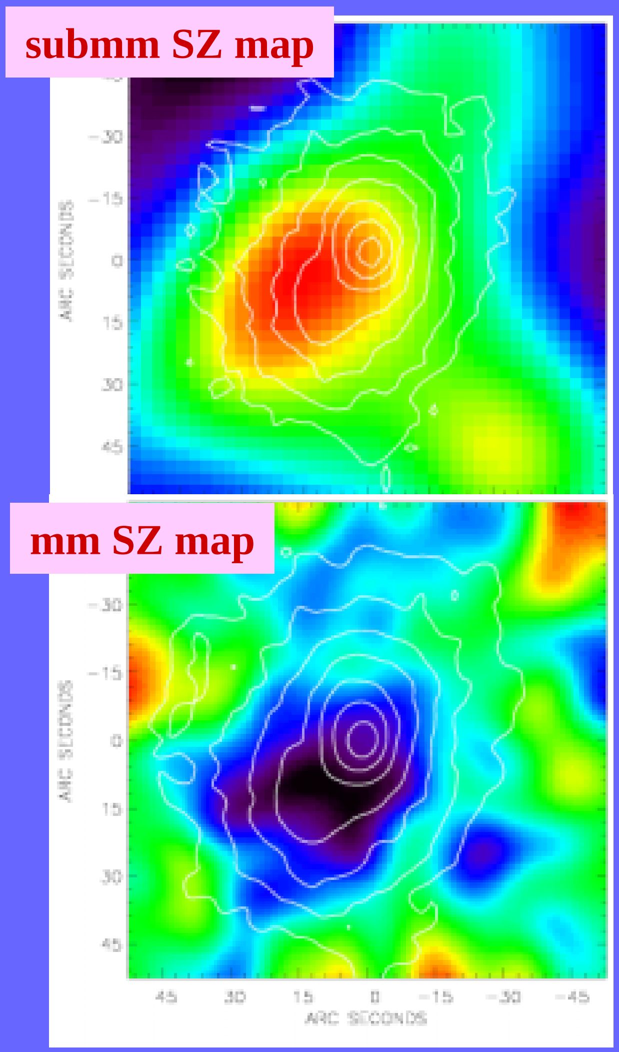
Reliability of galaxy clusters as cosmological probes



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Testing Cosmological Models with Galaxy Clusters

January 14, 2003

@ Ringberg Castle, Germany

submm/mm SZ maps of RX J1347-1145

Upper: submm (350GHz) with SCUBA at JCMT
Lower: mm (150GHz) with NOBA at Nobeyama
(Komatsu et al. 1999, 2001)

Precision cosmology with clusters

- $\sigma_8 - \Omega_0$ relation from cluster abundance
- Power spectrum from cluster distribution ($\mathbf{\Gamma}$, $\boldsymbol{\sigma}_8$, $\mathbf{\Omega}_0$, bias)
- ***consistent*** with CMB, SN and galaxy surveys

- Certainly useful and complementary, but can it be precise enough to be competitive with other probes (CMB and SN among others) ?
- Have we understood what the clusters are ?

What is ***the*** definition of 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

$\Delta I_{SZ} \propto n_e T_e$

Halos in N-body simulations

friend-of-friend

linking length = 0.2

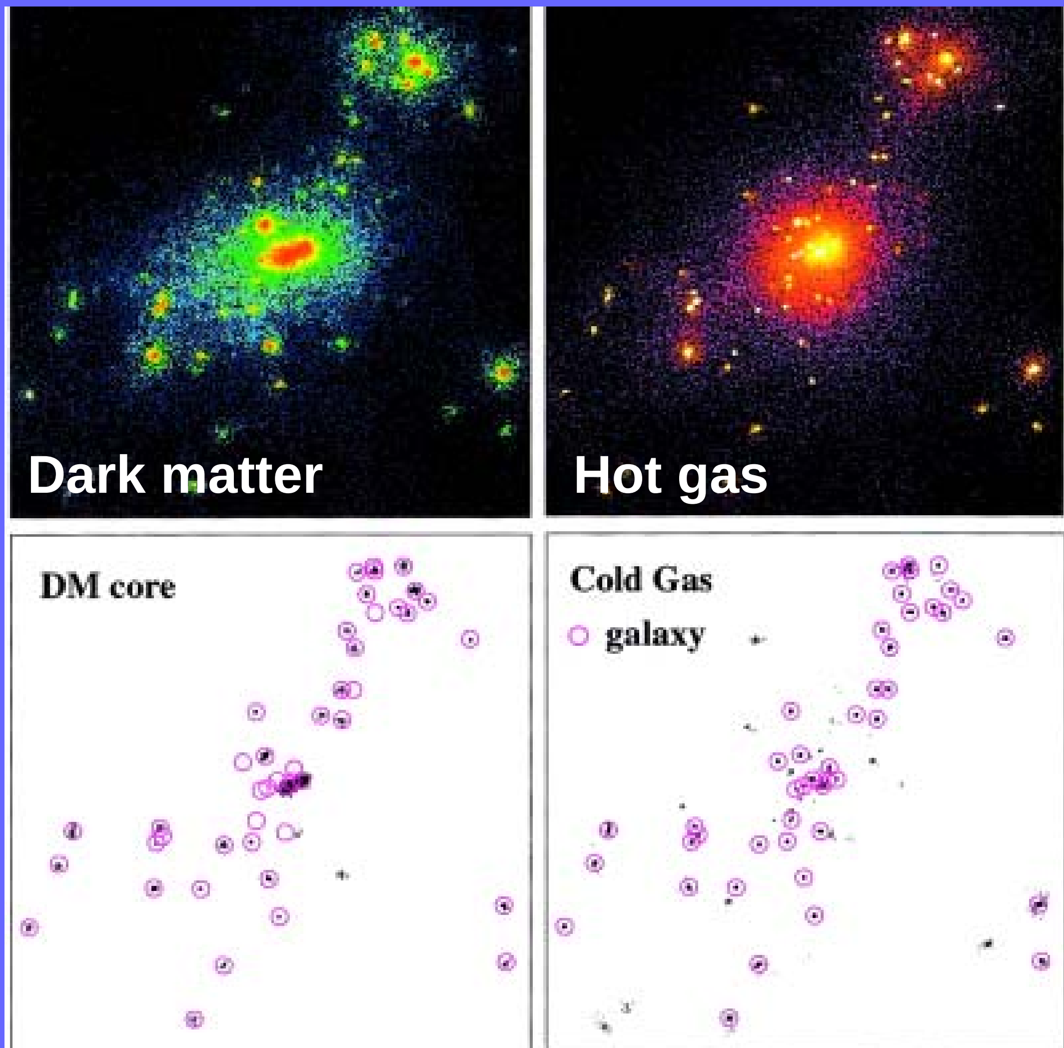
X-ray clusters

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

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

Relation between dark halos and clusters

A cluster-size halo ($8 \times 10^{14} M_{sun}$ at $z=0$)



- Globally similar distribution, but the precise relation is unclear because the definitions of clusters (especially at high z) are very ambiguous.

