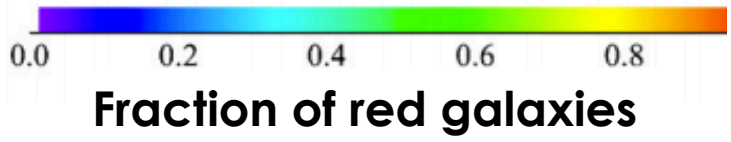
The Gas Content of Galaxies in Groups and Clusters: A Simulation Perspective

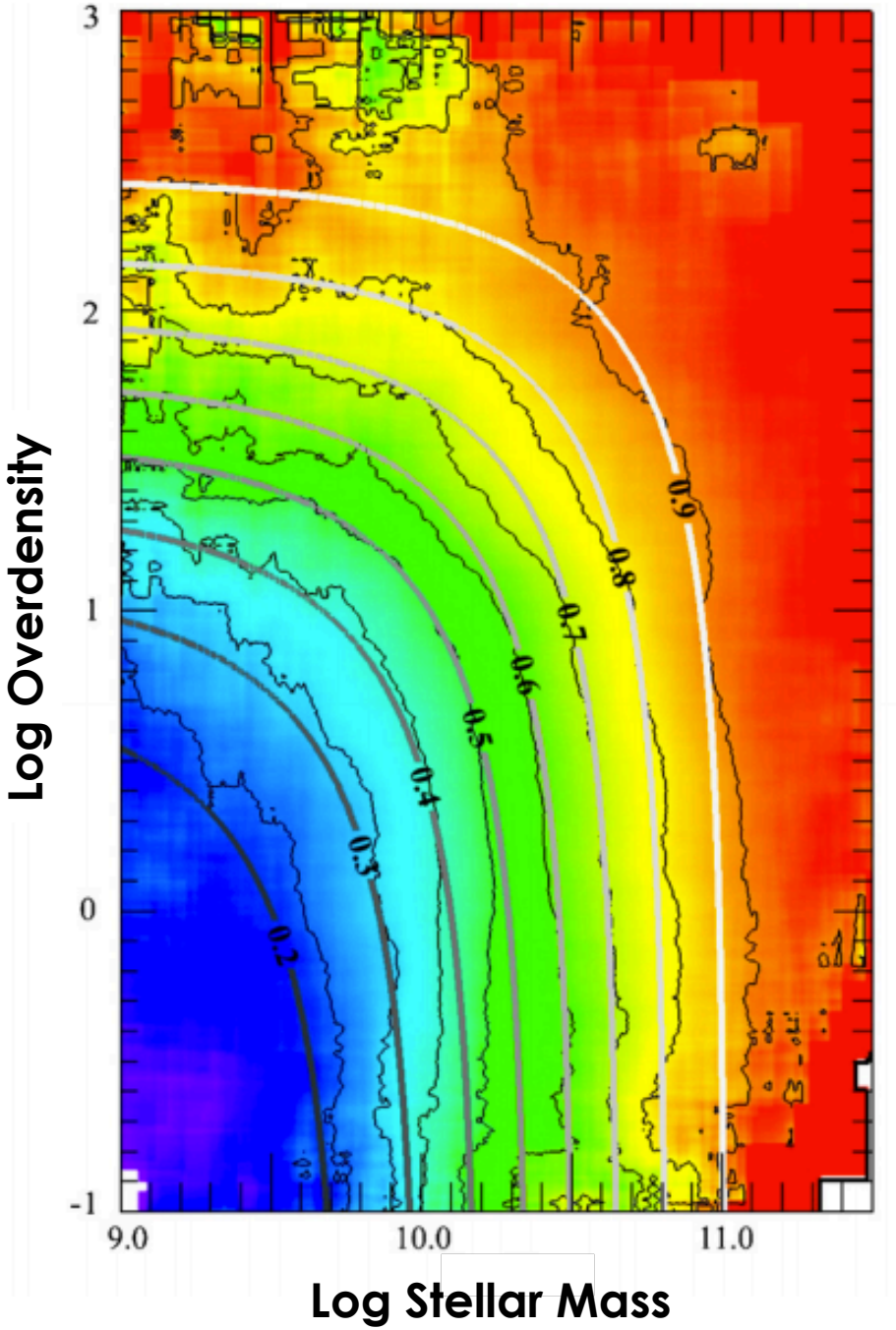
Greg Bryan (Columbia University)

What sets the color and gas content of galaxies?

Mostly just two things control a galaxy's color: mass and environment

Peng et al 2010





Gas Content: Environmental Effects

- Ram pressure stripping of cold, dense gas
- Suppressing accretion ("starvation")
- Tidal stripping, harassment, mergers
- Cooling of hot gas/AGN heating

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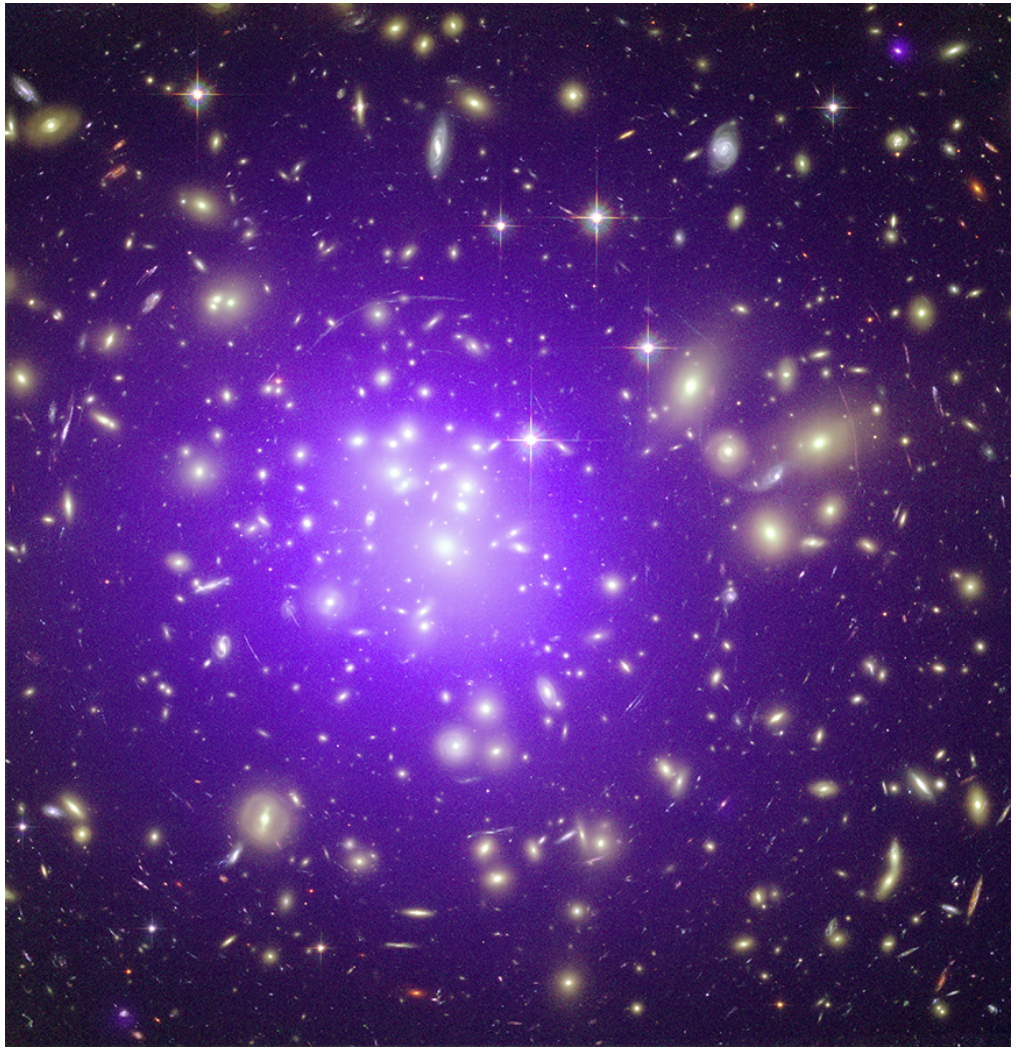
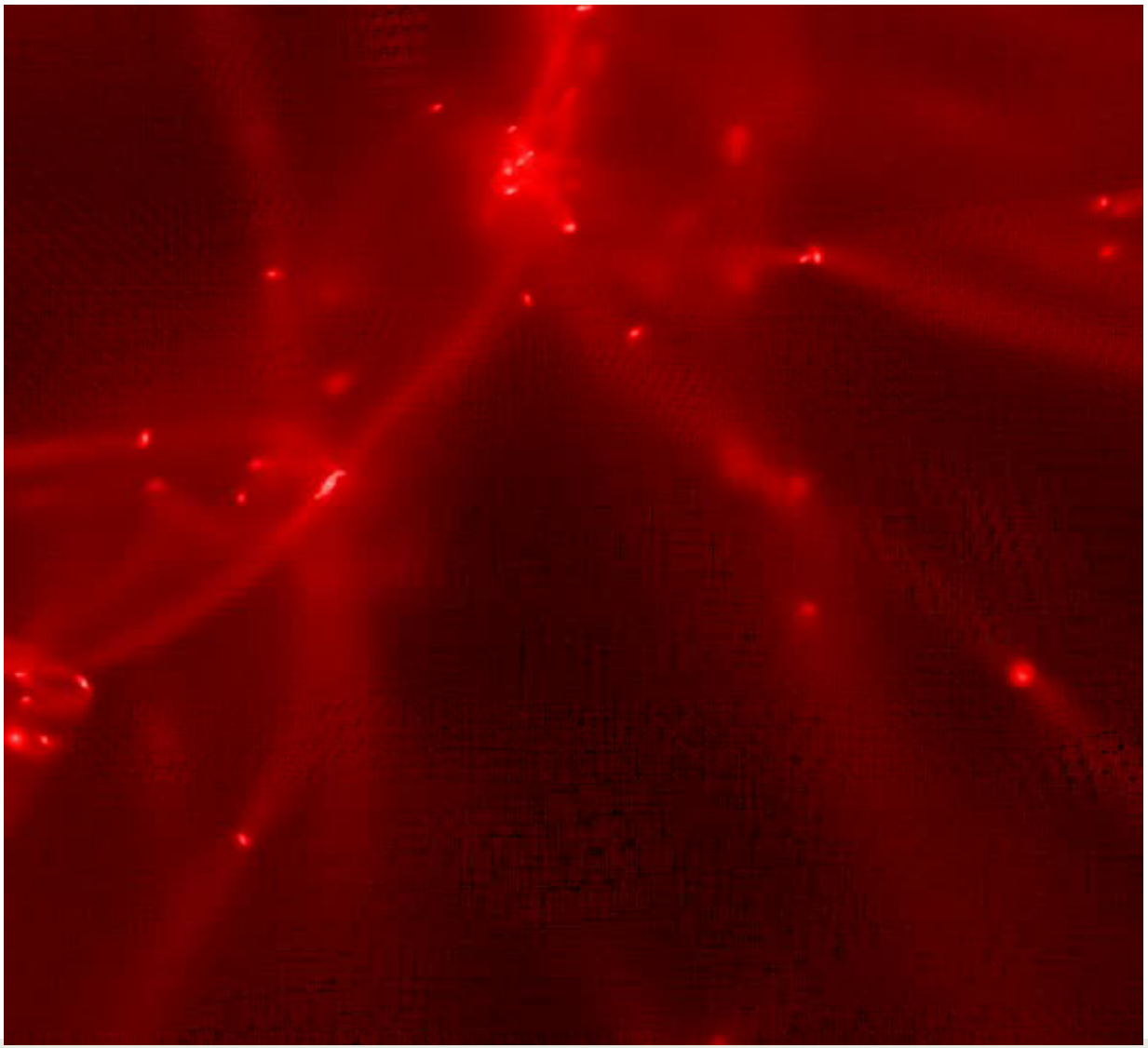
Clusters contain hot gas



Credit: X-ray: NASA/CXC/MIT/E.-H Peng et al; Optical: NASA/ STScI

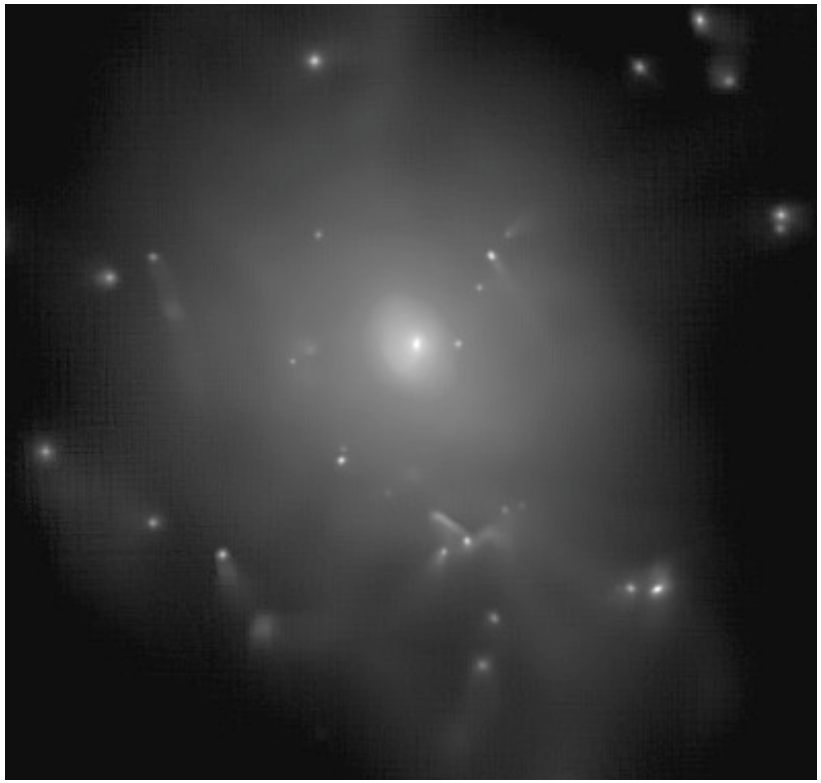
Cosmological cluster evolution

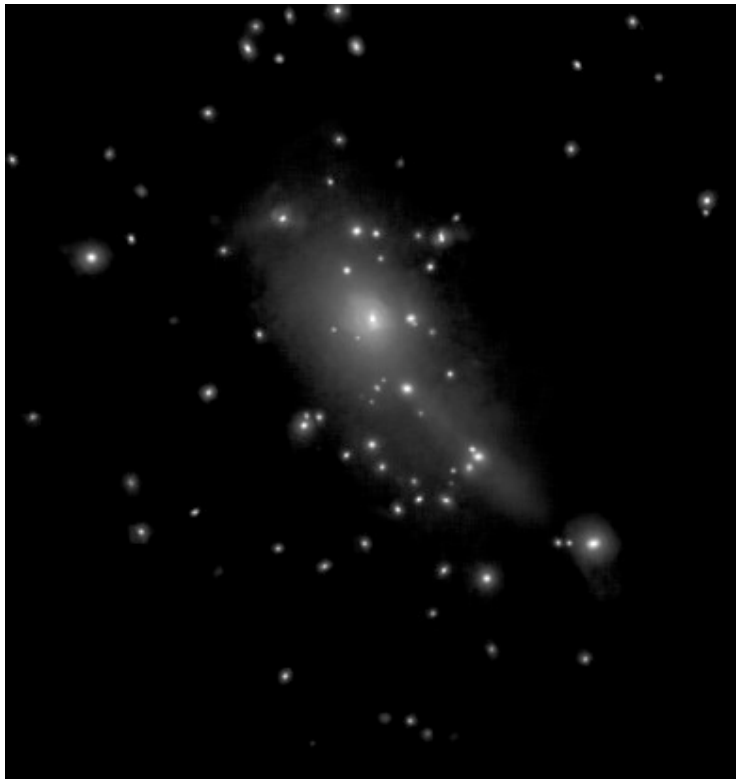


Gas density

Tonnesen & GB (2009)

