Dark Matter and Gravitational Lensing of Galaxy Clusters

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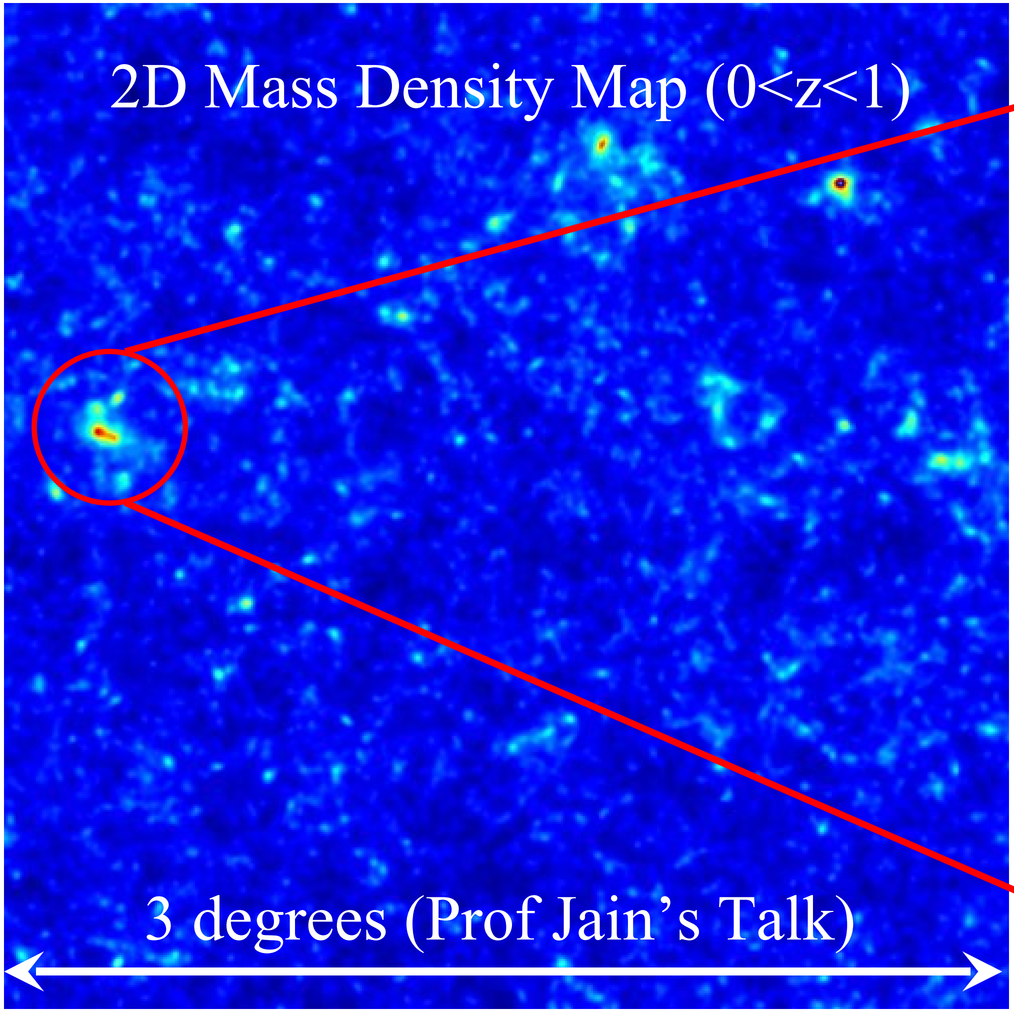
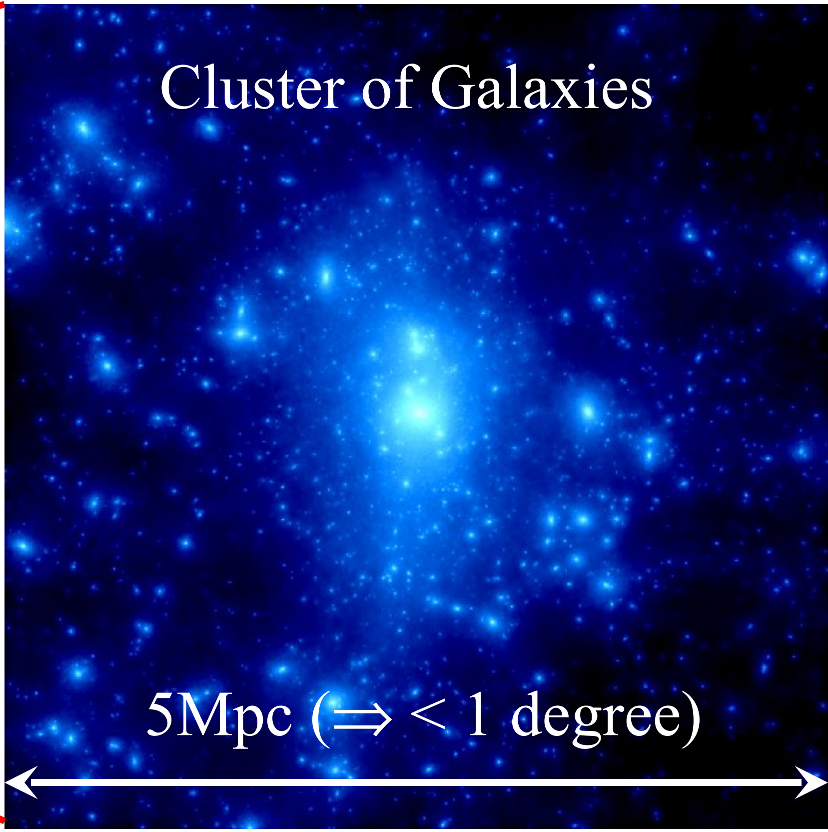
* Pink color: Tohoku U.

Gravitatoinal Lensing of Cosmic Hierarchical Structures

Stars – Galaxies – Clusters of Galaxies – Large-Scale Structure



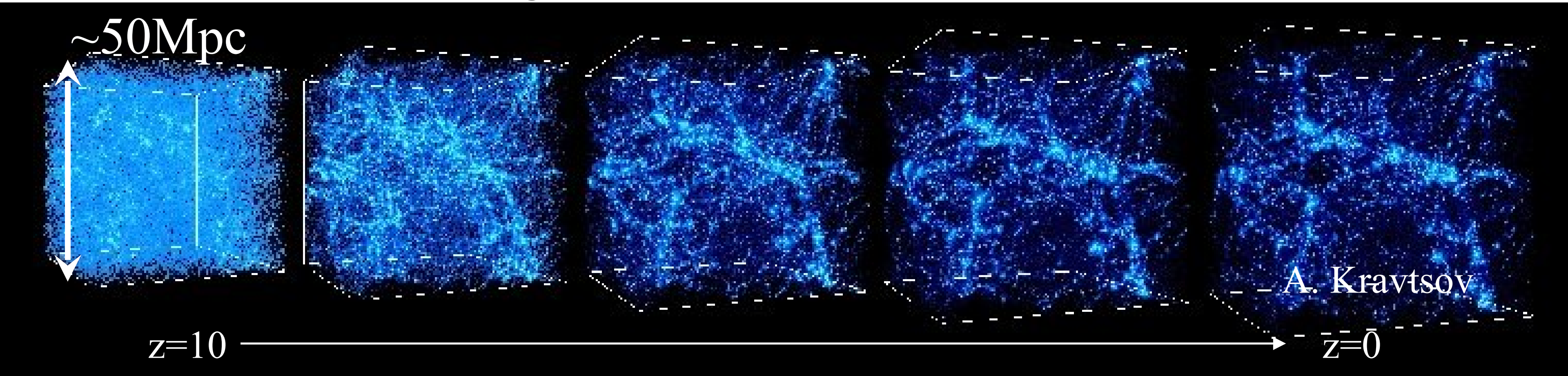
(Jain, Seljak & White 00)



(From Y. Hideki, NAOJ)

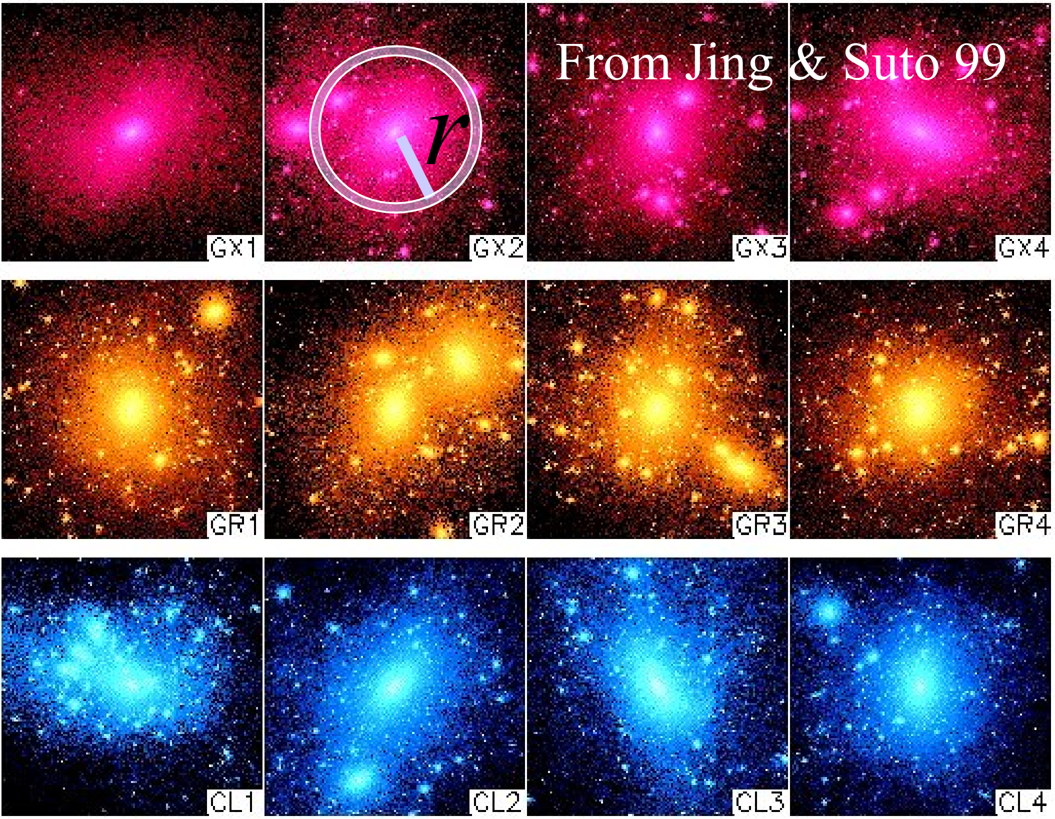
CDM Model of Structure Formation

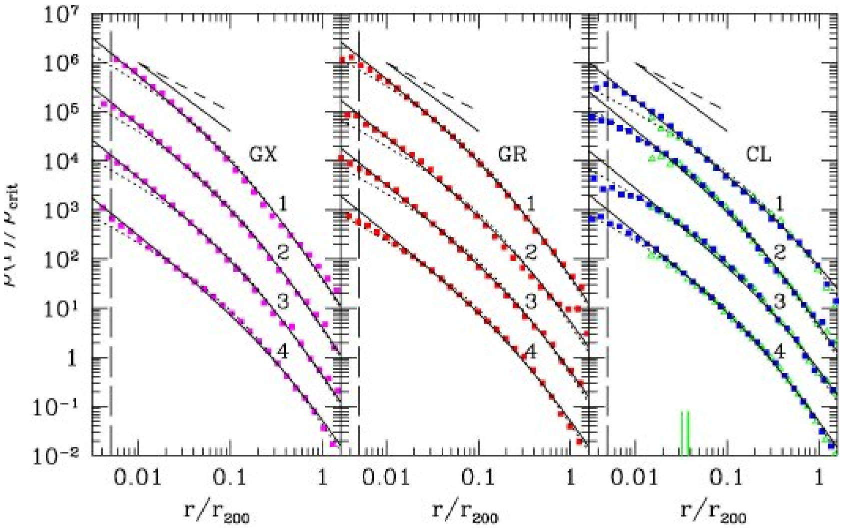
- Cold Dark Matter
  - Probably heavy particle (~100GeV), but yet unknown
  - Interact only via gravity
  - Negligible interaction and self-interaction
- CDM structure formation scenario
  - Initial conditions: precisely constrained from CMB
  - Use an N-body simulation to study the hierarchical structure formations
  - Bottom-up: smaller objects first formed, then larger ones formed via mergers and mass accretion



Mass Density Profile of DM Halos

- Simulation-based predictions: the appearance of a characteristic, universal density profile (Navarro, Frenk & White 96, 97; **NFW profile**)





NFW profile

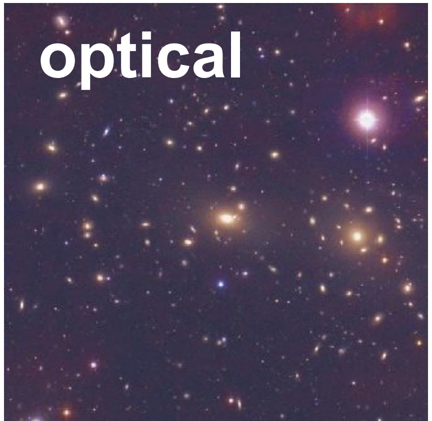
$$\rho(r) \propto \frac{1}{r(1 + r/r_s)^2}$$

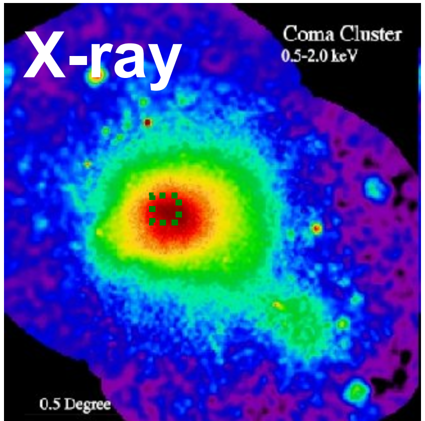
Outer: ρ∝r^-3

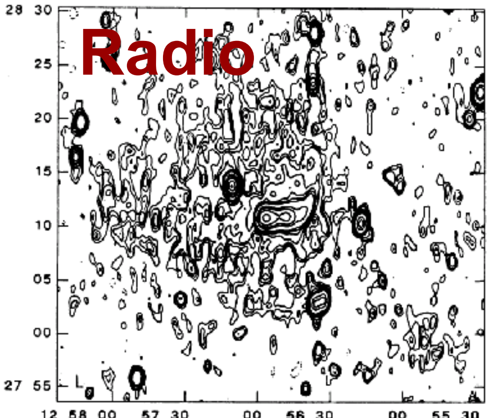
Inner: ρ∝r^-1

Galaxy Clusters and Gravitational Lensing

- Most massive gravitationally bound objects
  - 10^14 ~ 10^15 M_sun (100 – 1000 galaxies)
  - Strongest S/N of lensing signals
  - DM plays a dominant role to the formation processes; baryonic matter is important only on <10kpc
  - Suitable for testing an NFW profile ⇐ Gravitational lensing
- Astronomically very interesting objects to study
  - Seen with various wavelengths (radio, optical, X-ray)
  - Connection between DM (gravity), hot gas (baryonic matter) and galaxies (a tiny part of baryons)







