COSMO_SIMS

- van den Bosch, GO, Hahn & Burkert (arXiv:1711.05276)
- van den Bosch & GO (arXiv:1801.05427)
- GO, van den Bosch et al., in prep.
- Miller, van den Bosch & GO, in prep.

Dark matter subhalos in collisionless *N*-body simulations

Go Ogiya

(Observatoire de la Côte d'Azur, OCA)

In collaboration with

Frank van den Bosch (Yale); Tim Miller (Yale); Oliver Hahn (OCA); Andreas Burkert (Munich)

Collisionless systems (Binney & Tremaine for details)

- Systems in which
  - ✓Motion of particles is governed by the smooth potential field
  - ✓Two body scattering (collision) is not significant
  - ✓(Virtually) infinite number of particles are included

$$T_{\rm rel} = \frac{N}{8\log(N)} t_{\rm cross} > t_{\rm H}$$

- Examples
  - ✓Galaxies -> N>10^10
  - ✓Galaxy clusters -> N>10^13
  - ✓Dark matter halos -> N>10^50?

Substructures = satellite galaxies + dark matter subhalos

Why do we care about substructures?

Importance for a wide range of astrophysics

- Nature of dark matter particles
  - ✓Gravitational lensing
  - ✓Annihilation/decay signals
- Semi-analytic model of galaxy formation and evolution
- Stellar streams (e.g. Gaia)

Substructures = satellite galaxies + dark matter subhalos

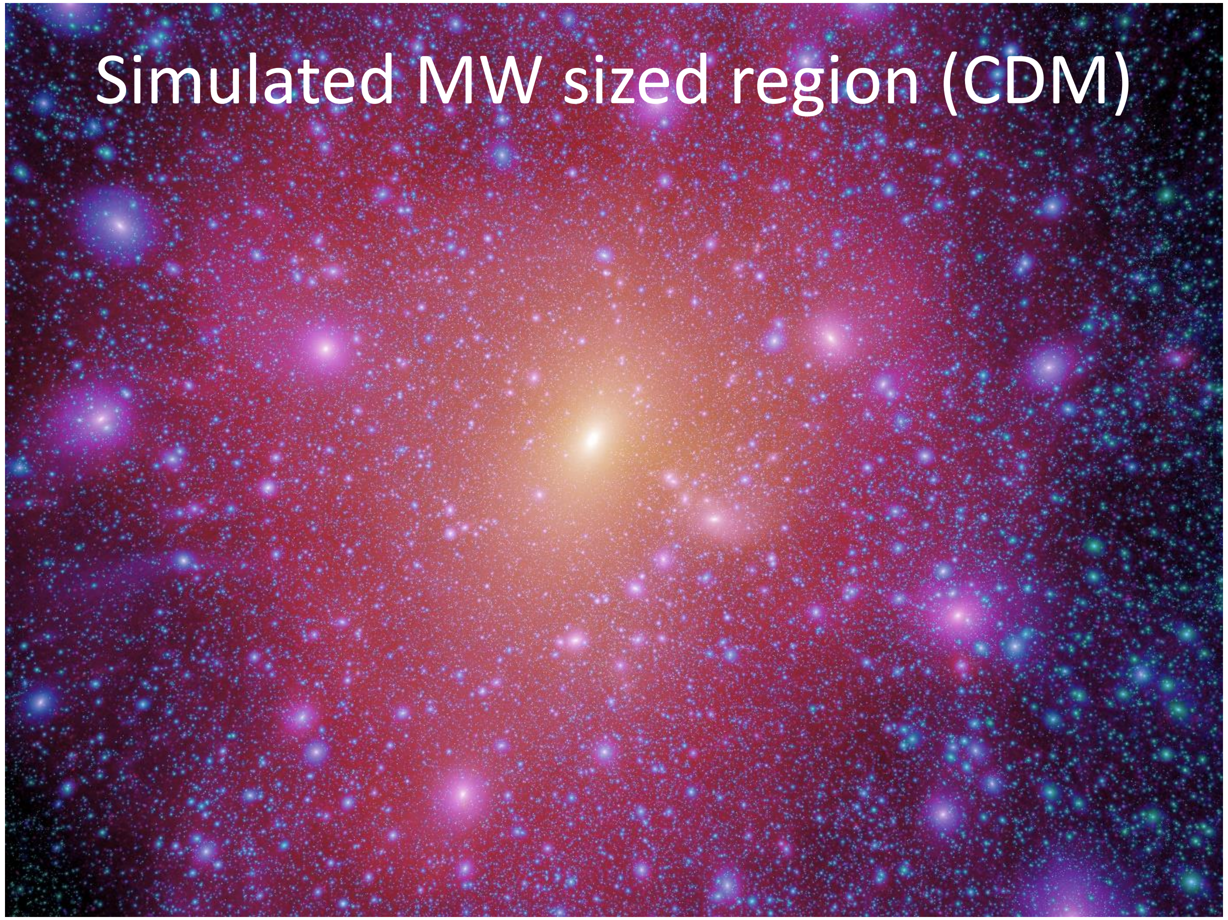
Why do we care about substructures?

Importance for a wide range of astrophysics

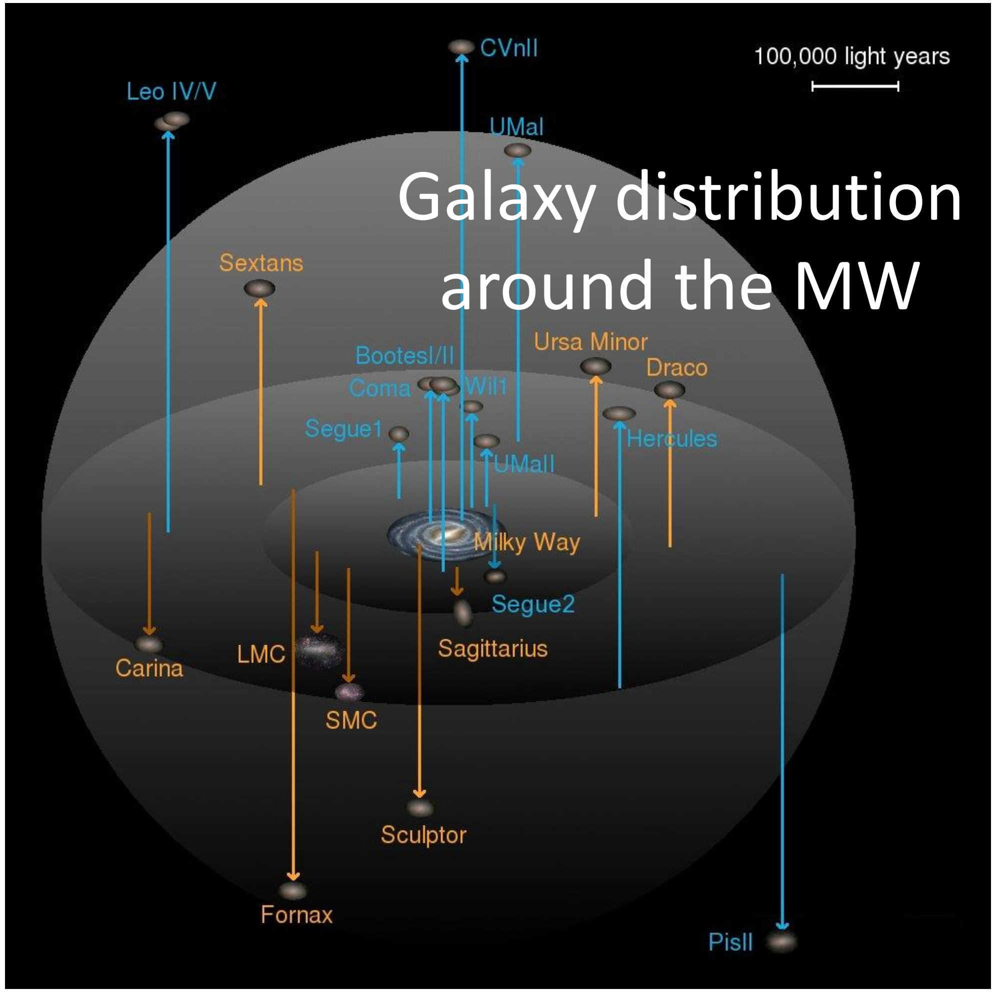
- **Nature of dark matter particles**
  - ✓**Gravitational lensing**
  - ✓**Annihilation/decay signals**
- **Semi-analytic model of galaxy formation and evolution**
- Stellar streams (e.g. Gaia)

Number + mass

Number of substructures

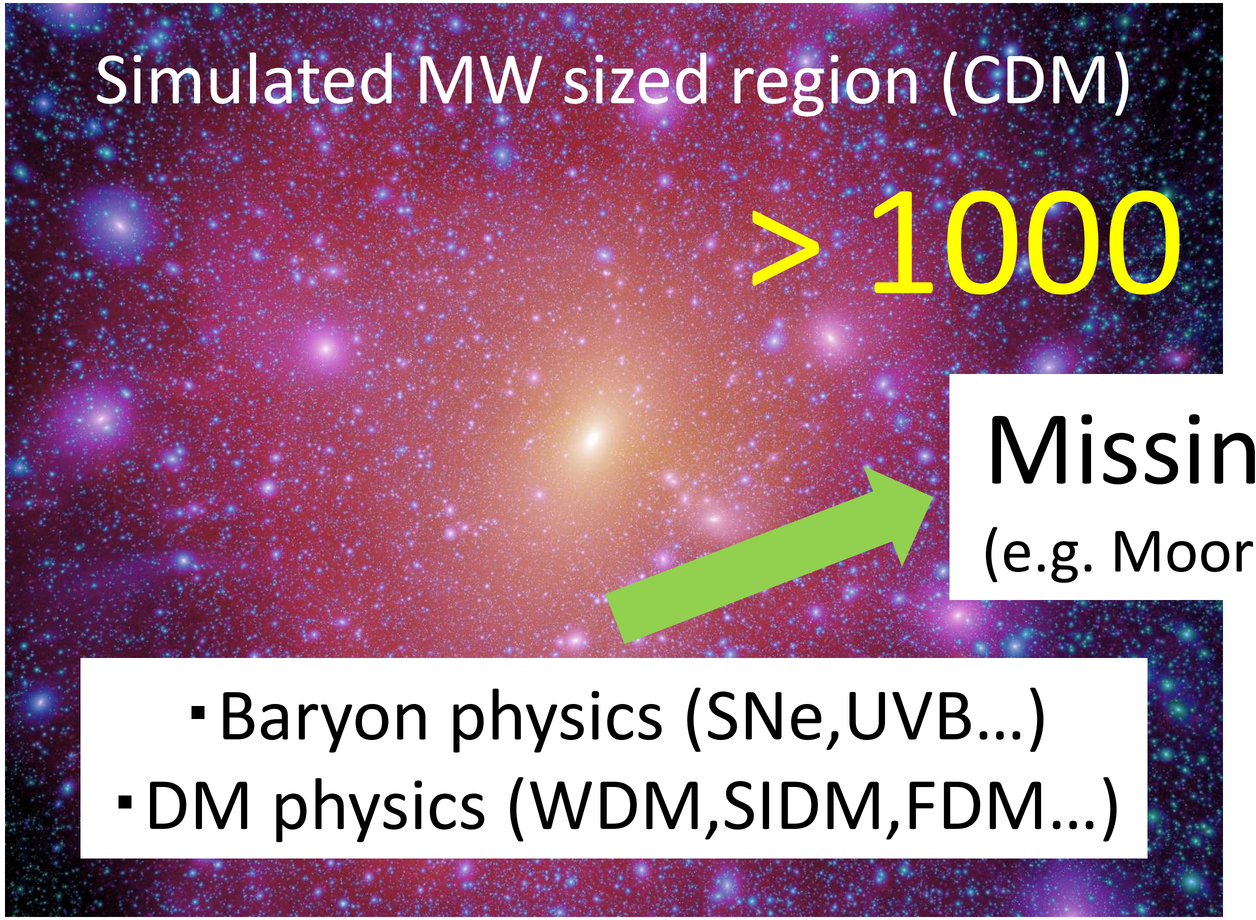


Springel et al. (2008)



http://lg-inventory.strw.leidenuniv.nl

Number of substructures



Simulated MW sized region (CDM)

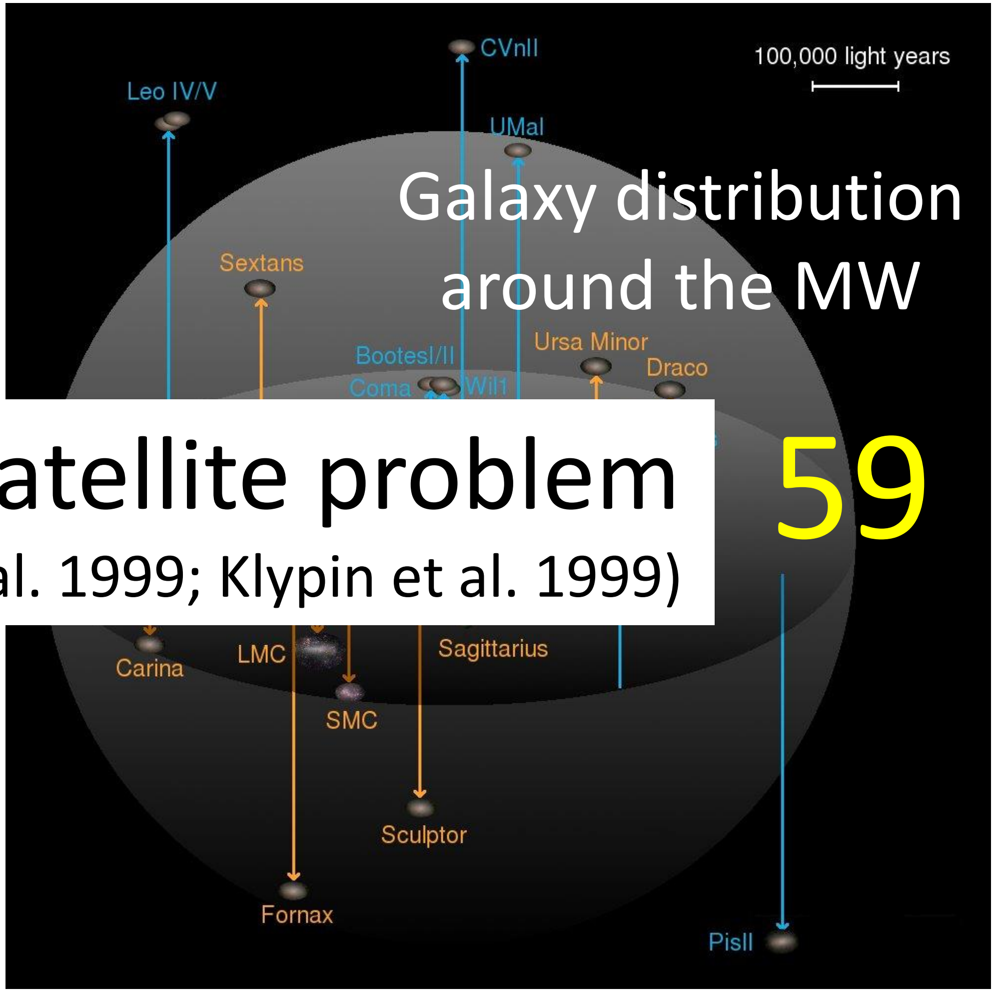
> 1000

- Baryon physics (SNe,UVB…)
- DM physics (WDM,SIDM,FDM…)

Springel et al. (2008)

Missing satellite problem

(e.g. Moore et al. 1999; Klypin et al. 1999)



Galaxy distribution around the MW

59

http://lg-inventory.strw.leidenuniv.nl

Substructures = satellite galaxies + dark matter subhalos

Why do we care about substructures?

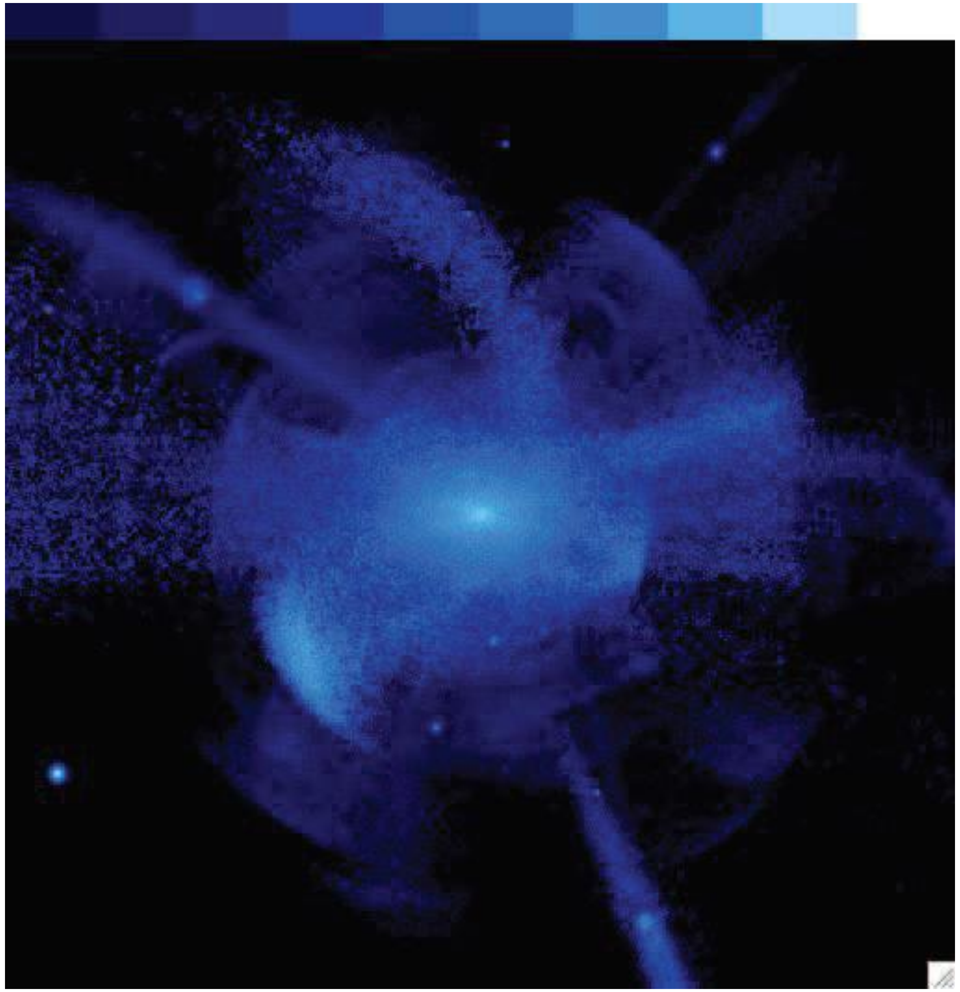
Importance for a wide range of astrophysics

- Nature of dark matter particles
  - ✓Gravitational lensing
  - ✓Annihilation/decay signals
- Semi-analytic model of galaxy formation and evolution
- **Stellar streams (e.g. Gaia)**

Number + mass

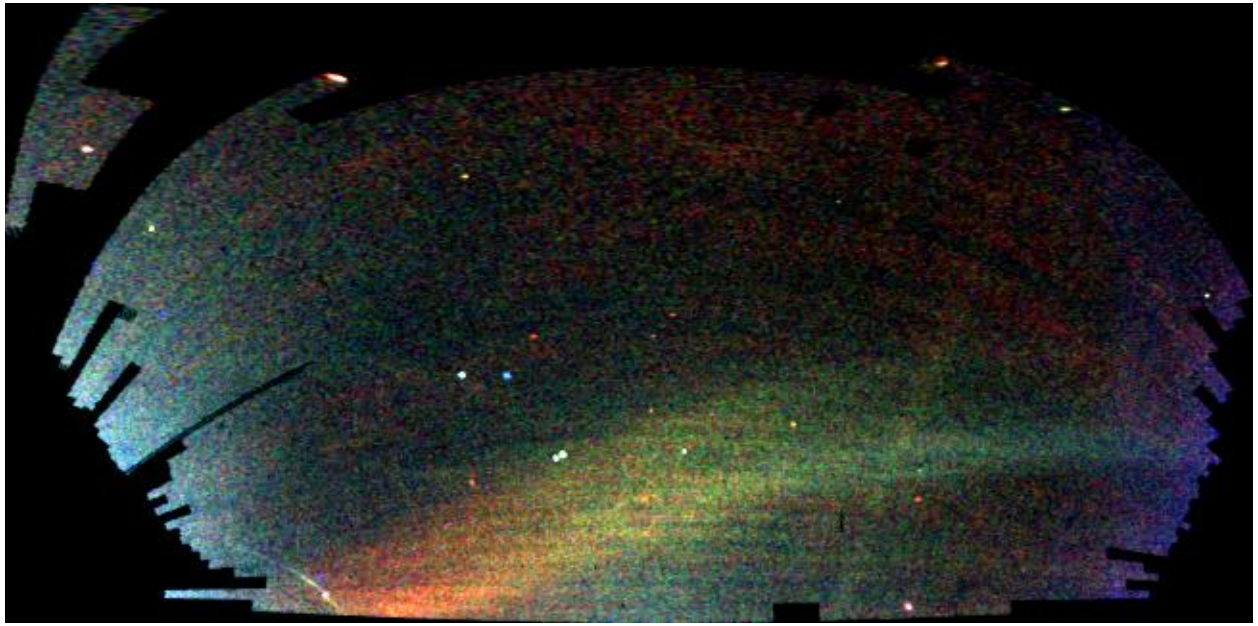
In addition, distribution and kinematics of stripped stars

Stellar streams in simulations and observations



Bullock & Johnston (2005)

Belokurov et al. (2006)



Why do we care about substructures?

