Subaru weak lensing study of X-ray luminous clusters

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INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

@BCG seminar, May 10, 2011


We all look forward to
Kevin and Alexie joining us this fall!
~70 researchers, 60% non-Japanese

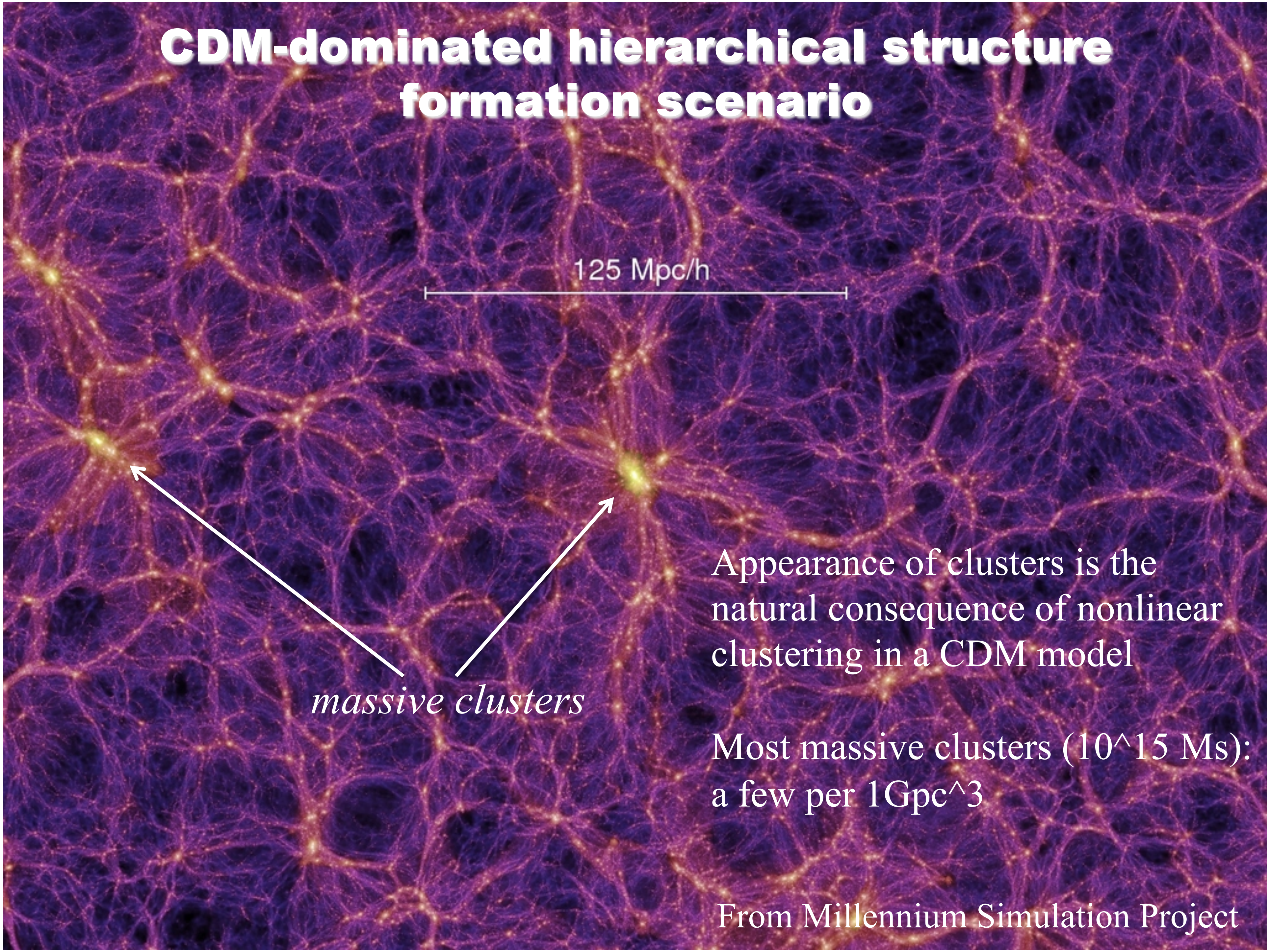

occupancy since Jan 18, 2010
~5900 m^2


interaction area ~400m²
like a
European town square
Piazza Fujiwara
Obelisk
"L'Universo è scritto in
lingua matematica"

Collaborators

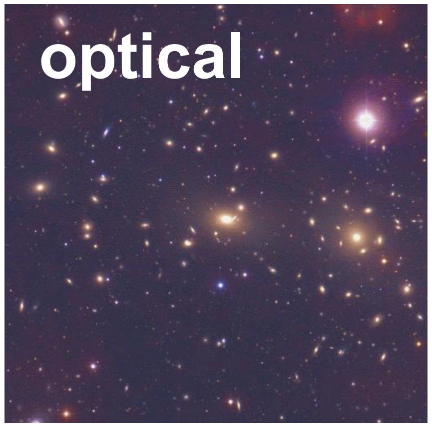
T. Futamase (Tohoku U.)
M. Oguri (NAOJ→IPMU)
N. Okabe (Taiwan)
G. P. Smith (Birmingham)
K. Umetsu (ASIAA Taiwan)
H. Miyatake (Tokyo)
LoCuSS team members
S. Mineo (Tokyo)

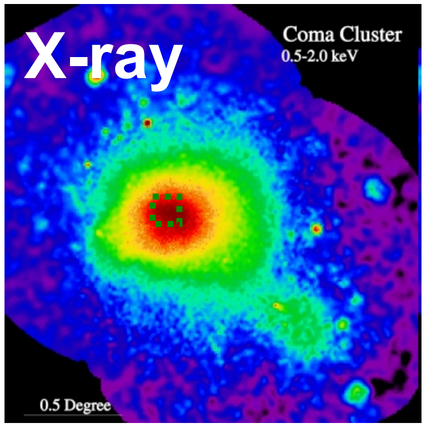
This talk is mainly based on
Okabe, MT, Umetsu, Futamase, Smith, arXiv:0903:1103, PASJ, 2010
Oguri, MT, Okabe, Smith, arXiv:1004.4214, MNRAS 2010
Okabe, MT, et al. in prep.

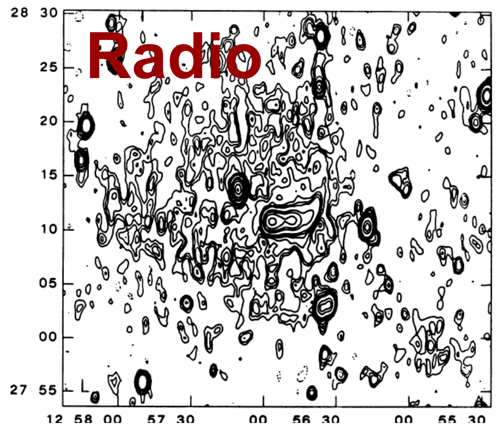

CDM-dominated hierarchical structure formation scenario
125 Mpc/h
massive clusters
Appearance of clusters is the natural consequence of nonlinear clustering in a CDM model
Most massive clusters (10^15 Ms): a few per 1Gpc^3
From Millennium Simulation Project

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**

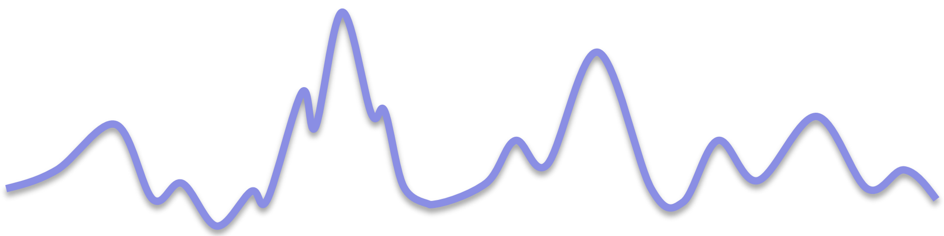






Cosmological Use of Clusters: Halo Mass Function

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

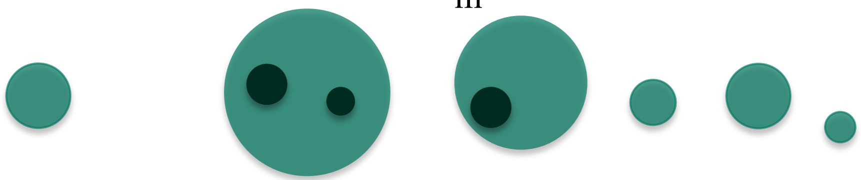


Gravitational instability

(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

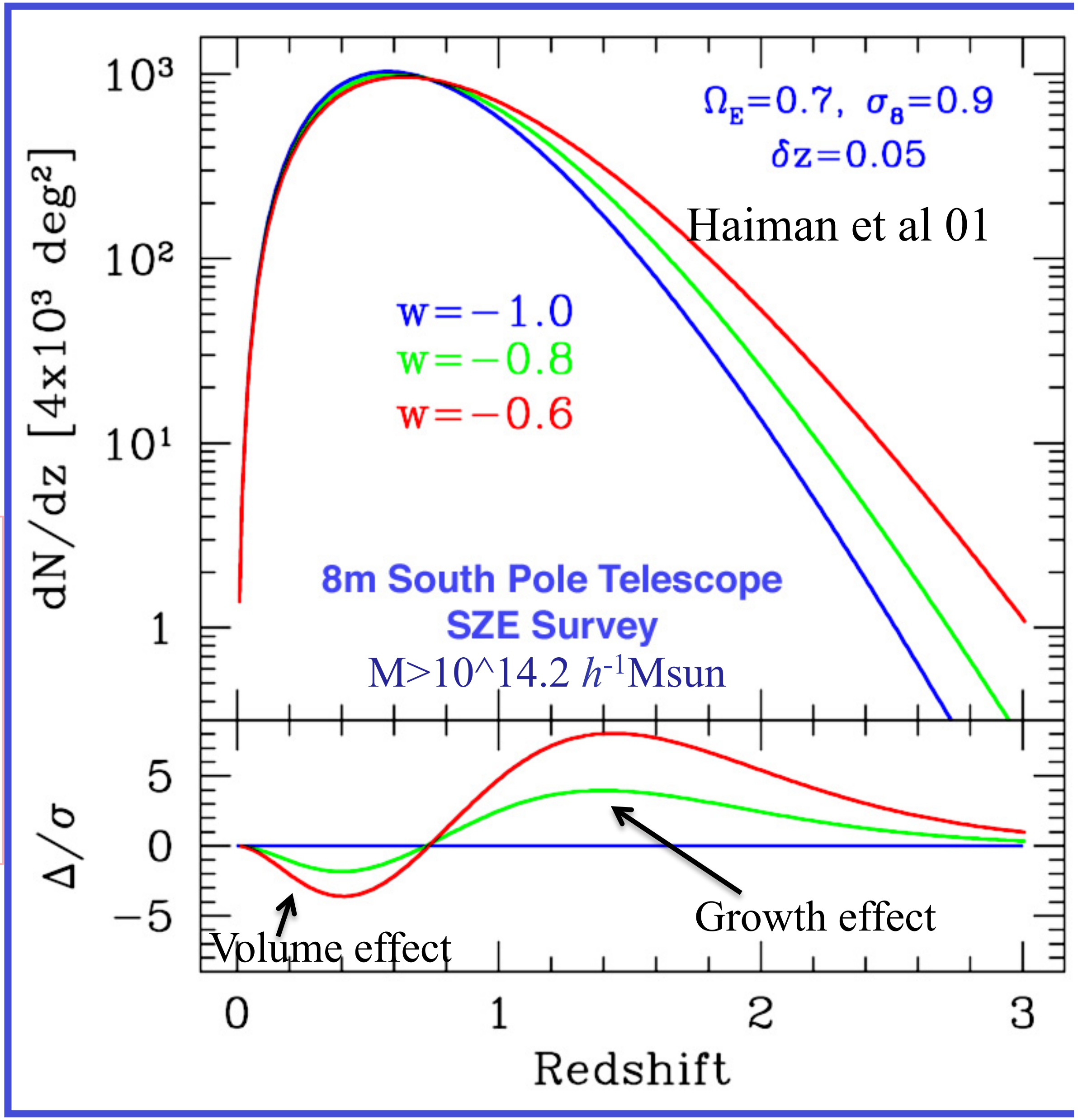
$$\frac{d^2N}{dzdM} = \Omega_S \frac{d^2V}{dzd\Omega}\frac{dn}{dM}$$

DE equation of state: w

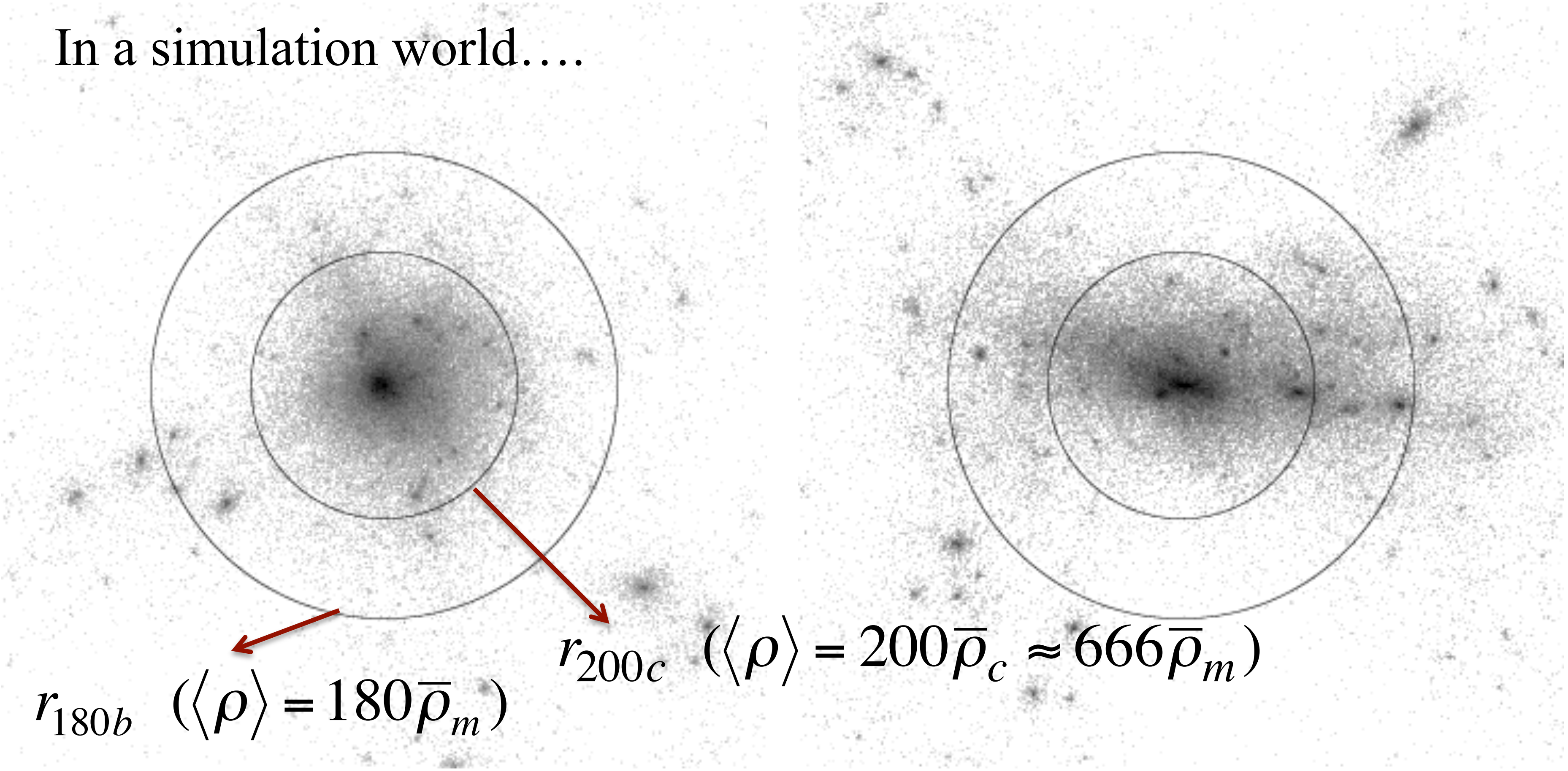
$$w \equiv \frac{p_{\rm de}}{\rho_{\rm de}}$$

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

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



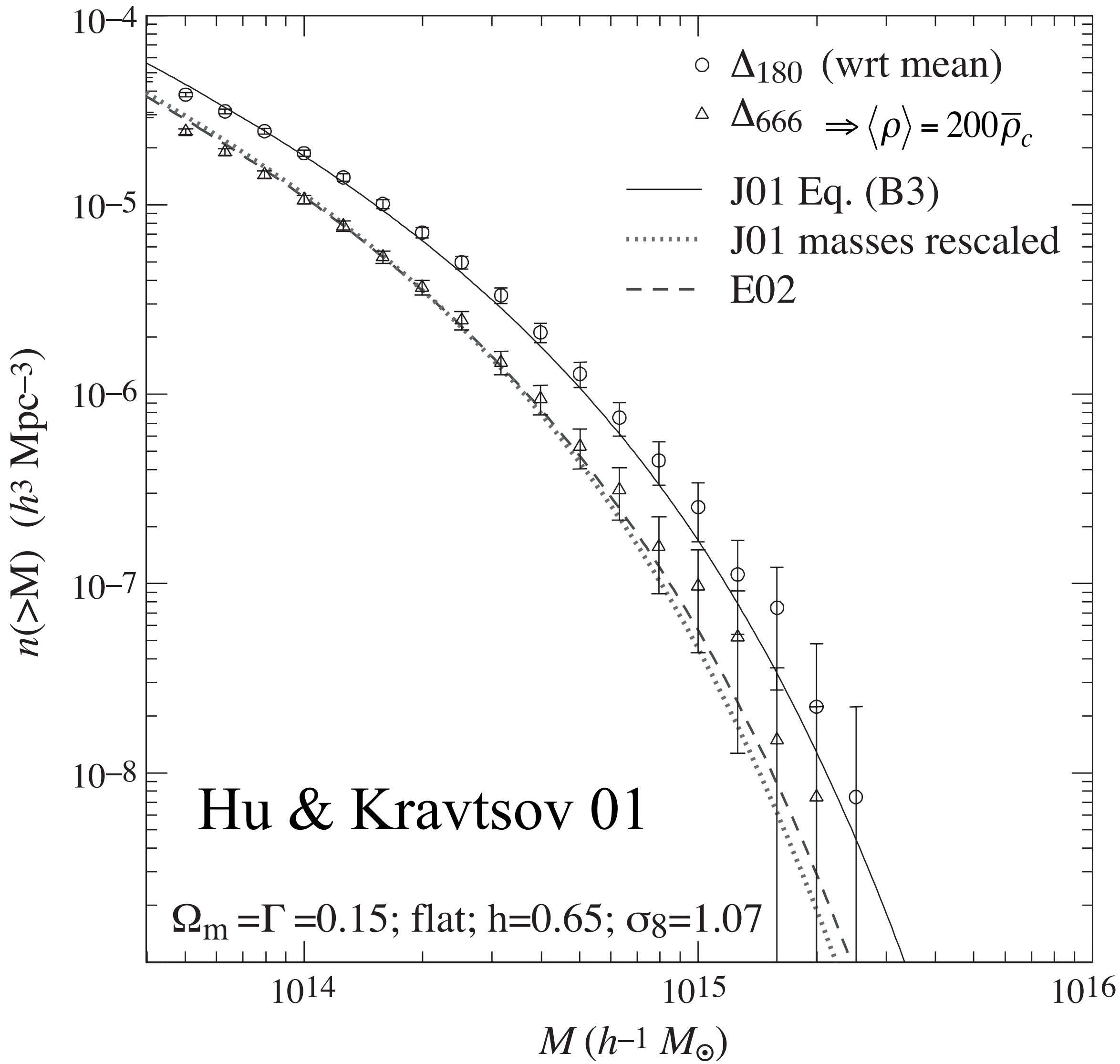
Issue: cluster mass



White 02

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

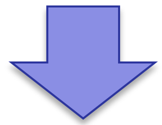
Cosmological Use of Clusters: Halo Mass Function



