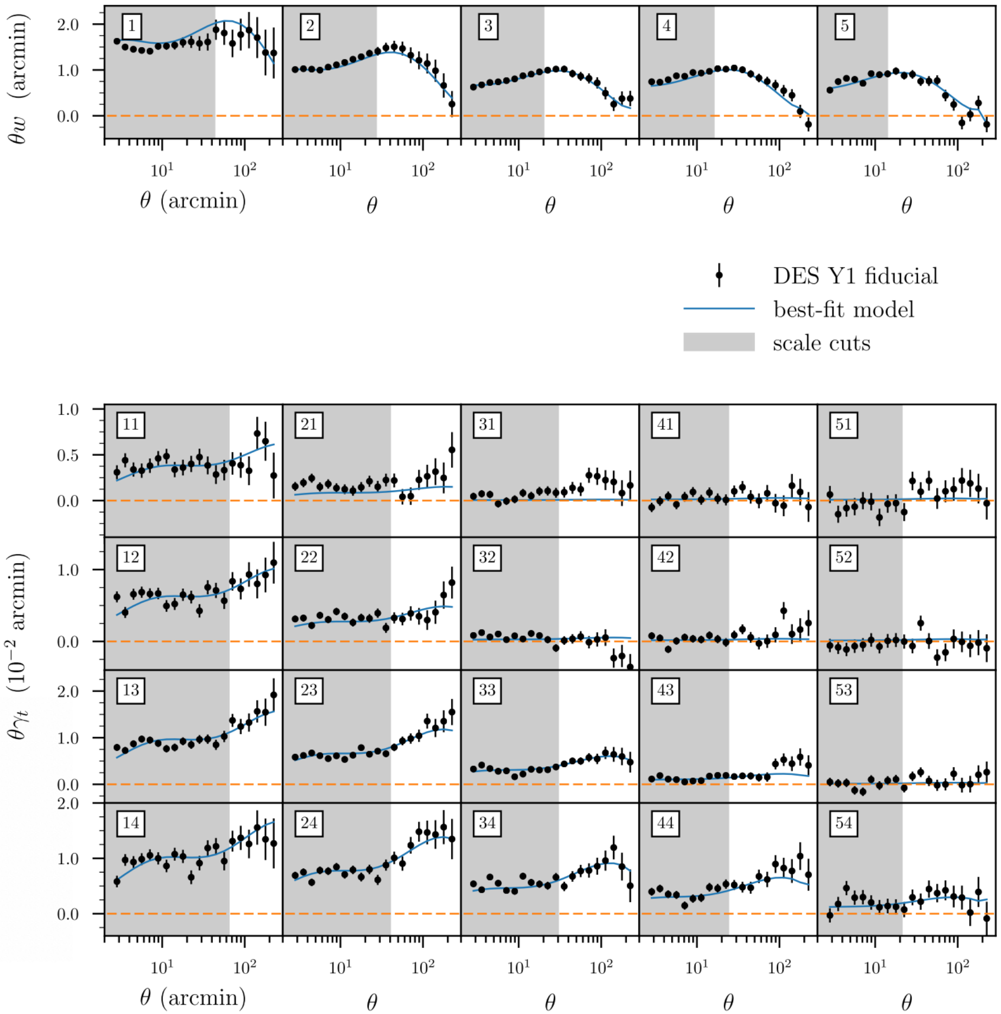
# Small scales modeling

## Using DES, ACT and Planck

With DES and ACT Collaboration

# ***Motivation:***
DES Year 1 results




**SNR** $w(\theta)$**+** $\gamma_t(\theta)$**:**

*Before* scale cuts: 120$\sigma$

*After* scale cuts: 42$\sigma$

We threw away 270/500 data-points!

Main modeling limiting factors:

1. **Galaxy Biasing**

2. **Baryonic feedback**

# 1. Galaxy Biasing

## with its application to DES Year 3 analysis

arXiv:2008.05991

Work done with Elisabeth Krause, Bhuvnesh Jain, Niall MacCrann… and DES Collaboration

# Goal:

- To model the small scale galaxy/matter clustering with minimal number of free parameters to maximize gain in cosmology constraints.
  - With aim to describe the projected statistics in real space

- Primarily two ways of modeling small scales:
  - Halo model (HOD): All matter is in virialized halos; physically motivated but functional form depends on tracers, hard to get right in the transition regime
  - Perturbation Theory (PT): Tracer independent, controlled expansion in increasingly higher order corrections

# PT intro

- Standard PT : Solve the fluid equations
    - Assumes matter is a perfect fluid

$$\dot{\delta} + \nabla \cdot [(1+\delta)\boldsymbol{v}] = 0, \quad \text{Continuity Equation}$$

$$\dot{\boldsymbol{v}} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\mathcal{H}\boldsymbol{v} - \nabla\phi, \quad \text{Euler Equation}$$

$$\nabla^2\phi = 4\pi G a^2 \bar{\rho}\delta, \quad \text{Poisson Equation}$$

- Gives an expansion in terms of linear $\delta$

$$\delta_{\mathrm{m}}(\mathbf{k}) = \sum \frac{1}{n!}\int \frac{d^3k_1}{(2\pi)^3}\cdots\frac{d^3k_n}{(2\pi)^3}(2\pi)^3\delta_{\mathrm{D}}(\mathbf{k}_{1..n}-\mathbf{k}) F_n(\mathbf{k}_1,..,\mathbf{k}_n)\delta_{\mathrm{L}}(\mathbf{k}_1)...\delta_{\mathrm{L}}(\mathbf{k}_n)\,.$$

Mode coupling gravitational kernels

- But we observe biased tracers of this $\delta$
    - Assume a deterministic relation
    - Bias ⟷ coefficients of expansion

$$\delta_{\mathrm{g}}(\mathbf{x}) = f\left[\delta_m(\mathbf{x})\right] \qquad \delta_{\mathrm{g}}^{\mathrm{local}}(\mathbf{x}) = \sum_{n=1}^{\infty}\frac{b_n}{n!}\delta_{\mathrm{m}}^n(\mathbf{x})\,.$$

- Other ‘non-local’ scalar quantities can contribute as well

shear

velocity divergence

$$\delta_{\mathrm{g}} \sim f(\delta_{\mathrm{m}}, \nabla_i\nabla_j\Phi, \nabla_i v_j) \sim f^{(1)}(\delta_{\mathrm{m}}) + f^{(2)}(\delta_{\mathrm{m}}^2, s^2) + f^{(3)}(\delta_{\mathrm{m}}^3, \delta_{\mathrm{m}}s^2, \psi, st) + \ldots\,.$$

- In case a spatial non-locality exists

$$\delta_{\mathrm{g}}(\mathbf{x}) = f\left[\delta_{\mathrm{m}}(\mathbf{x}')\right]$$

- Effective field theory:
    - Smooth $\delta$ to make is small
    - Truncate integrals

$$\delta_{\mathrm{g}} \sim f(\delta_{\mathrm{m}}, \nabla_i\nabla_j\Phi, \nabla_i v_j) \sim f^{(1)}(\delta_{\mathrm{m}}) + f^{(2)}(\delta_{\mathrm{m}}^2, s^2) + f^{(3)}(\delta_{\mathrm{m}}^3, \delta_{\mathrm{m}}s^2, \psi, st) + f^{\mathrm{grad}}(\nabla^2\delta_{\mathrm{m}}) + \ldots\,.$$

# Summary statistics — Power spectra

$$P_{\rm gm}(k) = \underbrace{b_1 P_{\rm mm}(k)}_{\text{Linear Bias}} + \underbrace{\frac{1}{2}b_2 P_{\rm b_1 b_2}(k) + \frac{1}{2}b_{\rm s} P_{\rm b_1 s^2}(k) + \frac{1}{2}b_{\rm 3nl} P_{\rm b_1 b_{3nl}}(k)}_{\text{1-Loop PT}} + \underbrace{(b'_{\nabla^2\delta} + c_{\rm s}^2)k^2 P^{\rm grad}_{\rm mm}(k)}_{\text{Higher-derivative + EFT}}$$

