Cosmological In-Fall of Galaxies towards the Bottom of Clusters

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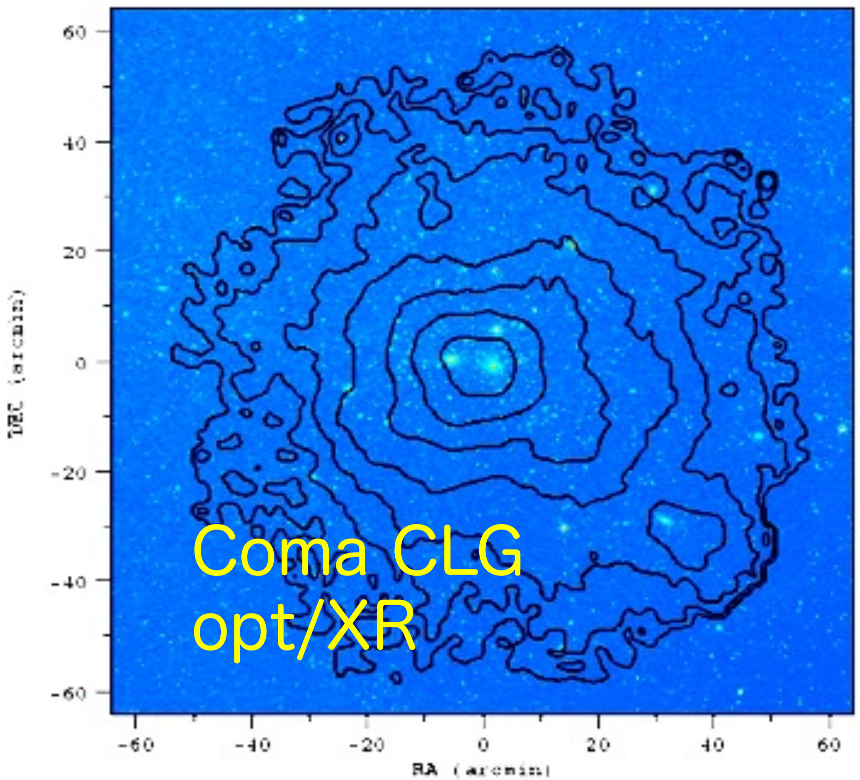

Gu+16, *ApJ.* 826, id.72
Gu+13, *ApJ.* 767, id.157
Takahashi+09, *ApJ* 707, 377
Makishima+01, *PASJ* 53, 401

Part I : Basics of CLGs

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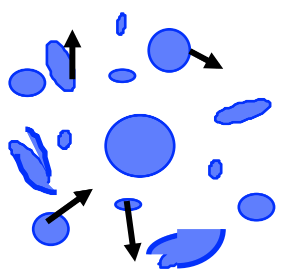
Part VI : Physics at CLG Cores

Part VII : Further Implications

A Cluster of Galaxies (CLG)

1. Galaxies ($10^{2\sim3}$)

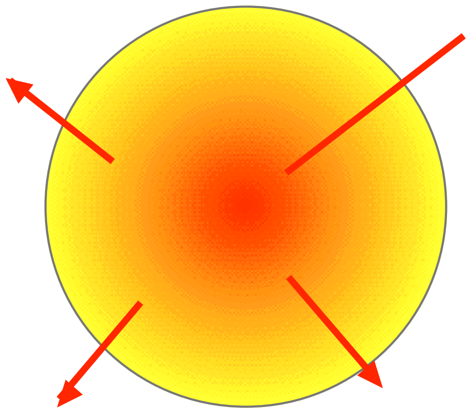
- ~5% of total mass
- Randomly moving with typ. velocity of 300-1000 km/s
- Most strongly concentrated



visible light

2. ICM (Intra Cluster Medium; hot plasma)

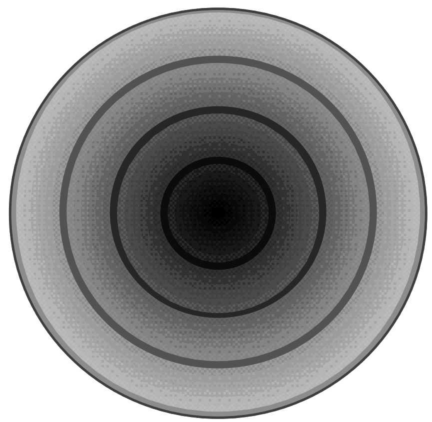
- Detectable in X-rays
- ~15% of tot. mass; the most dominant known component of baryons
- Heated & confined by gravity



X-rays

3. DM

- ~80% of the total mass
- Provides G-field necessary to confine galaxies and ICM.



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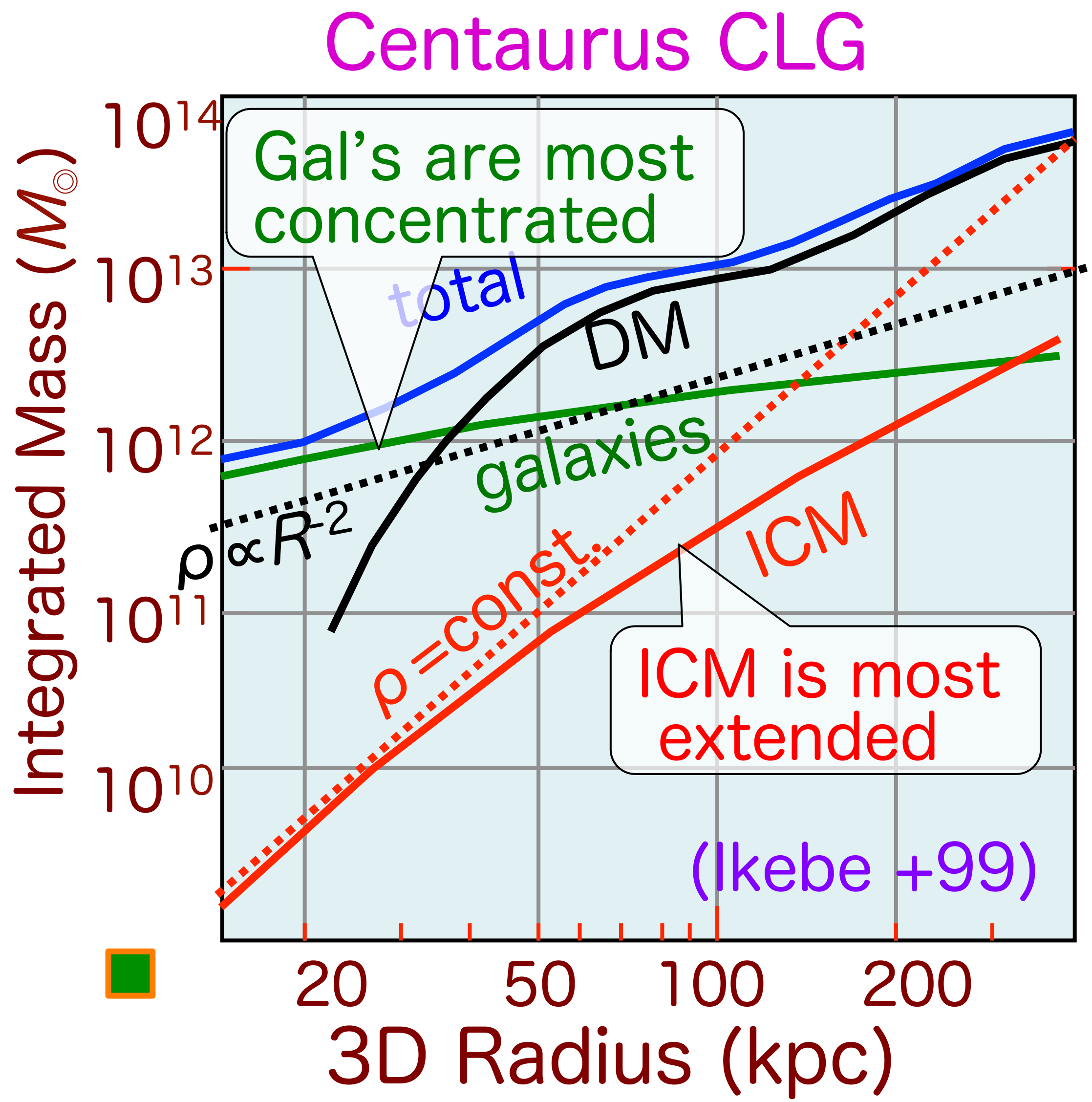
2a. Mass Distributions in Nearby CLGs

In nearby CLGs, the radial mass distributions are Gal's<DM < ICM.

This fact is well known, but how the 3 components came to show dif-fernt distributions?



