N-body + Hydrodynamical Simulations of Merging Clusters of Galaxies: Comparison with 1E0657-56

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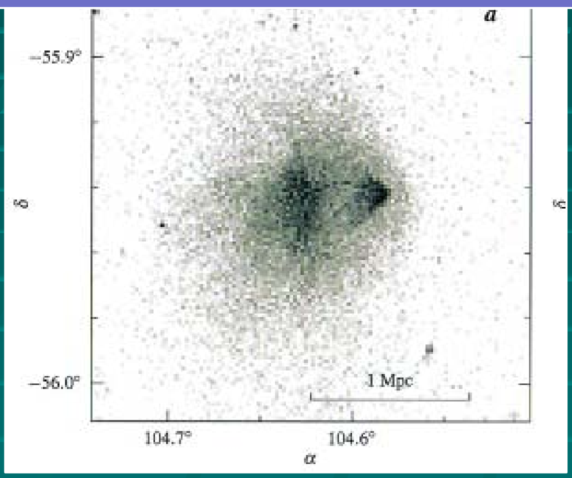
1E 0657-56 Cluster

X-ray image
(Markevitch et al. 2002)

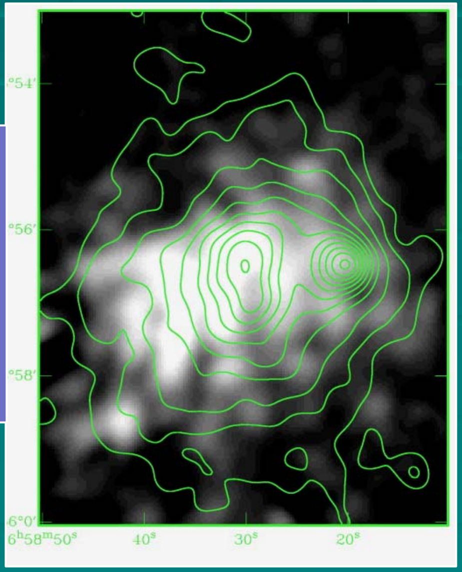


Liang et al. (2000)

Contour: X-ray

(ROSAT HRI)

