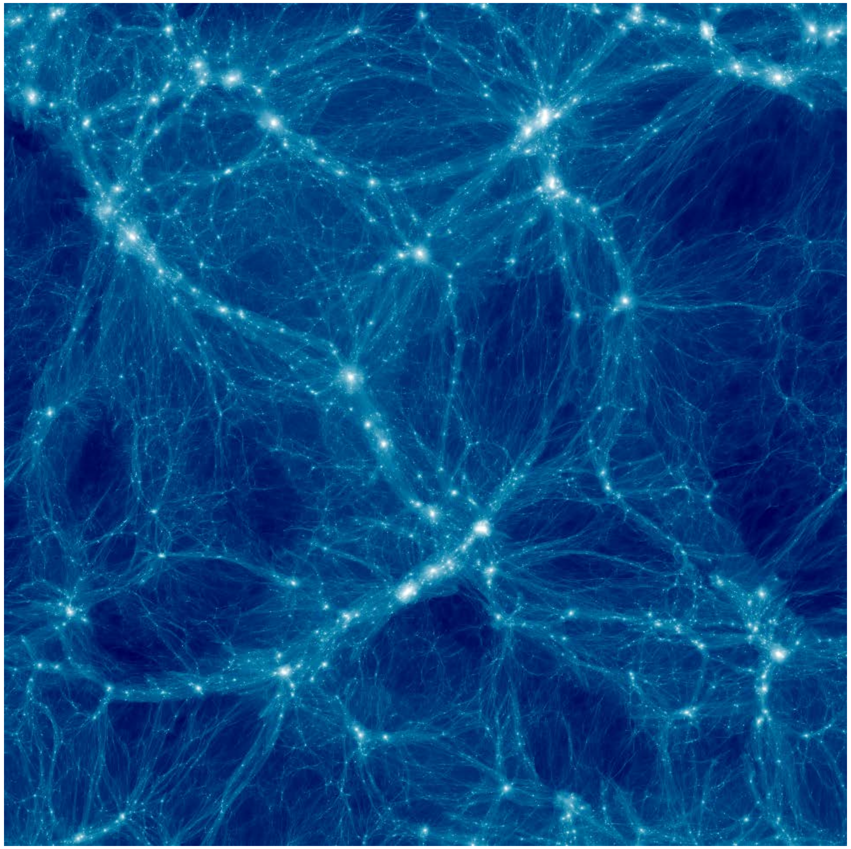
Student Seminar @ASIAA
November 19, 2015

Gravitational Lensing by Clusters of Galaxies

Keiichi Umetsu (ASIAA)

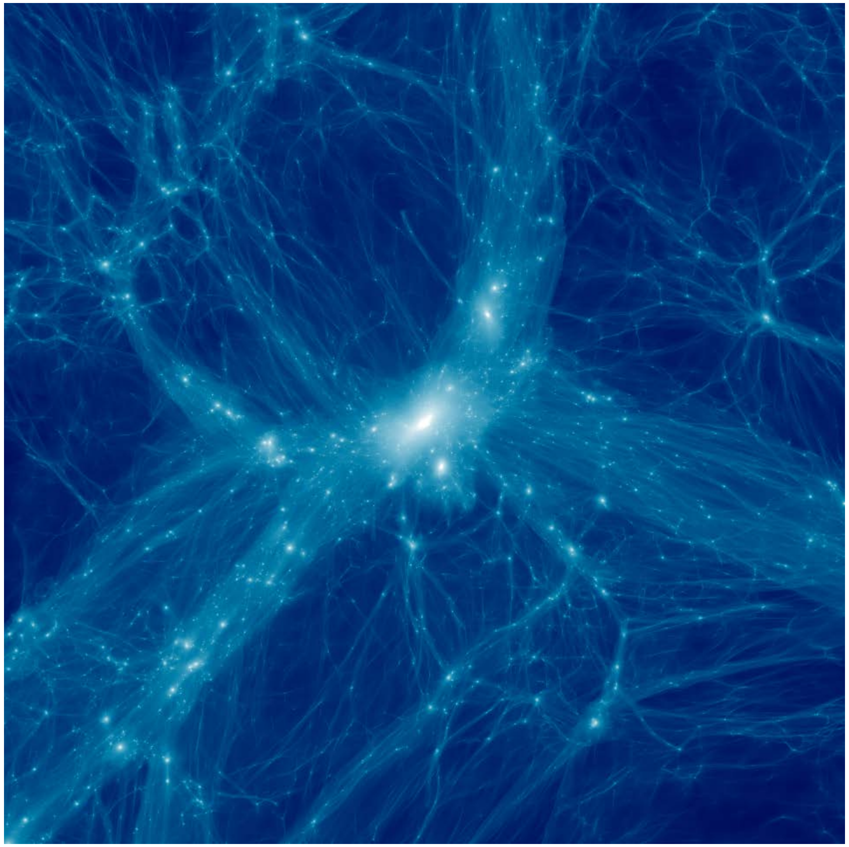
Galaxy Clusters: Building Blocks of the Universe

Large-scale structure of DM in the present-day universe



62.5Mpc/h

DM structure around a cluster-sized DM halo

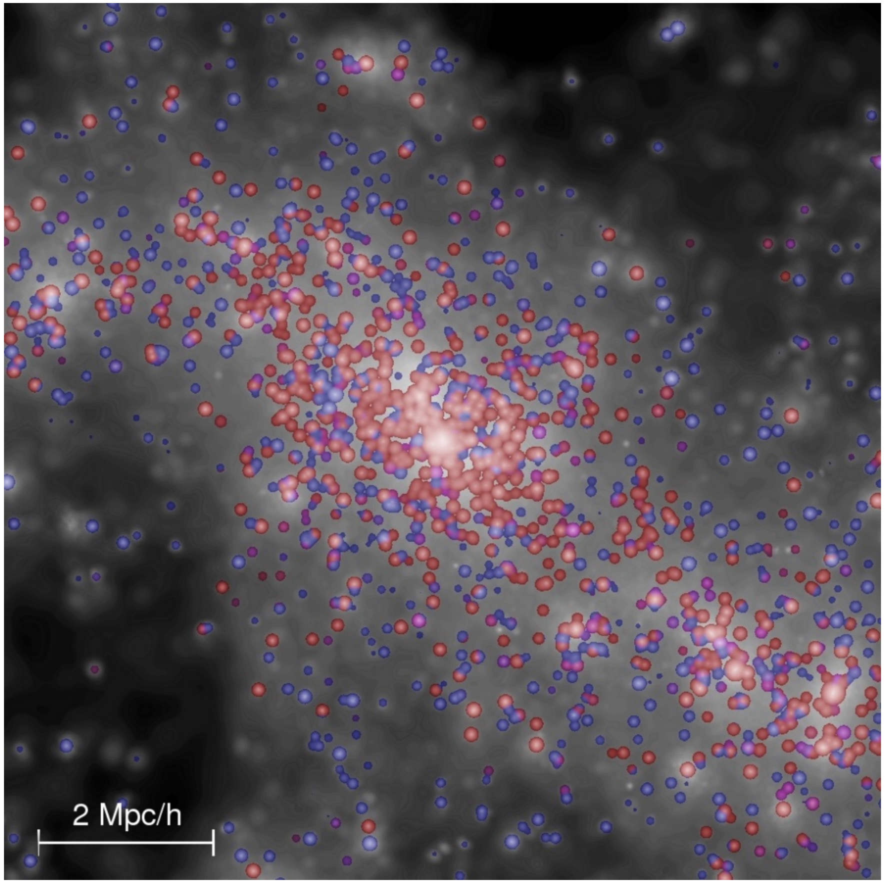


15Mpc/h

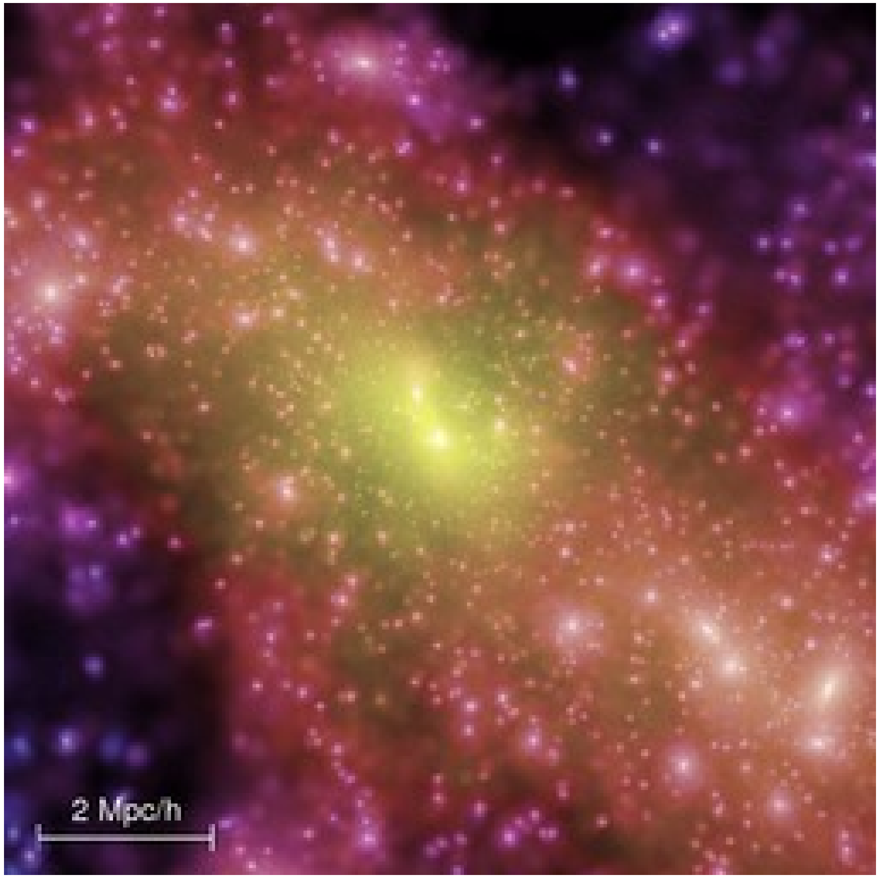
Λ cold dark matter (ΛCDM) simulations by Diemer & Kravtsov (2014)

Galaxies and Dark Matter in Clusters

Discrete galaxies



Underlying dark matter (~mass)

