Probing the Mass Distribution in Clusters of Galaxies using Weak + Strong Gravitational Lensing

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Outline of My Talk

1. **Motivation and Importance of Study**
   - Galaxy Clusters as Cosmological Probes
2. **Method: Cluster Gravitational Lensing**
   - Gravitational Lensing in Weak and Strong Regimes
3. **Highlights**
   - Current Lensing Constraints on DM Halo Mass Profile Shapes
4. **Future Work: The Largest Space-Telescope Cluster Survey, "*CLASH*"**
   - 524-orbit Hubble Multi-Cycle Treasury (MCT) program, "Cluster Lensing And Supernova survey with Hubble" (PI: Marc Postman, STScI)
5. **Summary**

Lensing Collaborators

Tom Broadhurst (Tel Aviv U., Israel → Bilbao, 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)
Masamune Oguri (NAOJ, Japan)
Toshifumi Futamase (Tohoku U., Japan)
Graham P. Smith (Birmingham U., UK)

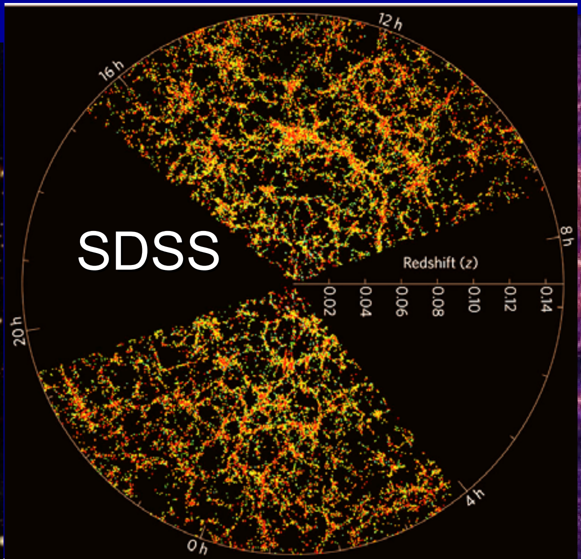
1. Motivation and Importance:

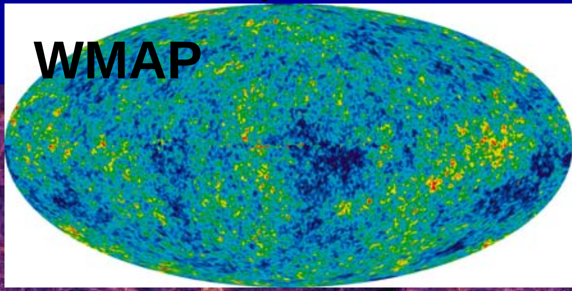
“Galaxy Clusters as Cosmological Probes”

Concordance Structure Formation Scenario

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

- **Background geometry and Initial conditions**, successfully constrained by linear theory & large-scale astrophysical observations:
  - CMB, large-scale clustering of galaxies (BAO), and SNIa distance measurements
- >70% of the *"present-day"* energy density is in the form of **Dark Energy**, leading to an accelerated cosmic expansion → suppressing the structure growth in later epochs
- ~85% of our *"material universe"* is composed of unknown **DM** – the majority of which being non-relativistic, effectively collisionless (cf. the Bullet cluster)
- Study **nonlinear** cosmic structure formation due to the **gravitational instability** using N-body simulations + perturbation theory ($0 < z < z_{dec} \sim 1100$)





Nature of CDM Structure Formation

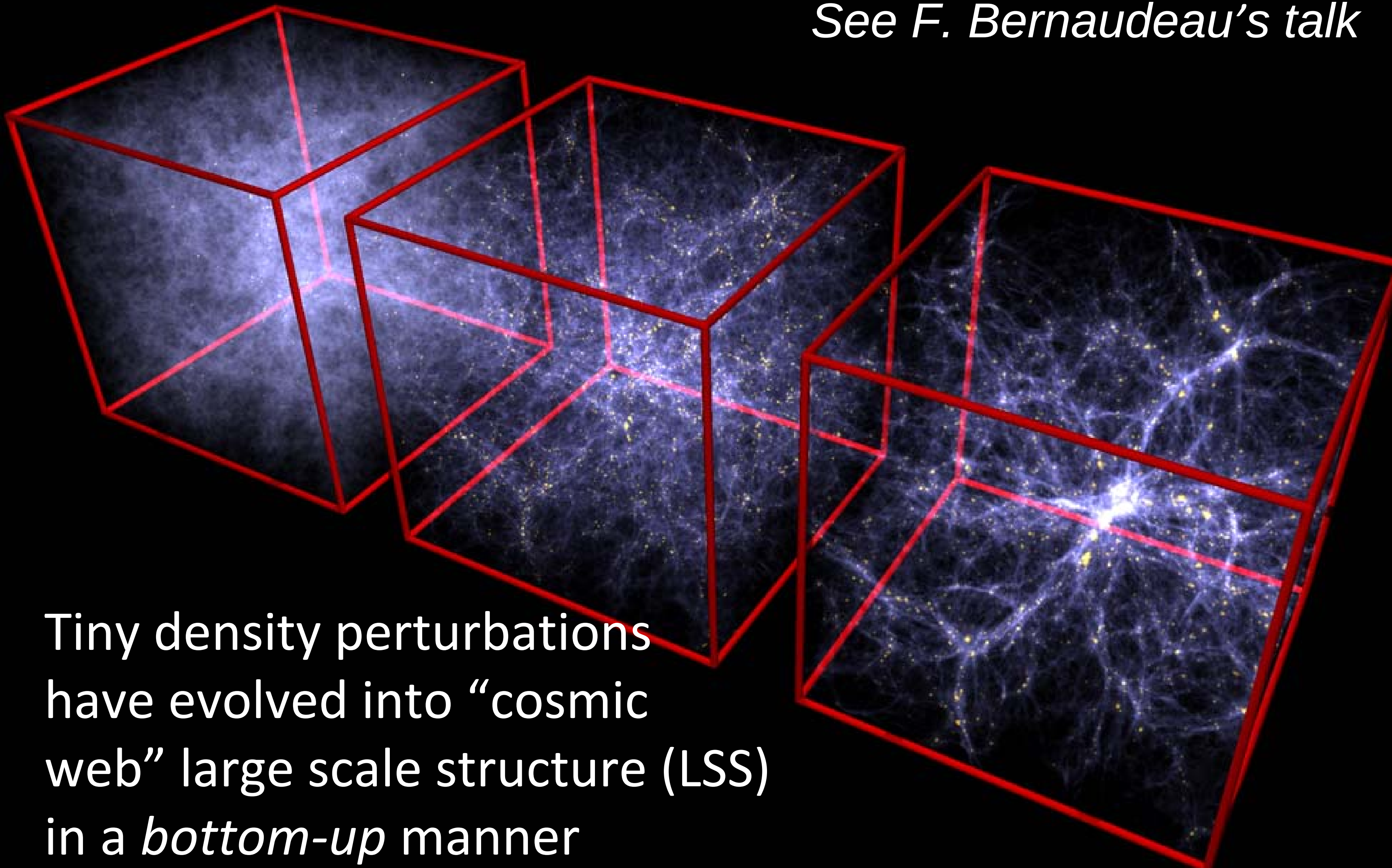
1. **Hierarchical growth**: Non-relativisitc (cold) nature of DM
   - Bottom up formation of structures in the CDM-dominated model
   - Smaller objects first form, and merge together into larger systems: i.e., galaxies -> groups -> clusters -> superclusters

2. **Anisotropic collapse**: Collisionless nature of DM
   - 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
   - Any small initial deviation from sphericity of a collapsing cloud gets magnified by tidal forces (e.g., Zel'dovich 1970; Shen et al. 2006)

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

Structure Growth: *Gravitational Instability*

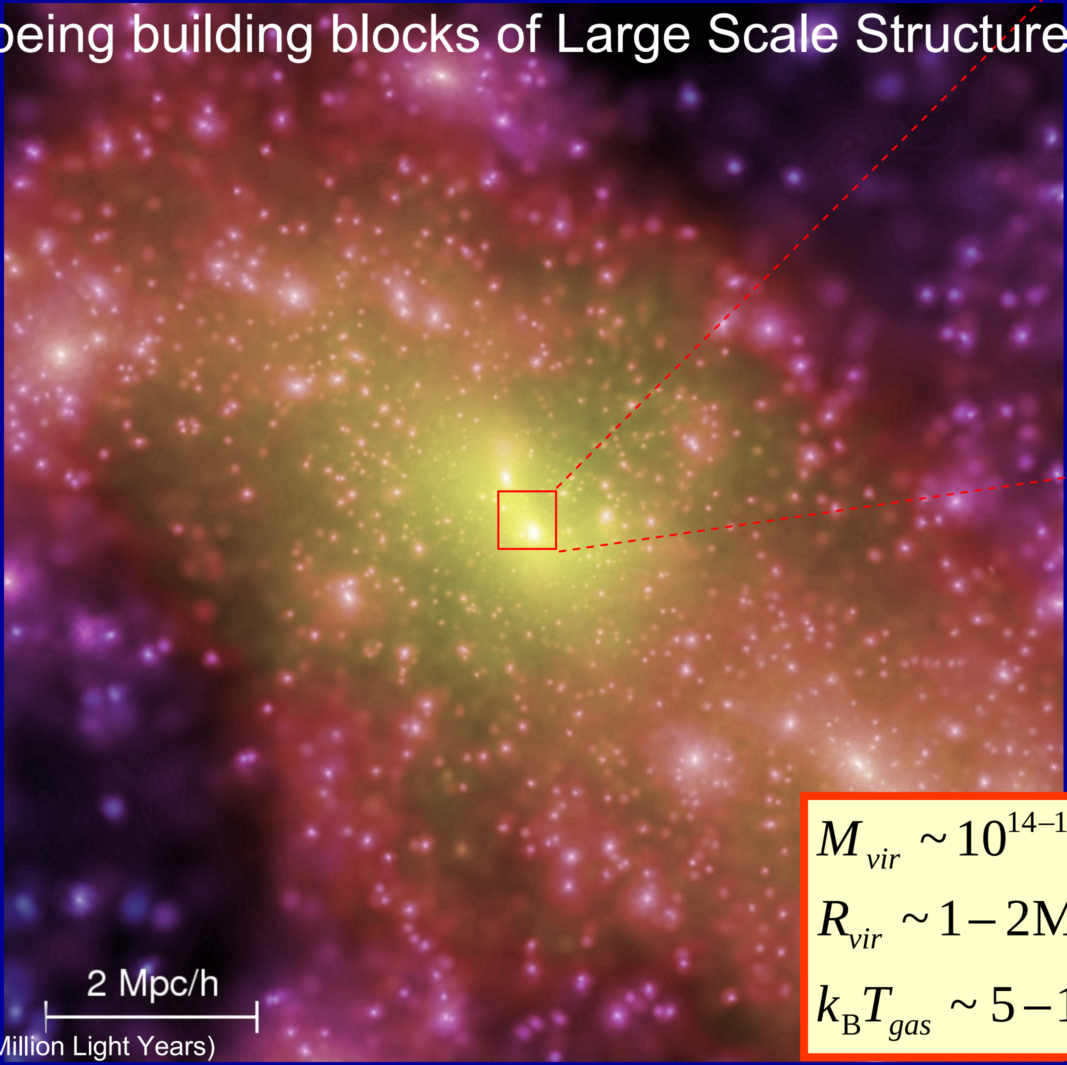
See F. Bernaudeau's talk



Tiny density perturbations have evolved into "cosmic web" large scale structure (LSS) in a *bottom-up* manner

Clusters of Galaxies

Clusters are identified as dense nodes of “Cosmic Web”, being building blocks of Large Scale Structure



Galaxy clusters: the 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 DM around a forming cluster (Springel et al. 2005, Nature, 435, 629)

Fundamental Questions

Massive Galaxy clusters as sensitive cosmological probes:

1) **(Pseudo) Equilibrium DM halo mass profile shapes:**

“How the shape of a cluster’s DM potential depends on cluster mass and redshfit?”

My talk

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

Mass Profile Shapes of CDM Halos

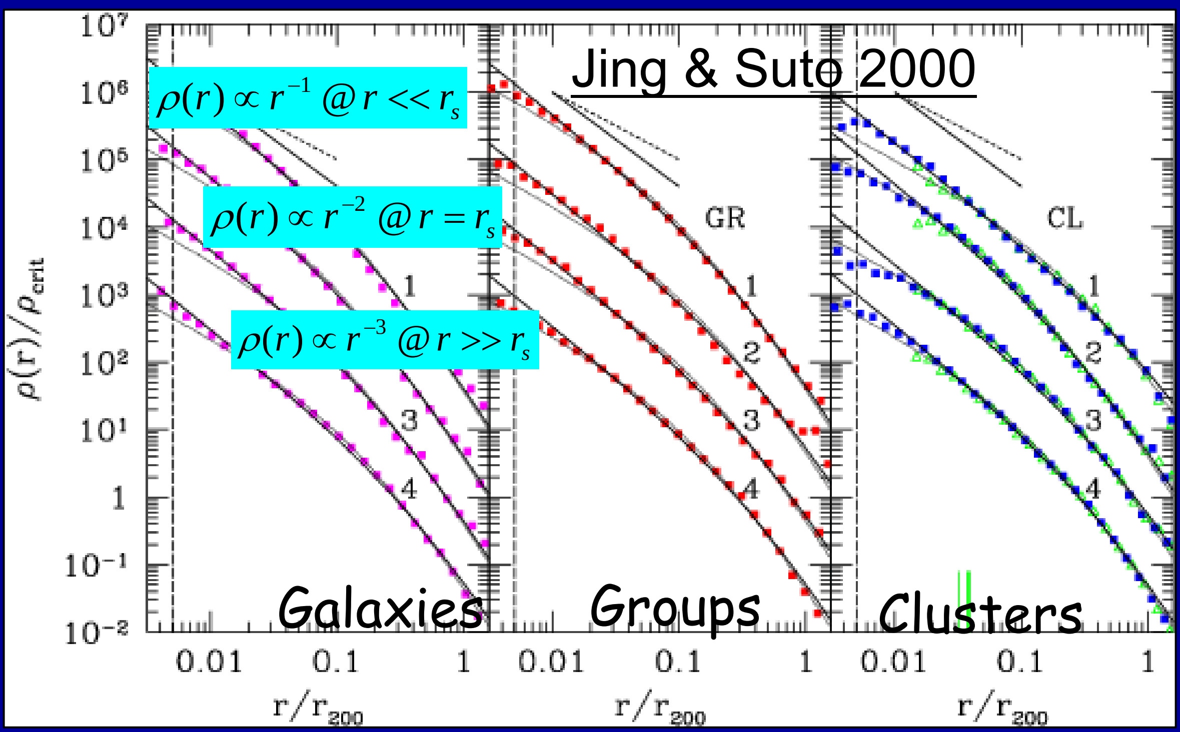
Empirical description of Cold Dark Matter (CDM) halos in cosmological N-body simulations: **"Navarro-Frenk-White" (NFW) universal density profile**

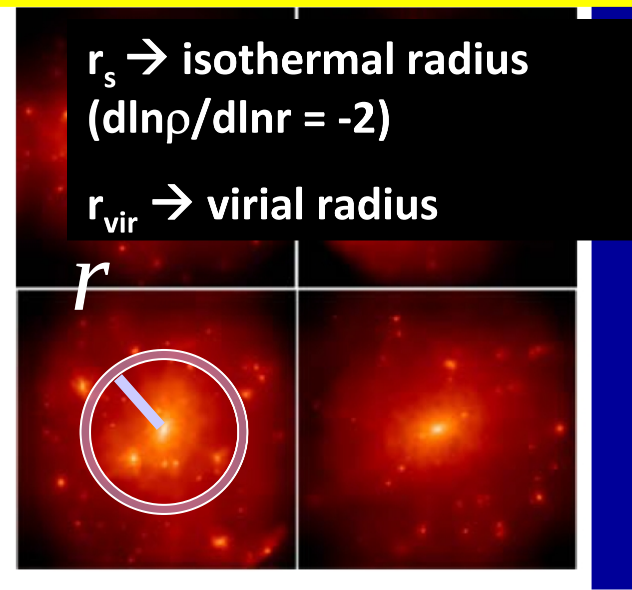
—Continuously steepening density profile with radius: central cusp slope of n(r) = –dlnρ/dlnr = 1 – 1.5 (cuspy but shallower than the isothermal body, n=2), asymptotic outer slope of n(r)→3

— It fits simulated DM halos that span ~9 orders of magnitude in mass (dwarf galaxies to clusters), insensitive to the initial conditions and background cosmology.

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

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



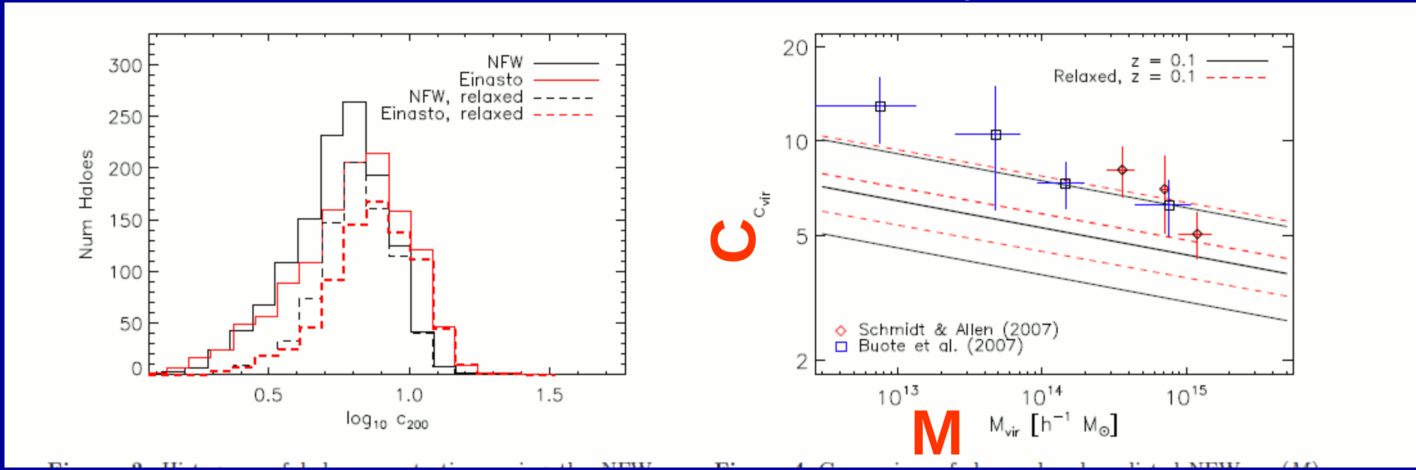


Halo Concentration-Mass (C-M) Relation

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

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

Duffy et al. 2008, MNRAS, 390, 64: $C_0 \sim 5.2$, $\alpha \sim 0.66$, $\beta \sim 0.084$



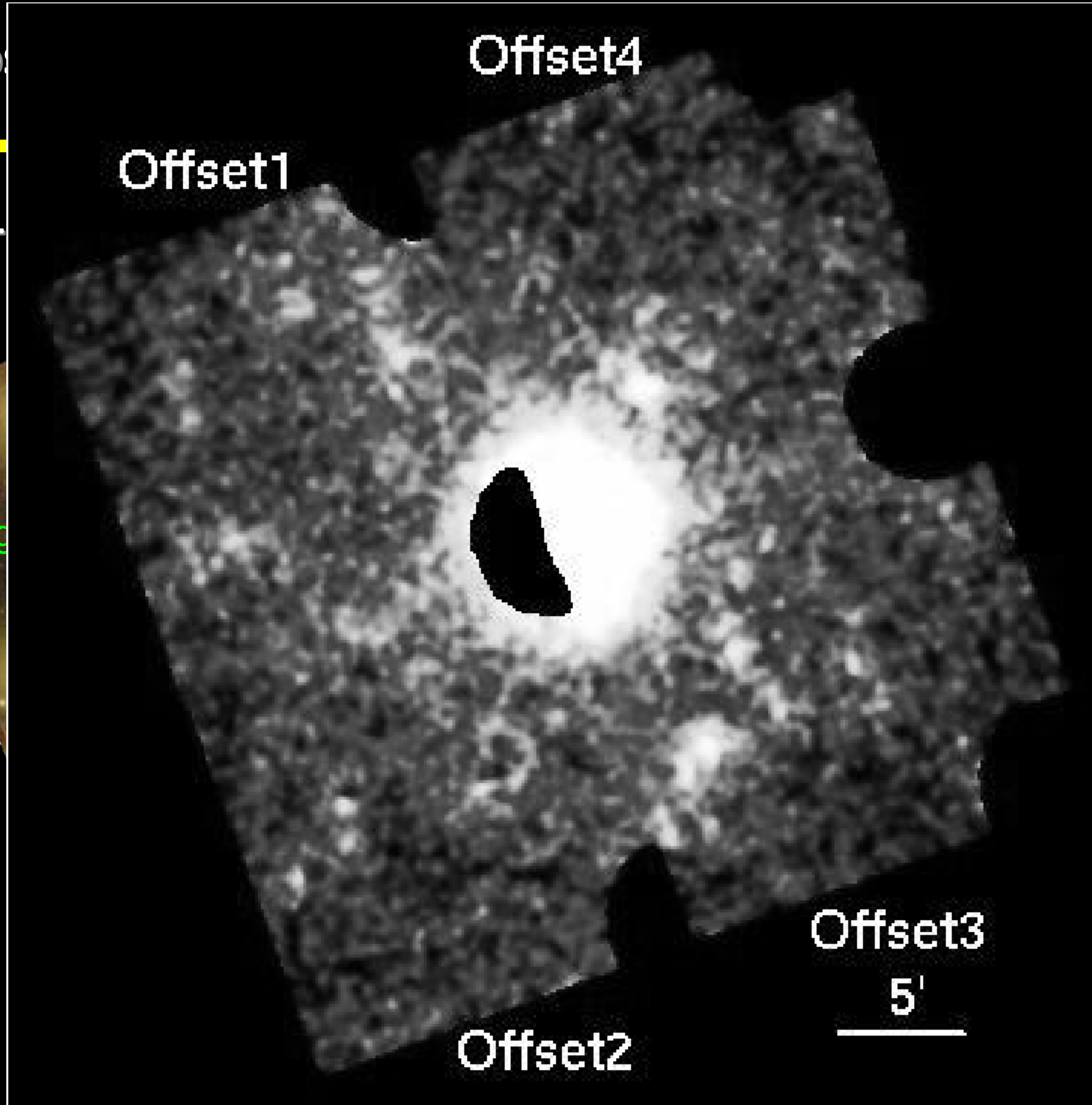
Halo concentration, c_{vir},$=r_{vir}/r_s$ **(>1)**: **indicator of halo formation epoch**

- In a hierarchical 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_{vir} is correspondingly larger, on average, for less massive DM halos.
- For massive cluster-sized DM halos, lower mass concentrations are expected, so that the curvature in the mass profile shapes is pronounced – good for observations!!

