Interaction Between the Hot Plasmas and Galaxies in Clusters: A Sample Study

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Gu+ 2013, ApJ, in press

RIKEN, 2013/3/14

Motivation: discrepant matter distributions

Dark Matter:

~ 85% of M_{tot}

$\rho \sim r^{-2.5}$

ICM:

~ 12% of M_{tot}

$\rho \sim r^{-2}$

kT = 2 ~ >10 keV

Galaxies:

~ 3% of M_{tot}

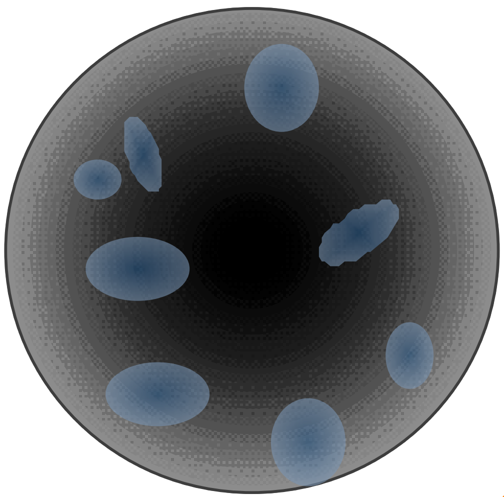
$\rho \sim r^{-3}$

cD galaxy

Components of a galaxy cluster

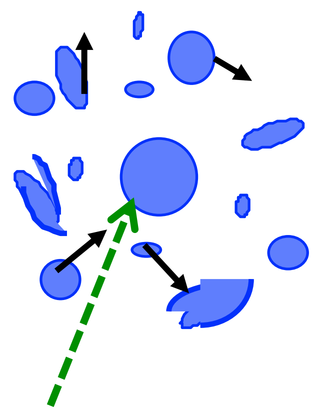
Dark matter

- ~85% of M_{tot}
- Subclumps



Galaxies

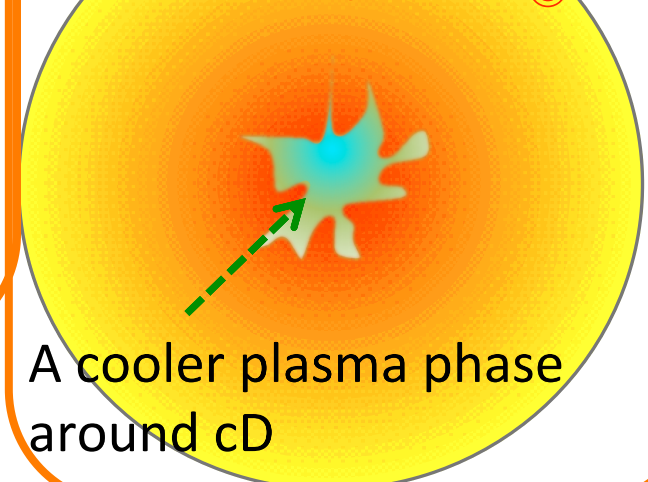
- ~3% of M_{tot}
- Moving within ICM at trans-sonic
- Strongest concentrated



Often a cD galaxy sitting at the center

ICM

- ~12% of M_{tot}
- Most dominant *known* baryonic component in the Universe
- kT_e = 2 ~ 15 keV
- Emit only X-rays
- Confined by gravity but most extended
- metallicity~0.3 $Z_{\odot}$

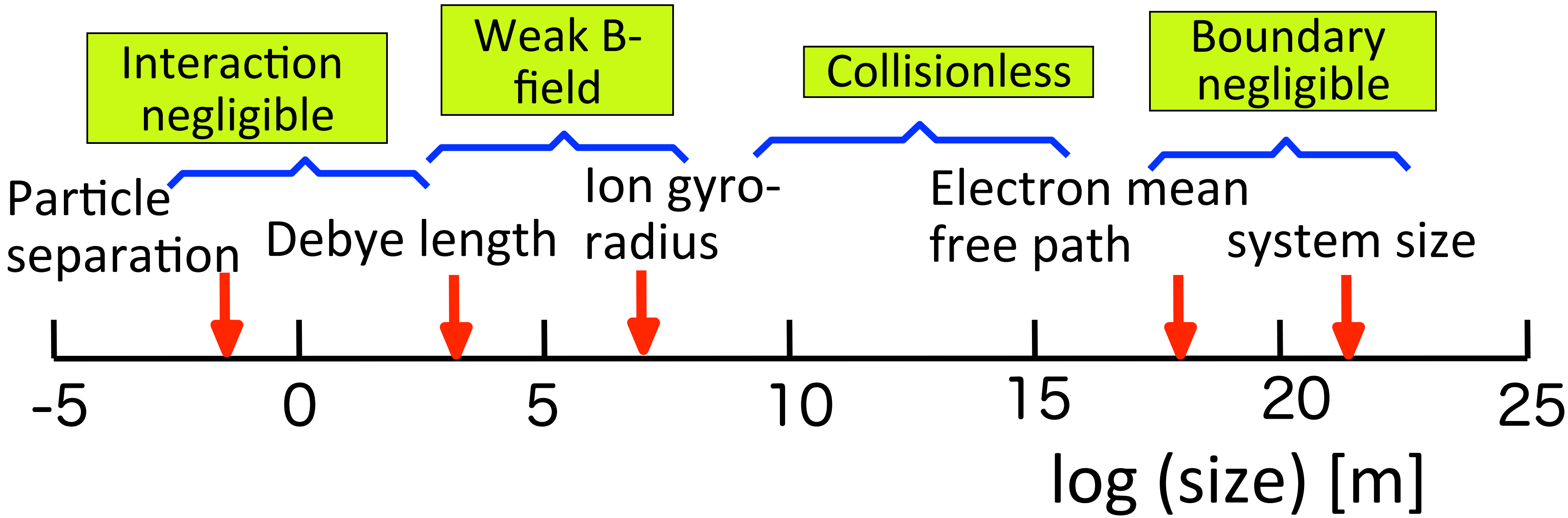


A cooler plasma phase around cD

ICM as a ideal plasma

kT= 2 〜15 keV　；　*n*= $10^{3〜4}$ m^{-3} (center)

magnetized to a few μG → plasma β〜 a few tens

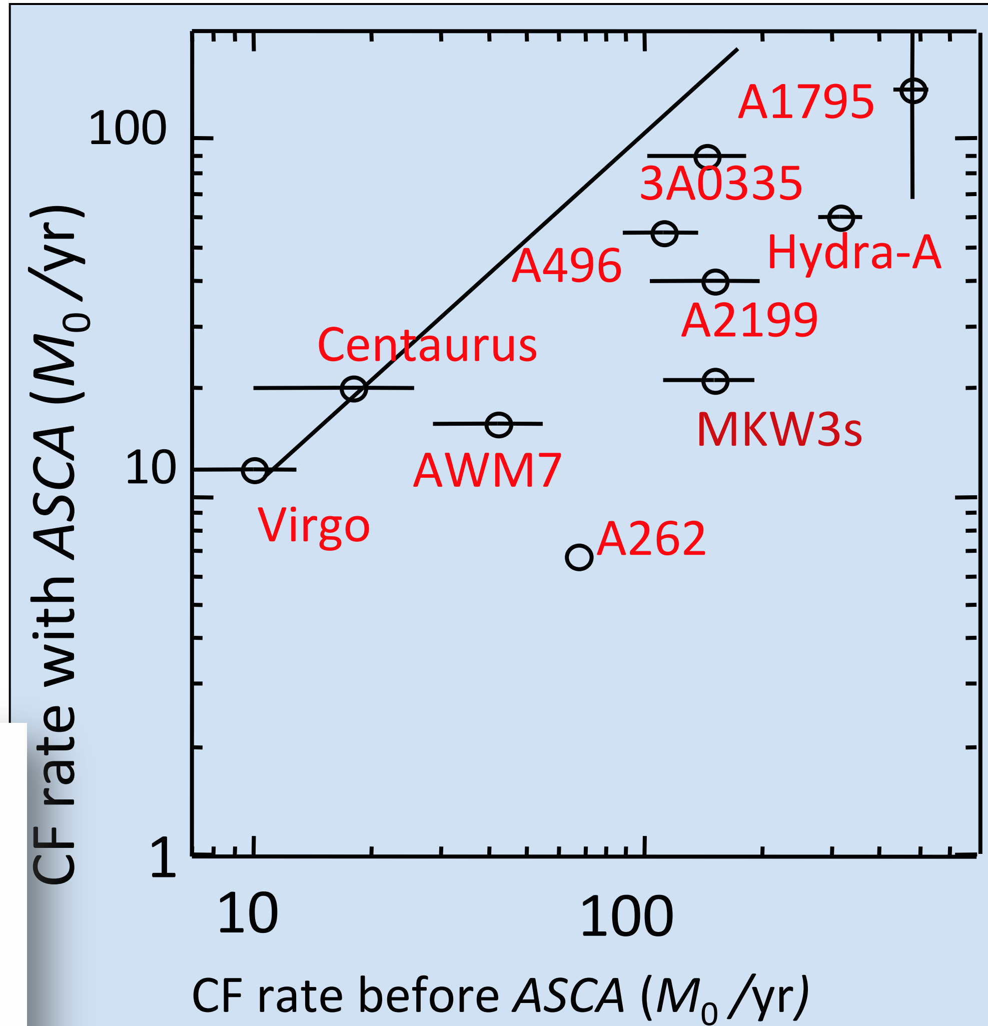


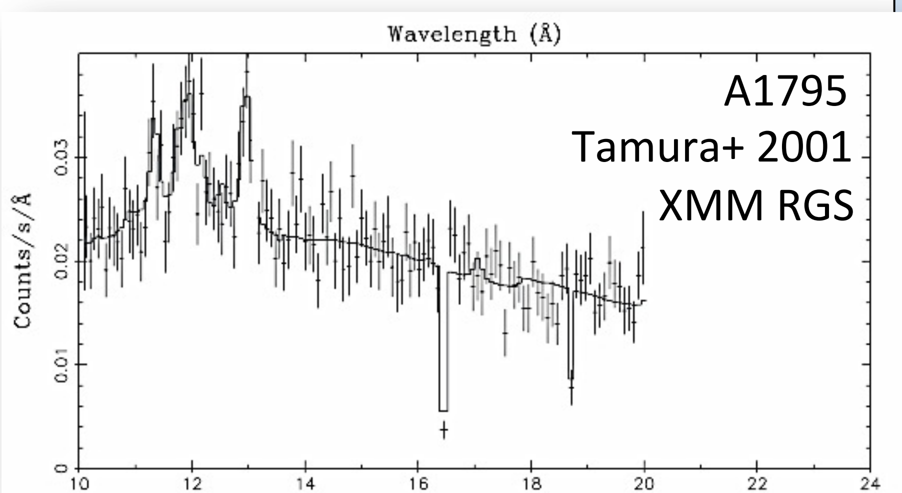
✧Confined stably by gravity (never happens in labo)

✧Many galaxies with ISM are moving in the ICM with transonic

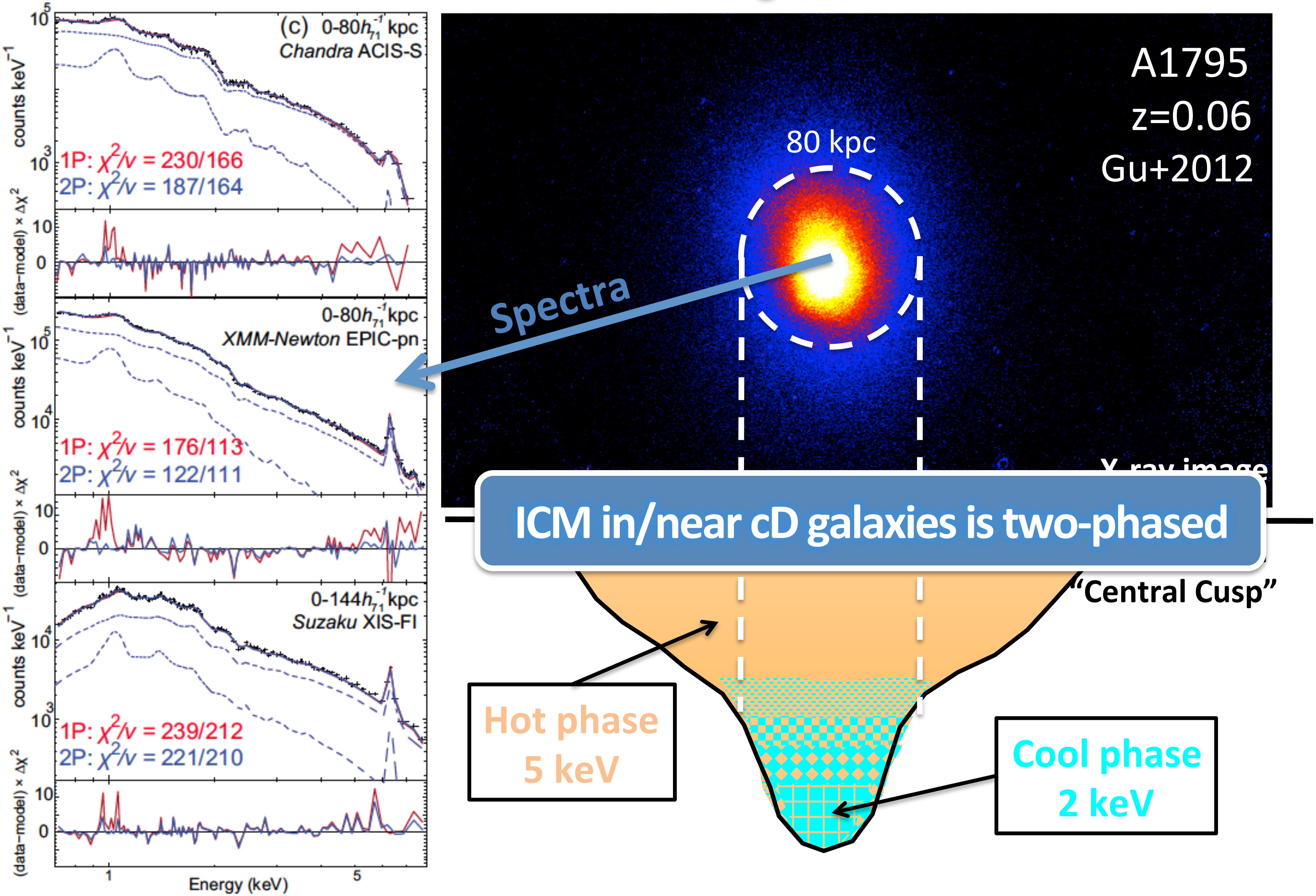
Motivation: need for ICM heating

- In many cluster center, radiative cooling time is ~ 0.1 Hubble time
- Cooling ICM flows into the central region
- The amount of cooled material is much lower than expected
- Some heating mechanism is needed

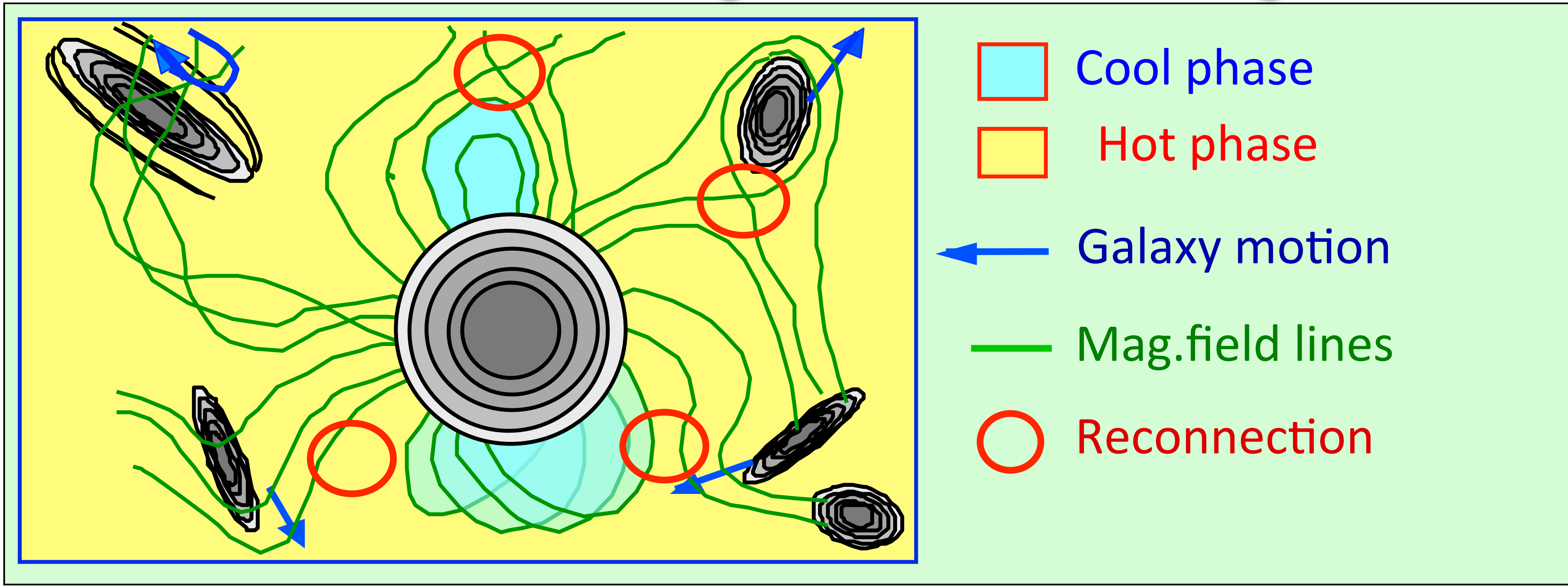




Evidence from ICM temperature



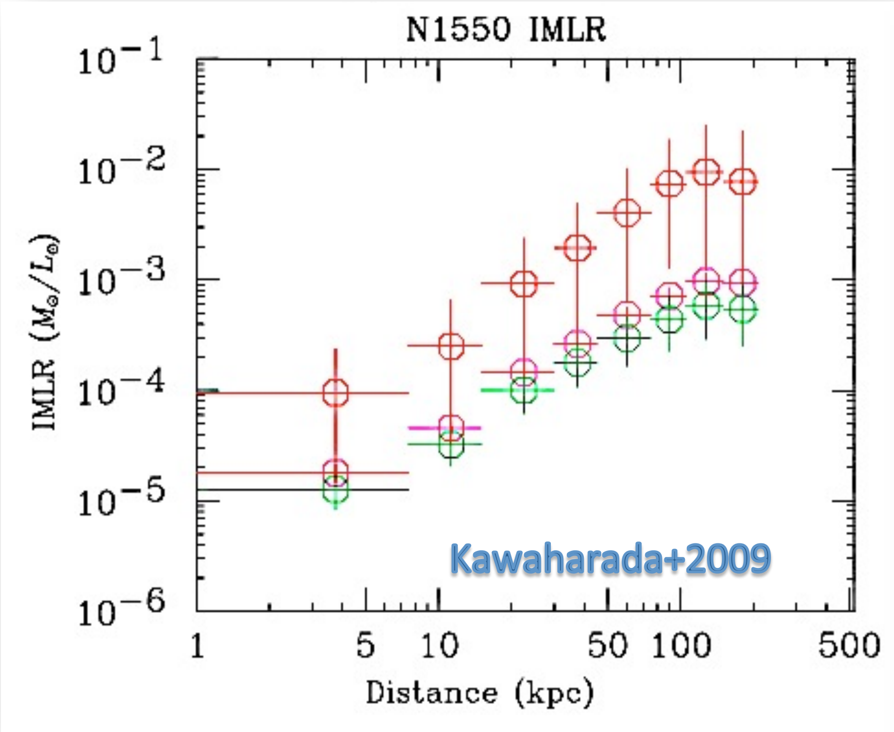
cD corona scenario (Makishima+2001)

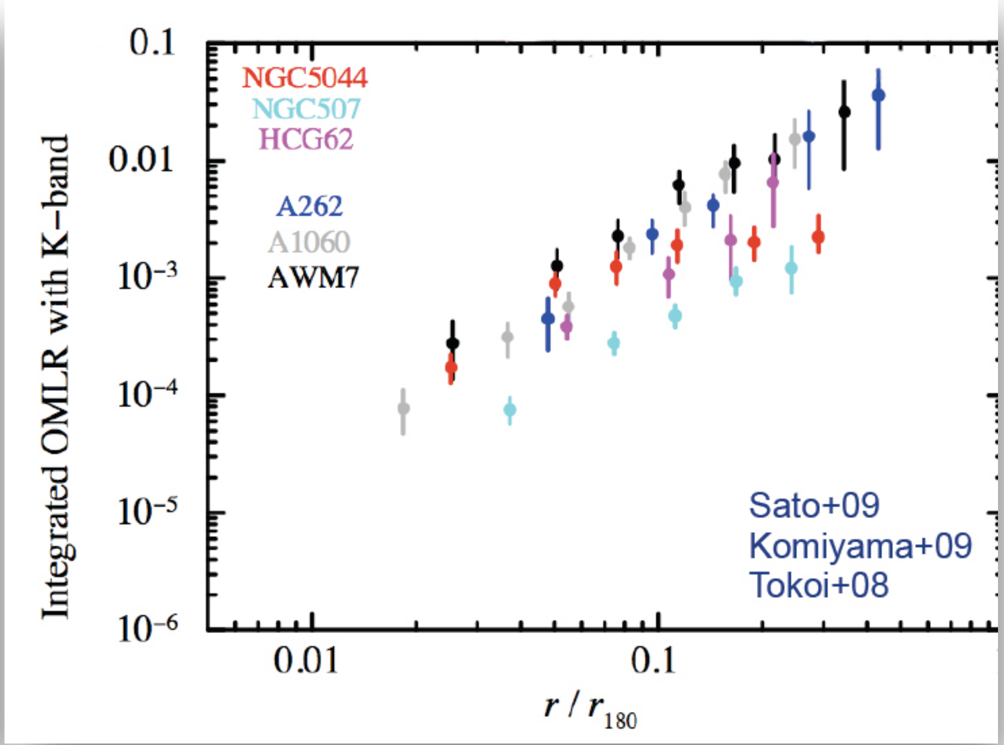


- Ordered magnetic field separate cool and hot phase ICM.
- The loop-like structure stabilizes the heating/cooling (Rosner+ 1976).
- Heating energy from MHD turbulence by galaxy motion/magnetic reconnection(Makishima+2001), or AGN feedback at the bottom of the loops (Gu+2012).

