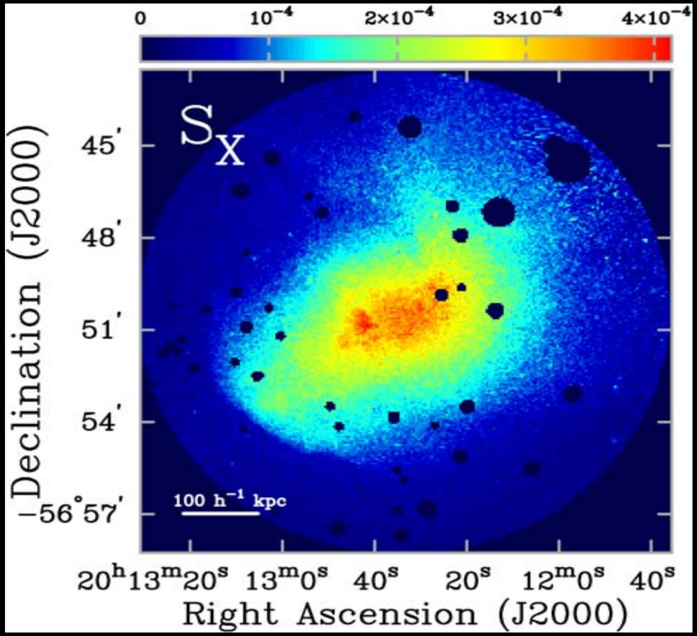
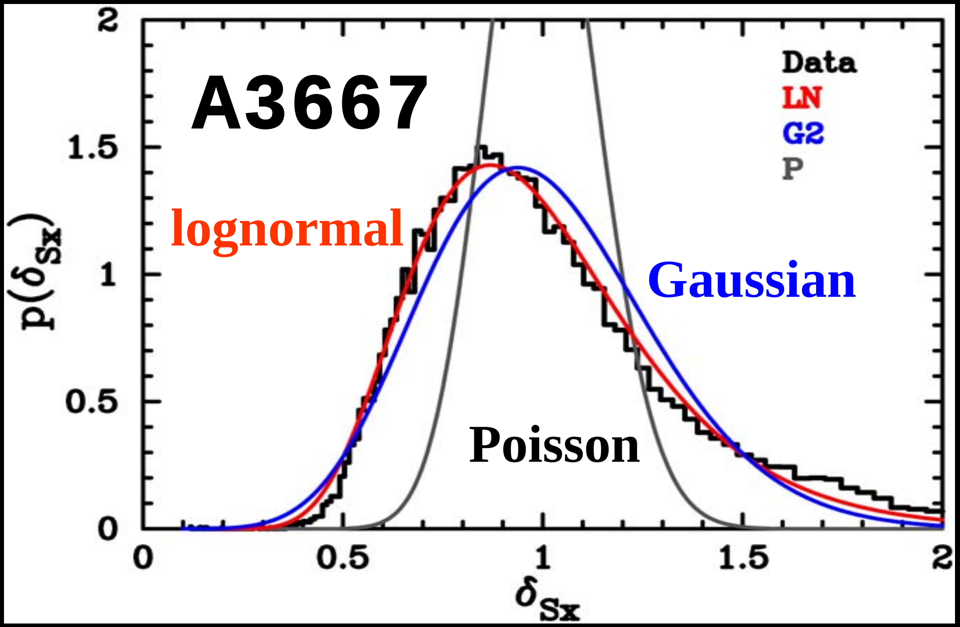
Inhomogeneities in Galaxy Clusters





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Large Scale Structure and Galaxy Formation with LAMOST

Kavli Institute for Astronomy and Astrophysics at Peking University

北京大学科维理天文与天体物理研究所 April 13-17, 2009

What are galaxy clusters ?

Abell (optical) clusters

the Abell radius

$m_3 < m < m_3 + 2$

richness class

Press-Schechter halos

spherical collapse

$\Delta_{vir} = 18\pi^2$

SZ clusters

ΔI_{SZ}

$\propto n_e T_e$

Halos in N-body simulations

friend-of-friend

linking length = 0.2

X-ray clusters

$S_x \propto n_e^2 T_e^{1/2}$

Definitely they are closely related, but the exact one-to-one correspondence is unrealistic

Fundamental limitation in cosmology with galaxy clusters

- Cosmological parameters
  - Observed cluster abundance as a function of T and z
  - Predicted halo abundance as a function of M and z
- M_{halo} – $T_{cluster}$ relation
  - M_{halo}: size of cluster ? Non-sphericity ?
  - $T_{cluster}$: non-isothermal, inhomogeneity in intra-cluster medium ?

Toward a more realistic model of galaxy clusters

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

References

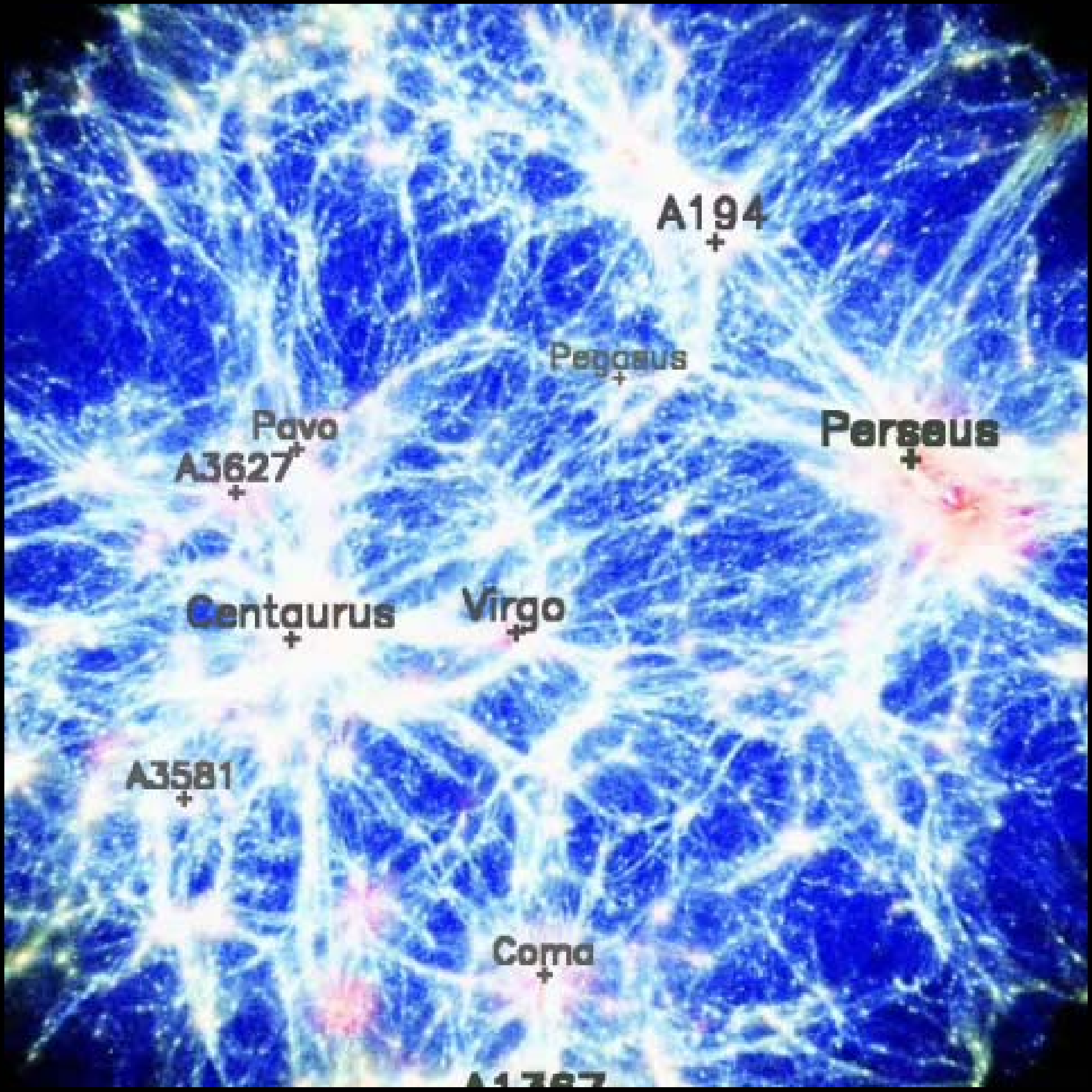
- **Hajime Kawahara, YS, Kitayama, Sasaki, Shimizu, Rasia + Dolag (2007)**
  - *Radial Profile and Lognormal Fluctuations of the Intracluster Medium as the Origin of Systematic Bias in Spectroscopic Temperature* ApJ 659(2007)257
- **Kawahara, Kitayama, Sasaki + YS (2008)**
  - *Systematic Errors in the Hubble Constant Measurement from the Sunyaev-Zel'dovich effect* **ApJ 674(2008)11**
- **Kawahara, Reese, Kitayama, Sasaki + YS (2008)**
  - *Extracting galaxy cluster gas inhomogeneity from X-ray surface brightness: a statistical approach and application to Abell 3667* **ApJ 687(2008) 936**

