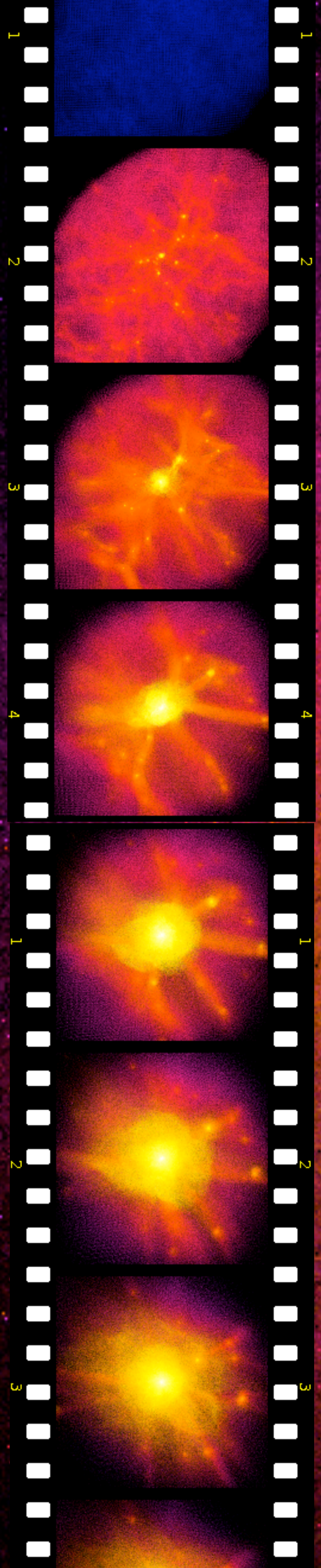
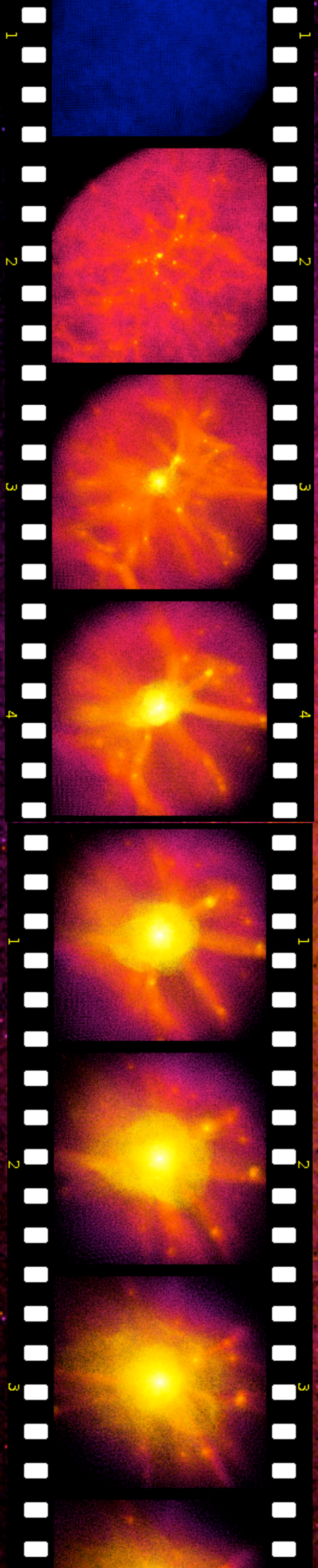


Shedding Light on Dark Satellites

Sarah Nickerson, Greg Stinson, Hugh Couchman, Jeremy Bailin, and James Wadsley

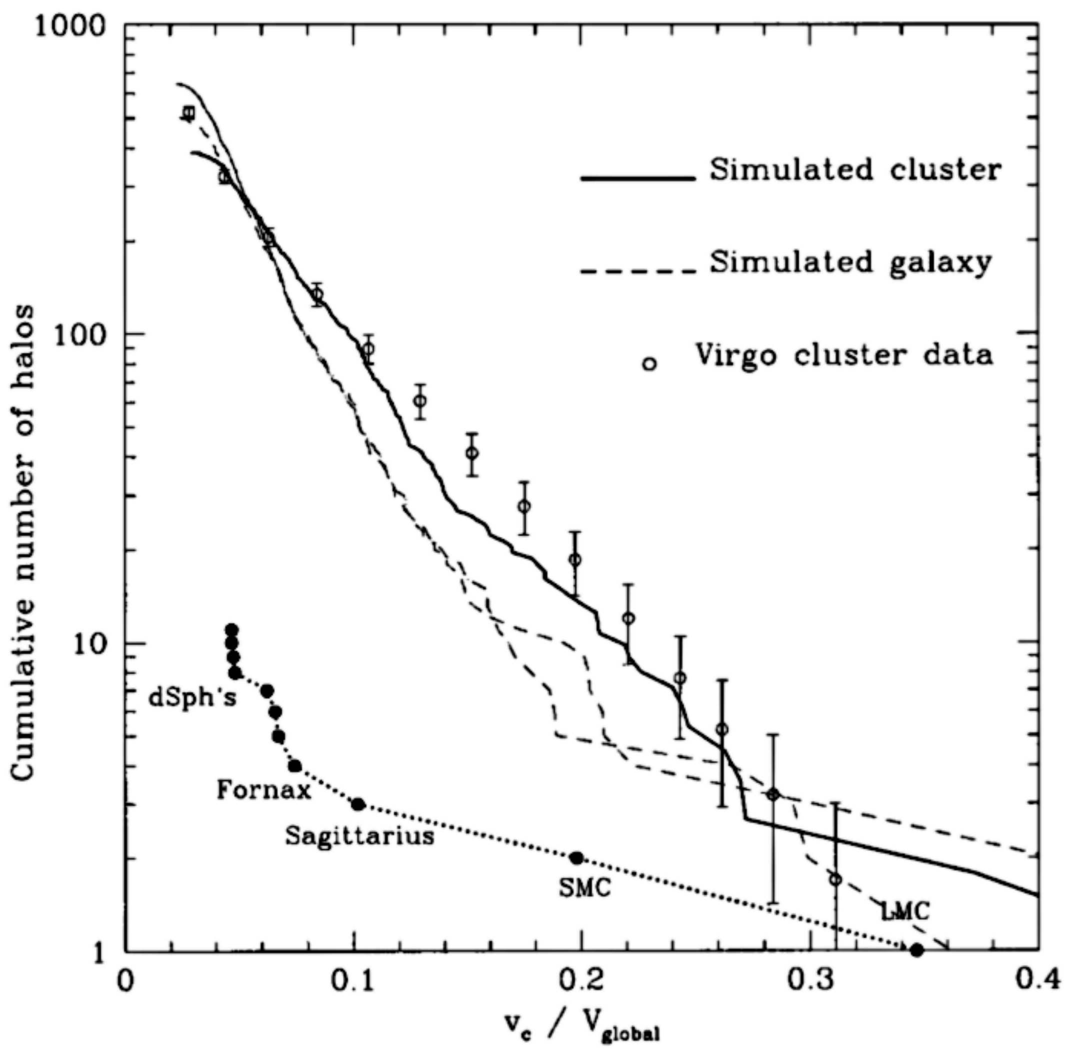
Department of Physics and Astronomy
McMaster University

SHARCNET™



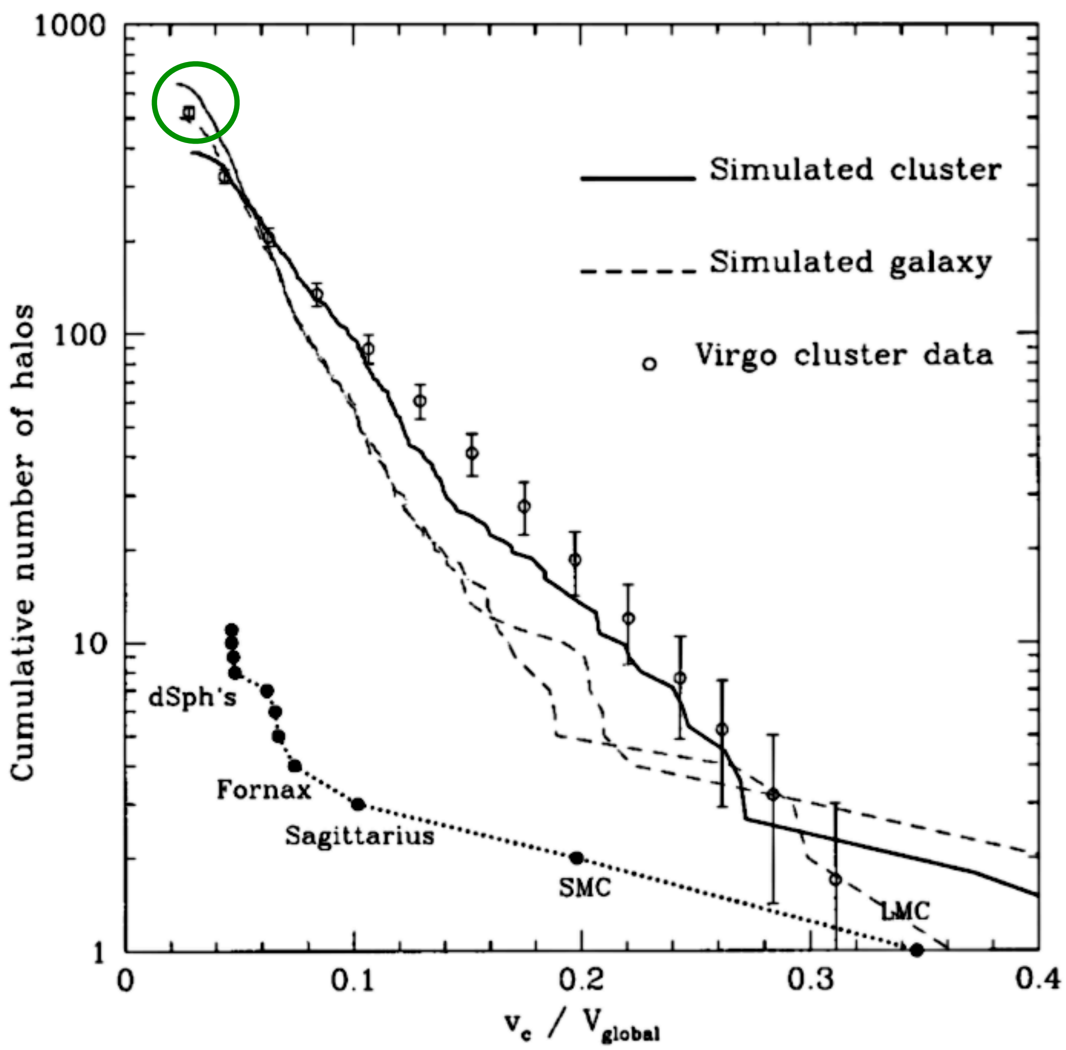
All is not well with ΛCDM cosmology...

Comparison of Number of Satellites in Dark Matter-Only Simulation to Observations



(from Moore, B. et al. 1999)

Comparison of Number of Satellites in Dark Matter-Only Simulation to Observations



Galaxy Cluster ✔

(from Moore, B. et al. 1999)

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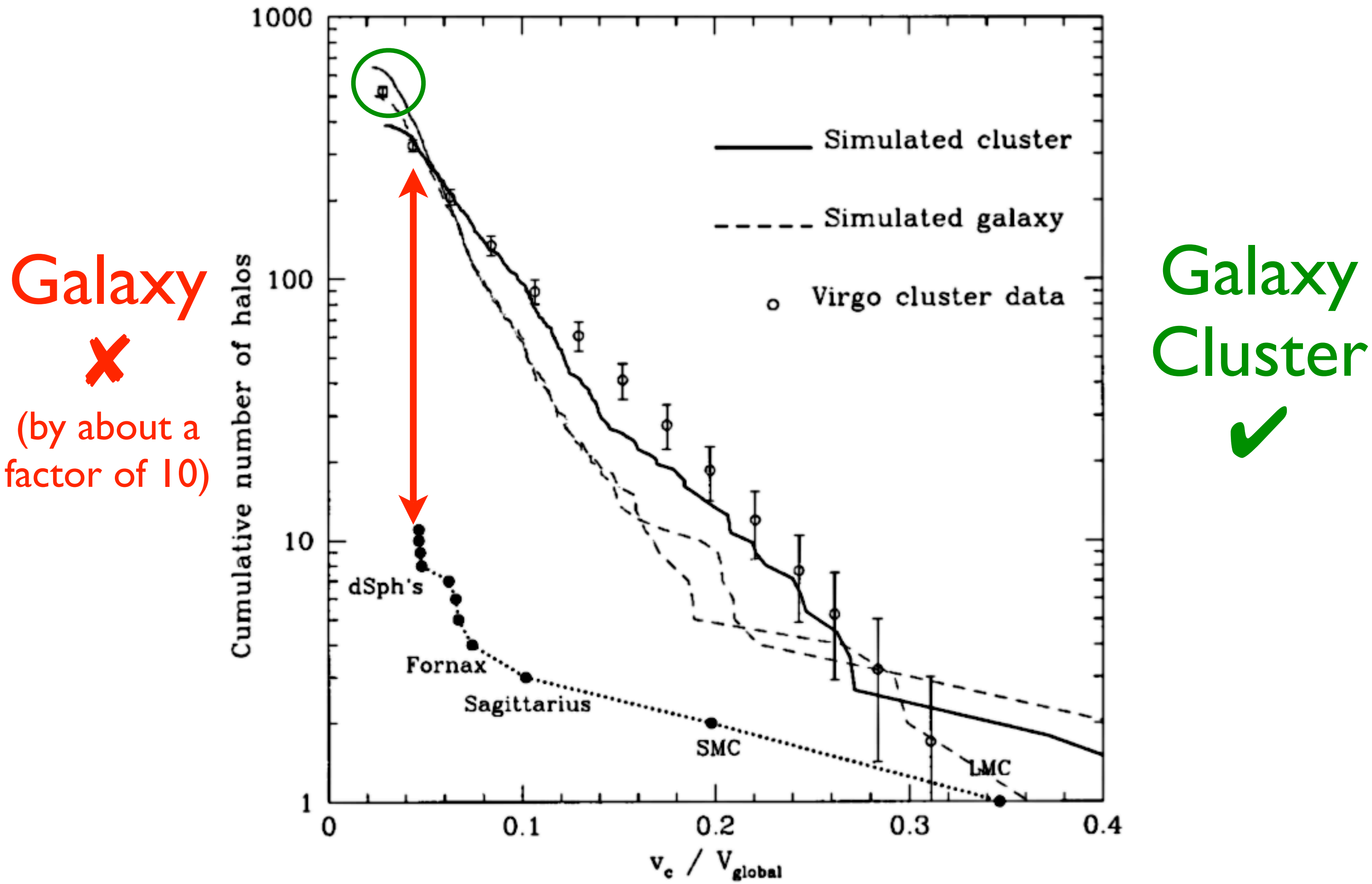
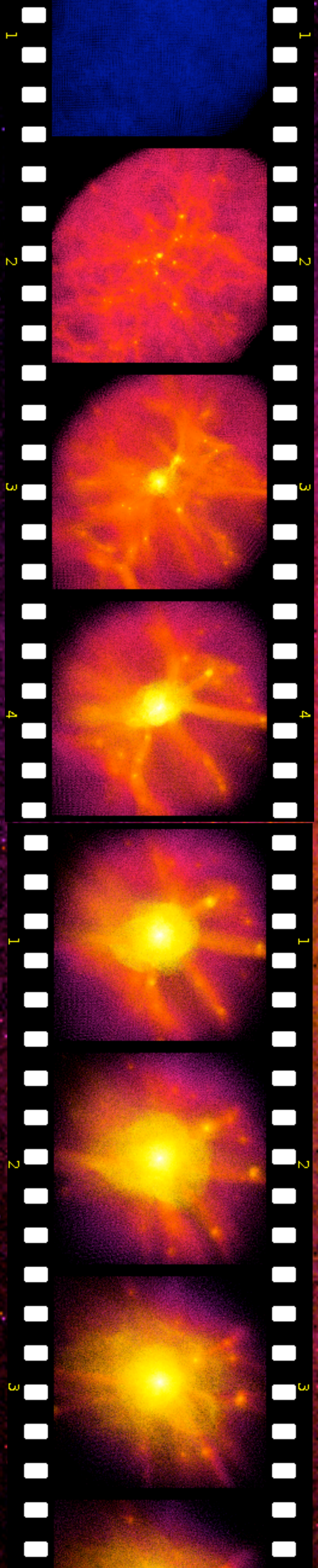


(from Moore, B. et al. 1999)