Gravitational Lensing of Cluster

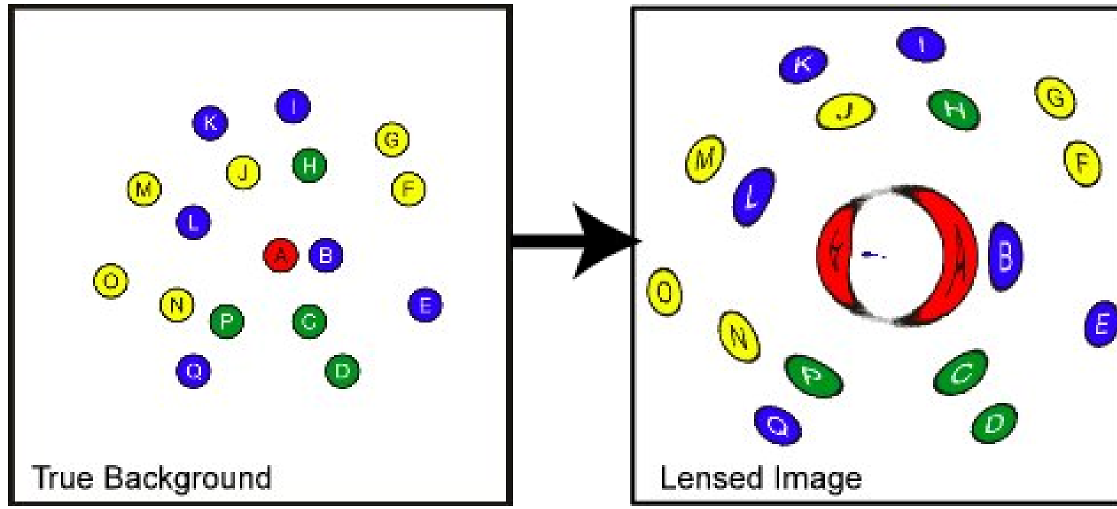
- a unique means of measuring mass (mainly DM) distribution -

•Strong Lensing

– Multiple Images

– Large Arcs, Ring

– Obvious Distortion

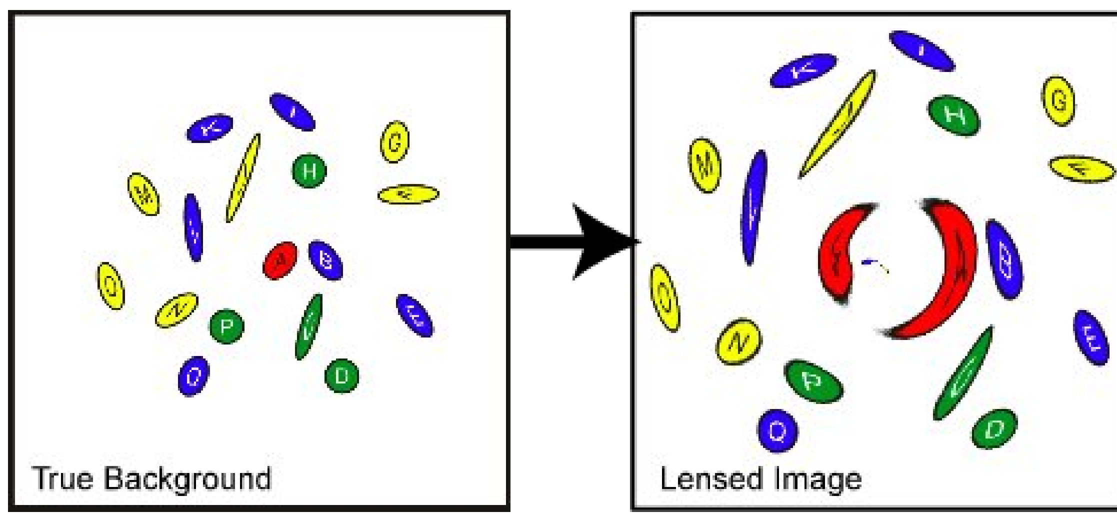


•Weak Lensing

– Slight Stretching

– Distortion small compared to initial shape

– Statistical lensing



HST and Subaru Telescope

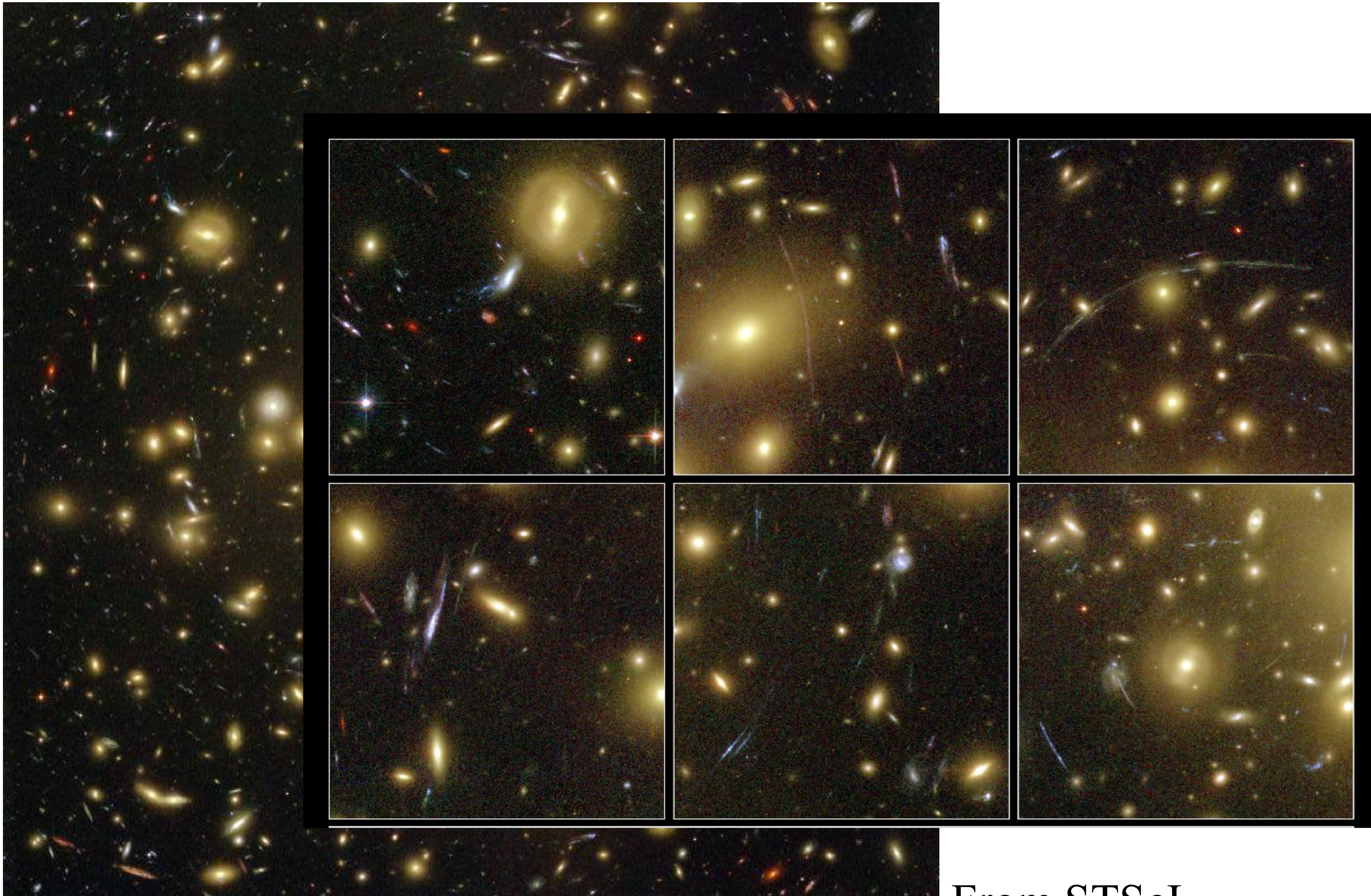
- 2.4m
- High angular resolution
- ~3'x3' FoV
- **Best instrument for measuring strong lensing in the innermost region**

- 8.2m
- High image quality among other 8m-class telescopes
- ~30'x30' FoV
- **For measuring weak lensing in the outer region**

Abell 1689 (Initial Result)

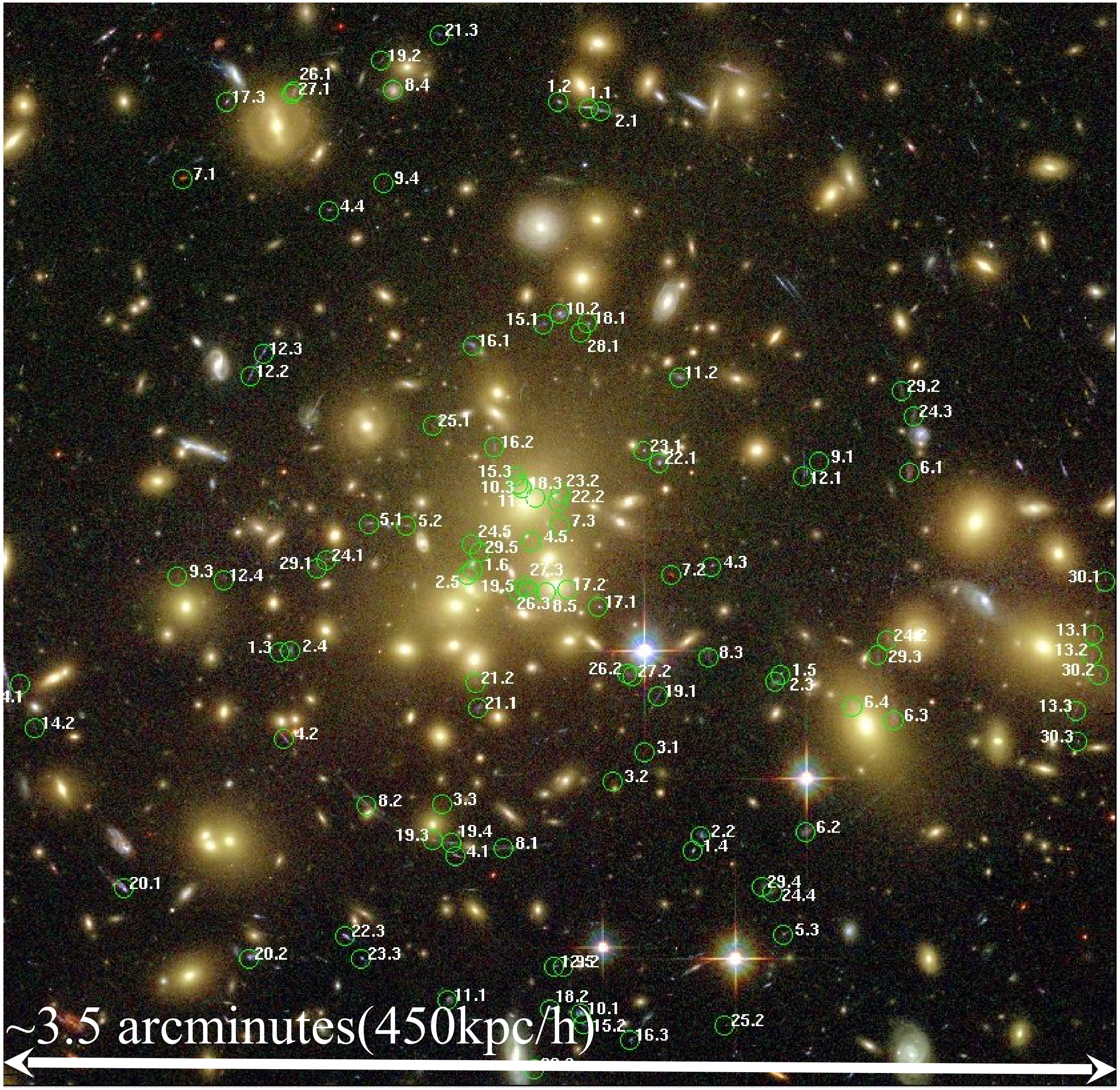
- One of most massive clusters @ z=0.183
  - $\sim 2\times10^{15} M_{sun}$ (~1000 gals), $r_{vir} \sim 2$Mpc
  - Known as strong lensing cluster: largest Einstein radius (≈50'' for z=3) ⇔ typically ~15''
  - X-ray temperature ~ 9keV (XMM: Anderson & Madejski 2004)
  - Velocity dispersion σ_{1D}=2400km/s (Targue et al. 1990) or 1400km/s (Girardi et al. 1997)
- Observed by ACS/HST and Subaru
- Best target cluster for studying gravitational lensing

ACS/HST Image of A1689



From STScI

ACS/HST Image of A1689 (contd.)



