Clusters of Galaxies as Cosmic Lenses

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Collaborators

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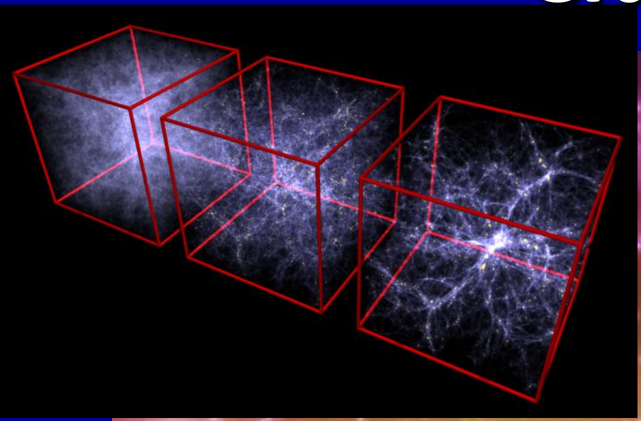
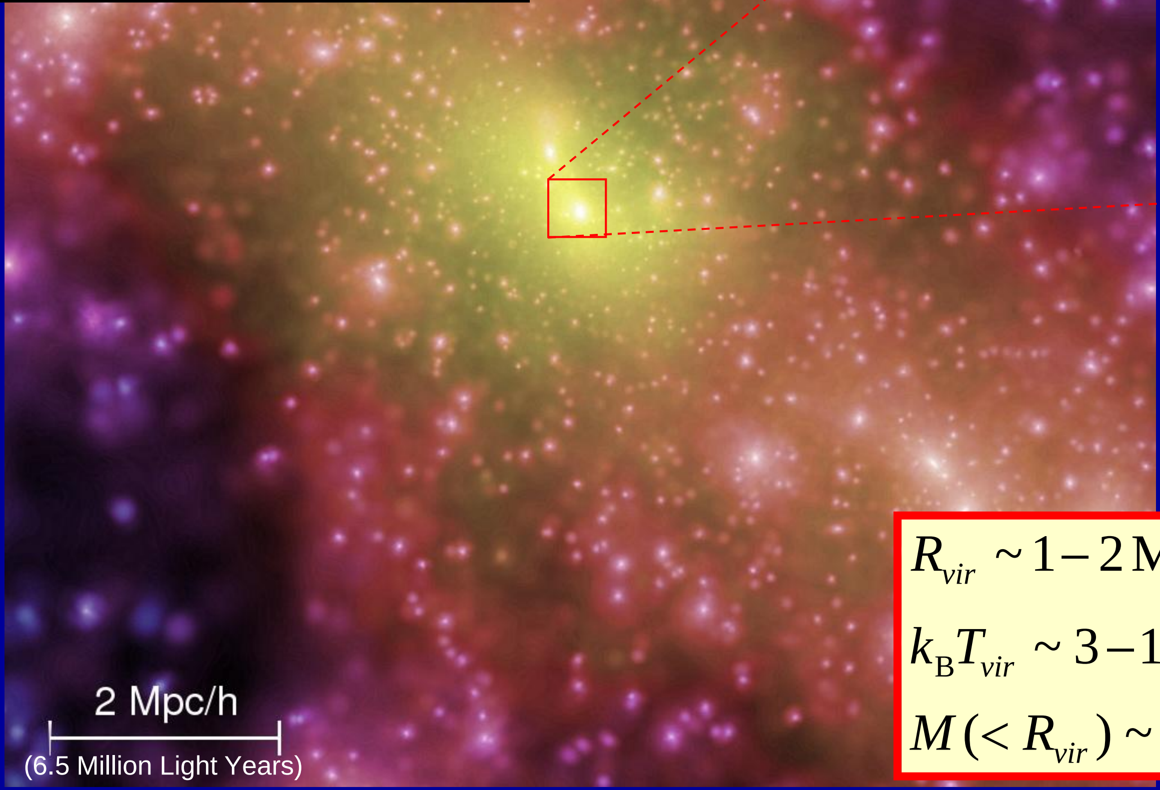
1. Importance of Galaxy Clusters

Clusters of Galaxies





Galaxy clusters: the largest DM halos, composed of 10^2 – 10^3 galaxies.

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

$$k_{\mathrm{B}} T_{vir} \sim 3-10\,\mathrm{keV},\;\; \sigma_v = 800-1300\,\mathrm{km/s}$$

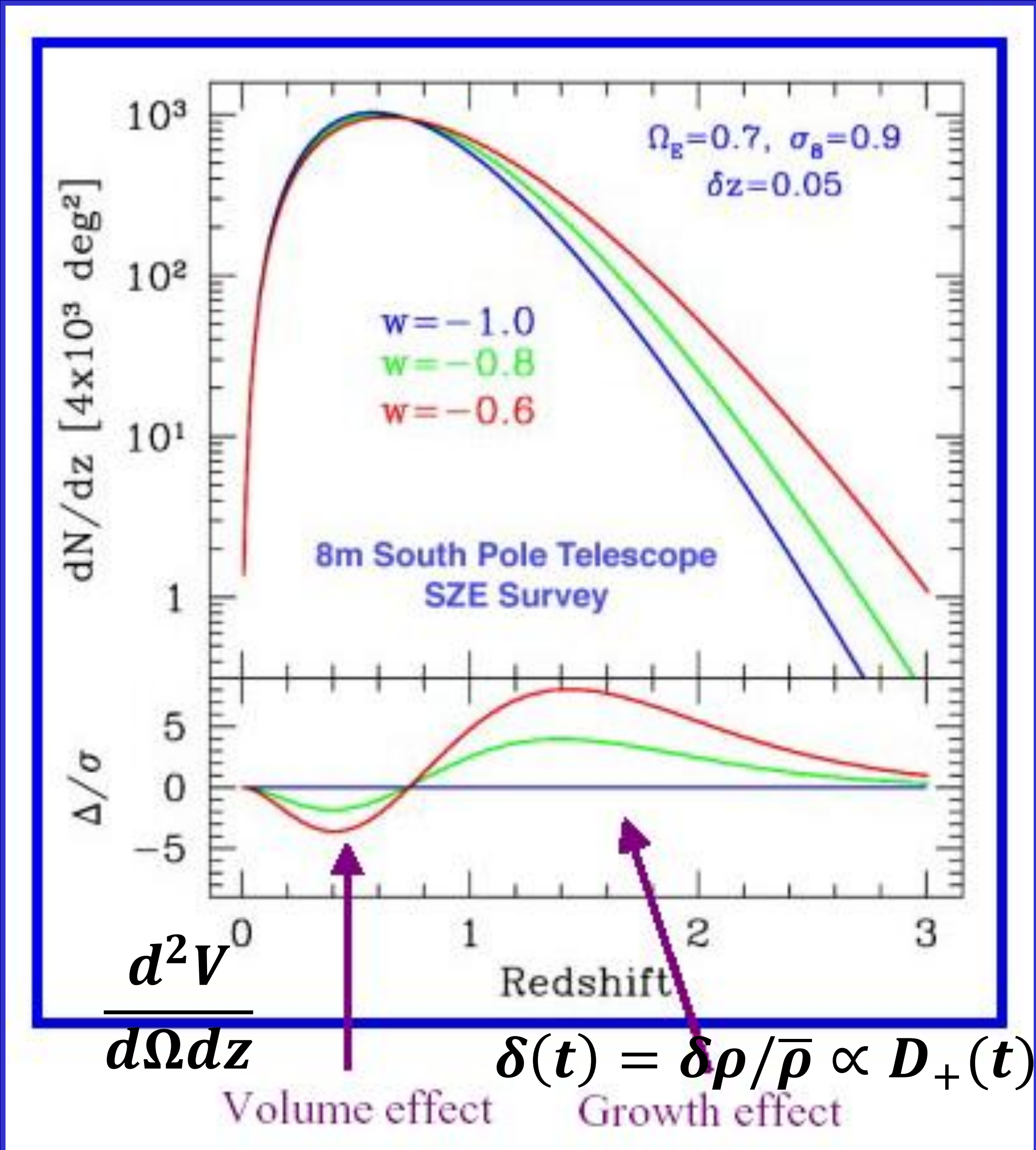
$$M(<R_{vir}) \sim 2 R_{vir}\sigma_v^2 / G \sim 10^{14-15} M_{\mathrm{sun}}$$

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

Why Galaxy Clusters?

- **Study the formation and structure of the largest bound structures in the Universe**
  - UV-Optical-IR → *Stars in galaxies* (~4% in mass)
  - X-ray / SZE → *Fully-ionized hot gas* (~13%)
  - Gravitational lensing → Total mass dominated by *Dark Matter* (~83%)
- Use these structures as “gravitational telescopes” to magnify galaxies in the distant universe.

Clusters as Cosmological Probes



Cluster counts $dN(z, > M)/dz$ 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, BAO, SNe.

The key is accurate determination of cluster mass and internal radial mass profile (aka, halo model) in any cluster cosmology.

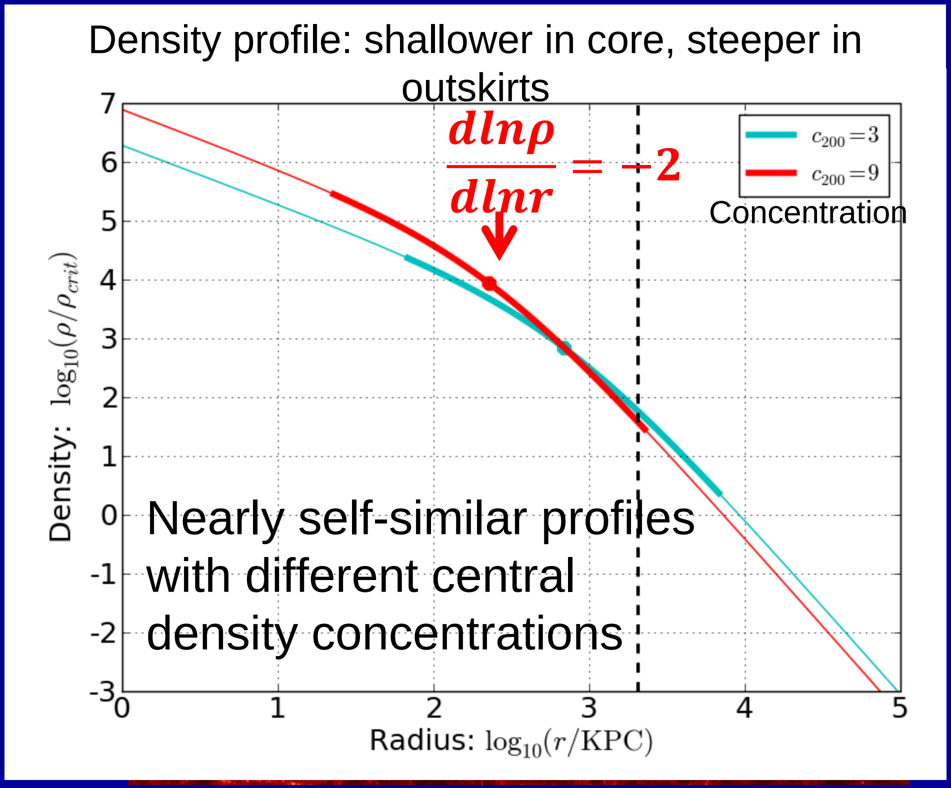
Simulation by the SPT team

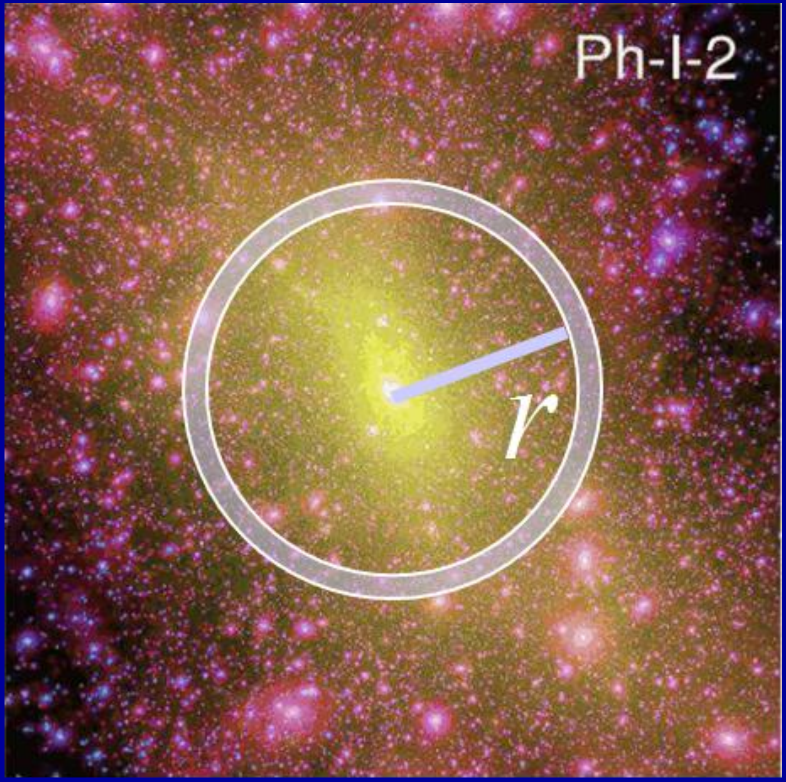
Clusters as DM Probes [1]: Merging Clusters

The Bullet Cluster (z=0.296) – One of the most energetic and rare events in the Universe (Markevitch+04; Clowe+06)

Clusters as DM Probes [2]: Internal Halo Structure

Cosmological simulations of structure formation consistently produce DM halos with a *roughly*-universal mass profile in quasi-gravitational equilibrium
[NFW / Sersic, Einasto]





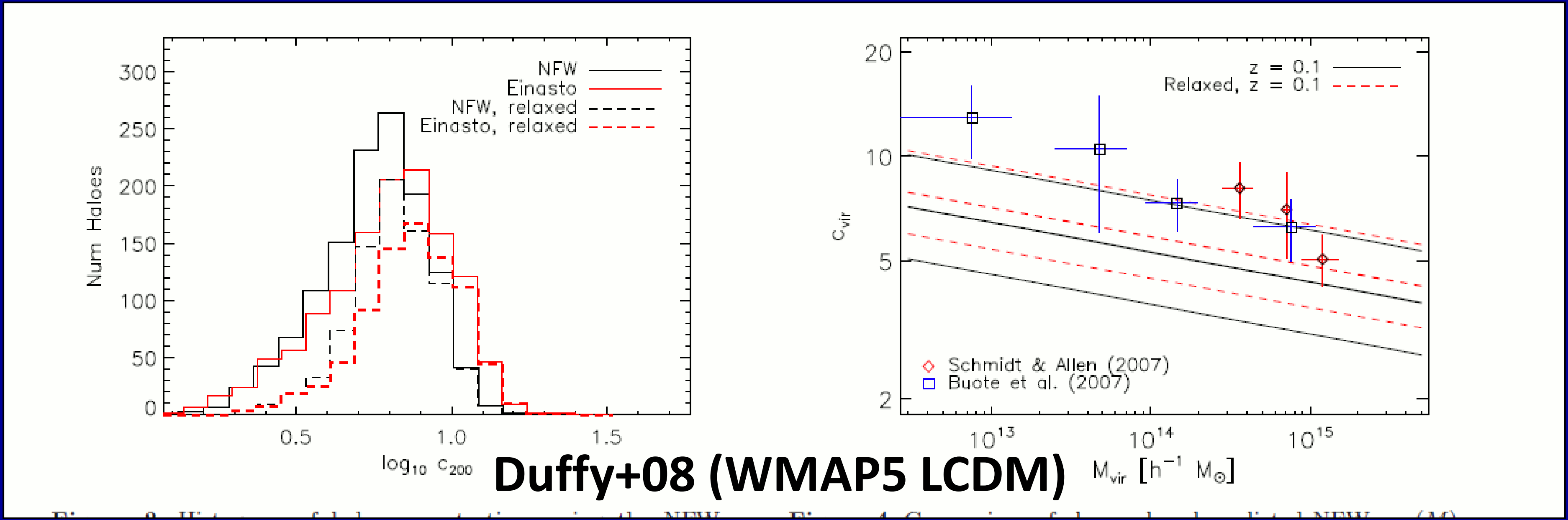
Clusters as DM Probes [3]: Mass vs. Concentration

In a hierarchical structure formation scenario (such as LCDM):

More massive clusters are less compact (less dynamically evolved).

"Concentration decreases with increasing mass".

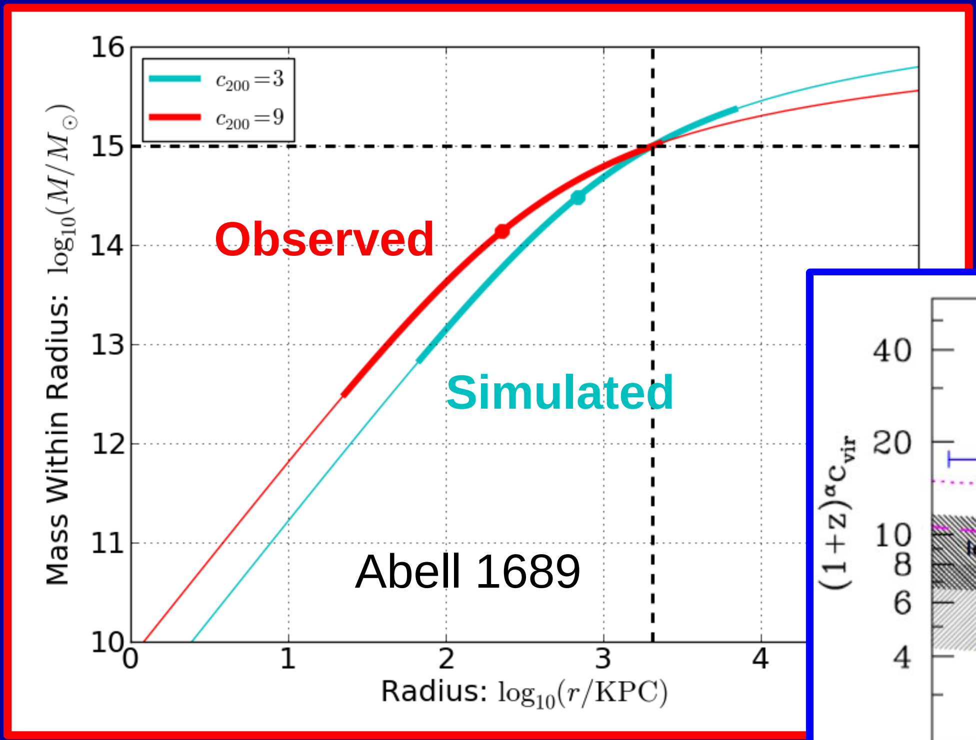
$$c_{\mathrm{vir}}(M_{\mathrm{vir}}) = \frac{R_{\mathrm{vir}}}{R_s} = \frac{\text{Virial radius}}{\text{Isothermal radius}}$$

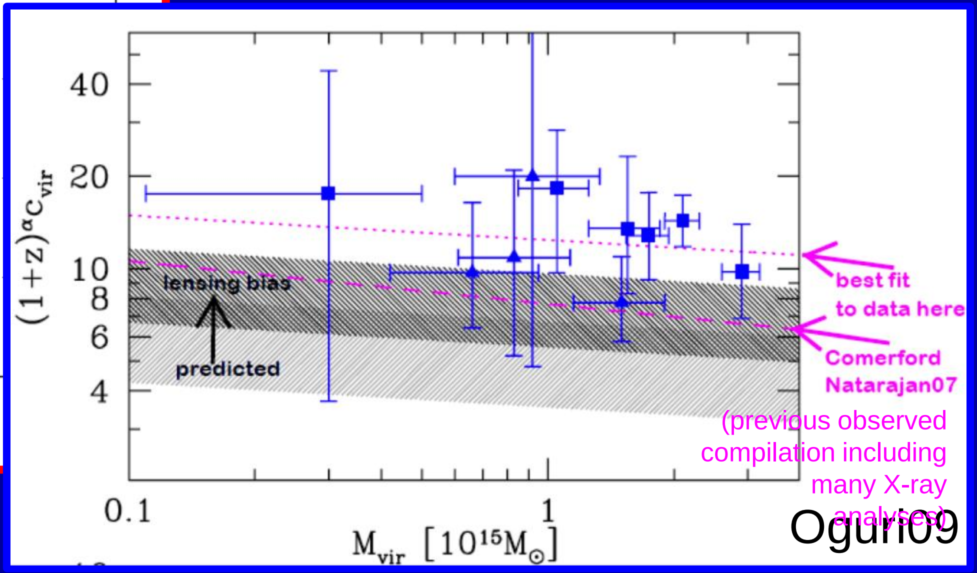


Duffy+08 (WMAP5 LCDM)