Clusters as co

Abell 1689 (z=0.1

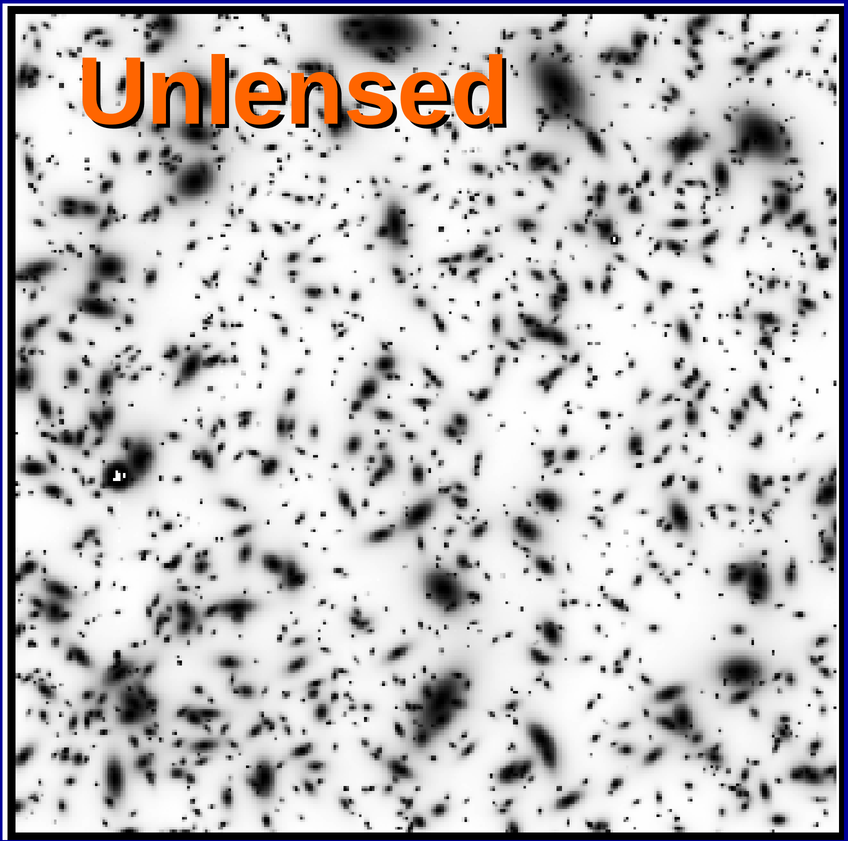
- *Subaru*
  Suprime-C
  34’x27’
- *HST/ACS*
  3.3’x3.3’
- *Chandra* ACIS
- AMiBA
- VLT/VIRMOS
- Suzaku/XIS

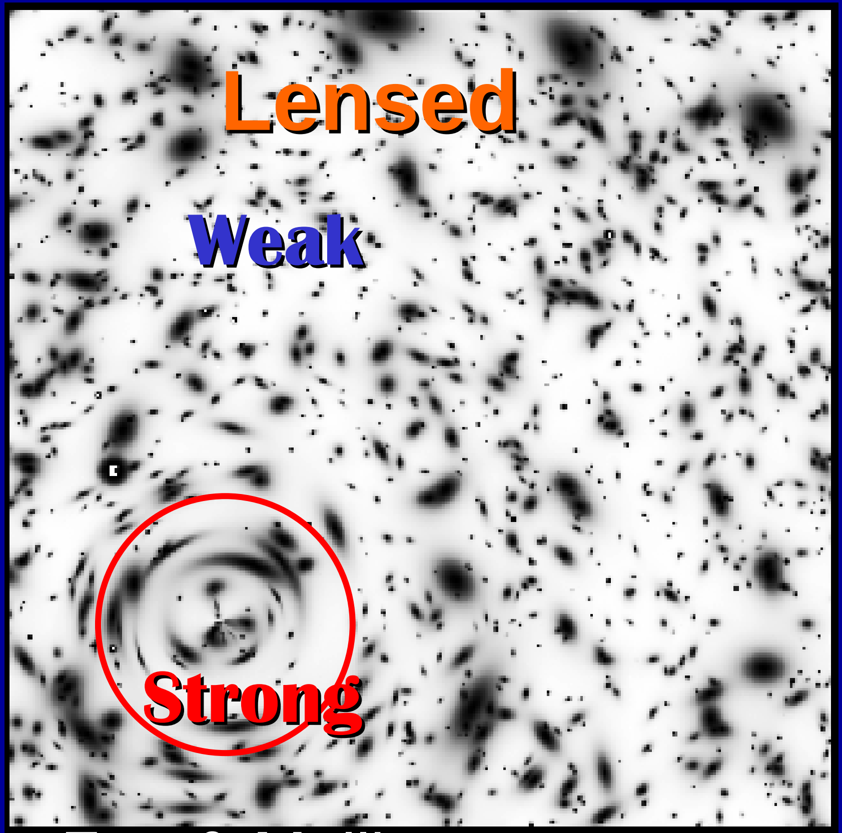


Method: Strong & Weak Gravitational Lensing

Cluster's deep potential well $\Phi(x)$ deforms local space time – light-ray deflection, or gravitational lensing

Observable image distortions of background galaxies can be used to derive the distribution of mass dominated by DM!





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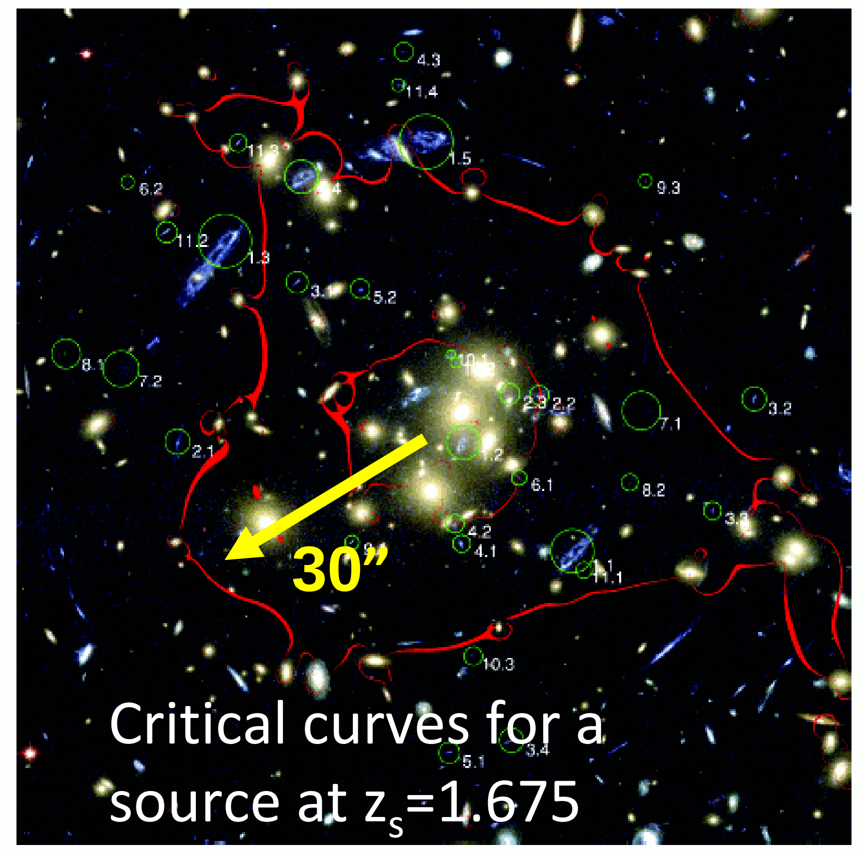
2. Cluster Gravitational Lensing

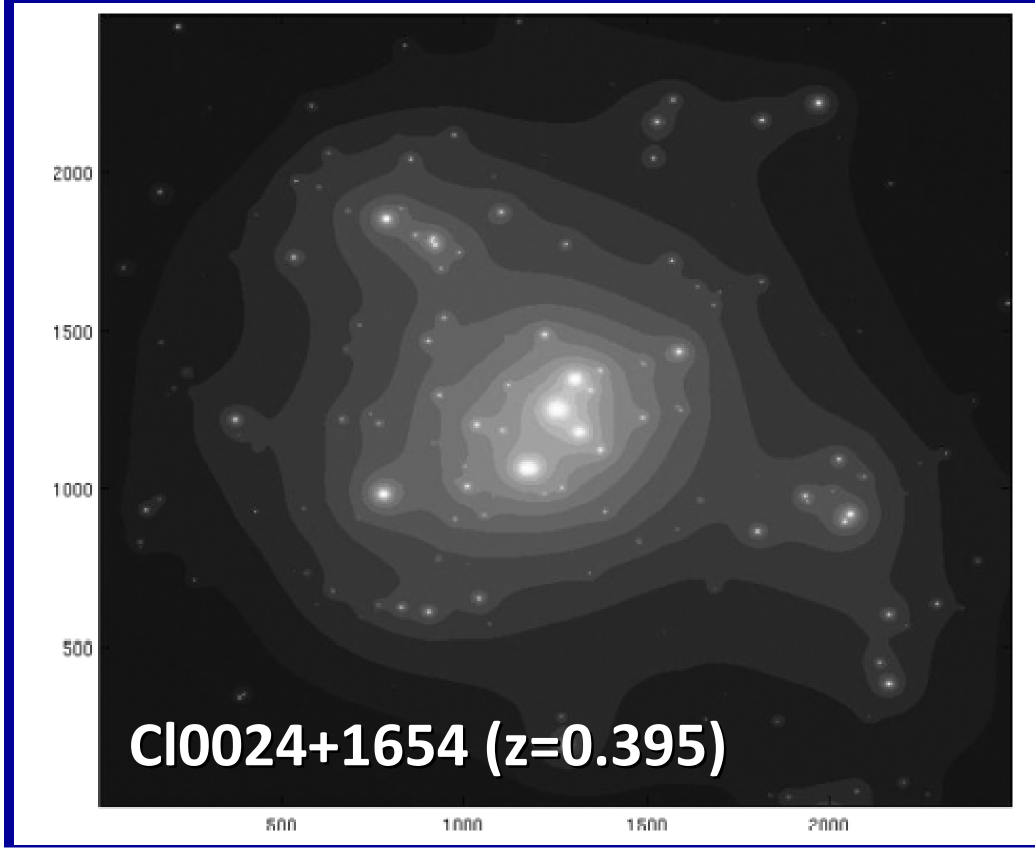
- **Strong Gravitational Lensing (SL)**
- **Weak Gravitational Lensing (WL)**
  - *Tangential Shape Distortion*
  - *Magnification bias*

Strong Lensing

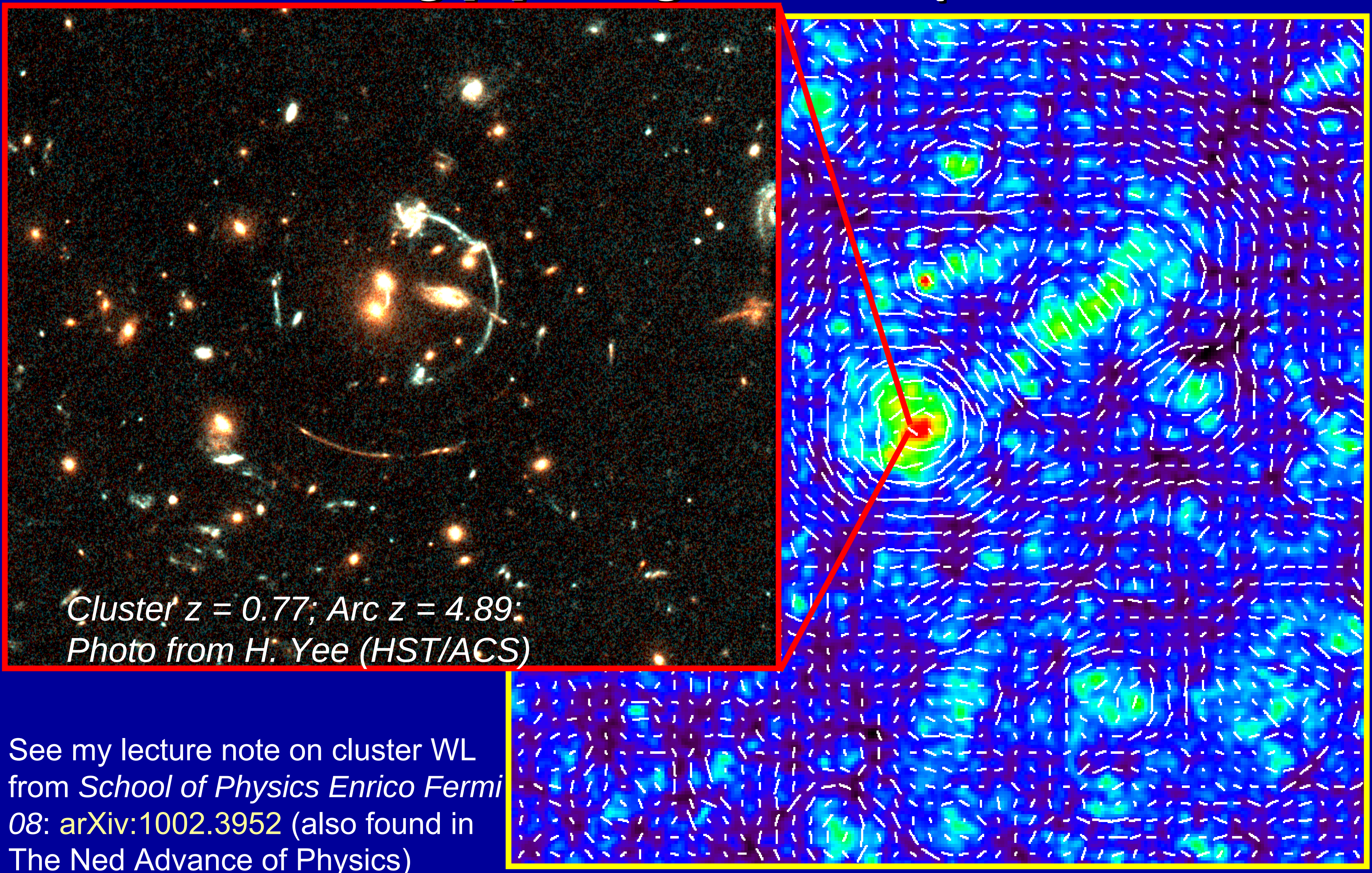
Strong-lensing phenomena include: **multiple imaging**, **high flux amplification**, **arc-like image features** due to gravitational light deflection of the order 1-60 arcsec in cluster cores

33 lensed images of *11* background galaxies identified in HST/ACS/NIC3 multiband images by SL analysis (Zitrin, Broadhurst, Umetsu+ 2009, MNRAS, 396, 1985)





Weak Lensing [1]: Tangential Shape Distortion



See my lecture note on cluster WL from *School of Physics Enrico Fermi 08*: arXiv:1002.3952 (also found in The Ned Advance of Physics)

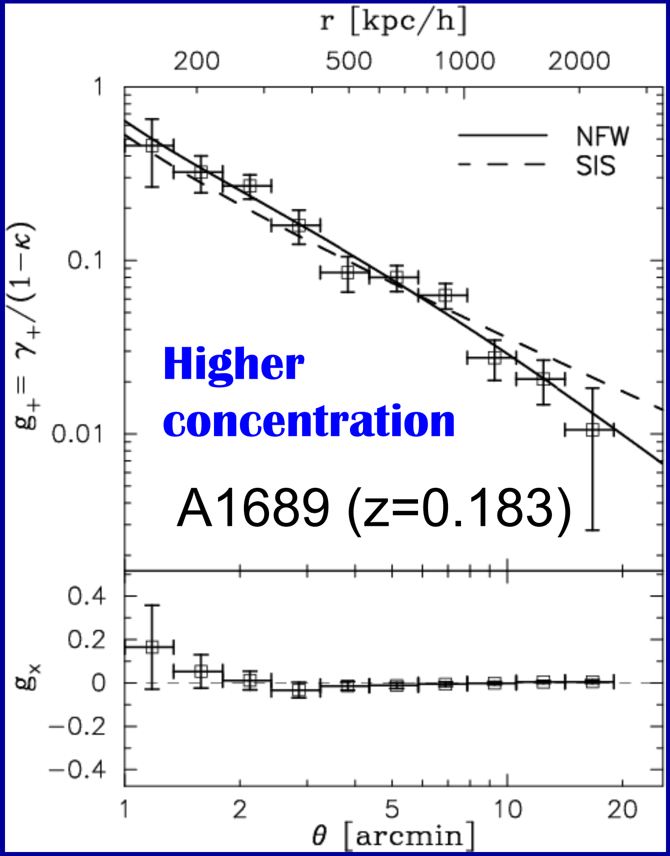
Simulated 3x3 degree field (Hamana 2002)