2b. Possible Explanations

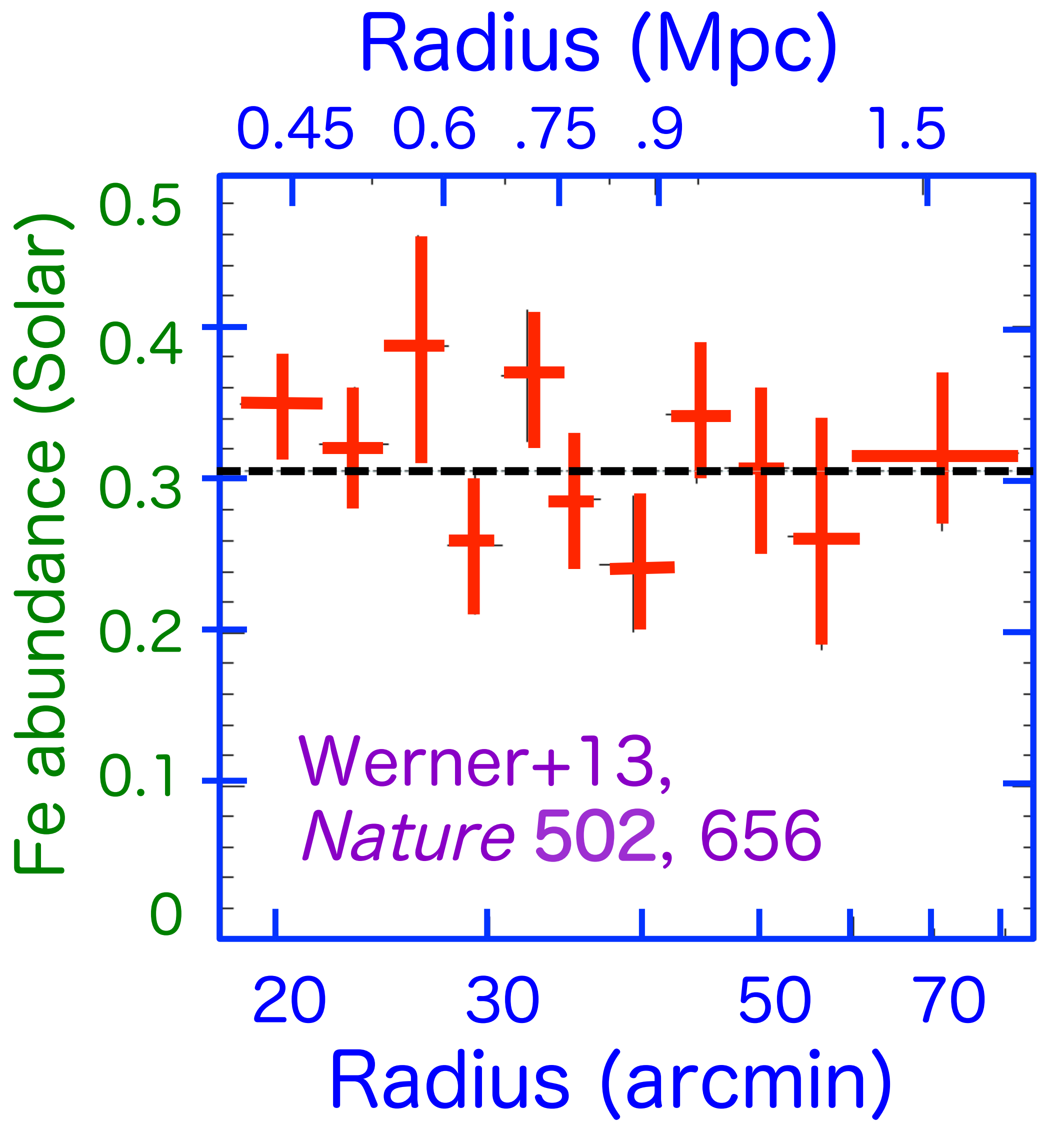
1) Gal's/stars formed with a higher efficiency in central regions of CLGs.
2) CLGs grew up by accretion of metal-poor gas onto their peripheries.
3) Gal's and ICM initially had simila[r] distributions, but gal's fell to the center relative to ICM.
4) ~~ICM expanded relative to gal's.~~

ICM metallicity should --> 0 towards CLG peripheries.

ICM should be metal enriched up to large radii

Energetically difficult

2c. Uniform ICM Metallicity at Large *R*



Observations of outskirts of nearby CLGs with *Suzaku*
==>
ICM metallicity is quite constant

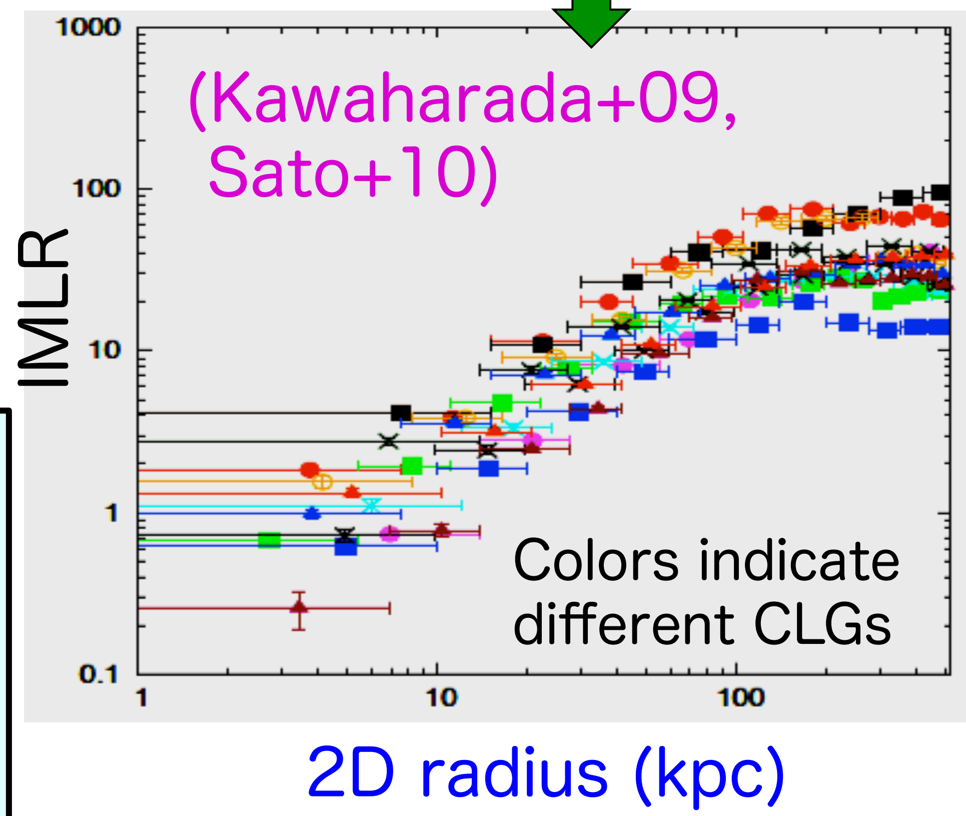
Scenarios 1) & 2) are ruled out, while 3) survives.

2d. Iron Mass to Light Ratio (IMLR)

IMLR = (Integ. Fe mass in ICM) /(Int. gal. light)
observed in nearby CLGs

Metals in ICM are more extended than gal's that must have produced them.

- ✧ Metals have ~~expanded to outer~~ regions?
- ✧ In the past, gal's were distributed to much larger radii than today.



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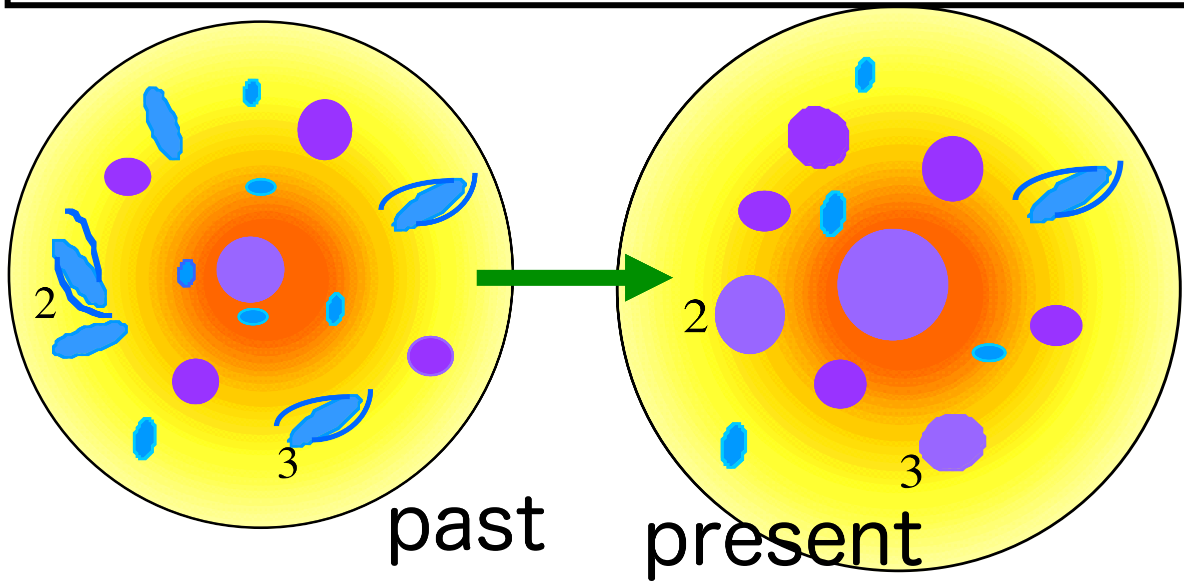
3a. Galaxy In-Fall Hypothesis Makishima+01

Gal's are moving randomly within cluster potential, with transonic velocities *wrt* ICM.

- ✧Gal's interacts with ICM via ram pressure and dyn. friction, and deposit energy and metals onto ICM.
- ✧Thus, gal's lost their dynamical energies in ~t_H, and fell down to the potential bottom.
- ✧ICM was heated and expanded relative to DM.



An energy-flow process from low-entropy gal's to high-entropy ICM.

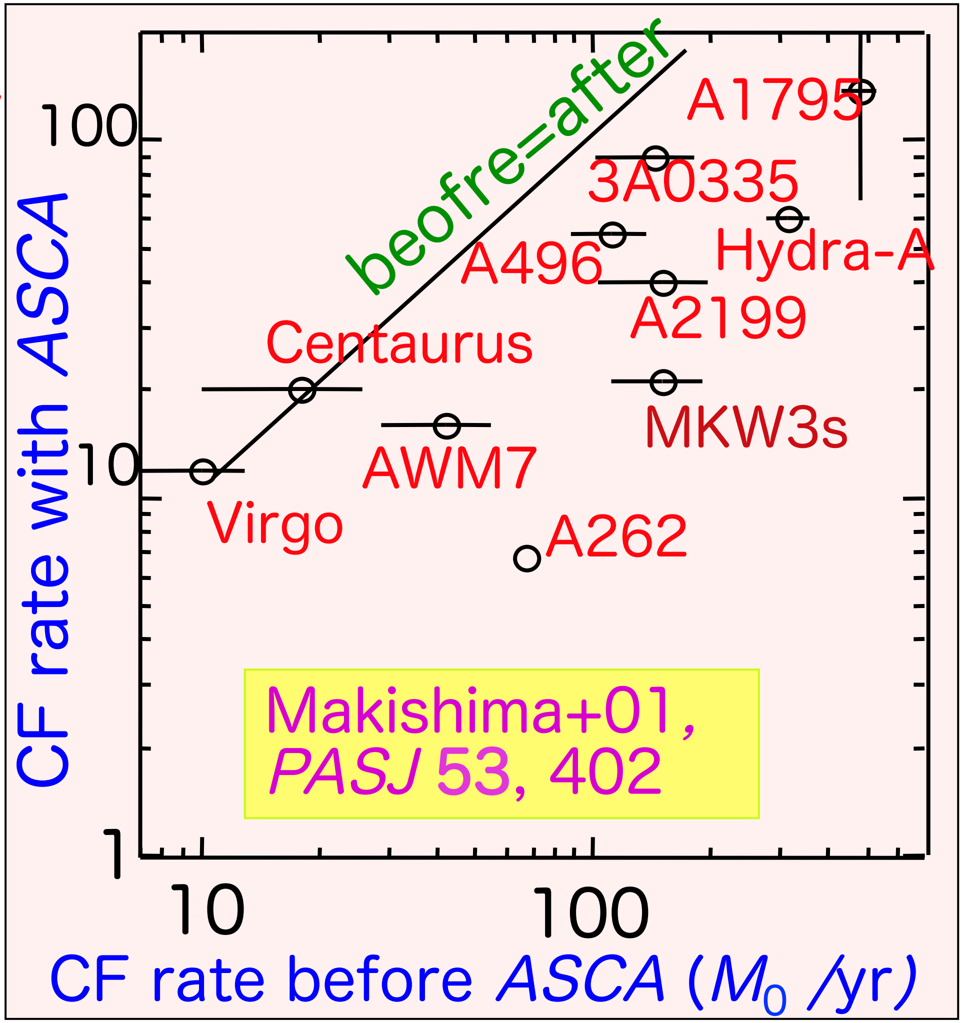
3b. What Stops Cooling Flows?