Motivation: extended metallicity distribution

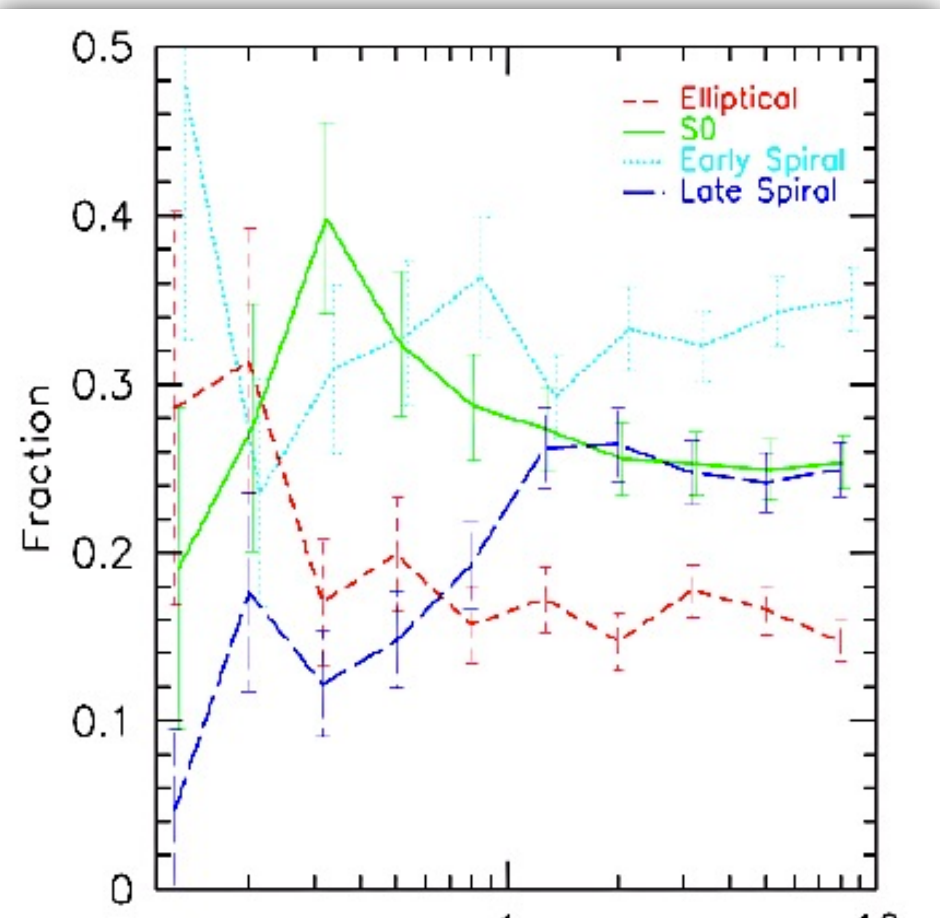
Metal-mass-to-light ratio: $\Phi(R) = M_{\mathrm{Fe,ICM}}(R) \,/\, L_{*}(R)$



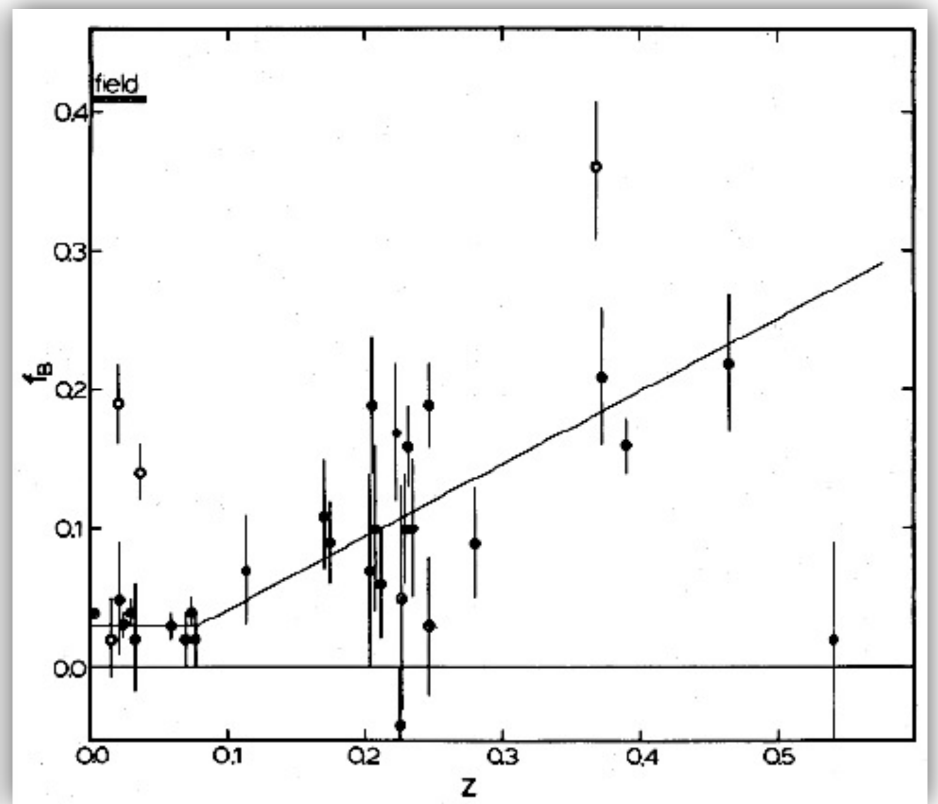


- ICM has a typical metallicity of ~0.3 solar: $M_{\mathrm{M,ICM}} \approx M_{\mathrm{M,Star}}$
- Metals produced in galaxies are widely distributed in the ICM

Motivation: galaxy environment effect



Goto+2003

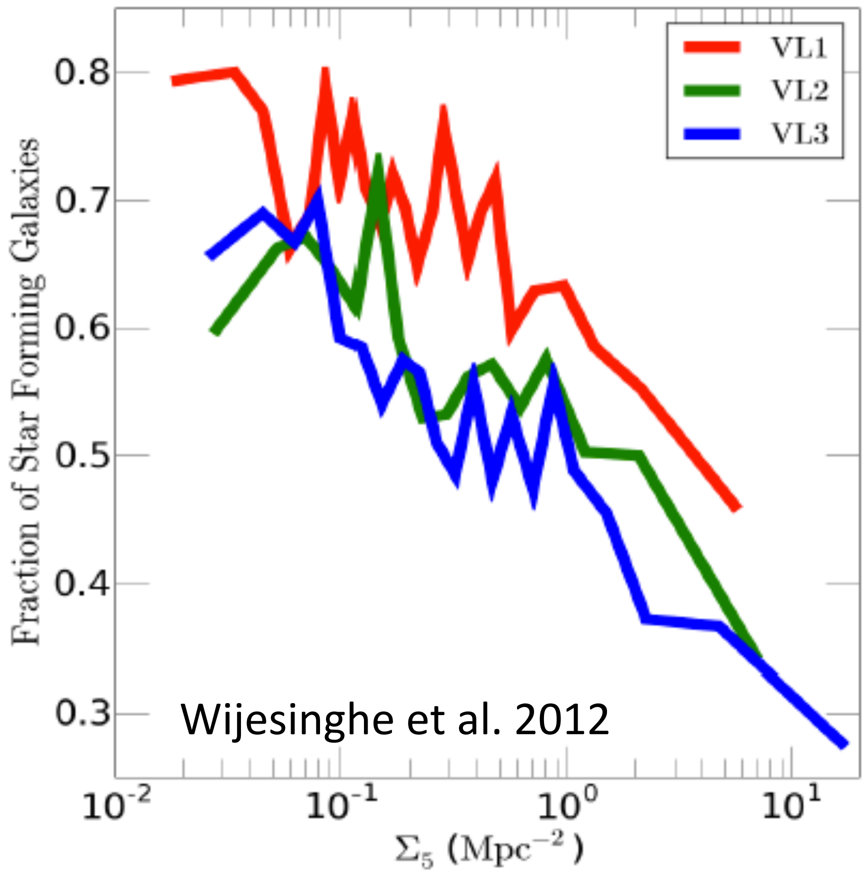


Butcher & Oemler 1984

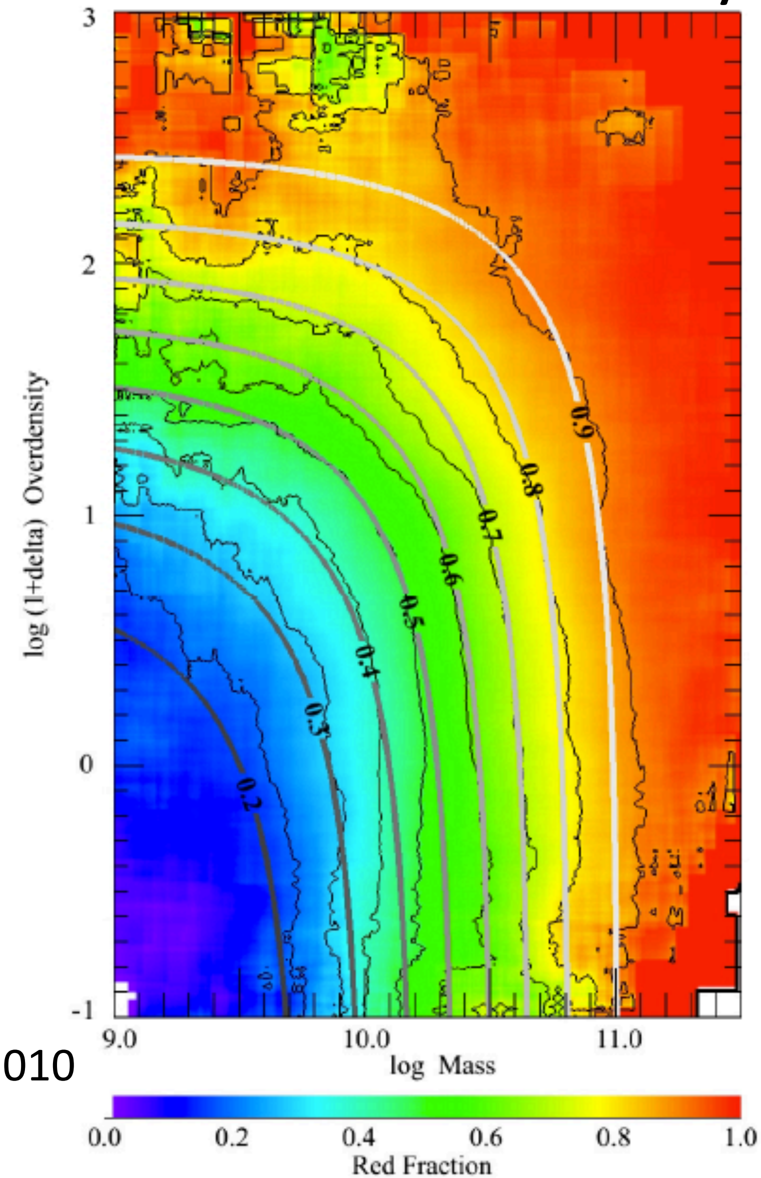
- Late-type galaxies decrease toward center
- Spiral fraction higher in distant clusters (z ~ 0.5)

Motivation: galaxy environmental effect

Star forming-Local density



Red fraction-Local density

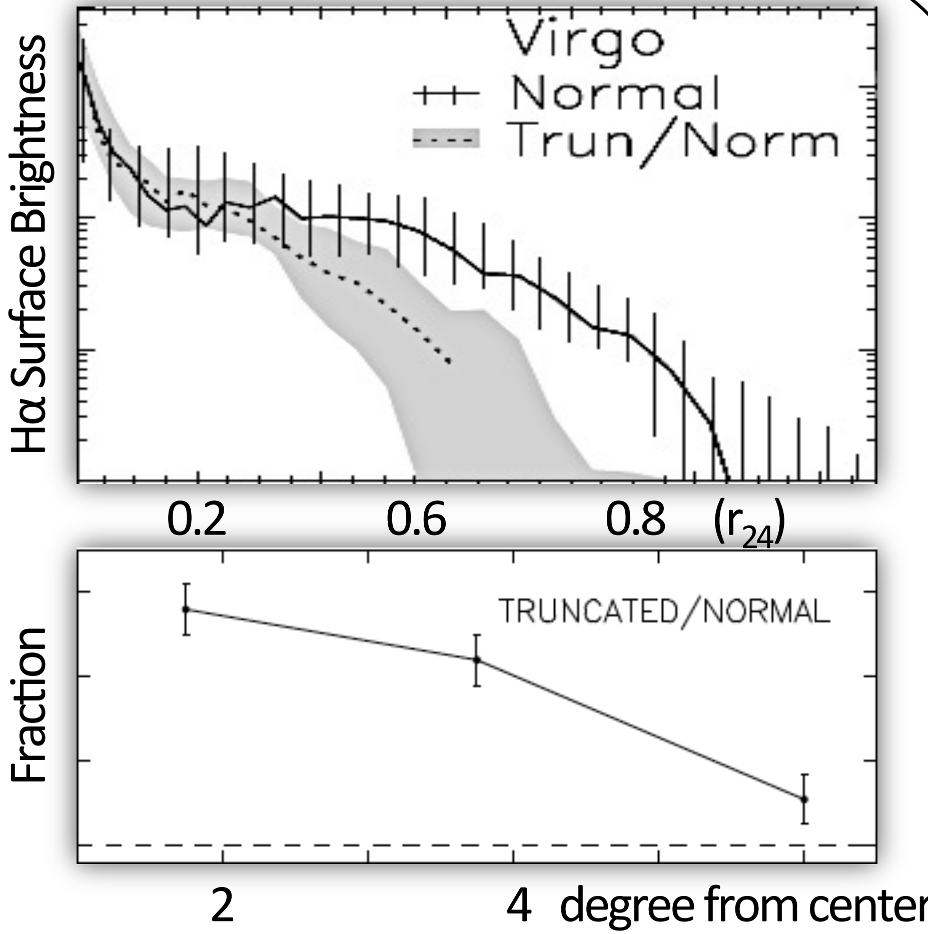


Peng et al. 2010
SDSS

Quenching the satellite star forming is independent on cluster/group halo mass.

Galaxy-ICM Interaction

➢ Ram pres. Strip.	observed
Extended ICM metal	observed
➢ Large cD galaxy	observed
➢ Environ. effect	observed
➢ ICM turbulence	observed?
➢ MHD heating	unknown
➢ Galaxy concentration relative to ICM	unknown



Truncated Hα disk and lower star forming in spirals in Virgo cluster central region (Koopmann + 2004)

Numerical estimate

Galaxy-to-ICM energy transfer rate

$$\mathrm{d}E/\mathrm{d}t = N\,\pi\,R_\mathrm{D}^{2}\,\rho_\mathrm{ICM}\,v^{3}$$

$$\approx 4 \times 10^{44}\,(N/500)\,(R_\mathrm{D}/10\ \mathrm{kpc})^{2}\,(\mathrm{n}/10^{-3}\ \mathrm{cm}^{-3})\,(v/500\ \mathrm{km\ s}^{-1})^{3}\ \mathrm{erg\ s}^{-1}$$

Typical ICM emissivity

$$L = 1.44 \times 10^{-27}\,\dot{g}\,T_\mathrm{ICM}^{1/2}\,n_\mathrm{e}\,\Sigma\,Z_\mathrm{i}^{2}n_\mathrm{i}$$

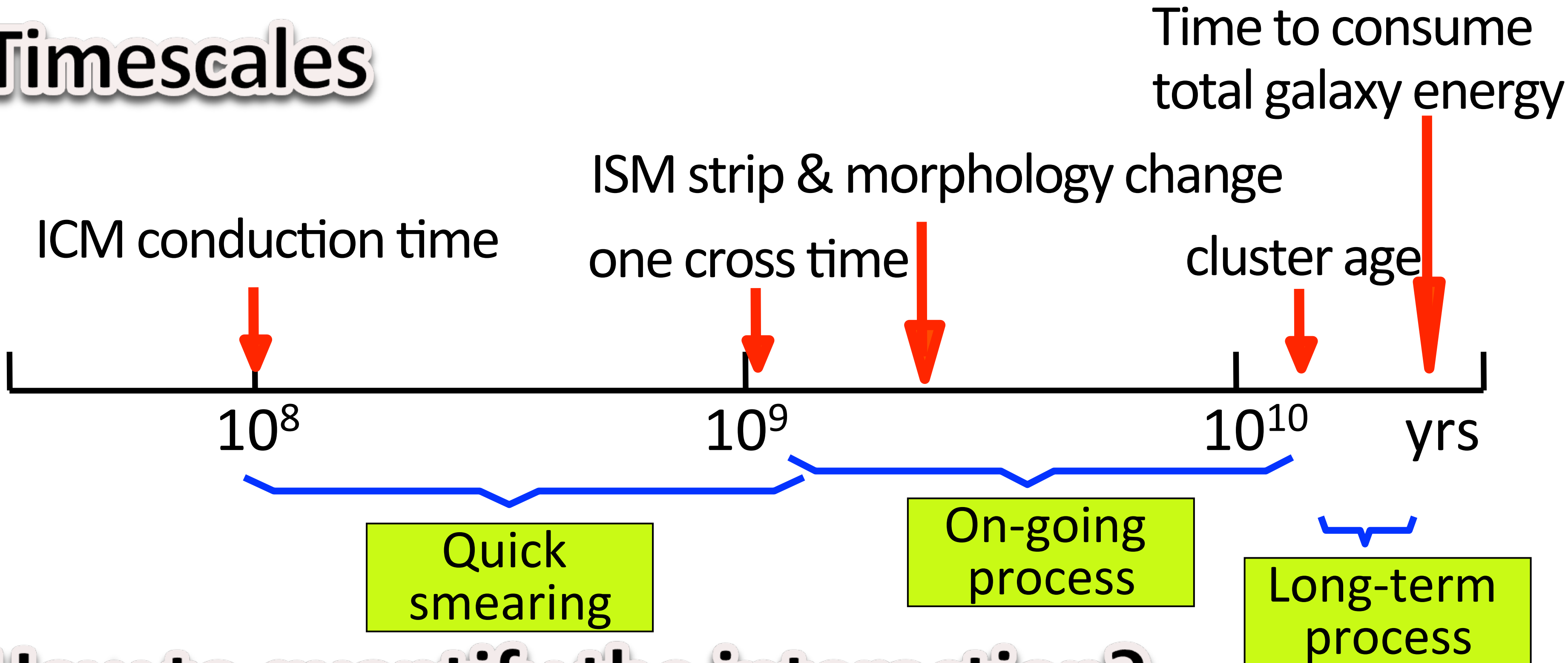
$$\approx 4.8 \times 10^{44}\,(T_\mathrm{ICM}/3 \times 10^{7}\ \mathrm{K})^{1/2}\,(n/10^{-3}\ \mathrm{cm}^{-3})^{2}\ \mathrm{erg\ Mpc}^{-3}\ \mathrm{s}^{-1}$$

Total kinetic energy of cluster galaxies

$$E \approx 5 \times 10^{62}\,(M_\mathrm{galaxy}/10^{14}\ \mathrm{M_o})\,(v/500\ \mathrm{km\ s}^{-1})^{2}\ \mathrm{erg}$$

$$E/(\mathrm{d}E/\mathrm{d}t) \approx 80\ \mathrm{Gyr}$$

Timescales



How to quantify the interaction?

