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Probing the Distribution of Mass in Galaxy Clusters using Subaru Weak Lensing Observations

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1. CDM Paradigm

Cold Dark Matter (CDM):

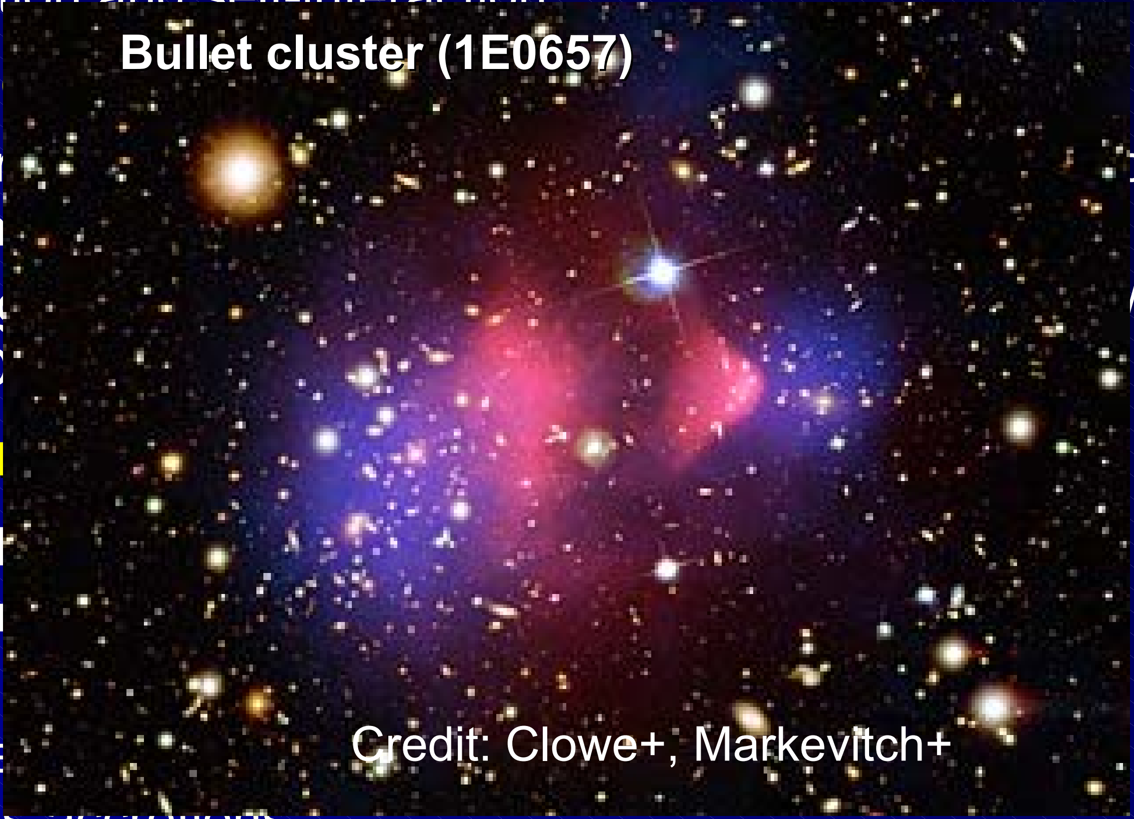
- Probably heavy particle (~100GeV), but yet unknown
- Interact only via gravity
- Negligible interaction and self-interaction

Astrophysical evid

- Small scales: Spi ... on
  fractions; collision
- Large scales: Lar ... h)
  ➔ needs DM (CD

Standard CDM stru

- Initial conditions,
- Use an N-body si
  formation
- Bottom-up: smalle
  mergers and mass-accretions

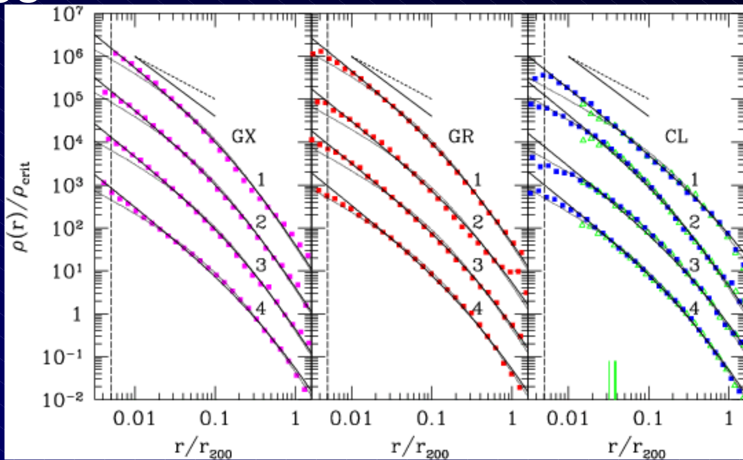


Characteristic of CDM Halos

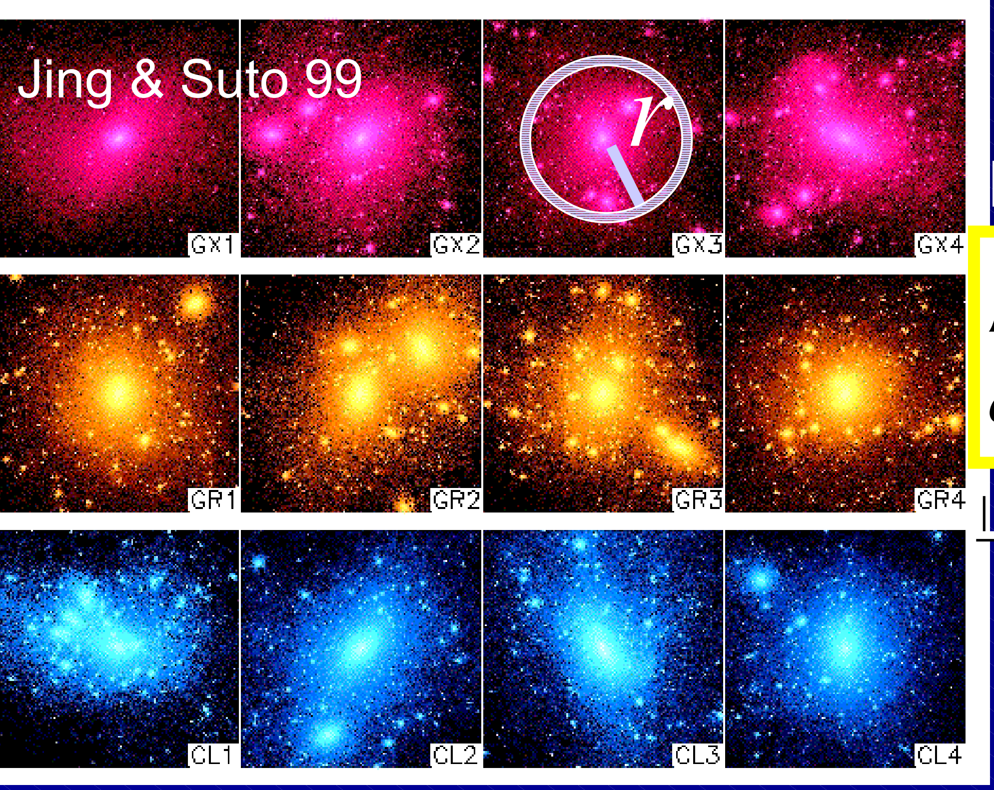
Simulation-based predictions for bound, non-linear objects:

characteristic, universal mass profile of CDM halos

→ Navaro, Frenk, & White 96, 97 (=NFW profile)



