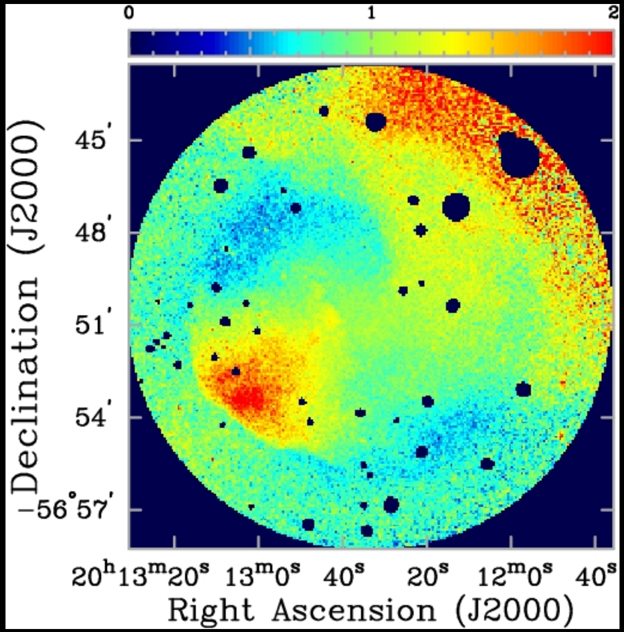
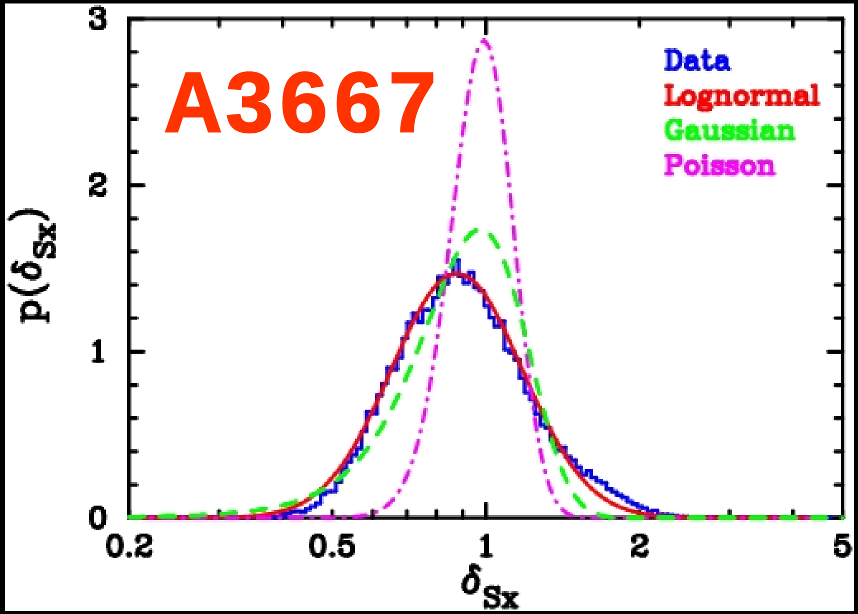
Log-normal fluctuations in intra-cluster medium and their impact on X-ray and SZ cluster observations





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The 3rd KIAS Workshop on *COSMOLOGY AND STRUCTURE FORMATION*, Oct. 27 - 28, 2008, Seoul

Recent work of Observational Cosmology Group, University of Tokyo (1)

- **Large-scale structure of the universe**
  - precise modeling of BAO for future dark energy survey: HSC & WFMOS on Subaru
    (Nishimichi et al. 2007,2008, Taruya et al. 2007, 2008)
  - bispectrum and nonlinear biasing of galaxies (Nishimichi et al. 2007)
  - constraints on the deviation from Newton's law of gravity from SDSS (Shirata et al. 2005, 2007)
  - prospects to constrain modified gravity models from future surveys
    (Yamamoto et al. 2006, 2007)
  - Galactic dust map against SDSS galaxy surface density distribution (Yahata et al. 2007)

Recent work of Observational Cosmology Group, University of Tokyo (2)

- **Spectroscopy of transiting extrasolar planets**
  - constraints on planetary atmosphere

    (Winn et al. 2004; Narita et al. 2005)
  - detection of the spin-orbit (mis)alignment via the Rossiter effect

    (Ohta, Taruya & Suto 2005, 2009; Winn et al. 2005, 2006, 2007; Narita et al. 2007)
  - a feasibility study to detect vegetation/plant signatures on exoplanets

    (Fujii et al. in preparation)

Recent work of Observational Cosmology Group, University of Tokyo (3)

- **WHIM:Warm/hot intergalactic medium**
  - a proposal of oxygen emission line survey with DIOS (Yoshikawa et al. 2003, 2004)
  - feasibility of an absorption line search with XEUS toward bright quasars and GRB afterglow (Kawahara et al. 2006)
- **Dark halos and galaxy clusters**
  - triaxial modeling of dark matter halos (Jing & Suto 2002; Oguri, Lee & Suto 2003; Lee, Jing & Suto 2005)
  - log-normal model for intra-cluster gas fluctuations and its impact on X-ray and SZ observations (Kawahara et al. 2006, 2007,2008)

Toward a more realistic model of galaxy clusters

- **beyond a spherical homogeneous isothermal β-model**
  - numerical simulations
  - empirical/analytic modeling
  - comparison with observations
- non-sphericity (i.e., triaxial)
- temperature profile (i.e., polytrope)
- *inhomogeneity in intra-cluster medium*

