# Slow Quenching of Satellite Galaxies at the Outskirts of Galaxy Clusters

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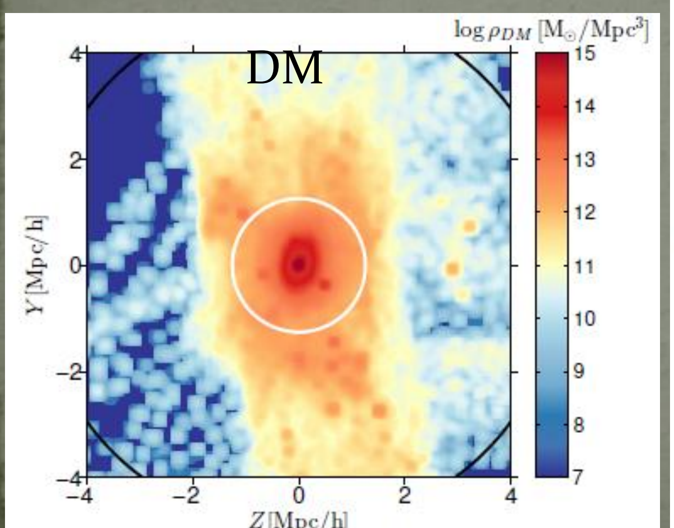
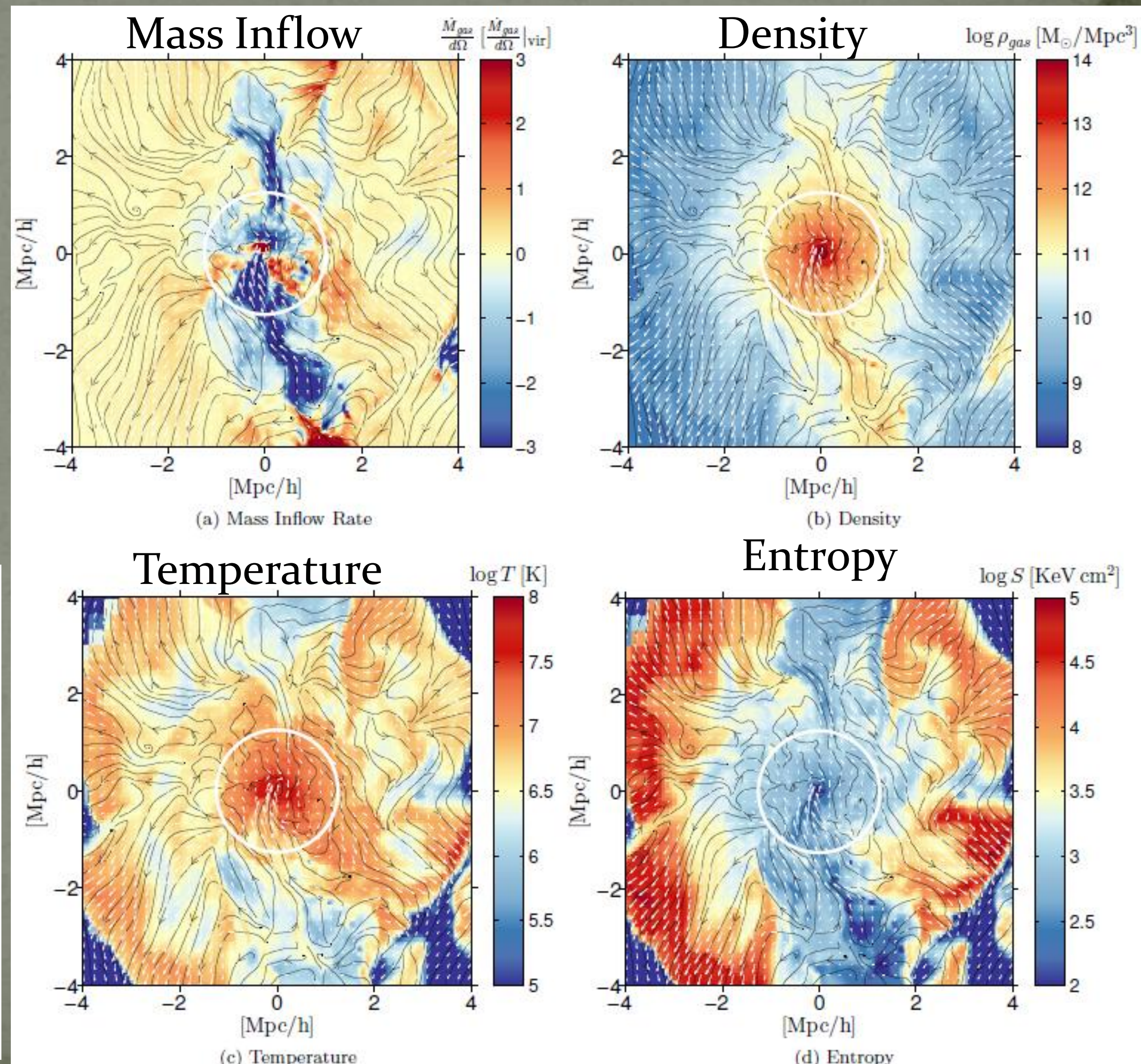
# Prologue: Where have all the Cold Flows Gone?

- They're still there!
- Account for most of the accretion.
- *Not* cooler than their surrounding.




(a) Mass Inflow Rate
(b) Density
(c) Temperature
(d) Entropy

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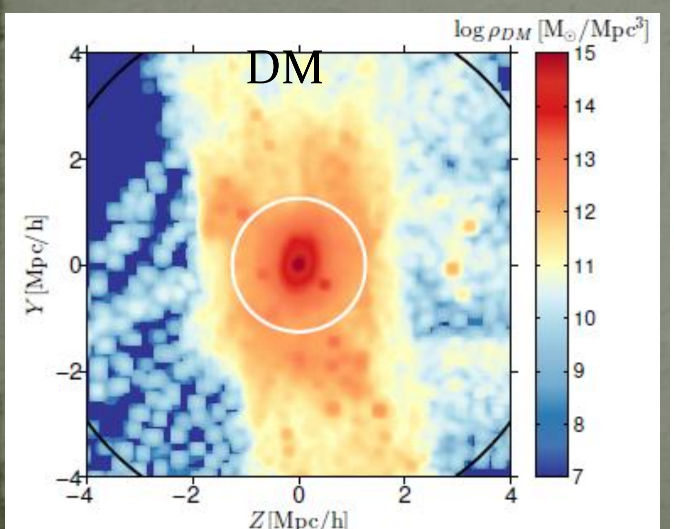
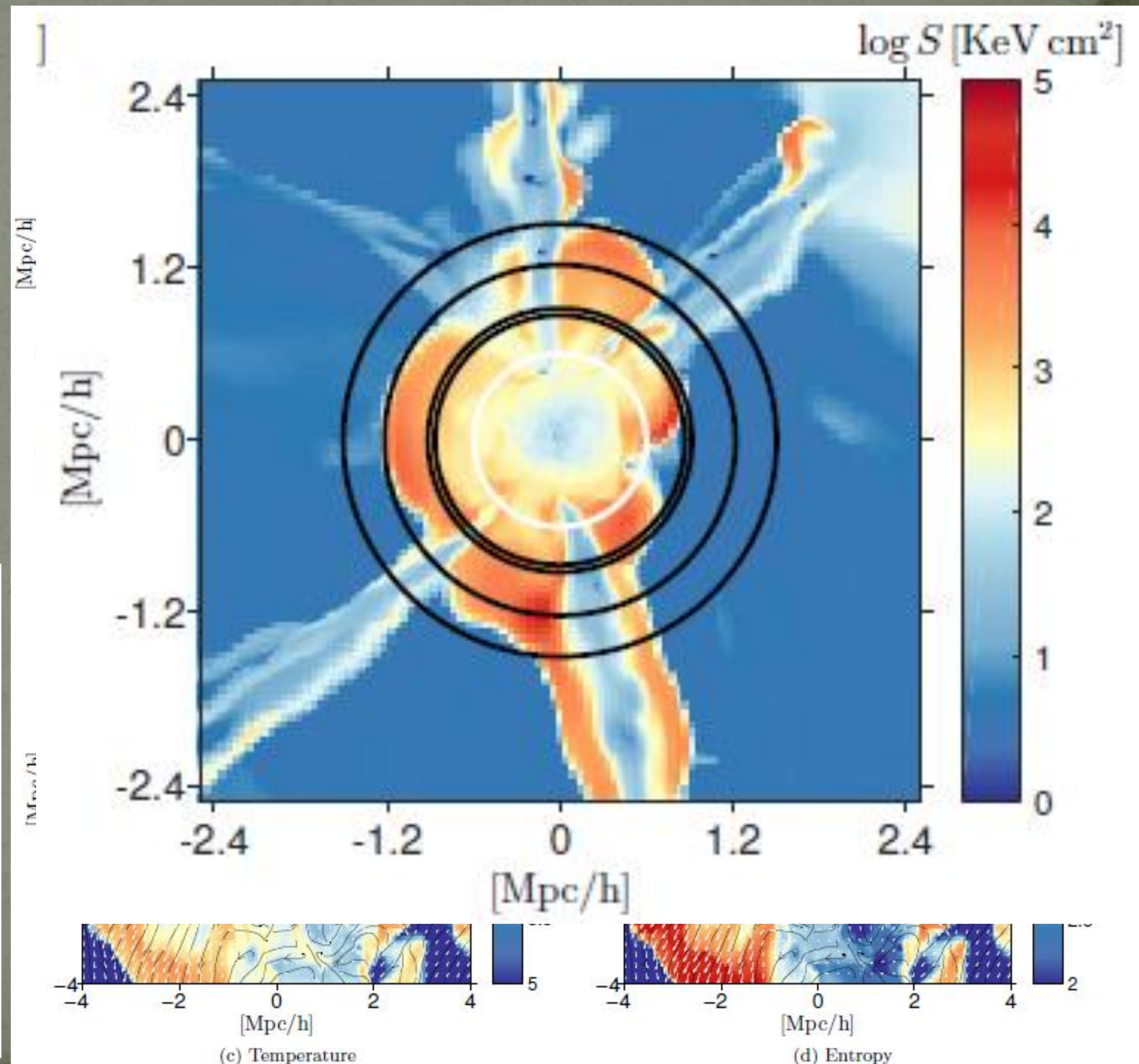
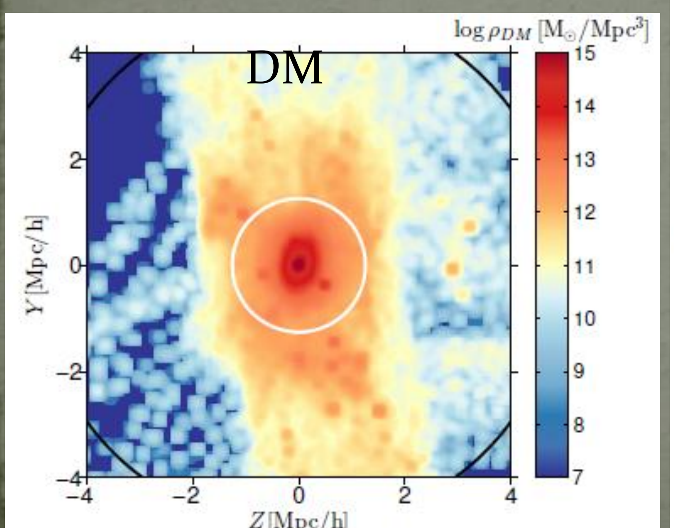


