Distributions of Baryons from the Virial Radius of Galaxy Clusters to Large Scales

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Outline

Part I.

Baryons in the Outskirts of Galaxy Clusters

- Introduction
- A Simple Physical Model for the Gas Distribution in Galaxy Clusters
- Density Jumps Near the Virial Radius of Galaxy Clusters

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Patej & Loeb, 2015b, arXiv: 1509.07506

Part II.

Baryons on Large Scales

- Introduction
- Quantifying the Color-Dependent Stochasticity of Large-Scale Structure

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Part III.

Galaxy Cluster Science in the Context of Next-Generation Galaxy Surveys

- The Dark Energy Spectroscopic Instrument (DESI)
- The DECam Legacy Survey (DECaLS)

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Galaxy Clusters

- Galaxy cluster composition:
  - Dark matter (~85%)
  - Baryonic matter:
    - ~10% galaxies
    - ~90% ICM gas
- Galaxy clusters can be used as probes of cosmology
  - Evolution of the cluster mass function $N(M, z)$

Optical: N. Benitez, T. Broadhurst, H. Ford, M. Clampin, G. Hartig, G. Illingworth, ACS Science Team, ESA

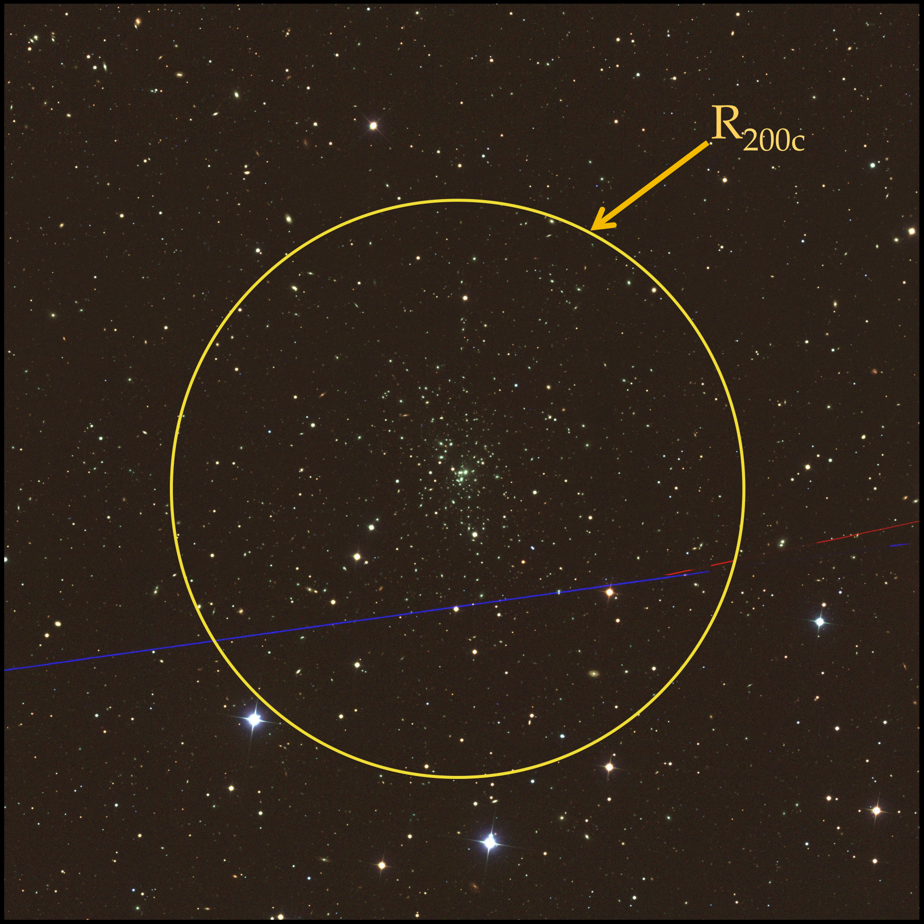
X-ray: NASA/CXC/MIT/E.-H Peng

Parameterizing Galaxy Clusters

- Sizes of galaxy clusters defined with respect to background densities $\rho_b(z)$
  - Masses M_Δ, radii R_Δ:

    $<\rho>(<R_\Delta) = \Delta x \rho_b(z)$

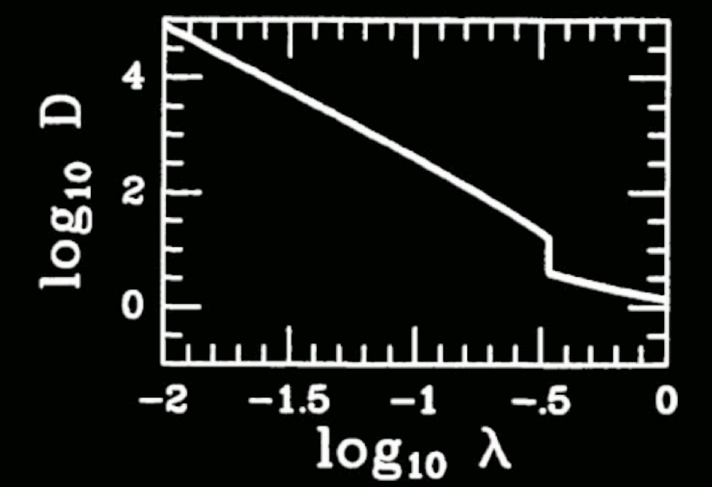
    $M_\Delta = M(<R_\Delta)$
  - Δ = 500, 200 commonly used
  - $\rho_b = \rho_c$ -> R_{200c}, $\rho_b = \rho_m$ -> R_{200m}
  - $R_{200m} \approx (1.2\text{-}1.7) x R_{200c}$
  - $R_{vir} \approx (1\text{-}1.3) x R_{200c}$

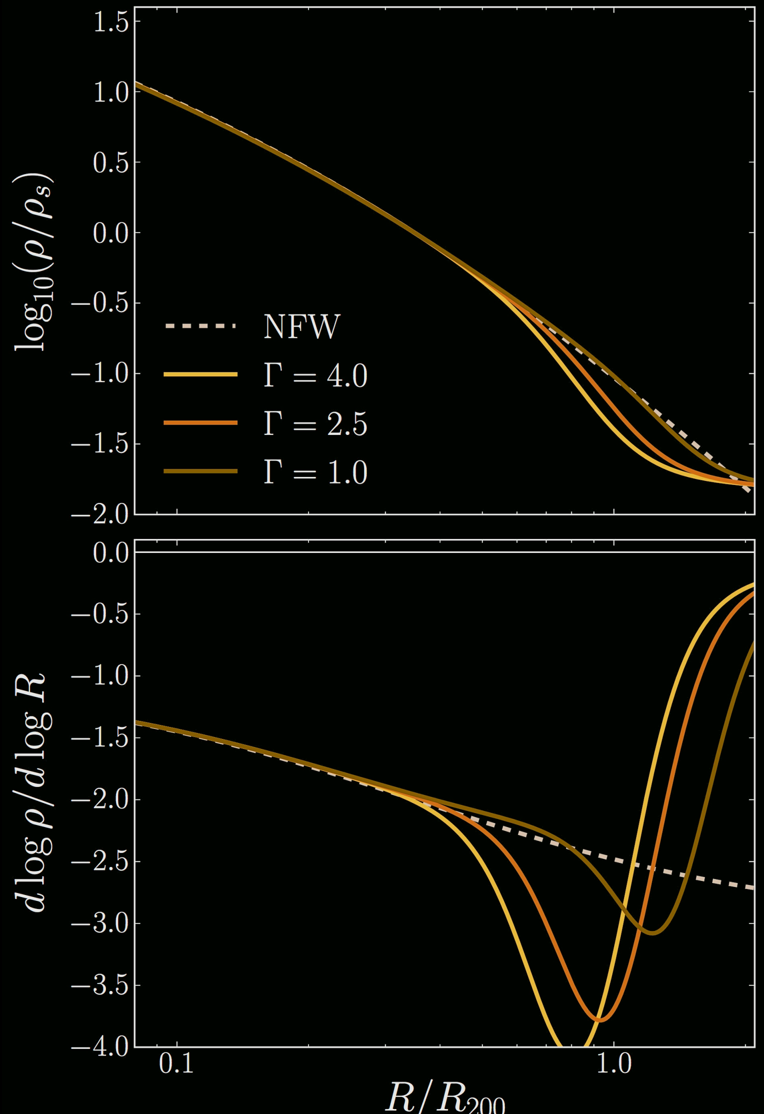


- Some typical cluster values:
  - M_{200c} ~ (2-20)x10^{14} $M_\odot$
  - R_{200c} ~ 1-2 Mpc

Galaxy Cluster Outskirts

- Density jumps in cluster outskirts predicted by models of structure formation (e.g., Bertschinger 1985) and recent simulations (e.g., Diemer & Kravtsov 2014)
  - Gas density jump: virial shock
  - Dark matter density jump

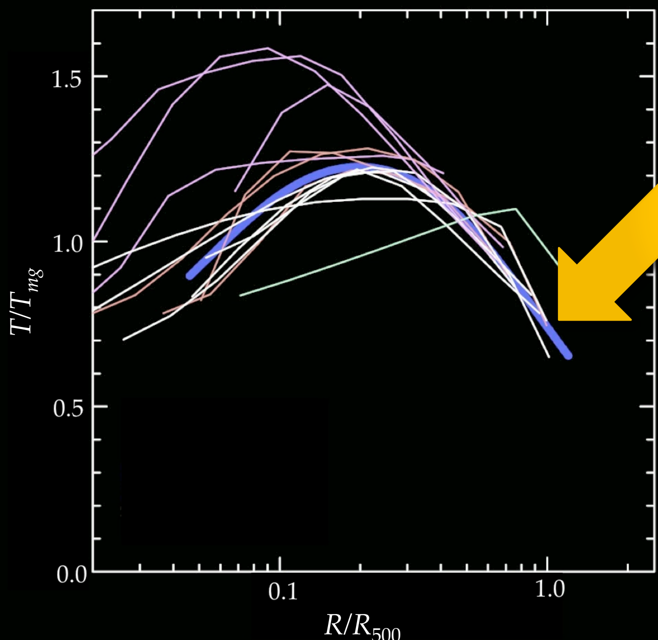


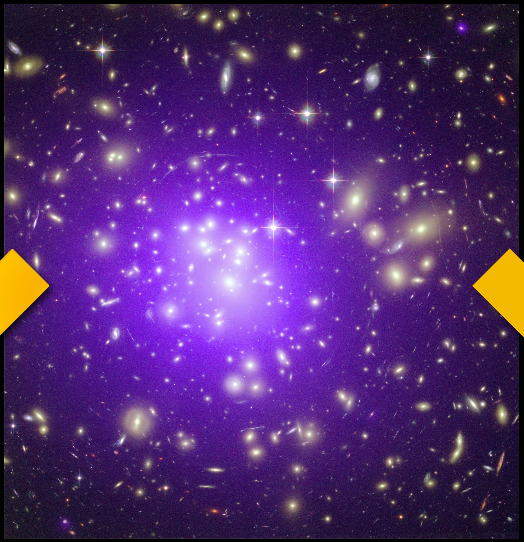


Above: Bertschinger 1985
Right: A variant on the model proposed by Diemer & Kravtsov (2014)

