ASIAA Luncheon Talk

Galaxy Clusters as Cosmic Lenses

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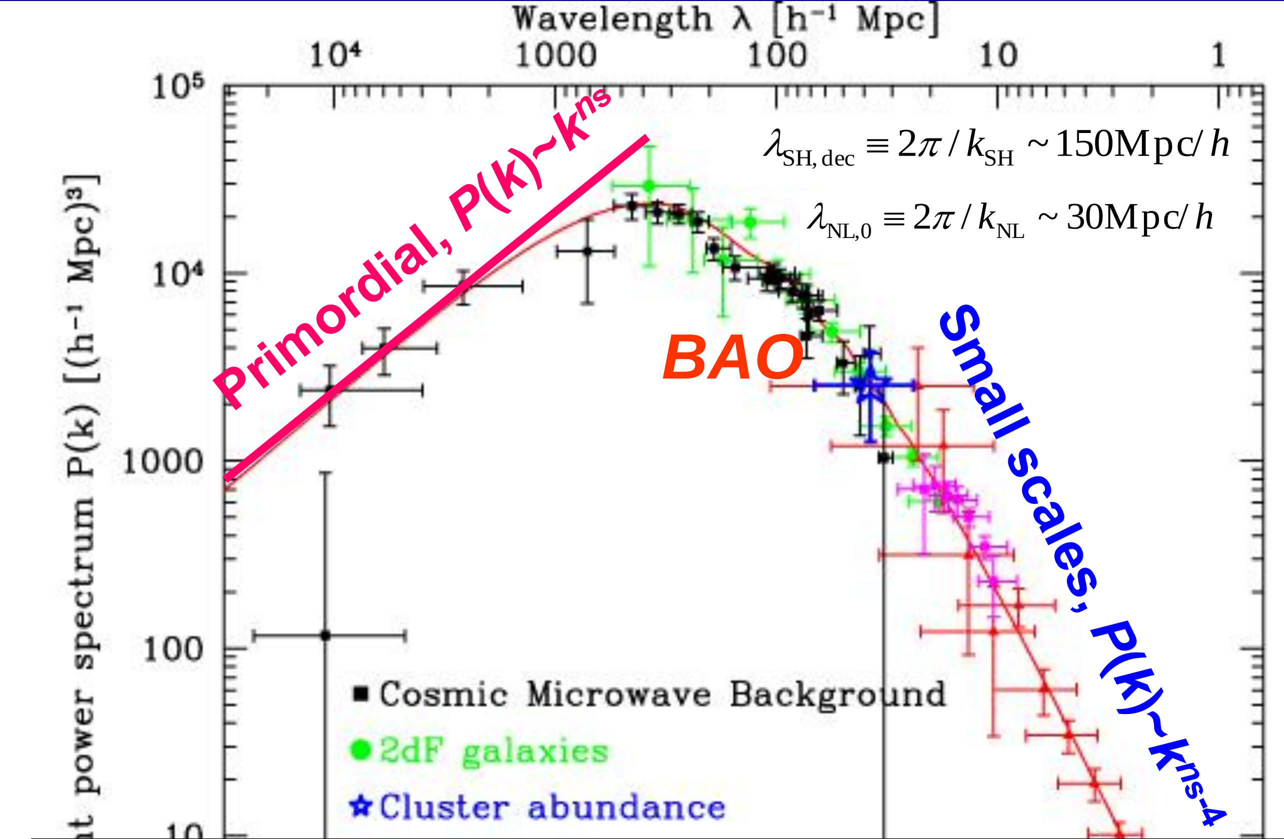
Matter PSD, $P(k)$: Data vs. ΛCDM



$P(k) \propto k^{n_s}$ with $n_s \sim 1$ @ $k \ll k_{eq} \sim 0.01$h/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 radiation era (z>3000)

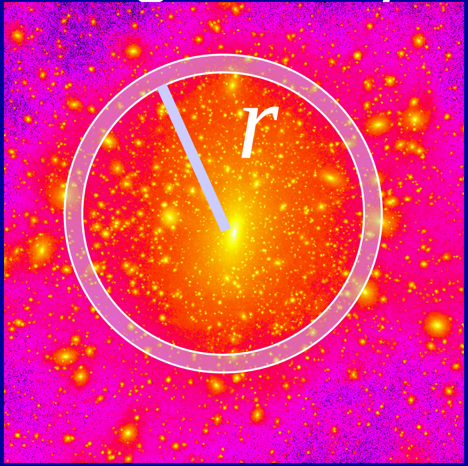
Nonlinear @ high-k modes,

Cosmic mean properties on "large scales" are well explained by ΛCDM.

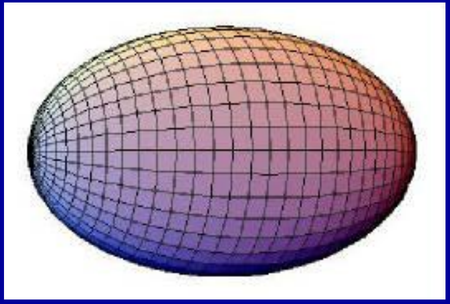
How about nonlinear scales where $\Delta := \Delta\rho/\langle\rho\rangle \gg 1$?

Predictions on (collisionless) CDM halos

- CDM mass profiles $\rho(r)$ are nearly universal
  - **Shape** is nearly independent of halo mass (**self-similar**), $\rho(r/r_s)/\rho_s=\eta(x)$
  - **Normalization**: the *more massive* a halo, the *less concentrated* it is.
- CDM halos are cuspy, with outwardly-steepening density slopes: $\gamma(r) := d\ln\rho/d\ln r$
  - $\gamma \sim -1$ at innermost radius, $\gamma \sim -3$ at large radius
  - **Self-annihilation** signature? $dL/dV \sim \rho^2 \langle\sigma v\rangle$