More individual case study? Galaxy environmental effect? ICM heating/ turbulence probe? Metal mass-to-light ratio?

Why not do more directly

Galaxy light distribution vs. ICM distribution for different-z

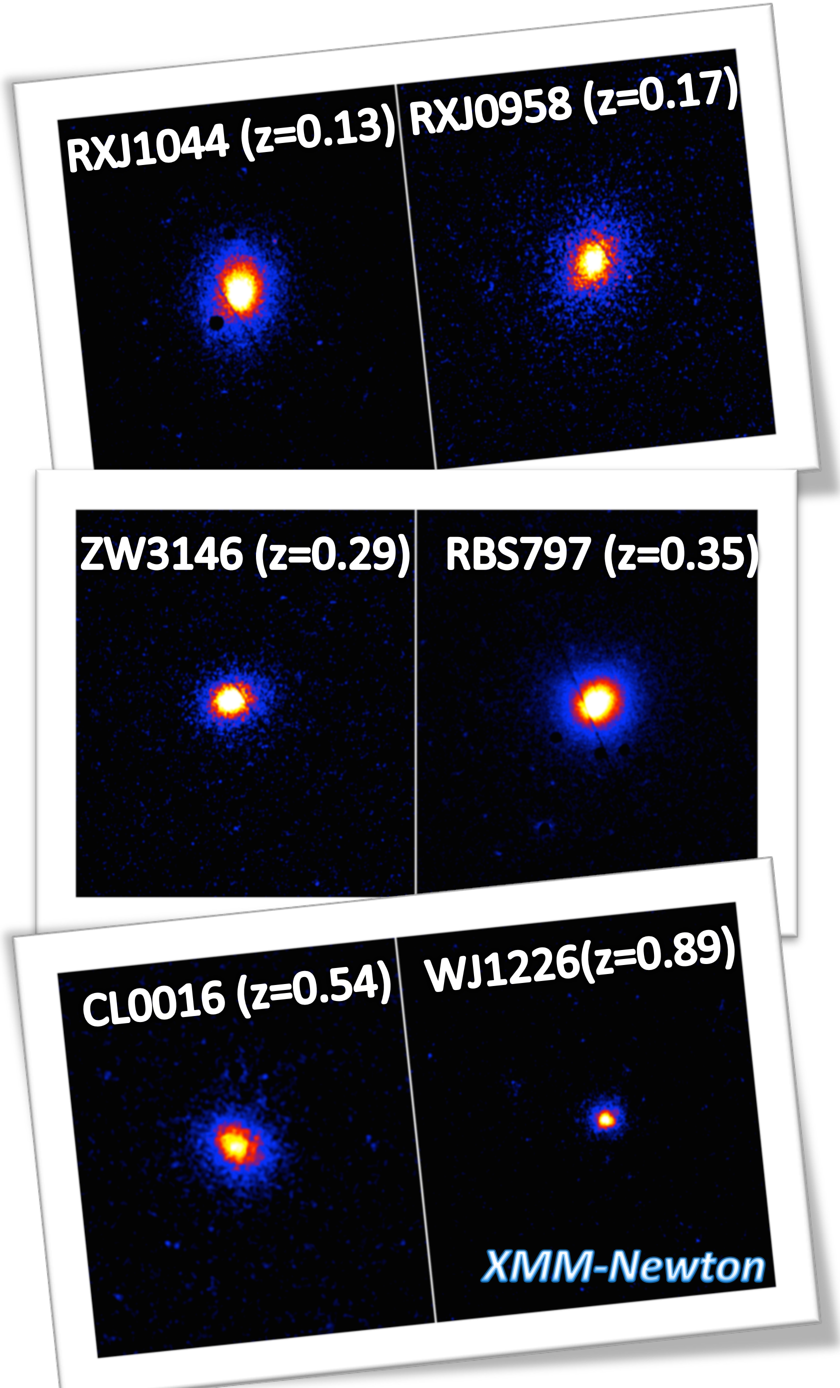
Cluster sample

We study a sample of **34** clusters, with redshift range of **0.1-0.9**.
The sample is selected via

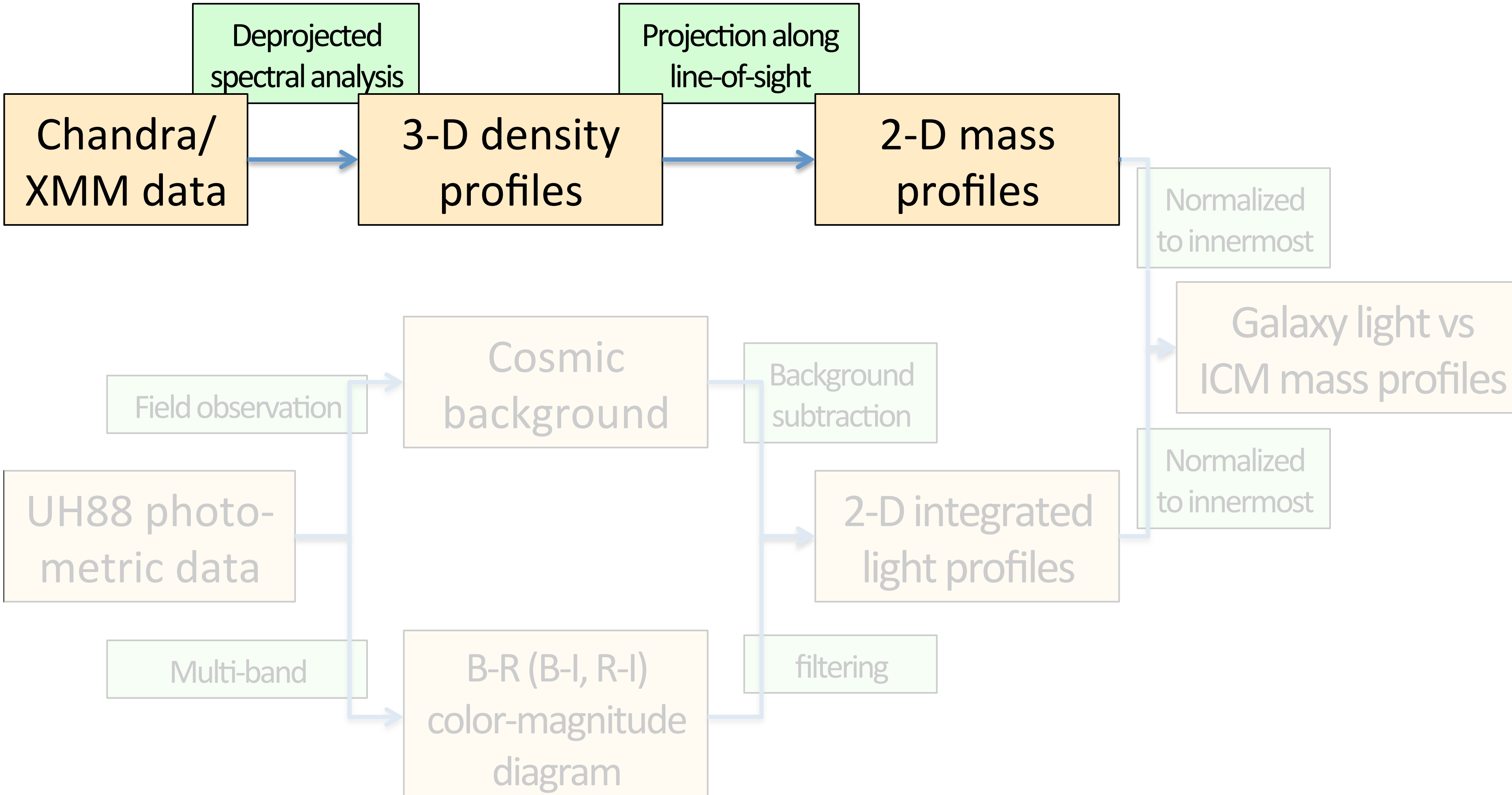
- Similar average ICM temperature (5±2 keV)
- Relaxed X-ray morphology
- Apparent central dominate galaxy

Datasets

- UH88 I-band image (PI: Dr. Inada)
- *XMM-Newton* for z<0.5
- *Chandra* (if available) for z>0.5

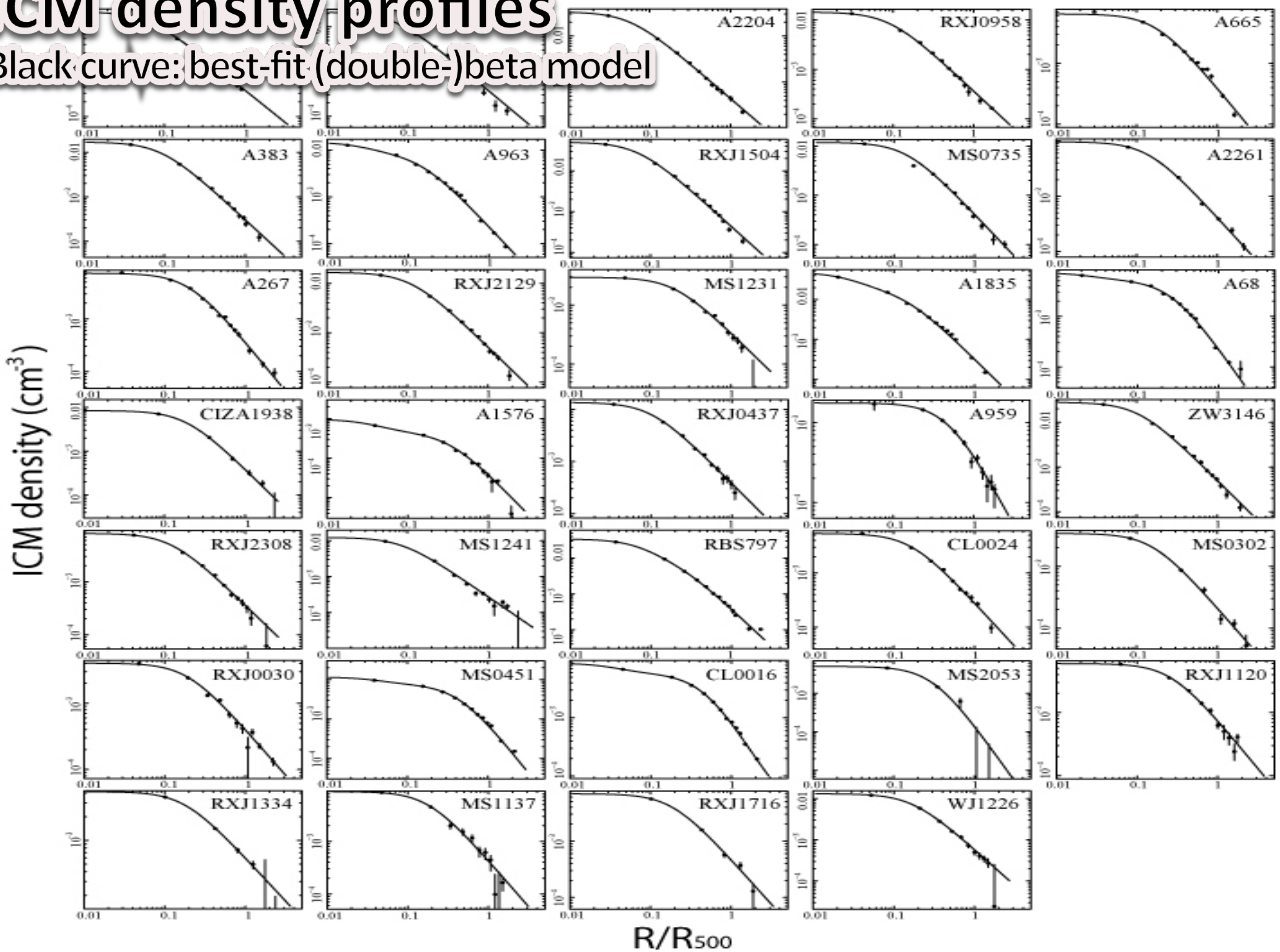


ICM mass profiles

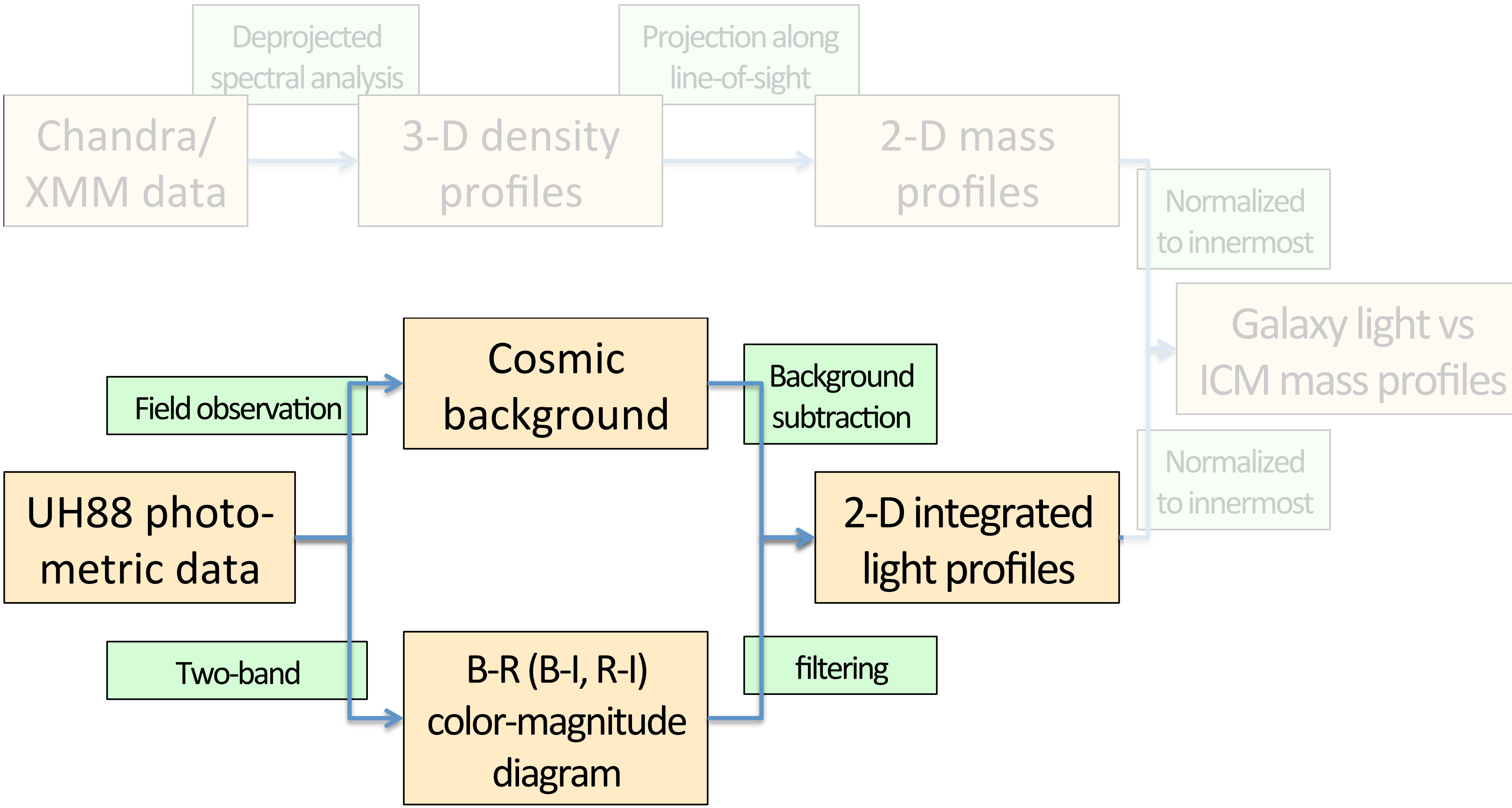


ICM density profiles

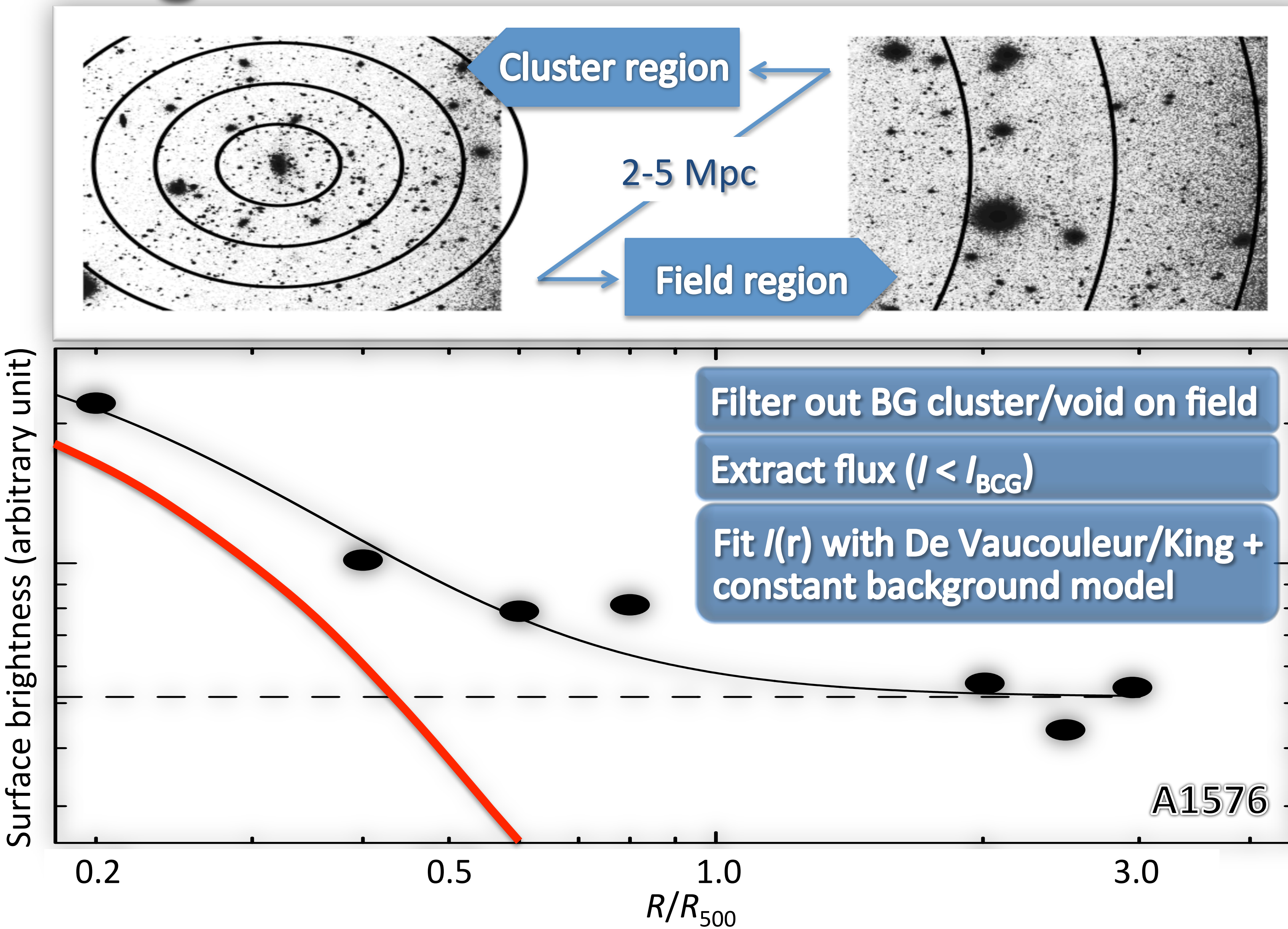
Black curve: best-fit (double-)beta model