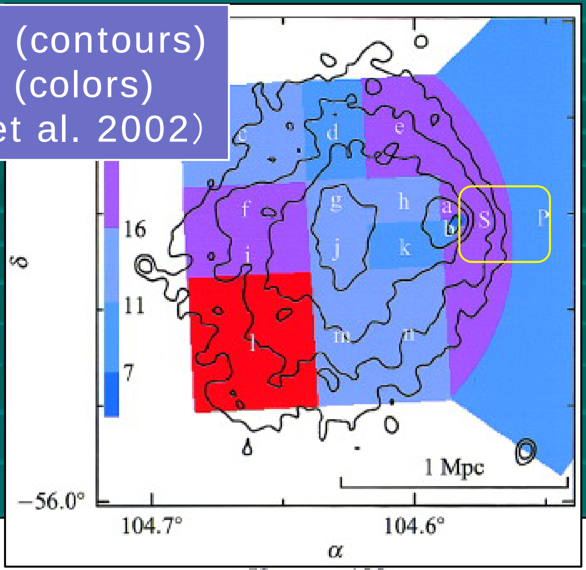
Gray scale: radio



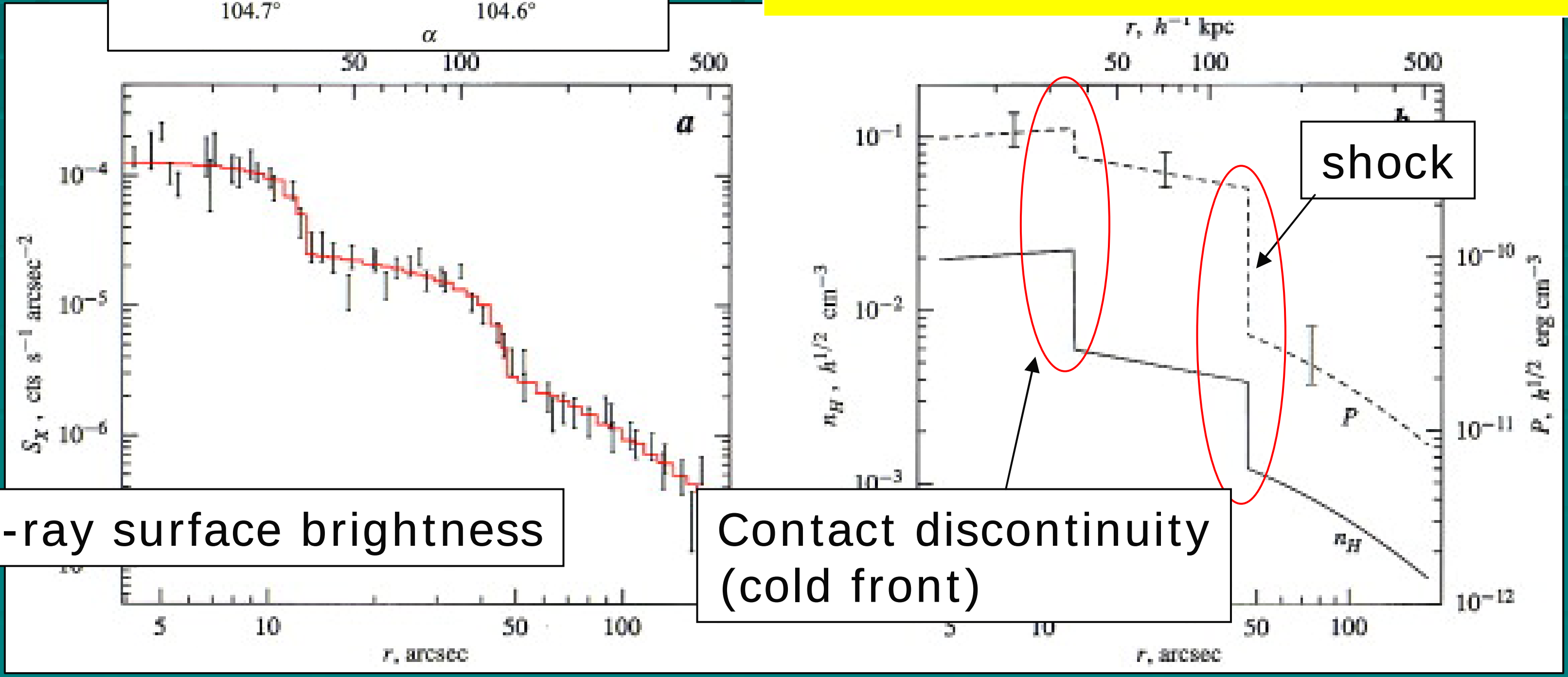
- z=0.296
- The hottest known cluster (～17keV)
- A very powerful radio halo
- First observational example of shocks in ICM
- Mass map through weak gravitational lensing

1E 0657-56: cold front & bow shock

X-ray image (contours)
Tenperature (colors)
Markevitch et al. 2002)



Density and pressure profiles in front of the substructure

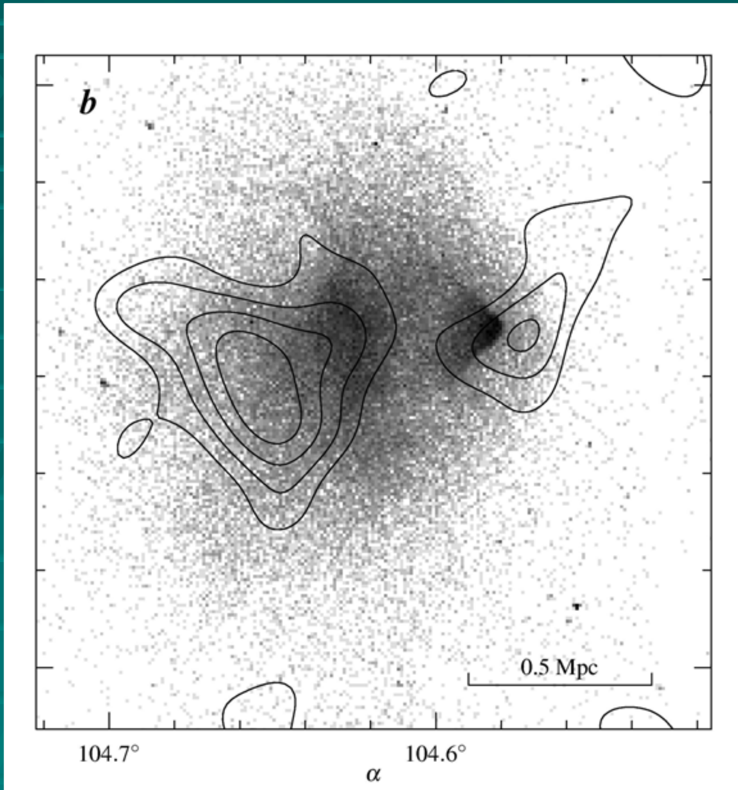


shock

X-ray surface brightness

Contact discontinuity (cold front)

