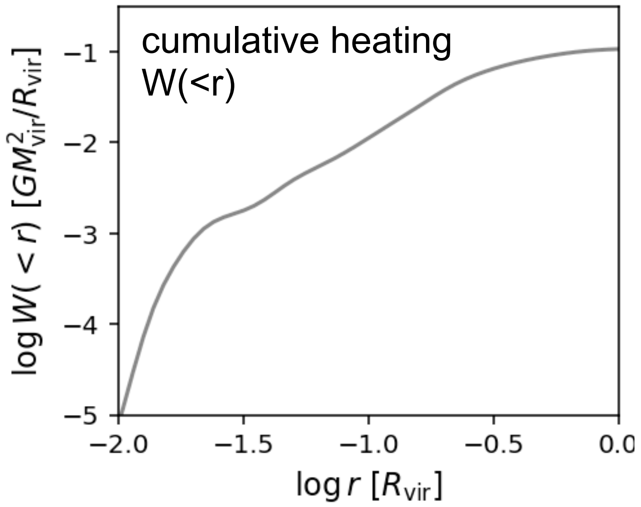
# Dynamical friction heating by a merger

- **SatGen** (Jiang et al. 2020) -- Analytical framework for satellite galaxy evolution

**orbital decay**
due to friction




**dynamical heating**
on the host



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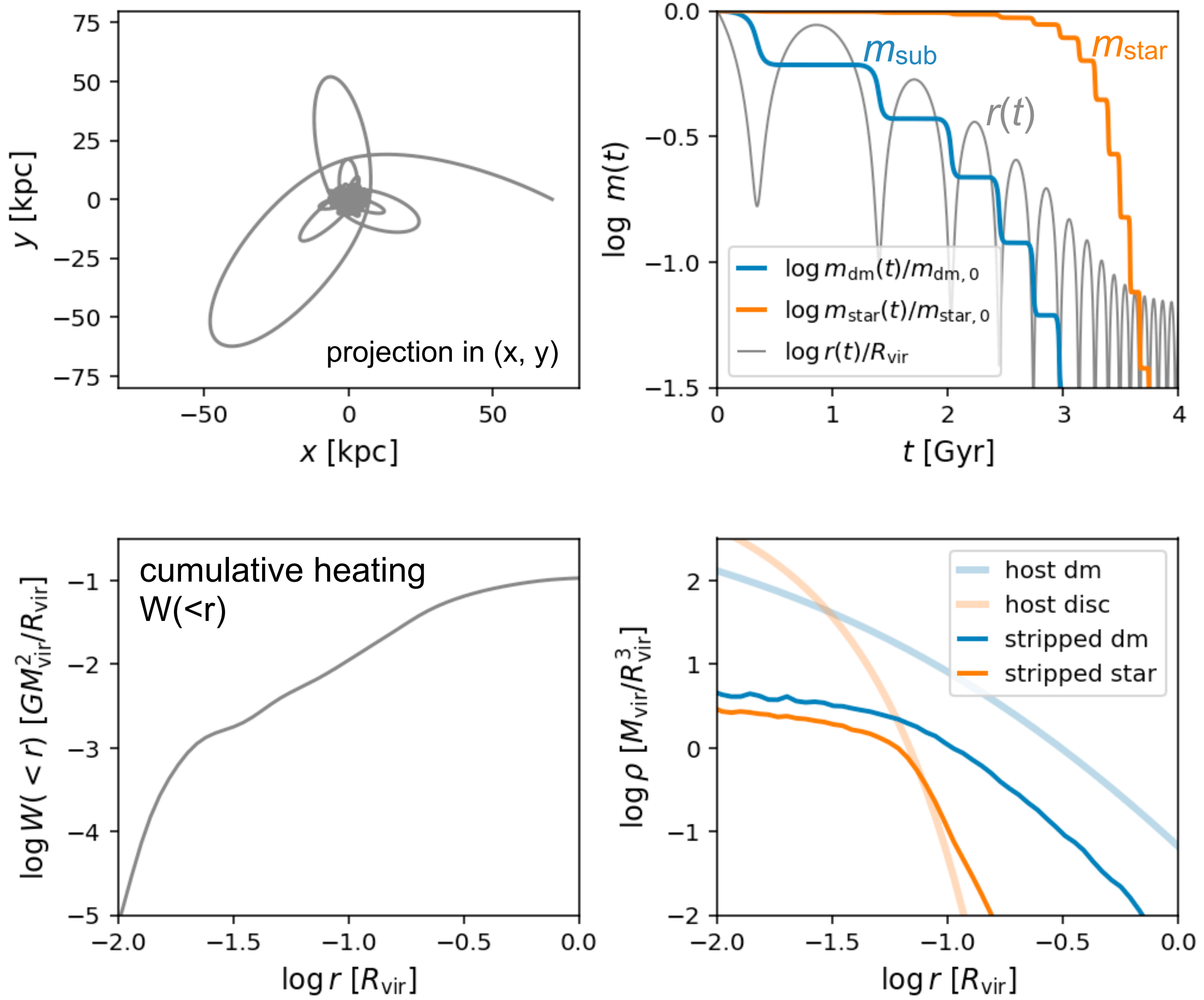
**mass deposited**
by satellites




*Zhaozhou Li@SJTU workshop*

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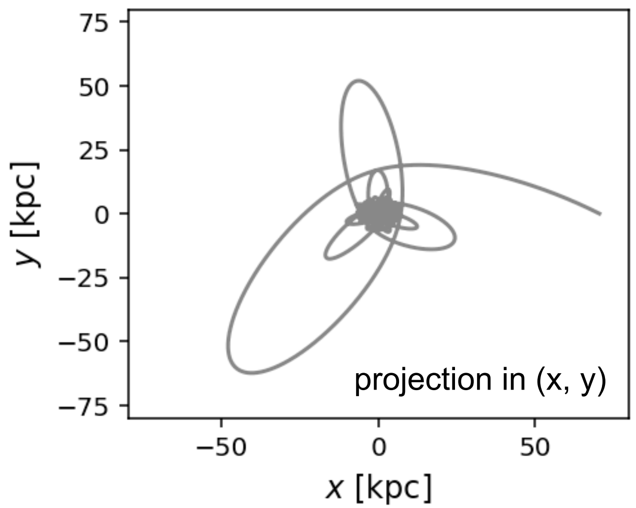


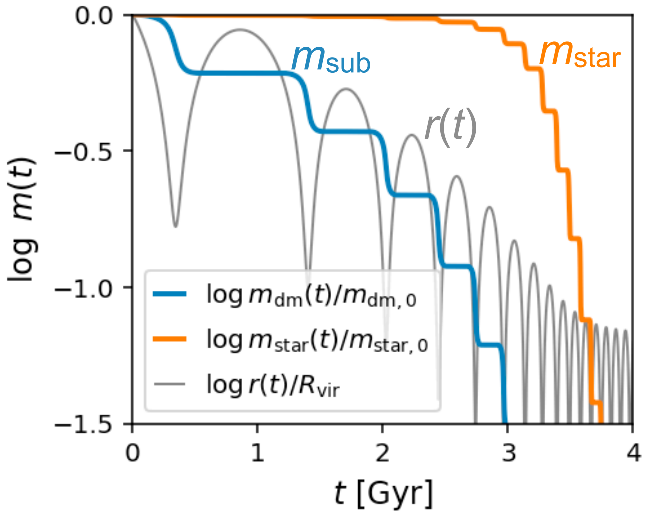


**mass evolution**
due to tidal stripping

Input of CuspCore2

**dynamical heating**
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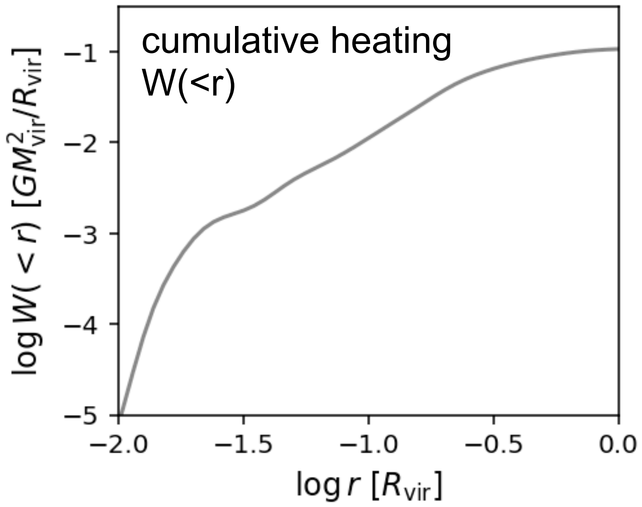


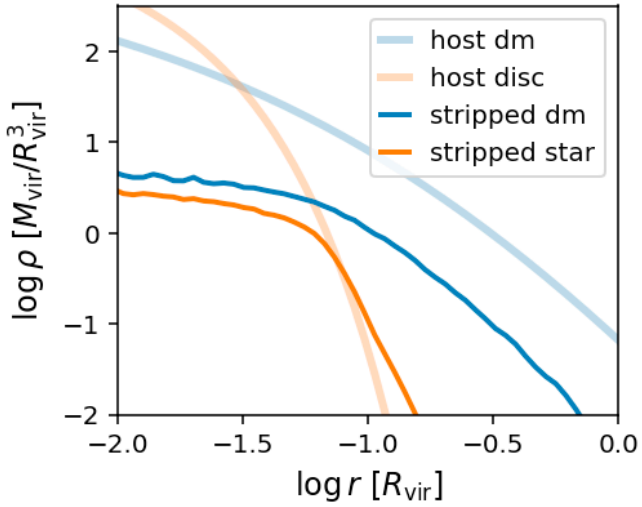


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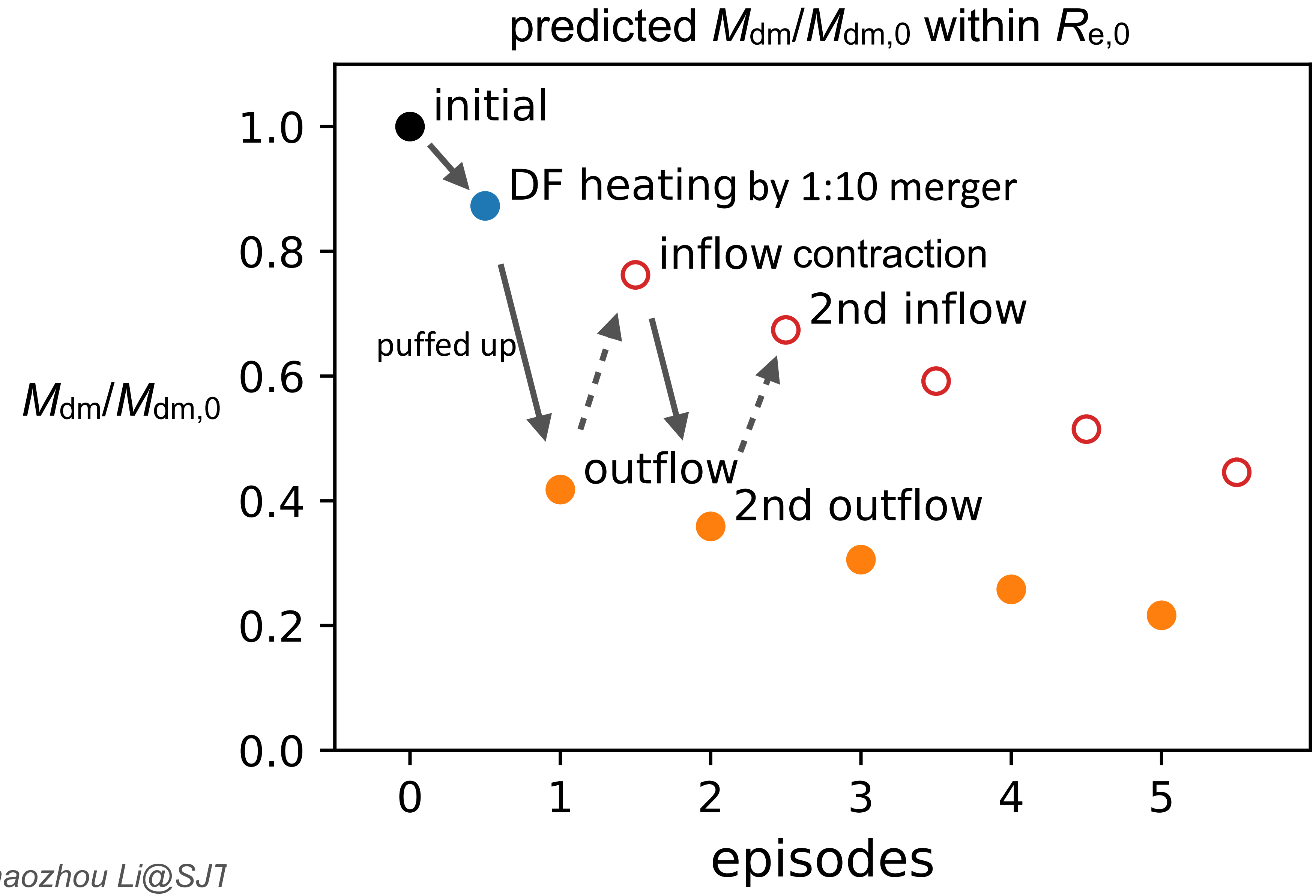
# Dyn friction heating + multi-episode gas outflows

Li+ 2023b, in prep

(El Zant+01, Pontzen+12, Dekel+21)

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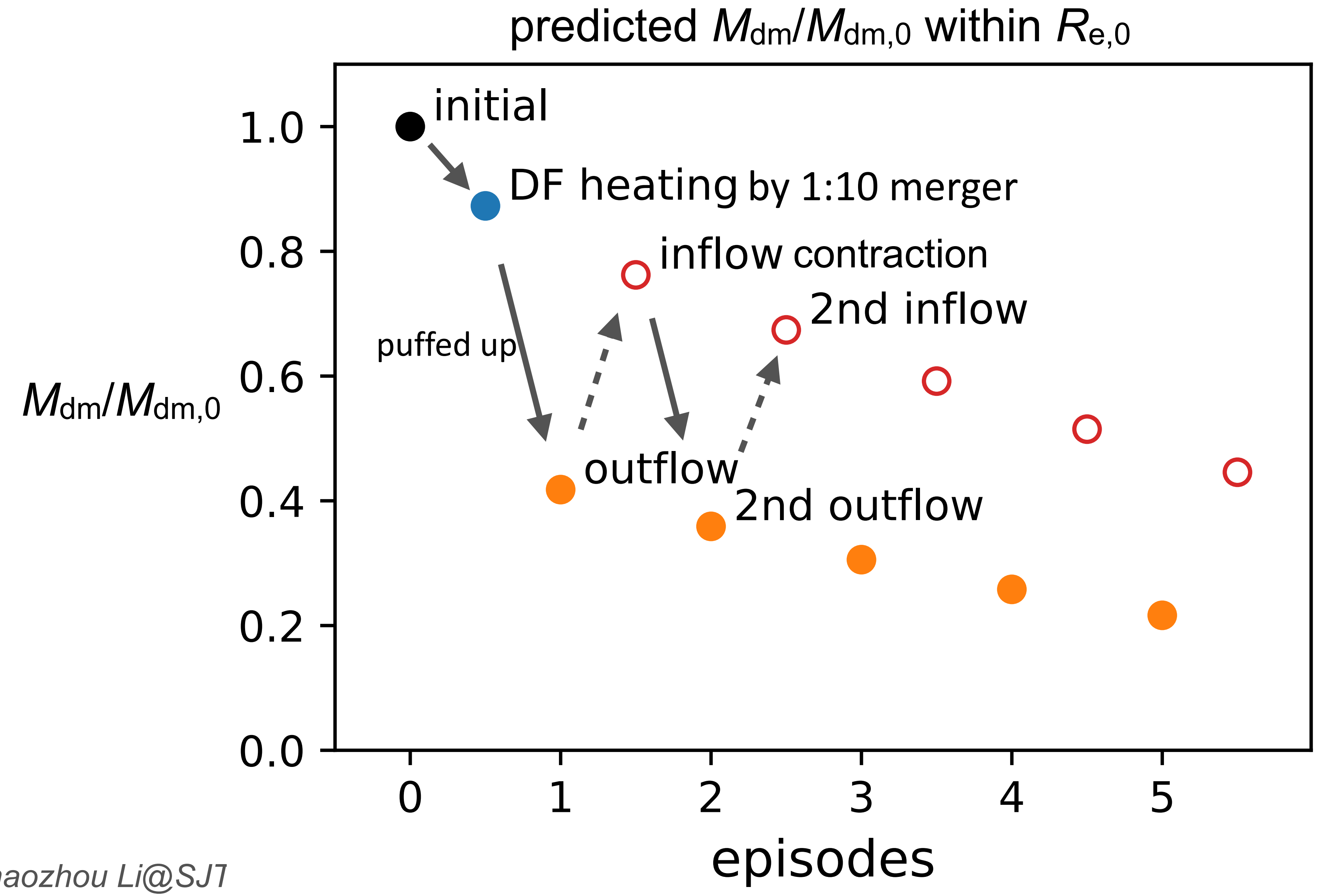


