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COSMO_SIMS

- van den Bosch, GO, Hahn & Burkert (arXiv:1711.05276)
- van den Bosch & GO (arXiv:1801.05427)
- GO, van den Bosch, Hahn & Burkert, in prep.
- GO (arXiv:1804.06421)

Evolution of tidally stripped dark matter subhalos

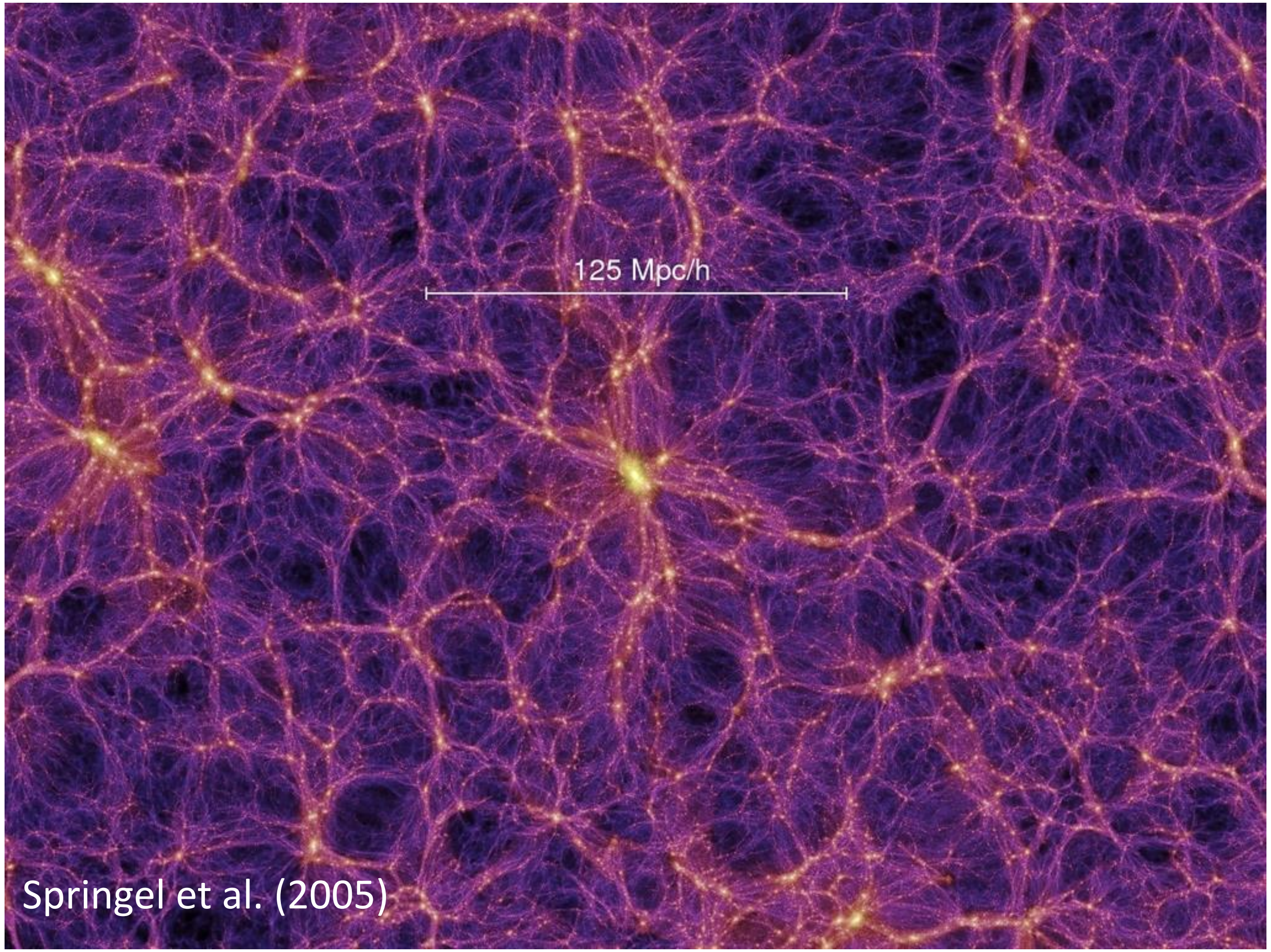
Go Ogiya (GO)

(Observatoire de la Côte d'Azur, OCA)

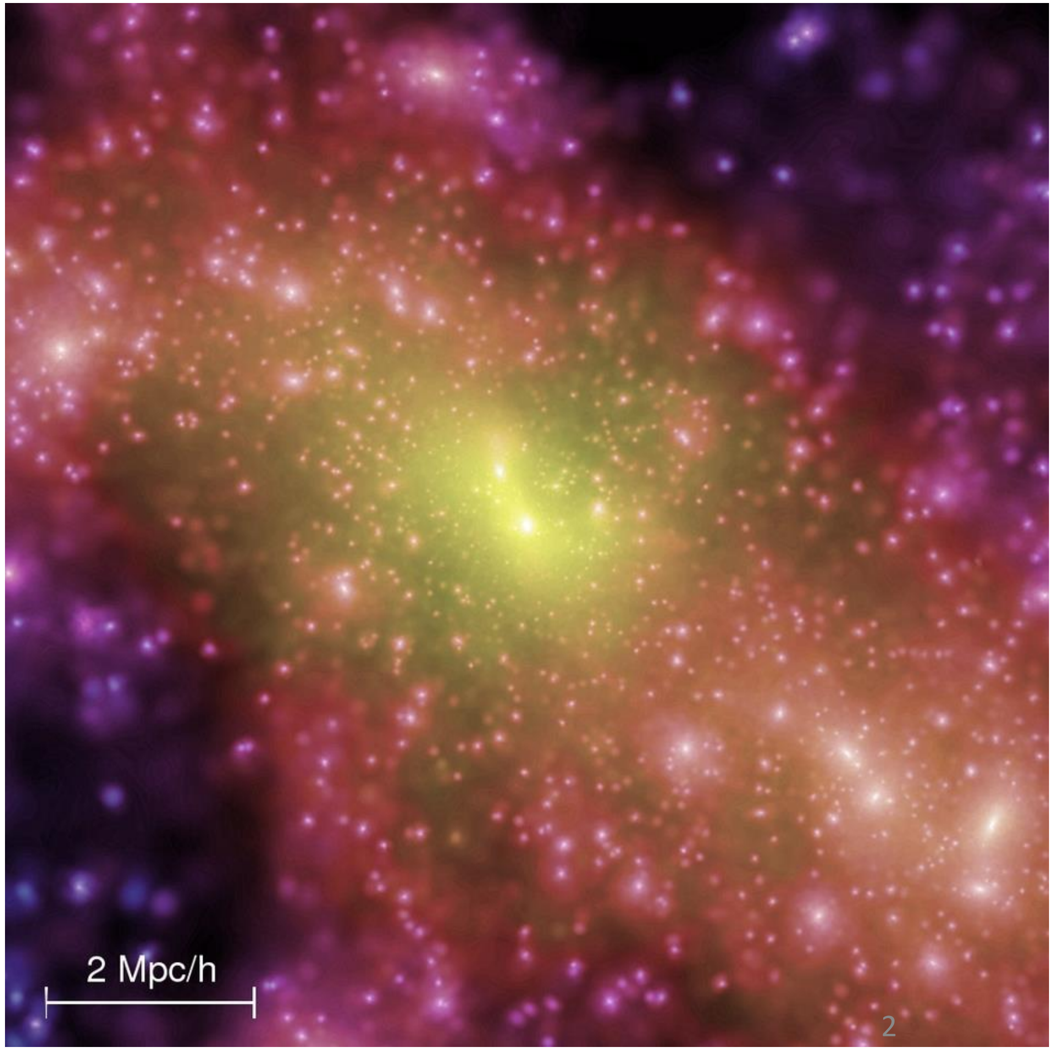
In collaboration with

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

Dark matter (DM) halos in cosmological sims

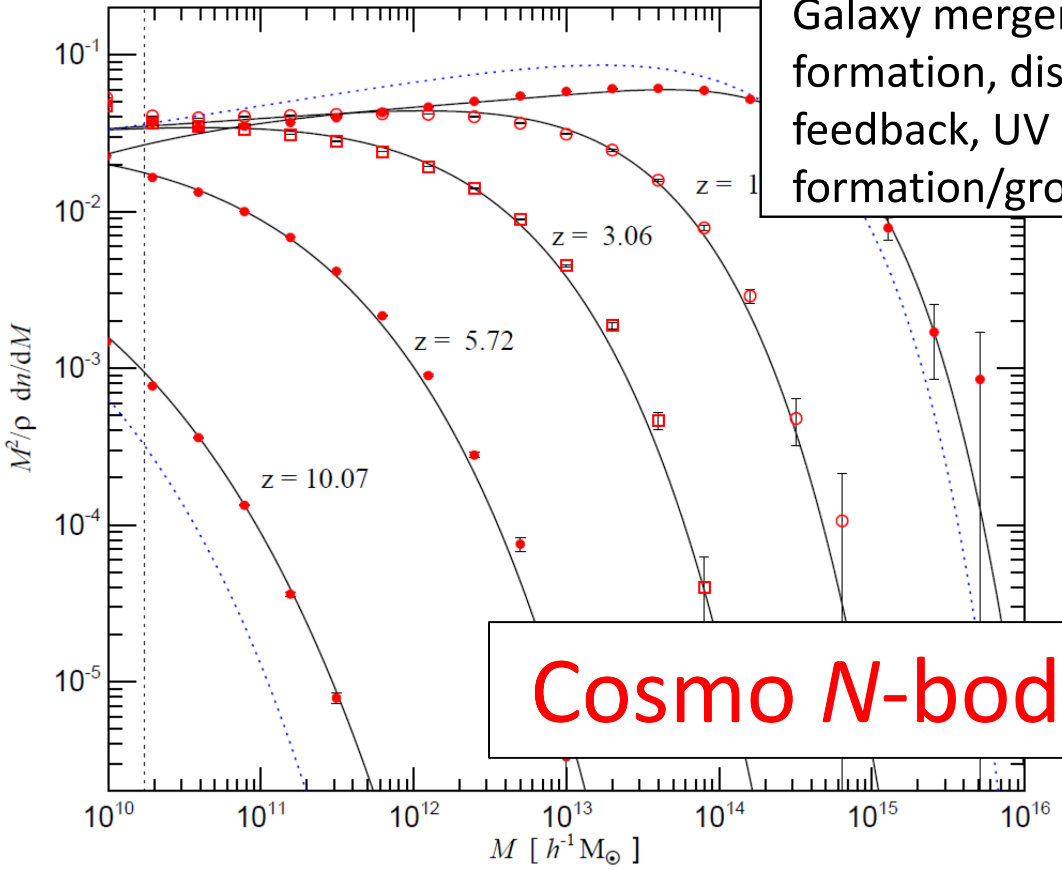


Springel et al. (2005)



DM halos and galaxy formation and evolution

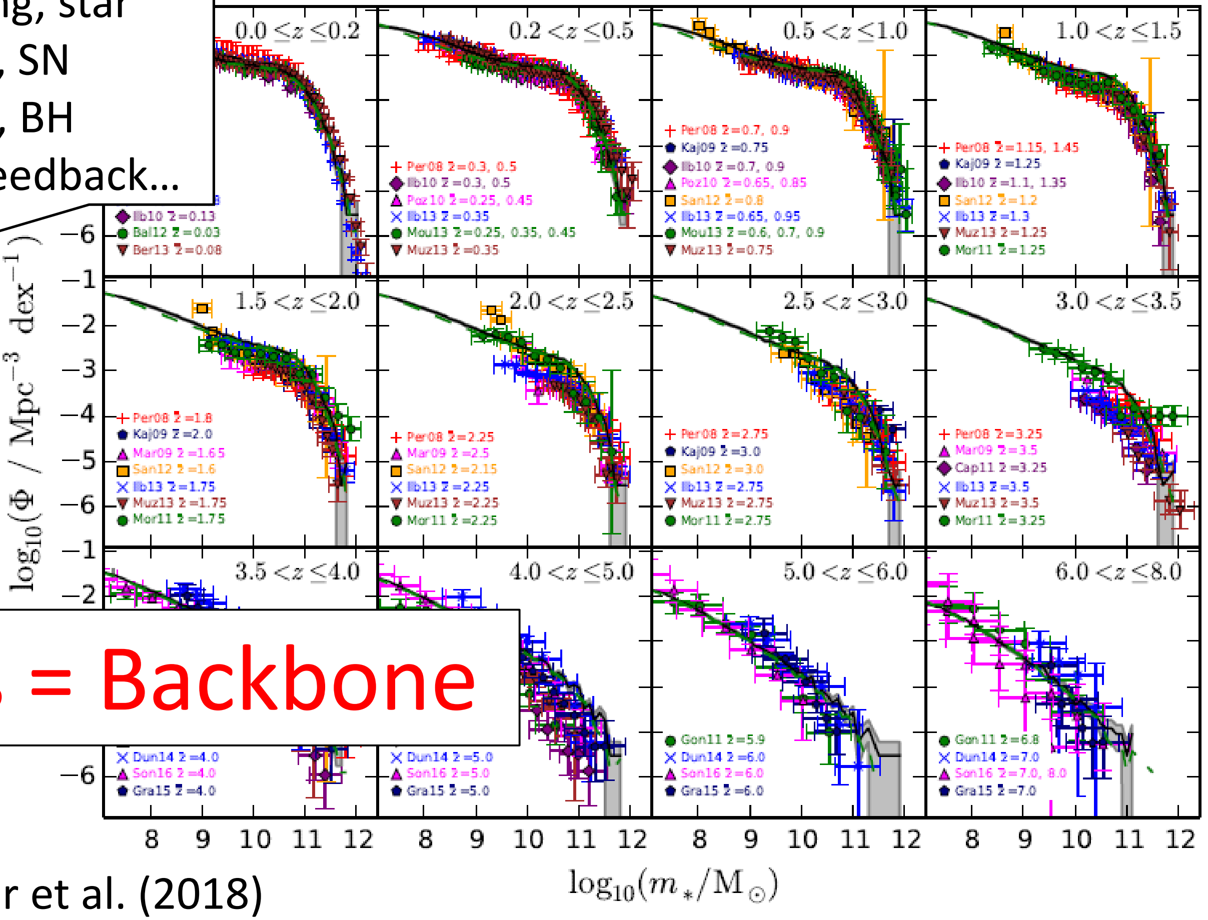
Halo mass function



Springel et al. (2005)

Galaxy mergers, gas cooling, star formation, disc formation, SN feedback, UV background, BH formation/growth, AGN feedback…

Galaxy luminosity function

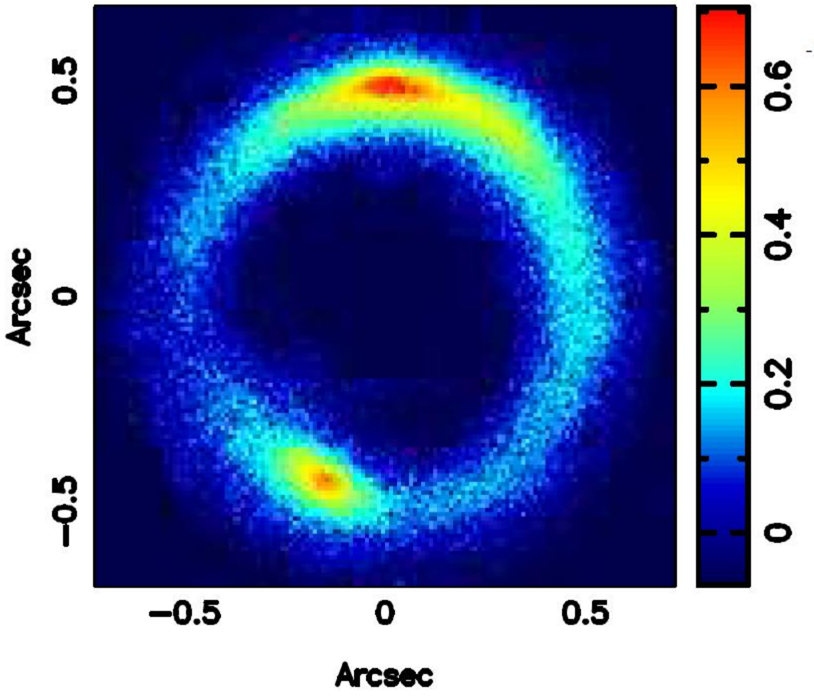


Moster et al. (2018)