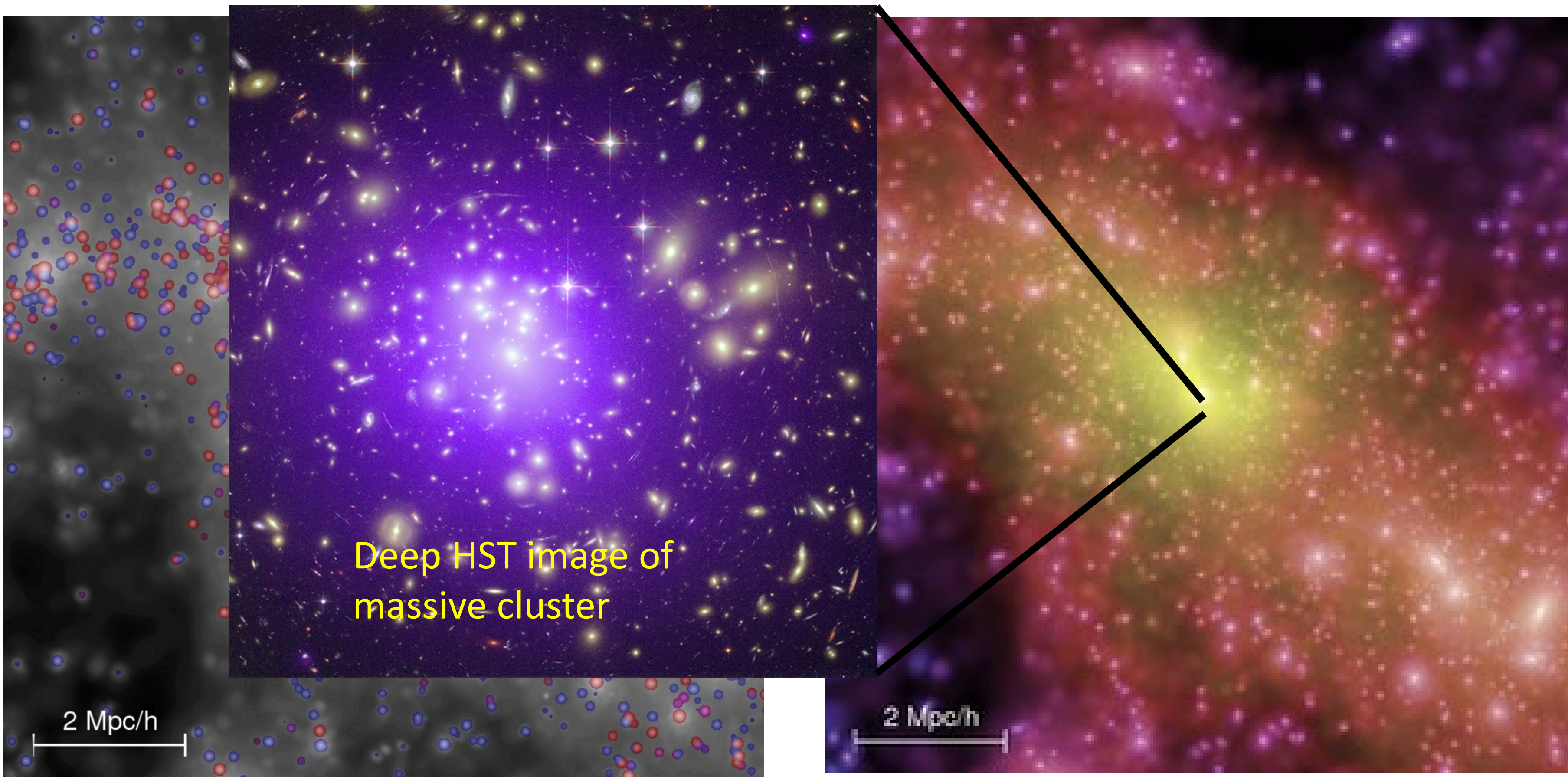


Millennium Simulation

Galaxies and Dark Matter in Clusters

Discrete galaxies

Underlying dark matter (~mass)

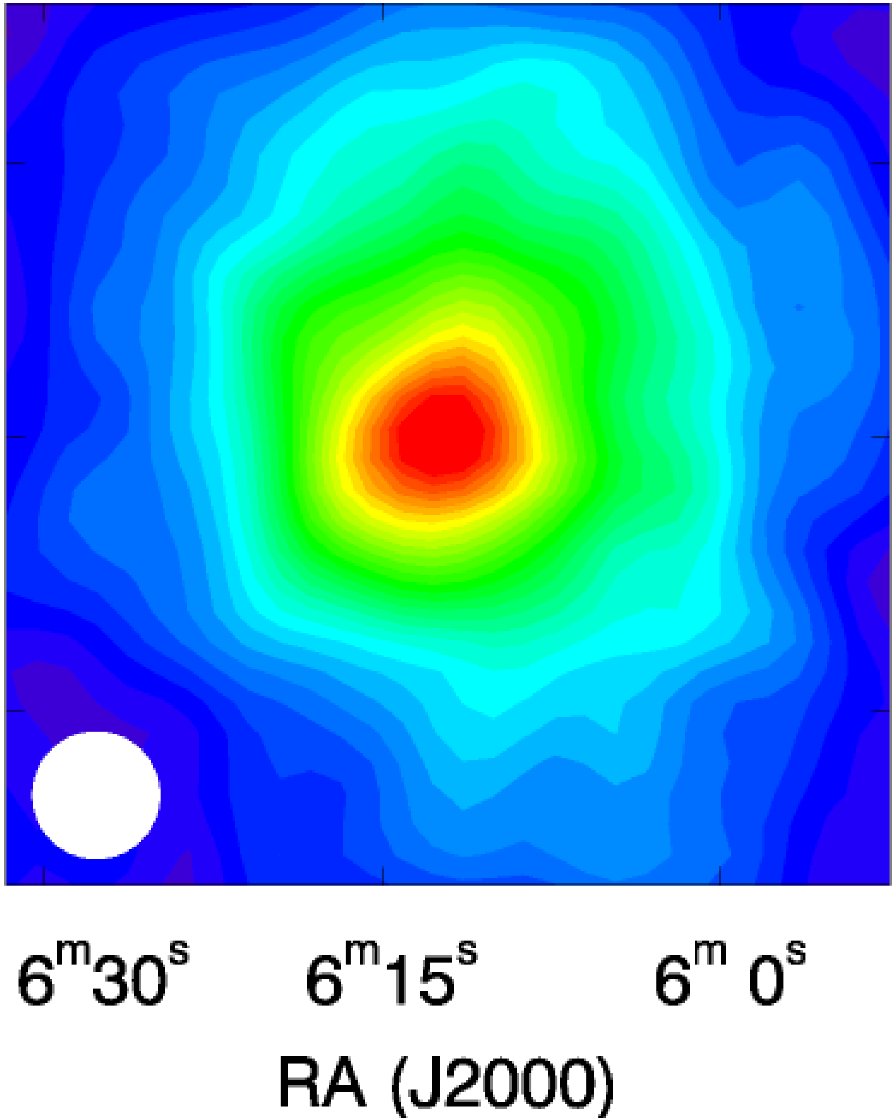


Millennium Simulation

Galaxy Cluster MACS J1206 (z=0.44)

Cluster member galaxies (*HST*)

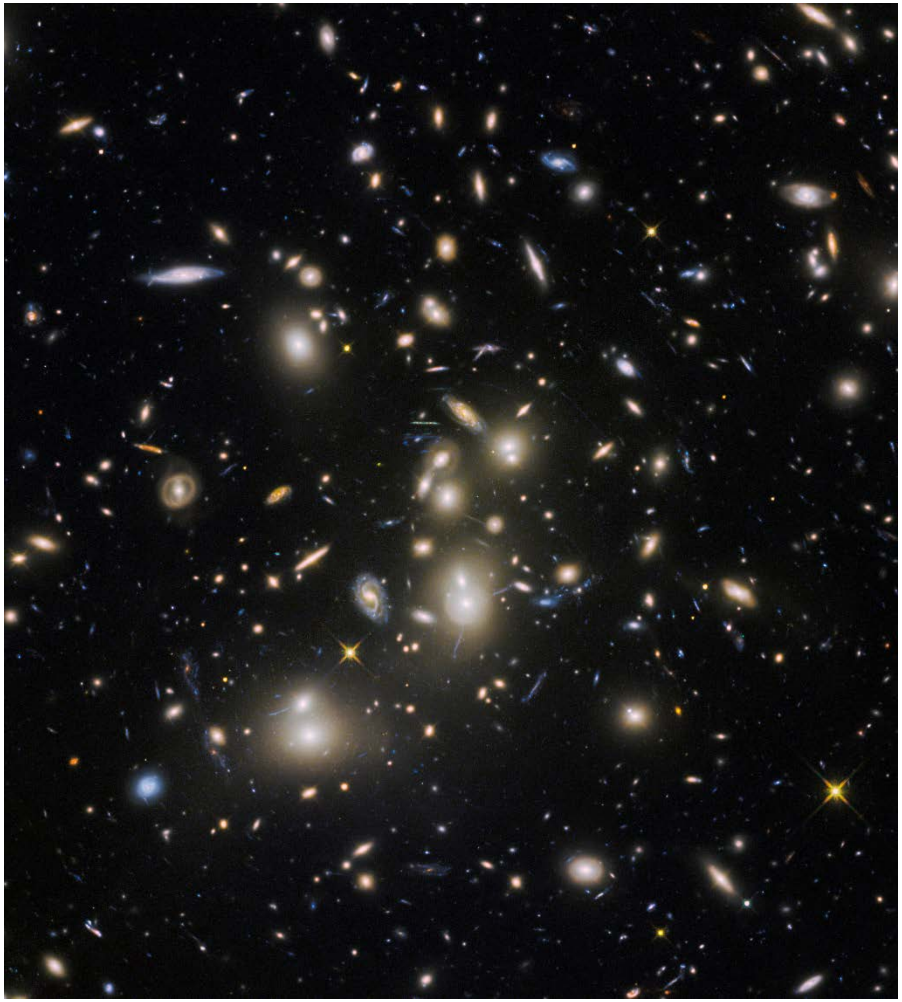
Sunyaev-Zel'dovich Effect



Umetsu et al. (2012)

Hubble Frontier Fields Cluster A2744

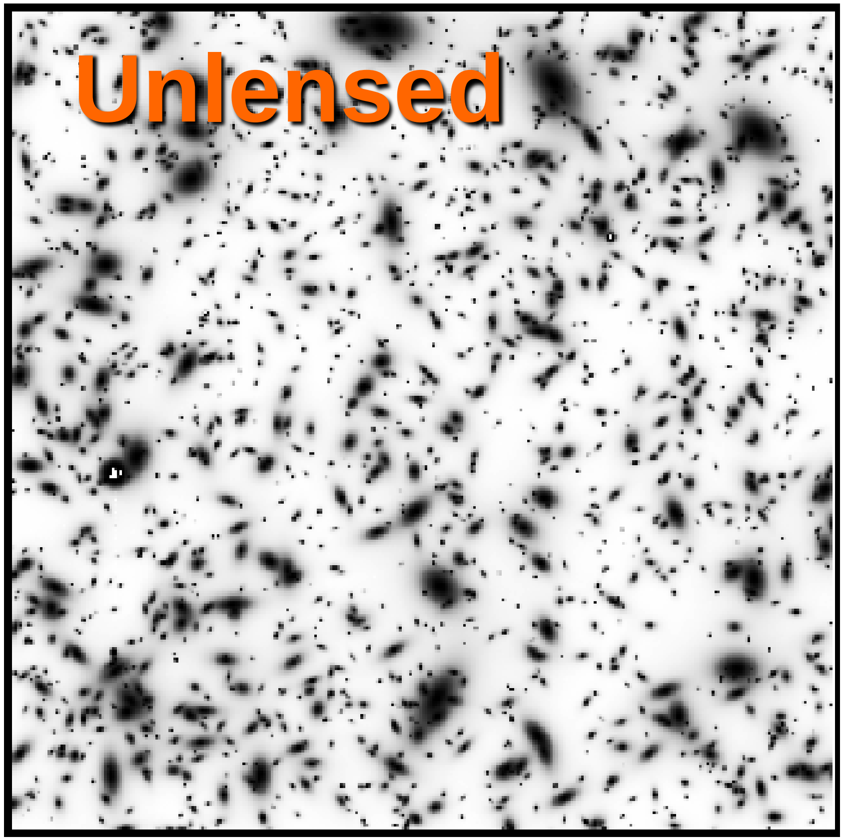
Cluster member galaxies (*HST*)

