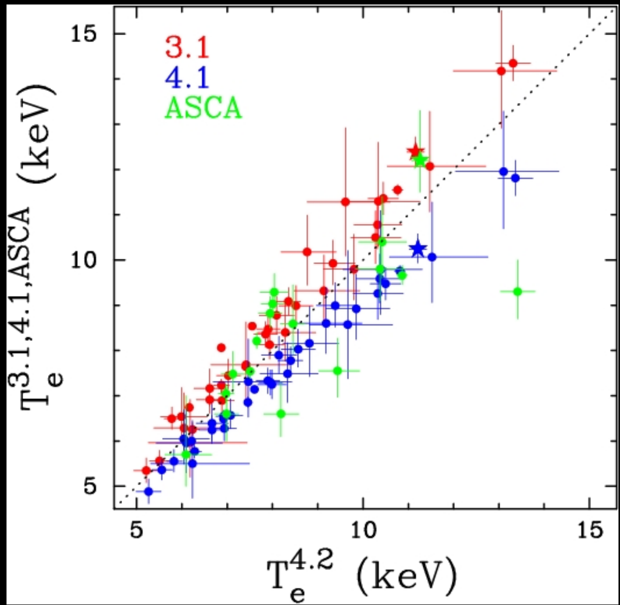
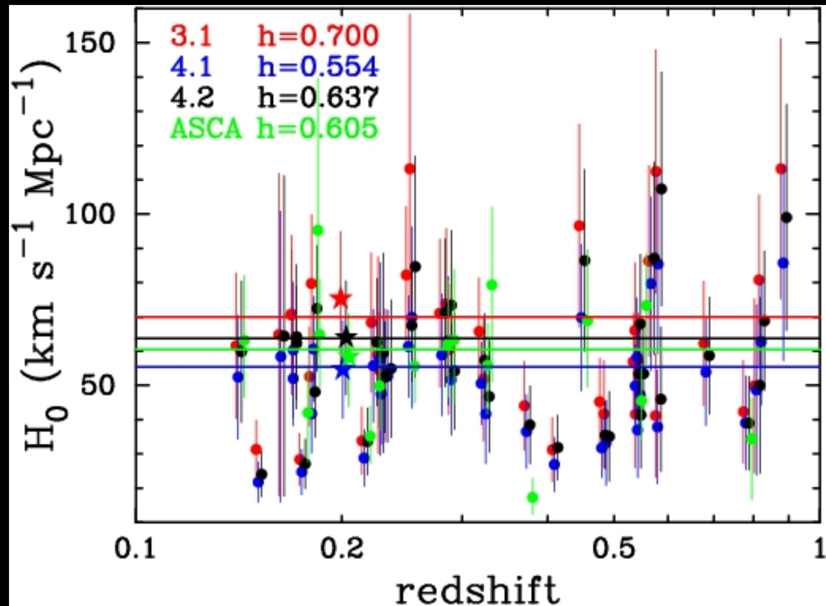
Cosmological implications of inhomogeneities in intra-cluster gas





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ASIAA seminar, 15:30- February 2, 2012

Theoretical Astrophysics Group in the University of Tokyo

- Professor: Yasushi Suto, Assistant Professor: Atsushi Taruya + 8 graduate students (one female, one from mainland China)
- Cosmology
  - Dark energy and baryon acoustic oscillation
  - Galactic dust extinction map and FIR emission of galaxies
  - Soft X-ray emission from warm–hot intergalactic medium
  - Modeling density profiles of galaxy clusters
- Exoplanet
  - Spin-orbit misalignment using the Rossiter-McLaughlin effect
  - Modeling scattered light of a second earth
  - Dynamical evolution of a few body planet system

Collaborators and references

- **E.Reese et al.(2010)**
  - *Impact of Chandra Calibration Uncertainties on Galaxy Cluster Temperatures; Application to the Hubble Constant* ApJ 721(2010)653
- **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 et al. (2008a)**
  - *Systematic Errors in the Hubble Constant Measurement from the Sunyaev-Zel'dovich effect* ApJ 674(2008)11
- **Kawahara et al. (2008b)**
  - *Extracting Galaxy Cluster Gas Inhomogeneity from X-ray Surface Brightness: A Statistical Approach and Application to Abell 3667* ApJ 687(2008)936

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}

$\propto n_e T_e$

X-ray clusters

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

Halos in N-body simulations

friend-of-friend

linking length = 0.2

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

Fundamental limitation in cosmology with galaxy clusters

- **Cosmological parameters from…**
  - 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 ?

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

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

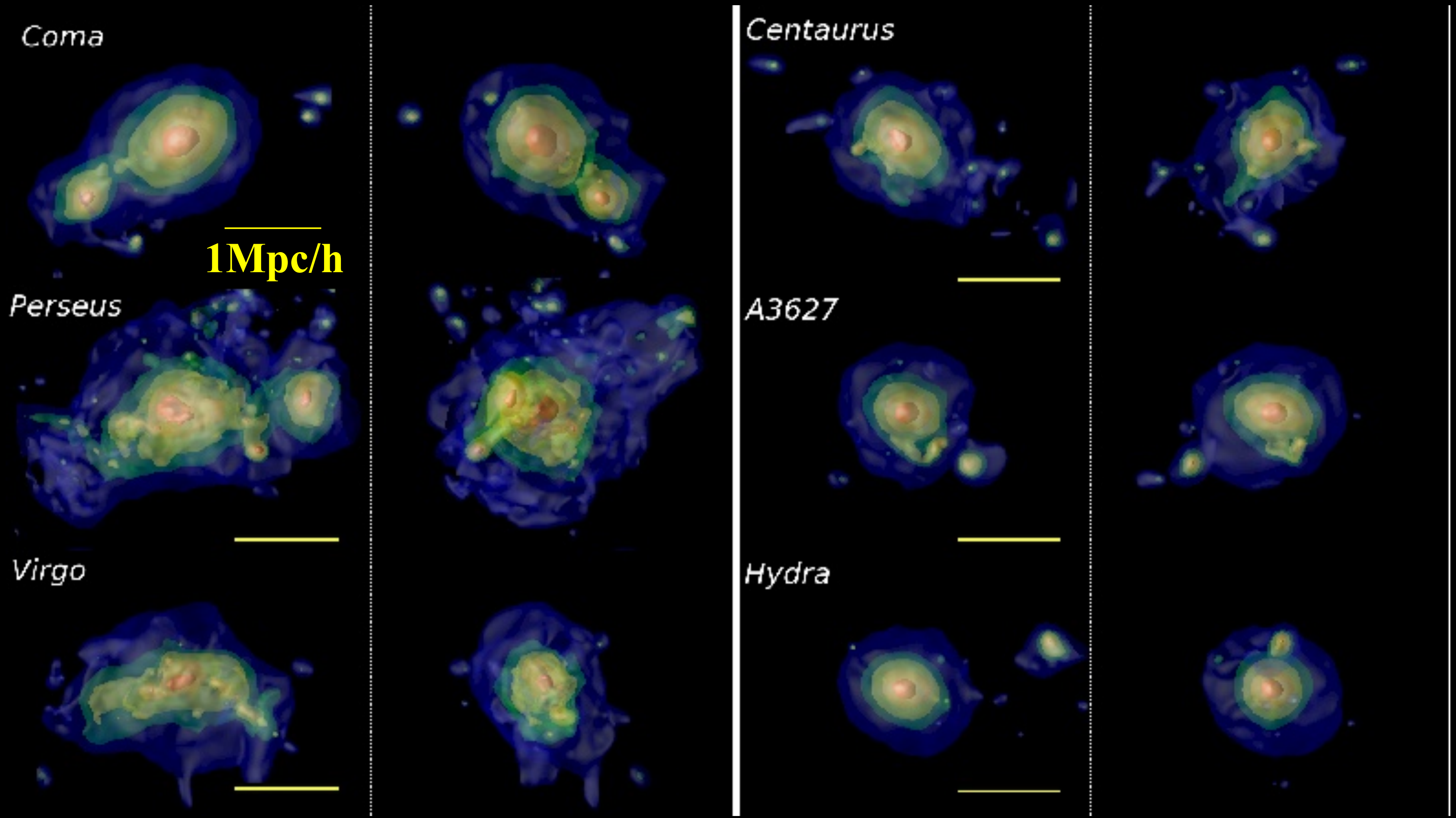
Except for idealized isothermal case, cluster temperature is ill-defined

	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)

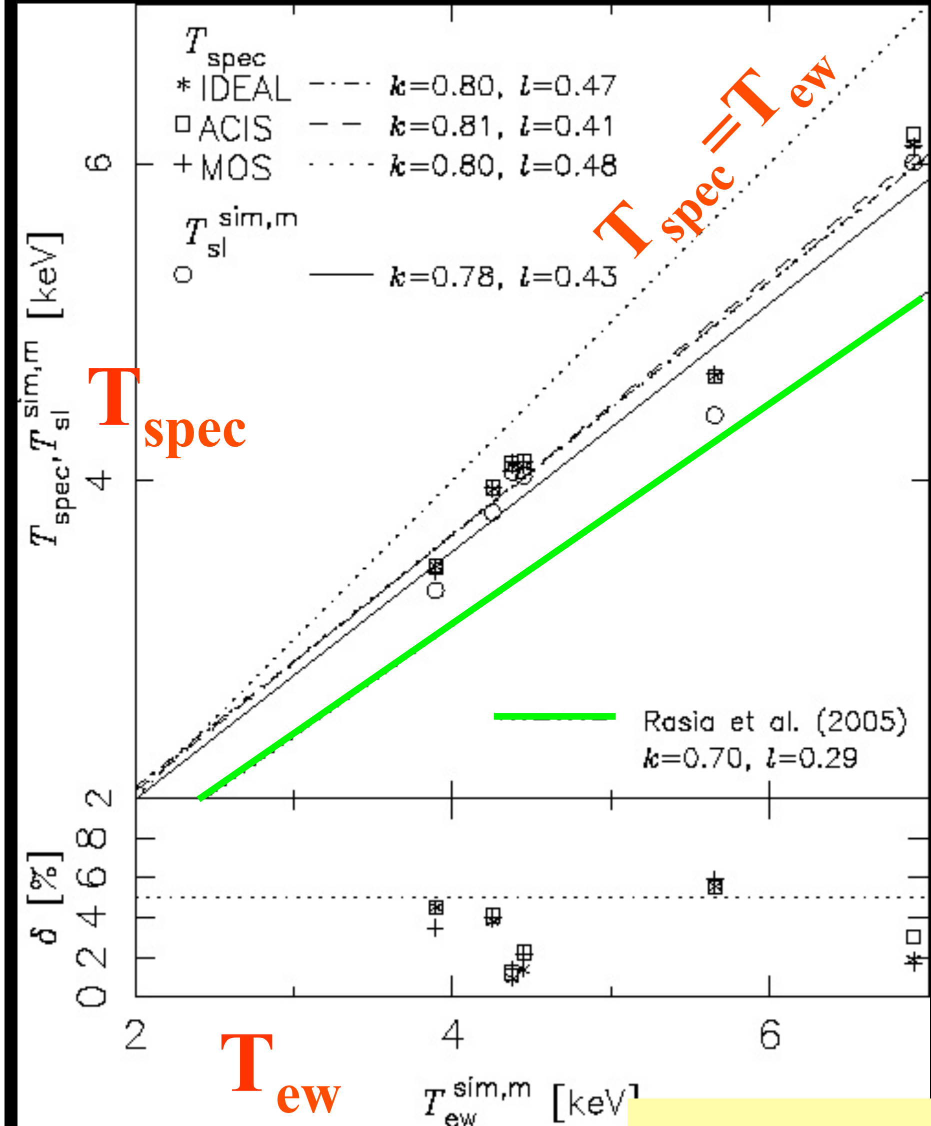
Simulated clusters in the local universe