Cosmo *N*-body sims = Backbone

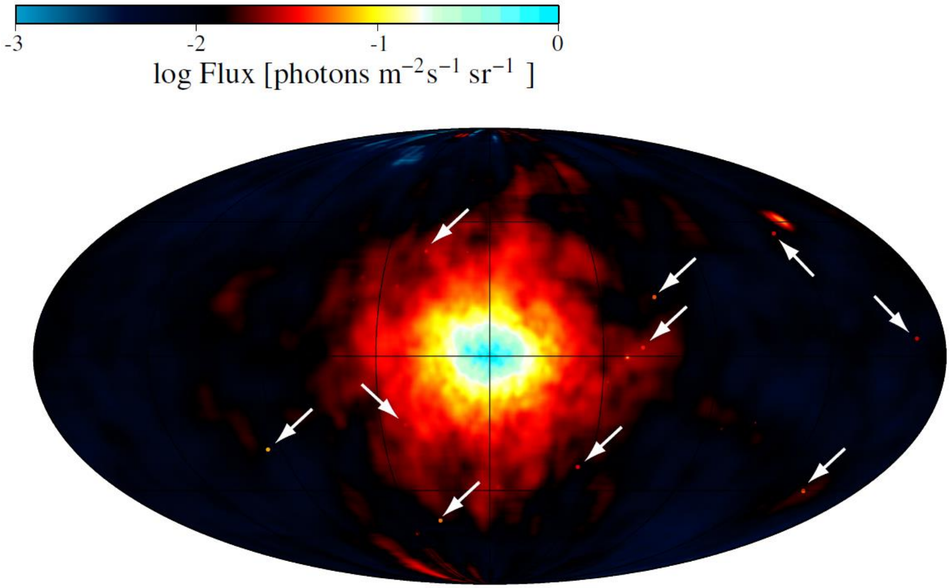
Subhalos in exploring the nature of DM

Gravitational lensing



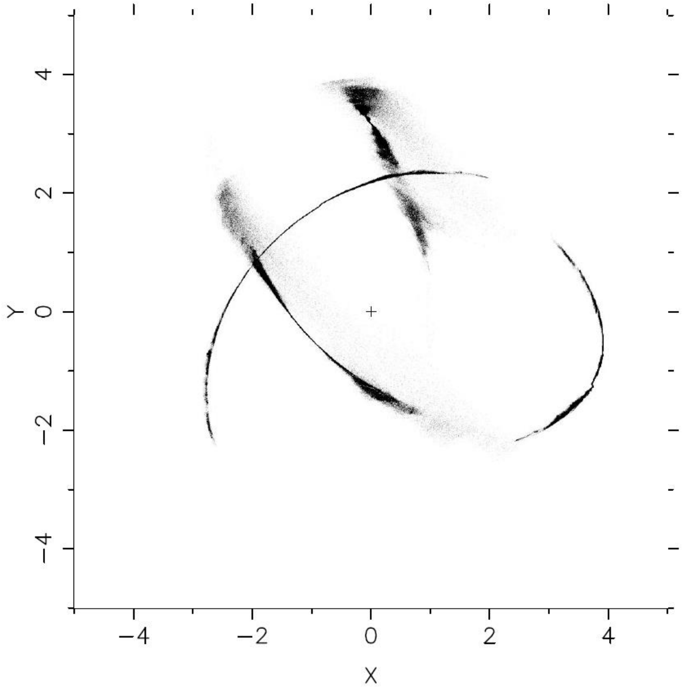
Vegetti et al. (2012)

Annihilation/decay signal



Ishiyama et al. (2010)

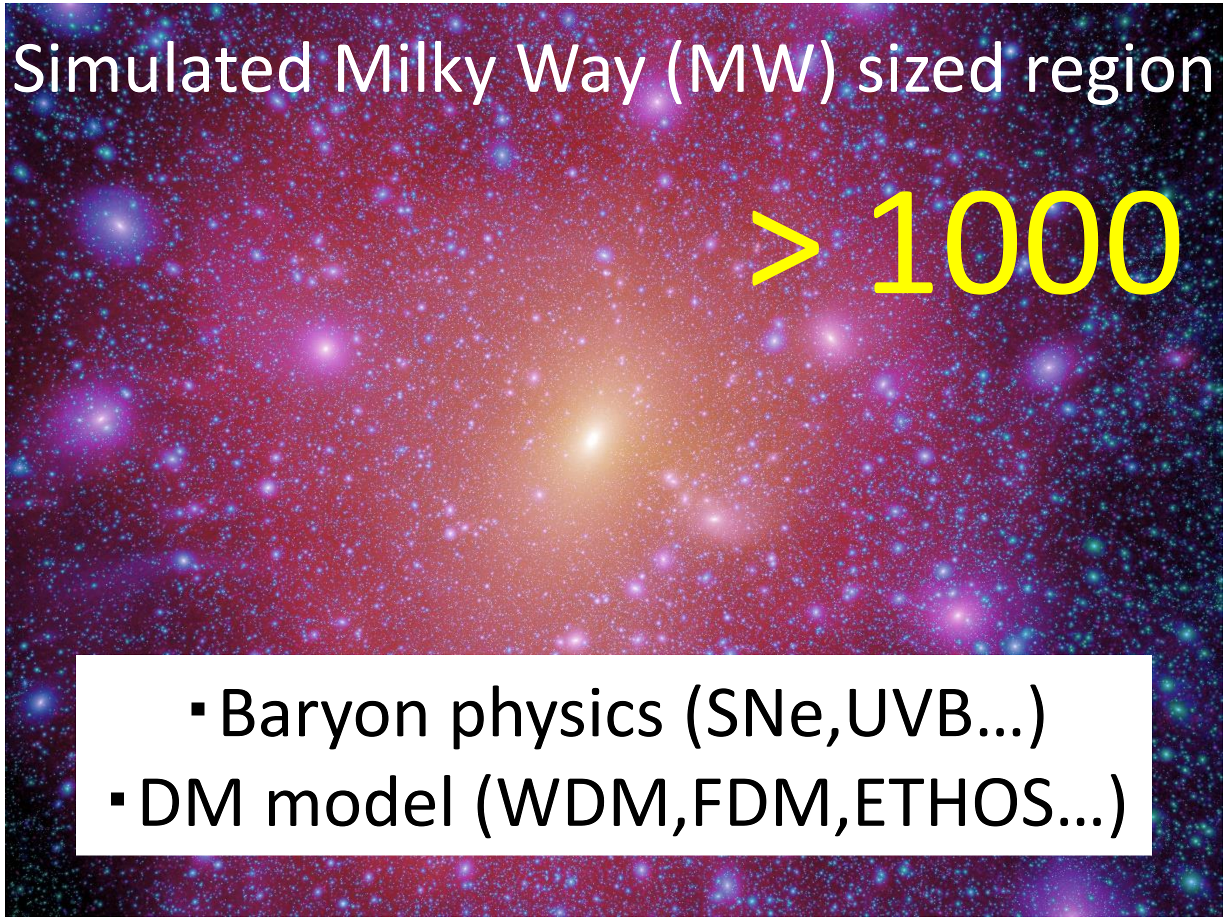
Gaps in stellar streams



Carlberg (2015)

Cosmo *N*-body sims = Baseline

Missing satellite problem

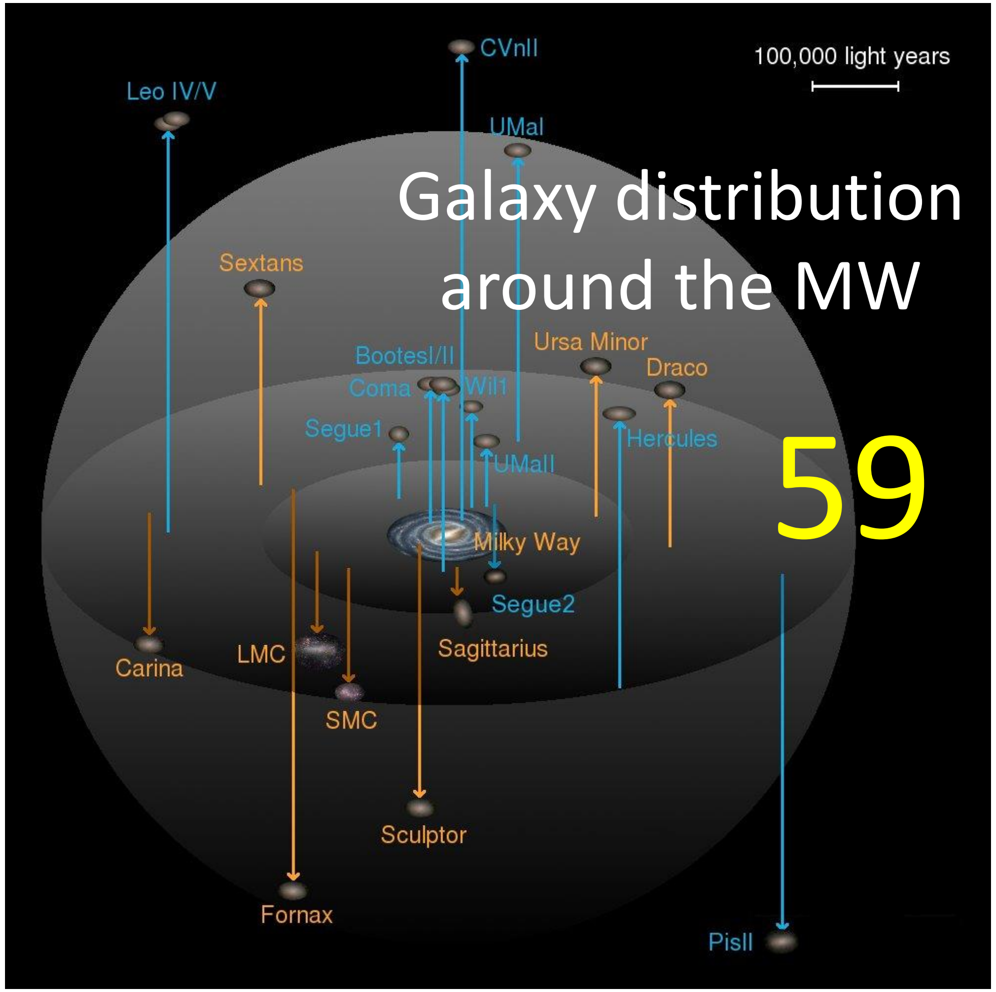


Simulated Milky Way (MW) sized region

> 1000

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

Springel et al. (2008)



Galaxy distribution around the MW

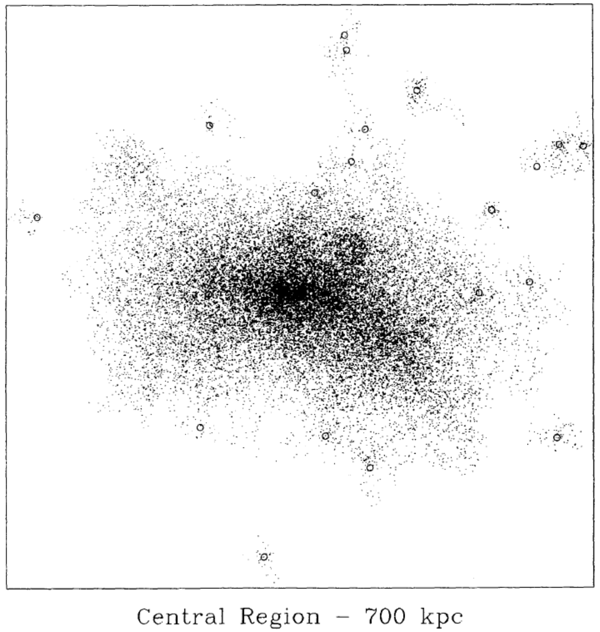
59

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

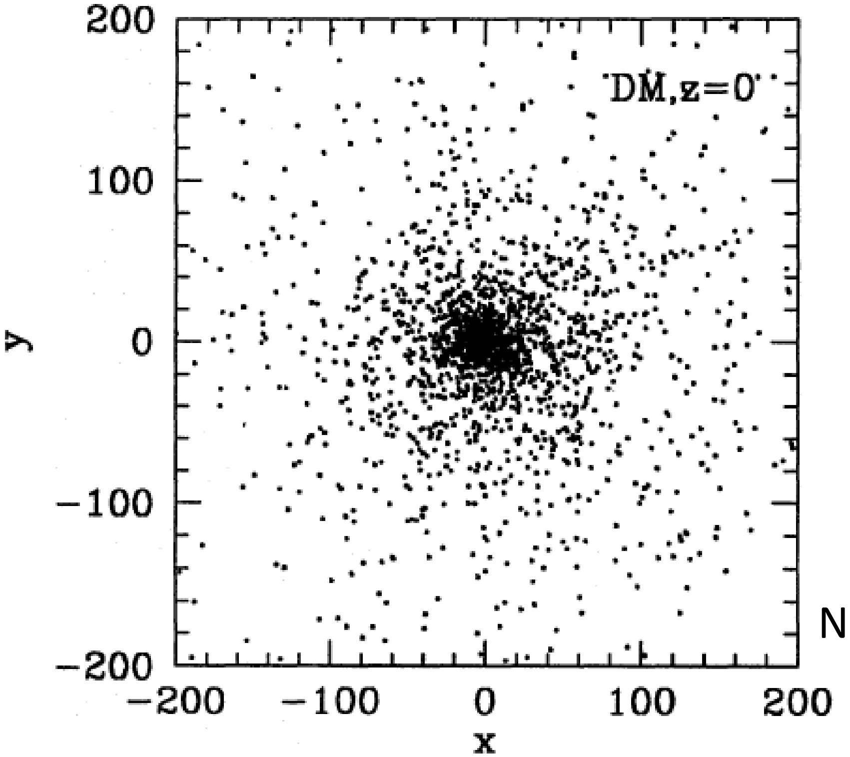
Over merging problem

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

Has been hidden behind the missing satellite problem



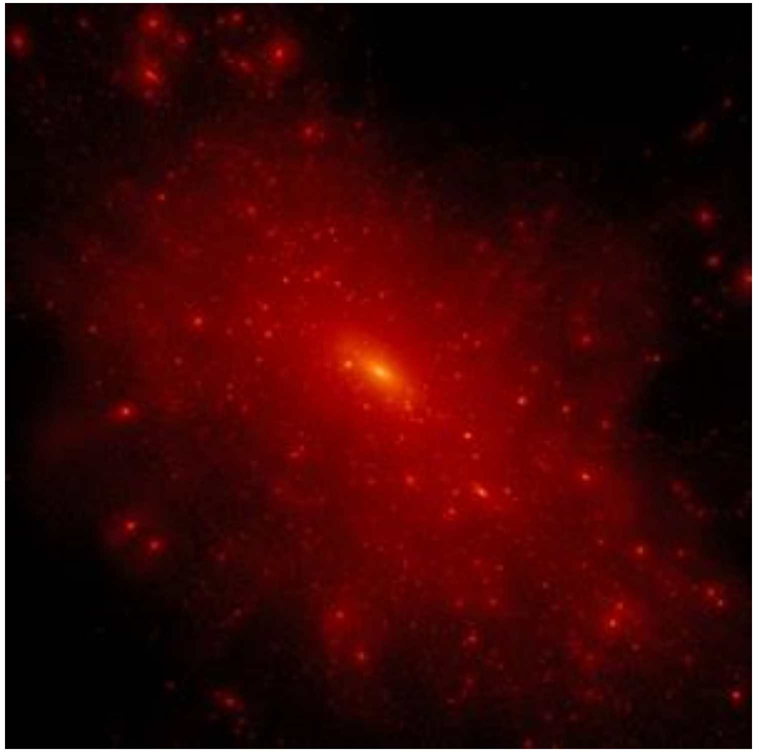
Summers et al. (1995)

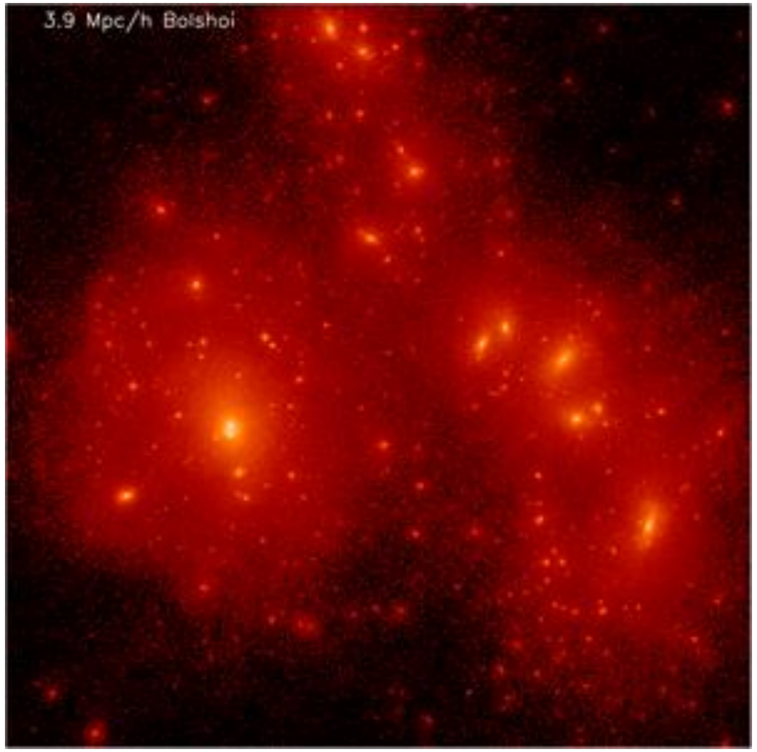


Navarro et al. (1995)