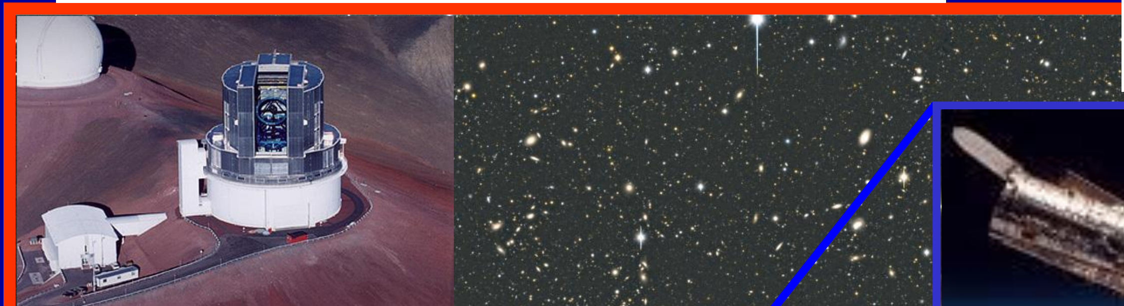
- CDM halos are clumpy
  - Abundant substructure (5%-20% in mass)
  - Massive (hence young) halos are substructure rich.
- CDM halos are triaxial
  - Preference for prolate configuration
  - Asphericity increasing toward the center

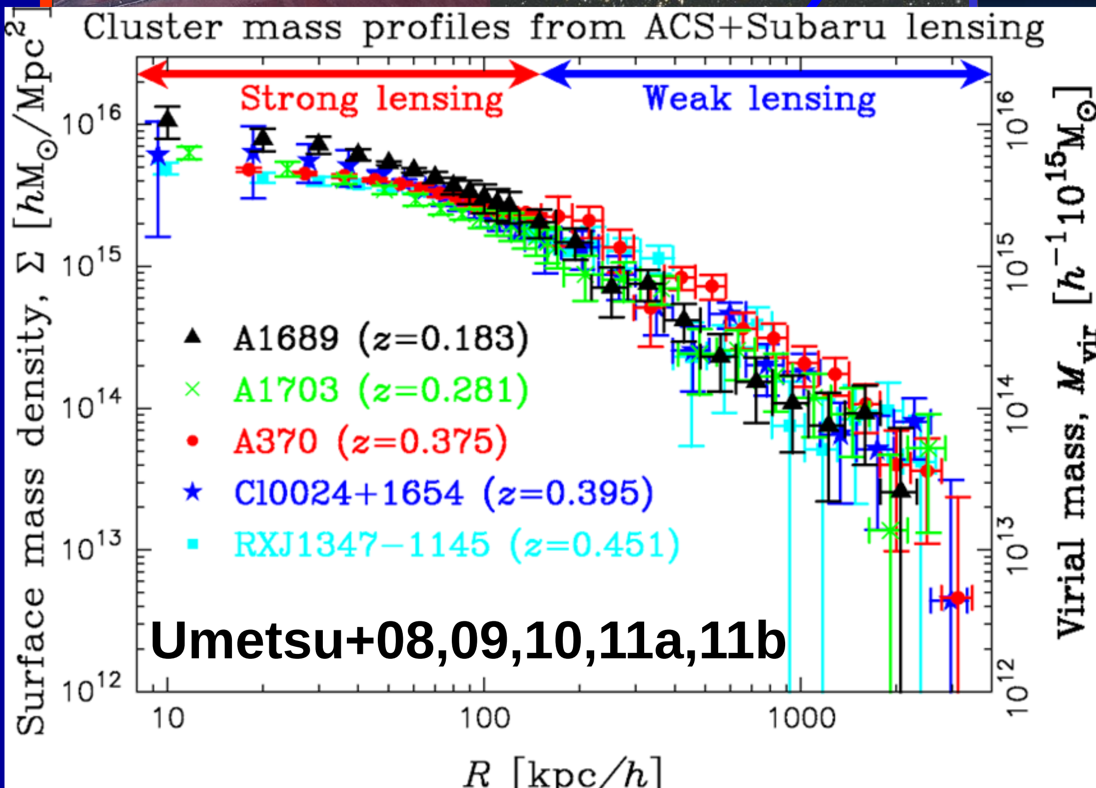


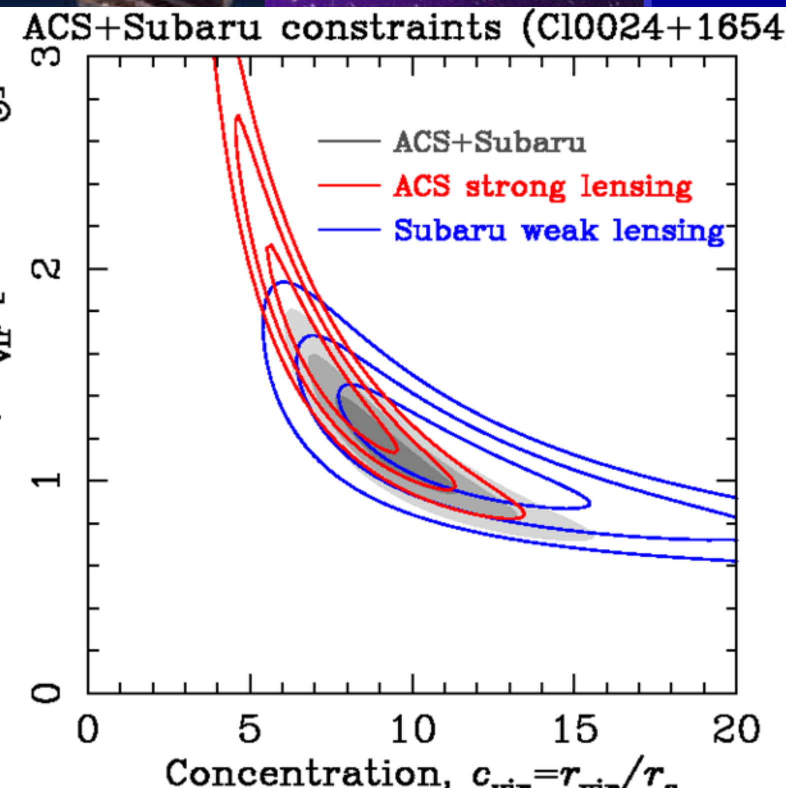
My Approach: Cluster Gravitational Lensing