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

Projected views of ***simulated clusters***



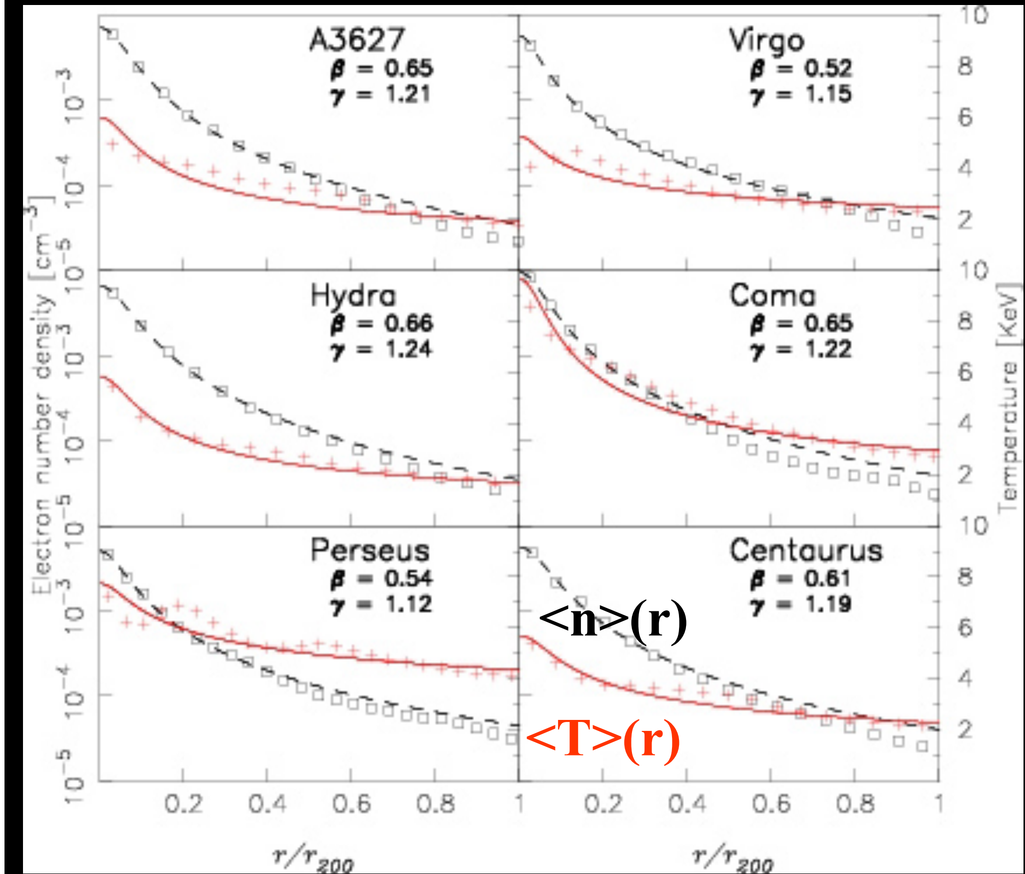
T_{spec} is systematically smaller than T_{ew}



- Spectroscopically more weight (more lines) toward cooler regions
  - Mazzotta et al. (2004) & Rasia et al. (2005) found T_{spec} ~0.7 T_{ew} from simulations
  - We confirm their results using simulated clusters of Dolag et al. (2005) T_{spec}~0.8 T_{ew} (see also Mathiesen & Evrard 2001)

Kawahara et al. ApJ 659 (2007)257

Origin of $T_{spec} < T_{ew}$ (1) mean 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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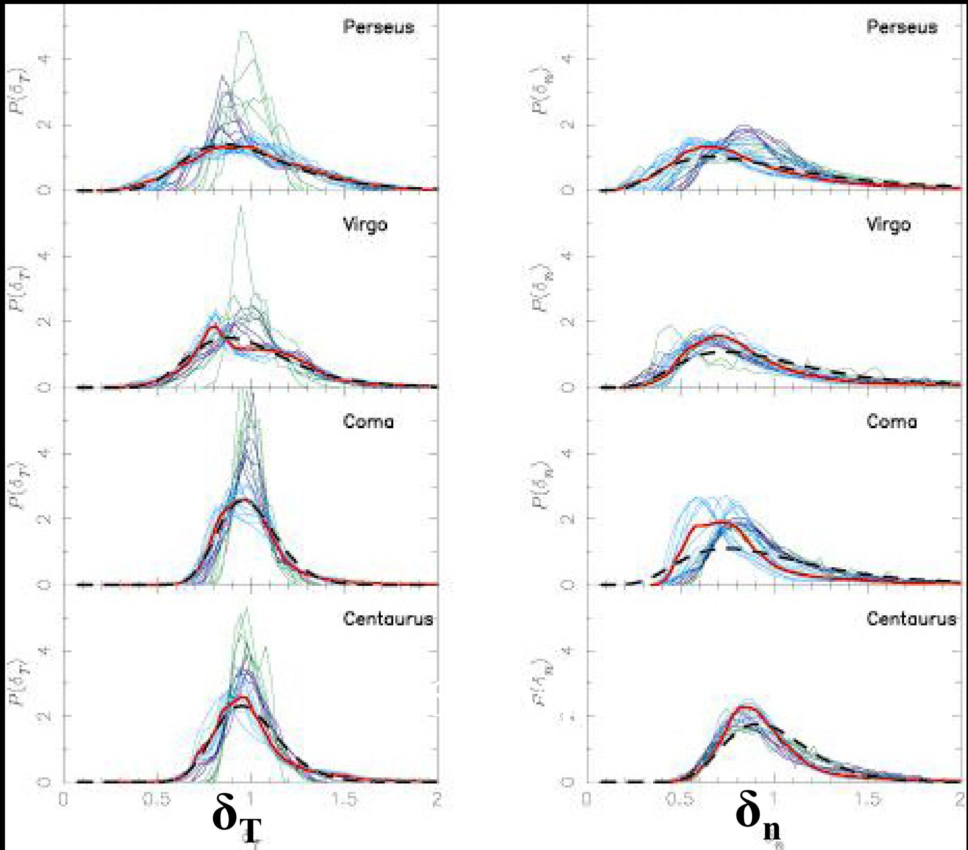
Origin of $T_{spec}<T_{ew}$ (2) Local inhomogeneity



- 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

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

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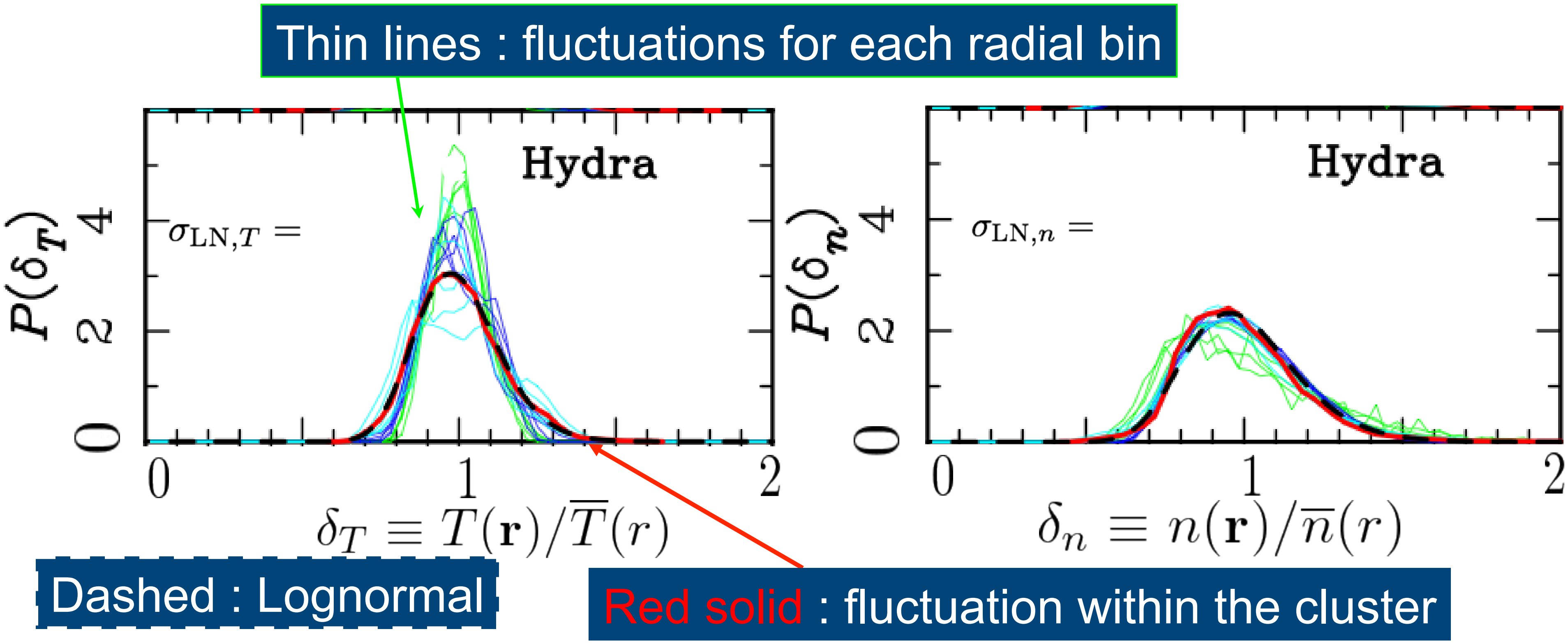
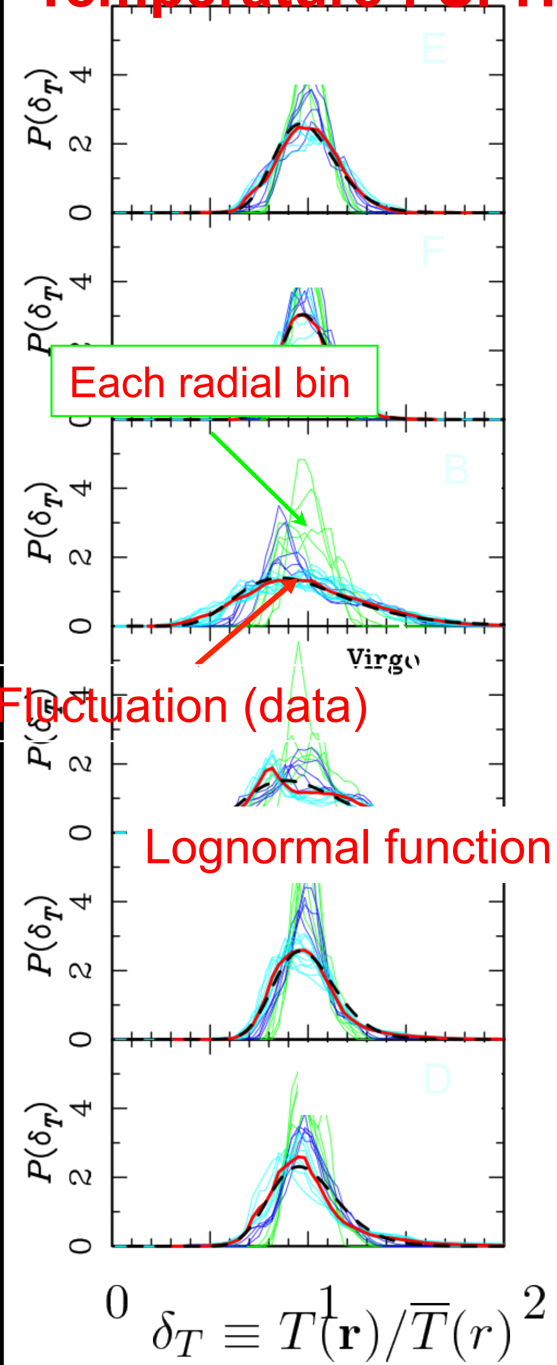
Lognormal Model from hydro simulations