SPH simulations in LCDM:
$N=128^3$ boxsize: 75 h^{-1}Mpc
Yoshikawa, Taruya, Jing & Suto
ApJ 558 (2001) 520

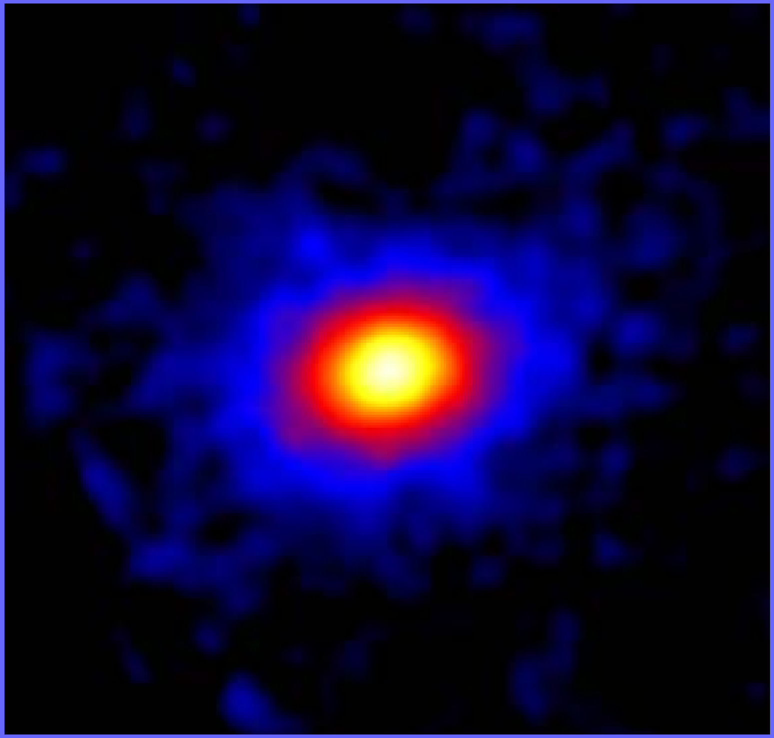
<u>Noises</u> for precision cosmology = <u>Signals</u> for cluster astrophysics

- Non-sphericity
- Substructure
- Gas mass fraction
- Gas density profile
- Gas temperature profile
- Mass-temperature relation
- Luminosity-temperature relation
- Non-gravitational heating

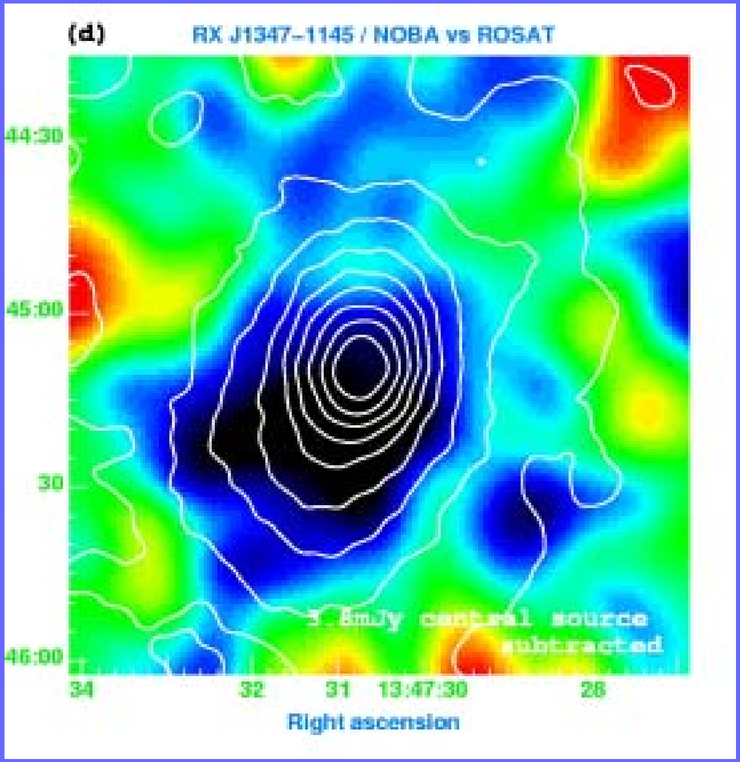
Will you be still more interested in continuing the discussion like whether Ω_0=0.3152 or Ω_0=0.3476, than exploring those non-trivial cluster properties ?

Many interesting/important astrophysical processes are involved. Values of cosmological parameters are not the end of the story !

Observed clusters are not spherical



Chandra X-ray Image of Cluster RBS797
(Jetzer et al. astro-ph/0201421)

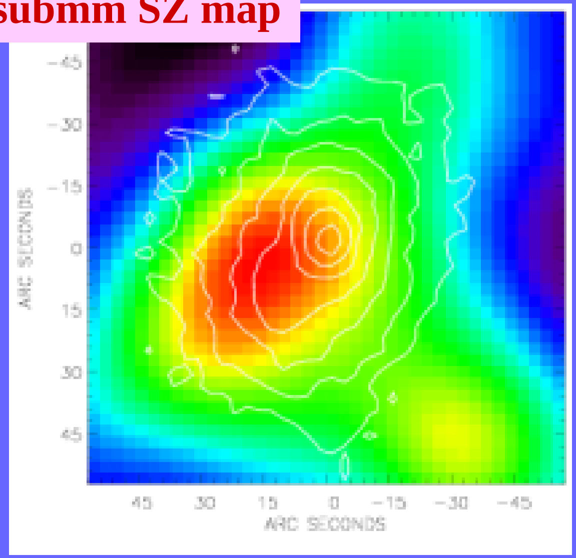


mm SZ(150GHz) map of RXJ1347-1145
(Komatsu et al. 2001, PASJ, 53, 57)

Submm SZ map (350GHz) of RX J1347-1145

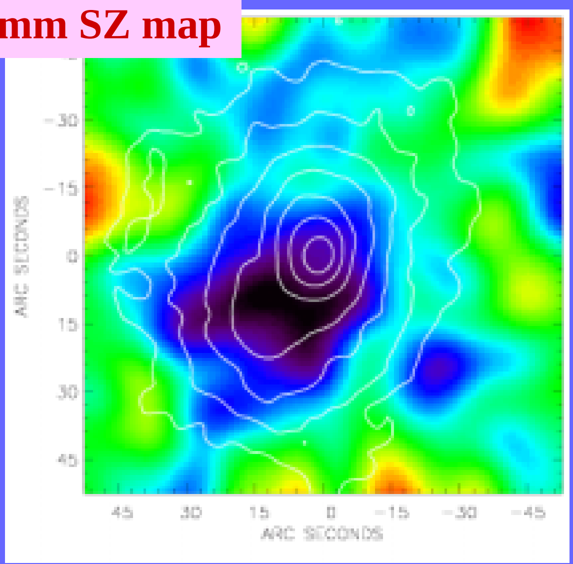
The first SZ map of a cluster in the submm band with SCUBA, JCMT. (contours: Chandra X-ray map)