Simulated clusters in the local universe

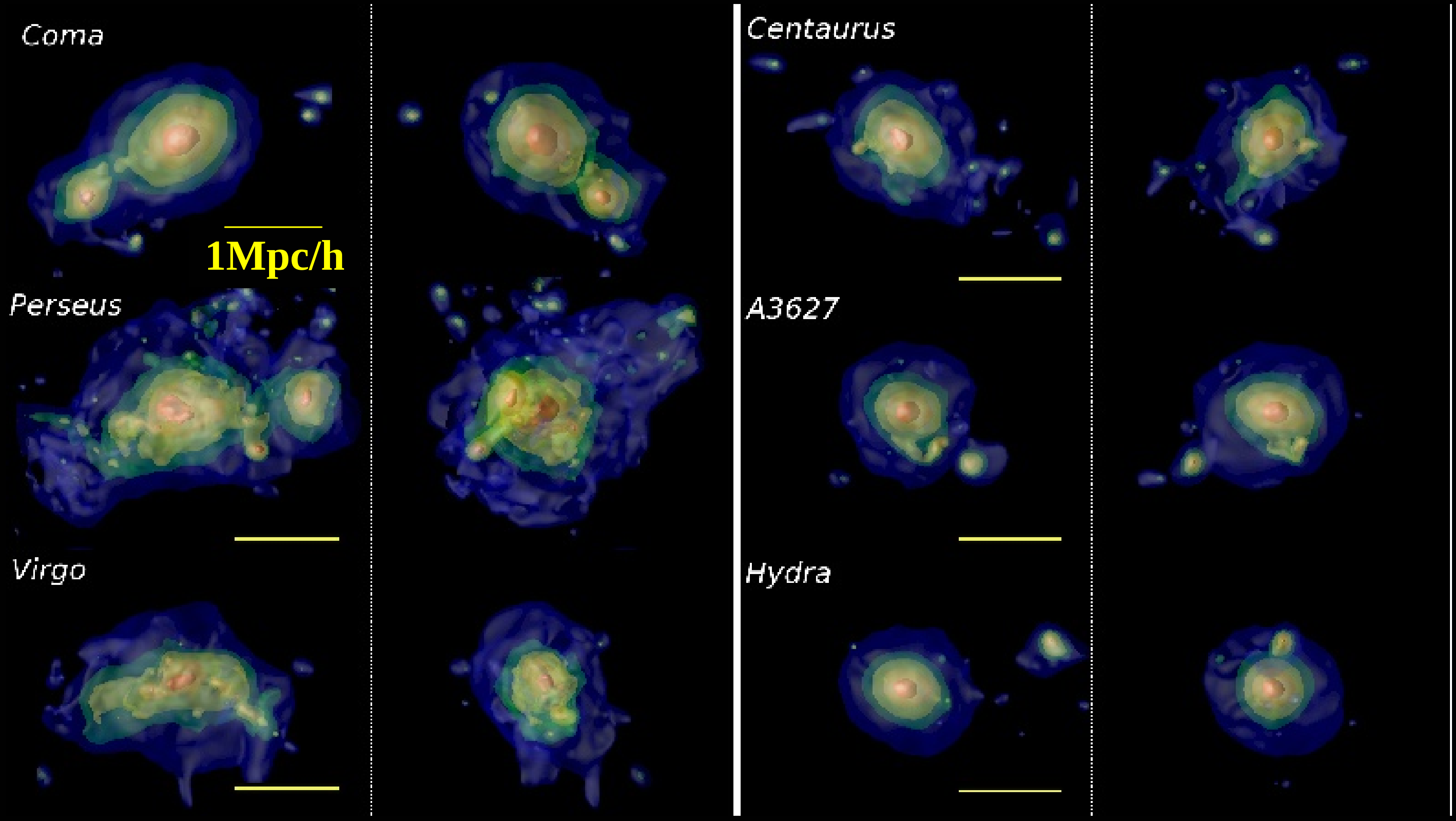
- SPH simulations (Dolag et al. 2005)
- Local universe distribution in a sphere of r=110Mpc
  - Initial condition: the observed galaxy density field of IRAS 1.2 Jy survey (smoothing over $5h^{-1}$Mpc), linearly evolving back to z=50 + random Gaussian fluctuations on smaller scales
  - + cooling, star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

Simulated local universe

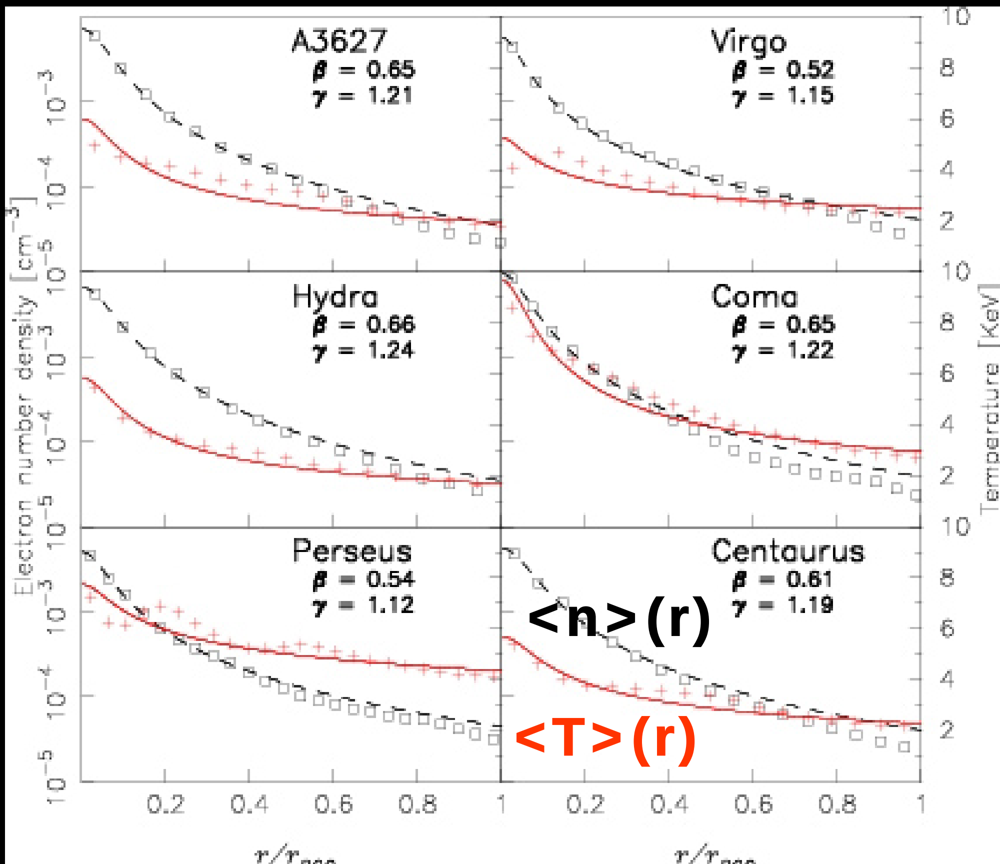
Dolag et al. (2005)