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 $\sigma_{\ln M}\sim 0.01$
  - The intrinsic distribution around the mean relation needs to be also understood

Vikhlinin et al. 2009: Chandra

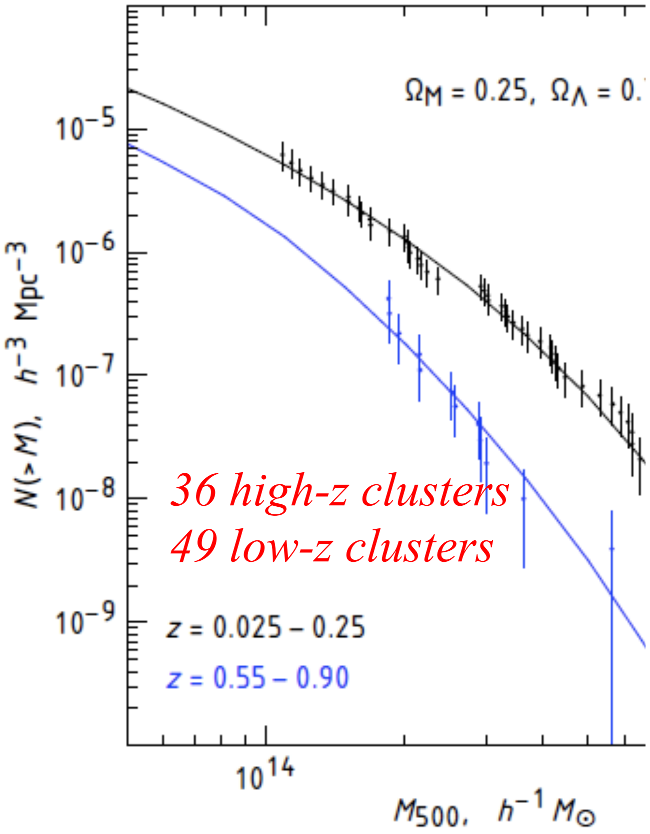
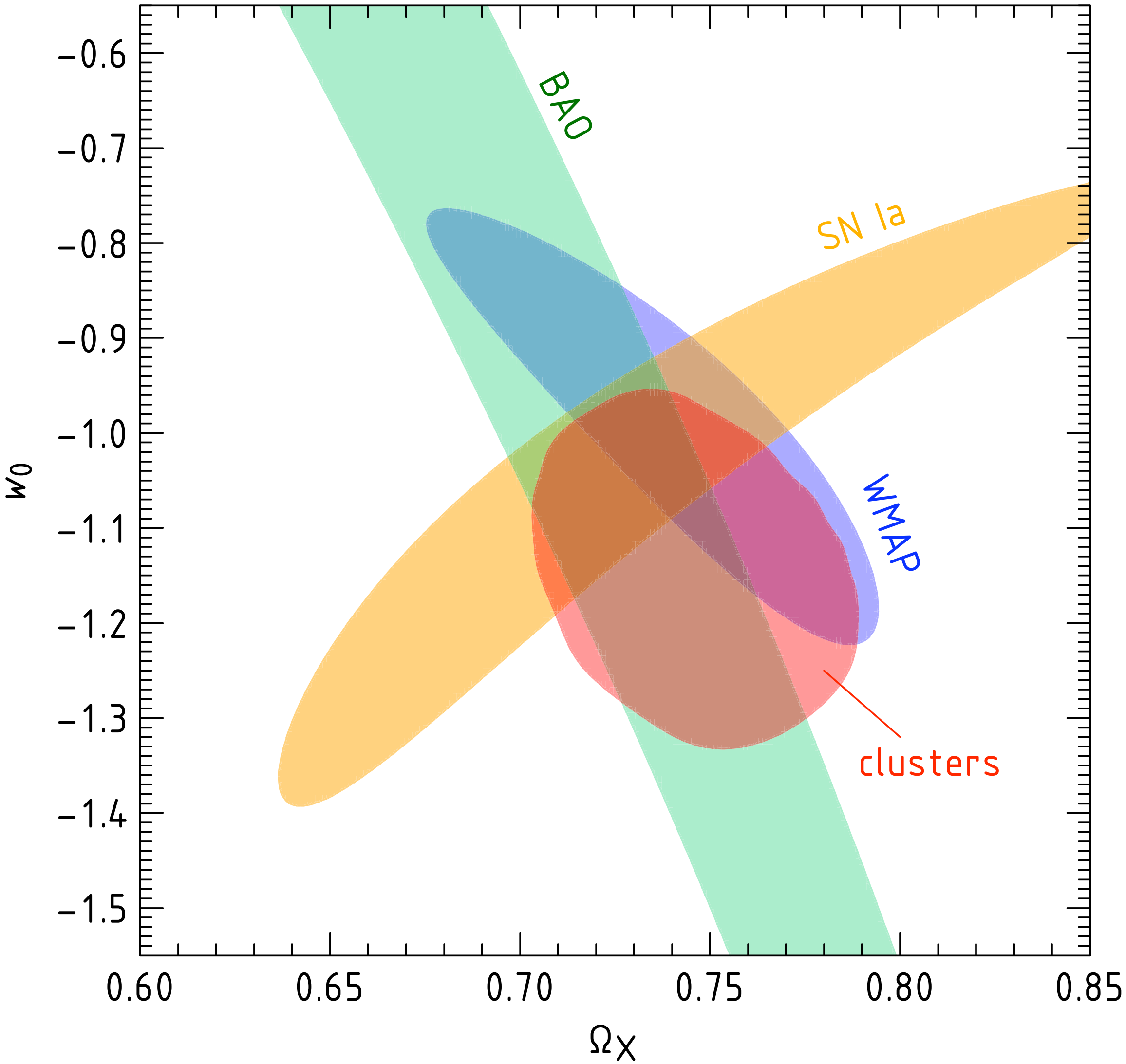
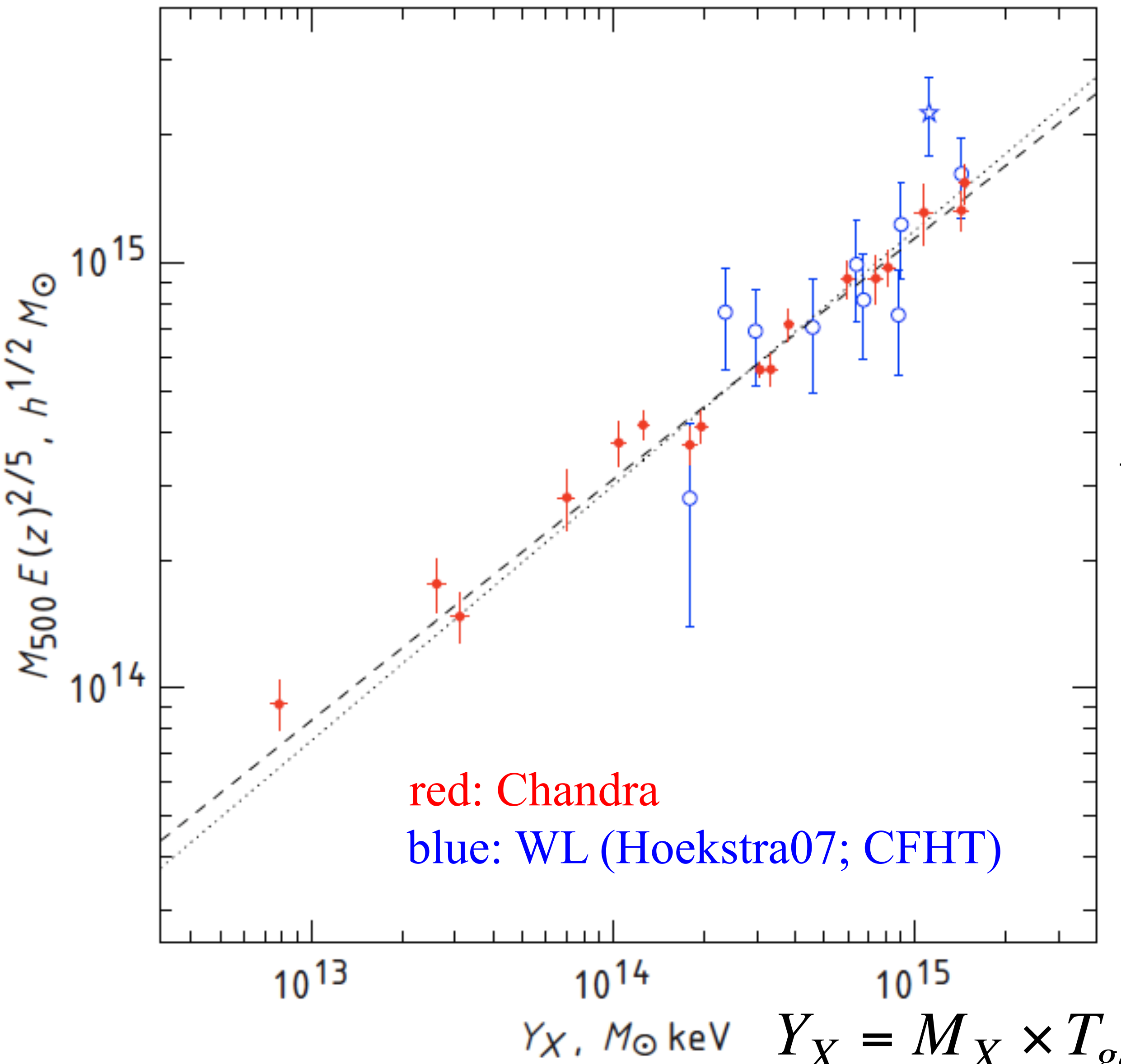


FIG. 2.— Illustration of sensitivity of the cluster mass fun
models (with only the overall normalization at $z = 0$ adjuste
from Fig. 1, which for the high-z cluster we show only the r
models are computed for a cosmology with $\Omega_\Lambda = 0$. Both t
function is changed because it is derived for 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



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

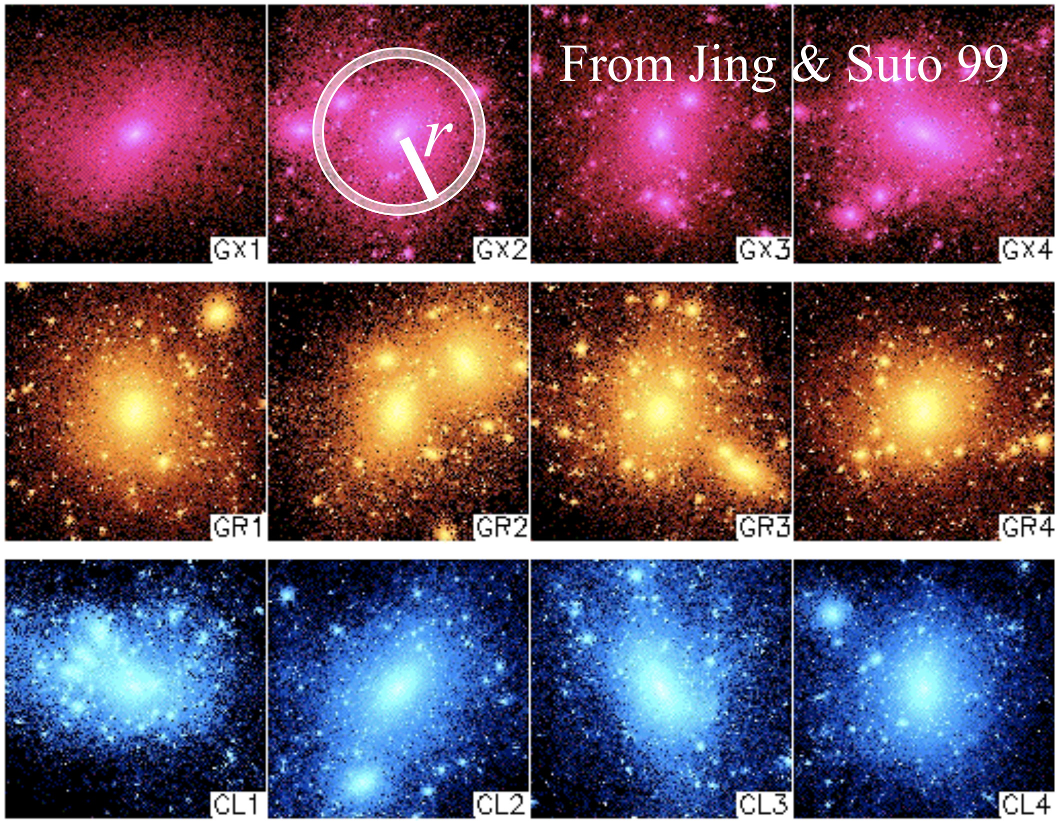
$$\frac{GM(<r)}{r^2} = -\frac{1}{\mu}\frac{d(\rho_{gas}kT)}{dr}$$

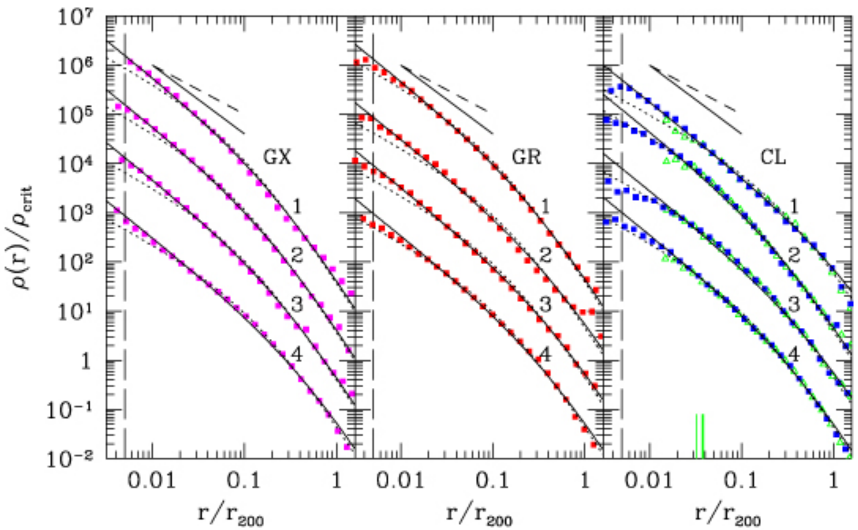
$\sigma_{\ln M} \sim 10\%$

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

Internal structure of halo

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





NFW profile

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

Outer: ρ∝r^-3

Inner: ρ∝r^-1

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

Model-dependent mass estimate: 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

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

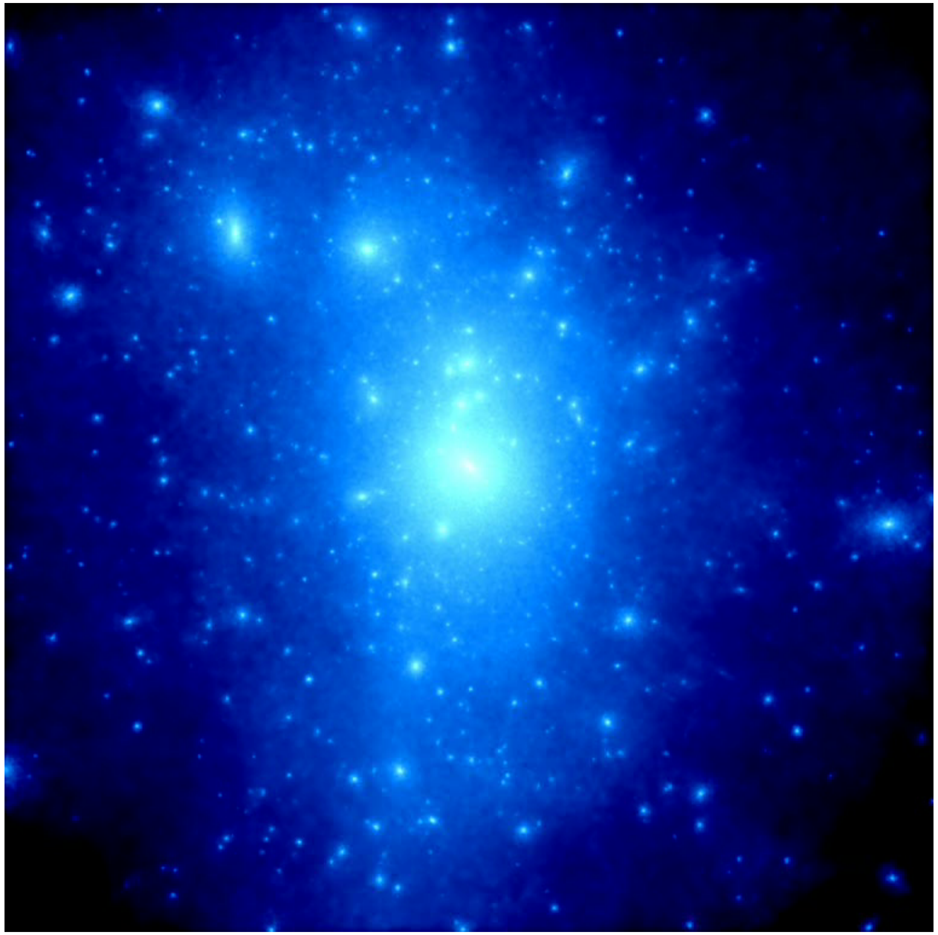
$$+\begin{cases} M_\Delta = \dfrac{4\pi}{3} r_\Delta^3 \overline{\rho}_m \Delta & : \text{defines the halo boundary for a given } \Delta \\ M_\Delta = \int_{r<r_\Delta} 4\pi r^2 dr\, \rho_{NFW}(r) & : \text{sets the interior mass of } \rho_{\rm NFW} \text{ to } M_\Delta \end{cases}$$

