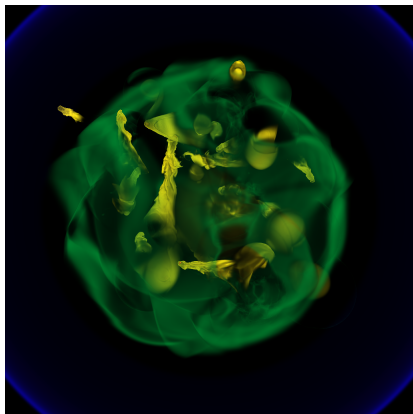


The Hydrodynamics of Galaxy Transformation in Groups



Rukmani Vijayaraghavan

NSF Astronomy & Astrophysics
Postdoctoral Fellow

University of Virginia

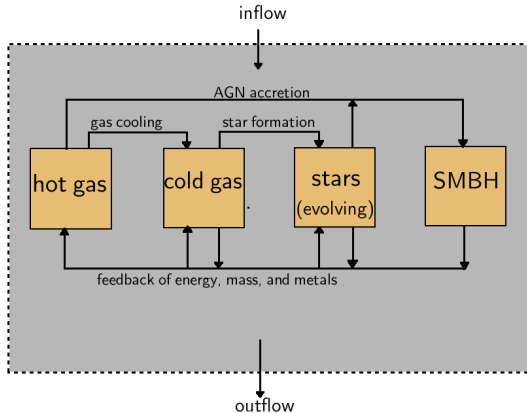
with

Paul Ricker (UIUC)

Craig Sarazin (U.Va)

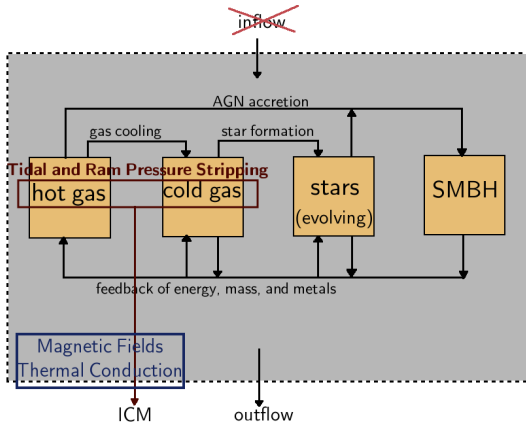


Evolution of Gas in Galaxies



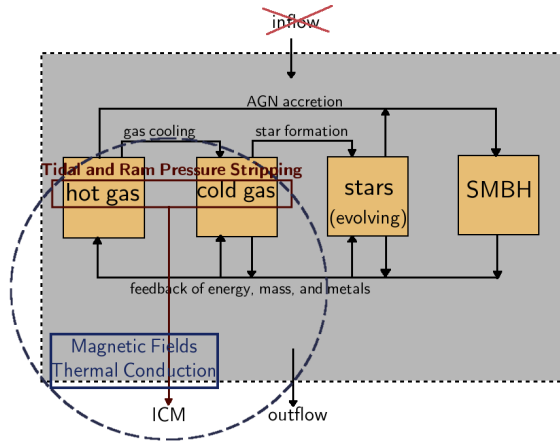
(Adapted from Mo, van den Bosch, and White 2010)

Evolution of Gas in Group & Cluster Galaxies



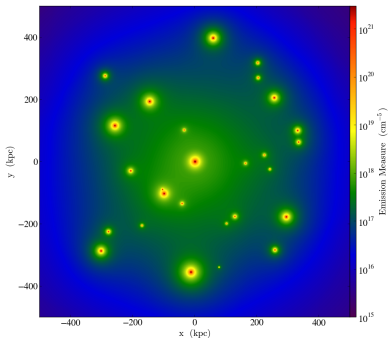
(Modified)

Evolution of Gas in Group & Cluster Galaxies



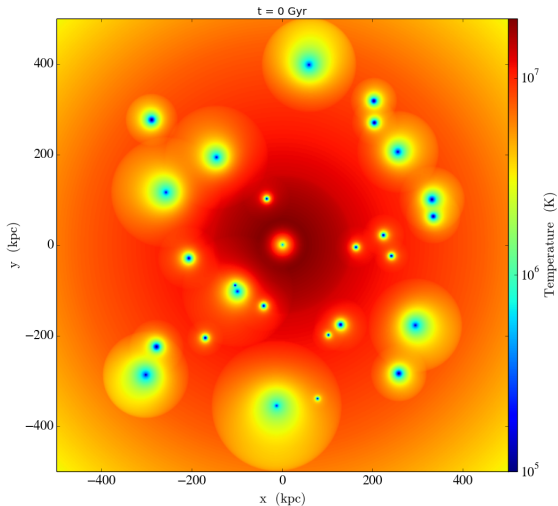
(Modified)

Simulating Galaxies' Gas Loss in Group & Cluster Environments



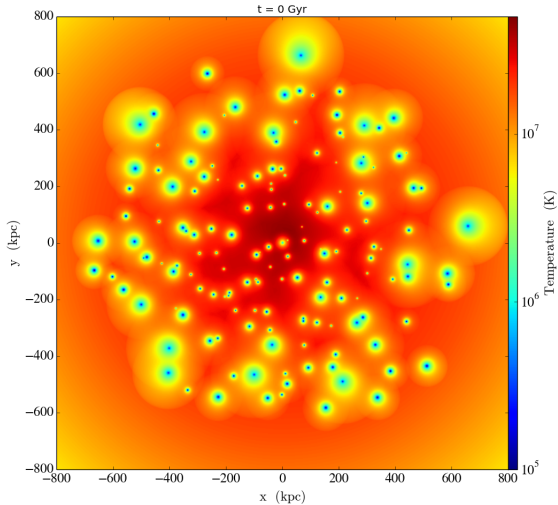
- N-body + Magnetohydrodynamic FLASH 4 simulations of galaxies in isolated group ($M_{\text{group}} = 3.2 \times 10^{13} M_{\odot}$) and cluster ($M_{\text{cluster}} = 1.2 \times 10^{14} M_{\odot}$).
- $10^6 M_{\odot}$ particles, 1.6 kpc maximum spatial resolution.
- 'Galaxies' are NFW spheres with hot gas coronae, live background halo.
- Galaxy masses are chosen from luminosity functions.

