Cool Cores, Conduction, and Virial Shocks:

Sculpting Cosmic Gas into Clusters

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"Sculpting Cosmic Gas into Clusters"

Central Density

* Thermal Instability *(McCourt, Sharma, et al. 2012)*
* Implications for Cool Cores *(Sharma, McCourt, et al. 2012)*
* Non-Self-Similarity *(Sharma, McCourt, et al., submitted)*

Outer Temperature

McCourt, Quataert, & Parrish, in prep.

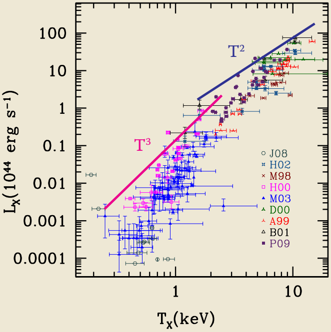
* Accretion History $\rightarrow T(r)$
* Conduction + MTI

What determines the ***density*** *of the gas* *in the* ***centers*** *of clusters?*

Motivation: Non-Self-Similarity

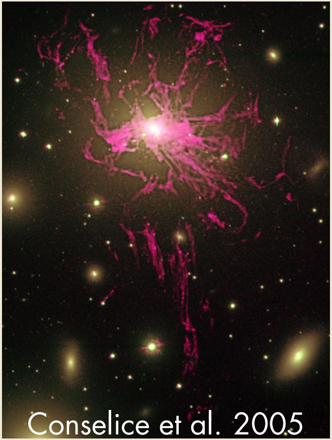
Assume that the gas properties scale with the dark matter:

- $\rho \sim M^0$
- $T \sim M/r \sim M^{2/3}$
- $L \sim \rho^2 T^{1/2} r^3 \sim T^2$



Gas in the centers of clusters has ***lower density*** and ***higher entropy*** than gravitational self-similar models predict.

Background: Thermal Instability in Clusters



Is the ICM Thermally Unstable?

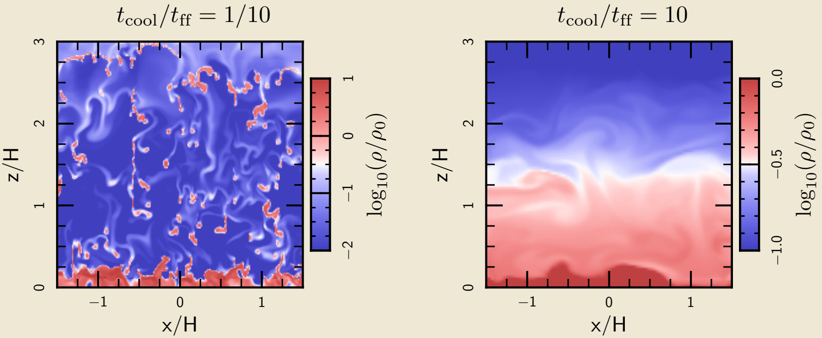
- Thermal instability suppressed in cooling-flows (Balbus & Soker 1989)
- Even some equilibria may be thermally stable (Kunz et al. 2010)

- Many heating mechanisms are thermally unstable (Gaspari et al. 2012)
- Multi-phase gas seen in many clusters (McDonald et al. 2010, 2011)

Assume **local thermal instability**

Background: The Face of Thermal Instability

(Assuming it exists...)