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

- Can infer the halo mass from the measured halo profile

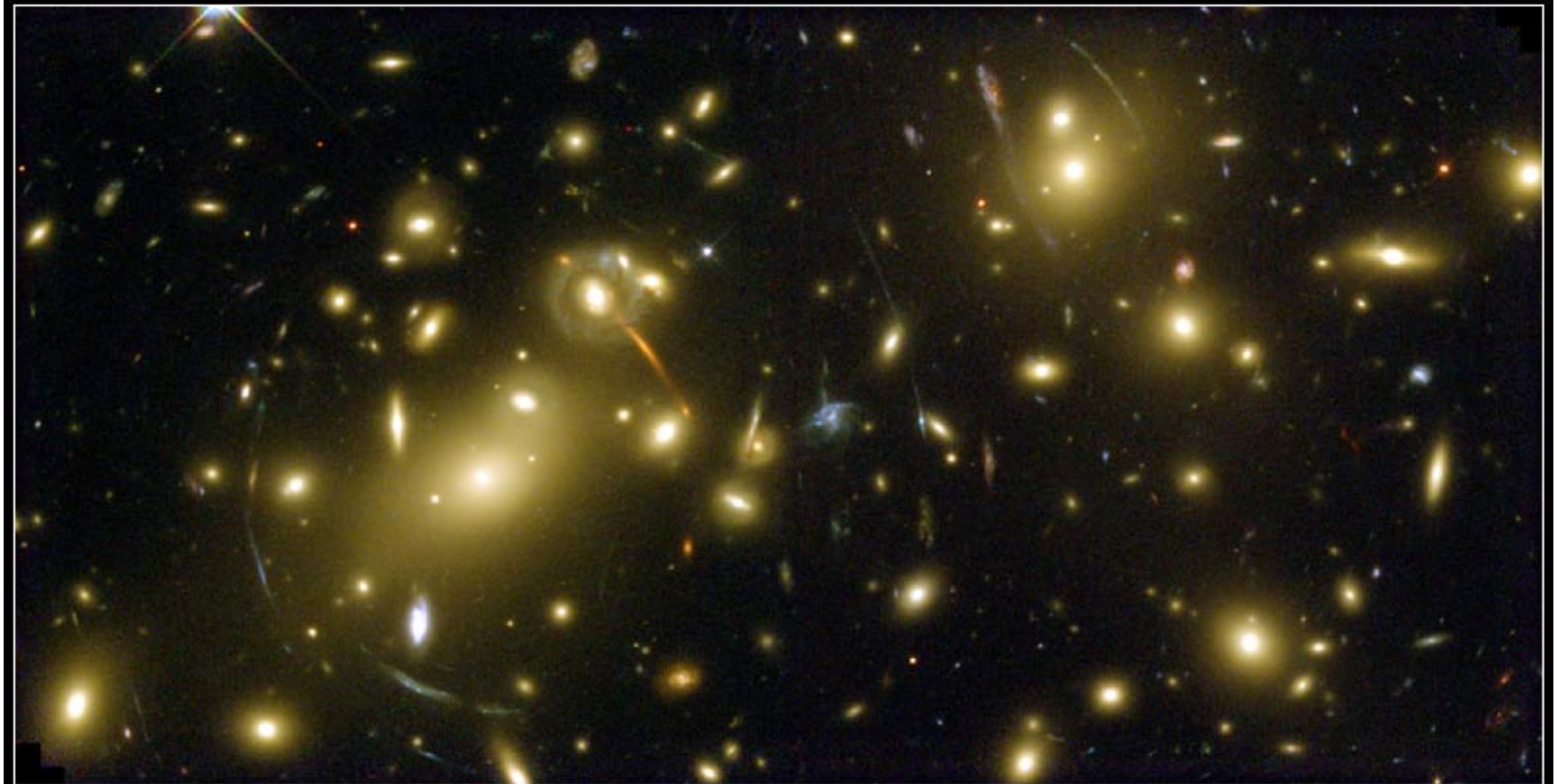
"Shape" of dark matter halo

- 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)



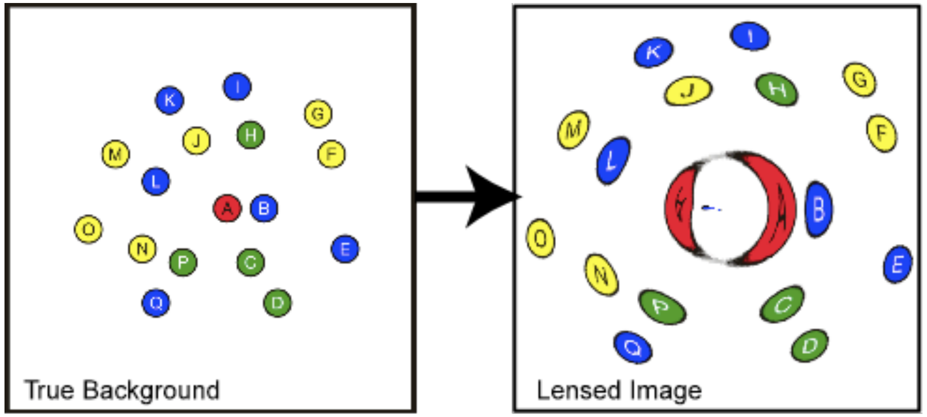
From H. Yahagi (Kyoto U.)

Gravitational Lensing
= method to "*see*" invisibles

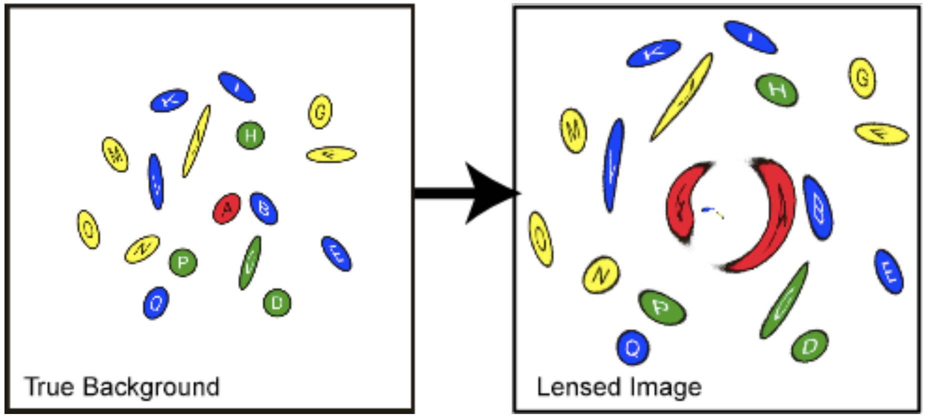


Galaxy Cluster Abell 2218 **HST • WFPC2**
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

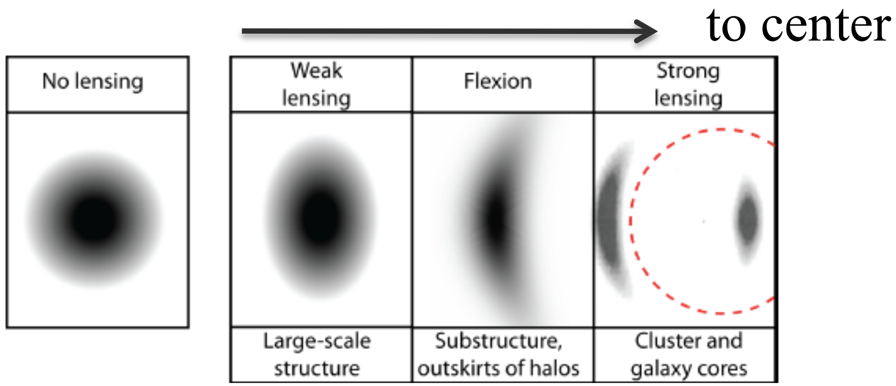
Strong and weak lensing



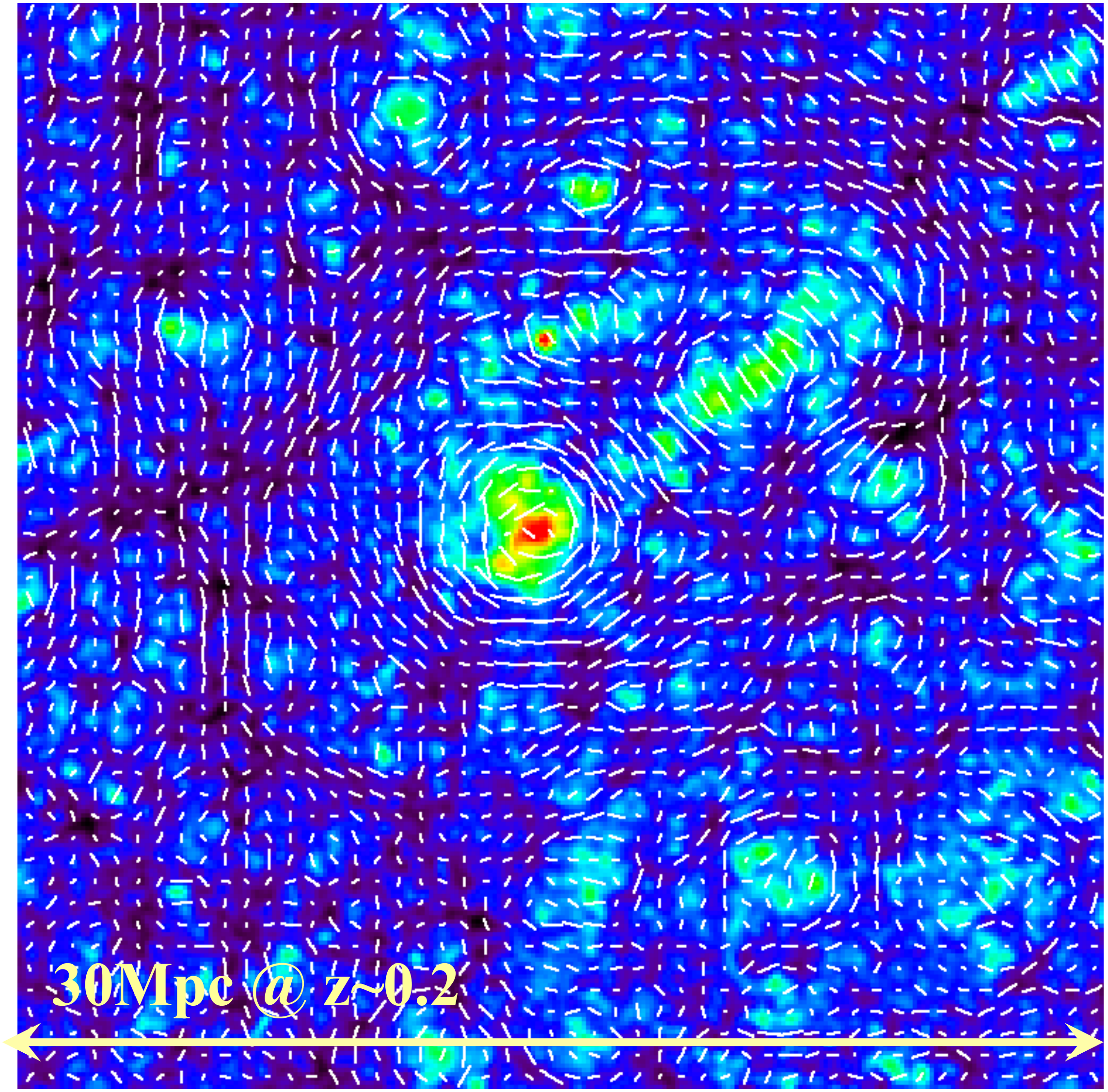
- **Strong Lensing**
  - Multiple Images
  - Large Arcs, Ring
  - Obvious Distortion



- **Weak Lensing**
  - Slight Stretching
  - Distortion small compared to initial shape
  - Statistical lensing
  - *Open up an opportunity to measure the mass distribution over the entire region*



A simulated lensing field



3x3 degree field (Hamana 02)

color: κ
sticks: γ

Lensing shear strength

$$\gamma = \frac{a-b}{a+b} \Leftarrow DM$$

- Tangential shear around κ peaks
- Filamentary structures washed out by projection
- The shear amplitudes
  - γ~0.1-0.01 around clusters
  - cosmic shear: γ~0.01

Weak lensing: such a small signal!

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:

Credit: Bridle et al 10

To have an accurate WL measurement, we need

- Excellent image quality
- Deep image (to reduce the intrinsic ell. noise)

Here we used the KSB method (Kasier, Squires & Broadhurst 95); we are also working on other methods (in progress)

Intrinsic star (point source)

Atmosphere and telescope cause a convolution

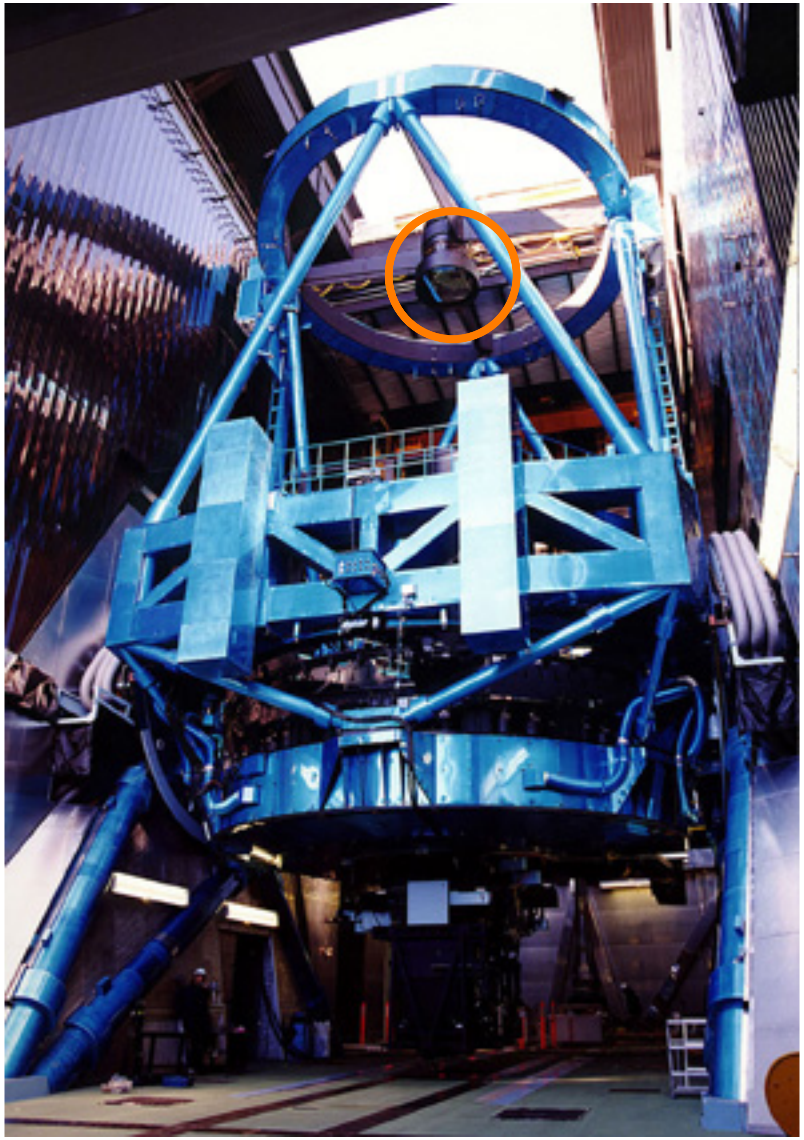
Detectors measure a pixelated image

Image also contains noise

Distortion on star image: O(0.01)

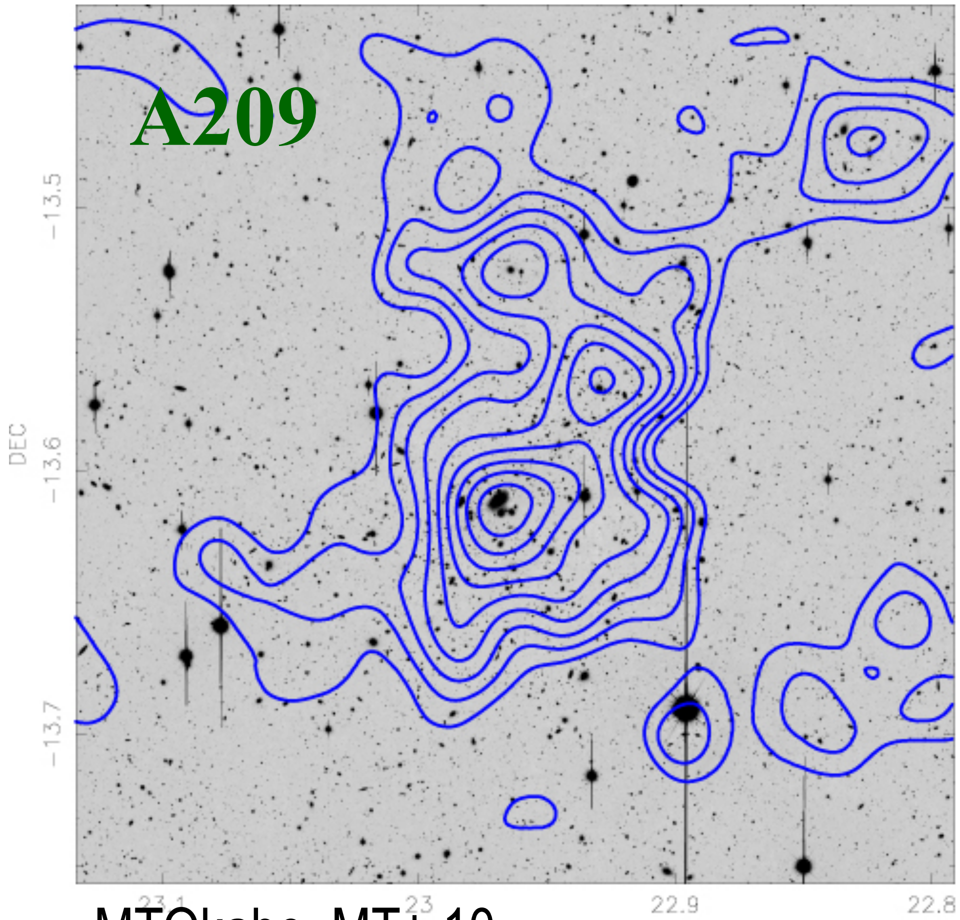
Subaru Telescope:
Best facility for WL measurement

- 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 (typically ~0.7arcsec)
- Deep images allow the use of many galaxies for the WL: higher spatial resolution