The Missing Satellites Problem

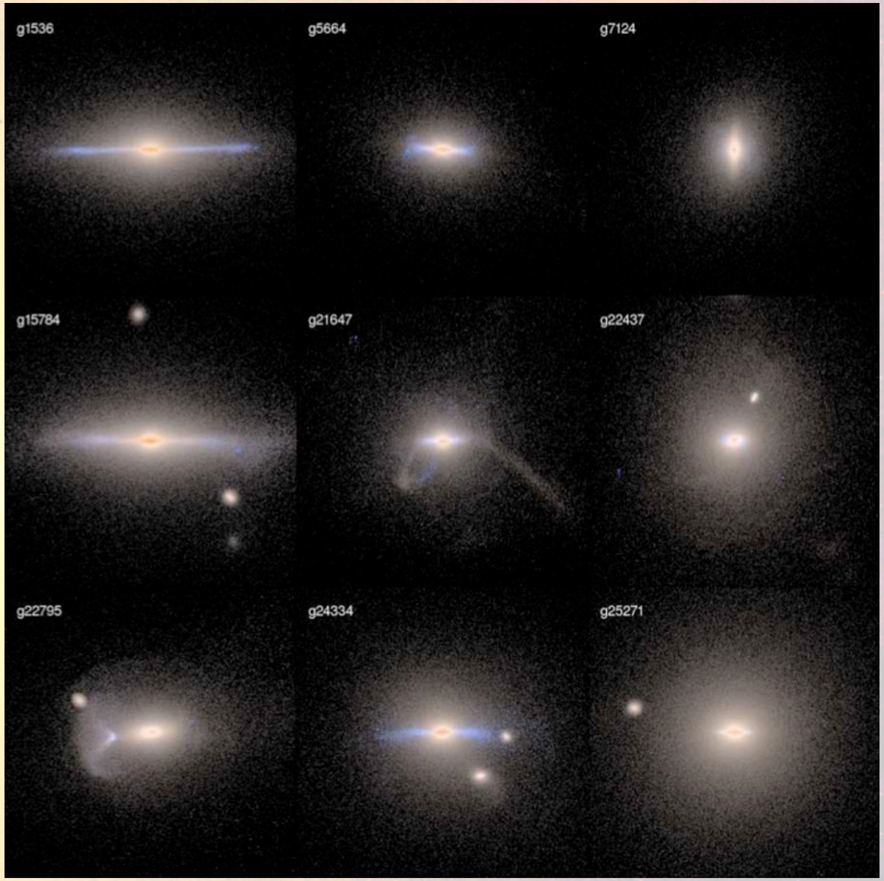
- Could there be satellites out there without any gas or stars that are invisible to observations?
- What would cause them to lose their baryons?
  - -Supernovae
  - -UV background
  - -Tidal stripping
  - -Ram pressure



The Simulation

McMaster Unbiased Galaxy Simulations (MUGS) Suite

- High resolution, smoothed particle hydrodynamics in a WMAP3 ΛCDM cosmology
- About ten million particles
- Step 1: Evolve dark matter-only, uniform 50 $(\mathrm{Mpc}/h)^3$ volume to redshift zero
- Step 2: Select random galaxies to get a good sample of angular momentum, mass, and merger history
- Step 3: Resimulate region of interest with higher resolution, more matter and baryons



(from Stinson, G. et al. 2010)

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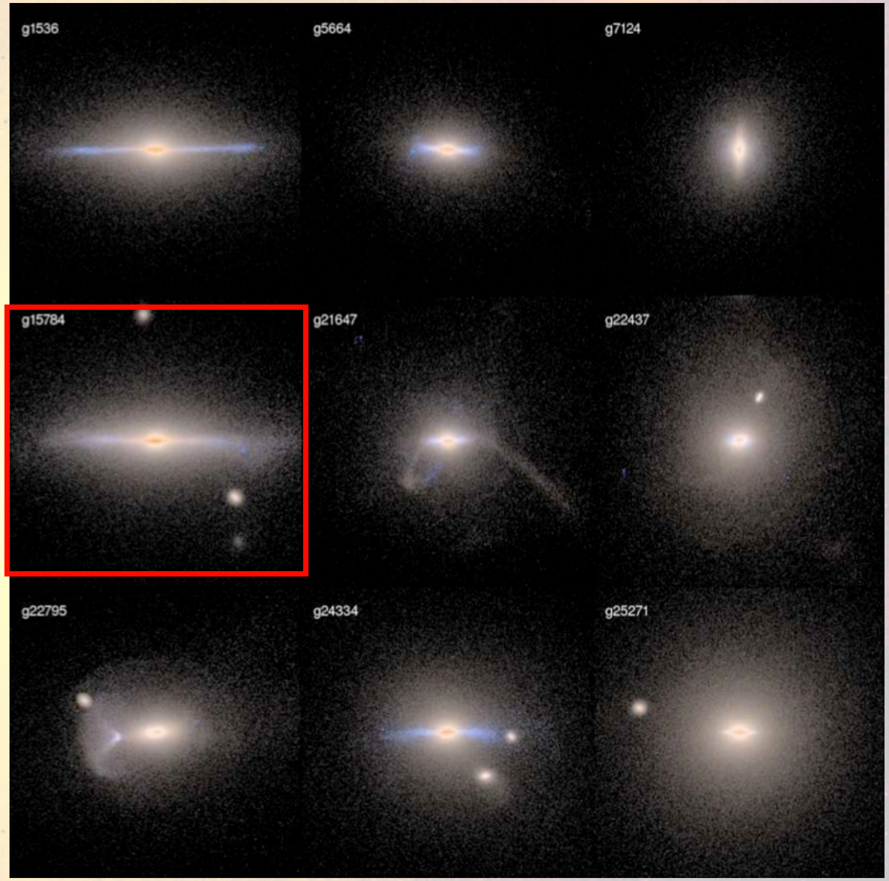
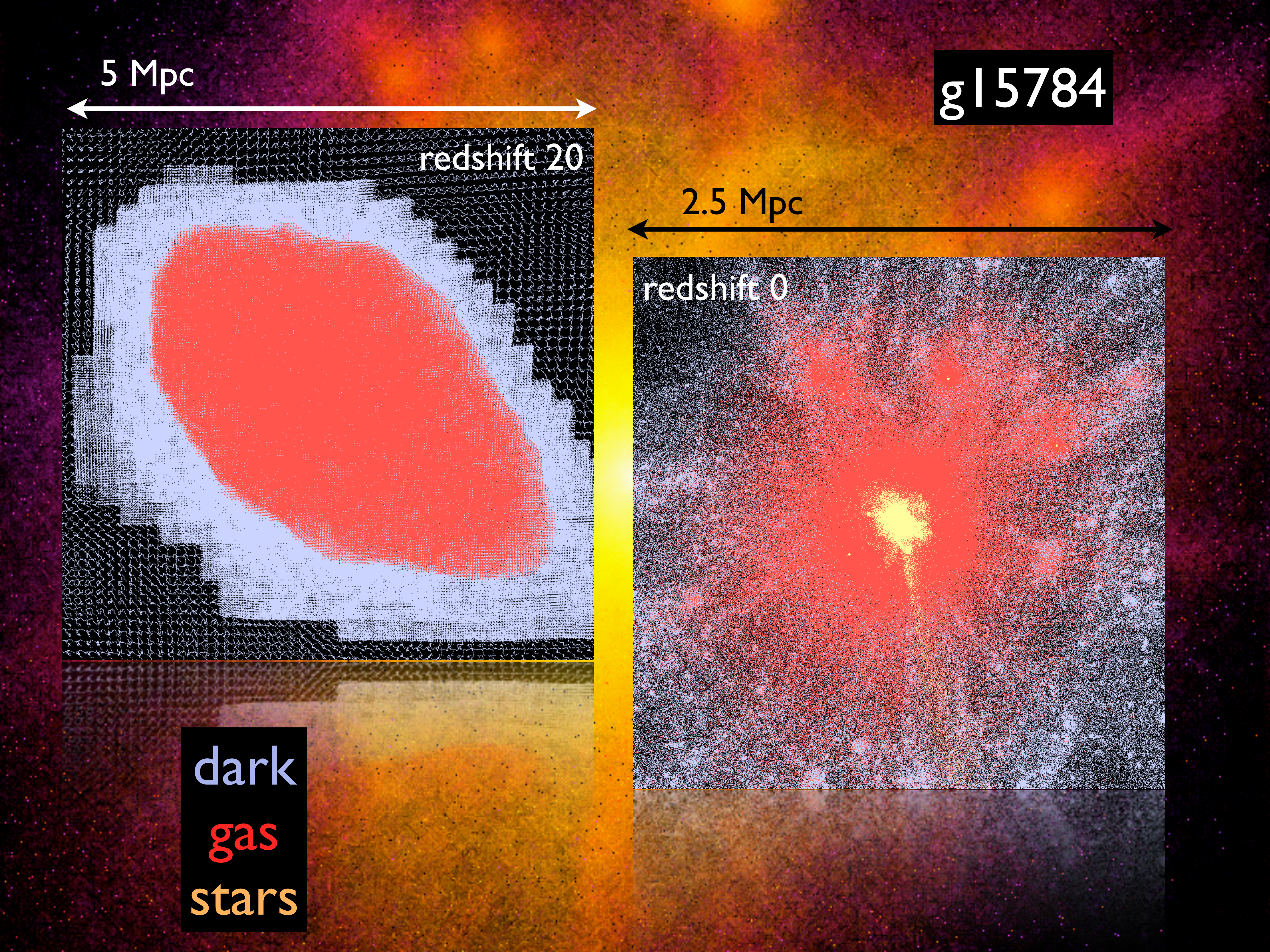


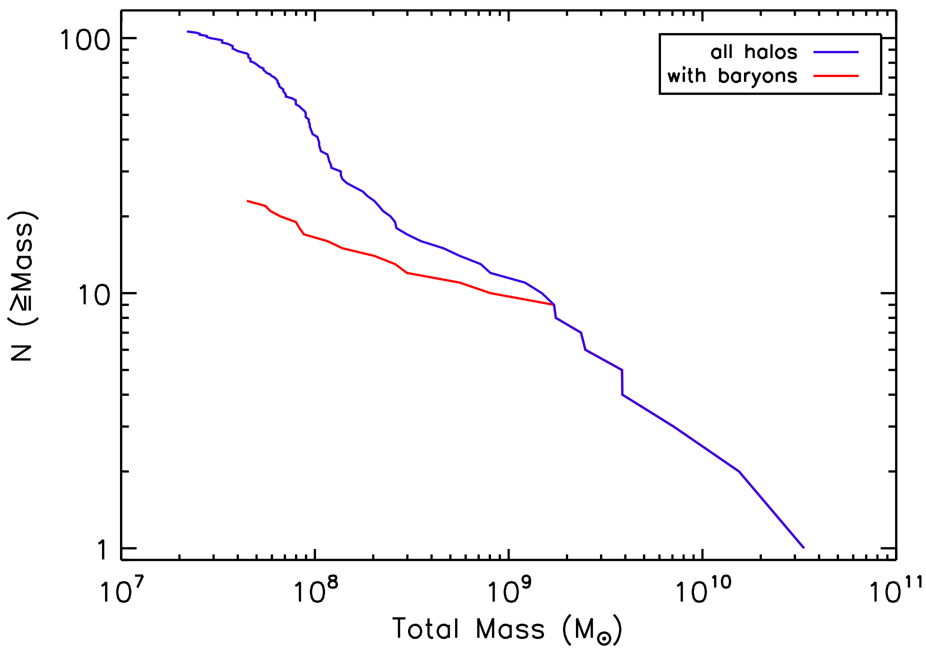
My analysis is focussed on one host galaxy's substructure: g15784

- Mass: $1.4\times10^{12}\ M_\odot$
- Mass/Light ~ 6.5

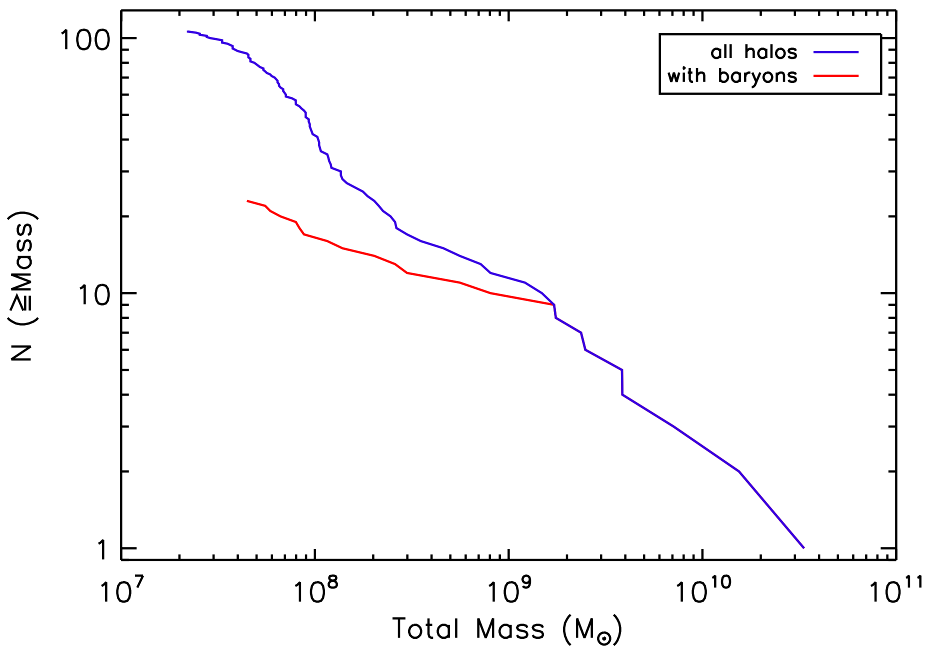
(from Stinson, G. et al. 2010)


g15784
5 Mpc
redshift 20
2.5 Mpc
redshift 0
dark
gas
stars

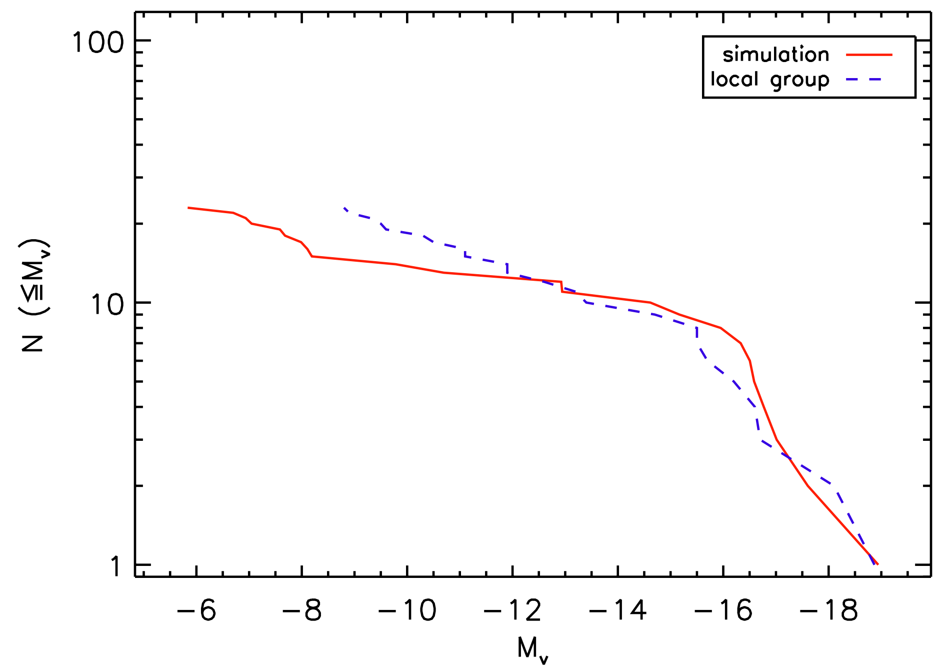
Cumulative Mass Function



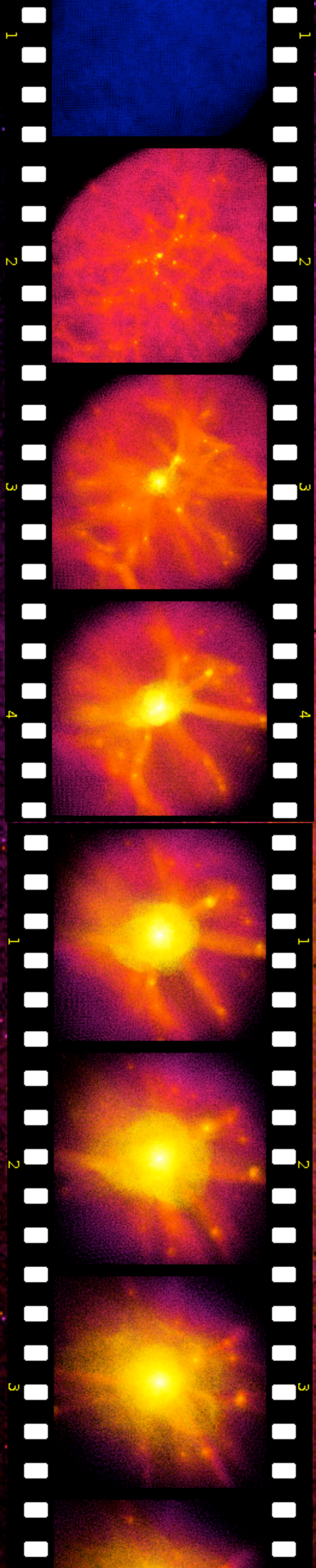
Cumulative Mass Function



Cumulative Luminosity Function



(data from Mateo, L. 1998 ARA&A, 36,435 and van den Bergh, S. 1991 PASP103,609)