*Thermal Instability does **not necessarily** imply Multi-phase gas.*

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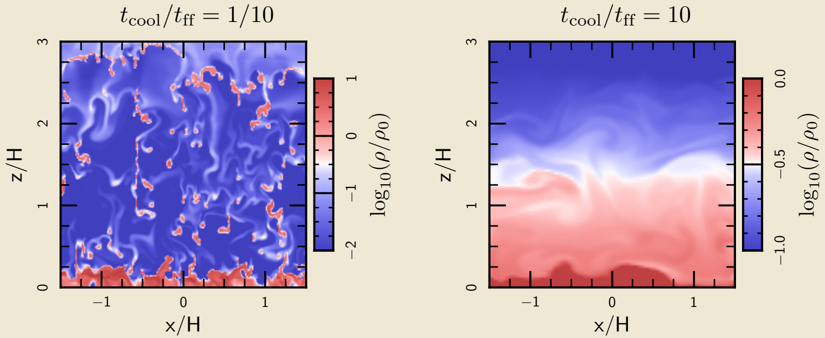
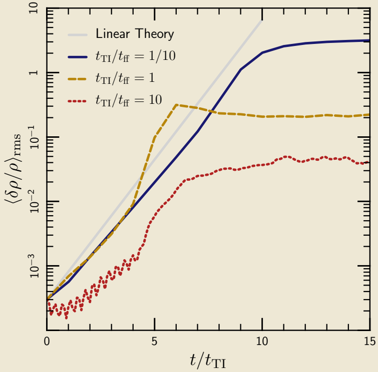


*Thermal Instability does **not necessarily** imply Multi-phase gas.*

See cold gas when $t_{\rm cool}/t_{\rm ff} \lesssim 10$

Background: Physics of the Saturation



- Perturbations initially grow exponentially...
- ...Saturate when $t_{\rm sink} \sim t_{\rm cool}$
- Final amplitude $\propto (t_{\rm cool}/t_{\rm ff})^{-2}$
- This is a *non-linear* effect

Background: Feedback Regulation

Feedback and cooling self-regulate to the critical threshold for non-linear thermal stability:

$$\min(t_{\rm cool}/t_{\rm ff}) \sim 10$$

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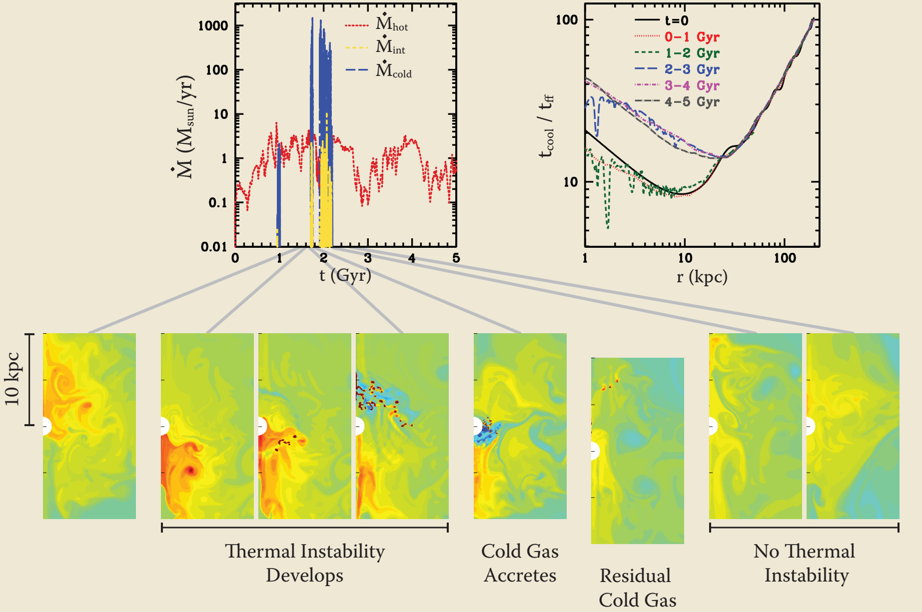

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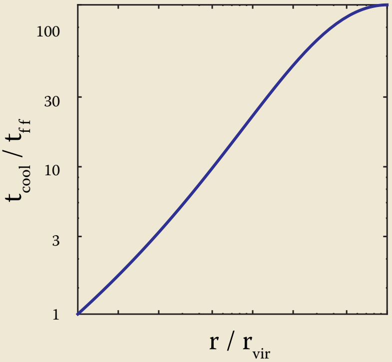
Method: Excavating Cool Cores



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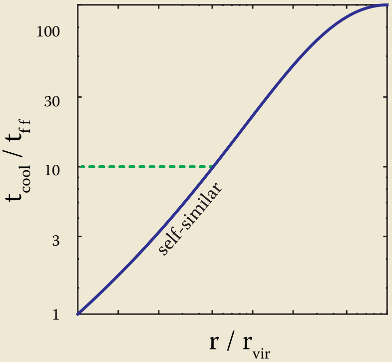