Observed vs. LCDM Clusters

The best-studied relaxed clusters appear to have more densely concentrated cores than simulated clusters of similar mass

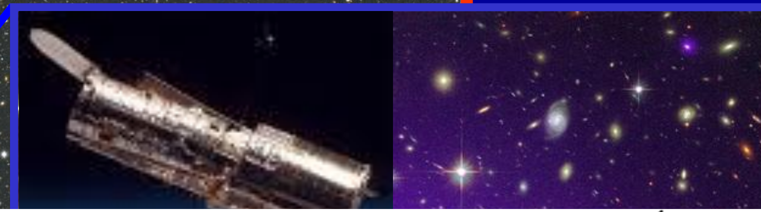


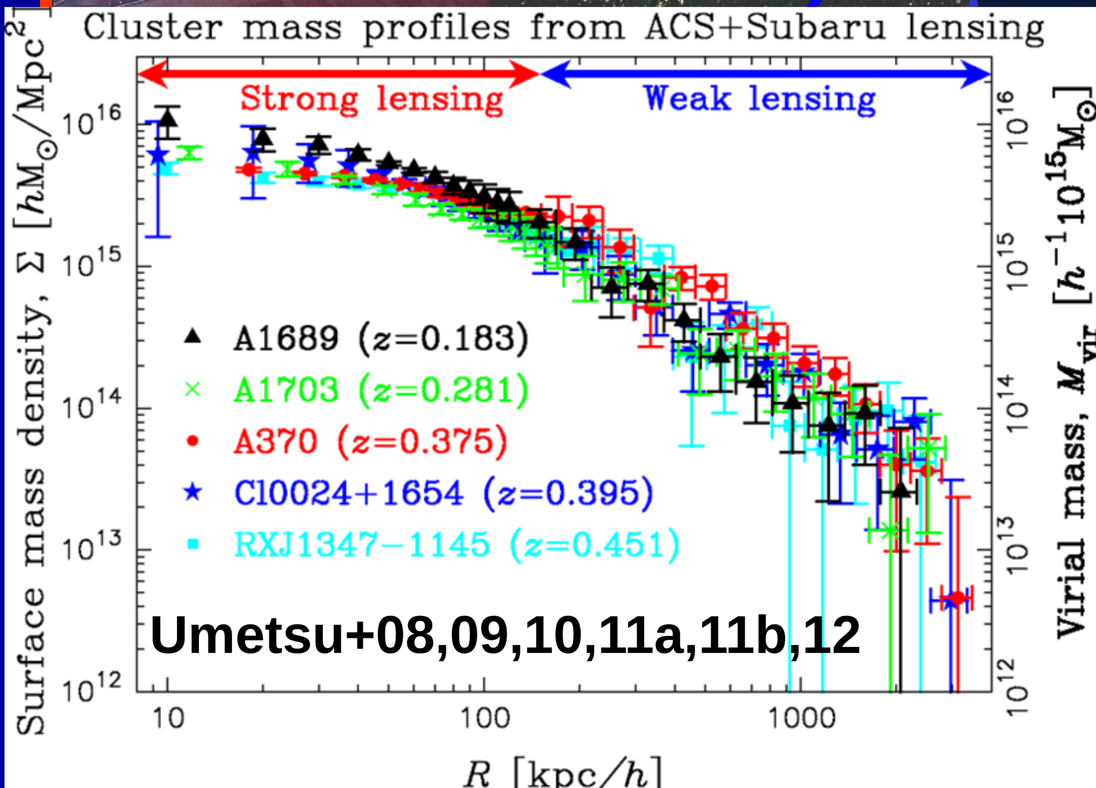


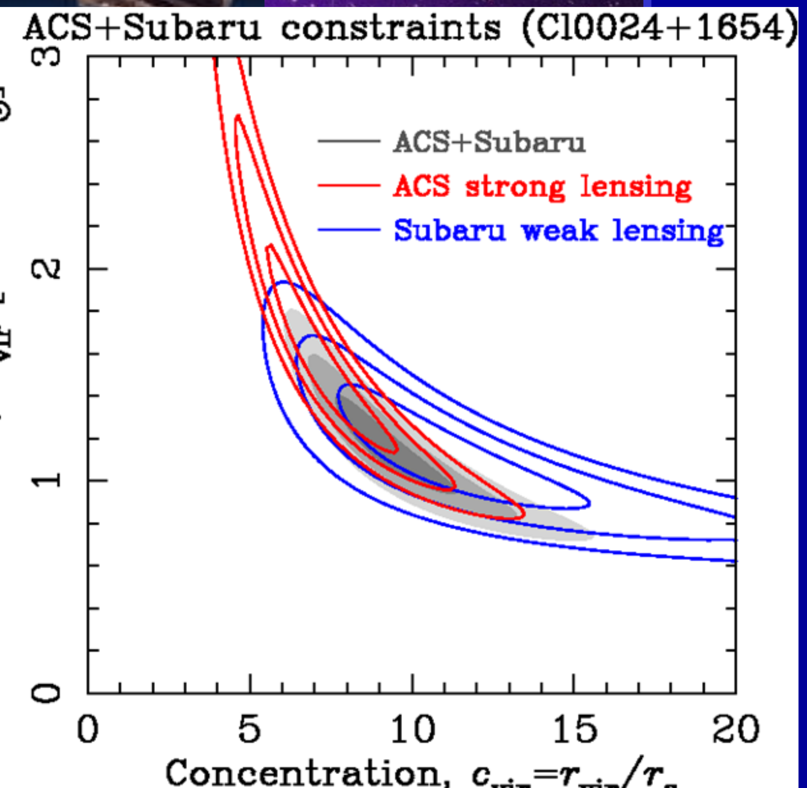
My Approach: Cluster Gravitational Lensing

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

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







2. Cluster Gravitational Lensing

Gravitational Bending of Light Rays

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

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

Gravitational field of deflecting matter

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

Small transverse excursion of photon momentum

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

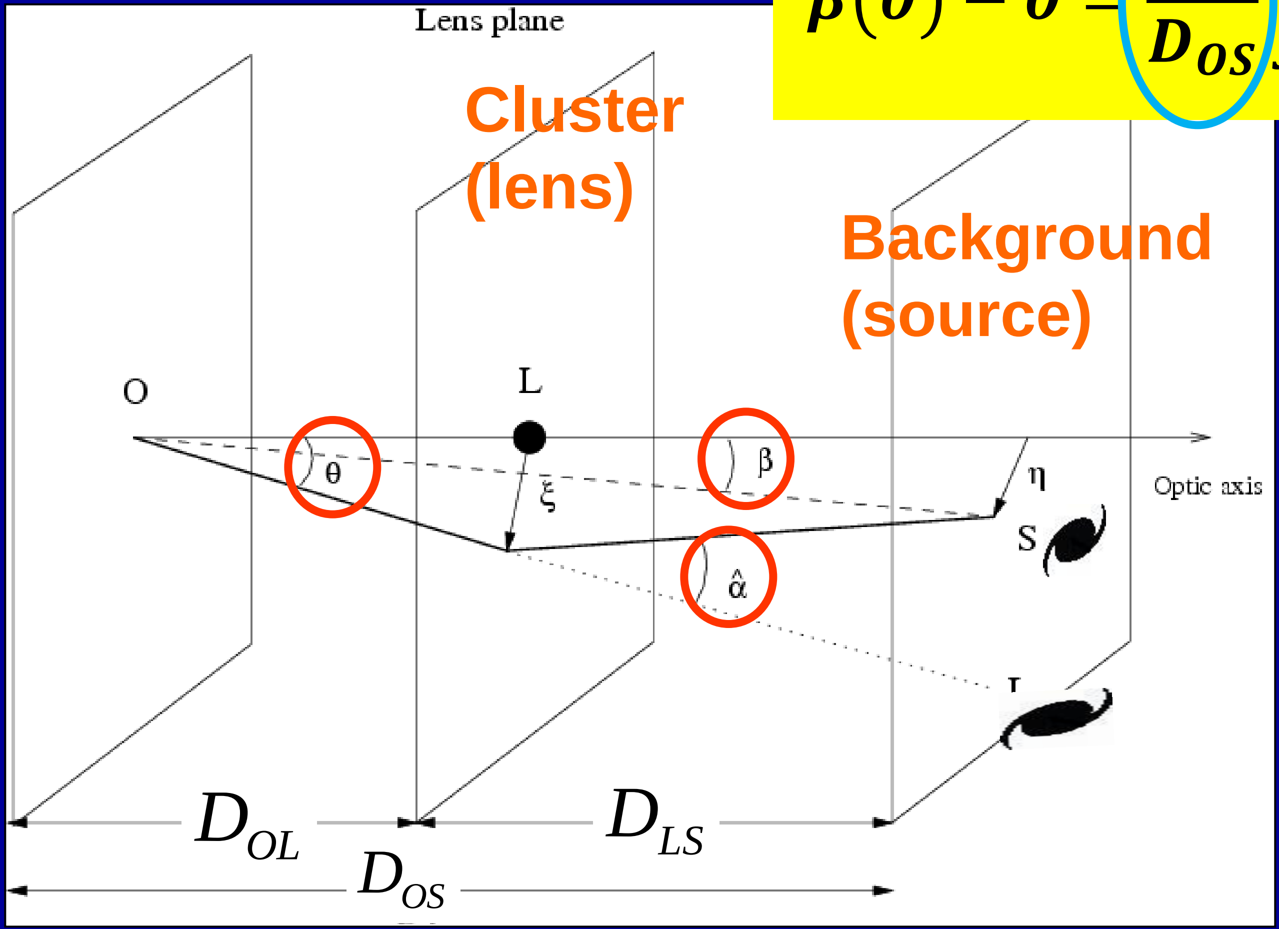
Cluster Lens Equation

Cosmological lens equation + single/thin-lens approximations

$\vec{\beta}$: true (but unknown) source position

$\vec{\theta}$: apparent image position

$$\vec{\beta}(\vec{\theta}) - \vec{\theta} = \frac{D_{LS}}{D_{OS}} \int \delta\vec{\hat{\alpha}}(\vec{\theta}) \equiv -\vec{\nabla}\psi(\vec{\theta})$$



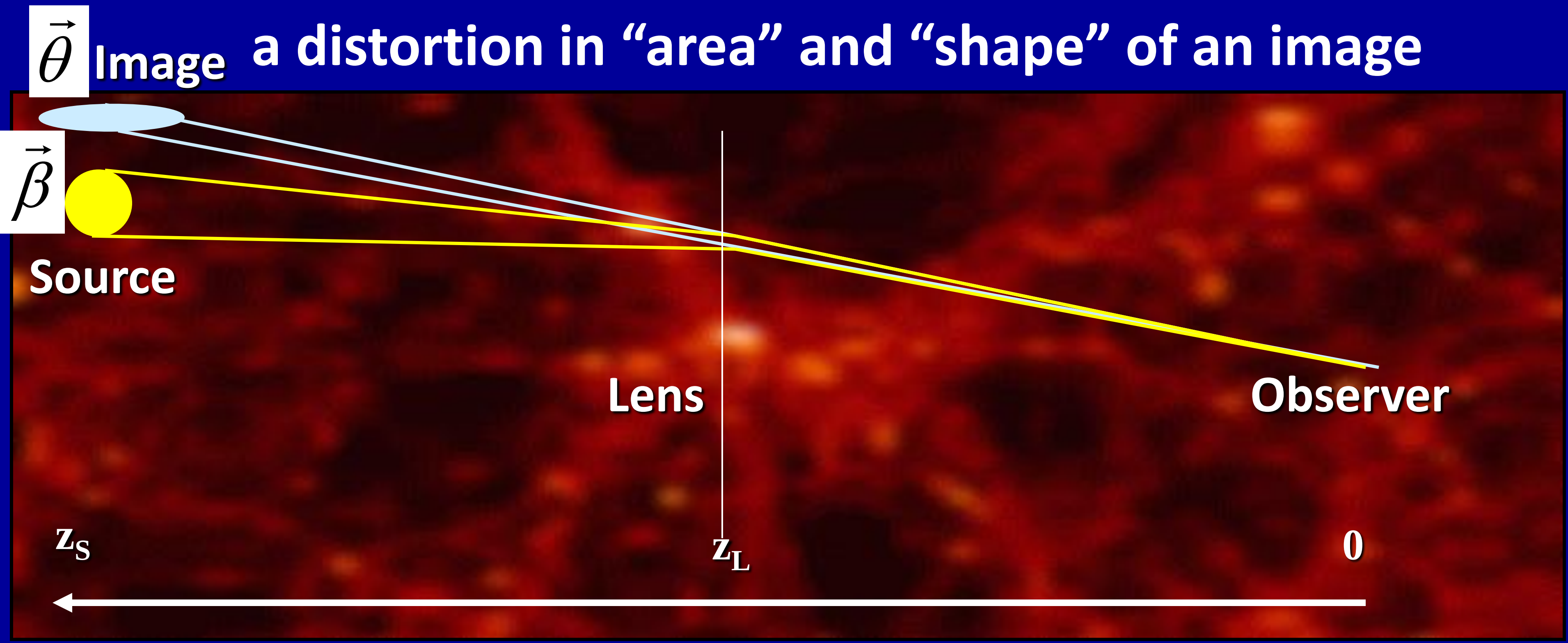
Angular diameter distances:

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

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

Shape and Area Distortions

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



Deformation of an image

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

Magnification of flux (solid angle)

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

Full Cluster Lensing Analysis

- **Strong Gravitational Lensing (SL)**

① **Bending of light**

② **Multiple imaging**

- **Weak Gravitational Lensing (WL)**

① **Distortion** (Shearing)

② **Dilution** (Purity of lensed galaxies)

③ **Depletion** (Magnification)

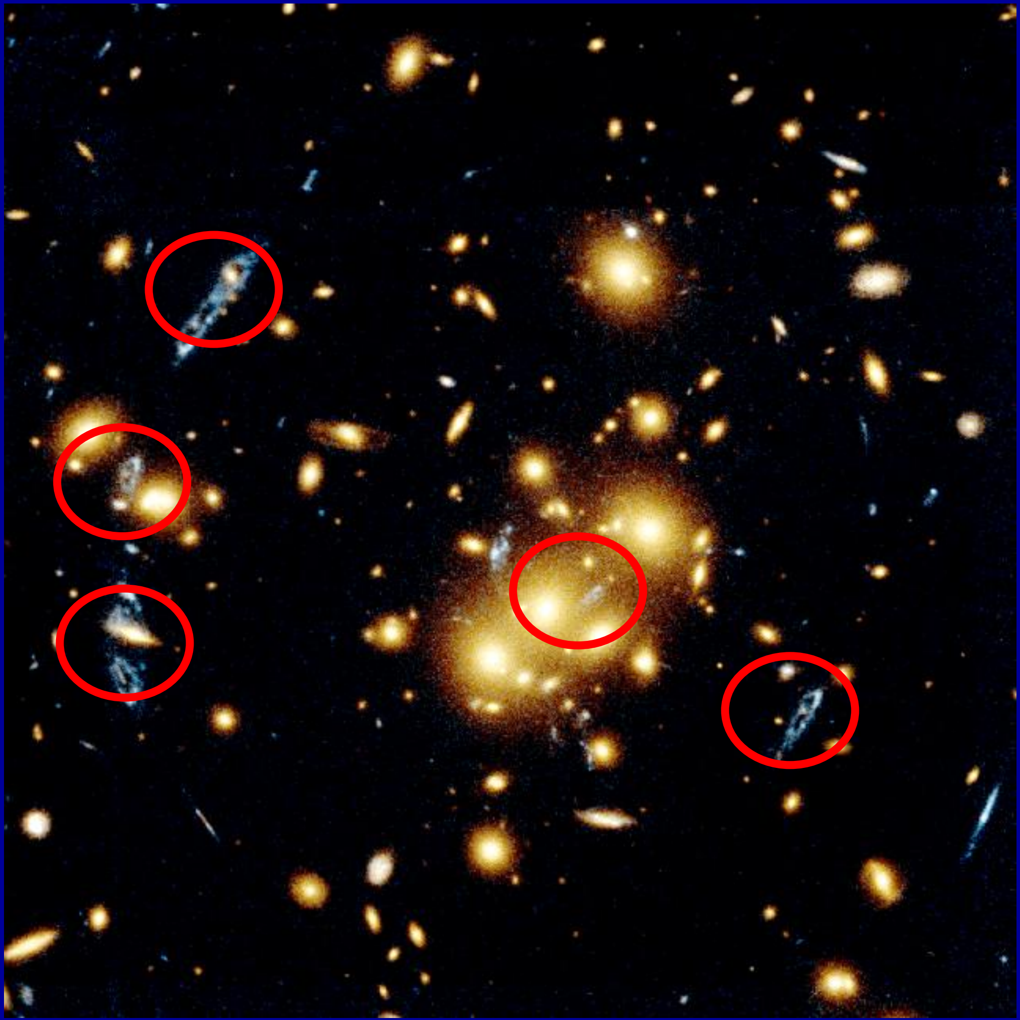
④ **Stacked** lensing analysis

See Umetsu et al. 2011b, ApJ, 738, 41 (arXiv:1105.0444)

Strong Lensing

Cluster Strong Lensing

SL phenomena include: **multiple imaging**, **high flux amplification**, **curved image features** due to light deflection in cluster cores.