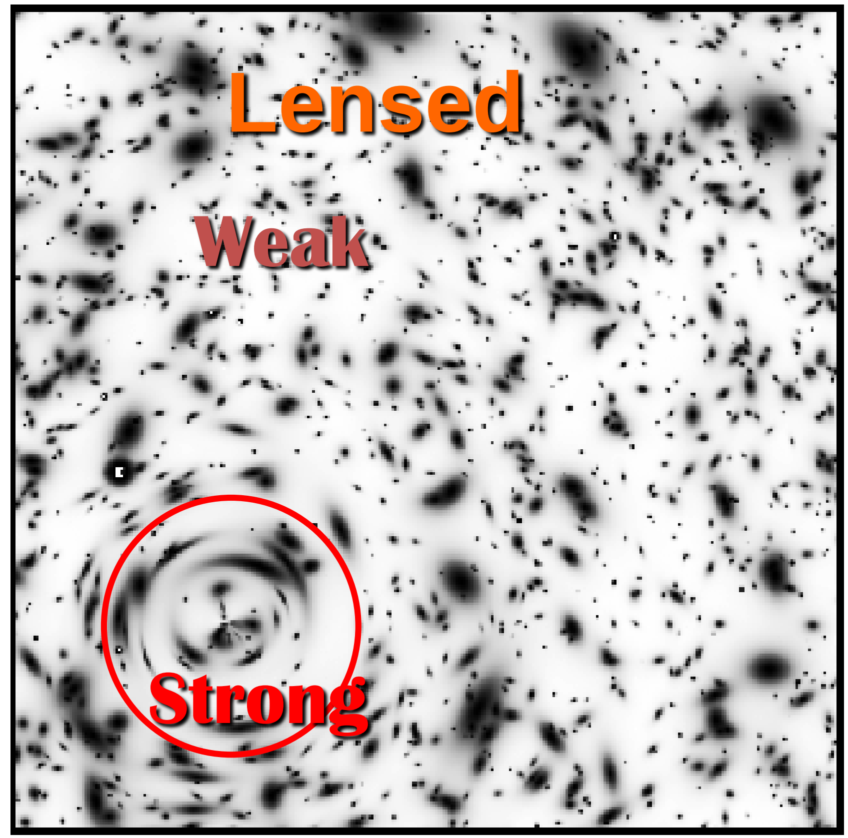


Intra-cluster Stellar Light

Credit: NASA (https://www.spacetelescope.org/images/archive/category/cosmology/)

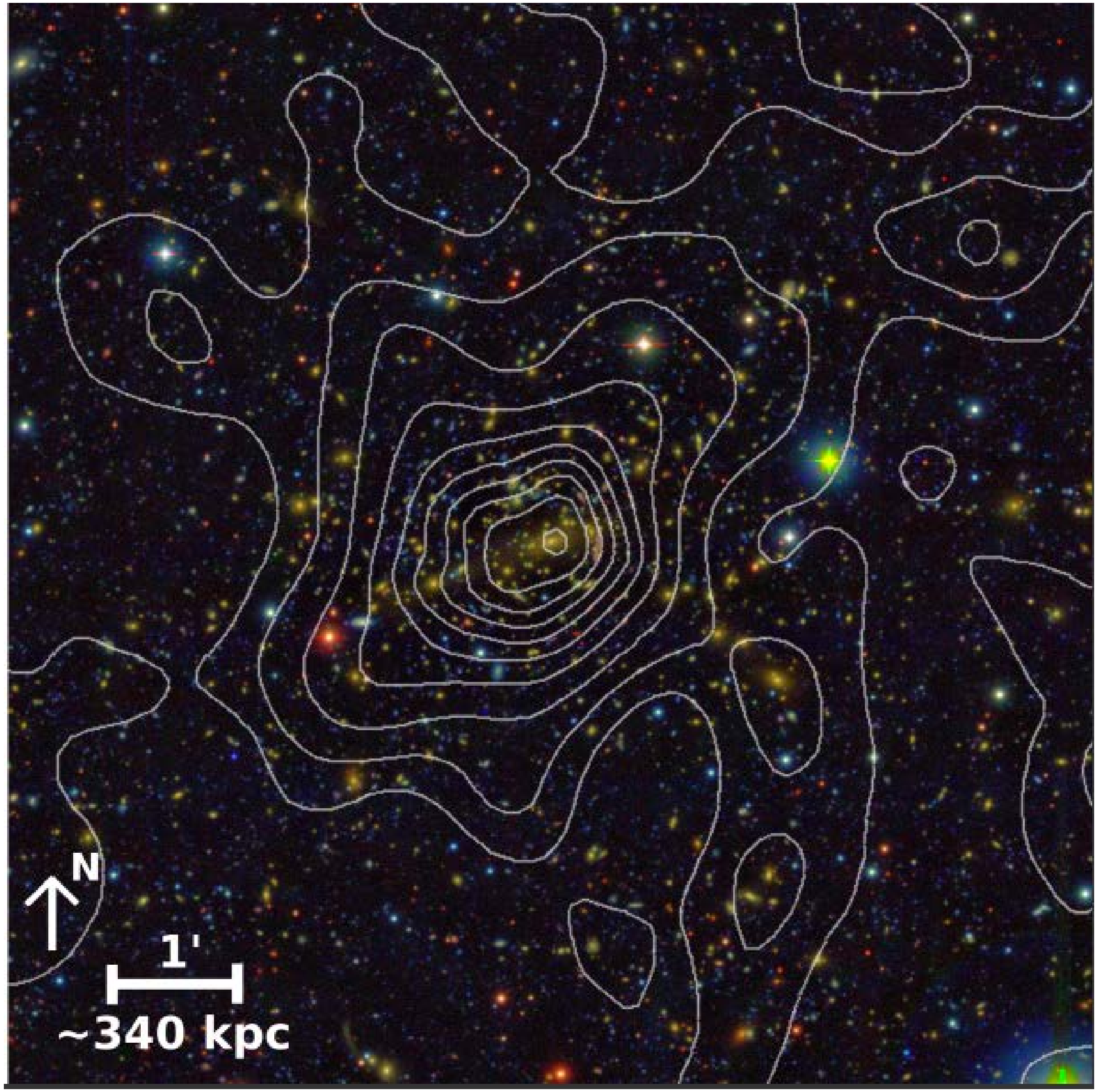
Gravitational Lensing





Fort & Mellier

Cluster Mass Reconstruction



MACS J1206 (z=0.44)

Strong-and-Weak lensing analysis (SaWLens: J. Merten) of CLASH *HST* + *Subaru* data

Umetsu et al. 2012

Gravitational Bending of Light

Lightrays propagating in an inhomogeneous universe will undergo **small transverse excursions** along the photon path

Bending angle: small transverse excursion of photon momentum ($|\Psi|/c^2 << 1$)

$$\delta\hat{\alpha} \approx \frac{\delta p_\perp}{p_\parallel} = -\frac{2}{c^2} \underbrace{\nabla_\perp \Psi(\chi_\parallel, \chi_\perp)}_{\text{Gravitational field of deflecting matter}} \delta\chi_\parallel$$

Gravitational field of deflecting matter

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

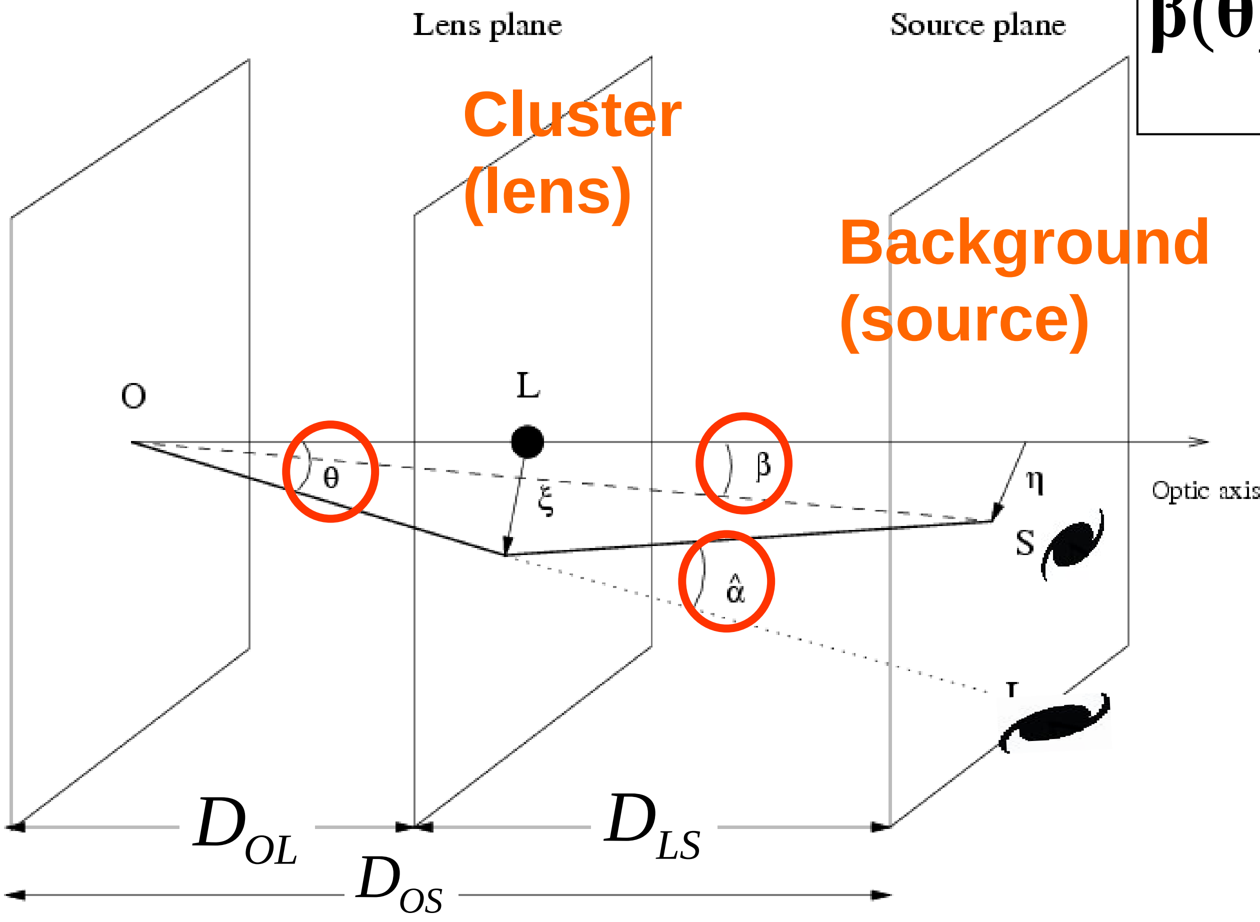
Cluster Lens Equation

Cosmological lens equation + thin-lens approximation

β: true (but unknown) source position

θ: apparent image position

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



Angular diameter distances:

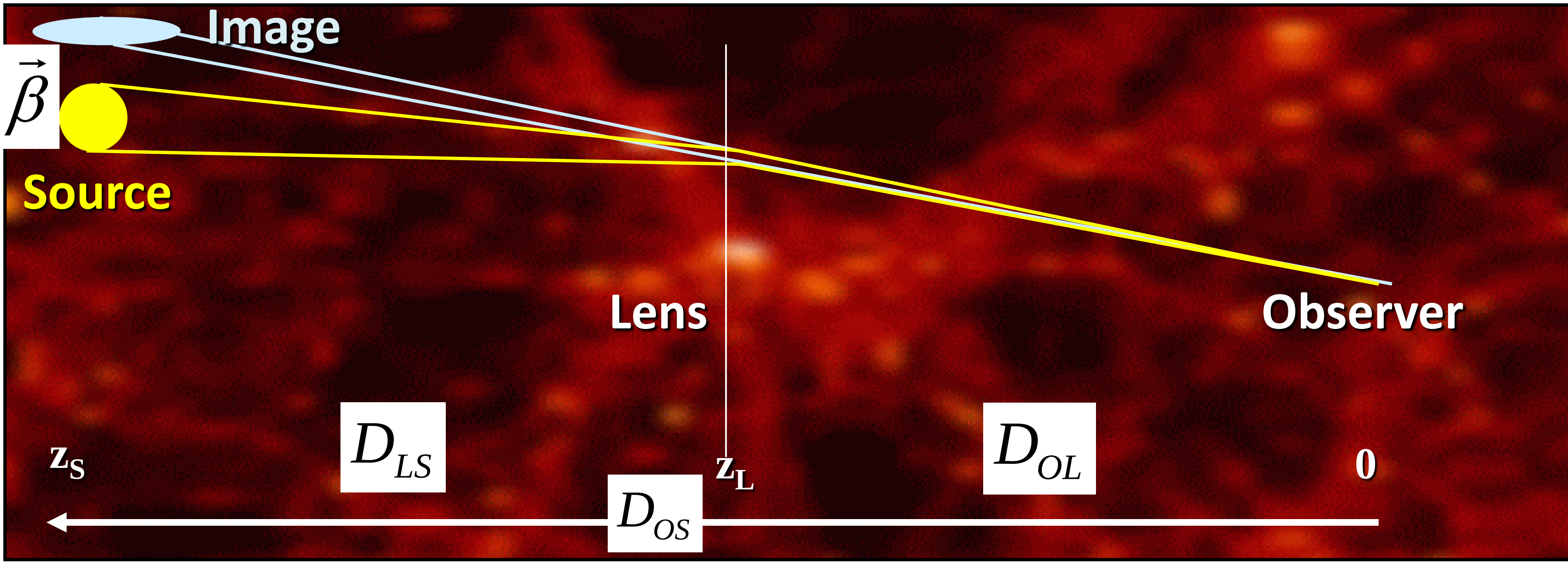
D_{OL}, D_{LS}, D_{OS} ~ $O(c/H_0)$

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

Deflection and Distortion

$$\boldsymbol{\beta}(\boldsymbol{\theta}) - \boldsymbol{\theta} = \frac{D_{\rm LS}}{D_{\rm OS}} \int_{\rm Observer}^{\rm Source} \delta\hat{\boldsymbol{\alpha}}(\boldsymbol{\theta}) \equiv -\boldsymbol{\nabla}\psi(\boldsymbol{\theta})$$

$\vec{\theta}$



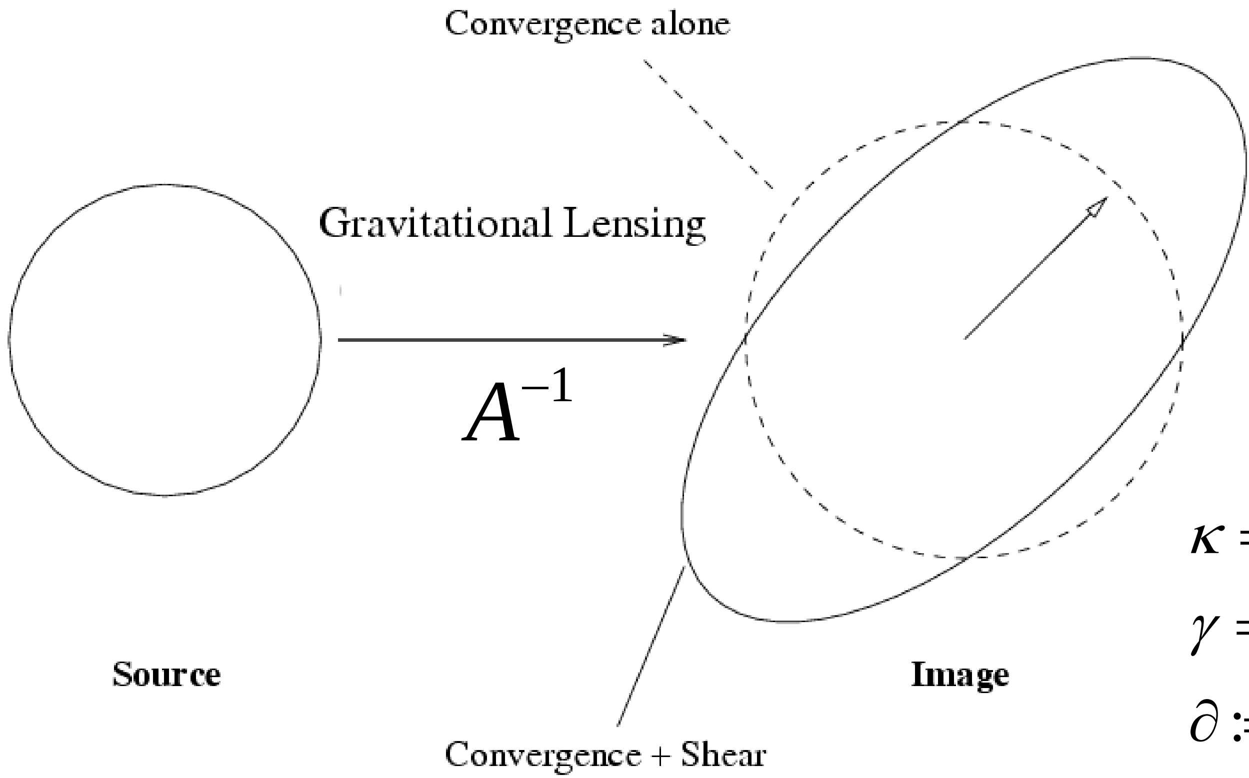
Deformation of an image

$$\delta\beta_i = (\delta_{ij} - \psi_{,ij})\delta\theta_j + O(\delta\theta^2)$$

Magnification, μ

$$\mu^{-1} = \det\left(\frac{\partial\boldsymbol{\beta}}{\partial\boldsymbol{\theta}}\right) = |1 - \nabla\nabla\psi|$$

Convergence (κ) and Shear (γ)



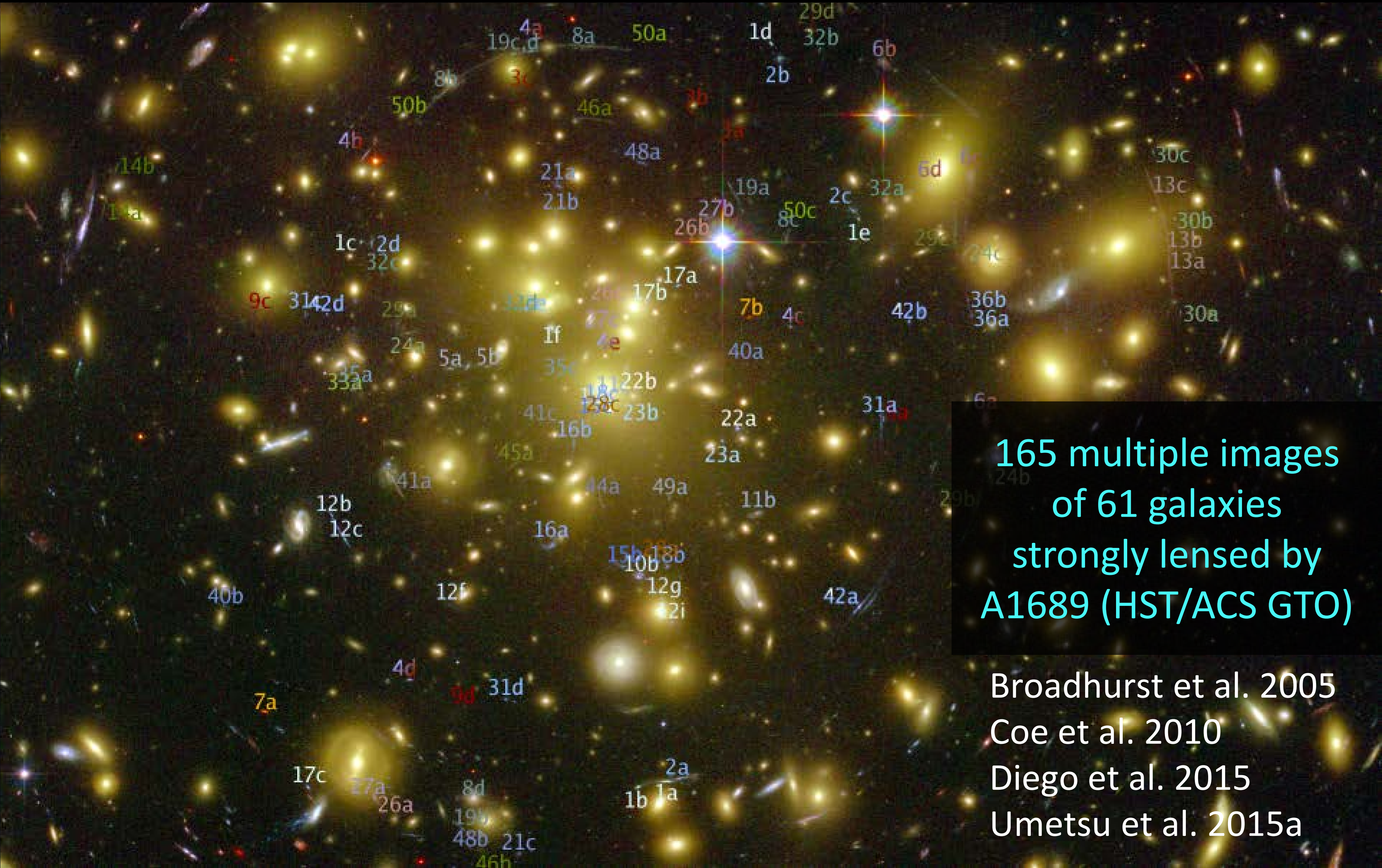
$$\kappa = \partial\partial^{*}\Psi / 2 = \Delta\Psi / 2$$

$$\gamma = \partial\partial\Psi / 2$$

$$\partial := \partial_x + i\partial_y = e^{i\phi}\partial_r$$

$$\mathcal{A}(\boldsymbol{\theta}) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} = (1-\kappa)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \begin{pmatrix} \gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{pmatrix},$$

