Subaru Weak Lensing Studies of X-ray luminous clusters

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INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

@KIAS, Nov 4, 2010

3rd year anniversary photo

We are rapidly growing!

~60% non-Japanese

We are still looking for new members

Collaborators

T. Futamase (Tohoku U.)

N. Okabe (Taiwan)

K. Takahashi (Tohoku U.)

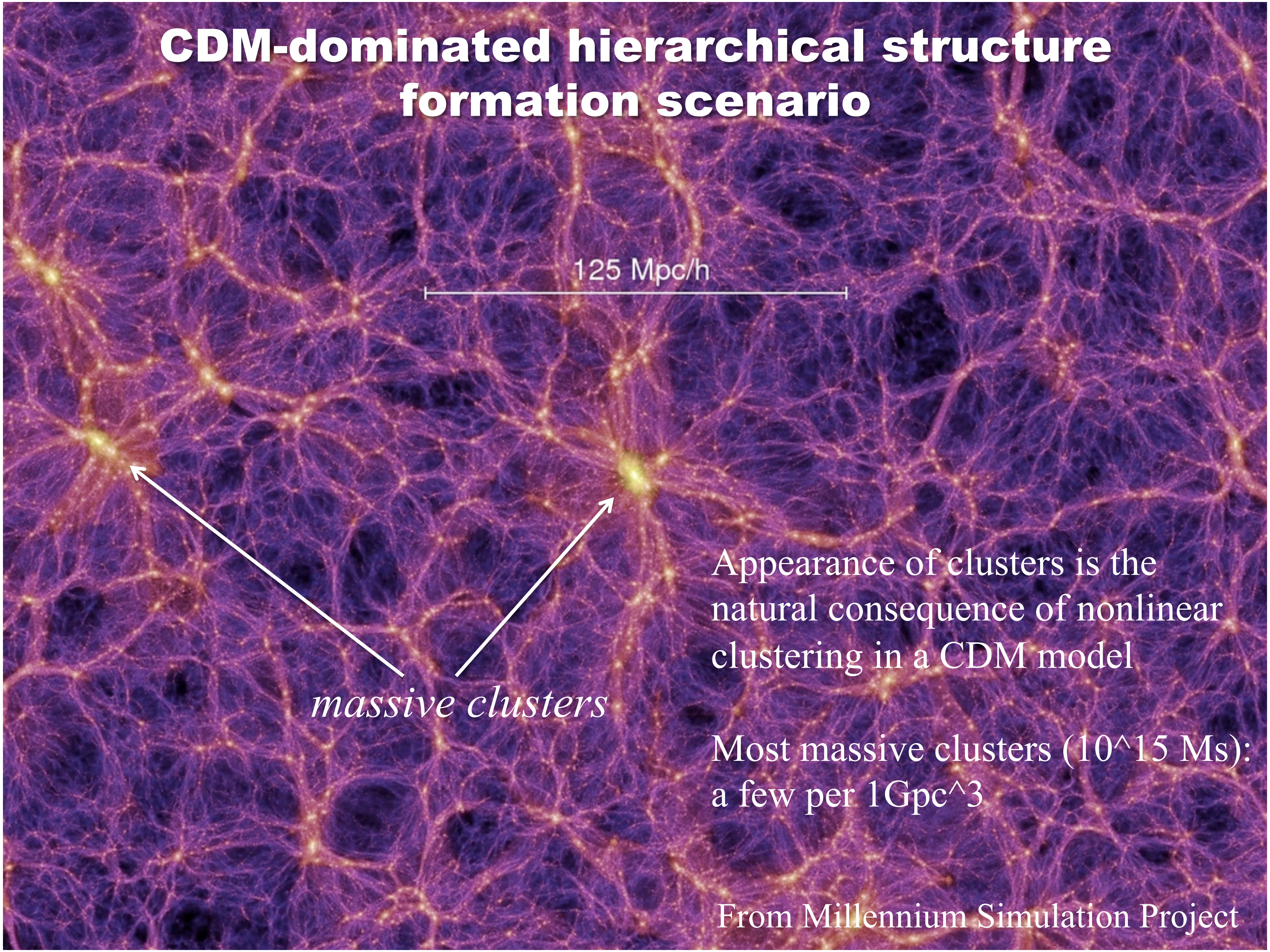
K. Umetsu (ASIAA Taiwan)

T. Broadhurst (Tel Aviv)

M. Oguri (NAOJ)

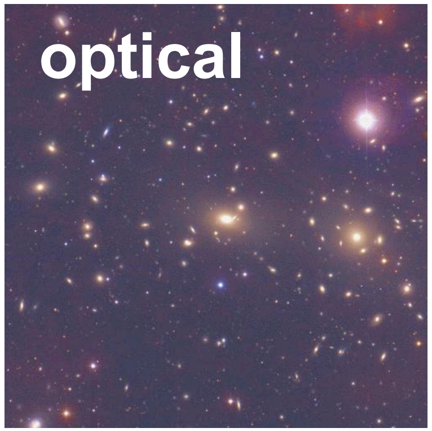
G. P. Smith (Birmingham)

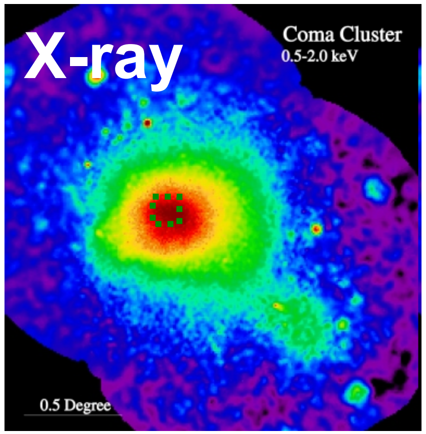
Most part of this talk is mainly based on
Okabe, MT, Umetsu, Futamase, Smith, arXiv:0903:1103, PASJ in press
Oguri, MT, Okabe, Smith, arXiv:1004.4214, MNRAS in press

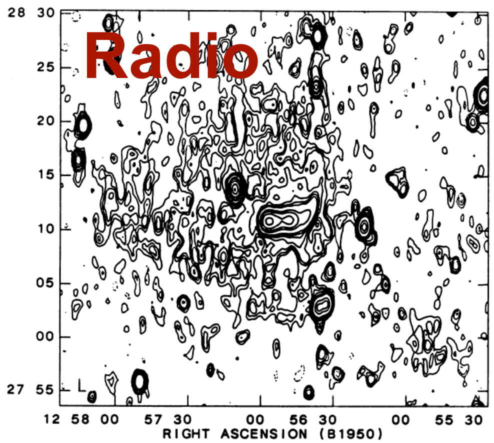

CDM-dominated hierarchical structure formation scenario
125 Mpc/h
massive clusters
Appearance of clusters is the natural consequence of nonlinear clustering in a CDM model
Most massive clusters (10^15 Ms): a few per 1Gpc^3
From Millennium Simulation Project

Galaxy Clusters

- Most massive gravitationally bound objects
  - 10^14 ~ 10^15 M_sun (100 – 1000 galaxies)
  - Strongest S/N of the lensing signals
  - DM plays a dominant role to the formation ⇔ for a galaxy, baryonic effect is important
  - Suitable for testing the CDM scenarios on small scales <1Mpc
- 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); **100:10:1**

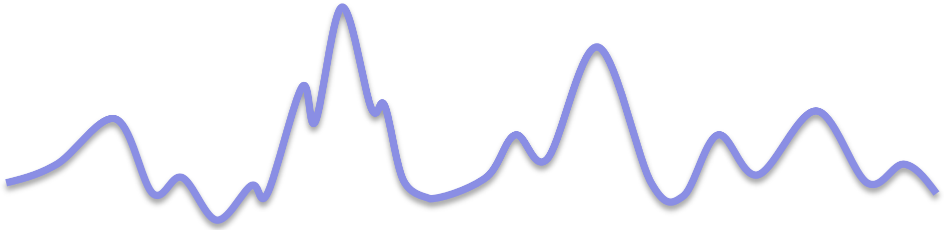






Cosmological Use of Clusters: Halo Mass Function

Tiny density fluctuations at z~1000: δ_m~10^-3

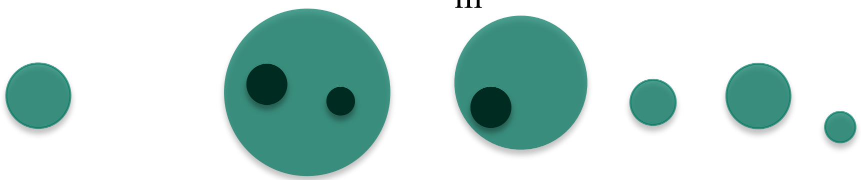


Gravitational instability

(gravity ⇔ cosmic expansion)

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\bar{\rho}_m\delta_m = 0$$

Halo formation at z~0: δ_m>>1



Gaussian seed density fluctuations

+

Spherical collapse model (or N-body simulation)

Mass function:

$$\frac{dn}{dM} \propto \exp\left(-\frac{\delta_c^2}{2\sigma^2(M)}\right)$$

@cluster mass scales

The mass function can be a powerful probe of cosmology (e.g. DE)

Halo mass function (contd.)

Angular number counts of clusters

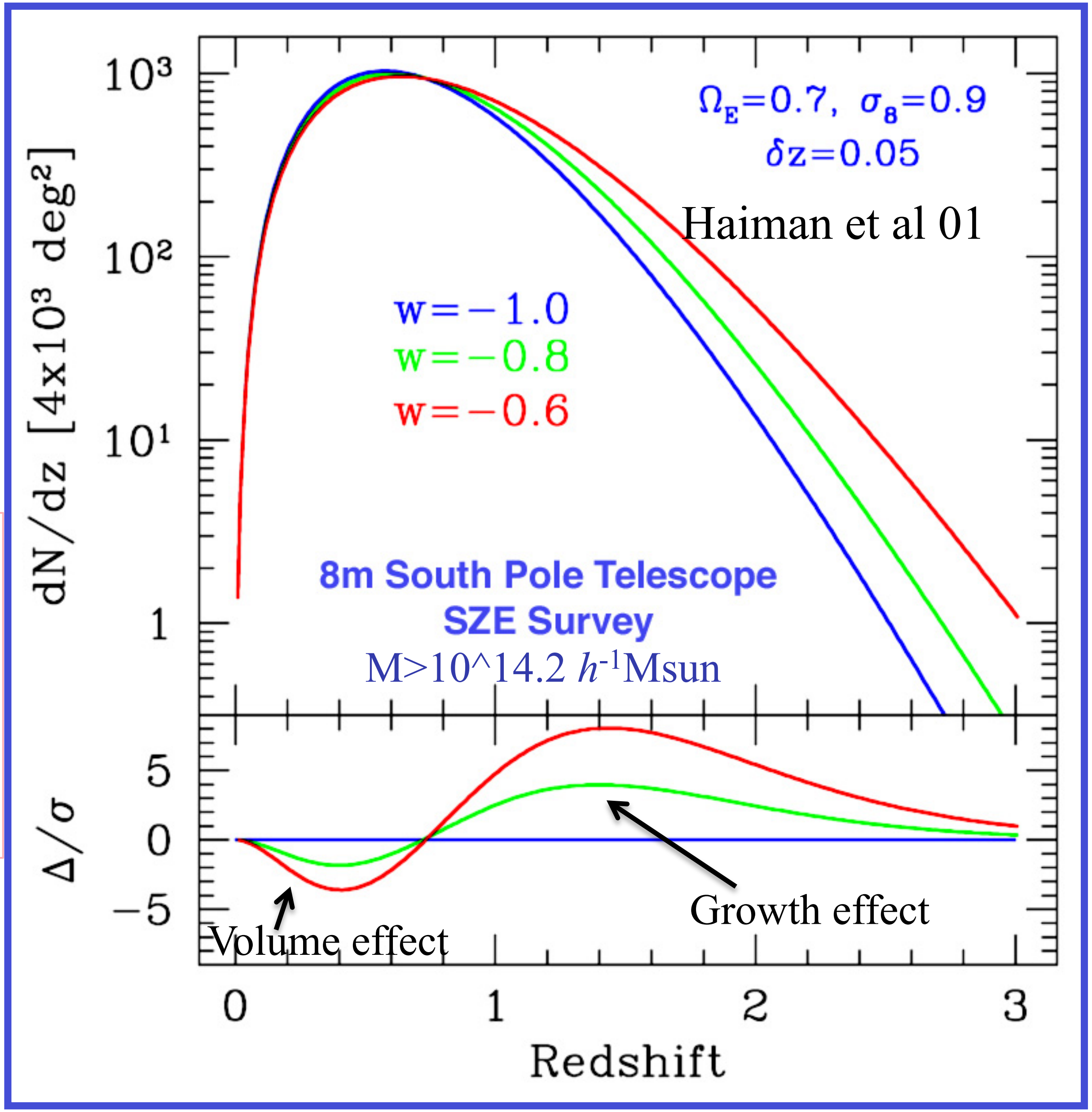
$$\frac{d^2N}{dzdM} = \Omega_S \frac{d^2V}{dzd\Omega}\frac{dn}{dM}$$

DE equation of state: w

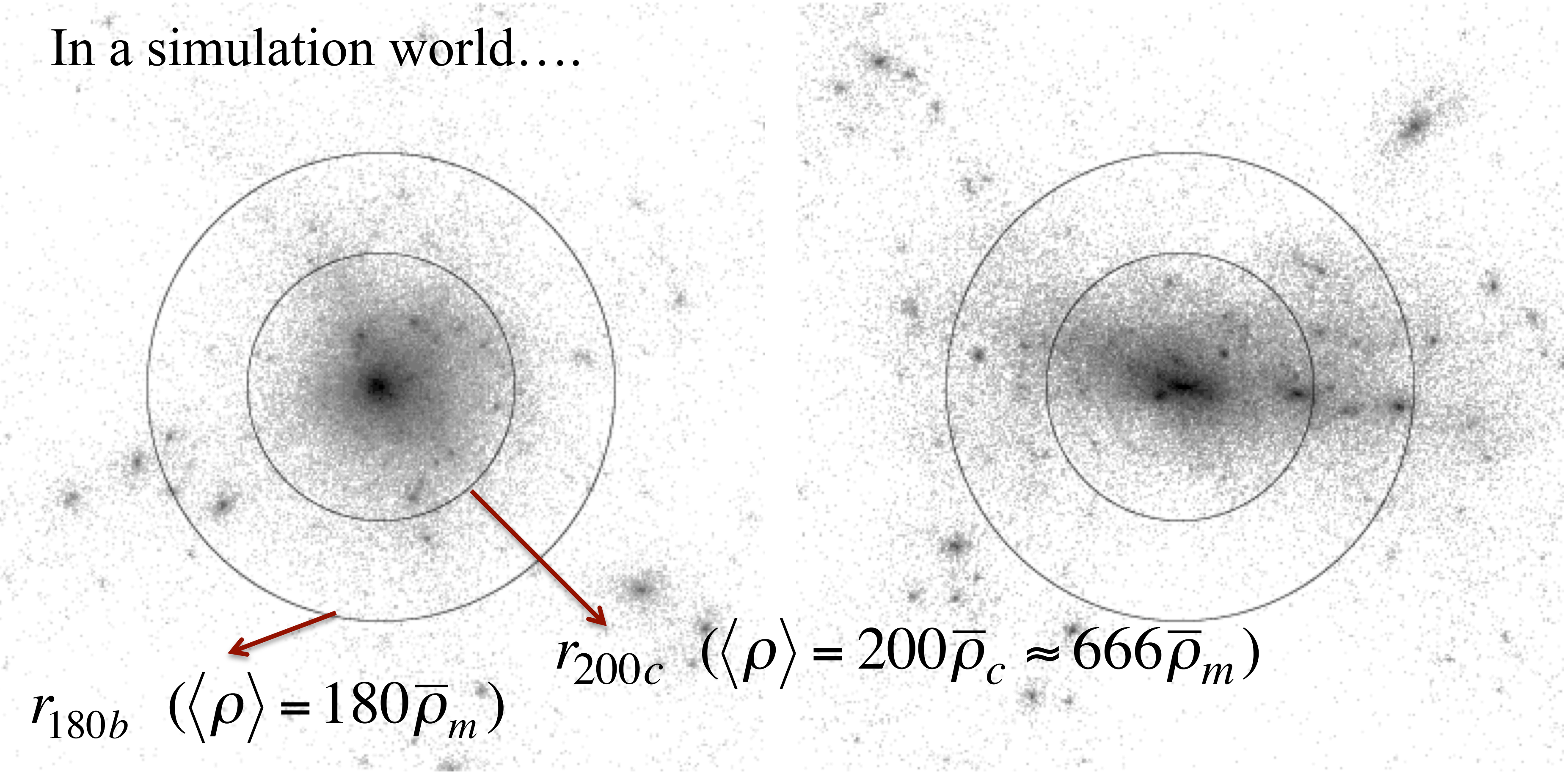
$$w \equiv \frac{p_{\rm de}}{\rho_{\rm de}}$$

$$\to \rho_{\rm de} \propto (1+z)^{3(1+w)} \quad \text{for} \quad w = \text{const.}$$

Note that the right plot uses σ_8 normalization: the same number density of clusters at present for all models



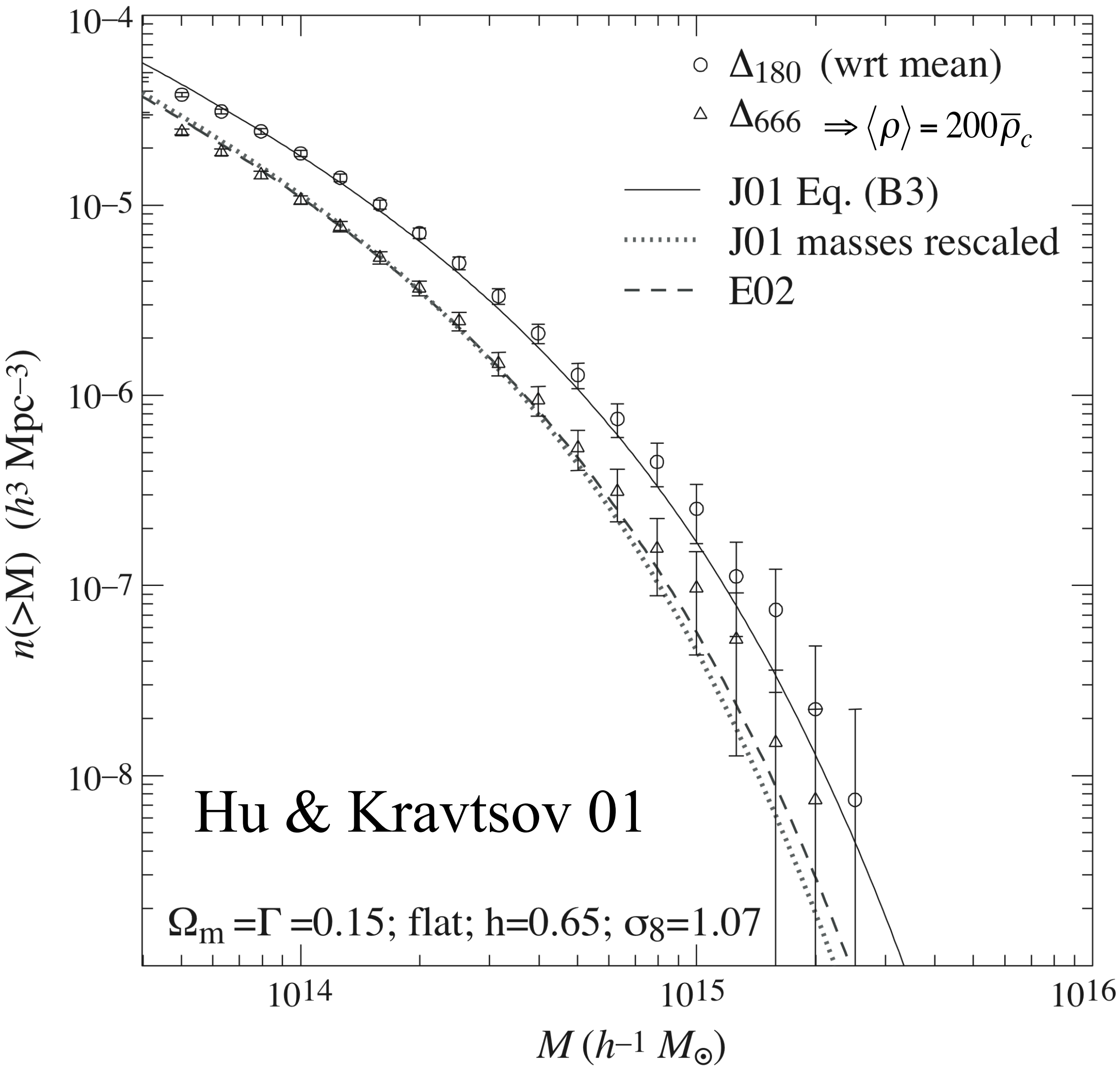
Issue: cluster mass



White 02

$$M_\Delta(<r_\Delta) = \int_{r<r_\Delta} d^3\boldsymbol{x}\, \rho(\boldsymbol{x}) \;\Rightarrow\; n(M_\Delta)$$

Cosmological Use of Clusters: Halo Mass Function



Gaussian seed density fluctuations

+

Spherical collapse model (or N-body simulation)

Mass function: $n(>M)$

$$\frac{dn}{dM} \propto \exp\left(-\frac{\delta_c^2}{2\sigma^2(M)}\right)$$

@cluster mass scales

The mass function can be a powerful probe of cosmology (e.g. DE)

Cluster mass (contd.)