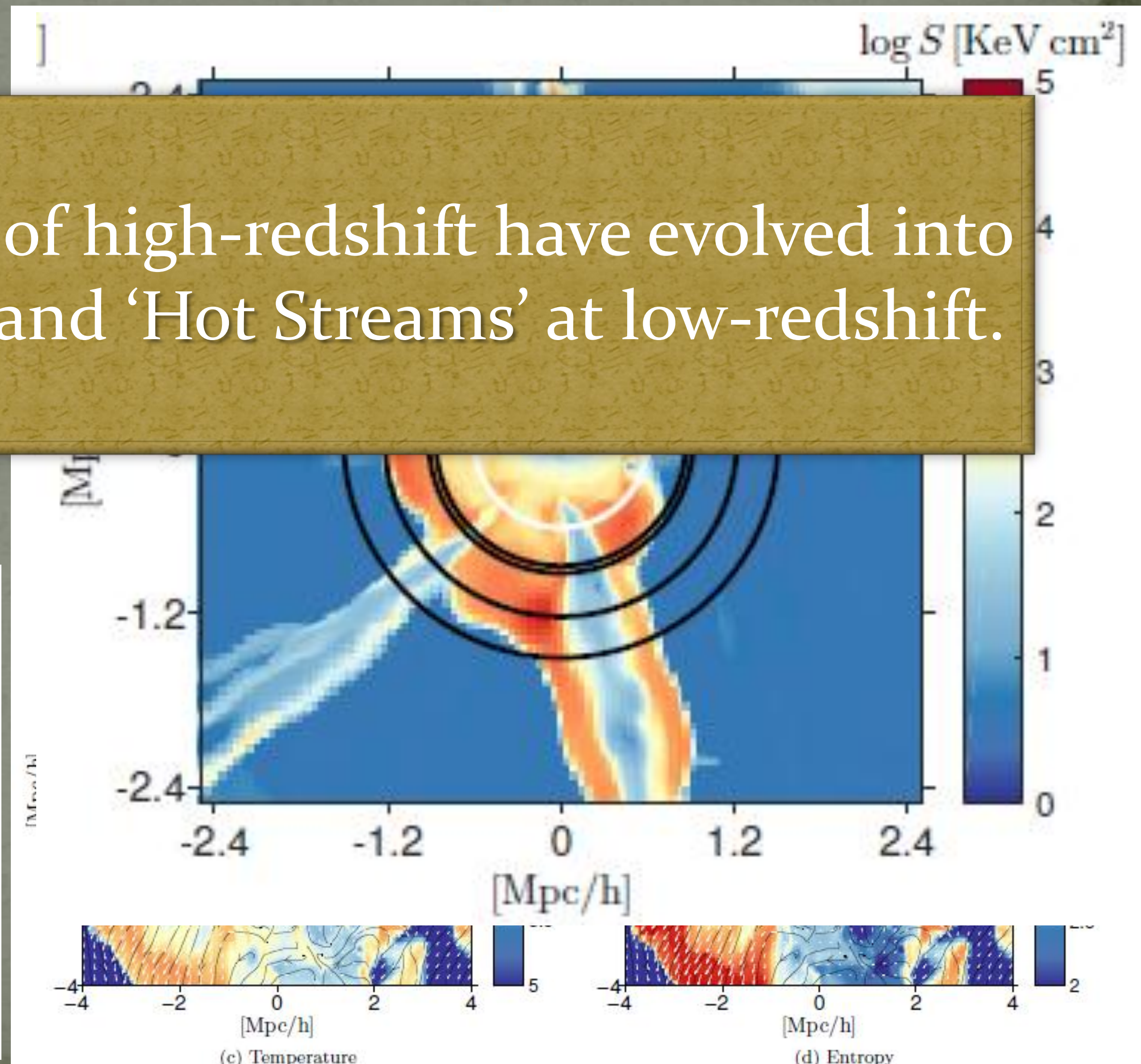



# Prologue: Where have all the Cold Flows Gone?

- They're still there!

The 'Cold Flows' of high-redshift have evolved into 'Warm Streams' and 'Hot Streams' at low-redshift.



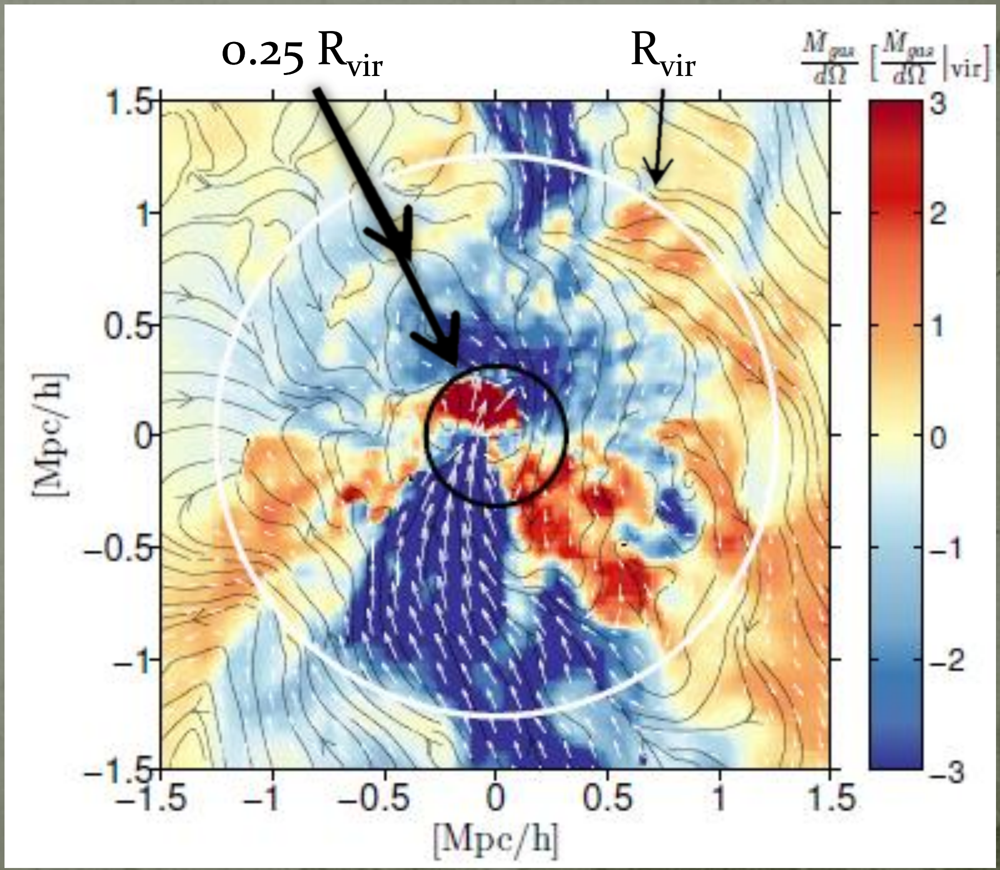



# Penetration Depth of Streams

- Streams can penetrate all the way to the center:

Zinger+, in prep.

- But not always.




End of Prologue

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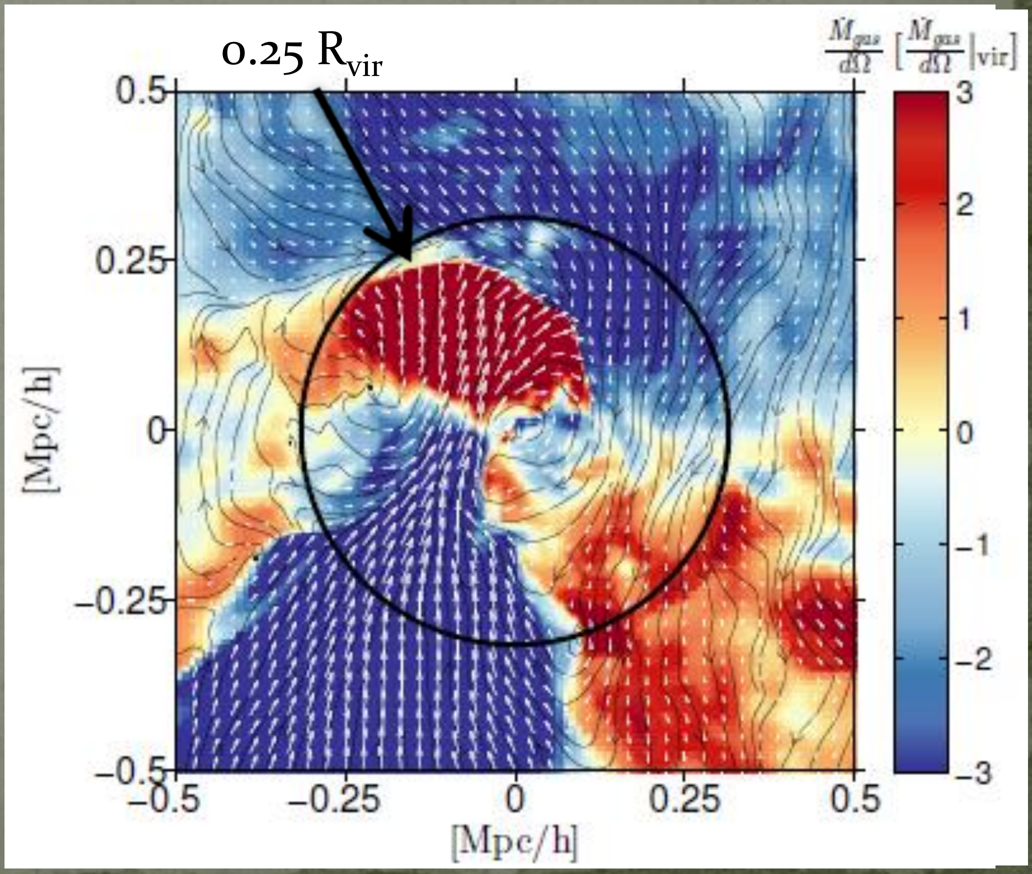