Collaborators and references

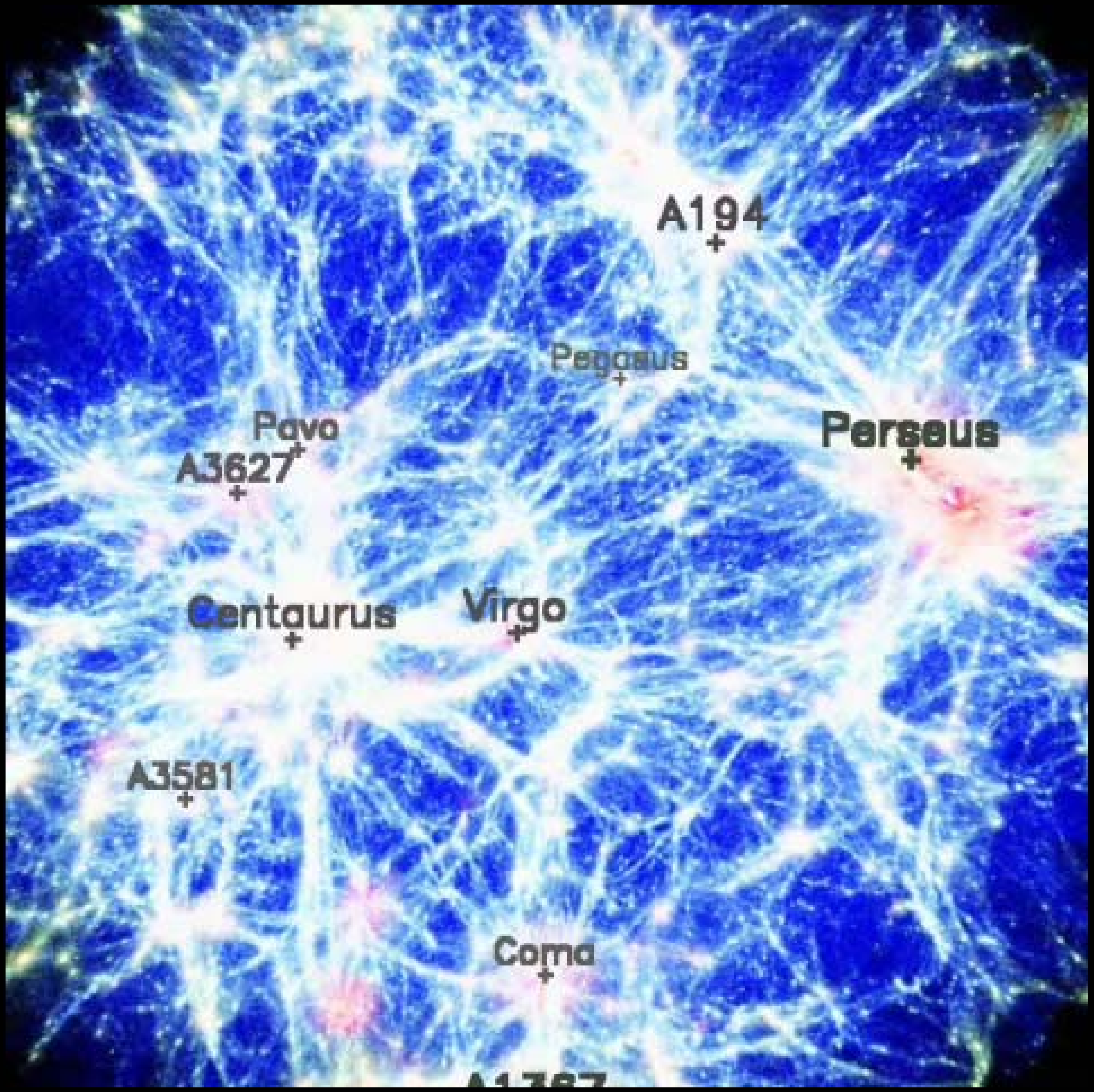
- **Hajime Kawahara (Univ. of Tokyo), Erik Reese (Univ. of Tokyo), Tetsu Kitayama (Toho Univ.), Shin Sasaki (Tokyo Metropolitan Univ.)**
- **Kawahara et al. (2007)**
  - *Radial Profile and Lognormal Fluctuations of the Intracluster Medium as the Origin of Systematic Bias in Spectroscopic Temperature* ApJ 659(2007)257
- **Kawahara, Kitayama, Sasaki + YS (2008)**
  - *Systematic Errors in the Hubble Constant Measurement from the Sunyaev-Zel'dovich effect* **ApJ 674(2008)11**
- **Kawahara, Reese, Kitayama, Sasaki + YS (2009)**
  - *Extracting galaxy cluster gas inhomogeneity from X-ray surface brightness: a statistical approach and application to Abell 3667* **arXiv:0807.2525, ApJ (2009) in press**

Simulated clusters in the local universe

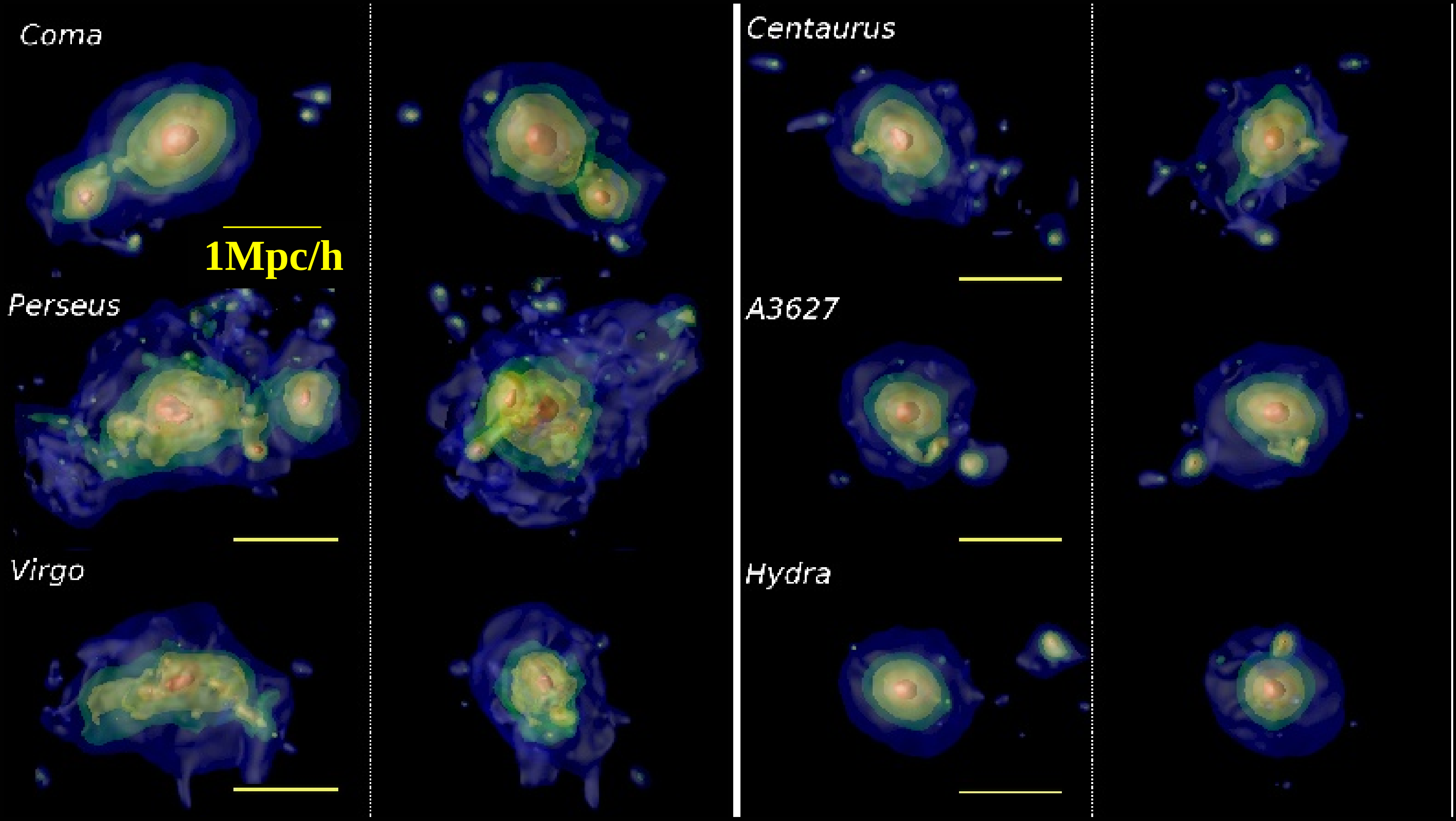
- SPH simulations (Dolag et al. 2005)
- Local universe distribution in a sphere of r=110Mpc
  - Initial condition: the observed galaxy density field of IRAS 1.2 Jy survey (smoothing over 5h^{-1}Mpc), linearly evolving back to z=50 + random Gaussian fluctuations on smaller scales
  - + cooling, star formation, SN feedback, and metalicity evolution in ΛCDM

