# How do Galaxies Interact with Intra-Cluster Medium (ICM)?

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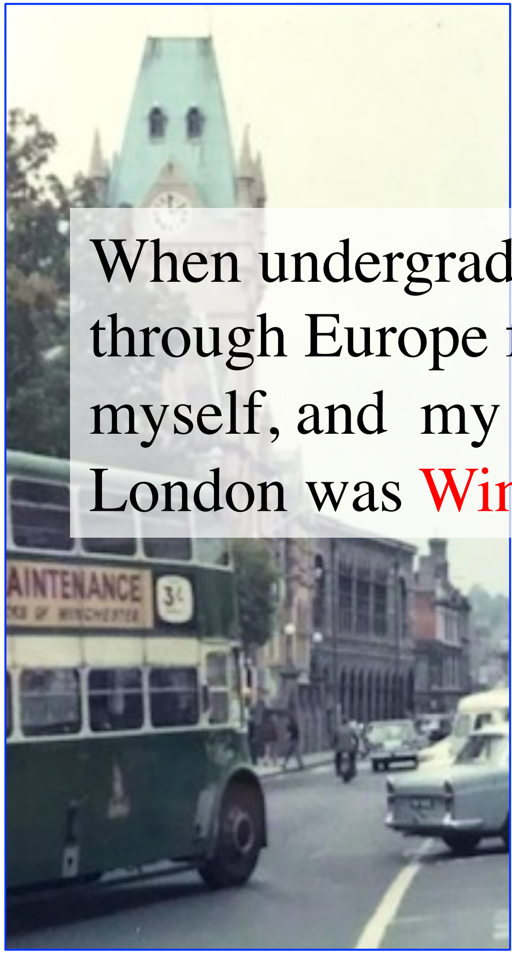
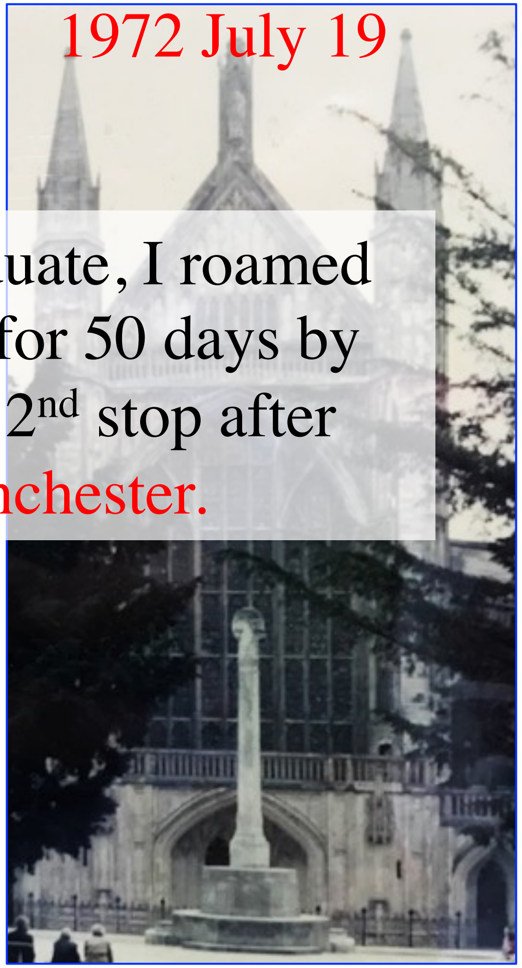
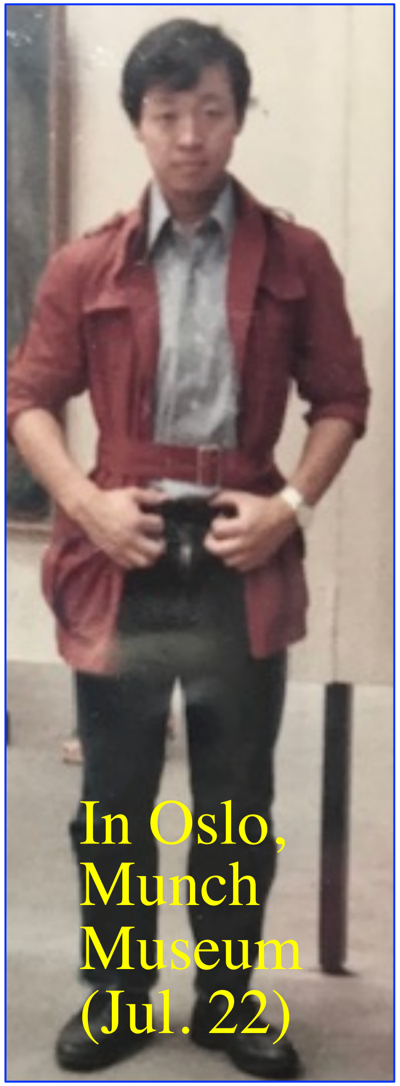


