# Cosmology and Astrophysics from small scales

## (Using DES, ACT and Planck)

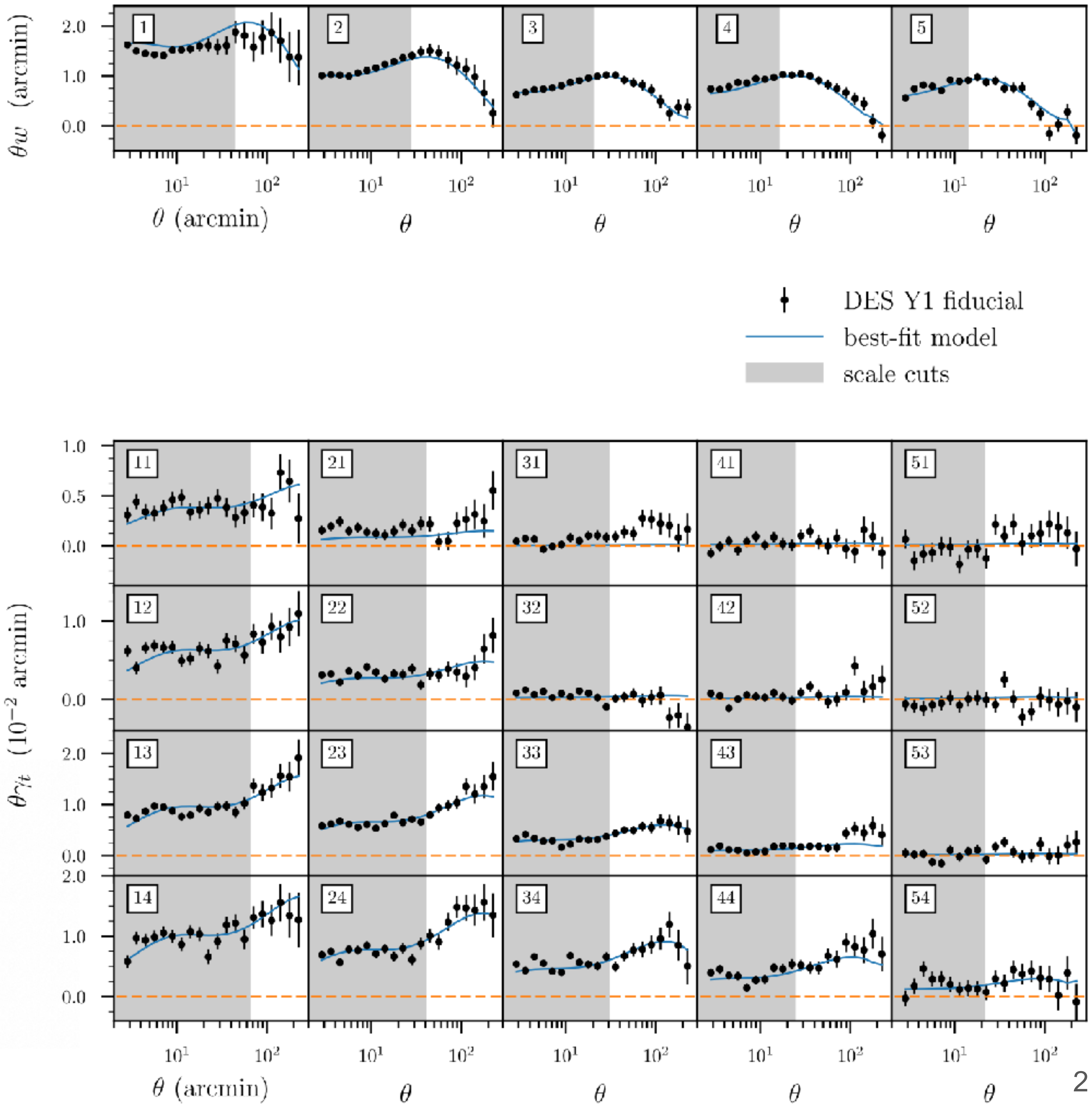
**Shivam Pandey**
**University of Pennsylvania**

**Work with DES and ACT collaboration**
**(especially Elisabeth Krause, Bhuvnesh Jain, Joe DeRose, Marco Gatti, Eric Baxter, Colin Hill, Niall MacCrann, Xiao Fang….)**

# ***Motivation:***

## DES Year 1 results (2017)

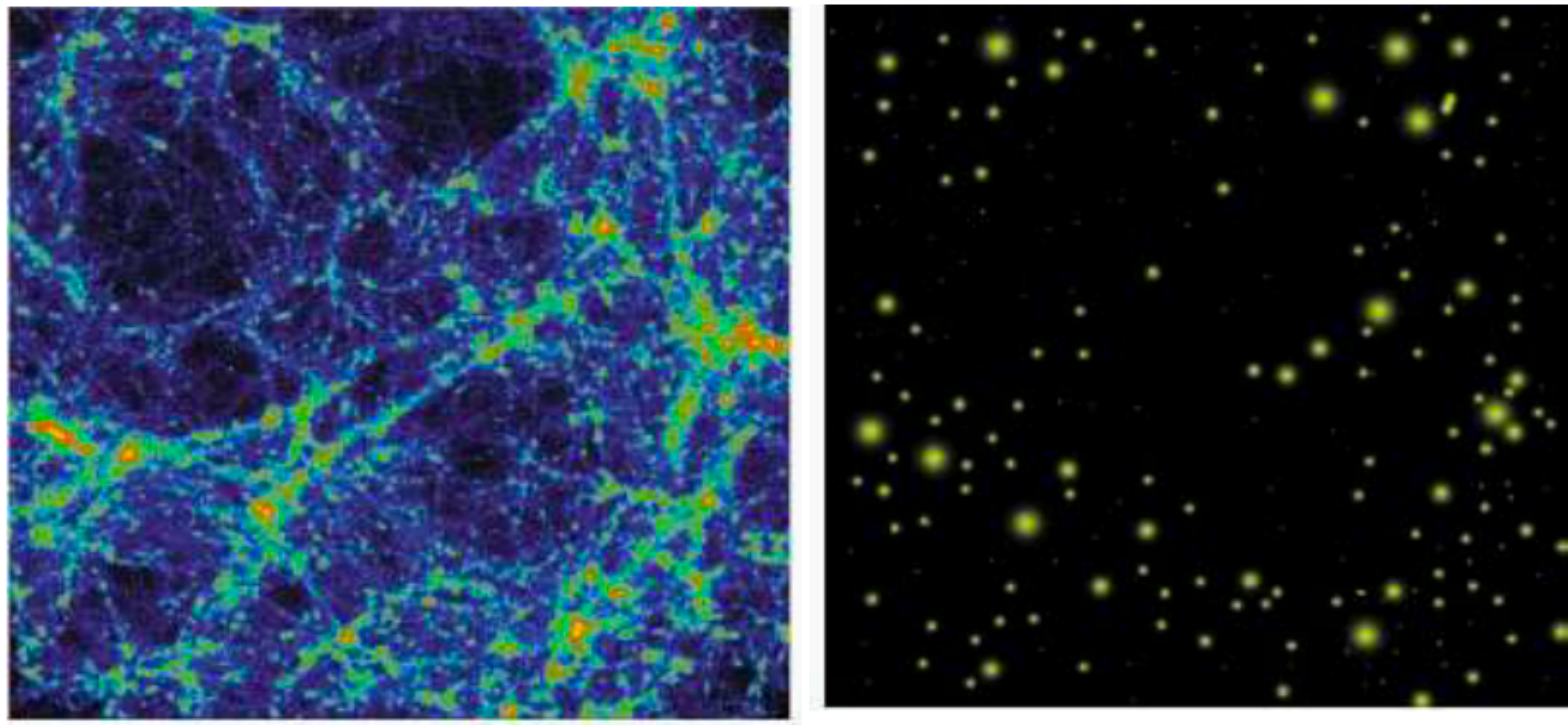
- **Analysis of data:**
  - **SNR of datavector ($w(\theta)$+ $\gamma_t$ $(\theta)$):**
    - *Before* scale cuts: 120$\sigma$
    - *After* scale cuts: 42$\sigma$
    - We threw away 270/500 data-points (gray band)!



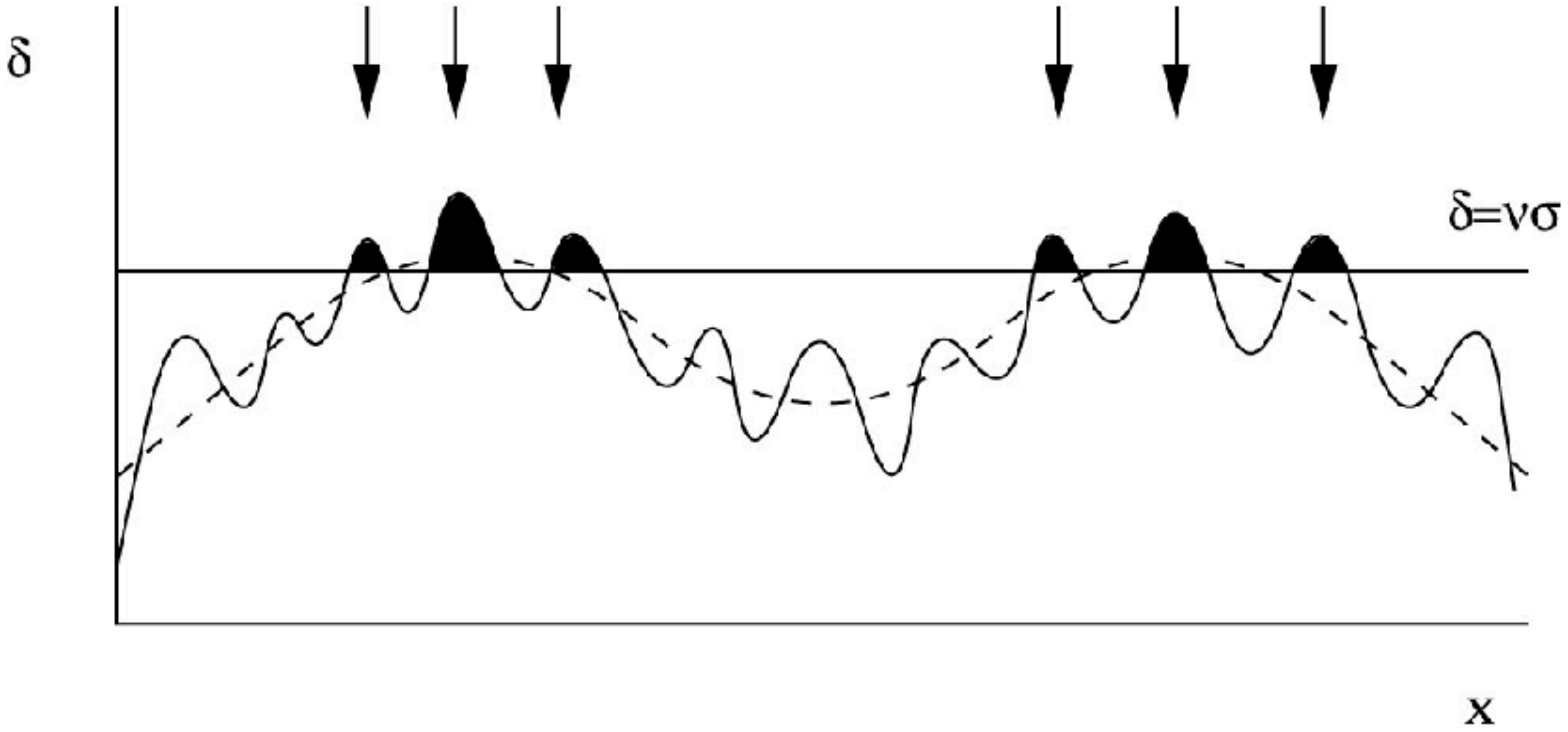
DES Collaboration et al

# Impact of (g)astrophysics on LSS

- We don’t observe all the components of the universe, only tracers of the full large scale structure
    - Most of the tracers, such as galaxies are a *biased* tracer of the underlying dark matter density field.
    - This biasing is very non-linear in general
- Poorly understood, high energy phenomena (like SN and AGN), impacts the distribution of LSS
- These constitute largest systematic uncertainty (and are crucial to understand for current and next-gen surveys)
    - Understanding these phenomena has implications for galaxy formation, non-linear dynamics, CGM/IGM physics, sims validation…



Illustris sims



Credits: John Peacock

# Main limiting factors

There are two main factors that limit the modeling applicability to weak lensing/clustering type analysis:

1. ***Galaxy biasing***:

- Non-linear galaxy-matter connection, especially on small scales.
- Pushing to smaller scales to recover more information about cosmology and astrophysics from the correlation functions

- **S. Pandey**, E. Krause et al. (arXiv:2008.05991)
- **S. Pandey** et al. (arxiv:2105.13545)
- E. Krause, X. Fang, **S. Pandey** et al. (arxiv:2105.13548)
- S. Goldstein, **S. Pandey** et al. (in prep.)

2. **Baryonic feedback**:

- Feedback of violent processes on large scale structures
- SZ effect (scattering of CMB from hot gas) encodes this information

- **S. Pandey**, E. J. Baxter et al. (arxiv:1904.13347)
- **S. Pandey**, E. J. Baxter, and J. C. Hill (arxiv:1909.00405)
- M. Gatti, **S. Pandey**, et al. (arxiv:2108.01600)
- **S. Pandey**, M. Gatti et al. (arxiv:2108.01601)
- **S. Pandey** et al (in prep.)

# 1. Galaxy Biasing

*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

- 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
    - $\delta_g = f^{(1)}(\delta_m) + f^{(2)}(\delta_m, \ldots.) + \ldots.$

# Summary statistics

- It is hard to infer the cosmology/astrophysics from galaxy over-density field $\delta_g$
- We consider 2pt statistics where principles of homogeneity and isotropy simplify things a lot: $\langle\delta_g\delta_g\rangle$ and $\langle\delta_g\delta_m\rangle$
- For example, the power spectra of $\langle\delta_g\delta_m\rangle$ :

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

- A five/six parameter model, complete up-to third order
- We model $P_{\mathrm{mm}}$ using numerical simulations (halofit, so $c_{\mathrm{s}}^2 = 0$)
    - As we want to test galaxy biasing, we fit to $P_{\mathrm{gg}}/P_{\mathrm{mm}}$ and $P_{\mathrm{gm}}/P_{\mathrm{mm}}$
    - We validate that our conclusions are insensitive to choice of $P_{\mathrm{mm}}$ modeling

