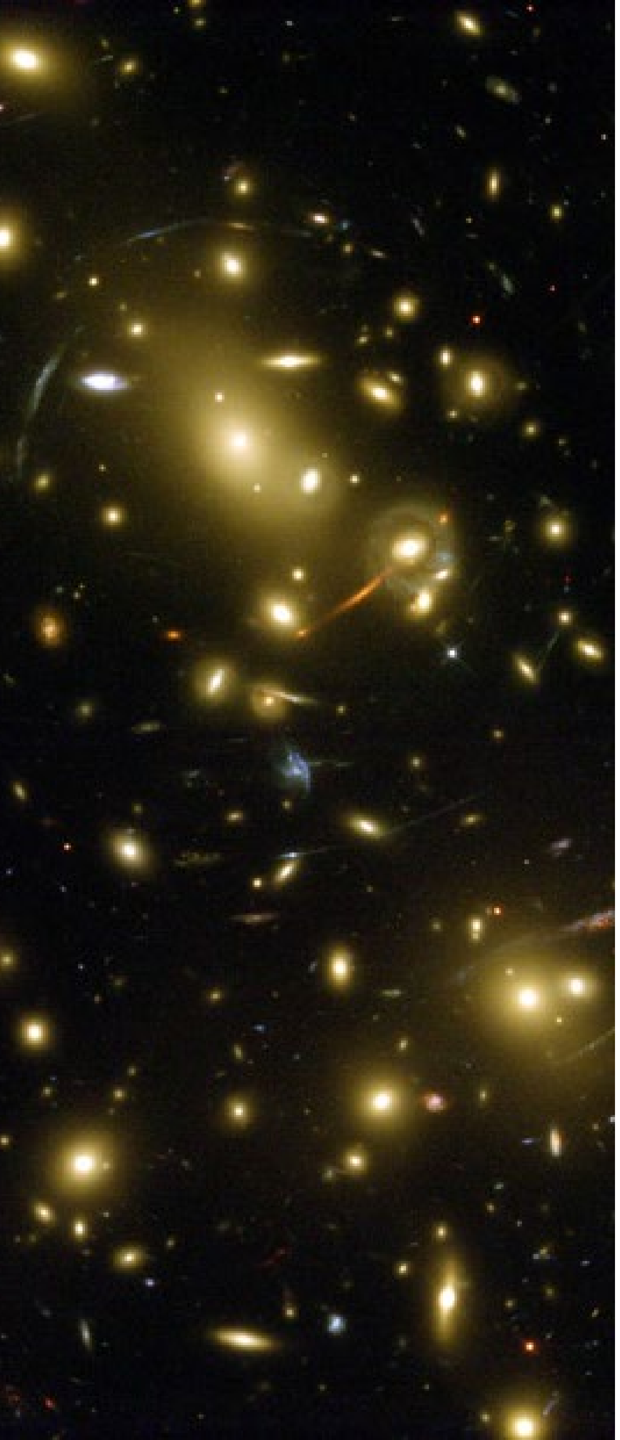

# Understanding the Quasi-Linear regime in the Halo Model using Dark Matter and Gas Profiles of Clusters

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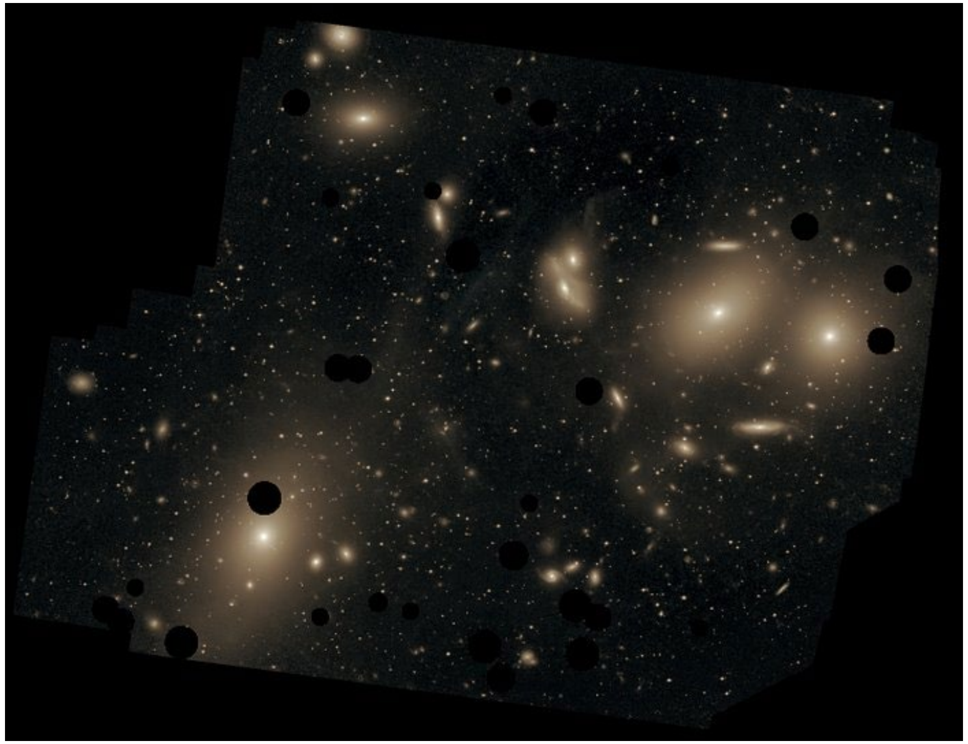
# Clusters of Galaxies

- Largest and most massive gravitationally bound structures in the Universe
- Laboratories in the sky to study a diverse set of astrophysical phenomena
- Formed at the sites of overdensities from the early universe, hence great tool to study the growth of the Large-Scale Structure
- e.g. Virgo Cluster, Coma Cluster