1E 0657-56: mass distribution



X-ray image (gray scale)
Surface mass density (contours)
Clowe et al. (2004)

- Mass distribution is investigated through weak lensing.
- Clear offsets of the mass density peaks from the X-ray peaks are found.
- Distribution of the member galaxies is quite similar to that of mass.

Does this structure occur because the ICM experiences ram pressure but the dark matter and galaxies do not ?

Numerical Method (N-body+Hydro)

- N-body：Particle Mesh(PM) method
- Self-gravity：FFT with isolated boundary conditions
- Hydrodynamics：Roe TVD method
  - zero gradient boundary conditions（but, only outflow is permitted）
- Number of the grid points 256×128×128
- Number of the N-body particles 256×128×128(≒4.2×10^6)
- VPP5000@NAOJ

Virialized Cluster Model

- DM: NFW model、ICM: β model　($r_c=r_s/2$)

DM density profile

$$\rho_{\rm DM}(r) = \frac{\delta_c \rho_{c0}}{(r/r_s)(1+r/r_s)^2},$$

ICM density profile

$$\rho_{\rm g}(r) = \rho_{\rm g,0}\left\{1+\left(\frac{r}{r_{\rm c}}\right)^2\right\}^{-\frac{3}{2}\beta}$$

- $r \geqq r_{vir}$　$\rho_{\rm DM}=0$ and $\rho_{\rm gas}$=constant
- DM velocity distribution is an isotropic Maxwellian. Radial profile of DM velocity dispersion is determined from the Jeans equation.

$$\frac{d}{dr}\left(\rho_{\rm DM}\sigma^2\right) = -\frac{GM_r}{r^2}\rho_{\rm DM}$$ with $$\sigma^2(r_{\rm out}) = \left.\frac{GM_r}{3r}\right|_{r=r_{\rm out}}$$

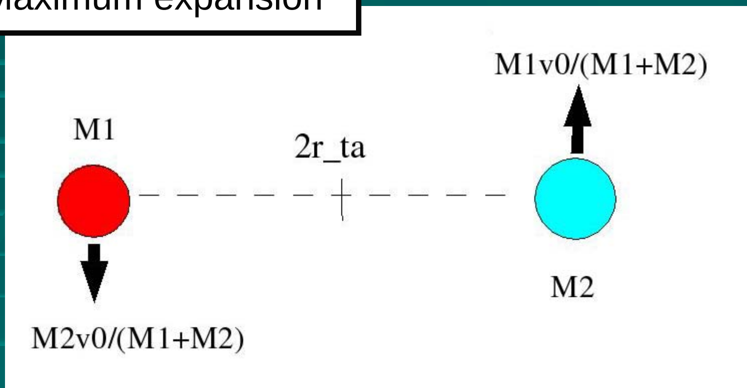
•Radial profile of ICM pressure is determined from the hydrostatic equation.

$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho_{\rm g}$$ with $$P(r_{\rm out}) = \left.\frac{1}{\beta}\frac{GM_r\rho_g}{3r}\right|_{r=r_{\rm out}}$$

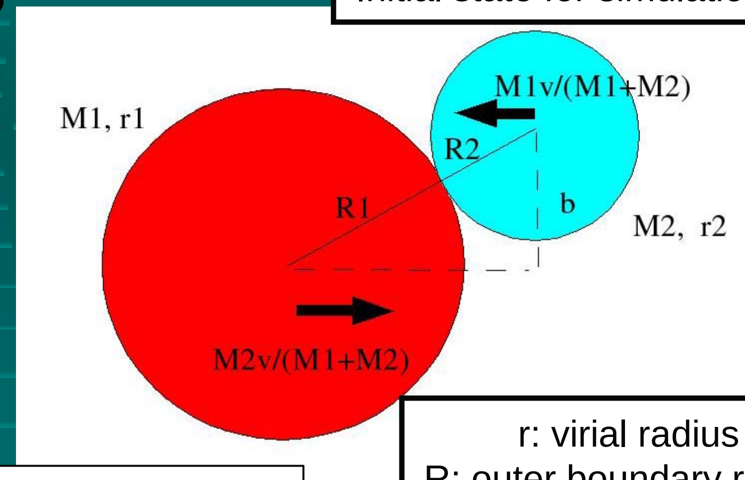
- $r \leqq r_{out}$　$M_{gas} / (M_{gas}+M_{DM}) = 0.1$

