Galaxy cluster masses from magnification and the effects of intracluster dust

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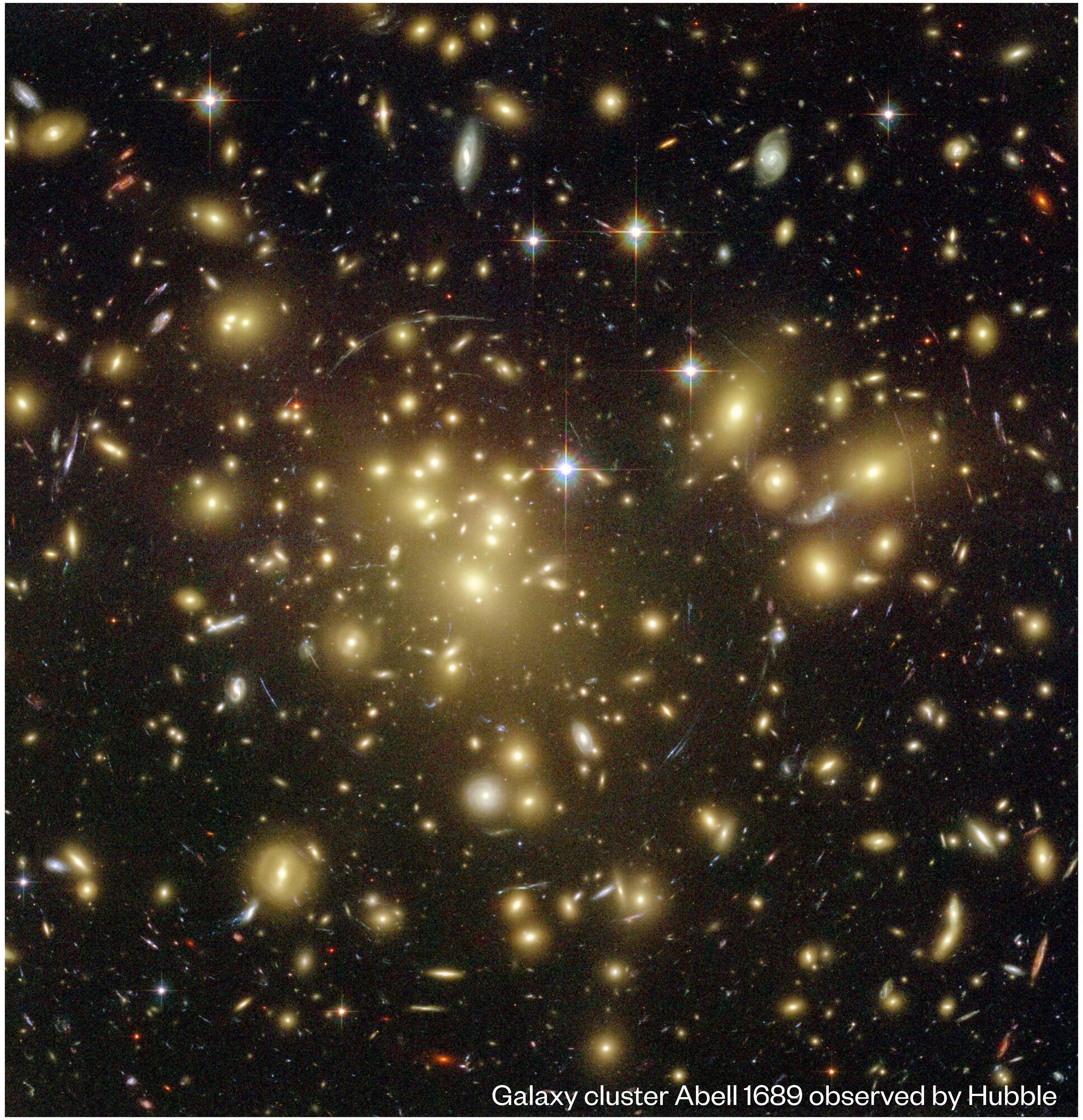
Galaxy clusters

- Largest bound objects in the universe $> 10^{14}\,\mathrm{M}_{\odot}$
- Composition
  - 85% dark matter
  - 12% hot gas
  - 3 % stellar mas
- Provided early evidence for dark matter through observations of galaxy velocities (Zwicky 1933)
- They provide strong constraints on the matter content, geometry, the nature of gravity and the formation of structure in the universe and **gravitational lensing gives information on all of this!**

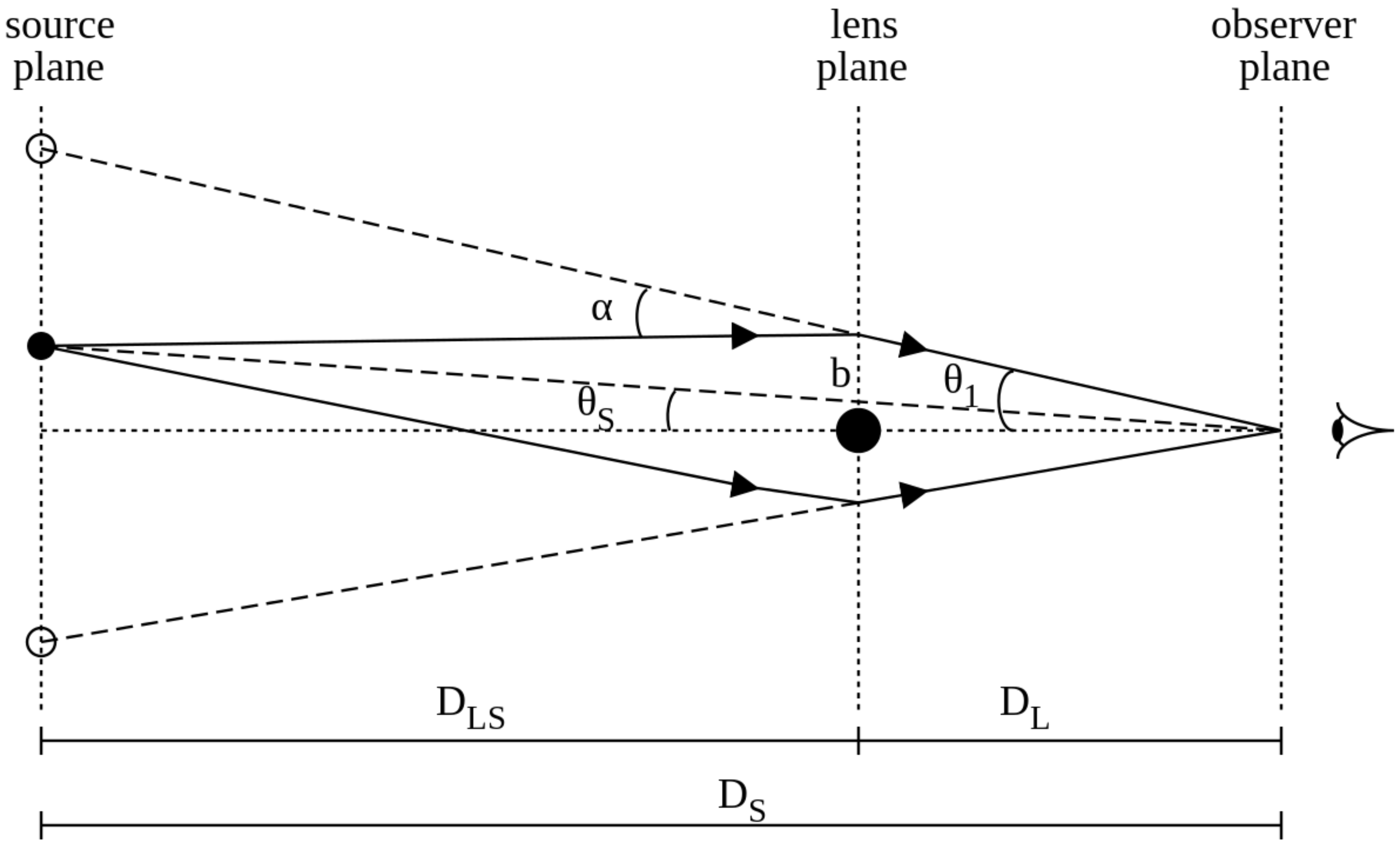

Galaxy cluster Abell 1689 observed by Hubble

Intracluster dust

- Dust may be thrown into the intracluster medium by
    - Supernova explosions
    - Ram pressure stripping
    - Tidal interactions
    - Super massive blackholes!
- However once in the medium they will be heated by the intracluster X-ray gas
- Dust can cool the intracluster medium but also inform us of the phenomena that may send dust into the medium

Cluster Lensing

- Shears galaxy images (primary probe)
- Increases galaxy magnitudes
- Galaxy surveys are magnitude limited, magnification **introduces faint galaxies** into the sample which we would not normally see
- Deflects galaxy images away from the cluster centre, which **reduces the number of galaxies** in radial annuli from the centre
- Magnification has different systematics than shear!

