Galaxy cluster mass estimate from weak lensing signal

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Galaxy Cluster Cosmology

Abell 1689

Largest gravitationally bound structures in the universe:

Composition: 86% dark matter, 12% ICM (hot gas), 2% galaxies

Galaxy Cluster Cosmology

Halo number density: $\frac{d^2N}{dzd\ln M} = A_{\rm survey}\frac{c}{H(z)}D_c^2(z)\frac{dn(M,z)}{d\ln M}$

Halo mass Function: $\frac{dn(M,z)}{d\ln M} = -\frac{\rho_m(z)}{M}f(\sigma_{\rm M},z)\frac{1}{\sigma_{\rm M}}\frac{d\sigma_{\rm M}}{d\ln M}$

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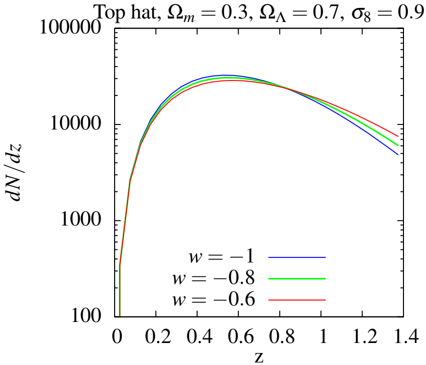


Uncertainty Sources

- Multiplicity function $f(\sigma_{\rm M}, z)$: nonlinear regime of halo/cluster formation.
  N-body simulations: results depend on the halo mass definition.
  - Tinker et al. (2008): 5% precision at $z = 0$.
  - McClintock et al. (2018): 1% precision at $z = 0$.

  The latter is required in the LSST era.
- Biased cosmological parameter estimators: cluster counts
  - Maximum likelihood estimators are not necessarily unbiased, even if they are consistent.
  - Study cases: maximum redshift, survey area, photometric and spectroscopic redshifts, mass uncertainty
  - Biases on Ω_c and σ_8 about 50% of the respective error bar, bias on $w \sim 30\%$: $z_{max} = 1.1$, spec-z and SZ-mass uncertainty, $40,000 \text{deg}^2$.
  - Joint analyses (combined probes): unbiased estimators in all study cases. M. Penna-Lima et al. JCAP 05 (2014) 039

Uncertainty Sources - photometric redshift

- $z^{\text{phot}} = z^{\text{true}} + z^{\text{bias}} \pm \sigma_z$, where $\sigma_z = \sigma_z^0(1+z)$;

$$P(z^{\text{phot}}|z^{\text{true}}) = \sqrt{\frac{2}{\pi}} \frac{e^{-\frac{\left(z^{\text{phot}} - z^{\text{true}}\right)^2}{2\sigma_z^2}}}{\sigma_z \left(1 - \text{erf}(z^{\text{true}}/\sqrt{2\sigma_z^2})\right)}$$

- Large surveys:
  Dark Energy Survey (DES) – 5 filters, 5,000 deg^2, $\sigma_z^0 = 0.03$, $z \lesssim 1.4$;
  Javalambre Physics of the Accelerating Universe Astrophysical Survey (J-PAS) – 56 filters, 8,500 deg^2, $\sigma_z^0 = 0.003$, $z \lesssim 1.0$;
  Euclid Satellite – 7 filters, $\sigma_z^0 = 0.025 – 0.053$, $z \lesssim 2.0$;

  Large Synoptic Survey Telescope (LSST) – 6 filters (ugrizy), 18,000 deg^2, $\sigma_z^0 \leq 0.02$, $z^{\text{bias}} < 0.003$, $z \lesssim 1.2$

Uncertainty Sources - cluster mass

- Main source of uncertainties.
- Mass is not directly observed.