1972 July 19



When undergraduate, I roamed through Europe for 50 days by myself, and my 2nd stop after London was Winchester.



In Oslo, Munch Museum (Jul. 22)

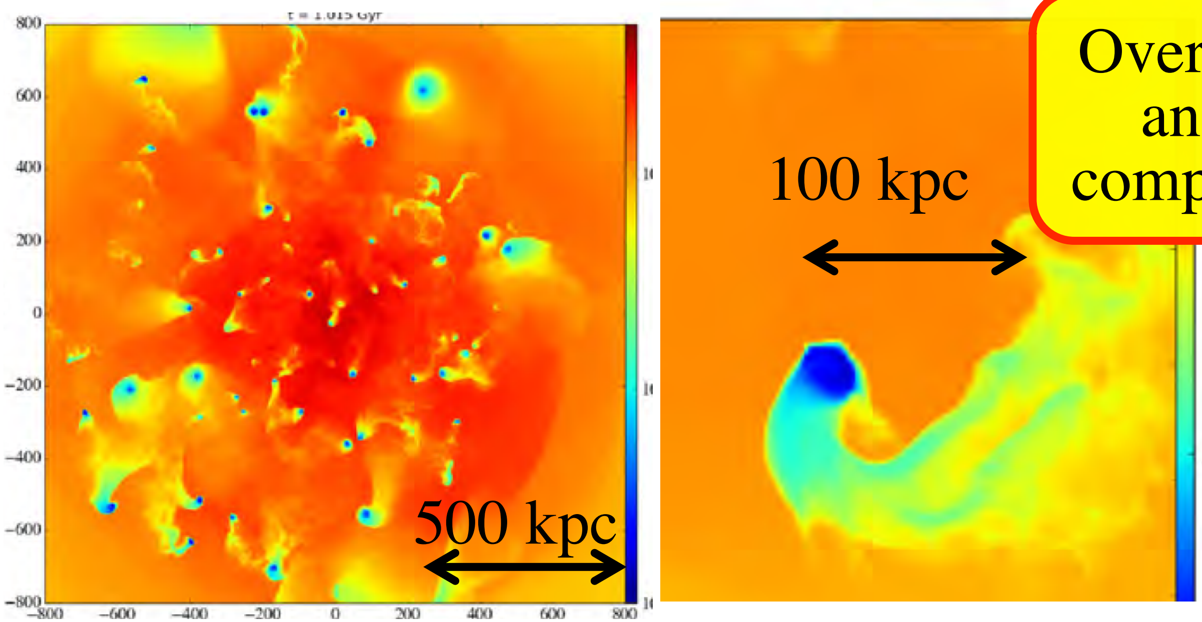
# 0. Introduction

Hereafter CLG

*PhD Thesis, Rukumani Vijayaraghavan (2015 U. Illinois)*

"Clusters of galaxies are harsh environments for their constituent galaxies. A variety of physical processes effective in these dense environments transform gas-rich, spiral, star-forming galaxies to elliptical or spheroidal galaxies with very little gas."