Multiple Imaging example:

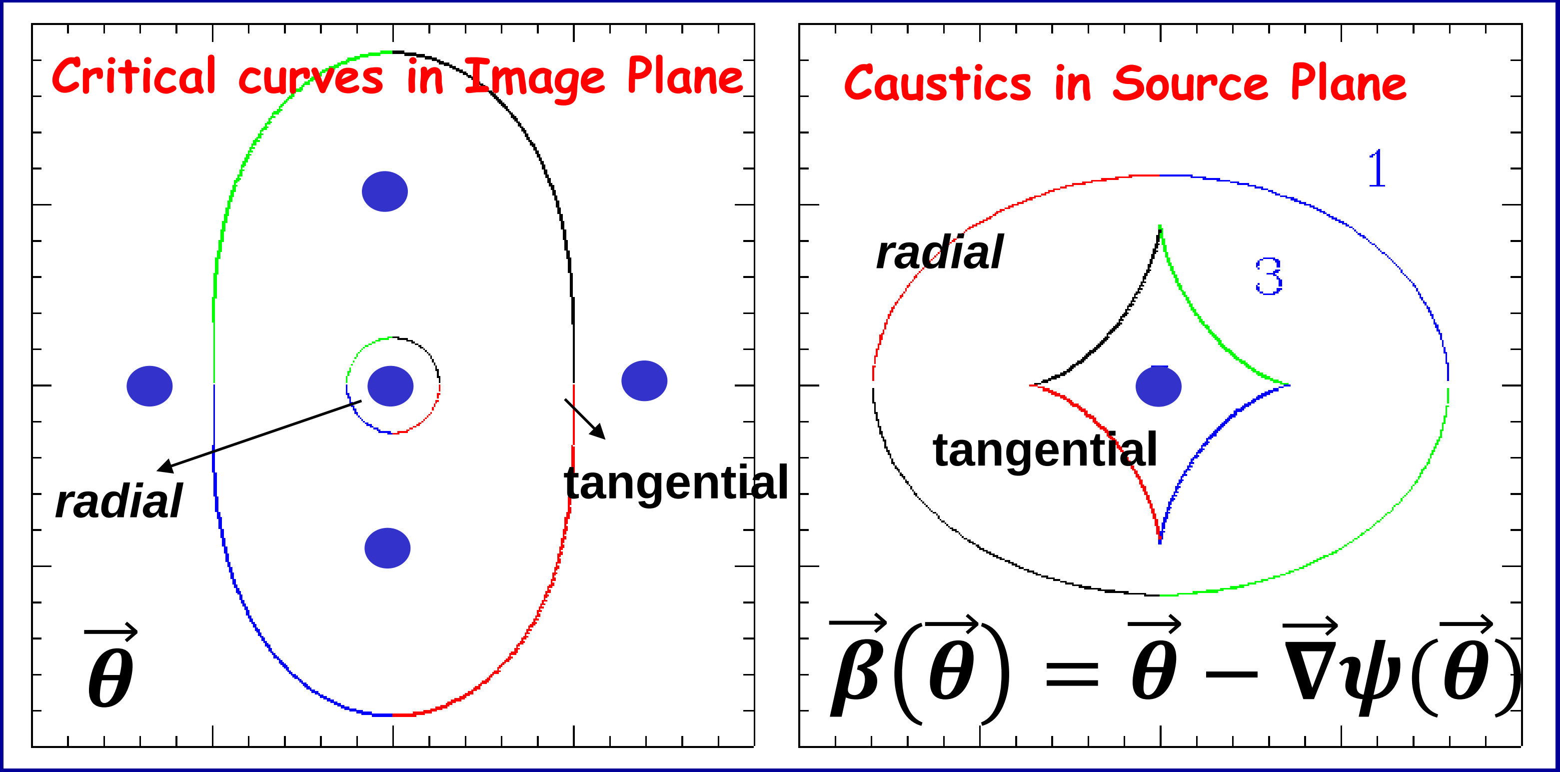
A source galaxy at z=1.675 has been multiply lensed into 5 images (Colley+96)

CL0024+1654 (z=0.395)

HST/WFPC2

Critical Curves and Caustics

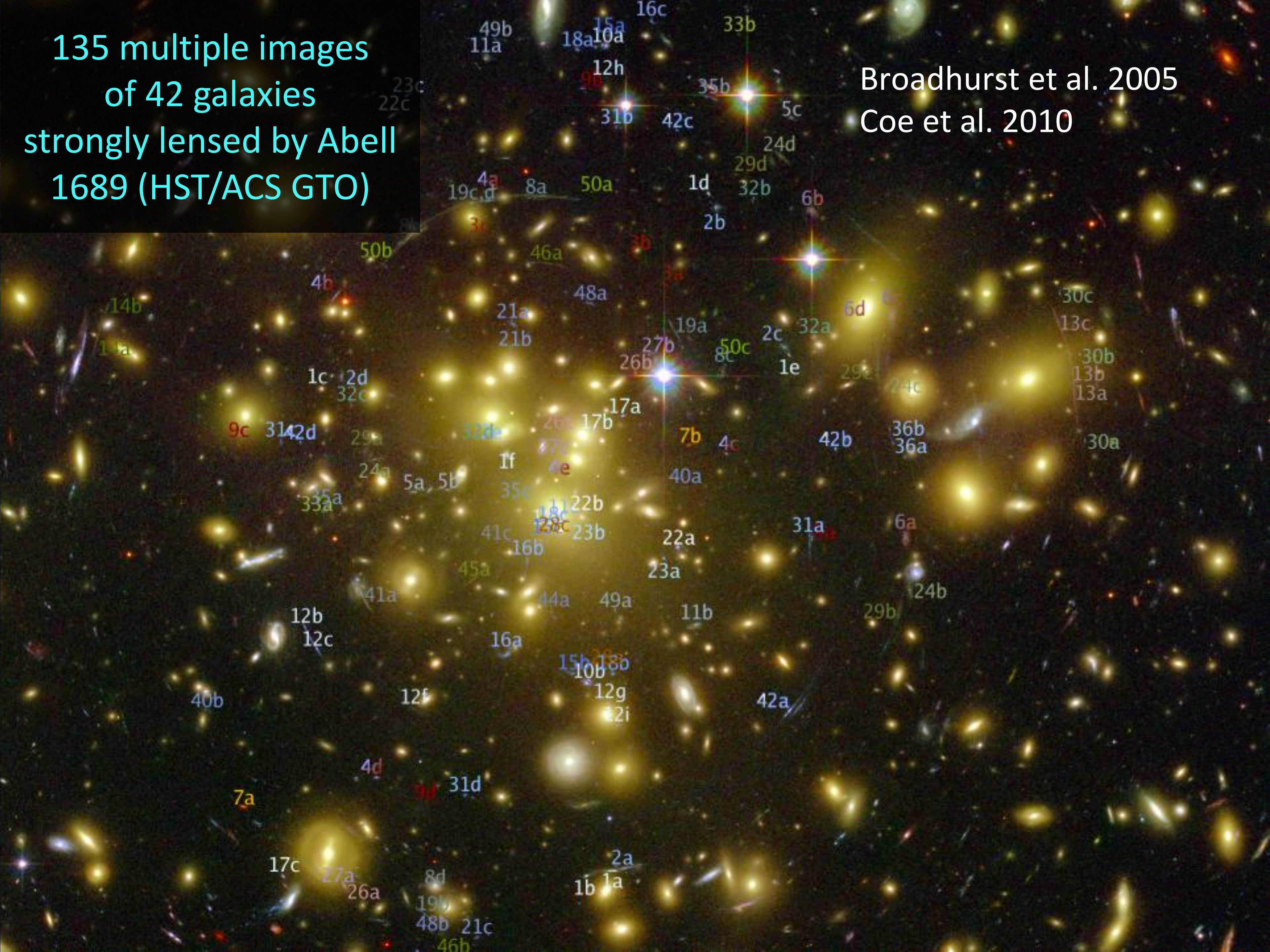
A general elliptical lens potential

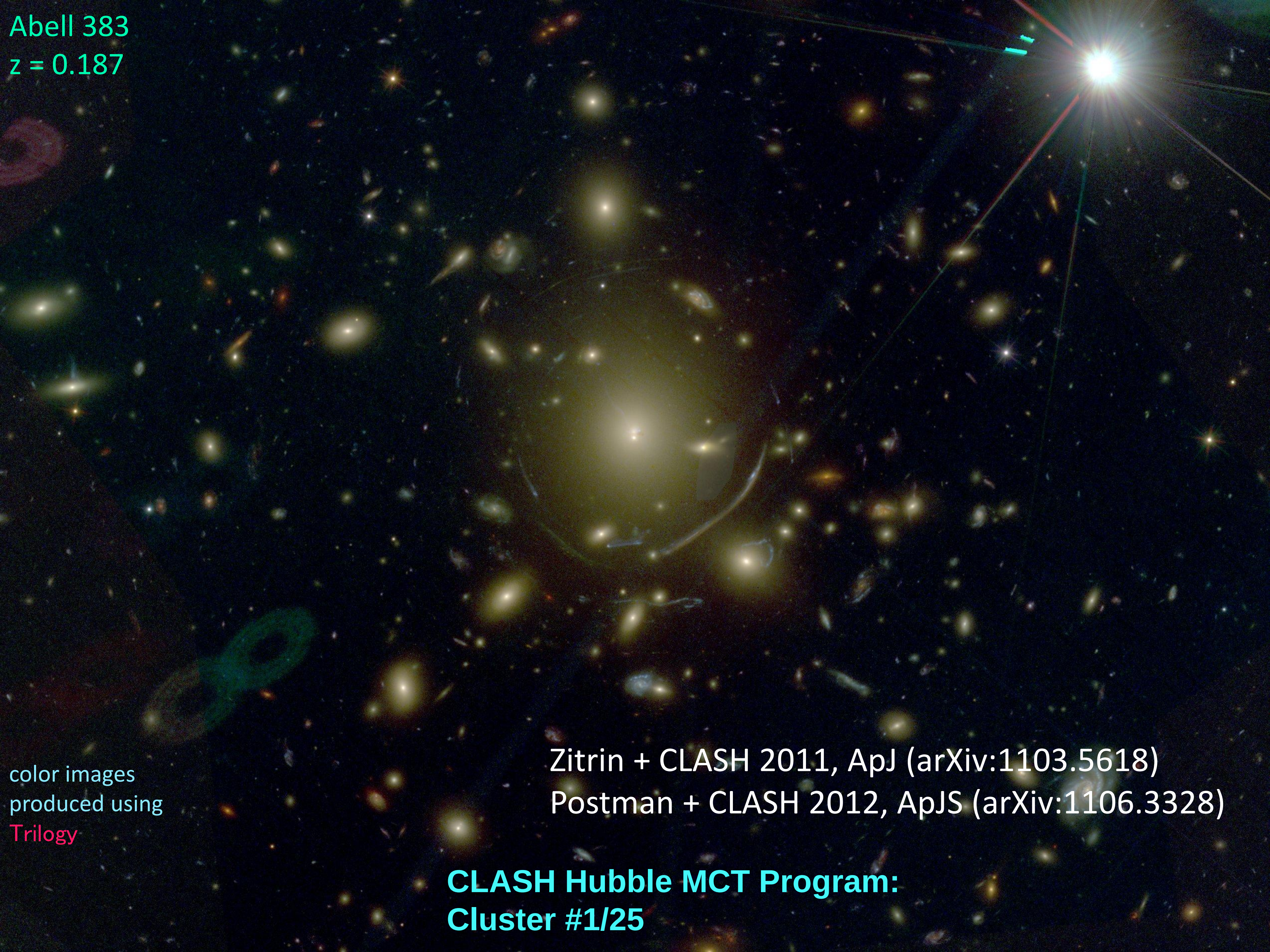


$$\vec{\beta}(\vec{\theta}) = \vec{\theta} - \vec{\nabla}\psi(\vec{\theta})$$

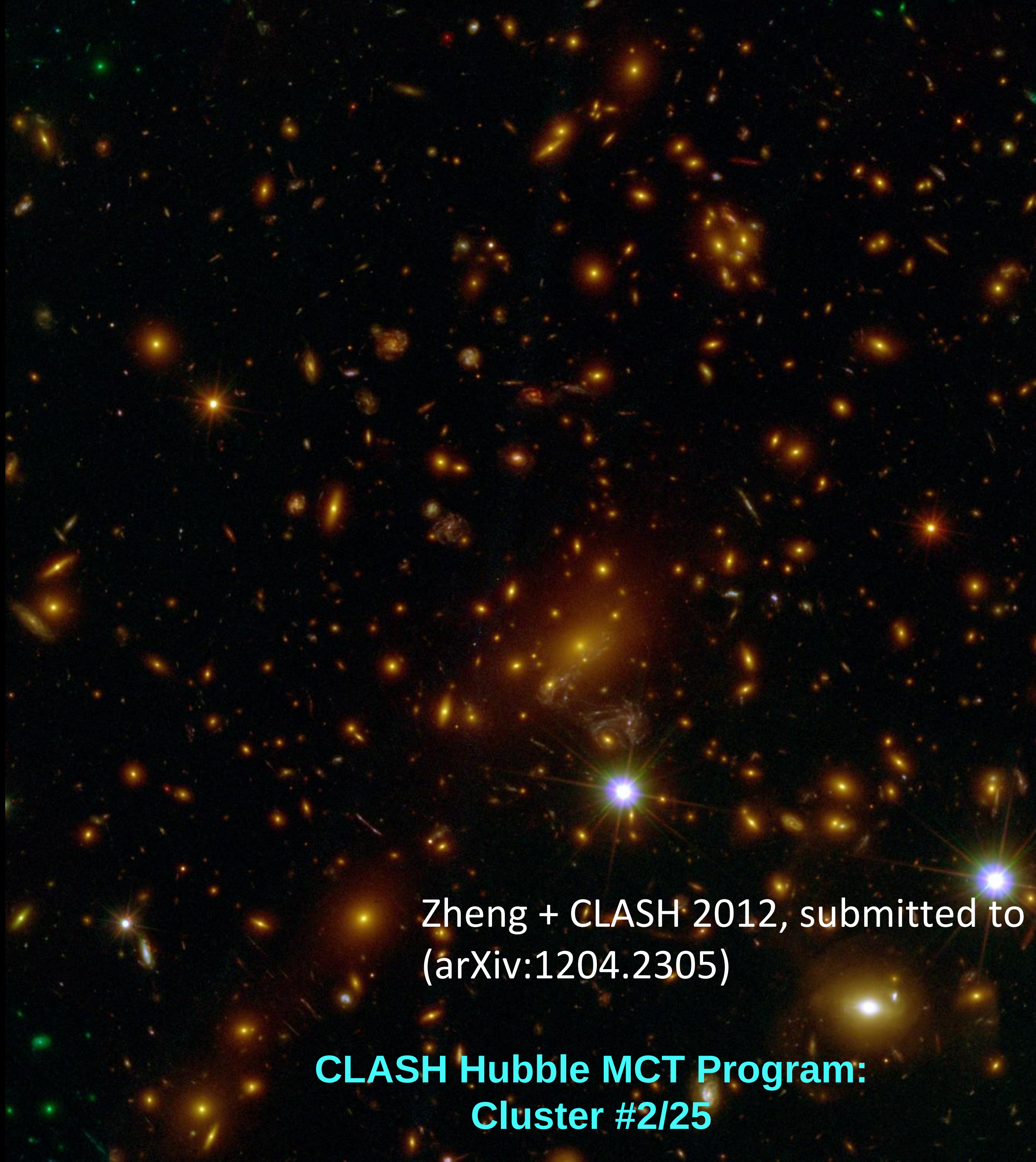
135 multiple images of 42 galaxies strongly lensed by Abell 1689 (HST/ACS GTO)

Broadhurst et al. 2005
Coe et al. 2010




Abell 383
z = 0.187
color images
produced using
Trilogy
Zitrin + CLASH 2011, ApJ (arXiv:1103.5618)
Postman + CLASH 2012, ApJS (arXiv:1106.3328)
CLASH Hubble MCT Program:
Cluster #1/25

MACSJ1149
z = 0.544

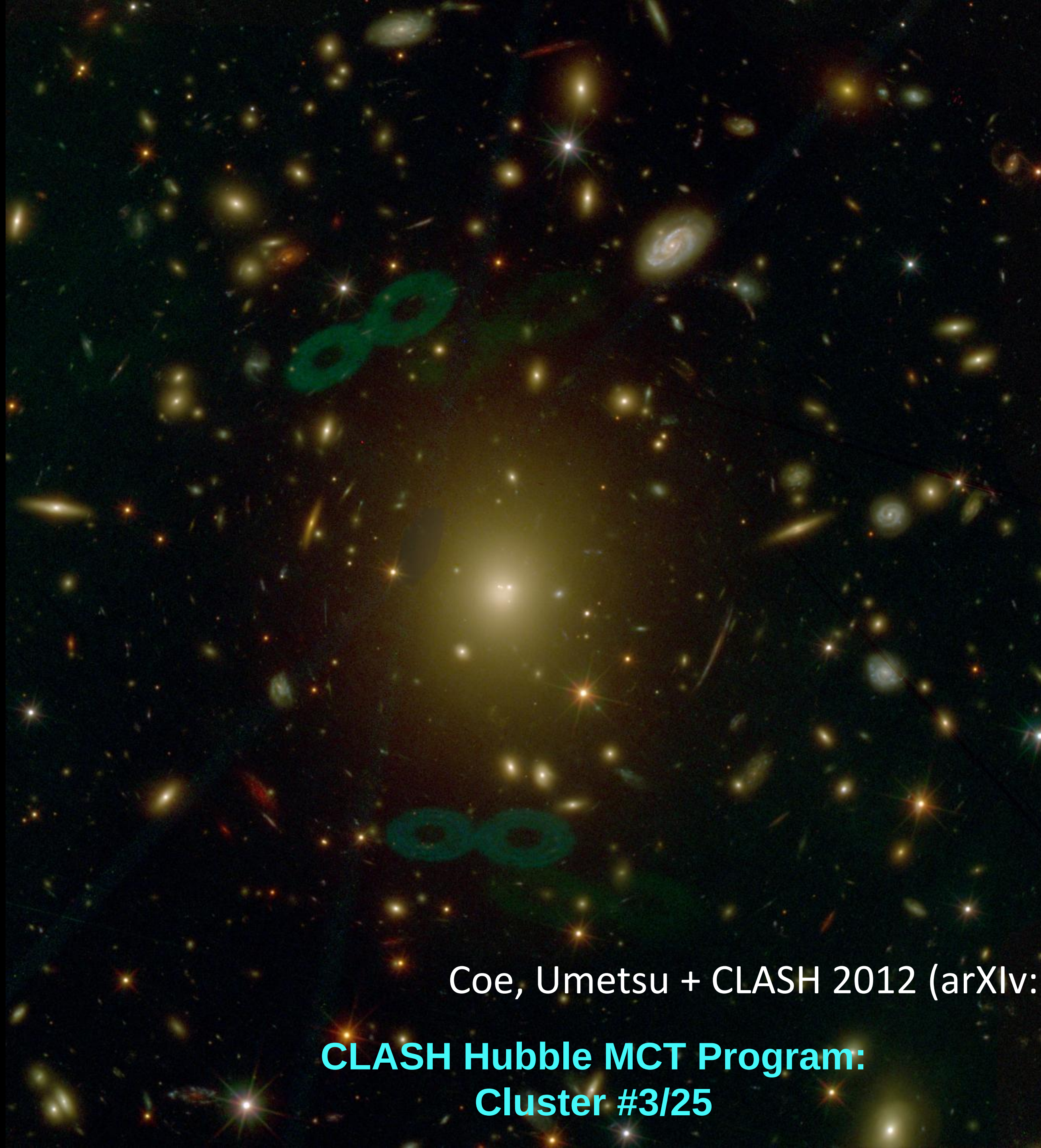


Zheng + CLASH 2012, submitted to Nature
(arXiv:1204.2305)

**CLASH Hubble MCT Program:
Cluster #2/25**

color images
produced using
Trilogy

Abell 2261
z = 0.224



color images
produced using
Trilogy

Coe, Umetsu + CLASH 2012 (arXIv:1201.1616)

CLASH Hubble MCT Program:
Cluster #3/25

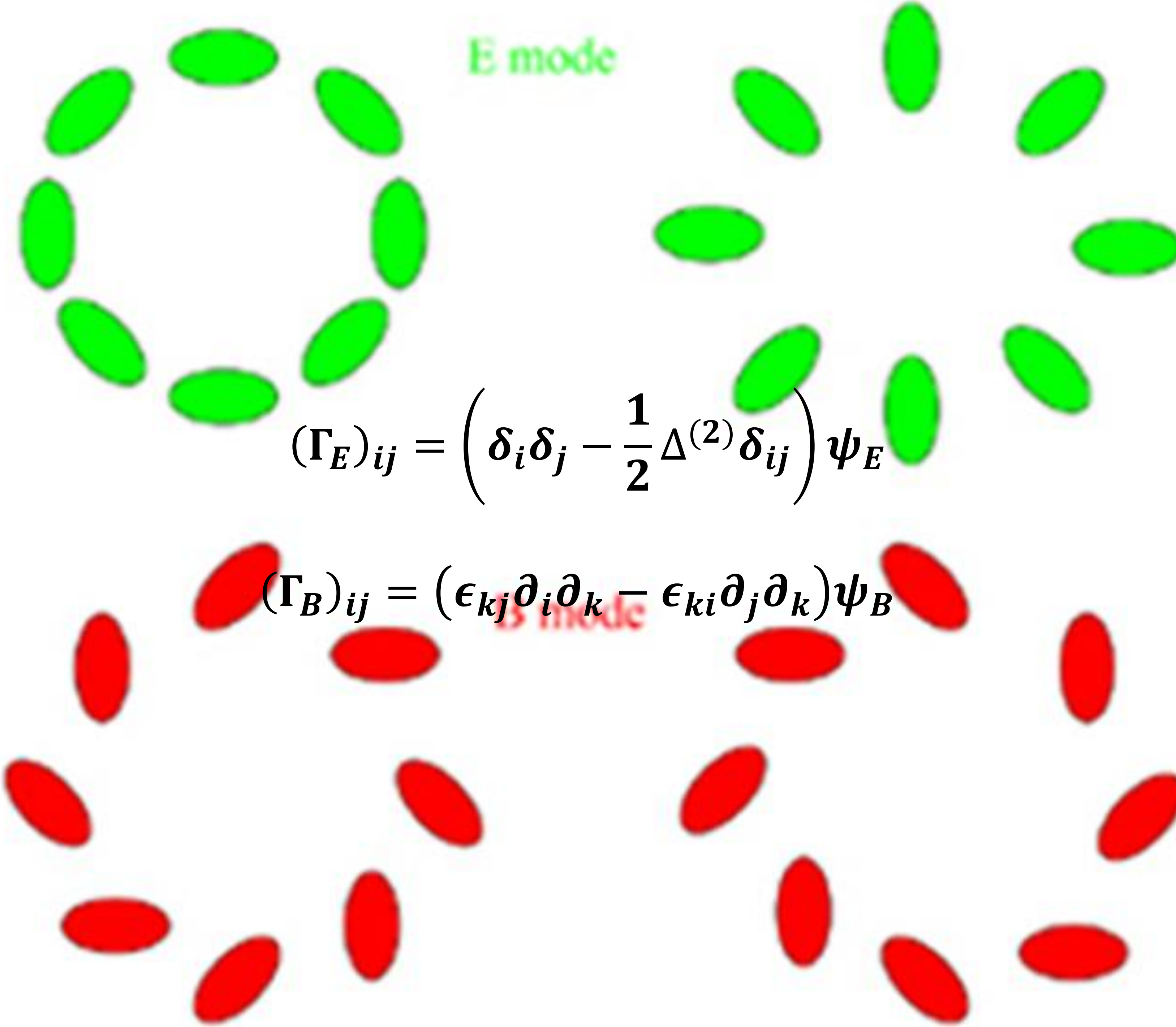
MACSJ1206-08
z = 0.439

color images
produced using
Trilogy

Umetsu + CLASH 2012 (arXIv:1204.3630)
Zitrin + CLASH 2012, ApJ (arXIv:1107.2649)