SUBARU wide-field imaging (*Suprime-Cam*) for weak lensing

High-resolution space imaging with *Hubble* for strong lensing

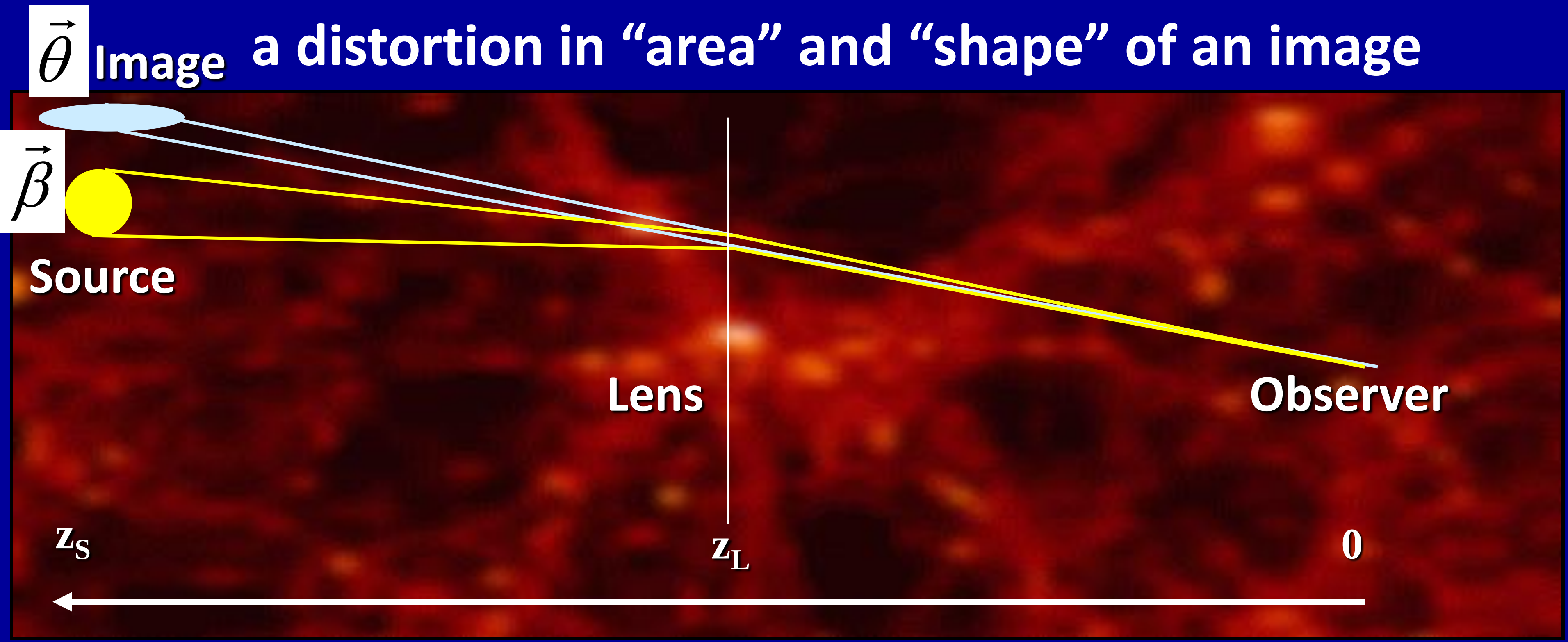






Shape and Area Distortions by Lensing

Differential deflection due to tidal force causes a distortion in “area” and “shape” of an image



Deformation of an image

$$\delta\beta_i = (\delta_{ij} - \psi_{,ij})\delta\theta_j + O(\delta\theta^2)$$
$$\approx \left[(1-\kappa)\delta_{ij} - \Gamma_{ij}\right]\delta\theta_j$$

Amplification of solid angle (i.e., flux)

$$\mu = \det\left(\frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}}\right)^{-1} = \frac{1}{(1-\kappa)^2 + \det\Gamma}$$

Strong Lensing [1]: Multiple Imaging

33* lensed images of ***11*** source galaxies identified in HST/ACS multicolor images by SL analysis (Zitrin, Broadhurst, Umetsu+09, MNRAS, 396, 1985)

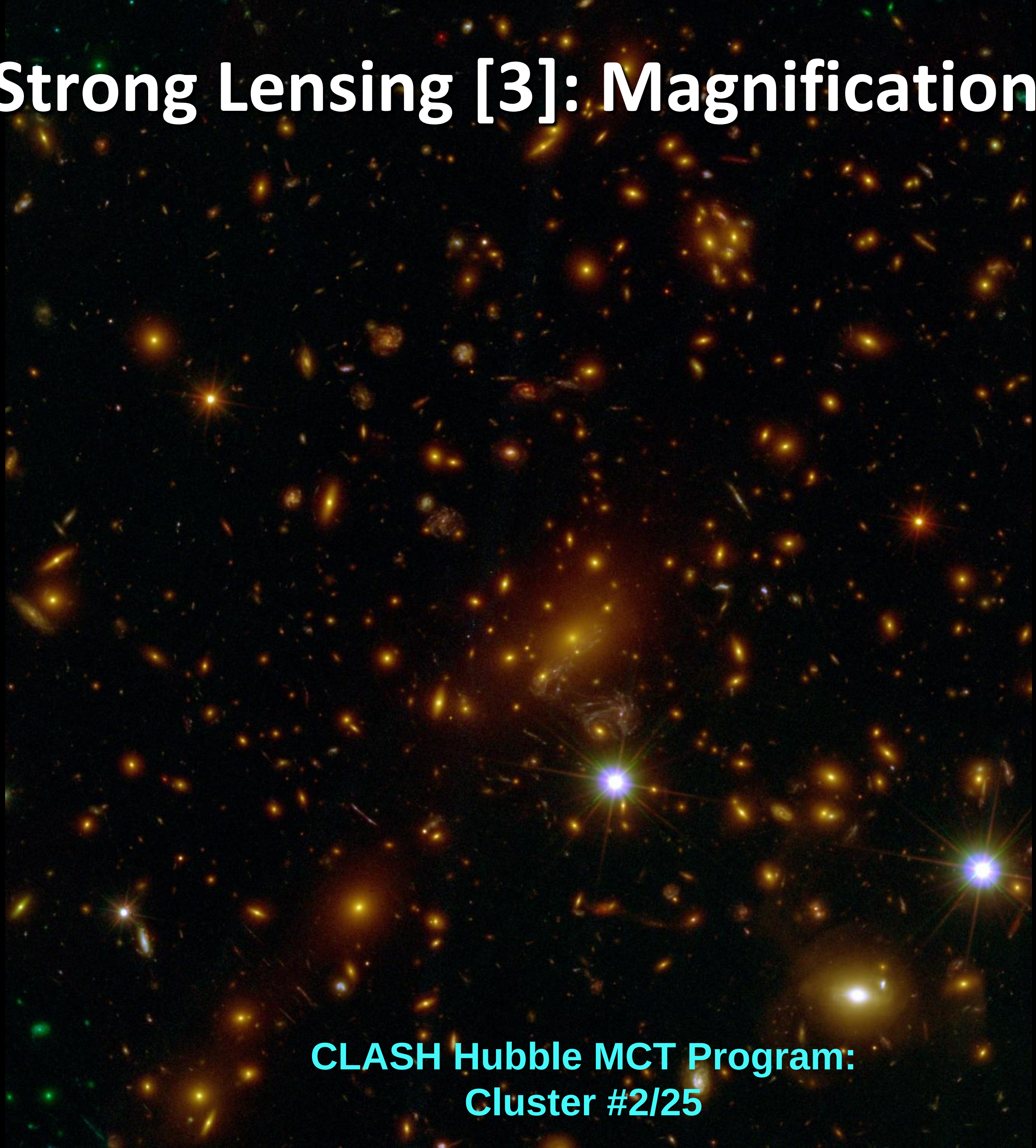
CL0024+1654 (z=0.395)