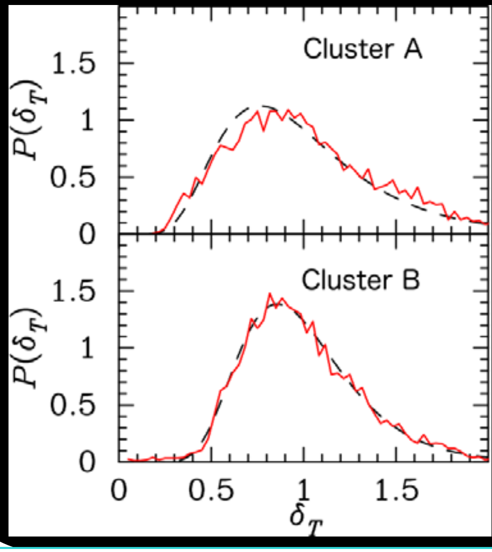
- Both the density and temperature fluctuations can be approximated by lognormal distribution:

$$P(\delta_x;\sigma_{\mathrm{LN},x})d\delta_x = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{LN},x}} \exp\left[\frac{-(\log\delta_x + \sigma^2_{\mathrm{LN},x}/2)^2}{2\sigma^2_{\mathrm{LN},x}}\right]\frac{d\delta_x}{\delta_x}$$

Temperature : SPH

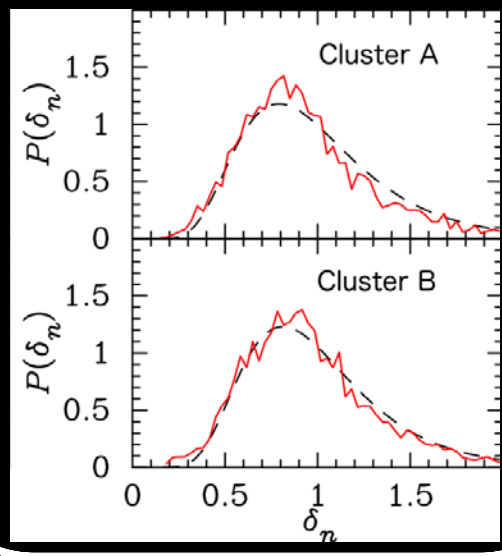


Temperature : Mesh

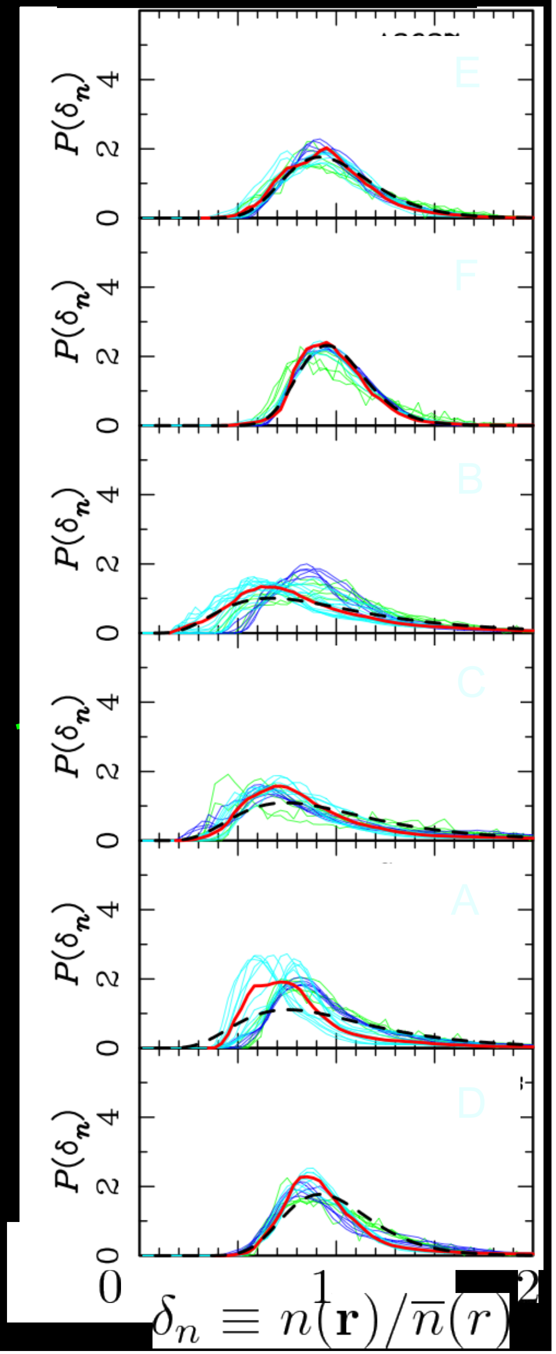


Other 6 + 2 clusters

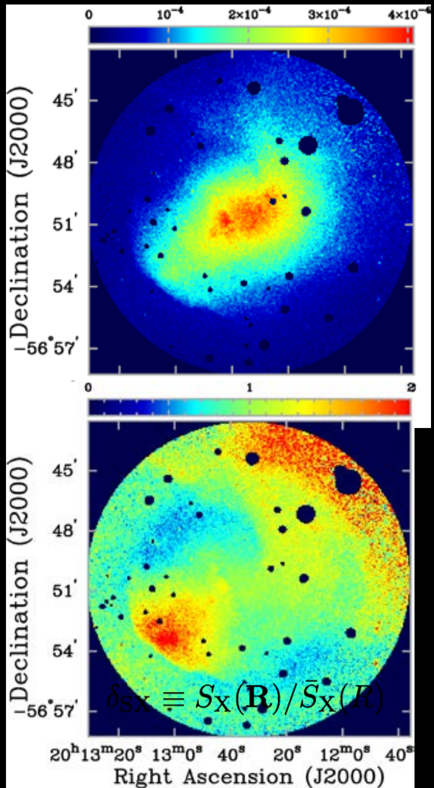
Density : Mesh

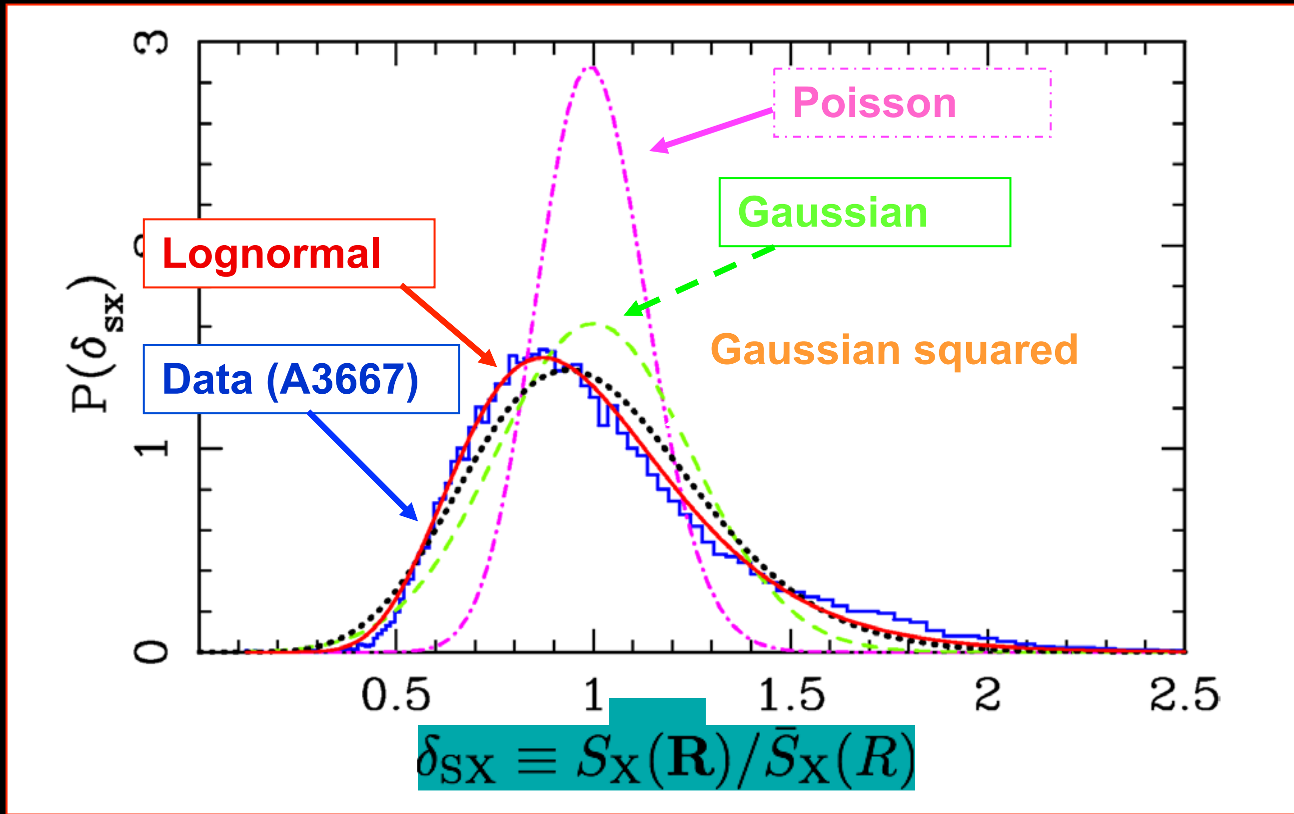


Density : SPH



Application to a real cluster: A3667





Good agreement with the Lognormal distribution

Estimated value of $\sigma_{LN,n} = \left[0.75 + \dfrac{50}{(\alpha_{Sx} - 0.2)^4}\right] \sigma_{LN,Sx}$ ~0.4

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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 are ignored
  - Radius independent σ assumed

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

  - Explain simulation results well

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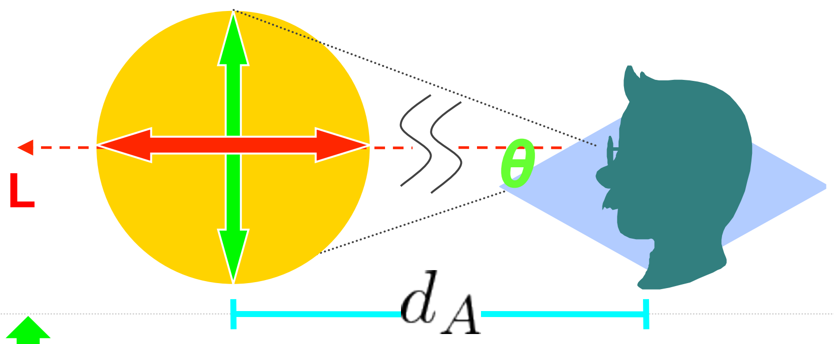
The Hubble constant measurement using galaxy clusters

