Lensing in clusters
Based on Kneib & Natarajan, Astron Astrophys Rev (2011)

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Constraining cluster mass distributions

- Massive clusters z$\sim$0.2-0.5 are well approximated as single-plane lenses.
- Lensing effect probes 2-D projected mass along the LoS.
- One actually probes the 2D Newton potential $\phi(x, y)$ from a 3-D density distribution $\rho(x, y, z)$.
- The projected surface mass density is $\Sigma(x, y) = \frac{\nabla^2 \phi(x,y)}{4\pi G}$

convergence, shear, deflection

The lensing parameters one derives from a lensing analysis are, convergence κ, shear γ and deflection angles $\overrightarrow{\alpha}$

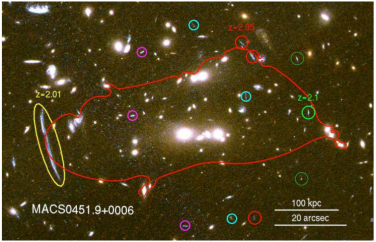
$$\overrightarrow{\alpha}(\overrightarrow{\theta}) = \overrightarrow{\nabla}_{\overrightarrow{\theta}}\varphi(\overrightarrow{\theta}), \quad (1)$$

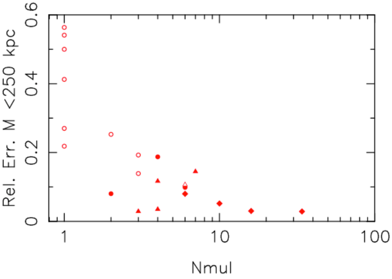
$$\kappa(\overrightarrow{\theta}) = \frac{1}{2}\left(\frac{\partial^2\varphi}{\partial\theta_1^2} + \frac{\partial^2\varphi}{\partial\theta_2^2}\right), \quad (2)$$

$$\gamma^2(\overrightarrow{\theta}) = \parallel \gamma(\overrightarrow{\theta}) \parallel^2 = \frac{1}{4}\left(\frac{\partial^2\varphi}{\partial\theta_1^2} - \frac{\partial^2\varphi}{\partial\theta_2^2}\right)^2 + \left(\frac{\partial^2\varphi}{\partial\theta_1\partial\theta_2}\right). \quad (3)$$

Modelling approaches

- parametric modelling: uses small number of clumps to describe the potential (Kneib, Natarajan 1996), SIS, PIEMD, NFW.
- non-parametric methods: uses tesselated mass distributions with no prior (Saha Williams 1997, Diego et al 2005, Coe et al 2010).





J Richard, E Jullo, M Limousin

From simple to more complex

- Basic: $M(<\theta_E) = \pi\Sigma_{crit} D_{OL}^2 \theta_E^2$
- Radial arc: unique probe to the center surface density (Fort et al. 1992, Smith et al. 2001, Sand et al. 2005, Gavazzi et al. 2003)
- The full mounty: likelihood approach, for the observed data D and parameters p of the model, N systems, n_i images: $\pounds = Pr(D|p) = \prod_{i=1}^{N} \frac{1}{\prod_{j=1}^{n_i} \sigma_{ij}\sqrt{2\pi}} exp^{-\chi^2/2}$ and each image contributes to $\chi_i^2 = \sum_{j=1}^{n_i} \frac{(\theta_{obj}^j - \theta_p^j)^2}{\sigma_{ij}^2}$. θ_p^j is the position predited by model p, and σ_{ij}^2 are errors.
- NB: Non-parametric models (Dye and Warren 2005, Suyu 2006), the S/N of each pixel.
- selecting images is an iterative process, a physically motivate mass speed up the process.

Parametric modeling of the various cluster mass components

A good cluster lens model must have:

- Dark Halo(s) for the cluster component(s) ϕ_{c_i} (DM + intracluster gas)
- Dark halos around massive galaxies (truncated because of tidal stripping) ϕ_{p_j}

$$\phi_{tot} = \sum_i \phi_{c_i} + \sum_i \phi_{p_j}$$

A popular model for galaxies is the physically motivated PIEMD (Brainerd 1996), that allows probing trucation and various mass/light ratio (Limousin 2008, Leautaud 2011 in COSMOS).