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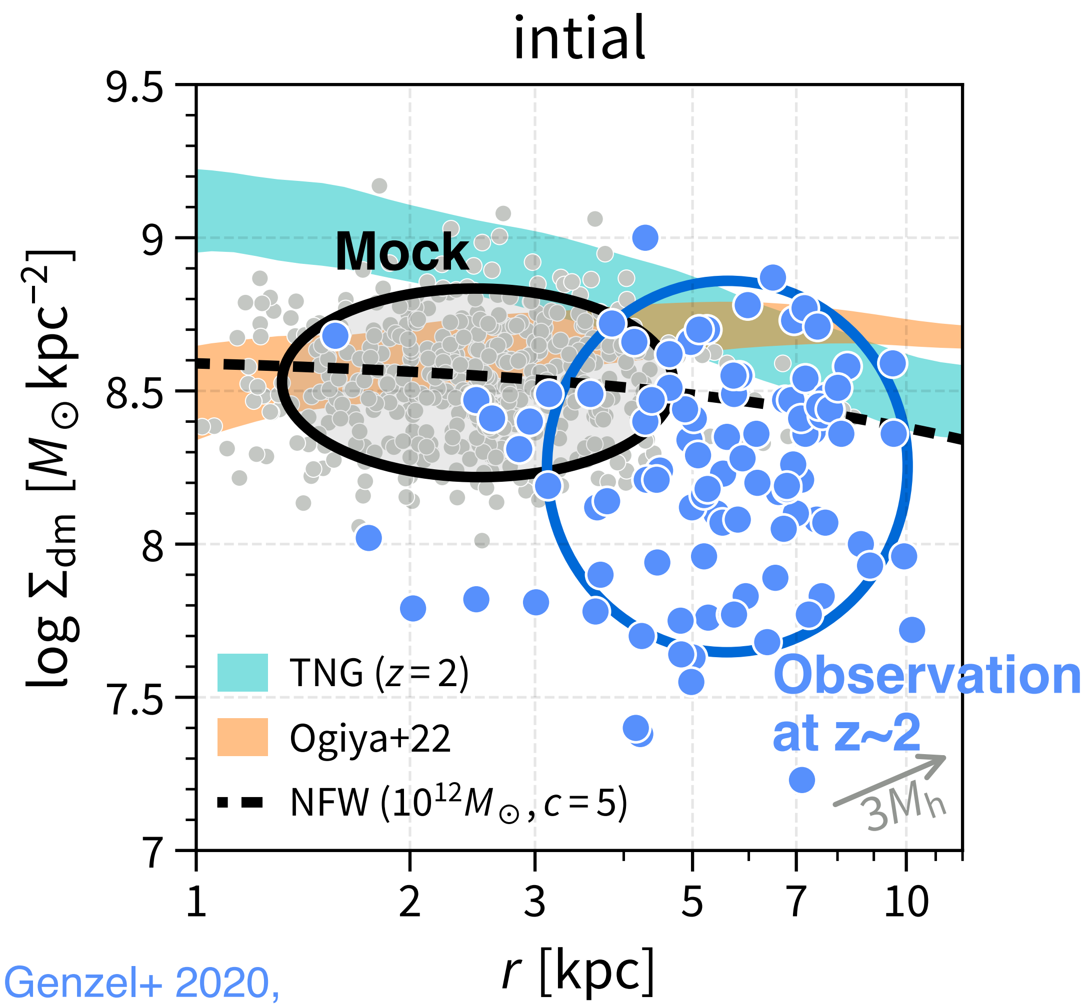
**+tidal evolution**
for satellites in group

# Model vs high-z observation: $\Sigma_{dm}(<R_e)$ vs $R_e$

Li+ 2023b, in prep




RC100, z~2, Genzel+ 2020,
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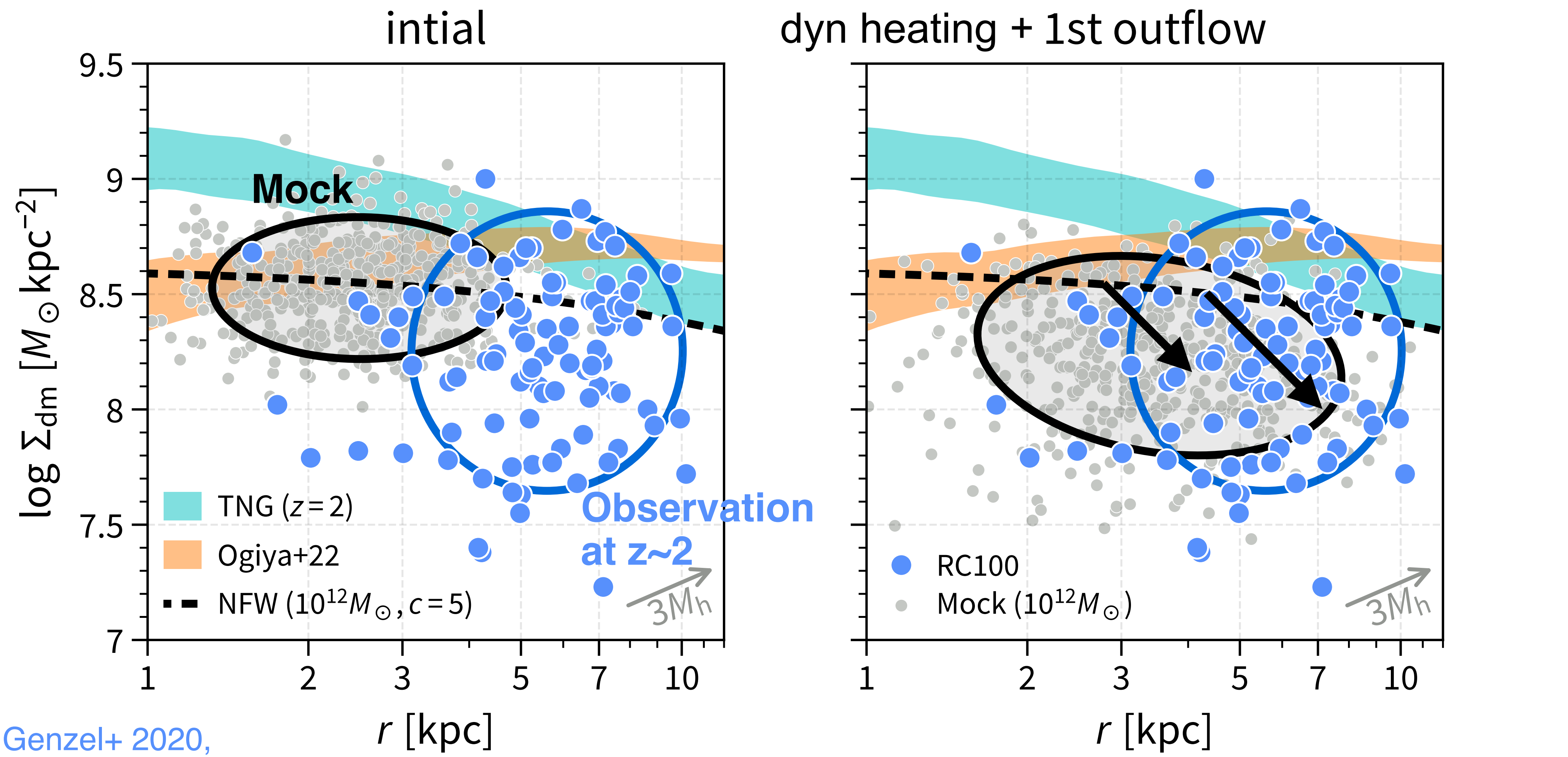


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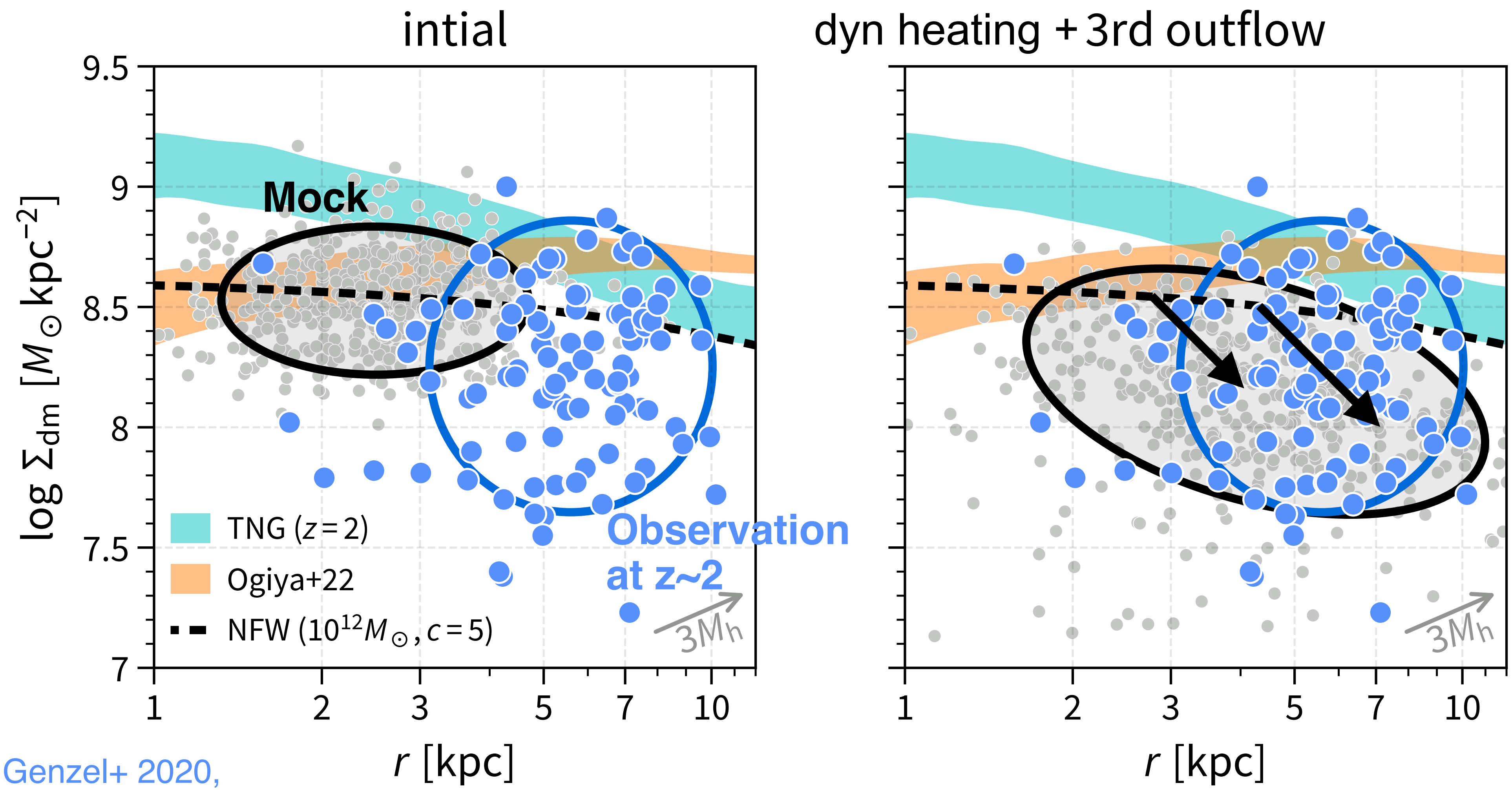


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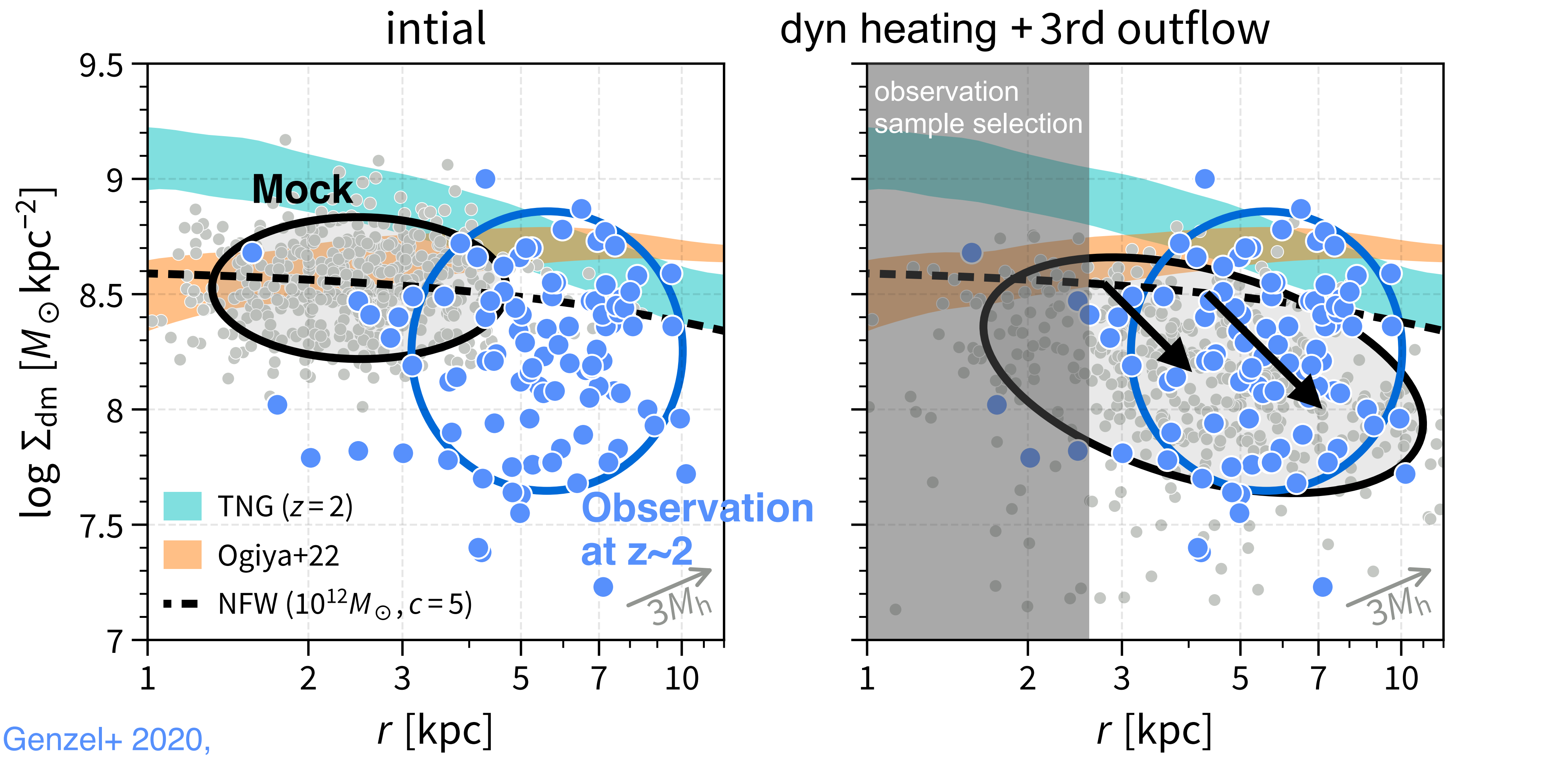


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# Model vs high-z observation: $f_{dm}$ vs $R_e$, $M_{star}$, $M_{bulge}$