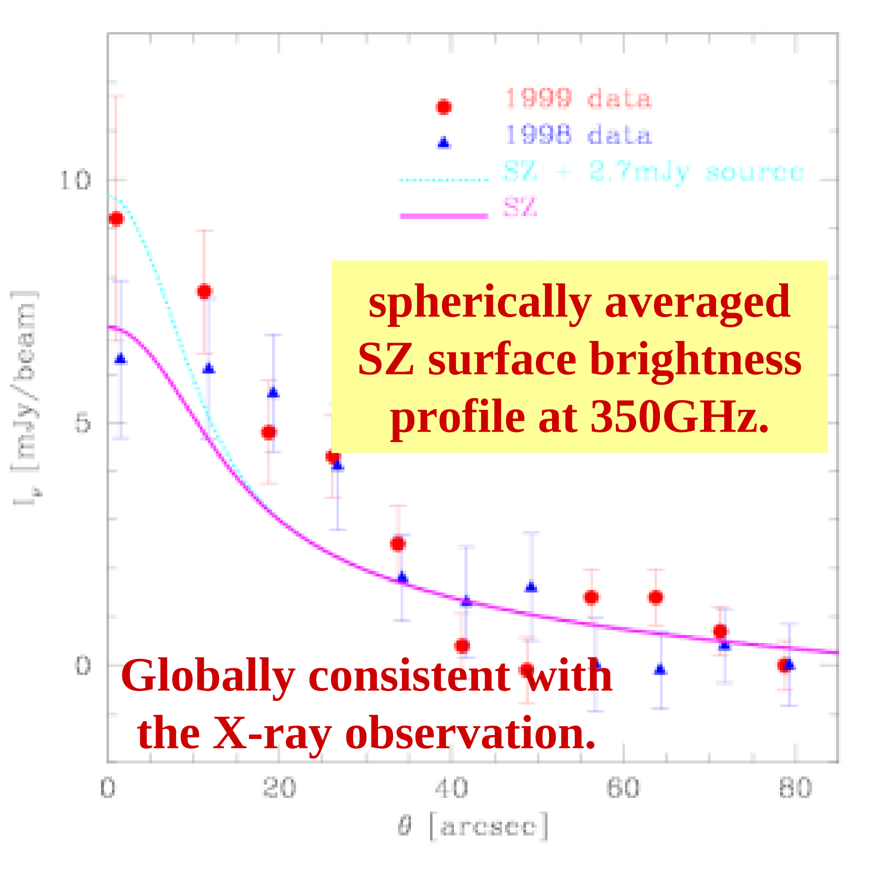
submm SZ map



The highest resolution (σ_{FWHM}=13'') SZ map of a cluster in the mm band with NOBA, Nobeyama

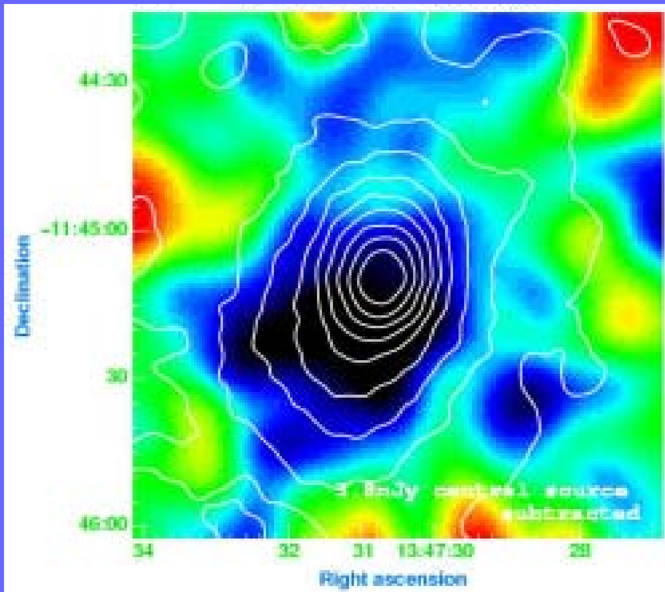
mm SZ map

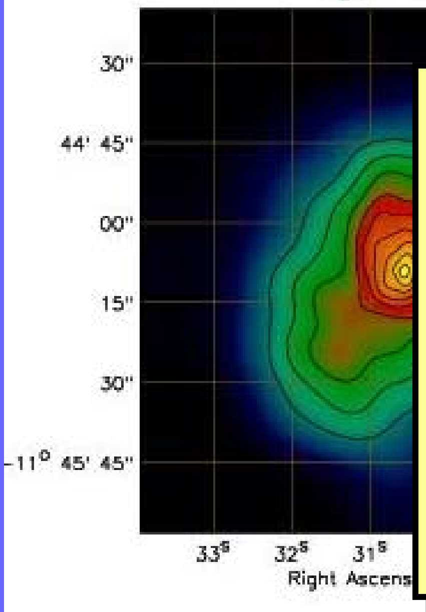


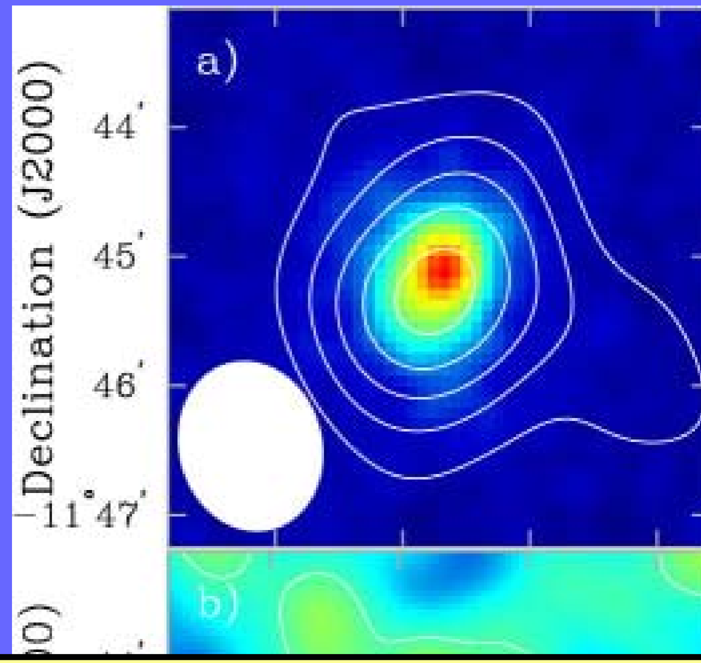


Komatsu et al.
ApJ 516 (1998) L1 : submm SZ
PASJ 53 (2001) 57 : mm SZ

Comparison with Chandra and BIMA observations







RXJ1347-1145

BIMA@30GHz
63”x80” beam
(10.3mJy point
source removed)

Carlstrom et al.
(2001)