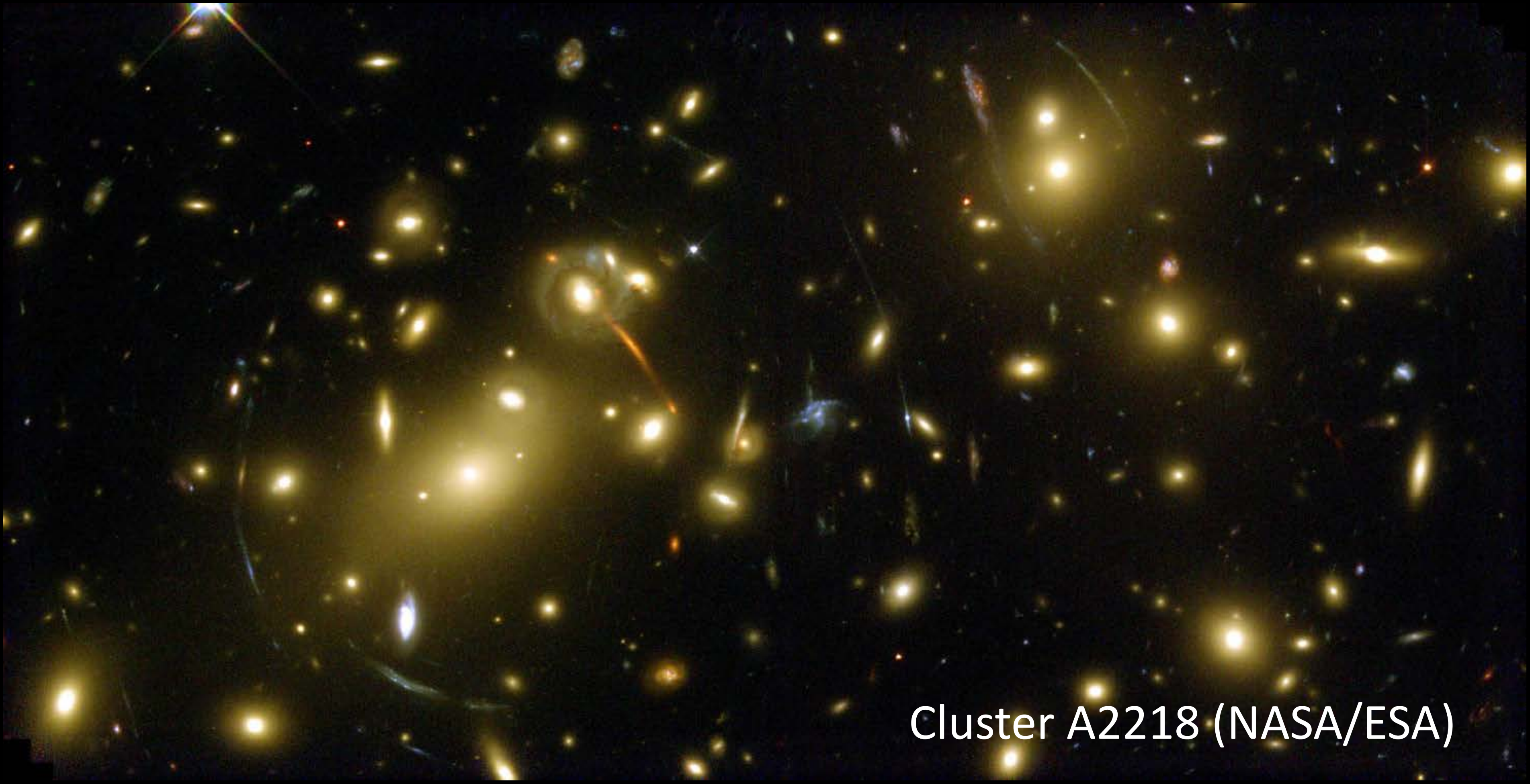
Multiple Imaging



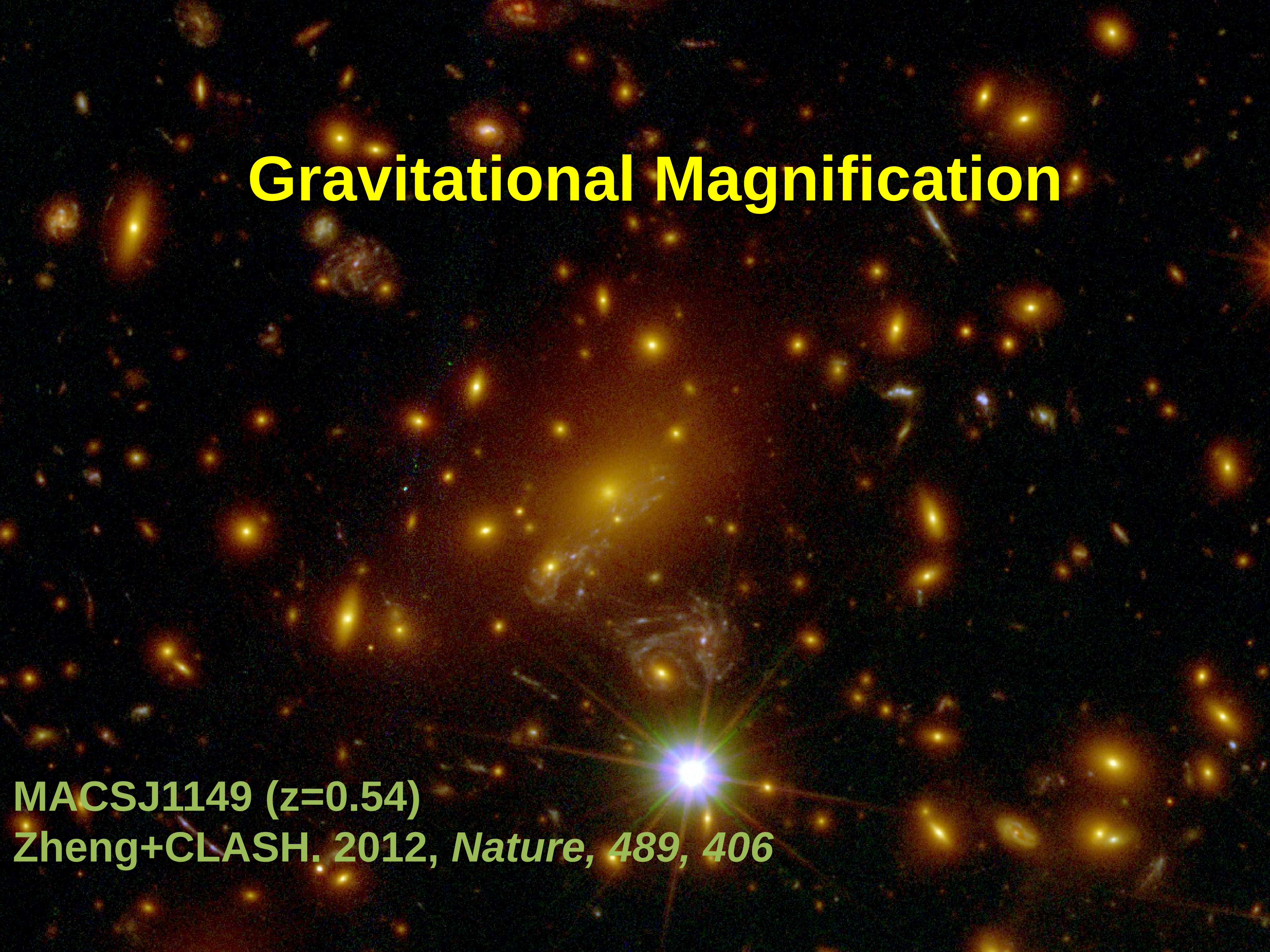
165 multiple images of 61 galaxies strongly lensed by A1689 (HST/ACS GTO)

Broadhurst et al. 2005
Coe et al. 2010
Diego et al. 2015
Umetsu et al. 2015a

Gravitational Shear



Gravitational Magnification



MACSJ1149 (z=0.54)
Zheng+CLASH. 2012, *Nature, 489, 406*

Convergence, κ

κ: weighted line-of-sight projection of density contrast $\delta=\delta\rho/\rho$

$$\kappa = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{\chi_s} d\chi\, \frac{r(\chi)r(\chi_s-\chi)}{r(\chi_s)}\frac{\delta}{a} = \int_{\mathrm{Observer}}^{\mathrm{Source}} d\Sigma\, \Sigma_{\mathrm{crit}}^{-1}$$

Surface mass density field

$$\Sigma(\boldsymbol{\chi}_\perp) = \int_0^{\chi_s} d\chi\, a(\rho-\bar{\rho}) = \int_{\mathrm{Observer}}^{\mathrm{Source}} dl\, \delta\rho$$

Critical surface mass density

$$\Sigma_{\mathrm{crit}} = \frac{c^2}{4\pi G}\frac{D_{\mathrm{OS}}}{D_{\mathrm{OL}}D_{\mathrm{LS}}}$$

- **Strong lensing**: $\Sigma \sim \Sigma_{\mathrm{crit}}$ @ cluster cores
- **Weak lensing**: $\Sigma \sim 0.1\, \Sigma_{\mathrm{crit}}$ @ outside cores
- **Cosmic lensing**: $|\Sigma| <\sim 0.01\, \Sigma_{\mathrm{crit}}$ @ LSS

Shear to Convergence (mass)

Shear tensor

Linear Stokes parameters

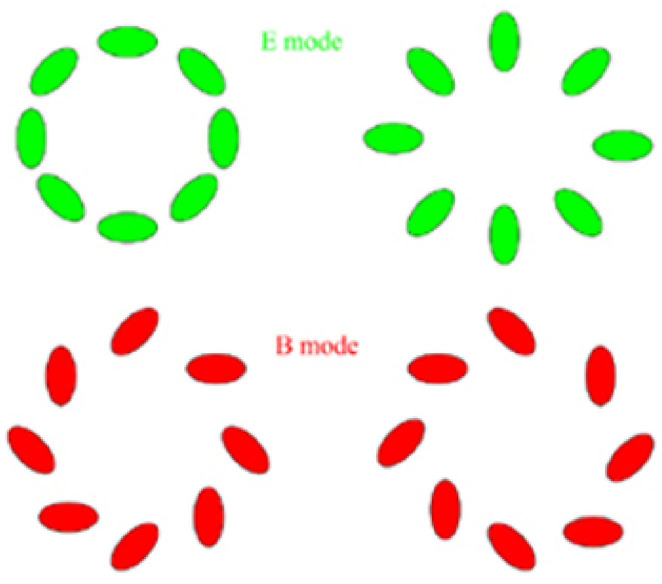
$$\Gamma_{ij} = \begin{bmatrix} +\gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{bmatrix} \Leftrightarrow \begin{bmatrix} +Q & U \\ U & -Q \end{bmatrix}$$

Shear-to-mass relation

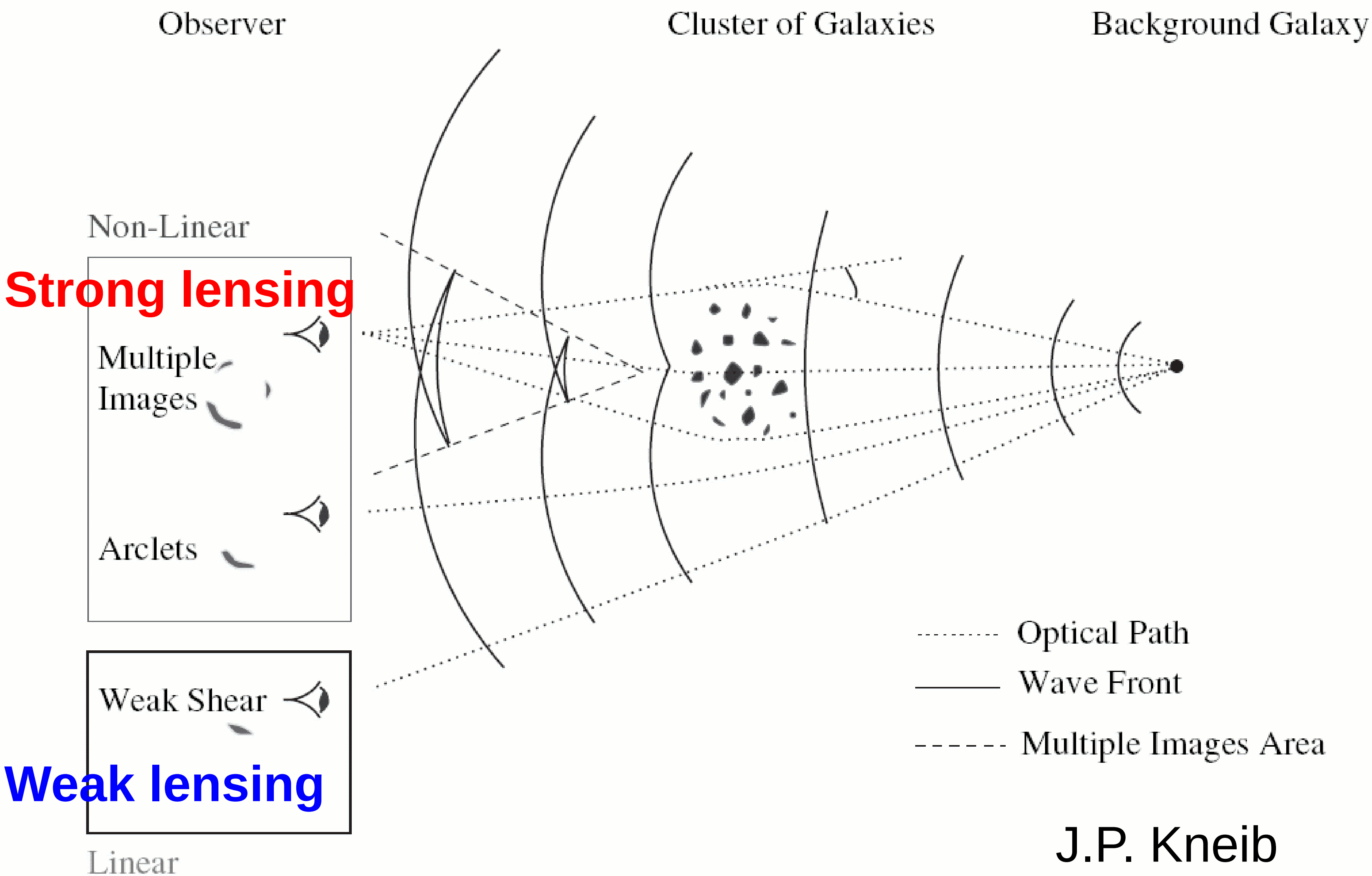
E mode

$$\Delta\kappa = \partial_i \partial_j \Gamma_{ij} \Leftrightarrow E$$

Kaiser & Squires (1993)