**Observation** (RC100, z~2)
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**Model prediction** after
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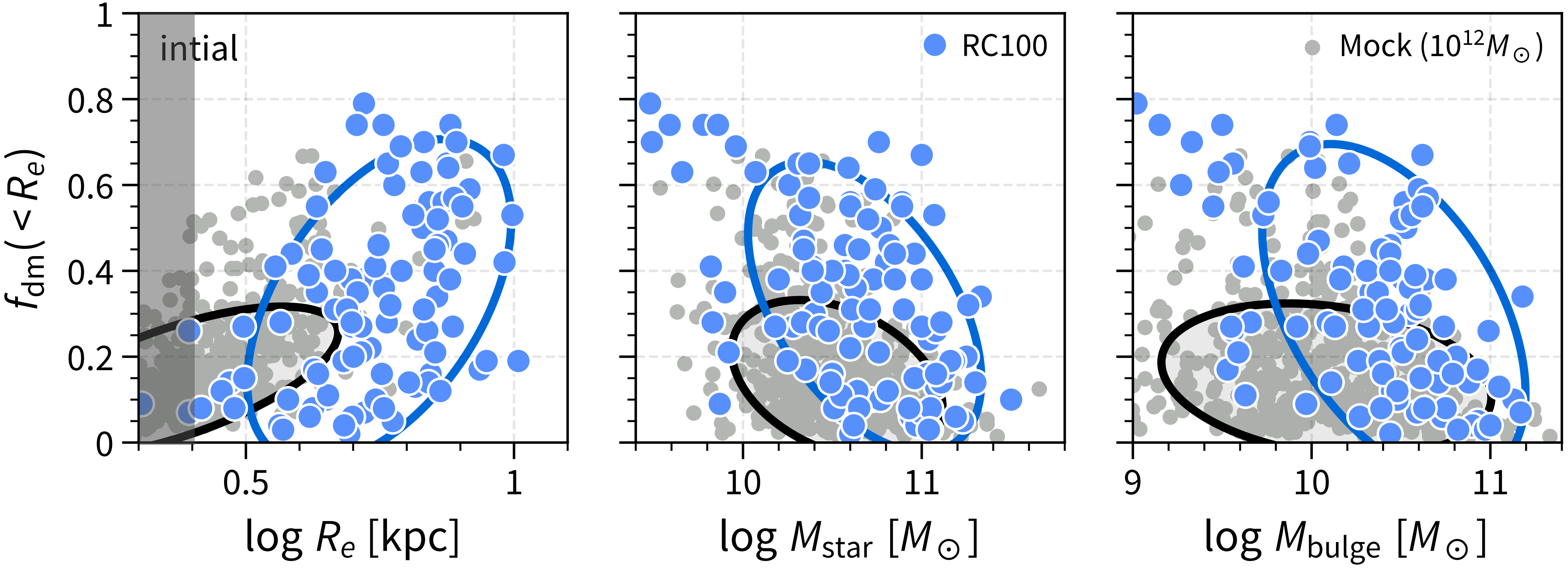


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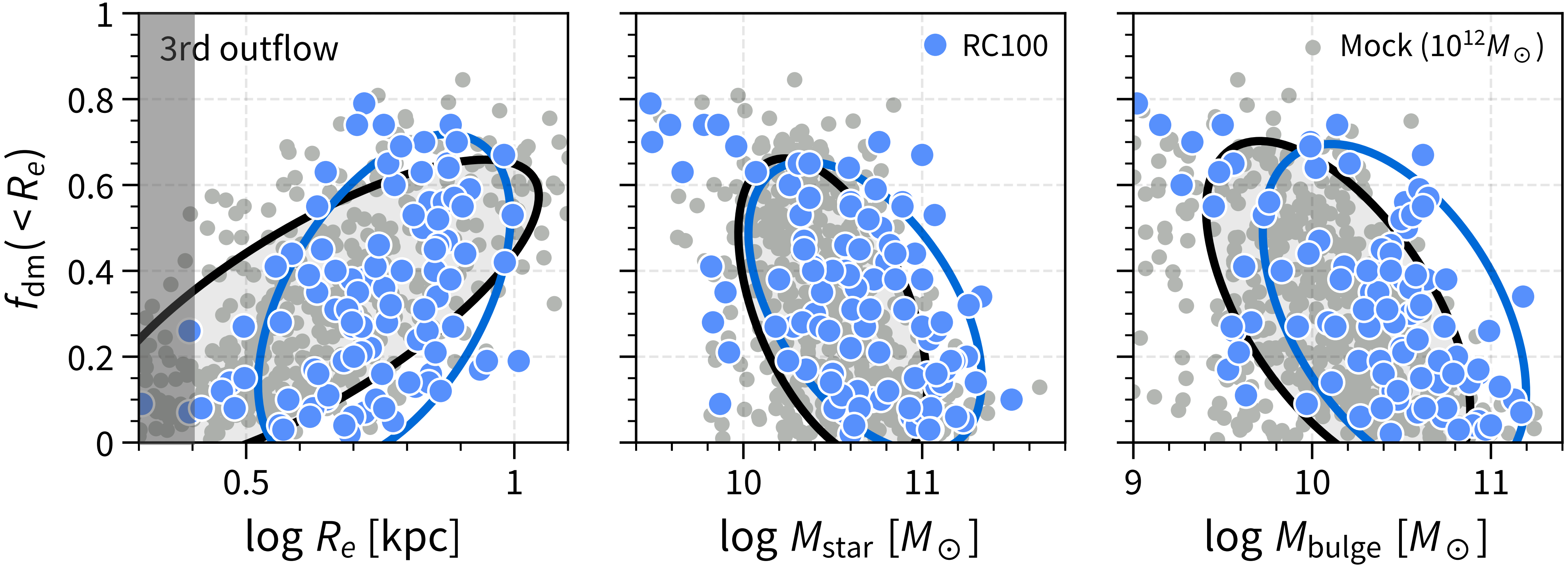


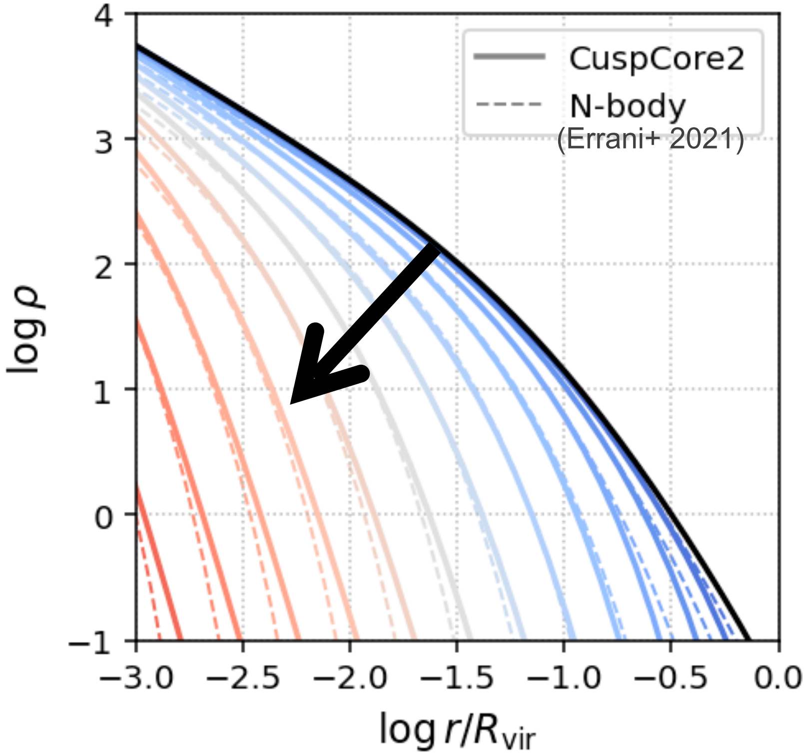

Li+ 2023b, in prep

# Tidal stripping of satellite galaxies

Li+ 2023c, in prep

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

NFW subhalo




central cusps can survive

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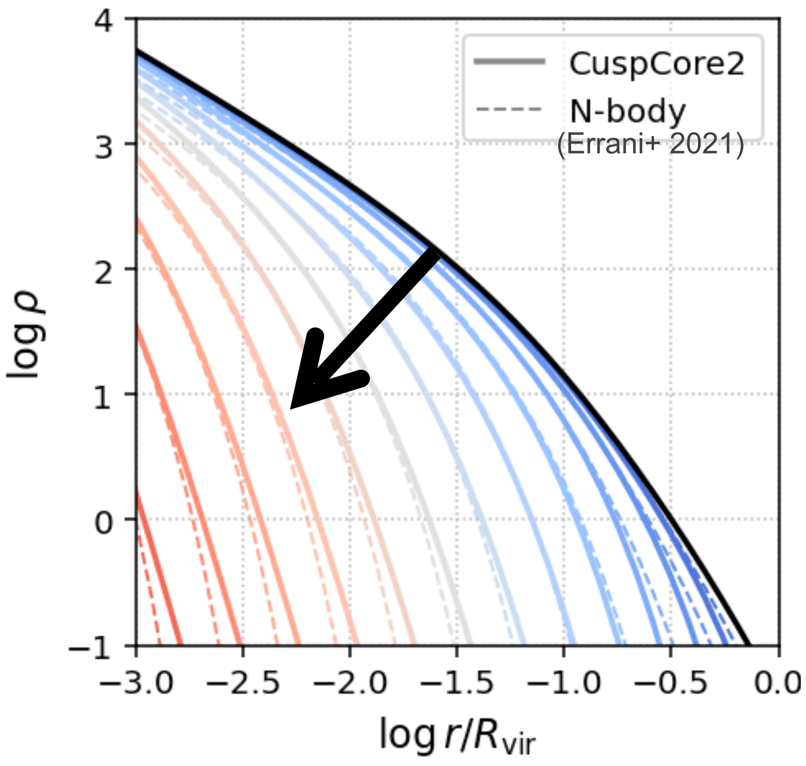


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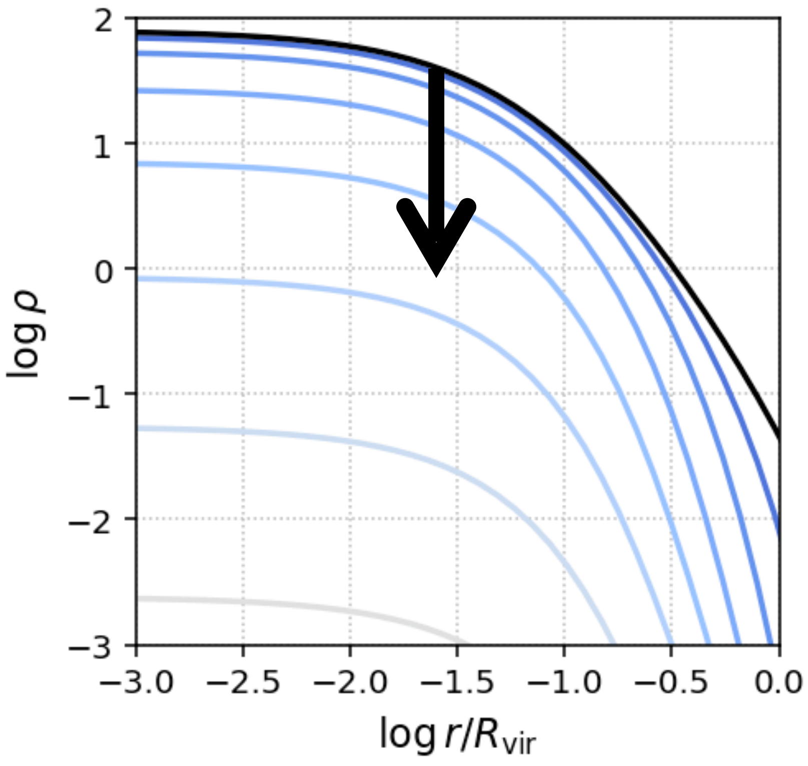


cores will undergo
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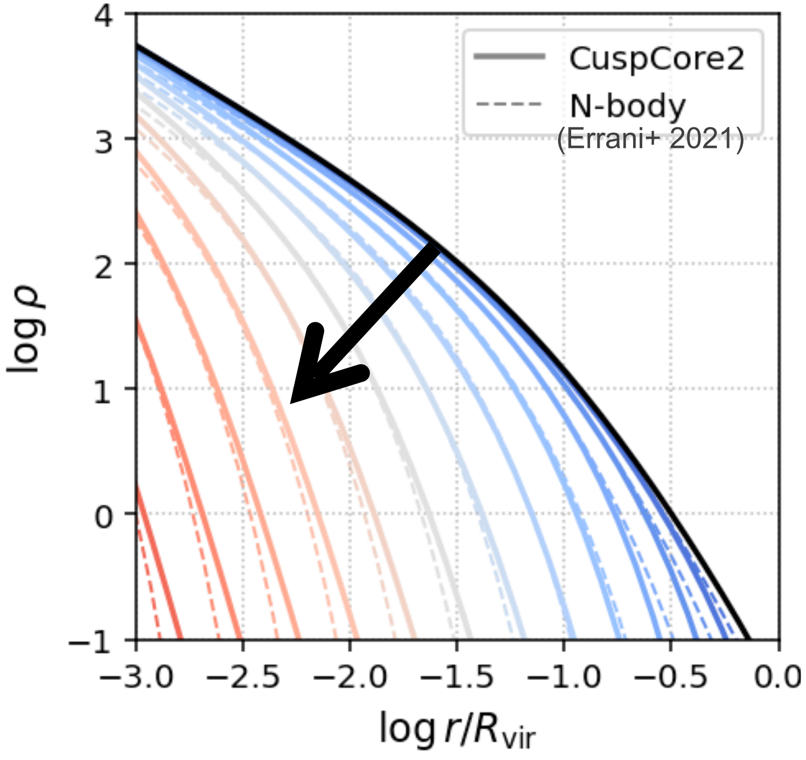


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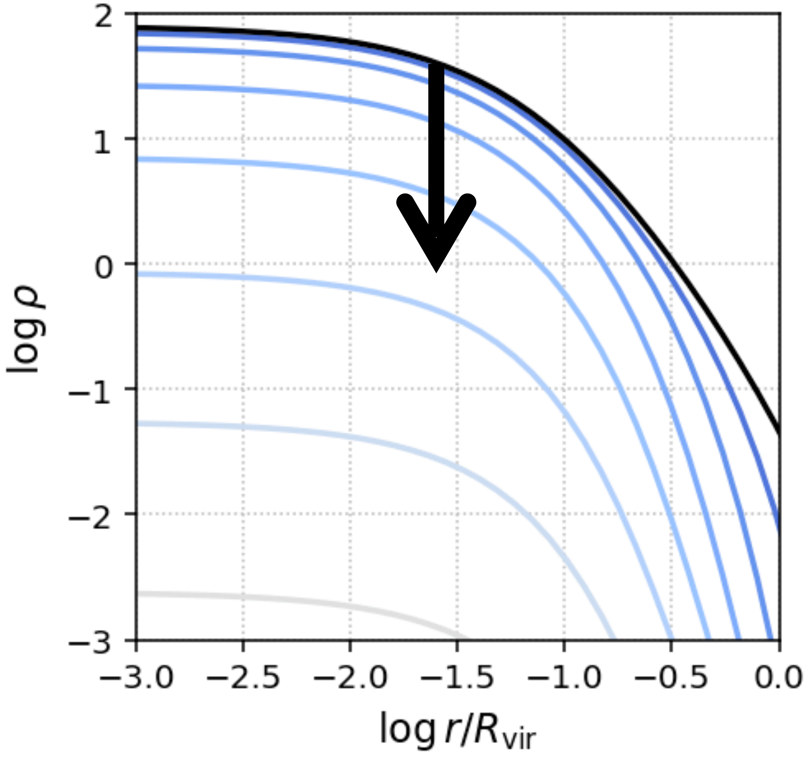