- In a real world, there is no unique definition of cluster mass; no clear boundary with the surrounding structures
  - Need to estimate the mass such that the definition is closer to the way used in simulations; e.g. spherical overdensity mass
- Have to infer cluster masses (including DM) from the observables (optical, X-ray, *lensing*)
- Cluster counting experiment requires the well-calibrated mass-observable relation for cosmology
  - For future surveys (e.g. SPT-like survey with 4000 deg^2), the mass proxy relation needs to be known to a few % accuracy $\sigma_{\ln M}\sim 0.01$

Vikhlinin et al. 2009: Chandra

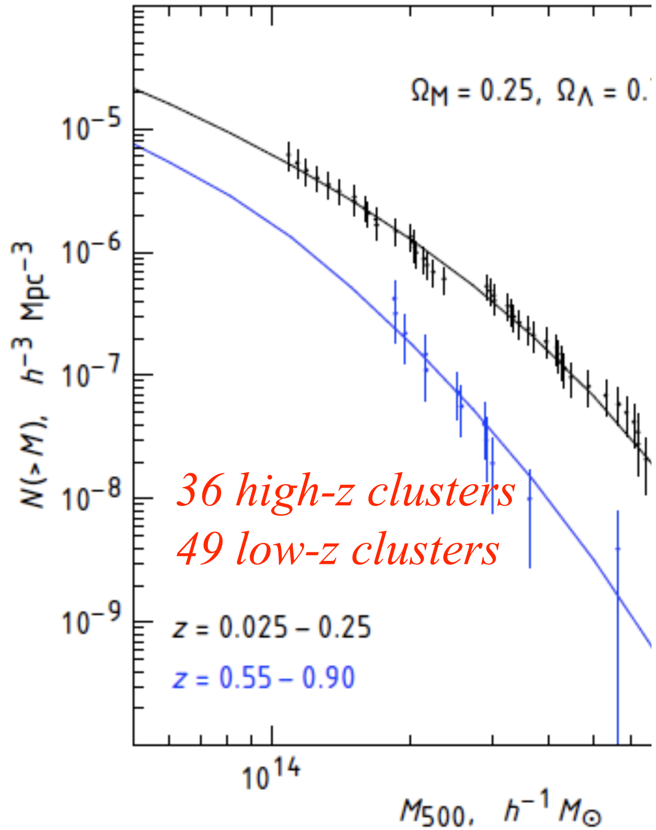
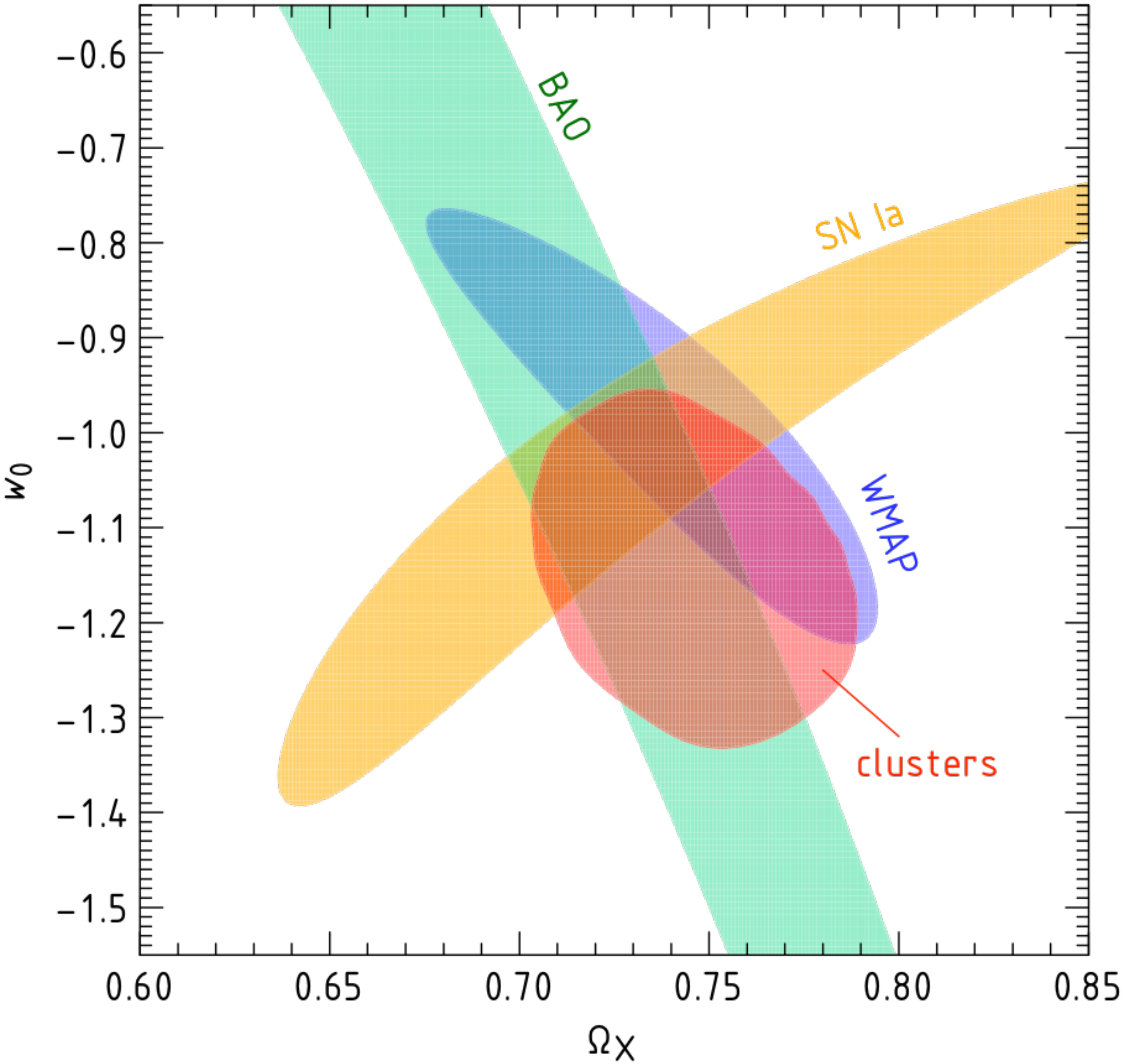
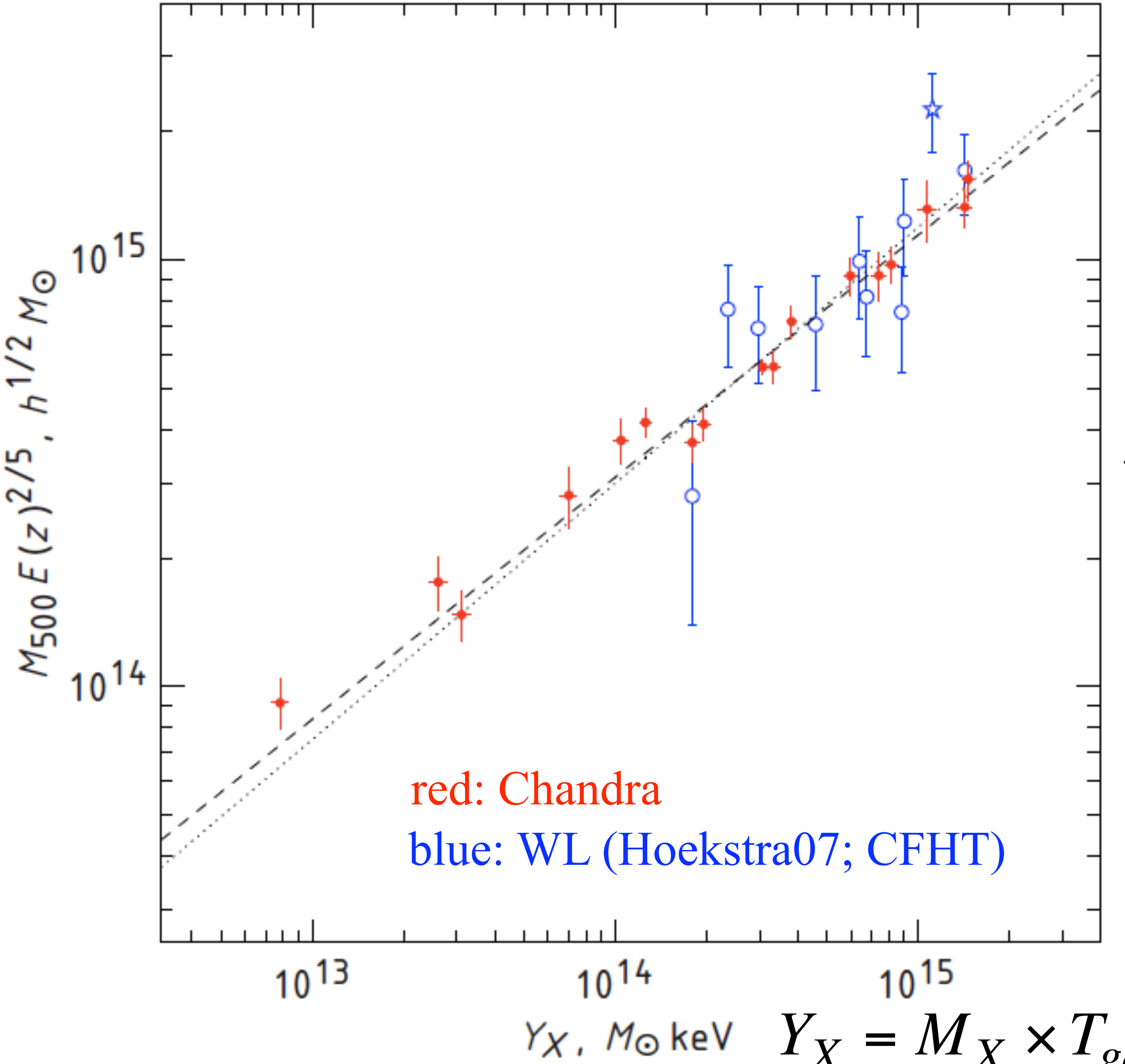


FIG. 2.— Illustration of sensitivity of the cluster mass fun
models (with only the overall normalization at $z = 0$ adjuste
from Fig. 1, which for the high-z cluster we show only the r
models are computed for a cosmology with $\Omega_\Lambda = 0$. Both t
function is changed because it is derived for a different dist
thresholds corresponding to $\Delta_{crit} = 500$ are different. Whe
of $z > 0.55$ clusters is in strong disagreement with the data



State-of-the-art mass proxy

Vikhlinin et al. 07



$$Y_X = M_X \times T_{gas,X}$$

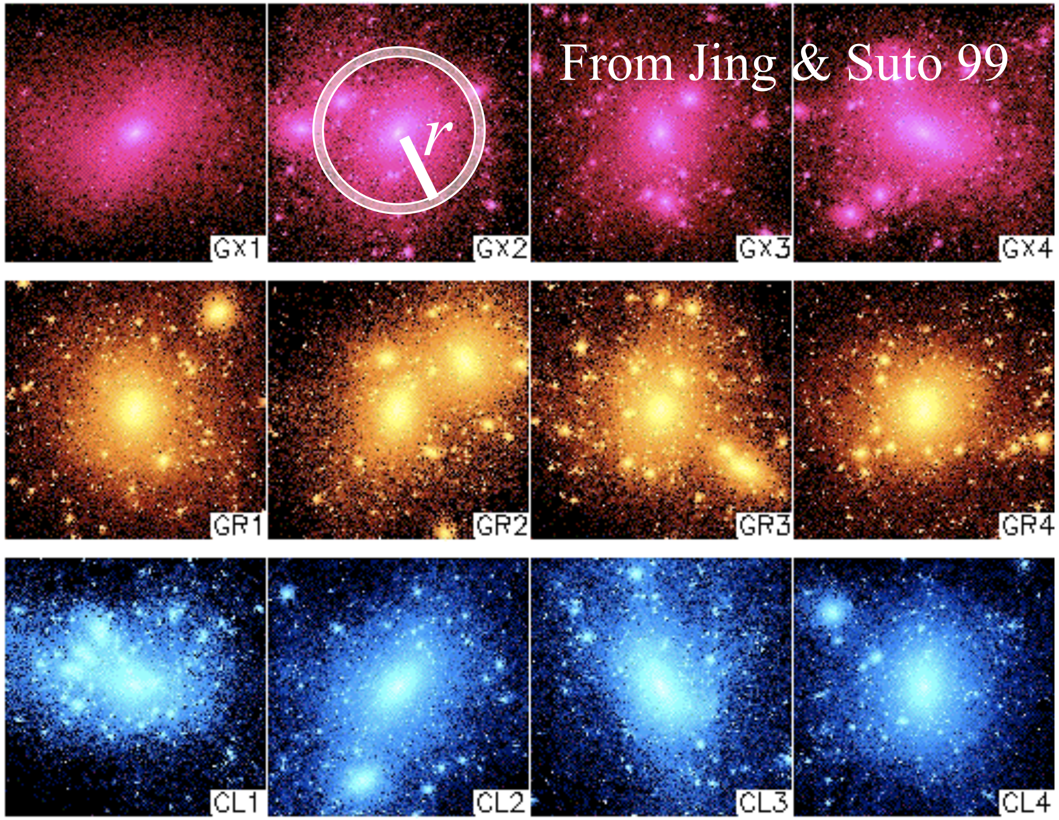
The dark matter mass is estimated assuming hydrostatic equilibrium in X-ray observables

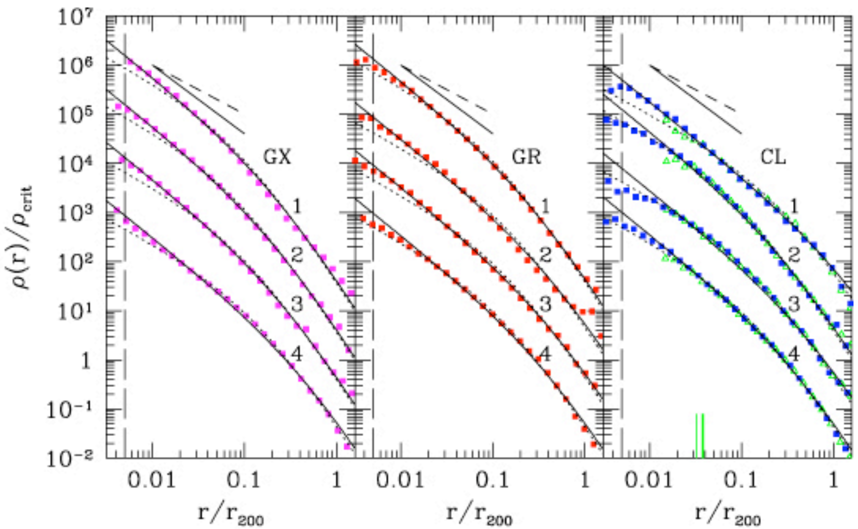
$$\frac{GM(<r)}{r^2} = -\frac{1}{\mu}\frac{d(\rho_{gas}kT)}{dr}$$

$\sigma_{\ln M} \sim 10\%$

Internal structure of halo

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





NFW profile

$$\boxed{\rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}}$$

Outer: ρ∝r^-3

Inner: ρ∝r^-1

In addition, halo shape is by nature triaxial (Jing & Suto 01)

NFW profile

- An NFW profile is specified by 2 parameters
- Useful to express the NFW profile in terms of the cluster mass and the halo concentration parameter

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

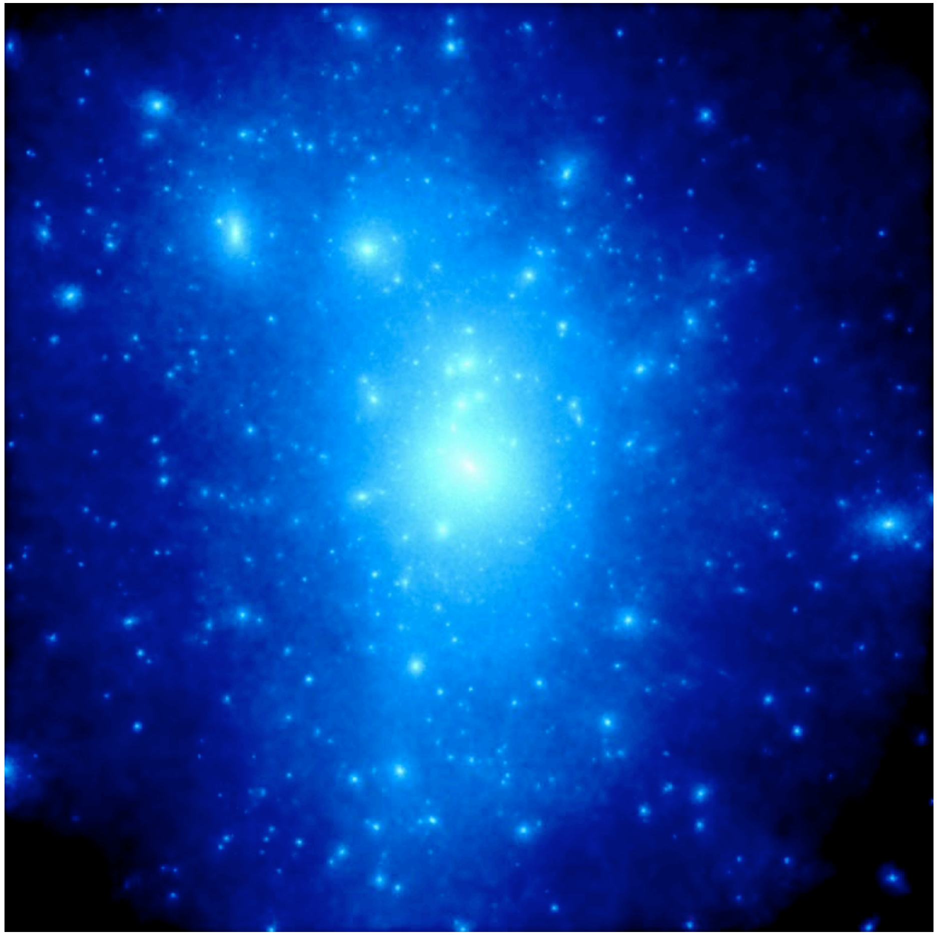
$$+\begin{cases} M_\Delta = \dfrac{4\pi}{3} r_\Delta^3 \bar{\rho}_m \Delta & : \text{defines the halo boundary for a given } \Delta \\ M_\Delta = \displaystyle\int_{r<r_\Delta} 4\pi r^2 dr\, \rho_{NFW}(r) & : \text{sets the interior mass of } \rho_{\mathrm{NFW}} \text{ to } M_\Delta \end{cases}$$

$$\Rightarrow \boxed{\rho_{\mathrm{NFW}}(r; M_\Delta, c_\Delta) \quad (\text{note}: c_\Delta \equiv r_\Delta / r_s)}$$

