On the formation process of dark matter deficient galaxies

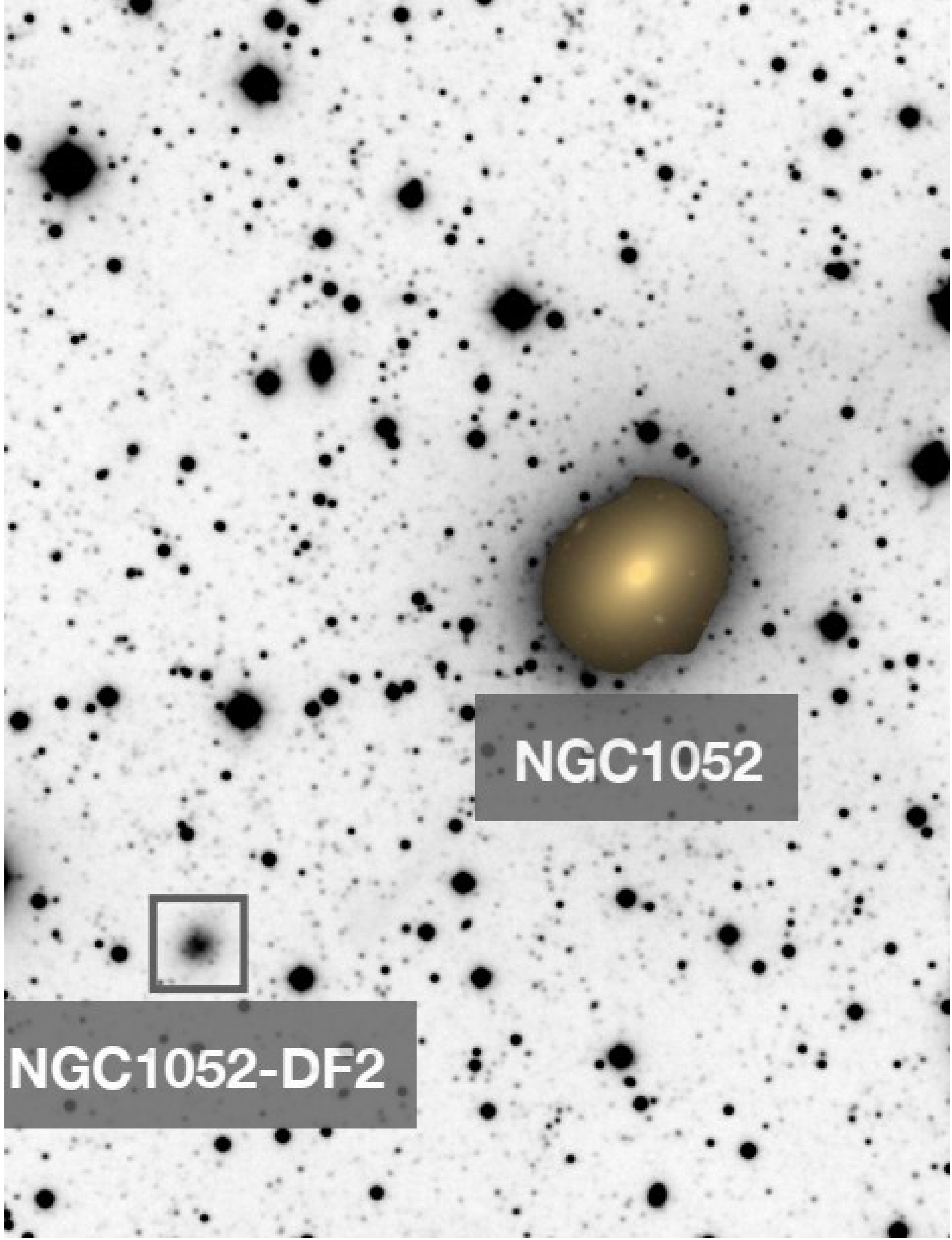
Go Ogiya (ZJU)

with Frank van den Bosch (Yale); Andi Burkert (Munich); Xi Kang (ZJU)

NGC1052-DF2 (DF2)

- Ultra diffuse galaxy (UDG) in the group of NGC1052
  - ✓Discovered by Karachentsev et al. (2000)
- Mstar = 2e8Msun

- Galaxy formation and evolution models expect Mhalo ~ 5e10Msun



Shen et al. (2021)

NGC1052-DF2 (DF2)

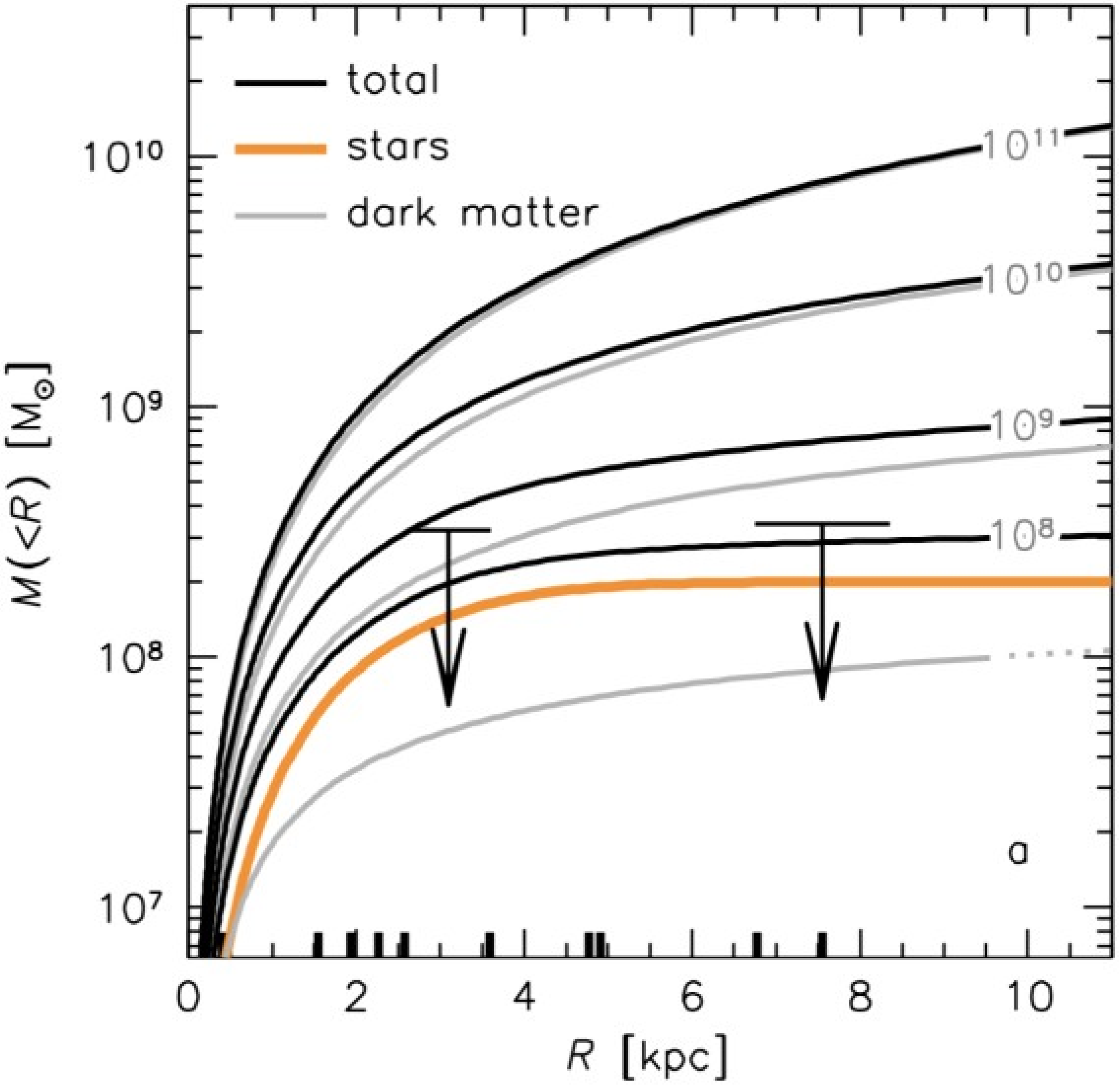
- van Dokkum et al. (2018) inferred the dynamical mass of DF2
  - 10 globular clusters = kinetic tracers

- Inferred dynamical mass = 3.4e8Msun within R=7.6kpc
  - Stellar mass ~ 2e8Msun
  - Dark matter (DM) mass ~ 1e8Msun
  - cf. Theoretical models expect ~ 5e10Msun

DF2 is a DM deficient galaxy

+ DMDGs in the same galaxy group and in the Virgo cluster, even in the field?

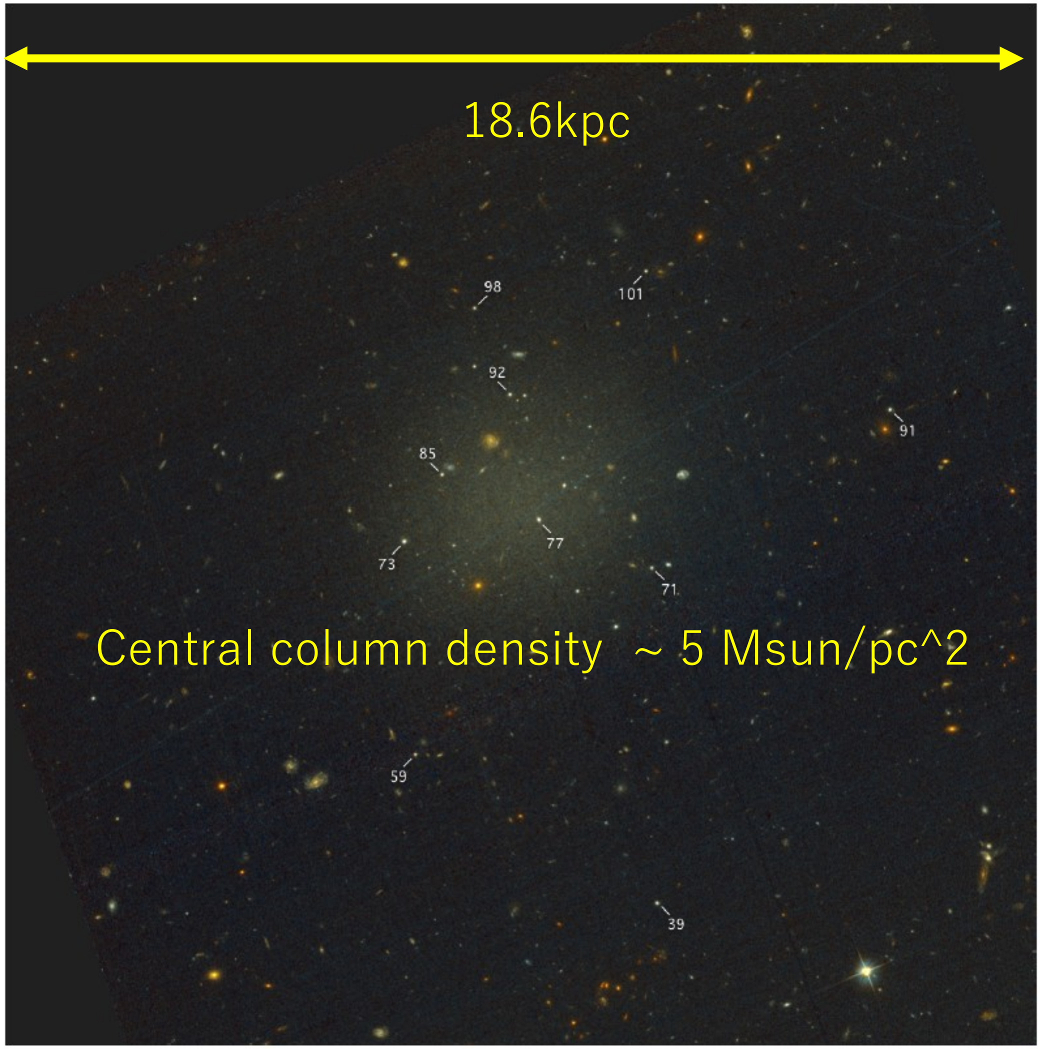
(e.g. van Dokkum+19, Guo+20, Toloba+23)



Notable properties of DM deficient gals

1. Extremely small DM mass
2. Diffuse stellar component

Q. Such extreme galaxies can be formed within the standard framework of galaxy formation?



van Dokkum et al. (2018)

Tidal interaction as a formation scenario

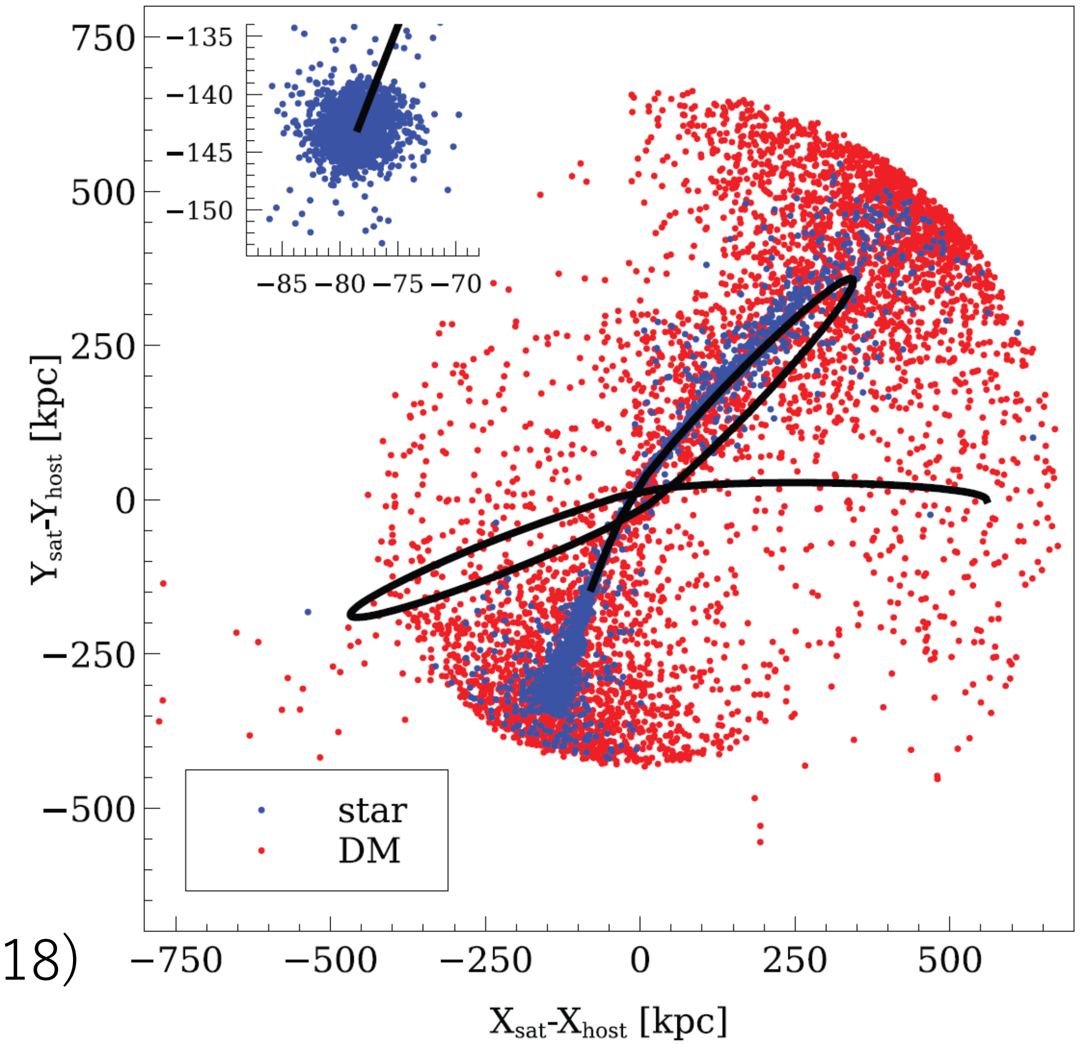
- Violent tidal massloss

→ Extremely small DM mass?

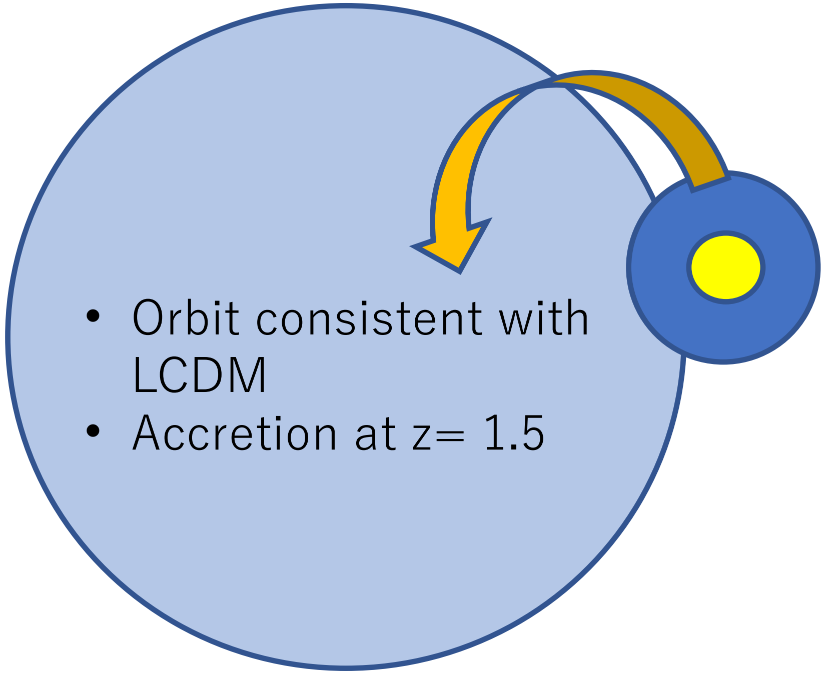
- Tidal puffing-up

→ Diffuse stellar component?

GO (2018)



Simulation setup

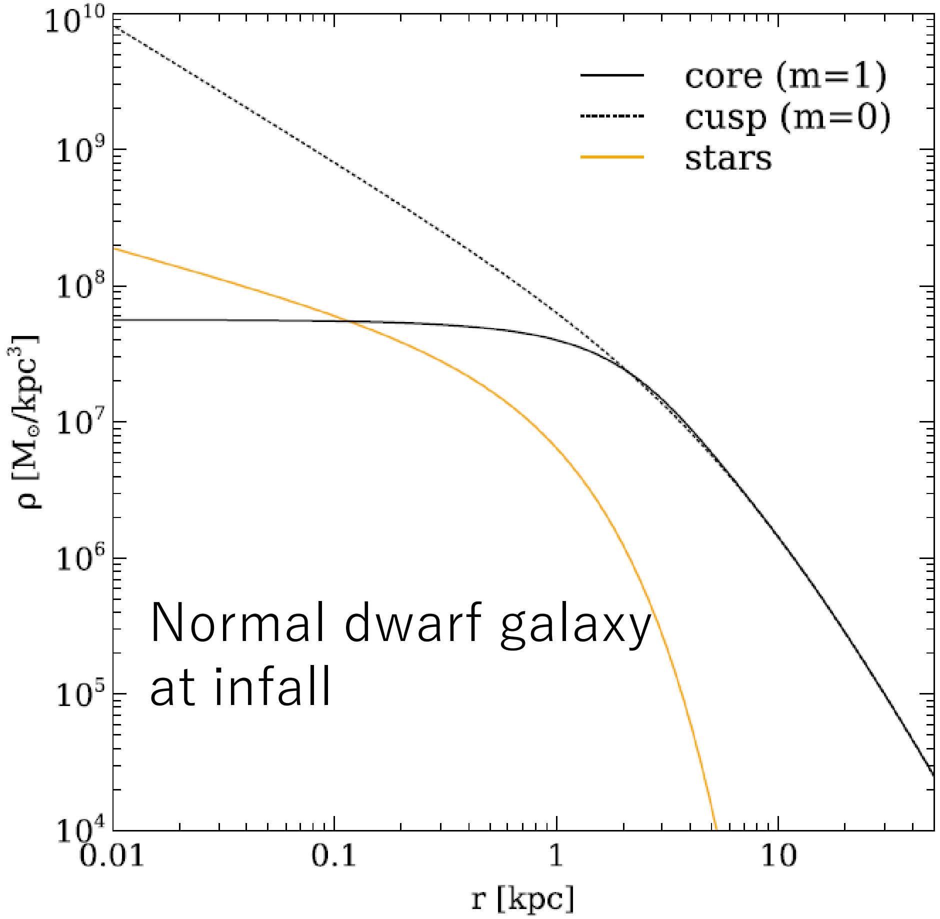


NGC1052 = time-varying NFW potential

✓ Mass growth (Correa et al. 2015)

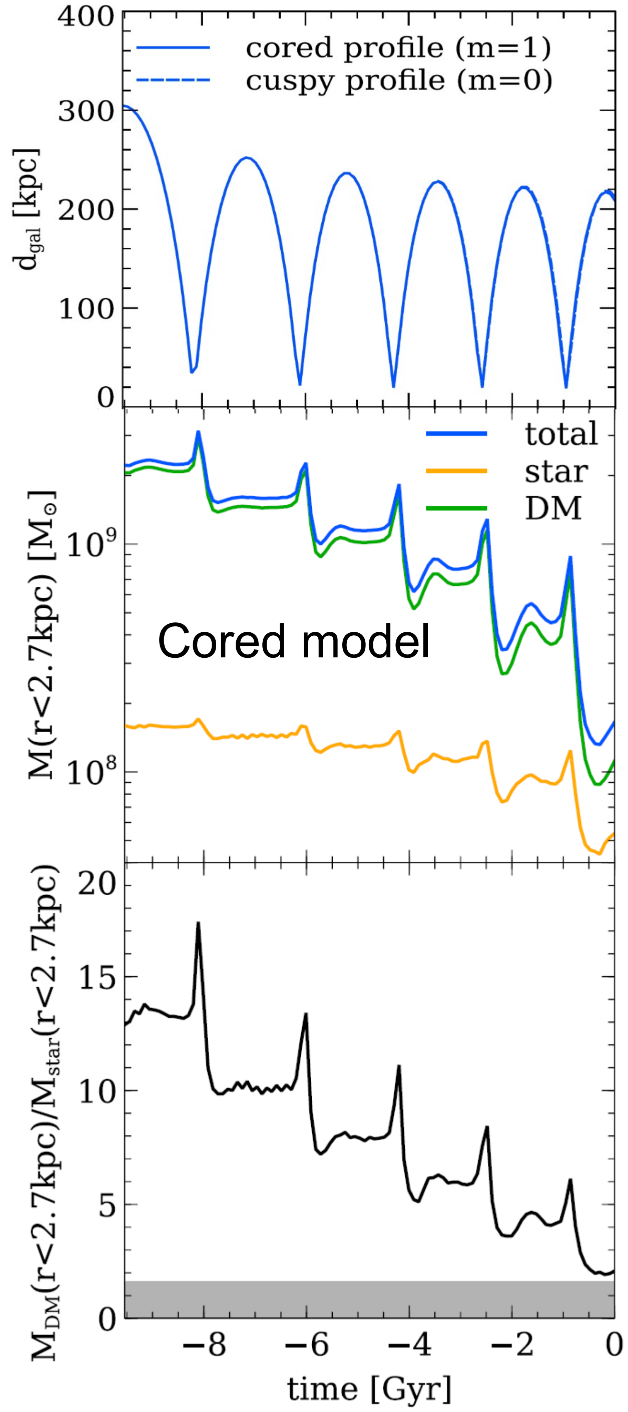
✓ c(M,z) relation (Ludlow et al. 2016)

Satellite = 2-component N-body system



DM deficiency

- Mass evolution at r=2.7kpc
  - Half-mass radius (Danieli et al. 2019)
- Massloss at each pericentric passage
- DM mass is reduced more significantly
- Transforming a normal satellite into a DM deficient galaxy



