エンレイソウの会＠北大 (2010.06.11)

Galaxy Cluster Gravitational Lensing as a Cosmological Probe

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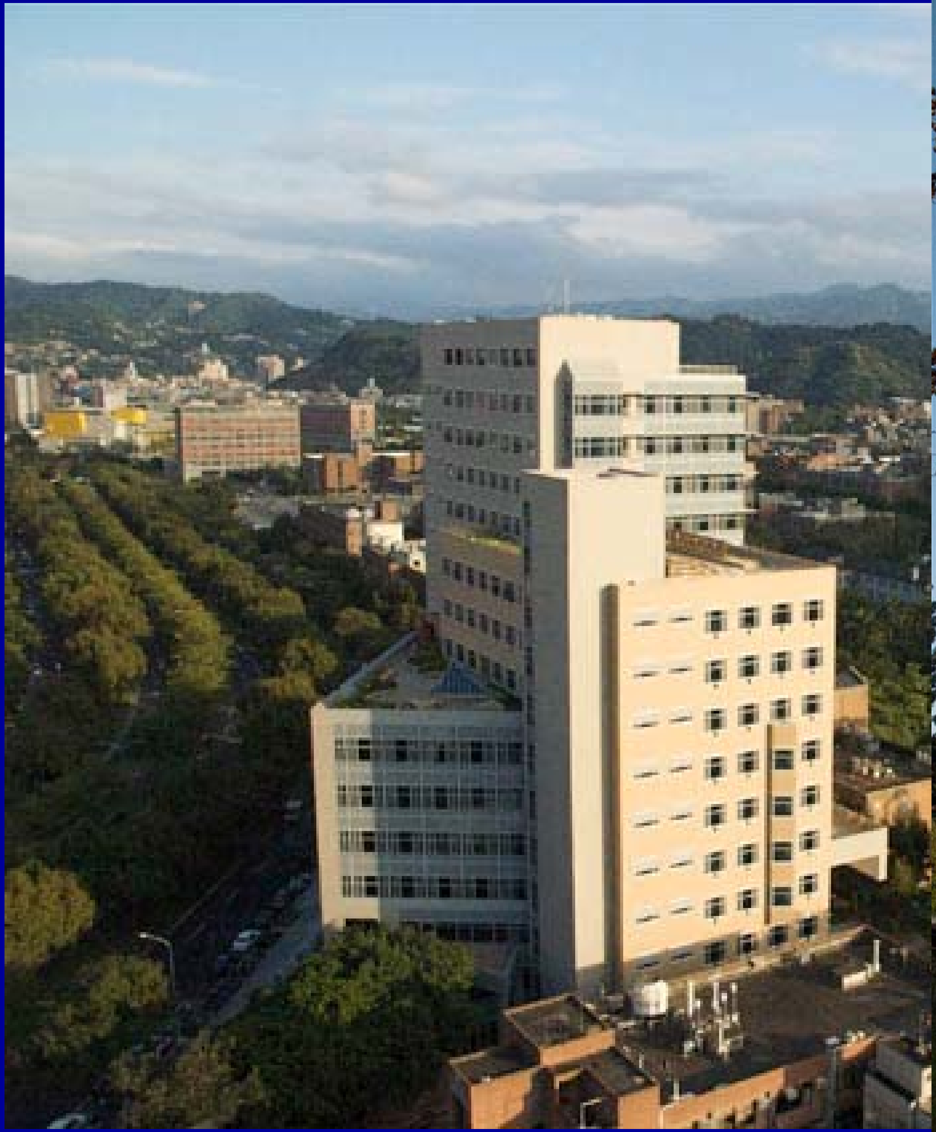
ASIAA in 国立台湾大学キャンパス



PERSONNEL at ASIAA (2010)

Director: Paul T.P. Ho

- 34 ASIAA Faculty (25 Regular, 9 Research)
- 13 Adjunct Faculty
- 27 Postdoctoral Fellows, 12 Visitors
- 14 Ph.D. Students, 17 Master Students
- 13 Undergraduate Students, Assistants
- 49 Technical Staff
- 24 Administrative Staff

Working Language: English

Staff: (Australia), Canada, China, France, India, Japan, Korea, Malaysia, Mexico, Spain, Switzerland, Taiwan, U.S., (Vietnam)

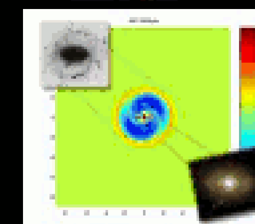
MAJOR ASIAA PROJECTS (2010)





SAO • SMA : Array Completed; Installed 400GHz

NTU • AMiBA : 7-element papers; 13-element installed



NTHU • TIARA; SIS Junction : 230, 345, 400, 690, 900 GHz

(NAOJ, PMO)

NCU • TAOS : 1st Science papers; TAOS-2

ASIM • CFD-MHD : 2-D Hydro Codes – 3-D

CFHT • WIRCam : 1st Science papers; SPIROU

NAOJ • ALMA-J : FEIC shipped 2nd FE to Chile

NRAO • ALMA-NA: 12m antenna, 5 FEs, ALS

NAOJ • Hyper Suprime Cam: filter exchanger, CCDs, lens

NTU • ASMAB: moved in

Outline of My Talk

1. **Motivation and Importance**
   - Clusters as a cosmological probe
2. **Method**
   - Weak and Strong Gravitational Lensing
3. **Targets and Data**
   - Subaru and Hubble Imaging
4. **Highlights**
5. **Summary**
   - Cluster lensing constraints on the mass density profile
6. **Upcoming Lensing Project**
   - 524-orbit Hubble Multi-Cycle Treasury program “Cluster Lensing And Supernova survey with Hubble (CLASH)” (PI: Marc Postman)

Collaborators (this talk)

Tom Broadhurst (Tel Aviv U., Israel → Spain)
Elinor Medezinski (Tel Aviv U., Israel → STScI)
Adi Zitrin (Tel Aviv U., Israel)
Doron Lemze (Tel Aviv U., Israel → STScI)
Yoel Rephaeli (Tel Aviv U., Israel)
Nobuhiro Okabe (ASIAA, Taiwan)
Sandor Molnar (ASIAA, Taiwan)
Bau-Ching Hsieh (ASIAA, Taiwan)
Masahiro Takada (IPMU, Japan)
Toshifumi Futamase (Tohoku U., Japan)
Graham P. Smith (Birmingham U., UK)

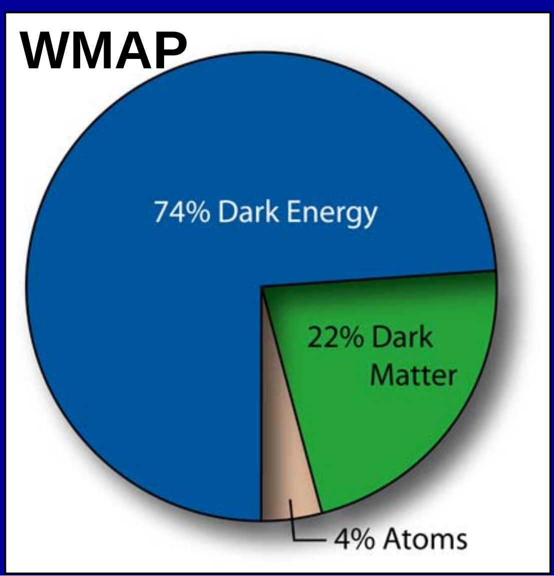
1. Motivation and Importance:

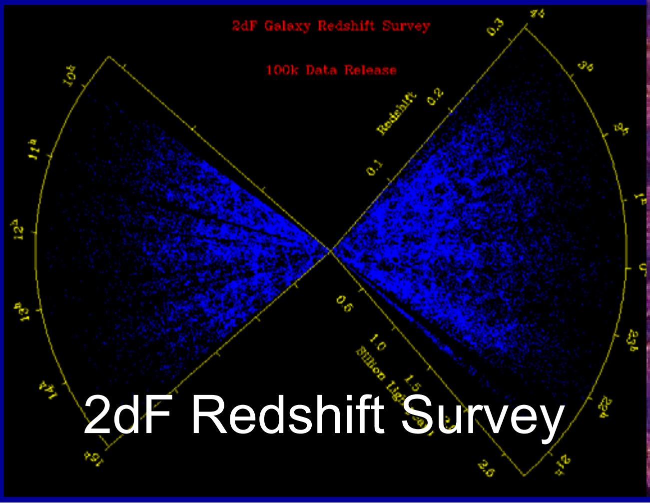
“Galaxy Clusters as Cosmological Probes”

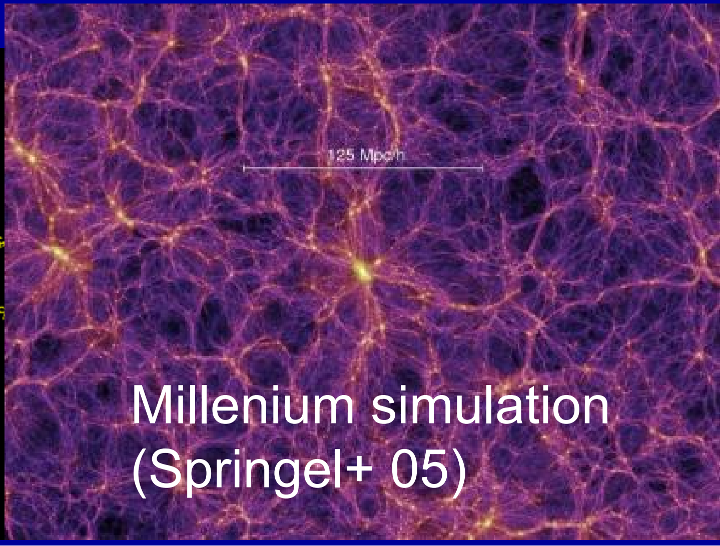
Concordance Structure Formation Scenario

Current paradigm of structure formation: Lambda Cold Dark Matter (LCDM)

- **Initial conditions**, precisely known from linear theory & Cosmic Microwave Background (CMB)"+" data (@ $z = z_{dec} \sim 1100$)
- >70% of the "*present-day*" energy density is in the form of Dark Energy, leading to an accelerated cosmic expansion.
- ~85% of our "*material universe*" is composed of unknown DM.
- Study cosmic structure formation due to the gravitational instability using N-body simulations + perturbation theory ($0 < z < 1100$)







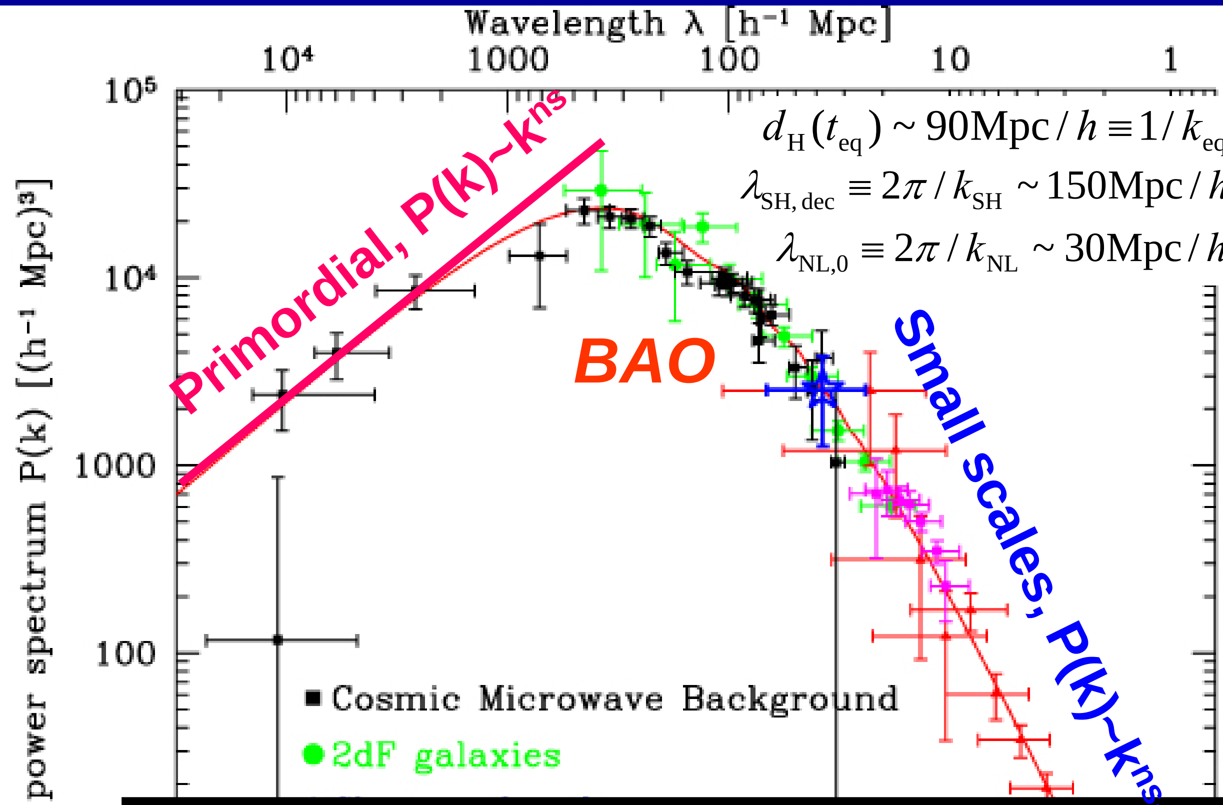
Nature of CDM Structure Formation

1. **Hierarchical growth**: Non-relativisitc (cold) nature of DM
   - bottom up formation of structures in the CDM model
   - smaller objects first form, and merge together into larger systems: i.e., galaxies -> groups -> clusters -> superclusters
2. **Anisotropic collapse**: Collisionless nature of DM
   - any small initial deviation from sphericity of a collapsing cloud gets magnified by tidal forces (e.g., Zel'dovich 1970; Shen et al. 2006)
   - gravitational collapse proceeds along sequence:
     - Collapse along smallest axis -> planar geometry ->wall
     - Collapse along middle axis -> filament
     - Collapse along longest axis -> triaxial (spheroidal) DM halos

After having collapsed into a clump, "virialization and emergence" of cosmic object

3. **Void formation**: δ ~ "-1" nonlinear structure
   - Under-dense regions, corresponding to density troughs in primordial density fields

Observed Matter P(k) vs. LCDM



Tegmark & Zaldarriaga 2002

$P(k) \propto k^{n_s}$ with $n_s \sim 1$
(n_s=1: Harrison-Zel'dovich spectrum)
@ $k \ll k_{eq} \sim 0.01h$/Mpc

Turn-over @ $k \sim k_{eq}$

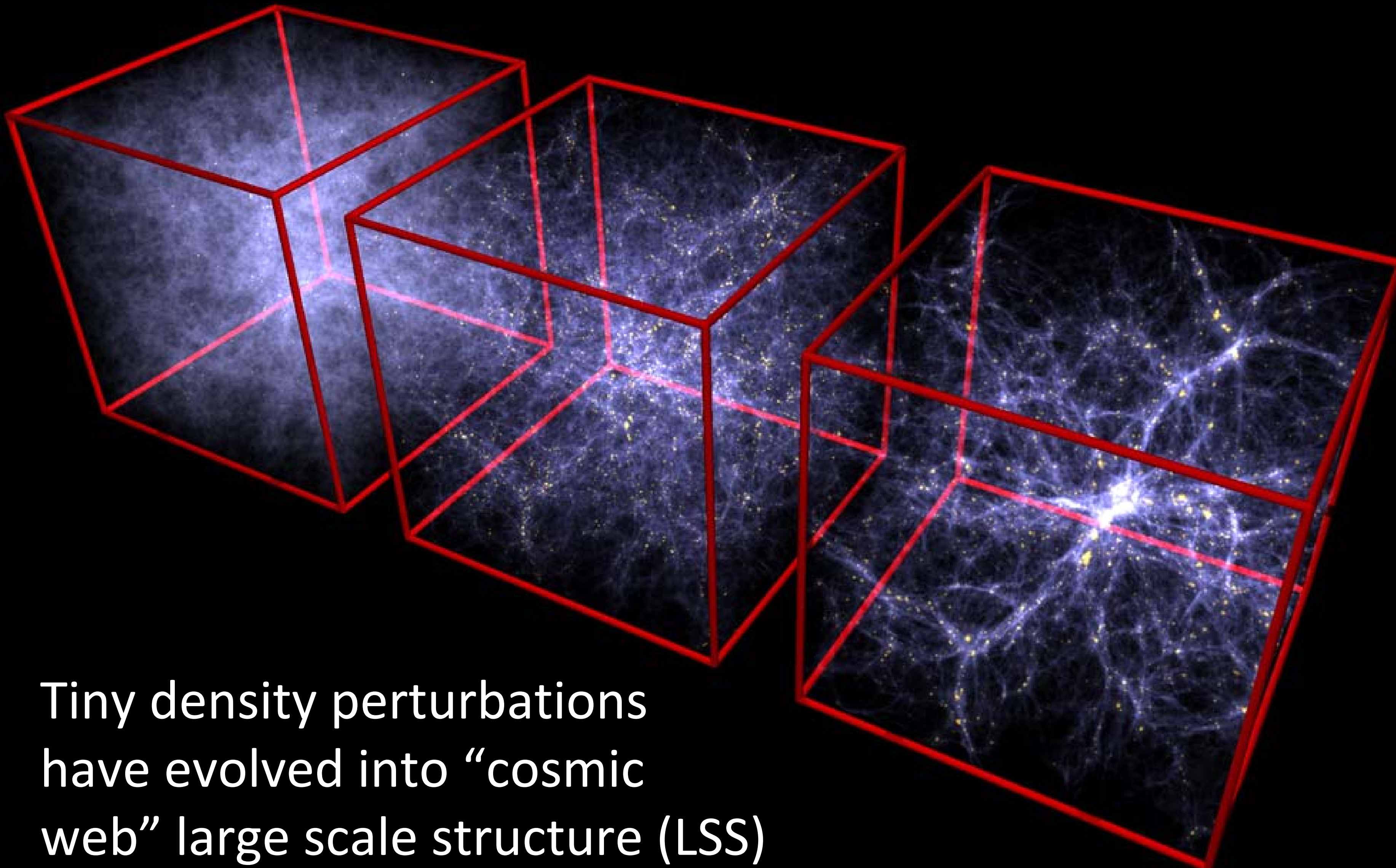
$P(k) \propto k^{(n_s-4)}$ @ $k \gg k_{eq}$
due to decay of $\Phi(k)$ on sub-horizon scales in the radiation era

...on

Nonlinear @ high-k modes,
$k > k_{NL} \sim 0.2h$/Mpc at z=0

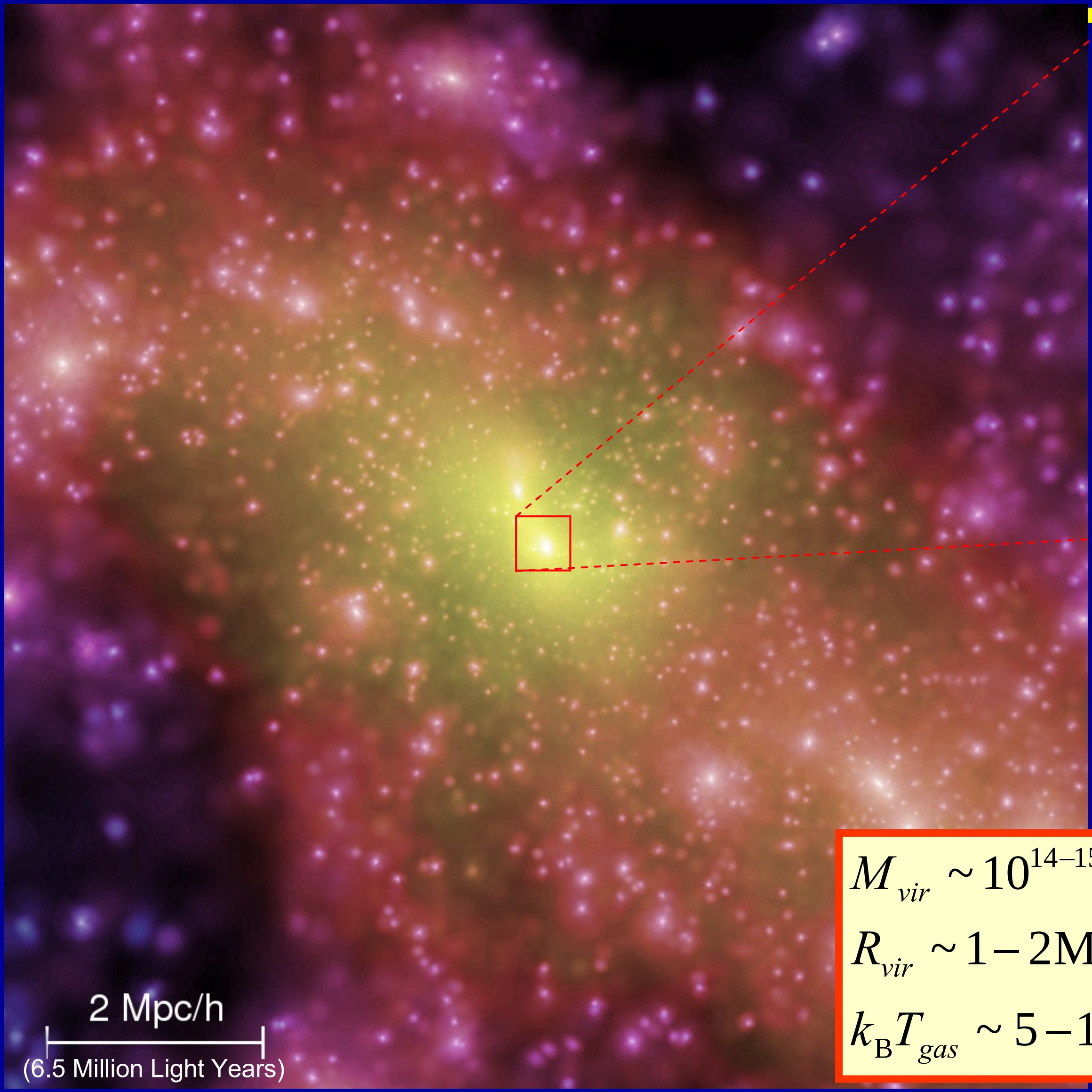
Cosmic mean properties on "large scales" (r>>1Mpc/h) are well explained by ΛCDM.
How about nonlinear scales (<1-10Mpc/h)?