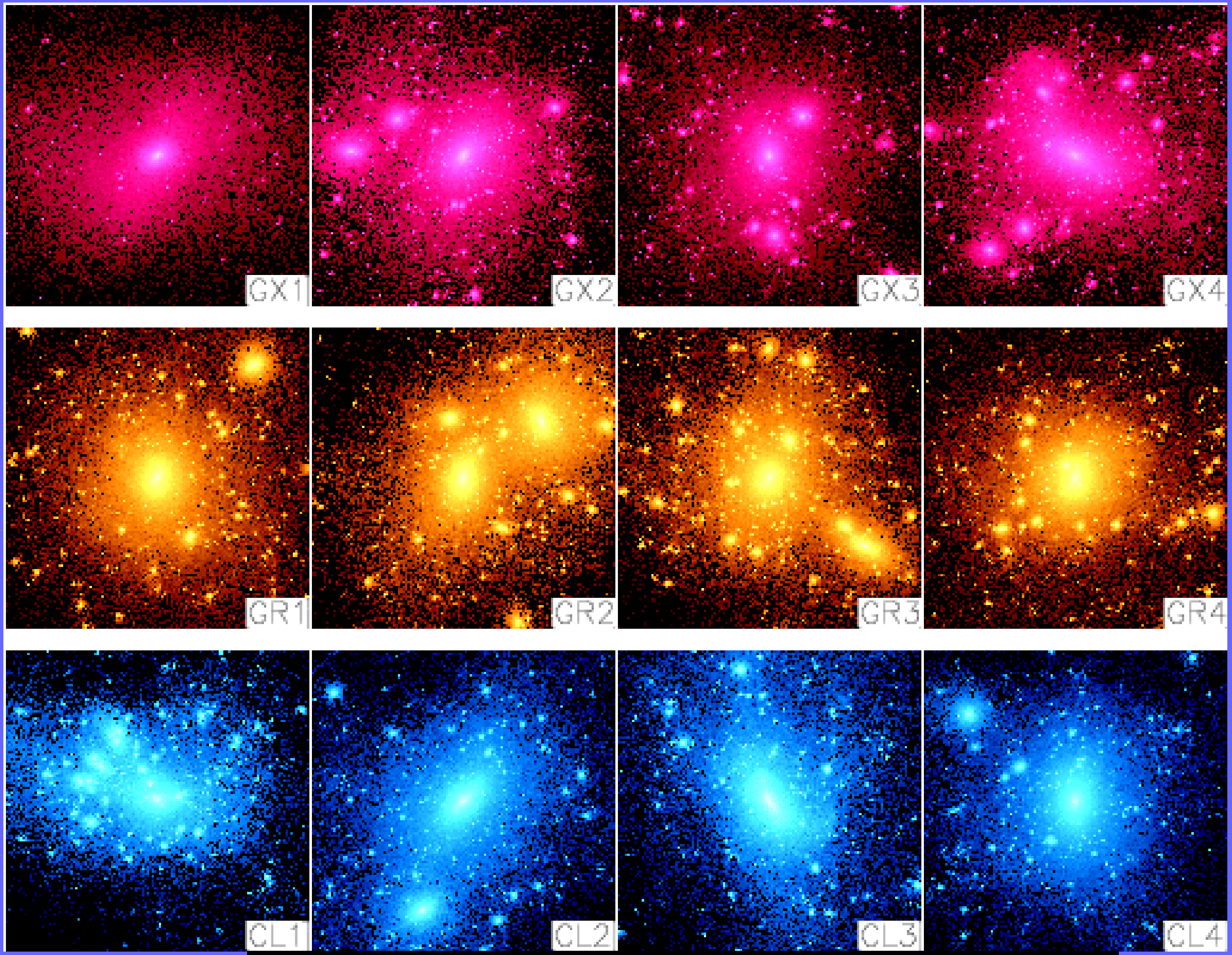
- Keck spectroscopy: Cohen & Kneib (2002)
- Chandra: Allen, Schmidt & Fabian (2002)
- non-spherical modeling is crucial, perhaps at high z in particular.
- Clusters are not so simple as we have pretended (?) to believe.