Bayesian modeling

State of the art parametric modelling is done under Bayesian modeling (Jullo et al. 2007). Bayesian approach allows a better parameter exploration and model comparison under the intrinsic degeneracies of lens modeling.

$$Pr(p|D,M) = \frac{Pr(D|p,M)Pr(p|M)}{Pr(D|M)} \qquad (4)$$

cf LENSTOOL http://www.oamp.fr/cosmology/lenstool/ (Jullo et al. 2007).

Probing the radial profile of the mass in cluster cores

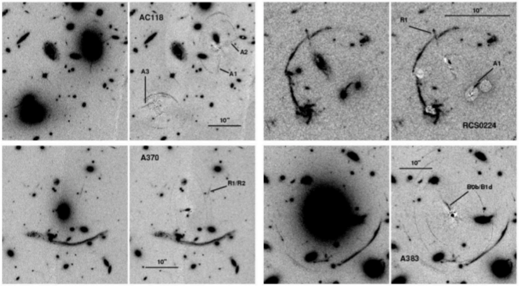
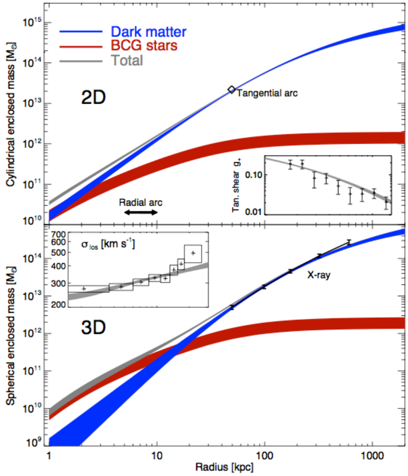


Fig. 19. Example of radial arcs found in the 4 cluster AC118, RCS0224, A370 and A383 (from Sand et al. 2005). The right side of each panel shows the BCG subtracted images.

- DM only simul predict cluster core $\rho_{DM} \propto r^{-\beta}$ and $\beta = -1$ NFW or ($\beta = -1.5$ Moore et a (1998)
- Lensing is the only technique probing the cluster core

Probing the radial profile of the mass in cluster cores



- Most precise techniques combine stellar dynamics in triaxial halo with lensing to compute independent profiles for DM and Baryonic matter.
- All recent results on Abell 383 points towards a DM $\beta < -1$ (Gavazzi 2003, Sand et al. 2005, Newman et al. 2011)
- Ongoing work for other clusters soon...

Non-parametric strong lensing modeling

- With advent of very high-quality data set. Non-parametric modelling is becoming popular (Saha, Williams 1997, Diego et al. 2005, Coe et al 2010, Zitrin et al. 2010)
- Non-parametric models replace profiles by pixel (or radial basis function) maps.
- Due to a large number of degrees of freedom, non-parametric models lead to more flexibility to probe a wide range of mass distributions (Bullet Cluster Bradac et al. 2005).
- NB: Non-parametric model are difficult to interpret and do not take into account known components (e.g. galaxy scale clumps).
- Hybrid schemes (mixing parametric and non-parametric techniques are promising (Jullo Kneib 2009).

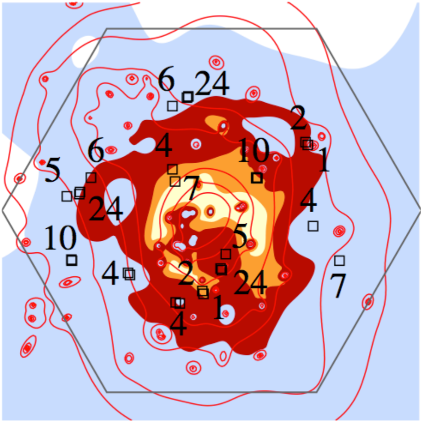


Fig. 21. Map of S/N ratio for the A1689 mass reconstruction using the JK09 "non–parametric" mass reconstruction. Colored contours bound regions with S/N greater than 300, 200, 100 and 10. The highest S/N region is at the center where there are the most constraints. Red contours are mean iso-mass contours. Black boxes mark the positions of the multiple-images used to constrain the mass distribution, and the numbers indicate the different multiple-image systems (from JK09).