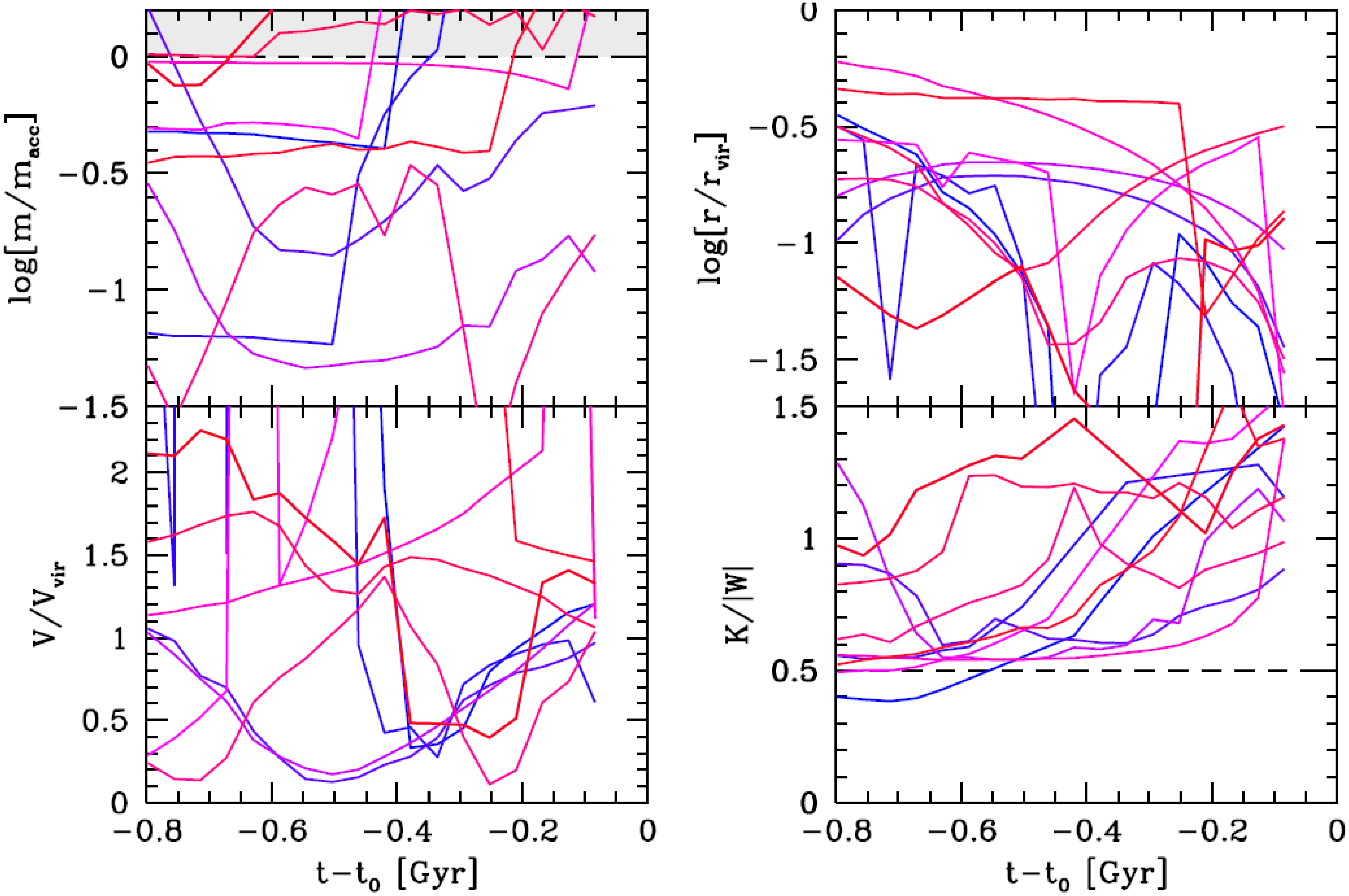
An example from a *high resolution* simulation

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

- How can we assess the reliability of simulated subhalos?
  -> van den Bosch & GO (2018)

- What is the true tidal evolution of dark matter subhalos?
  -> GO, van den Bosch, Hahn & Burkert, 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)
- Instantaneous mass removal (Hayashi et al. 2003)

van den Bosch, GO, Hahn & Burkert
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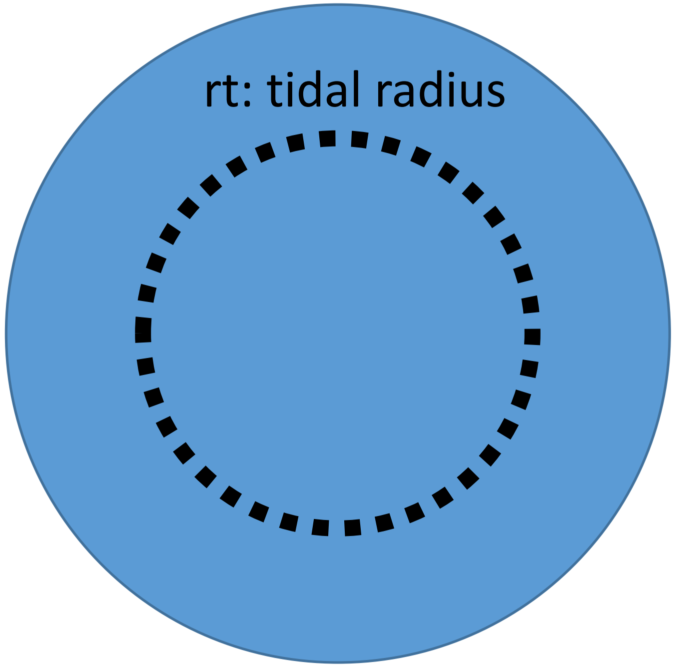
- **Instantaneous mass removal (Hayashi et al. 2003)**

Hayashi et al. (2003)

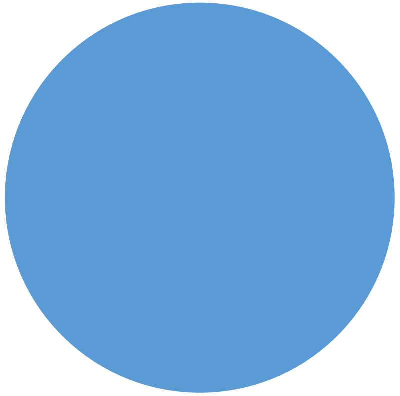
- Instantaneous mass removal at r>rt by tidal force



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



Navarro, Frenk & White (NFW, 1997)

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

Hayashi et al. (2003)

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

-> Complete disruption of an NFW halo

A part of the remnant can be bound (negative energy)

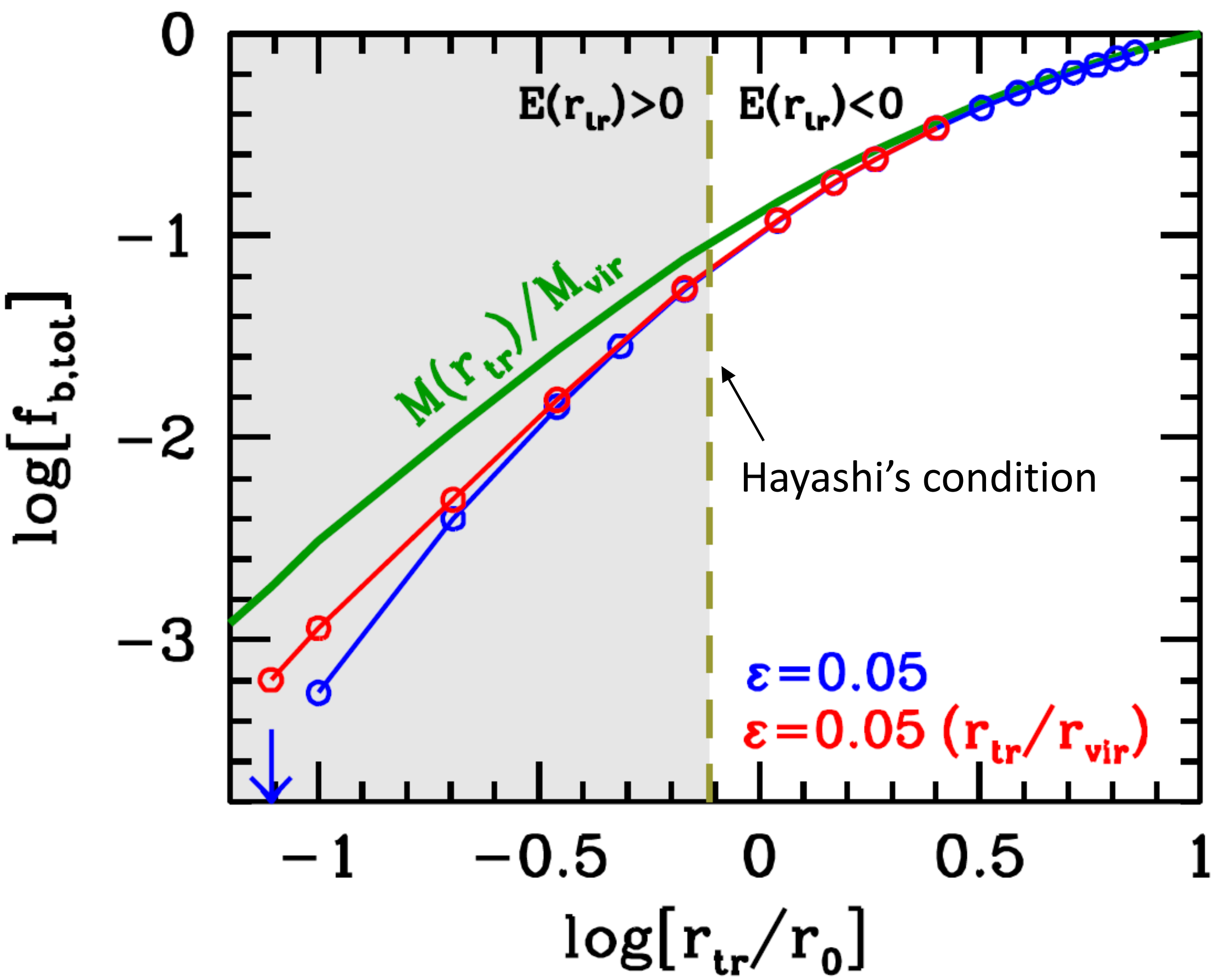
-> Not the complete disruption

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

Instantaneous mass loss

- Bound mass fraction of systems instantaneously removed mass at r>rt
  - ✓In isolation
  - ✓After evolution of 50Gyr

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



van den Bosch, GO, Hahn & Burkert
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  - ✓ 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 disruptions in current simulations real or artificial?
  -> van den Bosch, GO, Hahn & Burkert (2018)

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  -> van den Bosch & GO (2018)

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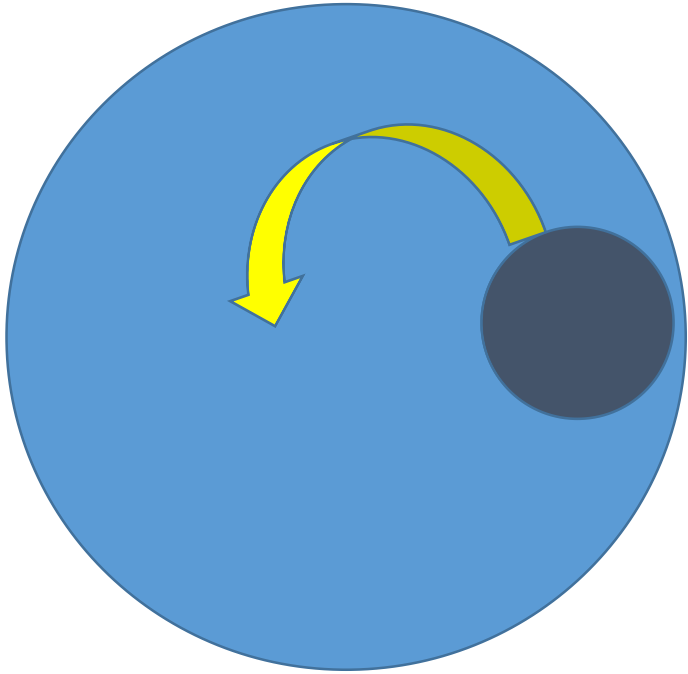
>1000 idealized simulations

Navarro, Frenk & 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)

← Small ε

Large ε →

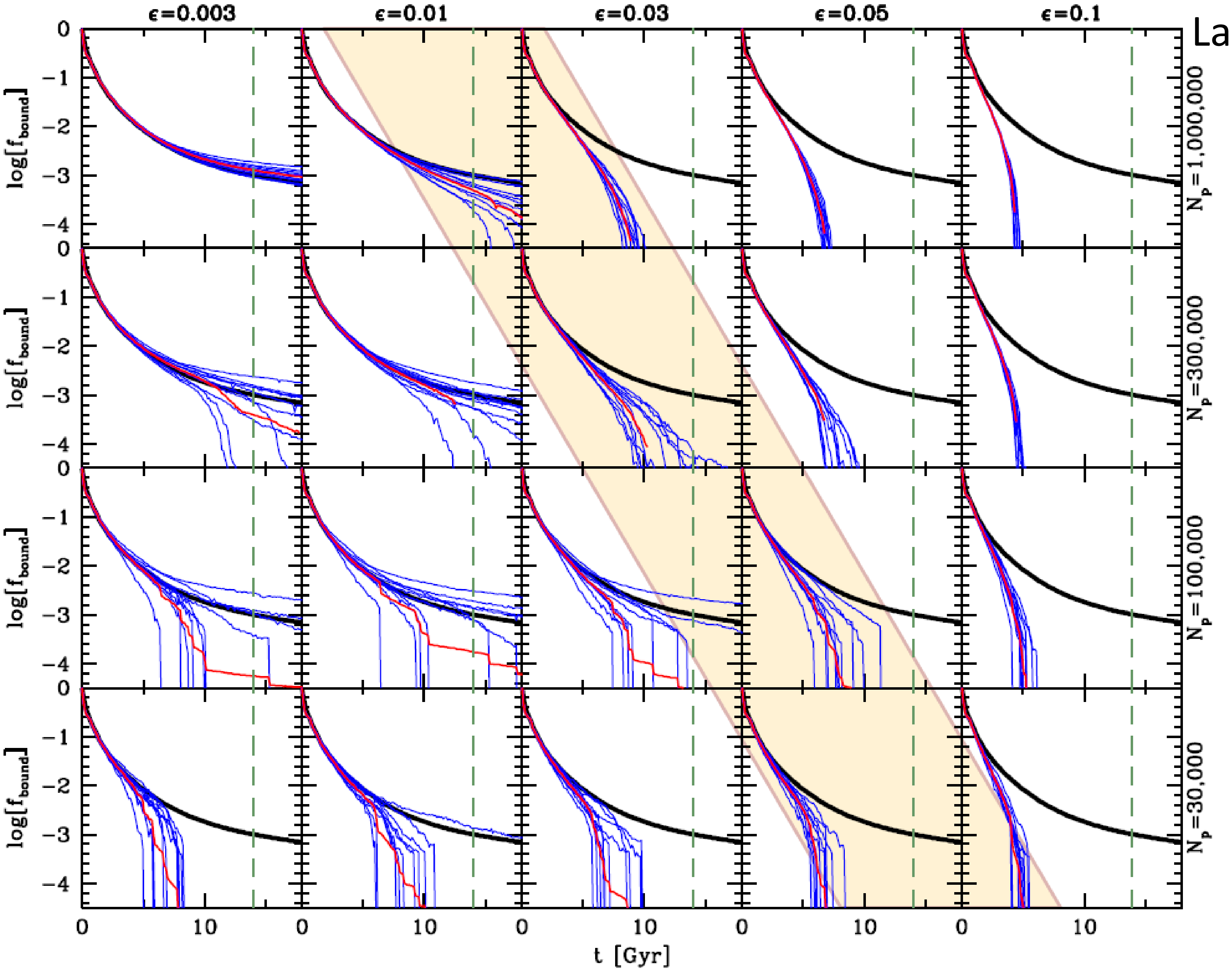
(Same orbits)

Black: converged (true) results

Blue: 10 random realizations

Red: average

Shaded: cosmo. sims



↑ Large N

Small N ↓

van den Bosch & GO (arXiv:1801.05427)

What collisionless *N*-body simulations actually solve

- Galaxies, galaxy clusters, DM halos = Collisionless systems
  - ✓Particle motion is governed by the smooth potential field
  - ✓With the *infinite* number of particles