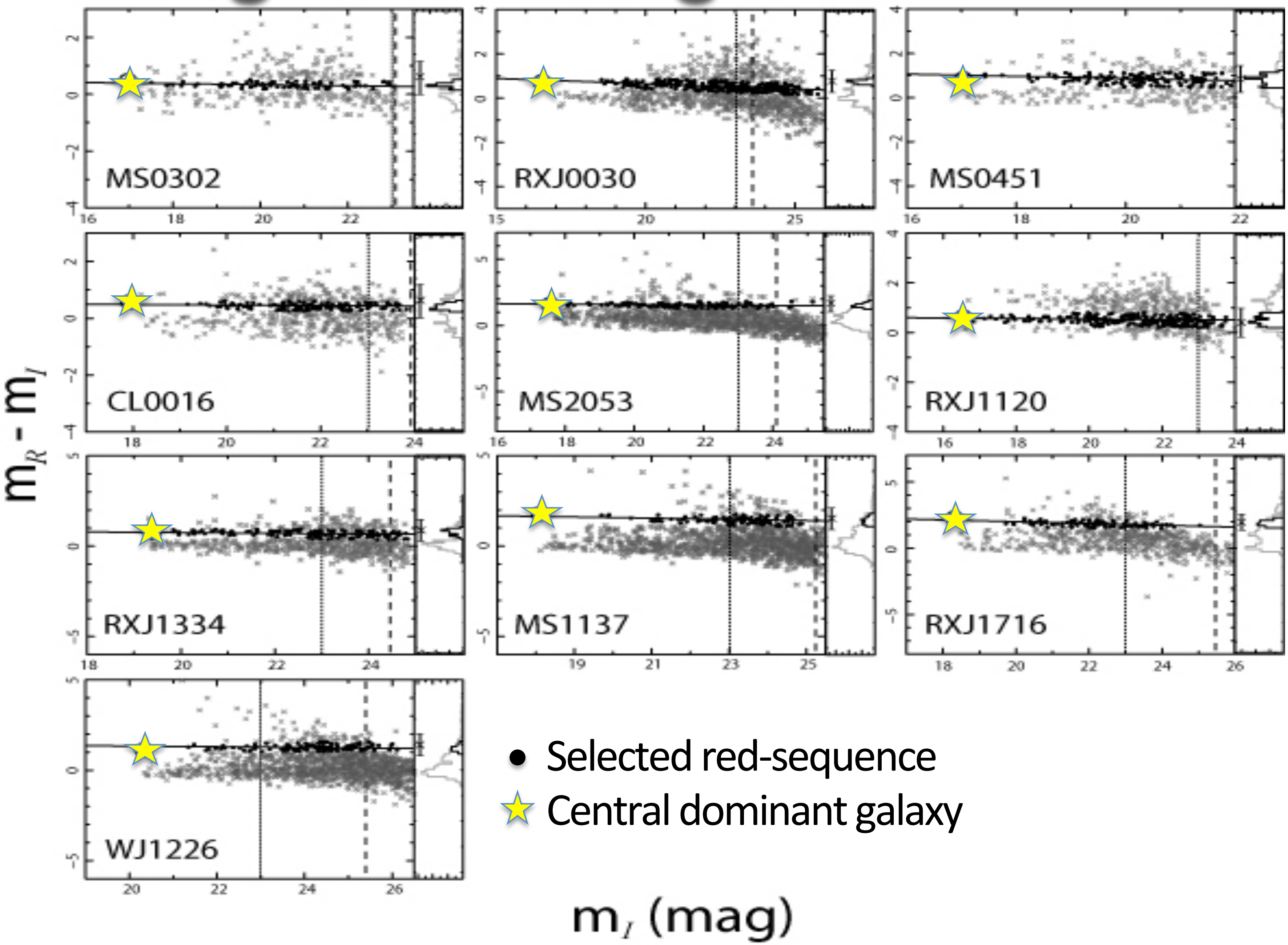
Galaxy light profile



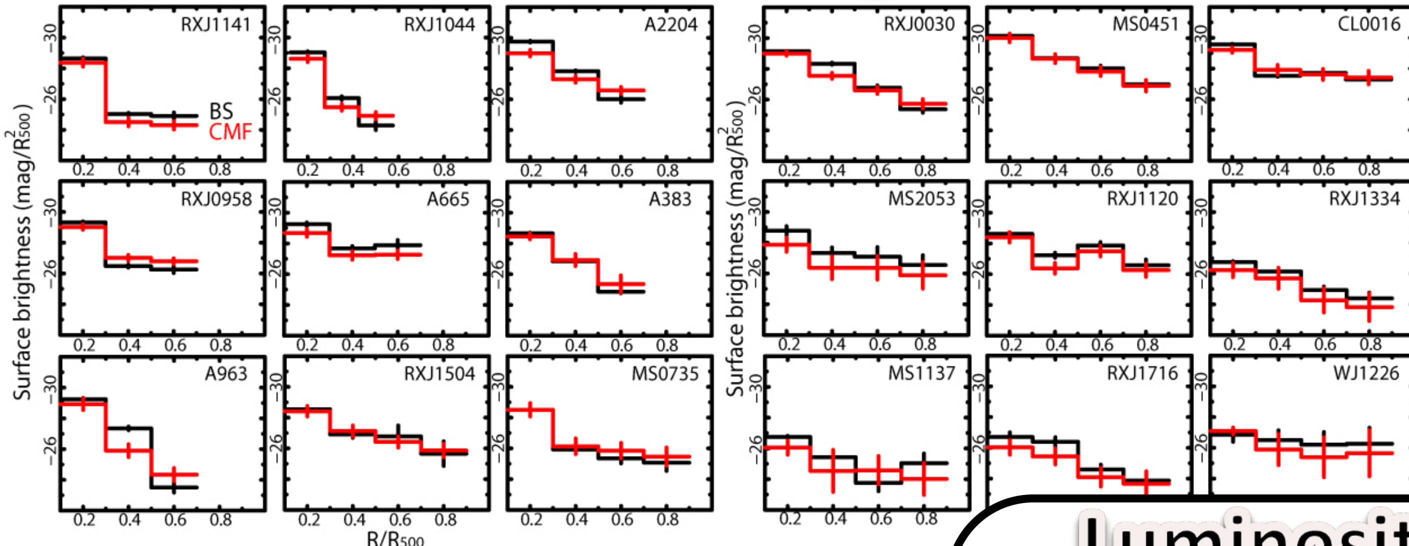
Background subtraction



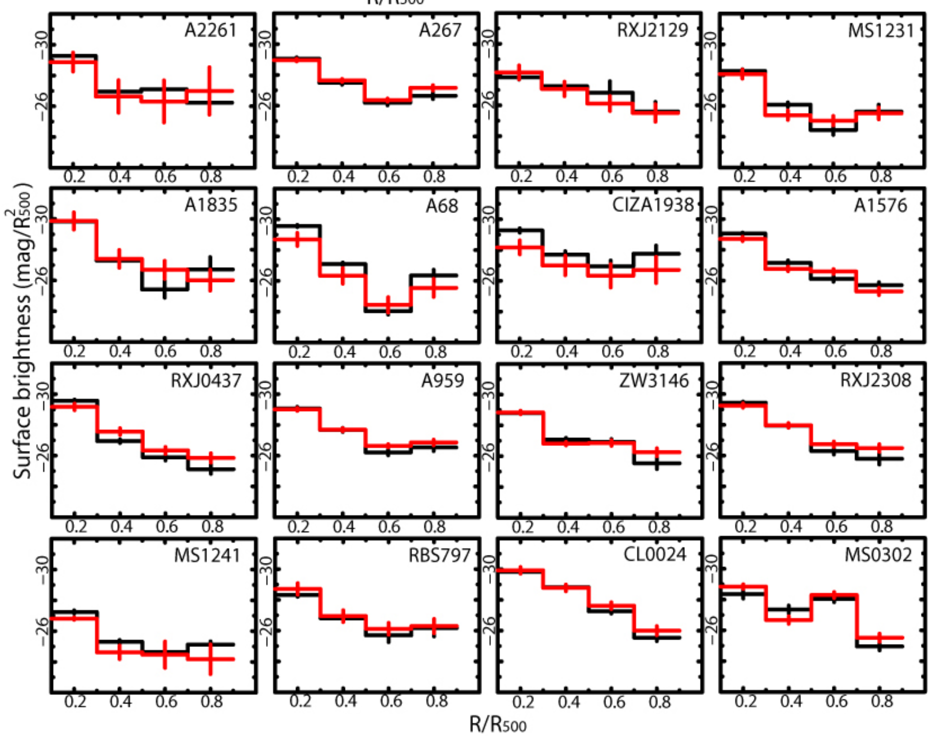
Color-Magnitude Filtering



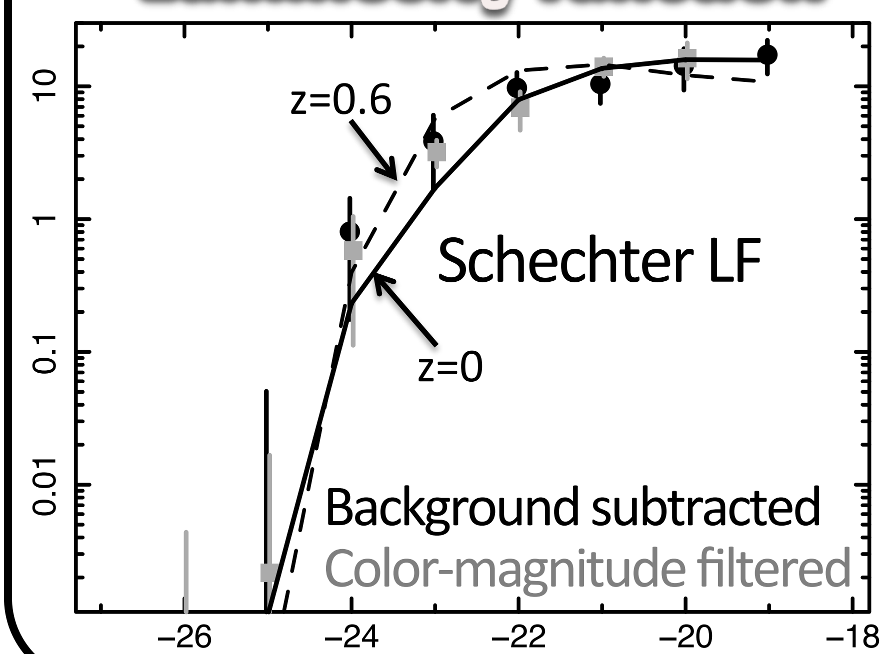
I-band surface brightness



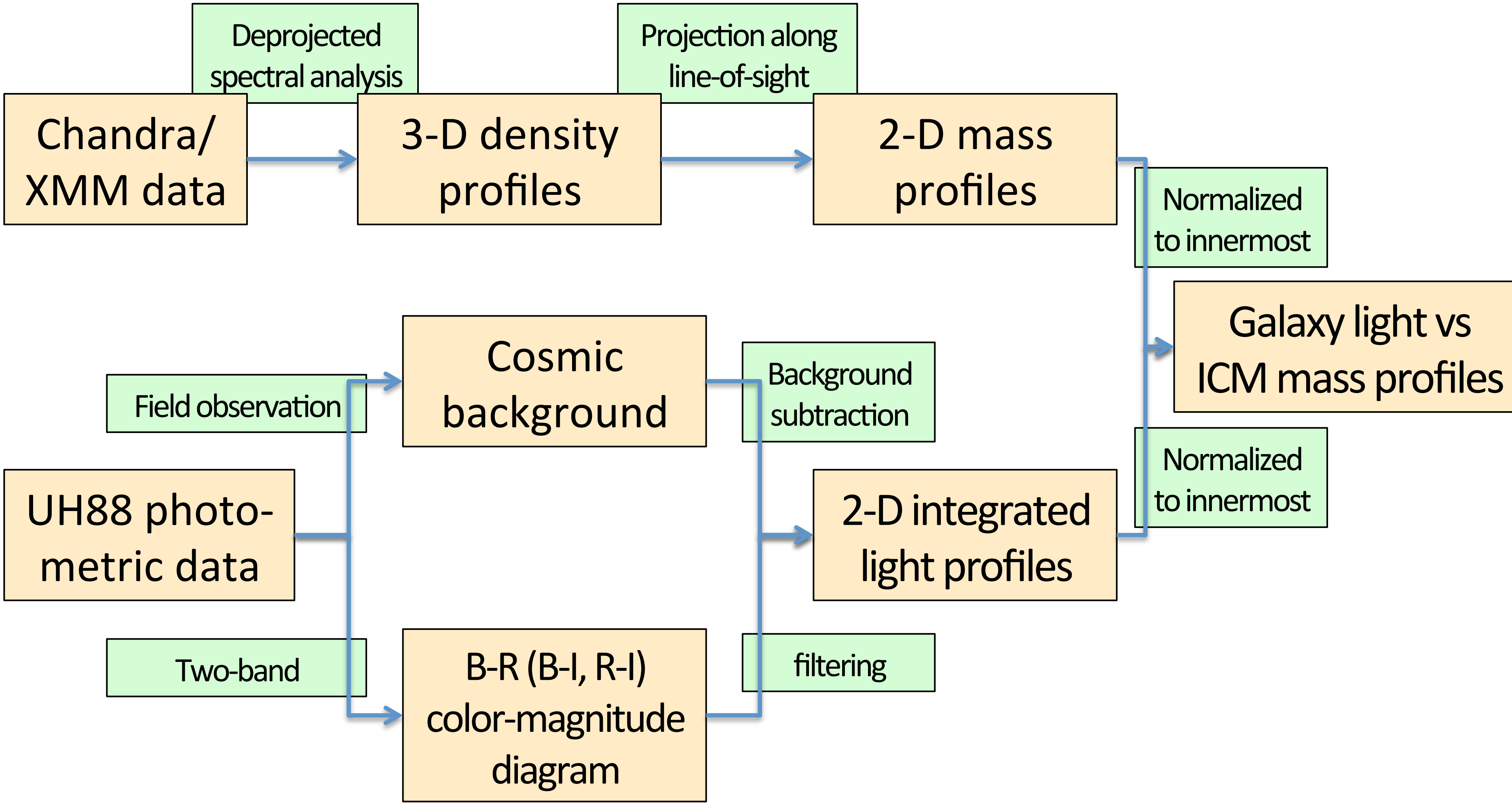
Red: color-magnitude filtered
Black: background subtracted