✧ At CLG centers, radiative cooling time of ICM is a few percent of t_H

✧ Cooling ⇒ ICM pressure ↓ ⇒ ICM in flow ⇒ density ↑ ⇒ Cooling rate ↑ : runaway "cooling flows (CFs)"

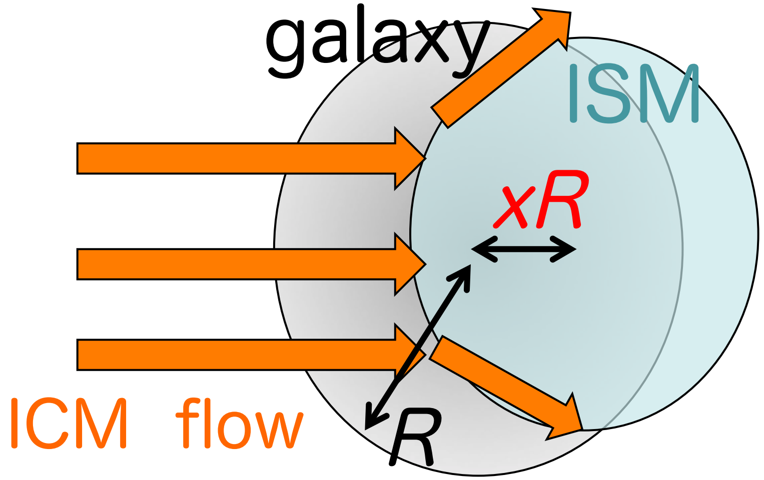
✧ Cool ICM measured with *ASCA* was << predicted : No CFs in CLGs (KM+01)

✧ Hidden mechanism of ICM heating ==> The motion of gal's becomes a candidate.



3c. Galaxy vs ICM :(1) Ram Pressure

- ICM, in-flowing with velocity v, exerts ram pressure to ISM.
- ISM is displaced by xR, if the pressure is not too high.
- By gravity, the displaced ISM pulls the whole galaxy.



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

fractional ISM mass; ICM density; galaxy mass; in-flow velocity

- When x<1, ISM is bound, and keep interacting.
- Even an elliptical galaxy (γ~0.01) can fully interact with the in-flowing ICM.

3d. Galaxy vs ICM :(2) Dyn. Friction

✧When a massive particle encounters a lighter particle, the former gives energy to the latter unless the former has a very low velocity.

e.g.1: An interplanetary spacecraft can get energy through "fly by" around planets.

e.g.2 : Ions and electrons in a plasma are in thermal equilibrium when $V_i = v_e \,\mathrm{sqrt}(m_e / M_i)$.

✧In a CLG, a moving gal. scatters DM and ICM particles by gravity, giving energy to them. Dynamical friction.

✧The effect is larger when a more massive gal. is moving more slowly.

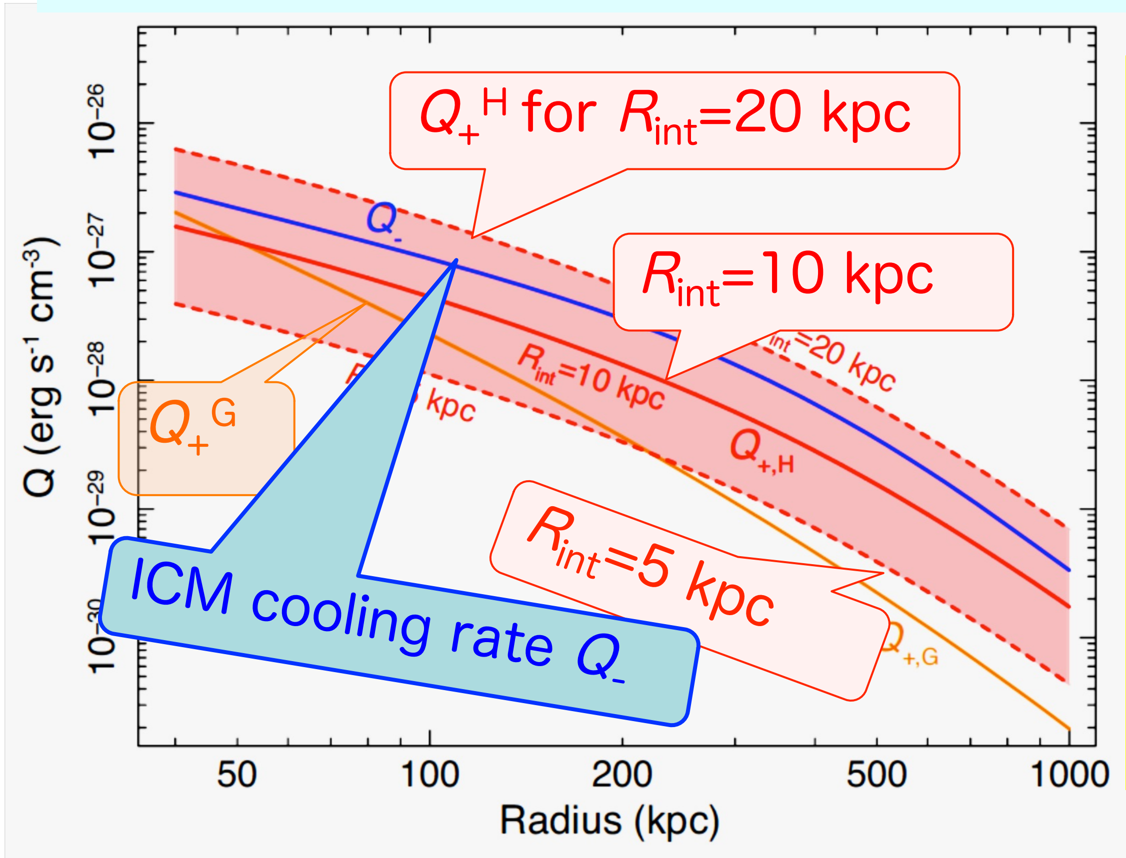
3d. Galaxies can Stop ICM Cooling

Volume heating rate by moving galaxies

- ram press. : $Q_+^{\mathrm{H}} = \pi (n_{\mathrm{gal}} \rho_{\mathrm{icm}}) R_{\mathrm{int}}^2 v^3$
- dyn. friction : $Q_+^{\mathrm{G}} = 4\pi (n_{\mathrm{gal}} \rho_{\mathrm{tot}}) (G M_{\mathrm{g}} / v)^2$

M_g: *mass*
v : velocity
R_{int}: interaction radius
n_g: no. density of galaxies.

Q_+ and Q_- as a function of R
(clculated from 340 CLG data)



With R_{int}~10 kpc, our scenario can provide:

- A sufficiently high heating luminosity,
- Over ~t_{H},
- With detailed Q_+ vs Q_- balance.

Thus, the CF puzzle solved (Gu+KM *in prep*)

3e. Advantages of Our Hypothesis

Our hypothesis (KM+01, Gu+13,16) can explain several observed facts of high importance:

- How the present-day CLGs have come to show the gal's < DM < ICM distributions.
- Why the predicted Cooling Flows are not taking place anywhere in the Universe.
- How ICM was uniformly metal enriched out to the very periphery, and the IMLR.

But any hypothesis needs to be verified via experiments or observations.

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4a. The First Attempt

Aim : Show that galaxies are mor
distributed in distant CLGs than i

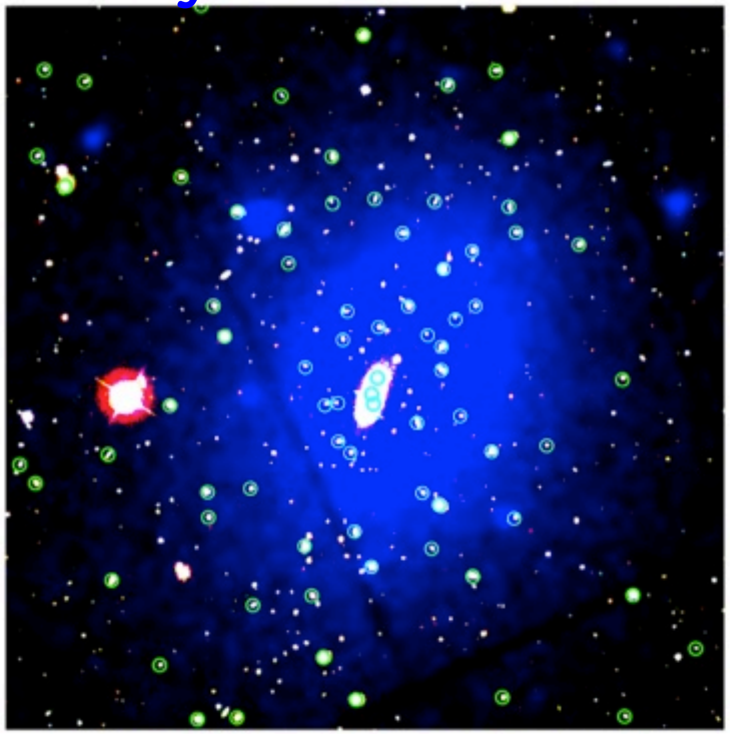
Method :

1. Selected 34 CLGs with redshift z
2. Observed them by ourselves in n with the UH88 telescope, and de integrated gal.light distribution $L(R)$ for each CLG.
3. Analyzed archival X-ray data (*Chandra* & *XMM-Newton*) of the same 34 CLGs, and derived integrated ICM mass $M(R)$ for each of them.
4. Took the ratio $L(R)/M(R)$, and averaged them over appropriate redshift intervals.