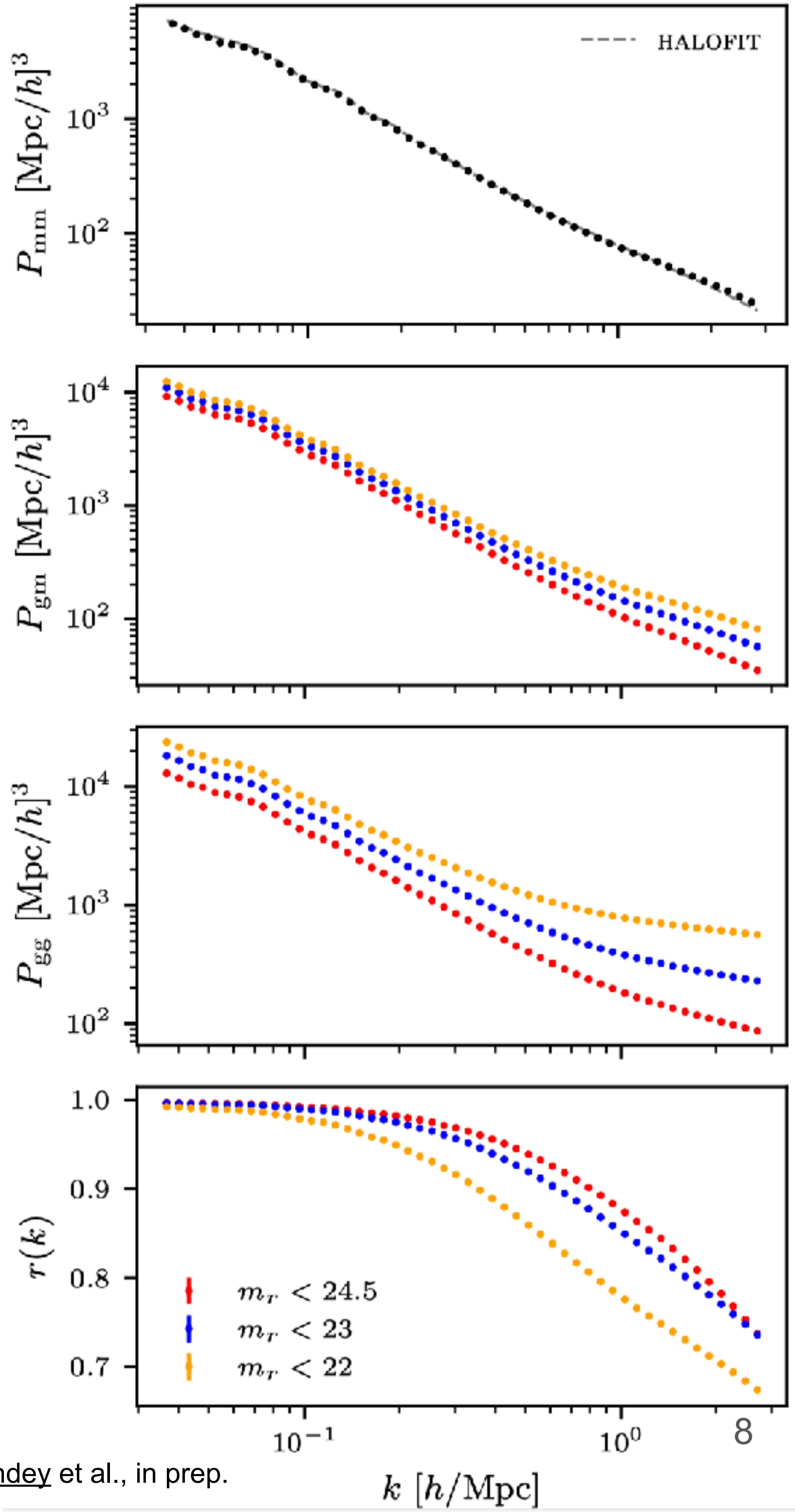
# Questions we want to answer

- How many of bias parameters, especially $b_{\rm s}$, $b_{\rm 3nl}$ and $b_{\rm k}$ can we fix/remove?
    - PT written in lagrangian coordinates should be equivalent to the eulerian picture. Performing the equivalence $b_{\rm s}$ and $b_{\rm 3nl}$ can be 'predicted' as a function of $b_1$ (plus some additional contributions)
    - Co-evolution values
        - $b_s = (-4/7) \times (b_1 - 1) + b_s^{\rm Lag}$
        - $b_{\rm 3nl} = (b_1 - 1) + b_{\rm 3nl}^{\rm Lag}$
    - Assuming spatial locality : $b_{\rm k} = 0$
    - How does the answer depend on scales/accuracy we probe the 2pt functions
- Do our conclusions depend upon doing the analysis in fourier or configuration space ($\xi_{\rm gg}$ and $\xi_{\rm gm}$)?

# Validation on LSST-like sims

- Uses Cosmo-DC2 sims, based on Outer-rim sims. Doing validation at z=1.0 snapshot.
- We fit to *three different galaxy samples*, selected at different r-band thresholds, 22, 23 and 24.5 (probing massive to lower-mass halos)
- *We test in both fourier and configuration space*
- *We test three models:*

  - *Fiducial Model:* $b_1, b_2, b_s, b_{3\rm nl}$, and $b_{\rm k}$ vary freely
  - *Three Parameter Model:* $b_1, b_2$, and $b_{\rm k}$ vary freely with $b_s$ and $b_{3\rm nl}$ fixed at their co-evolution values
  - *Two Parameter Model:* $b_1$ and $b_2$ freely with $b_s$ and $b_{3\rm nl}$ at their co-evolution values and $b_{\rm k}$ set to zero

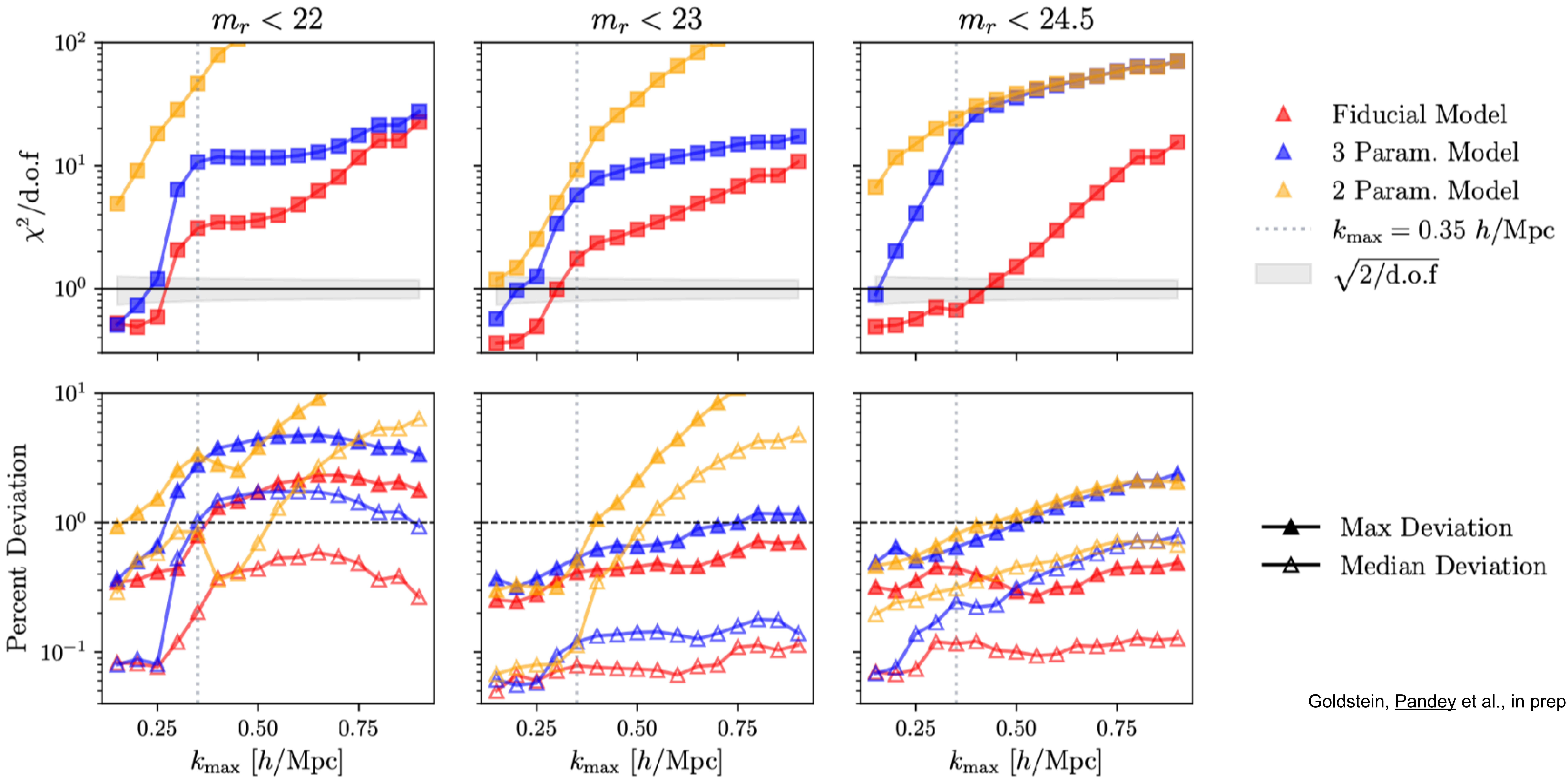


Goldstein, Pandey et al., in prep.

# Fitting in fourier space; $k_{\max} = 0.35\,h\mathrm{Mpc}^{-1}$

Goldstein, Pandey et al., in prep.

# Goodness-of-fit in fourier space

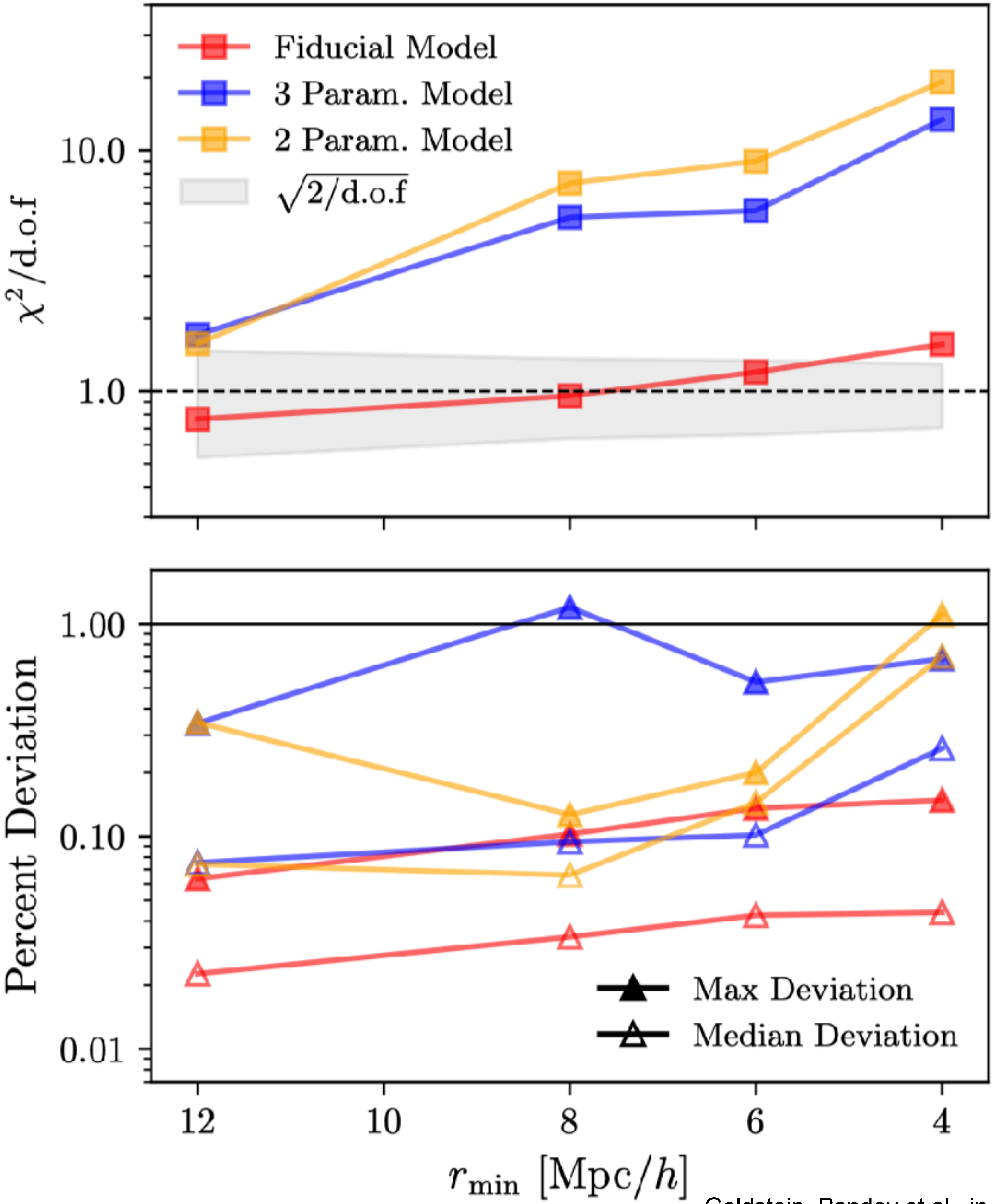


Goldstein, Pandey et al., in prep.

For the expected LSST galaxy sample, $m_r < 24.5$, we expect a 2-parameter model to be good enough to 2% and 5-parameter to be good enough to ~0.4%

# Goodness-of-fit in configuration space ($m_r < 23$)

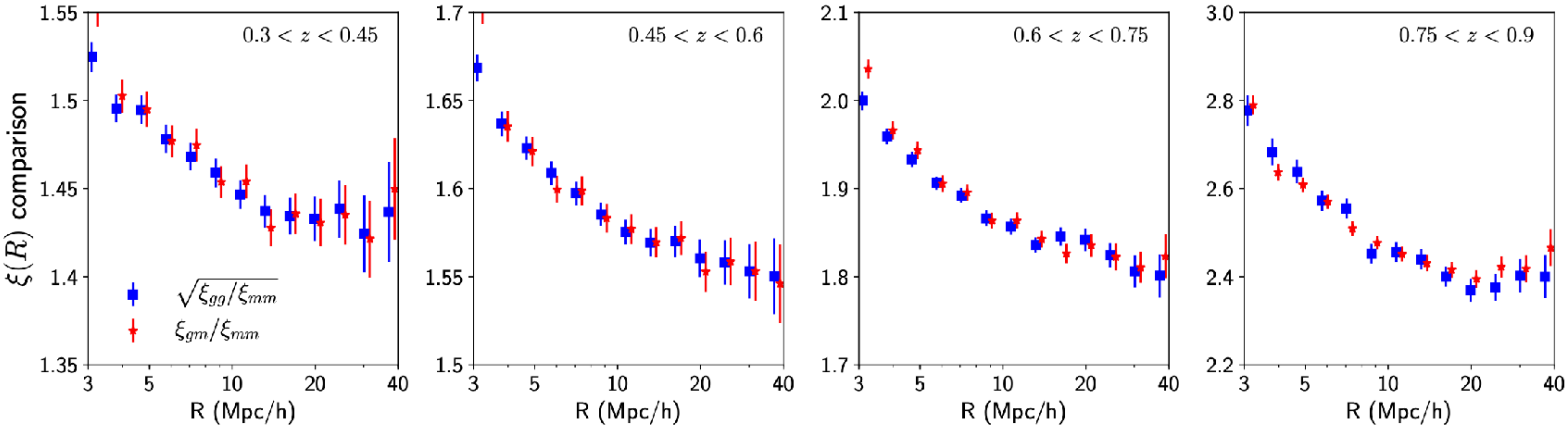
- We find similar results in configuration space
- Fiducial model with 5 free parameters works very well
- We get sub-percent fits with all the models at various scale cuts.
- A 2-parameter model suffices for target accuracy of 1-percent or less down to 4Mpc/h (for $m_r < 23$ sample)



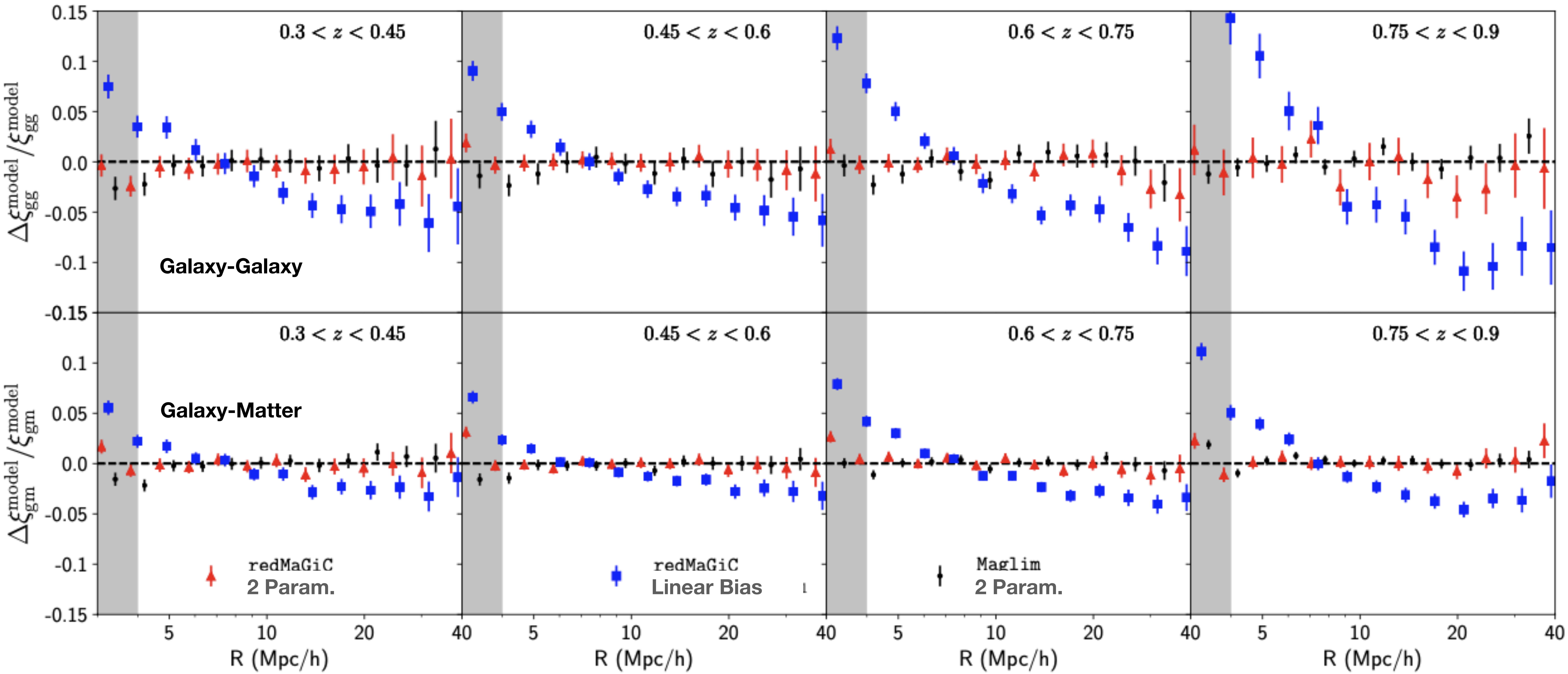
Goldstein, Pandey et al., in prep.