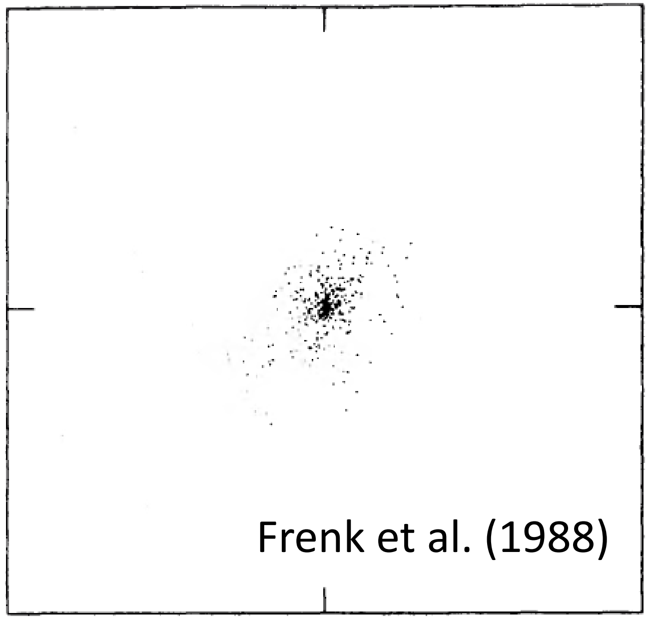
Importance for a wide range of astrophysics

- **Nature of dark matter particles**
  - ✓**Gravitational lensing**
  - ✓**Annihilation/decay signals**
- **Semi-analytic model of galaxy formation and evolution**
- Stellar streams (e.g. Gaia)

Number + mass

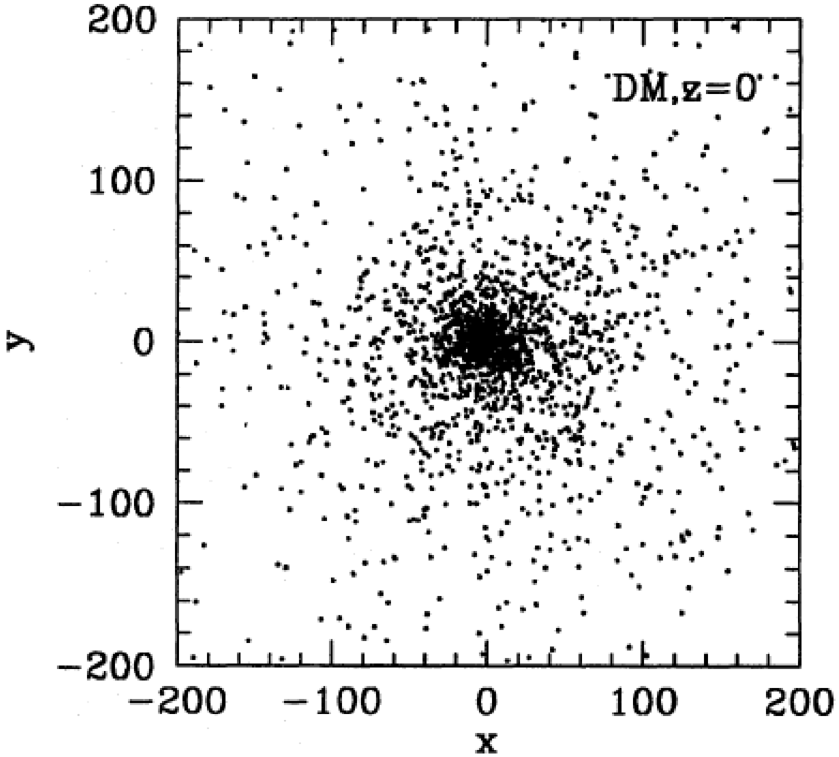
This talk

How are simulations reliable?


Frenk et al. (1988)

Prior to 1997, no or too few substructures in simulations *because of the lack of resolution*

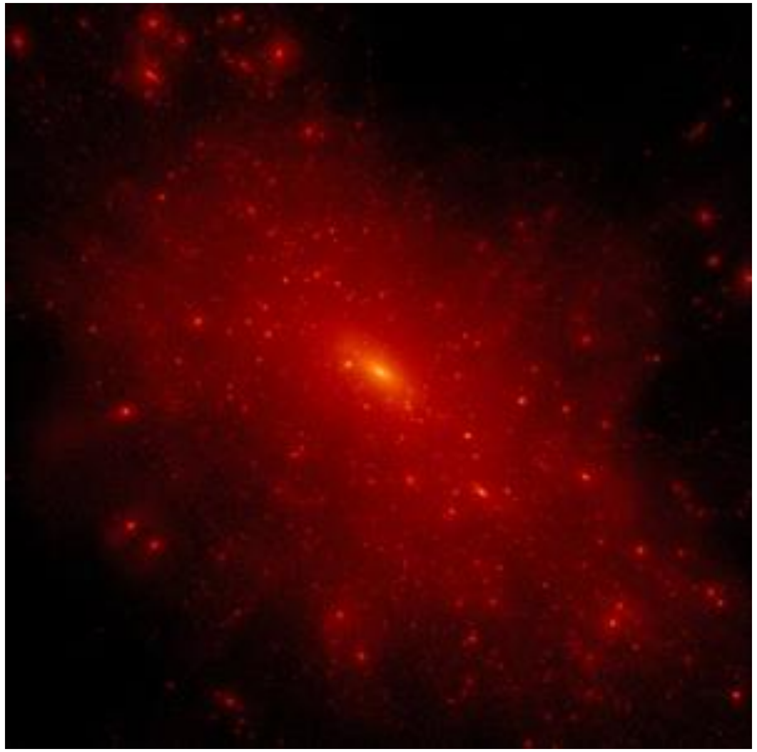
Over merging problem

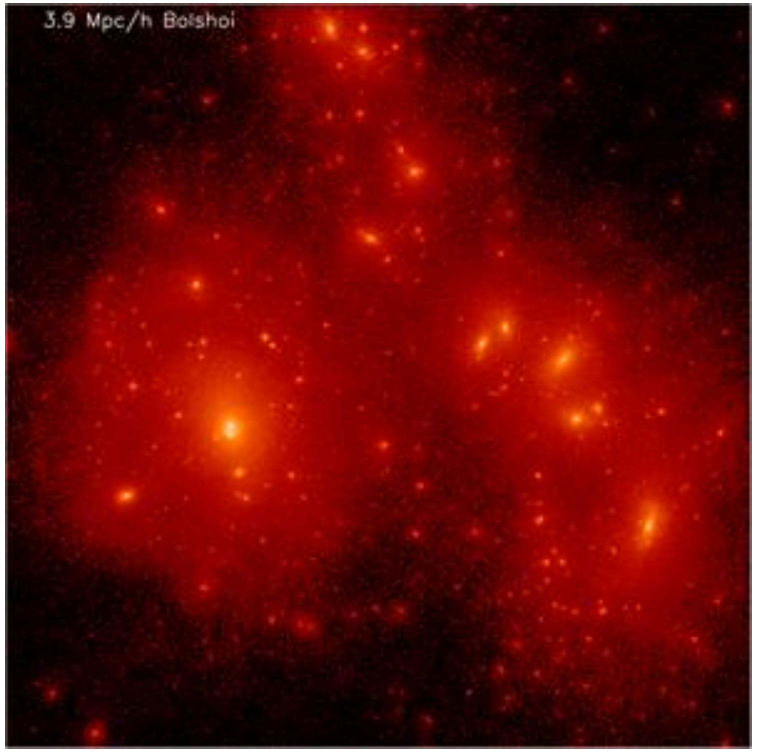


Navarro et al. (1995)

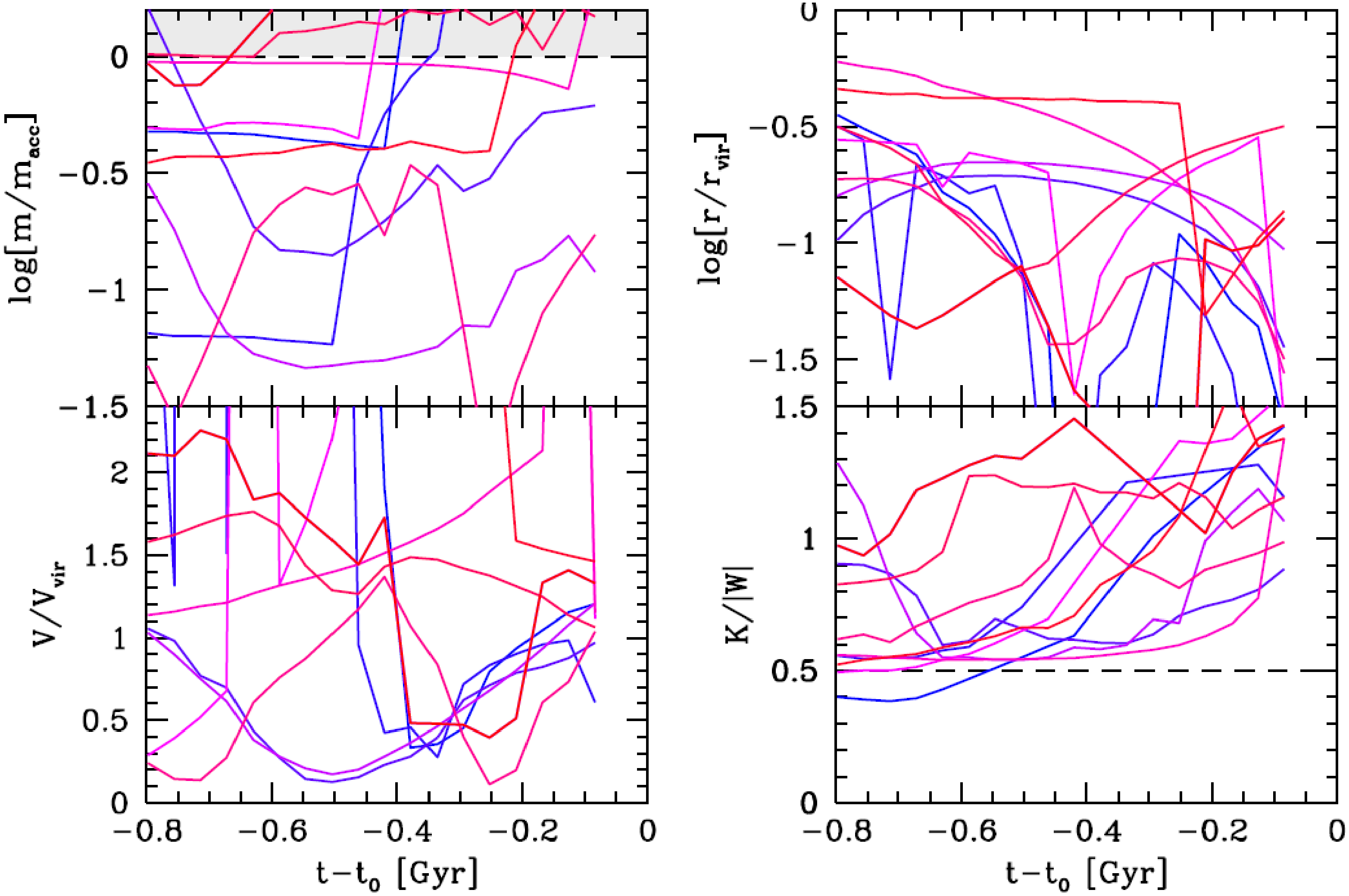
An example from a *high resolution* simulation

- van den Bosch (2017)
  - ✓Subhalo disruptions are common in the Bolshoi simulation (Klypin et al. 2011)
  - ✓65 (90) percent of subhalos accreted at z=1 (2) are disrupted by z=0





An example from a *high resolution* simulation



van den Bosch (2017)
[Data from the Bolshoi simulation
by Klypin et al. 2011]

80 percent of disruptions may be artificial…

Questions

- Are the subhalo disruption in current simulations real or artificial?
  -> van den Bosch, GO, Hahn & Burkert (2018)

- If artificial, how can we assess subhalos in simulations?
  -> van den Bosch & GO (2018)

- What is the true mass evolution of dark matter subhalos?
  -> GO, van den Bosch et al., in prep.

Questions

- **Are the subhalo disruption in current simulations real or artificial?**
  -> van den Bosch, GO, Hahn & Burkert (2018)

- If artificial, how can we assess subhalos in simulations?
  -> van den Bosch & GO (2018)

- What is the true mass evolution of dark matter subhalos?
  -> GO, van den Bosch et al., in prep.

van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Q. Are the disruptions real or artificial?

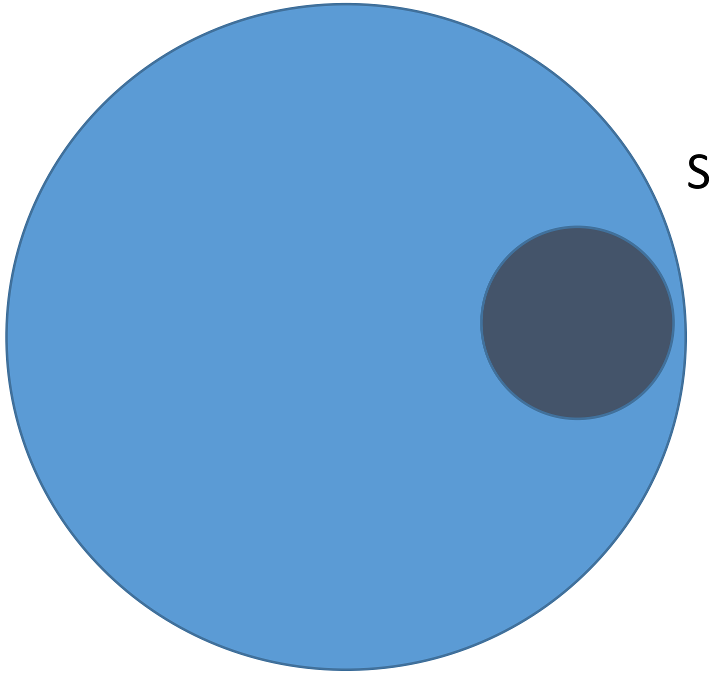
- Analytically estimated the mass-removing efficiency of
  - -Physical mechanisms
    - ✓Tidal shocking by the host halo
    - ✓Impulsive heating by subhalo-subhalo encounters
    - ✓Tidal stripping
  - -Artificial mechanisms
    - ✓Artificial two-body relaxation
    - ✓Heating due to encounters with particles in the host halo
    - ✓(When particles in the host halo are more massive)

Some parameters

Navarro, Frank & White (NFW, 1997)

$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})[1+(r/r_{\rm s})]^2}$$

$$c \equiv R_{\rm v}/r_{\rm s}$$



Host halo (ch=5)

Subhalo (cs=10)

Mhost/Msub = 1000

van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Q. Are the disruptions real or artificial?

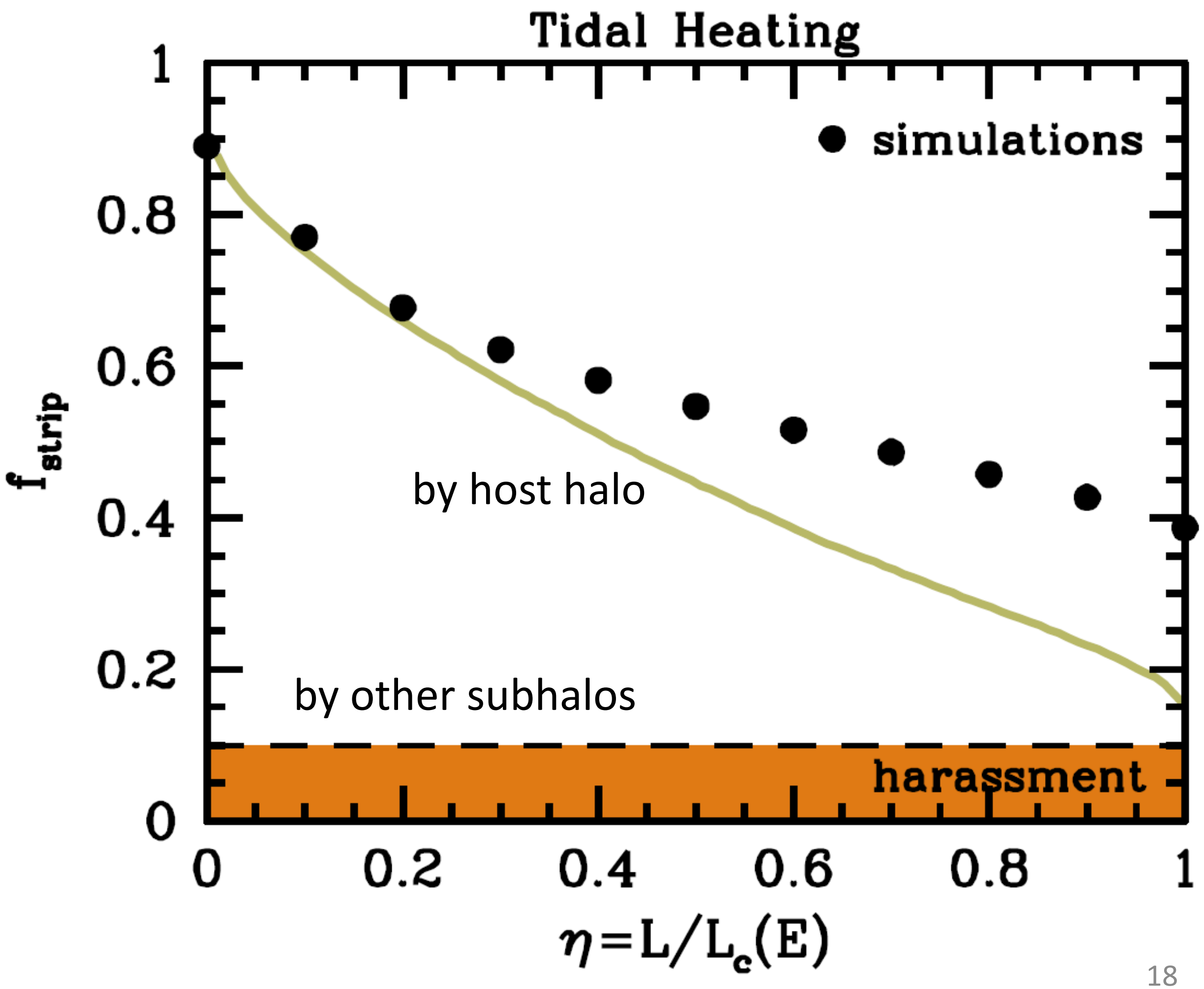
- Analytically estimated the mass-removing efficiency of
  - -**Physical mechanisms**
    - ✓ **Tidal shocking by the host halo**
    - ✓ **Impulsive heating by subhalo-subhalo encounters**
    - ✓ **Tidal stripping**
  - -Artificial mechanisms
    - ✓ Artificial two-body relaxation
    - ✓ Heating due to encounters with particles in the host halo
    - ✓ (When particles in the host halo are more massive)

van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Impulsive heating

- Comparison at t=Tr
- Analytical estimation (line)
  - ✓Heating by host dominates
- Simulations (circle)
  - ✓Using numerical parameters to get reliable results