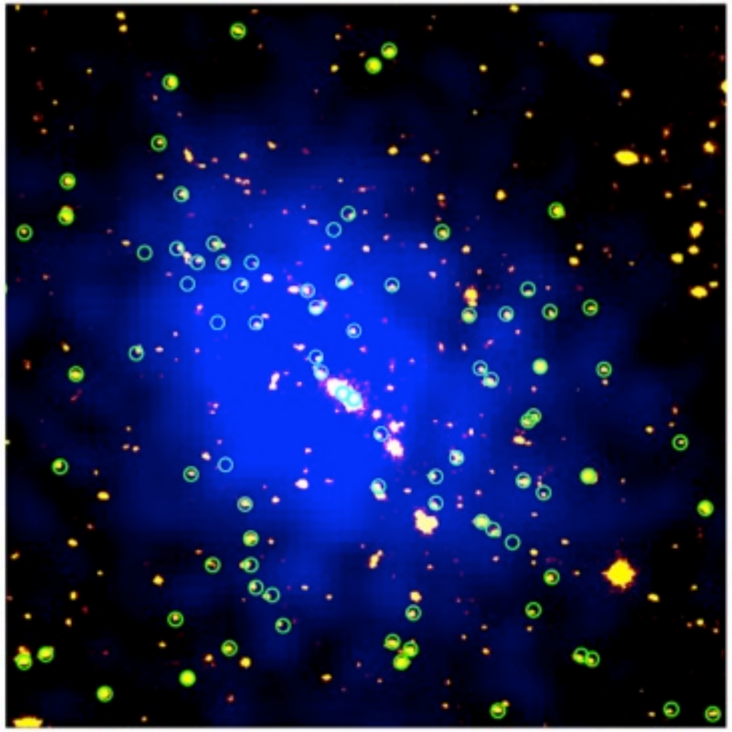
4b. Some Raw Data

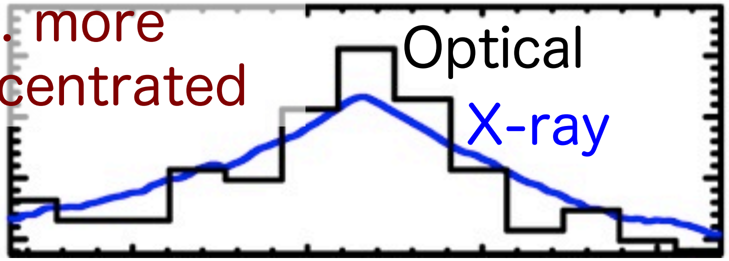
X-ray brightness (blue) on an optical picture. Identified members circled.

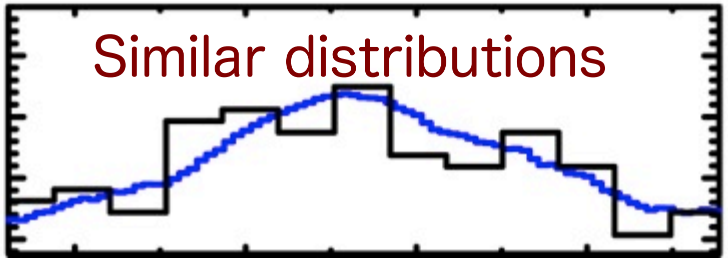
A nearby CLG @z≒0.1



A distant CLG @z≒0.5





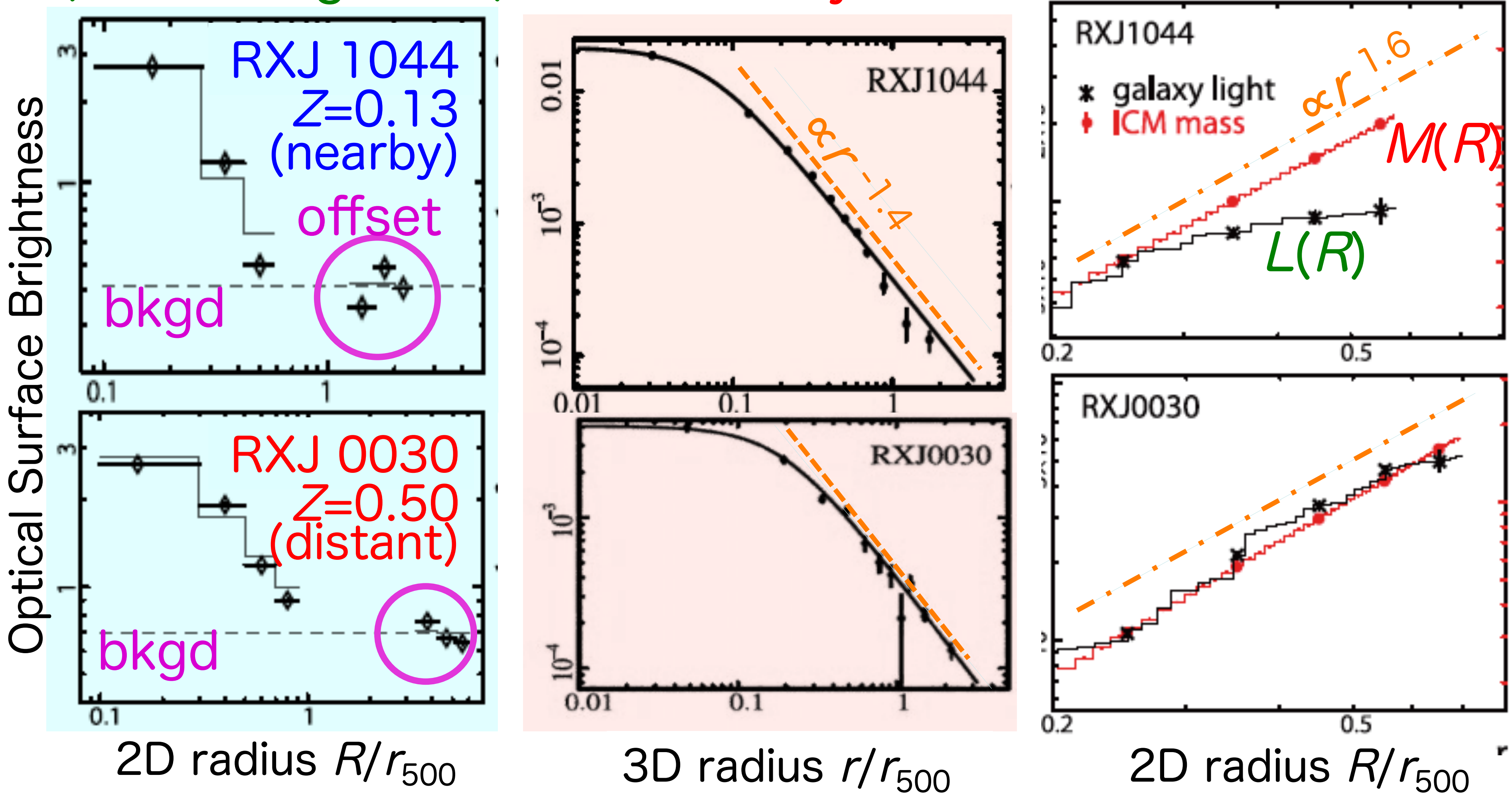


4c. Optical and X-ray Radial Profiles

★ Opt. Data (incl. Background)

◆ ICM Density from X-ray Data

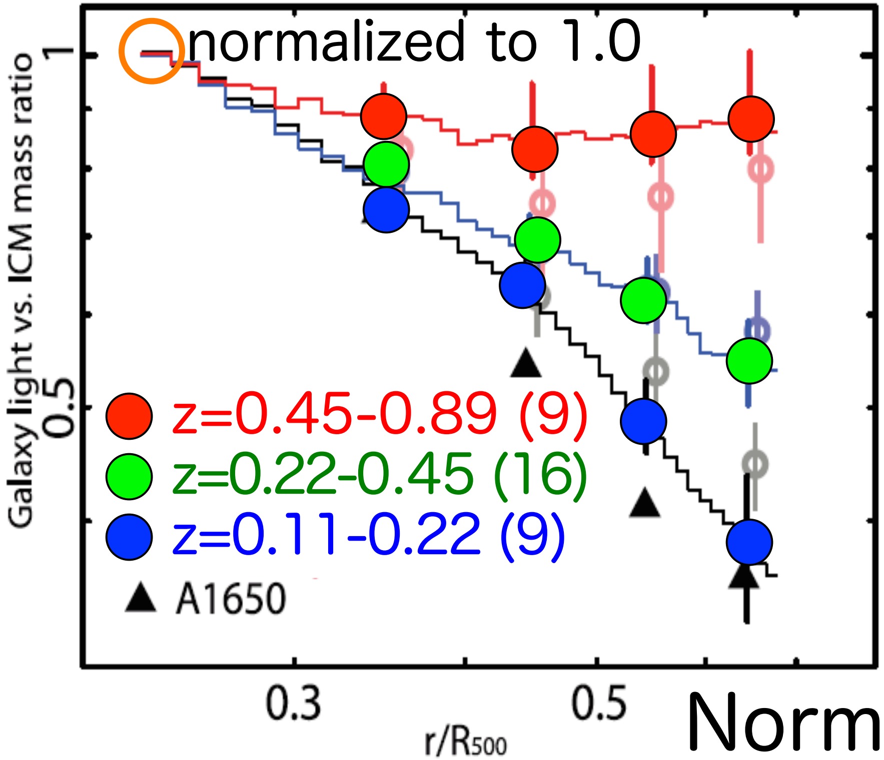
2D-Integrated mass profiles



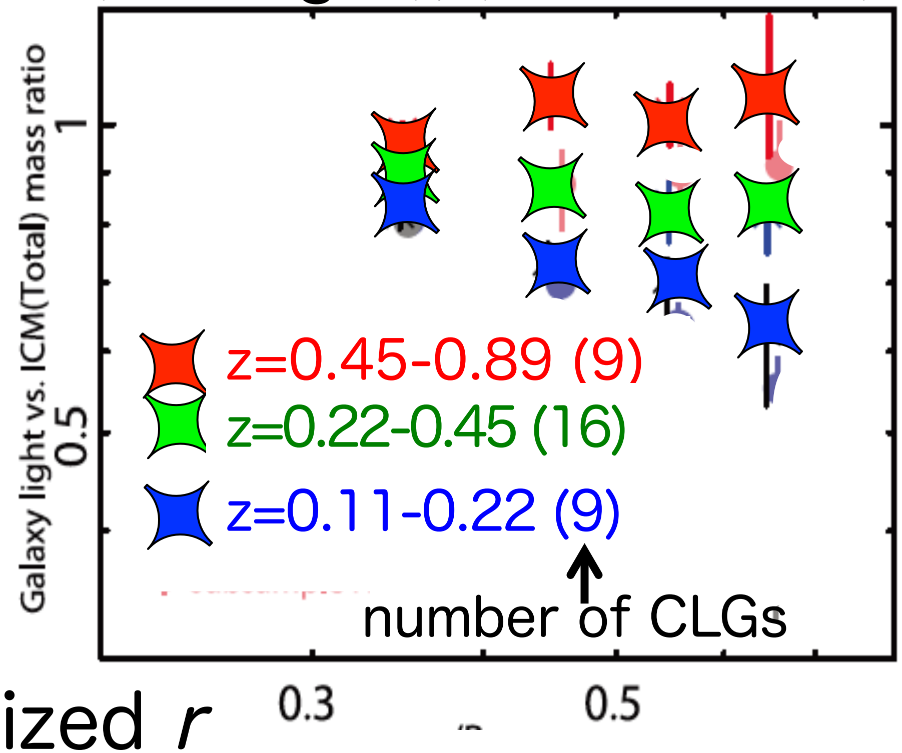
4d. Evolution of the 3 Components

Gu *et al.*, *Astrophys J.* 767, id.157 (2013)