CLASH Hubble MCT Program:
Cluster #6/25

Weak Lensing



$$(\boldsymbol{\Gamma}_E)_{ij} = \left(\delta_i \delta_j - \frac{1}{2}\Delta^{(2)}\delta_{ij}\right)\psi_E$$

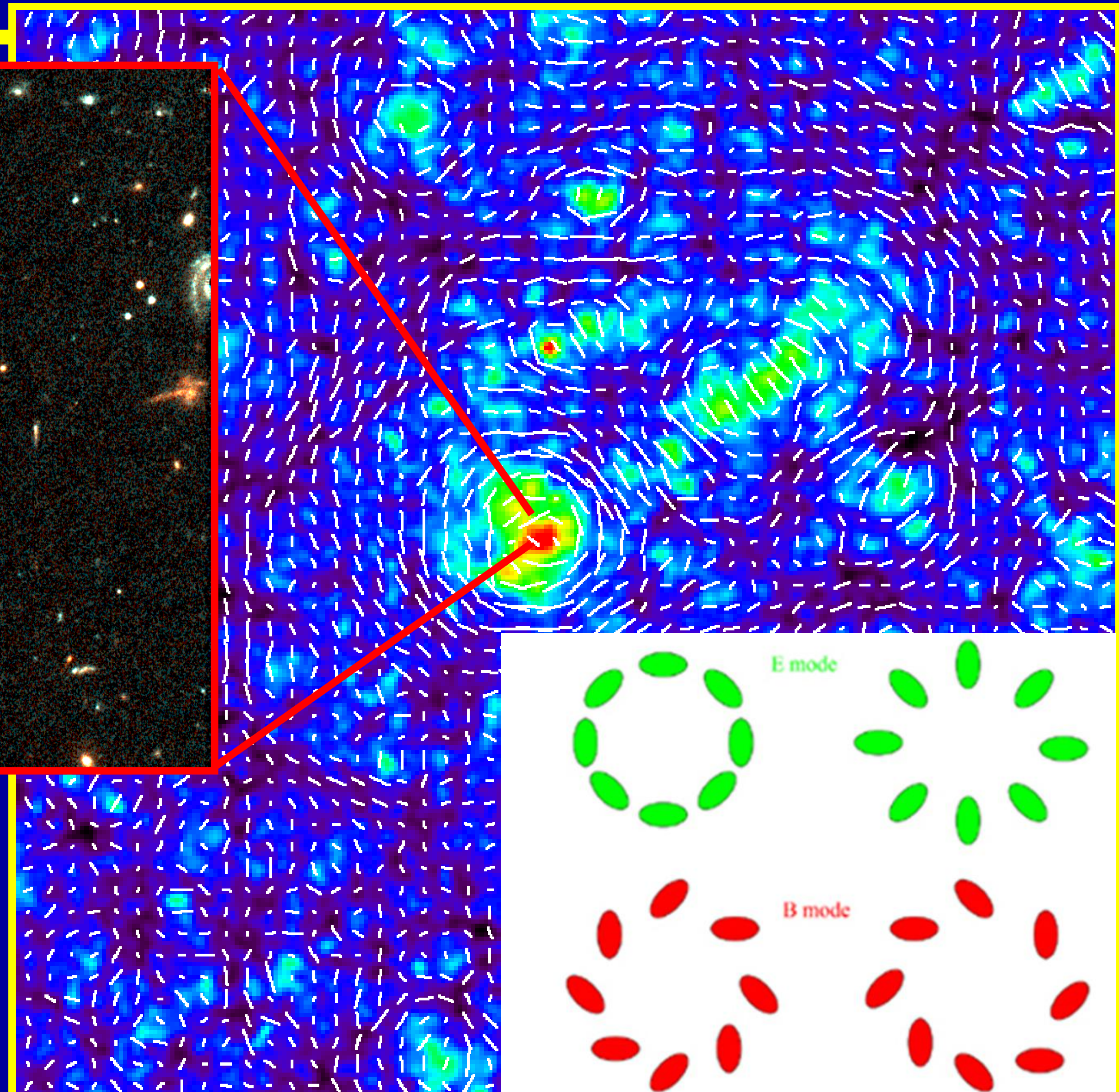
$$(\boldsymbol{\Gamma}_B)_{ij} = \left(\epsilon_{kj}\partial_i\partial_k - \epsilon_{ki}\partial_j\partial_k\right)\psi_B$$

Weak Lensing [1]: Gravitational Shear

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

Shear to mass inversion

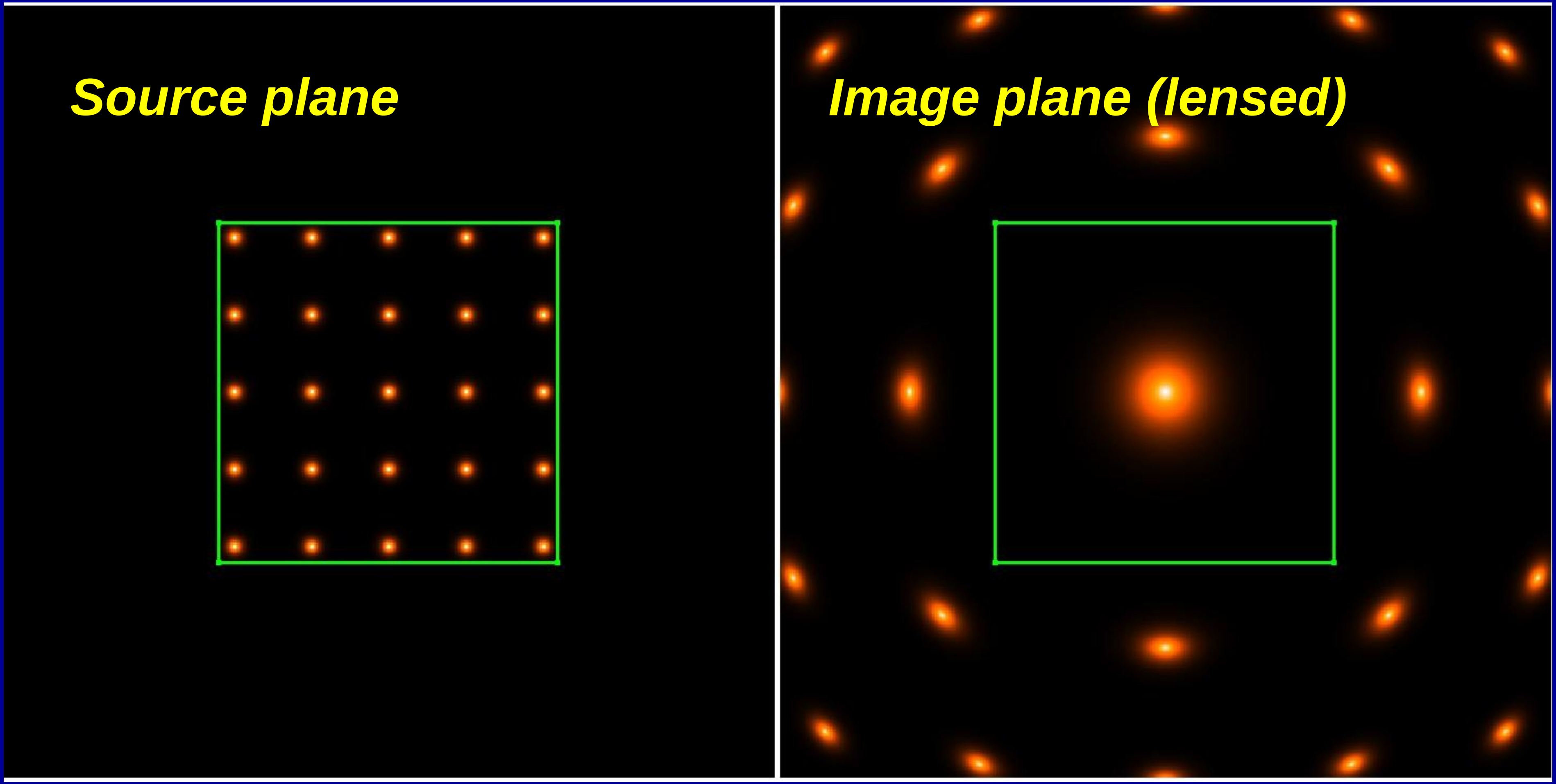
$$\kappa = \Delta^{(2)^{-1}}\left(\partial^i \partial^j \Gamma_{ij}\right)$$



Simulated 3x3 degree field (Hamana 02)

Weak Lensing [2]: Magnification

Sky expands due to gravitational magnification



Leading to a depletion of counts-in-cells

Magnification Bias

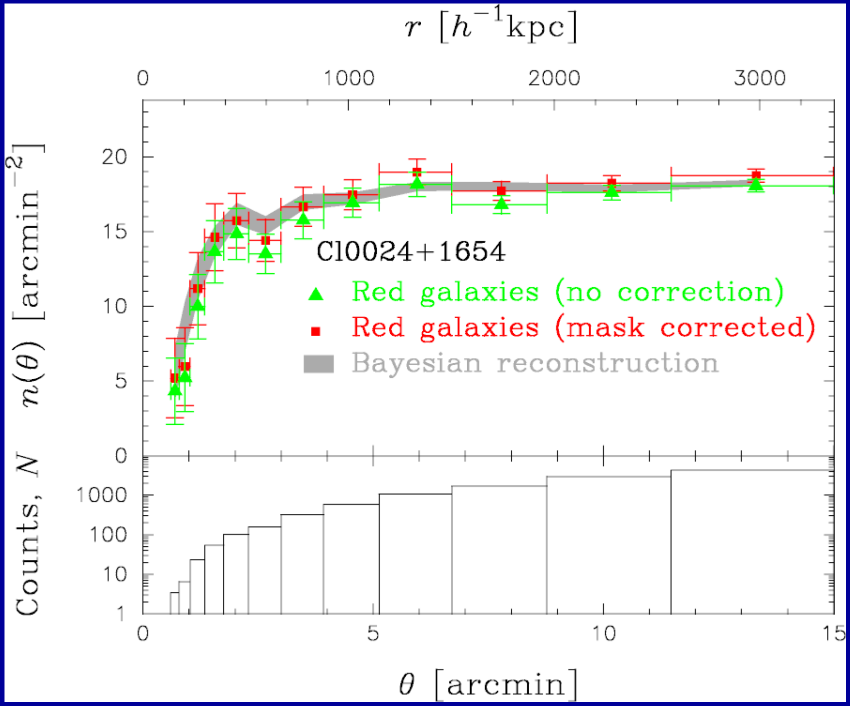
Lensing-induced fluctuations in background counts:

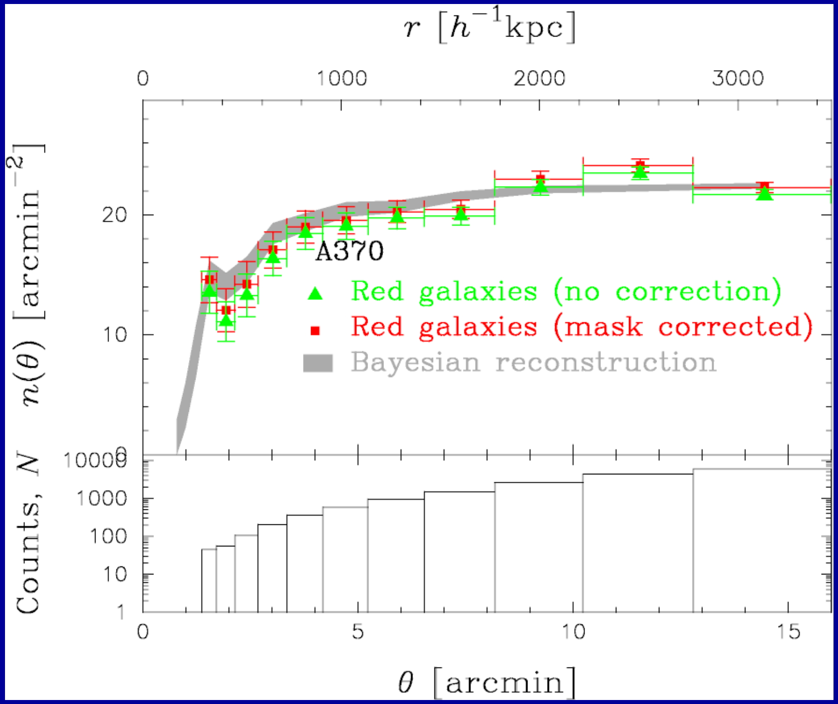
$$\frac{\delta n(\boldsymbol{\theta})}{n_0} = \mu^{s-1}(\boldsymbol{\theta}) - 1 \approx 2(s-1)\kappa(\boldsymbol{\theta})$$

with unlensed Luminosity Function of BG galaxies

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

When the count-slope is shallow (s<1), a net deficit of counts results: the case for **faint red galaxies** (Broadhurst, Taylor, Peacock 1995)

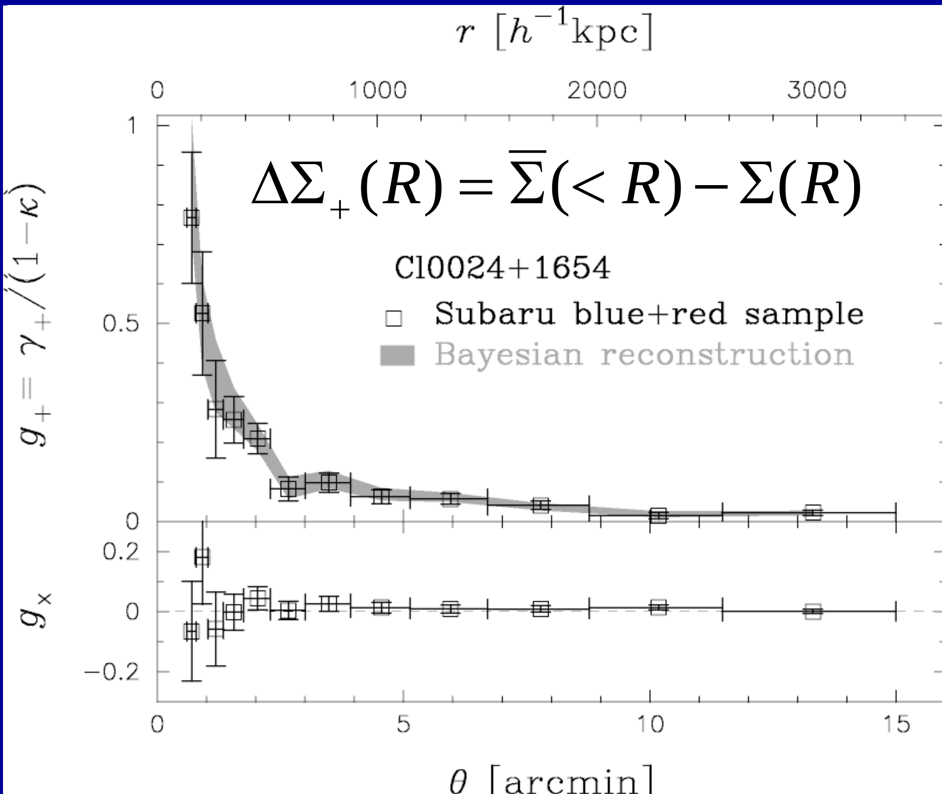




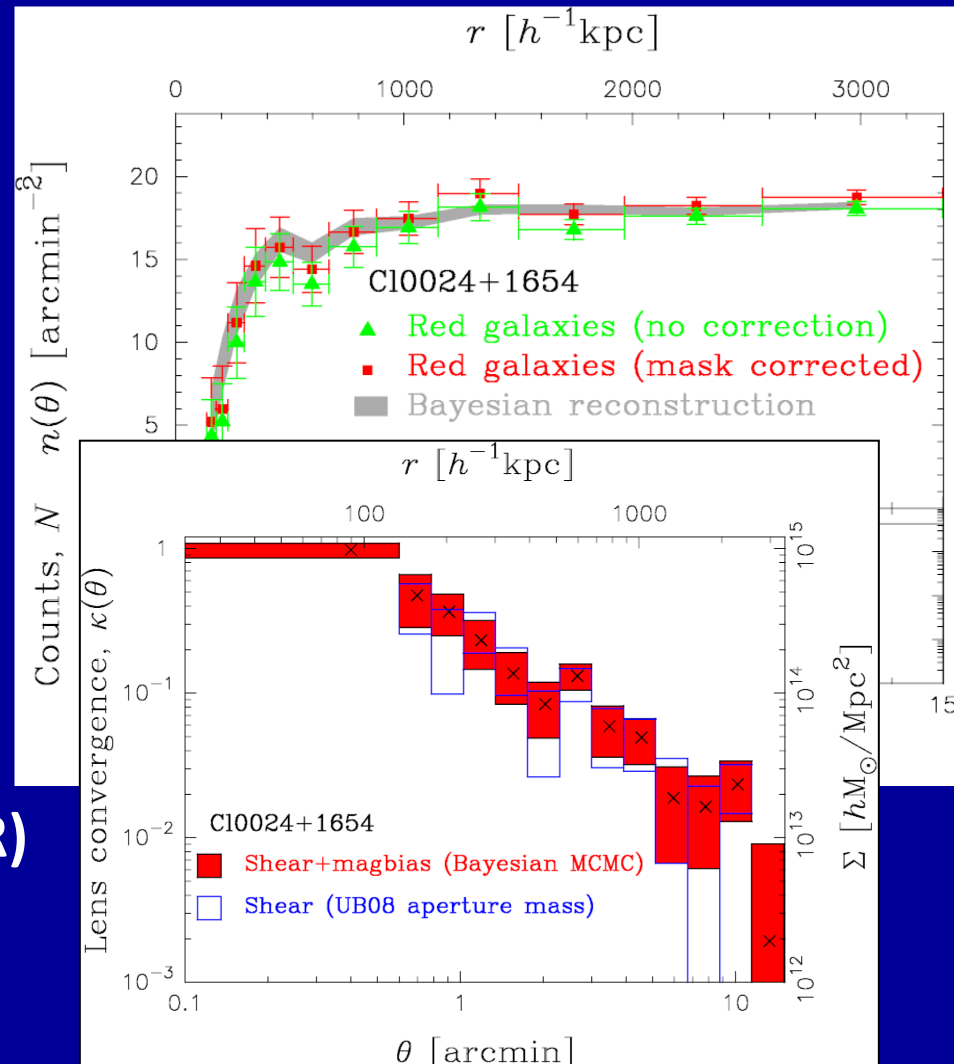
Umetsu et al. 2011a, ApJ, 729, 127

Combining Distortion and Magnification

Tangential distortion (shear)



Number counts (magnification bias)

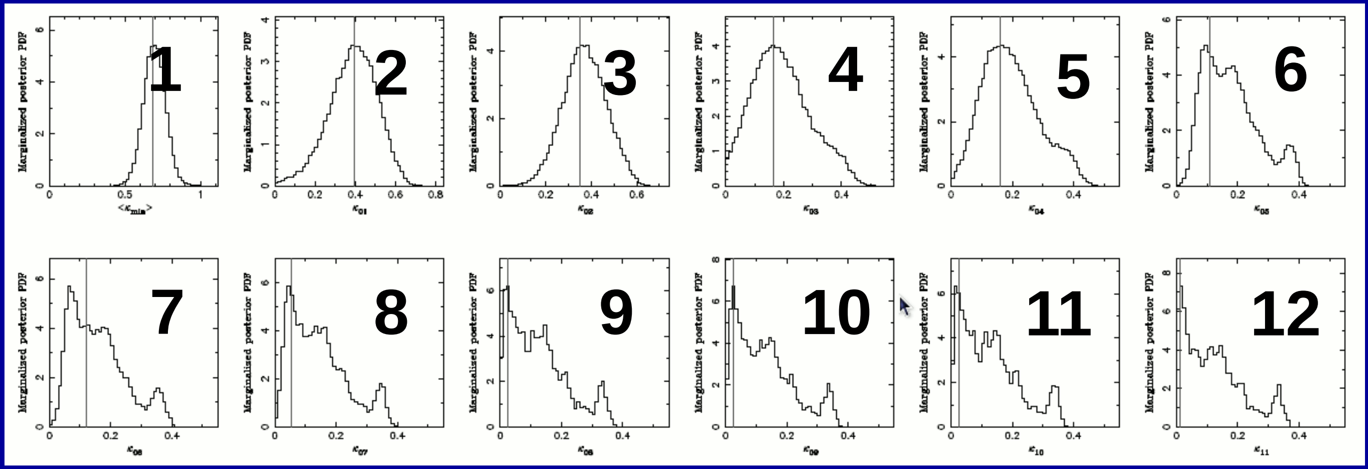


A unique mass profile solution Σ(R) can be obtained from Bayesian analysis of WL shear + mag-bias (Umetsu et al. 2011a)

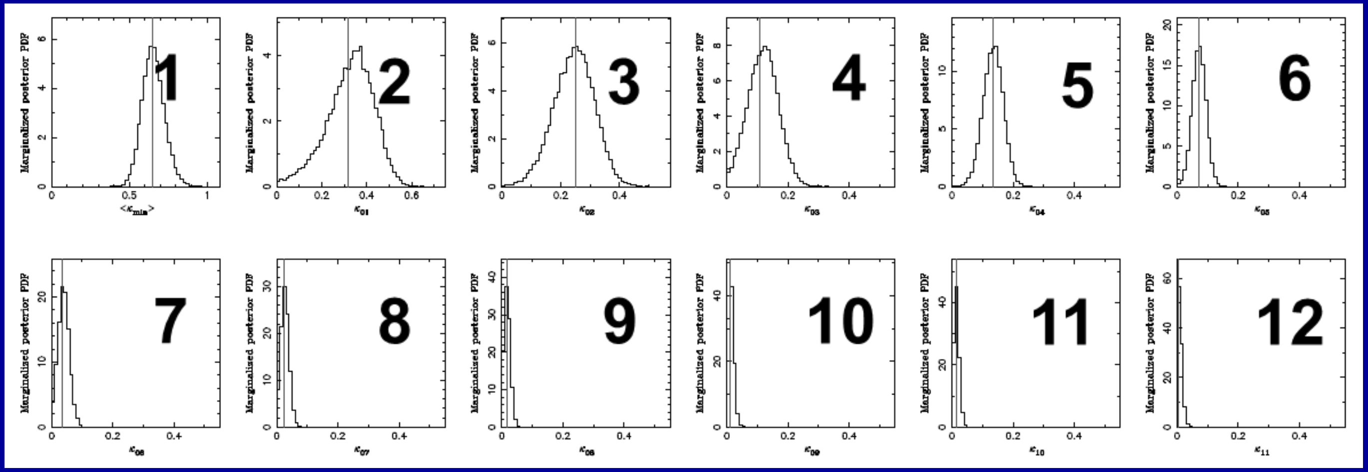
What we gain by adding magnification?