End of Prologue

# Slow Quenching of Satellite Galaxies at the Outskirts of Galaxy Clusters

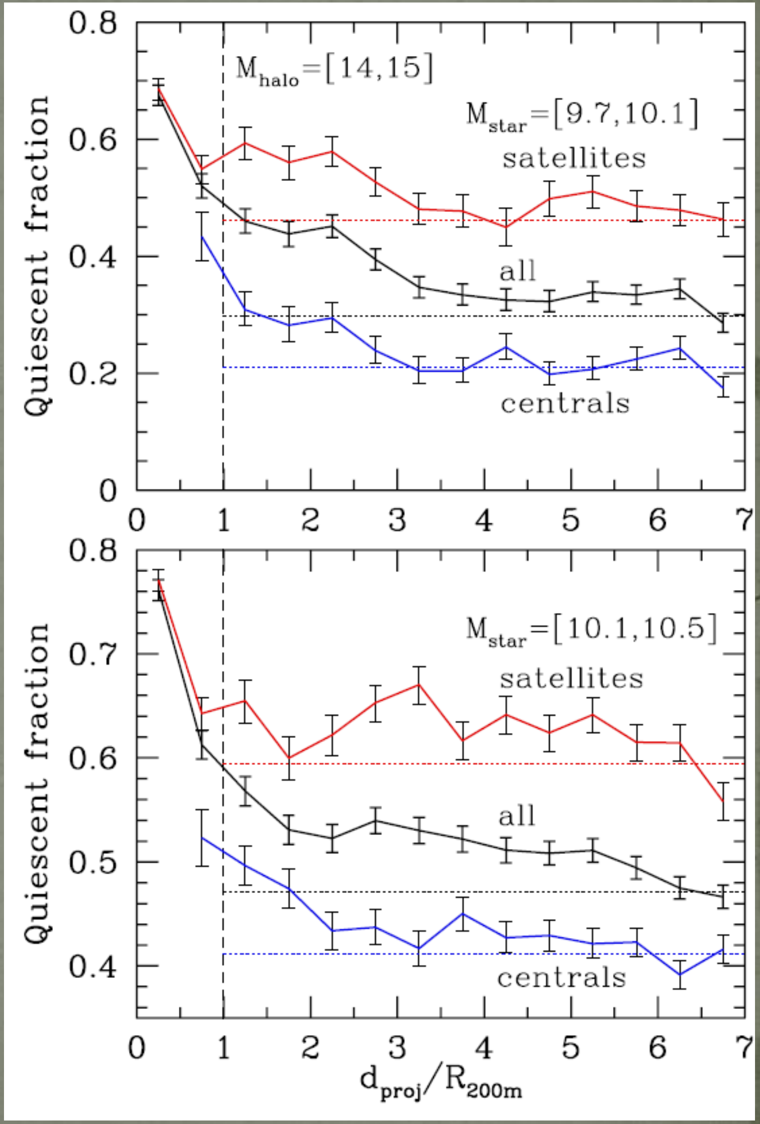
What do you mean when you say ‘outskirts’?

Zinger+, in prep.

# Motivation

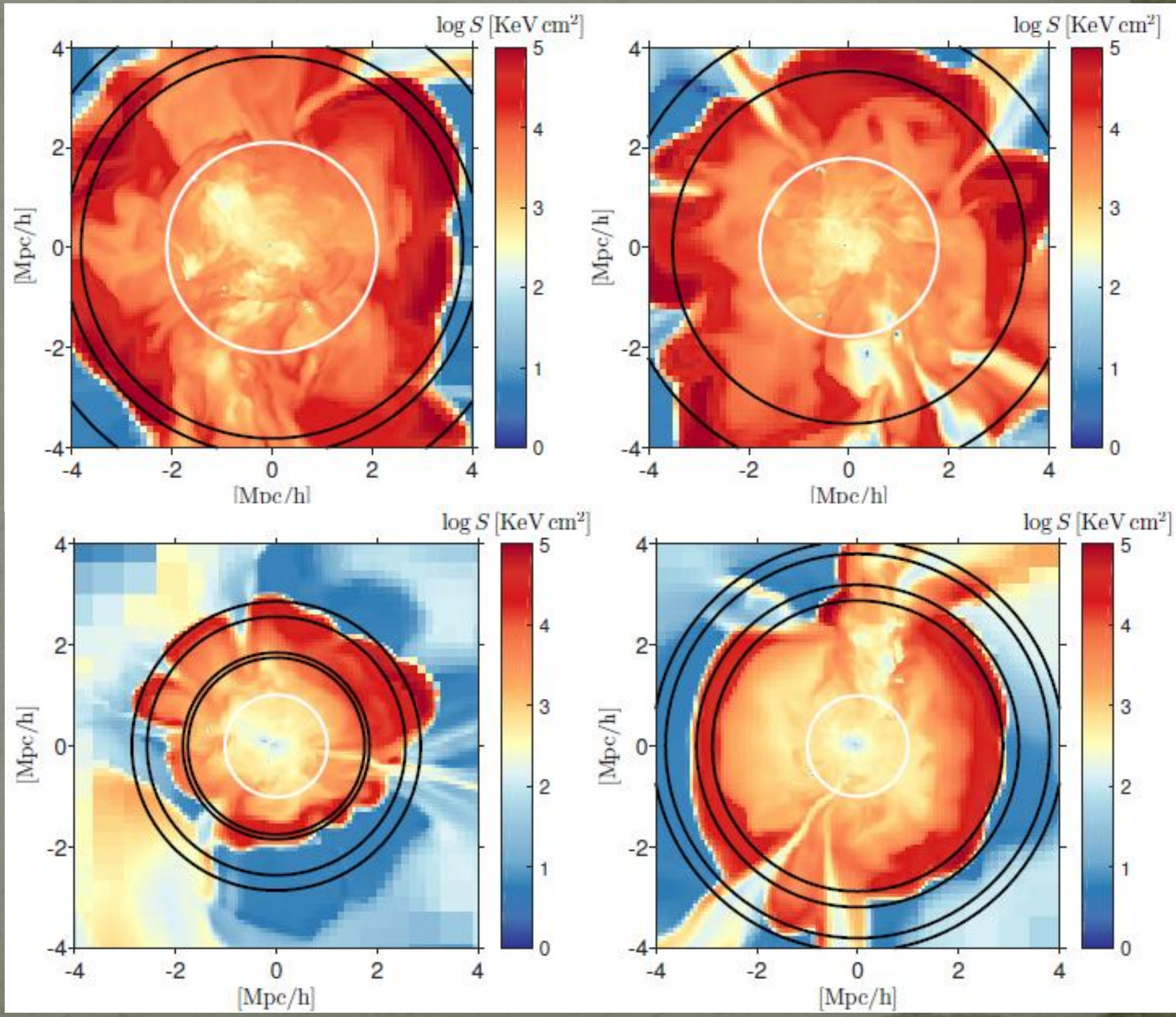
Wetzel+ 2014

- Galaxies in clusters are more likely to be quenched, and contain less gas than galaxies in the field.
- This relation extends beyond the virial radius of clusters, to distances of several times $R_{vir}$.
- Suggested solutions:
  - Pre-processing.
  - Splashback galaxies.
- Another solution: cluster influence extends beyond $R_{vir}$.