Simulated local universe

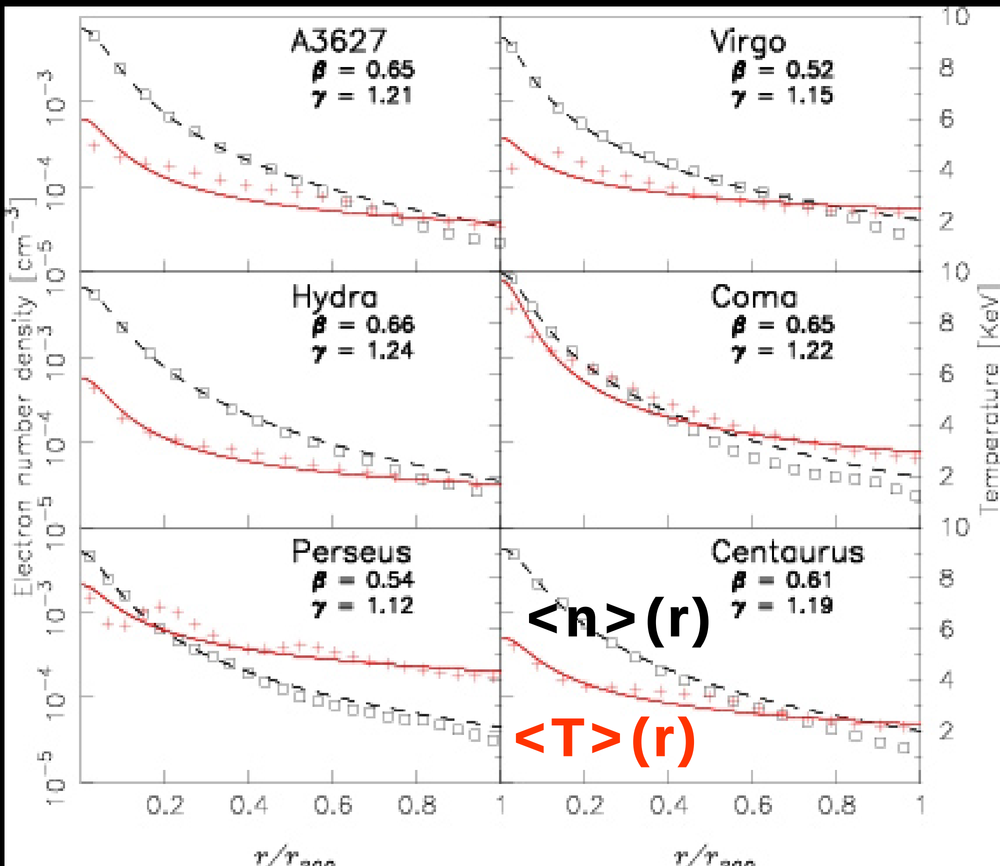
Dolag et al. (2005)



Projected views of ***simulated clusters***



modeling ICM fluctuations (1) mean (spherical) radial profile



- Density and temperature radial profiles of simulated clusters
- **Polytropic β model**

$$<n>(r) = n_0 \left[\frac{1}{1+(r/r_c)^2} \right]^{3\beta/2}$$

$$<T>(r) = T_0 [<n>(r)/n_0]^{\gamma-1}$$

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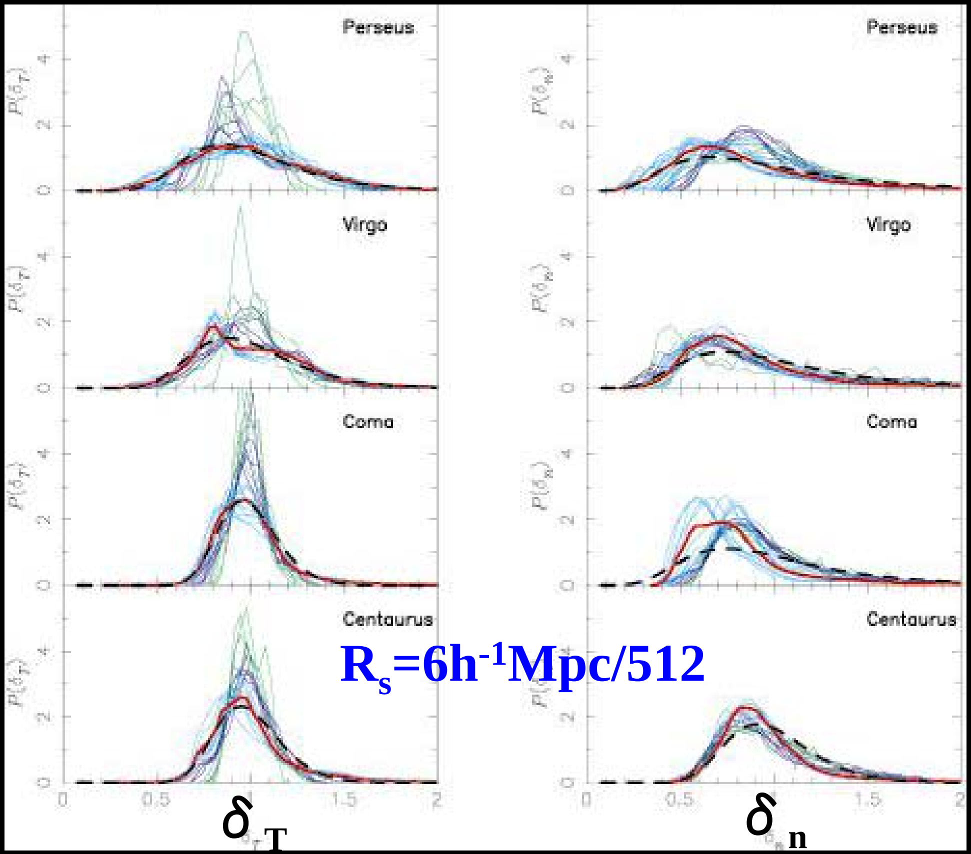
modeling ICM fluctuations (2)
log-normal PDF for local inhomogeneity



- **Local inhomogeneities of density and temperature of simulated clusters**
  - $\delta_n = n(r,\theta,\phi)/\langle n \rangle(r)$
  - $\delta_T = T(r,\theta,\phi)/\langle T \rangle(r)$
- **Log-normal PDF provides reasonable approximations**

$$P_{LN}(\delta)d\delta = \frac{1}{\sqrt{2\pi\sigma}}\exp\left[-\frac{(\log\delta+\sigma^2/2)^2}{2\sigma^2}\right]\frac{d\delta}{\delta}$$

Kawahara et al. ApJ 659 (2007)257

Implications

① **underestimate bias for X-ray spectroscopic temperature of clusters**

② underestimate bias for H_0 estimate from SZ observations

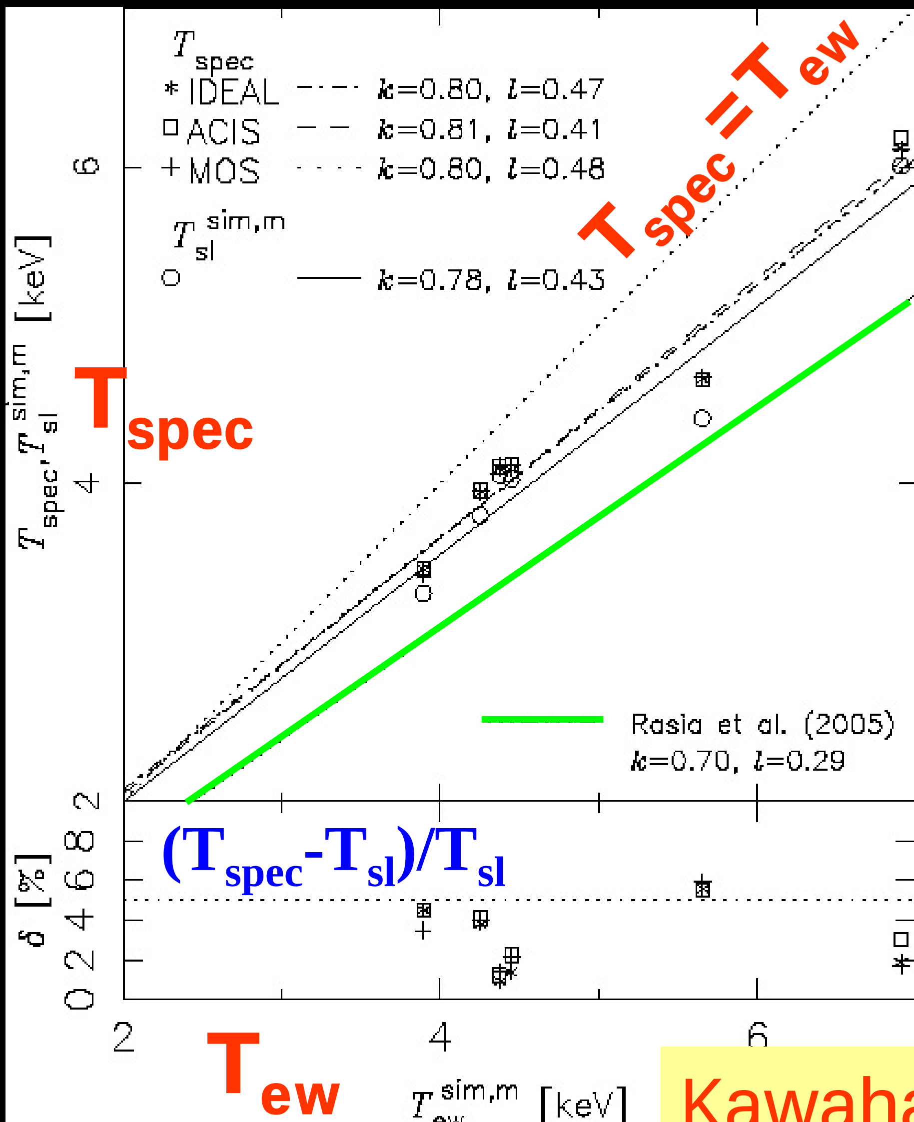
③ reconstruction of the 3D ICM fluctuation distribution from X-ray surface brightness (2D) observational data