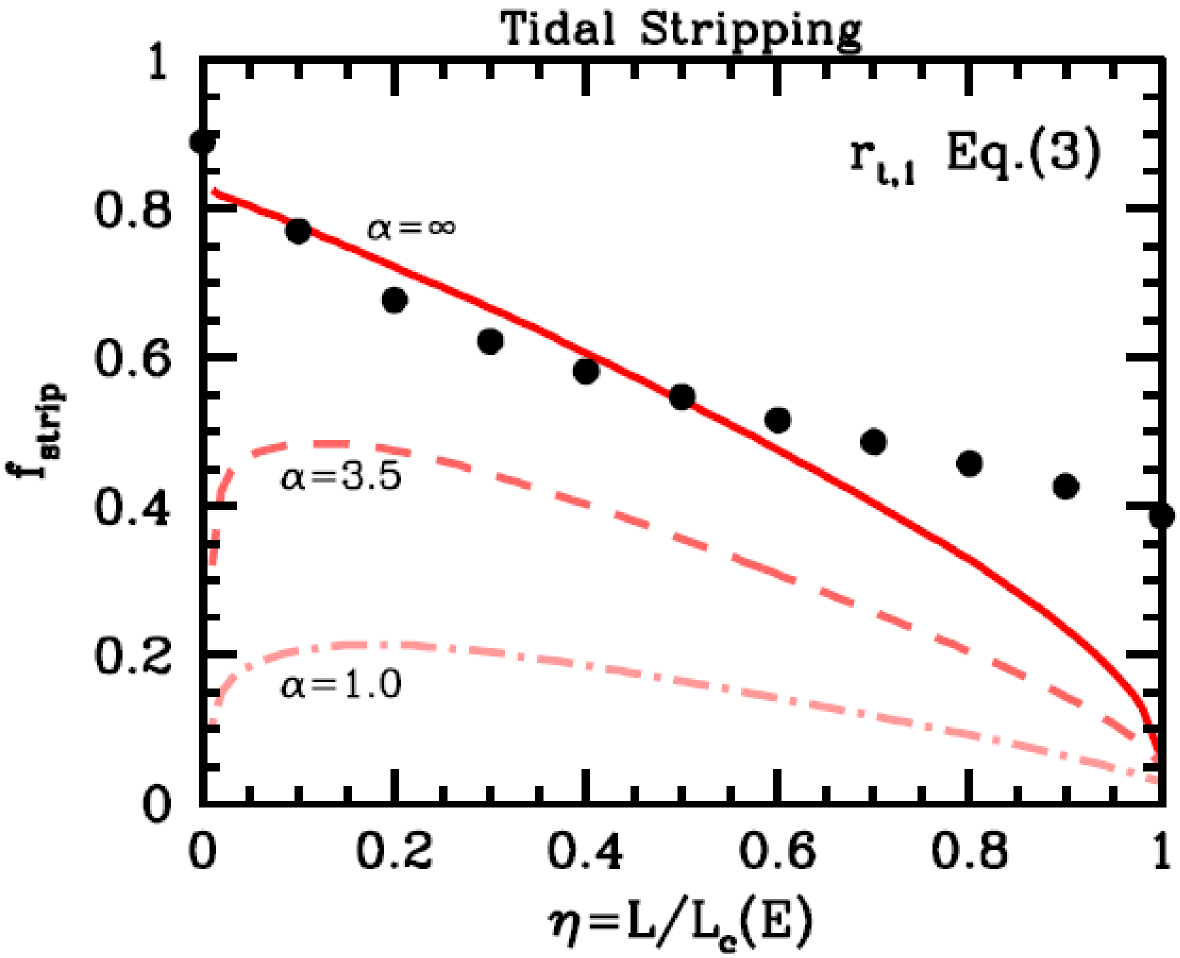
e.g. Gnedin et al. (1999); Gnedin & Ostriker (1999)



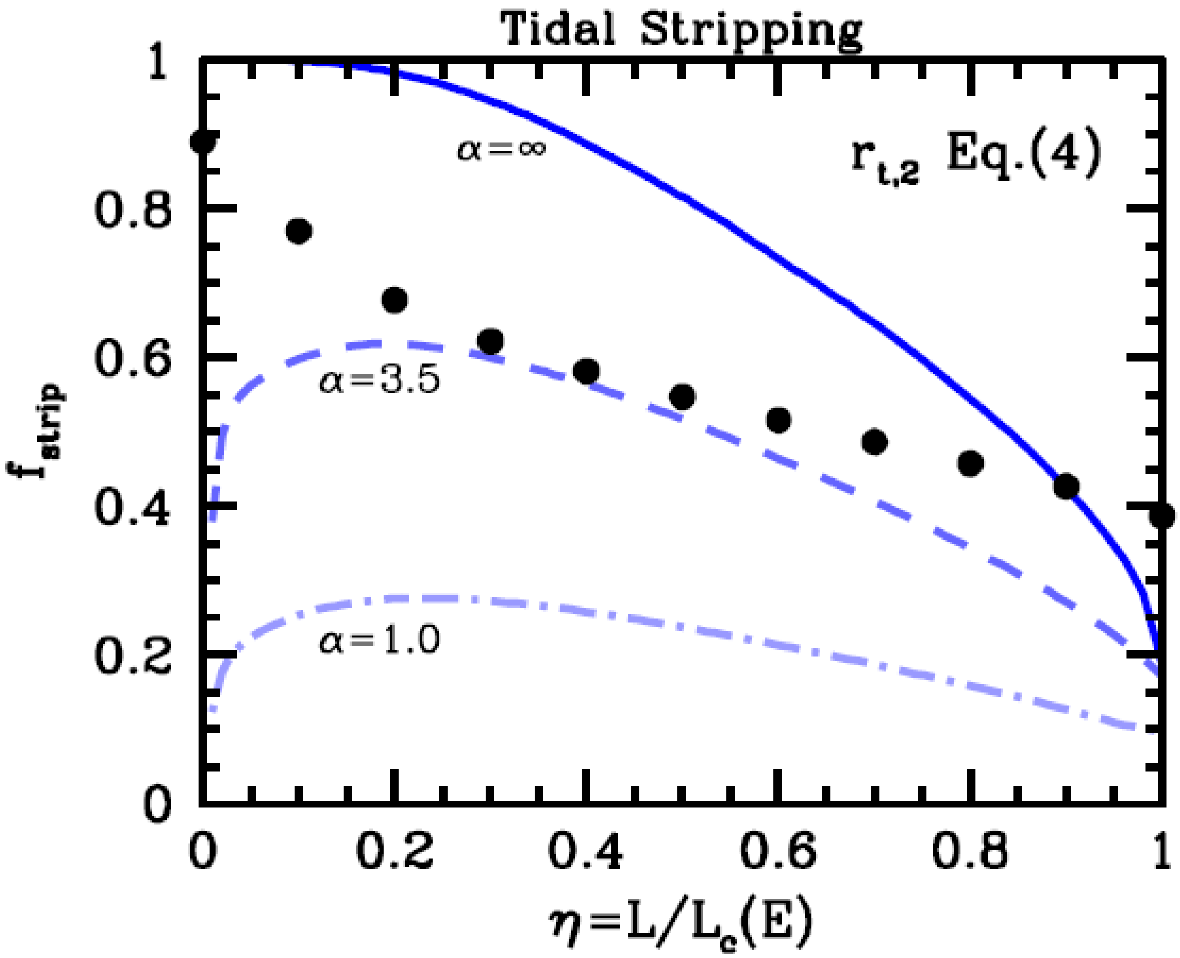
van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Tidal stripping

e.g. Tormen et al. (1998)



e.g. King (1962); Tollet et al. (2017)



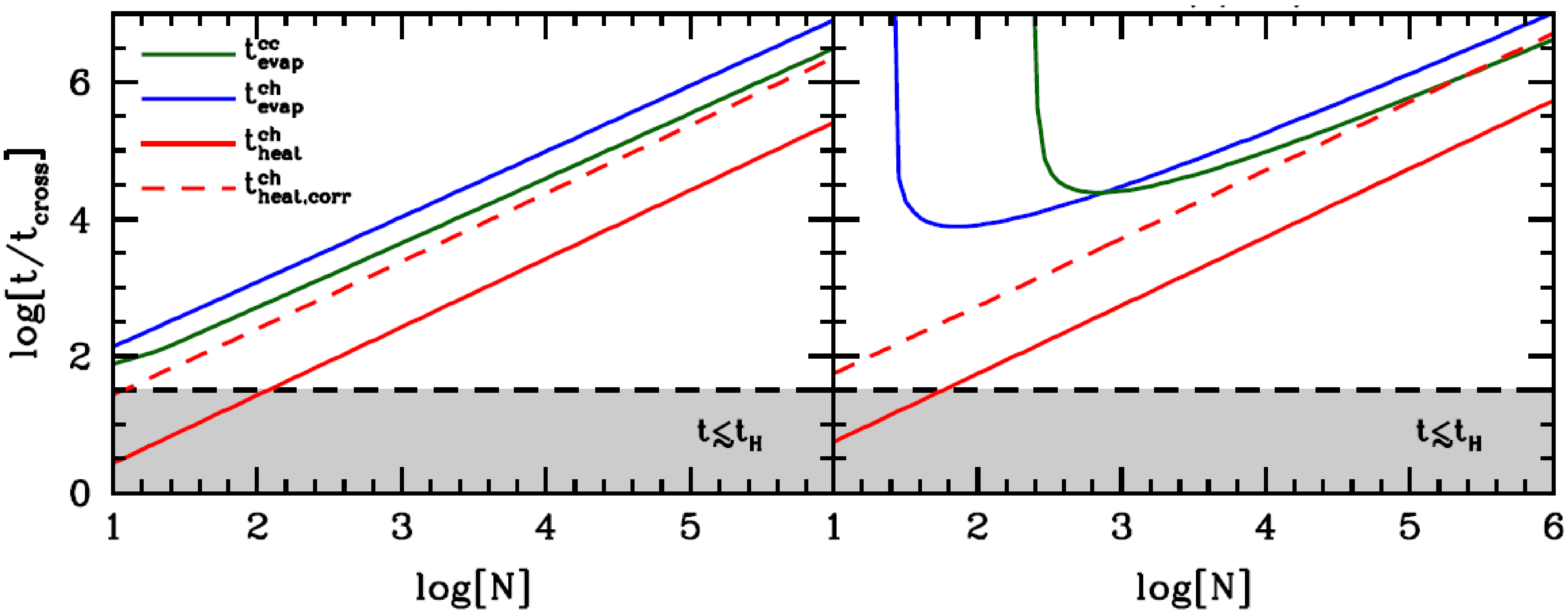
van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Q. Are the disruptions real or artificial?

- Analytically estimated the mass-removing efficiency of
  - ✖ -Physical mechanisms
    - ✓ Tidal shocking by the host halo
    - ✓ Impulsive heating by subhalo-subhalo encounters
    - ✓ Tidal stripping
  - -**Artificial mechanisms**
    - ✓ **Artificial two-body relaxation**
    - ✓ **Heating due to encounters with particles in the host halo**
    - ✓ **(When particles in the host halo are more massive)**

van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Timescales of evaporation



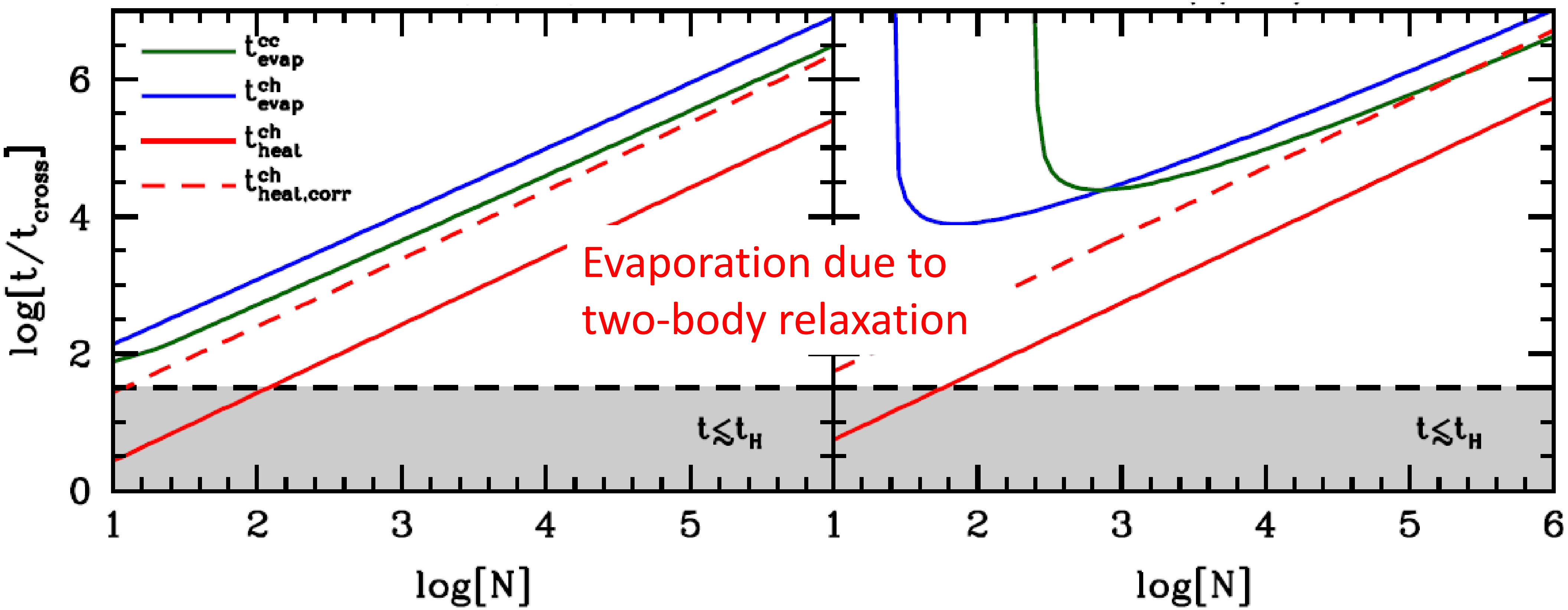
van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Timescales of evaporation

e.g. Binney & Tremaine

$$T_{\rm evap} = \frac{15N}{\log(\Lambda)} t_{\rm cross}$$

$$\Lambda = \min\{N, r_{\rm s}/4\epsilon\}$$



Evaporation due to two-body relaxation

van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Timescales of evaporation

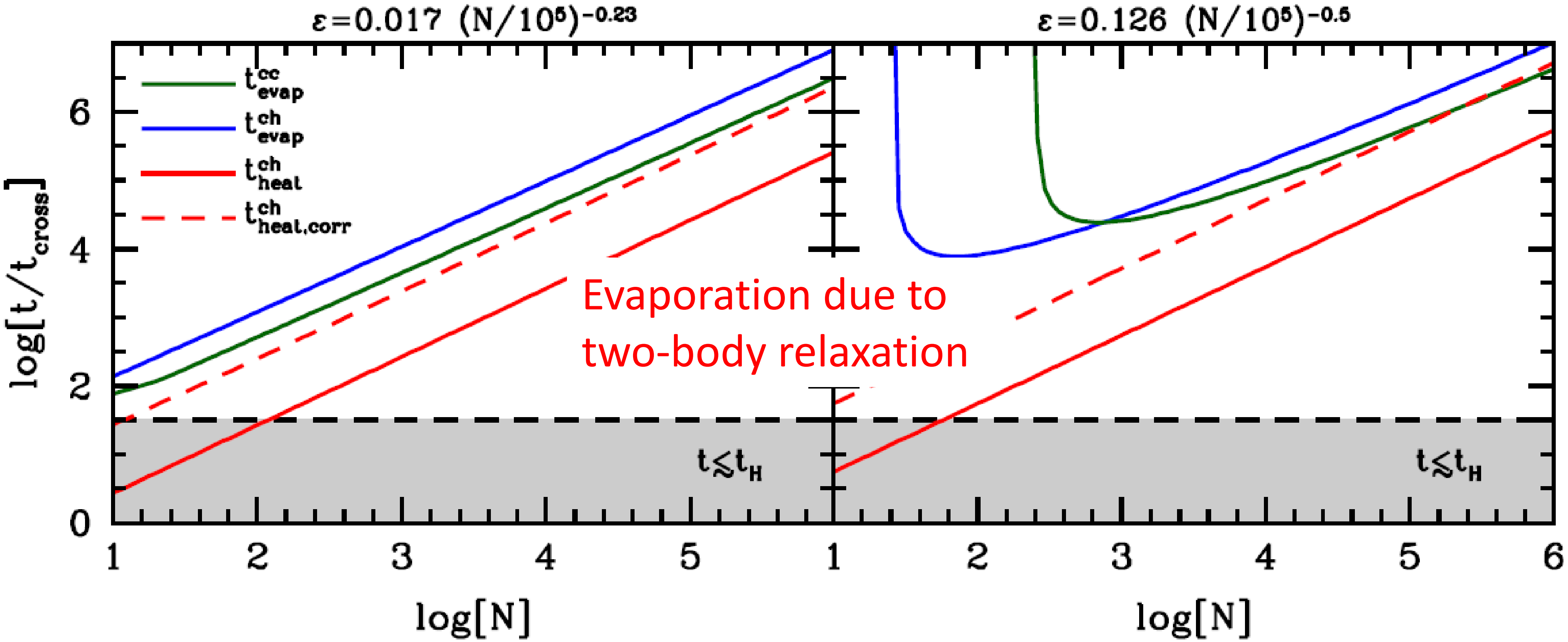
e.g. Binney & Tremaine

$$T_{\rm evap} = \frac{15N}{\log\left(\Lambda\right)} t_{\rm cross}$$

$$\Lambda = \min\left\{N, r_{\rm s}/4\epsilon\right\}$$

Dehnen (2001)

Power et al. (2003)



Evaporation due to two-body relaxation

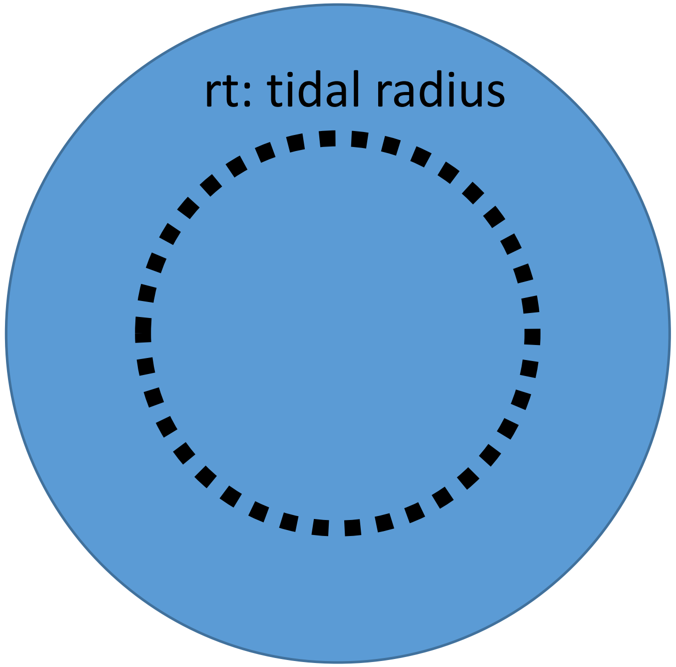
van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Q. Are the disruptions real or artificial?