Meet the Satellites

Three Classes of Satellites

Three Classes of Satellites

1. Accumulate baryons above the cosmic mean and retain gas and stars to redshift zero

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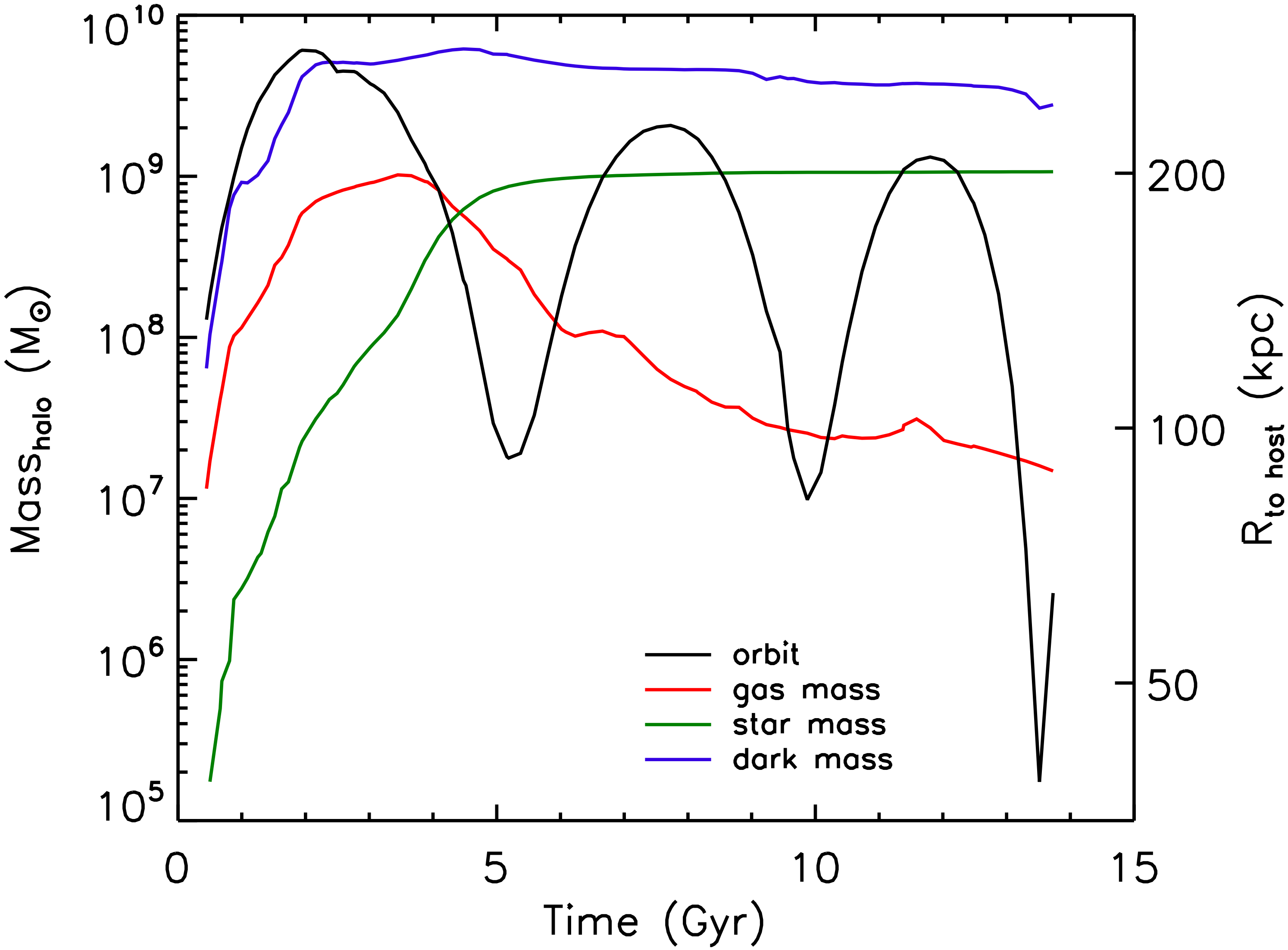
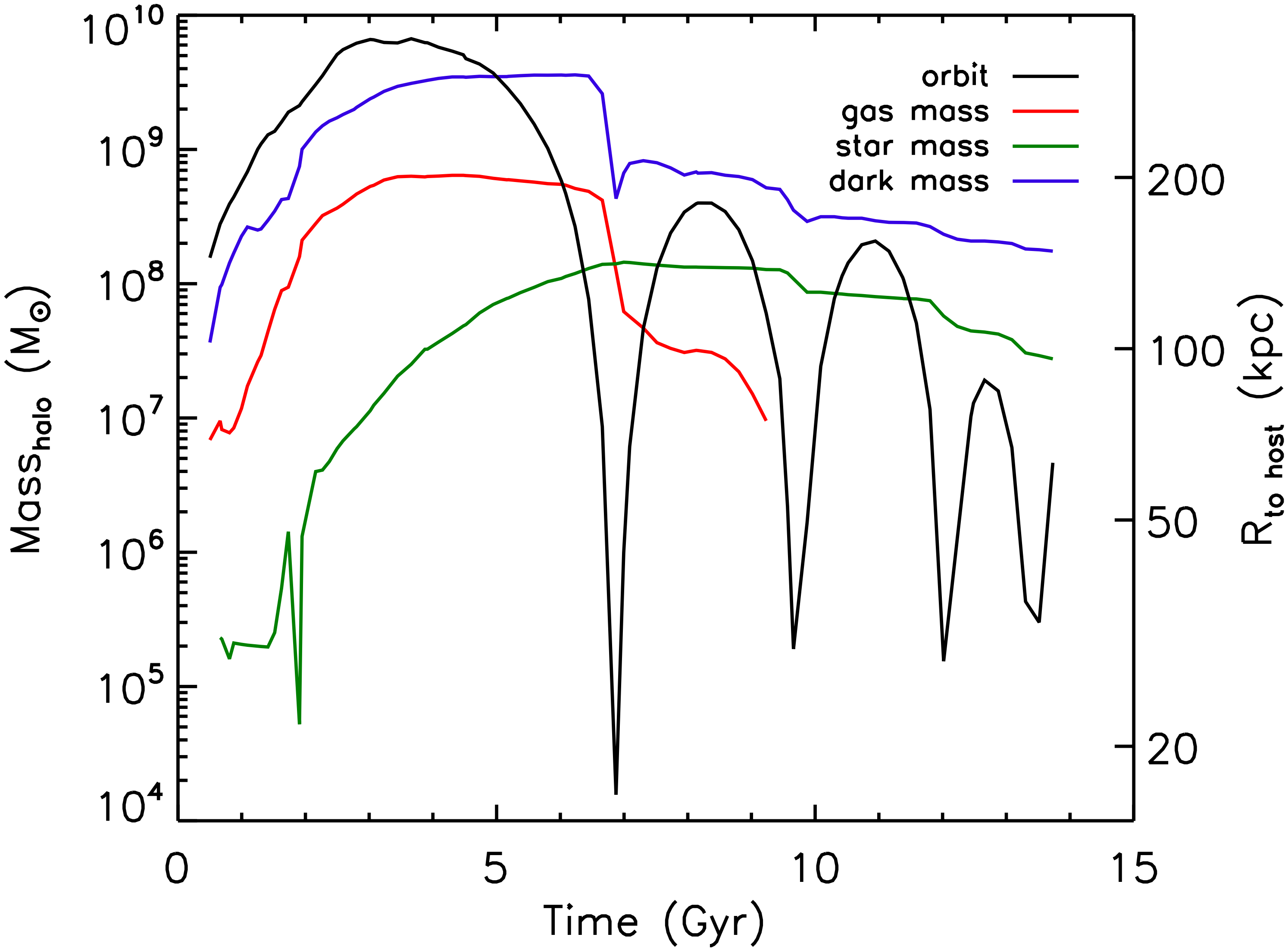
Three Classes of Satellites

1. Accumulate baryons above the cosmic mean and retain gas and stars to redshift zero
2. Accumulate enough gas to form stars, but the gas (and rarely the stars too) is stripped before it reaches redshift zero
3. Only have a smattering of gas that is quickly stripped

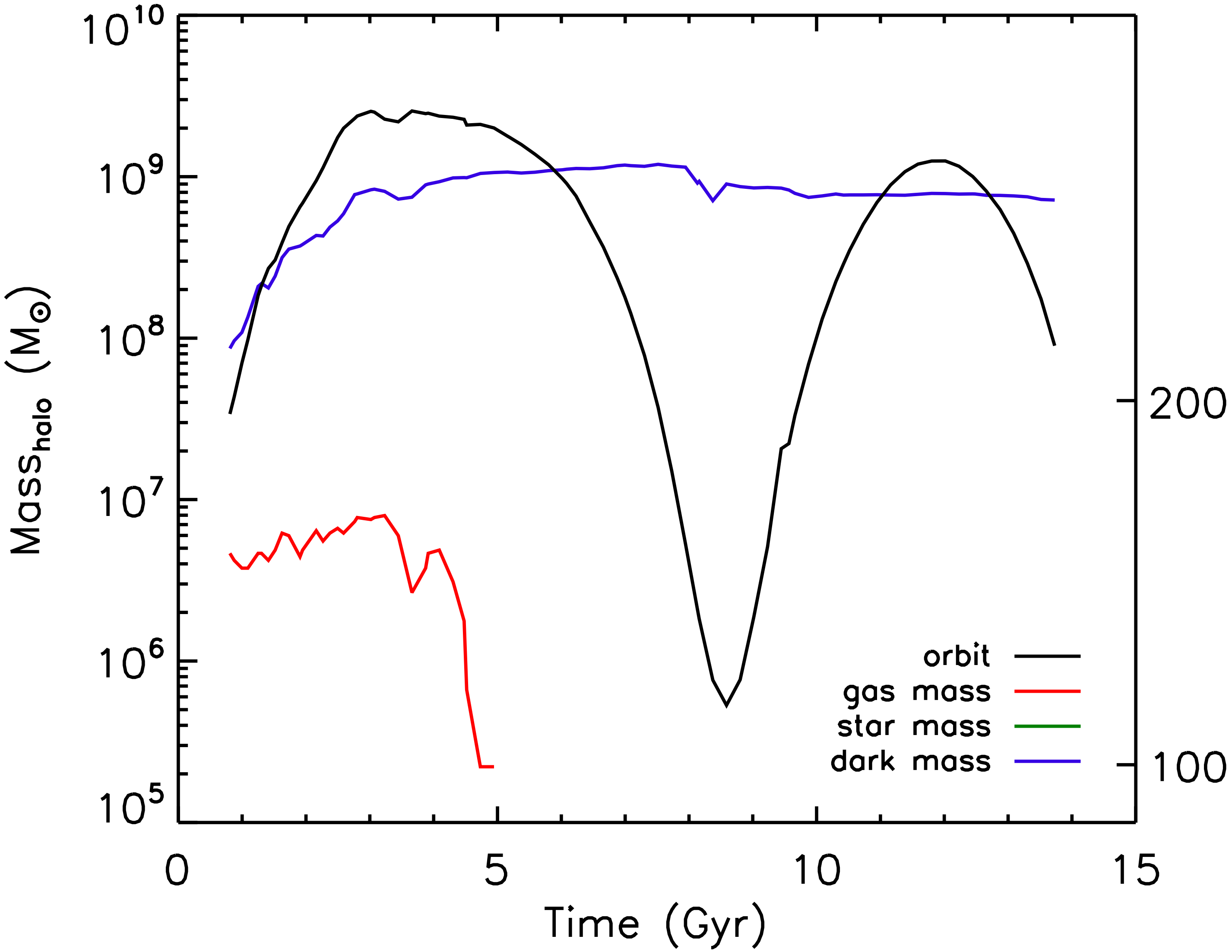
1. Accumulate baryons above the cosmic mean and retain gas and stars to redshift zero (final mass: $3.9 \times 10^9 M_\odot$)



2. Accumulate enough gas to form stars, but gas is stripped before it reaches z=0 (final mass: 2.0x10^{8} $M_{\odot}$)



3. Only have a smattering of gas that is quickly stripped (final mass: $7.2 \times 10^8\ M_\odot$)



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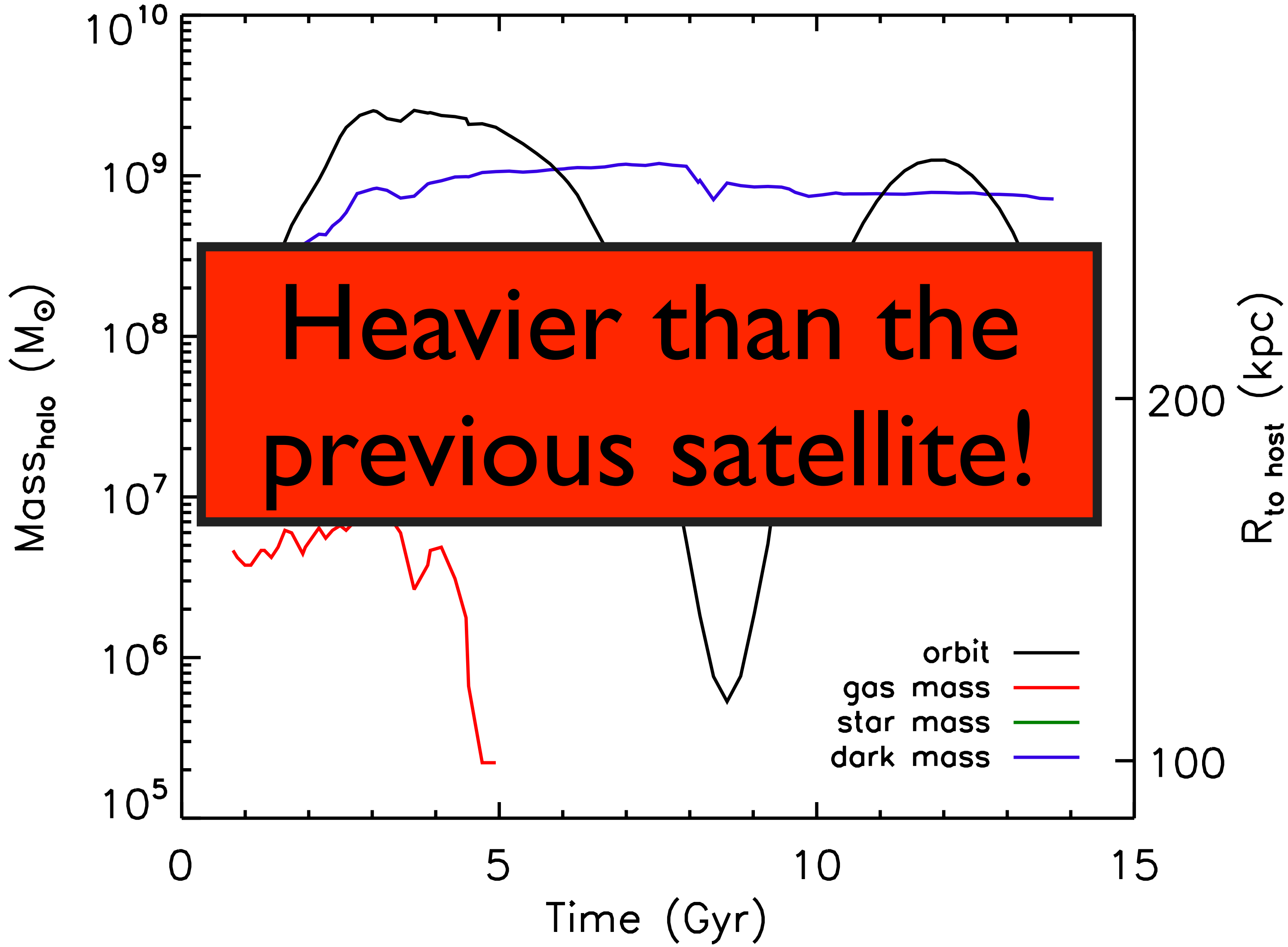
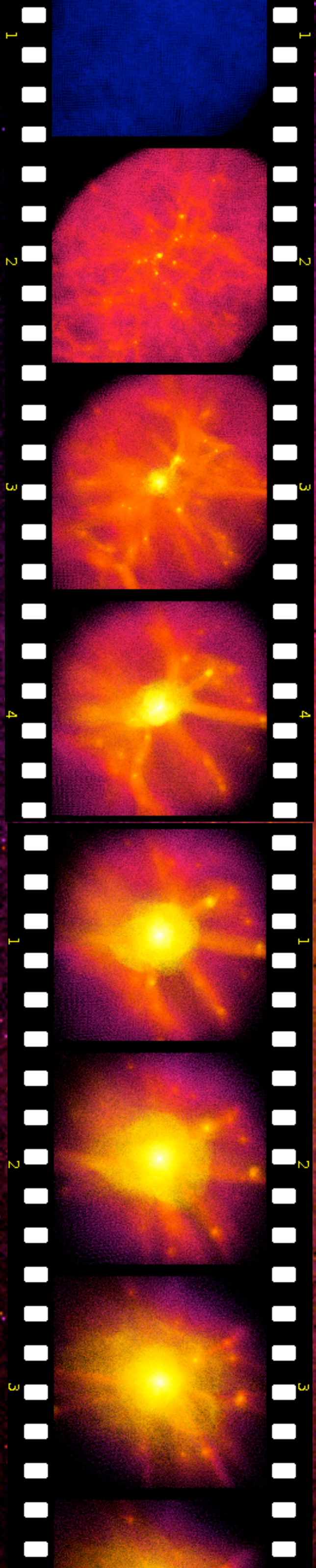
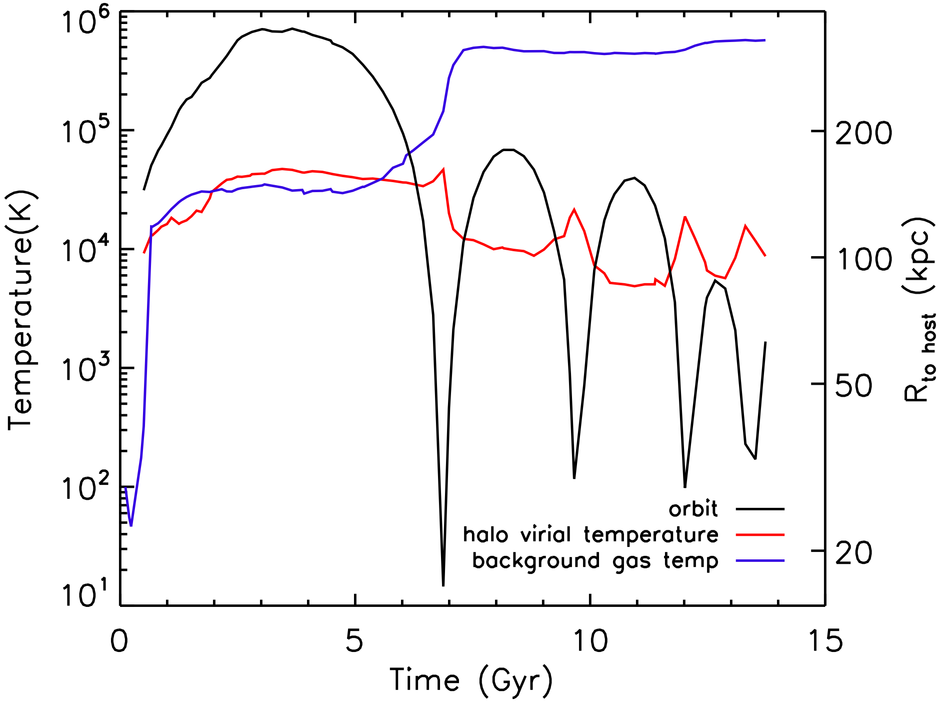