mass-weighted, emission-weighted, and spectroscopic temperatures of clusters

$$\langle T \rangle_w = \frac{\int T W dV}{\int W dV}$$

	definition	W (weight)	
T_m	mass–weighted	n	
T_{ew}	emission–weighted	$n^2\Lambda(T)$	simulation
T_{spec}	spectroscopic	spectral fit	observation
T_{sl}	spectroscopic–like	$n^2T^{-0.75}$	Mazzotta et al. (2004)

T_{spec} is systematically smaller than T_{ew}



- Mazzotta et al. (2004) & Rasia et al. (2005) found $T_{spec} \sim 0.7\ T_{ew}$ from simulations
- Simulated clusters of Dolag et al. (2005)
  $T_{spec} \sim 0.85\ T_{ew}$
  (see also Mathiesen & Evrard 2001)

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An analytic model for T_{spec}/T_{ew}

- Spherical polytropic β -model as global mean radial profiles
- Log-normal density and temperature fluctuations
  - Density and temperature correlations ignored
  - Radius independent dispersion adopted
- ⇒ We obtain an analytic model for the temperature underestimate, T_{sl}/T_{ew}
  - Explain numerical simulations well

Kawahara et al. ApJ 659 (2007)257

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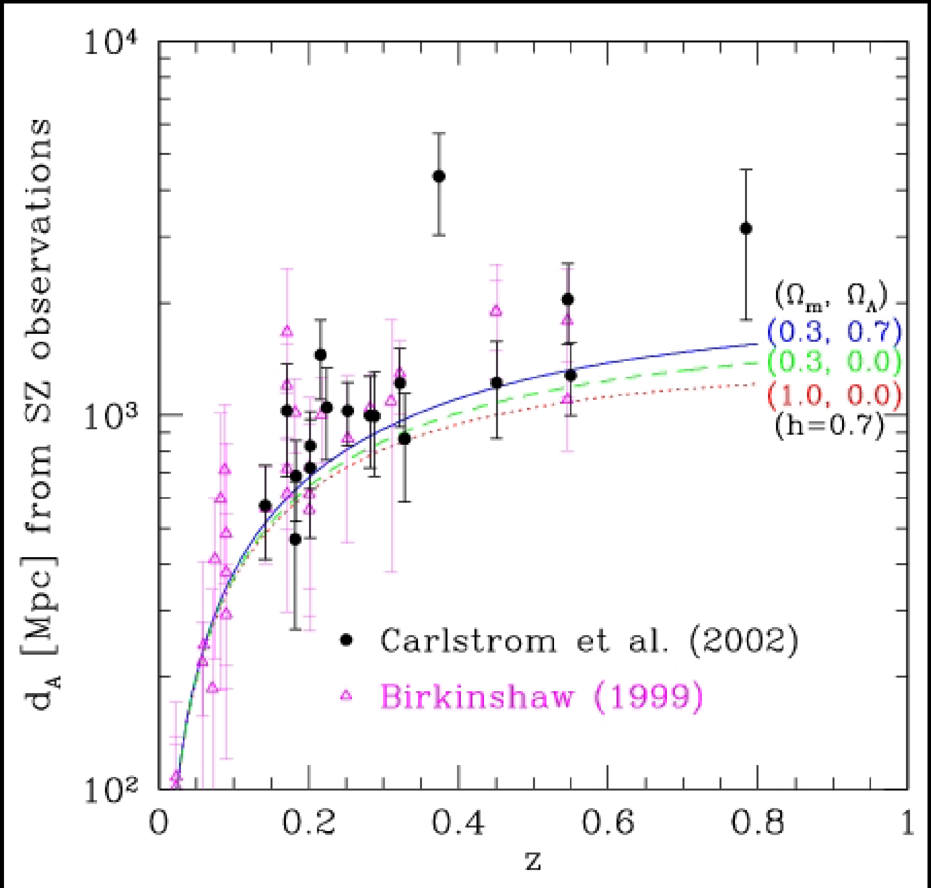
H_0 estimated from the SZ effect



- **WMAP:**
  - **73±3 km/s/Mpc (Spergel et al. 07)**
- **ROSAT+SZ:**
  - **60±3 km/s/Mpc (Reese et al. 2002)**
- ***Systematically lower ?***
  - **But Bonamente et al. (2006) reported that $76.9^{+3.9}_{-3.4}{}^{+10.0}_{-8.0}$ km/s/Mpc from Chandra+SZ…**

Isothermal β-model fit

- Polytropic density and temperature profiles

$$< n > (r) = n_0 \left[\frac{1}{1 + (r / r_c)^2} \right]^{3\beta/2}$$

$$< T > (r) = T_0 [< n > (r) / n_0]^{\gamma - 1}$$

- core radius estimated from X-ray + SZ

$$r_{c,iso\beta}(T_{spec}) = \frac{y(0)^2}{S_X(0)} \frac{m_e^2 c^4 \Lambda(T_{spec})}{4\pi(\sigma_T k T_{spec})^2 (1+z)^4} \frac{G(\beta_{fit})}{G(\beta_{fit}/2)^2}$$

$$\beta_{fit} = \beta \frac{\gamma + 3}{4}$$

Analytic modeling of SZ H_0 measurement

- Spherical polytropic β -model as mean radial profiles
- Log-normal density and temperature fluctuations
- **Still force to fit to the isothermal β -model,** and the estimated H_0 is biased as

Kawahara et al. ApJ 674(2008)11

$$f_{H,polyLN|iso\beta} \equiv \frac{H_{0,est}}{H_{0,true}} = \chi_\sigma \; \chi_T(T_{ew}) \frac{\chi_T(T_{spec})}{\chi_T(T_{ew})}$$

inhomogeneity $\chi_\sigma = \exp(\sigma^2_{LN,n} - \sigma^2_{LN,T}/8) \approx (1.1-1.3)$

