Mass distribution in galaxy clusters: strong lensing and dynamical mass analysis

Mauricio Carrasco

Institut für Theoretische Astrophysik (ITA), Universität Heidelberg

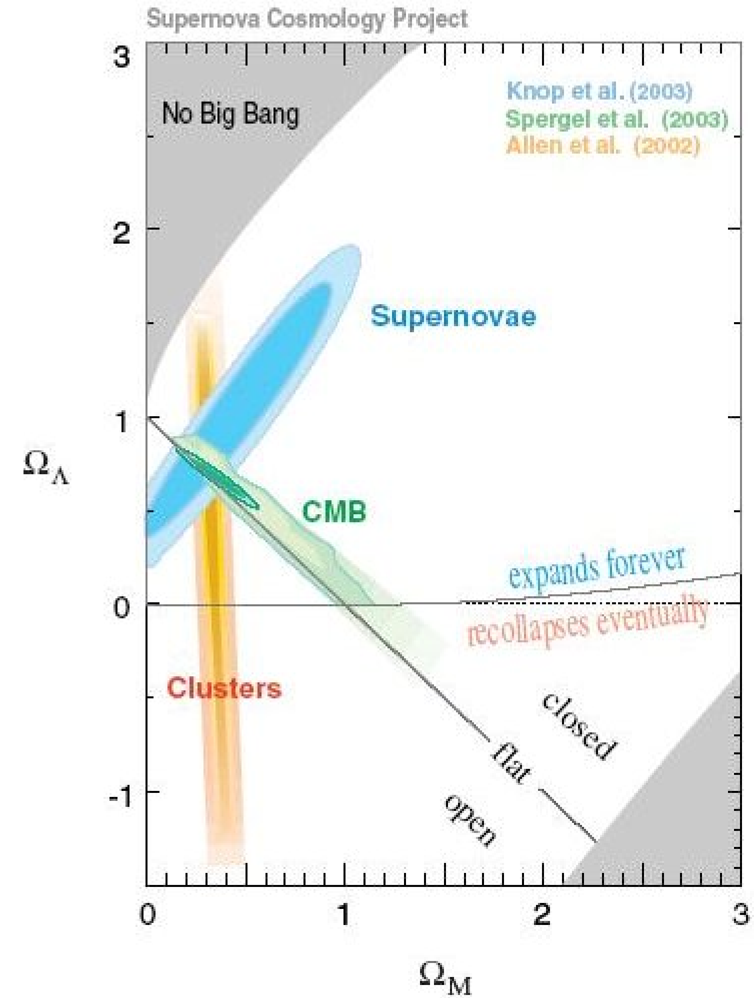
M. Maturi, M. Bartelmann, G. Seidel, K. Huber, and ITA team
F. Barrientos, T. Anguita, M. Gladders, M. Oguri, M. Bayliss, and RCS team
A. Zitrin, M. Meneghetti, D. Coe, J. Merten, and CLASH Team.

Cosmological Framework

- Current observational constraints support:
  - flat Universe $\Omega = \Omega_\Lambda + \Omega_M \sim 1$
  - dark energy component $\Omega_\Lambda \sim 0.7$
  - matter density component $\Omega_M \sim 0.3$
  - Hubble constant $H_0 \sim 70$ km s^{-1}Mpc^{-1}

$$H^2(z) = H_0^2\left[\Omega_r(1+z)^4 + \Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

$$H^2(z) = H_0^2\left[\Omega_M(1+z)^3 + \Omega_\Lambda\right]$$

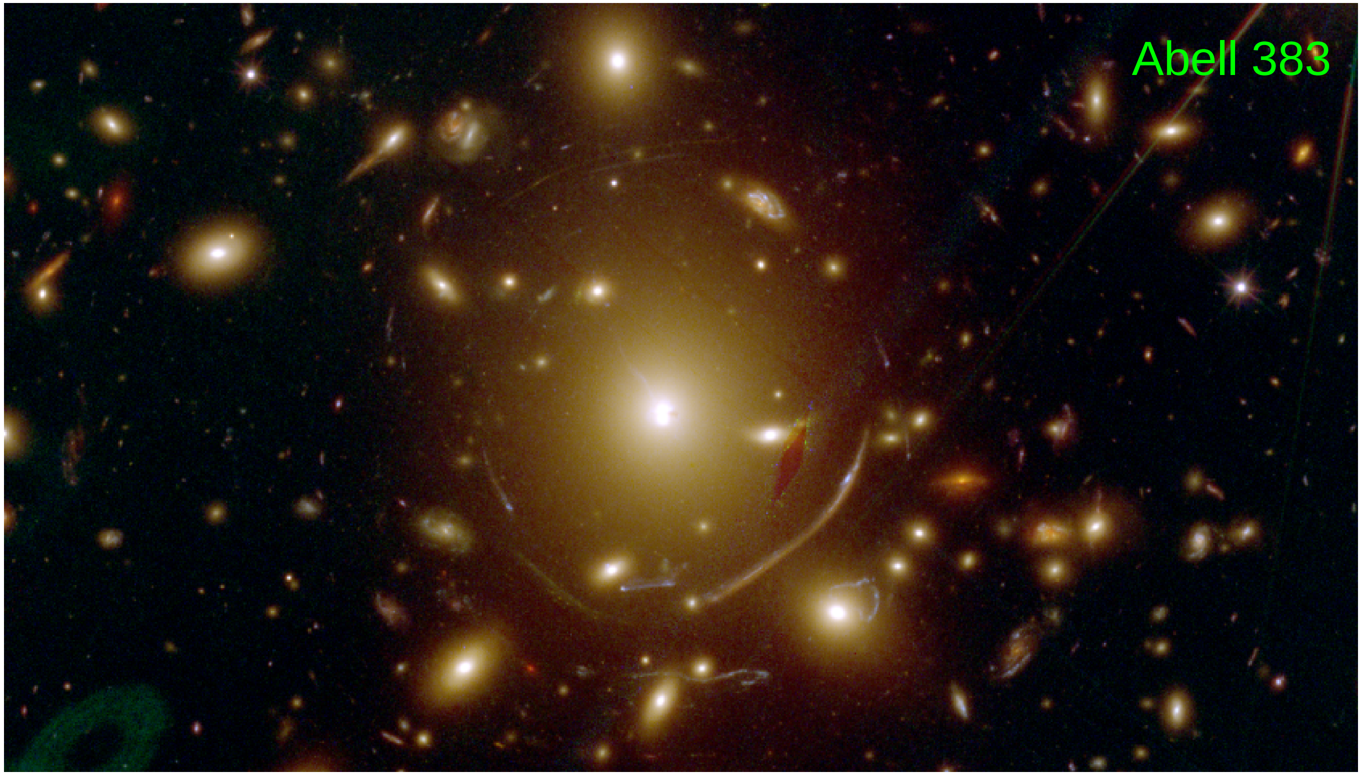


Galaxy Clusters

Matter density component – Dark matter

- The largest objects which are small enough to have come into dynamical equilibrium.
- The smallest objects which are big enough to contain a fair sample of the materials in the Universe, particularly of baryonic and non-baryonic matter.

~ 80 - 85 %
is Dark Matter (DM)



Galaxy Clusters

Mass measurements: velocity dispersion

- Scaling relations: the velocity distribution of galaxies can be converted into mass estimates.

$$M_{200} = \frac{10^{15}}{h(z)} \left(\frac{\sigma_{DM}}{\sigma_{15}} \right)^{1/\alpha} M_{\odot}$$

$$b_v \equiv \frac{\sigma_{\rm gal}}{\sigma_{\rm DM}} \Rightarrow \langle b_v \rangle_{\rm sim} = 1.00 \pm 0.05$$

Evrard et al. (2008)

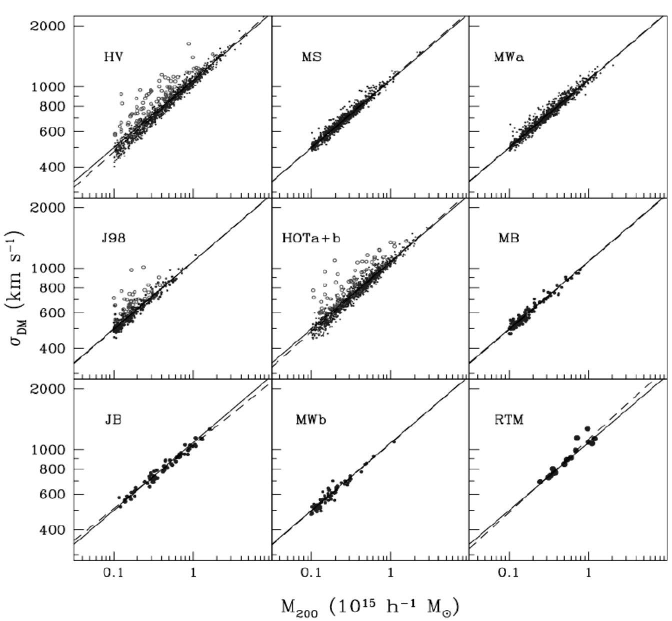
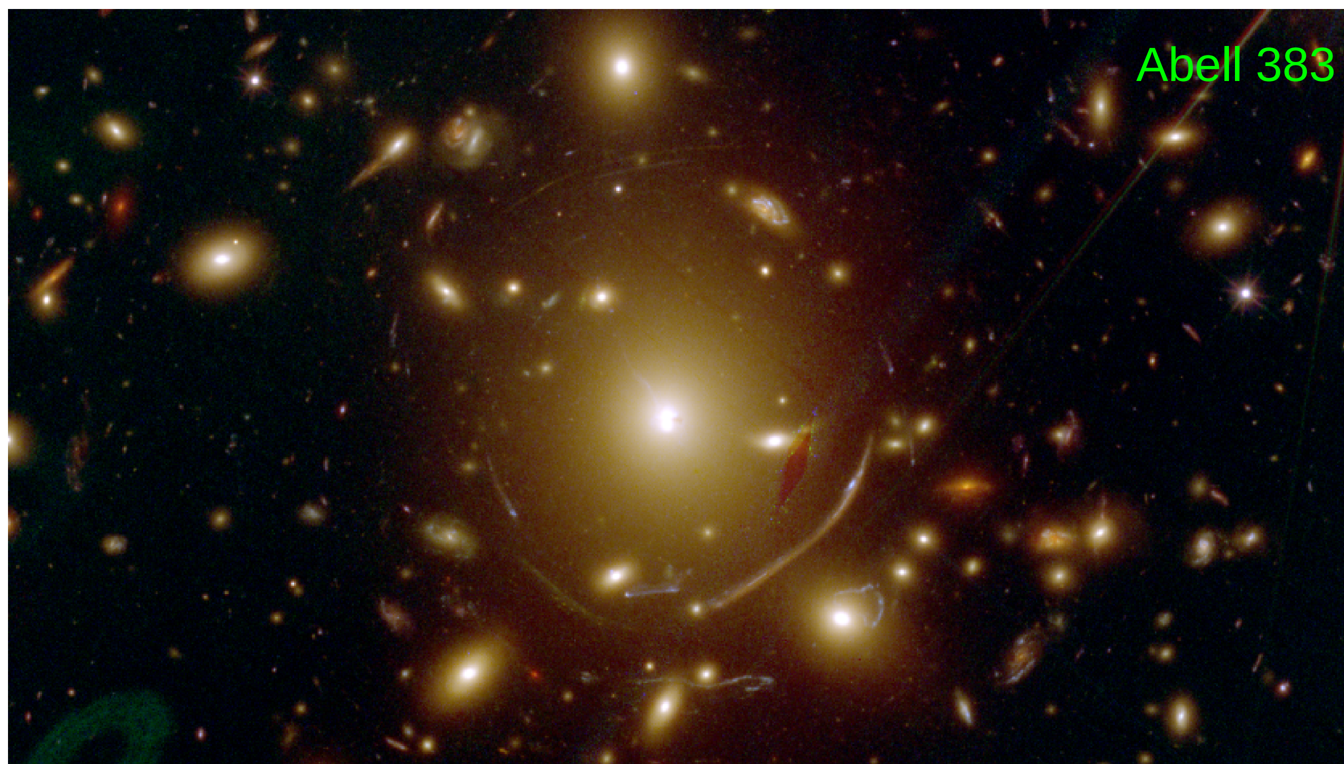


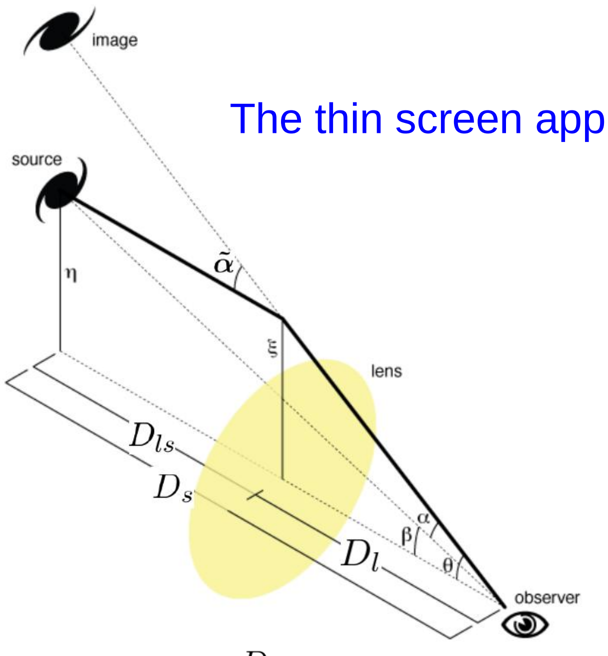
FIGURE 2.12: The figure shows the $\sigma_{DM} - M_{200}$ relation for several cosmologies, as well as the "universal" best-fit previously described by Eq. 2.50. This figure was taken from Evrard et al. (2008)



Mass measurements: strong lensing (SL)

- Gravitational lensing is the most robust way to probe the total matter distribution because the light deflection is independent of the nature of the matter and of its state.