Unprecendented Angular Resolution

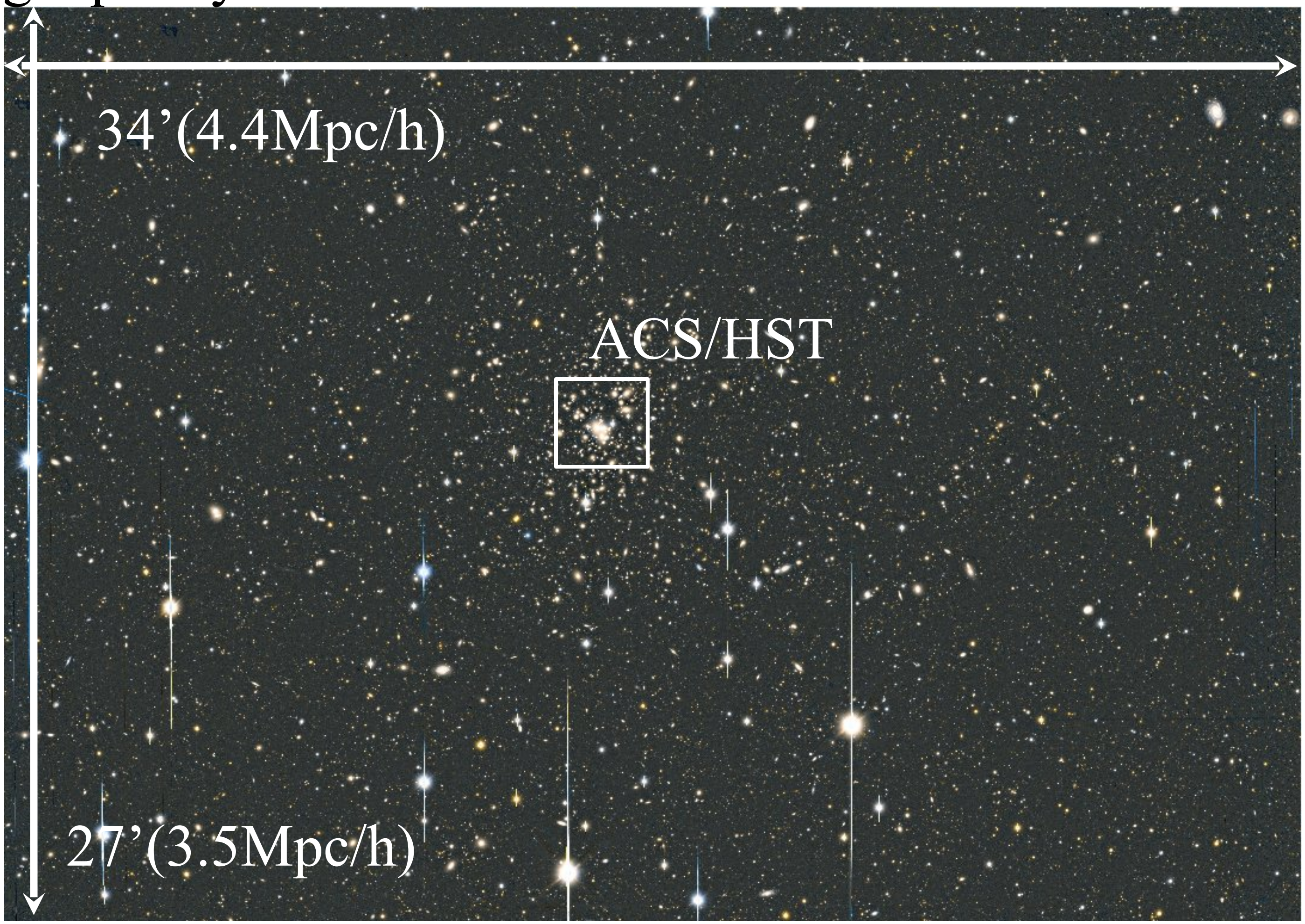
Allows to find 106 candidates of multiple images for 30 background galaxies (⇔ before ACS, typical few arcs per cluster)

Allows a precise modeling of the mass distribution

(Broadhurst et al. 2004)

Subaru *V* and *i*' data of A1689

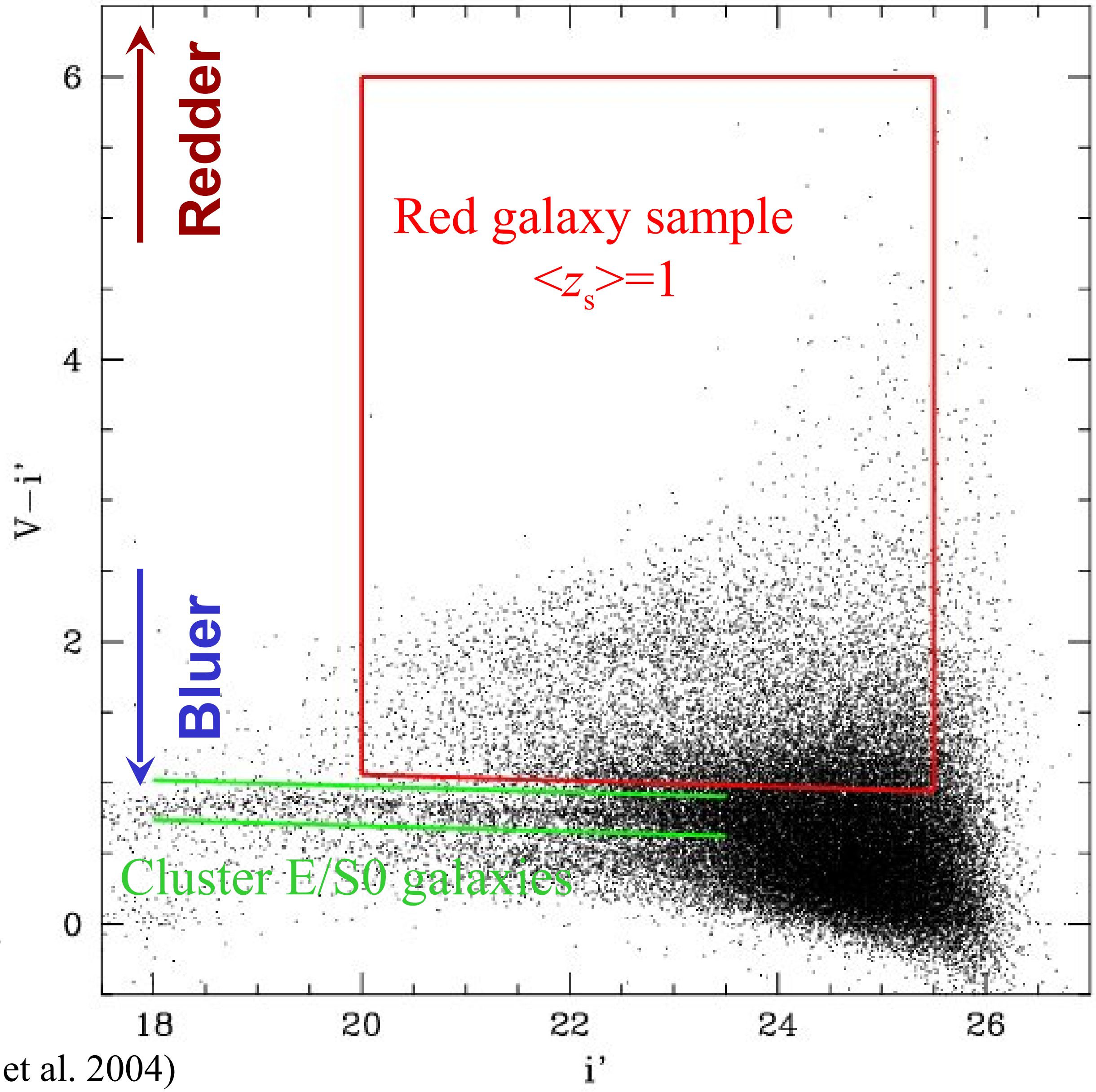
- Field of View: 34' × 27'
- Subaru is most suitable instrument for WL measurement among other 8-m class telescopes thanks to its wide FoV and excellent image quality



Background Galaxy Selection

- Exposure time
  - V: 1920s (V_{lim}=26.5)
  - i': 2640s (i'_{lim}=25.9)
- Seeing conditions
  - FWHM: $V+i'$ 0.88''
- Red galaxy sample (very likely background)
  - $V–i'$>CM+0.22
  - i'<25.5
  - ~10 arcmin^{-2} galaxies

* previous works used faint red+blue galaxies (~40 arcmin^-2)



(Clowe & Schneider 2000; Bardeau et al. 2004)

WGL: Shearing of Background Galaxy Images

Observable: ellipticity in background galaxy images

$$\gamma \equiv \frac{a-b}{a+b} = \gamma_{GL} + \gamma_{int}$$

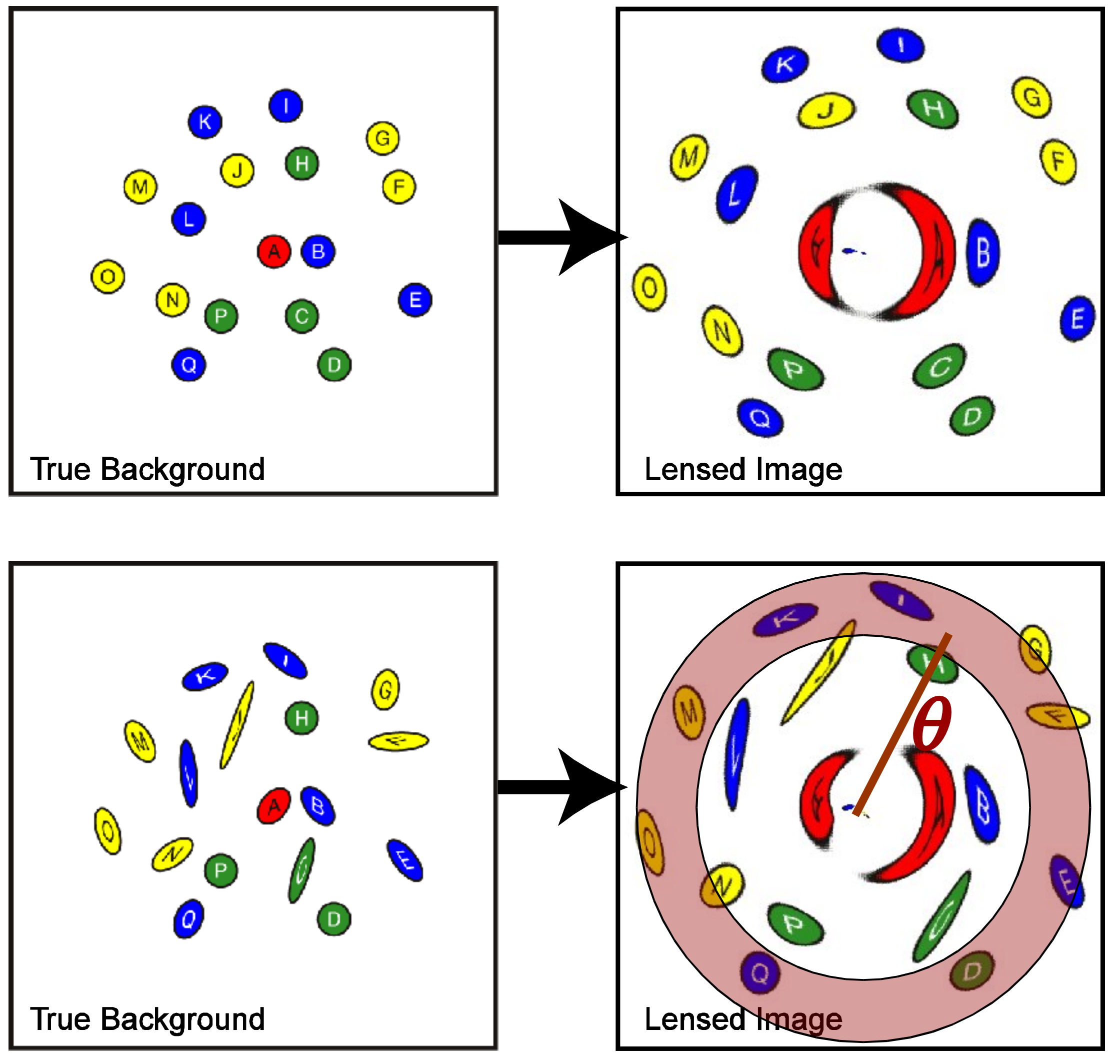
For a cluster

$$\gamma_{GL} \approx O(0.1), \quad \sigma_{int} \approx 0.3$$

Assumption: $\langle \gamma_{int,i} \rangle = 0$

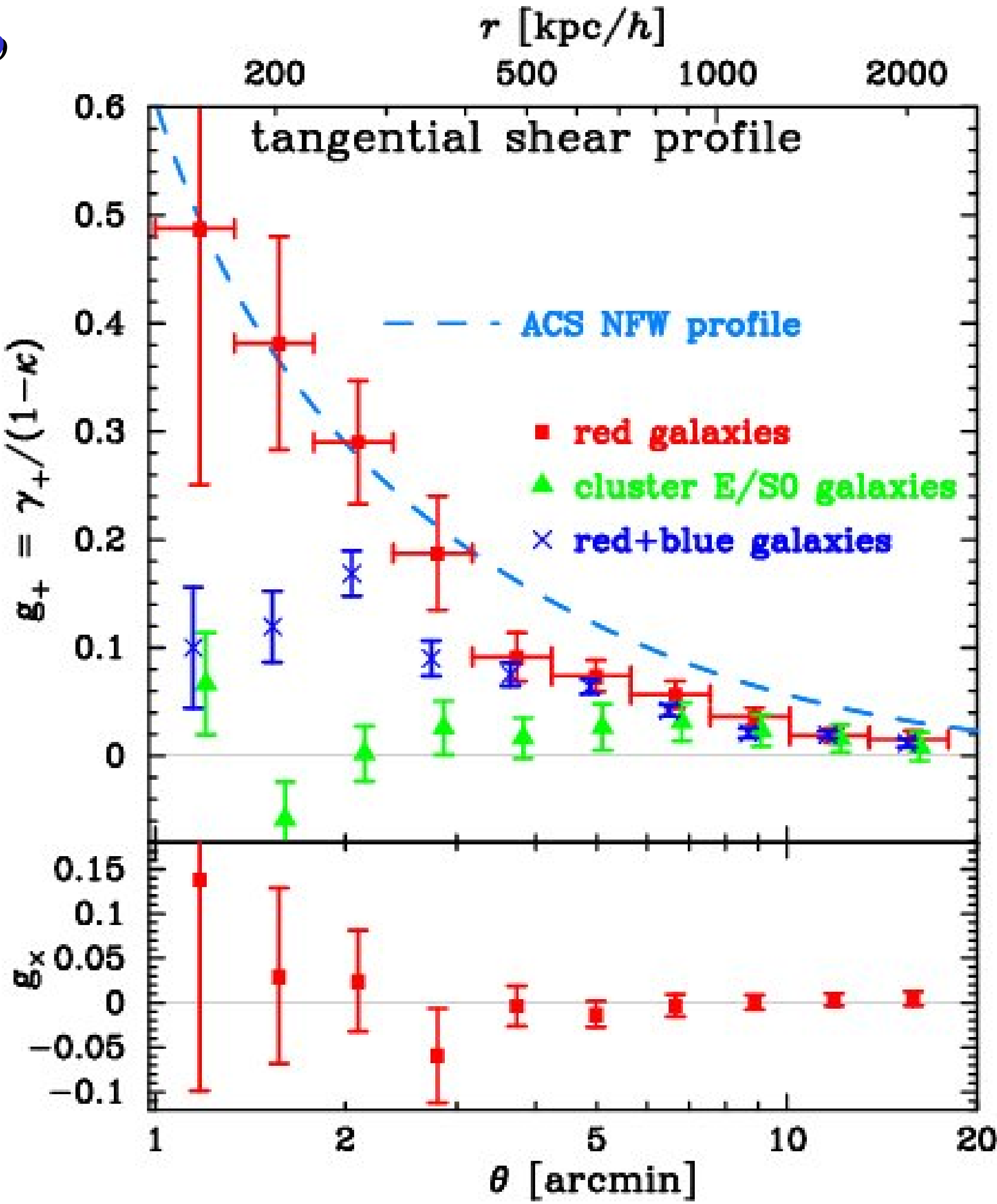
(random orientation)

$$\langle \gamma_{+} \rangle_{\varphi}(\theta) = \gamma_{GL}(\theta) + \frac{\sigma_{int}}{\sqrt{N_g}}$$

