Perseus Large-Scale Cold Fronts

Merger Simulations

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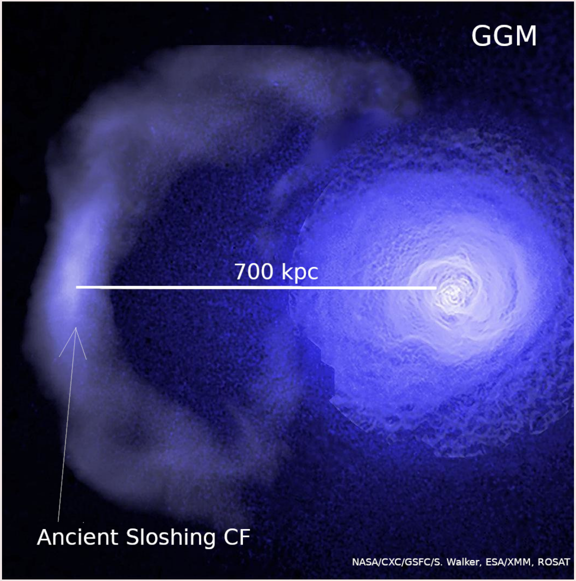
Context

- **Perseus** (brightest galaxy cluster in X-band) shows a richness of sloshing cold front
(CF) = sharp surface brightness discontinuities, the brighter (and therefore denser) side of the discontinuity is the colder side

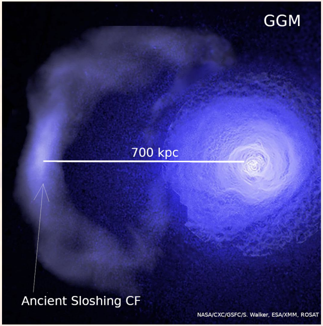
- Off-axis passage of a **subcluster** $\rightarrow$ transfer angular momentum to the gas gravitational potential $\rightarrow$ spiral-shaped CF (sloshing CF)

- **Ancient CF**: Simionescu et al. (2012) and Walker et al. (2018) have found a CF 700 kpc from the core to the east (nearly half the virial radius) in Perseus



GGM $\sim$ Surface brightness gradient (shows edges)

¿? How old is the CF at around 700 kpc (half virial radius)?



¿? Does the age of that CF depend on the initial conditions of the simulations?

¿? Under which conditions large-scale CFs do not get disrupted?

¿? Are there simulations that do not reproduce at all the observations?

Method

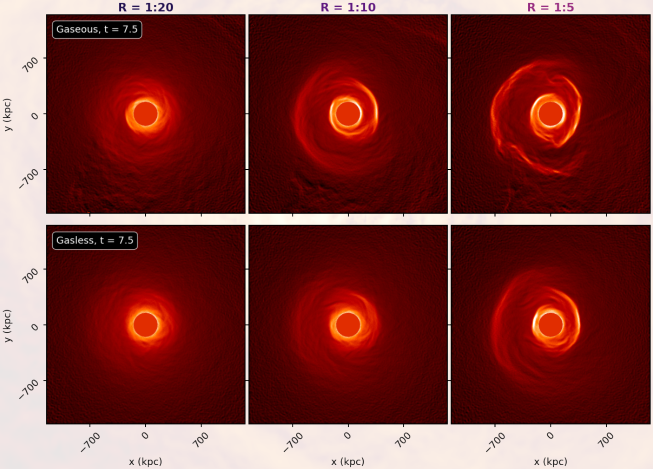
- AREPO simulations: magnetized ($\beta = P_{\rm th}/P_{\rm B}$), fully ionized ideal fluid + virialized DM halos
- Perseus-like main cluster
- infalling subcluters with mass ratio $R = M_{200c,\rm sub} : M_{200c,\rm main}$, and velocity $\vec{v}_{\rm sub}$
- parametric study of a merger

Physical Parameter	**Possible Values**
gas content of the gas	gaseous / gasless
mass ratio	R = 1:20, 1:10, 1:5, 1:2
incident angle	$\theta = 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ$
initial velocity	$v = v_{sub} = 1300, 1500, 2000$ km s^{-1}
magnetic field	off, $\beta = 100, 200, 1000$

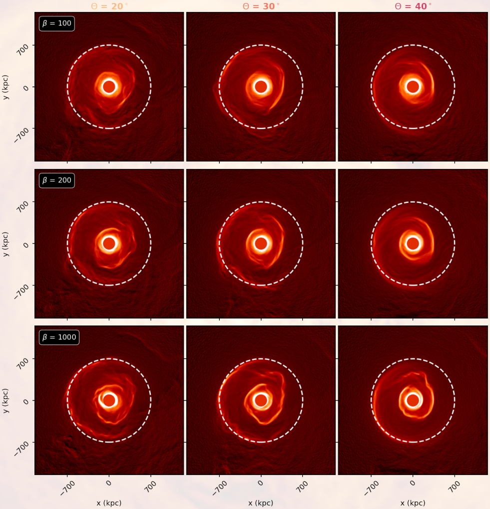
NB: previous investigations GASLESS subcluster to make CF that are not too messy