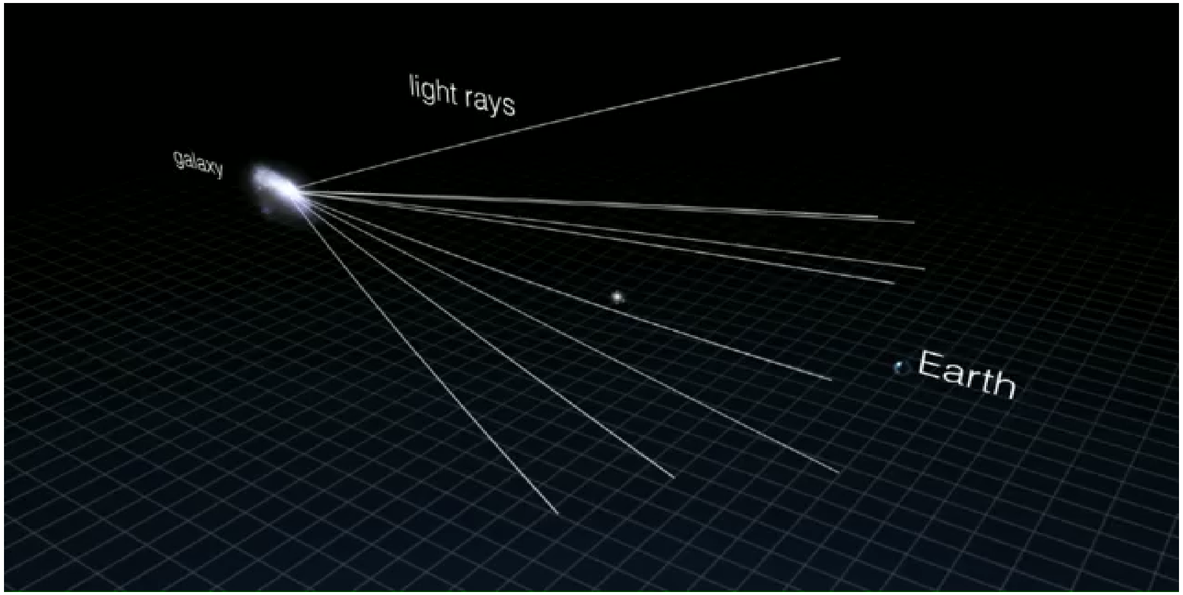
The thin screen approximation



$$\boldsymbol{\beta} = \boldsymbol{\theta} - \frac{D_{ls}}{D_s}\tilde{\boldsymbol{\alpha}}(D_l\boldsymbol{\theta})$$

$$\tilde{\boldsymbol{\alpha}}(\boldsymbol{\xi}) = \frac{4G}{c^2}\int d^2\xi'\,\Sigma(\boldsymbol{\xi}')\,\frac{\boldsymbol{\xi}-\boldsymbol{\xi}'}{|\boldsymbol{\xi}-\boldsymbol{\xi}'|^2}$$

Abell 383



Mass measurements: strong lensing (SL)

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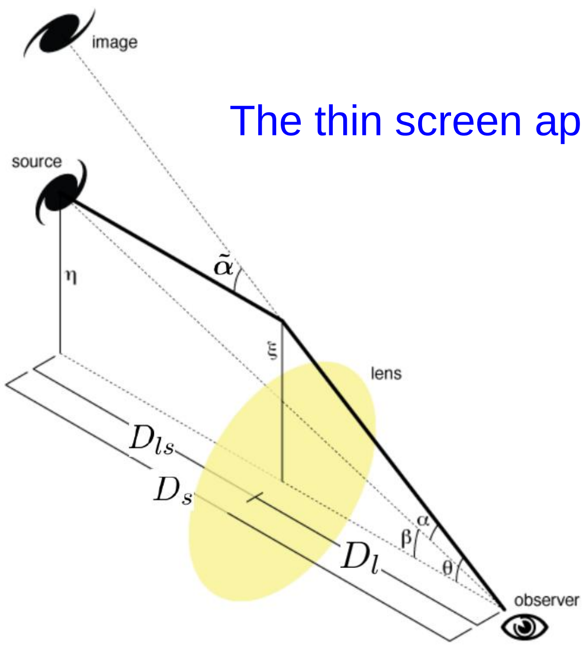

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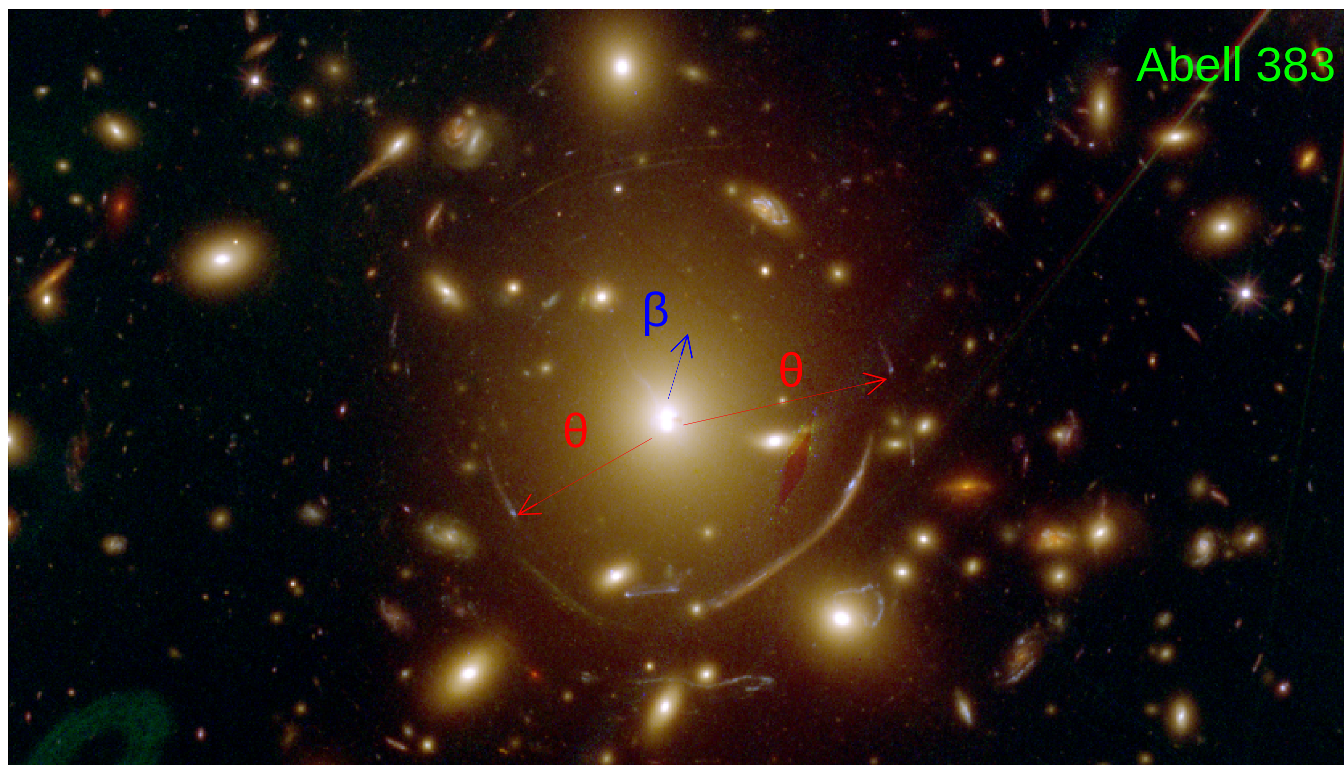


Goal

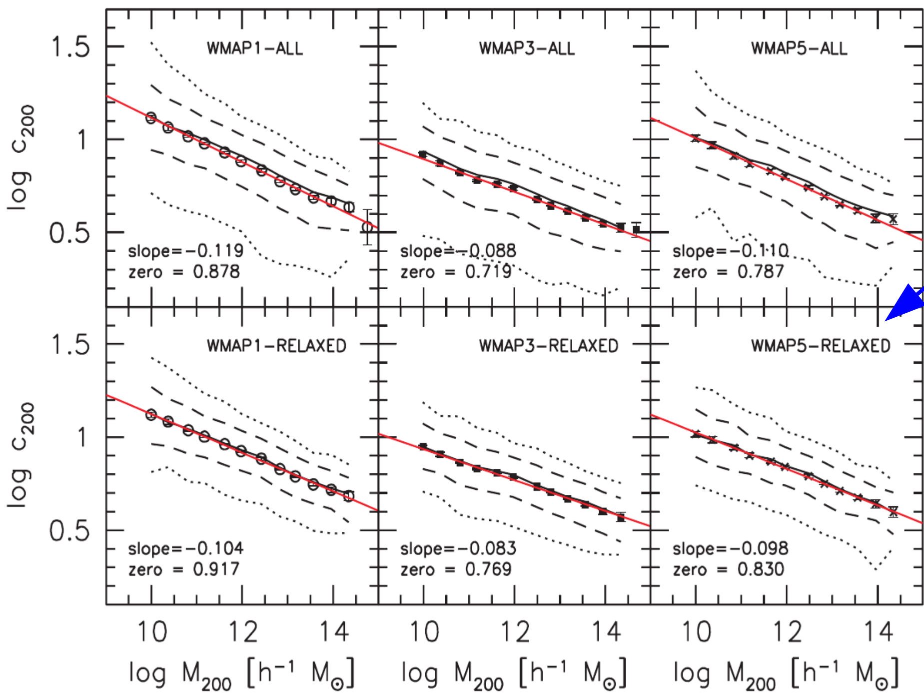
Matter density component: Concentration – mass relation

- In the ΛCDM cosmological framework, numerical simulations have shown a very well-defined correlation between the concentration of the halos and their masses

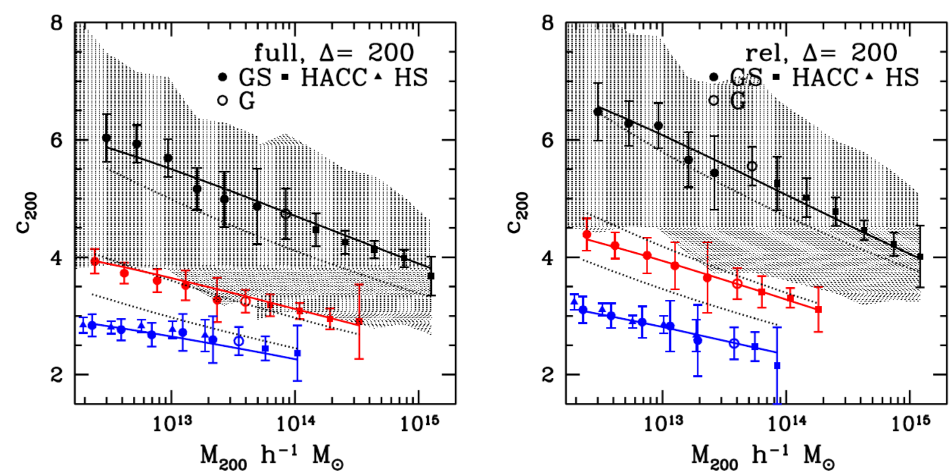
⇨ c − M relation: less massive halos are expected to be more concentrated than more massive ones

$$c_{200}(M_{200}) = c_n \times \left(\frac{M_{200}}{M_{piv}\ h^{-1} M_{\odot}} \right)^{\alpha}$$

σ_8



Macciò et al. (2008)

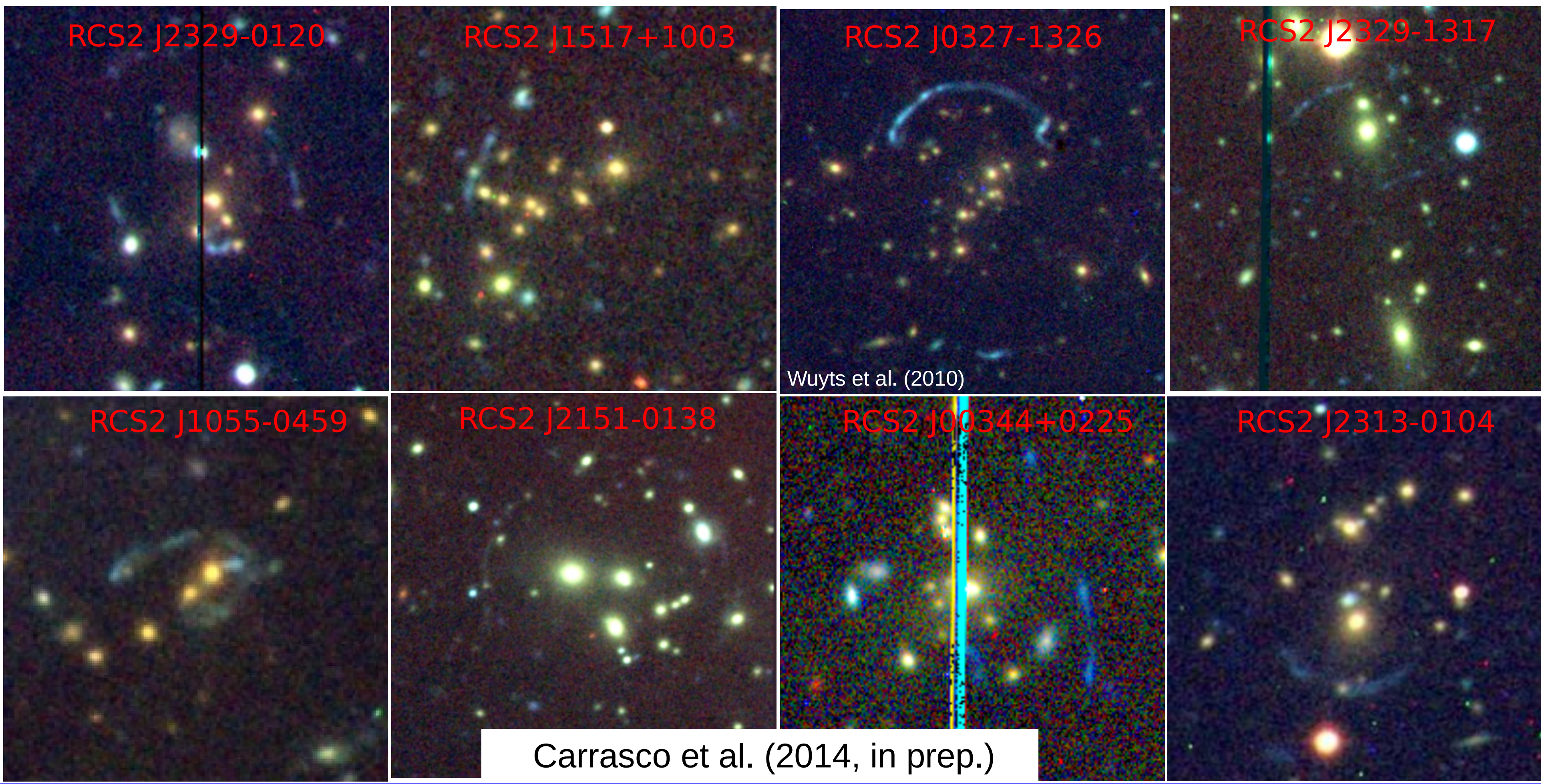


Bhattacharya et al. (2013)

RCSGA sample

RCSGA: 29 SL selected galaxy clusters

- Red-sequence Cluster Survey Giant Arcs → RCSGA survey (Gladders et al in prep)
  → Visual inspection of the Red-sequence Cluster Survey 2 (RCS2)



Carrasco et al. (2014, in prep.)