Tangential Distortion Profile

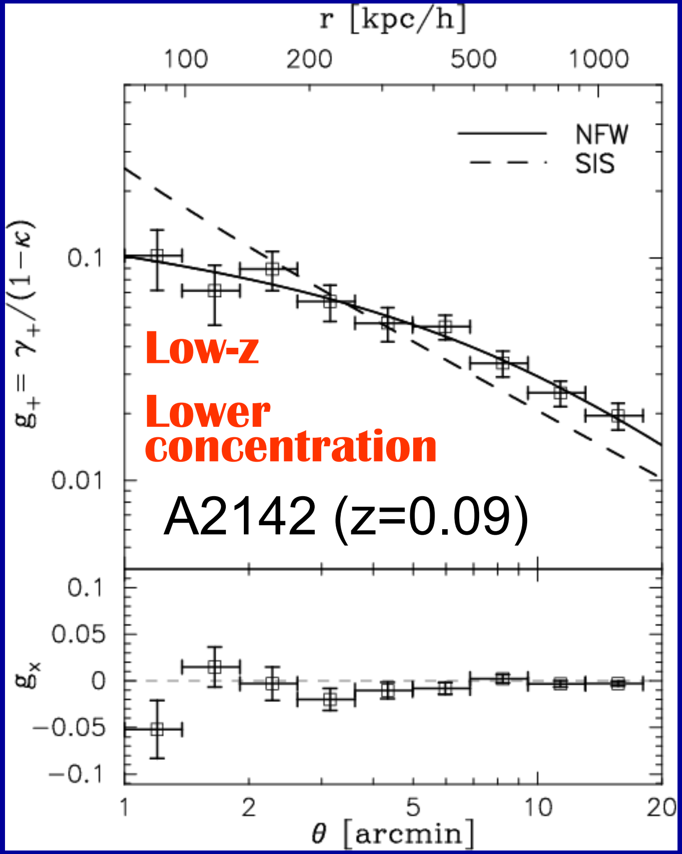
$$\gamma_+(r) \propto \Delta\Sigma_m(r) \equiv \overline{\Sigma}_m(<r) - \Sigma_m(r)$$

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

Mean tangential ellipticity of background 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



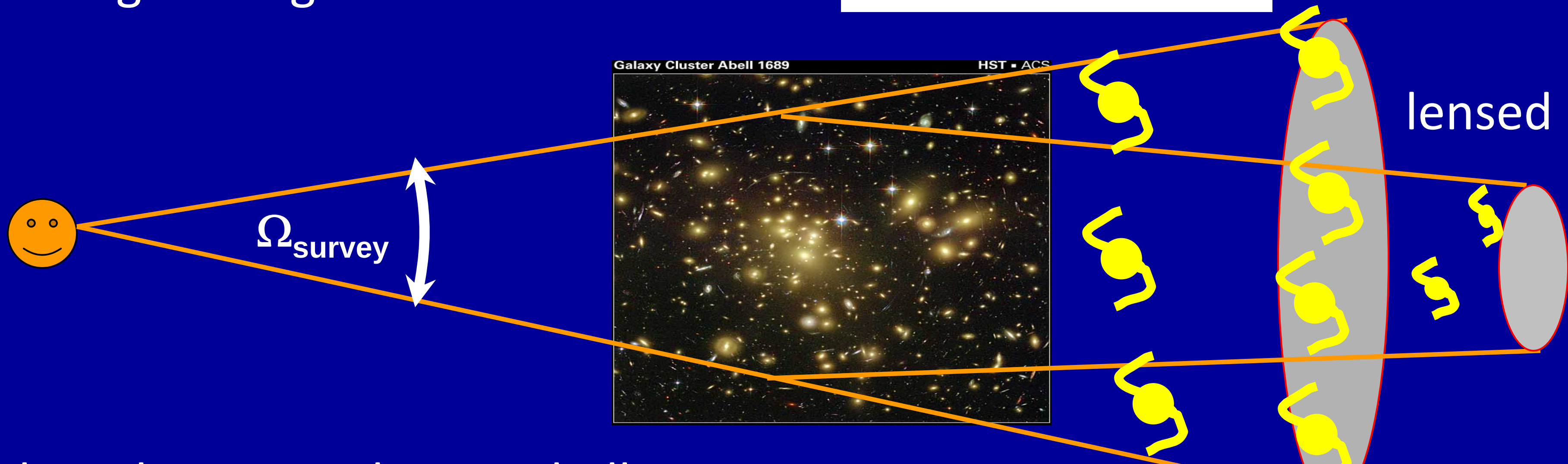
Umetsu, Birkinshaw, Liu+ 09, ApJ, 694, 1643

Weak Lensing [2]: Magnification Bias

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

$$\delta n(\boldsymbol{\theta})/n_0 = \mu^{s-1}(\boldsymbol{\theta}) - 1 \approx 2(s-1)\Sigma_m(\boldsymbol{\theta})/\Sigma_{crit}$$

with unlensed flux-limited counts of background galaxies $n_0(>F) \propto F^{-s}$

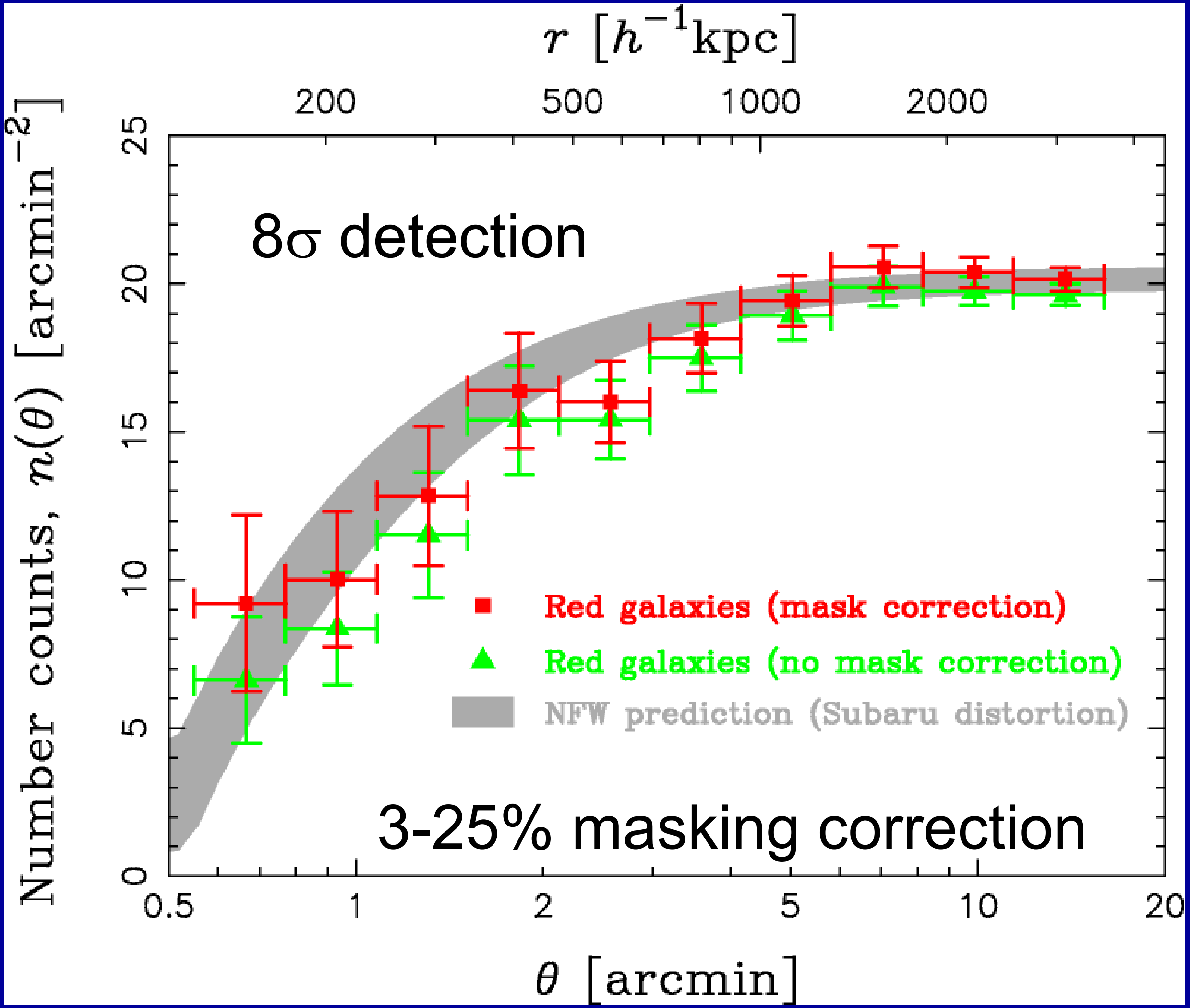


When the count-slope is shallow, i.e., s<1, a net deficit of counts is expected.

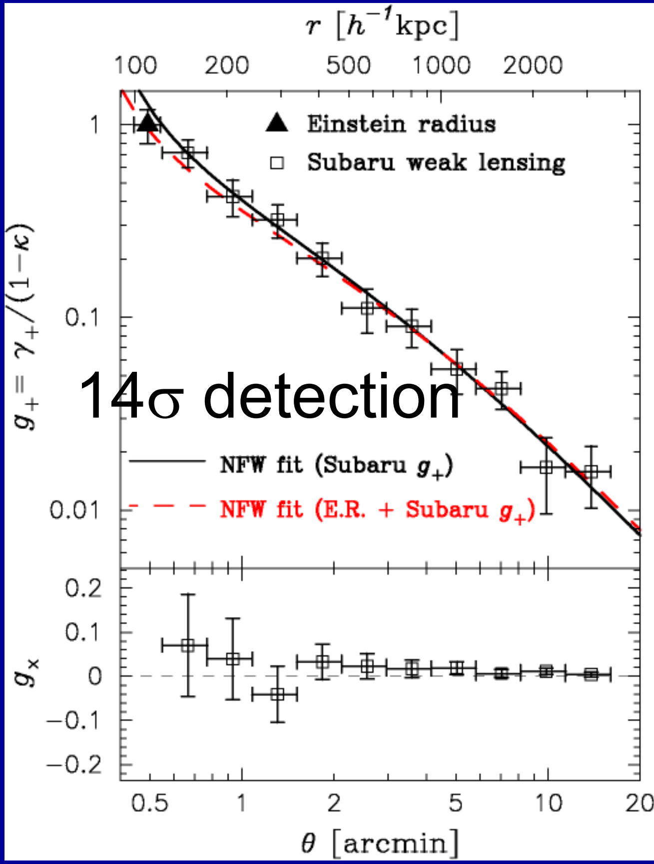
Figure courtesy of Masahiro Takada

WL Distortion vs. Magnification

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



Distortion of faint background galaxies



Umetsu, Medezinski, Broadhurst et al. 2010, ApJ, 714, 1470

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

Based on data taken with:

Suprime-Cam on the *Subaru* telescope ,

ACS on the *Hubble* Space Telescope,

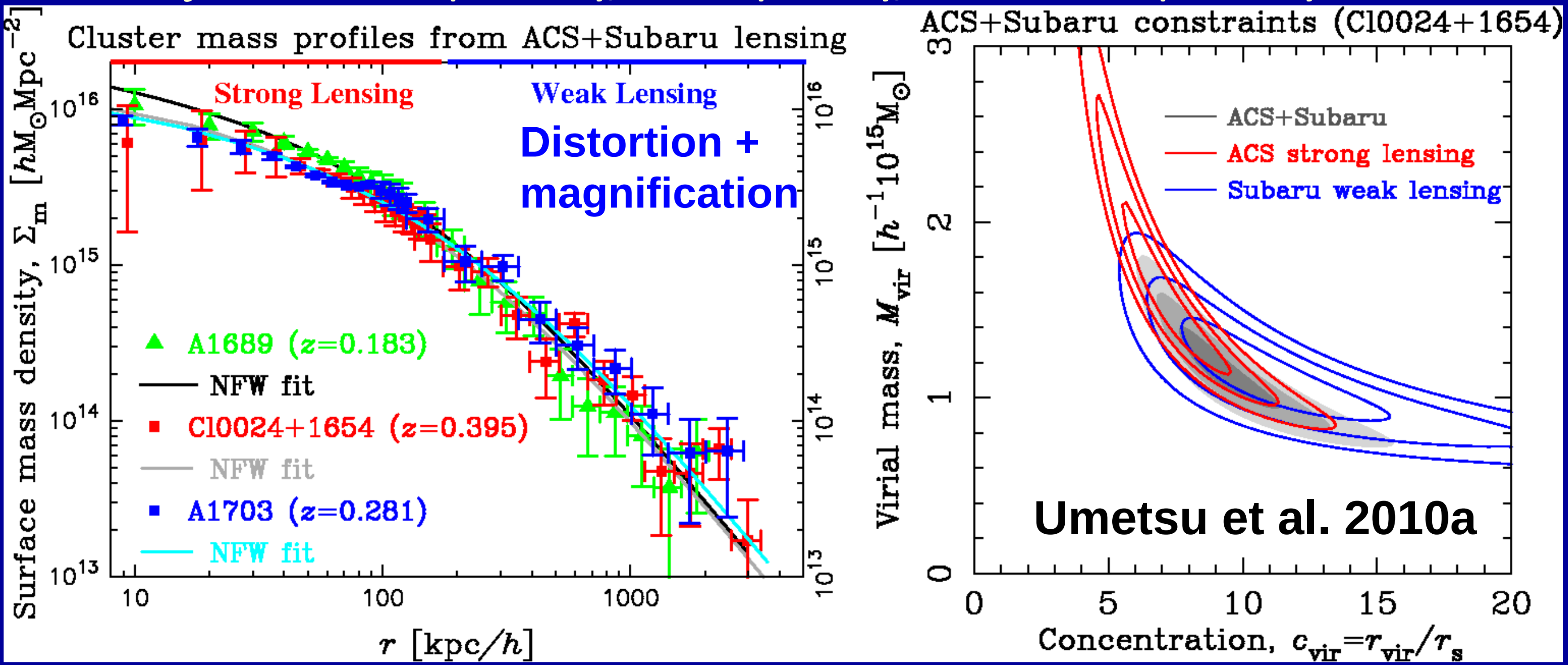
VLT/VIRMOS, AMiBA, Chandra, Suzaku/XIS, etc.

[1] Full Weak + Strong Lensing Analysis

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

→ Probing the mass density profile over 2 decades in radius: 1%-150% of R_{vir}

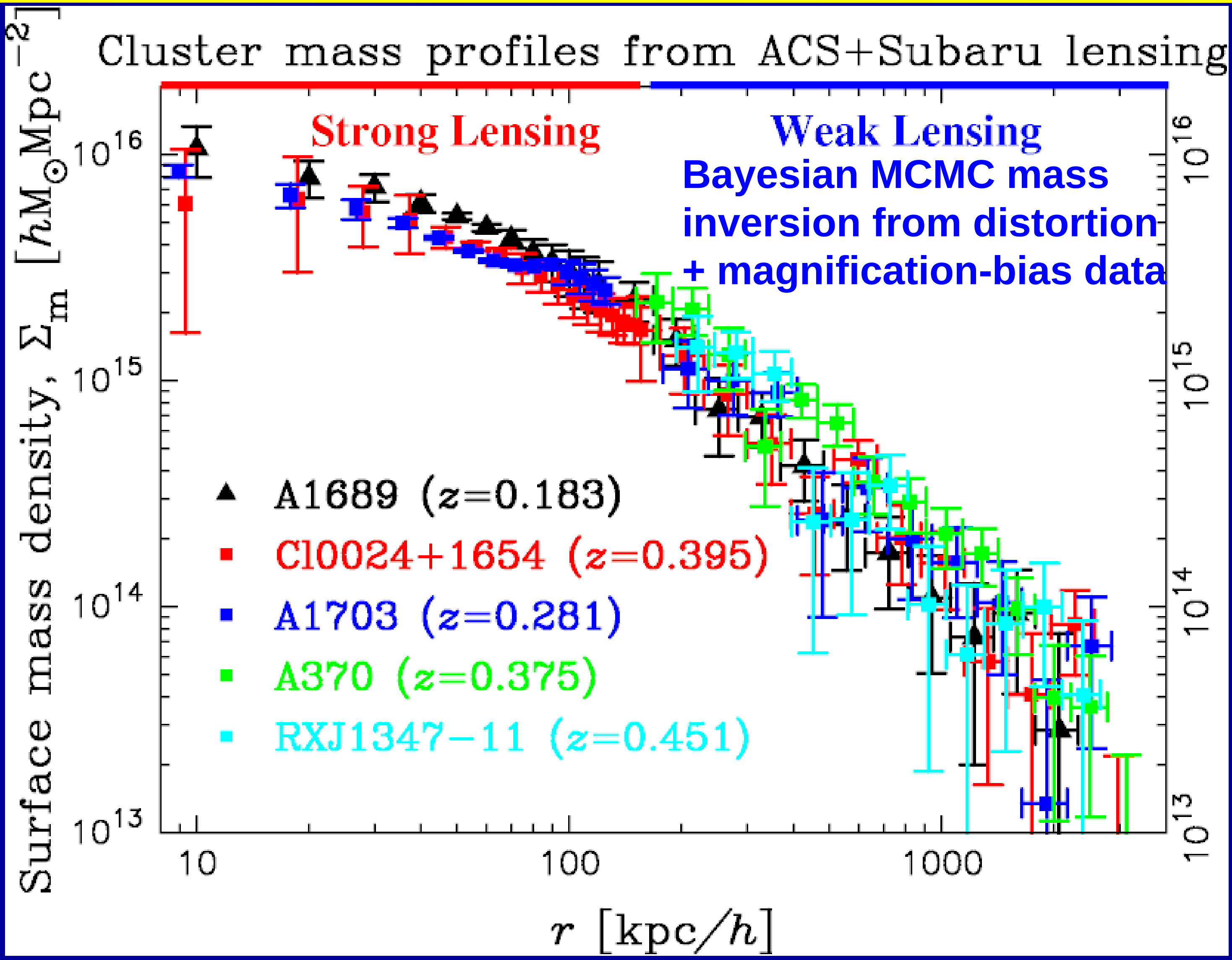
Results for Abell 1689 (z=0.183), A1703 (z=0.28), Cl0024+1654 (z=0.395)



The profile shapes are consistent with CDM over 2-decades of radius where physical processes are governed by the gravity

Broadhurst, Takda, Umetsu et al. 2005; Umetsu & Broadhurst 2008; Lemze et al. 2009 (A1689);
Umetsu et al. 2010a; Zitrin, Broadhurst, Umetsu+2009 (Cl0024+1654), 2010 (A1703);
Umetsu et al. 2010b in prep (A1689, A1703, A370, Cl0024+1654, RXJ1347-11)

Sample of Full Mass Profiles



Umetsu et al. 2010b (in prep)

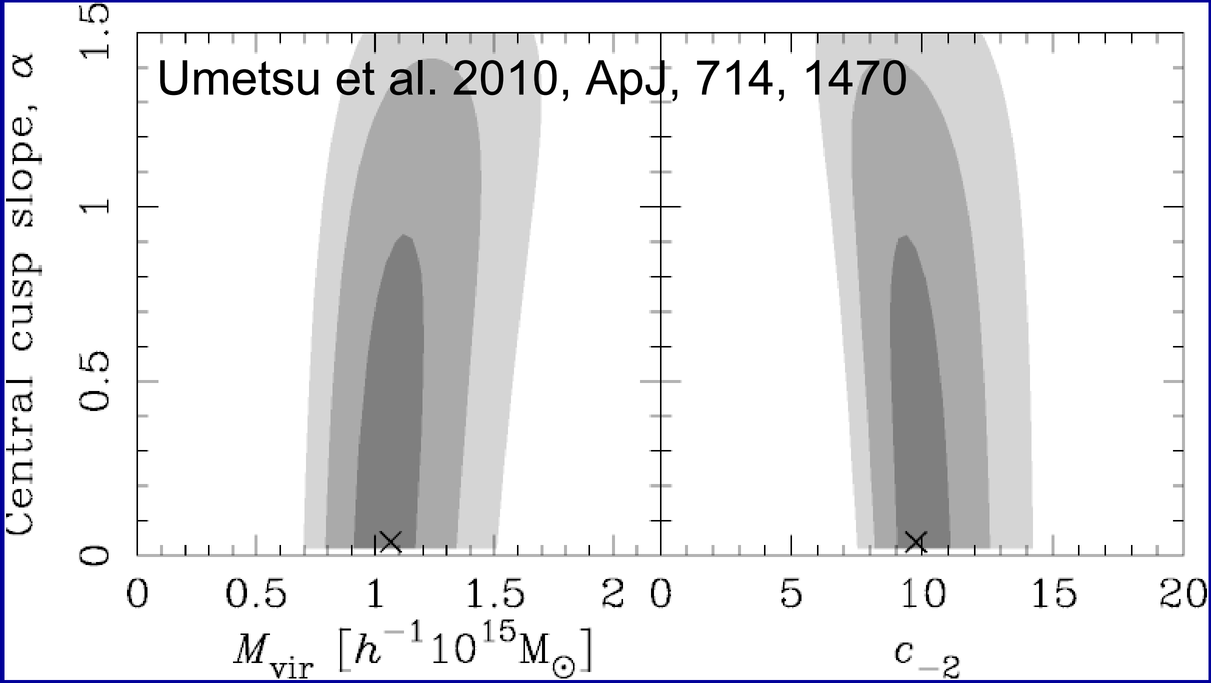
Lensing Constraints on the Central Cusp Slope

