WHAT CAN CLUSTER GALAXIES CAN TELL US ABOUT THEIR HOST ENVIRONMENTS?

LYNDSAY OLD - RESEARCH FELLOW @ ESAC
ESAC 17TH JANUARY 2019

Radek Wojtak, Gary Mamon, Frazer Pearce, Meghan Gray + Galaxy Cluster Mass Reconstruction Project team
Michael Balogh, Howard Yee, Irene Pintos-Castro, Adam Muzzin, Greg Rudnick, Remco van der Burg + the GOGREEN team
GALAXY CLUSTER BASICS

- Dark Matter: 83%
- Intra Cluster Medium: 15%
- Galaxies: 2%

Image: Galaxy cluster with a pie chart depicting the composition of dark matter, intra cluster medium, and galaxies.
GALAXY CLUSTER BASICS

NASA/ESA Hubble Frontier Field Abell 2744

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GALAXY CLUSTER BASICS

- **Dark Matter**: 83%
- **Intra Cluster Medium**: 15%
- **Galaxies**: 2%
OBSERVING GALAXY CLUSTERS

• Optical & infrared: over densities, red sequence
  (e.g., Abell 1958, Gladders & Yee 2000)

• X-ray bright: $L_X \sim 10^{43}-10^{45}$ erg s$^{-1}$
  (e.g., Forman et al. 1972, Vikhlinin et al. 2009).

• Sunyaev-Zeldovich effect
  (e.g., Sunyaev & Zeldovich 1972, Hasselfield et al. 2013).

• Gravitational lensing
  (e.g., Bartlemann et. al., 2010, Applegate et al. 2012).
Adapted from Allen et al. 2011
Galaxy clusters could emerge as the most powerful cosmological probe if the masses of the clusters can be accurately measured.

- Cosmic Visions Report (2016)
Any technique that uses galaxy properties as a mass proxy
e.g., positions, velocities, colours & luminosities
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e.g., positions, velocities, colours & luminosities

- Independent proxy to SZ, X-ray, lensing
- Relatively $\alpha$
- Critical for detecting lower mass clusters (bulk of mass function!)
- Extended galaxy distribution: clusters can be probed out to large radii
- 2-for-1: dynamical analysis provides information on virialisation state
HOW WELL CAN WE MEASURE HOW MUCH CLUSTERS WEIGH?

\[
\log(M_{200c}, \text{True}) / M_\odot
\]

Measured cluster mass vs. ‘True’ cluster mass

- 'True' cluster mass
- Measured cluster mass
HOW WELL CAN WE MEASURE HOW MUCH CLUSTERS WEIGH?

Measured cluster mass vs. ‘True’ cluster mass.
HOW WELL CAN WE MEASURE HOW MUCH CLUSTERS WEIGH?

![Graph showing the relationship between measured and true cluster masses.](graph.png)
HOW WELL CAN WE MEASURE HOW MUCH CLUSTERS WEIGH?

\[ \log(M_{200c}, \text{Recovered}/M_\odot) \]

\[ \sigma \text{ method 1} \]

\[ \sigma \text{ method 2} \]

'Device' cluster mass

Measured cluster mass
HOW WELL CAN WE MEASURE HOW MUCH CLUSTERS WEIGH?

[Graph showing the relationship between 'True' cluster mass and Measured cluster mass. The graph has a linear trend line.]
→ First systematic, homogenous study of 25 cluster mass estimation techniques

GCMRP goals:
1. Scatter, bias and completeness
2. Impact of uncertainties on cluster-cosmology
3. Methods consistent?
4. Best application of techniques to upcoming data-sets
THE GALAXY CLUSTER MASS RECONSTRUCTION PROJECT

→ First **systematic, homogenous study** of 25 cluster mass estimation techniques

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Co-authors: Radek Wojtak, Gary Mamon, Frazer Pearce, Meghan Gray, Ramin Skibba, Darren Croton, Alex Saro, Tiit Sepp, Cristobal Sifón, Elmo Tempel, Peter Behroozi, Reinaldo de Carvahlo, Andrea Biviano, Juan Muñoz-Cuertas, Eduardo Rozo, Eli Rykoff, Daniel Gifford, Anja von der Linden, Mike Merrifield, Volker Müller, Chris Power, Stuart Muldrew, Yang Wang, Richard Pearson & Trevor Ponman.
DM only

Add galaxies - SAM & HOD models

3 mock group/cluster catalogues

D. Croton, R. Skibba

577 clusters with $\log M_{200c} > 14 M_{\text{solar}}$
THE GALAXY CLUSTER MASS RECONSTRUCTION PROJECT

DM only → Add galaxies - SAM & HOD models → 3 mock group/cluster catalogues

For the 968 systems:
- $M_{200c}$
- Velocity dispersion
- Radius
- Galaxy membership

Participants return membership & cluster parameters → Blind test at 3 day workshop: give participants galaxy catalogues
### The Mass Measurement Techniques

**Step 1 = cluster finding**

**Step 2 = members**

**Step 3 = mass**

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### The Mass Measurement Techniques

**Step 2 = members**

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- **Friends-Of-Friends algorithm**
- **Phase space: within a certain distance and velocity from cluster centre**
- **Red sequence: selecting galaxies of a certain colour**
THE MASS MEASUREMENT TECHNIQUES

Step 3 = mass

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$M \propto \sigma^3$

Positions & velocities of galaxies e.g., caustics

Number of galaxies above a given luminosity threshold

RMS radius/ DM profile fitted to obtain radius.