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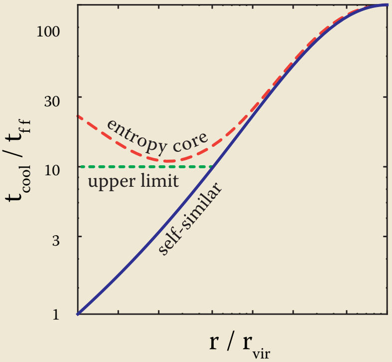

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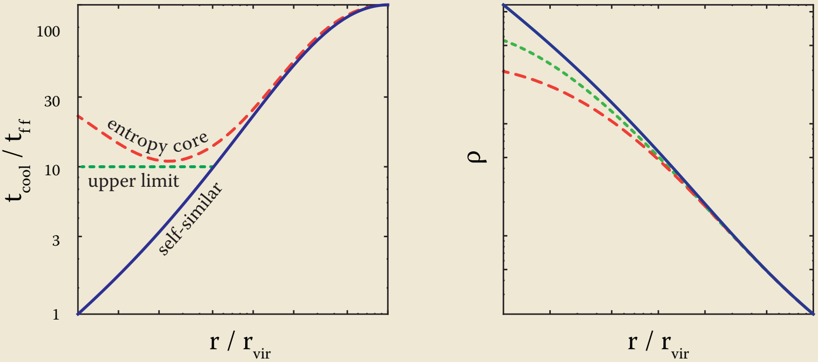

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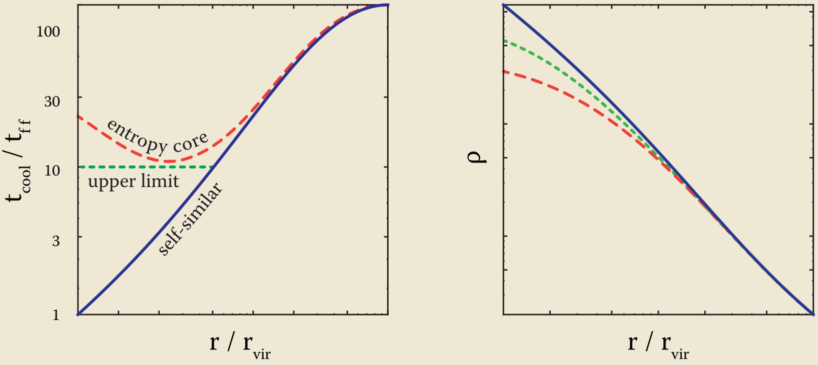
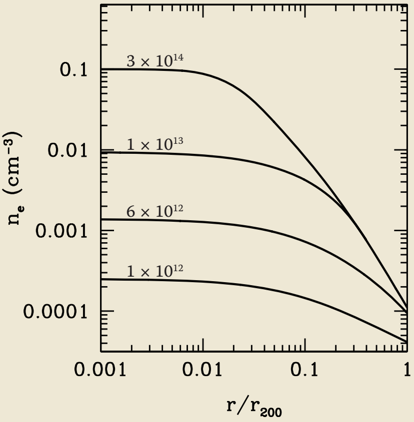


cf. Voit et al. (2001)

Results: Core Size w/ Mass



High-Mass Halos

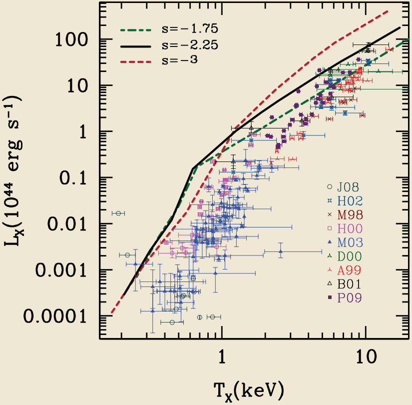
- High Temperature
- Long Cooling Time
- ⇒ **small core**

