ASIoP Colloquium Talk

Galaxy Cluster Gravitational Lensing as Cosmological Probes

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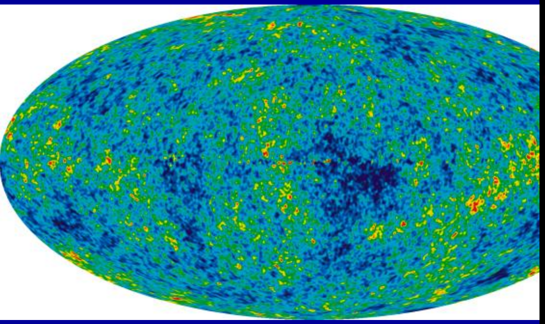
Contents

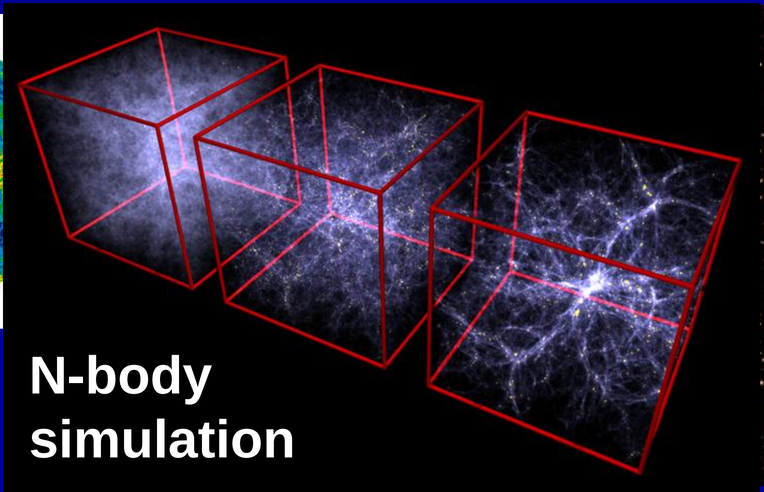
1. Structure Formation Scenario

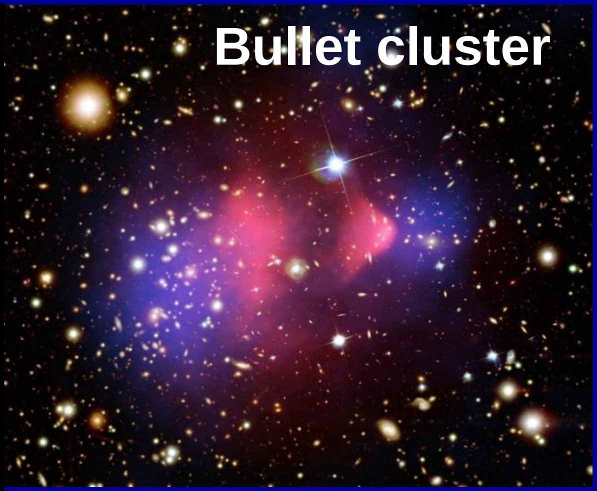
Current paradigm of structure formation: Lambda Cold Dark Matter (LCDM)

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

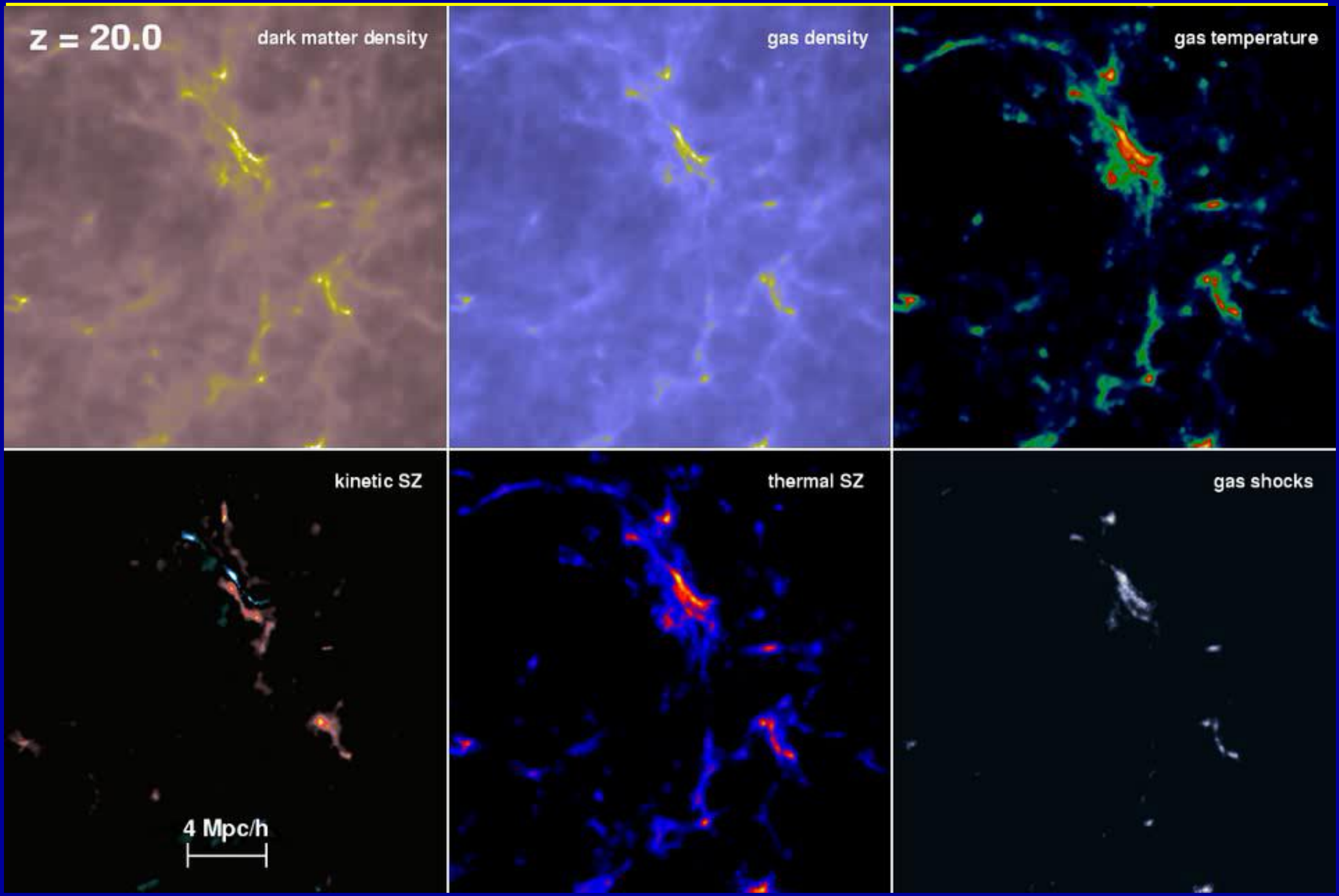


Cosmic seeds in CMB (WMAP)





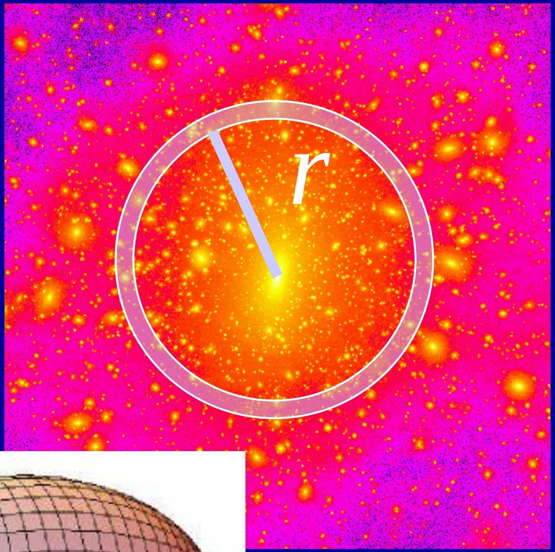
Simulated Cluster Formation (LCDM)

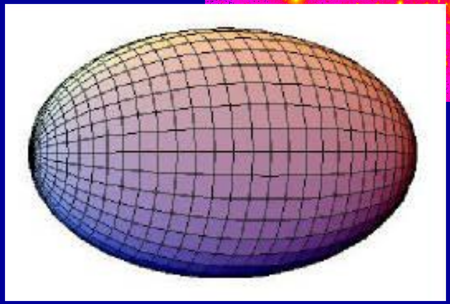


Credit: Volker Springel (*Data Visualization*)

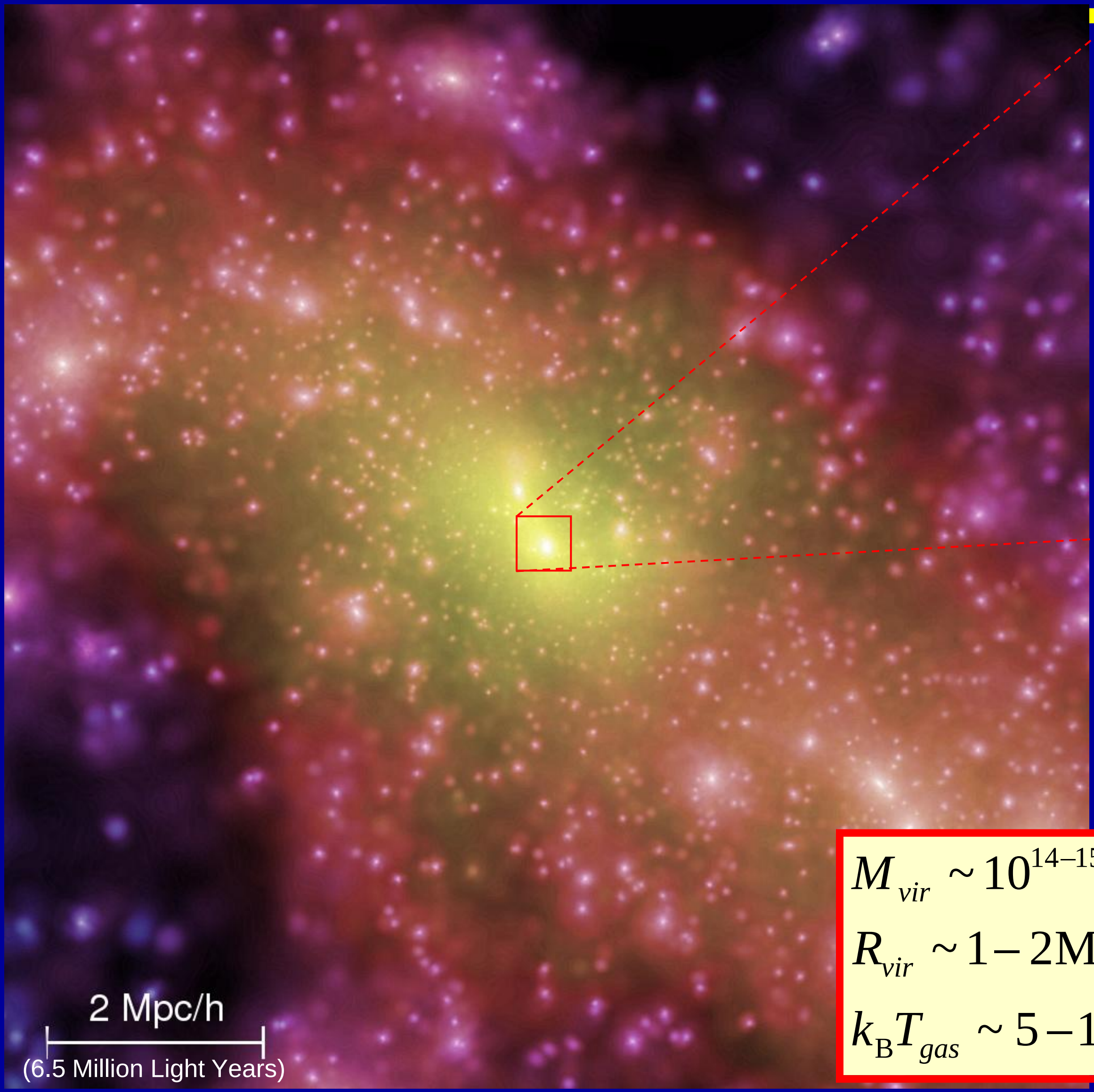
Predicted properties of CDM halos

- CDM mass profiles $\rho(r)$ are nearly universal
  - **Shape** is approximately independent of halo mass (**self-similar**)
  - **Normalization**: the more massive a halo, the LESS concentrated it is.
  - Origin of the universal profile?
- CDM halos are cuspy, $\rho(r) \sim r^{-\alpha}$ (α~<1) at $r \rightarrow 0$
  - Progressively steepening with radius
  - Annihilation signal?
- CDM halos are clumpy
  - Abundant substructure (~20% in mass)
  - Overabundance of galactic satellites in LCDM?
- CDM halos are triaxial
  - Preference for prolate configuration
  - Asphericity increasing toward the center





Clusters of Galaxies



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

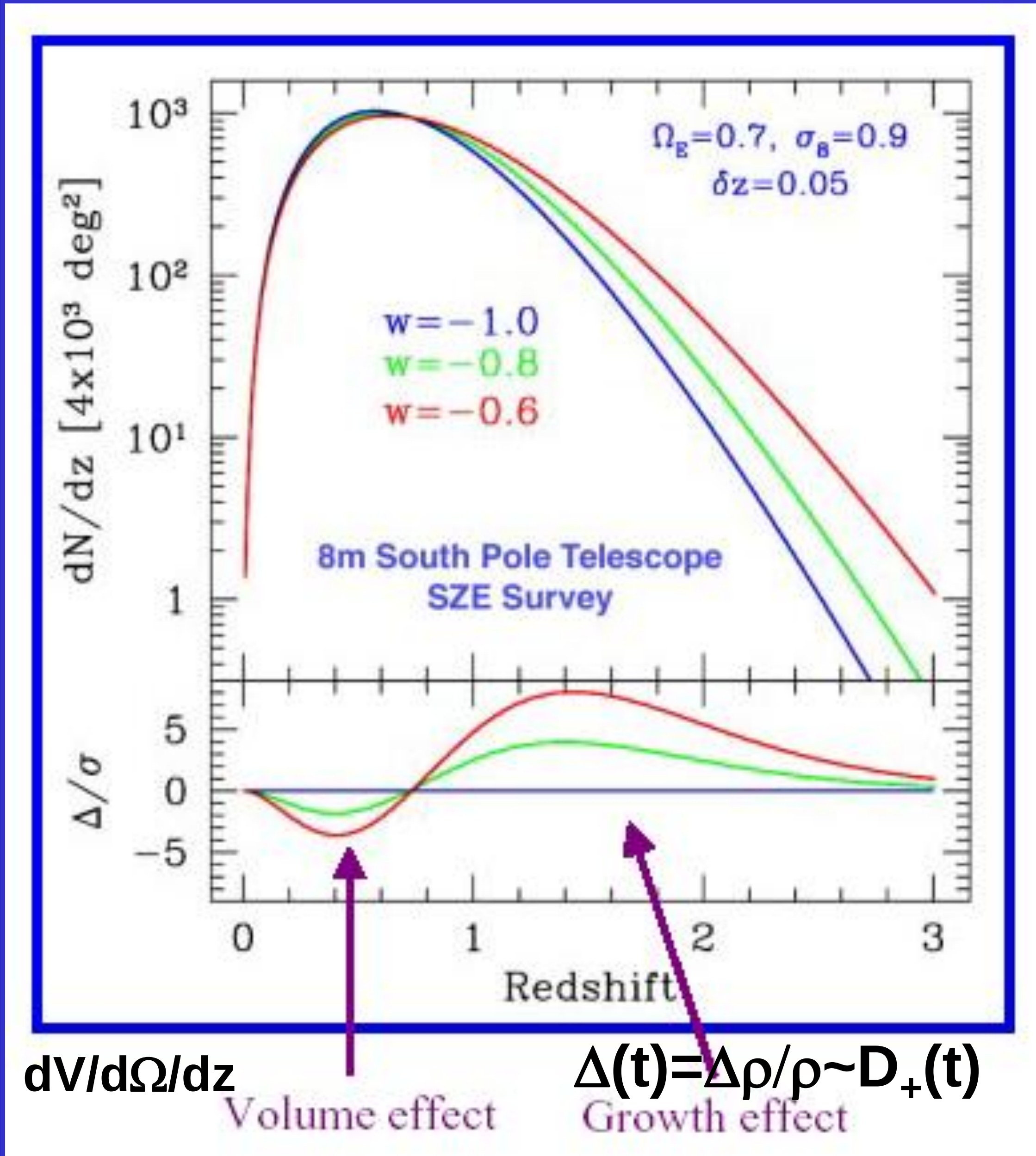
$$M_{vir} \sim 10^{14-15} M_{\rm sun} / h$$

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

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

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

Clusters as Cosmological Probes



[Left] Cluster counts dN(z)/dz predictions for different DE EoS, $w=P/(\rho c^2)$, 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 mass profile (aka, halo model) in any cluster cosmology.

Simulation by the SPT team

Fundamental Questions in Cluster Cosmology

1) **Quasi-Equilibrium mass profile shape of DM halos:**

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

2) **DM vs. 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?”

