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Weak lensing cluster masses in the LSST DESC simulations

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Cosmology with galaxy cluster abundance

Galaxy clusters:

- Are the largest gravitationally bound objects in the Universe
- Mass > 10^{14} solar masses
- Richness λ: linked to the number of galaxies within a cluster
- LSST : Rubin observatory will detect $o(10^5)$ galaxy clusters

Cosmology with galaxy clusters

- Cluster abundance : Count the number of clusters in redshift & richness intervals.
- Cluster abundance is a useful probe for cosmology.

In a redshift and richness bin, the expected cluster abundance is given

$$N = \Omega_s \int_{z_\alpha}^{z_\beta} dz \frac{d^2V(z)}{dz d\Omega} \int_{\lambda_{\alpha'}}^{\lambda_{\beta'}} d\ln\lambda \int_{M_{\min}}^{M_{\max}} dm \frac{dn(m,z)}{dm} \boxed{P(\ln\lambda \,|\, m, z)}$$

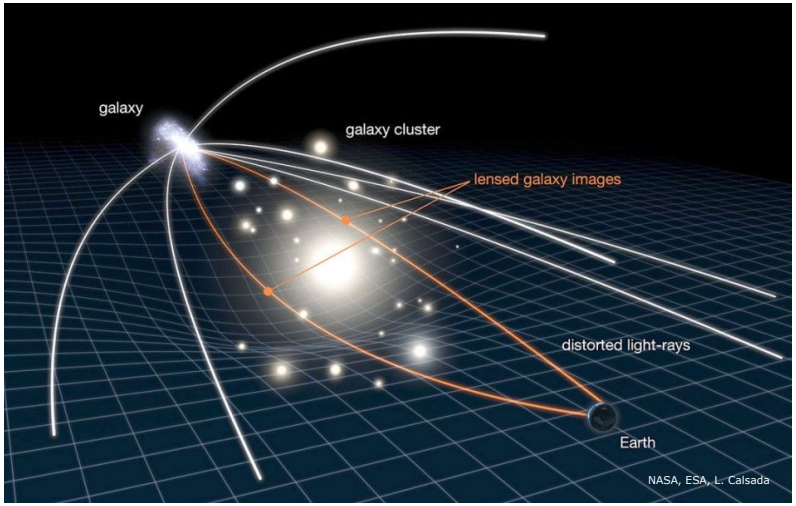
differential comoving volume (cosmology)

Halo mass function (cosmology + large scale structure formation)

Mass-richness relation

Weak lensing is a powerful tool to constrain galaxy cluster masses.

Weak gravitational lensing



- Gravitational lensing modifies the observed background galaxy shapes.
- Distortion is sensitive to the excess surface mass density around the cluster $\Delta\Sigma$.
- Taking the average observed ellipticities of galaxies at a distance R:

$$\widehat{\Delta\Sigma}(R) = \langle \Sigma_{\rm crit}(z_s, z_l)\ e_{+,s} \rangle |_R$$

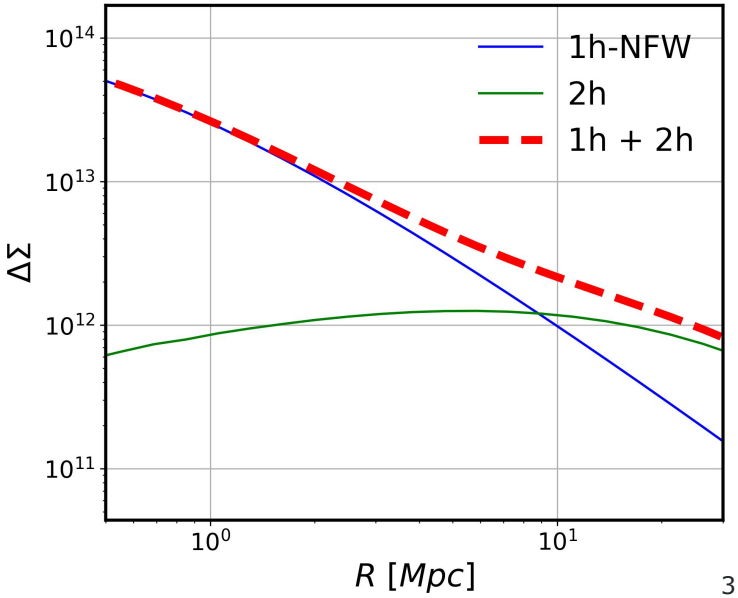
Tangential ellipticity

- The predicted shear signal is given by the sum of two contributions;

$$\Delta\Sigma(R) = \Delta\Sigma_{\rm single}(R) + \Delta\Sigma_{\rm 2h}(R)$$

1h-term: depends on the single halo mass (< 5 Mpc)