- What form should $P_{\rm mm}$ and $P^{\rm grad}_{\rm mm}$ take?
- There are five bias parameters, how many can we fix/remove?
    - $b_{\rm s}$ and $b_{\rm 3nl}$ can be 'predicted' as a function of $b_1$

$$\text{Model A}: \frac{\xi_{\rm gm}}{\xi_{\rm mm}} = b_1$$

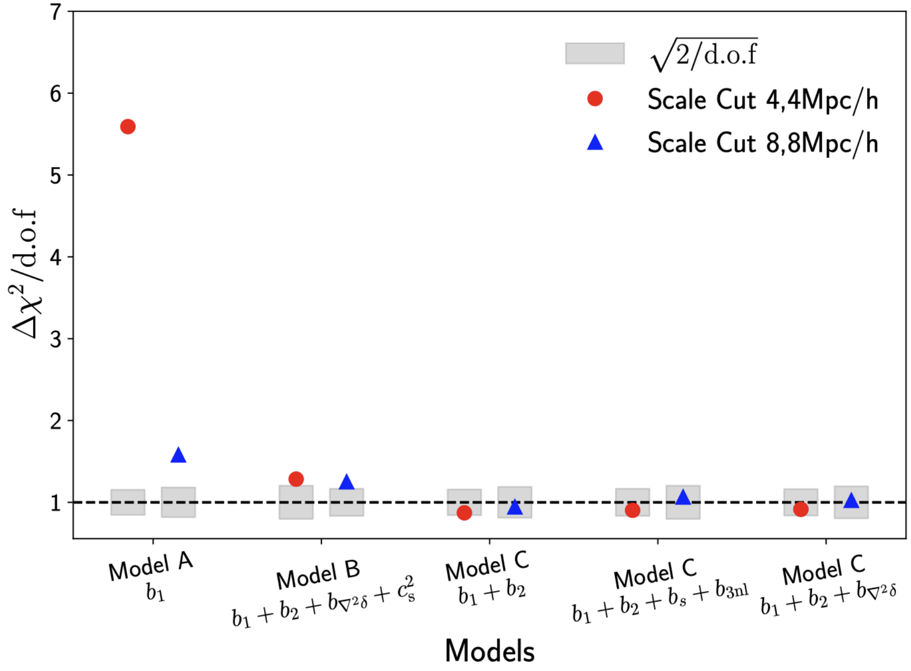
$$\text{Model B}: \frac{\xi_{\rm gm}}{\xi_{\rm mm}} = \frac{\mathcal{F}\left[b_1 P^{\rm 1-loop}_{\rm mm}(k) + P^{\rm 1-Loop}_{\rm gm}(k) + k^2 b_{\nabla^2\delta} P_{\rm lin}(k)\right]}{\mathcal{F}\left[P^{\rm HF}_{\rm mm}(k)\right]}$$

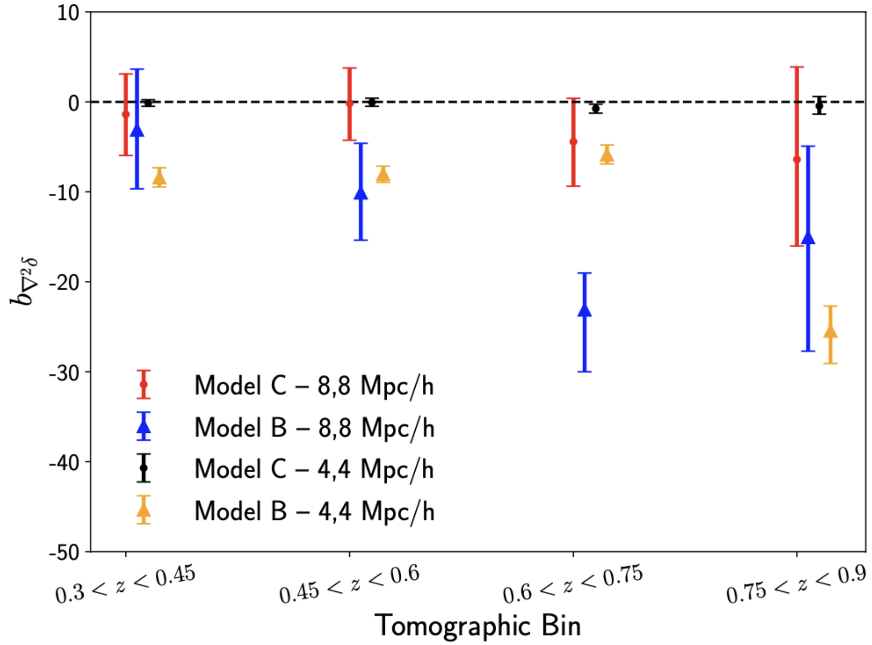
$$\text{Model C}: \frac{\xi_{\rm gm}}{\xi_{\rm mm}} = \frac{\mathcal{F}\left[b_1 P^{\rm HF}_{\rm mm}(k) + P^{\rm 1-Loop}_{\rm gm}(k) + k^2 b_{\nabla^2\delta} P^{\rm HF}_{\rm mm}(k)\right]}{\mathcal{F}\left[P^{\rm HF}_{\rm mm}(k)\right]},$$

| Models | $P_{\rm mm}$ | $P^{\rm grad}_{\rm mm}$ | Remarks |
|---|---|---|---|
| Model A | $P^{\rm HF}_{\rm mm}$ | 0 | Linear bias model |
| Model B | $P^{\rm 1-loop}_{\rm mm}$ | $P_{\rm L}$ | 1-Loop EFT model |
| Model C | $P^{\rm HF}_{\rm mm}$ | $P^{\rm HF}_{\rm mm}$ | *Fiducial* model |

# Simulations

- We use DES-like simulation (MICE) and fit the 3D correlation functions at fixed cosmology:
    - 3D quantities are much higher SNR
    - Testing on 3D at fixed cosmology is a direct test of the bias model. It is more stringent than Y3 requirements.
- We test our model on two different galaxy catalogs:
    - redMaGiC sample consisting of mostly red galaxies with small photo-z errors
    - Maglim sample consisting of $z$-dependent magnitude limited catalog
- Both catalogs (in the following results) have ~2million galaxies and occupy one octant of sky
- We split the catalog into four redshift (tomographic) bins, from $0.3 < z < 0.9$