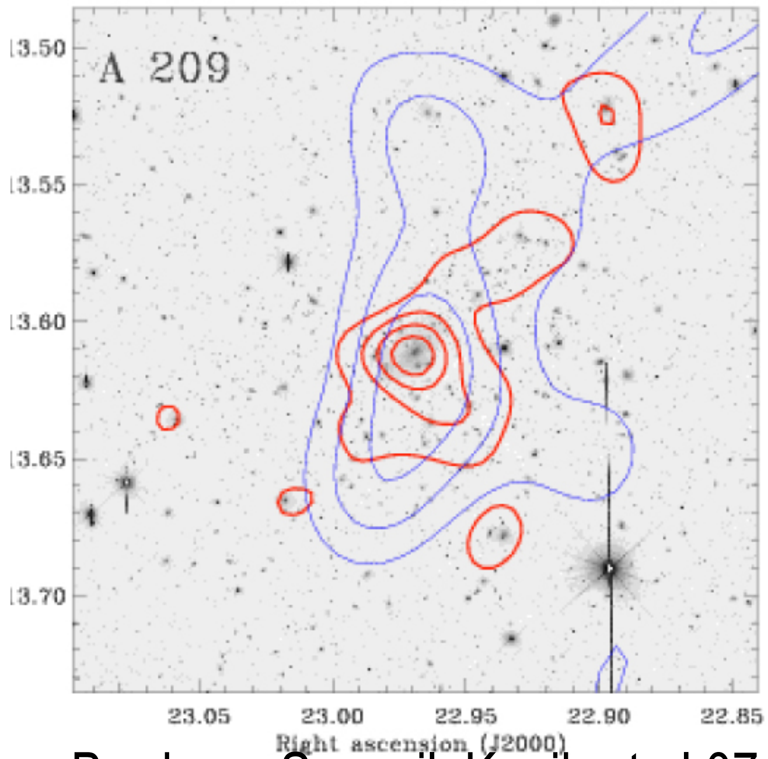
Subaru capability for WL measurement

Subaru S-Cam



MTOkabe, MT+ 10

CFHT (blue: mass)

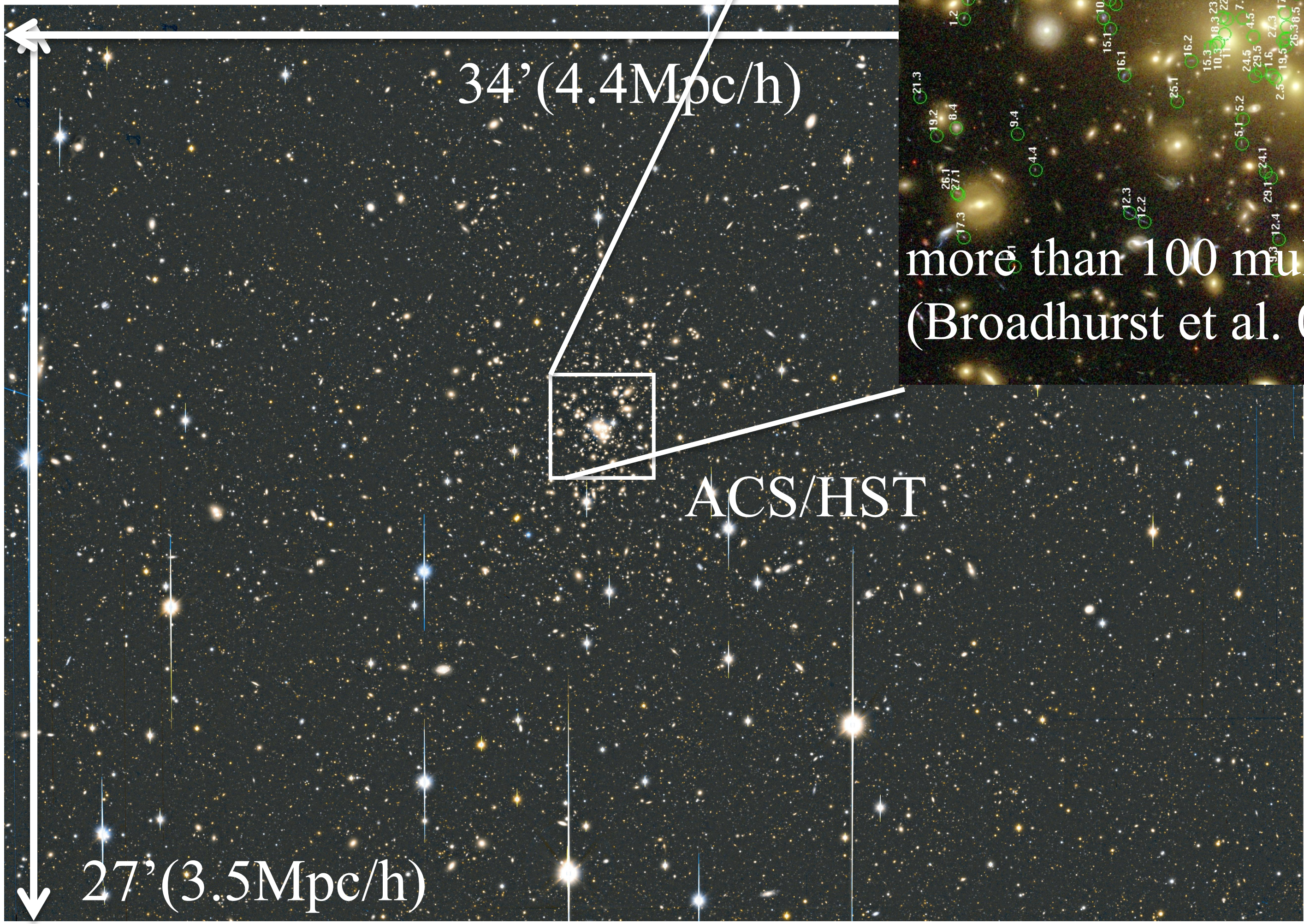


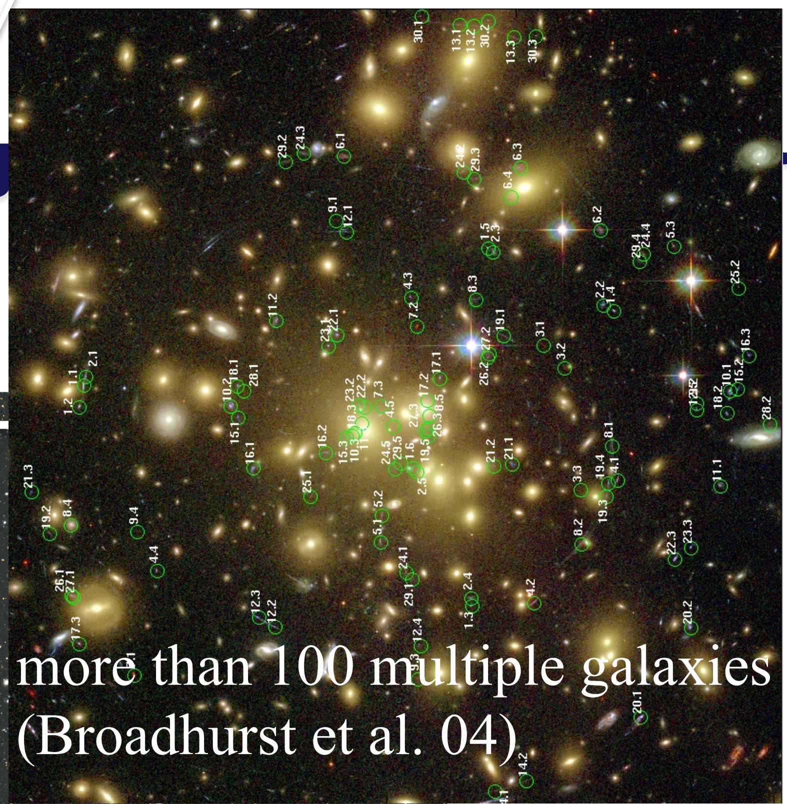
Bardeau, Soucail, Kneib et al.07

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

Subaru FoV = Virial reg ~0.2

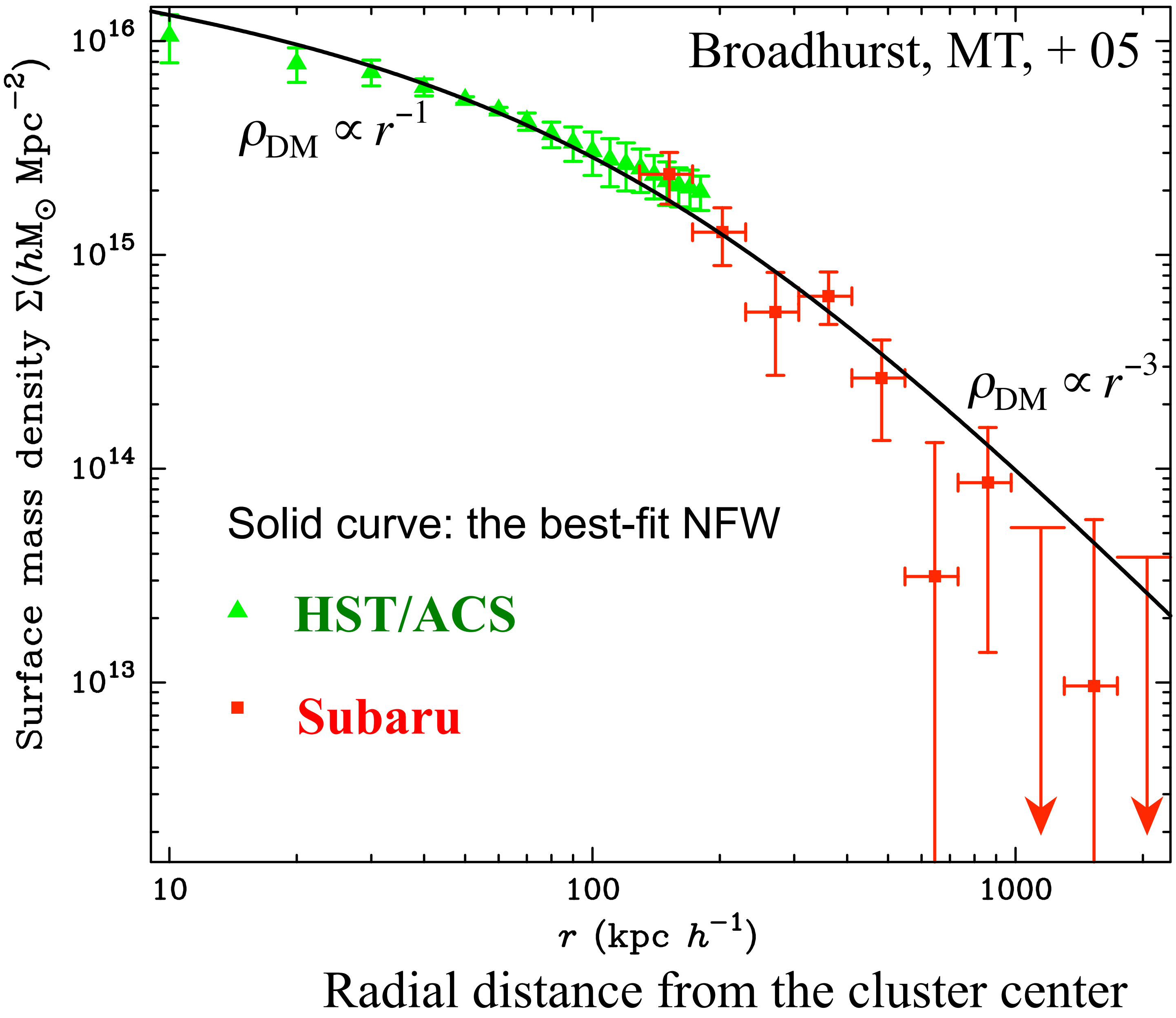
Example: A1689 (z=0.18)





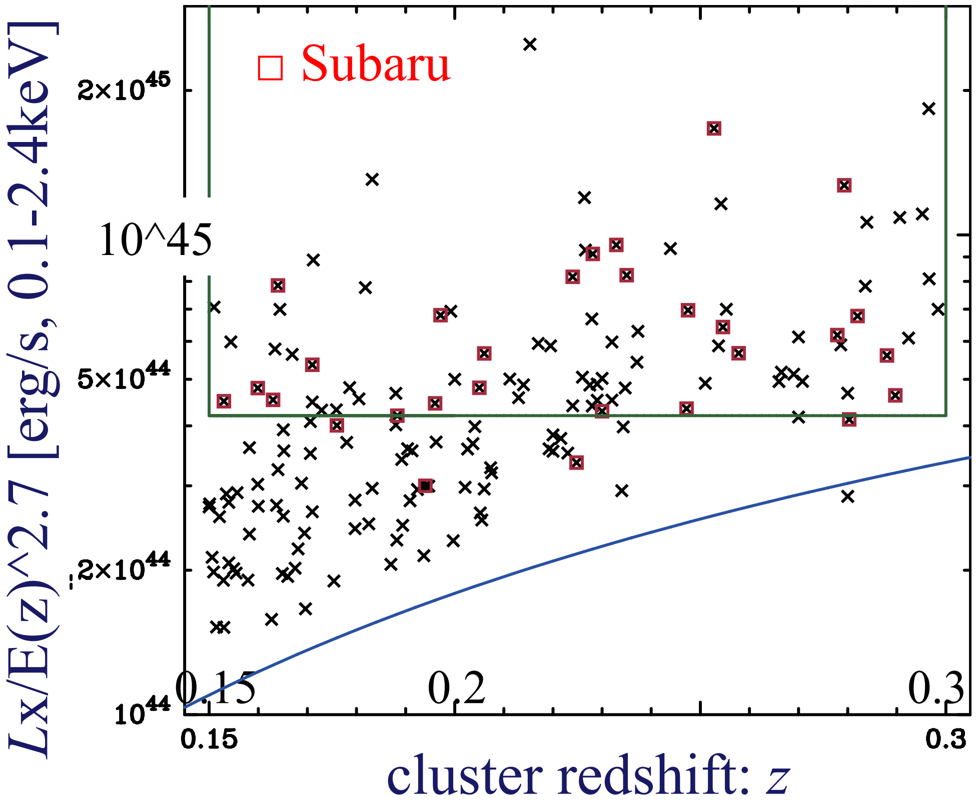
- Virial radius of a massive cluster ~Mpc
- Subaru FoV covers the virial region of a cluster at z~0.2

The best case: A1689 (z=0.18)



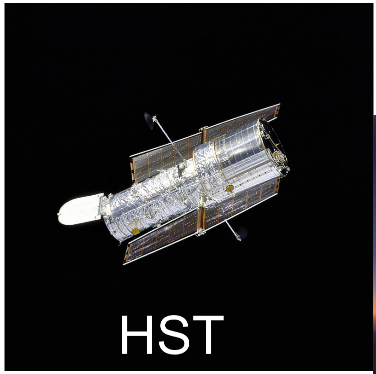
LoCuSS
(The Local Cluster Substructure Survey)

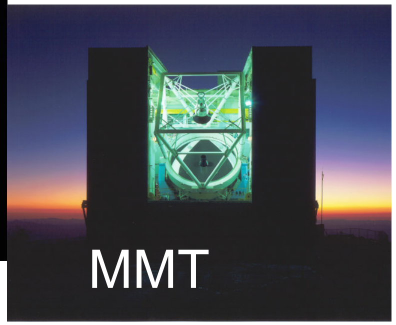
- International collaboration (PI: G.P.Smith; Europe, Japan, USA)
- Explore a systematic study of ~100 X-ray luminous clusters in the redshift range 0.15-0.3
- The multi-wavelengths: *Subaru*, Palomar, VLT, UKIRT, HST, GALEX, Spitzer, Chandra, XMM, SZA, *MMT/Hectospec*

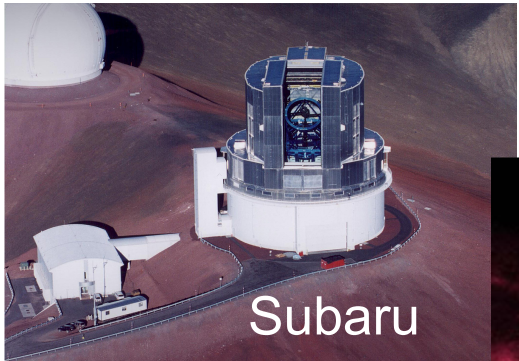


- Subaru/Suprime-Cam data for ~30 clusters (24 have 2 filter data)
  - ***Unbiased*** cluster sample (not based on strong lensing)
  - The FoV of S-Cam matches the virial region of clusters at the target redshifts (~0.2)
  - Now ~60 clusters (as of April 2011)

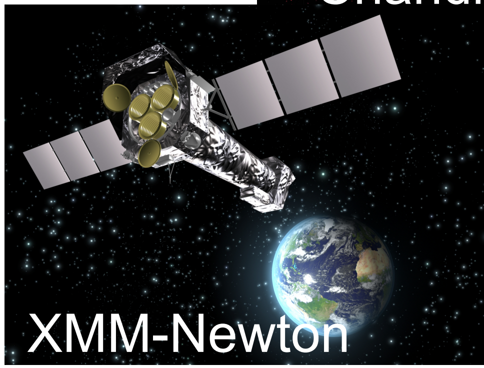
Multi-wavelength study of galaxy clusters