Matching using theoretical halo mass function & cluster r-band luminosity function
• We perform a **likelihood fitting** analysis assuming a model where there is a linear relationship between \( \log M_{200, \text{rec}} \) and \( \log M_{200, \text{true}} \). Log and residual offsets in the recovered mass are drawn from a normal distribution.

• We use the parallel-tempered MCMC sampler **emcee** (Foreman & Mackay 2013) to efficiently sample the parameter space.

• RMS: encompasses both scatter and bias and, hence, delivers the overall uncertainty.

• Scatter in the recovered mass, \( \sigma_{M_{\text{Rec}}} \), delivers a measure of the intrinsic scatter.

• Bias (at pivot mass)
GCMRP: HIGHLIGHTS

- RMS in mass is higher than expected, factor of ~2-12, & mass dependant!

![Graph](chart.png)

Old et al. 2014, Old et al. 2015 (1403.4610, 1502.07347)
• RMS in mass is higher than expected, factor of ~2-12, & mass dependant!

Scatter if we assume all 968 clusters have the same mass!
• RMS in mass is higher than expected, factor of ~2-12, & mass dependant!

• Many methods overestimate high mass clusters - severe implications due to steeply falling cluster mass function

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• We see a mass bias (overestimation) for dynamically disturbed clusters

Owers et al., 2011, Abell 2744
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We see a mass bias (overestimation) for dynamically disturbed clusters

Old et al. 2017 (1709.10108)
• Contamination and incompleteness give rise to overestimation & underestimation of measured masses respectively

• Kinematic methods more sensitive to incompleteness

Wojtak et al. 2018 (1806.03199)
• Contamination and incompleteness give rise to overestimation & underestimation of measured masses respectively.

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• $M_{\text{rec}} - M_{\text{true}}$ relation flattens due to a mass-dependent selection of cluster members & mass-dependent response of estimators to imperfect membership.

• Flattening results in suppression in mass function at low masses & amplification at high masses… $\Omega_m$ biased down by $\sim 10\%$ and $\sigma_8$ biased up by $\sim 7\%$

Wojtak et al. 2018 (1806.03199)
GCMRP: FUTURE

Data set still unblinded — available for testing new cluster mass estimation techniques!

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- Kinematic methods more sensitive to incompleteness.

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Wojtak et al. 2018 (1806.03199)
GALAXY EVOLUTION IN & OUT OF CLUSTERS

At low redshift

Dressler 1980

Fraction of galaxy population

Spirals, Irregulars

Ellipticals

See also: Oemler 1974, Balogh et al. 20014, Hogg et al. 2004, Blanton et al. 2005
At intermediate redshifts

Planck clusters, z~0.6, ~ Universe was ~8 Gyr old : van der Burg et al. 2018
WHAT PROCESSES GOVERN THE LIFE & DEATH OF GALAXIES?

Illustrated by Aeree Chung

- Ram pressure stripping
  Gunn & Gott 1972
- Merging
  Mihos 2004
- What a galaxy may go through...
- Harassment
  Moore et al. 1996
- STARS / ISM / ICM
- Turbulent viscous stripping
  Nulsen 1982
- Tidal compression/truncation
  Byrd & Valtonen 1990/Merritt 1983
- Starvation
  Larson 1980
- Thermal evaporation
  Cowie & Songaila 1977
These mechanisms act on different timescales and are location dependent!
WHAT ABOUT AT HIGHER REDSIFTS?

• At $z > 1$, Universe was ~eight times denser. Expect that gas accretion rates, star-formation rates (SFRs) were much higher than the present day.

• Properties of typical galaxies in $z > 1$ clusters are almost completely unknown!
Gemini Observations of Galaxies in Rich Early ENvironments survey (GOGREEN)

~440 hrs Gemini MOS of galaxies in 21 groups + clusters at $1 < z < 1.5$ (PI: Balogh, GCLASS, SpARCS)
Deep imaging multi-band imaging: Subaru, VIMOS, CFHT, MMT, Magellan, HAWK-I, HST
How is Star Formation (SF) distributed in these clusters?

Is there a difference in SF properties at z=0 & z=1?
→ Deep imaging multi-band imaging: Subaru, VIMOS, CFHT (PI: Old), MMT, Magellan, HAWK-I

- How is Star Formation (SF) distributed in these clusters?
- Is there difference in SF between cluster and field?
- Is there a difference in SF properties at z=0 & z=1?

E.g., using [OII] emission as SFR proxy
Following Gilbank et al., 2010: empirically corrected SFR from [OII] luminosity
Following Gilbank et al., 2010: empirically corrected SFR from [OII] luminosity
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Completeness limits & flux calibration!
Watch out for the following GOGREEN early science results!

I. Buildup of the red sequence in massive clusters (J. Chan, UC Riverside)

II. Environment-dependent ages of quiescent galaxies at 1<z<1.5 (K. Webb, U. Waterloo)

III. The environmental dependence of the star forming main sequence at 1<z<1.5 (L. Old)

IV. The quiescent galaxy population of 1<z<1.5 groups (A. Reeves, U. Waterloo)

V. First Data Release (M. Balogh, U. Waterloo)

VI. + HST morphology!

Thanks Gemini!