RCSGA sample

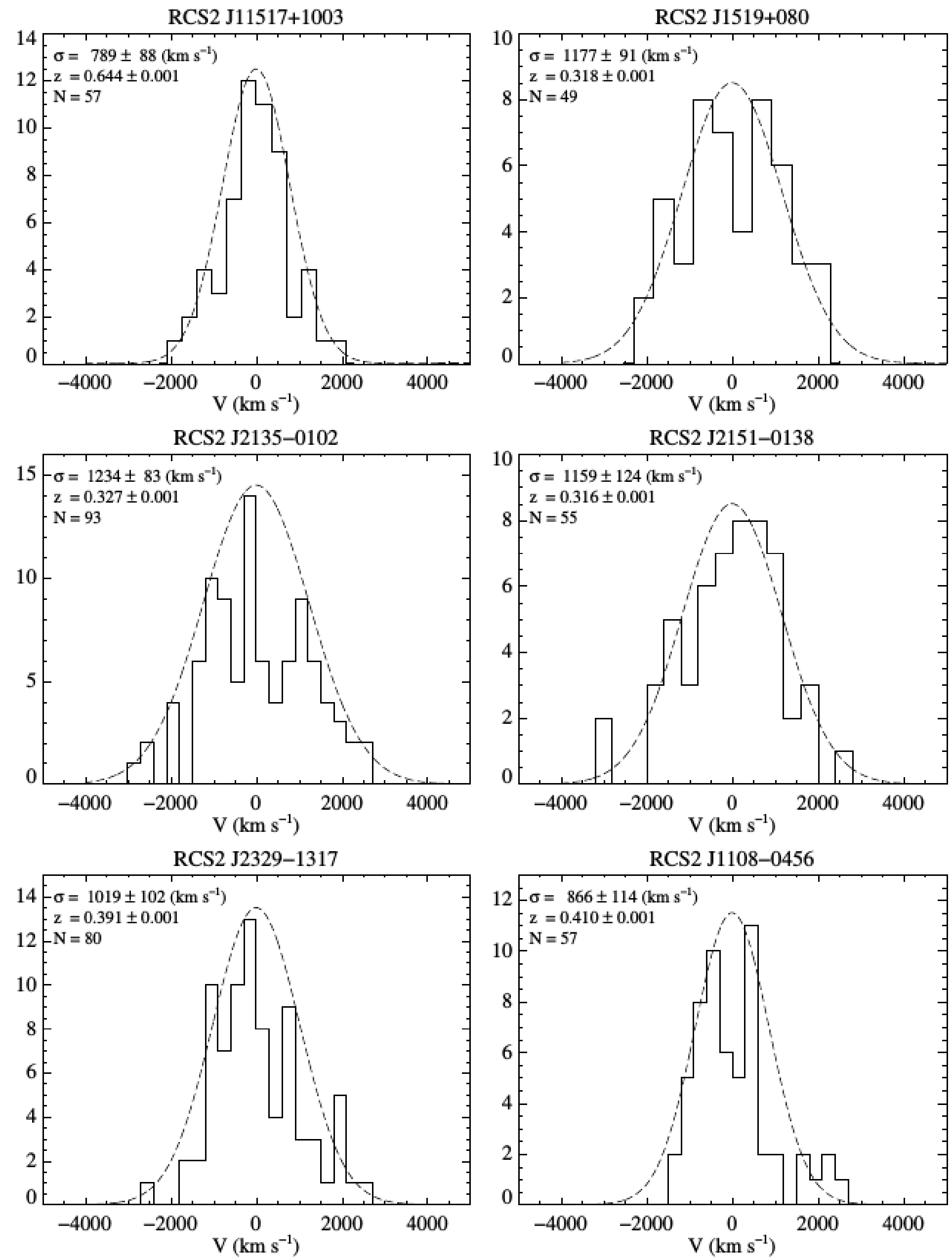
RCSGA: 29 SL selected galaxy clusters

- VLT / Magellan / Gemini spectroscopic data
    - > 2500 spectra
    - ~ 1100 cluster members
    - <N> ~ 38 members per clusters
    - only 5 clusters with N < 20
- Velocity dispersion ⇨ Dynamical mass

Evrard et al. (2008) → $M_{200} = \frac{10^{15}}{h(z)} \left(\frac{\sigma_{DM}}{\sigma_{15}} \right)^{1/\alpha} M_\odot$

$$2.80 \times 10^{13} \leq M_{200}/h^{-1}M_\odot \leq 2.84 \times 10^{15}$$

$$0.22 < z < 1.01$$



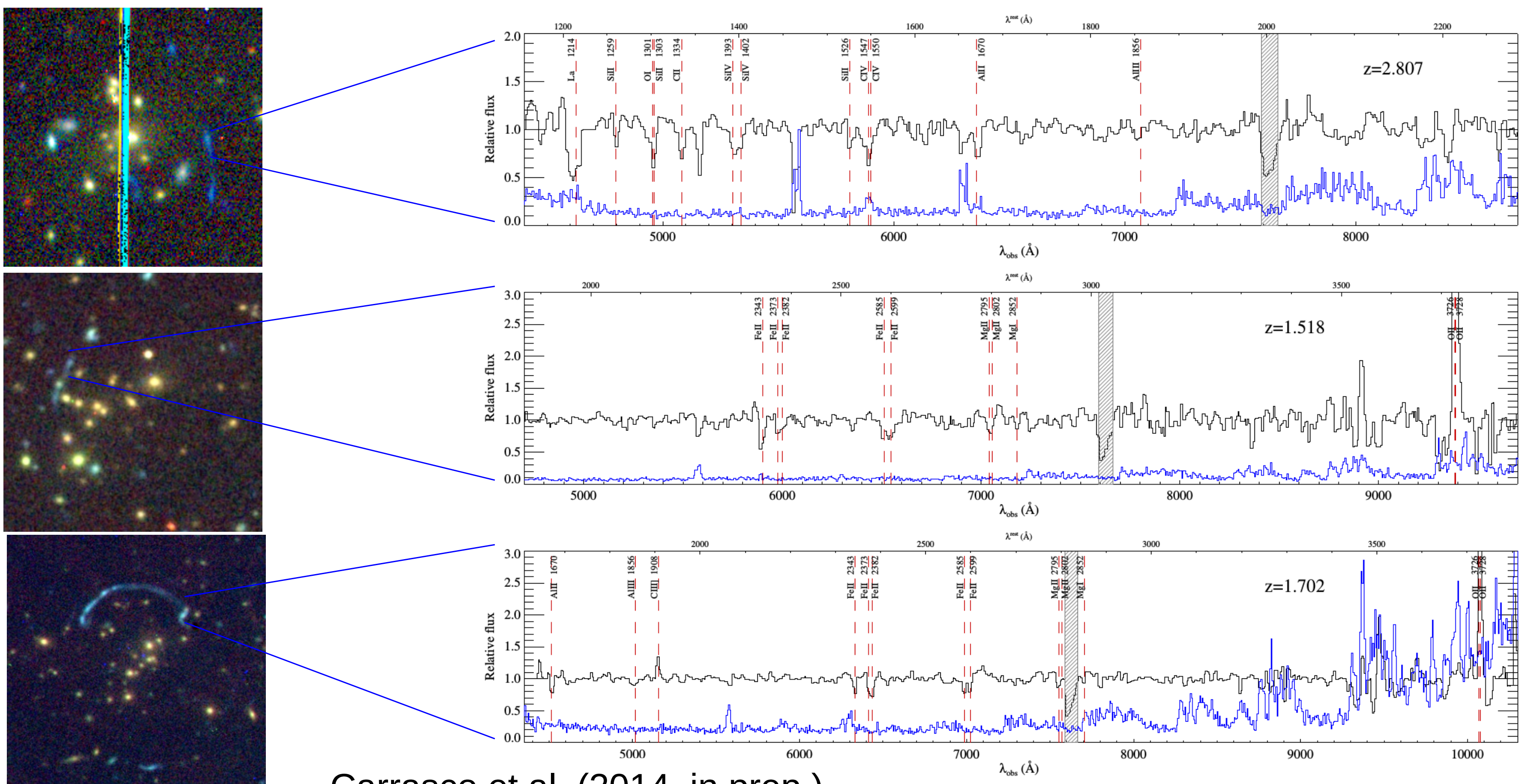
Carrasco et al. (2014, in prep.)

RCSGA sample

RCSGA: 51 lensed galaxies

- VLT / Magellan / Gemini spectroscopic analysis has also confirmed 51 lensed galaxies

  → 34 background sources   0.8 < z < 3.2



Wuyts et al. (2010)

Carrasco et al. (2014, in prep.)

Mass distribution reconstruction

Lenstool: Parametric method – 8 free parameters (Jullo et al. 2007)

- Main halos → eNFW profile

$$\rho(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2} \qquad c_{200} := \frac{r_{200}}{r_s}$$

$$c_{200}, \; r_s, \; (\text{R.A., Dec.}), \; e_\Sigma, \; \theta_e$$

6 free parameters

- Galaxy halos → PIEMD profile

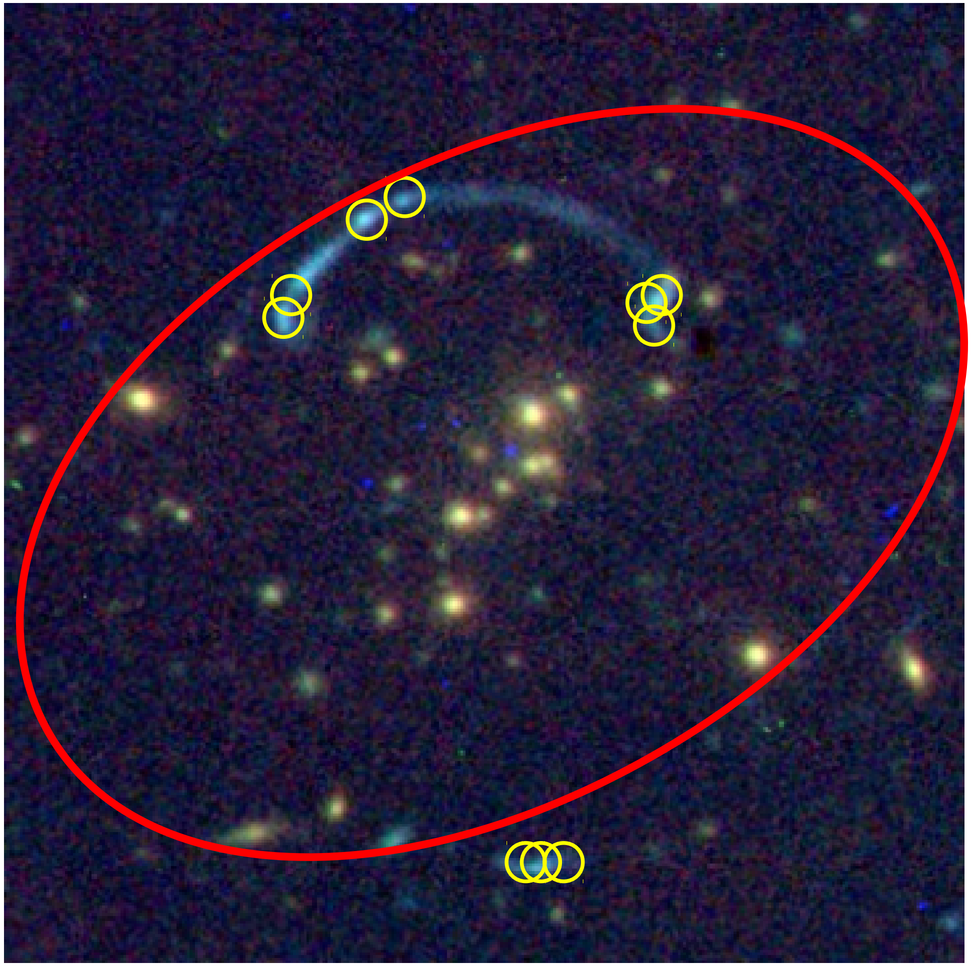
$$\rho(r) = \frac{\rho_0}{(1+r^2/r_{core}^2)(1+r^2/r_{cut}^2)}$$

$$\sigma_0^\star, \quad r_{cut}^\star, \; r_{core}^\star$$

$r_{core}^\star \Rightarrow 0.15 - 0.30$ kpc

2 free parameters

RCS2 J0327-1326



Wuyts et al. (2010), Sharon et al. (2012)