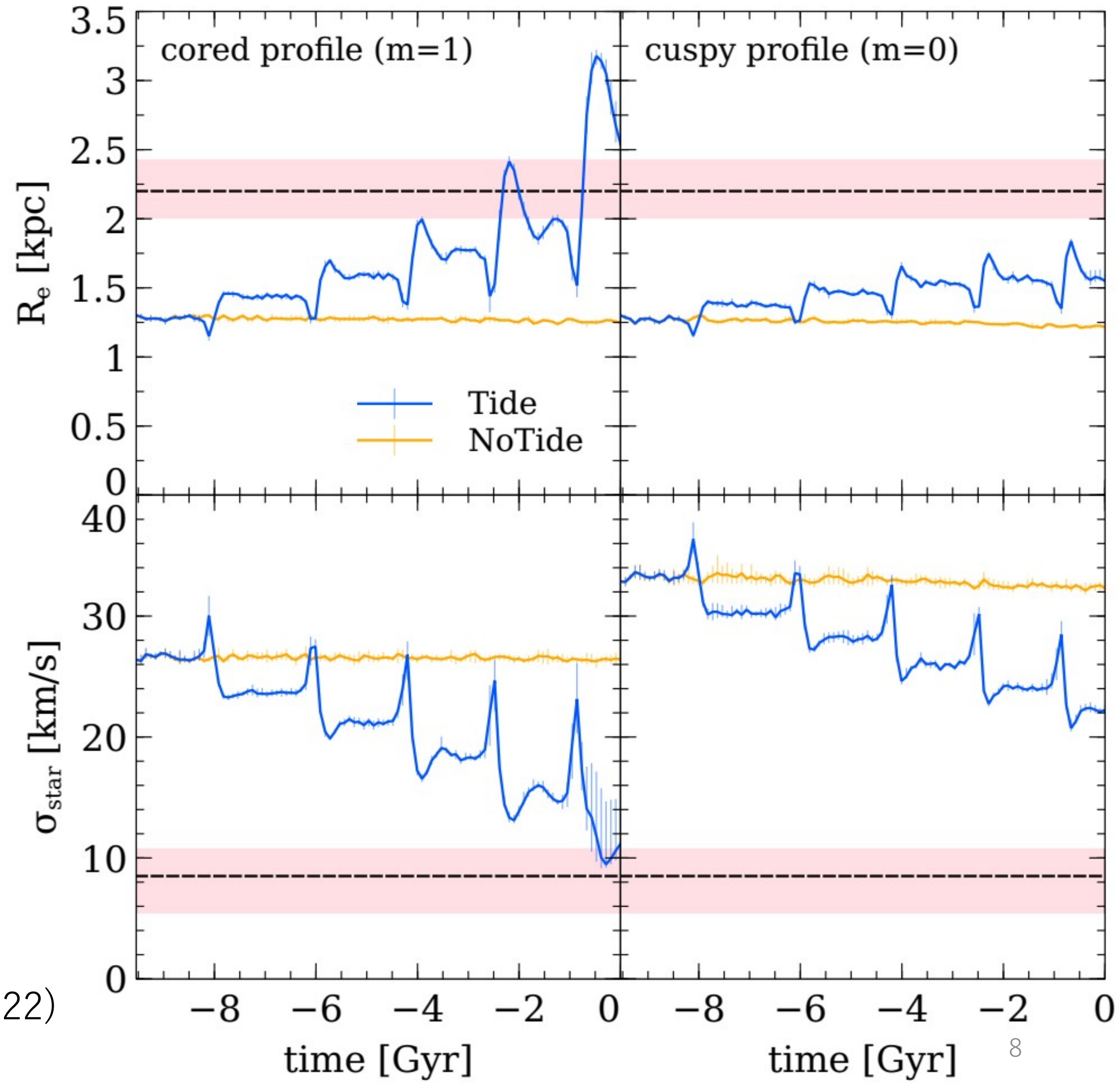
GO, van den Bosch & Burkert (2022)

Gal. properties

- “Observe” the satellite galaxy model from 100 different orientation angles
  - ✓Line: median
  - ✓Err bar: 15-85 percentile

- Re and σ star stay const in the absence of tide

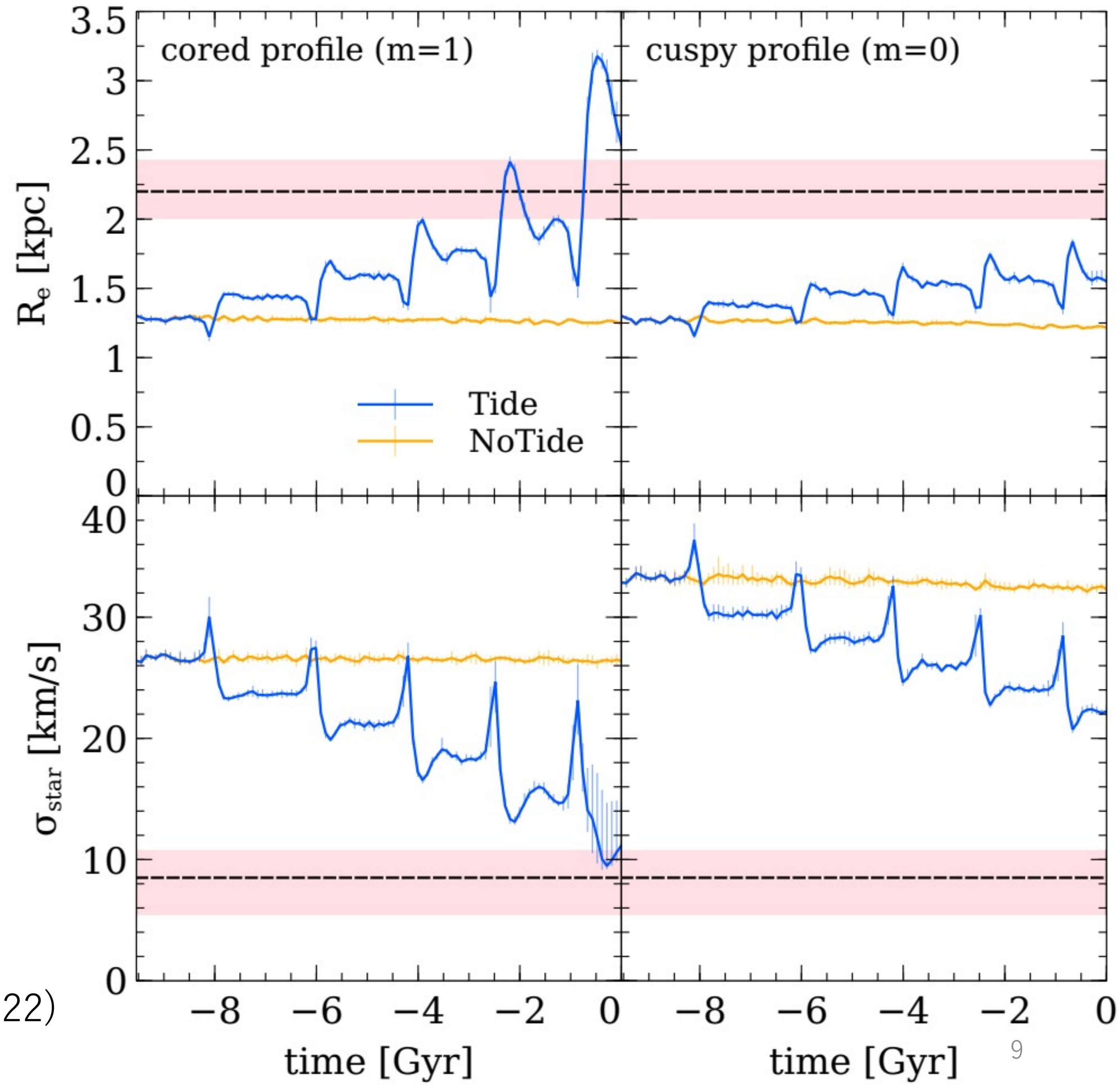
GO, van den Bosch & Burkert (2022)



Gal. properties

- Galaxy size increases at each pericentric passage
  - ✓Energy injection through tidal shock

- Observations (pink) reasonably reproduced

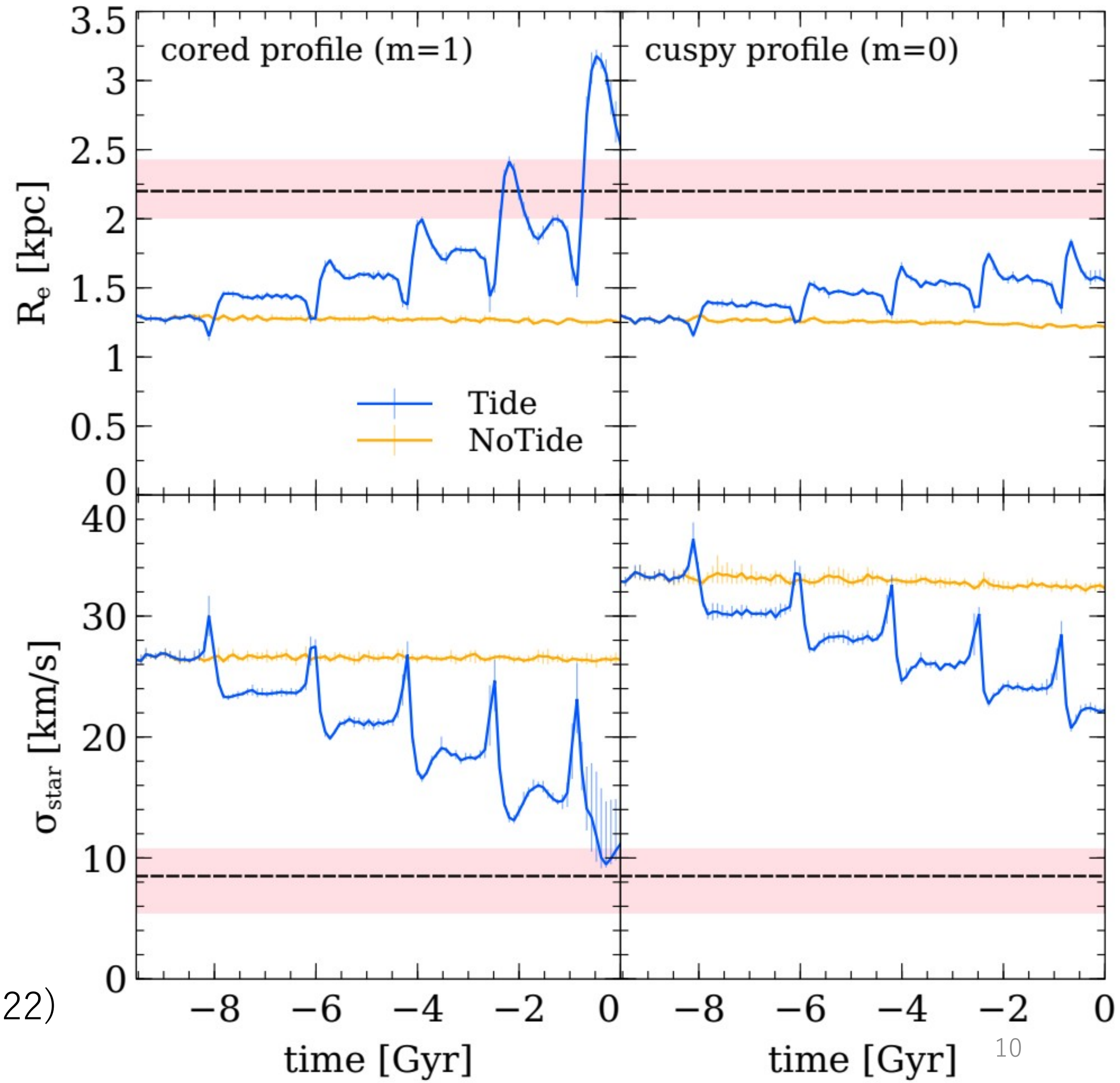


GO, van den Bosch & Burkert (2022)

Gal. properties

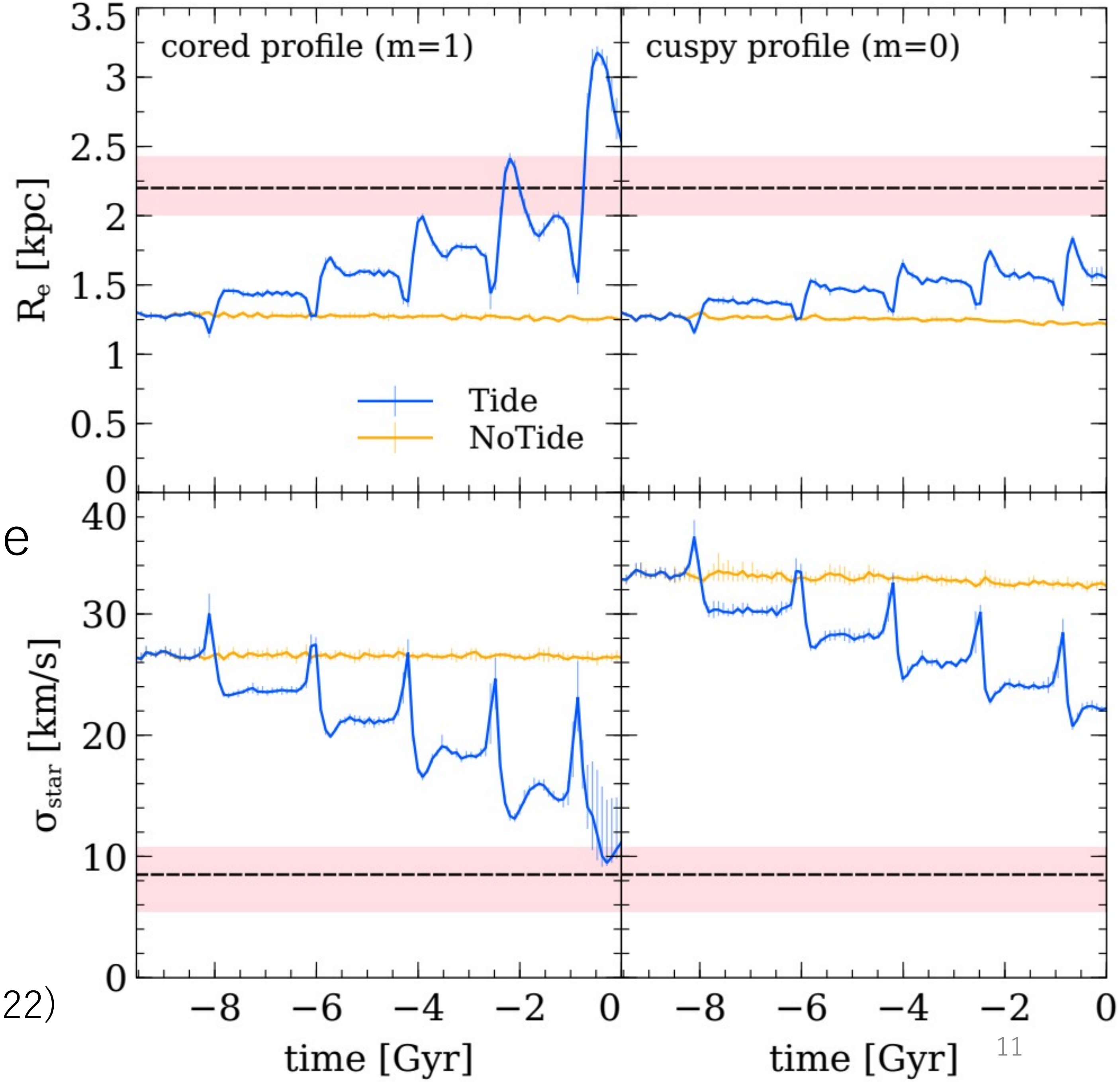
- Stellar vel dispersion increases at each pericentric passage
  - ✓Energy injection
- Decreases in a short time
  - ✓Re-virialization
  - ✓Galactic potential shallowed by tidal stripping
- Observations (pink) reasonably reproduced

GO, van den Bosch & Burkert (2022)



Gal. properties

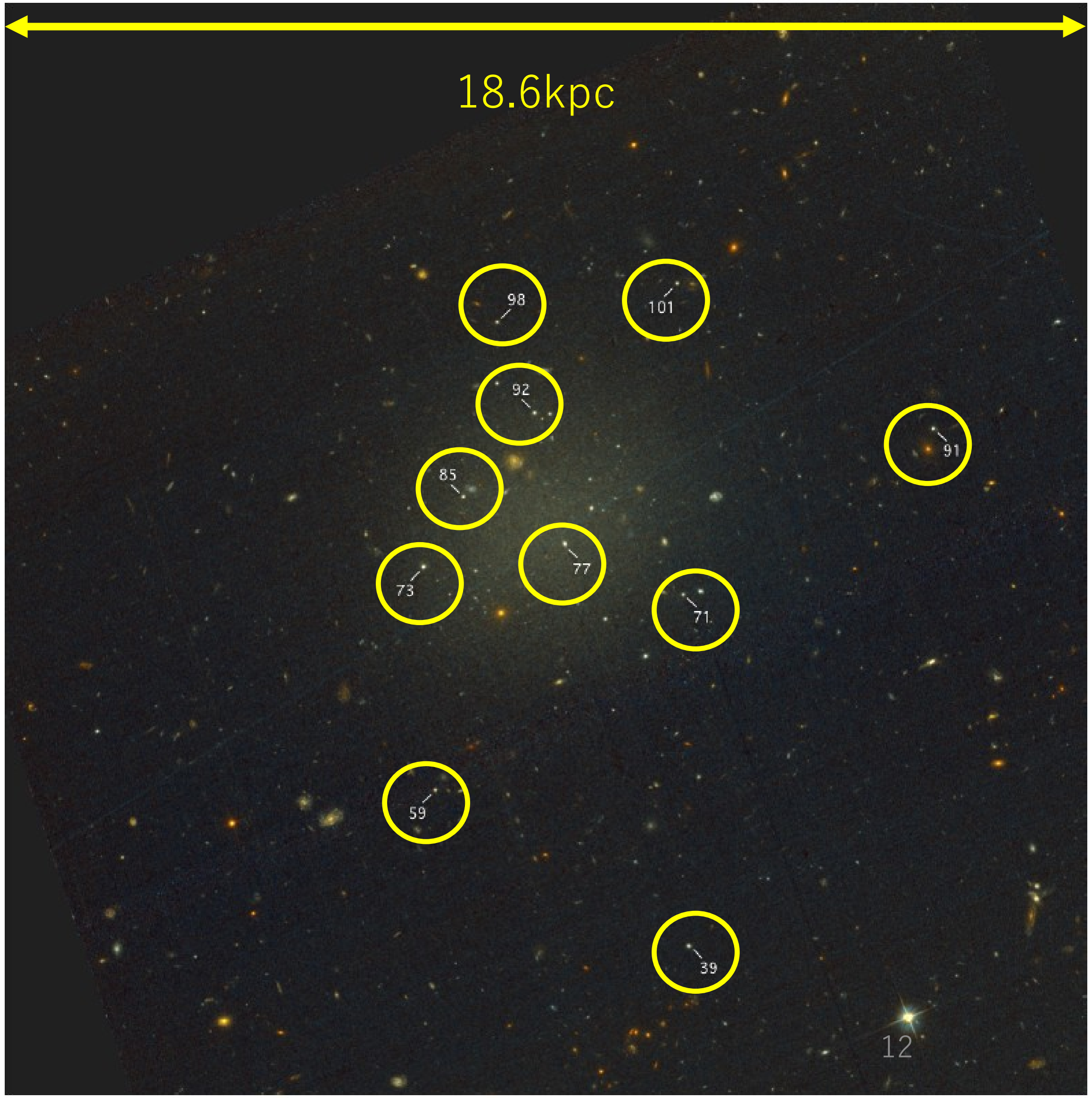
- Impacts less significant in cuspy counterpart
  - More resilient to tidal force
  - Adiabatic shielding
    - e.g. Spitzer (1987)



GO, van den Bosch & Burkert (2022)

Globular clusters in DF2

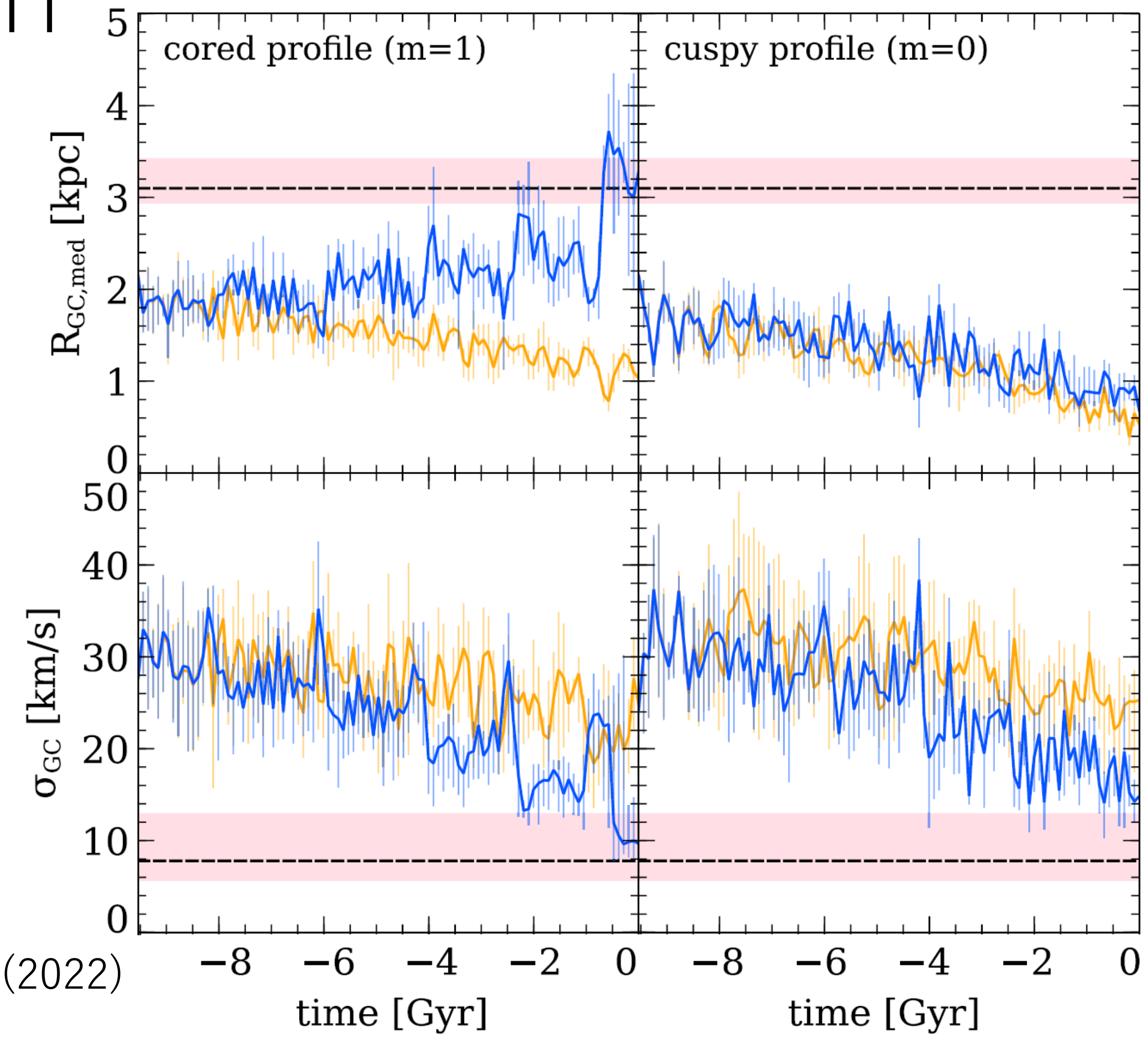
- 10 globular clusters (GCs)
  - Each has ~1e6Msun
  - Orbital decay due to dynamical friction
- Extended distribution
  - Rgc = 3.1kpc
  - cf. Re = 2.2kpc
  - Can the tidal scenario explain it?