Structure Growth: *Gravitational Instability*



Tiny density perturbations have evolved into "cosmic web" large scale structure (LSS)

Galaxy Clusters



Clusters of galaxies: largest self-gravitating systems (aka, DM halos) with $\delta >> 1$, composed of $10^{2\text{-}3}$ galaxies.

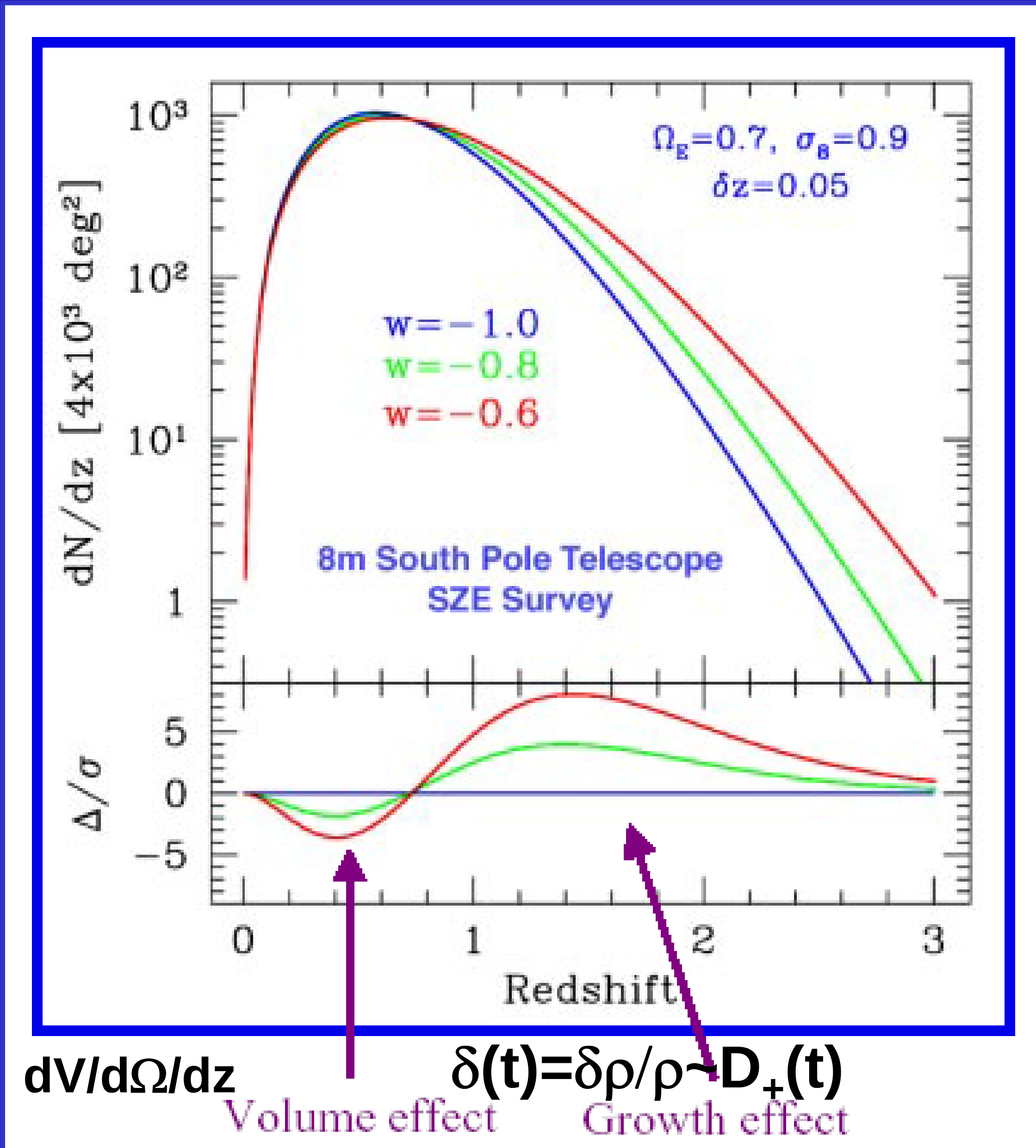
$$M_{vir} \sim 10^{14-15} M_{\rm sun} / h$$

$$R_{vir} \sim 1-2 {\rm Mpc} / h \;\Rightarrow\; t_{dyn} = 3-5 {\rm Gyr} < {\rm t_H}$$

$$k_{\rm B} T_{gas} \sim 5-10 {\rm keV}$$

Simulation of dark matter around a forming cluster (Springel et al. 2005)

Clusters as Cosmological Probes



Cluster count N(z) predictions for different DE equation-of-state, $w=P/(\rho c^2)$, normalized to the local universe

Cosmological test with structure formation in 0<z<3

Complementary to CMB observations (@z~1100)

Simulation by the SPT team

Fundamental Questions

Massive Galaxy clusters as sensitive cosmological probes:

1) **Equilibrium dark matter (DM) mass profile shapes:**

   "How the shape of a cluster's DM potential depends on cluster mass and redshfit?" ***today's topic***

2) **DM and Baryons:**

   "How the baryons distribute within the gravitational potential wells of clusters?"

3) **DM and Dark Energy (DE):**

   "How the number of clusters of a given mass should increase with time? How its growth rate depends on the background cosmology?"

Compare complementary cluster observations with testable predictions of models of structure formation

Objective (this talk):
Equilibrium DM Mass Profile Shapes

- **Theoretical interest**: ***what is the final state of the cosmological self-gravitating system ?***
  - **Forget cosmological initial conditions but reflect the nature of DM (EoS, collisional nature)?**
  - **Keep initial memory somehow?**
- **Practical importance**: ***testable predictions for galaxies and galaxy clusters***
  - **can distinguish the underlying cosmological model through comparison with observations: i.e., galactic rotation curve, gravitational lensing, X-ray/Sunyaev-Zel'dovich effects**

Concordance Universal CDM Density Profile

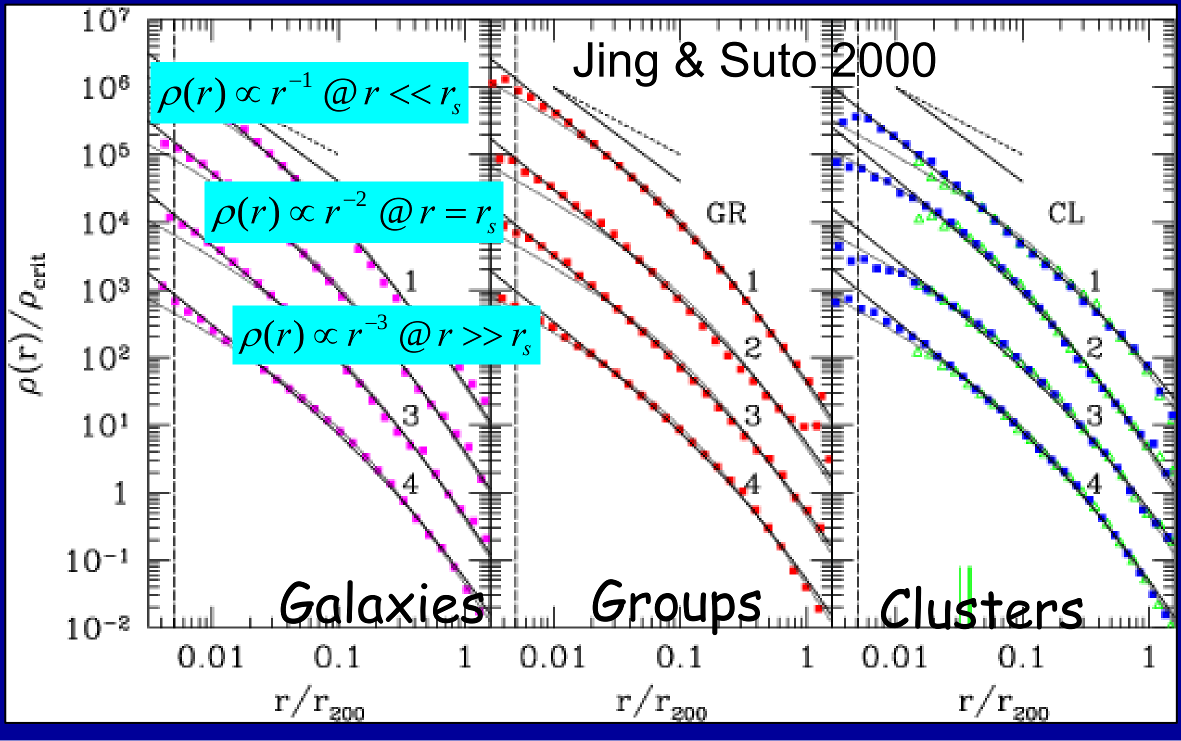
***Empirical predictions** from cosmological N-body simulations of CDM structure formation*: **"Navarro-Frenk-White" (NFW) density profile**

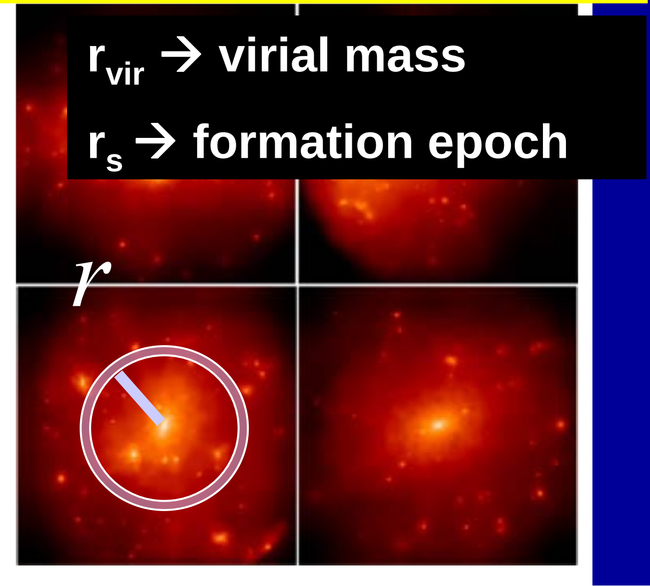
— The universal profile fits simulated DM halos that span ~9 orders of magnitude in mass (dwarf galaxies to clusters) regardless of the initial conditions and cosmology.

— Not a single power-law but continuously steepening density profile with radius: central cusp slope of n(r)=–dlnρ/dlnr=1 – 1.5 (cuspy but shallower than the isothermal body, n=2), outskirt slope of n(r)=3

$$\rho(r)/\rho_s = (r/r_s)^{-1}(1+r/r_s)^{-2}$$

$$c_{vir} := r_{vir}/r_s$$



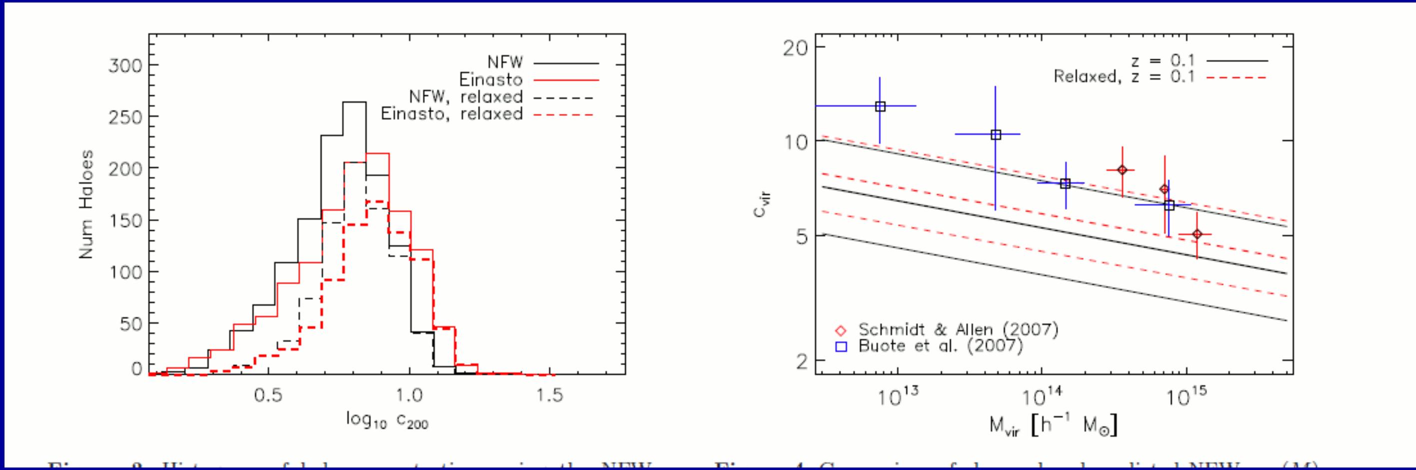


LCDM Prediction by Duffy+2008

Median C-M relation of N-body CDM halos in the WMAP5 cosmology (σ_8=0.8)

$$\langle c_{\rm vir} \rangle = c_0 (1+z)^{-\alpha} \left(\frac{M_{\rm vir}}{10^{15} M_{\rm sun}/h} \right)^{-\beta}$$

$C_0 \sim 5.2$, $\alpha \sim 0.66$, $\beta \sim 0.084$



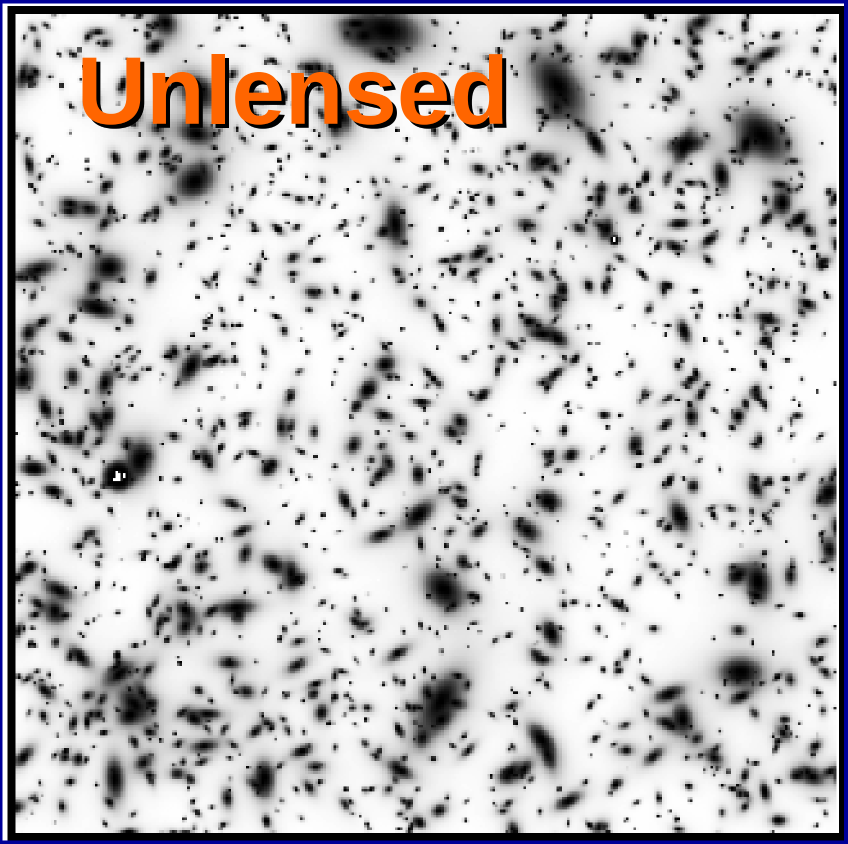
Degree of concentration, $c_{\rm vir}$,: **implications for epoch of halo formation**

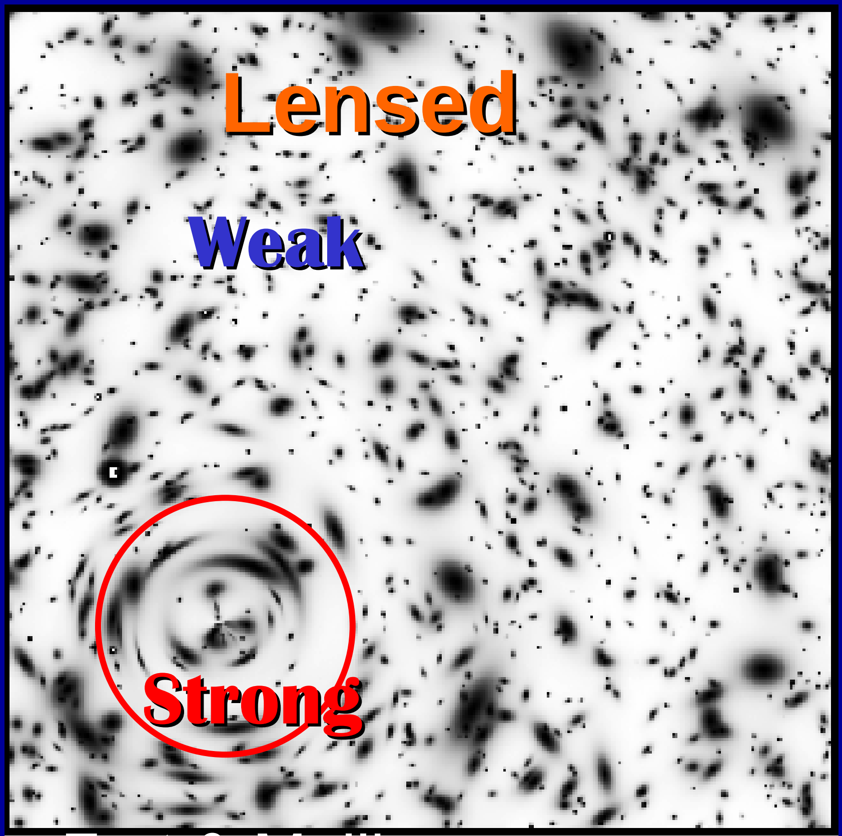
- In a hierarchical bottom-up clustering scenario, the smaller the object, the earlier its formation epoch.
- The cosmic mean density $\rho_{m0}(1+z)^3$ is higher in earlier epochs, so that $c_{\rm vir}$ is correspondingly higher (on average) for less massive halos.

Method: Gravitational Lensing

Gravitationally-lensed images of background galaxies carry the imprint of $\Phi(x)$ of intervening cosmic structures:

Observable weak shape distortions can be used to derive the distribution of matter (i.e., mass) in a model independent way!!





Fort & Mellier

2. Cluster Gravitational Lensing

My lecture notes on

"**Cluster Weak Gravitational Lensing**"

from "Enrico-Fermi Summer School 2008, Italy" found @

arXiv:1002.3952

Theoretical backgrounds and basic concepts on cosmological lensing and observational techniques are summarized in these lecture notes.