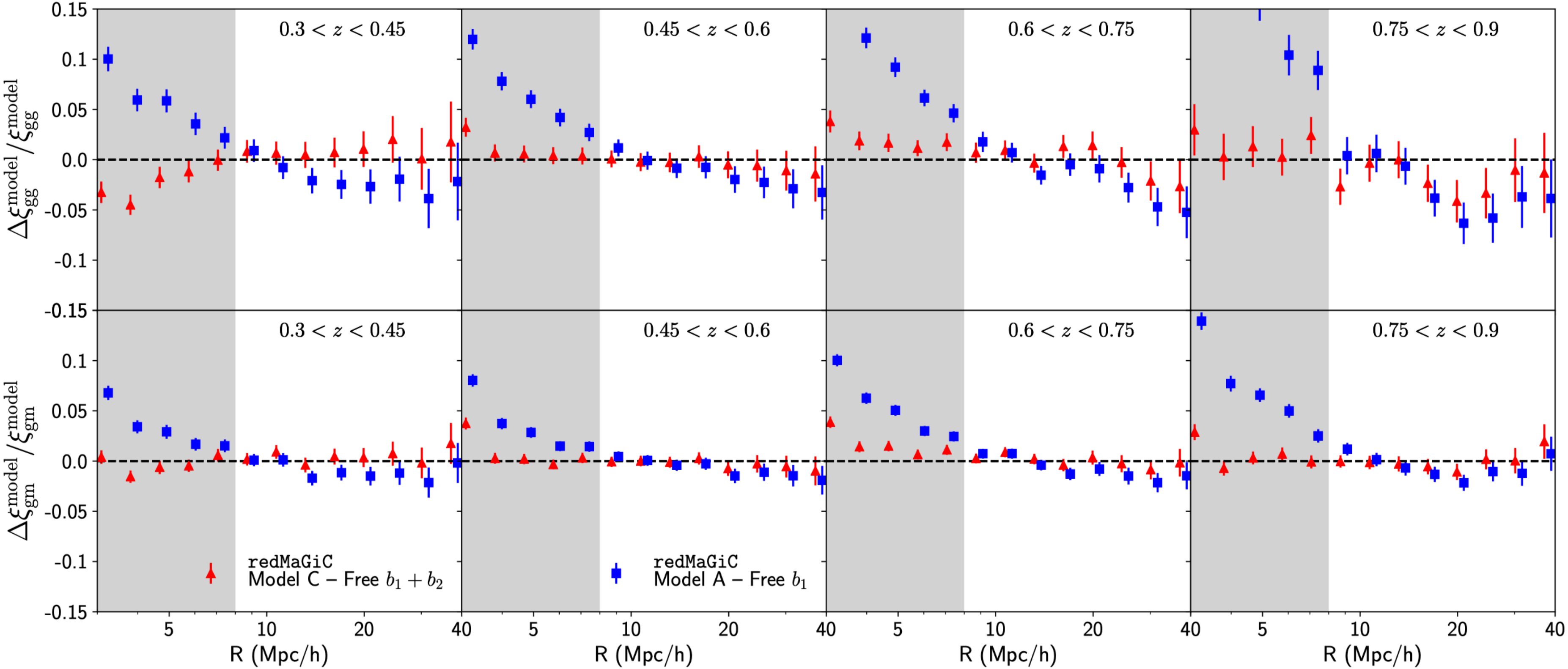


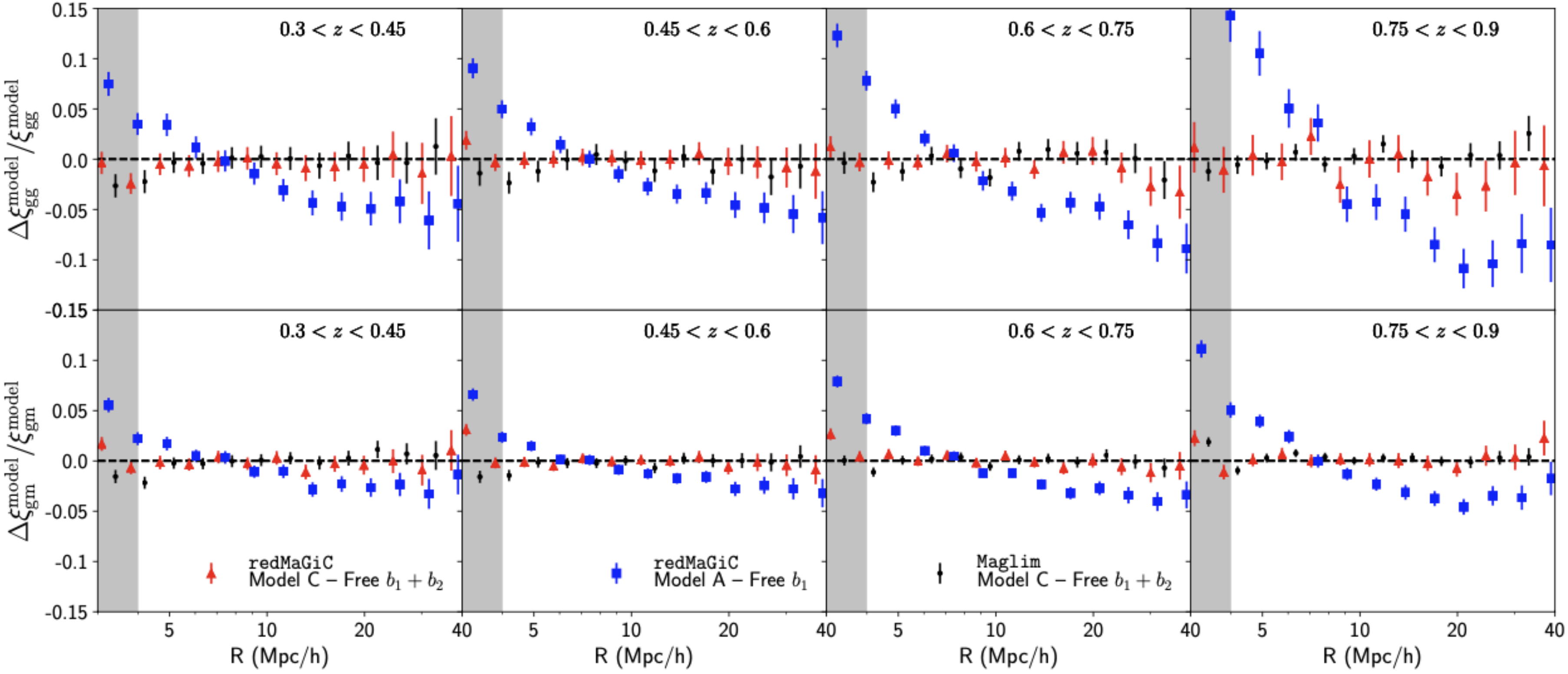




Results for the redMagic sample:

- Using Model C we get very good fit, even down to $4\,\mathrm{Mpc}/h$.
- Moreover, we can fix higher-derivative bias to zero and $b_s$, $b_{3nl}$ to co-evolution value. So we get a good fit with just 2 free parameters.

# Residuals of model at scale cut of $8\,\mathrm{Mpc}/h$

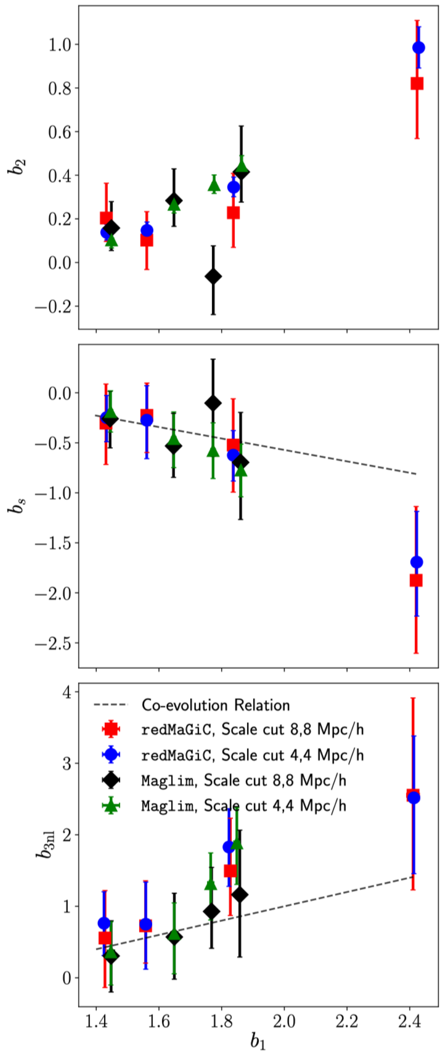





Model C gives residuals within 2% for both galaxy samples: redMaGiC and Maglim down to $4\,\mathrm{Mpc}/h$

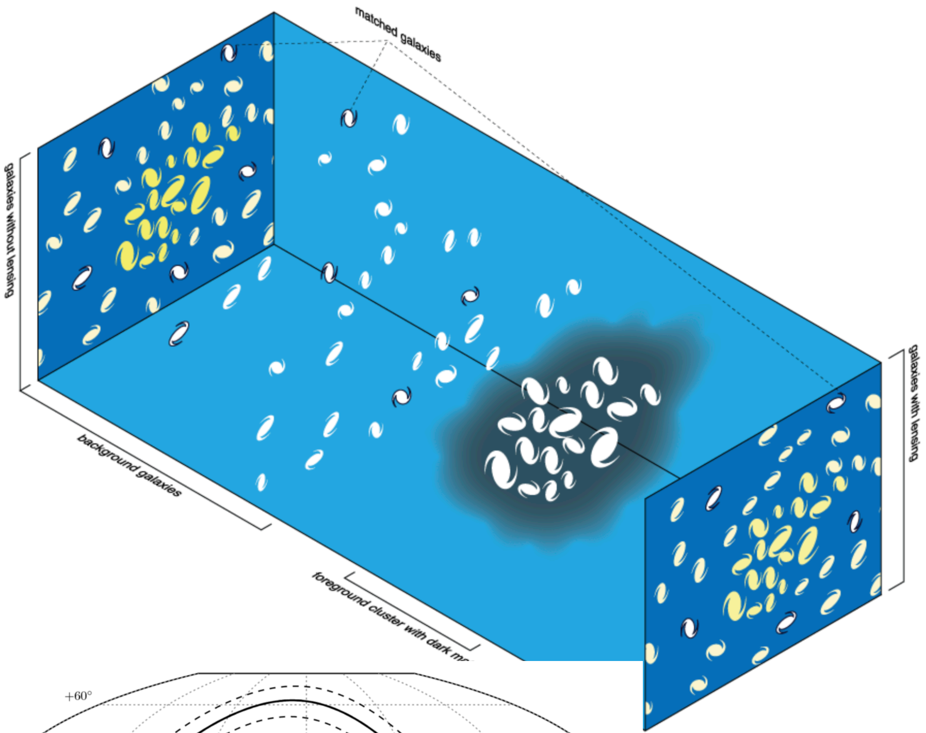
# Constraints on bias parameters

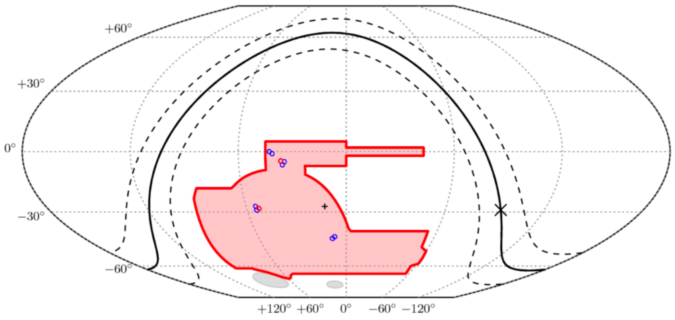
- The constraints on the parameters are consistent between the two scale cuts
- The relation between $b_s$ - $b_1$ and $b_{3nl}$ - $b_1$ is consistent with the co-evolution relation
- These results are for much more constraining 3D statistics. For the projected statistics, the results will be even more consistent