$$d \approx 54.8 \text{ M Ly} \approx 16.5 \text{ Mpc}$$

$$M_{cl} \approx 1.2 \times 10^{15} M_{\odot}$$

$$N_{gal} \approx 1200$$

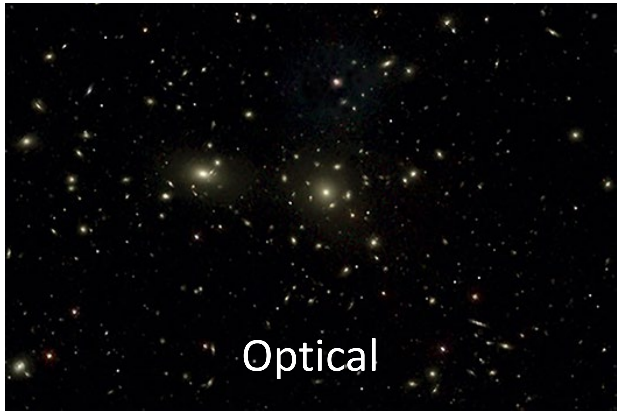
# Anatomy of a Cluster

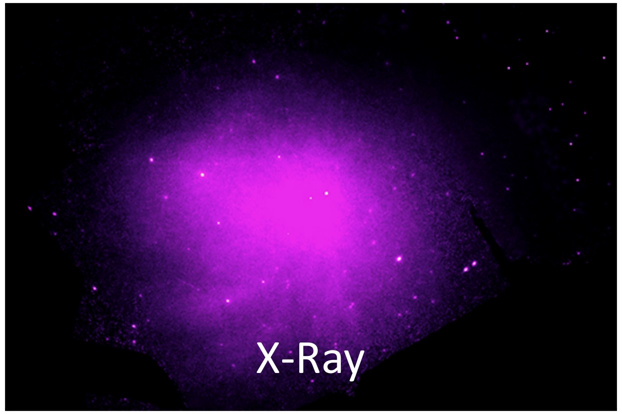
- Galaxy clusters look different depending on how one looks at them!
- Optical regime – Luminous Galaxies act as tracers of sub-structure, distortion in shapes due to lensing
- X-Ray regime – One of the brightest X-Ray sources, mostly from hot gas in form of Bremsstrahlung, Inverse Compton effect etc.

$$M_* \approx 2\%\ M_{cl} : \text{stars in galaxies}$$

$$M_{gas} \approx 13\%\ M_{cl} : \text{hot gas (1-10 keV)}$$

$$M_{DM} \approx 85\%\ M_{cl} : \text{dark matter}$$



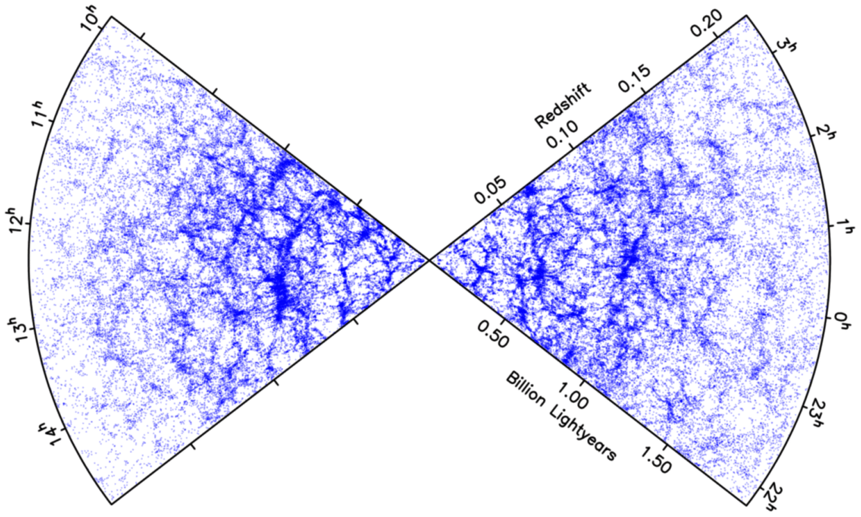




# Quantifying the ‘Clustering’

- We need a statistical tool to understand the distribution of galaxies and mass in clusters
- The Two-Point Correlation Function is a statistical measure of ‘lumpiness’ at different scales
- Since galaxies are tracers of mass, studying lumpiness in galaxies relates to understanding the mass distribution.
- The two-point correlation function forms a Fourier pair with the ‘Power Spectrum’ in k-space.
- $\xi(r)$ and $P(k)$ and higher order correlation function and power spectra are pillars of modern cosmology

$$\xi(|x_1 - x_2|) \equiv \langle \delta(x_1)\delta(x_2) \rangle$$

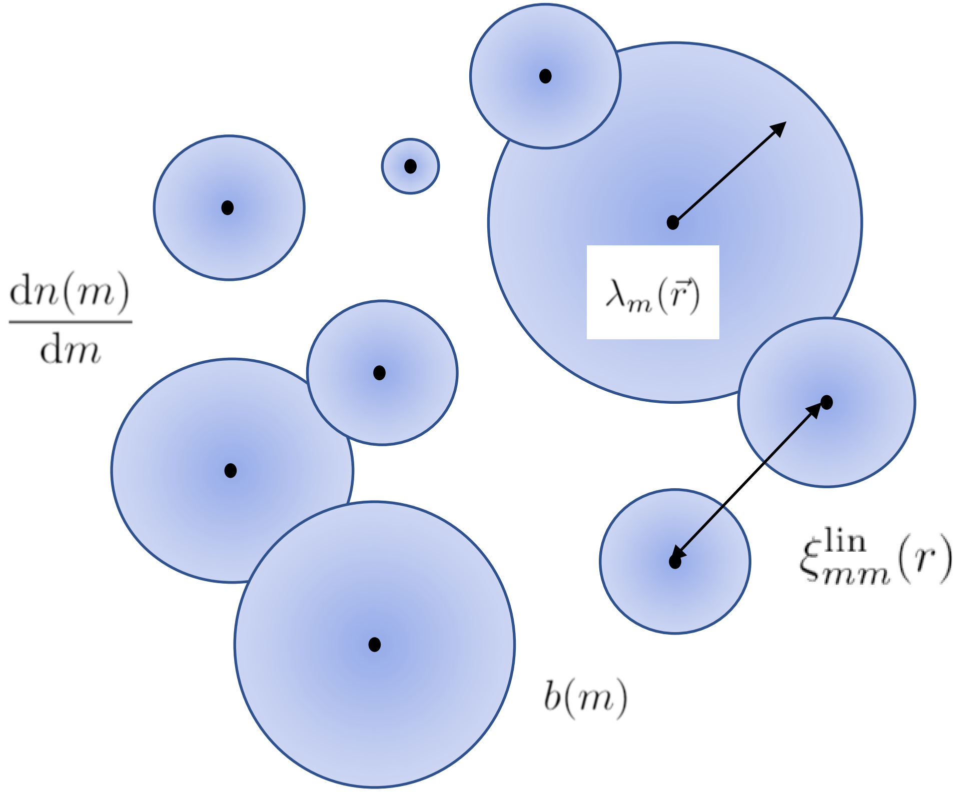
$$\delta(x) \equiv \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$$