Final-state density slope, sensitive to the nature of DM



NFW density profile

$$\rho_{3D}(r) \propto r^{-1}(1+r/r_s)^{-2}$$

$$c_{vir}(M_{vir}, z_{vir}) := r_{vir}/r_s$$

Outer: $\rho \propto r^{-3}$

Inner: $\rho \propto r^{-1}$

LCDM prediction (Bullock+ 01)

$$< c_{vir} > = \frac{8}{1+z_{vir}} \left(\frac{M_{vir}}{10^{14} M_{sun}/h} \right)^{0.13}$$

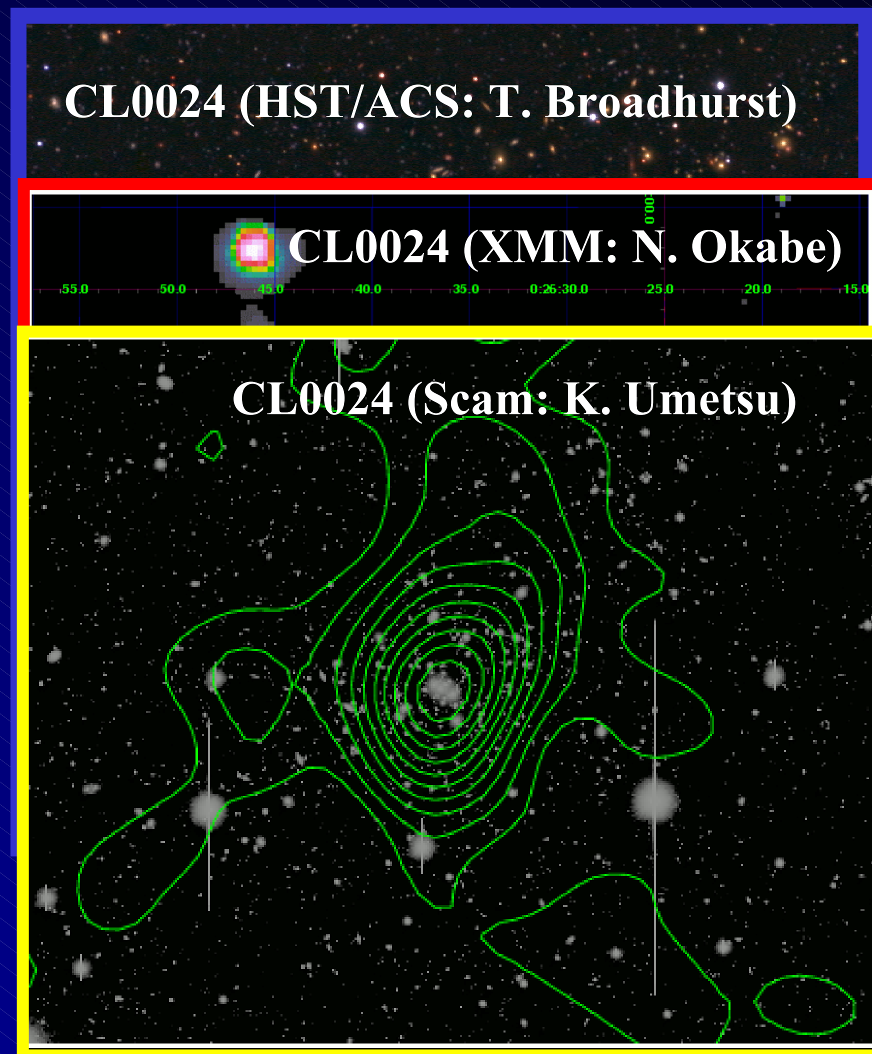
Galaxy Clusters – Most Massive Halos

Most massive bound structures:

- Mass = $10^{14} – 10^{15}$ M_{sun}
- **DM** plays a dominant role in cluster formation
- Baryons are important only on <10kpc ~ 0.5--1% of virial radii
- Suited for testing NFW profiles

➔ **Constrain the nature of DM**

➔ **Small-scale (<1Mpc) test of the CDM paradigm**



- **Weak lensing**

Useful astrophysical probes:

- Observed in many wavelengths (Radio, Optical, X-ray)

2. Gravitational Lensing

- Direct probe of matter distribution
  - Governed solely by gravity
  - No assumption about physical/dynamical state of the system
- Sensitive probe of geometry of the universe
  - Distance (ratio), volume vs. DE
- Cosmic structure formation imprinted