Marginalized PDFs of Σ(R) in N=12 radial bins: A1689

Shear data alone



Shear + magnification

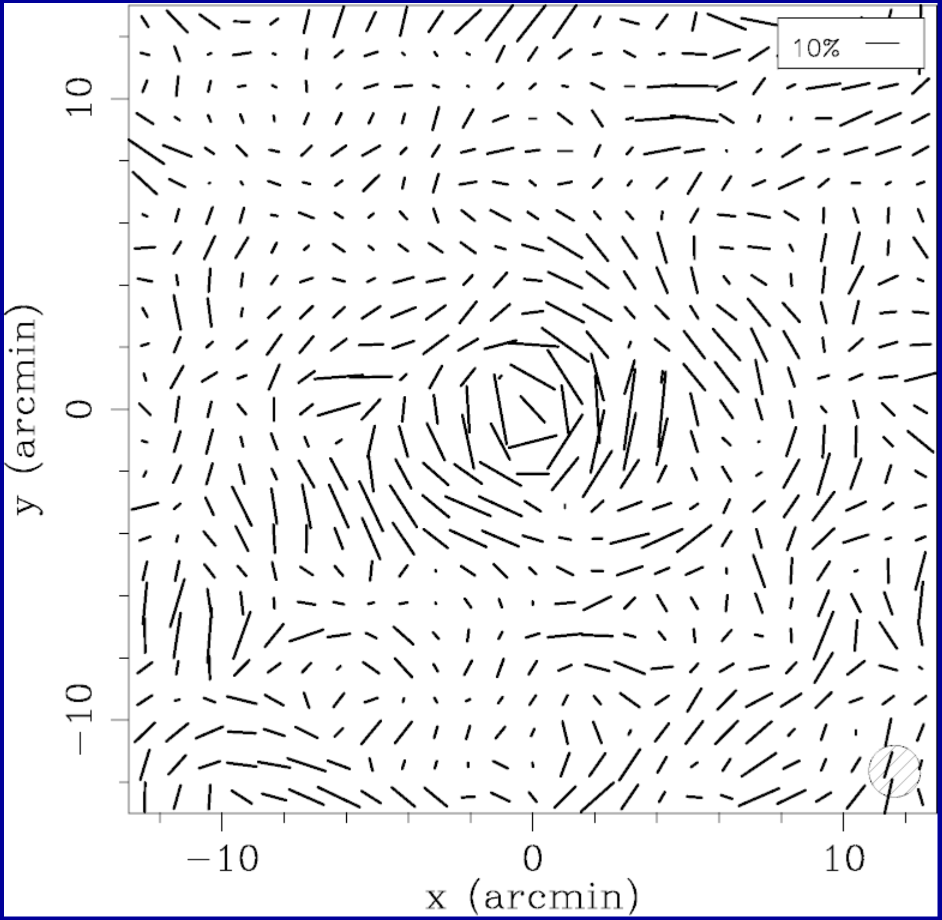


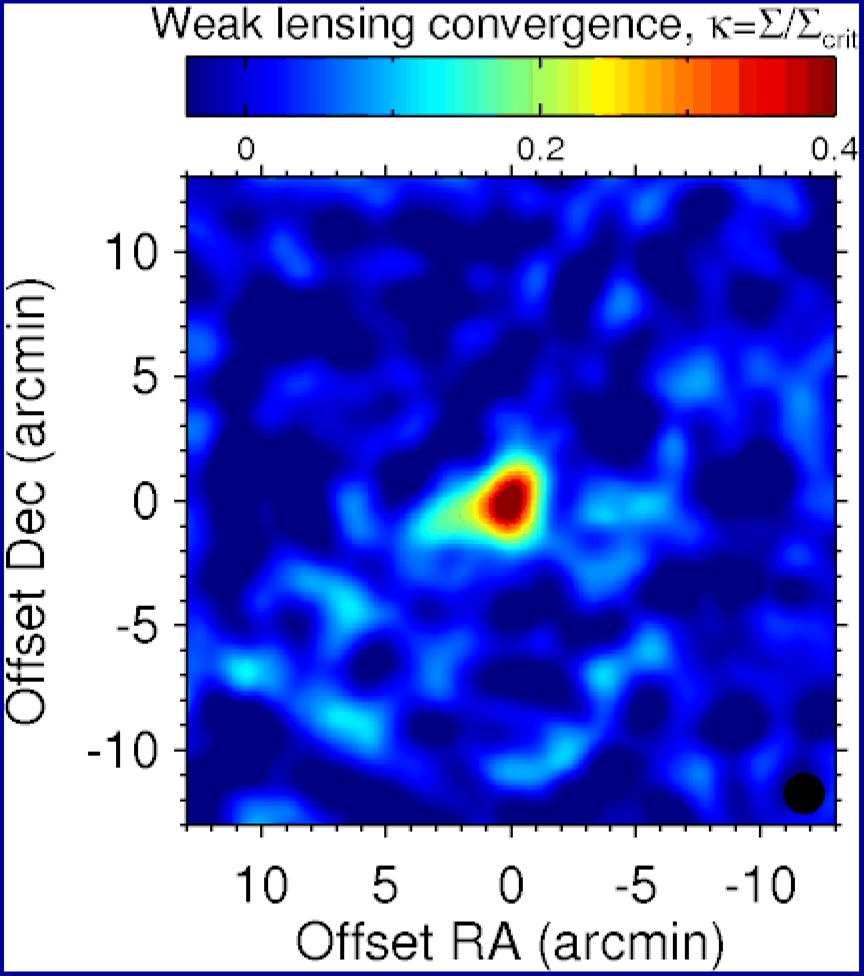
Umetsu et al. 2011a

- **Mass-sheet degeneracy is fully broken**
- **~30% improvement in mass determination**