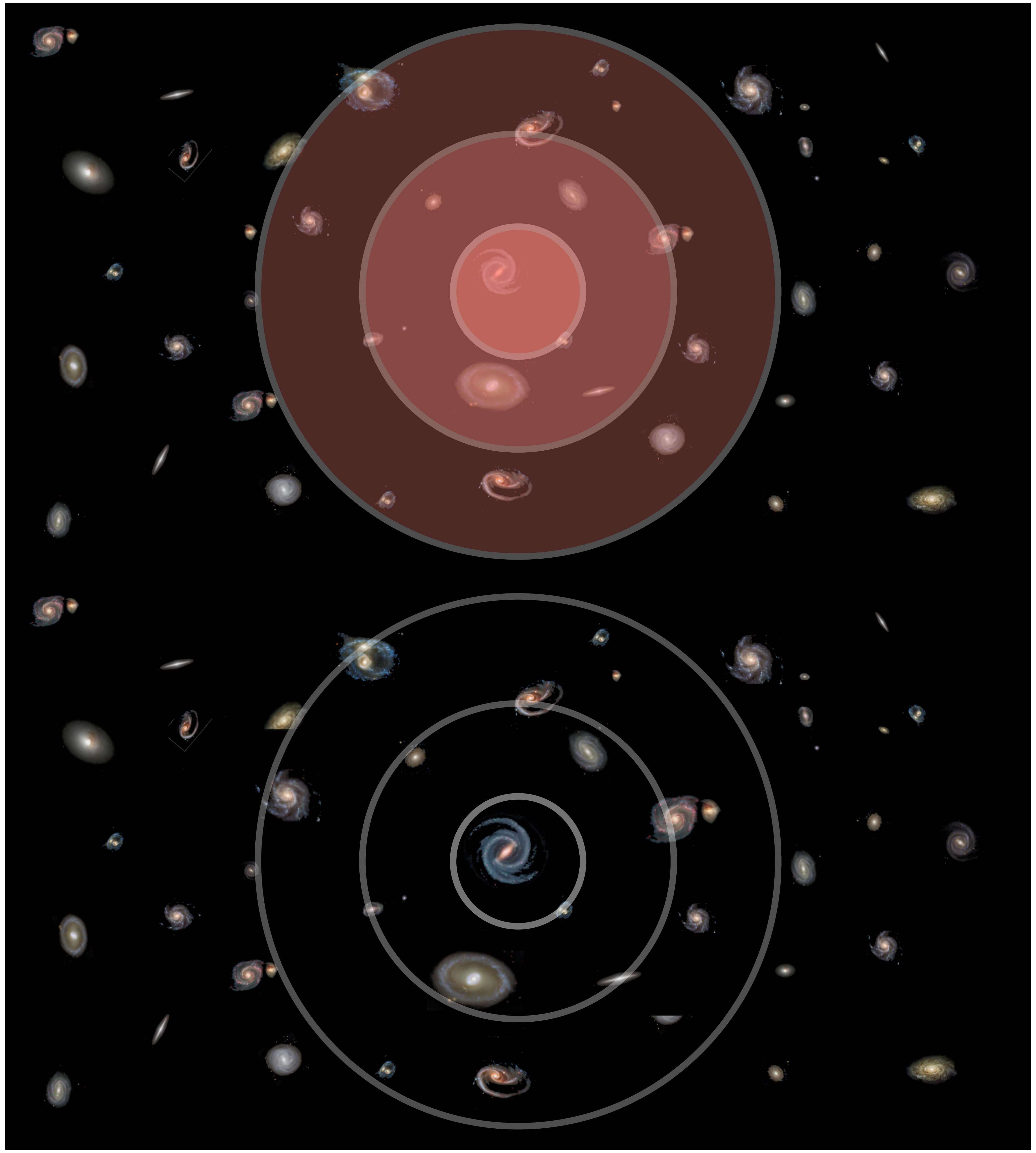


Dust and magnification

- Dust
    - Reduces background galaxy magnitude
- Lensing
    - Galaxies appear further from the cluster centre
    - Increase galaxy magnitudes
- However the dust effects are wavelength dependent!
- Galaxy magnitude is m, κ is the lensing convergence, τ_λ is the optical dust depth at a given wavelength, $\vec{\theta}$ is the position of a background galaxy and $\vec{\alpha}$ is the lensing angle

$$m_{obs} \approx m_{int} - \frac{5}{2ln10}\left(2\kappa - \tau_\lambda\right)$$

$$\vec{\theta}_{obs} = \vec{\theta}_{int} + \vec{\alpha}_{lens}$$



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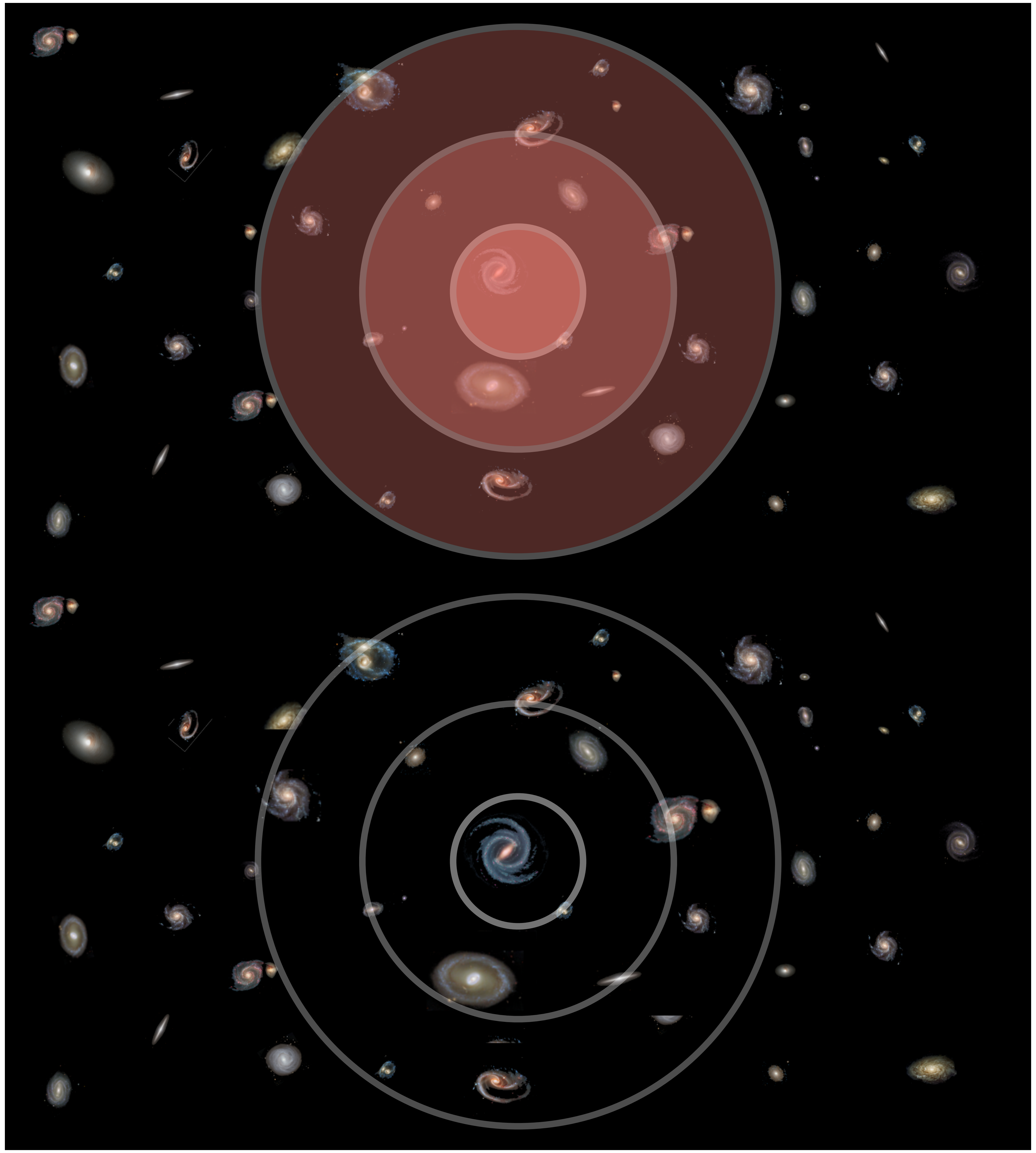
$$\delta m_{lens} \approx 0.1$$