Environmental effects: Gas stripping, tidal effects





5 Mpc

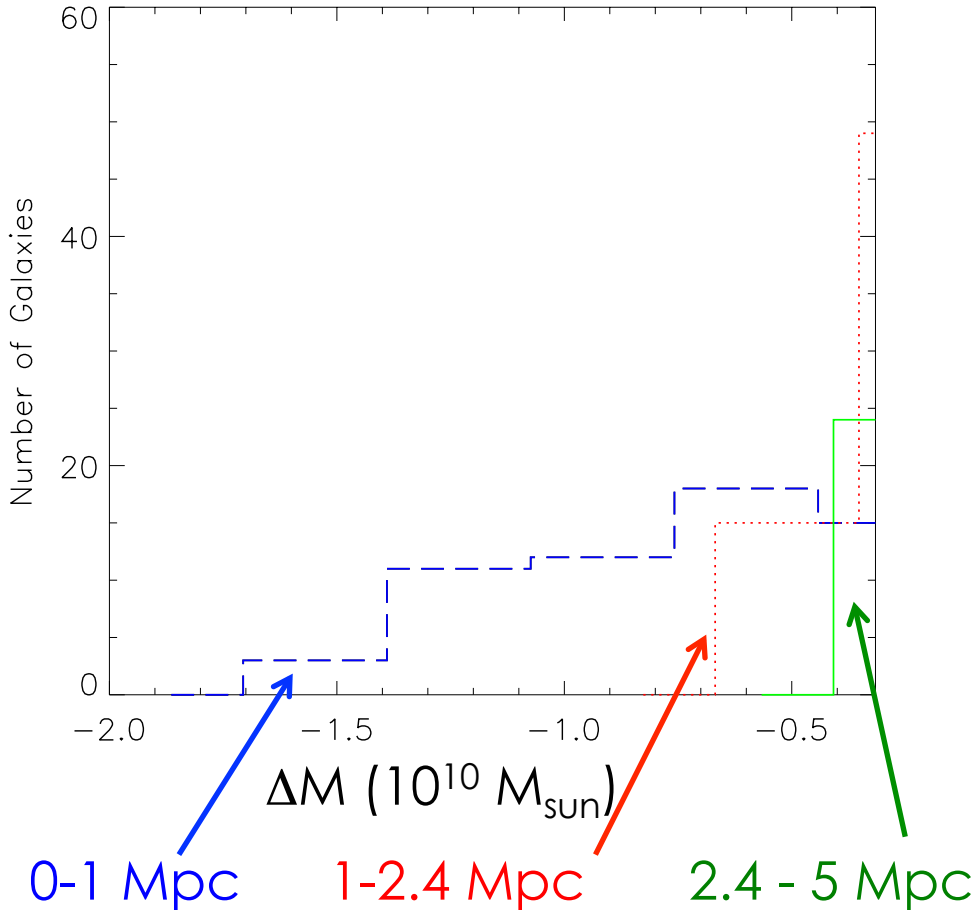
Gas

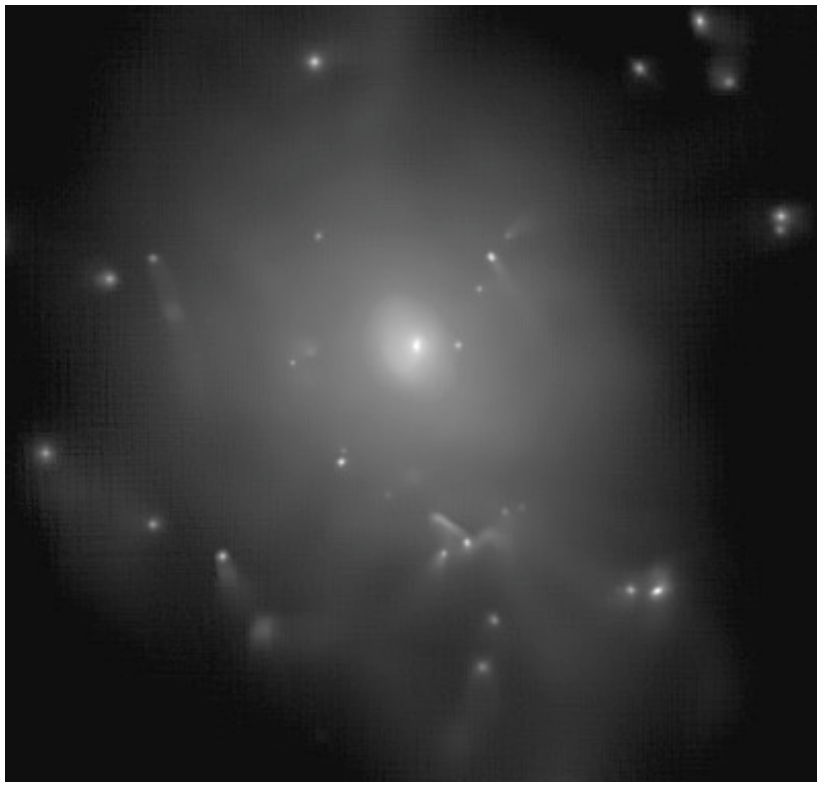
stars

Tonnesen & GB (2009)

Cosmological simulation: gas loss

Which galaxies lose gas?





Ram pressure stripping

Piontek et al (2003)

Analytic-Numerical Comparisons

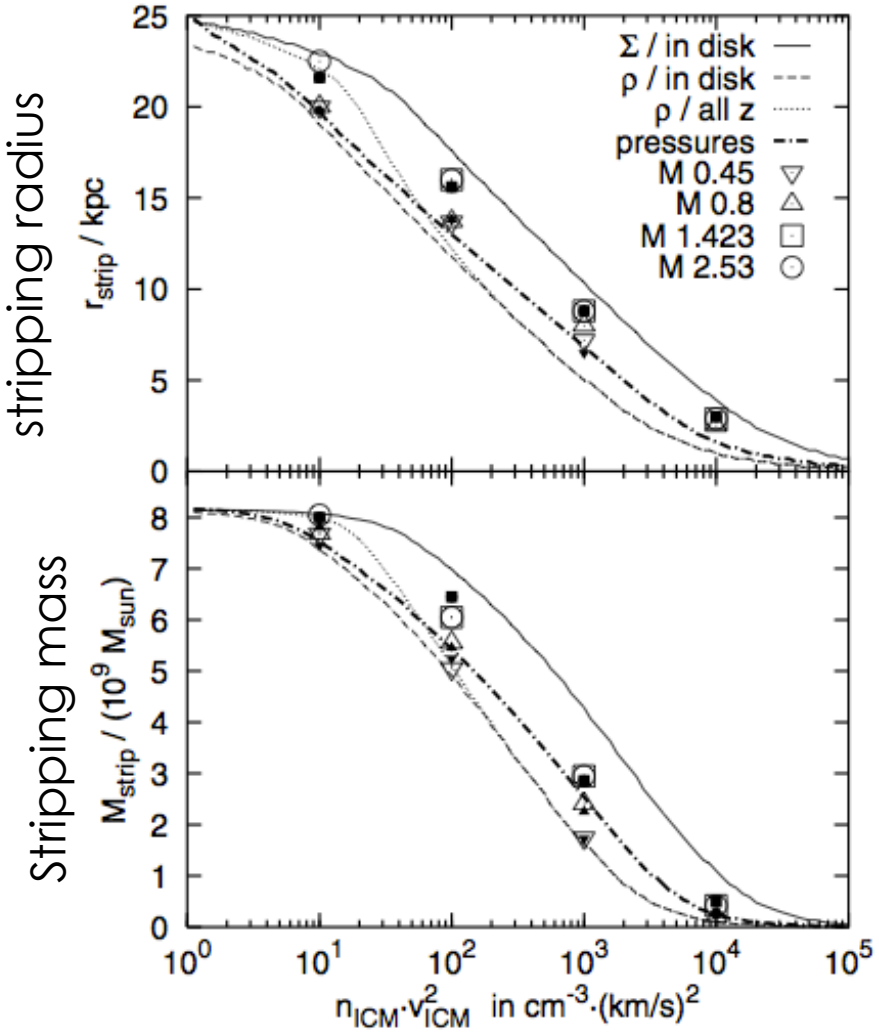
- Analytic prescription for stripping:

$$\rho_{ICM} v_{ICM}^2 = P_{ram} > f_{grav} = 2\pi G \Sigma_* \Sigma_{gas}$$

(Gunn & Gott 1972)

- Can be used to predict radius at which stripping occurs
- When compared to simulations, this works remarkably well

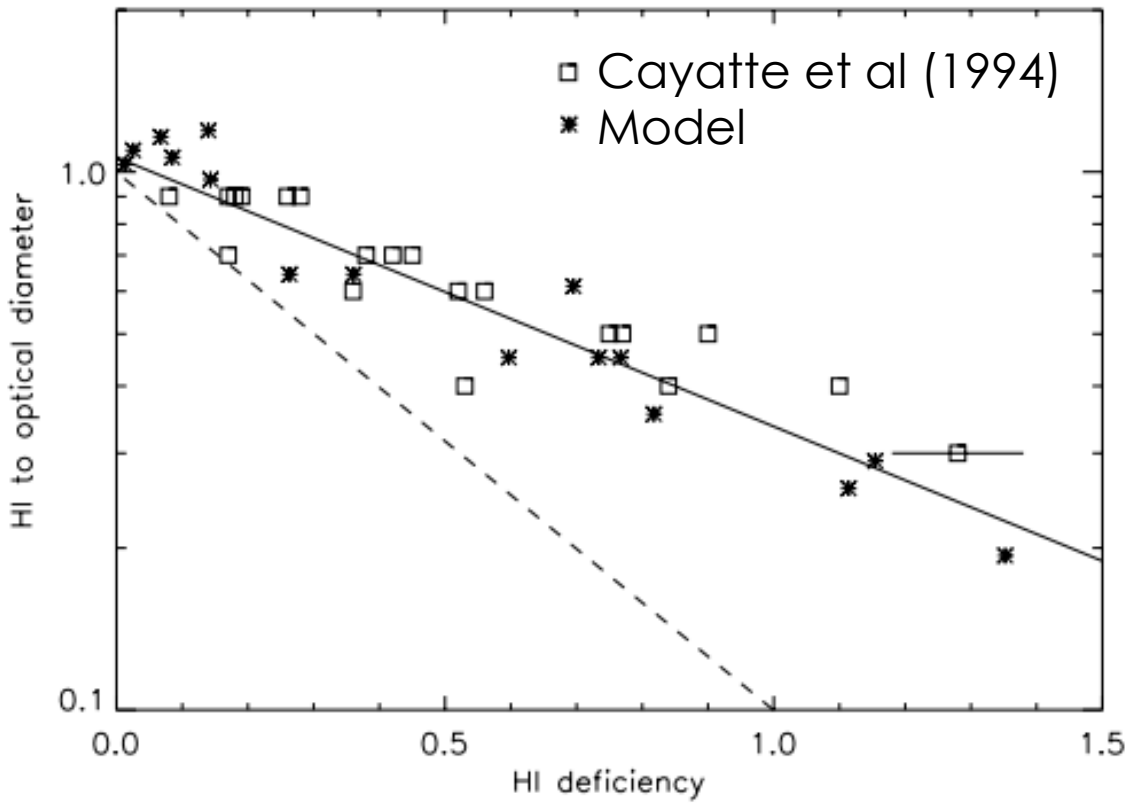
Roediger & Hensler (2005)



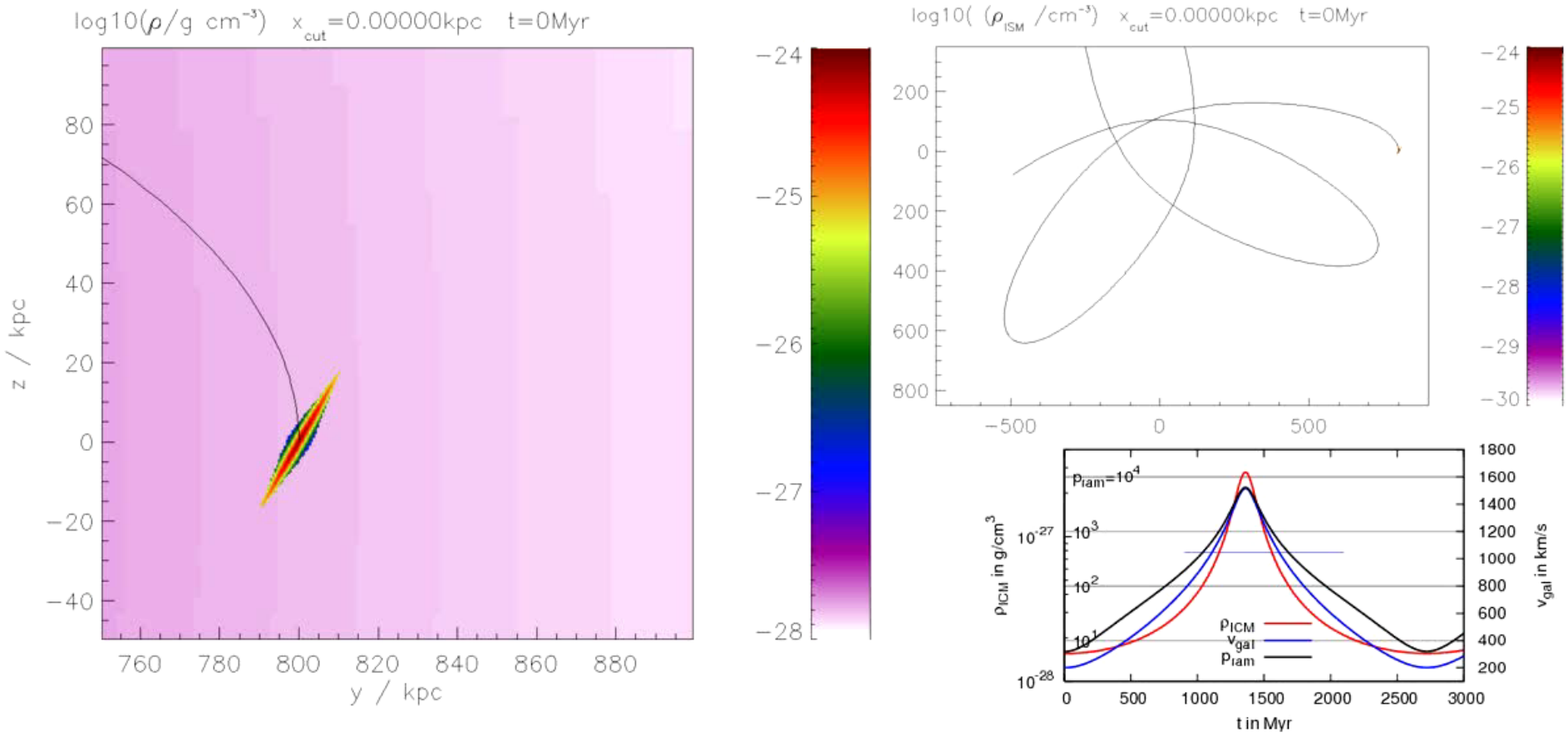
(also Vollmer 2001 with sticky-particle sims)

RPS: Comparison to Observations

- Predicted amount of mass loss (HI deficiency) and stripping radius (relative to optical)
- Vollmer et al (2001)

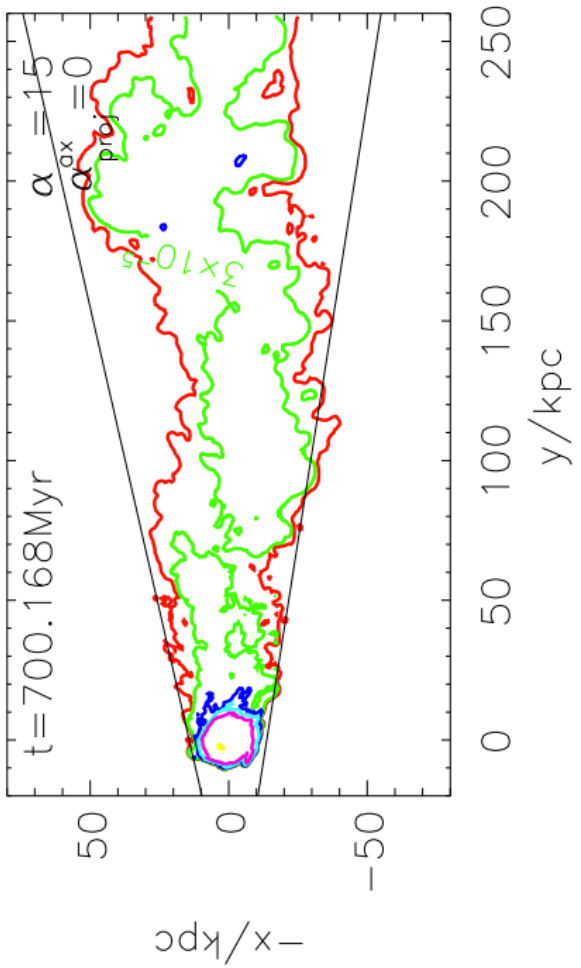


Ram pressure stripping

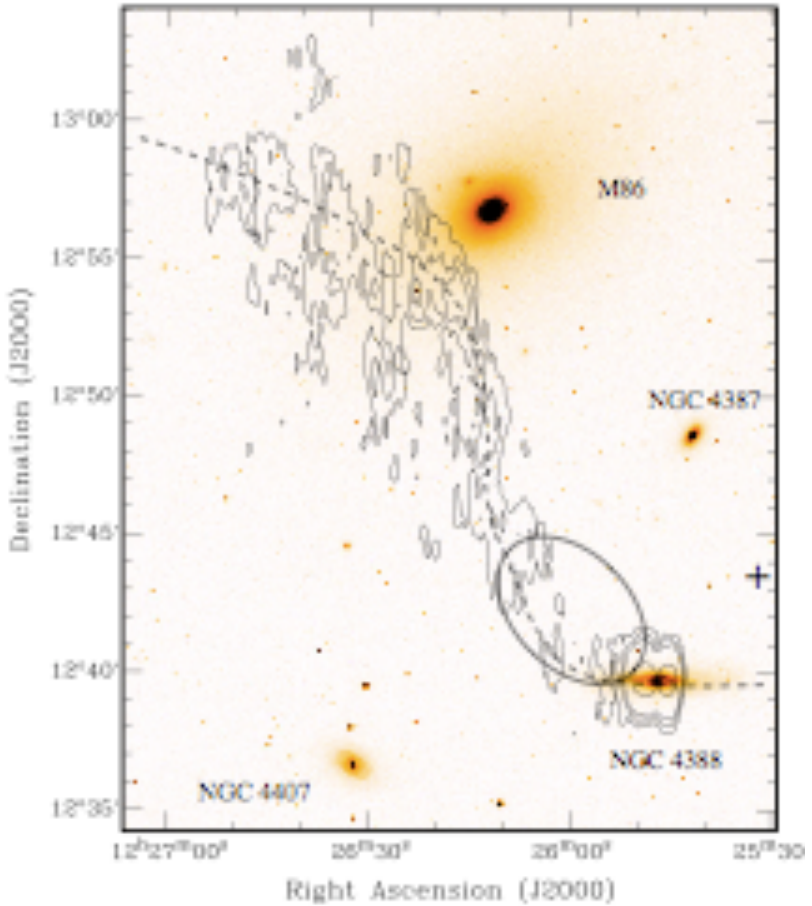


Roediger et al (2008)