Deflection Field:
Gravitational Bending of Light Rays

Gravitational deflection angle in the weak-field limit (|Φ|/c^2<<1)

Light rays propagating in an inhomogeneous universe will undergo **small transverse excursions** along the photon path: i.e., **light deflections**

Bending angle

$$\delta\hat{\alpha} \approx \frac{\delta p_{\perp}}{p_{\parallel}} = -\frac{2}{c^2}\nabla_{\perp}\Psi(x_{\parallel}, x_{\perp})\delta x_{\parallel}$$

Small transverse excursion of photon momentum

$$\hat{\alpha}^{\mathrm{GR}} = 2\hat{\alpha}^{\mathrm{Newton}} \rightarrow \frac{4GM}{c^2 r} = 1.''75\left(\frac{M}{M_{sun}}\right)\left(\frac{r}{R_{sun}}\right)^{-1}$$

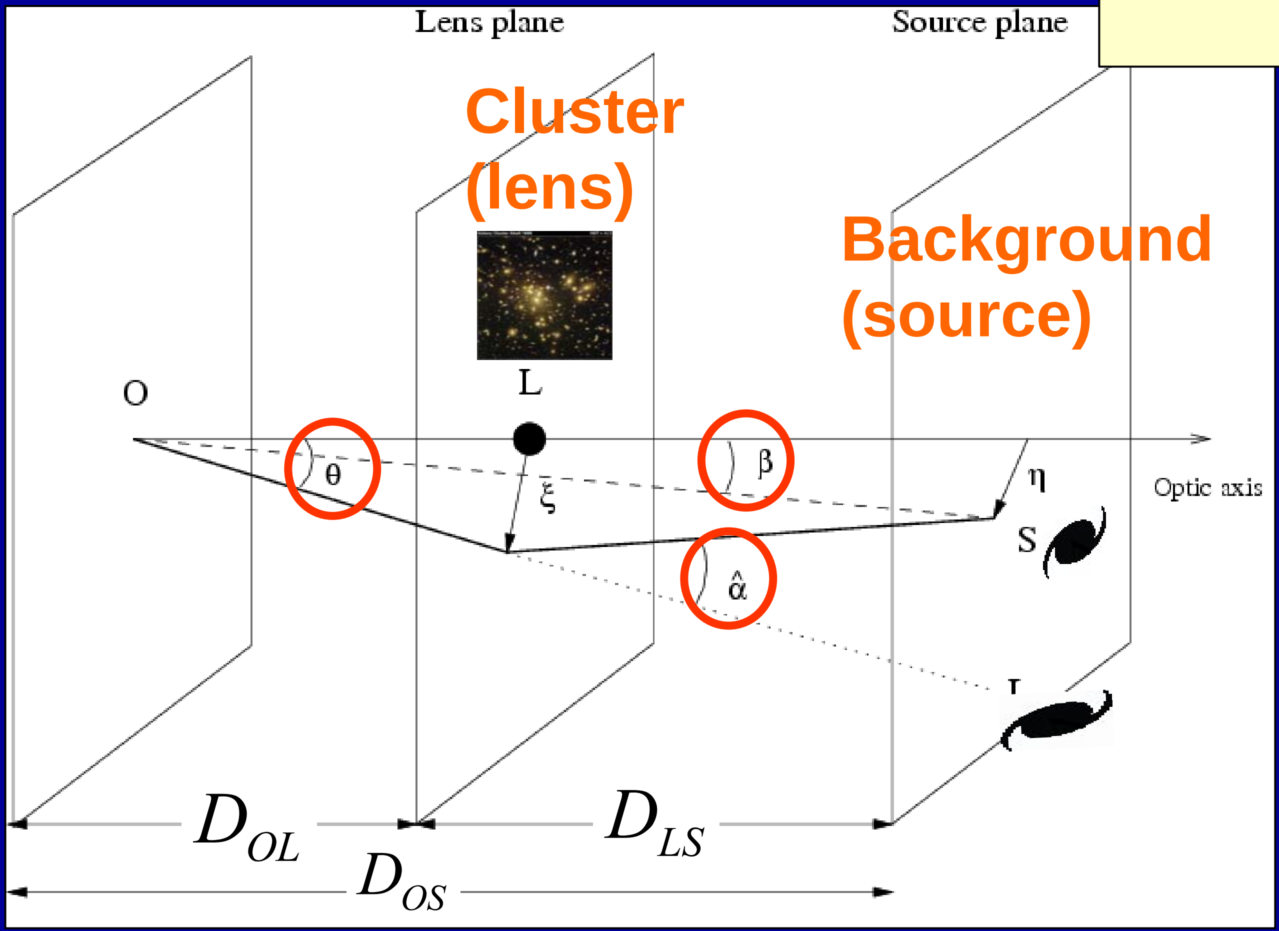
Lens Equation

Lens equation **(Cosmological lens eq. + single/thin-lens approx.)**

β: true (but unknown) source position

θ: apparent image position

$$\boldsymbol{\beta} - \boldsymbol{\theta} = \frac{D_{LS}}{D_{OS}} \hat{\boldsymbol{\alpha}}(\boldsymbol{\theta}) \equiv \boldsymbol{\alpha}(\boldsymbol{\theta})$$



Poisson eq (2D):

div $\alpha = \nabla\cdot\alpha \equiv 2\kappa$

$\kappa(\theta) \propto \Sigma(\theta)$

D_{OL}, D_{LS}, $D_{OS} \sim O(c/H_0)$

For a rigid derivation of cosmological lens eq., see, e.g., Futamase 95

Gravitational Lensing in Galaxy Clusters

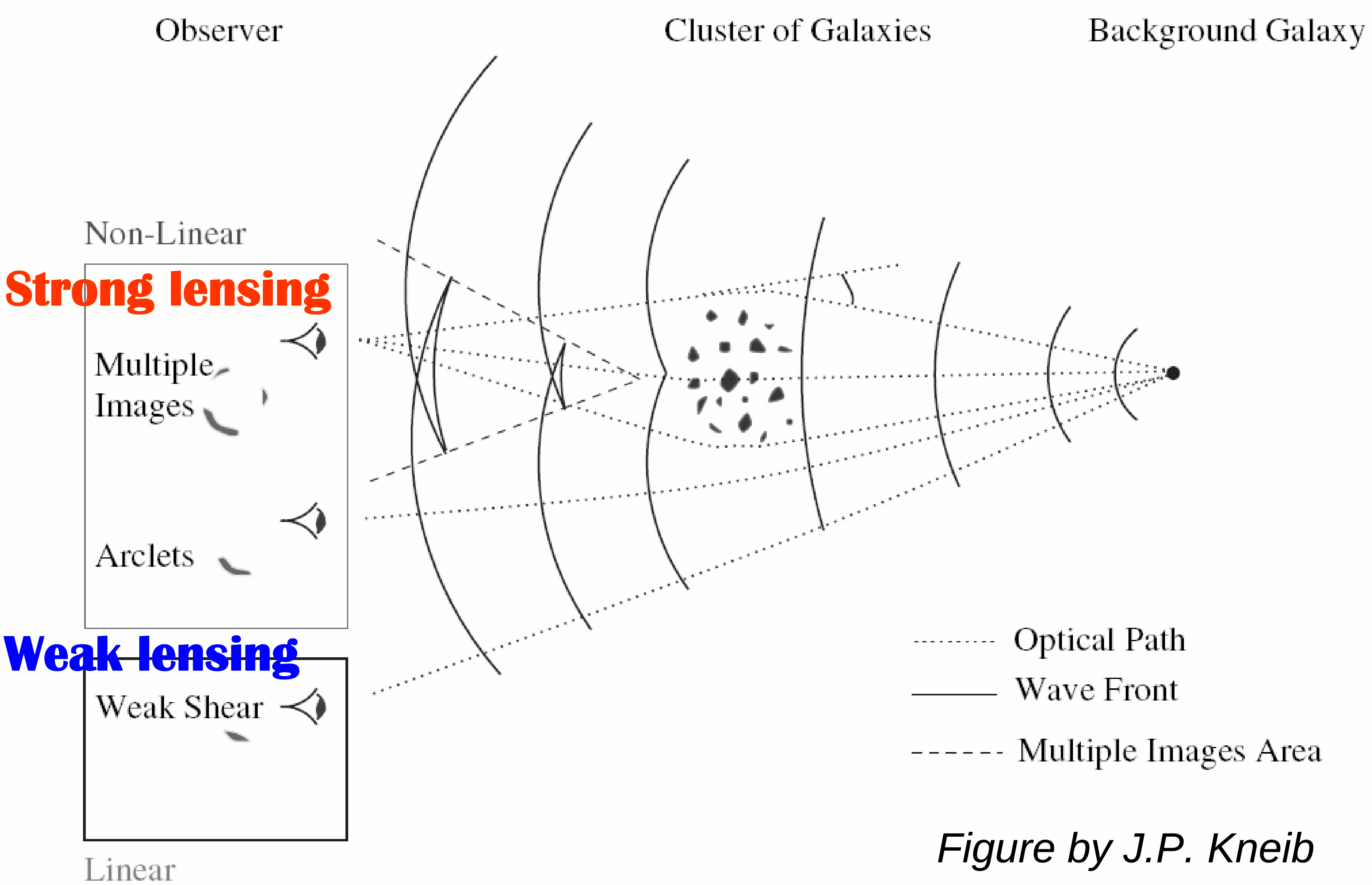
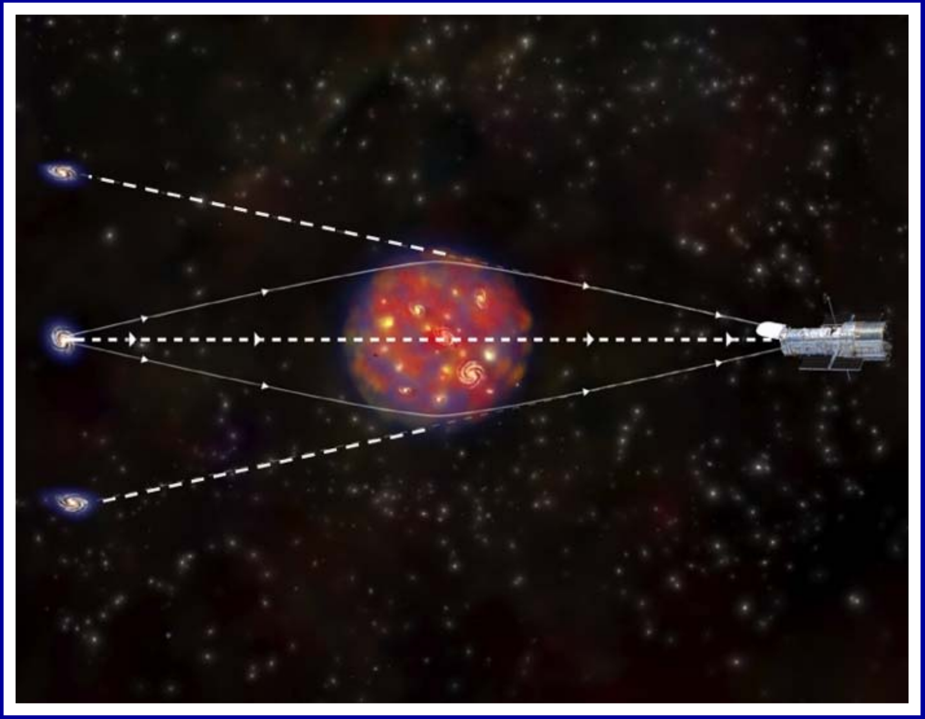


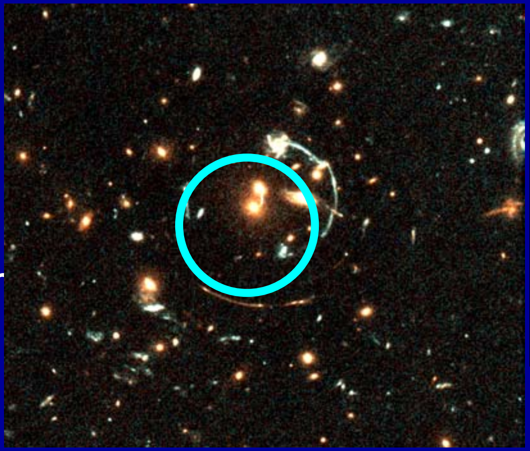
Figure by J.P. Kneib

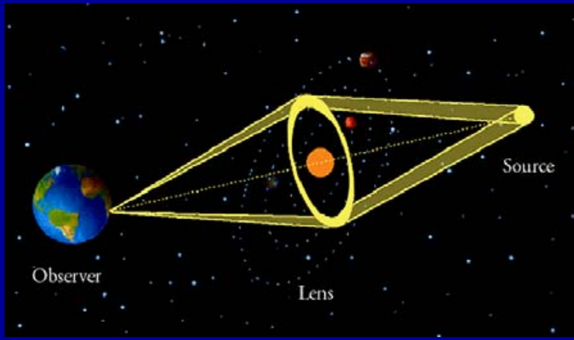
Strong Lensing: Clusters as Cosmic Telescopes

Strong Lensing Basics:

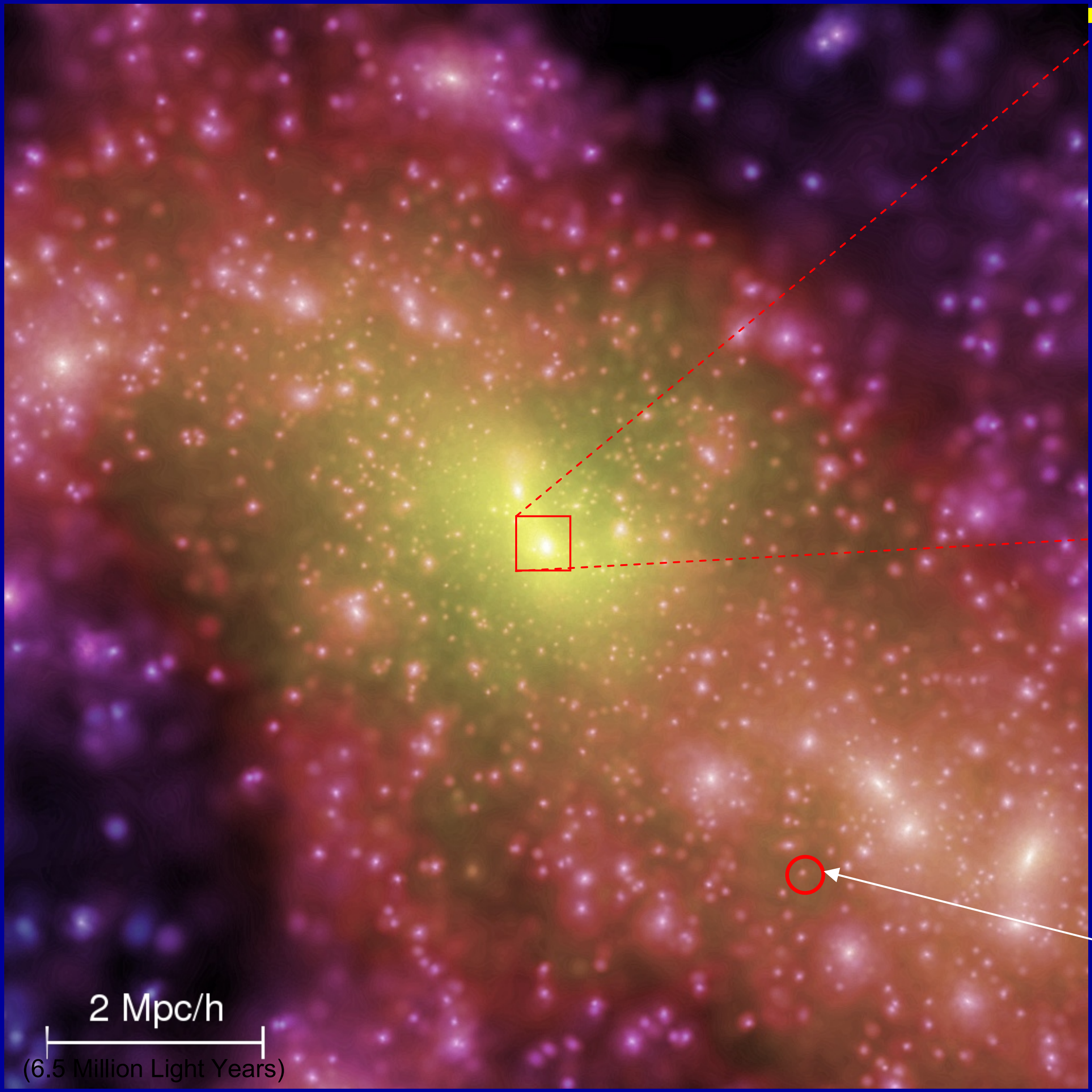
- Cluster's deep potential well deforms local space-time – light-ray deflection.
- Provides large areas of high flux magnification (μ ~ 10) → natural gravitational telescope
- *Tradeoff*: Dilution of the source-plane area (=1/μ).
- Shows multiply-imaged background galaxies in the cluster core region.
- Luminous arc- and ring-like images formed around the tangential critical curve with an Einstein radius θ_{Ein}.







Strong Lensing to Map the Central Cluster Mass Distribution



Simulation of dark matter around a forming cluster (Springel et al. 2005)

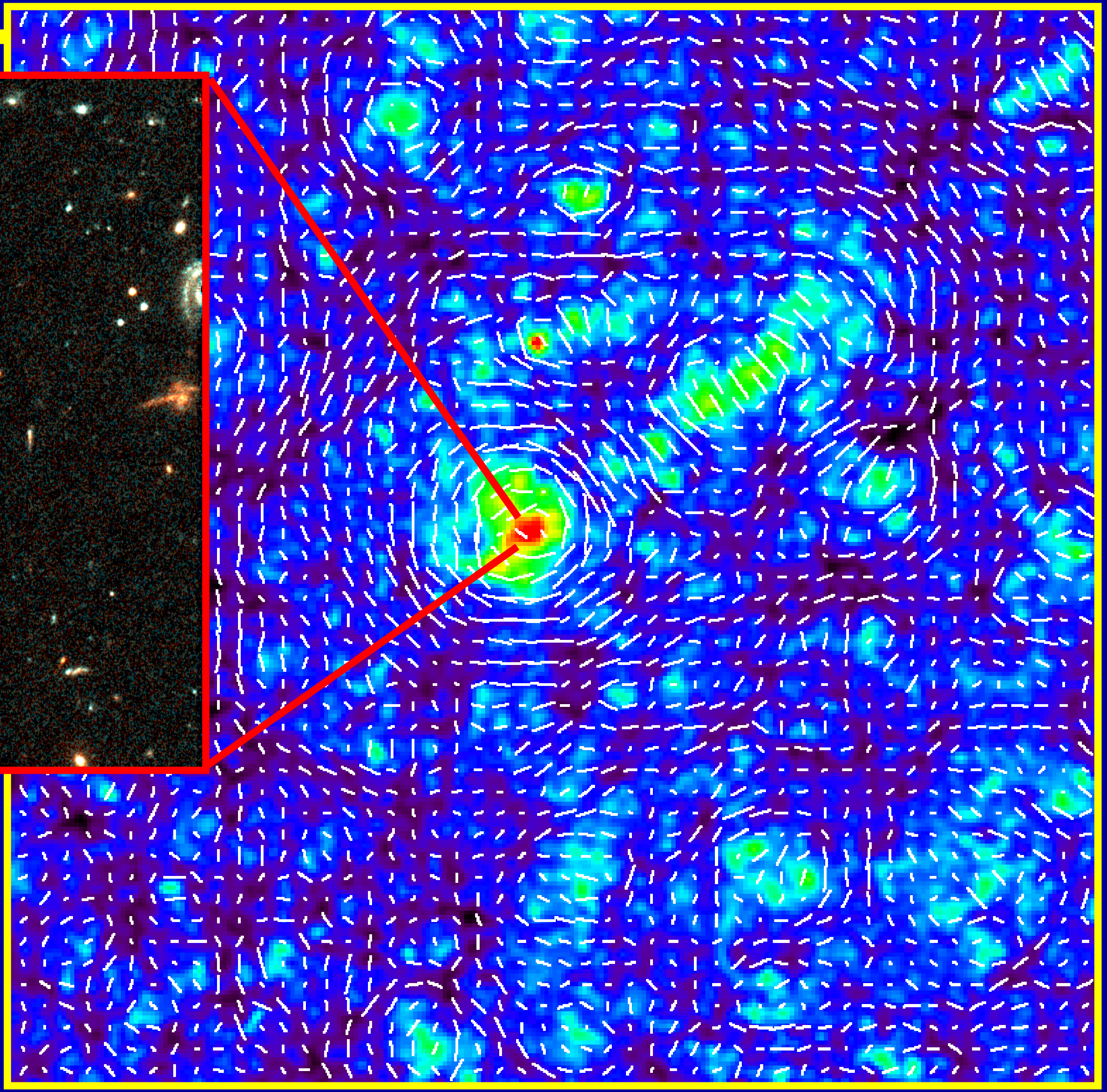
Deep HST image of massive cluster

$$R \propto \frac{\theta_{Einstein}}{\sqrt{N_{Arcs}}}$$

WHERE R IS THE RESULTING SPATIAL RESOLUTION OF THE DARK MATTER MAP

Weak Lensing [1]: Tangential Shape Distortion

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



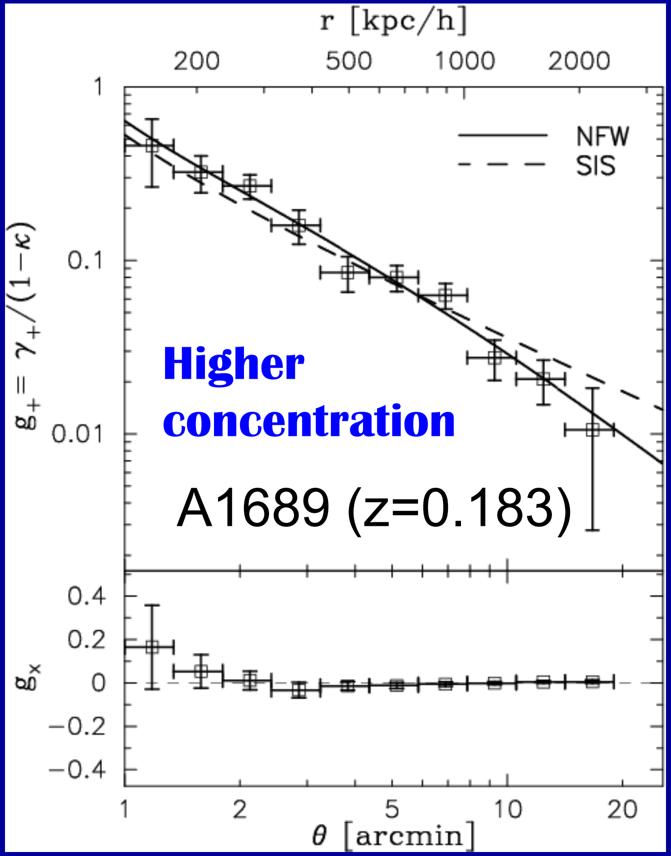
Simulated 3x3 degree field (Hamana 02)

Tangential Distortion Profile (contd.)

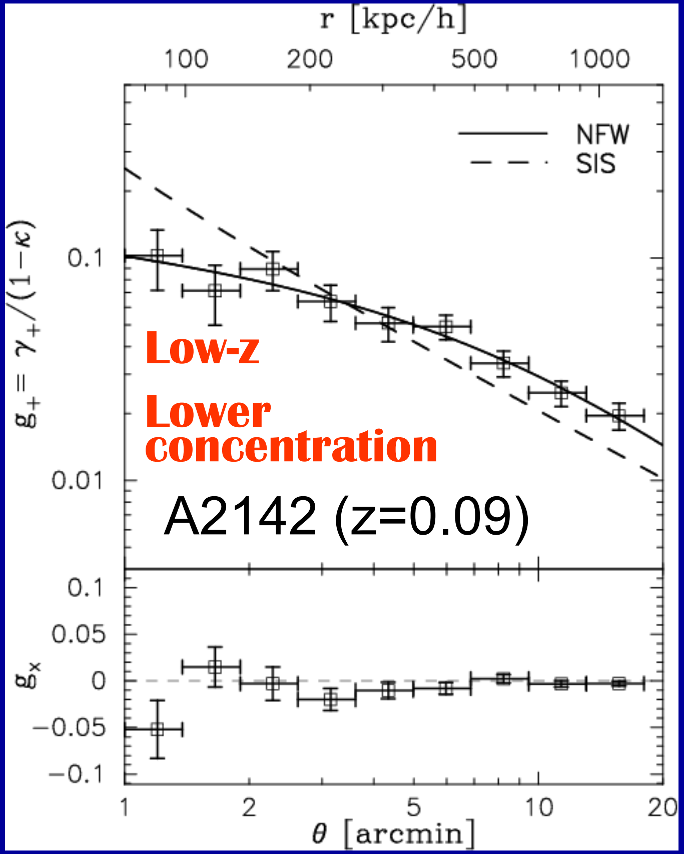
$$\gamma_+(r) \propto \Delta\Sigma_m(r) \equiv \overline{\Sigma}_m(<r) - \Sigma_m(r)$$

Measure of tangential coherence of distortions around the cluster (Tyson & Fisher 1990)

Mean tangential ellipticity of BG galaxies (γ_+) as a function of cluster radius; uses typically (1-2) x 10^4 background galaxies per cluster, yielding typically S/N=5-15 per cluster.