- Analytically estimated the mass-removing efficiency of
  - ✖ -Physical mechanisms
    - ✓ Tidal shocking by the host halo
    - ✓ Impulsive heating by subhalo-subhalo encounters
    - ✓ Tidal stripping
  - ✖ -Artificial mechanisms
    - ✓ Artificial two-body relaxation
    - ✓ Heating due to encounters with particles in the host halo
    - ✓ (When particles in the host halo are more massive)
- **Instantaneous mass removal (Hayashi et al. 2003)**

vs. Hayashi et al. (2003)

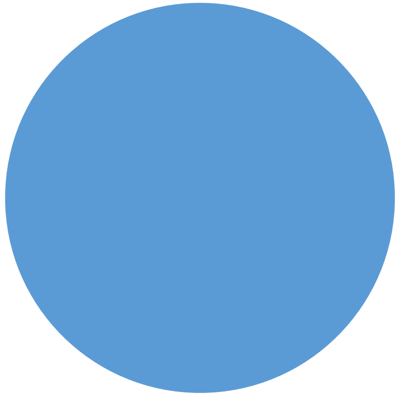
- Instantaneous mass removal at r>rt by tidal force



vs. Hayashi et al. (2003)

- Instantaneous mass removal at r>rt by tidal force
- If rt<0.77rs, the total binding energy of the remnant becomes positive

->complete disruption of an NFW halo



vs. Hayashi et al. (2003)

- Instantaneous mass removal at r>rt by tidal force
- If rt<0.77rs, the *total* binding energy of the remnant becomes positive

->complete disruption of an NFW halo

Part of the remnant can be bound (negative energy)

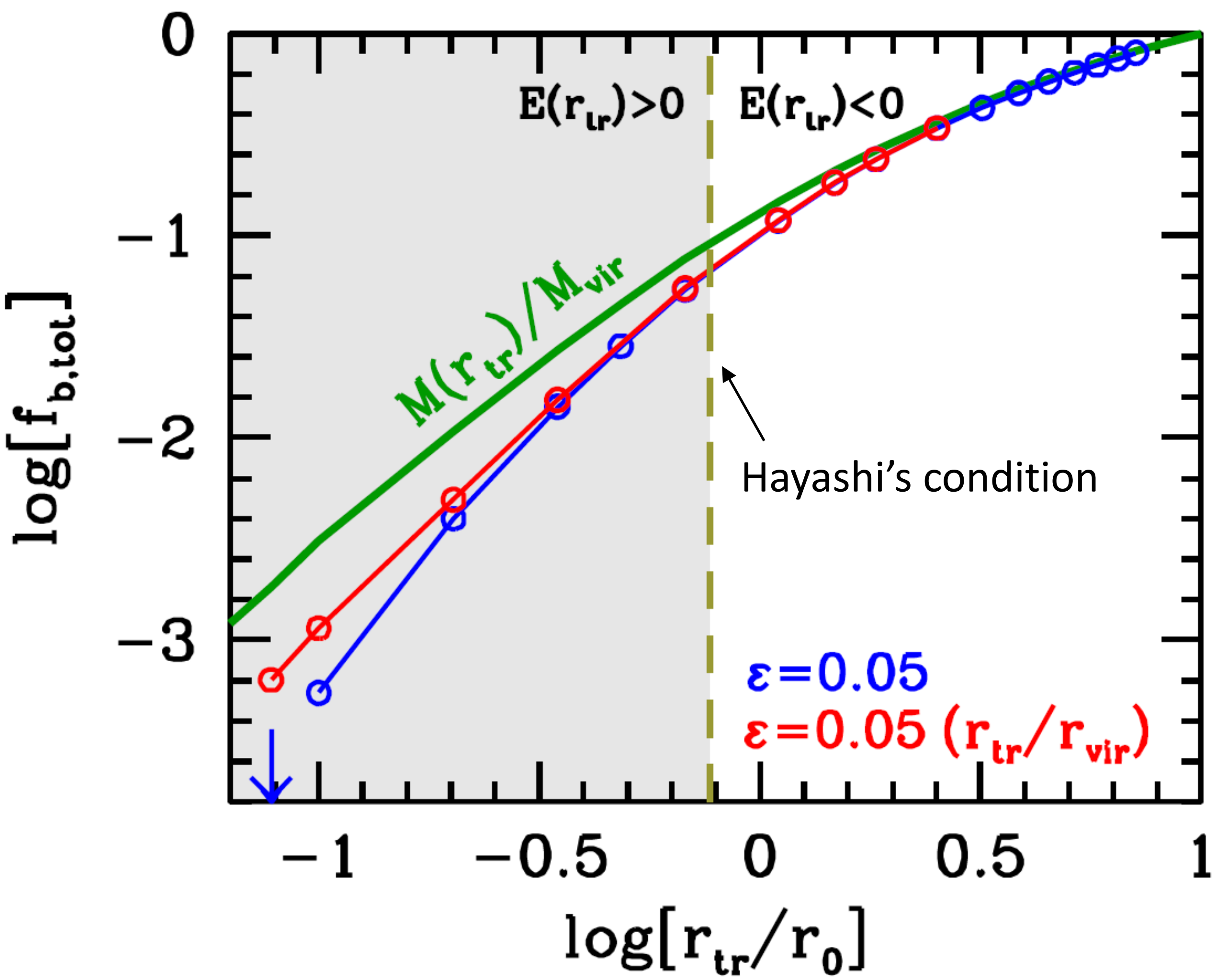
-> not complete disruption

van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

vs. Hayashi et al. (2003)

- Bound mass fraction of systems instantaneously removed mass at r>rt
  - ✓After evolution of 50Gyr
  - ✓No host

- Part of remnant remains bound even if Hayashi's condition is satisfied



van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Q. Are the disruptions real or artificial?

- Analytically estimated the mass-removing efficiency of

✖ -Physical mechanisms

  - ✓ Tidal shocking by the host halo
  - ✓ Impulsive heating by subhalo-subhalo encounters
  - ✓ Tidal stripping

✖ -Artificial mechanisms

  - ✓ Artificial two-body relaxation
  - ✓ Heating due to encounters with particles in the host halo
  - ✓ (When particles in the host halo are more massive)

✖ Instantaneous mass removal (Hayashi et al. 2003)

A. Most of disruptions would be driven by
other artificial mechanisms

Questions

- Are the subhalo disruption in current simulations real or artificial?
  -> van den Bosch, GO, Hahn & Burkert (2018)

- **If artificial, how can we assess subhalos in simulations?**
  -> van den Bosch & GO (2018)

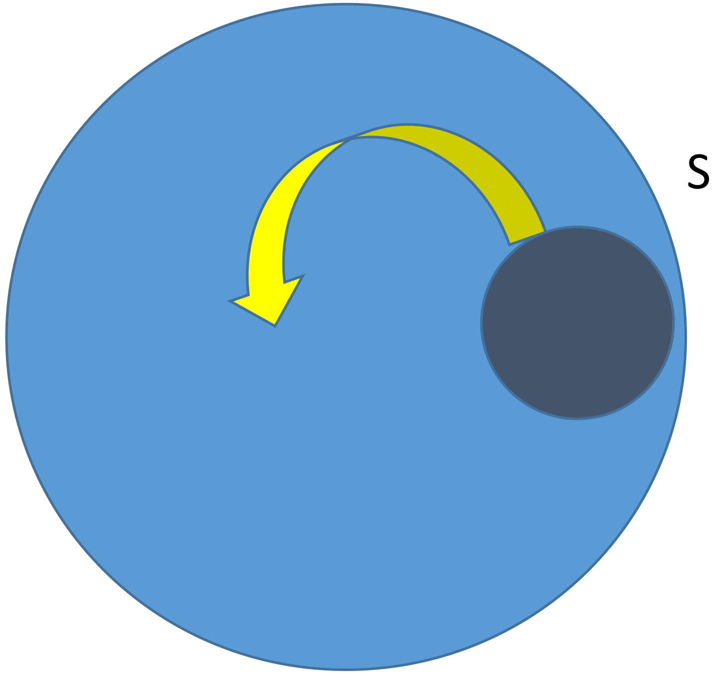
- What is the true mass evolution of dark matter subhalos?
  -> GO, van den Bosch et al., in prep.

>1000 idealized simulations

Navarro, Frank & White (NFW, 1997)

$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})[1+(r/r_{\rm s})]^2}$$

$$c \equiv R_{\rm v}/r_{\rm s}$$



Host halo = fixed potential (ch=5)

Subhalo = *N*-body system (cs=10)

Mhost/Msub = 1000 -> can neglect dynamical friction

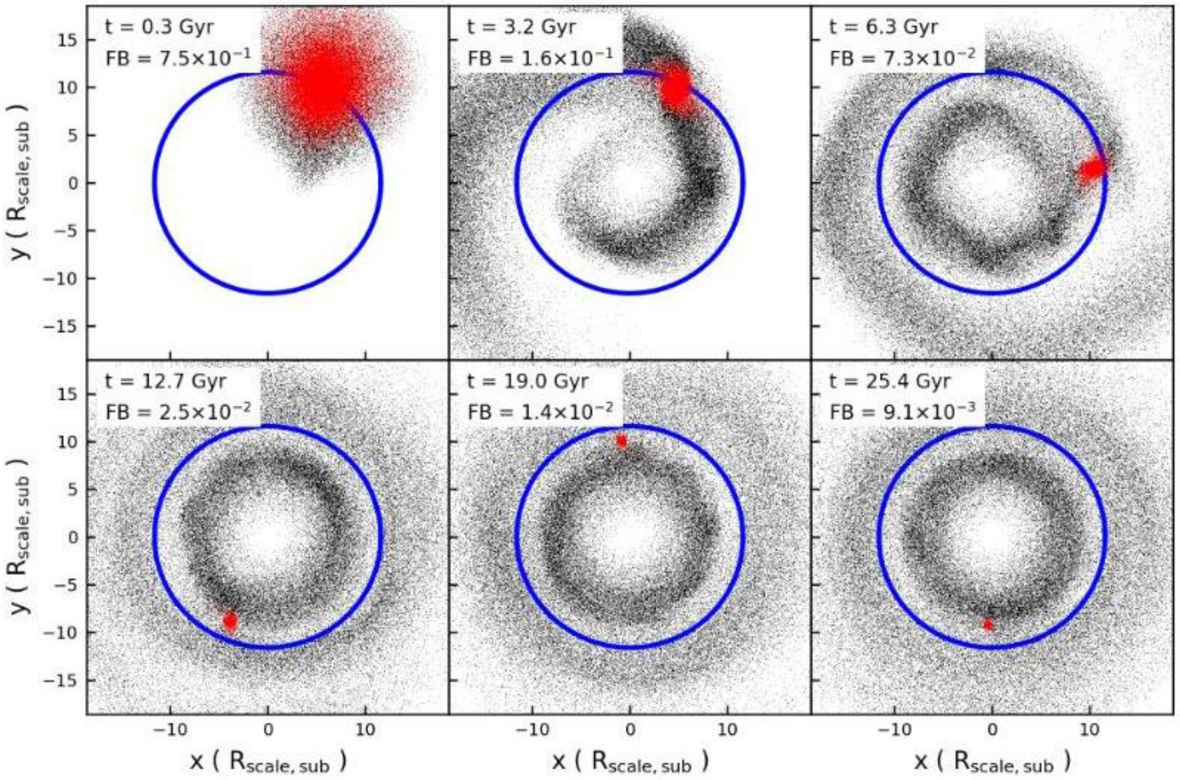
$$\tau_{\rm decay} \sim \frac{M_{\rm host}}{M_{\rm sub}} \tau_{\rm ff}$$

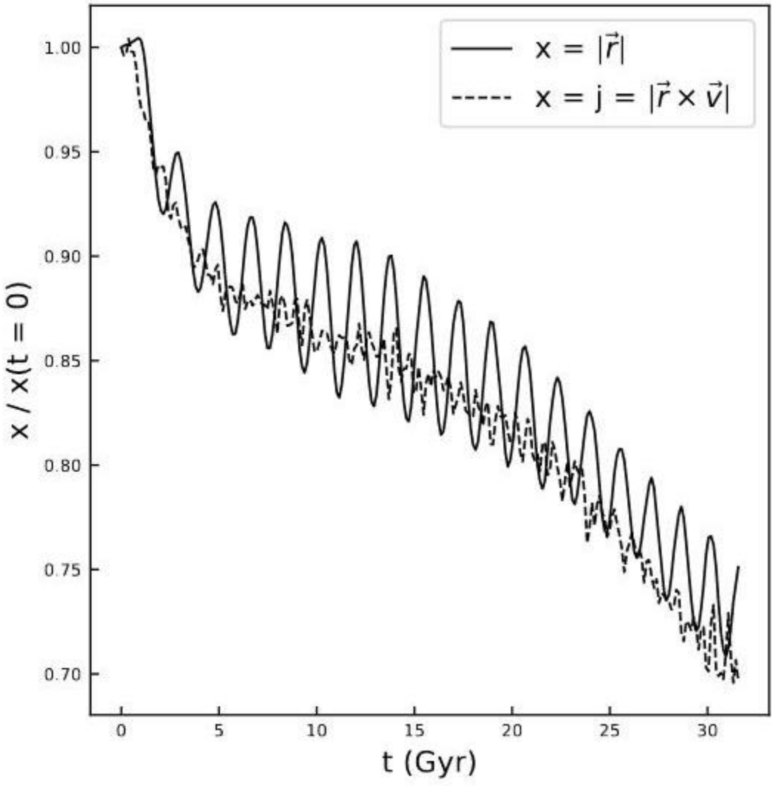
Vary numerical parameters
(and orbital parameters)

Miller, van den Bosch & GO, in prep.
See also Fujii et al. (2006); Fellhauer & Lin (2007); van den Bosch & GO (2018)

Friction force by stripped matter

- Use of an analytical potential -> absence of classical DF (Chandrasekhar 1943)
- But orbit shrinks and angular momentum is lost

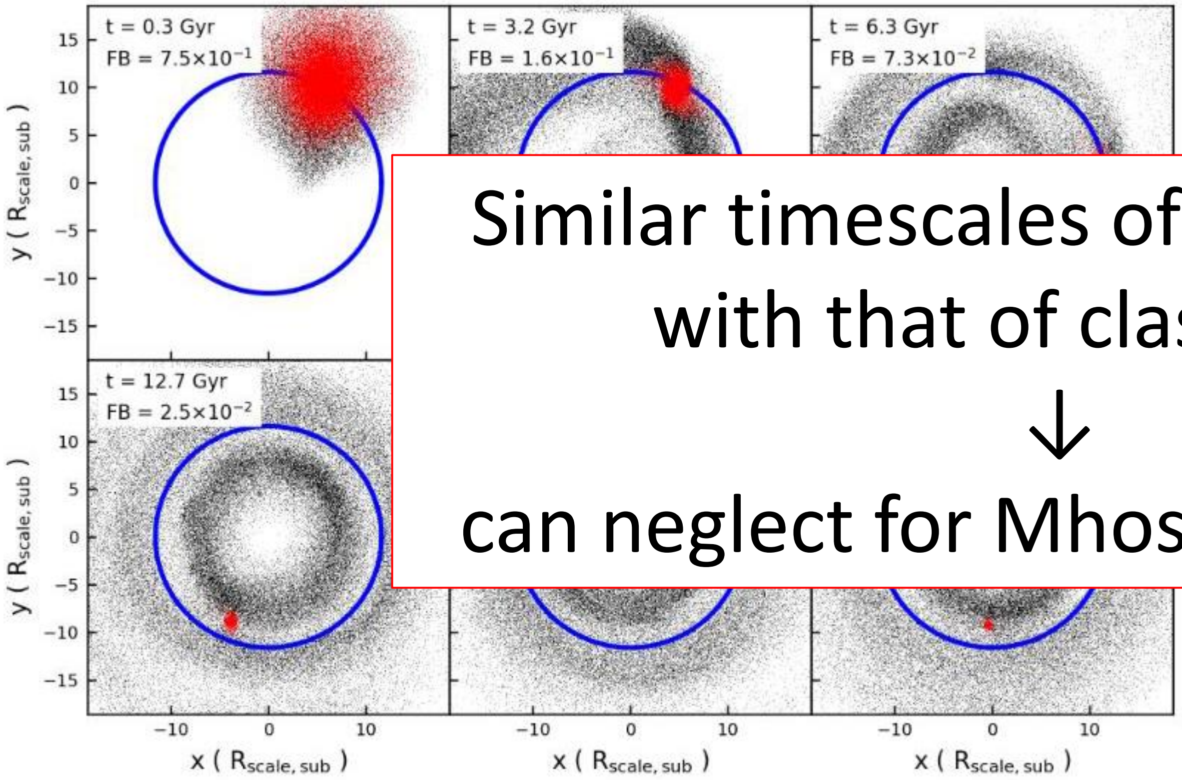


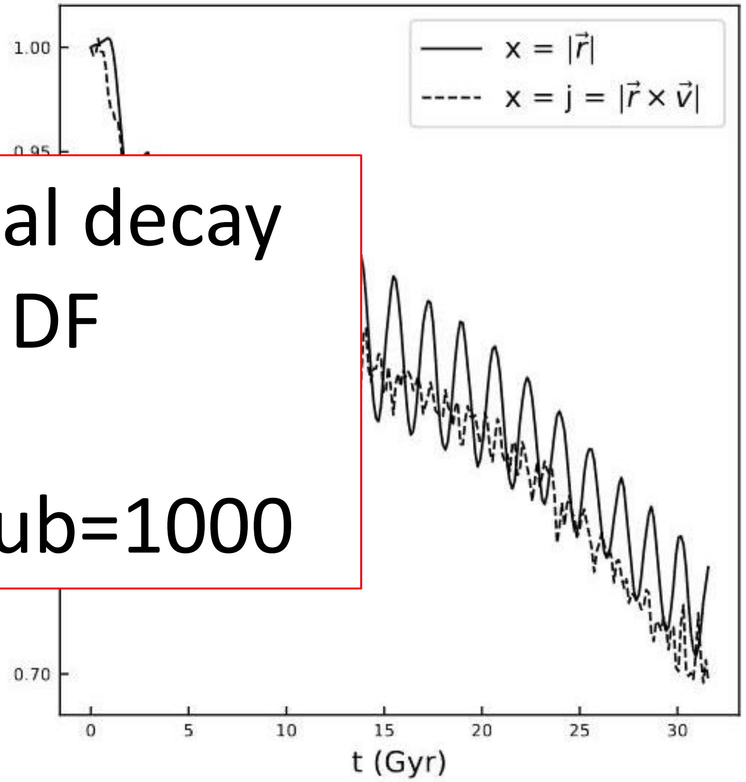


Miller, van den Bosch & GO, in prep.
See also Fujii et al. (2006); Fellhauer & Lin (2007); van den Bosch & GO (2018)

Friction force by stripped matter

- Use of an analytical potential -> absence of classical DF (Chandrasekhar 1943)
- But orbit shrinks and angular momentum is lost





Similar timescales of orbital decay with that of classical DF
↓
can neglect for Mhost/Msub=1000