Projected views of ***simulated clusters***



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



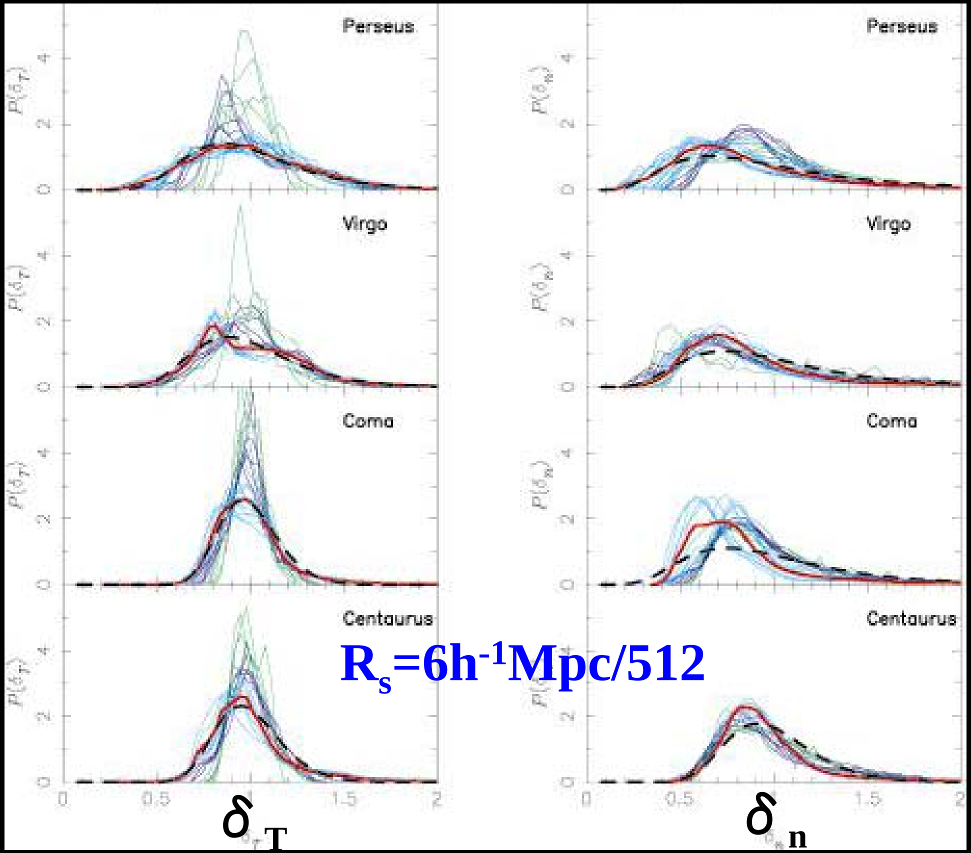
- Density and temperature radial profiles of simulated clusters
- **Polytropic β model**

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

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

Kawahara et al. ApJ 659 (2007)257

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

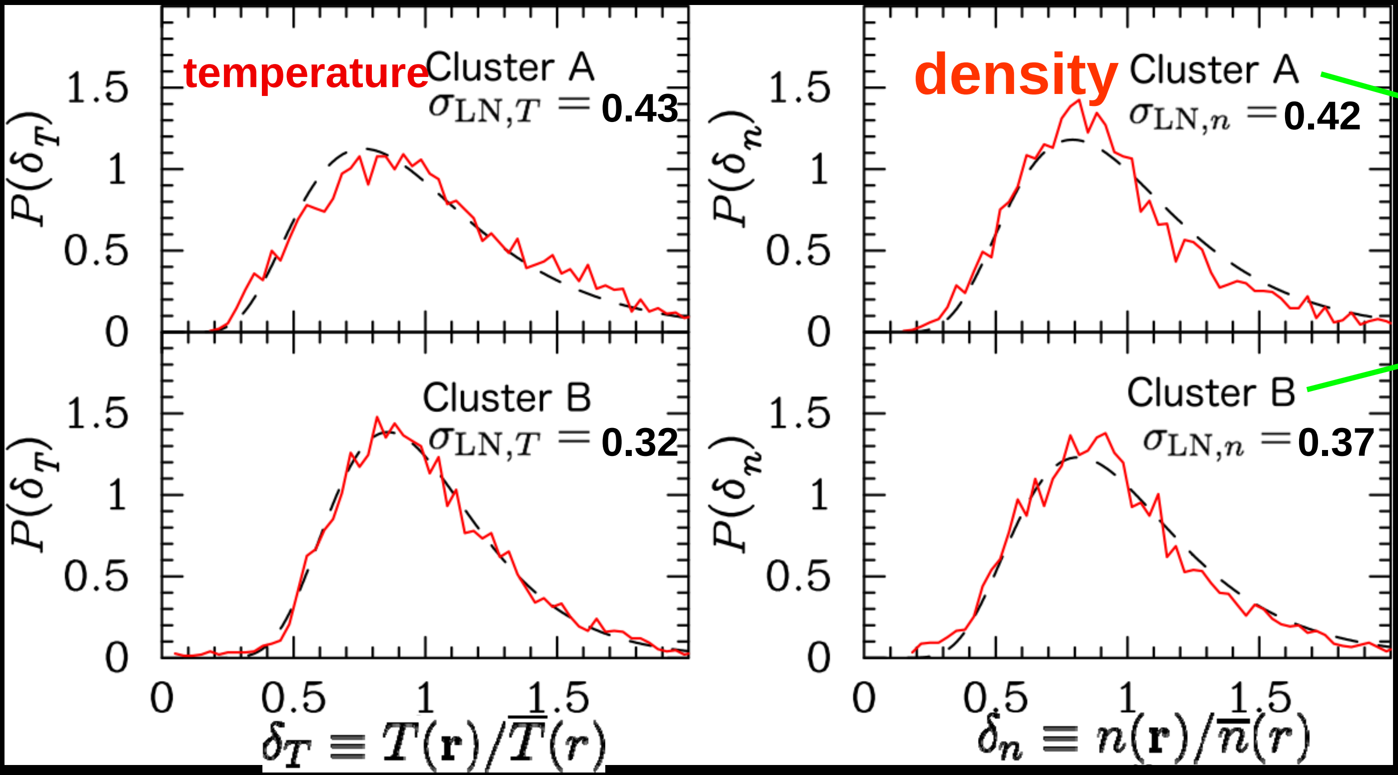


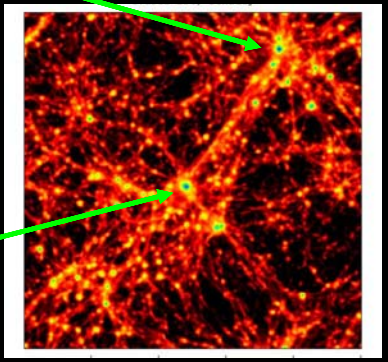
- Local inhomogeneities of density and temperature of simulated clusters
  - $\delta_n = n(r, \theta, \phi) / \langle n \rangle (r)$
  - $\delta_T = T(r, \theta, \phi) / \langle T \rangle (r)$
- Log-normal PDF provides reasonable approximations

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

Kawahara et al. ApJ 659 (2007)257

Both SPH and mesh simulations show log-normal distribution





Mesh hydro simulation data
(D.Ryu private communication)

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

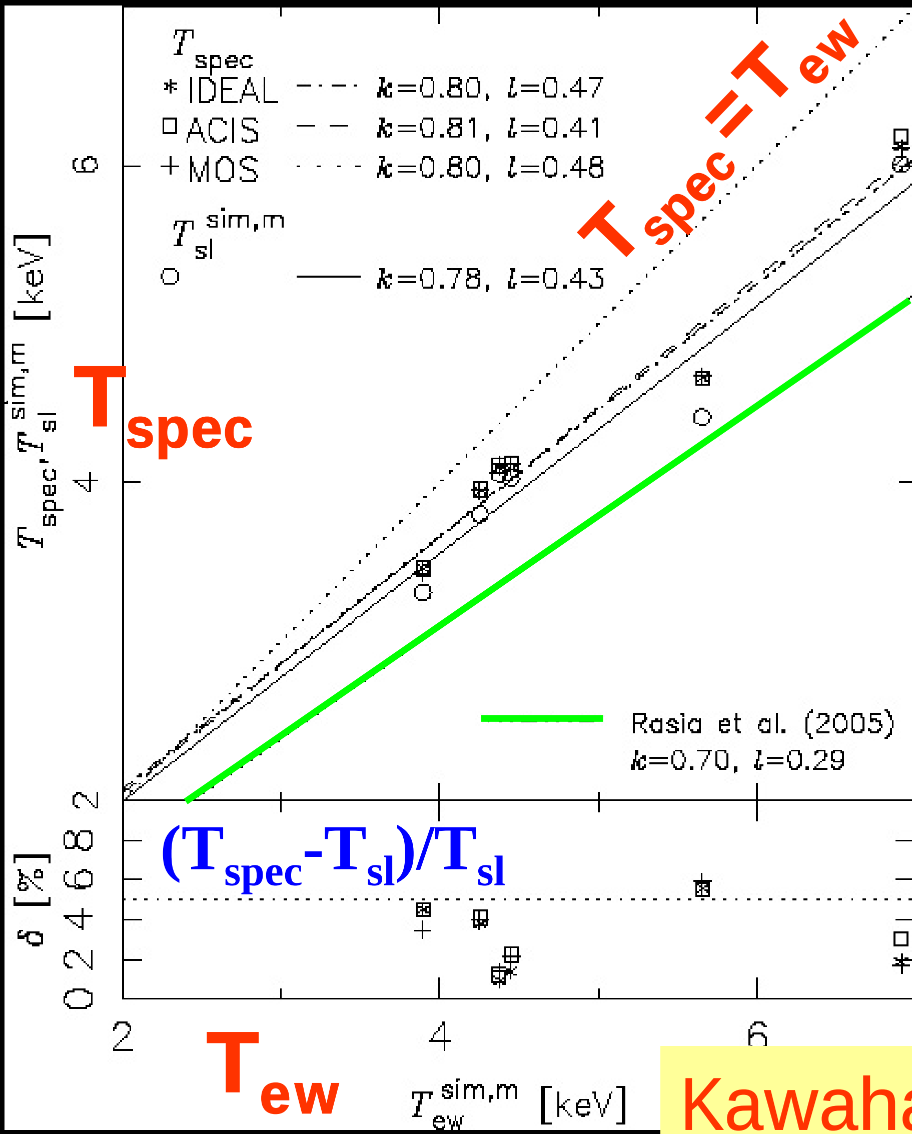
mass-weighted, emission-weighted, and spectroscopic temperatures of clusters