HST/ACS


Abell 383
z = 0.187
Strong Lensing [2]: Giant Arcs
Zitrin+11 (arXiv:1103.5618)
CLASH Hubble MCT Program:
Cluster #1/25

MACSJ1149
z = 0.544

Strong Lensing [3]: Magnification

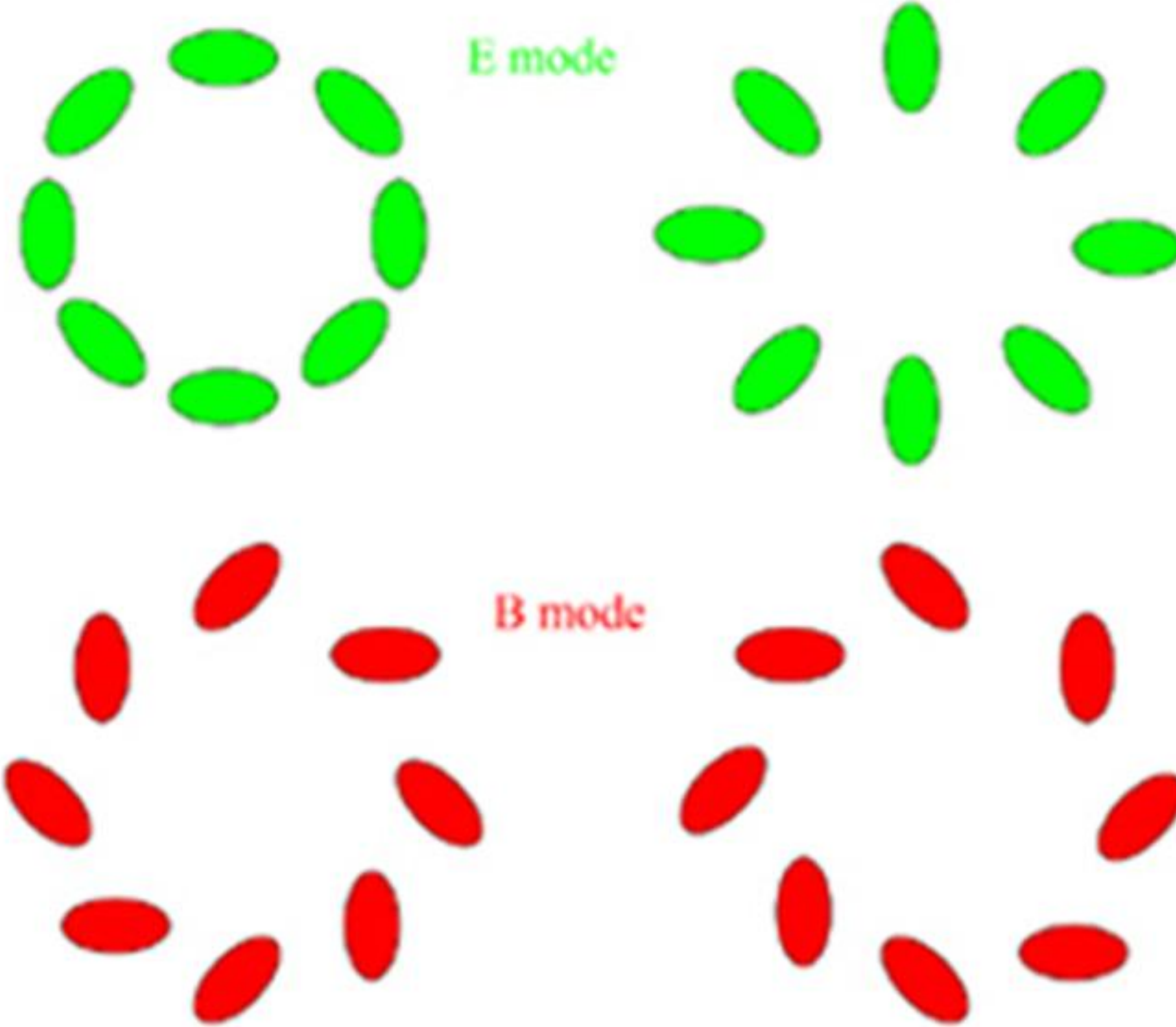


CLASH Hubble MCT Program:
Cluster #2/25

Strong Lensing [4] Tangential Arcs

Abell 2261
z = 0.224

CLASH Hubble MCT Program:
Cluster #3/25


E mode
B mode

Weak Lensing [2]: Magnification Bias

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

$$\frac{n(\boldsymbol{\theta})}{n_0} = \mu^{s-1}(\boldsymbol{\theta}) \approx 1 + \underline{2(s-1)\kappa(\boldsymbol{\theta})}$$