Determining the relationships between survey observables and halo mass represents the most difficult and complex challenge for cluster cosmology. LSST DESC Science Roadmap

- Mass proxies:
  - X-ray: total luminosity L_x, temperature T_x, thermal energy $Y_x = M_{gas} T_x$
  - mm (Sunyaev-Zeldovich effect): Compton-y parameter Y_{SZ}
  - Optical/IR: richness λ, weak lensing (WL) shear

Unbinned cluster count:

$$\frac{d^2 N(\lambda_i, z_i^{\rm phot}, \vec{\theta})}{dz^{\rm phot} d\lambda} = \int d\ln M \int d\lambda^{true} \int dz^{true} \Phi(M, z)$$

$$\times \quad \frac{d^2 N(M, z^{true}, \vec{\theta})}{dz^{true} d\ln M} P(\lambda_i|\lambda^{true})\, P(\lambda^{true}|\ln M)\, P(z_i^{\rm phot}|z^{true})$$

Mass scale calibration

- The mass proxy relations must be calibrated to within 5% level over the mass and redshift ranges in order to access the full constraining power of galaxy clusters. Hao, Rozo and Wechsler (2010), von der Linden et al. (2014)
- WL most promising - absolute mass (not sensitive to gas astrophysics).
- WL individual mass estimates incur smaller bias than X-ray, but they are noisy.
- Use multi-wavelength data to measure low-scatter mass proxies relations (e.g., X-ray) and their covariances identifying the optimal combination of follow-up observables to enhance LSST cluster science.

In general we can write

$$\ln\left(M_{\mathcal{O}}/M_0\right) = \ln(1 - b_{\mathcal{O}}) + A_{\mathcal{O}} \ln\left(M_{true}/M_0\right),$$

where $\mathcal{O}$ refers to an observable (e.g., X-ray, SZ...), M_0 is the pivot mass, $b_{\mathcal{O}}$ and $A_{\mathcal{O}}$ are the bias and slope, respectively.

- Cluster cosmology: self-calibration (mass calibration + cosmology)
- Multi-wavelength analyses

Mass scale calibration (e.g. WL and SZ)

- The SZ relation is usually calibrated with WL measurements assuming $A_{SZ} = A_{WL} = 1.0$ e $b_{WL} = 0.0$

$$\frac{M_{SZ}}{M_{WL}} = 1 - b_{SZ}.$$

  See, e.g., von der Linden et al. 2014, Hoekstra et al. 2015 and Simet et al. 2017.
- Previous analyses provided underestimated error bars of b_{SZ}.
- Mainly due to strong assumptions on the other parameters.

Pseudo cluster counts

New method to calibrate the mass-observable relations (also self-calibration):

$$\mathcal{L} = \prod_i \frac{1}{N} \int_{-\infty}^{\infty} d\ln M_{True} \;\; n(M_{True}, z^i) P(M_{PL}^{(i)}, M_{CL}^{(i)} | M_{True}, \vec{\theta}),$$

where

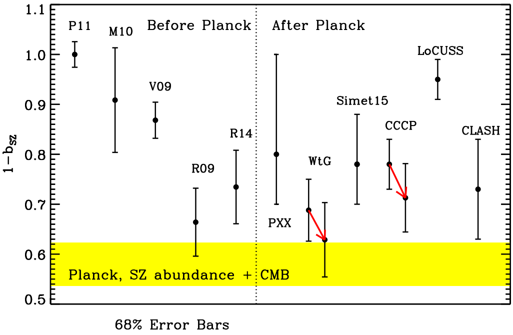
$$\begin{aligned} P(M_{PL}, M_{CL} | M_{True}, \vec{\theta}) \;\; &= \;\; \int d\ln M_{SZ}\, d\ln M_L \;\; P(M_{PL} | M_{SZ}) \\ &\times P(M_{CL} | M_L) P(\ln M_{SZ}, \ln M_L | M_{True}, \vec{\theta}) \end{aligned}$$

and

$$n(M_{True}, z) = f(M_{True}) \frac{dn(M_{True}, z)}{d\ln M_{True}} \frac{d^2 V}{dz d\Omega}.$$