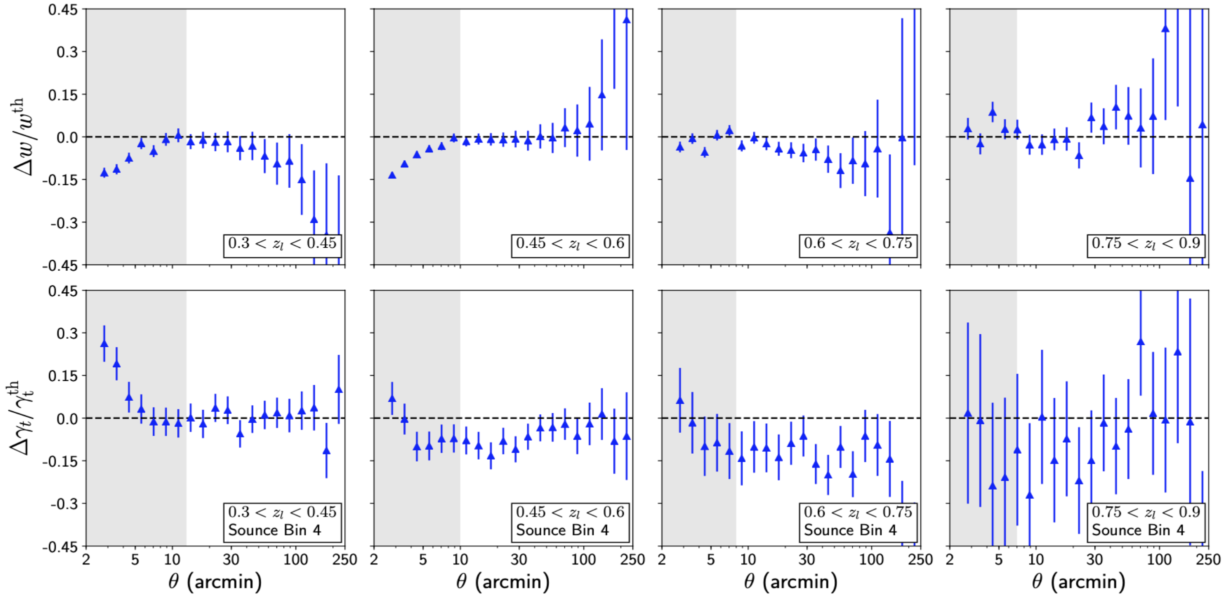


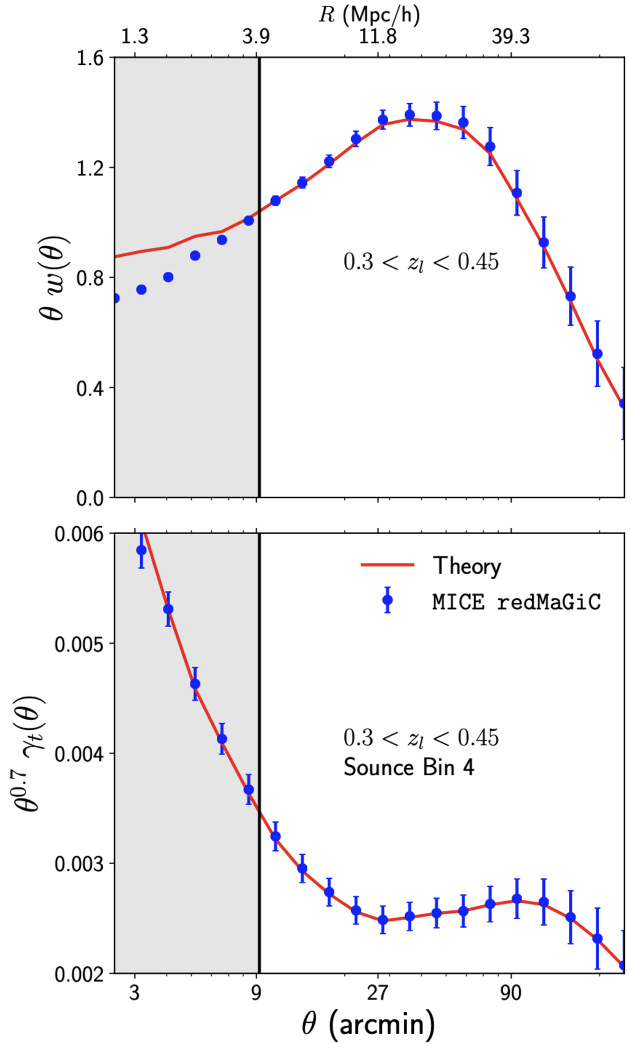
# Projected statistics

- In photometric surveys (like DES) we do not have precise redshifts, so we analyze projected statistics.
- $\xi_{\mathrm{gg}} \rightarrow w(\theta)$ (galaxy clustering)
- $\xi_{\mathrm{gm}} \rightarrow \gamma_{\mathrm{t}}(\theta)$ (galaxy-galaxy lensing)
- $\xi_{\mathrm{mm}} \rightarrow \xi_{+}/\xi_{-}$ (cosmic shear 2pt)





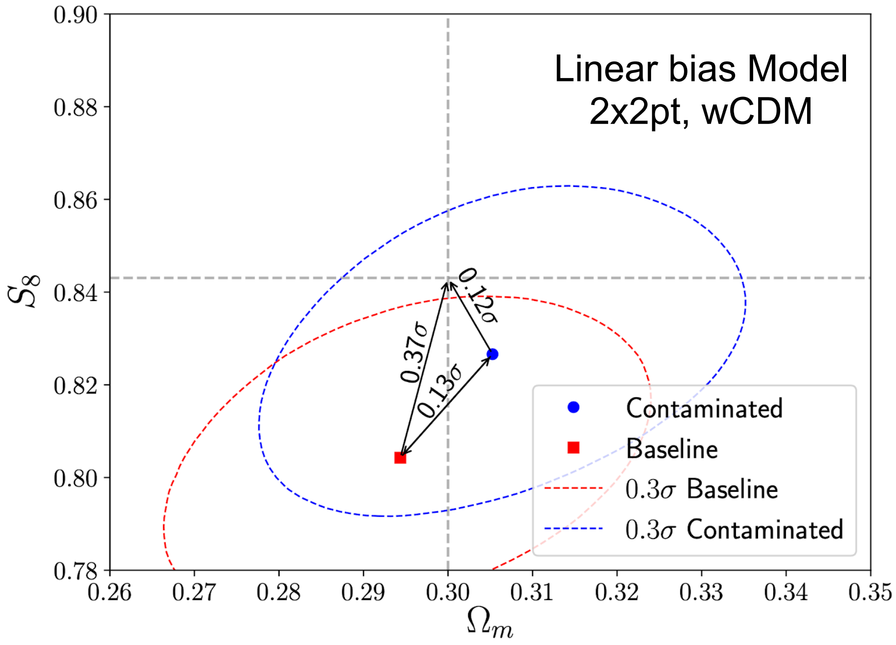




Right (→) Transforming 3D measurements to 2D shows that our best-fit model is a much better fit than required by the 2D error-bars (more stringent than Y3)

Top (↑) Residuals on measured projected correlation functions at fixed cosmology, gives reduced $\chi^2$ ~1.

# Complications in projected statistics

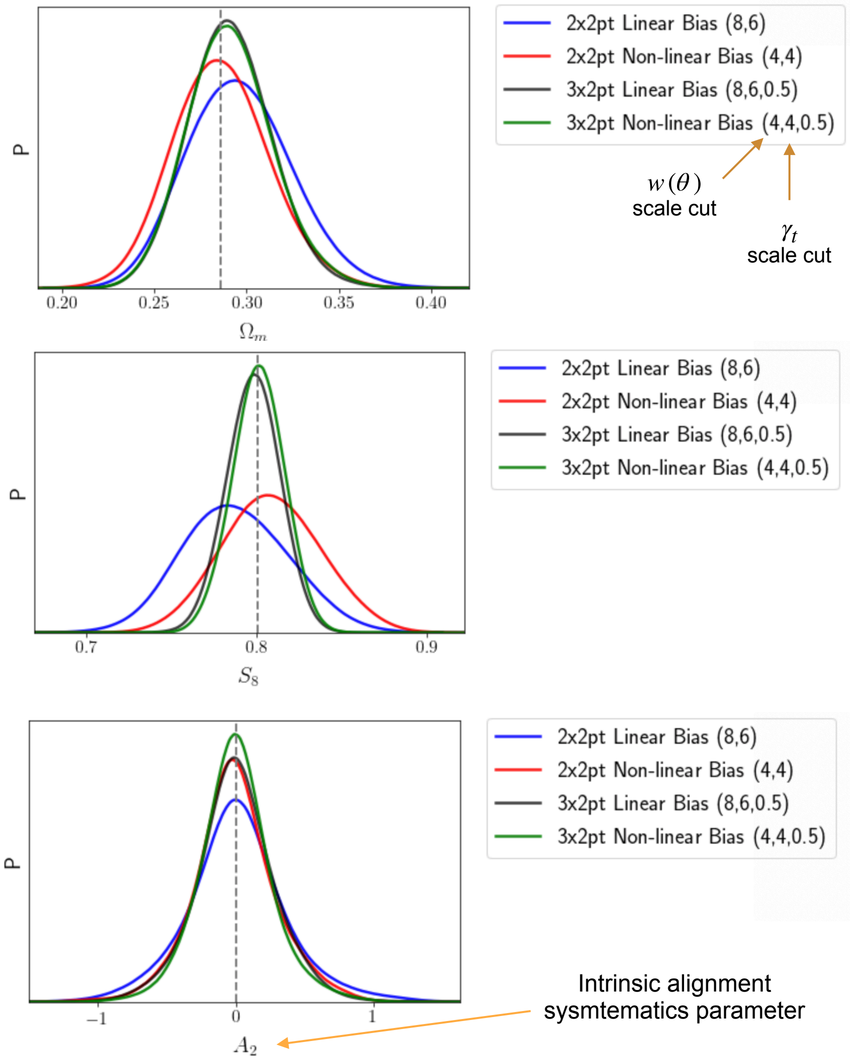
- Projection effects
  - We are usually concerned about getting unbiased cosmology constraints
  - But due to smaller constraining power and degeneracies between various parameters, we do not retrieve input cosmology even when analyzing noiseless simulated DV.
  - Related to projection of large volume of unconstrained parameters' posterior