$3 \times 10^{13} M_{\odot}$ Group



Vijayaraghavan & Ricker 2015, MNRAS, 449, 2312

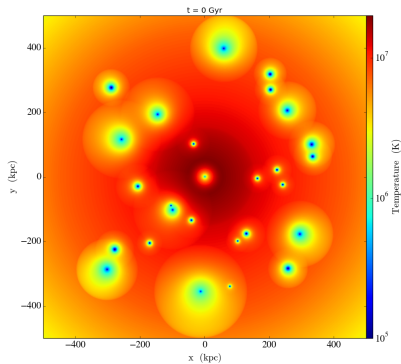
$1.2 \times 10^{14} M_{\odot}$ Cluster



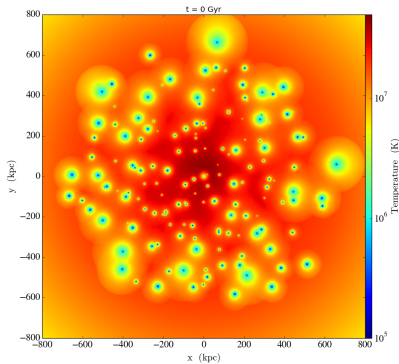
Vijayaraghavan & Ricker 2015, MNRAS, 449, 2312

Ram Pressure Stripping, $t = 0$ Gyr

Group



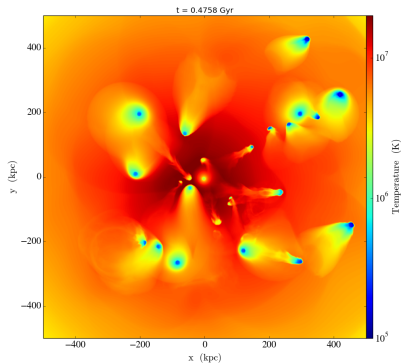
Cluster



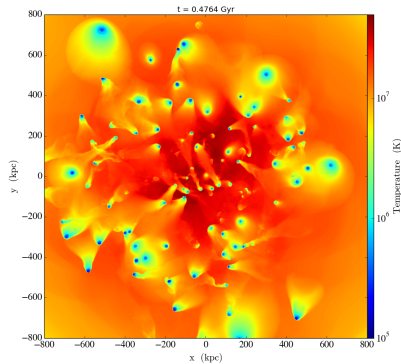
Vijayaraghavan & Ricker 2015, MNRAS, 449, 2312

Ram Pressure Stripping, $t = 0.48$ Gyr

Group



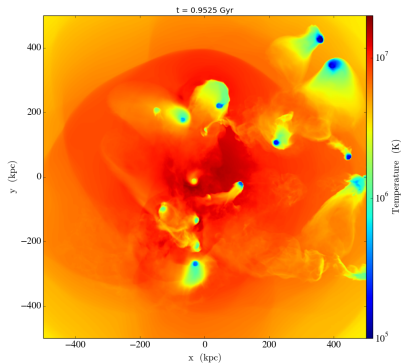
Cluster



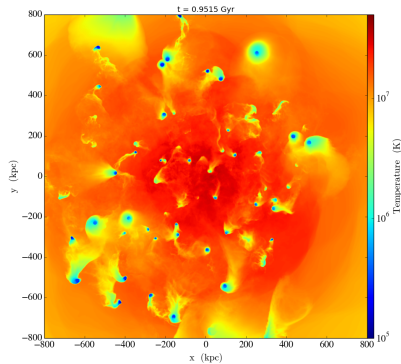
Vijayaraghavan & Ricker 2015, MNRAS, 449, 2312

Ram Pressure Stripping, $t = 0.95$ Gyr

Group



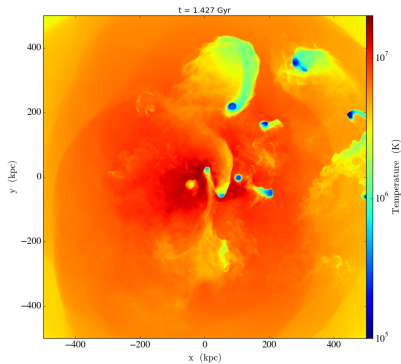
Cluster



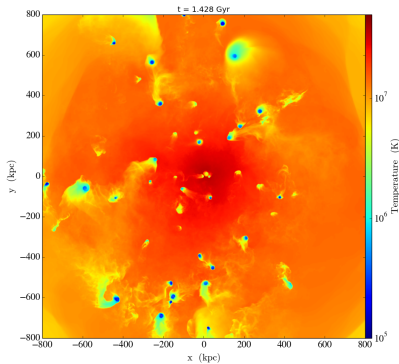
Vijayaraghavan & Ricker 2015, MNRAS, 449, 2312

Ram Pressure Stripping, $t = 1.43$ Gyr

Group



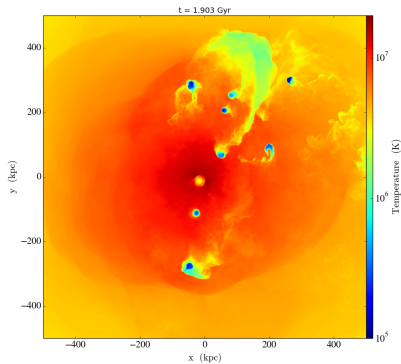
Cluster



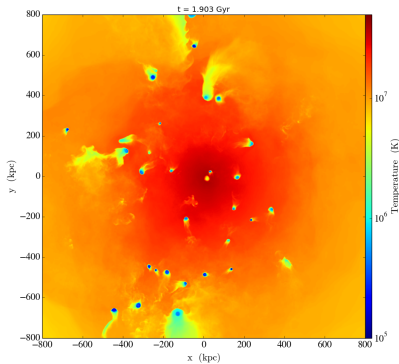
Vijayaraghavan & Ricker 2015, MNRAS, 449, 2312