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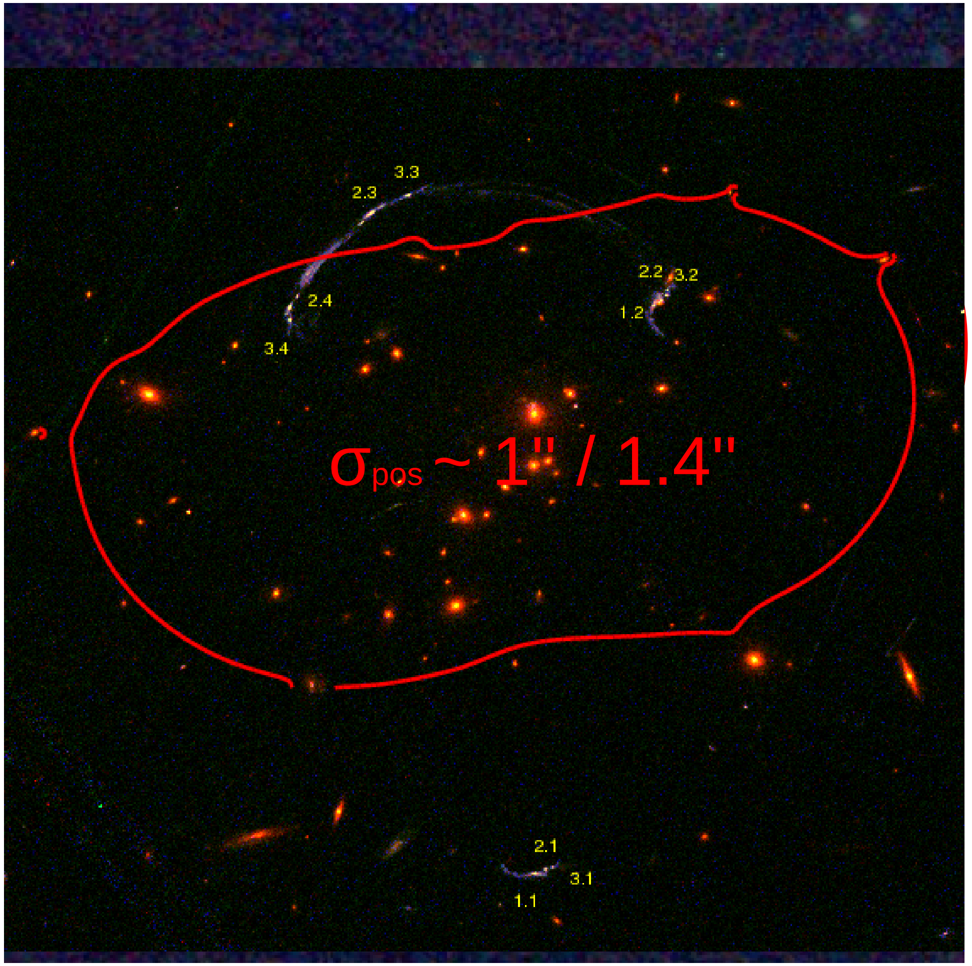


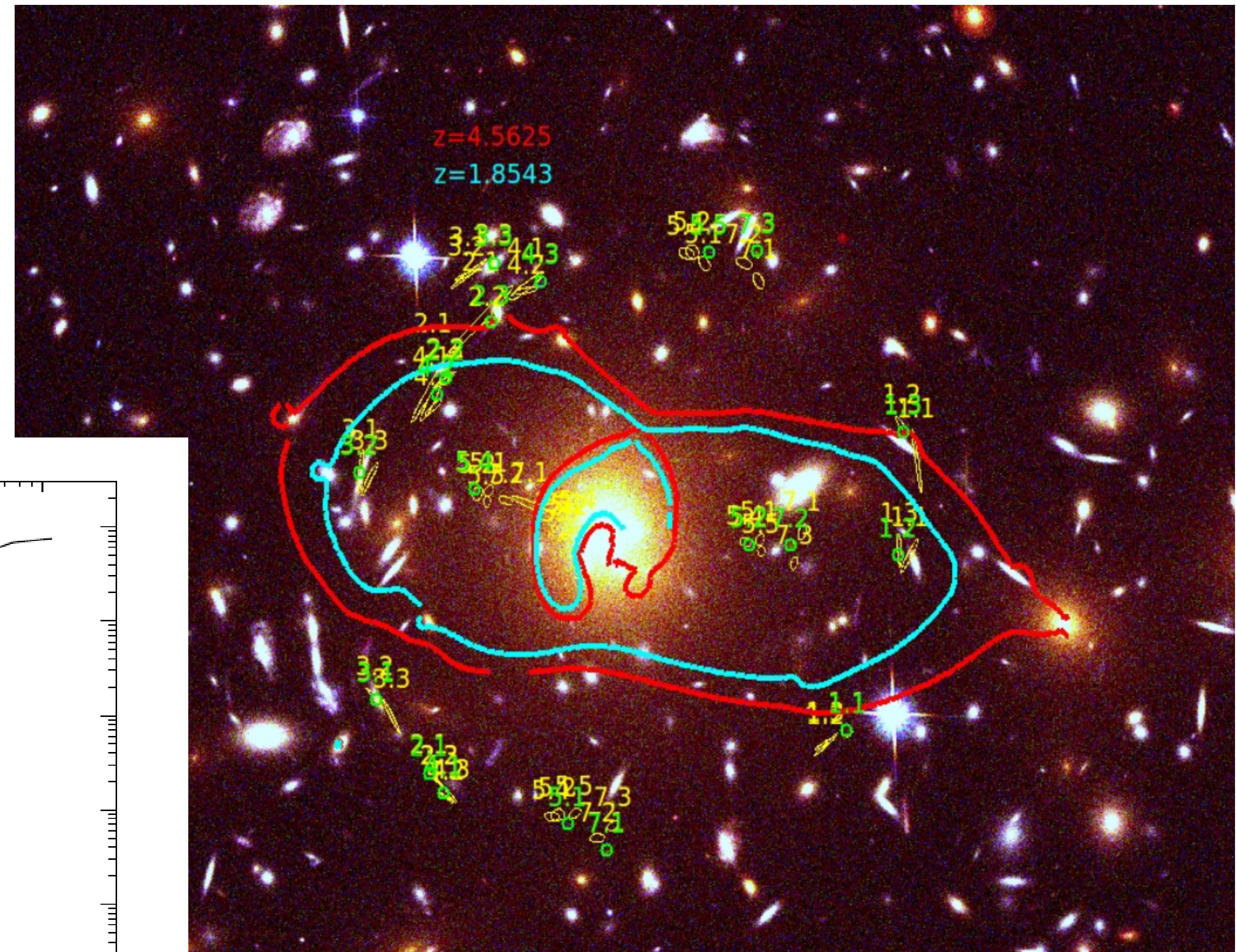
Wuyts et al. (2010), Sharon et al. (2012)

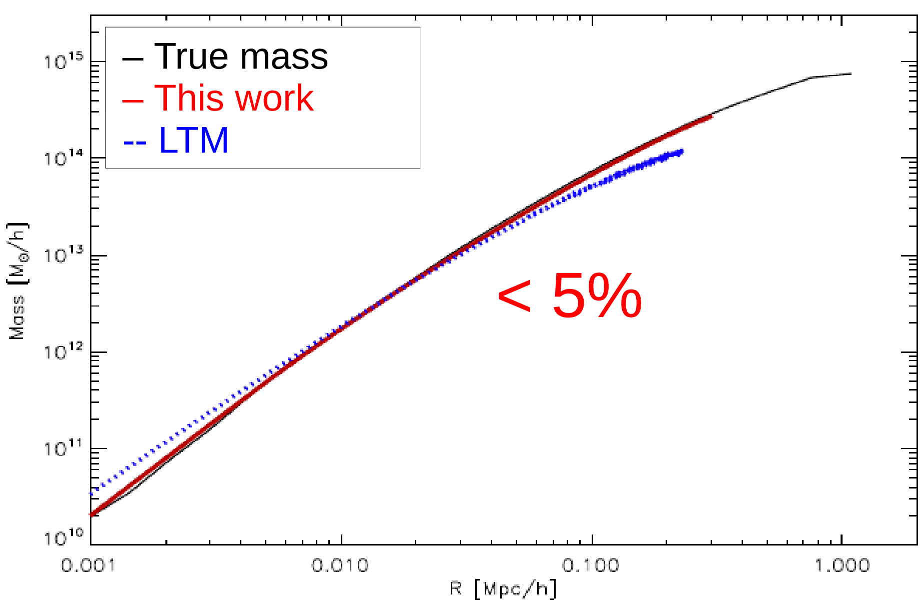
Mass distribution reconstruction

Lenstool: Parametric method – 8 free parameters (Jullo et al. 2007)

G1 proyection XZ

- Massimo's simulated clusters
  - MOKA + SkyLens (Giocoli et al. 2010)
  - Σ ~ 1'' / 1.4''

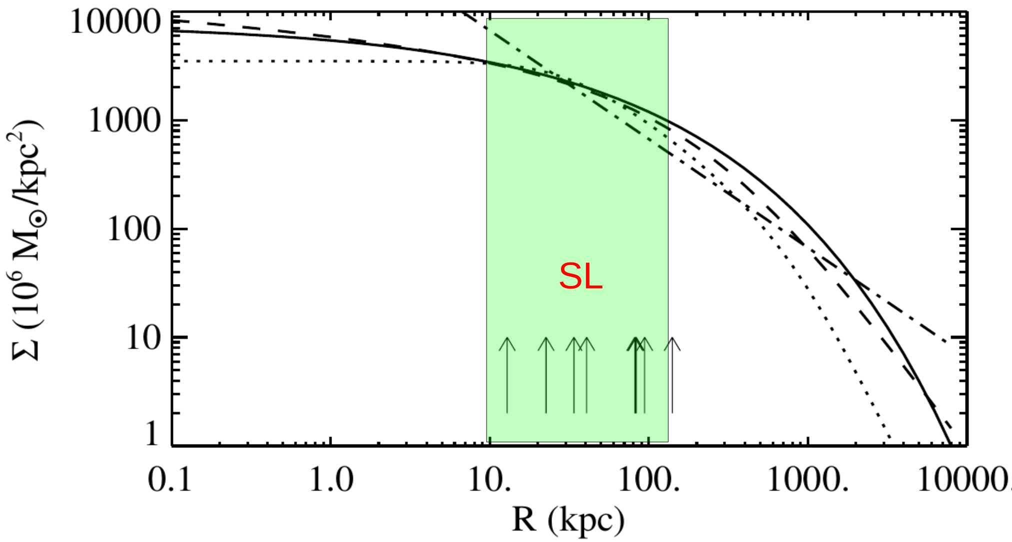


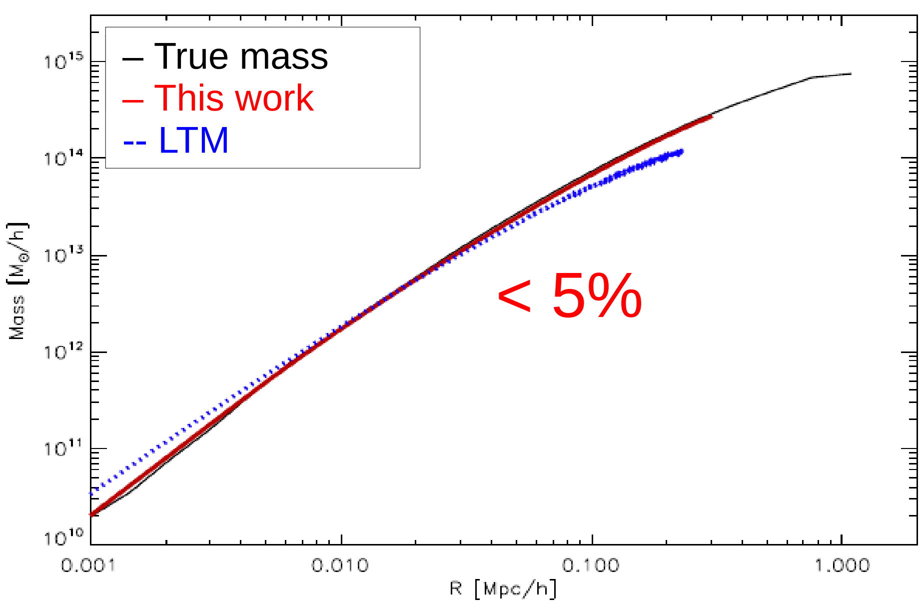


Mass distribution reconstruction

Lenstool: Parametric method – 8 free parameters

(Jullo et al. 2007)