$$S_8 = \sigma_8 \left( \frac{\Omega_m}{0.3} \right)^{0.5}$$

# Where does the information gain go?

- Large number of systematics parameters in addition to bias parameters, so all the SNR gain is not transferred to cosmology
- Stay tuned-in for imminent DES Year 3 results!



# 2. Baryonic feedback

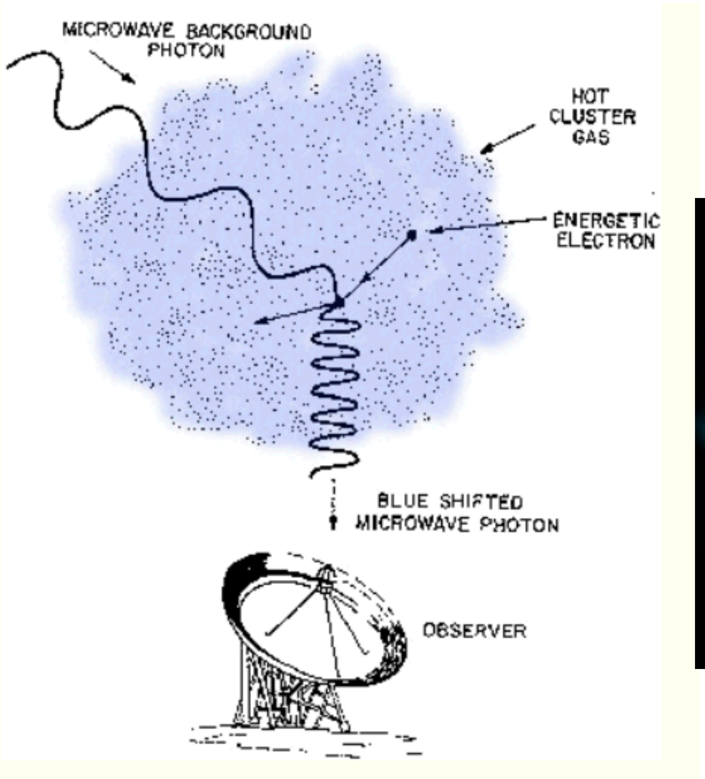
DES x (ACT + Planck) Cross-correlations
(with Eric Baxter, Marco Gatti, Colin Hill, Bhuvnesh Jain, Adam Lidz, DES and ACT Collaboration)

# tSZ introduction

1. Cluster halo is filled with hot ($10^8$ K) gas

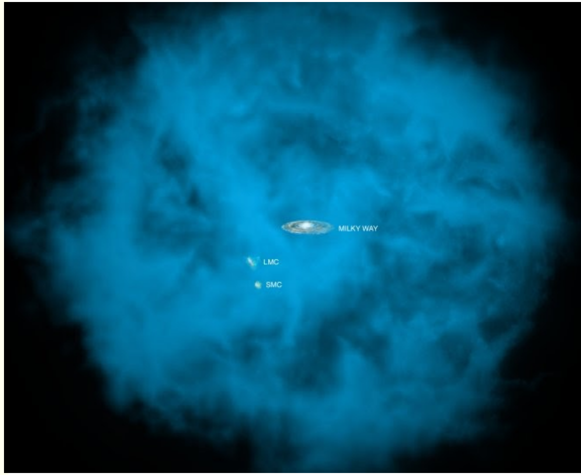
2. Much more baryonic mass in the gas than in all the stars in the galaxies (~90% in big halos)

3. Compton-$y$ parameter derived from CMB distortion is sensitive the integrated pressure (and hence to thermal energy of hot gas)




Credits : L. Van Speybroeck

$$y = \frac{\sigma_T}{m_e c^2} \int_0^\infty dl \, P_e(l),$$

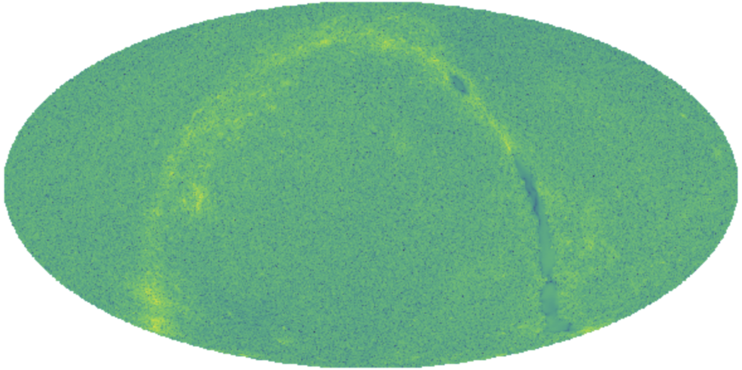



Credits: NASA Chandra Obs.

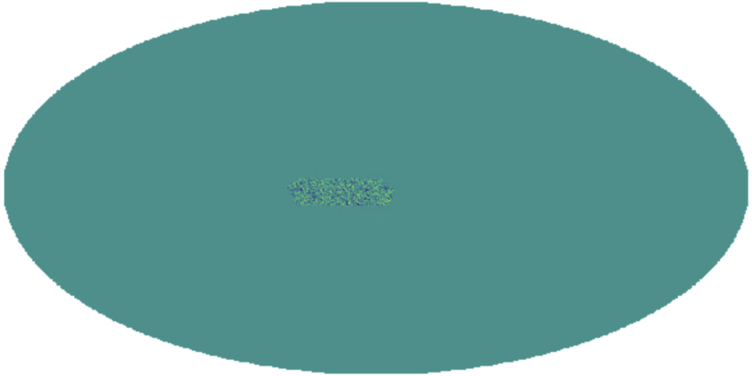
# Motivation:

- Compton-y is directly sensitive to the (integrated) pressure of the gaseous halos and any feedback process will imprint its signature on it.
- Cross-correlation with tracers of large scale structure can address several open questions. E.g. it can isolate the importance of the feedback in different redshifts, different halo masses and different environment conditions.
- It is also less sensitive to contamination from dust (as compared to auto-correlations of the Compton-$y$) and hence more robust.

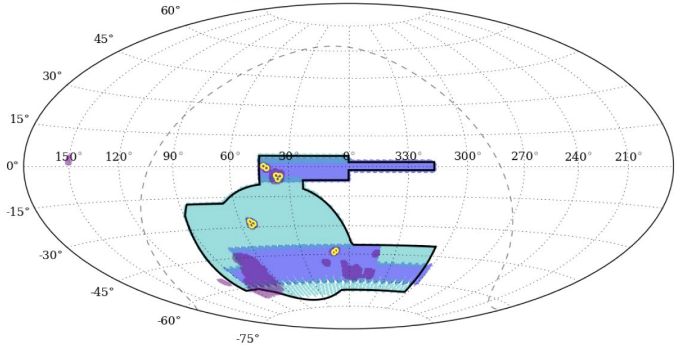
# Data Products



Planck y-map, All sky area with 10arcmin beam



ACT + Planck y-map in D56 area
450 sq degrees with ~2arcmin beam and lower noise




DES data (~4200 sq degrees):

- Redmagic galaxies (z < 1)
  - ~2.6 million galaxies
- Magnitude limited galaxy (z < 1)
  - ~10.7 million galaxies
- Mass map (kappa)/shear catalog
  - constructed from ~100 million galaxies till z ~ 1.5