Weak Lensing [3]: Power of Stacking Analysis

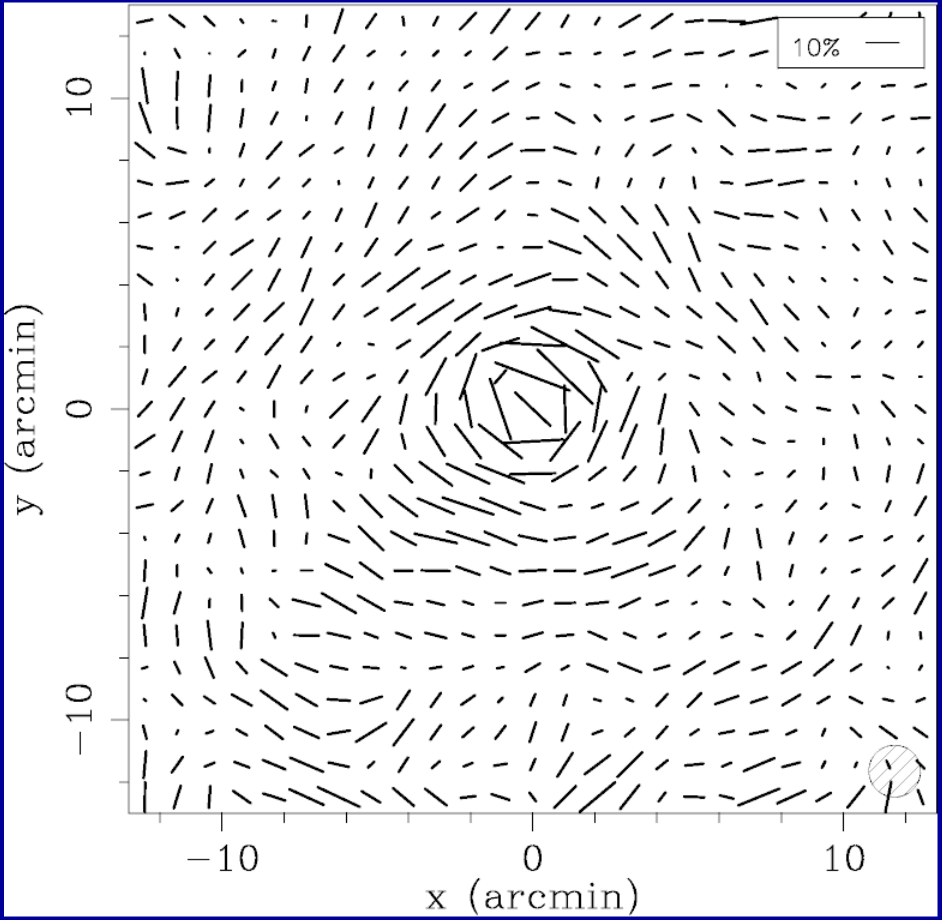
Subaru shear data: N=1

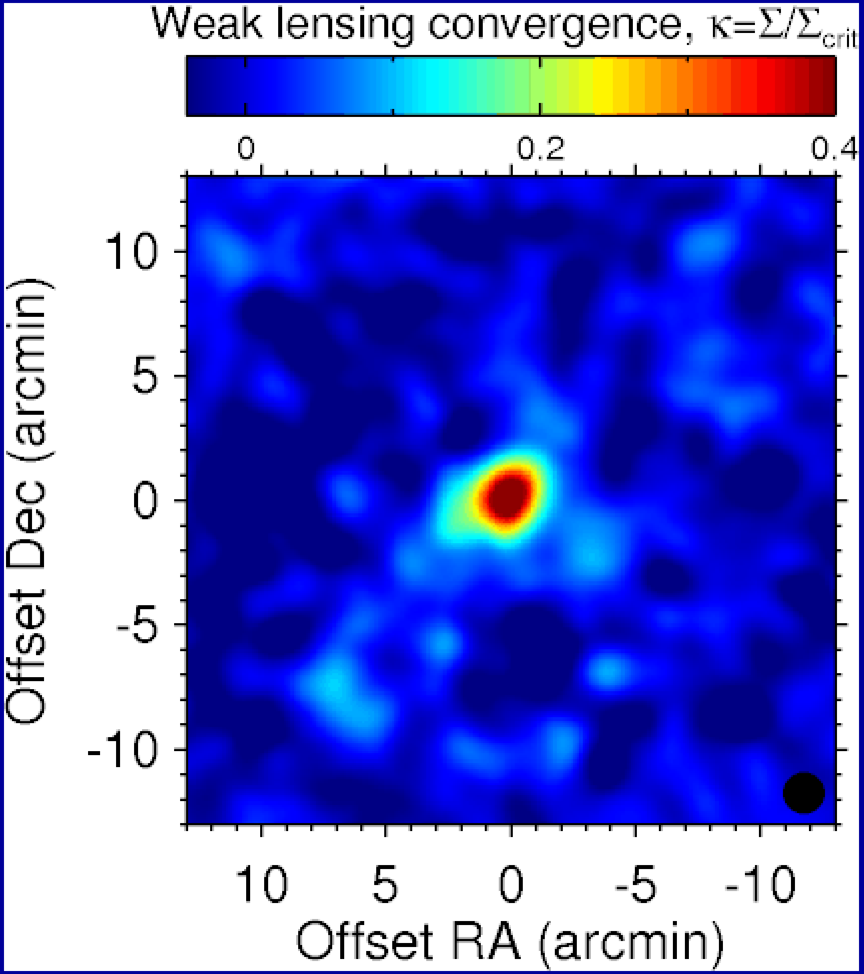




Weak Lensing [3]: Power of Stacking Analysis

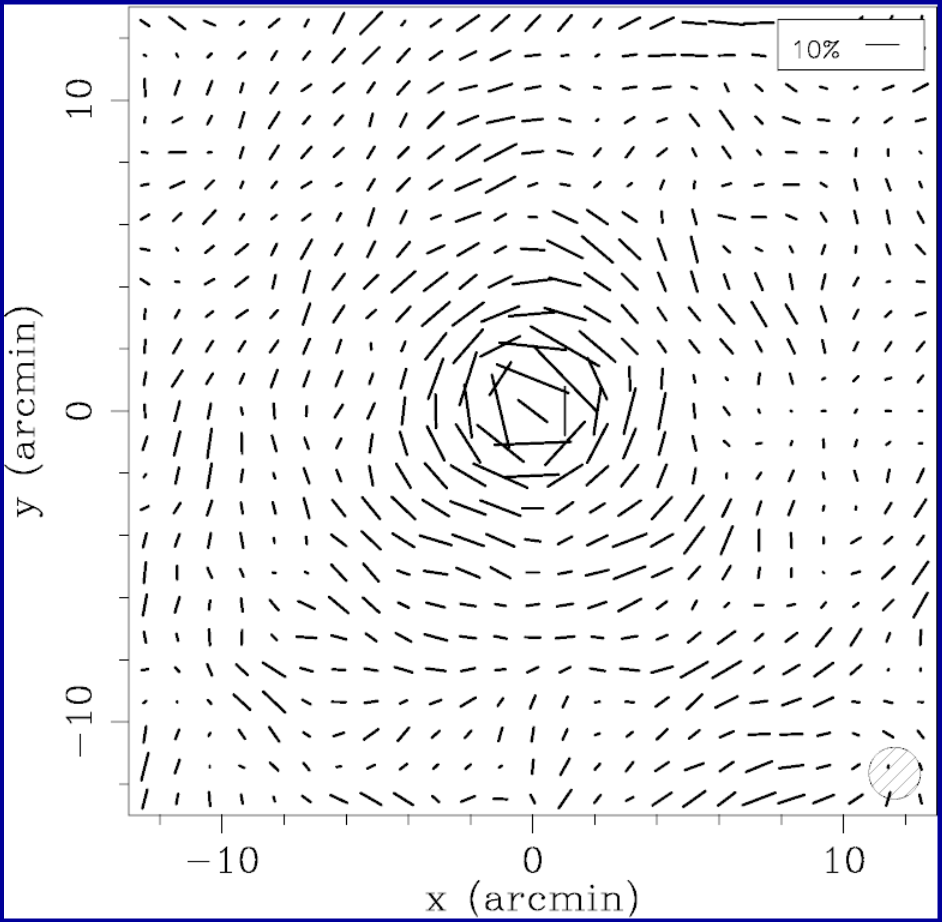
Subaru shear data: N=2

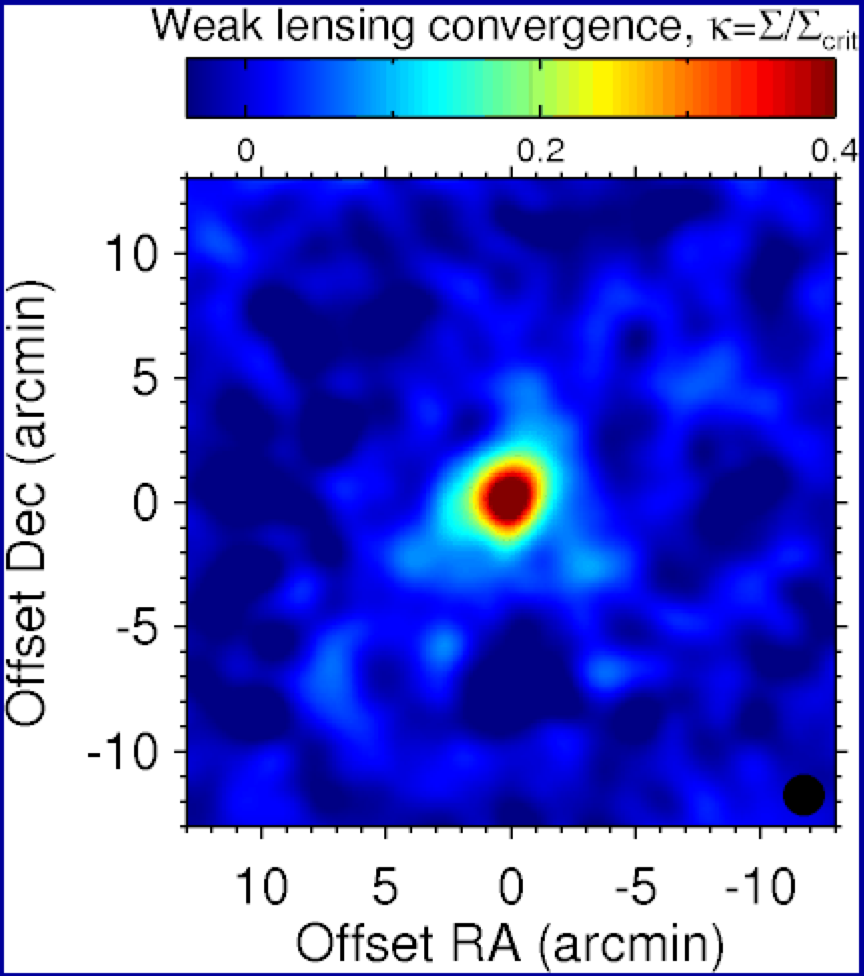




Weak Lensing [3]: Power of Stacking Analysis

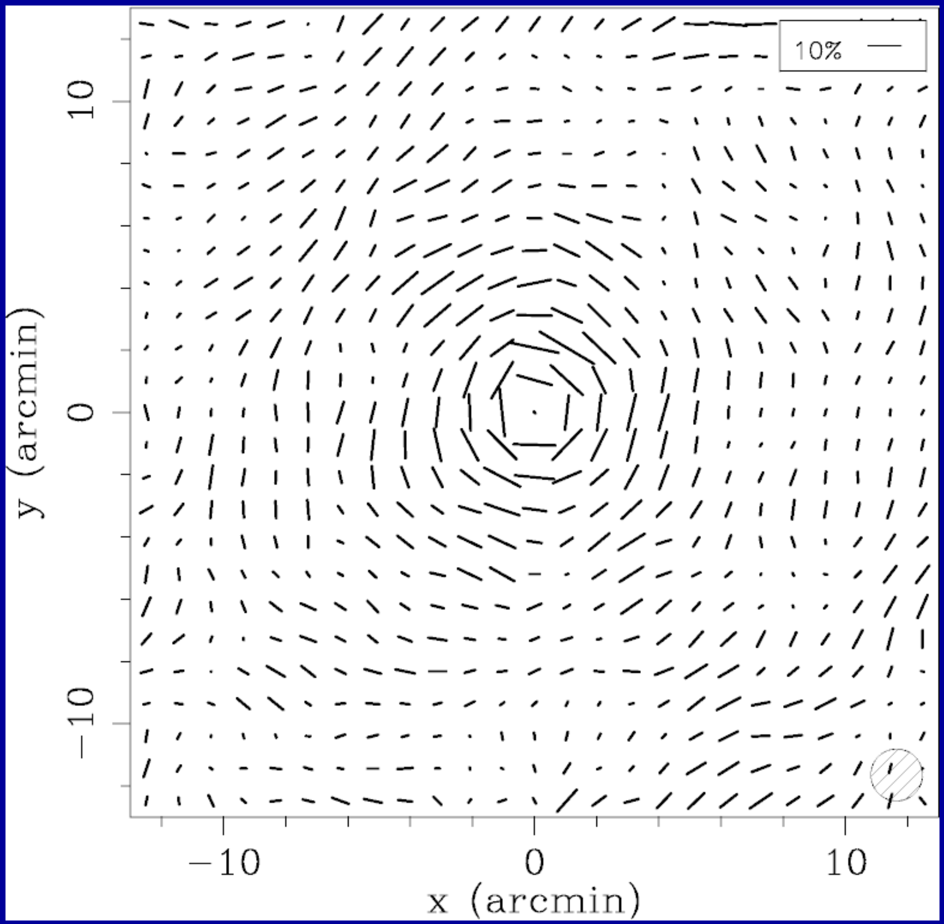
Subaru shear data: N=3

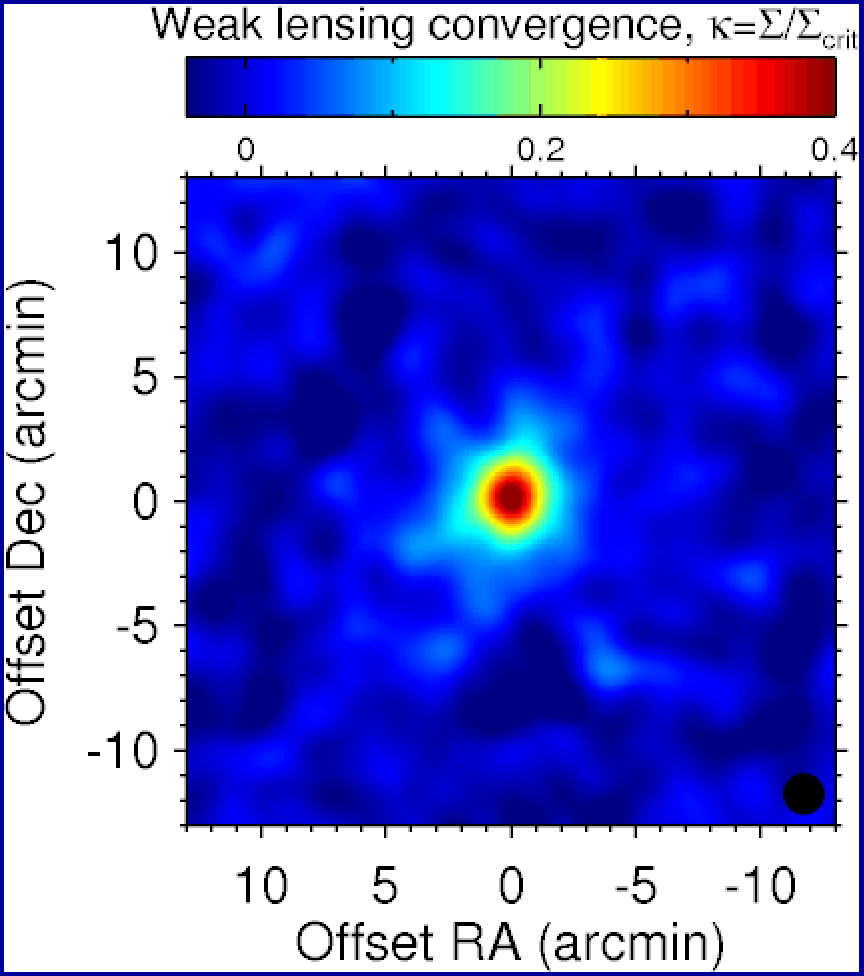




Weak Lensing [3]: Power of Stacking Analysis

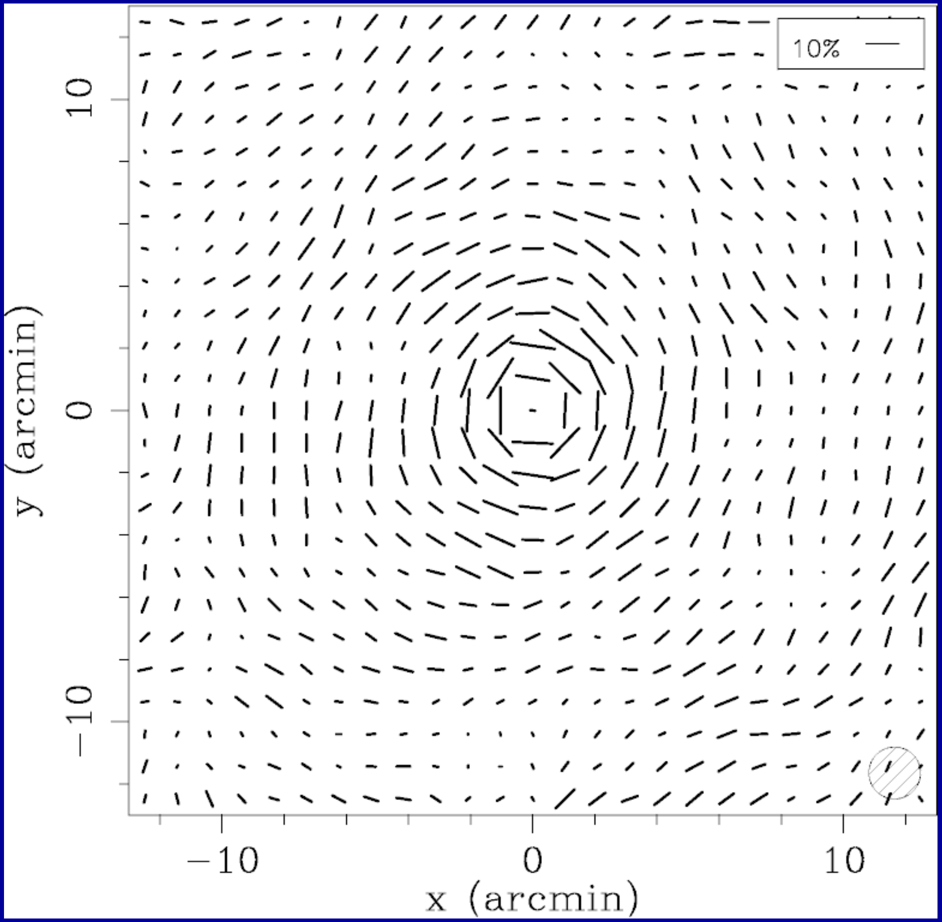
Subaru shear data: **N=4**

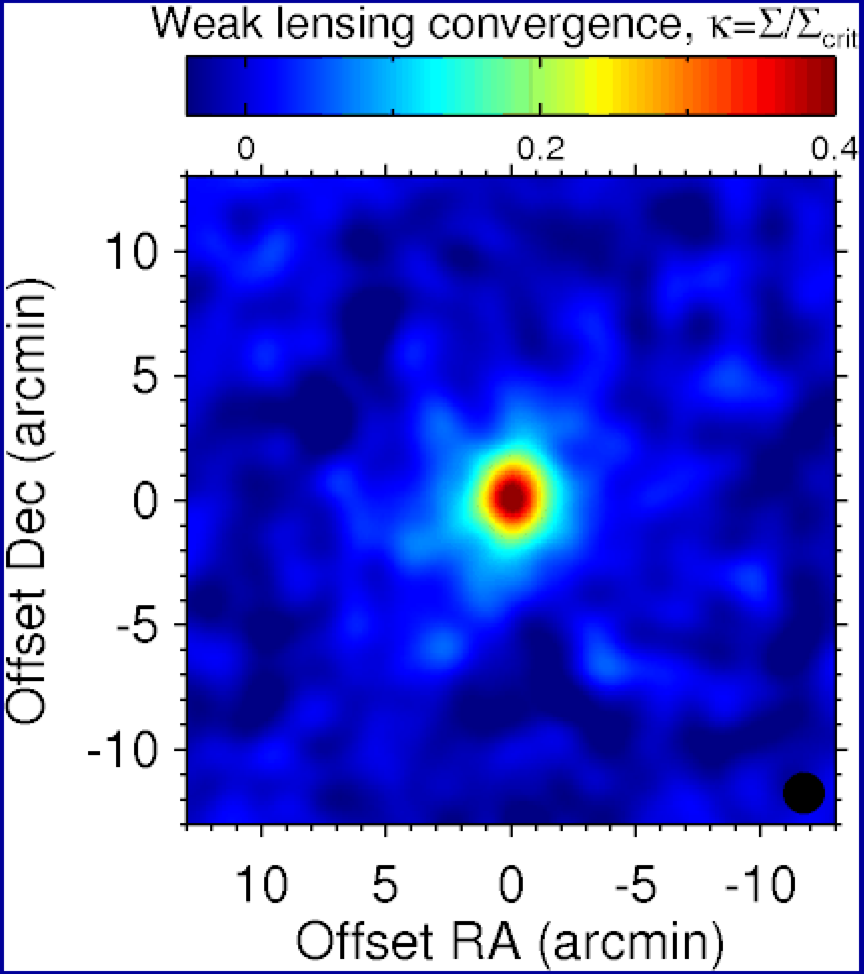




Weak Lensing [3]: Power of Stacking Analysis

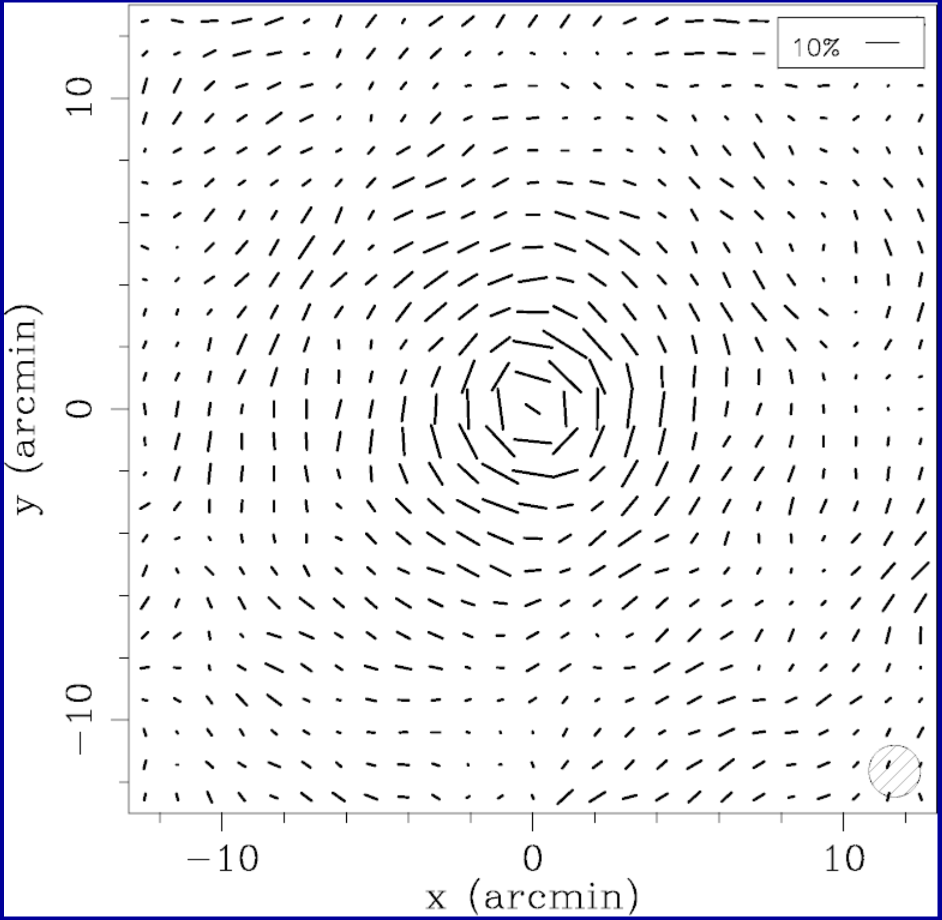
Subaru shear data: N=5

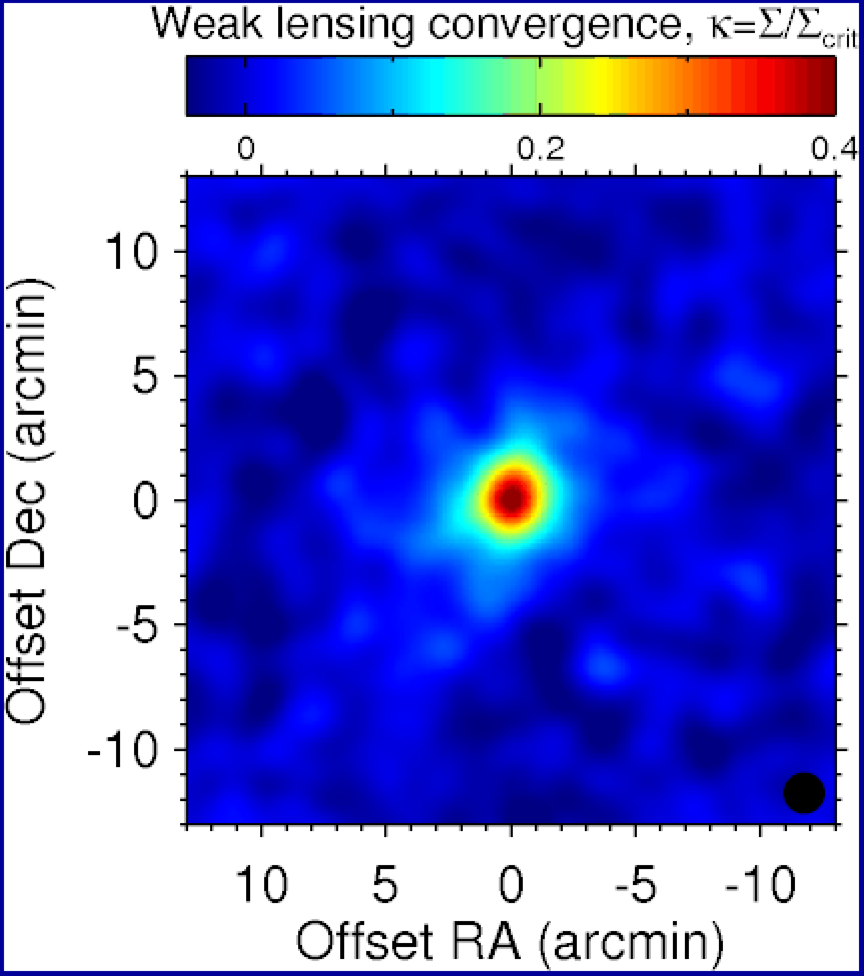




Weak Lensing [3]: Power of Stacking Analysis

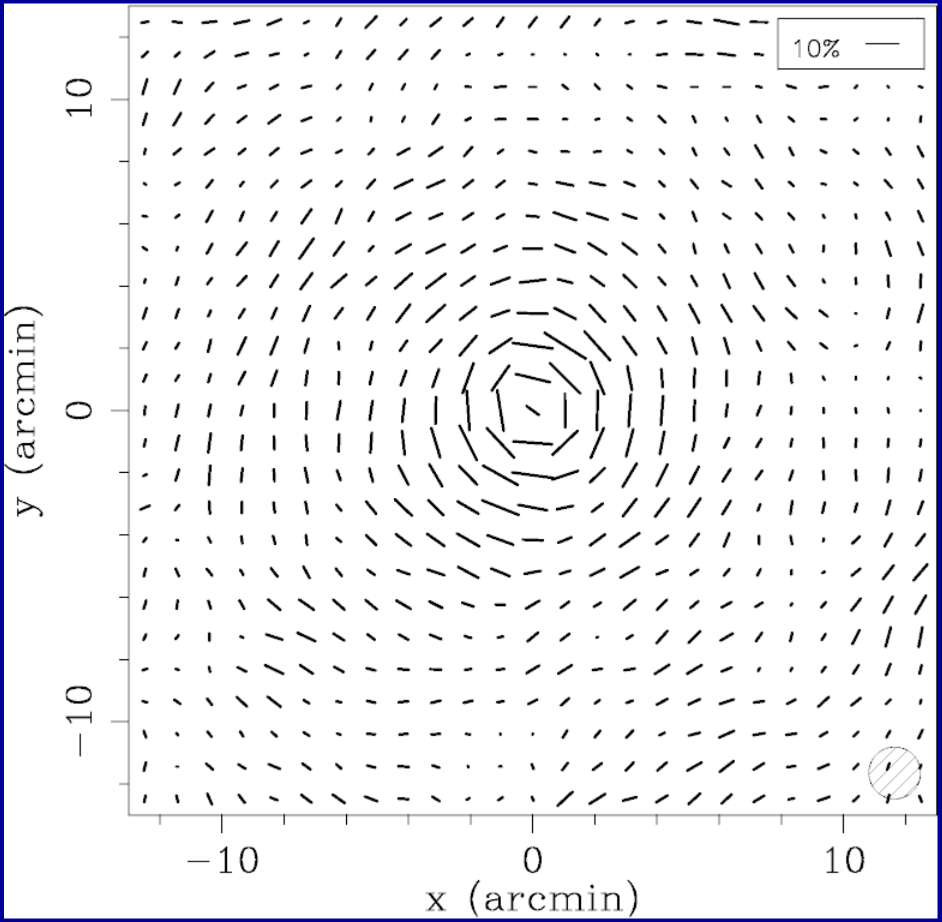
Subaru shear data: N=6

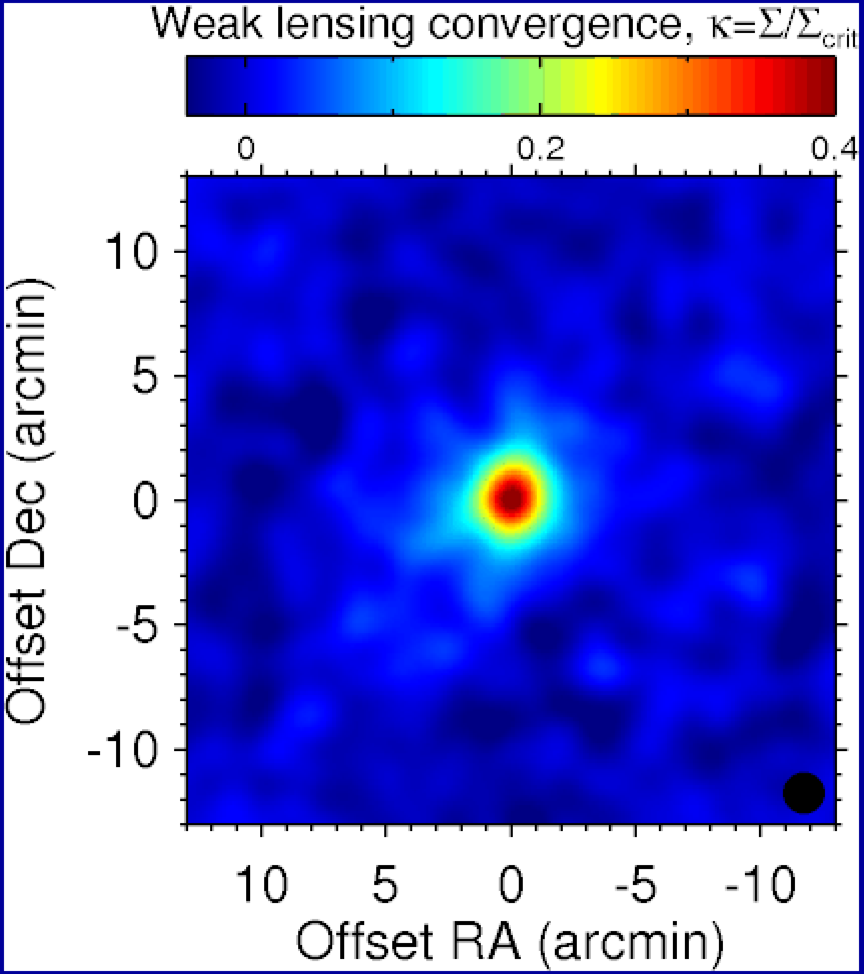




Weak Lensing [3]: Power of Stacking Analysis

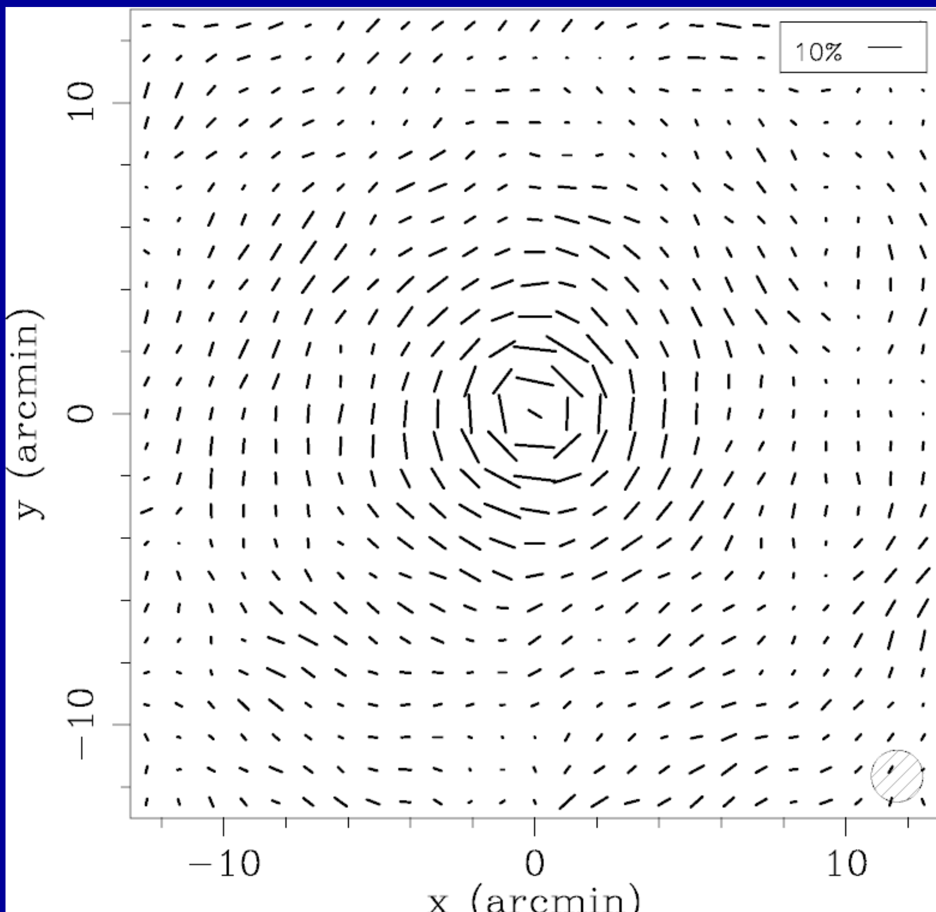