$$\xi(r) = \frac{1}{2\pi^2} \int dk k^2 P(k) \frac{\sin(kr)}{kr}$$

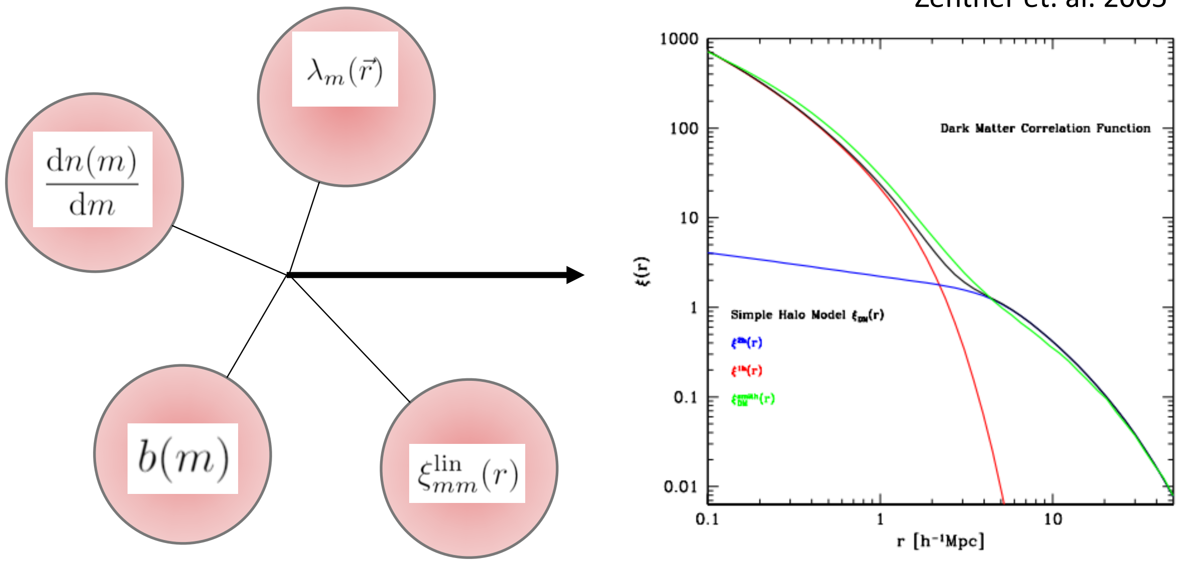
# How is dark-matter distributed in clusters?

- Halo Mass Function - quantifies how many halos of a certain mass exist at a given redshift and in a given cosmology
- Halo Density Profile – It gives the mass density of clusters as a function of radius e.g., NFW profiles from numerical sims
- Halo Bias – Since galaxies are biased tracers of DM, we need this term to go from number densities to DM densities
- Linear DM correlation function – It describes the density contrast of the universe as a function of scale



Zentner et. al. 2005

# The Halo Model for LSS




- It's a model that describes clustering of dark matter under the assumption that the dark matter is portioned over haloes
- The dark matter profile is given as a sum of the 'one-halo' term and the 'two-halo' term
- One Halo term comes from galaxy pairs within the halo, Two Halo term incorporates galaxy pairs across different haloes.
- One Halo dominates the small scale, non-linear regime and Two Halo dominates the linear, large-scale profile.

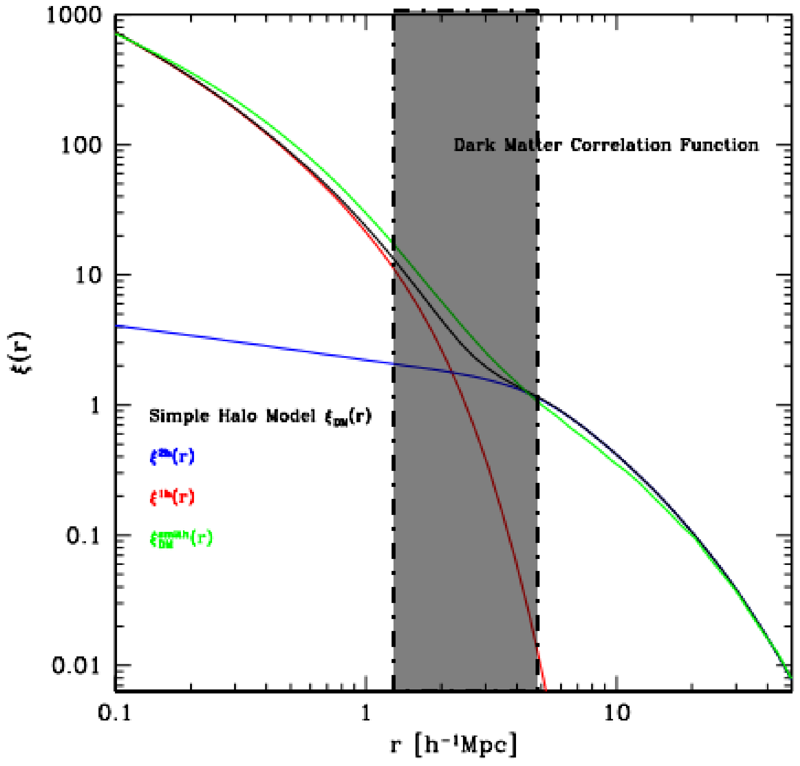
$$\xi_{\mathrm{DM}}(r) = \xi_{\mathrm{1h}}(r) + \xi_{\mathrm{2h}}(r)$$

$$\xi_{\mathrm{1h}} = \frac{1}{\rho_M^2} \int \mathrm{d}m\; m^2 \frac{\mathrm{d}n(m)}{\mathrm{d}m} \int \mathrm{d}^3x\; \lambda_m(\vec{x})\lambda(\vec{x}+\vec{r})$$

$$\xi_{\mathrm{2h}} = \frac{1}{\rho_M^2} \int \mathrm{d}m_1 \int \mathrm{d}m_2 m_1 \frac{\mathrm{d}n(m_1)}{\mathrm{d}m_1}\; m_2 \frac{\mathrm{d}n(m_2)}{\mathrm{d}m_2} \times \int \mathrm{d}^3x \int \mathrm{d}^3y\; \lambda_{m_1}(\vec{x})\lambda_{m_2}(\vec{y}) \times \xi_{hh}(\vec{x}-\vec{y}+\vec{r} \,|\, m_1, m_2)$$

# The Quasi-Linear Regime

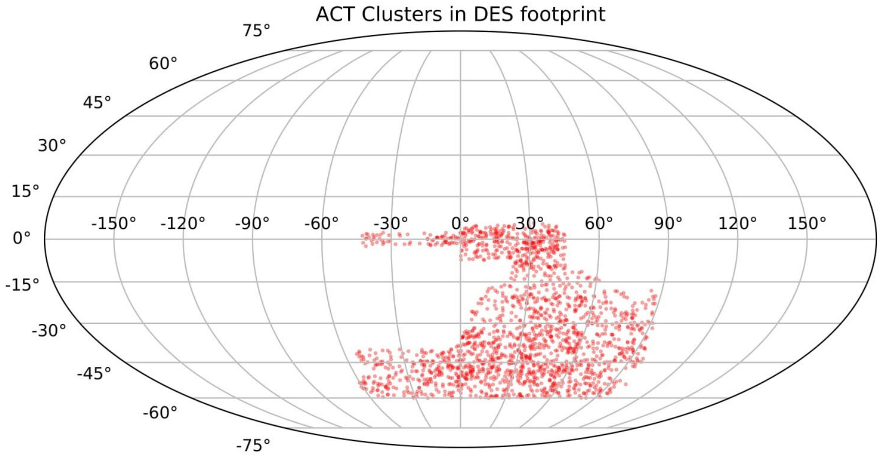
- It refers to the transition between 1-halo and 2-halo terms
- Direct sum of the two terms inadequately explains the profiles at roughly 1-5 Mpc, which is close to the virial radius of clusters
- The ‘linear correlation function’ in the 2-halo term cannot explain some non-linear effects near the transition e.g., Galaxy Splashback Effect