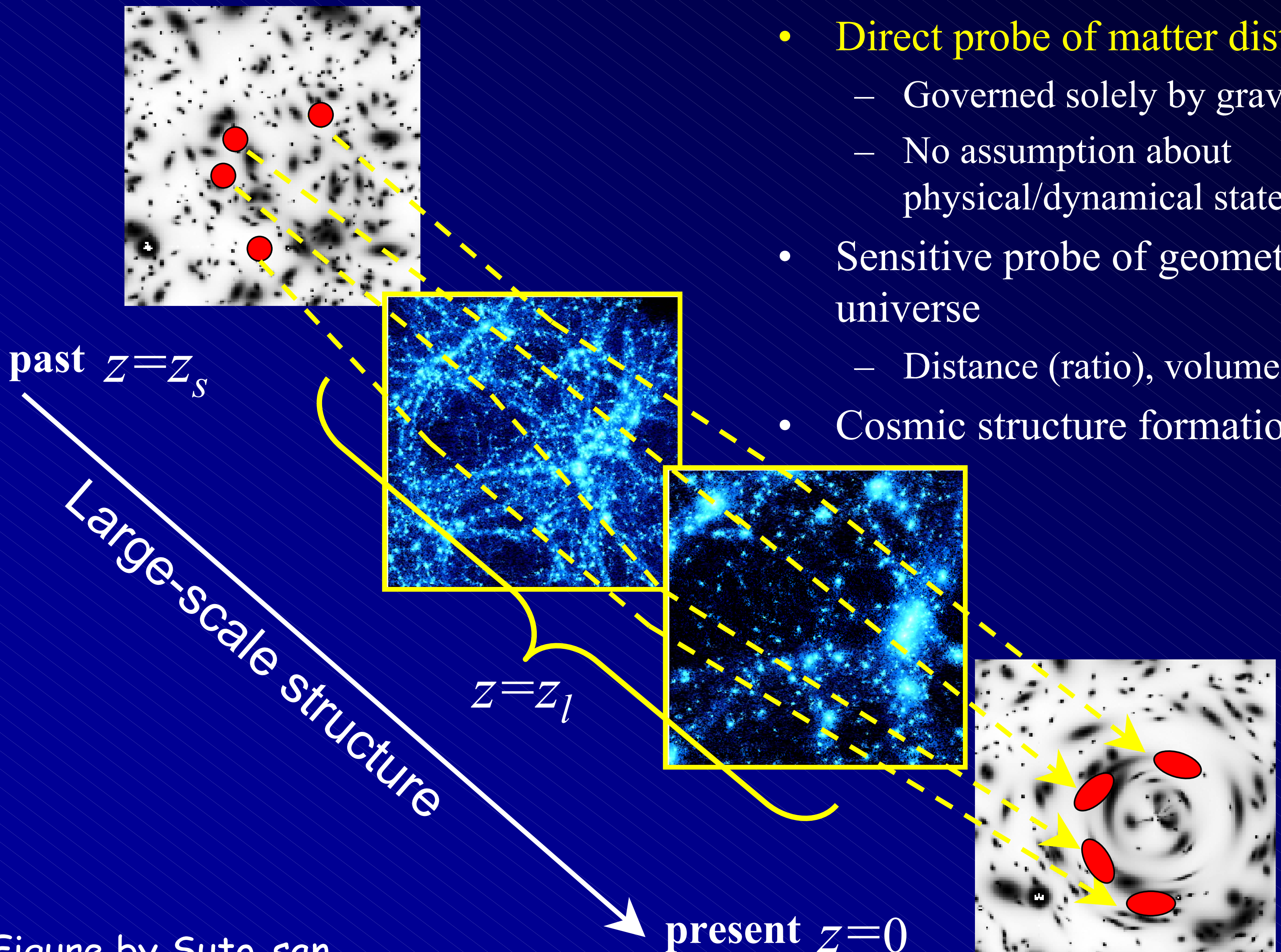


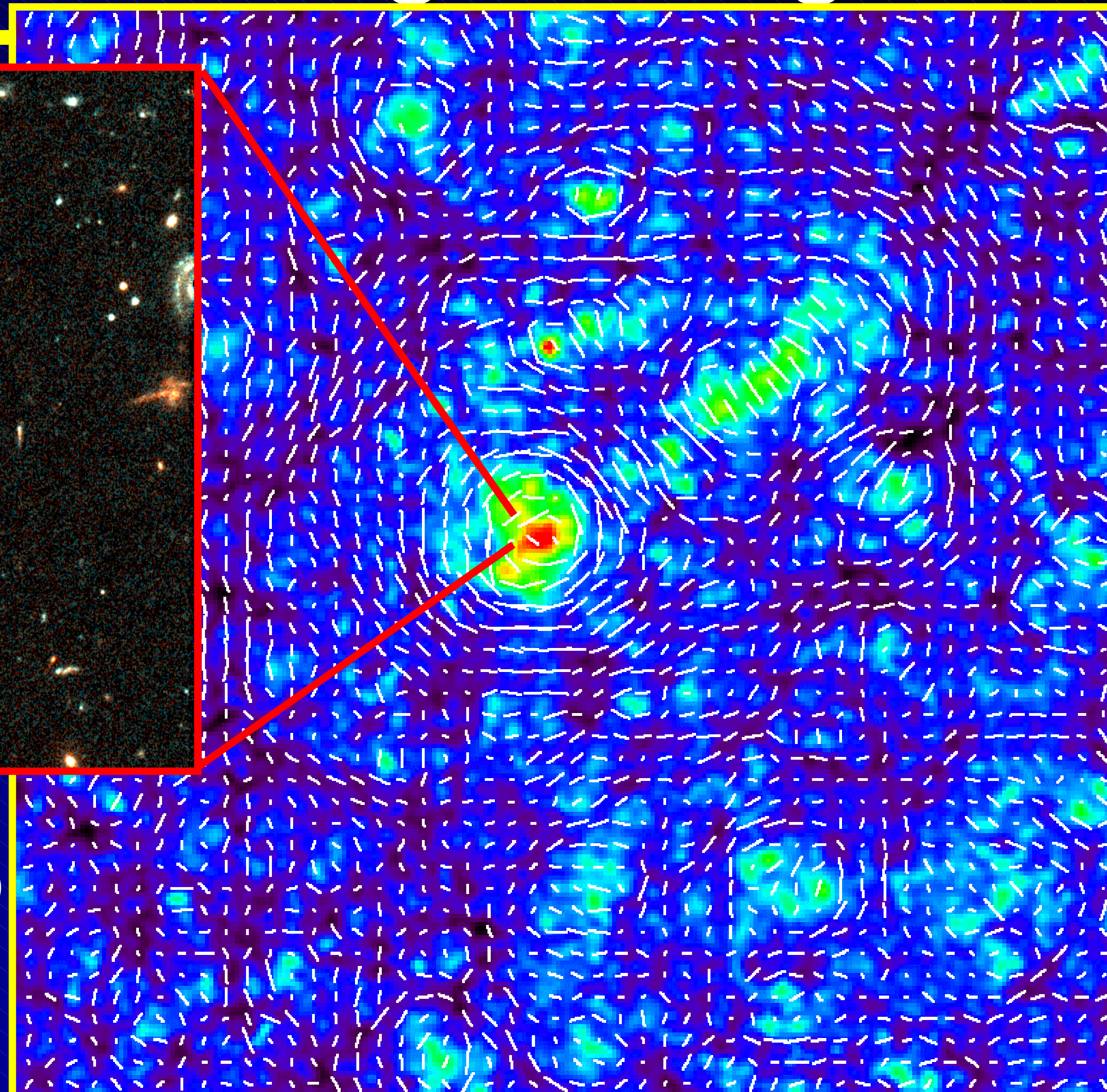
Figure by Suto-san

Weak and Strong Lensing

Cluster z = 0.77; Arc z = 4.89:
Photo from H. Yee (HST/ACS)

$$\kappa = \frac{1}{2}\Delta\psi,$$

$$\boldsymbol{\gamma}_{ij} = \left(\partial_i\partial_j - \frac{1}{2}\delta_{ij}\Delta\right)\psi = \begin{pmatrix} +\gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{pmatrix}$$



Simulated 3x3 degree field (Hamana 02)

3. Mass profile of A1689 (z=0.183)

- Relaxed, round cluster
- Less feature of substructures
- Strong(est) lensing cluster

References:

- Broadhurst, Takada, Umetsu et al. 2005 (ApJL)
  [Strong+Weak lensing mass profile]
- Oguri, Takada, Umetsu, Broadhurst 2005 (ApJ)
  [projection effect of halo triaxiality]
- Umetsu, Takada et al. 2006 (in prep)
  [analysis, mapmaking]
- Medezinski, Broadhurst, Umetsu et al. 2006 (ApJ, accepted)
  [weak lensing dilution effect]
- Umetsu & Okabe 2006; Okabe & Umetsu 2006 (in prep)
  [Subaru+XMM study of 6 merging clusters]