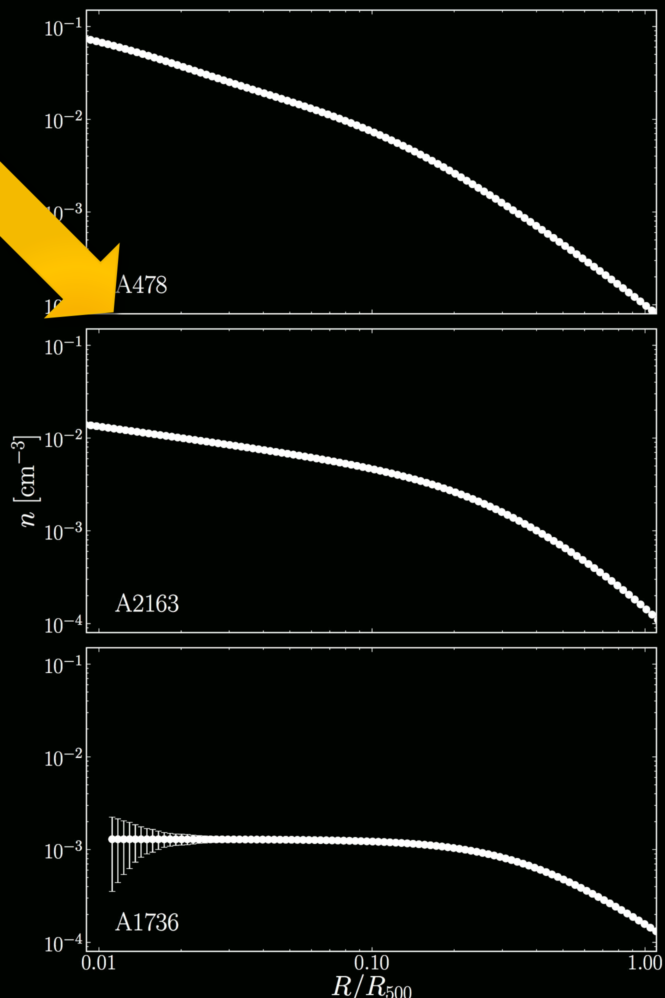
X-ray Observations of Cluster Gas

Temperature





Density



Above: Vikhlinin et al. (2006)
Right: Data from Vikhlinin et al. (2006, 2009)

Cluster Gas Modeling

- Simple:
  - Standard β-Model (Cavaliere & Fusco-Femiano 1976)
    - Assumptions: hydrostatic equilibrium, isothermal cluster gas

$$n_g(r) = \frac{n_0}{\left(1 + (r/r_c)^2\right)^{3\beta/2}}$$

  - Alternatives: NFW, SIS, most other well-known profiles
- Complex:
  - Double Beta Model:

$$n_g(r) = \frac{n_{0,1}}{\left(1 + (r/r_{c,1})^2\right)^{3\beta_1/2}} + \frac{n_{0,2}}{\left(1 + (r/r_{c,2})^2\right)^{3\beta_2/2}}$$

  - Vikhlinin Model:

$$n_g^2(r) = n_{0,1}^2 \frac{(r/r_c)^{-\alpha}}{\left(1 + (r/r_{c,1})^2\right)^{3\beta_1 - \alpha/2}} \frac{1}{\left(1 + (r/r_s)^\gamma\right)^{\epsilon/\gamma}} + \frac{n_{0,2}^2}{\left(1 + (r/r_{c,2})^2\right)^{3\beta_2}}$$

- **Can we find a simple alternative with fewer parameters that is in line with the latest X-ray observations?**

Deriving the Models

- Begin with three assumptions:
  - Spherical symmetry
  - Virial shock & DM density jump at a radius *s* ~ virial radius, modeled as sharp cut-offs
  - Ansatz: $\frac{1}{f_g} M_g(x) = M_{DM}(\xi x^n)$
- Apply three simple conditions:
  - $M_g(<s) = f_g M_{DM}(<s)$ (inner profile)
  - $\rho_g(r>s) = f_g \rho_{DM}(r>s)$ (outer profile)
  - $\Gamma_g = \rho_g(s^+)/\rho_g(s^-)$, $\Gamma_{DM} = \rho_{DM}(s^+)/\rho_{DM}(s^-)$; $\Gamma = \Gamma_g/\Gamma_{DM}$ (shock, density jump)

New Models for the Gas Density

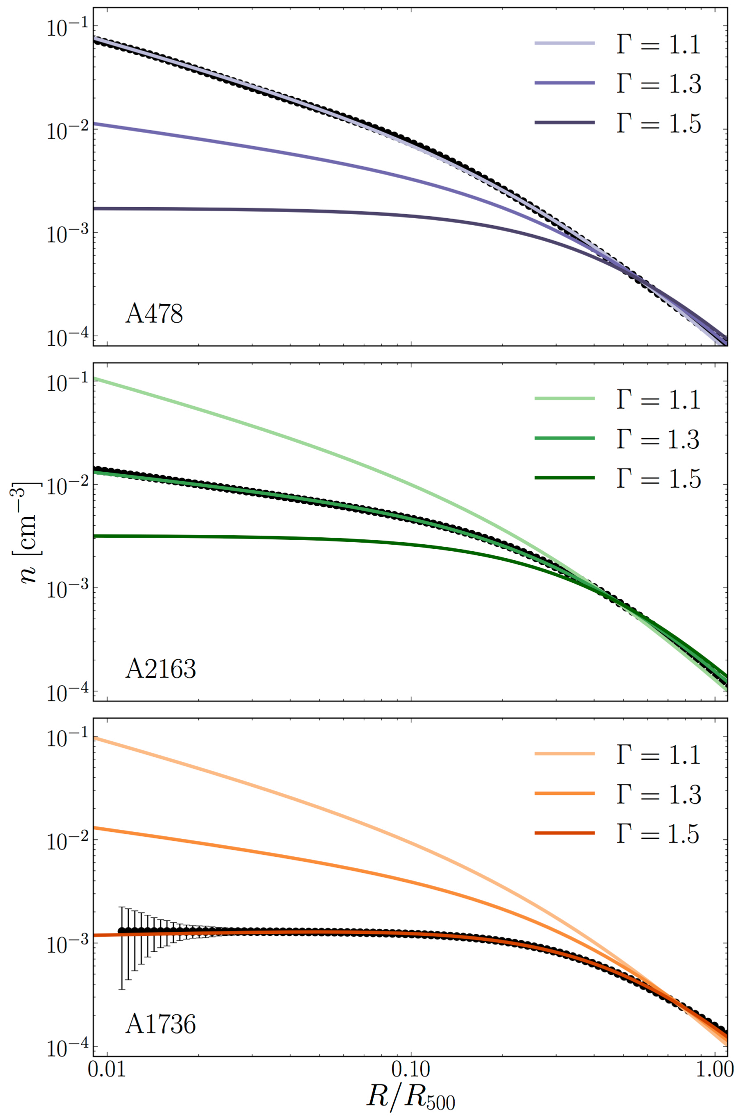
- Assume NFW for DM inner profile:

$$\rho_{DM}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

- Resulting inner gas profile ($\Gamma=\Gamma_g/\Gamma_{DM}$):

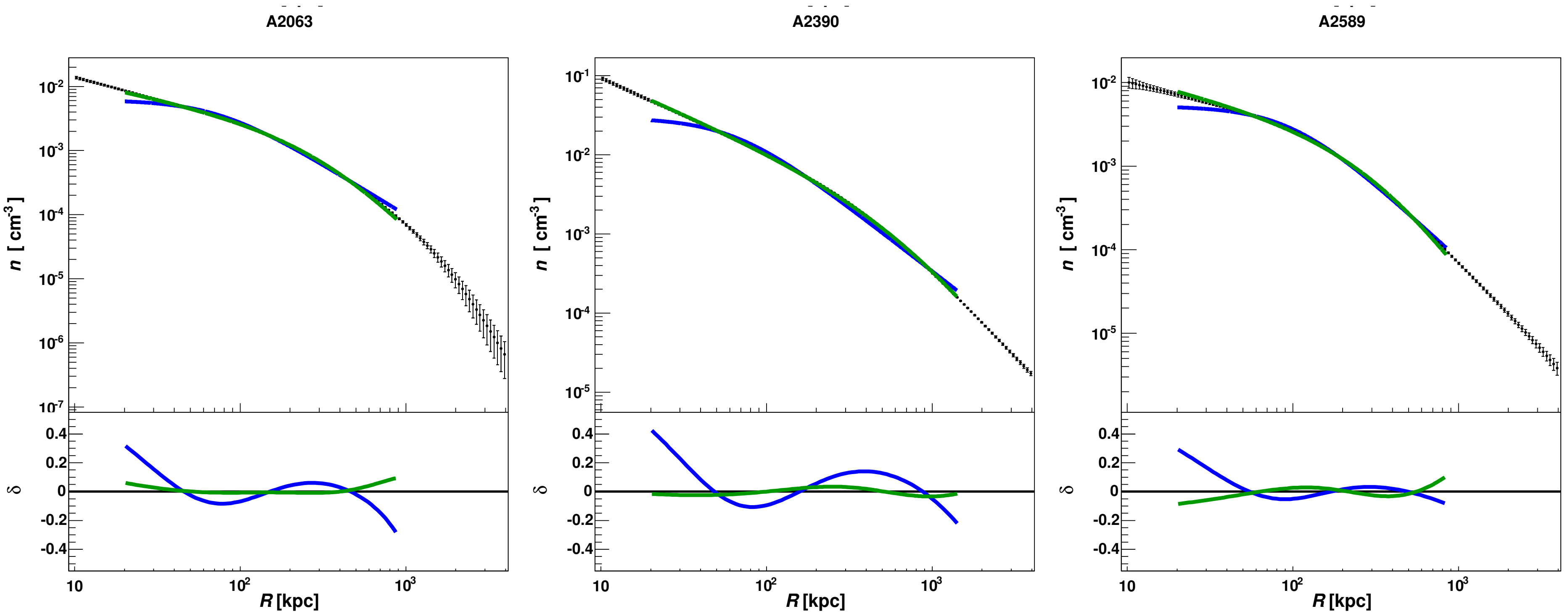
$$\rho_g(r) = \Gamma f_g \rho_s \frac{(r/s)^{2\Gamma-2}}{r/r_s(1+(s/r_s)(r/s)^{\Gamma})^2}$$

(Patej & Loeb 2015a)