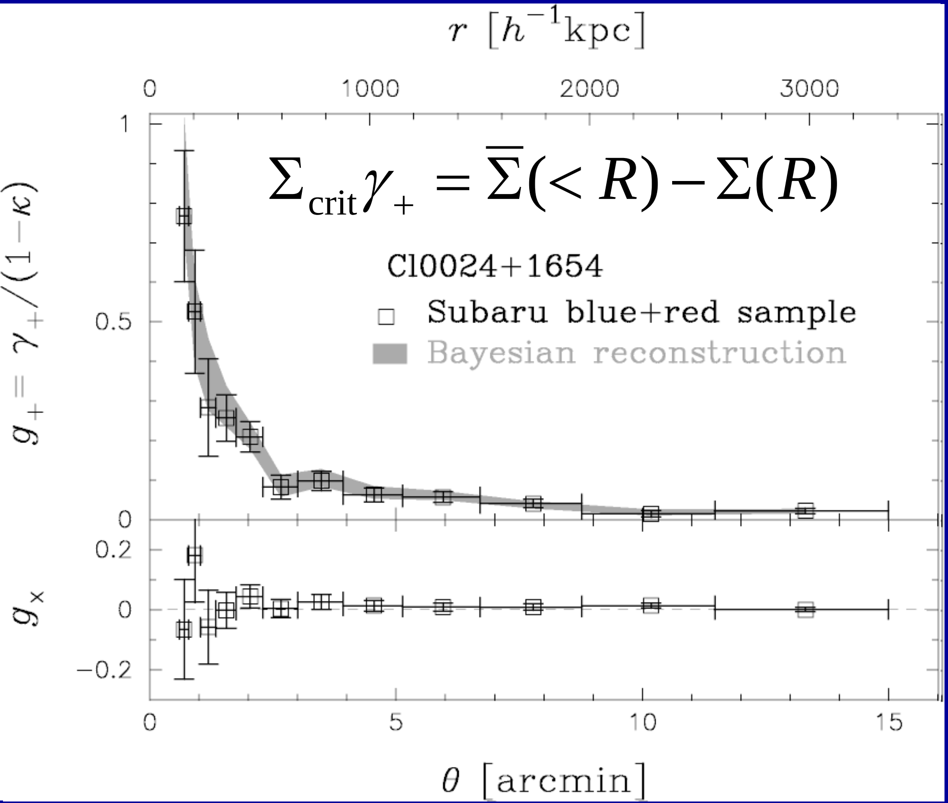
with faint-end slope, *s*, of unlensed Luminosity Function, $n_0(>F)$

$$n_0(>F) \propto F^{-s}$$

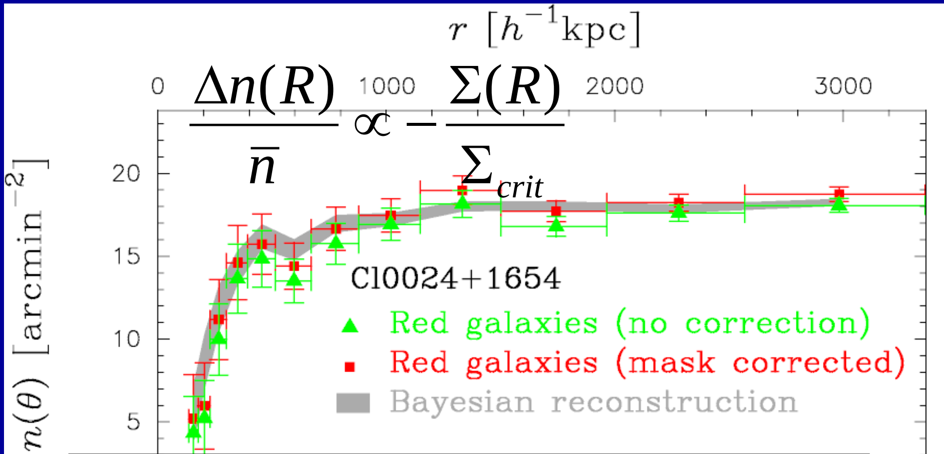
When the faint-end slope is shallow, i.e., s<1, a net deficit of counts is expected (the case for **red galaxies**)

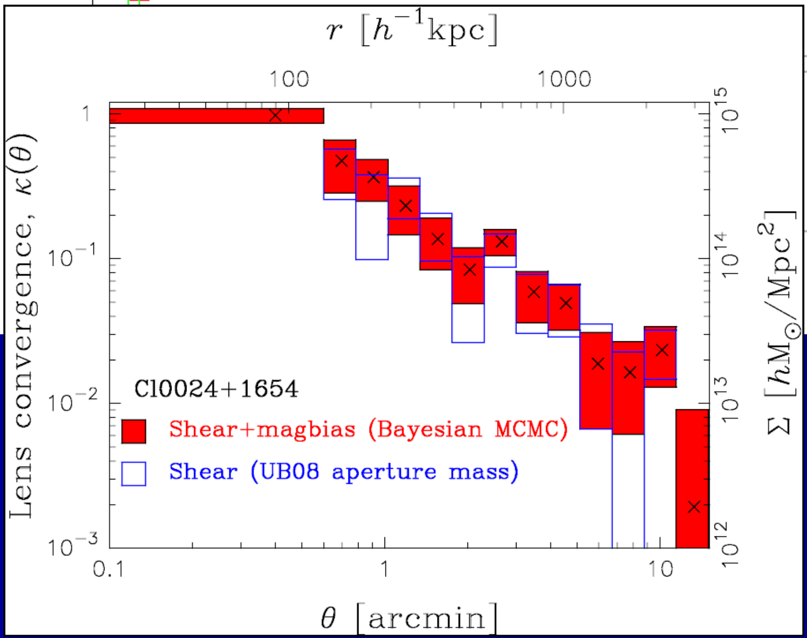
Shear and Magnification Combined

Tangential shear radial profile



Number counts (magnification bias)