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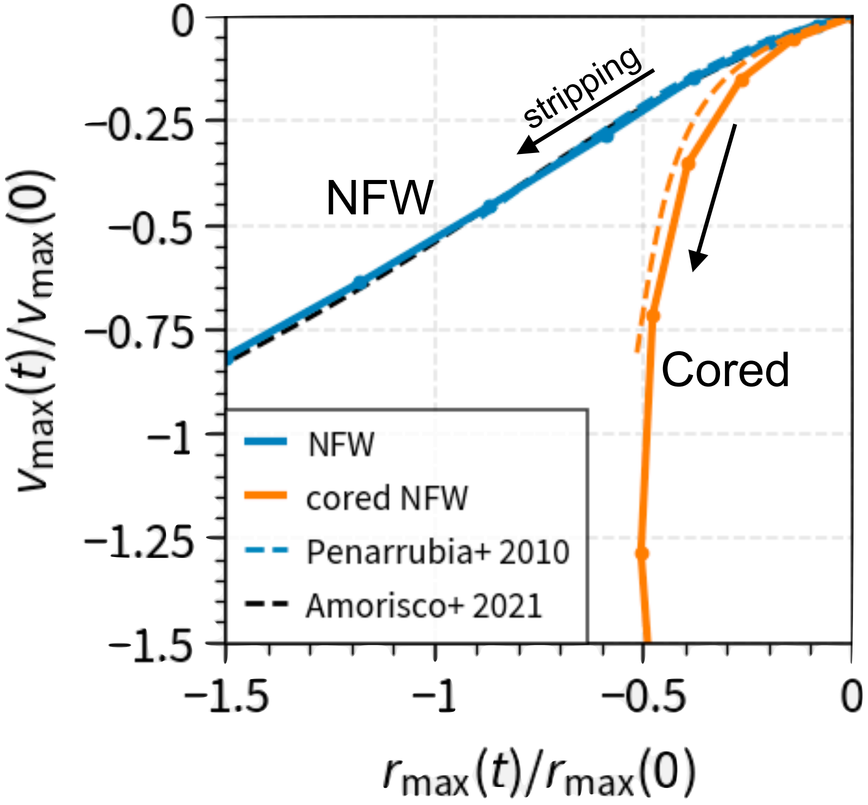
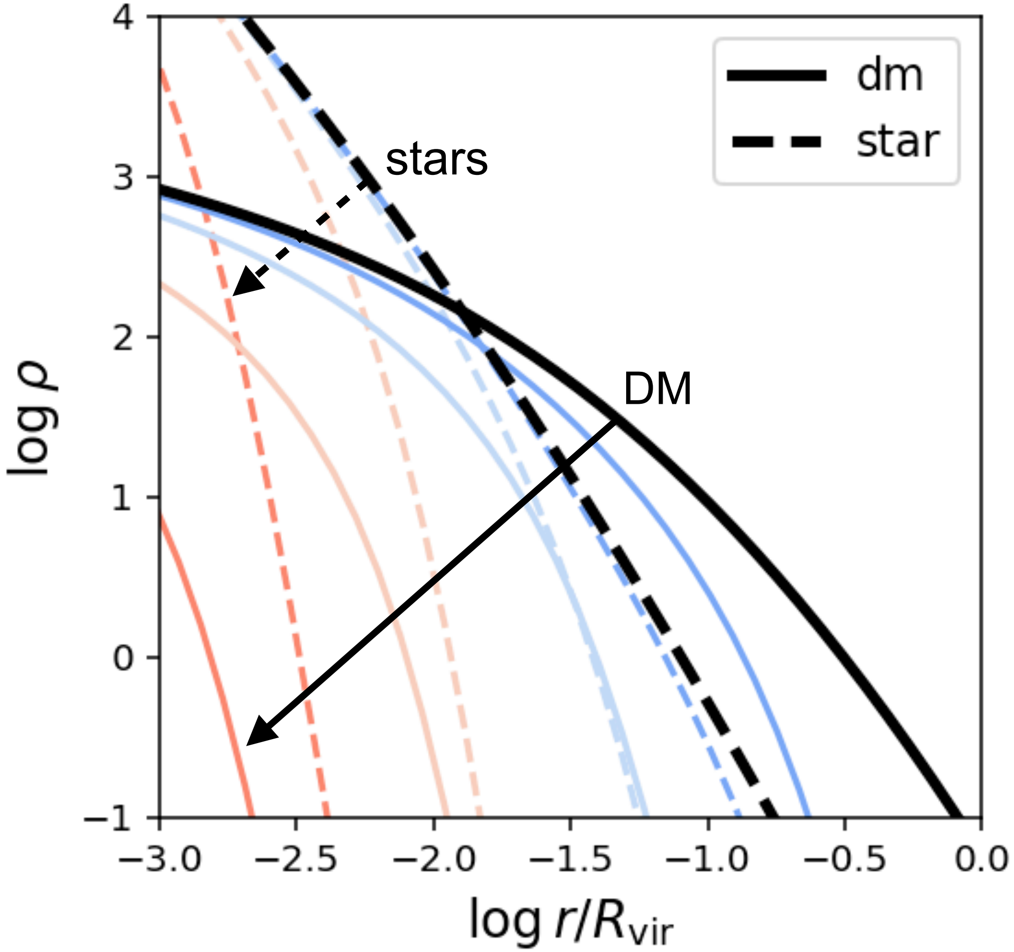
tidal track: $v_{max}(t)$ vs $r_{max}(t)$



# DM-deficient: differential response of DM/stars to tidal stripping

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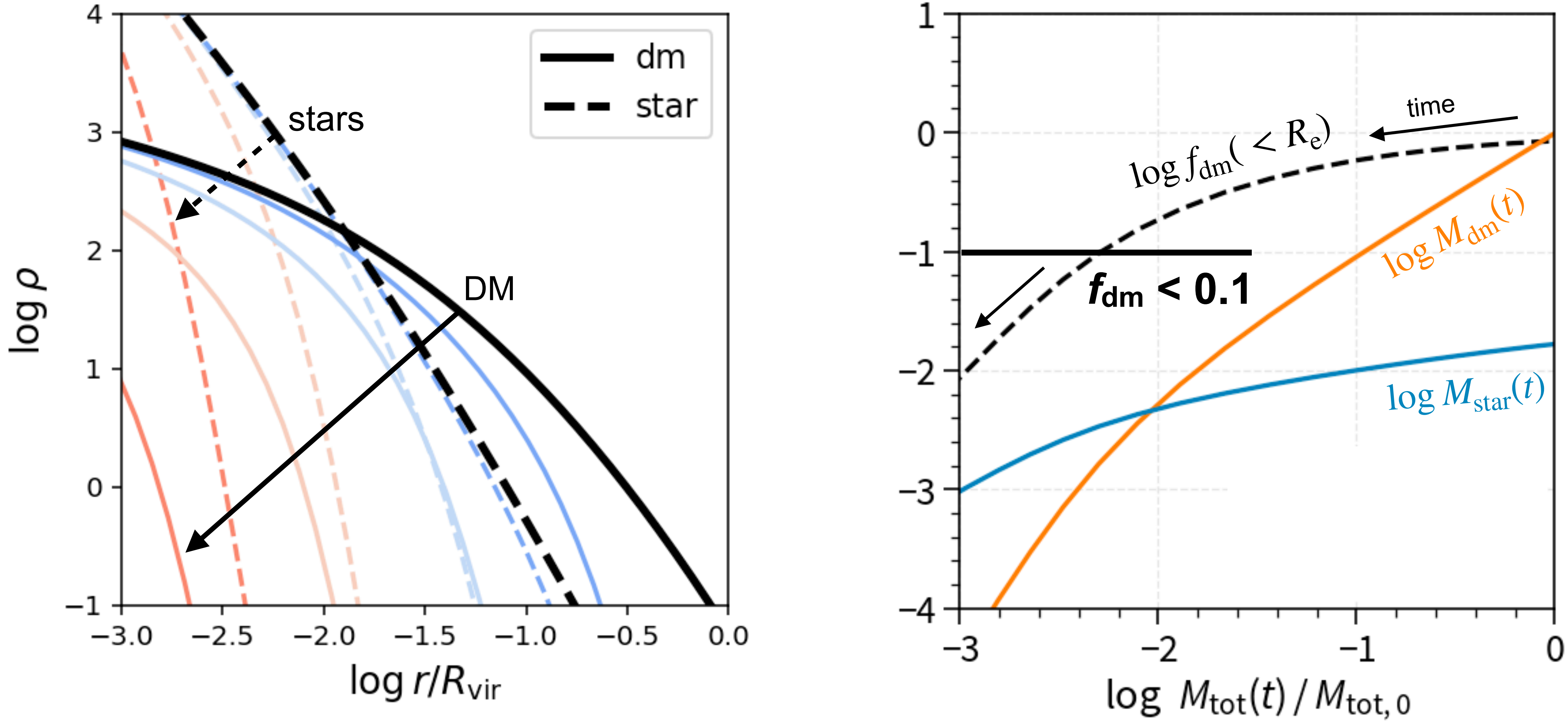


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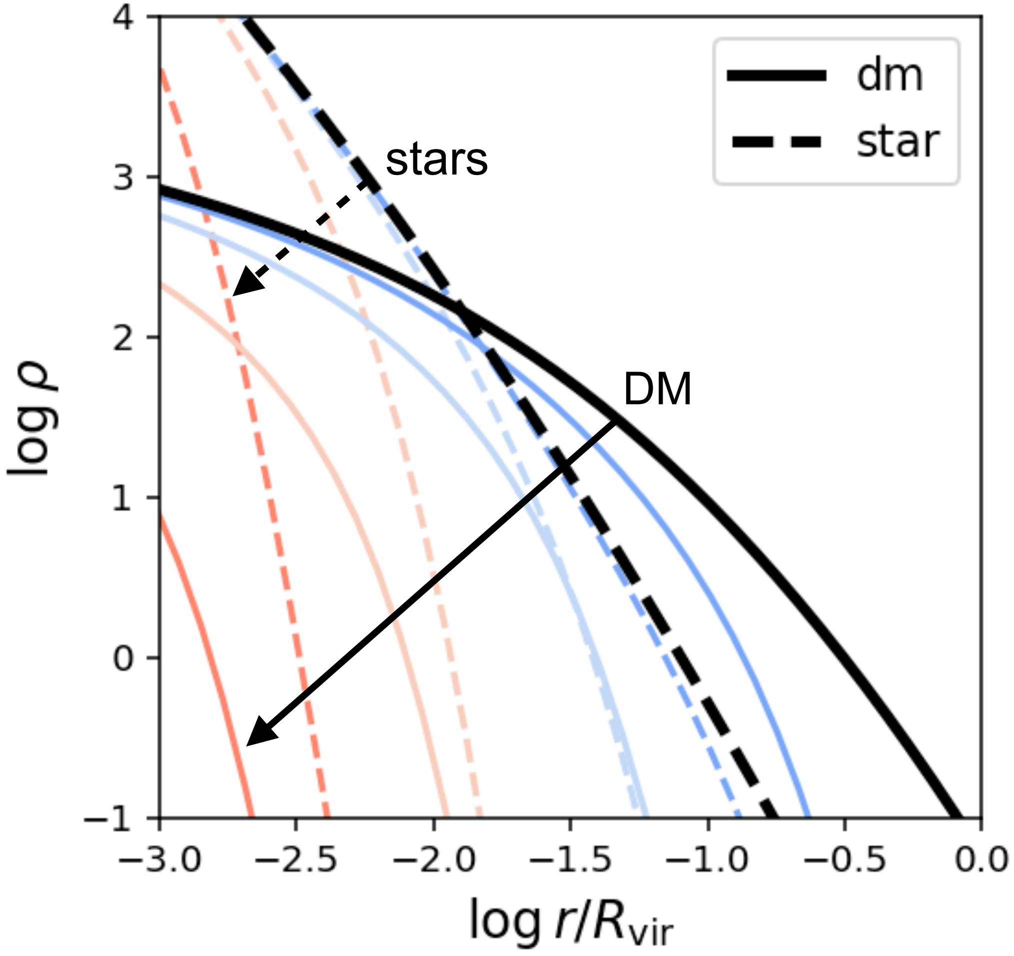


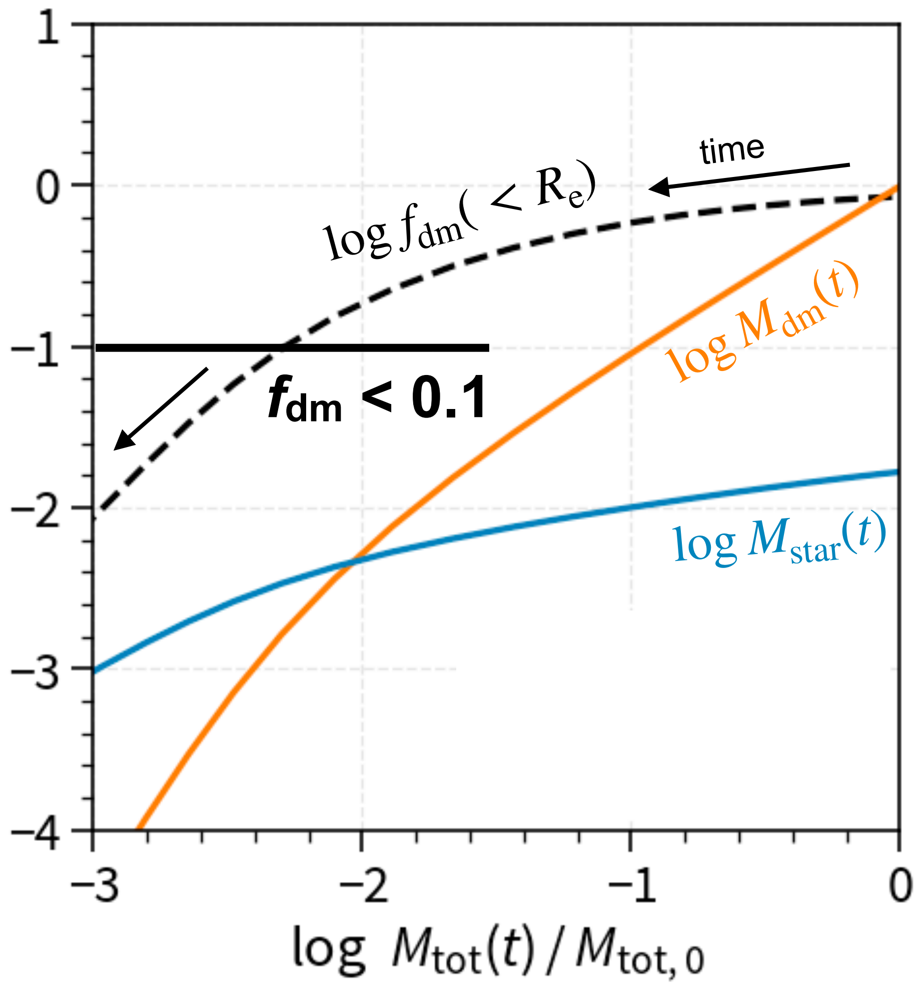


Li+ 2023c, in prep

To explore: initial profiles and orbits ⇔ structure diversity

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

# Subhalo evolution with tidal shock heating

Resettling via **CuspCore2**
after **tidal shocking** (Gnedin+ 99)

$$E' = E + \Delta K(r)$$
$$\Delta K(r) = \frac{1}{2}\langle(\Delta \boldsymbol{v})^2\rangle_{\hat{\boldsymbol{n}}} \times \mathscr{A}_{\rm ad}(r)$$

$\int \boldsymbol{F}_{\rm tid}(t) {\rm d}t$

adiabatic correction
$[1 + 2\tau_{\rm tid}^2/\tau_{\rm sub}^2(r)]^{-1.5}$

Question: tidal stripping vs shock heating?

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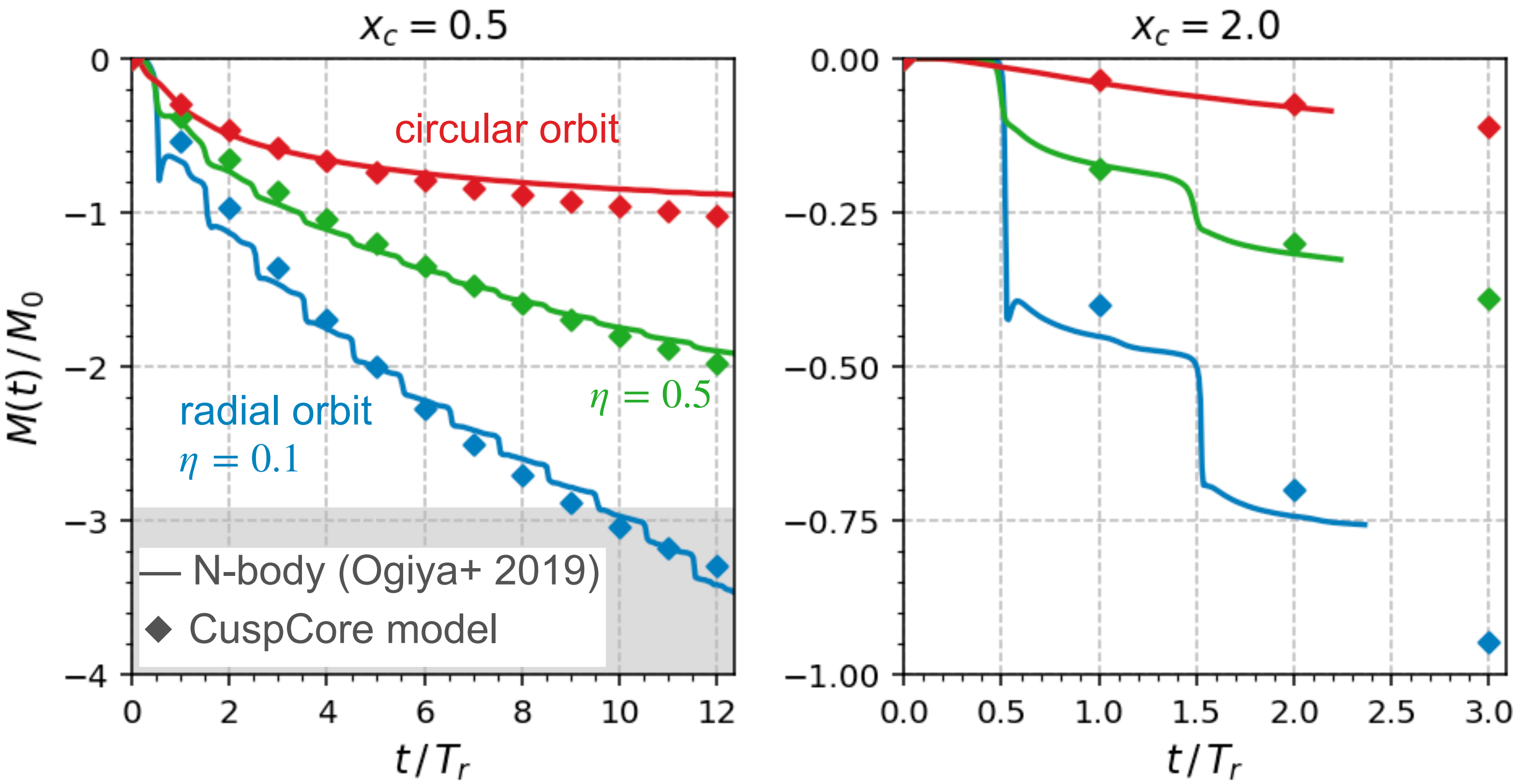
low-energy orbits | high-energy orbits