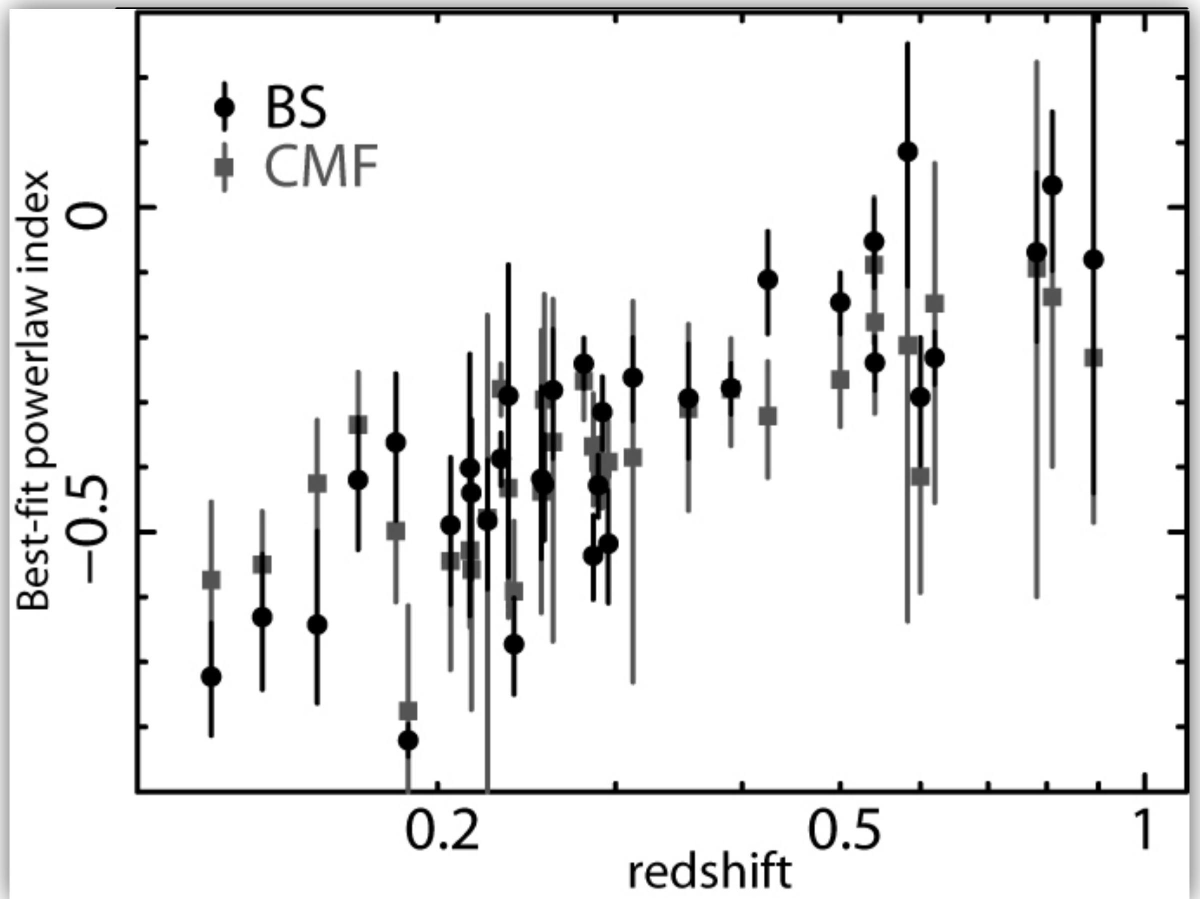
Luminosity function



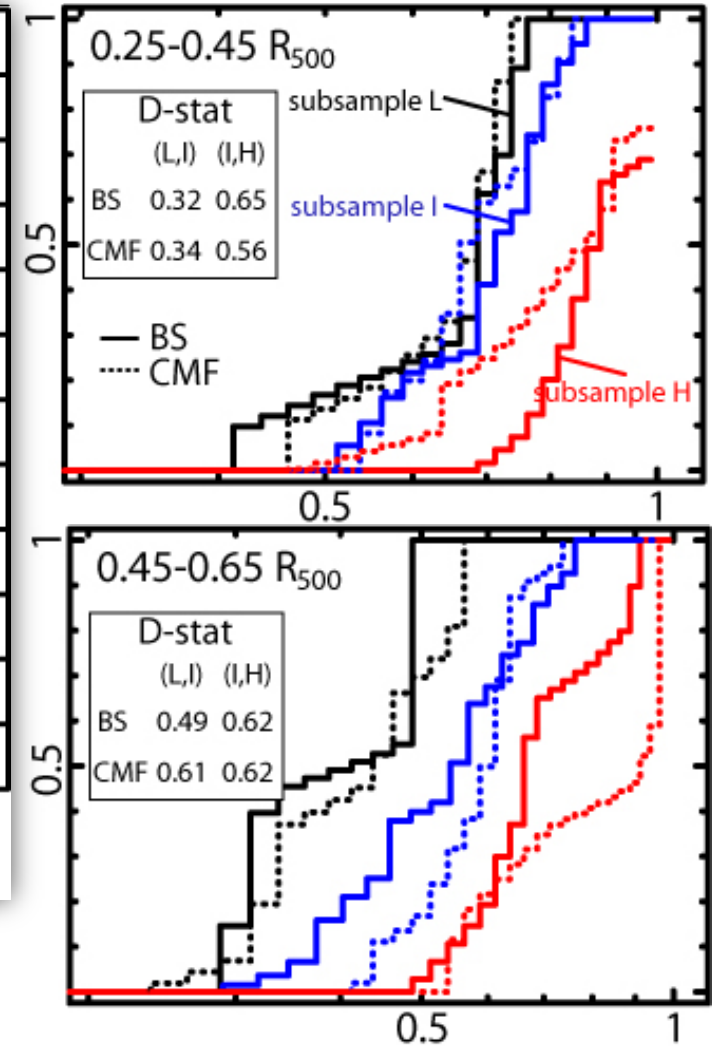
Galaxy light vs ICM mass profile



Galaxy light vs. ICM mass ratio profiles



K-S cumulative distribution

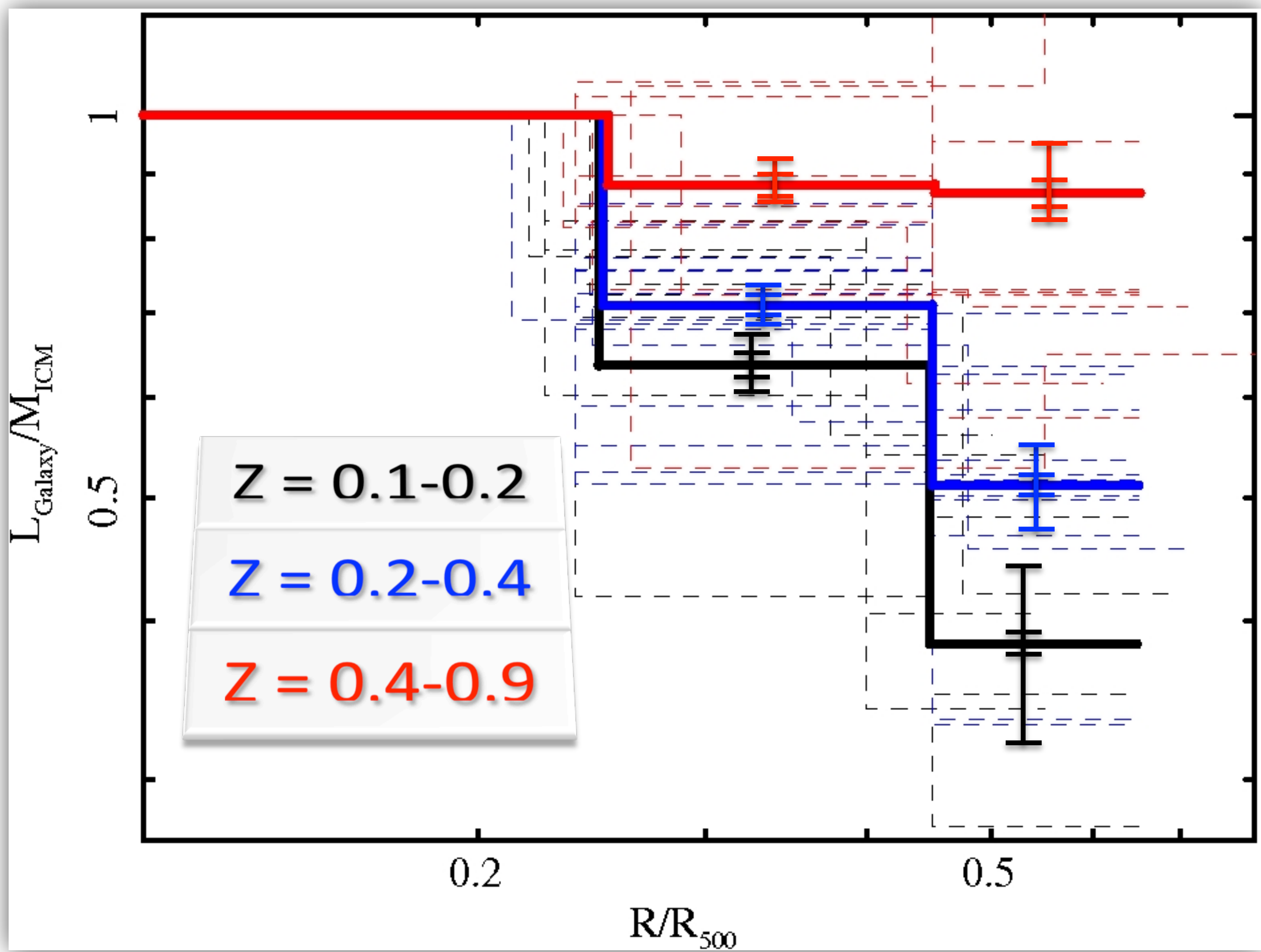


Stellar-to-ICM ratio concentrated by half @ $0.5R_{500}$ (95% level)

Is the evolution = galaxy-ICM interaction?

- **Error sources for background subtraction method**
  - ✓ Data statistics
  - ✓ Systematic uncertainties on optical background (i.e., cosmic variance)
- **Redshift-dependent systematic biases**
  - ✓ Radius-dependent star formation rate: galaxy number test
  - ✓ ICM temperature dependence test
  - ✓ Cosmic expansion
- **Astrophysical effects**
  - ✓ Dynamical friction: faint galaxy test

Uncertainties Analysis



Statistic error
(X-ray/optical data)

+

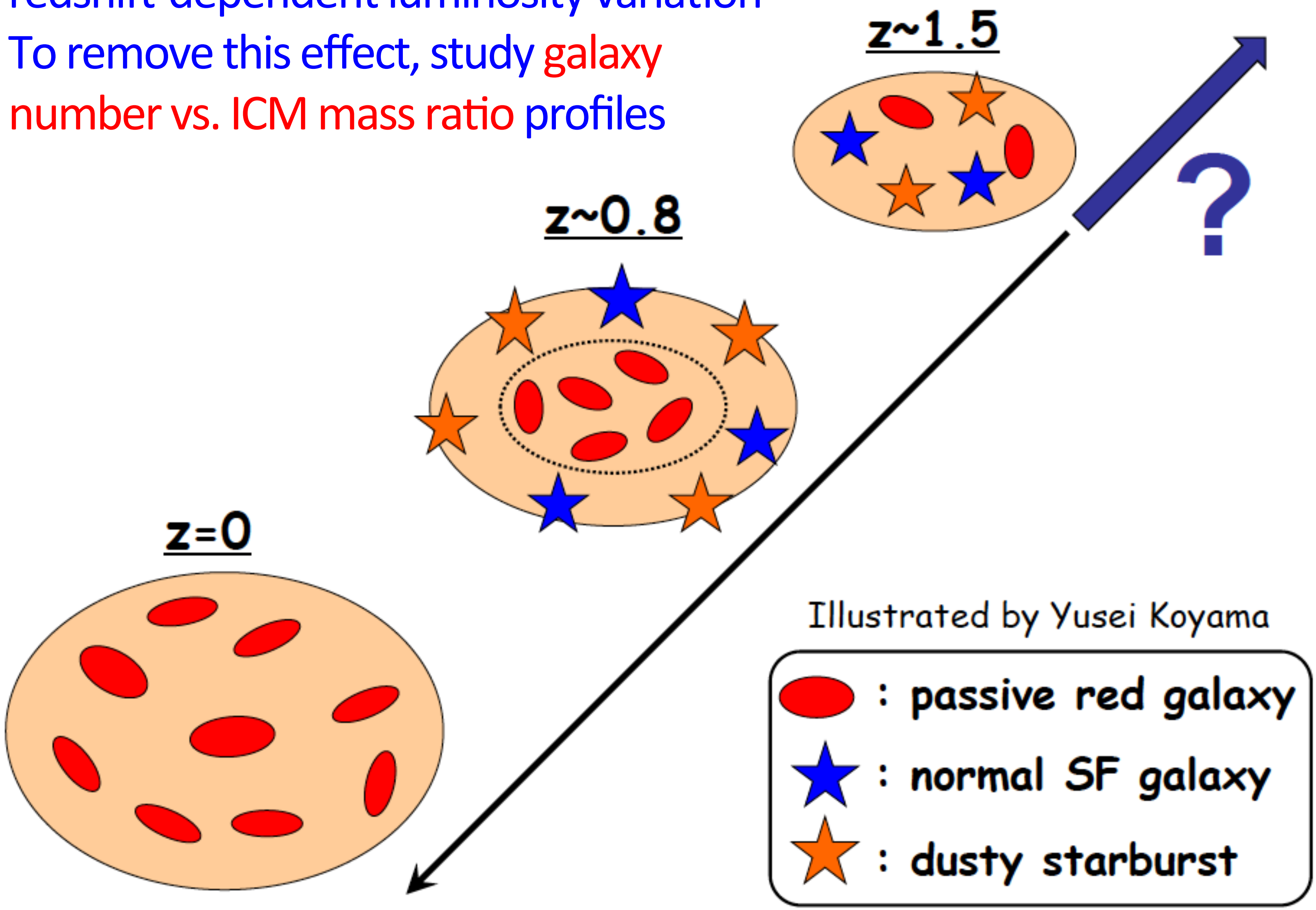
Systematic error (*i.e.*, cosmic variance ~ 20-30% of optical background)

Monte-Carlo

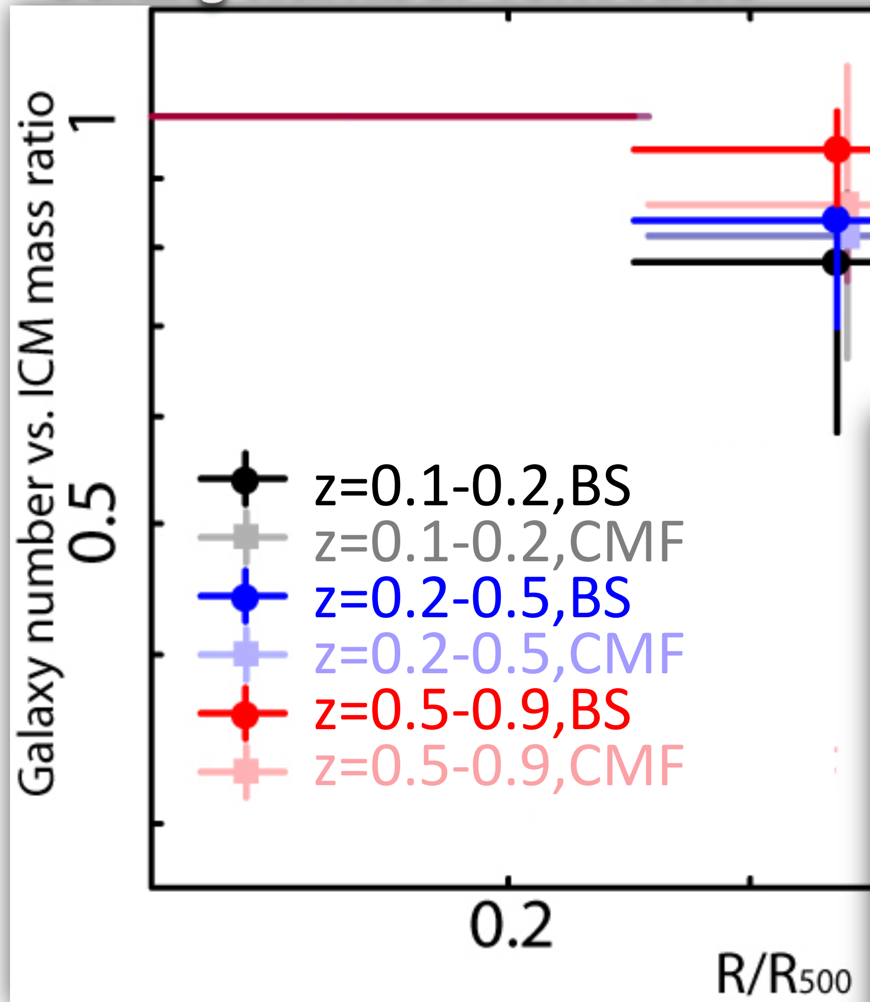
K-S test shows significant evolution on 90%

Courtesy: T. Kodama (NAOJ)

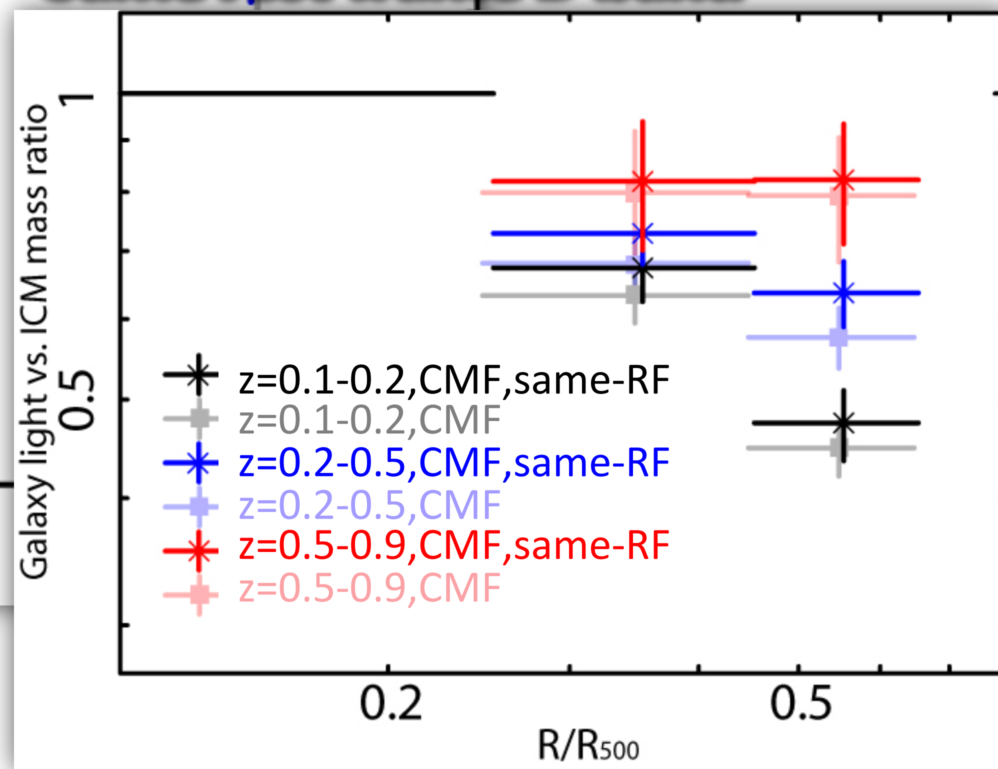
- Galaxy population/SF rate evolution → redshift-dependent luminosity variation
- To remove this effect, study galaxy number vs. ICM mass ratio profiles



Galaxy number-ICM ratio



Same rest-frame B-band

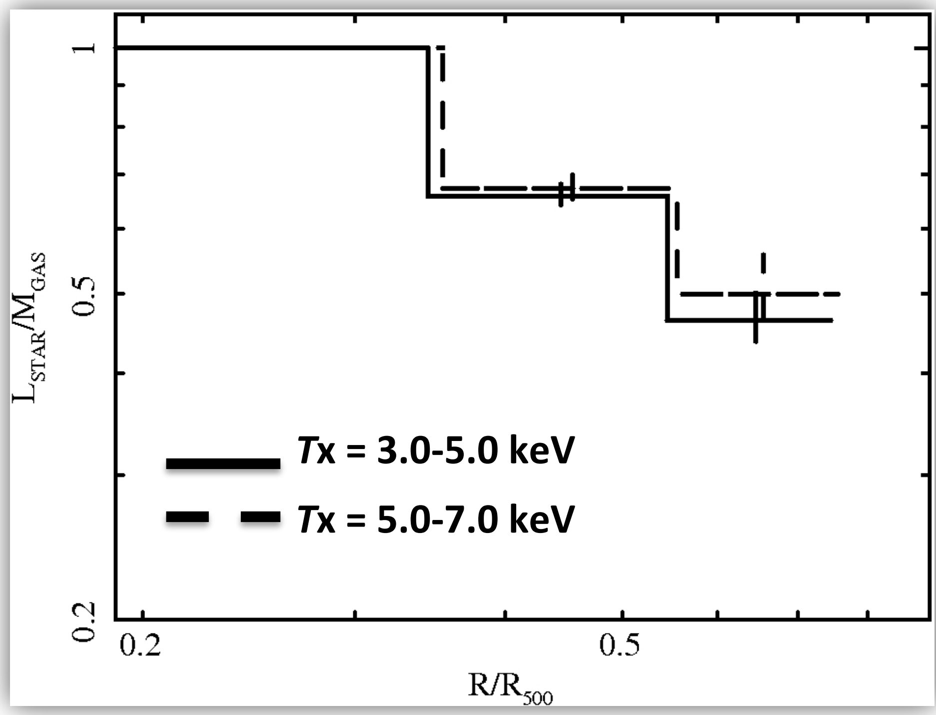


- ✗ Cluster color gradient
- ✗ Over-luminous BCG
- ✗ Variation of galaxy luminosity by e.g., star formation

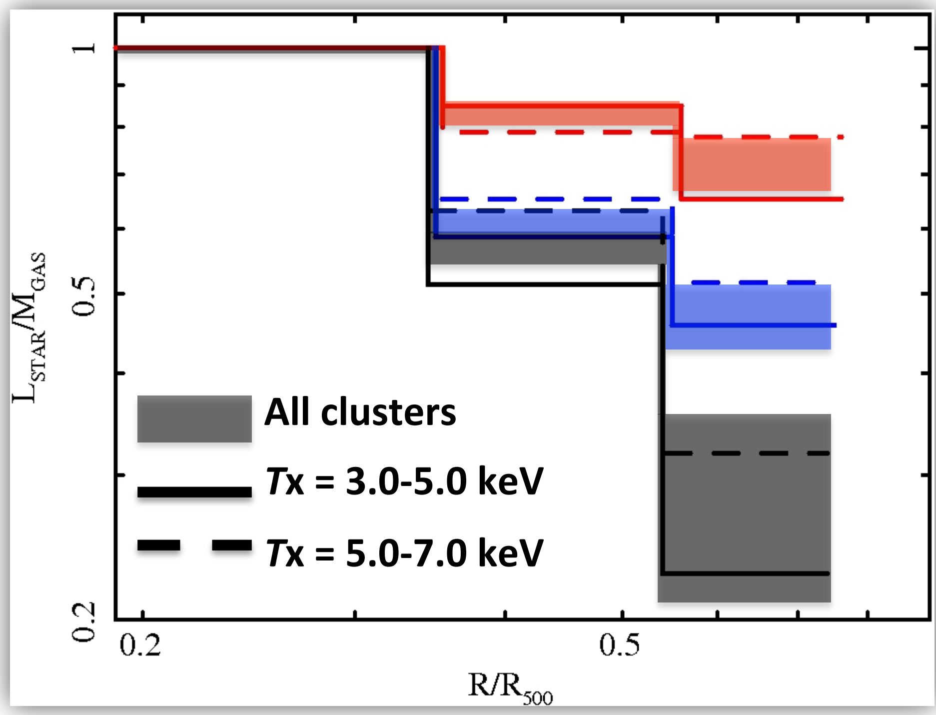
Cluster temperature dependence test

- Low *Tx* (potential depth) cluster affected more strongly by heating
- Compare the light-to-ICM ratio between low- and high- *Tx* subsample

Average profile of entire sample



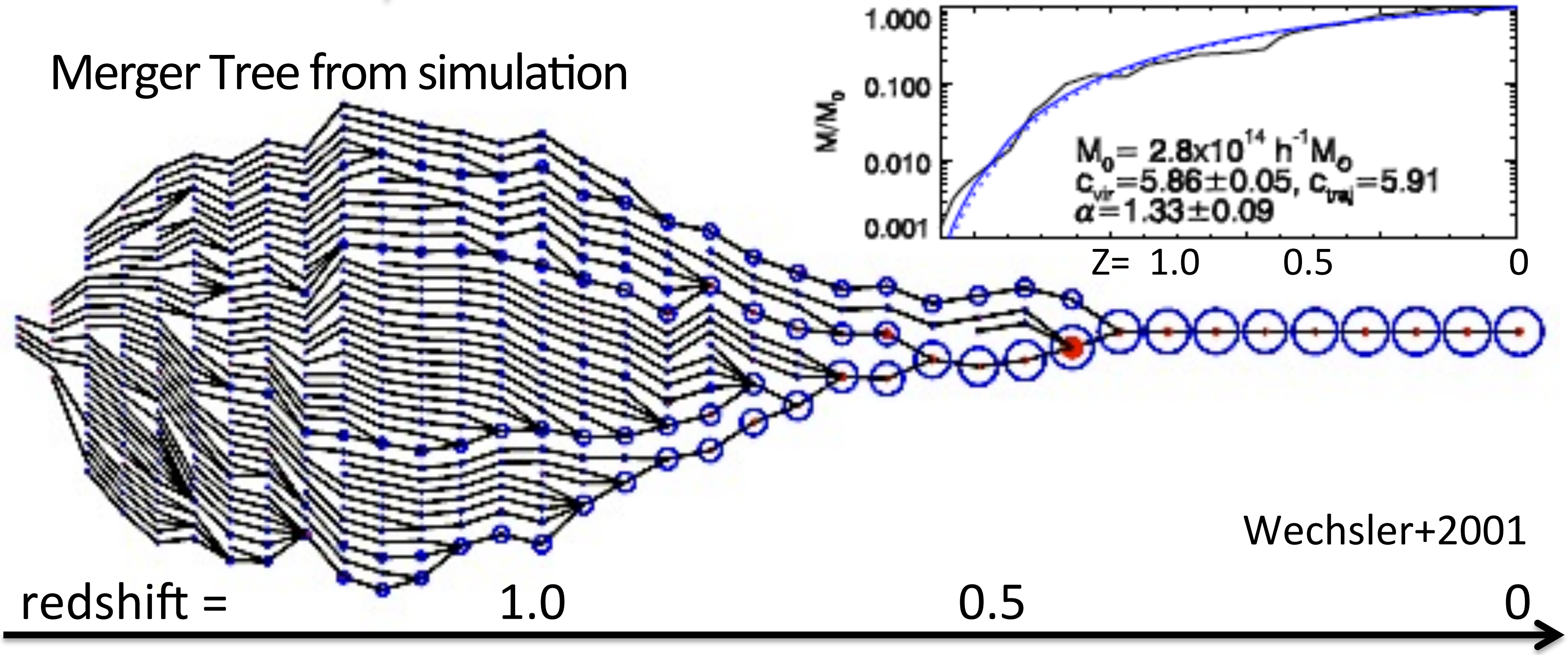
Average profile of each subsample



The optical-to-X-ray evolution not caused by the cluster temperature/potential depth difference