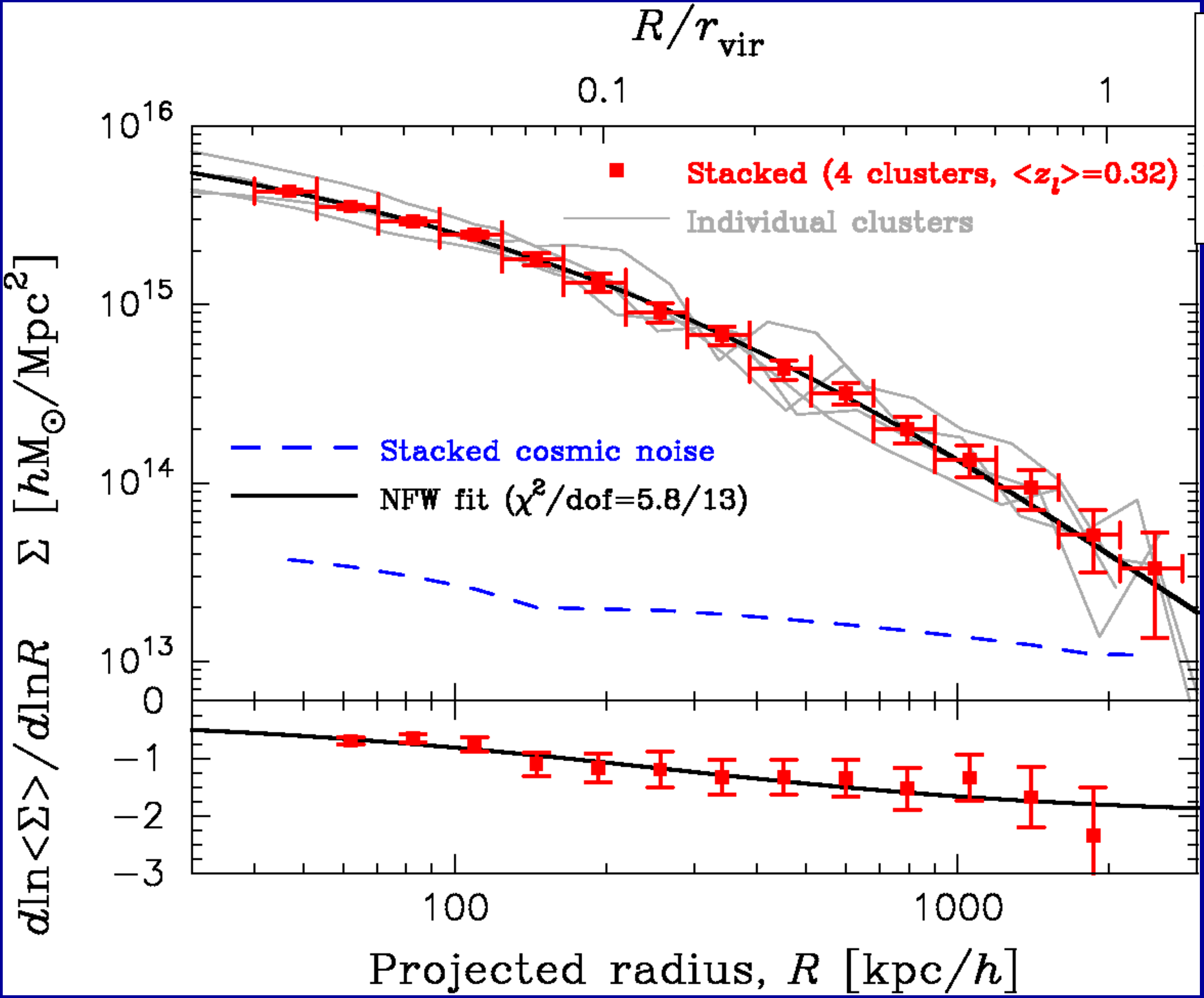




A unique mass-profile solution (Σ) can be obtained from a Bayesian analysis of joint WL shear + magnification measurements

Umetsu+2011a, 2011b

Highlights: 58σ cluster mass profile averaged from the highest-quality SL+WL data



Stacking clusters by

$$\langle\Sigma\rangle = \left(\sum_n C_n^{-1}\right)^{-1}\left(\sum_n C_n^{-1}\Sigma_n\right)$$

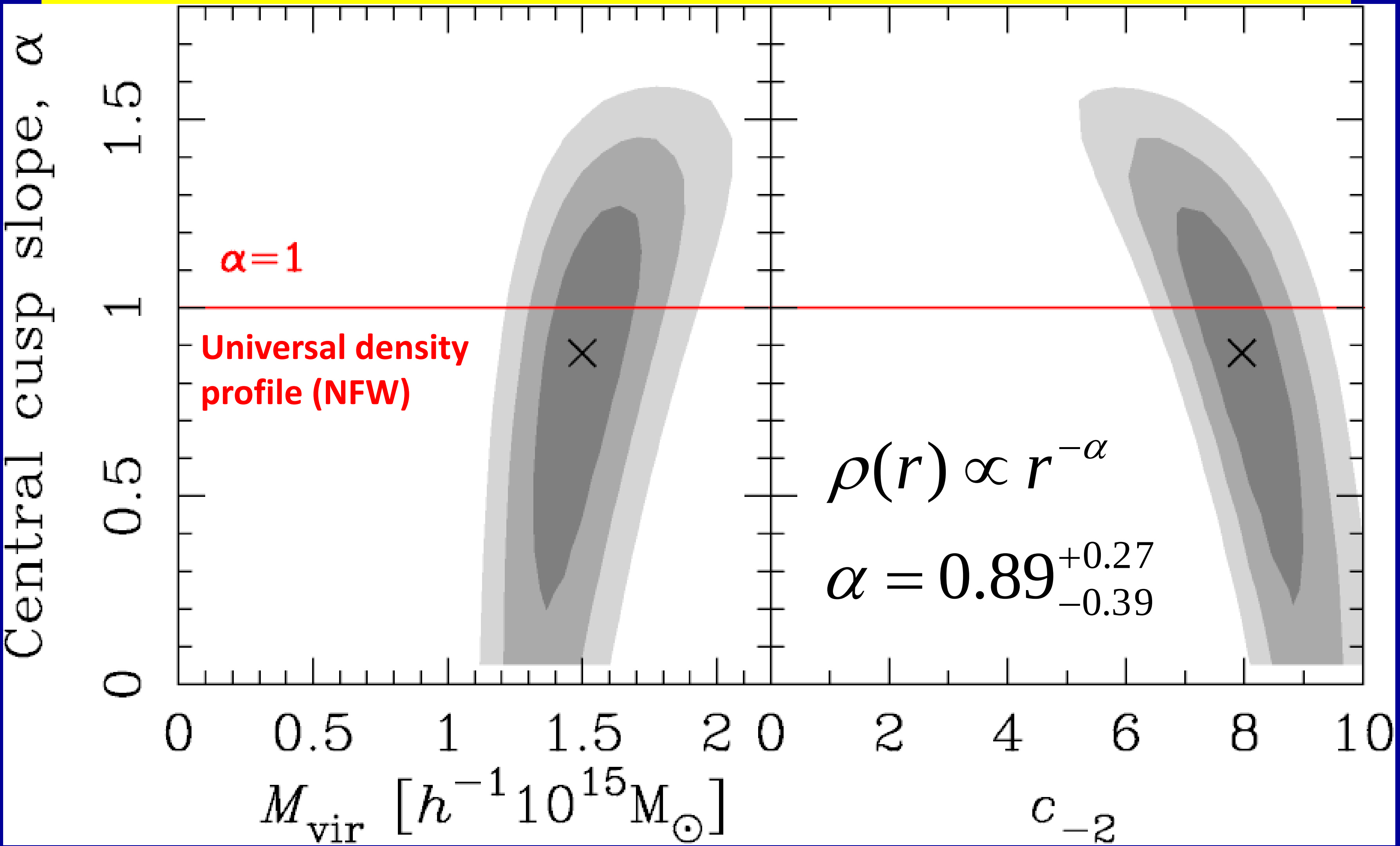
2-parameter CDM universal profile gives an excellent fit over 2-decades of radius