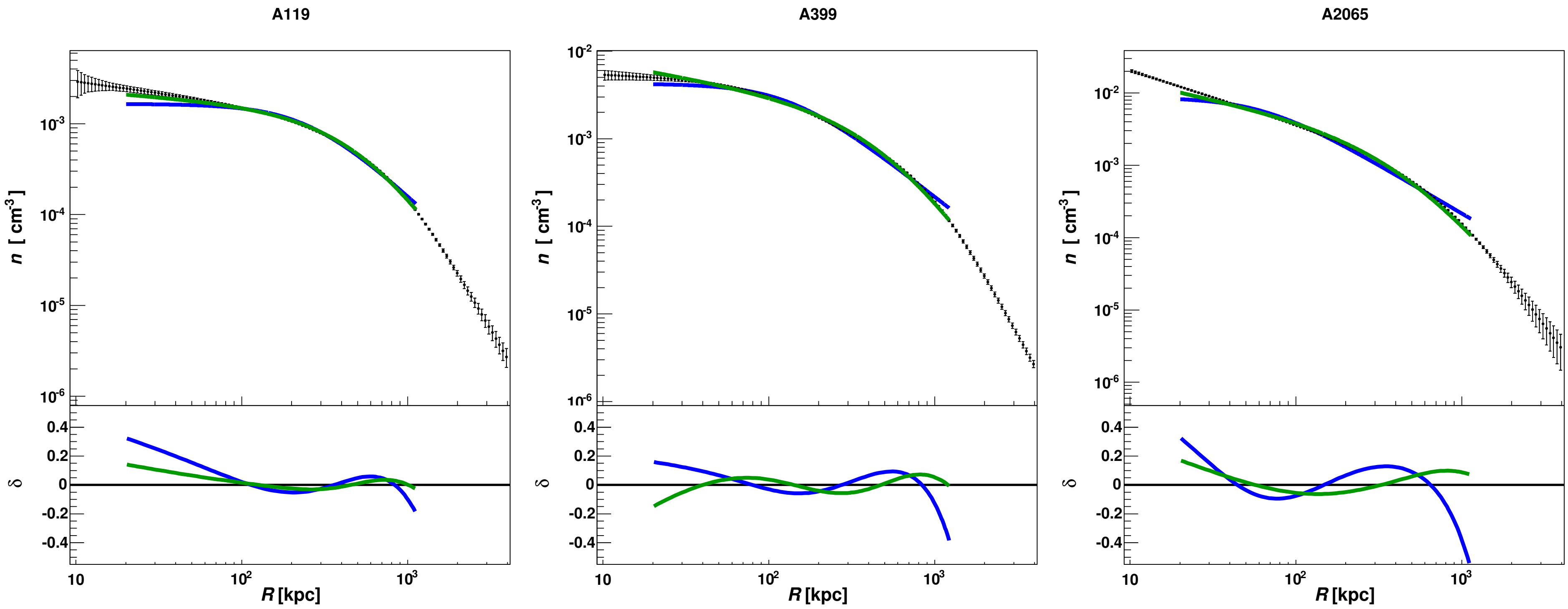
Comparison with β-Model

- Relaxed Clusters:



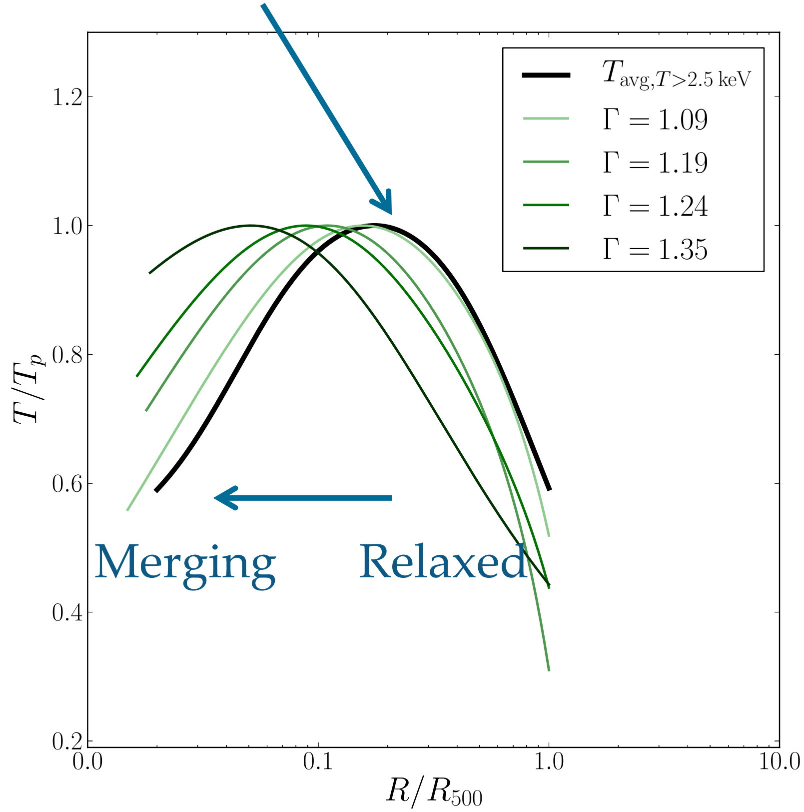
Comparison with β-Model

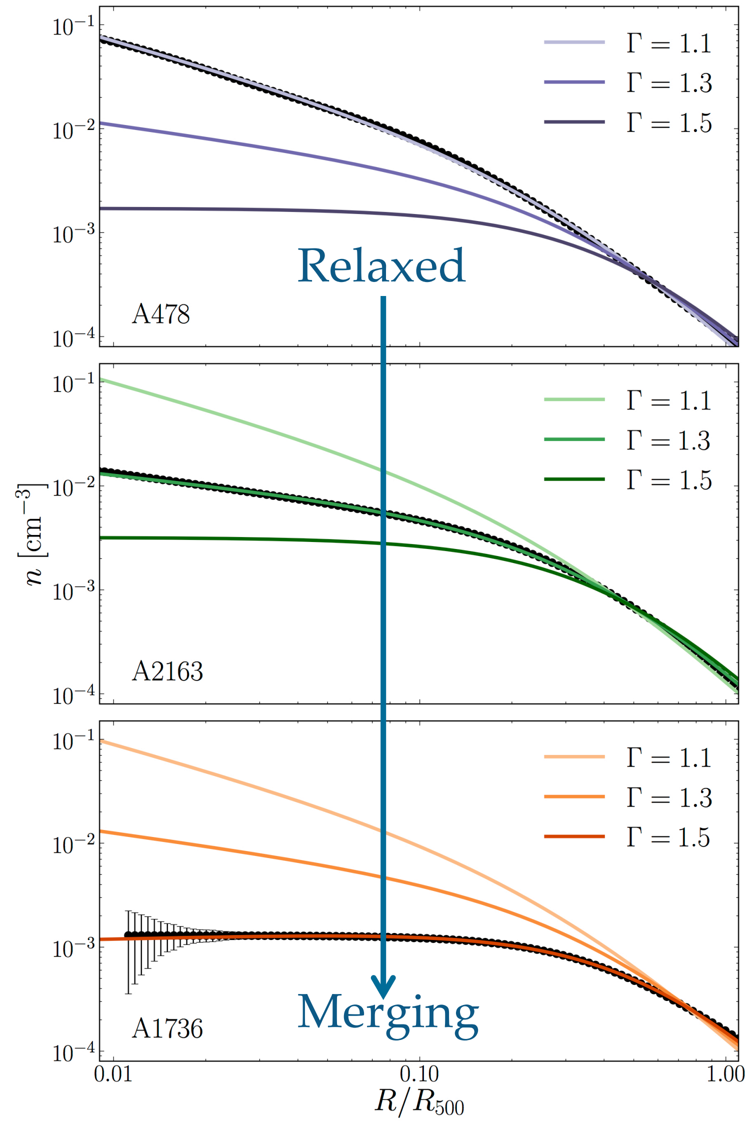
- Merging Clusters:



Comparison with X-ray Observations

Average relaxed cluster T profile of Vikhlinin et al. (2006)





Prospects

- We used simple assumptions to guide the derivation of new families of gas profiles; the fiducial profile is consistent with X-ray observations of cluster interiors and is simpler than competing models
- Later simulations of Lau et al. (2015) agree with our model's predictions for how gas traces DM in cluster outskirts
- Can extend models with additional physics of galaxy clusters
- Future observational efforts can constrain density jumps via weak lensing and deep X-ray data

Density Jumps in Galaxy Profiles

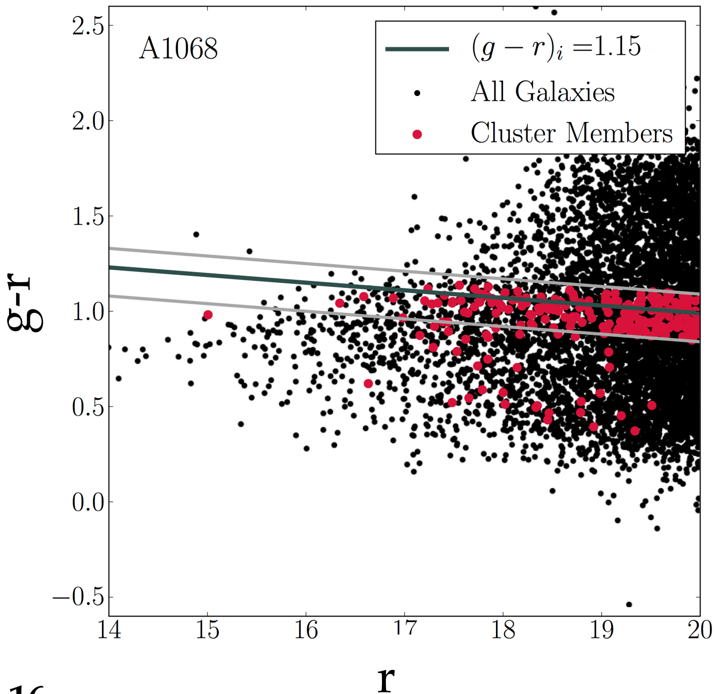
- Detecting the dark matter density jump in data would provide a test of the nature of dark matter

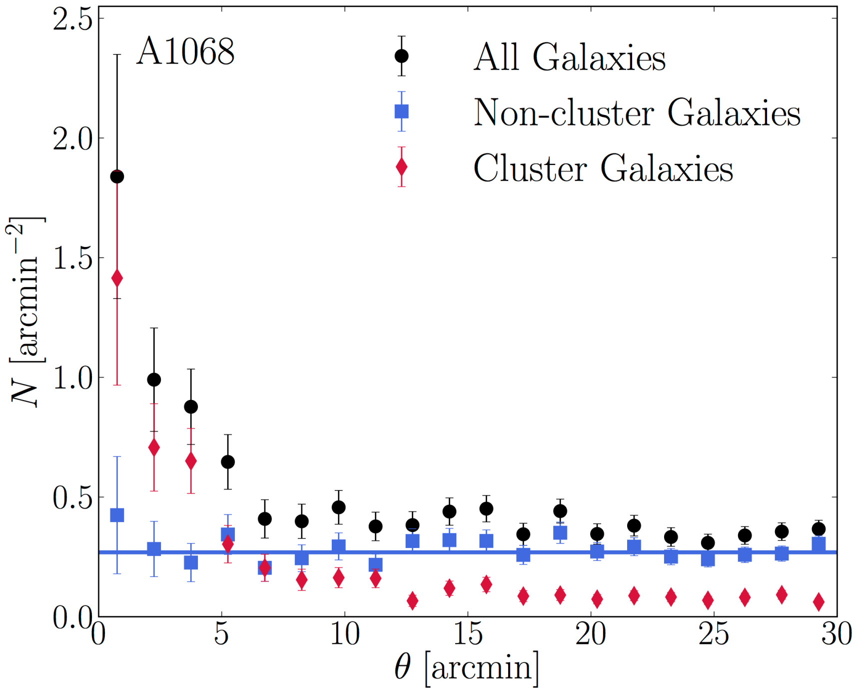
- Since the cluster member galaxies are expected to follow similar collisionless dynamics as the dark matter, the density jump should be present in the galaxy distribution as well