Simulated ***halos*** are not spherical

galaxies
~ $5\times10^{12}M_{sun}$

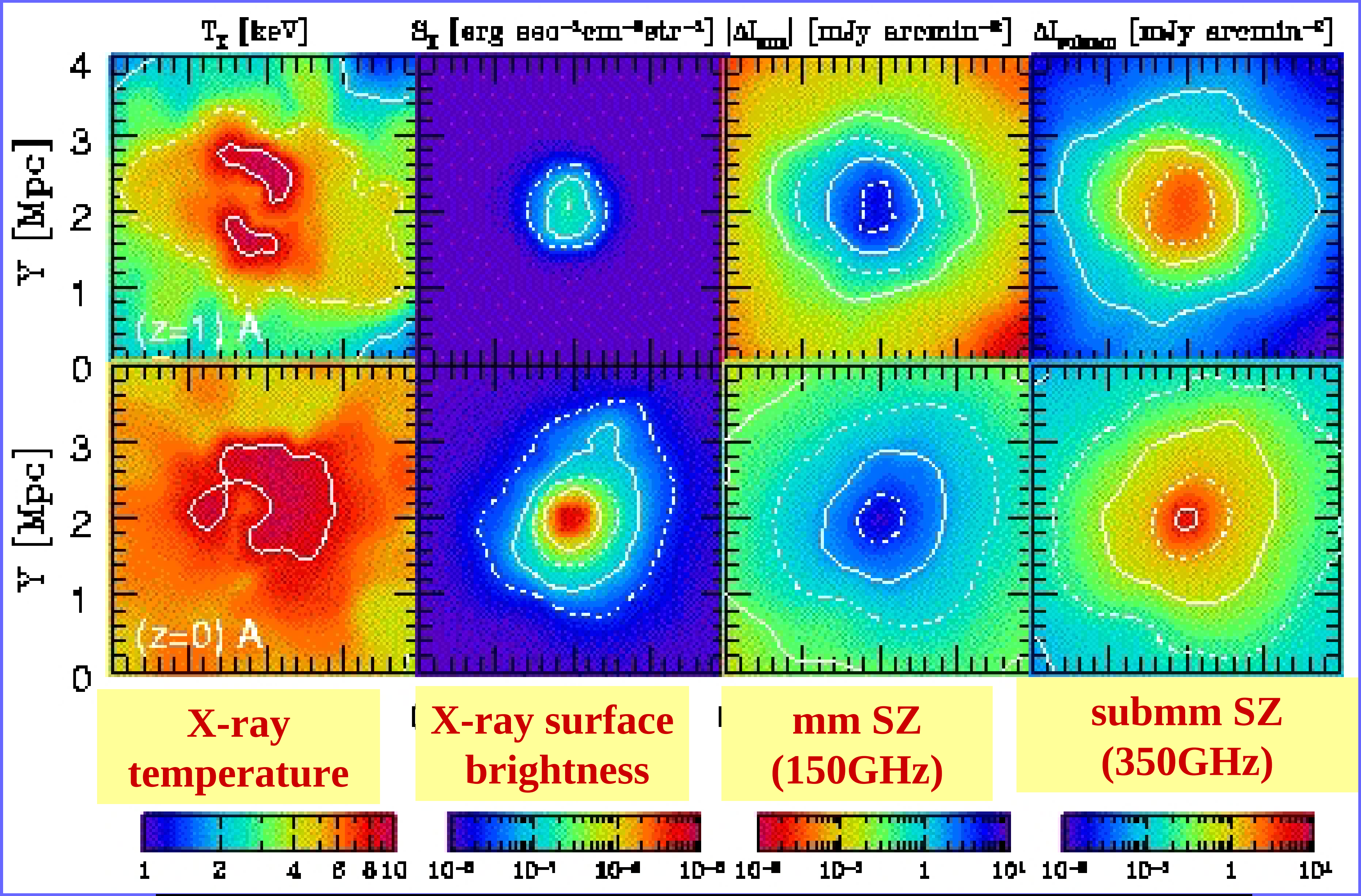
groups
~ $5\times10^{13}M_{sun}$

clusters
~ $3\times10^{14}M_{sun}$



Jing & Suto ApJ 529 (2000) L69

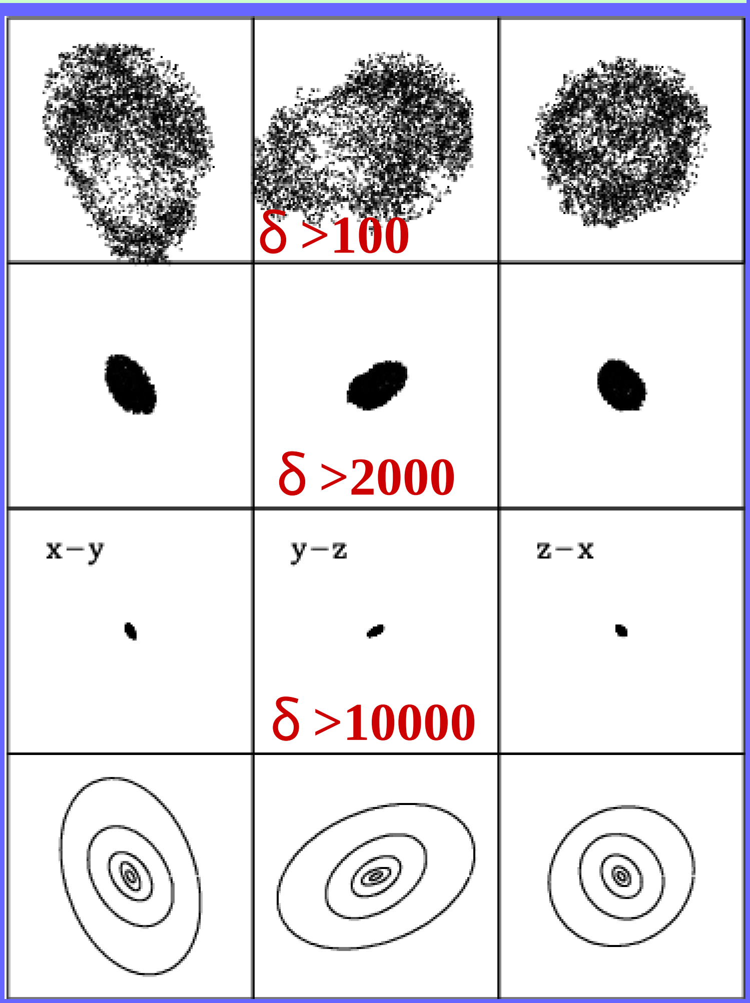
Simulated ***clusters*** are not spherical, either



Yoshikawa, Itoh & Suto, PASJ 50 (1998) 203

An improved model for dark matter halo: ***triaxial*** universal density profile

Isodensity of a cluster-scale halo



$$\rho(R) = \frac{\delta_c \rho_{crit}}{(R/R_s)^{\alpha}(1+R/R_s)^{3-\alpha}}$$

$$R^2(\rho) \equiv \frac{X^2}{a^2(\rho)} + \frac{Y^2}{b^2(\rho)} + \frac{Z^2}{c^2(\rho)}$$

Jing & Suto, ApJ, 574 (2002) 538

- The triaxial description for the dark halo density profiles improves in principle the reliability of interpretation of (future) X-ray, SZ, and lensing observations.

Gas and temperature profiles in triaxial dark halos

- **density profile of triaxial dark matter halo:**

$$\rho(R) = \frac{\delta_c \rho_{crit}}{(R/R_0)\ (1+R/R_0)^2}; \quad R^2 = x^2 + \frac{y^2}{1-e_b^2} + \frac{z^2}{1-e_c^2}$$

- **hydrostatic equilibrium gas profiles:**

isothermal $: \rho_g = \rho_{g0} \exp[-K^{-1}(\Phi - \Phi_0)], \quad K = \frac{kT_g}{\mu m_p}$

polytropic $: \rho_g = \rho_{g0} \left(\frac{T_g}{T_{g0}} \right)^{1/(\gamma-1)}, \quad T_g = T_{g0} \frac{1-\gamma}{K_0 \gamma} (\Phi - \Phi_0)$

$$\Phi(\vec{r}) = -\pi G \left(\frac{bc}{a} \right) \int_0^\infty \frac{[\psi(\infty) - \psi(m)]}{\sqrt{(\tau + a^2)(\tau + b^2)(\tau + c^2)}} d\tau ,$$

$$\psi(m) = 2 \int_0^m \rho(R) R dR .$$

Gravitational potential

Lee & Suto ApJ 585 (2003) March 1st issue, in press.

Empirical fits to the profile of triaxial halo potential

- **ratio of halo and gas eccentricities:**

gas eccentricities

spherical radius

$$\frac{\varepsilon_{b(c)}^{2}}{e_{b(c)}^{2}} = \frac{6(1+u)\ln(1+u) + u^{3} - 3u^{2} - 6u}{2u^{2}[(1+u)\ln(1+u) - u]}, \quad u = \frac{r}{R_0}$$

halo eccentricities

scale radius

- **triaxial modeling of the halo potential:**

$$\exp[-(\Phi - \Phi_0)] = \left[\frac{1 + (\xi/\xi_B)^p}{1 + (\xi/\xi_A)^p}\right]^q, \qquad \xi^2 = \frac{1}{R_0^2}\left(x^2 + \frac{y^2}{1-\varepsilon_b^{\ 2}} + \frac{z^2}{1-\varepsilon_c^{\ 2}}\right)$$

- **empirical fitting formula for the free parameters:**

$$\xi_A = (1.33 + 0.11\mu)^{-1}, \qquad \xi_B = (0.14 + 0.05\mu)^{-1}$$

$$p = 1, \quad \mathrm{q} = 0.42 - 0.19\mu, \qquad \mu \equiv \mathrm{e_b}^3 + \mathrm{e_c}^3$$

Lee & Suto (2003), in preparation.