Low-Mass Halos

- Lower Temperature
- Shorter Cooling Time
- ⇒ **large core**

(Minimum) **Core size determined by Thermal Instability**

Applications



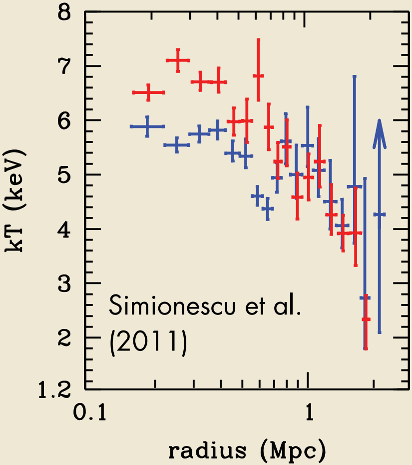
Also:

- gas fraction
- core size & entropy
- stellar mass
- baryon fraction

Assuming global thermal balance, these properties are ~independent of the feedback mechanism

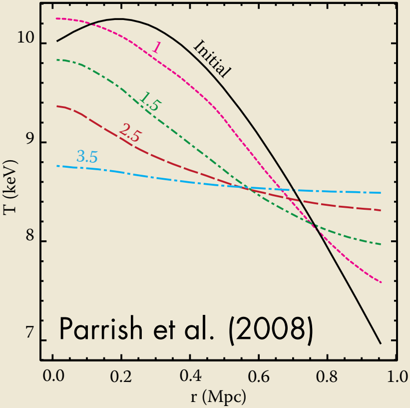
*What determines the **temperature** of the gas at **large radii** in clusters?*

Motivation



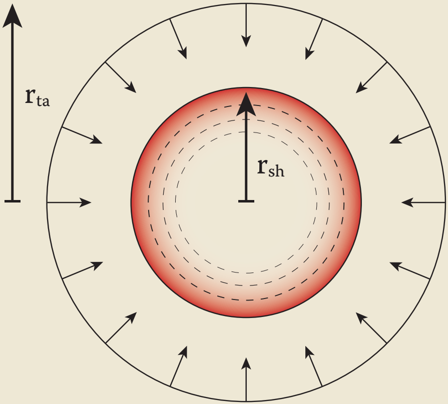
- $\nabla T < 0 \Rightarrow \mathrm{MTI}$
- $t_{\rm cond} \sim r_{\rm vir}^2/\chi \sim 1\,{\rm Gyr} \lesssim t_{\rm age}$

Motivation



In simulations of **isolated** clusters, the ICM becomes isothermal after ~Gyr.

Model: Entropy Generation at the Shock



$$\frac{1}{2}v_i^2 = \frac{GM_{sh}}{r_{sh}} - \frac{GM_{sh}}{r_{ta}}$$

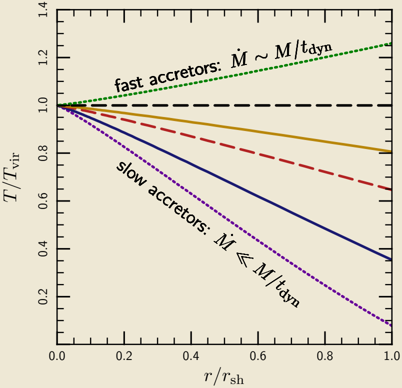
$$\rho v = \frac{1}{4\pi r_{sh}^2}\frac{dM}{dt}$$

+ Jump Conditions

$\rightarrow K(r_{sh})$

(e. g. Voit et al. 2003)

Results: Adiabatic Evolution



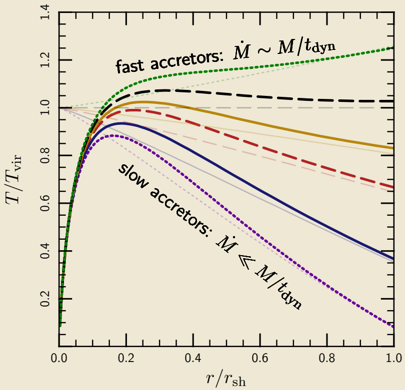
In the case of **Adiabatic Evolution**, this is a simple problem.