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

Except for idealistic isothermal case, cluster temperature is ill-defined

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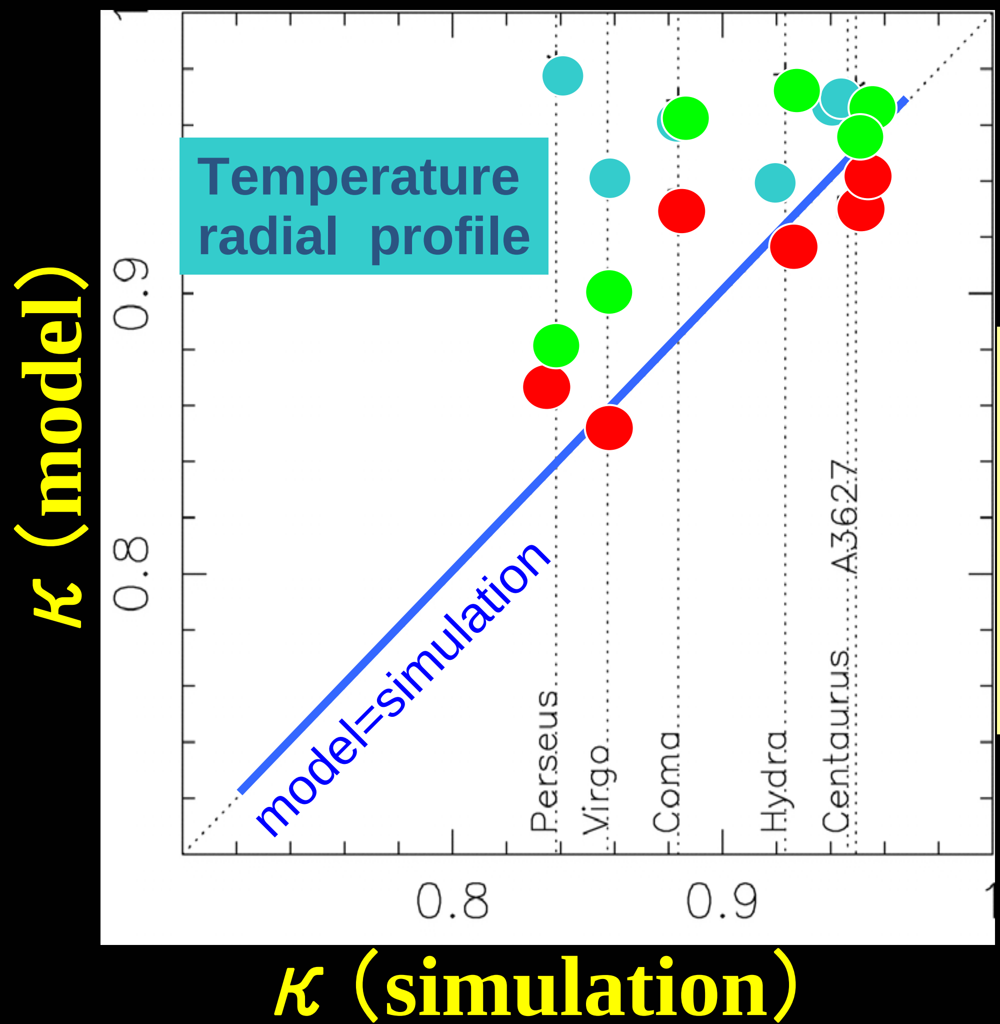
An analytic model for T_{spec}/T_{ew}

- Spherical polytropic β -model as global mean radial profiles
- Log-normal density and temperature fluctuations
  - Density and temperature correlations may be ignored
  - Radius independent σ assumed

$$\frac{T_{sl}}{T_{ew}} = \frac{T_{sl}^{RP}}{T_{ew}^{RP}} \exp\left(-1.25\,\sigma_{LN,T}^{2}\right)$$

  - Explain numerical simulations well

Comparison between analytic models and simulations



Temperature inhomogeneity

$$\kappa_{\rm model} \equiv \frac{T_{\rm sl}^{\rm model}}{T_{\rm ew}^{\rm model}} \equiv \kappa^{\rm RP}\kappa^{\rm LI}$$

$$= \frac{T_{\rm sl}^{\rm RP}}{T_{\rm ew}^{\rm RP}} \exp(-1.25\sigma_{LN,T}^{2})$$

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Implications

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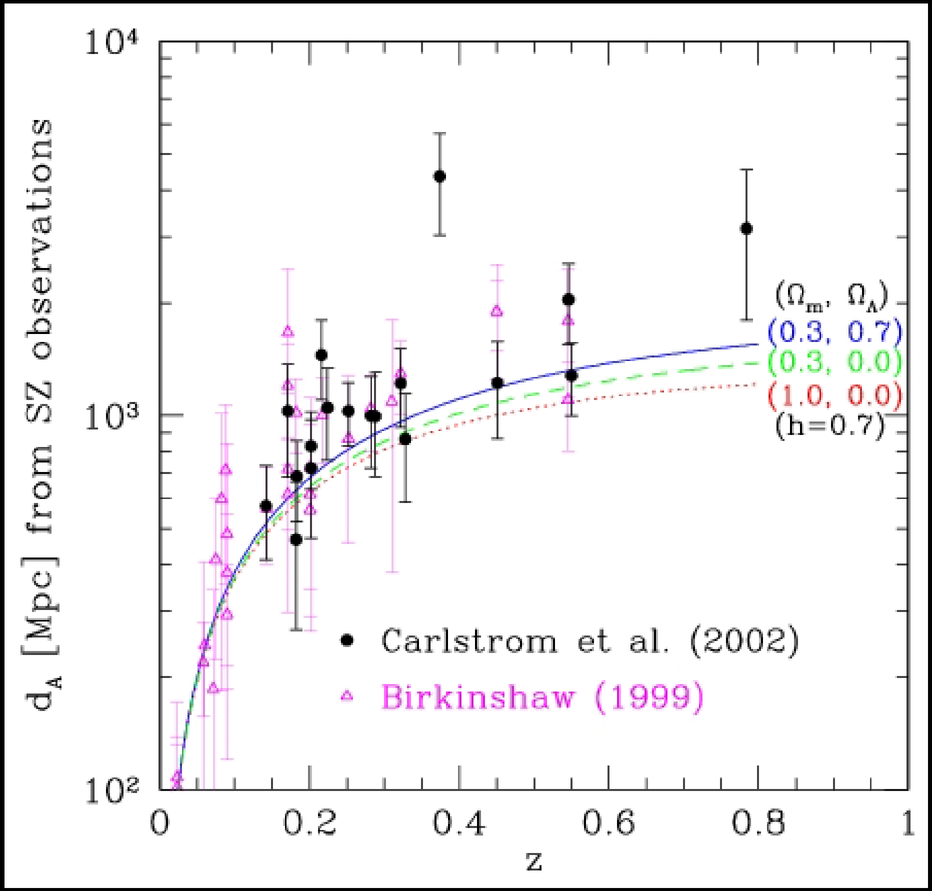
H_0 estimated from the SZ effect