HST and Subaru Telescope

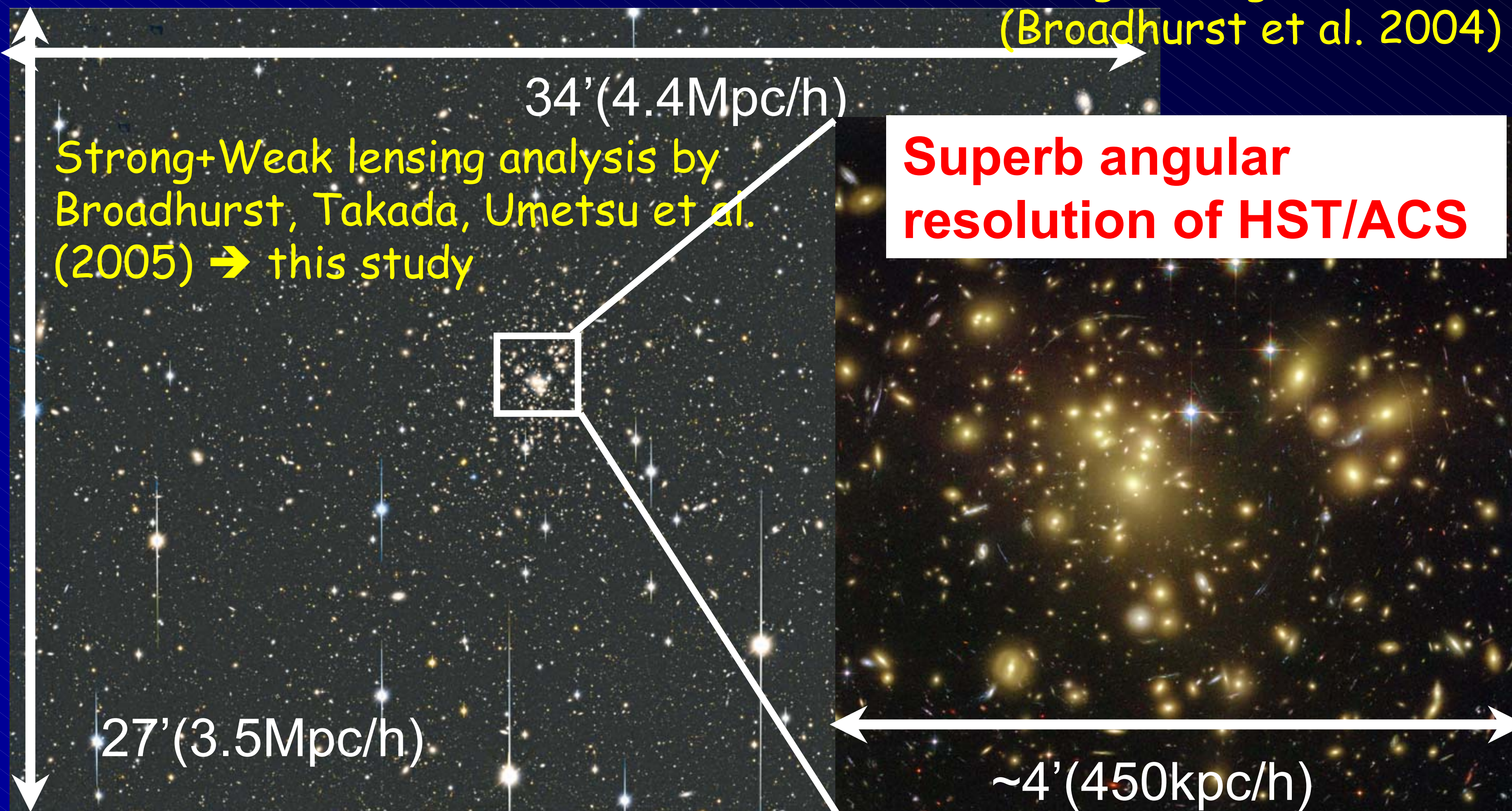
- D=2.4m
- Superb angular resolution
- ~ 3' x 3' Field-of-View (FoV)
- Ideal instrument for **strong lensing** in the innermost region

- D=8.3m
- High image quality (PSF) among 8-10m ground-based telescopes
- Wide ~30' x 30' FoV (Suprime-Cam)
- Ideal instrument for **weak lensing** out to cluster virial radii, r_vir

Subaru + HST for Lensing

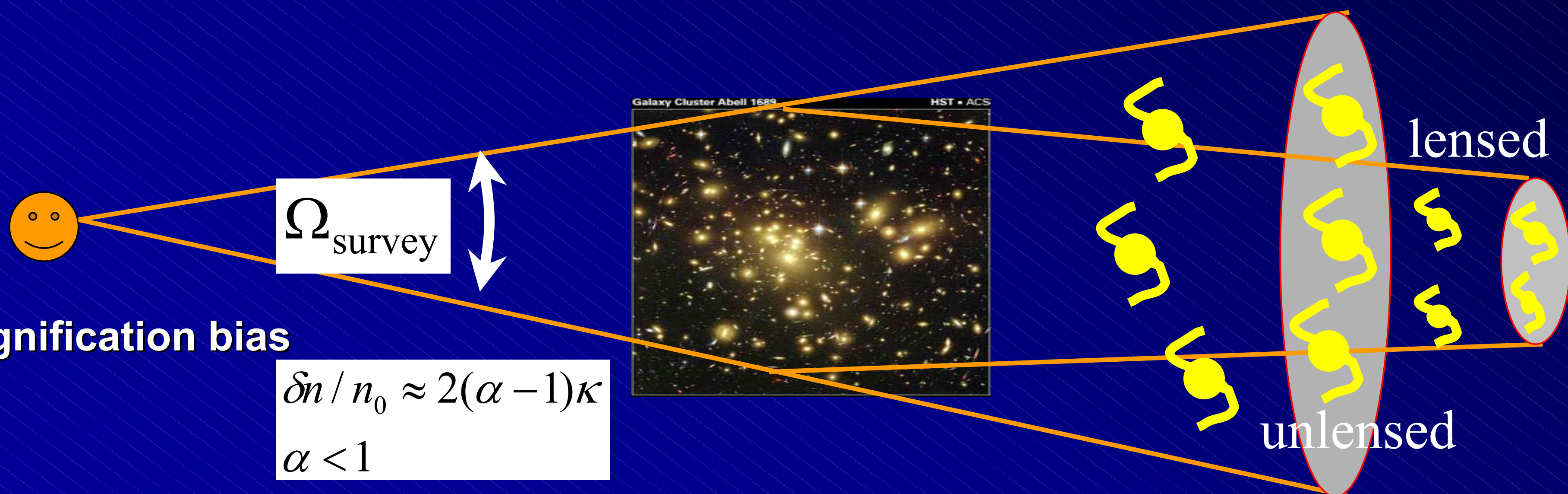
Wide-field imaging of Subaru/Suprime-Cam

Revealing 106 lensed multiple images of 30 background galaxies (Broadhurst et al. 2004)