4) **Primordial non-Gaussianity:**

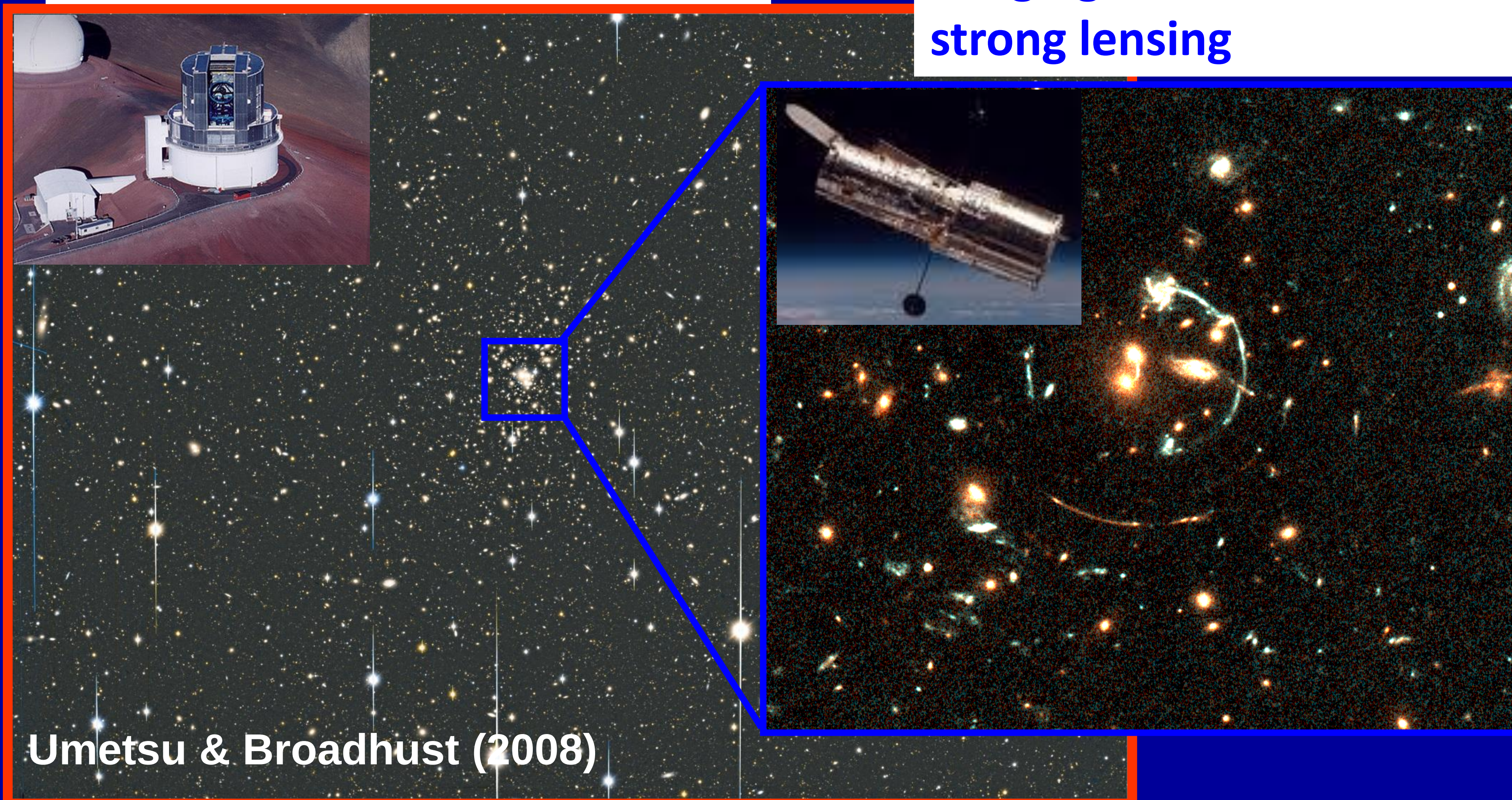
“What is the degree of non-Gaussianity in primordial density fluctuations?”

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

My Approach: Cluster Gravitational Lensing

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

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

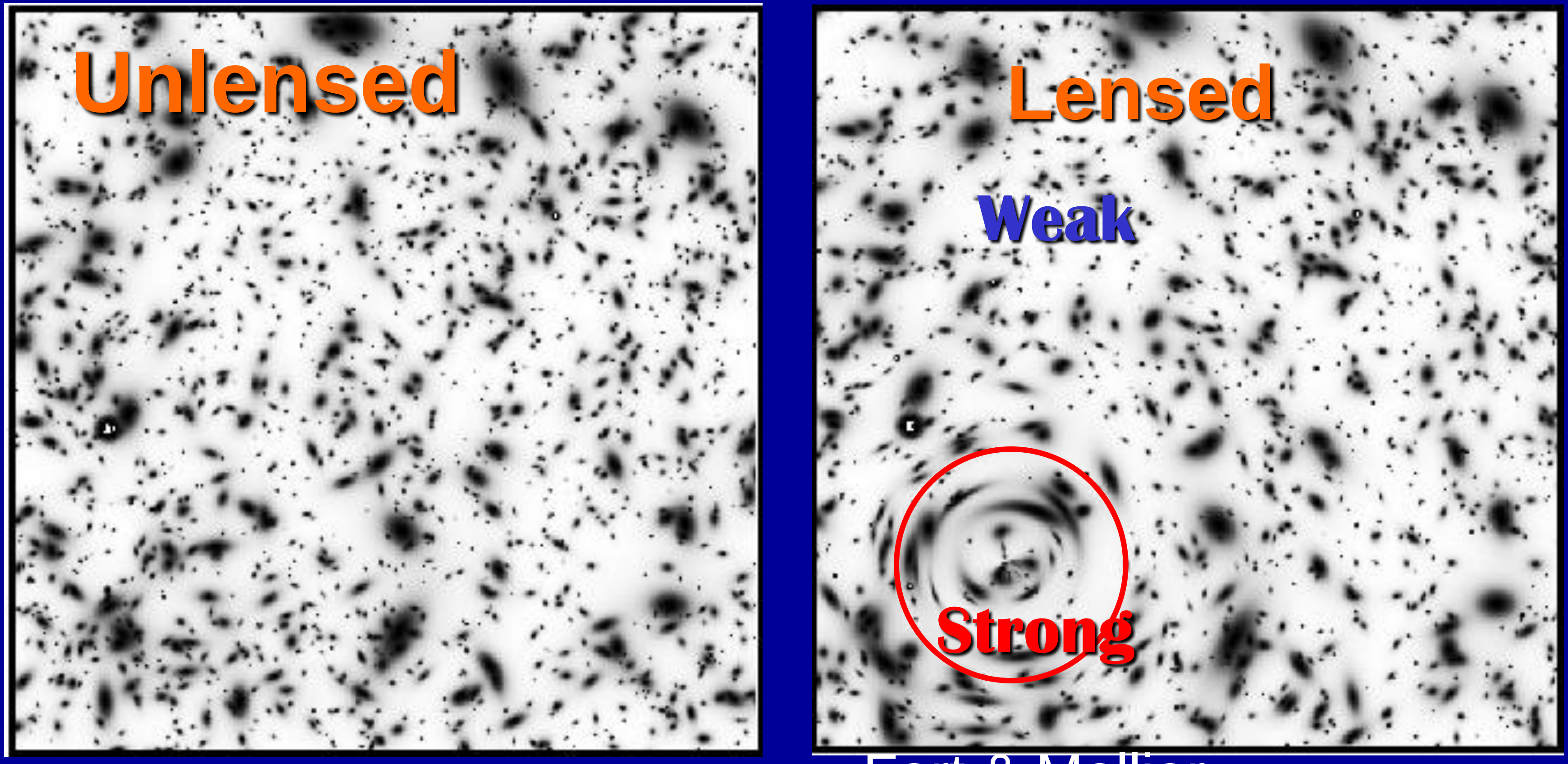


Observable deformation of background galaxy shapes and expansion of the sky can be used to map the DM distribution in large scale structure in the Universe.

2. Gravitational Lensing

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

Gravitational lensing is based only on gravity, so is the most direct method to study the Dark Side of the Universe!



Fort & Mellier

Gravitational Bending of Light Rays

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

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

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

Small transverse excursion of photon momentum

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

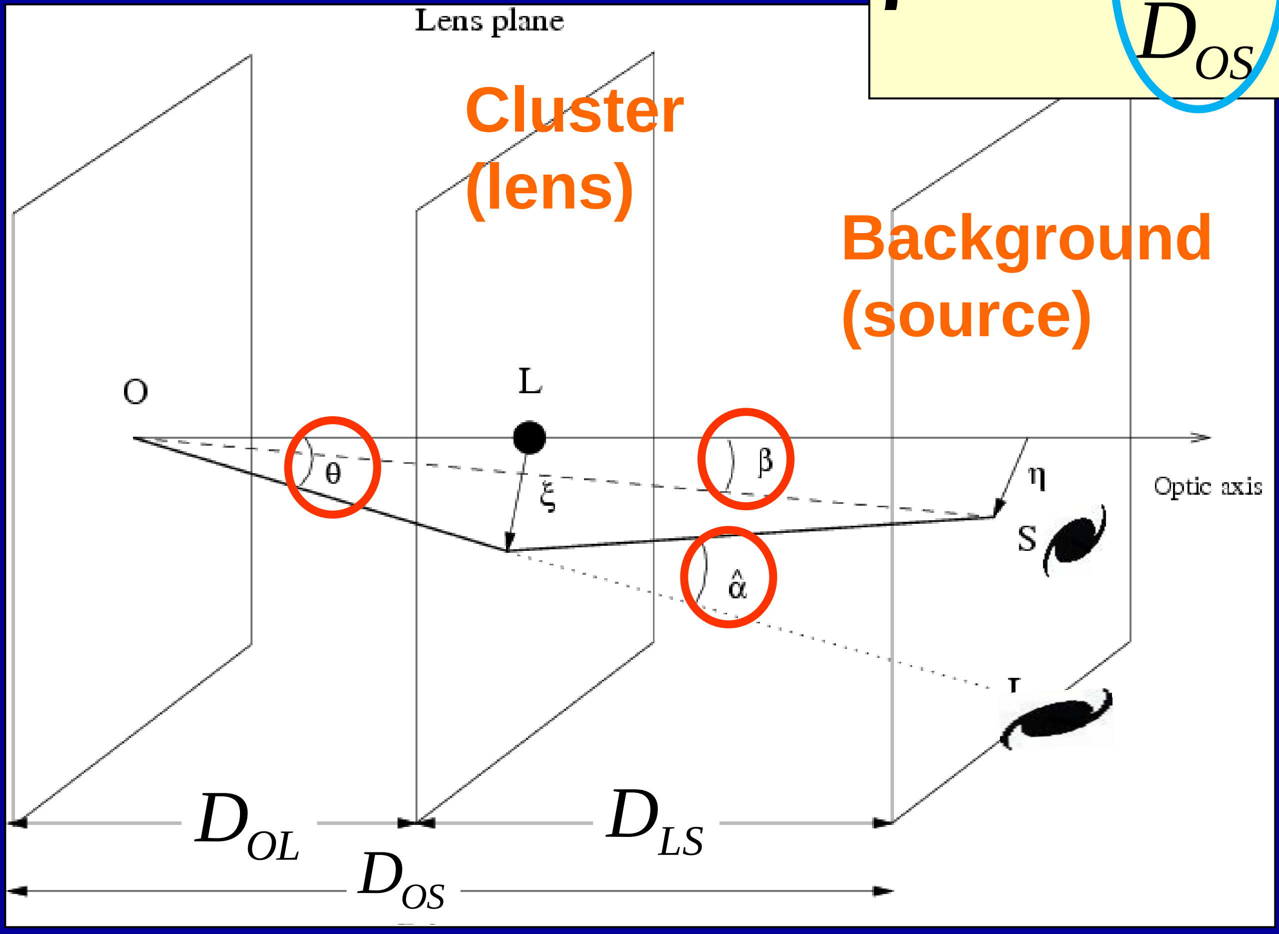
Lens Equation (for cluster lensing)

Cosmological lens equation + single/thin-lens approximations

β: true (but unknown) source position

θ: apparent image position

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



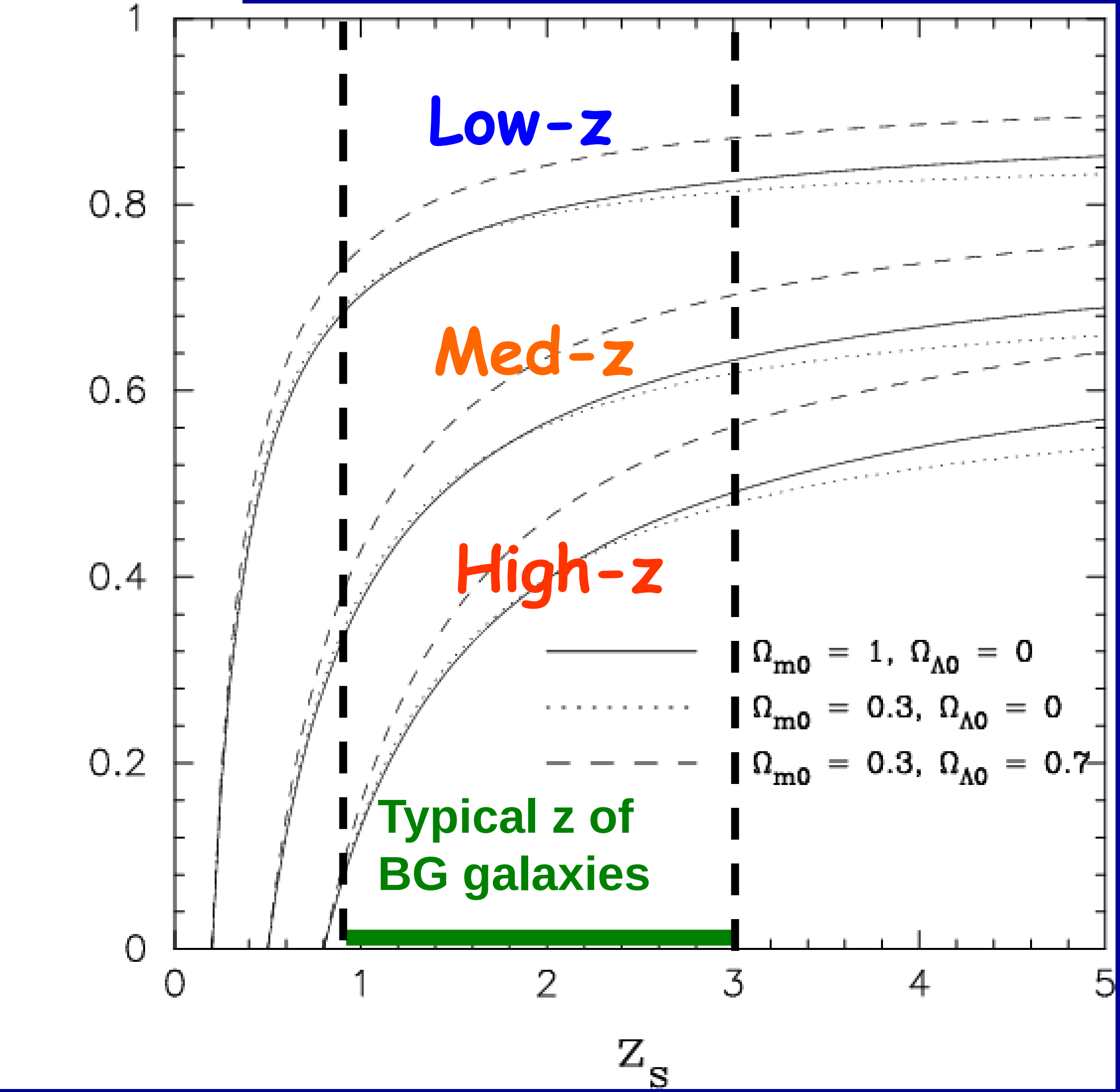
Angular diameter distances:

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

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

Geometric Scaling of Lensing Signal

D_{LS} / D_{OS} **Distnace raito as a function of source z, zs**



Per-source sensitivity for a given lens

Low-z lens:

zL=0.2

Med-z lens:

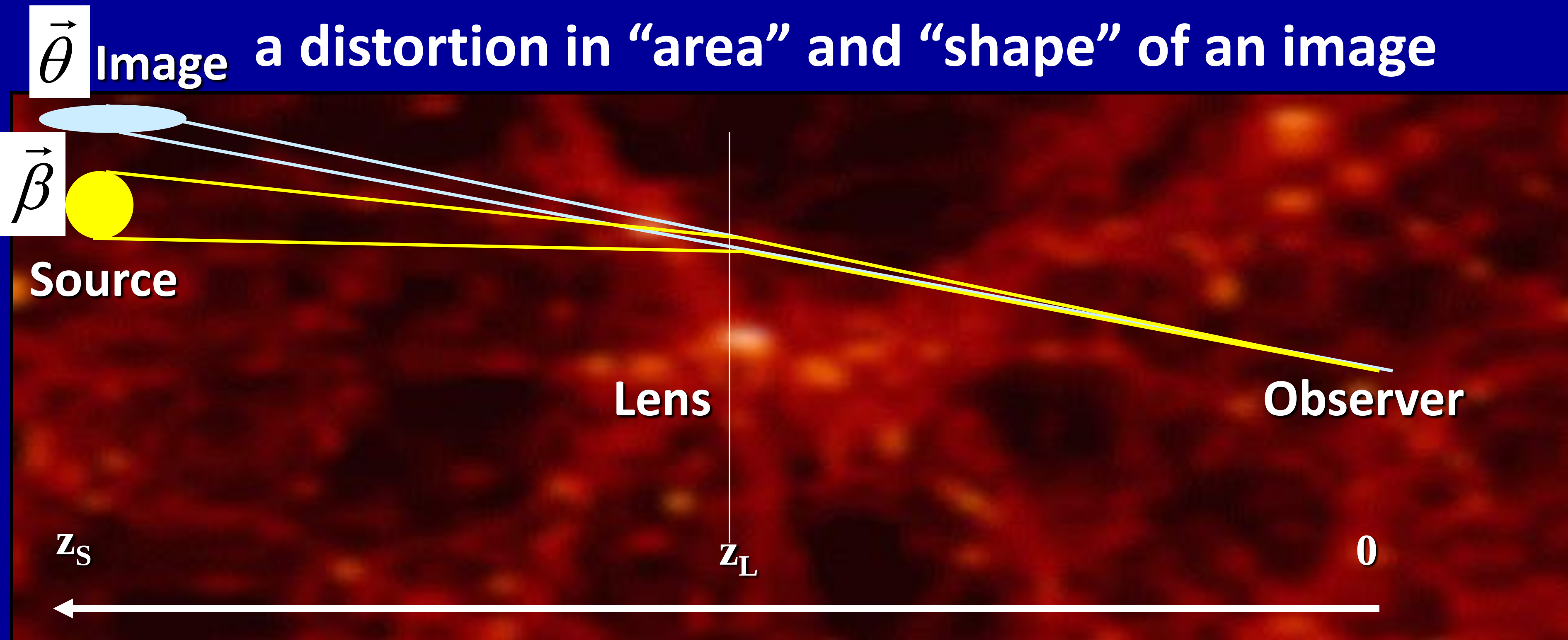
zL=0.5

High-z lens:

zL=0.8

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)

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

Physical Meaning of κ

Lens Convergence: weighted projection of mass overdensity $\delta\rho$

$$\kappa(\boldsymbol{\theta}) \equiv \frac{1}{2}\Delta^{(2)}\psi(\boldsymbol{\theta}) = \int dD\, \delta\rho \left(\frac{c^2}{4\pi G} \frac{D_{OS}}{D_{OL} D_{LS}} \right)^{-1} \approx \frac{\Sigma(\boldsymbol{\theta})}{\Sigma_{\rm crit}}$$

Critical surface mass density

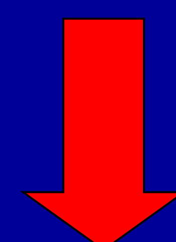
$$\Sigma_{\rm crit}(z_L, z_S; \Omega_m, \Omega_\Lambda, H_0) = \frac{c^2}{4\pi G} \frac{D_{OS}}{D_{OL} D_{LS}}$$

Strong lensing κ~1 @ cluster cores (r < 100kpc/h)

Weak lensing κ~0.1 @ outside cluster cores (r > 100kpc/h)

Cosmic shear κ~0.01 @ large scale structure

probability



Note, this is only a crude definition, as lensing also depends on the (trace-free) tidal shear field, Γ.