2h-term: contribution from neighboring halos (power spectrum, halo bias)



Stacked shear estimation

- Stacked shear signal :
  - measurement of the shear for an ensemble of cluster within a redshift and richness bin

$$\widehat{\Delta\Sigma}(R) = \frac{1}{\sum_{l=1} W_l} \sum_{l=1} W_l \, \widehat{\Delta\Sigma}_l(R)$$

W_l = include effect of shape measurement and photometric redshift errors of background galaxies

Weak lensing mass estimation

1. Modelling the excess surface density :
   a. 1-halo term NFW : depends on the mass and concentration, use of concentration-mass (c-M) relation for the fit of the single mass (Diemer, Krastov, 2015)
   b. 1-halo + 2-halo term (halo bias : Thinker, 2010)

4 modelling choices

	1h	1h + 2h
c-M	1 < R < 5 Mpc	1 < R < 10 Mpc
Free c	1 < R < 5 Mpc	1 < R < 10 Mpc

Radial range involved

2. Likelihood for mass estimation :
   a. Errors on $\Delta\Sigma$ estimated by bootstrap resampling

$$\ln L(\theta) \propto -\sum_{i=1} \left(\frac{\widehat{\Delta\Sigma}(R_i) - \Delta\Sigma_{\rm th}(R_i)}{\sigma_{\widehat{\Delta\Sigma}}(R_i)} \right)^2$$

The Data Challenge 2 of LSST DESC

- DC2 : based on N-body dark matter simulation (440 deg^2, volume $(4.2\ Gpc)^3$, $z_{max} = 3$)
- Semi-analytical galaxy modelling to produce galaxy catalog

For weak lensing, we need source and lens catalogs

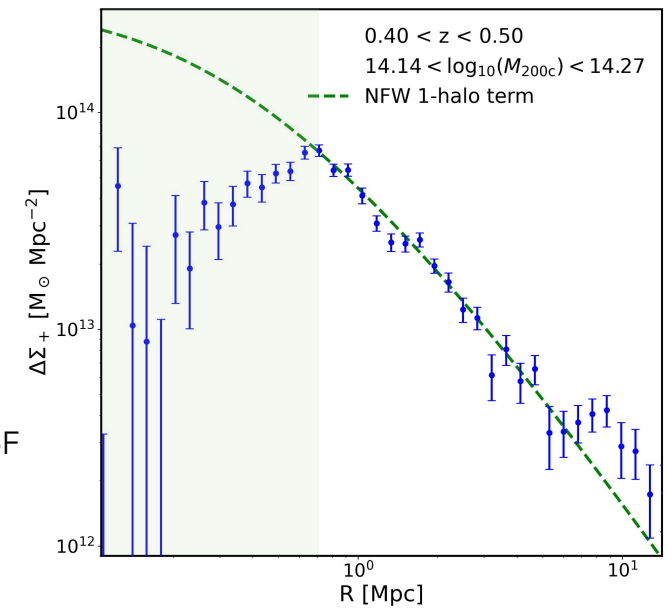
Galaxy catalog

cosmoDC2: known properties of galaxies.

- known redshifts, shear from ray-tracing, magnitudes, intrinsic ellipticities, etc.
- Small scales : non-physical attenuation of the shear signal

Lens catalogs

1. Output of cosmoDC2 : catalog of dark matter halos identified by FoF halo finder, with halo properties (mass, triaxiality, etc.)
2. redMaPPer galaxy cluster catalog:
   - Detection of overdensities of red sequence galaxies
   - Richness cut > 20
   - $0.2 < z_{cluster} < 1.2$