Gas-Loss Mechanisms

UV Background

2. Accumulate enough gas to form stars, but gas is stripped before it reaches z=0 (final mass: $2.0 \times 10^8 M_{\odot}$)



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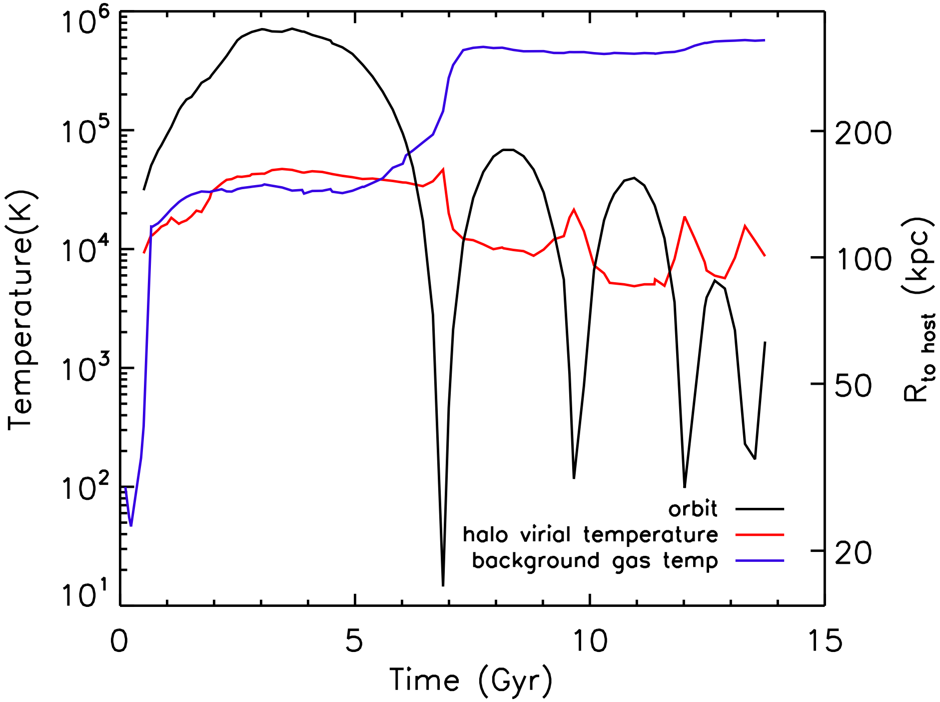

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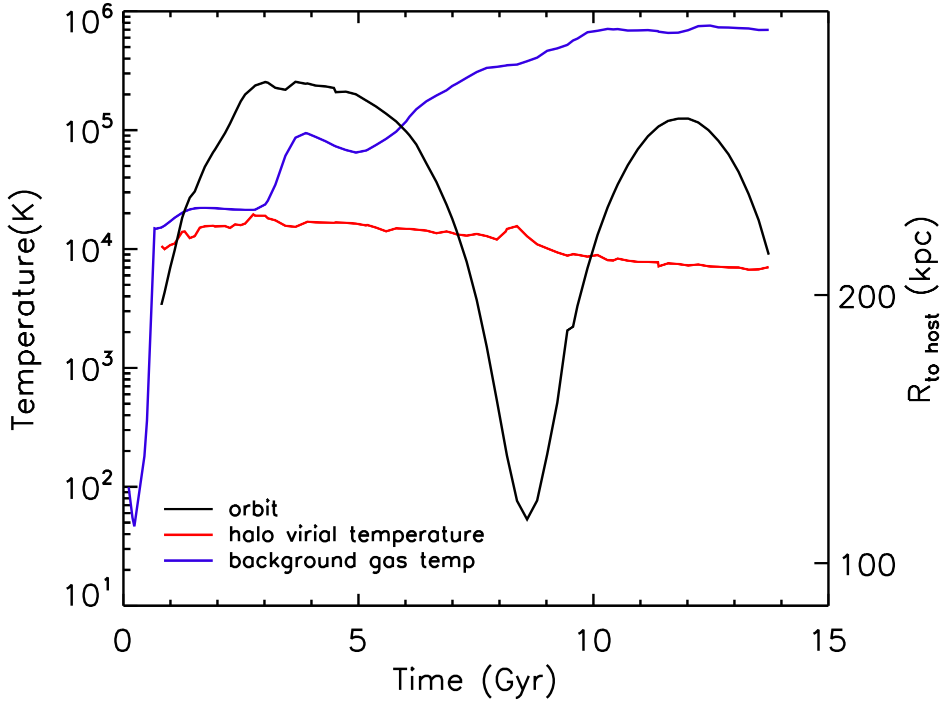
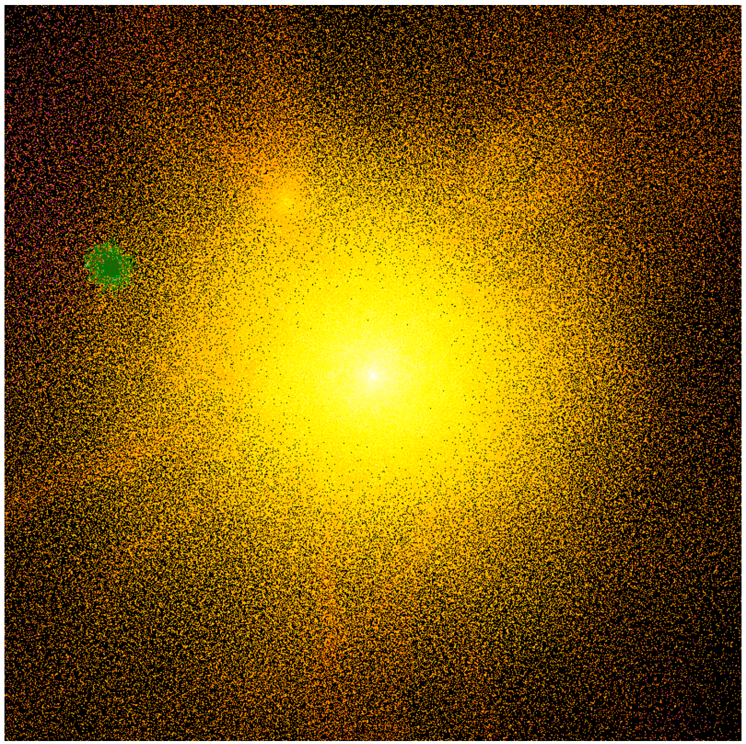


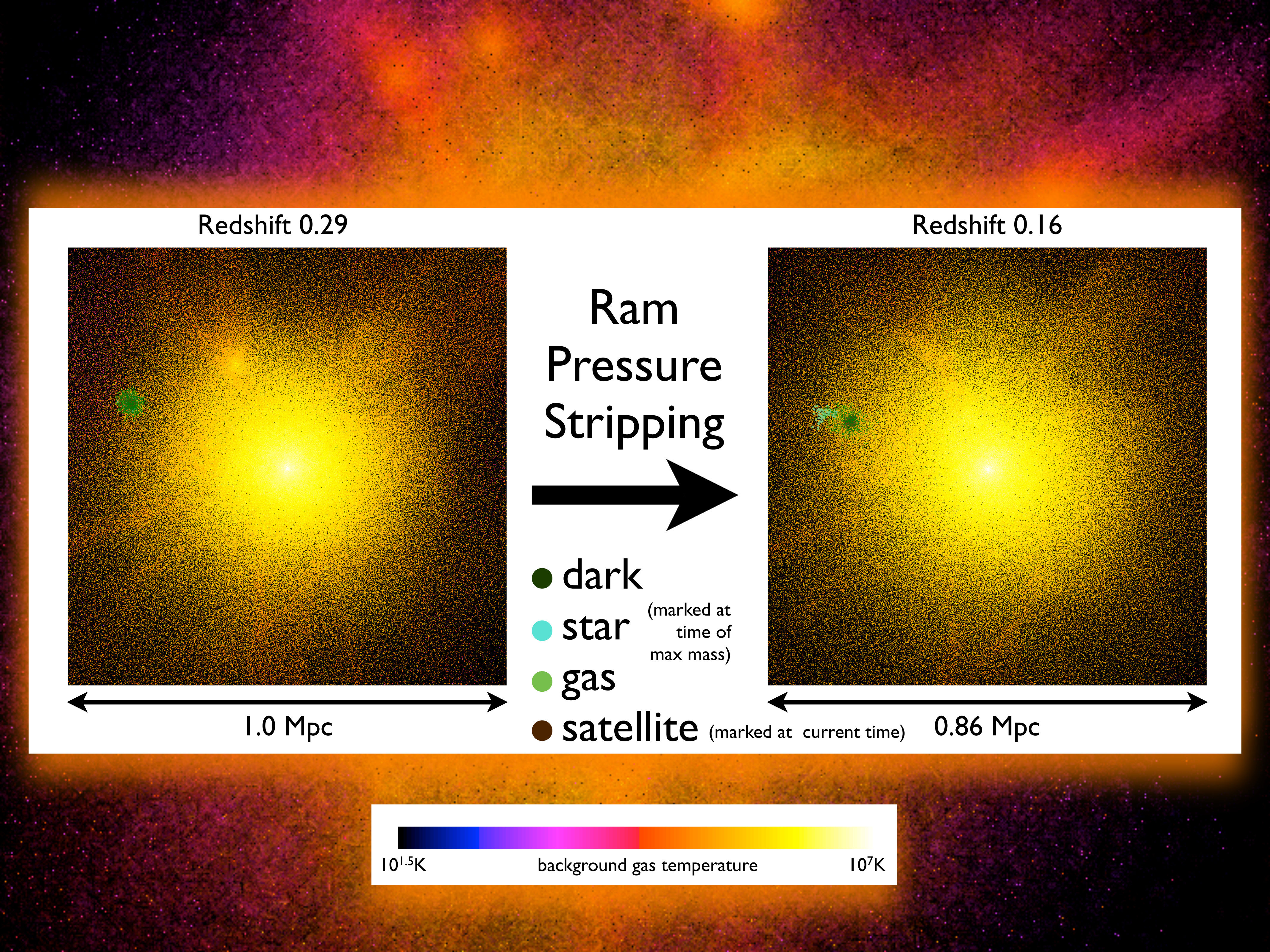
Redshift 0.29



1.0 Mpc

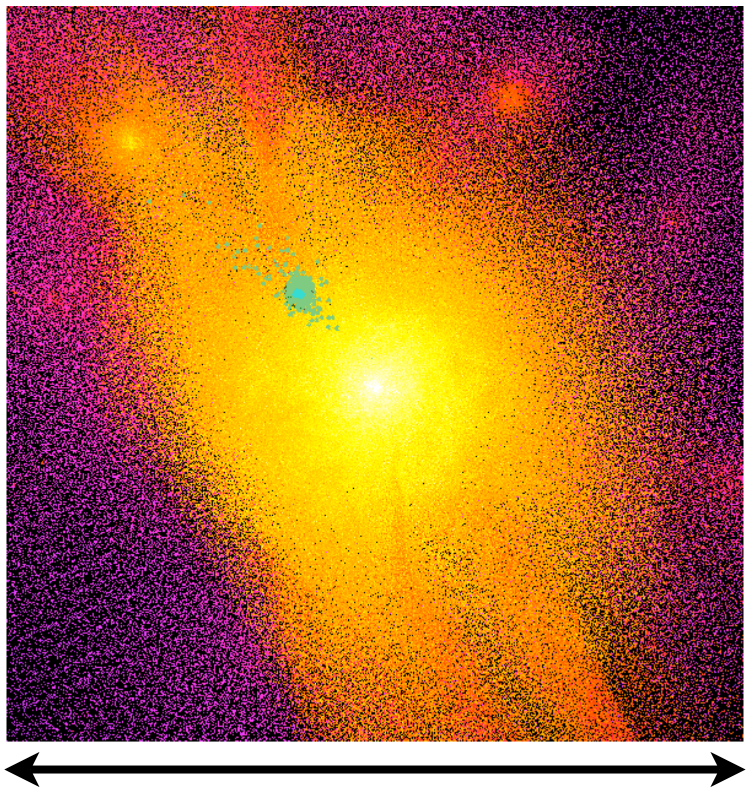
- dark
- star (marked at time of max mass)
- gas
- satellite (marked at current time)