GC orbital evolution

In the absence of tides (orange),

- GC orbit gradually decays due to dynamical friction
- σ gc decreases too

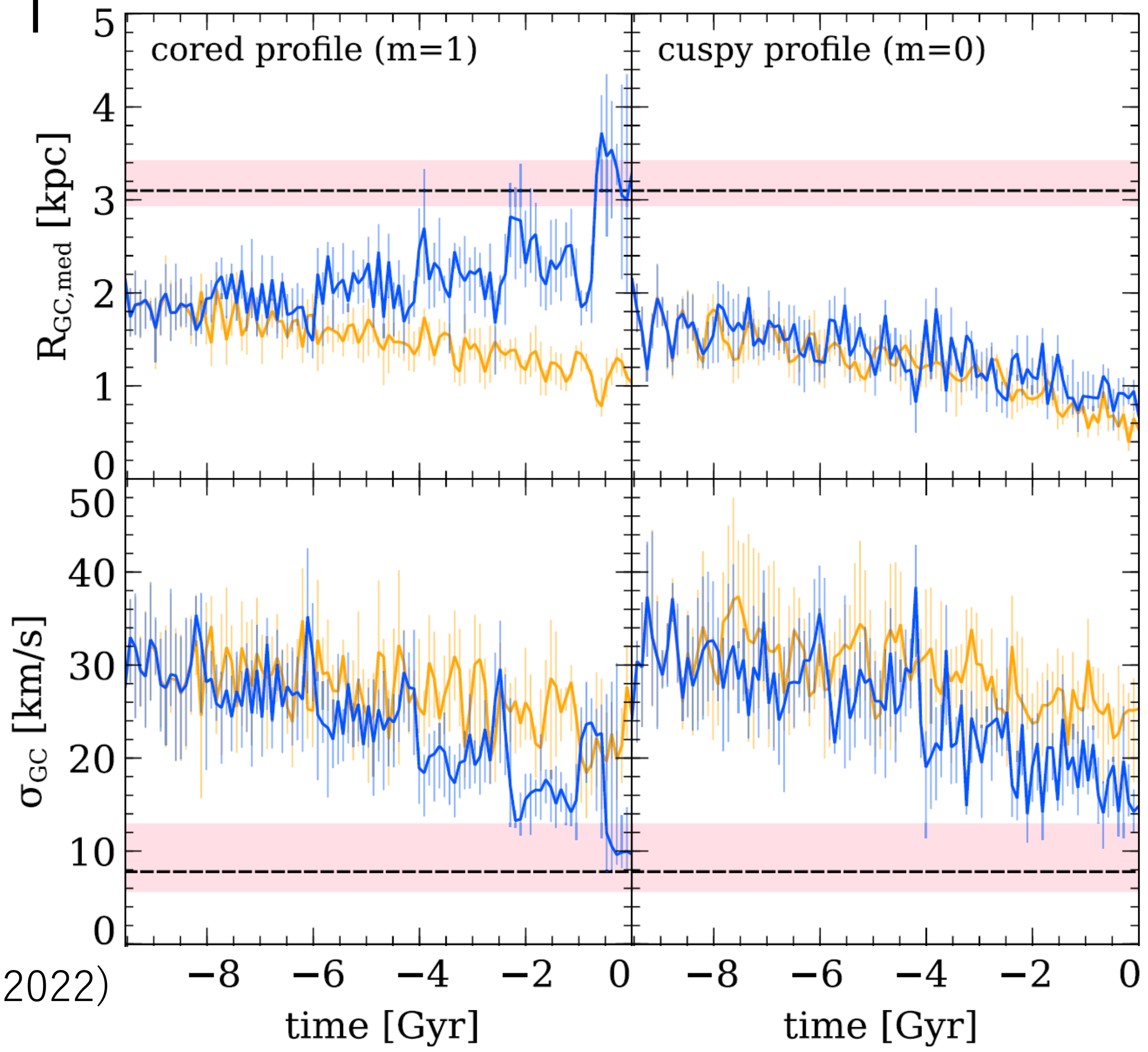


GO, van den Bosch & Burkert (2022)

GC orbital evolution

Considering tides (blue),

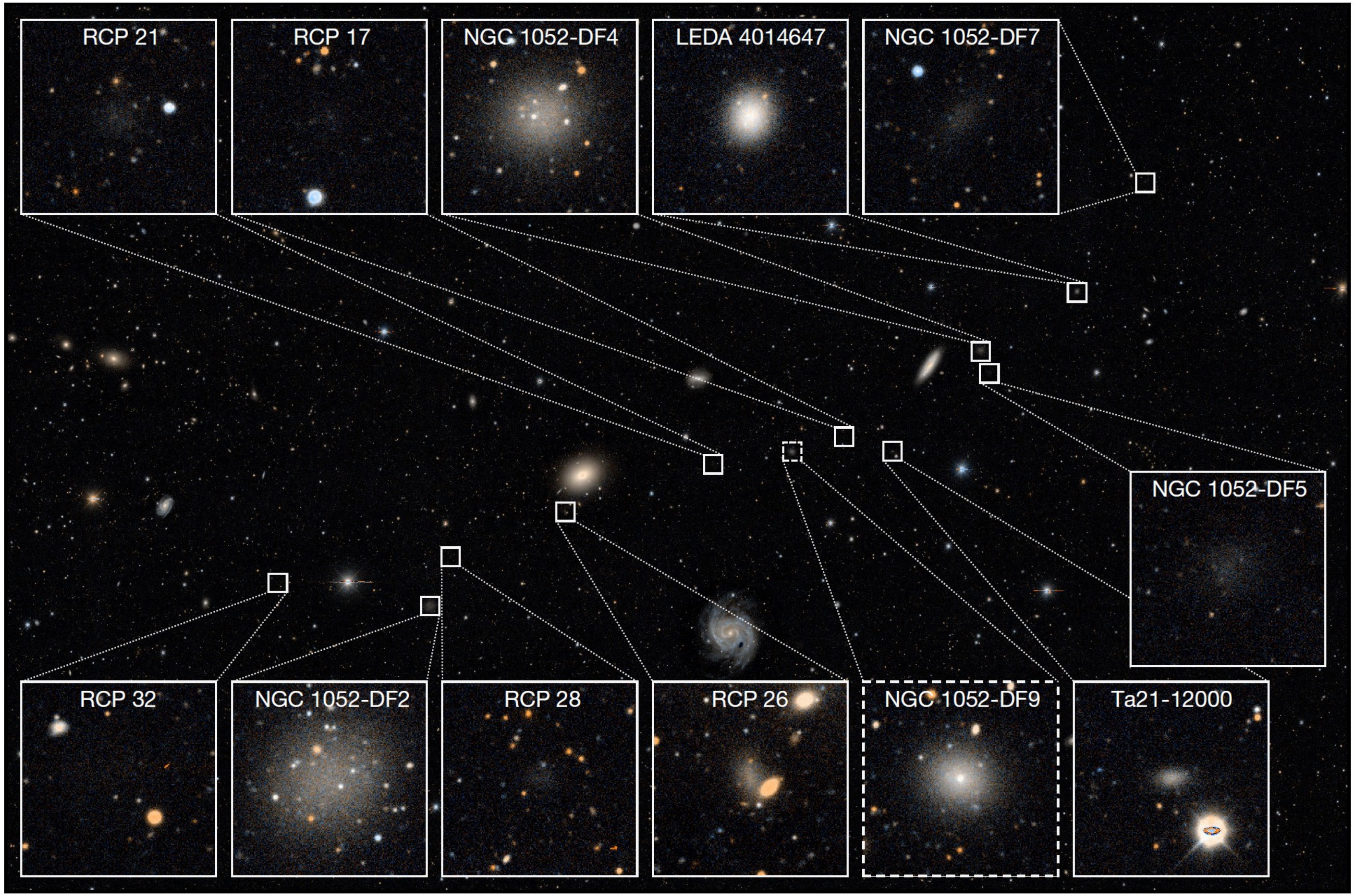
- Rgc behaves like Re
  - ✓Rapid increase at each pericenter
  - ✓Compete with orbital decay due to dynamical friction
- σ gc behaves like σ star
- Observations reproduced (pink) assuming the cored model



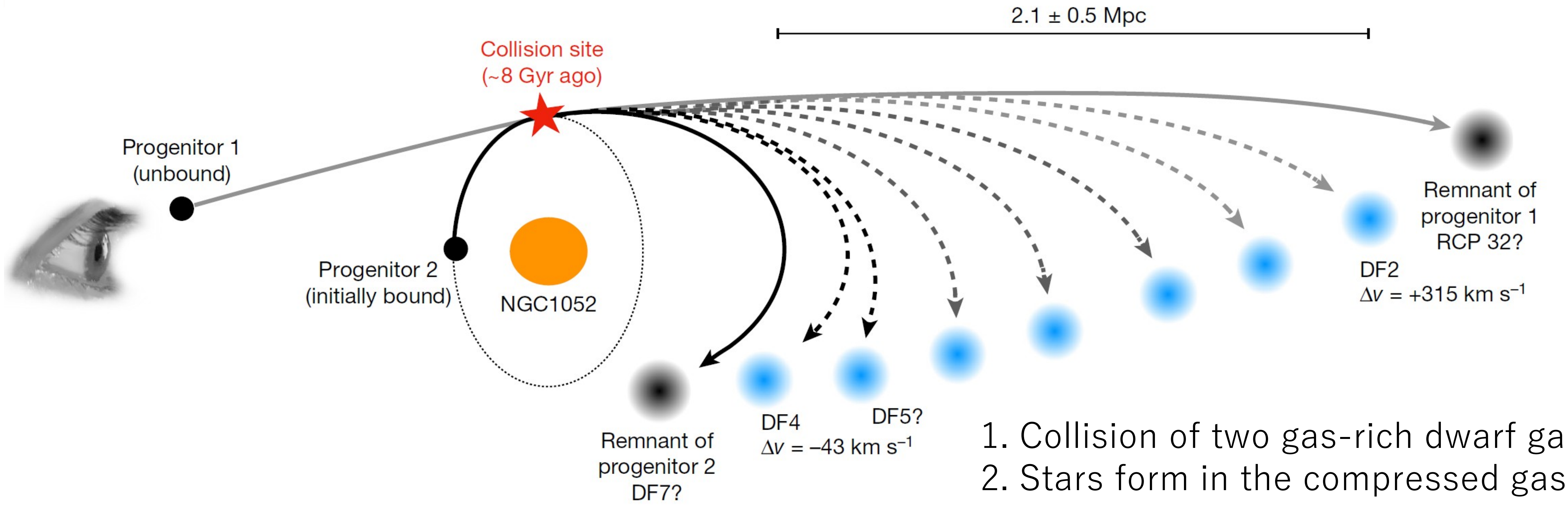
GO, van den Bosch & Burkert (2022)

Trail of diffuse galaxies?

van Dokkum et al. (2022a)



Galaxy collision formation scenario



van Dokkum et al. (2022a)

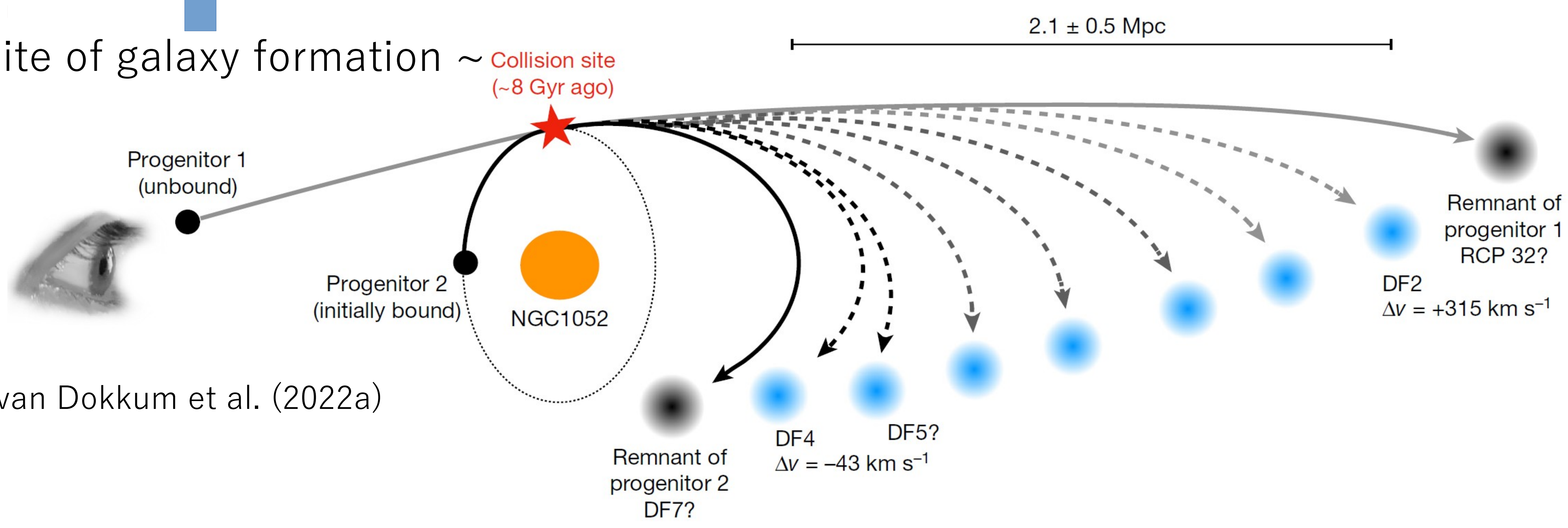
1. Collision of two gas-rich dwarf gals
2. Stars form in the compressed gas
3. DM and pre-existing stars pass through it

→ **Origin of DM deficient gals?**

Galaxy collision formation scenario

- GCs can be stripped from the formed DMDGs
- Distribution was more extended (dyn friction)

Site of galaxy formation ~



van Dokkum et al. (2022a)

Semi-analytic modeling of GC orbits

- Global potential of DF2 + Dynamical friction

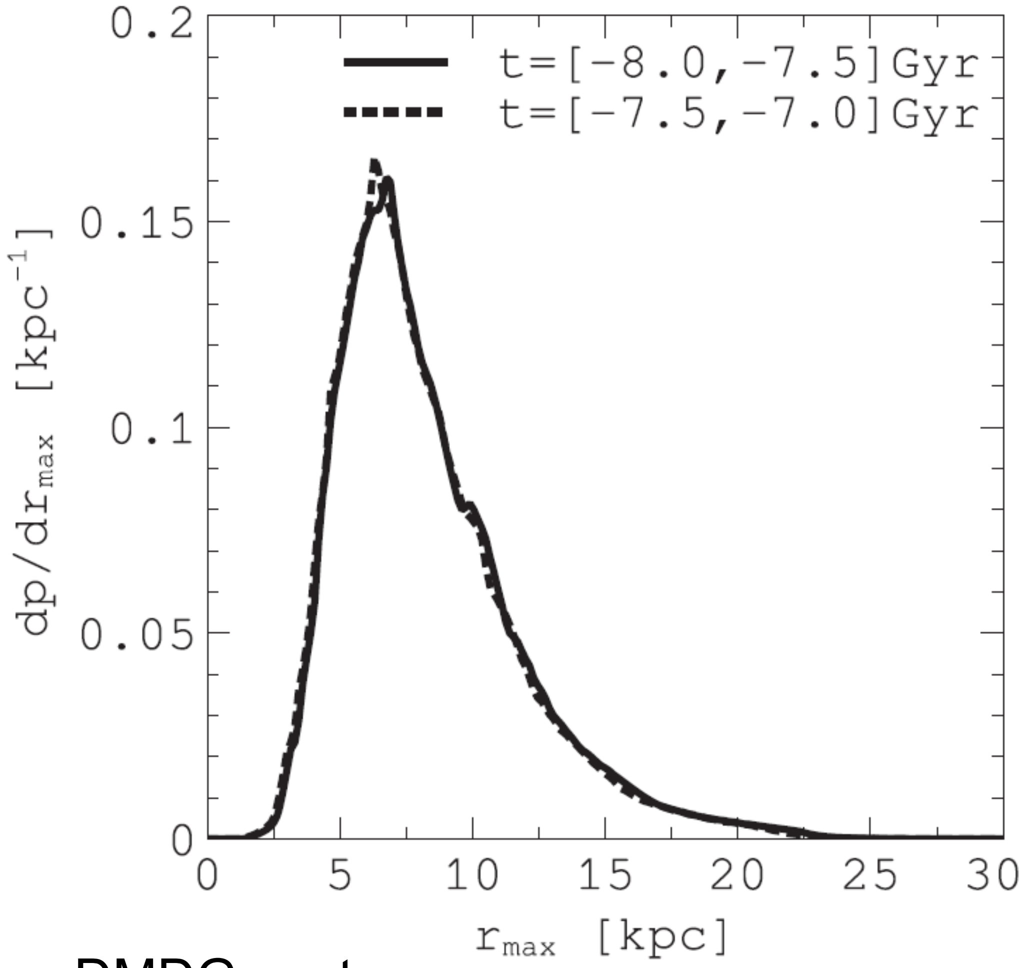
- “Final” condition of GCs
  -Observations → X, Y, Vz and M
  -Drawing → Z, Vx and Vy
  (Sersic profile + Gaussian distribution; Dutta Chowdhury et al. 2019)

- Trace back the orbital evolution from t=0 to t=-8Gyr

What was the GC distribution at formation?

- GCs are expected to form at collision (t~-8Gyr)
- Maximum radius of GCs in two time-windows
- rmax = 5-10kpc
- cf. observed Rgc = 3.1kpc

GO, van den Bosch, Burkert & Kang (2022)

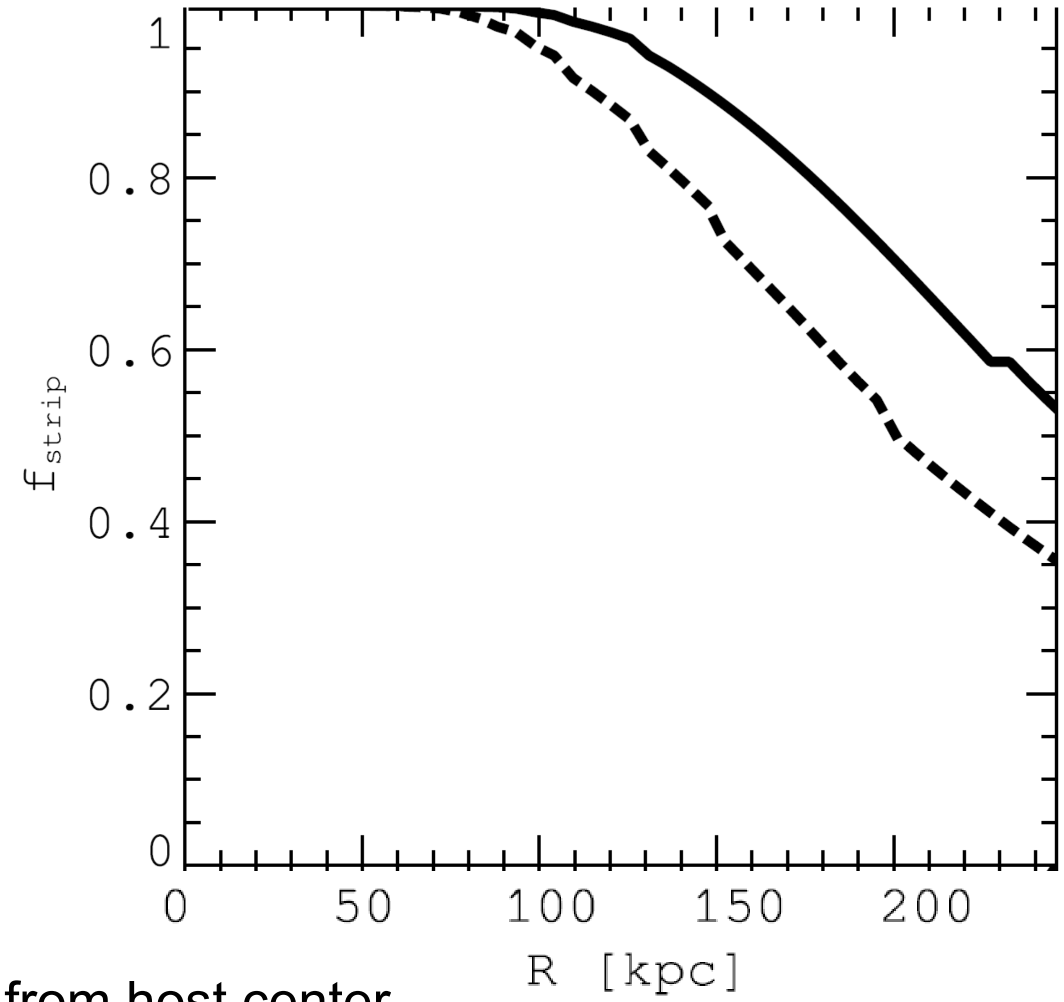


Distance from DMDG center

How many GCs were stripped?

- Combine the rmax distribution and analytic model of tidal radius
  - e.g., at R < 120kpc, more than 80% of GCs will be stripped
- N of GCs = Challenge
  - Difficult to make tens of massive GCs (Lee et al. 2021)

GO, van den Bosch, Burkert & Kang (2022)



Distance from host center

Summary

- Discovery of dark matter deficient galaxies

- Tidal massloss scenario reproduces observations of DF2
  - Extremely low DM mass
  - Distribution and velocity dispersion of stars and GCs

- N of GCs to form is a challenge for the galaxy collision scenario

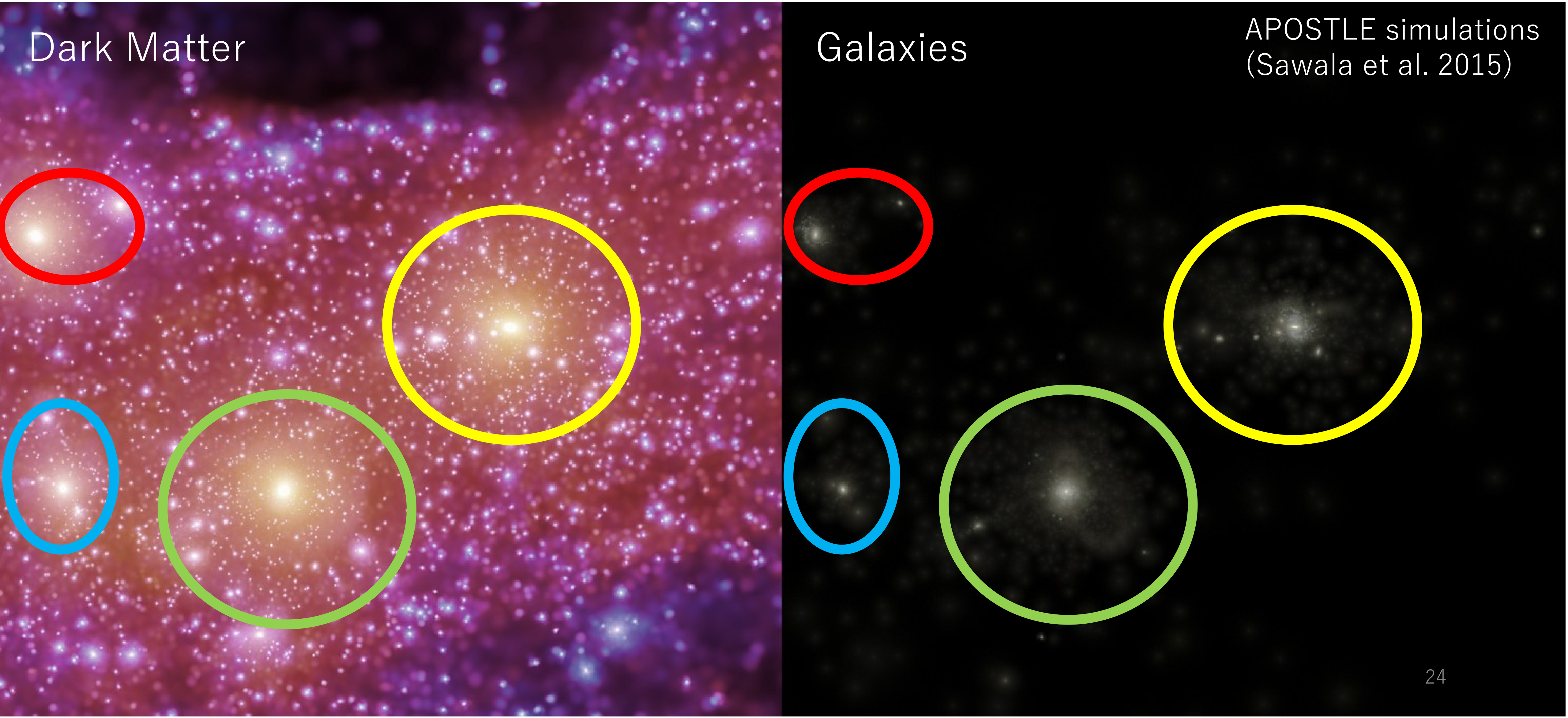
  - GC distribution was more extended than observed

  → Making them susceptible to the tidal force

谢谢!
Questions?