Ram Pressure Stripping, $t = 1.9$ Gyr

Group



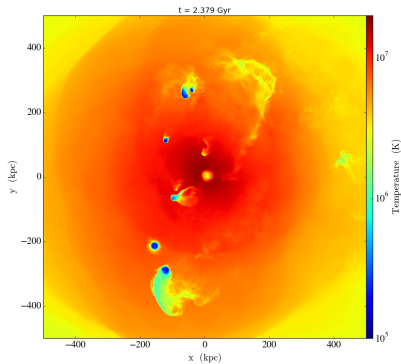
Cluster



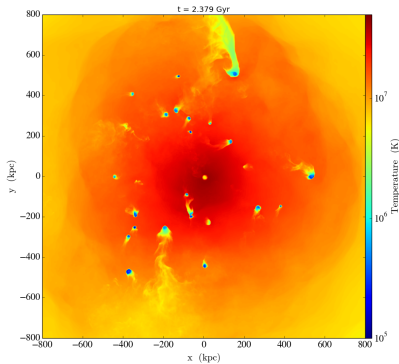
Vijayaraghavan & Ricker 2015, MNRAS, 449, 2312

Ram Pressure Stripping, $t = 2.4$ Gyr

Group



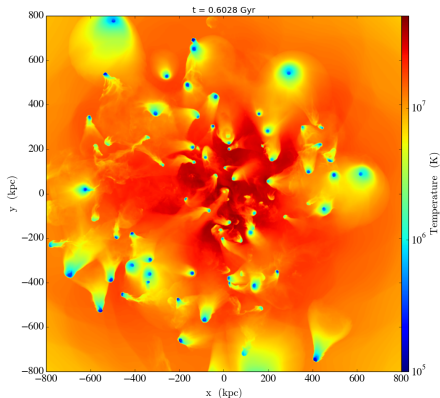
Cluster



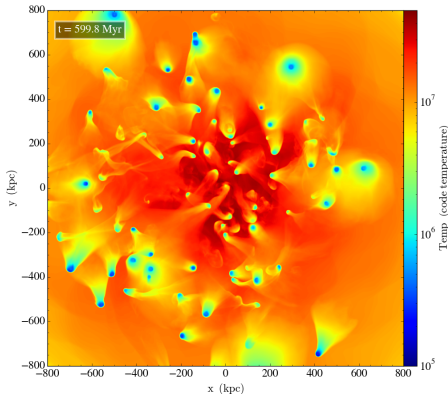
Vijayaraghavan & Ricker 2015, MNRAS, 449, 2312

Effect of Magnetic Fields on Stripped Tails

No Magnetic Fields



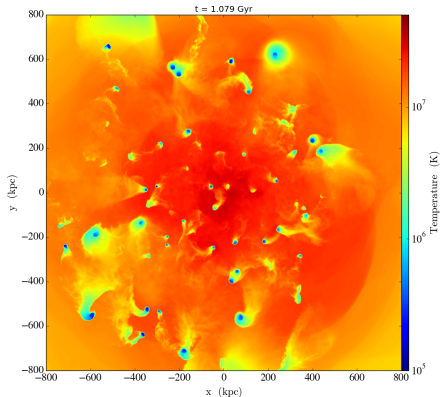
With Magnetic Fields



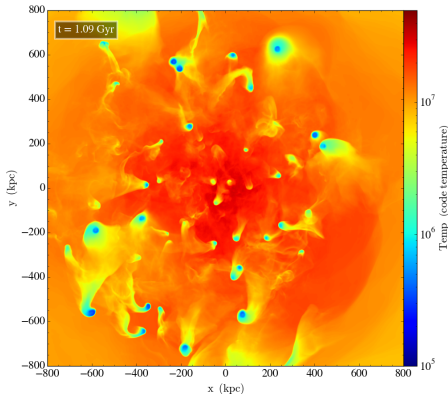
Vijayaraghavan & Ricker 2016, ApJ, submitted

Effect of Magnetic Fields on Stripped Tails

No Magnetic Fields

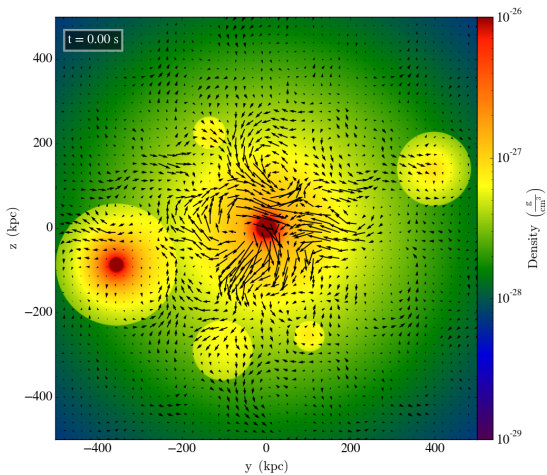


With Magnetic Fields



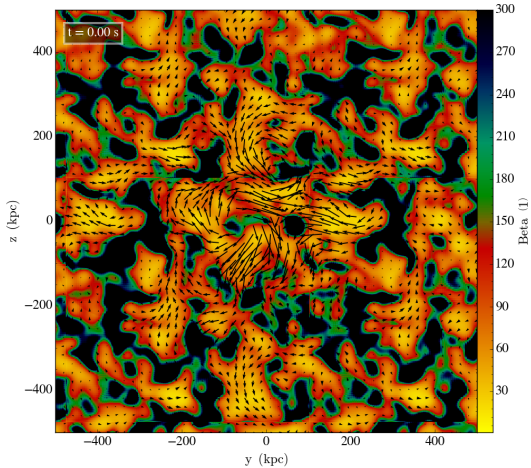
Vijayaraghavan & Ricker 2016, ApJ, submitted