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

Generalized NFW (gNFW) profile with 3 free parameters:

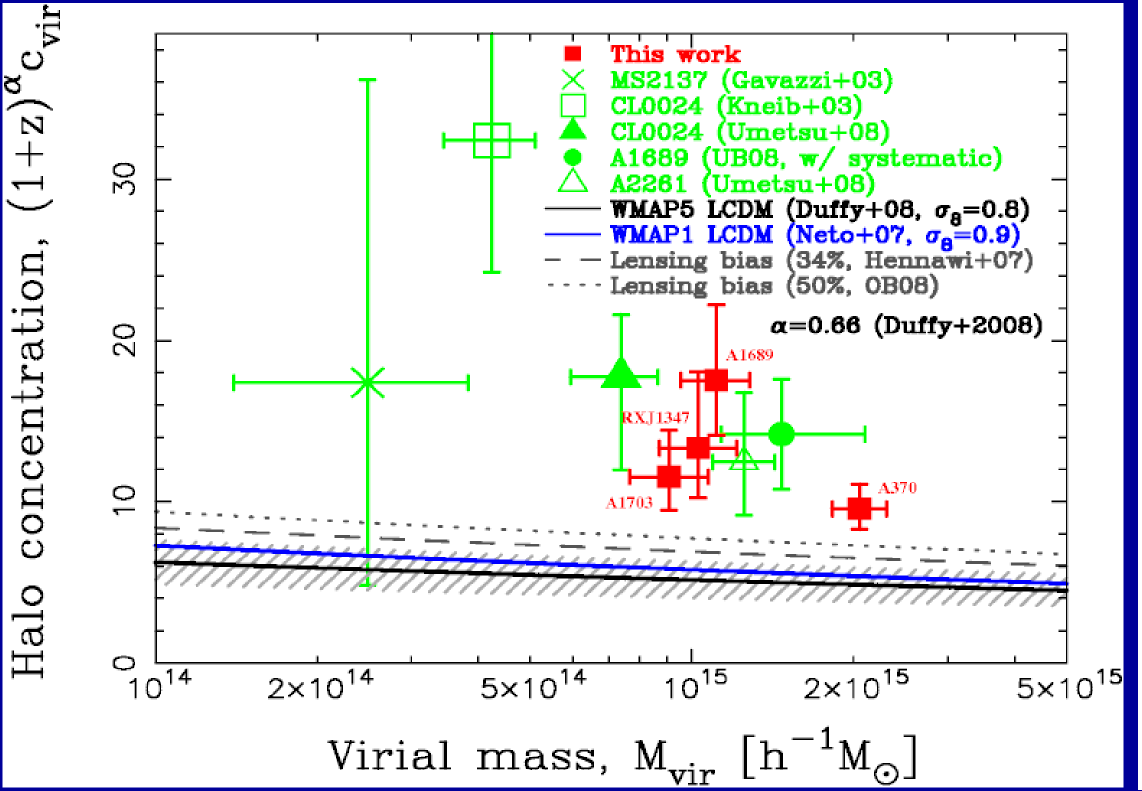
$$\rho(r)/\rho_s = \frac{1}{(r/r_s)^{\alpha}(1+r/r_s)^{(3-\alpha)}}$$

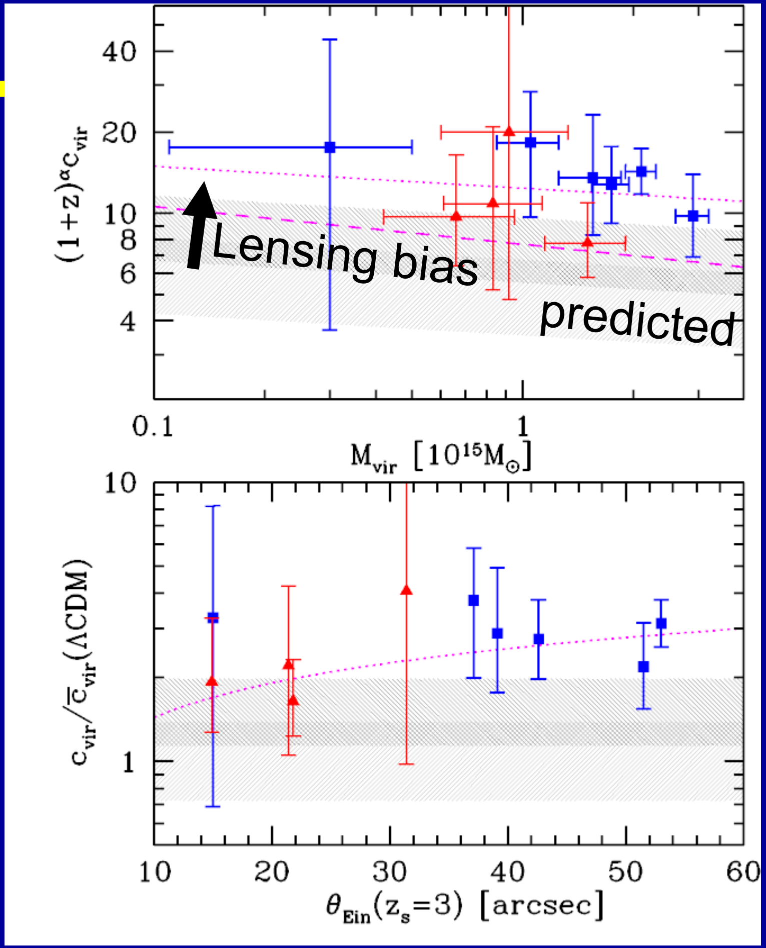
$$c_{-2} := \frac{r_{vir}}{(2-\alpha)r_s}$$



- Central cusp slope $\alpha < 1$ at 68.3%CL from the combined strong and weak lensing constraints --- NFW (α=1) is still consistent
- Cored profile (α~0) is preferred (e.g., Newman+09; Jee+09)
- Needs stellar kinematic data to better constrain the inner slope at 0.001-0.1 R_{vir} (Newman+09)

[2] Lensing Tests of “C vs. M” for Massive Strong-Lensing Clusters





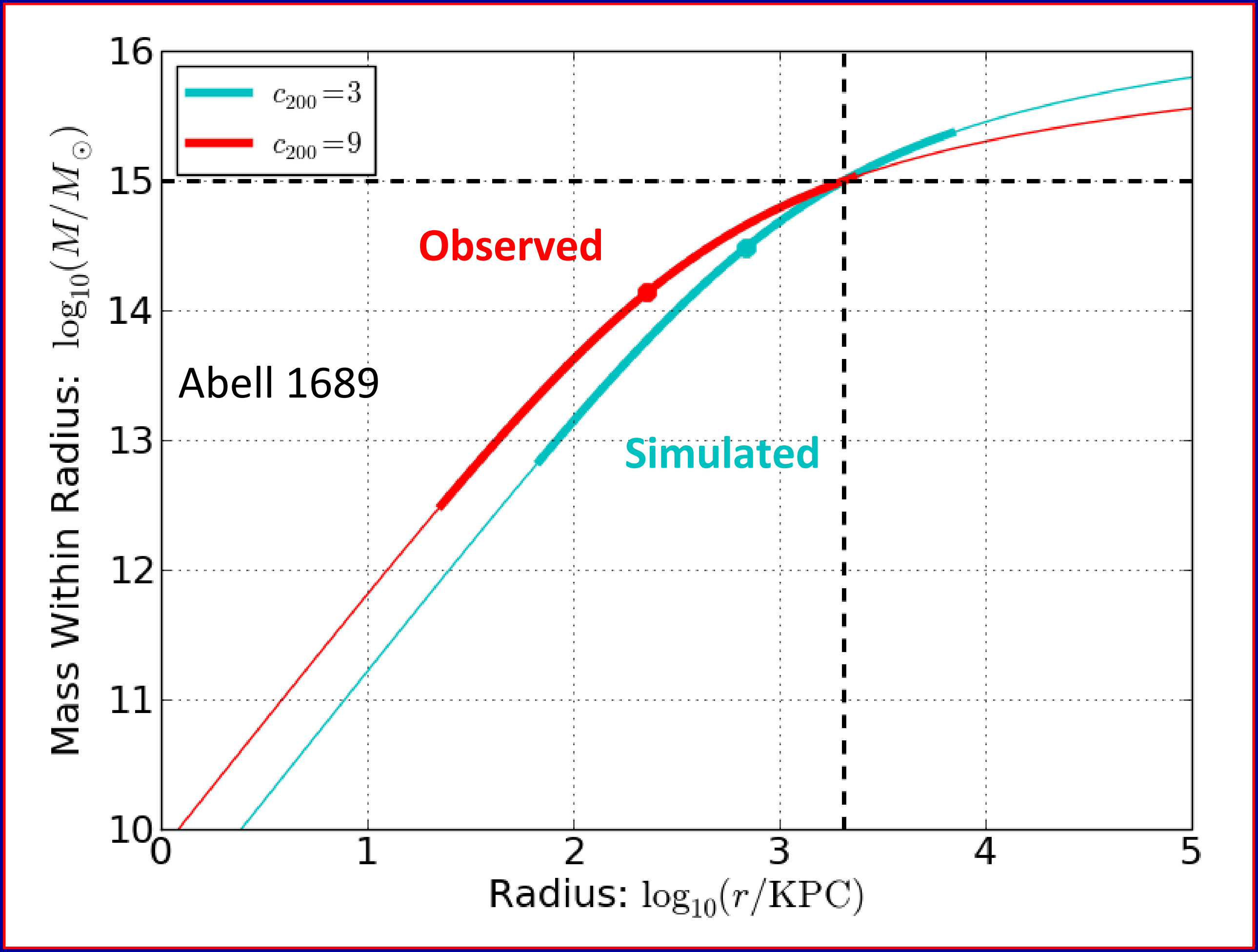
Left) Broadhurst, Umetsu, Medezinski et al. 2008, ApJ, 685, L9 (BUM+2008)

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

*Taking into account an orientation bias correction of about **+20%,** discrepancy is still 4σ. With a **50% bias** correction, it still represents a 3σ deviation (BUM+2008)*

Some "lensing-biased" clusters appear over-concentrated

Cumulative mass profile, $M_{2D}(<r)$



Strong Lensing → | ← Weak Lensing

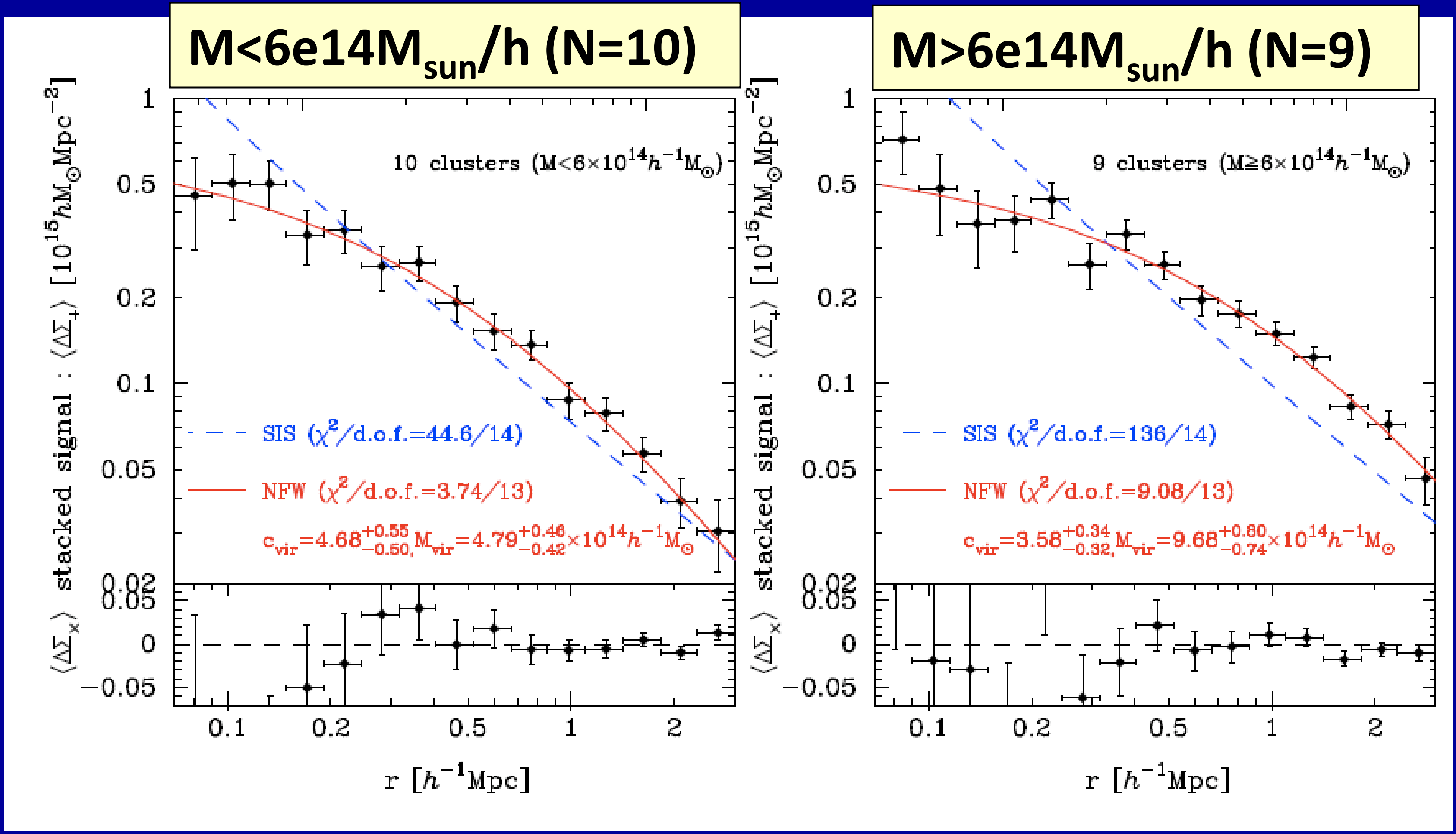
Possible explanations for high observed concentrations: C= 10 or 5?

- **Lensing selection bias**
  - SL bias towards intrinsically high concentration halos (Hennawi+07)
  - Triaxial orientation bias (Oguri & Blandford 2009)
  - Significant (25-50%) but probably not sufficient?
- **Baryons: Gas cooling vs. AGN feedback**
  - Baryonic cooling is probably not a major effect if AGN feedback is taken into account (Duffy et al. '10; Mead et al. '10)
  - Adiabatic contraction will increase the cusp slope α (↑), while shallow slopes α<~1 preferred in observed clusters: e.g., A1689, Cl0024+16 (Umetsu+10), A611 (Newman+09), XMM2235 at z=1.4 (Jee+09)
- **Clusters formed earlier than in LCDM?**
  - e.g., Non-Gaussianity? Early Dark Energy? (Sadeh & Rephaeli 2008; Grossi & Springel 2009)
  - say, Ω_{de}~0.1 at z=6? (see also D. Coe e tal. 10, arXiv:1005.0398)

[3] Subaru-WL Stacked Cluster Analysis

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

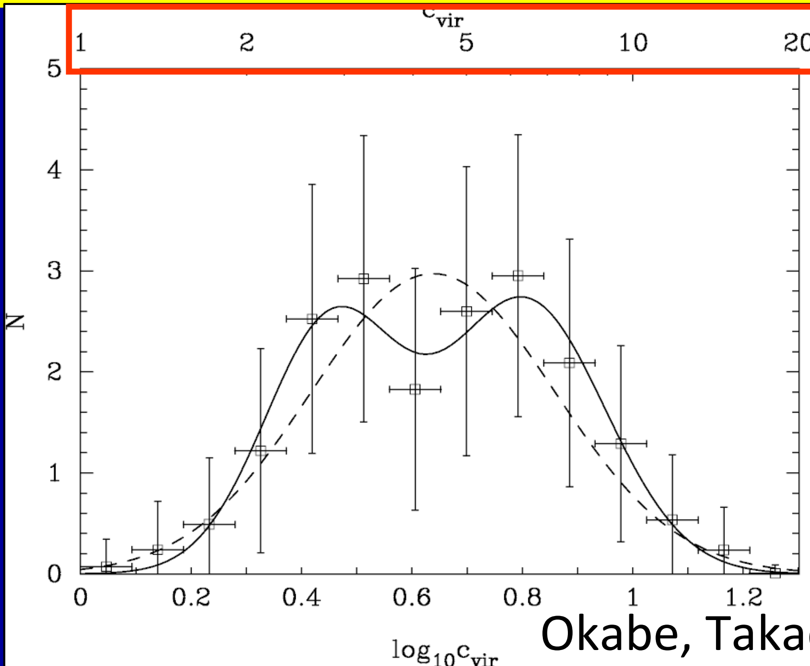
→ less sensitive to substructures/asphericity of individual clusters

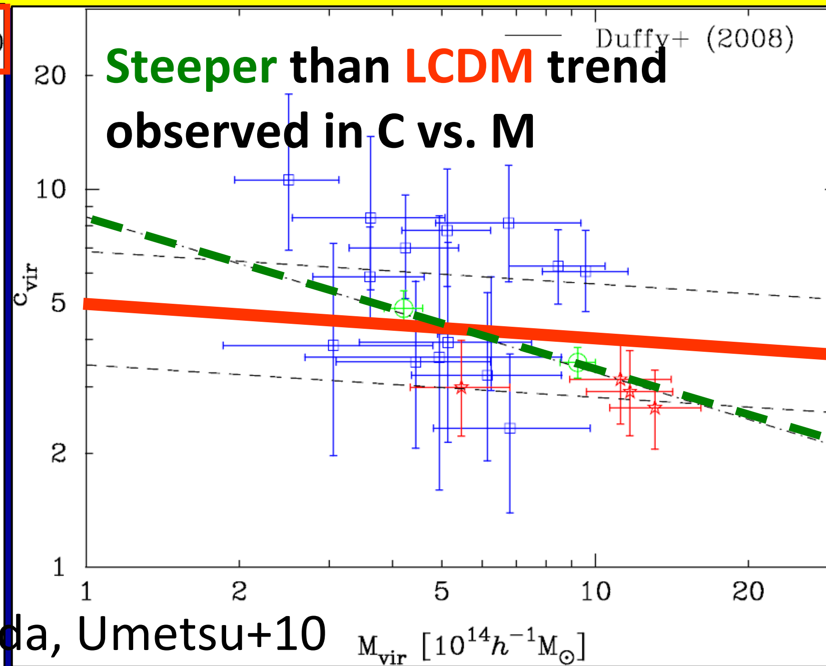


SIS rejected @6 and 11 σ levels (Okabe,Takada,Umetsu+ 2010, PASJ, 62, 811)