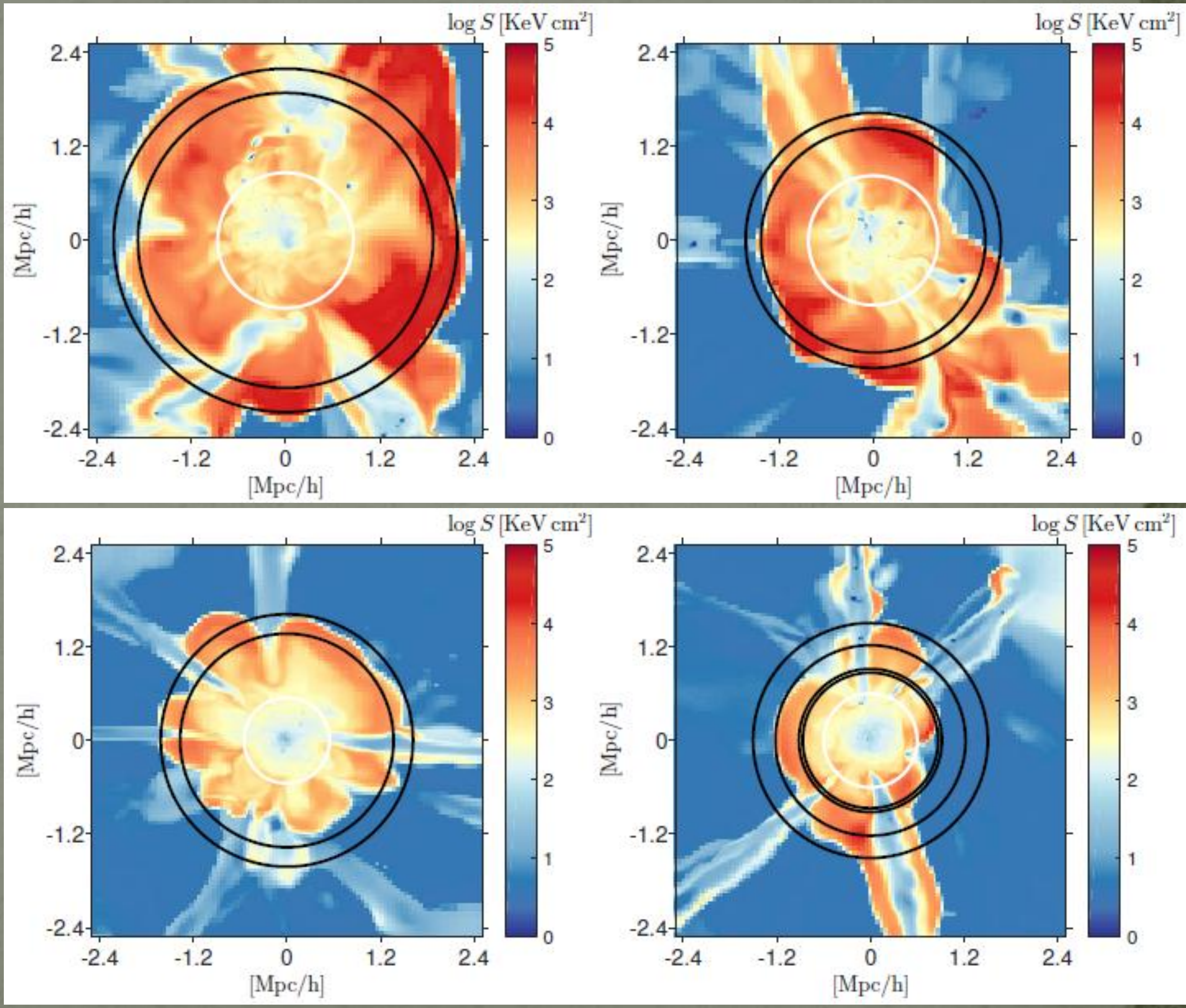
# Virial Shock Extends to >$2R_{vir}$

- Shocks are only 'kinda' spherical



# Virial Shock Extends to >2$R_{vir}$

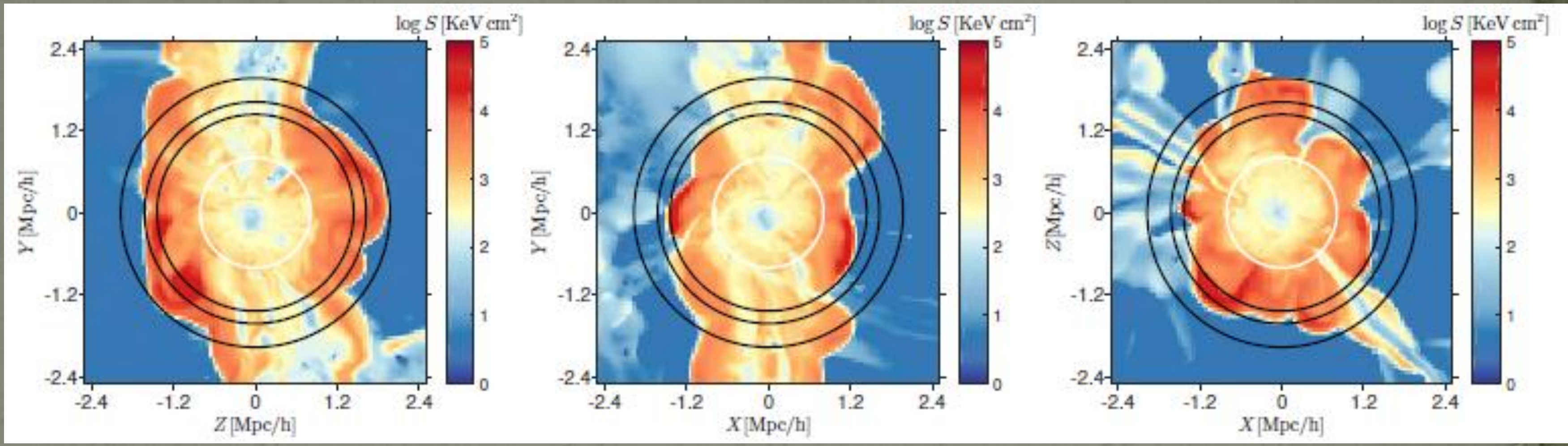
- Shocks are only 'kinda' spherical
- Shock extends beyond $R_{vir}$ as early as z=0.6
- Shocks found around halos & filaments