- 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 collisionality

← Small ε

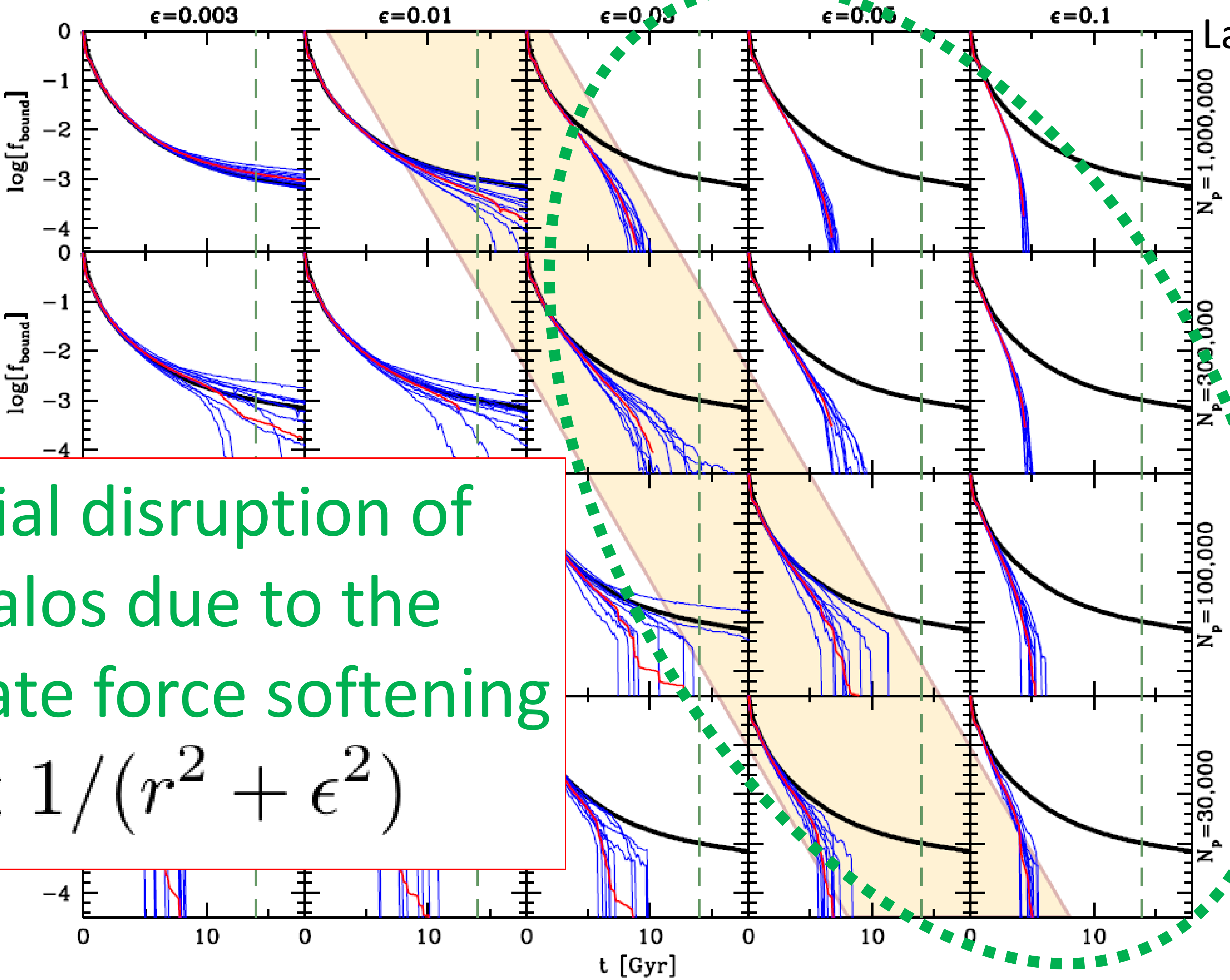
Large ε →

(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

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

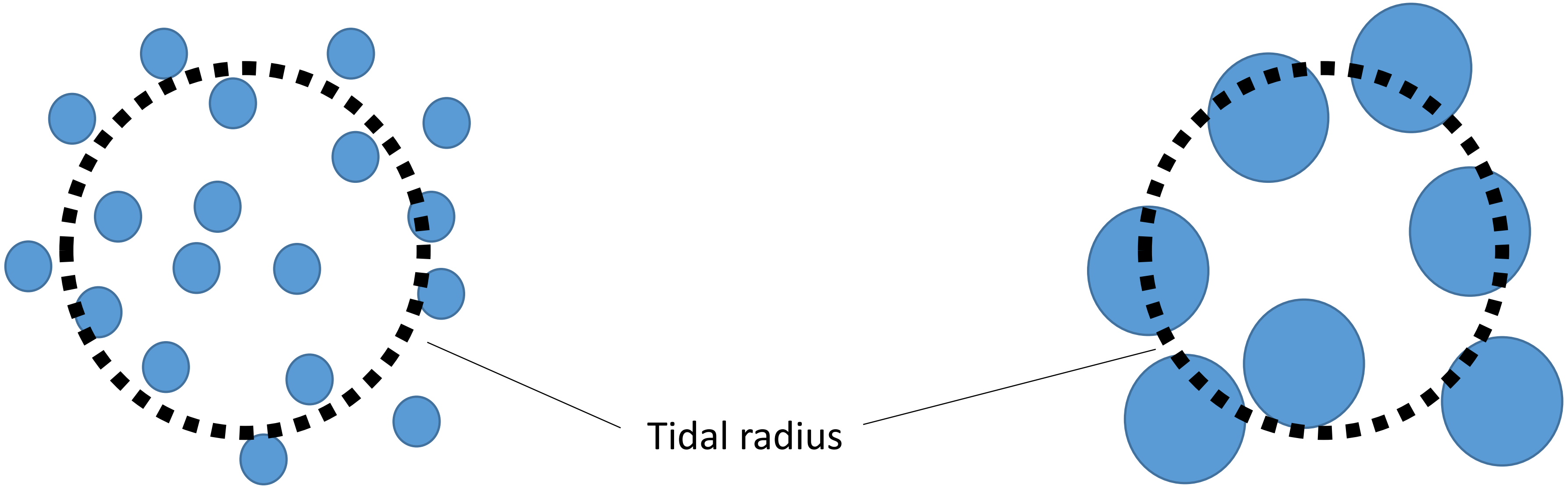
van den Bosch & GO (arXiv:1801.05427)

Instability triggered by discreteness noise

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

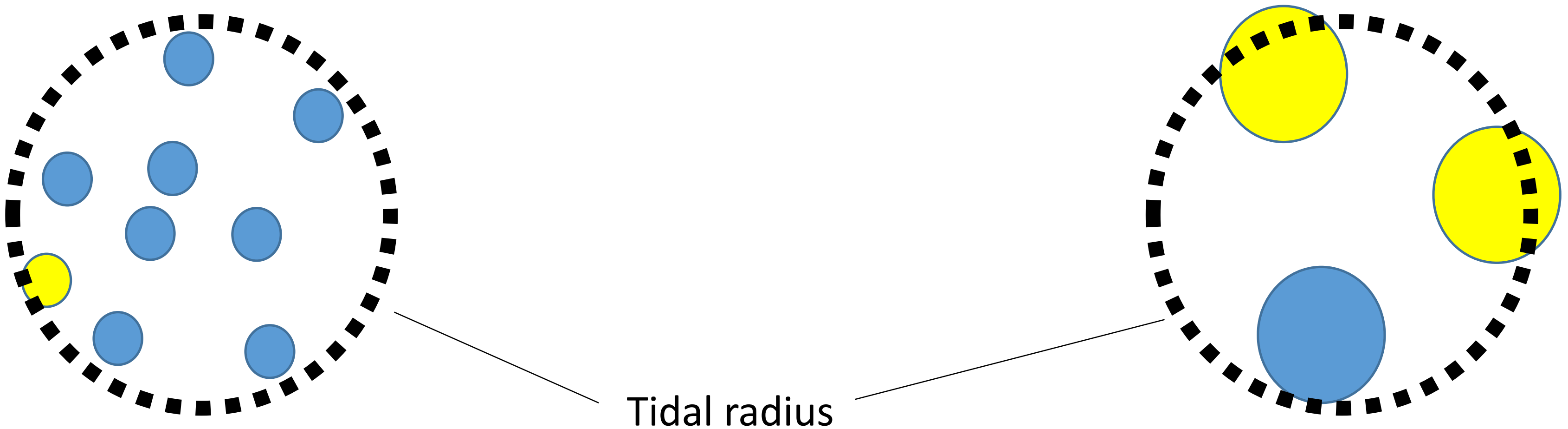
Instability triggered by discreteness noise

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



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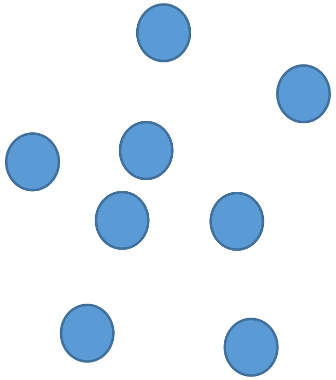
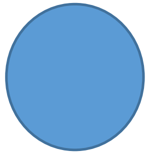
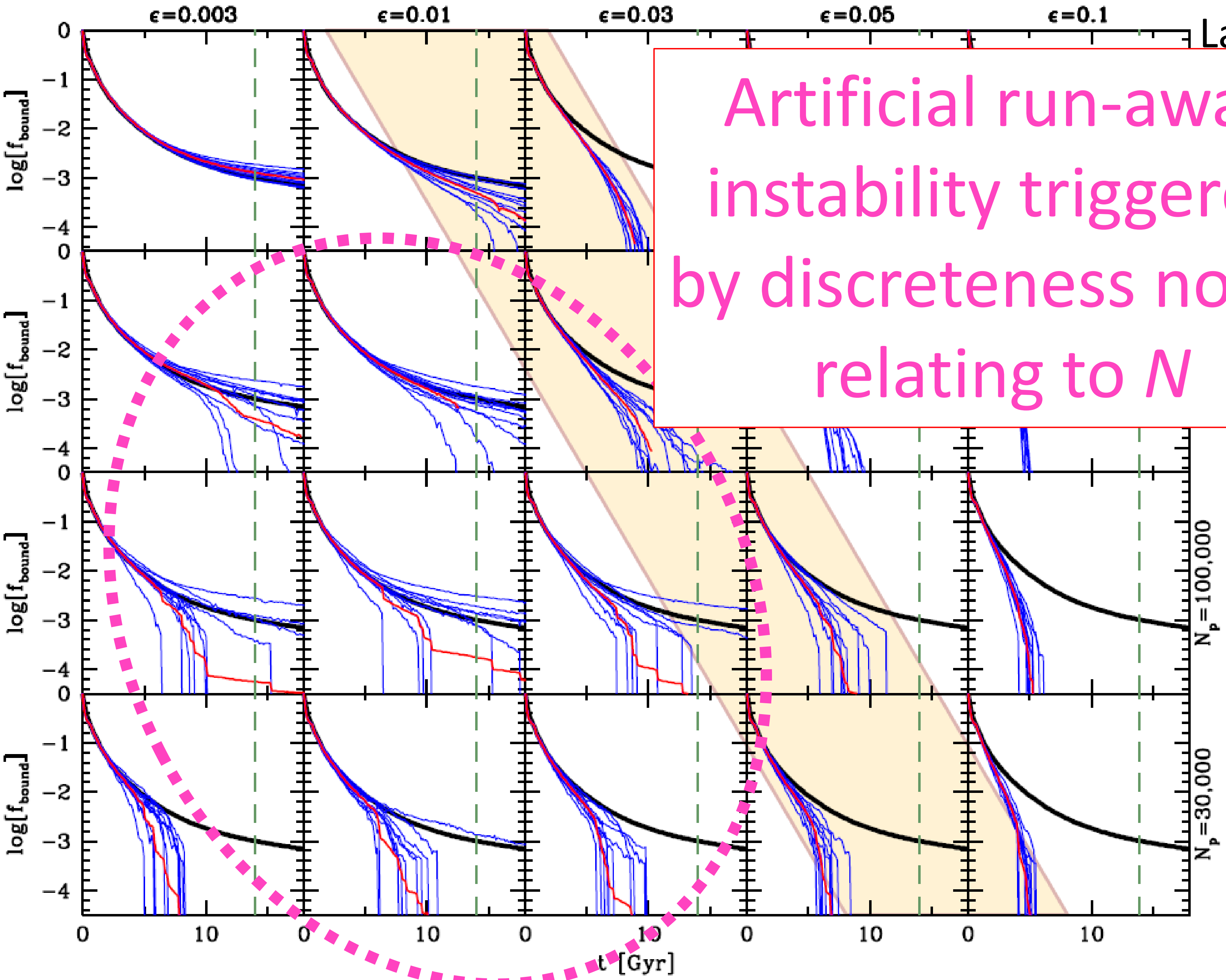


Can be disrupted
The other way around is possible



← 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

← Small ε

Large ε →

(Same orbits)

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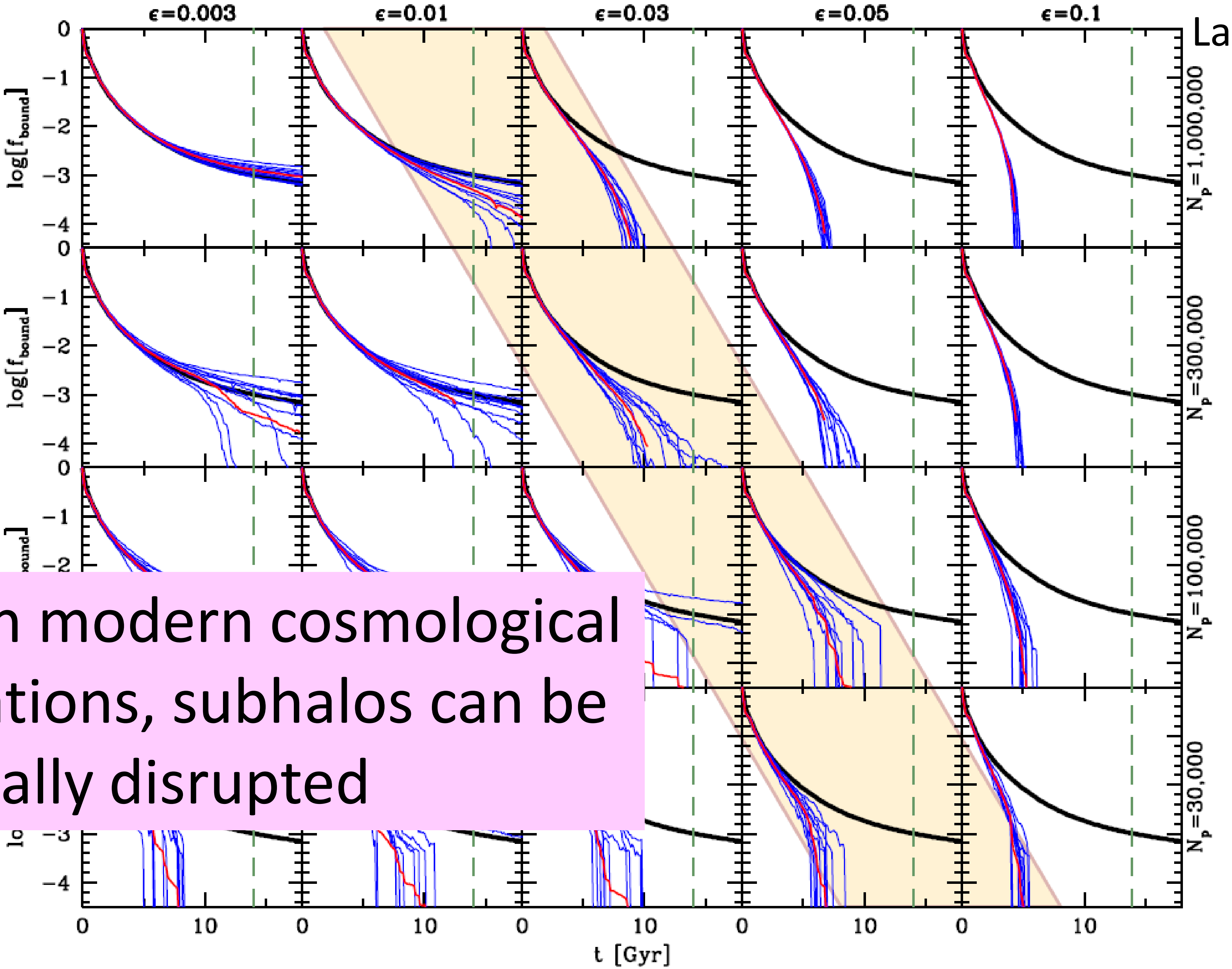


← Large N

Small N →

Even in modern cosmological simulations, subhalos can be artificially disrupted

van den Bosch & GO (arXiv:1801.05427)

Questions

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

- How can we assess the reliability of simulated subhalos?
  -> van den Bosch & GO (2018)

- **What is the true tidal evolution of dark matter subhalos?**
  -> GO, van den Bosch, Hahn & Burkert, in prep.

(Semi-)Analytic modeling of tidal evolution

- Can complement cosmological simulations

- Complicatedly coupled effects
  - Tidal heating, tidal stripping, dynamical friction etc.
  - Difficult to construct fully analytic treatment

- Fudge parameters
  - To integrate the coupled effects
  - To model them with a simple analytic prescription

- Calibration with numerical simulations
  - Artefacts?
  - Parameter space?

GO, van den Bosch, Hahn & Burkert, in prep.

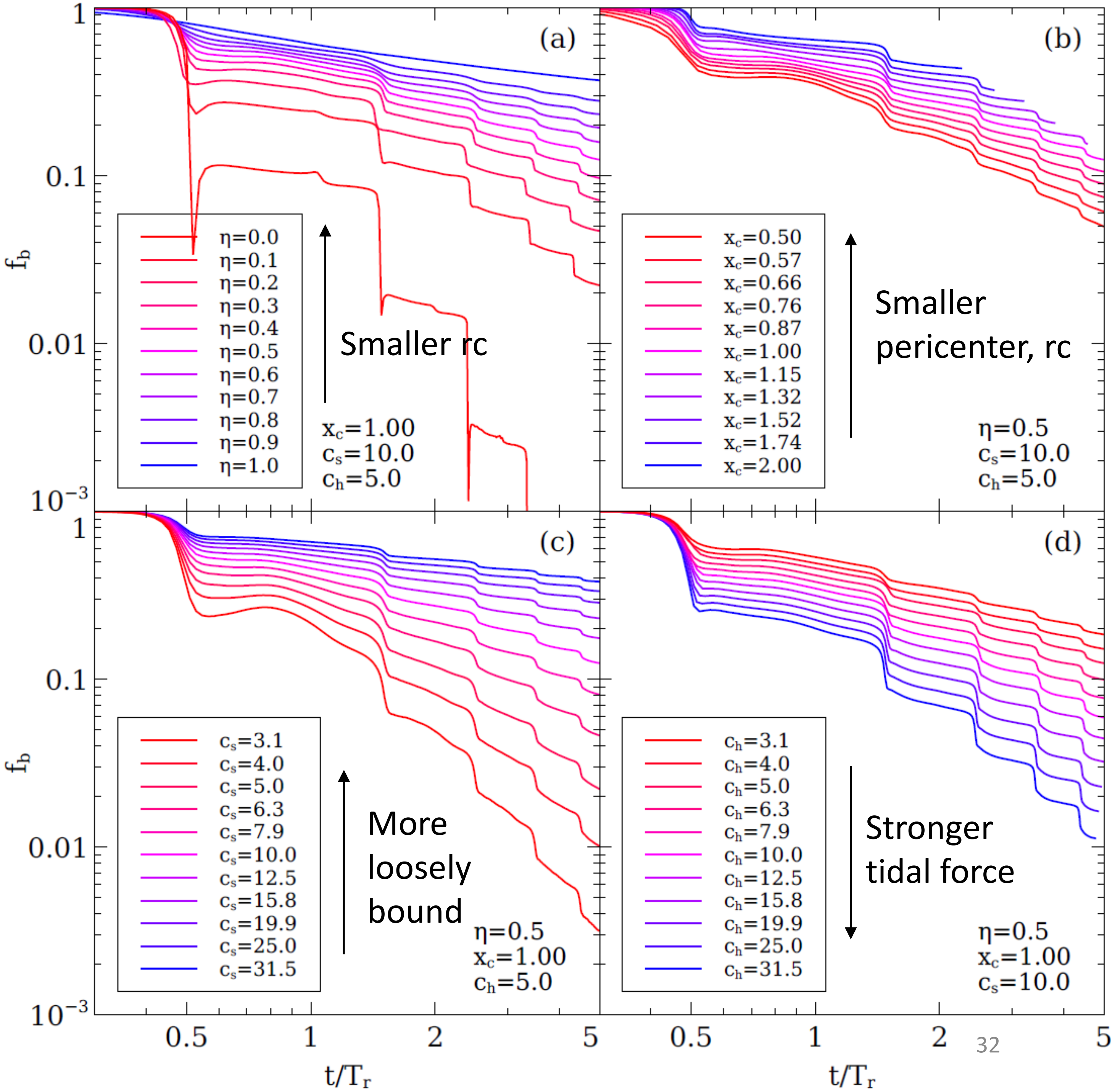
DASH: Dynamical Aspects of SubHalos

- Public library of idealized *N*-body simulations
  - Fulfill the numerical criteria, broad parameter space
  - Orbital and mass evolution + radial profiles

- First data release
  - 4 parameters are varied
    - 2 orbital + 2 halo concentration parameters
    - >2000 simulations
  - Minor mergers
    - Allow to use an analytical potential for the host halo
  - NFW halos, no baryon

Mass evolution

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



GO, van den Bosch, Hahn & Burkert, in prep.