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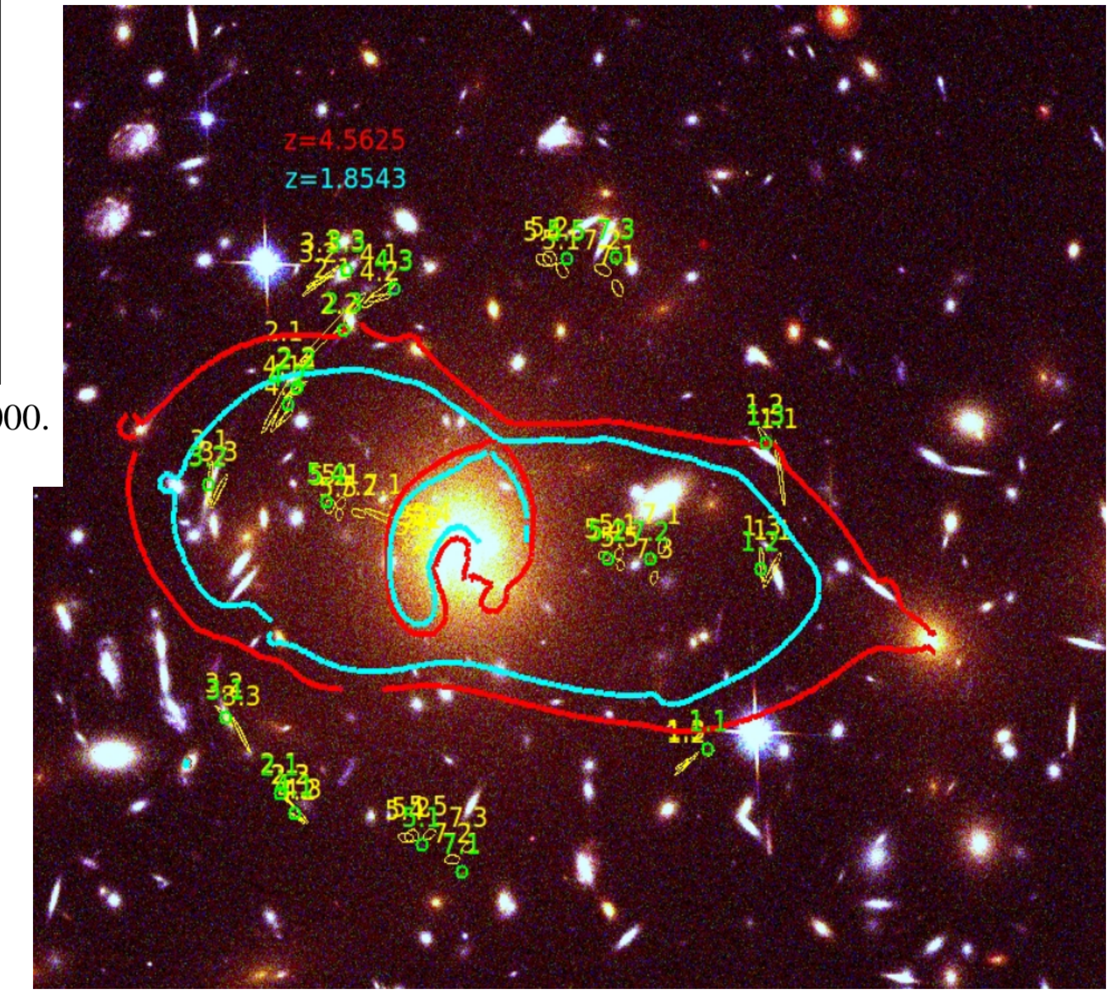
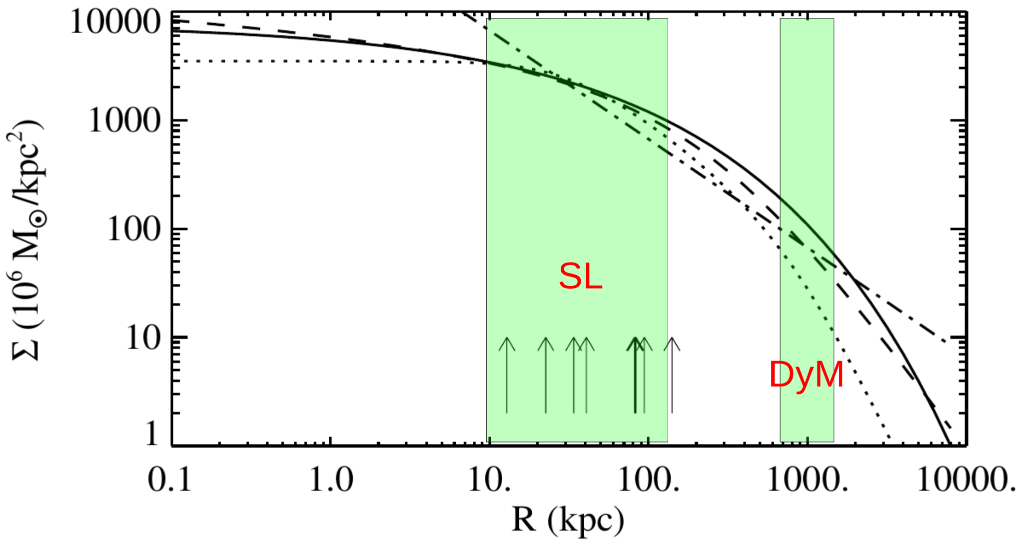
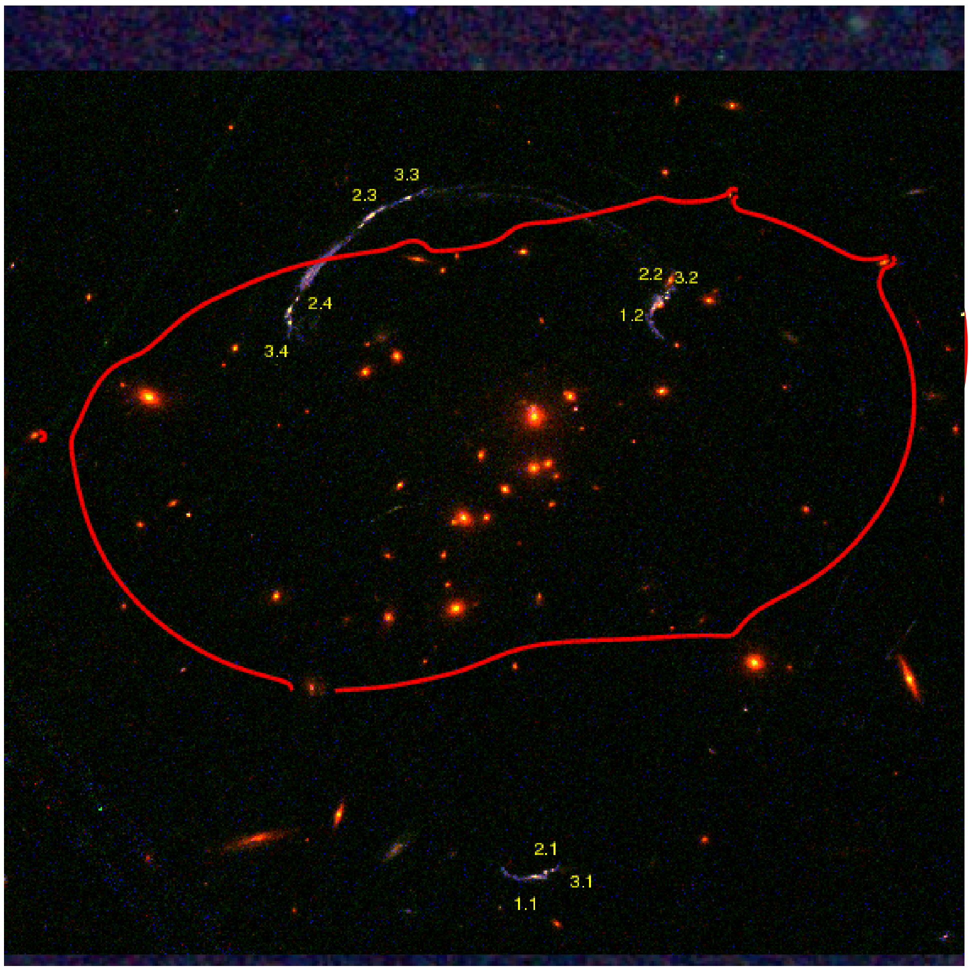


Mass distribution reconstruction

Lenstool: Parametric method – SL and Dyn constraints



RCS2 J0327-1326



Wuyts et al. (2010), Sharon et al. (2012)

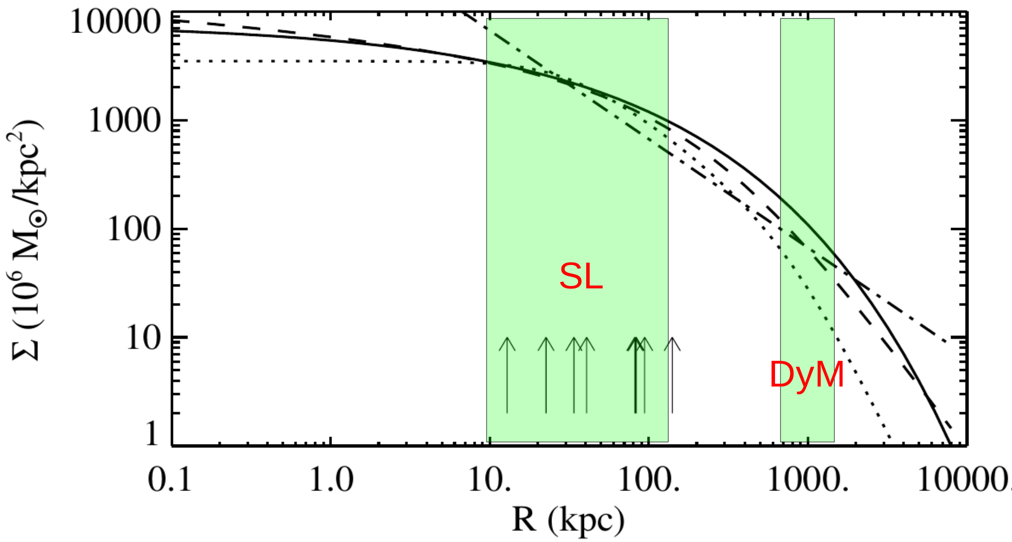
- Dynamical mass (Dyn) constraints

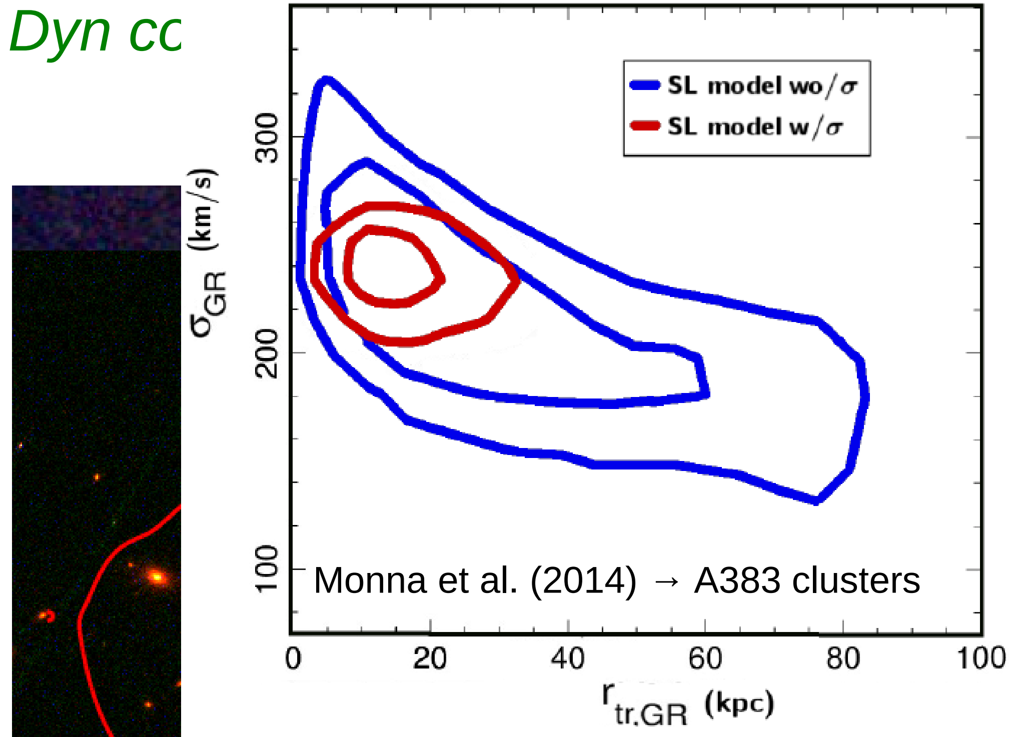
$$\chi^2_{mass}(M^{obs}_{200}, c_{200}, r_s) = \left(\frac{M^{obs}_{200} - M^{pred}_{200}(c_{200}, r_s)}{\Delta M} \right)^2$$

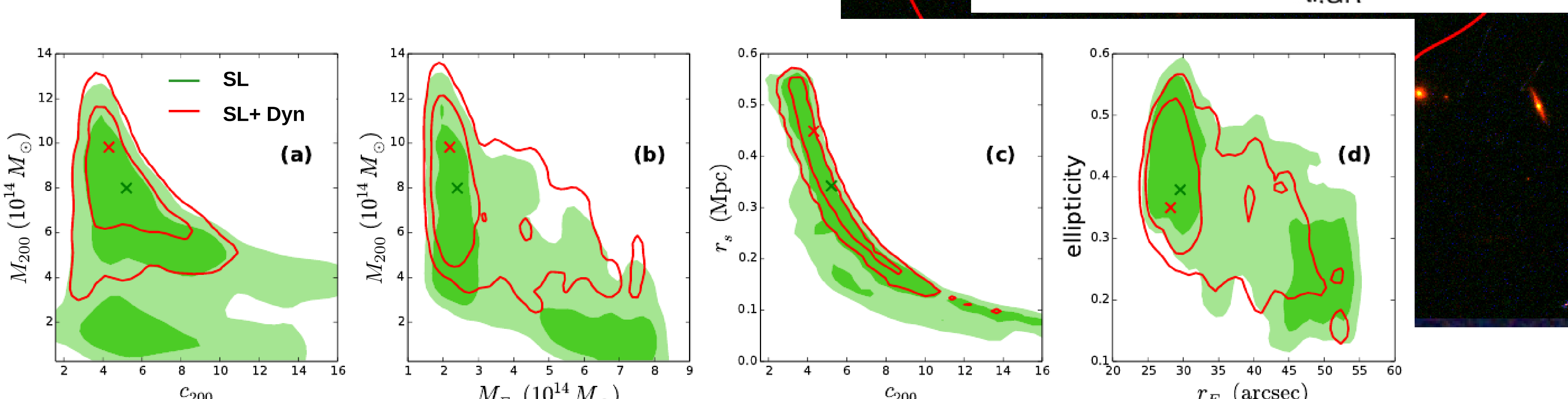
$$\chi^2_{tot} = \chi^2_{SL} + \chi^2_{mass}$$