Over $t_H$, a galaxy "sweeps" an ICM mass which is comparable to its own mass

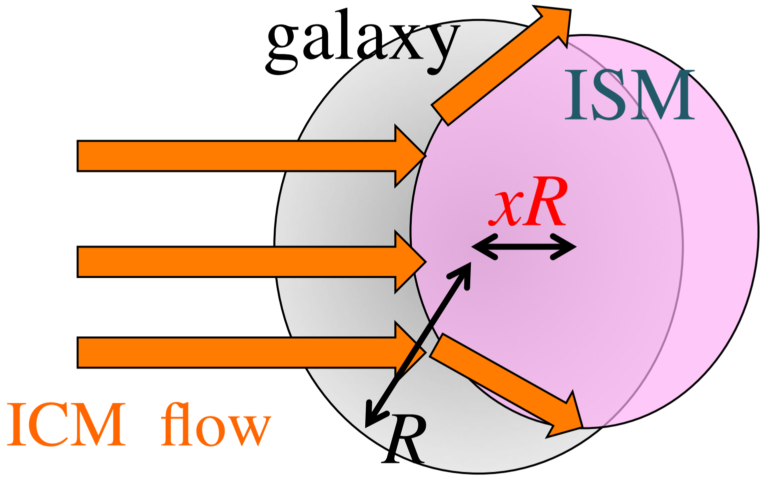



Temperature maps of ICM in a simulated young CLG (Vijayaraghavan +Ricker 2017)

*ASCA* results => Gal's interact strongly with ICM (KM+01).

# 1. Galaxies Do Interact with ICM

- ICM, in-flowing with velocity *v*, exerts ram pressure and viscous friction to ISM.
- If the force is mild, it displaces ISM by *xR* (Roediger +2015).
- By gravity, the displaced ISM pulls the whole galaxy.