Appendix

Galaxies live in dark matter halos



NGC1052-DF2 (DF2)

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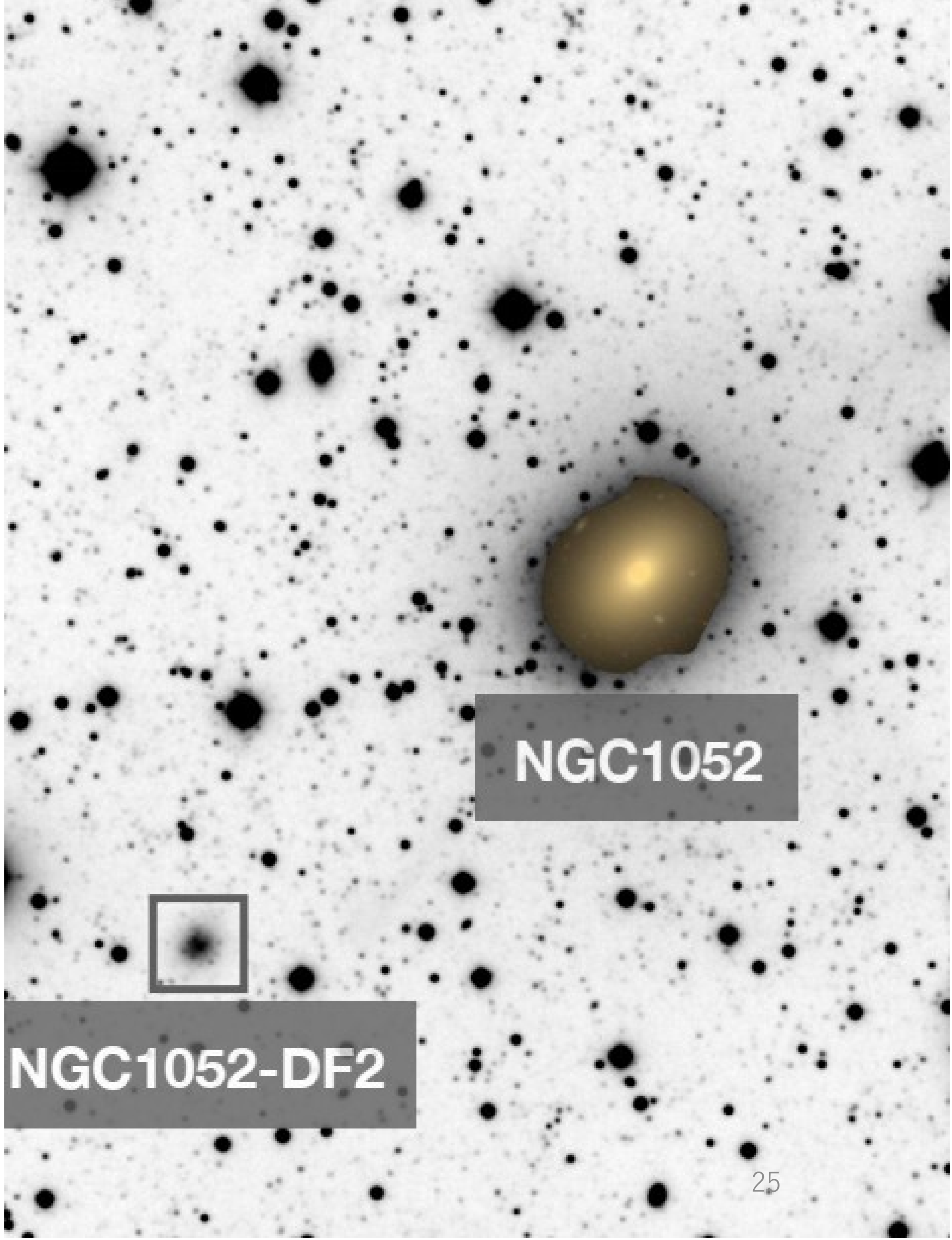

Shen et al. (2021)

NGC1052-DF2 (DF2)

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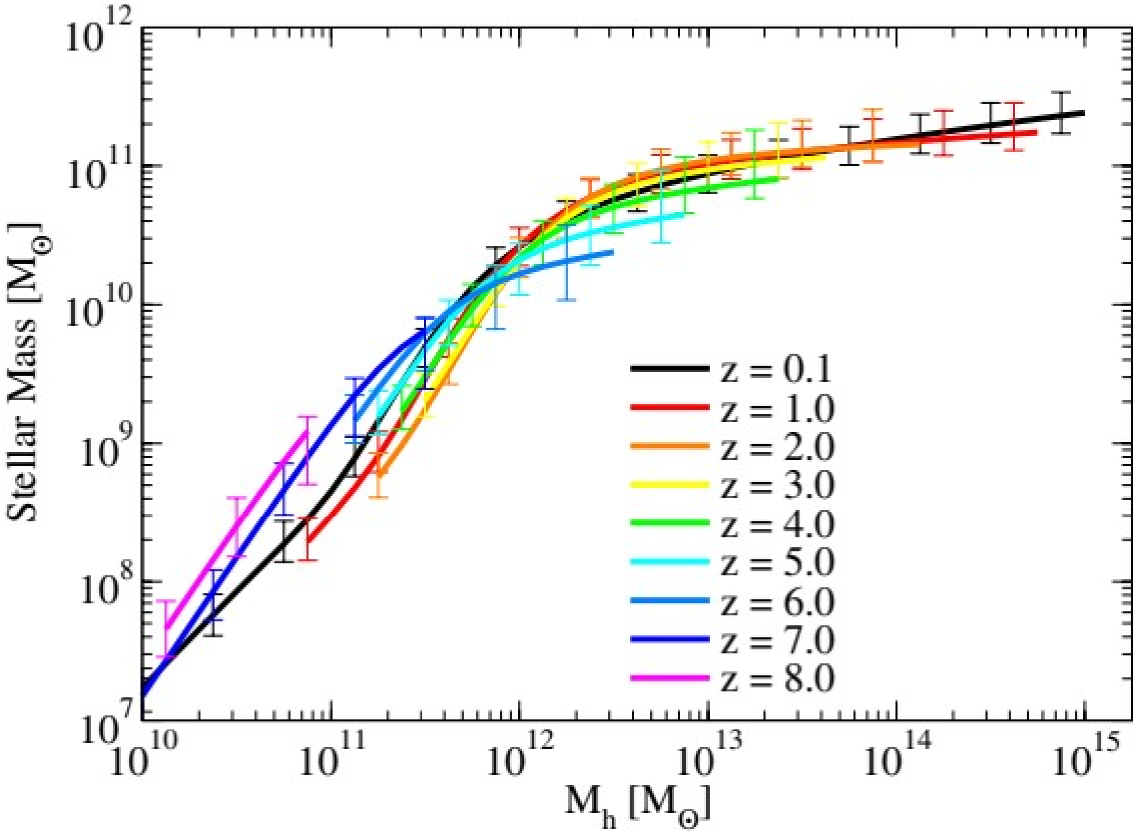
- Galaxy formation and evolution models expect Mhalo ~ 5e10Msun

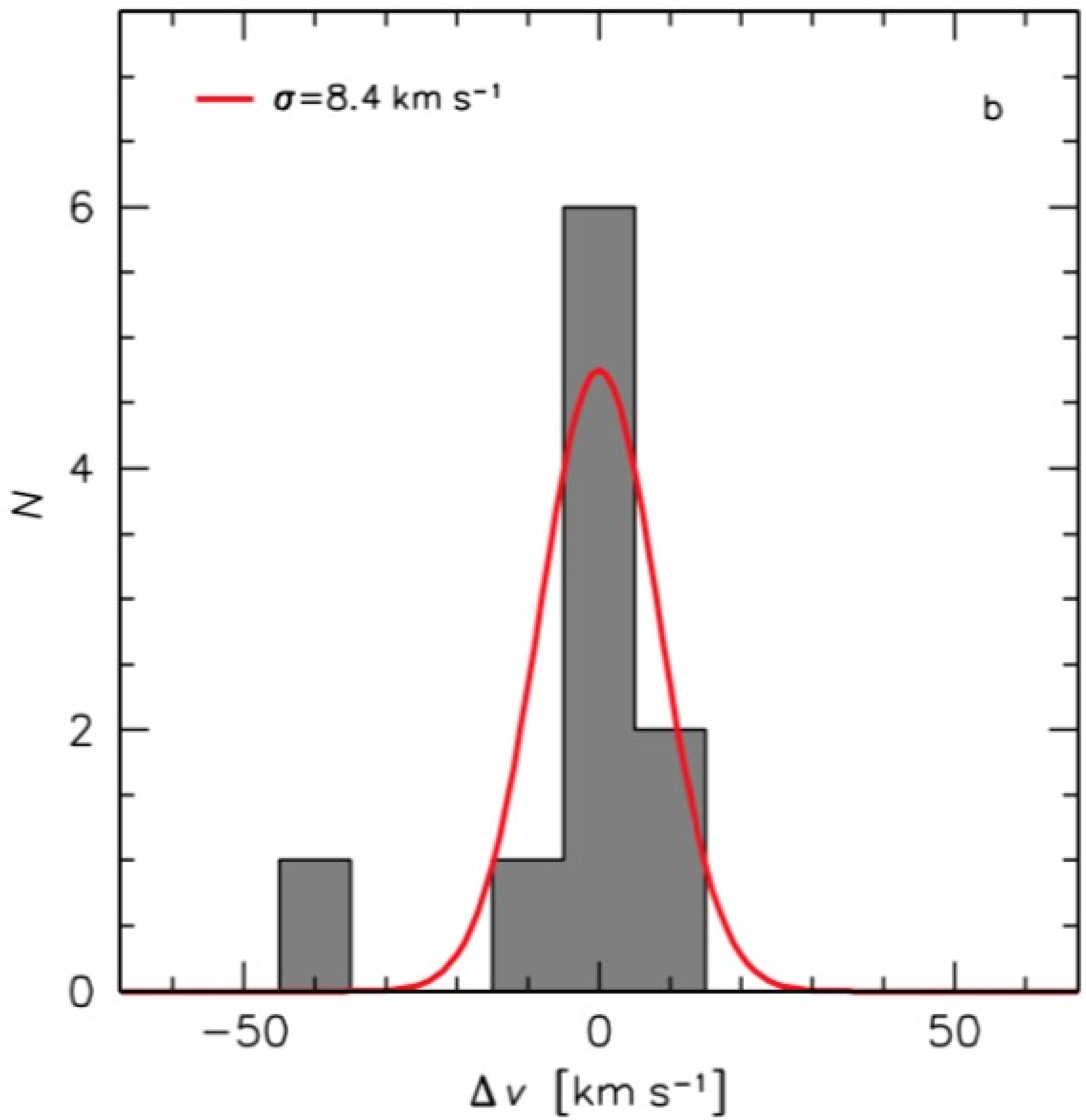


Behroozi et al. (2013)

NGC1052-DF2 (DF2)

- van Dokkum et al. (2018) inferred the dynamical mass of DF2
  - 10 globular clusters = kinetic tracers

$$\sigma^2 \sim \frac{GM}{r}$$



Active debate on DF2

Q. Low confidence due to small N of kinetic tracers?

-Martin et al. (2018); Laporte et al. (2018)

A. Dynamical mass inference with diffuse stellar lights and planetary nebulae agree with van Dokkum+

-Danieli et al. (2019); Emsellem et al. (2019)

Active debate on DF2

Q. Bias due to data processing schemes?

-Hayashi & Inoue (2018)

A. More sophisticated Jeans analysis agrees with van Dokkum+

-Wasserman et al. (2019)

Active debate on DF2

Q. Shorter distance to DF2 (13Mpc) -> DF2 is a normal galaxy?

-Trujillo et al. (2019)

-cf. van Dokkum+ supposed 20Mpc

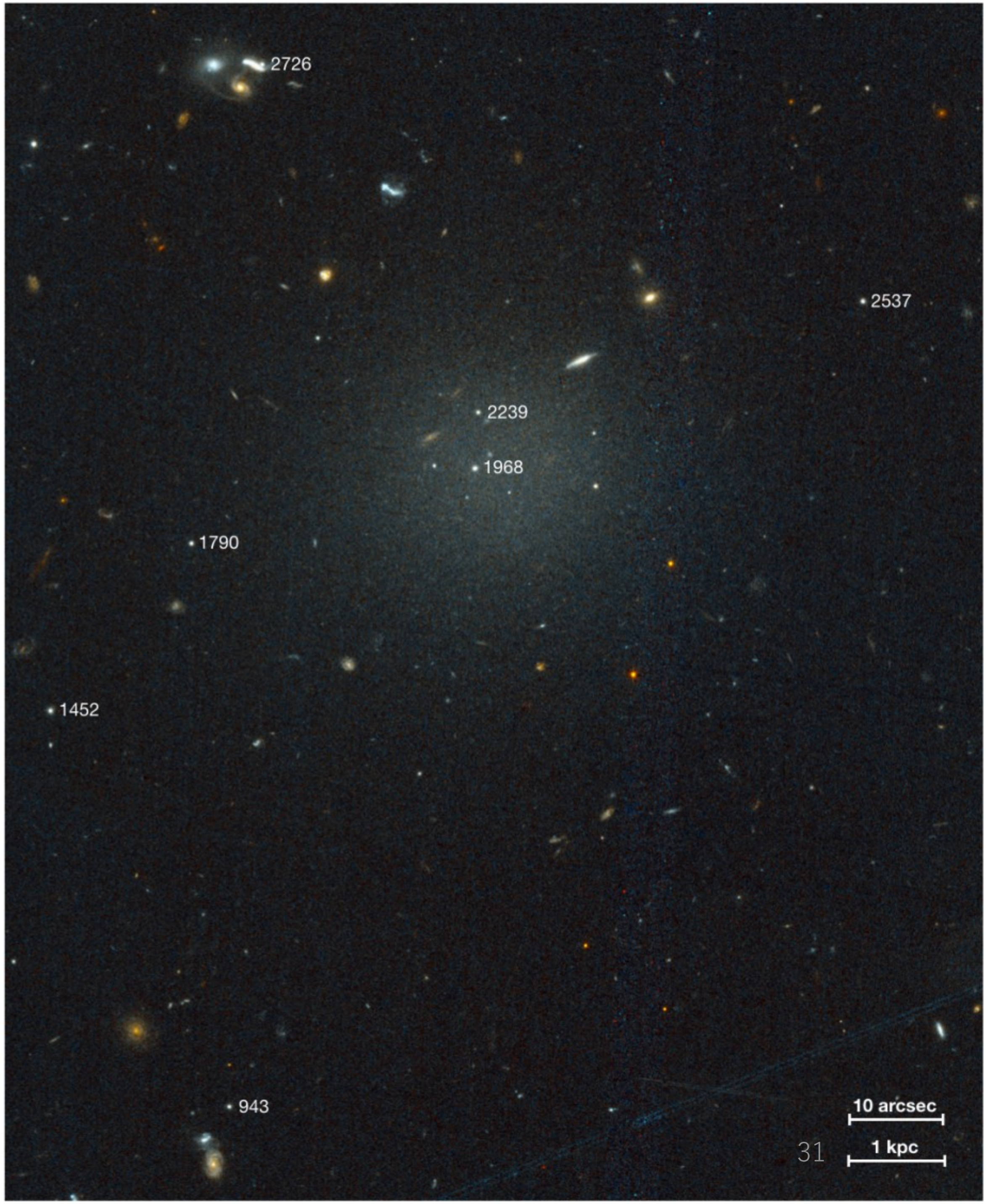
A. D = 22Mpc based on deeper observation data, making DF2 more abnormal

-Shen et al. (2021)

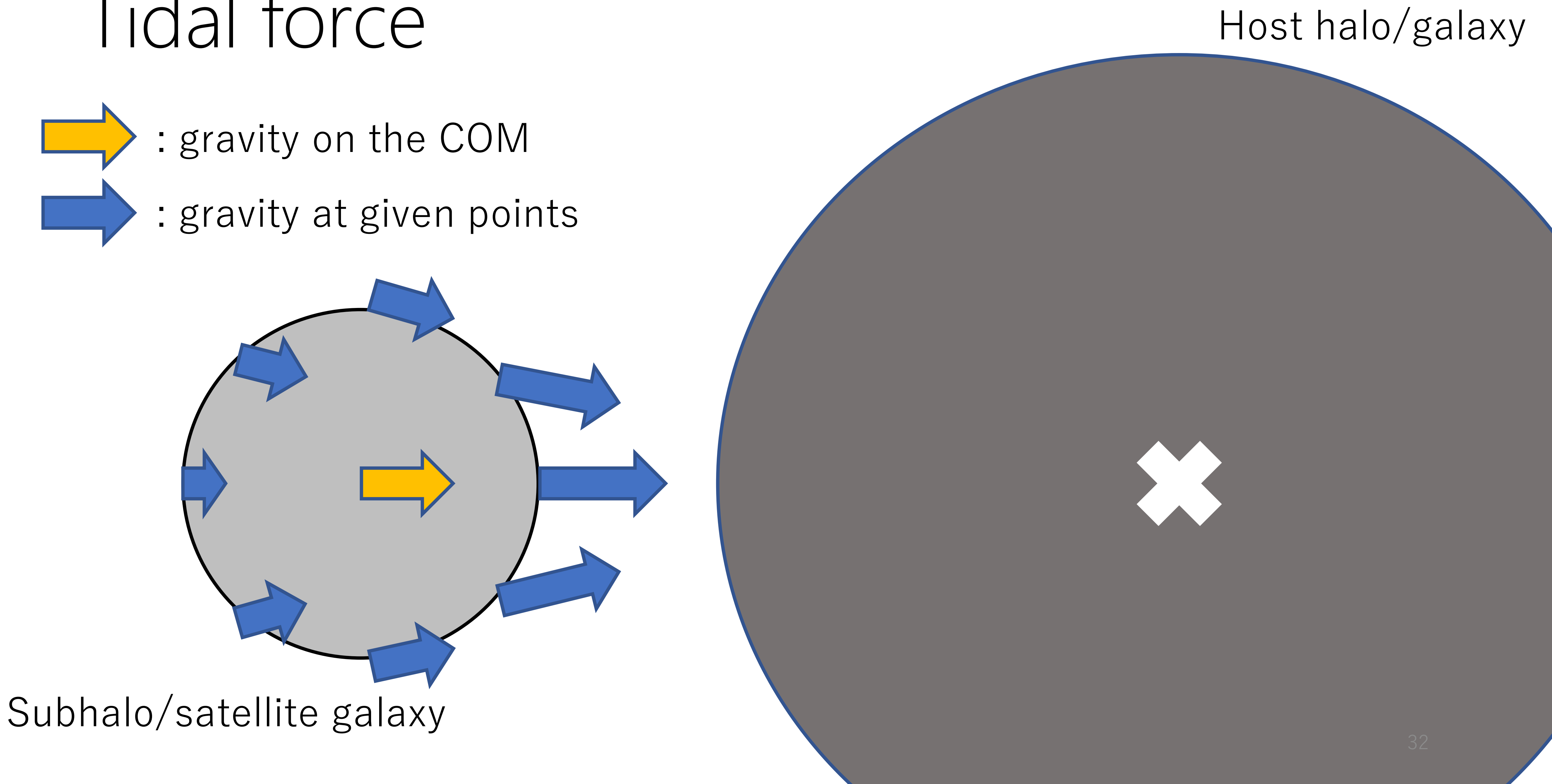
NGC1052-DF4

- Second DM deficient galaxy
- Resembles to DF2
  - Stellar mass
  - DM mass
  - Size
  - Globular clusters

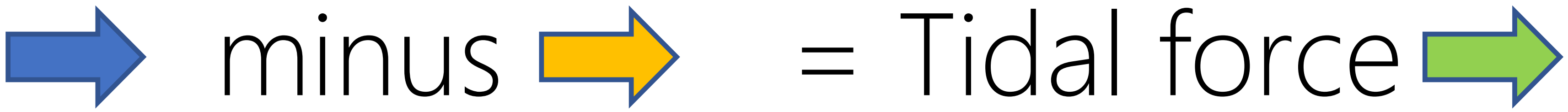
van Dokkum et al. (2019)

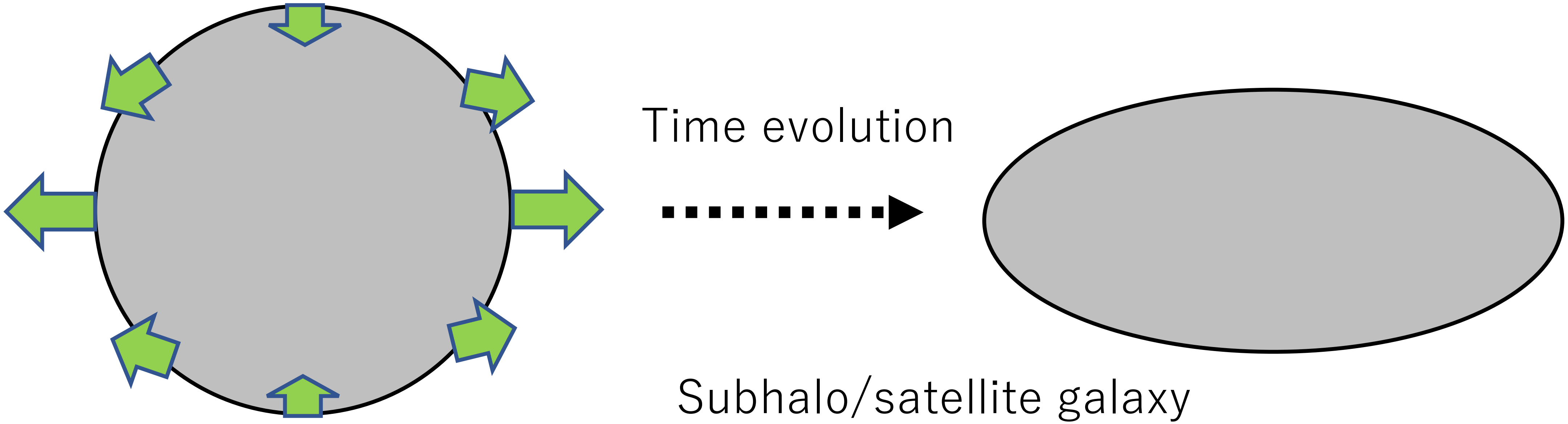


Tidal force



: gravity on the COM
: gravity at given points
Host halo/galaxy
Subhalo/satellite galaxy