Umetsu & Broadhurst 2008, ApJ, 684 , 177



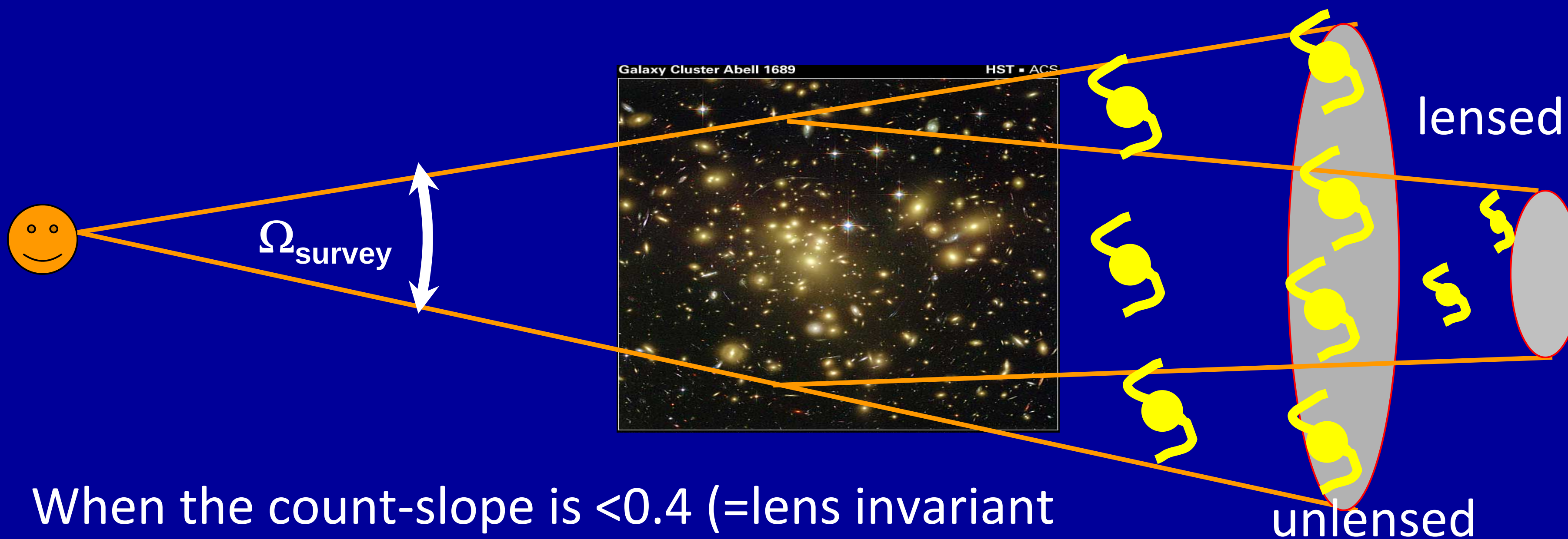
Umetsu et al 2009, ApJ, 694, 1643

Weak Lensing [2]: Magnification Bias

Magnification bias: Lensing-induced fluctuations in the background density field (Broadhurst, Taylor, & Peacock 1995)

$$\delta n(\boldsymbol{\theta}) / n_0 \approx -2(1-2.5\alpha)\kappa(\boldsymbol{\theta})$$

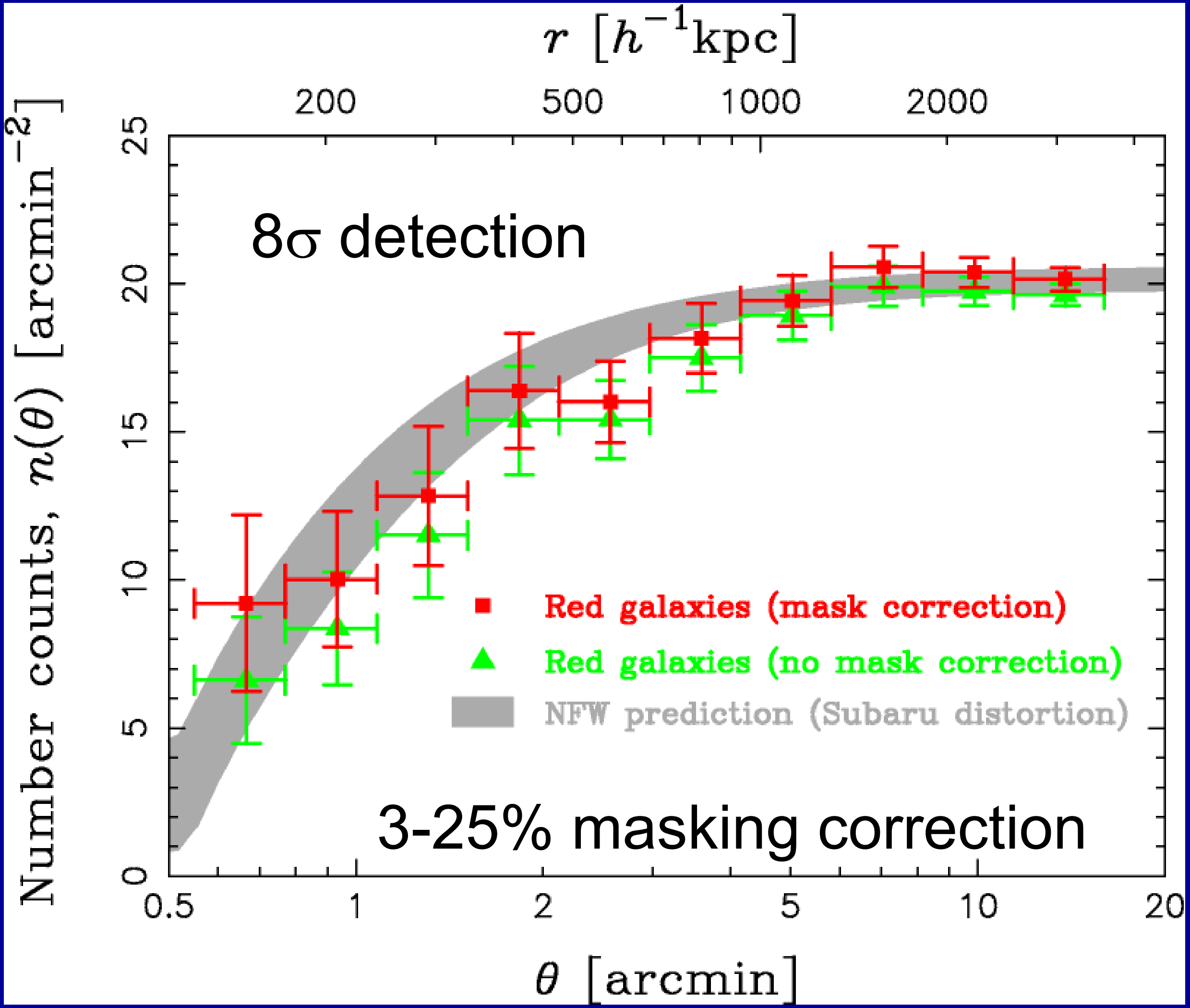
with unlensed counts of background galaxies $n_0(<m) \propto 10^{\alpha m}$



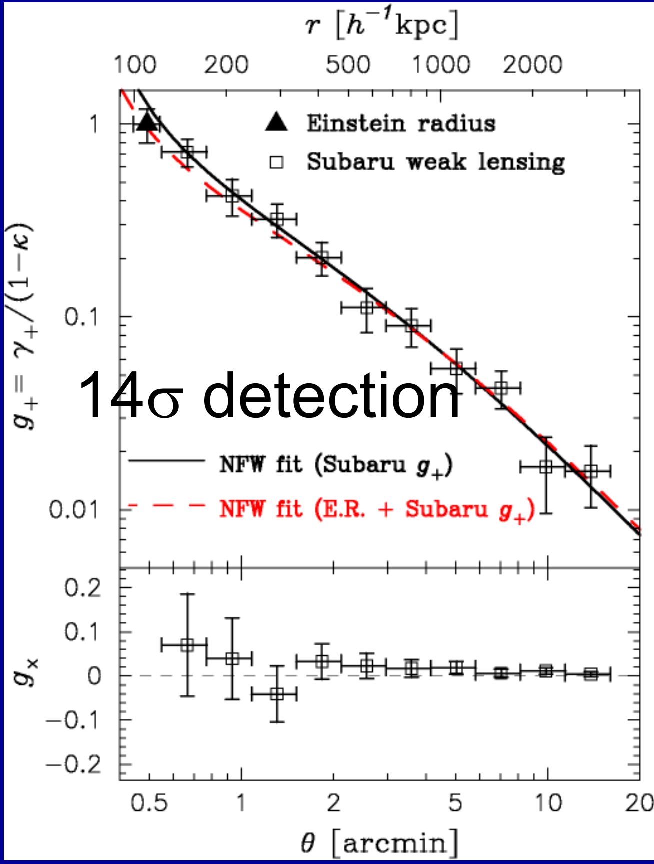
When the count-slope is <0.4 (=lens invariant slope), a net deficit is expected.

Example: WL Distortion vs. Magnification

Count depletion of "red" galaxies in CL0024+1654 (z=0.395)



Distortion of "blue+red" sample



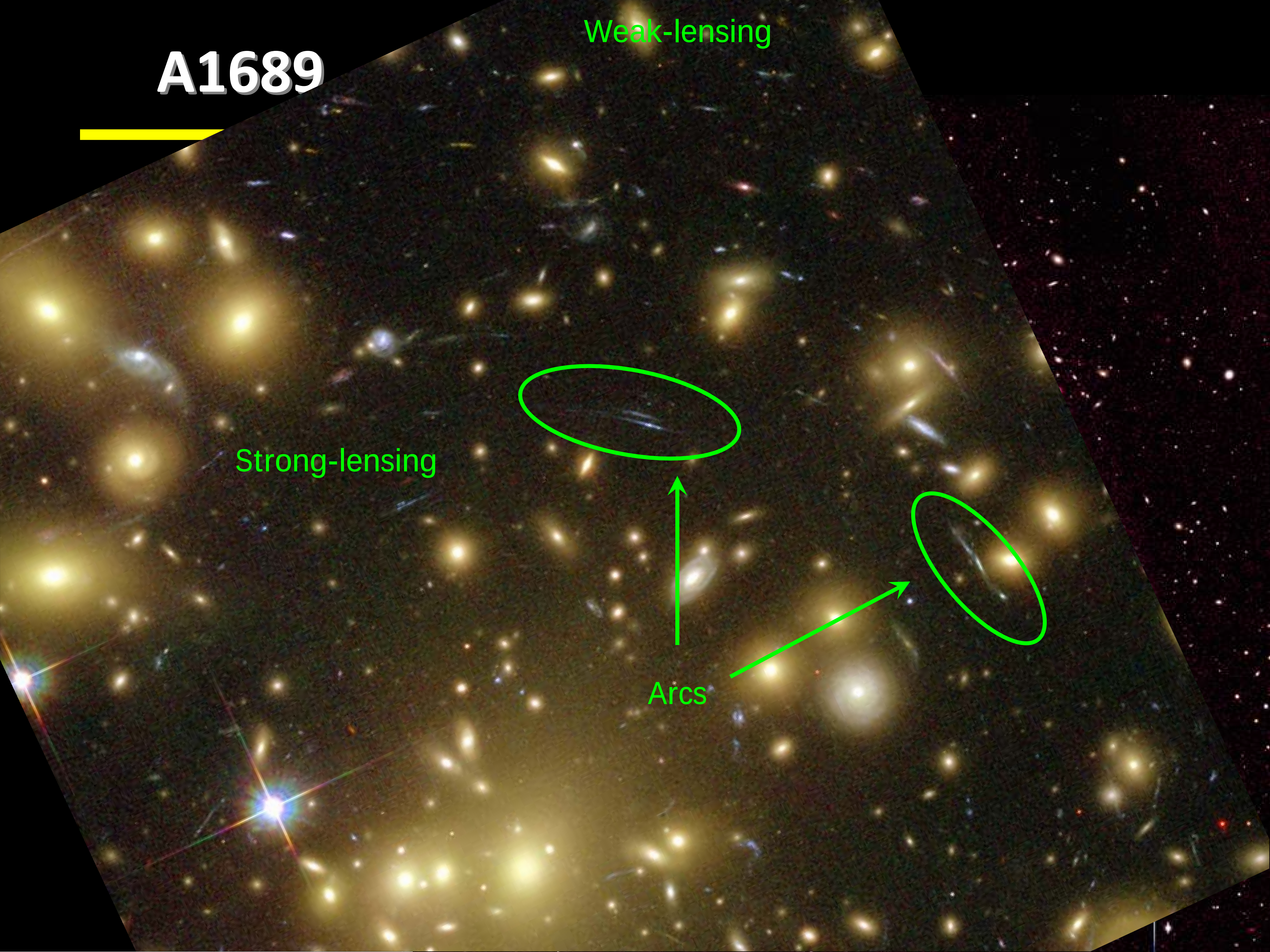
Umetsu et al. 2010, ApJ, 714, 1470

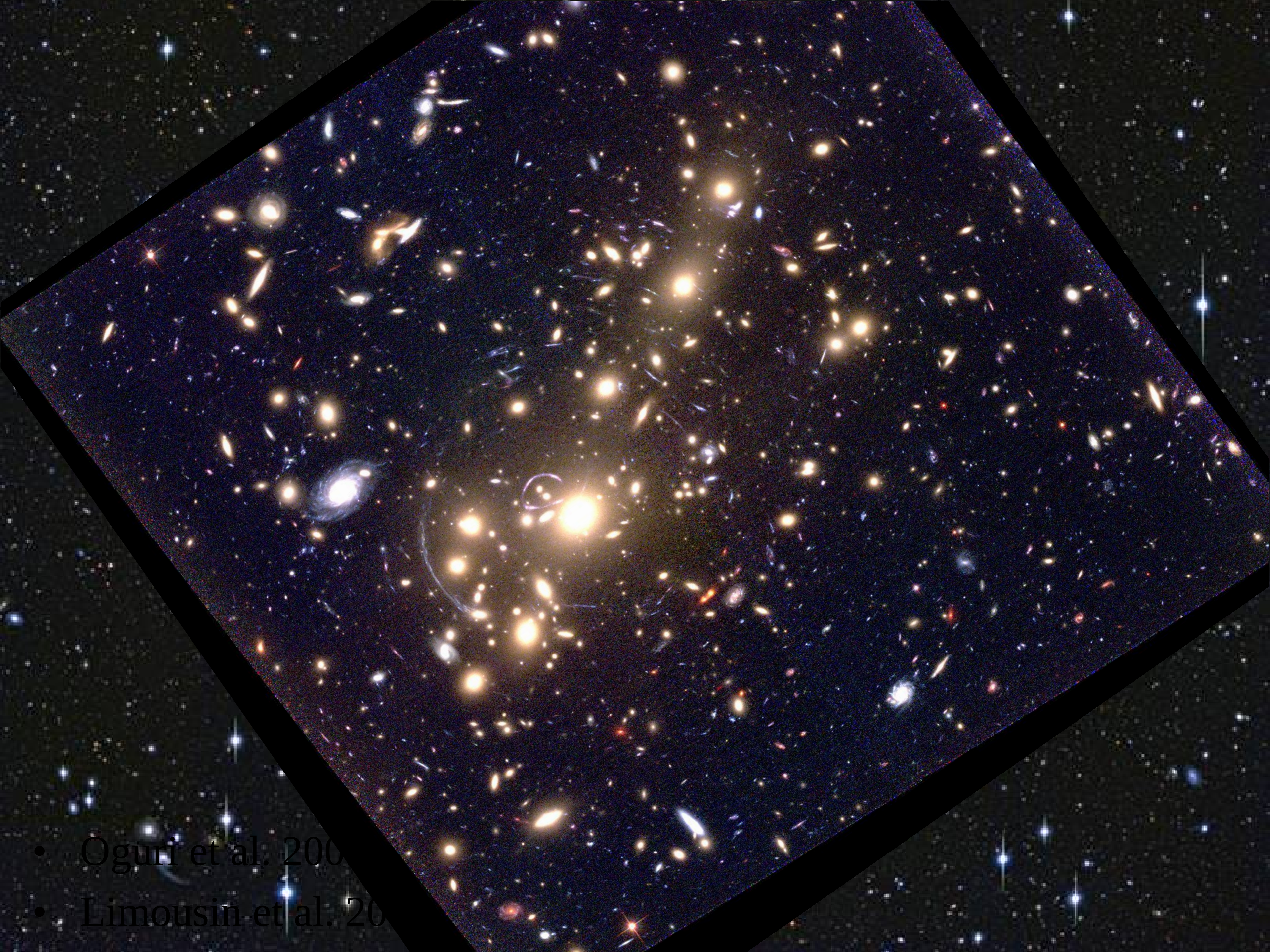
3. Targets and Data:
Subaru and Hubble Imaging

Massive clusters (>$10^{15}M_{sun}$/h) with strong lensing phenomena

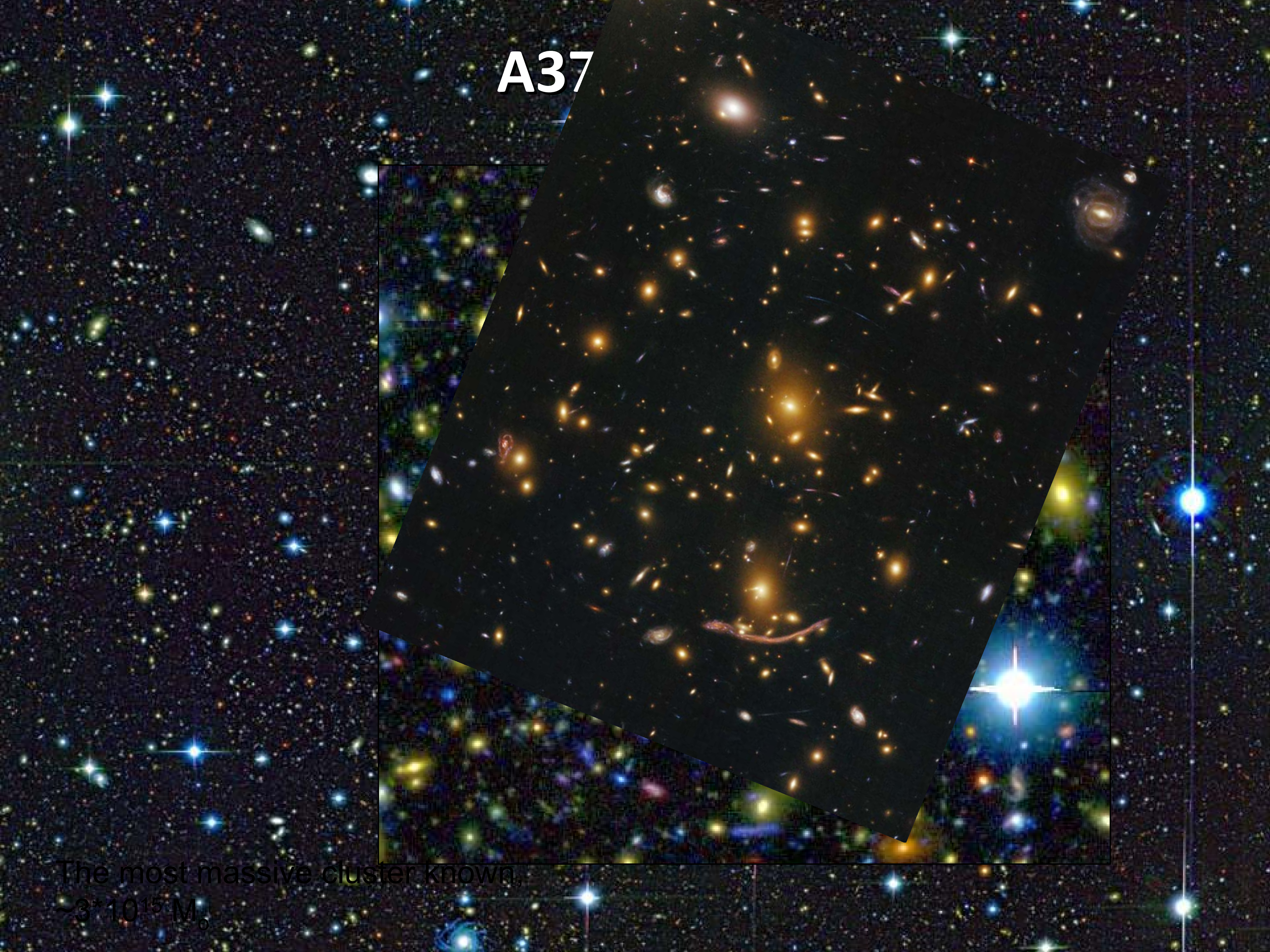
- A1689 (z=0.183)
- A1703 (z=0.281)
- A370 (z=0.375)
- Cl0024+1654 (z=0.395)
- RXJ1347 (z=0.451)