# Validation on DES-like simulations (full lightcone)

- We use DES-like simulation (MICE) and fit the 3D correlation functions at fixed cosmology
  - We test our model on two different galaxy catalogs replicating DES data
    - redMaGiC sample consisting of mostly red galaxies with small photo-z errors
    - Maglim sample consisting of $z$-dependent magnitude limited catalog, has larger number of galaxies



Pandey et al. 2021

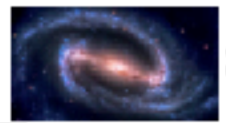


Pandey et al. 2021

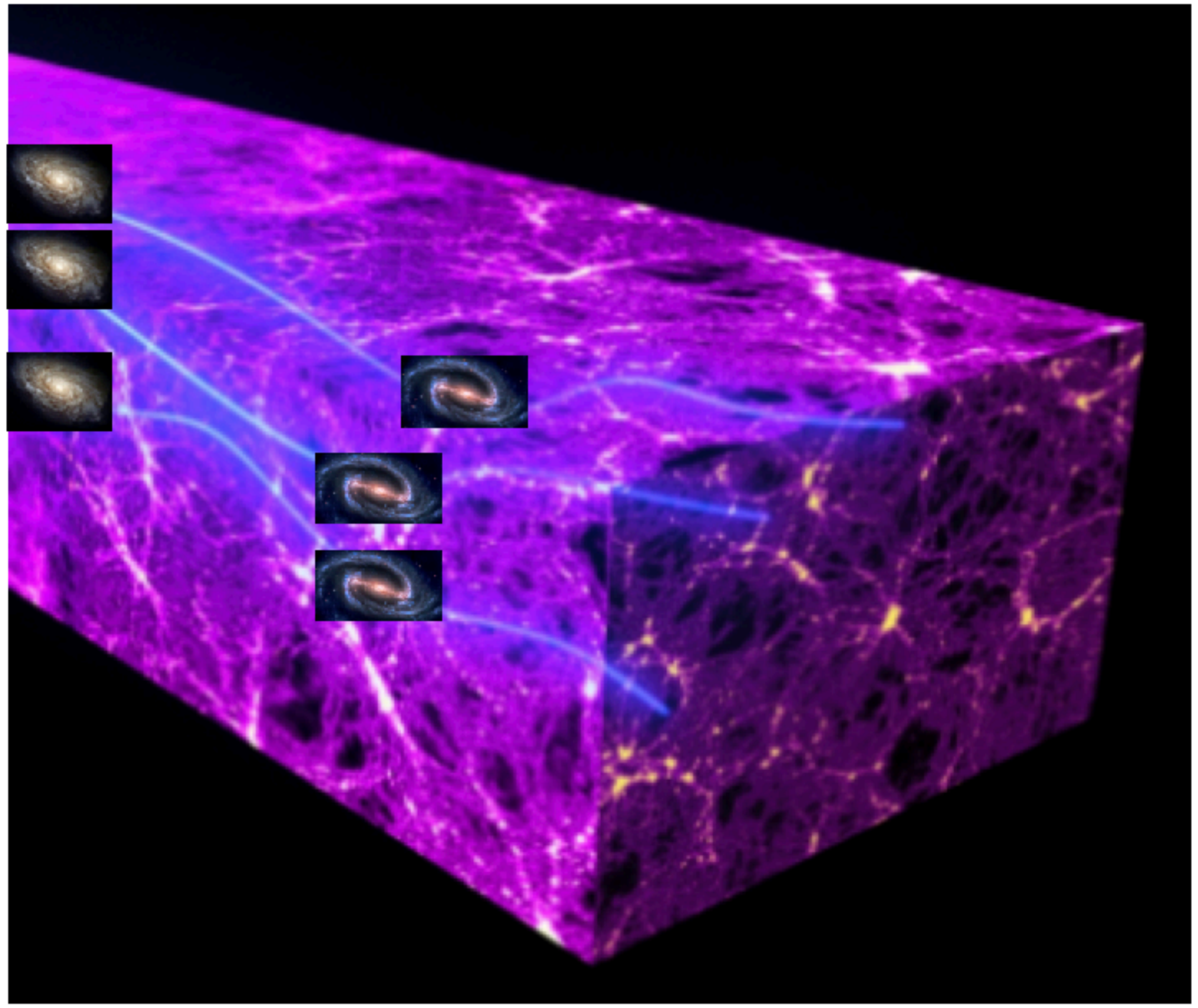
The two-parameter non-linear bias model, gives residuals within 2% for both galaxy samples: redMaGiC and Maglim down to $4\,\mathrm{Mpc}/h$

# Application to DES-Y3 data

- Dark Energy Survey (DES) is a leading photometric survey, covering ~4000 deg$^2$

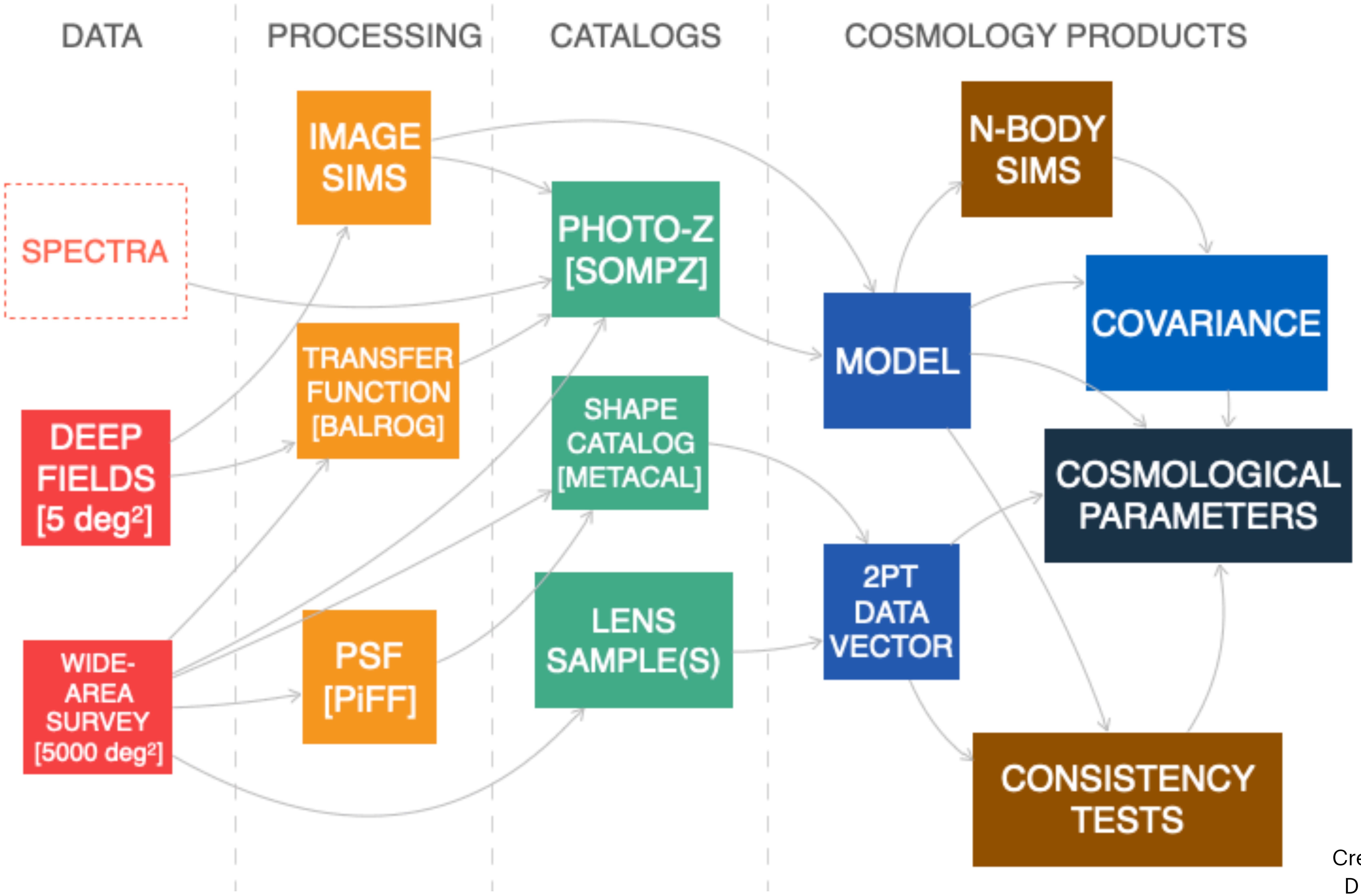
- DES extracts positions and shapes of galaxies from images.
- Intrinsic shape of galaxies get distorted by weak lensing caused by all the matter between us and the galaxy.
- From *position* (foreground lens =  = L) and *shapes* (background source =  = S) of the galaxies, we construct three 2-pt functions by cross-correlating them:
  - SS = shear-2pt = $\xi_{+/-}$ $\}$ $1 \times 2\,\mathrm{pt}$
  - LL = galaxy clustering = $w(\theta)$
  - LS = galaxy-galaxy lensing = $\gamma_t(\theta)$