★ (Gal.light)/(ICM mass)



★ (Gal. light)/(Total mass)



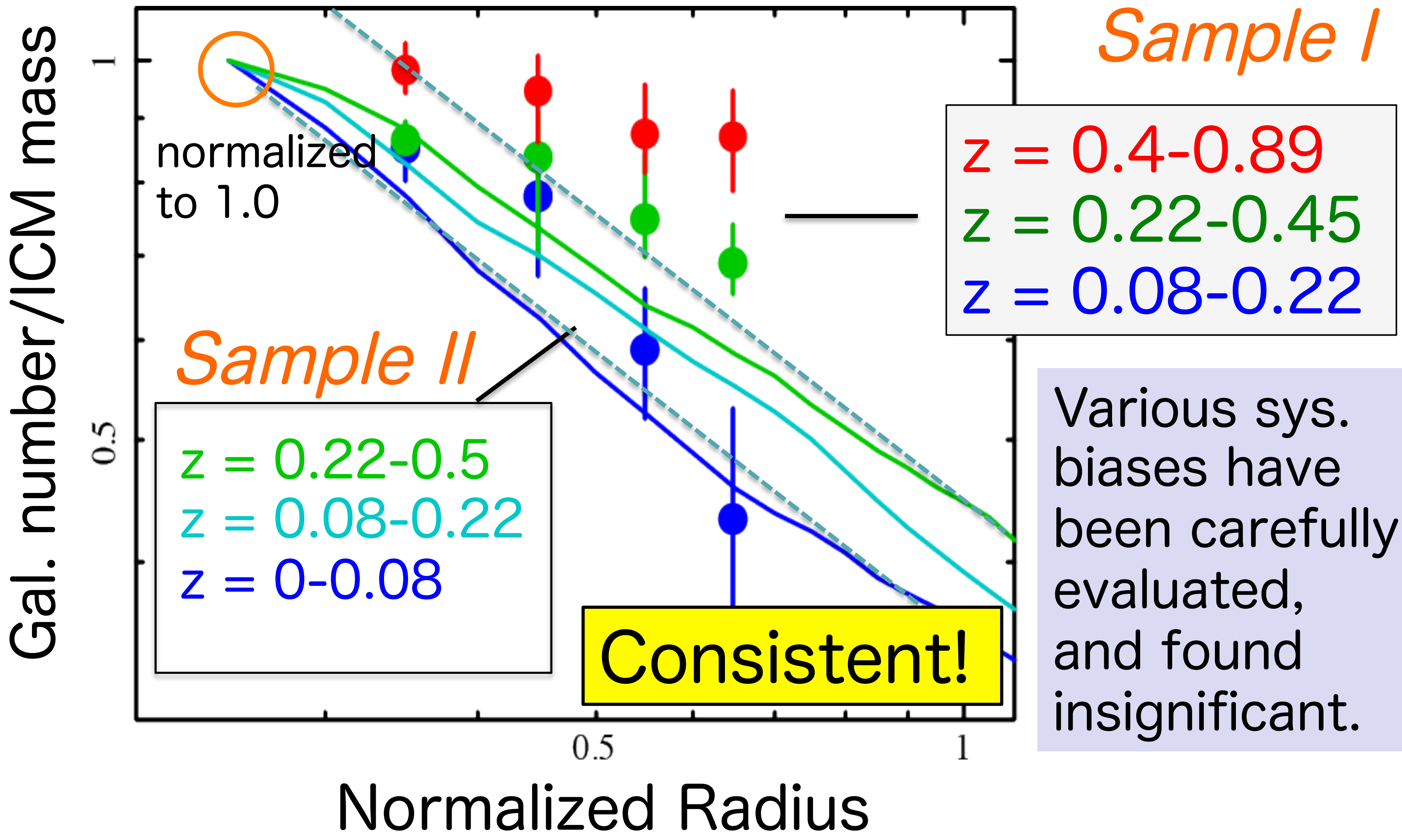
Normalized *r*

From *z*~0.9 to *z*~0, gal's became more concentrated *wrt* both ICM and the total mass.

4e. The 1s and 2nd Samples

	1st Sample	2nd Sample
No. of CLGs	34	340
z range	0.11-0.89	0-0.5
Optical data	Observed with UH88 by ourselves, photometric	SDSS archive, photo.+spec.
X-ray data	Archive, *Chandra* & *XMM-Newton*	
Publication	Gu+13, *ApJ.* **767**, id.157	Gu+16, *ApJ.* **826**, id.72

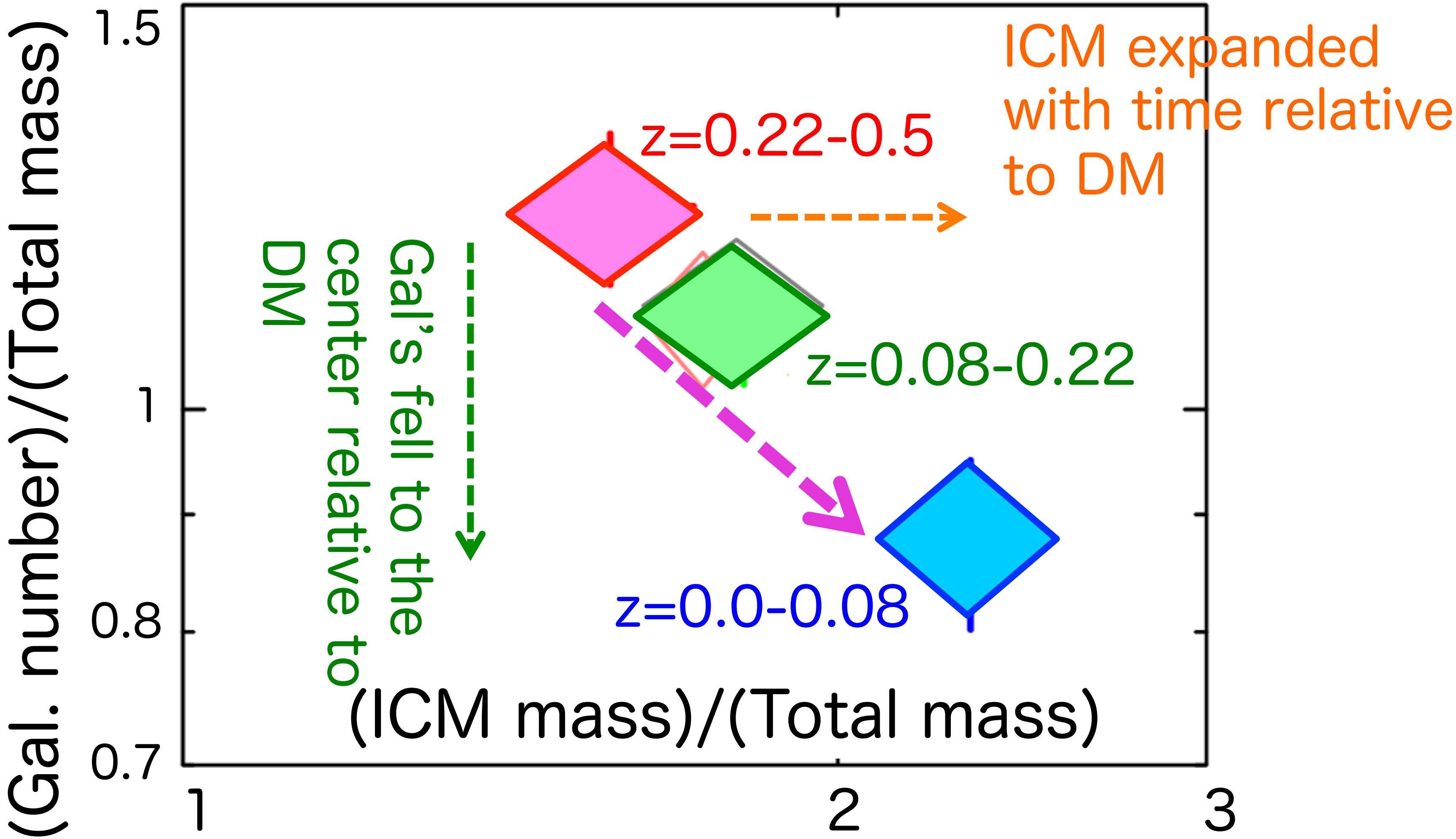
4f. Results from the Two Samples



Various sys. biases have been carefully evaluated, and found insignificant.

4g. Evolution of the 3 Components

Calculated at a radius of r_{500}
and normalized to 1.0 at at 0.25 r_{500}



4h. An Interim Summary

blue=
obs. facts

- ✧ At z~1, the 3 mass components in a CLG had nearly the same radial distributions.
- ✧ As moving randomly, gal's interacted with ICM, and were deprived of metals they produced. ==> Explains the observed uniform metallicity.
- ✧ Gal's lost dynamical energy and fell to the center, whereas ICM received that energy and expanded. ==> Explains the present-day mass distributions.
- ✧ Over t_{H}, the energy given from gal's to ICM balances, at all radii, the radiative cooling of ICM ==> Explains the absence of Cooling Flows.
- ✧ Our hypothesis has almost been verified.