Attenuation due to the ray-tracing resolution

Workflow

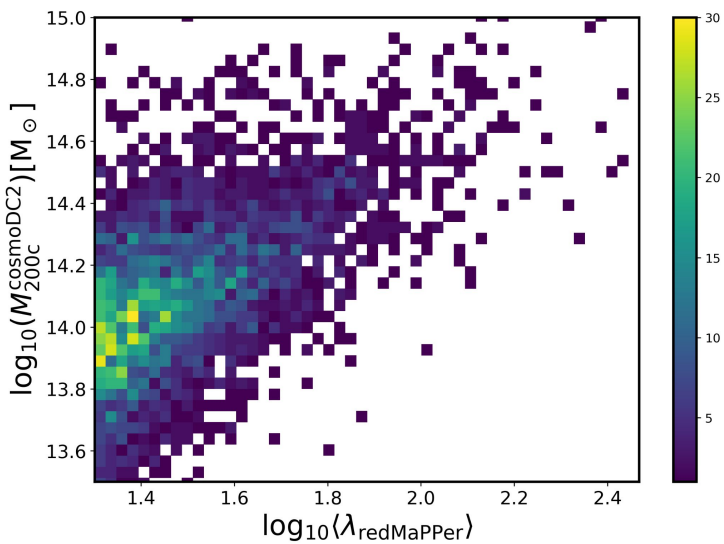
1. Estimation of the "true" mass richness relation
2. Effect of the WL **modelling choices** of the excess surface density on the mass-richness relation

	1h	1h + 2h
c-M relation	1 < R < 5 Mpc	1 < R < 10 Mpc
Free concentration	1 < R < 5 Mpc	1 < R < 10 Mpc

"*True*" mass-richness relation

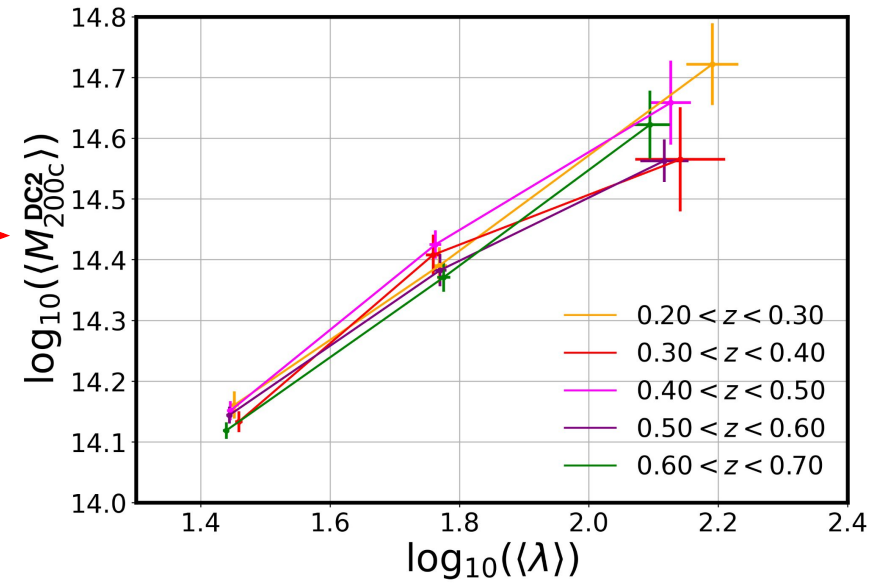
Build an individual mass-richness-redshift catalog :

- Perform a geometrical match of redMapper detected clusters with cosmoDC2 dark matter halos
- After matching, each cluster have DC2 halo mass, redMaPPer richness, redshift.



Individual Mass-richness relation in the M200c-richness plan (approx 4000 clusters)