Gravitational Shear Field

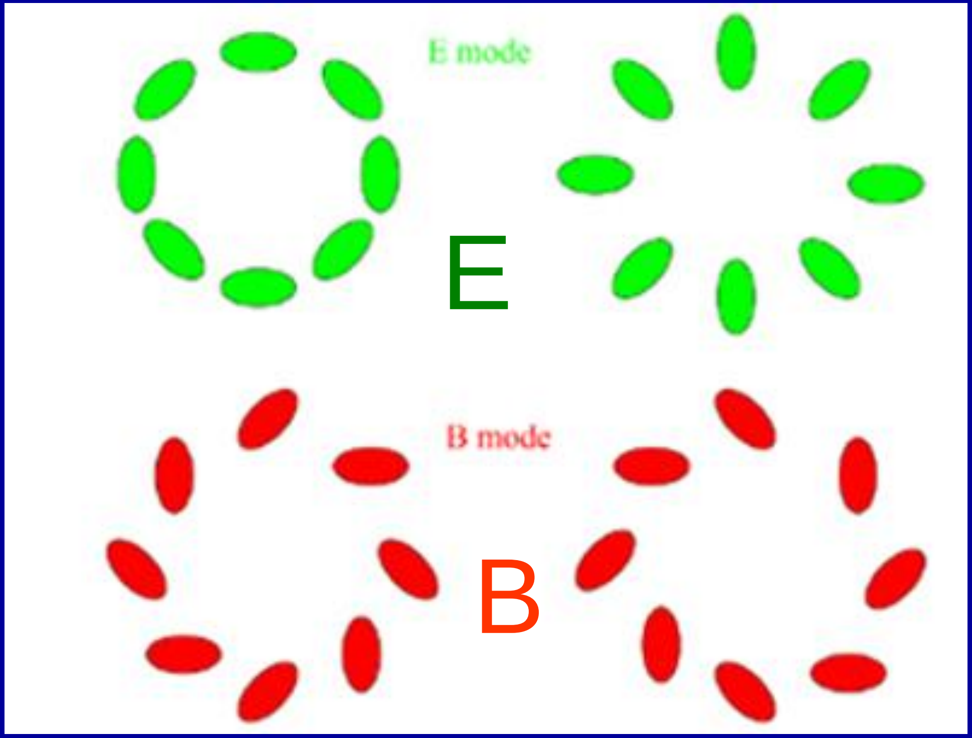
Shear matrix with 2-DoF can be expressed with 2 independent scalar potentials (e.g., Crittenden+2002):

$$\Gamma_{ij} = \left(\partial_i \partial_j - \frac{1}{2}\delta_{ij}\Delta^{(2)}\right)\psi_E + \frac{1}{2}\left(\varepsilon_{kj}\partial_i\partial_k + \varepsilon_{ki}\partial_j\partial_k\right)\psi_B$$

$$\psi_E = \psi \text{ (lens potential)}$$

$$\psi_B = 0$$

In the weak-lensing limit, B-mode = 0



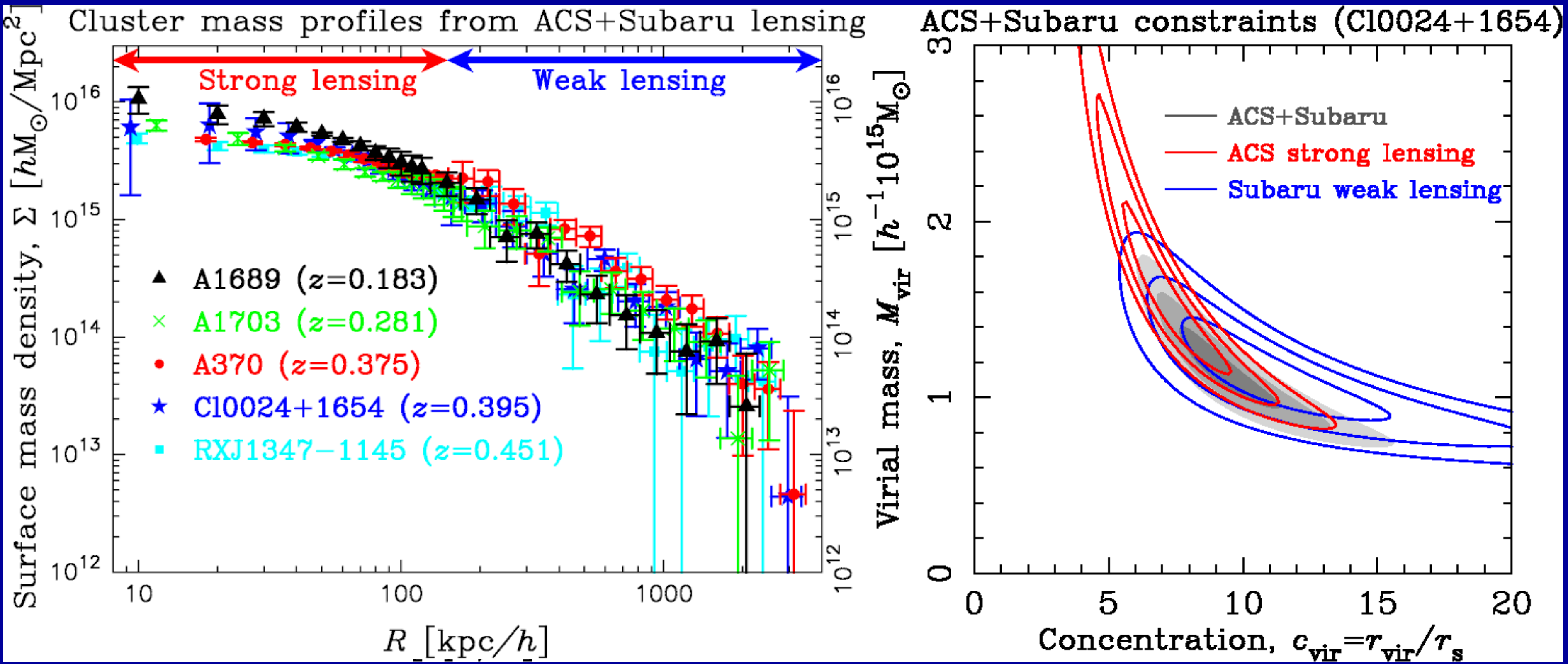
B-mode "signal" can be used to monitor residual systematic effects in lensing measurements:

e.g., residual PSF anisotropies

Both Strong and Weak Lensing are needed

Combining complementary Weak and Strong Lensing:

→ Probing cluster mass profiles in the full range [0.5%, 150%] R_{vir}



Umetsu & Broadhurst 08; Umetsu+09; Umetsu+10; Umetsu+11a; Umetsu+11b

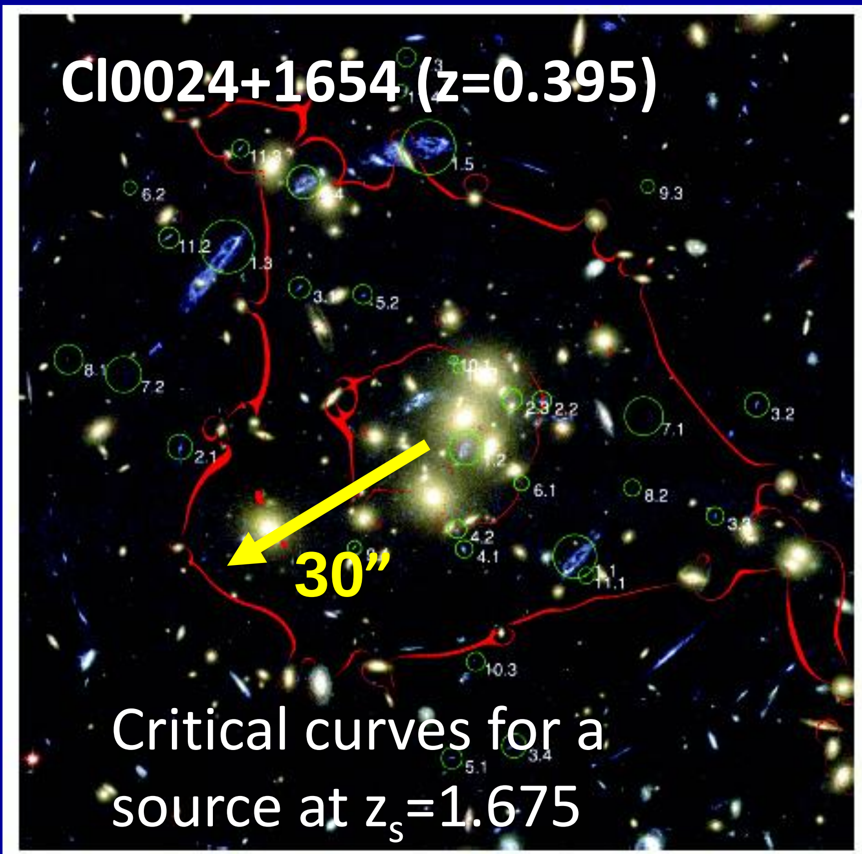
Strong and Weak Lensing

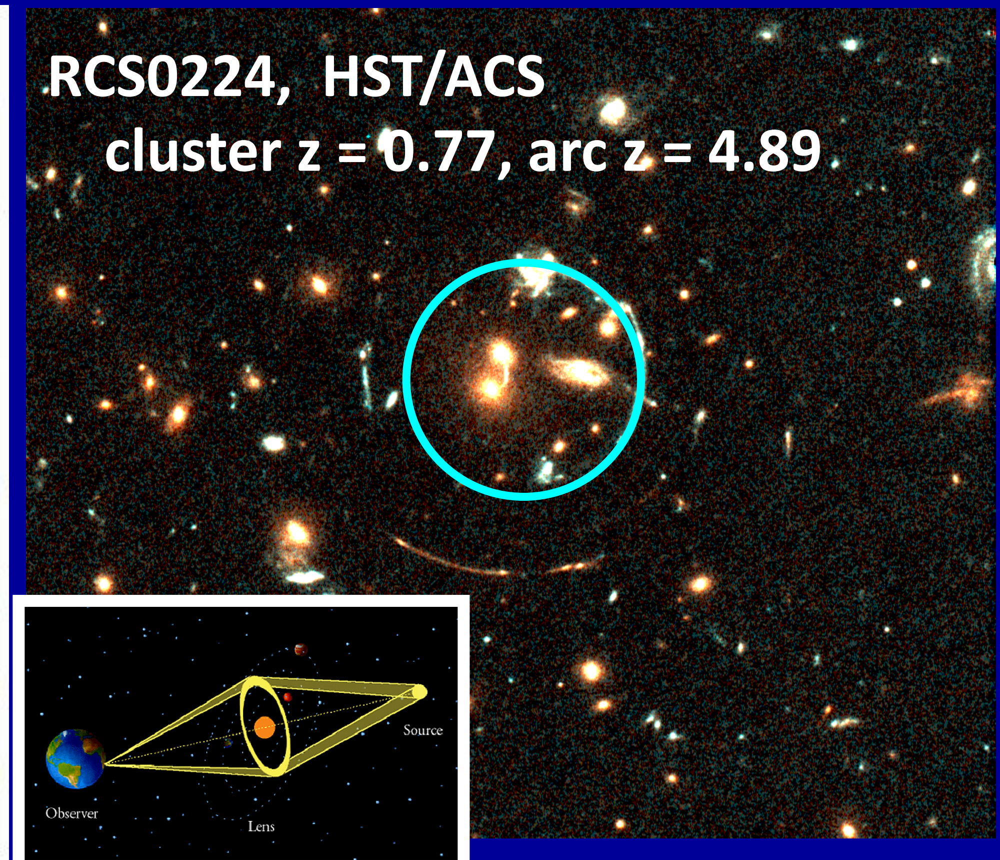
- **Strong Gravitational Lensing (SL)**
- **Weak Gravitational Lensing (WL)**
  - *Tangential shear*
  - *Magnification bias*
  - *Stacked lensing analysis*

Cluster Strong Lensing

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

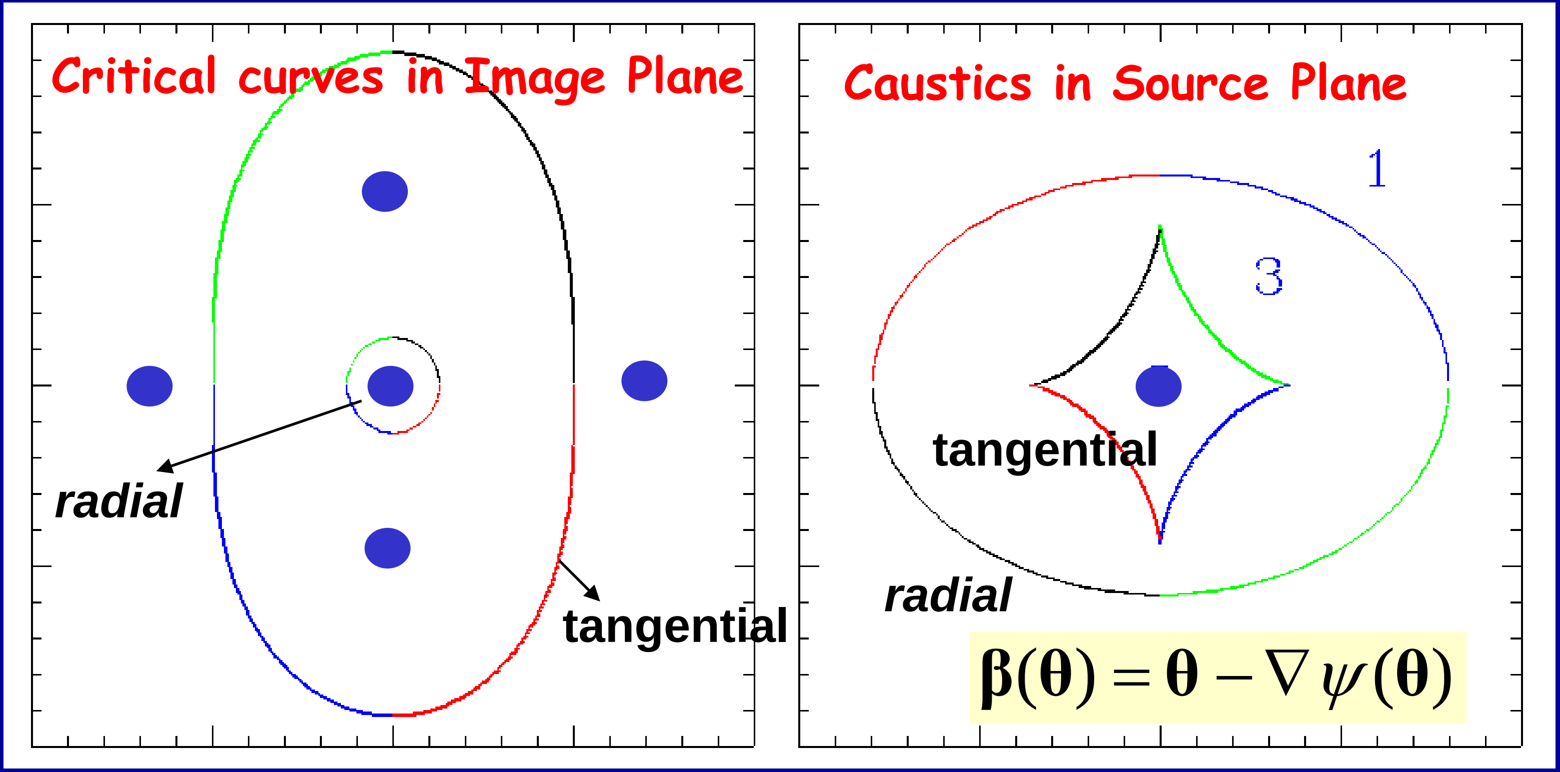
[Left] 33 lensed images of *11* BG galaxies identified in HST multiband images by SL analysis (Zitrin, Broadhurst, Umetsu+09, MNRAS, 396, 1985)





Critical Curves and Caustics

A general elliptical lens potential



$$\beta(\theta) = \theta - \nabla\psi(\theta)$$

Multiple Imaging and Magnification

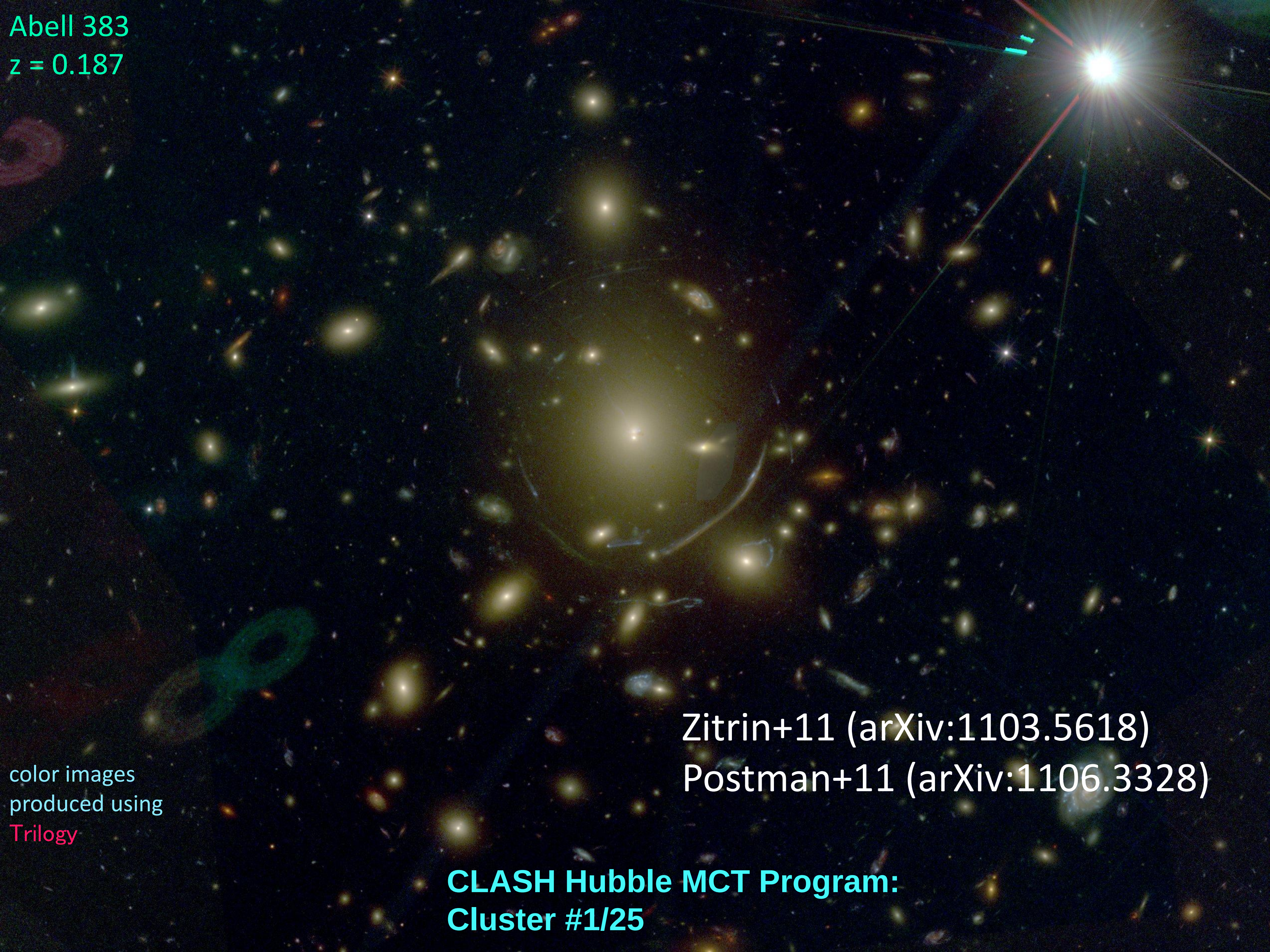
A source galaxy at z=1.675 has been multiply lensed into 5 apparent images