More evidence needed

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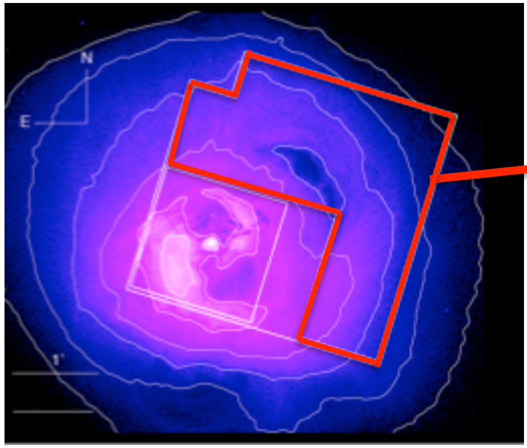
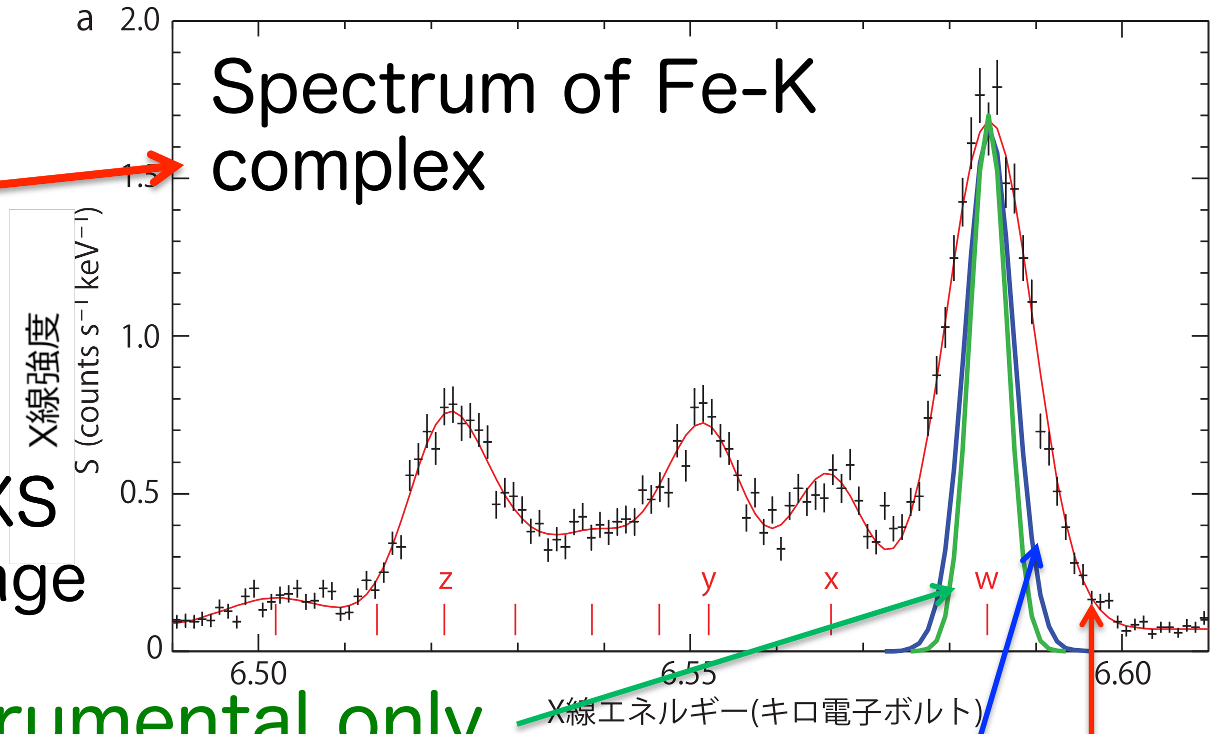
5a. Hitomi Results on the Perseus CLG

(*Nature* 535, 117, 2016)

50 kpc



FOV of *Hitomi* SXS
on a *Chandra* Image



Instrumental only

+ Thermal Doppler (80 km/s)

+Turbulent motion (σ=164 km/s)

(line-of-site component)

Very subsonic

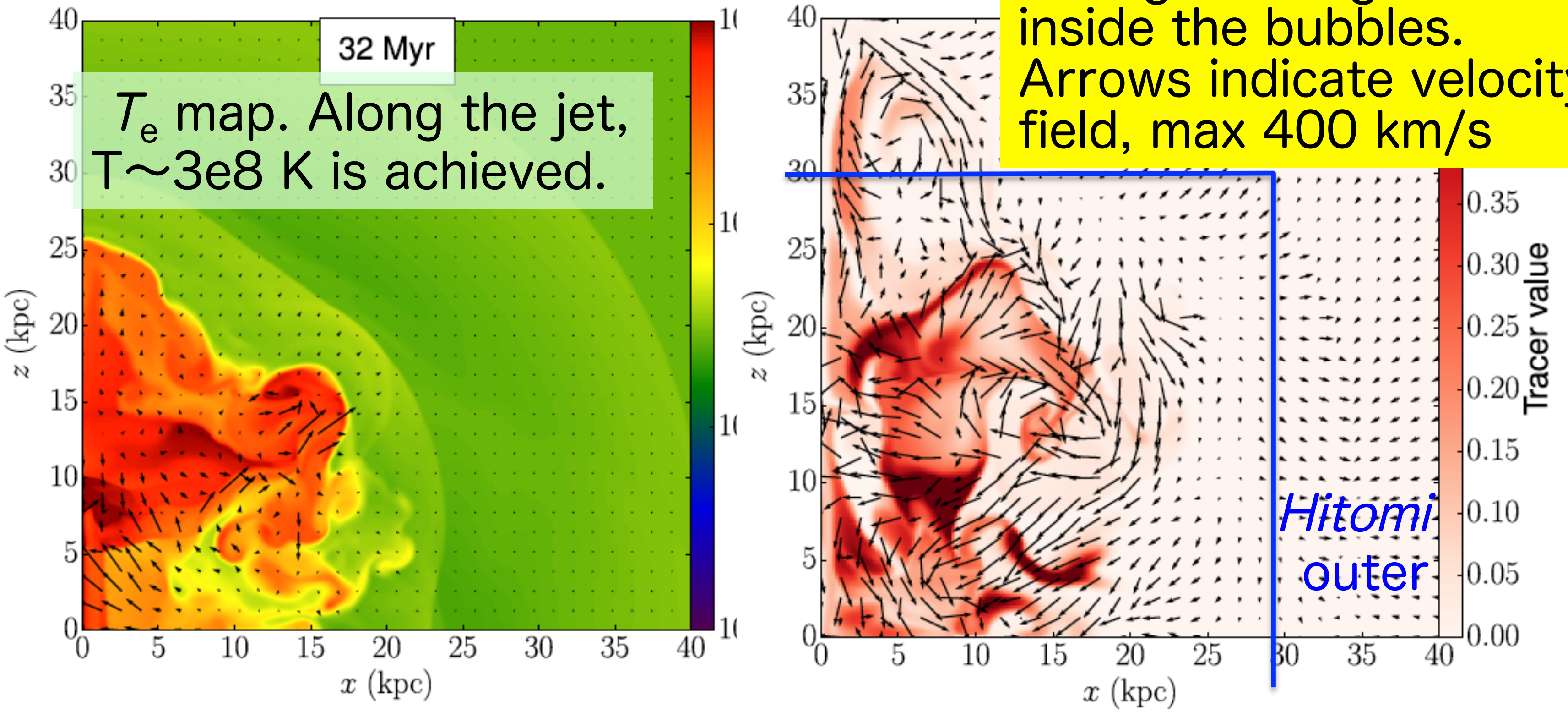
5b. "AGN Feedback" Scenario for ICM Heating

Hillel & Soker (2016), 3D Hydro

In ICM, jest from the central AGN create hot bubbles, which heat ICM via mixing, shocks, and turbulence.

"*The turbulence is subsonic in agreement with Hitomi, but the turbulence it too localized to globally heat ICM.*"

Mixing of hot gas created inside the bubbles. Arrows indicate velocity field, max 400 km/s



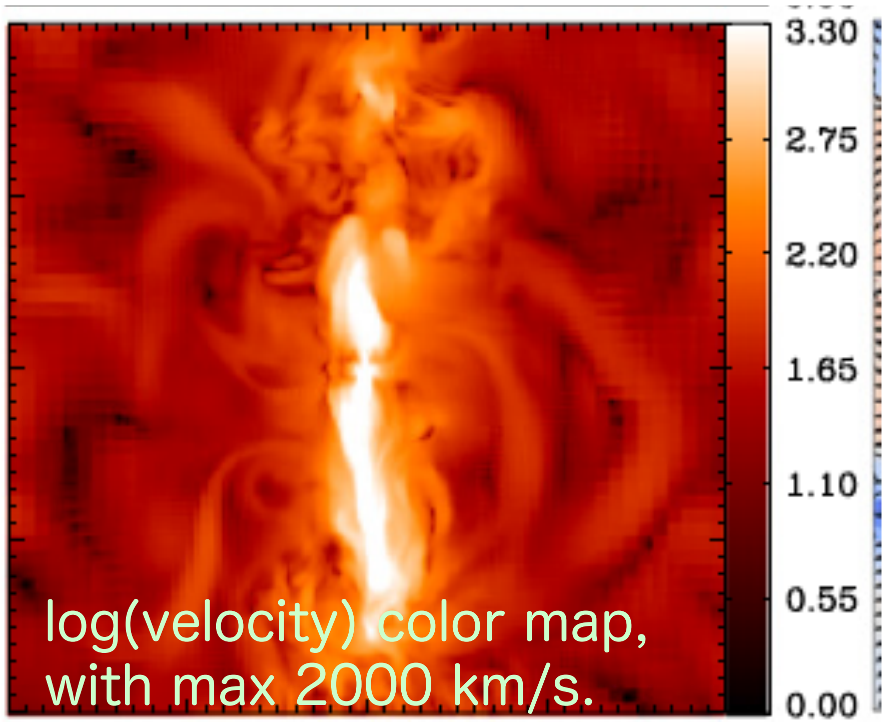
5c. Other Simulations of AGN Feedback

Reynolds +15, 3D Hydro

"*Intermittent AGN explosions create g-mode sound waves in the ICM, which then decay into volume-filling subsonic turbulence. However, the heating efficiency is too low to suppress the ICM cooling*.

The AGN feedback scenario has difficulty in creating vol. filling, subsonic turbulence with high efficiency

Yang & Reynolds 2016:
3D MHD including cooling & conduction. *"AGN-created turbulence is very localized, and supersonic"*. Disagrees with the *Hitomi* results.