Subaru shear data: N=7

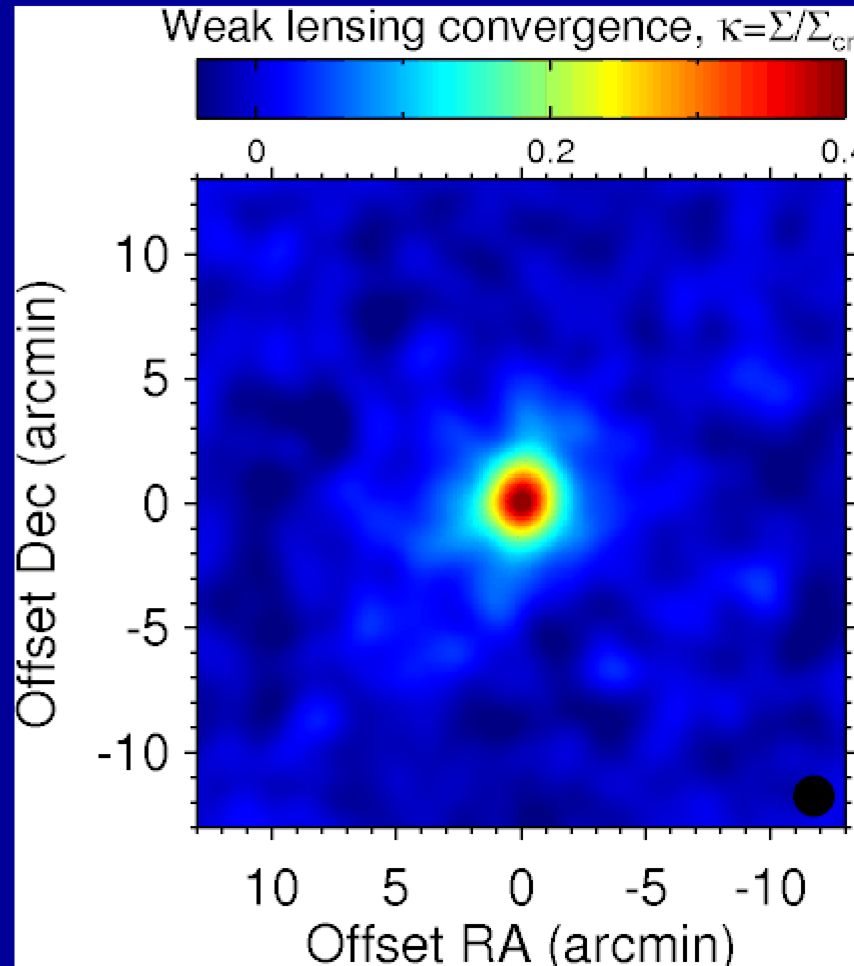




Weak Lensing [3]: Power of Stacking Analysis

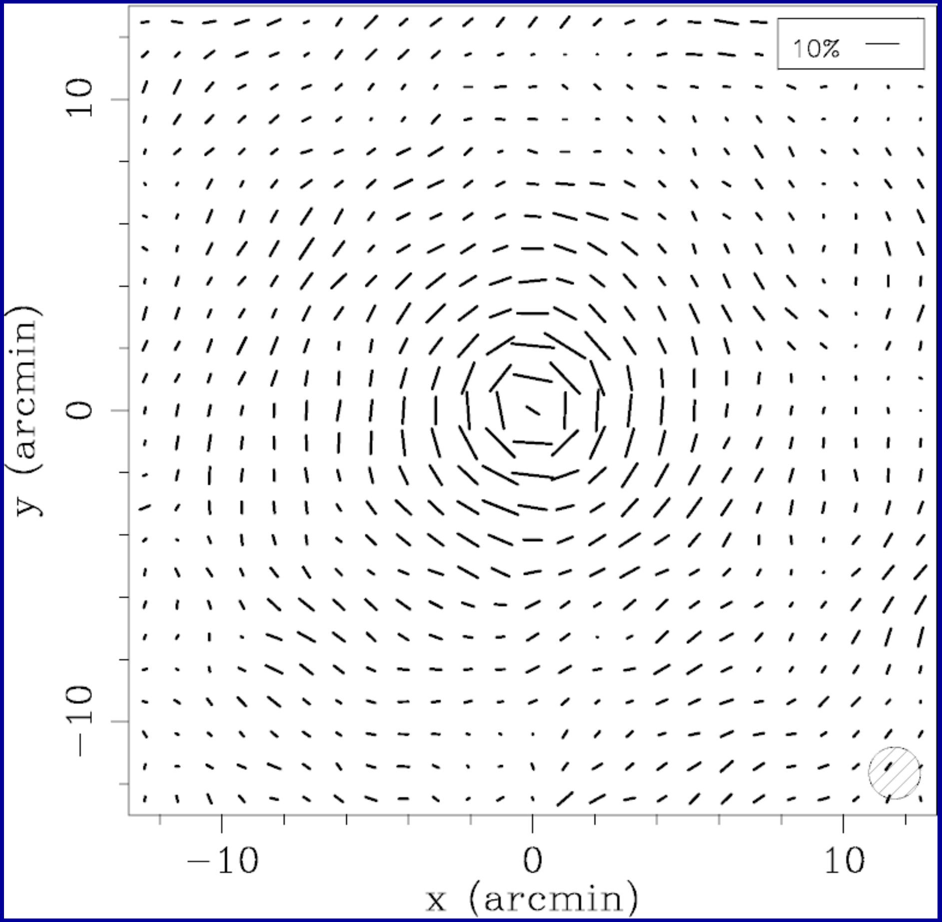
Subaru shear data: N=8

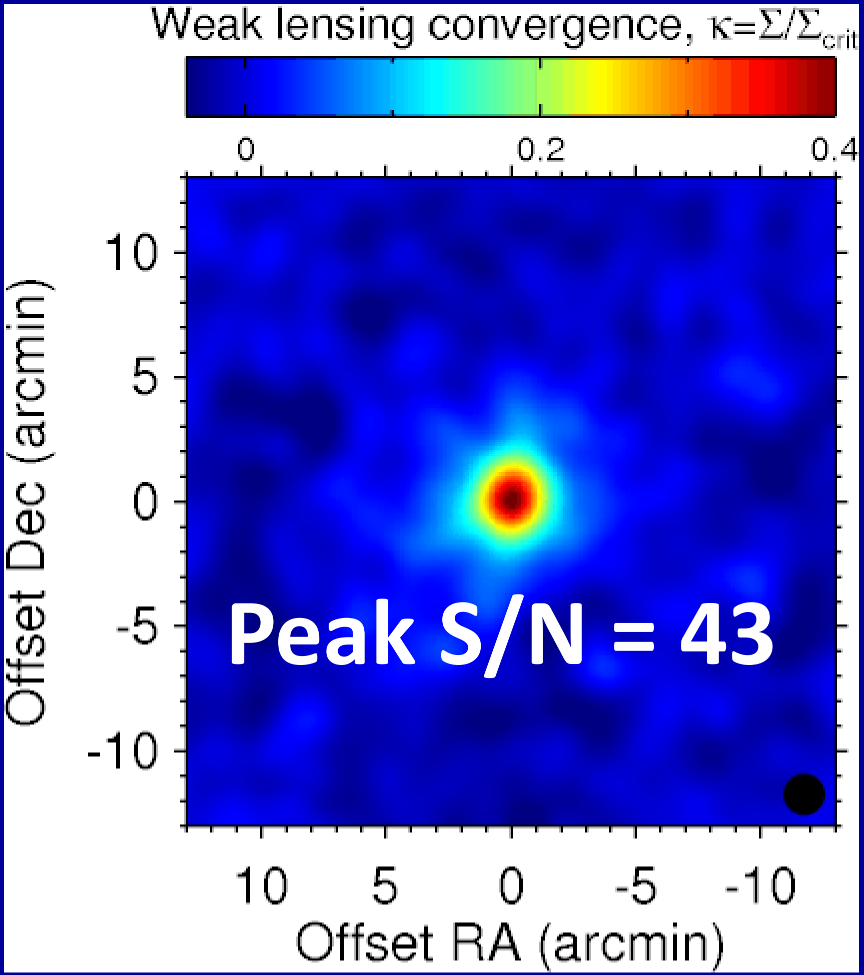




Weak Lensing [3]: Power of Stacking Analysis

Subaru shear data: **N=9**



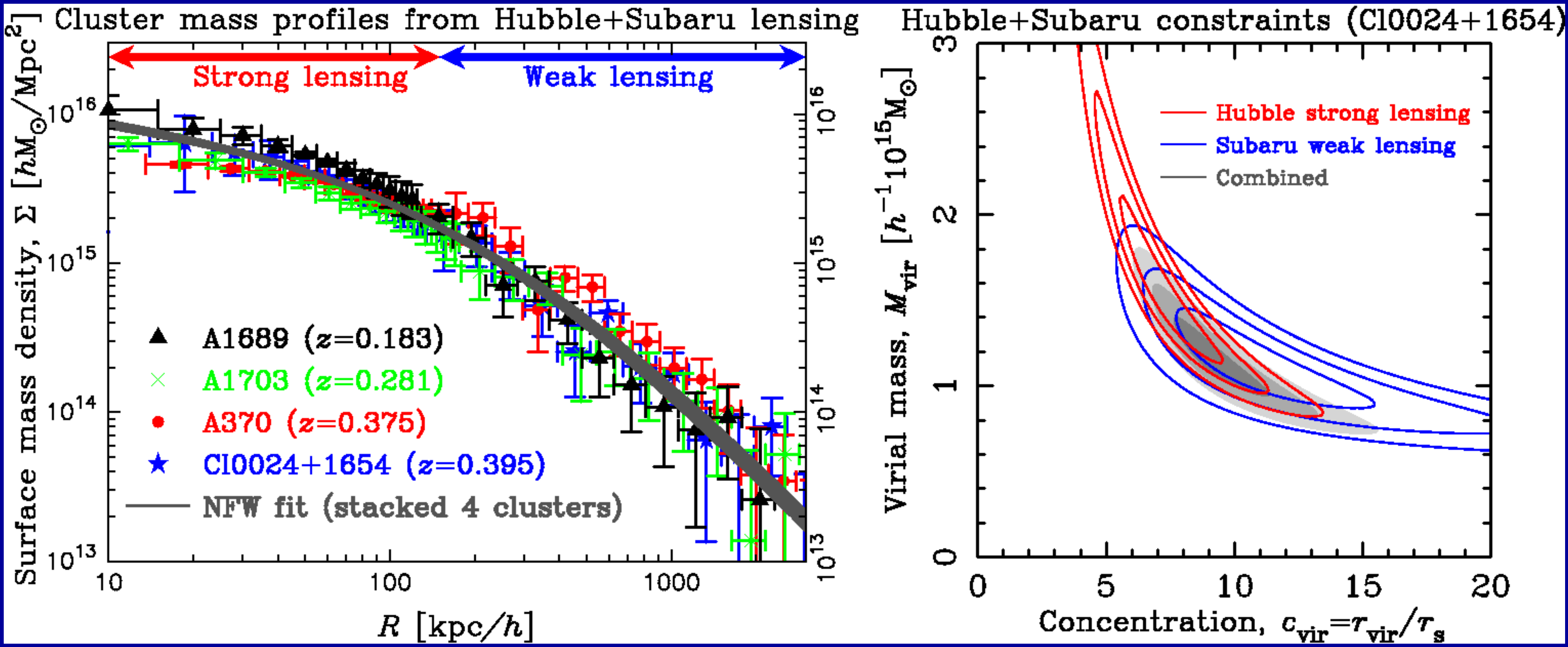


Incoherent contributions, such as asphericcity, substructures, cosmic shear (uncorrelated LSS contributions), as well as intrinsic shape noise, being averaged out by stacking clusters, due to the isotropic nature of the universe

Combining Full Lensing Constraints
[Weak shear, magnification, strong lensing]

Strong and Weak lensing contribute roughly equal logarithmic coverage of radial mass profile for massive galaxy clusters:

→ ***Hubble*+SUBARU** probe the full cluster radial range [0.5%, 150%]



Umetsu+2008, 2009, 2010, 2011a, 2011b

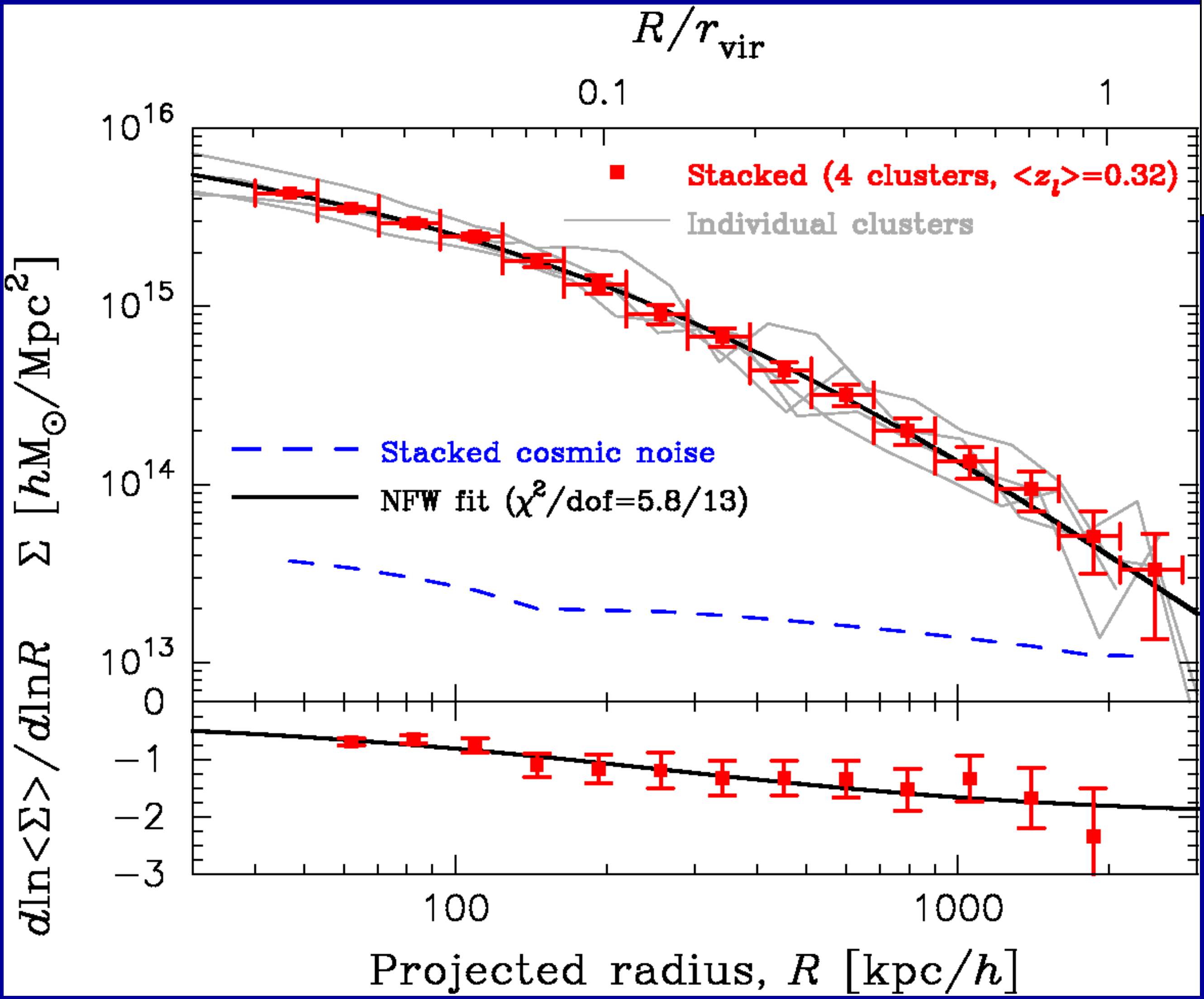
This has been extended to the 512-orbit *Hubble* CLASH program (PI: M. Postman).