- Can infer the halo mass from the measured halo profile

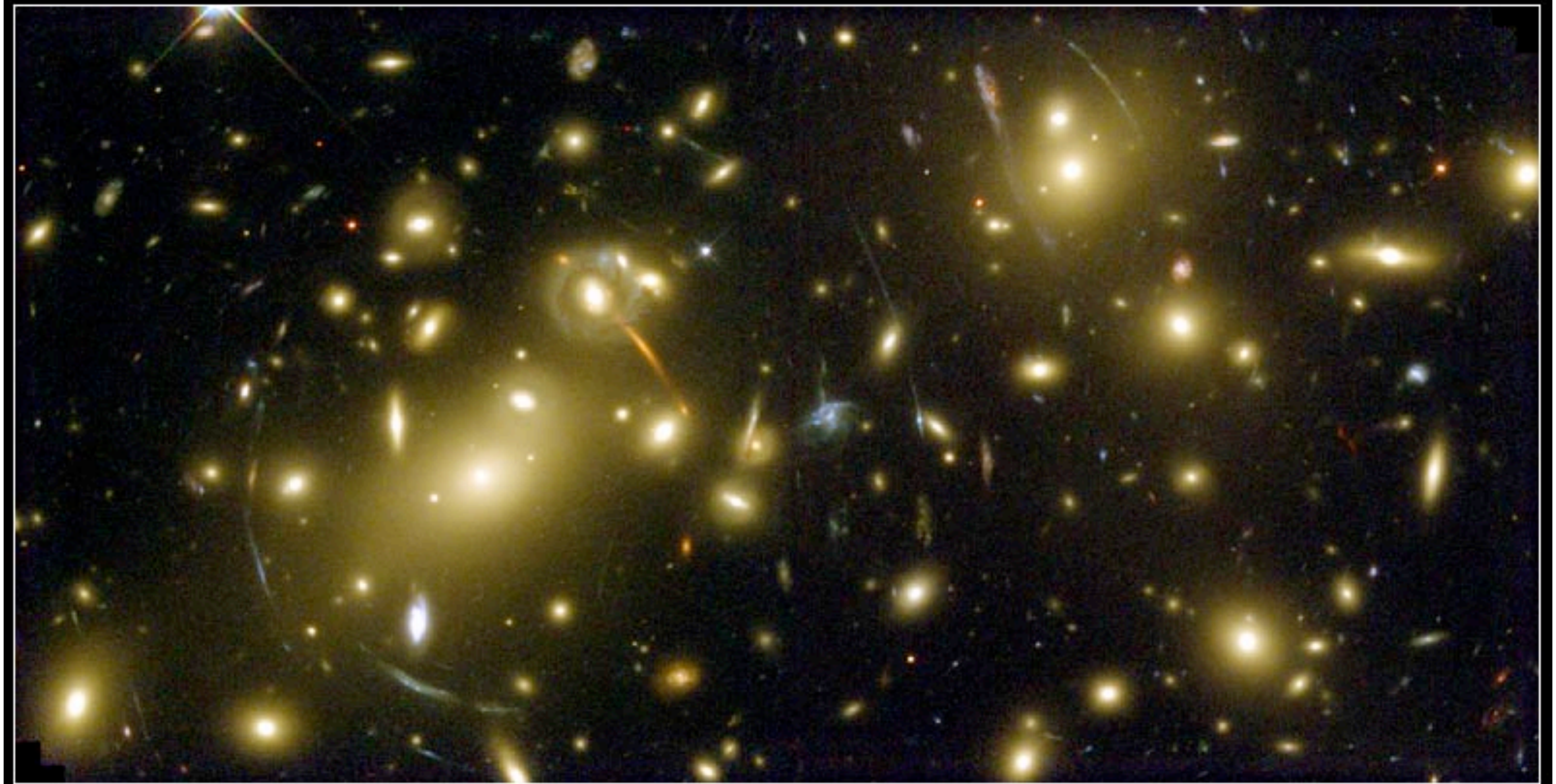
“Shape” of dark matter halo

- Mass accretion onto a cluster region is preferentially along the surrounding filamentary structures
- Therefore, the mass accretion is not spherical
- Shape of dark matter halos is triaxial by nature, even in a statistical sense
- A triaxial halo model gives a better fit to simulated halos (Jing & Suto 01)



From H. Yahagi (Kyoto U.)

Gravitational Lensing
= method to "*see*" invisibles



Galaxy Cluster Abell 2218 HST • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

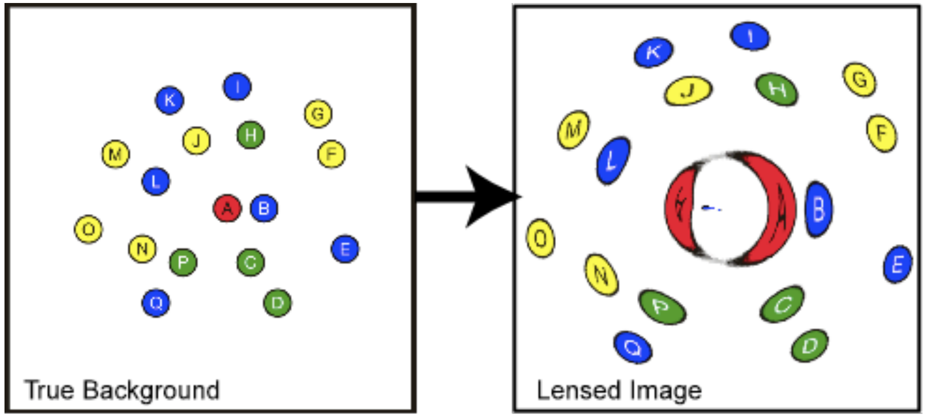
Note: strong and weak lensing

•Strong Lensing

– Multiple Images

– Large Arcs, Ring

– Obvious Distortion

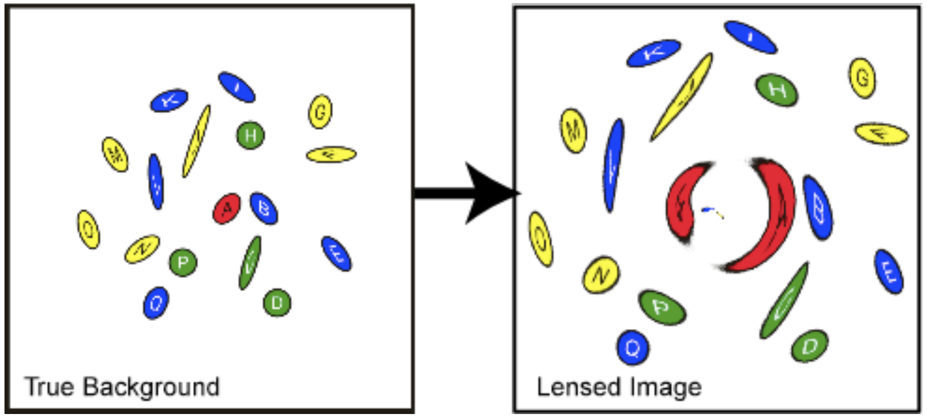


•Weak Lensing

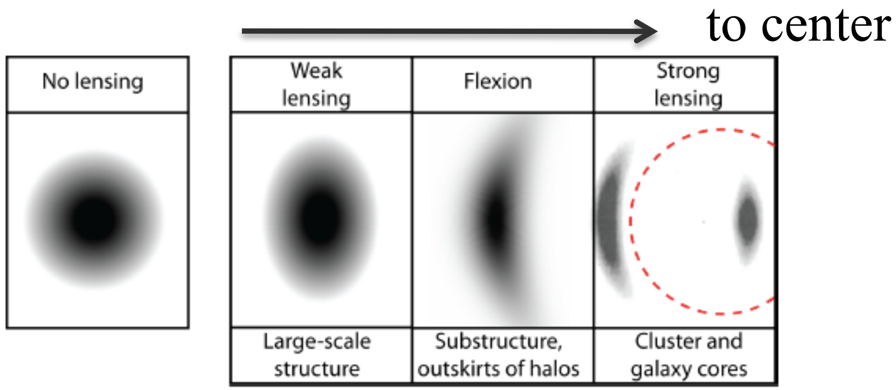
– Slight Stretching

– Distortion small compared to initial shape

– Statistical lensing



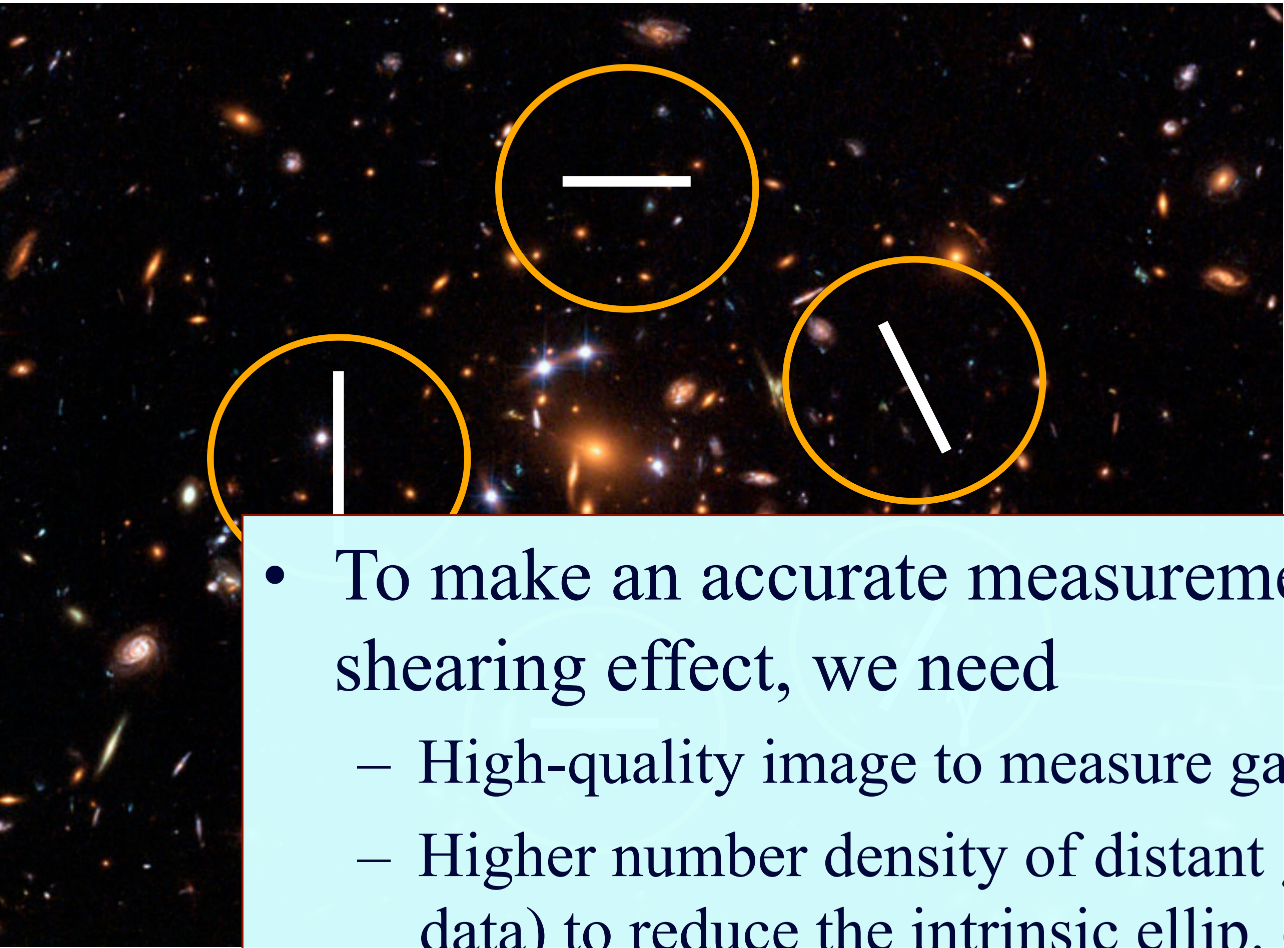
These two regime lensing are very complementary! The combination allows to probe the entire region of cluster (Broadhurst, MT+05)



Measuring shear (contd.)

Kaiser, Squires & Broadhurst 95

- In reality source galaxy has intrinsic shape: **$|\varepsilon|\sim 0.3$**



- *Step 1*: Quantify the shape of each galaxy in terms of its surface brightness profile

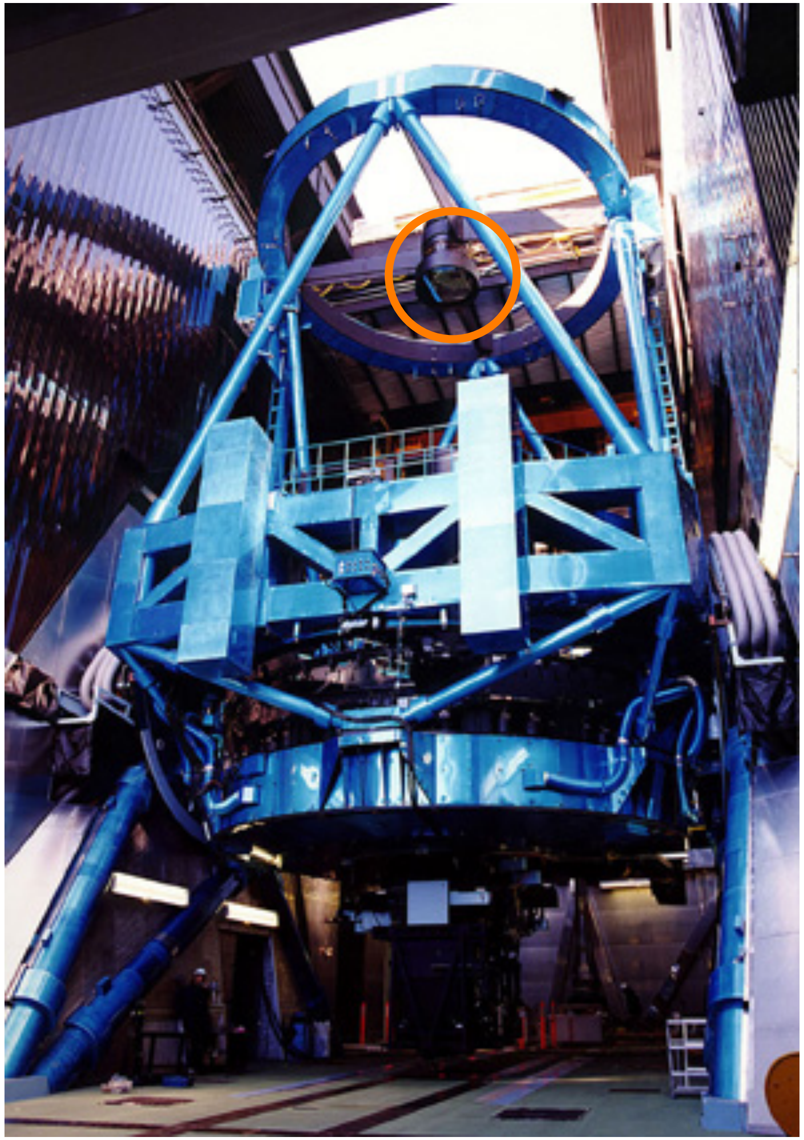
$$\boxed{\gamma_i^{\mathrm{obs}} \approx \gamma_i + \varepsilon_i}$$

Step 2: If the intrinsic shapes have random orientations

- To make an accurate measurement of the lensing shearing effect, we need
  - High-quality image to measure galaxy shapes
  - Higher number density of distant galaxies (i.e., deep imaging data) to reduce the intrinsic ellip. contam.