Subaru WL Results: Observations vs. Theory

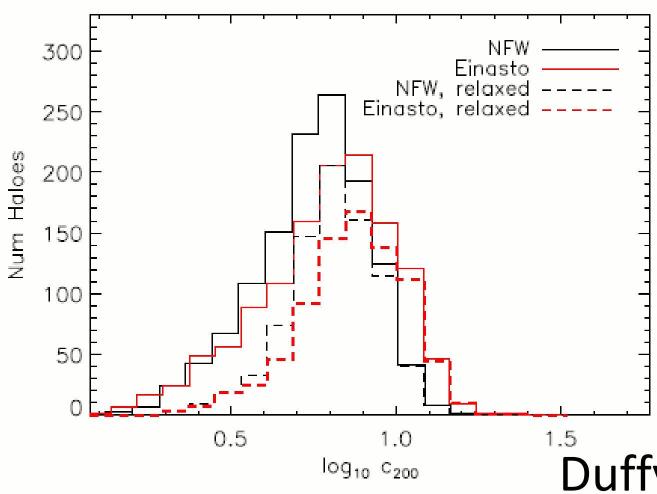
Subaru WL (19 clusters)

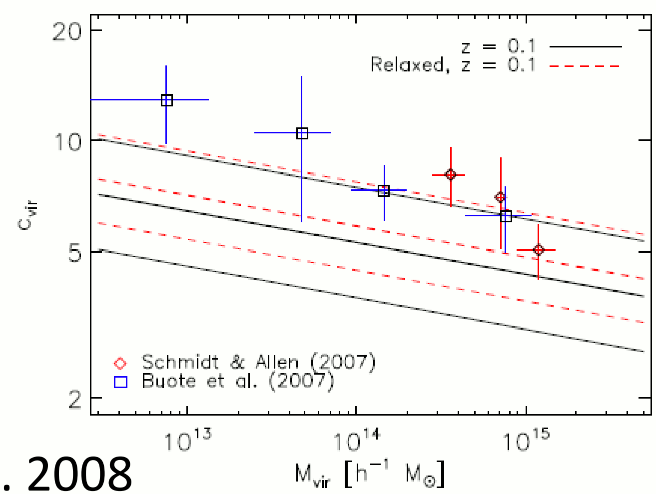




Okabe, Takada, Umetsu+10

LCDM theory



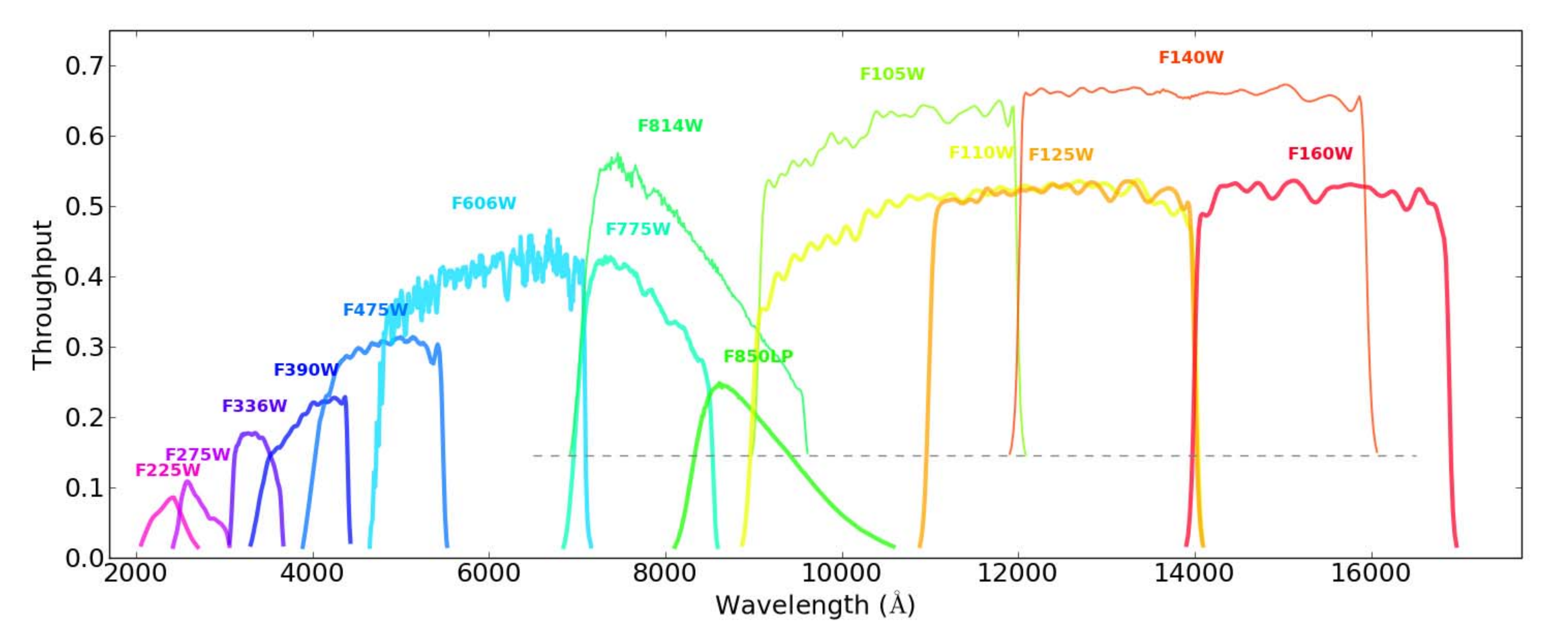


Duffy et al. 2008

4. Cluster Lensing And Supernova survey with Hubble: CLASH

A 524-orbit HST MCT Program (HST Cycles 18-20 over the next 3 years from Nov. 2010)

PI: Marc Postman (STScI)



http://www.stsci.edu/~postman/CLASH/

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Larry Bradley	STScI
Thomas Broadhurst	Tel Aviv University (TAU) / IAA
Dan Coe	Jet Propulsion Laboratory (JPL) / Caltech
Megan Donahue	Michigan State University
Rosa Gonzales-Delgado	IAA
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Ole Host	University College London (UCL)
Leopoldo Infante	Universidad Católica de Chile
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Daniel Kelson	Carnegie Institute of Washington
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Dani Maoz	TAU / Wise Observatory
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Adi Zitrin	TAU

Post-doctoral fellow

Graduate student

Cluster Sample Size Justification

Observational

- Want to measure mean "concentration" of DM profile to ~10% accuracy:

$$N_{CL} \approx (\sigma_{tot} / f)^2$$

$$f = 0.10$$

$$\sigma_{tot}^2 = \sigma_{LSS}^2 + \sigma_{int}^2 + \sigma_{Meas}^2$$

σ_{LSS} = 0.13 (e.g., Hoekstra et al. 2003)

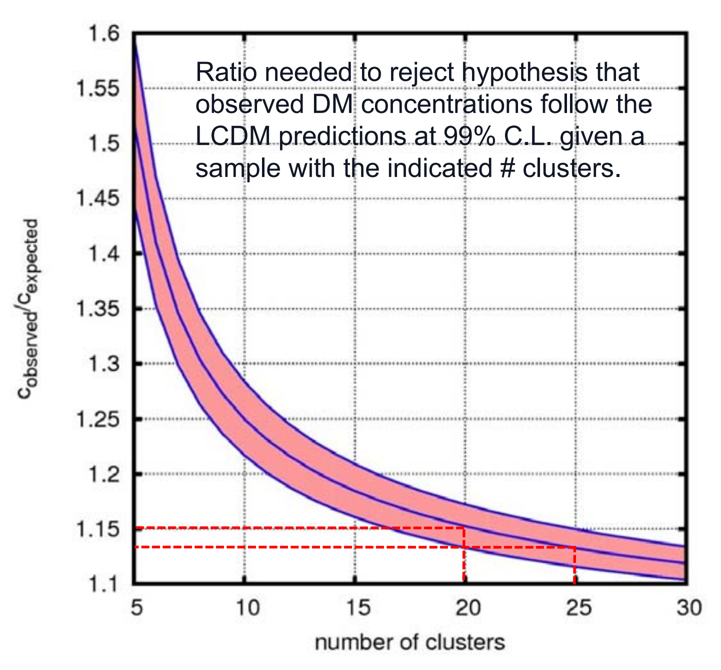
σ_{int} = 0.30 (e.g., Neto et al. 2007)

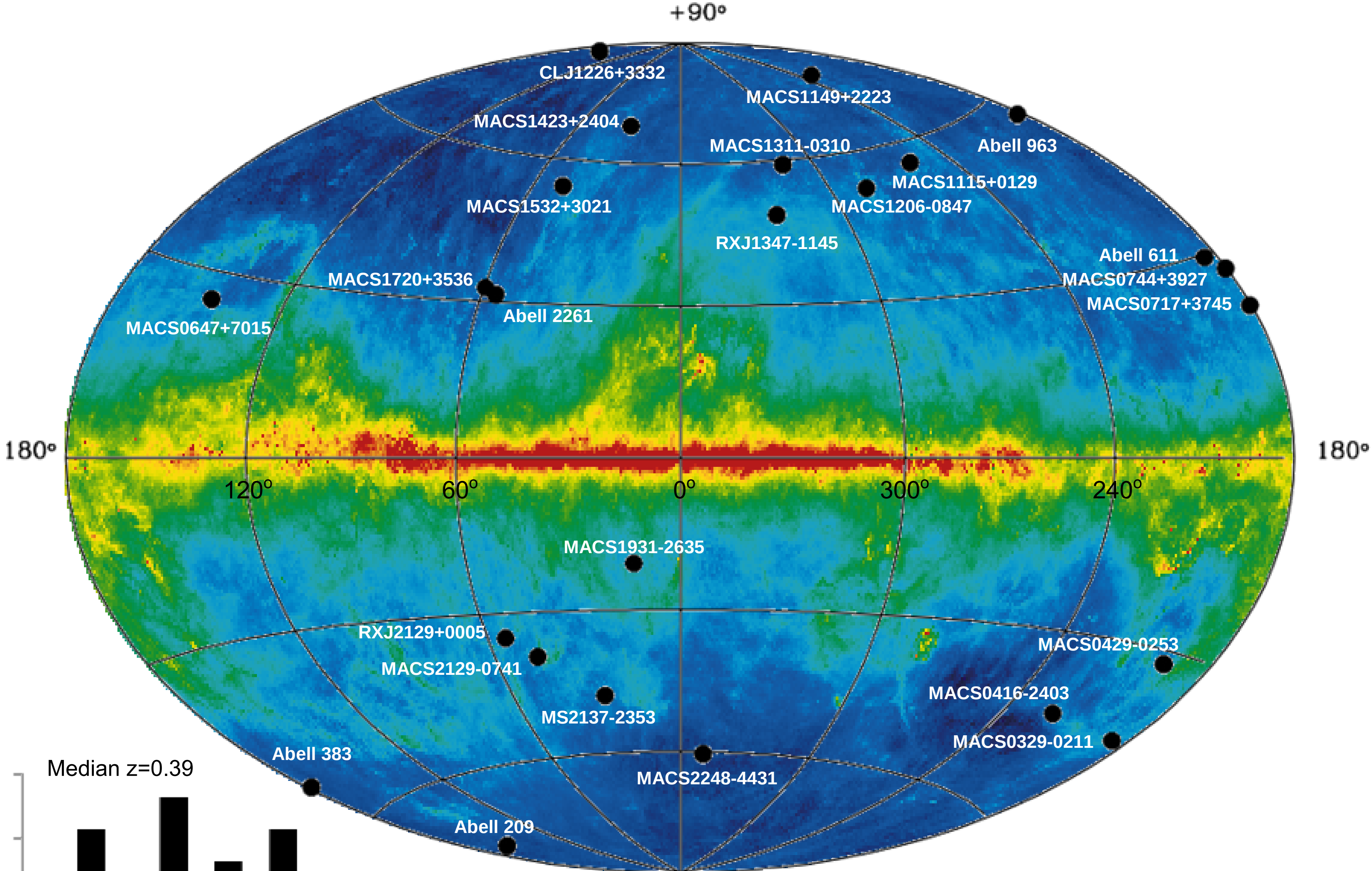
$\sigma_{Meas} = 0.22 (N_{arc, CL0024} / N_{arc})^{1/2}$ (Umetsu et al. 2010)

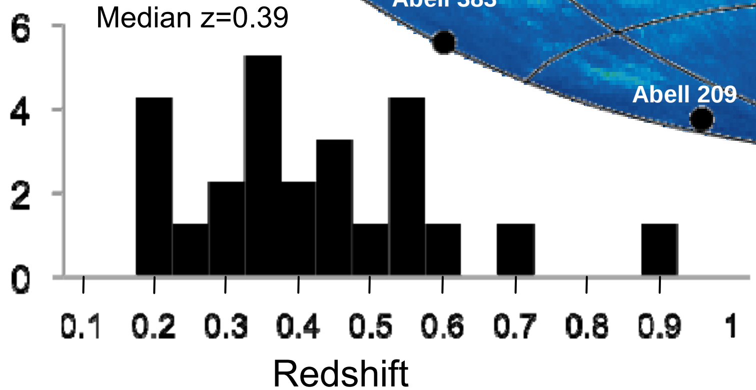
$$N_{CL} = 24$$

Theoretical

- N-body simulations show DM profile concentration distns are log-normal with $\sigma \sim 0.25 \pm 0.03$ (e.g., Jing 2000; Meneghetti et al. 2009).







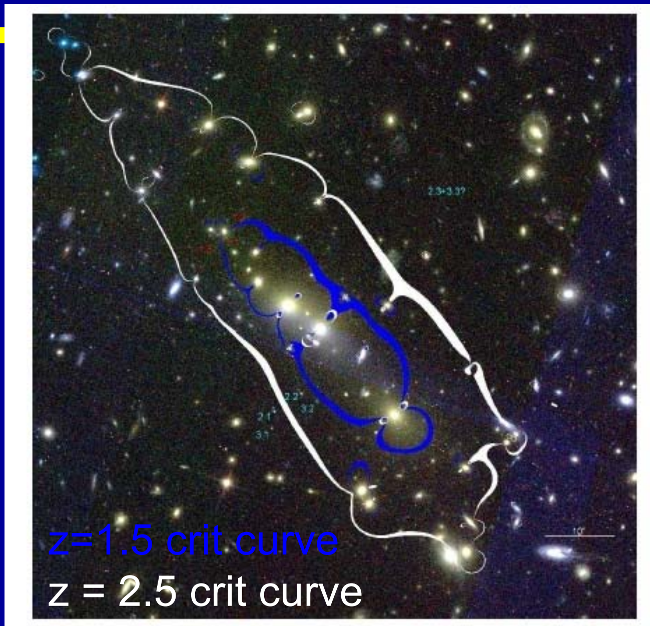
25 clusters in the CLASH sampl

20 X-ray selected relaxed cluste

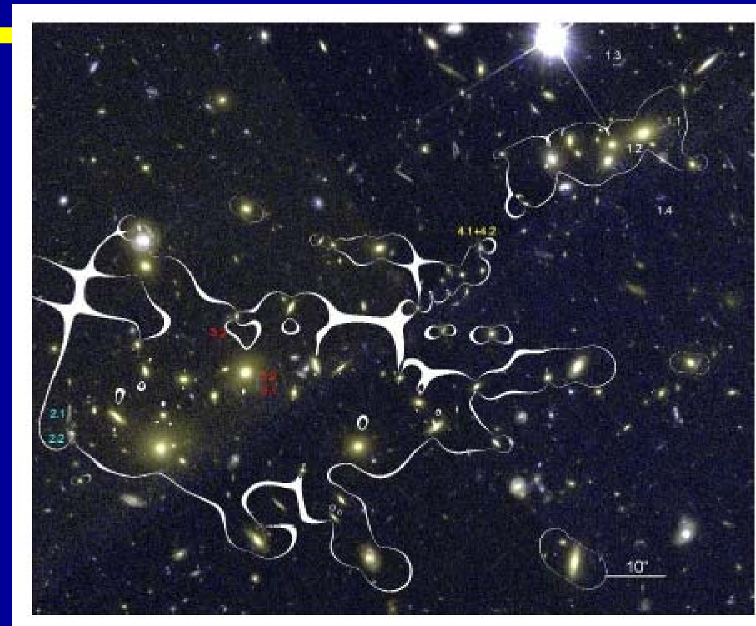
and 5 high-magnification cluste

Background: Schlegel et al. Galactic Extinction Map

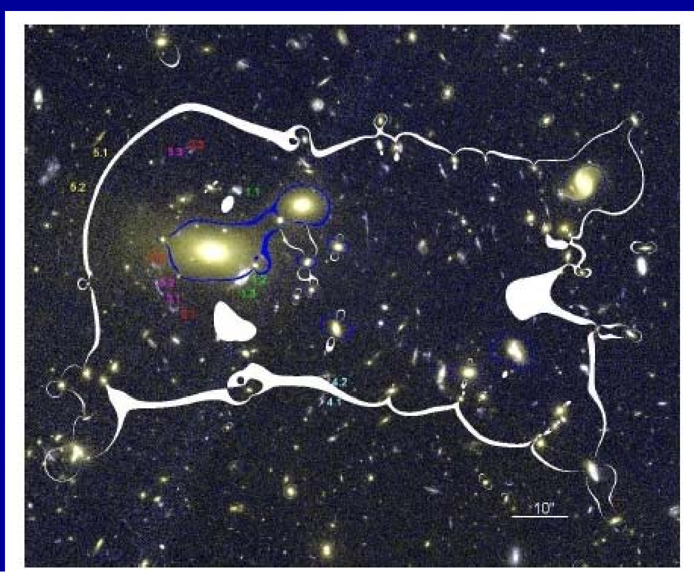
MACS J0018+1626, z = 0.55



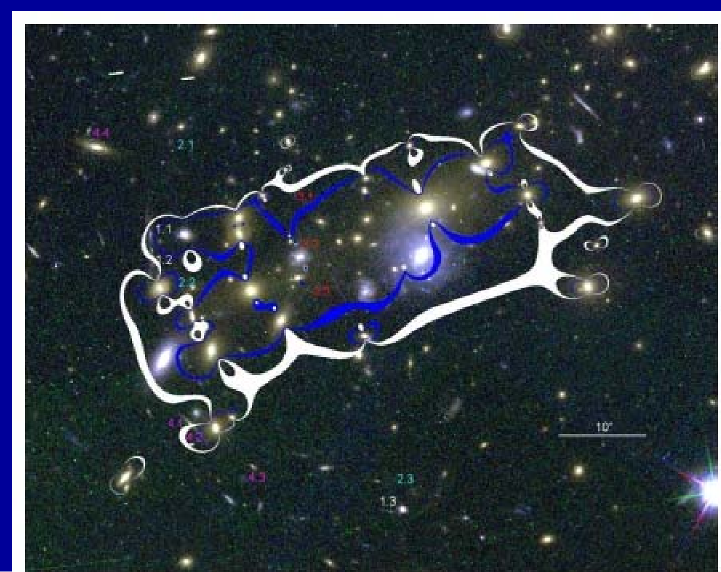
MACS J0025-1222, z = 0.58



MACS J0257-2325, z = 0.51



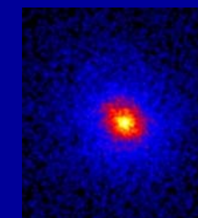
MACS J0454-0300, z = 0.54



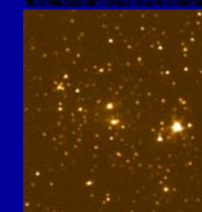
Multiple Facilities Will be Used

- HST 524 orbits: 25 clusters, each imaged in 14 passbands with ACS/WFC3 (0.23–1.6 μm)

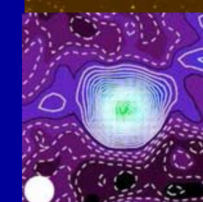

- Chandra x-ray Observatory archival data and possibly new data. (0.5 – 2 keV)