How to make initial conditions for mergers

Maximum expansion



Initial state for simulations



r: virial radius
R: outer boundary radius

energy conservation
Angular momentum conservations

$$-\frac{GM_1M_2}{2r_{\rm ta}} + \frac{1}{2}Mv_0^2 = -\frac{GM_1M_2}{R_1+R_2} + \frac{1}{2}Mv^2$$
$$2Mv_0r_{\rm ta} = Mvb$$

Using scaling relation $R \propto M^{(5+n)/6}$ and $r_{ta} = 2\, r_{vir}$ (Spherical collapse model), we obtain the following equations

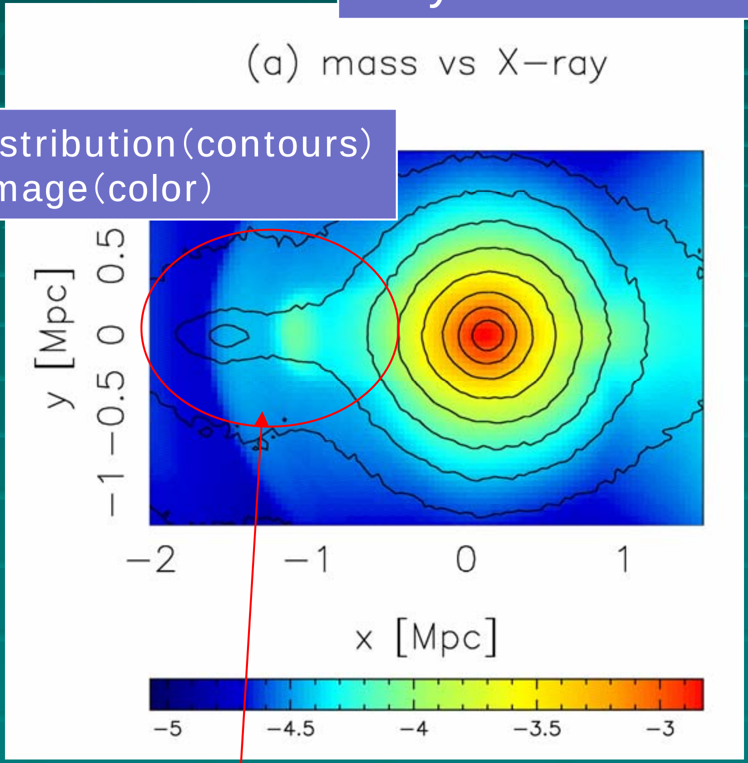
$$v^2 = \frac{2GM_1}{R_1}(1+\alpha)\left\{\frac{1}{1+\alpha^{(5+n)/6}} - \frac{1}{4(1+\alpha)^{(5+n)/6}}\frac{R_1}{r_1}\right\}\left\{1 - \frac{1}{16(1+\alpha)^{(5+n)/3}}\left(\frac{b}{r_1}\right)^2\right\}^{-1}$$
$$\alpha = \frac{M_2}{M_1}$$

$$\lambda \equiv \frac{J|E|^{1/2}}{G(M_1+M_2)^{5/2}} = \frac{vb}{(GM_1R_1)^{1/2}}\frac{\alpha^{3/2}}{(1+\alpha)^{7/2}}\left\{\frac{1}{1+\alpha^{(5+n)/6}} - \frac{R_1v^2}{2GM_1}\frac{1}{1+\alpha}\right\}^{1/2}$$

