Galaxy cluster mass estimate from weak lensing signal

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Galaxy Cluster Cosmology

Abell 1689

Largest gravitationally bound structures in the universe:

86% DM, 12% ICM (hot gas), 2% galaxies

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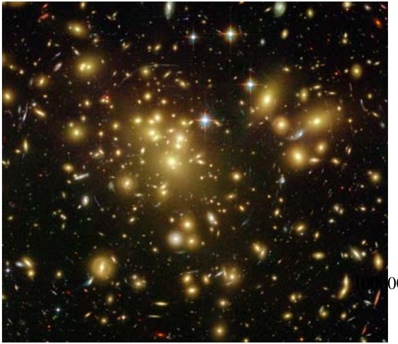
MF: $$\frac{dn(M,z)}{d \ln M} = -\frac{\rho_m(z)}{M} f(\sigma_{\mathrm{M}}, z) \frac{1}{\sigma_{\mathrm{M}}} \frac{d\sigma_{\mathrm{M}}}{d \ln M}$$

Galaxy Cluster Cosmology



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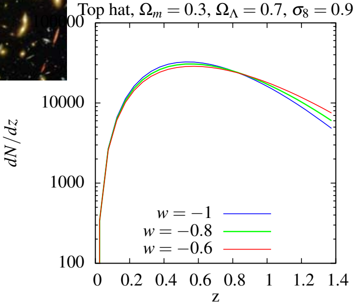

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Uncertainty Sources

- Multiplicity function $f(\sigma_{\mathrm{M}}, z)$: 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 such that this uncertainty is negligible in the LSST era.
- Biased cosmological parameter estimators: cluster counts
  - Bias on Ω_c, σ_8 and w: $\sim 25\%$ of the respective error bar.

  M. Penna-Lima et al. JCAP 05 (2014) 039
- Photometric redshift
  - $z^{\mathrm{phot}} = z^{true} + z^{\mathrm{bias}} \pm \sigma_z^0(1+z)$
  - 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, $\sigma_z^0 = 0.003$, $z \lesssim 1.5$;
    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, $\sigma_z^0 \leq 0.02$, $z^{\mathrm{bias}} < 0.003$, $z \lesssim 1.0$

- 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:

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

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

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.

Mass scale calibration *Planck* and CLASH

- $\ln\left(M_{\mathcal{O}}/M_0\right) = \ln(1 - b_{\mathcal{O}}) + A_{\mathcal{O}} \ln\left(M_{true}/M_0\right)$
- The SZ relation is usually calibrated with WL measurements assuming $A_{SZ} = A_{WL} = 1.0$ e $b_{WL} = 0.0$

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

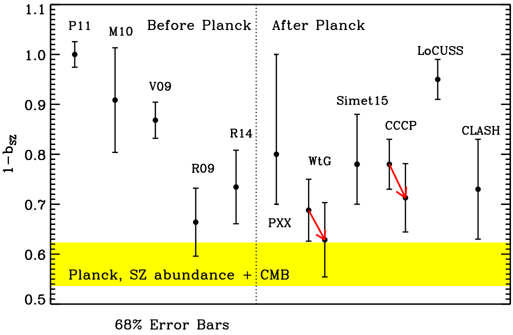
- Previous analyses provided underestimated error bars of b_{SZ}.
- Mainly due to strong assumptions on the other parameters.
- Introduced a new method to calibrate the mass-observable relations: pseudo cluster counts.

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

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

e

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



- *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.

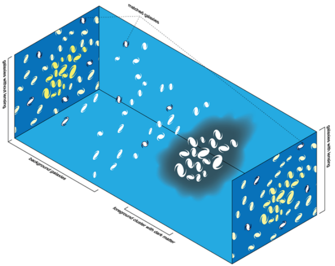
M. Penna-Lima, J. Bartlett, E. Rozo, J-B Melin, et al., A&A 604, A89 (2017), arXiv:1608.05356

Cluster Science Roadmap

- **CLMassMod**: Cluster masses from weak-lensing shear maps
- Quantify mass-modeling systematics
- DESC - Galaxy Clusters Key Projects
  - Absolute Mass Calibration I (DC1): Analyze shear maps from DM only simulations.
  - Absolute Mass Calibration II (DC2): Extend to DM + baryons simulations.
  - Analysis of DC3 Mock Lightcone and pre-cursor data. CC/SV observing plan: Apply to DC3 and cluster precursor dataset.

Lensing masses with photo-z distributions

- Background galaxies are magnified and distorted by the gravitational potencial 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 $\beta_s = \frac{D_{LS}}{D_S}\frac{D_\infty}{D_{L,\infty}}$
- Convergence $\kappa(R)$ and tangential shear $\gamma(R)$ are functions of the surface mass density $\Sigma(R)$:
  $\kappa(R) = \frac{\Sigma(R)}{\Sigma_c}$,
  $\gamma(R) = \frac{\Delta\Sigma}{\Sigma_c} = \frac{\overline{\Sigma}(<R)-\Sigma(R)}{\Sigma_c}$,
  where $\Sigma_c = \frac{c^2}{4\pi G}\frac{D_S}{D_L D_{LS}}$.



By Michael Sachs

Lensing masses with photo-z distributions

- 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 $\Sigma(R) = \Sigma_\rho(R) = \int \mathrm{d}\chi \, \rho\left(\sqrt{R^2 + \chi^2}\right)$
- 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)

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

  This term introduces two new parameters: the fraction of miscentered clusters p_{cc}, and the offset between the true and the estimated center R_{off}.

- 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.

Improvements

- No-weak shear $\Delta\Sigma_{nw}$: massive clusters may not satisfy the weak lensing regime, i.e., $g_t \approx \gamma_t$, if $\gamma_t << 1$ and $\kappa << 1$.
- Central point mass associated to the BCG. $\Delta\Sigma_{BCG}$

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

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:

- Diemer & Kravtsov, Einasto, ...

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
- 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