SIS model is rejected at >60σ significance

Lensing observations are consistent with that, DM is non-relativistic (cold) and effectively collisionless on the relevant scales.

Umetsu et al. 2011b, ApJ in press (arXiv:1105.0444)

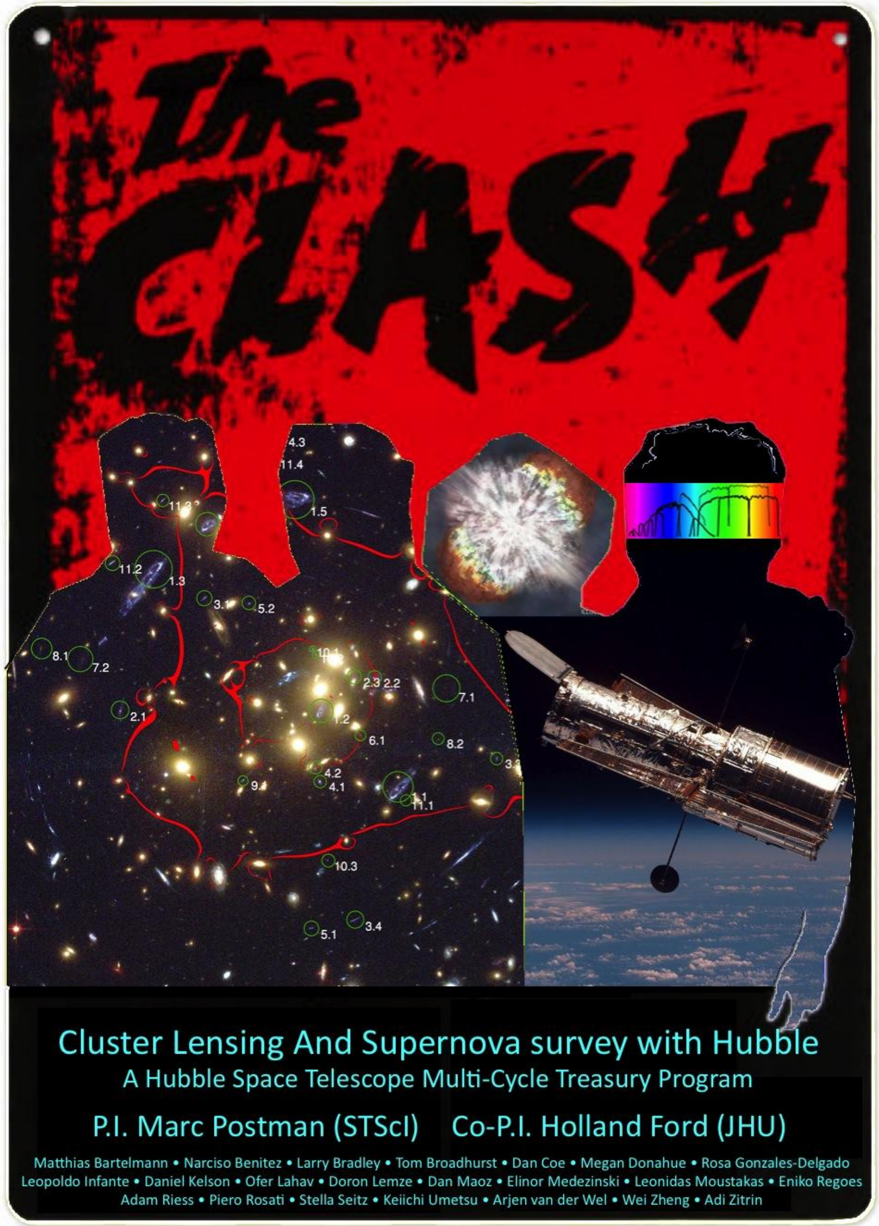
Constraint on Central Cusp Slope



Slightly shallower than, but consistent with, the CDM universal density profile (cf. Navarro et al. 2010)

Umetsu et al. 2011b

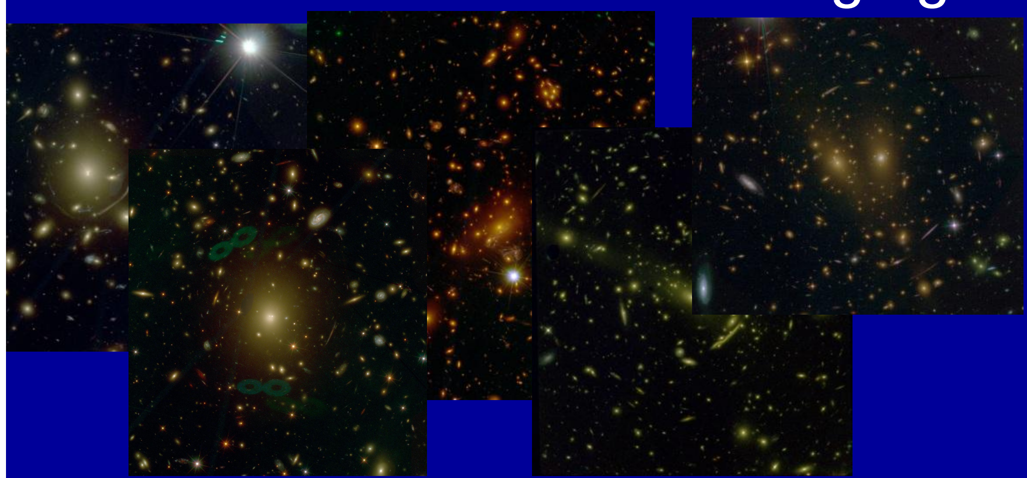
More² Hubble data to come!