- SZ: primary distance indicator
- Assumption : the spherical isothermal β model



: **Angle θ from X-ray map**

$$d_A = L/\theta$$

$$H_0 = \frac{cz}{d_A(z)}\left[1 + \frac{2\lambda_0 - \Omega_0 - 6}{4} z + \mathcal{O}(z^2)\right]$$

: the **SZ effect**

$$\frac{-\Delta I}{I} \propto y \approx n T L$$

+ X-ray brightness

$$S_{\rm x} \propto n^2 \Lambda_{\rm x}(T)\, L$$

+ spectroscopic T

$$T = T_{\rm spec}$$

length L

Isothermal β-model fit by force

- Isothermal β-model fit to 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

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

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

Analytic modeling of H_0 measurement

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

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

inhomogeneity

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

non-isothermality

$$\chi_T(T_{ew}) = J(\beta, \gamma, r_c / r_{vir})^{1.5} \left[\frac{G(\beta(\gamma+3)/8)}{G(\beta\gamma/2)} \right]^2 \approx (0.8 - 1)$$

temperature bias

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

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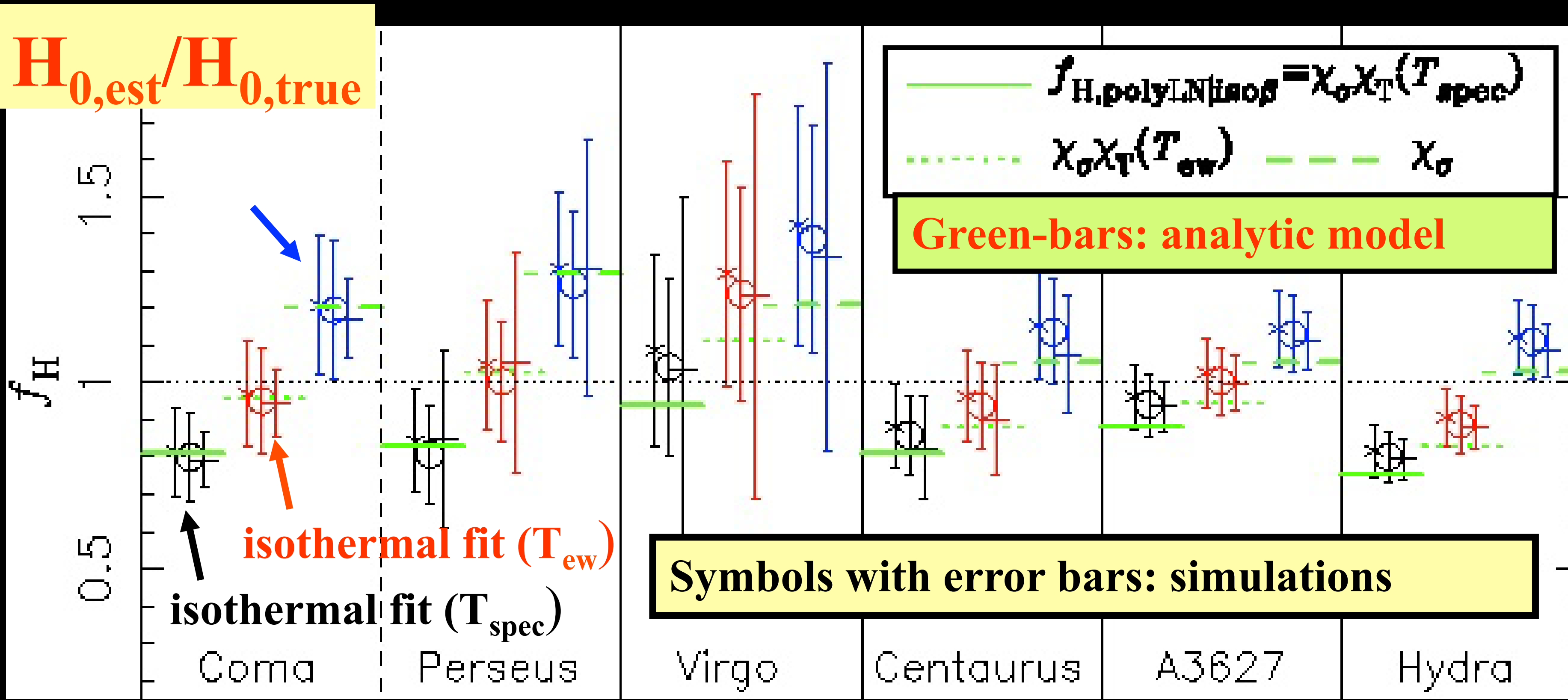
Analytic model vs simulated clusters



- **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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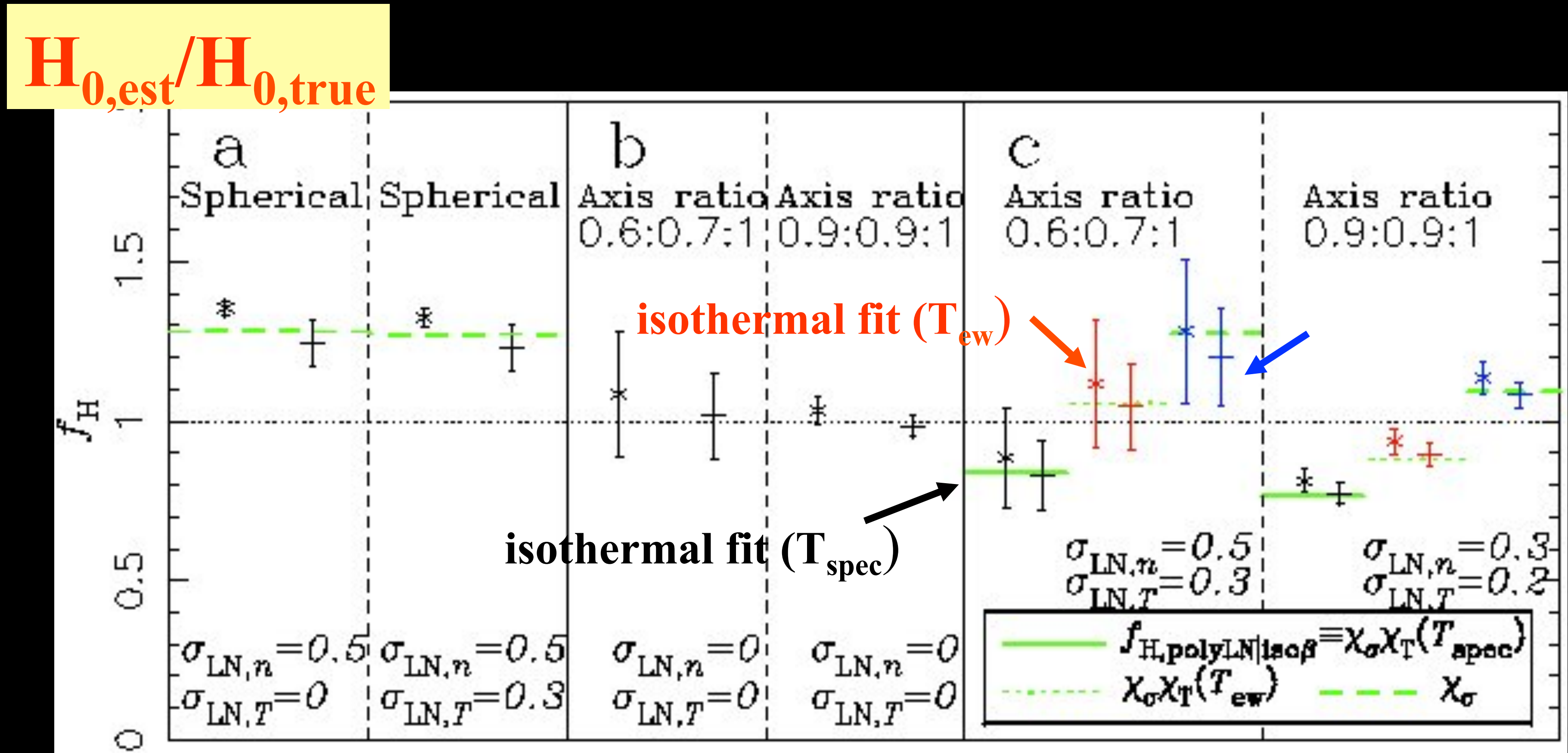
Non-spherical effect : triaxial clusters