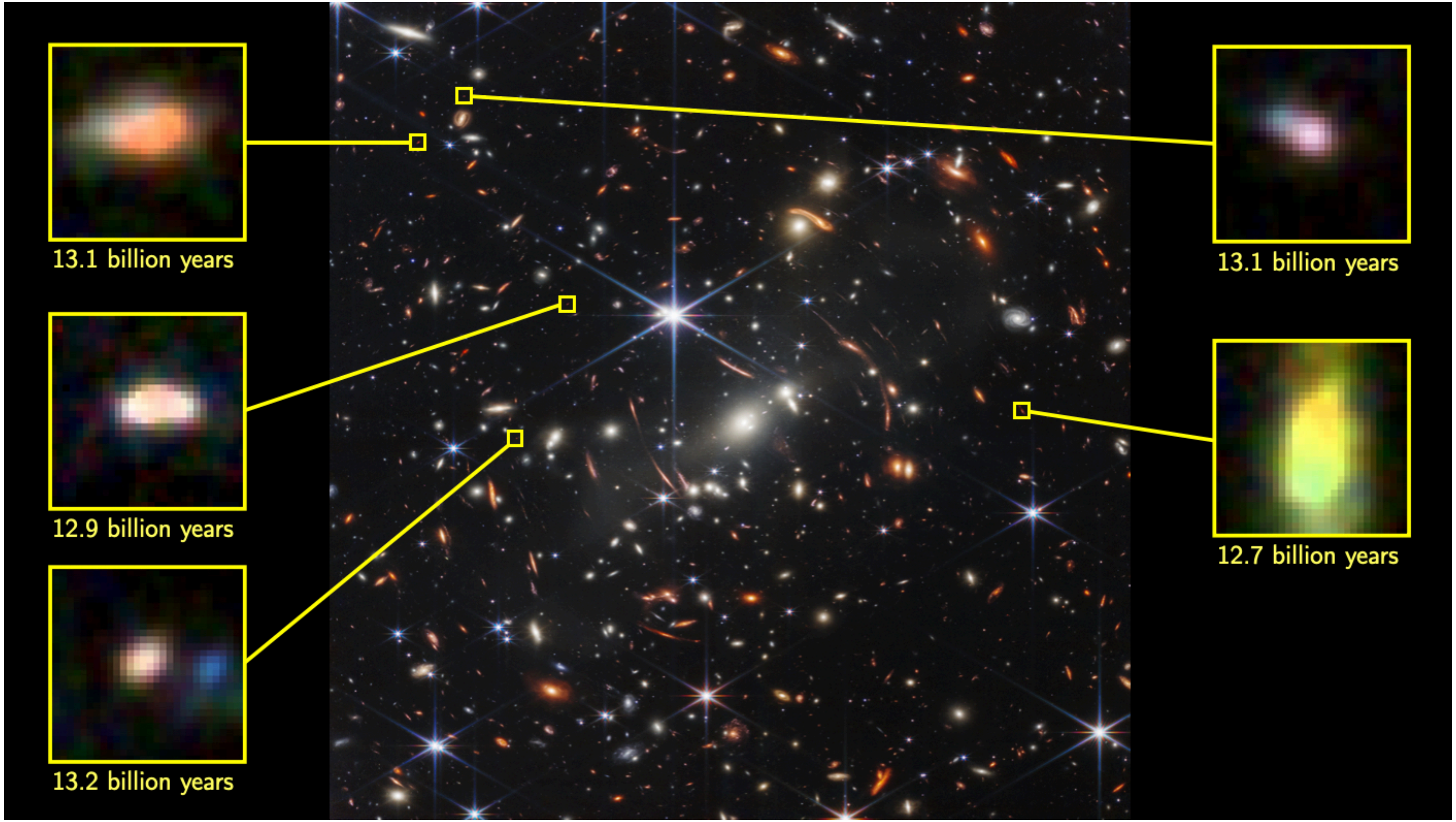

number of orbits

Li+ 2023c, in prep

Question: tidal stripping vs shock heating?

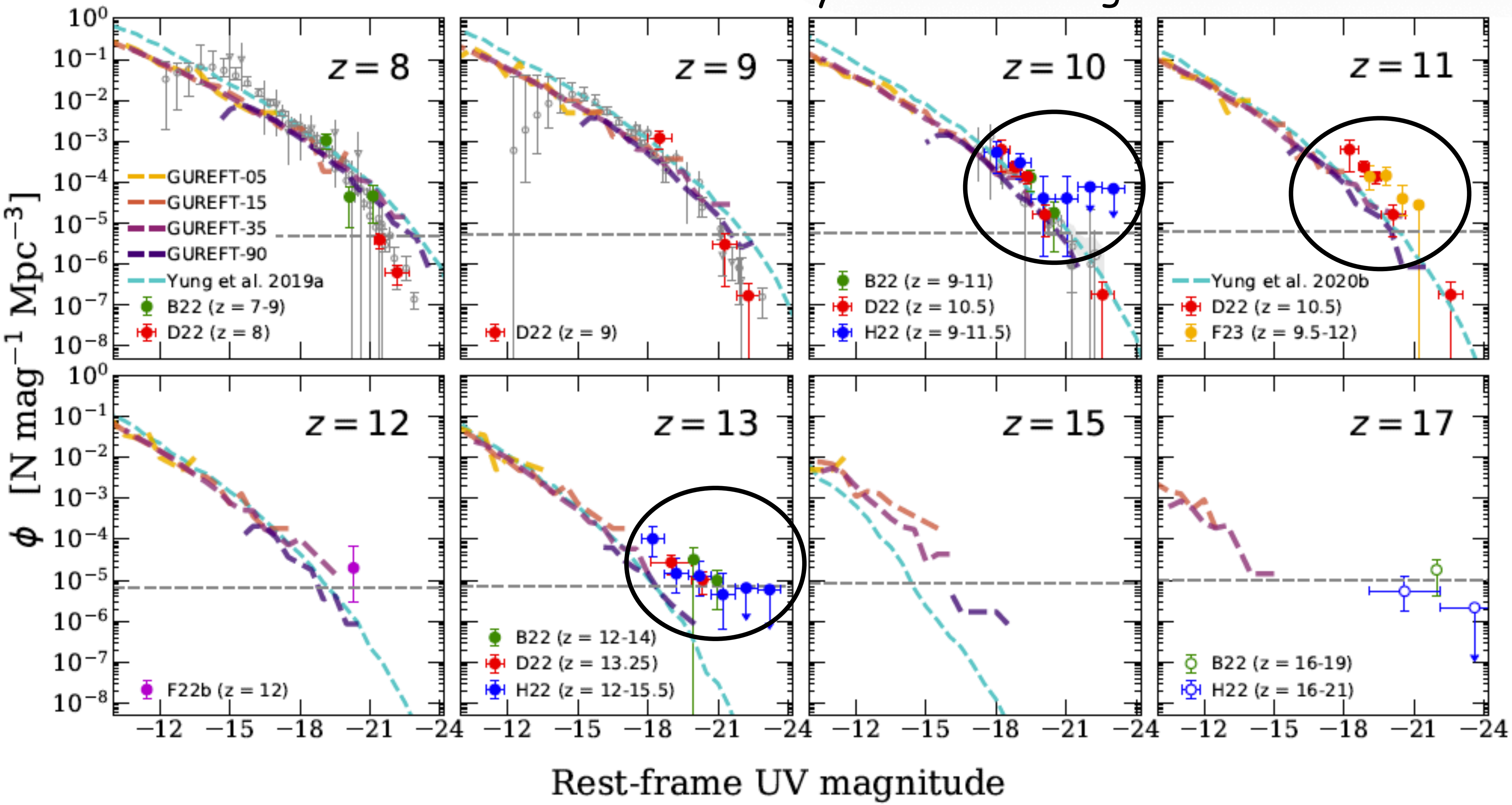
# JWST: Tens of Galaxies at z~8-12 (16?)

t ~ 400-600 Myr

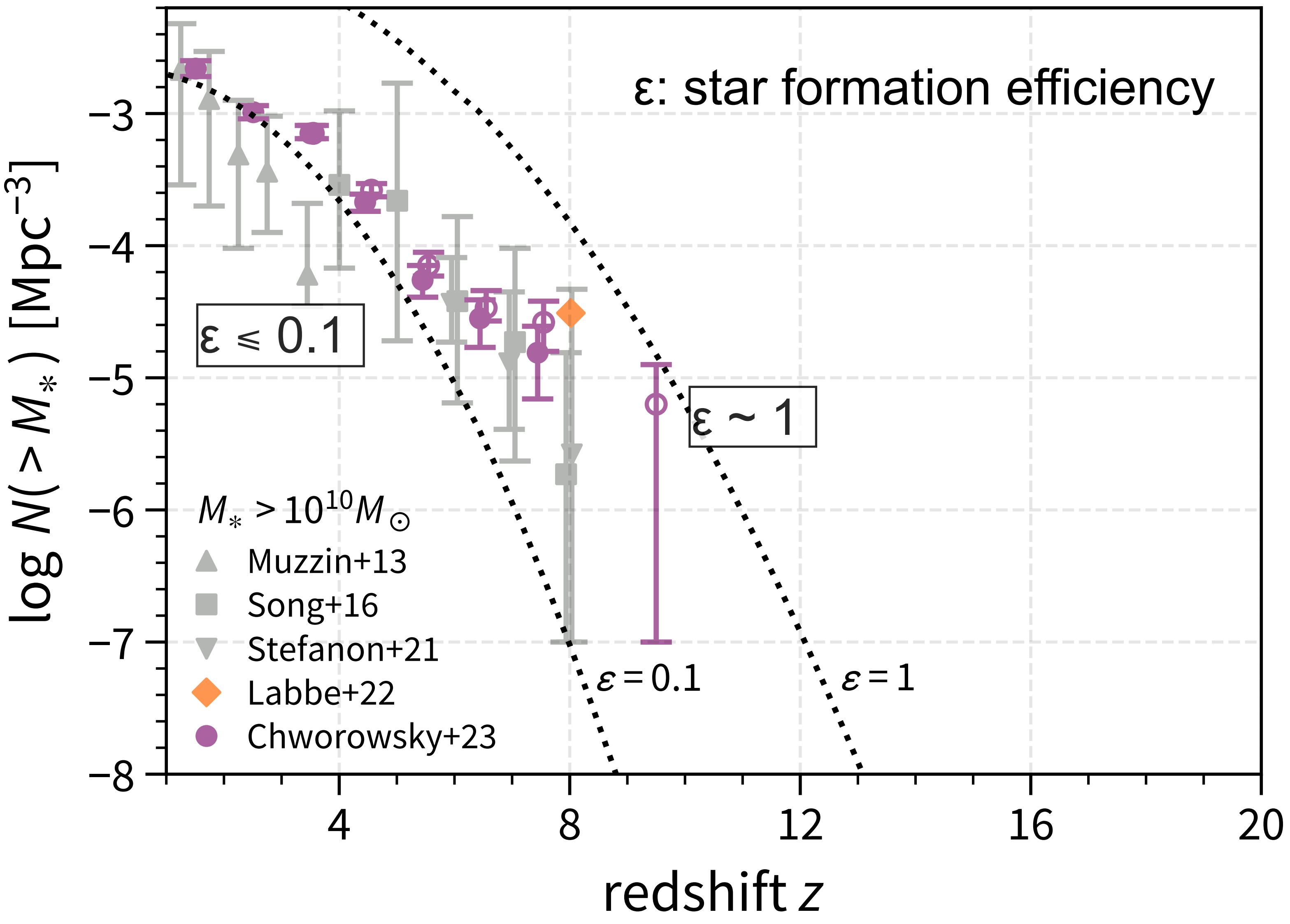


# Puzzle: excess of bright galaxies at z~10 from JWST

Observation vs semi-analytic models Yung+ 23



# Puzzling excess of bright galaxies at z~10 from JWST



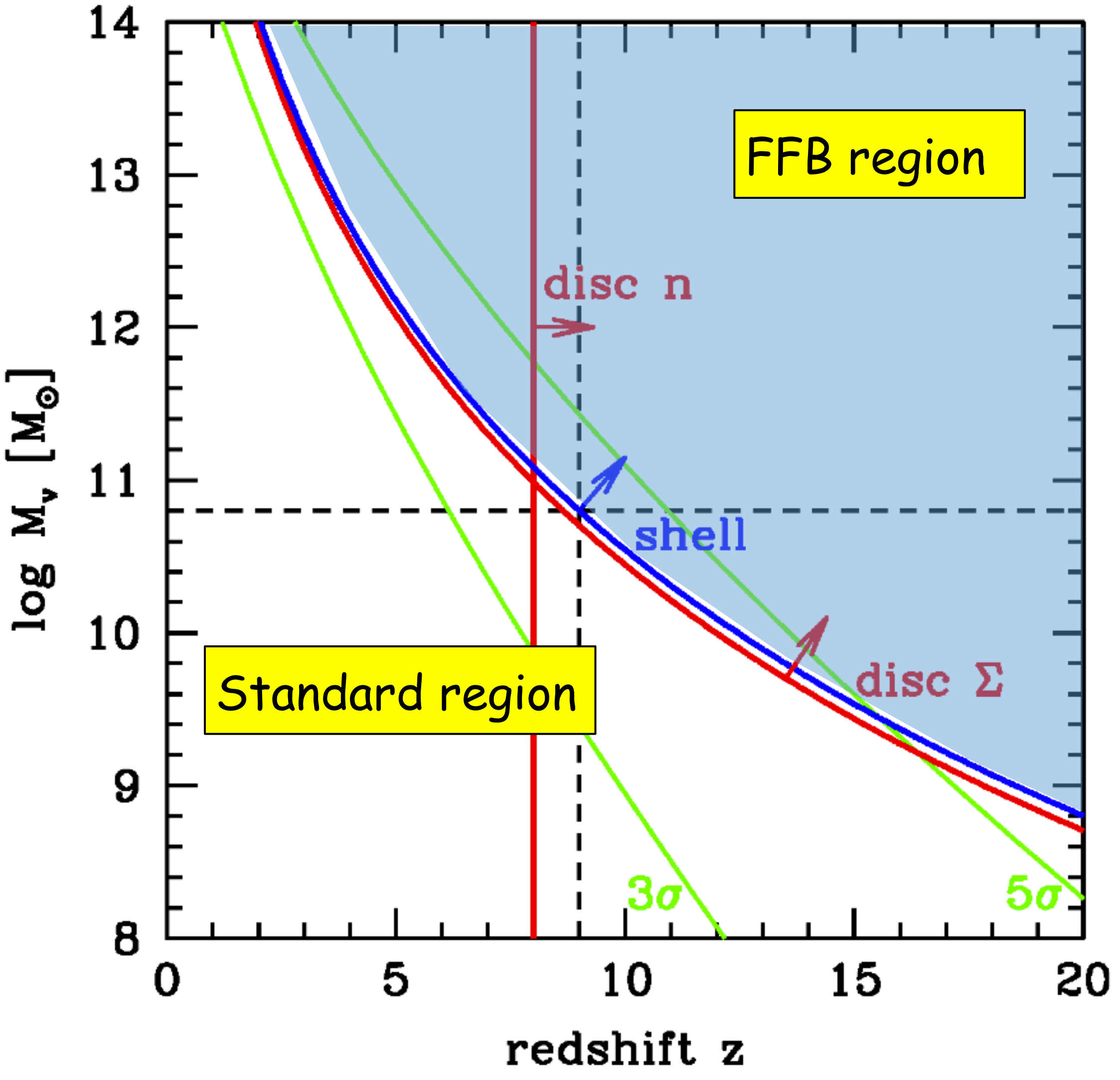
# FFB: Feedback-Free Starbursts

Dekel (incl. Li)+ 2023

Feedback-free starbursts $M^* \sim f_b M_{halo}$ when $n \sim 3\times10^3$ cm$^{-3}$, $\Sigma \sim 3\times10^3$ $M_\odot$ pc$^{-3}$