M. Penna-Lima, J. Bartlett, E. Rozo, J-B Melin, et al., A&A 604, A89 (2017), arXiv:1608.05356

Calibrating the *Planck* cluster mass scale with CLASH



- *Planck* and *Cluster Lensing And Supernova survey with Hubble* (CLASH): 21 clusters in common.
- We fit 11 parameters: A_{SZ}, b_{SZ}, σ_{SZ}, A_L, b_L, σ_L, ρ, selection function
- Reduced tension between CMB and clusters, 1.34σ.

M. Penna-Lima, J. Bartlett, E. Rozo, J-B Melin, et al., A&A 604, A89 (2017), arXiv:1608.05356

WL cluster mass estimation

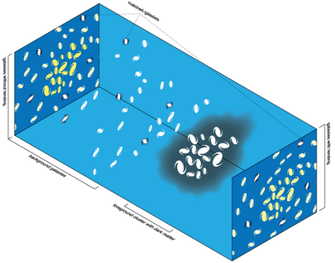
- Requirements (von der Linden et al. MNRAS 433 (2014) 3):
  - estimates of the distortion of each galaxy image due to the cluster (shear);
  - estimates of the redshifts of the galaxies used in the WL analysis (dependency on cosmological distances);
  - assumption about the mass distribution of the cluster (mass density profile).
- Individual cluster mass estimation: massive clusters - $M \gtrsim 2 \times 10^{14} h^{-1} M_\odot$ (small fraction of the catalog).
- Mean cluster mass estimation: stack clusters in redshift and richness bins.

Weak Lensing

- Background galaxies are magnified and distorted by the gravitational potential of the cluster (lens).
- Measured quantity - reduced shear: the ellipticities of galaxies (e_1, e_2) (bulge and disk) corrected for point spread function (PSF) effects. Tonegawa et al. (2018)
- Reduced shear (theory):

$$g = \frac{\beta_s(z_b)\gamma_\infty(R)}{1 - \beta_s(z_b)\kappa_\infty(R)},$$

where $\beta_s = \frac{D_{LS}}{D_S}\frac{D_\infty}{D_{L,\infty}}$.



By Michael Sachs

- Convergence $\kappa(R)$ and tangential shear $\gamma(R)$:

$$\kappa(R) = \frac{\Sigma(R)}{\Sigma_c}, \quad \gamma(R) = \frac{\Delta\Sigma}{\Sigma_c} = \frac{\overline{\Sigma}(< R) - \Sigma(R)}{\Sigma_c},$$

where $\Sigma_c = \frac{c^2}{4\pi G}\frac{D_S}{D_L D_{LS}}$.

- Surface mass density:

$$\Sigma_\rho(R) = 2\int_0^\infty \rho(R,z)dz$$

- Average surface density:

$$\overline{\Sigma}_\rho(< R) = \frac{2}{R^2}\int_0^R R'\Sigma_\rho(R')dR'$$

- Individual cluster mass estimation
- Mass estimates using the full photometric redshift posterior distributions of individual galaxies.
- Method used in the Weighing the Giants analyses. von der Linden et al. (2014), Applegate et al. (2014)
- They showed systematic biases in the mean mass of the sample can be controlled.
- In their analyses $\Sigma(R) = \Sigma_\rho(R) = \int \mathrm{d}z\, \rho(R, z)$
- ρ is the matter density profile.
- Navarro-Frenk-White (1996) (NFW):
  $\rho(r) = \frac{\delta_c \rho_{crit}}{(r/r_s)(1+r/r_s)^2}, \quad \delta_c = \frac{\Delta}{3} \frac{c^3}{\ln(1+c) - \frac{c}{1+c}},$
  c is the concentration parameter and r_s is the scale radius.