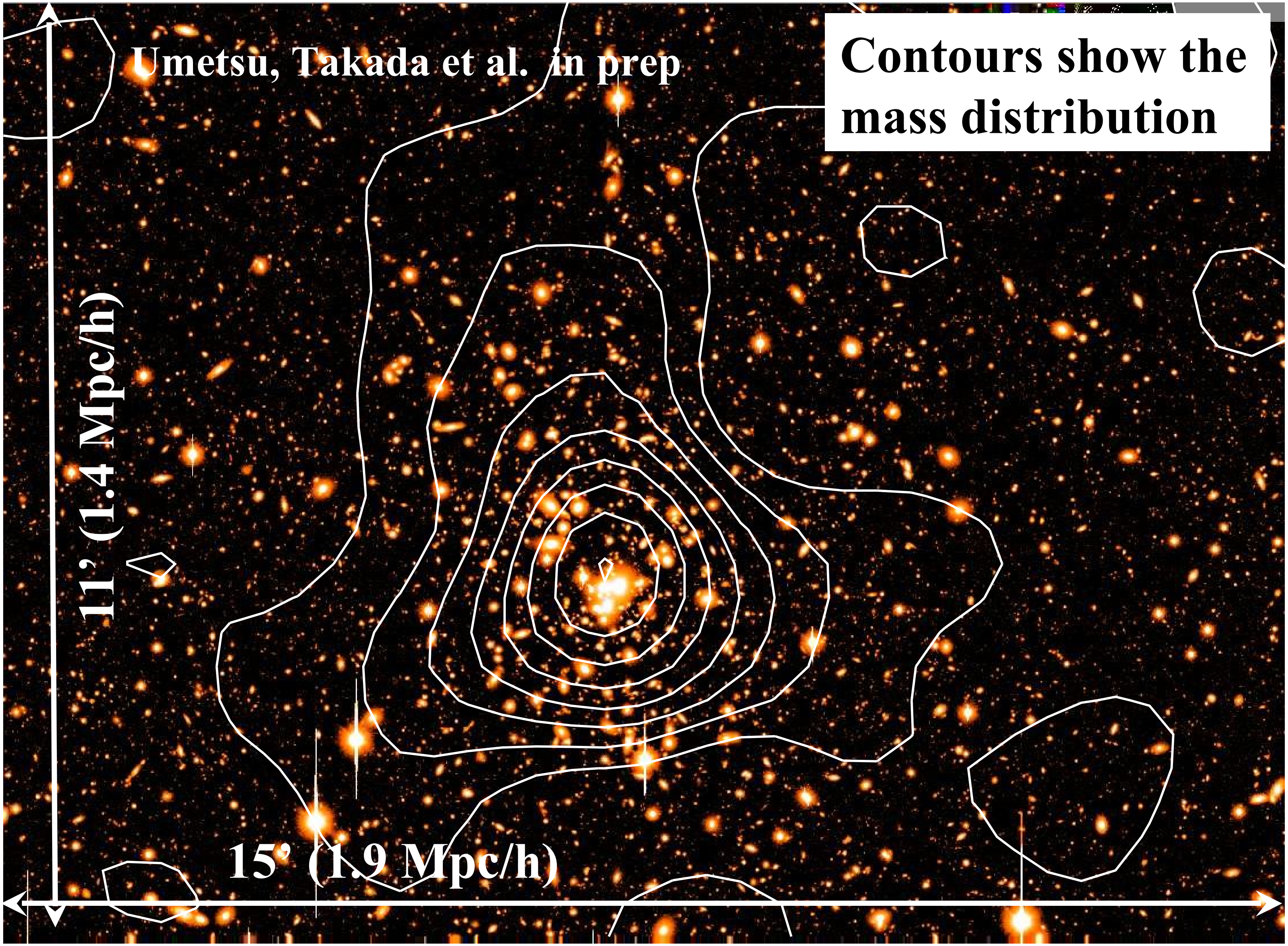


Result (Broadhurst, MT, Umetsu et al. ApJL, 05)

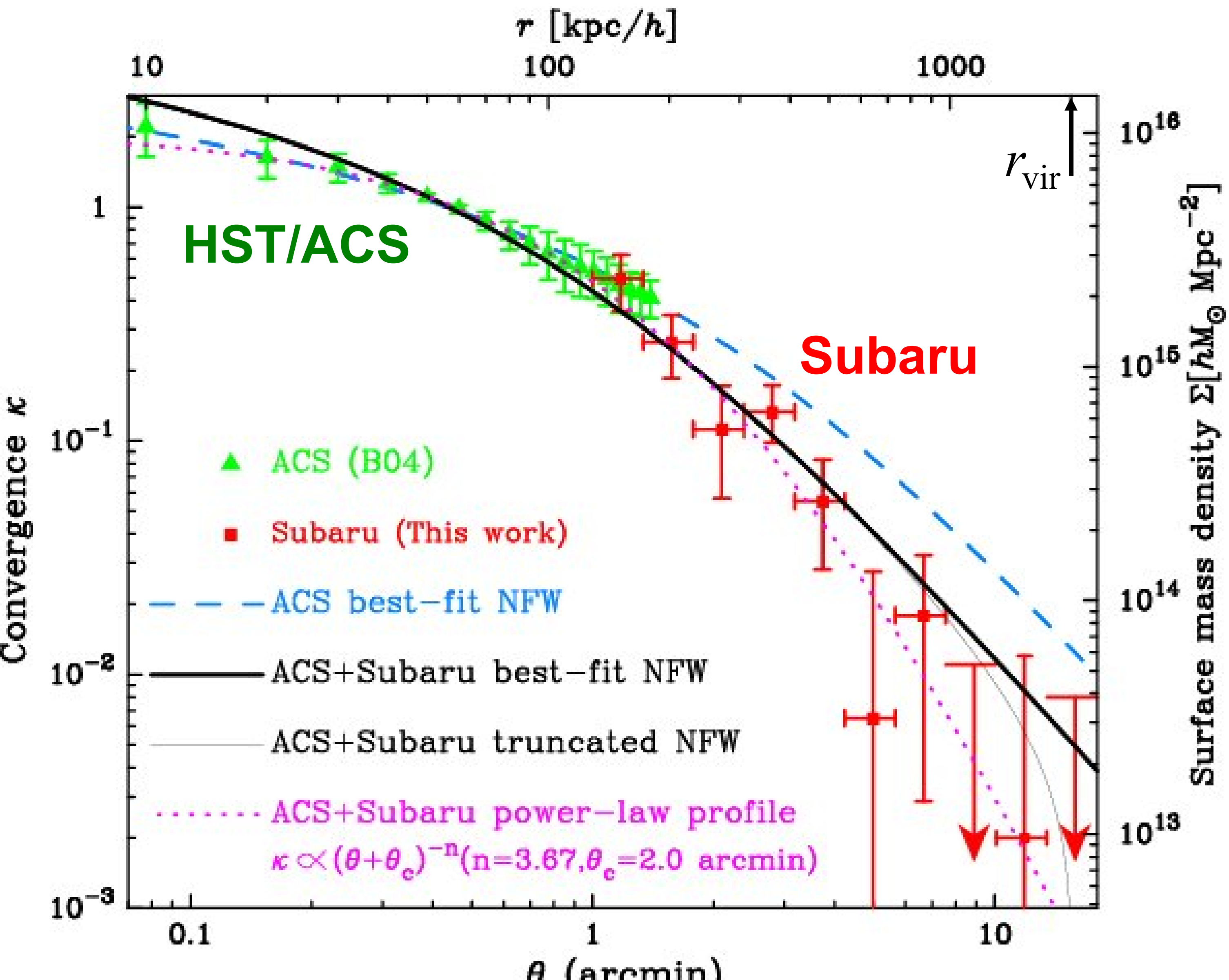
- Significant S/N (12σ in total), up to 20' in radius
- Stronger distortion with decreasing radius
- A secure selection of background galaxies leads to the correct signal, otherwise a factor of 2-5 underestimation (Clowe & Schneider 2001; Bardeau et al. 2004)
- Test of the systematics: a signal of g_x is consistent with null signal



Result: Mass Map



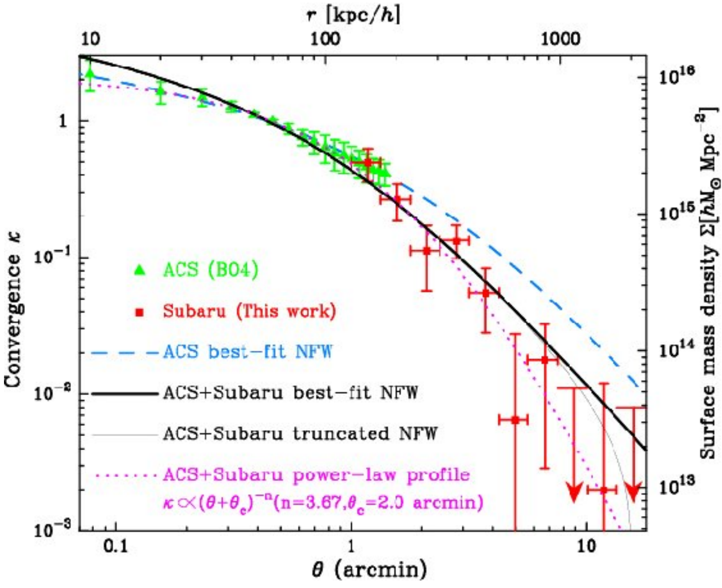
Result: Mass Reconstruction



22 data points

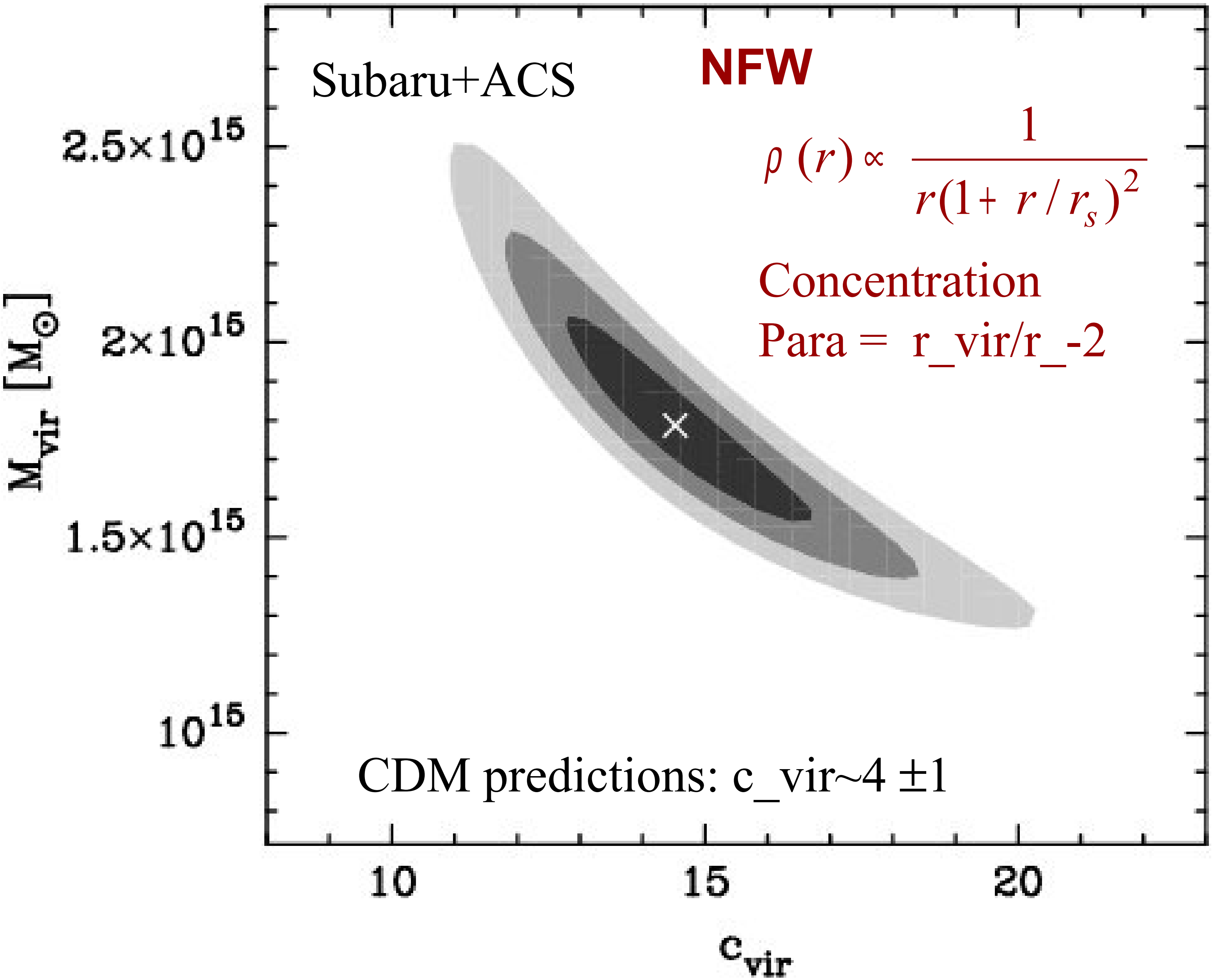
- **Best-fit NFW**
  - $\chi^2_{min}/\text{dof.} = 18./20$
  - $M_{vir} = 1.7^{+0.05}_{-0.05} \times 10^{15} M_s$
  - $r_{vir} = 2.0 \pm 0.02 \text{Mpc}/h$
  - $c_{vir} = 14.5 \pm 0.4$
  - $\Leftrightarrow \ c_{exp} \approx 4 \pm 1$
- **Best-fit CPL**
  - $\chi^2_{min}/\text{dof.} = 15/19$
  - $n = 3.67^{+0.1}_{-0.08}$
  - $\theta_c = 2.0'^{+0.04}_{-0.06}$
  - $(r_c = 259 \text{kpc}/h)$
- **CSIS**
  - $\chi^2_{min}/\text{dof.} = 151/20$