Weak Lensing Analysis Method

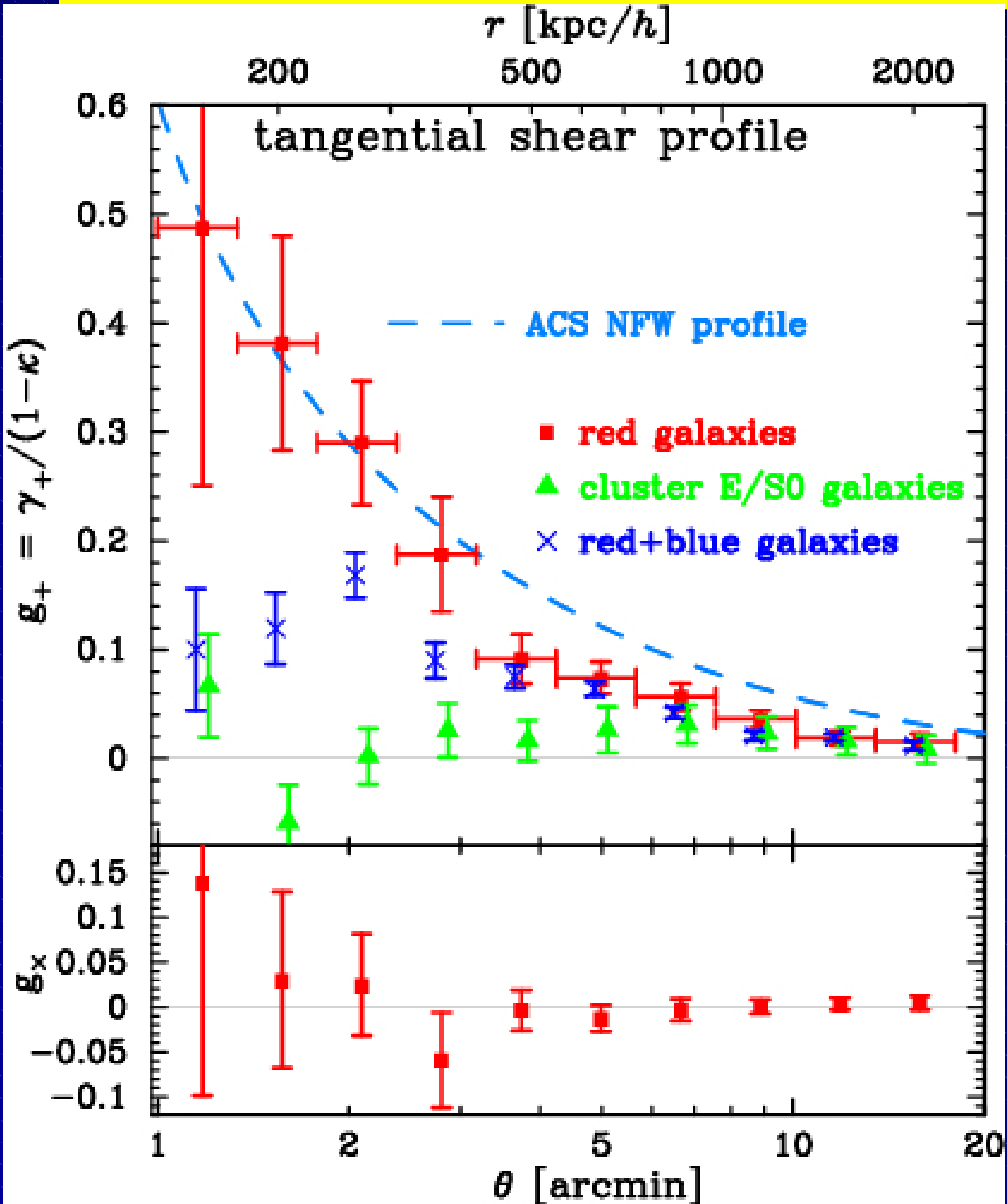
- Make a secure selection of the background population (z>z_lens), identified above the red-sequence of cluster-member galaxies
- Combine WL (1) shape-distortion and (2) area-distortion [magnification bias] measurements to derive a model-independent, mass density profile, $\kappa(\theta)$
  - Distortion alone ➔ mass-sheet degeneracy (no constraint on l=0 mode)
  - Magnification bias ➔ breaking the degeneracy (noisier in general)
- Combine SL (10<r<200kpc/h) and WL (130<r<2000 kpc/h) mass profile to test the NFW model on 10<r<2000 kpc/h for a direct comparison with CDM models.



Magnification bias

$$\delta n / n_0 \approx 2(\alpha - 1)\kappa$$
$$\alpha < 1$$

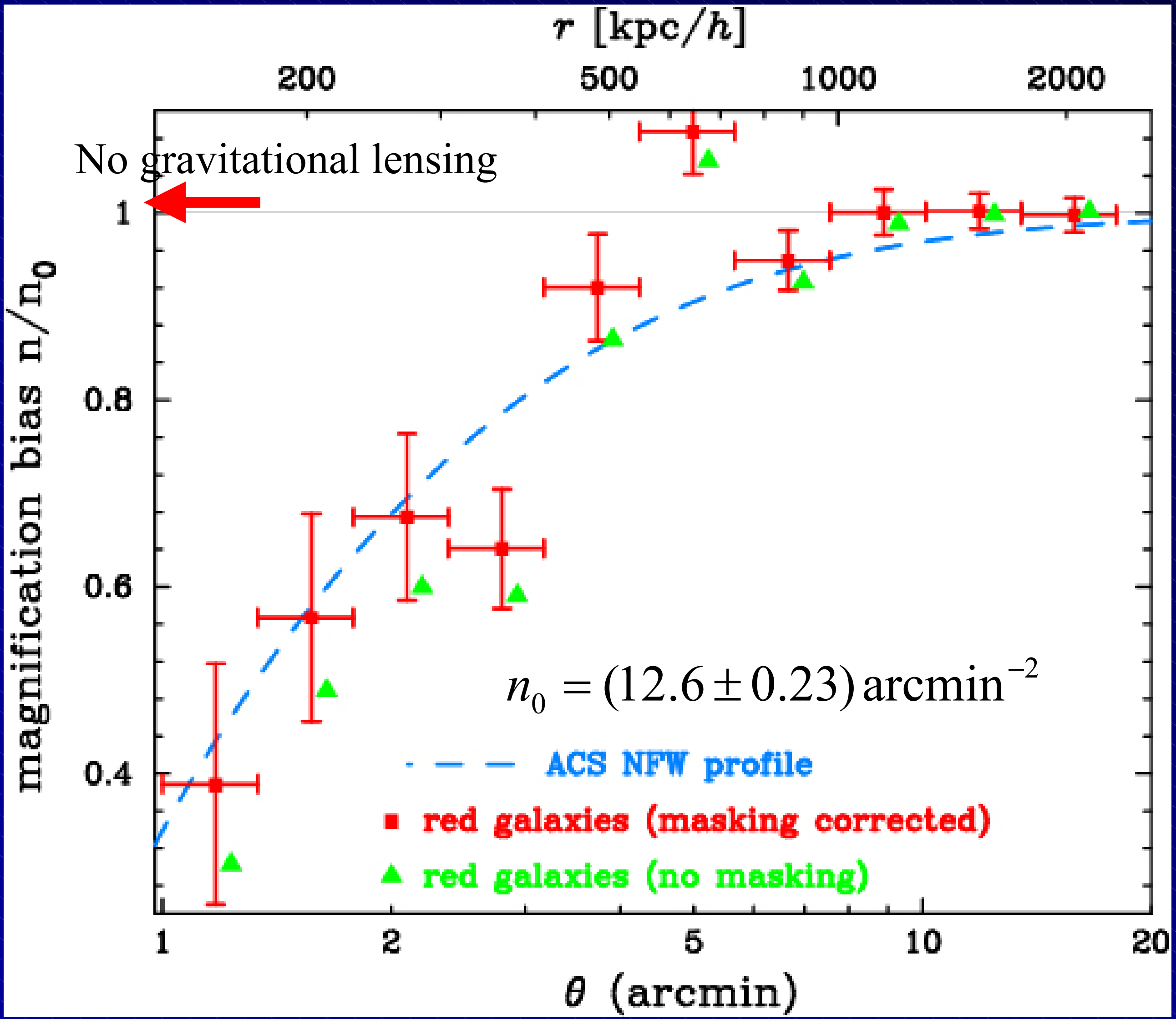
Measurement (I): tangential shear



- Significant S/N of 12 σ (■)
- Underestimates signal by a factor of 2 - 5 without a secure background selection (x) (cf., Clowe & Schneider 01; Bardeau et al. 04)
- Good agreement with ACS @ r < 3', but the signal strength @ r > 3' is weaker than expected
- Null-detection of B-mode signal, g_X → No systematics