CL0024+1654 (z=0.395)

HST/WFPC2

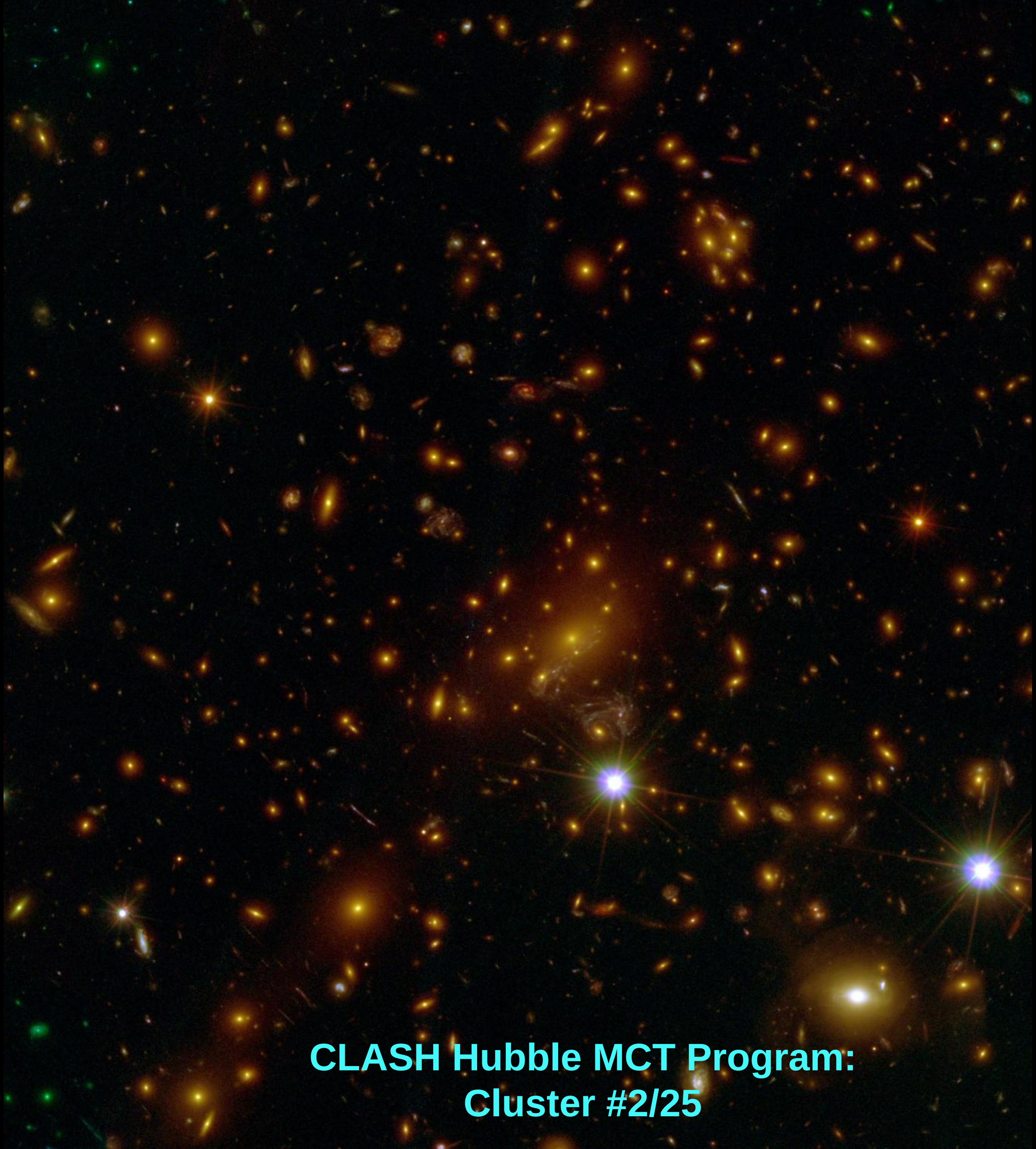
Tangential arcs and multiple imaging

A1689 (z=0.183): One of the most massive clusters known. A total of >100 lensed images of ~30 BG galaxies identified by SL modeling (Broadhurst+05)



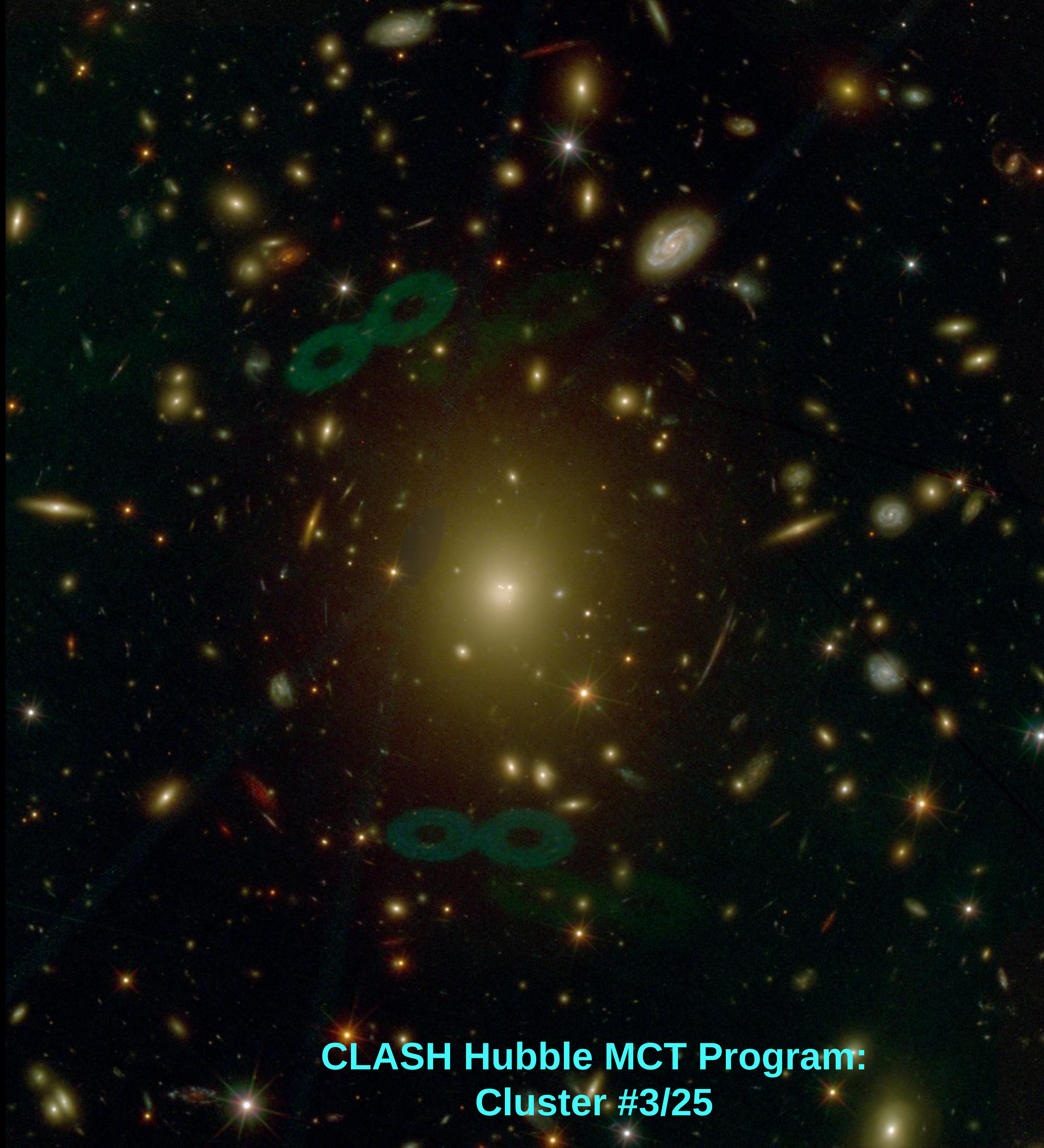
Abell 383
z = 0.187
color images produced using Trilogy
Zitrin+11 (arXiv:1103.5618)
Postman+11 (arXiv:1106.3328)
CLASH Hubble MCT Program:
Cluster #1/25

MACSJ1149
z = 0.544



color images
produced using
Trilogy

Abell 2261
z = 0.224



color images
produced using
Trilogy

Cluster Weak Lensing

Toward highest-possible lensing precision:

① Tangential **Shear** (Distortion)

② **Magnification** bias (Depletion)

③ **Stacked** Weak Lensing Analysis

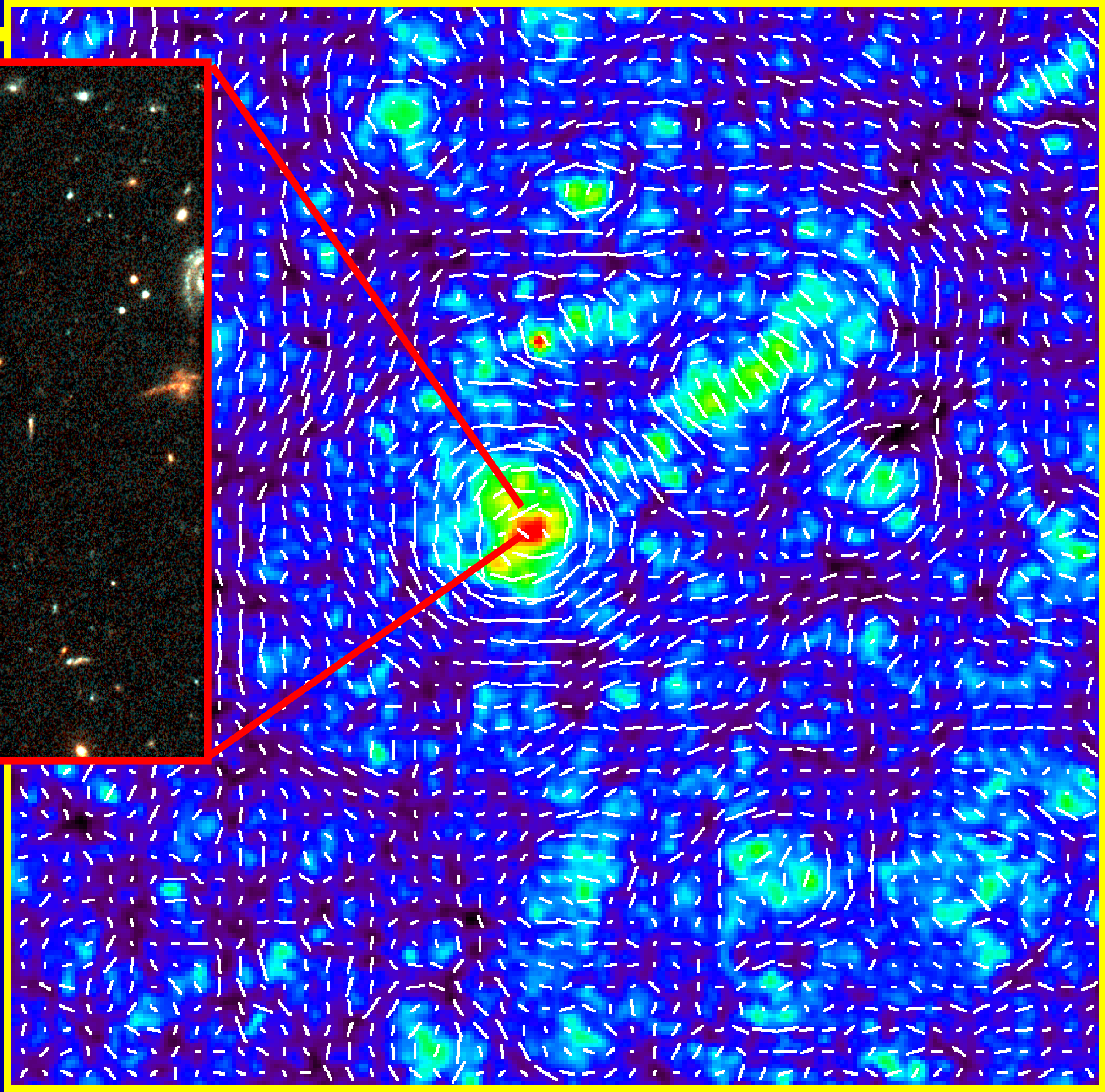
Se my lecture notes on

"**Cluster Weak Gravitational Lensing**"

from the "International School of Physics Enrico Fermi 2008, Italy"
(also found at the Net Advance of Physics) arXiv:1002.3952

Weak Lensing [1]: Tangential Shearing

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



Simulated 3x3 degree field (Hamana 02)

Shear to mass inversion

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

Weak Lensing [2]: Magnification Bias

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

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

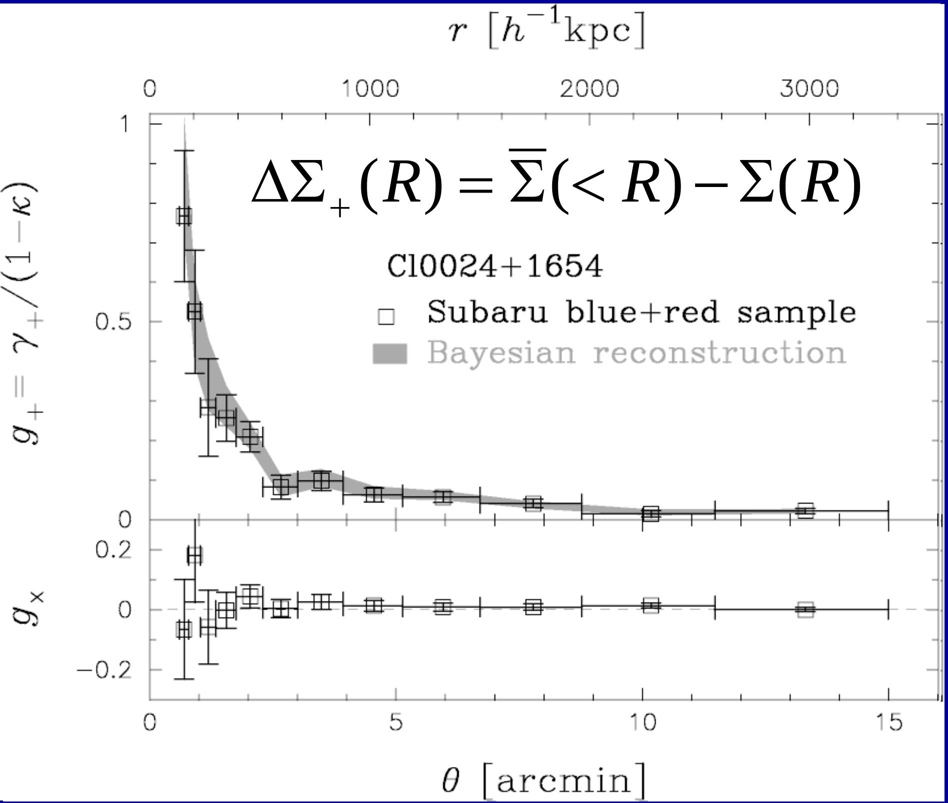
with unlensed Luminosity Function of background galaxies

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

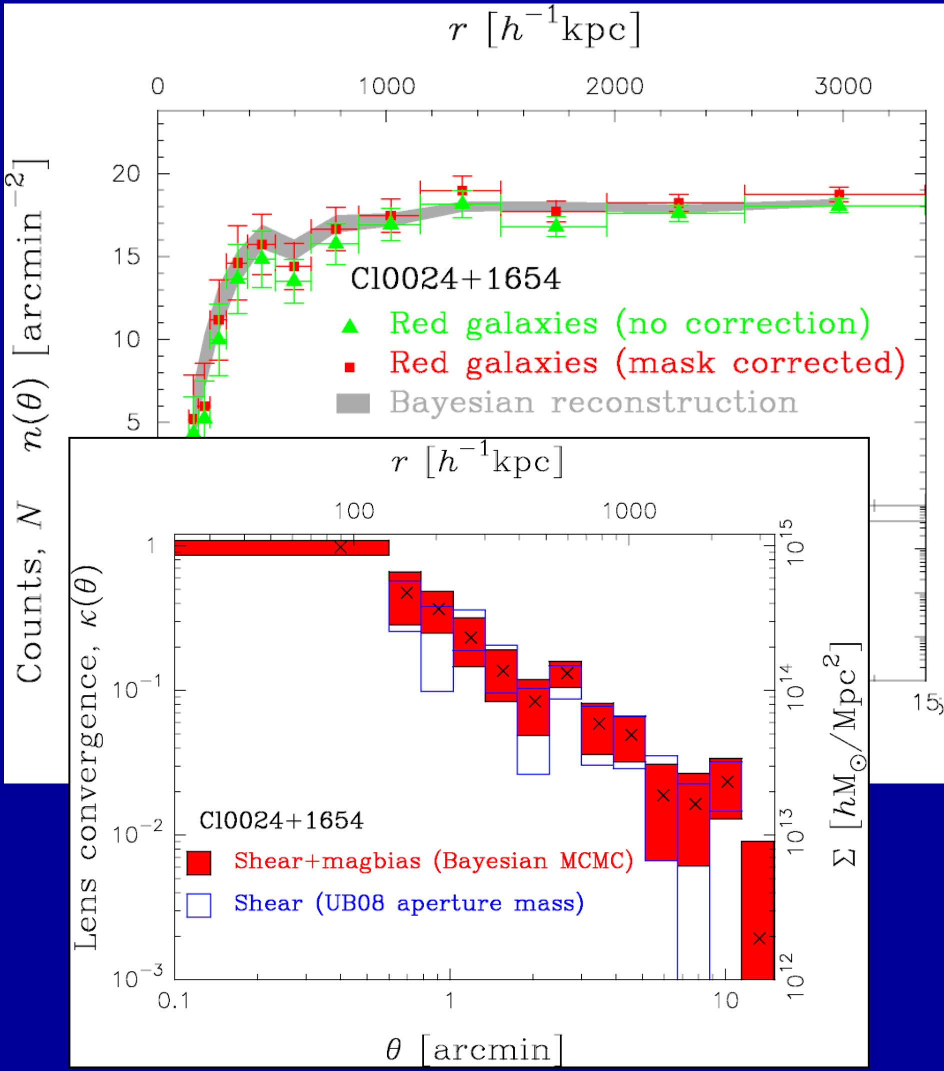
When the count-slope is shallow, i.e., s<1, a net deficit of counts is expected (the case for **red BG galaxies**)