Cluster weak lensing modeling

- Weak lensing signal in outskirts of clusters must be treated statistically ($\sim$ percent level).
- Weak lensing is prone to strong observational errors (PSF variations, foreground contamination).
- Reconstruction methods are not straitghtforward (reduced shear g or amplification).
- Observations: space HST Massey (2010), ground : CFHT12K Bardeau Hoekstra (2007), Megacam Gavazzi, Soucail (2007) Shan 2010, SuprimeCam (Okabe et al 2010)
- shape measure: clean sample, direct method IMCAT (Kaiser 1995), (Rhodes et al., Hoekstra 2000), reverse method IM2SHAPE Bridle et al. 2002, LENSFIT Miller 2007, Kitching et al. 2008. SHAPELETS Refregier 2003. The best methods have improved through challenges STEP, GREAT8 and 10 (Bridle, Kitching 2011).

From galaxy shape to mass maps

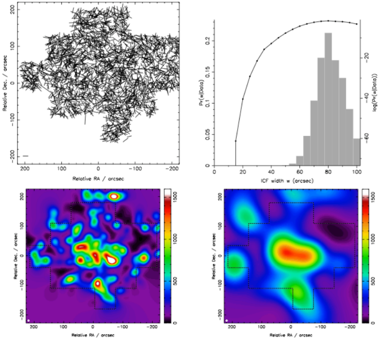


Fig. 23. Maximum entropy mass reconstruction (Marshall et al. 2002, Marshall 2003) of the X-ray luminous cluster MS1054 at $z = 0.83$ using Hoekstra's *HST* dataset (Hoekstra et al. 2000). (Top Left) Distribution of the positions of galaxies used in the mass reconstruction. (Top Right) Evidence values for different sizes of the Intrinsic Correlation Function (ICF). (Bottom) Two mass reconstructions illustrate the case of 2 different values for the ICF: (left) small ICF with a low evidence value, (right) large ICF with the largest evidence.

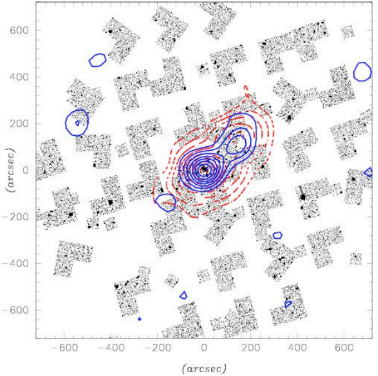


Fig. 24. The 39 WFPC2/F814W, and the 38 STIS/50CCD pointings sparsely covering the Cl0024+1654 cluster. The (red) dashed contours represent the number density of cluster members as derived by Czoske et al. (2001). The blue solid contour is the mass map built from the joint WFPC2/STIS analysis derived using the LensEnt software (Bridle et al. 1998; Marshall et al. 2002).

Measuring total mass and mass profiles

- Direct method: aperture mass densitometry Fahlman 1994 Clowe 1998: sum up tangential weak shear within a radius θ_1. $M(<\theta) = \pi D_{OL}^2 \theta^2 \Sigma_{crit} \zeta(\theta)$ (used in Hetterscheidt et al. 2005 Hoekstra 2007, Okabe et al 2010)
- assumes that all background galaxies are at same redshift.
- Semi-direct Method: surface density estimator (Mandelbaum et al. 2005): $\Delta\Sigma(r)$, this estimator is then computrd directly from parametrized models. Latest paper Gruen et al. 2011.
- Parametric method: fitting directly the weak lensing signal with a parametric models (following strong lensing method). Used in Metzler et al. 1999, 2001, King 2001.