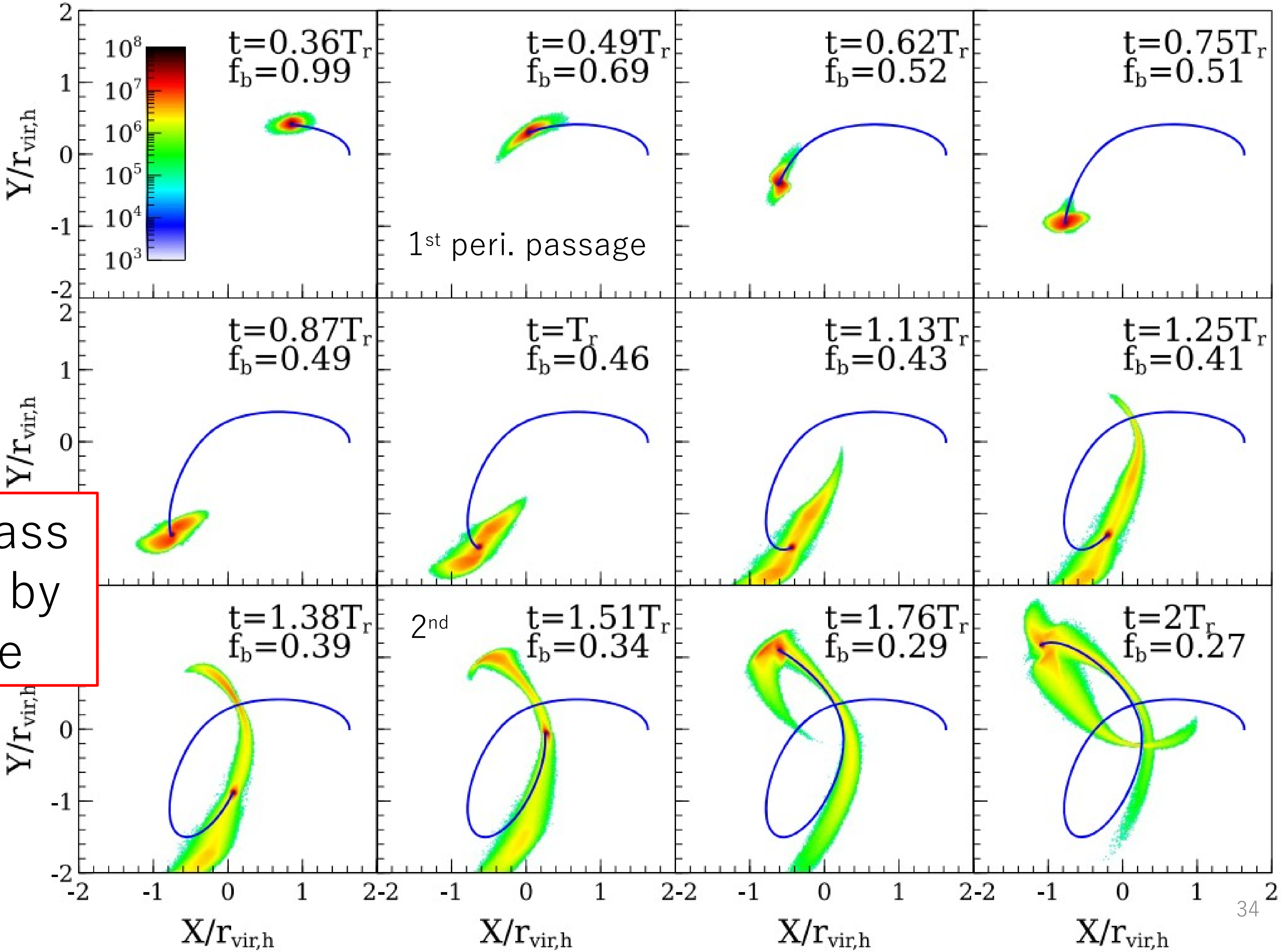
Subhalo/satellite galaxy

- is deformed
- is dynamically heated up
- loses its mass (tidal stripping)

GO et al. (2019)

fb = M/Mi

Subhalo mass is reduced by tidal force

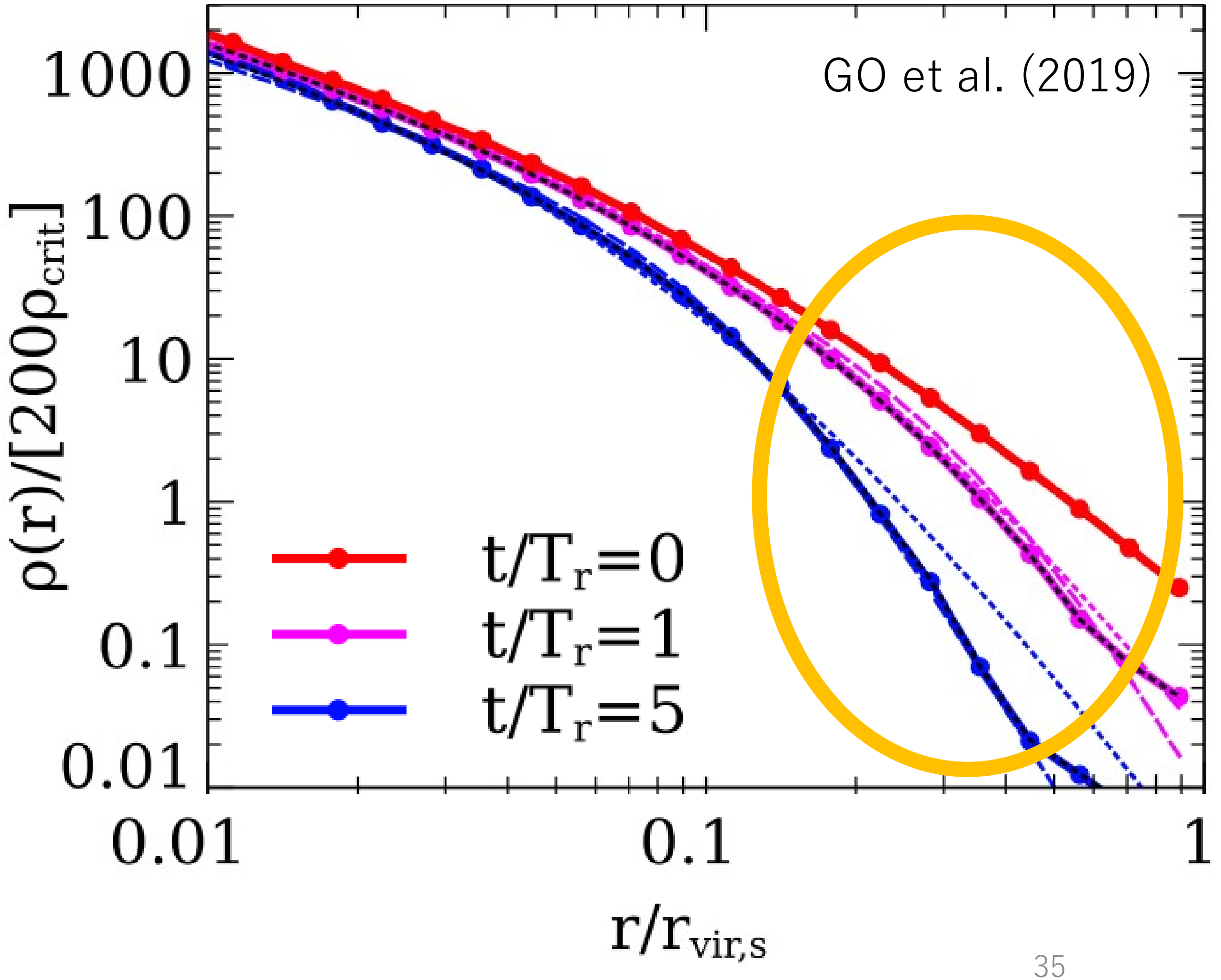


Tidal interaction of DF2 vs NGC1052

- Halo outskirt is sensitive to tidal force
- A large fraction of DM mass is in the halo outskirt

↓

Small DM mass?



Tidal interaction of DF2 vs NGC1052

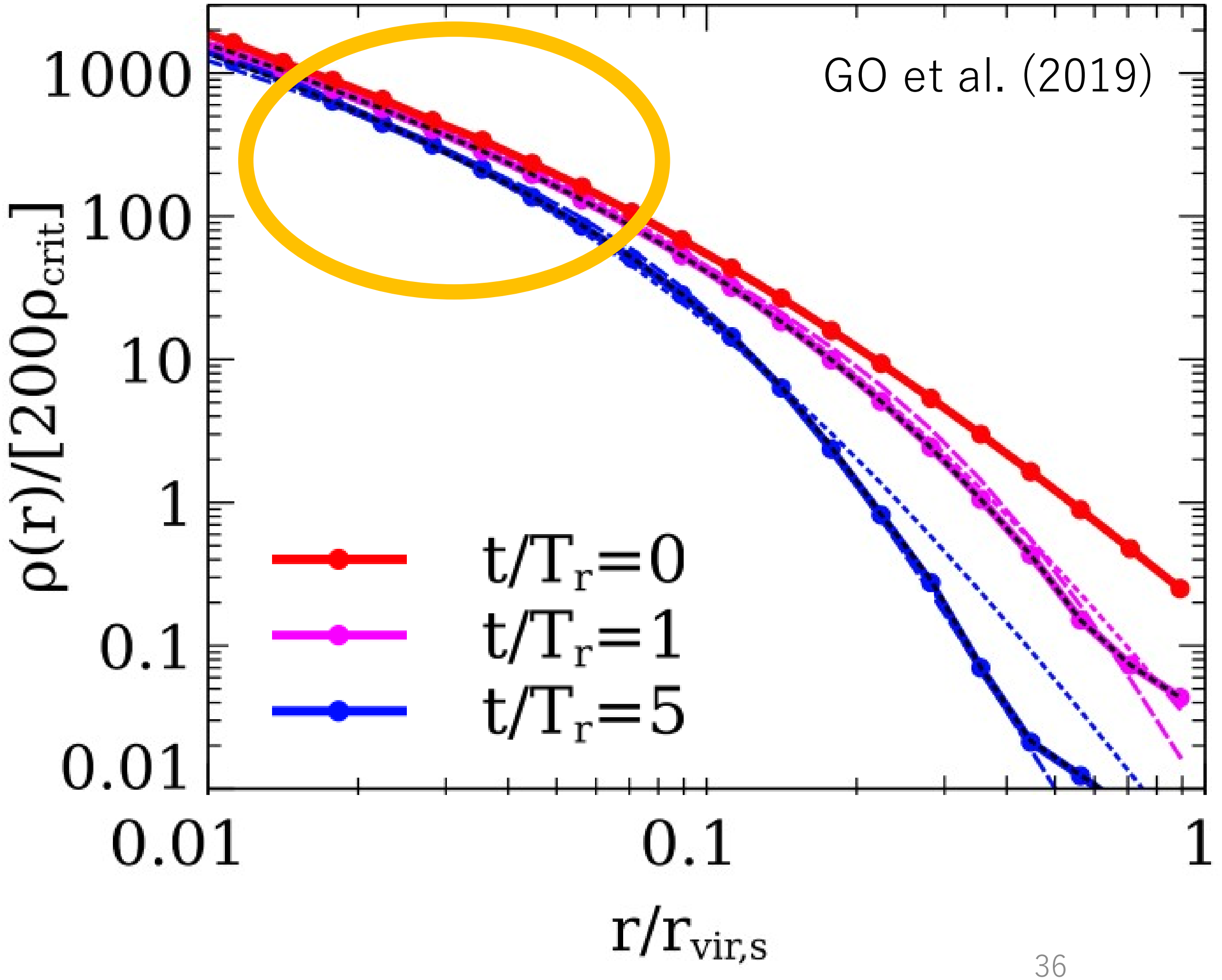
- Stars are in the halo center
- More resilient to tidal force

- Shallowing the galaxy potential
- Injection of kinetic energy by impulsive tidal shock

Puffing-up of stellar component

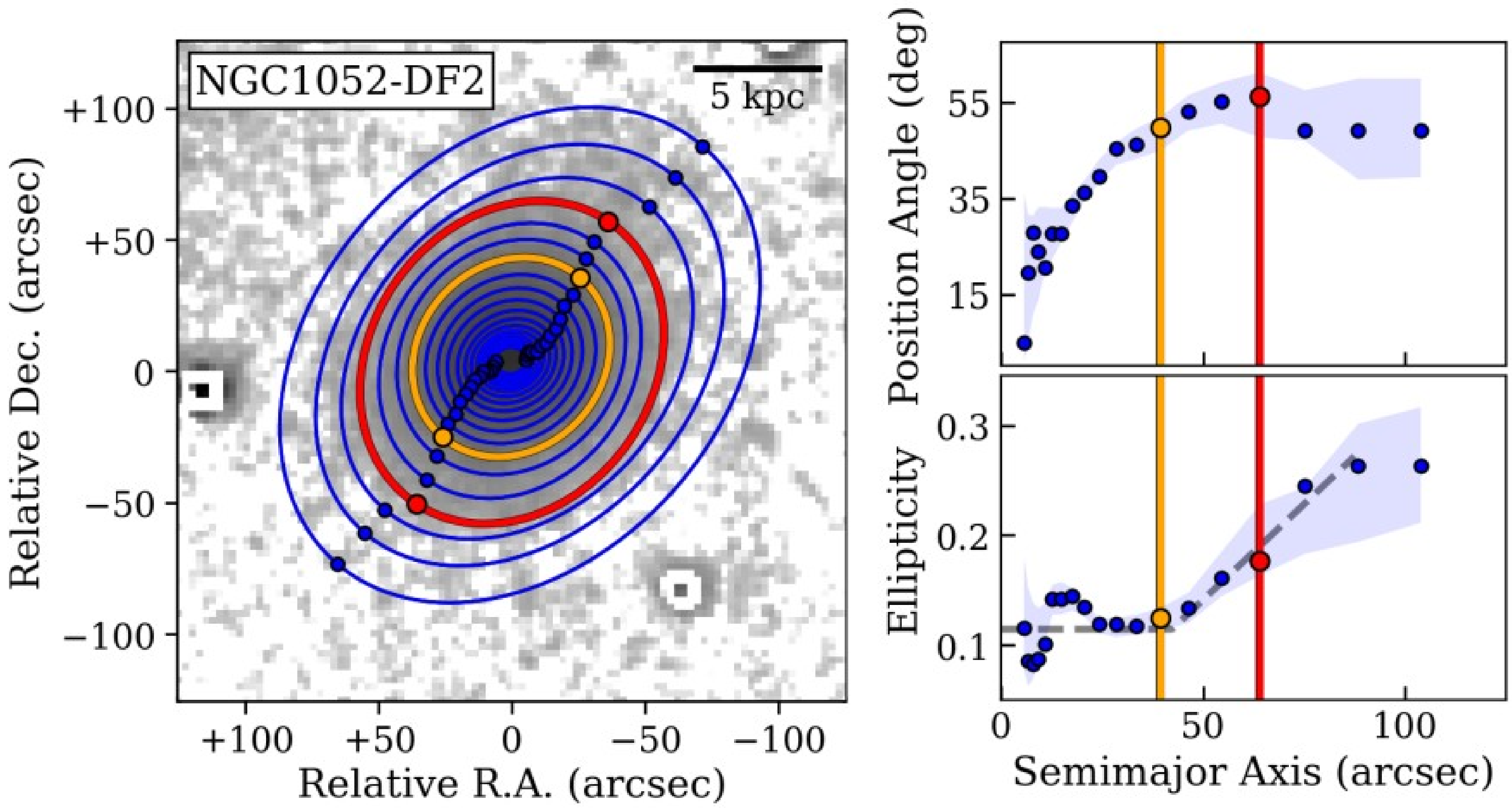
↓

Diffuse stellar component?

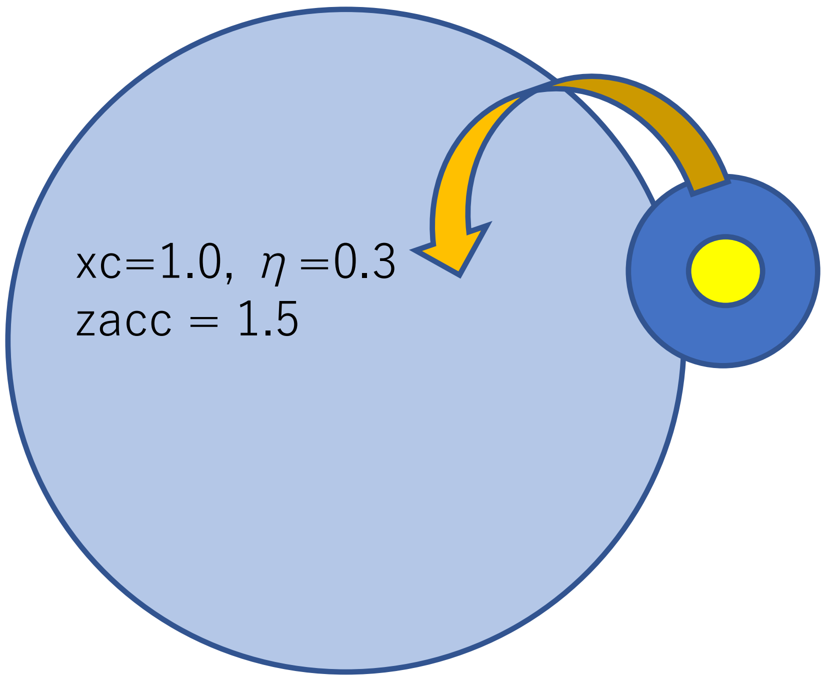


Tidally deformed DF2

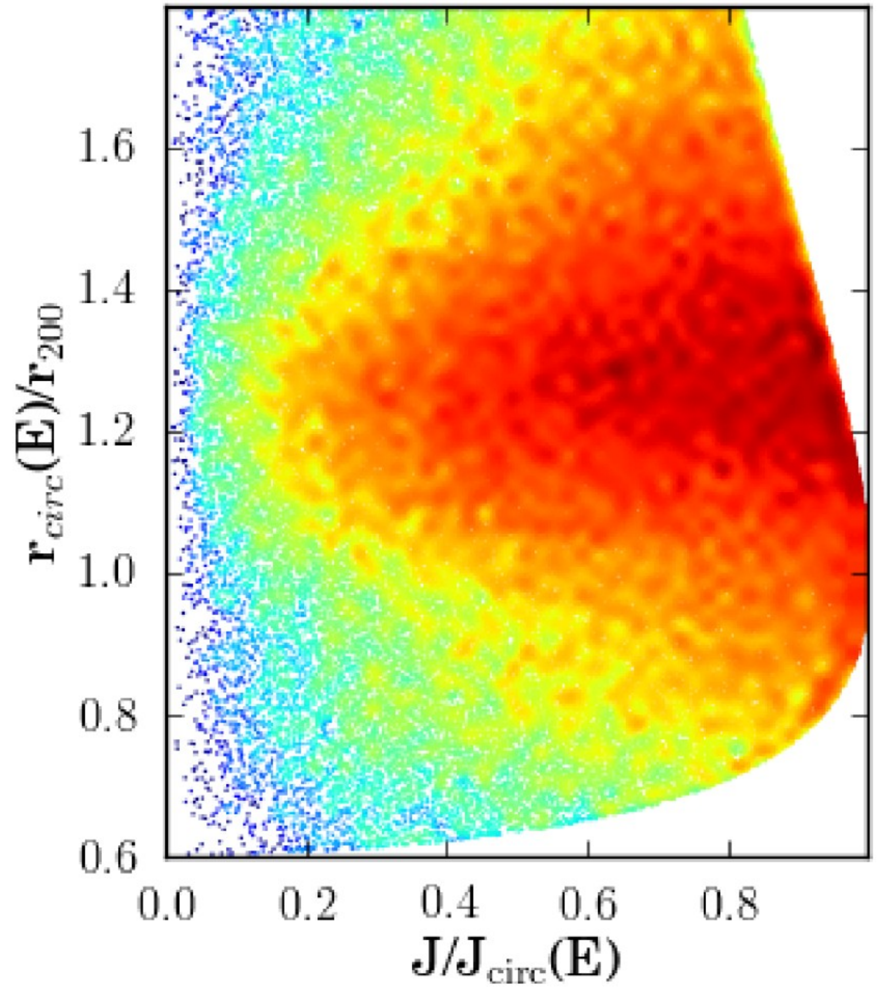
Keim et al. (2022)
See also Montes et al. (2020)



Simulation setup



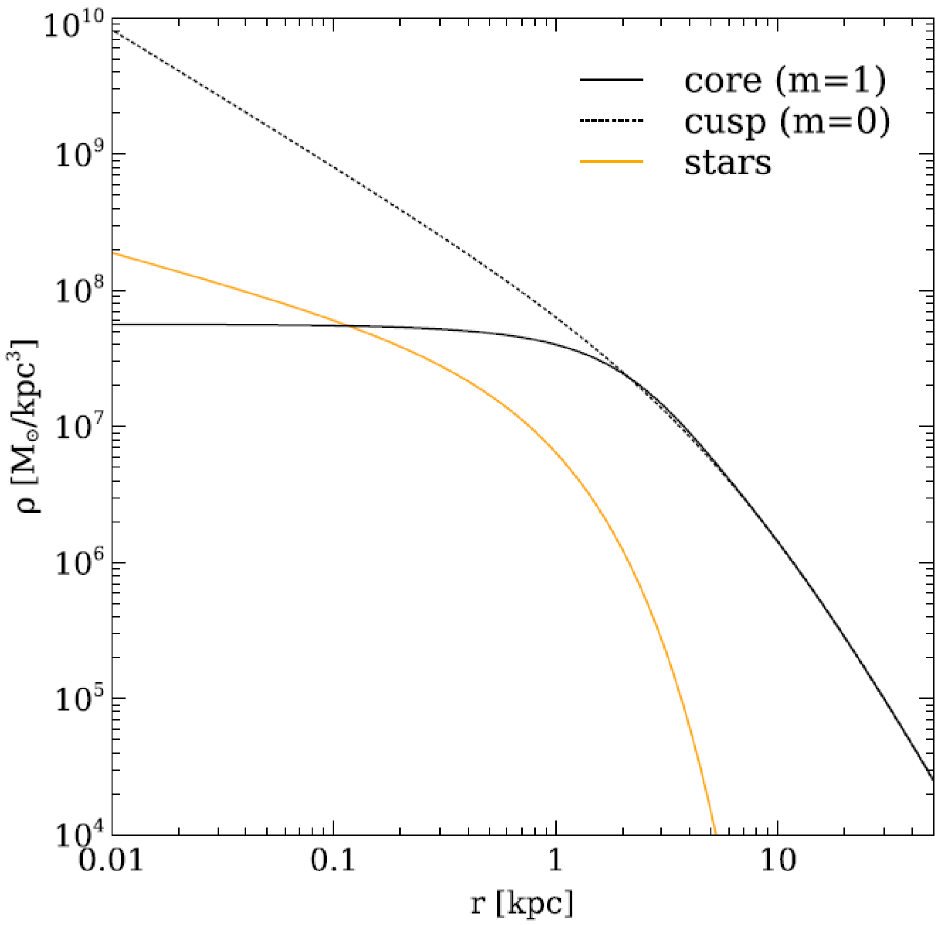
Jiang et al. (2015)
See also Li et al. (2021)



NGC1052 = time-varying NFW potential

- ✓ Mass growth (Correa et al. 2015)
- ✓ c(M,z) relation (Ludlow et al. 2016)

Satellite = *N*-body



- Stars -> Deprojected Sersic profile

(Prugniel & Simien 1997)

  - ✓ Re=1.25kpc (van der Wel et al. 2014)
  - ✓ n=1
  - ✓ M=2e8Msun

- DM halo -> Transformed NFW profile

(Read et al. 2016)