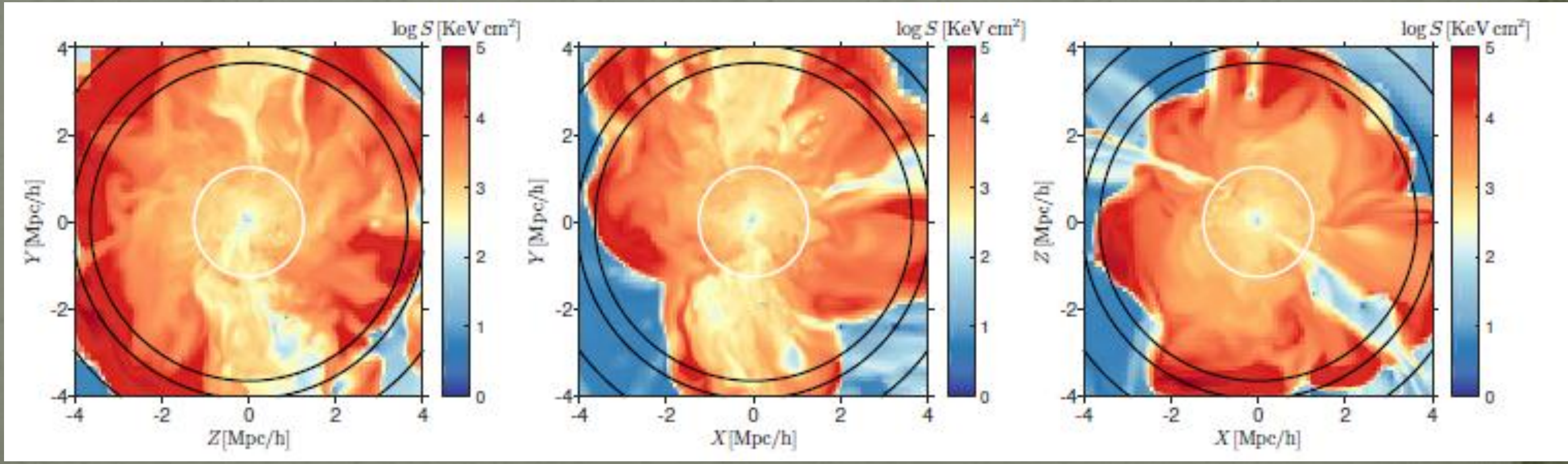

See also:
Keshet et. al 2012

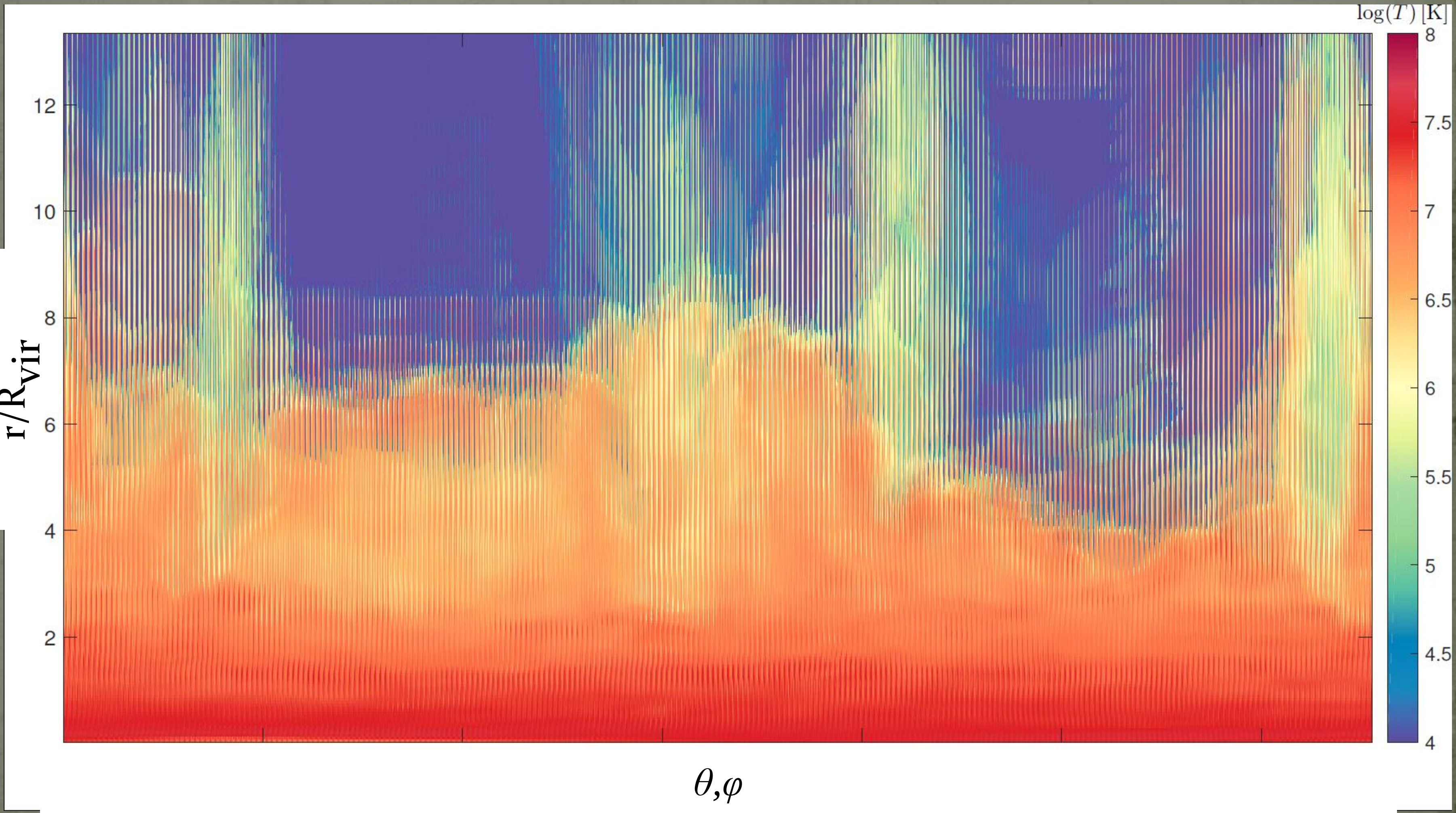
# Virial Shock Extends to $>2R_{vir}$

z=0.6




z=0

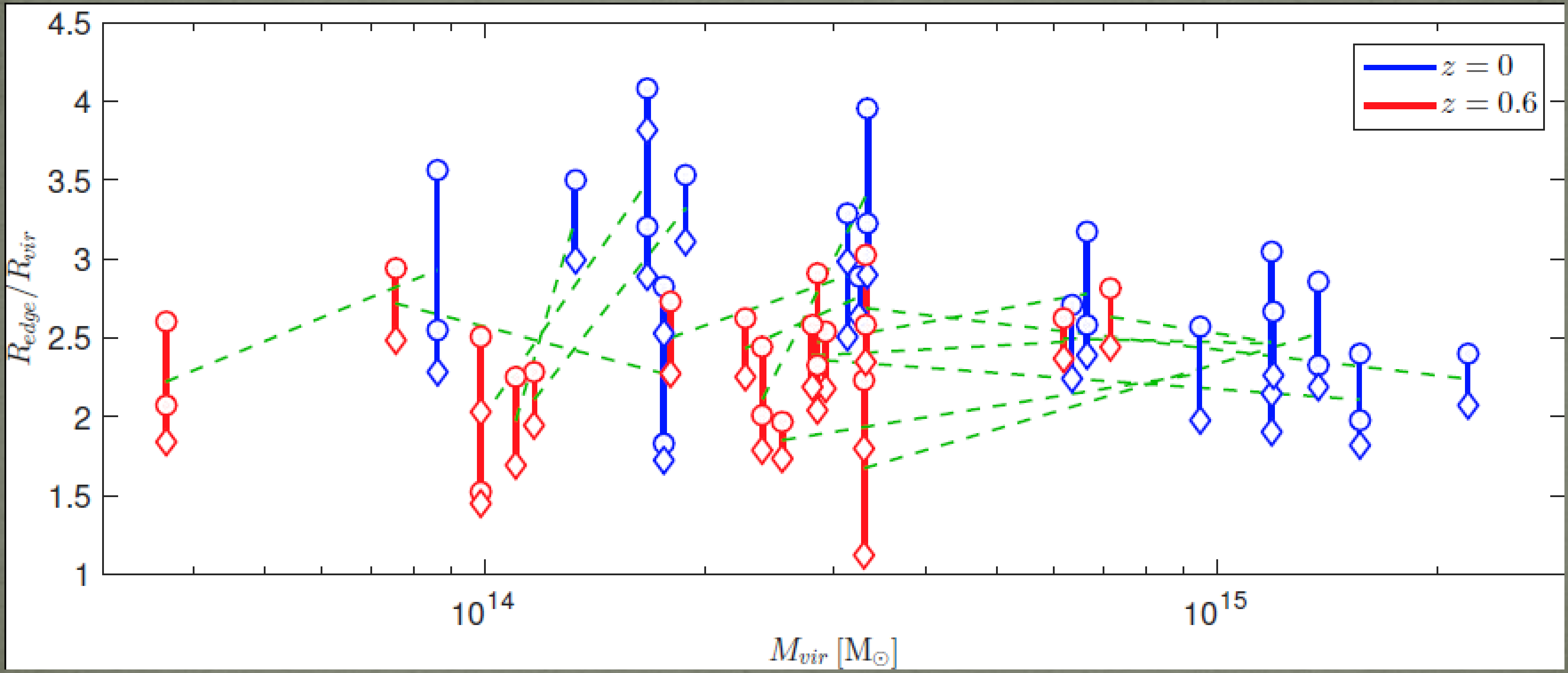




log(T) [K]
8
7.5
7
6.5
6
5.5
5
4.5
4
12
10
8
6
4
2
r/R_vir
θ,φ

# Finding the Shock Edge

- Shock radius between 2-4Rvir
- No clear trend with redshift for a given cluster



# SF Quenching Beyond $R_{vir}$

- Important Distinction:
  - Galaxy stripping: removal of cold gas within the galaxy, results in almost immediate quenching .
  - Starvation/Strangulation: removal of hot gas reservoir. Star formation can continue until cold gas is consumed.
- Possible mechanisms:
  - Ram-Pressure Stripping $P_{ram} = \rho_{ICM} \left( \vec{v}_{sat} - \vec{v}_{ICM} \right)^2$
  - Tidal Stripping – Strong radial dependence
  - Thermal Evaporation ($\propto T^{3/2}$ )

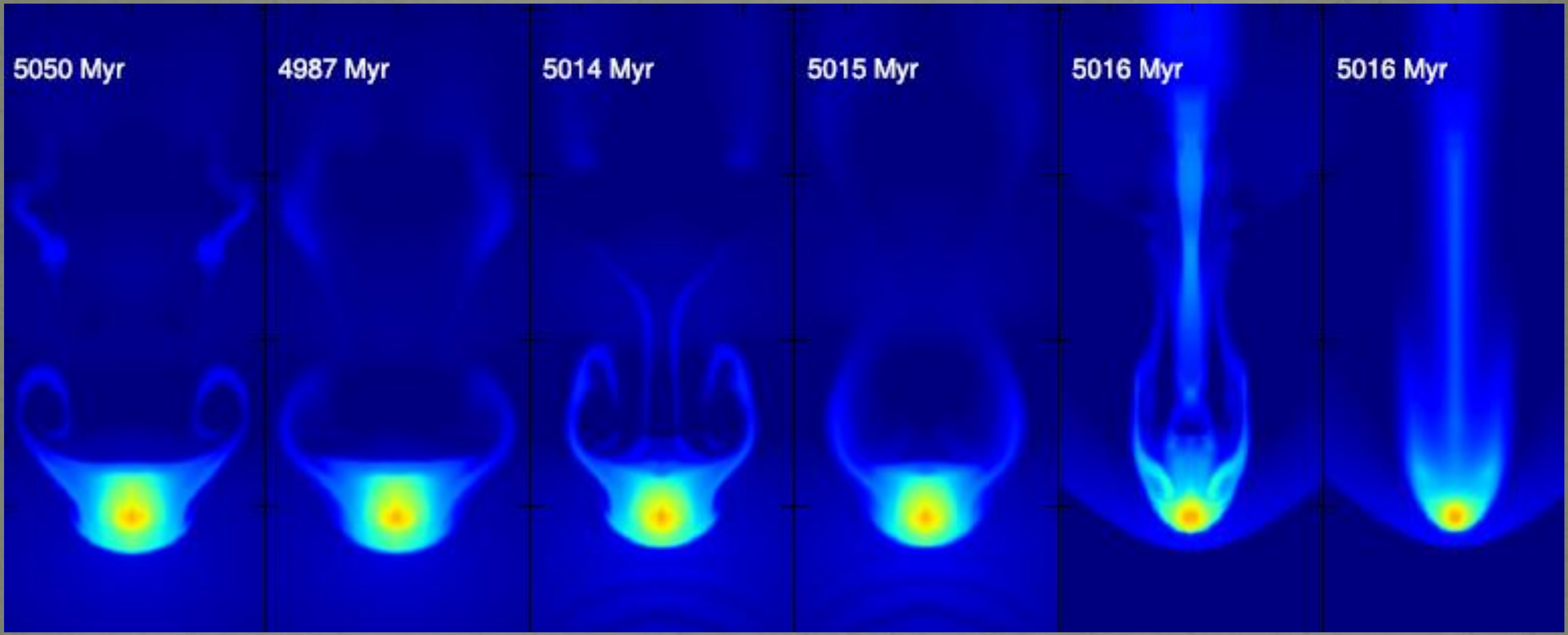
# Can Quenching Occur Beyond $R_{vir}$?

Our Method:

- Ram Pressure Stripping is dominant mechanism.
- Address starvation and galaxy stripping separately.
- Use analytical Toy-Models.
- Employ Toy-models using our simulations

# I. Stripping the Gas Halo

Close+ 2013



# I. Stripping the Gas Halo

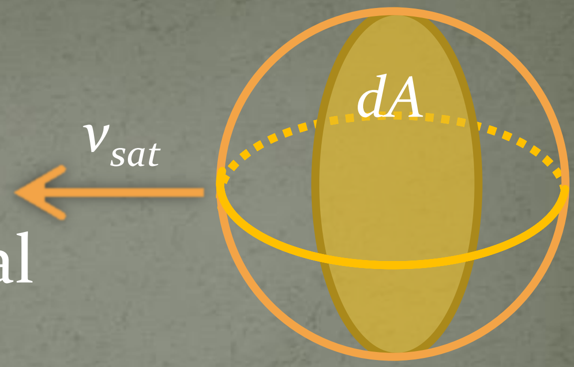
- Model assumptions:
  - The ICM is modeled as an Isothermal sphere.
  - Halos of satellites are also Isothermal spheres.
  - Satellites travel at $V_{vir}$ of the cluster.
  - The ICM is at rest (on average).
  - Stripping is instantaneous.
- Ram-pressure is compared to the gravitational binding force and a stripping radius can be defined.

$$\rho \propto r^{-2}$$

$$v_{sat} = \sqrt{\frac{GM_C}{R_C}}$$

$$\mathrm{P}_{ram}(r_p) = \frac{F_{grav}}{dA} \Rightarrow \ell_{strip}(r_p) \Rightarrow m_{strip}(r_p)$$

# Gravitational Binding




- Several ways to assess the gravitational binding force $F_{grav}/dA$:
  - Spherical shells
  - Cylindrical tube
  - Use pressure as proxy (hydro-static approximation)

- All these methods result in

Fudge Factor

$$\frac{F_{grav}}{dA} = \epsilon \frac{GM_{sat}(\ell)\rho_{sat}(\ell)}{\ell}, \quad \epsilon \sim O(1)$$

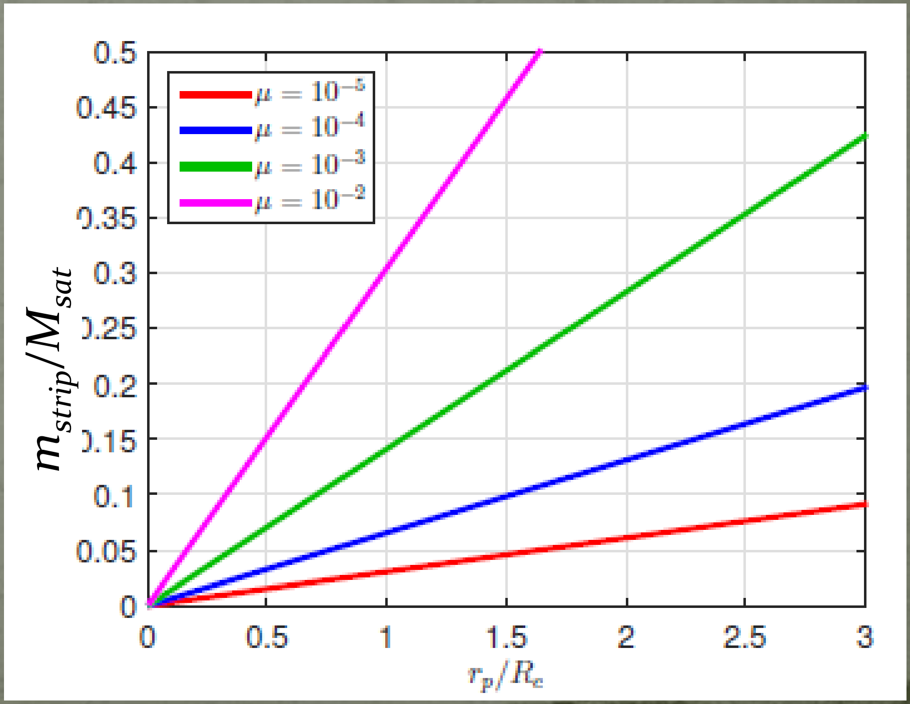
# Gas Halo Stripping

- Comparing the ram-pressure to the gravitational binding results in

$$\frac{m_{strip}}{M_{sat}} \simeq 0.05\left(\frac{\epsilon}{0.5}\right)^{-\frac{1}{2}}\left(\frac{M_{sat}}{10^{11}}\right)^{\frac{1}{3}}\left(\frac{M_C}{10^{15}}\right)^{-\frac{1}{3}}\frac{r_p}{R_C}$$