Some Results

Different Masses

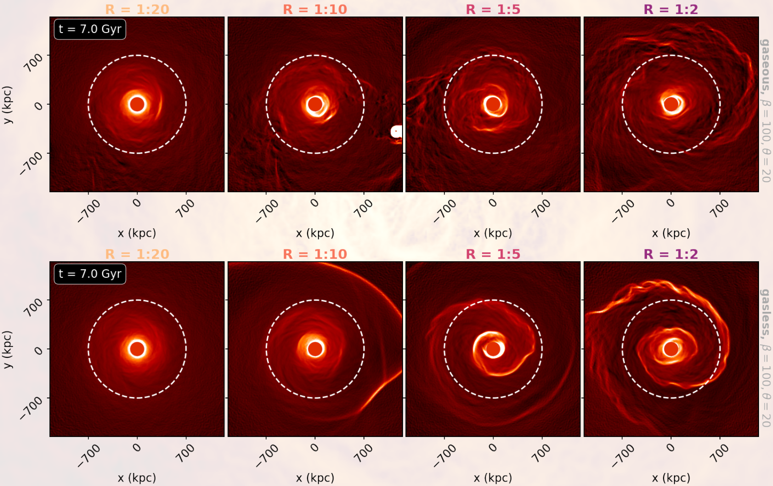


- We can reproduce CF at large radii if mass ratio not too small



- If only one passage, no need to invoke gasless cluster
- If only one passage, the expansion speed of CF is (in first approximation) independant of the parameters

Multiple passages (different mass and gas content)



- Multiple passages of the subcluster make the CF "messy"

Conclusions

- CF at 700 kpc after 7-8 Gyr from pericenter passage (in case of one single passage)
- The shape of the CF depends on the history of the passages of the subcluster
- Multiple passages of the subcluster make the CF "messy"
- No need to invoke gasless subcluster simulations to explain the "unmessy" spiral-like CF. Simulations of mergers with gaseous subcluster show a preserved sloshing CF if there is just one passage of the subcluster
- If mass ratio too small, not very visible CF (true for both gasless and gaseous subclusters)
- ancient CF not blurred out over time, sharp, structure preserved

Appendix

Perseus-like profiles

The total density profiles of the main cluster is chosen as a superNFW (sNFW) profile [**?**].:

$$\rho_{\rm sNFW}(r) = \frac{3M}{16\pi a^3}\frac{1}{x(1+x)^{5/2}}, \quad (1)$$

where concentration parameter $x = c_{\rm sNFW} = r/a$,

$$M_{\rm sNFW}(r) = M\left[1 - \frac{2+3c_{\rm sNFW}}{2(1+c_{\rm sNFW})^{3/2}}\right]. \quad (2)$$

$\rho_{\rm sNFW} \propto r^{-3.5}$ at large radii, and its mass profile converges as $r \rightarrow \infty$.

Perseus-like profiles

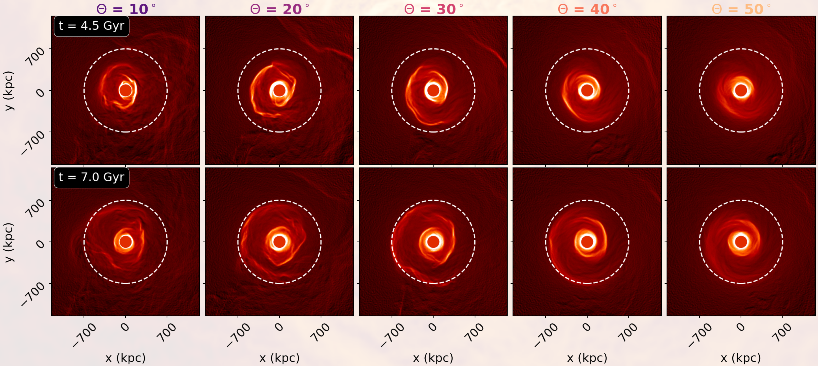
The three-dimensional gas density distribution of the main cluster is modeled by a Vikhlinin 2006 profile with a flat slope at small radii:

$$\rho = \frac{\rho_{c1}}{[1+(r/r_{c1})^2]^{1.5\beta_1}} + \frac{\rho_{c2}}{\left(1+r^2/r_{c2}^2\right)^{1.5\beta_2}} \frac{1}{\left(1+r^\gamma/r_s^\gamma\right)^{\varepsilon/2\gamma}}. \quad (3)$$