  - ✓ M=6e10Msun
  - ✓ c=6.6
  - ✓ core or cusp

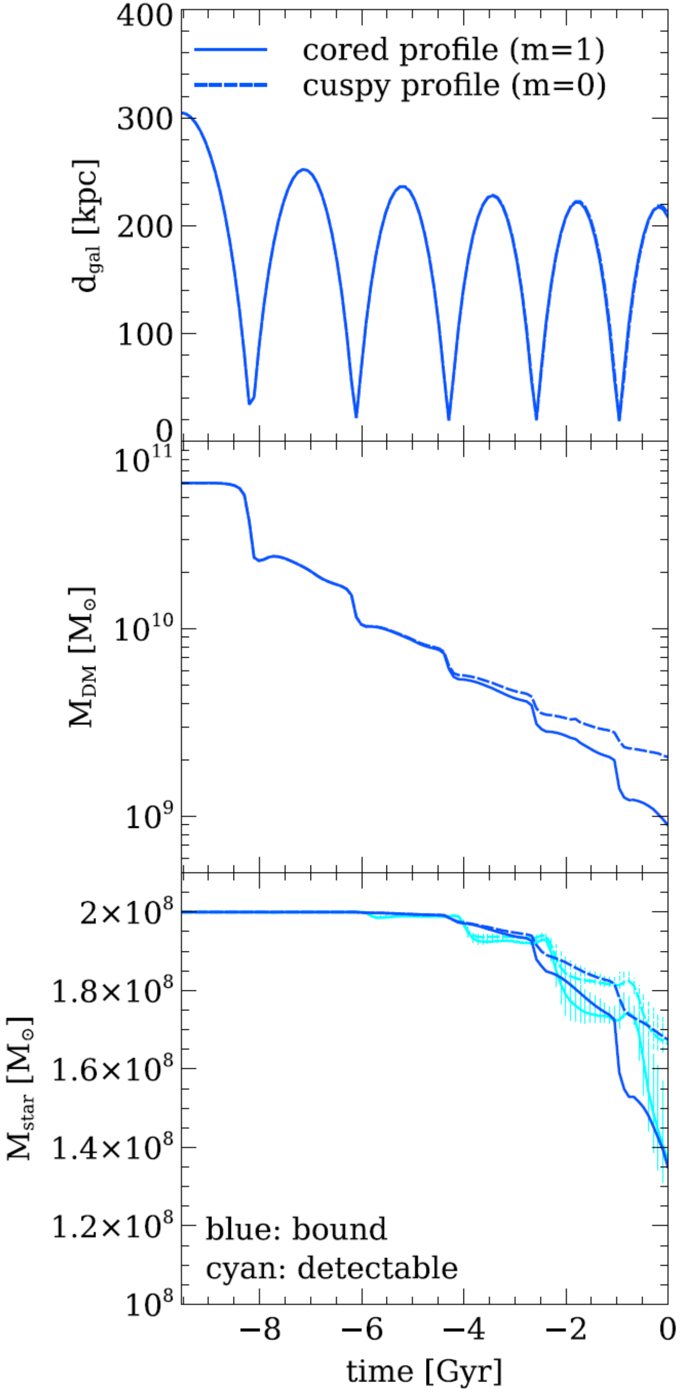
- Numerical params
  - ✓ N = 15Mio -> mp = 4e3Msun
  - ✓ Softening = 14pc
  - ✓ Results numerically converged

Orbit and mass evolution

- Satellite orbit shrinks due to
  - ✓ Growth of the host
  - ✓ Self-friction

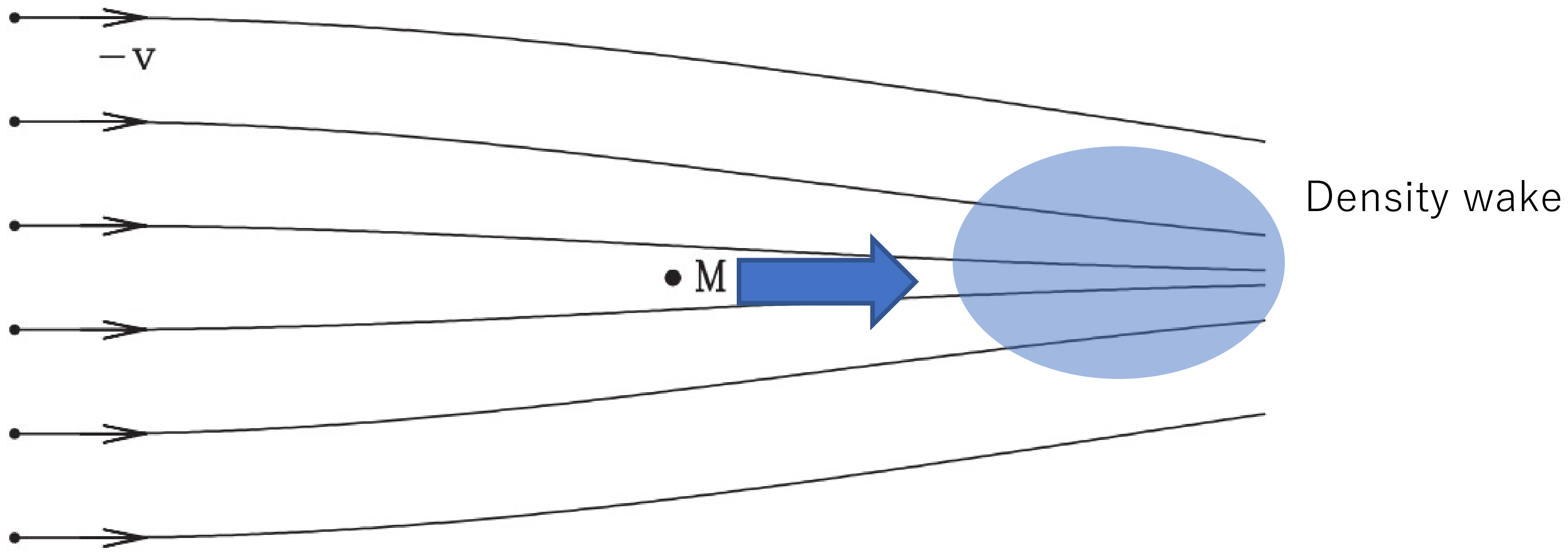
- Massloss at each pericentric passage
  - ✓DM mass is reduced by a factor of ~70
  - ✓Reduction of the stellar mass is 30%
  - ✓Stronger impacts in the cored model

GO, van den Bosch & Burkert (2022)



Dynamical friction

- Deceleration force due to the density wake

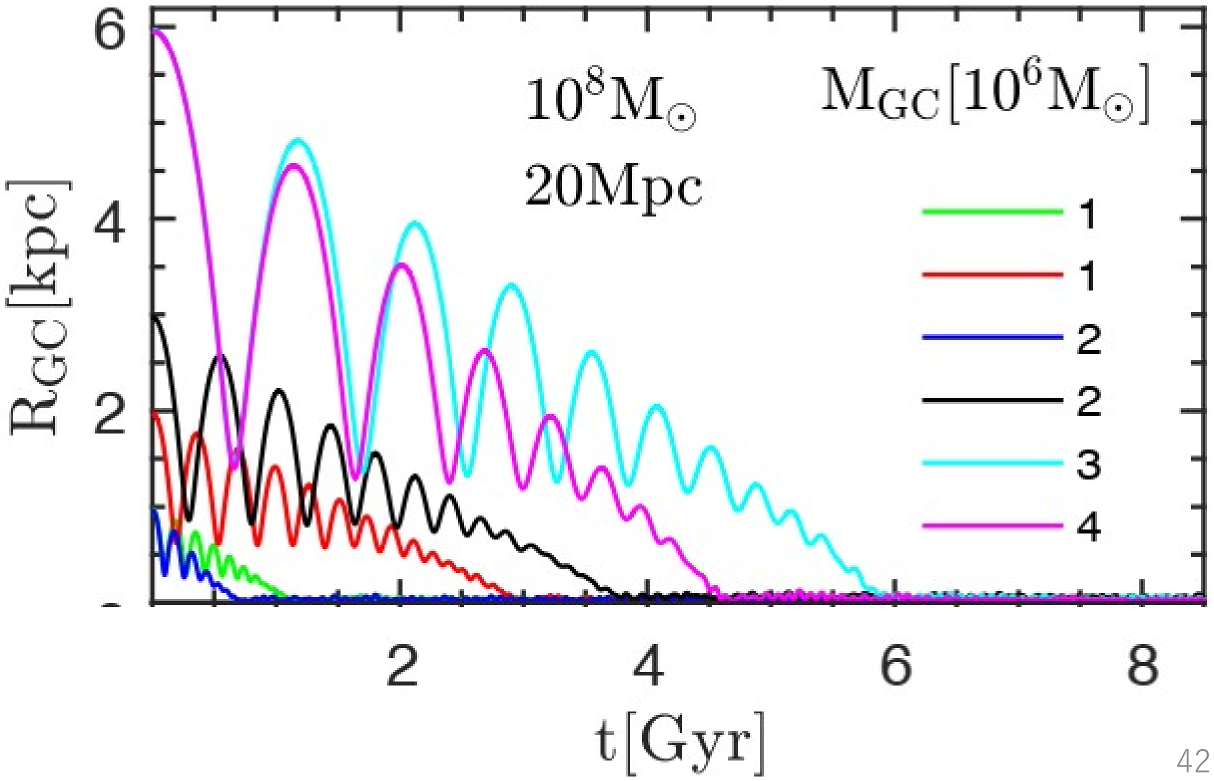


Chandrasekhar (1943)

Orbital decay due to dynamical friction

- Nusser (2018)
  - Mdyn ~ 1e8Msun, single GC -> sinking within a few Gyr

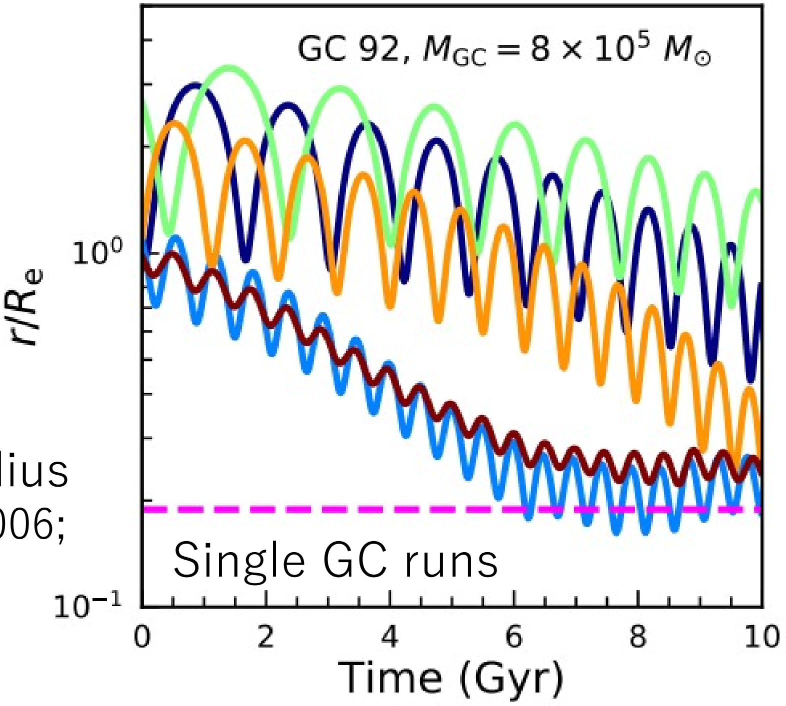
$$t_{\rm DF} = \frac{1.17}{\ln \Lambda} \frac{M_{\rm gal}(r)}{M_{GC}} t_{\rm cross}$$

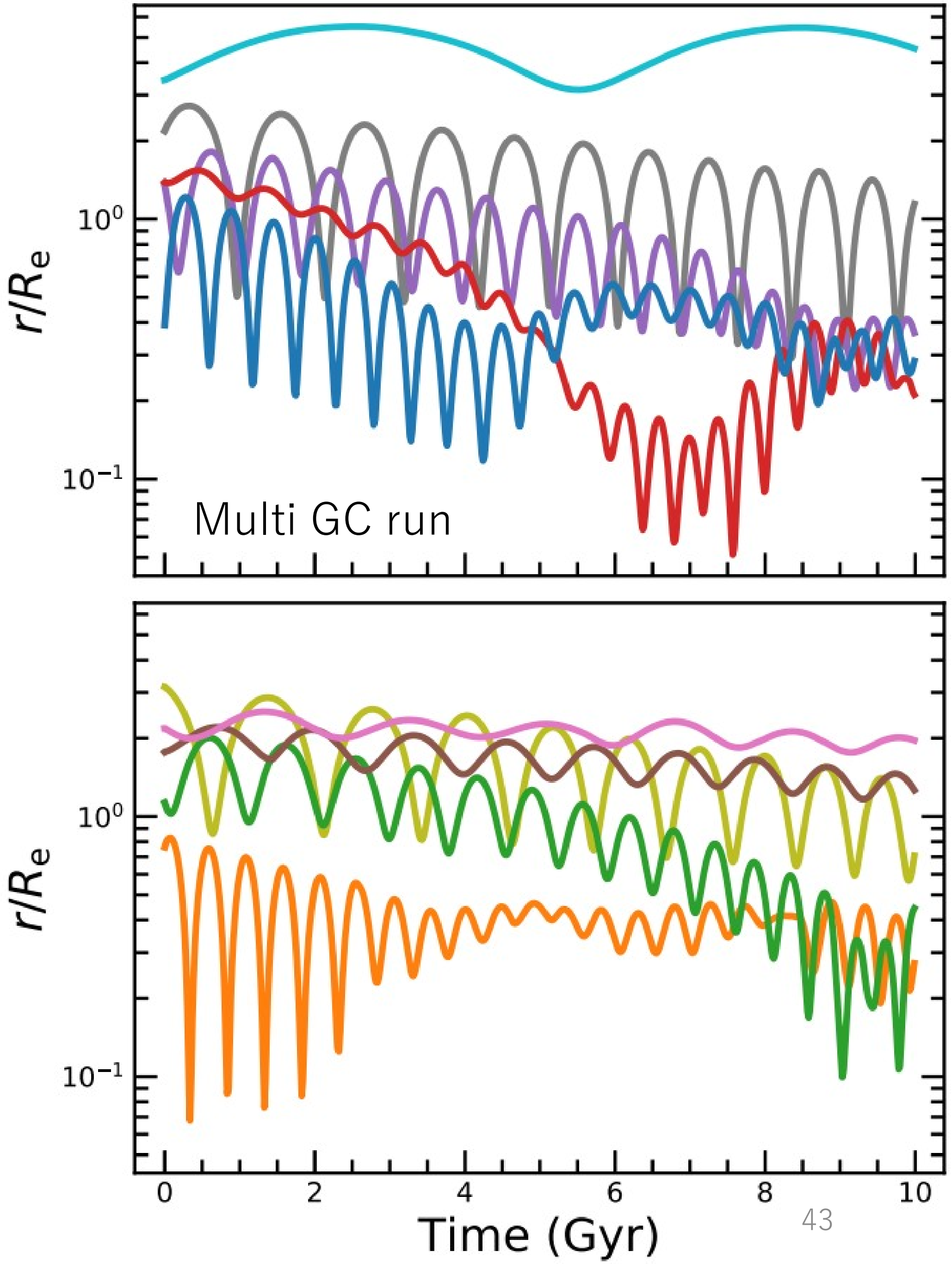


GC-GC scattering as dynamical buoyancy

- Dutta Chowdhury et al. (2019)
  - Mdyn ~ 1e8Msun, multiple GCs

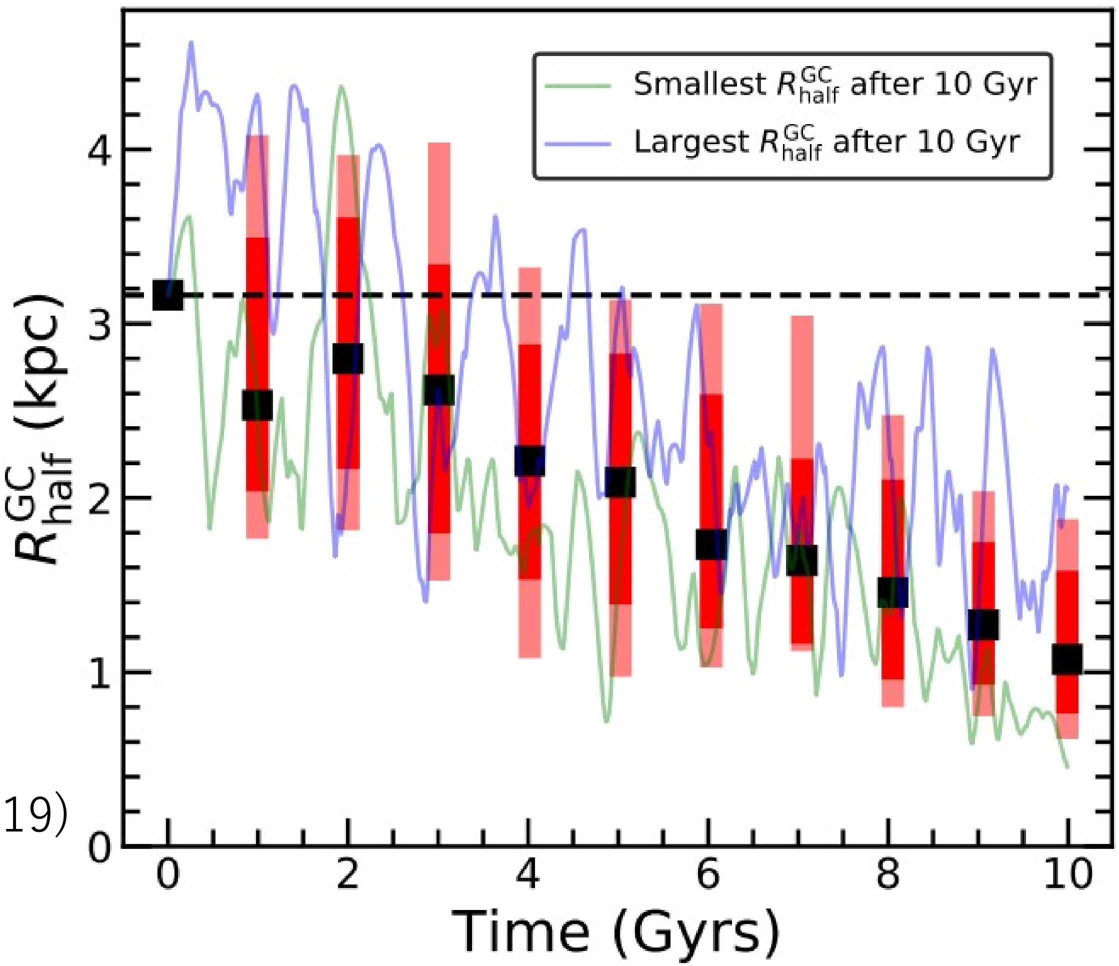
Core stalling radius
(e.g. Read et al. 2006;
Inoue 2011)





Need other buoyancy forces

Even if dynamical buoyancy of GC-GC scattering is considered, GC orbits gradually decays



Dutta Chowdhury et al. (2019)

Tidal interaction as another buoyancy?

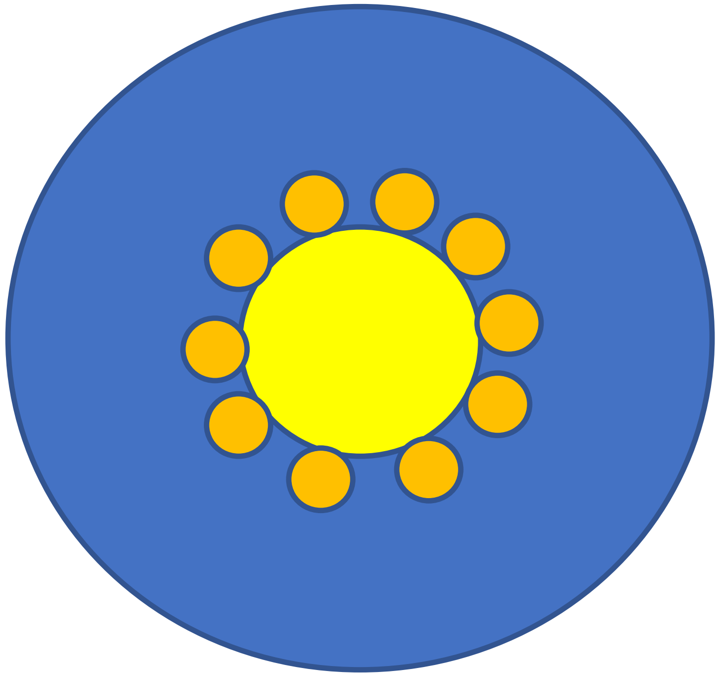
- Shallowing the galaxy potential (tidal stripping)
- Injection of kinetic energy by impulsive tidal shock

} Expansion of GC orbits

⇕

Orbital decay due to dynamical friction

Simulation setup



- Mass of 10 star particles around r=2.5kpc is increased to 1e6Msun
  - e.g. Forbes et al. (2017); Hudson & Robison (2018)
  - Distribution consistent with obs within ~100Myr

Simulation setup

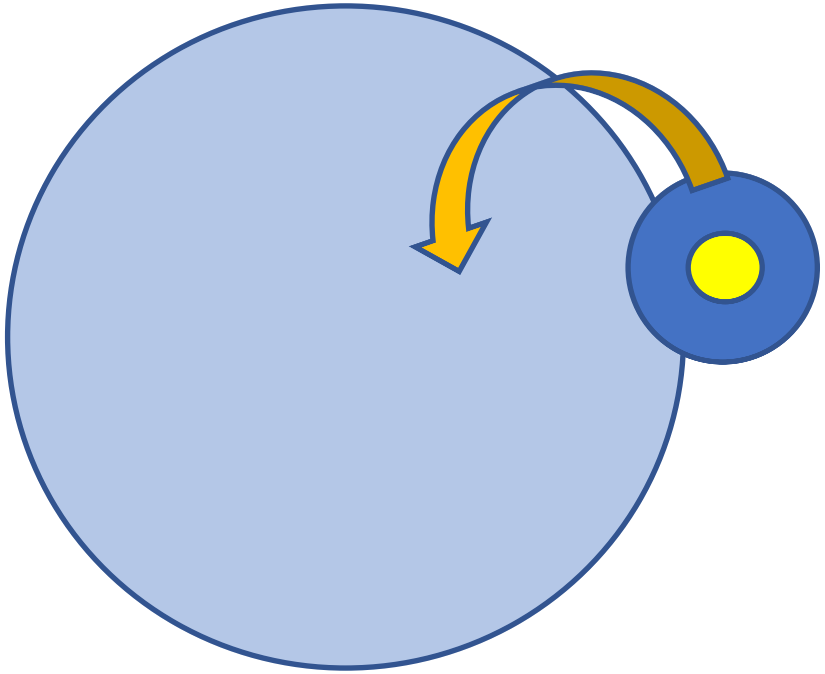
Initial density structure

$$\rho(r) = \frac{\rho_0}{(r/r_0)^\alpha [1 + (r/r_0)]^{\beta-\alpha}}$$

$$c \equiv R_\mathrm{v}/r_0$$

NGC1052 = fixed potential

- NFW halo (α =1, β =3)
  - ✓ M=1.1e13Msun
  - ✓ ch=5.8 (van Gorkom et al. 1986)