Density profile

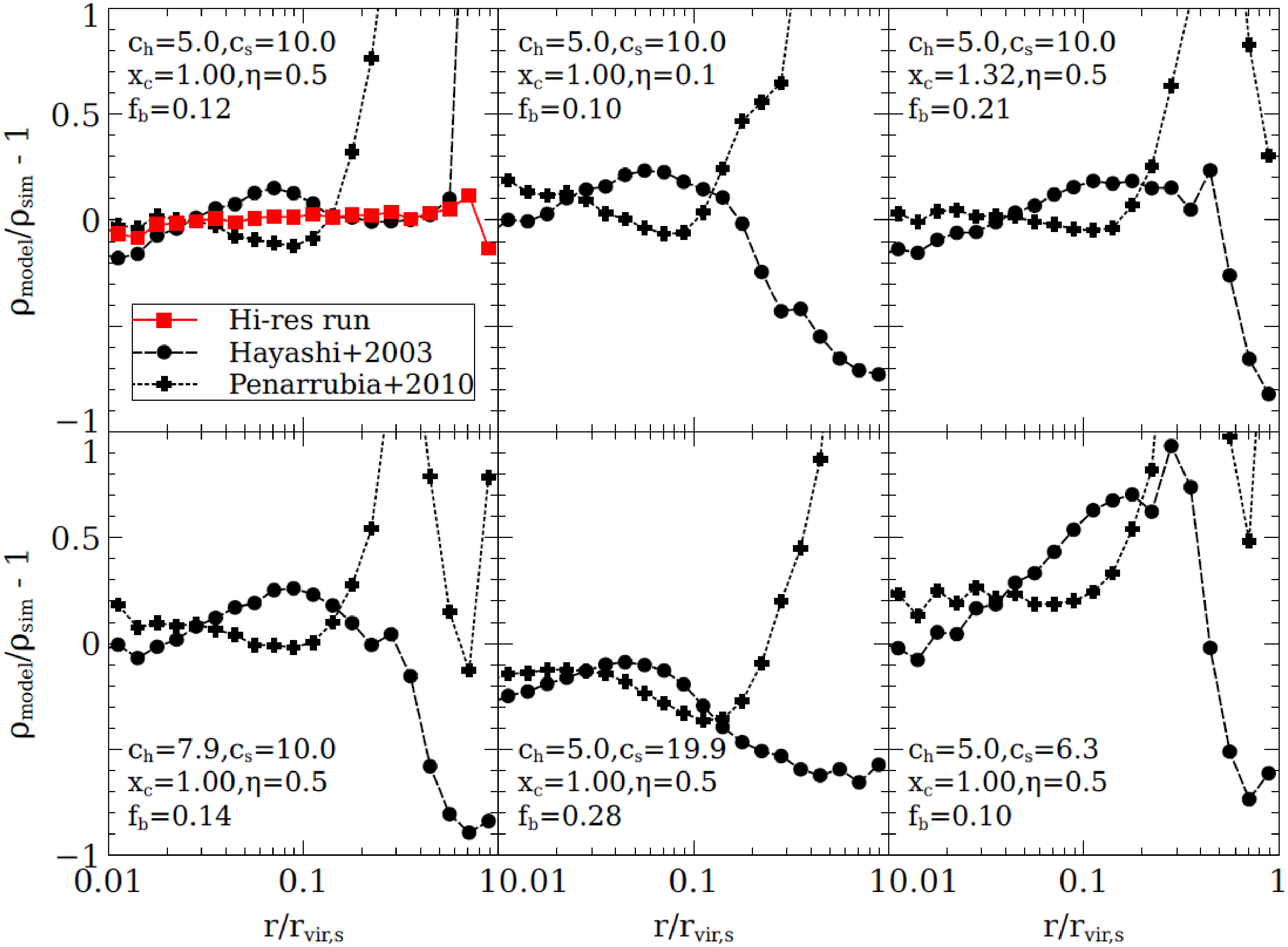
- Numerically converged (red)

- Comparison with empirical relations

  Room to improve

- Tailored large dataset

  -> Machine Learning



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Observatoire de la CÔTE d'AZUR

LAGRANGE

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

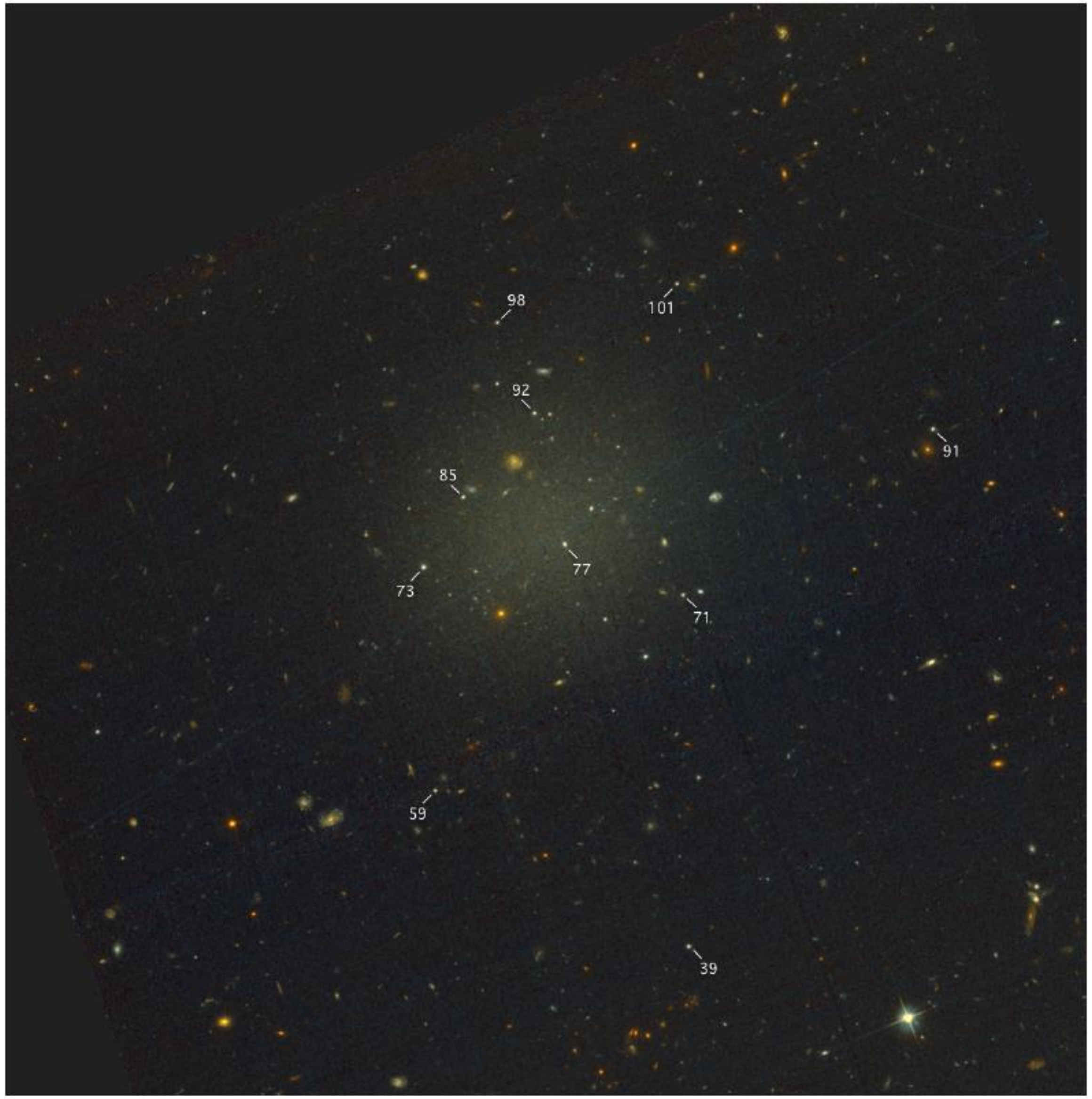
Go Ogiya

(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)



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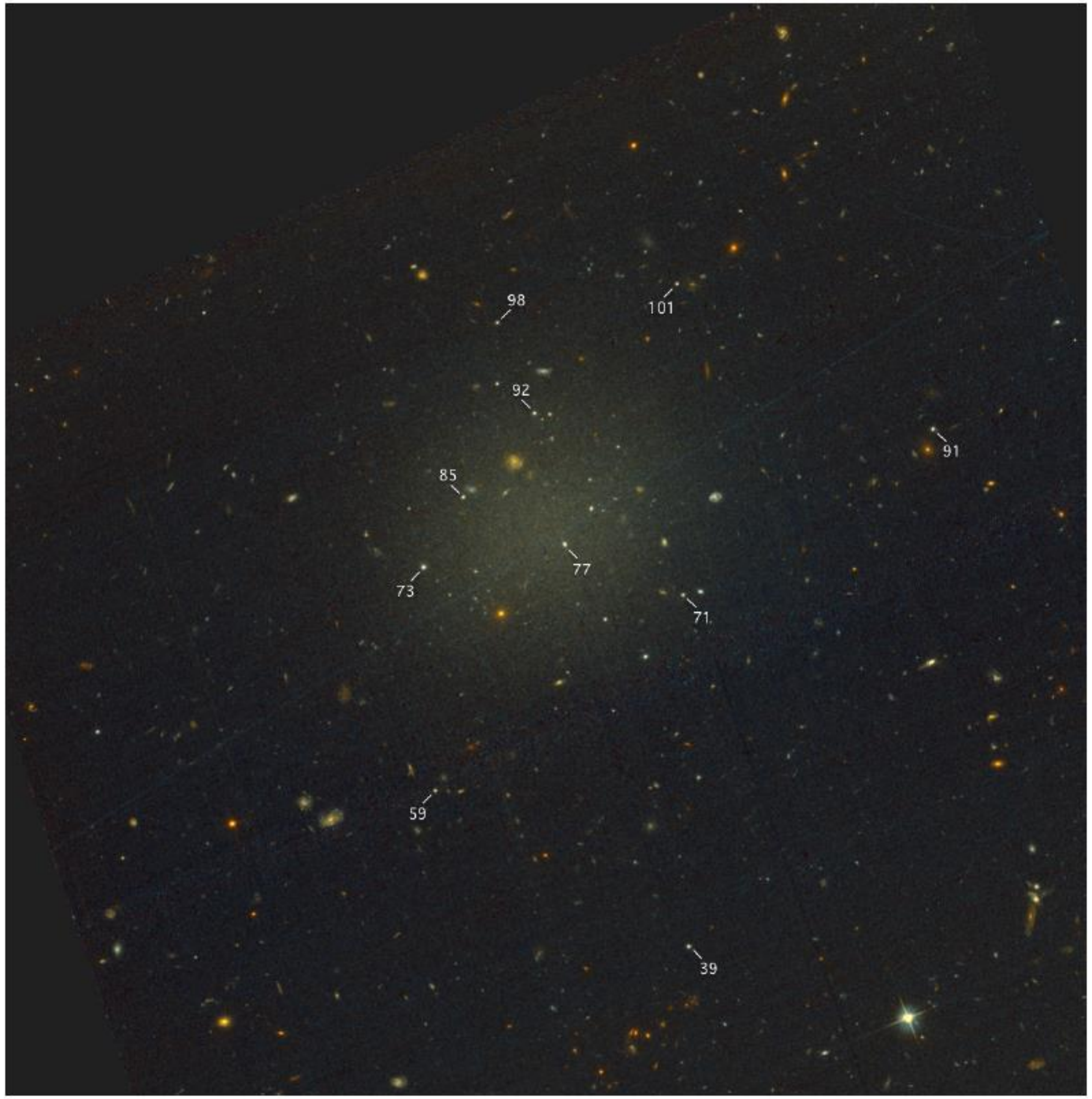
- Mstar = 2e8Msun
- Abundance matching models -> Mhalo=4.9e10Msun
  - ✓e.g., Moster et al. (2013)
- van Dokkum et al. (2018) inferred Mhalo ~ 1e8Msun or less
  - ✓Kinematics of 10 globular clusters
  - ✓Large uncertainties (Martin et al. 2018; Laporte et al. 2018; Hayashi & Inoue 2018)



Simulation setup

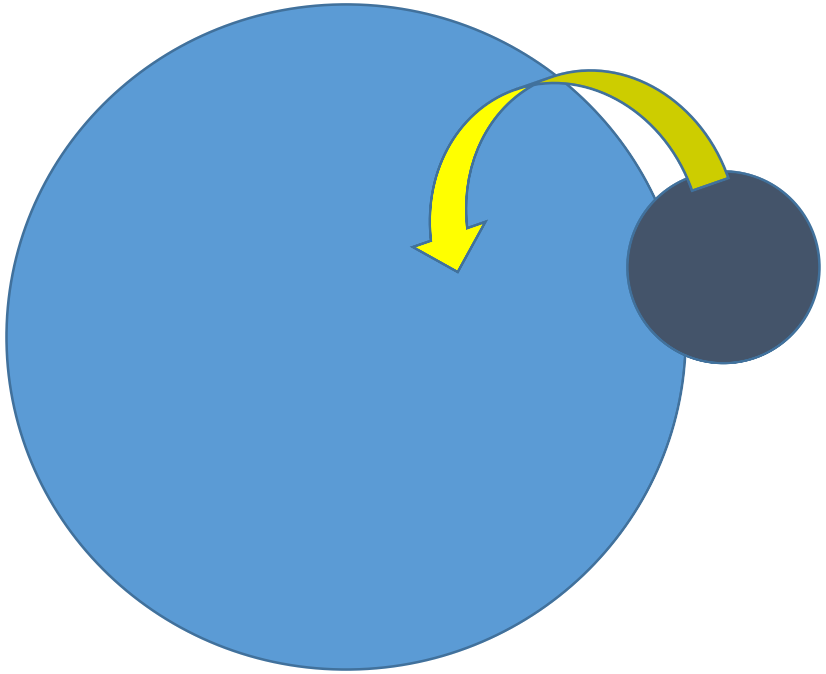
NGC1052 = fixed potential

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

Initial density structure

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

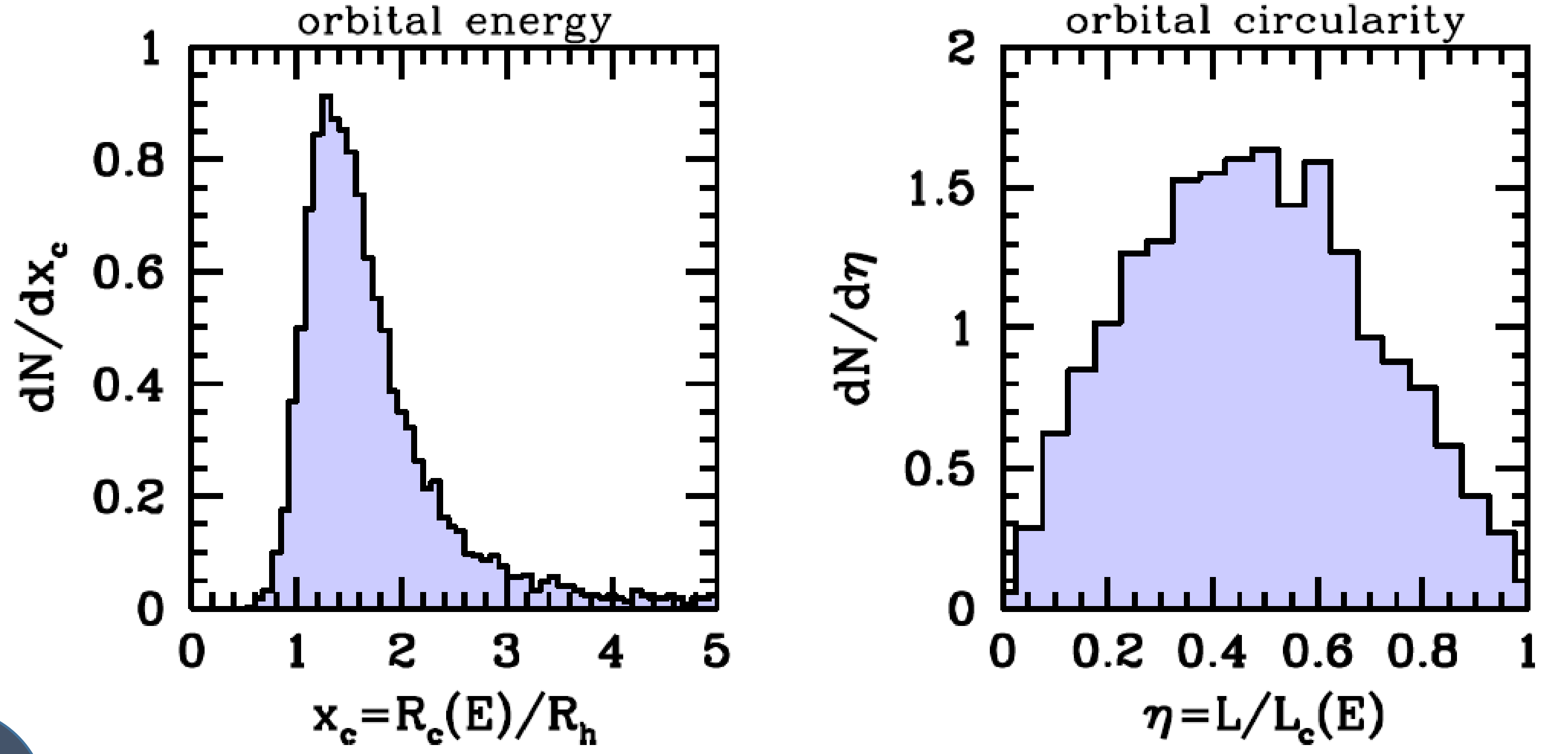
$$c \equiv R_{\rm v}/r_0$$



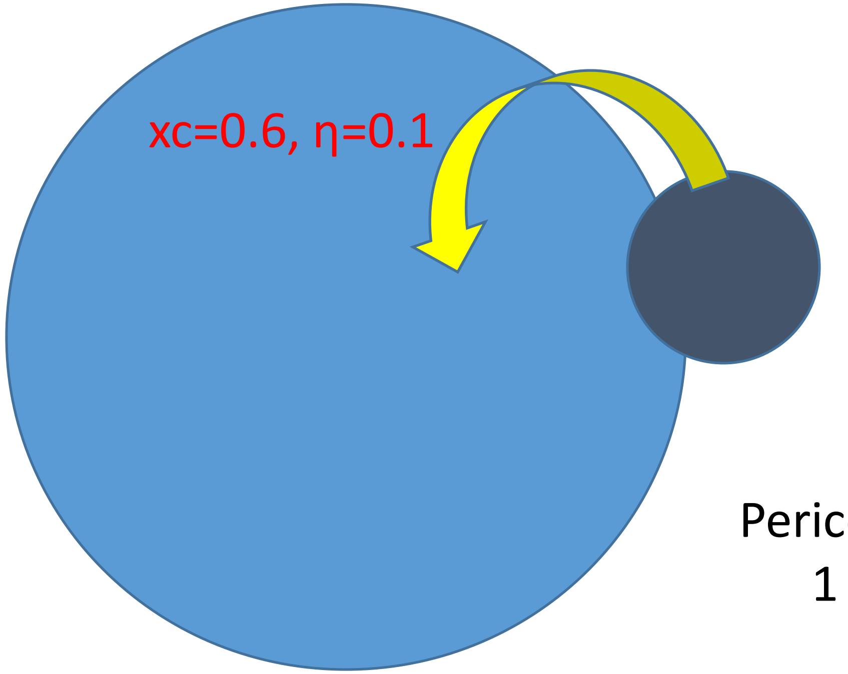
Satellite = *N*-body

- 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=11.2 (Ludlow et al. 2016)