Mass Reconstruction and its Indications



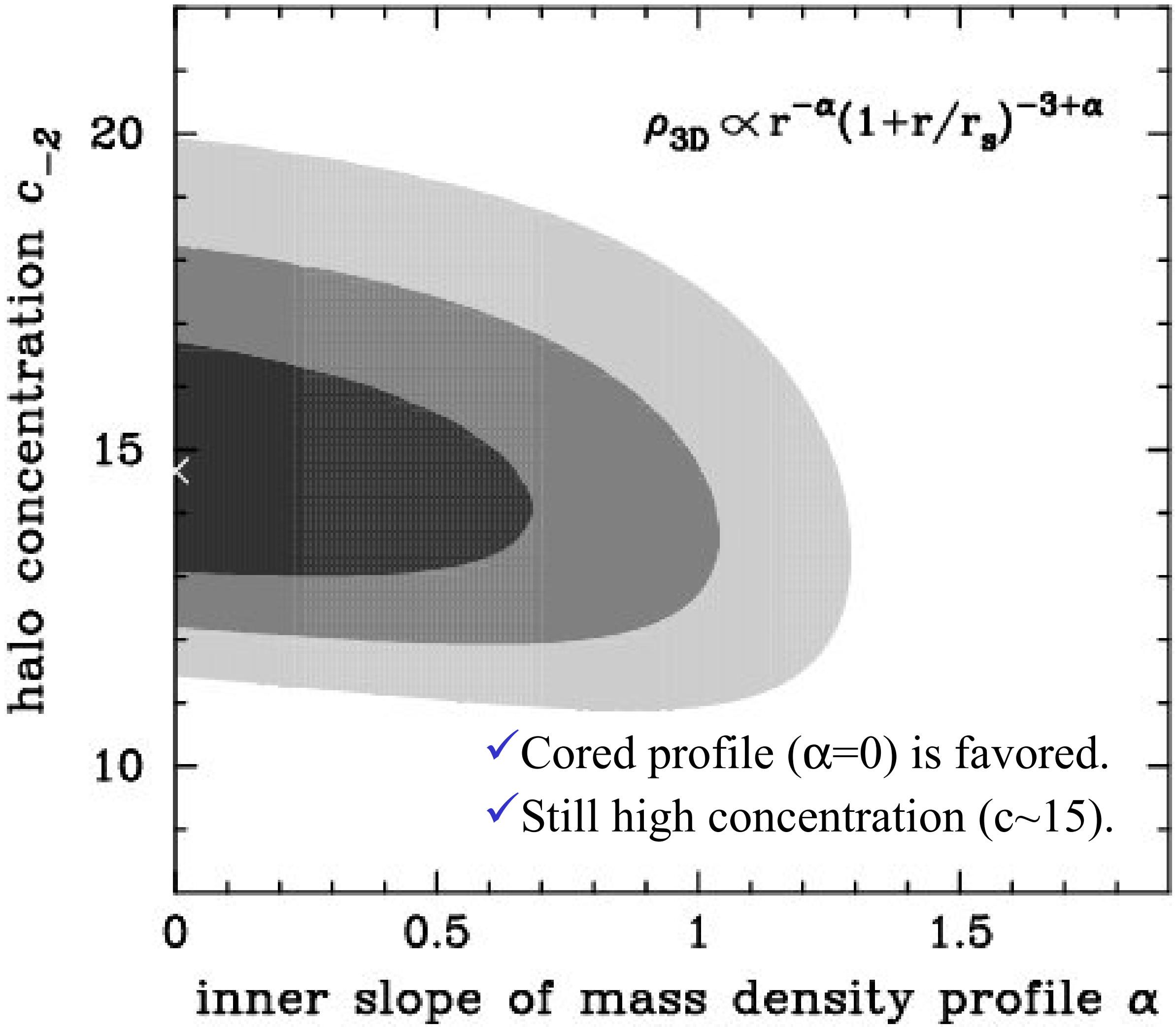
- Succeeded to probe the mass distribution from 10kpc to ~2Mpc in radius
- The 2D radial profile can't be fitted by a single power law, but can be fitted by the CDM prediction, an NFW profile.
- However, possible conflicts between the CDM predictions and the lensing results are found
  - **A large concentration** (the ratio of the radius r^-2 to the virial radius): c~14 compared to the theoretical expectation c~4
    - Various subsequent studies on this issue: e.g., a statistical fluke
  - **An inner slope is shallower than r^-1?**

Constraints on NFW Halo Mass-Concentration



An Inner Slope: Generalized NFW Profile

DM density profile: $\rho \propto r^{-\alpha}(1+r/r_s)^{-3+\alpha}$



✓Cored profile (α=0) is favored.

✓Still high concentration (c~15).

Other clusters

✓c~12 for MS2137 (Gavazzi et al. 2003)

✓c~22 for Cl0024 (Tyson et al. 1998; Kneib et al. 2003)

✓α~0.5 for **A383, MS2137**, A963, MACS1206, A1201; α~1 for RXJ1133 (Sand et al. 2002, 2004)

Possible origin

✓Baryon contraction (c↑, α↑ Gnedin et al. 2004), but seems difficult

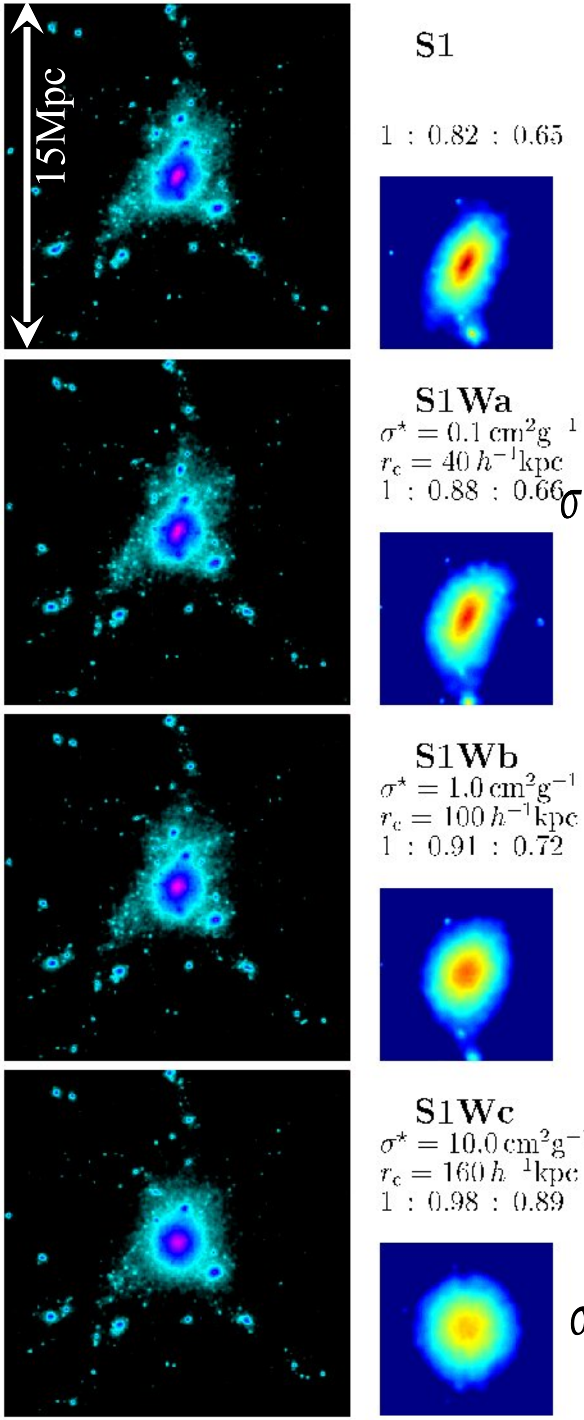
✓DM nature?(α↓ Yoshida et al. 2000)

✓AGN heating? ⇔ cooling flow problem

Self-interacting DM Scenario

(Spergel & Steinhardt, PRL ,00)

- Yoshida et al. (2000) performed N-body simulations of halo region for self-interacting DM scenario.
- The self-interaction leads to more isotropic velocity distribution, compared to the collisionless scenario.
- The resulting halo has a rounder shape and its inner profile generally has a shallower slope ($\alpha<1$) (even a cored structure if sigma is large enough).



$\sigma_{DM} = 0.1 g^{-1} cm^2$

$\approx 10^{-25} \frac{cm^2}{GeV}$

$\sigma_{DM} = 1 g^{-1} cm^2$

$\sigma_{DM} = 10 g^{-1} cm^2$

Future Prospects

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

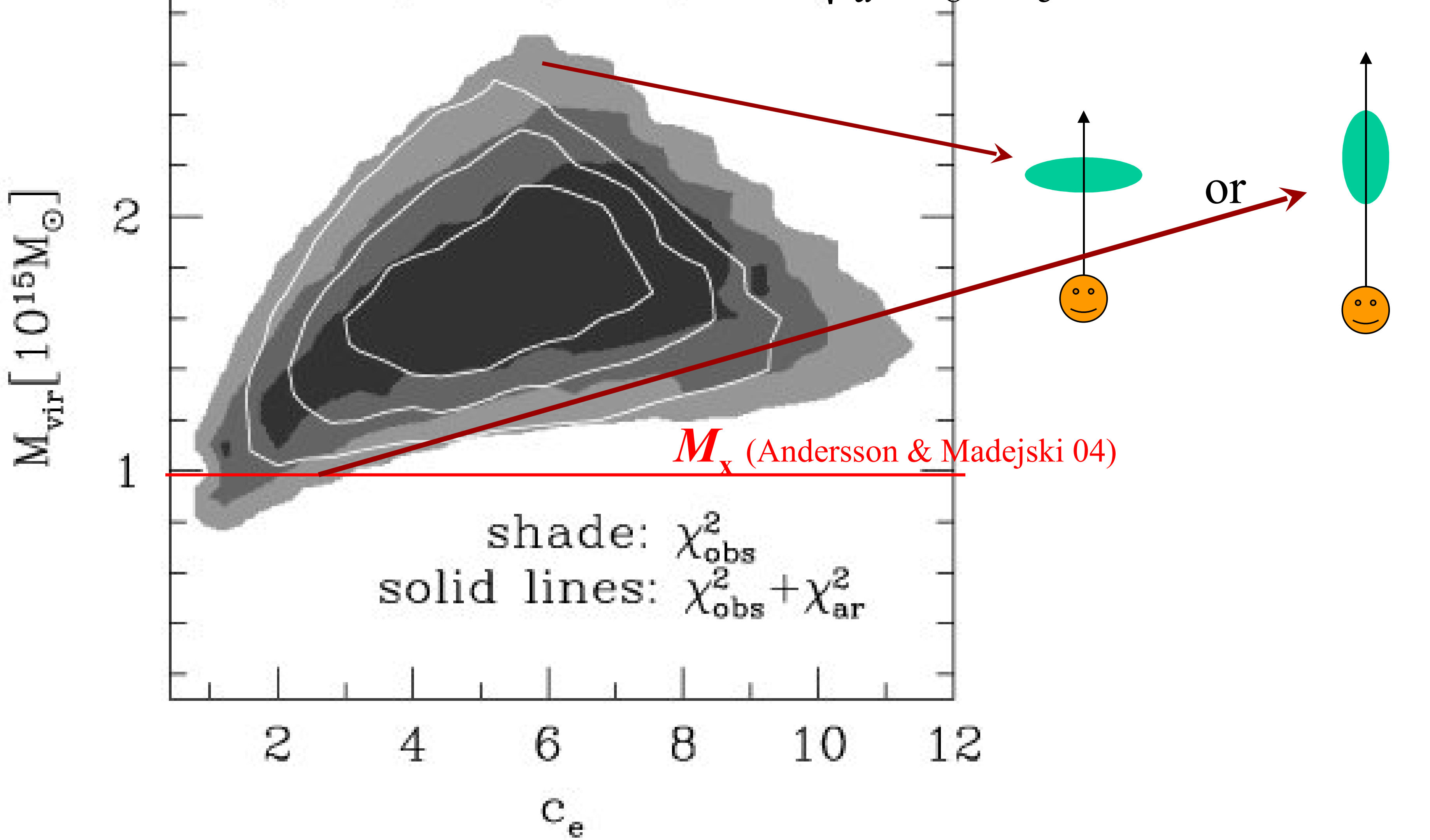
- Subaru observation (PI: Prof. Futamase)
  - 3 nights so far allocated (however, not so good weather unfortunately): have collected data for ~15 clusters
- HST/ACS observation (PI: G.P.Smith)
  - 143 orbits observations (starting form 2007 Jan)
  - Will observe the central region of 143 clusters
- Also other wavelengths data (X-ray, radio etc) are available for sub-sample of clusters
- We expect that this project will deliver us an important clue to resolving the nature of DM.