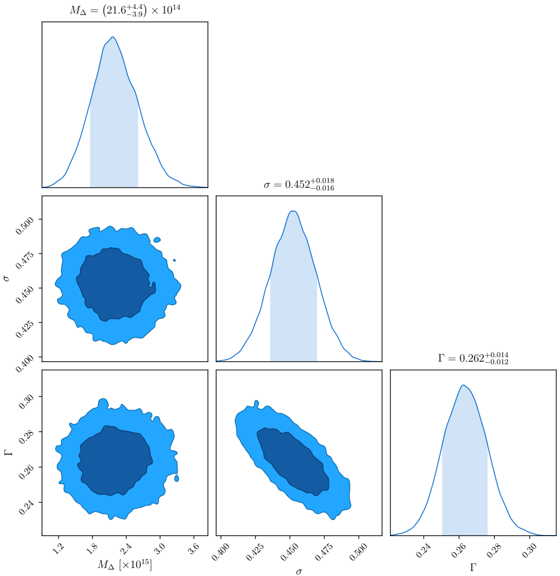
Lensing masses with photo-z distributions

Posterior

$$\mathcal{P}(M|\hat{g}) = P(M) \int_{\forall\alpha} P(\vec{\alpha}) \prod_i \int_z P(\hat{g}_i|g(z,M),\vec{\alpha}) P_i(z) dz d\vec{\alpha},$$

- $P(M)$: prior on the cluster mass
- $P(\hat{g}_i|g(z,M),\vec{\alpha})$: Voigt distribution (convolution of Gaussian and Lorentz distributions)
- $P_i(z)$: redshift probability distribution of the i-th galaxy
- $\vec{\alpha}$: Voigt profile and shear calibration parameters
- $g(z,M)$ $(\hat{g})$: reduced shear (measured)

Lensing masses with photo-z distributions



Improvements

Effects to take into account to compute the surface mass density $\Delta\Sigma$ (in addition to the cluster/halo profile term $\Delta\Sigma_\rho(R)$):

- Miscentering: the observed systems may be incorrectly centered affecting the shear profile. Johnston et al. 2007
- 2-halo term $\Delta\Sigma_{2h}$: correction to the halo profile for larger scales than $\approx$ the Virial radius (or R_Δ) due to the surrounding matter. Depends on the halo bias and the linear matter power spectrum.
- No-weak shear $\Delta\Sigma_{nw}$: massive clusters may not satisfy the weak lensing regime, i.e., $g_t \approx \gamma_t$, if $\gamma_t \ll 1$ and $\kappa \ll 1$.

- Central point mass associated to the BCG. $\Delta\Sigma_{BCG}$

$$\Delta\Sigma = \frac{M_{BCG}}{\pi R^2} + p_{cc}\left[\Delta\Sigma_{\rho}(R) + \Delta\Sigma_{nw}(R)\right] + (1 - p_{cc})\Delta\Sigma_{misc}(R) + \Delta\Sigma_{2h}(R),$$

where *pcc* the fraction of miscentered clusters.
See, e.g., Parroni et al. (2017), Vitorelli et al. (2018), Pereira et al. (2018), Cibirka et al. (2017) and references therein.

- Implement other matter density profiles, e.g., Diemer & Kravtsov.

Independent implementation: Numerical Cosmology library (NumCosmo) Vitenti and Penna-Lima ascl:1408.013, github

Conclusions and next steps

- Absolute cluster mass calibration - WL most promising
- Relative cluster mass calibration (LSST follow-up with X-ray data)
- Requirements to better constrain cosmological models

- Individual cluster mass estimates via WL: simulations and WtG
- Implemented in NumCosmo
- Include corrections to compute the surface mass density and, consequently, the reduced shear: miscentering, 2-halo term, ...
- Implement other matter density profiles: Diemer & Kravtsov, Einasto, ...
- Obtain cluster mass estimates: DC2 and real data
- Cluster mass - a “problem” to cosmology but an opportunity to astrophysics.