- **Need methods to probe galaxy density jump observationally**

Data

- Sample of 56 clusters (~16 groups) at $0.1 < z < 0.3$ from Rines et al. (2013)
- Select cluster members via SDSS photometry and R13 spectroscopy





Models

- Density Jump model (variant on model of Diemer & Kravtsov 2014):

$$n_{\rm DJ}(r) = n_{\rm NFW}(r)\left[1+\left(\frac{r}{r_t}\right)^{\beta}\right]^{-\frac{\gamma}{\beta}} + n_m\left[b_e\left(\frac{r}{5R_{200}}\right)^{-s_e}+1\right]$$

$$r_t = \left(0.62 + 1.18e^{-2\Gamma/3}\right) \times R_{200}$$

- Alternative model:

$$n_{\rm NFWO}(r) = n_{\rm NFW}(r) + n_m\left[b_e\left(\frac{r}{5R_{200}}\right)^{-s_e}+1\right]$$

- Project both models along line-of-sight:

$$N(R) = 2\int_R^{\infty} \frac{n(r)r}{\sqrt{r^2 - R^2}}dr$$

Information Criteria

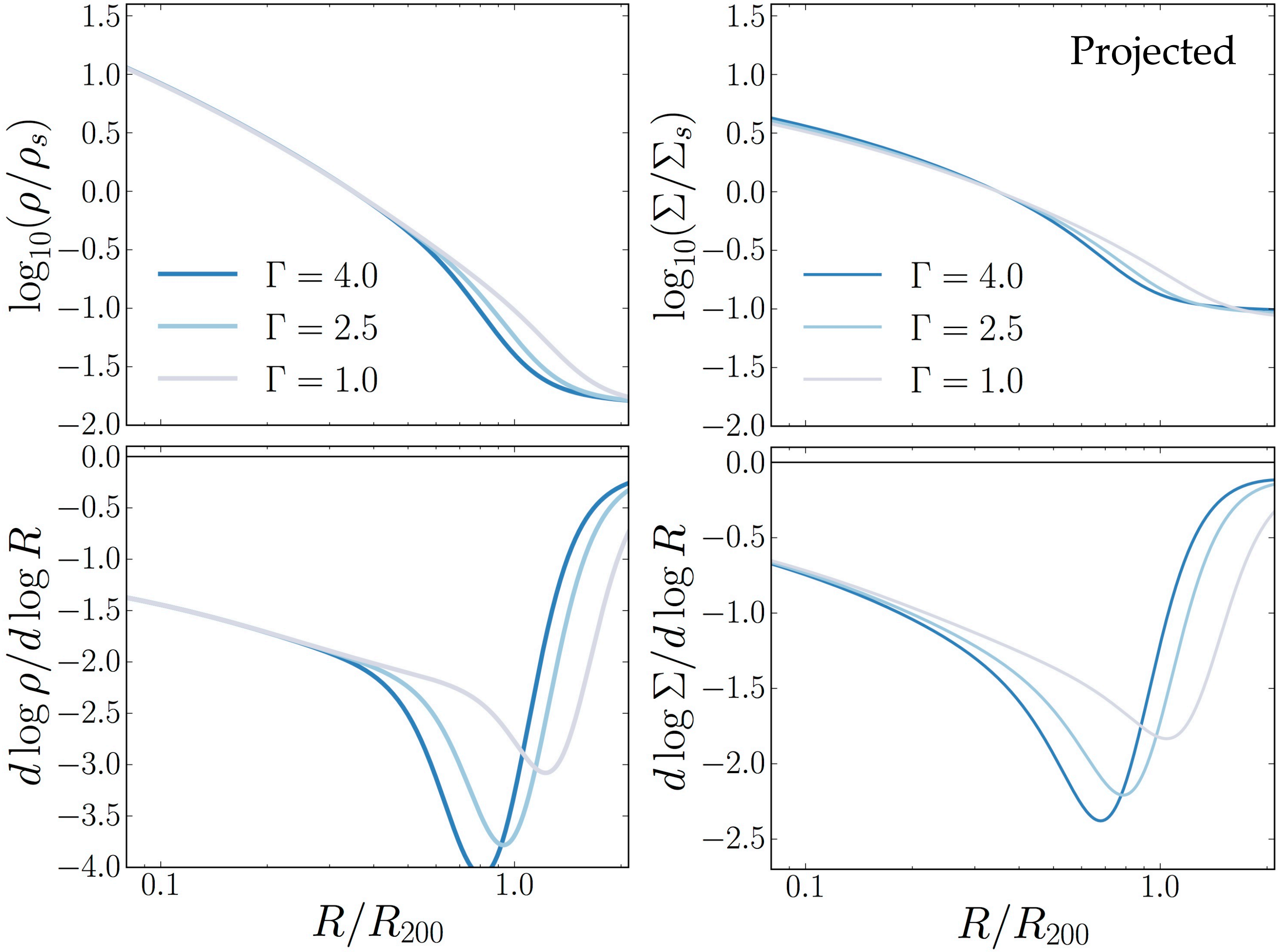
- Aikake Information Criterion (Aikake 1974) and Bayesian Information Criterion (Schwartz 1978) provide a means of comparing the fits

$$\mathrm{AIC} = \chi^2 + 2p + \frac{2p(p+1)}{\mathcal{N} - p - 1}$$

$$\mathrm{BIC} = \chi^2 + p\ln(\mathcal{N})$$

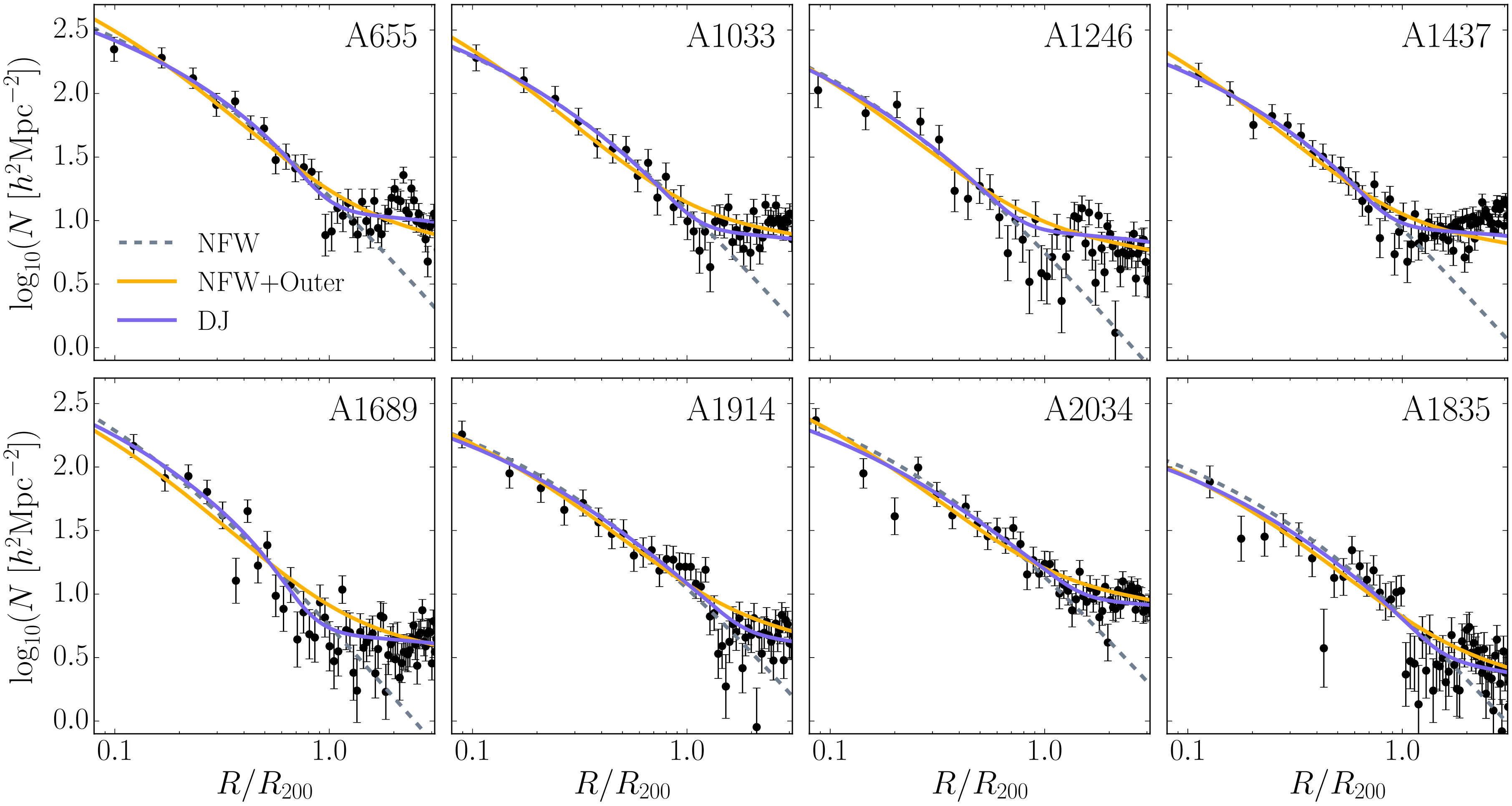
- Compute differences ΔIC:
  - ΔIC = 1-5 indicate positive evidence in favor of the model with the lower IC value
  - ΔIC > 5 indicate strong evidence in favor of the model with the lower IC value