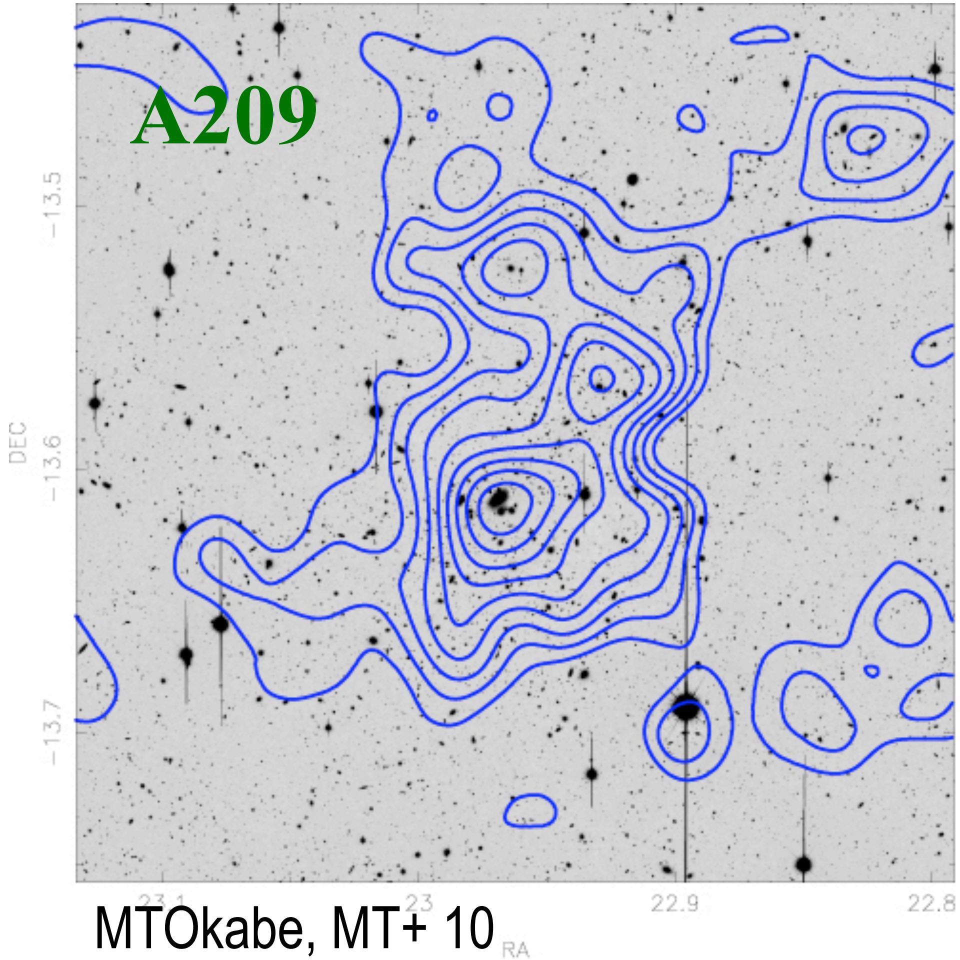
Subaru Telescope: Best facility for WL measurement

- Only Subaru has the prime focus camera, Suprime-Cam, among other 8-10m class telescope: the wide field-of-view (0.25 sq deg)
- Excellent image quality allows accurate shape measurements of galaxies
- Deep images allow the use of many galaxies for the WL: higher spatial resolution



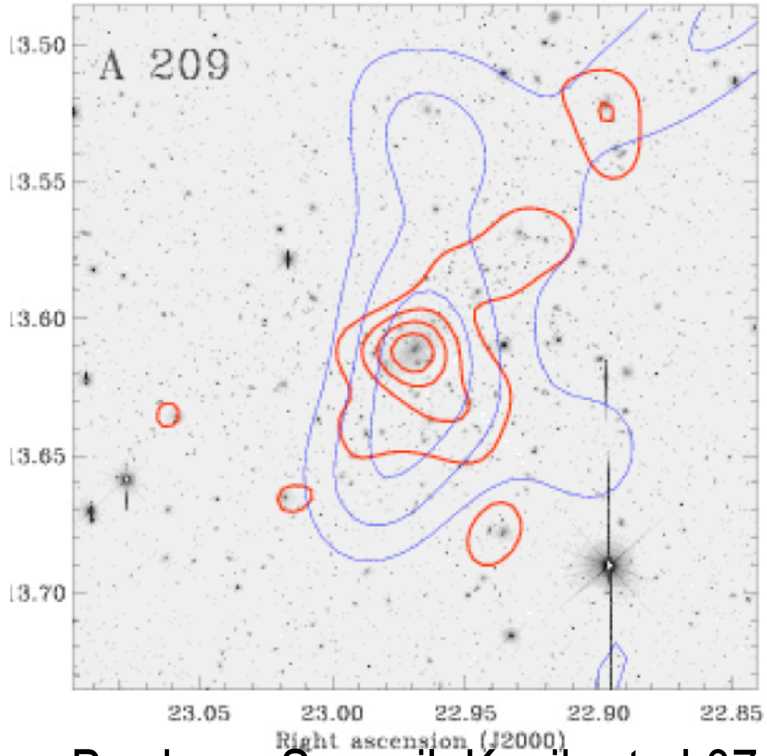
Subaru capability for WL measurement

Subaru S-Cam



MTOkabe, MT+ 10

CFHT (blue: mass)

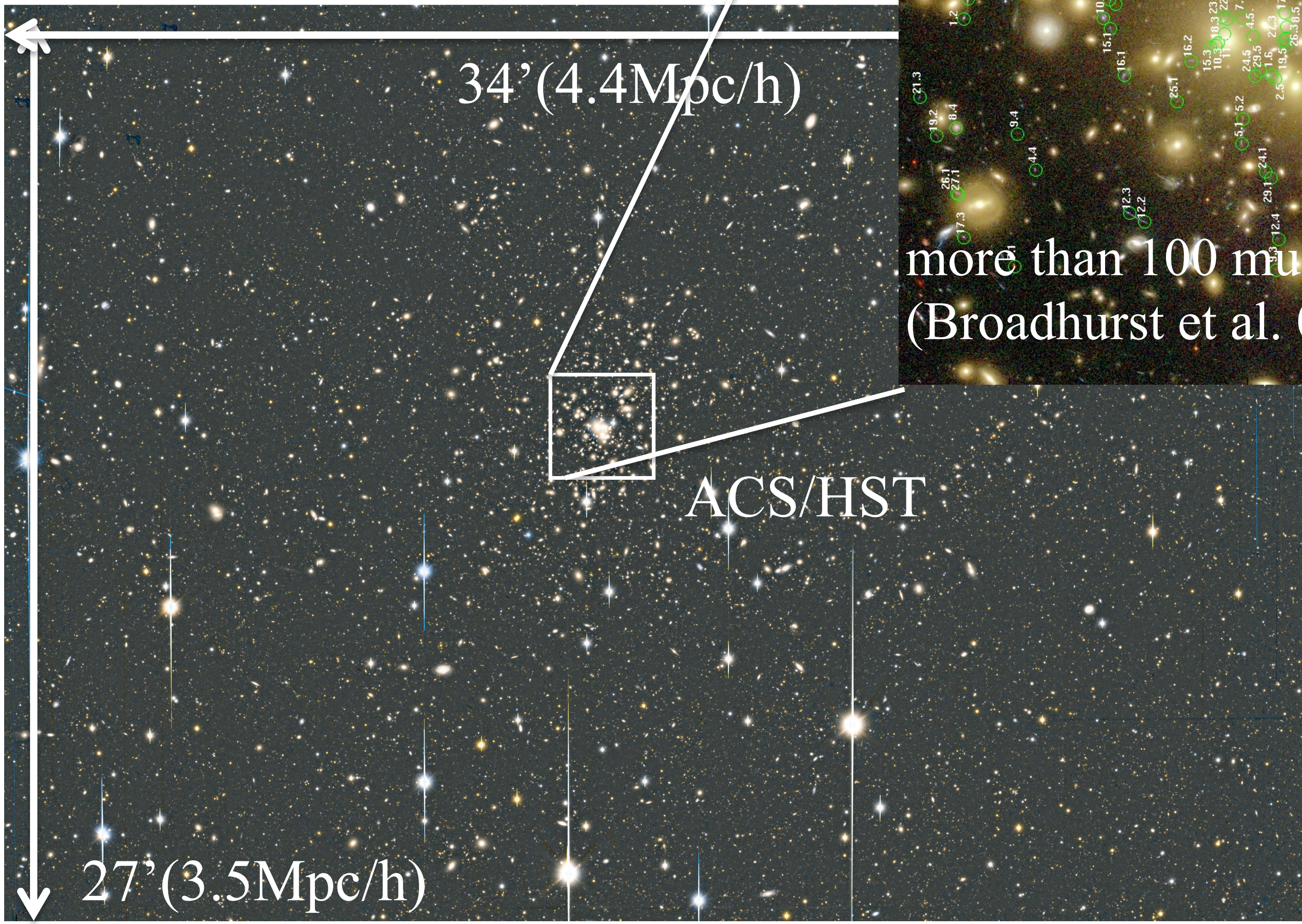


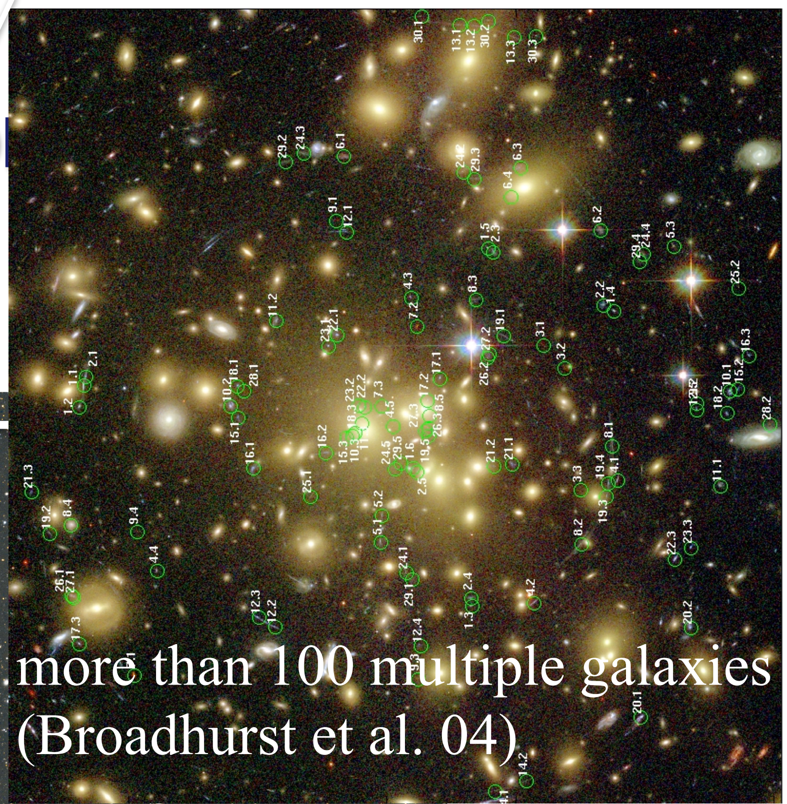
Bardeau, Soucail, Kneib et al.07

- Subaru (S-Cam) is currently the best instrument for measuring WL signal, thanks to the excellent image quality

Subaru fo

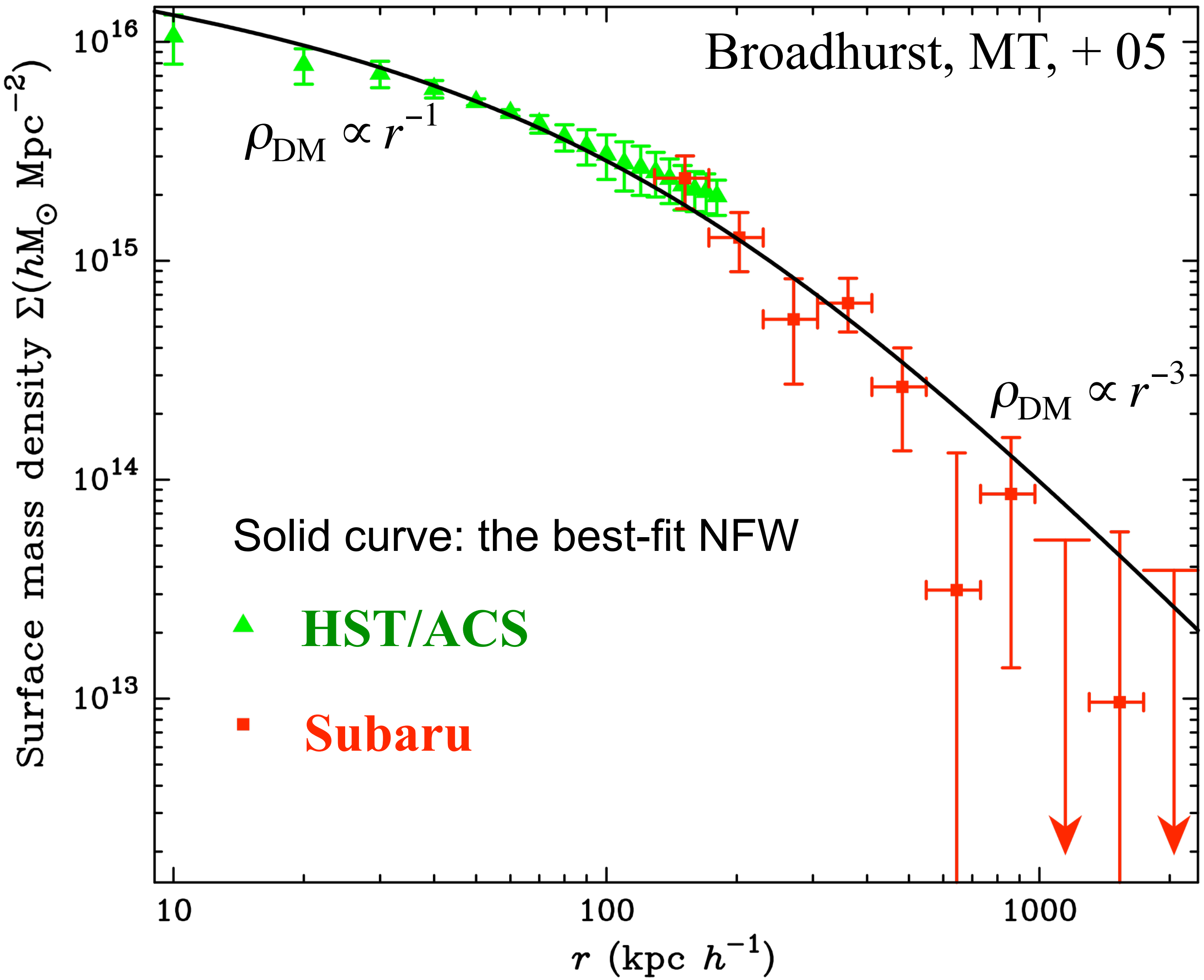
Example: A1689 (z=0.18)





- Virial radius of a massive cluster ~Mpc
- Subaru FoV covers the virial region of a cluster at z~0.2

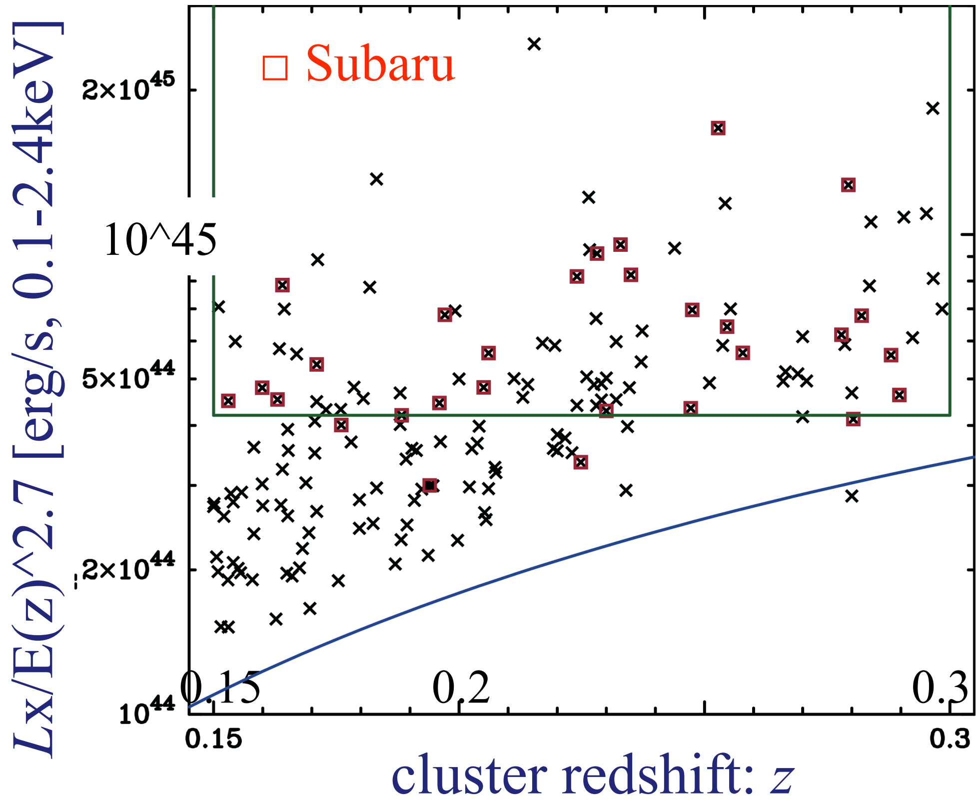
The best case: A1689 (z=0.18)



Radial distance from the cluster center

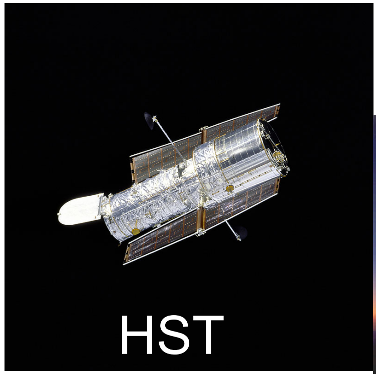
LoCuSS
(The Local Cluster Substructure Survey)

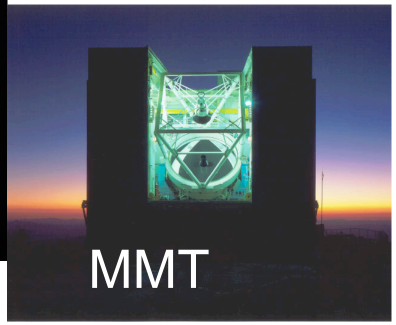
- International collaboration (PI: G.P.Smith; Europe, Japan, USA)
- Explore a systematic study of ~100 X-ray luminous clusters in the redshift range 0.15-0.3
- The multi-wavelengths: *Subaru*, Palomar, VLT, UKIRT, HST, GALEX, Spitzer, Chandra, XMM, SZA, *MMT/Hectospec*

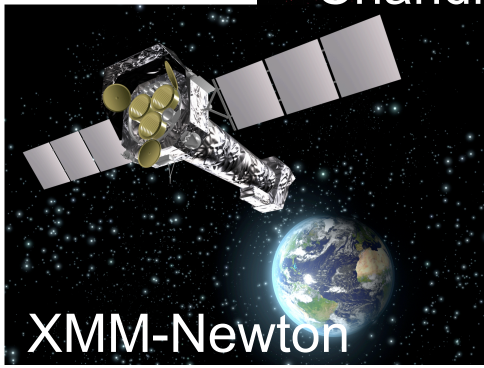


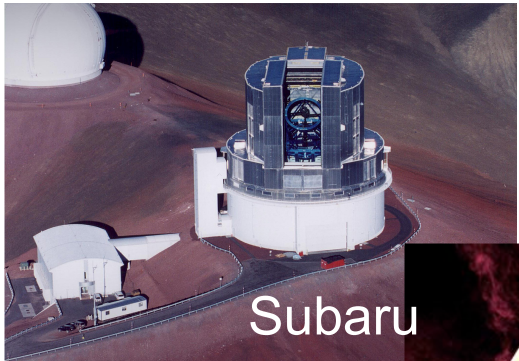
- Subaru/Suprime-Cam data for ~30 clusters (24 have 2 filter data)
  - ***Unbiased*** cluster sample (not based on strong lensing)
  - The FoV of S-Cam matches the virial region of clusters at the target redshifts (~0.2)
  - Add more clusters: ~60 clusters within this year