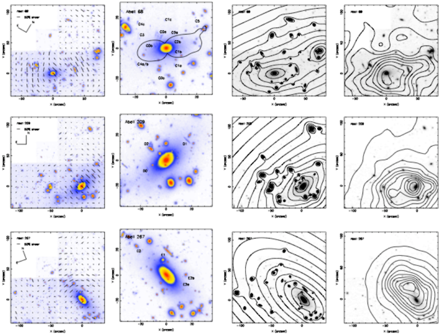
Cluster triaxiality

- Spherical symetry is not a good approximation for clusters
- Triaxial cluster can explain observed discrepancy between the high concentration measured in lensing clusters wrt to DM simulations. Gavazzi (2005). This is the case fro A1689 (Andersson 2004 Lemze 2008, Riemer-Sorensen 2009, Peng 2009).
- Combining X-rays, SZ and lensing analysis allow us to probe triaxiality (Mahdavi et al. 2007). Excellent results on A478.
- Study on MACS J1423.8+2404 (Morandi et al. 2010) shows a triaxial halo with axial ratio 1.53±0.15 (plane of sky) and 1.44±0.07 (line of sight), x-ray + weak lensing.

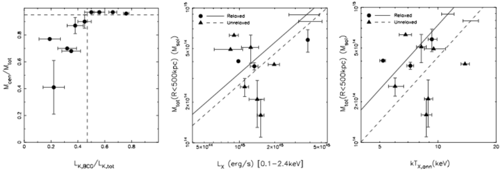
Mass distribution of cluster samples

- Compare lensing analysis of cluster samples with X-ray luminosity, temperature, velocity dispersions, SZ
- Are cluster relaxed? How much substructure in clusters? How triaxial are they? What are the signatures of merger events? How important are projections?
- Observations can be compared to numerical simulations $\rightarrow$ test formation paradigm.

Early work

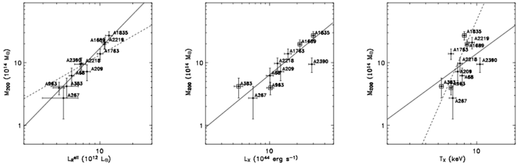


- Challenge is to define and collect a statistically significant dataset spanning a range of spatial scales.
- Early work: Luppino et al. 1999, Allen et al. 2001 2002, Dahle el al 2002, Smith et al 2003.
- Lensing clusters imaged by HST are likely to be biased toward massive end at all redshifts. (+ projection effects)
- X-ray selection is less biased ($\propto$ ICM electron density^2): work of Smith 2001 2005 12 clusters $z \sim 0.2$ $L_X > 8 \text{x} 10^{44}$erg/s (0.1-2.4 keV) from XBACS catalog.



Smith et al. 2005

70% show strong lensing signal. Relaxation defined by: dominant core ($M_{core}/M_{tot} > 0.95$), dominant central galaxy, alignment between x-ray and mass distrib. 7 clusters are disturbed, bi or tri modal → recent merging activity.



Bardeau et al. 2007

Follow-up in BRI CFHT12K does not show large difference between relaxed and unrelaxed clusters at larger radii.

NEED FOR LARGER SAMPLES!
Ongoing work with 50 x-ray clusters by Hoekstra et al. 2012...
TBD (Canadian Cluster Comparison Project)

on-going and future cluster lensing surveys

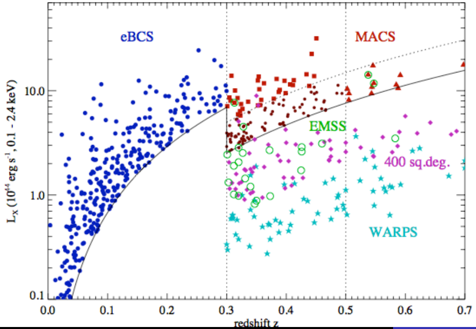
- 4 techniques are used to search for clusters:
  - photometric searches Red-sequence surveys (RCS Gladders), CFHTLS, new surveys starting VST KIDS, Dark Energy Survey (DES), Subaru
  - x-ray selected cluster: (i) ROSAT based MAssice Cluster Survey (MACS Ebeling et al. 2001), REFLEX (Boehringer 2004) (ii) dedicated search WARPS, SHARC, ROSAT deep cluster survey, XMM DCS, XMM LSS (Scharf, Collins Fassbender, Romer Rosati, Pierre).
  - SZ search: Atacama Cosmology Telescope Cluster survey (Hinck 2010, Marriage Hand 2011). South Pole Telescope Cluster survey (Chang 2009, Vanderlinde Plagge 2010), Planck (Ade 2011).
  - Weak and strong lensing searched based on photometric surveys or follow-up of x-ray and SZ clusters.