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

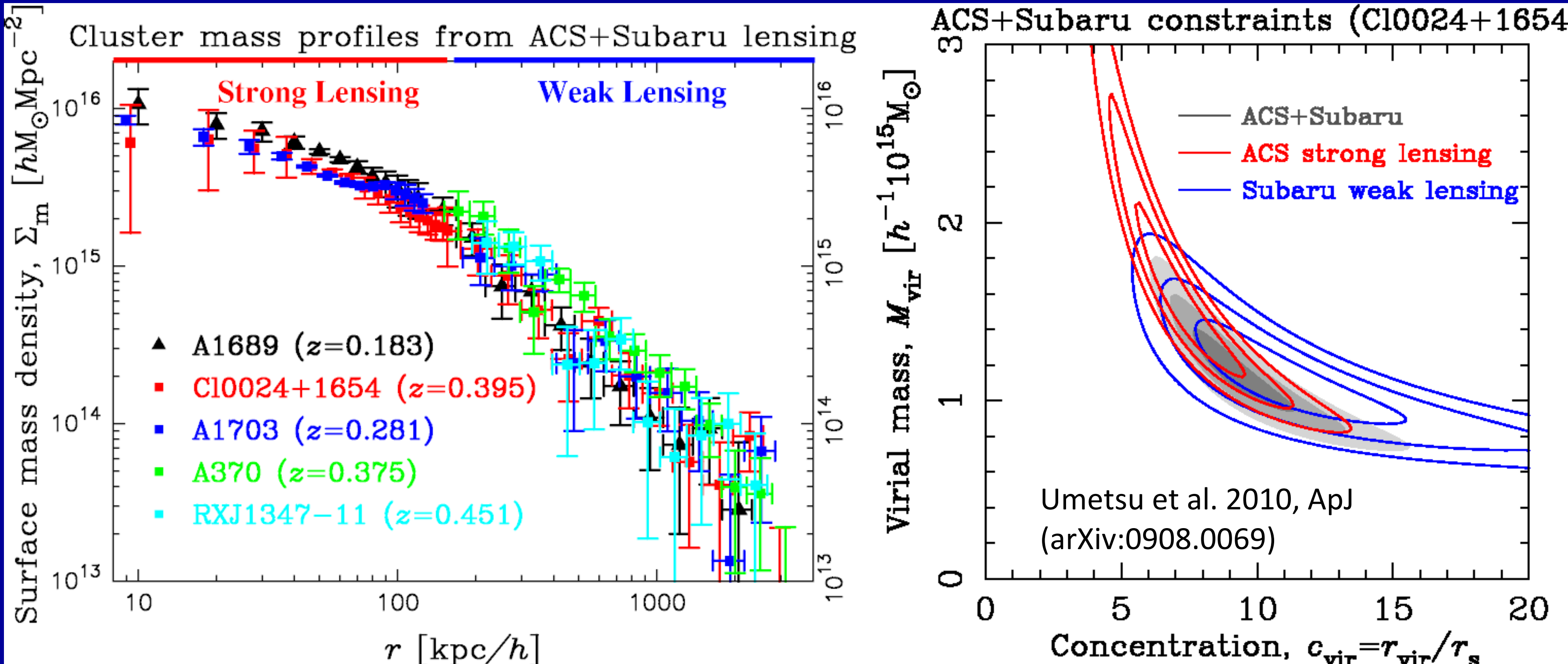



- Multiscale SZE observations (0.15’-23’) proposed (Bolocam, AMiBA, Mustang)

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


Both Strong & Weak Lensing Measurements Needed for Good Constraints



Umetsu+2010b: Full weak-lensing constraints from distortion + magnification
MCMC analysis for 5 massive clusters

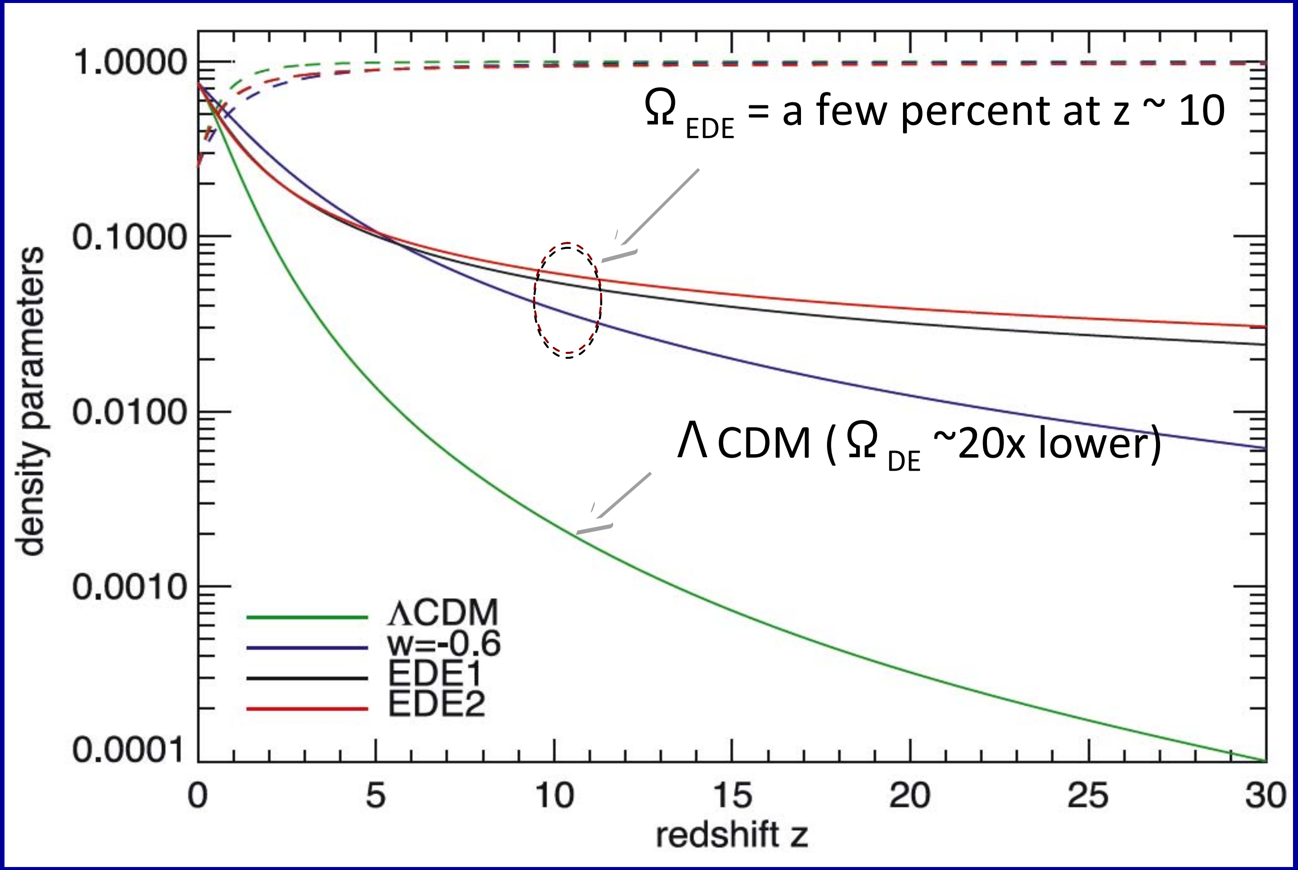
CLASH data will allow us to definitively derive the representative mass profile shapes and robustly measure the cluster DM concentrations and their dispersion as a function of cluster mass *and their evolution with redshift.*

5. Summary

- **Cluster mass profile shapes**
  - Mass profile shapes have been measured over 2 decades in radius (0.01-1.5 R_{vir}) for several massive clusters from detailed strong and weak lensing analyses.
  - 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 stellar velocity dispersion measurements at <10kpc/h in order to constrain the inner cusp slope (cf. Newman et al. 2009)
- **Mass vs. concentration relation and its evolution**
  - High mass concentrations found for ~10 massive (strong-lensing biased) clusters from joint WL+SL analyses (Broadhurst et al. 2008; Oguri et al. 2009).
  - Needs more clusters (~25) to definitively determine the "representative" mass profile shapes, in particular (M,C), from joint WL+SL analyses.

Supplemental Slides

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



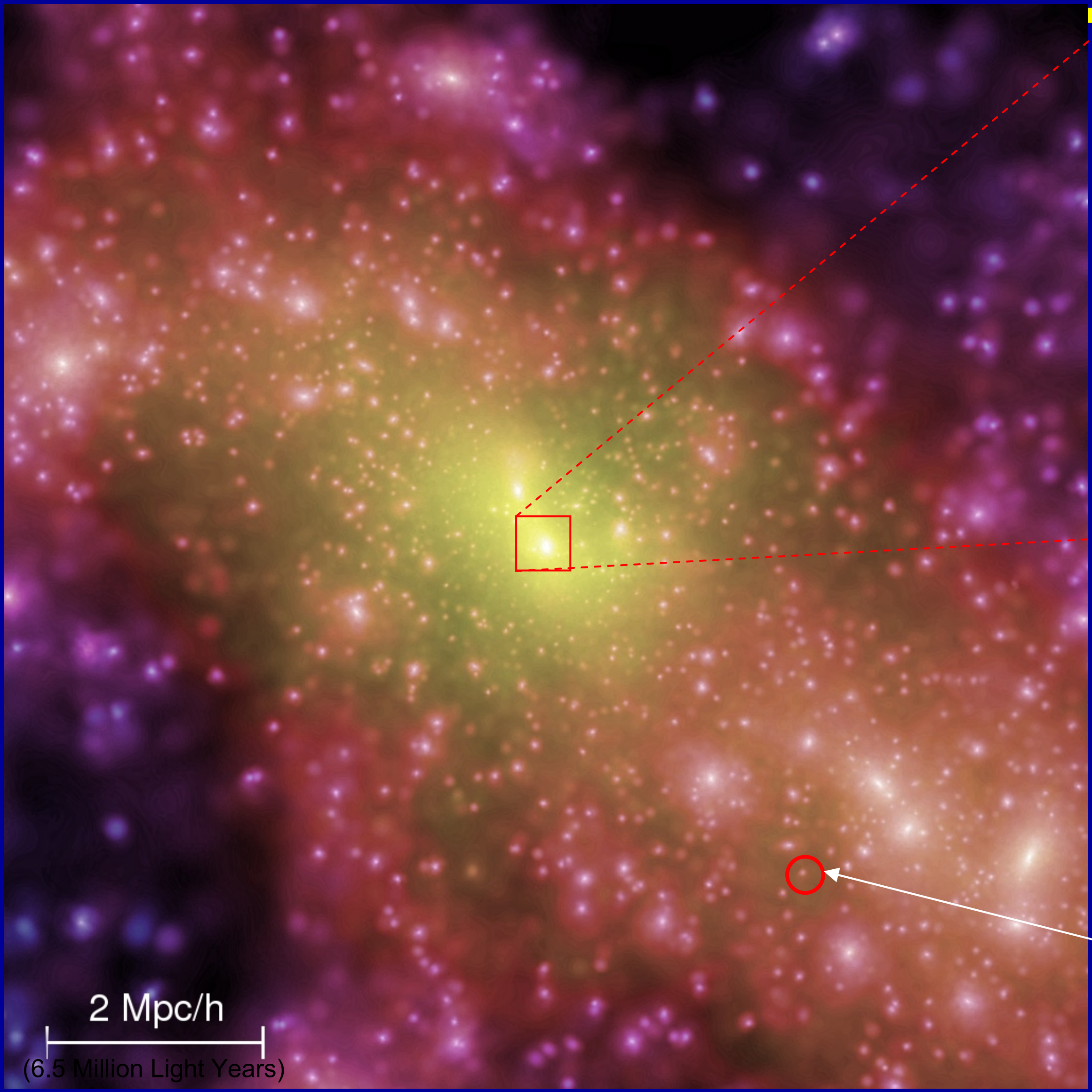
Grossi & Springel 2009

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.*

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

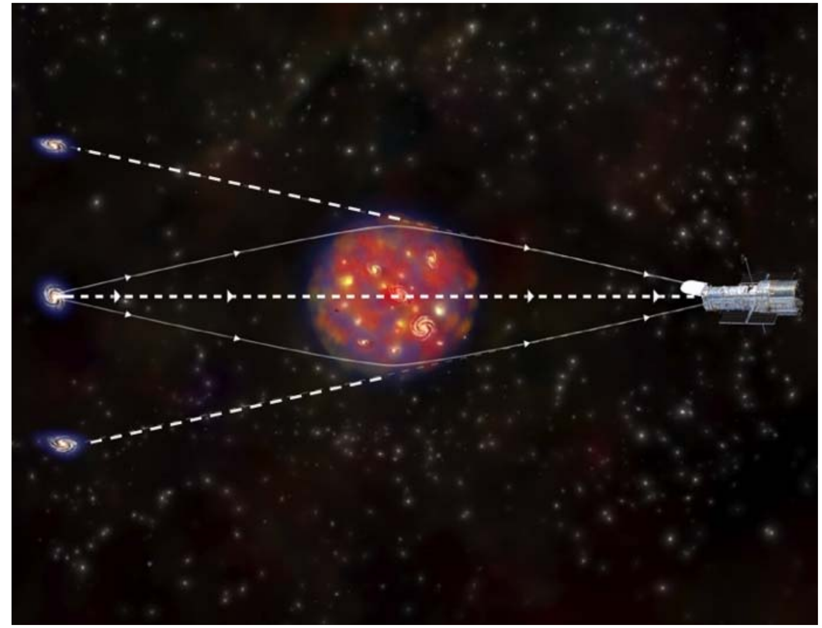
Nature of CDM Structure Formation

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**: $\delta \sim$ "-1" nonlinear structure
   – Under-dense regions, corresponding to density troughs in primordial density fields

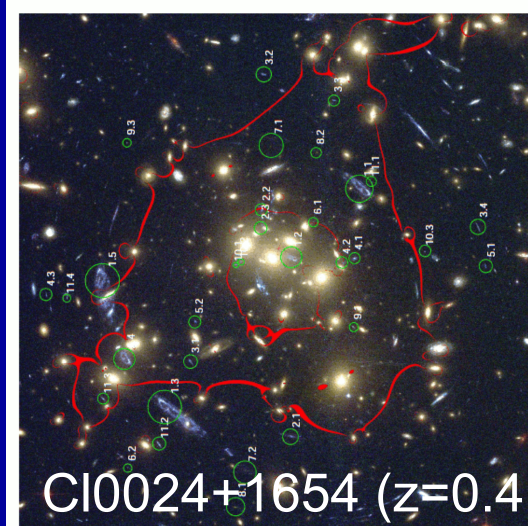
Strong Gravitational Lensing

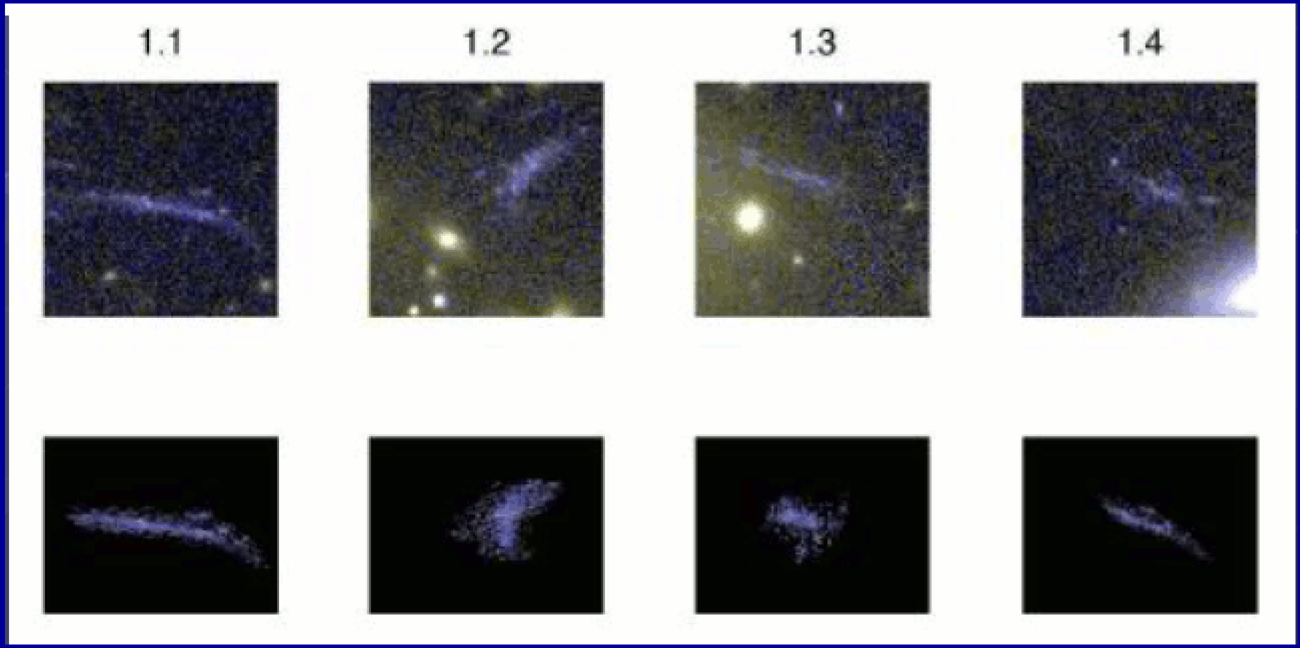


Strong Lensing Basics:

- Provides large areas of high **flux magnification** (μ ~ 10) → natural gravitational telescope
- *Tradeoff*: Dilution of the source-plane area (=1/μ), or **area distortion**.
- Reveals **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}.