$10^{1.5}$K background gas temperature 10^{7}K



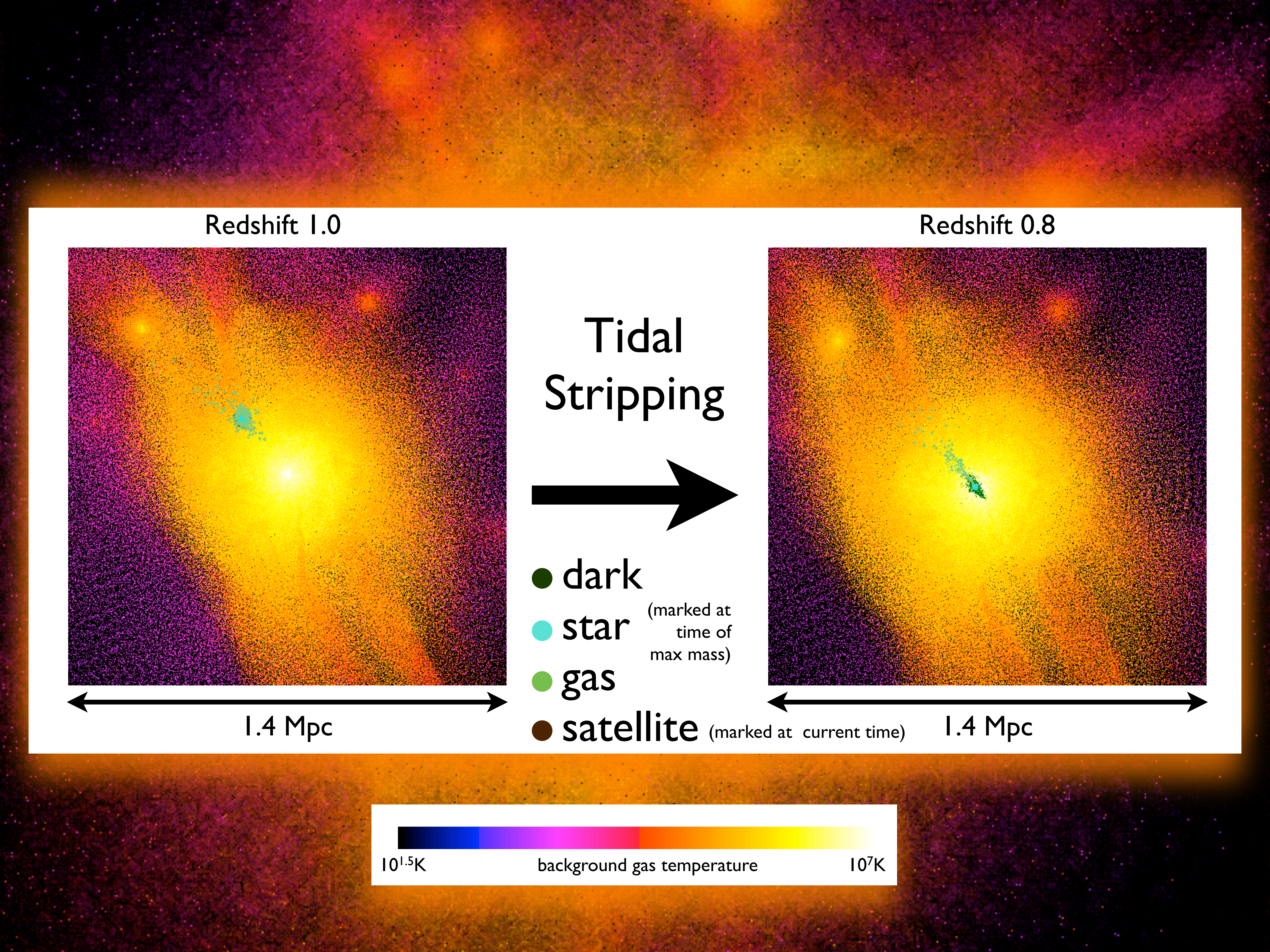
Redshift 0.29
Redshift 0.16
Ram Pressure Stripping
1.0 Mpc
0.86 Mpc
dark
star
(marked at time of max mass)
gas
satellite
(marked at current time)
$10^{1.5}$K
background gas temperature
10^{7}K

Redshift 1.0



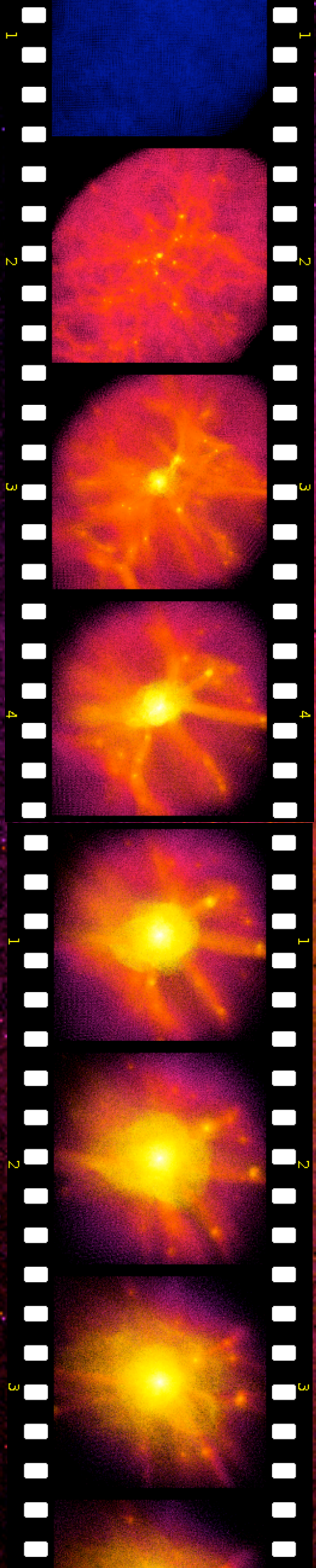
1.4 Mpc

- dark
- star (marked at time of max mass)
- gas
- satellite (marked at current time)


Redshift 1.0
Redshift 0.8
Tidal Stripping
dark
star
(marked at time of max mass)
gas
satellite (marked at current time)
1.4 Mpc
1.4 Mpc
10^1.5 K
background gas temperature
10^7 K

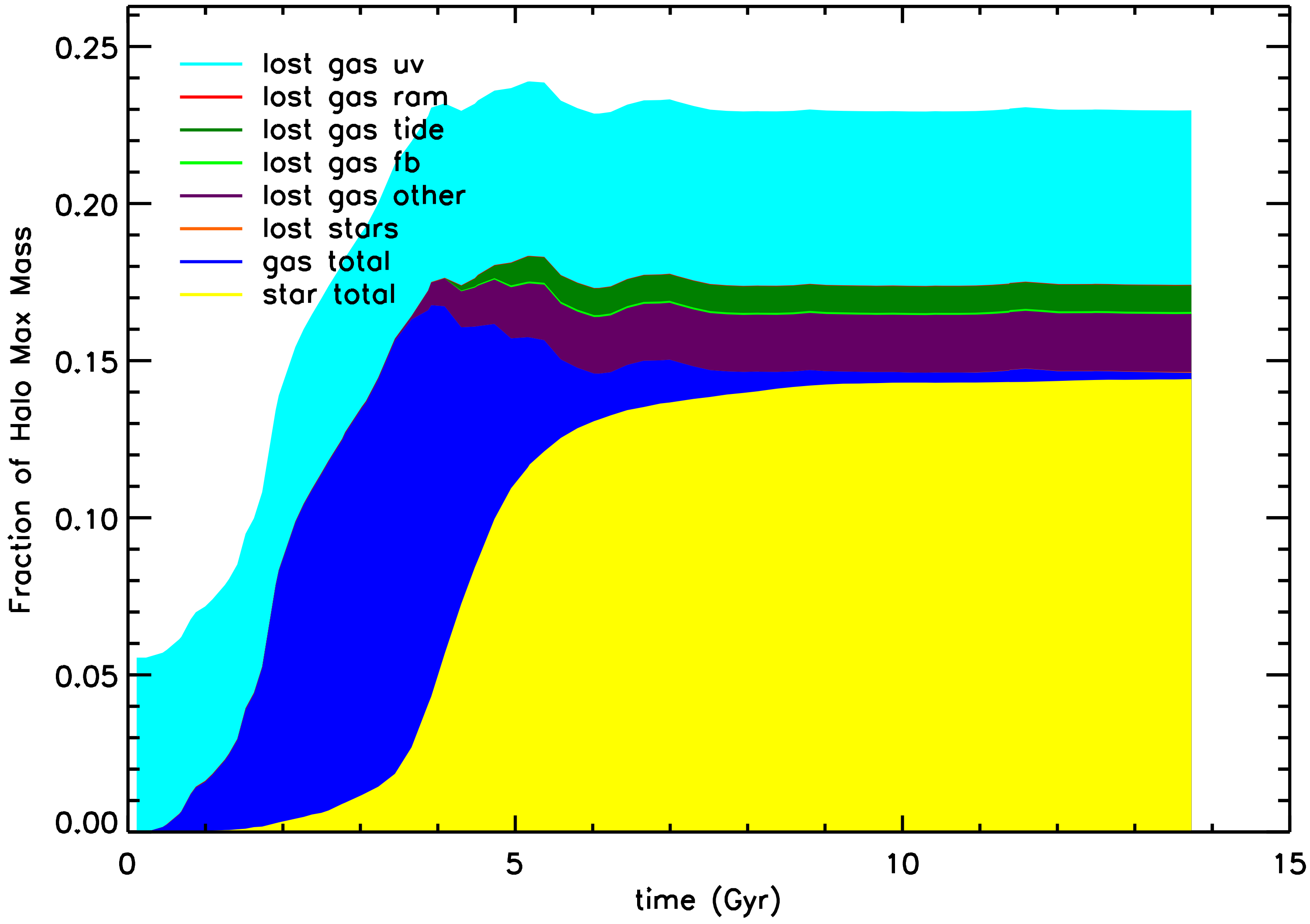
Stellar Feedback

- A particle affected by stellar feedback from supernovae has its cooling turned off
- This causes it to heat up, and gain enough energy to escape the halo



The Big Picture

1. Accumulate baryons above the cosmic mean and retain gas and stars to redshift zero (final mass: $3.9 \times 10^9\ M_\odot$)



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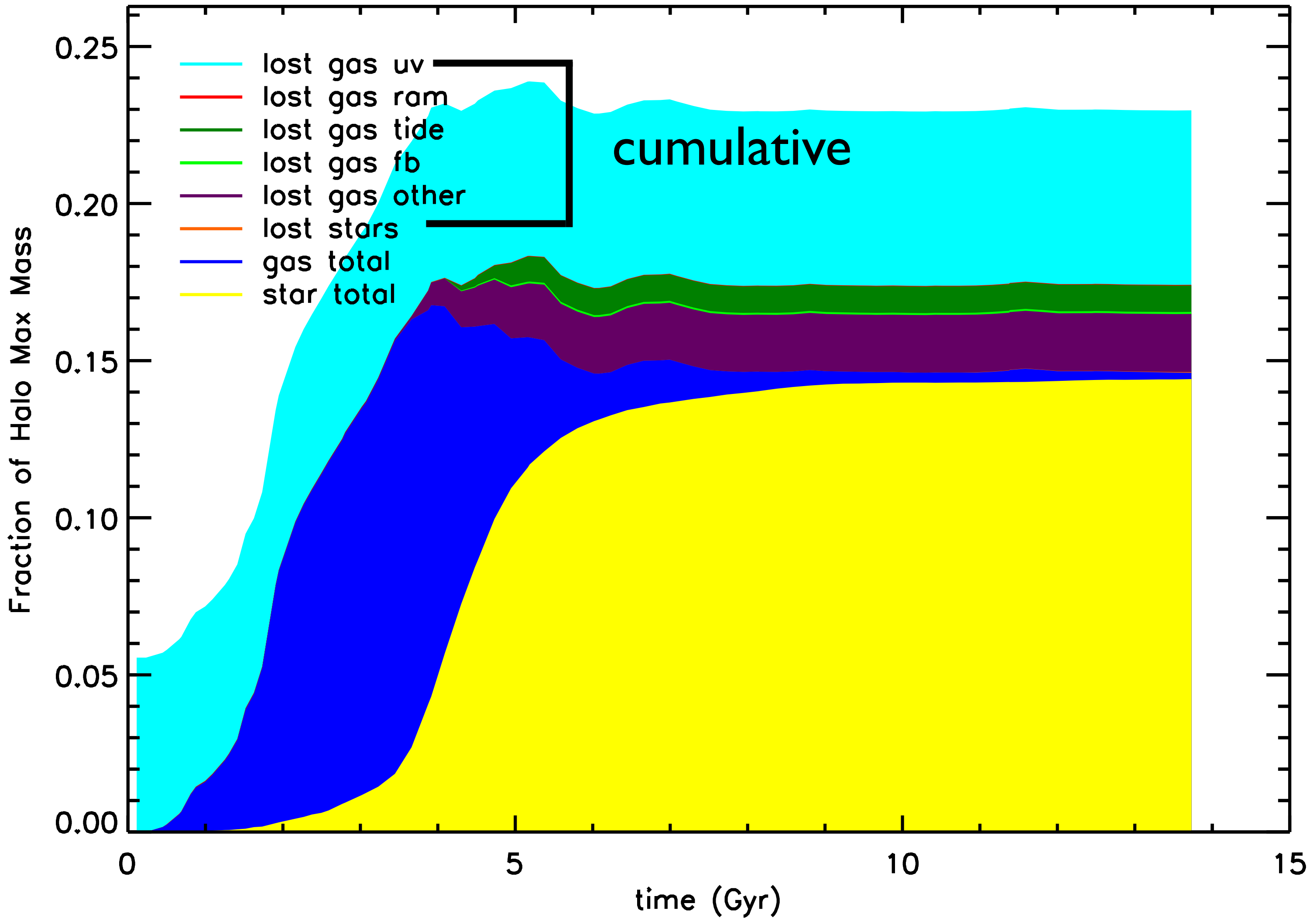

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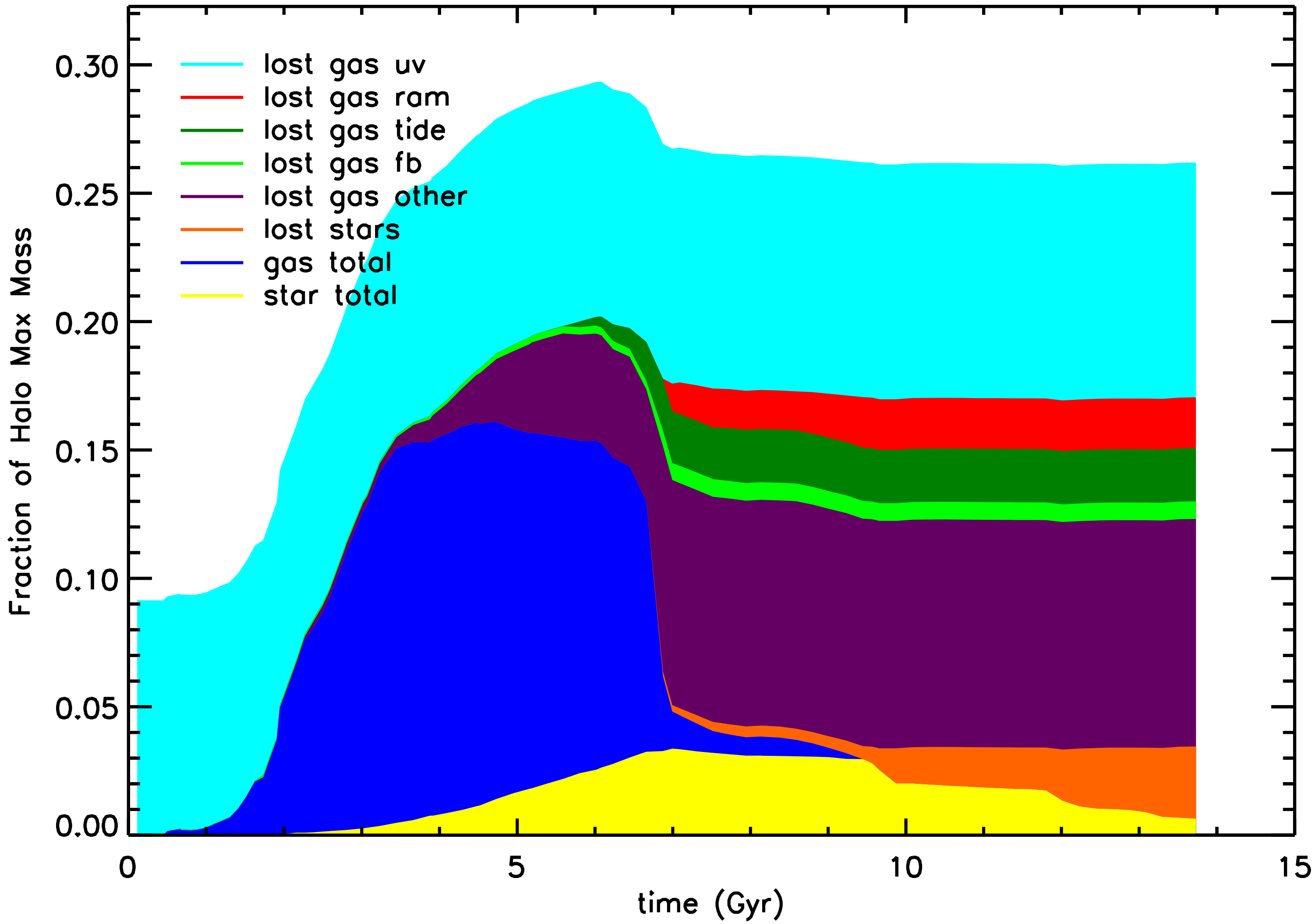