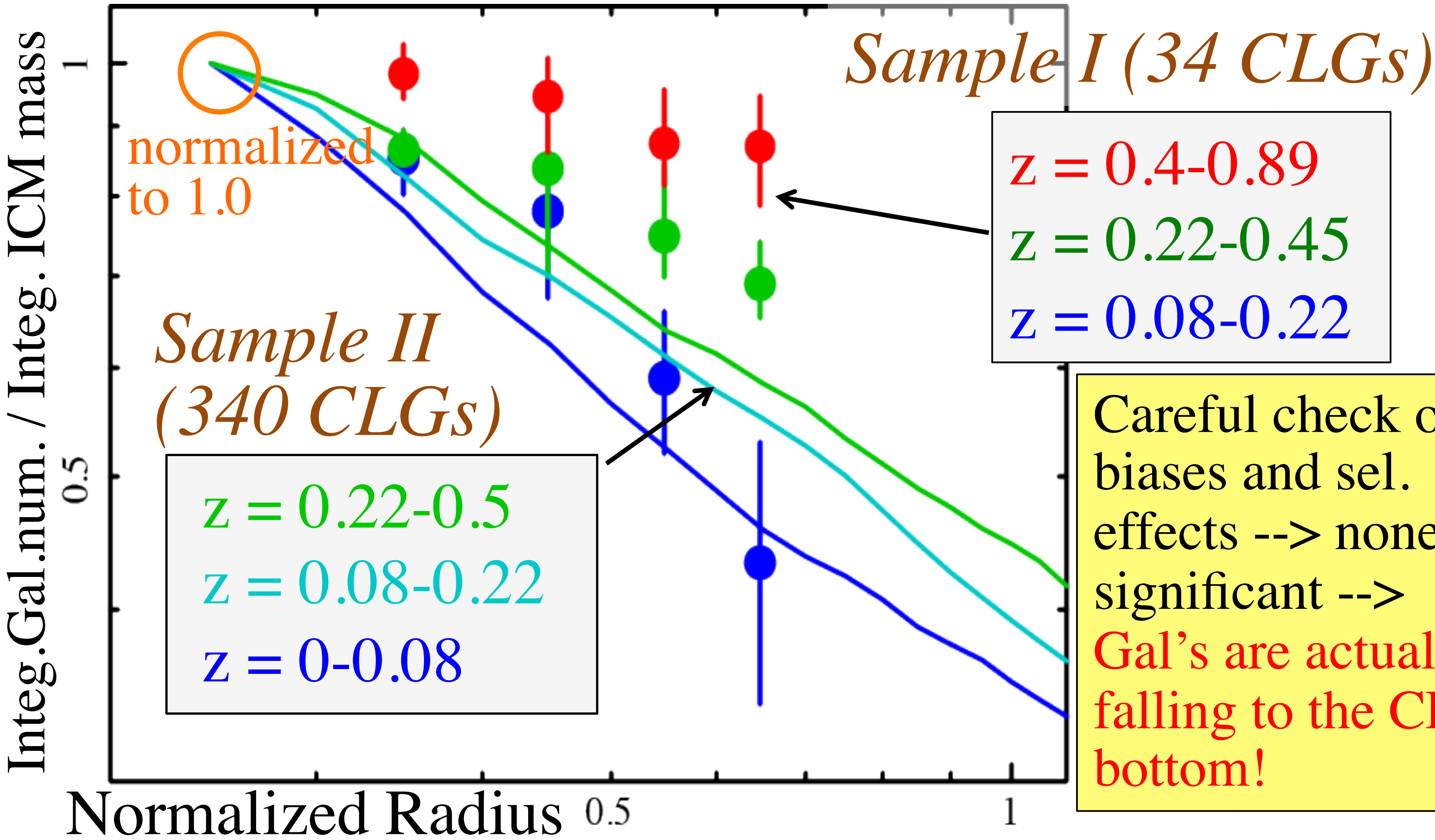

$$x \sim 0.5\ (\gamma/0.01)^{-1}\ (R/10\text{kpc})^{4}\ (n_e/10^{-3})\ (M_g/10^{11}M_0)^{-2}\ (v/10^{8})^{2}$$

fractional ISM mass ($\gamma$); ICM density ($n_e$); galaxy mass ($M_g$); in-flow velocity ($v$)

- When $x<1$, ISM is bound, keep interacting with ICM, and transmitting the ram pressure to the whole galaxy.
- Dynamical friction provides additional interaction.

# 2. The Cosmological In-fall of Galaxies

Using two samples, we studied the optical/X-ray angular extent ratios of CLGs for their evolution (Gu, Gandhi, KM+13; Gu+16).




Careful check of biases and sel. effects --> none is significant --> Gal's are actually falling to the CLG bottom!

# 3. Distributions of Various Components

- At z~1, DM, gal's, and ICM had similar distributions.
- Towards z~0, gal's have been falling to the center relative to ICM, most likely due to the ICM drag.
- The prediction by KM+01 confirmed by Gu+13&16.

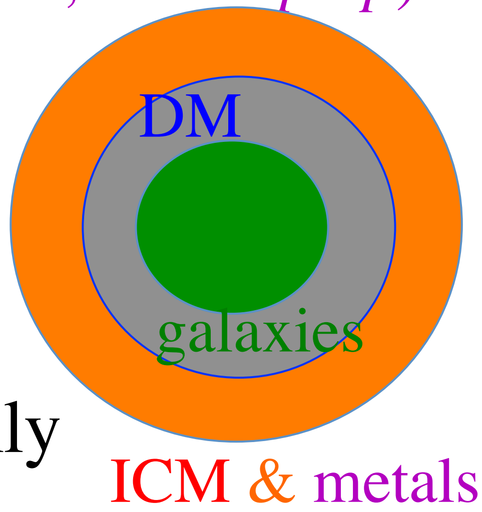
As immediate consequences, several well-known facts about present-day CLGs can be explained (Gu,KM+*in prep*).

✧ At z~0, gal's < DM, because they lost energies as they interacted with ICM.

✧ By receiving the energy from gal's, ICM > DM (and > gal's) at z~0.