- **WMAP:**
  - **73±3 km/s/Mpc (Spergel et al. 07)**
- **ROSAT+SZ:**
  - **60±3 km/s/Mpc (Reese et al. 2002)**

- ***Overlooked systematic effects ?***

H_0 from 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

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

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

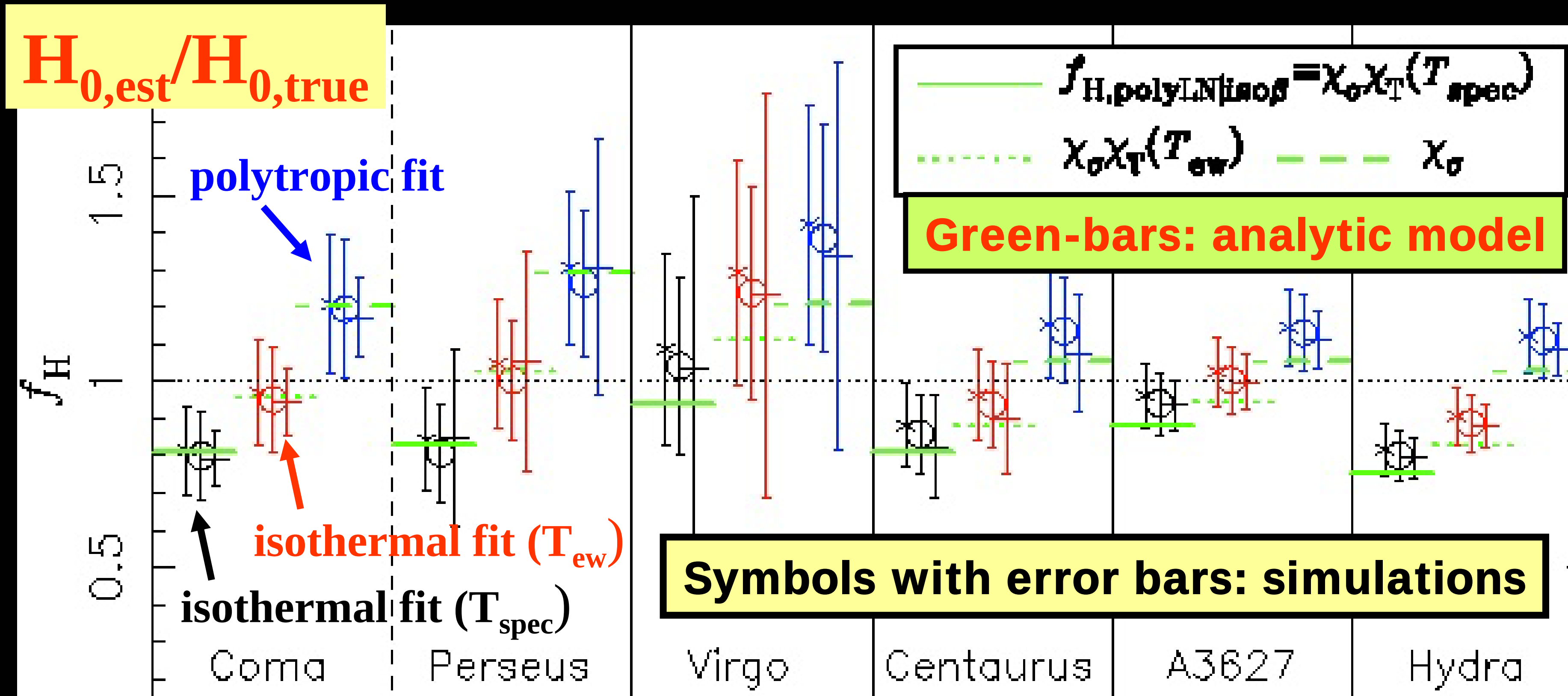
non-isothermality

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

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***

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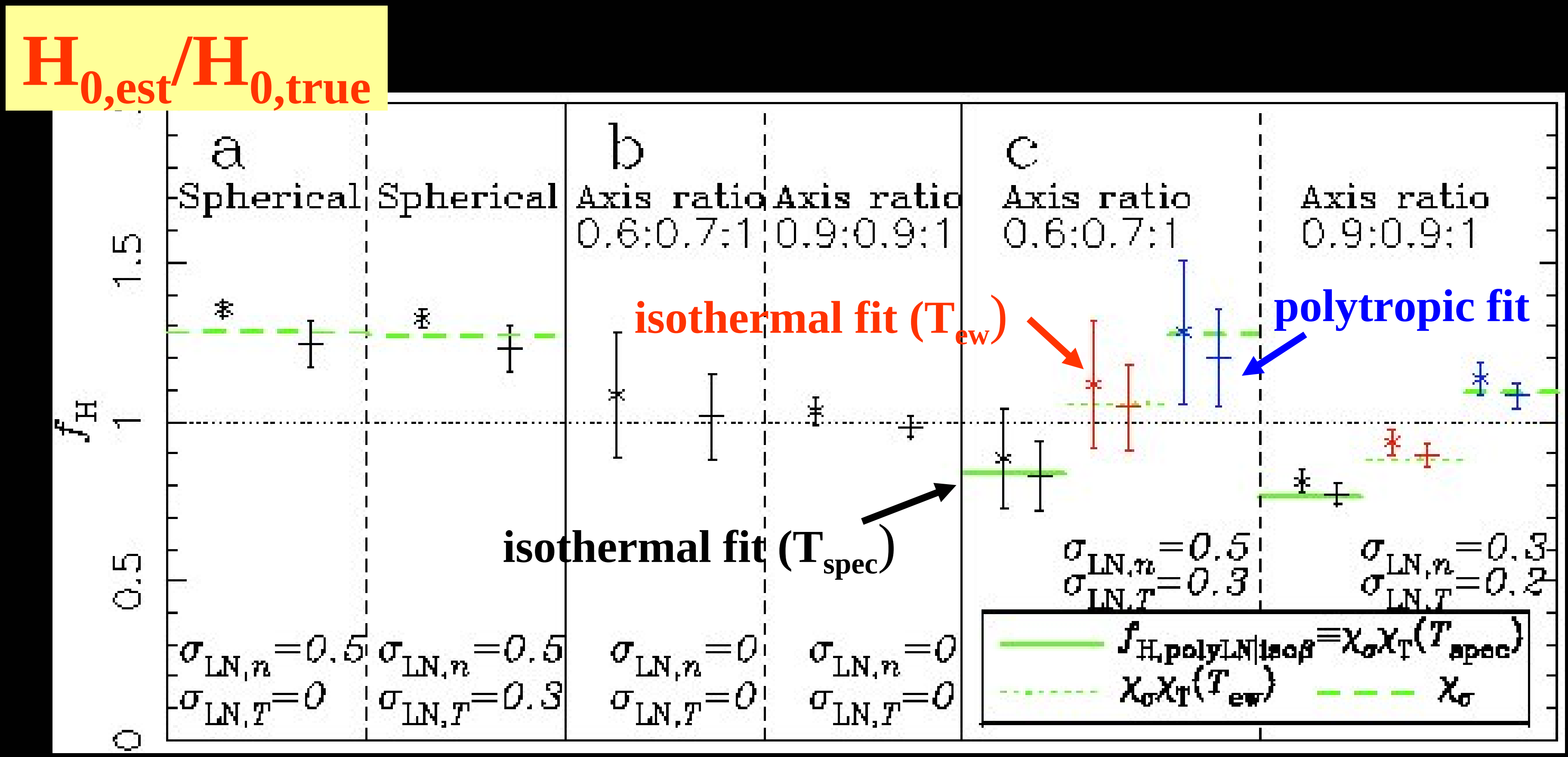
Non-spherical effect : triaxial clusters