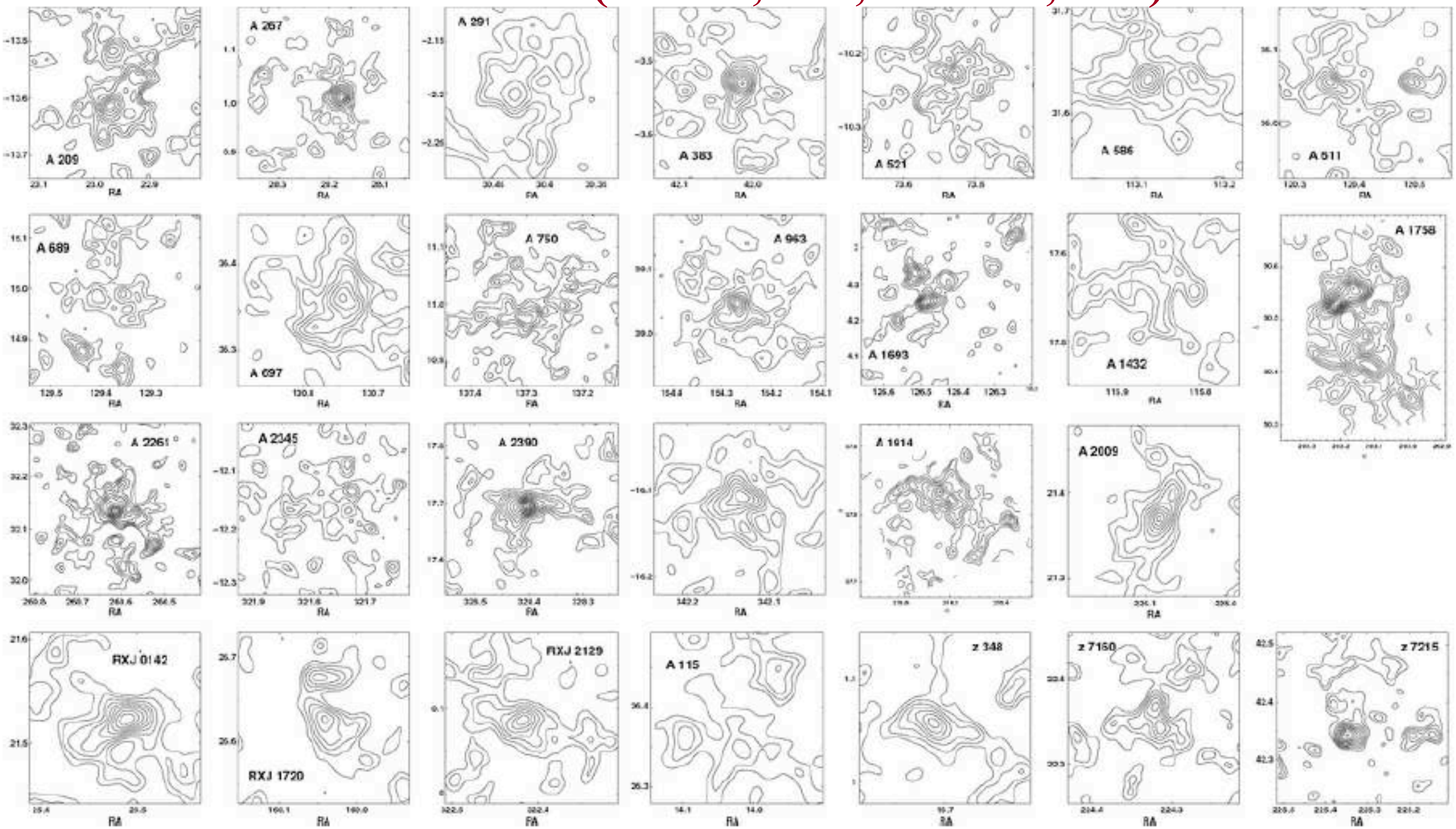
UKIRT



SZA

LoCuSS: Subaru weak lens study

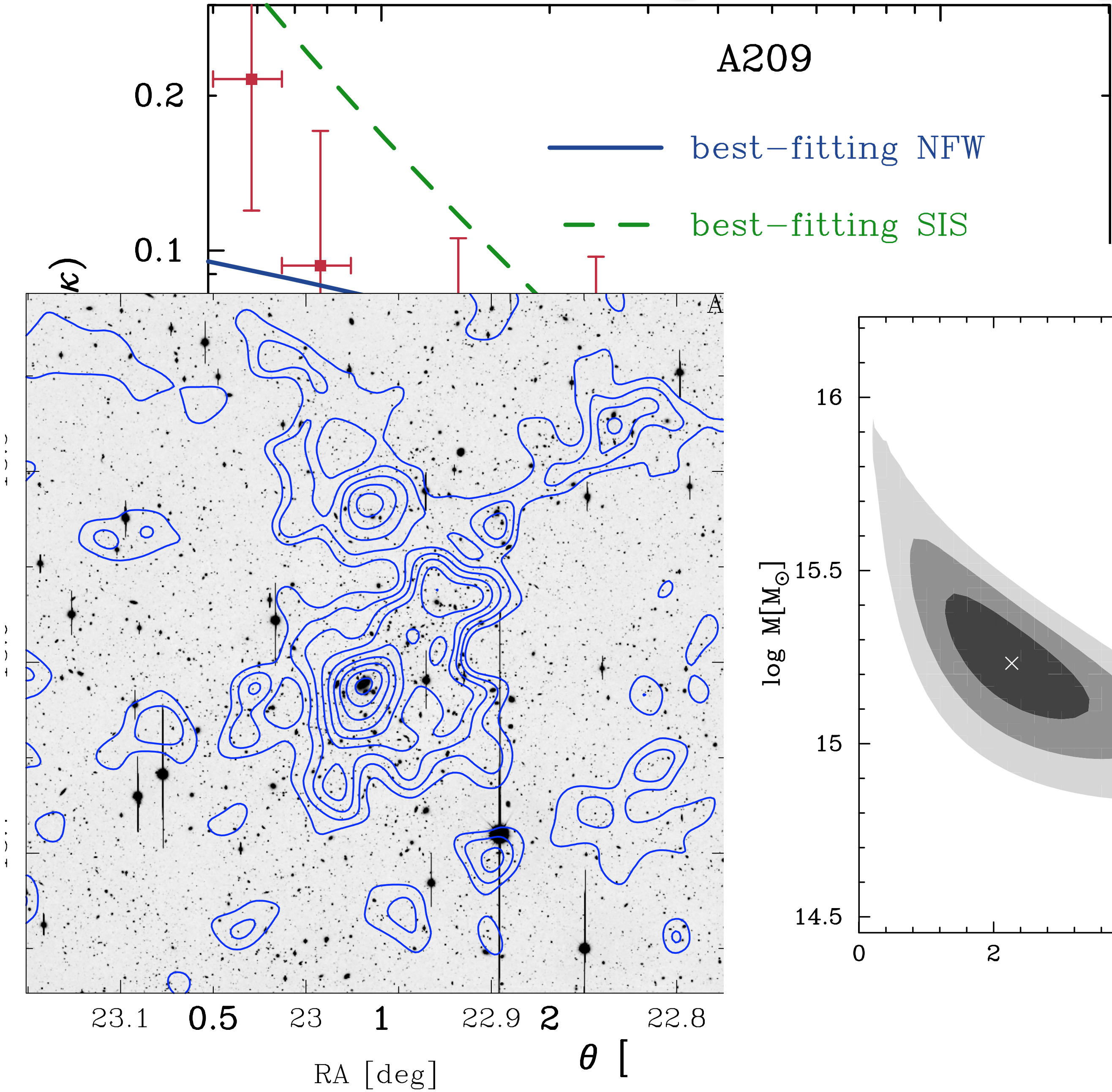
~30 clusters (Okabe, MT, Umetsu,+ 10)

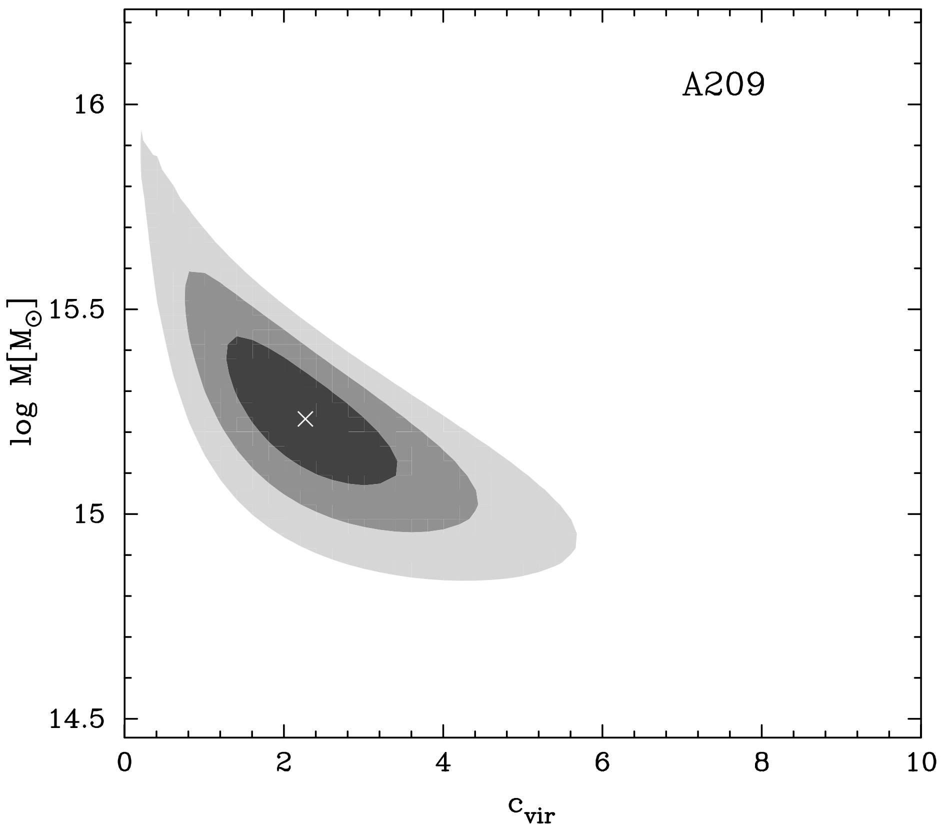


- Subaru is a superb facility for WL measurement
- A detailed study of cluster physics (e.g. the nature of dark matter)

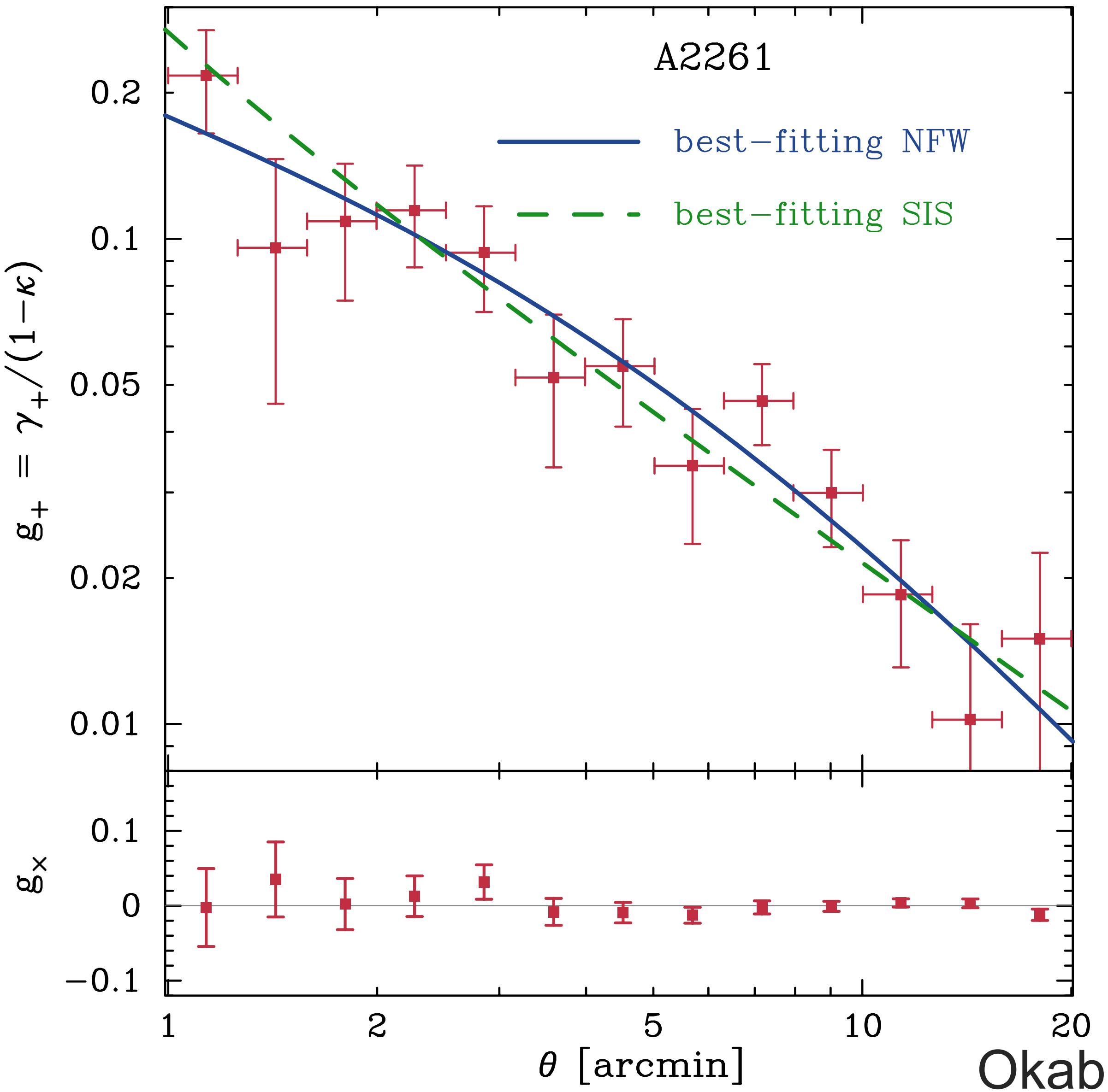
1D shear fitting: an example of A209

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



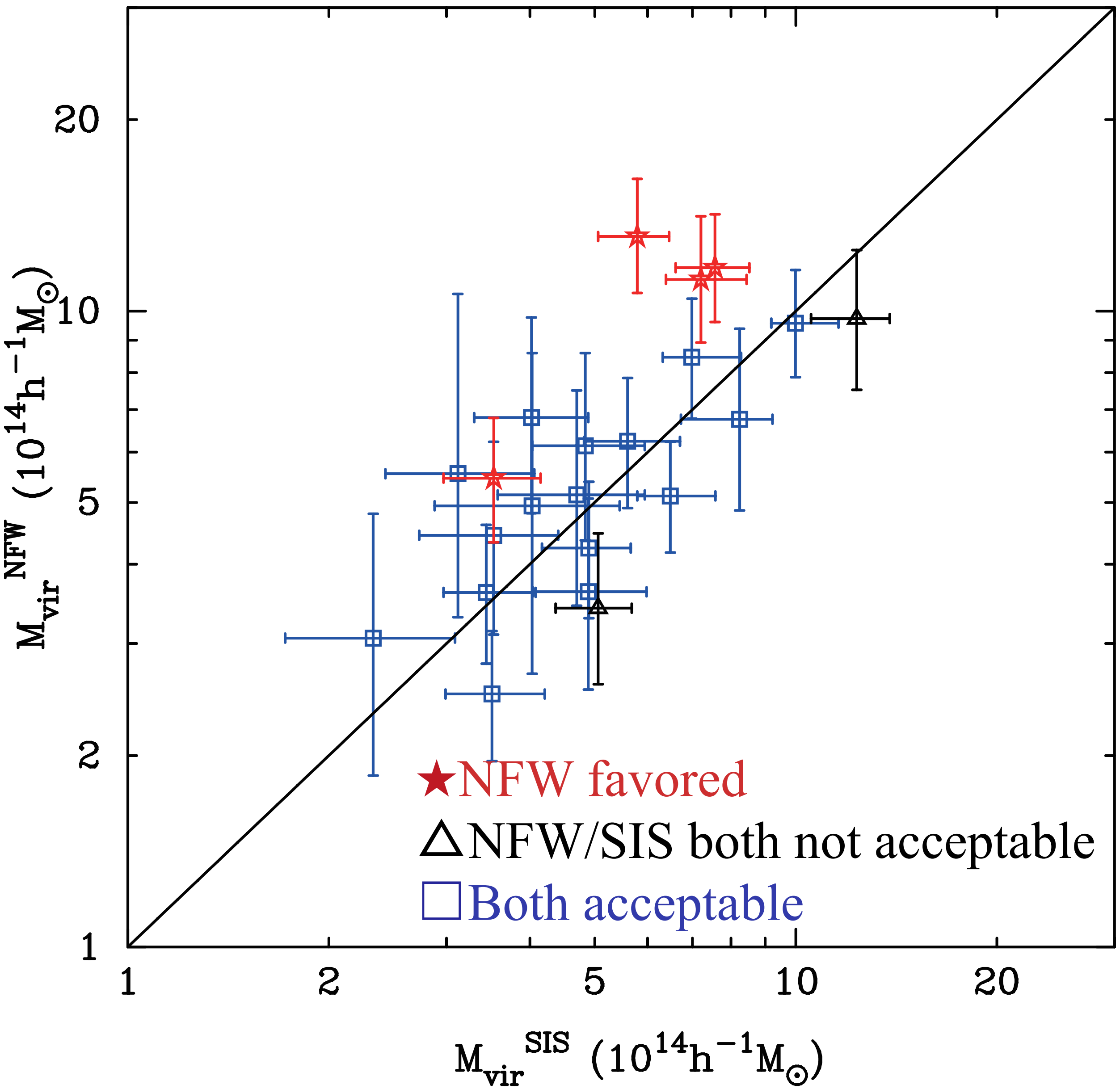


Example 2: A2261



Okabe, MT, 10

Virial mass estimation

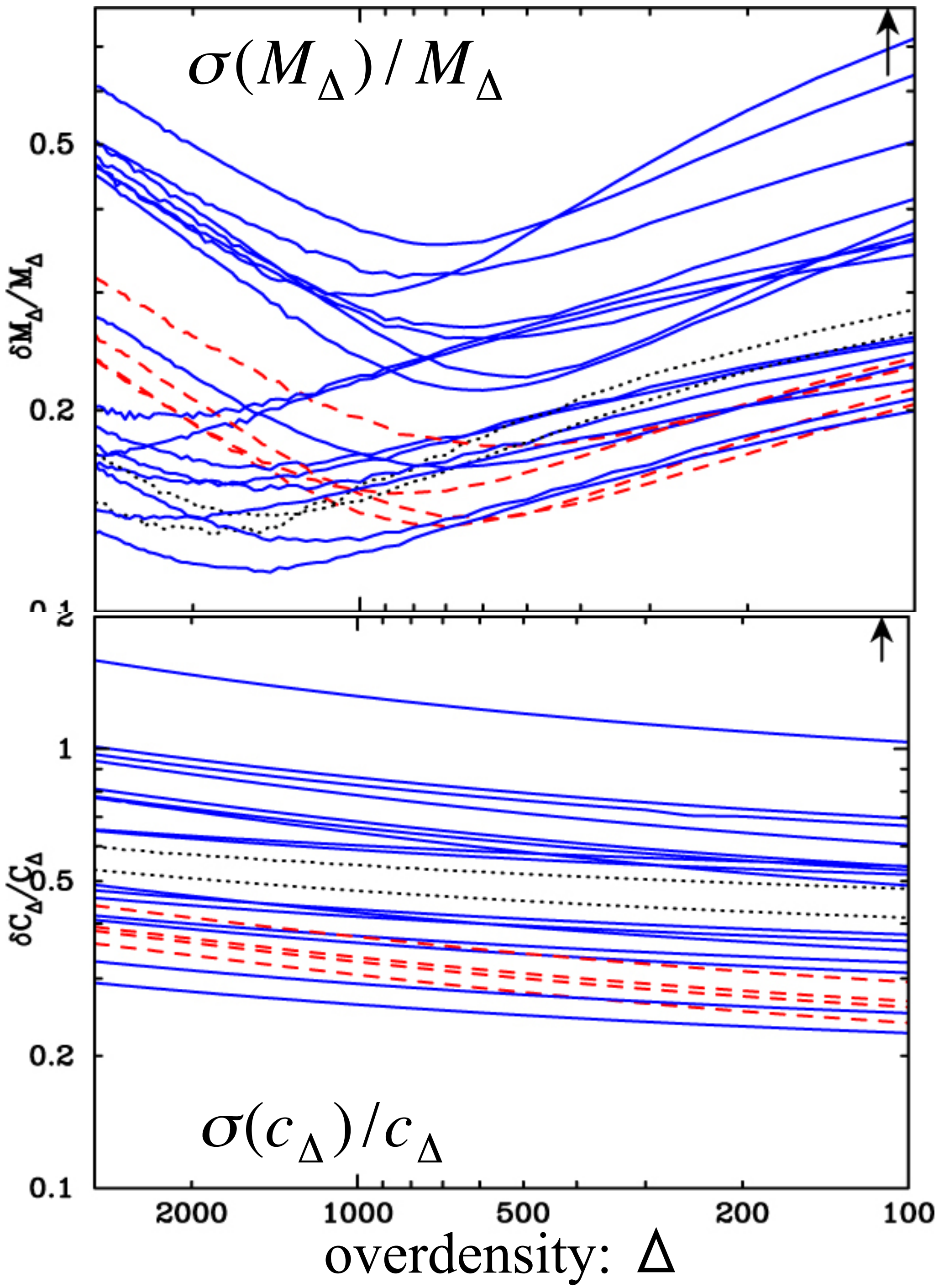


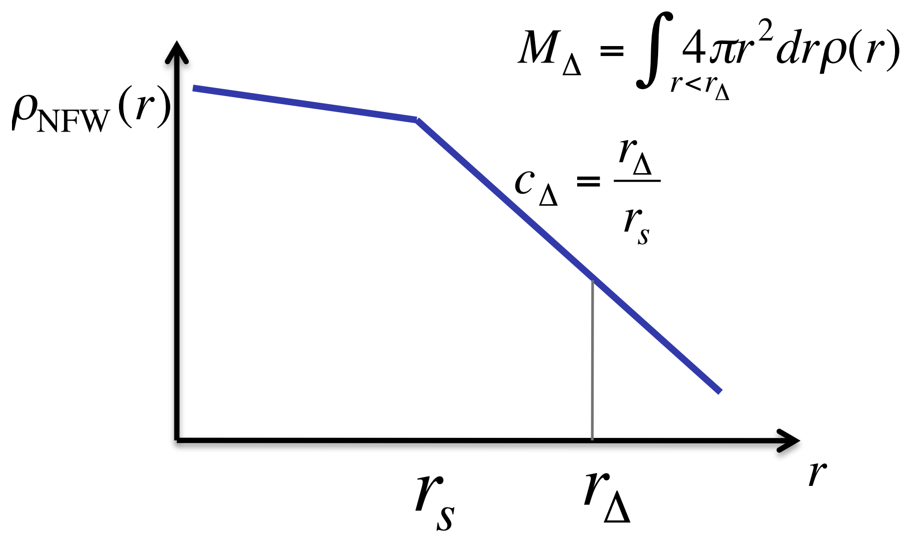
$$\rho_{NFW} \propto \frac{1}{(r/r_s)(1+r/r_s)^2}$$

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

- **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.)