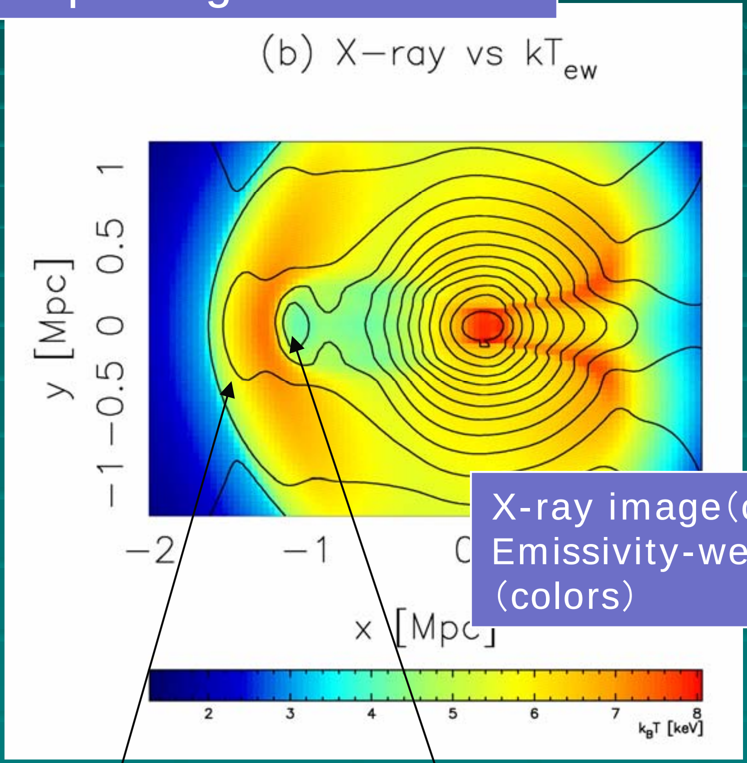
$(M_1, r_1, R_1, \alpha, n, \lambda)$
⬇
(v, b)

Comparison with 1E0657-56

Head on merger with mass ratio=16:1,
1Gyr after the core passage



Mass distribution（contours）
X-ray image（color）



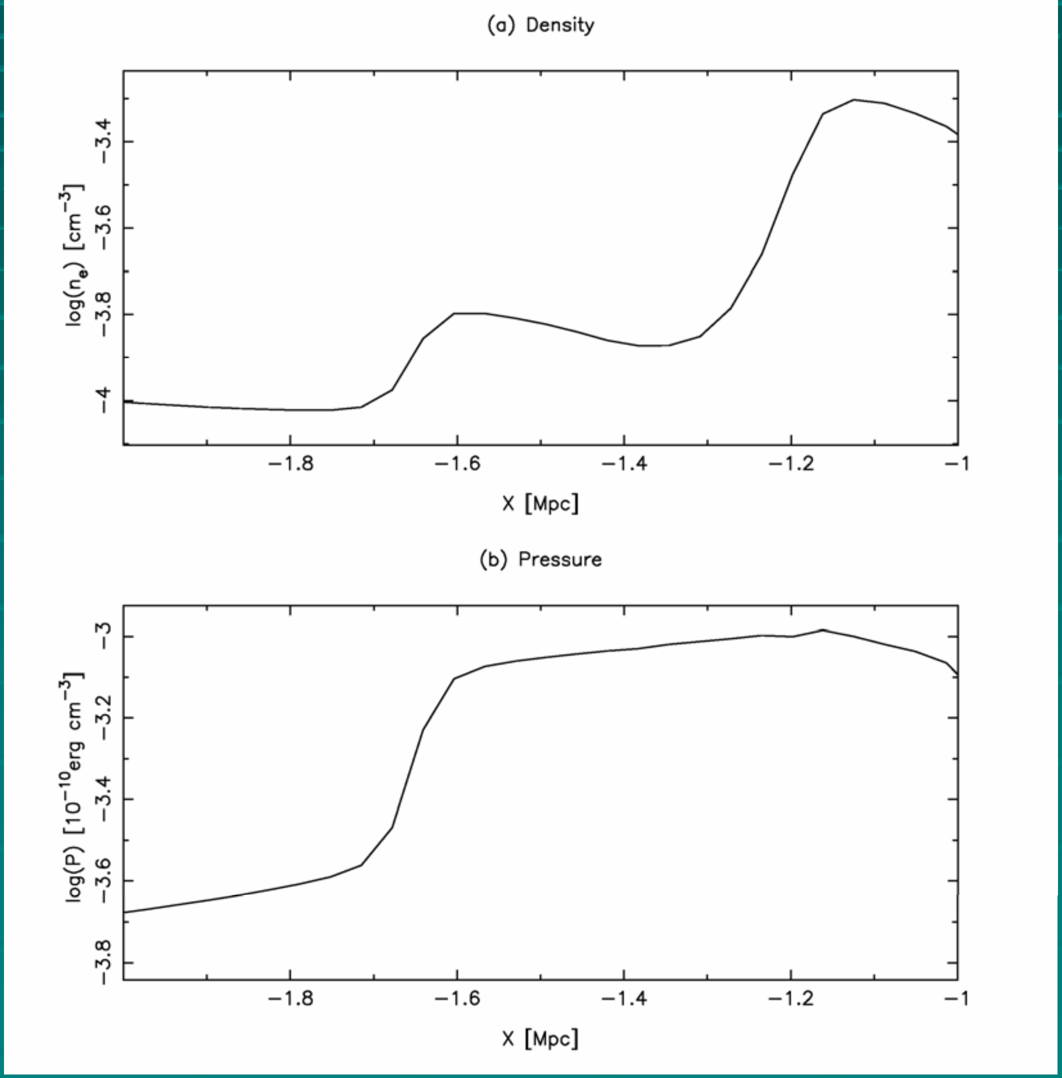
X-ray image（contours）
Emissivity-weighted kT
（colors）