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

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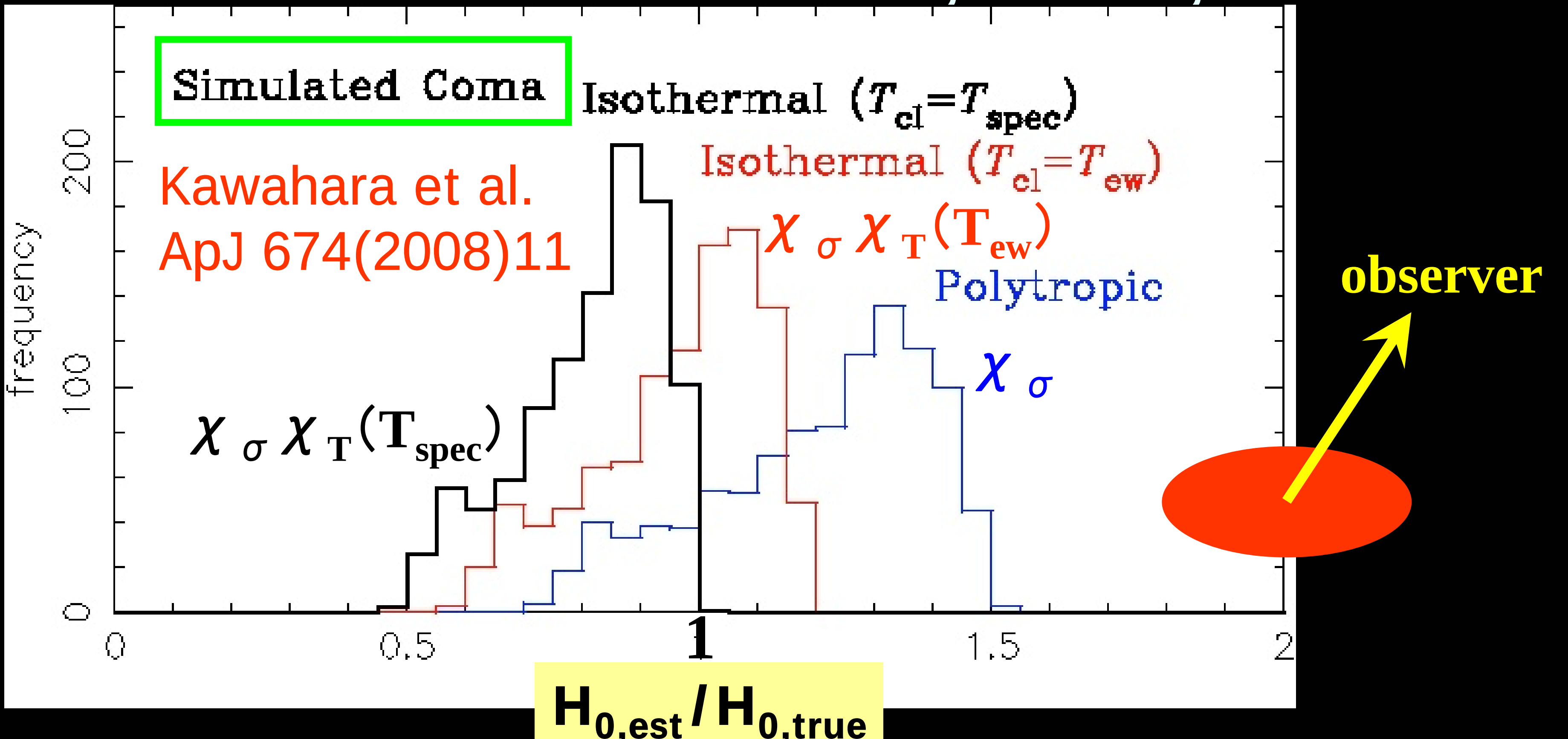
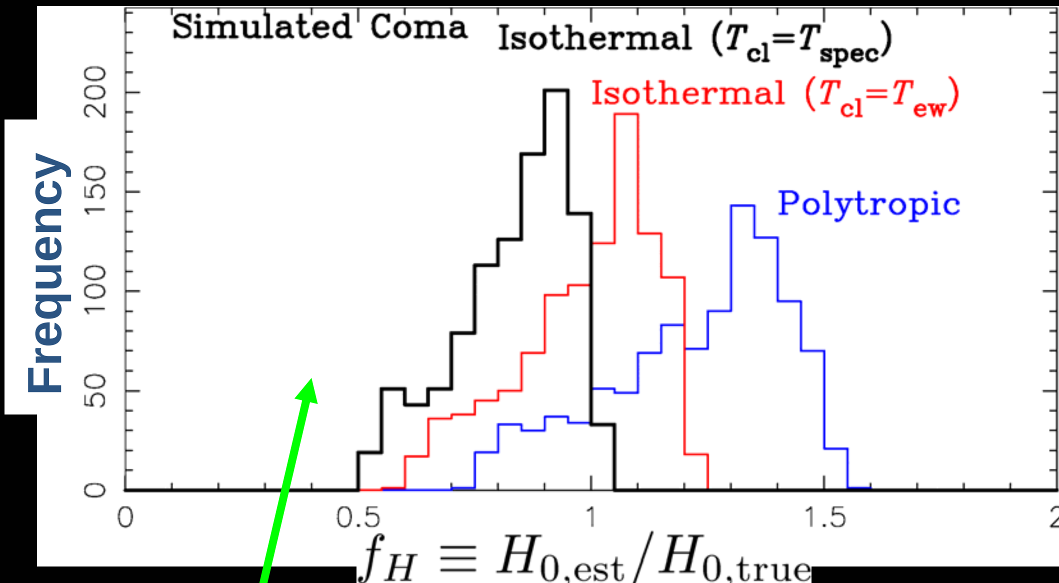
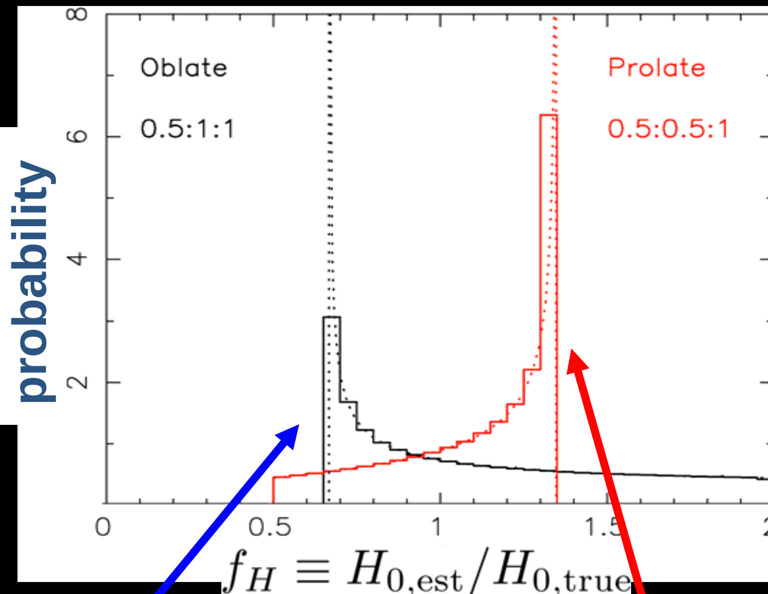
Distribution of $H_{0,est} / H_{0,true}$



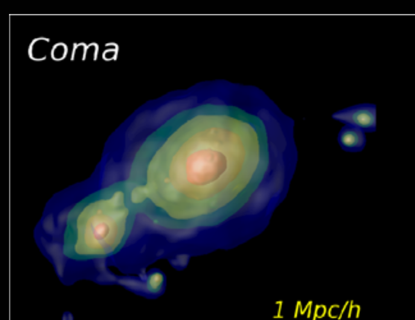
- Skewed distribution due to the prolateness
- Previous studies did not find the large bias because they set $T_{cl}=T_{ew}$ instead of T_{spec} (Inagaki, Suginohara & YS 1995, Yoshikawa, Itoh & YS 1998), consistent with our results of the isothermal fit with T_{ew}

Asymmetry in the estimated H_0

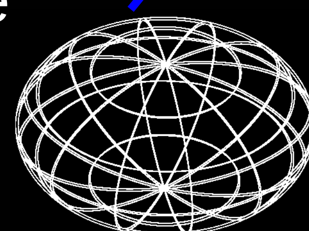




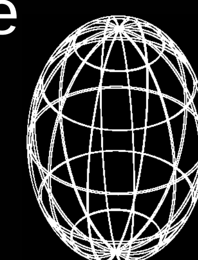
- simulation



- oblate



- prolate



● distribution function of $H_{0,est}$ from many SZ clusters
⇔ overall average shape of clusters (oblate or prolate)