Cosmic growth of galaxy clusters

Merger Tree from simulation



Approximately we have

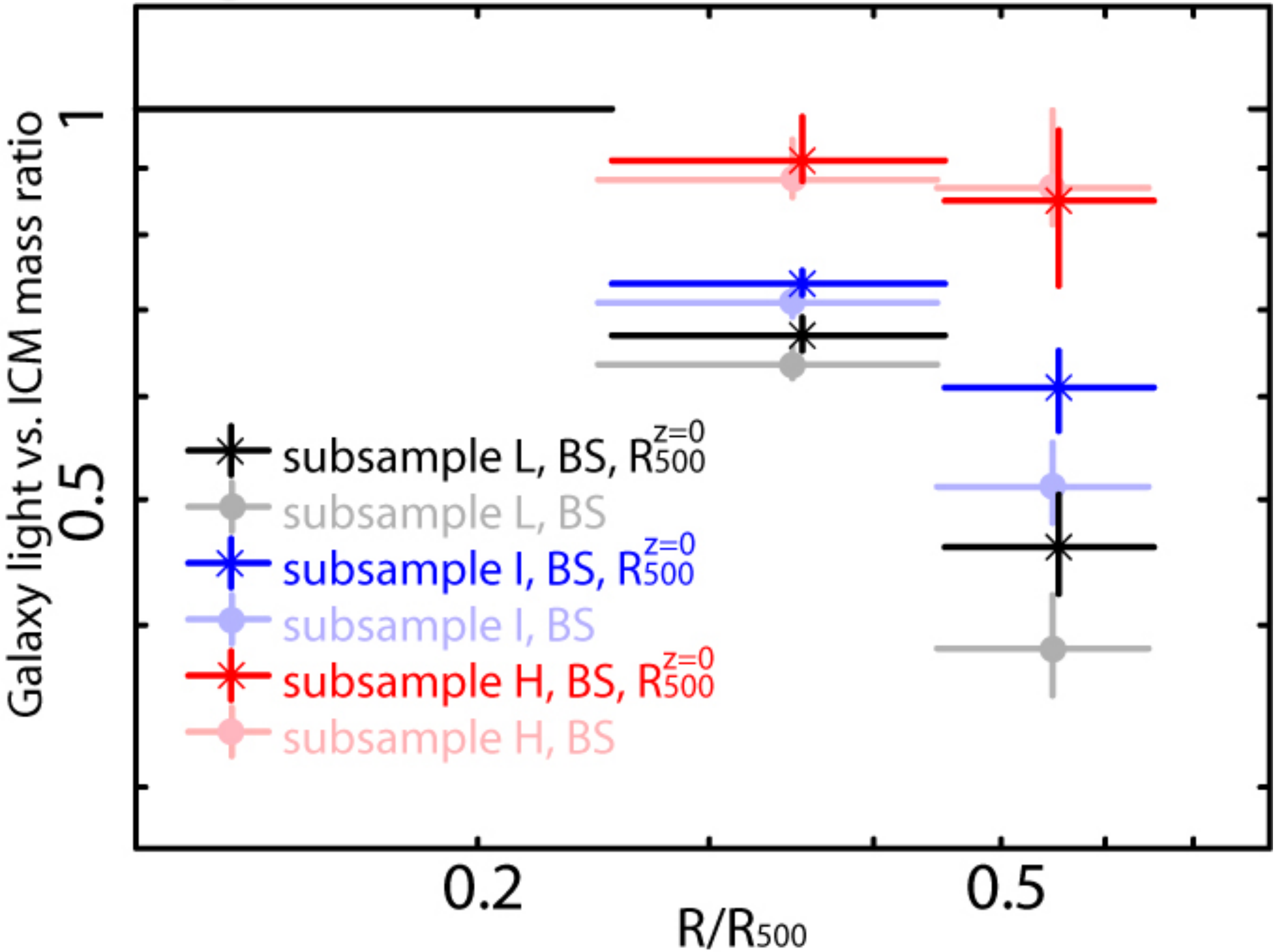
$$M(Z) = M_0\, e^{-1.33 \times Z}$$

$$T(Z) \sim M(Z)^{0.7}$$

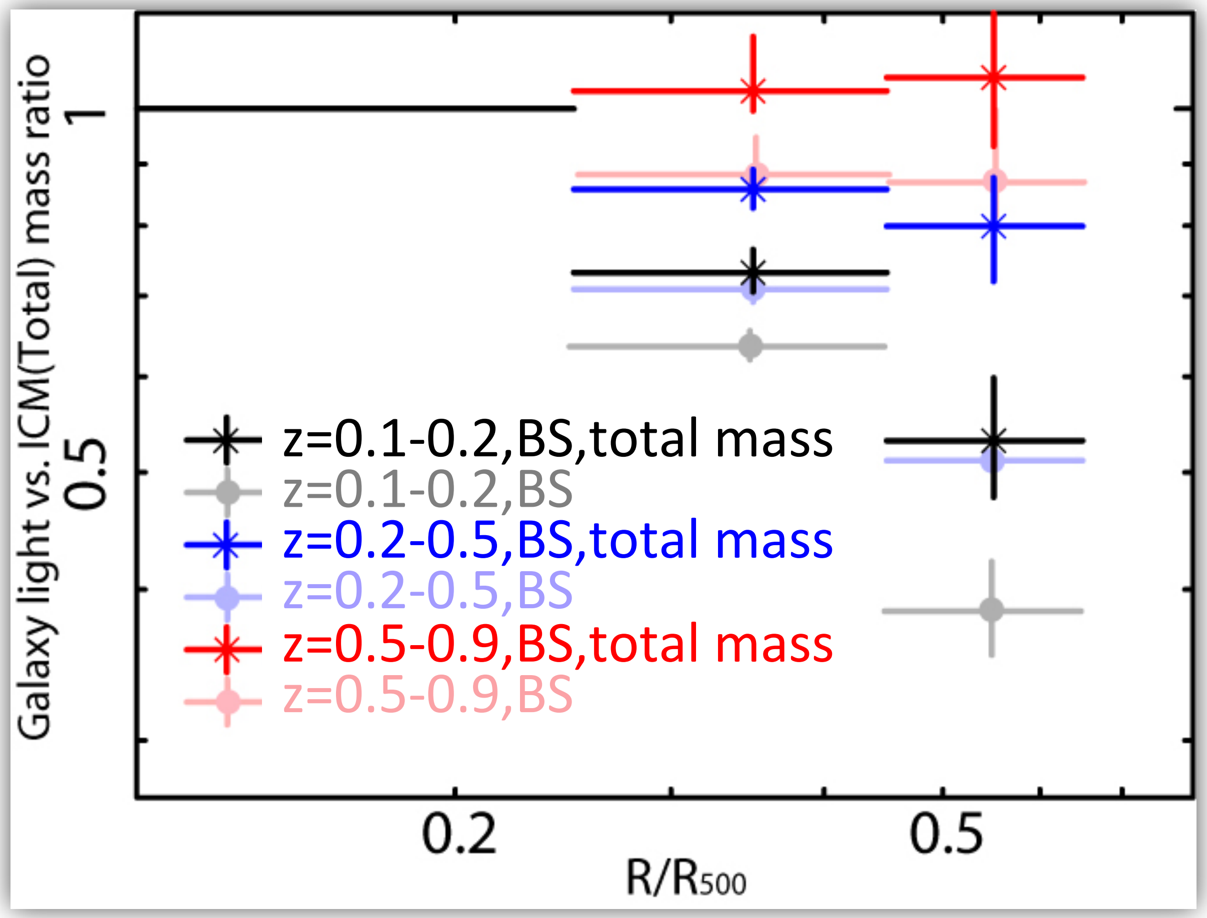
$$R(Z) \sim T(Z)^{0.63}$$ → scale increase by ~ 2 from z=1 to 0

To account for the scale increase, normalize virial radius to z=0

Scaled by the cluster size at z=0



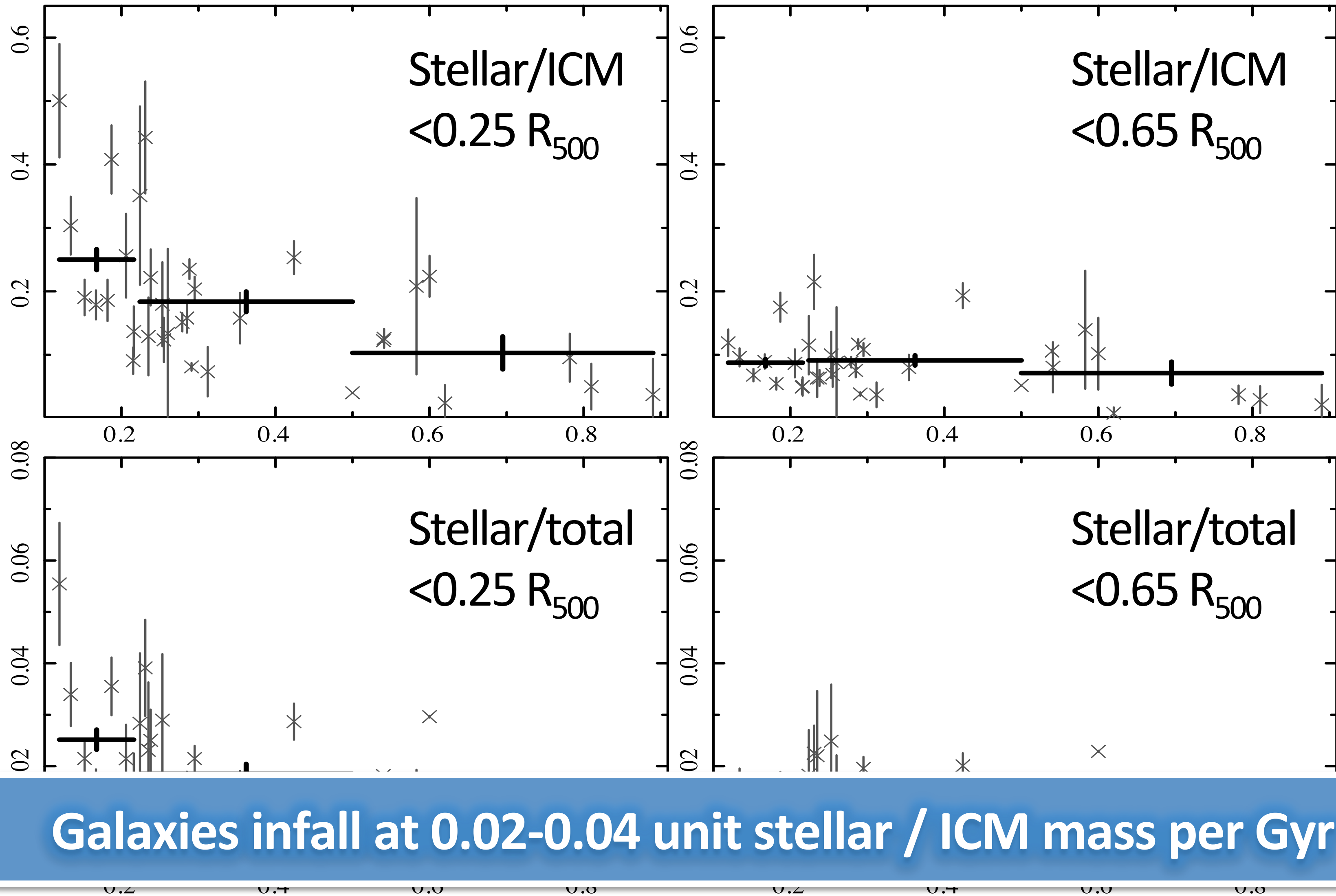
Galaxy light vs. total mass ratio profile



- Galaxy/ICM/DM follow similar distribution at high-z
- Concentration: galaxy<DM<ICM

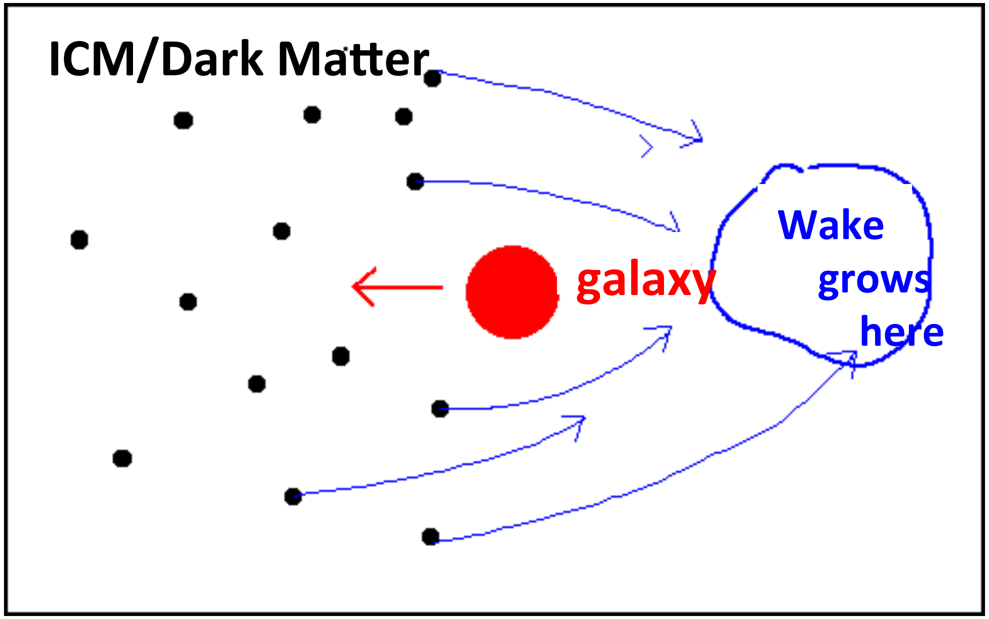
Galaxy infall rate

Compare the stellar mass with ICM/total mass in same absolute unit $M_\odot$



Galaxies infall at 0.02-0.04 unit stellar / ICM mass per Gyr

Dynamical friction



$$F_{DF} = -4\pi\rho(GM_{galaxy})^2 \ln\Lambda \,[\mathrm{erf}(X)-(2X/\sqrt{\pi})\exp(-X^2)]\,/v^2$$

Loss rate of galaxy angular momentum

$$dL/dt = M_{galaxy} v\, dr/dt \approx F_{DF} \times r$$

decay of galaxy orbit

$$dr/dt \approx -\,4\pi\rho G^2 M_{galaxy} r/v^3$$

Numerical estimate of DF effect

Assuming cluster matter following Navarro-Frenk-White (NFW) distribution:

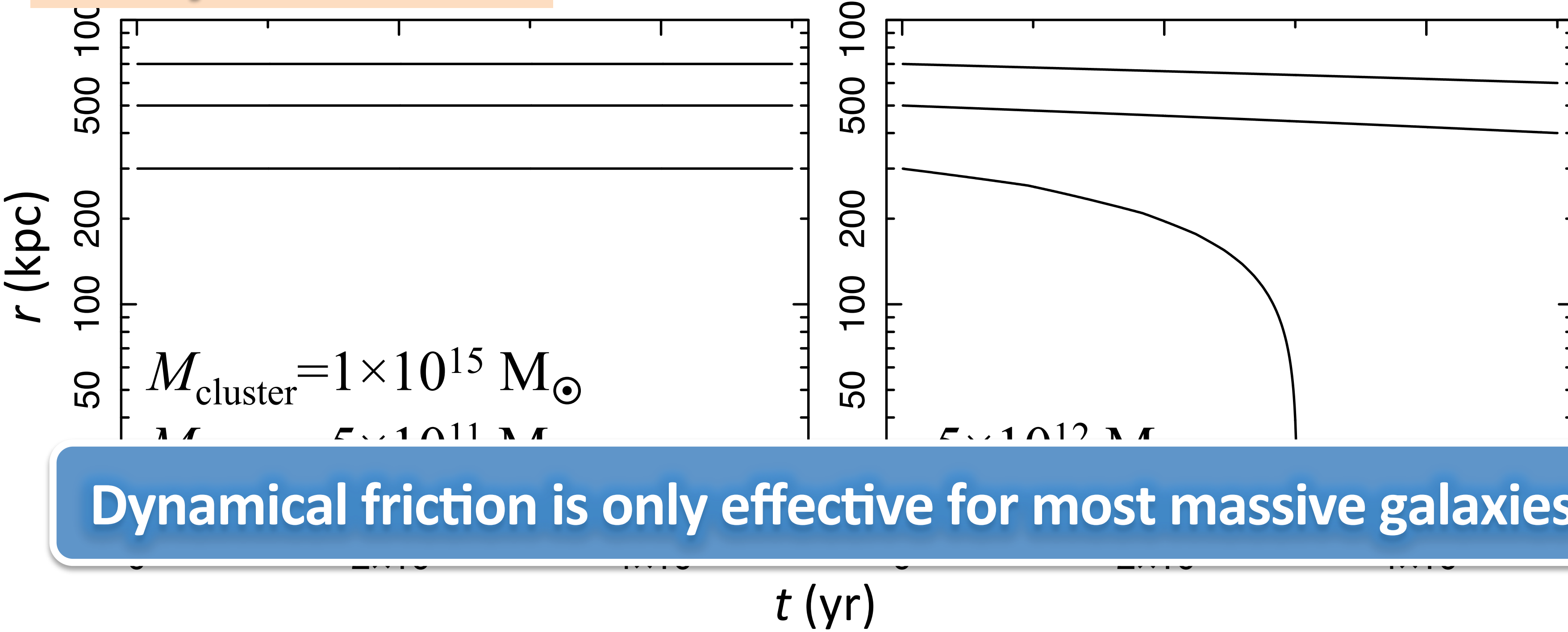
$$\rho = \rho_0/(r/R_S(1 + r/R_S)^2)$$

Orbit velocity is $$v = (2GM/r)^{1/2}$$

where enclosed mass M is

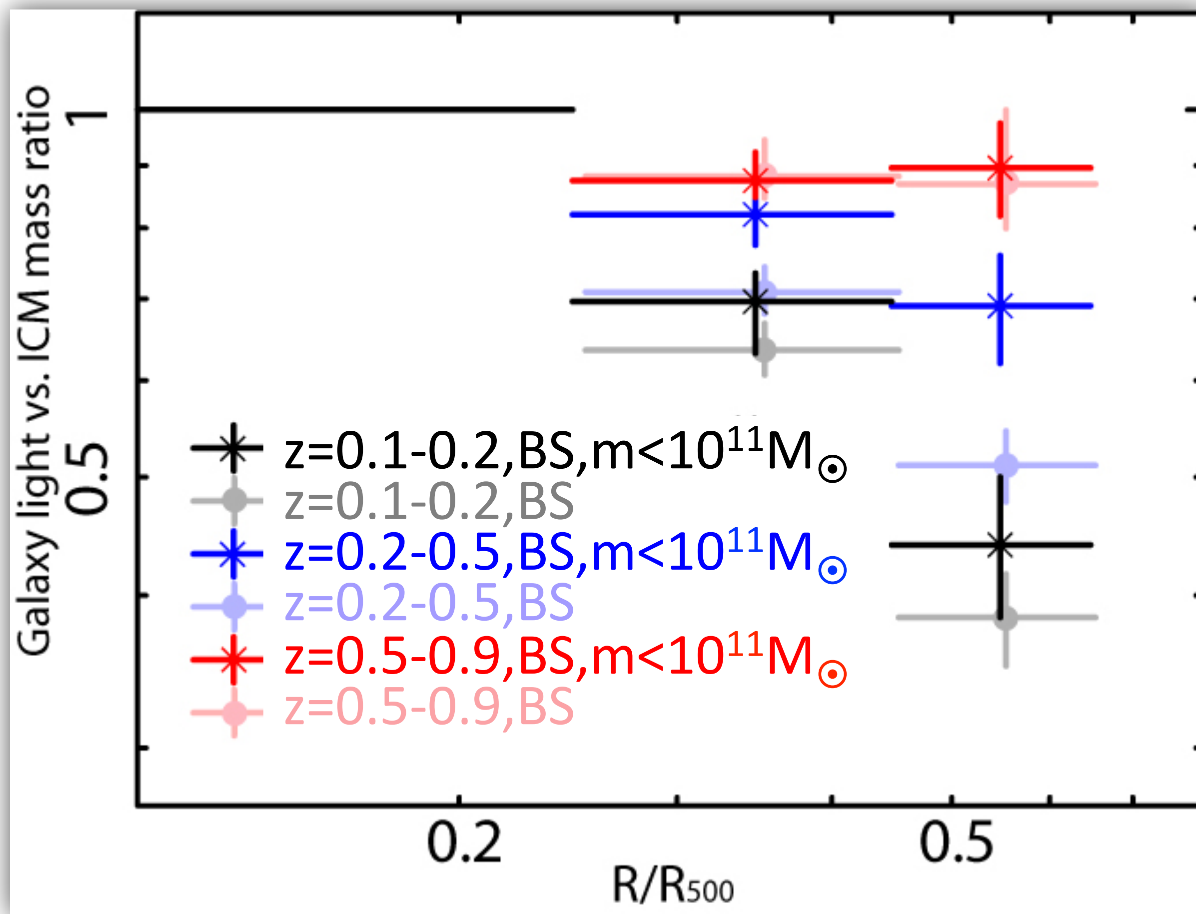
$$M = 4\pi\rho_0 R_S{}^2[\ln((R_S+r)/R_S)\text{-}r/(R_S+r)]$$