Strong and Weak Lensing



J.P. Kneib

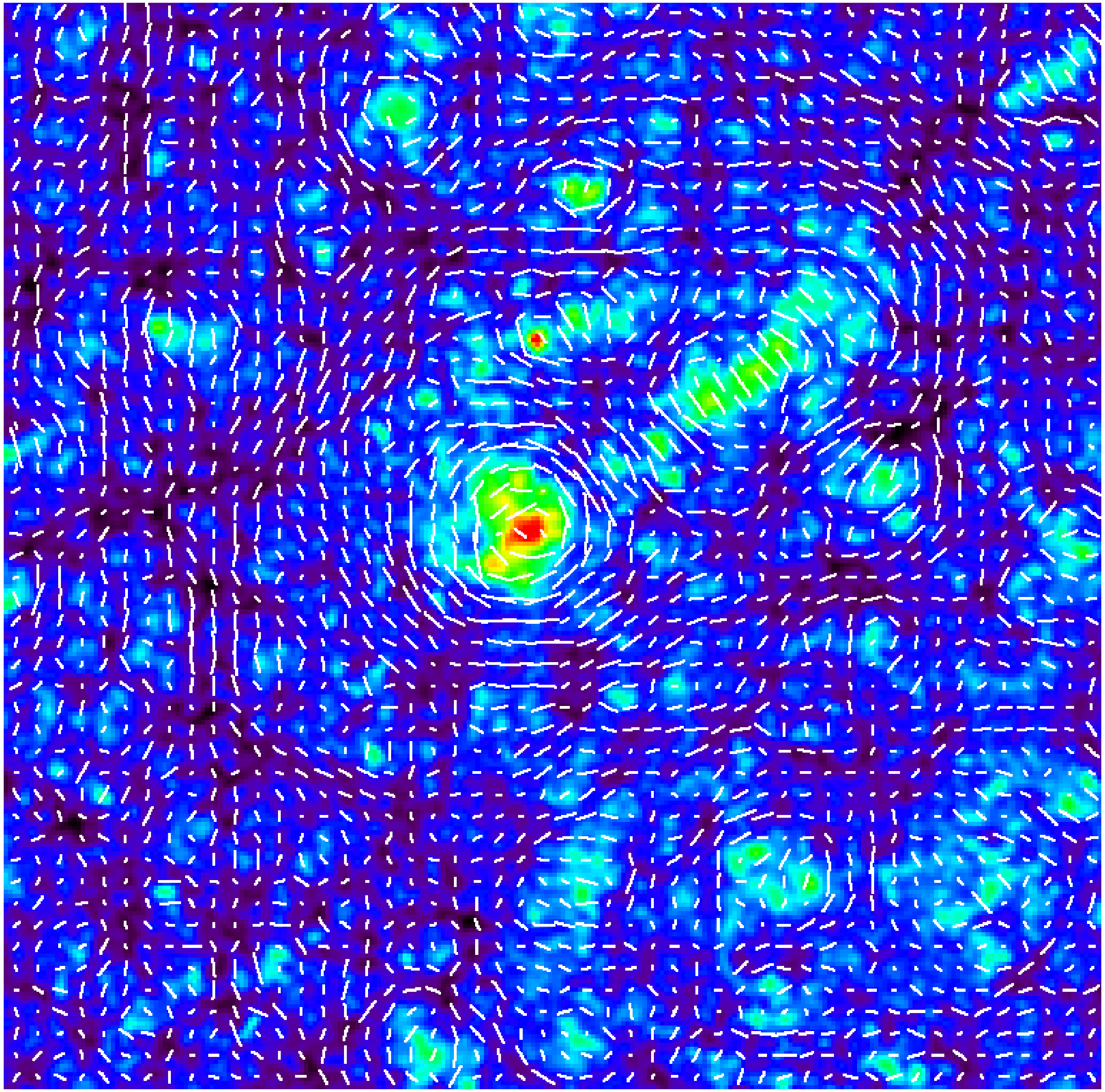
Weak Shear Field

Weak shear is observable

$$\gamma := \gamma_1 + i\gamma_2 = \frac{a-b}{a+b} e^{2i\phi}$$

Cosmic shear: a few %

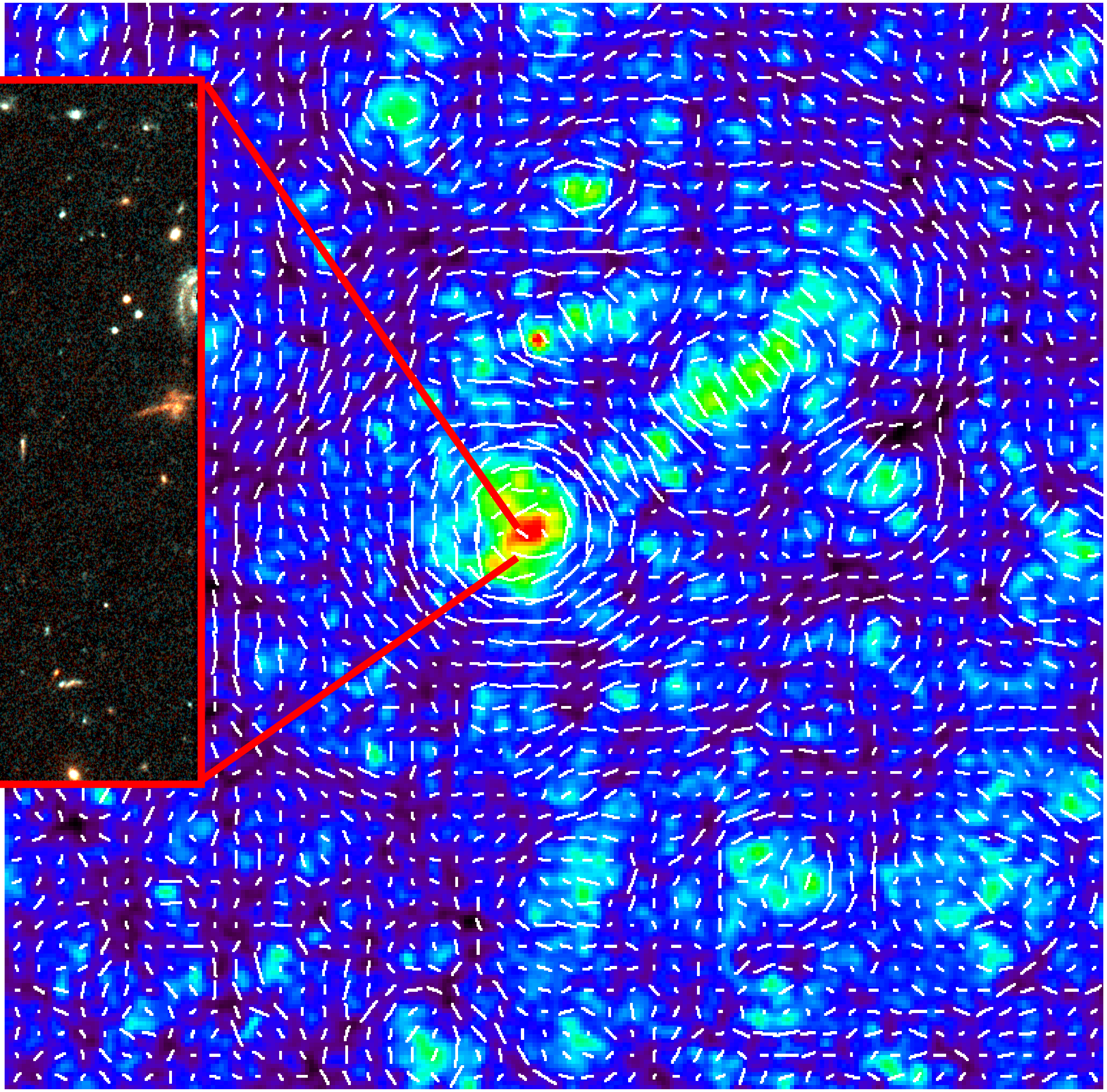
Cluster shear: 10-20%



Simulated 3x3 degree field (Hamana 02)

Weak Shear Field

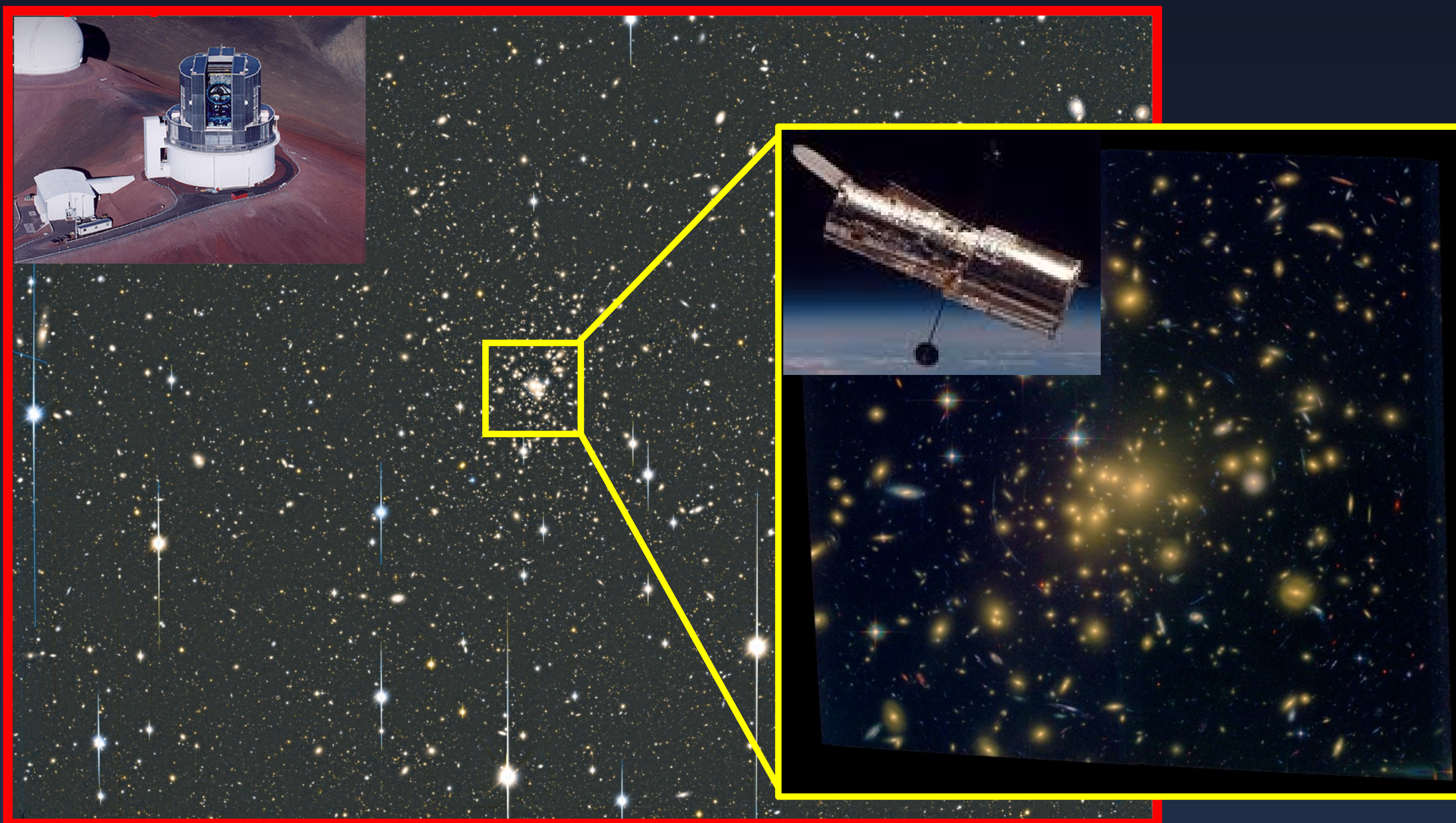
Cluster z = 0.77; Arc z = 4.89:
Photo from H. Yee (HST/ACS)