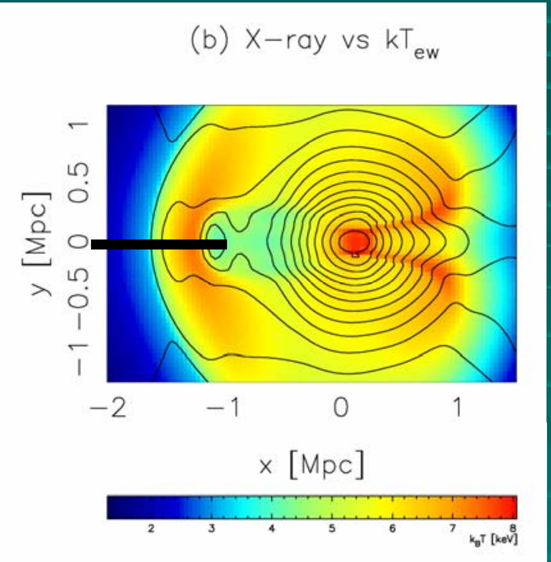
Bow shock

Cold front
(contact discontinuity)

X-ray peak lagged behind mass peak

Bow shock and Cold Front





Discussion on the Rum Pressure Stripping Conditions（1）

Consider the head-on merger of two NFW clusters with masses M_1 and M_2 (M_1>M_2). If the gravity on the subcluster's ICM is weaker than the rum pressure force, the ICM will be stripped from the subcluster's potential.

$$\frac{Gm_2\rho_2}{r_2^2} < A(\pi r_2^2\rho_1 v^2)(\frac{4}{3}\pi r_2^3)^{-1},$$

$r_{1,2}$: virial radius $\rho_{1,2}$: central gas density r_2: scale radius m_2: mass inside r_2
A: fudge factor of an order of unity, likely A<1