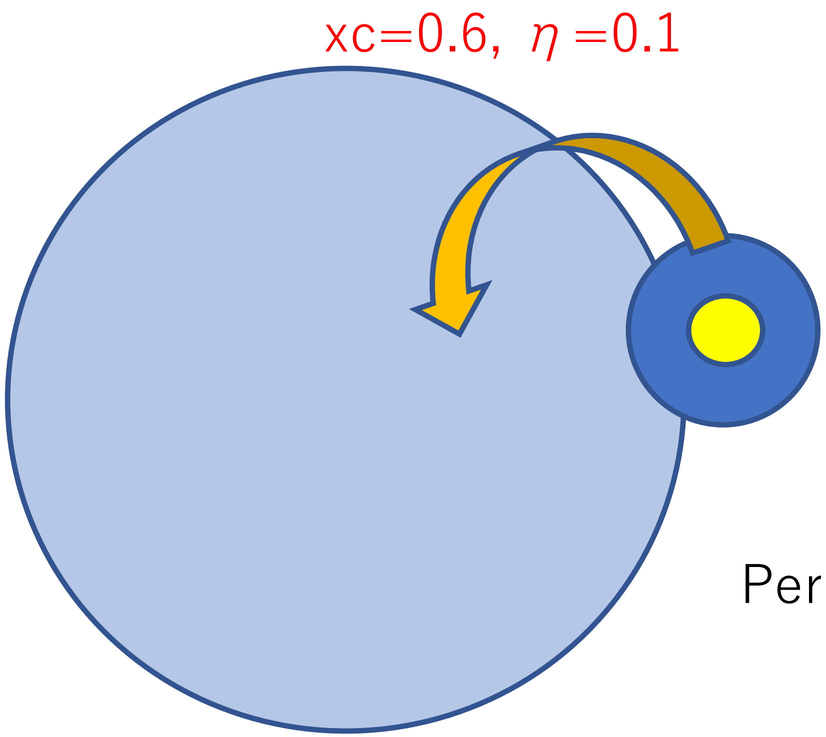


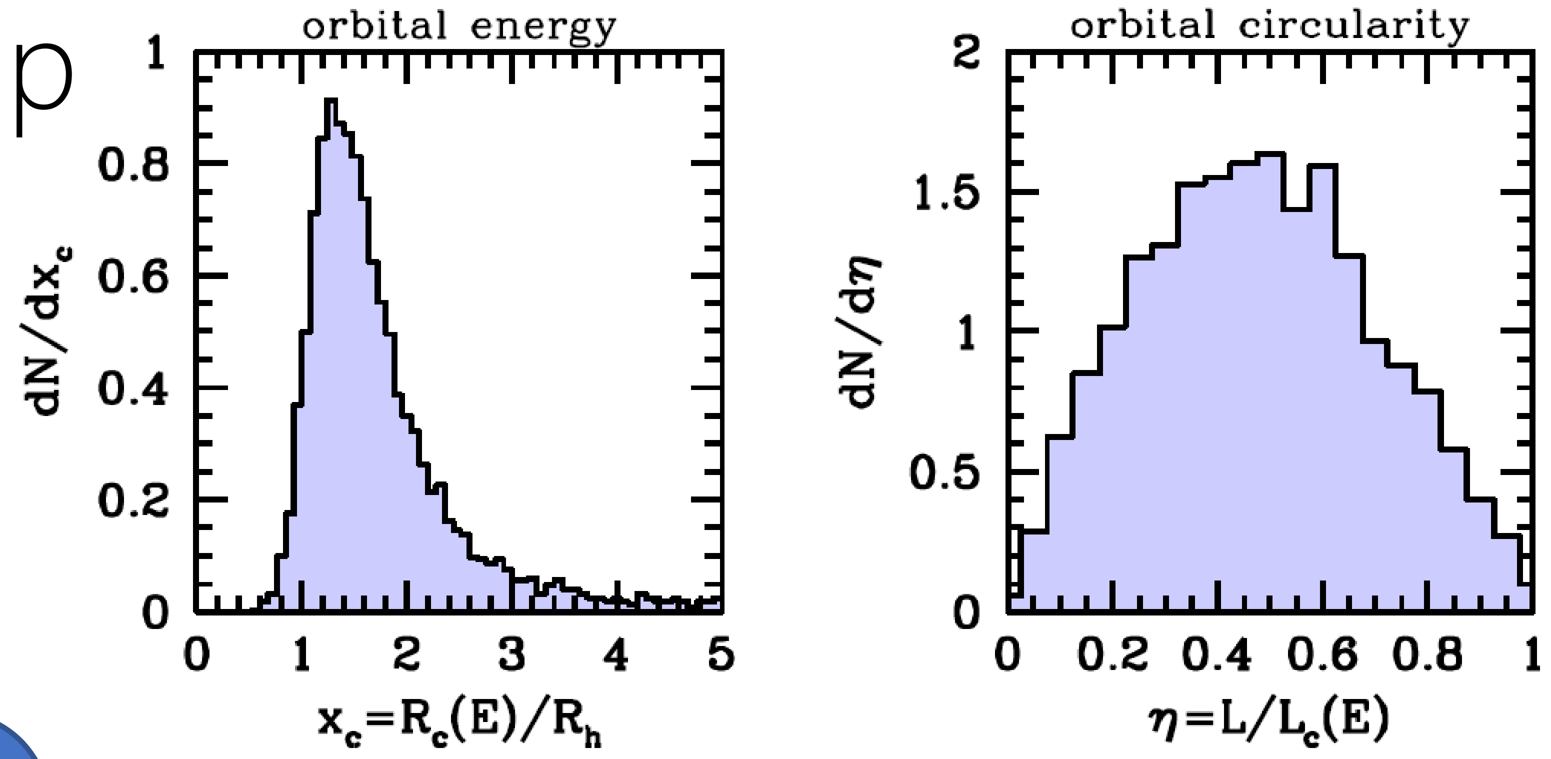
Satellite = *N*-body

- Stars -> Hernqust (1990; α =1, β =4)
  - ✓ M=2e8Msun
  - ✓ Re=0.93kpc (Lange et al. 2015)
- DM halo
  - ✓ M=4.9e10Msun
  - ✓ α =0.1 (Di Cintio et al. 2014) or 1.0 (NFW), β =3
    - Penarrubia et al. (2010); Errani et al. (2015)
  - ✓ cs=11.2 (Ludlow et al. 2016)

van den Bosch, GO, Hahn & Burkert (2018)

Simulation setup

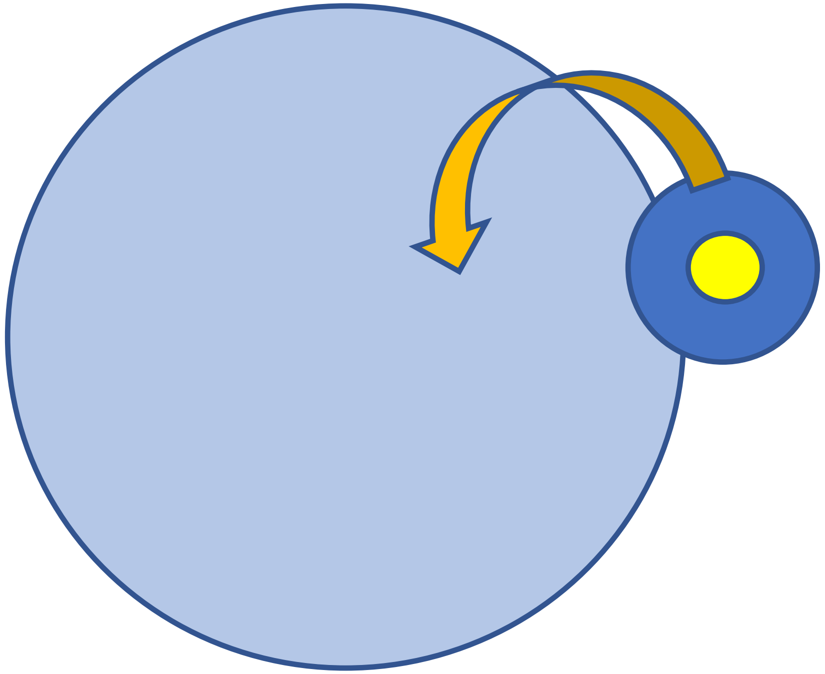




Initially at apocenter

Pericenter = 0.003Rv,h ~ 1kpc
1 percentile (Wetzel 2011)

Simulation setup



Subhalo = N-body system

- Number of particles, N
  - Stars -> N=409,600
    - ✓ M=2e8Msun
  - DM halo -> N=100,352,000
    - ✓ M=4.9e10Msun

  -> mass resolution = 510Msun

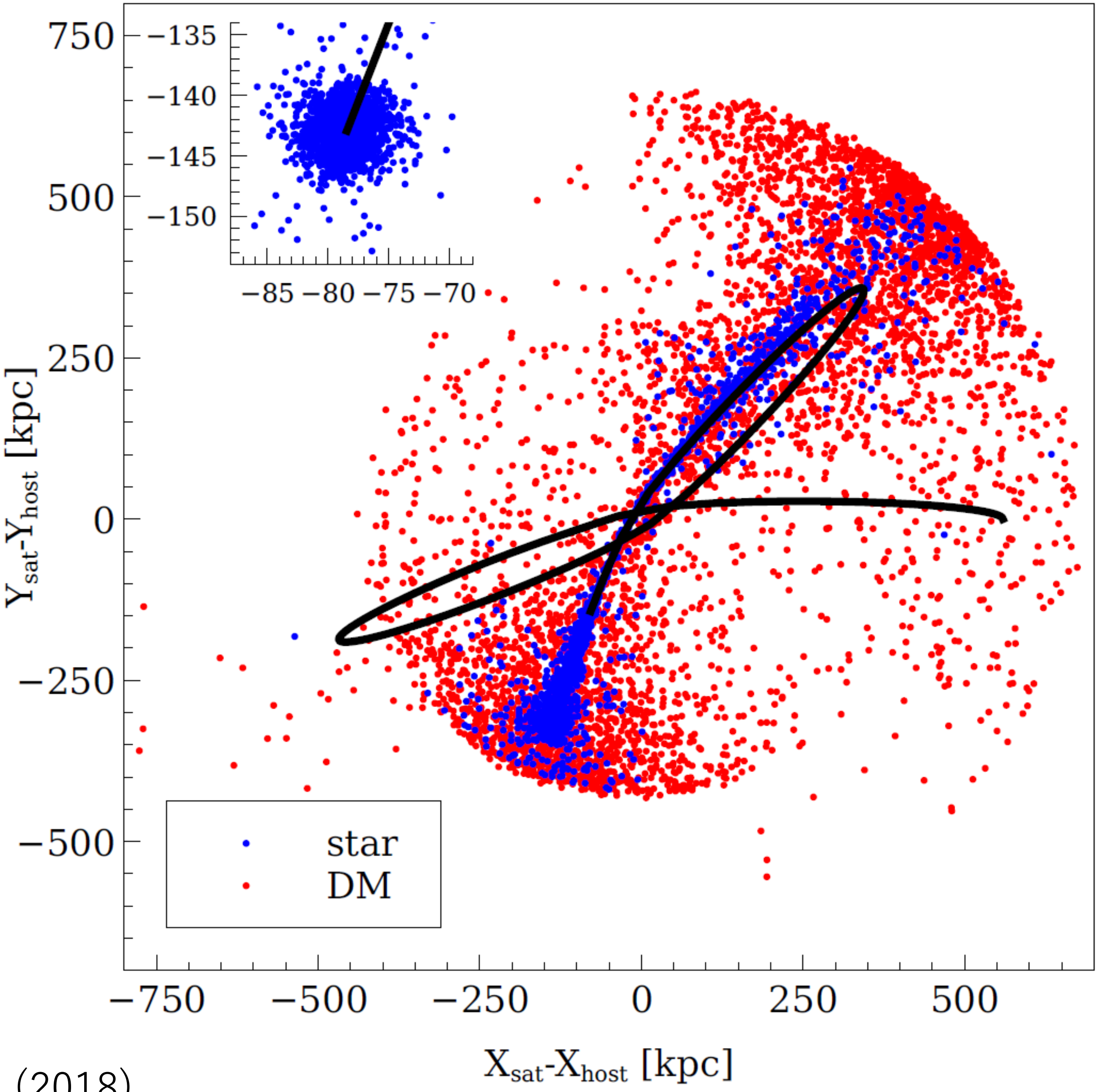
- Softening parameter, ε =0.03kpc
  - Results would be reliable at t=10Gyr
    - ✓ Power et al. (2003); van den Bosch & GO (2018)
- Tree code for GPU clusters (GO et al. 2013)

Distribution of stripped matter

- Result from the run of the cored model
  - ✓ Similar distribution in the run of the cuspy model

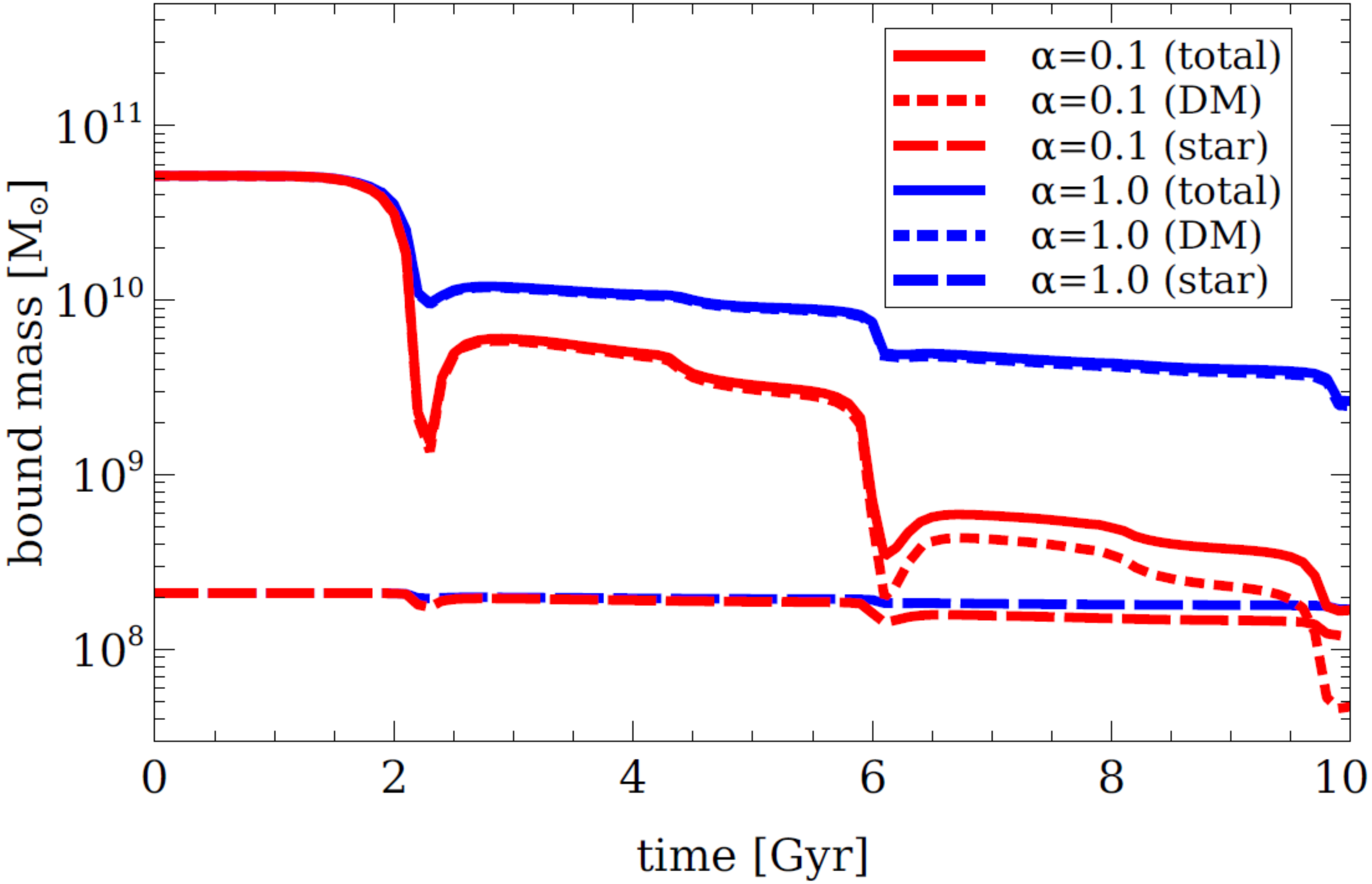
- DM significantly stripped

- Bulk of stars is settled at the tip of the line (center of the satellite)



GO (2018)

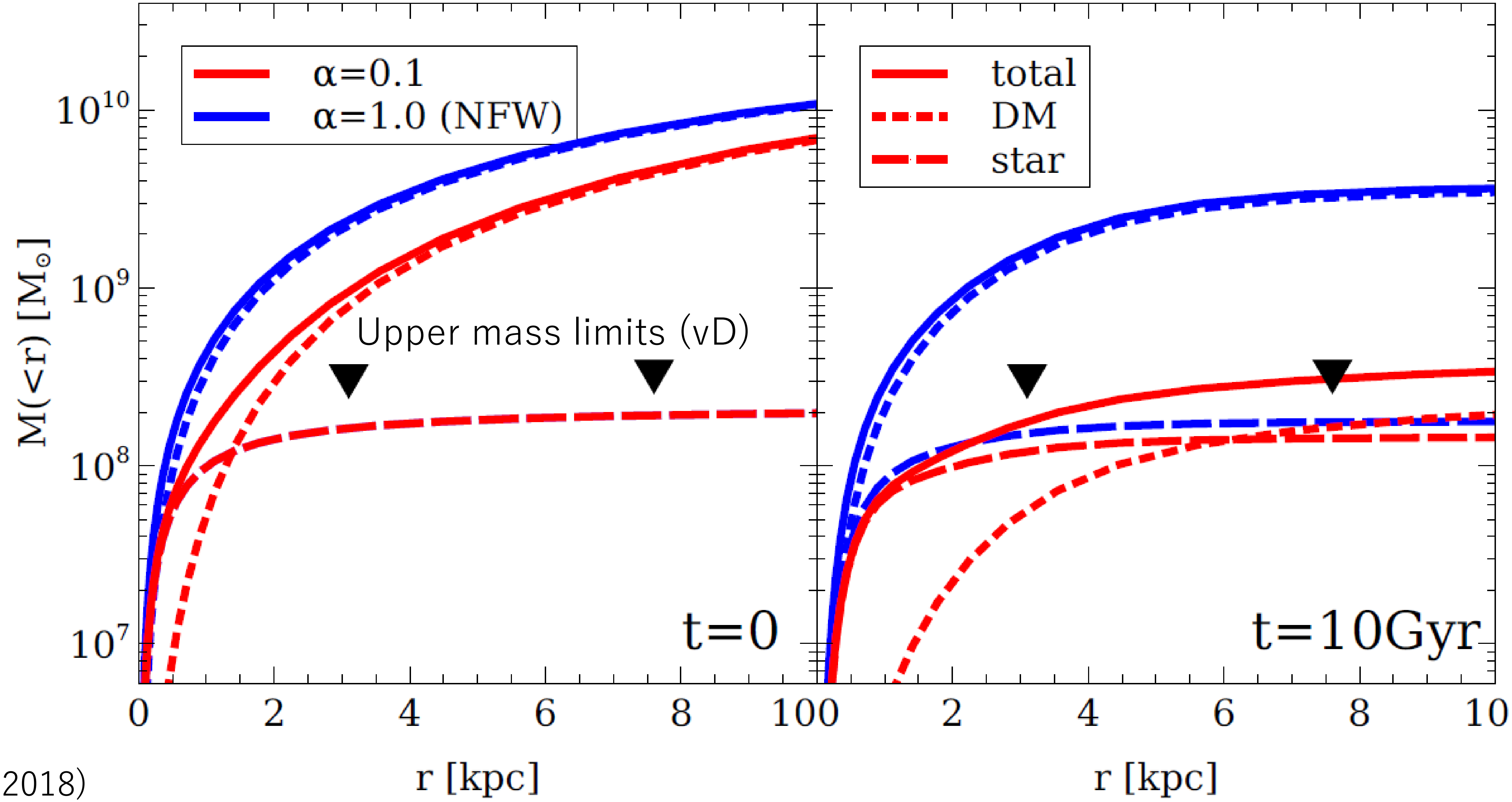
Mass evolution



GO (2018)

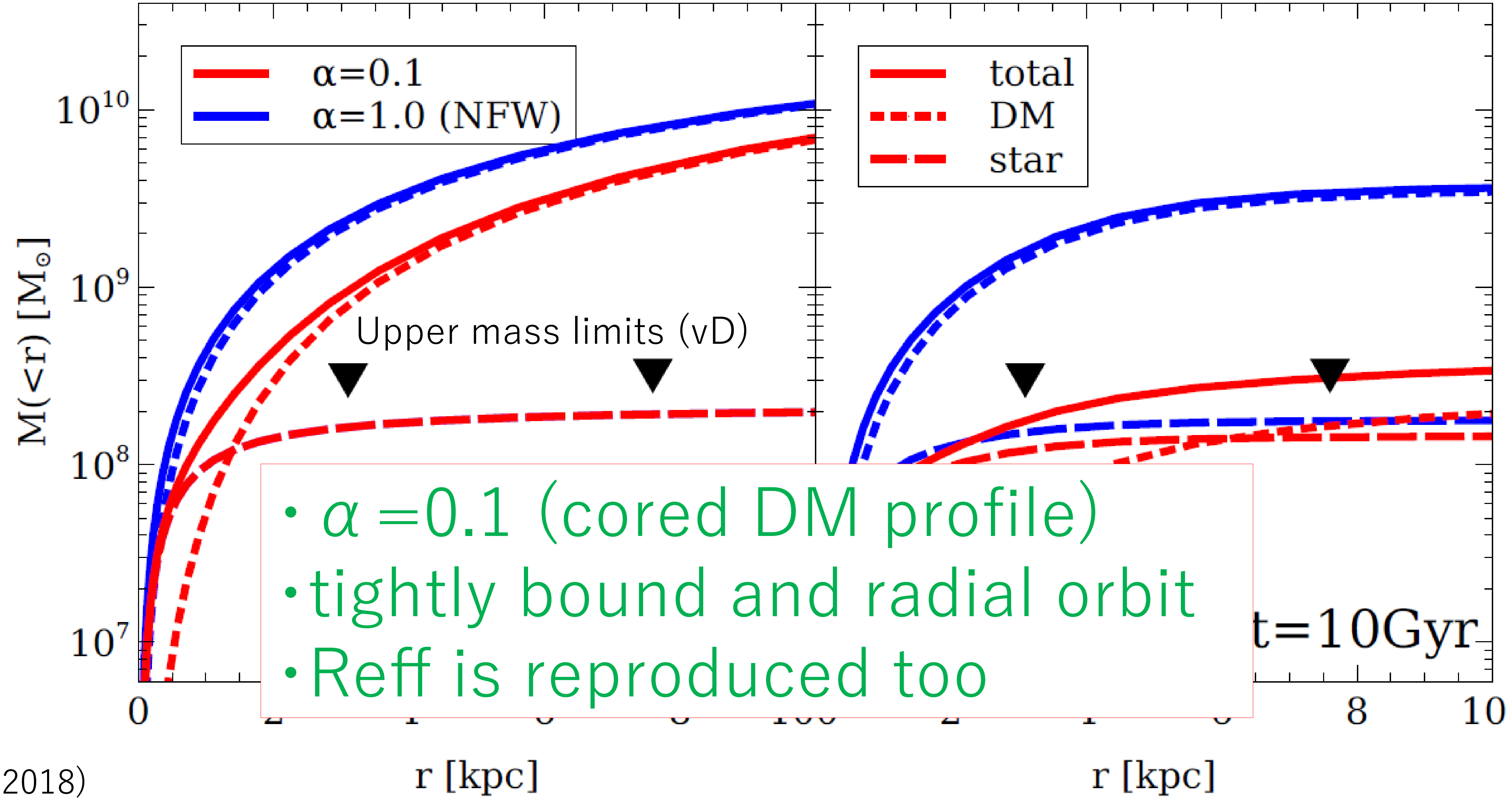
- DM mass reduced significantly in $\alpha = 0.1$ (cored) model
  - By a factor of ~1000 at 10Gyr
- Less significant reduction in $\alpha = 1.0$ (cuspy) model
- Stellar mass does not change significantly in both models

Comparison with van Dokkum et al. (vD)



GO (2018)

Comparison with van Dokkum et al. (vD)



- $\alpha = 0.1$ (cored DM profile)
- tightly bound and radial orbit
- Reff is reproduced too

GO (2018)

Caveat on the Ogiya (2018) model

- Galaxy structure and merger orbital parameters are assumed to follow observations and empirical relations at $z = 0$