Projection along the line of sight

(x, y, z): halo principal axis frame, (x', y', z'): observer's frame

(θ, ϕ): the polar coordinates of z' direction in the halo frame

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} -\sin\phi & -\cos\phi\cos\theta & \cos\phi\sin\theta \\ \cos\phi & -\sin\phi\cos\theta & \sin\phi\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}$$

$$\Sigma(x', y') = \int_{-\infty}^{\infty} \mathrm{L}(\xi^2)\,dz' = \frac{2}{\sqrt{f}} \int_{0}^{\infty} \mathrm{L}(z''^2 + \lambda^2)\,dz'', \quad \lambda^2 = \frac{1}{f}(Ax'^2 + Bx'y' + Cy'^2)$$

$$A = \frac{\cos^2\theta}{1-\varepsilon_c^2}\left(\sin^2\phi + \frac{\cos^2\phi}{1-\varepsilon_b^2}\right) + \frac{\sin^2\theta}{1-\varepsilon_b^2}, \quad B = \cos\theta\sin 2\phi\left(1 - \frac{1}{1-\varepsilon_b^2}\right)\frac{1}{1-\varepsilon_c^2}$$

$$C = \left(\frac{\sin^2\phi}{1-\varepsilon_b^2} + \cos^2\phi\right)\frac{1}{1-\varepsilon_c^2}, \qquad f = \sin^2\theta\left(\cos^2\phi + \frac{\sin^2\phi}{1-\varepsilon_b^2}\right) + \frac{\cos^2\phi}{1-\varepsilon_c^2}$$

Binney, MNRAS 212(1985) 767

Evaluating non-sphericity of clusters from hydrostatic equilibrium model in triaxial halos

- triaxial halo density profile

  ↓ **fitting model**

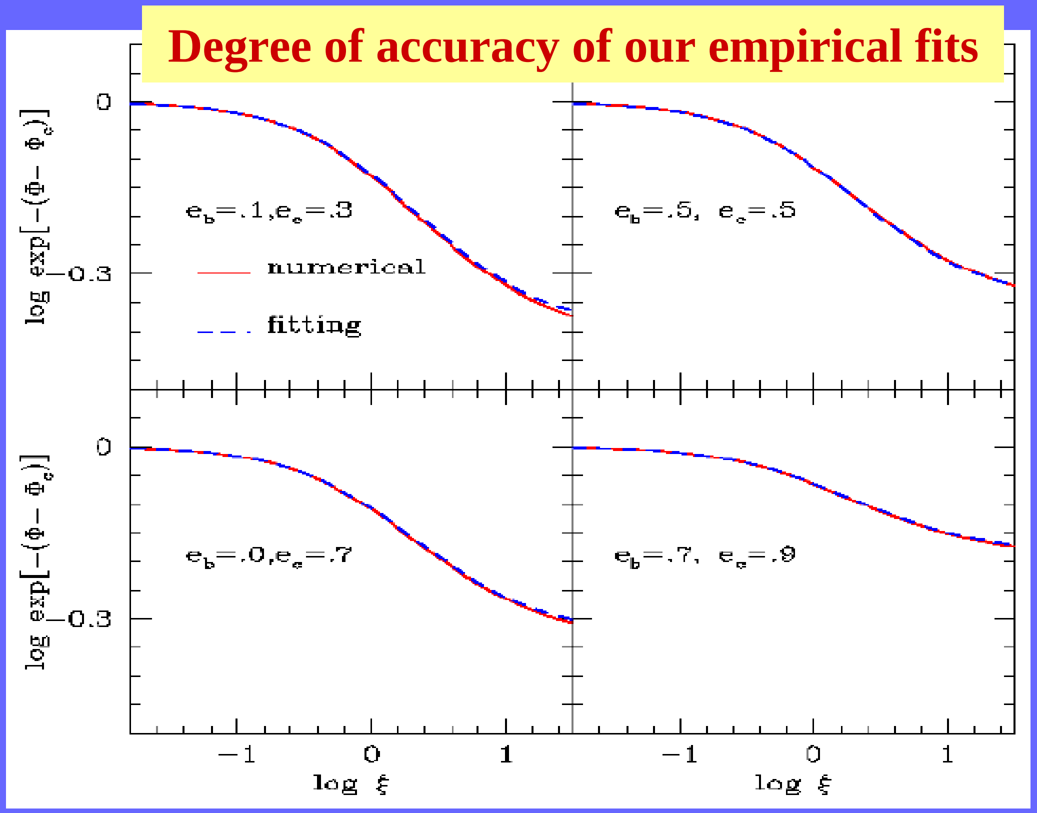
- triaxial halo potential profile

  ↓ **hydrostatic equilibrium**

- 3D gas and temperature profiles

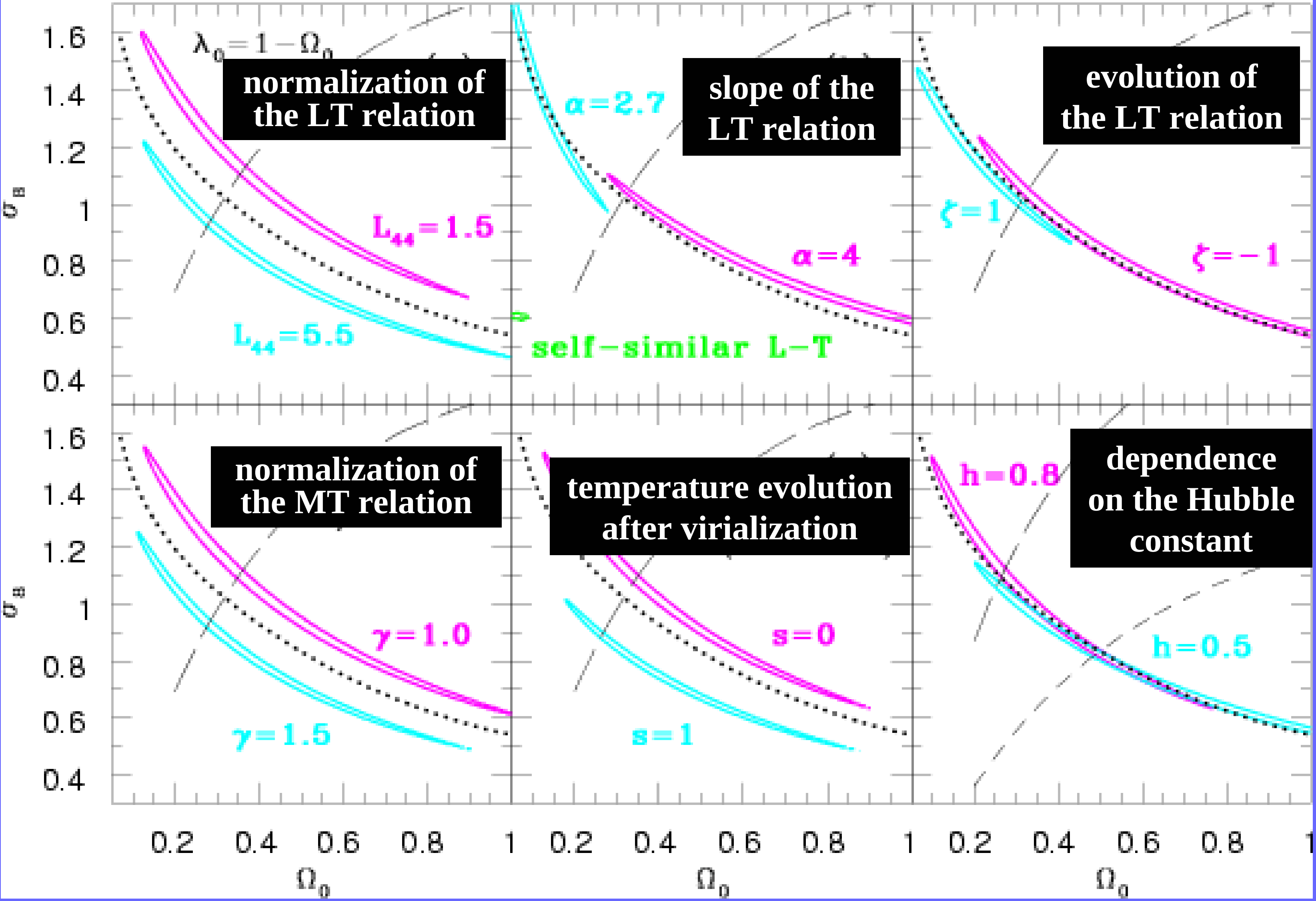
  ↓ **projection along the line-of-sight**