← Small ε

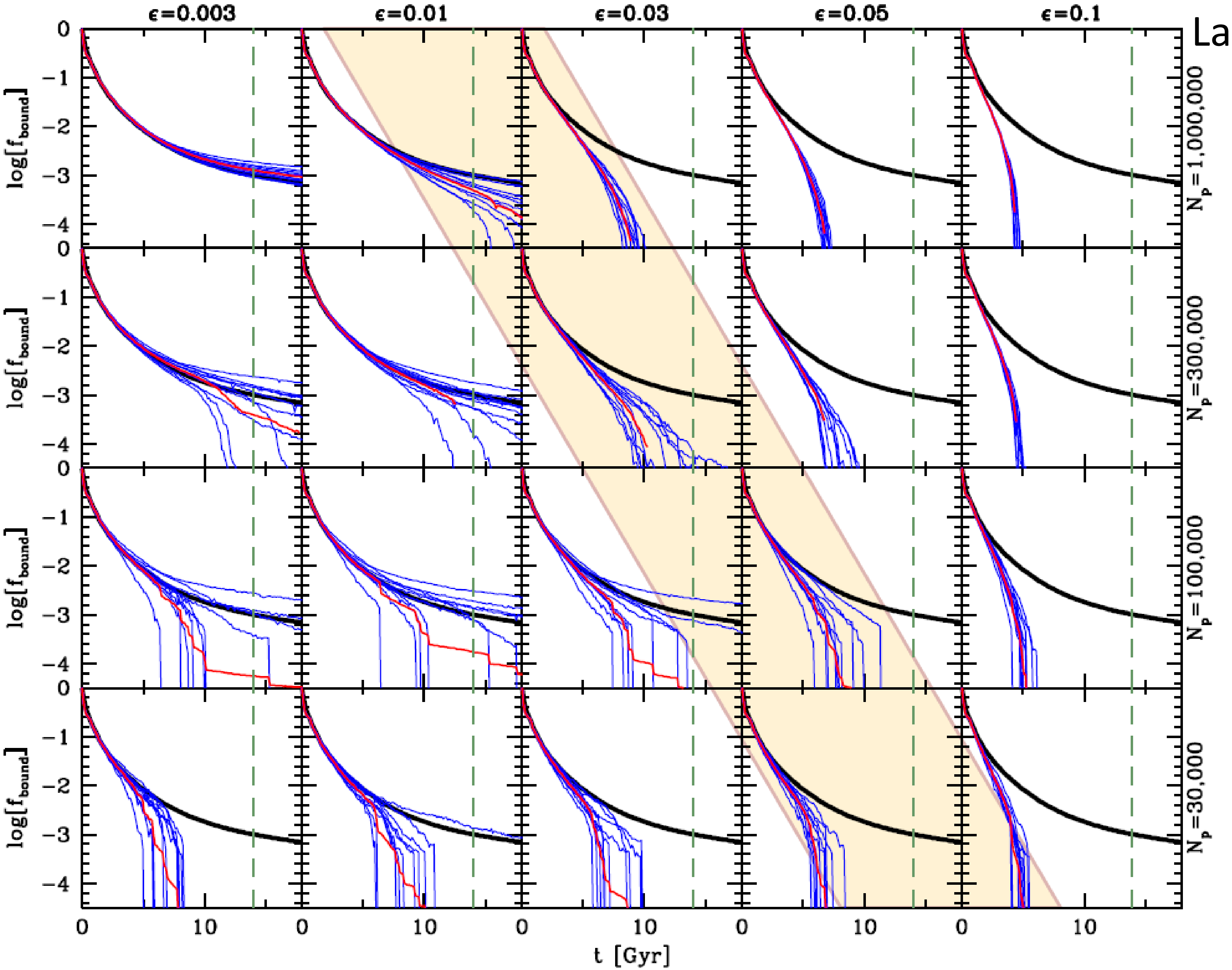
(Same orbits)

Black: converged (true) results

Blue: 10 random realizations

Red: average

Shaded: cosmo. sims



Large ε →

↑ Large N

Small N ↓

van den Bosch & GO
(arXiv:1801.05427)

What collisionless *N*-body simulations actually solve

- Galaxies and galaxy clusters and their DM halos should be collisionless systems with the *infinite* number of particles
  - ✓Particle motion is governed by the smooth potential field
- Simulations have the *finite* number of particles
  - ✓Two-body scattering may play a role = can be collisional

Newtonian force

Collisionless *N*-body sims

$$a \propto 1/r^2 \quad \Rightarrow \quad a \propto 1/(r^2 + \epsilon^2)$$

ε: softening parameter

Suppress two-body scattering to ensure
the nature of collisionless systems

← Small ε

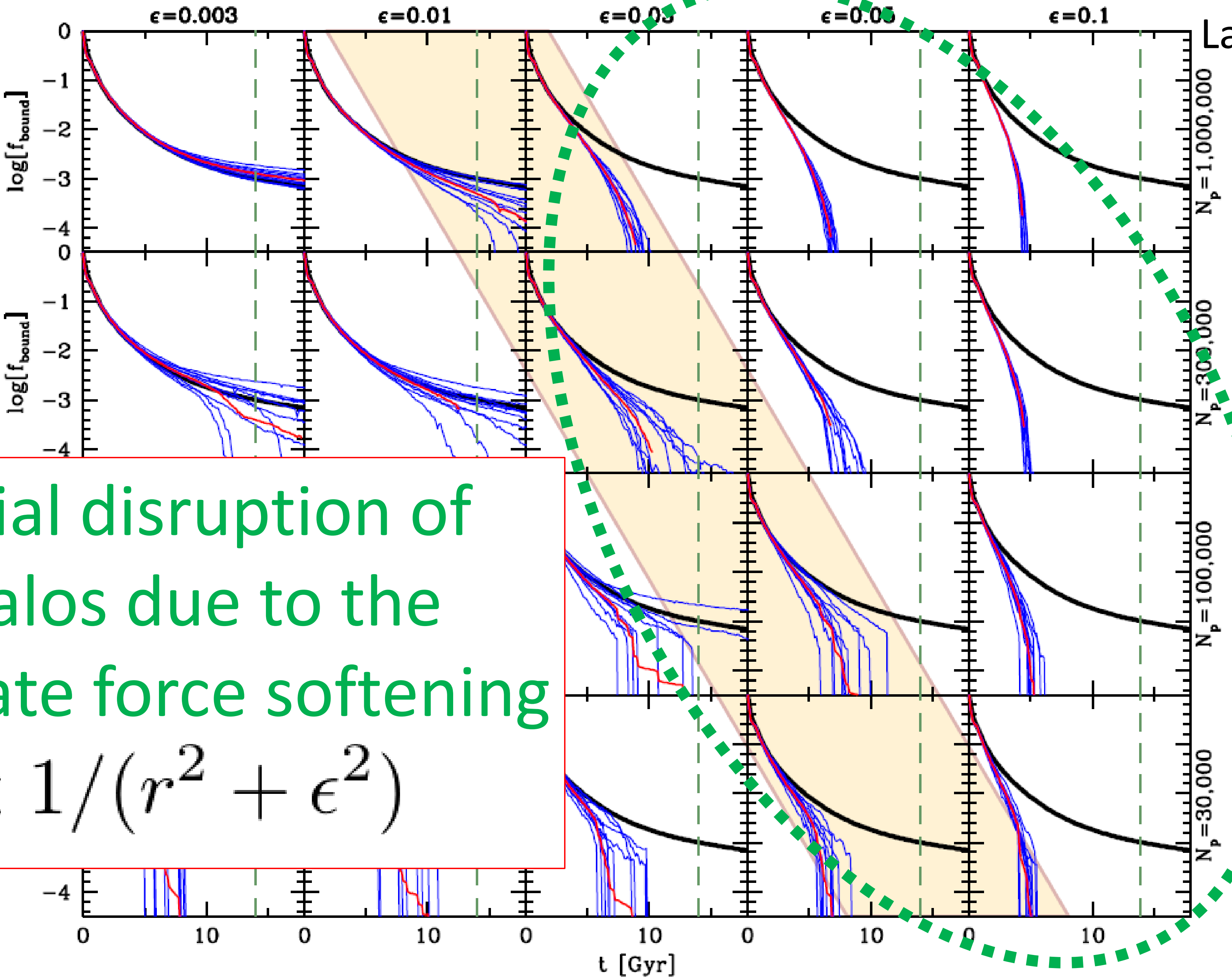
Large ε →

(Same orbits)

Black: converged (true) results

Blue: 10 random realizations

Red: average



↑ Large N

Small N ↓

Artificial disruption of subhalos due to the inadequate force softening

$$a \propto 1/(r^2+\epsilon^2)$$

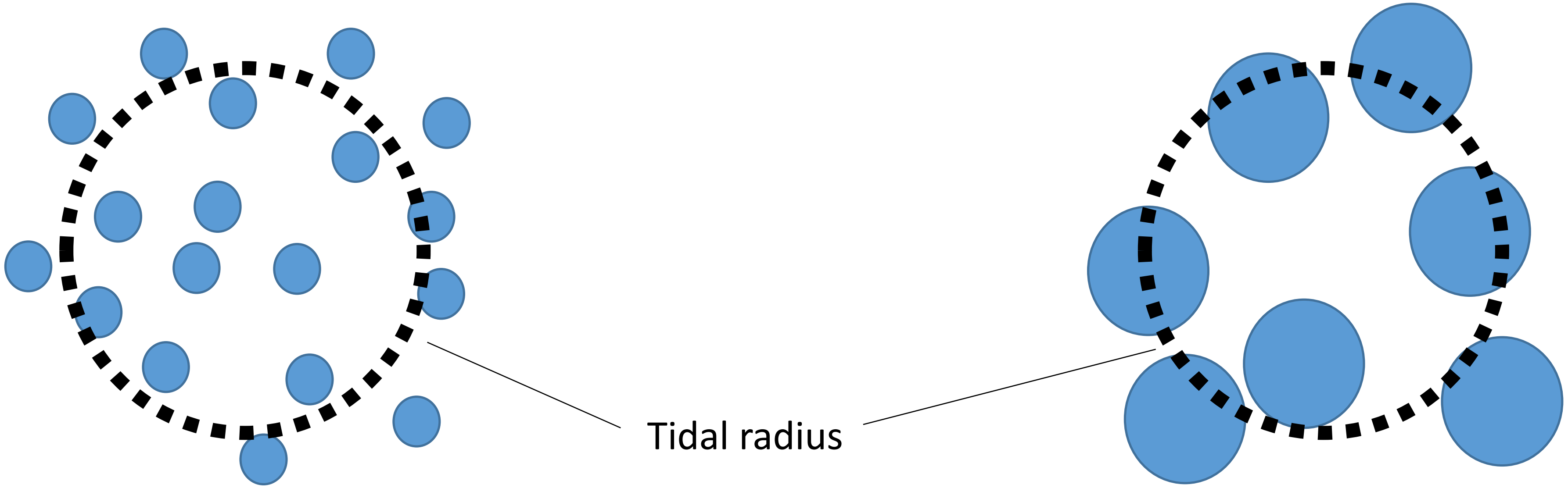
van den Bosch & GO (arXiv:1801.05427)

Instability triggered by discreteness noise

Modeling a system with the same mass of M, but with different N

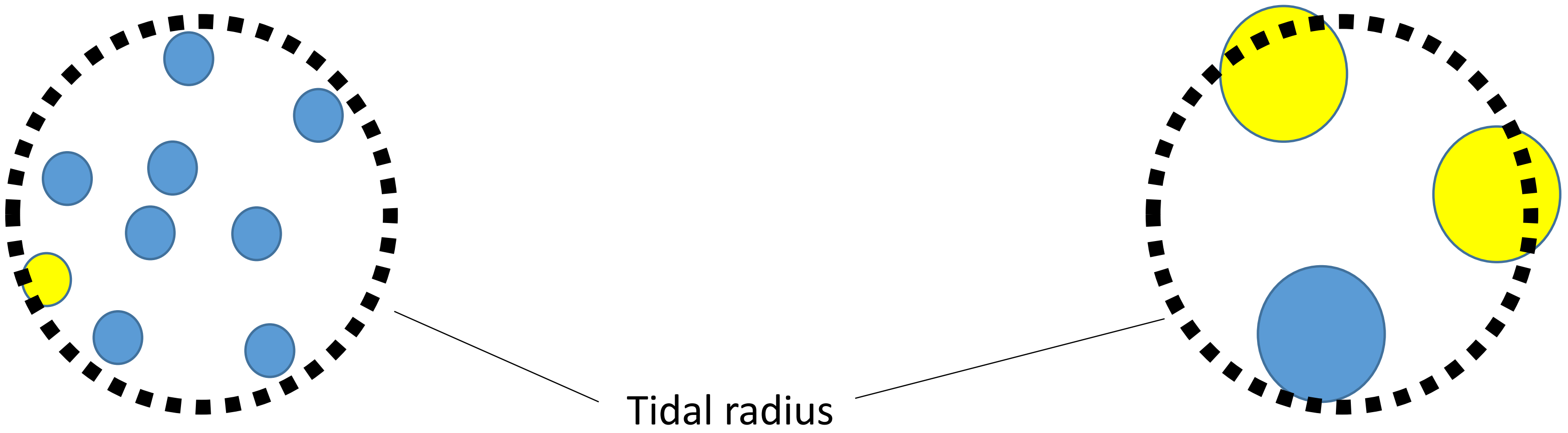
Instability triggered by discreteness noise

Modeling a system with the same mass of M, but with different N



Instability triggered by discreteness noise

Some of remained particles may escape from the system during the subsequent relaxation process



Instability triggered by discreteness noise

Some of remained particles may escape from the system during the subsequent relaxation process

Can be disrupted

← Small ε

Large ε →

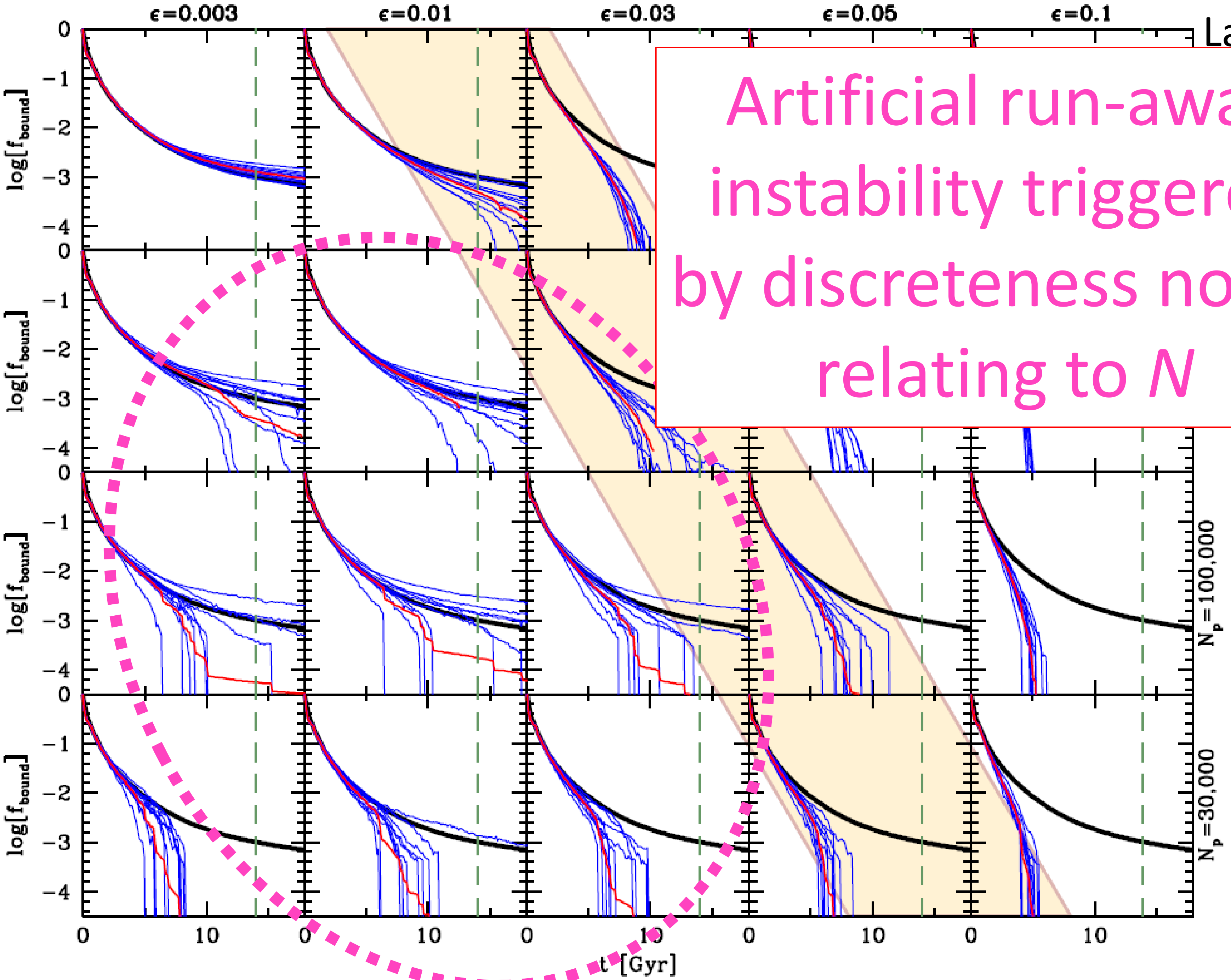
(Same orbits)

Black: converged (true) results

Blue: 10 random realizations

Red: average

Shaded: cosmo. sims



Artificial run-away instability triggered by discreteness noise, relating to *N*

Small N →

van den Bosch & GO (arXiv:1801.05427)

van den Bosch & GO
(arXiv:1801.05427)

Q. How can we assess subhalos in simulations?

A. When subhalos break

1) $$\frac{GM_{\rm tot}(t)}{2r_{\rm h}(t)\epsilon} > \lim_{r\to 0}\frac{GM(t_{\rm acc},r)}{r^2}$$

or

2) $$N(t) > 80N(t_{\rm acc})^{0.2}$$

they are not reliable

Questions

- Are the subhalo disruption in current simulations real or artificial?

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

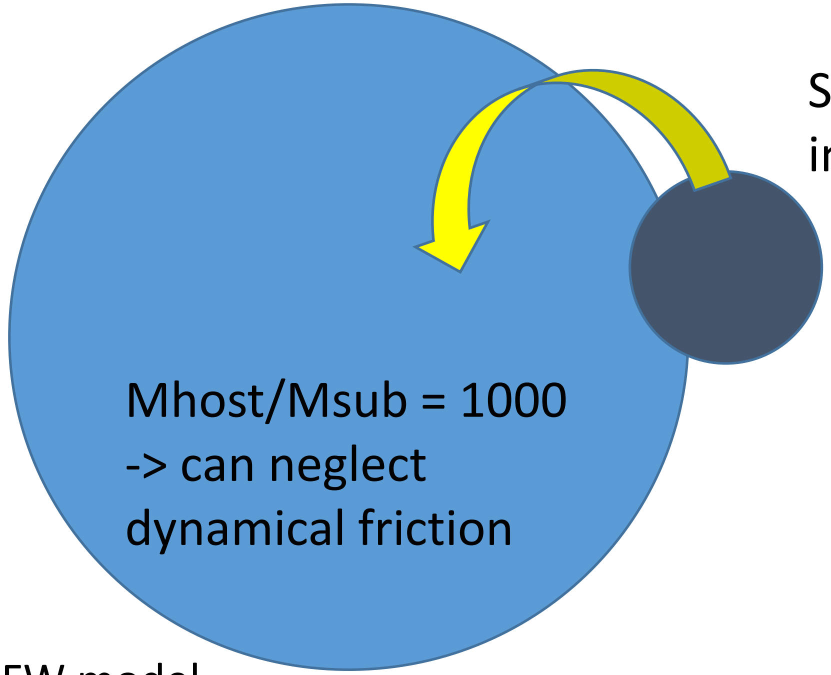
- If artificial, how can we assess subhalos in simulations?

  -> van den Bosch & GO (2018)

- **What is the true mass evolution of dark matter subhalos?**

  -> GO, van den Bosch et al., in prep.