A1689

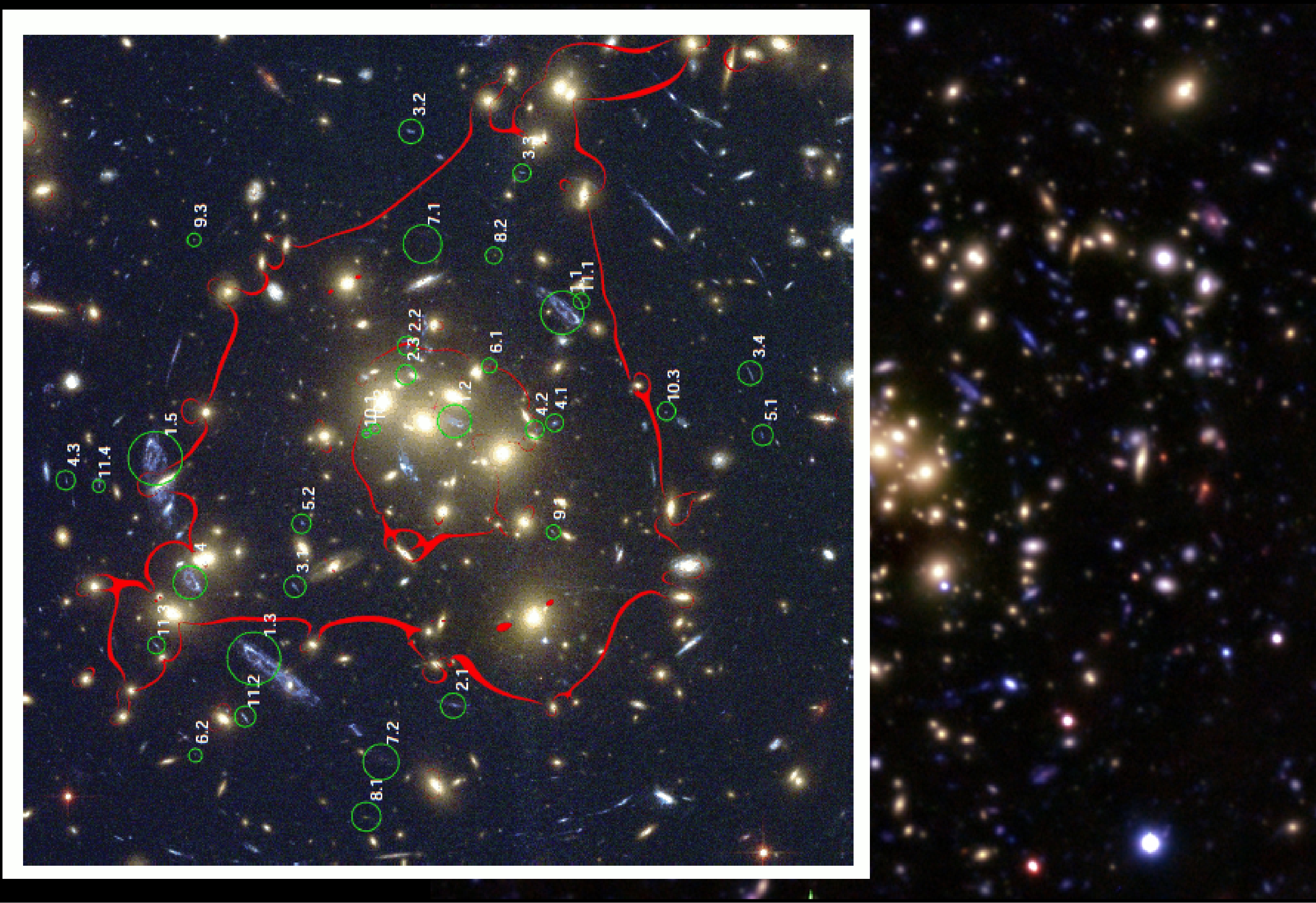




- Oguri et al. 200
- Limousin et al. 20


A37
The most massive cluster known,
~3*10^15 M_o

Cl0024+1654 (z=0.395)

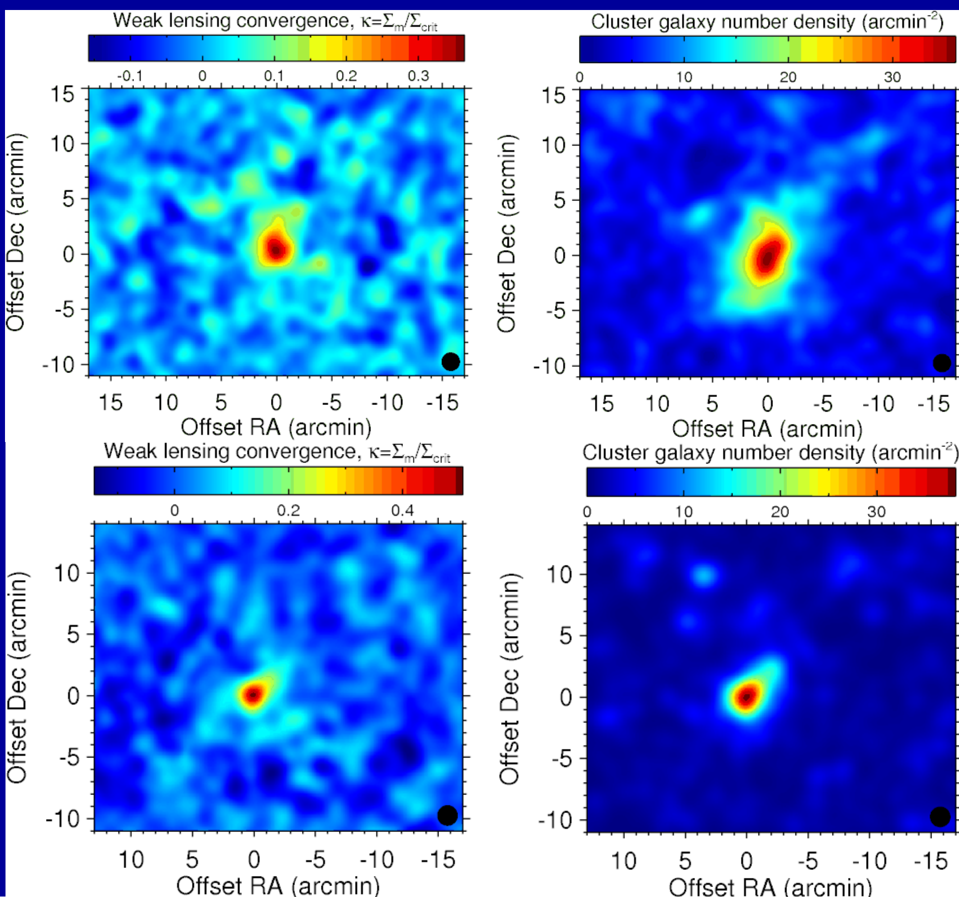


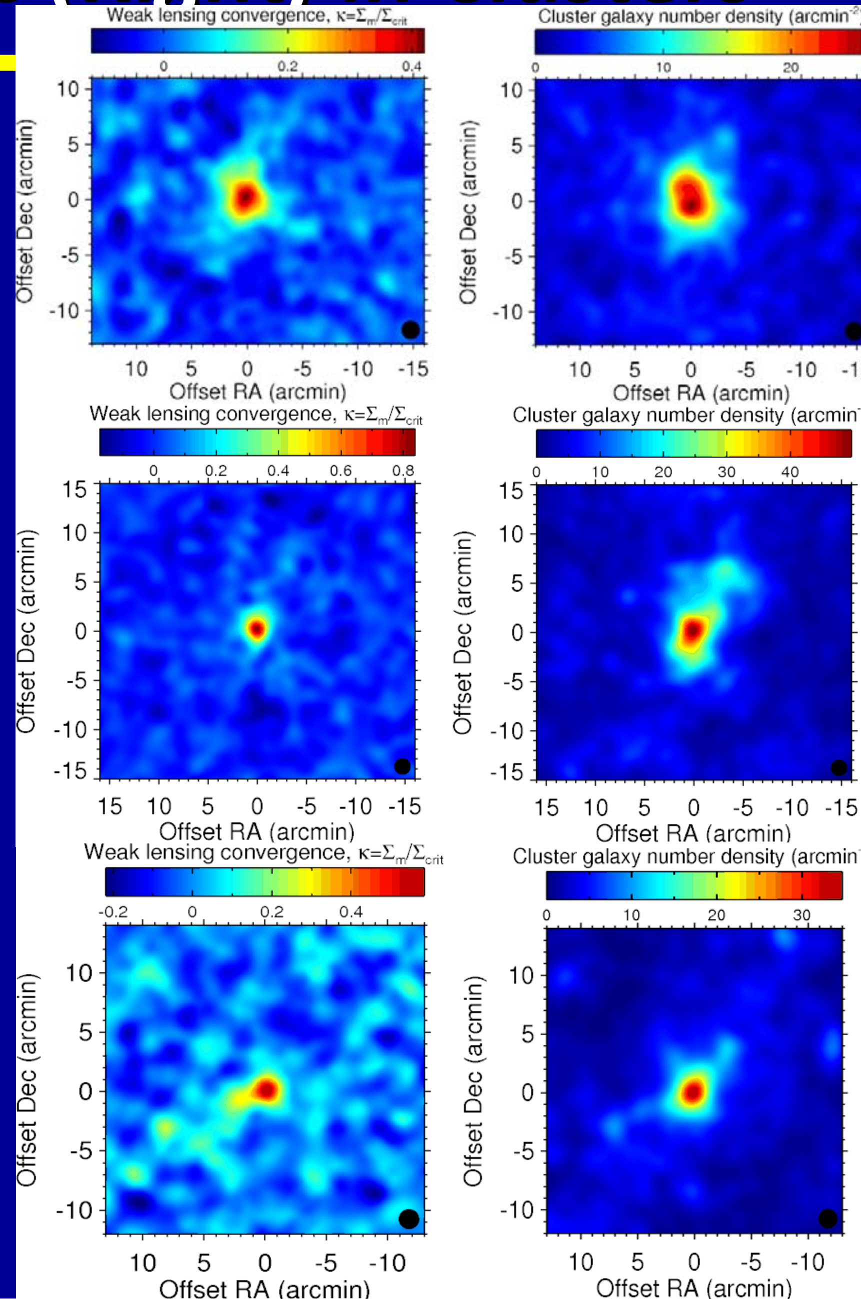
DM (Left) vs. Galaxies (Right) in Clusters

A1689 (z=0.18)

A1703 (z=0.28) A370 (z=0.38)

Cl0024 (z=0.40) RXJ1347(z=0.45)





4. Highlights of Cluster Lensing Constraints on the DM Halo Density Profiles

<u>**Selected References (Cluster Projects 2005-2010):**</u>

Broadhurst, Takada, **KU** et al. 2005, ApJL
Oguri, Takada, **KU**, & Broadhurst 2005, ApJ
KU, Tanaka, Kodama et al. 2005, PASJ
Medezinski, Broadhurst, **KU** et al. 2007, ApJ
Okura, **KU**, & Futamase 2007, ApJ
Okura, **KU**, & Futamase 2008, ApJ
Okabe & **KU** 2008, PASJ
Broadhurst, **KU**, Medezinski et al. 2008, ApJL
KU & Broadhurst 2008, ApJ
KU, Birkinshaw, Liu et al. 2009, ApJ
Lemze, Broadhurst, Barkana, Rephaeli, & **KU** 2009, ApJ
Zitrin, Broadhurst, **KU** et al. 2009, MNRAS
KU, Medezinski, Broadhurst et al. 2010, ApJ
Kawaharada, Okabe, **KU** et al. 2010, ApJ
Medezinski, Broadhurst, **KU** et al. 2010, MNRAS
Okabe, Takada, **KU** et al. 2010, PASJ, in press
Zitrin, Broadhurst, **KU** et al. 2010, MNRAS, accepted
Medezinski, Broadhurst, **KU** et al. 2010, ApJ, submitted

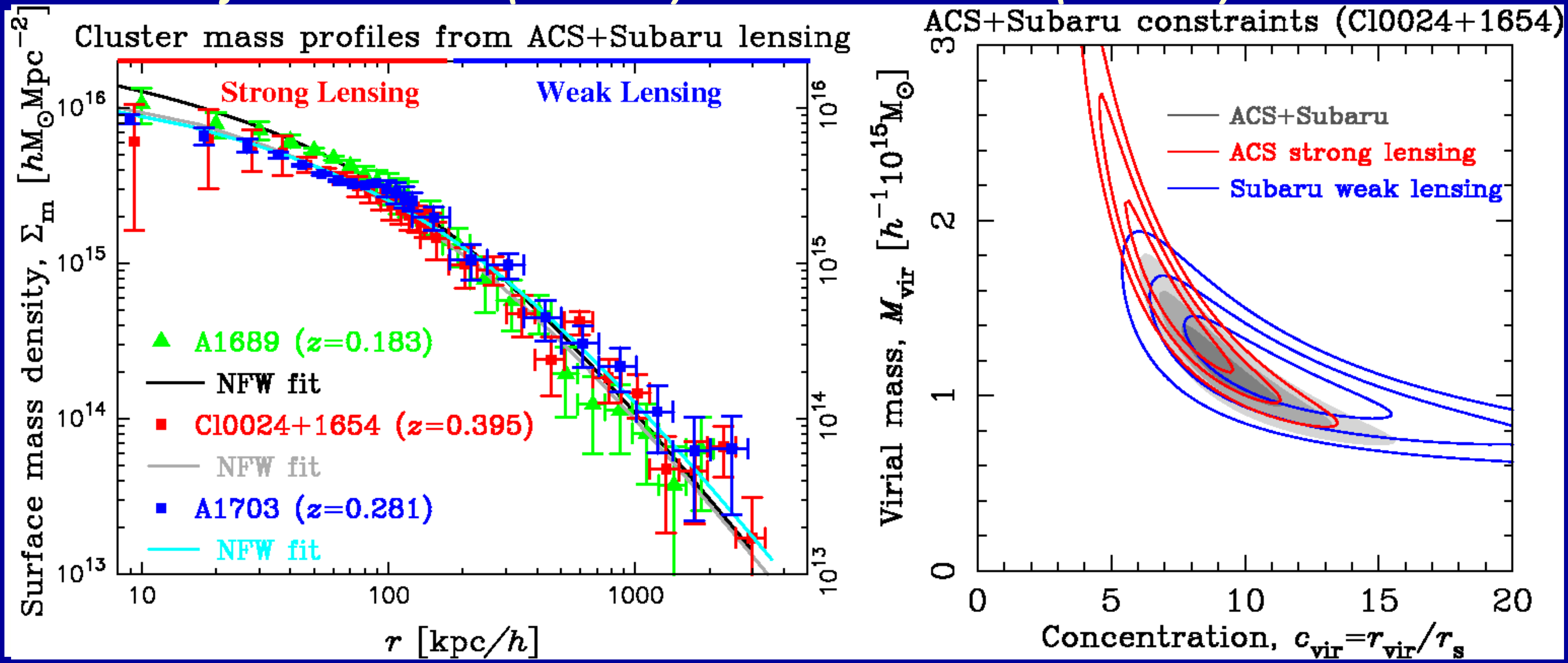
Based on <u>Subaru/Suprime-Cam</u>, HST/ACS, VLT/VIRMOS, AMiBA, Chandra, Suzaku/XIS, etc.

[1] Full Weak + Strong Lensing Analysis

Combining Weak (Subaru) and Strong (HST/ACS) lensing data:

→ Probing the mass density profile from 10kpc/h to >2000kpc/h

Results for Abell 1689 (z=0.183) and Cl0024+1654 (z=0.395)



The profile shapes are consistent with CDM (NFW) over the entire cluster, but the degree of concentration appears to be higher than LCDM.

Broadhurst, Takda, Umetsu et al. 2005; Umetsu & Broadhurst 2008; Lemze et al. 2009 (A1689); Umetsu et al. 2010 (CL0024+1654); Umetsu et al. 2010b in prep (5 clusters)

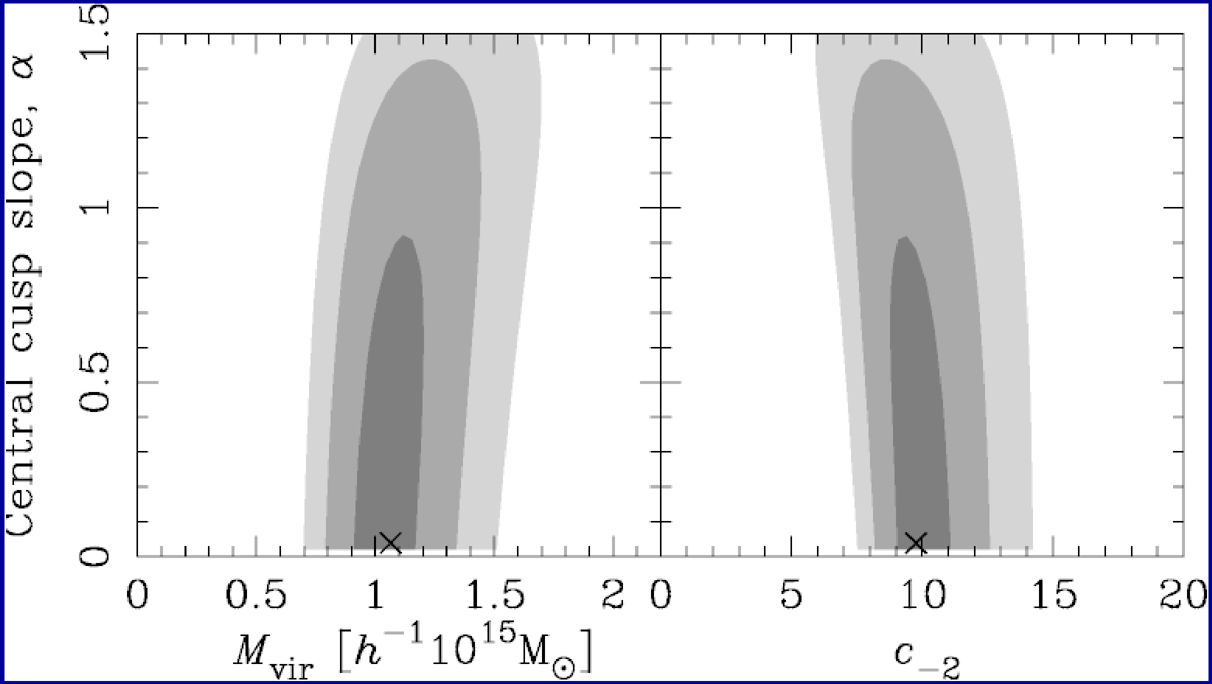
Lensing Constraints on the Central Cusp Slope

Weak + strong lensing constraints on CL0024+1654 (z=0.395)

Generalized NFW (gNFW) profile w/ 3 free parameters:

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

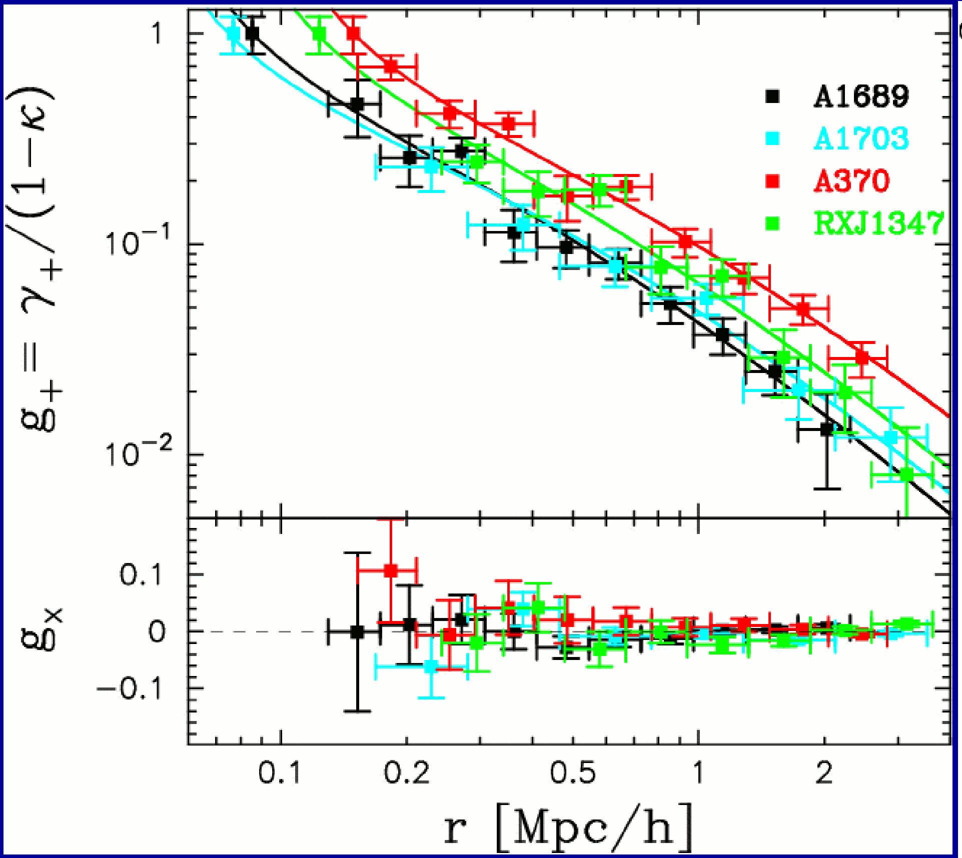
$$c_{-2} := \frac{r_{vir}}{(2-\alpha)r_s}$$