Weak-Lensing Shear and Magnification

Tangential shear radial profile



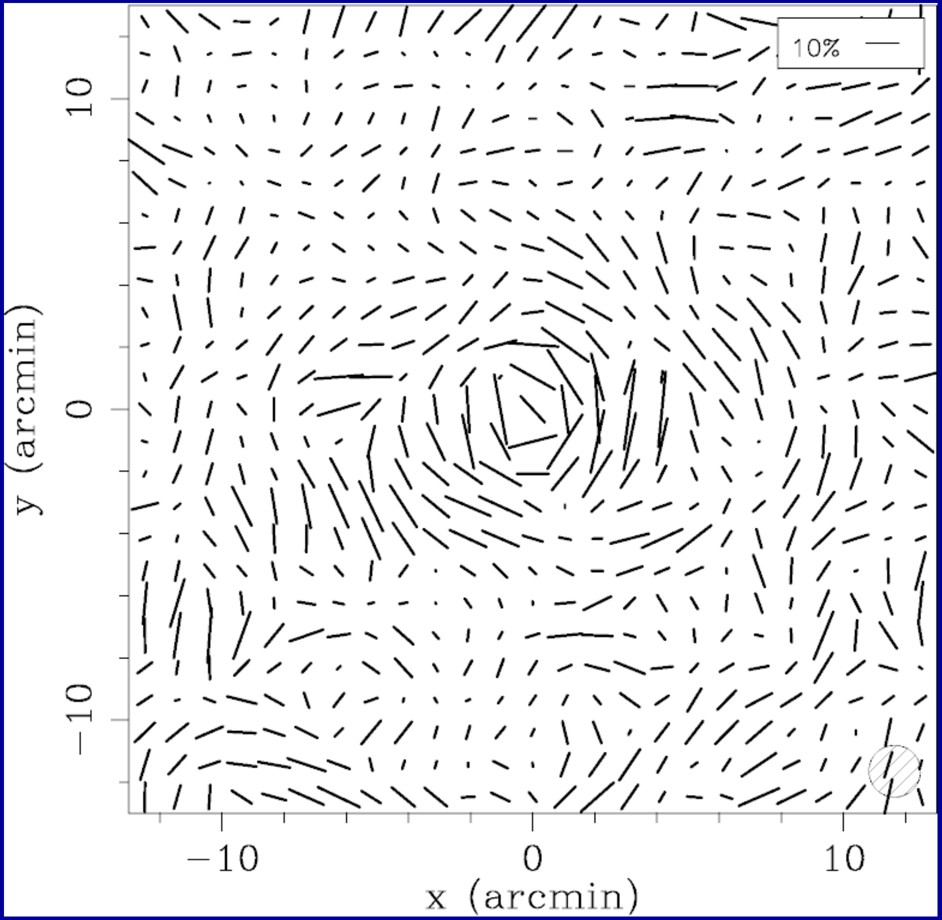
Number counts (magnification bias)

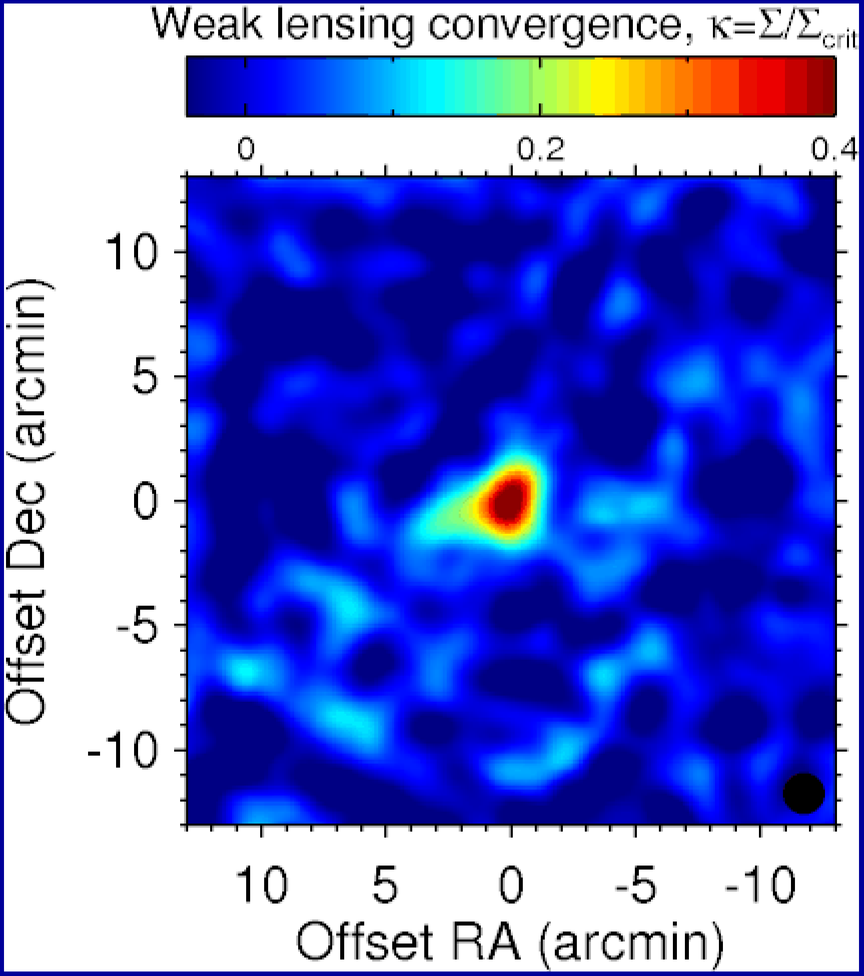


A unique mass profile solution (Σ) can be obtained from joint WL shear + magnification profiles: Umetsu+2011a