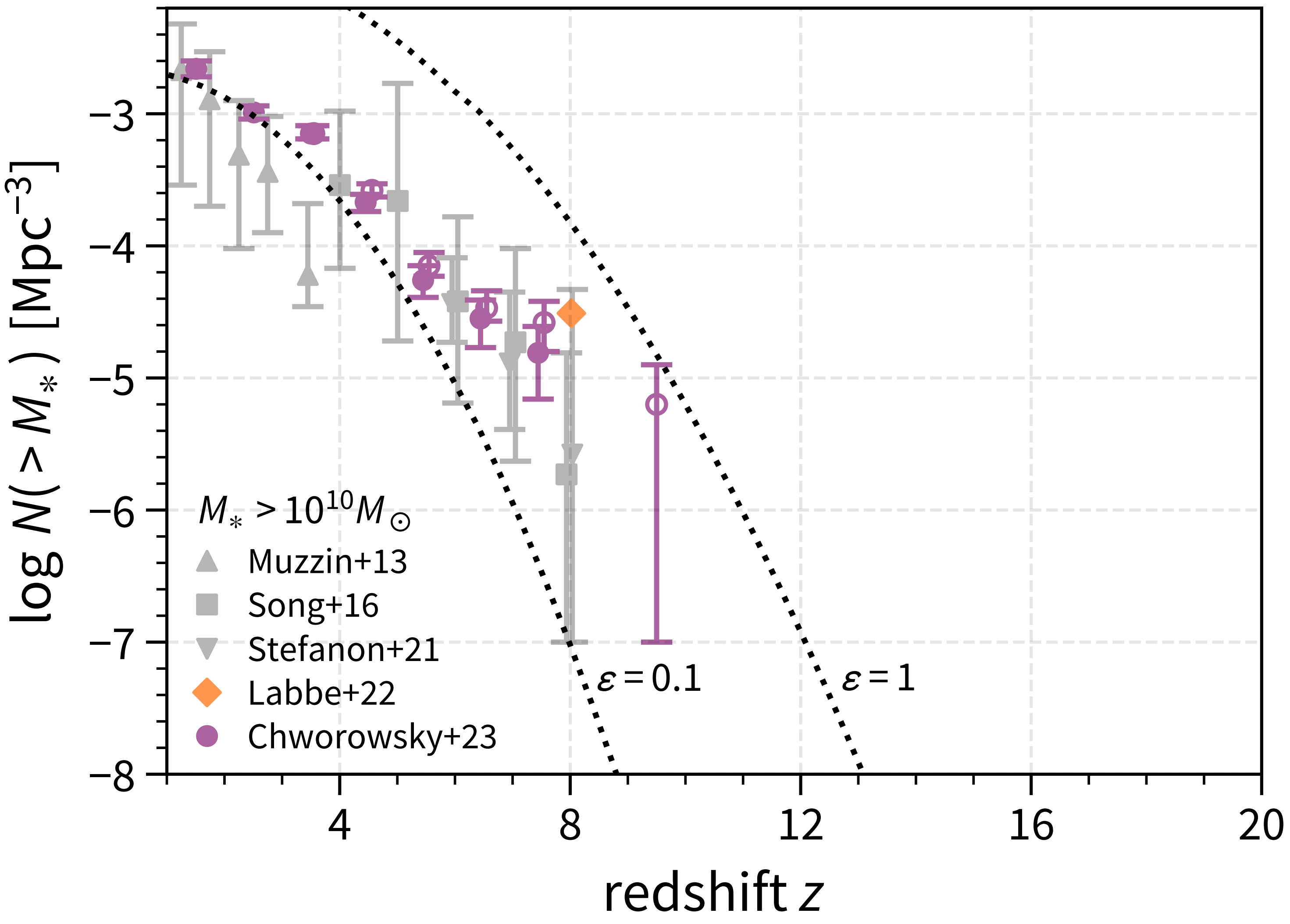
- $t_{ff} < t_{fbk} \sim 1$ Myr at low metallicity
- starbursts: $t_{cool} < t_{ff}$
- self-shielding $M_{cluster} > 10^4$ $M_\odot$
- efficient feeding by cold streams

Valid at z~10 in halos $M_{halo} > 10^{10.5}$ $M_\odot$ (lower $M_{halo}$ at higher z)



# FFB: Number density of massive galaxies in time

preliminary




FFB:
Feedback-Free Starbursts
Dekel (incl. Li)+ 2023

Li, Dekel+, in prep

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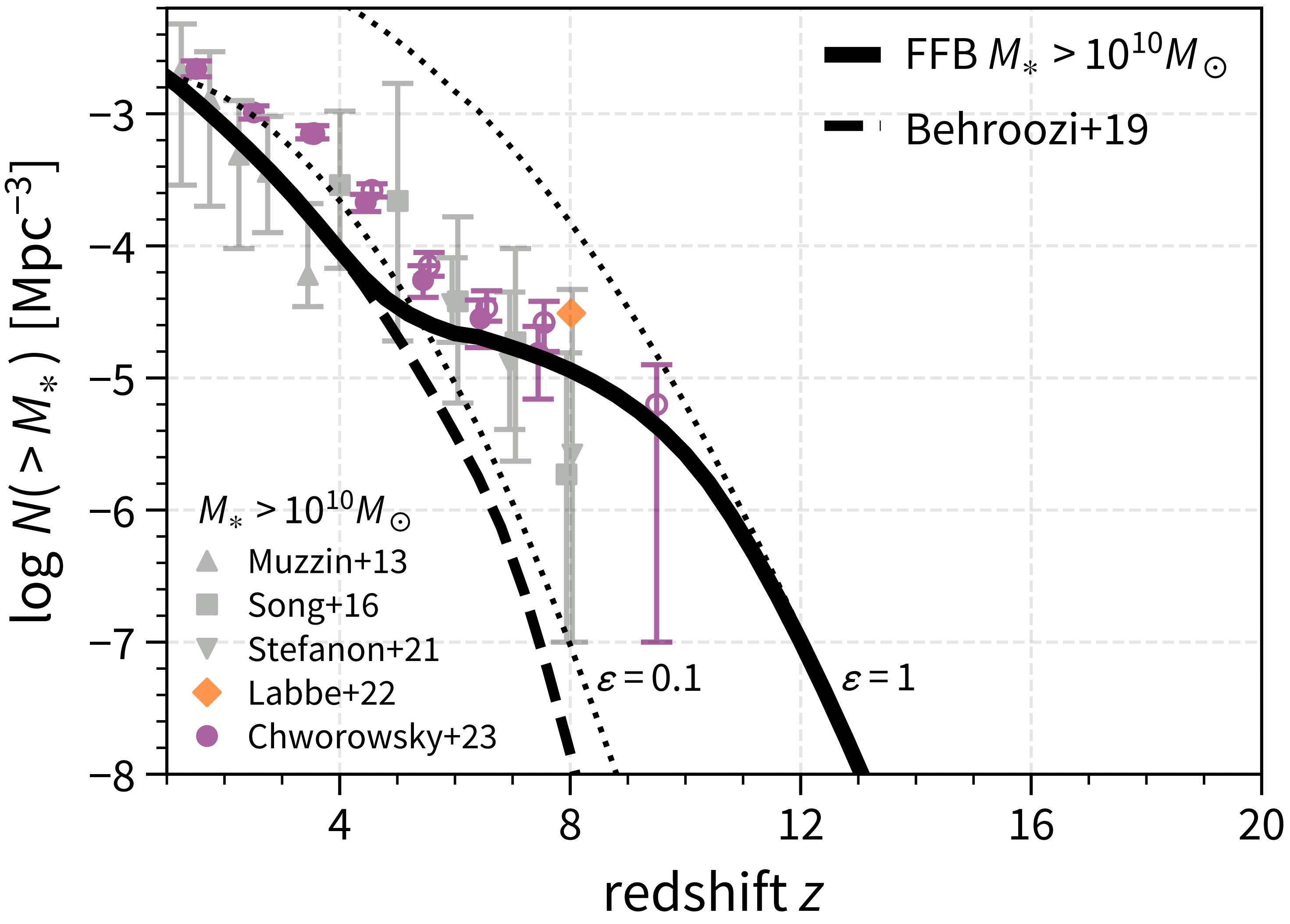
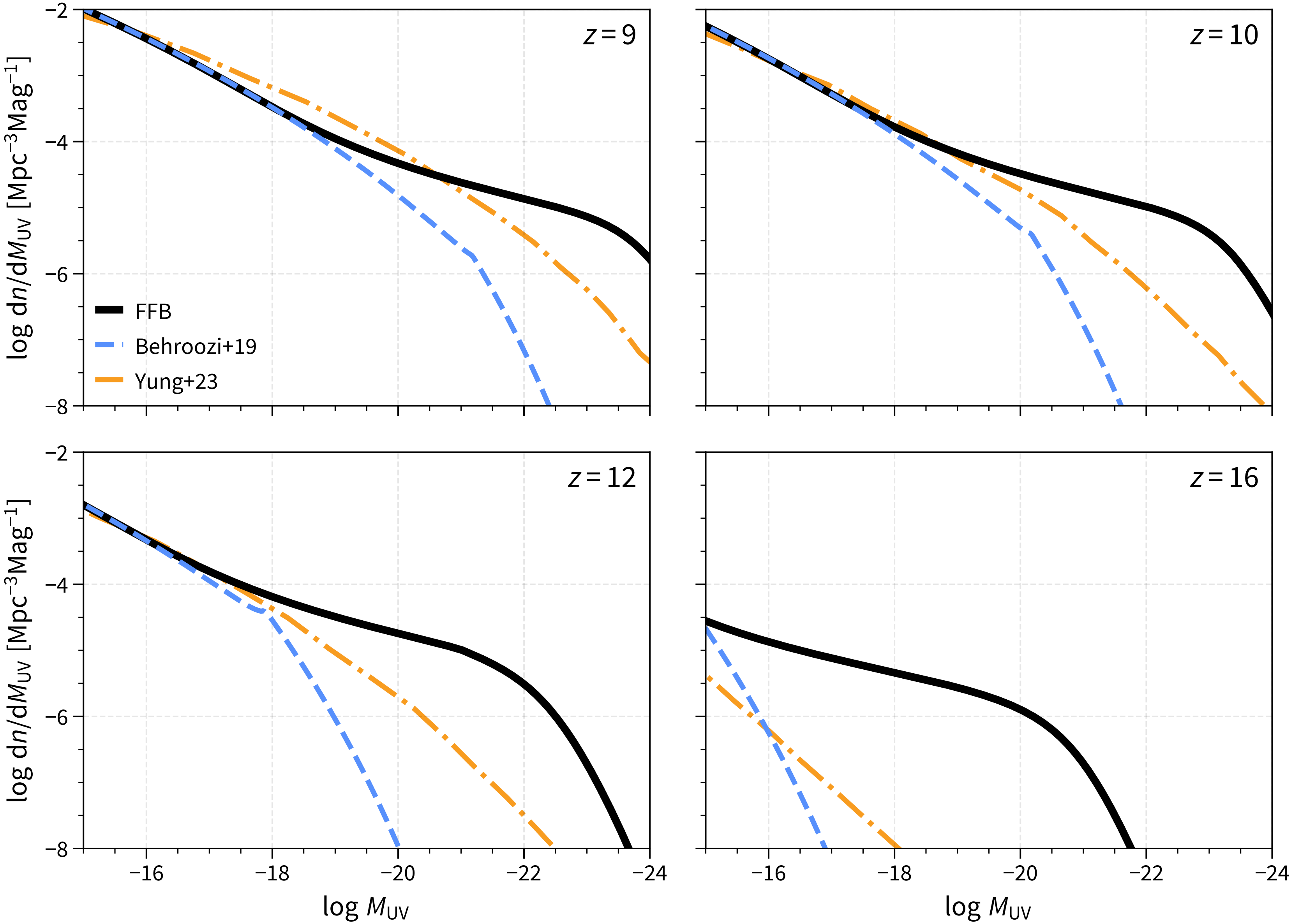



FFB:
Feedback-Free Starbursts
Dekel (incl. Li)+ 2023

Li, Dekel+, in prep

# FFB: UV luminosity Function



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Dekel (incl. Li)+ 2023

Li, Dekel+, in prep

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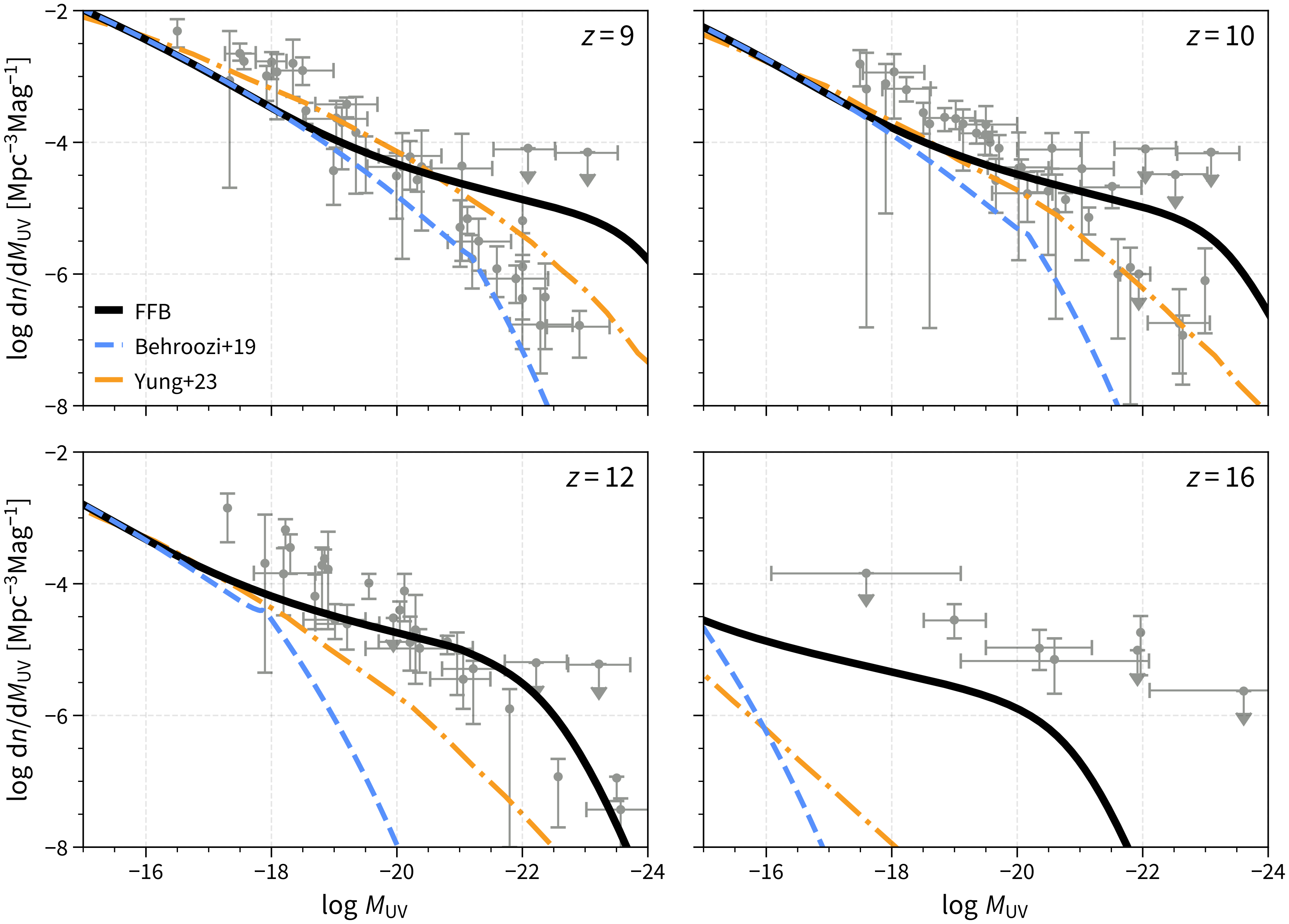