Density



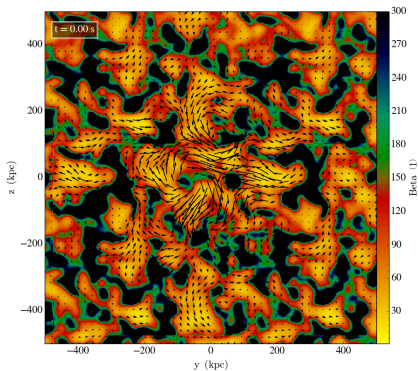
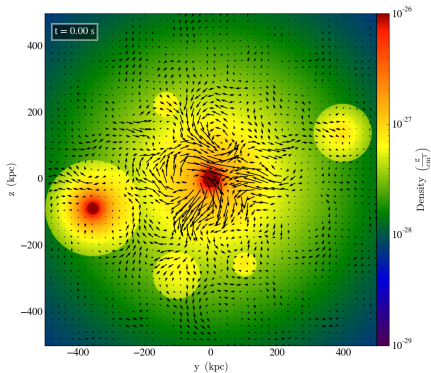
Vijayaraghavan & Ricker 2016, ApJ, submitted

$$\beta = P_{\text{thermal}}/P_{\text{magnetic}}$$



Vijayaraghavan & Ricker 2016, ApJ, submitted

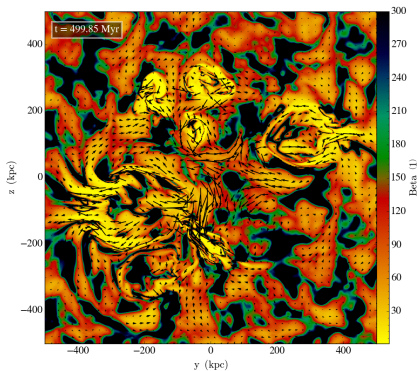
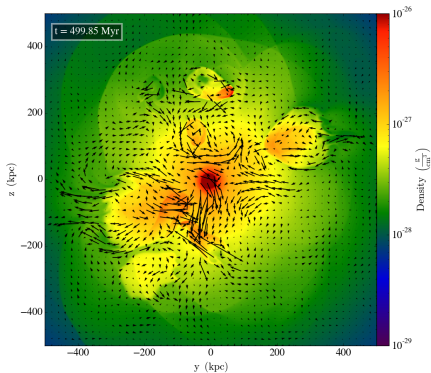
Density and β , $x = 0$ kpc



$$\beta = P_{\text{thermal}}/P_{\text{magnetic}}$$

Vijayaraghavan & Ricker 2016, ApJ, submitted

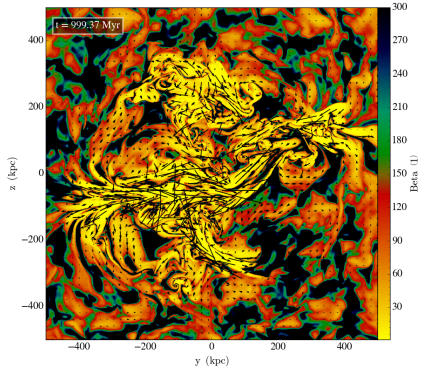
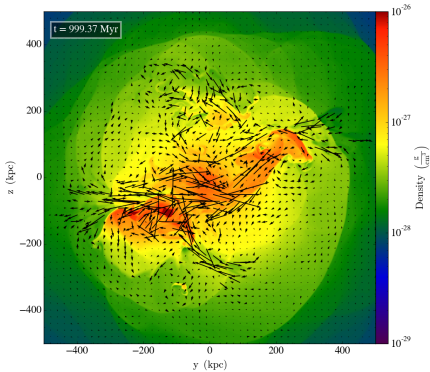
Density and β , $x = 0$ kpc



$$\beta = P_{\text{thermal}}/P_{\text{magnetic}}$$

Vijayaraghavan & Ricker 2016, ApJ, submitted

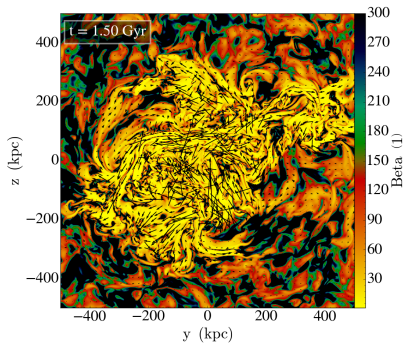
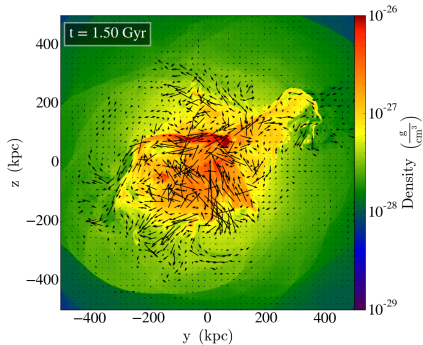
Density and β , $x = 0$ kpc



$$\beta = P_{\text{thermal}}/P_{\text{magnetic}}$$

Vijayaraghavan & Ricker 2016, ApJ, submitted

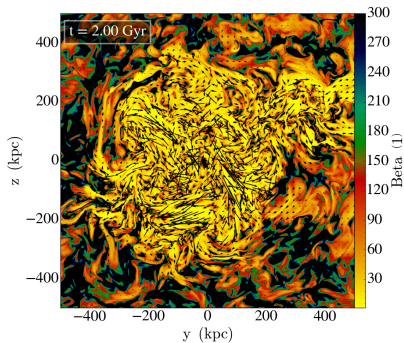
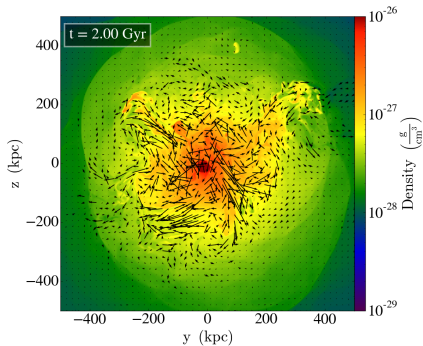
Density and β , $x = 0$ kpc