Measurement (II): magnification bias

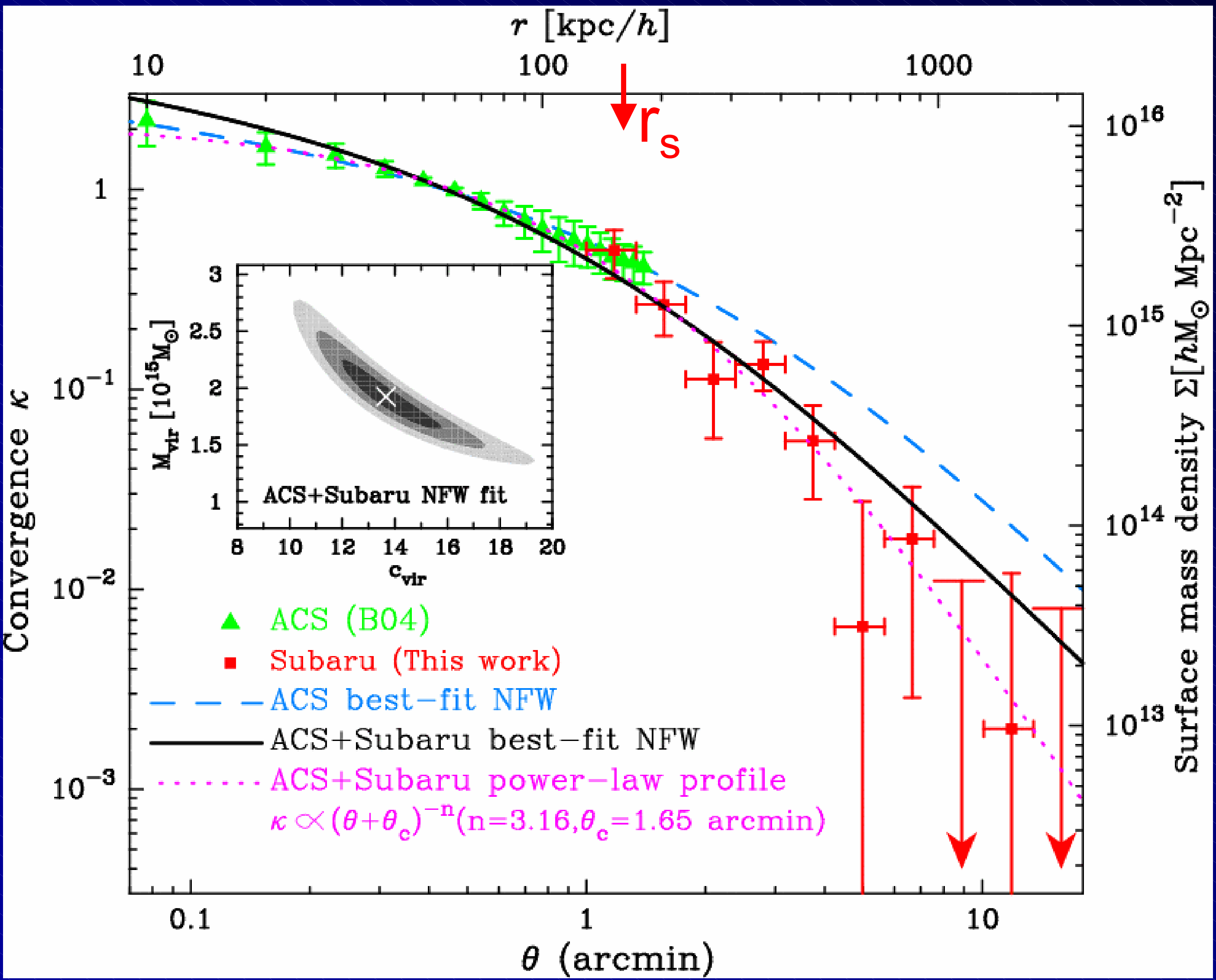
Number counts as a function of radius



- Significant detection of a **depletion** of red galaxy counts (9.3 σ)
- Signal @ r>3' is weaker than expected from the ACS result
- Masking effect by member galaxies corrected (■)

Mass-Density Profile: $0.005r_{vir}$ to r_{vir}

22 data points



- **Best-fit NFW**

$$\chi^2_{min}/\mathrm{dof.} = 13./20$$

$$M_{vir} = 1.93^{+0.2}_{-0.2} \times 10^{15} M_{sun}$$

$$r_{vir} = 2.0 \pm 0.1 \mathrm{Mpc}/h$$

$$c_{vir} = 13.7^{+1.4}_{-1.1}$$

$$\Leftrightarrow c_{CDM} \approx 4 \pm 1$$

- **Best-fit CPL**

$$\chi^2_{min}/\mathrm{dof.} = 4.5/19$$

$$n = 3.16^{+0.81}_{-0.72}$$

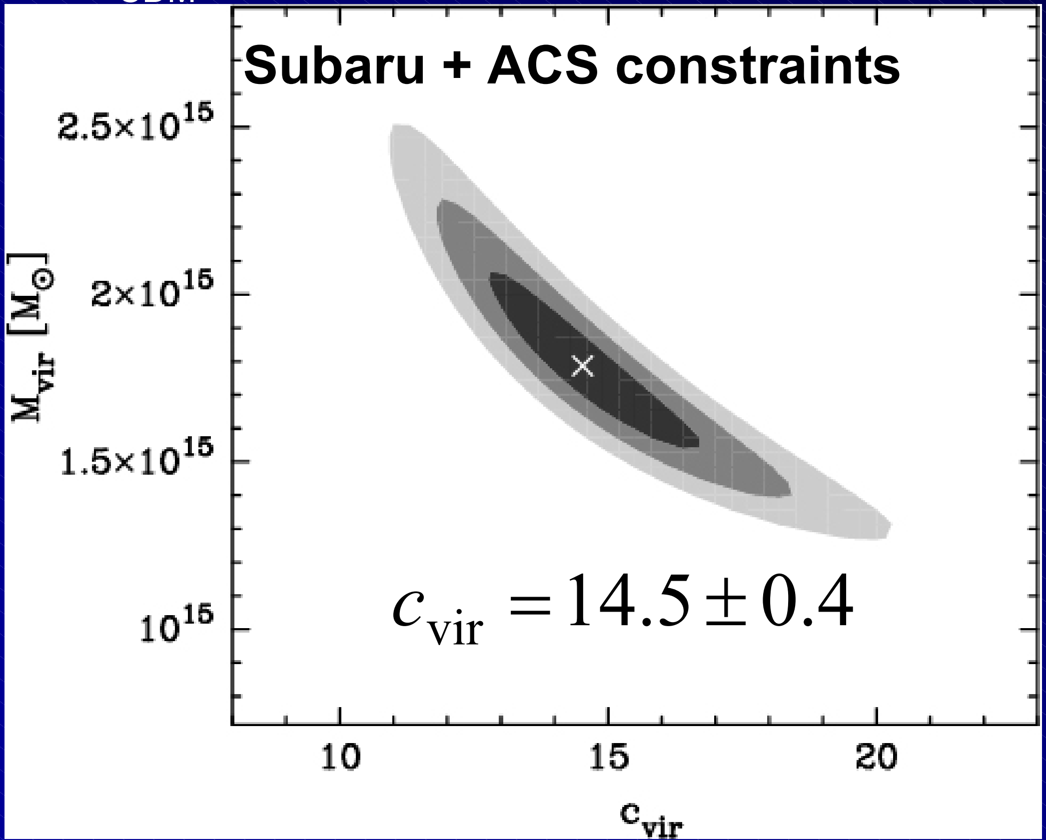
$$r_c = 214^{+99}_{-78} \mathrm{kpc}/h$$