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

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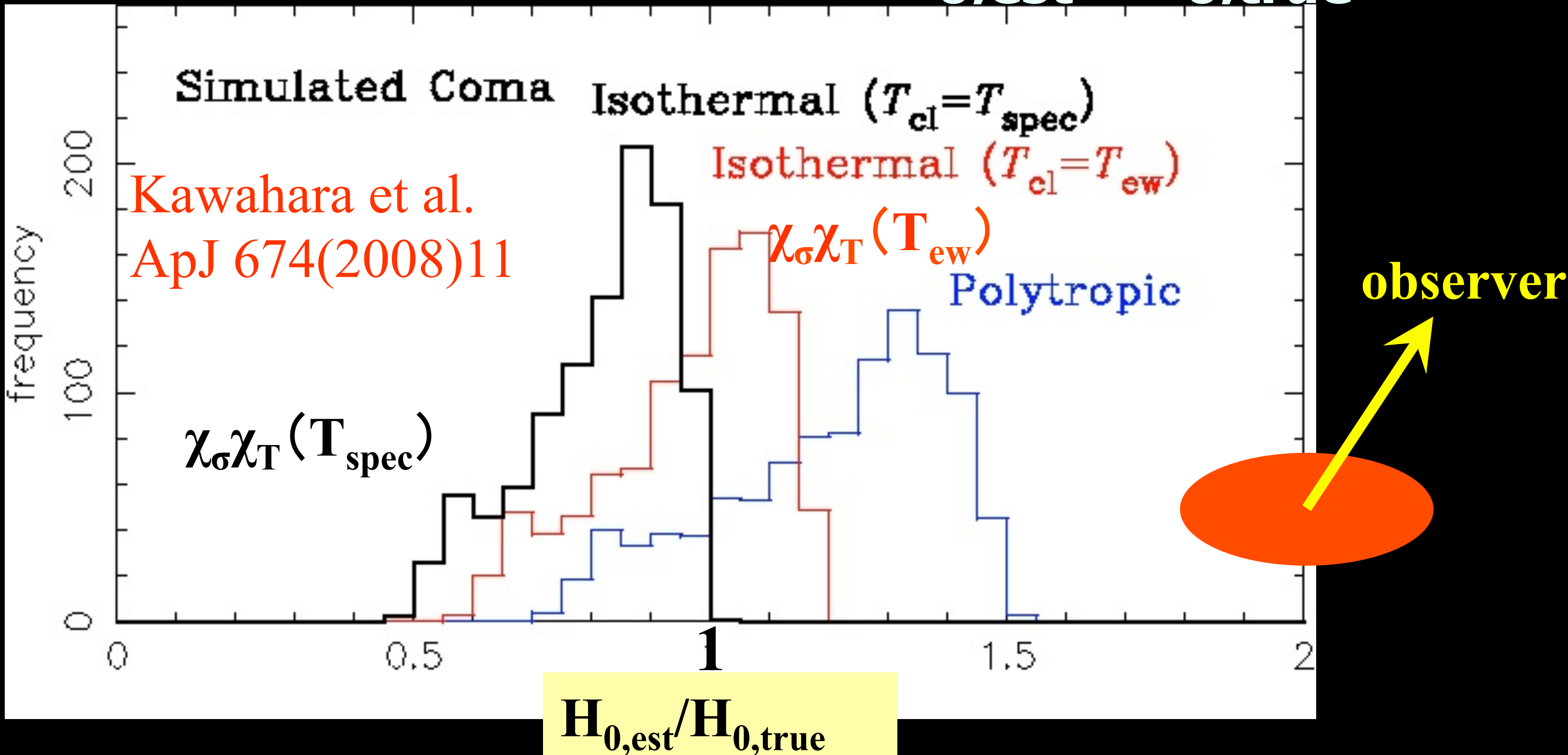
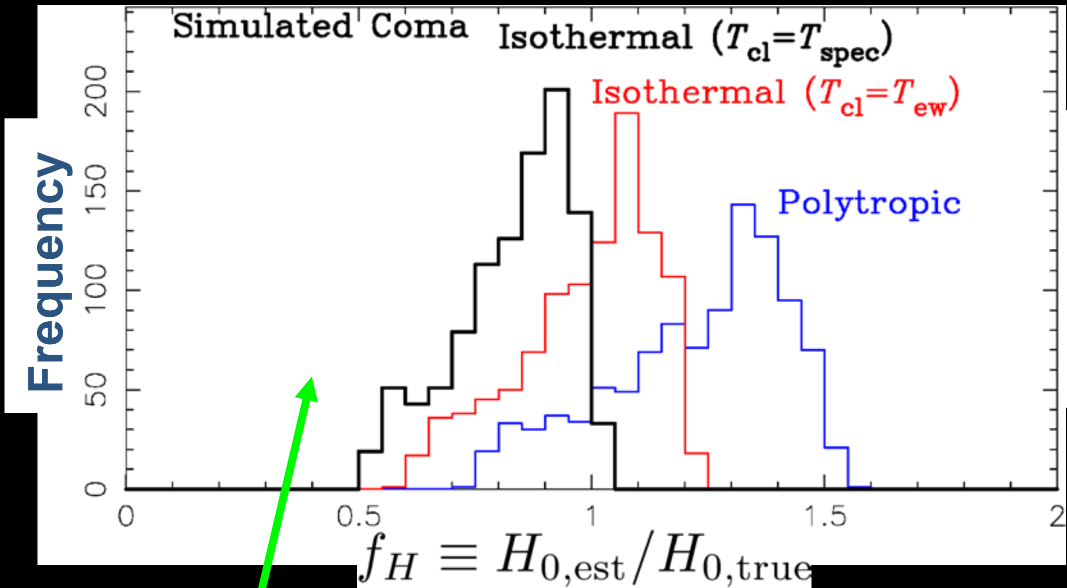
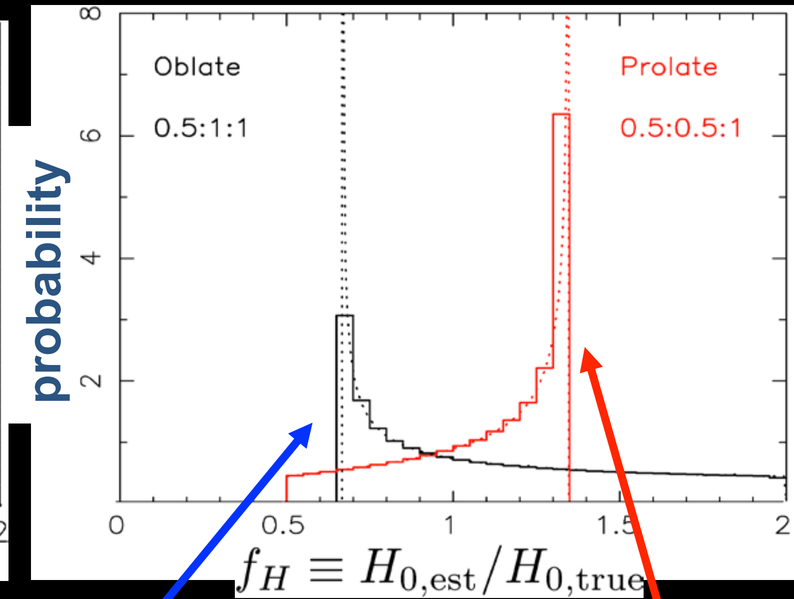
Distribution of $H_{0,est}/H_{0,true}$



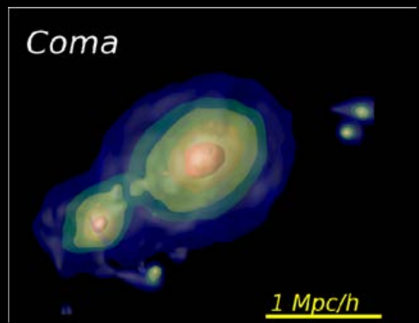
- Skewed distribution due to the prolateness
- Previous studies did not find the large bias because we set $T_{cl}=T_{ew}$ instead of T_{spec} (Inagaki, Suginohara & YS 1995, Yoshikawa, Itoh & YS 1998), consistent with our results of the isothermal fit with T_{ew}

Asymmetry in the estimated H_0

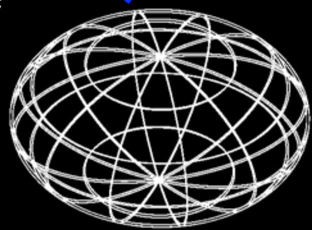




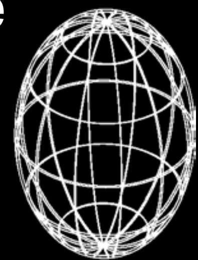
- simulation



- oblate



- prolate

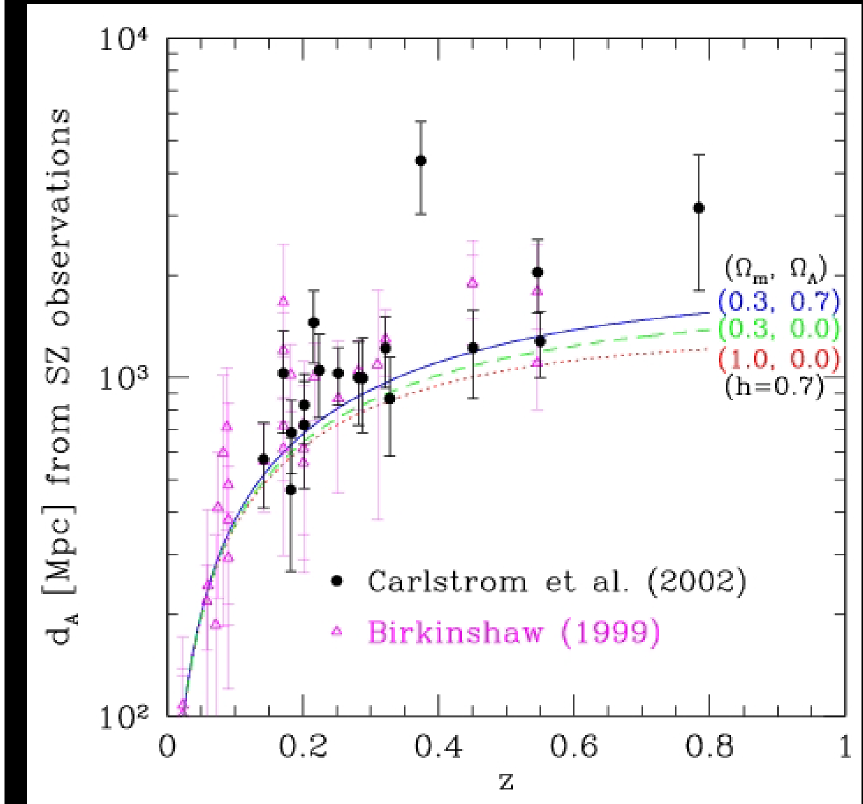


● distribution function of $H_{0,est}$ from many SZ clusters
⇔ overall average shape of clusters (oblate or prolate)

Summary of theoretical predictions

- $H_{0,est}/H_{0,true}$= 0.8-0.9 from simulated clusters
- Analytic modeling of H_0 from the SZ effect
- $H_{0,est}/H_{0,true}$= 0.8-0.9 from simulated clusters is well explained by the combination of inhomogeneity and non-isothermality of ICM
- Is this consistent with the existing SZ observations ?

H_0 estimated from the SZ effect



- ROSAT+SZ:
  - 60 ± 3 km/s/Mpc (Reese et al. 02)
- Chandra+SZ
  - $76.9^{+3.9}_{-3.4}{}^{+10.0}_{-8.0}$ km/s/Mpc (Bonamente et al. 06)
- WMAP:
  - 73 ± 3 km/s/Mpc (Spergel et al. 07)
- Which is believable (if any at all !) ?

Same SZ but different X-ray data

- Reese et al. (2002)
  - 60 km/s/Mpc with ROSAT
- Bonamente et al. (2006)
  - 77 km/s/Mpc with Chandra
  - calibration data ver.3.1
- Chandra calibration data revision (2009)
  - Jan. 2009 ver.4.1: effective area of mirror
  - Dec. 2009 ver.4.2: ACIS (AXAF CCD Imaging Spectrometer) contamination model