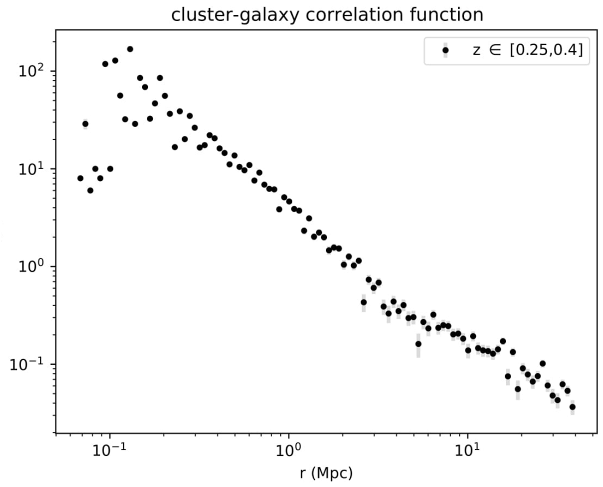


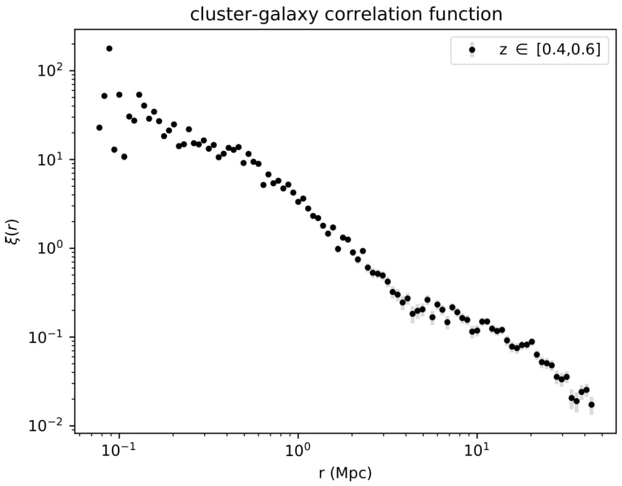

$$\xi_{hh}(r \mid m_1, m_2) = b(m_1)b(m_2)\xi^{\rm lin}_{mm}(r)$$

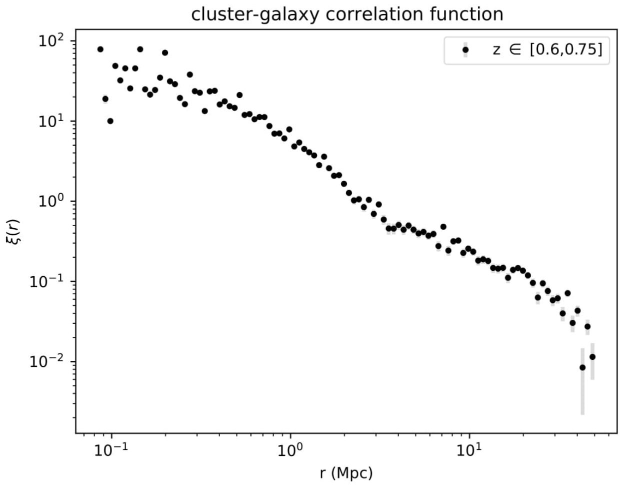
# Cluster-Galaxy Correlation Functions

- It's a cross correlation between two fields with point sources
- Indirect tracer of dark matter profile
- We use ACT's SZ selected clusters and RedMaGiC's magnitude limited galaxy samples
- The data is divided into redshift bins and a correlation function is computed



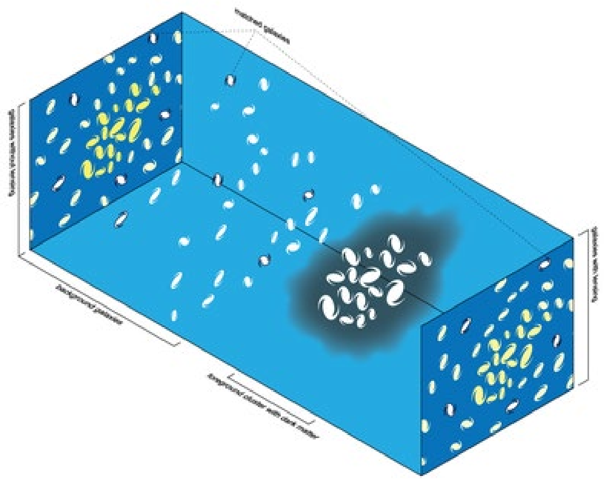



# Shear Profiles using Weak-Lensing

- Clusters are massive! They bend the light in the background
- Distortions in light bundles translates to changes in the actual shapes of galaxies – DES METACAL shape catalog
- The Shear Profile is the measurement of the tangential shear, which is again a two-point correlation function, but of a spin-2 field
- It's a direct tracer of dark matter profile of clusters