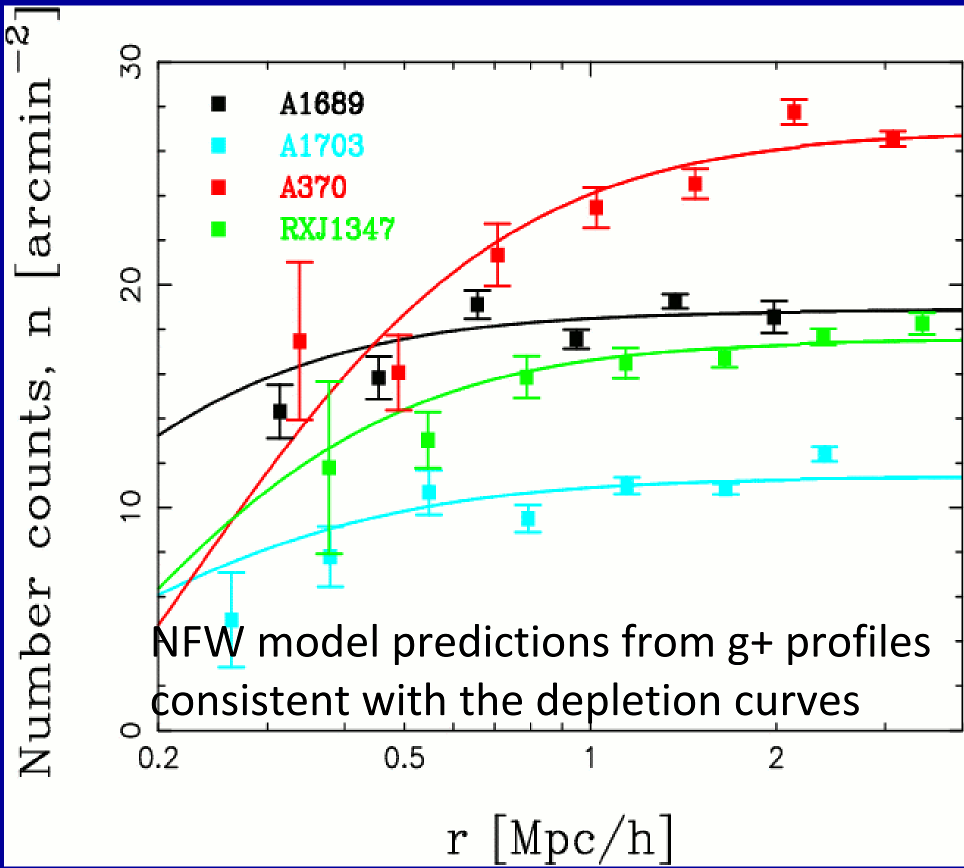


- Central cusp slope α < 1 at 68.3%CL from the combined strong and weak lensing constraints – yet consistent with NFW.
- Cored profile (α~0) is preferred (cf. Tyson et al. 1998; CDM crisis)
- Note CL0024 is the result of a line-of-sight collision of 2 similar-mass clusters, viewed approximately 2-3Gyr after impact (see Umetsu et al. 2010, ApJ, 714, 1470)

[2] Testing LCDM by Cluster Lensing Profiles

Compare "**WL distortion + Einstein-radius**" constraints (left) with "**WL magnification bias**" (right) in 4 high-mass clusters:

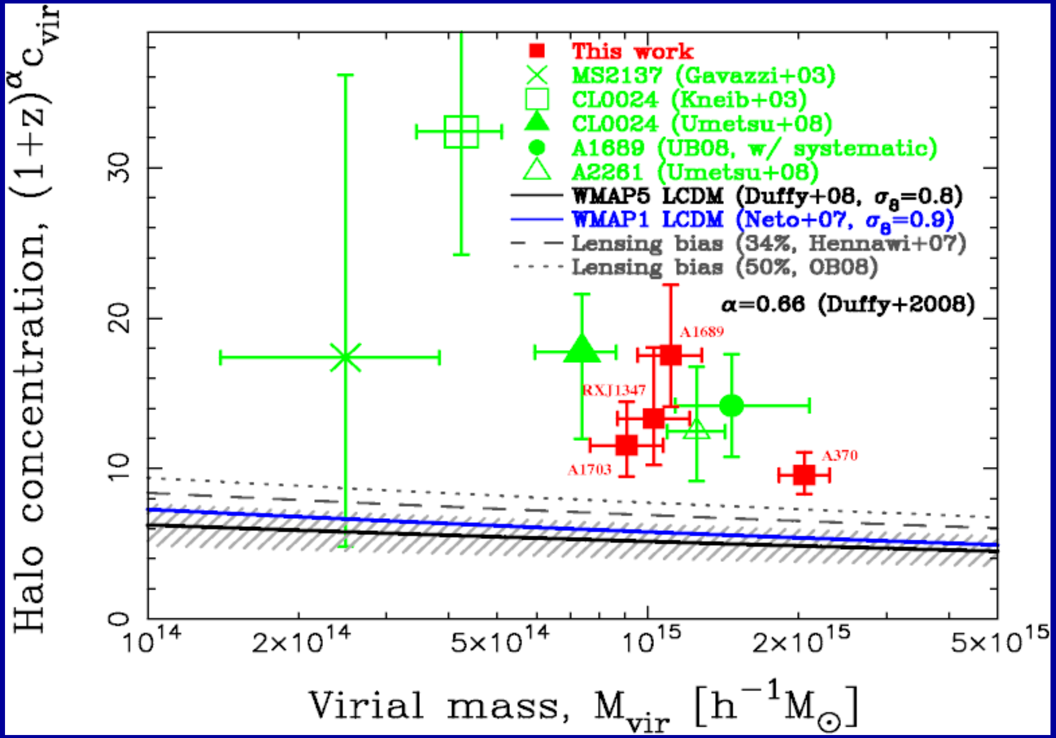


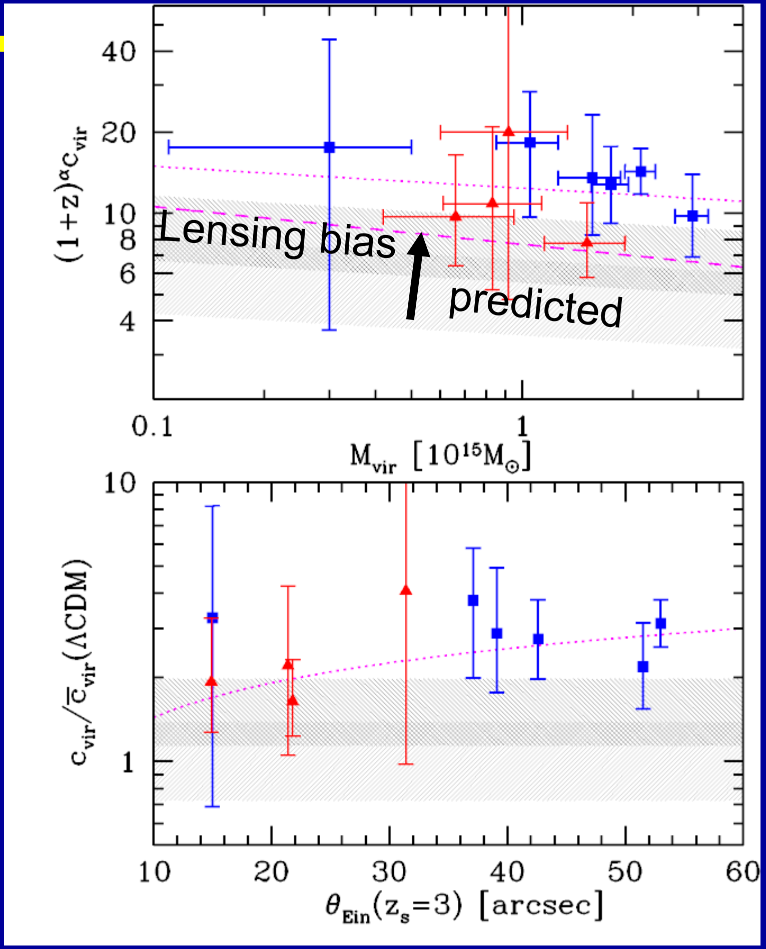


Observed curves are similar in form, well described by CDM-consistent NFW profiles

Broadhurst, Umetsu, Medezinski+ 2008, ApJ, 685, L9

First Lensing Tests of the C-M Relation





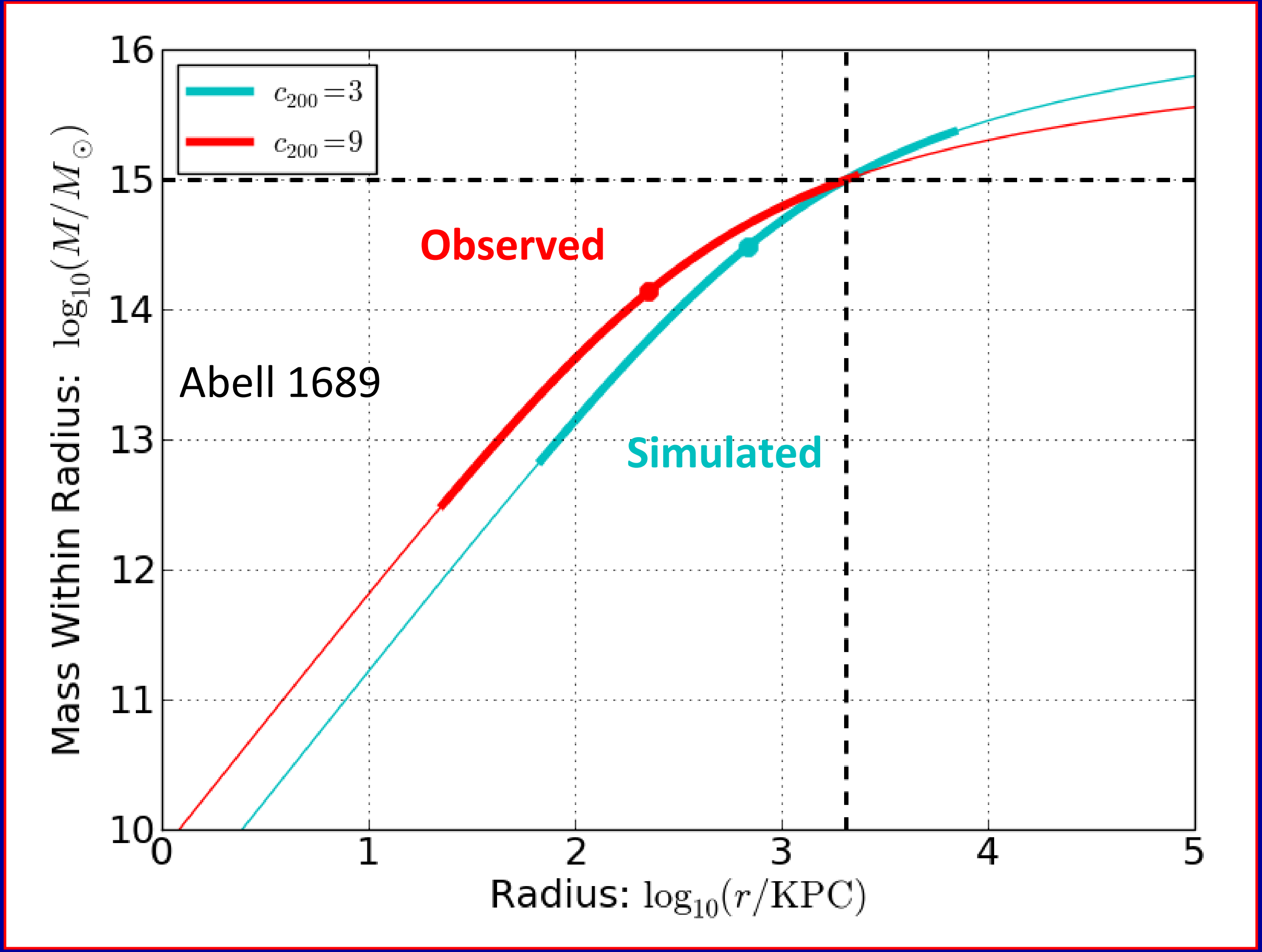
*Taking into account an orientation bias correction of +**18%,** discrepancy is still 4σ.*
*With a **50% bias** correction, it represents a 3σ deviation (BUM+2008)*

Left) Broadhurst, Umetsu, Medezinski+ 2008, ApJ, 685, L9 (BUM+2008)

Right) Oguri et al. 2009, ApJ, 699, 1038

Some (lensing-biased) clusters appear over-concentrated

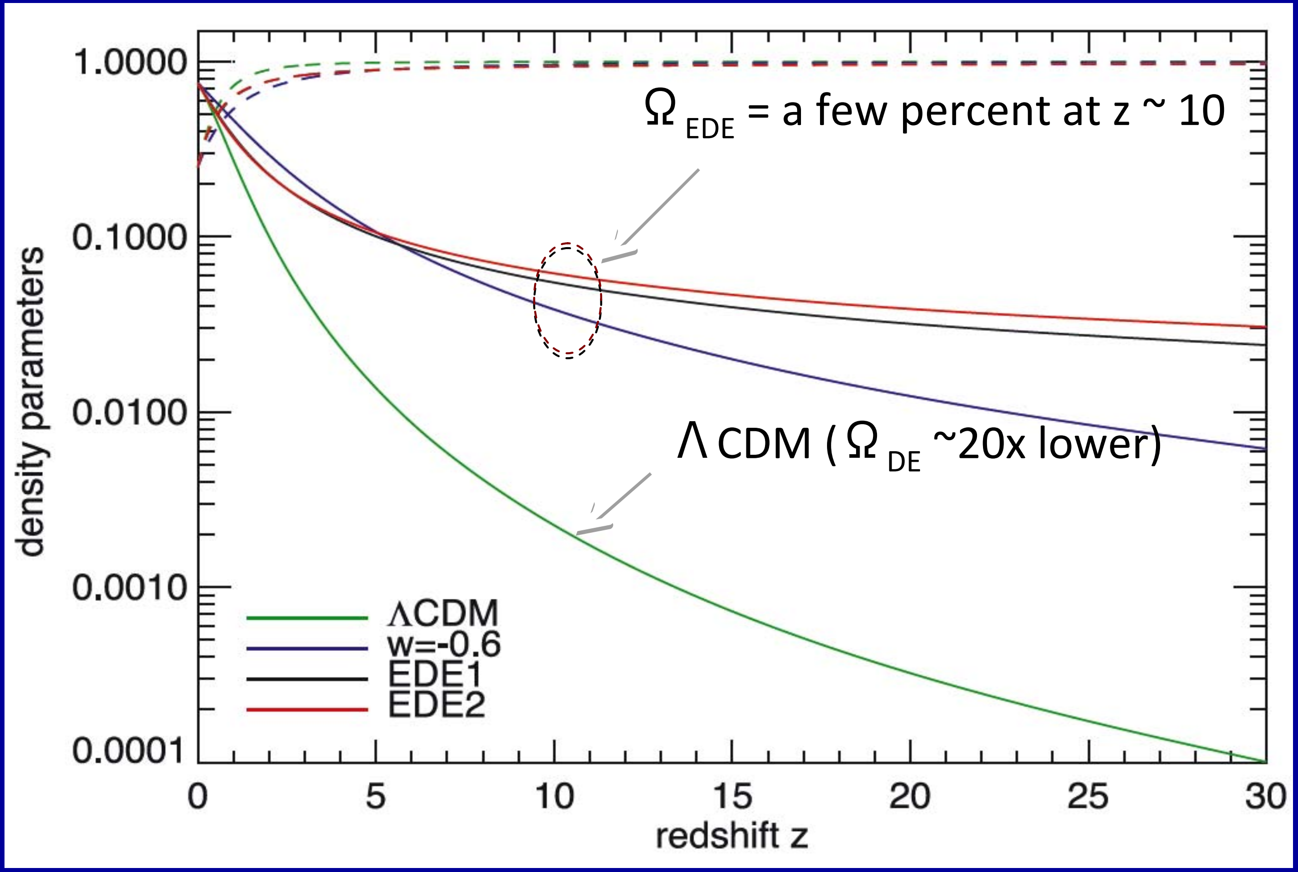
Strong Lensing → | ← Weak Lensing



Possible explanations for high observed concentrations

- **Lensing selection bias**
  - Strong lensing bias towards intrinsically high mass concentration halos (Hennawi et al. 2007)
  - Triaxial orientation bias (Oguri & Blandford 2009)
  - Significant (25-50%) but probably not sufficient
- **Baryons and adiabatic contraction**
  - Probably not a major effect in clusters if AGN feedback is taken into account (Duffy et al. 2010; Mead et al. 2010)
  - A.C. will increase the inner cusp slope α ($\uparrow$), while shallow slopes α<~1 preferred in A1689 and CL0024+1654.
- **Clusters formed earlier than in LCDM**
  - Early Dark Energy (e.g., Sadeh & Rephaeli 2008; Grossi & Springel 2009)?

Clusters with high concentrations and early formation times *may* be giving us hints of "Early Dark Energy" (EDE)?



Grossi & Springel 2009

Dark energy suppresses the growth of structure.

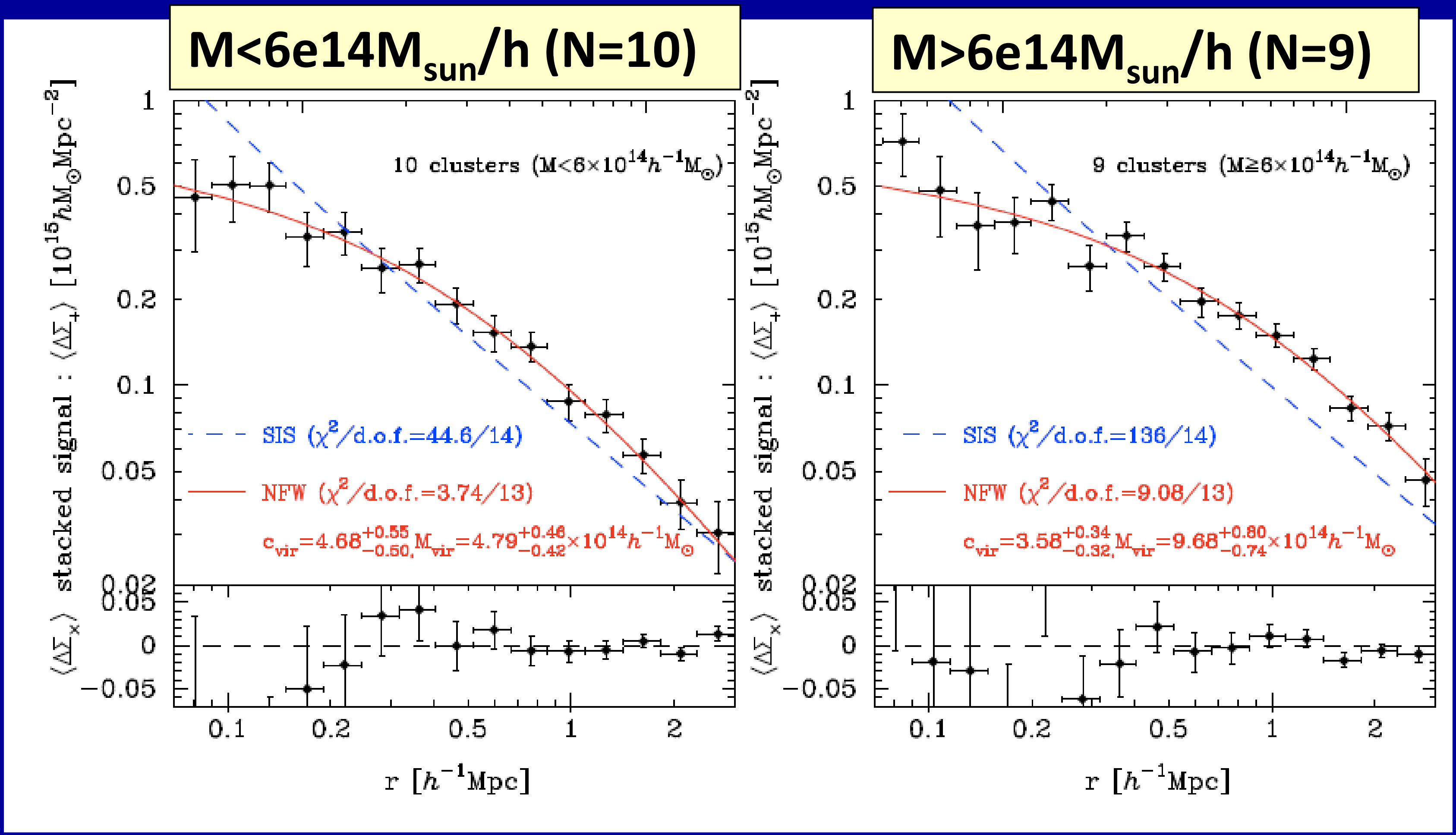
In EDE models, cluster growth was suppressed earlier.