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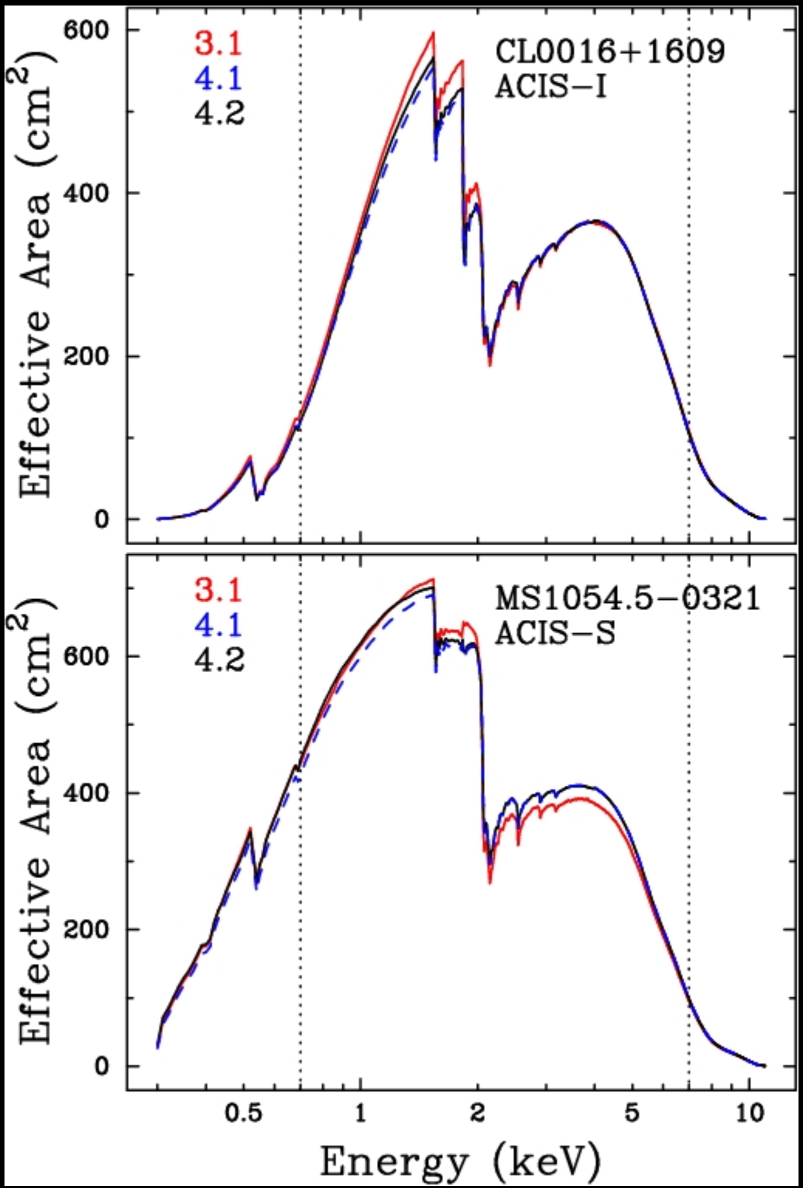
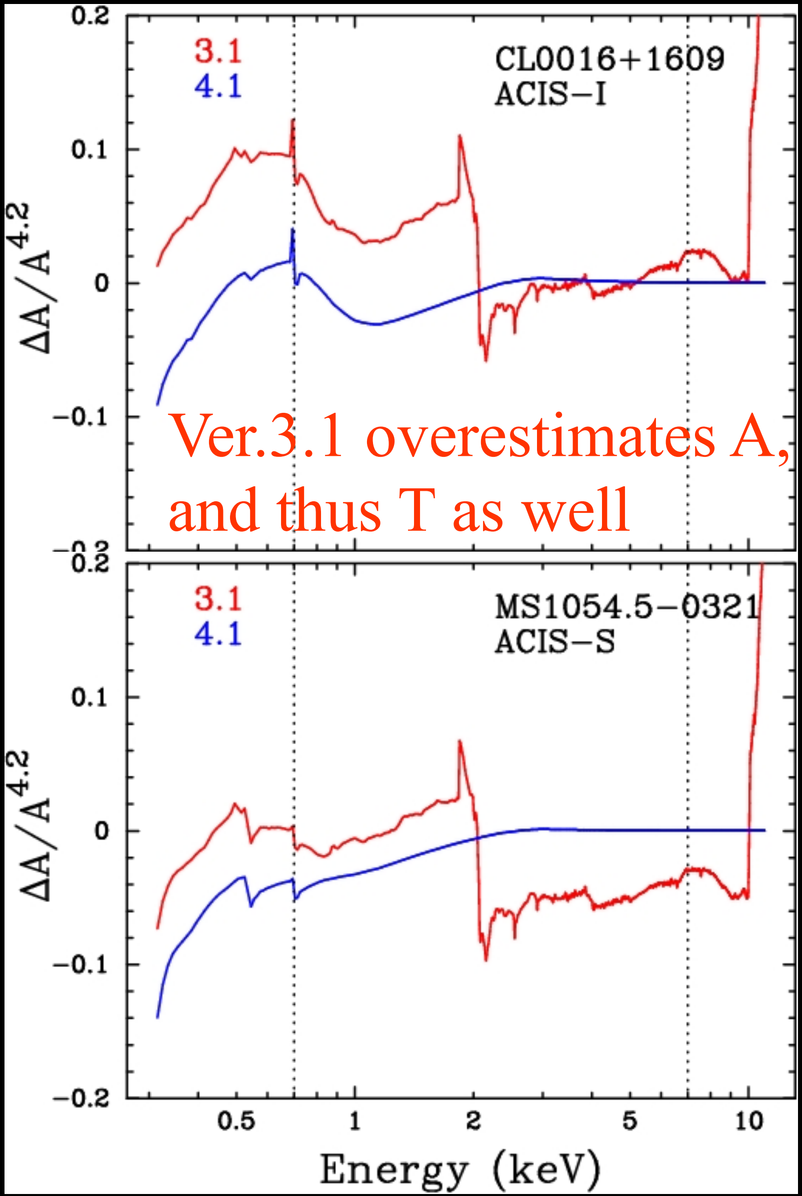
Effective areas for different calibrations

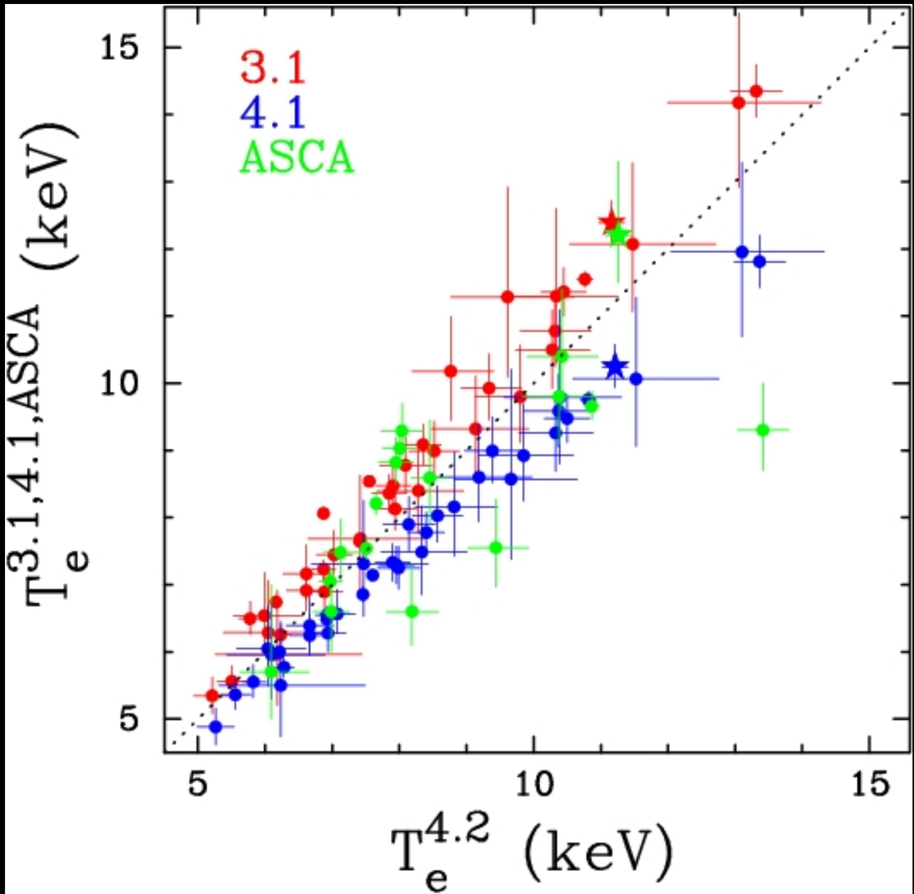
Majority of clusters are observed with ACIS-I (front illuminated chips)

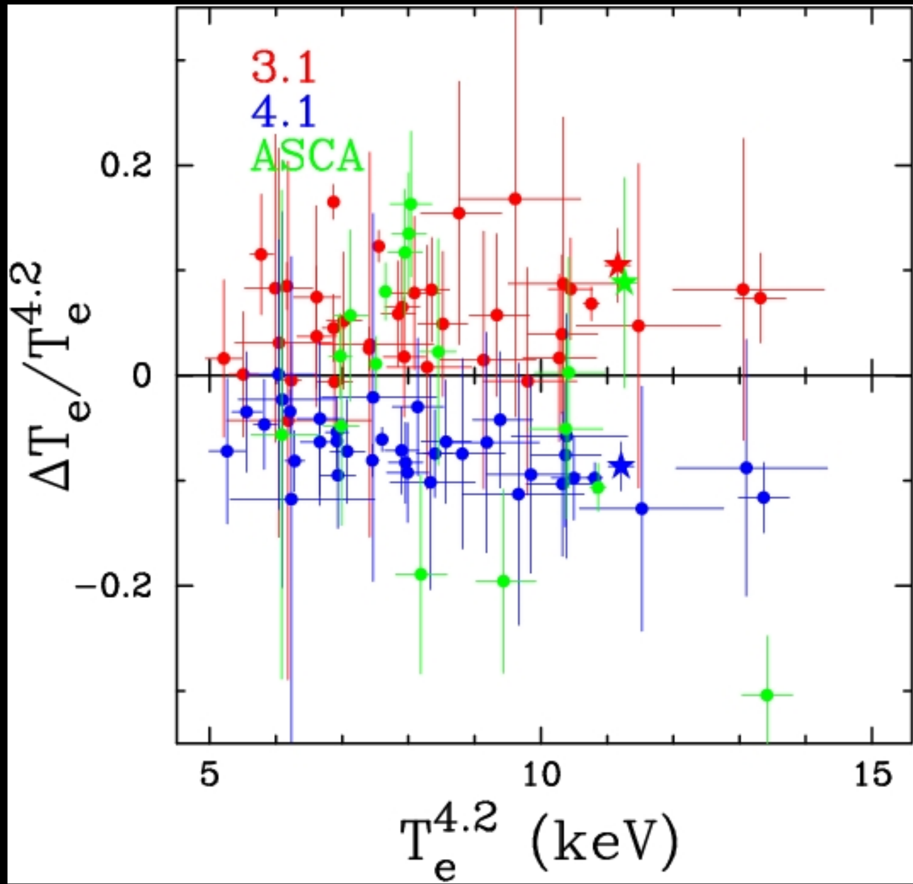




Ver.3.1 overestimates A, and thus T as well

Spectroscopic temperatures





- Relative to the latest calibration data (ver.4.2)
  - Ver. 3.1 overestimates T by 6%
  - Ver. 4.1 underestimates T by 7%