Density Jumps in Projection



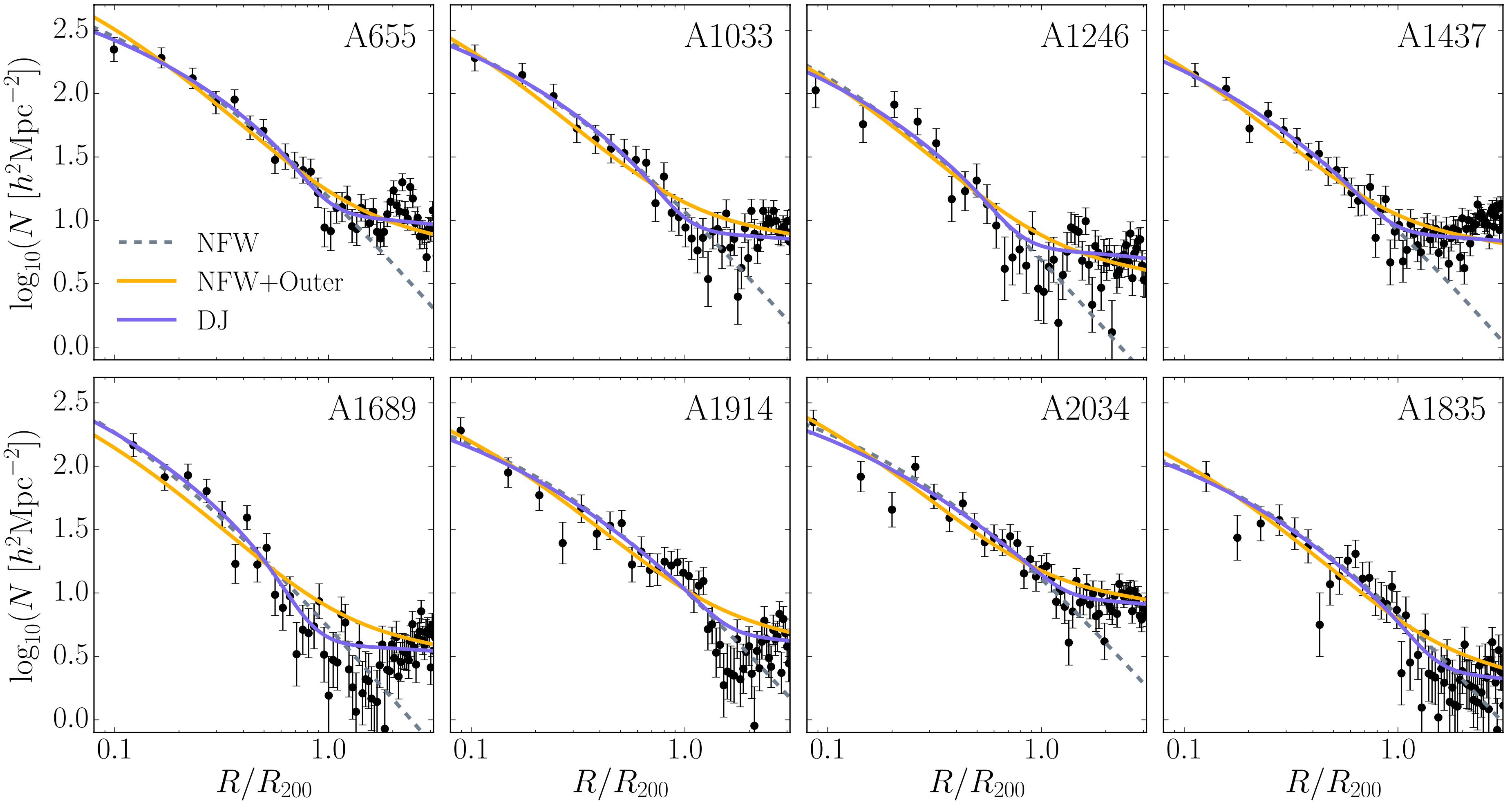
Results

- Photometric Selection (8 clusters with $\Delta IC > 5$)



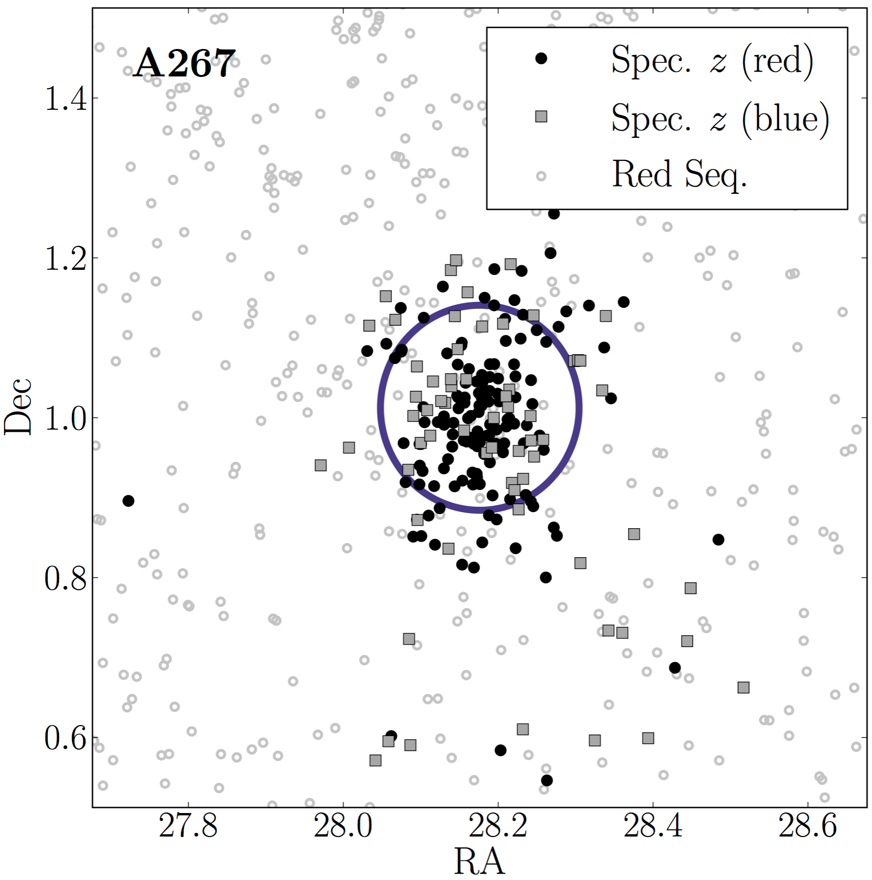
Results

- Photometry + Spectroscopy (16 clusters with $\Delta IC > 5$)



Prospects

- Detecting the density jump is challenging, but potentially possible in massive clusters
- Having a clean cluster member selection out to large radii is key
- Future work will require dense spectroscopy or secure photometric redshifts in outskirts
- Weak lensing can probe dark matter jump; comparison to the galaxy feature will yield insights into the dynamics of dark matter vs galaxies



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Introduction

- Galaxy redshift surveys use observed galaxy distribution to probe large-scale structure (LSS)
- Galaxies as tracers of underlying matter distribution: need to understand bias in order to make cosmological inferences
- Galaxy bias well-studied on small scales (< 40 h^{-1} Mpc; e.g., Swanson et al. 2008, Zehavi et al. 2011)
- **We will examine the bias to test whether galaxies trace LSS on larger scales**

Introduction

- Basic question: do massive red and blue galaxies at z~0.6 trace the same large-scale structure on intermediate scales (20<R<100 Mpc/h)?
- Approach: with

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x})}{\bar{\rho}} - 1 \quad \rightarrow \quad \delta_b(\mathbf{x}) = b_b\delta(\mathbf{x}), \quad \delta_r(\mathbf{x}) = b_r\delta(\mathbf{x})$$

- Correlation function: $\xi(\mathbf{R}) = \langle\delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{R})\rangle$

$$\begin{aligned} \xi_{bb}(\mathbf{R}) &= b_b^2\xi(\mathbf{R}), \\ \xi_{rr}(\mathbf{R}) &= b_r^2\xi(\mathbf{R}), \\ \xi_{br}(\mathbf{R}) &= b_b b_r\xi(\mathbf{R}) \end{aligned} \quad \rightarrow \quad r_\xi \equiv \frac{\xi_{br}}{\sqrt{\xi_{bb}\xi_{rr}}} = 1$$

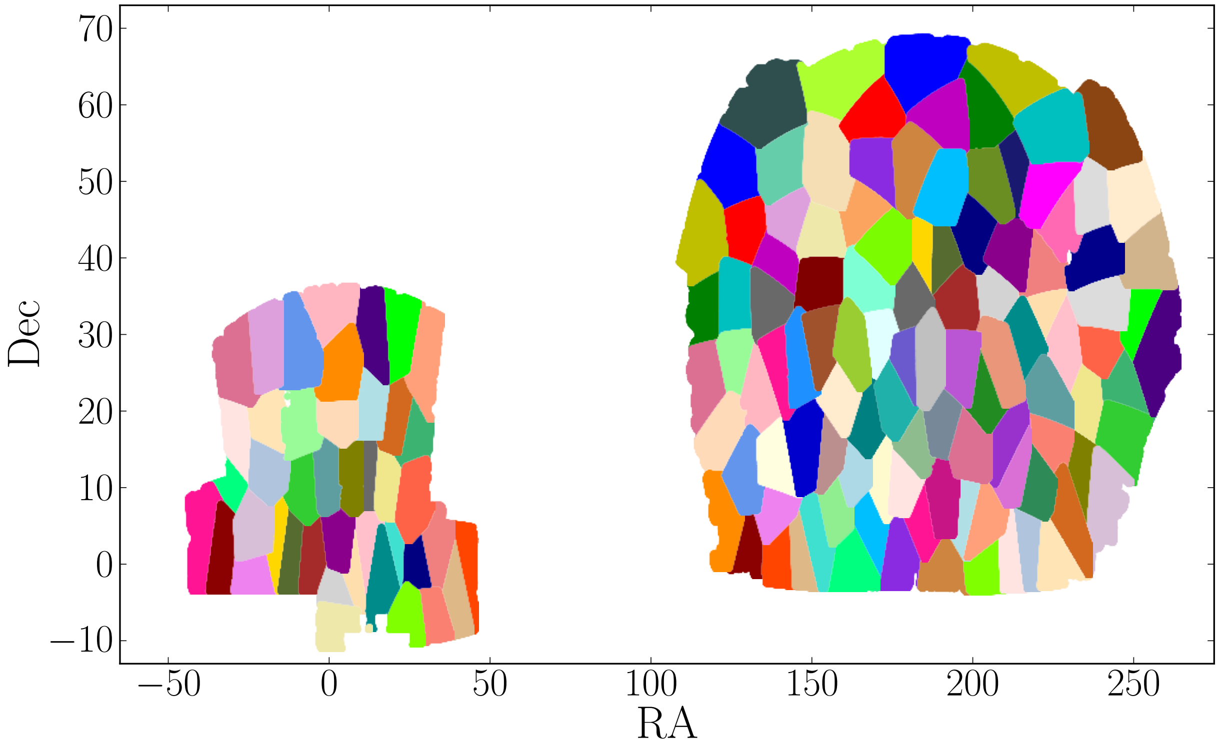
- But what if bias is stochastic? Define a random bias field (Dekel & Lahav 1999) for g=b,r:

$$\epsilon_g(\mathbf{x}) \equiv \delta_g(\mathbf{x}) - b_g\delta(\mathbf{x}) \quad \rightarrow \quad r_\xi \neq 1$$