Stripped tails



Roediger et al (2006)

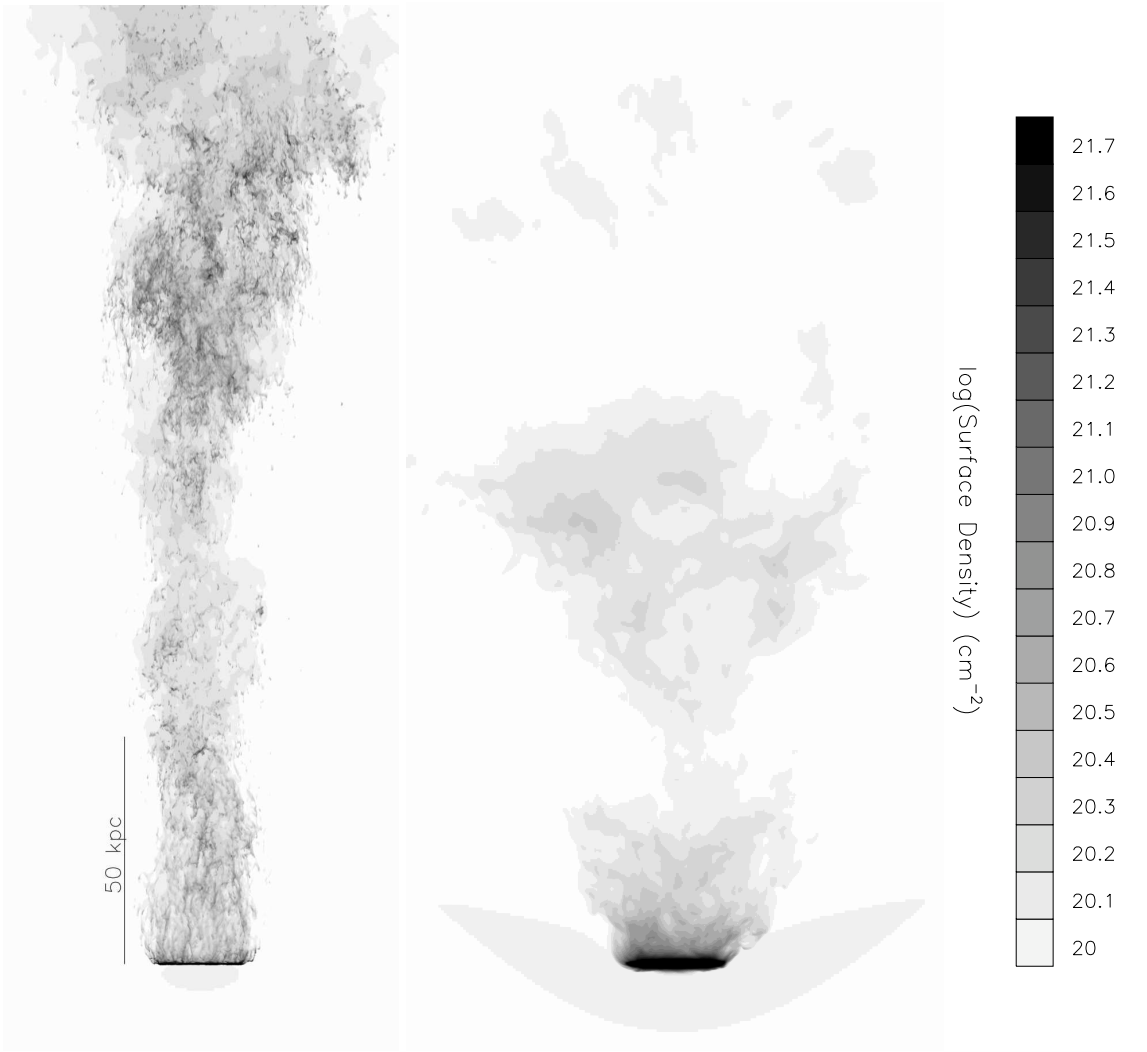


Osterloo & van Gorkom (2005)

RPS: Impact of Radiative Cooling

Cooling

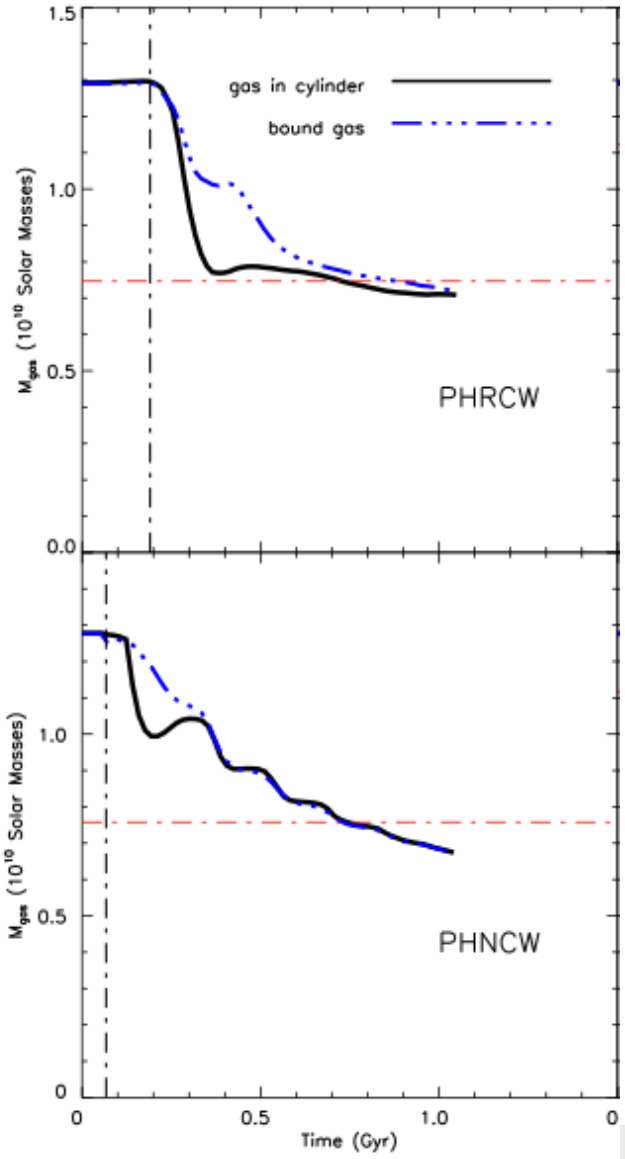
No cooling



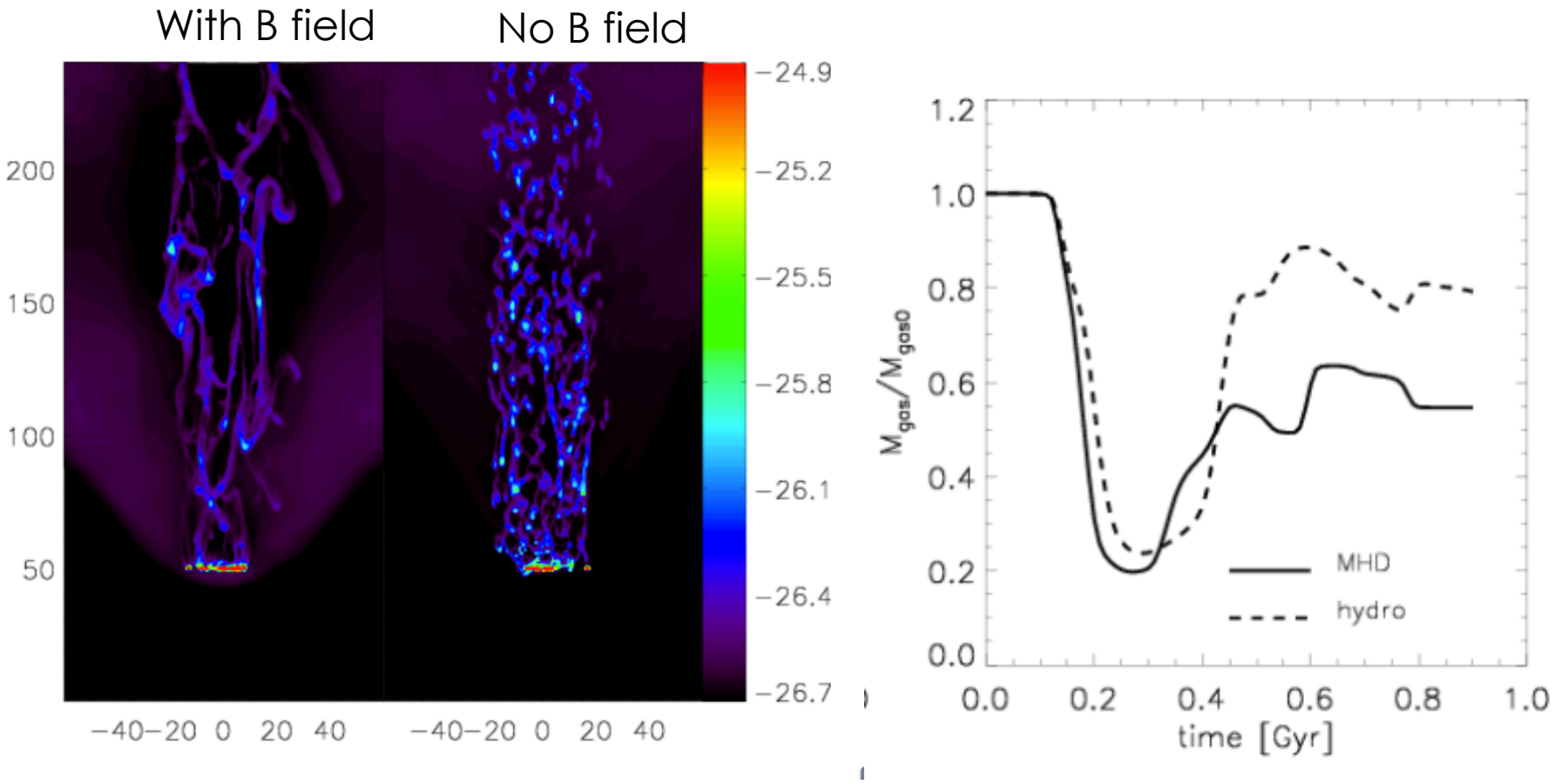
Tonnesen & GB (2009)

Impact of Radiative Cooling

- Radiative cooling produces a very different looking tail, but the mass of gas stripped still agrees with the Gunn and Gott prescription

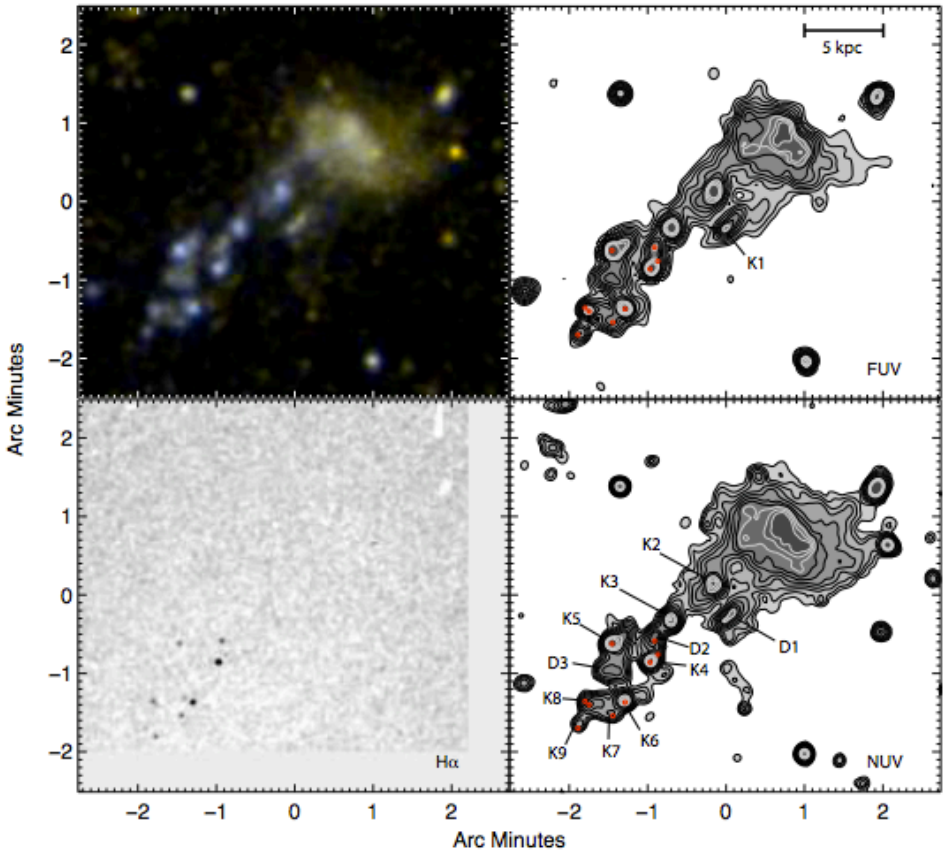


RPS: Impact of Magnetic Field

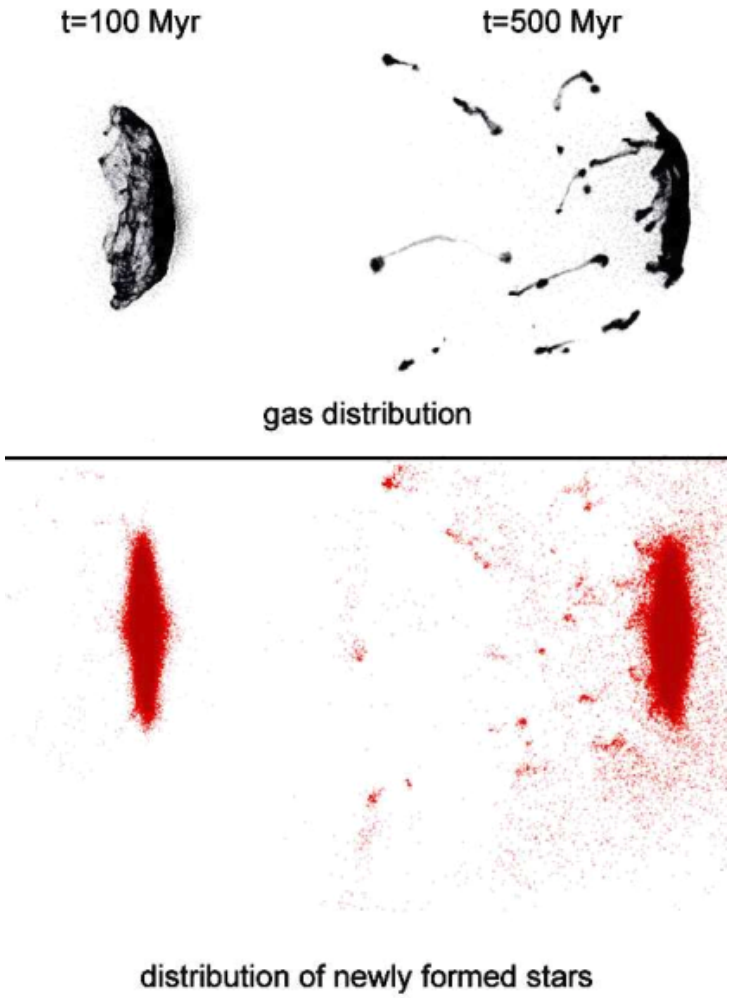


Ruszkowski et al (2012)