5d. ICM Turbulence with Our Scenario

Gal's dyn. energy $\xrightarrow{\tau_1}$ Kinetic en. of ICM turbulence $\xrightarrow{\tau_2}$ ICM entropy $\xrightarrow{\tau_c}$ X-ray radiation

excitation of turb. by gal's

dissipation of turb. velocity σ

radiative cooling

- ✧ Steady state: $M_{icm}\sigma^2 \sim M_{gal} v^2 \times (\tau_2/\tau_1)$
- ✧ In CLG cores, $M_{icm} \sim M_{gal}$
  v =gal. vel. dispersion~700 km/s,
  $\tau_1 \sim 0.1\, t_H$ (from the calc.of Q_+),
  $\tau_2 \sim \tau_c \sim 0.01\, t_H$ (no entropy change)
- ✧ $\sigma = v\, \mathrm{sqrt}\{(M_{gal}/M_{icm})(\tau_2/\tau_1)\} \sim 220$ km/s

Agrees with the *Hitomi* result, σ=164 km/s

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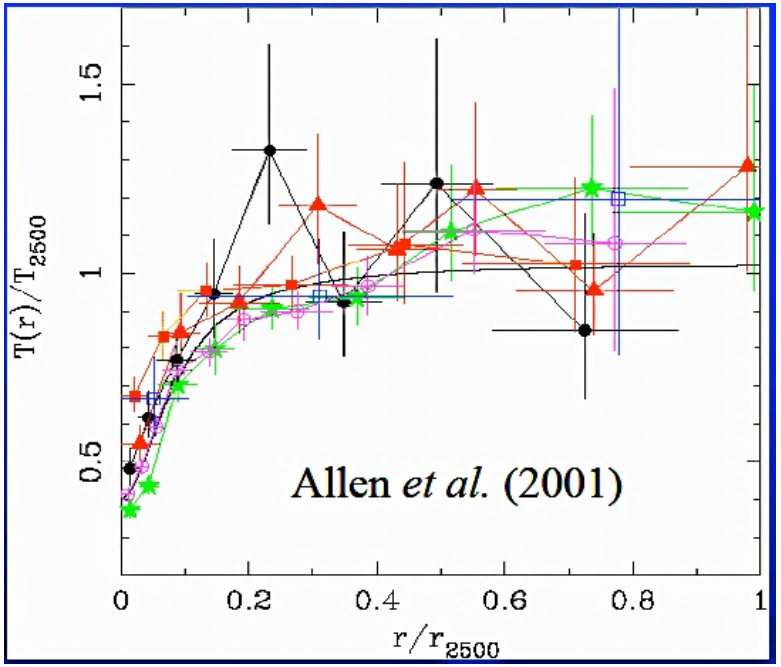
6a. Further Puzzles in CLG Cores

Although the ICM heating mechanism was identified, several puzzles still remain in core regions of CLGs.

Even though CFs are absent, T_e shows clear drop towards CLG centers, following a universal scaling law.

- ✧ How such multi-*T* condition is realized against heat conduction ?
- ✧ How can we explain the scaling relation?
- ✧ How is the cool component thermally stabilized?

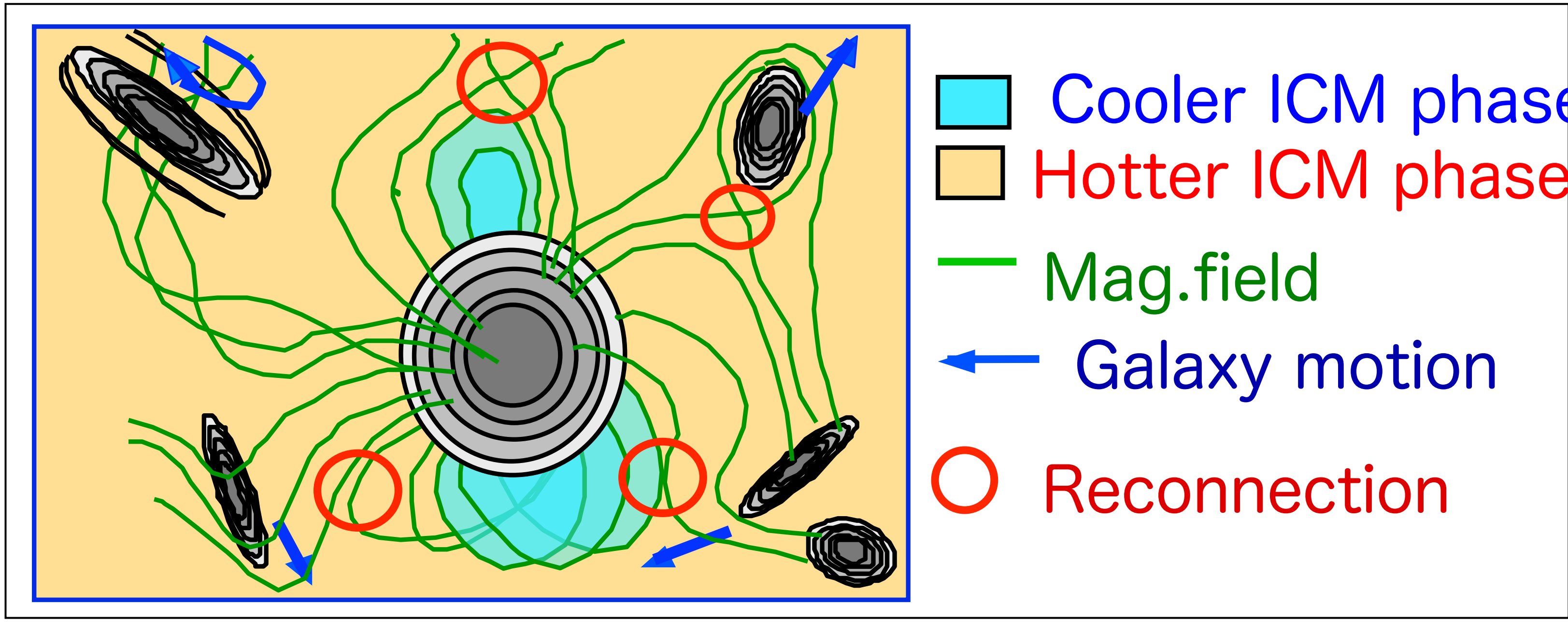


(Allen+01; Kaastra+04)

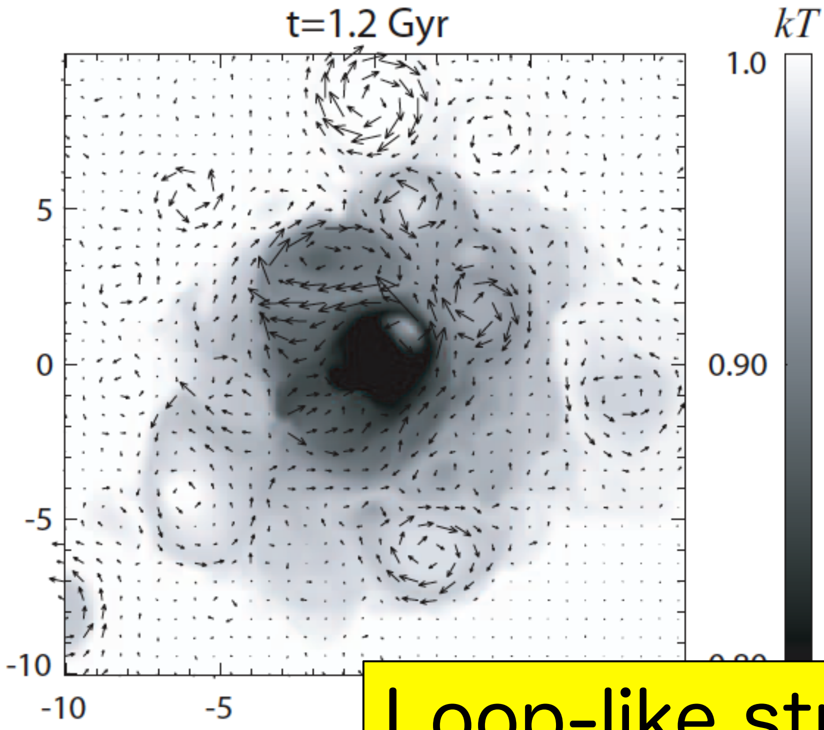
6b. The cD Corona Hypothesis

(Makishima+01)

- ✧Closed MF loops around a cD galaxy confine cooler ICM, while open MF region is filled with hotter ICM.
- ✧MF lines thermally decouple the two phases.
- ✧ The cooler phase is thermally stabilized by Rosner-Tucker-Vaiana mech. (1978) of Solar coronae.

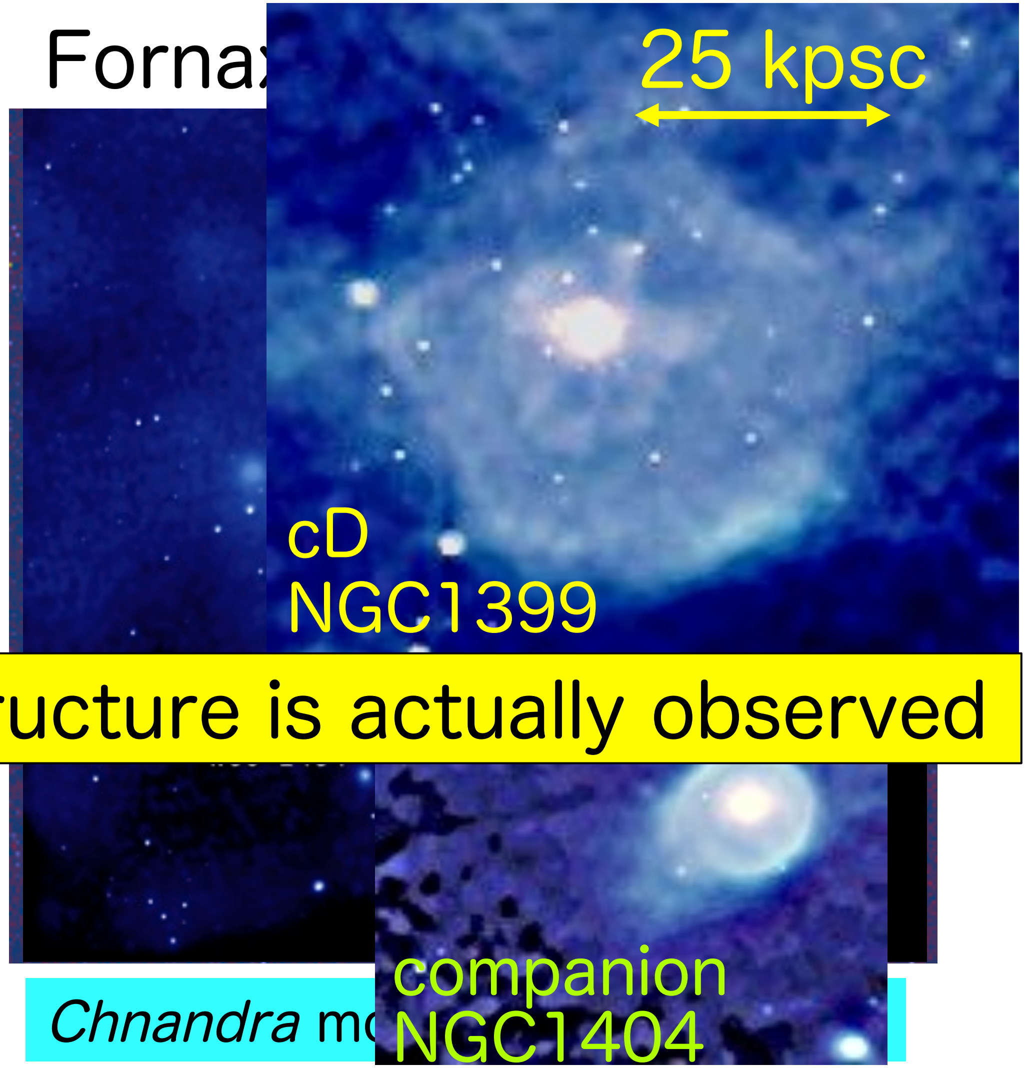


6c. Evidence (1): Loop-Like Structures



Simulation by Asai+07. T_e(gray) and MF (arrows) in a (300 kpc)^2 region are shown. MHD, conduction, and rad. cooling included.