$\Big\}$ $2 \times 2\,\mathrm{pt}$



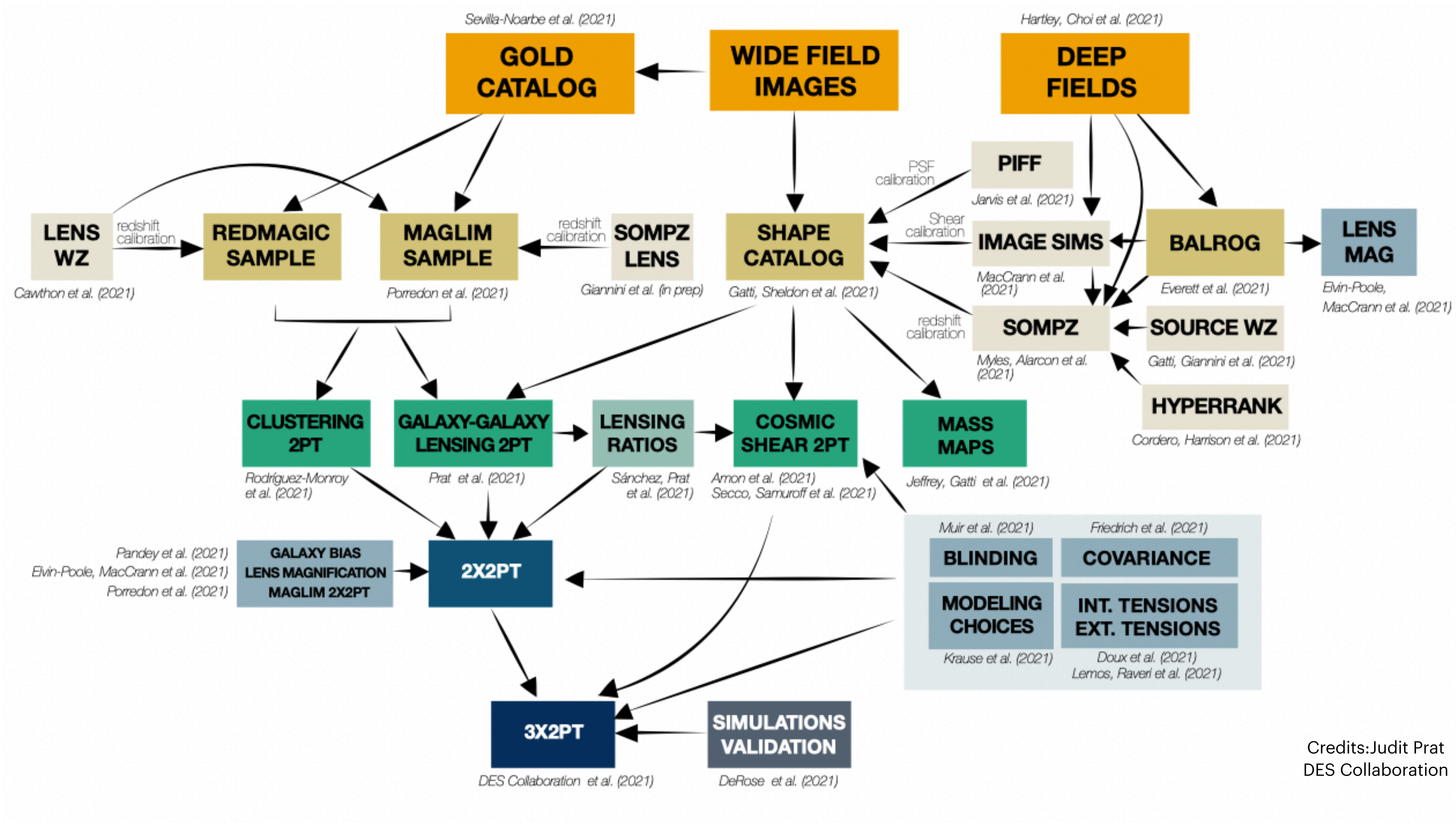
Credits : Wikipedia

# Schematic of DES analysis pipeline



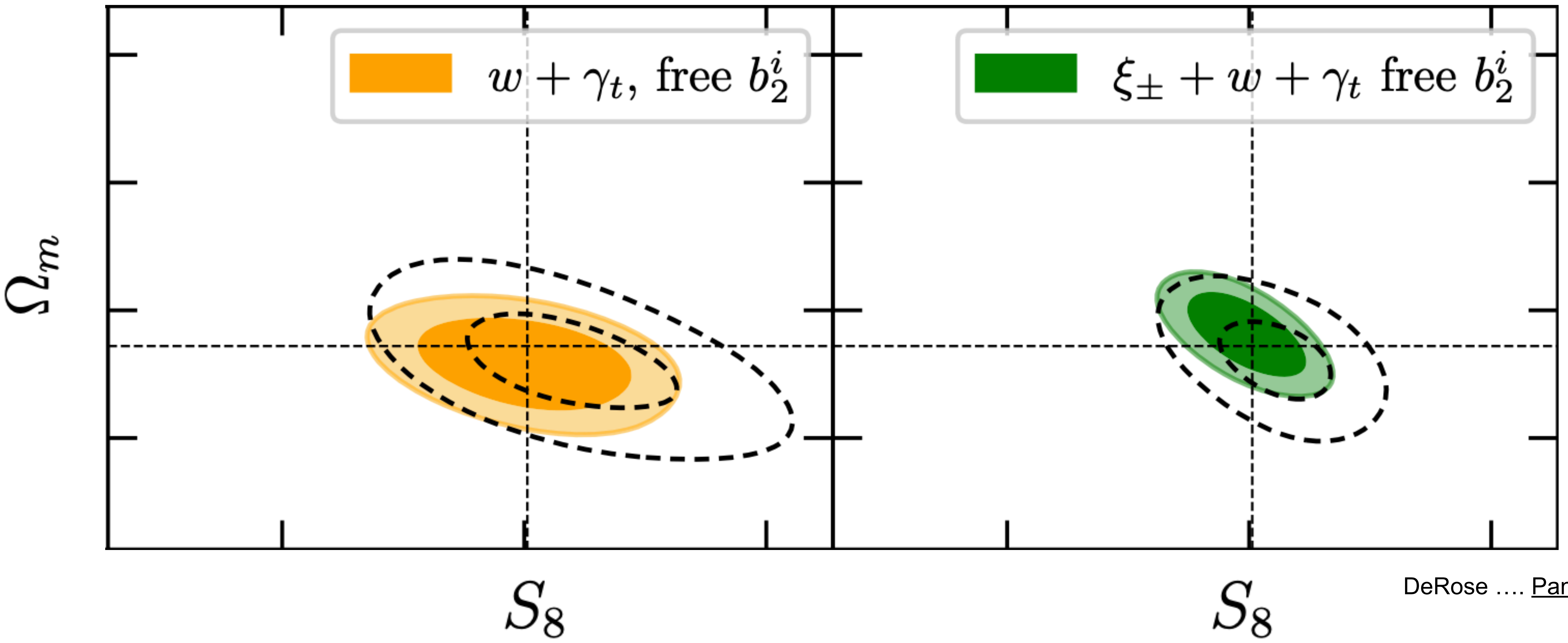
Credits: Cyrille Doux
DES Collaboration

# Various aspects detailed in ~30 papers



Credits:Judit Prat
DES Collaboration

# Validation of NL-bias on simulated DES-like realizations

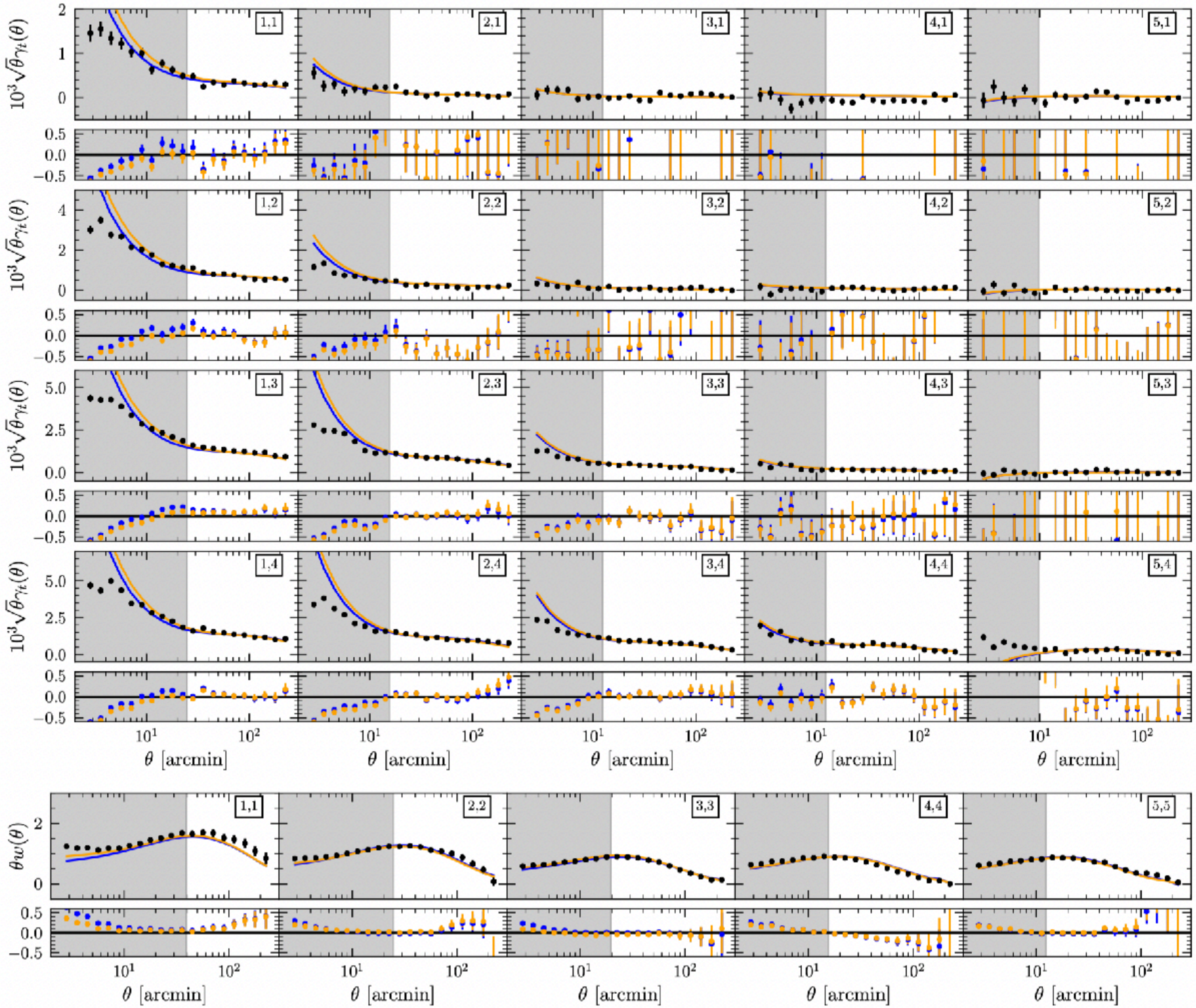


DeRose …. Pandey et al. 2021

- Analyzing angular scales corresponding to 4Mpc/$h$ or larger
- Filled contours use covariance scaled by $1/\sqrt{N_{\rm sims}}$, require cross-hairs to lie within 1$\sigma$ contours for model to be consistent.

# Final measurements
(redMaGiC sample here)

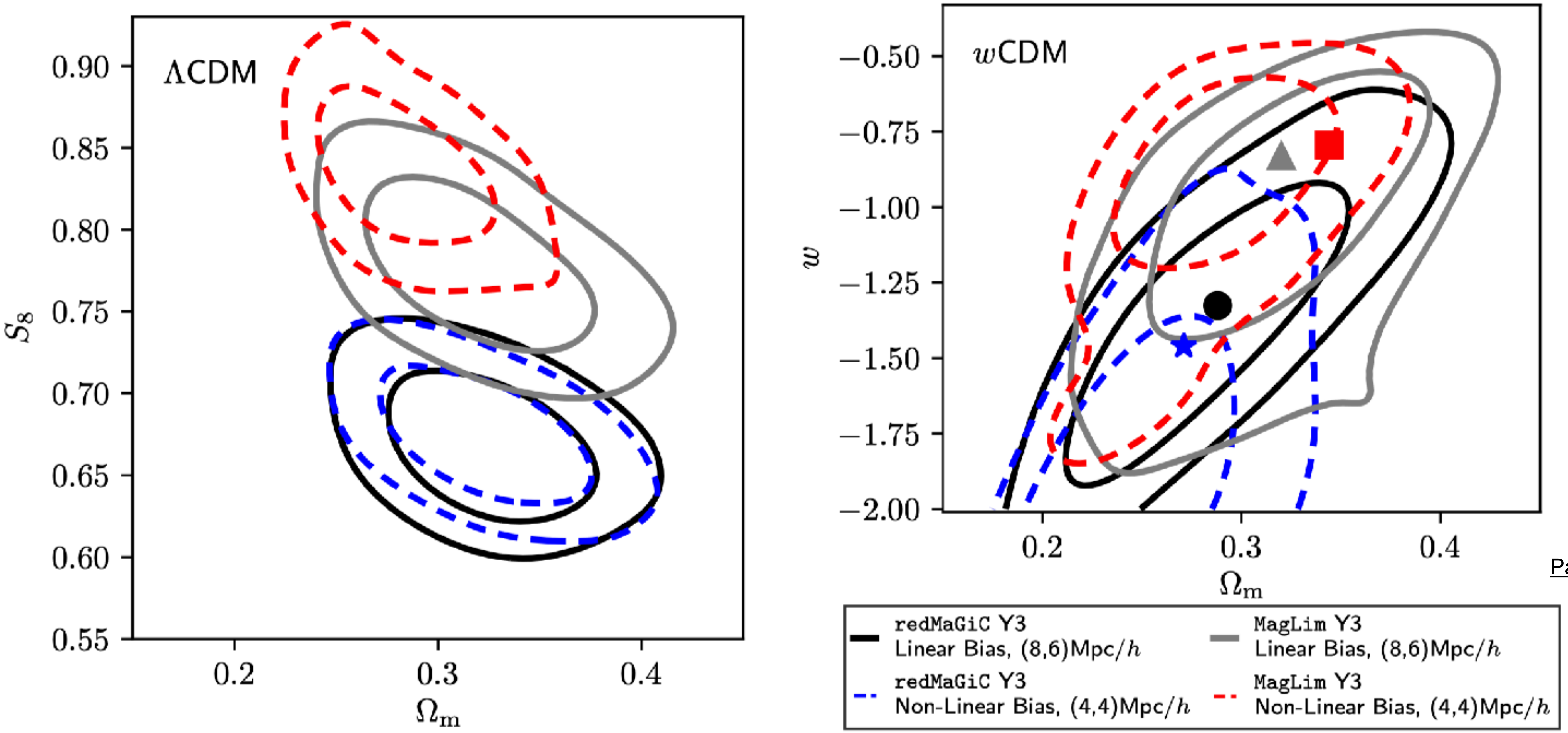
- $w(\theta)$ detected at 171$\sigma$, $\gamma_t(\theta)$ at 121$\sigma$; joint detection at 196$\sigma$:
  - With linear bias model, we analyze 81$\sigma$ of total signal
  - With non-linear bias, we use 106$\sigma$ worth of SNR
  - Able to analyze extra 25$\sigma$ worth of SNR with NL-bias model



*Pandey* et al.

# Result on data using $w(\theta) + \gamma_t(\theta)$

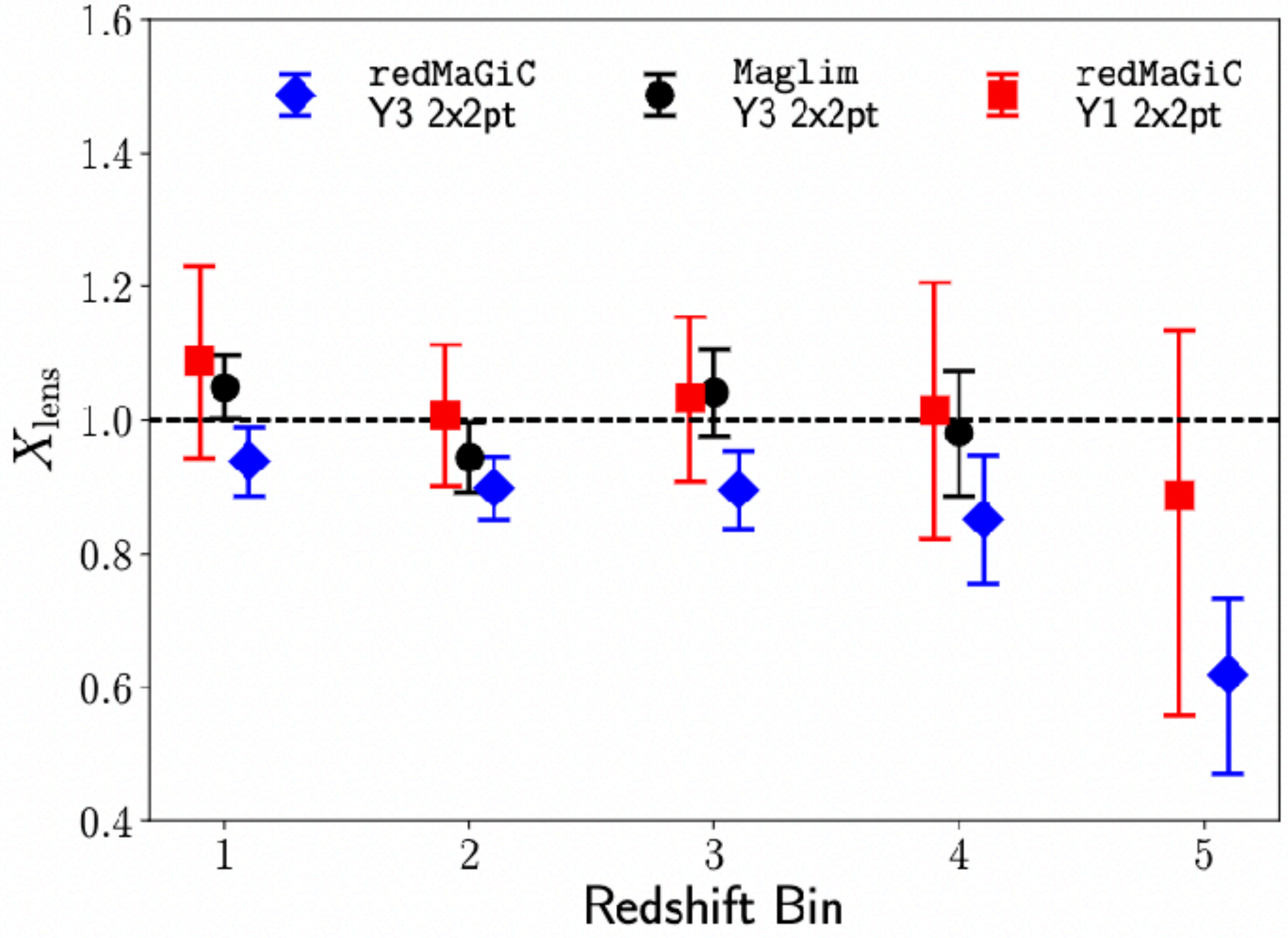
- Results with two different lens samples. Using NL bias model at smaller scales results in 25-40% gain in cosmological constraints
- The redMaGiC sample suffers from additional systematic, resulting in lower S8 constraints