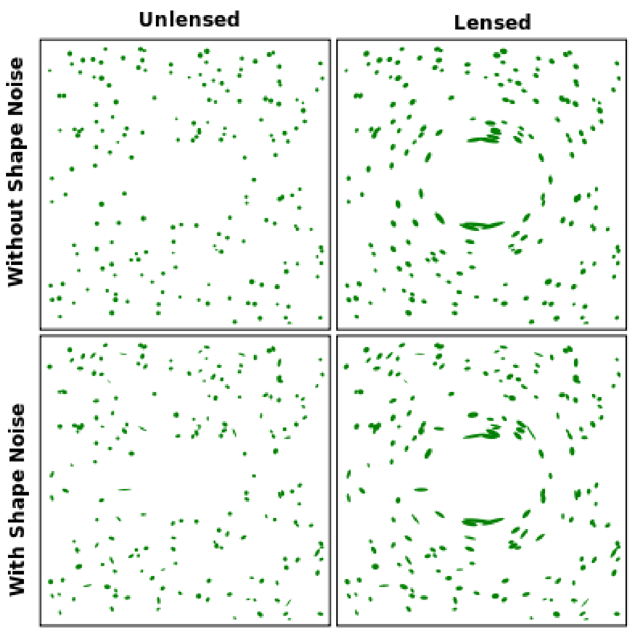
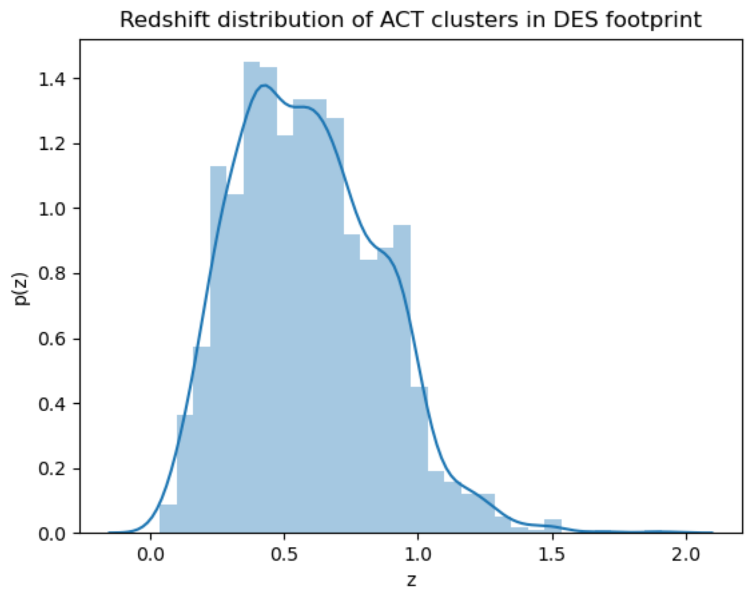
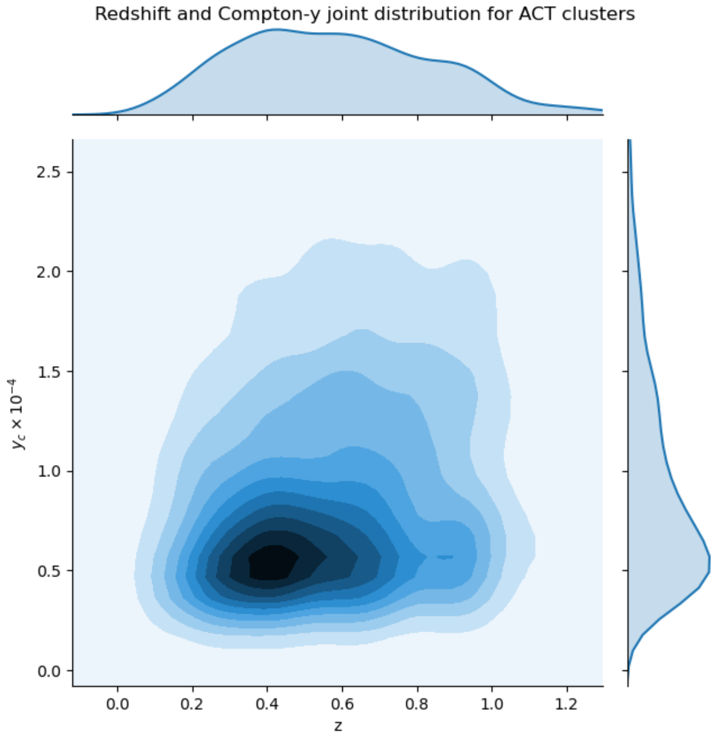
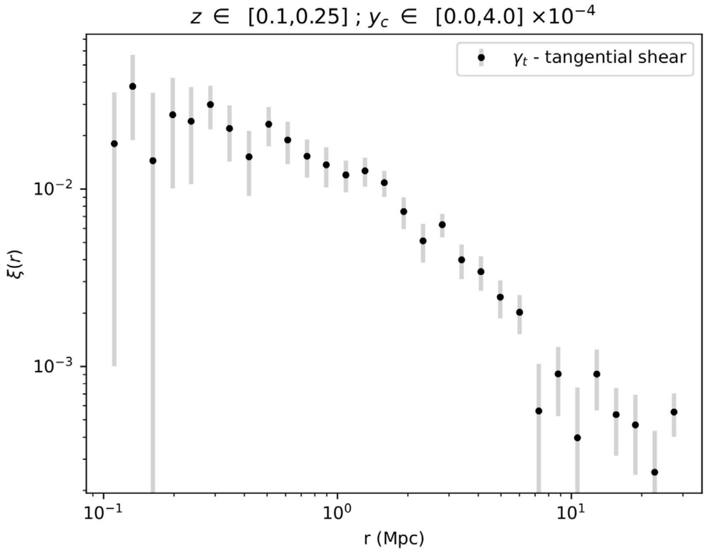
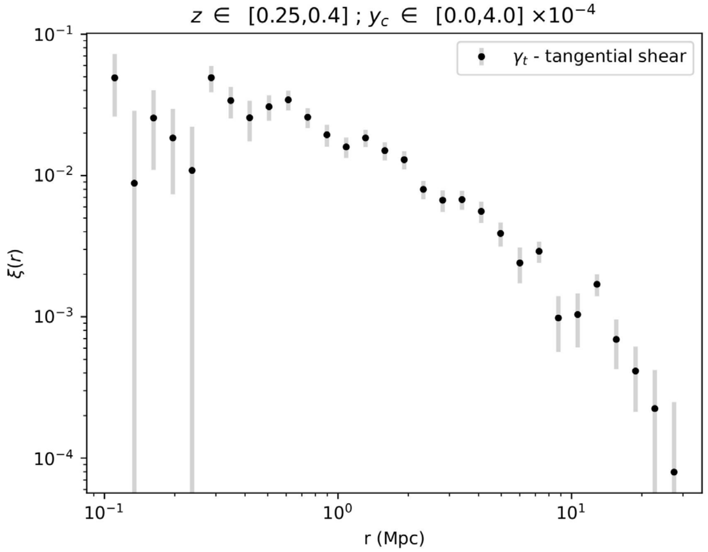


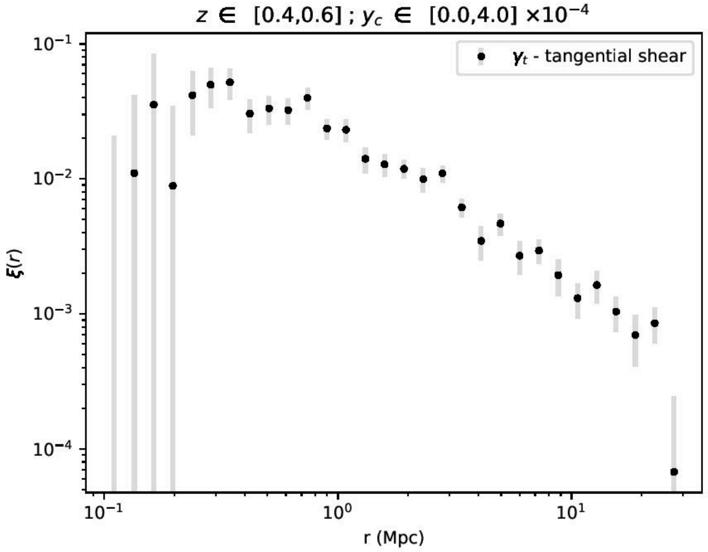

Fig: Wikipedia


Redshift distribution of ACT clusters in DES footprint
p(z)
z


Redshift and Compton-y joint distribution for ACT clusters
$y_c \times 10^{-4}$
z