Summary

- Gravitational lensing is a unique means of probing the mass distribution in a galaxy cluster
- Combining strong and weak lensing, Subaru and HST, can be a powerful way to reconstruct the mass distribution from ~10kpc to ~Mpc.
- The mass distribution obtained provides us an important clue to resolving the nature of DM.
- We are conducting the international collaboration of the ultimate study of lensing clusters in order to make a quantitative test of CDM predictions on small scales

Effect of DM Halo Asphericity

$$\rho(R) \propto R^{-1}(1+R/R_0)^{-2}, \quad R = c\sqrt{\frac{X^2}{a^2}+\frac{Y^2}{b^2}+\frac{Z^2}{c^2}}\,(c \geq b \geq a)$$



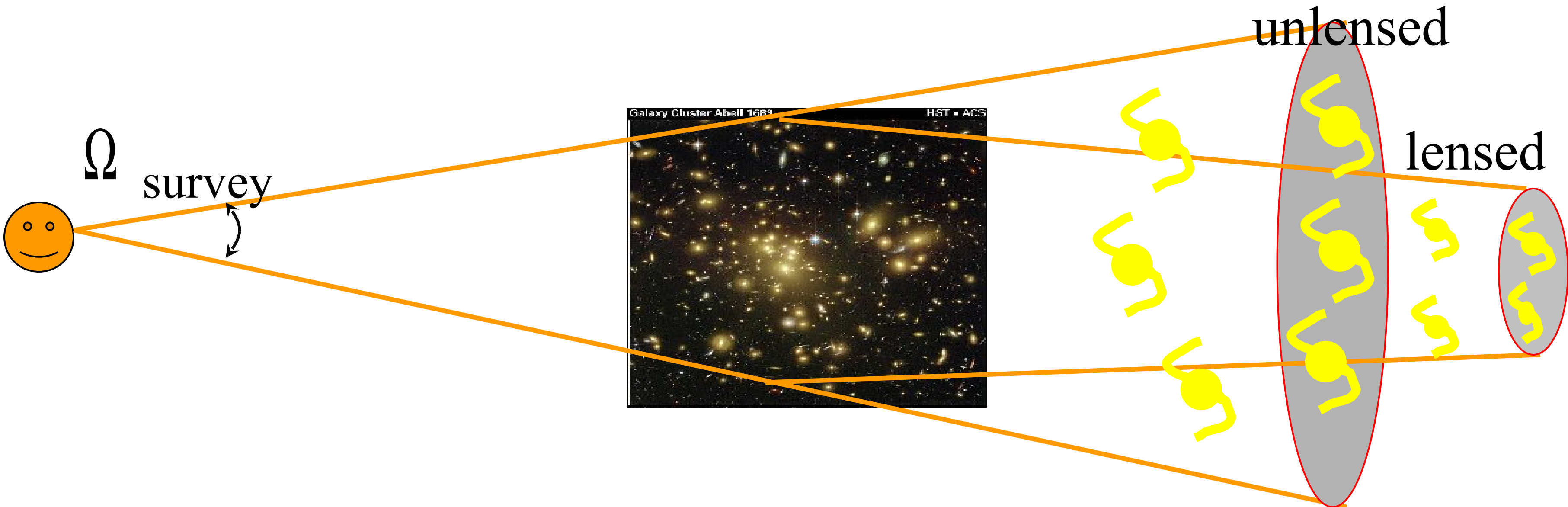
Another WL observable: Magnification Bias

- Lensing of a cluster leads to a change in the number counts of background galaxies brighter than a given limit: $n(m<m_{cut})$
  - Negative effect: Reduces an observed solid angle compared to blank field
  - Positive effect: Brightens a galaxy so that it may be included in a sample
- If the intrinsic number counts is given by

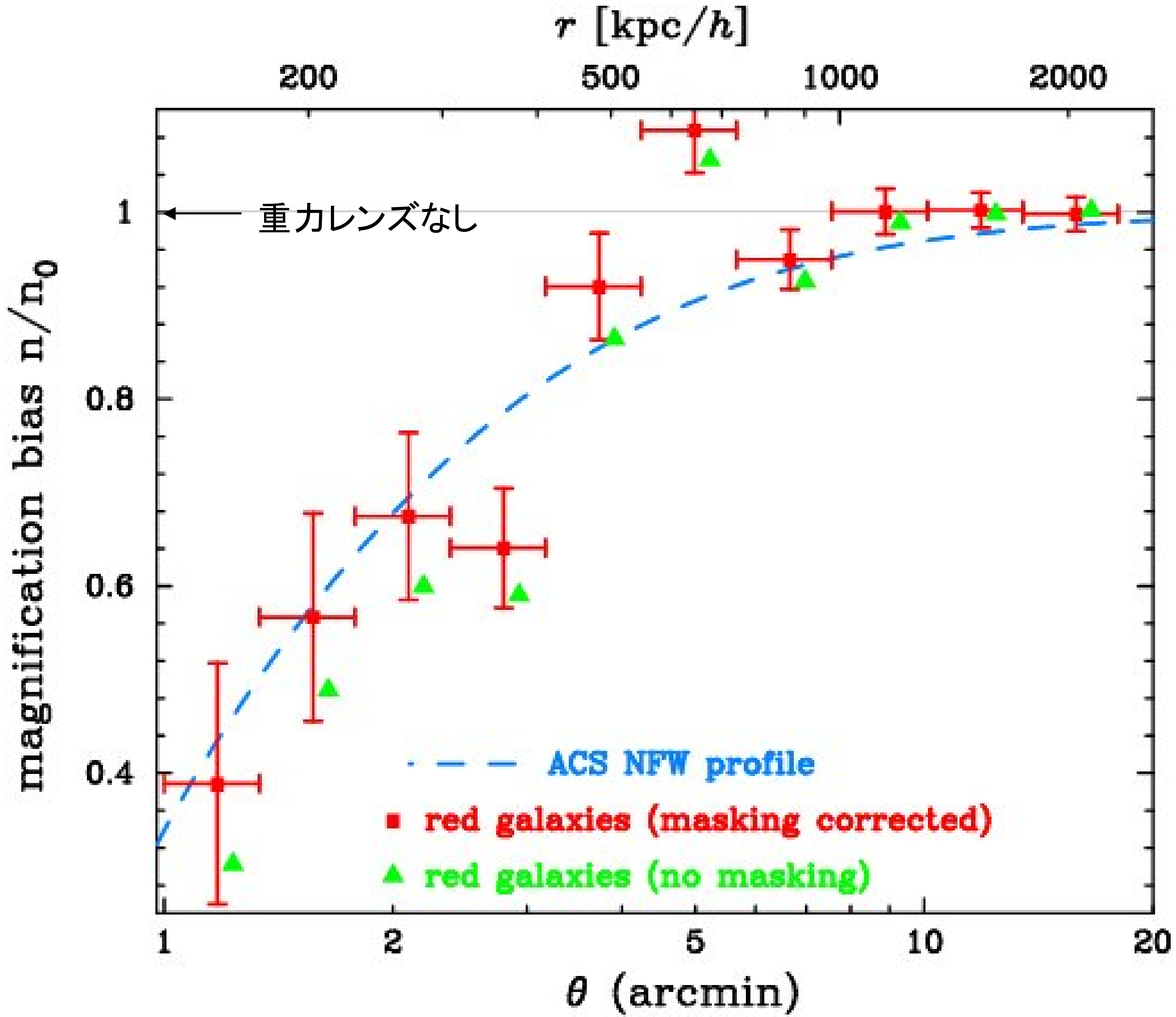
$$n_0(m < m_{cut}) \propto 10^{ms} \qquad (s = 0.22 \pm 0.03 \text{ for red galaxy sample})$$

$\Rightarrow$ Observed counts would be

$$n(m < m_{cut}) = \mu^{2.5s-1} n_0(m < m_{cut}), \quad \mu = \left|(1-\kappa)^2 - \gamma_T^2\right|^{-1} \approx 1 + 2\kappa$$



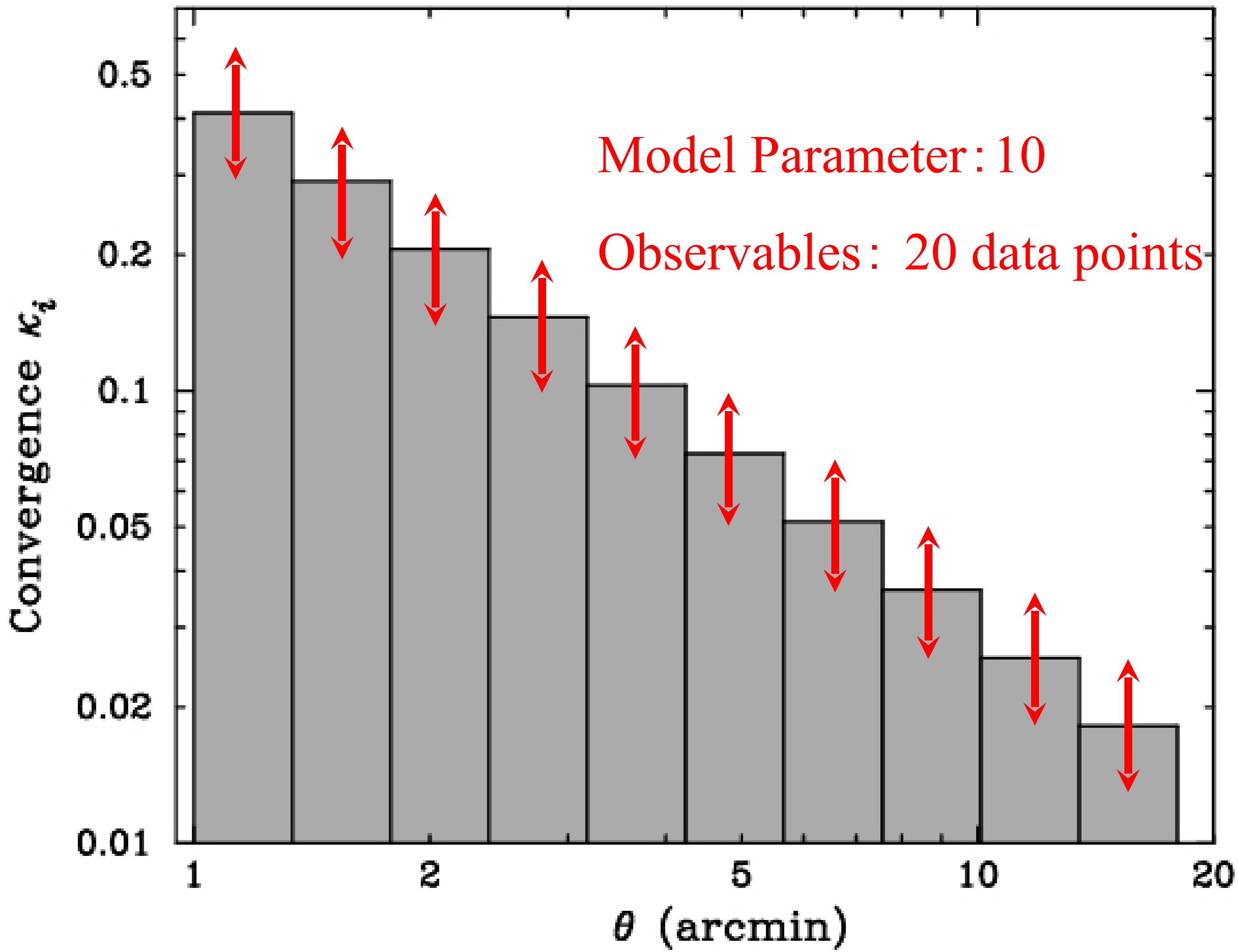
Result: Magnification Bias



- A significant S/N (9.25σ)

Model-Independent Mass Profile Reconstruction

Find the best-fit model, $\kappa(\theta_i)$, to reproduce the two measurements.



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(Spergel & Steinhardt 2000)