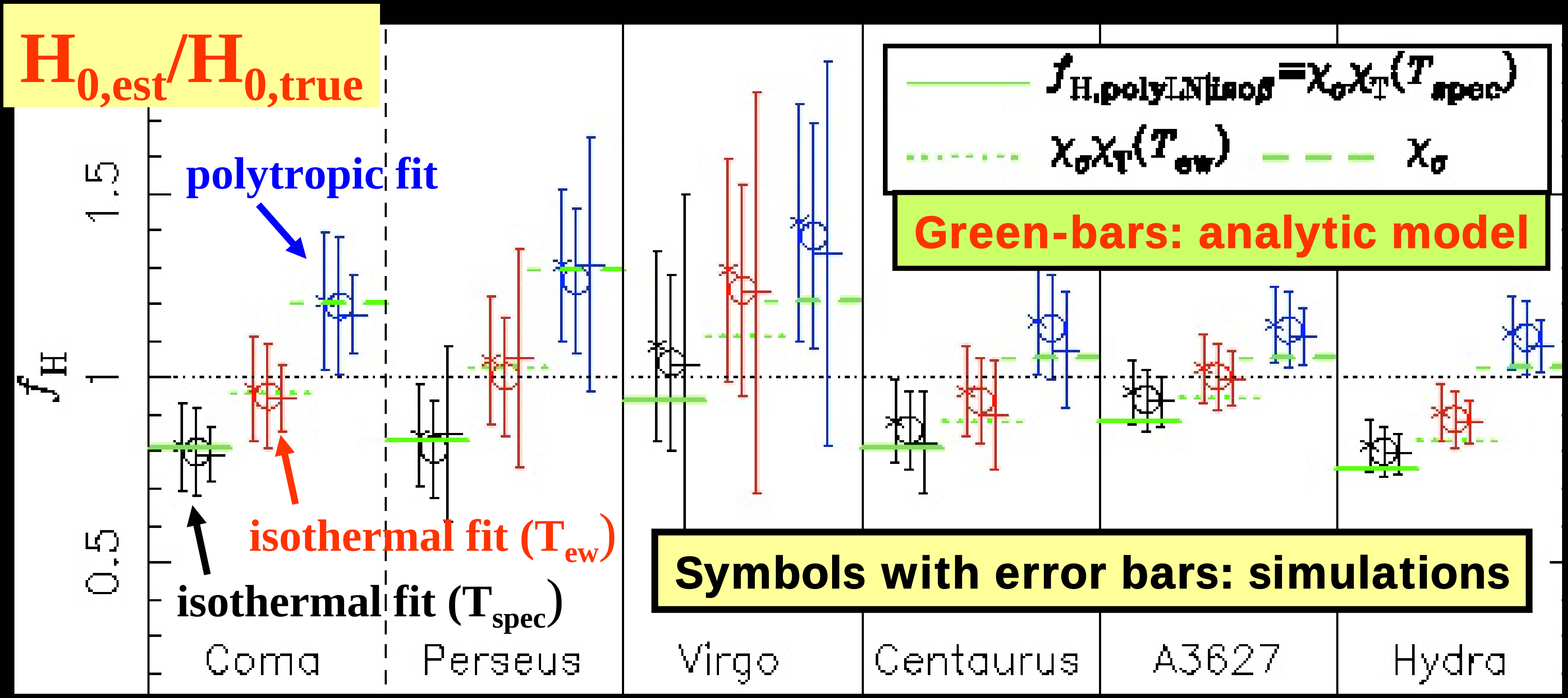
non-isothermality

$$\chi_T(T_{ew}) = J(\beta, \gamma, r_c/r_{vir})^{1.5} \left[\frac{G(\beta(\gamma+3)/8)}{G(\beta\gamma/2)}\right]^2 \approx (0.7-0.9)$$

temperature bias

$$\frac{\chi_T(T_{spec})}{\chi_T(T_{ew})} \approx \left(\frac{T_{spec}}{T_{ew}}\right)^{1.5} \approx (0.8-0.9)$$

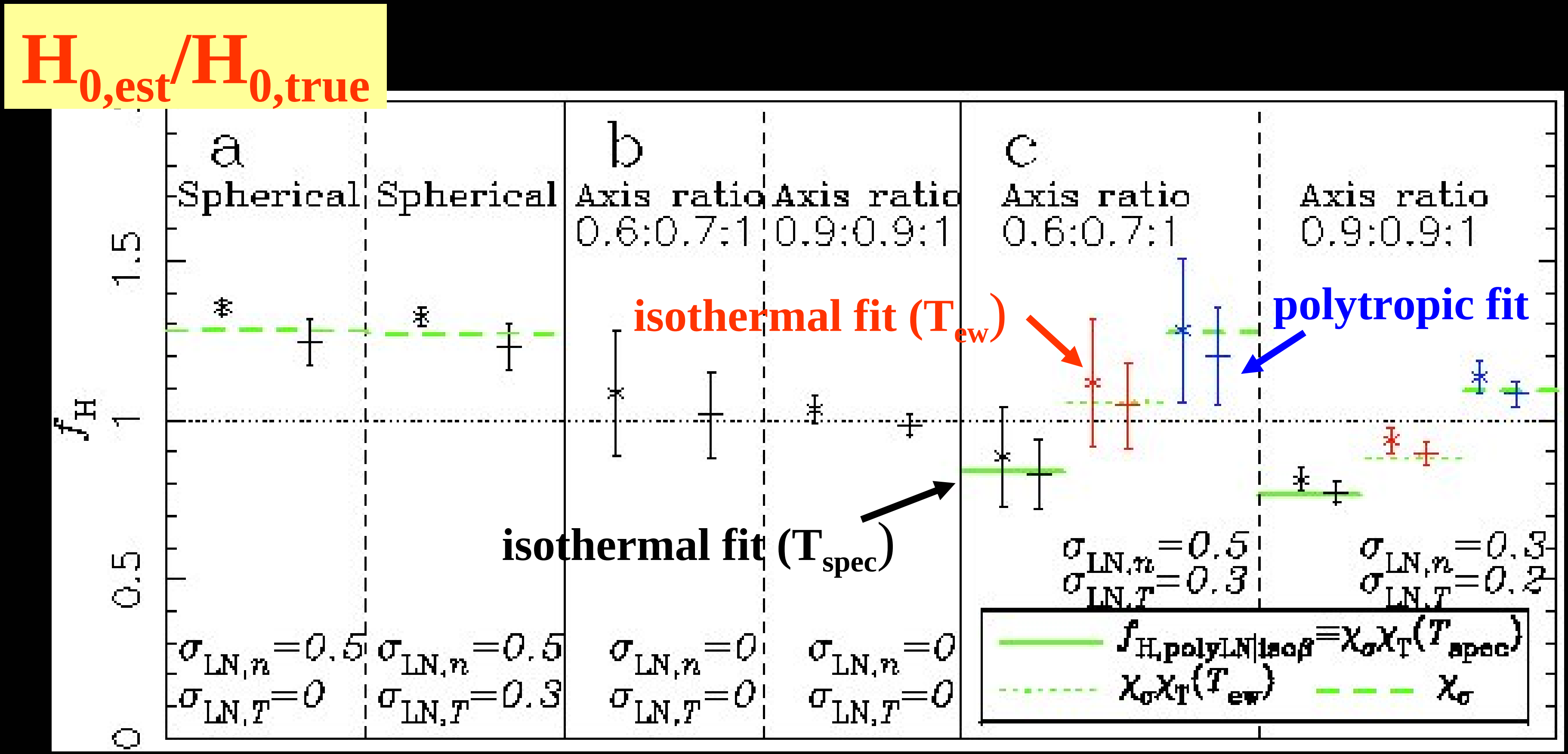
Analytic model vs simulated clusters



- Mean values are in good agreement with the analytic model
- *Additional small bias expected due to non-sphericity of clusters even after averaging over l.o.s. angles*