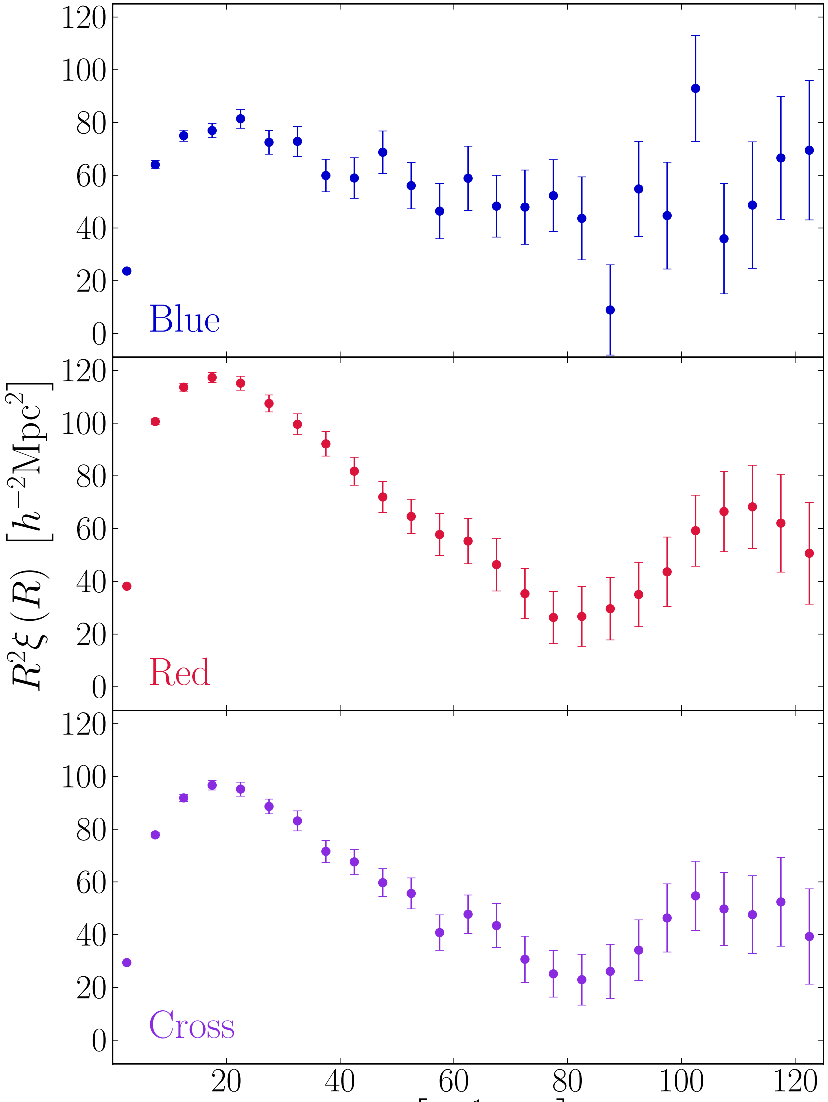
- Key to discerning the presence of stochasticity: measure r!

Data

- BOSS/CMASS sample of galaxies from SDSS DR12 at $0.55 < z < 0.65$
- Separate galaxies using Masters et al. (2011) color cut
  - g-i > 2.35 → red, g-i < 2.35 → blue
- Generate regions for jackknife error estimation
  - Method: Voronoi tesselation

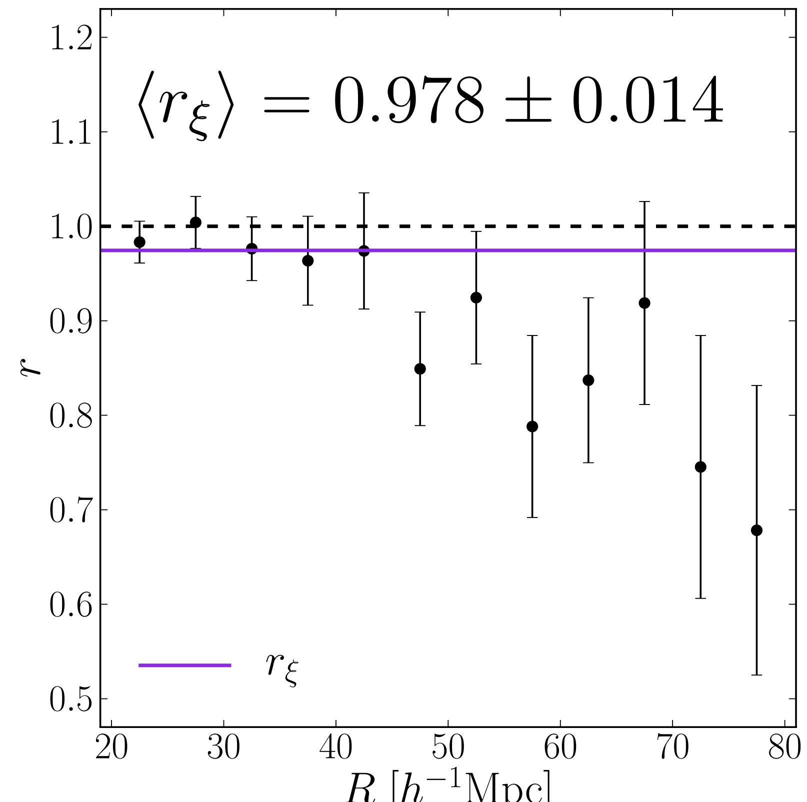


Measuring r



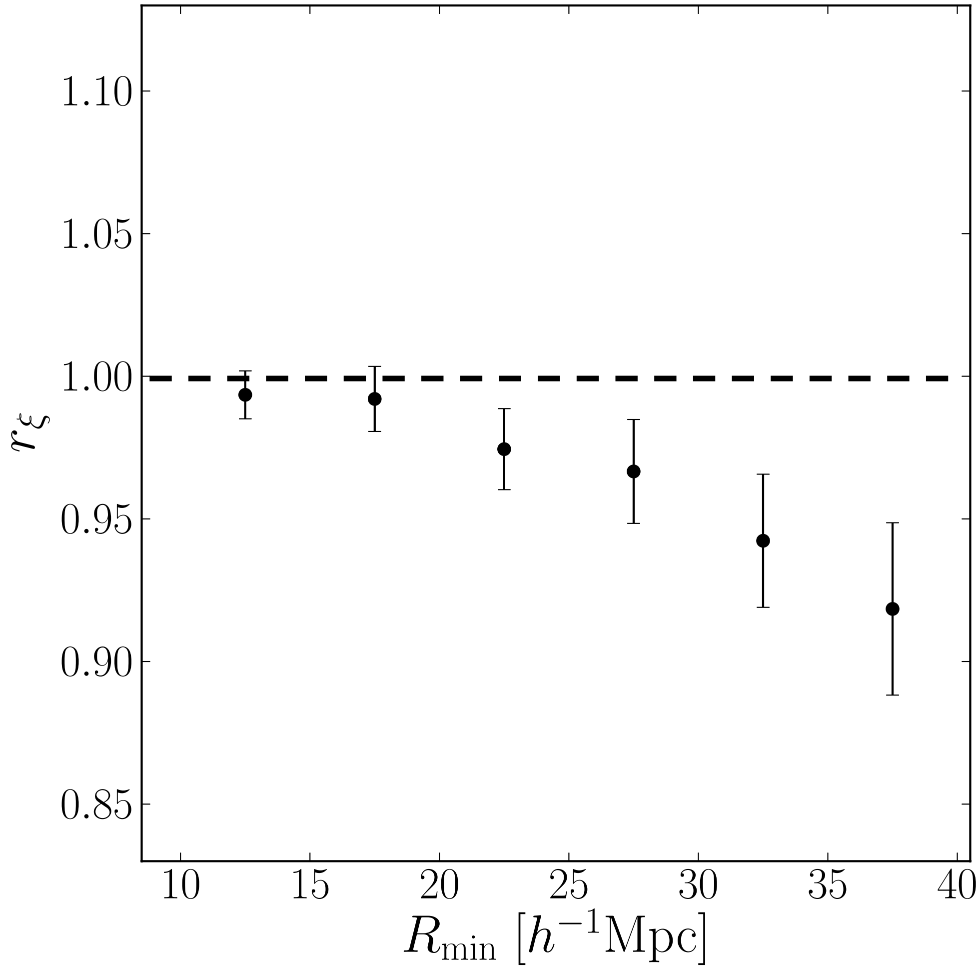
$$\xi(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}$$

$$r_\xi = \frac{\xi_{br}}{\sqrt{\xi_{rr}\xi_{bb}}}$$



Measuring r

- Varying the minimum fitting radius

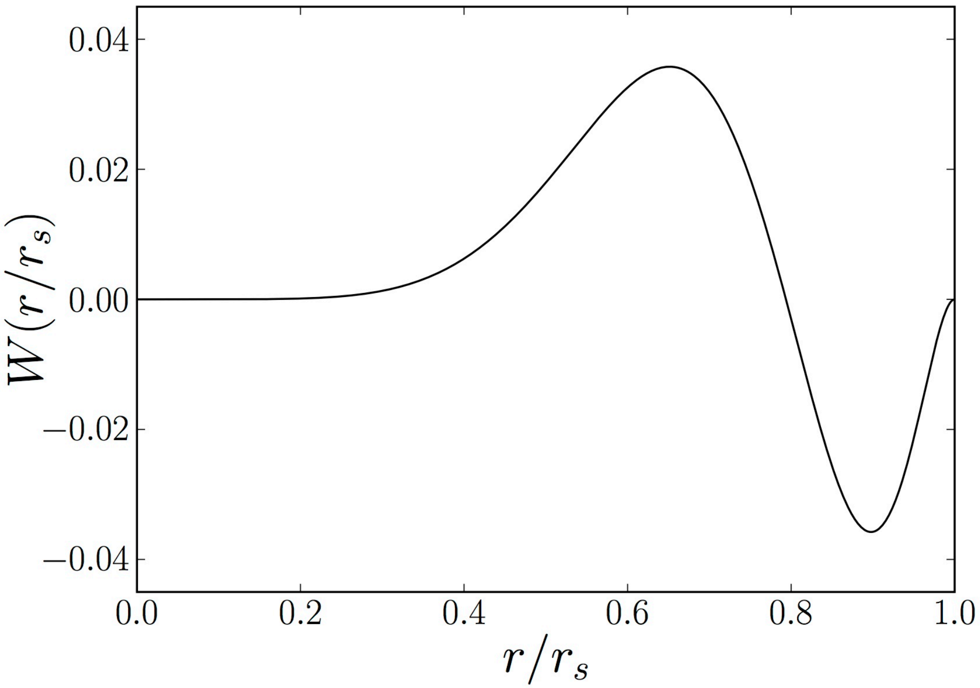


Measuring r

- Due to apparent large-scale systematics, useful to consider a statistic that is more immune
- Xu, et al. (2010) statistic:

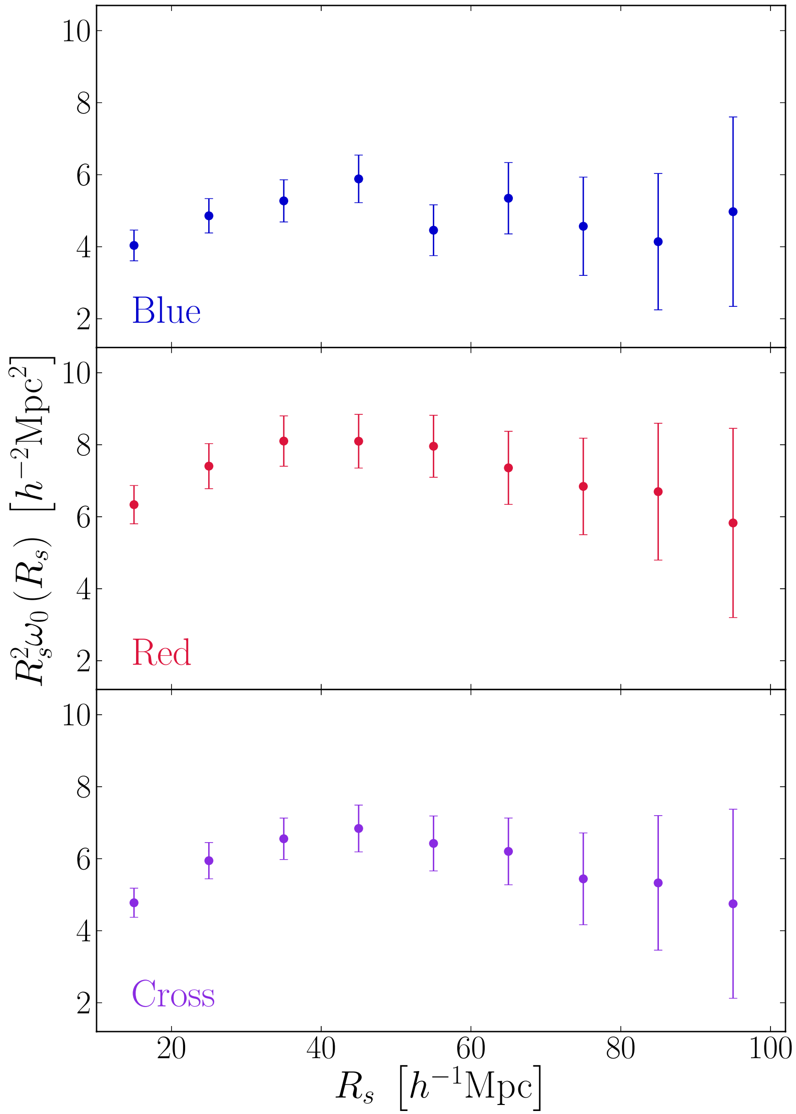
$$\omega(r_s) \equiv 4\pi \int r^2 dr W(r, r_s)\xi(r)$$

$$\omega(r_s) = \frac{V}{N_D^2} \sum_j \frac{W(r_j, r_s)}{\Phi(r_j)}$$



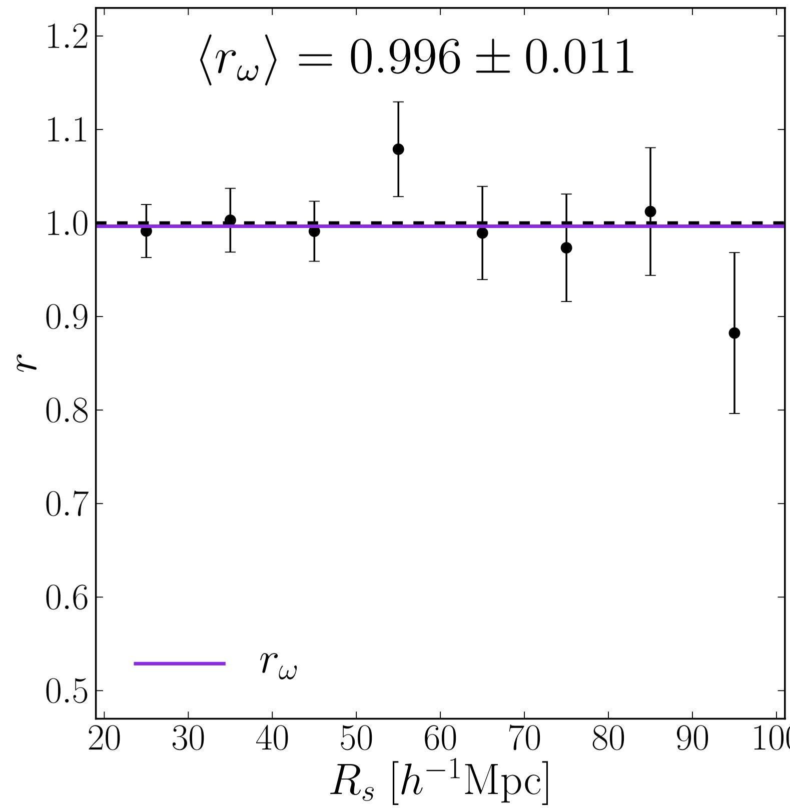
- ω can be expressed as a simple count over pairs (Padmanabhan et al. 2007)

Measuring r



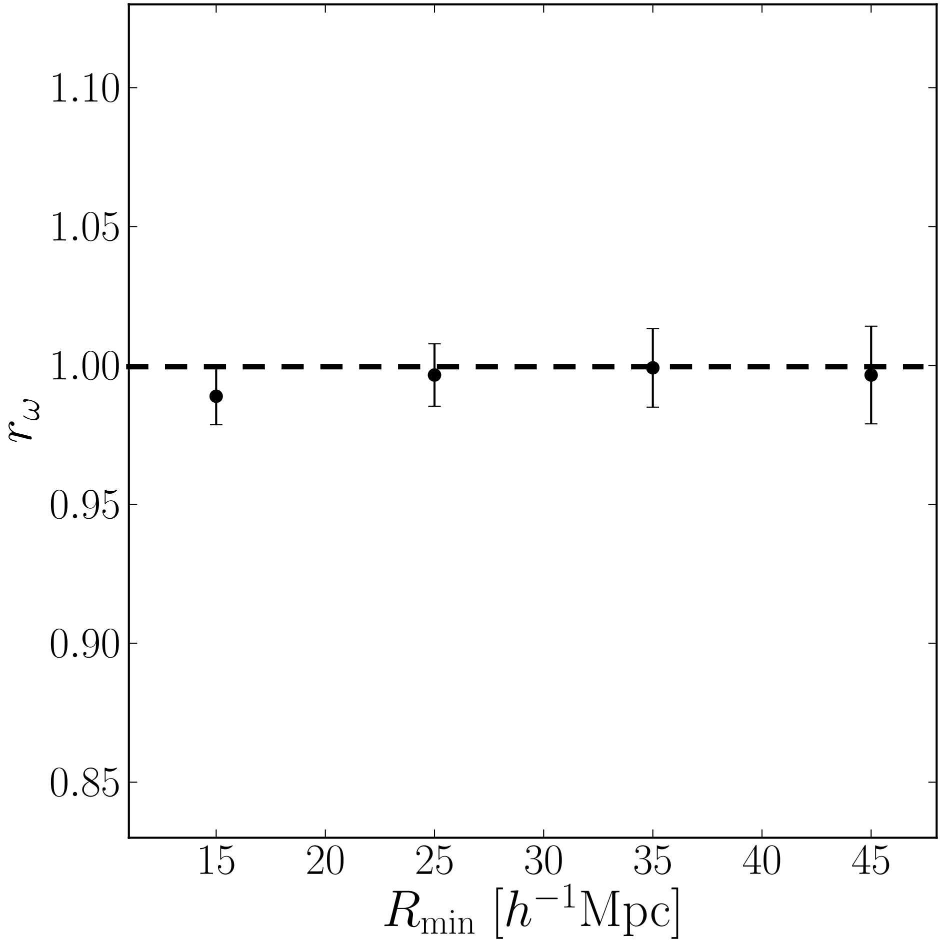
$$\omega(r_s) = \frac{V}{N_D^2}\sum_j \frac{W(r_j, r_s)}{\Phi(r_j)}$$

$$r_\omega = \frac{\omega_{br}}{\sqrt{\omega_{rr}\omega_{bb}}}$$



Measuring r

- Varying the minimum fitting radius



Prospects

- At the sensitivity of BOSS, we find that red and blue galaxies do trace the same large-scale structure
  - We find low levels of stochasticity between massive red and blue galaxies at $z\sim0.6$, with 2σ bounds of $r > 0.95$ using correlation functions and $r > 0.974$ using the ω statistic
- The ω statistic is a promising tool for analyzing the stochasticity; will likely benefit future investigations at larger scales

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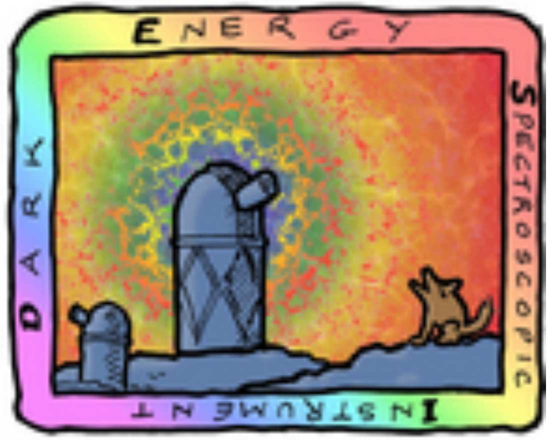
DESI

- The Dark Energy Spectroscopic Instrument: next-generation galaxy redshift survey
- Successor to SDSS-III/BOSS and SDSS-IV/eBOSS and headquartered here at LBNL
- First light in 2019
- Will measure redshifts for 21 M high redshift galaxies, 2 M quasars, 10 M bright galaxies
- Requires imaging surveys for target selection: DECaLS, MzLS, BASS



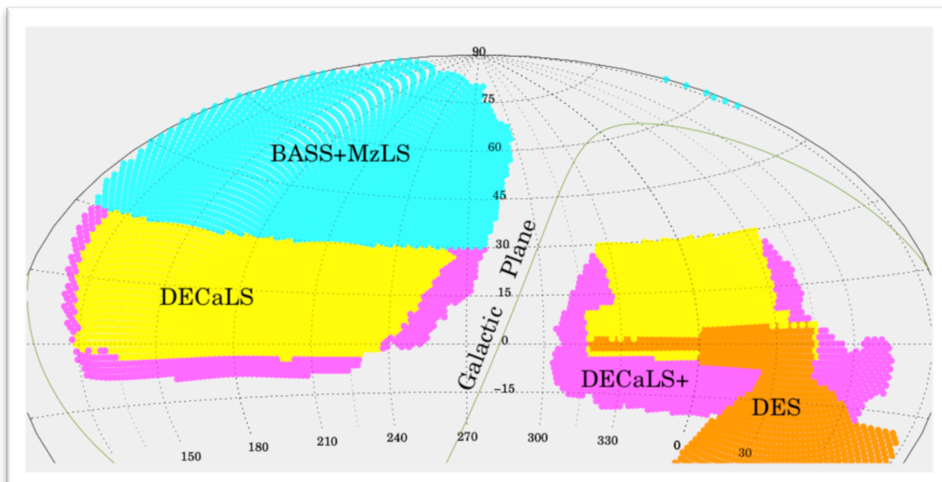


Image courtesy of A. Dey

DECaLS

- The DECam Legacy Survey: necessary imaging survey for DESI targeting and public legacy survey
- High-quality Blanco/DECam *grz* imaging of 6700 sq deg of the SDSS footprint at -10 < Dec < +30
- Data Release 1 already available at legacysurvey.org