Towards the centre of a cluster we expect

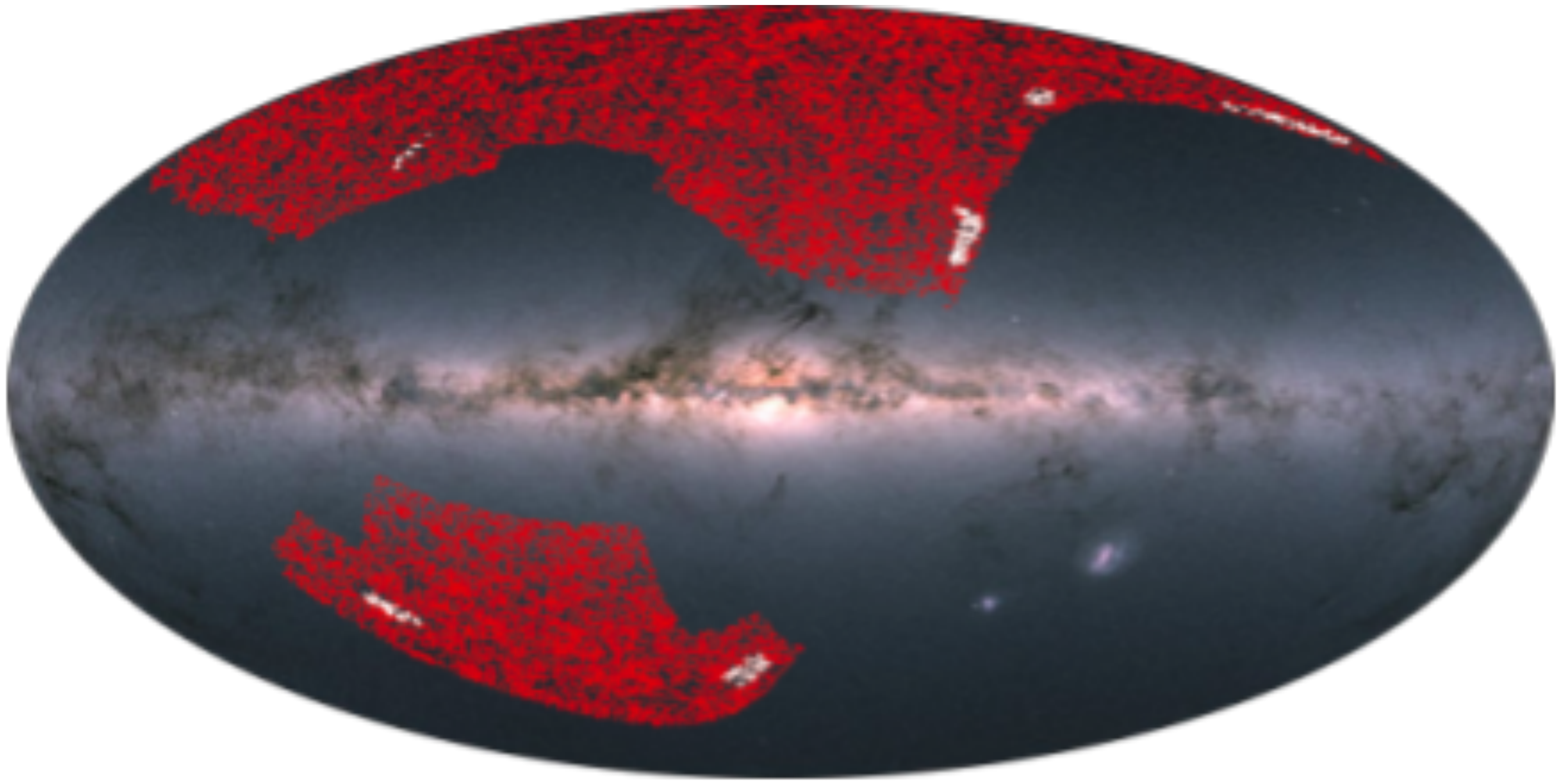
$$\delta m_{dust} \approx 0.01$$



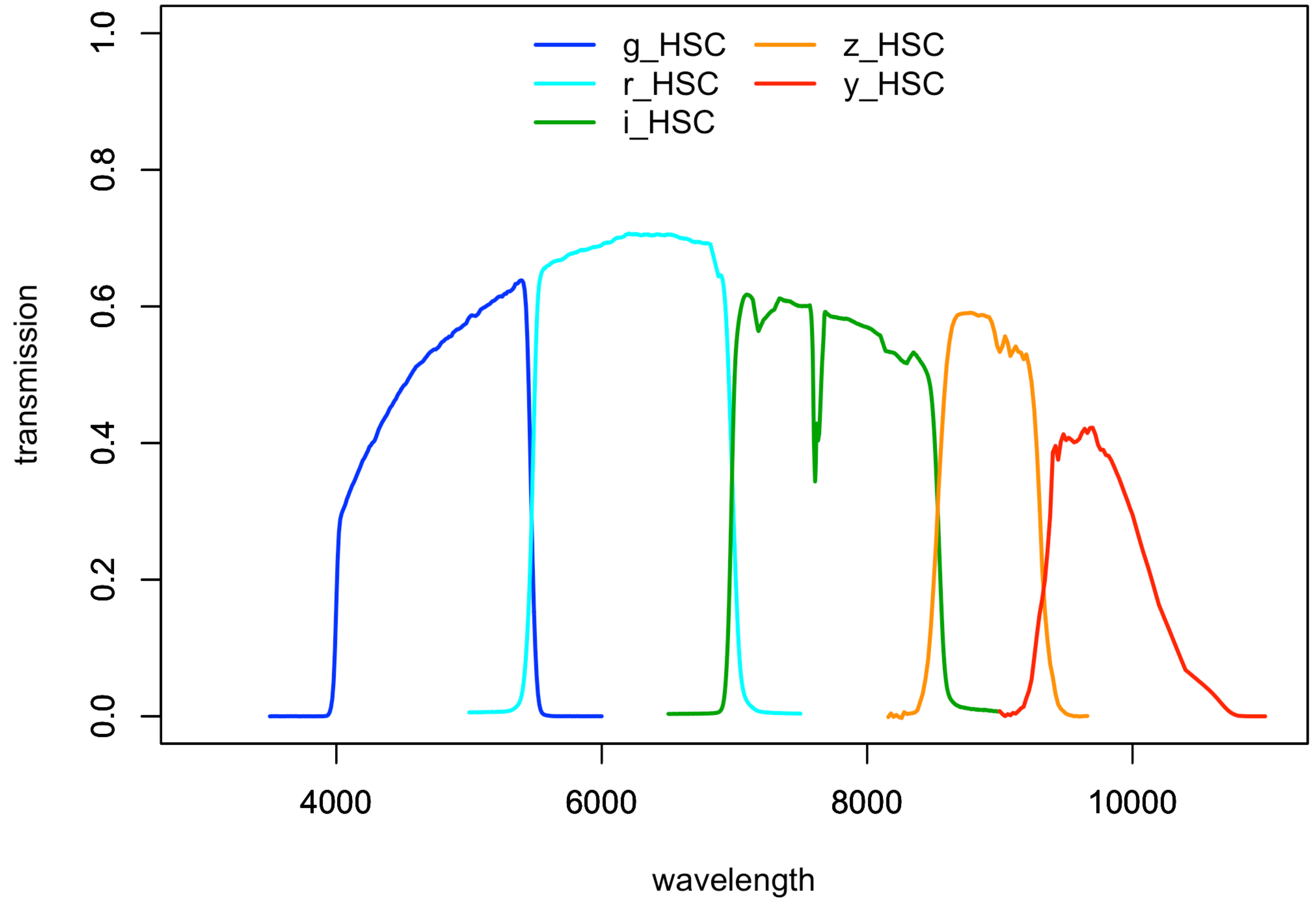
Objectives

- Joint measure of cluster dust content and cluster masses with **magnification**
- Introduce a **new** (and hopefully improved) likelihood which incorporates galaxy clustering, magnitude and redshift information

Redmapper clusters and Hyper Suprime Cam



- 458 SDSS Redmapper clusters are found in the HSC field
- Red dots are SDSS Redmapper clusters
- White dots are Redmapper clusters within the HSC field
- HSC has a high galaxy density $n_{gal} \approx 20\,[arcmin^2]$
- 5 magnitude bands (grizy) important for dust searches
- HSC is a good testing ground for Rubin LSST (weak lensing)