- **Cored SIS**

Strongly rejected (10σ!!)

NFW Halo Parameters: M_{vir} vs. C_{vir}

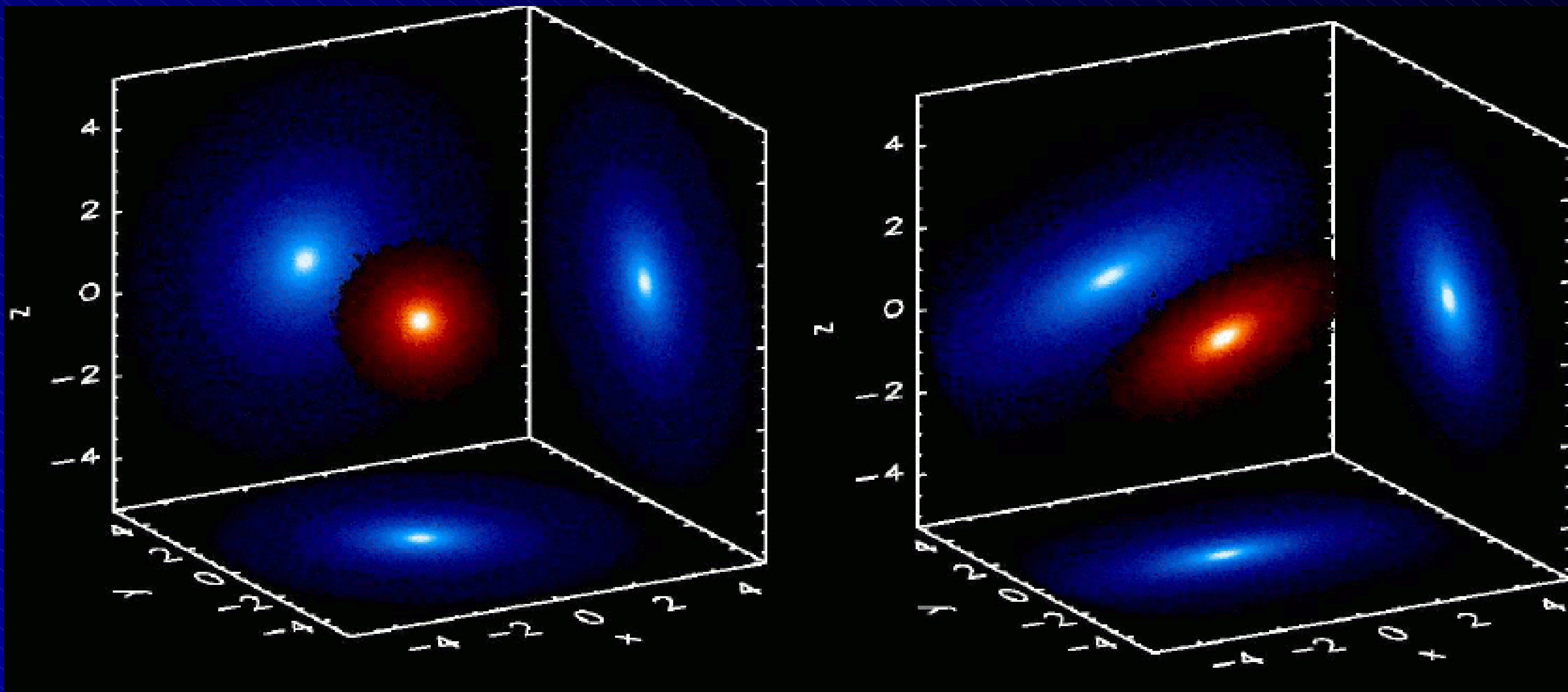
- Very large M_{vir} : $M_{vir} \sim 10^{15}$ M_{sun}
- Mass discrepancy with X-ray ($M_{lens} \sim 2 M_{X\text{-ray}}$) @ 5 σ
- Very high concentration: factor >3 larger than the CDM prediction for a massive halo ($c_{CDM} \sim 4$ by Bullock et al. 01)



Too Steep Mass Profile !?

- **Selection Effect?**
  - Selection bias for Strong Lensing Clusters?
    ➔ *the largest Einstein radius (50") on the sky!!*
  - Early cluster formation?
  - Only 1-2% CDM halos show c~14 (Hennawi+ 05)
- **Dark Matter Nature?**
  - Self-interaction? [σ/m=0.5-5 cm^2/g] (Spergel & Steinhardt 00; Yoshida+ 00) → α ↓
  ➔ Constraints by Markevitch+ 04, $\sigma/m < 1 cm^2/g$
  - Baryon contraction? (Gnedin+ 04; Lin+ 06) α ↑ c_{vir} ↑
  ➔ important @ small scales <10kpc ←→ r_s = 145kpc/h
- **Projection Effect of the Cluster Halo itself?**
  - DM halos being highly triaxial due to collisionless nature of DM and filamentary nature of structure formation (Jing & Suto 02)