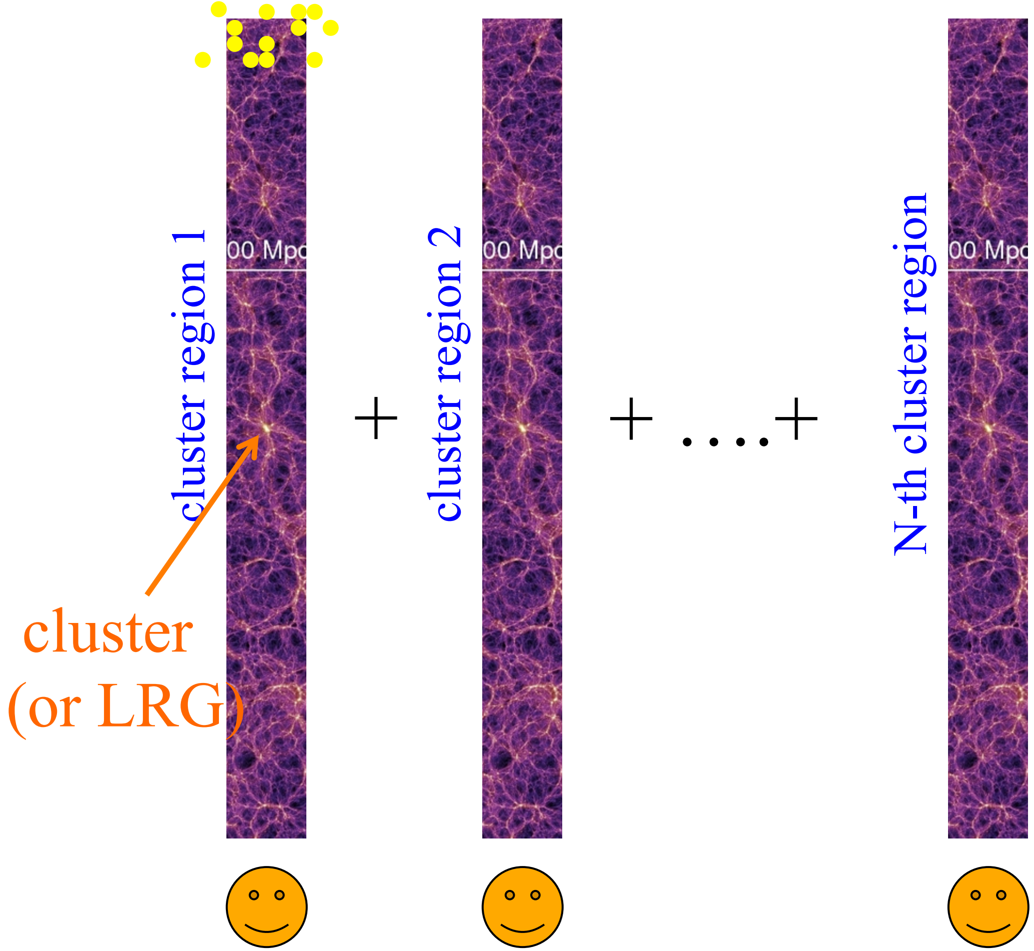
- A best accuracy in *M* is 10-20% when Δ=500-1000 is assumed
  - Over the radii the lensing signals have a largest S/N
- The concentration parameter is most accurately measured for the virial definition

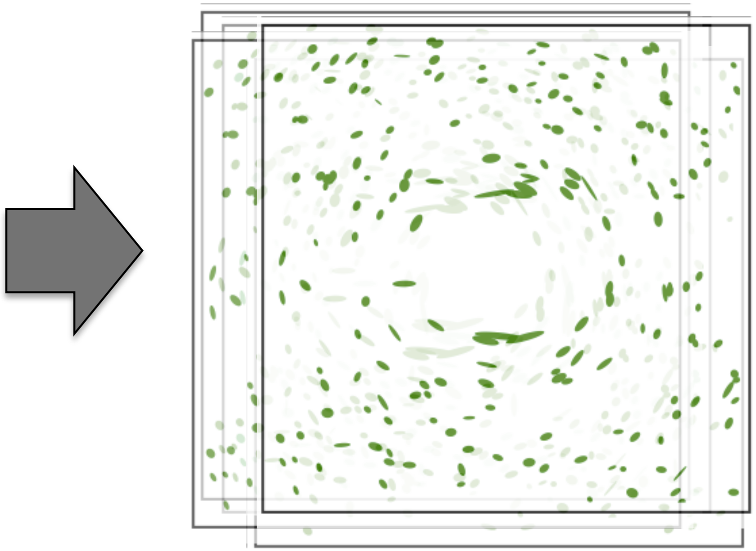
Stacked Lensing

Also see Oguri & MT 11

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

projection effect





Less affected by projection effect, intrinsic alignment, sys. errors ....

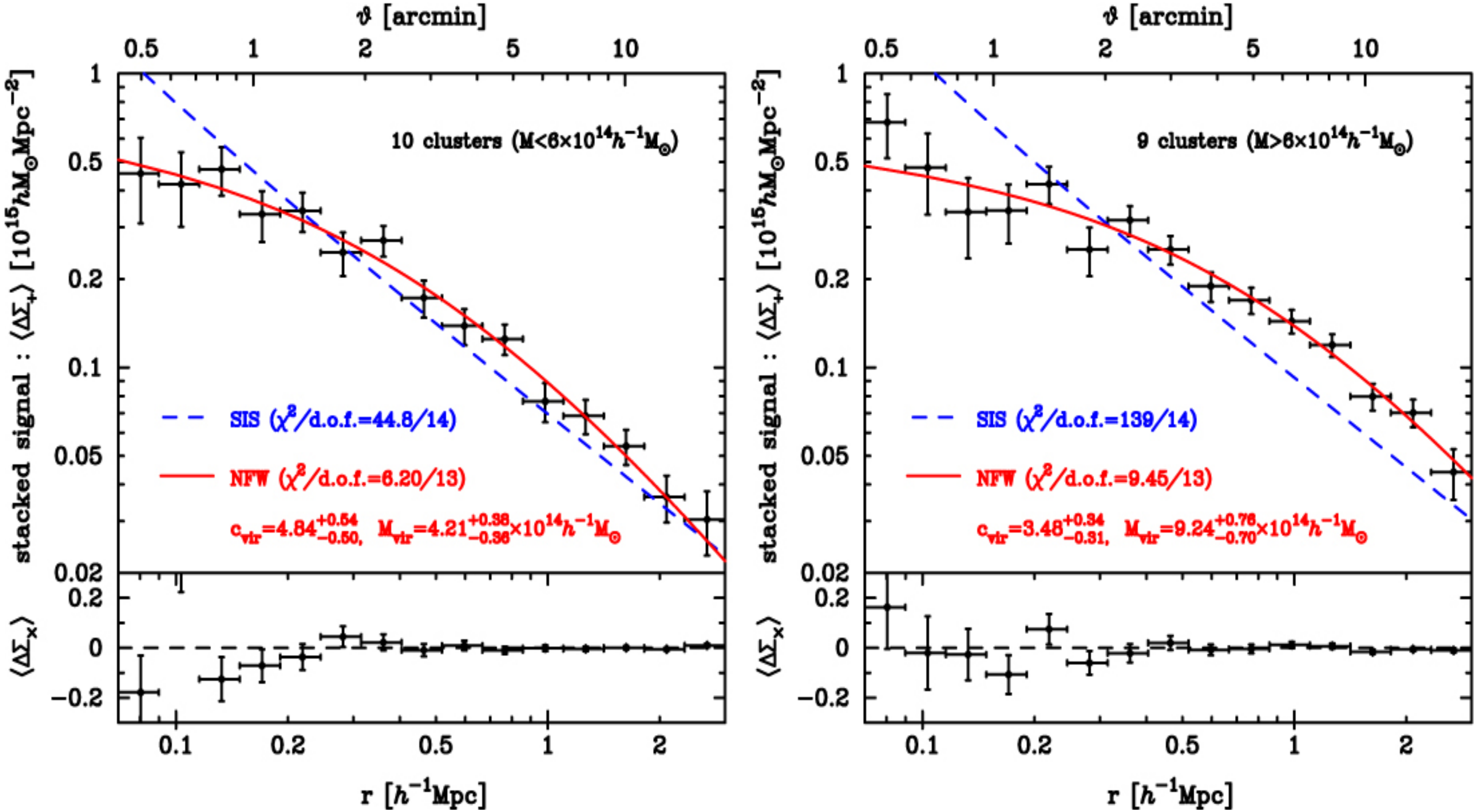
$$\langle\gamma_+\rangle(\theta) = \frac{1}{N_{cl}}\sum_{a=1}^{N_{cl}}\sum_{|\vec{\theta}'|\subset\theta}\gamma_{+(a\text{-th cluster})}(\vec{\theta}') \approx \left\langle\gamma_+^{\rm cluster}\right\rangle(\theta)$$

Note: halo center

Results: stacked lensing

Okabe, MT+10

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

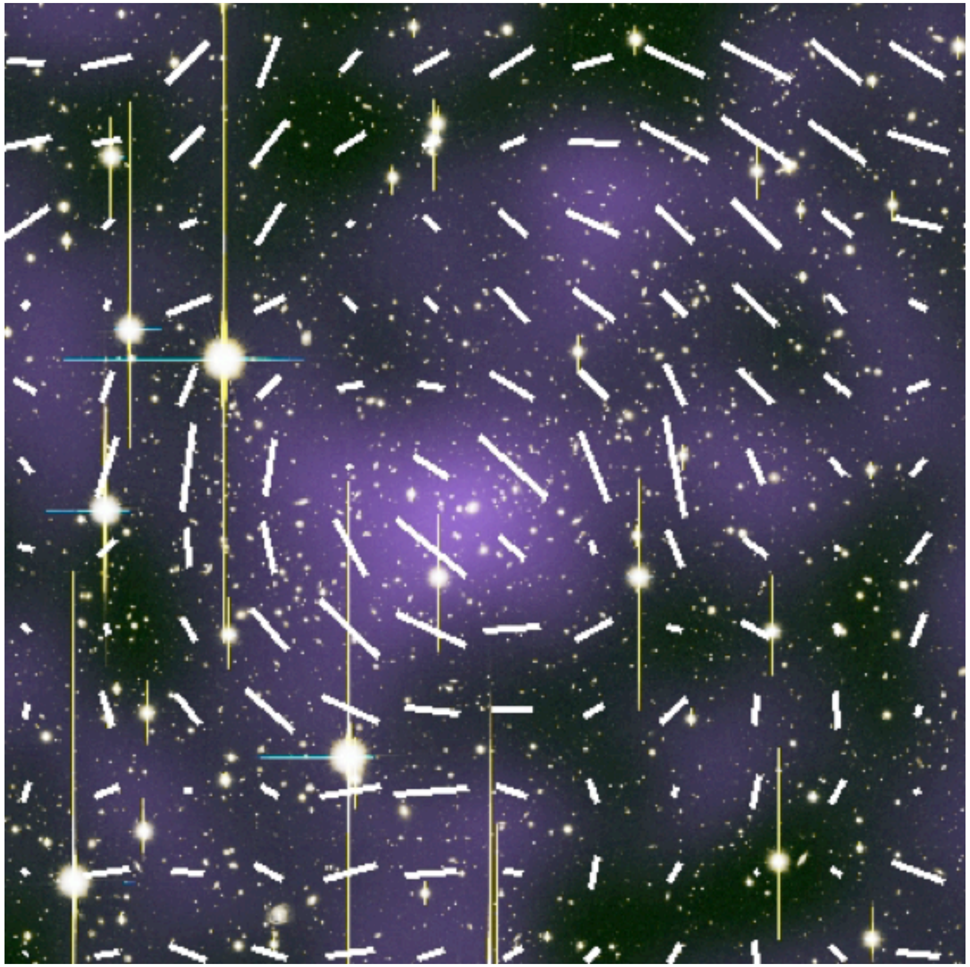


$$\Delta\chi^2 = \chi^2_{\rm SIS} - \chi^2_{\rm NFW} = 39 \text{ and } 129 \text{ for low- and high-mass samples, respectively}$$

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:

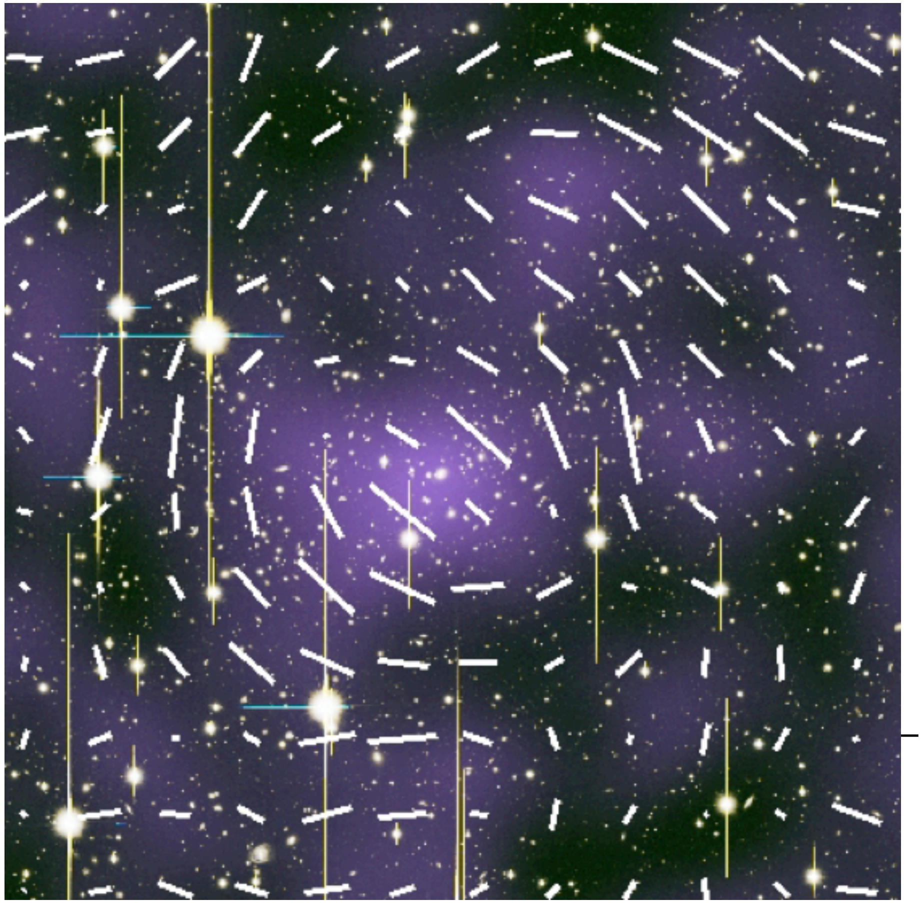
$$\kappa(x, y) = \kappa_{\rm sph}(\zeta),$$

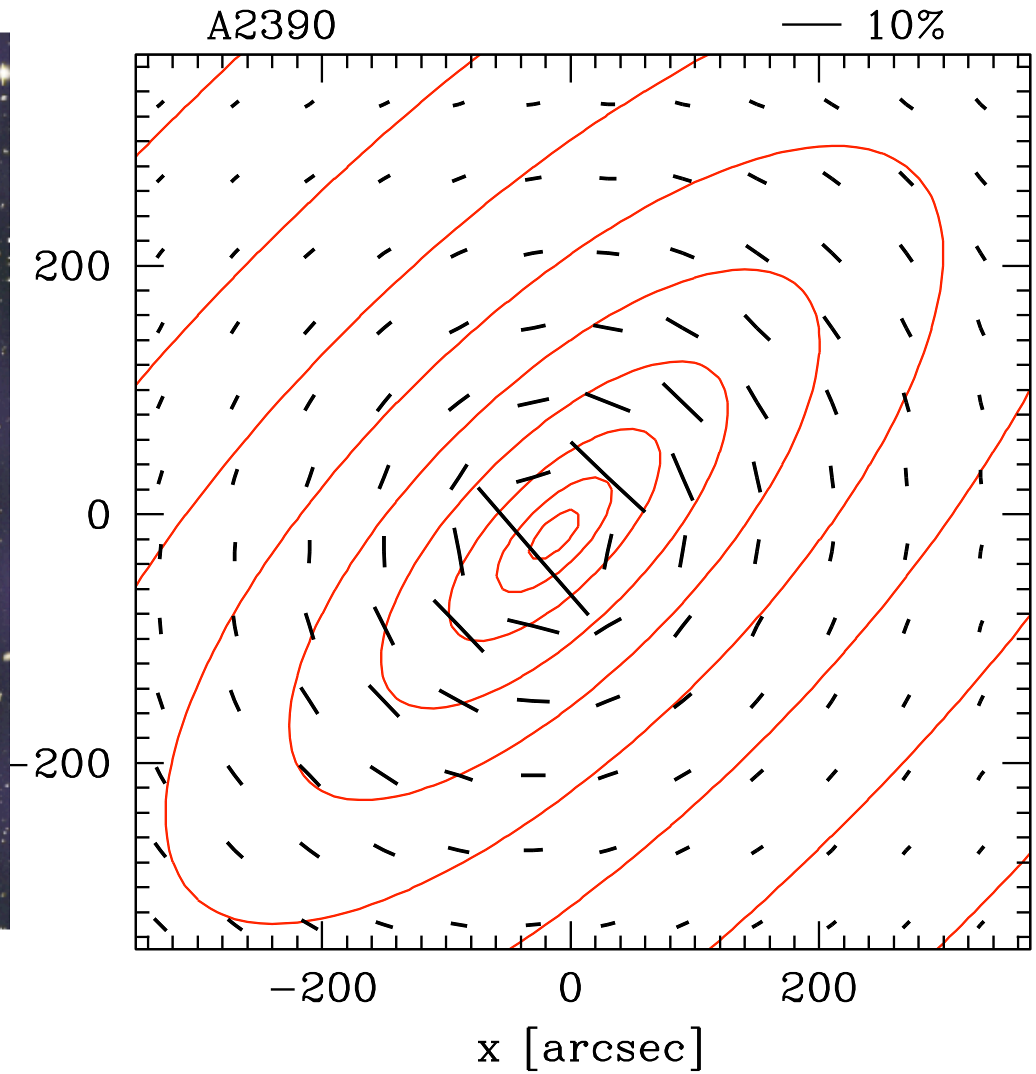
$$\zeta^2 = \frac{x'^2}{1-e} + (1-e)y'^2,$$