Collision velocity v

$$v^2 \simeq \frac{2G(M_1+M_2)}{R_1+R_2},$$

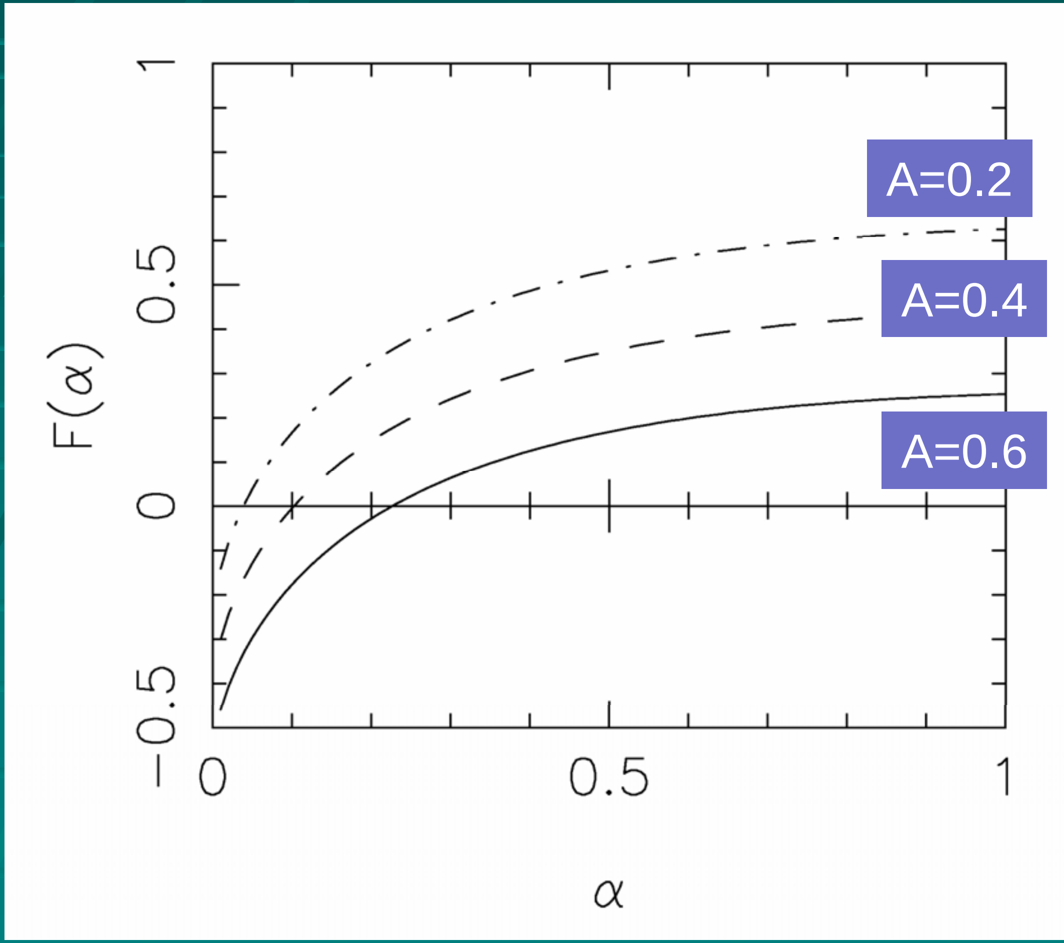
Introduce a new parameter $\alpha \equiv M_2/M_1$. Then, $R_2/R_1= \alpha^{1/3}$, $\rho_1/\rho_2= \alpha^{-x}$ (in the ΛCDM, x～0.25). The above-mentioned condition becomes

$$F(\alpha : M_1) \equiv \alpha^{2/3-x}\frac{1+\alpha^{1/3}}{1+\alpha} - \frac{3A}{2g(\alpha M_1)c(\alpha M_1)} < 0.$$

$c=r_2/R_2$: oncentration parameter

$$g(M_2) \equiv \frac{m_2}{M_2} = \frac{\ln 2 - 1/2}{\ln(1+c) - c/(1+c)},$$

Discussion on the Rum Pressure Stripping Conditions(2)



F(α)<0: ram pressure dominant

α=M_2/M_1

When α is less than ∼0.1, ram pressure dominates the gravity.

ICM is more easily stripped from the less massive subcluster.

Discussion on the Rum Pressure Stripping Conditions（3）

- Ram pressure ≪gravity
  - Gas behaves like DM.
  - DM peaks will correspond with X-ray peaks.
- Ram pressure ≫ gravity
  - ICM in the substructure cannot penetrate the larger cluster’s center.
  - The larger cluster’s ICM is so hot that it cannot be bound by the substructure’s potential.
  - Mass peaks are associated with no X-ray peaks.
- Ram pressure ≒gravity
  - Clear off-set of the mass peak from the X-ray peak

Summary

- We study dynamical evolution of merging clusters of galaxies using N-body + hydrodynamical simulations.
- We investigate the X-ray and mass structures in the merging galaxy cluster 1E0657-56.
- We first reproduce a clear off-set of an X-ray peak to a mass peak in N-body + hydrodynamical simulations.
- We discuss the ram pressure-stripping conditions in the mergers of two clusters with an NFW density profile using a simple analytic model.
  - ICM is more easily stripped from the smaller subclusters.
  - The ram pressure dominates the gravity of the substructure when the smaller cluster’s mass is less than approximately one tenth of the larger cluster’s mass.
- The characteristic X-ray and mass structures found in 1E0657-56 suggest that the mass ratio between the progenitors is close to the above-mentioned critical value.