Simulation setup



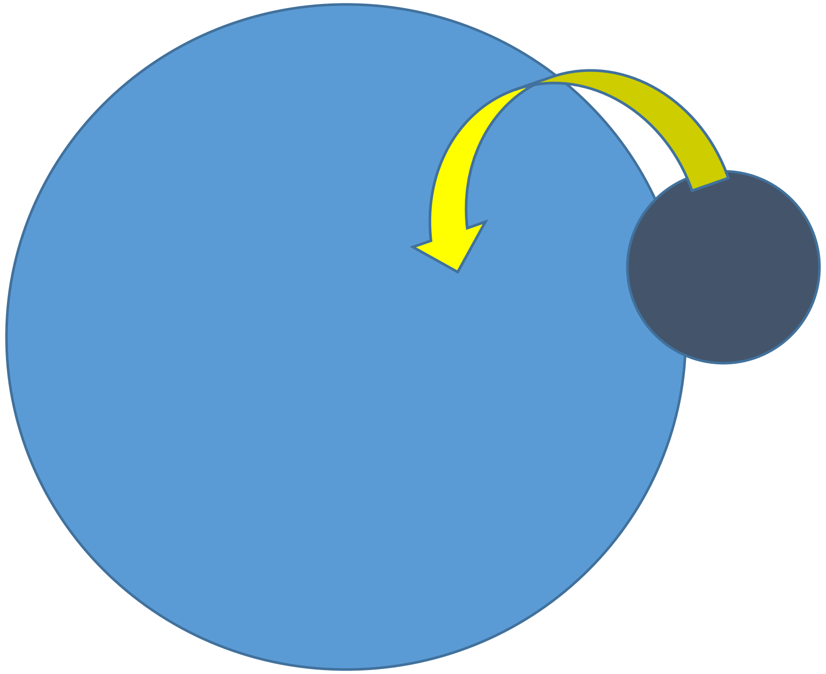
van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)



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

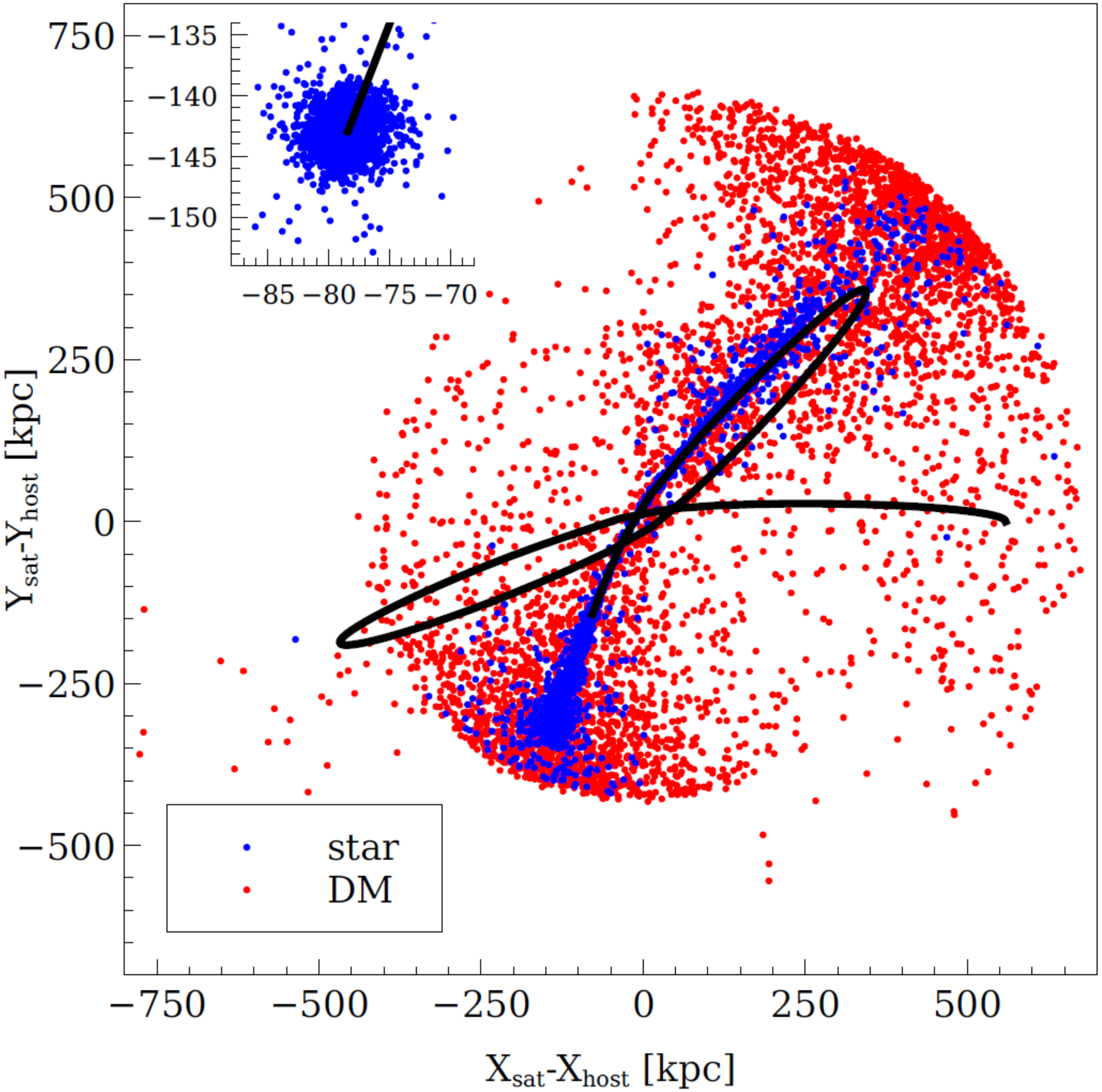
- ➢ Softening parameter, ε=0.03kpc
  - Results would be reliable at t=10Gyr
    - ✓ Power et al. (2003); van den Bosch & GO (2018)
- ➢ Opening angle, θ=0.6
  - Tree code for GPU clusters (GO et al. 2013)

Distribution of stripped matter

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

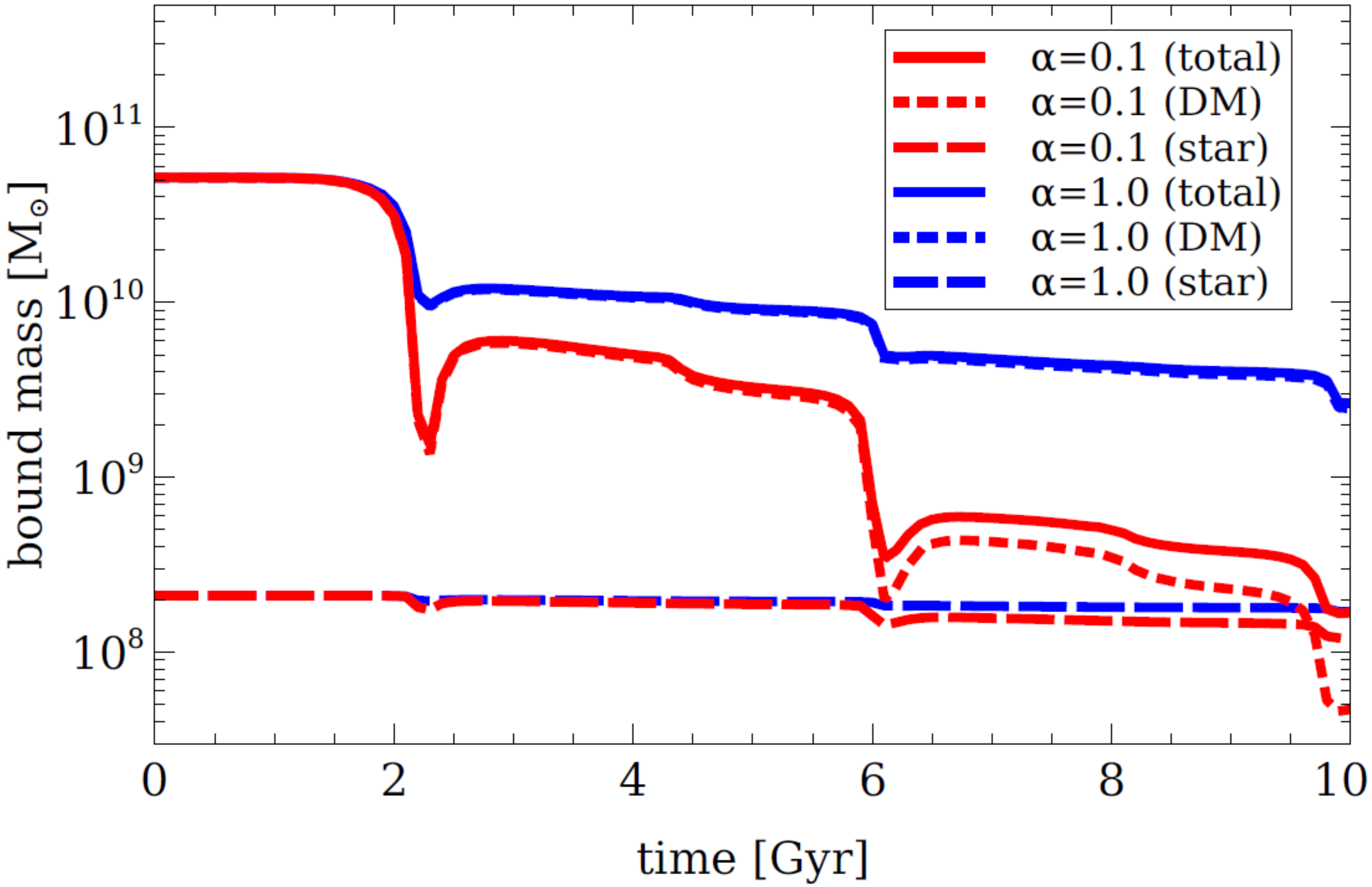
- DM significantly stripped

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



GO (arXiv:1804.06421)

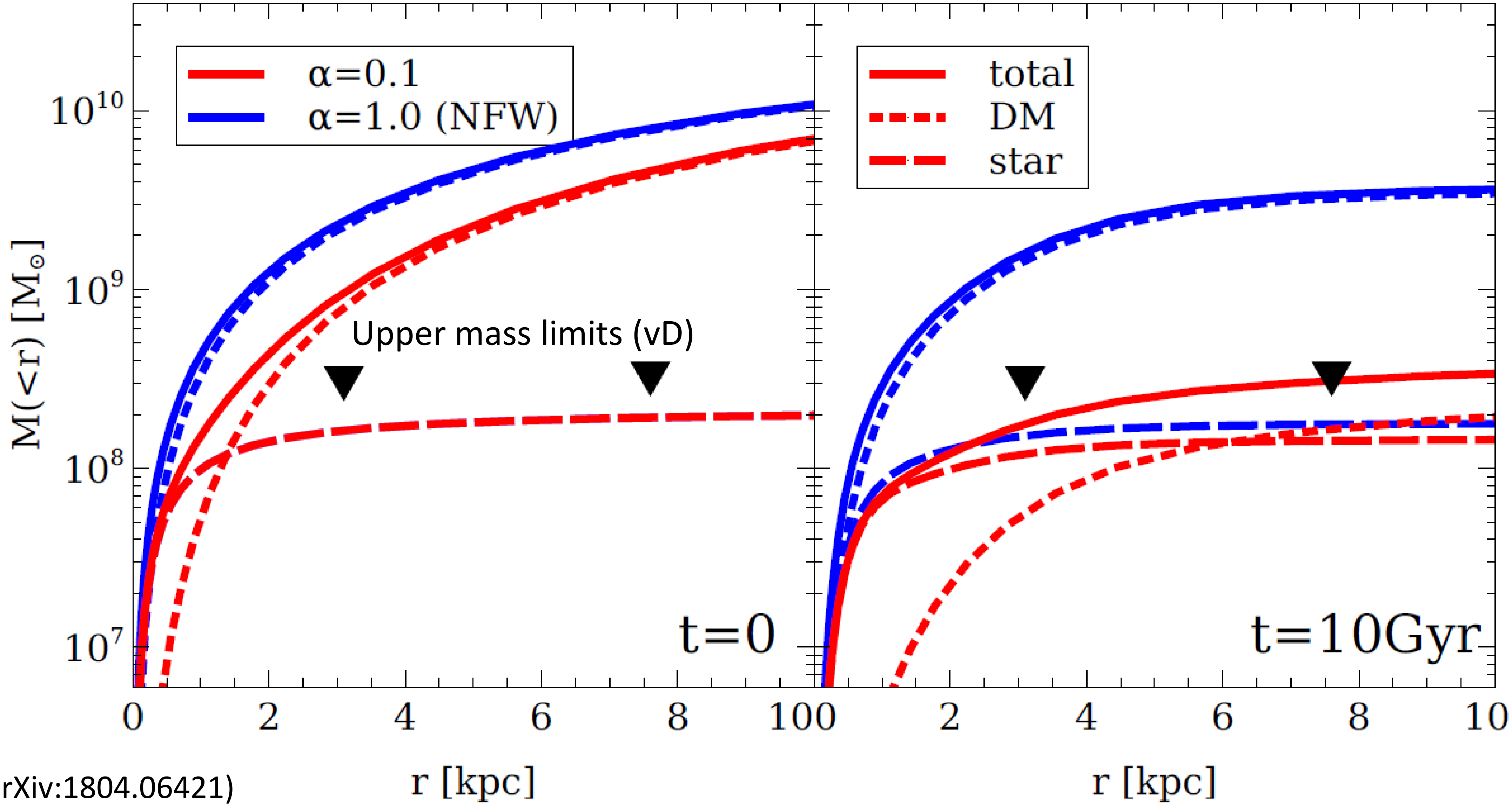
Mass evolution



GO (arXiv:1804.06421)

- 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

Comparison with van Dokkum et al. (vD)



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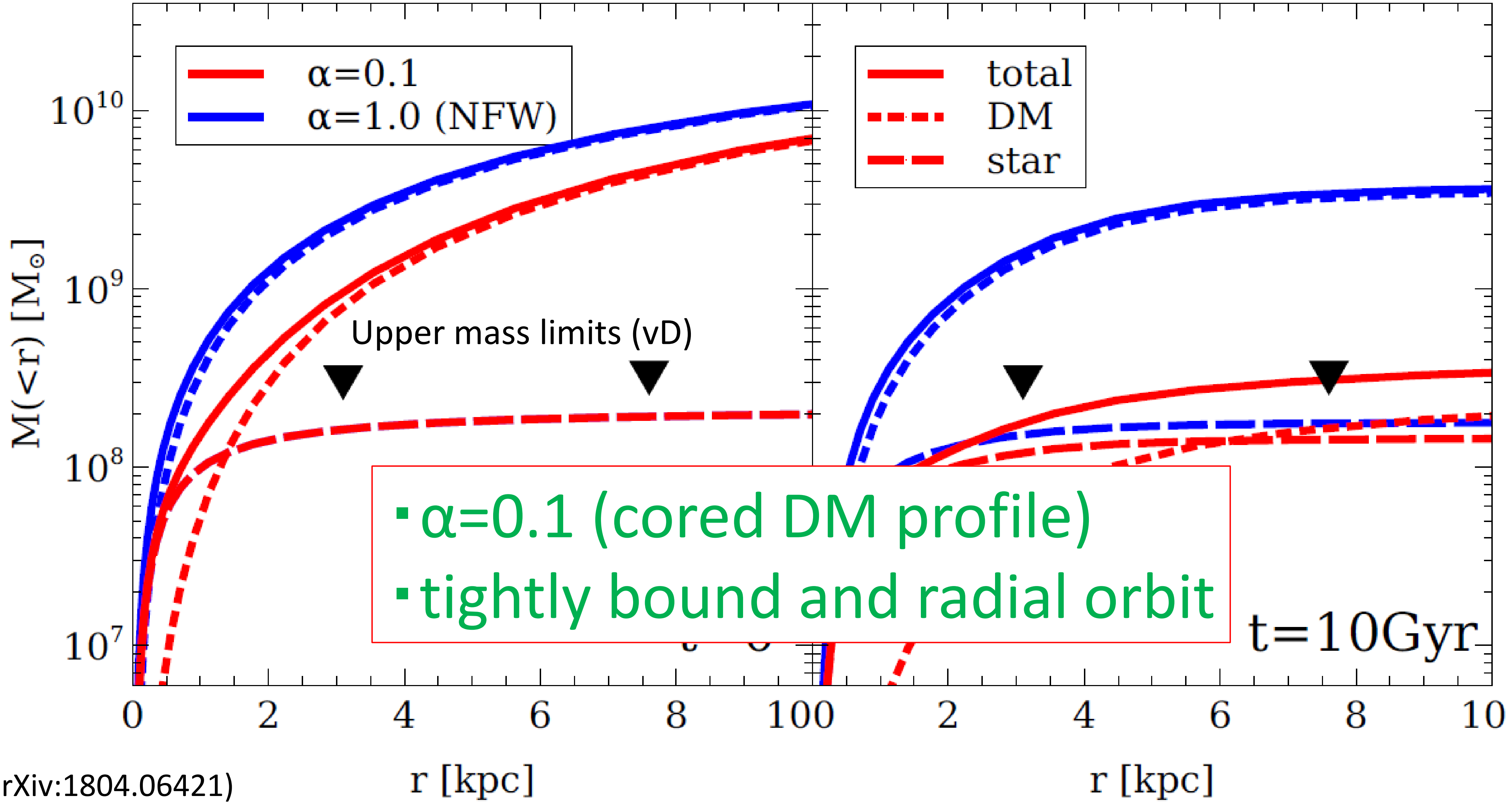


Upper mass limits (vD)

- α=0.1 (cored DM profile)
- tightly bound and radial orbit

GO (arXiv:1804.06421)

Summary

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

A1: Most of them should be artificial

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

Q2: How can we assess the reliability of simulated subhalos?