Galaxy orbit vs. time:



Dynamical friction is only effective for most massive galaxies

Low-mass galaxy light vs. ICM mass ratio



Dynamical friction alone insufficient to explain the evolution

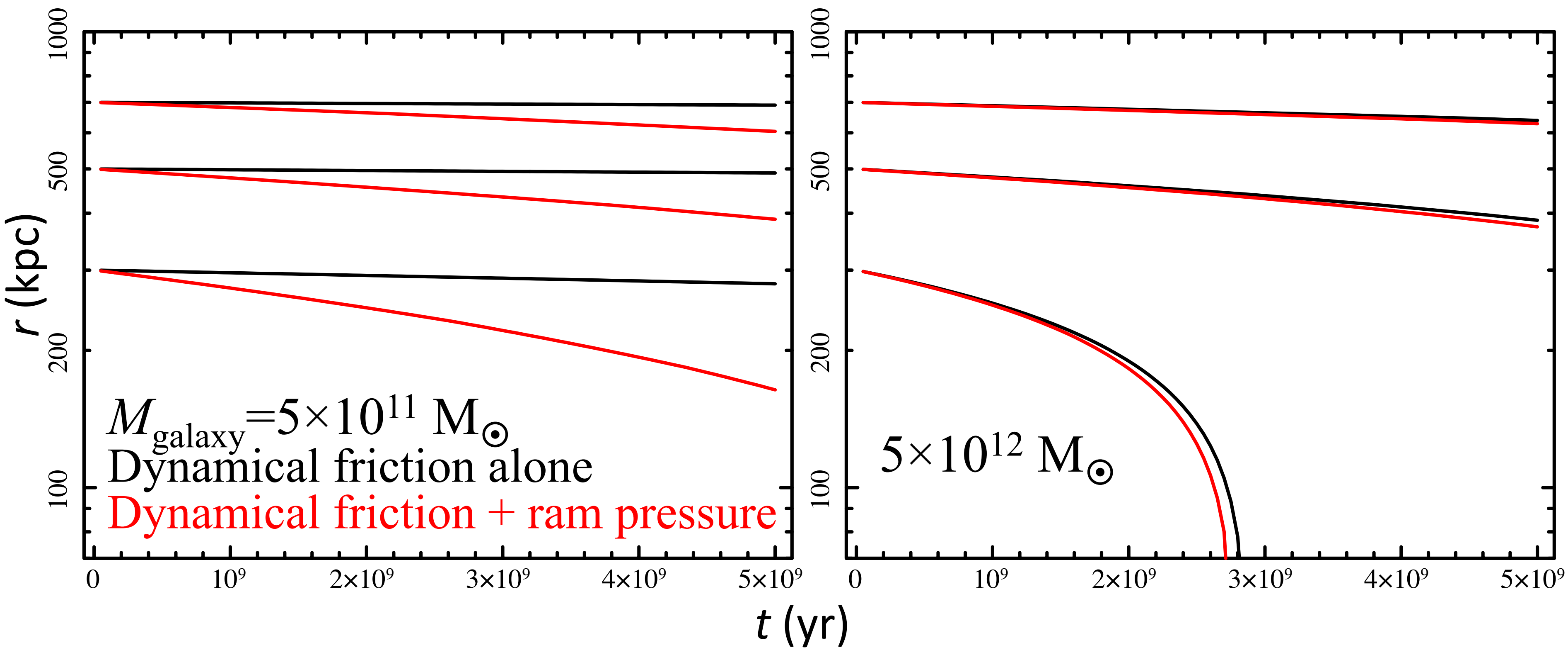
Consider ICM drag

Ram pressure

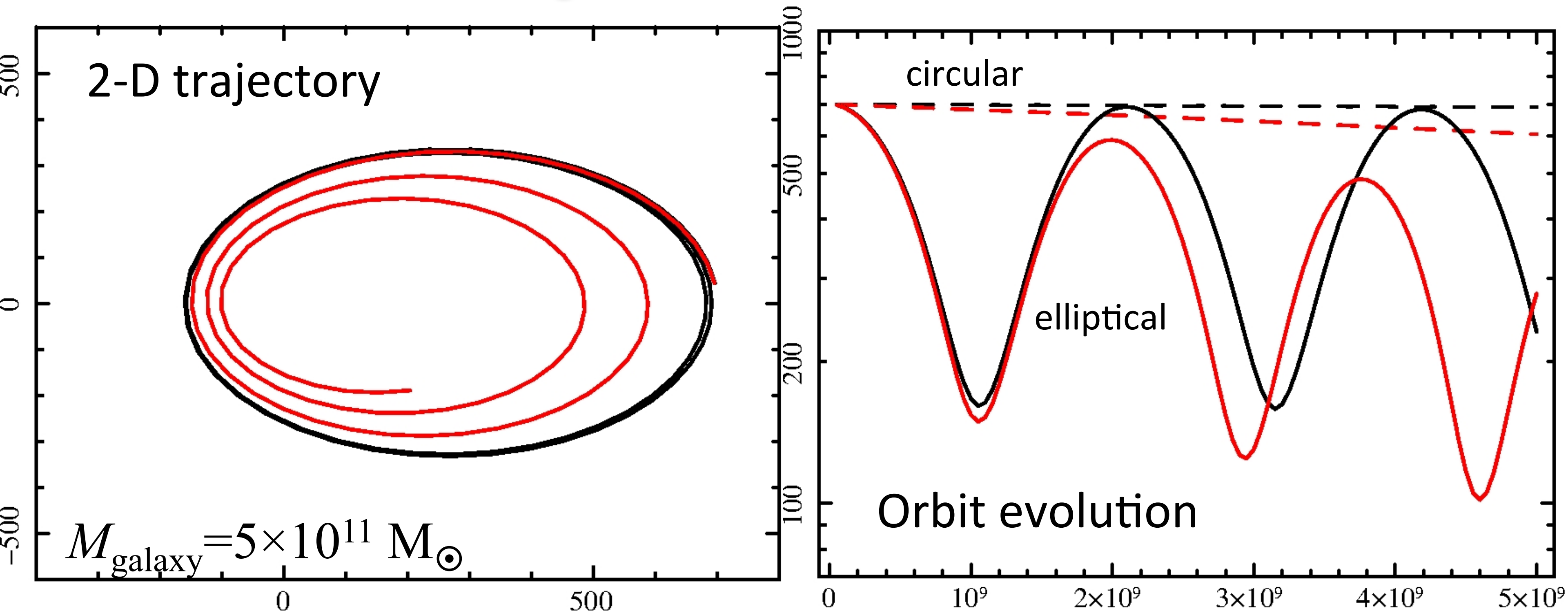
$$F_{RP} = \pi R_{Int}^2 \rho_g v^2, \quad R_{Int} \sim 5 \text{ kpc}$$

decay of galaxy orbit

$$\mathrm{d}r/\mathrm{d}t \approx (F_{DF} + F_{RP}) r / v M_{galaxy}$$



More-realistic elliptical orbit



Dynamical friction alone

Dynamical friction + ram pressure

Infall is more apparent in elliptical than in circular case

Summary

- Galaxy light vs ICM mass profiles concentrated by half from z = 0.9 to z = 0.1

- None of the errors (statistical, cosmic variance) and biases (virial radius error, evolution of radius-dependent star formation rate, ICM temperature difference, cosmic expansion, etc) is significant against the observed evolution. Dynamical friction alone is insufficient to explain the evolution.

- This result provides important support for galaxy-ICM interaction model.

Interaction Between the Hot Plasmas and Galaxies in Clusters: A Case of N4388

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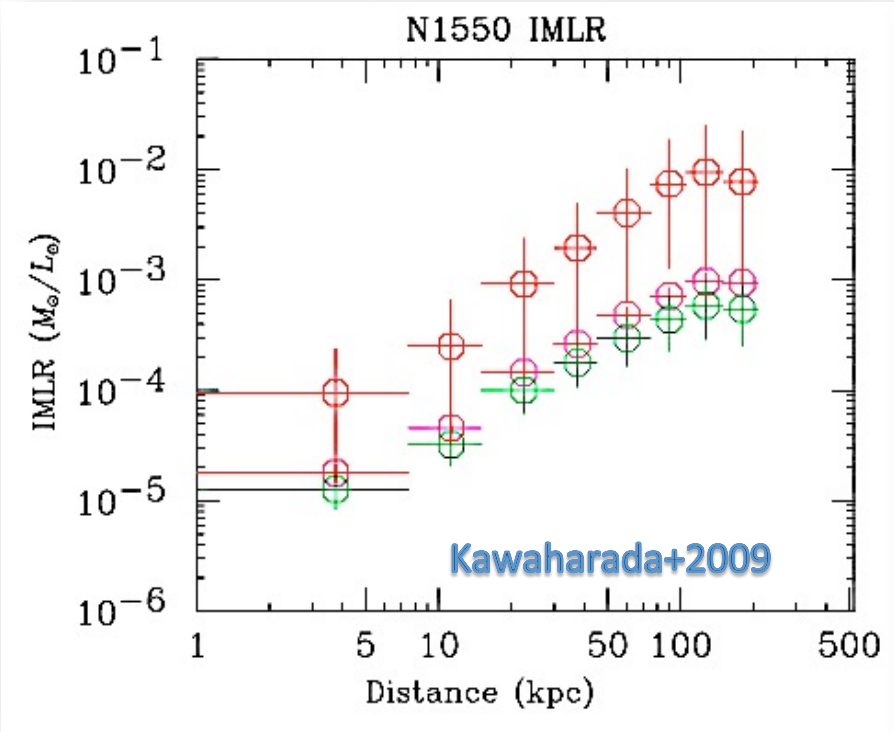
Kazuo Makishima (Univ. of Tokyo)

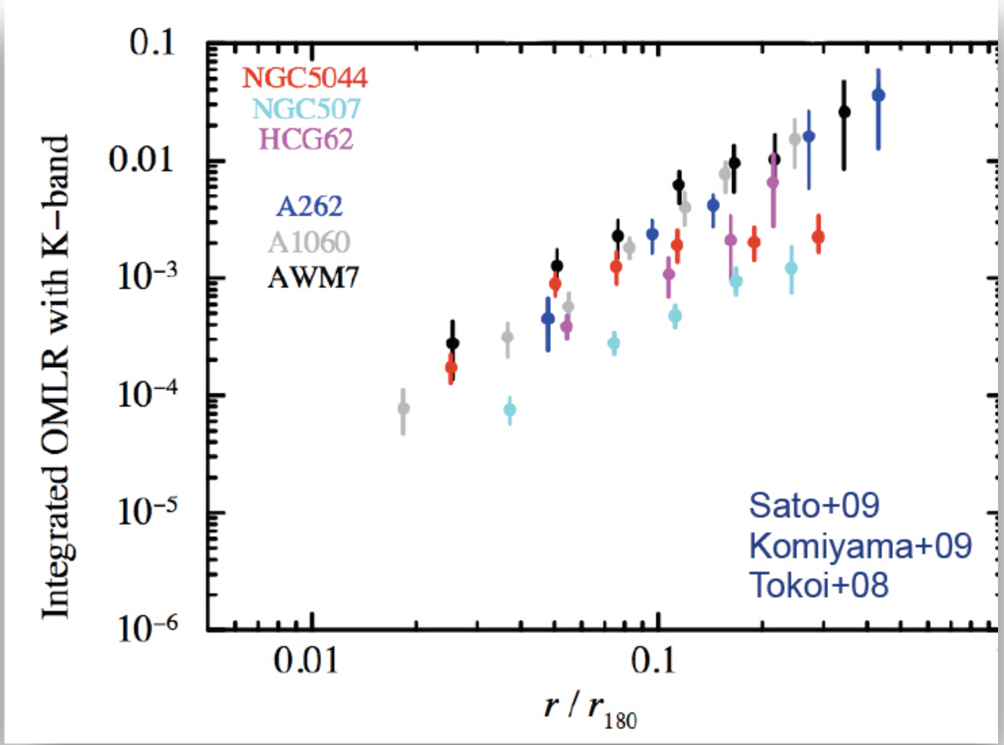
Gu+ 2013, to be submitted
Yagi+2013, in prep

RIKEN, 2013/3/14

Motivation: metal enrichment in the ICM

Metal-mass-to-light ratio: $\Phi(R) = M_{\mathrm{Fe,ICM}}(R) / L_{*}(R)$





- ICM has a typical metallicity of ~0.3 solar: $M_{\mathrm{M,ICM}} \approx M_{\mathrm{M,Star}}$
- Metals produced in galaxies are widely distributed in the ICM

How was the ICM enriched?

- Pre- (early) enrichment by quasars/SNe superwind

Many unknowns (quasar efficiency, star forming rate, IMF)

- AGN jet/bubble from cD galaxies

Transport metal only from cD galaxies

- Galaxy-ICM interaction (e.g., ram pressure stripping)

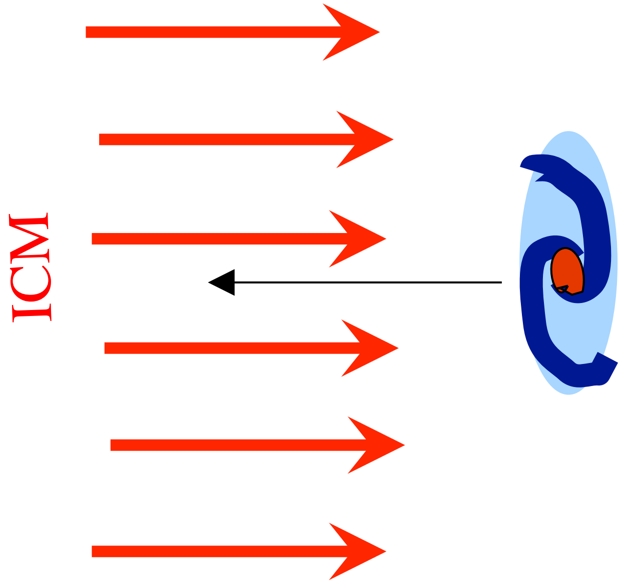
◆ Efficiency in removing the galactic gas/ISM

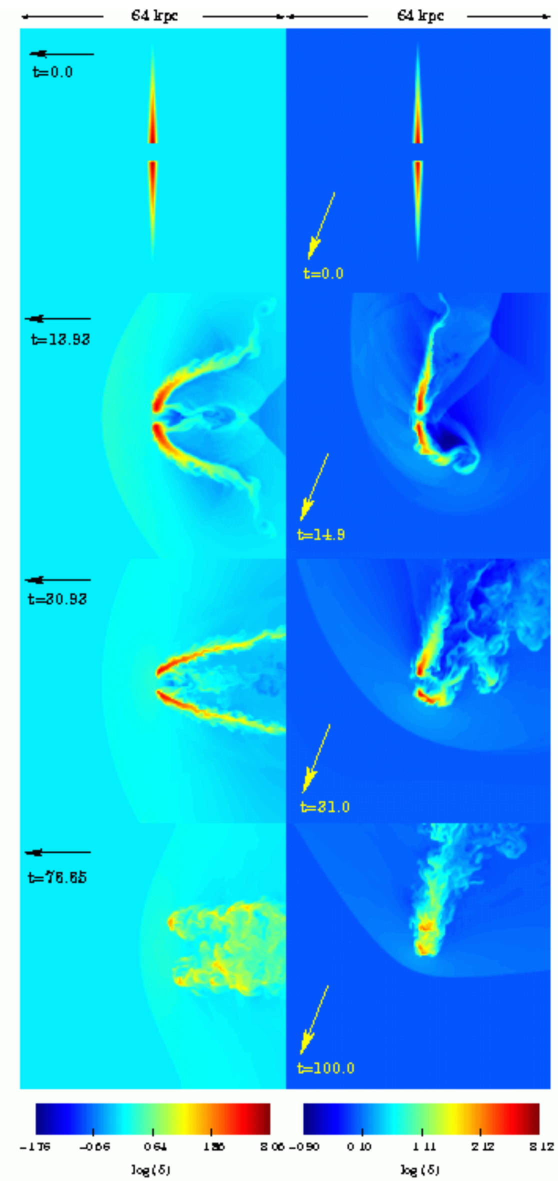
Where/when does stripping occur?