Star Formation in Stripped Tail

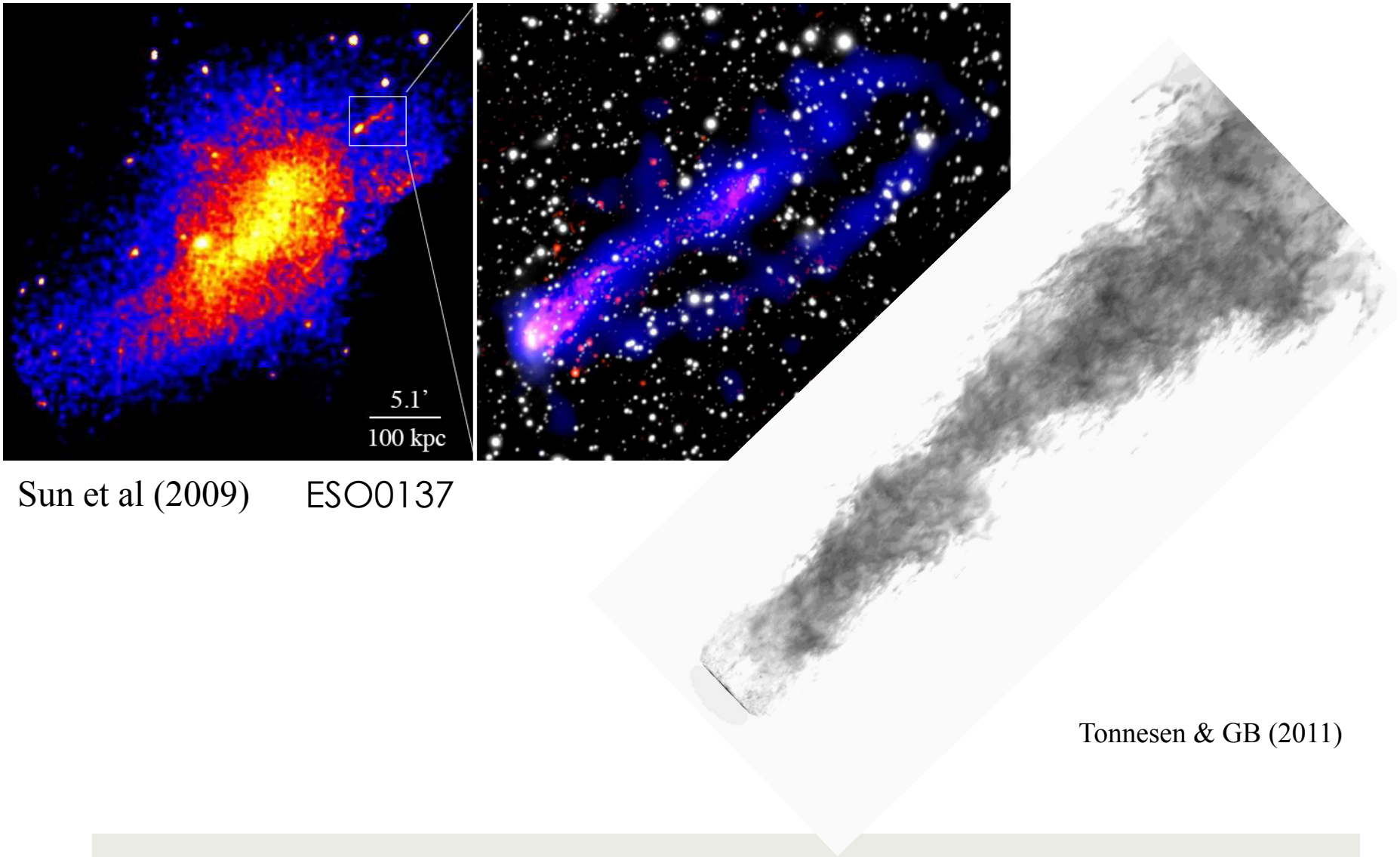


Hester et al (2008)



Kapferer et al (2008)

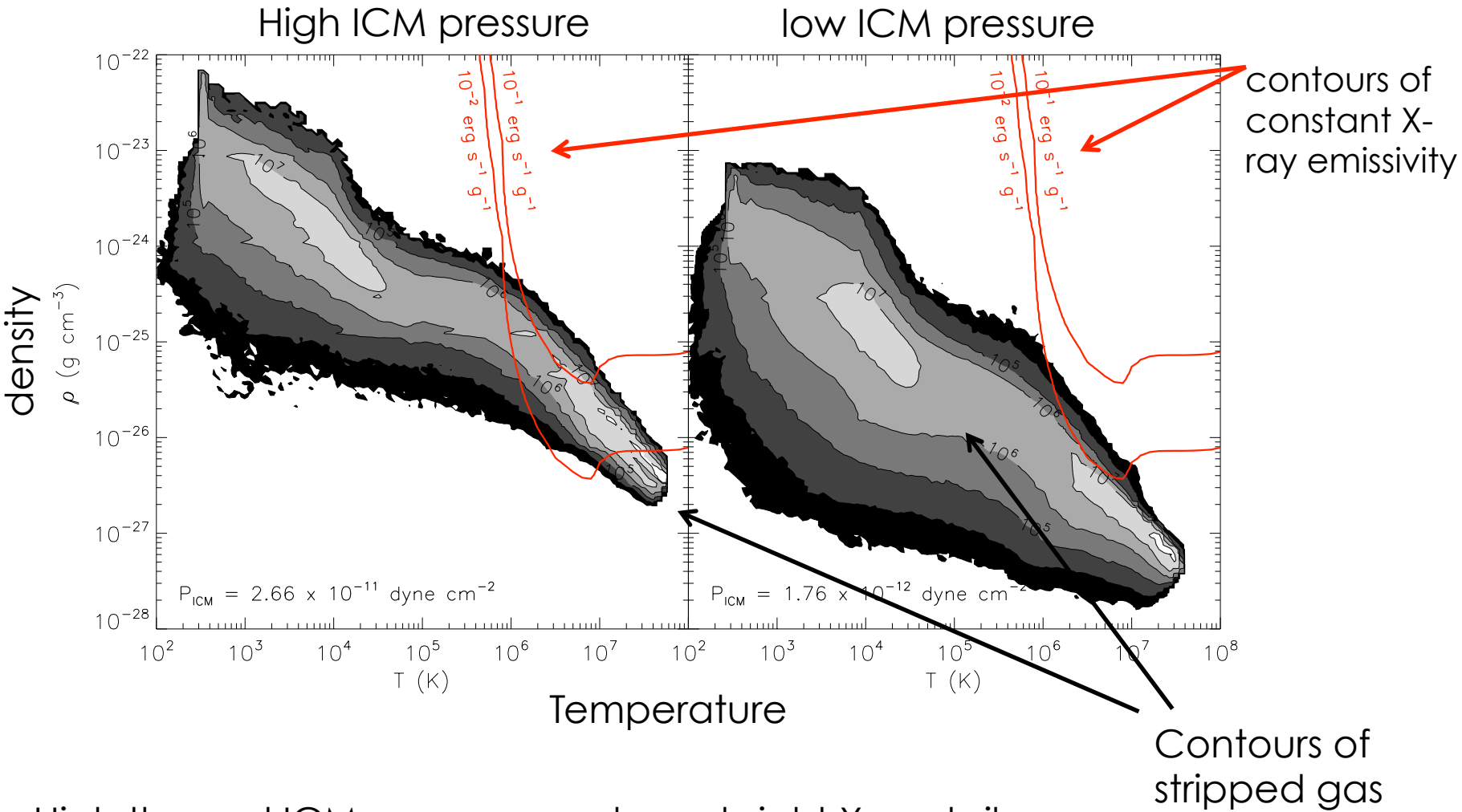
Observing stripped tails in X-ray



Sun et al (2009) ESO0137

Tonnesen & GB (2011)

What controls the X-ray brightness of tails?



High thermal ICM pressure produces bright X-ray tails

Tonnesen & GB (2011)

What about groups?

- Ram pressure: $P = \rho v^2$
  - cluster velocity: $v \sim M^{1/3}$
- RPS more important for clusters than groups
  - also more important for low mass galaxies (dwarfs) for a given cluster size
- But we see environmental effects in groups: why?

Gas Content: Environmental Effects

- Ram pressure stripping of cold, dense gas
- Suppressing accretion ("starvation")
- Tidal stripping, harassment, mergers
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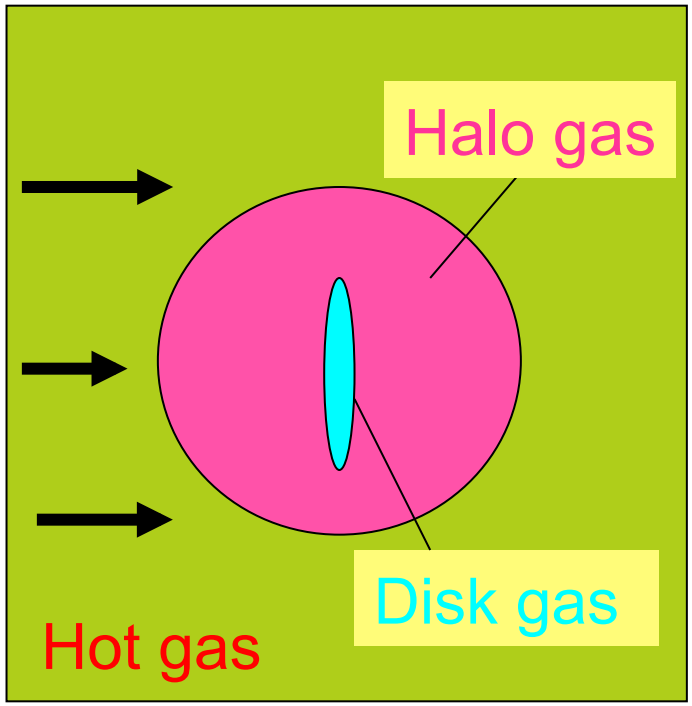
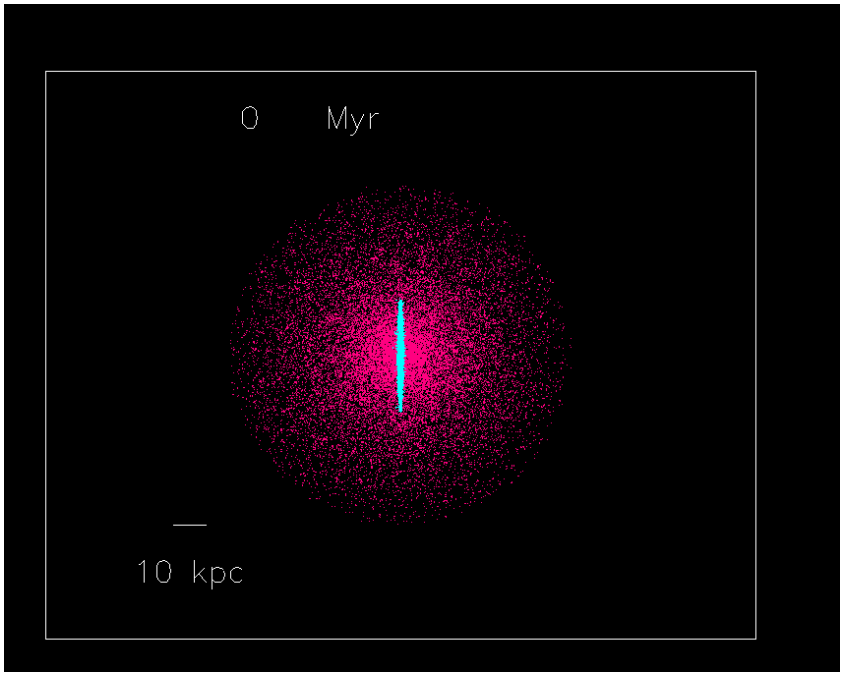
Simulating halo gas stripping



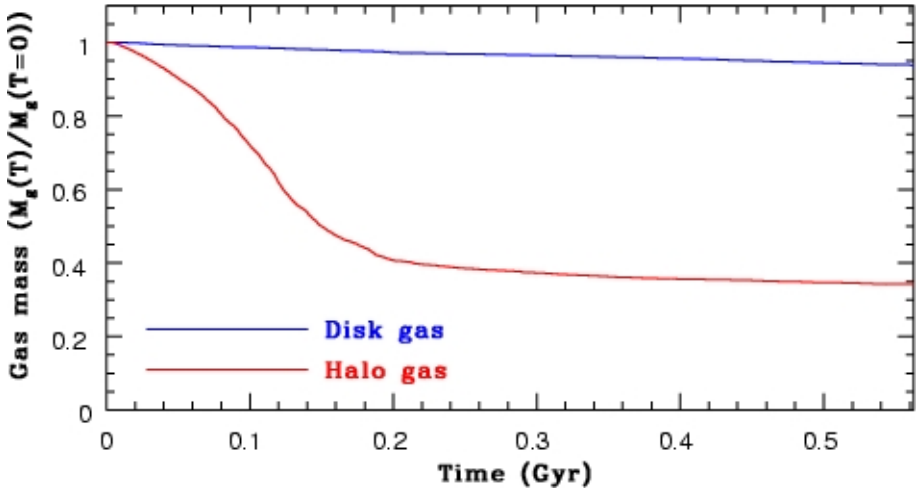


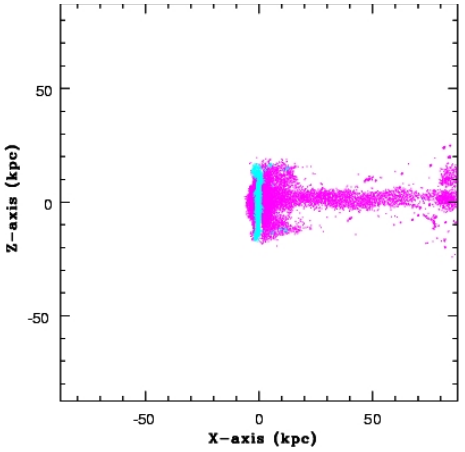
V=500 km/s $T=10^7$ K ($M_{cl}=10^{14}$ M_{sun})
$M_d=6*10^{10}M_{sun}$,v_c=220 km/s,B/D=0.2

(Bekki 2009) (also McCarthy et al 2008)

Cluster: F_{strip}=0.65 (Halo)

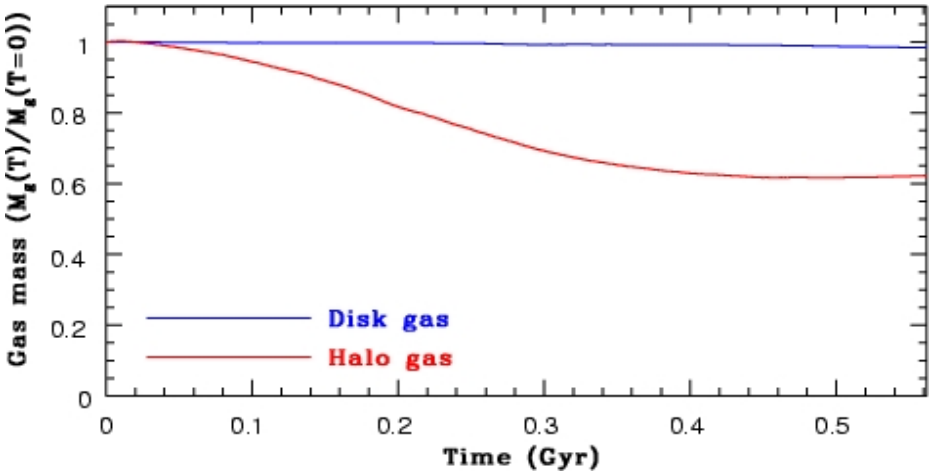
(V=500 km/s, T=10^7 K [M_{cl}=10^{14} M_{sun}])

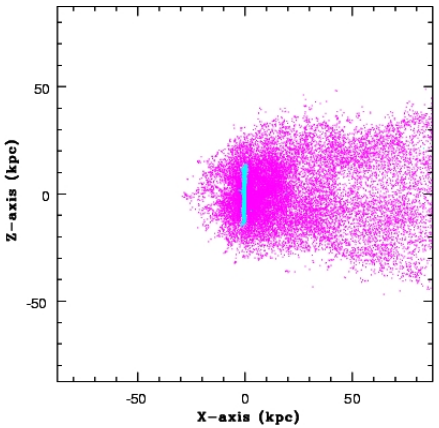




Group: F_{strip}=0.38 (Halo)

(V=200 km/s, T=3*10^6 K [M_{cl}=10^{13} M_{sun}])