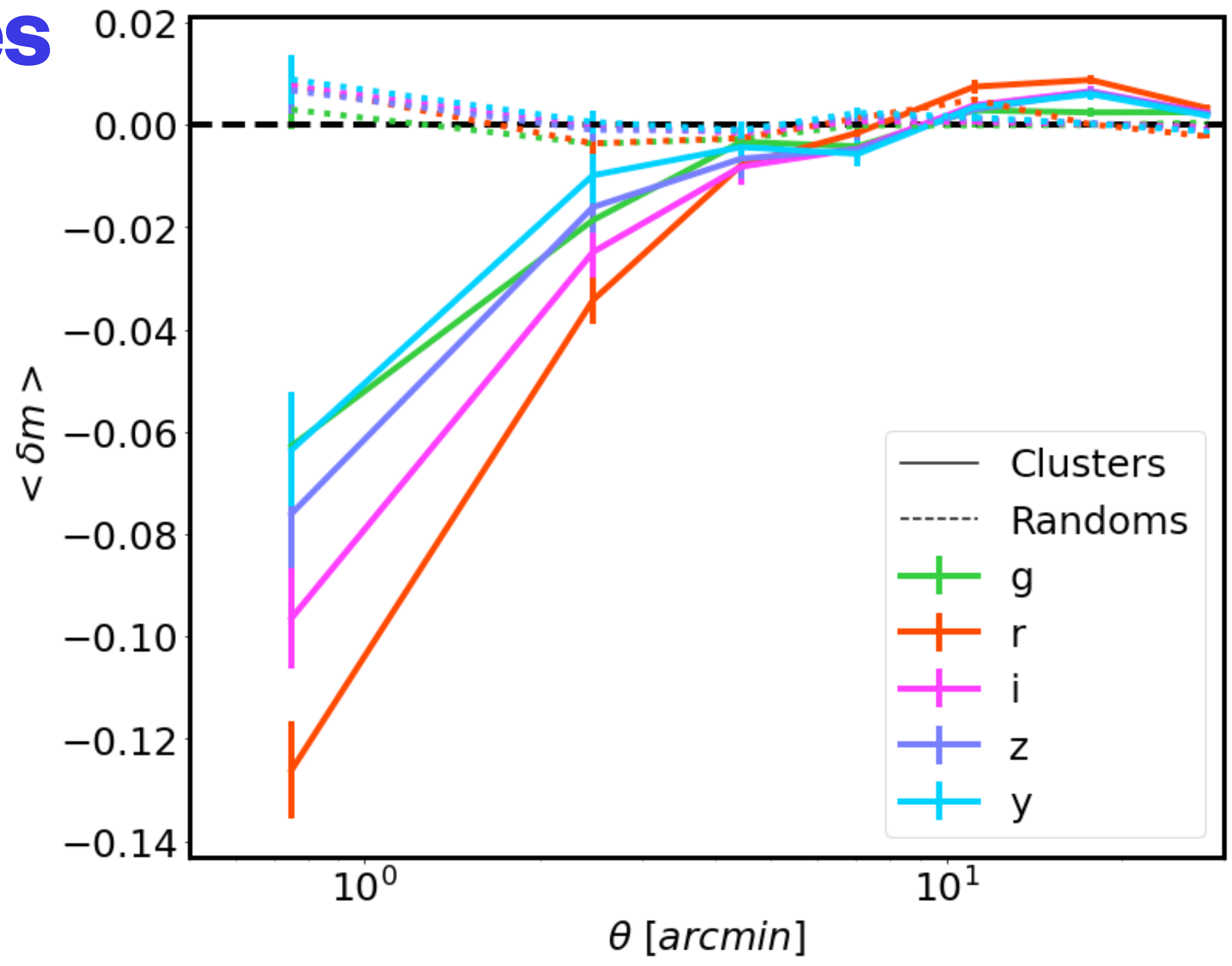


Stacked magnitude profiles

- Using a subsample of 90 clusters in the redshift interval $0.2 < z_{cluster} < 0.3$
- We measure the average magnitude for a stack of clusters in annuli from the cluster centre
- Clear chromatic signal
- **Attention!** Lensing introduces colour changes, faint galaxies which are introduced to the sample have different colours to bright galaxies
- These profiles have been used to measure dust, not strictly true (Menard et al. 2009)

$$\langle \delta m \rangle = \langle m(\theta) \rangle - \left\langle m_{field} \right\rangle$$

$$m_{obs} \approx m_{int} - \frac{5}{2ln10}\left(2\kappa - \tau_{\lambda}\right)$$



Galaxy number counts

- We need to consider both the shift in galaxy position and the magnitude change
  - Lensing deflects galaxy images away from the cluster centre reducing the number of galaxies
  - Lensing introduces faint galaxies into the sample by increasing their brightness
  - Dust dims galaxies, reducing the number of galaxies
- n is the number density if galaxies, α is the **slope of the galaxy magnitude function** and as before κ is the lensing convergence, τ_λ is the optical dust depth at a given wavelength
- α is calculated from the global galaxy distribution

$$\vec{\theta}_{obs} = \vec{\theta}_{int} + \vec{\alpha}_{lens}$$

$$m_{obs} \approx m_{int} - \frac{5}{2ln10}\left(2\kappa - \tau_\lambda\right)$$

$$\alpha = 2.5\frac{dlog_{10}n}{dm}\Big|_{m_{cut}}$$

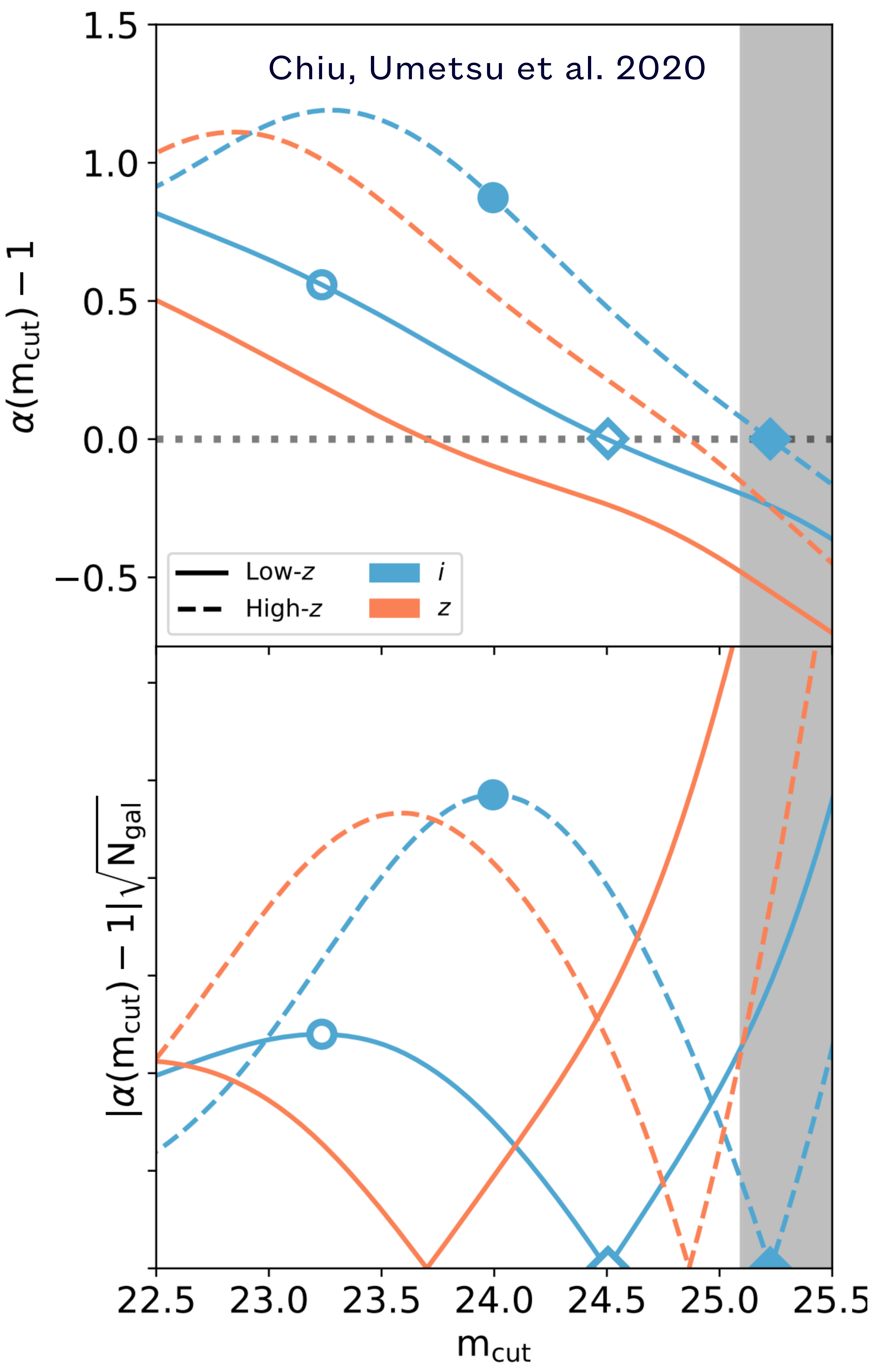
New term due to dust that we have introduced

$$n_{obs}(\vec{\theta}) \approx n_{int}(\vec{\theta})\left[1 + \boxed{\alpha(e^{-\tau_\lambda} - 1)} + 2\kappa(\alpha - 1)\right]$$

The usual method

$$n_{obs}(\vec{\theta}) \approx n_{int}(\vec{\theta})\left[1 + 2\kappa(\alpha - 1)\right]$$