# Data products

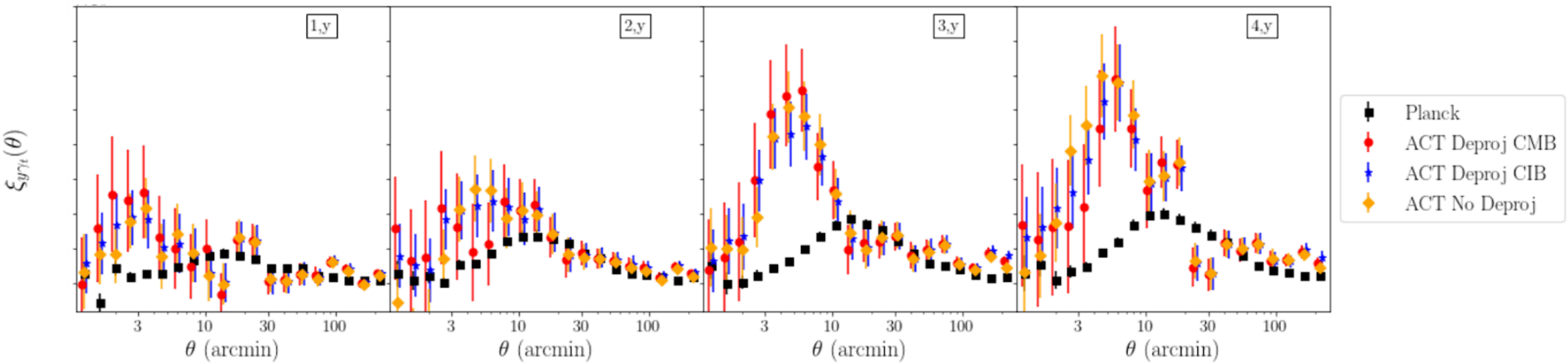
- Possible cross-correlations:
  - galaxy x y ($\langle gy \rangle$) for two different galaxy samples
  - shear x y ($\langle \kappa y \rangle$) where kappa is convergence (related to total mass)
    - $\langle \gamma_t y \rangle$ where $\gamma_t$ is the tangential shear and can be obtained directly from the shear catalog.
      - Theoretically it is closely related to $\langle \kappa y \rangle$
      - Does not have to rely on creation of $\kappa$ - map

# What are interesting outputs of this study?

- *Highest SNR measurements of shear x y and galaxy x y to-date.* Including ACT will improve the small scale constraints and low-mass halo constraints.
- *Inferred constraints on the pressure profiles and Y500-M500* related at fixed cosmology and understand the cosmology dependence
- Understand the role/importance of various astrophysical systematics like CIB, radio sources and intrinsic alignments in deep 1-halo regime for y cross-correlations
  - This is crucial for a full cosmology study using these probes
- *Compare the measurements with predictions from various hydro-simulations to rule-out/support the feedback prescriptions used there.*
- Having a general (and easily extensible) halo model theory code to consistently model the 2-point correlation functions and covariance (including non-gaussian term) of various probes constructed out of galaxy, shear and compton-y.

# *Shear x y* : Measurements

*Blinded; Preliminary*




Source bin 1
Planck S/N: 11.99
ACT S/N: 7.68

Source bin 2
Planck S/N: 15.38
ACT S/N: 6.93

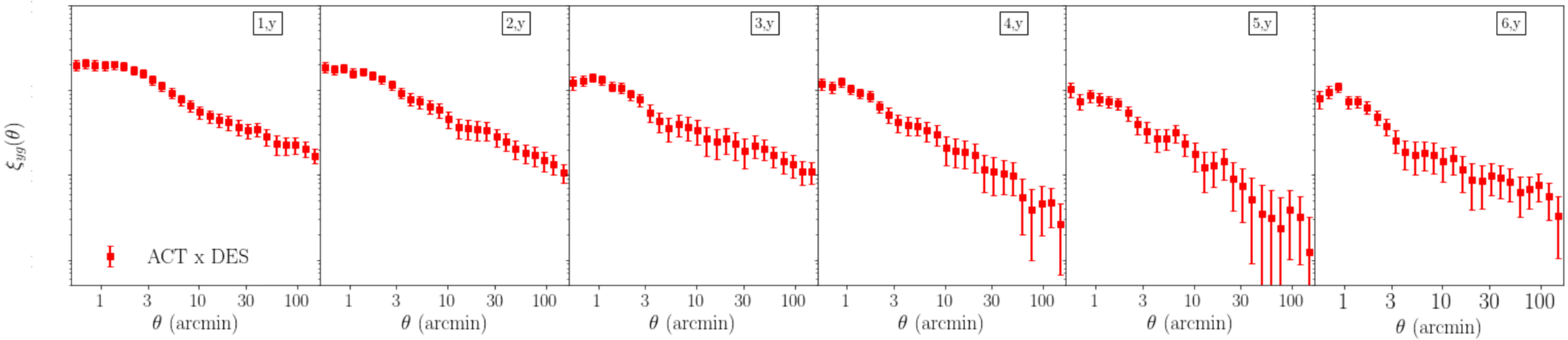
Source bin 3
Planck S/N: 17.15
ACT S/N: 9.82

Source bin 4
Planck S/N: 19.53
ACT S/N: 10.56

- The three y-maps showing different ways of dealing with contaminants. Not a significant leakage of any contaminant in the measurements

# *Galaxy x y* : Measurements

*Blinded; Preliminary*




Source bin 1
ACT S/N: 15.1

Source bin 2
ACT S/N: 15.8

Source bin 3
ACT S/N: 17.7

Source bin 4
ACT S/N: 16.2

Source bin 5
ACT S/N: 15.0

Source bin 6
ACT S/N: 13.7

Result with Deproj-CIB map and Maglim sample as significant bias due to dust here
Primarily because of smaller halo masses

# Thermal energy of Universe

- In large scales, the correlation between tracer and the pressure of halos can be written as

$$P_{Pg}^{\text{two-halo}}(k, z) = b_g(z)\langle bP_e(z)\rangle P_{\text{lin}}(k, z).$$

- $\langle bP_e \rangle$, the bias-weighted-pressure of the is also a measure of average thermal energy of universe at redshift of tracer, $z$

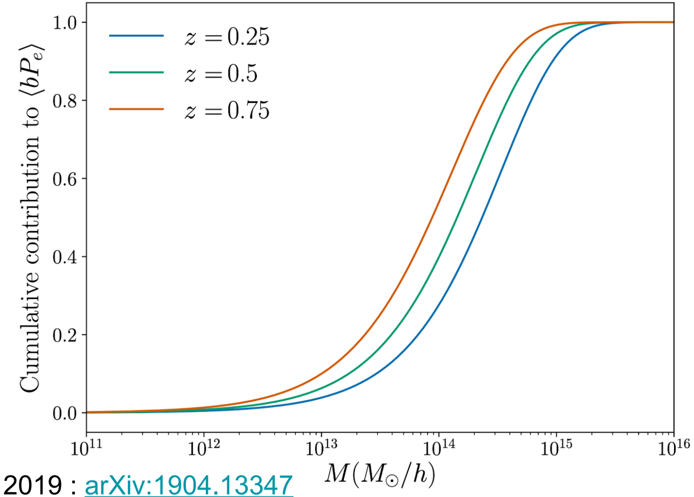
Halo mass function

Halo bias

Thermal Energy

$$\langle bP_e\rangle(z) \equiv (1+z)^3 \int_0^\infty \frac{dn}{dM} b(M, z) E_T(M, z) dM.$$

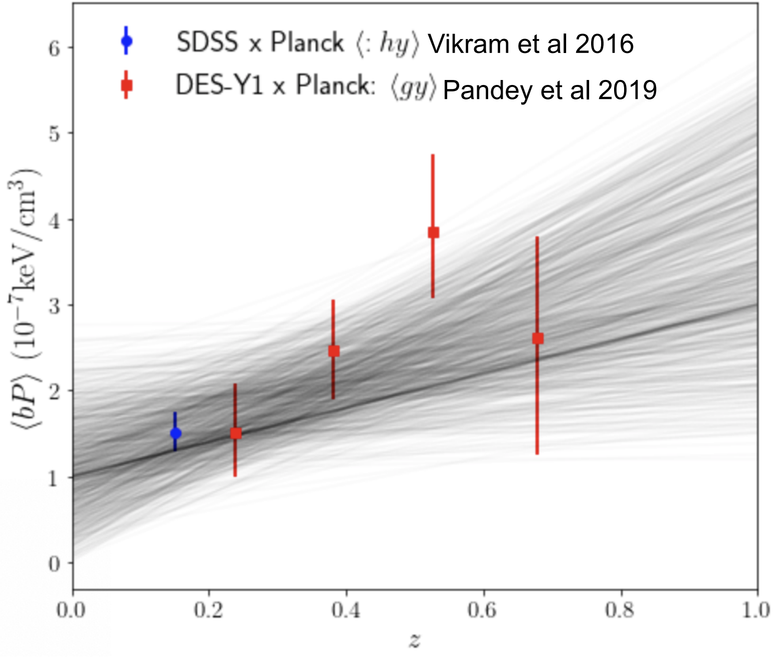
- Since Compton-$y$ is sensitive to pressure, this allows to constrain $\langle bP_e \rangle$ and hence also the average thermal energy of the Universe