binned

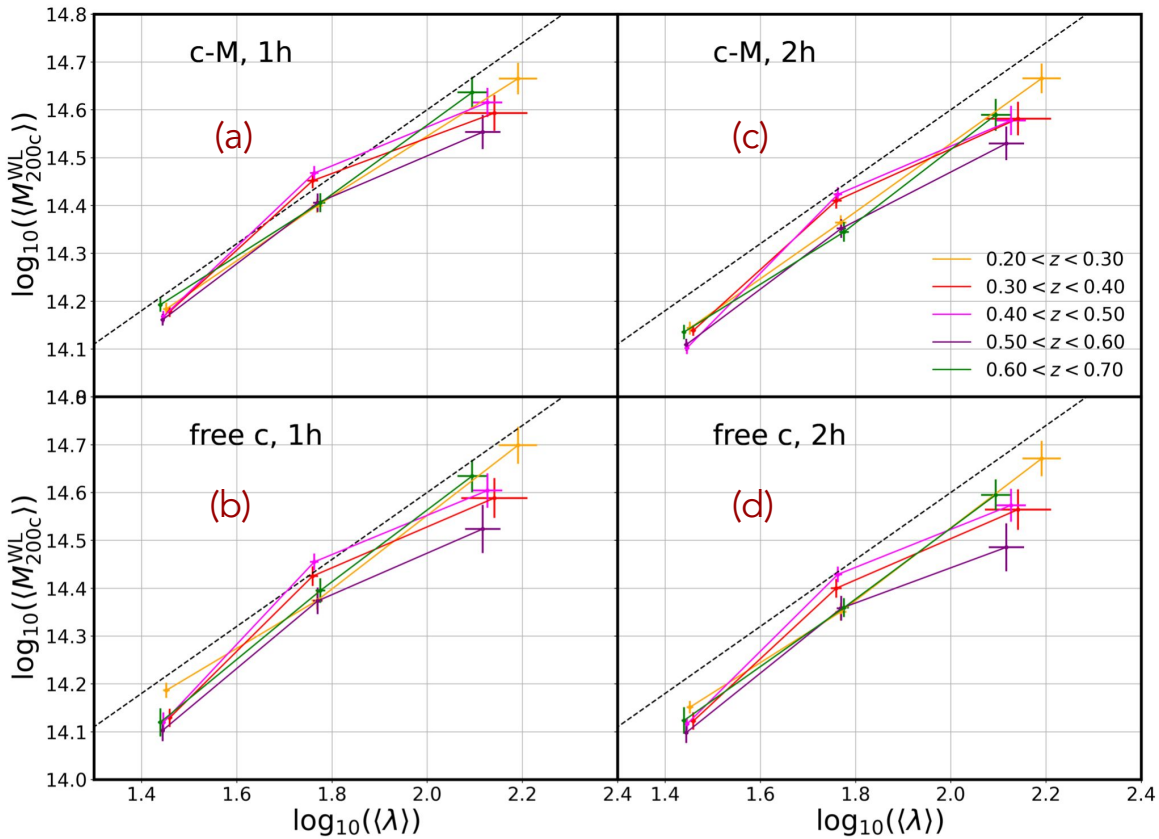


Binned mass-richness relation, in different richness-redshift bins

WL mass-richness relation : Effect of modelling choices

1. Fit the cluster masses by considering de 4 modelling choices of the excess surface density
2. Constrain the mass-richness relation
3. Compare to "*true*" mass-richness relation

	1h	1h + 2h
c-M	(a)	(c)
free c	(b)	(d)



*The arbitrary black line is in the same location in each plot

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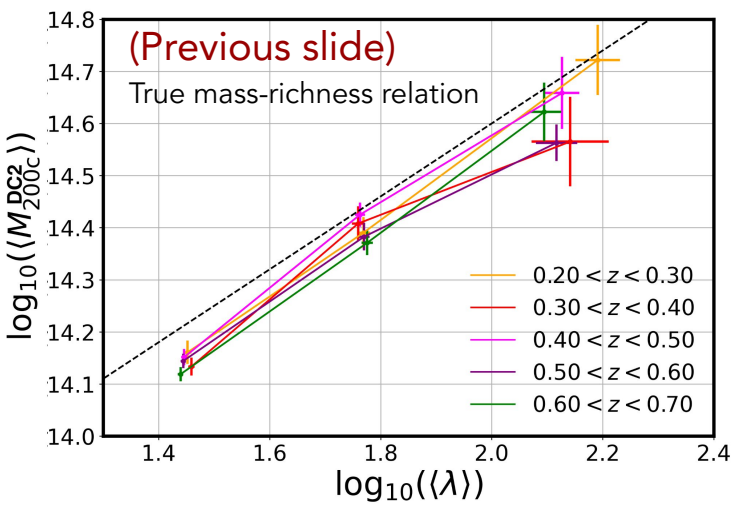