A2: Two conditions relating to ε and *N*

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

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

A3: Improve analytic models and complement cosmo sims with the DASH library

-> GO, van den Bosch, Hahn & Burkert, in prep.

- Tidal interaction between NGC1052 and a satellite galaxy

-> Possible formation path of the UDG lacking DM

-> GO (arXiv:1804.06421)

Appendix

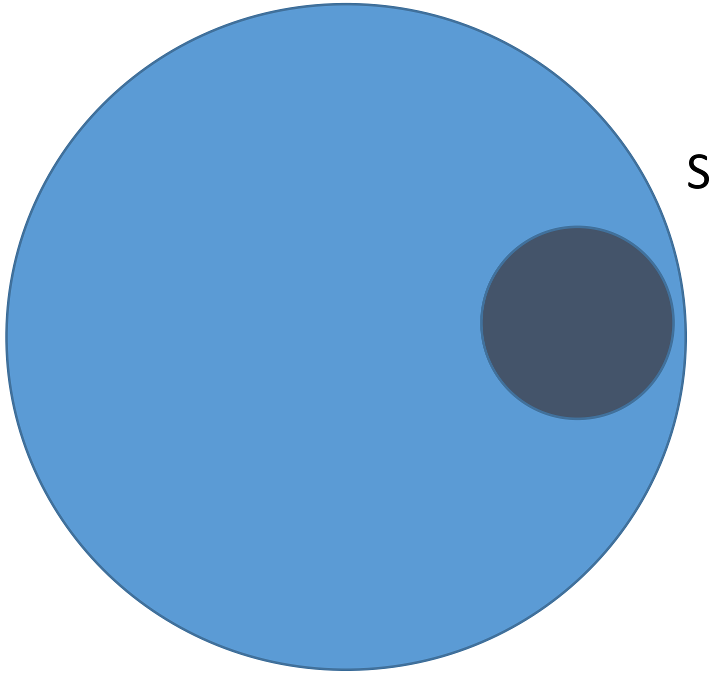
Collisionless systems (Binney & Tremaine for details)

- 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?

Some parameters



Host halo (ch=5)

Subhalo (cs=10)

Mhost/Msub = 1000

Navarro, Frank & White (NFW, 1997)

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

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

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
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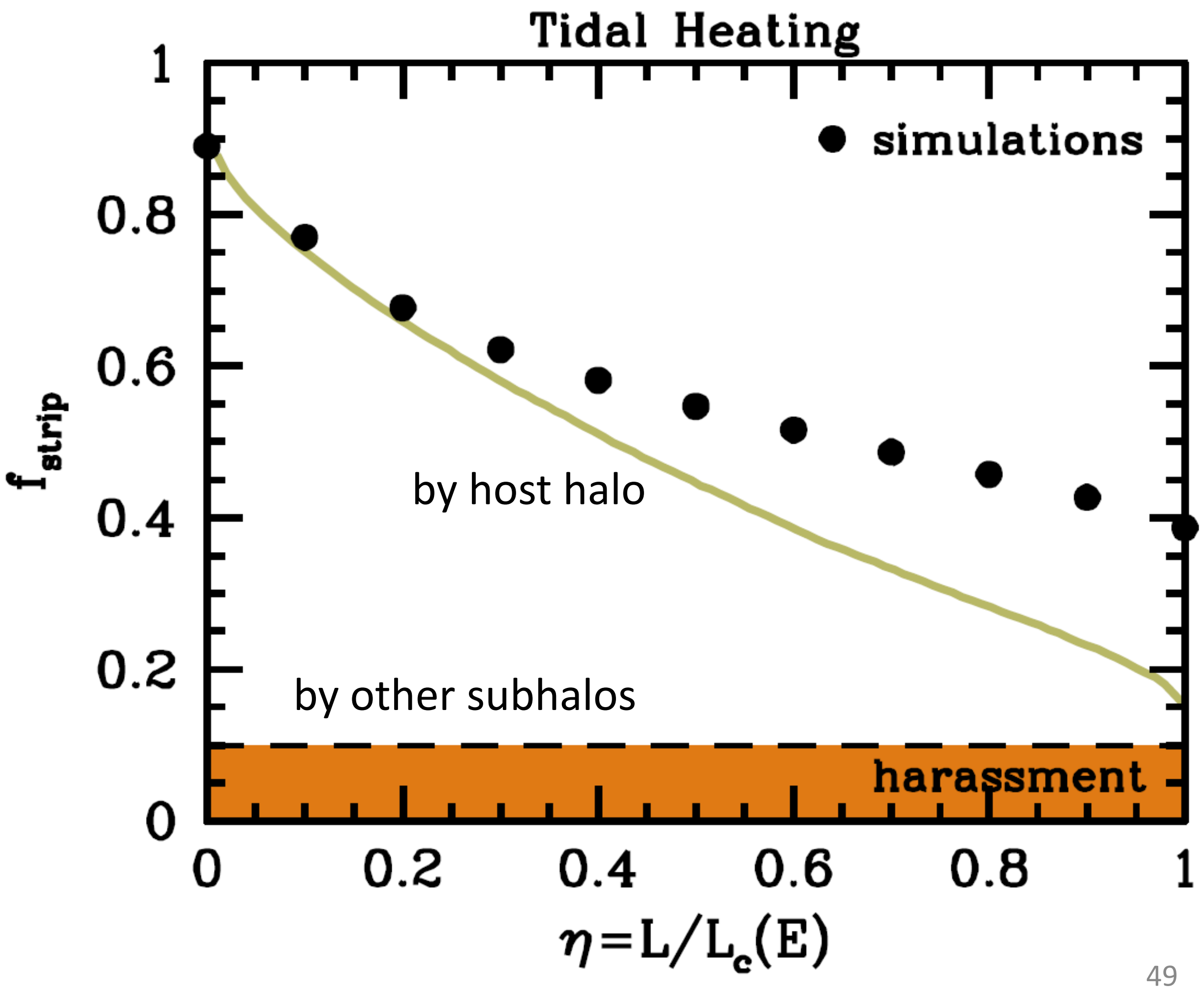
Impulsive heating

- Comparison at t=Tr

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

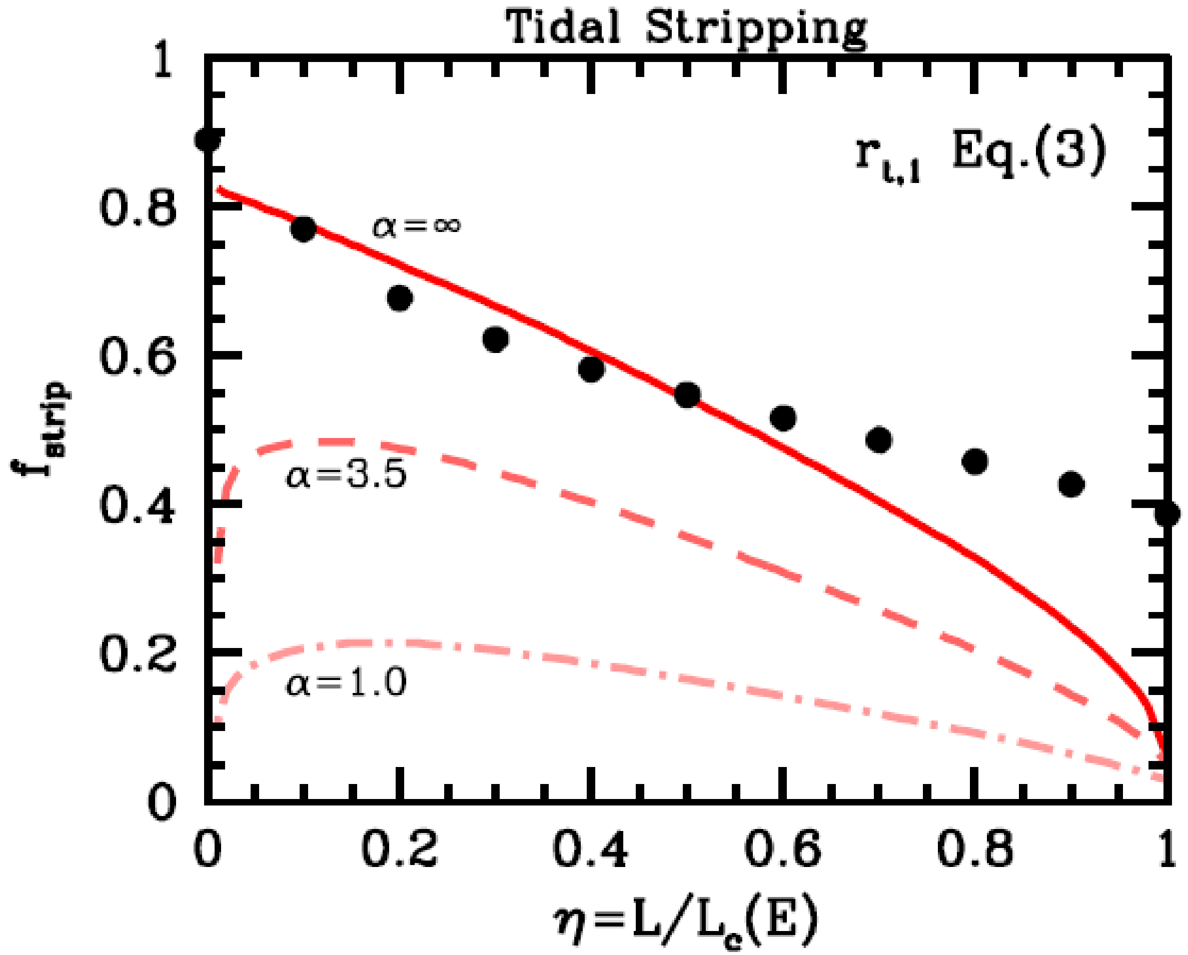
e.g. Gnedin et al. (1999); Gnedin & Ostriker (1999)



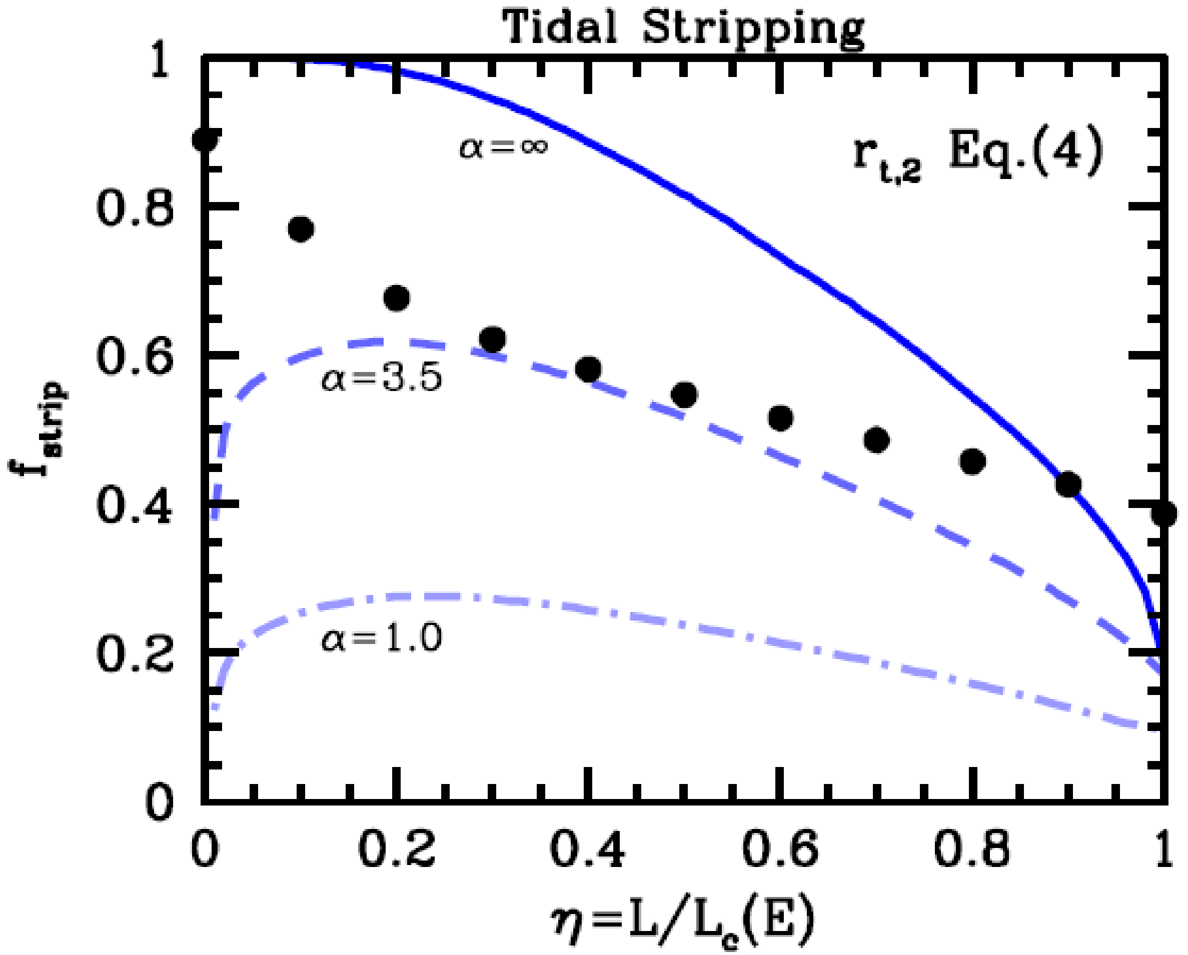
van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Tidal stripping

e.g. Tormen et al. (1998)



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



van den Bosch, GO, Hahn & Burkert
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van den Bosch, GO, Hahn & Burkert
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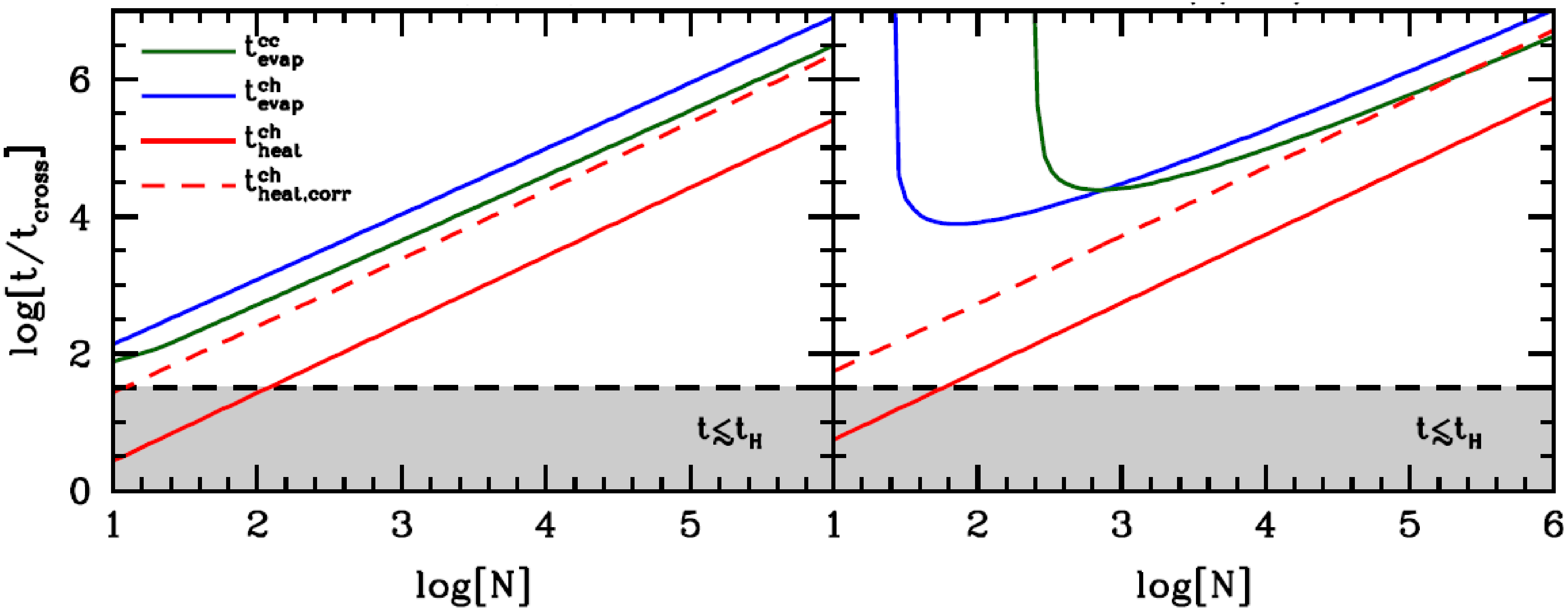
Timescales of evaporation