Multi-wavelength study of galaxy clusters







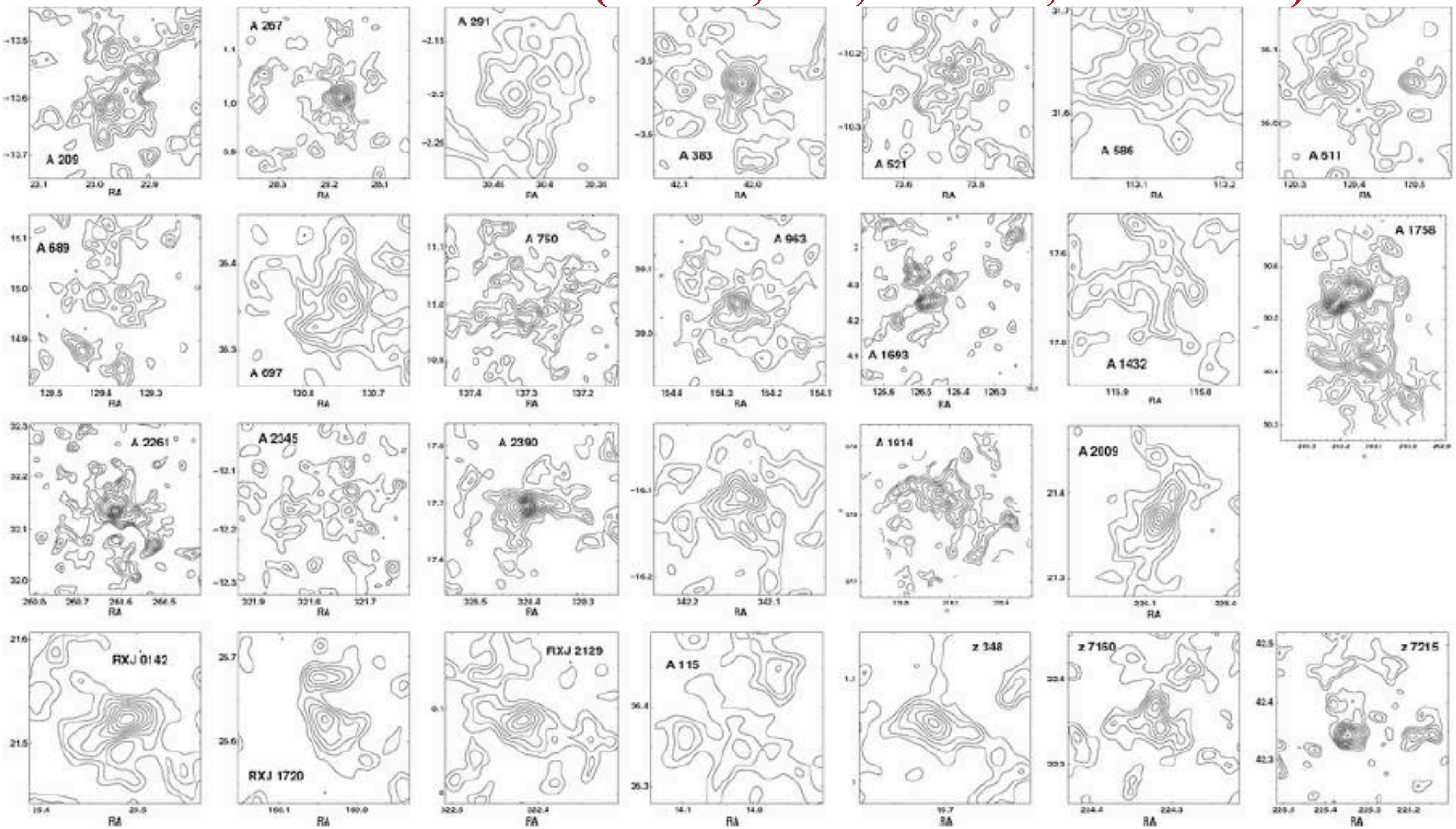



UKIRT


SZA

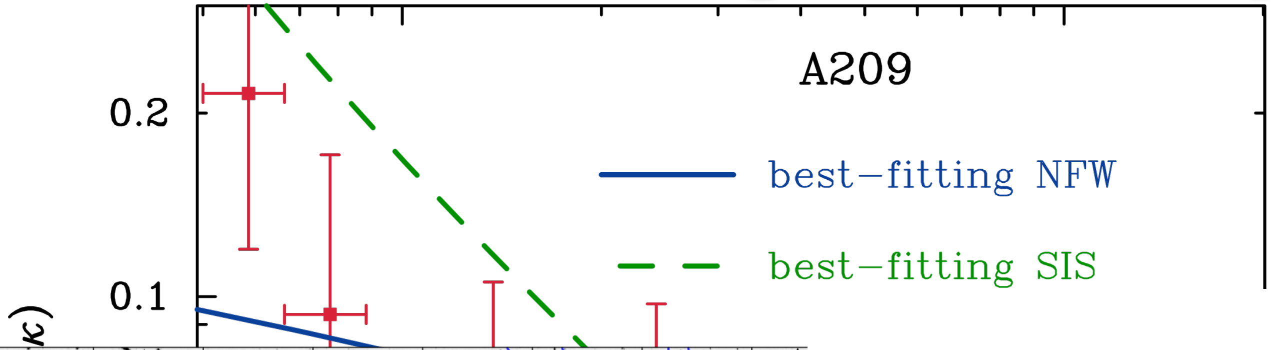
LoCuSS: Subaru weak lens study

~30 clusters (Okabe, MT, Umetsu, Smith+ 10)

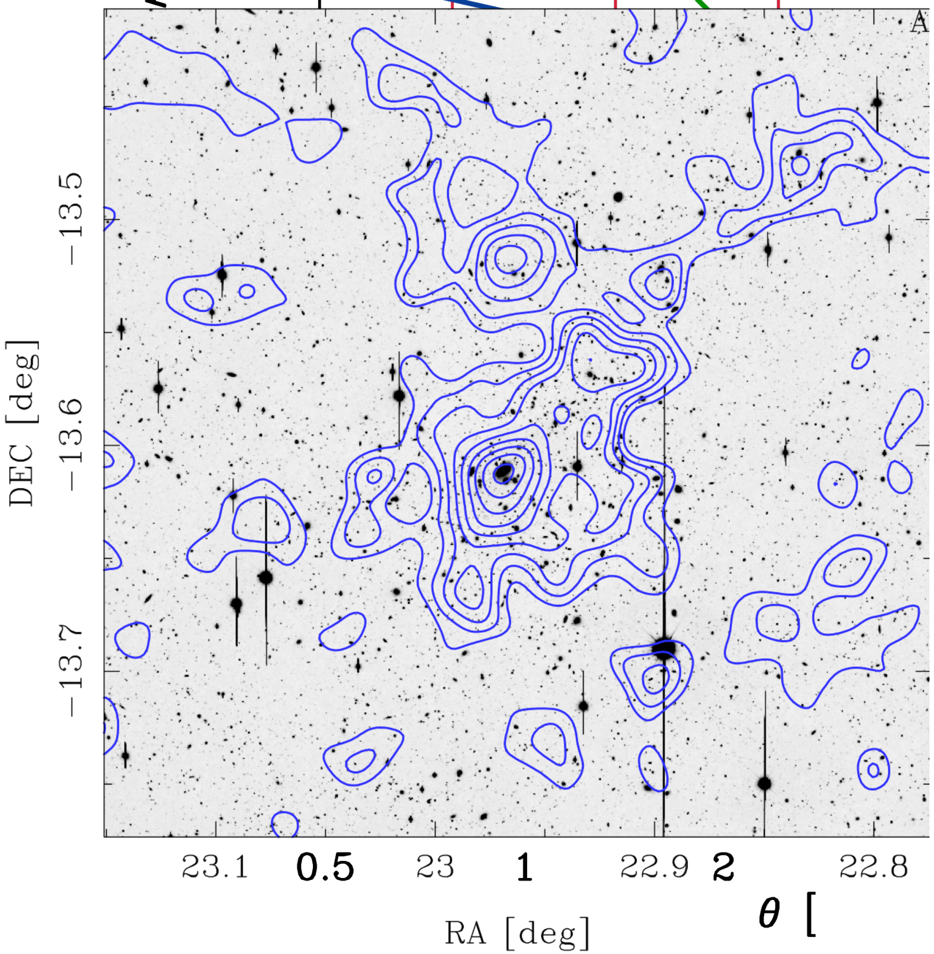


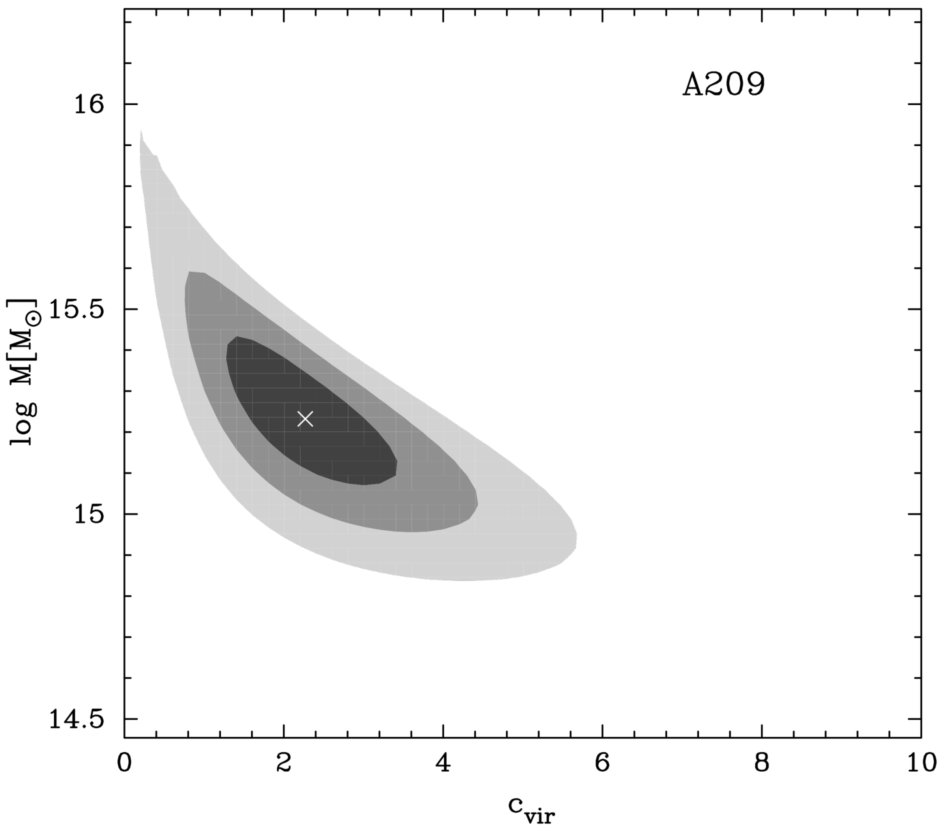
- Subaru is a superb facility for WL measurement
- A detailed study of cluster physics (e.g. the nature of dark matter)

1D shear fitting: an example of A209

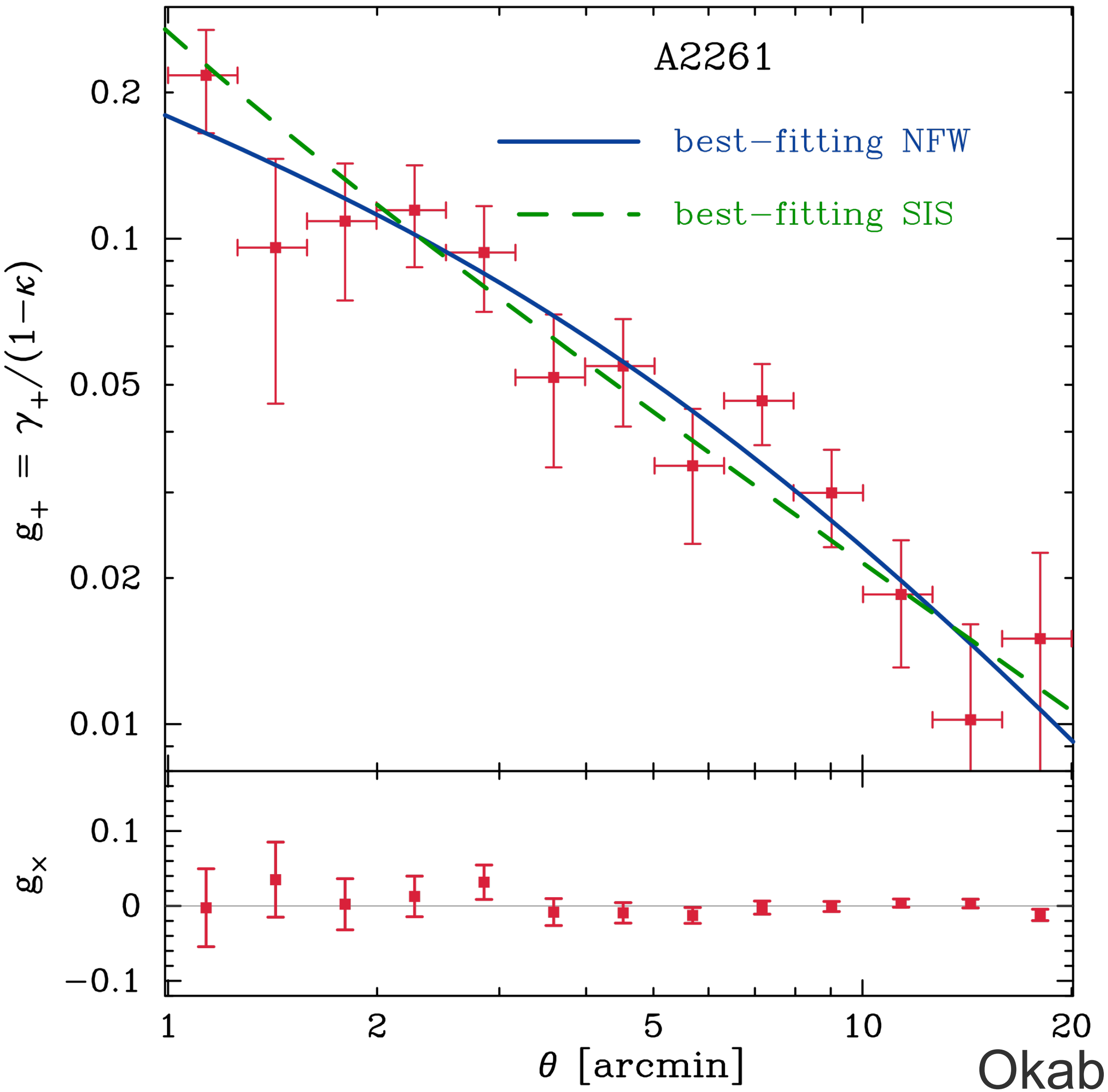


$$\rho_{\mathrm{NFW}} \propto \frac{1}{(r/r_s)(1+r/r_s)^2}$$



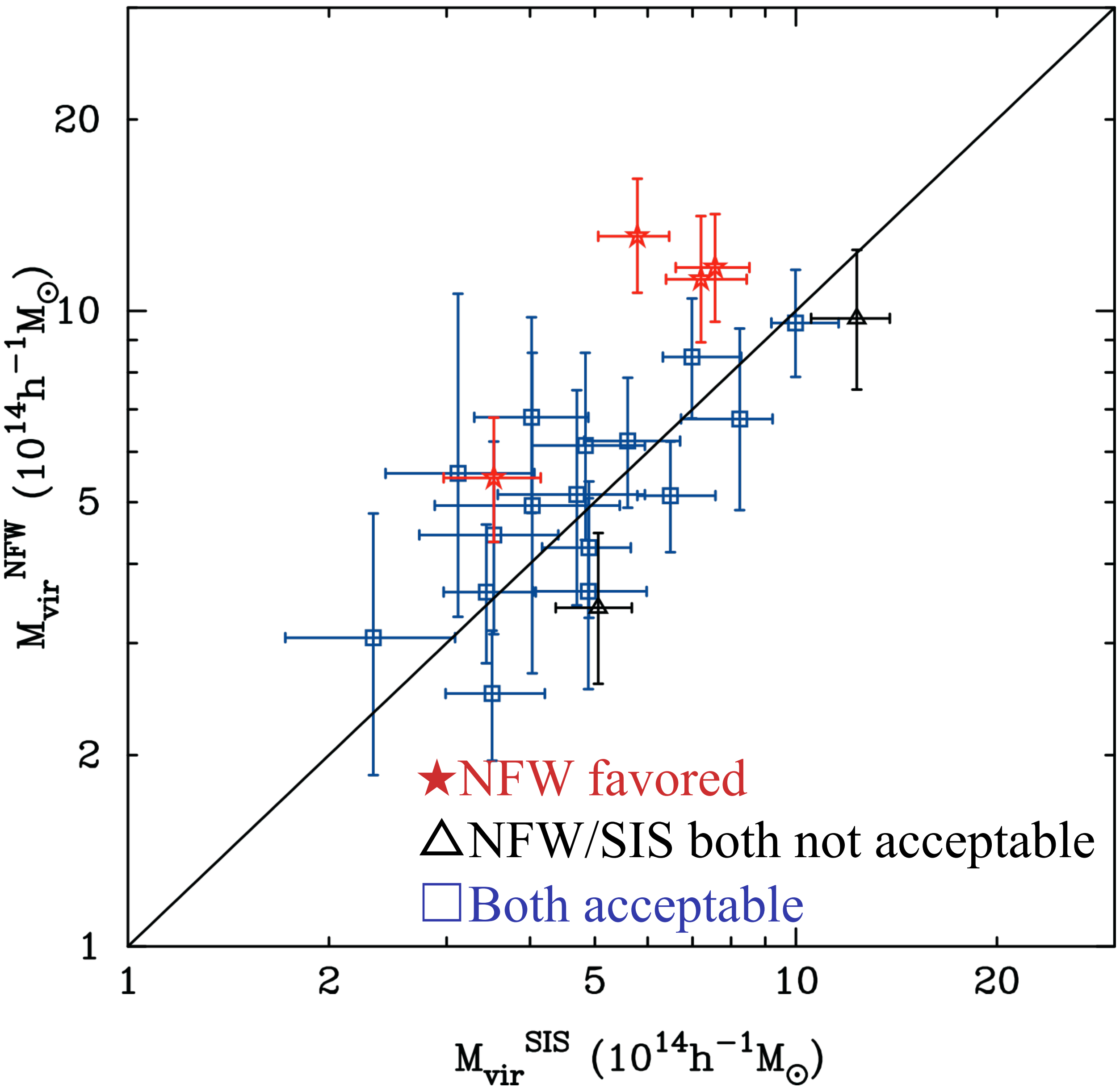


Example 2: A2261



Okabe, MT, 10

Virial mass estimation

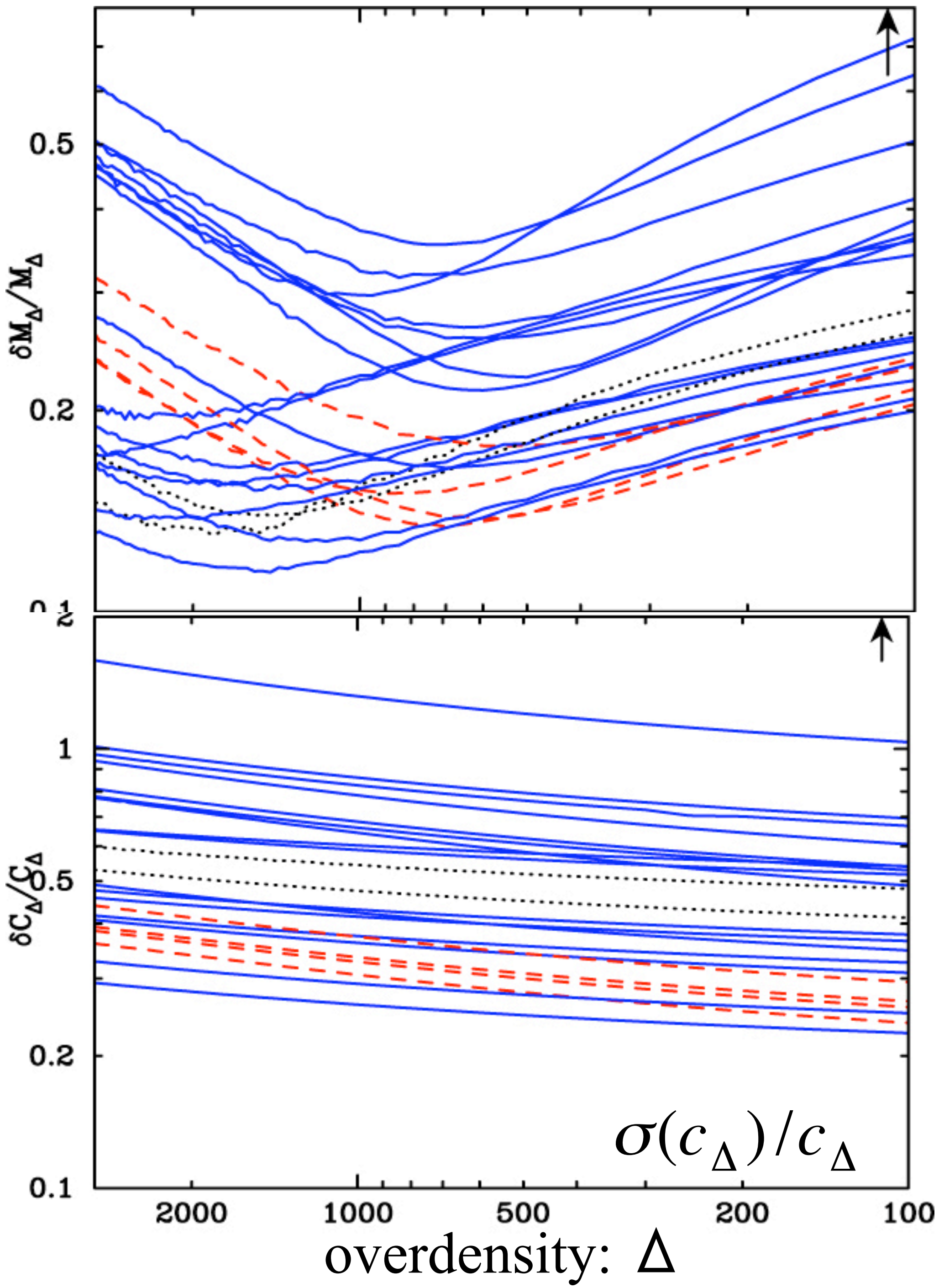


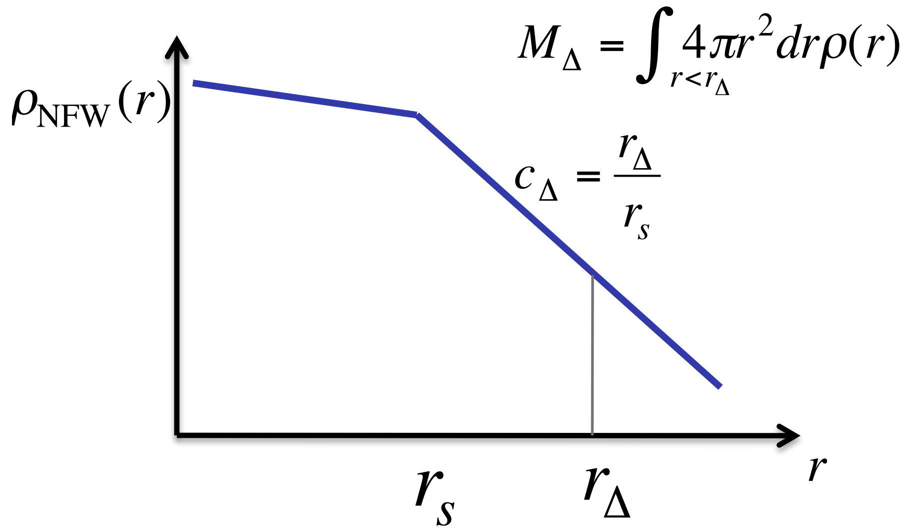
$$\rho_{\mathrm{NFW}} \propto \frac{1}{(r/r_s)(1+r/r_s)^2}$$

$$\rho_{\mathrm{SIS}} \propto \frac{1}{r^2}$$

- **All clusters: S/N>5 (typically S/N~10)**
- The mass estimates depend on the model assumed for the fitting
- The virial mass determination: accuracy 20-30%
- M_{NFW}/M_{SIS}~1.19