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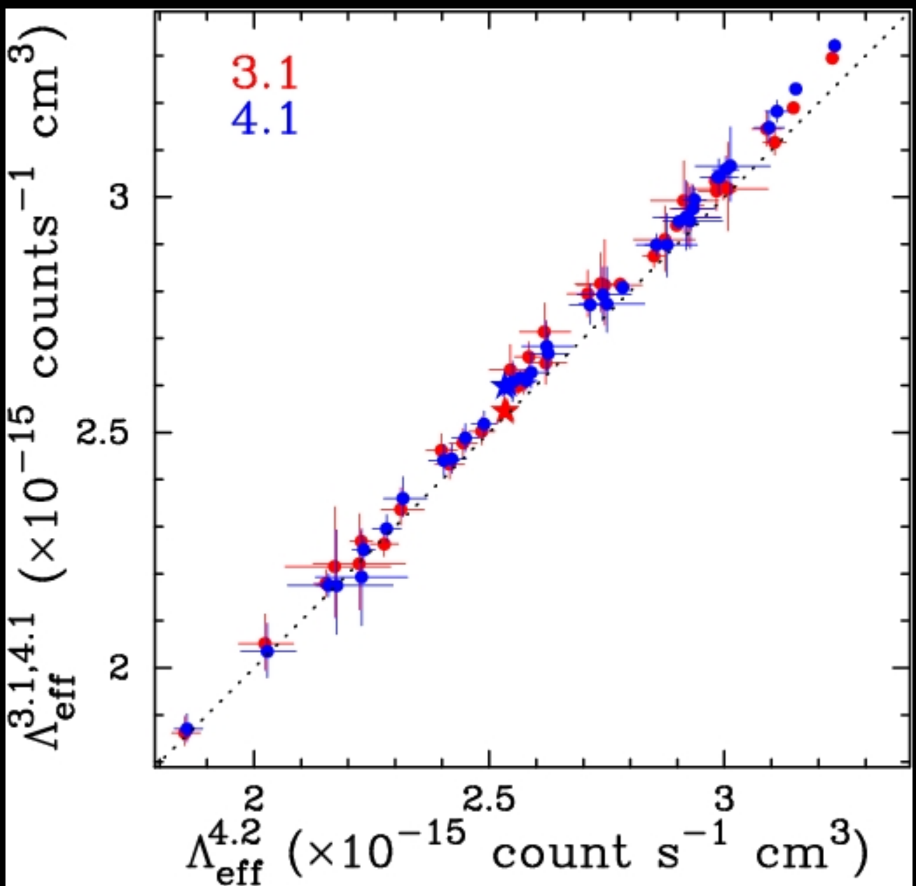
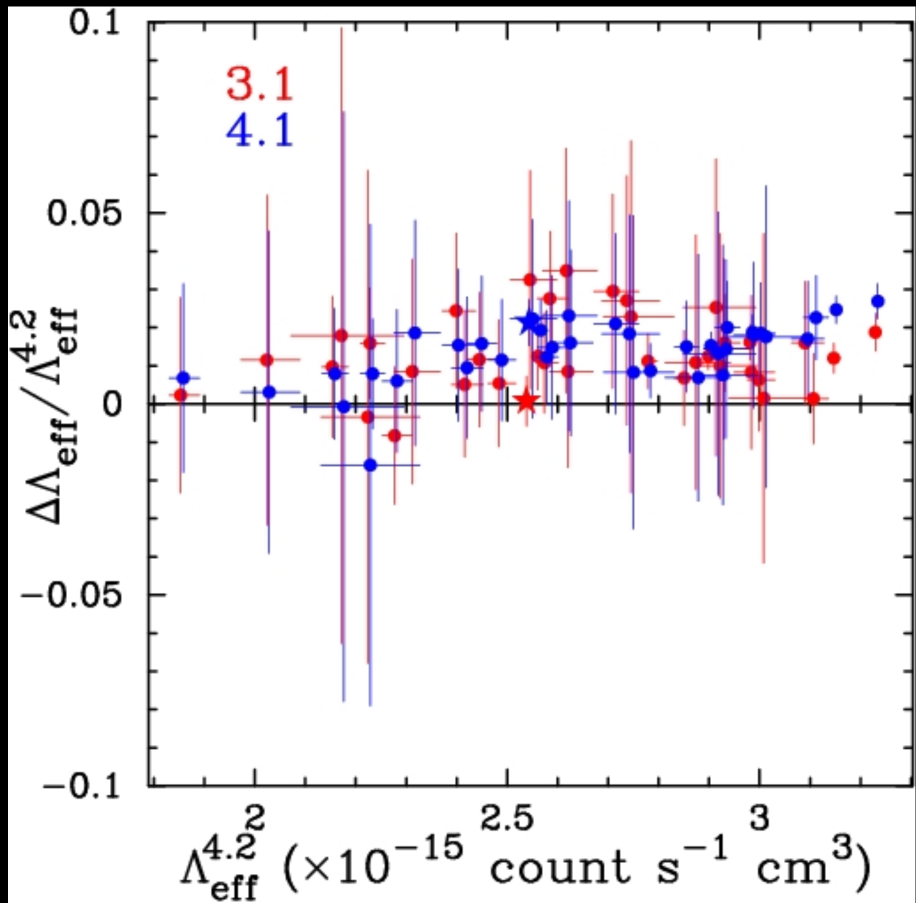
X-ray emissivitiy





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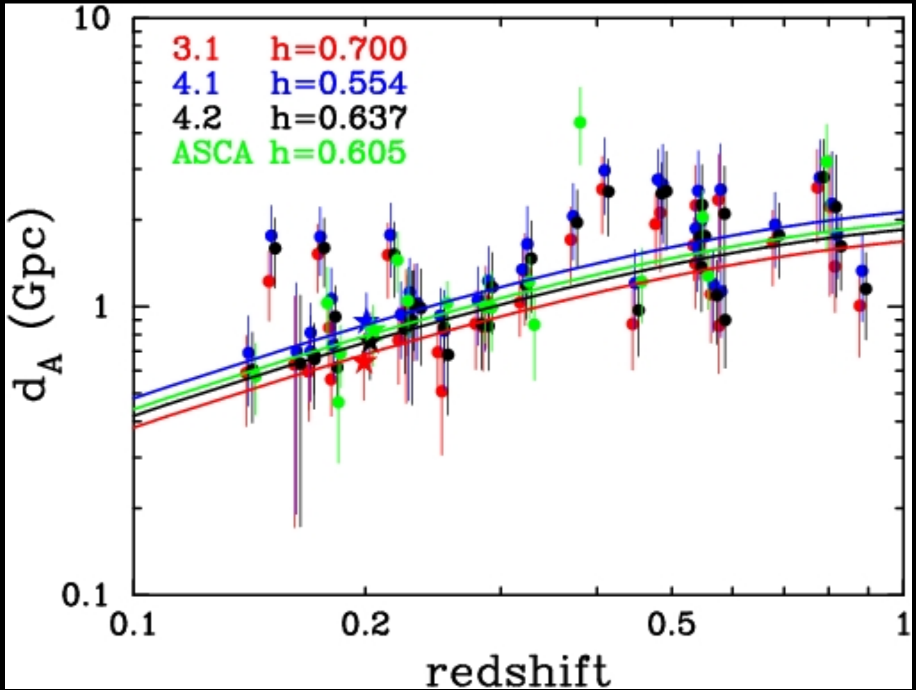
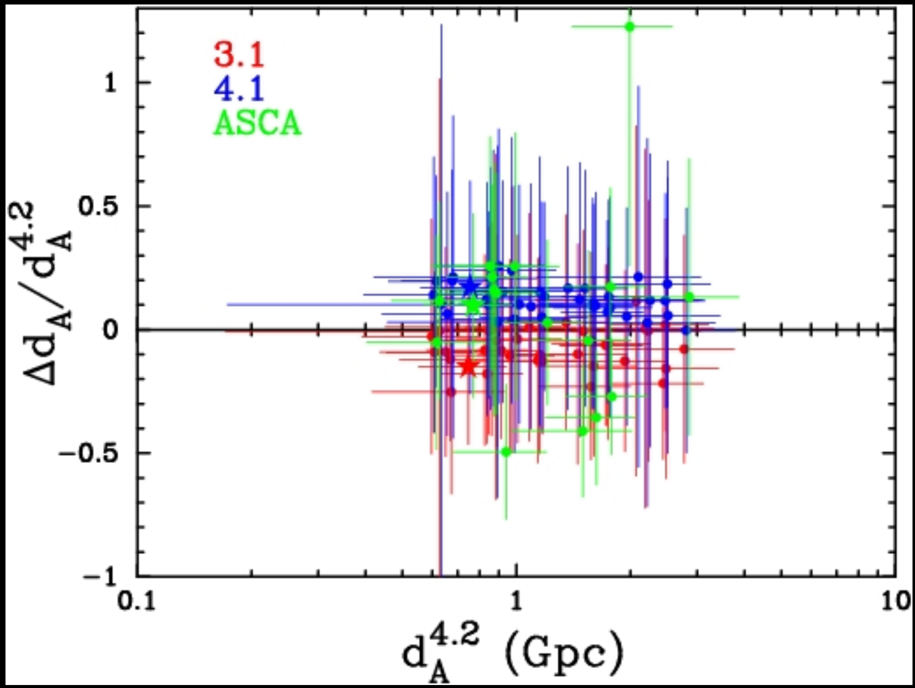
Angular diameter distances





Ω_Λ=0.73, Ω_m=0.27 assumed

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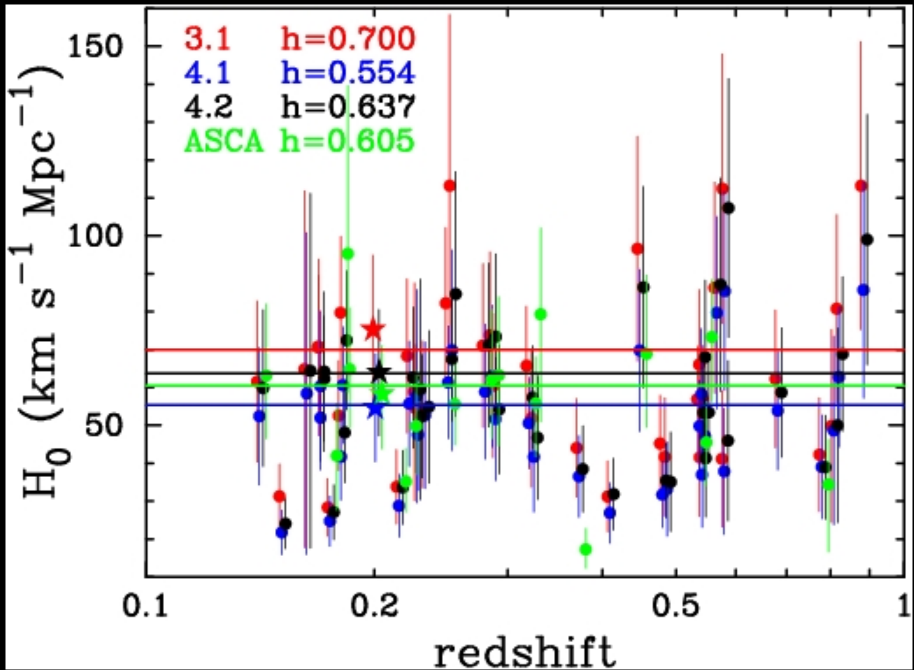
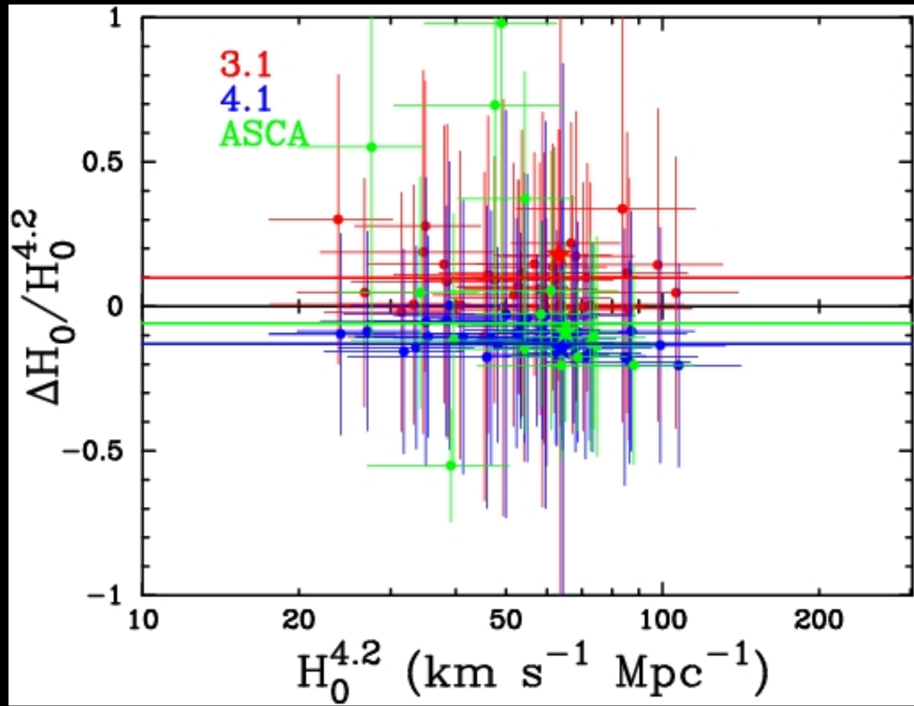
The Hubble constant of each SZ cluster