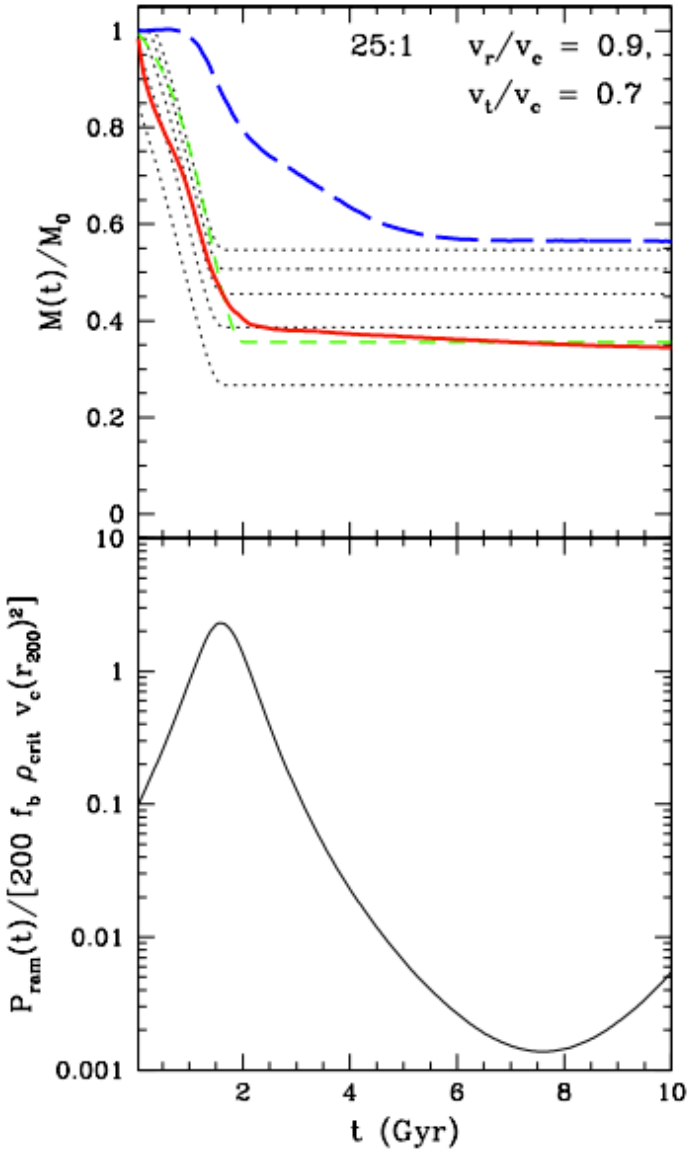


(Bekki 2009)

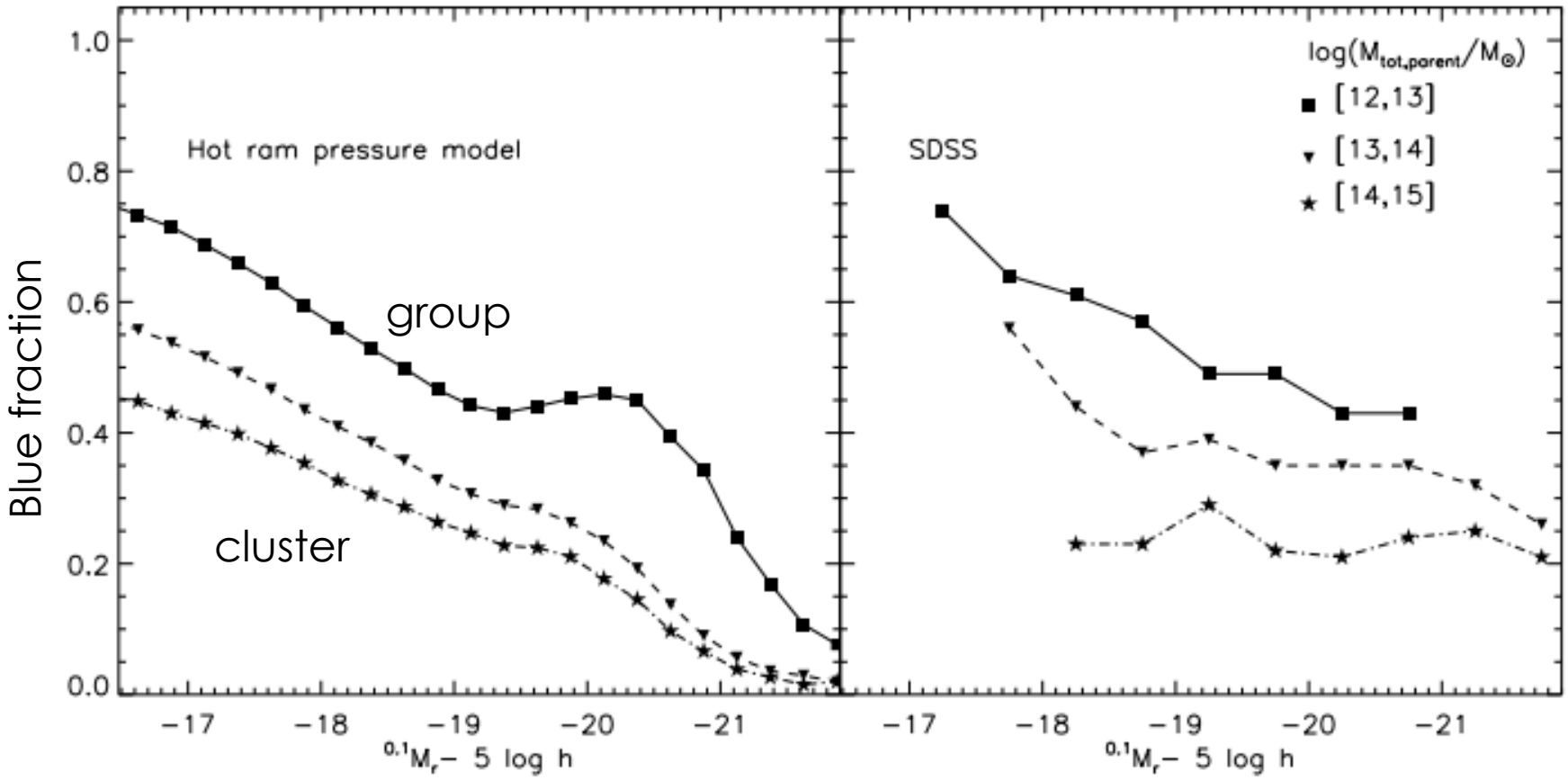
Halo stripping: analytic prescription

- McCarthy et al (2008) simulated halo stripping and found that a simple extension of the Gunn-Gott Prescription worked well.

$$P_{\rm ram} \equiv \rho_{\rm gas,p} v_{\rm sat}^2 > P_{\rm grav} \equiv \alpha_{\rm rp} \frac{G M_{\rm tot,sat}(r) \rho_{\rm gas,sat}(r)}{r}$$



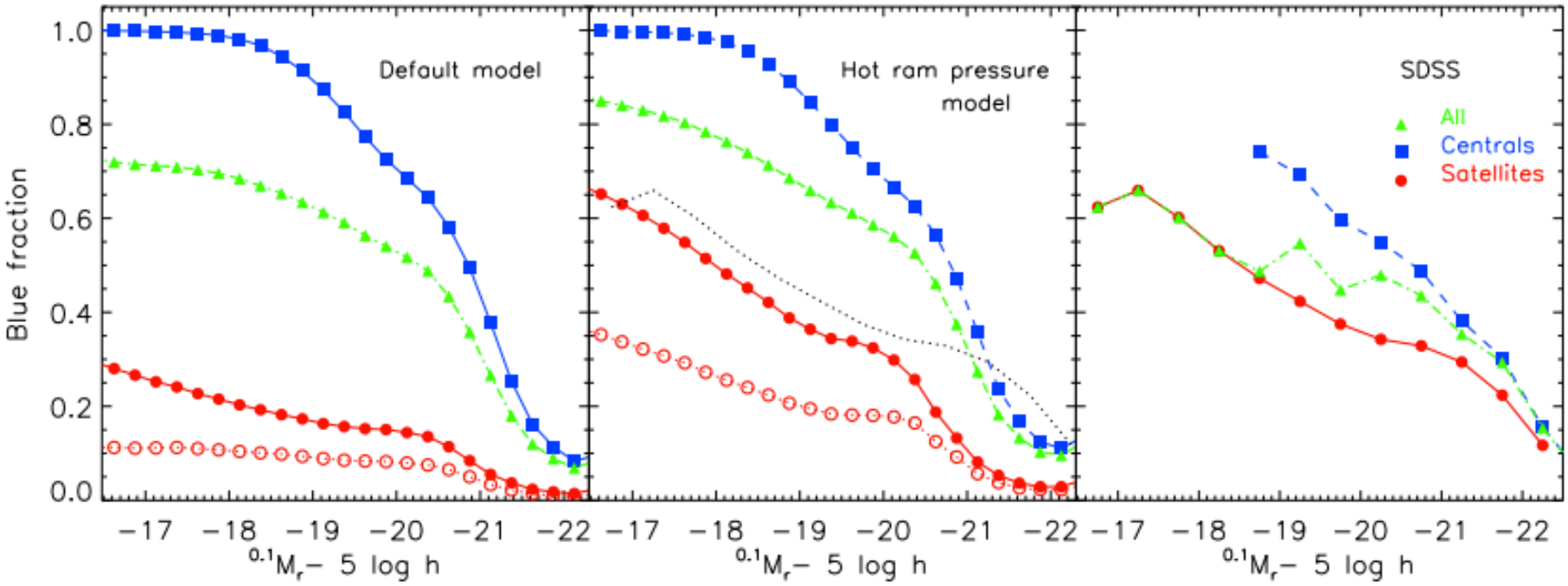
Starvation implemented in semi-analytic model



luminosity

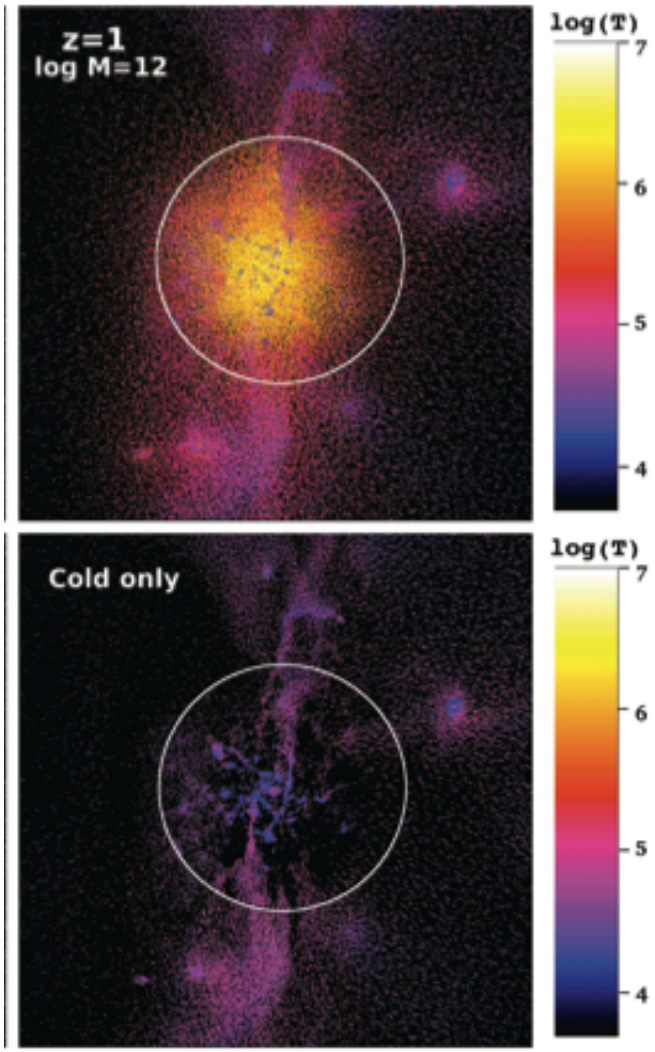
Font et al (2008)

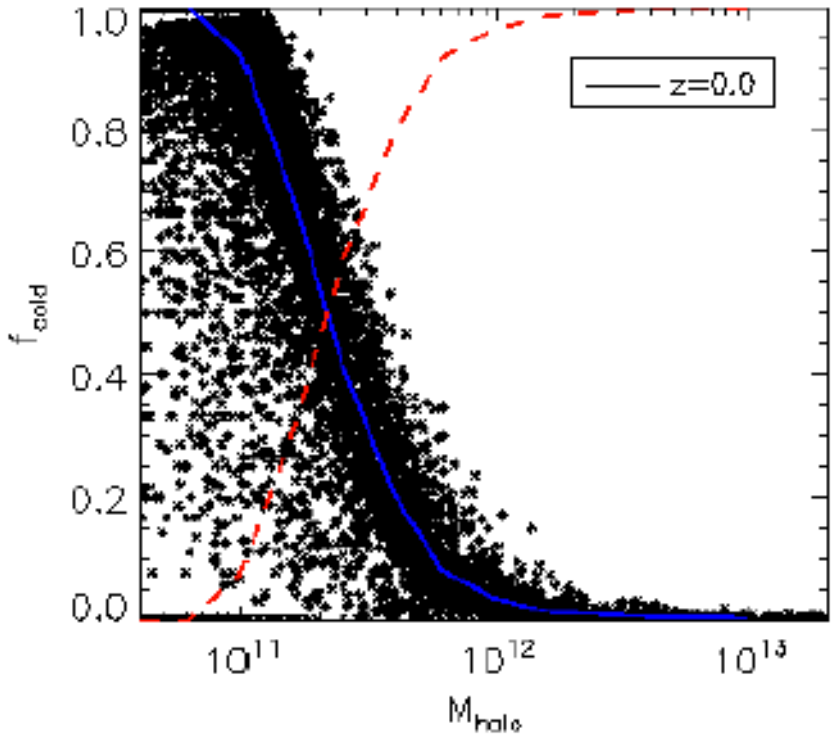
Impact of Delayed Starvation



Font et al (2008)

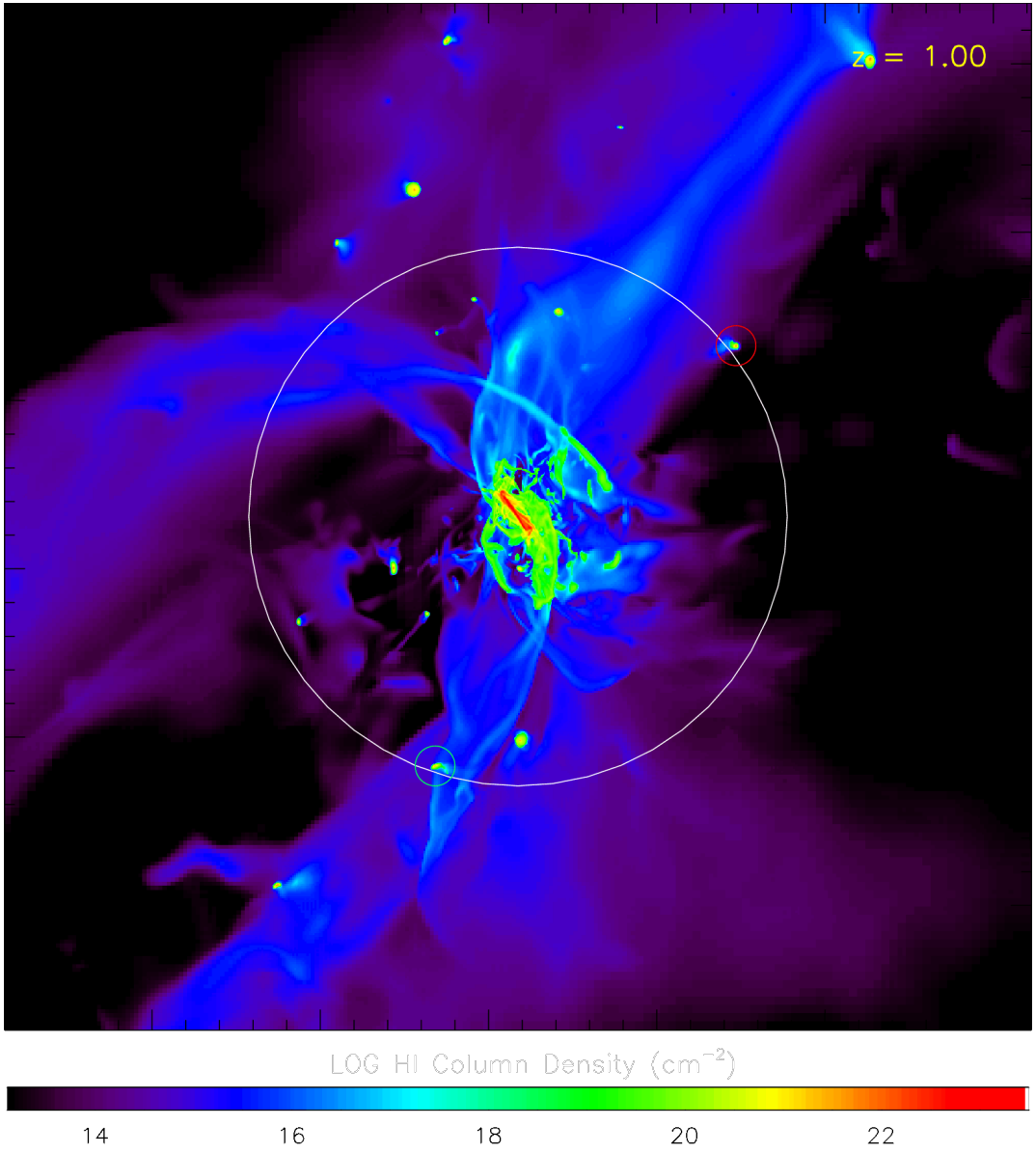
What does gas accretion actually look like?