A 524-orbit HST Multi Cycle Treasury Program (2010-2012)

CLASH = Cluster Lensing And Supernova survey with Hubble

- 25 carefully-selected clusters at 0.2<z<0.9
- 16 WFC3/ACS band imaging

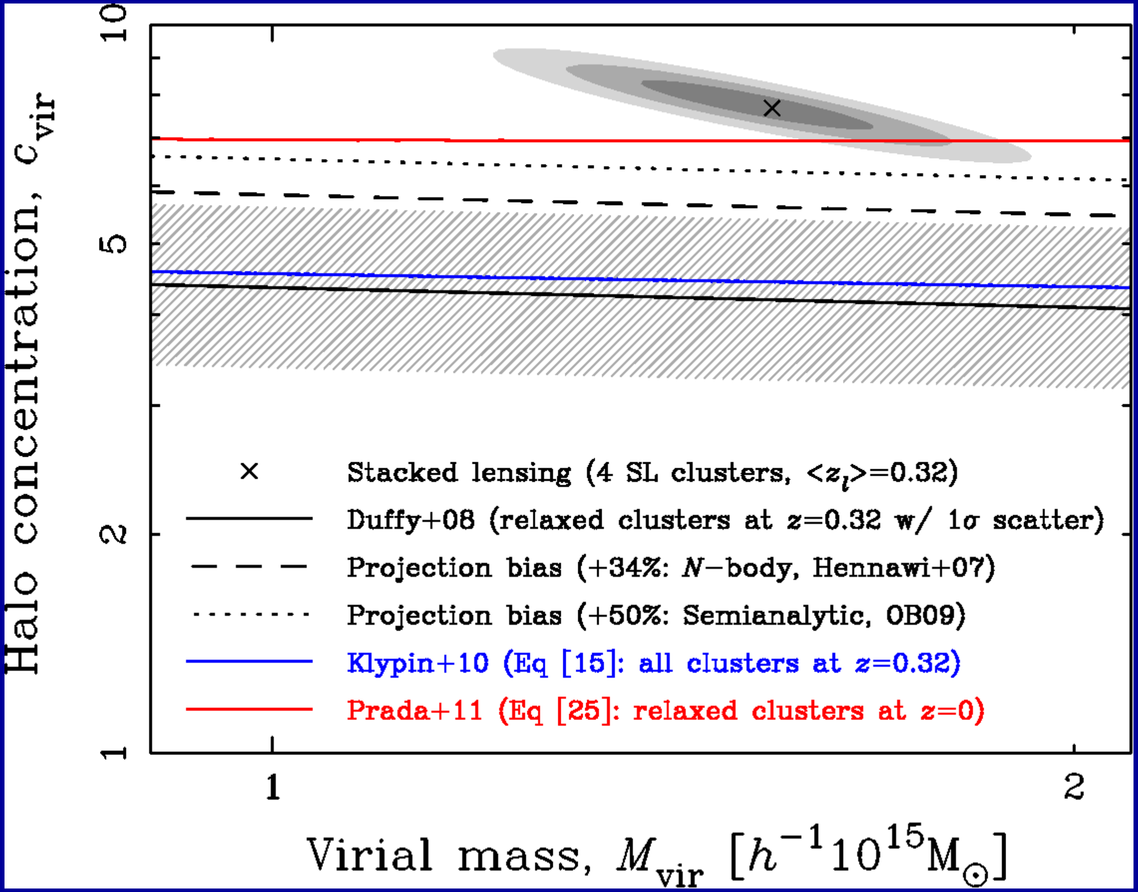


Postman+11 (arXiv:1106.3328)

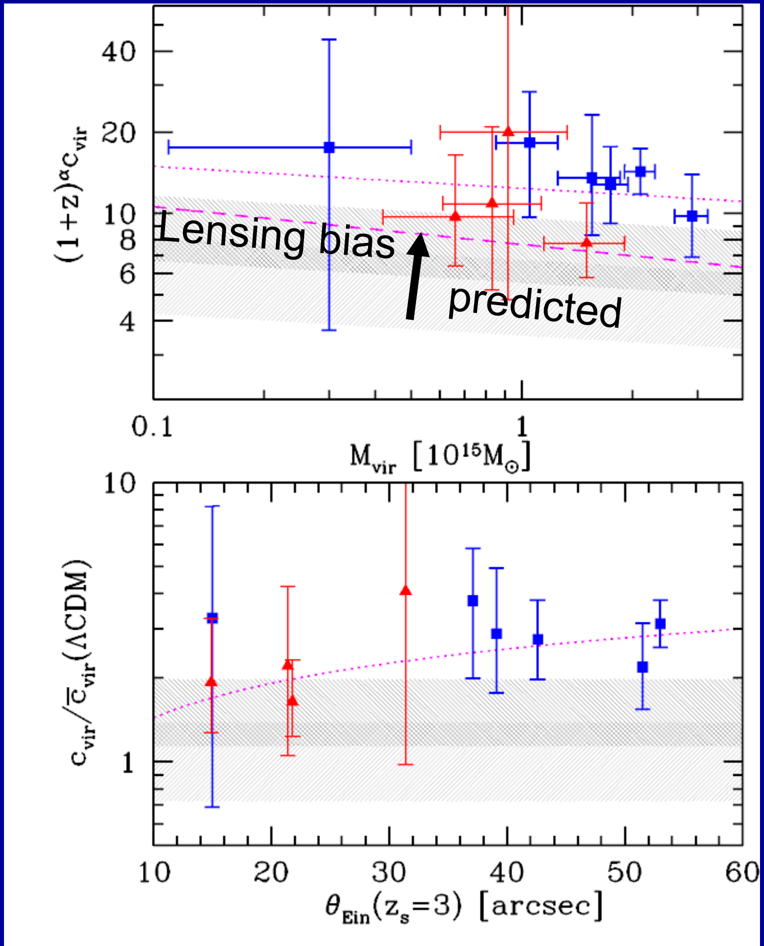
Thank You!

Halo central density somewhat higher than LCDM predictions??

Observed "lensing" clusters are more concentrated than LCDM?



Umetsu et al. 2011b



Oguri et al. 2010

Broadhurst, Umetsu, Medezinski+08