Mass distribution reconstruction

Lenstool: Parametric method – SL and Dyn cc





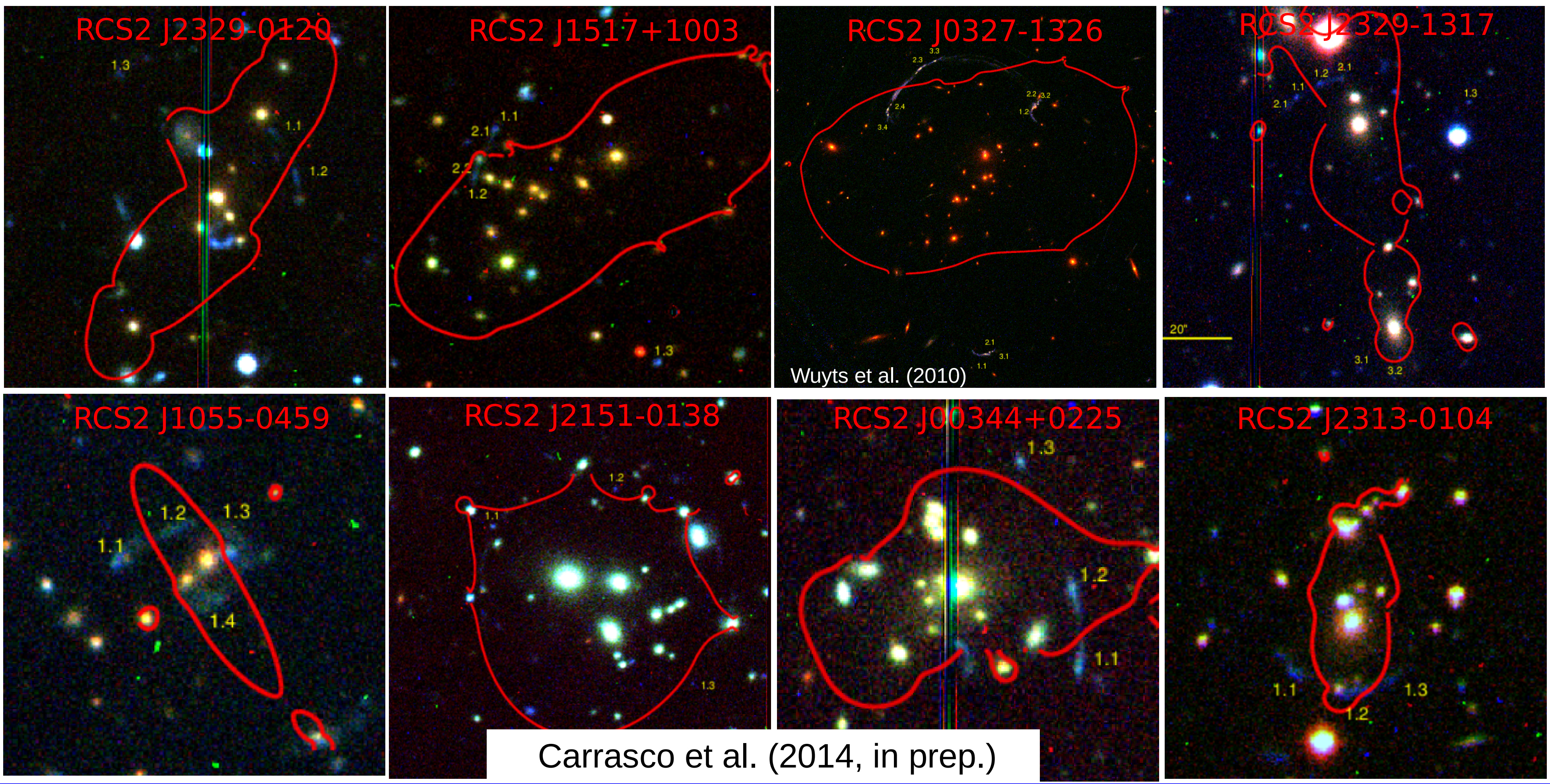


Sifon et al. (2013) → PLCK G004.5 – 19.5 clusters

Mass distribution reconstruction

Lenstool: Parametric method – SL and Dyn constraints

- 29 SL & DyM mass reconstructions



Carrasco et al. (2014, in prep.)

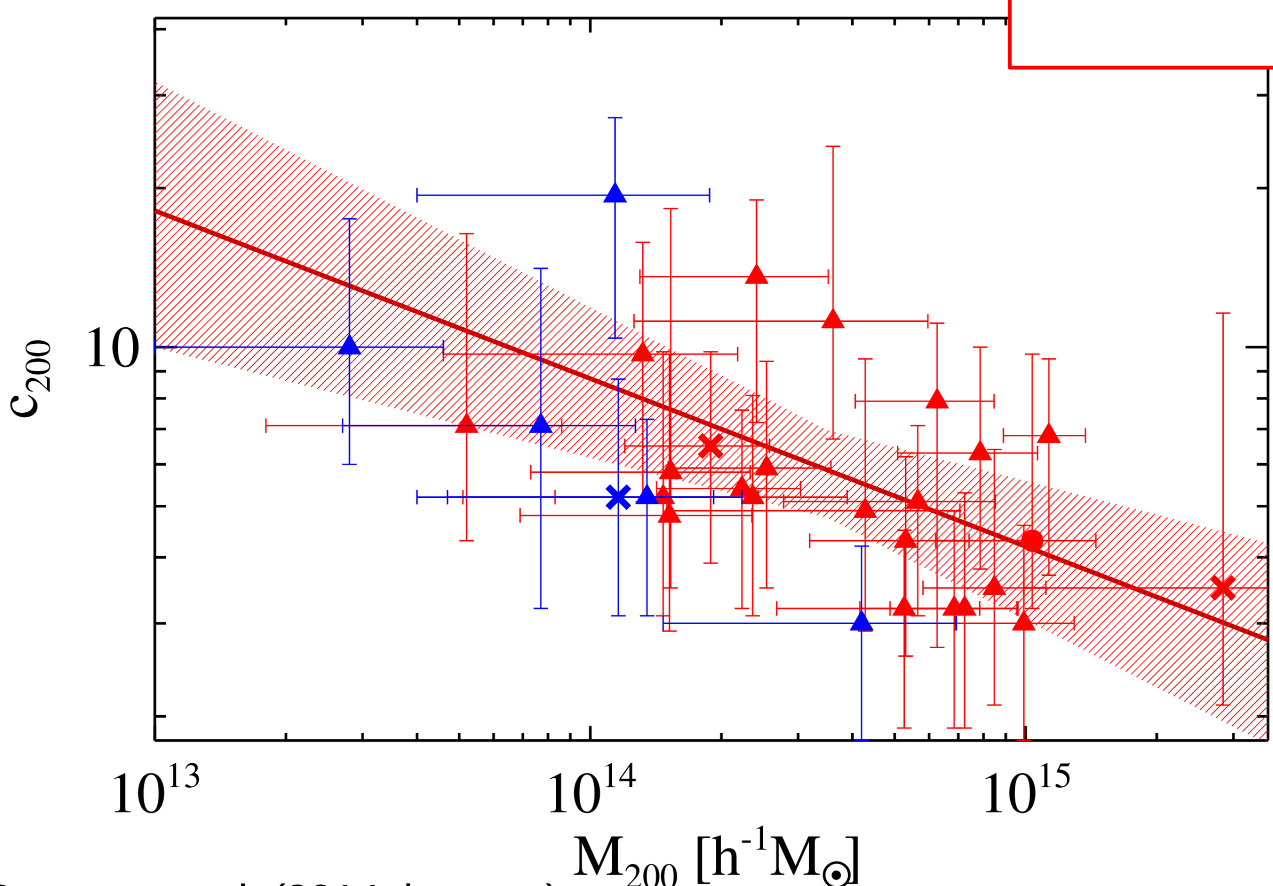
Concentration – mass relation

c – M relation for 27 RCSGA clusters

- 26 clusters from RCSGA survey + 1 from Sifón et al. (2014)

27 SL selected galaxy clusters

$$c_{200} = (5.80 \pm 1.08) \times \left(\frac{M_{200}}{3.61 \times 10^{14}\, h^{-1} M_{\odot}} \right)^{-0.32 \pm 0.11}$$



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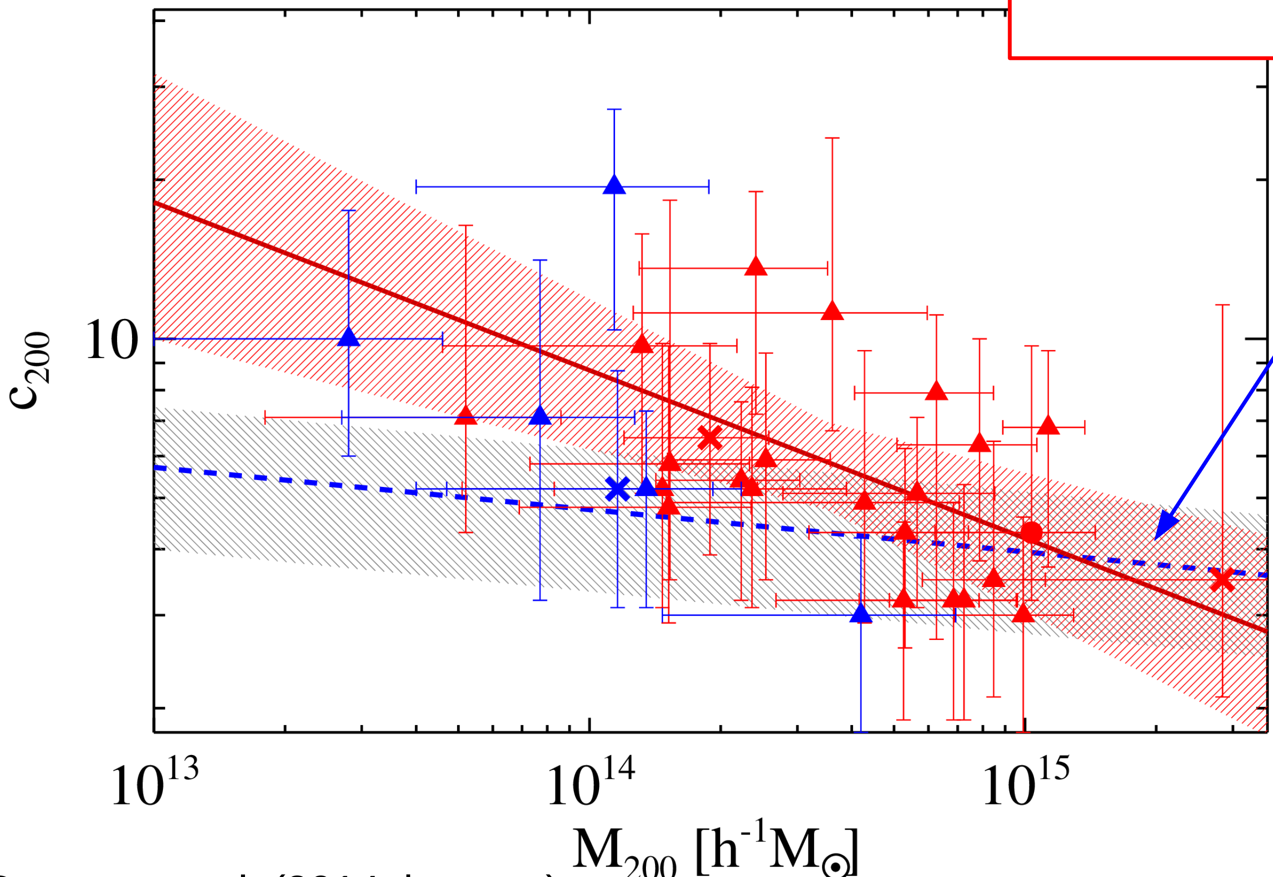


Carrasco et al. (2014, in prep.)

Battacharya et al. (2013)

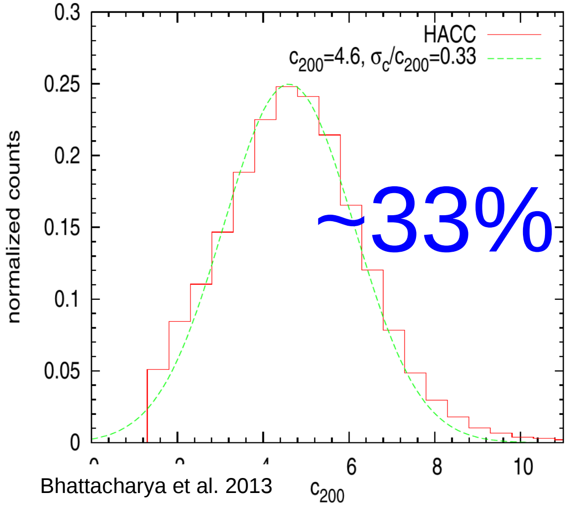
→ Normal population at z = 0

$M_{200} \sim 8 \times 10^{14} h^{-1} M_{\odot}$

⇨ $C_{200} \sim 4.3$ ~ 11%

Concentration – mass relation

c – M relation for 27 RCSGA clusters



GA survey + 1 from Sifón et al. (2014)

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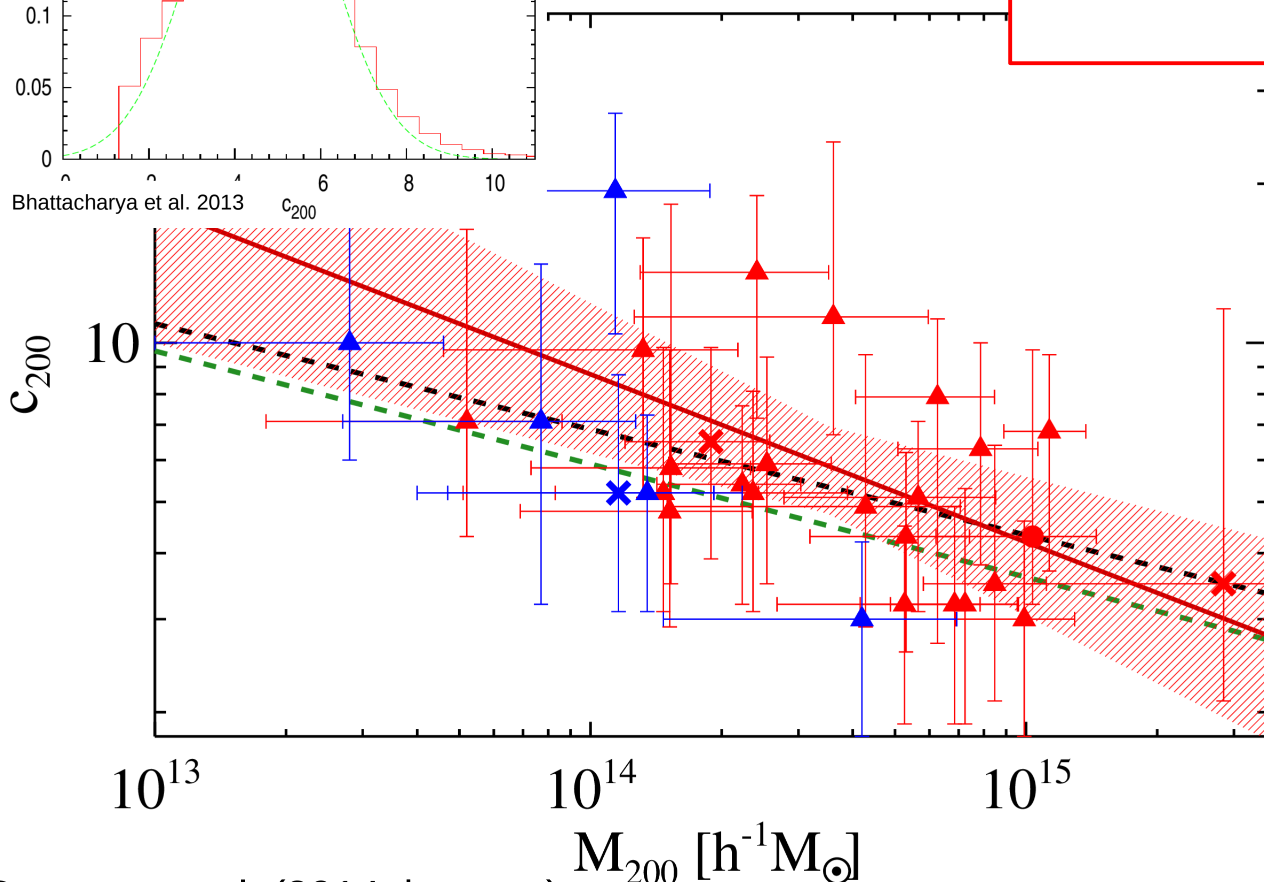


Carrasco et al. (2014, in prep.)