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 ?*

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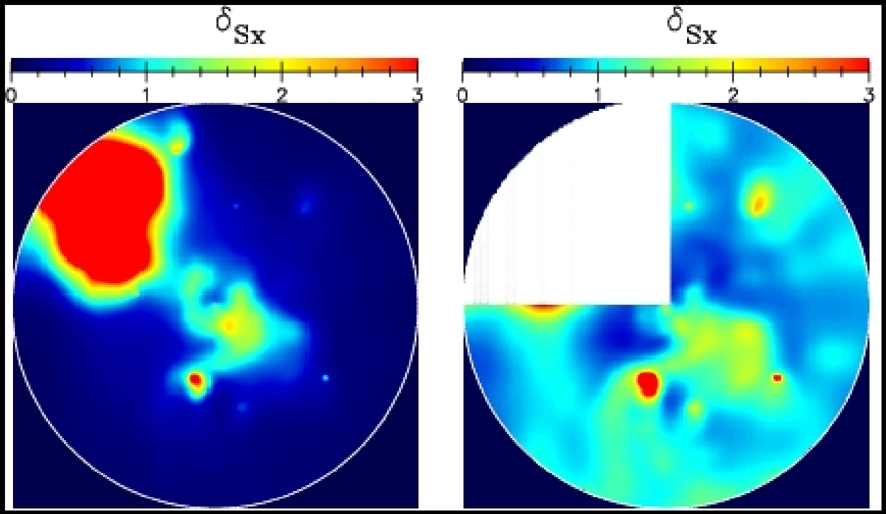
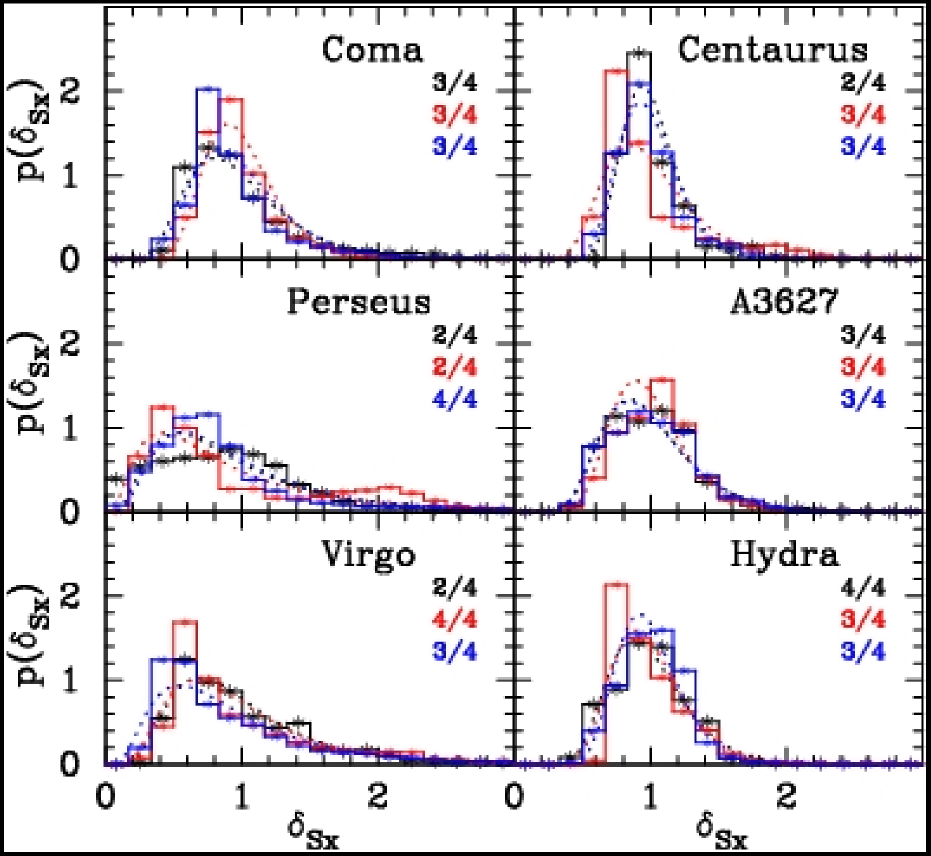
2D projection effect: test with simulated clusters

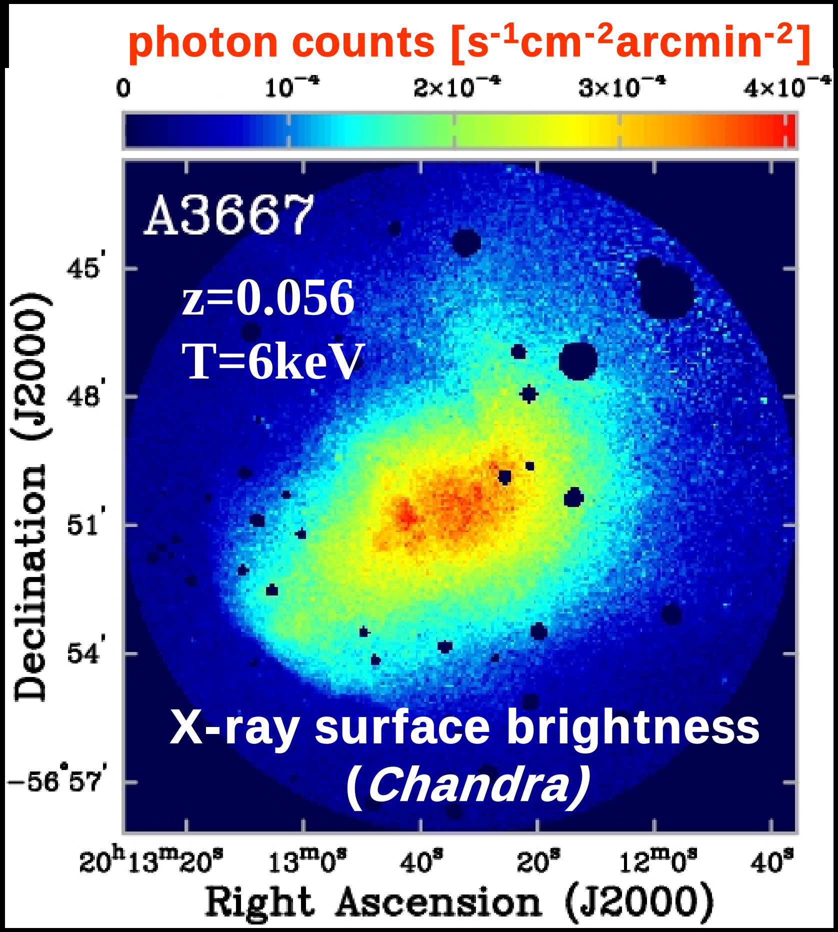


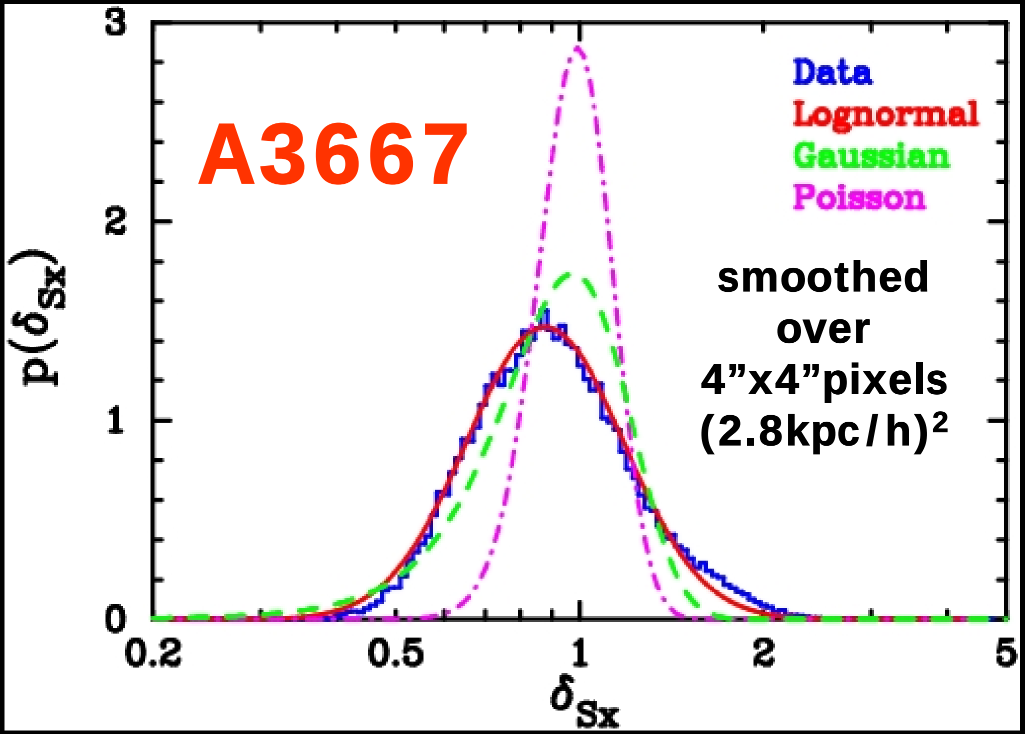


if a prominent substructure resides in a quarter, the quarter is removed in the analysis

- 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 !