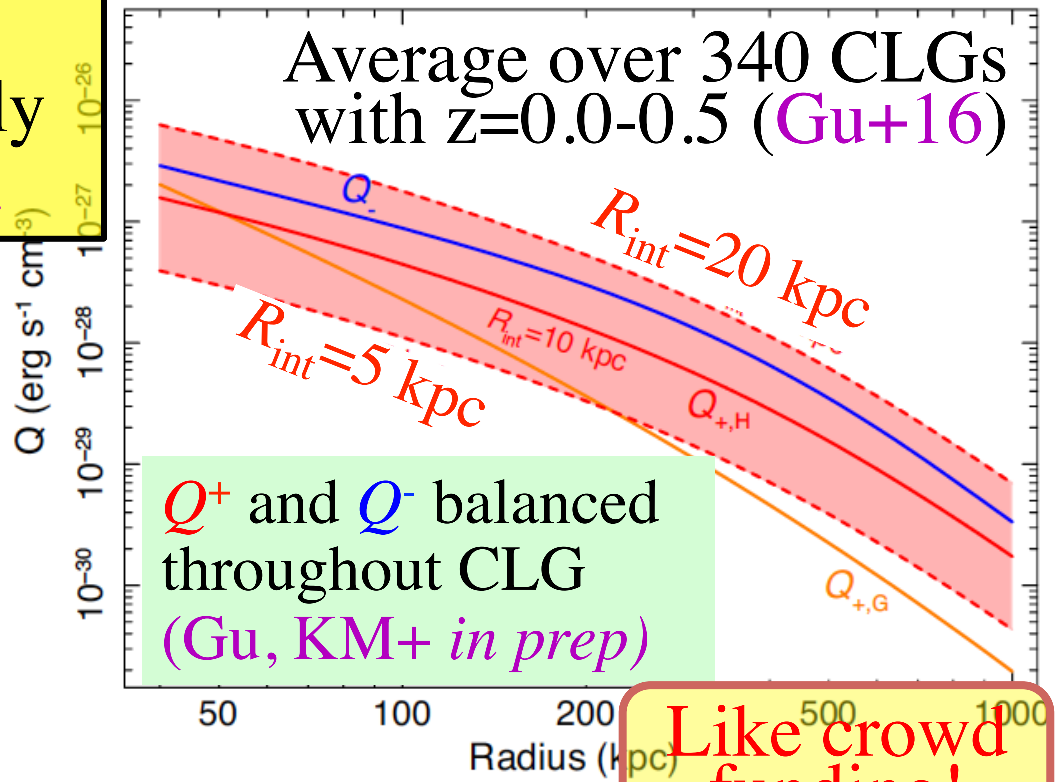
✧ Gal's, widely distributed at z~1, uniformly metal-enriched ICM out to periphery.

✧ At z~0, metals in ICM > gal's (Kawaharada+09).



# 4. Heating/Cooling of the ICM

The energy lost by gal's will heat ICM ubiquitously and uniformly (KM+01).




$Q^+$ and $Q^-$ balanced throughout CLG (Gu, KM+ *in prep*)

Heating/cooling rate (Sarazin 1988, KM+01):

$$Q^- = \Lambda(T,Z)\, n_i n_e$$

$$Q^+ = \pi R_{int}^2\, n_{gal}\, n_e m_p v^3$$

Interaction radius

Like crowd funding!

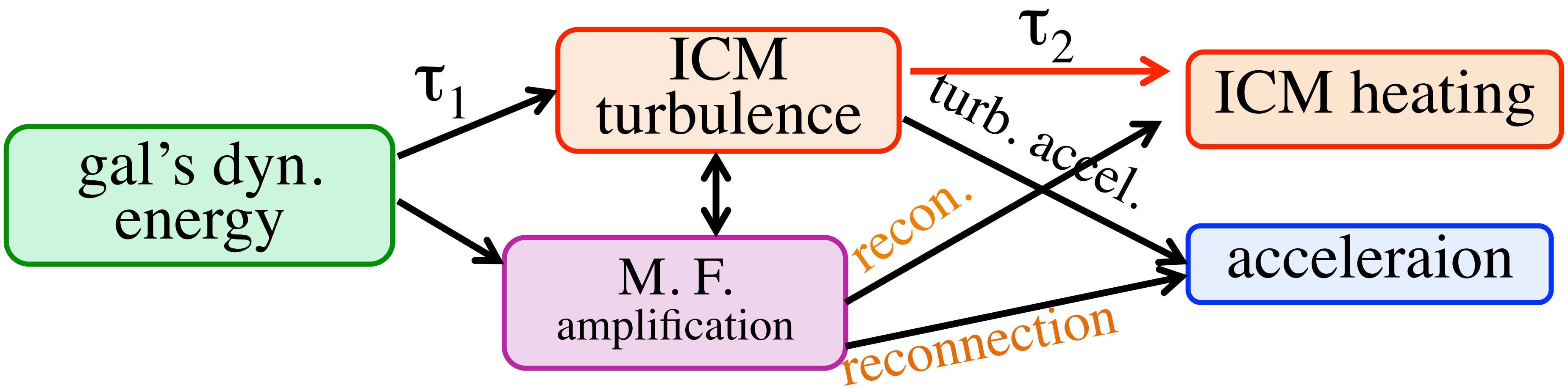
✧ ICM cools very locally, only in the core region. Thermal energy of ICM therein cannot sustain the high core $L$x.