- - - - Oguri et al. (2012)

- - - - Meneghetti et al. (2014)

→ SL population z = 0.45

$M_{200} \sim 8 \times 10^{14} h^{-1} M_{\odot}$

⇨ C_{200} ~ 4.3 ~ 10%

$M_{200} \sim 1 \times 10^{14} h^{-1} M_{\odot}$

⇨ C_{200} ~ 8.7 ~ 38%

Concentration – mass relation of 73 galaxy clusters

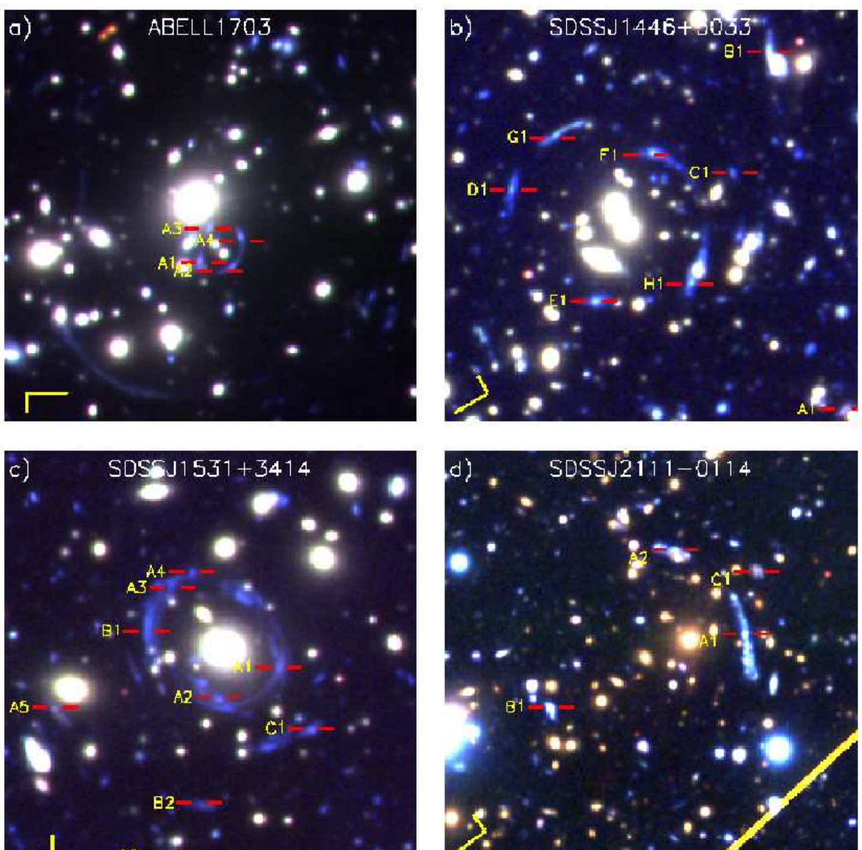
The largest robust dataset of concentration parameters

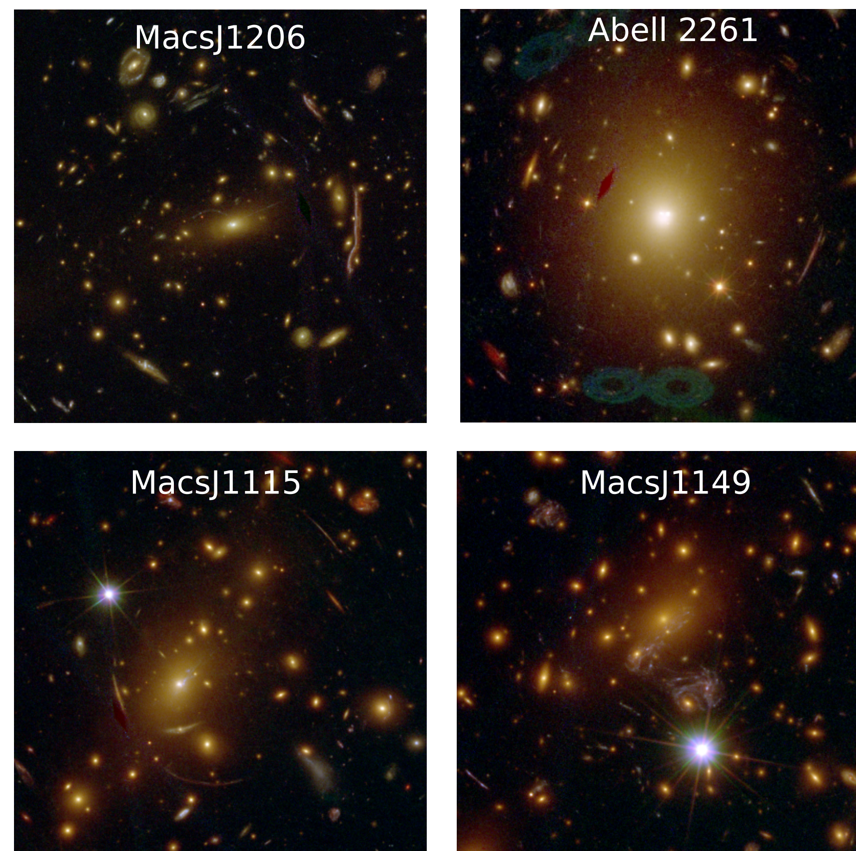
- SGAS survey (Oguri et al. 2012)
  - SDSS
  - SL selected

  27 clusters

- CLASH survey (Merten et al. 2014)
  - HST
  - X-ray selected

  19 clusters



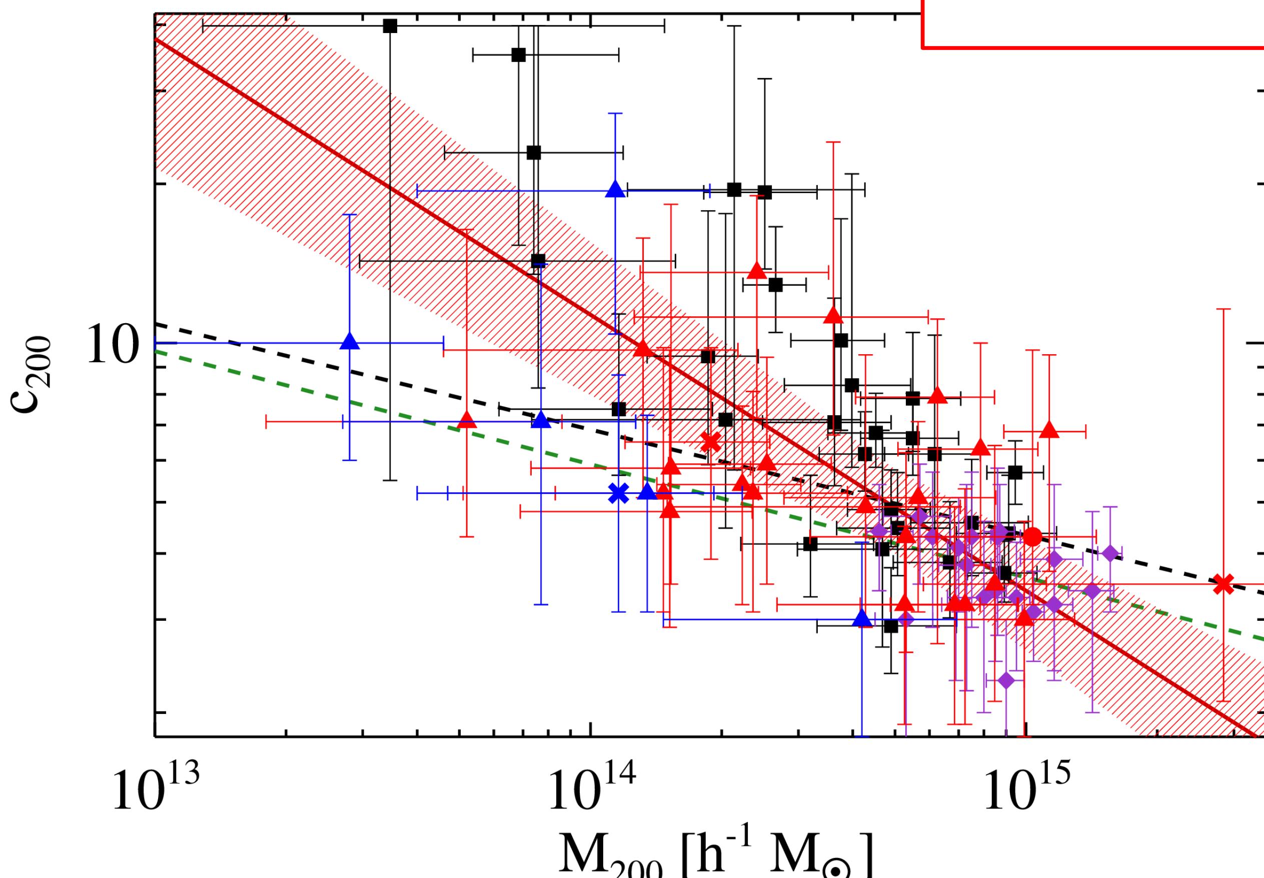


Concentration – mass relation of 73 galaxy clusters

The largest robust dataset of concentration parameters

▲▲ This work
■ 27 SL selected clusters from Oguri et al. (2012)
◆ 19 X-ray selected clusters from Merten et al. (2014)

$$c_{200} = (4.75 \pm 0.84) \times \left(\frac{M_{200}}{5.26 \times 10^{14}\ h^{-1} M_{\odot}} \right)^{-0.52 \pm 0.09}$$



- - - - Oguri et al. (2012)

- - - - Meneghetti et al. (2014)

→ SL population z = 0.45

$M_{200} \sim 8 \times 10^{14} h^{-1} M_{\odot}$

⇨ *$c_{200} \sim 3.9$* ~ 6%

$M_{200} \sim 1 \times 10^{14} h^{-1} M_{\odot}$

⇨ *$c_{200} \sim 11$* ~ 78%

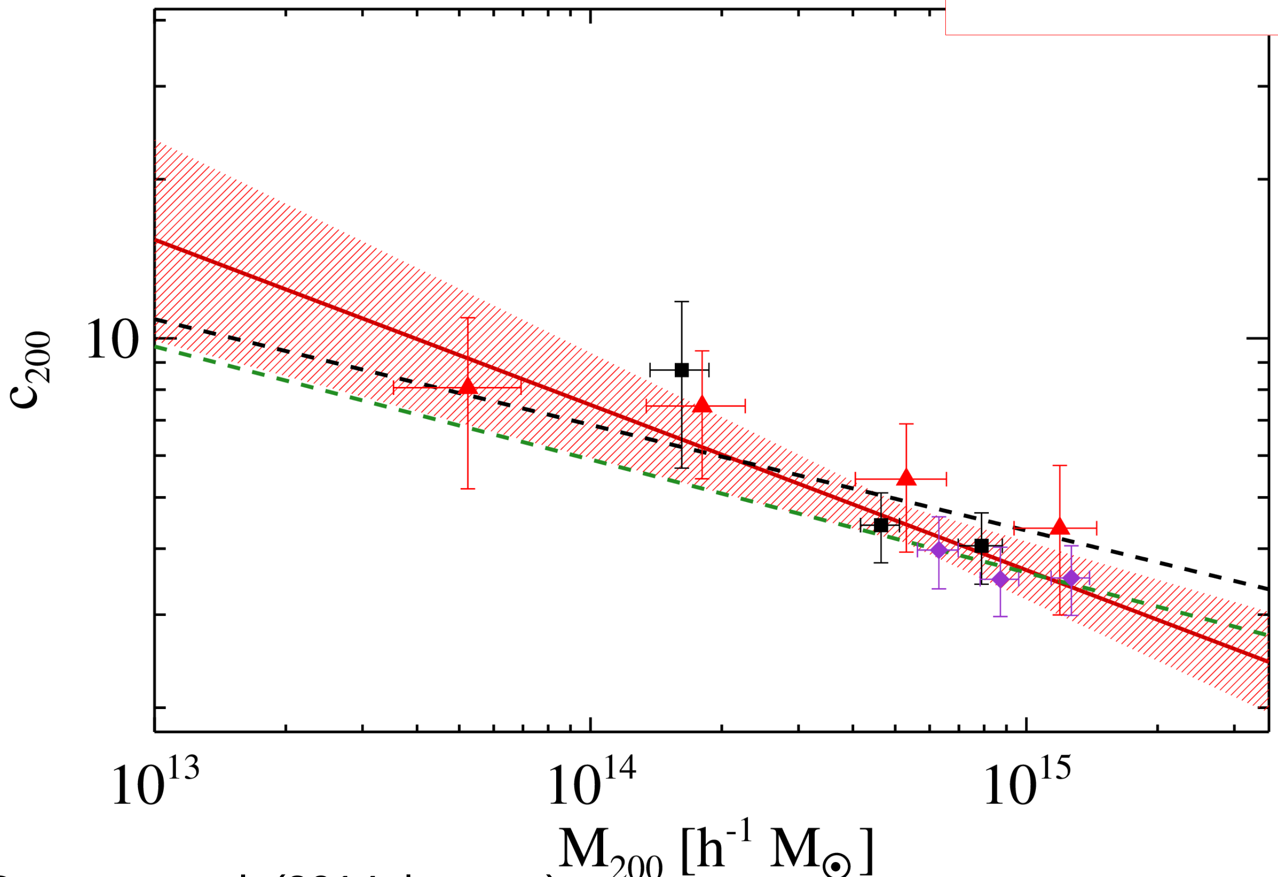
Carrasco et al. (2014, in prep.)