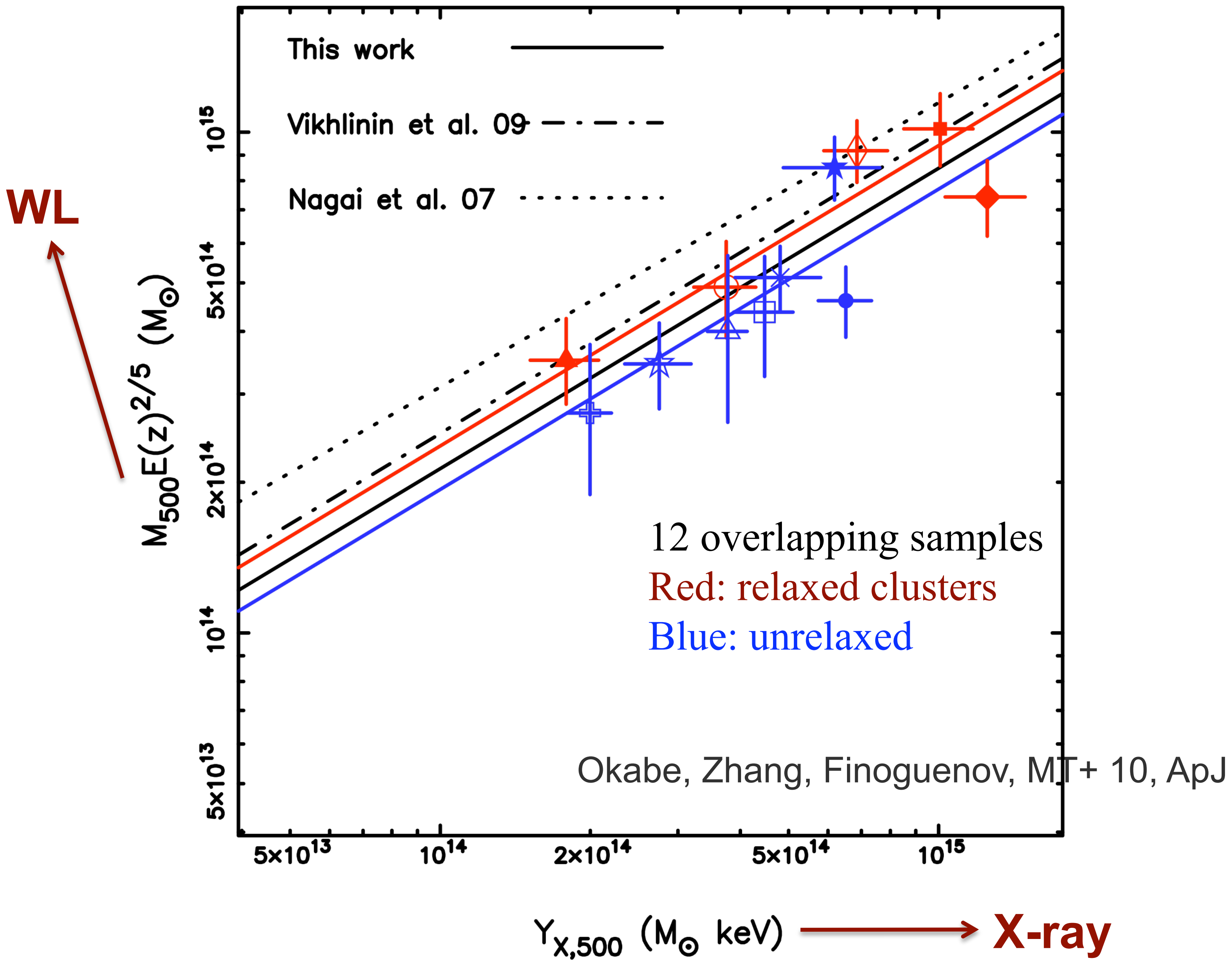
Mass determination (contd.)



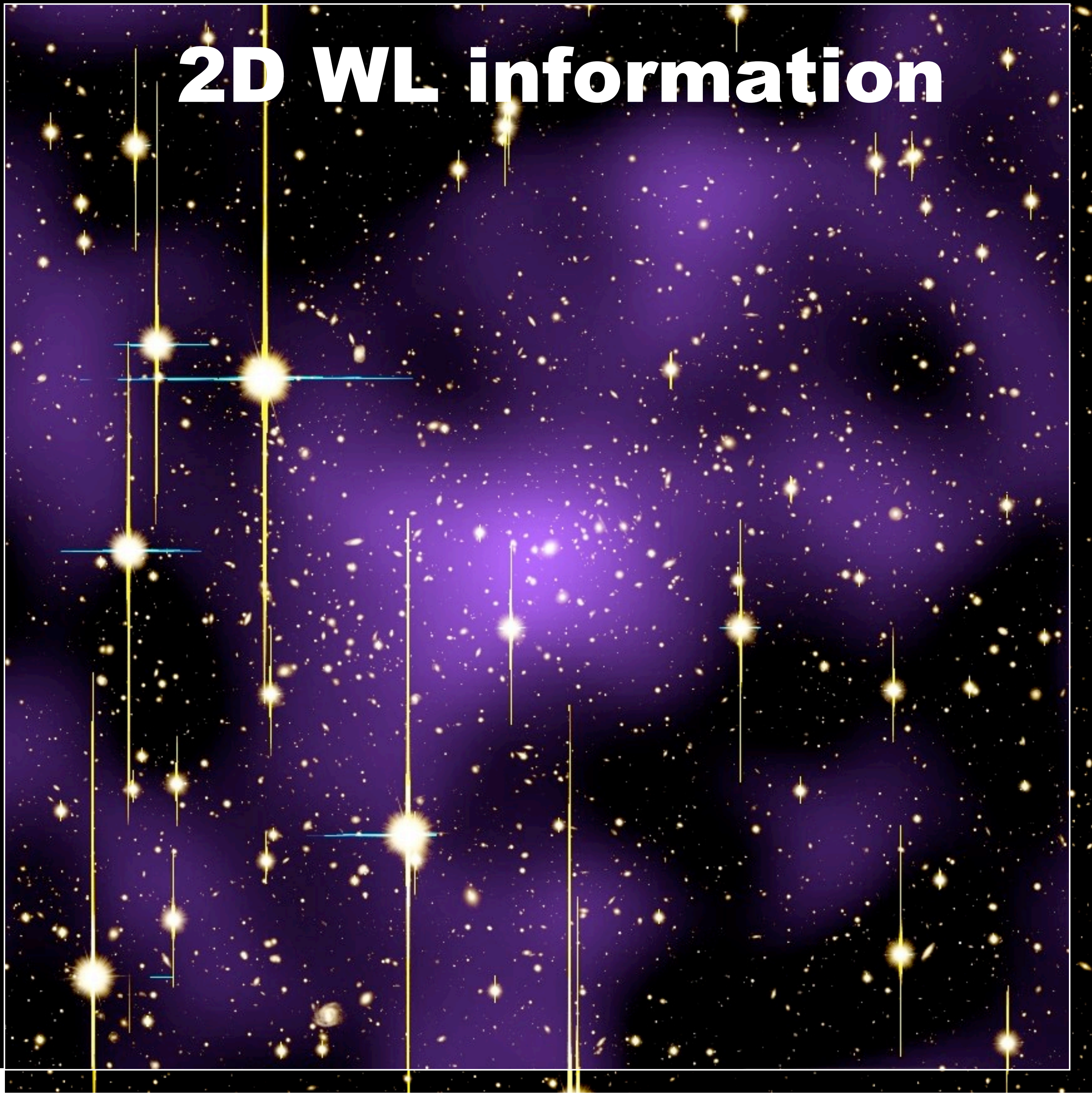


- A best accuracy in M is 10-20% when Δ=500-1000 is assumed
  - Over the radii the lensing signals have a largest S/N
- The concentration parameter is most accurately measured for the virial definition

WL vs. X-ray (Subaru vs. XMM)



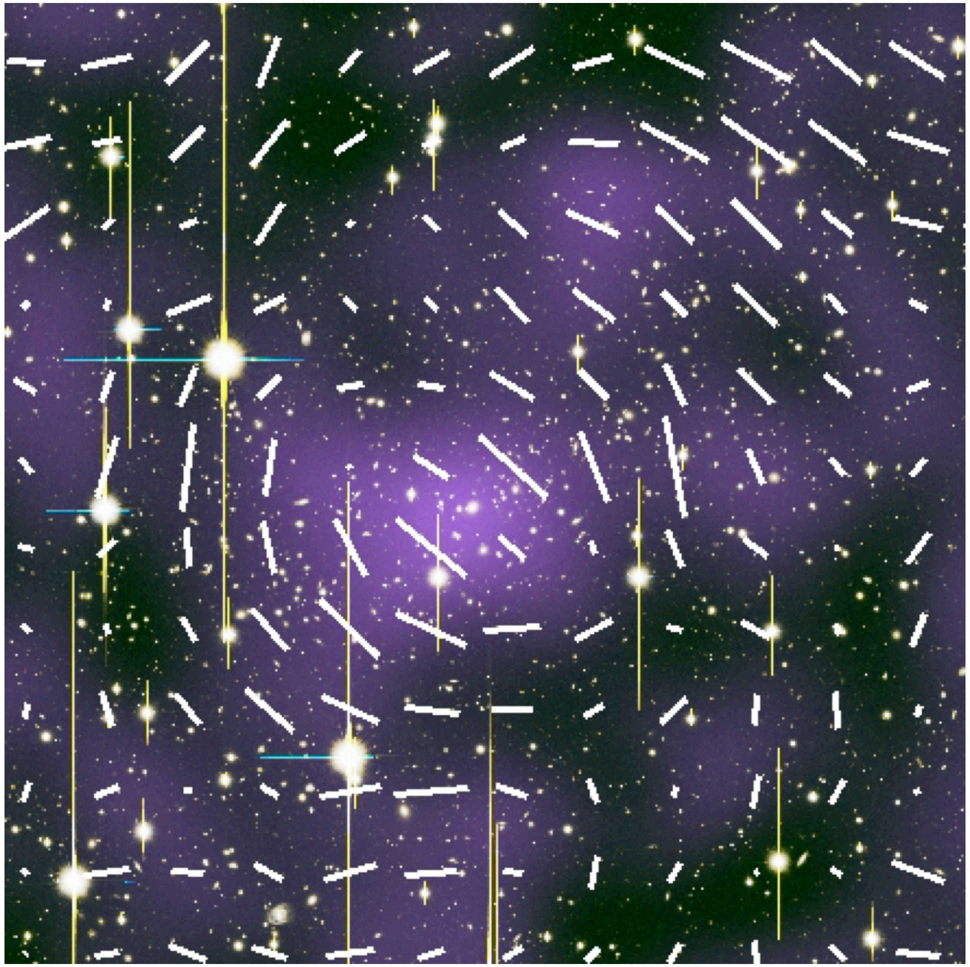
2D WL information



Full use of 2D shear map

Oguri, MT, + 10

A2390



- The cluster mass distribution is far from spherical symmetry, as predicted from the collisionless CDM model.
- Jing & Suto showed that simulated halos can be better described by a triaxial halo model than the spherical one
- Projecting the triaxial halo model along the l.o.s. gives the 2D mass density:

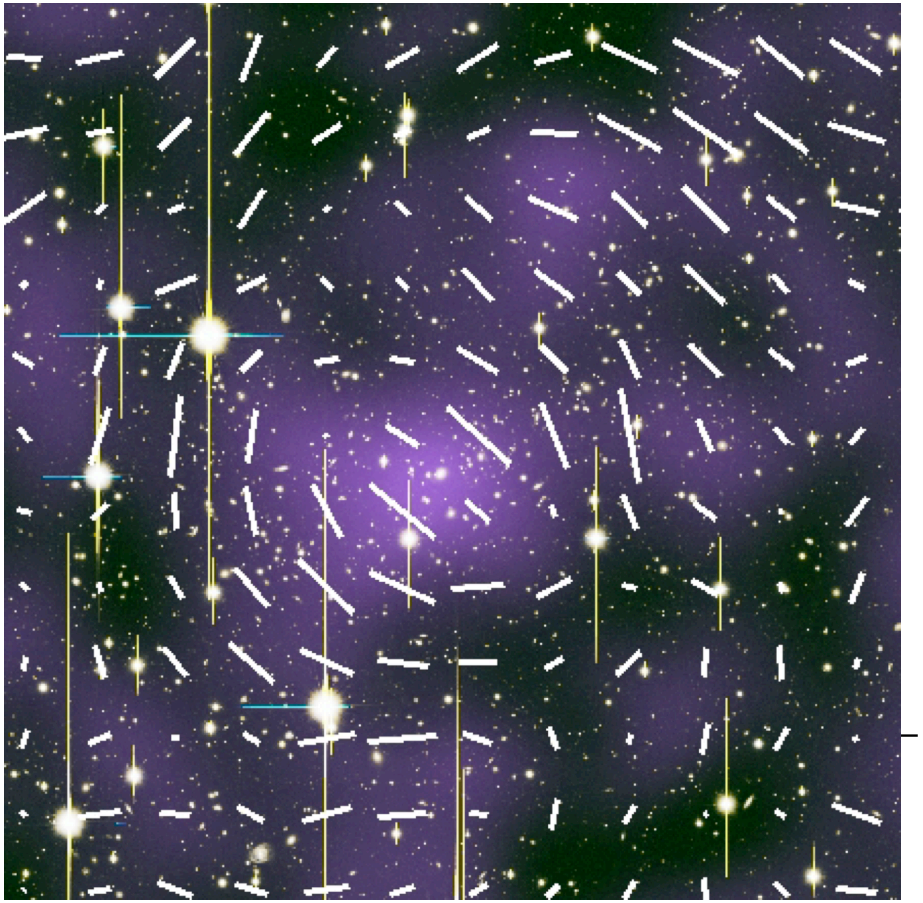
$$\kappa(x, y) = \kappa_{\rm sph}(\zeta),$$

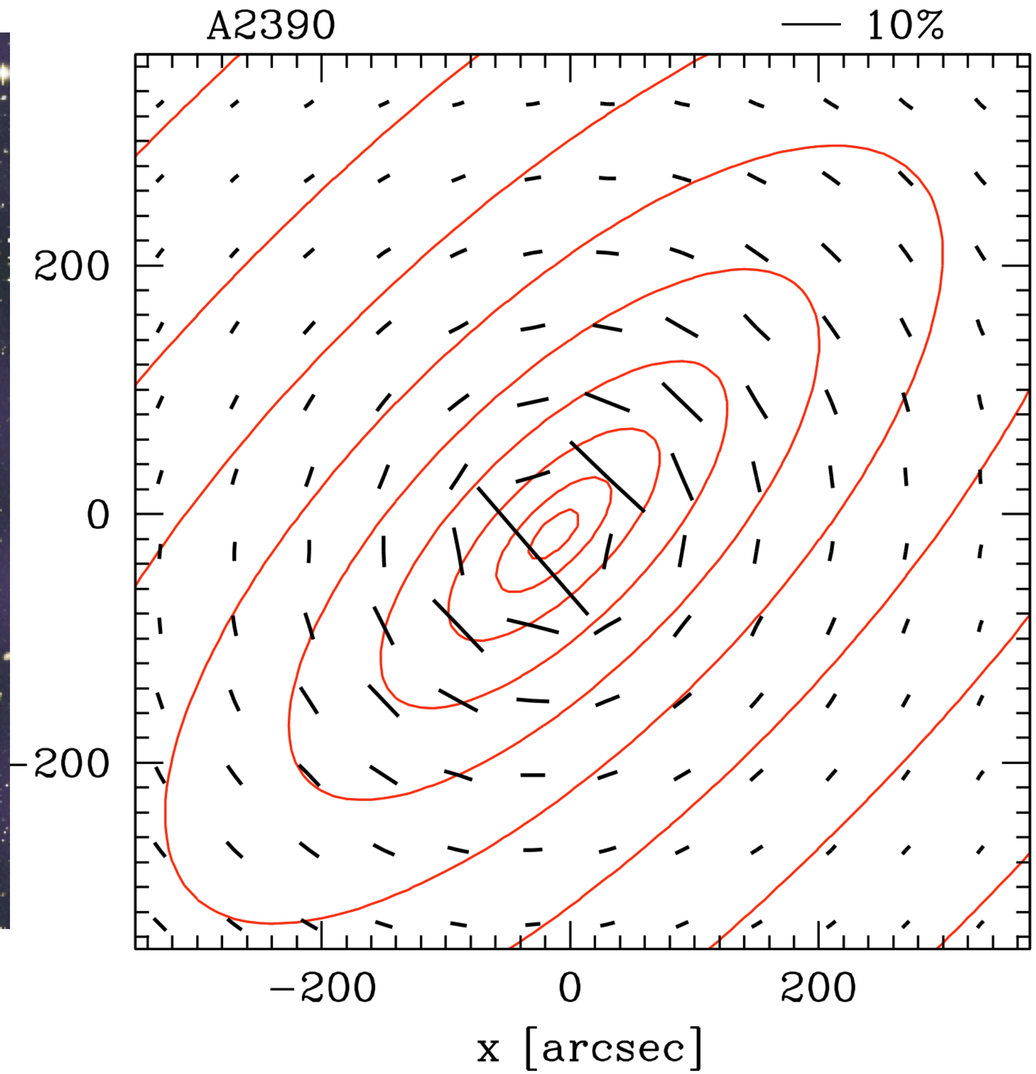
$$\zeta^2 = \frac{x'^2}{1-e} + (1-e)y'^2,$$

$$x' = x\cos\theta_e + y\sin\theta_e,$$

$$y' = -x\sin\theta_e + y\cos\theta_e,$$

2D shear fitting





- In this particular case, e_2D=1-b/a
- Note that the iso-contours of shear amplitudes are not elliptical, needs to solve the 2D Poisson equation.