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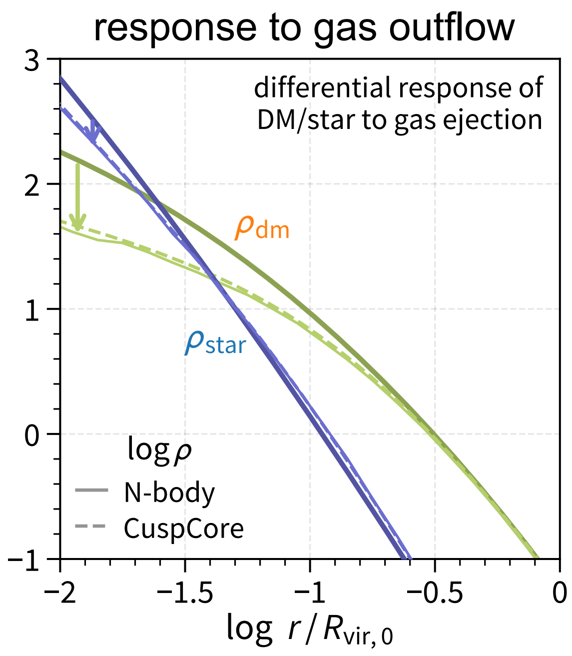
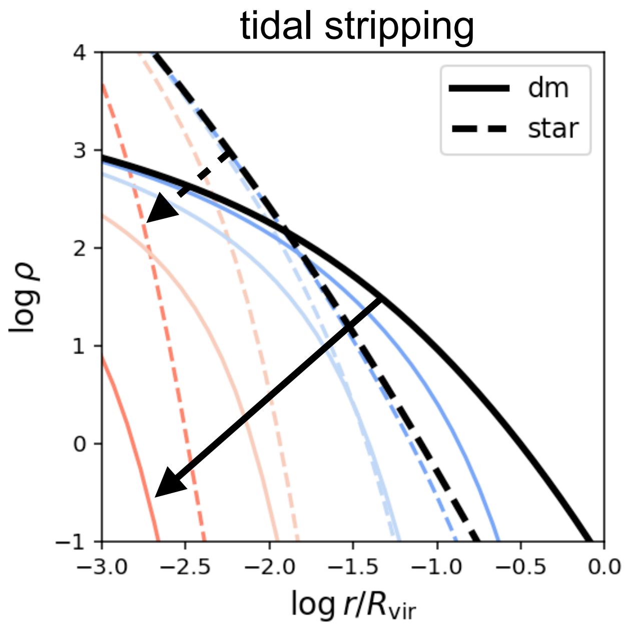
# Summary

- **CuspCore2**: model for structural evolution driven by **outflow**, dynamical **heating**, and **tidal stripping**
  ➡accurate, cheap, and flexible
- Key for taking out DM: **differential response** of DM/stars
  - DM-deficient massive galaxies at z~2 or field UDGs [repeated] strong **outflows** + [optional] heating by merger
  - DM-deficient ultra compact/diffuse galaxies may occur naturally via **tidal evolution**
- **Next**: explore and constrain the param space [$\rho_{\mathrm{init}}(r)$, $f_{\mathrm{gas}}$, orbit...] in comparison with observation
- Public code will be available