Concentration – mass relation

Stacking analysis

▲ This work
■ 27 SL selected clusters from Oguri et al. (2012)
◆ 19 X-ray selected clusters from Merten et al. (2014)

$$c_{200} = (4.21 \pm 0.26) \times \left(\frac{M_{200}}{6.30 \times 10^{14}\ h^{-1} M_{\odot}} \right)^{-0.31 \pm 0.09}$$



Oguri et al. (2012)
Meneghetti et al. (2014)

→ SL population z = 0.45

$M_{200} \sim 8 \times 10^{14} h^{-1} M_{\odot}$

⇨ $c_{200} \sim 3.9$ **~ 6%**

$M_{200} \sim 1 \times 10^{14} h^{-1} M_{\odot}$

⇨ $c_{200} \sim 7.5$ **~ 17%**

Carrasco et al. (2014, in prep.)

Concentration – mass relation of 73 galaxy clusters

The largest robust dataset of concentration parameters

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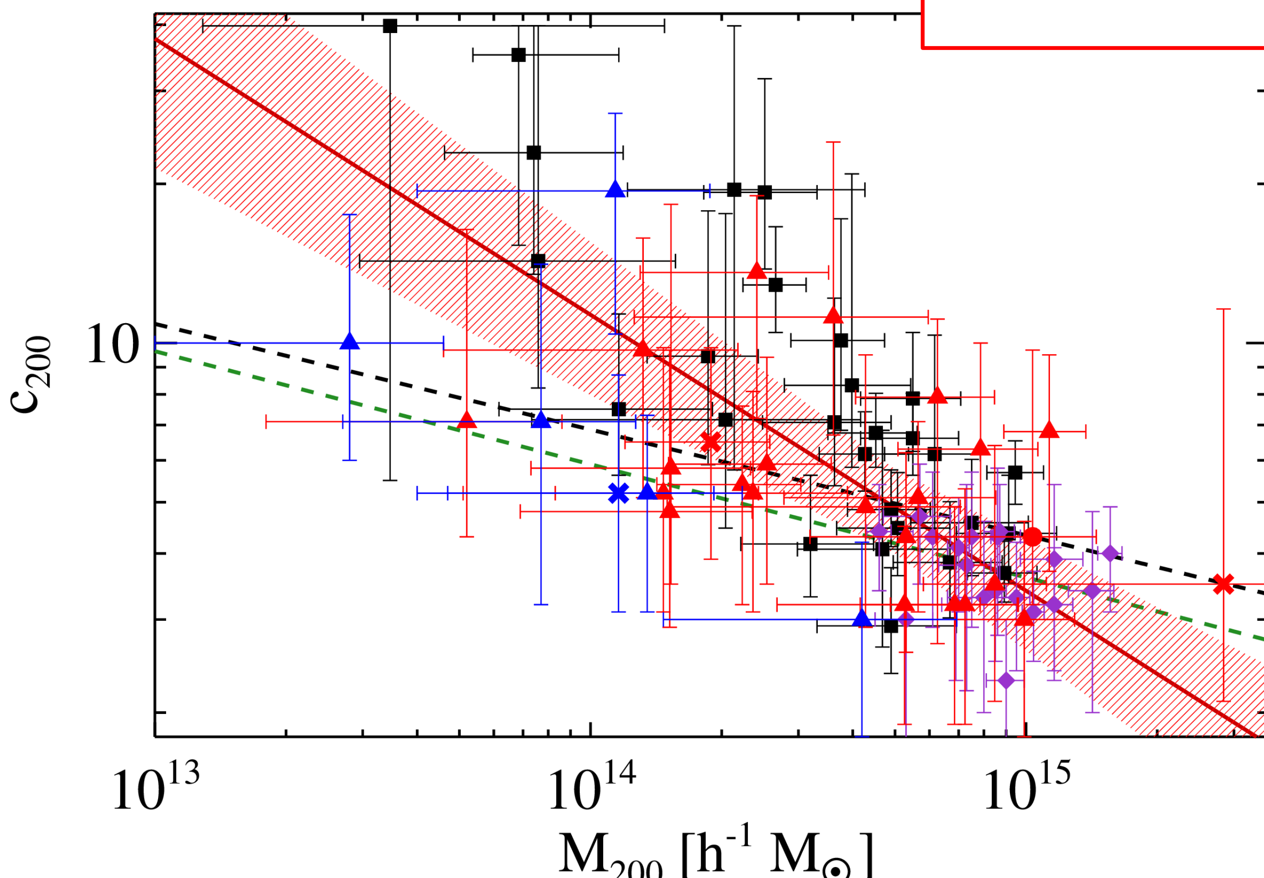

Carrasco et al. (2014, in prep.)

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⇨ *c_{200} ~ 3.9* ~ 6%

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⇨ *c_{200} ~ 11* ~ 78%

Concentration – mass relation of 73 galaxy clusters

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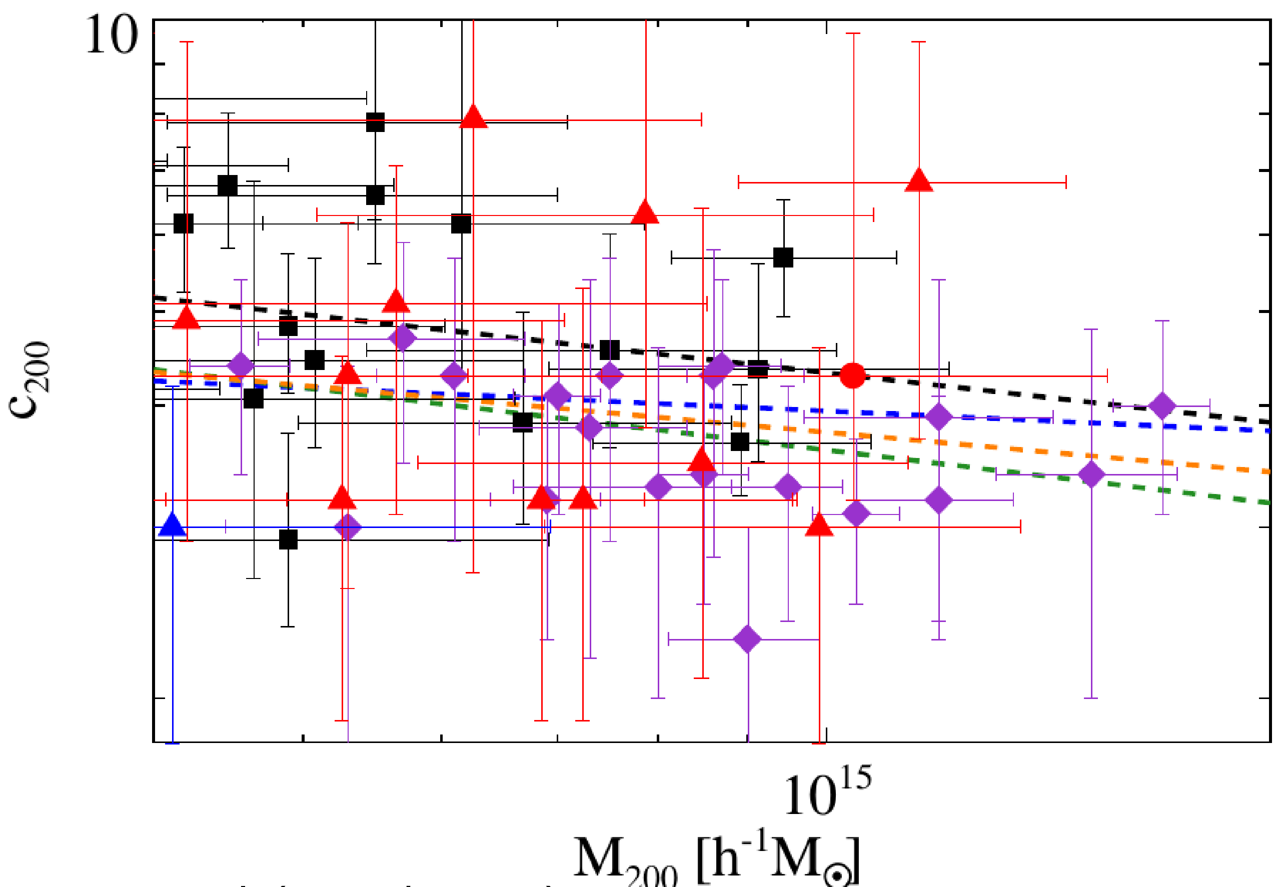


- - - - Bhattacharya et al. (2013)
- - - - Oguri et al. (2012)-SL
- - - - Meneghetti et al. (2014)-SL
- - - - Meneghetti et al. (2014)-X-ray

→ SL population z = 0.45

$$M_{200} \sim 8 \times 10^{14} h^{-1} M_\odot$$

⇨ *C_{200} ~ 3.9* ~ 6%

Carrasco et al. (2014, in prep.)

Mass distribution reconstruction

New non-parametric method

Merten et al. (2009)

$$\chi^2_{\rm total} = \chi^2_{\rm weak} + \chi^2_{\rm strong} + \chi^2_{\rm reg} + \ldots$$
$$+\chi^2_{\rm X-ray} + \chi^2_{\rm tSZ} + \chi^2_{\rm kinematics} + \chi^2_{\rm ext.\ mult.\ im.}$$

Huber et al. (2014, in prep)

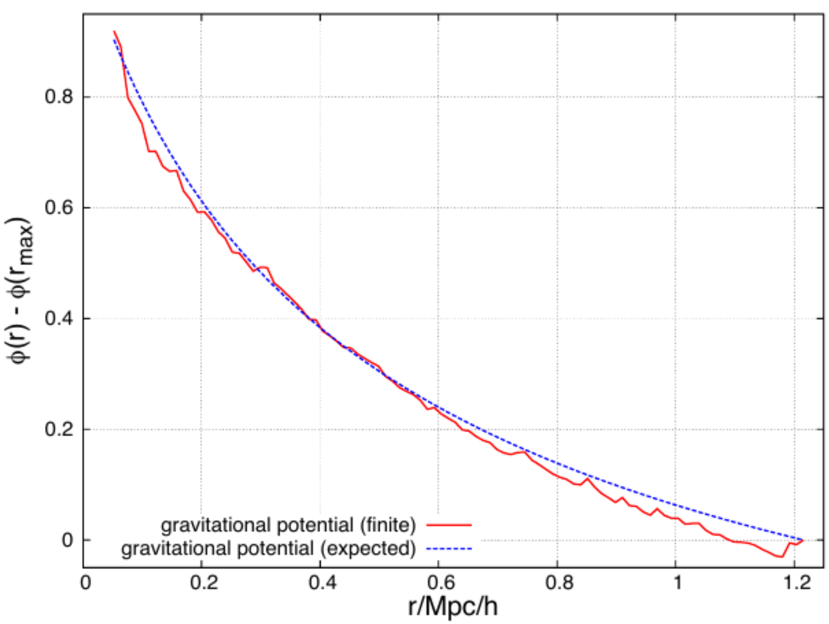
Konrad et al. (2013)

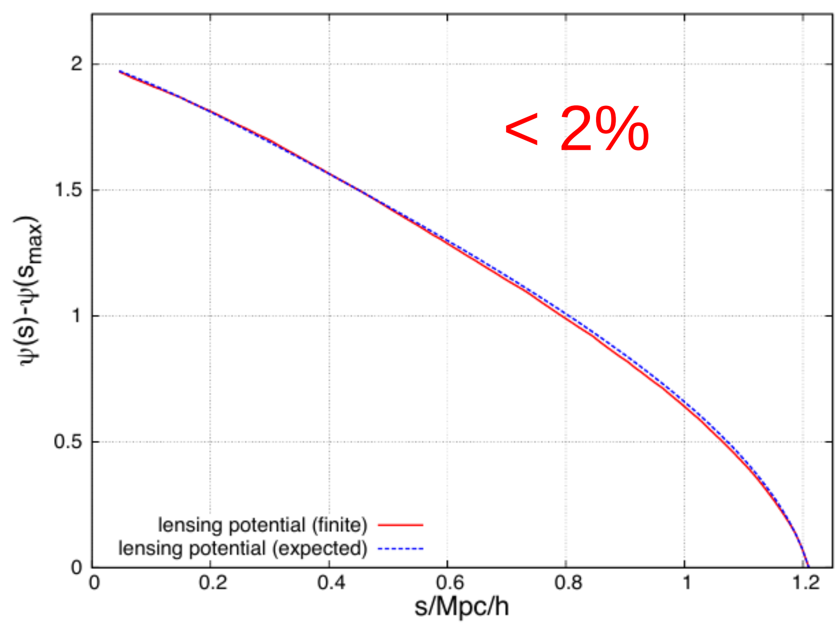
Majer et al. (2014)

Sarli et al. (2014)

Deprojections
→ Richardson-Lucy algorithm

$$\chi^2_\nu = \left(\mathbf{d}_\nu - \mathcal{O}_\nu \psi\right)^{\rm T} \mathcal{C}_\nu^{-1} \left(\mathbf{d}_\nu - \mathcal{O}_\nu \psi\right)$$





Conclusions

- We are lucky... there's a lot of work to do.