Targeted cluster surveys: LoCuSS

- The Local Cluster Substructure Survey (LoCuSS): extend Smith et al. 2005 (~ 80 clusters $0.15 < z < 0.3$) goals: get mass, structure and thermodynamics of a volume limited sample. (Ebeling et al.), weak lensing of 30 clusters (with Subaru Okabe et al. 2010, Zhang 2010, Marrone 2011) $\rightarrow$ NFW profiles confirmed, Mass concentration relation consistent with ΛCDM (contrary to previous work on large Einstein radius clusters!). First SZ-WL results on 18 clusters, seems to confirm a projection bias for WL prolate undisturbed clusters compared to disturbed clusters.
- The MAssive Cluster Survey: : 124 X-ray luminous clusters $0.3 < z < 0.7$
- ESO distant cluster survey
- Red-sequence cluster surveys
- The Multi-Cluster Treasury: CLASH survey

Targeted cluster surveys: MACS

The MAssive Cluster Survey: : 124 X-ray luminous clusters $0.3 < z < 0.7$: many are strong lenses (Zitrin et al. 2011a: 12 clusters HST follow-up $z > 0.5$). Many clusters being studied (Limousin et al 2010, 2011, Morandi 2010, Bradac 2008). MACSJ0717.5+3745 (Ebeling et al. 2004) shows a merger of four structures (Jauzac et al. 2011 weak lensing measurement using 18 pointings HST). MACS sample is significantly richer in arcs than RCS.



Targeted cluster surveys: other

- ESO distant cluster survey: $z > 0.6$ optical selection of 20 fields of Las Campanas Distant Cluster Survey. Spectroscopy and photomery follow-ups on the most distants clusters. Clowe et al (2006) compare mass measurements of 13 EDiSC clusters with luminosities and finds dependence of cluster mass-to-light ratio with redshift.
- Red-sequence cluster surveys: Gladders, Yee 2002, 2005. RCS2 1000 deg^2, among 10^4 cluster sample, a small sub-sample show strong lensing events. Appart from identifying them TBD.
- The Multi-Cluster Treasury: CLASH survey, Postman et al. HST follow-up of 20 X-ray clusters. TBD.

Cluster lenses in wide cosmological surveys

Non targeted surveys are rich source of lenses at all scales. They triggered new automated detection procedures $\rightarrow$ much need for EUCLID, WFIRST.

- The SDSS: not optimized for lens search (too shallow, poor seeing). Henawi et al. discovers 16 lenses, 21 candidates among 240 clusters. Those samples are statistically clean, will help defining selection functions. Kubo and Diehl (2009) identify 10 strong lenses in the Sloan Bright Arc Survey. Bayliss follow-up 26 Strong lensing cluster among SDSS/RCS.

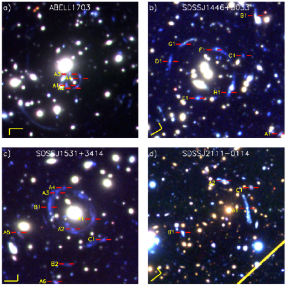


Fig. 30. SDSS discovered strong lensing clusters – *a*) Abell 1703, *b*) SDSS J1446+3033, *c*) SDSS J1531+3414, and *d*) SDSS J2111-0114. Color composite images are made from g, r, i imaging obtained with Subaru/SuprimeCam. All images are $75'' \times 75''$. Background sources are bracketed by red lines and labeled. Source labels with the same letter but different numbers (e.g. A1, A2, etc.) have the same redshifts to within the measurement errors, and are presumed to be the same source,

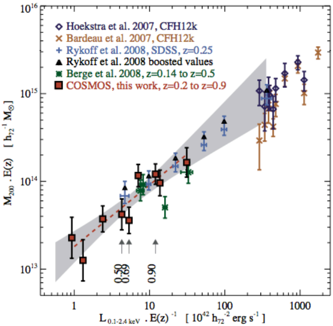
Cluster lenses in CFHT-LS 170 deg^2

Much more successful than SDSS (deeper imaging, better resolution).