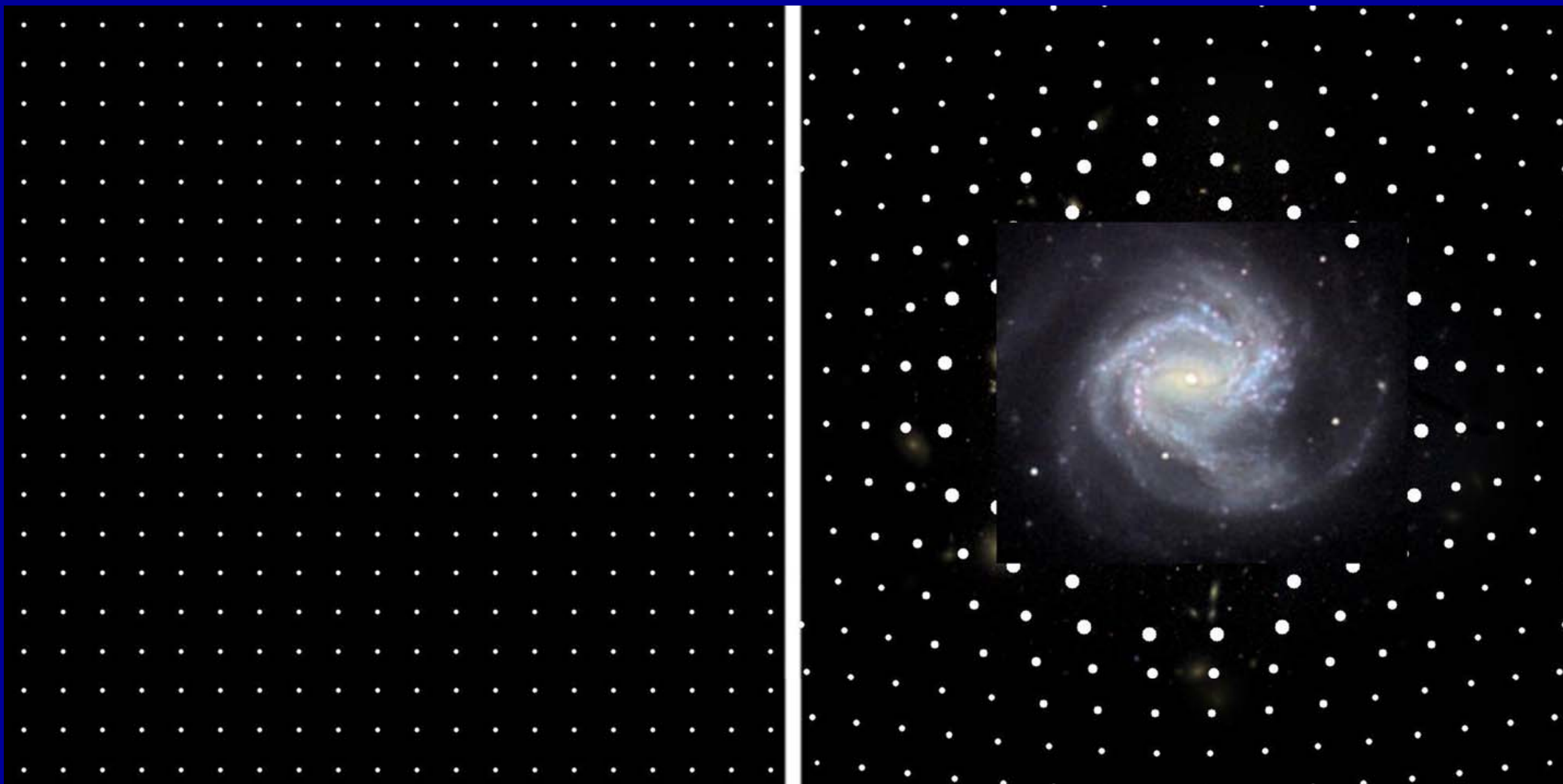
***HST/ACS* images**




1.1
1.2
1.3
1.4

Gravitational Lens Magnification

Unlensed (Source plane) **Lensed (Image plane)**

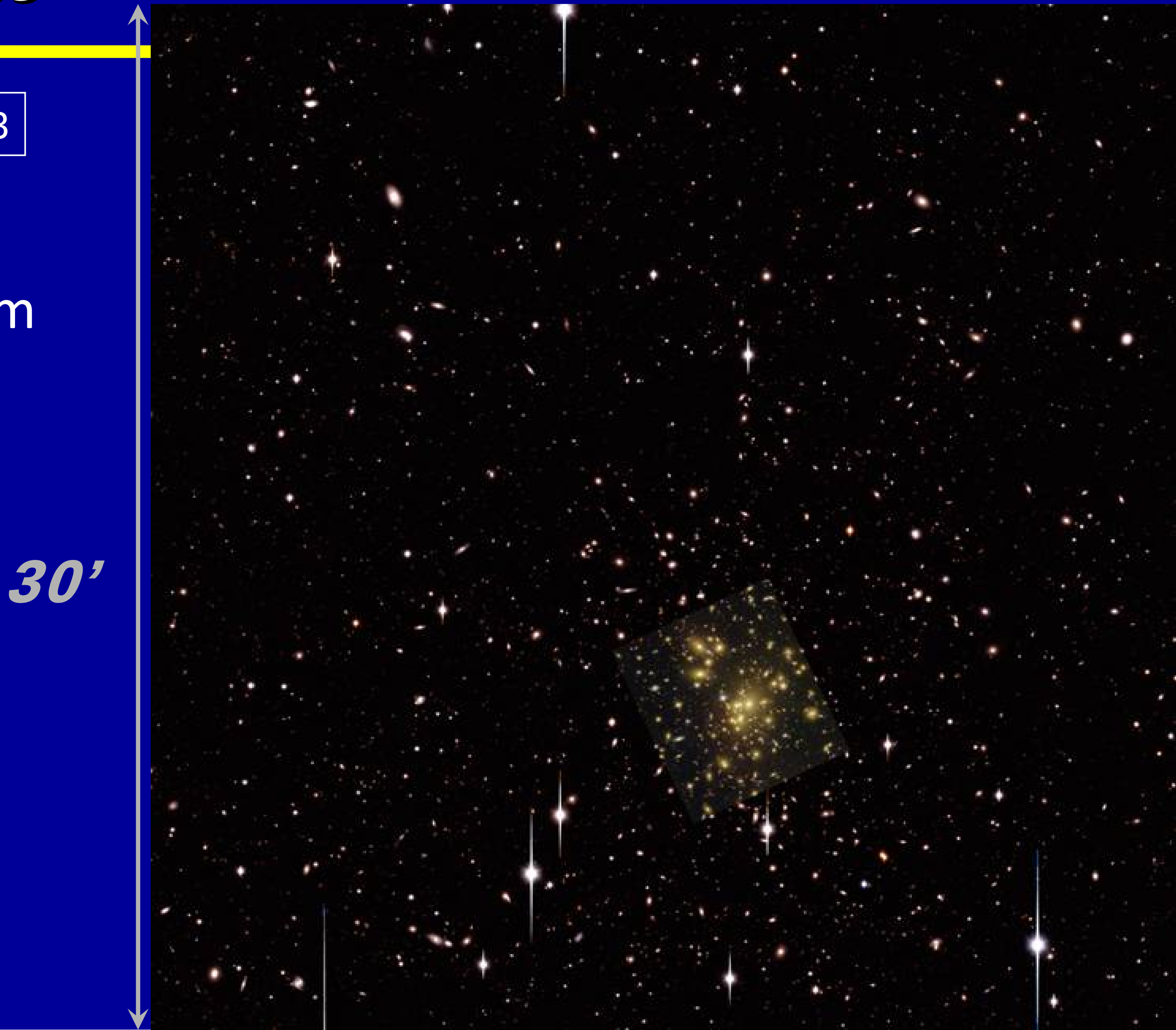


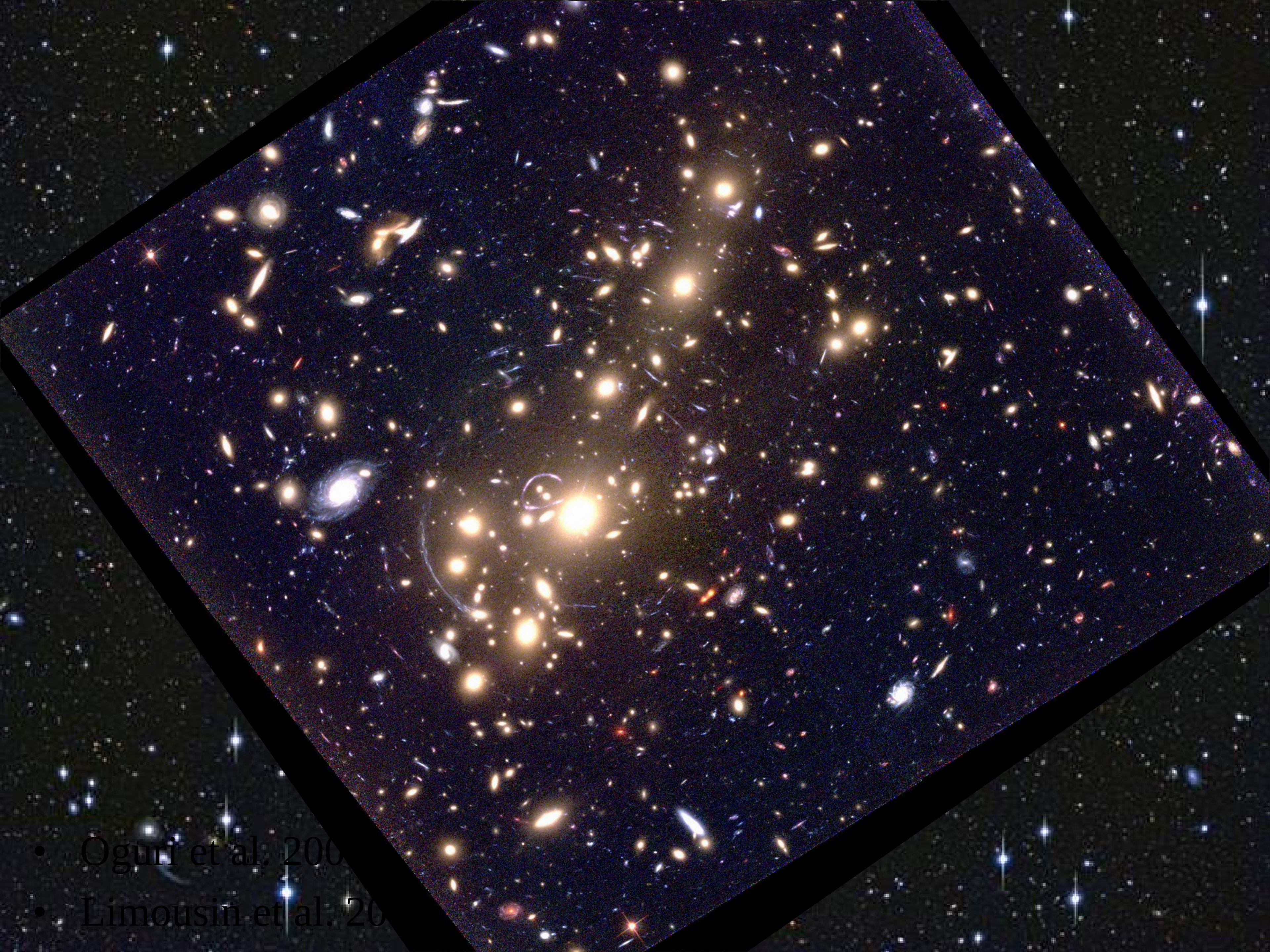
Credit: Joerg Colberg, Ryan Scranton, Robert Lupton, SDSS

A1689

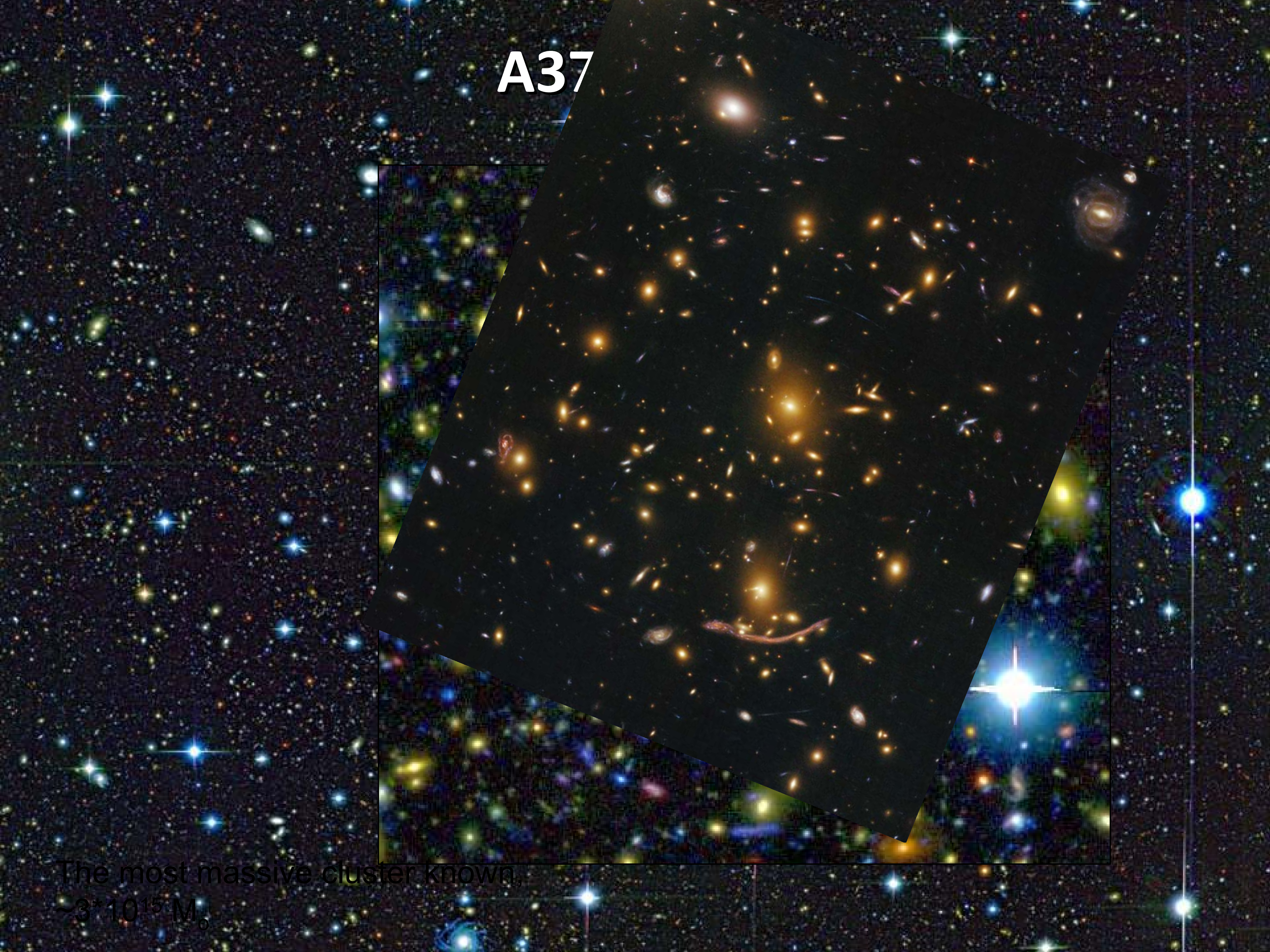
z = 0.183

- *Subaru* SuprimeCam 34’x27’
- *HST* ACS 3.3’x3.3’

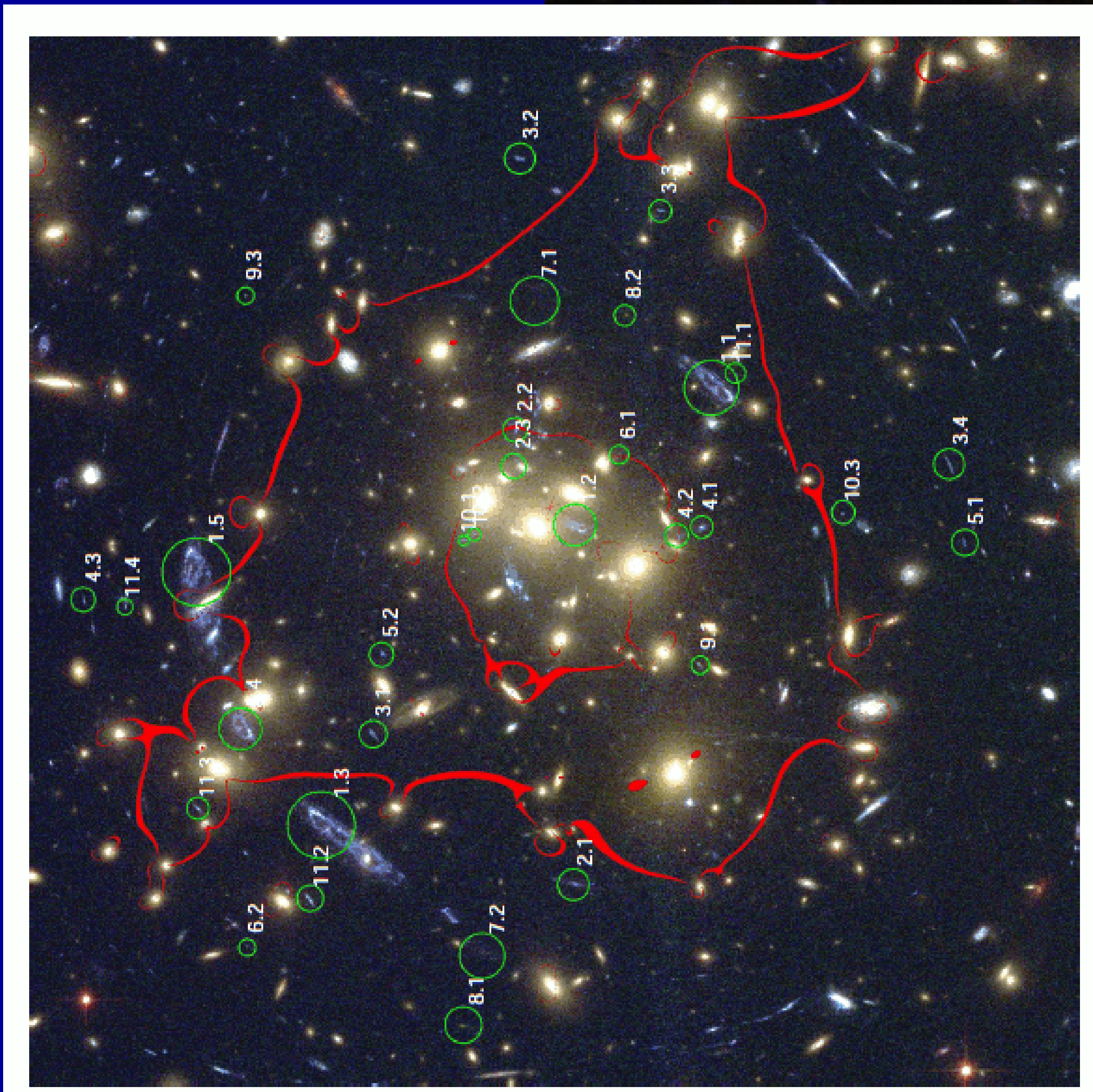




- Oguri et al. 200
- Limousin et al. 20


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

Cl0024+1654 (z=0.395)

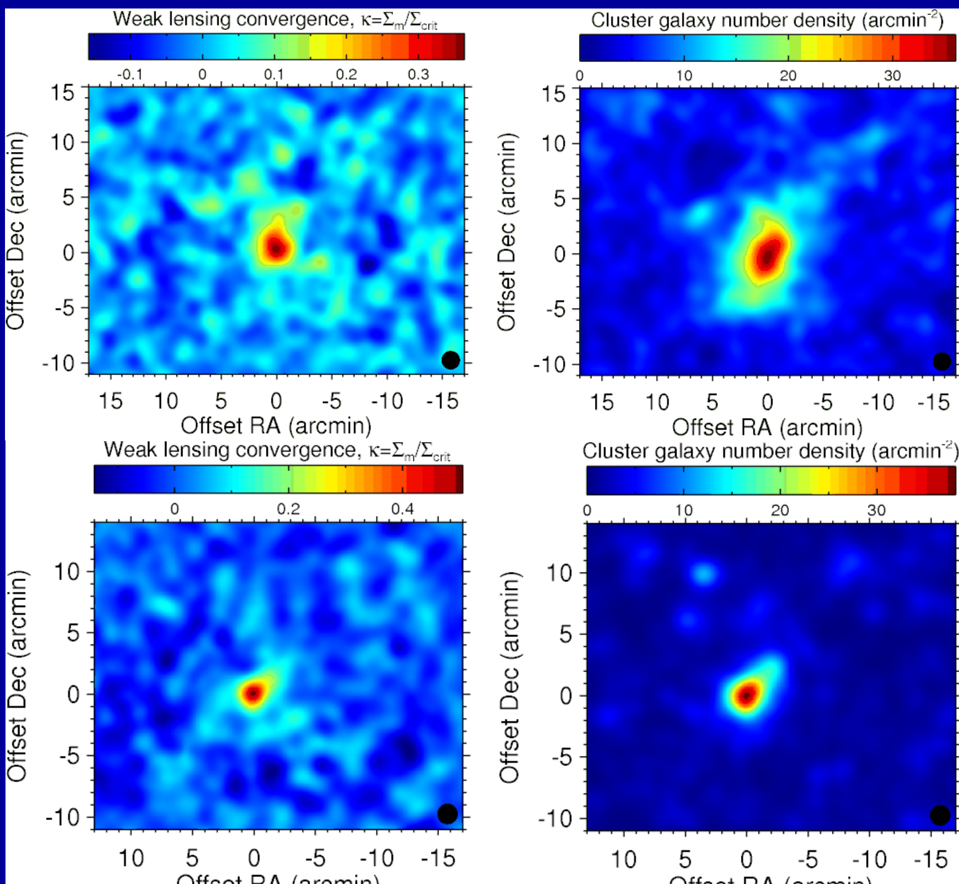


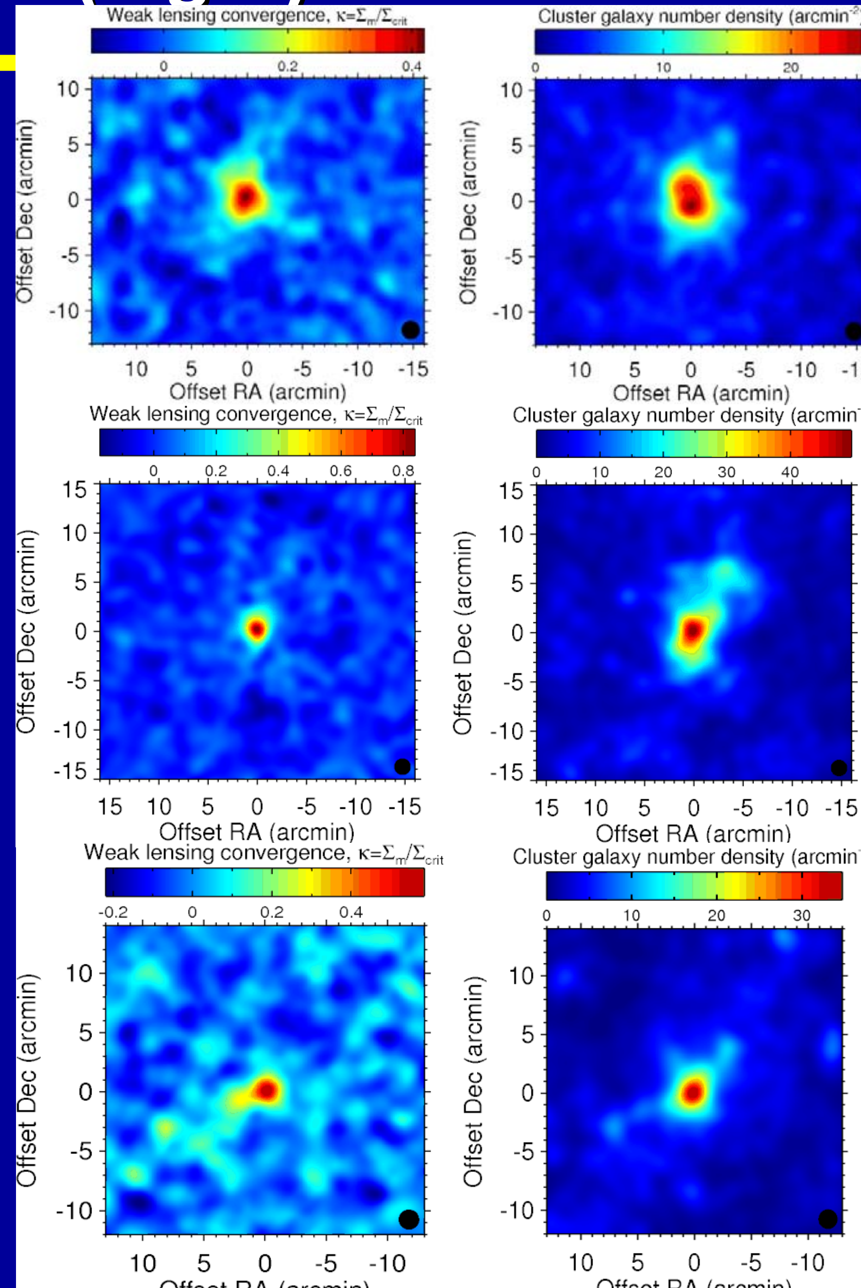
Mass (Left) vs. Galaxies (Right) in Clusters