Keres et al 2005, 2009

Simulating Gas Accretion

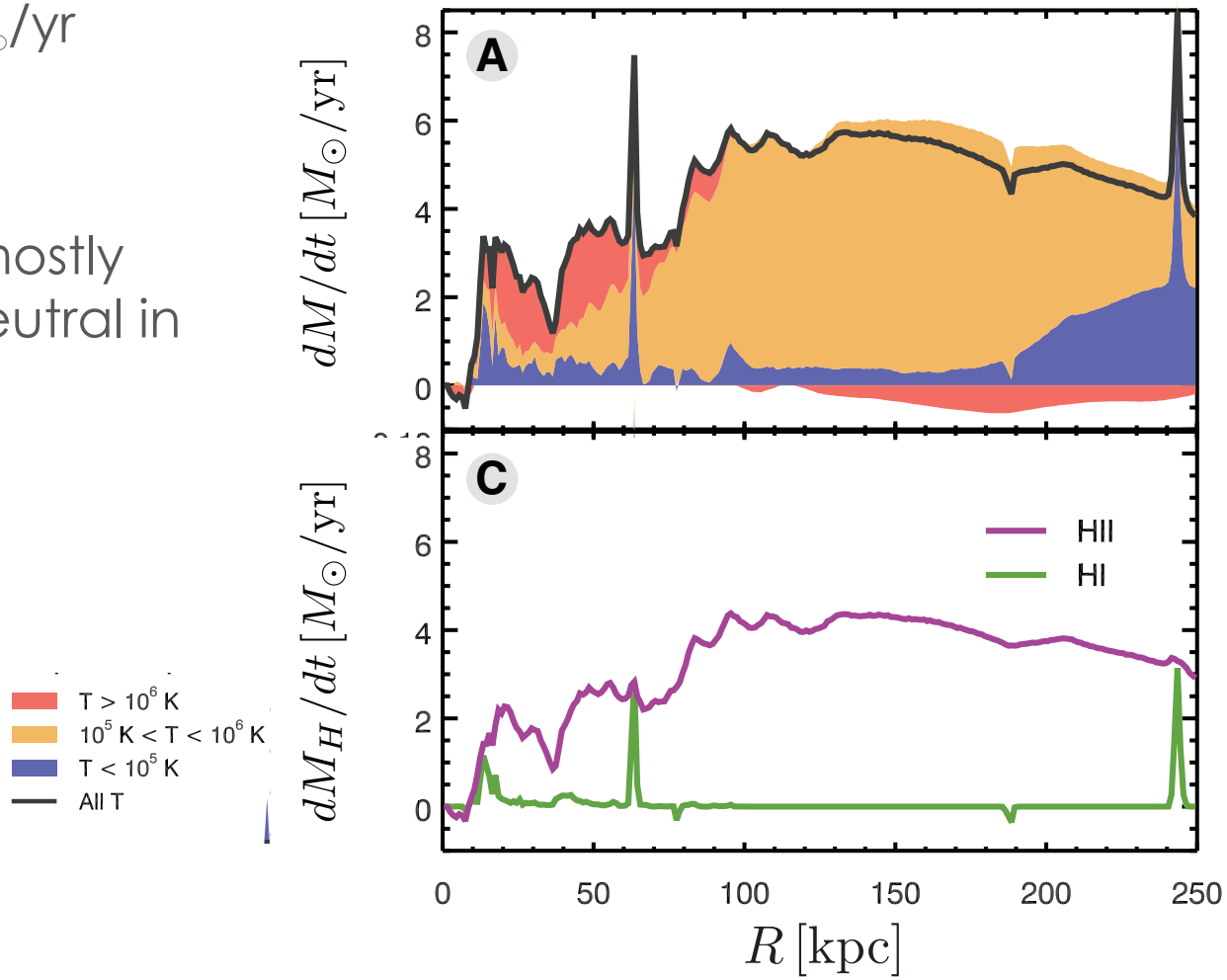


HI Map

Joung et al (2012)

At z~0 inflowing gas is warm and ionized

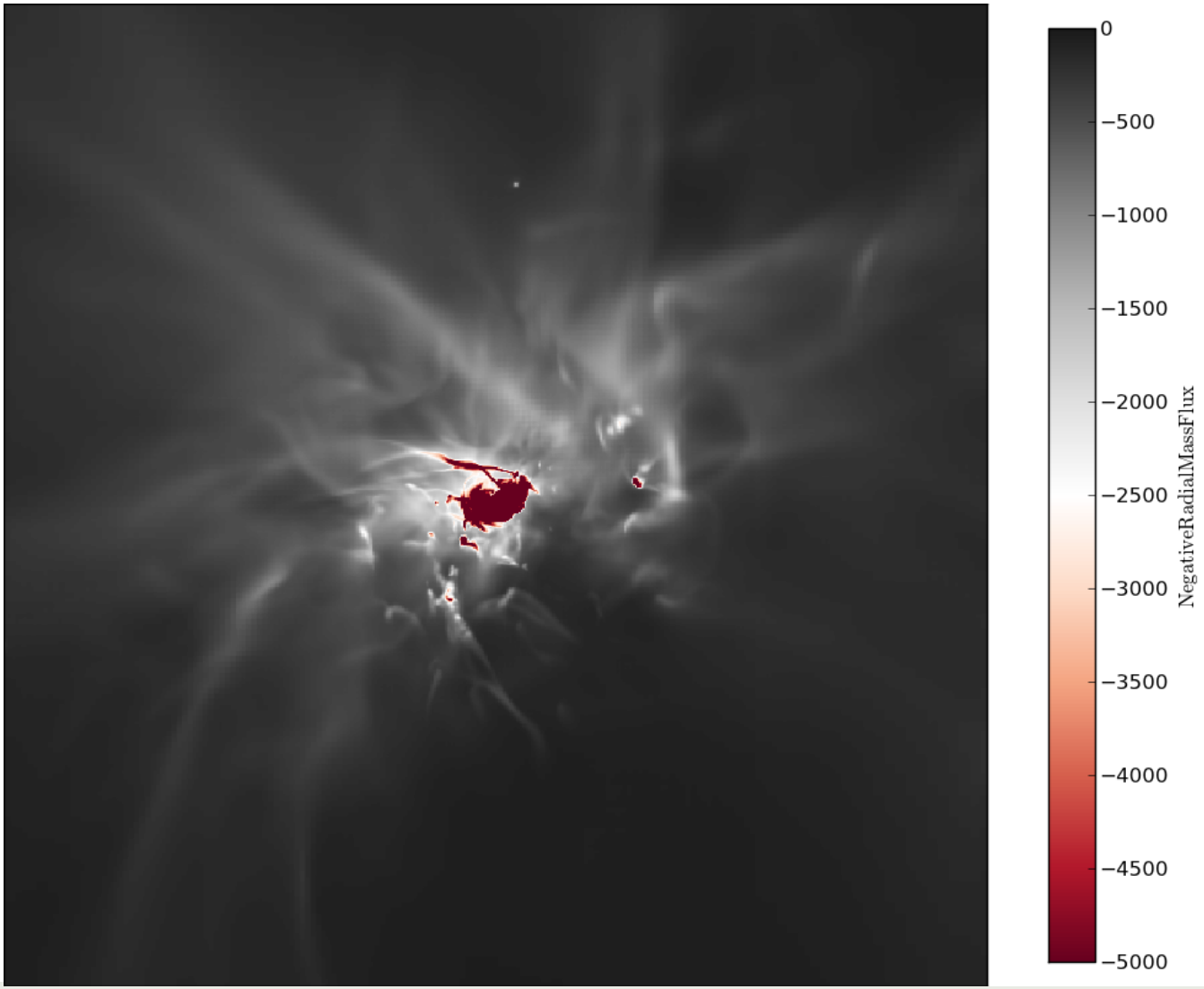
- inflow rate ~ 4 $M_\odot$/yr
- gas is warm-hot
- inflowing gas is mostly ionized (~10 % neutral in center)



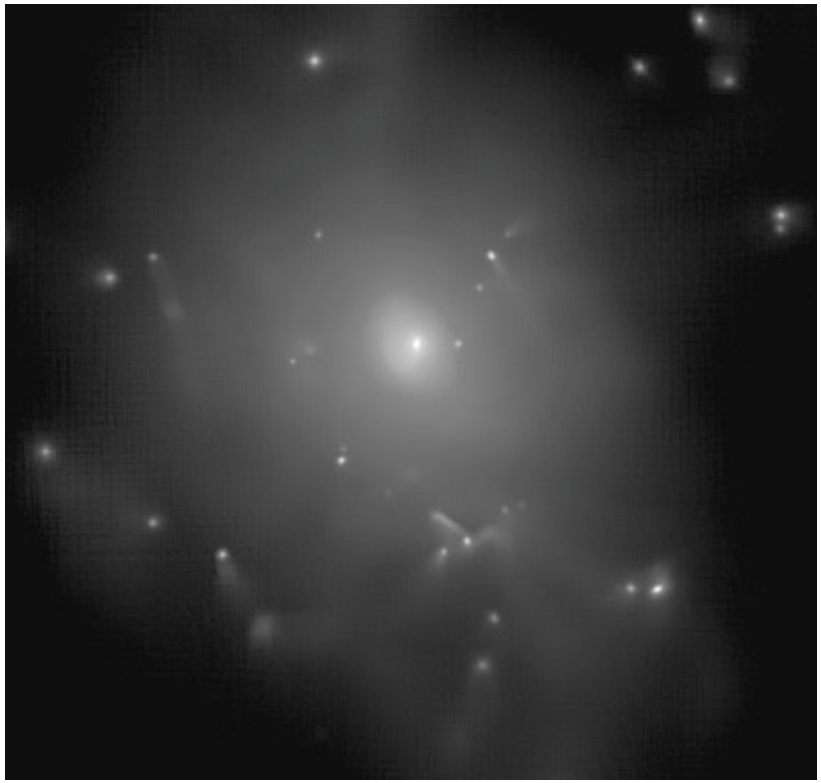
Filamentary accretion of ionized gas

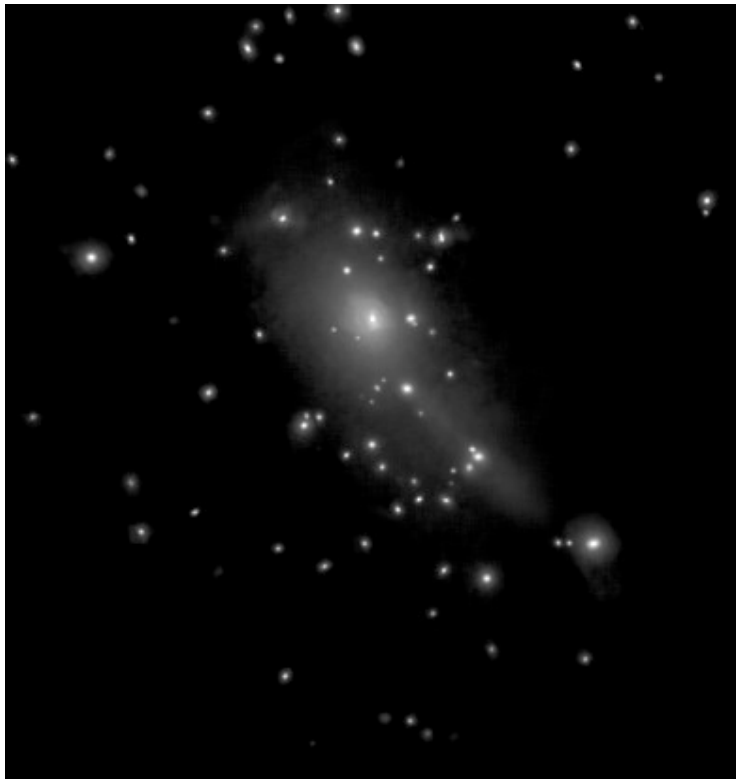
Map of Radial Mass Flux

Joung et al (2012)



Starvation in a Cosmological Simulation





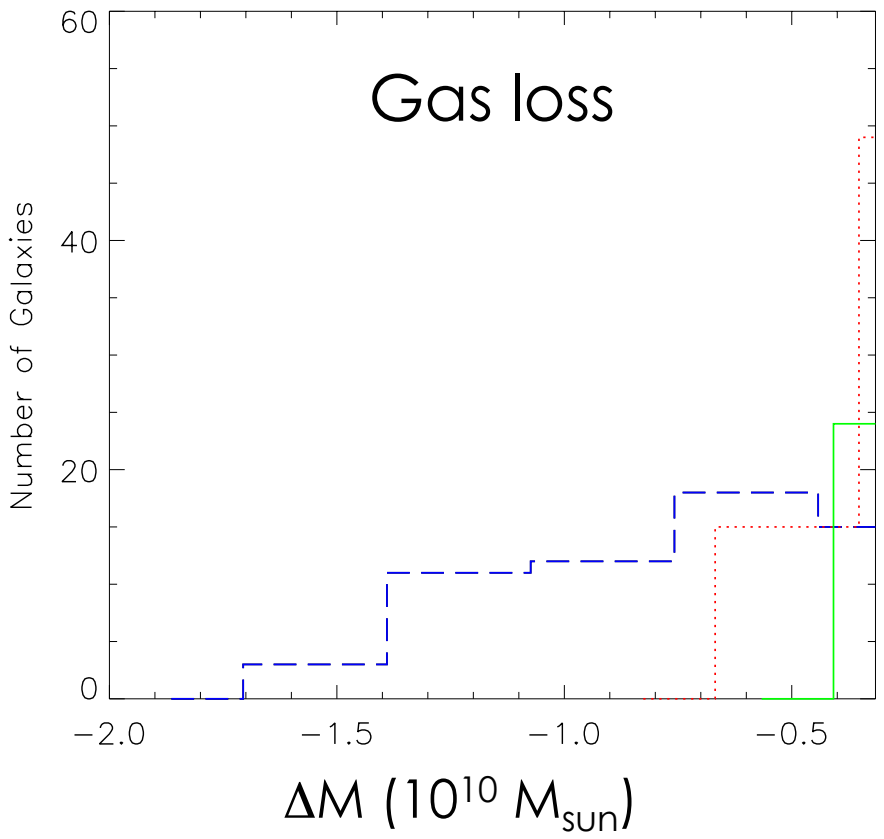
5 Mpc

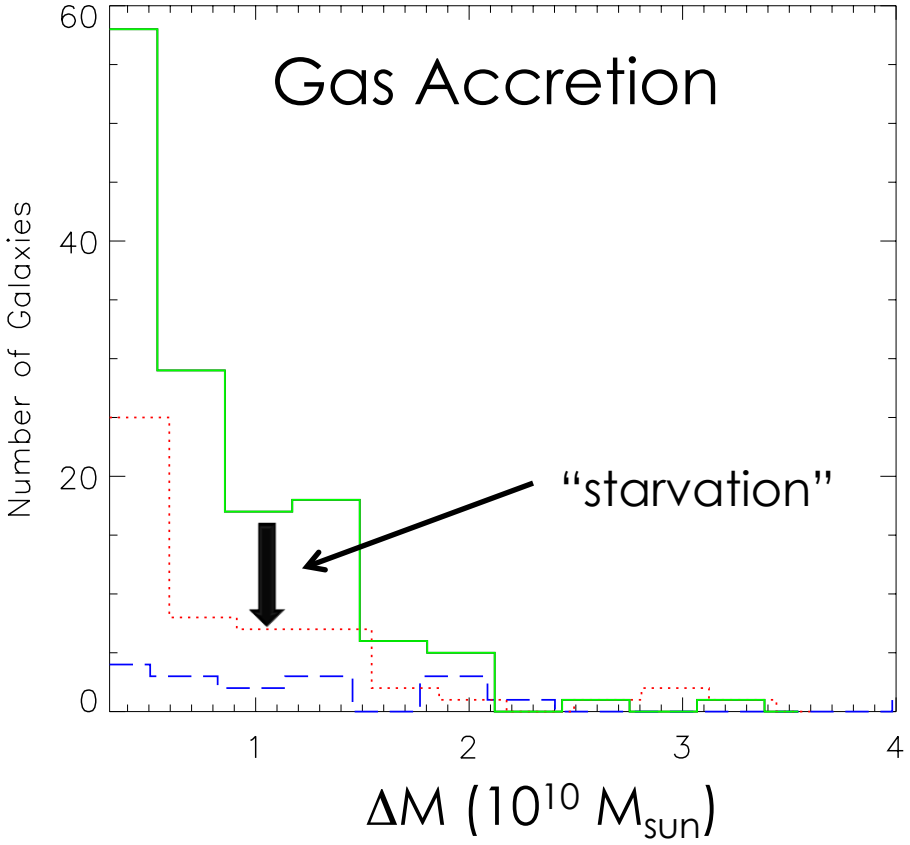
Gas

stars

Tonnesen & GB (2009)