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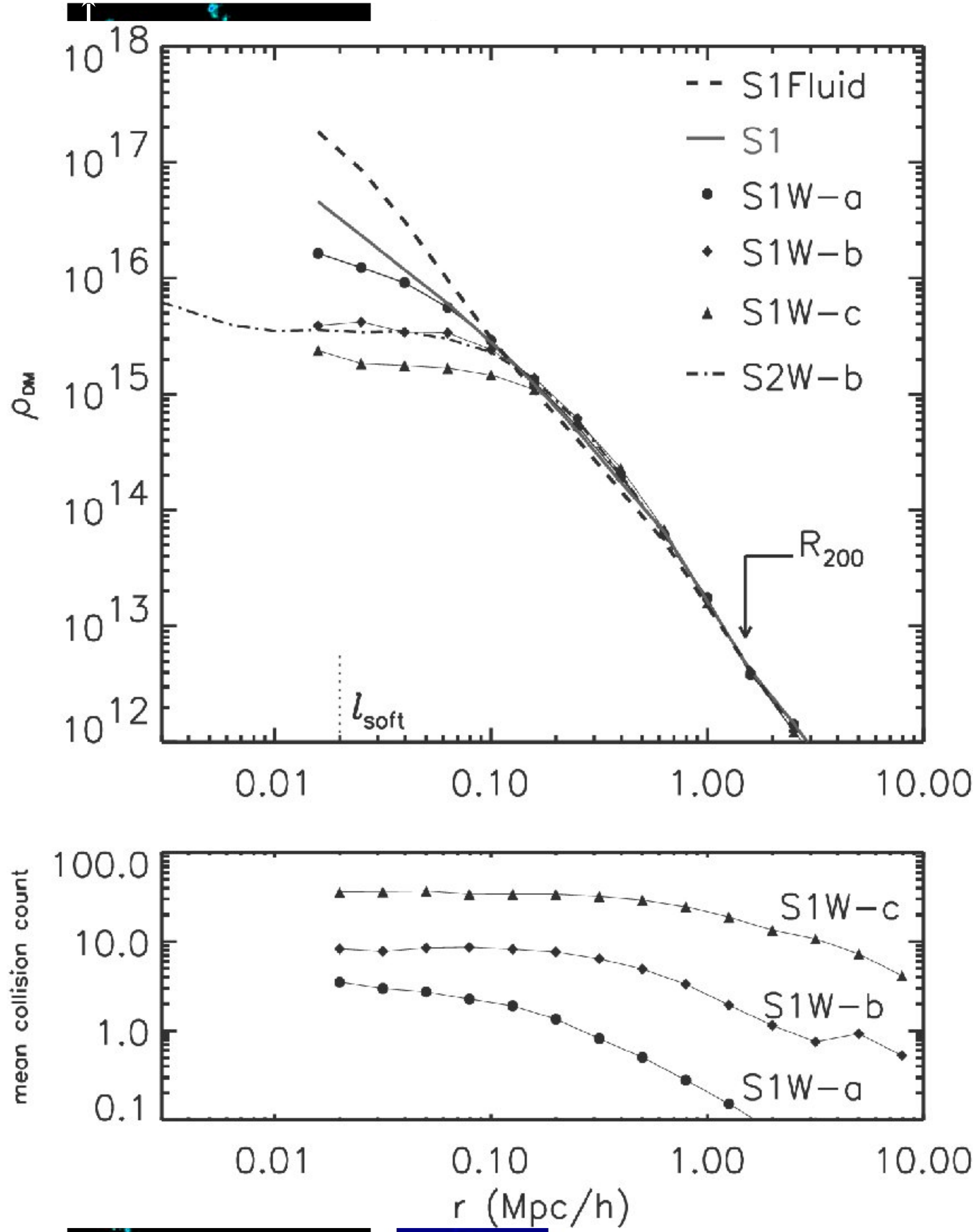
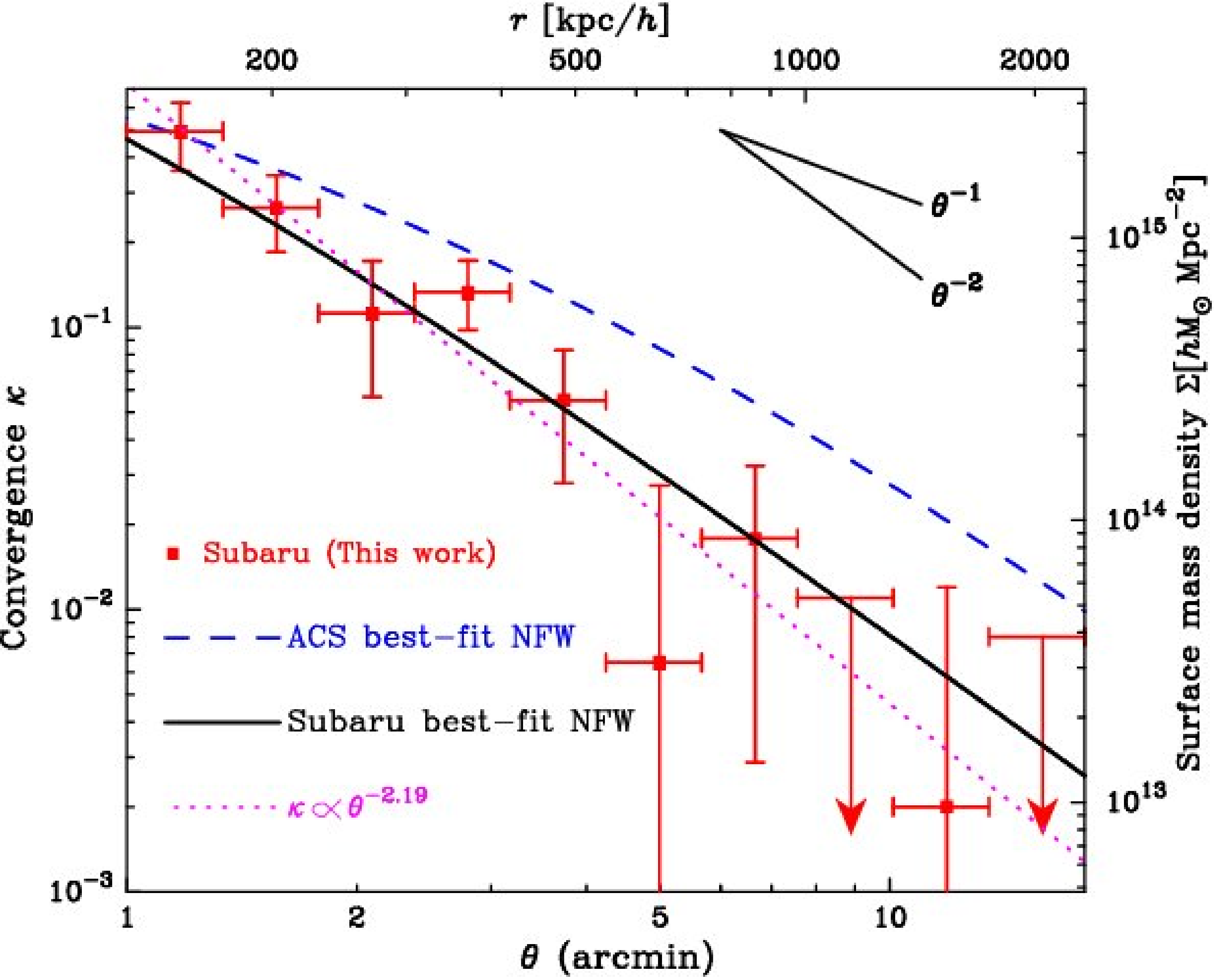
- The self-interaction leads to more isotropic velocity dispersion compared to the collisionless scenario.
- The resulting halo profile is shallower ($\alpha<1$) and has a cored structure in the inner region.



Mass Profile Reconstruction



- Best-fit model
  $\chi^2_{min}/\mathrm{dof.} = 12.4/8$
- Best-fit NFW
  $\chi^2_{min}/\mathrm{dof.} = 7.4/8$

$M_{vir} = 1.6 \pm 0.3 \times 10^{15} M_s$

$r_{vir} = 1.9 \pm 0.1 \mathrm{Mpc}/h$

$c_{vir} > 30$

$\Leftrightarrow \quad c_{exp} \approx 4 \pm 1$

- Best-fit PL
  $\chi^2_{min}/\mathrm{dof.} = 4.7/8$

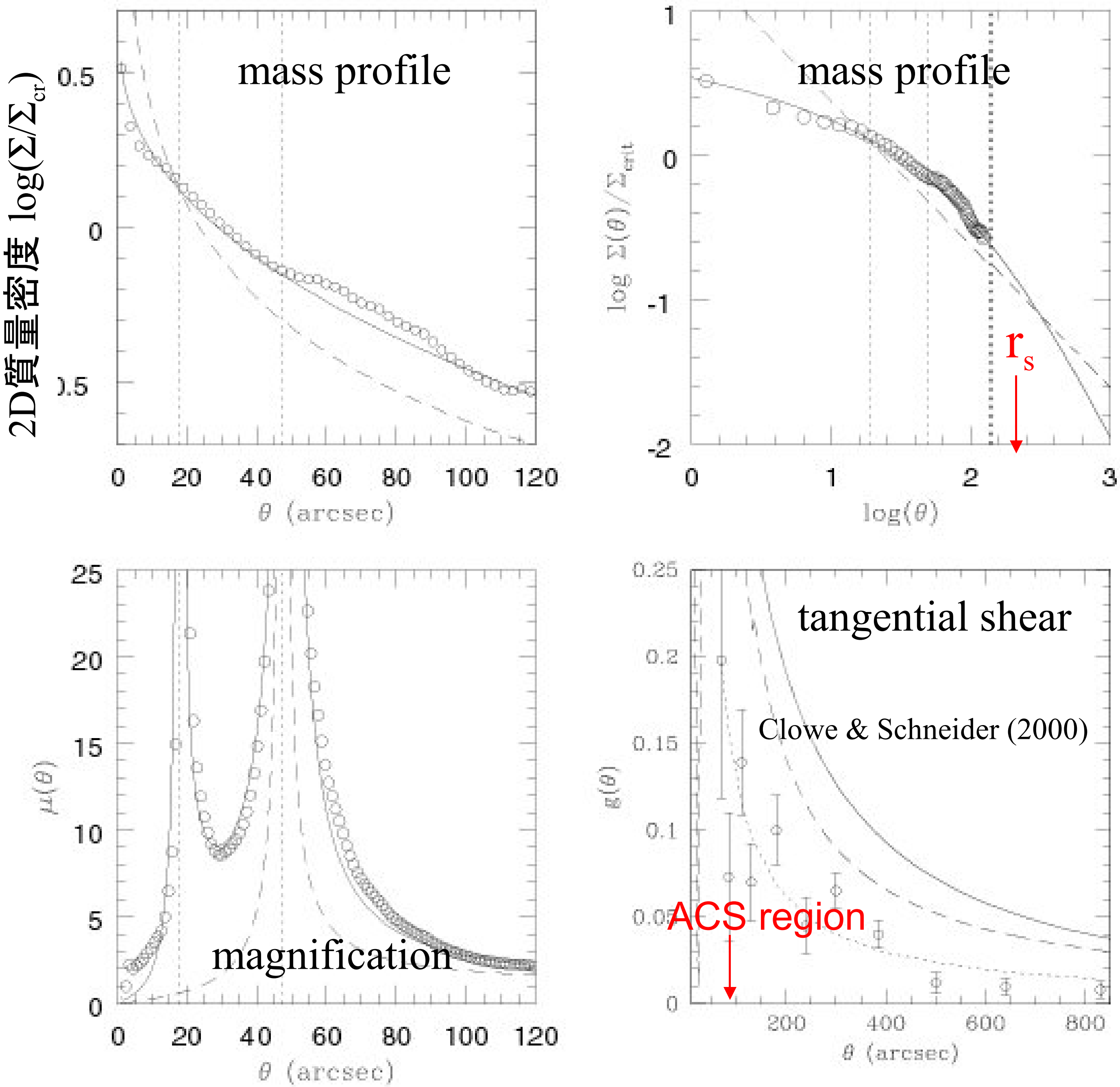
$n = 2.2 \pm 0.02$

$(3D : n \approx 3.2)$

- SIS
  $\chi^2_{min}/\mathrm{dof.} = 27./9$

3σで棄却

Mass Reconstruction Result of the ACS data (B04)



重要な結果

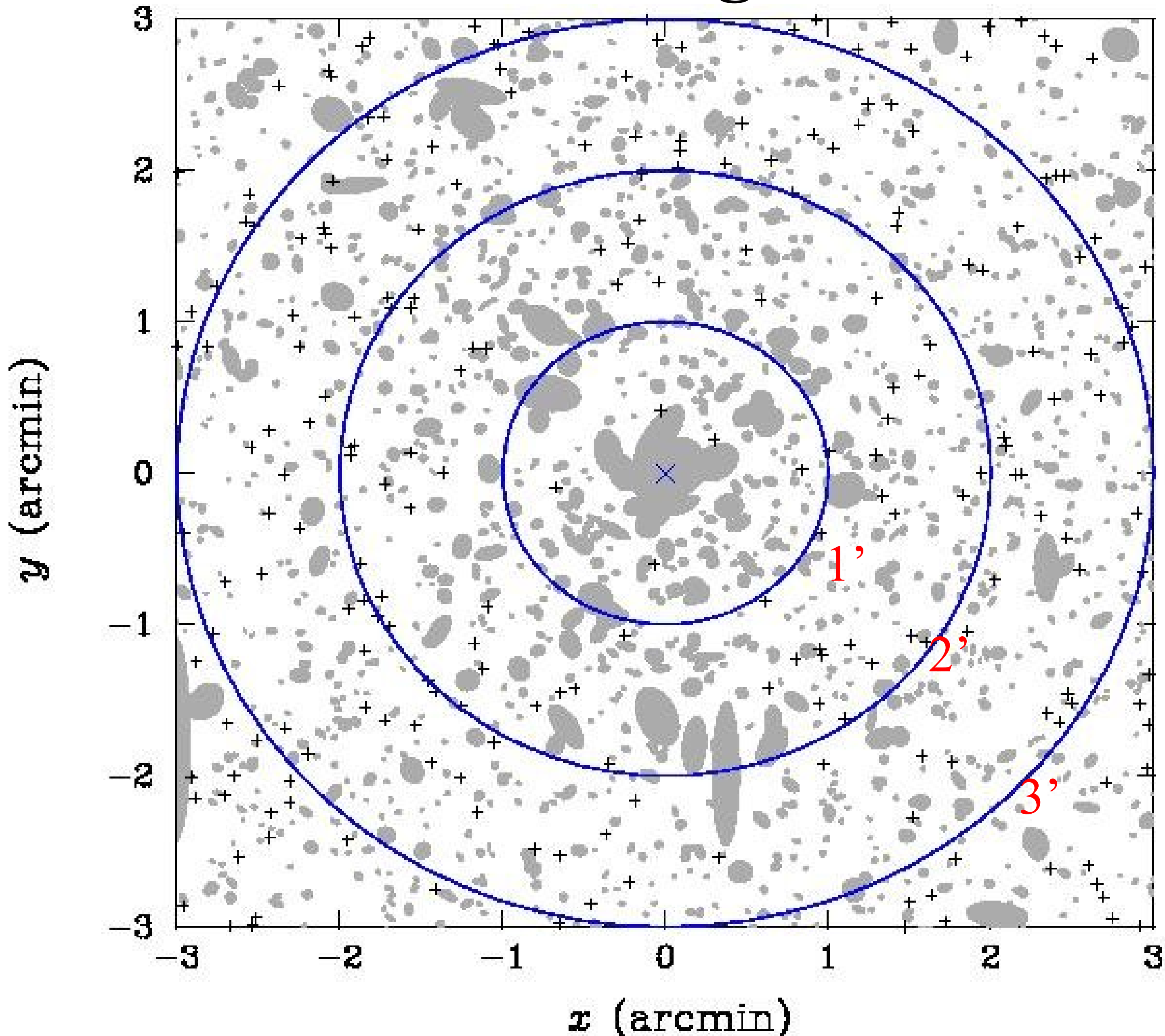
A1689の質量分布の勾配は半径と共に緩やかになっている。NFWはデータを良い精度で再現する。

問題点

1.ACSのデータは、中心領域だけ ($<r_s$=300kpc,$<r_{vir}$=2Mpc)