✧ Gal's cool globally: every time a galaxy passes the CLG core, it loses a small fraction of its dynamical energy.

# 5. The Mild ICM Turbulence

✧Moving gal's lose energy on a time scale $\tau_1 \sim 0.1 t_H$ (in CLG cores), mainly by creating ICM turbulence (Vijayaraghavan+Ricker 17).

✧Turbulence dissipates on an MHD time scale, $\tau_2 \sim R_{gal}/v_A \sim$ 5e-3 $t_H$, where $v_A \sim 200$ kms/s $v_A$ is the Alfven velocity which is close to σ




✧ Steady state, in CLG cores: $M_{ICM}\,\sigma^2 \sim M_{gal}\, v^2\, (\tau_2/\tau_1)$ -->

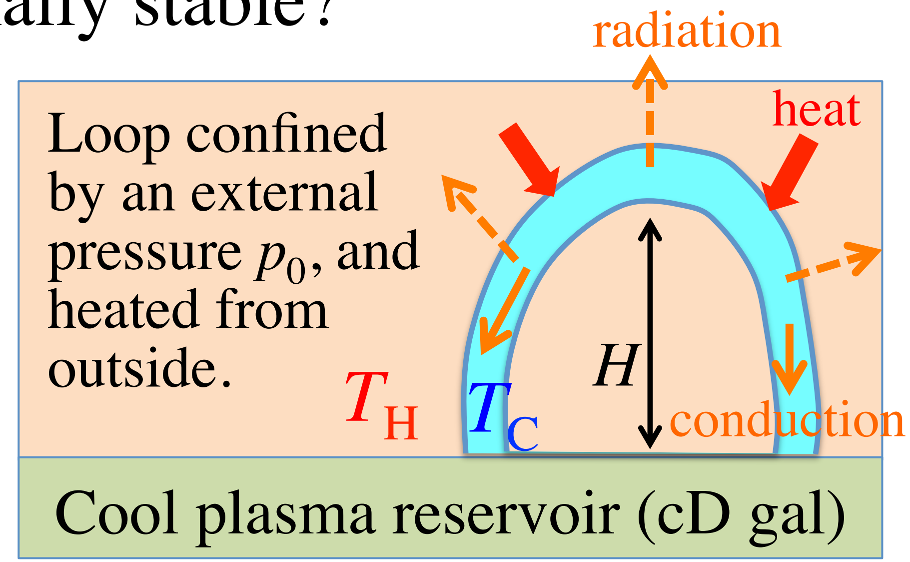
$\sigma \sim v \times \mathrm{sqrt}\{(M_{gal}/M_{ICM})(\tau_2/\tau_1)\} \sim v\ \mathrm{sqrt}\{1 \times 0.05\} \sim 200$ km/s

✧ The *Hitomi* results from the Perseus core can be explained in a natural way (Gu, KM+19, *in prep*).

# 6. Stability of the 2T Structure

- ✧ICM in a cool core is described by 2T (Ikebe+99, Takahashi+09, Gu+12), with $T_H \sim 2T_L$ (Allen+01; Kaastra+04).
- ✧The two phases may be in a pressure equilibrium. But, cooling rate $\propto n_e^2$, and any heating rate $\propto n_e$. How is the 2T configuration kept thermally stable?