Cosmological simulation





Distance from cluster center: 0-1 Mpc 1-2.4 Mpc 2.4 - 5 Mpc

Gas Content: Environmental Effects

- Ram pressure stripping of cold, dense gas
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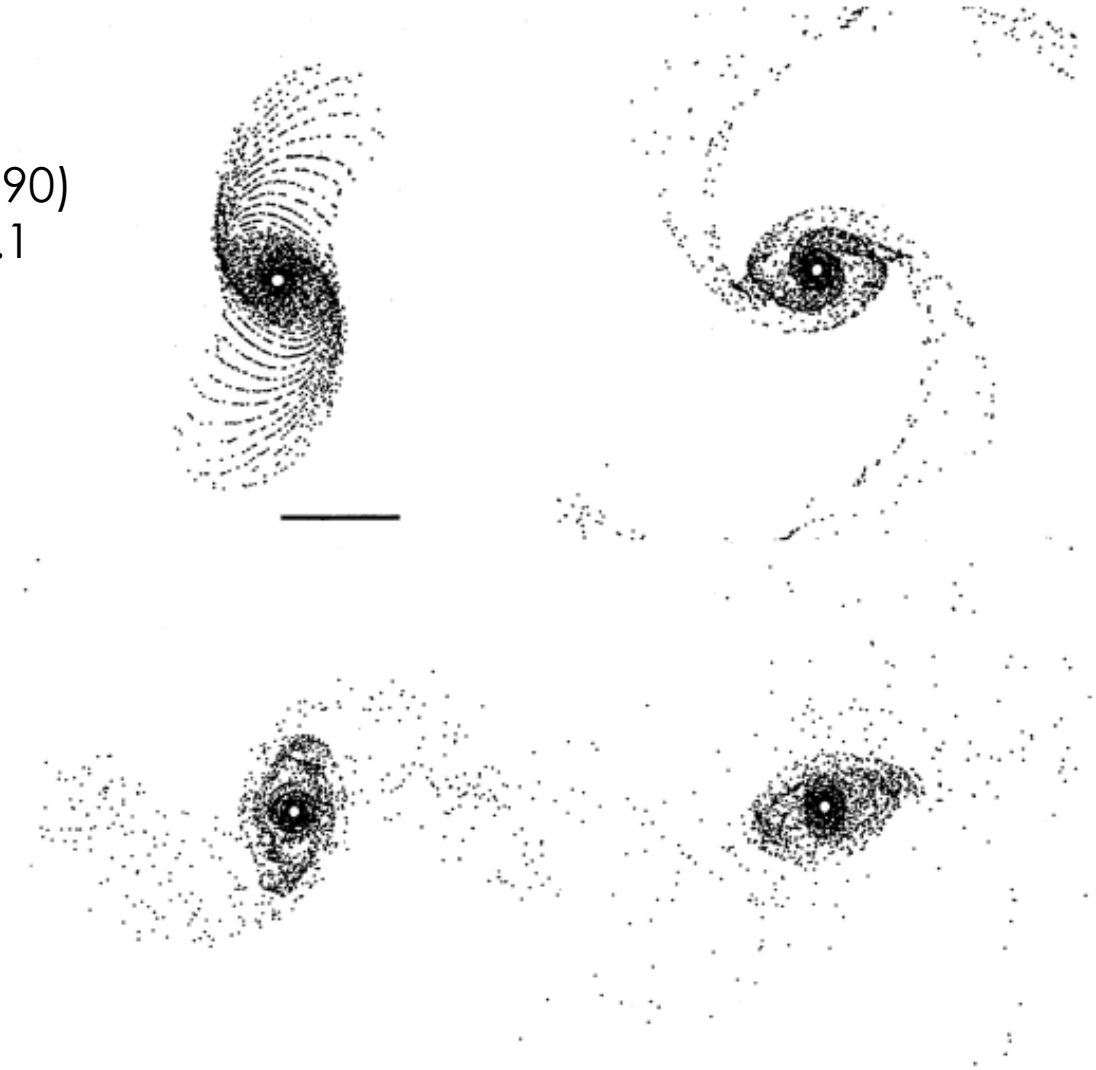
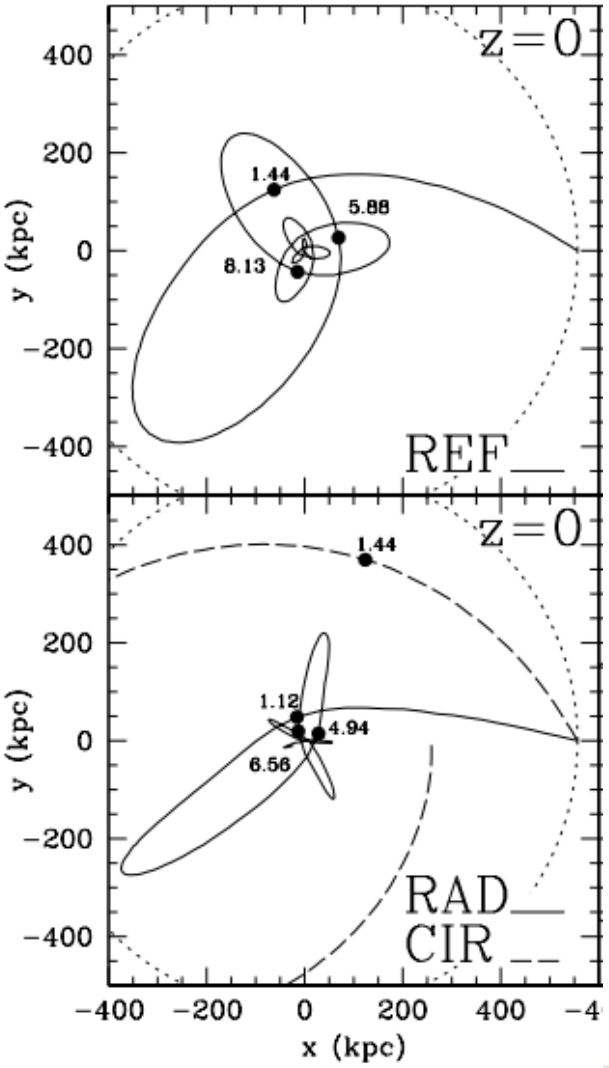
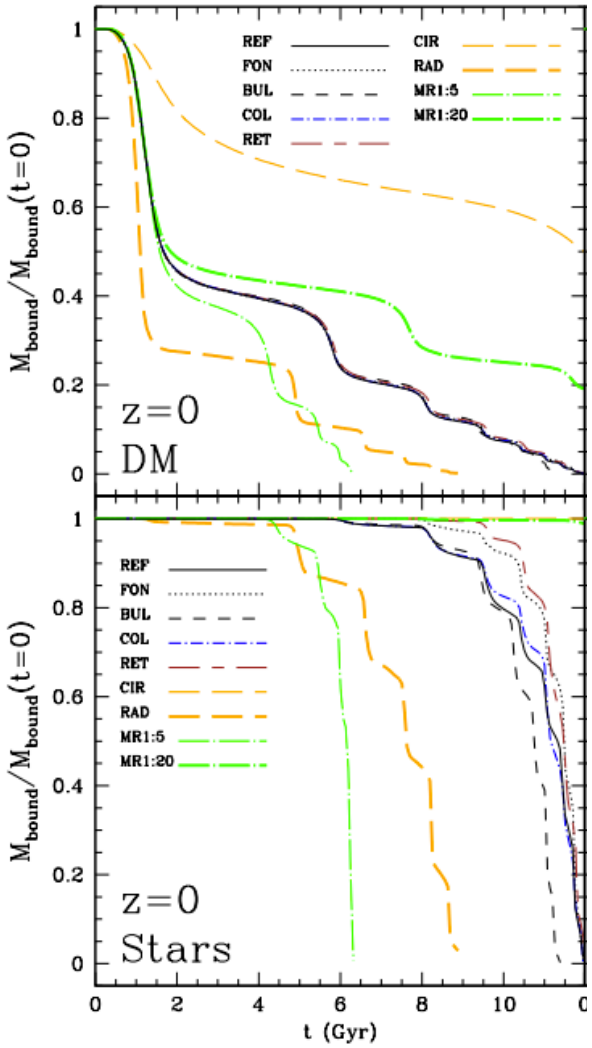
Impact of Cluster Potential

Byrd and Valtonen (1990)
$P = (M_c/M_g)(r_g/r_c)^{-3} = 0.1$



Disk galaxy in a group environment





Disk and gas tidally stripped when:

mean density inside orbit = mean density inside disk

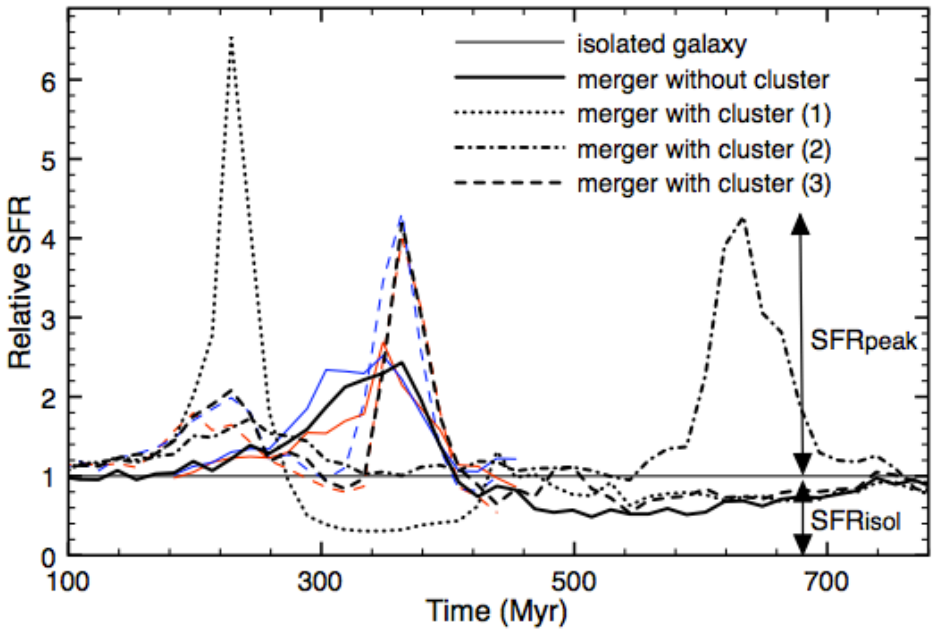
DM halo stripped well before disk

Villalobos et al (2012)

Tidal Effects on merger gas

- Generally mergers in clusters are rare (more common in clusters)
- Martig & Bournaud (2009) modeled galaxy-galaxy merger inside a cluster/ group potential, finding that it could enhance star formation over simple merger.

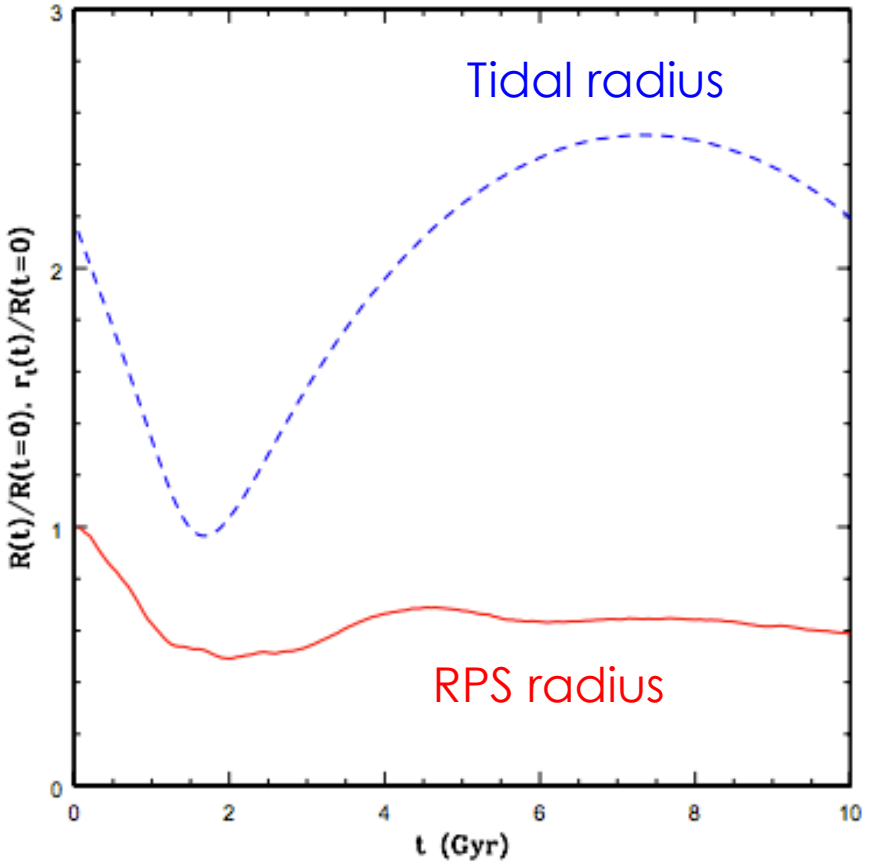
Galaxy merger within a cluster



Martig & Bournaud (2009)

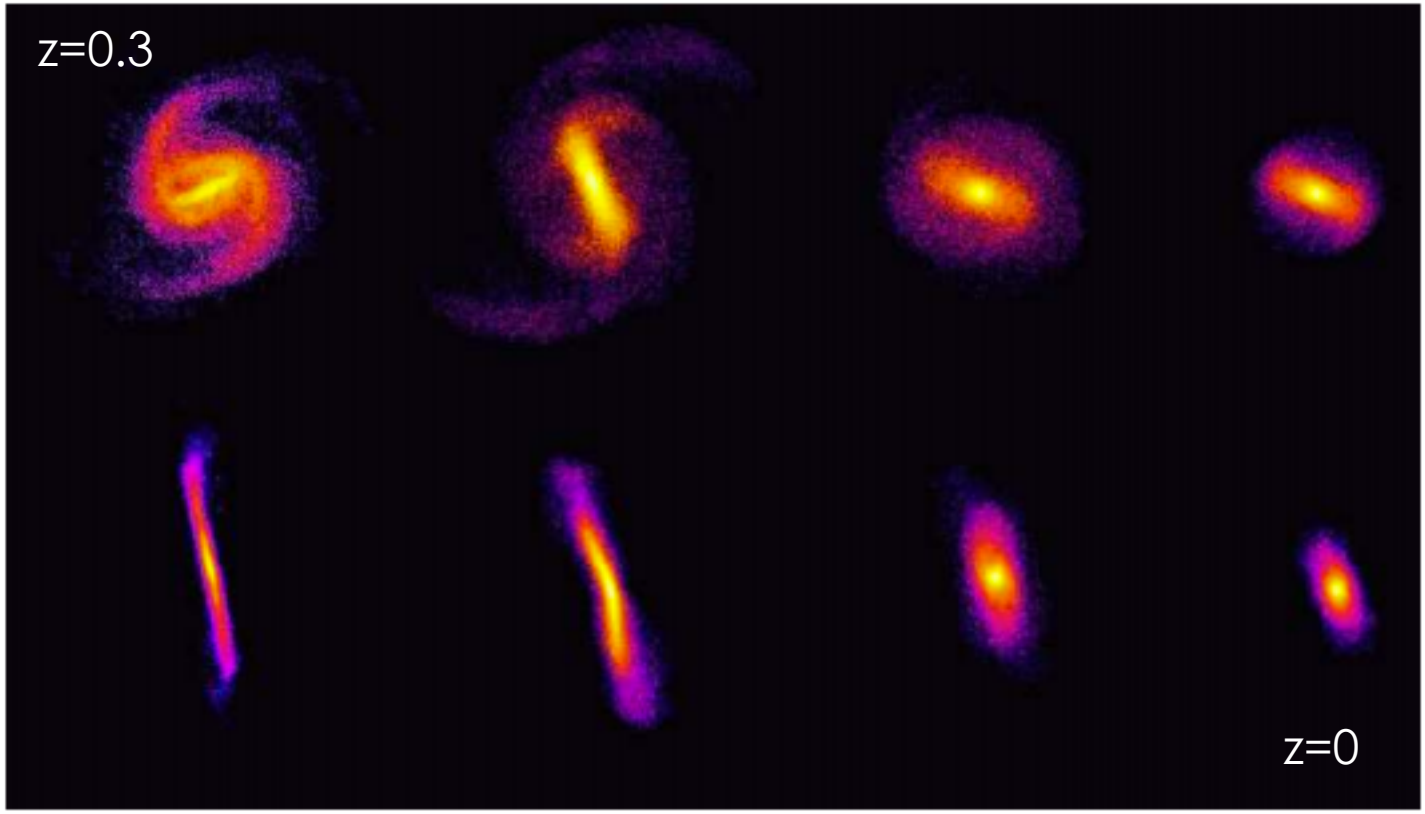
Tidal stripping of halo gas?