Making empirical function, fb(t; a, b,…)



Host halo = fixed potential

Subhalo = *N*-body
initially at apocenter

Mhost/Msub = 1000
-> can neglect
dynamical friction

NFW model

$$\rho(r) = \frac{\rho_s}{(r/r_s)[1+(r/r_s)]^2}$$

$$c \equiv R_v/r_s$$

- Numerical parameters
  - ✓ N=10^7
  - ✓ ε=0.0003Rv,s
  - ✓ θ=0.7

  Results reliable when fb>0.002
  (van den Bosch & Ogiya 2018)
- Vary orbital parameters
  - ✓ Orbital energy (xc)
  - ✓ Angular momentum (η)

  54 runs for now
- Vary structural parameters (next step)

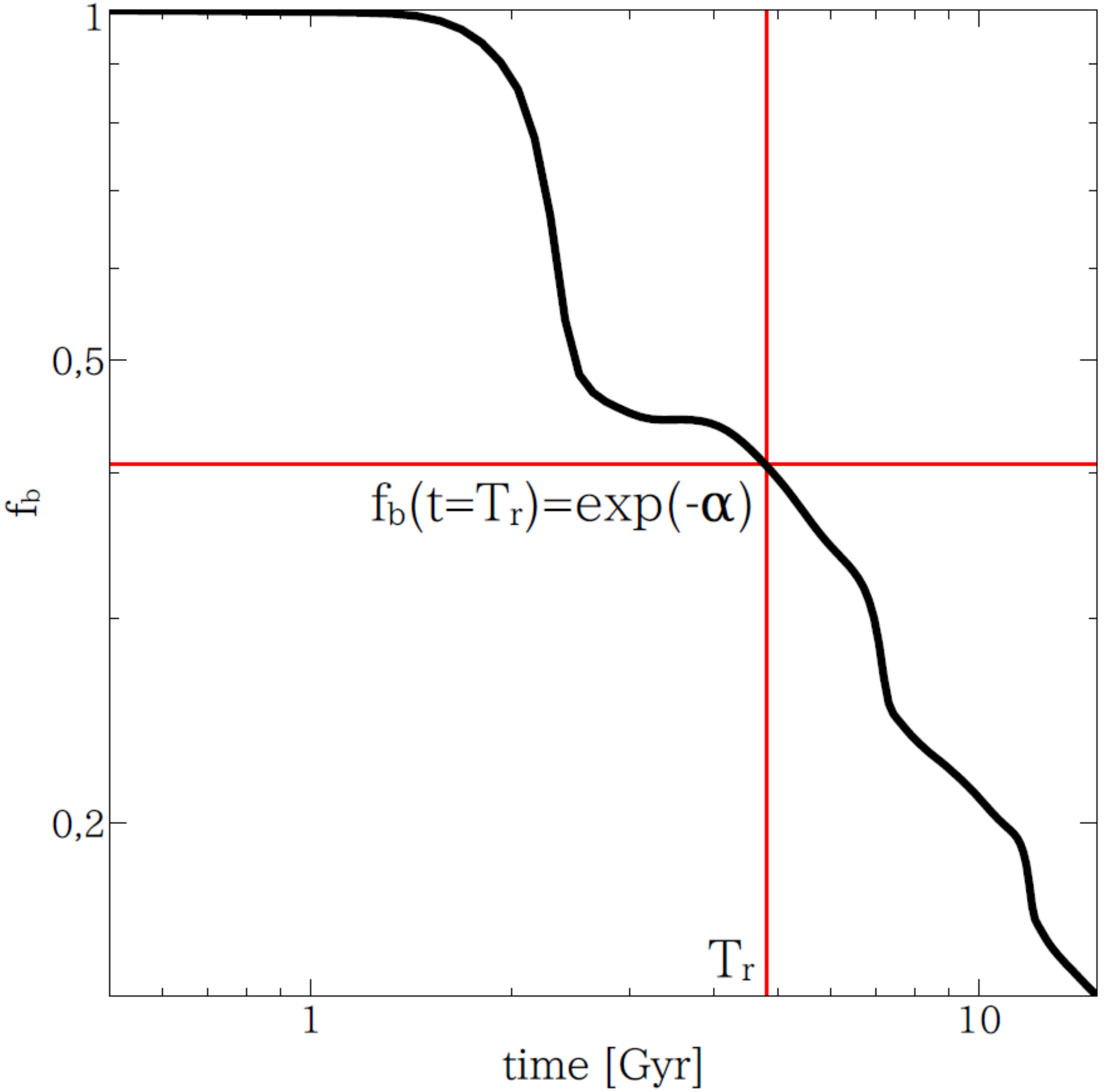
Ogiya, van den Bosch et al., in prep.

Fitting formula for fb(t)

Modeling the evolution of fb in two steps

Step 1. When the subhalo reaches at the apocenter after the 1st pericentric passage, i.e. at t=Tr,

$$f_{\rm b}(t=T_{\rm r}) = \exp\left(-\alpha\right)$$



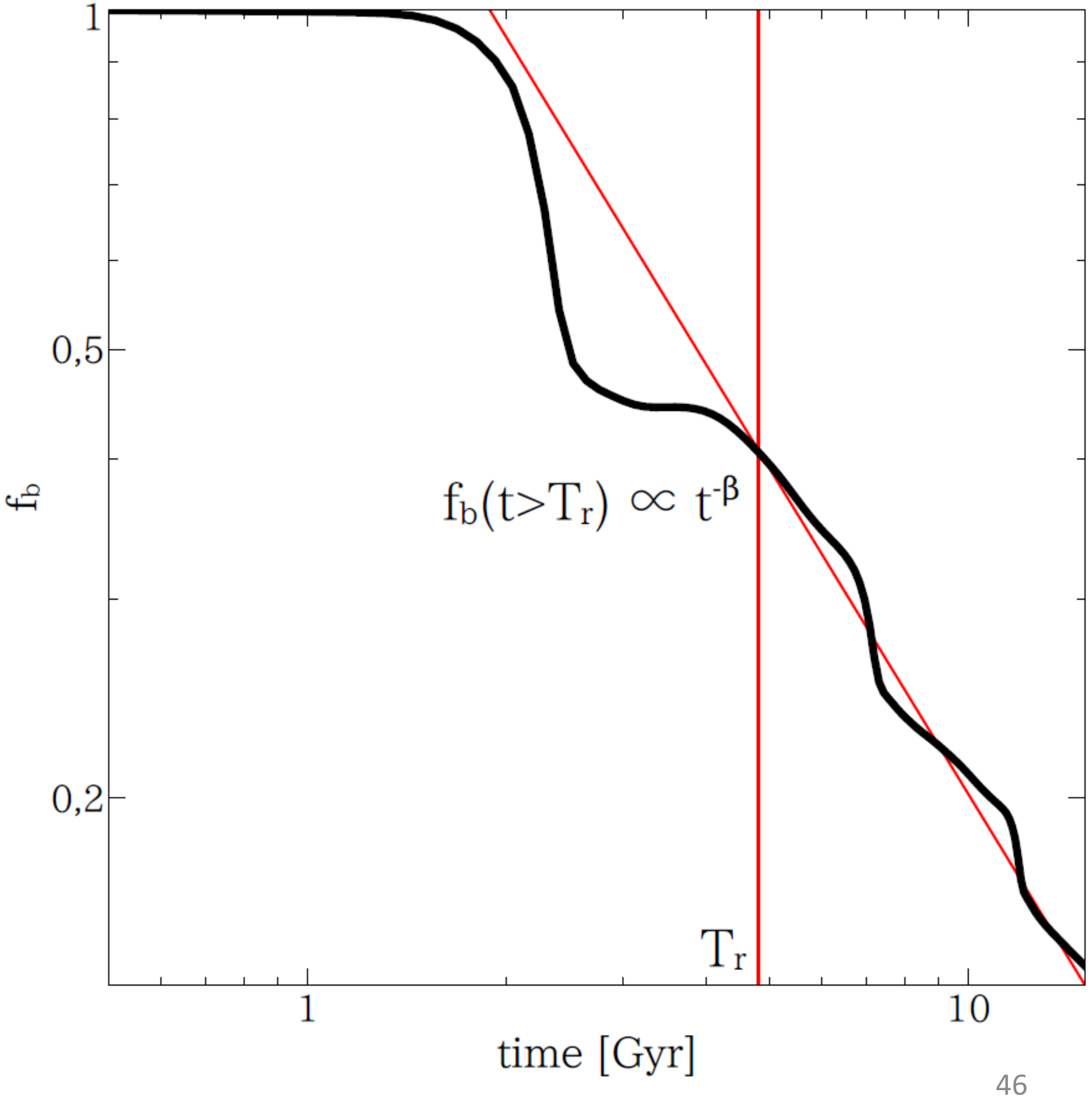
Ogiya, van den Bosch et al., in prep.

Fitting formula for fb(t)

Modeling the evolution of fb in two steps

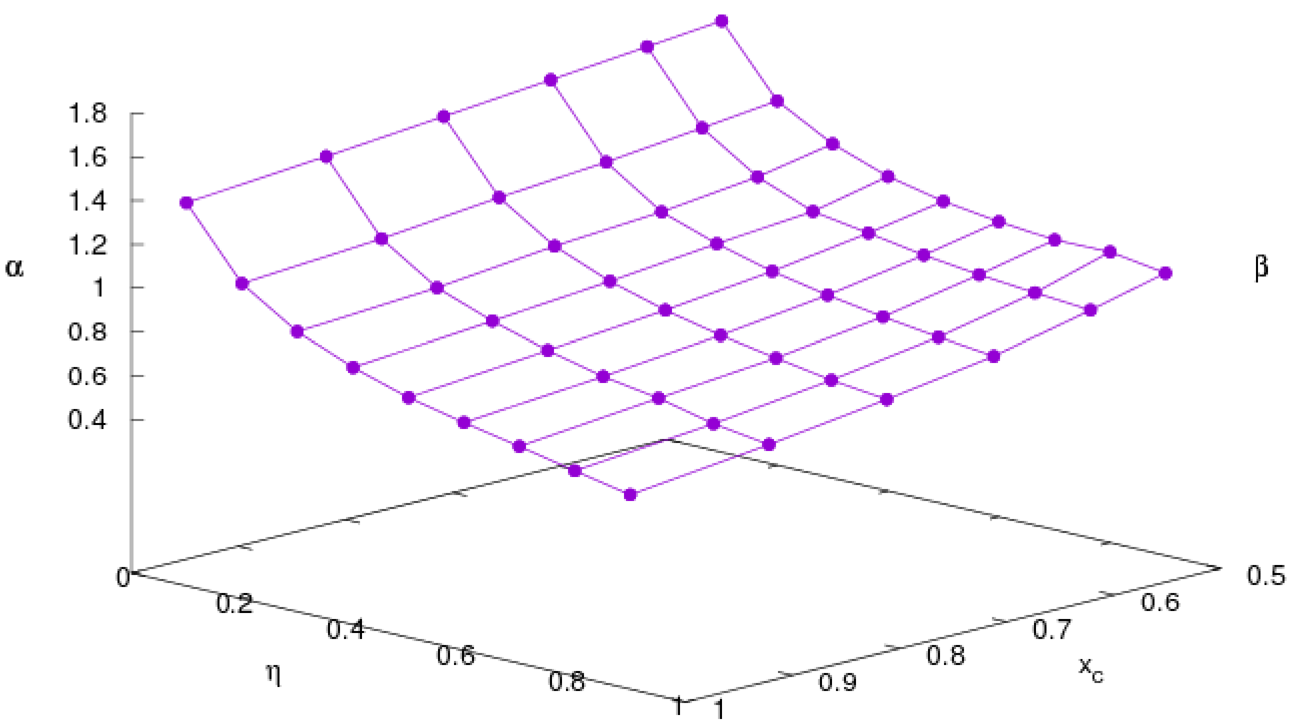
Step 2. At t > Tr,

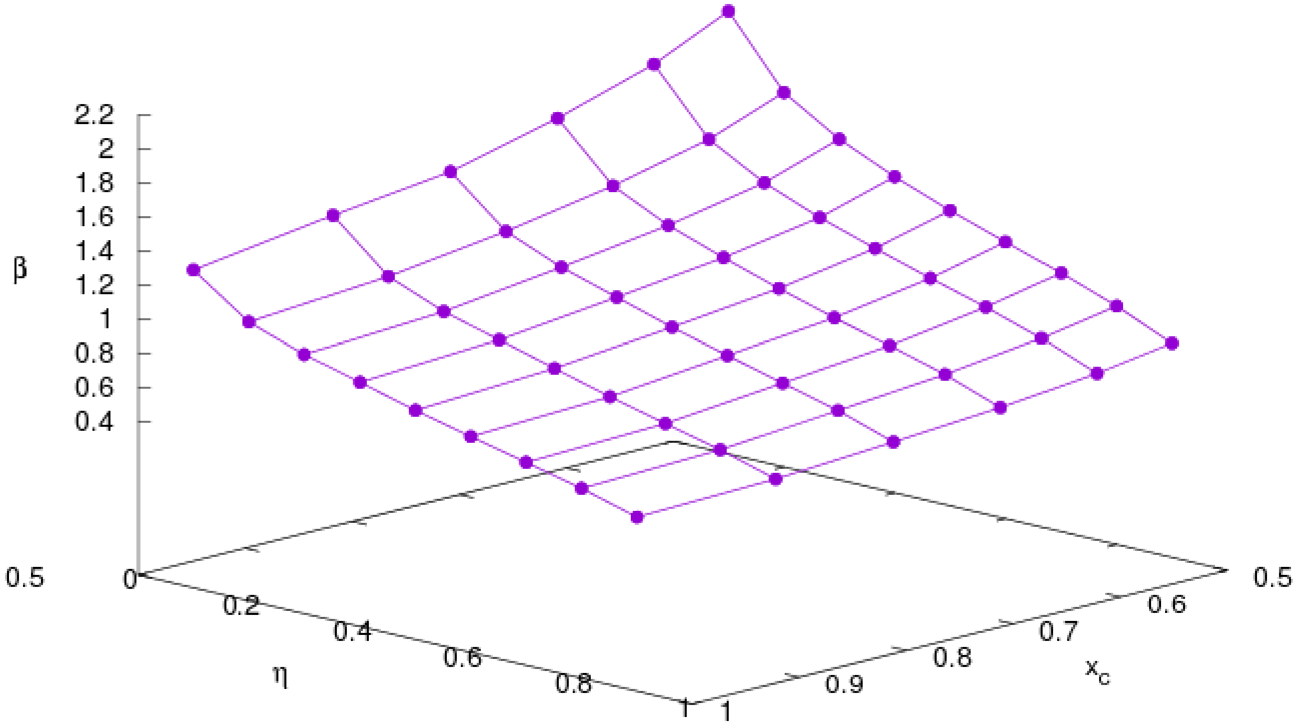
$$f_{\rm b}(t > T_{\rm r}) \propto t^{-\beta}$$



Ogiya, van den Bosch et al., in prep.

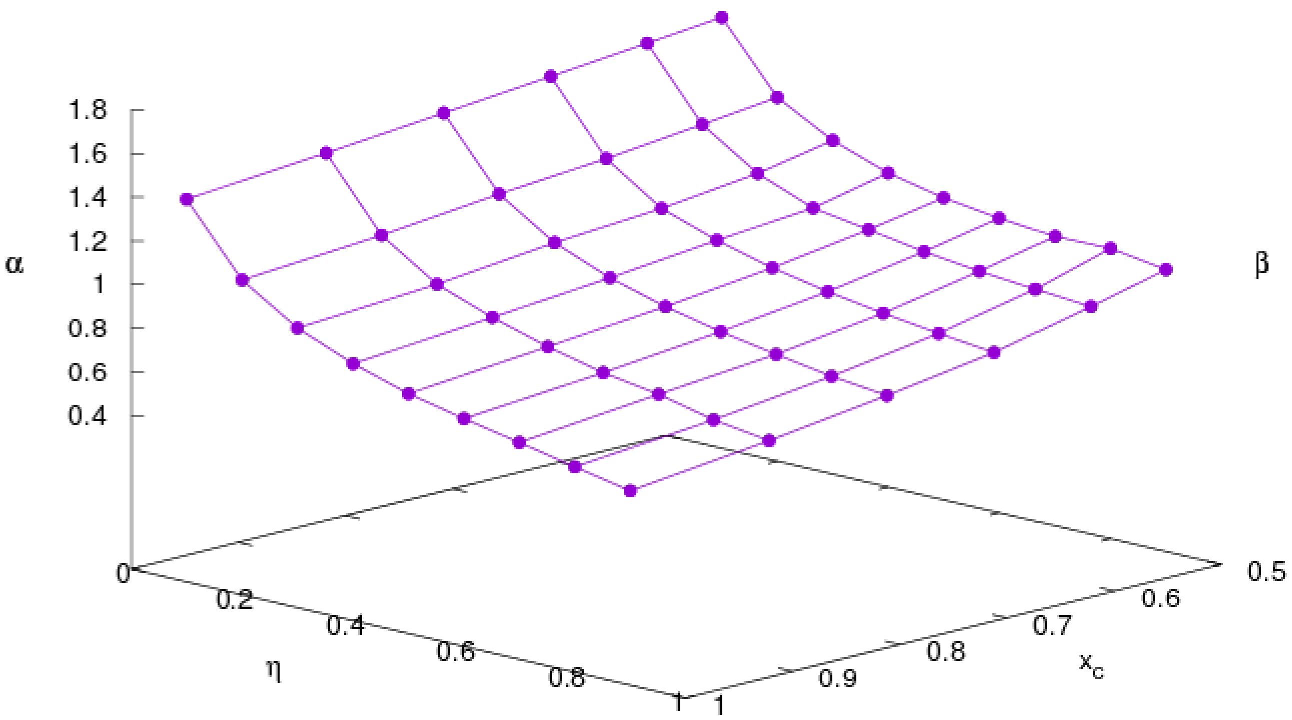
α and β in space of orbital parameters





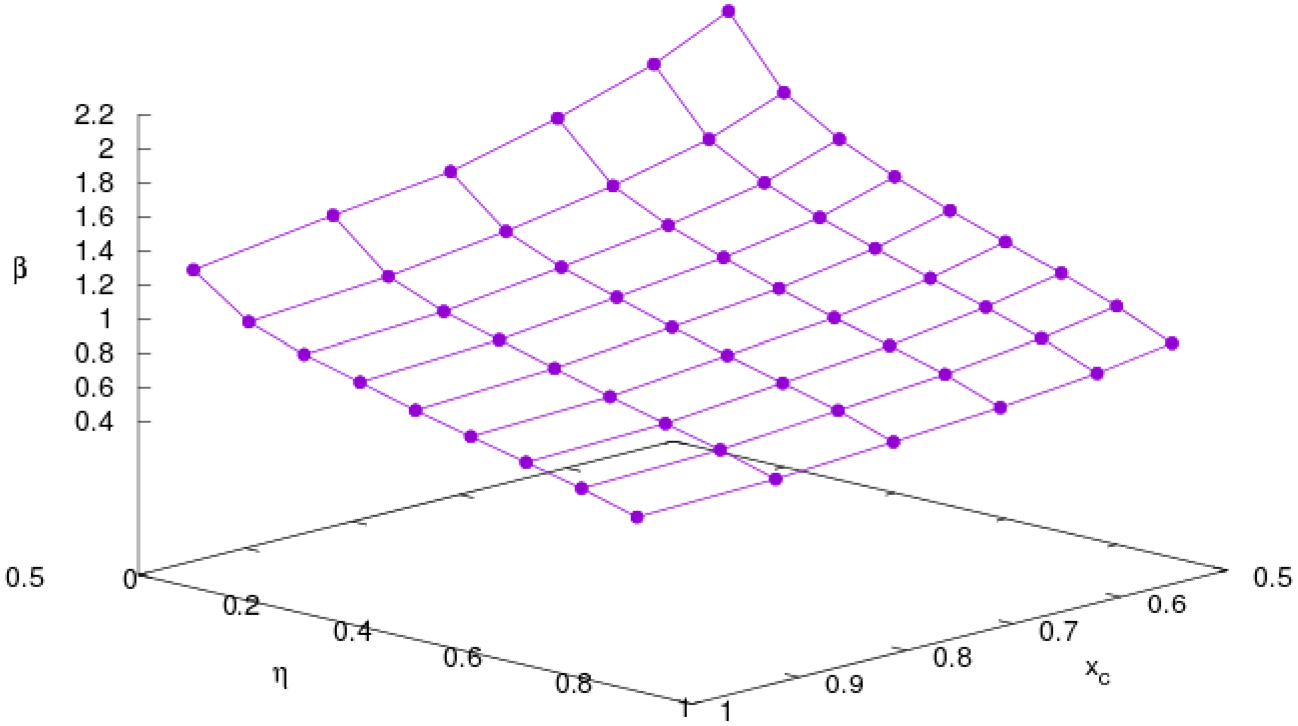
Ogiya, van den Bosch et al., in prep.