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

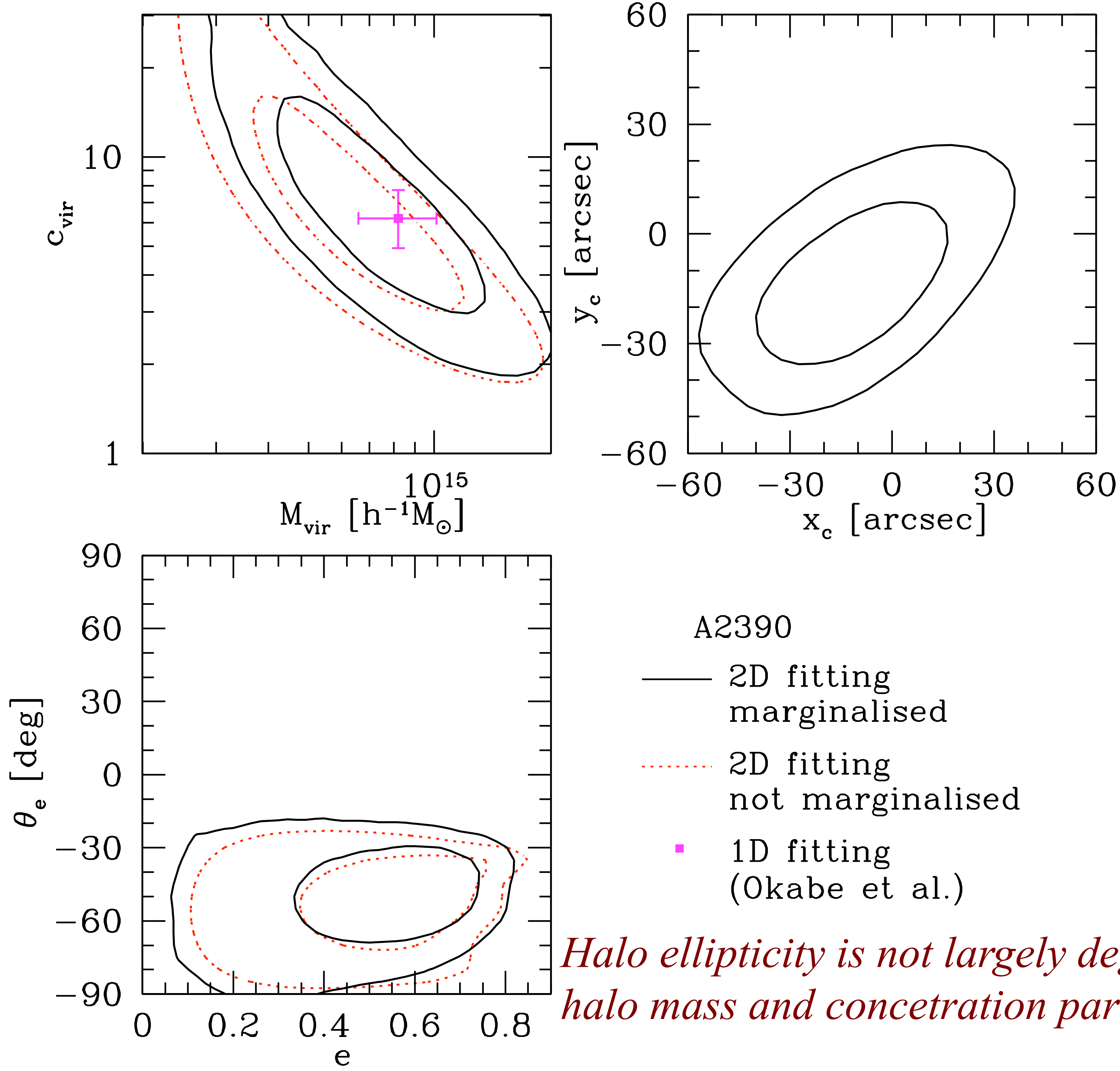
$$y' = -x\sin\theta_e + y\cos\theta_e,$$

2D shear fitting

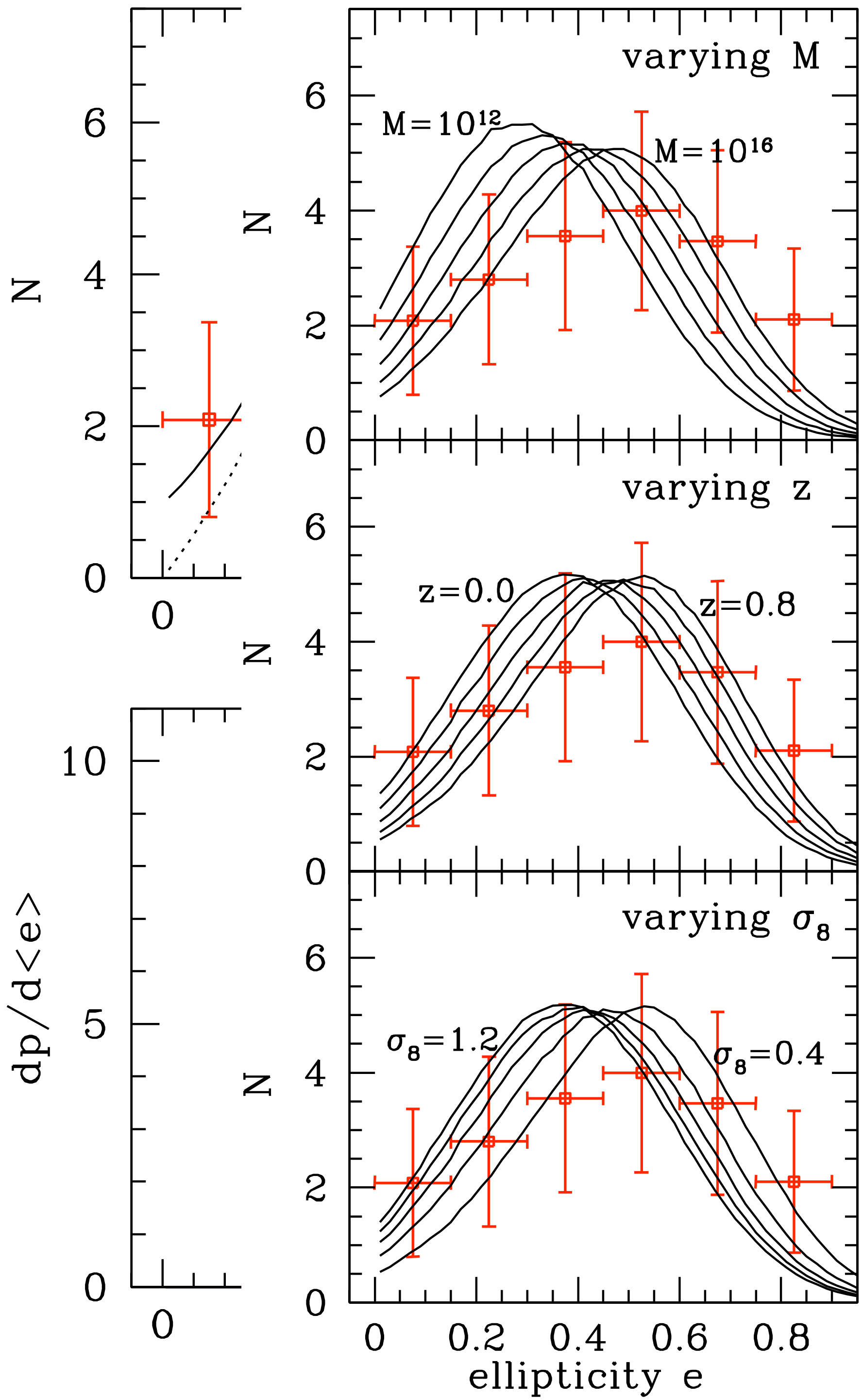




- In this particular case, e_2D=1-b/a
- Note that the iso-contours of shear amplitudes are not elliptical, needs to solve the 2D Poisson equation.



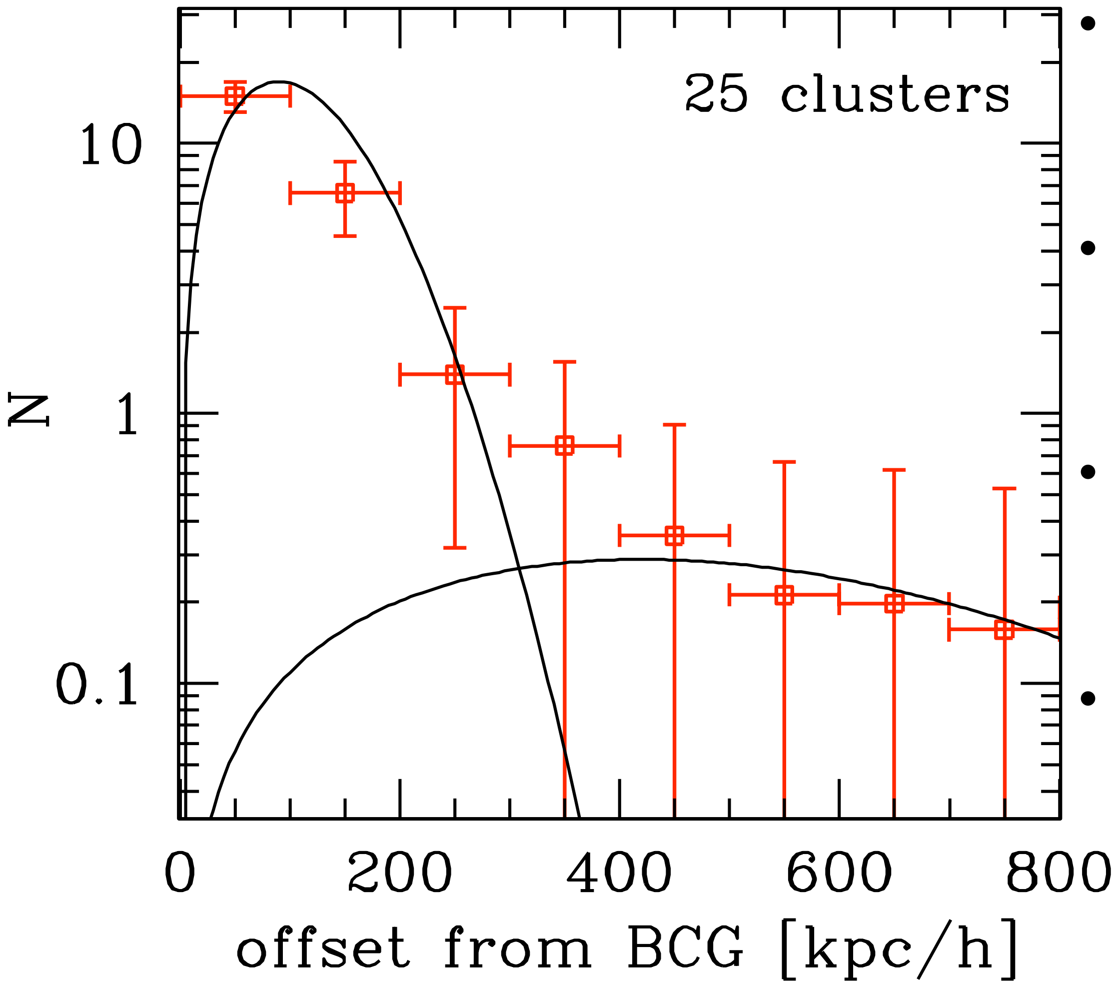
Halo ellipticity is not largely degenerate with halo mass and concetration parameters



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

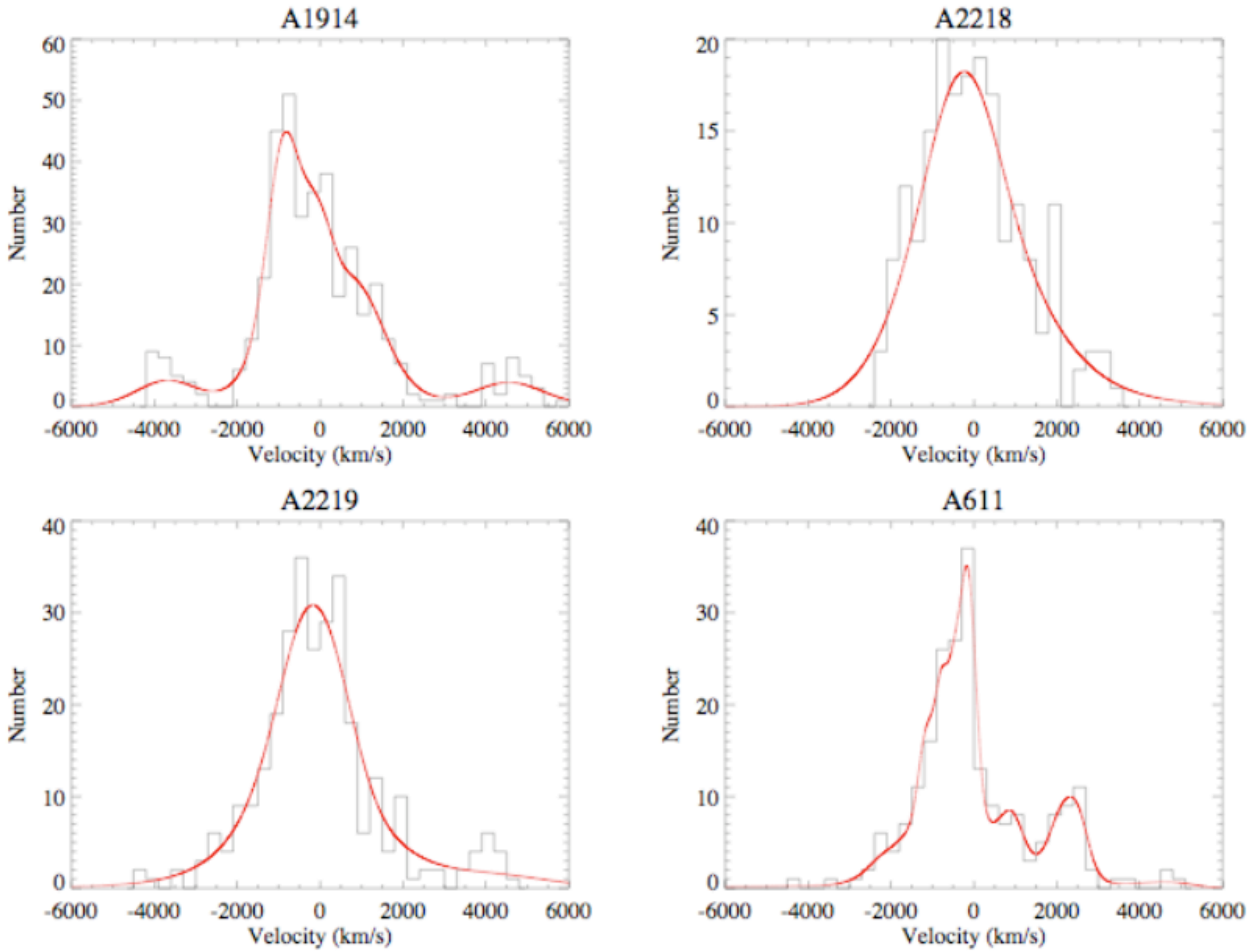
Halo center



- 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

Test of gravity on cluster scales?