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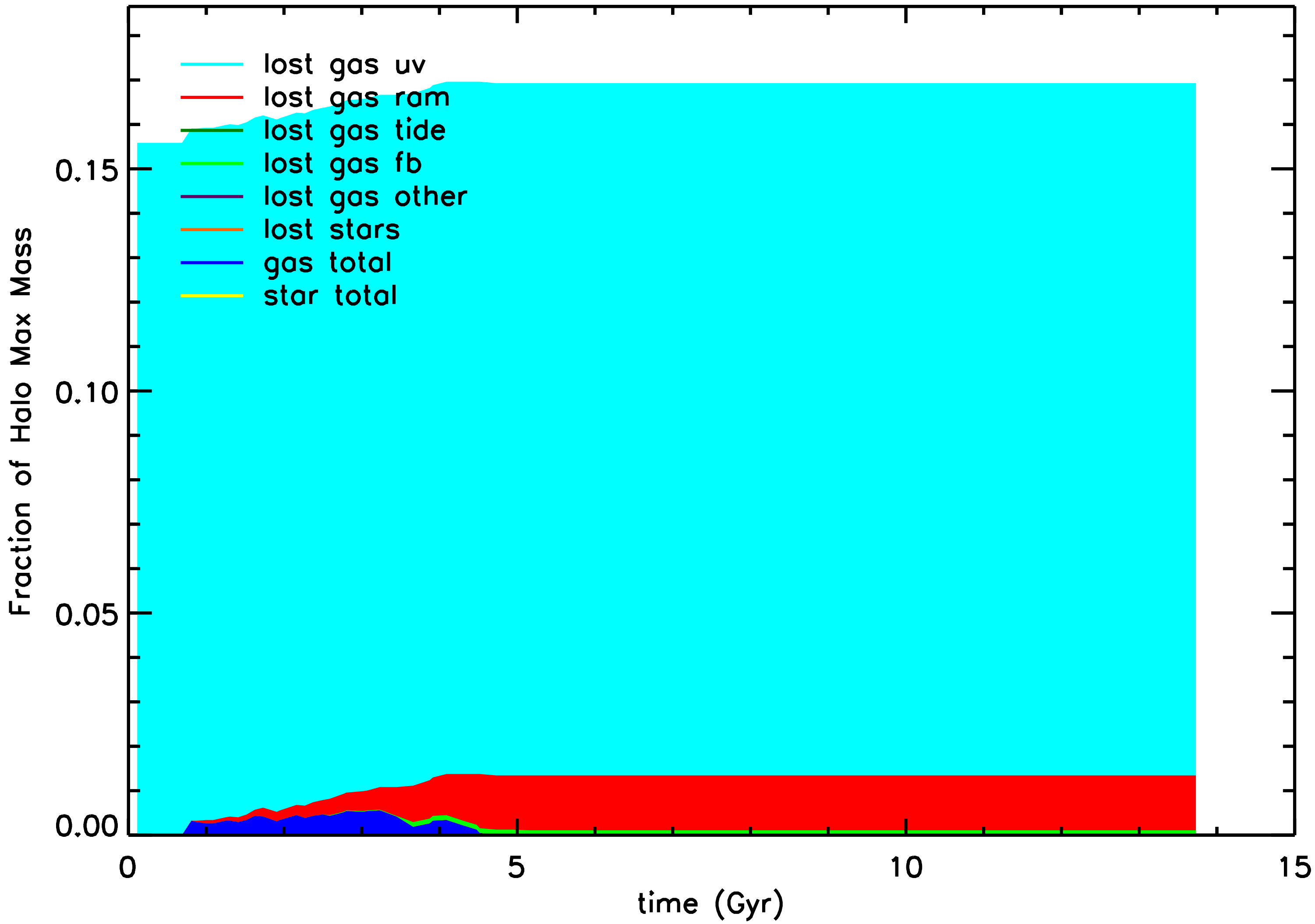
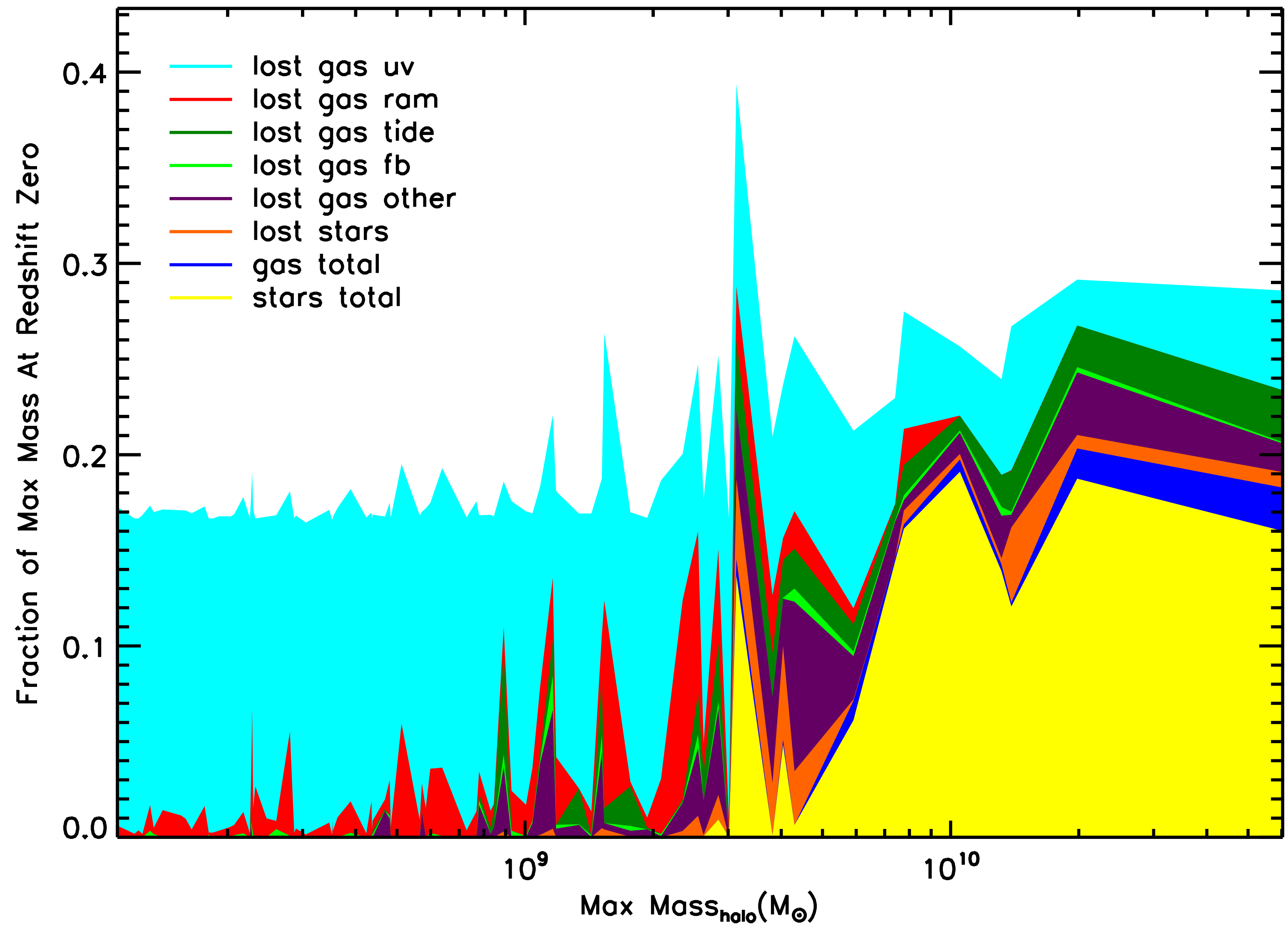


Gas Loss for All Satellites

(as a function of the maximum mass they ever achieve)



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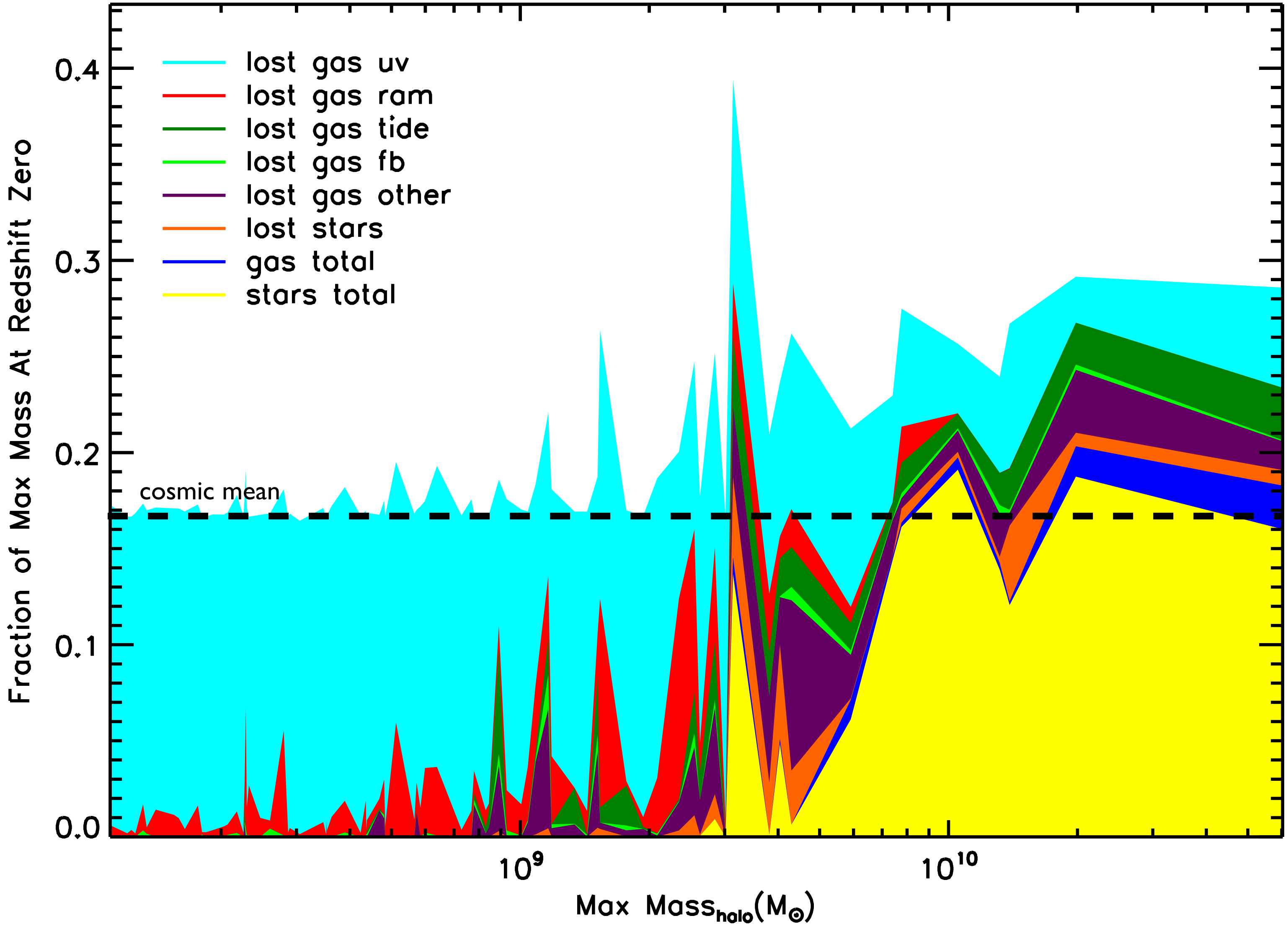

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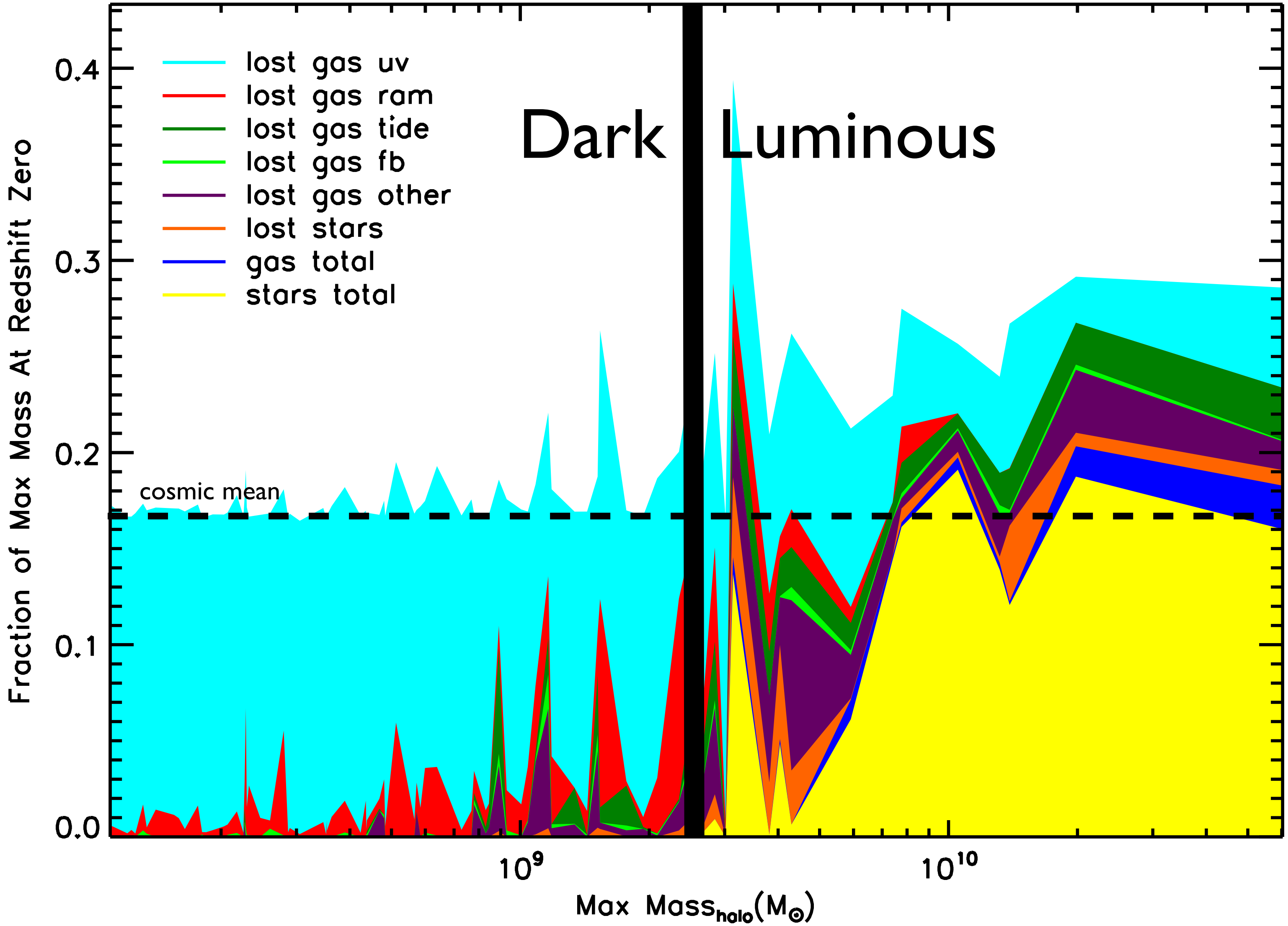

Conclusions

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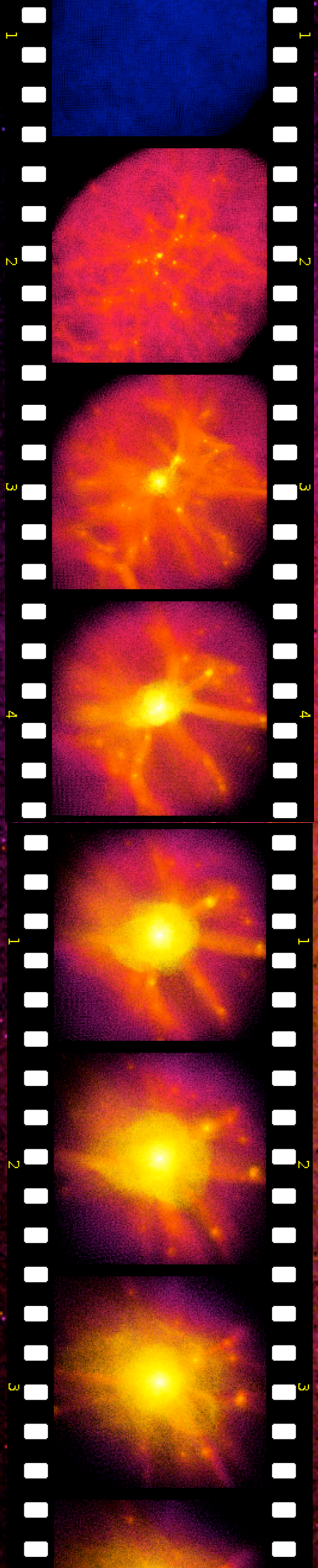
Conclusions

- Dark satellites: uv background removes most of the gas, followed by ram pressure stripping
- Luminous satellites: tidal stripping is more prominent
- Stellar feedback is surprisingly weak