- McCarthy et al (2008) found that ram pressure stripping of a galaxy's hot halo was always more effective than tidal stripping



McCarthy et al (2008)

Galaxy-galaxy encounters (Harassment) can transform disks



Mastropietro et al (2004)

Gas Content: Environmental Effects

- Ram pressure stripping of cold, dense gas
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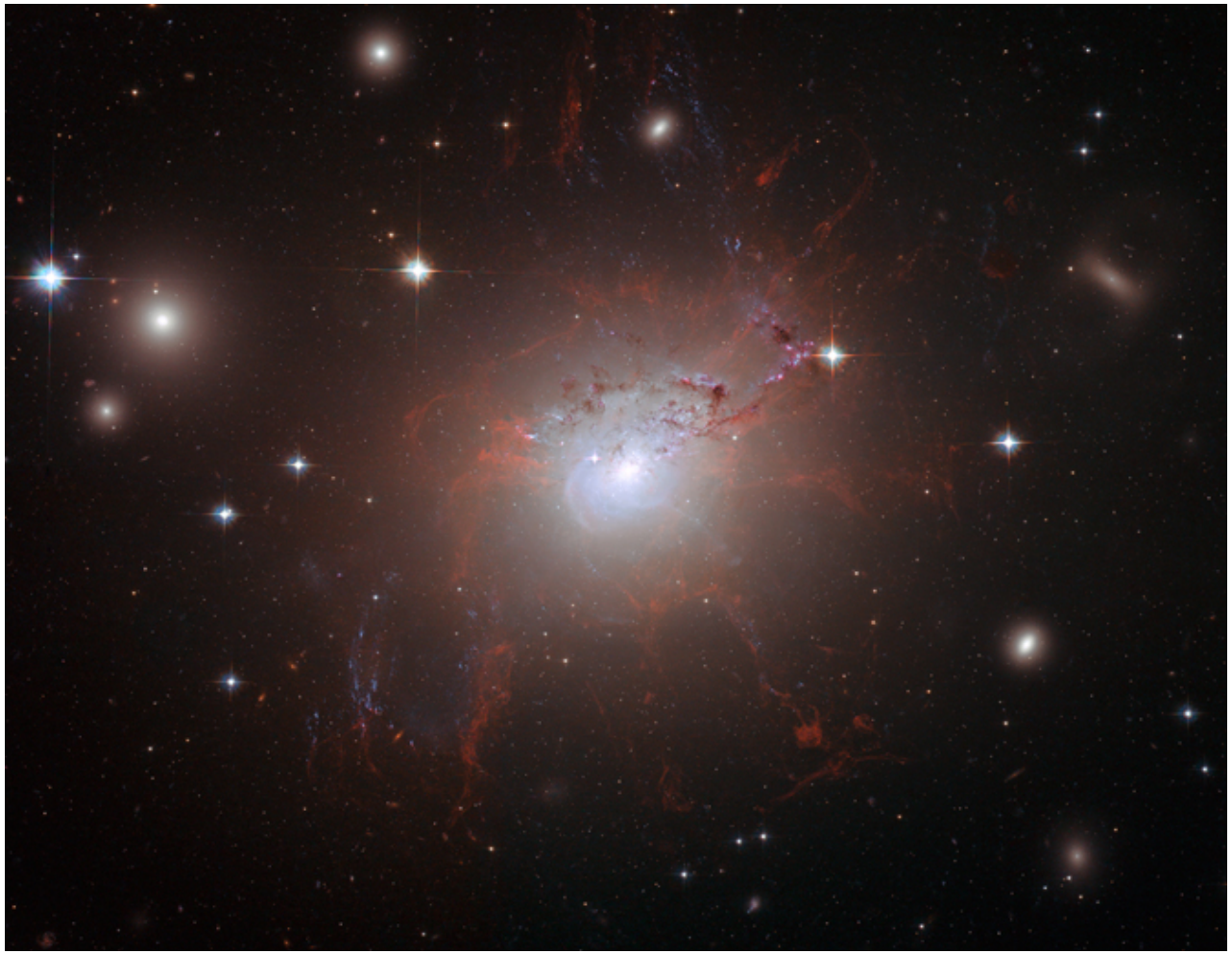
Cooling of hot gas in Clusters

Evidence of cooling and star formation in Cool core clusters

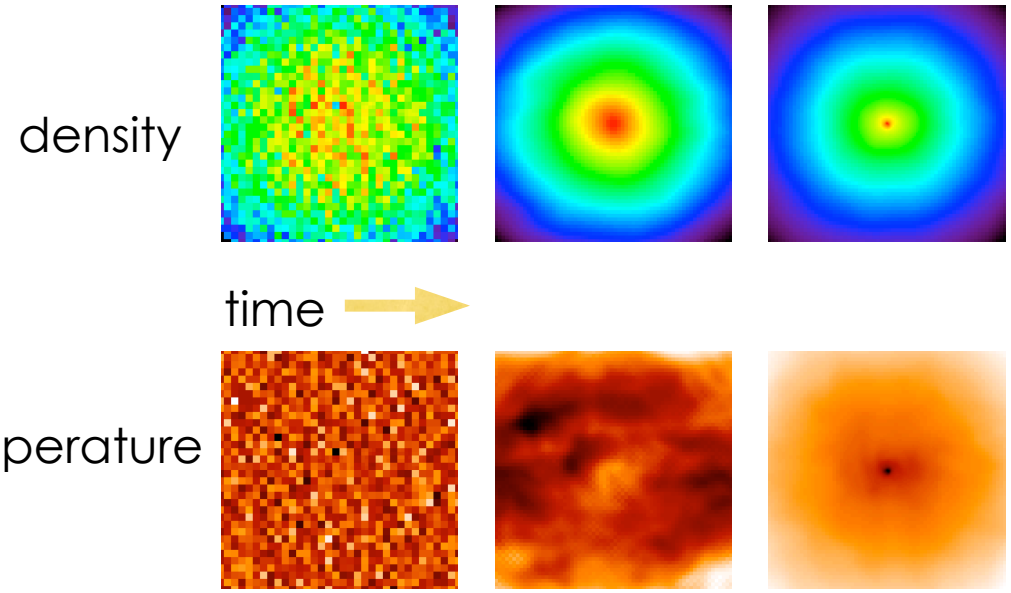


Perseus – credit: NASA/ESA

Static cluster gas is NOT thermally unstable

- Cluster gas is a temperature and density such that it would be thermally unstable if in a uniform medium
- BUT, in a stratified medium, it is not (locally) thermally unstable (Balbus & Soker 1989)

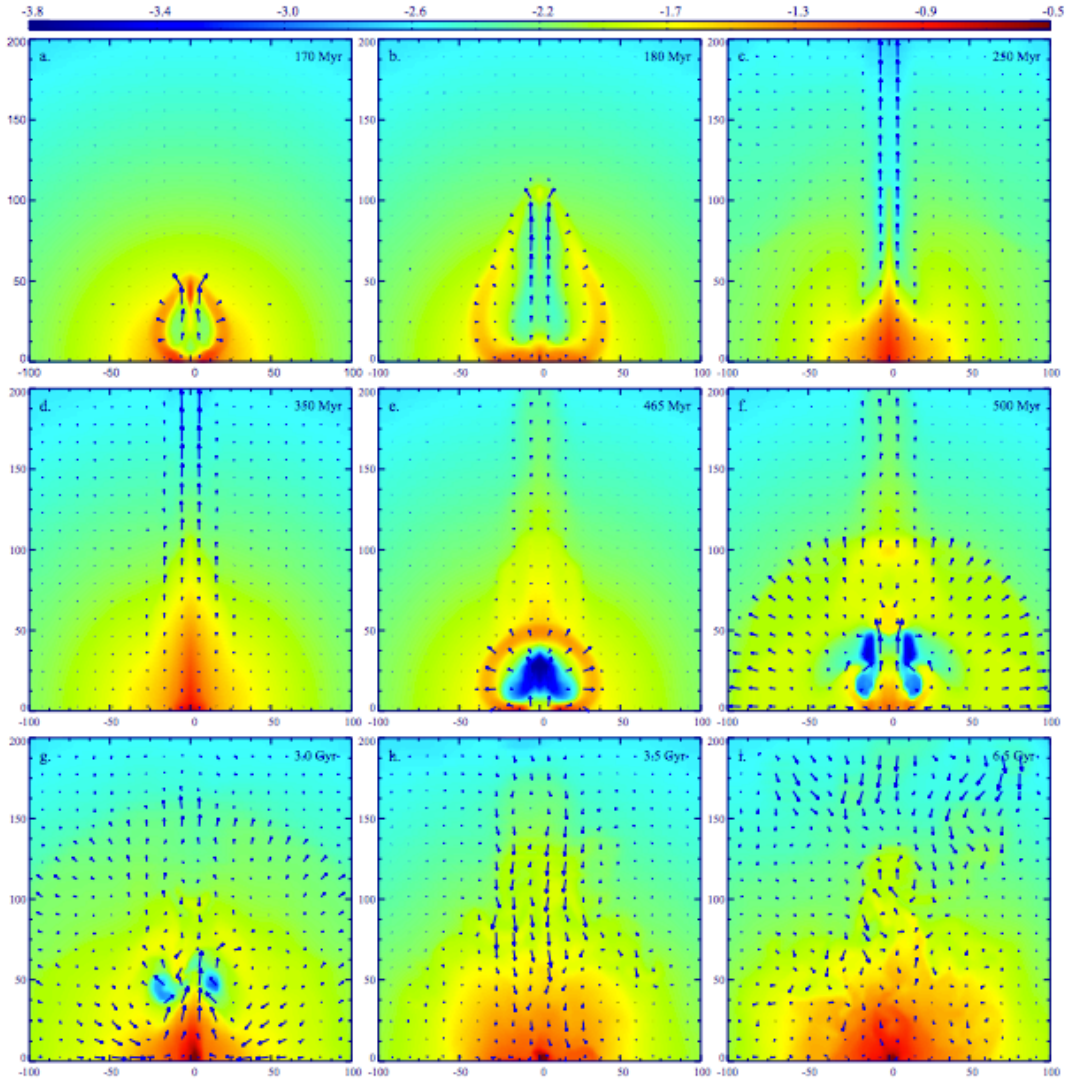
Focus on central 16 kpc of cluster



Li & GB (2012)

However it is globally unstable!
(but gas only cools out in very center)

AGN Feedback can suppress cooling

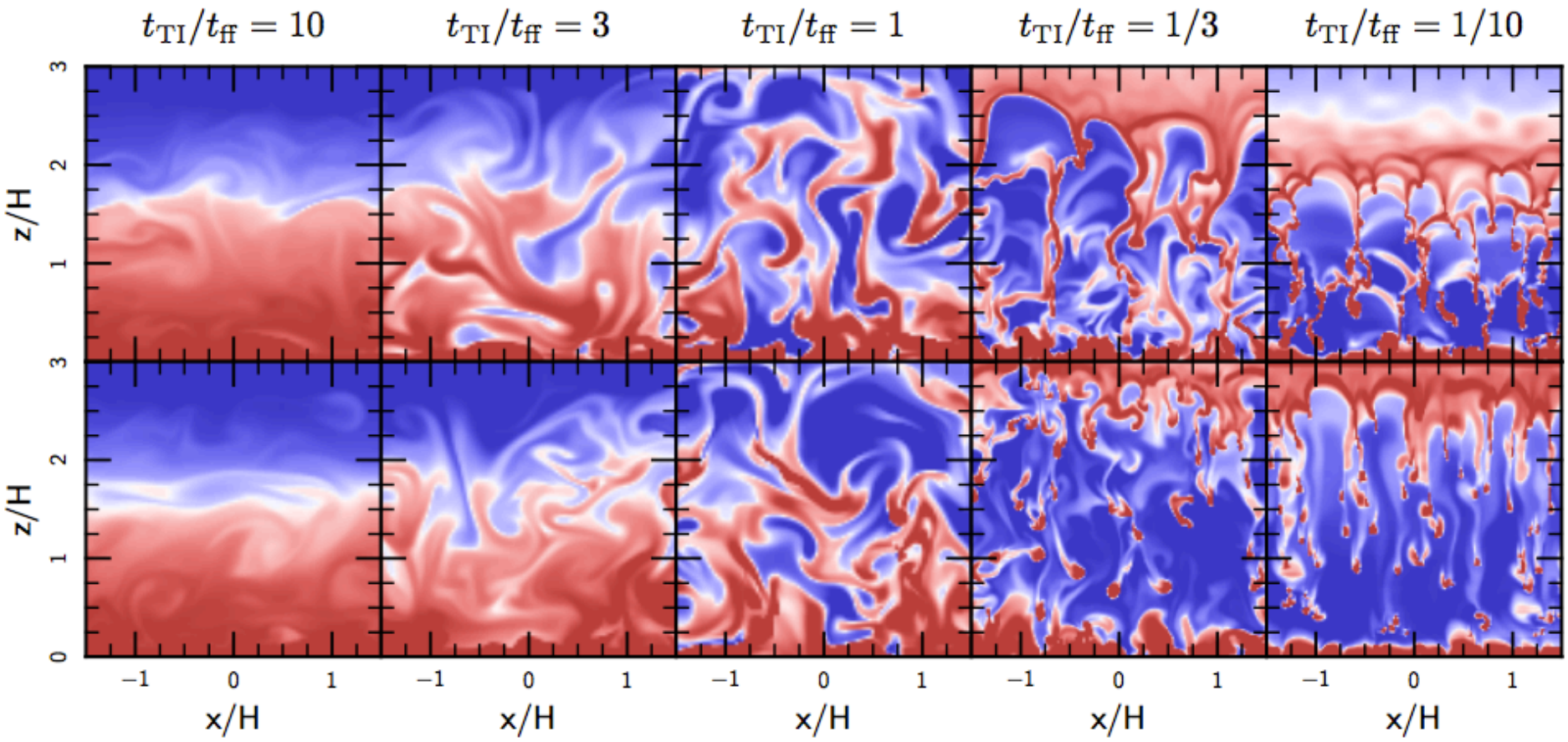


An AGN jet that is triggered when gas cools can limit cooling
(if parameters well chosen)

But no filaments?

Gaspari et al (2012)

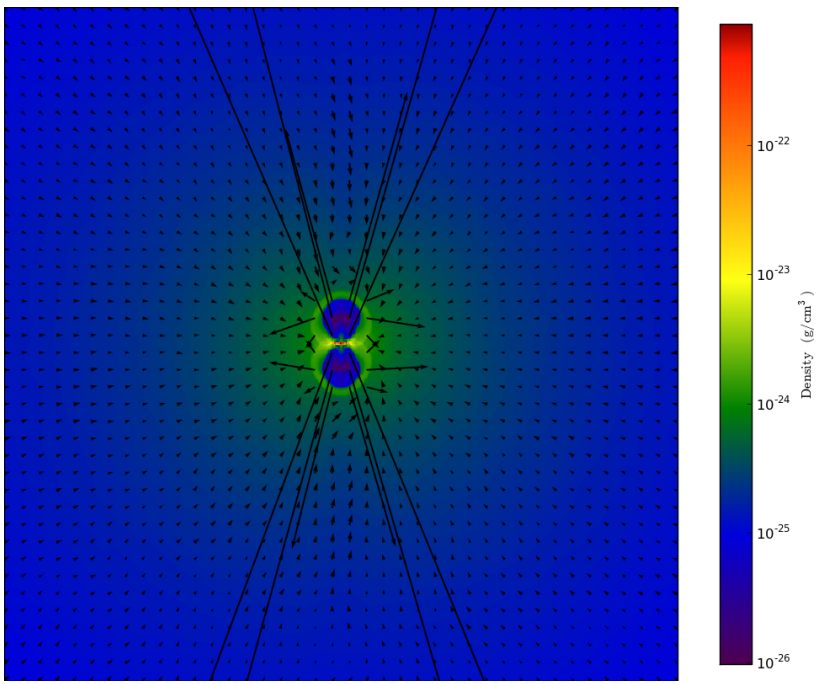
If the gas is heated uniformly, it can be thermally unstable



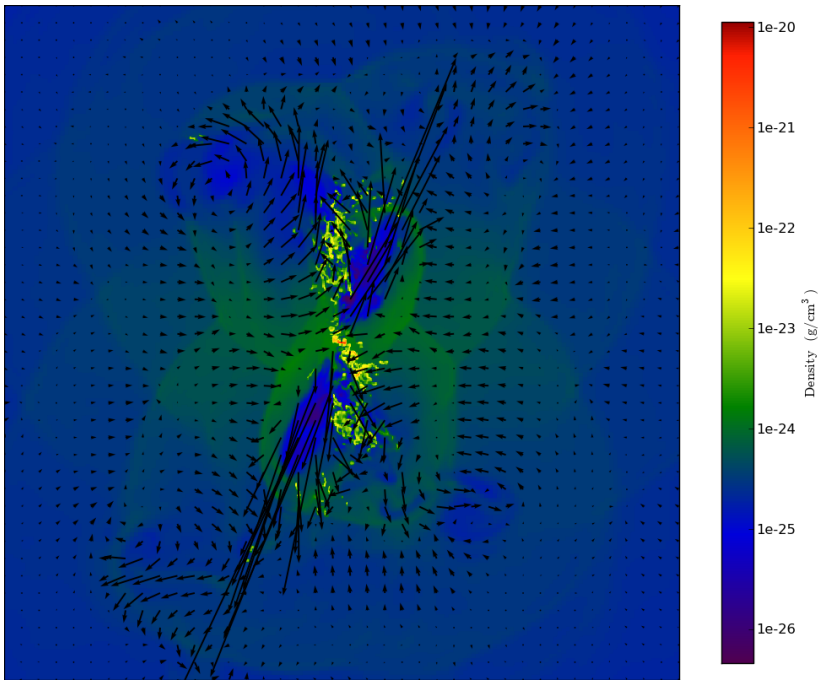
McCourt et al (2012)

If highly resolved, jet heating also can result in thermal instabilities

Density slices (~ 10 pc resolution)



t = 1 Myr



t = 100 Myr

Summary

- Ram pressure stripping of cold, dense gas
- Suppressing accretion ("starvation")
- Tidal stripping, harassment, mergers
- Cooling of hot gas/AGN heating