- Very efficient stripping

$$\mu = \frac{M_{sat}}{M_C}$$



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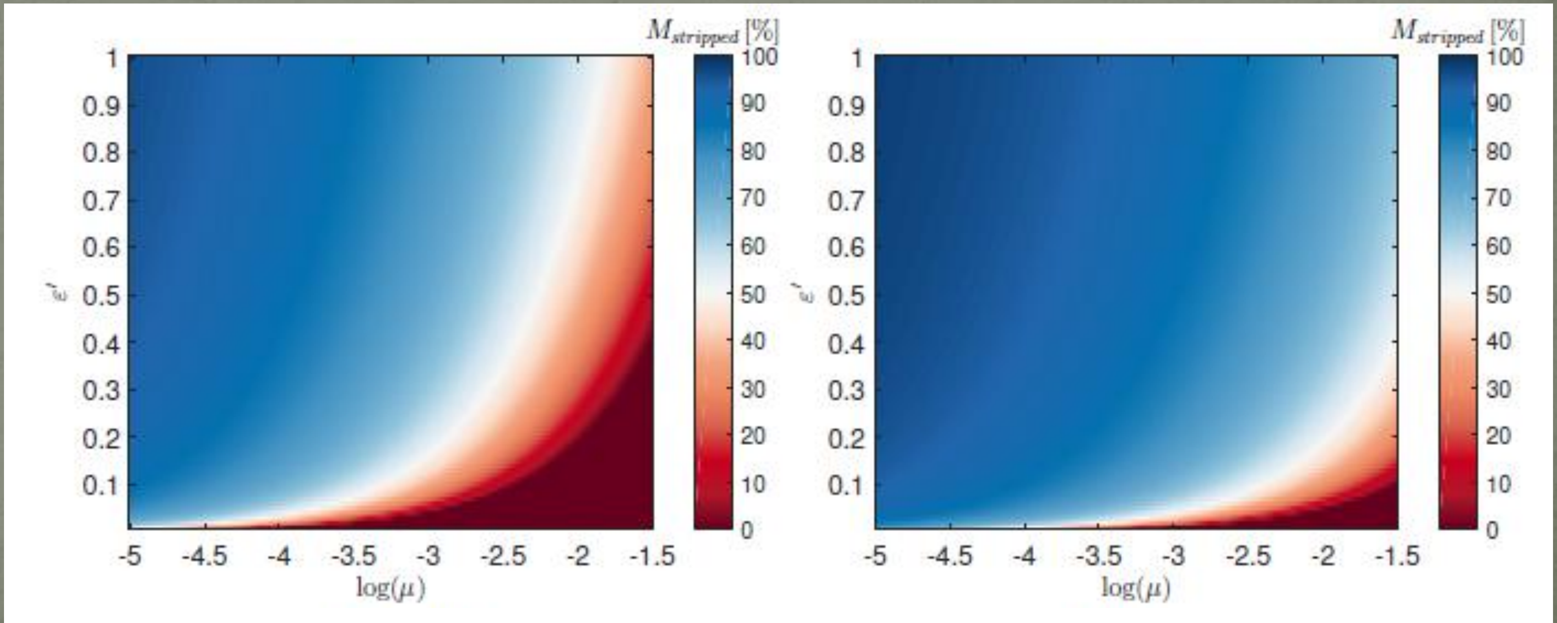
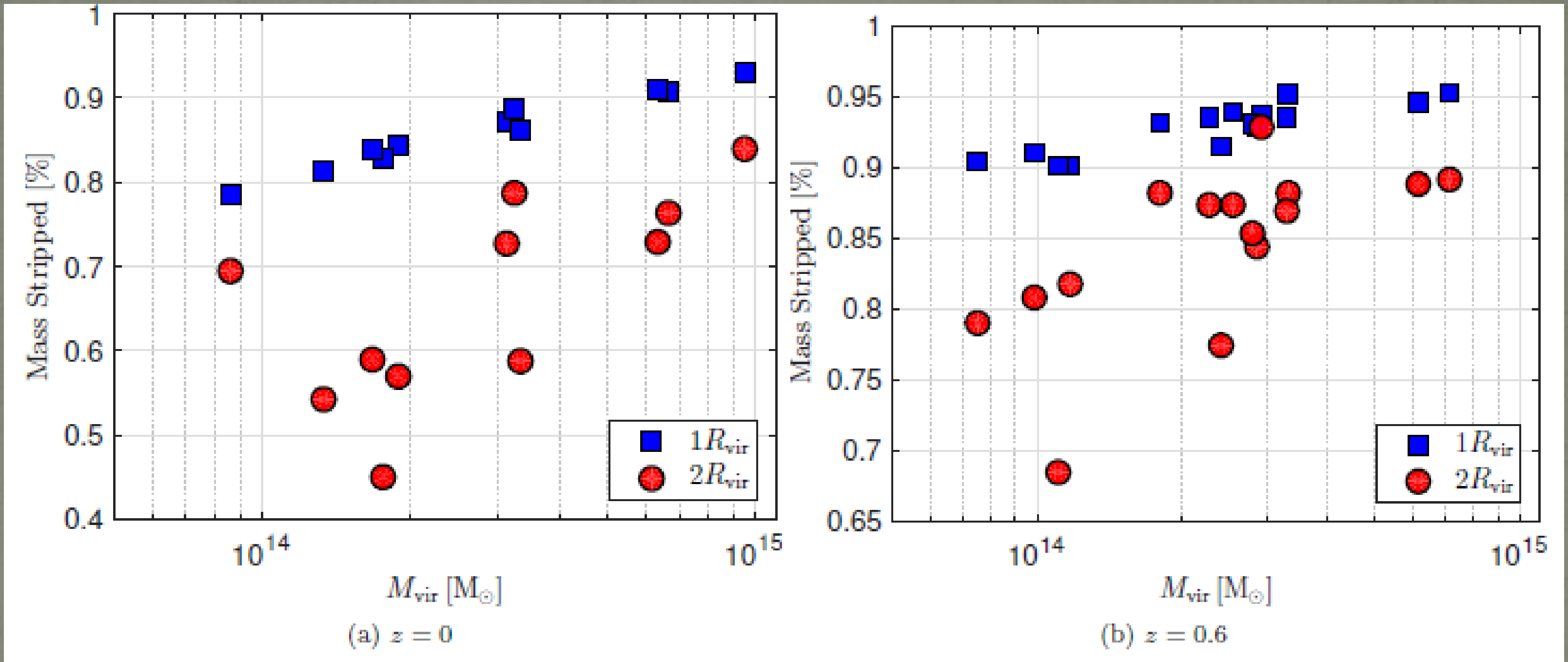