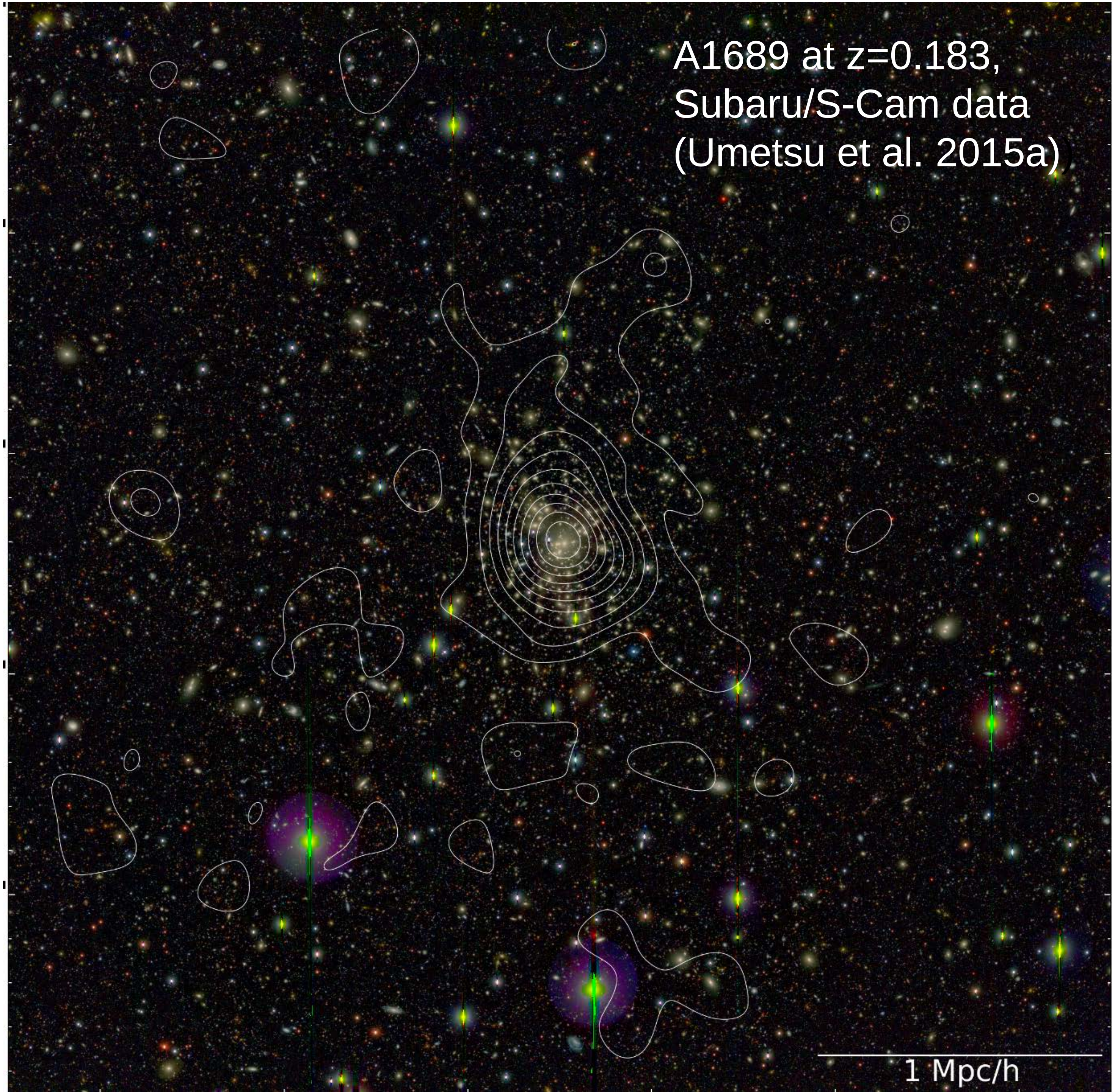
Simulated 3x3 degree field (Hamana 02)

SUBARU (S-Cam) multi-color imaging for wide-field weak

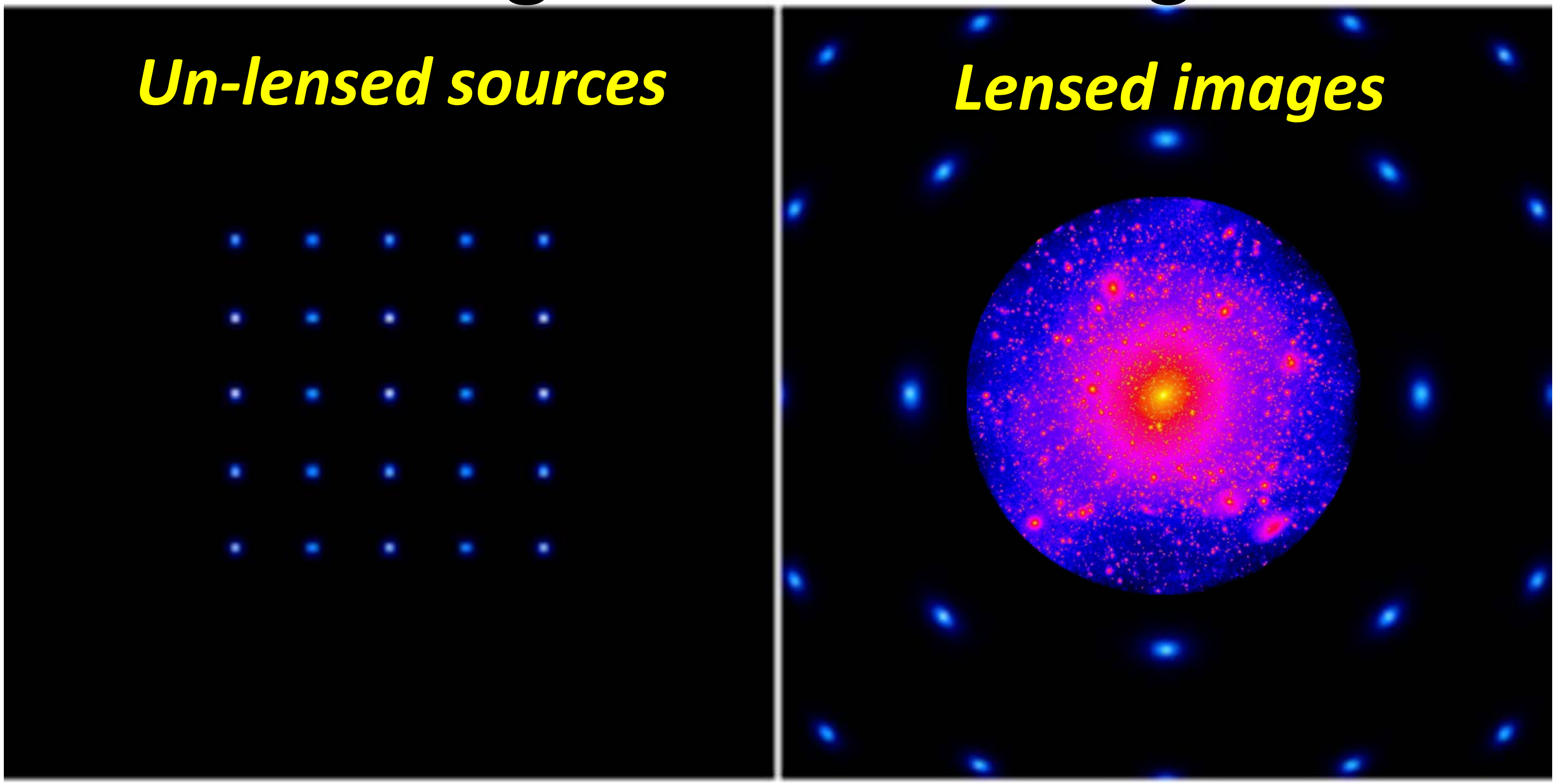
High-resolution space imaging with *HST* (ACS/WFC3) for strong lensing



34 arcmin


A1689 at z=0.183,
Subaru/S-Cam data
(Umetsu et al. 2015a)
1 Mpc/h

Weak-Lensing Shear and Magnification



- **Shear**
  - ✓ Geometric shape dist: $\delta e_+ \sim \gamma_+$
- **Magnification**
  - ✓ Flux amplification: μF
  - ✓ Geometric area dist: $\mu \Delta \Omega$