α and β in space of orbital parameters



$$\alpha(x_c, \eta) = \alpha_0 x_c^{\alpha_1} \eta^{\alpha_2}$$

α0=0.63; α1=-0.32; α2=-0.45



$$\beta(x_c, \eta) = \beta_0 x_c^{\beta_1} \eta^{\beta_2}$$

β0=0.57; β1=-0.42; β2=-0.56

Ogiya, van den Bosch et al., in prep.

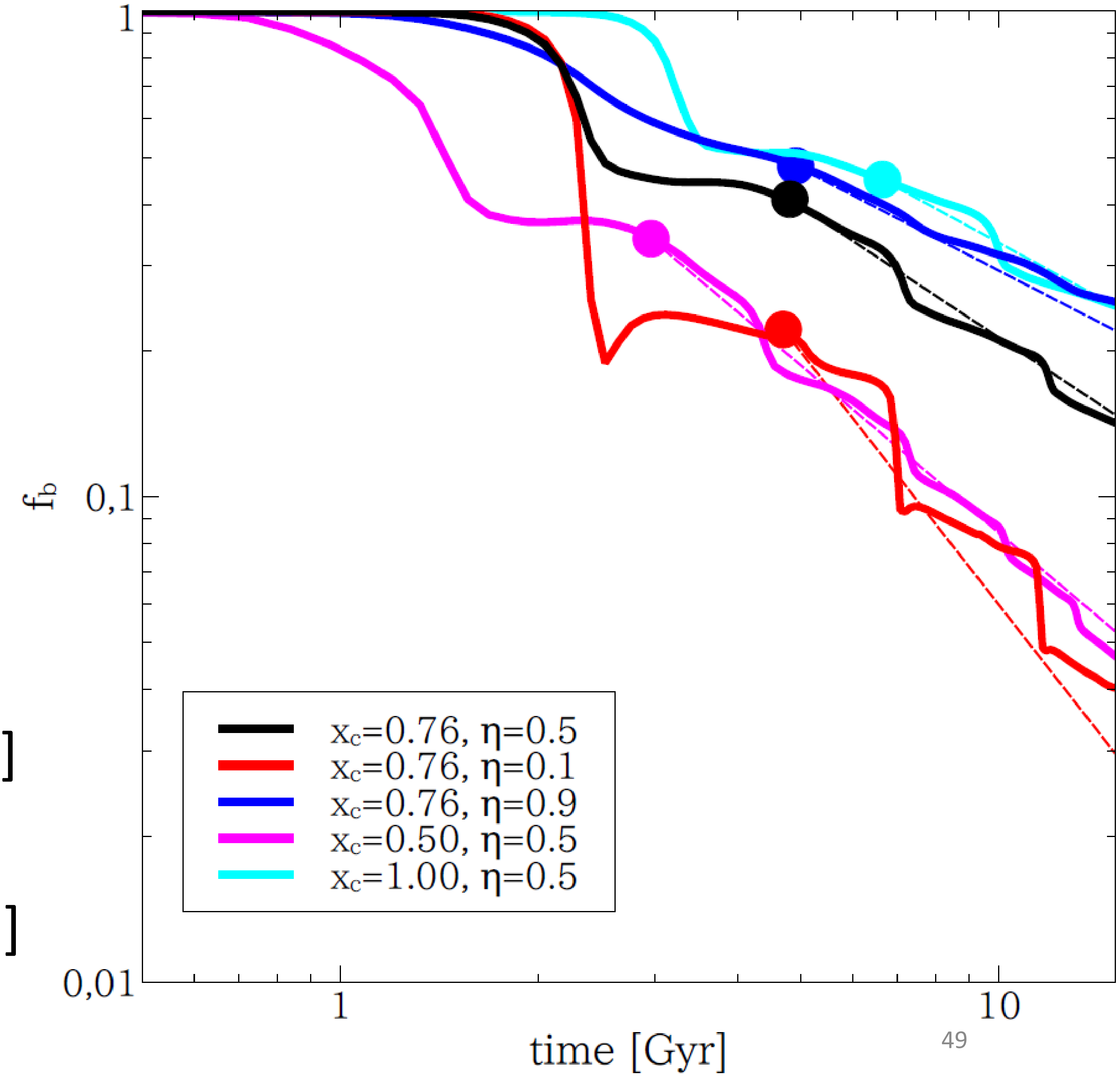
Does it work?

- Apply it for some simulations [solid line]

0. Compute Tr with xc, η and parameters of the host

1. $f_{\rm b}(t = T_{\rm r}) = \exp(-\alpha)$ [filled circle]

2. $f_{\rm b}(t > T_{\rm r}) \propto t^{-\beta}$ [dotted line]



Summary

Q1: Are the subhalo disruption in current simulations real or artificial?

A1: Most of them should be artificial

-> van den Bosch, GO, Hahn & Burkert (arXiv:1711.05276)

Q2: If artificial, how can we assess subhalos in simulations?

A2: Two conditions relating to ε and *N*

-> van den Bosch & GO (arXiv:1801.05427)

Q3: What is the true mass evolution of dark matter subhalos?

A3: Making empirical function, fb(t; xc, η, ch, cs), using hires simulations

-> GO, van den Bosch et al., in prep.

European Research Council
Established by the European Commission
© ERC
COSMO_SIMS

Observatoire de la CÔTE d'AZUR

LAGRANGE

Tidal interaction as a possible origin of the ultra diffuse galaxy lacking dark matter

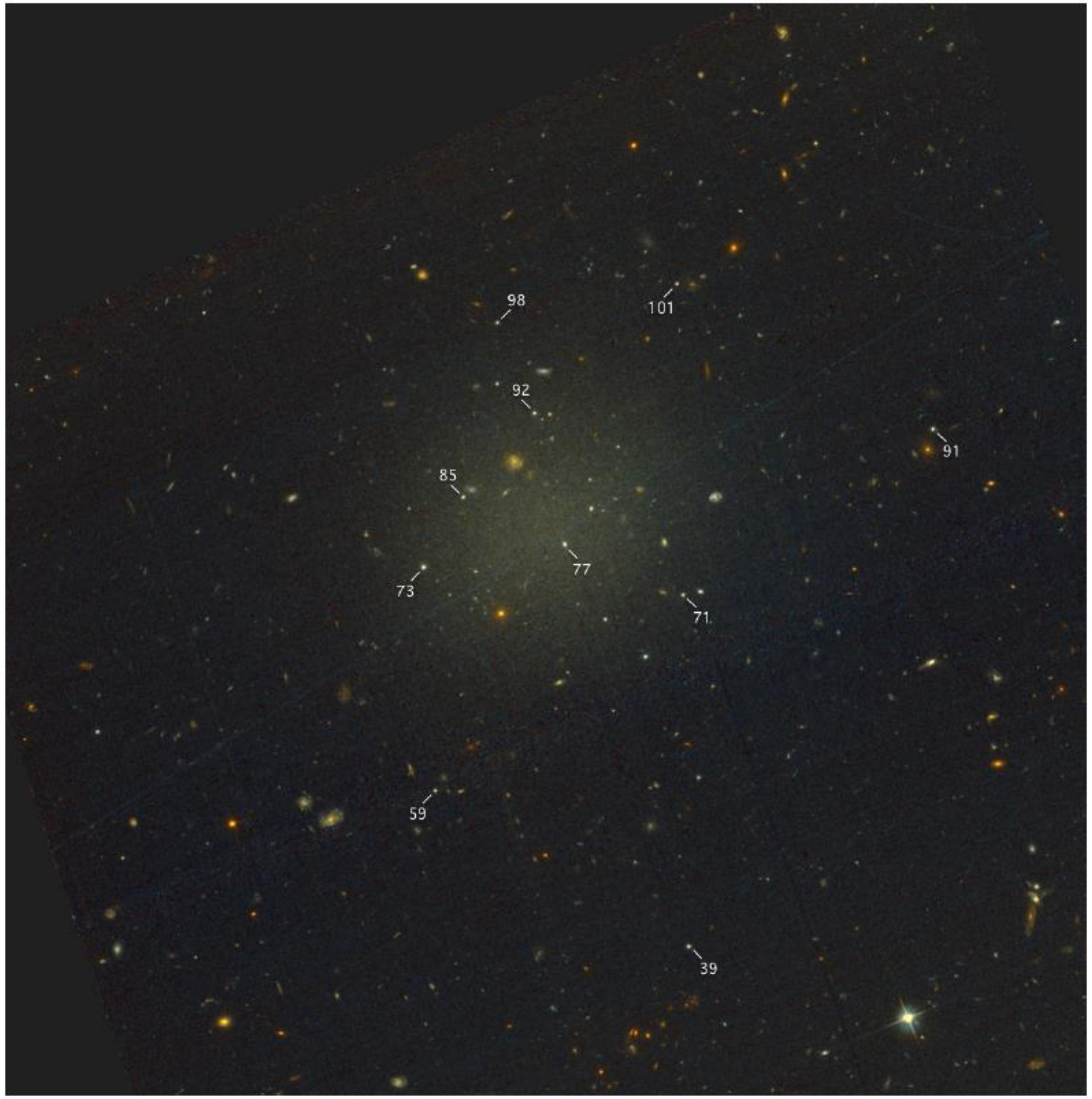
Go Ogiya

(Observatoire de la Côte d'Azur, OCA)

GO (arXiv:1804.06421)

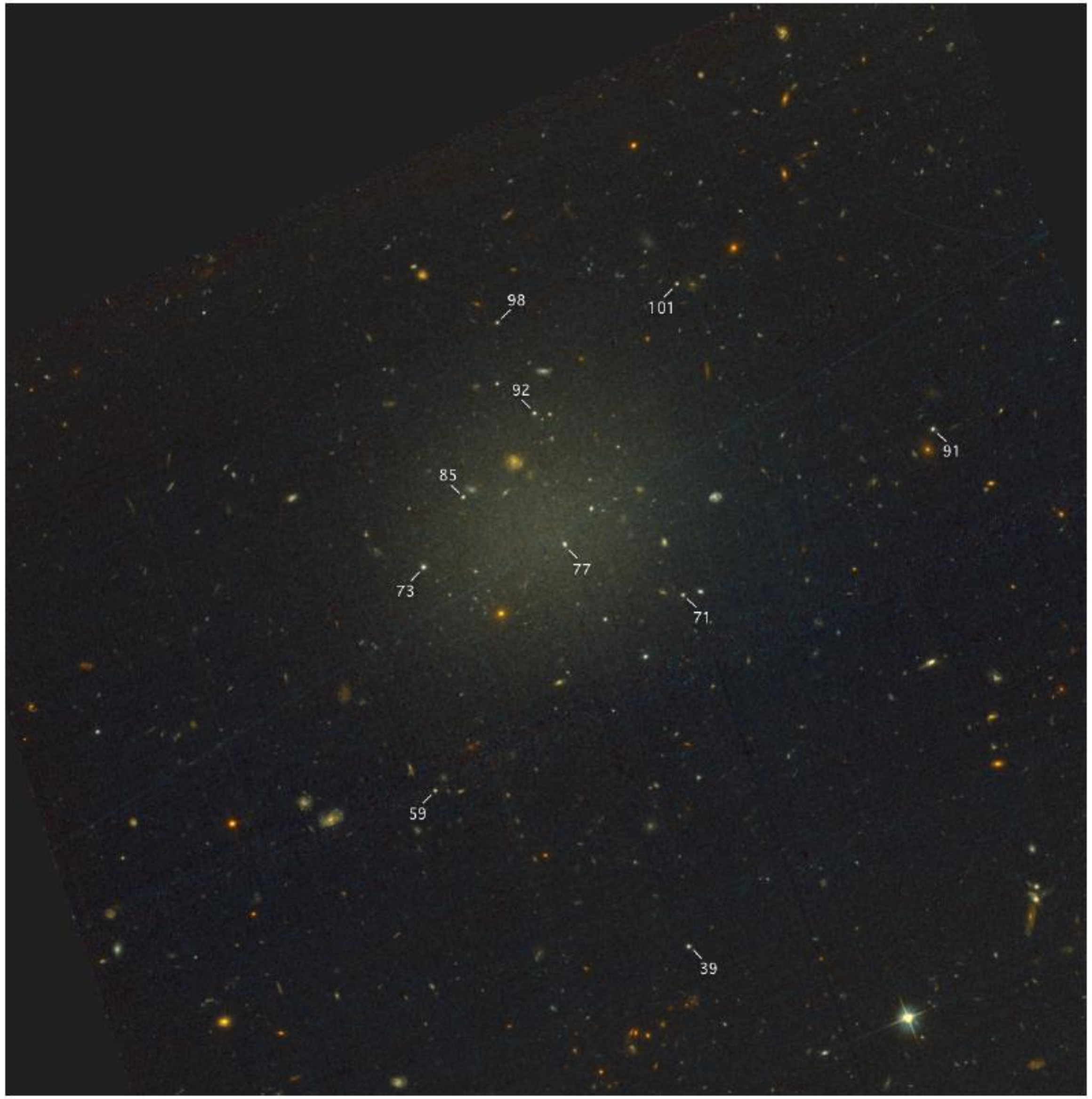
NGC1052-DF2

- UDG in the group of NGC1052
    - ✓Discovered by Karachentsev et al. (2000)
- Mstar = 2e8Msun
- Abundance matching models
  -> Mhalo=4.9e10Msun
    - ✓e.g. Moster et al. (2013)



NGC1052-DF2

- UDG in the group of NGC1052
  - ✓Discovered by Karachentsev et al. (2000)
- Mstar = 2e8Msun
- Abundance matching models -> Mhalo=4.9e10Msun
  - ✓e.g. Moster et al. (2013)
- van Dokkum et al. (2018) inferred Mhalo ~ 1e8Msun or less
  - ✓Kinematics of 10 globular clusters
  - ✓Large uncertainties (Martin et al. 2018; Laporte et al. 2018)
  - ✓MOND (Famaey et al. 2018)



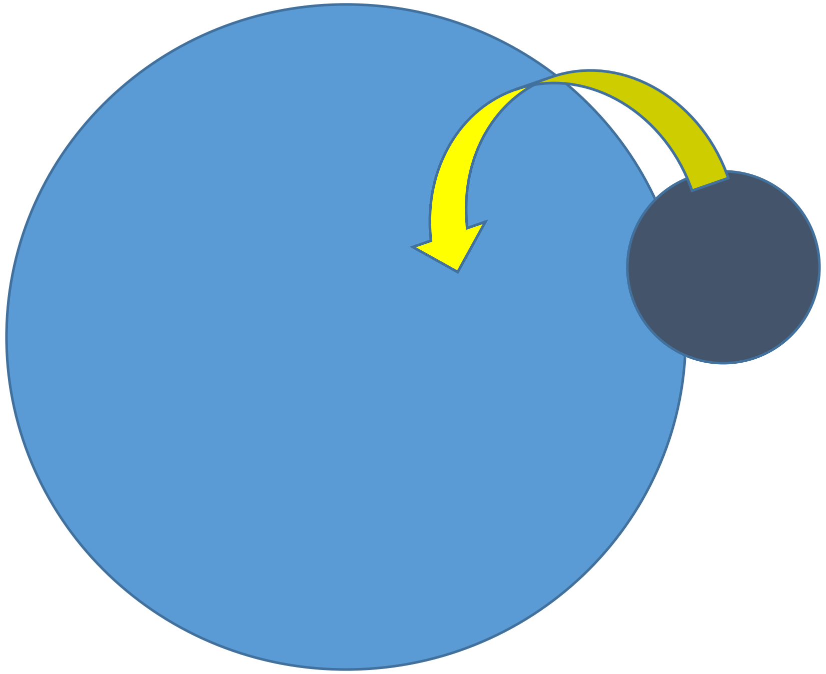
Simulation setup

NGC1052 = fixed potential
- NFW halo (α=1, β=3)
  - ✓ M=1.1e13Msun
  - ✓ ch=5.8 (van Gorkom et al. 1986; Ludlow et al. 2016)

Initial density structure

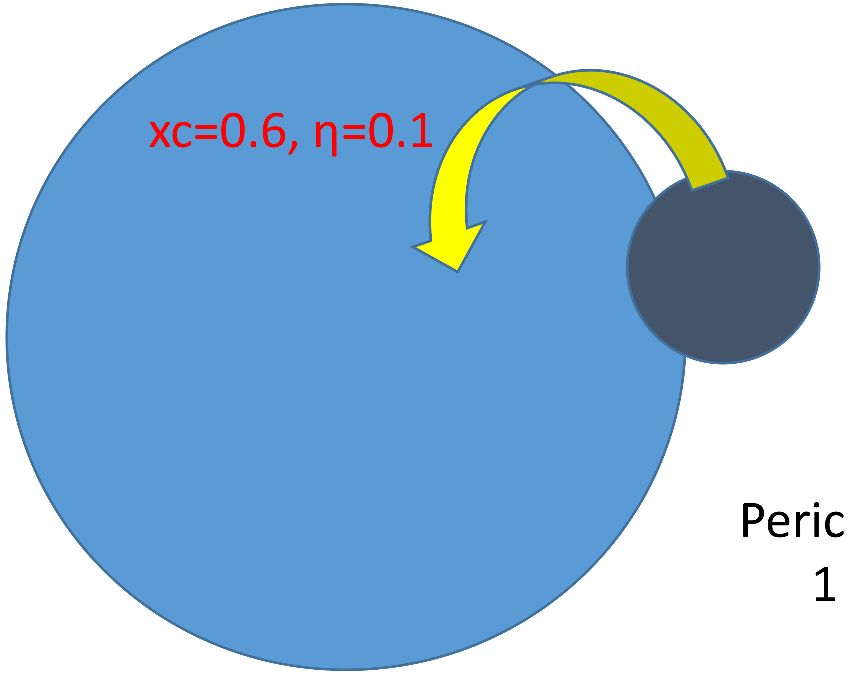
$$\rho(r) = \frac{\rho_0}{(r/r_0)^\alpha [1 + (r/r_0)]^{\beta-\alpha}}$$

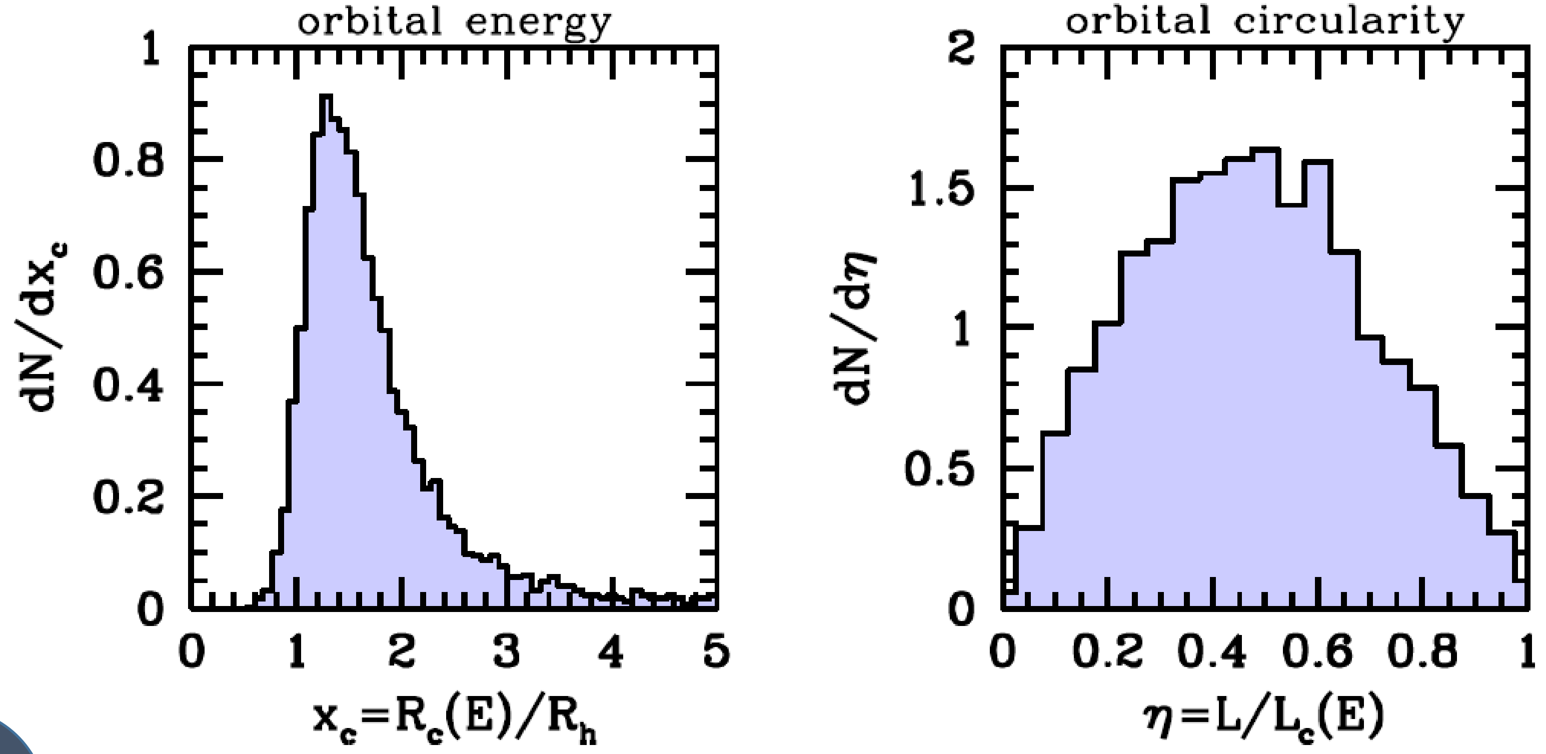
$$c \equiv R_\mathrm{v}/r_0$$



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=9.6 (r0=8kpc, Oman et al. 2015)