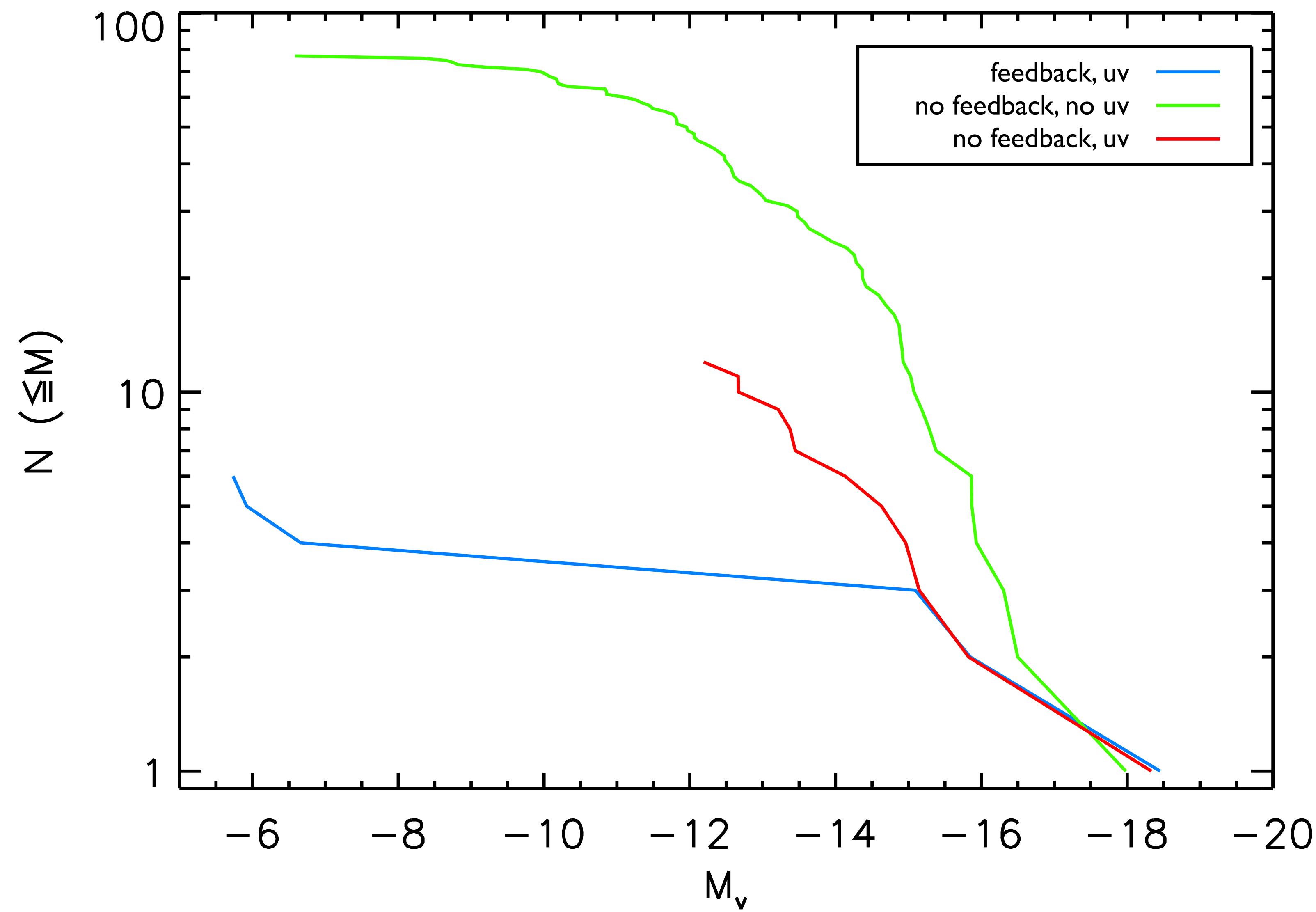
Whether a satellite ends up dark or luminous is determined by the maximum mass it ever achieves, not is mass at redshift zero

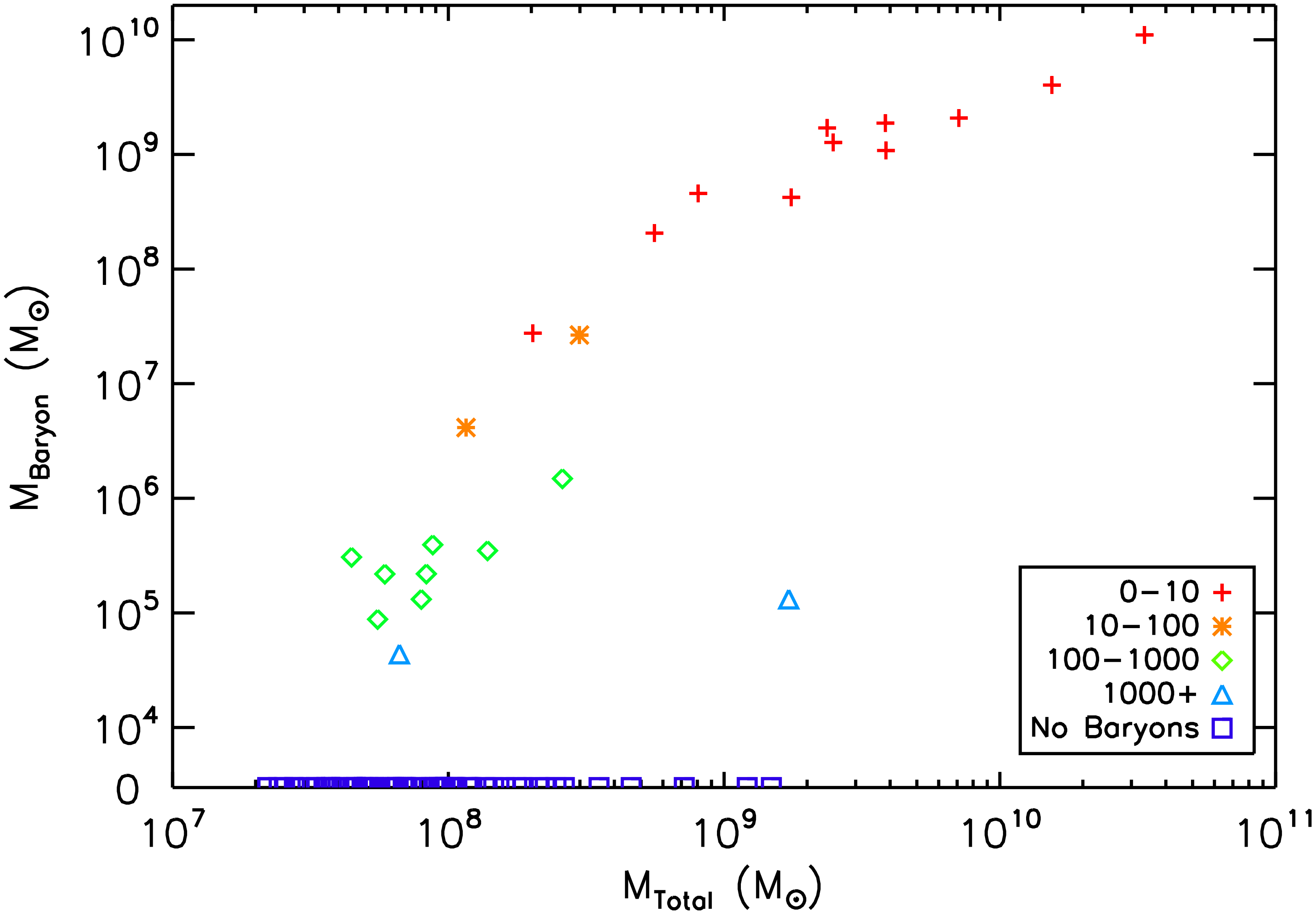


Thank You!


GALAXY CAT
ASKZ:
I CAN HAS MOAR
SUBSTRUCTURE?
ICANHASCHEEZBURGER.COM

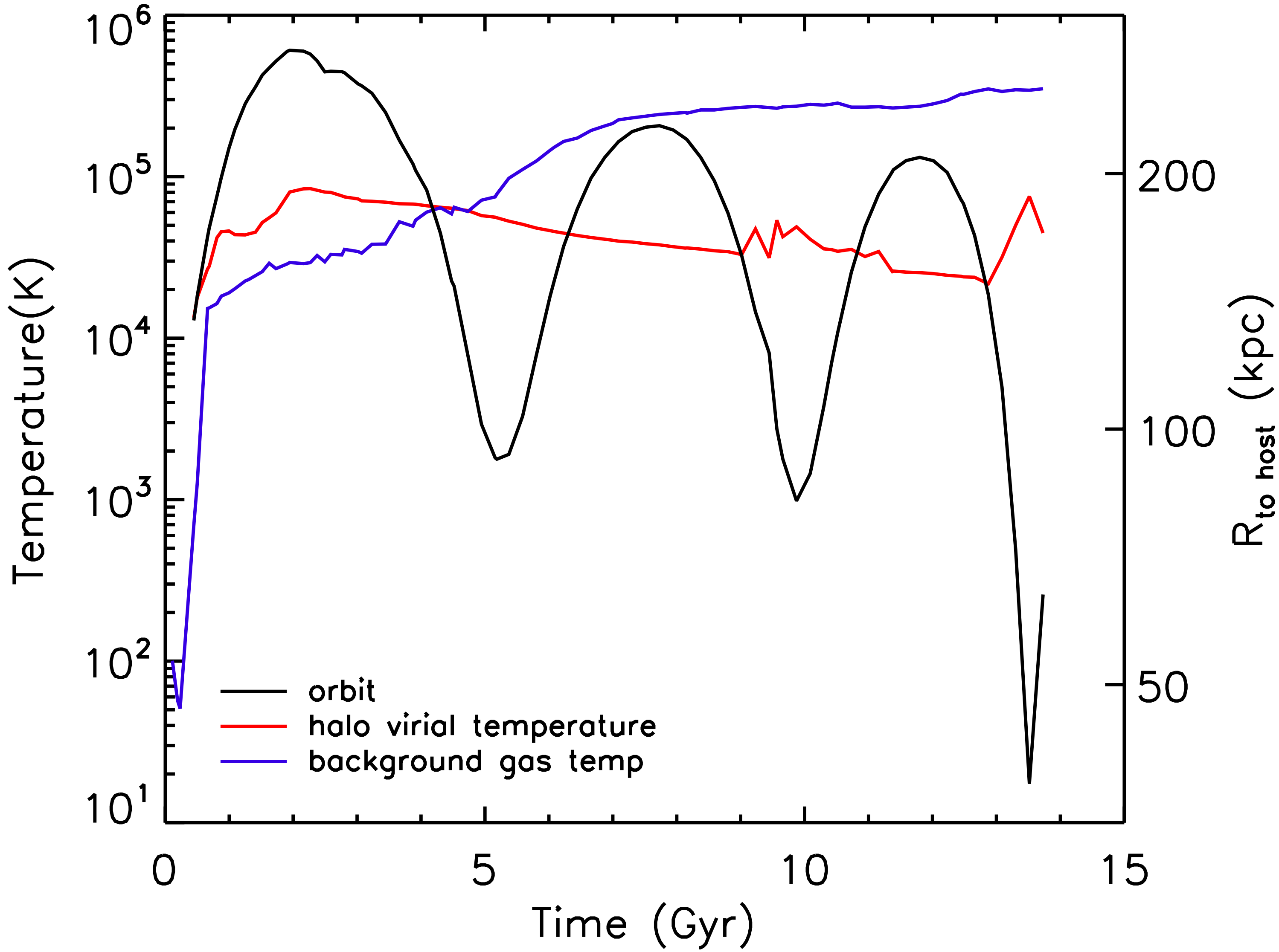
Comparing Luminosity Functions: g5664



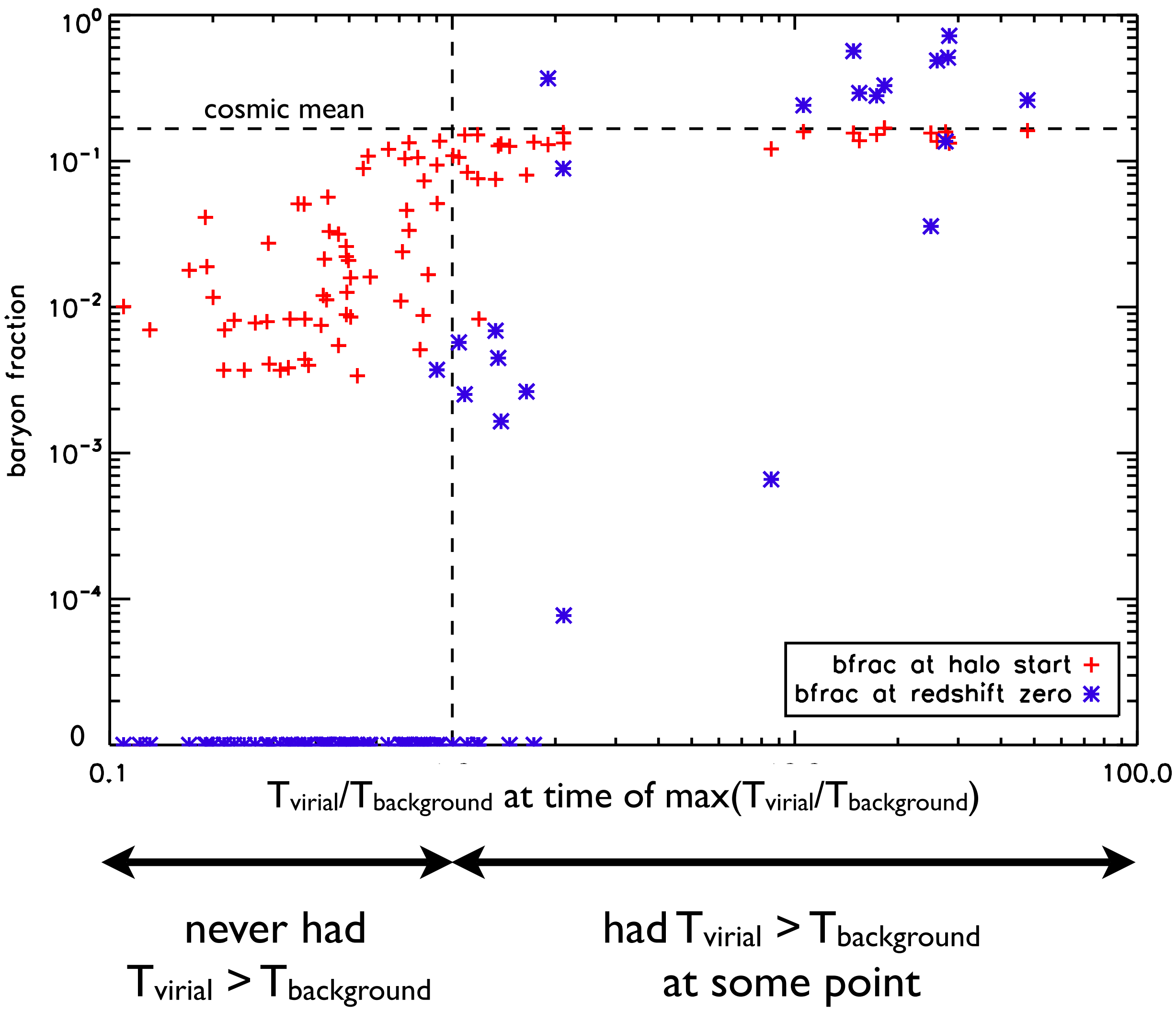


M_{Baryon} ($M_\odot$)
M_{Total} ($M_\odot$)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
0
10^7
10^8
10^9
10^{10}
10^{11}
0–10
10–100
100–1000
1000+
No Baryons

1. Accumulate baryons above the cosmic mean and retain gas and stars to redshift zero (final mass: $3.9\times10^9\ M_\odot$)