- $T(0) = T_{\rm vir}$
- $T(\text{out}) = T_{\rm sh}$

Temperature Gradient set by Accretion Rate

$(t_{\rm dyn} \times d \ln M/dt)$

Results: Adiabatic Evolution



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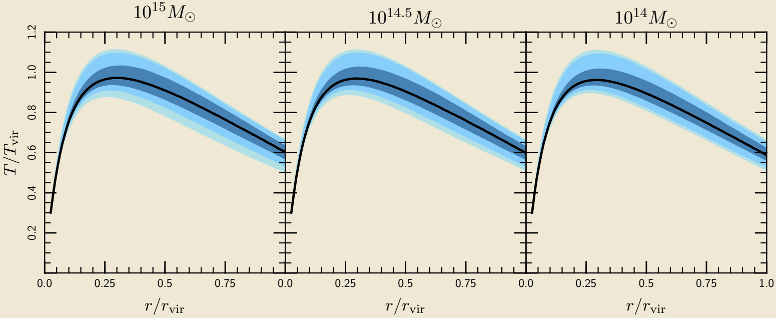
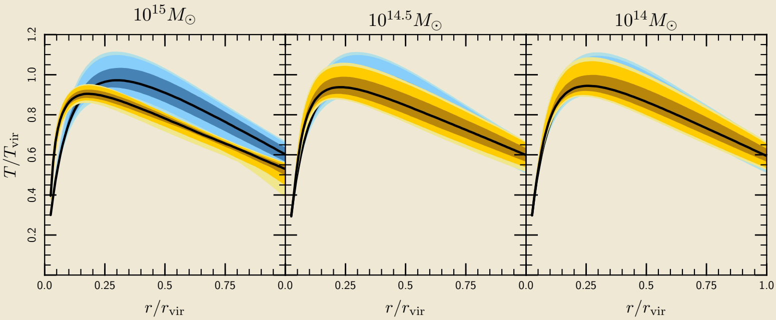
Dispersion in Accretion Histories



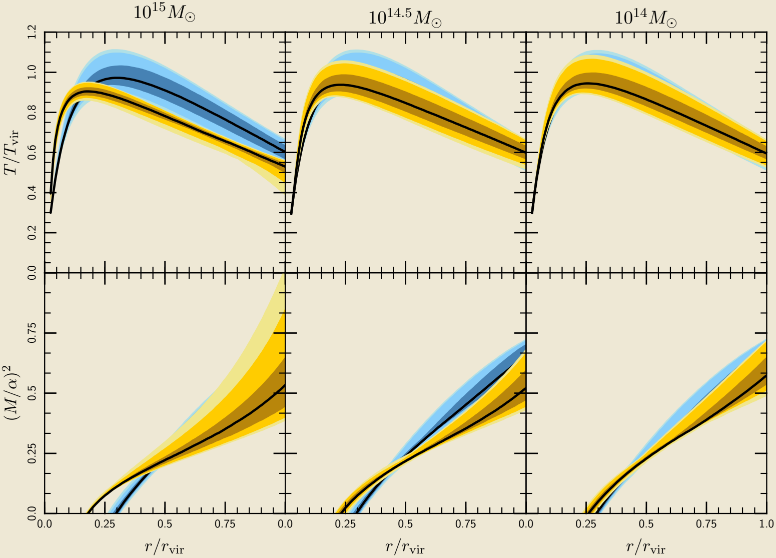
Accretion histories from McBride et al. 2009

Effect of Conduction



Accretion histories from McBride et al. 2009

Application: MTI & Non-Thermal Pressure Support



Accretion histories from McBride et al. 2009

Conclusions

Density Cores

- *Assuming that the ICM is thermally unstable*, multiphase gas forms only when $t_{\mathrm{cool}}/t_{\mathrm{ff}} \lesssim 10$.
- Cooling and feedback self-regulate to the critical threshold for stability.
- This sets a density ceiling (or entropy floor) for the gas $\Rightarrow$ *non-self-similarity*.

Temperature Gradients

- A cluster's accretion rate determines its temperature gradient
- This temperature gradient persists even with thermal conduction
- Importance of the MTI may be non-monotonic with halo mass. ($3\times10^{14}\ M_{\odot}$ is the sweet spot).