- Choose **one magnitude cut** which gives a α which maximises the signal
  - This is a game between the best value of α and keeping as many galaxies as possible
  - Does not make much use of galaxy magnitude or redshift information
- Chiu, Umetsu et al. 2020, Schmidt et al. 2010, Broadhurst, Taylor and Peacock 1994



Incorporating galaxy magnitude and redshift information

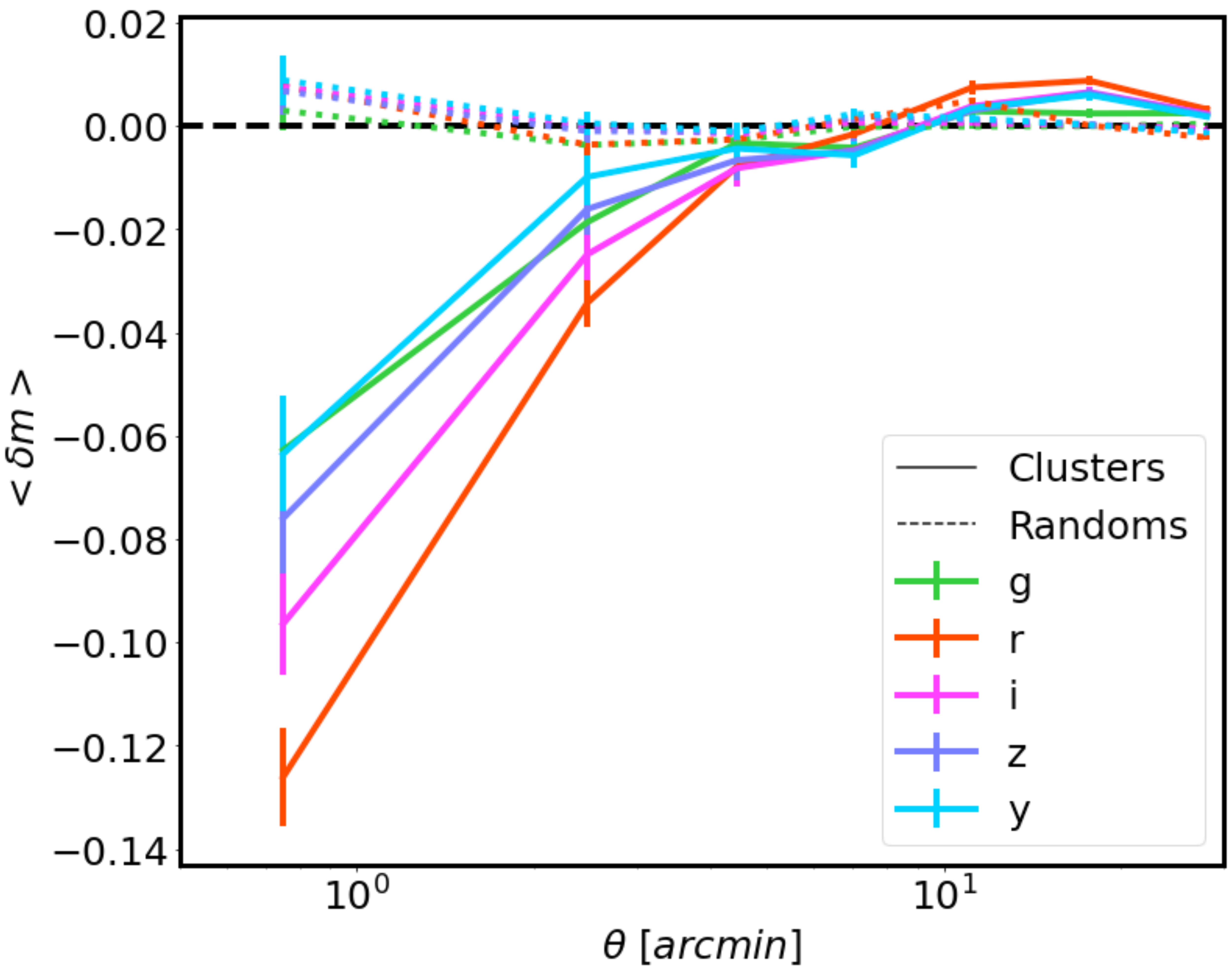
- Bin observed galaxy distribution into **magnitude and redshift bins**
- α must now incorporate galaxies which **leave and enter** the magnitude bin
- The lensed/dusted galaxy distributions can be calculated from the unlensed/undusted distributions
- Dust depends on wavelength and angular separation
- Convergence depends on galaxy redshift and angular separation

$$\alpha = -2.5\left(\frac{dlog_{10}n}{dm}\Big|_{m_{high}} - \frac{dlog_{10}n}{dm}\Big|_{m_{low}}\right)$$

$$n_{obs}(\overrightarrow{\theta}, m, z_{gal}) \approx n_{int}(\overrightarrow{\theta}, m, z_{gal})\left[1 + \alpha(m, z_{gal})(e^{-\tau_\lambda(\overrightarrow{\theta})} - 1) + 2\kappa(\overrightarrow{\theta}, z_{gal})(\alpha(m, z_{gal}) - 1)\right]$$

Future work

- Estimate stacked cluster masses on mocks
- Incorporate dust models into the mock and our likelihood
- Estimate dust content and cluster masses with Redmapper clusters and HSC galaxies



Poisson likelihood

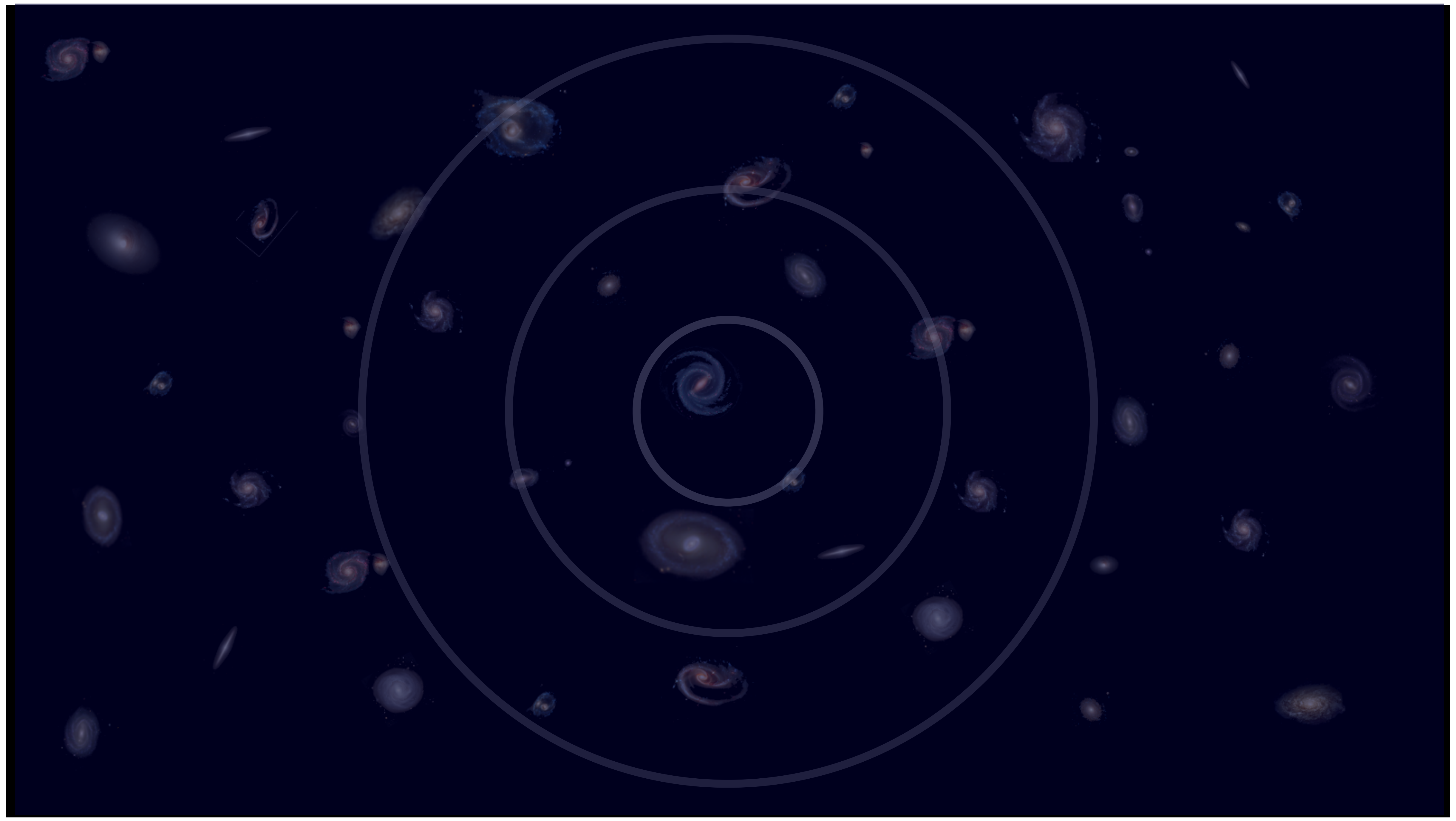
- Analogous to that used in cluster abundance cosmology
- Simply measure the galaxy counts, $n_{meas,k}$ in bins, k, of θ , redshift, and magnitude and compare to the theoretical expectation $n_{obs,k}$
- Uses **more information** than the standard method!