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Dark Matter Halos Look a Bit Like a Football

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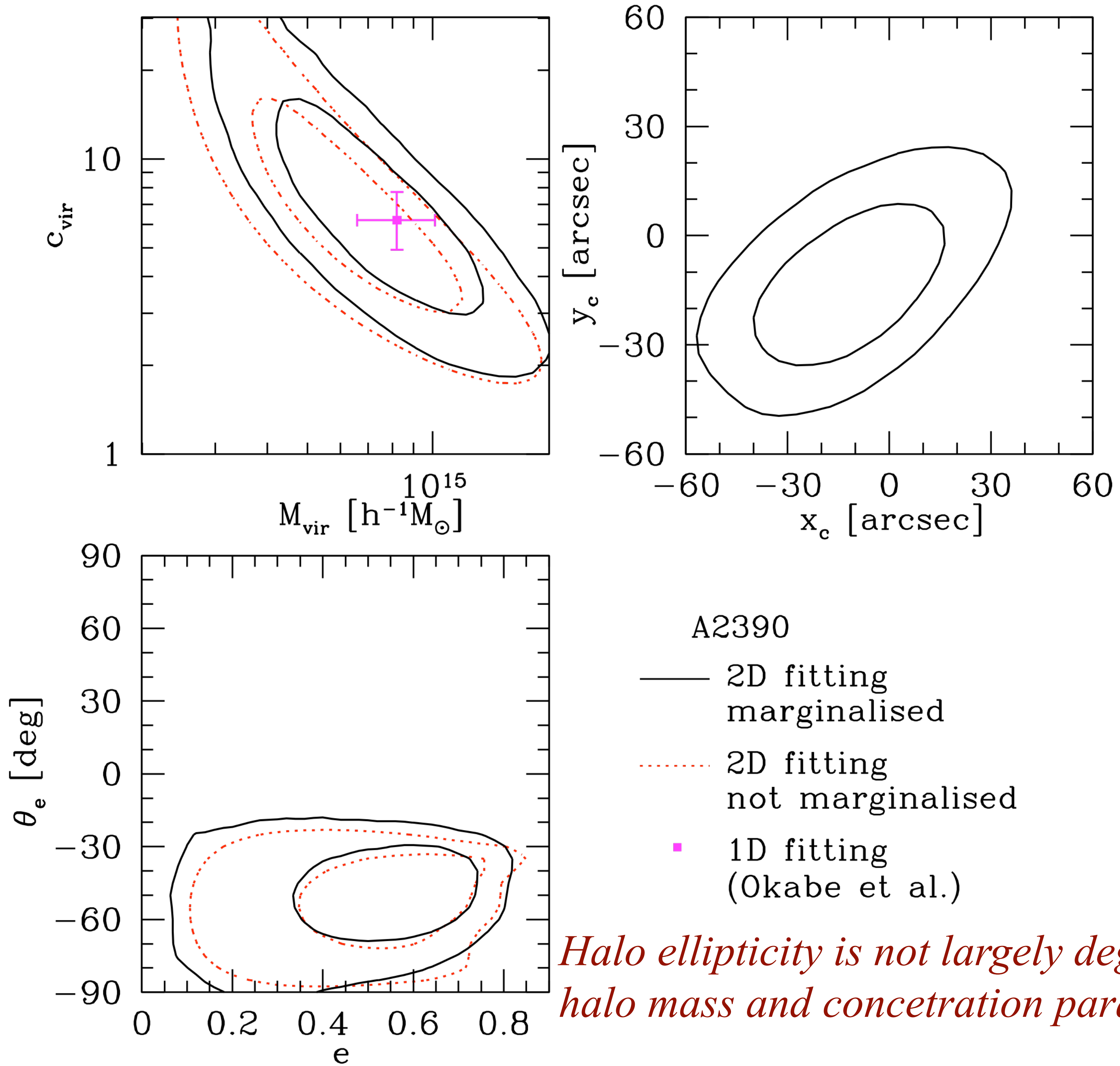
Dark matter is distributed throughout the universe in giant, football-shaped clumps, according to new, indirect images of the mysterious substance that holds galaxies and galaxy clusters together. The work provides more evidence that dark matter, even on the largest scale, strongly affects the visible cosmos with its gravity and remains virtually unaffected in return.

ENLARGE IMAGE

Cosmic gridiron. Dark matter halos (purple) tend to be flattened, like footballs.

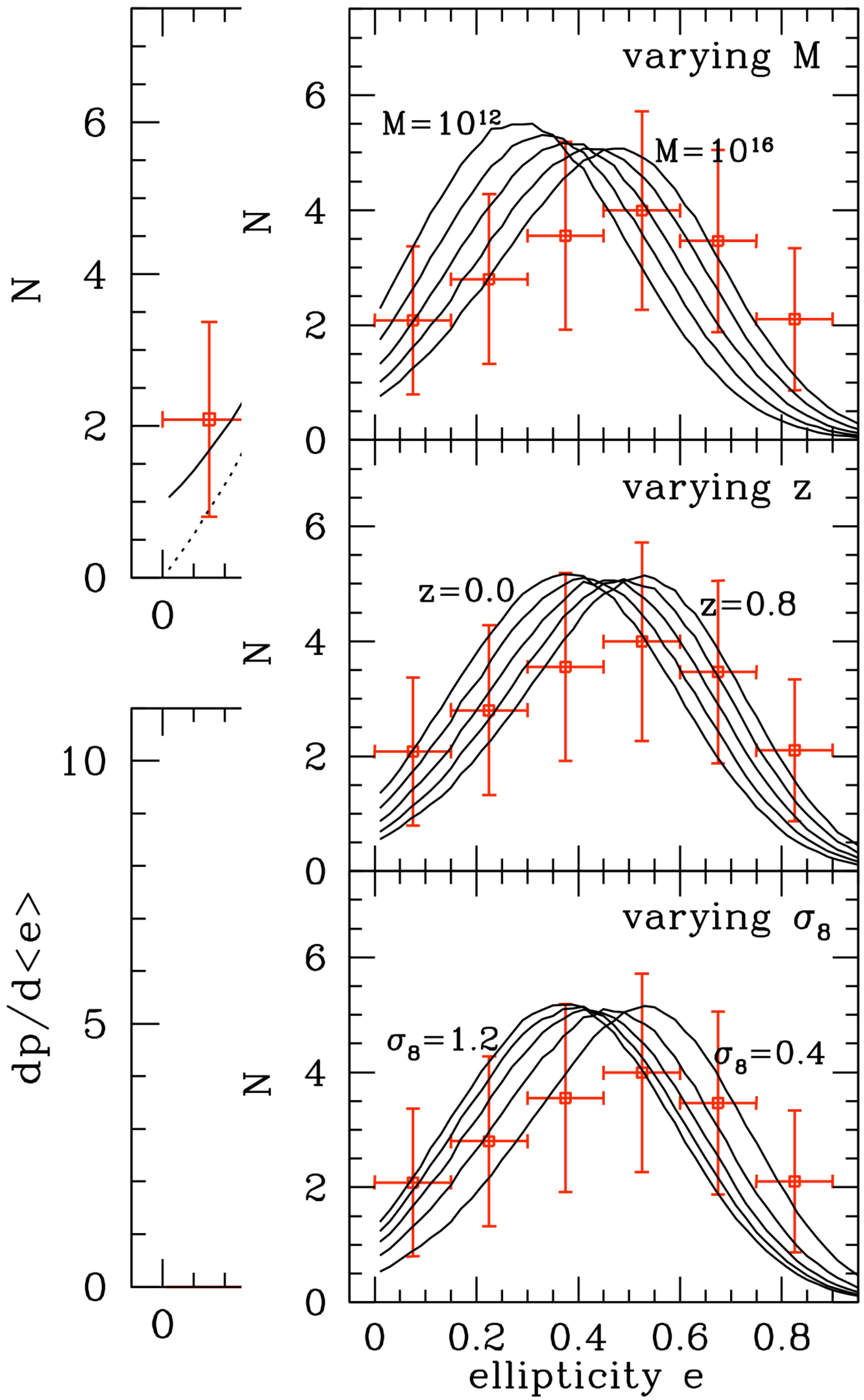
Credit: Subaru Telescope/National Astronomical Observatory of Japan

For decades, astronomers have known that galaxies don't seem to contain enough mass, and therefore gravity, to prevent their constituent stars from flying off into space. Ditto the vast galactic clouds of gas and dust that are necessary to form new stars and solar systems. Even the supermassive black holes were found to be quite puny, in terms of gravitationally binding a galaxy together. Then in the 1970s, astronomer Vera Rubin and colleagues published papers that posited evidence of something called dark matter, which seemed to permeate galaxies and explain why Newton's laws of motion



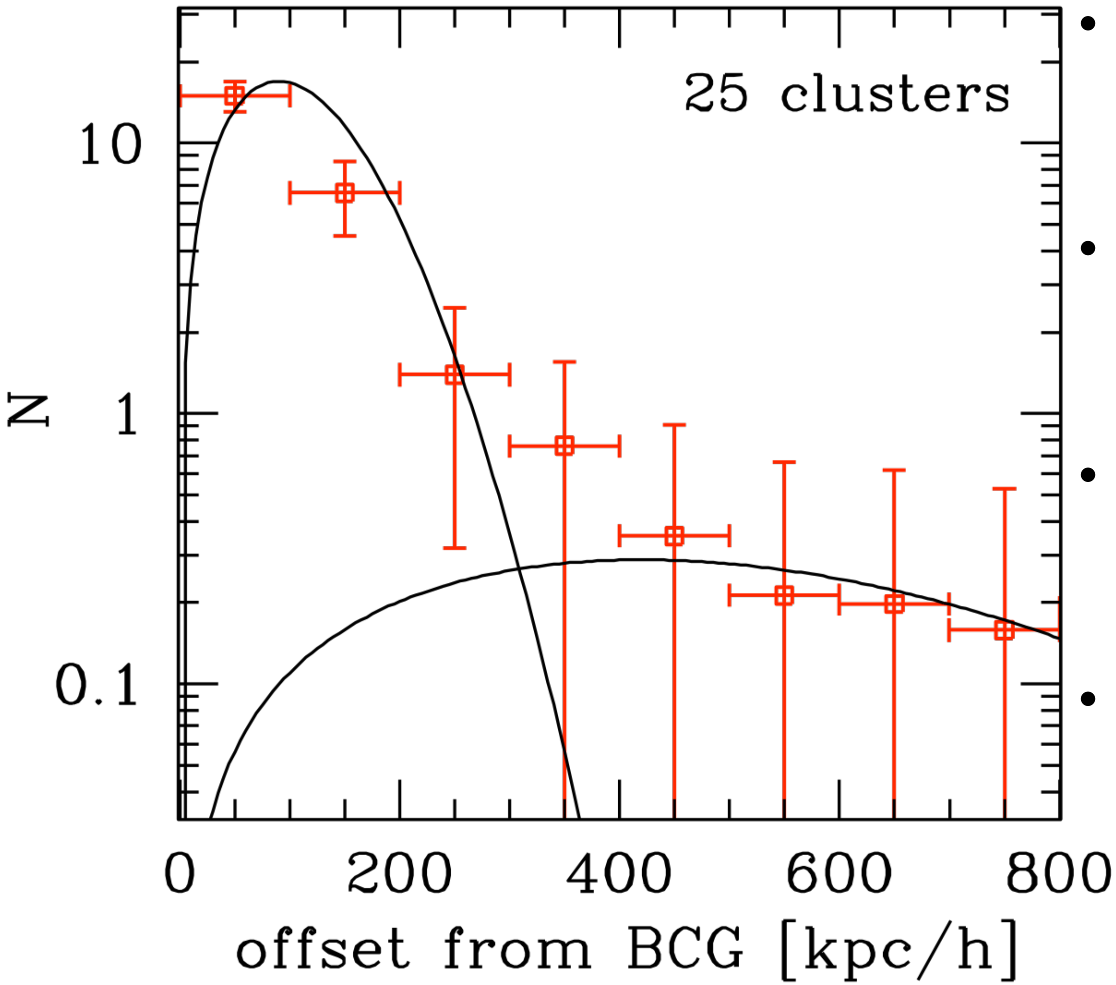
Halo ellipticity is not largely degenerate with halo mass and concetration parameters

A detection of halo ellipticity



- A significant detection of halo ellipticity for 18 clusters, at 7σ level compared to the spherical model
- The ellipticity ~0.5 on average
  - X-ray images show e~0.2-0.3
  - Galaxy scales: e~0.2
  - Can exclude MOND?
- Remarkable agreement with the CDM predictions
- Not enough to discriminate the model differences

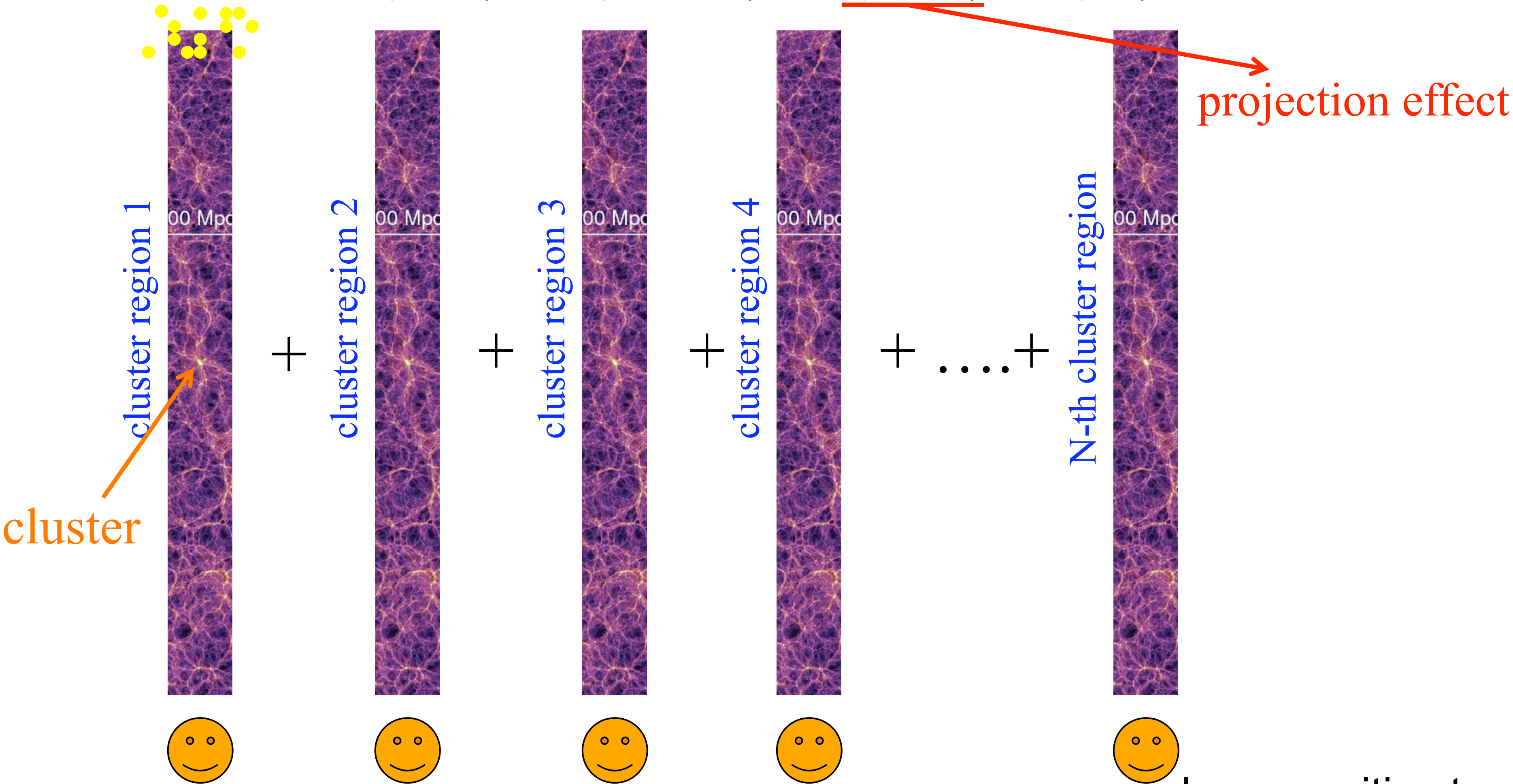
Halo center



- Halo center, constrained from lensing, is close to the position of brightest central galaxy
- However, some clusters (about 10% fraction) show large offsets
- Imply that the BCG is oscillating around the potential well for some clusters
- Quantify the impact of systematic errors in the stacked cluster lensing analysis

Advantage of stacked cluster lensing

$$\gamma_+^{\rm obs}(\theta_i) = \gamma_+^{\rm cluster}(\theta_i) + \gamma_+^{\rm LSS}(\theta_i) + \varepsilon_+(\theta_i)$$



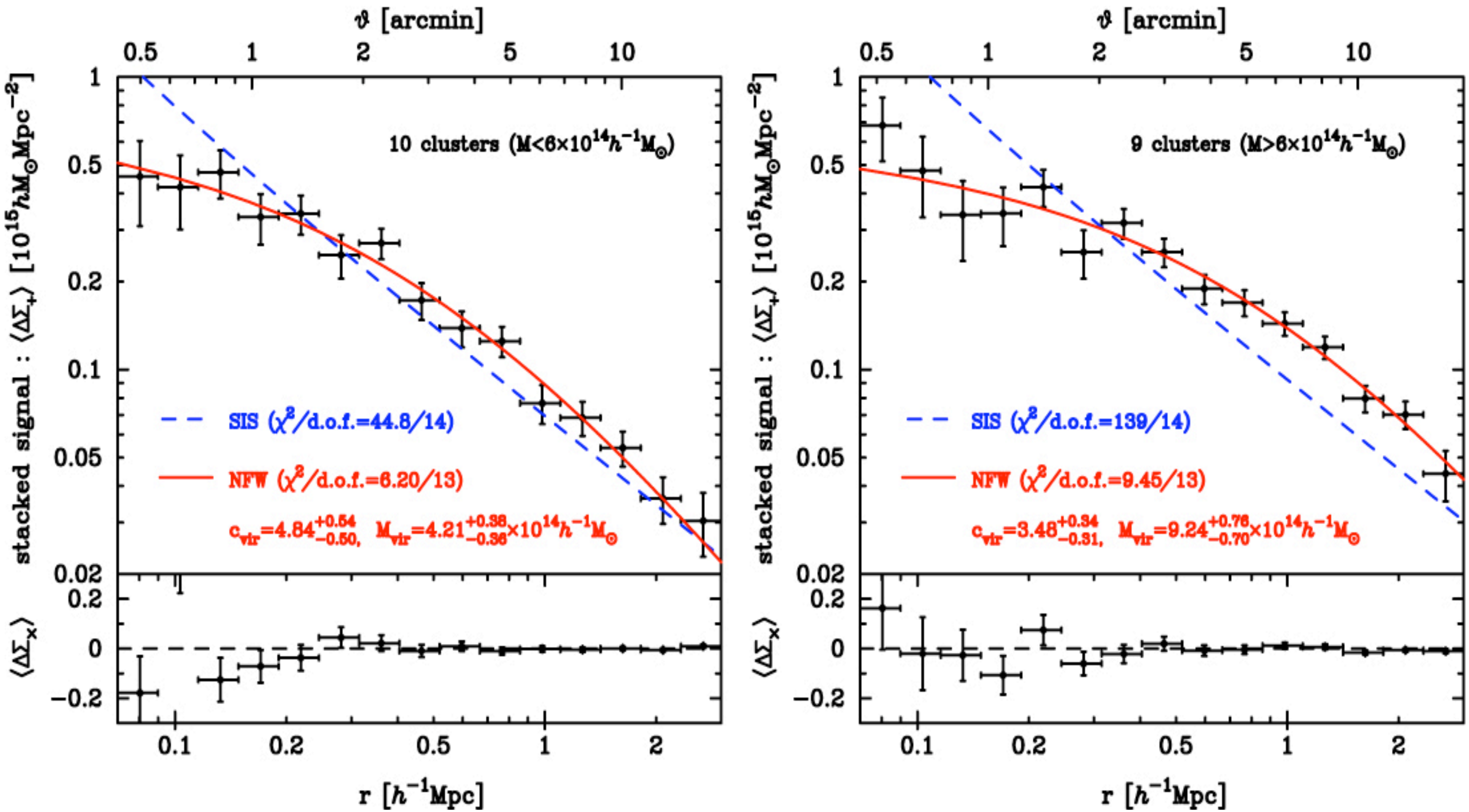
$$\langle\gamma_+\rangle(\theta) = \frac{1}{N_{cl}}\sum_{a=1}^{N_{cl}}\sum_{|\vec\theta'|\subset\theta}\gamma_{+(a\text{-th cluster})}(\vec\theta') \approx \left\langle\gamma_+^{\rm cluster}\right\rangle(\theta)$$

less sensitive to projection effect, intrinsic alignment, ...