$z \in [0.1,0.25]$ ; $y_c \in [0.0,4.0] \times 10^{-4}$
$\gamma_t$ - tangential shear
$\xi(r)$
r (Mpc)

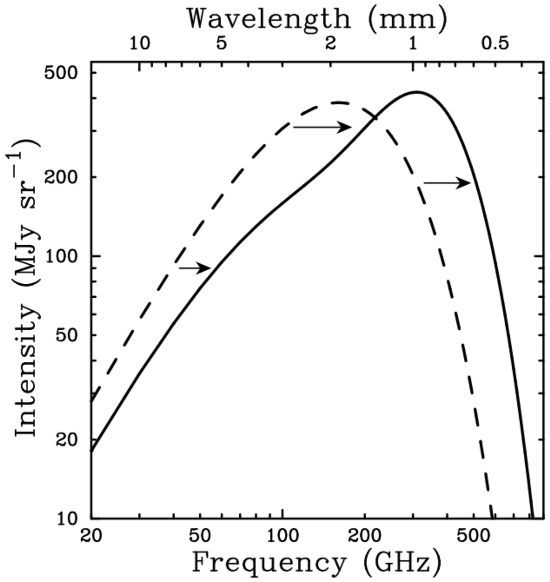

$z \in [0.25,0.4]$ ; $y_c \in [0.0,4.0] \times 10^{-4}$
$\gamma_t$ - tangential shear
$\xi(r)$
r (Mpc)

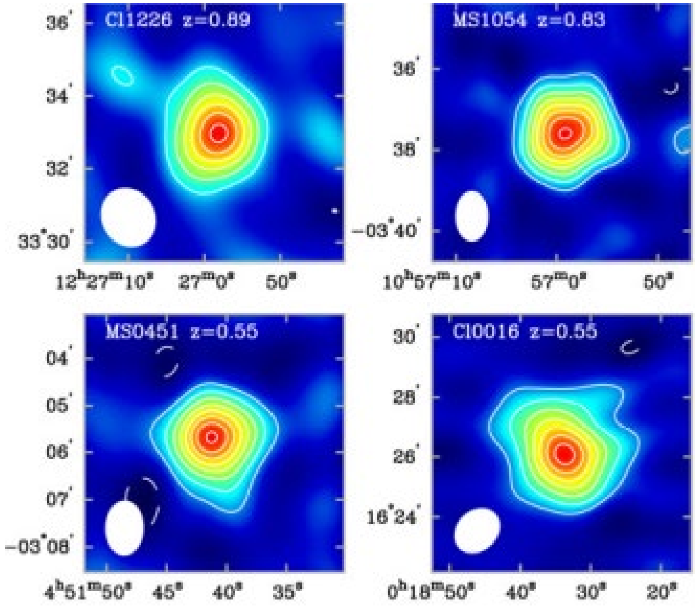

$z \in [0.4,0.6]$ ; $y_c \in [0.0,4.0] \times 10^{-4}$
$\gamma_t$ - tangential shear
$\xi(r)$
r (Mpc)

# Thermal SZ Effect

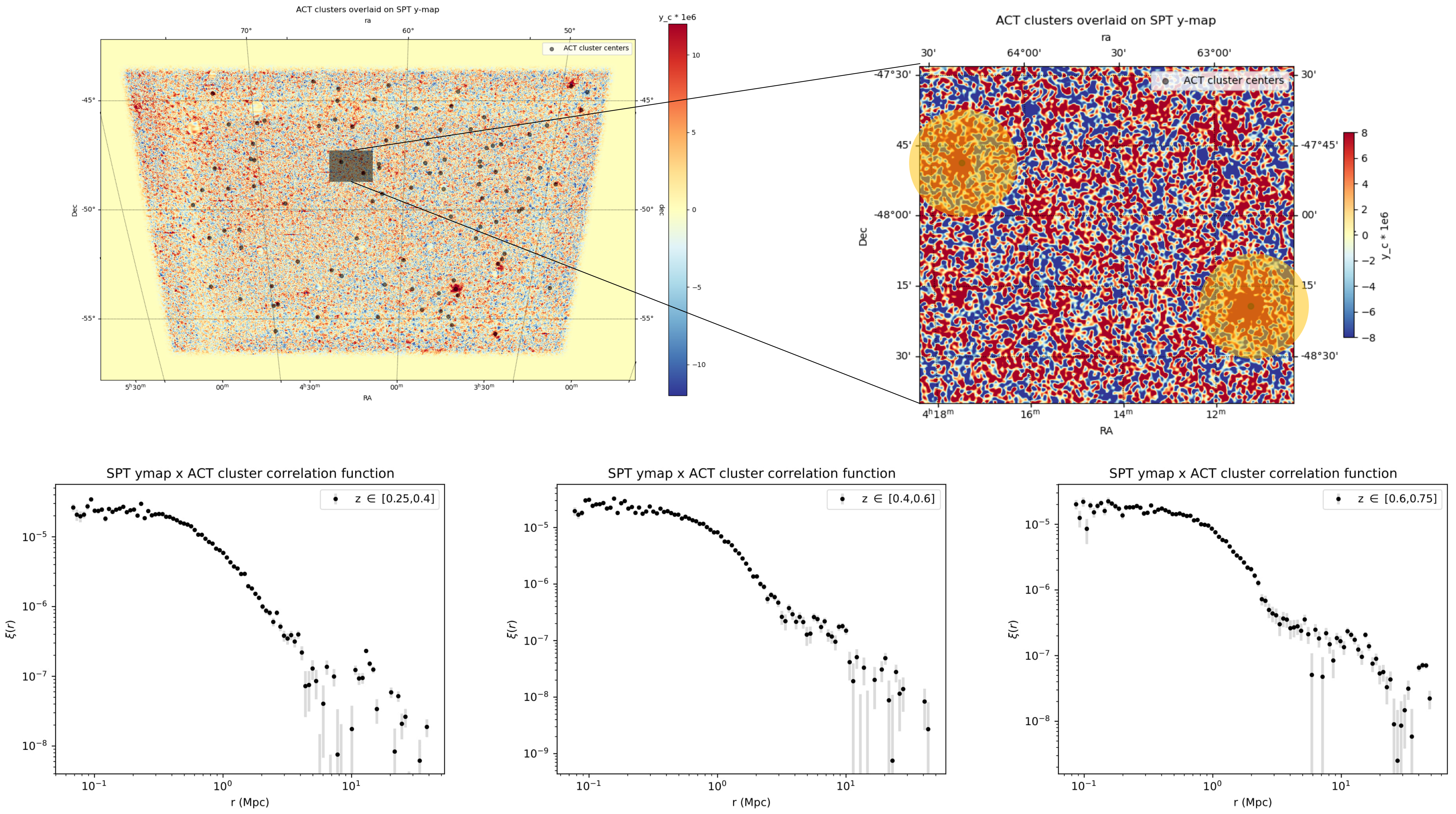
- Spectral distortion of the cosmic microwave background (CMB) through inverse Compton scattering by high-energy electrons in galaxy clusters
- We use a derived parameter – ‘Compton – y’ aka Temperature-weighted pressure along line of sight
- We use SPT’s y-maps and obtain a cross-correlation with ACT clusters in different redshift bins

$$\frac{\Delta T_{SZ}}{T_{CMB}} \propto \ y \equiv \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \ \mathrm{d}l$$