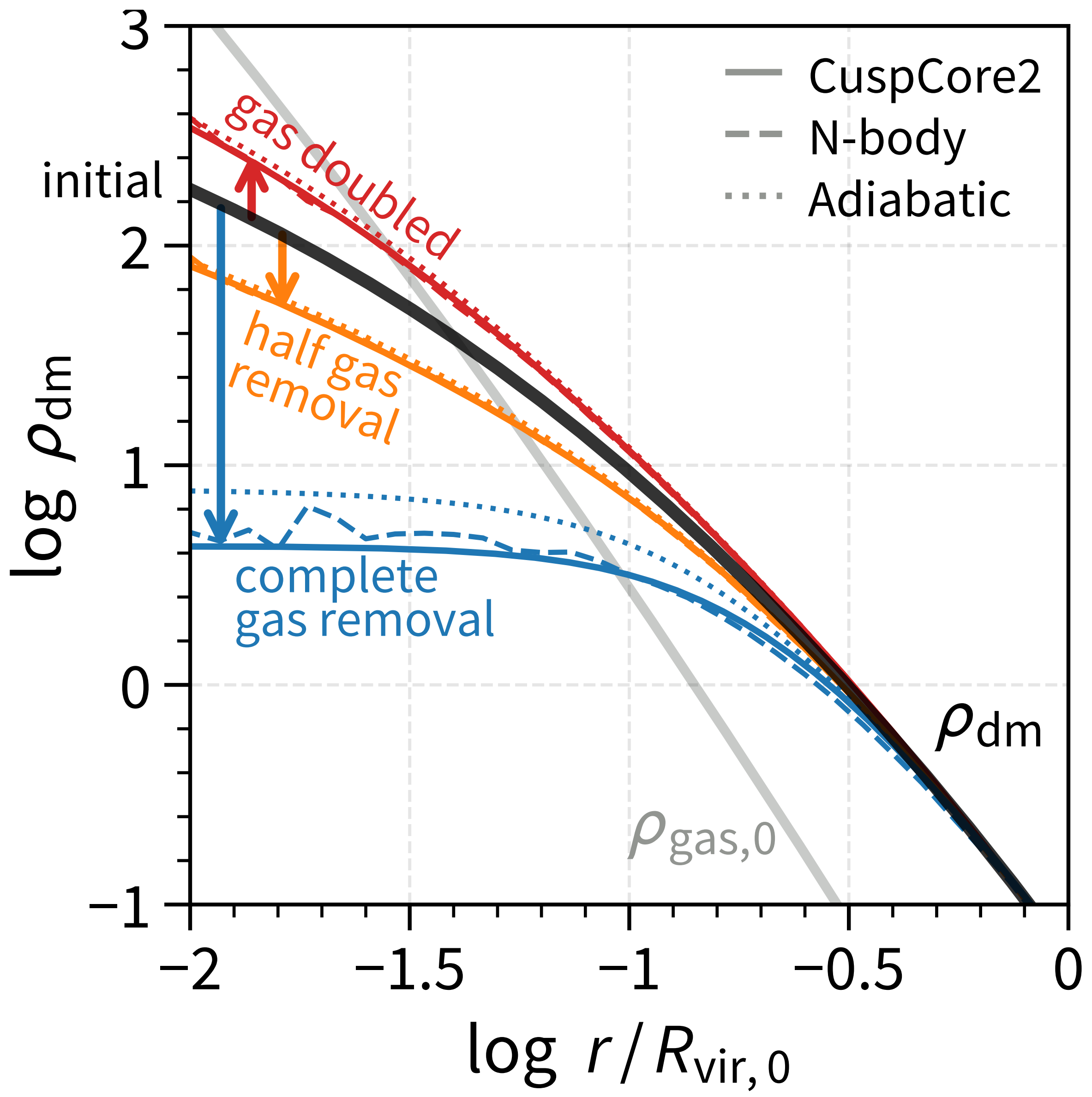


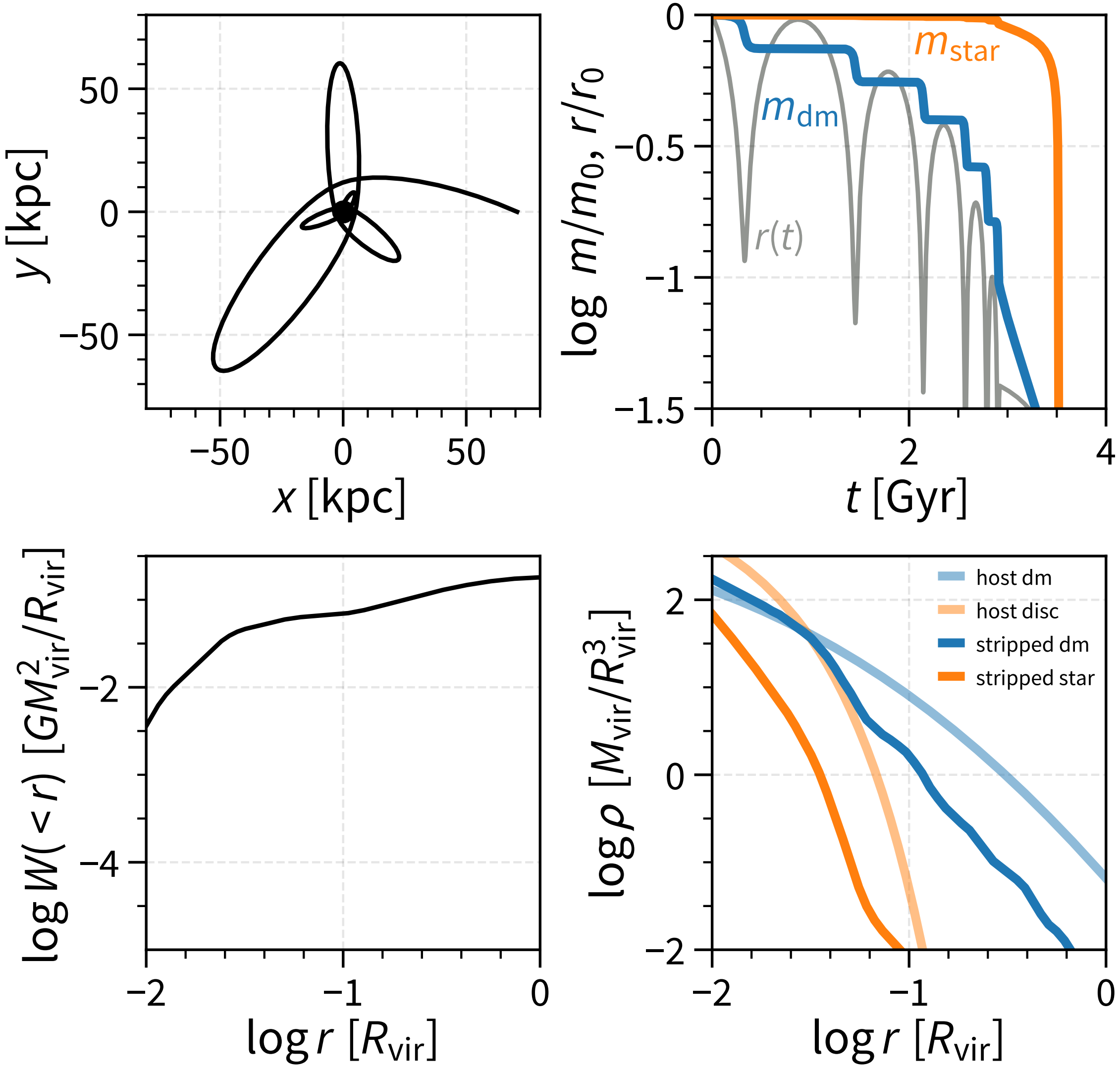

zhaozhou.li@mail.huji.ac.il
Li+ 2023a, arXiv: 2206.07069
Li+ 2023b, c, in prep

# Supplements

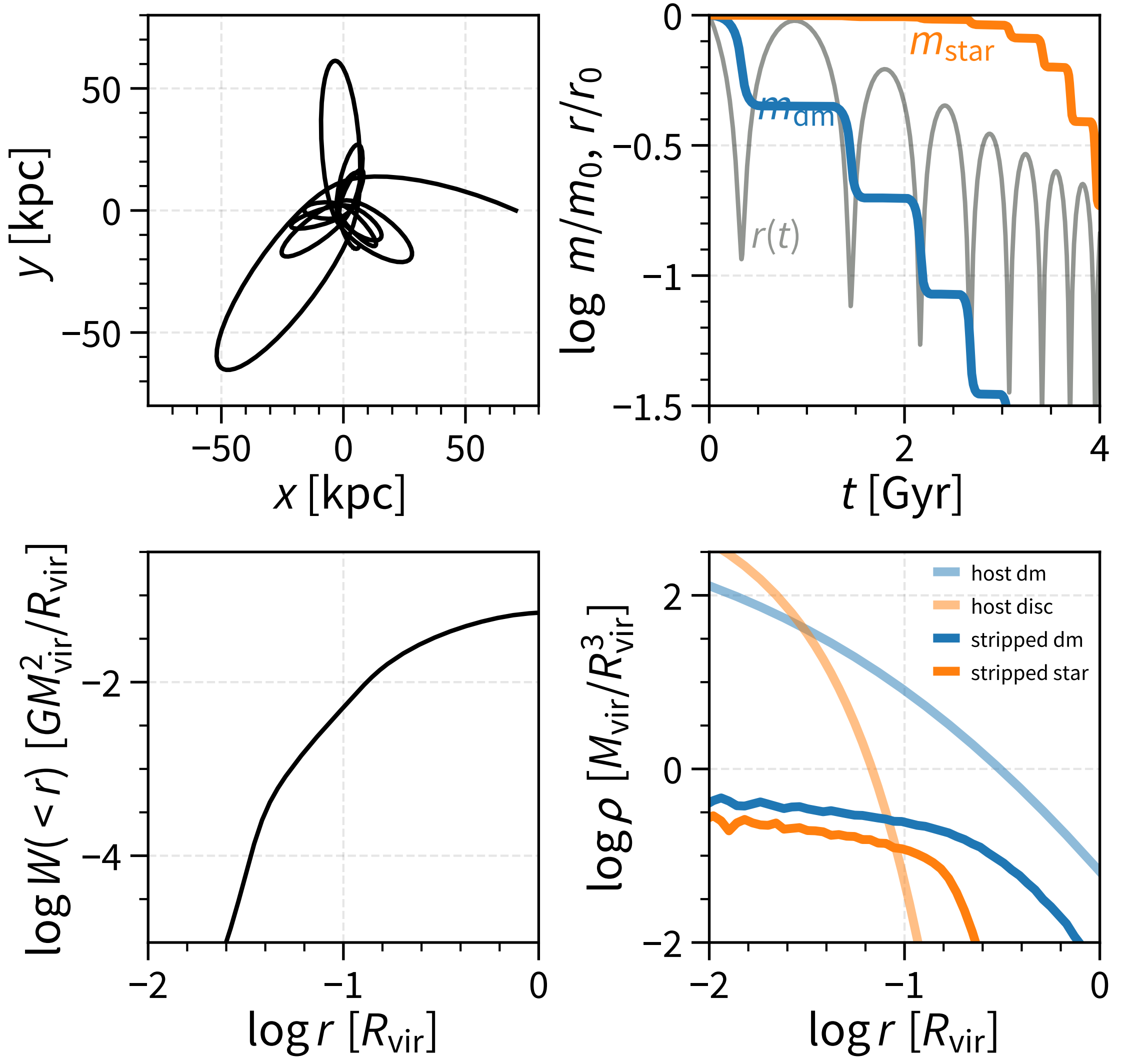
# Halo response to gas inflow/outflow

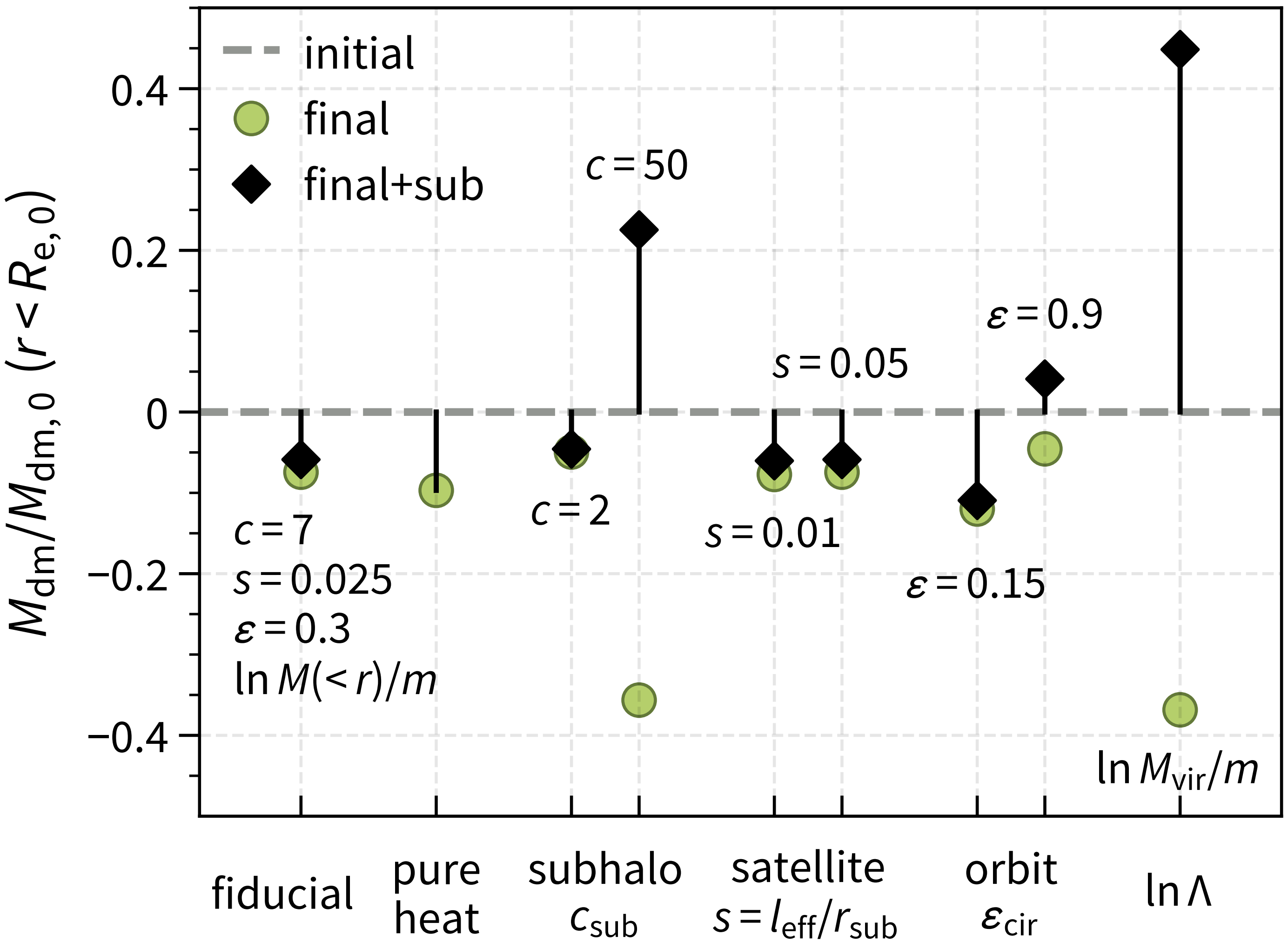


# very compact satellite



# very diffuse satellite

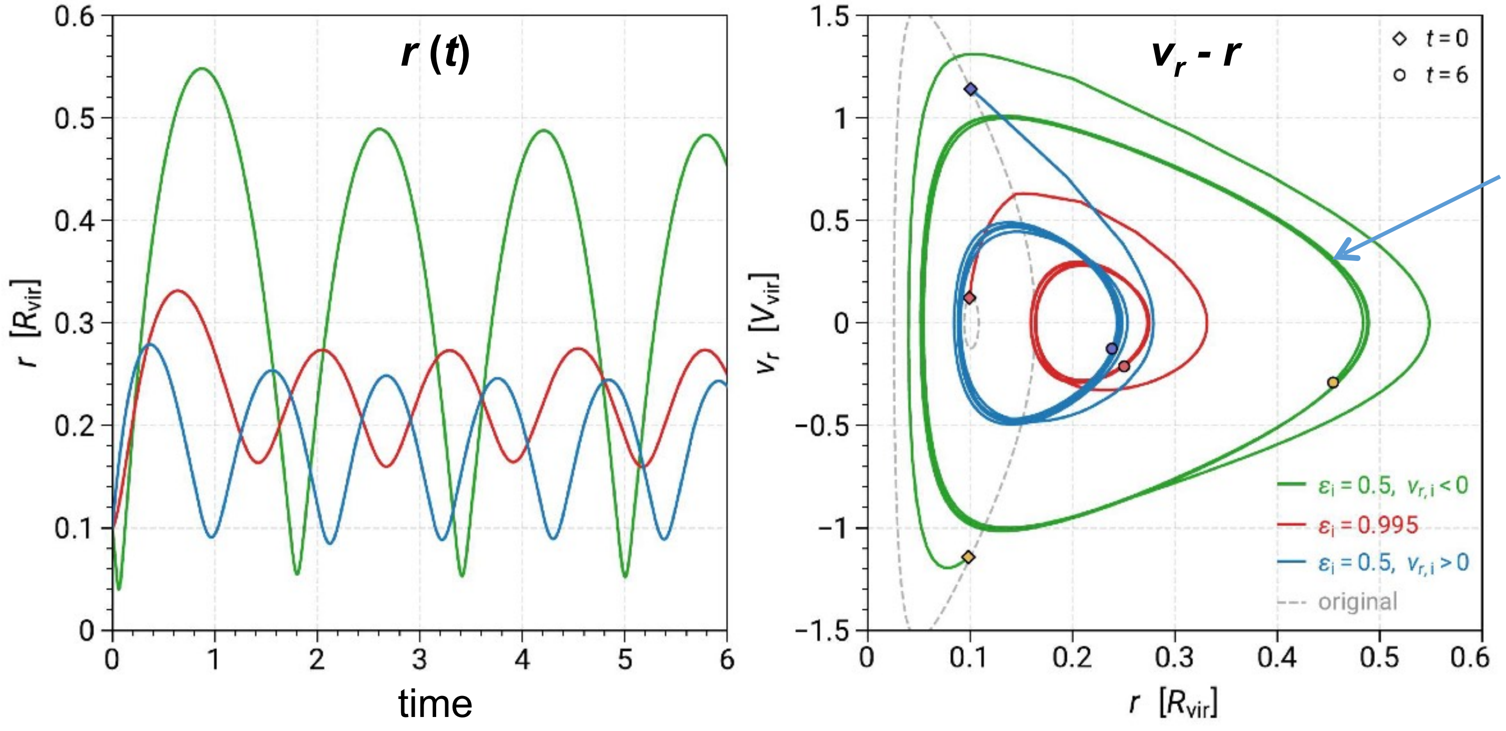




initial
final
final+sub
$M_{\rm dm}/M_{\rm dm,0}\ (r<R_{\rm e,0})$
0.4
0.2
0
−0.2
−0.4
$c=50$
$s=0.05$
$\varepsilon=0.9$
$c=7$
$s=0.025$
$\varepsilon=0.3$
$\ln M(<r)/m$
$c=2$
$s=0.01$
$\varepsilon=0.15$
$\ln M_{\rm vir}/m$
fiducial
pure heat
subhalo $c_{\rm sub}$
satellite $s=l_{\rm eff}/r_{\rm sub}$
orbit $\varepsilon_{\rm cir}$
$\ln\Lambda$

# Relaxation: Continued evolution due to redistribution of DM

Orbits of three particles with same $r_{\text{init}}$ & $E_{\text{init}}$ →



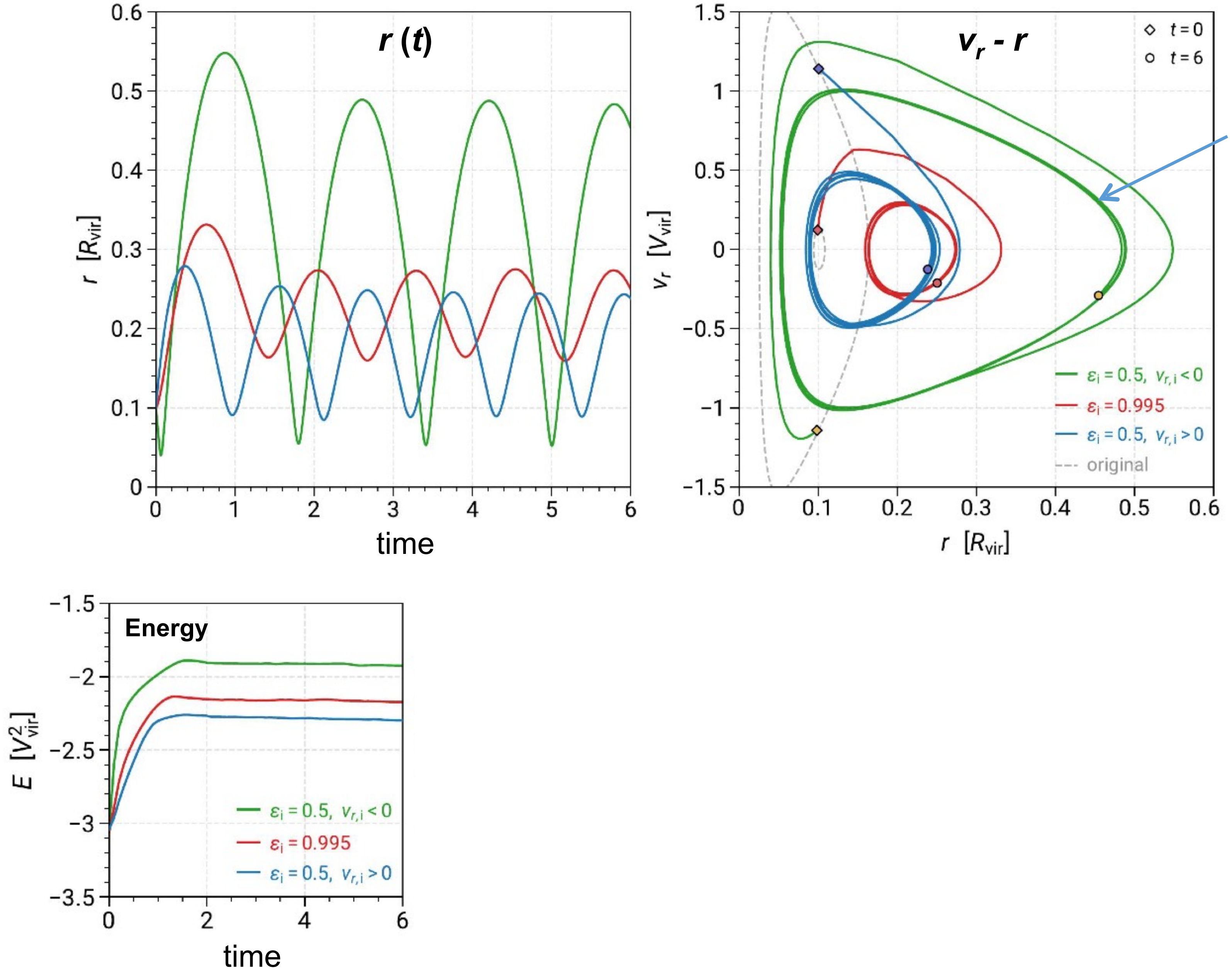

radial action
$J_r$ = Area/2$\pi$

# Relaxation: Continued evolution due to redistribution of DM

Orbits of three particles with same $r_{\rm init}$ & $E_{\rm init}$ →

- ➢ Diffusion of $E$ due to redistribution of DM itself

$$\Delta E = \int_{t_1}^{t_2} \frac{\partial}{\partial t} U(r,t)\, dt$$

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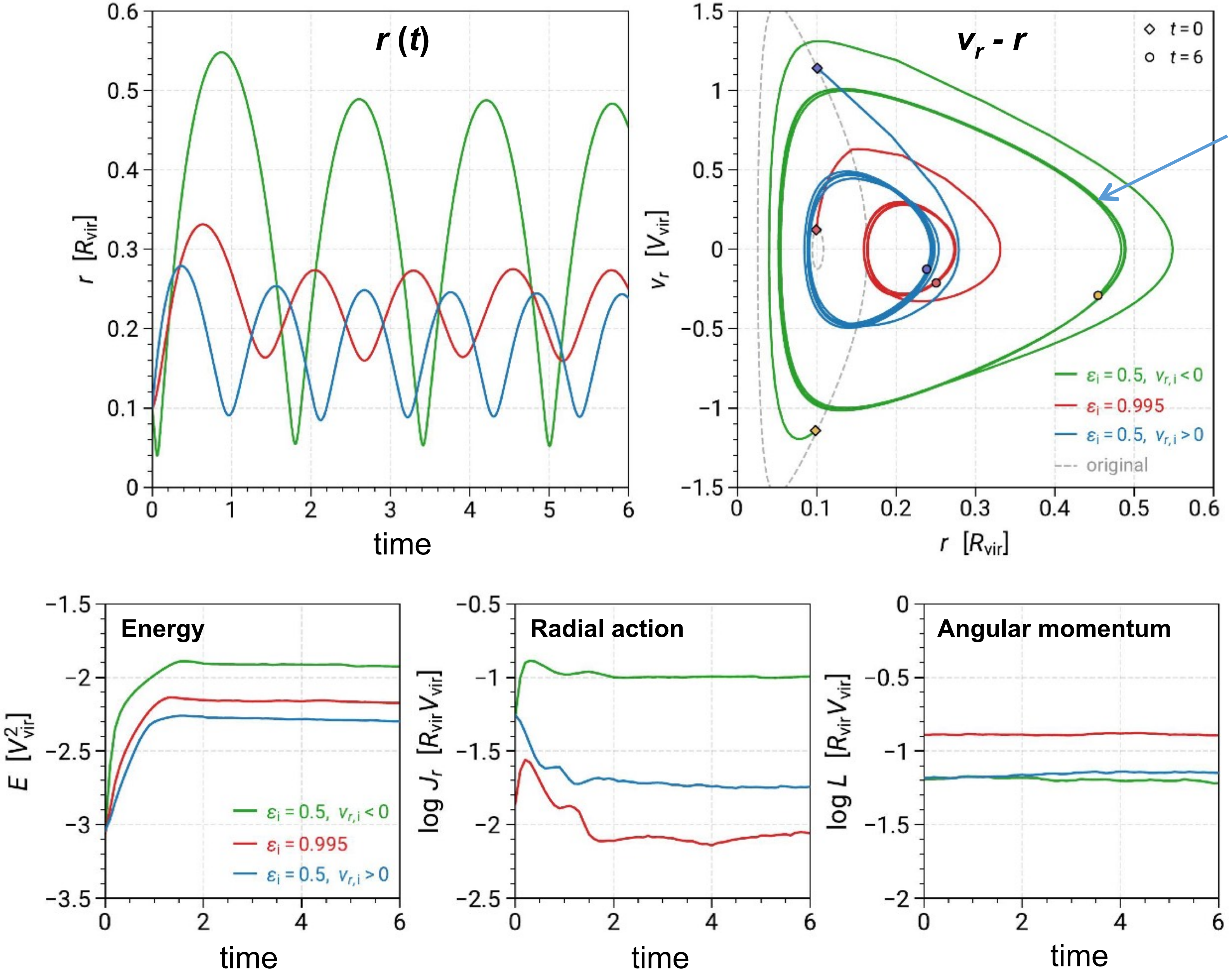


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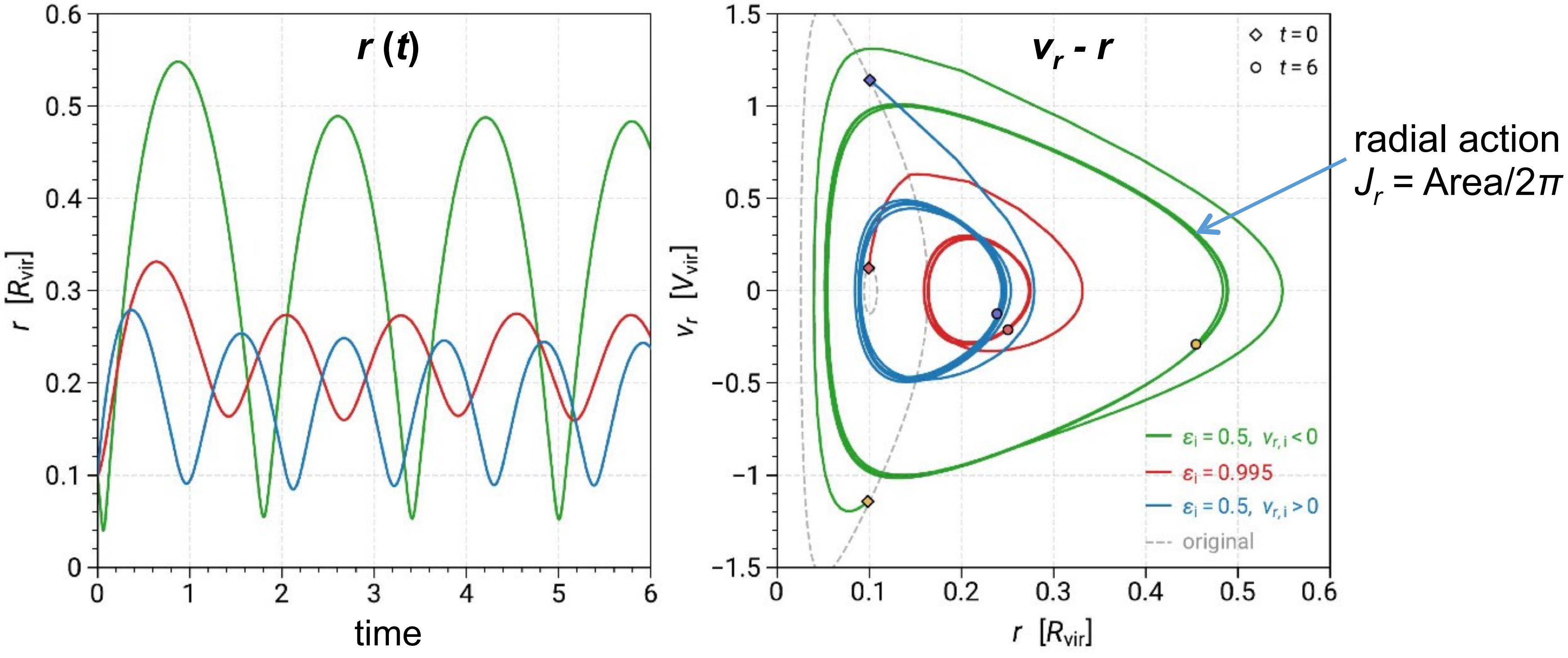


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$$\Delta E = \int_{t_1}^{t_2} \frac{\partial}{\partial t} U(r,t)\,dt$$

➢ Similar diffusion of $J_r$, non-adiabatic

➢ Orbits expand in the 1st period and roughly stabilize afterwards