- observed X-ray, SZ, and/or lensing profiles (2D)



➡ **fits for position angles and 3D eccentricities (axis-ratios) of clusters (hosting halos)**

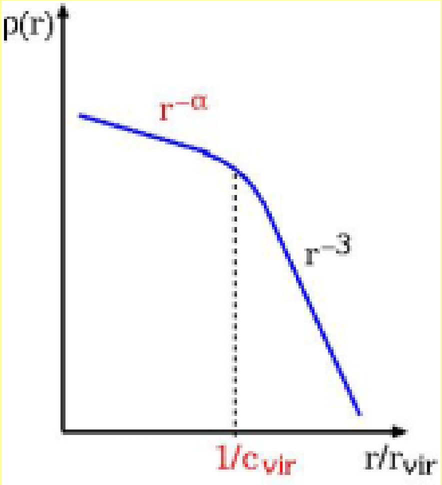
Systematic uncertainties in $\sigma_8 - \Omega_0$ other than non-sphericities



Kitayama & Suto, ApJ 490 (1997) 557
basically the same even after 6 years…

From spherical dark matter to gas density profiles

Halo density profile



$$\rho(r) = \frac{\delta_c \rho_{crit}}{(r/r_s)^{\alpha}(1+r/r_s)^{3-\alpha}}$$

$$c_{vir}(M) \equiv \frac{r_{vir}(M)}{r_s(M)} = \frac{9}{1+z}\left(\frac{M}{2\times 10^{13} h_{70}^{-1} M_{Sun}}\right)^{-0.13}$$

Hydrostatic equilibrium gas distribution

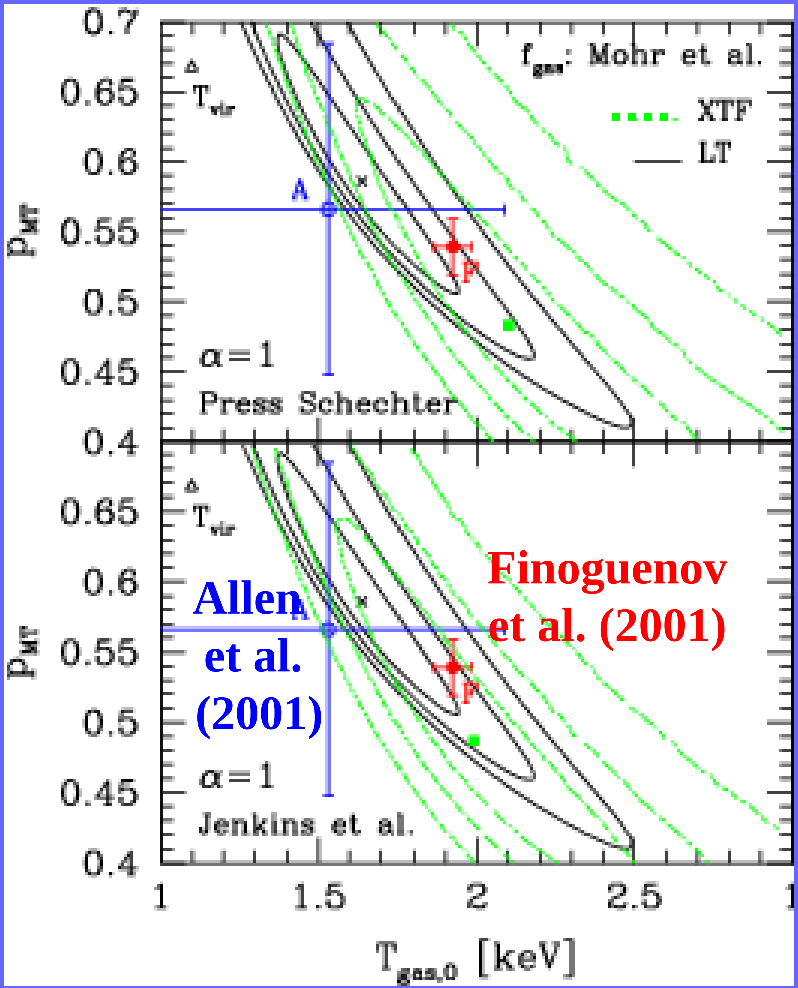
$$\rho_{gas}(r) = \rho_{gas,0} \exp\left[\frac{2c_{vir}}{m(c_{vir})}\frac{T_{vir}}{T_{gas}} f(x)\right]$$

$$f(x) = 1 - \frac{\ln(1+x)}{x} \quad (\alpha = 1)$$

$$= 2\sqrt{\frac{1+x}{x}} - \frac{2}{x}\ln(\sqrt{x}+\sqrt{1+x}) \quad (\alpha = 3/2) \quad \Rightarrow \quad \text{analytic !}$$

Makino, Sasaki & Suto (1998); Suto, Sasaki & Makino (1998)
Shimizu, Kitayama, Sasaki & Suto (2003) ApJ 587, April 1st issue

Limits on a parameterized M-T relation from the observed L-T relation and X-ray temperature function