Kawahara et al. ApJ 674(2008)11

Non-spherical effect : triaxial clusters



- Synthetic triaxial clusters (Jing & YS 2002) + polytropic β + log-normal fluctuations

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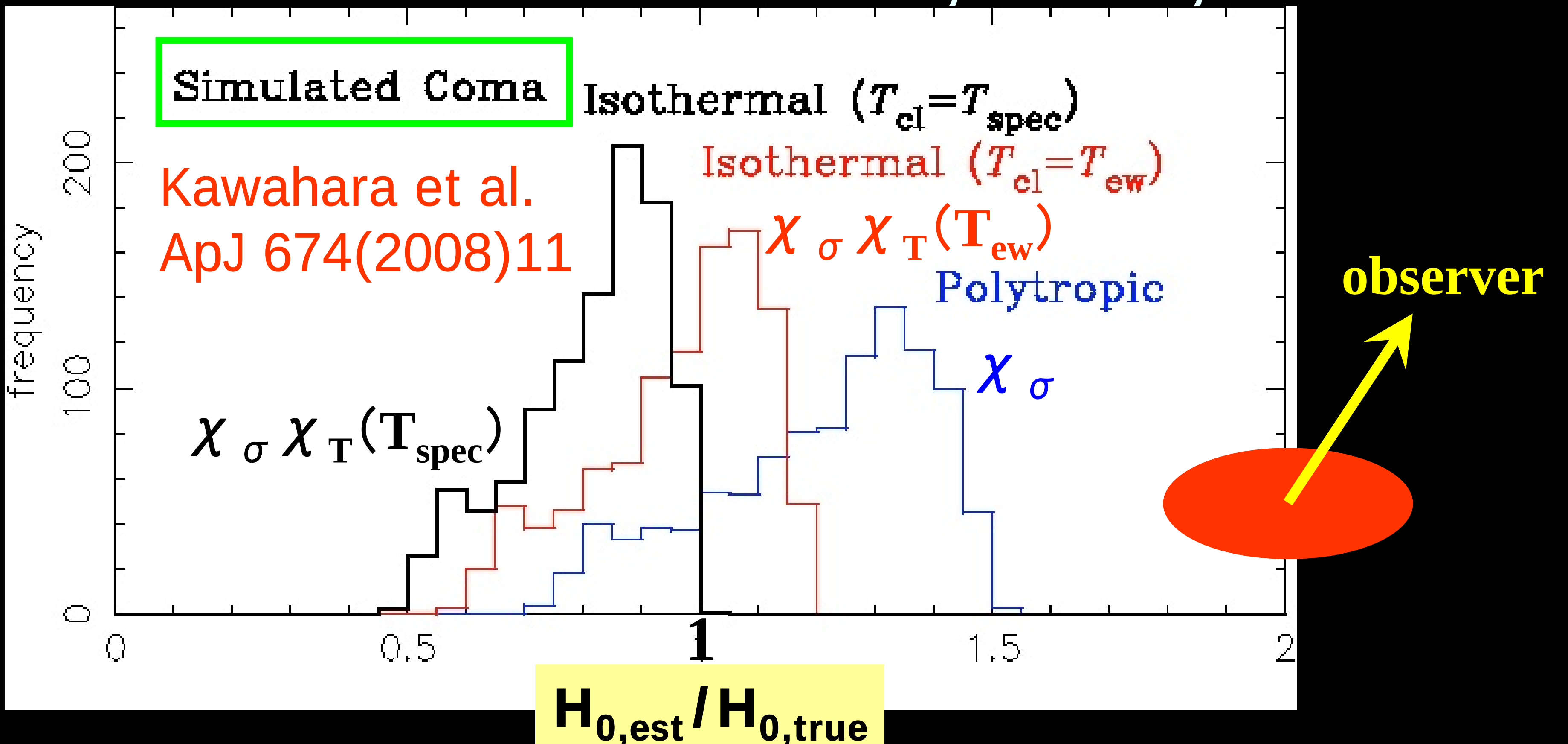
Distribution of $H_{0,est}/H_{0,true}$



- Skewed distribution due to the prolateness
- Previous studies did not find the large bias because they set $T_{cl}=T_{ew}$ instead of T_{spec} (Inagaki, Suginohara & YS 1995, Yoshikawa, Itoh & YS 1998), consistent with our results of the isothermal fit with T_{ew}

Implications

① underestimate bias for X-ray spectroscopic temperature of clusters

② underestimate bias for H_0 estimate from SZ observations

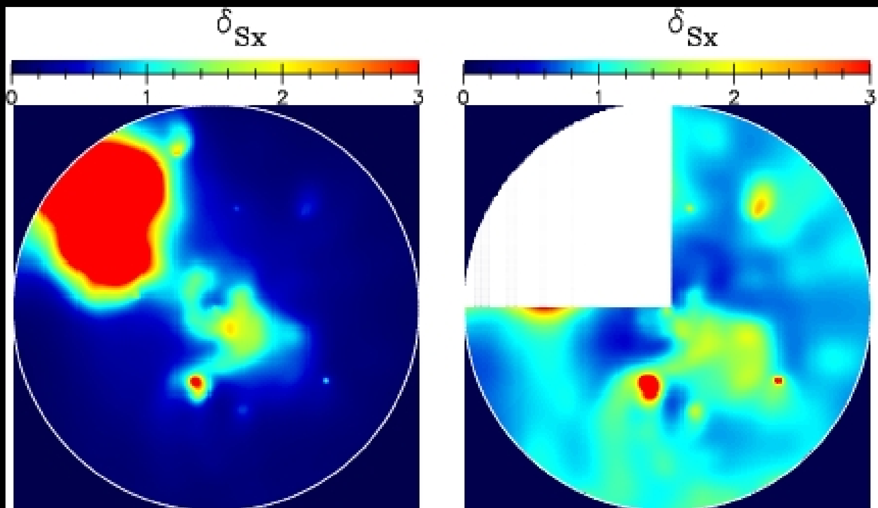
③ **reconstruction of the 3D ICM fluctuation distribution from X-ray surface brightness (2D) observational data**

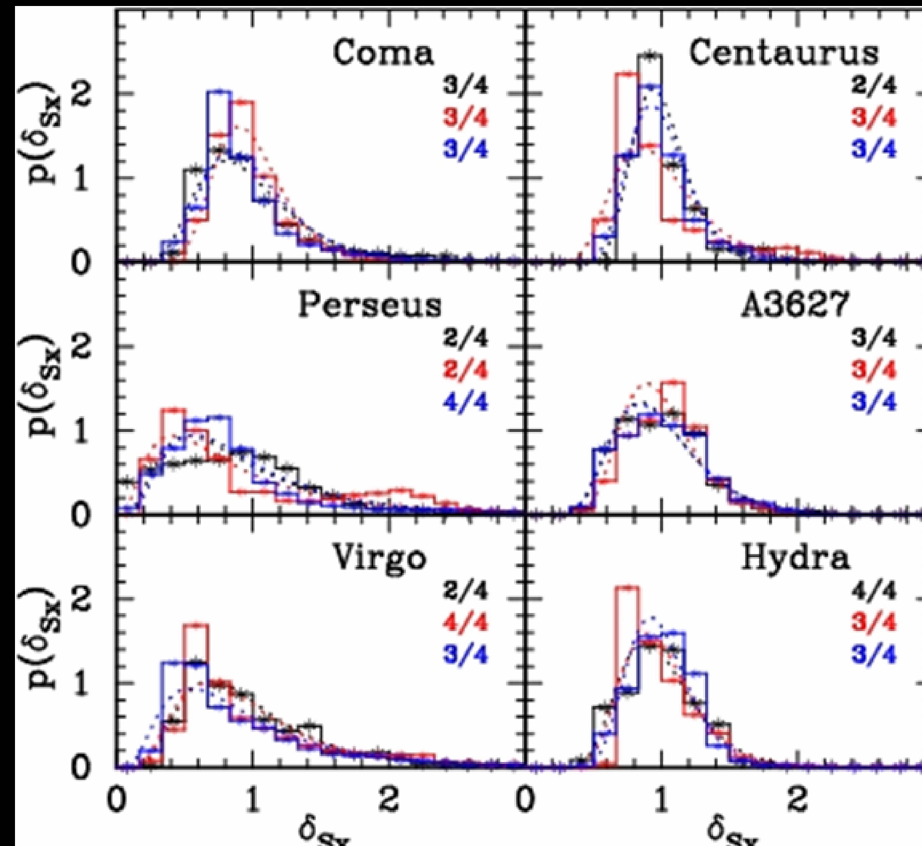
Do observed ($\neq$simulated) clusters show log-normal signature ?