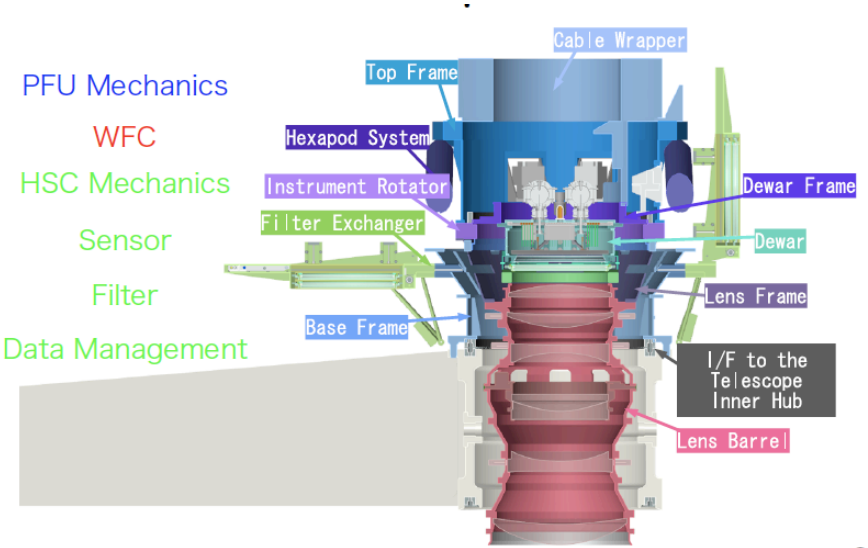
Results: stacked lensing

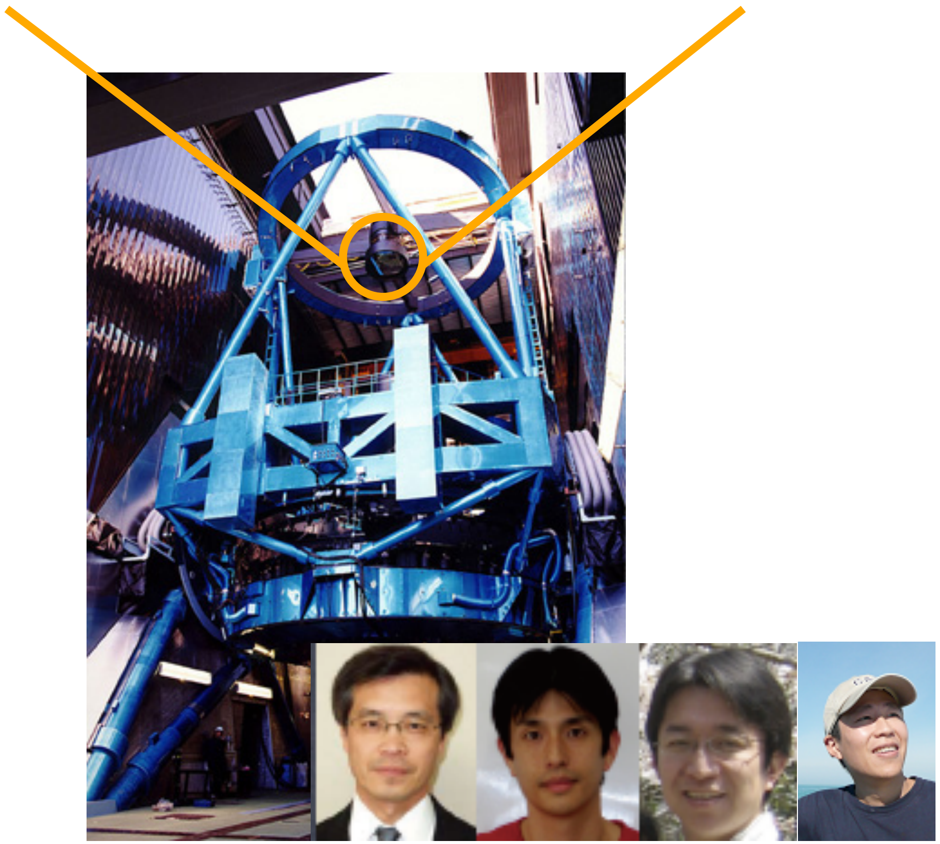
Okabe, MT+10

- For Subaru data, only ~10 clusters are enough to obtain the high S/N signals



$\Delta\chi^2 = \chi^2_{\rm SIS} - \chi^2_{\rm NFW} = 39$ and 129 for low- and high-mass samples, respectively

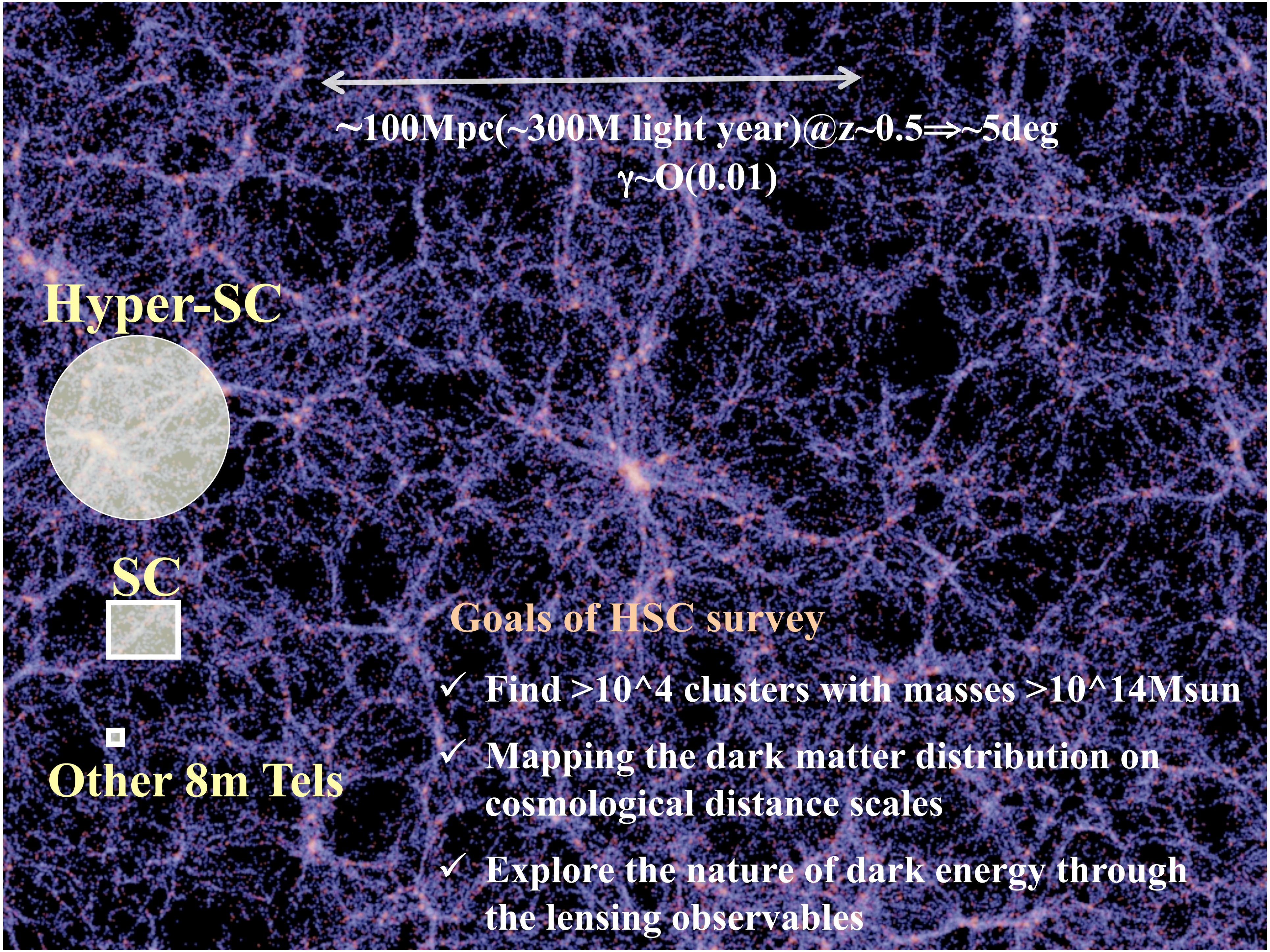




Hyper Suprime Camera Project

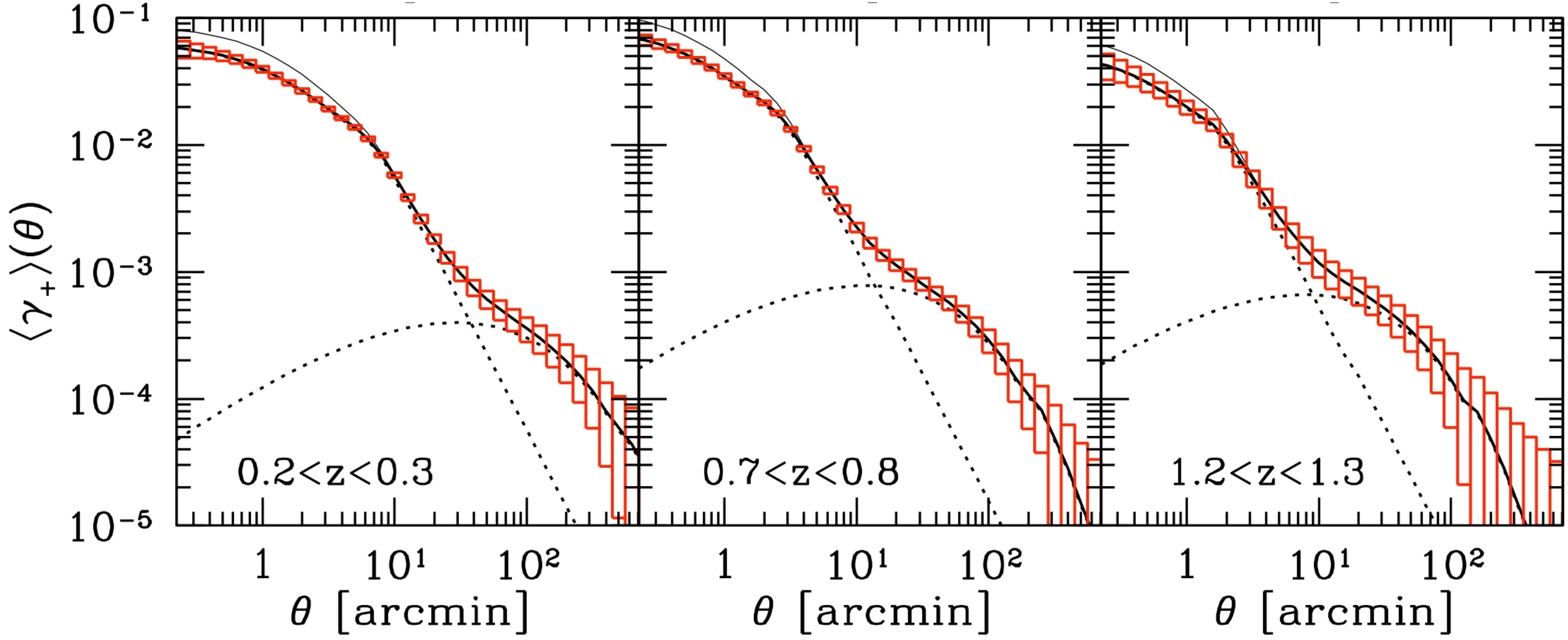
- Upgrade the prime focus camera
- **Funded, started since 2006**
- International collaboration: **Japan (NAOJ, IPMU, Tokyo, Tohoku, Nagoya), Princeton, Taiwan**
  - IPMU members (H. Aihara, MT, N. Yoshida): leading this project
- Field-of-View: ~10×Suprime-Cam
- Keep the excellent image quality
- ~2000 sq. deg weak lensing survey starting from late 2012- (~5 years)

  Note: the current WL surveys ~100 sq. deg (but shallow)


~100Mpc(~300M light year)@z~0.5⇒~5deg
γ~O(0.01)
Hyper-SC
SC
Other 8m Tels
Goals of HSC survey
✓ Find >10^4 clusters with masses >10^14Msun
✓ Mapping the dark matter distribution on cosmological distance scales
✓ Explore the nature of dark energy through the lensing observables

HSC can ...

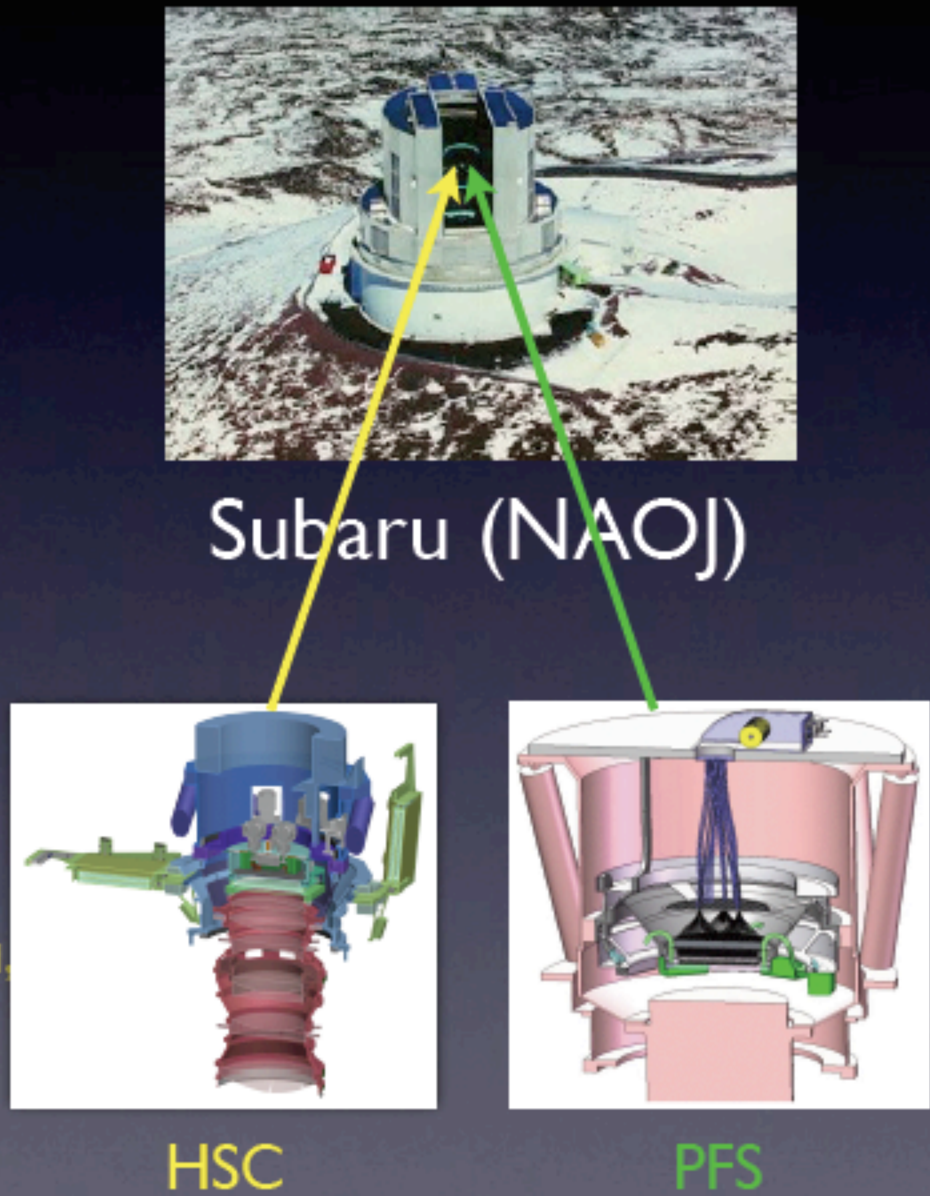
Oguri & MT 10



- HSC can achieve a high S/N detection of stacked WL signals out to z~1.3
- Small-angle signals are from one halo around each LRG (the mean halo mass and the average shape of mass profile)
- Large-angle signals are from the mass distribution in large-scale structure surrounding LRGs.

Revealing Dark Energy

- Japan is behind in this area
- measure the rate of acceleration
- ~100M galaxies
- precision imaging of galaxy shapes
  ⇒world class
- precision wide field spectrograph to measure distances ⇒ world leading!
- push the Japanese technology in precision control, optics, detectors, materials
- Mitsubishi Electric, Canon, Hamamatsu, Kyocera have been involved in R&D



Summary

- Gravitational lensing offers a unique means of measuring dark matter distribution in a cluster
- Subaru is the best facility for making accurate weak lensing measurements
- Measuring cluster masses is of critical importance for doing cosmology with cluster counting statistics
  - Various systematic issues need to be carefully studied: projection effect, miscentering effect, model uncertainty, source redshifts, ….
- Radial density profile and shape of dark matter distribution can be used to test the CDM predictions on small scales that are not constrained by CMB
- Carrying out cluster weak lens studies with Subaru data (so far 30 clusters, ~60 clusters until the end of 2010)
  - Finding the measured profile is consistent with NFW profile
  - A significant detection of the dark matter halo ellipticity, consistent with the CDM prediction
- The pilot study in preparation with Subaru HSC survey, aimed at exploring the nature and properties of DM and DE