Simulation setup



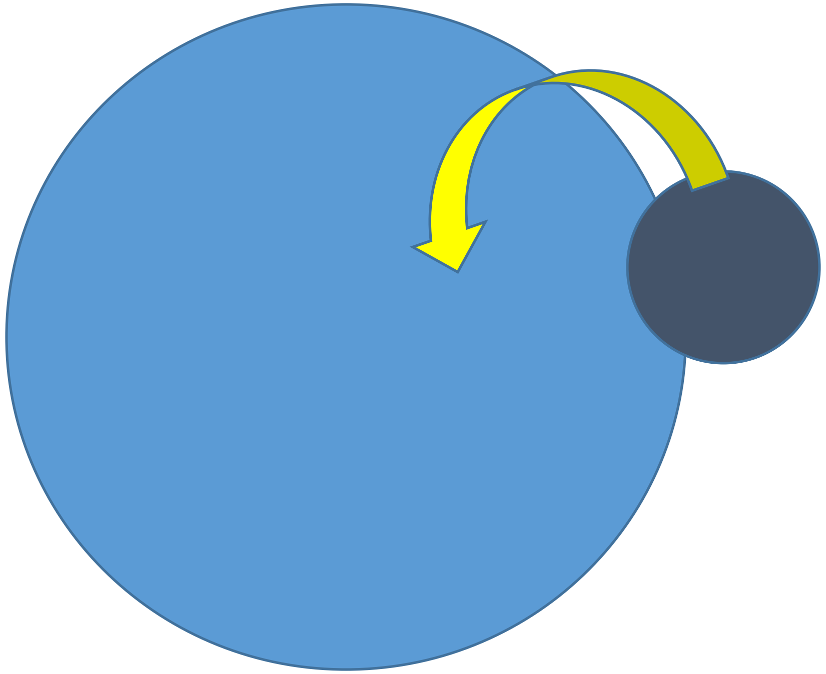


Initially at apocenter

van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

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

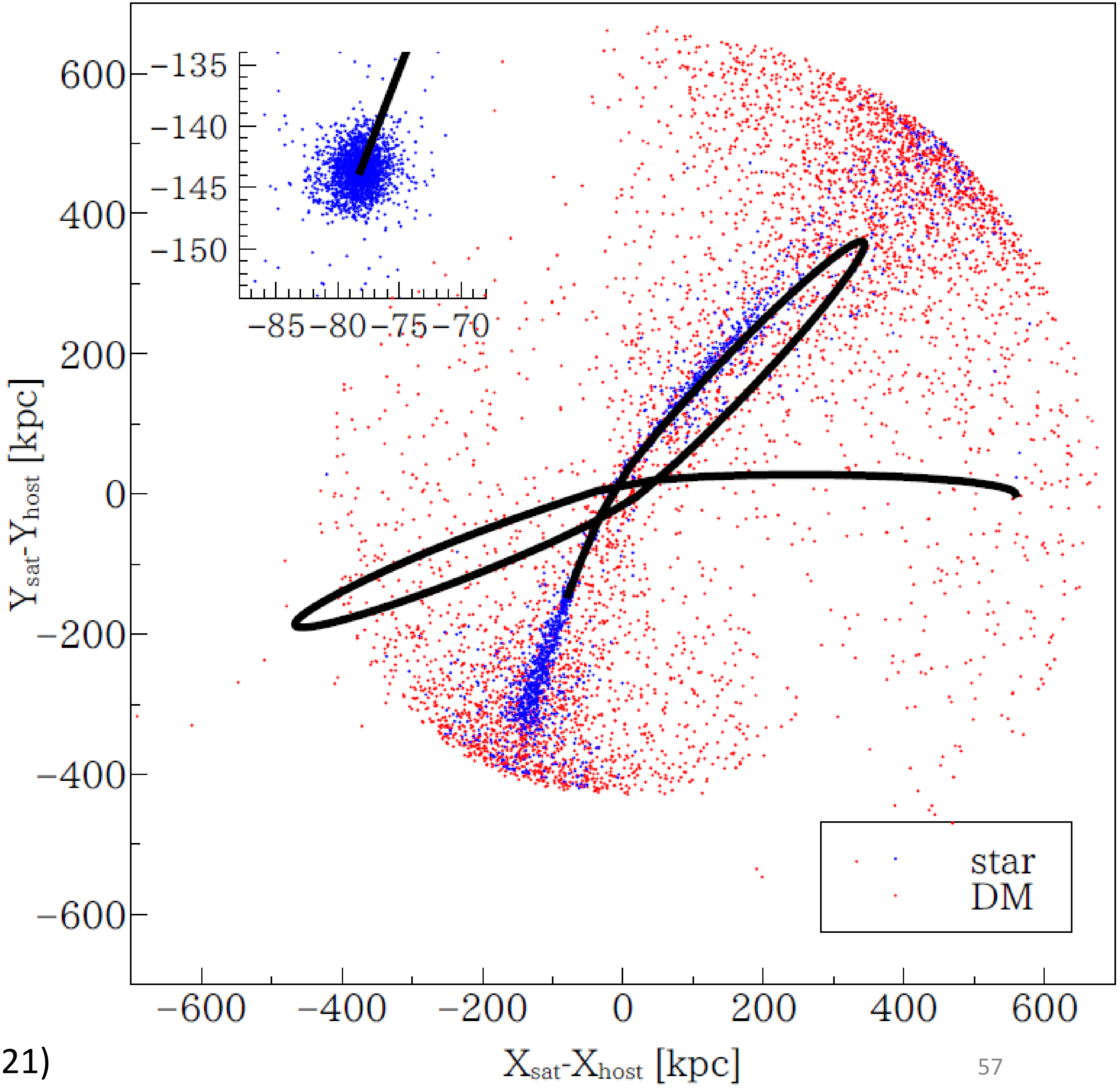
- ➢ Softening parameter, ε=0.03kpc
  - Profiles reliable r>0.1kpc
    - ✓ Power et al. (2003); van den Bosch & GO (2018)
- ➢ Opening angle, θ=0.6
  - Tree code for GPU clusters (GO et al. 2013)

Distribution of stripped matter

- Result from the run of α=0.1
  - ✓ Similar distribution in the run of α=1.0

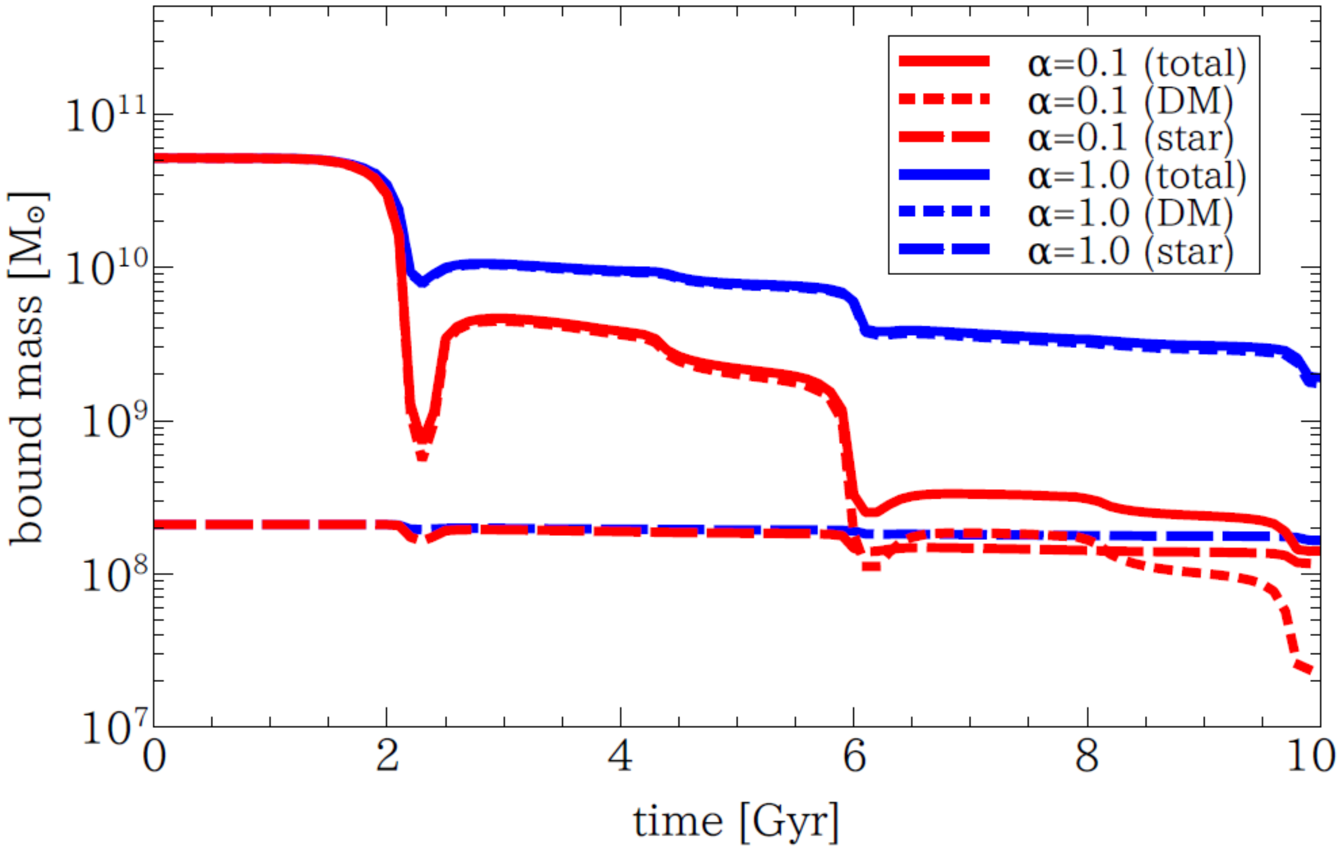
- DM significantly stripped

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



GO (arXiv:1804.06421)

Mass evolution



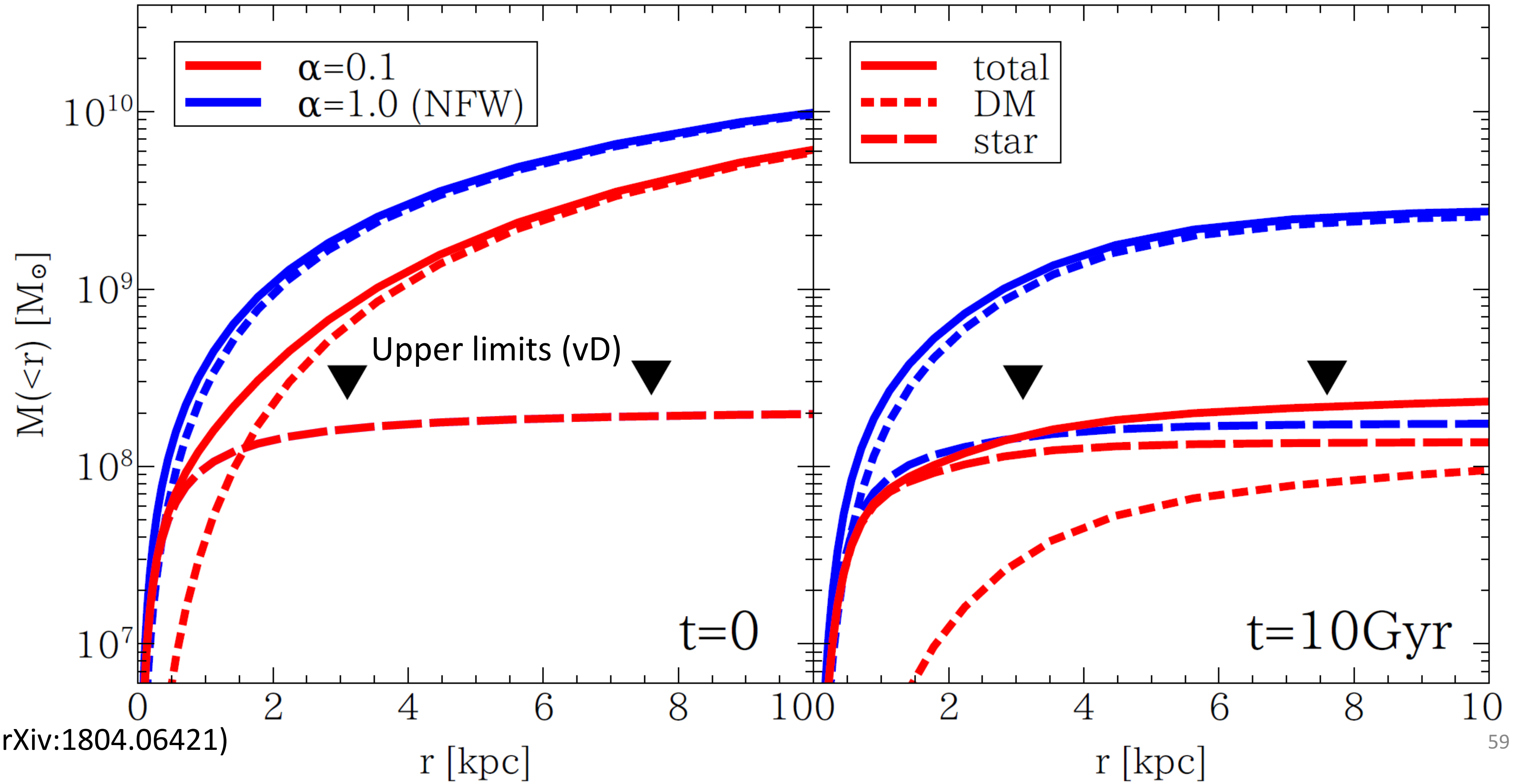
- Stellar mass does not change significantly in both models

- DM mass reduced significantly in α=0.1 model
    - By a factor of ~1000 at 10Gyr

- Less significant reduction in α=1.0 model

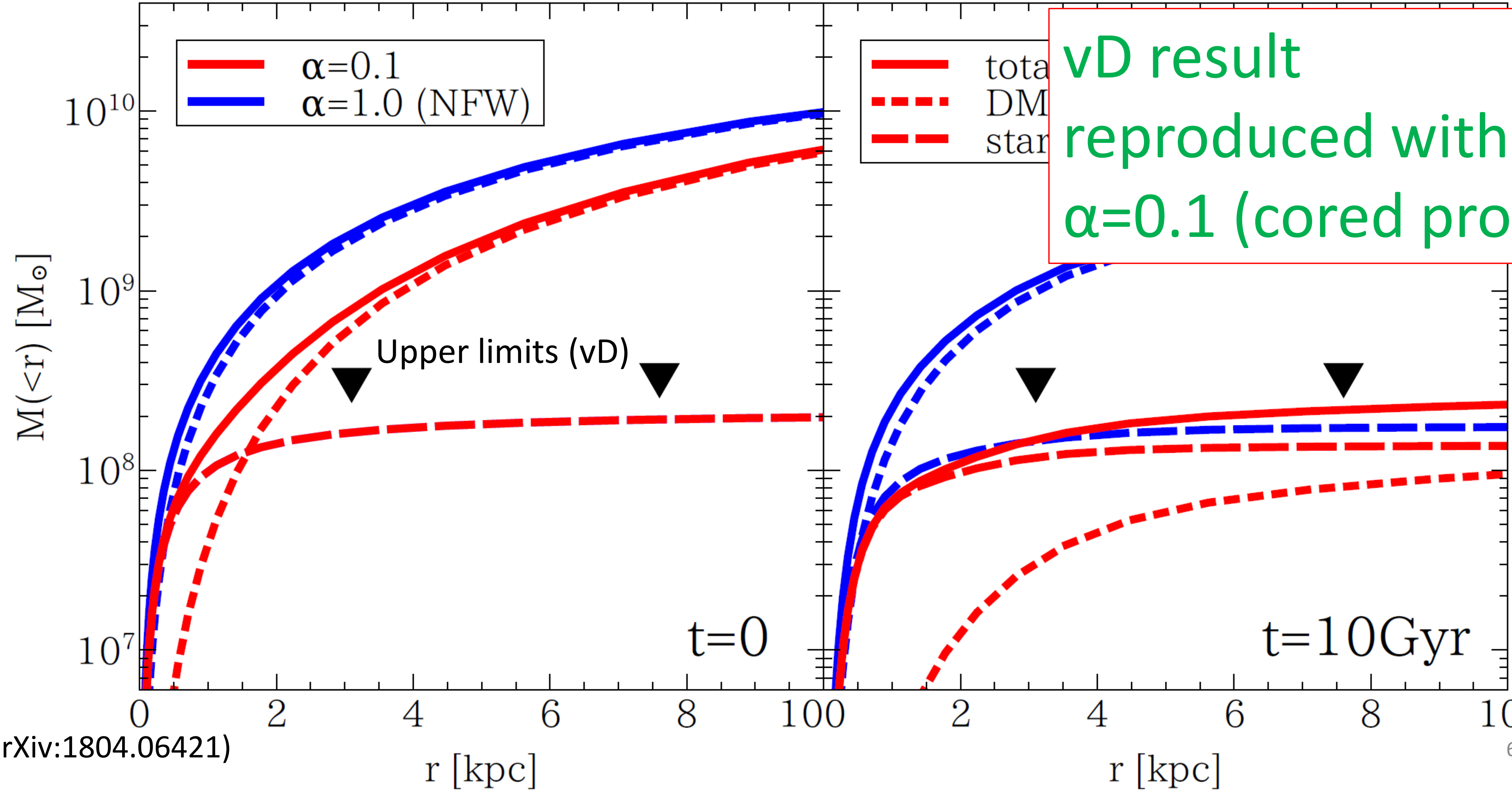
GO (arXiv:1804.06421)

Comparison with van Dokkum et al. (vD)



GO (arXiv:1804.06421)

Comparison with van Dokkum et al. (vD)



vD result reproduced with α=0.1 (cored profile)

GO (arXiv:1804.06421)

Summary

- Tidal interaction between NGC1052 and a satellite galaxy

  -> formation of the UDG lacking DM? (GO, arXiv:1804.06421)

- Reproduced the van Dokkum results with
  1. Cored density profile for the DM halo
     - ✓ Core size as large as the largest one observed
  2. Tightly bound and quite radial orbit
     - ✓ In the tails of the distribution

  -> May explain its rarity