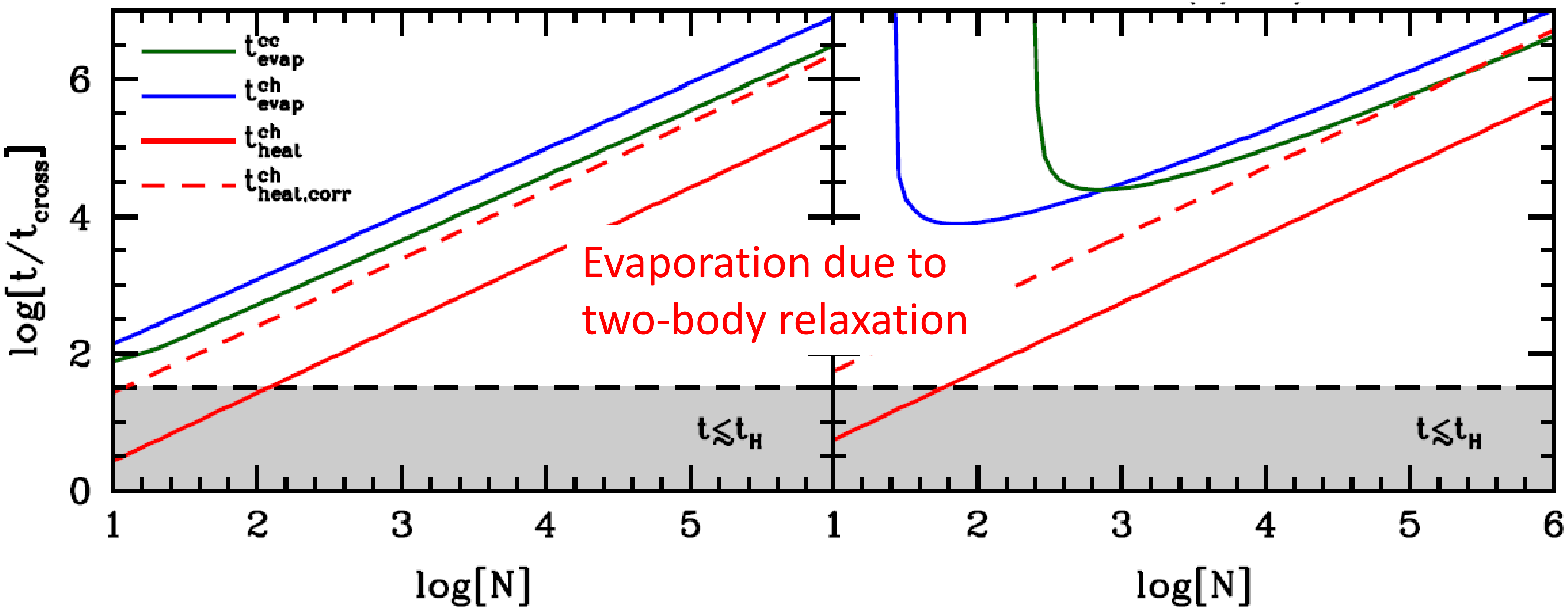
van den Bosch, GO, Hahn & Burkert
(arXiv:1711.05276)

Timescales of evaporation

e.g. Binney & Tremaine

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

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



Evaporation due to two-body relaxation

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

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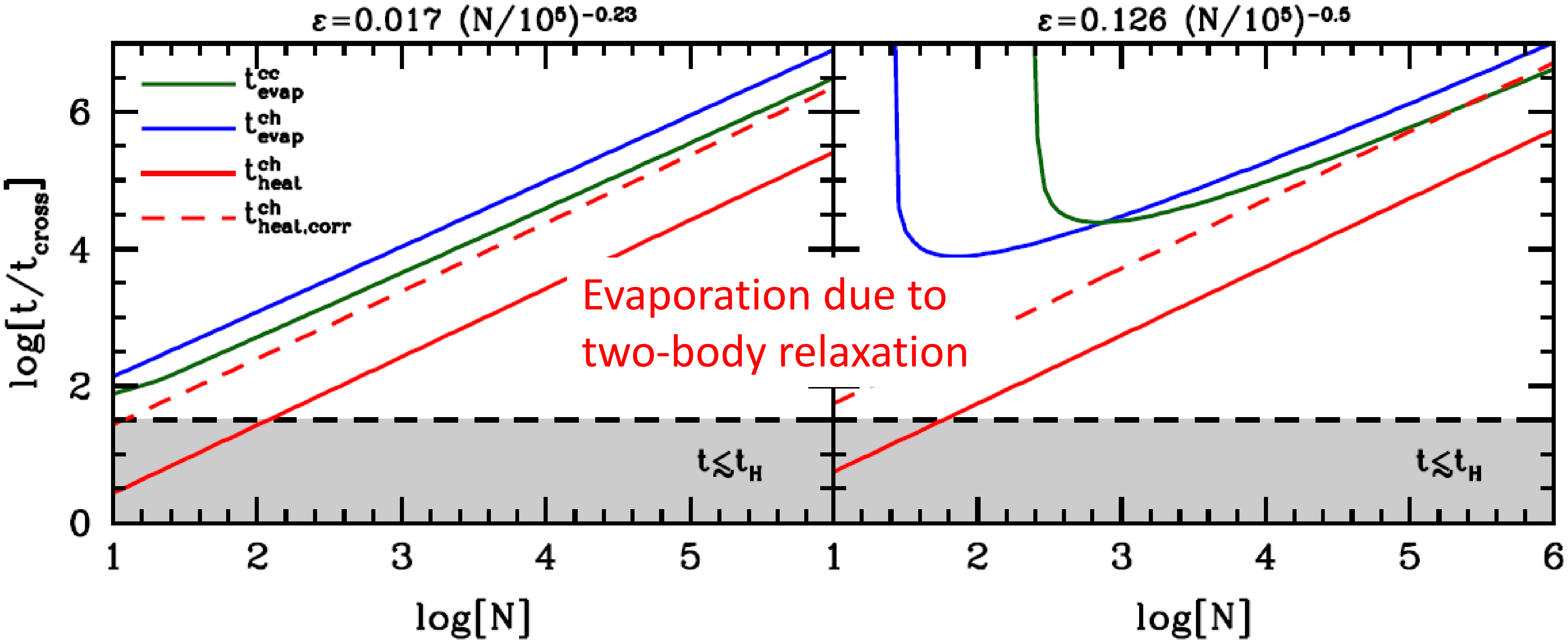
Dehnen (2001)

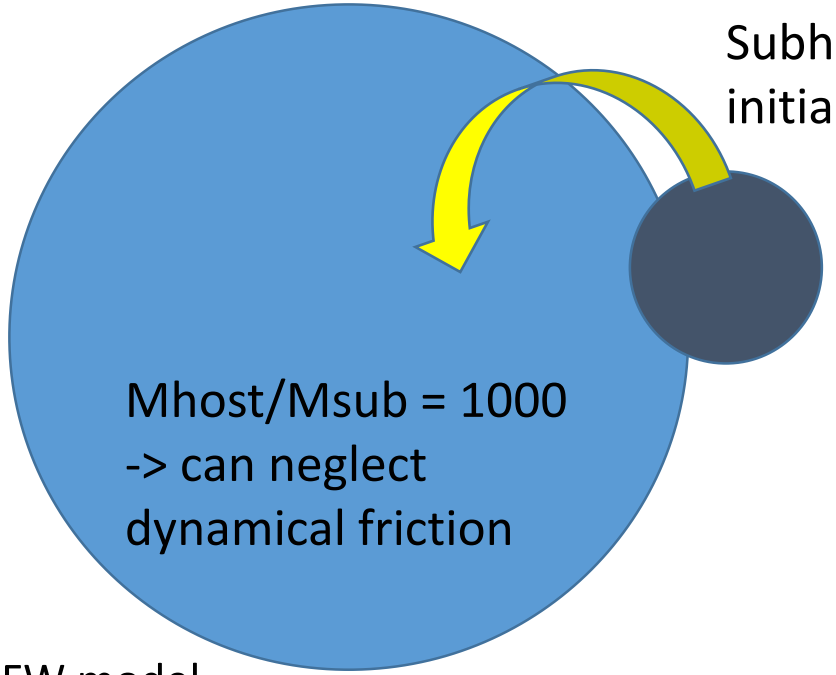
Power et al. (2003)



Evaporation due to two-body relaxation

GO, van den Bosch, Hahn & Burkert, in prep.

Making the DASH library



Host halo = fixed potential

Subhalo = *N*-body
initially at apocenter

Mhost/Msub = 1000
-> can neglect
dynamical friction

NFW model

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

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

- Numerical parameters
  - ✓ *N*=10^6
  - ✓ ε=0.0003Rv,s
  - ✓ θ=0.7

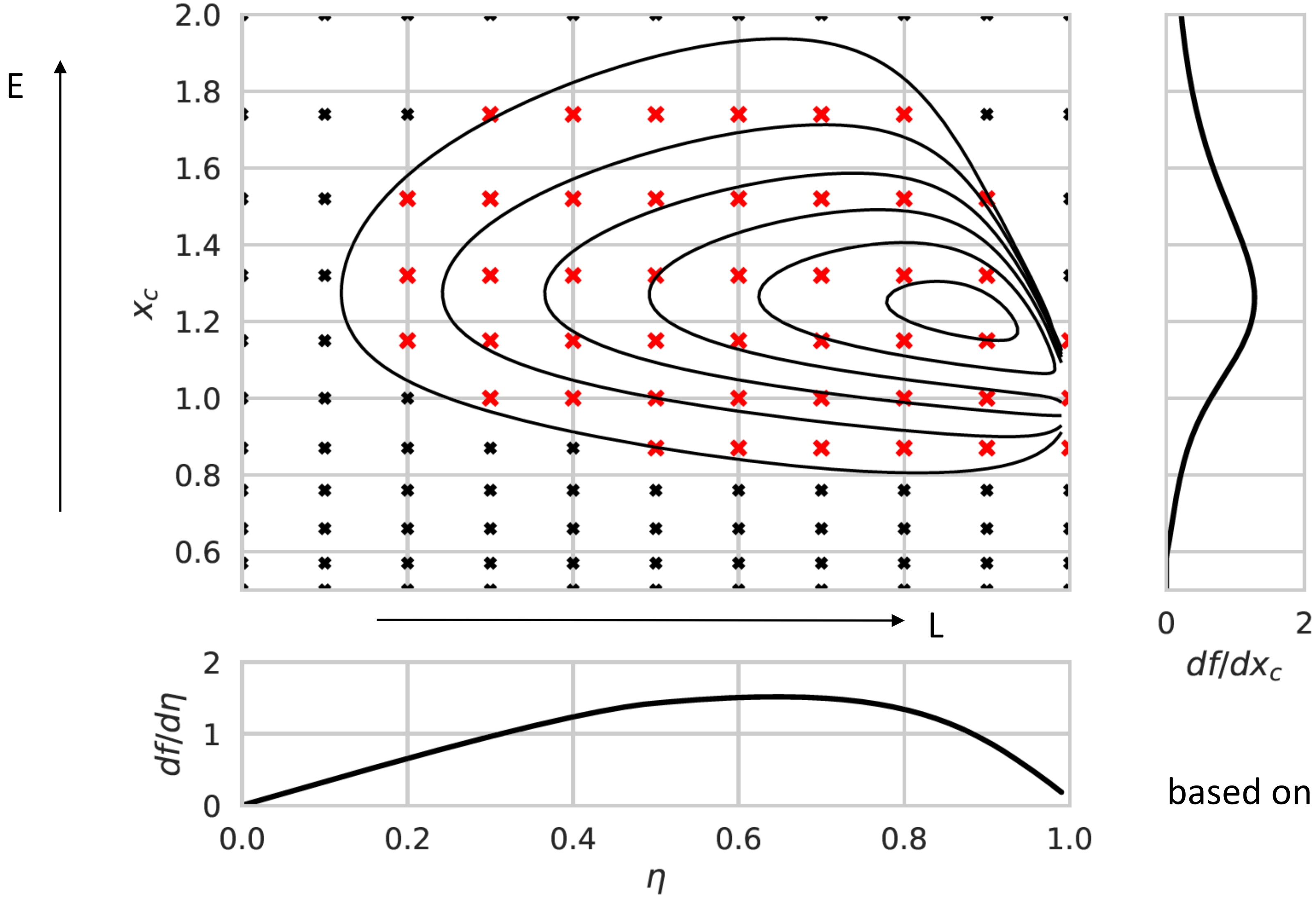
Results reliable when fb>0.001
(van den Bosch & Ogiya 2018)

- Vary orbital parameters
  - ✓ Orbital energy (xc)
  - ✓ Angular momentum (η)
- Vary structural parameters
  - ✓ Halo concentrations
  - ✓ Inner density slope
  - ✓ etc.

>2000 runs

GO, van den Bosch, Hahn & Burkert, in prep.

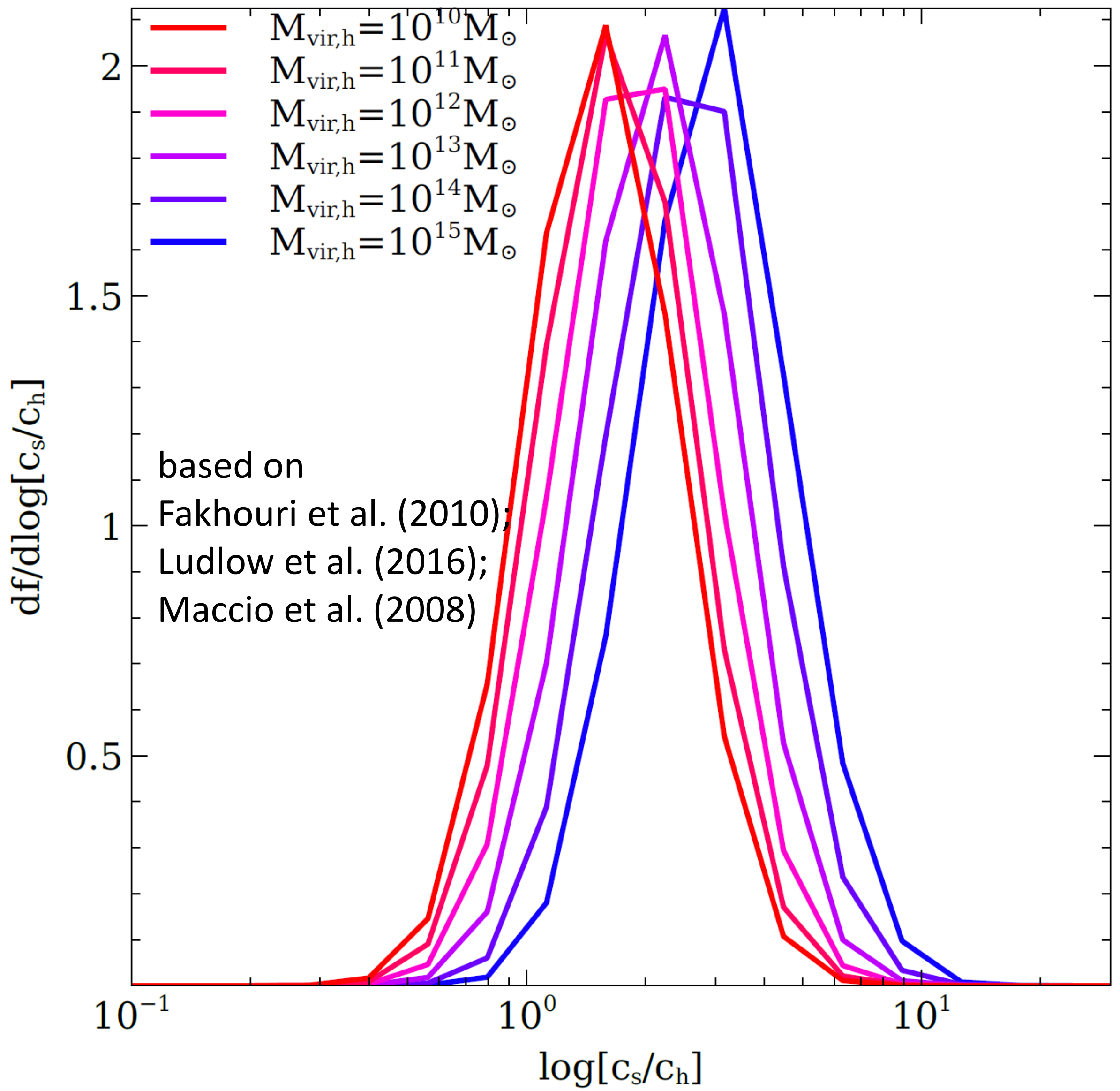
Orbital parameters



based on Jiang et al. (2015)

GO, van den Bosch, Hahn & Burkert, in prep.

Halo concentration parameters



based on
Fakhouri et al. (2010);
Ludlow et al. (2016);
Maccio et al. (2008)