- So far we did not directly confirm the presence of log-normal fluctuations in real ICM
- projection effect: 2D surface brightness PDF from the 3D log-normal PDF in density and temperature ?
- *how to reconstruct the 3D log-normal nature from the observed 2D X-ray data ?*

Kawahara, Reese et al. arXiv:0807.2525,ApJ (2009) in press

2D projection effect: test with simulated clusters

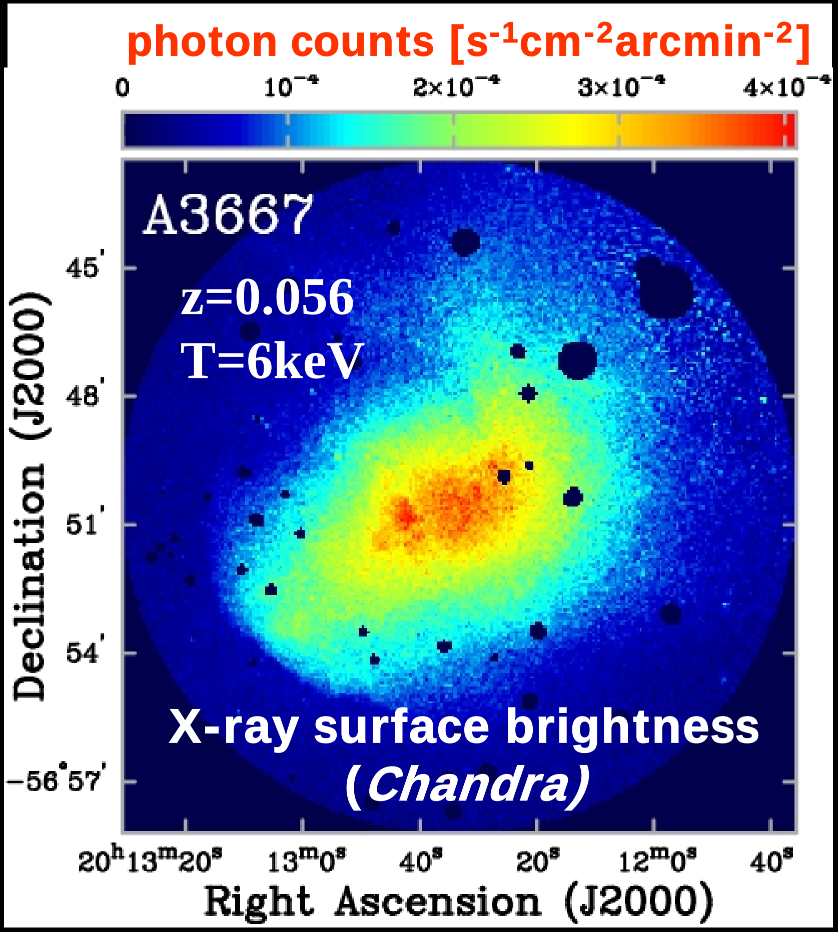


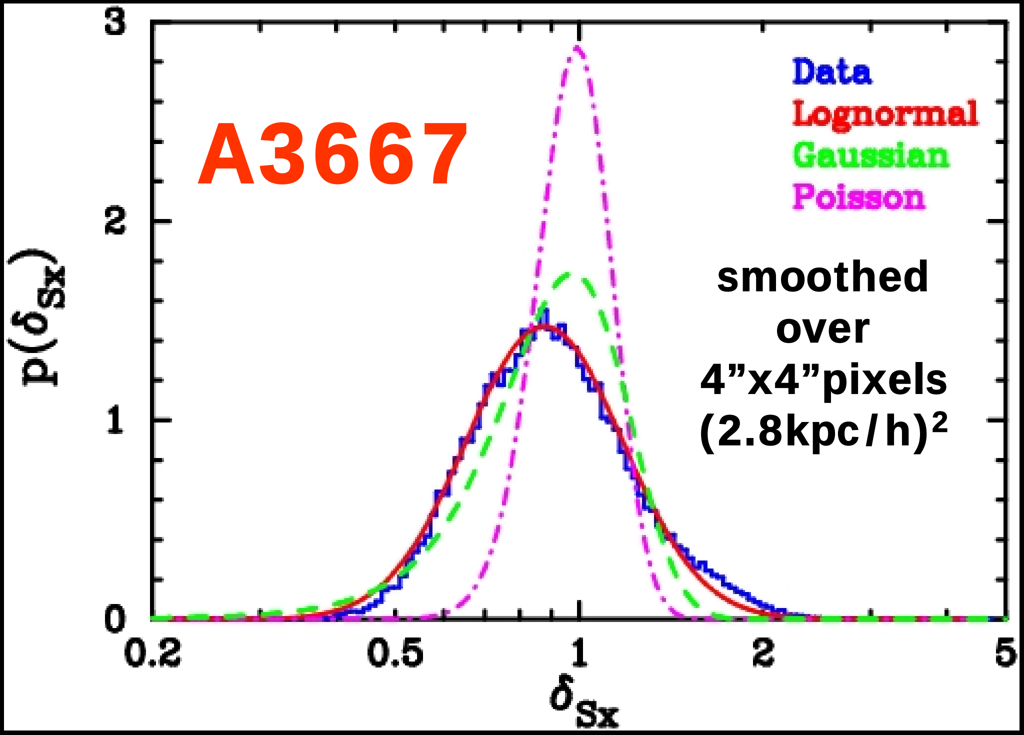


if a prominent substructure resides in a quarter, the quarter is removed in the analysis

- 3D log-normal PDF of gas and temperature results in 2D log-normal PDF of X-ray surface brightness

Application to Abell 3667





first observational detection of log-normal fluctuation in real ICM !