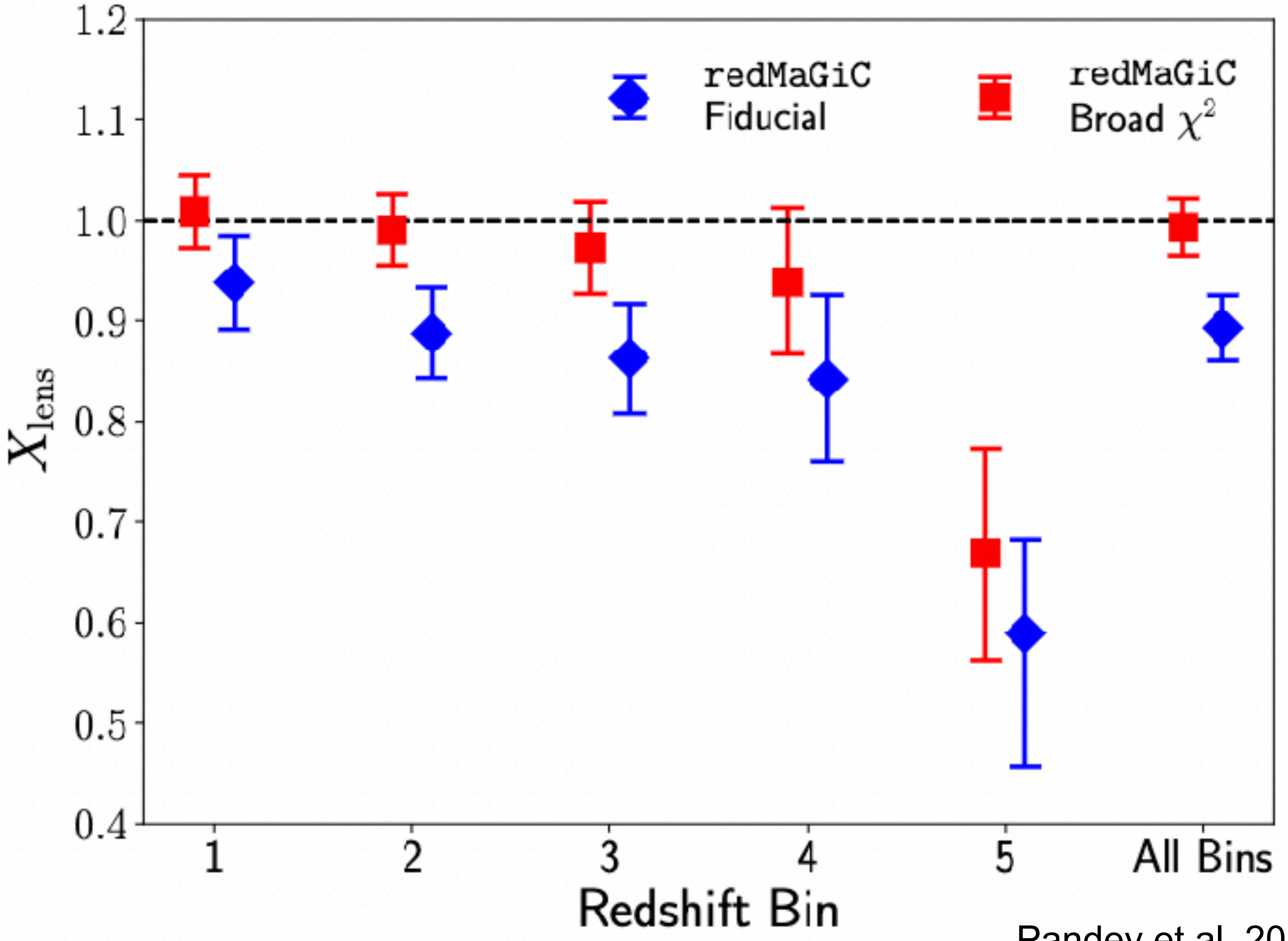


Pandey et al. 2021

# redMaGiC discrepancy

- We found that with the Y3-redmagic sample, the galaxy clustering and galaxy-galaxy lensing have ‘highly’ de-correlated amplitudes
- We parameterized it with $X_{\mathrm{lens}} = b_{\gamma_t(\theta)}/b_{w(\theta)}$, and expect it to be 1.
- With fiducial redmagic, this is significantly smaller than 1, in a redshift-, sky-area and scale- independent way.
- We track it down to some color-based un-corrected Y3 photometric issue which redmagic picks up.
    - Checks against this kind of discrepancy would potentially be very important for LSST!
- ‘updated’ 2x2pt cosmology results in updated version of 2x2pt-redmagic paper (Pandey et al 2021), soon to be on arxiv.





Pandey et al. 2021

# Conclusions (part1)

- Analysis of small scales LSS correlations are complicated but can have significant returns by providing tight cosmology/astrophysics constraints.
- We developed and validated a hybrid PT model, using calibrations from simulations
  - *This model in general can describe correlations at sub-percent level*
  - A two parameter version of this model is sufficient at 2% accuracy
- *We apply this model to latest DES data, finding 20-40% improvement in cosmological constraints.*
- Cosmological information in small scales of 2pt functions saturate:
  - More work is needed to extend these kind of models to higher order statistics.

# 2. Baryonic feedback with tSZ xcorr

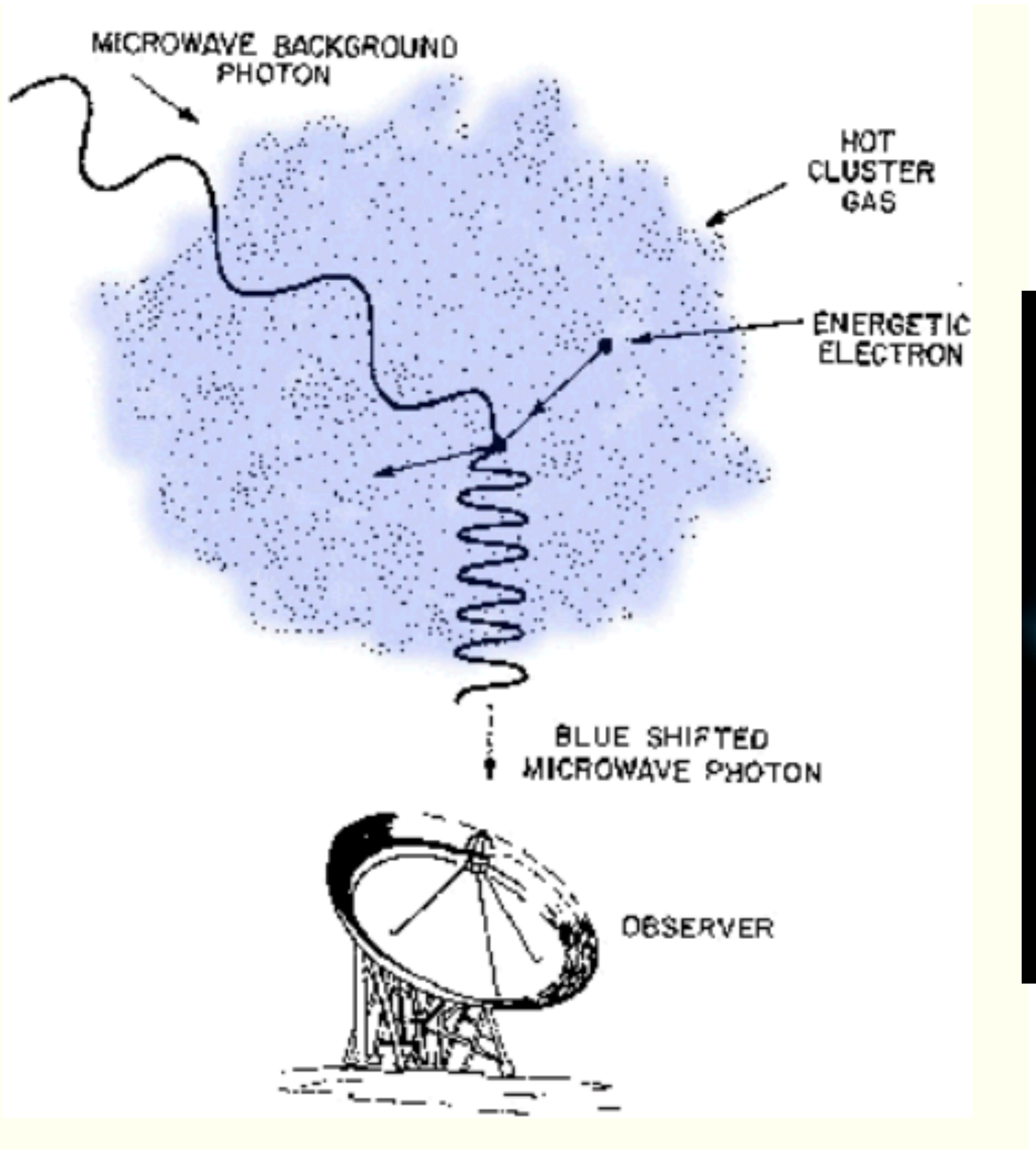
## Using DES, ACT and Planck

# tSZ introduction

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

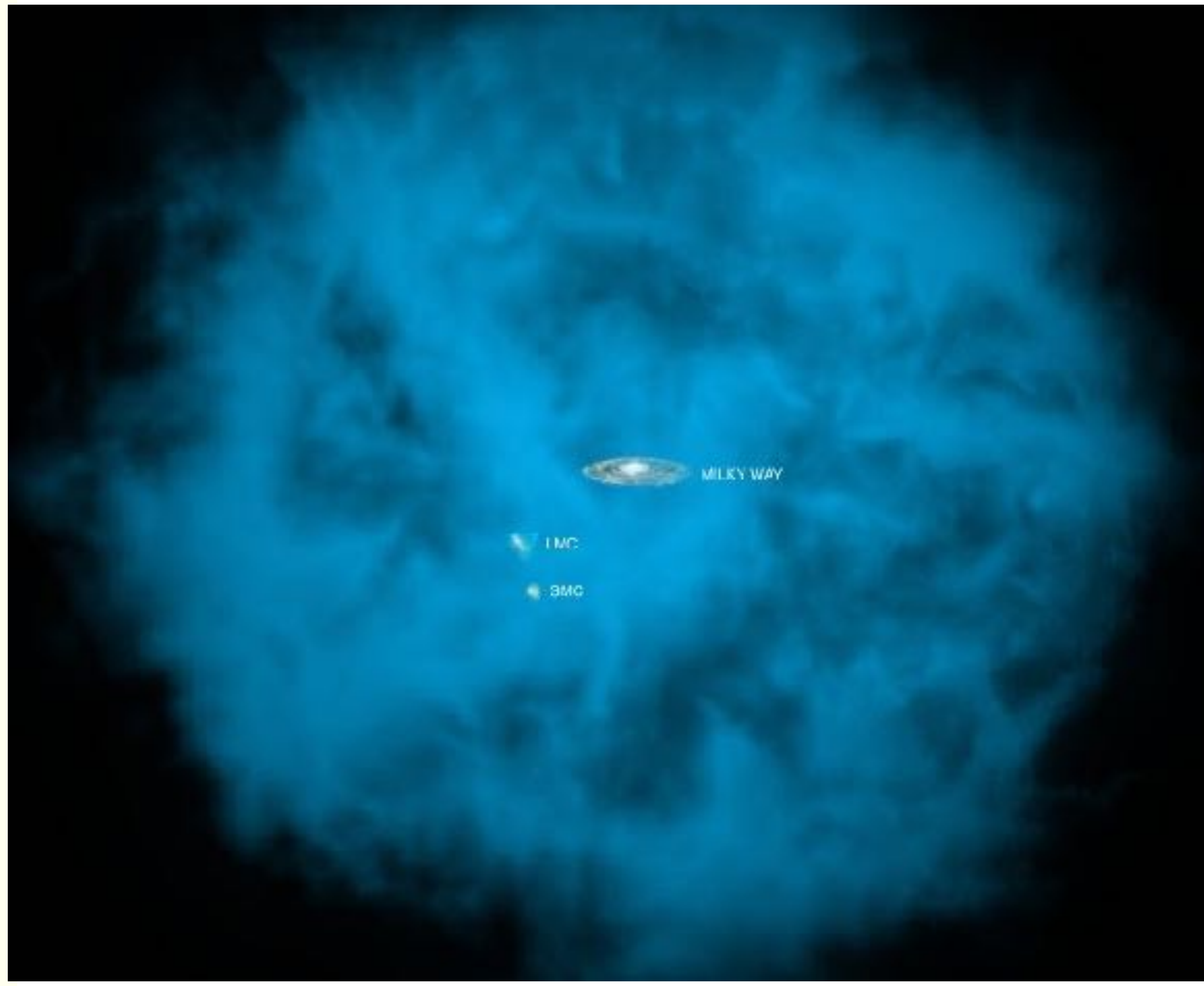
2. Much more baryonic mass in the gas than in all the stars in the galaxies (~90% in big halos)

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.

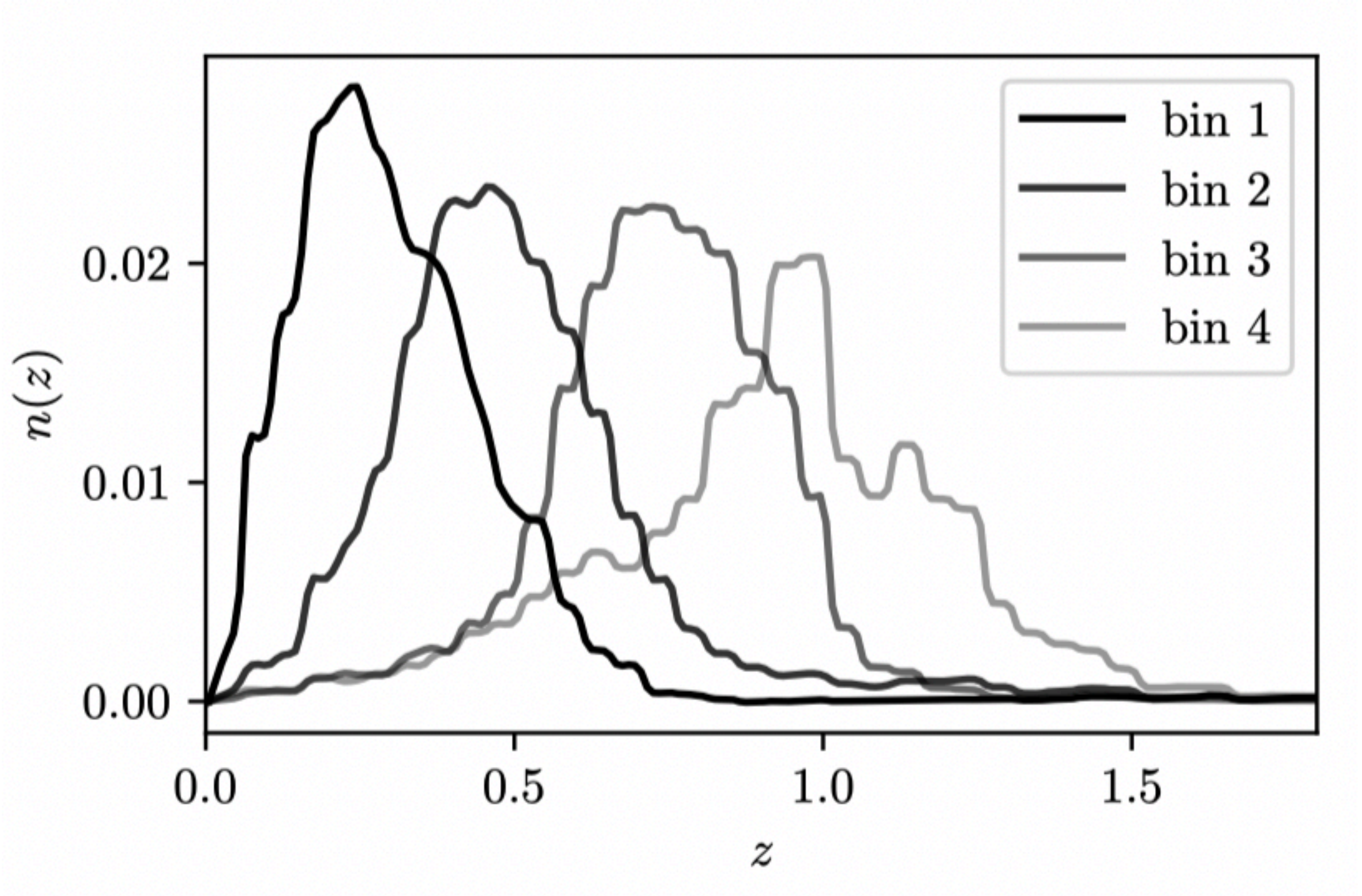
# Motivation:

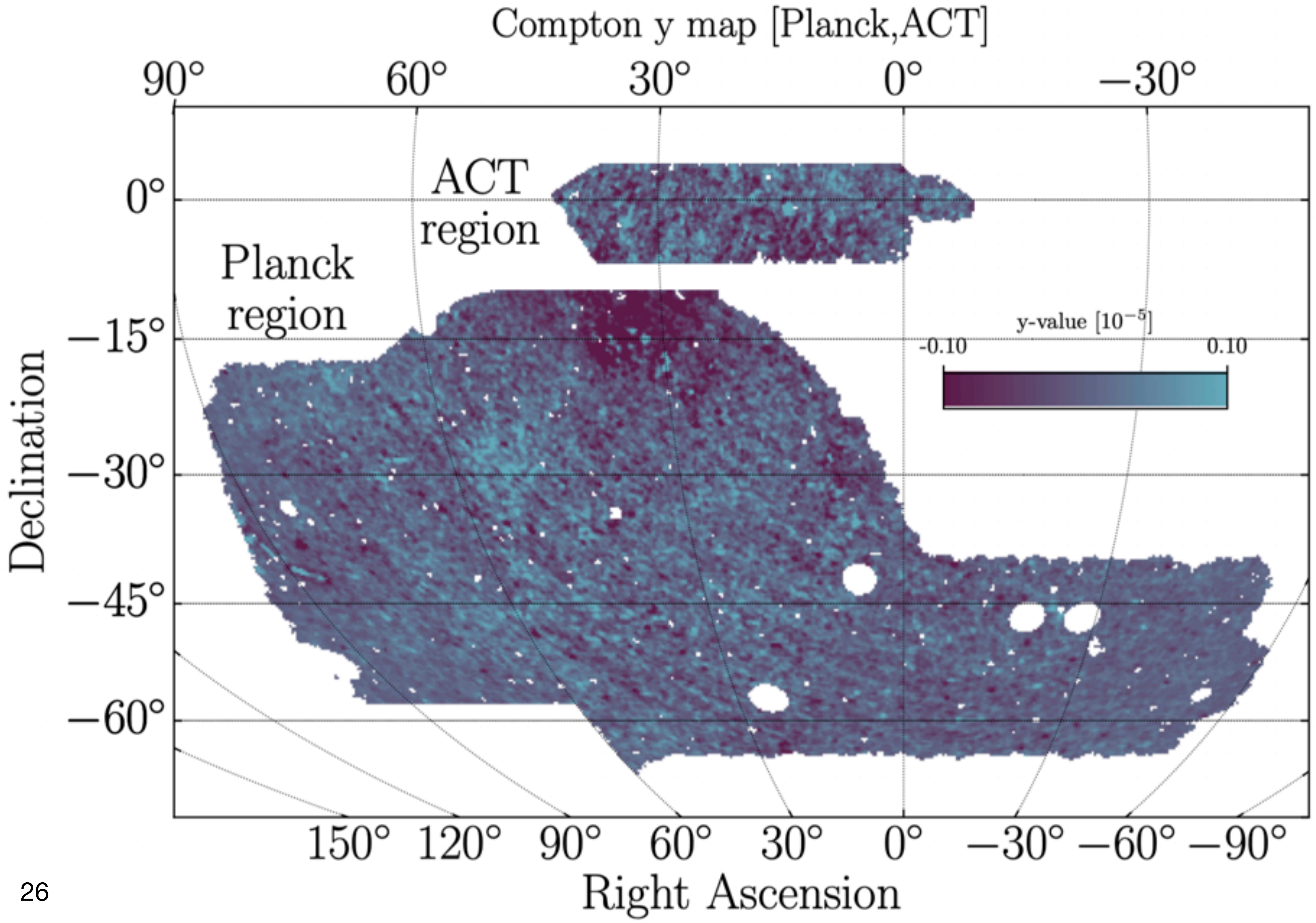
- Compton-y is directly sensitive to the (integrated) pressure of the gaseous halos and any feedback process will imprint its signature on it.
- Cross-correlation with tracers of large scale structure can address several open questions. E.g. it can isolate the importance of the feedback in different 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.
- **Next part of the talk focuses on shear x y**

# Measurements

# Sky and redshift coverage of dataset

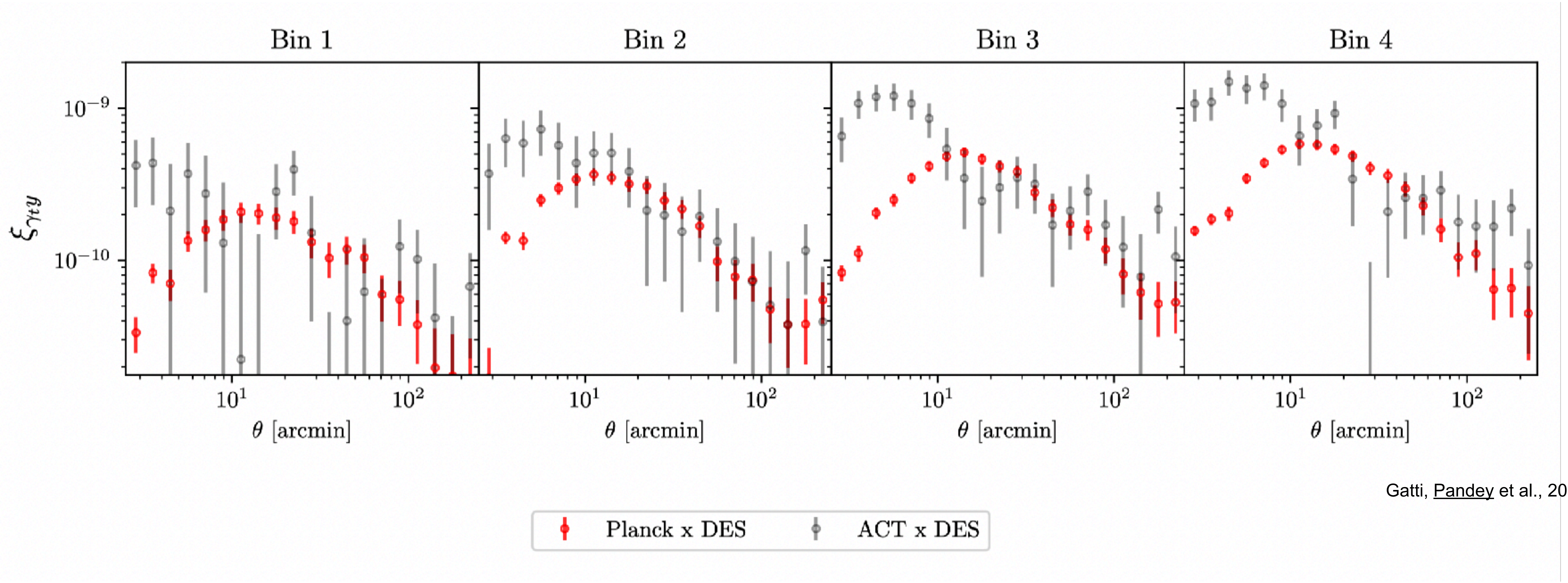
- ACT data used in D56 region, Planck in rest
- DES Y3 *shear catalog* is estimated with 100million source galaxies is divided into four tomographic bins <u>covering redshifts z<2</u>.





Gatti, <u>Pandey</u> et al., 2021

# Final tomographic measurements

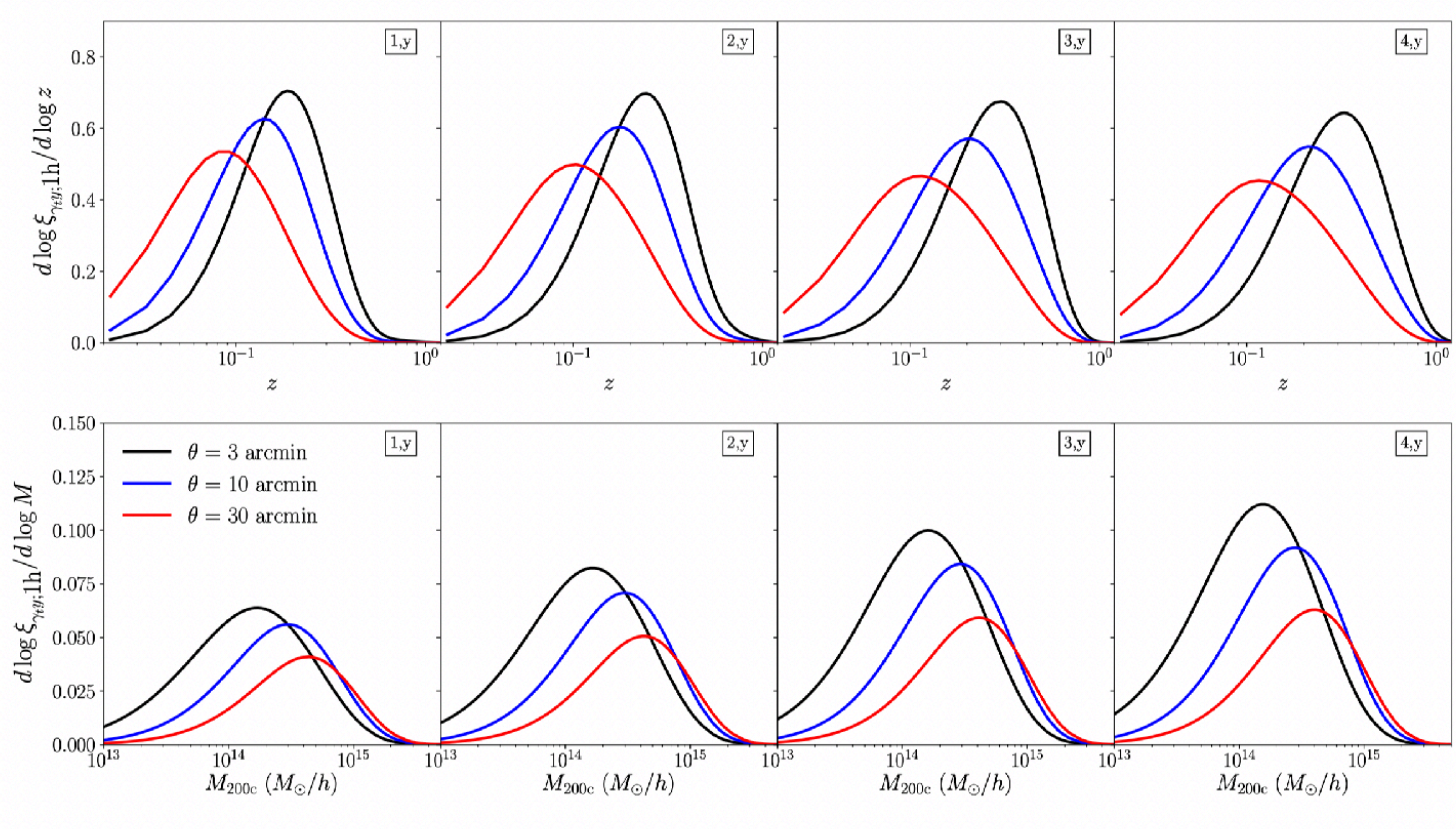


Gatti, Pandey et al., 2021

- ~*20 sigma statistical detection of signal* (highest to-date)
  - Covariance is estimated using analytical halo model which includes contribution from Poisson number fluctuation of massive clusters.
- Difference between *Planck x DES* and *ACT x DES* in small scale entirely due to differences in the beam sizes of Compton-y maps.

# Why is this measurement interesting?

- Probes dark matter and pressure profiles directly
- *Sensitive to halos of mass between ~5e13-5e14*; hence bridging gap between <*galaxy x y*> and <yy>



Pandey et al., 2021

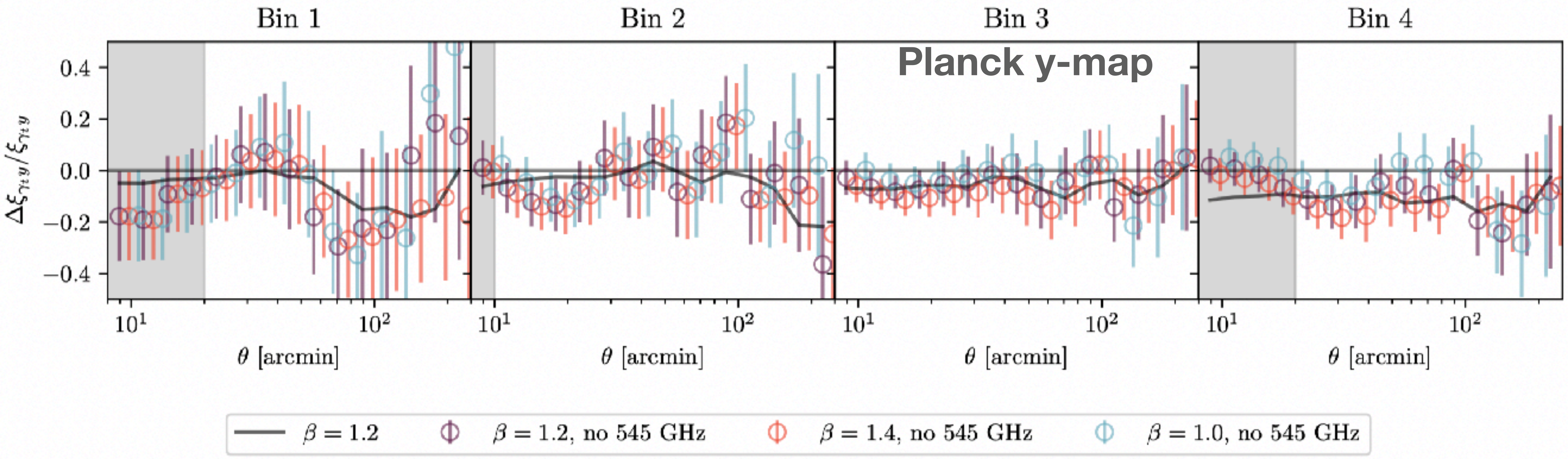
# Robustness tests

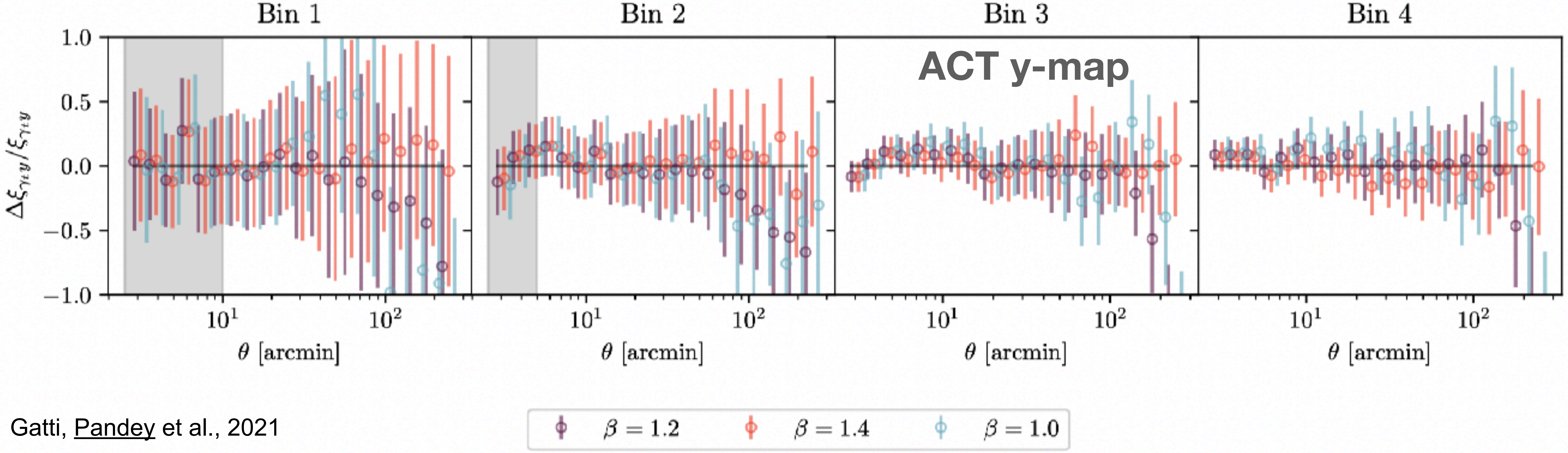
# Measurement and Theory Robustness tests

Validate the scales used to get cosmological and astrophysical conclusions

- Compton-y
  - Leakage of Cosmic infrared background (CIB)
  - Leakage of radio sources
- Cosmic shear
  - See Gatti, Sheldon et al 2021 for extensive tests of the DES Y3 shear catalog. This same catalog is used for DES Y3 cosmology results.
  - Intrinsic alignment of source galaxies will correlate with Compton-y (include this in the theory model)