Fornax

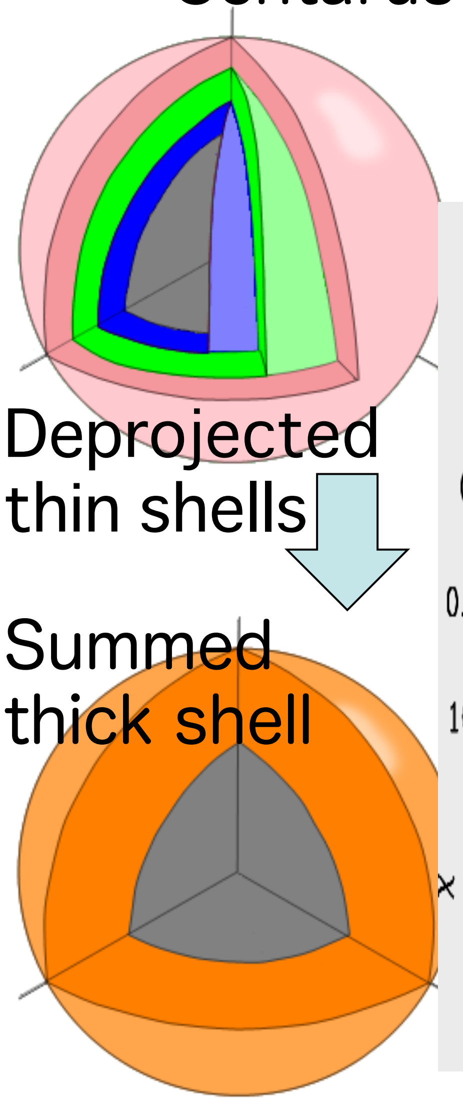


Loop-like structure is actually observed

Chnandra m

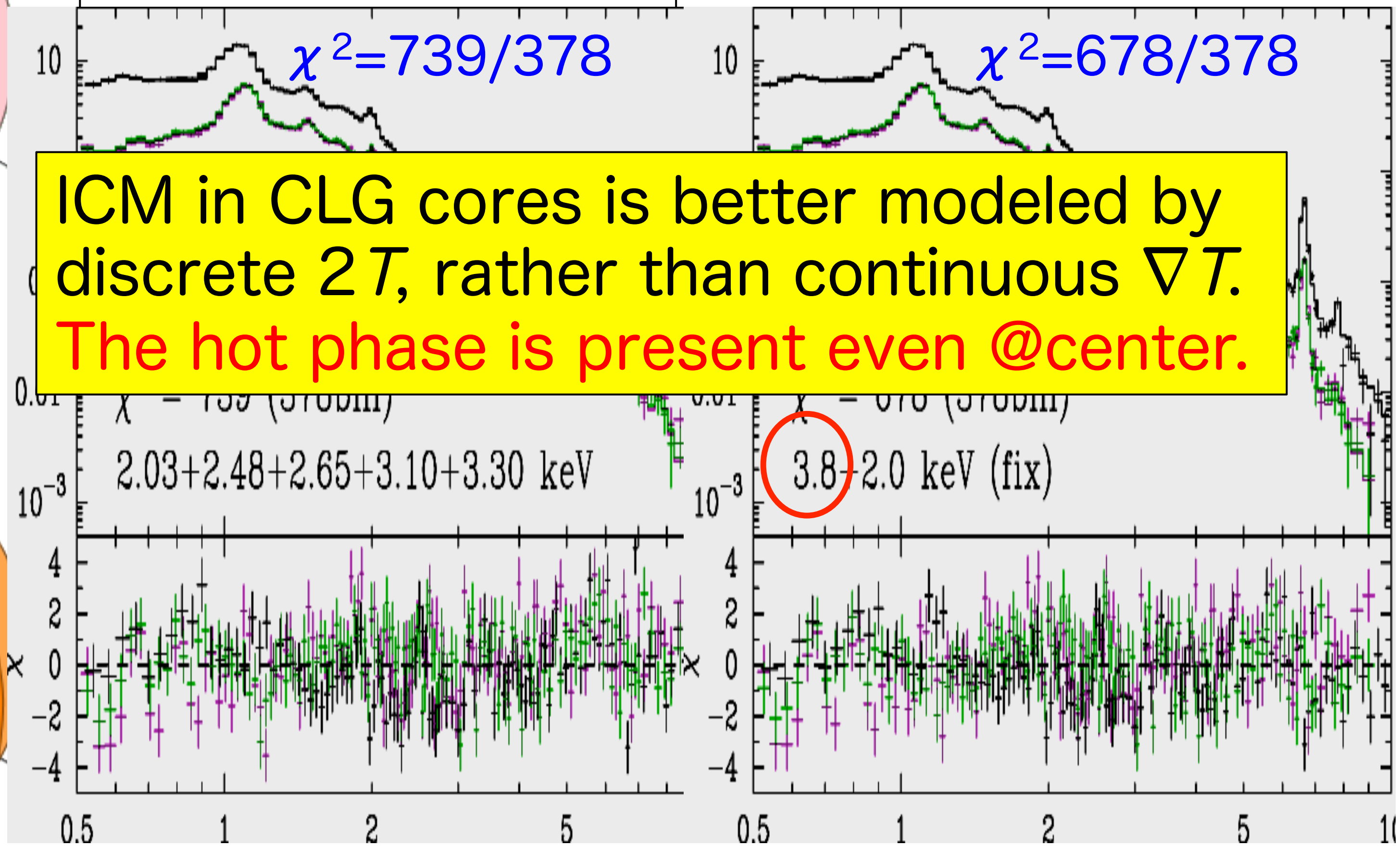
6d. Evidence (2): 2T Property

Centarus CLG With *XMM-Newton* (I.Takahashi+09)



Fit with "1 phase with ∇T" model

Fit with 2T model



ICM in CLG cores is better modeled by discrete $2T$, rather than continuous ∇T.

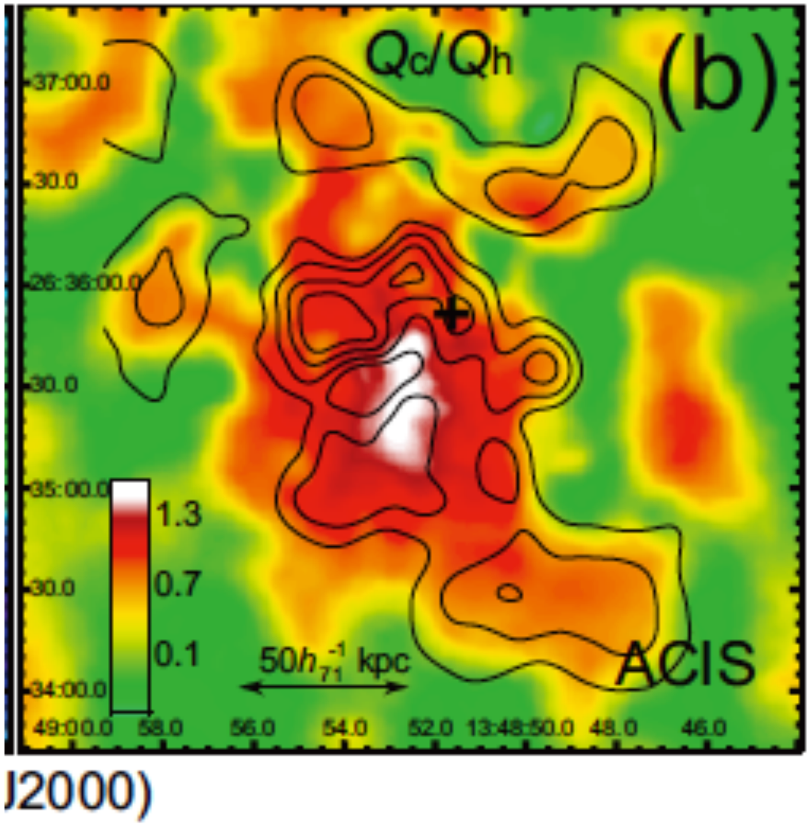
The hot phase is present even @center.

6e. Evidence (3) : Metallicity

Abell 1795 core region observed with *Chandra.*

- *contours*: Metallicity
- *color* : Cool/Hot emission measure ratio.

(Gu+12)



The cool phase is clearly more metal enriched than the hot phase.

Metals created in the cD galaxy are trapped inside the magnetosphere.

The cD corona is observationally supported.

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7a. Remaining Tasks

1. *Observational*: with future high-resolution X-ray missions (e.g., XRISM), measure that gal's with high line-of-sight velocity indeed drags ICM around them.
2. *Numerical*: Perform scaled up versions of the Asai+07 simulation.
3. *Theoretical*: understand how subsonic but trans-Alfvenic turbulence in a compressible fluid is dissipated.

7b. Origin of "Environmental Effects"

- Evolutionary effects
  Blue disturbed spiral gals in high z CLGs
  Red dwarf spheroidals in low z CLG

- Spatial effects
  Spiral galaxies dominate CLG periphery
  Ellipticals/spheriodals in CLG centers

The origin of these effects is still unknown, but we speculate that the galaxy vs. ICM interaction is playing a fundamental role.

Conclusion

Our "cosmological galaxy infall + cD corona" scenario can explain the following puzzles with CLGs in a consistent way.

1. In nearby CLGs, how gal's < DM < ICM in radial distribution produced?

2. What stops cooling flows?

3. How ICM was metal enriched uniformly?

4. How to explain the low σ with *Hitomi* ?

5. What is the nature of cool ICM core?

6: What produce the environmental effects?

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Our "cosmological galaxy infall + cD corona" scenario can explain the following puzzles with CLGs in a consistent way.

1. In nearby CLGs, how gal's < DM < ICM in radial distribution produced?
2. What stops cooling flows?
3. How ICM was metal enriched uniformly?
4. How to explain the low σ with *Hitomi* ?
5. What is the nature of cool ICM core?

6: What produce the environmental effects?