$$\beta = P_{\text{thermal}}/P_{\text{magnetic}}$$

Vijayaraghavan & Ricker 2016, ApJ, submitted

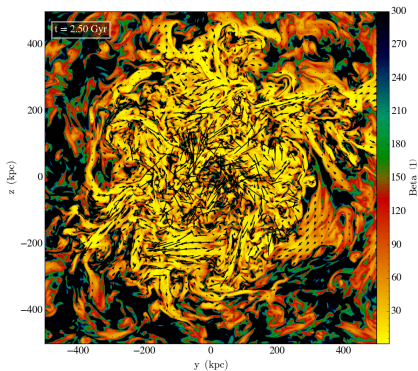
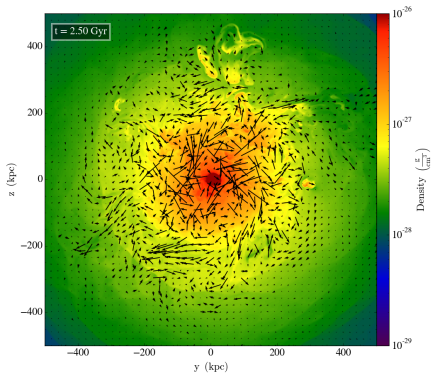
Density and β , $x = 0$ kpc



$$\beta = P_{\text{thermal}}/P_{\text{magnetic}}$$

Vijayaraghavan & Ricker 2016, ApJ, submitted

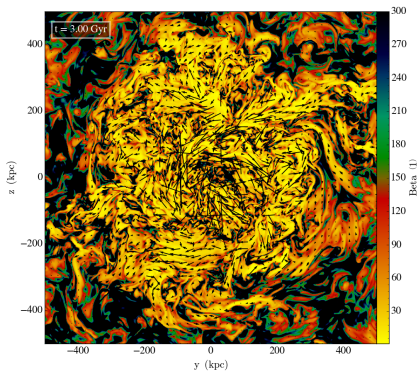
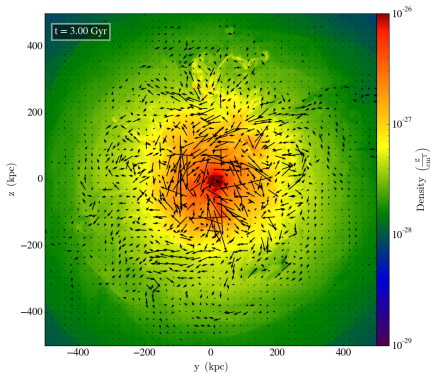
Density and β , $x = 0$ kpc



$$\beta = P_{\text{thermal}}/P_{\text{magnetic}}$$

Vijayaraghavan & Ricker 2016, ApJ, submitted

Density and β , $x = 0$ kpc

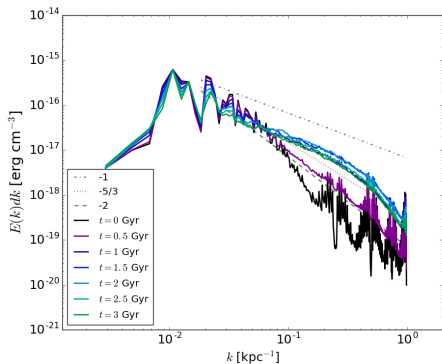


$$\beta = P_{\text{thermal}}/P_{\text{magnetic}}$$

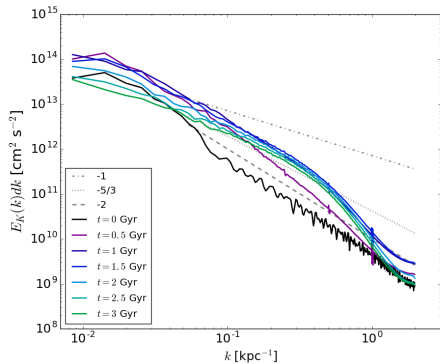
Vijayaraghavan & Ricker 2016, ApJ, submitted

Galaxies Amplify Magnetic Fields, Inject Turbulence

$$E_B = B^2/8\pi$$



$$E_K = v^2$$



Vijayaraghavan & Ricker 2016, ApJ submitted

Thermal Conduction

$$\mathbf{Q} = -\kappa \nabla T_e$$
$$\kappa = \epsilon \delta_T \kappa_{Sp} \propto n_e \lambda_e T_e^{1/2}$$

$$\lambda_e \simeq 22 \text{ kpc} \left(\frac{T_e}{10^8 \text{ K}} \right)^2 \left(\frac{n_e}{10^{-3} \text{ cm}^{-3}} \right)^{-1}$$

Thermal Conduction between the ICM and hot ISM: Saturated Heat Flux

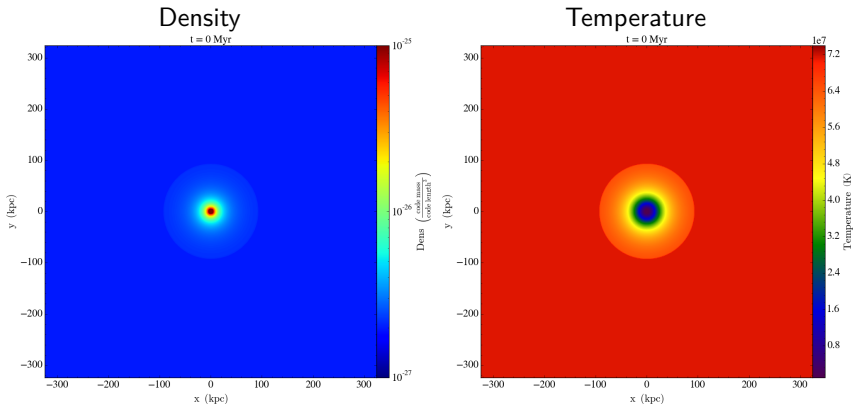
$$Q_{\text{sat}} = 0.4 \left(\frac{2k_B T_e}{\pi m_e} \right)^{1/2} n_e k_B T_e$$