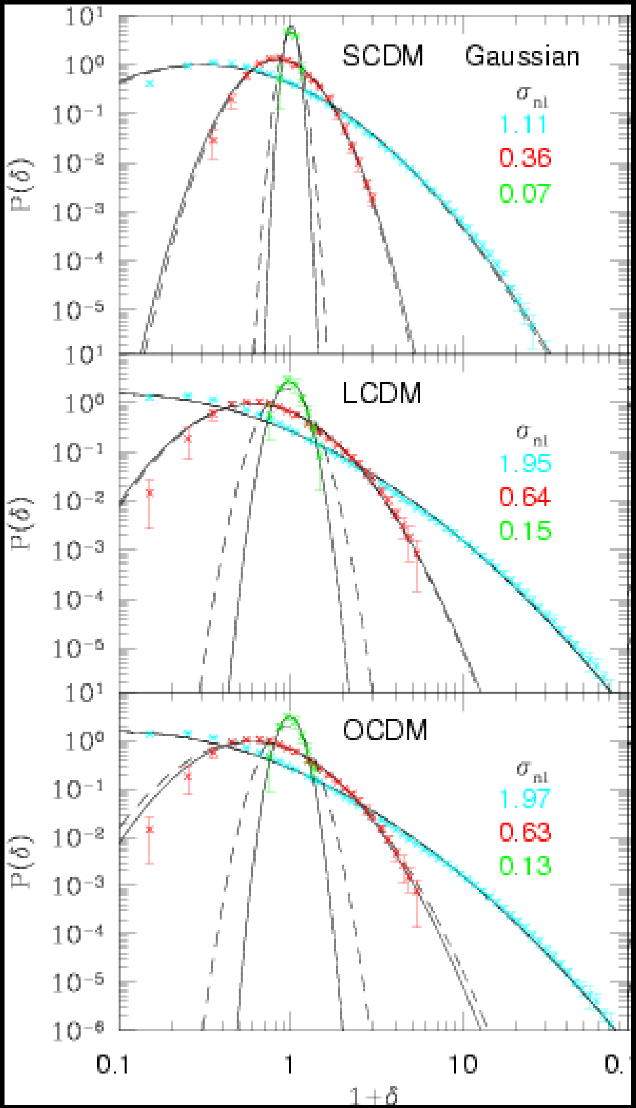
$\sigma_{LN,Sx,A3667}$ = **0.3: consistent with other simulated clusters**

Kawahara, Reese et al. arXiv:0807.2525,ApJ (2009) in press

a remaining question: origin of log-normal fluctuations ?

- generic statement
  - addition of independent random fields
    $\Rightarrow$ Gaussian
  - multiplication of independent random fields
    $\Rightarrow$ log-normal
- Indeed log-normal distribution is very common in a variety of phenomena
  - cosmological density field
  - surface density of interstellar medium
  - self-gravity ? turbulence ?

log-normal PDF in cosmological density field



- initial condition：random–Gaussian

  ⬇ **collisionless N-body simulation**

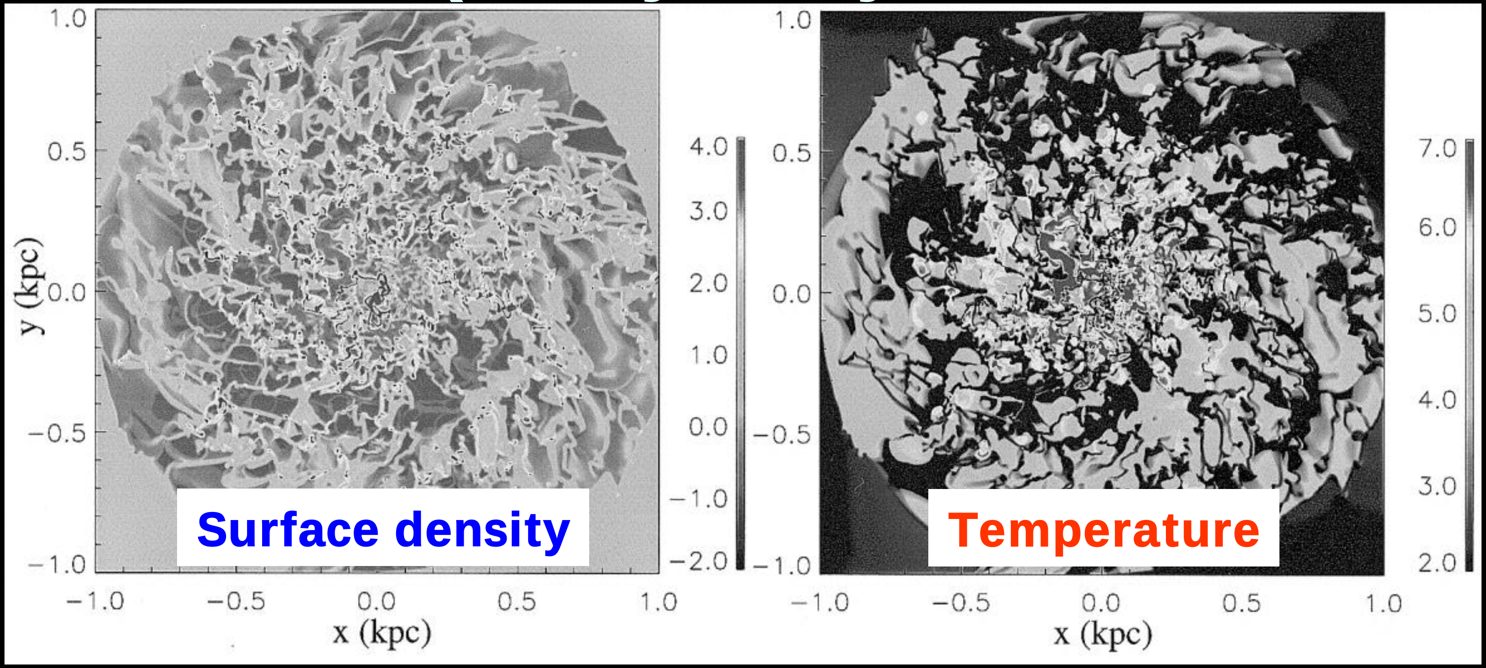
- approximately log–normal PDF due to nonlinear gravity (>a few Mpc)

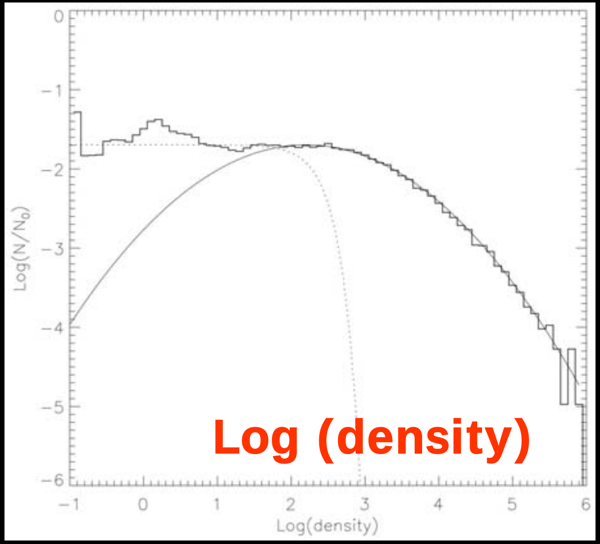
$$P_{LN}(\delta) = \frac{1}{(1+\delta)\sqrt{2\pi \ln(1+\sigma^2)}} \exp\left[-\frac{[\ln\sqrt{1+\sigma^2}(1+\delta)]^2}{2\ln(1+\sigma^2)} \right]$$

- empirical model for non–Gaussianity generated by cosmological nonlinear gravitational evolution for $0.1 < \rho/\langle\rho\rangle < 1000$

Kayo, Taruya & Suto, ApJ 561(2001)22

log-normal PDF for interstellar medium in Galactic disk (2D hydrodynamic simulation)





log-normal behavior in high-density regions for $10^2 < \rho / < \rho > < 10^6$

Wada & Norman ApJ 547(2001)172

Summary

- **Analytic modeling of ICM fluctuations for the first time: log-normal PDF**
  - Previous claim of the cluster temperature underestimate bias
  - It is consistent with Chandra data of A3667
  - $H_{0,est}/H_{0,true}$= 0.8-0.9 is expected for SZ due to fluctuations and non-isothermality of ICM
    - Consistent with Reese et al. (2002), but not with Bonamente et al. (2006)
    - Direct comparison between ROSAT and Chandra analyses is now in progress (Reese et al. 2009)