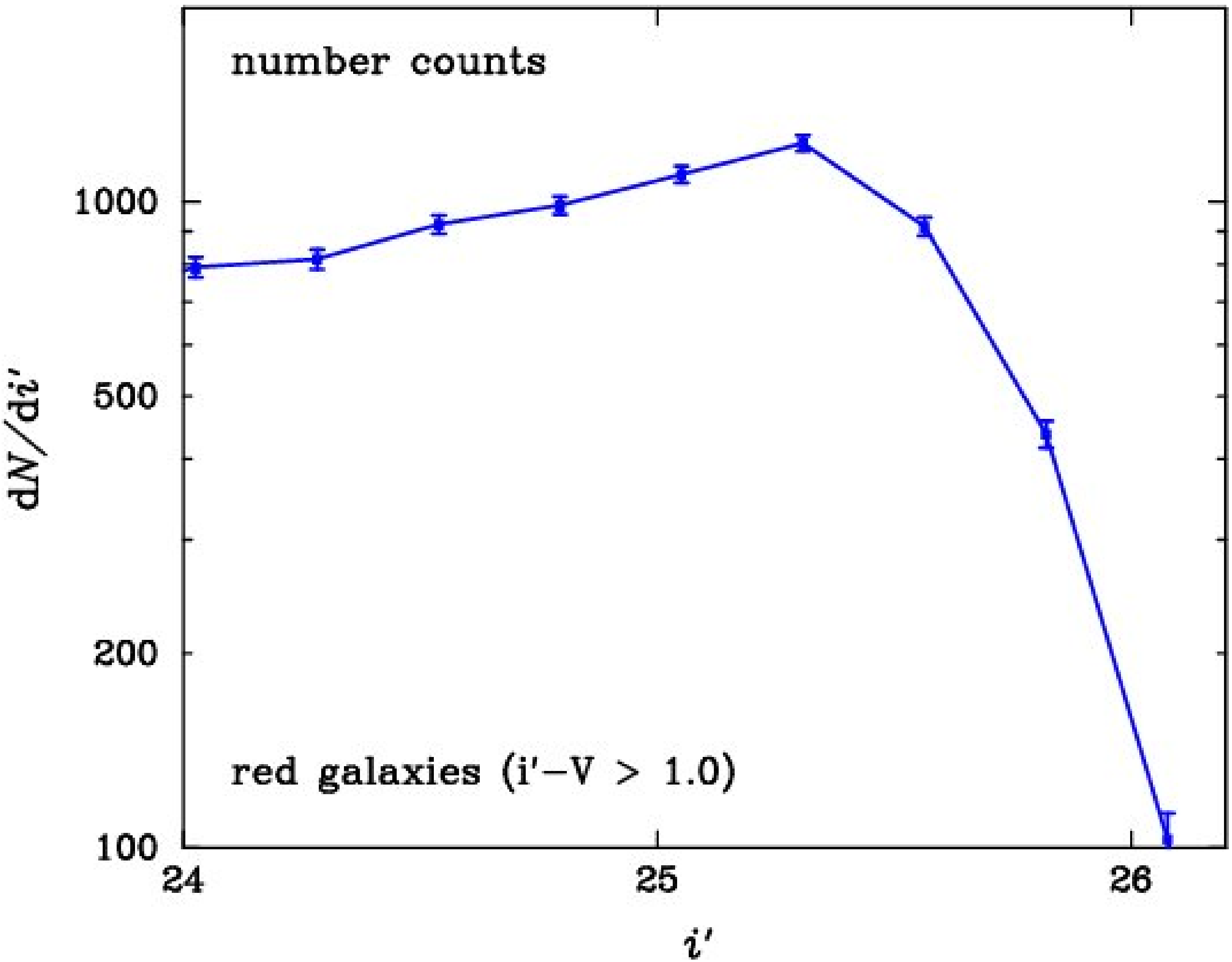
2.弱い重力レンズ効果観測とのfactor of 2-3のズレ

Masking effect

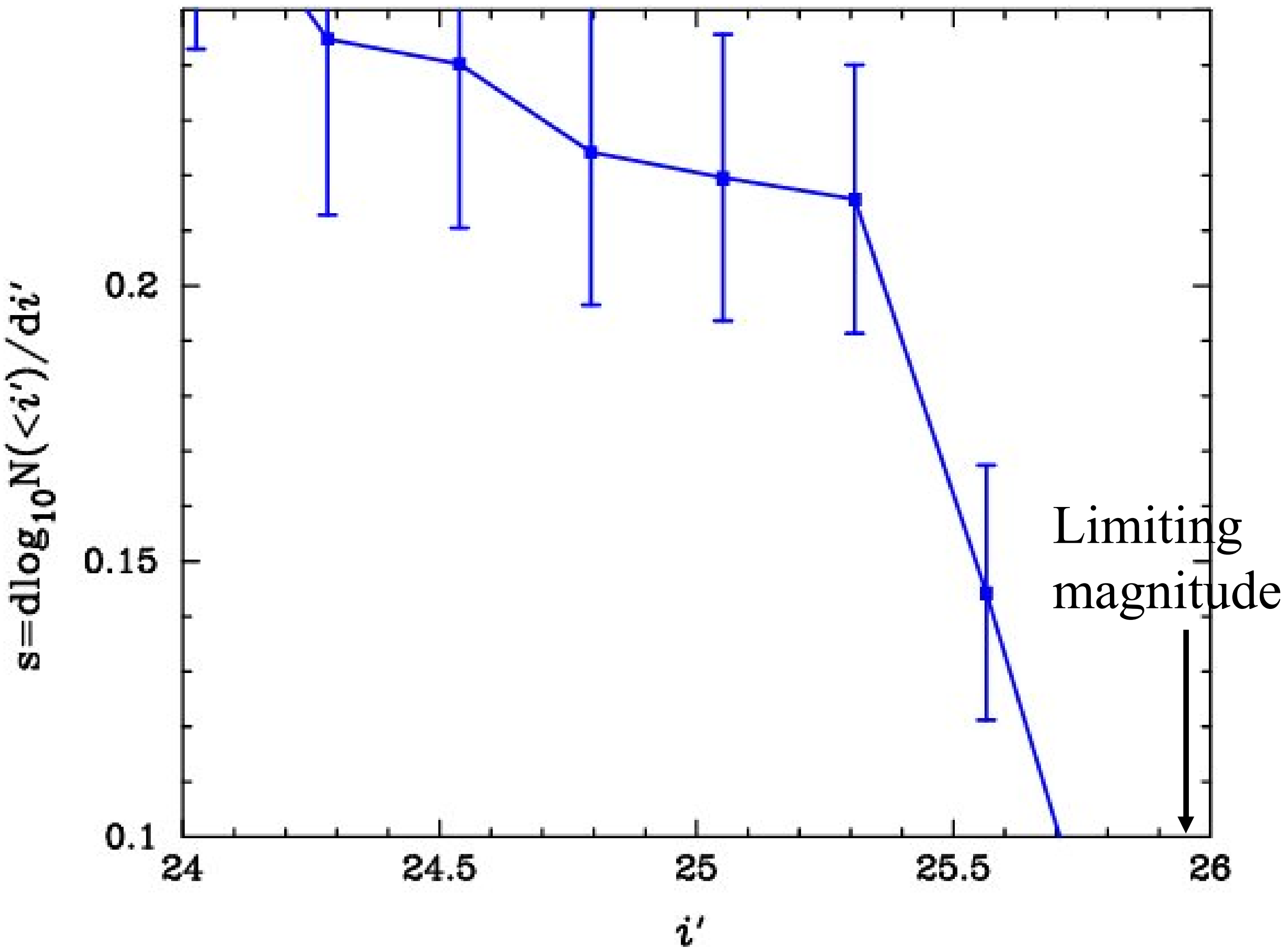


2分以下の領域では、masking areaは約20%の割合い

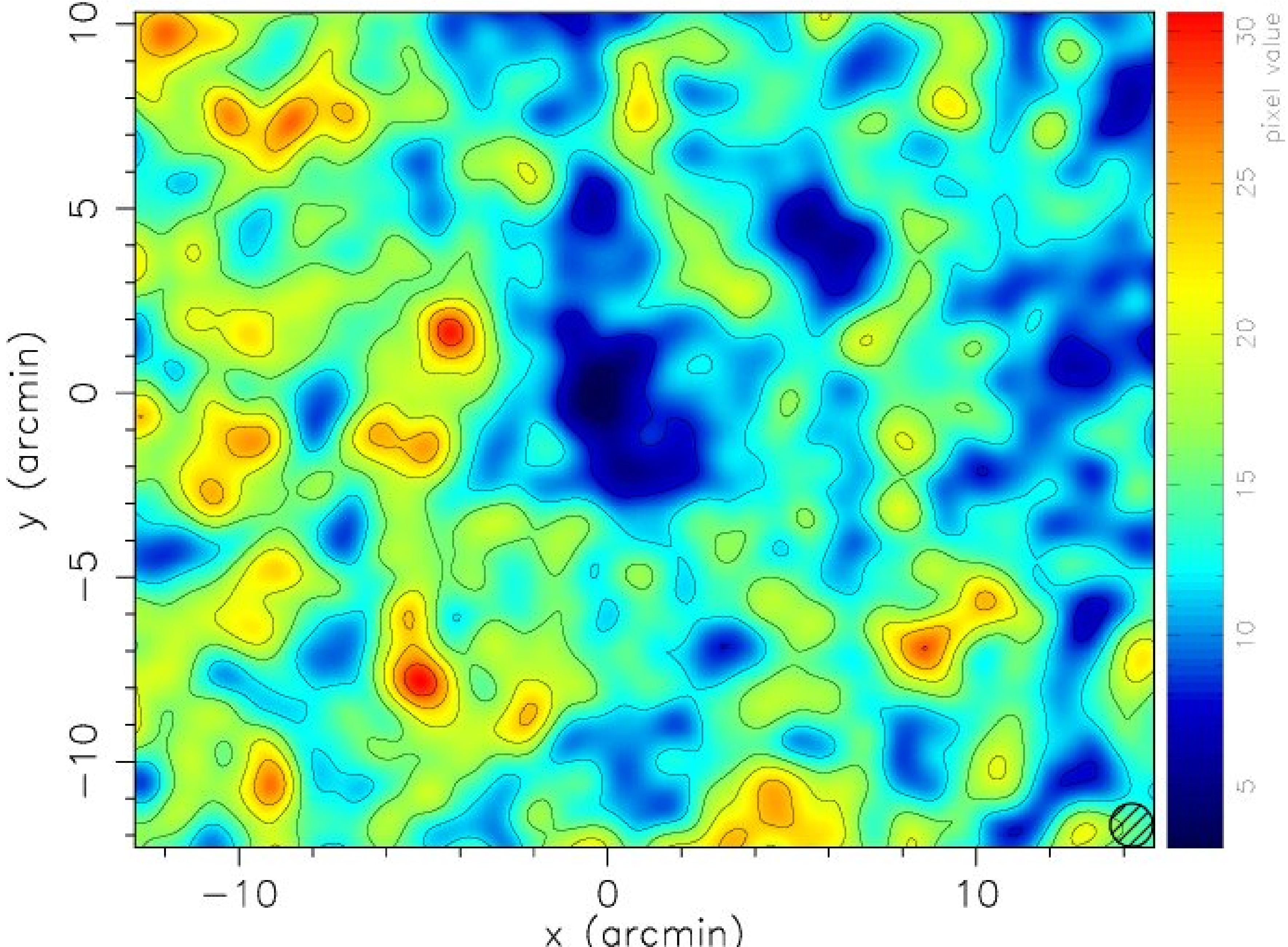
The Unlensed Number Counts(1)



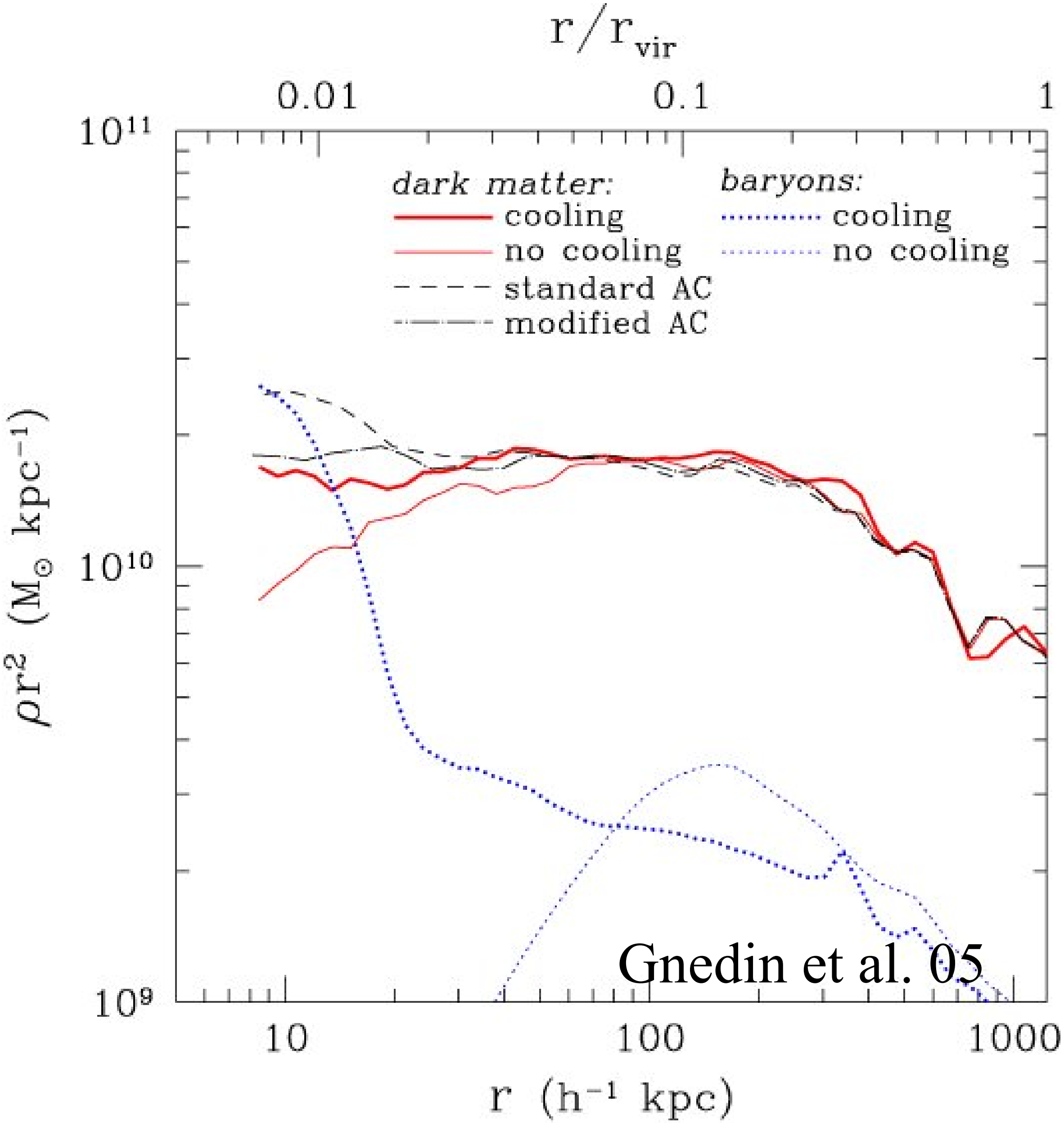
The Unlensed Number Counts(2)



Mass(Shear) Map vs Smoothed Number Counts Map



Baryonic Effect on Halo Mass Profile



- At r<10kpc, baryon is dominant to the total matter
- The slope of total matter steapens