- DF2 is a satellite galaxy and must have been accreted earlier

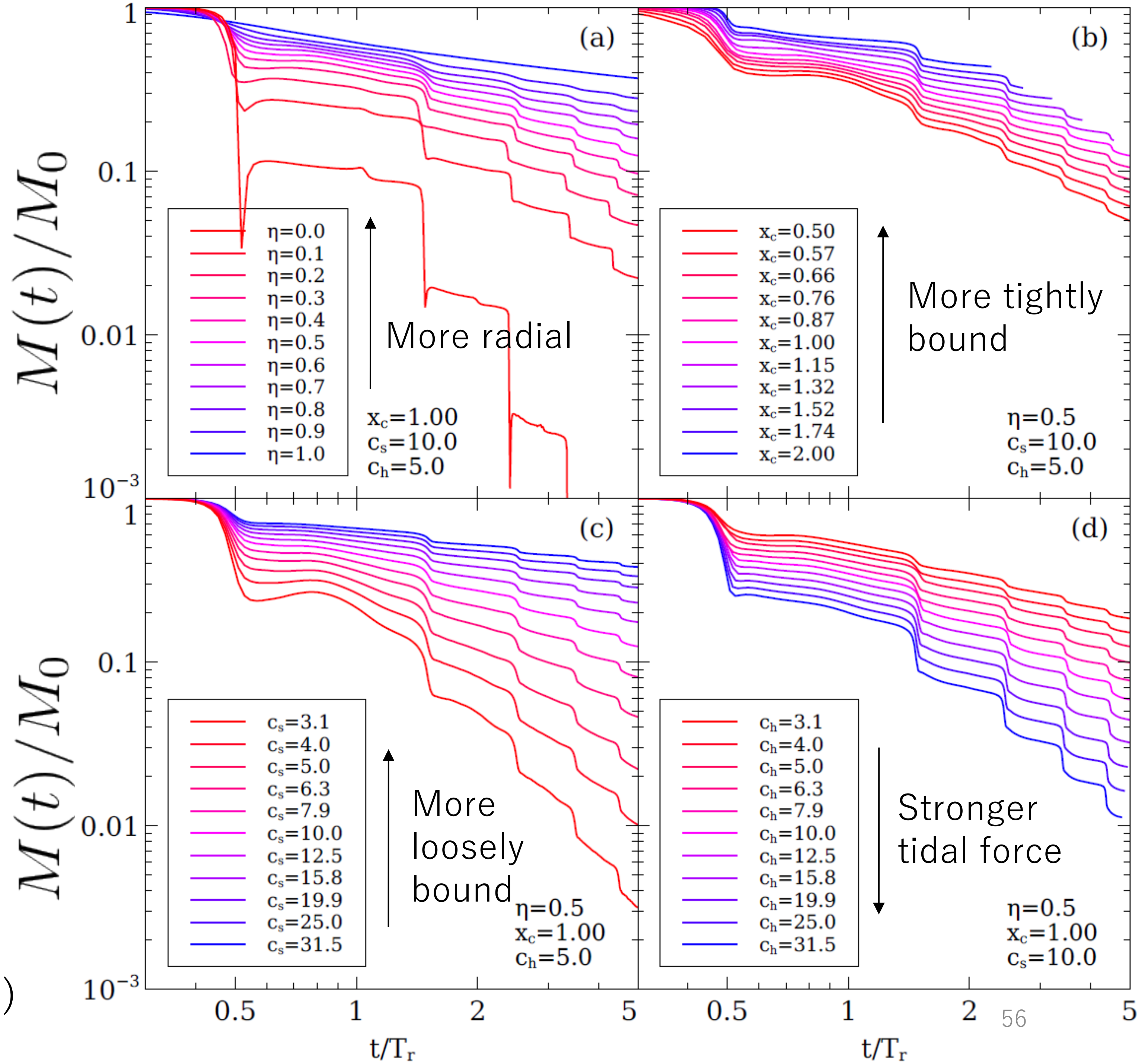
- Accreted higher z -> Smaller orbits
  - Stronger tidal force, larger number of pericentric passage
    -> More significant tidal massloss
  - Even satellites with a NFW halo might reproduce the observation

DASH library (GO et al. 2019)

- Idealized N-body simulations of minor halo mergers
  - Both halos follow the NFW density profile initially
  - Large mass ratio -> Dynamical friction is negligible, orbit is 'frozen'
    -> Host halo = analytical potential
  - Scale free nature of gravity -> scalable to any small mass subhalos
  - Fulfill numerical criteria (van den Bosch & GO 2018)
- 2 orbital parameters + 2 halo concentrations
  - >2000 simulations

Mass evolution

- Tr: radial period
- More significant mass loss
  - On more radial and tightly bound orbits
  - With less (more) concentrated sub- (host) halos

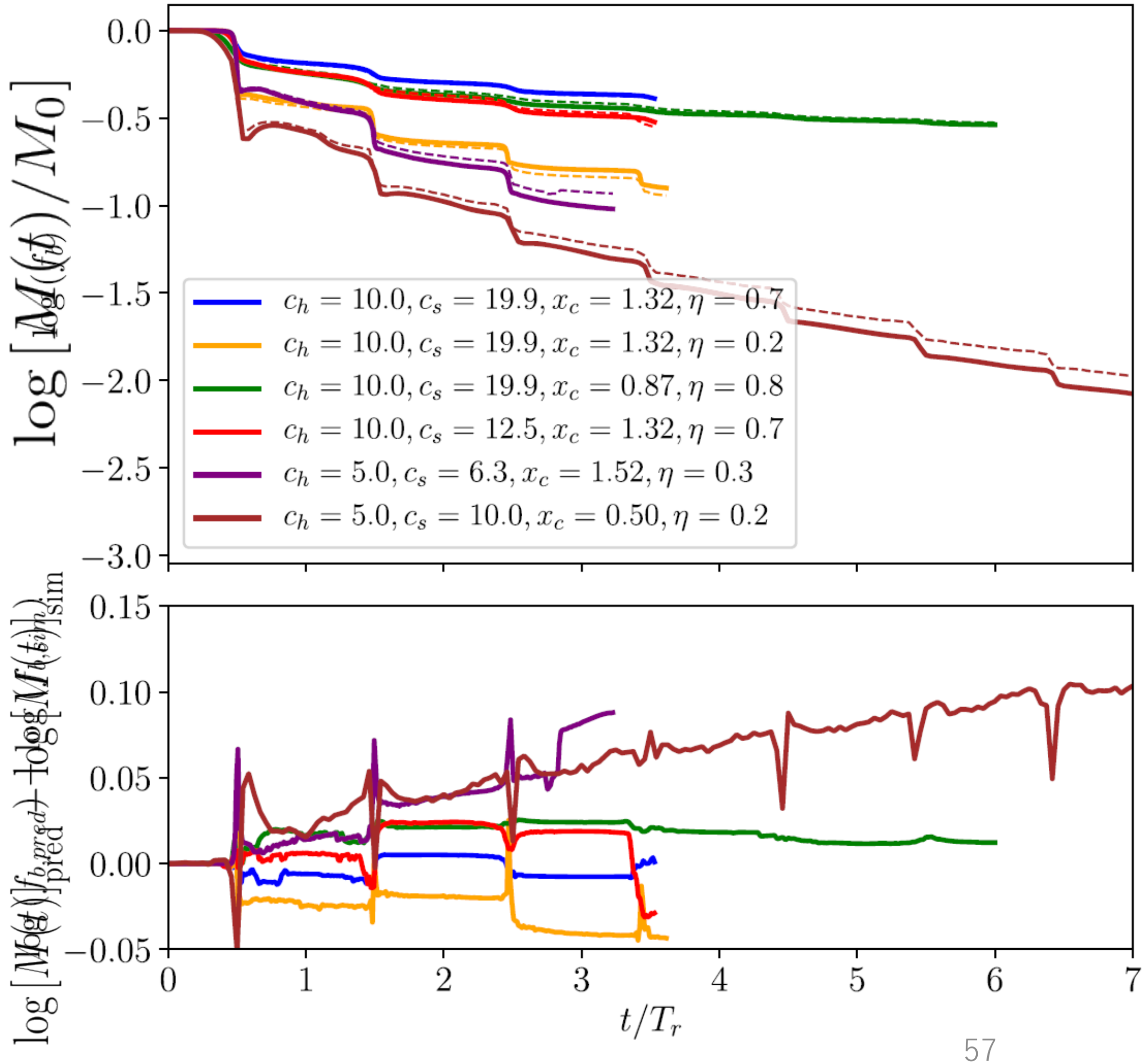


GO et al. (2019)

Machine Learning model

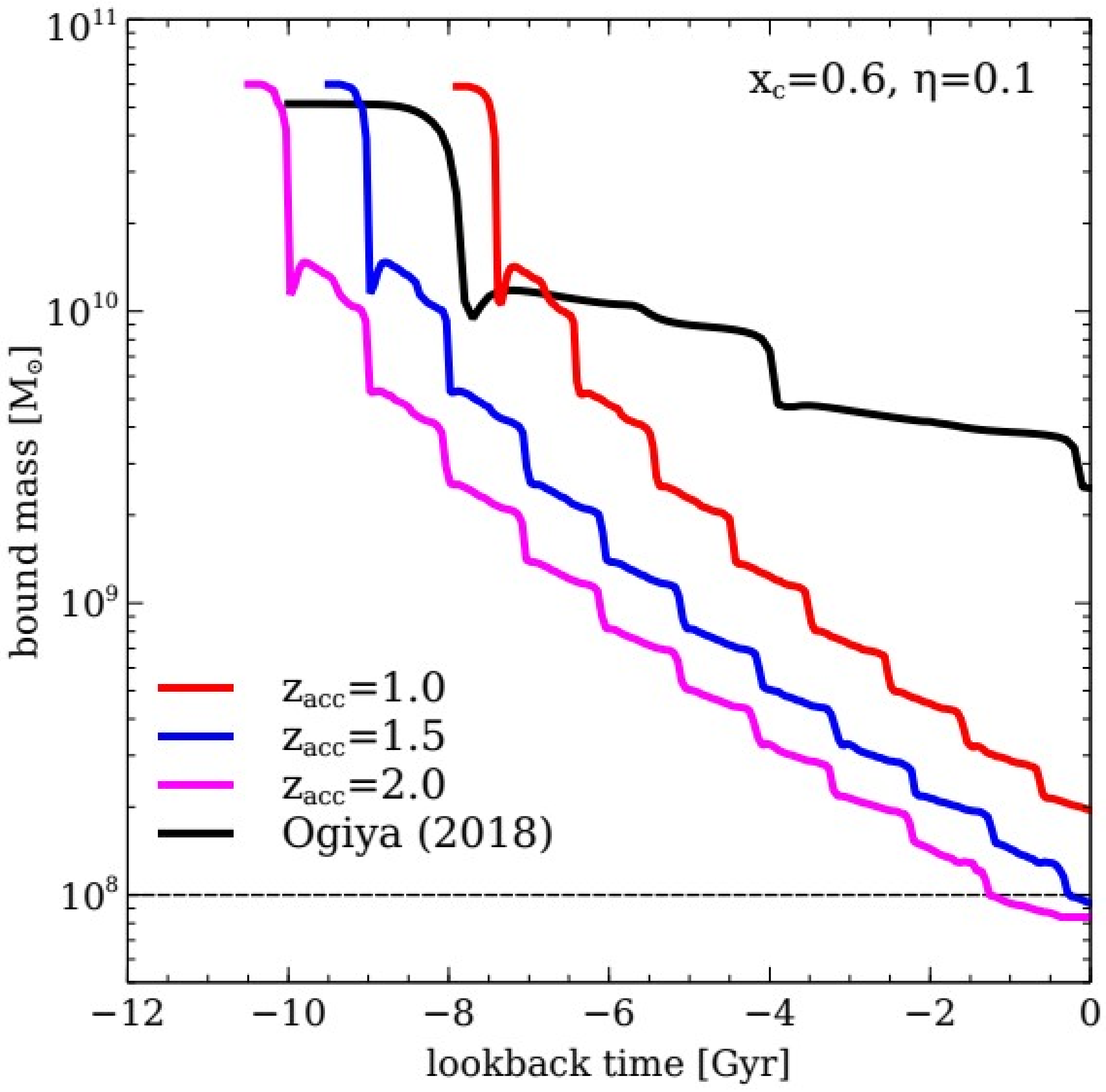
GO et al. (2019)

- Trained a machine learning (ML) model describing the mass evolution
  - Accurate at the 0.1 dex level



ML prediction

- Bound mass evolution in the cuspy model
- Color lines = prediction by the ML model
- The mass criteria can be satisfied if DF2 accreted early enough (z > 1.5)

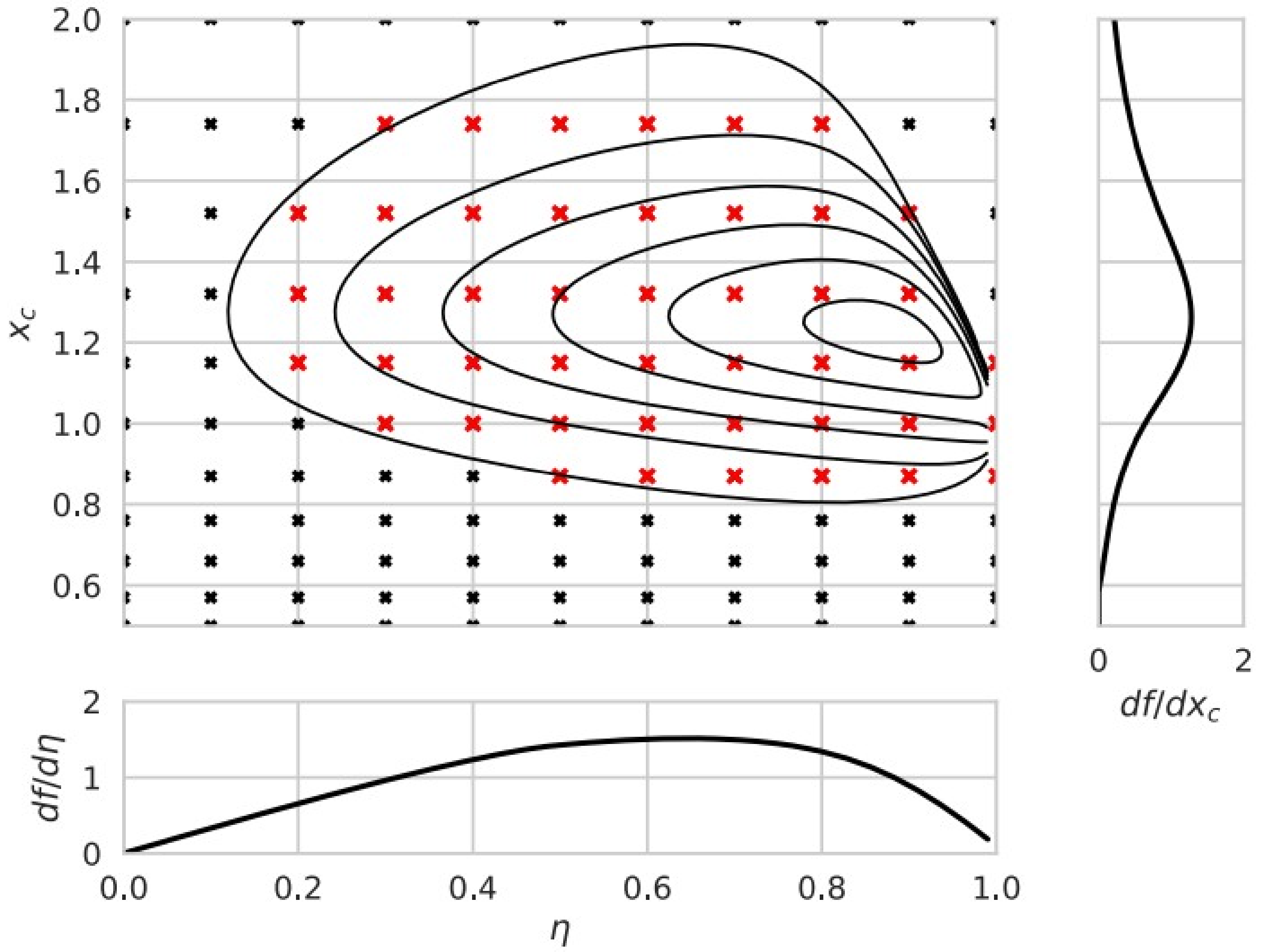


How rare is DF2?

- Test if the bound mass below the critical value
  - >10000 models

- PDF of orbital params

(Jiang et al. 2015)



How rare is DF2?

- DF2 is possible but very rare
- Considering orbit contraction due to the smooth mass growth of the host, prob. increased

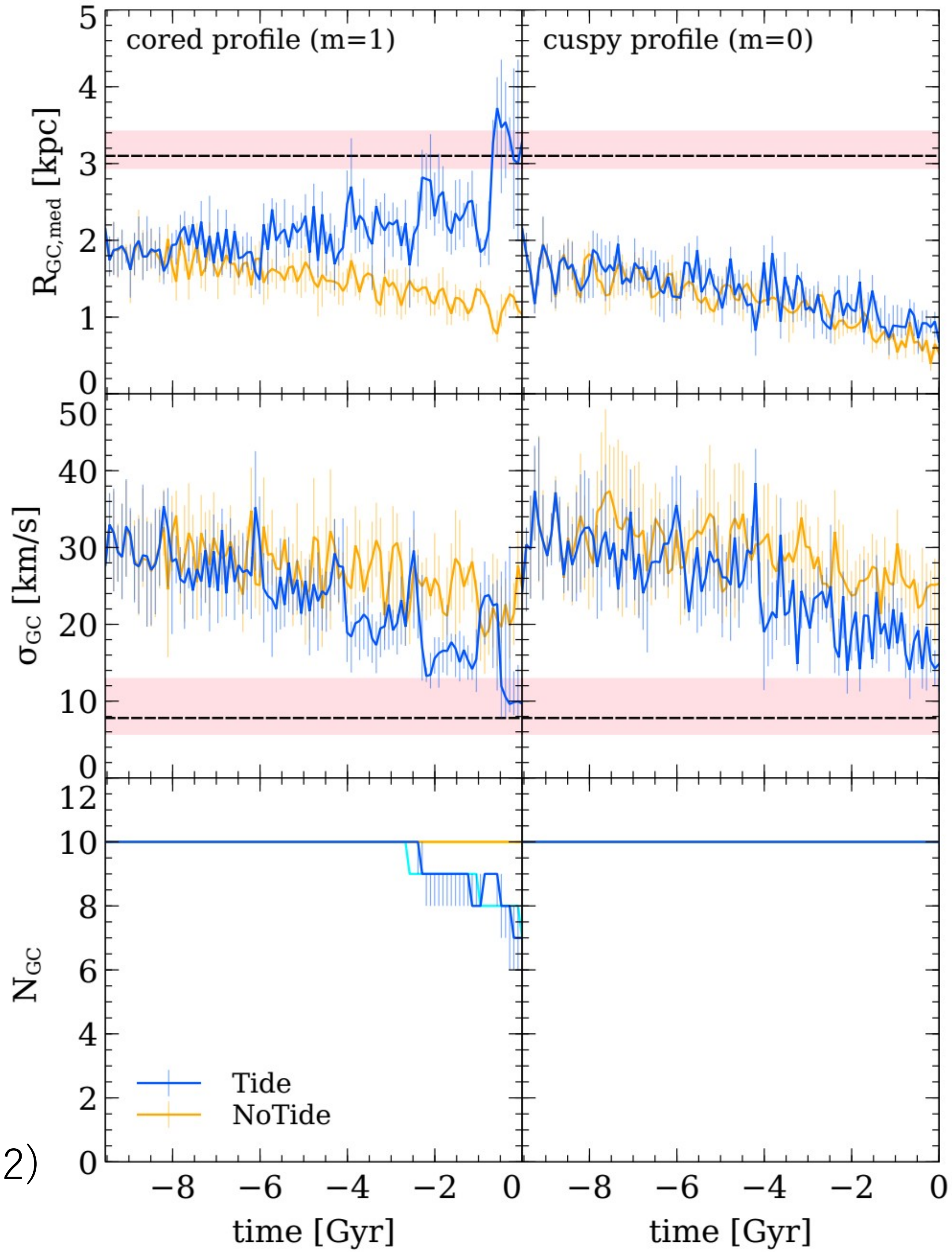
z_{acc}	$P_{no\text{-}cont}$	$P_{with\text{-}cont}$
0.0	–	–
1.0	0.0	0.0
1.5	3.6×10^{-5}	2.8×10^{-4}
2.0	3.3×10^{-5}	3.7×10^{-4}

GO, Taylor & Hudson (2021)

GC orbital evolution

- Some GCs can escape from the satellite galaxy
  - ✓10GCs in the simulation
- Including more GCs in the simulation, observed N of GCs may be explained
  - ✓12 or more GCs expected
    - - Burkert & Forbes (2019)

GO, van den Bosch & Burkert (2022)



GCs in the mini-bullet cluster scenario

Pros

Extremely high pressure environment in the galaxy collision

- → Formation of multiple GCs at the collision
  (Silk 2019; Lee et al. 2021)
- → Explain homogeneous properties of GCs?
  (Fensch et al. 2019; van Dokkum et al. 2022b)

Caveats

GCs should have felt dynamical friction
→ Distribution of GCs was more extended than observed
→ Such GCs were susceptible to the tidal force

Tidal puffing-up does not help as only one encounter is expected

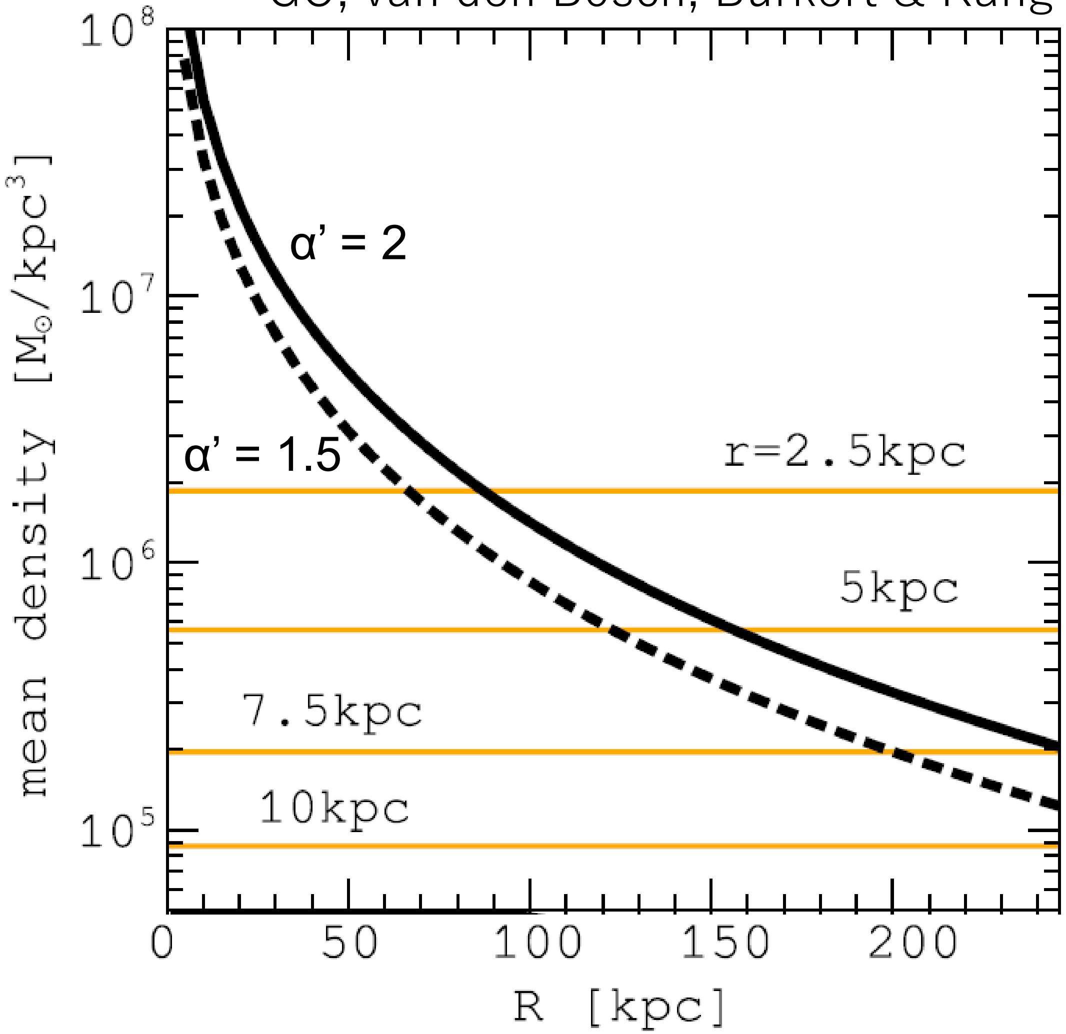
How susceptible are GCs to the tidal force?

- Comparison of the mean densities of DF2 and NGC1052
  (indicator of tidal susceptibility)

$$\bar{\rho}_{\rm sat}(r_{\rm t}) \quad \text{vs} \quad \alpha' \bar{\rho}_{\rm host}(R),$$

- e.g. GCs at r=5kpc will be stripped from DF2 if the formation place was R~120kpc

GO, van den Bosch, Burkert & Kang (2022)



How many GCs are stripped?

- Cumulative distribution of satellite galaxies
  -Han et al. (2016)

- Weighting fstrip with the satellite number, 33-59 GCs should have been formed originally
  - ✓ Difficult to form such a large number of massive GCs (Lee at al. 2021)
  - ✓ **N of GCs = Challenge for the scenario**

GO, van den Bosch, Burkert & Kang (2022)