E. Egami (Arizona) and his collaborators: MMT (6.5m, 300 fibers)
~200-300 members/cluster for 30 clusters (~20 clusters as of May 2009)



$$\gamma \sim \nabla^2(\Phi + \Psi)$$

$$\mathbf{v} \sim \nabla\Psi$$

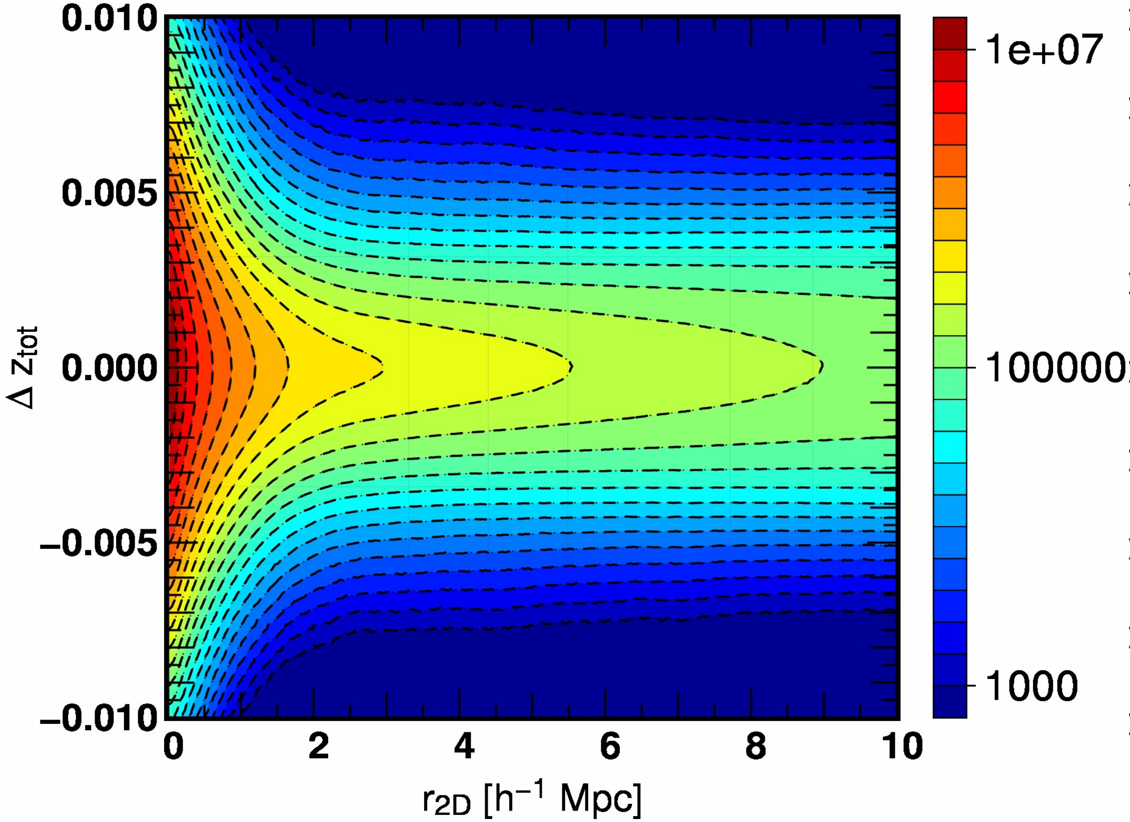
or

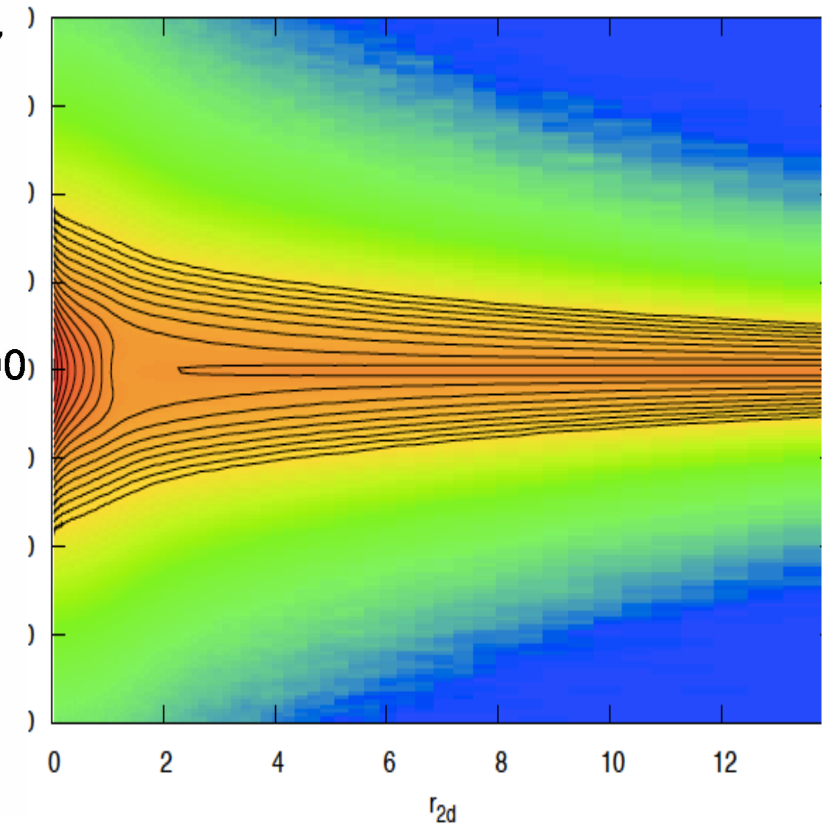
$$M_{\rm wl}\,{\rm vs.}\,M_{\rm dyn}$$

Also see Schmidt 10

Velocity field around clusters

- Building the theoretical model (Lam, Nishimichi, Schmidt, MT in prep.)

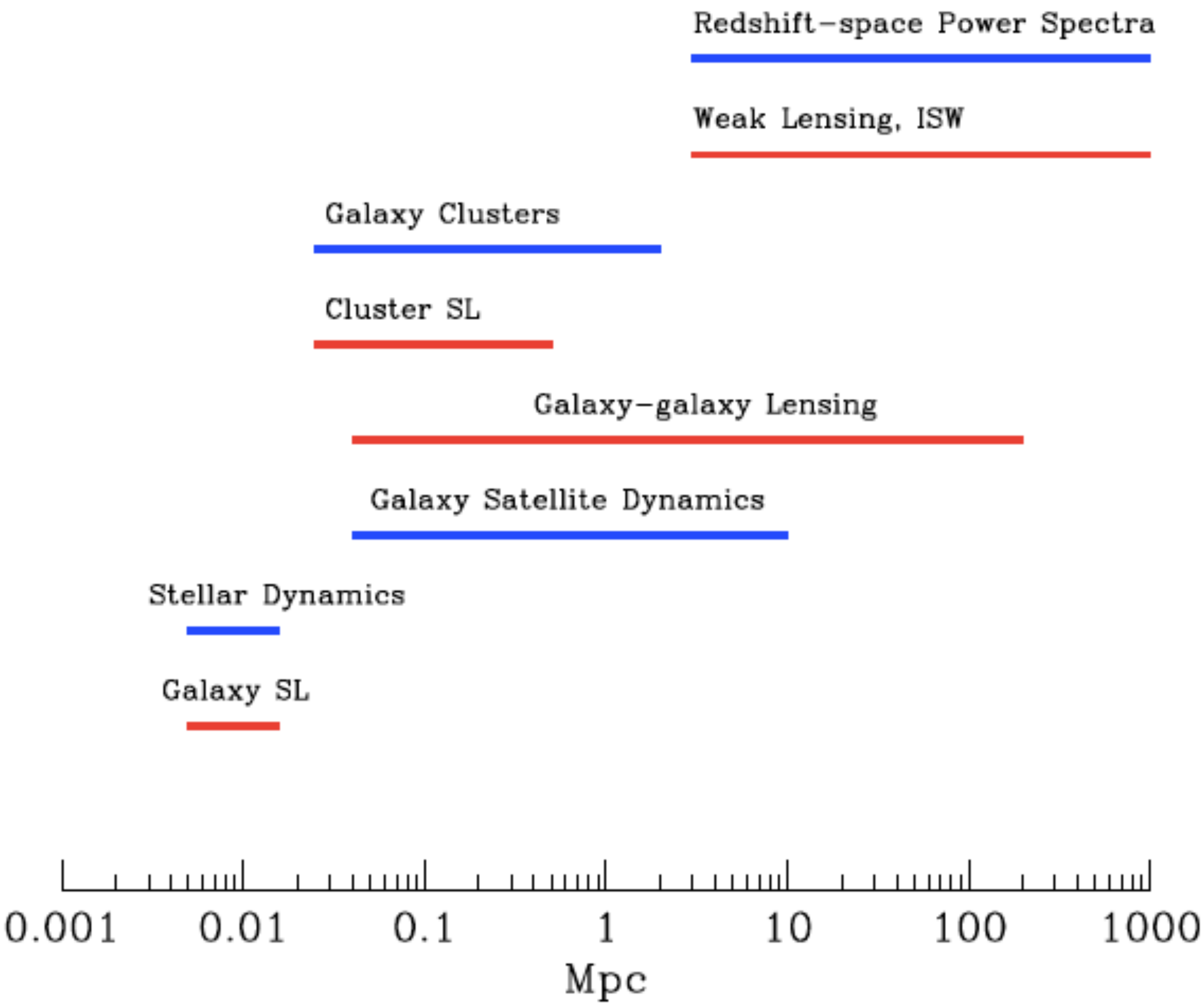


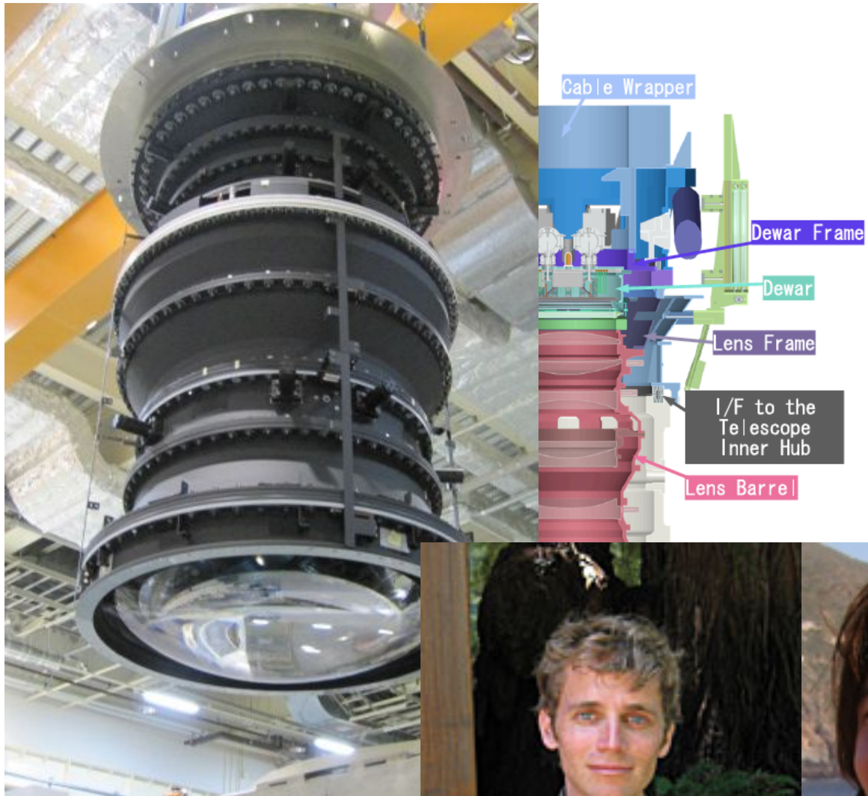


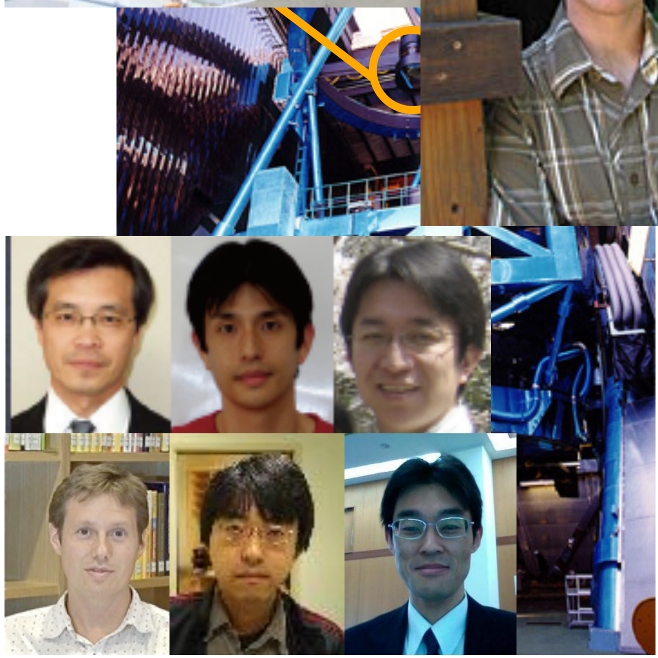
From N-body simulations

From halo model (virial velocity + in-fall motion)

Complementarity of different methods

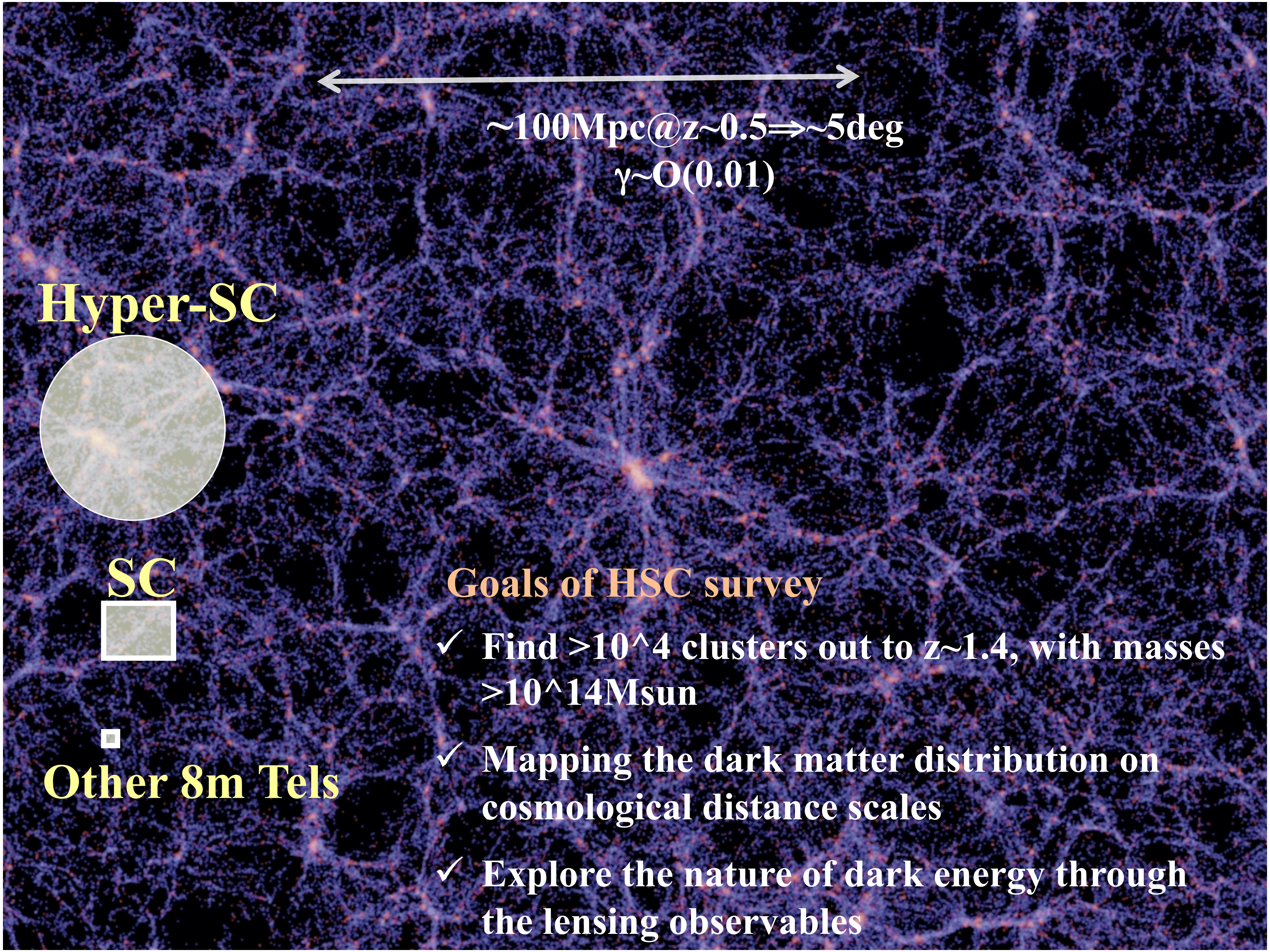






Hyper Suprime Camera Project

- Upgrade the prime focus camera
- **Funded, started since 2006**
- rnational collaboration: **Japan OJ, IPMU, Tokyo, Tohoku, oya), Princeton, Taiwan**
- IPMU members (H. Aihara, MT, N. Yoshida, …): leading this project
- l-of-View: ~10×Suprime-Cam
- Keep the excellent image quality
- ~1500 sq. deg weak lensing survey starting from late 2012- (~5 years)
  Note: the current WL surveys ~100 sq. deg (but shallow)

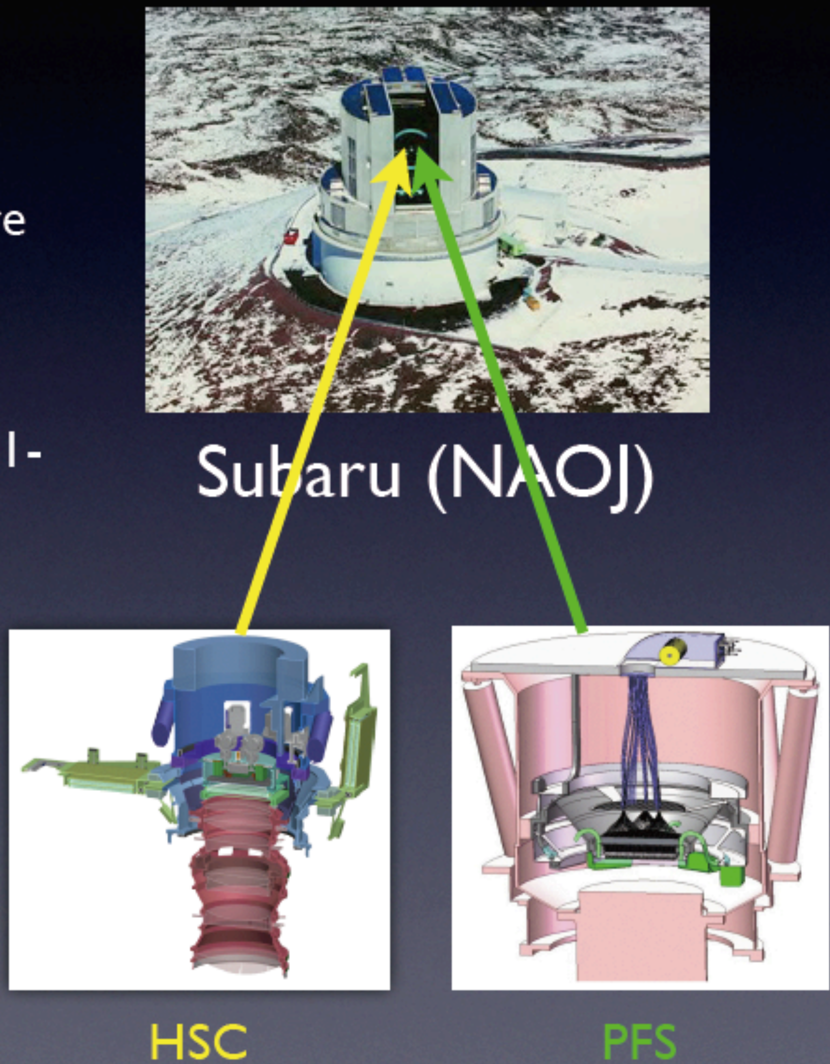

~100Mpc@z~0.5⇒~5deg
γ~O(0.01)
Hyper-SC
SC
Other 8m Tels
Goals of HSC survey
✓ Find >10^4 clusters out to z~1.4, with masses >10^14Msun
✓ Mapping the dark matter distribution on cosmological distance scales
✓ Explore the nature of dark energy through the lensing observables

From Hitoshi's slide

SuMIRe

Subaru Measurement of Images and Redshifts

- 8.2 m telescope, excellent seeing 0.6", wide field of view 1.77 sq. dg.
- HyperSuprimeCam: weak lensing survey, based on growth of structure
  - 0.9 B pixels, 3 ton camera
  - billions of galaxies
  - ~$50M, nearly fully funded, 2011-
- PrimeFocusSpectrograph: baryon acoustic oscillation
  - 2400 fibers, 2000 sq. dg.
  - >2M redshifts, 380–1300nm
  - ~$55M, ~$20M raised, 2016?-
- same telescope for both imaging and spectroscopy *like SDSS!*



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
- The pilot study in preparation with Subaru HSC survey, aimed at exploring the nature and properties of DM and DE