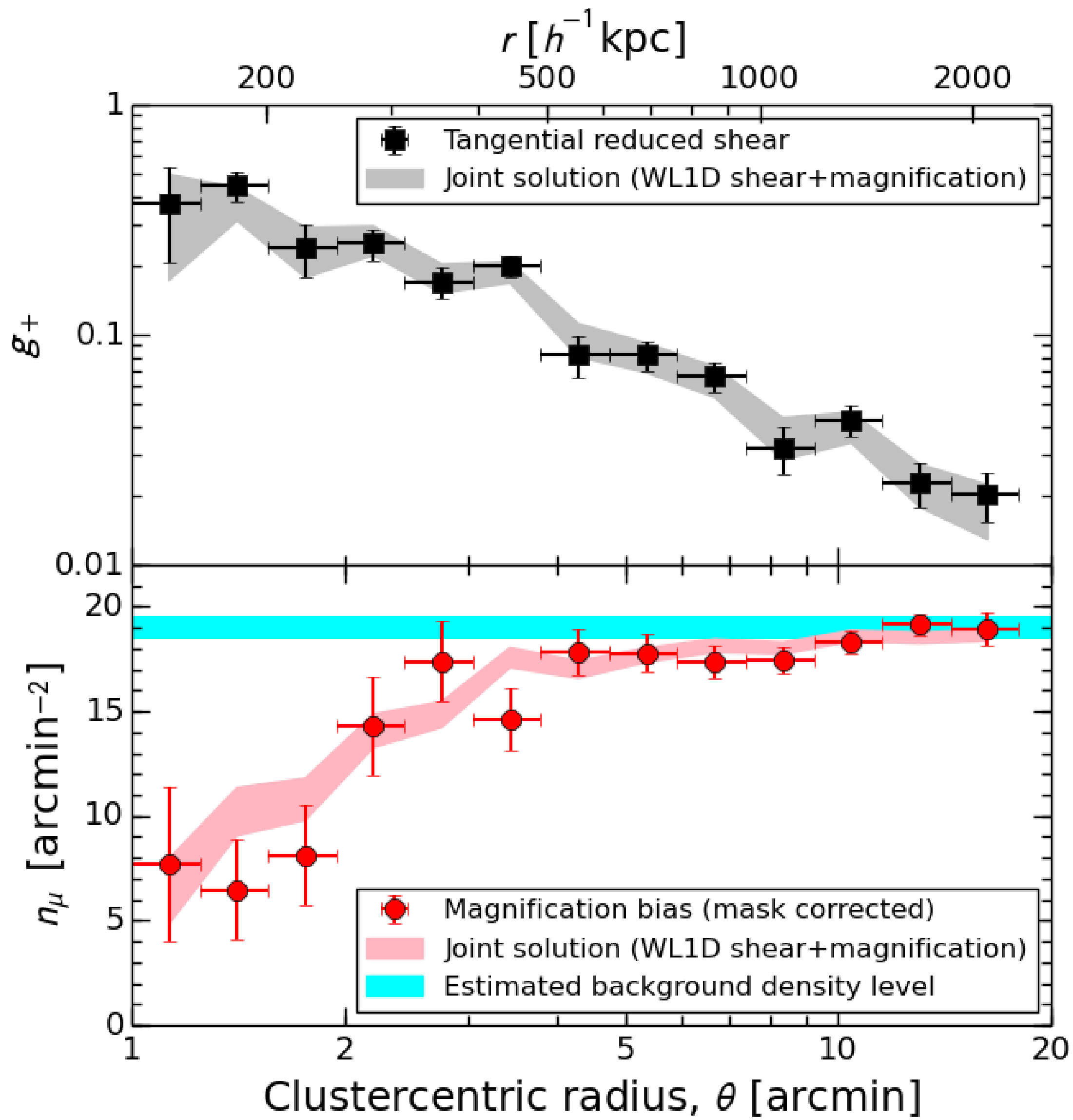
Sensitive to "modulated" matter density

$$\Sigma_{\mathrm{crit}} \gamma_+ = \Delta\Sigma \equiv \Sigma(<R) - \Sigma(R)$$

Sensitive to "total" matter density

$$\mu \approx 1 + 2\kappa; \quad \Sigma_{\mathrm{crit}} \kappa = \Sigma$$

Shear vs. Magnification



Tangential reduced shear

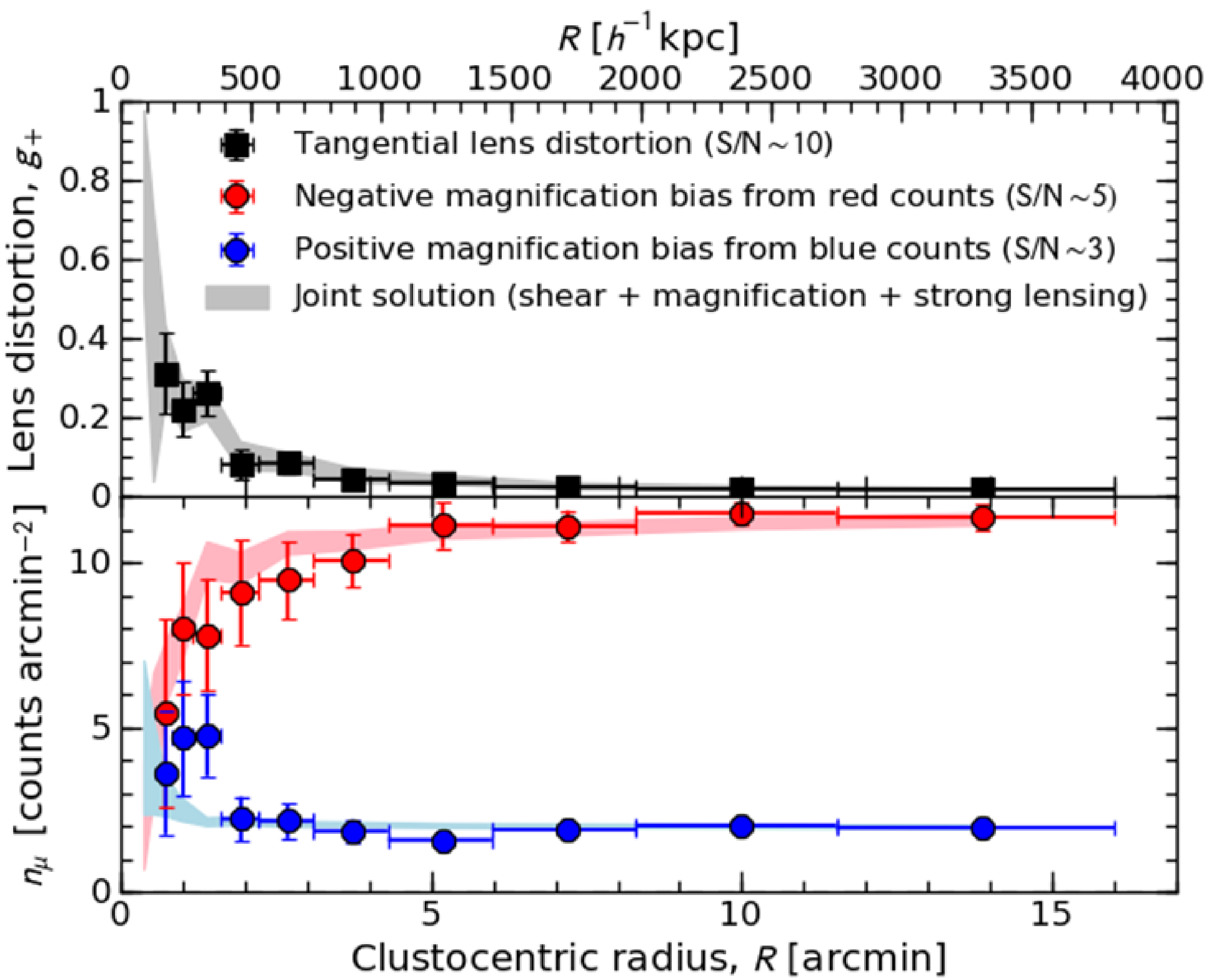
$$g_+ \approx \gamma_+ = \Delta\Sigma / \Sigma_{\rm crit}$$

Number count depletion due to magnification bias

(Broadhurst, Taylor, & Peacock 1995)

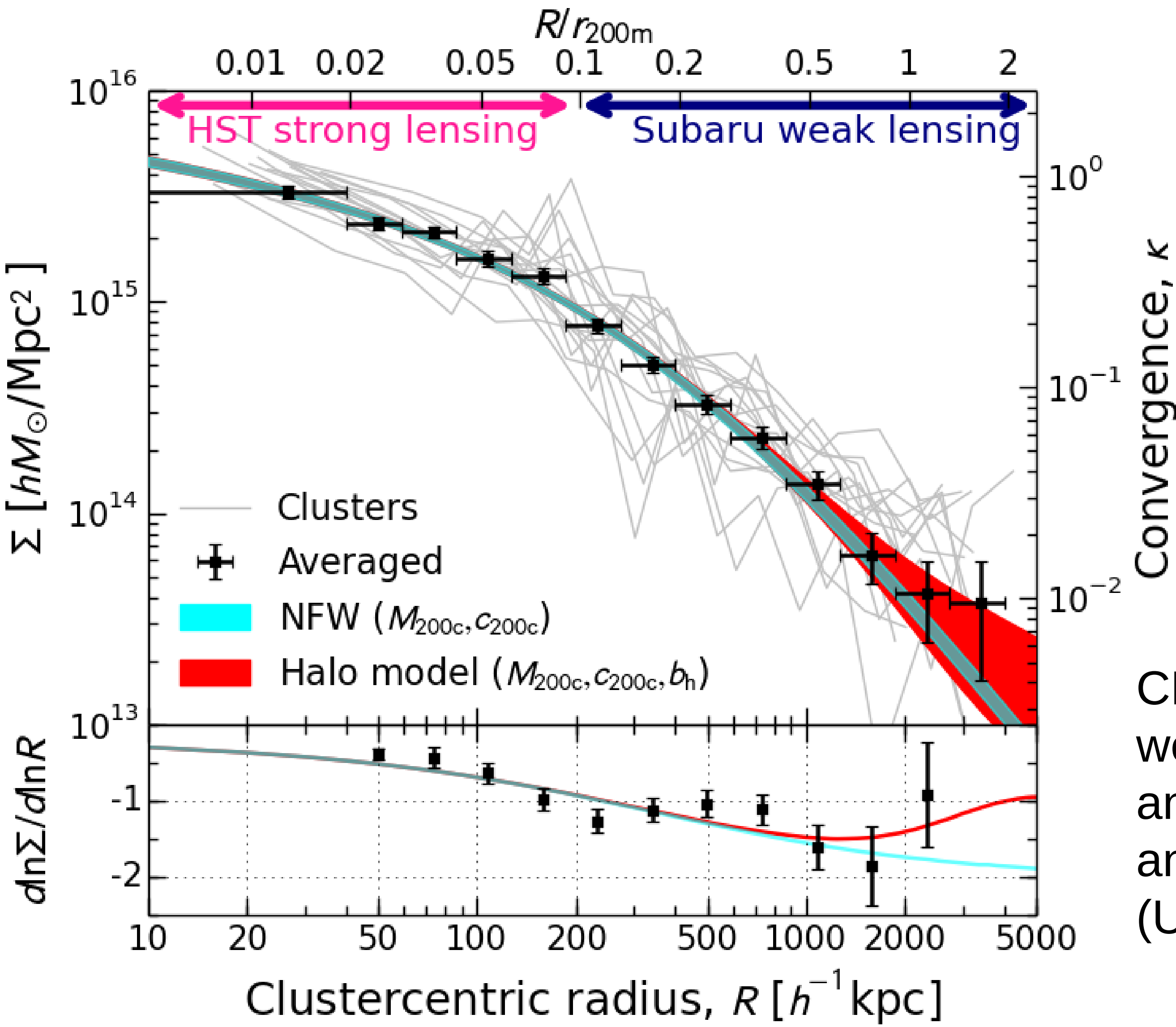
A1689 Subaru/S-Cam data (Umetsu et al. 2015a)

Multi-probe Cluster Lensing Analysis



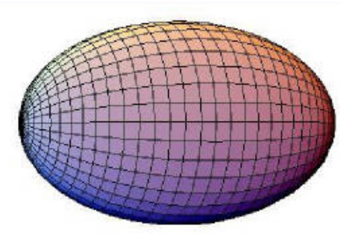
MACSJ1206 CLASH
(Umetsu 2013)

Multi-probe Stacked Lensing Analysis



CLASH strong-lensing, weak-lensing shear and magnification analysis of 16 clusters (Umetsu et al. 2015b)

Cluster Weak Lensing Applications



- 2D mass reconstruction
  - Halo asphericity
  - Mass distribution in merging clusters
    - DM properties from X-ray/SZE-WL offsets (*Bullet* cluster)
    - Cluster infall velocity (pairwise halo velocity)
    - Cluster physics (shock heating, particle acceleration, etc)
- Intra-halo mass profiles
  - Mass measurements/calibration for cluster cosmology
  - Mass vs. concentration relation
- Outskirt and large-scale mass profiles
  - Halo bias, matter power spectrum ($P(k)$, σ_8)
  - Screening mechanisms in modified gravity theory