$$ln\mathscr{L} = \sum_k n_{meas,k}\, ln\, n_{obs,k} - \sum_k n_{obs,k}$$

$$n_{obs}(\overrightarrow{\theta}, m, z_{gal}) \approx n_{int}(\overrightarrow{\theta}, m, z_{gal})\left[1 + \alpha(m, z_{gal})(e^{-\tau_\lambda(\overrightarrow{\theta})} - 1) + 2\kappa(\overrightarrow{\theta}, z_{gal})(\alpha(m, z_{gal}) - 1)\right]$$

Mock result validation

- We generate random positions within the HSC footprint and inject a fake cluster signal
  - **Lensed galaxy positions**
  - Lensed/~~dusted~~ galaxy magnitudes



$$\vec{\theta}_{obs} = \vec{\theta}_{int} + \vec{\alpha}_{lens}$$

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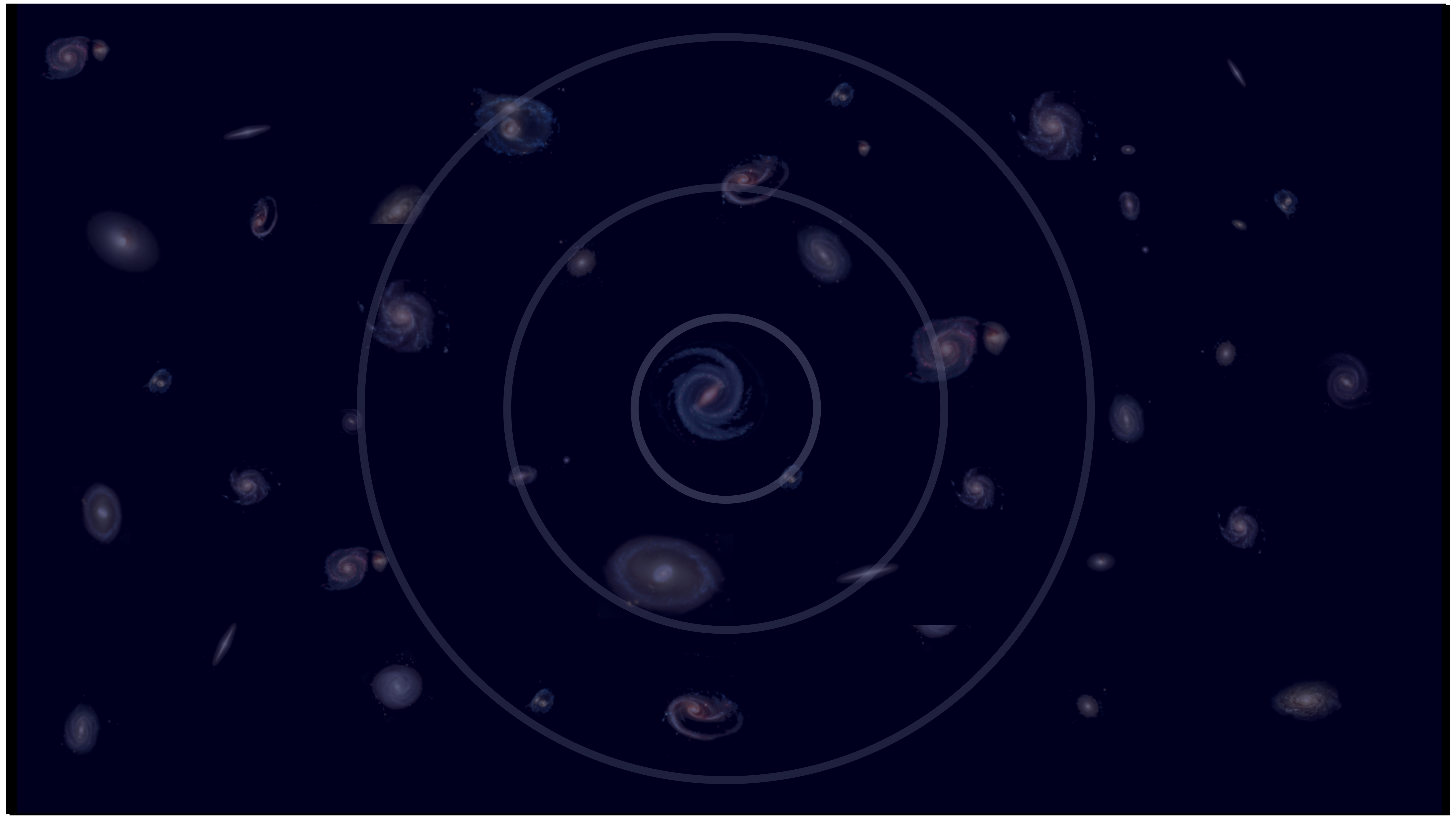

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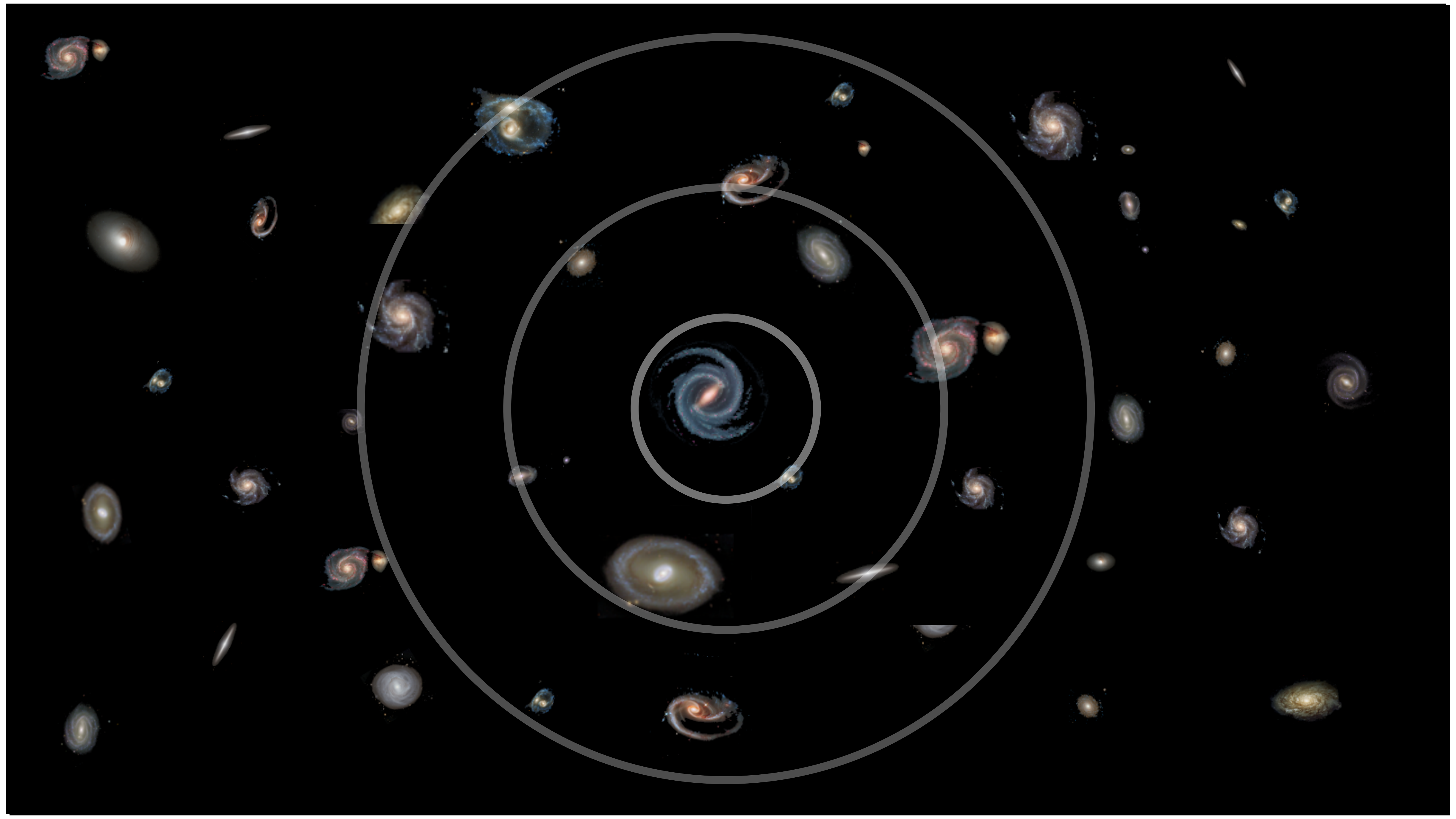