# Impact of CIB
(residual wrt to no-cib deprojection)

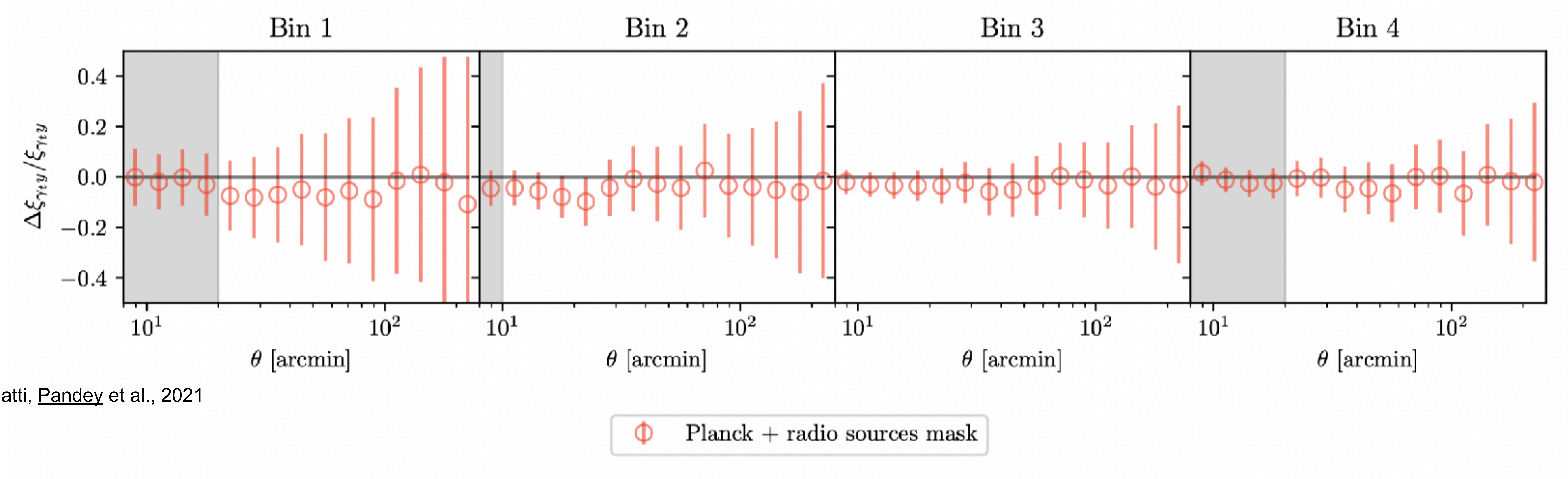




Gatti, Pandey et al., 2021

- Assuming CIB has modified black-body spectra (with index $\beta$)
- *For Planck x DES we use CIB-deprojected y-map*
  - We remove the scales below 20’ for fourth bin as sensitive to map making choices.
- ACT x DES is robust as they use multiple low-frequency and low-noise temperature maps from ACT

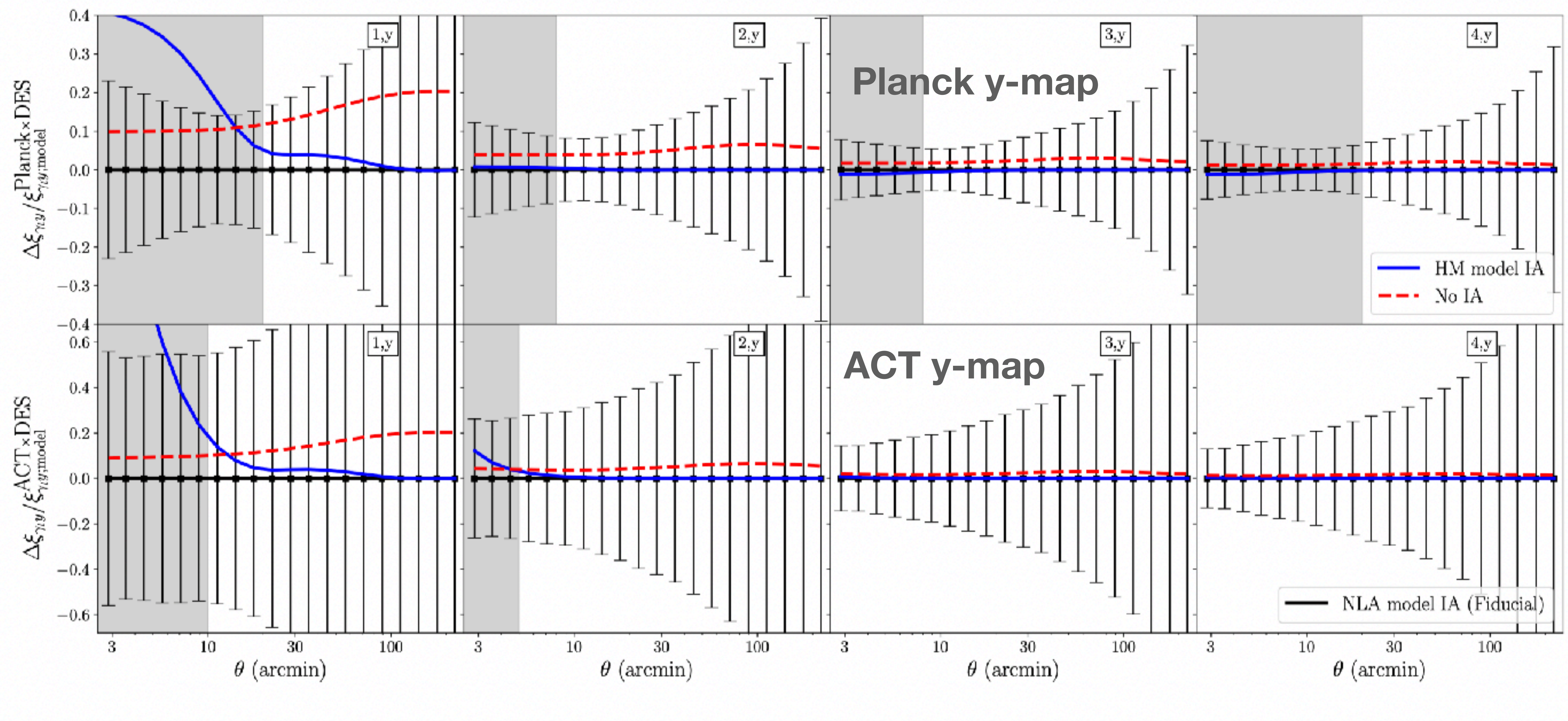
# Impact of radio sources



Gatti, Pandey et al., 2021

- Masking 10’ region of sky around radio sources detected at above 5mJy from ACT survey.
- The measurements are fully consistent with the fiducial measurements

# Intrinsic alignment (IA) of galaxies



Pandey et al., 2021

- We forward model the impact of IA in our theory predictions using a simple non-linear version of linear-alignment model (NLA).
    - We check its impact by comparing shear x y predictions with NLA model (black) to a more complicated halo model (blue)
    - This dictates the scale cuts for first two bins.

# Results

# Astrophysics and Cosmology from the measurements

- We model the signal with halo model framework:
  $\langle \gamma_{\mathrm{t}} y \rangle = \text{1-halo} + \text{2-halo} + \langle \text{IA} \times y \rangle \sim f(\text{cosmology}) \times g(\text{pressure-profile})$
- The cosmology and the pressure-profile will be degenerate so we perform analysis by:

  A. Varying cosmology (with Planck/DES priors) but fixing pressure profiles to various hydrosims:
    - OWLS (REF, AGN, AGN8.5)
    - Battaglia et al 2010 & 2012
    - Illustris-TNG

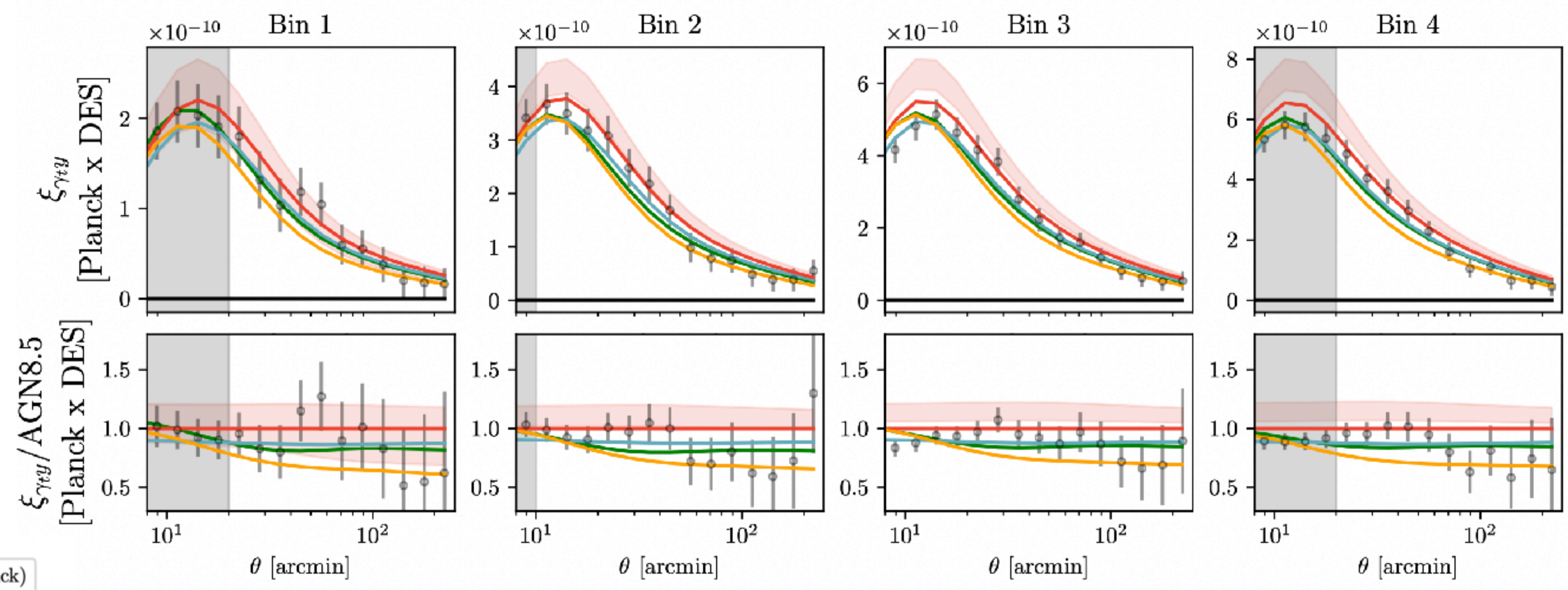
  B. Fixing cosmology to DES-Y1 or Planck-2018 and varying pressure profiles with different models:
    - Generalized NFW model
      - Battaglia et al 2012 model (vary four parameters controlling pressure profile shape)
      - Arnaud et al 2010 model (infer and compare mass bias)

# A. Varying cosmology + fixing pressure profiles to various hydrosims

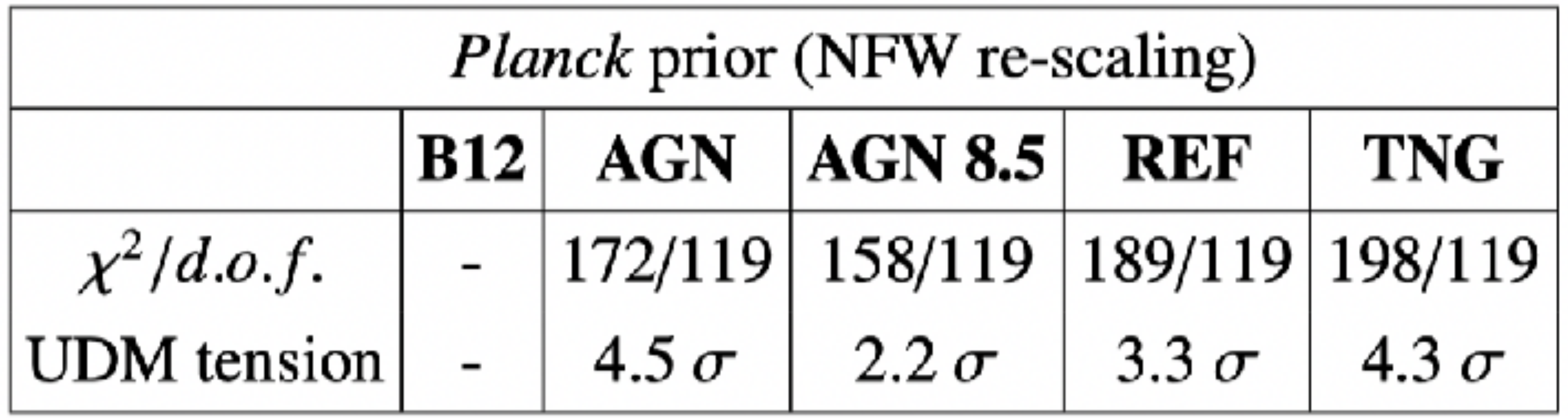
- Incorporating impact of baryonic physics on dark matter (and shear) profiles:

  1. Aggressive:
     - Rescale the shear-profile with ratio of matter power spectrum with and without baryons
  2. Conservative:
     - Modify the NFW profile by including bloating and dilution parameters (Mead et al 2015)
     - Note that we currently ignore the connection between modification of pressure and dark matter profiles due to same feedback (and we let data constrain any such connection).