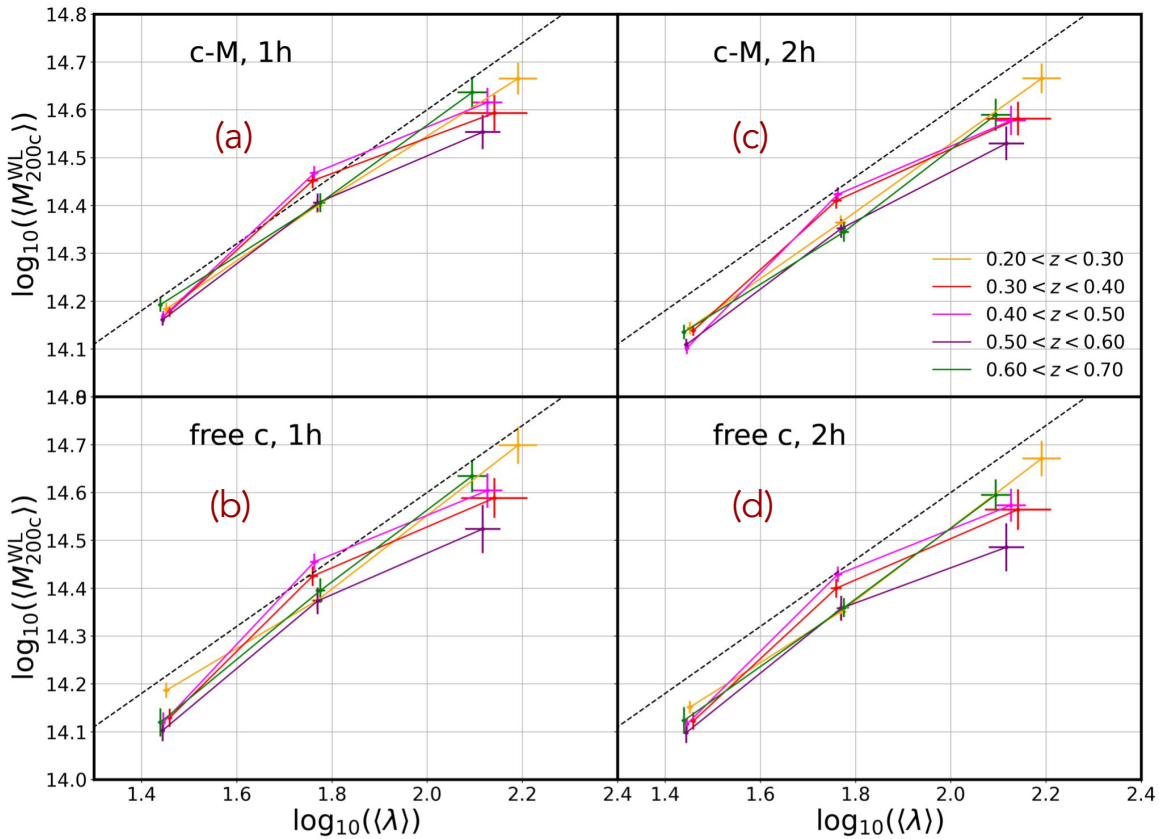

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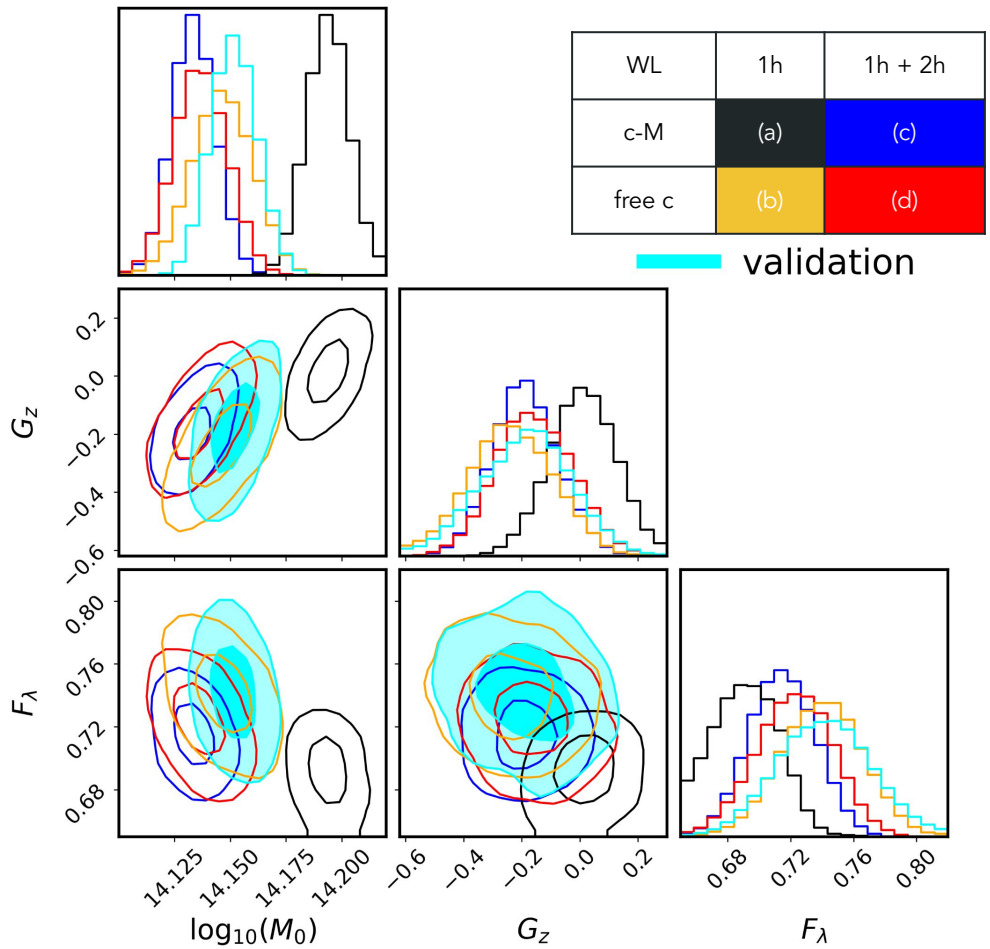
Results : Constraints on mass-richness relation