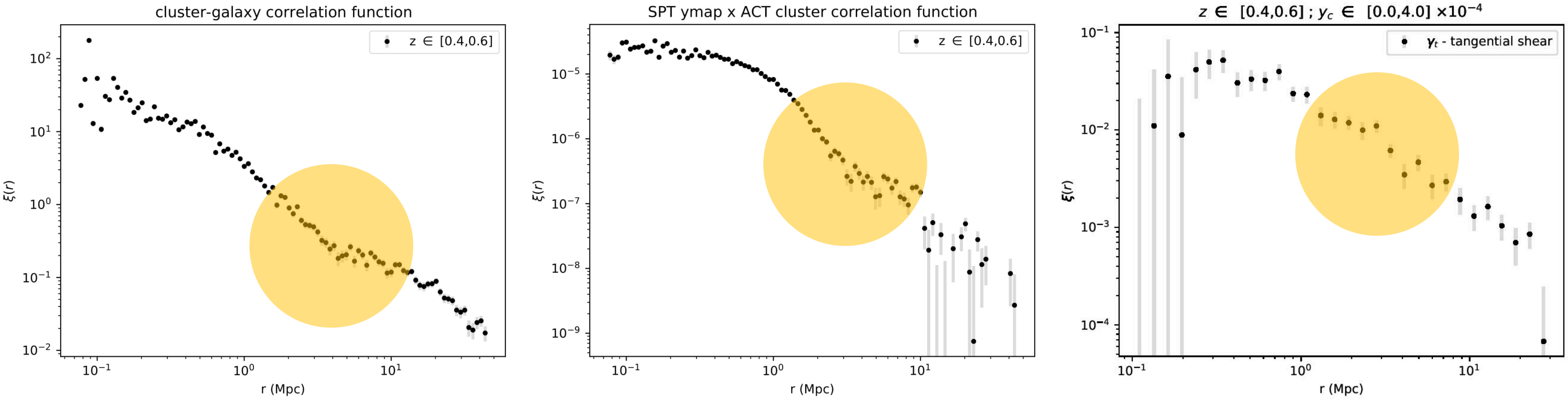




Carlstrom, Holder, Reese (2002)



ACT clusters overlaid on SPT y-map
ACT cluster centers
y_c * 1e6
RA
Dec
SPT ymap x ACT cluster correlation function
z ∈ [0.25,0.4]
z ∈ [0.4,0.6]
z ∈ [0.6,0.75]
ξ(r)
r (Mpc)

# The Quasi-Linear regime in the 3 tracers




Discontinuity at roughly 2-3 Mpc in all three profiles, which can be used to constraint a parameter that smoothens the transition!

# Ongoing work…

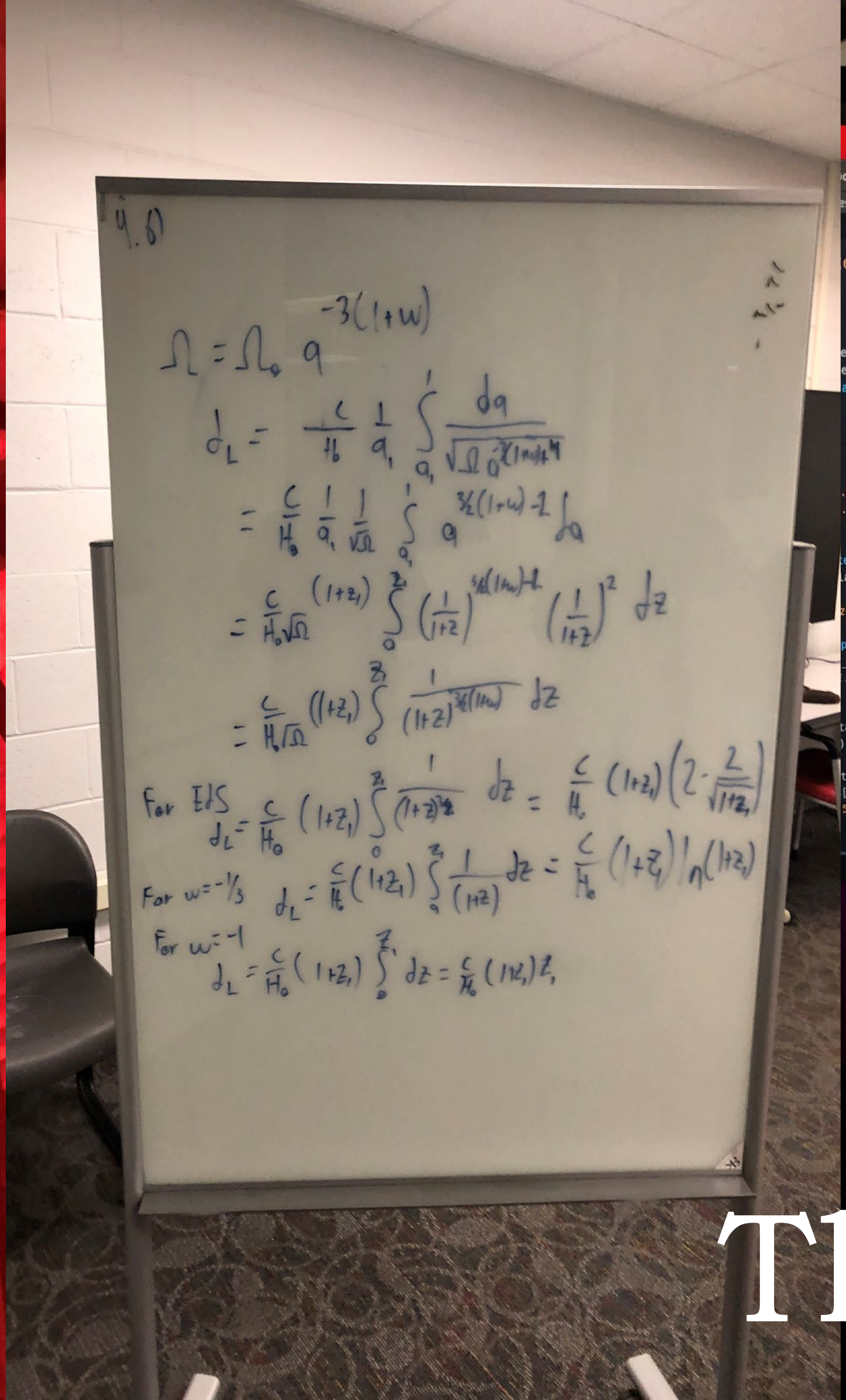
- We are making small adjustment to the halo model in the fitting process by introducing a ‘softening parameter’ as follows:

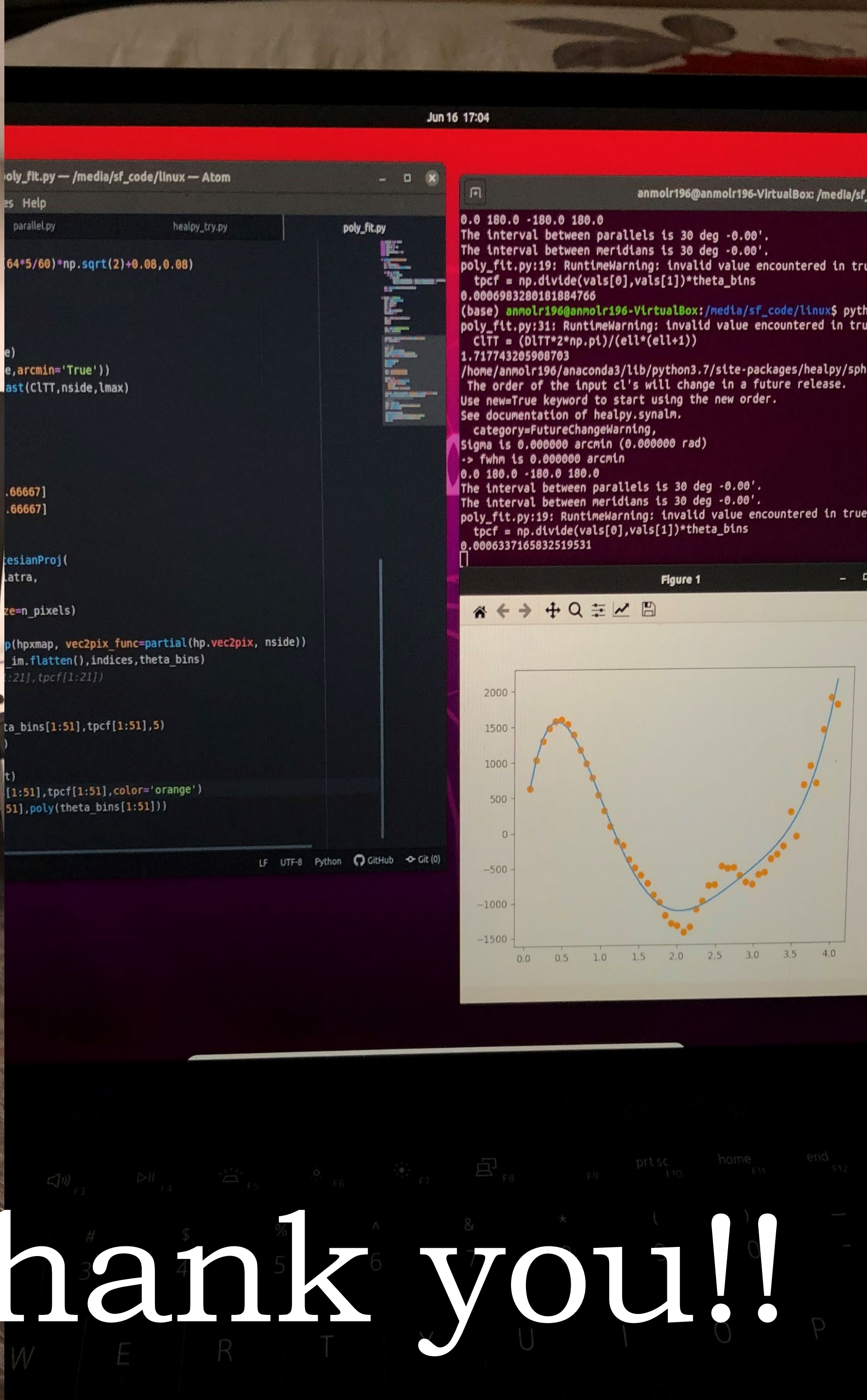
$$\xi_{\rm DM}(r) = \left[(\xi_{\rm 1h}(r))^{\alpha} + (\xi_{\rm 2h)}(r))^{\alpha}\right]^{\frac{1}{\alpha}}$$

- We also plan on testing the robustness of dark matter halo-model to describe gas profiles by looking at deviations at different scales.

# Summary

- Halo Model inadequately explains the quasi-linear regime due to intrinsic assumptions in the model
- One can cross-correlate various datasets to compute dark matter and gas profiles of clusters
- Modifying the Halo Model by introducing softening parameter and fitting it to the profiles can yield constraint to the parameters
- The softening parameter smoothens out the transition between 1h and 2h terms and can be a potential fix to the halo model without changing the ingredients


4.6)
$\Omega = \Omega_0 a^{-3(1+w)}$
$d_L = \frac{c}{H_0}\frac{1}{a_1}\int_{a_1}^{1}\frac{da}{\sqrt{\Omega_0 a^{-3(1+w)+4}}}$
$= \frac{c}{H_0}\frac{1}{a_1}\frac{1}{\sqrt{\Omega}}\int_{a_1}^{1} a^{3/2(1+w)-2}\,da$
$= \frac{c}{H_0\sqrt{\Omega}}(1+z_1)\int_0^{z_1}\left(\frac{1}{1+z}\right)^{3/2(1+w)-2}\left(\frac{1}{1+z}\right)^2 dz$
$= \frac{c}{H_0\sqrt{\Omega}}(1+z_1)\int_0^{z_1}\frac{1}{(1+z)^{3/2(1+w)}}\,dz$
For EdS $d_L = \frac{c}{H_0}(1+z_1)\int_0^{z_1}\frac{1}{(1+z)^{3/2}}\,dz = \frac{c}{H_0}(1+z_1)\left(2-\frac{2}{\sqrt{1+z_1}}\right)$
For $w=-1/3$ $d_L = \frac{c}{H_0}(1+z_1)\int_0^{z_1}\frac{1}{(1+z)}\,dz = \frac{c}{H_0}(1+z_1)\ln(1+z_1)$
For $w=-1$
$d_L = \frac{c}{H_0}(1+z_1)\int_0^{z_1}dz = \frac{c}{H_0}(1+z_1)z_1$


Jun 16 17:04
poly_fit.py — /media/sf_code/linux — Atom
parallel.py
healpy_try.py
poly_fit.py
The interval between parallels is 30 deg -0.00'.
The interval between meridians is 30 deg -0.00'.
poly_fit.py:19: RuntimeWarning: invalid value encountered in true_divide
tpcf = np.divide(vals[0],vals[1])*theta_bins
Figure 1
LF UTF-8 Python GitHub Git (0)

# Thank you!!