$(l_T \lesssim \lambda_e)$

$$Q_{\text{eff}} = \left(\frac{1}{Q} + \frac{1}{Q_{\text{sat}}} \right)^{-1} = \frac{\kappa T_e}{l_T + 4.2 \lambda_e} \frac{\nabla T_e}{|\nabla T_e|}$$

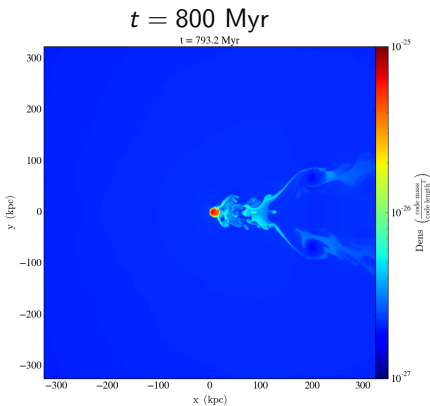
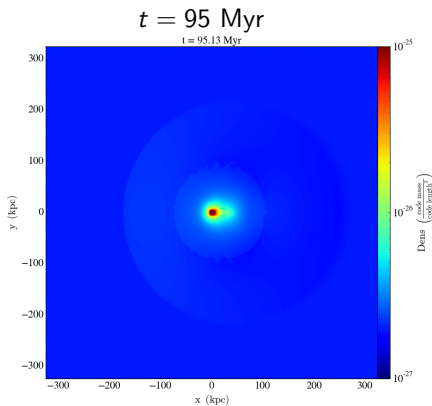
Galaxy in Wind Tunnel

Initial setup



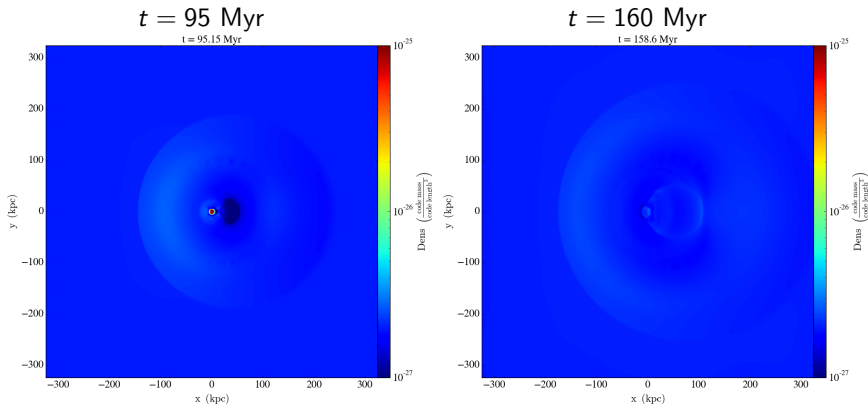
Vijayaraghavan & Sarazin, in prep.

No Conduction



Vijayaraghavan & Sarazin, in prep.

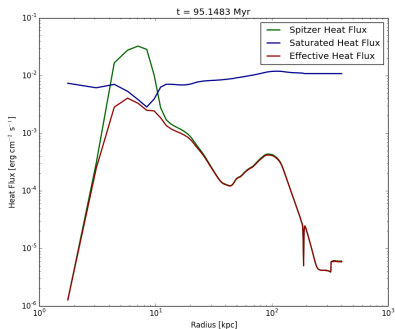
Isotropic Saturated Thermal Conduction



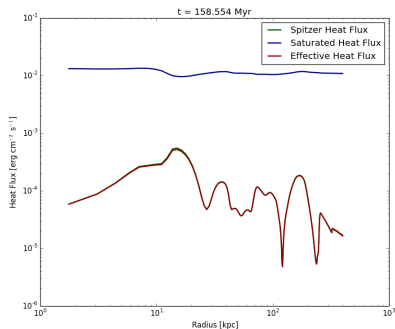
Vijayaraghavan & Sarazin, in prep.

Effective Heat Flux

$t = 95 \text{ Myr}$

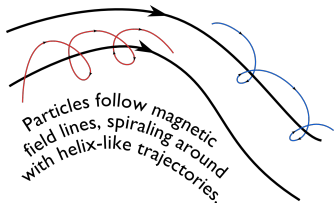


$t = 160 \text{ Myr}$



Vijayaraghavan & Sarazin, in prep.

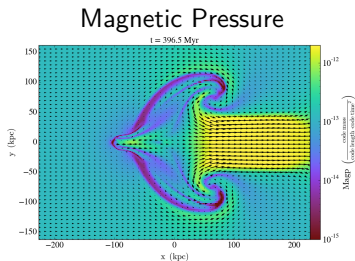
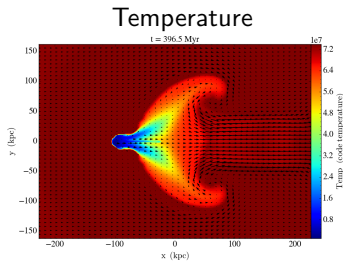
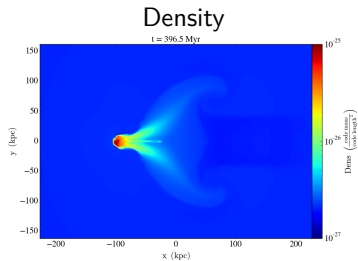
Anisotropic Thermal Conduction