- CFHTLS: SL2S Cabanac et al. 2007, More et al. 2012, 40 group scale, 120 candidates. Limousin et al. 2009 studied mass and light distribution of 13 groups, encovering redshift trends in mass and groups luminosities. Group lensing is a niche for flexion analysis. First large-scale structure maps of lenses.
- CFHTLS: weak lensing on Deep fields (Gavazzi et al. 2007). First maps of weak lensing peaks. Catalog of lensing selected clusters (Shan et al.2011). Bergé et al. 2008 combined analysis of XMM-LSS and CFHTLS , contrained $\sigma_8 = 0.92^{+0.26}_{-0.30}$. More work coming...

Cluster lenses in COSMOS survey 2 deg^2 HST + X-rays.

- COSMOS: very deep, allows probing fainter clusters at higher redshift. Faure et al. 2007, 2008, Strong Lensing map of COSMOS $z < 2$ no correlation between lens loci and COSMOS large structures. Leauthaud 2010: weak lensing study of 200 x-ray groups.



Leauthaud et al. 2010

Cluster lenses as nature's telescopes

Many applications uses cluster magnifying power to study highredshift sources.
cf Kneib & Natarajan AAR 2012.

Cosmological constraints from cluster lensing

Cf Eric Jullo's talk coming next!

Comparison of observed lensing cluster properties with theoretical predictions

Prediction: Cosmological DM-only simulation predict over a large range NFW profiles for clusters.
Observations: Lensing analyses probe total mall in 0.1-5 Mpc and tend to show various inner concentrations.

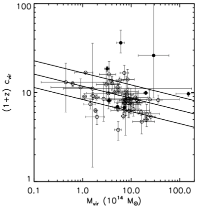


Fig. 44. Observed cluster concentrations and virial masses derived from lensing (filled circles) and X-ray (open circles) measurements. For reference, the solid lines depict the best-fit power law to our complete sample and its 1-σ scatter. The lensing concentrations appear systematically higher than the X-ray concentrations, and a Kolmogorov-Smirnov test confirms that the lensing results likely belong to a different parent distribution. This figure is from Comerford & Natarajan 2007.

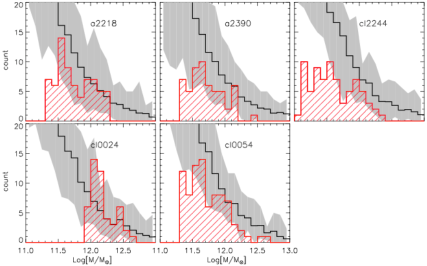
Plausible reasons:

- contamination of other structure line of sight
- projection biases
- physical feedback of baryons over DM

Comerford & Natarajan 2007.

Mass function of substructure in cluster halos

No substructure crisis in clusters between ΛCDM (Millenium, Springel 2005) and galaxy-galaxy lensing analyses in clusters. Natarajan et al. 2007

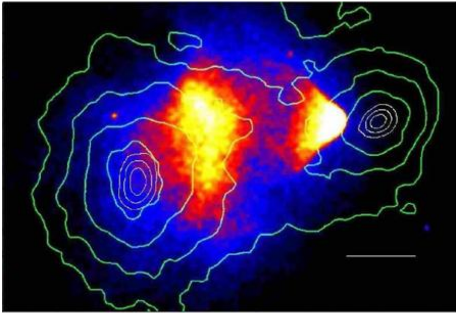


Substructure crisis at galaxy scales must come from evolutionary reasons (baryonic feedback).

Group-scale analyses shall also be interesting!

Does Dark Matter exist?

The bullet cluster and other clusters showing different distributions between WL and ICM are convincing (Bradac et al. Clowe 2006).



Future prospects

Space missions: JWST, EUCLID, WFIRST(?) and ground-based project (LSST, DES, TMT?, E-ELT) will bring lensing studies into a distinct new level.

Radio observations: ALMA (SKA?) is expected to boost the field of lensed galaxy combining velocity field data and galaxy shapes.

THANK YOU!