$r_p$=2 $R_{vir}$ $r_p$=1 $R_{vir}$

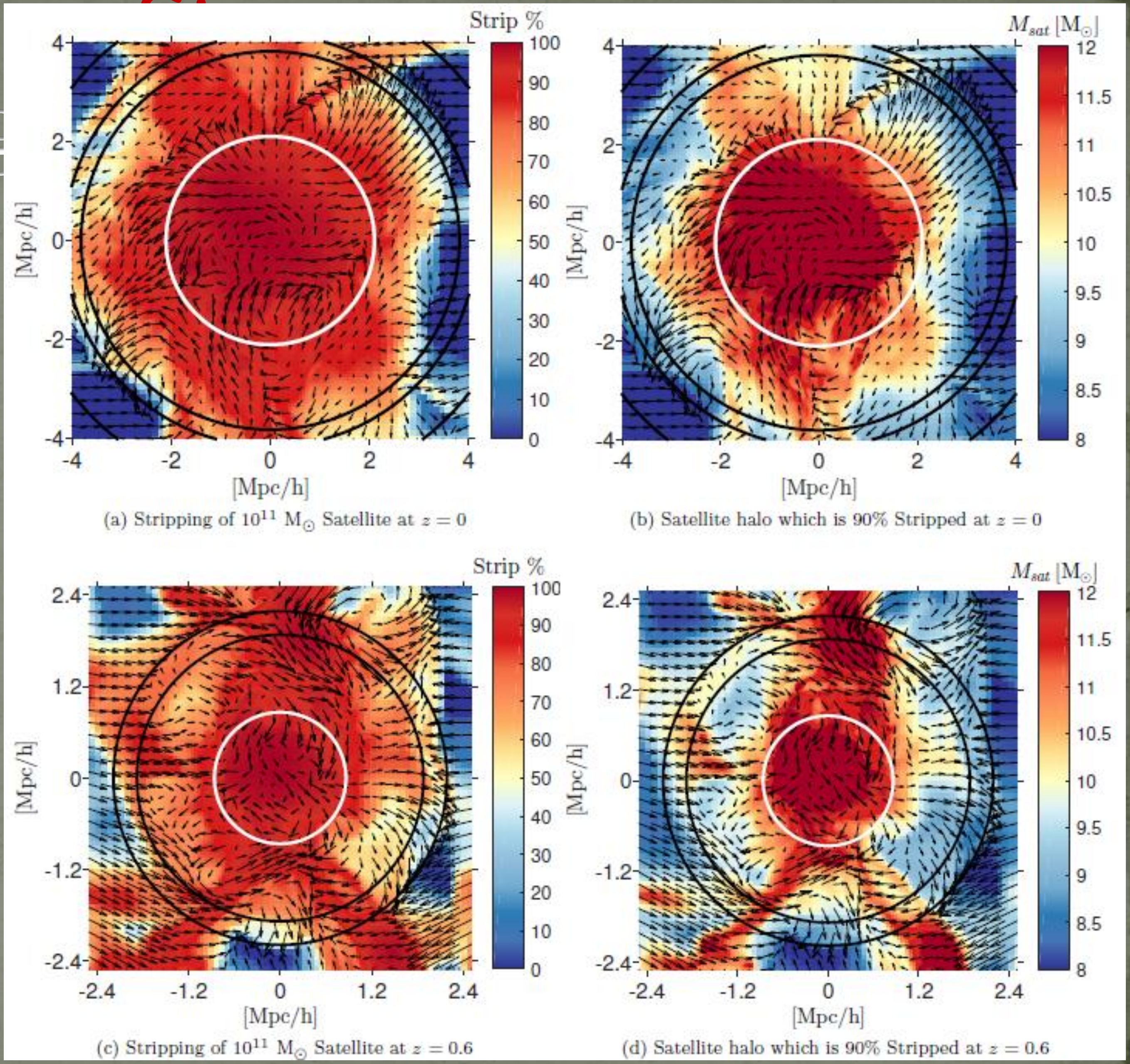
$$\mu = \frac{M_{sat}}{M_C}$$

# Stripping in ~~Realistic~~ Simulated Clusters

For a $M_{sat}=10^{11}\ M_{\odot}$



# Stripping



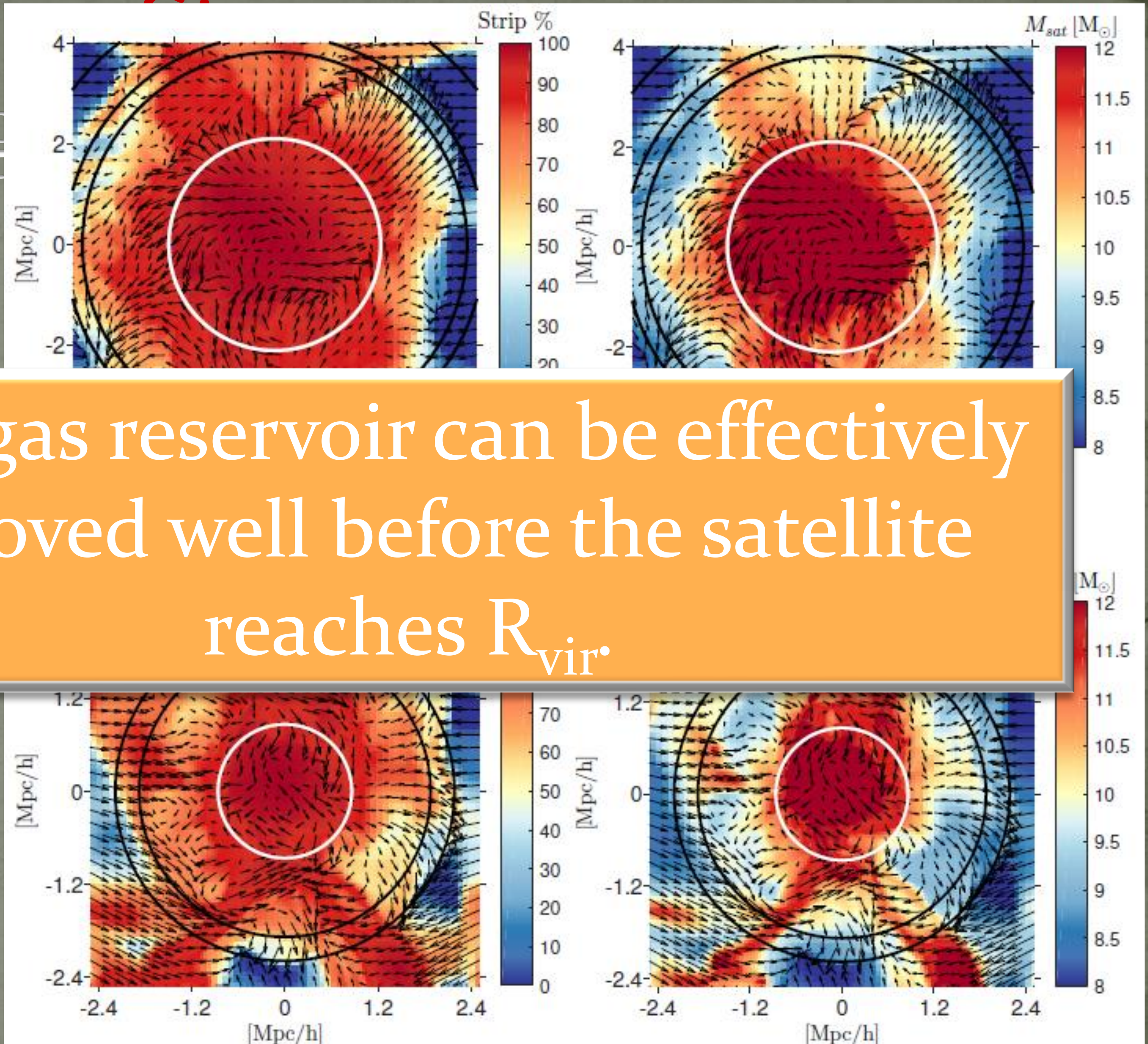

(a) Stripping of $10^{11}$ M$_\odot$ Satellite at $z = 0$

(b) Satellite halo which is 90% Stripped at $z = 0$

(c) Stripping of $10^{11}$ M$_\odot$ Satellite at $z = 0.6$

(d) Satellite halo which is 90% Stripped at $z = 0.6$

# Stripping




(c) Stripping of $10^{11}$ $M_\odot$ Satellite at $z = 0.6$

(d) Satellite halo which is 90% Stripped at $z = 0.6$

Halo gas reservoir can be effectively removed well before the satellite reaches $R_{vir}$.

# II. Stripping from Galaxies

- Model assumptions:
  - ICM is modeled as an isothermal sphere.
  - Galaxies travel face-on, at the virial velocity.
  - The total binding force is dominated by the component within the disk (true for outer parts of the disk).

# Galaxy Model

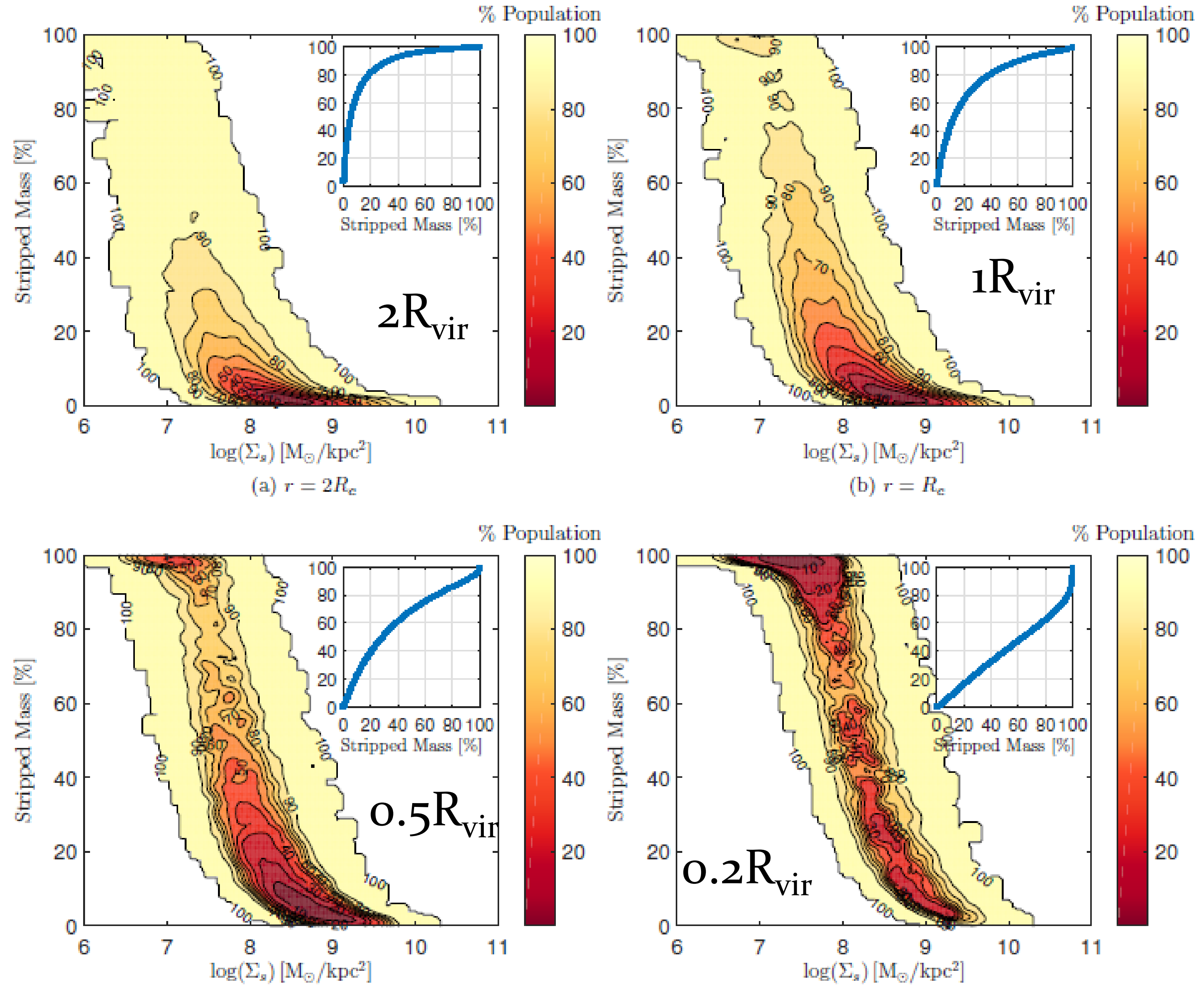
- Galaxy model contains several components:
  - Stellar disk - exponential: $\Sigma_s$, $R_s$
  - Gaseous disk - exponential: $f_{gs}=M_g/M_s$, $\beta=R_g/R_s$
  - Stellar Bulge - Hernquist: $f_{bs}=M_b/M_s$, $\xi=R_b/R_s$
  - Dark Matter Halo - NFW: $M_{vir}$, $c_{vir}$, $\lambda$

$$F(R) = -\pi G \Sigma_s^2 f_{gs} \beta^2 e^{-\beta R} \left[ B_1(R) + f_{gs}\beta^3 B_\beta(R) + \frac{2 f_{bs}\xi^2}{R\left(1+\xi R\right)} + \frac{2M_H(R)}{M_s R^3} \right]$$

$$R = \frac{R}{R_s}, \quad B_\nu(x) = I_0\left(\nu\frac{x}{2}\right)K_0\left(\nu\frac{x}{2}\right) - I_1\left(\nu\frac{x}{2}\right)K_1\left(\nu\frac{x}{2}\right)$$

# Galaxy Model

- Mock catalogs were constructed to cover the large parameter space of the model.
- Parameters were chosen to reflect realistic galaxies:
  - Specific Angular momentum is conserved and equal to that of the DM halo (MMW 98).
  - Adiabatic contraction of the halo is accounted for.
  - Values of parameters were randomly selected based on observations and simulations.
  - Unstable galaxies were removed.