- In the ICM, electron $r_g \ll \lambda_e$
- $r_g \sim 10^8$ cm; $\lambda_e \sim 1 - 10$ kpc
- $\mathbf{Q}_{\text{Spitzer}} = -\kappa \hat{\mathbf{e}}_B (\hat{\mathbf{e}}_B \cdot \nabla T_e)$
- Four magnetic field orientations:
 - $\mathbf{B} \parallel \mathbf{v}_{\text{ICM}}$, continuous
 - $\mathbf{B} \perp \mathbf{v}_{\text{ICM}}$, continuous
 - $\mathbf{B} \parallel \mathbf{v}_{\text{ICM}}$ in ICM shielding galaxy, toroidal field in ISM
 - $\mathbf{B} \perp \mathbf{v}_{\text{ICM}}$, in ICM shielding galaxy, toroidal field in ISM

Magnetized ICM, No Conduction

$\mathbf{B} \parallel \mathbf{v}_{\text{ICM}}, t = 400 \text{ Myr}$



Vijayaraghavan & Sarazin, in prep.

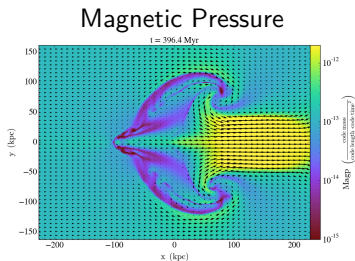
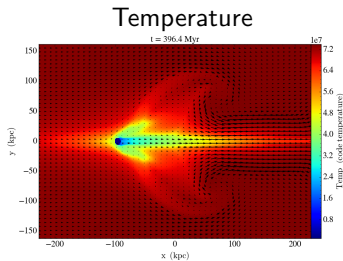
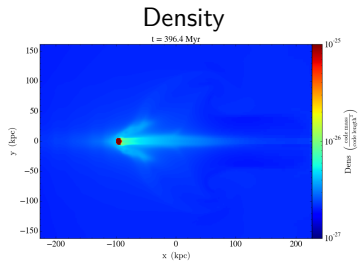
Rukmani Vijayaraghavan (U.Va.)

The Hydrodynamics of Galaxy Transformation

Dec 12 2016

Magnetized ICM: Anisotropic Conduction

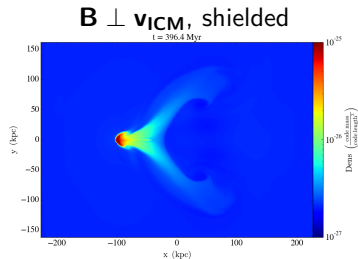
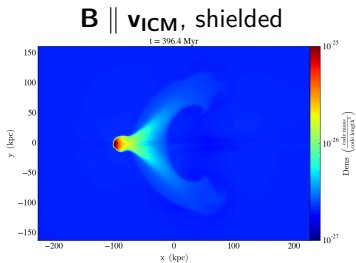
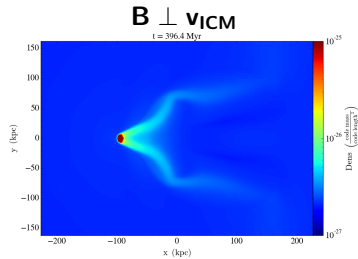
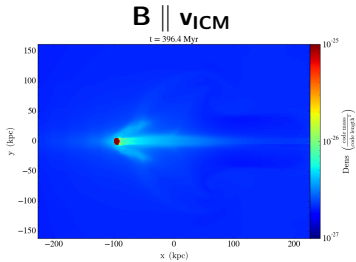
$$\mathbf{B} \parallel \mathbf{v}_{\text{ICM}}, t = 400 \text{ Myr}$$



Vijayaraghavan & Sarazin, in prep.

Density

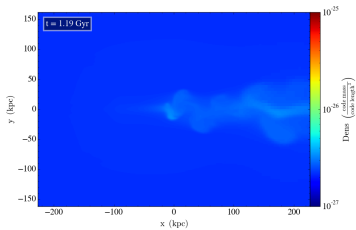
$t = 400$ Myr



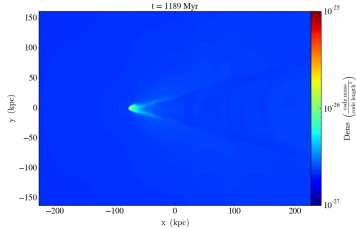
Density

$t = 1200$ Myr

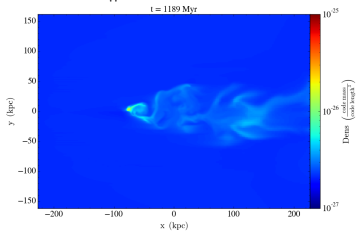
B \parallel \mathbf{v}_{ICM}



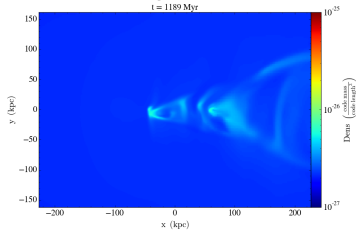
B \perp \mathbf{v}_{ICM}



B \parallel \mathbf{v}_{ICM} , shielded

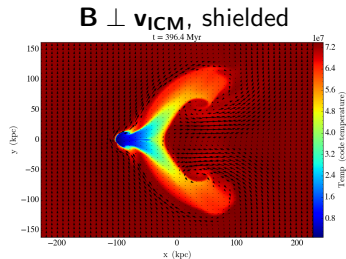
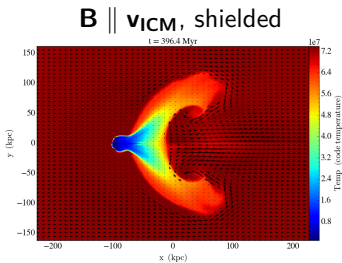
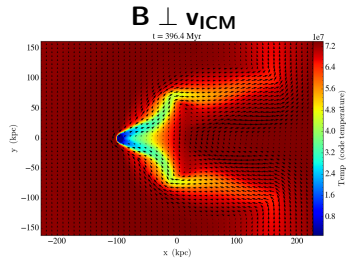
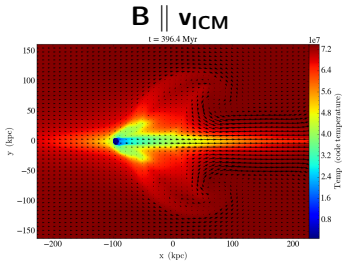


B \perp \mathbf{v}_{ICM} , shielded



Temperature

$t = 400$ Myr



Vijayaraghavan & Sarazin, in prep.