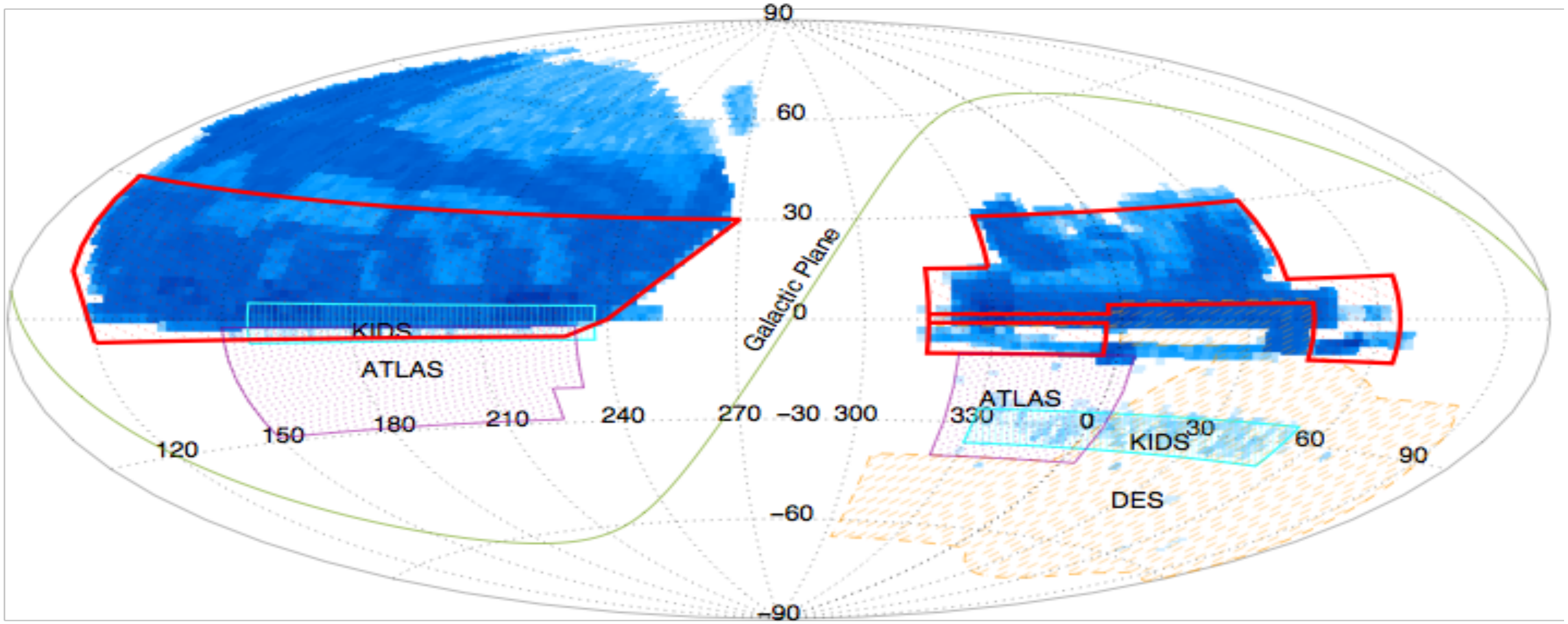
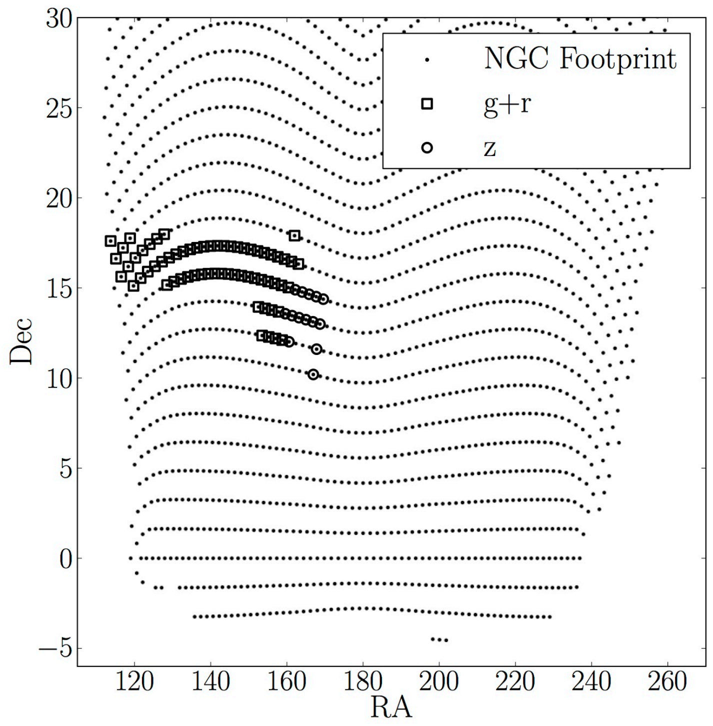


Image courtesy of D. Schlegel

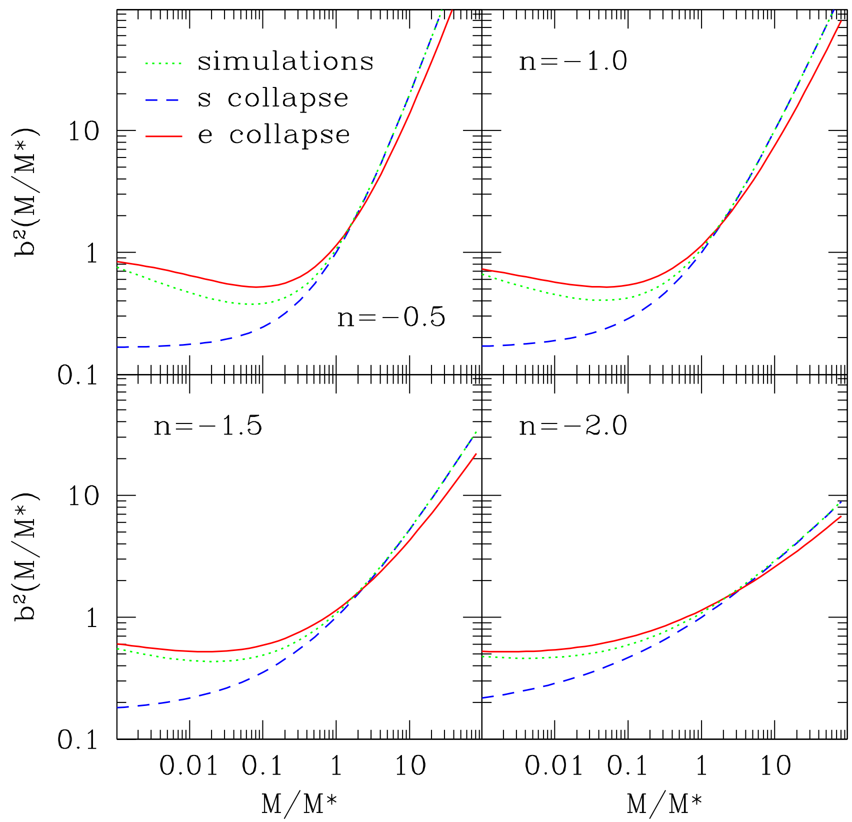
DECaLS

- Scheduling & Observing Strategy:
  - Requirements:
    - g+r back-to-back in moon-down time
    - z in moon-up time and twilight
    - Passes selected depending on conditions
    - Exposure times scaled to conditions
  - Priorities:
    - Avoid moon & planets
    - Avoid large slews
    - Maximize immediate scientific use



Galaxy Clusters and DESI

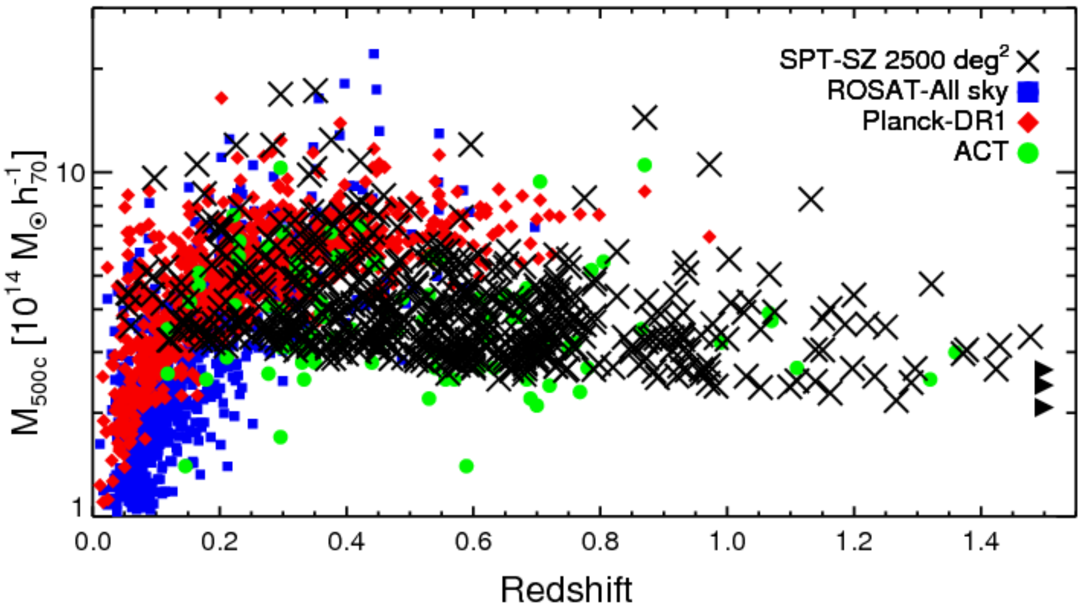
- DESI will enable a wealth of cluster-related projects
  - Spectra of cluster members out to z~1
  - Cluster cosmology: N(m,z)
    - DESI: redshifts
    - ACT, Planck: cluster detection, SZ masses
    - eROSITA: low-z cluster detection, X-ray masses
    - Imaging Surveys: lensing masses
  - Use clusters as tracers of mass distribution
    - Measure bias parameter of clusters and derive mass
    - Measure BAO



Above: Sheth, Mo, & Tormen (2001)

Galaxy Clusters and DESI

- Clusters cont.
  - Photometry +Spectroscopy
    - Can detect clusters/ groups to lower mass ranges than SZ, X-rays
    - Some methods already implemented for SDSS, DES, etc



Above: Bleem et al. (2015)

Summary

- Galaxy Cluster Outskirts
  - Density jumps in the gas, dark matter, and galaxy profiles are predicted by long-standing analytical models of structure formation and recent simulations
  - Observing these density jumps will provide compelling evidence in favor of our current understanding of the processes of infall and accretion, and test the nature of dark matter and the dynamics of galaxies in cluster outskirts
  - A feature consistent with the density jump should be detectable in massive clusters
- Large Scales
  - On large scales, galaxies of different types are expected to roughly trace the same large-scale structure
  - We tested this prediction using massive red and blue galaxies from BOSS/CMASS, finding that these types of galaxies do trace the same LSS, with low stochasticity ($r > 0.95$)
- Many interesting possibilities with galaxy clusters will be possible in the near future using DESI!