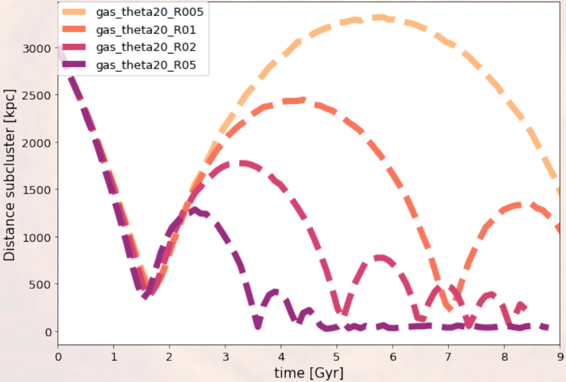
Comparing the observed gas density in [**?**, **?**], we modeled the initial main gas density profile with these parameters: the core radius of the first β-model $r_{c1} = 55$ kpc, a critical electronic density $n_{e,c1} = 4.5 \times 10^{-2}$ cm^{-3}, which correspond to a critical density $\rho_{c1} = \times 10\ M_\odot$ kpc^{-3}, and the beta parameter $\beta_1 = 1.2$. For the second term in Vikhlinin profile, we used a critical electronic density $n_{e,c2} = 4 \times 10^{-3}$ cm^{-3}, radii scales $r_{c2} = 180$ kpc and $r_s = 1800$ kpc, and parameters $\beta_2 = 0.6$, $\gamma = 3$, $\varepsilon = 3$.

Different Angles

Most probable value of θ is $\sim$ 30 (ref: Li et al 2020)



Subcluster Distance from Main Cluster



Initial velocity

- difficult to distinguish between effect of multiple passages and the parameters
- most probable velocity is v(R=200c)
- $v_{\rm sub} = 2000 \rightarrow$ subcluster does not come back for most angles

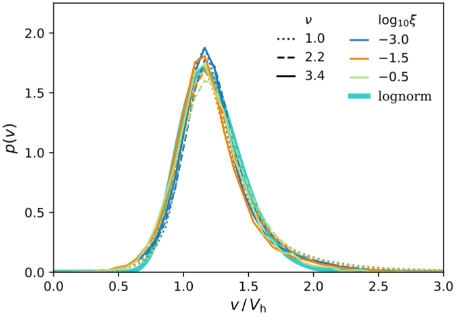


Figure 4. Infall velocity distribution for different host mass ν and sub-to-host ratio ξ bins. ν and ξ of each bin are indicated by the line style and color, respectively. The cyan thick solid line shows our model (Equation (1)), which is a log-normal distribution.

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Initial angle and mass ratio

- most probable angle $\sim$ 30 for R $=$ 1:5

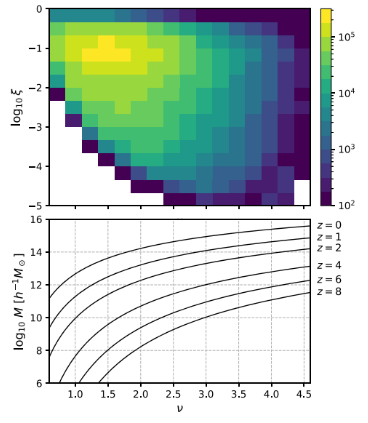

Figure 1. Number of halo pairs binned by the host halo's peak height, ν, and the sub-to-host mass ratio, $\xi = m/M_h$. The relations between mass and ν at various z are shown in the lower panel for reference.

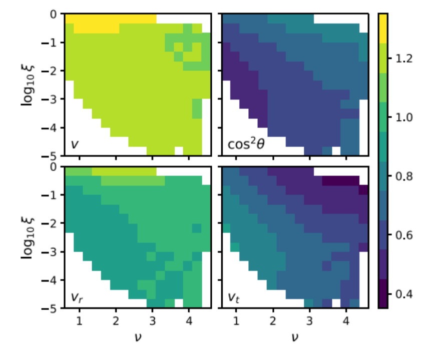

Figure 3. Orbital parameters as a function of the host mass ν and sub-to-host ratio ξ. The four panels show respectively the median values of v, v_r, and v_t and the mean of $\cos^2\theta = v_r^2/v^2$ for merging halos binned by ν and ξ. All velocities are shown in units of the host virial velocity. The subhalos with higher ν or ξ are more likely to fall along the radial direction due to smaller v_t, though they have a similar v_r and almost the same total velocity as their low ν, ξ counterparts.