Rukmani Vijayaraghavan (U.Va.)

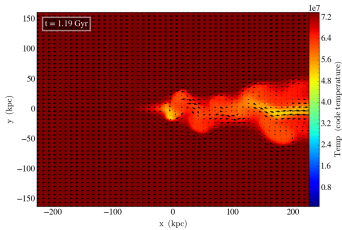
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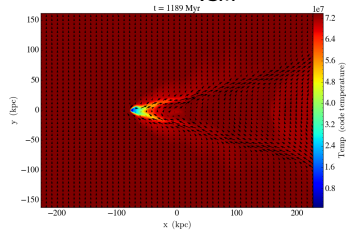
Temperature

$t = 1200$ Myr

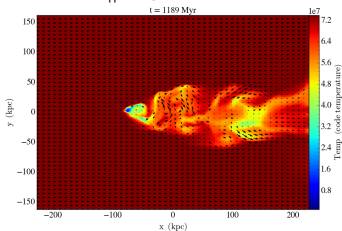
$\mathbf{B} \parallel \mathbf{v}_{\text{ICM}}$



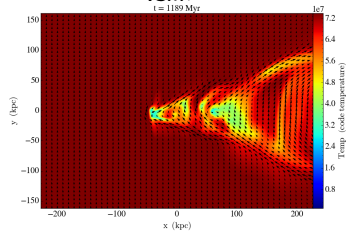
$\mathbf{B} \perp \mathbf{v}_{\text{ICM}}$



$\mathbf{B} \parallel \mathbf{v}_{\text{ICM}}$, shielded



$\mathbf{B} \perp \mathbf{v}_{\text{ICM}}$, shielded



Vijayaraghavan & Sarazin, in prep.

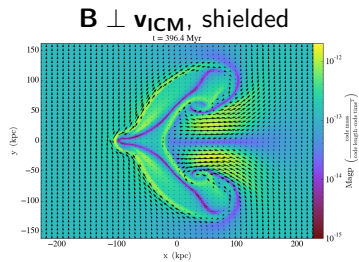
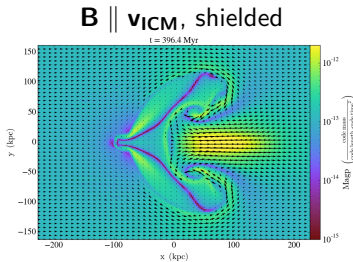
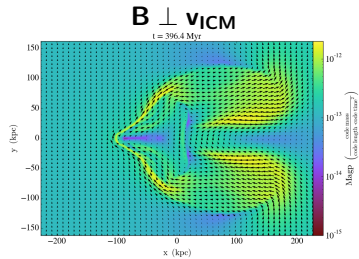
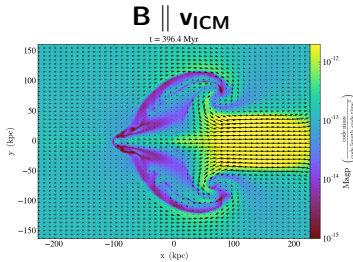
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Magnetic Pressure

$t = 1200$ Myr



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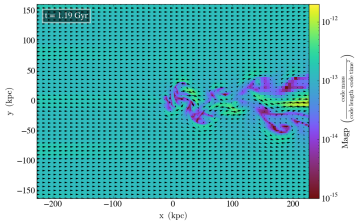
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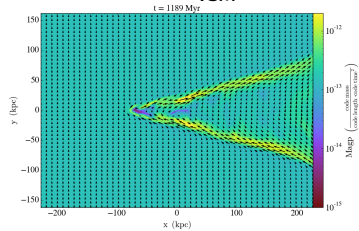
Magnetic Pressure

$t = 1200$ Myr

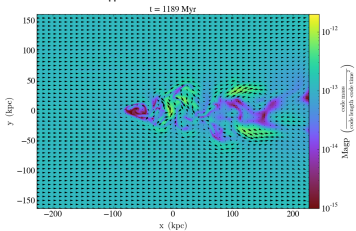
$\mathbf{B} \parallel \mathbf{v}_{\text{ICM}}$



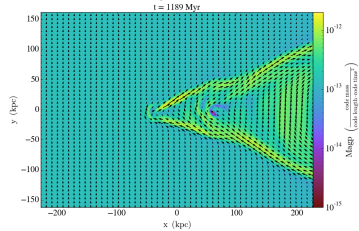
$\mathbf{B} \perp \mathbf{v}_{\text{ICM}}$



$\mathbf{B} \parallel \mathbf{v}_{\text{ICM}}$, shielded



$\mathbf{B} \perp \mathbf{v}_{\text{ICM}}$, shielded



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Summary

- Ram pressure strips gas within $t \simeq 2 - 3 \text{Gyr}$.
- Magnetic fields suppress shear instabilities, but are not strong enough to overcome ram pressure.
- Isotropic saturated thermal conduction evaporates hot ISM gas within 160 Myr; $\sim 500 \text{ Myr}$ for massive galaxies.
- Anisotropic thermal conduction can suppress evaporation, but ram pressure stripping still effective.