Pandey et al 2019 : [arXiv:1904.13347](arXiv:1904.13347)

# $\langle bP_e \rangle$ from shear x y

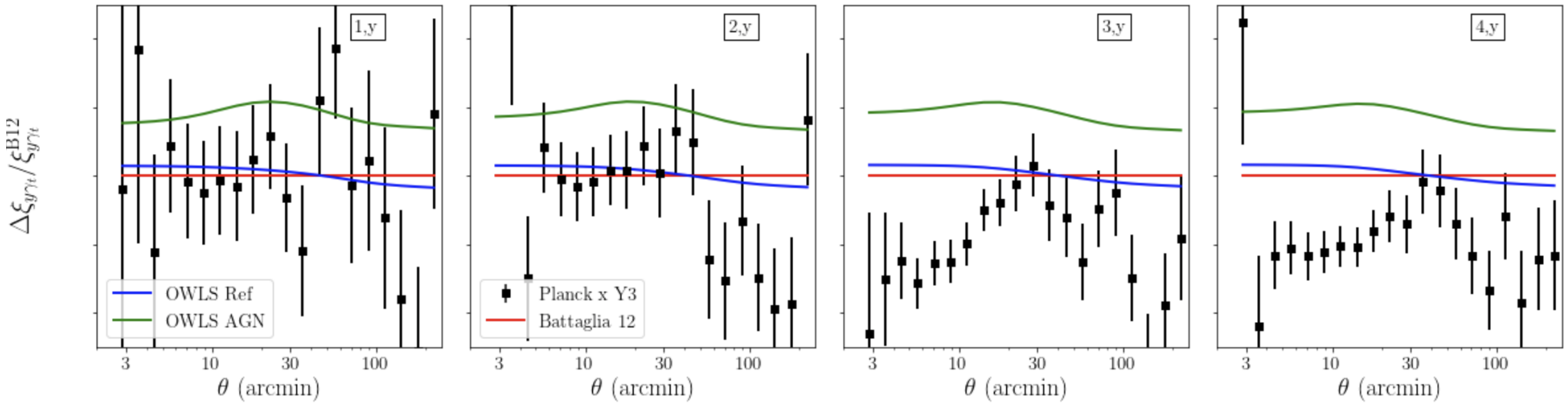
The $\langle bP_e \rangle$ measurements from shear x y compared to previous SDSS and DES cross-correlations with Planck-y map. Assumed a linear $\langle bP_e \rangle$ vs $z$ relation to get this plot with free slope and amplitude at $z$=0.




*Blinded; Preliminary*

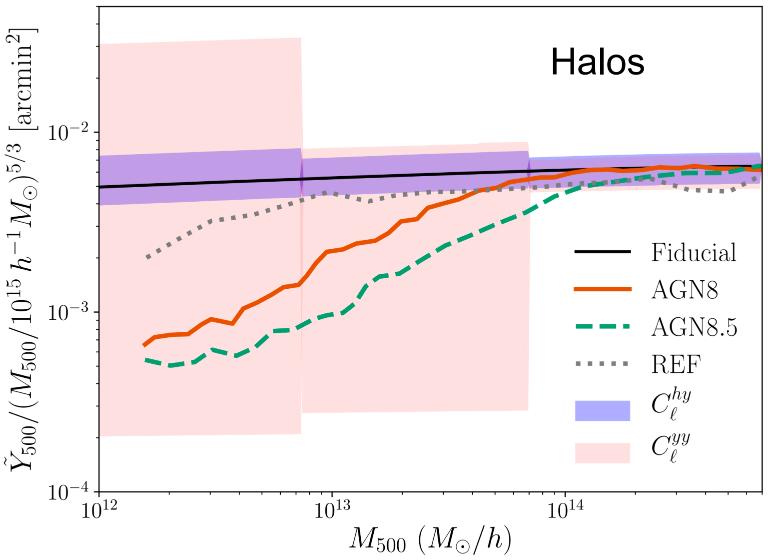
# Residuals of different hydrosims models at a single cosmology

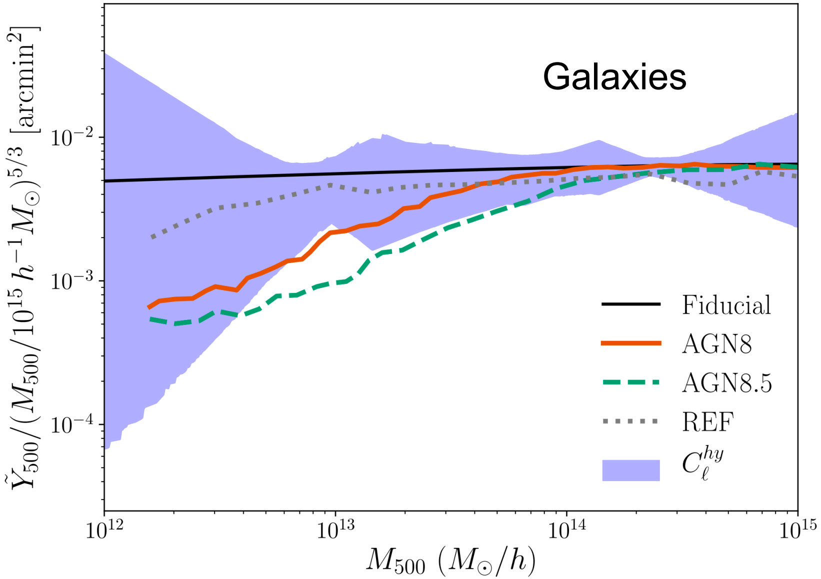
*Blinded; Preliminary*




- Comparison of this signal as well as inferred 3D profiles will inform the feedback prescriptions for simulations

# Model



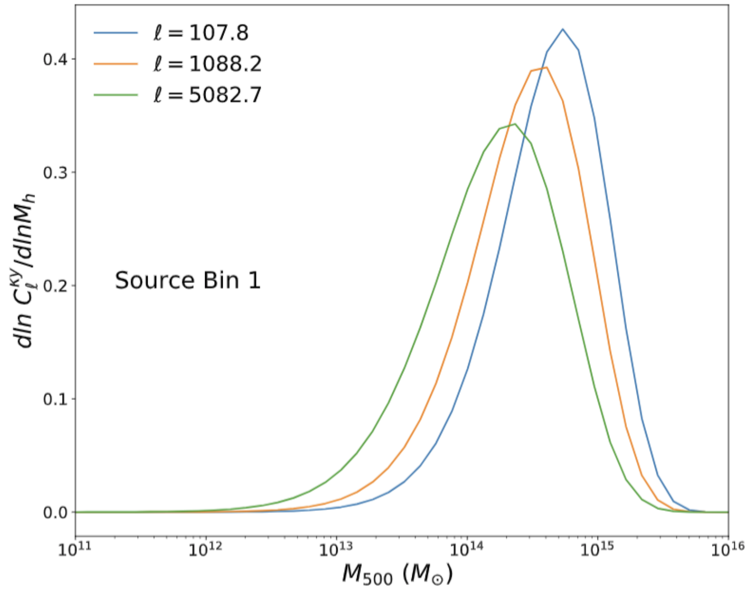

Pandey, Baxter and Hill 2019 : arXiv:1909.00405
Forecasted DESI x S4 constraints with break model

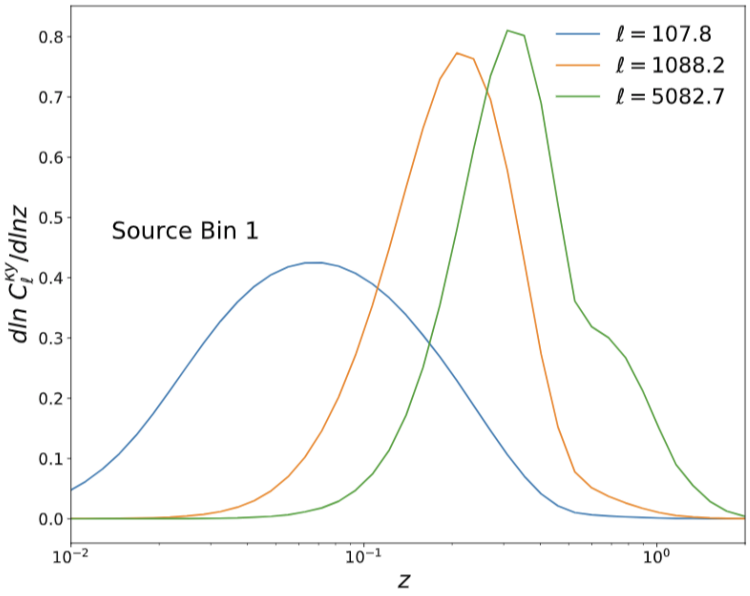
- Feedback is more important in smaller mass halos
- To decouple the low and high mass constraints, we propose using a 'break model'
- Pursue a Halo-Model approach and infer the pressure profile from the measurements

$$P_e(r|M,z) \rightarrow \begin{cases} P_e^{\mathrm{B}}(r|M,z)\,, \quad M \geq M_{\mathrm{high}} \\ P_e^{\mathrm{B}}(r|M,z)\left(\frac{M}{M_{\mathrm{high}}}\right)^{\alpha_{p,\mathrm{mid}}}, M_{\mathrm{low}} < M < M_{\mathrm{high}} \\ P_e^{\mathrm{B}}(r|M,z)\left(\frac{M}{M_{\mathrm{high}}}\right)^{\alpha_{p,\mathrm{mid}}}\left(\frac{M}{M_{\mathrm{low}}}\right)^{\alpha_{p,\mathrm{low}}}, M < M_{\mathrm{low}} \end{cases}$$