The Rosner, Tucker, and Vaiana (1978) mechanism, proposed for Solar coronae and confirmed with *Yohkoh* (Kano+Tsuneta 95) ==> The loop interior is stable!




$$T_C^{max}\ (\text{keV}) \sim 2.2\ \{(p_0/10^{-10}\text{cgs})\ (H/30\text{kpc})\}^{1/3} \propto T_h^{3/4}$$

(Takahashi+09; Gu+12; Gu, KM+ *in prep*)

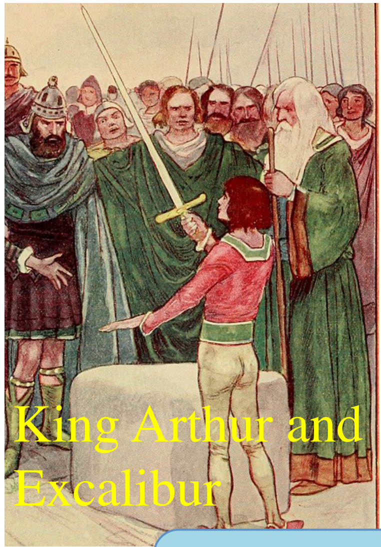
# 7. The Origin of Environmental Effects

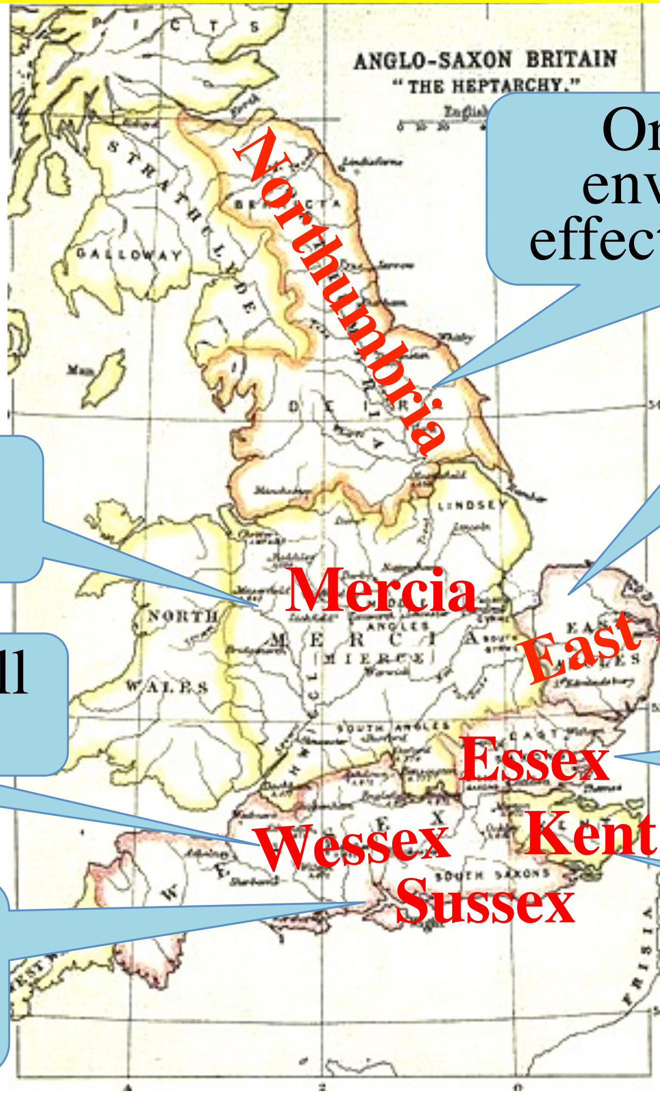
The environmental effects : Fractional spiral gal's decrease with time, and towards CLG centers ==>
At least qualitatively, these effects can be attributed to the galaxy vs. ICM interactions.

- ✧ ICM will remove ISM from spiral gal's, via ram pressure stripping and viscous friction.
- ✧ A spiral galaxy will dump its angular momentum onto ICM by launching twisted Alfven waves.
- ✧ Similarly, a pair of spirals will dump their orbital angular momentum, and merge into an elliptical.

# 8. Our Scenario can Rule the Heptarchy

**Gal's vs. ICM interaction; ordered mag. structure**




- Origin of the environmental effects on galaxies (Northumbria)
- Stable 2T structure with $T_H \sim 2T_L$ (East Anglia)
- Sufficient ICM heating luminosity (Mercia)
- Observed galaxy infall from z~1 to z~0 (Wessex)
- Mild ICM turbulence (Essex)
- Present-day distributions of the 3 components (Sussex)
- Uniform ICM metallicity (Kent)