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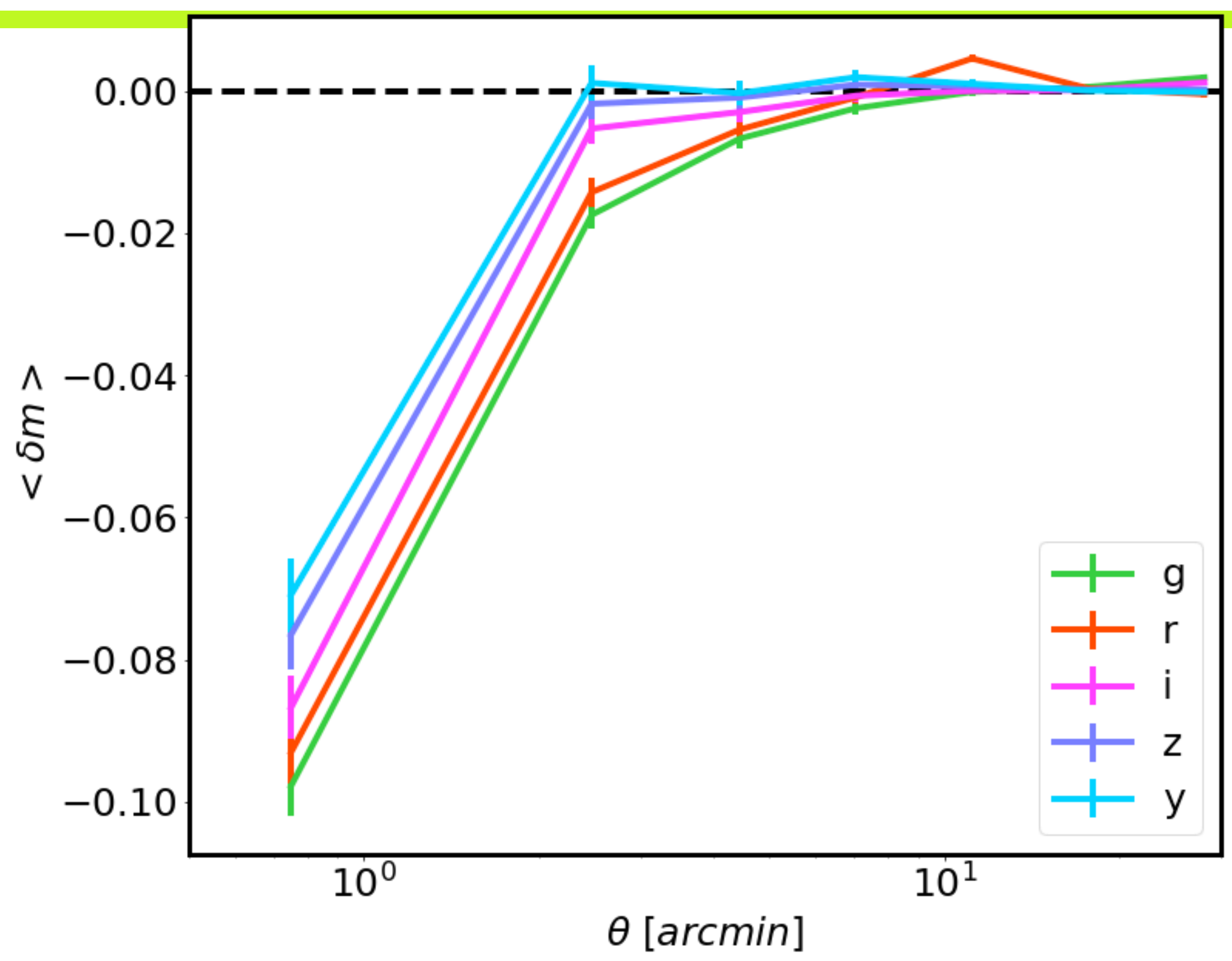
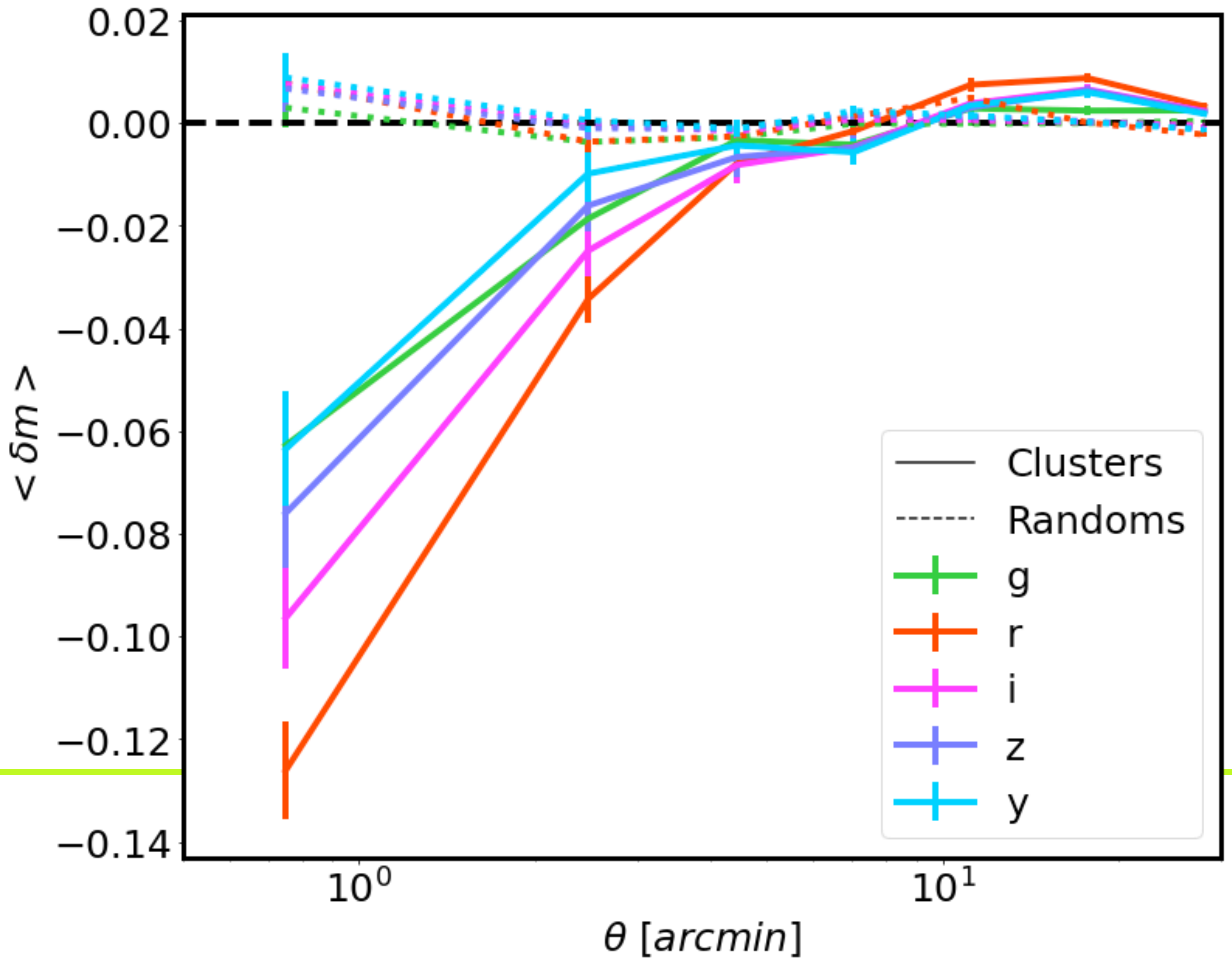
Mock results

- For these mocks we have only injected the cluster signal, **no dust,** we still see chromatic effects
- For reference we measure the signal around random points in the HSC footprint