Weak Lensing [3]: Power of Stacking Analysis

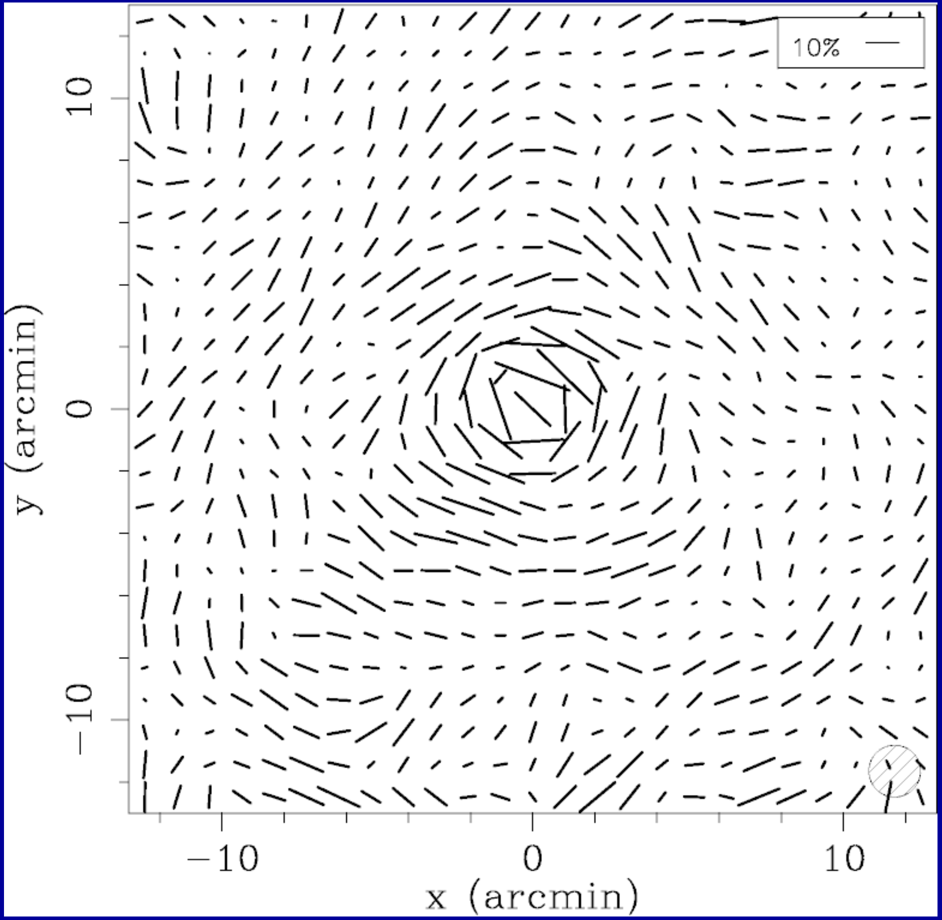
Subaru shear data: N=1

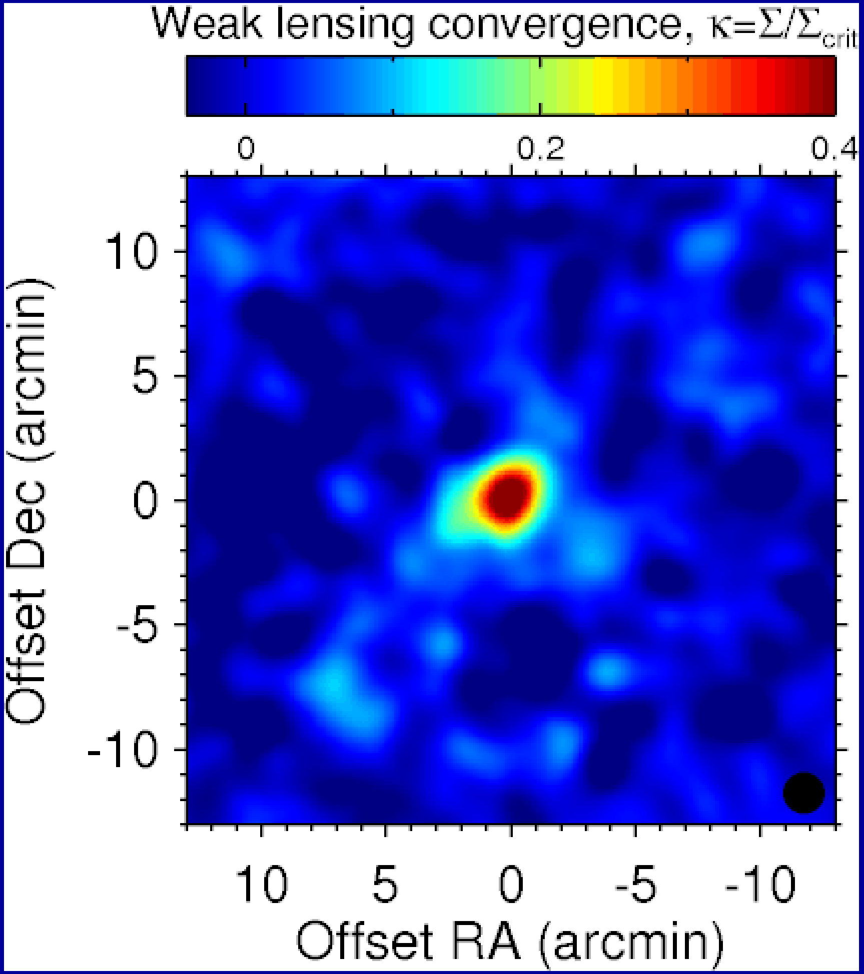




Weak Lensing [3]: Power of Stacking Analysis

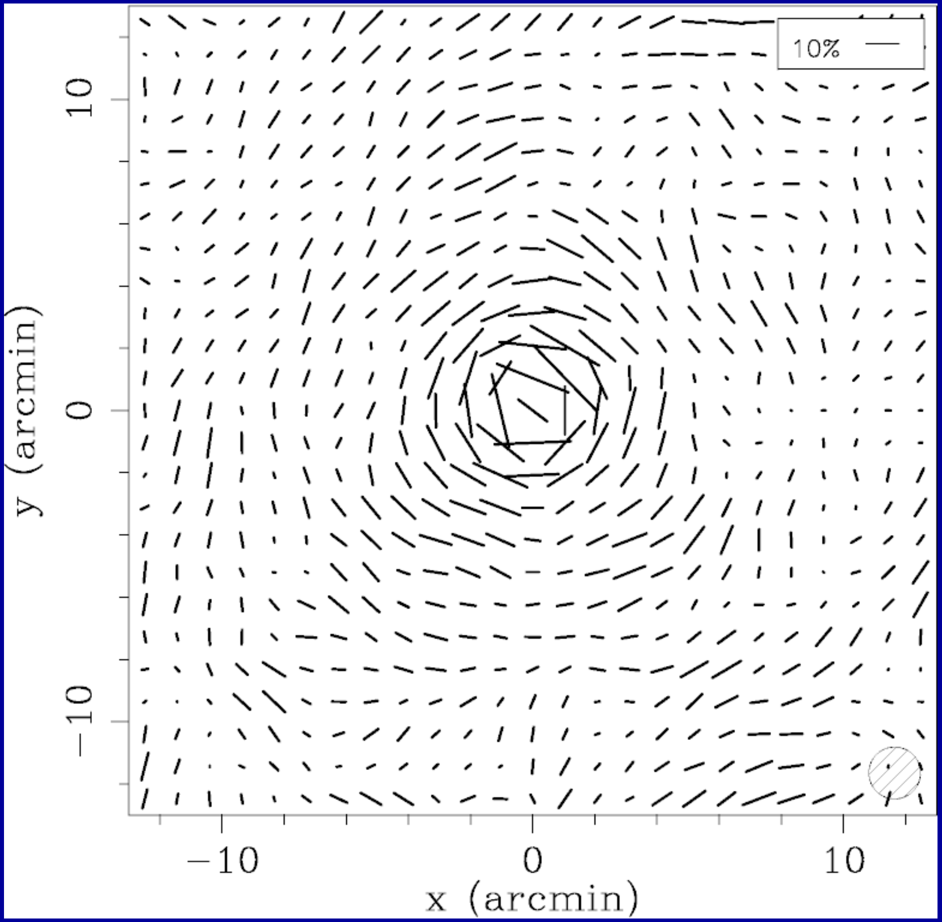
Subaru shear data: N=2

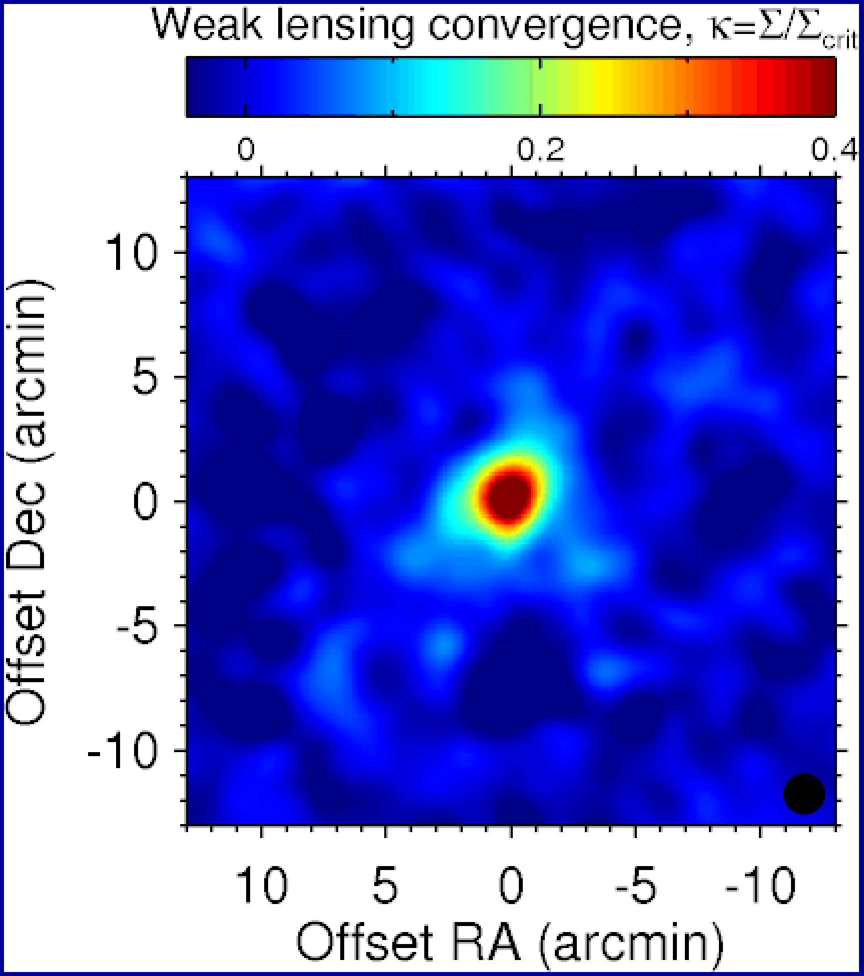




Weak Lensing [3]: Power of Stacking Analysis

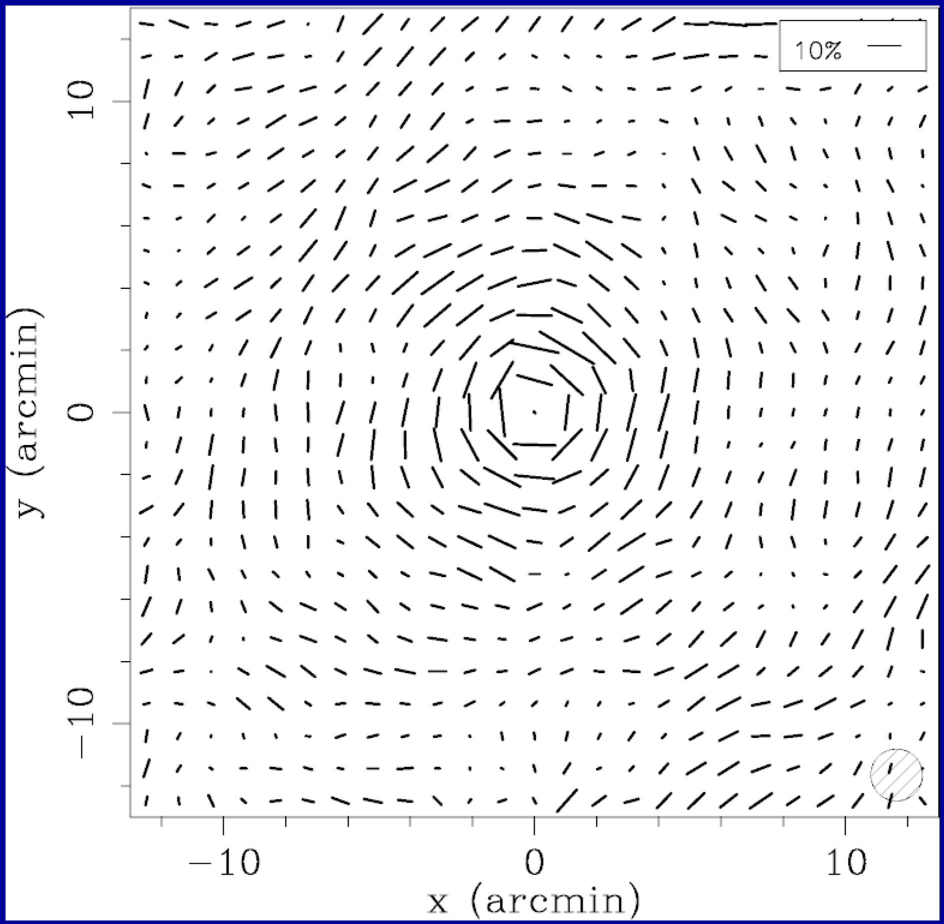
Subaru shear data: N=3

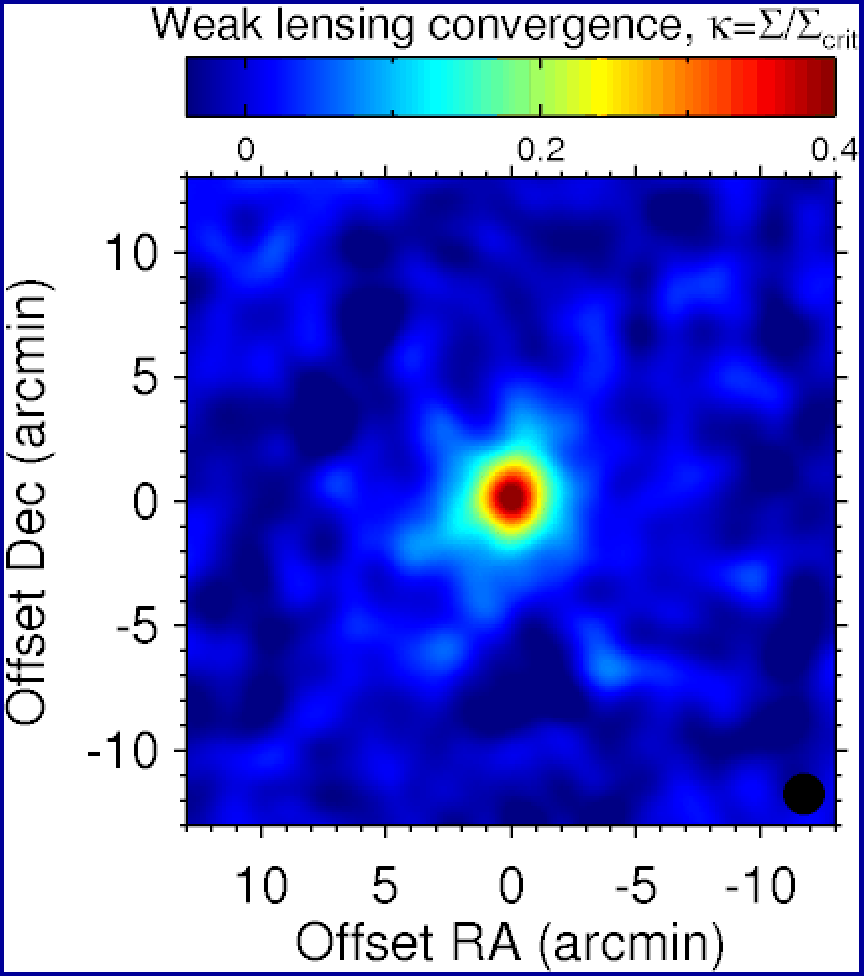




Weak Lensing [3]: Power of Stacking Analysis

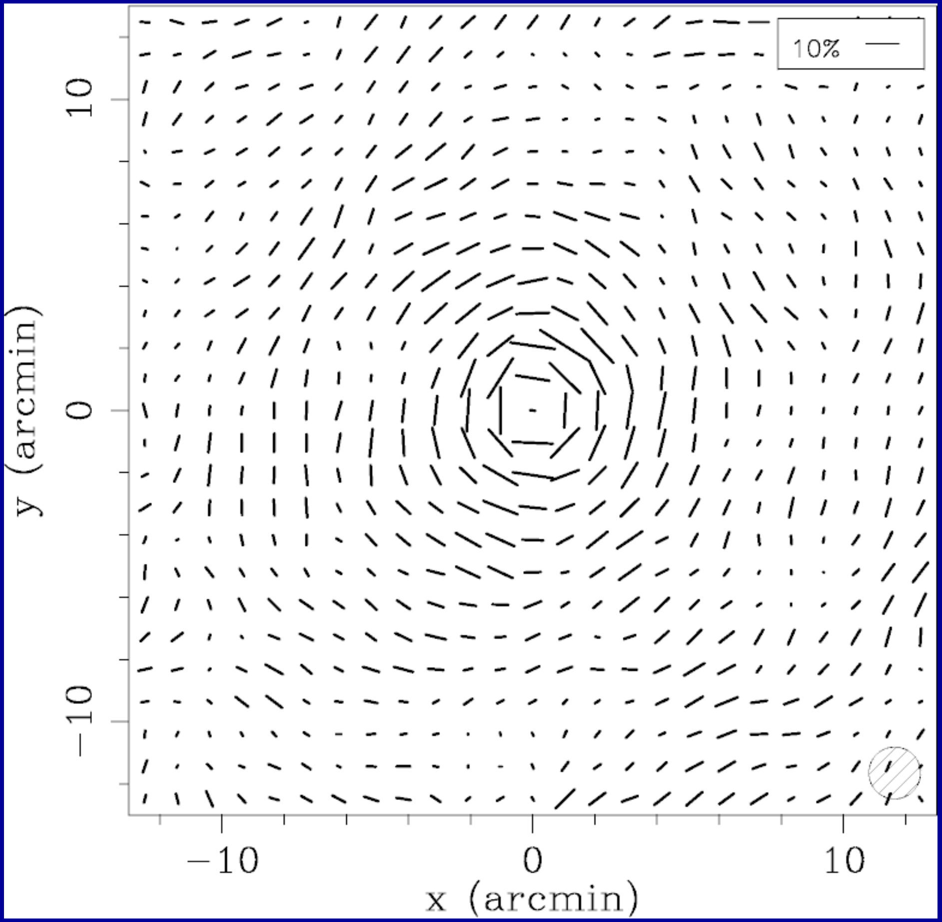
Subaru shear data: N=4

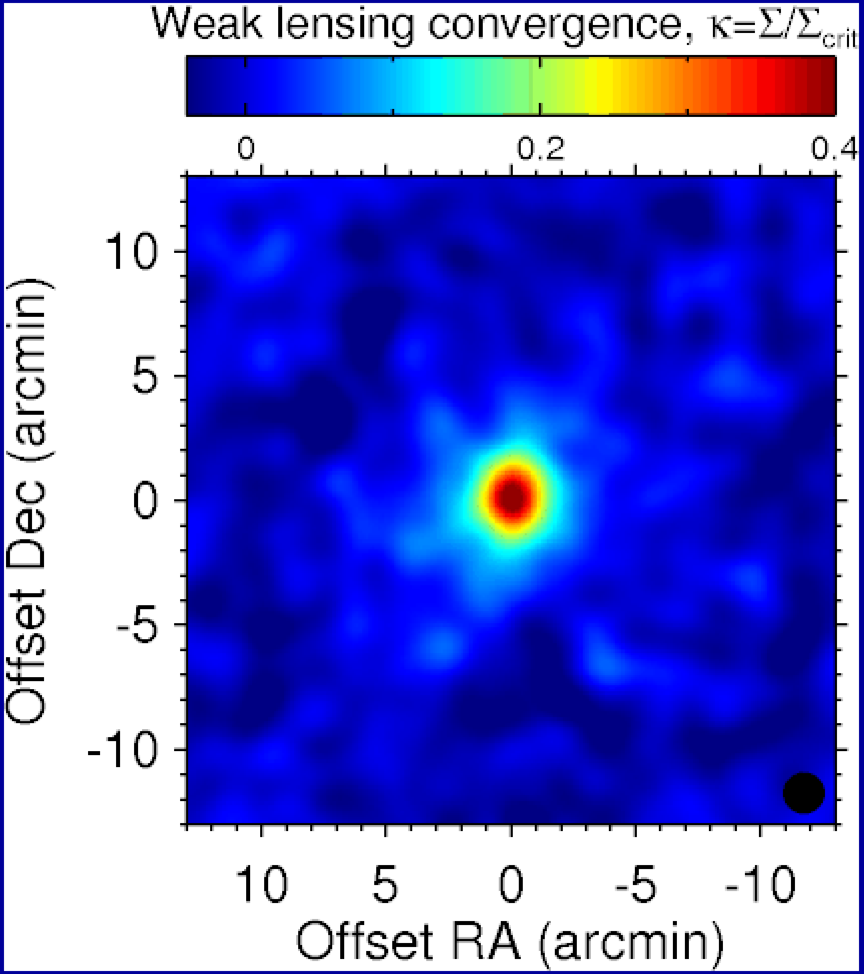




Weak Lensing [3]: Power of Stacking Analysis

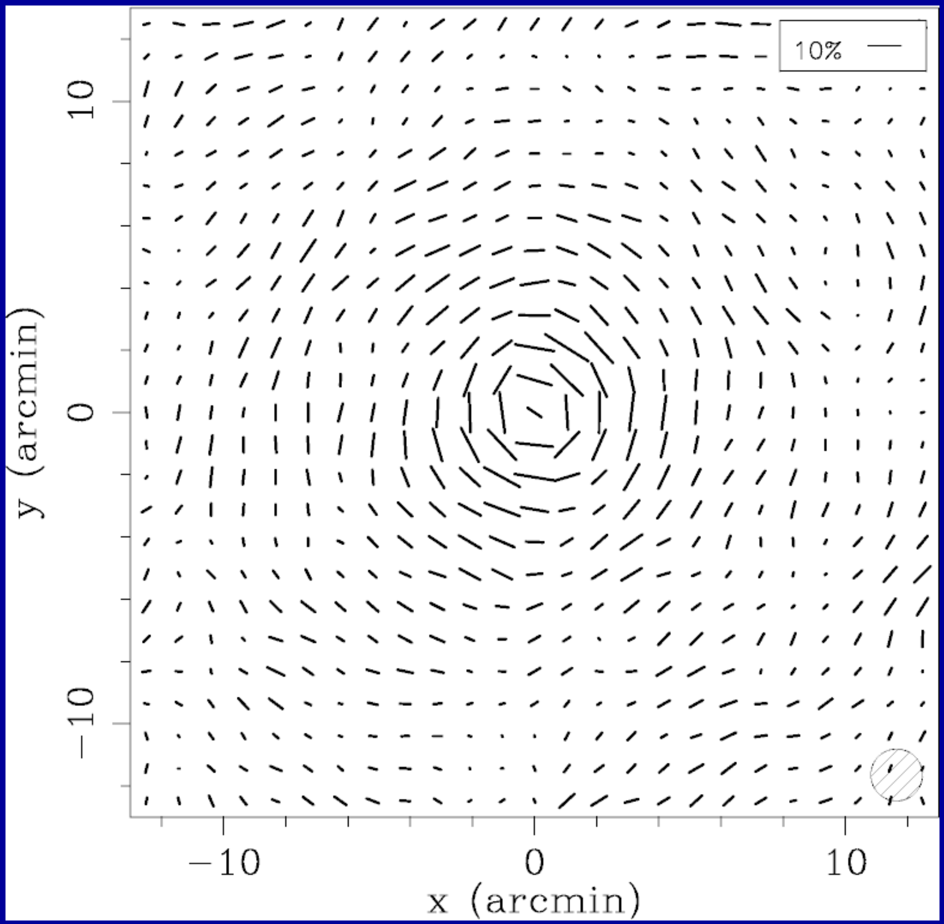
Subaru shear data: **N=5**

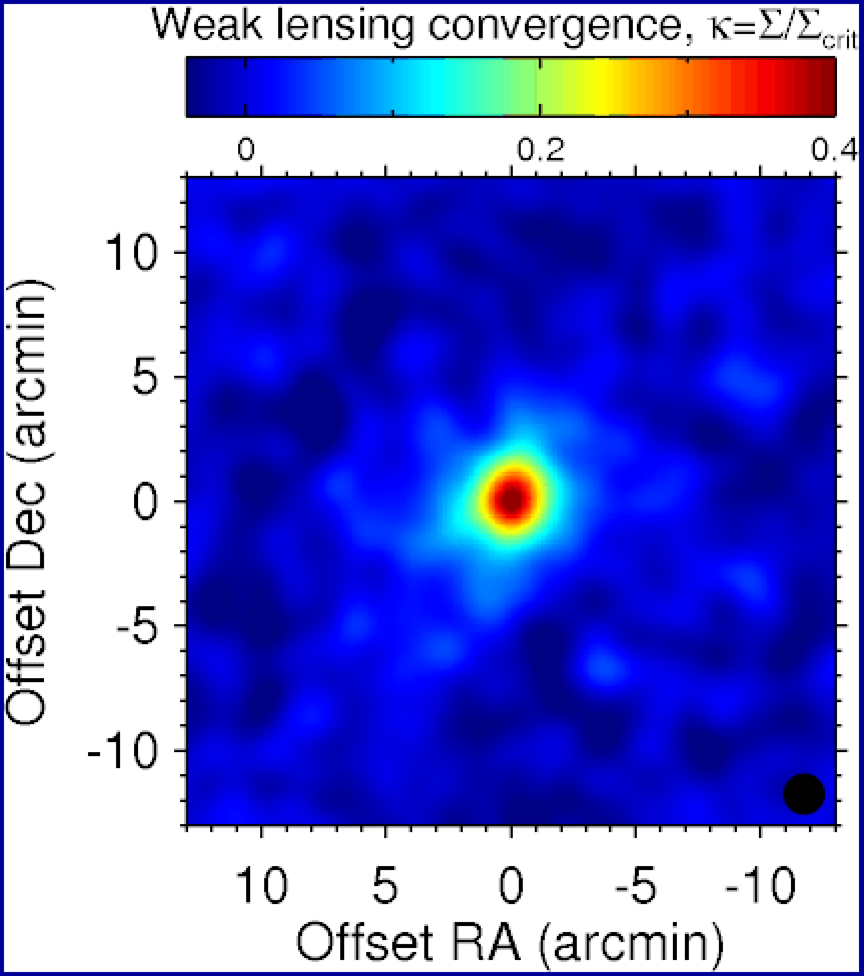




Weak Lensing [3]: Power of Stacking Analysis

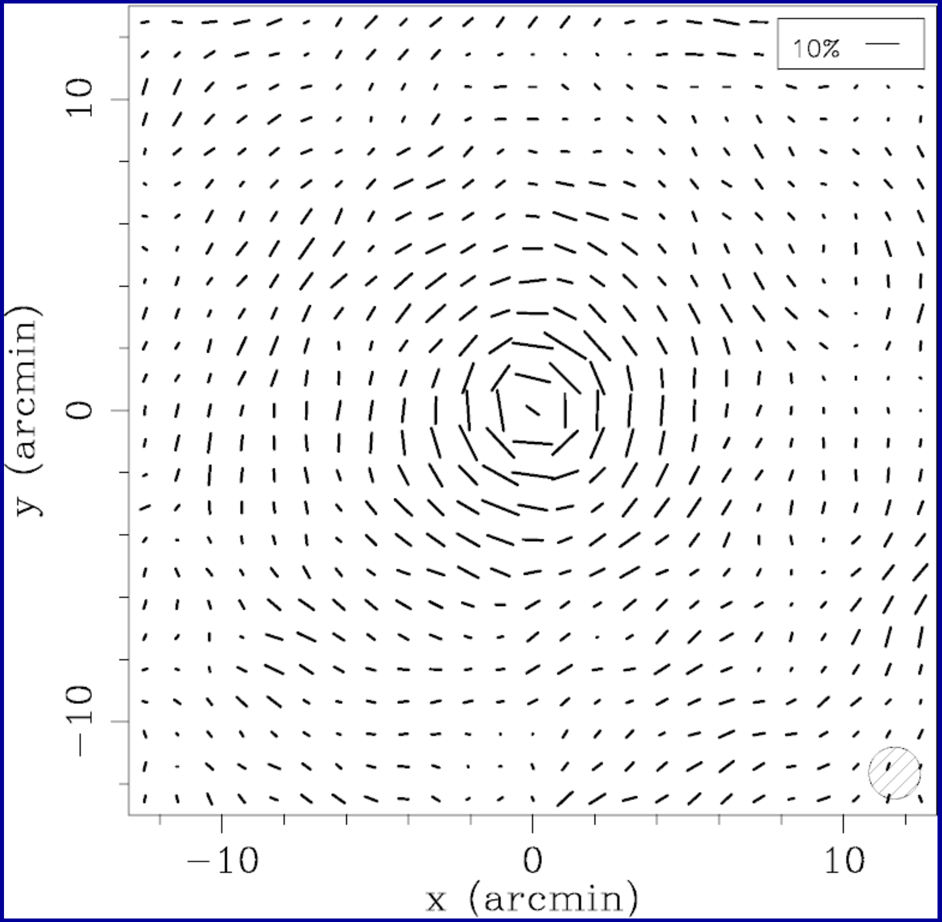
Subaru shear data: N=6

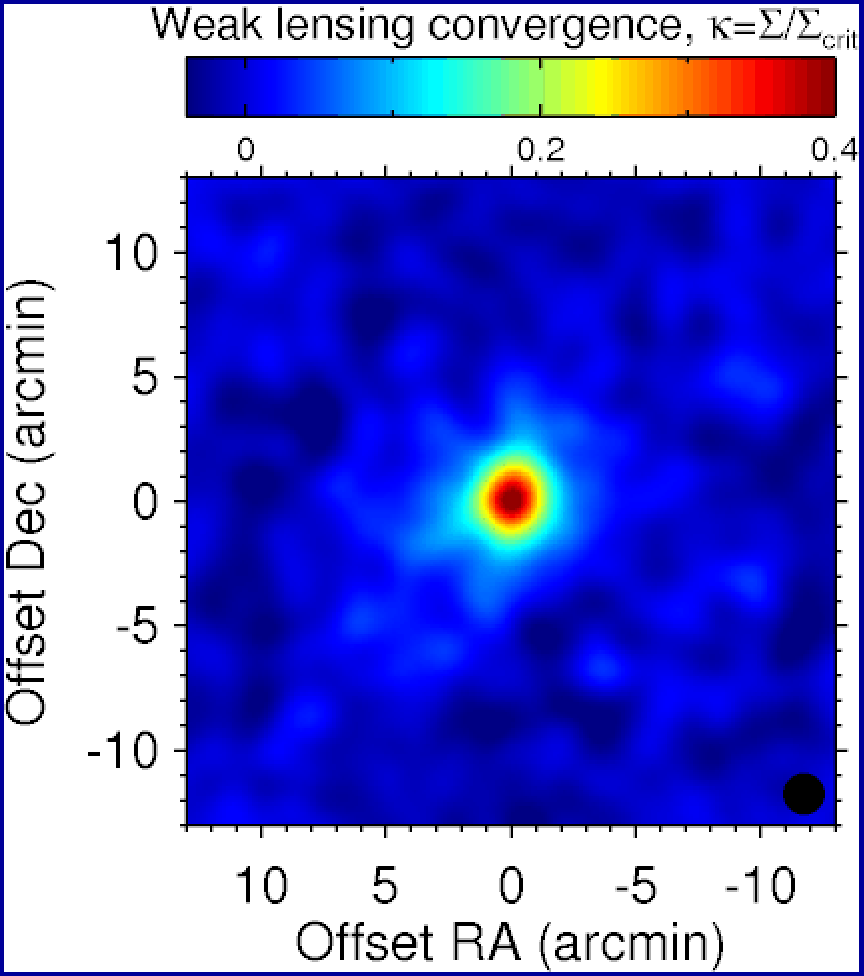