Constrain M-λ the relation (McClintock et al., 2019)

$$\langle M_{200c} | \lambda, z \rangle = M_0 \left(\frac{\lambda}{\lambda_0} \right)^{F_\lambda} \left(\frac{1+z}{1+z_0} \right)^{G_z}$$

- Leaving free the concentration + 1-halo term (orange) gives most consistent results
- The use of 2-halo term (blue + red) gives 1-sigma compatible results, with slightly lower biased normalization
- Fixing the mass-concentration relation (black) gives more than 2-sigma tension with the normalization → needs to be repeated using c-M relation directly from the simulation.



Conclusions

- The Data Challenge 2 supports the upcoming cosmological analysis with LSST. This work:
  - is part of the validation of the DC2 catalogs (Kovacs et al., 2021, arXiv:2110.03769),

Validating Synthetic Galaxy Catalogs for Dark Energy Science in the LSST Era

Eve Kovacs,[1] Yao-Yuan Mao,[2,*] Michel Aguena,[3] Anita Bahmanyar,[4] Adam Broussard,[2] James Butler,[5] Duncan Campbell,[6] Chihway Chang,[7,8] Shenming Fu,[9,10] Katrin Heitmann,[1] Danila Korytov,[1] François Lanusse,[11] Patricia Larsen,[1] Rachel Mandelbaum,[6] Christopher B. Morrison,[12] Constantin Payerne,[13] Marina Ricci,[3] Eli Rykoff,[14,15] F. Javier Sánchez,[16] Ignacio Sevilla-Noarbe,[17] Melanie Simet,[18] Chun-Hao To,[14,15] Vinu Vikraman,[1] Rongpu Zhou,[19] Camille Avestruz,[20,21] Christophe Benoist,[22] Andrew J. Benson,[23] Lindsey Bleem,[1] Aleksandra Ćiprijanović,[16] Céline Combet,[13] Eric Gawiser,[2] Shiyuan He,[24] Remy Joseph,[25] Jeffrey A. Newman,[19,26] Judit Prat,[5] Samuel Schmidt,[27] Anže Slosar,[28] Joe Zuntz,[29] and The LSST Dark Energy Science Collaboration (LSST DESC)

  - Contributes to the development of DESC tools for galaxy cluster science.

- This work on DC2 seems to show that:
  - leaving free concentration + 1-halo term gives consistent results with “true” M-λ relation,
  - the use of c-M relation may yield biased results will soon be checked with DC2 c-M relation

- In this work : ideal shapes, redshifts. Related studies :
  - Test the effect of photometric redshift of background galaxies,
  - more realistic galaxy catalogs are produced from the measured shapes of galaxies on Rubin-like processed images, and using LSST pipeline (so called DC2object catalog). Test the effect of the shape measurement on the WL mass-richness relation.

Perspective : include mass-richness relation in cluster abundance cosmological analysis.

Thank you for your attention !