Mocks

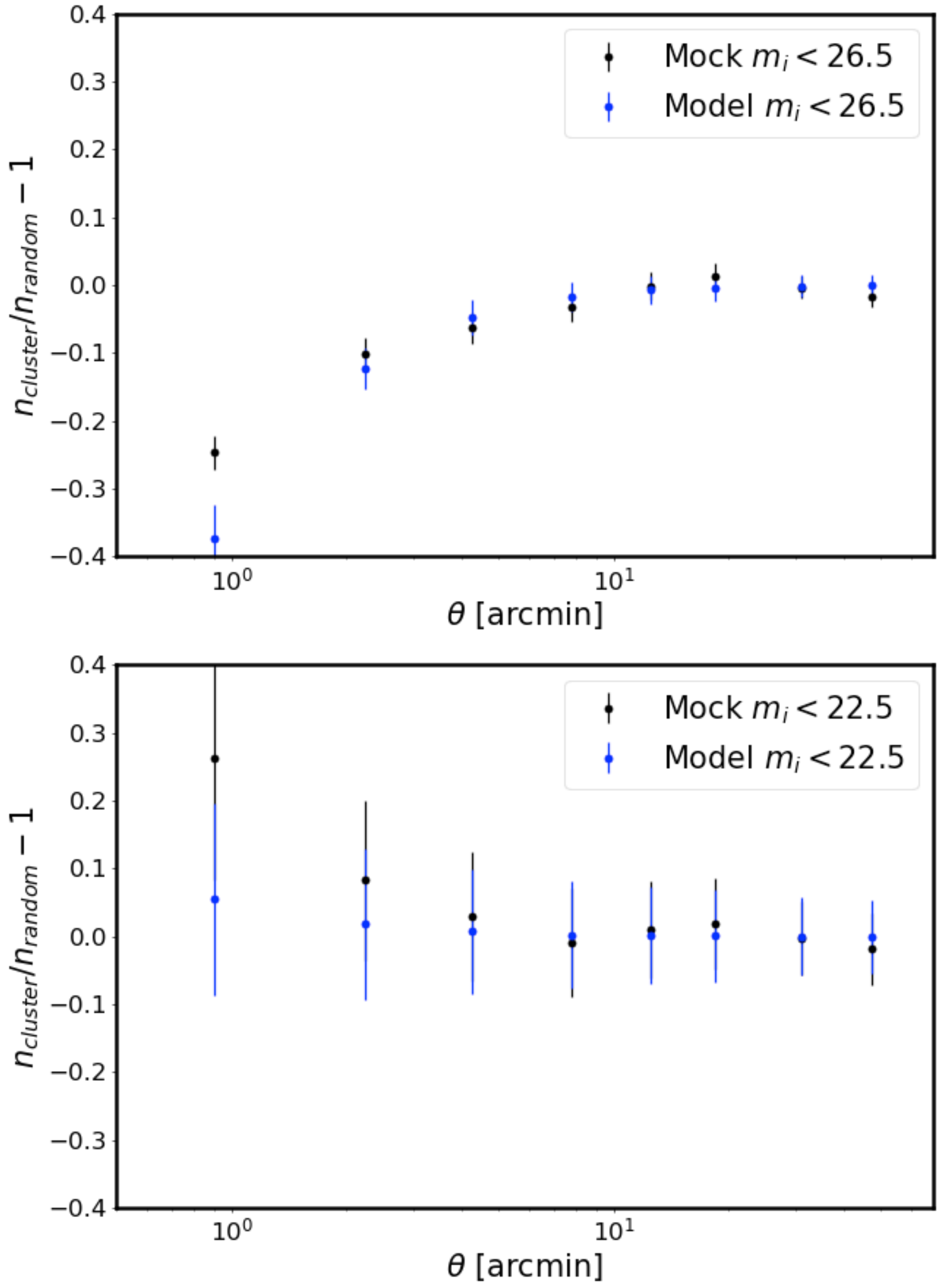


Redmapper clusters

Mock results

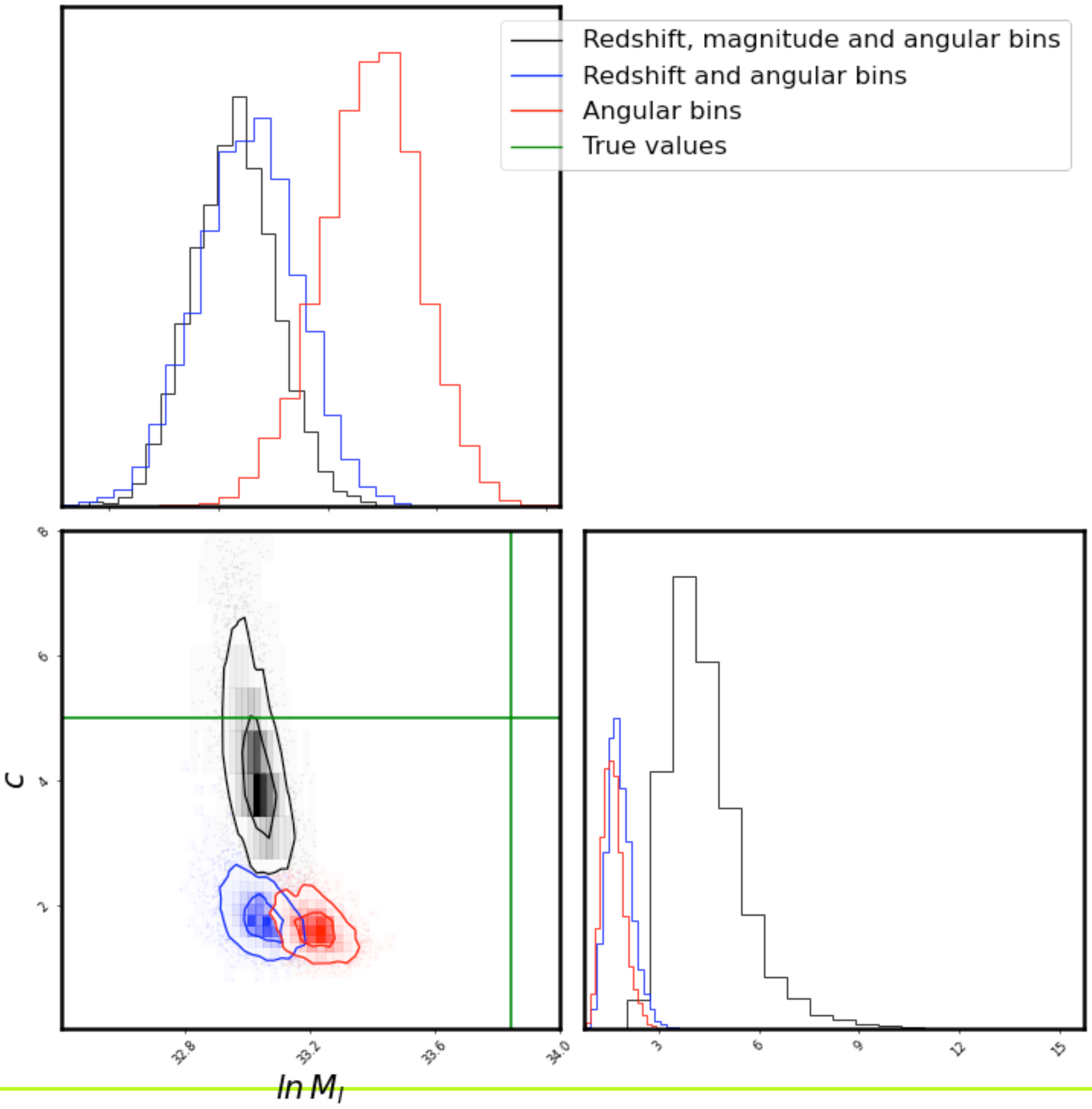
- For these mocks we have only injected the cluster signal, **no dust,** we still see chromatic effects
- Galaxy counts in agreement with predictions
    - Here for two different magnitude cuts

$$n_{obs}(\overrightarrow{\theta}, m, z_{gal}) \approx n_{int}(\overrightarrow{\theta}, m, z_{gal})\left[1 + 2\kappa(\alpha - 1)\right]$$



Cluster mass estimates

- Work in progress
- 275 synthetic clusters
- 3 different cases, only angular bins is the standard method
  - 16 i-band magnitude bins between 20 and 26.5
  - 5 redshift bins between 0.6 and 3
  - 7 angular bins between 1.5 and 55 arc minutes
- MCMC estimation of the cluster concentration, c, and the cluster mass, M_l
- **Clearly not working yet**
  - Biased
  - Errors underestimated



Galaxy source count dipole

$$n_{obs}(\overrightarrow{\theta}) = n_{int}(\overrightarrow{\theta})\left(1 + [2 + x(1+\alpha)]\beta cos(\theta) + 2[x-1]\kappa(\overrightarrow{\theta})\right)$$

- Kinematic dipole, galaxies are (de)magnified into the sample and angles on the sky change, from observer motion
  - $\beta = v/c$
  - $x = \frac{dln\, n_{int}}{dln\, f}|_{f_{lim}}$ slope of the galaxy luminosity function
  - α is the (power law) shape of the galaxy flux spectrum
- Lensing dipole from local structures
- The effects can be completely distinguished with different magnitude cuts, **the value of x changes**
- Galaxy source counts ~3 times larger than Planck inferred velocity

Galaxy source count dipole

$$n_{obs}(\vec{\theta}) = n_{int}(\vec{\theta})\left(1 + [2 + x(1+\alpha)]\beta cos(\theta) + 2[x-1]\kappa(\vec{\theta})\right)$$

- Using Tiwari et al. 2015 measurements we can constrain the dipoles
- For the red band $x \approx 1$
- Clearly magnification by local structures cannot resolve the issue