Weak Lensing [3]: Power of Stacking Analysis

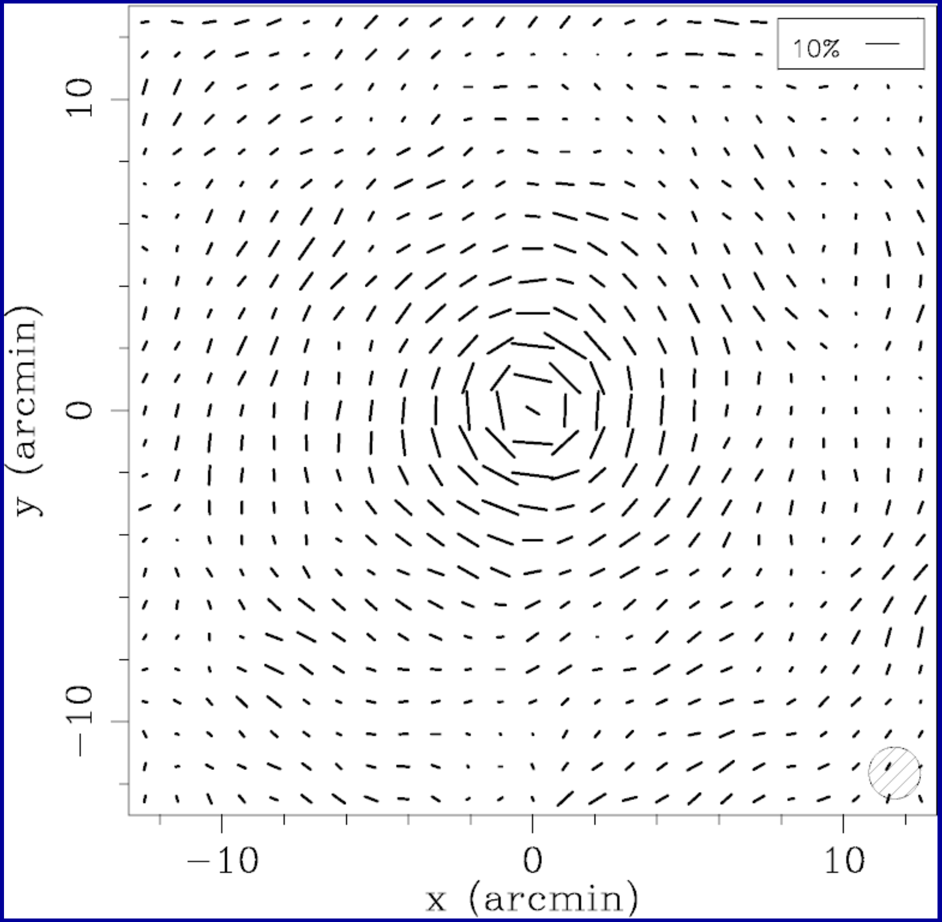
Subaru shear data: N=7

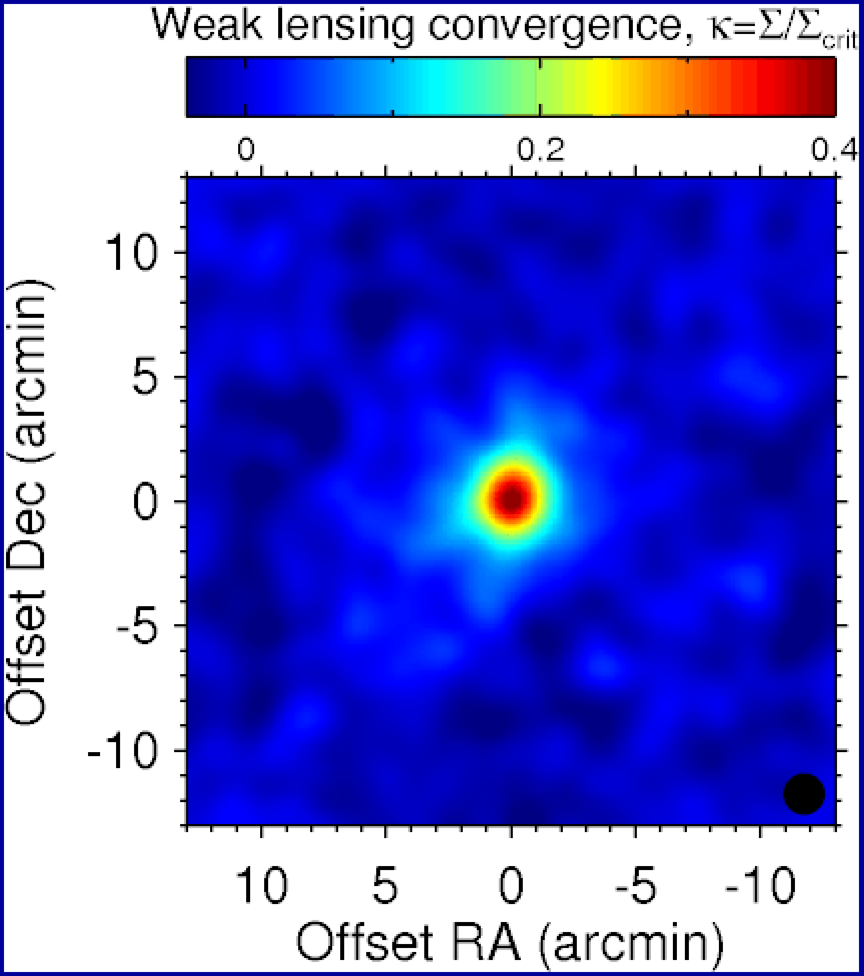




Weak Lensing [3]: Power of Stacking Analysis

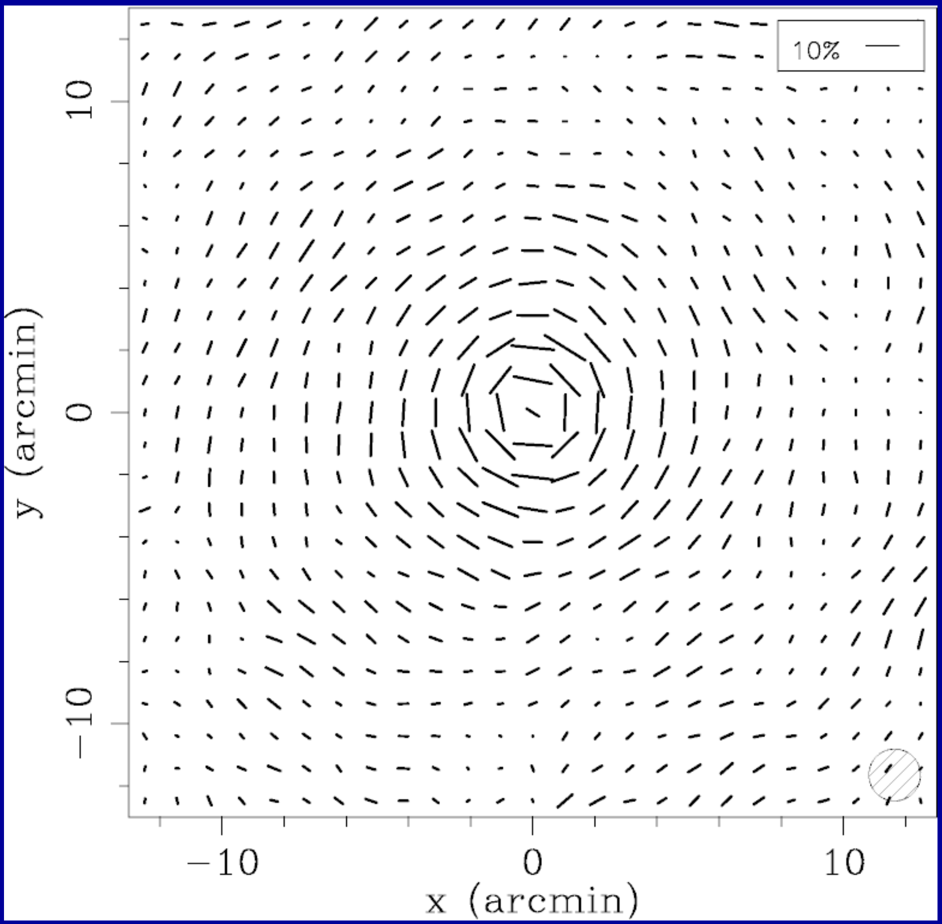
Subaru shear data: N=8

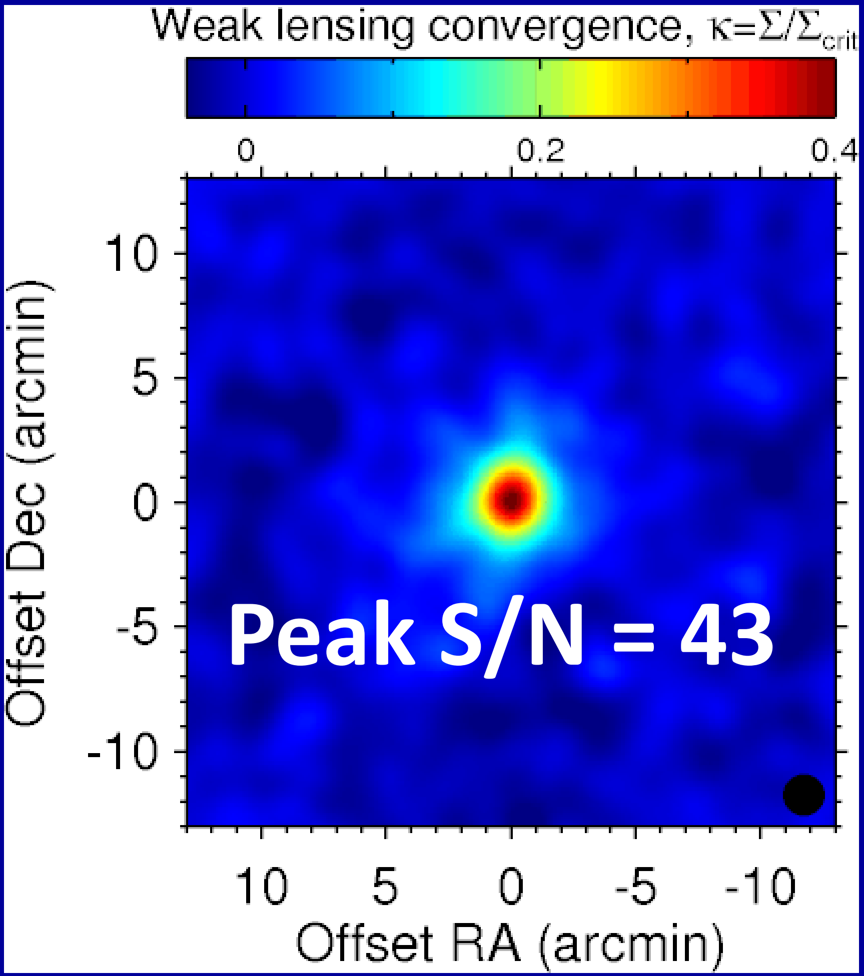




Weak Lensing [3]: Power of Stacking Analysis

Subaru shear data: N=9

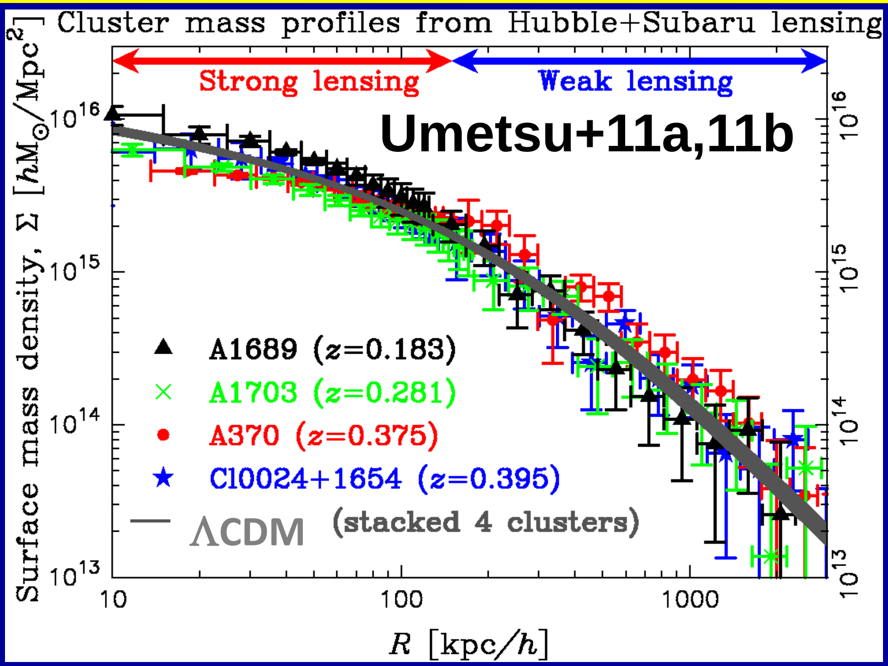


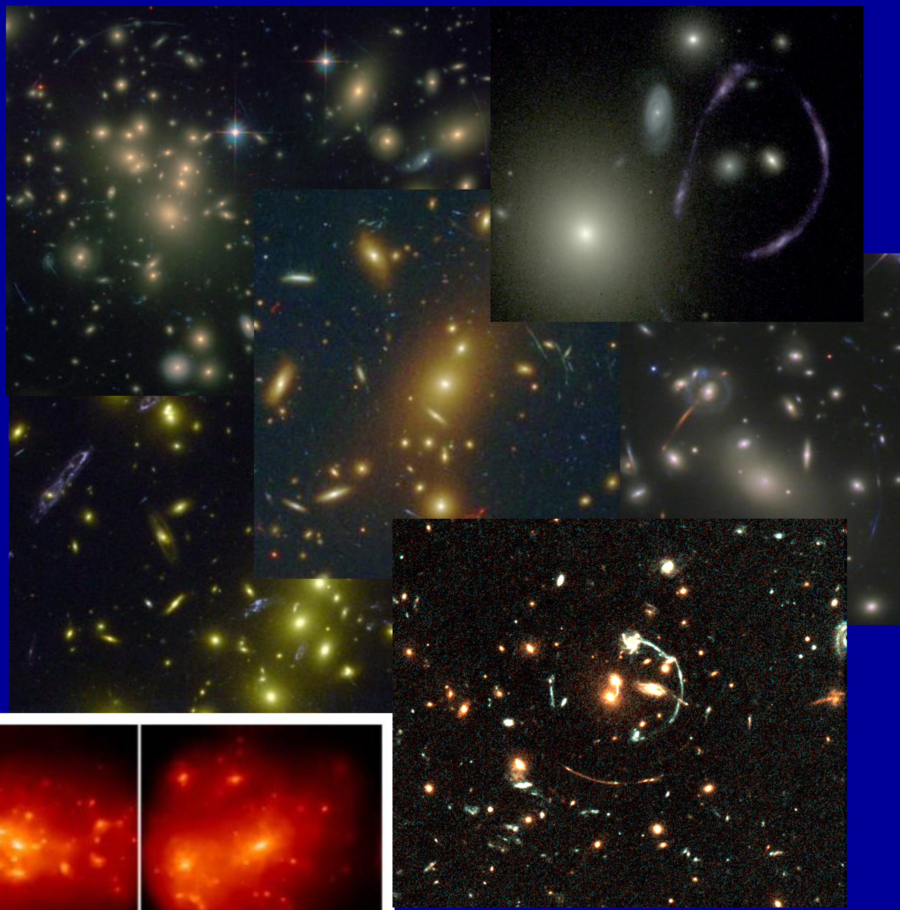


Incoherent contributions, such as aspehericcity, substructures, cosmic shear (uncorrelated LSS contributions), as well as intrinsic shape noise, being averaged out by stacking clusters, due to the isotropic nature of the universe

3. Radial Mass Profiles of Galaxy Clusters:
LCDM Predictions vs. Lensing Observations

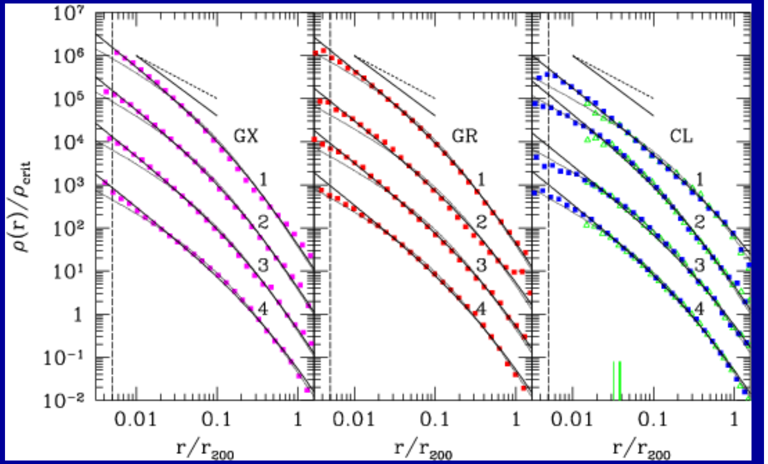
Data

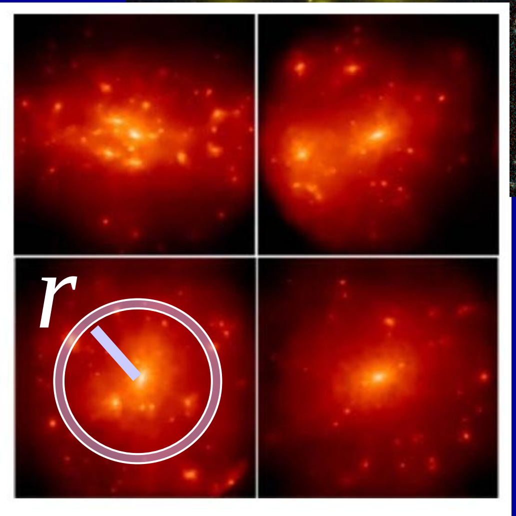




CDM universal density profile (NFW)