So clusters must have started forming earlier *to achieve the abundances observed today.*

[3] LoCuSS Stacked Cluster WL Analysis

Stacking WL distortion profiles of an "unbiased" sample of clusters

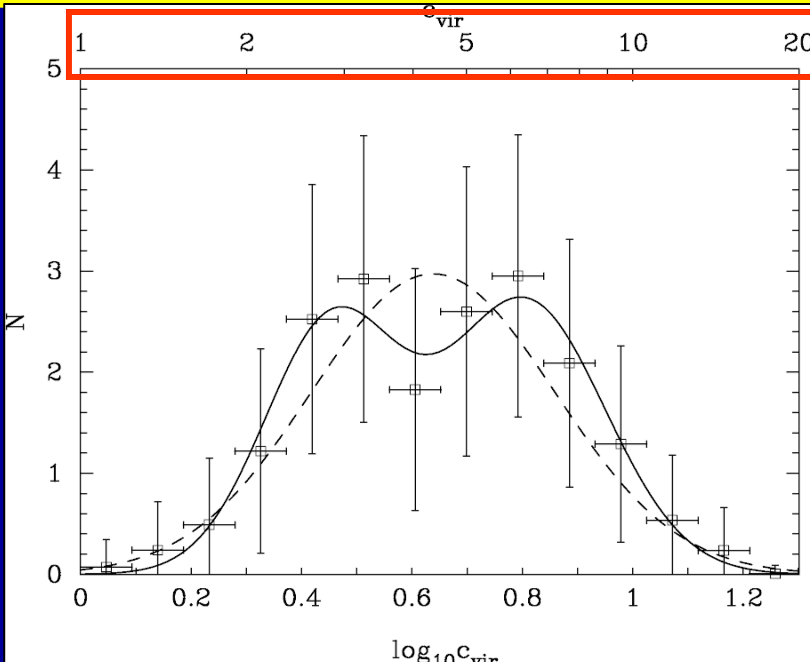
→ less sensitive to substructures/asphericity of individual clusters

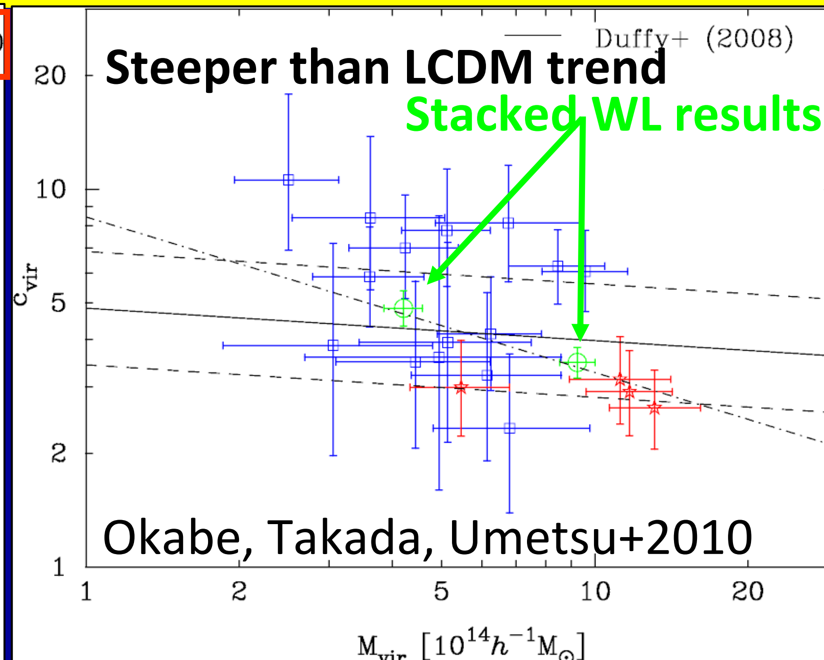


SIS rejected @6 and 11 σ levels (Okabe,Takada,Umetsu+ 10, arXiv:0903.1103)

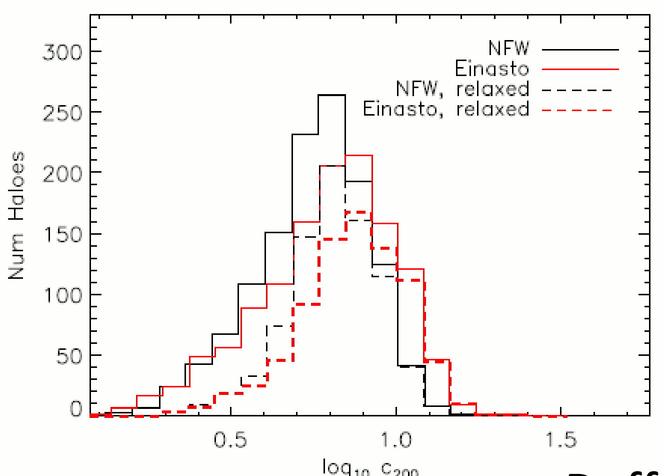
Subaru WL Results: Observations vs. Theory

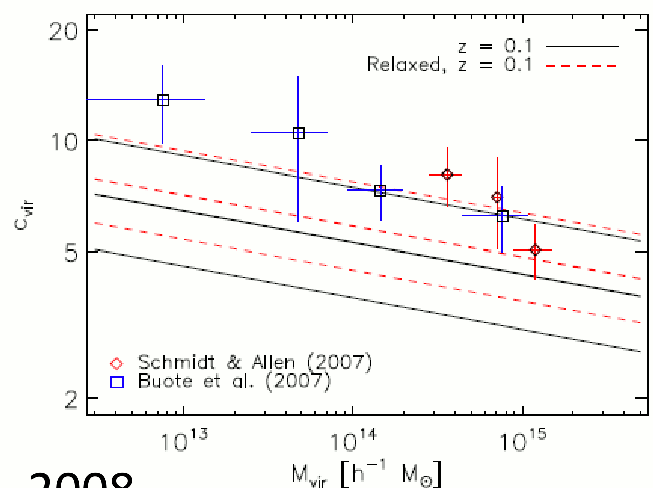
Subaru WL (19 clusters)





LCDM theory





Duffy et al. 2008

[4] Weak-Lensing Distance-Redshift Relation

Medezinski, Broadhurst, Umetsu, Benitez, Taylor 2010, submitted to MNRAS

Factorizing the distortion signal strength (in the weak lensing limit):

$$\gamma_+(\theta, z_s) \propto \frac{D_{LS}(z_s)}{D_{OS}(z_s)}\left(\overline{\Sigma}(<\theta) - \Sigma(\theta)\right) \propto \frac{r(\chi_S - \chi_L)}{r(\chi_S)}$$

$$r = f_K(\chi)$$ *Angular comoving distance*

$$\chi(z) = \int_{1/(1+z)}^{1} \frac{da}{a^2 H(a)}$$ *Comoving distance*

For a fixed cluster lens (potential and distance), the signal strength $\langle\gamma_+\rangle$ is proportional to the distance ratio D_{LS}/D_{OS}.

Compare the shear amplitude $\langle\gamma_+\rangle$ between two-different background populations "i,j" with different mean depths:
$\Gamma_{ij} \equiv \langle\gamma(z_i)\rangle / \langle\gamma(z_j)\rangle$ - *the shear-ratio statistic*

We expect the shear amplitude $\langle\gamma_+(z)\rangle$ increases with increasing background depth $\langle z\rangle$, purely due to the cosmological geometric effect, providing a new geometric cosmological test.

In practice, how to measure it? Is it feasible?

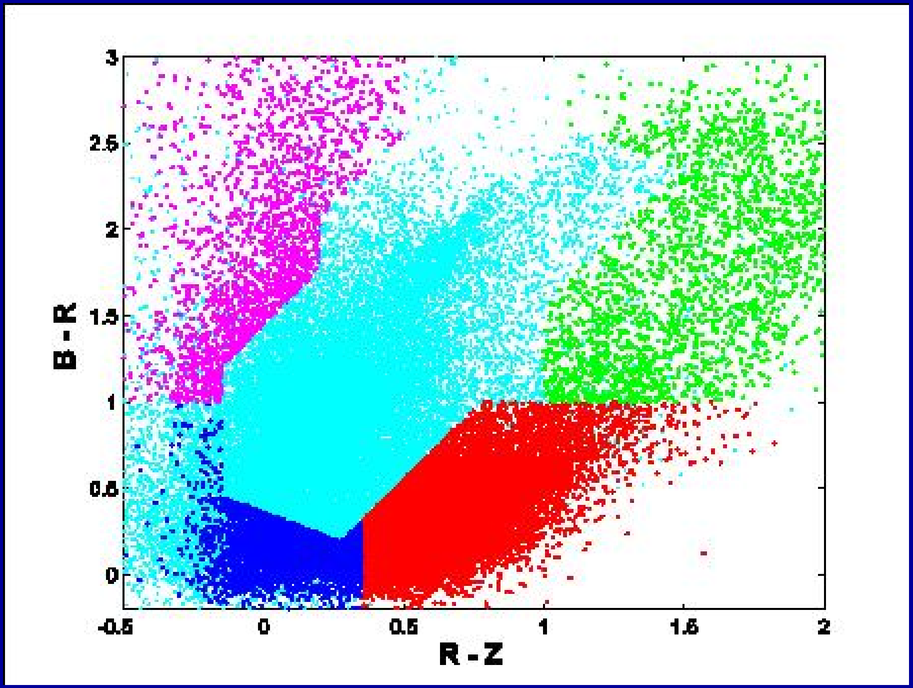
Weak Lensing Samples

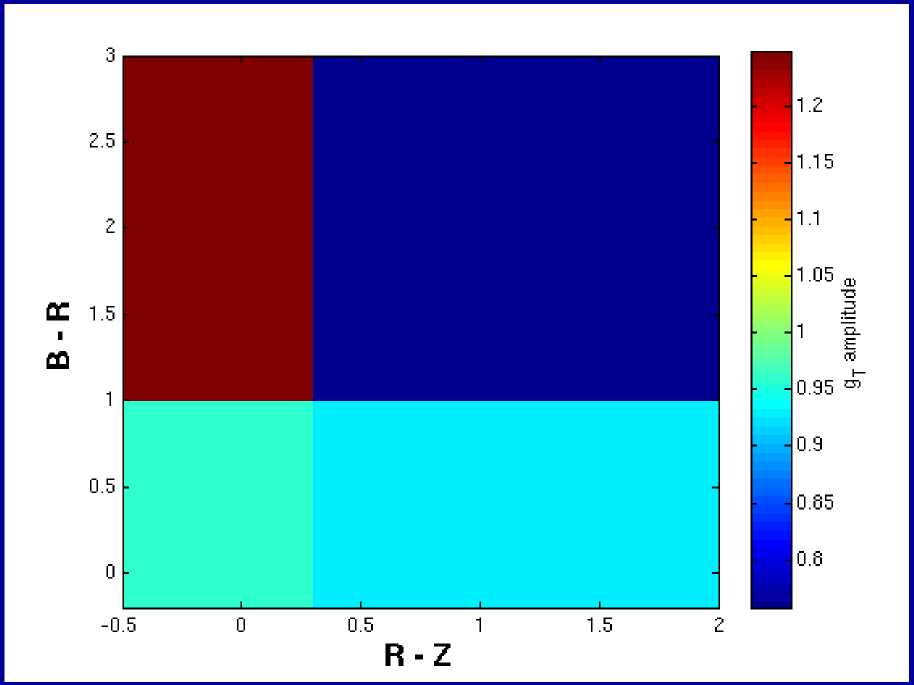
Select **background** galaxy samples –"red", "blue", "green" and "dropouts" and measure their lensing profile:

- **Red** – background
- **Blue** – background
- **Green** – **background**
- **Pink** – **background** (high-z dropouts)

- Mean signal strength $<g_+>$ in color-color (CC) space

higher lensing amplitude for the B-dropout galaxy sample (pink), lower for the green galaxy sample

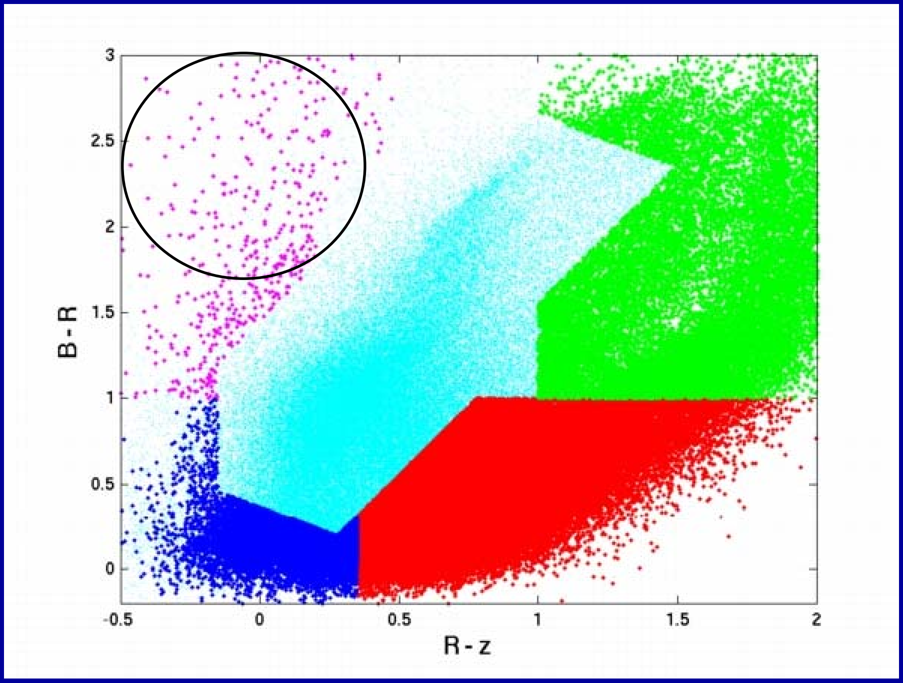




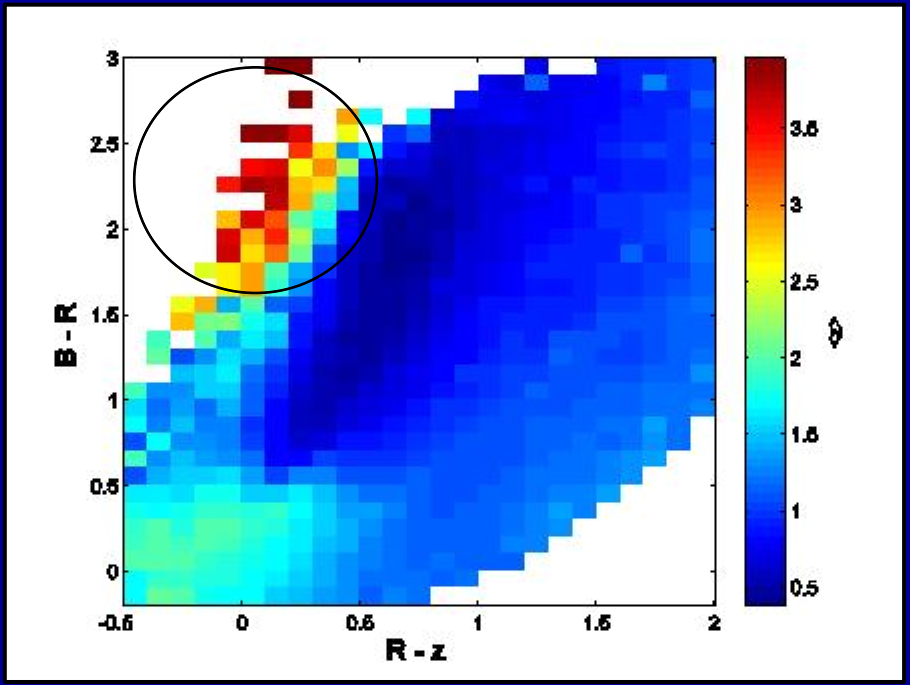
Calibrating with COSMOS Redshifts

- 30-band wide-field (2 sqdeg) survey (Capak et al. 2007)
- Photometric-redshift catalog (Ilbert et al. 2009)
- Deep COSMOS survey as a reference for “CC-selection” and “depth calibration”

Galaxy samples in CC-space

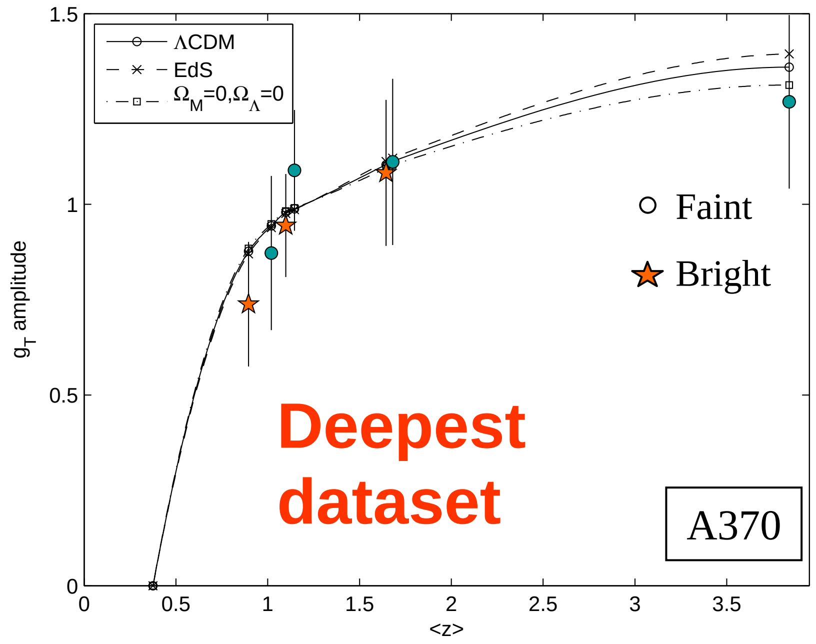


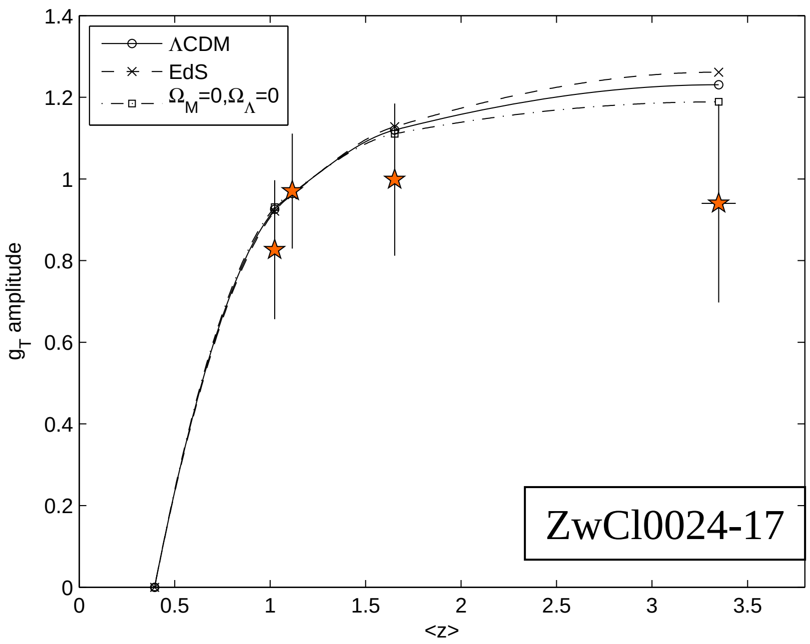
$\langle z_{phot} \rangle$ in CC-space

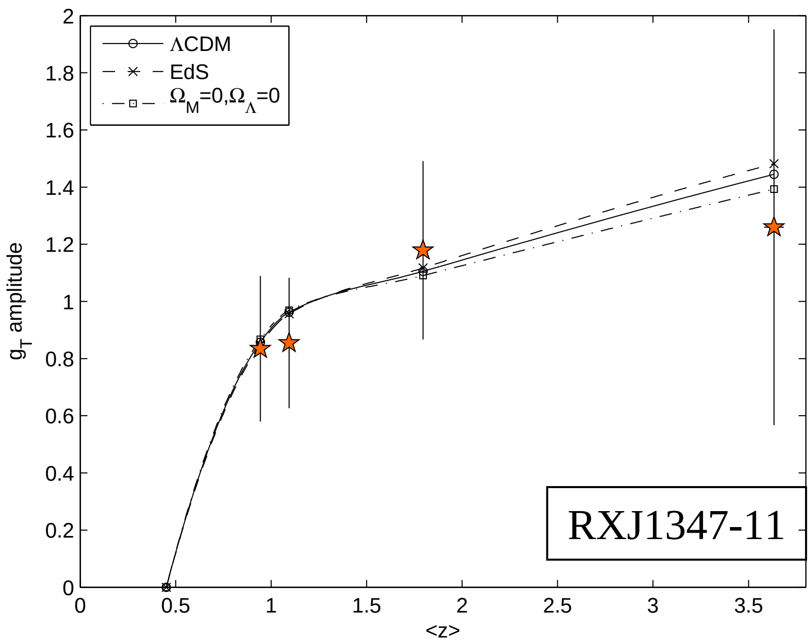


First Measurement

Derived mean g_T amplitude vs. redshift relation behind 3 massive clusters (Medezinski, Broadhurst, KU+ 2010)







Prospects for a Dark Energy Constraint

Sensitivity for the DE equation-of-state (EoS) parameter (Taylor et al. 2007):

$$\frac{\Delta w}{w} = \frac{2}{\gamma_t} \left(\frac{d \ln \Gamma}{d \ln w} \right)^{-1} \frac{\sigma_e}{\sqrt{N_b}},$$

Using $\Gamma(w) \sim |w|^{-0.02}$ (Taylor+ 07) and summing over background galaxies behind 25 massive clusters (γ=0.05, σ_e=0.3, N_b=1.25x10^6; taking A370 as our guide), we have:

$\Delta w \sim 0.6$ @w = -1 (cosmological constant)

Other geometric probes (SNIa and BAO): $\Delta w \sim 0.3$

Our shear-ratio statistic has a different parameter degeneracy from others, so that combining WL with other probes will improve the sensitivity to determine the DE EoS parameter.

Summary

- **Cluster mass profile shapes**
  - Full mass profile shapes have been measured for several massive clusters from detailed strong and weak lensing analyses.
  - In all cases, the overall mass profile shows a continuously steepening radial trend, well approximated by an Navarro-Frenk-White profile expected for collisionless, non-relativistic (cold) DM.
  - Needs more clusters (~25) to definitively determine the representative mass profile shapes, in particular the inner and outer density slopes $d\ln\rho/d\ln r$, from joint WL+SL analyses.
- **Mass vs. concentration relation and its evolution**
  - High mass concentrations found for ~10 massive (strong-lensing biased) clusters from joint WL+SL analyses
  - So far cluster weak-lensing observations are focused at $0.1<z<0.3$ (e.g., LoCuSS) → needs a wide redshift coverage to higher z (~1).
- **Shear-ratio statistic as a geometric DE probe**
  - We have developed a new purely geometric method to measure the cosmological distance vs. z relation using cluster WL.
  - Currently the sample size is too small to constrain the background geometry, but the WL method is promising and can be combined with other geometric probes to better constrain DE.