$\sigma_{LN,Sx,A3667}=0.3 \rightarrow \sigma_{LN,n}=0.4$

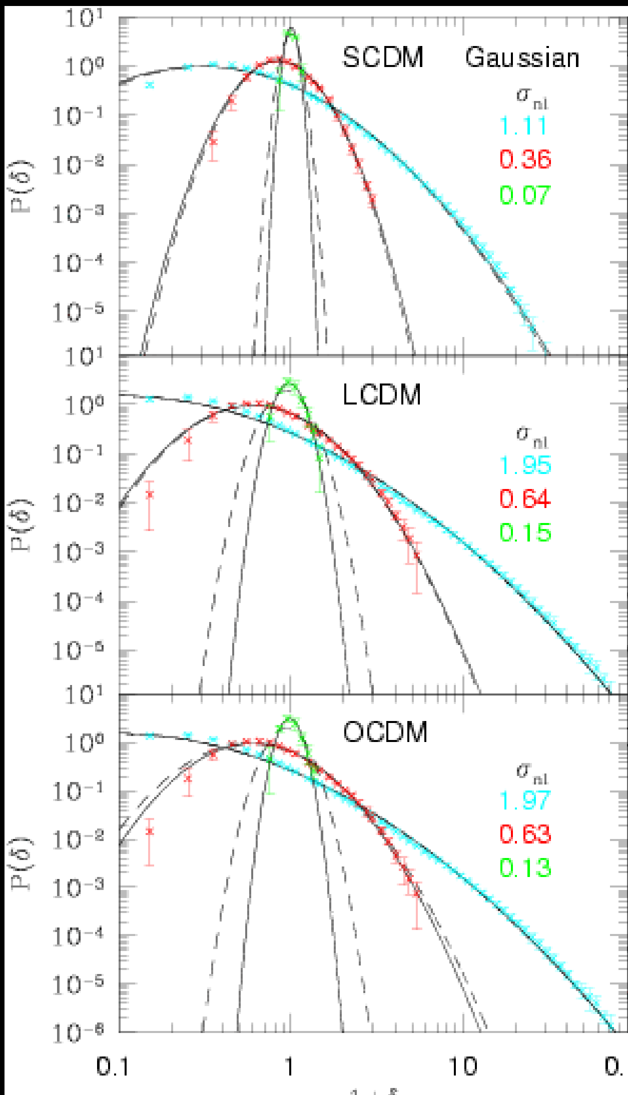
consistent with average values of simulated clusters

Kawahara, Reese et al. ApJ 687(2009)936

a remaining question: origin of log-normal fluctuations ?

- generic statement
  - addition of independent random fields
    ⇒ Gaussian
  - multiplication of independent random fields
    ⇒ 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**

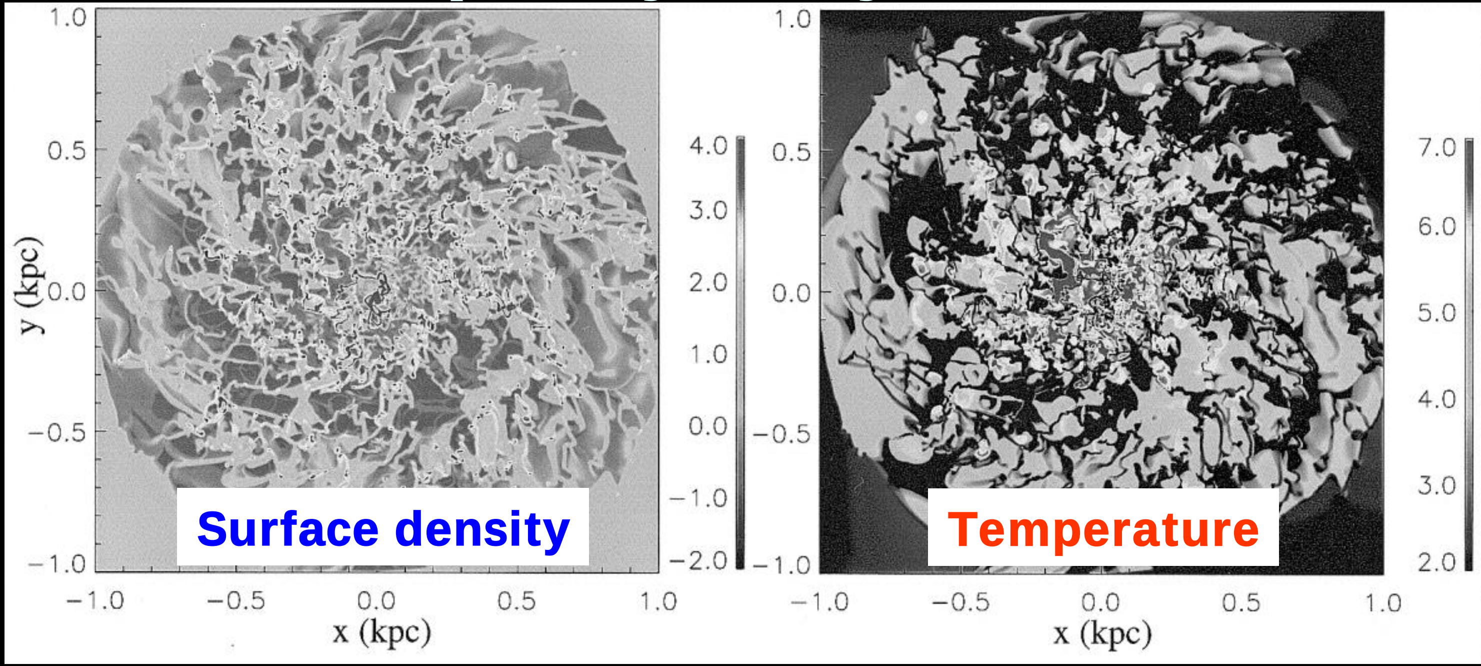
- approximately log-normal PDF due to nonlinear gravity (>a few Mpc)

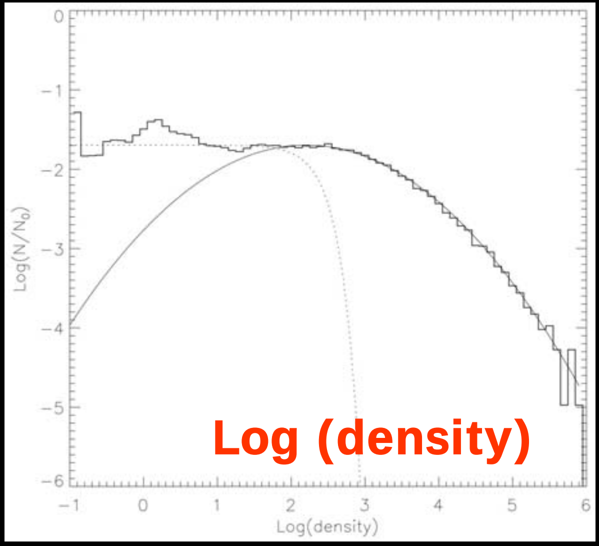
$$P_{LN}(\delta) = \frac{1}{(1+\delta)\sqrt{2\pi \ln(1+\sigma^2)}} \exp\left[-\frac{[\ln \sqrt{1+\sigma^2}(1+\delta)]^2}{2\ln(1+\sigma^2)} \right]$$

- 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 $10^2 < \rho/\langle\rho\rangle < 10^6$

Wada & Norman ApJ 547(2001)172

Summary

- **Analytic modeling of ICM inhomogeneity for the first time: log-normal PDF**
  - Previous claim of the cluster temperature underestimate bias is analytically understood
  - Consistent with Chandra data of A3667
  - $H_{0,est}/H_{0,true} = 0.8\text{-}0.9$ is expected for SZ due to inhomogeneity + non-isothermality of ICM
    - Consistent with Reese et al. (2002)
    - Direct comparison between ROSAT and Chandra analyses is now in progress (Reese et al. 2009)