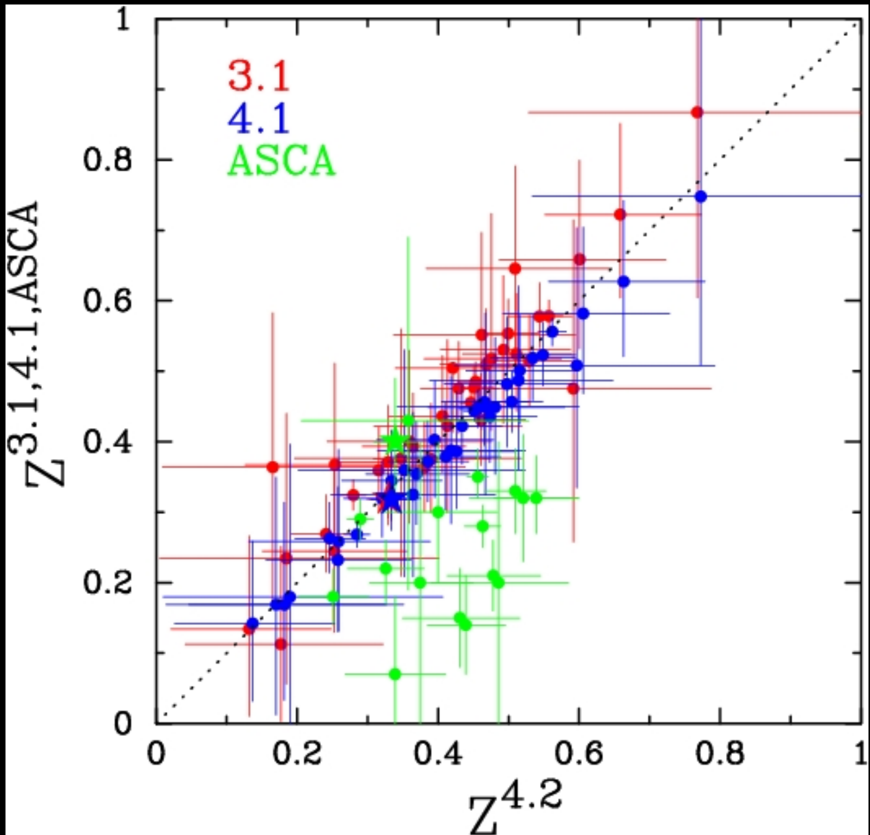


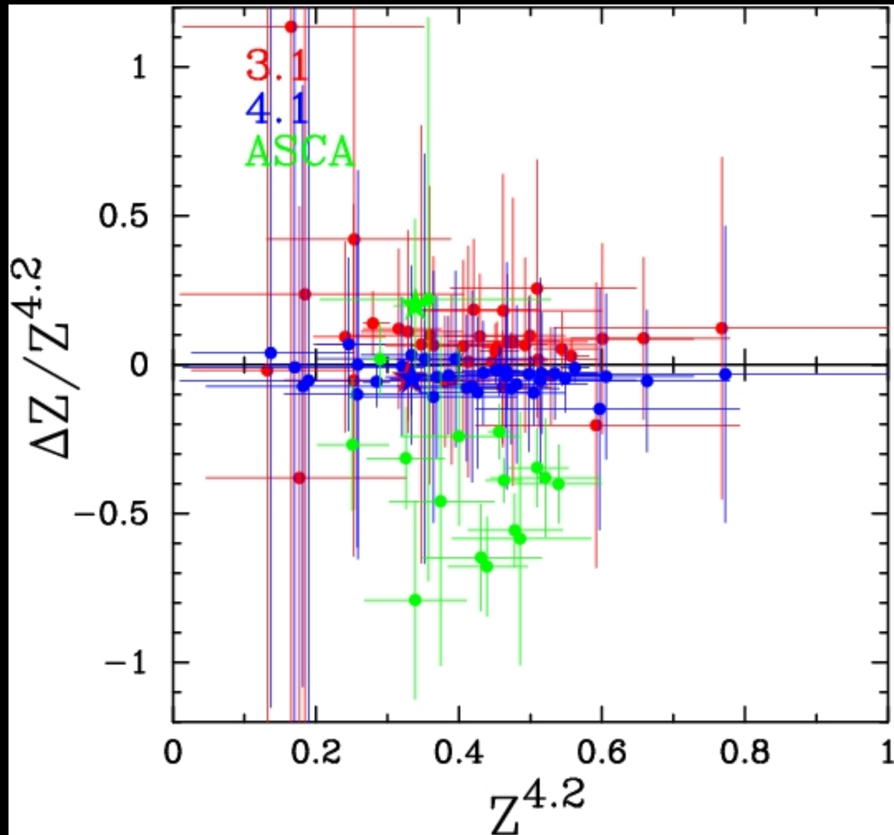


$$\frac{H_{0,2}}{H_{0,1}} = \left(\frac{T_2}{T_1}\right)^2 \frac{\Lambda_2^{\rm eff}(T_1)}{\Lambda_2^{\rm eff}(T_2)} \frac{\Lambda_1^{\rm eff}(T_1)}{\Lambda_2^{\rm eff}(T_1)} \frac{A_1(E_{\rm fid})}{A_2(E_{\rm fid})}$$

(Ω_Λ=0.73, Ω_m=0.27) Reese et al. ApJ 721(2010)653

Abundances





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Summary of comparison

Table 3. Compilation of Mean Ratios: Updated A2163 N_H

parameter	3.1/4.2	4.1/4.2	3.1/B06	4.1/B06	4.2/B06	*ASCA*/4.2
T_e	1.06 ± 0.05	0.93 ± 0.03	1.05 ± 0.11	0.92 ± 0.10	0.99 ± 0.11	0.98 ± 0.12
Z	1.08 ± 0.21	0.96 ± 0.04	1.16 ± 0.43	1.03 ± 0.31	1.08 ± 0.34	0.66 ± 0.28
$\Lambda_{\rm eff}$	1.01 ± 0.01	1.01 ± 0.01	1.03 ± 0.07	1.03 ± 0.07	1.02 ± 0.07	...
$f_{(\nu,T_e)}$	0.998 ± 0.002	1.002 ± 0.001	0.999 ± 0.003	1.003 ± 0.004	1.001 ± 0.003	...
$A(1\mathrm{kev})$[a]	1.01 ± 0.02	0.95 ± 0.01	0.96 ± 0.10	0.91 ± 0.10	0.95 ± 0.10	...
d_A[b]	0.93 ± 0.08	1.13 ± 0.06	1.06 ± 0.24	1.29 ± 0.29	1.15 ± 0.25	1.07 ± 0.37

[a]B06 are the effective areas from the 3.1 calibration using only those data sets that appear in Bonamente et al. 2006.

[b]B06 are the published distances from Bonamente et al. 2006.

- Systematic difference between different calibration data of Chandra

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Compilation of H_0 results

H_0	DL A2163 N_H	Updated A2163 N_H	No A2163
χ^2 Full sample	38	38	37
$H_0^{3.1}$	$82.8 \pm 4.6(75.9)$	$70.0 \pm 3.7(40.6)$	$69.7 \pm 3.7(40.5)$
$H_0^{4.1}$	$58.4 \pm 3.1(42.4)$	$55.4 \pm 2.9(34.3)$	$55.5 \pm 2.9(34.3)$
$H_0^{4.2}$	$68.8 \pm 3.7(52.2)$	$63.7 \pm 3.3(38.8)$	$63.7 \pm 3.4(38.8)$
χ^2 R02 overlap	17	17	16
$H_0^{3.1}$	$90.1 \pm 7.0(48.5)$	$66.9 \pm 4.7(15.8)$	$66.1 \pm 4.8(15.5)$
$H_0^{4.1}$	$58.2 \pm 4.1(21.2)$	$52.3 \pm 3.6(11.8)$	$52.2 \pm 3.8(11.8)$
$H_0^{4.2}$	$70.1 \pm 5.1(28.7)$	$60.5 \pm 4.3(14.4)$	$60.2 \pm 4.4(14.3)$
Avg Full sample	38	38	37
$H_0^{3.1}$	66.1 ± 30.3	62.9 ± 21.7	62.6 ± 21.9
$H_0^{4.1}$	52.5 ± 17.2	51.3 ± 15.4	51.2 ± 15.6
$H_0^{4.2}$	59.7 ± 22.1	58.0 ± 18.9	57.8 ± 19.1
Avg R02 overlap	17	17	16
$H_0^{3.1}$	68.3 ± 36.1	61.2 ± 17.6	60.4 ± 17.7
$H_0^{4.1}$	51.8 ± 16.9	49.2 ± 12.0	48.9 ± 12.3
$H_0^{4.2}$	60.0 ± 23.3	56.1 ± 15.5	55.6 ± 15.9
χ^2 B06 refit	38		37
H_0^{B06}	$76.2 \pm 4.1(55.9)$	$\cdots$	$73.5 \pm 4.1(51.7)$
χ^2 R02 refit	18	17	16
H_0^{R02}	$60.8 \pm 4.0(16.5)$	$60.5 \pm 4.1(16.4)$	$60.7 \pm 4.3(16.4)$

DL:
Dickey & Lockman (1990)

R02:
Reese et al. (2002)

B06:
Bonamente et al. (2006)

$\Omega_\Lambda=0.73$
$\Omega_m=0.27$
assumed

Ups and downs of H_0 from SZ+Xray

X-ray data	H_0 [km/s/Mpc]	reference
ROSAT+ASCA	60 ± 3	Reese et al. (2002)
Chandra: ver.3.1	$77^{+3.9}_{-3.4}$	Bonamente et al. (2006)
WMAP	73 ± 3	Spergel et al. (2007)
Chandra: ver. 3.1	70.0 ± 3.7	this work
Chandra: ver. 4.1	55.4 ± 2.9	this work
Chandra: ver. 4.2	63.7 ± 3.3	this work

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Conclusions

- X-ray calibration is not robust as believed before
  - Cluster temperature may vary ±7%
  - H_0 combined with SZ may vary ±12%
- If the latest Chandra calibration data (ver.4.2) is the most reliable, $H_0(SZ) \sim 0.9 H_0(WMAP)$
  - This might indicate the presence of the inhomogeneities in intra-cluster medium (Kawahara et al. 2008a)
- Possible systematics for cluster cosmology in general
  - Mass-temperature relation of clusters
  - Cluster abundances and σ_8
- ***The goal of cluster cosmology is not to find a good (but boring) agreement with WMAP+others. Look for inconsistency !***