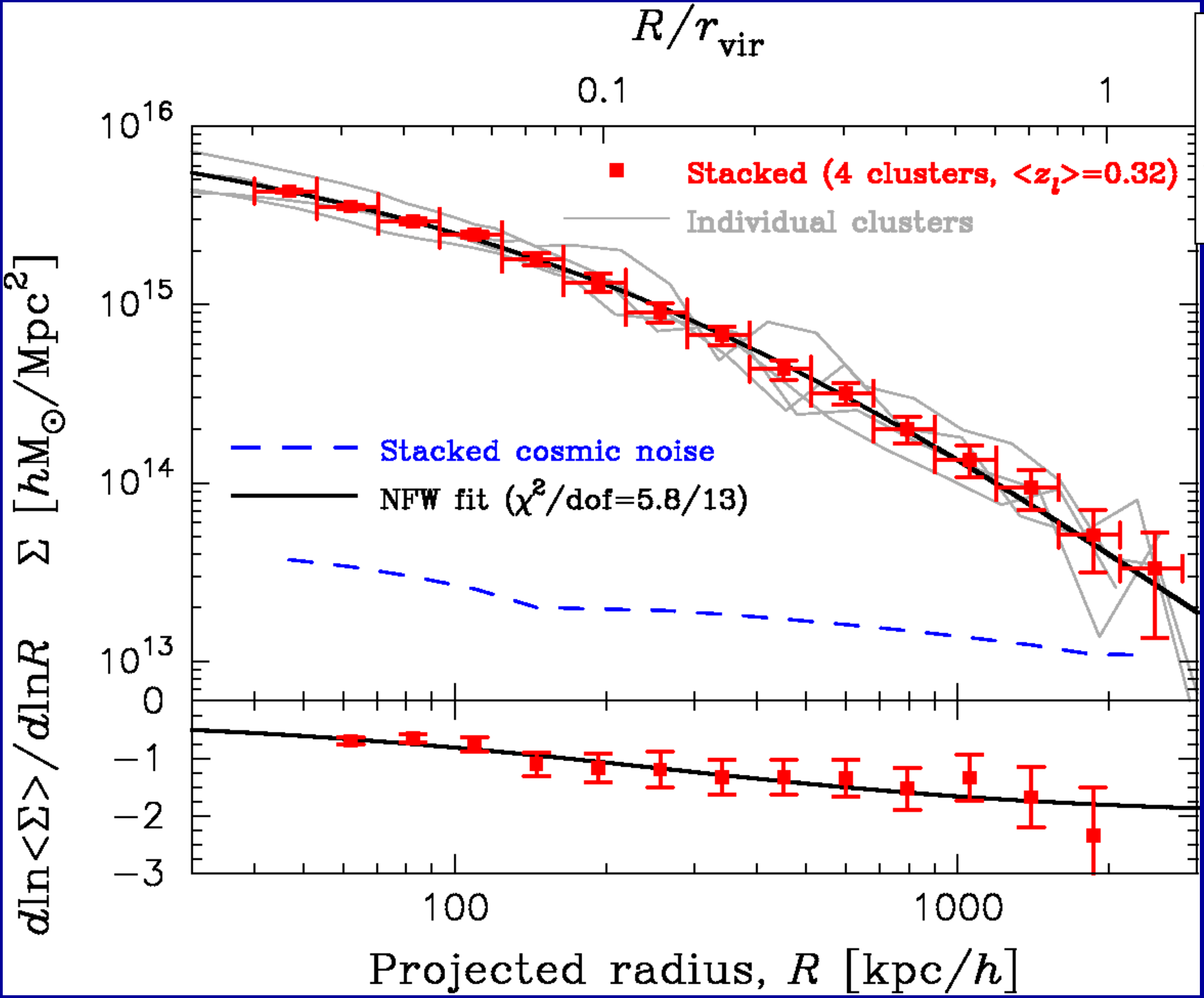
ΛCDM theory





(1) Testing the mass profile “shape”

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



Stacking clusters by

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

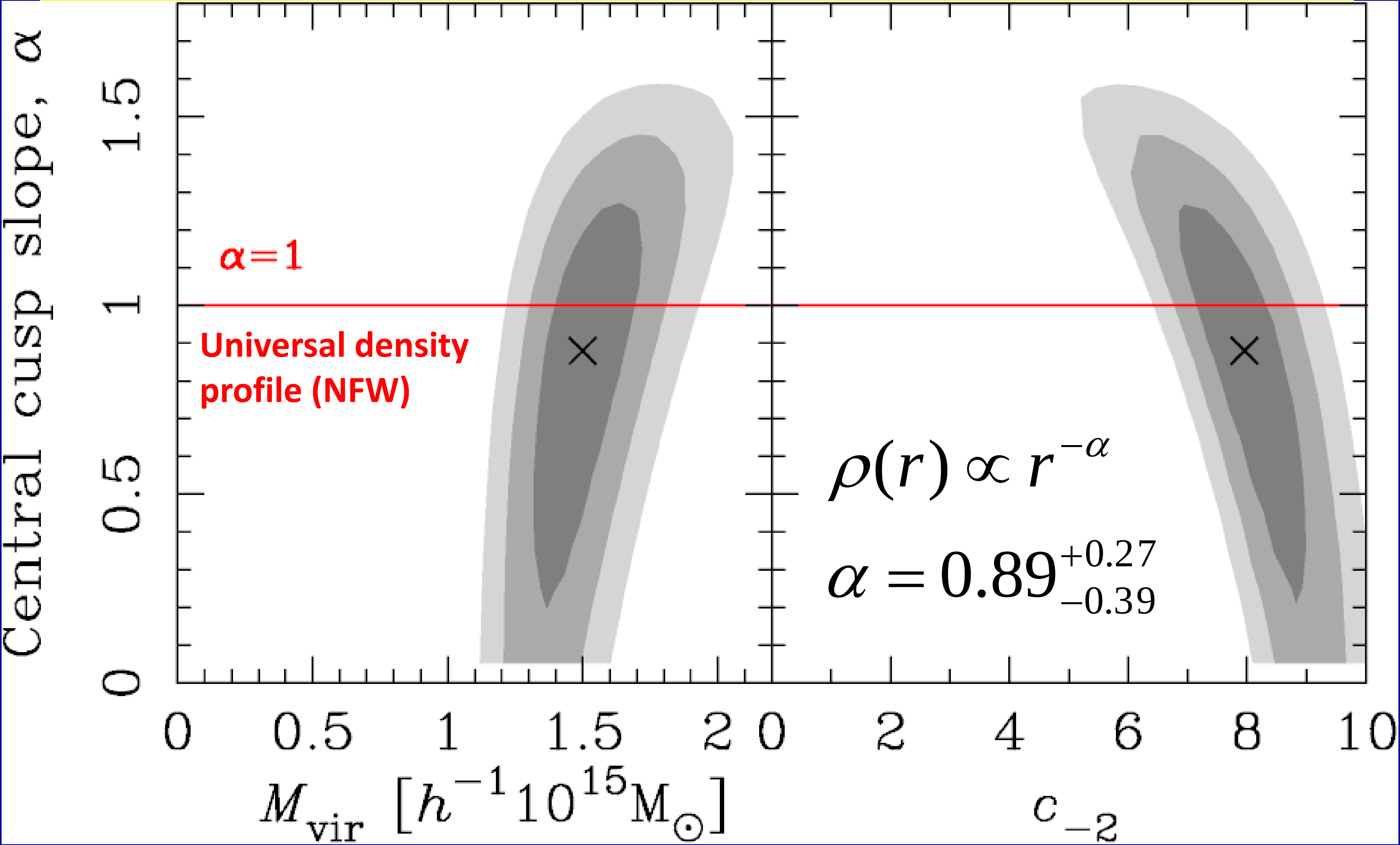
2-parameter universal profile gives an excellent fit over ~2-decades of radius

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



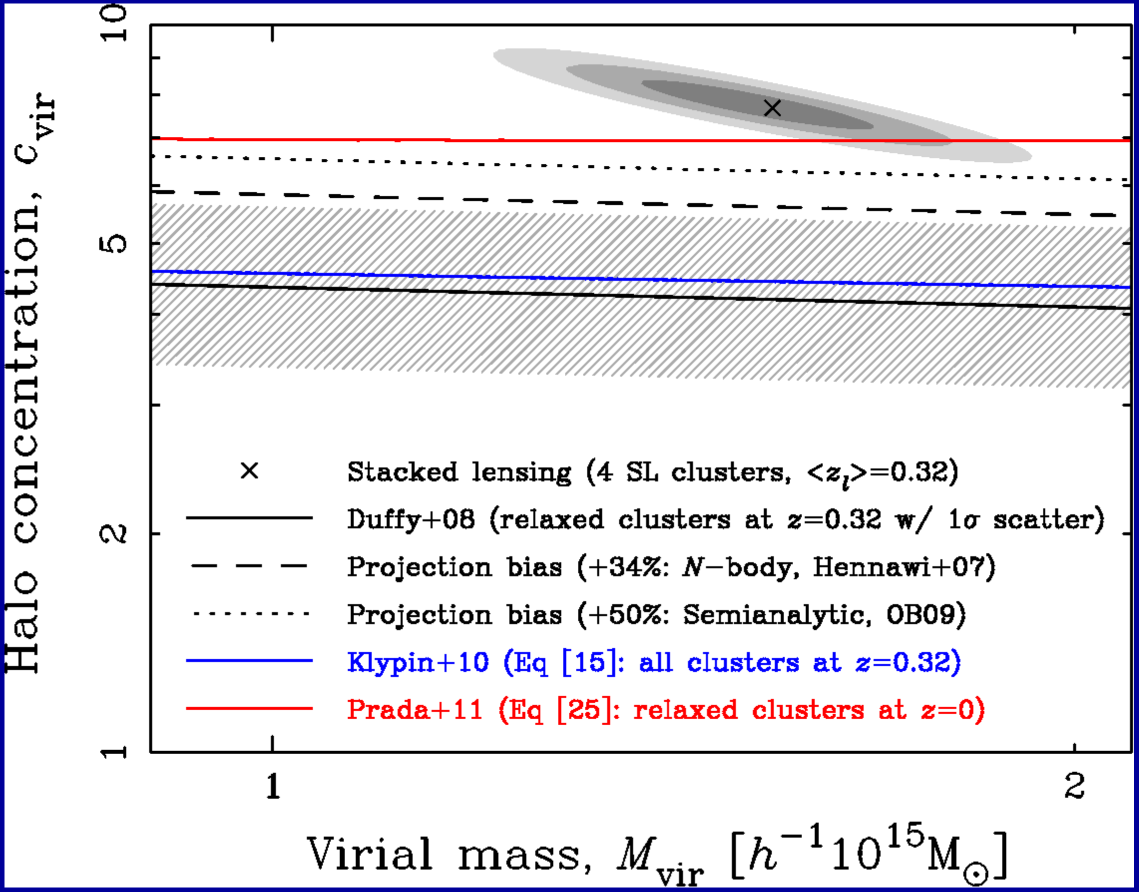
Slightly shallower than, but consistent with, the CDM universal density profile (cf. Navarro et al. 2010)

Umetsu et al. 2011b

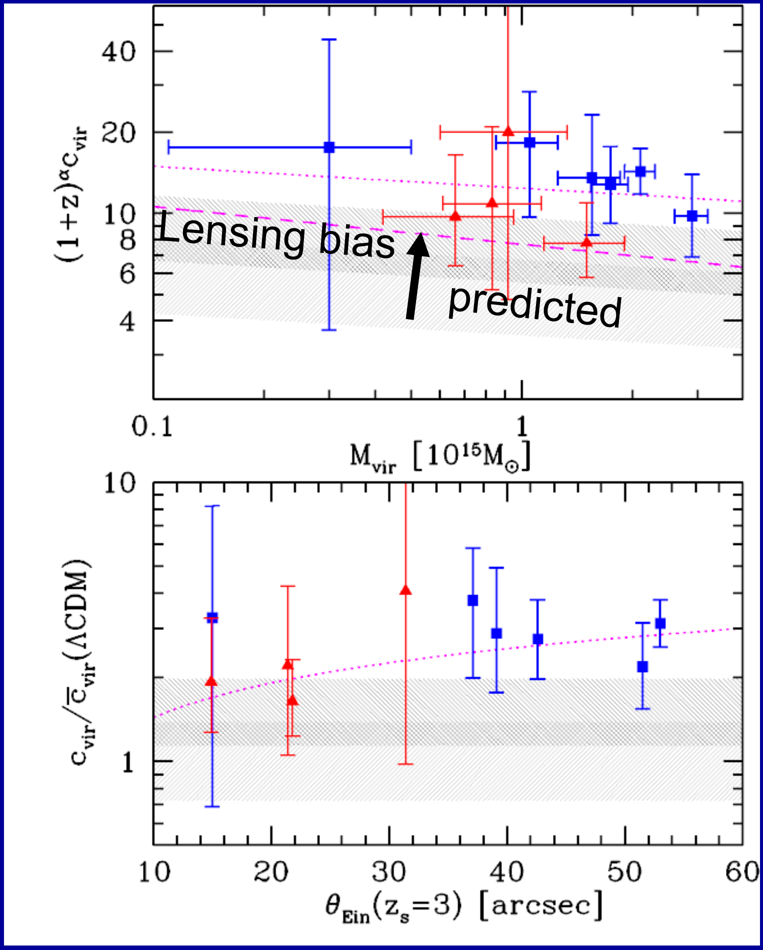
(2) Testing the mass profile “normalization”

Halo central density somewhat higher than LCDM predictions??

Observed lensing clusters are more concentrated than LCDM?



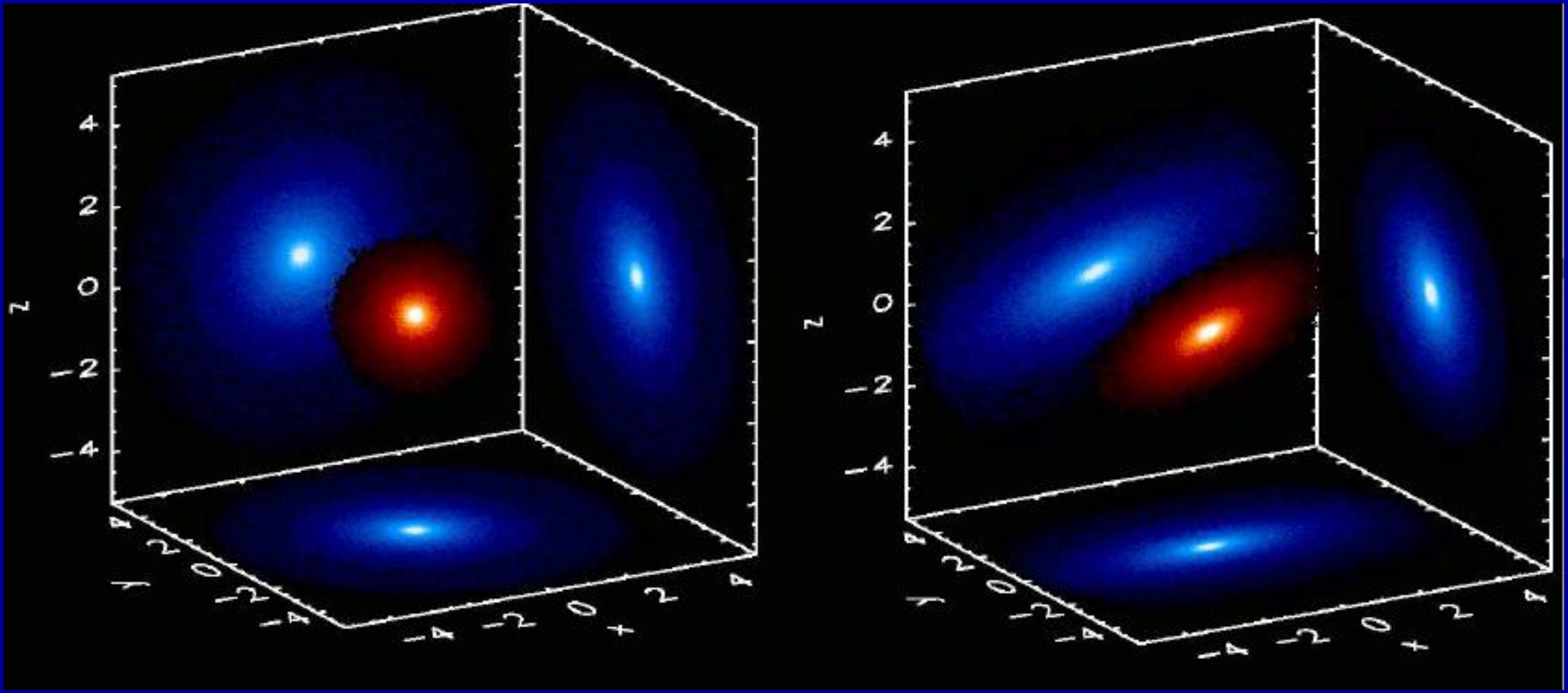
Umetsu et al. 2011b



Oguri eta l. 2010

Broadhurst, Umetsu et al. 2008

Projection Effect by Halo Triaxiality



Spherical

Triaxial (prolate)

Hennawi, Dalal, Bode, Ostriker 2007

Possible explanations for observed high concentrations

- **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
- **Clusters formed earlier than in LCDM?**
  - Early Dark Energy (Sadeh & Rephaeli 08; Grossi & Springel 09) or primordial non-Gaussianity?
- **N-body simulations**
  - High-mass clusters are very rate objects – only 8 relaxed halos with $M>10^{15}M_{sun}/h$ found in the Millennium simulation (500Mpc/h box), suffering from cosmic variance.
  - The latest simulation predicts >50% higher concentrations than previous simulations for high-mass clusters (Prada+11, arXiv:1104.5130).

Summary

- Cluster mass profile shape reconstructed from WL+SL is fully consistent with the standard form predicted for 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.
- The mass concentrations from WL+SL are high for high-mass clusters ($M>10^{15}M_{sun}$), but be consistent with LCDM if a sizable lensing-projection bias and intrinsic scatter is considered.
  - High-mass clusters formed earlier than in LCDM?
  - If the findings from the latest N-body simulation are confirmed, observations and LCDM models come closer.
- These issues will be definitively tested by the ongoing "**Cluster Lensing And Supernova survey with Hubble**" (CLASH: PI M. Postman, KU as Co-I) for a carefully-selected sample of 25 clusters with 5-30e15Msun ($0.2<z<0.9$).

Thank you!