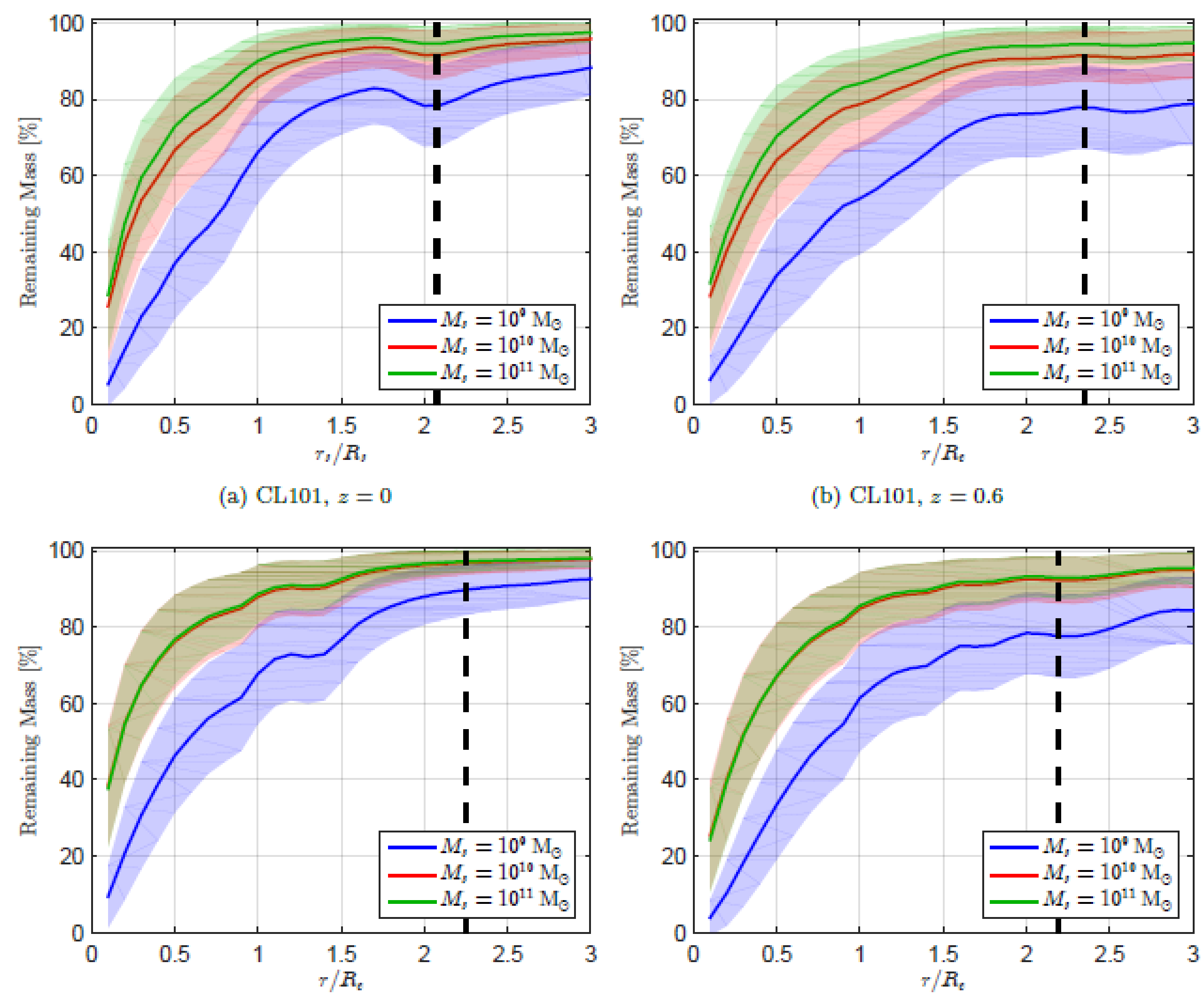
(a) $r = 2R_c$

(b) $r = R_c$

(c) $r = 0.5R_c$

(d) $r = 0.2R_c$

# Stripping in Simulated Clusters




(a) CL101, $z = 0$

(b) CL101, $z = 0.6$

(c) CL3, $z = 0$

(d) CL3, $z = 0.6$

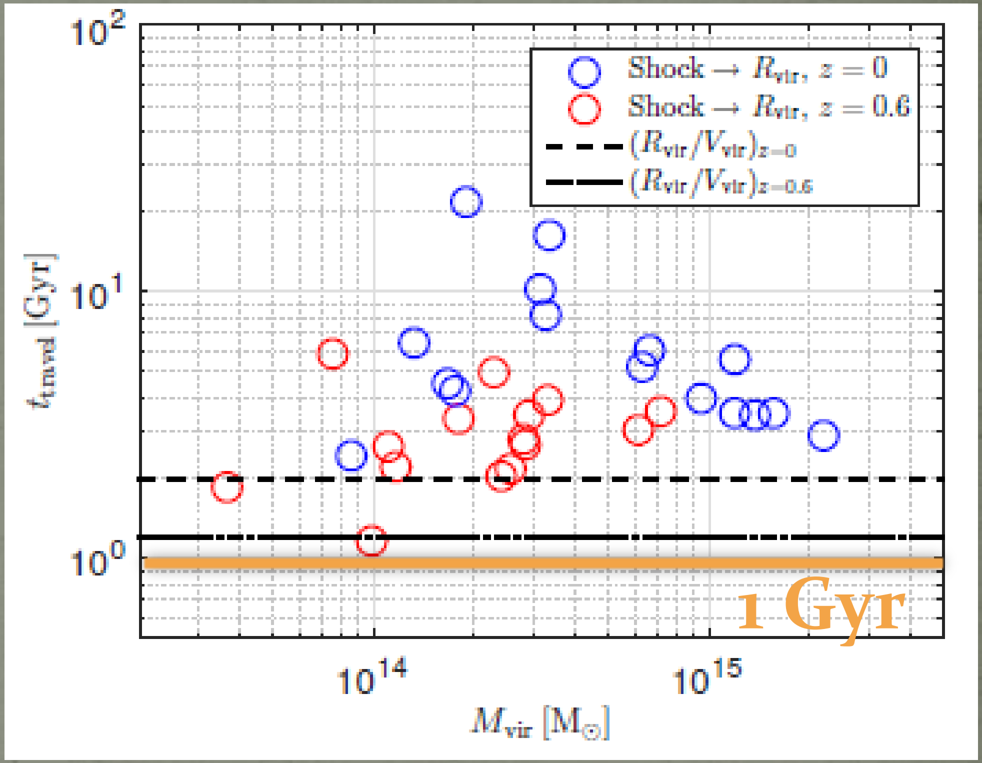
# Galaxy Stripping Results

- Mass stripping via RPS is ineffective beyond the virial radius.
- Only at ~0.5 $R_{vir}$ does significant stripping occur.
- Since gas is removed preferentially from the outside in, the relation between mass loss and SF reduction is not linear: 70% of the gas must be removed for a 50% reduction in SF.
- Quenching of SF beyond $R_{vir}$ can occur through starvation, *if* the gas depletion occurs before the satellites reach the virial radius.

# Travel Time

$$t_{travel} = \int_{R_{out}}^{R_{in}} \frac{dr}{\langle v_r \rangle}$$

- Typical travel times between the shock and $R_{vir}$ are of order several Gyr.



# Depletion Time

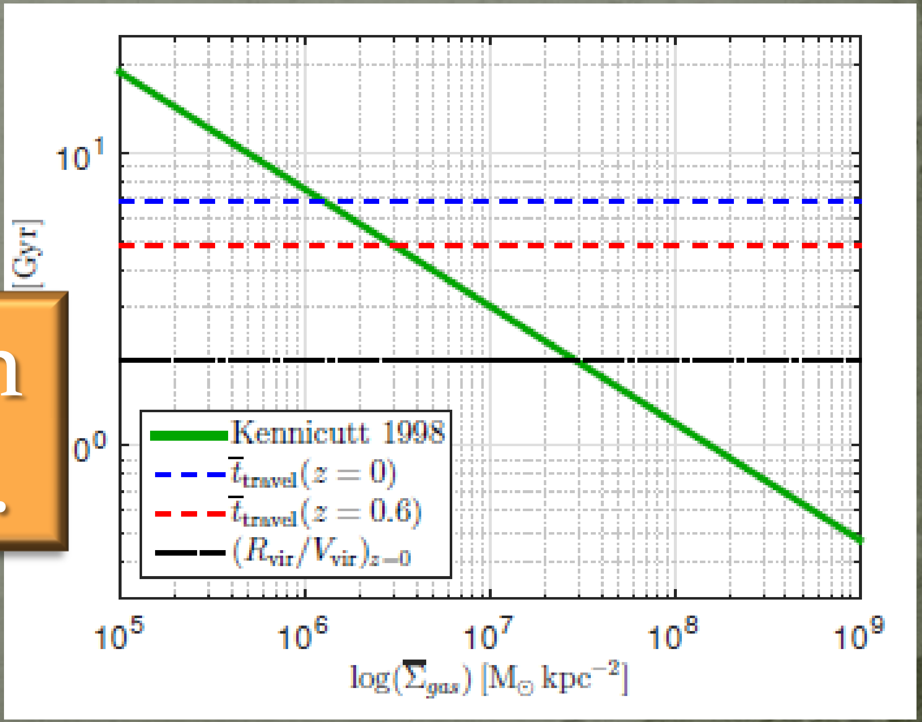
- The gas in the disk is depleted by SF and outflows

$$\dot{\Sigma}_{gas} = -\Sigma_{SFR} - \Sigma_{outflow} = -(1+\tau)\Sigma_{SFR} = -(1+\tau)A\Sigma_{gas}^{\alpha}$$

- Depletion time is defined as a drop to 10% of the initial surface density

\overline{\Sigma}_{SFR}

$$t_{\rm depl} = 3.01\left(\frac{\Sigma_{gas}}{10^{7}\ \mathrm{M_{\odot}kpc^{-2}}}\right)^{-0.4}\ \mathrm{Gyr}$$




**Galaxies can quench before reaching $R_{vir}$**

# Accounting for SF Galaxies

- Satellites travelling along gas streams may experience reduced RPS: ‘dynamical sheilding’ (remember the Prologue).
- For some satellites, the depletion time may be longer than the travel time.
- Even in the inner regions, some galaxies can still retain their gas.

# Conclusions

- The environmental influence of the ICM extends out to 2-3 $R_{vir}$.
- RPS can remove the gas reservoir from satellites, but *not* the gas from the galaxy itself.
- Galaxies can quench by starvation in the interval between crossing the shock and reaching $R_{vir}$.
- RPS *can* remove gas from within the galaxies in the inner regions of the cluster ($<0.5R_{vir}$).
- SF galaxies can still be accounted for.

# Thank you