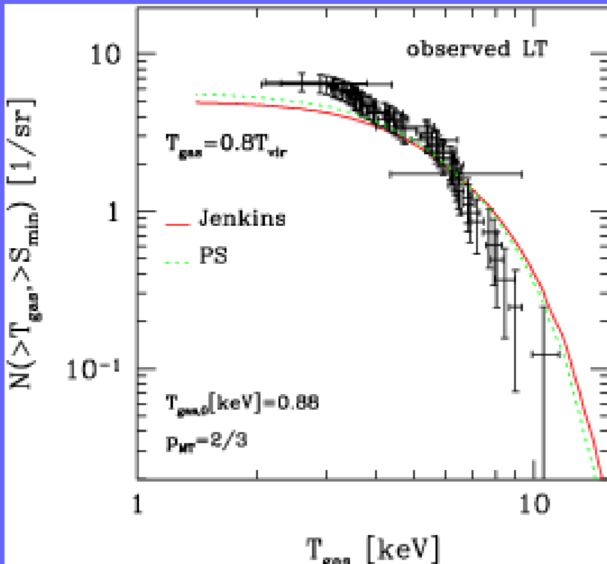
- NFW (spherical) halo density profile
- Assume hydrostatic equilibrium and isothermal for gas distribution
- Parameterize the M-T relation as

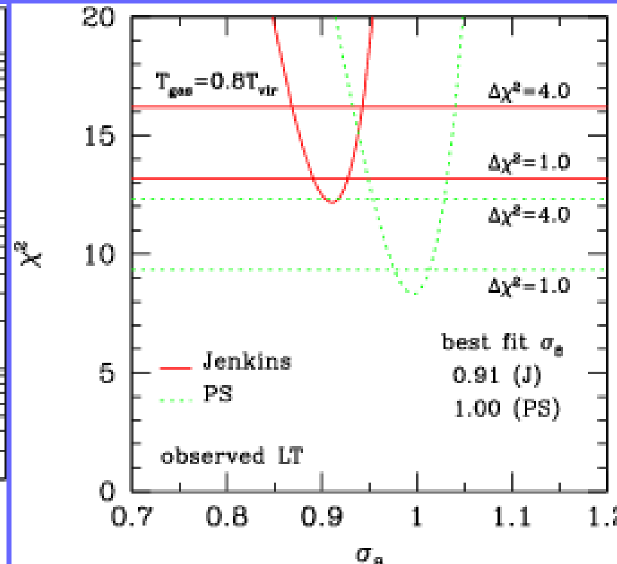
$$T_{gas} = T_{gas,0}\left(\frac{M_{vir}}{10^{14} h_{70}^{-1} M_{Sun}}\right)^{p_{MT}}$$

- Press & Schecter (1974) and Jenkins et al. (2001) for halo mass function
- Gas mass fraction from Mohr, Mathiesen & Evrard (1999)
- X-ray cluster sample with temperature compiled by Ikebe et al. (2002)

Shimizu, Kitayama, Sasaki & Suto, ApJ 587(2003) April 1st issue

σ_8 from the observed Xray temperature function





Self-similar MT relation

XTF at (5〜7) keV

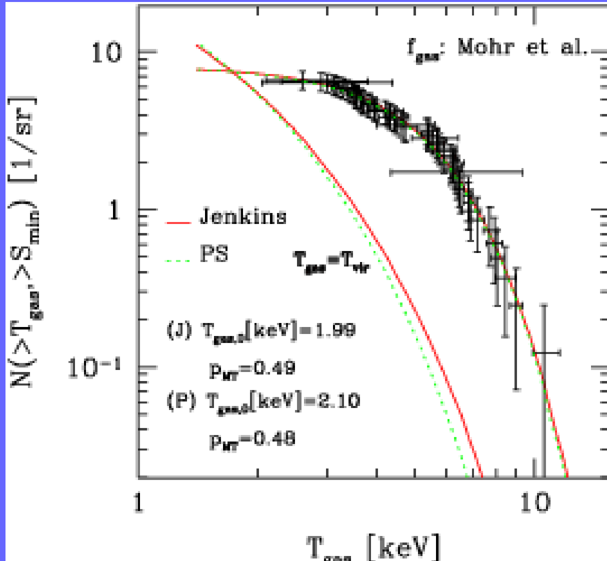
σ_8=1.0 (PS)

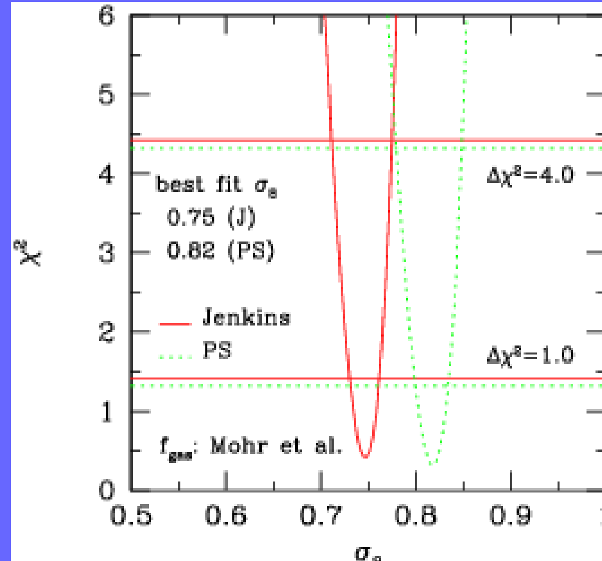
σ_8=0.9 (Jenkins et al.)

Ω_0=0.3, λ_0=0.7, h=0.7

CDM assumed

(Shimizu et al. 2003)





best-fitted MT relation

XTF at (2.5 〜10) keV

σ_8=0.82 (PS)

σ_8=0.75 (Jenkins et al.)

Summary of this ***disorganized*** (sorry !) talk

- **In 1998, we obtained *the submm SZ map* (350GHz , σ_{FWHM}=15'') of a cluster (RX J1347-1145) , for the first time, with SCUBA, JCMT.**
- **In 2000, we discovered substructure of RX J1347-1145 from *the highest angular resolution mm SZ map* (150GHz , σ_{FWHM}=13'') with NOBA (NObeyama Bolometer Array). This is subsequently confirmed by Chandra observation (Allen et al. 2002), indicating the potential power of the future SZ mapping.**
- **We are working on an improved modeling of gas and temperature profiles of clusters based on the triaxial halo model in order to properly *extract properties of real clusters* from observations, *not only for cosmology.***
- **We used the cluster statistics (LT relation and temperature function) to quantify the cluster properties (MT relation for instance) *adopting Ω_0 and λ_0 rather than solving for them.* Logically this is simply equivalent to addressing systematics for cosmological parameter estimate, but conceptually very different; *CMB and SN tell us nothing about the MT relation of clusters.***

My personal point of view…

- Clusters of galaxies have certainly played, and promise to play, an important role in cosmology, but...
- In the up-coming precision cosmology era, it is fair to say that ***σ_8 is a function(al) of Ω_0, the mass-temperature relation, the luminosity temperature relation, the halo mass function, the gas mass fraction, and the gas/temperature profiles…***
- It is misleading to say "clusters determine σ_8 as a function of Ω_0" , at least to people ***outside*** the cluster community.
- A simple modeling of clusters is overdue, and should be replaced by more physical one which incorporates non-sphericity, substructure, non-gravitational heating, feedback.
- ***The goal of the (next generation) cluster surveys is not the precision cosmology, but is to understand "what are the clusters of galaxies".***