Projection Effect by Halo Triaxiality

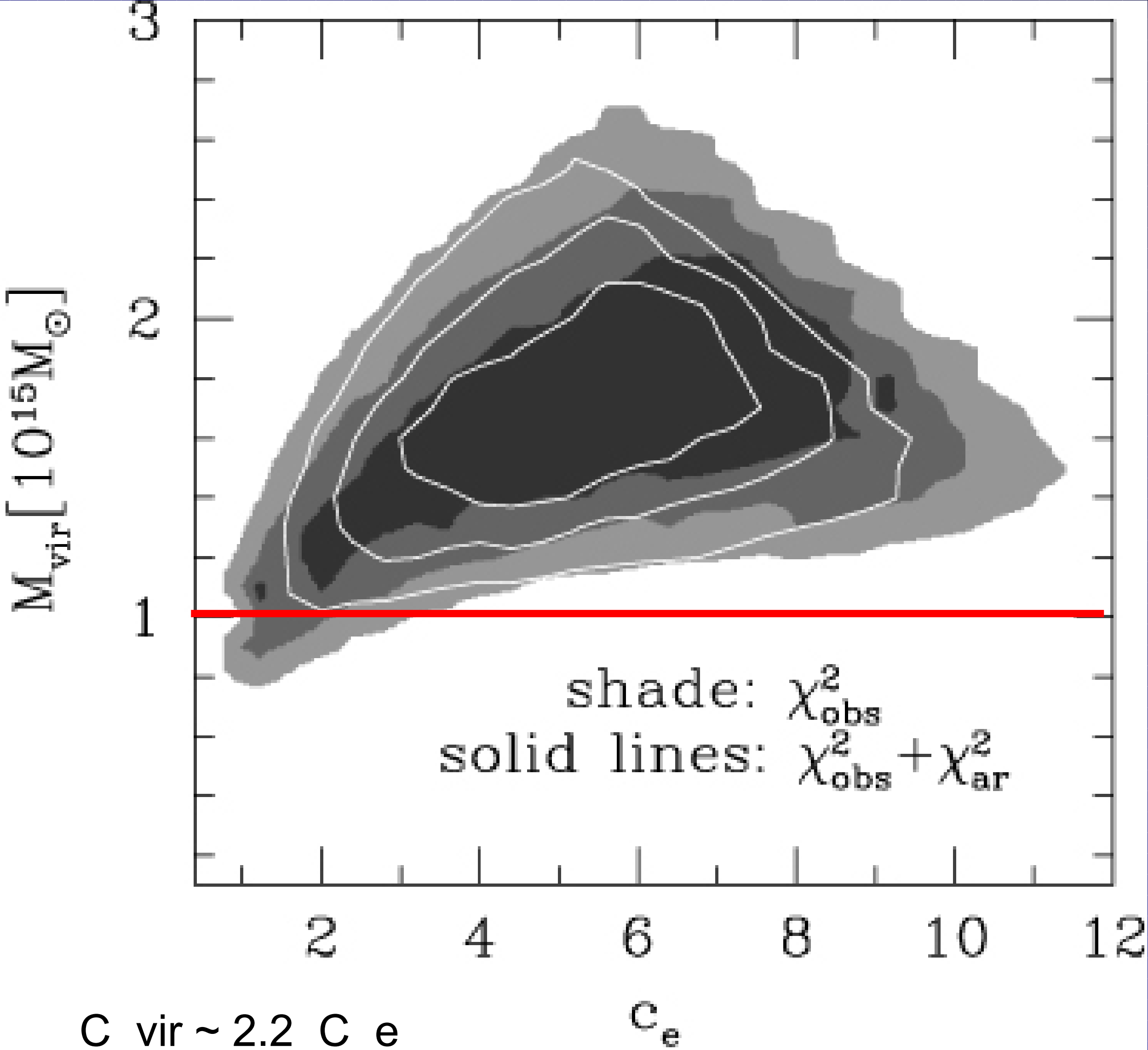


Spherical

Tri-axial

Hennawi, Dalal, Bode, Ostriker 05

CDM Halo Triaxial Prior (N-body) relaxing the cluster Mass/Concentration



C_vir ~ 2.2 C_e

Solid: with prior info on the CDM halo triaxial shapes (Jing & Suto 02)

M_x

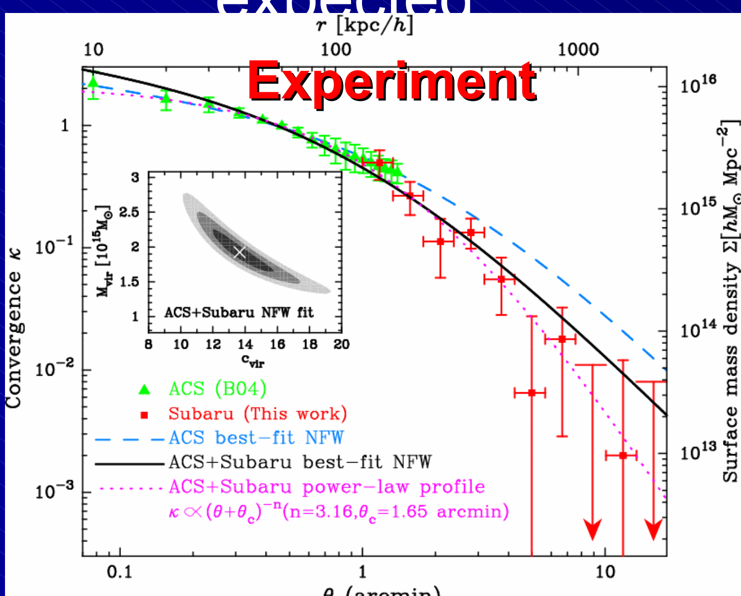
(Andersson & Madejski 04)

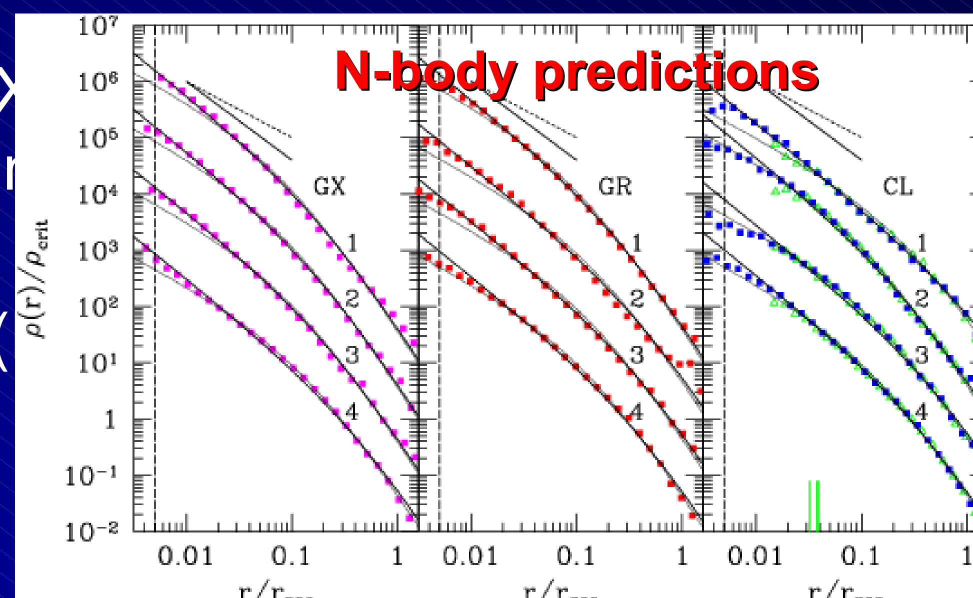
M_x consistent with lensing within 3σ confidence region

OTUB 2005

Halo Triaxiality cures the problem?

- Projection Effect of Tri-axial Halo (OTUB 05)
  - About 6% of triaxial CDM halos being consistent with A1689 @ 2 sigma, using prior information of triaxial shapes found from N-body simulations (Jing & Suto 02)
  - Elongated structure along the Line-of-Sight expected





Future Prospects

International collaboration: **"The Ultimate Gravitational Lensing Study of Galaxy Clusters"**

- Subaru observations (PI. Prof. Futamase): have collected data for ~15 clusters
- HST/ACS (PI: G.P. Smith): Will observe the central region of 143 clusters
- X-ray/radio data available for a sub-sample of clusters
- Aim to constrain the nature of DM