◆ Fraction of stripped ISM mixed into ICM

Evaporation/condensation timescale

Ram Pressure Stripping (RPS)





Quilis et al. 2000

Gas disk will be up to radius R if:

$$\rho_h v^2 > 2\pi G \Sigma(R) \Sigma_g(R)$$

Force due to ICM

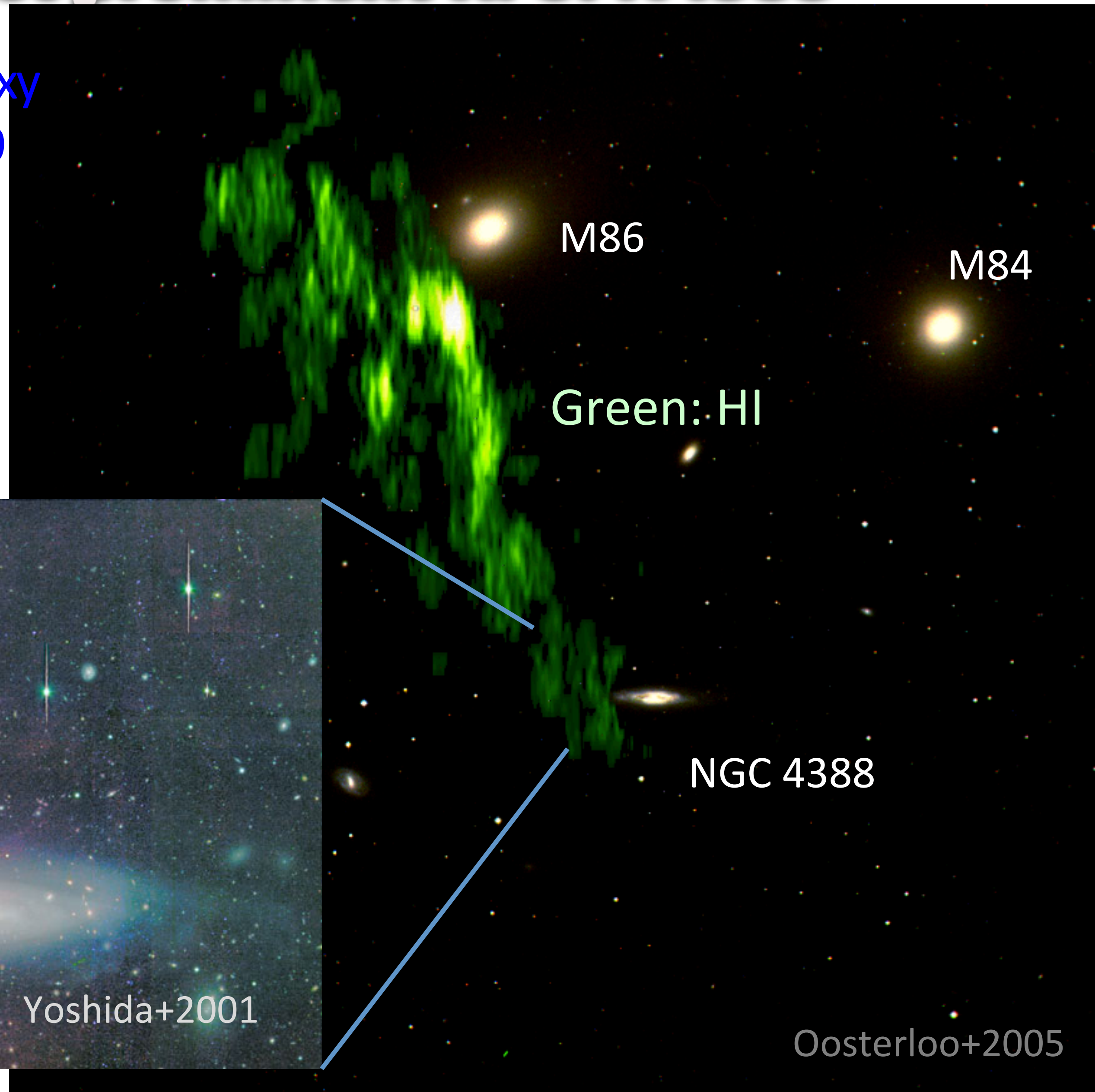
Gravitational restoring force

Gunn & Gott, 1972

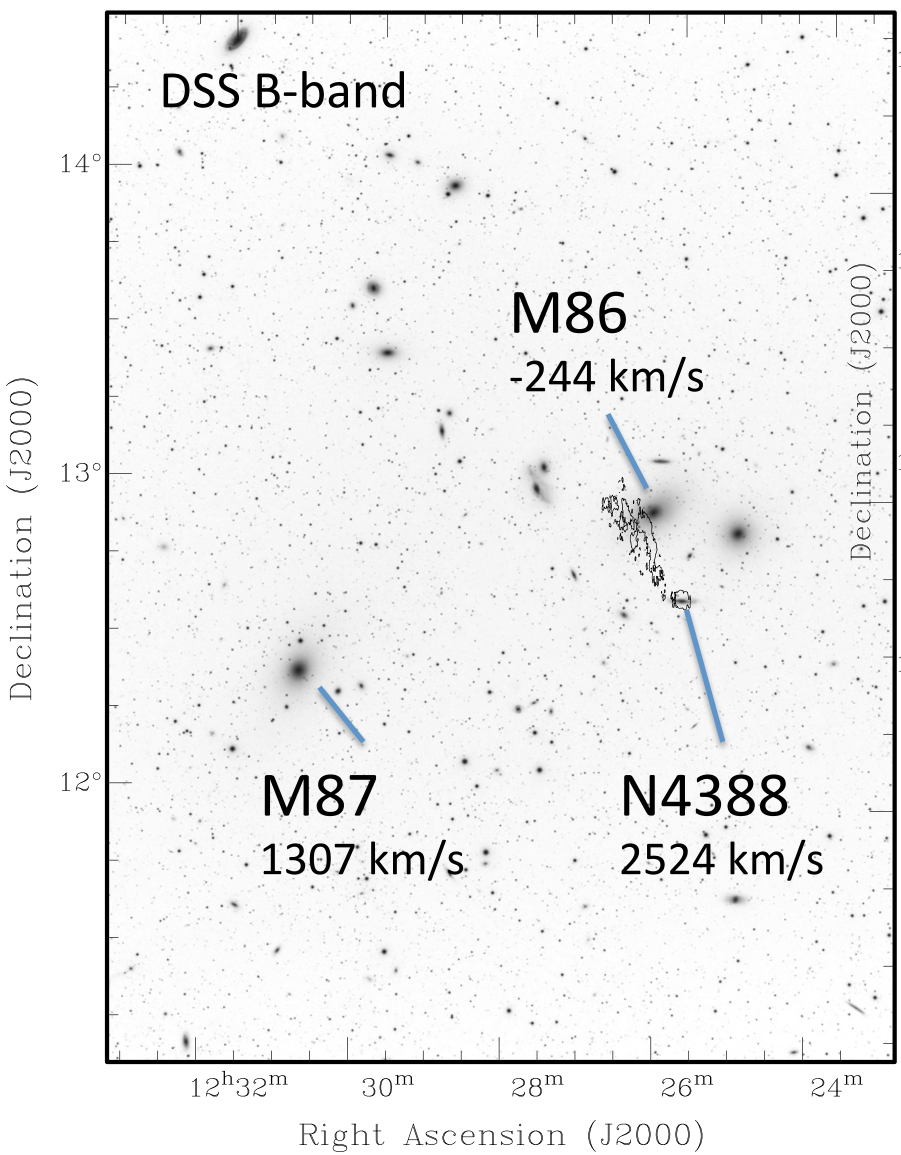
Most prominent RPS: N4388

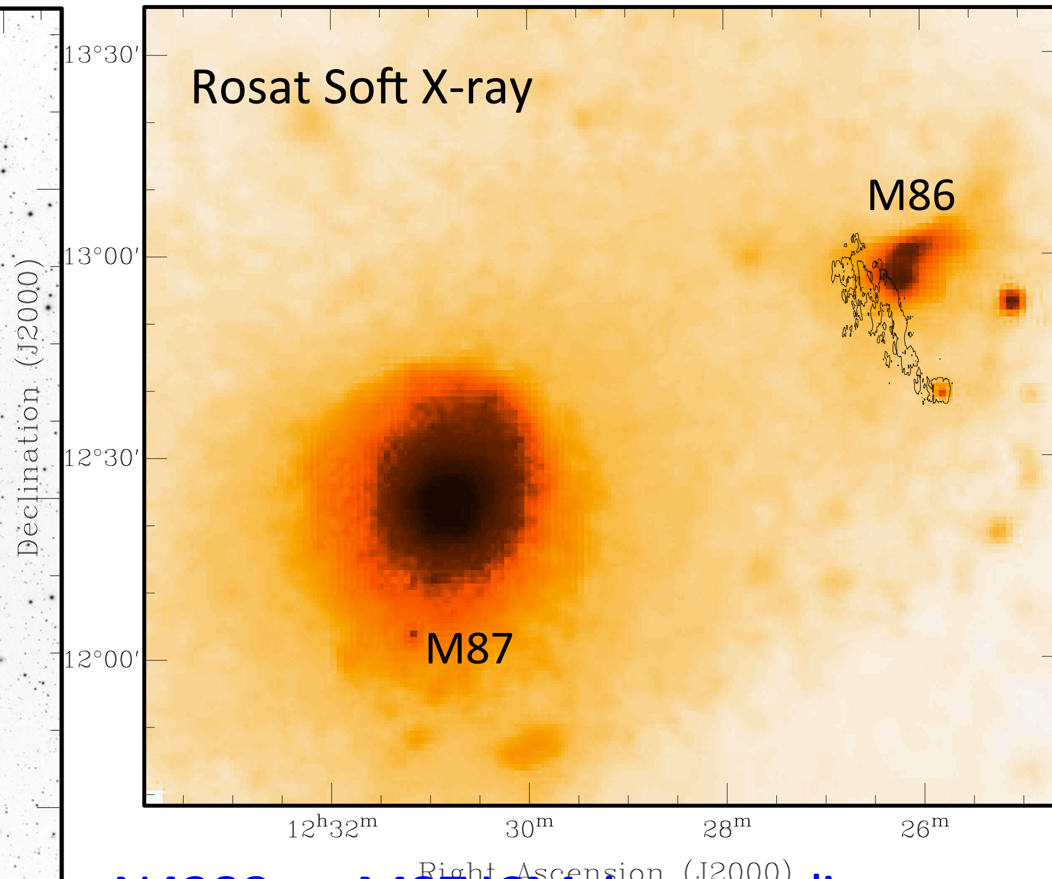
Active (Seyfert 2) galaxy N4388 expelling > 3e9 solar mass gas!

- >100 kpc HI tail
- ~ 200 Myr ago



Where does the interaction occur?

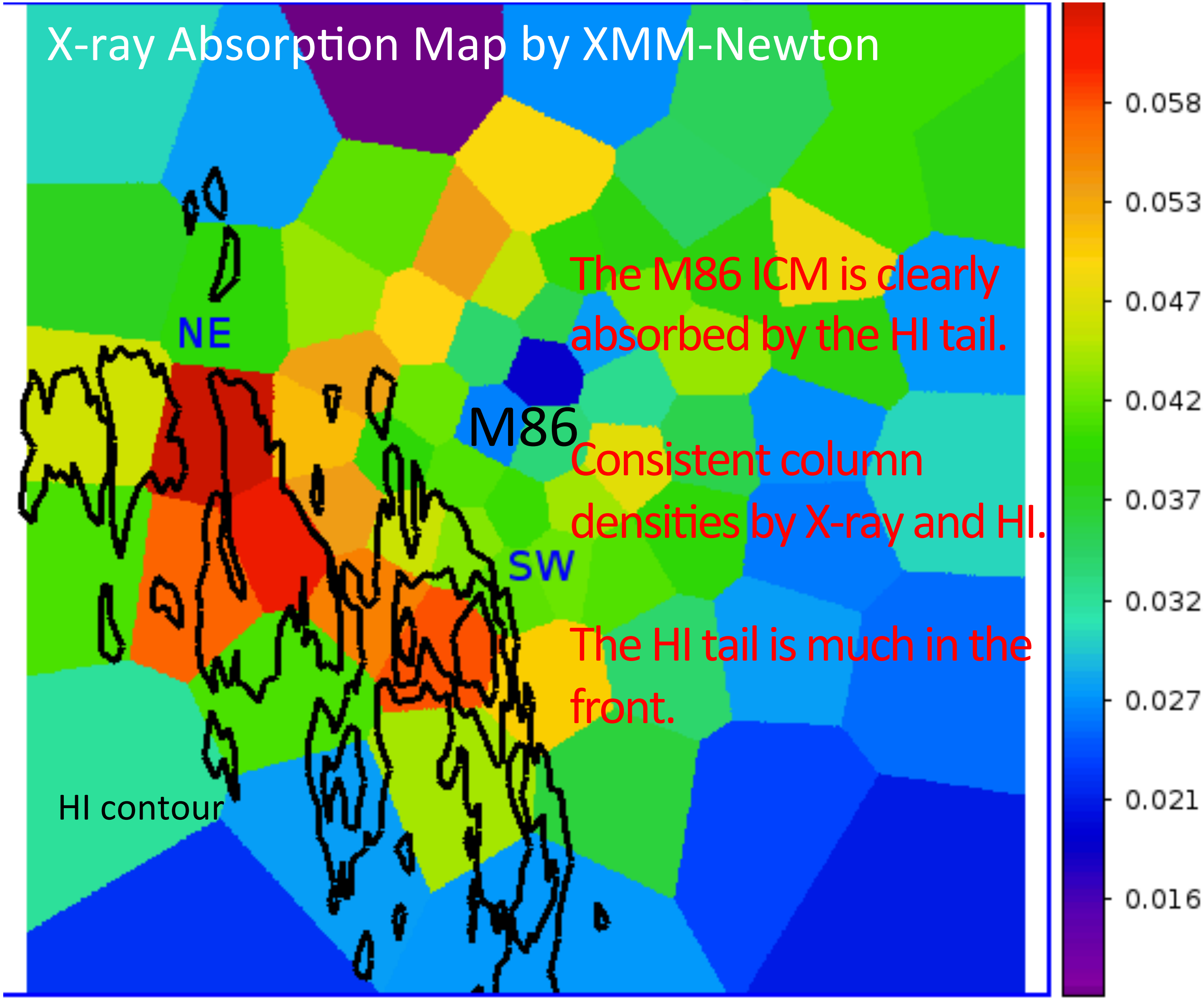


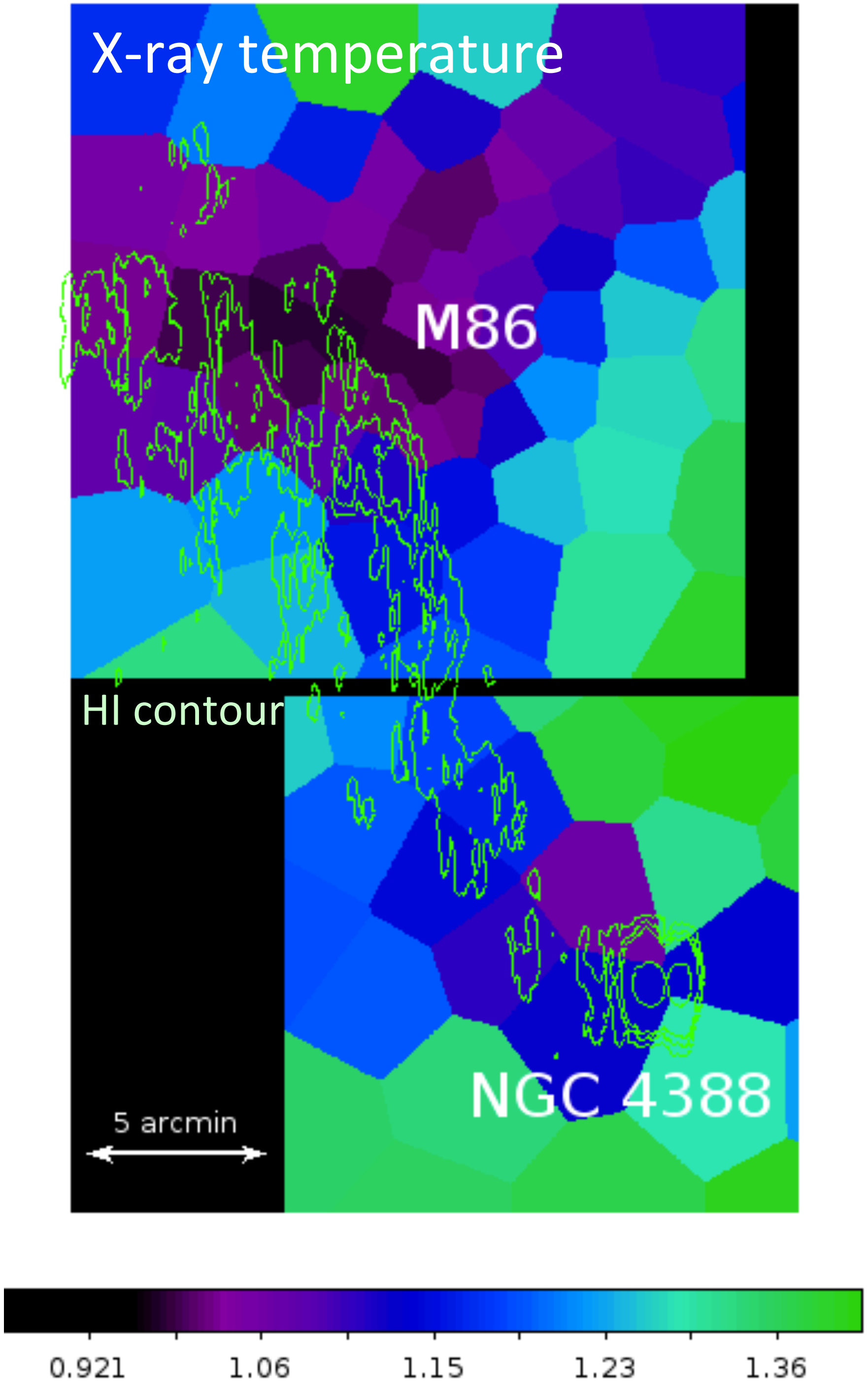


N4388 vs. M87 ICM: intermediate relative velocity/ICM density

N4388 vs. M86 ICM: extreme relative velocity/ICM density

Our result: N4388 vs. M87





Fate of stripped gas
1. mixed into ICM

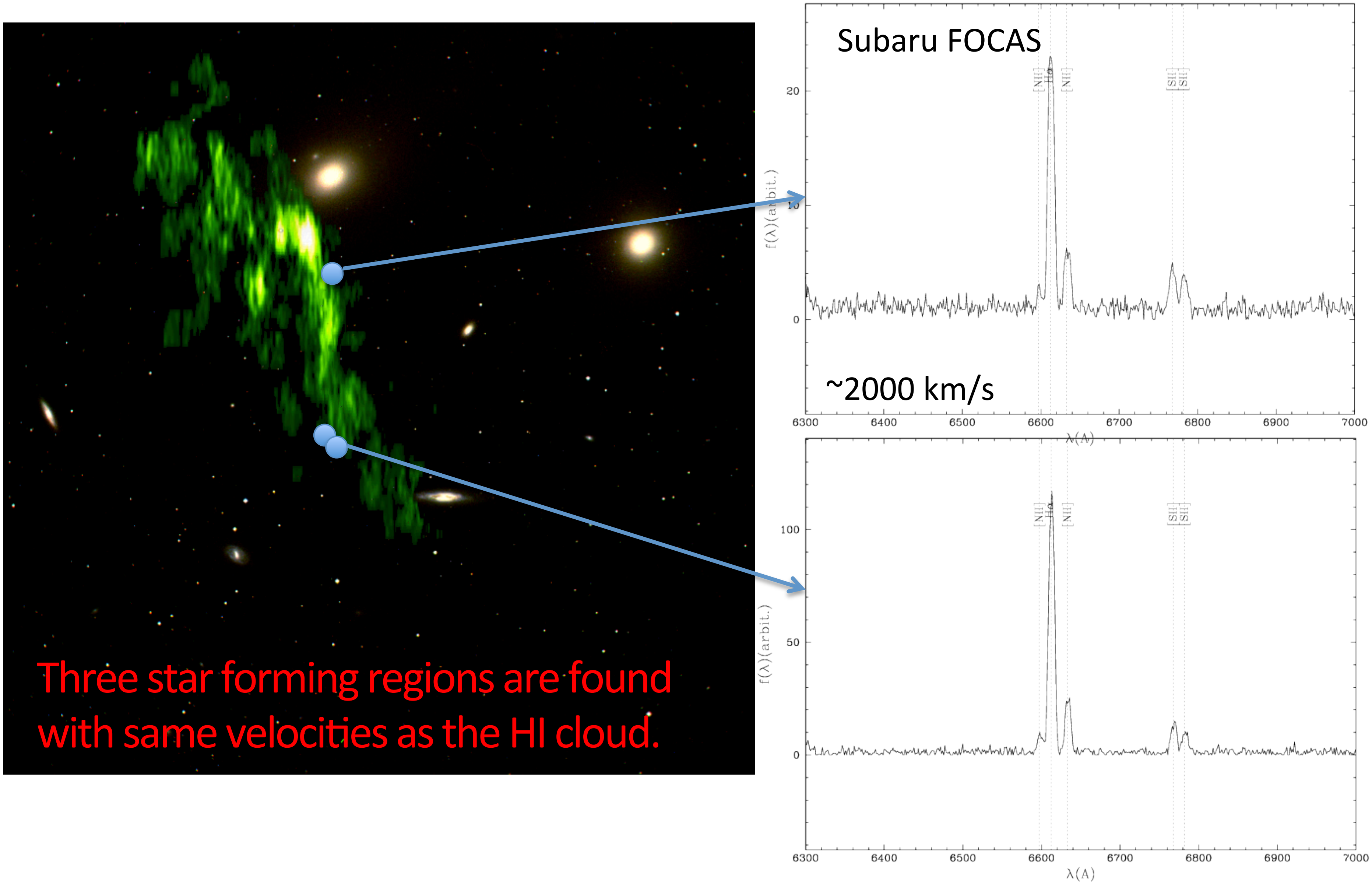
A long low-kT strip is detected along the HI emission.

Two-phased fitting gives a strip kT of 0.89 keV, and a gas mass of 6e8 solar mass > HI gas mass.

Very high hot-to-cold gas ratio in the tail.

Some of the stripped gas has ionized into ICM phase.

Fate of stripped gas
2. condensed to molecular



Summary

- N4388 is interacting with the M87 ICM. Ram pressure stripping works efficiently in general on infalling galaxies.

- Both evaporation and condensation work on the stripped gas.

To conclude the seminar

- **Galaxies infall continuously towards cluster center over the Hubble time.**
- **Galaxy-ICM interactions (e.g., ram pressure) work effectively on infalling galaxies.**

This study goes on