3. Highlights of Strong+Weak Lensing Results on the Best-Studied Clusters

A1689, A1703, A370, Cl0024+17

(0.2<z<0.4, M>1e15Msun)

First Application of Stacked Strong + Weak Cluster Lensing



Stacking clusters by

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

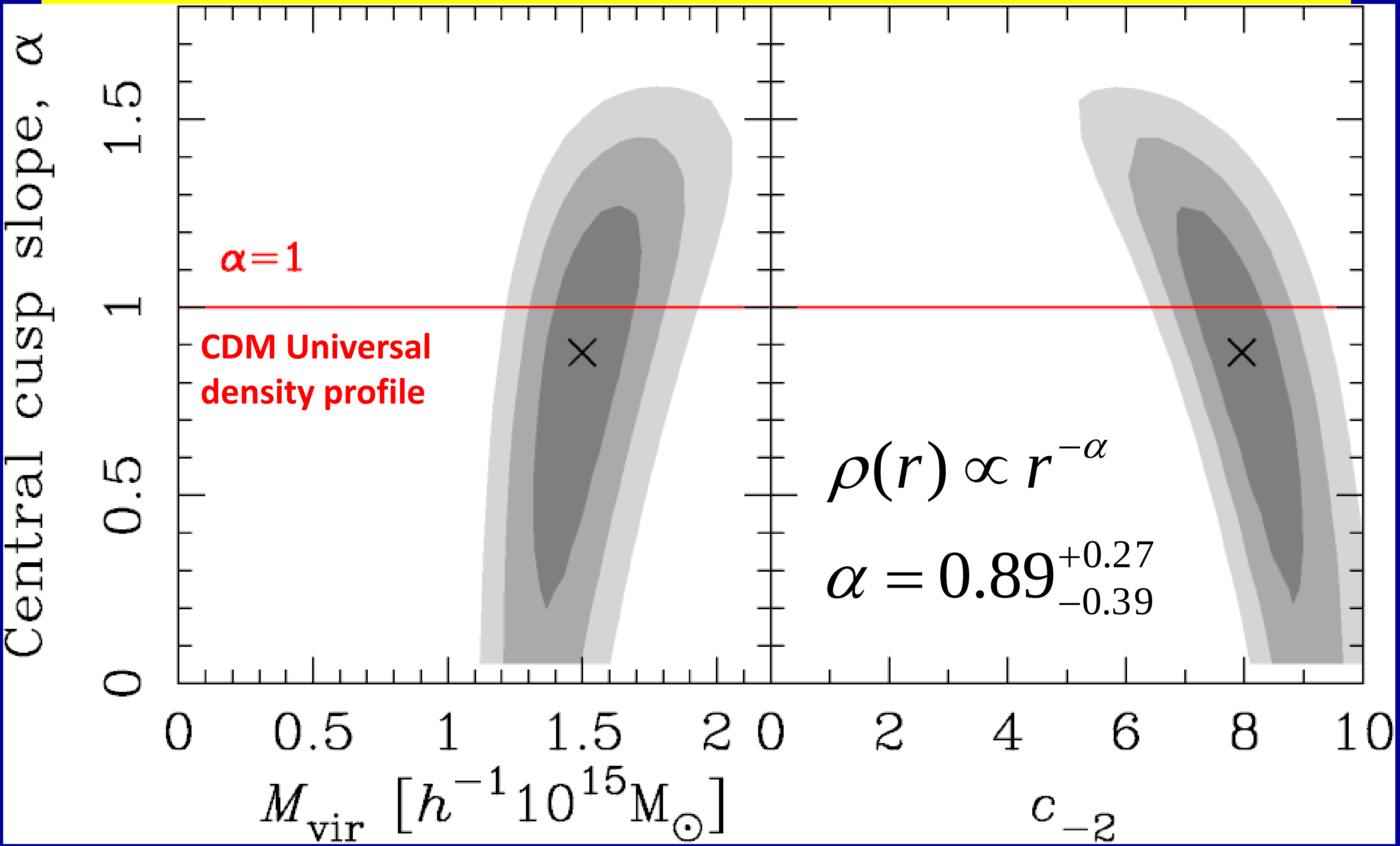
Total S/N = 58σ

Exclude central R<2$d_{\rm off}$ =40kpc/h to avoid smoothing from BCG-DM *miscentering* !!

A single NFW gives an excellent fit over ~2-decades of radius → consistent with CDM

Umetsu et al. 2011b, ApJ, 738, 41 (arXiv:1105.0444)

Constraint on Central Cusp Slope

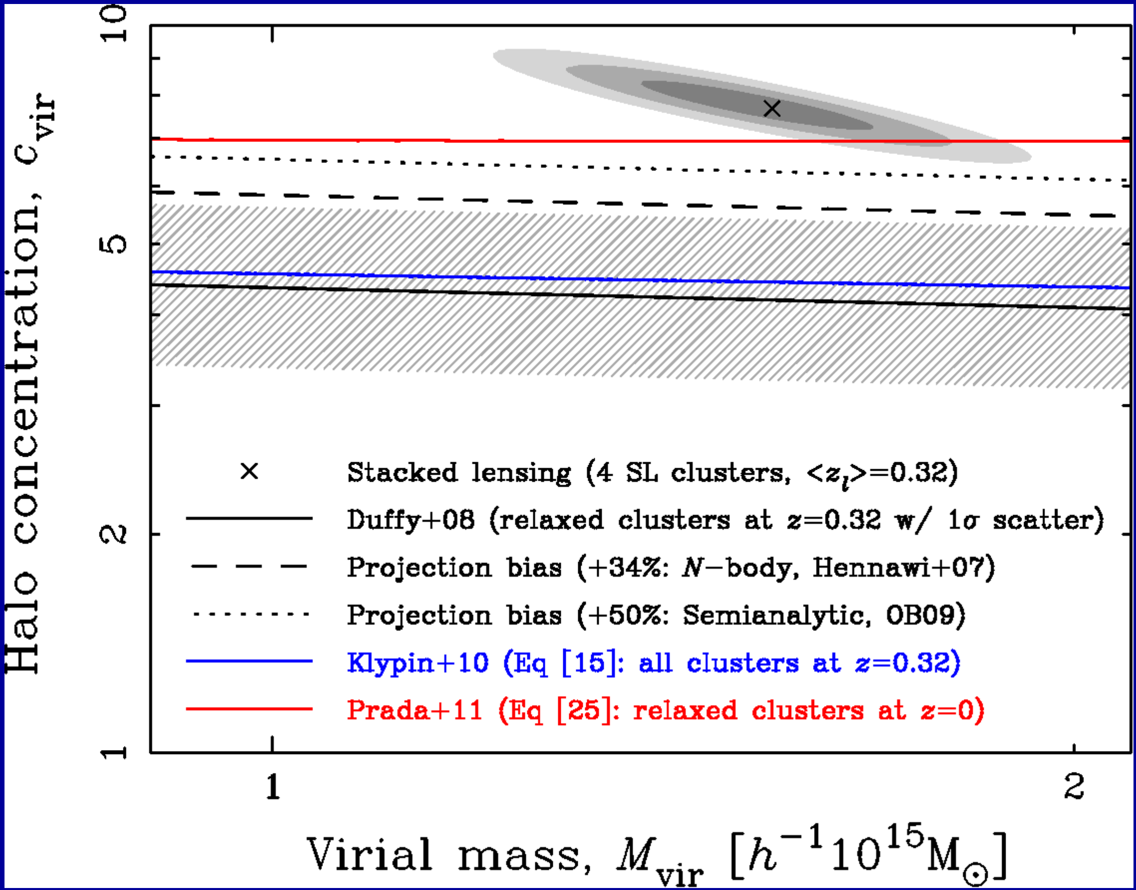


Slightly shallower than, but consistent with, the CDM universal density profile (cf. Navarro et al. 2010)

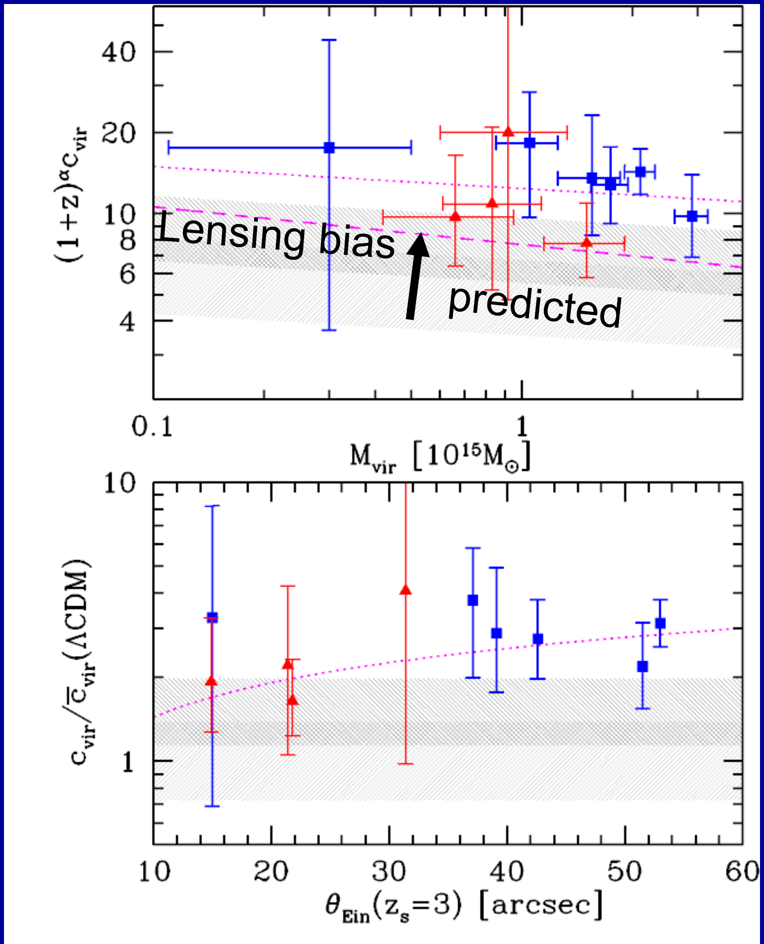
Umetsu et al. 2011b

Halo Mass vs. Concentration

The best studied clusters appear to be more densely concentrated than simulated clusters of similar mass.

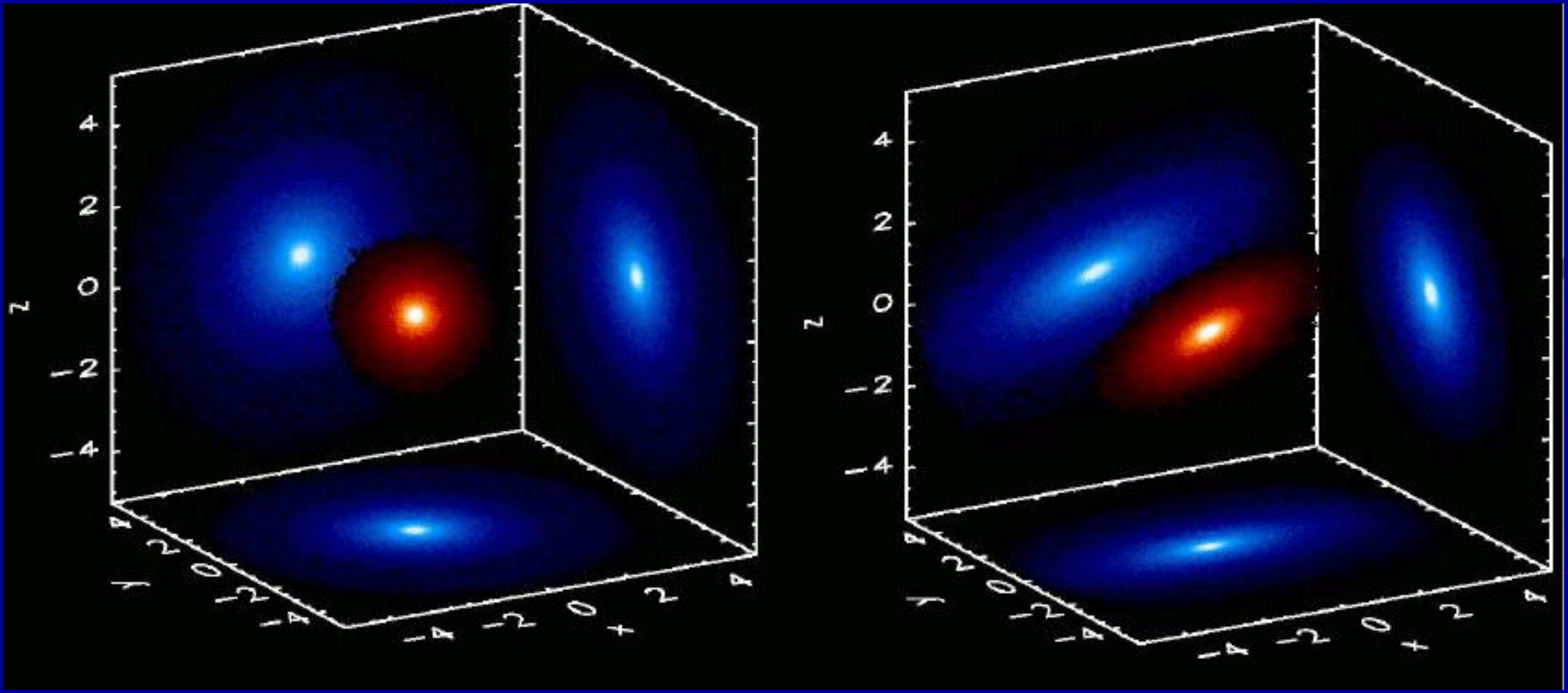


Umetsu et al. 2011b



Oguri+10; Broadhurst+08

Projection Effect by Halo Triaxiality



Spherical

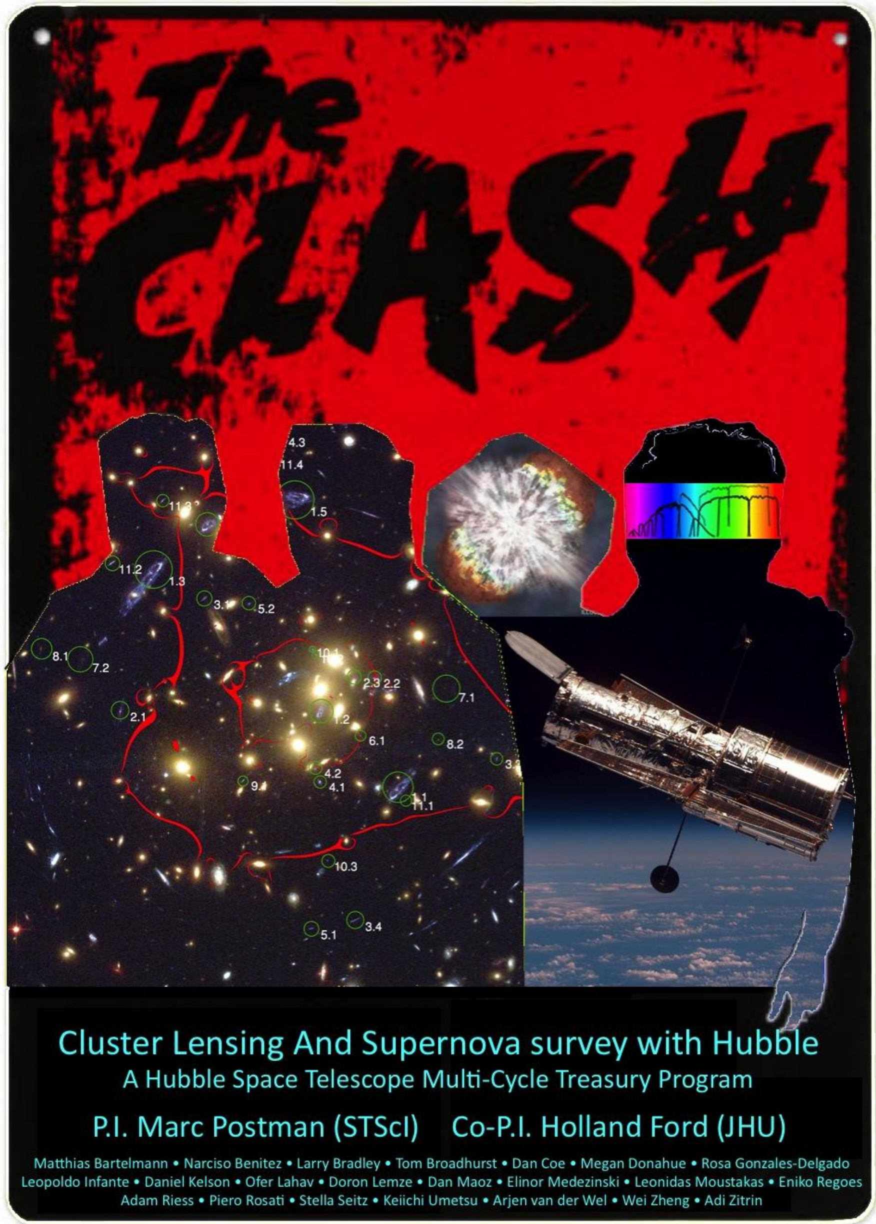
Triaxial (prolate)

Hennawi, Dalal, Bode, Ostriker 2007

Implications

- **Lensing projection and selection bias?**
  - Selection bias towards intrinsically high-c halos (Hennawi +07)
  - Triaxial orientation bias (Oguri & Blandford 09)
  - Significant (30-50%) but probably not sufficient??
- **Simulation values too low?**
  - High-mass clusters are very rare objects – only 8 relaxed halos with $M>10^{15}M_{sun}/h$ found in the Millennium simulation (500Mpc/h box), suffering from cosmic variance.
  - Some of recent simulations predict ~50% higher concentrations than previous simulations for high-mass clusters (Klypin et al. 2011, Prada et al. 2011).
- **Clusters formed earlier than in LCDM?**
  - Early Dark Energy (Sadeh & Rephaeli 08; Grossi & Springel 09) or primordial non-Gaussianity?

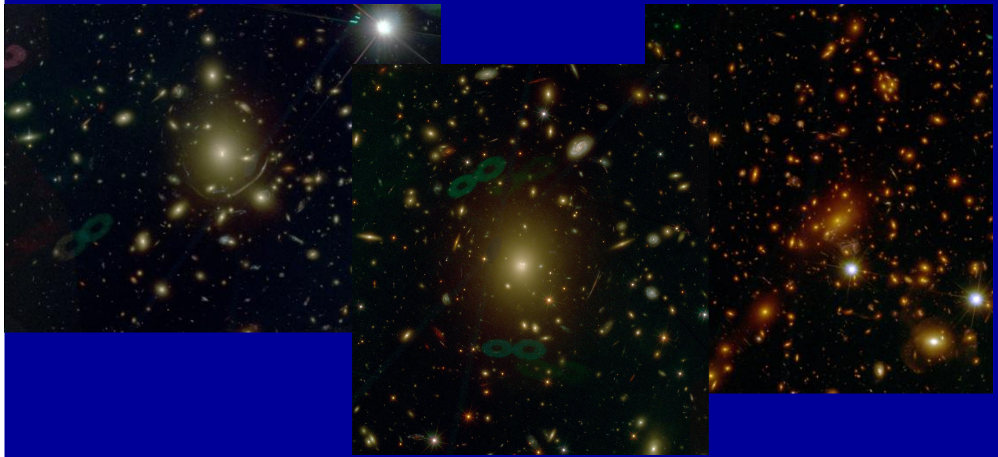
This led to the HST *CLASH* program.



524-orbit HST Multi Cycle Treasury Program (-2013/04)

CLASH = Cluster Lensing And Supernova survey with Hubble

- 20 X-ray + 5 lensing selected clusters at 0.2<z<0.9
- 16 WFC3/ACS band imaging



Postman+12, ApJS (arXiv:1106.3328)

4. Preliminary Results from the CLASH Program

Several papers on individual clusters published by CLASH

- Zitrin et al. 2011a, ApJ (A383, strong lensing)
- Zitrin et al. 2011b, ApJ (MACS J1206, strong lensing)
- Zitrin et al. 2012, ApJL (MACS J0329, strong lensing)
- Coe, Umetsu et al. 2012, ApJ, submitted (A2261, full lensing, X-ray)
- Umetsu et al. 2012, ApJ, submitted (MACS J1206, full lensing, X-ray, SZE)
- Zheng et al. 2012, Nature, submitted (MACS J1149, z~9.6 galaxy candidate)

CLASH-SZE consortium related publications

- Zitrin et al. 2011c, MNRAS (A383, Bolocam 150GHz)
- Sayers et al. 2012, ApJL (Planck clusters, Bolocam 150GHz)
- Umetsu et al. 2012, ApJ, submitted (MACS J1206, Bolocam 150GHz)
- Mroczkovski et al. 2012, ApJ, submitted (MACS J0717, Mustang 90GHz + Bolocam)

Preliminary CLASH results (8/25 clusters)

Umetsu+CLASH 2012b, in prep.

Characteristics of CLASH Clusters

- **X-ray selected clusters:** 6 (20) clusters in CLASH
  - **No orientation and lensing selection bias**
- **Lensing-selected clusters:** 2 (5) in CLASH, 4 in Umetsu+11
  - **Higher central projected density, orientation bias?**

Summary

- Cluster Gravitational Lensing has come to fruition and become a powerful probe of DM halo structure.
  - Weak lensing distortion (shear), magnification, and strong lensing
- Cluster mass profile "shape" reconstructed from lensing is consistent with the family of CDM models:
  - Lensing observations are consistent with that, DM is non-relativistic (negligible free-streaming scale) and effectively collisionless on astrophysical scales.
- Concentration in best-studied, spectacular lensing clusters (c~7.7) is 50-100% higher than LCDM predictions (c~4-5).
  - Selection and/or triaxial orientation bias?
  - If true, clusters formed earlier than LCDM? Early dark energy?
- Concentration in CLASH clusters (8/25 so far) is close to the latest, large cosmological simulations (Bhattacharya+12), which give a higher-than-previous normalization (c~5-6) in the c-M relation.
  - If the findings from the latest N-body simulation are confirmed, observations and LCDM models come closer.

Thank you!