A1689 (z=0.18)

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

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

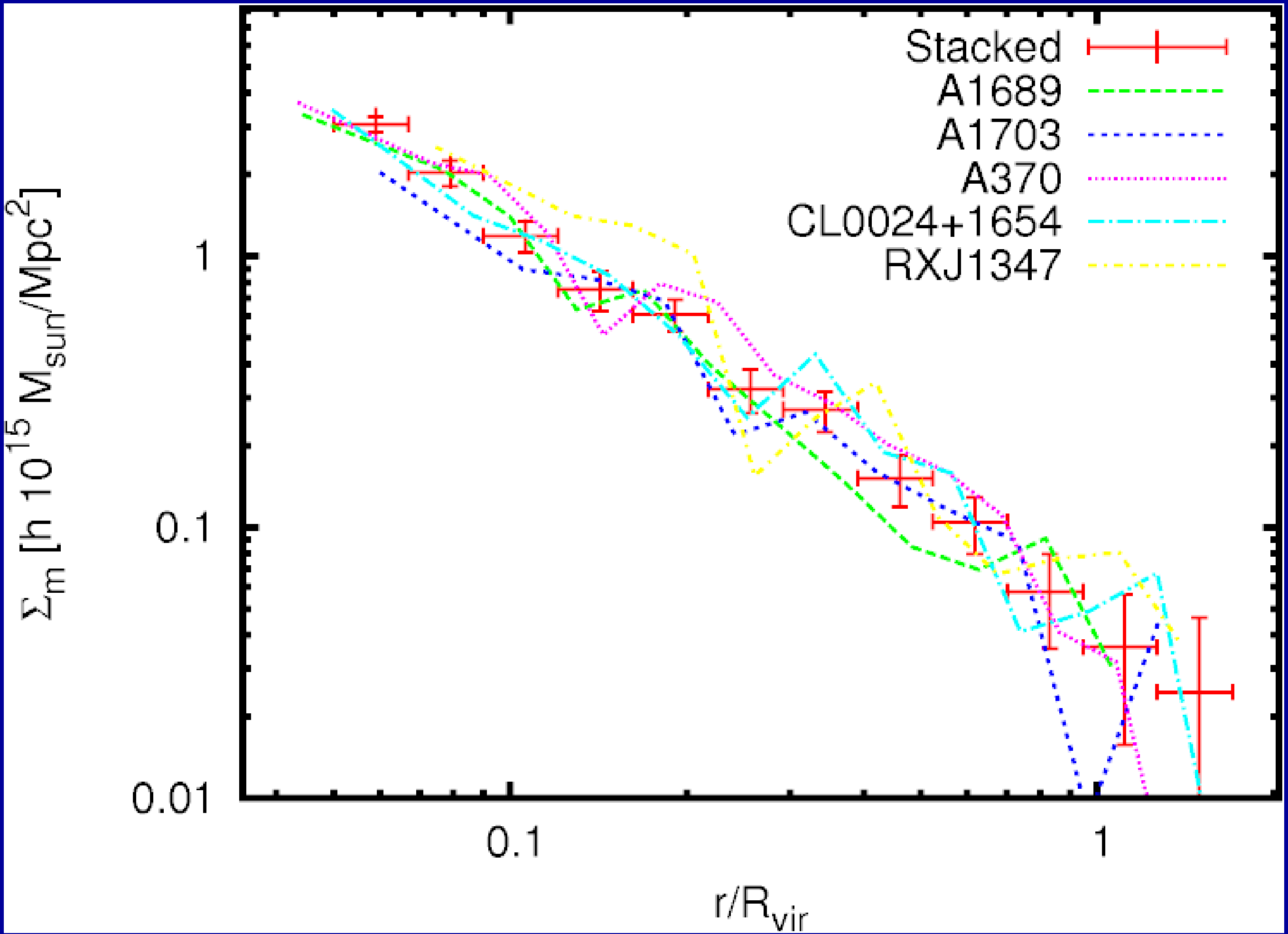




Preliminary results: Stacked Mass Profile

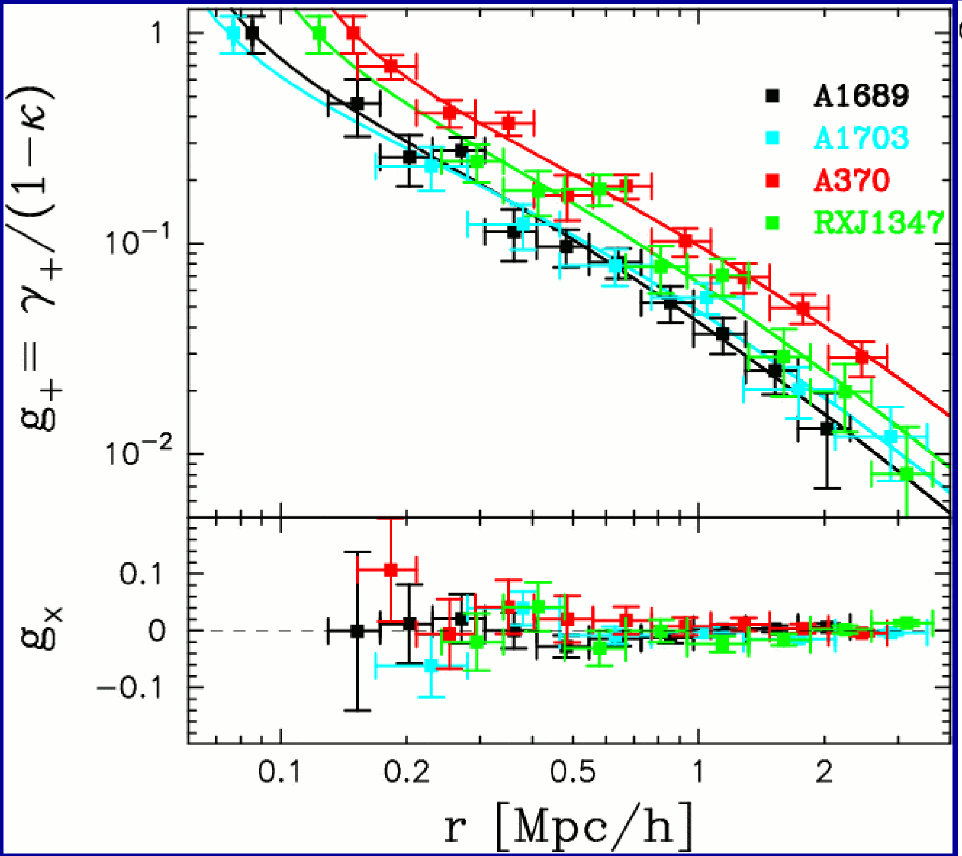
Stacking non-parametric WL mass profiles:

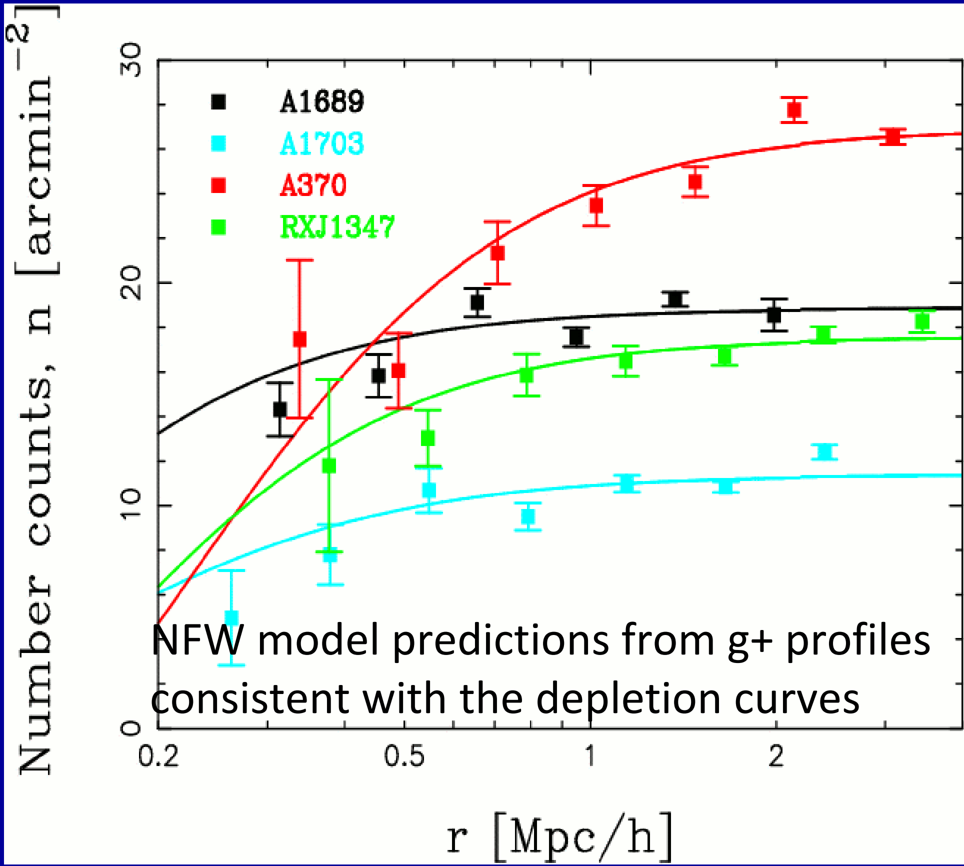
Model-independent constraints on the mass profile shapes and outer density slope, $d\Sigma_m/dR$



[2] Testing LCDM by Cluster Lensing Profiles

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

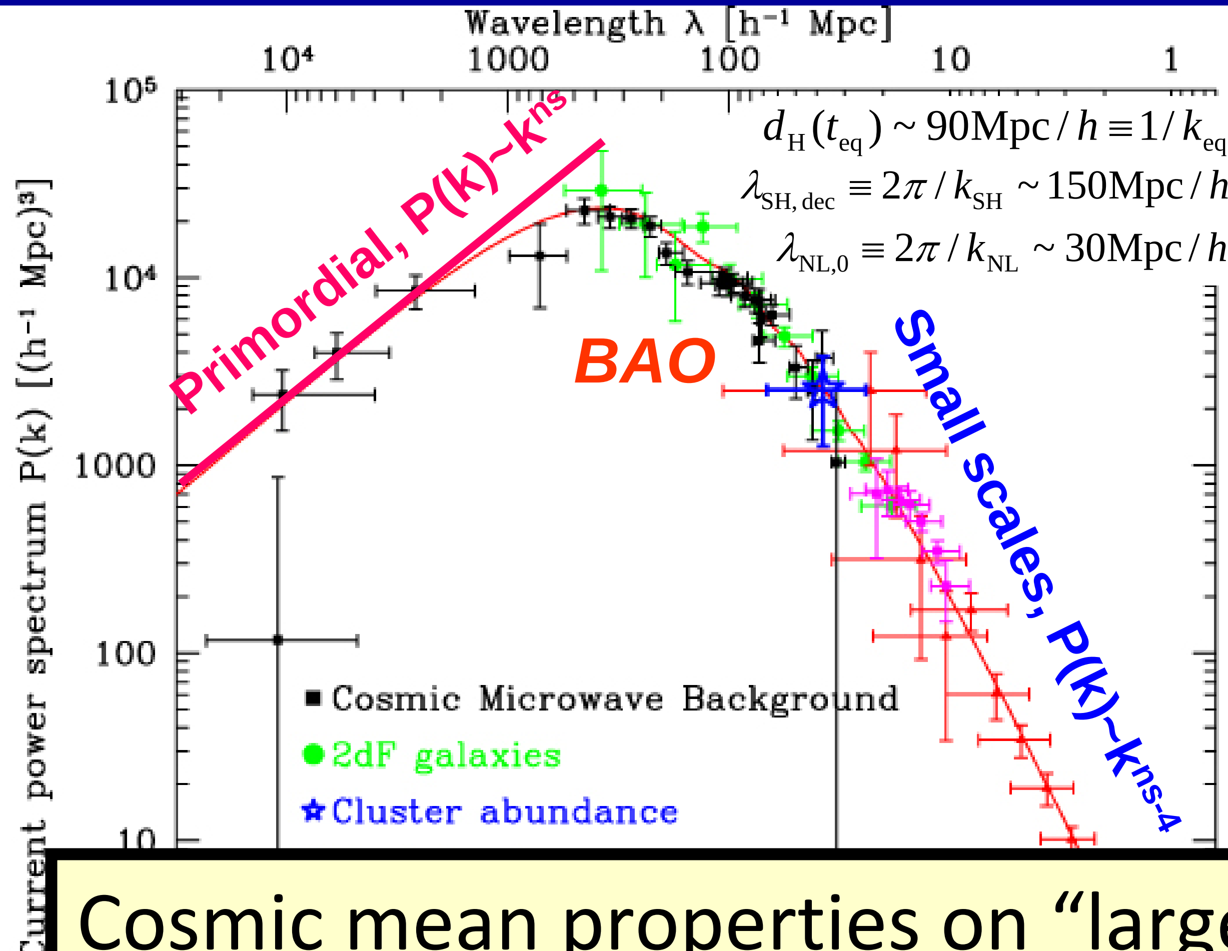




Observed curves are similar in form, well described by CDM-consistent NFW profiles

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

Matter Power Spectrum P(k): LCDM vs. Observations



$P(k) \propto k^{\wedge}n_s$ with $n_s \sim 1$
(n_s=1: Harrison-Zel'dovich spectrum)

@ $k \ll k_{eq} \sim 0.01h$/Mpc

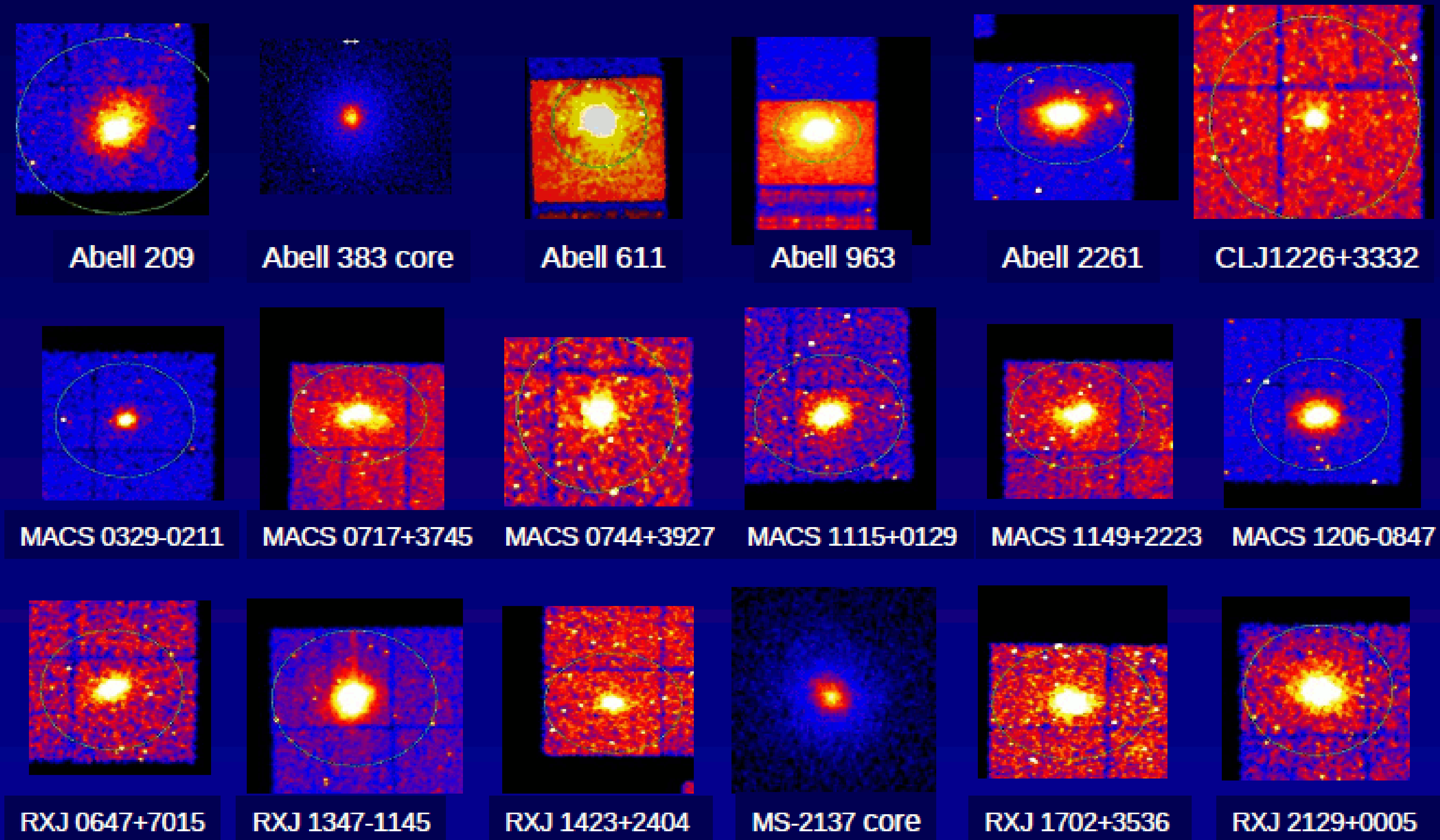
Turn-over @ $k \sim k_{eq}$

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

$k > k_{NL} \sim 0.2h$/Mpc at z=0

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

CLASH: An HST Multi-Cycle Treasury Program



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