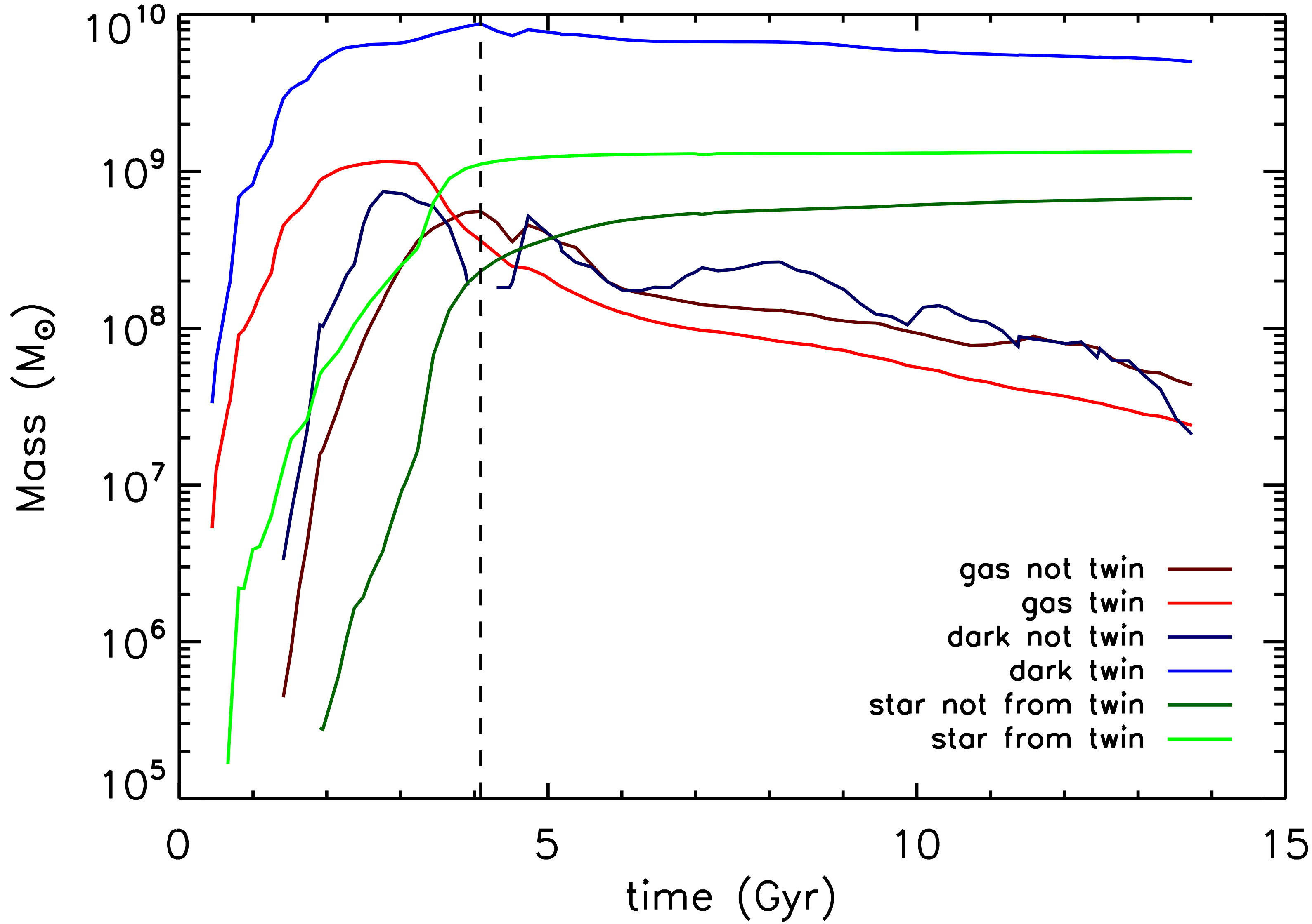


Baryon Fraction as a function of virial/background gas temperature

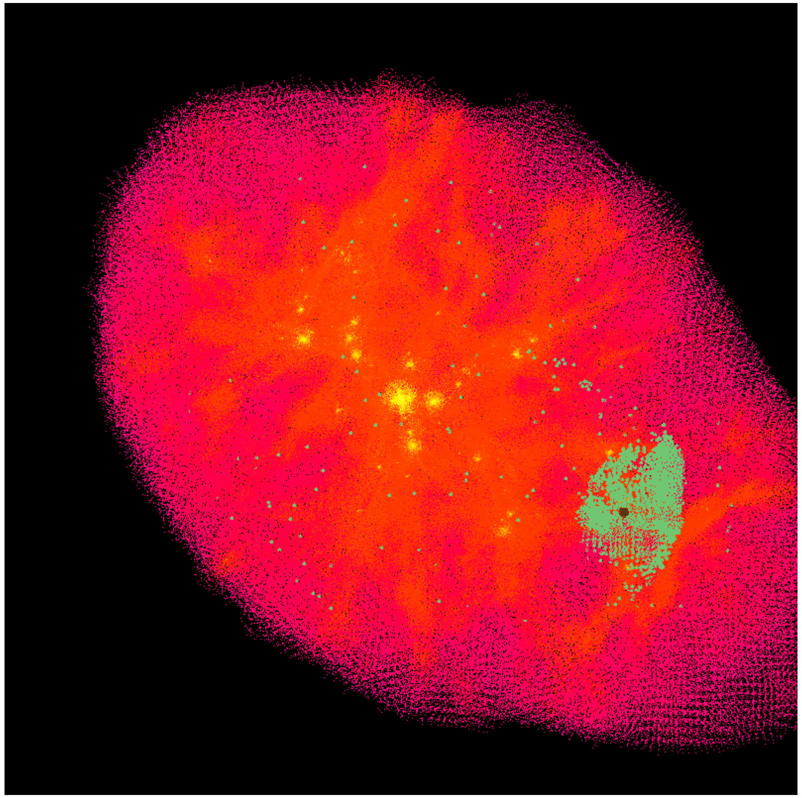


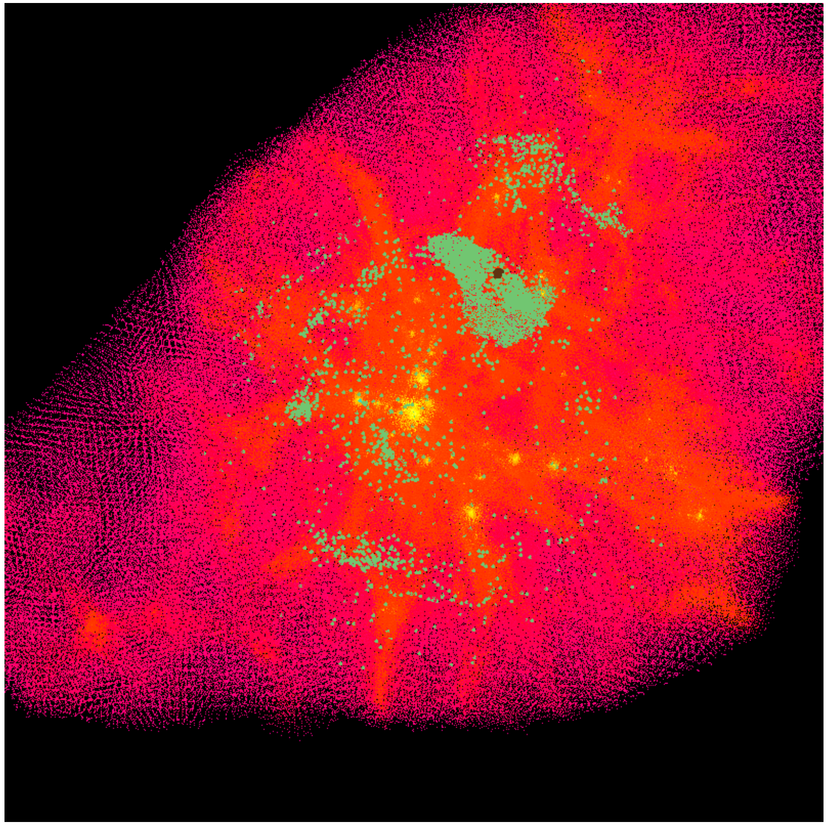
- With one exception, the only halos that retain baryons at redshift zero are those that had a higher virial temperature than their background gas

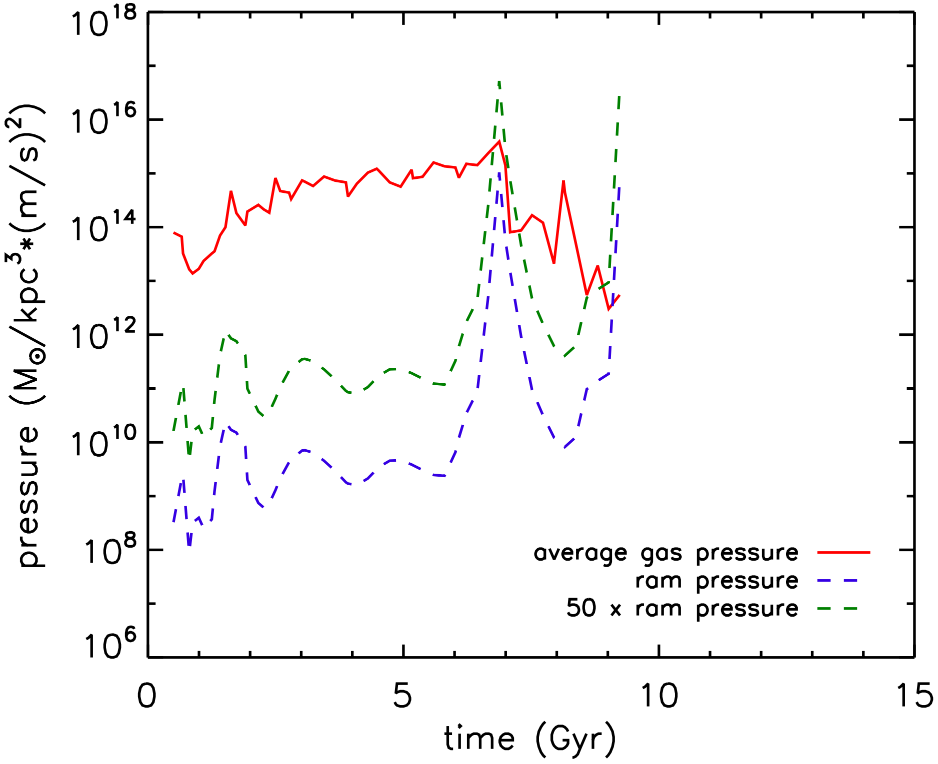
- Almost all of the halos that have a higher virial than background temperature also begin with high baryon fractions



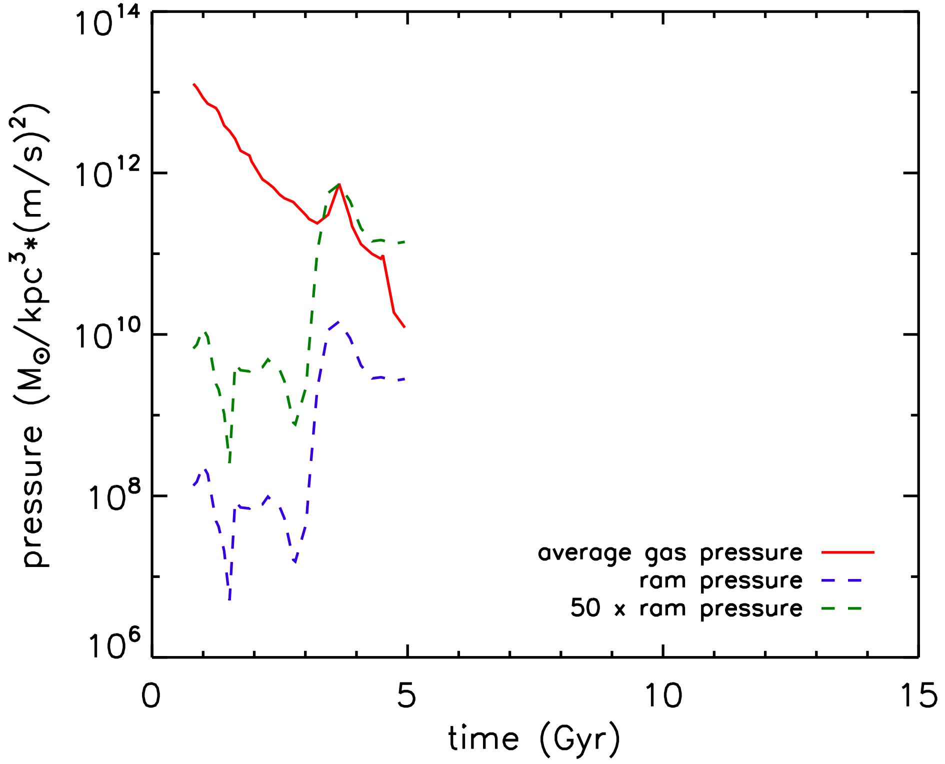
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
Mass ($M_\odot$)
0
5
10
15
time (Gyr)
gas not twin
gas twin
dark not twin
dark twin
star not from twin
star from twin







pressure (M⊙/kpc³*(m/s)²)
time (Gyr)
average gas pressure
ram pressure
50 x ram pressure



pressure (M⊙/kpc³*(m/s)²)
time (Gyr)
average gas pressure
ram pressure
50 x ram pressure

Stellar Feedback

- A particle affected by stellar feedback has its cooling turned off
- This causes it to heat up, and gain enough energy to escape the halo

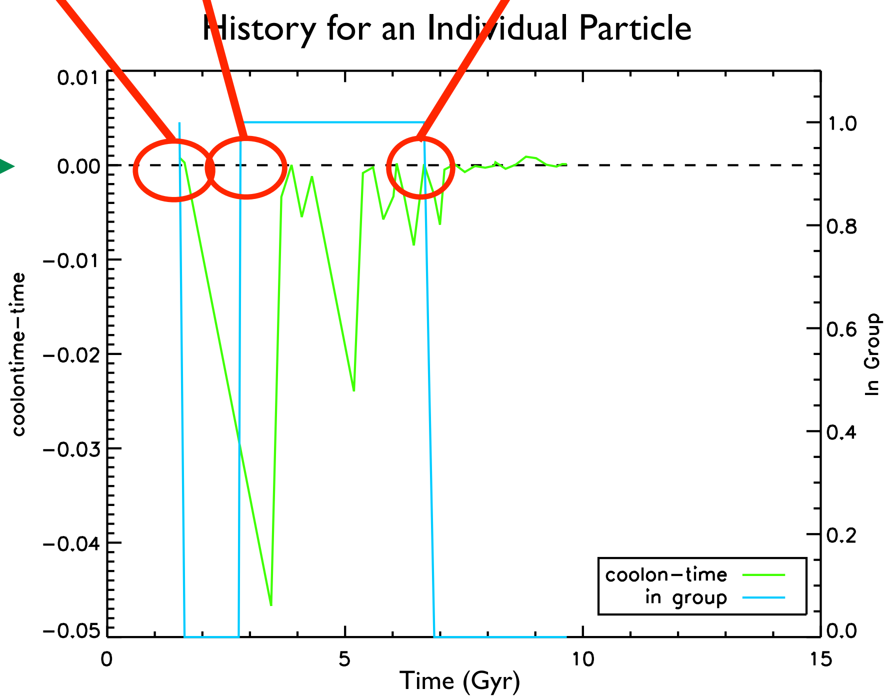
gets kicked out of halo due to sf

rejoins halo again

sf succeeds in kicking it out for good

coolontime > time the cooling has been turned off by supernovae and particle heats up

coolontime < time the cooling has turned on and the particle cools



1 ⇒ particle in group

0⇒particle left group

note: this particle leaves and enters the group twice

The Missing Satellites Problem

Simulation of Dark Matter Halos

Galaxy Cluster Galaxy

(from Moore, B. et al. 1999)

McMaster Unbiased Galaxy Simulations (MUGS) Suite

- High resolution, smoothed particle hydrodynamics in a WMAP3 ΛCDM cosmology
- Ten million particles
- Step 1: Evolve dark matter only, uniform 50 $(Mpc/h)^3$ volume to redshift zero
- Step 2: Resimulate region of interest (the virial radius) with higher resolution, more matter and baryons

Within the virial radius at z=0 for g15784 (the focus of my work):

	individual particle mass ($M_\odot$)	total particles	total mass ($M_\odot$)
dark	$\sim 10^6$	1.1×10^6	1.2×10^{12}
stars	$\sim 10^5$	2.4×10^6	1.1×10^{11}
gas	$\sim 10^5$	4.8×10^5	1.1×10^{11}
total	N/A	$\sim 4 \times 10^6$	$\sim 1.4 \times 10^{12}$

Mass/Light ~ 6.5

Analysis

- To find substructure: Amiga Halo Finder
  - adaptive mesh refinement code
  - hierarchical gridding
- To find a subhalo's luminosity: Starbust 1999
  - For each star, use bi-linear interpolation of its age and metallicity from luminosity grid
  - Sum magnitude of all stars in subhalo

Amiga: Knollmann, S. & Knebe, A. 2009, arXiv:0904.3662v1[astro-ph.CO]

Starburst99: Leitherer, C et al. 1999 ApJ, 123, 3

UV Background

- Each gas particle is twinned from a dark matter particle in the virial radius
- Mark all dark matter in a satellites at its point of maximum gas, then identify its gas twin, i.e. background gas
- The escape temperature for a satellite (what a particle needs to overcome the potential well)

$$T_{virial} = \frac{2G\mu m_p M_{halo}}{3kR_{halo}}$$

- If $T_{virial} < T_{backgroud}$, satellite never accumulates much gas
- Define uv loss as as the twinned gas that never entered the satellite

Ram Pressure and Tidal Stripping

- Tidal stripping

$$\frac{M_{satellite}(r)}{r^3} < \frac{2M_{host}}{R_{host}^3}$$

- Ram pressure stripping

$$P_{ram} \sim \rho_{IGM} v_{halo}^2 > \frac{\sigma_{halo}^2 \rho_{gas}}{3}$$

Future Work

- Too many lost gas particles in the "other" category: need to re-examine criterion
- Stellar feedback an surprisingly weaker than expected
- Look at the satellites in more galaxies within the MUGS suite