CLASH:

Cluster Lensing And Supernova survey with Hubble

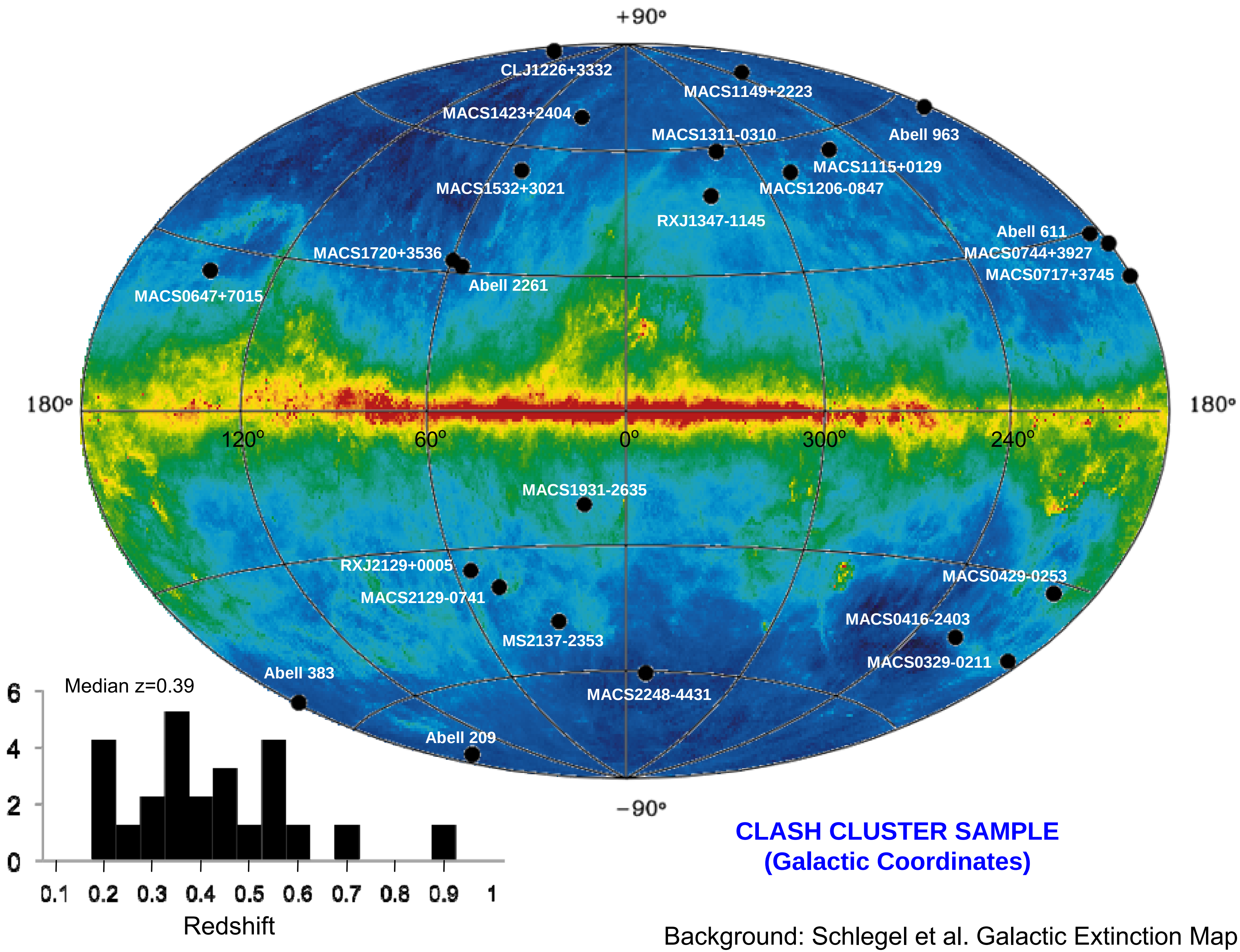
An HST Multi-Cycle Treasury Program designed to place new constraints on the fundamental components of the cosmos: dark matter, dark energy, and baryons.

WFC3 (UVIS + IR) and ACS will be used to image 25 relaxed clusters in 14 passbands from 0.22 - 1.6 microns. Total exposure time per cluster: 20 orbits.

Clusters chosen based on their smooth and symmetric x-ray surface brightness profiles. Minimizes lensing bias. All clusters have T > 5 keV with masses ranging from ~5 to ~30 x $10^{14}\ M_\odot$. Redshift range covered: $0.18 < z < 0.90$.

Multiple epochs enable a $z > 1$ SN search in the surrounding field (where lensing magnification is low).

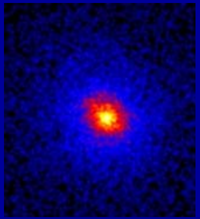
Marc Postman (P.I.)	Megan Donahue	Dani Maoz	Stella Seitz
Matthias Bartelmann	Rosa Gonzales-Delgado	Elinor Medezinski	Keiichi Umetsu
Narciso Benitez	Holland Ford	Leonidas Moustakas	Arjen van der Wel
Larry Bradley	Leopoldo Infante	Eniko Regoes	Wei Zheng
Tom Broadhurst	Daniel Kelson	Adam Riess	Adi Zitrin
Dan Coe	Ofer Lahav	Piero Rosati	


+90°
CLJ1226+3332
MACS1149+2223
MACS1423+2404
Abell 963
MACS1311-0310
MACS1115+0129
MACS1532+3021
MACS1206-0847
RXJ1347-1145
Abell 611
MACS1720+3536
MACS0744+3927
MACS0717+3745
Abell 2261
MACS0647+7015
180°
120°
60°
0°
300°
240°
180°
MACS1931-2635
RXJ2129+0005
MACS0429-0253
MACS2129-0741
MACS0416-2403
MS2137-2353
MACS0329-0211
Abell 383
MACS2248-4431
Median z=0.39
Abell 209
−90°
6
4
2
0
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Redshift
CLASH CLUSTER SAMPLE
(Galactic Coordinates)
Background: Schlegel et al. Galactic Extinction Map

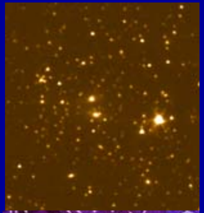
Multiple Facilities Will be Used

- HST 524 orbits: 25 clusters, each imaged in 16 passbands. (0.23 – 1.6 μ m)

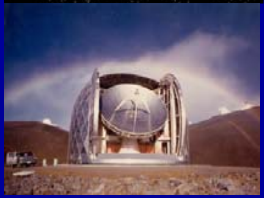
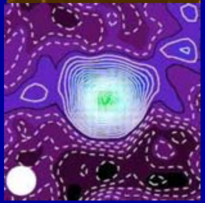

- Chandra x-ray Observatory archival data and possibly new data. (0.5 – 2 keV)

- Spitzer IR Space Telescope archival data and possibly new data (3.6, 4.5 μ m)

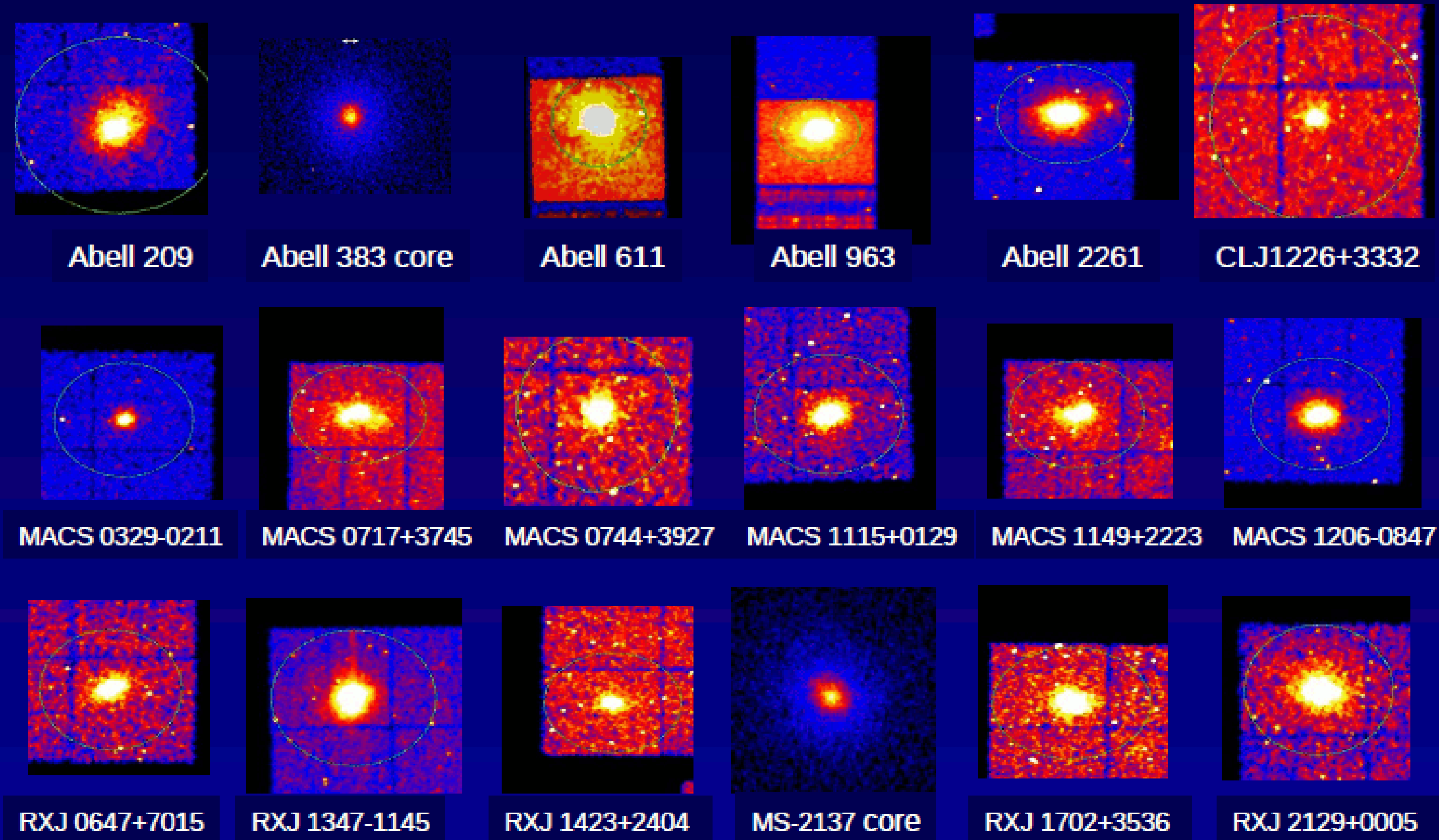



- tSZE observations proposed to augment existing data (Bolocam@150GHz, AMiBA)

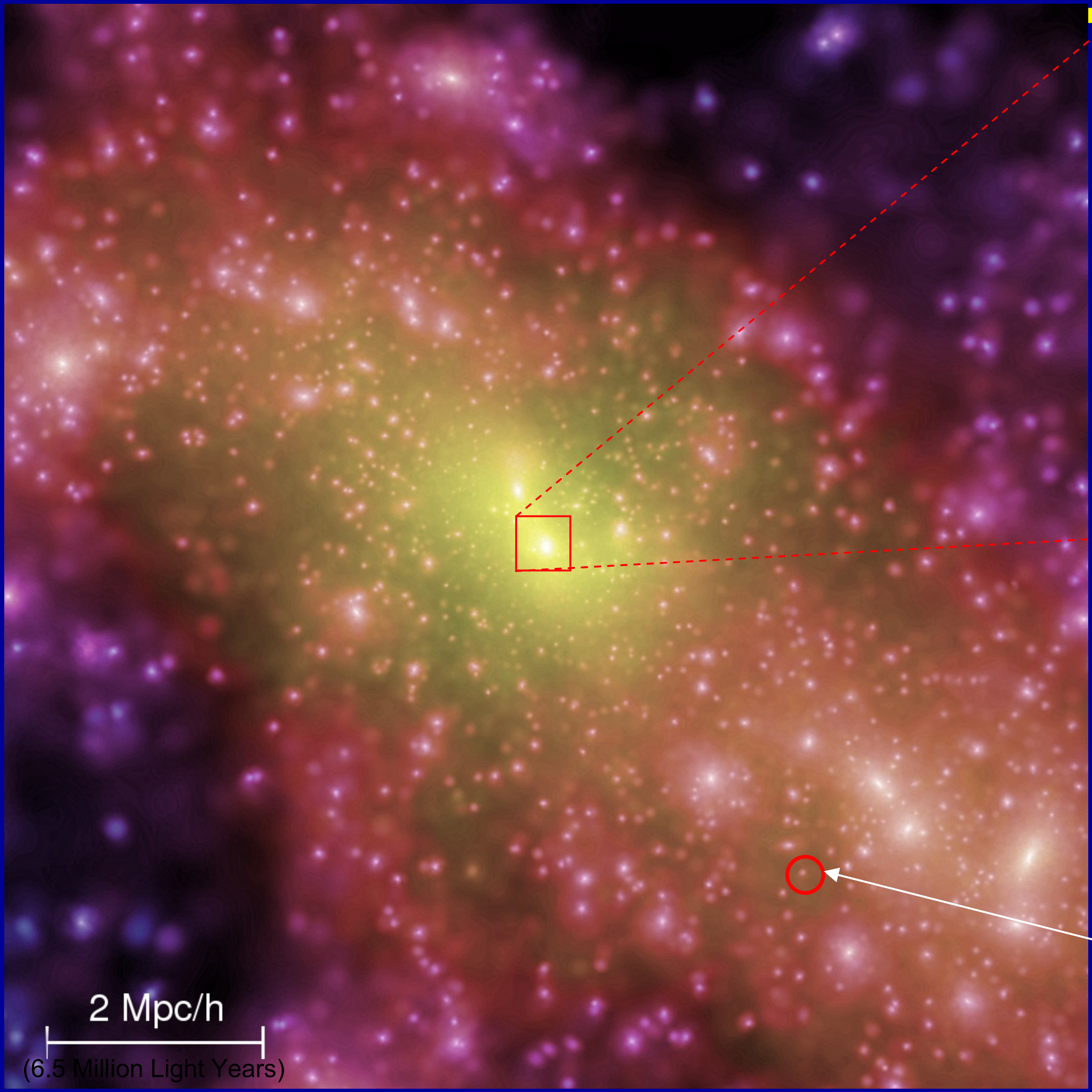
- Subaru wide-field imaging (0.4 – 0.9 μ m)
- GTC, VLT, and Magellan Spectroscopy


CLASH: An HST Multi-Cycle Treasury Program



Cutouts of Chandra images of 18 of the 25 CLASH clusters from ACCESS database

CLASH: An HST Multi-Cycle Treasury Program



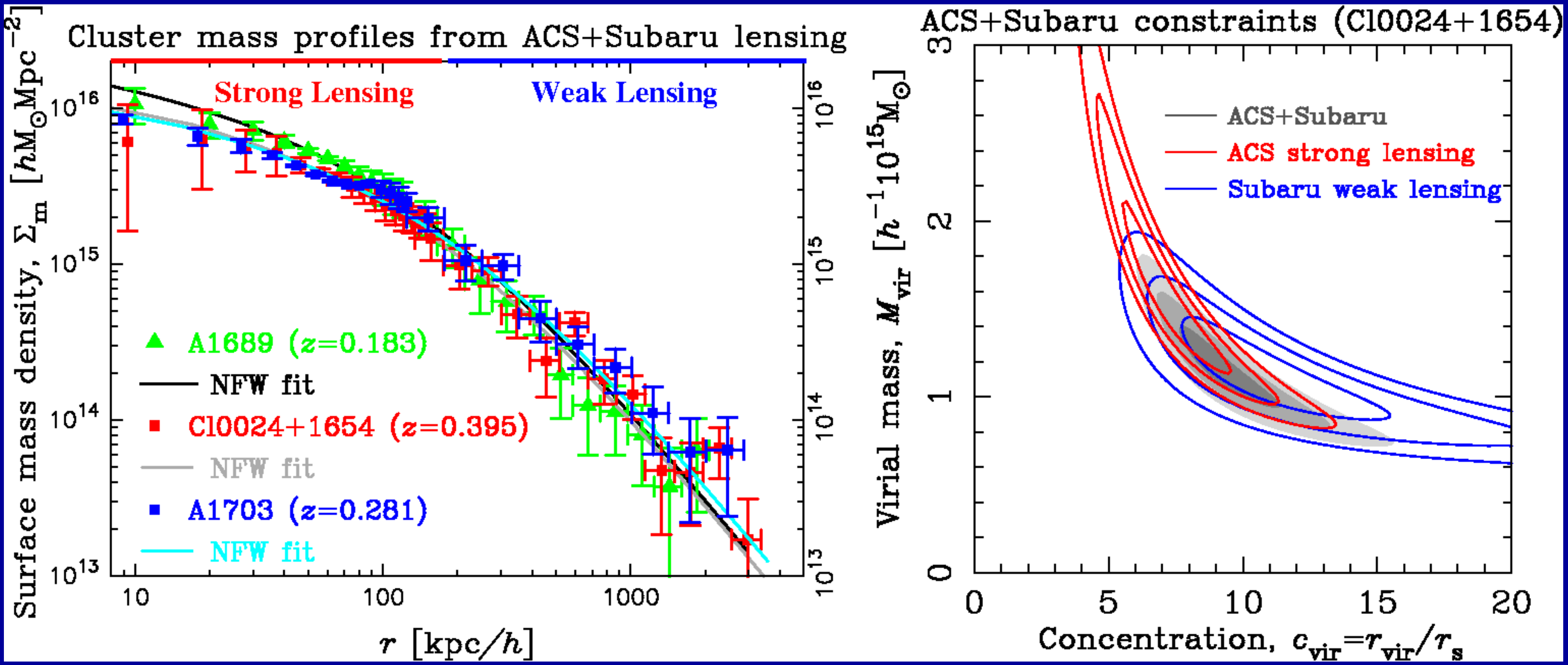
Simulation of dark matter around a forming cluster (Springel et al. 2005)

Deep HST image of massive cluster

$$R \propto \frac{\theta_{Einstein}}{\sqrt{N_{Arcs}}}$$

WHERE R IS THE RESULTING SPATIAL RESOLUTION OF THE DARK MATTER MAP

Both Strong & Weak Lensing Measurements Needed for Good Costraints



Umetsu et al. 2010

Both strong AND weak lensing measurements are needed to make accurate constraints on the DM profile.

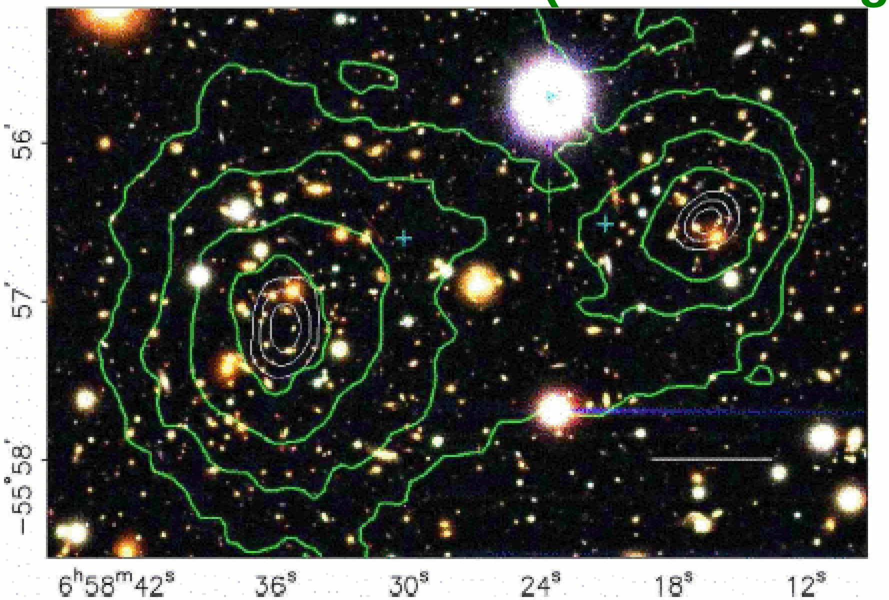
CLASH data will allow us to definitively derive the representative equilibrium mass profile shape and robustly measure the cluster DM concentrations and their dispersion as a function of cluster mass *and their evolution with redshift.*

Fin

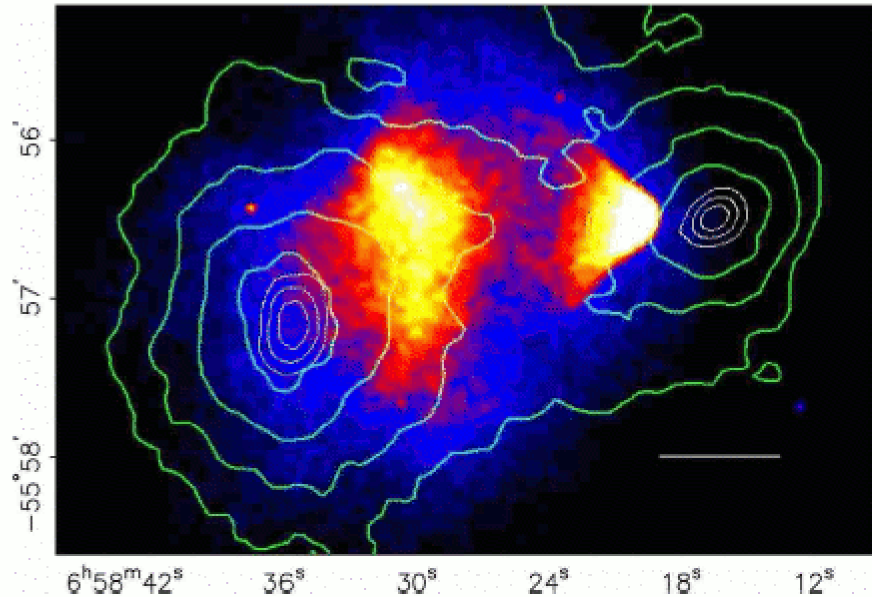
Bullet Cluster (z=0.3): DM Evidence

A head-on, super-sonic (M~3) collision of un-equal mass clusters in the sky plane:

Galaxies vs. Mass (weak lensing)



ICM vs. Mass



Clear offset between DM/galaxy concentrations and gas halos, constraining the DM self-interaction cross section: $\sigma/m < 1 cm^2/g$

Clowe et al. 2004; Markevitch et al. 2004