$P_e^{\mathrm{B}}$ = gNFW Pressure profile from Battaglia et al 2012

# Sensitivity of shear x y to different halo mass/redshift

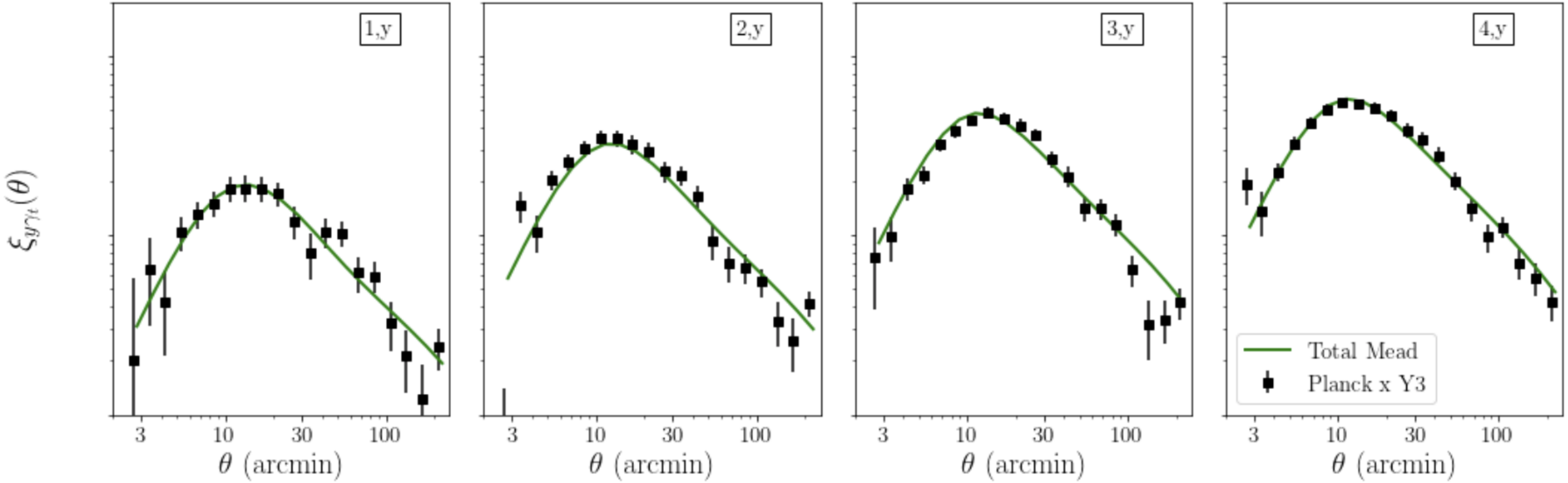



- ACT has much smaller beam compared to Planck y-map
- This helps in pushing to smaller scales, smaller mass halos and to higher redshifts

*Blinded; Preliminary*

(Planck x DES)

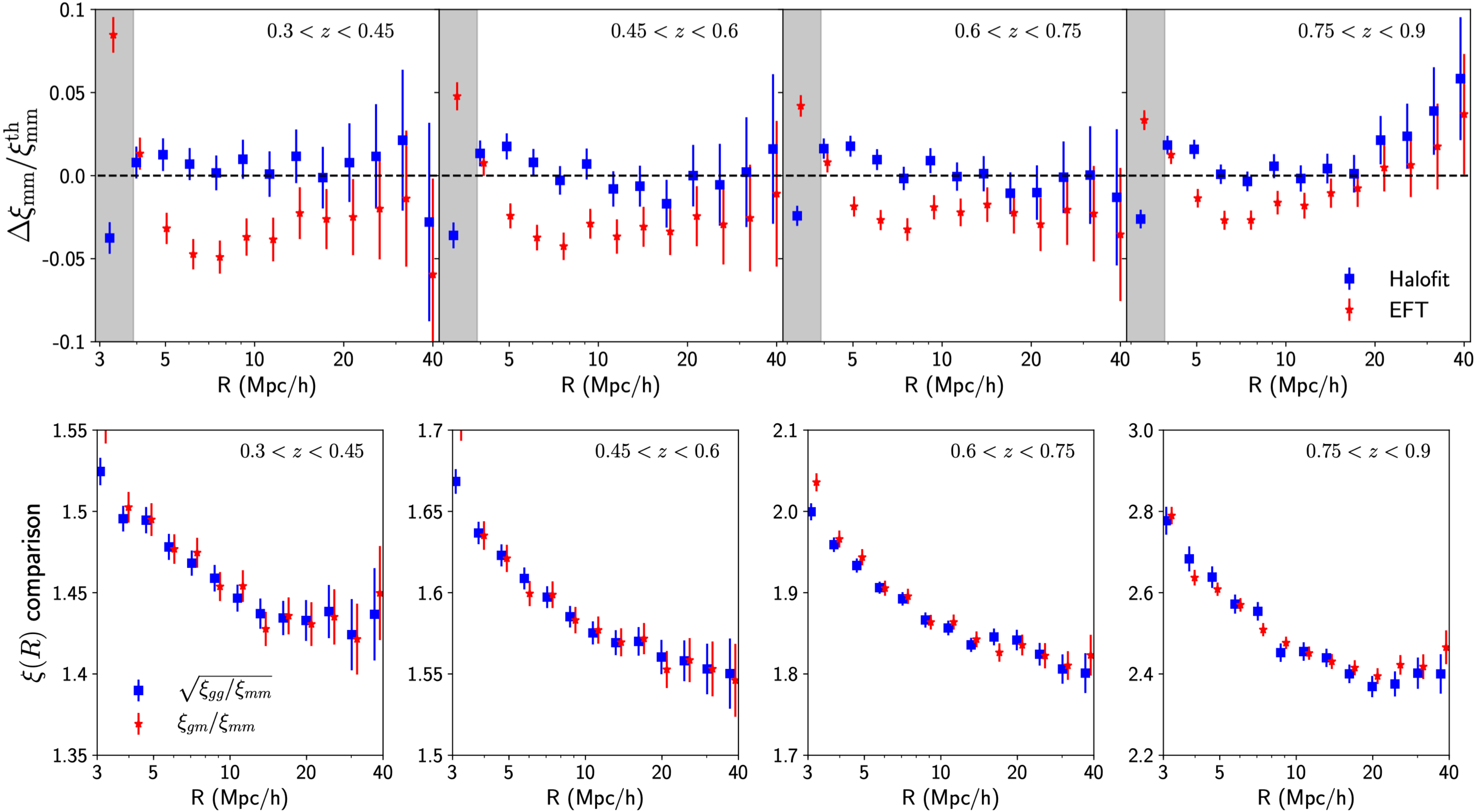



Preliminary fits to shear x y

# Conclusion

- Correlations constructed out of galaxy positions, galaxy shapes and Compton-y are a highly informative probe of large scale structure
- Pushing our analysis to smaller scales with optimum modeling will give more robust and tighter constraints on the cosmological parameters
    - Necessary to utilize the information content of the data
- For projected statistics, we need methods to counter the complications due to projection effects and degeneracy — *stay tuned in for DES Y3 results*!
- Compton-y cross-correlations will constrain pressure profiles and inform the feedback prescriptions in the hydro-dynamical simulations — *stay tuned in for DES x ACT results*!

# Extra Slides



$0.3 < z < 0.45$
$0.45 < z < 0.6$
$0.6 < z < 0.75$
$0.75 < z < 0.9$
$\Delta\xi_{\rm mm}/\xi_{\rm mm}^{\rm th}$
R (Mpc/h)
Halofit
EFT
$\xi(R)$ comparison
$\sqrt{\xi_{gg}/\xi_{mm}}$
$\xi_{gm}/\xi_{mm}$

# 3D statistics on Buzzard

- Box transition issue on the sims for the second bin.