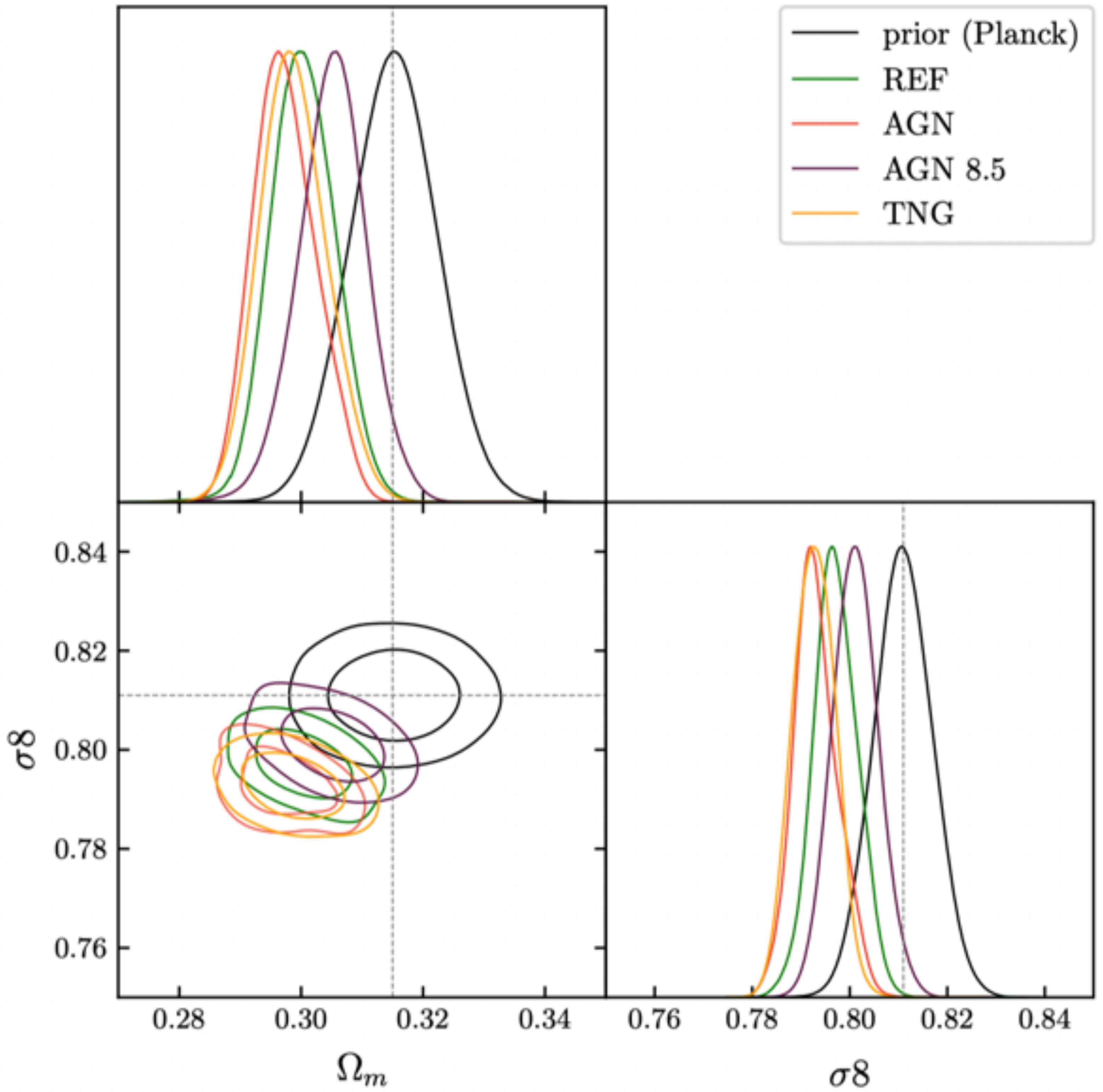
# 1. Aggressive



Gatti, Pandey et al., 2021

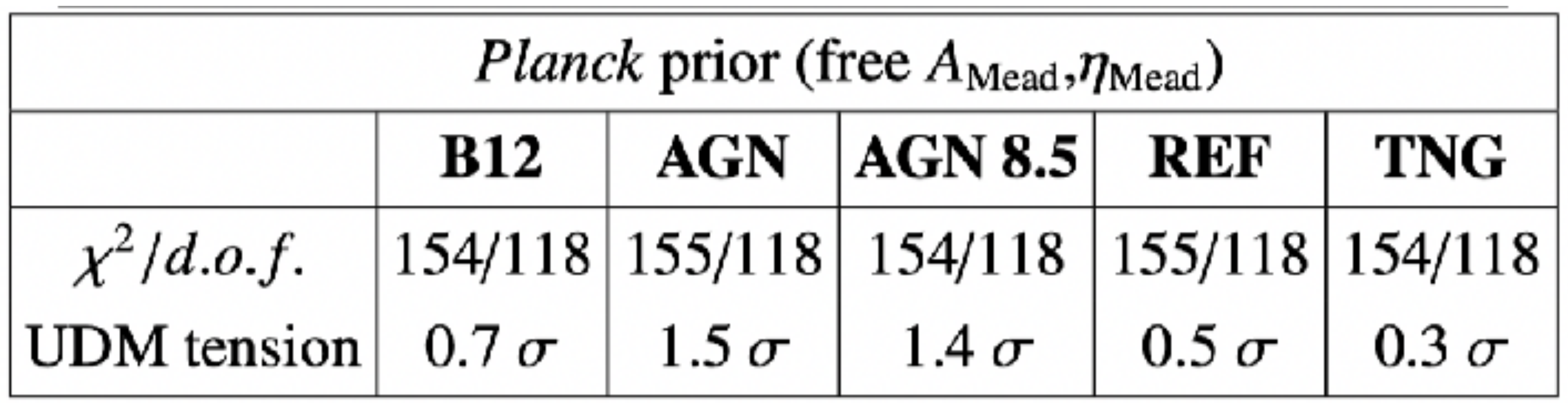


| *Planck* prior (NFW re-scaling) | | | | | |
|---|---|---|---|---|---|
| | **B12** | **AGN** | **AGN 8.5** | **REF** | **TNG** |
| $\chi^2/d.o.f.$ | - | 172/119 | 158/119 | 189/119 | 198/119 |
| UDM tension | - | 4.5 $\sigma$ | 2.2 $\sigma$ | 3.3 $\sigma$ | 4.3 $\sigma$ |

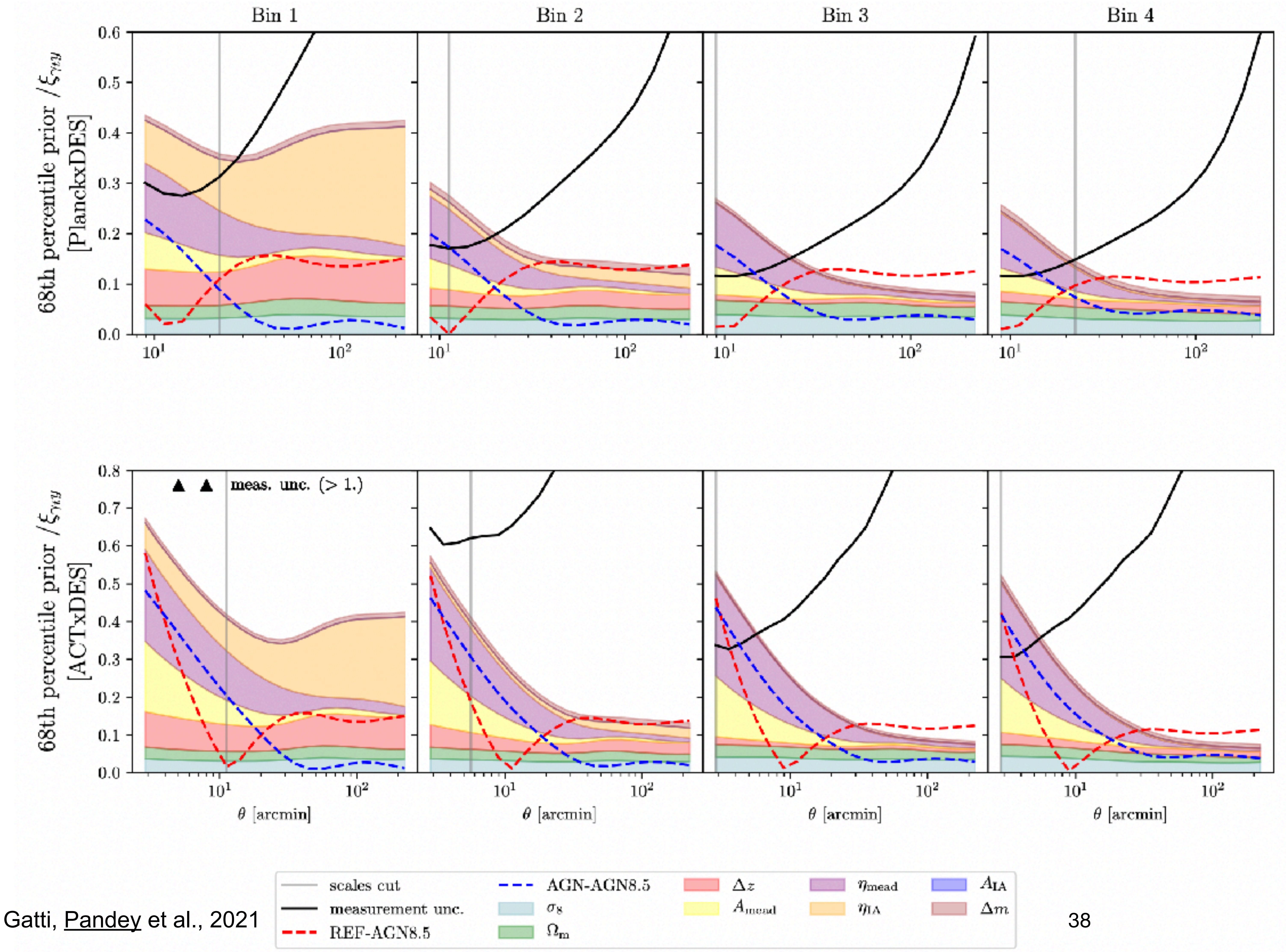


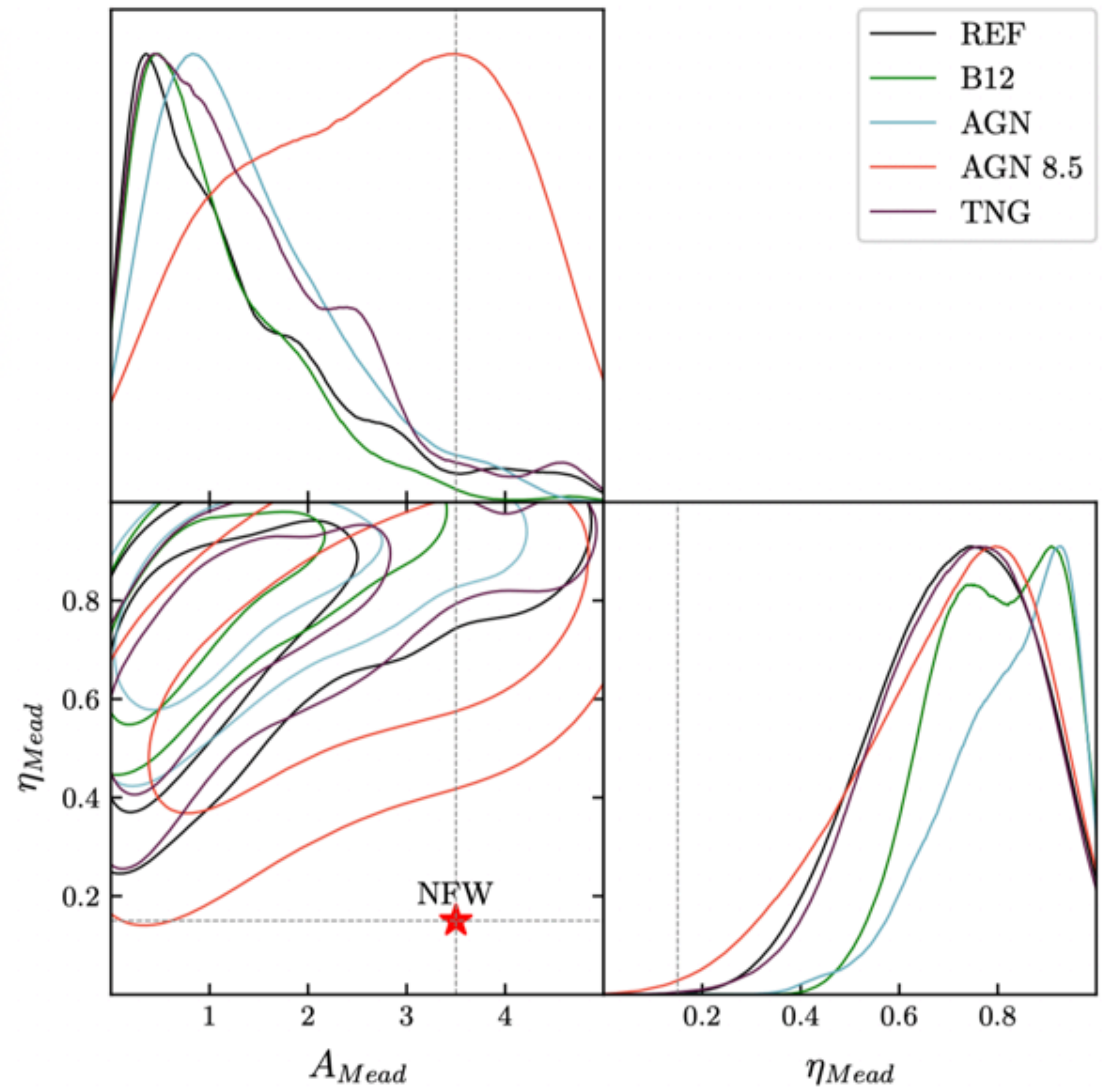
- AGN-8.5 is preferred at Planck cosmology priors

# 2. Conservative



| *Planck* prior (free $A_{\rm Mead}$,$\eta_{\rm Mead}$) | | | | | |
|---|---|---|---|---|---|
| | **B12** | **AGN** | **AGN 8.5** | **REF** | **TNG** |
| $\chi^2/d.o.f.$ | 154/118 | 155/118 | 154/118 | 155/118 | 154/118 |
| UDM tension | 0.7 $\sigma$ | 1.5 $\sigma$ | 1.4 $\sigma$ | 0.5 $\sigma$ | 0.3 $\sigma$ |





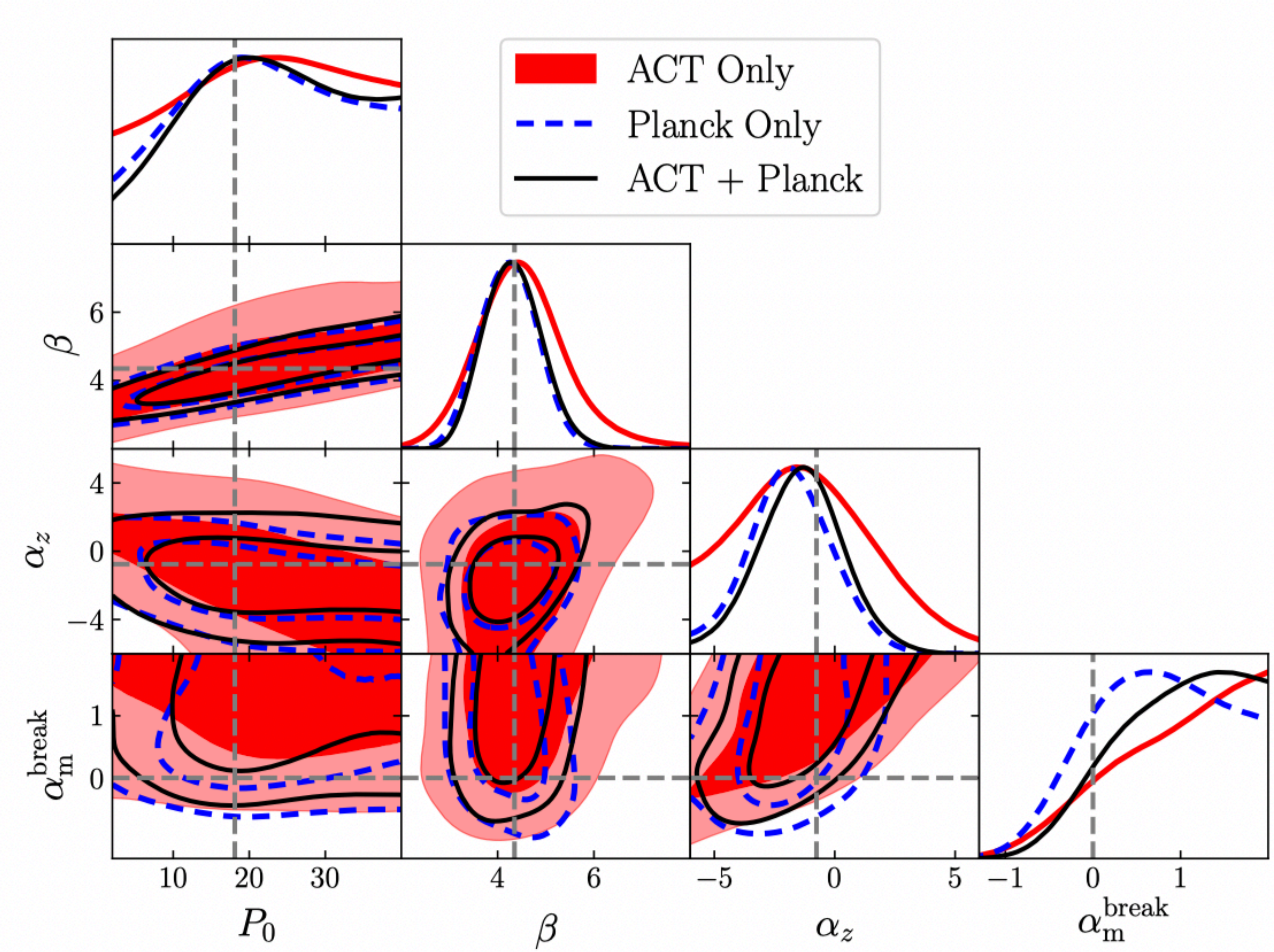
- We lose the ability to demarcate between pressure profile models when also changing DM profile.
- Deviation of DM profile from NFW is detected.

Gatti, Pandey et al., 2021

# B. Fixing cosmology and varying pressure profiles  parameters

## *Break Model*

- Generalized NFW model
- Dashed lines show the best-fit values from Battaglia-12 simulations.
- In terms of posterior mass, preference for steeper evolution of profile with halo redshift and mass (at lower mass end)



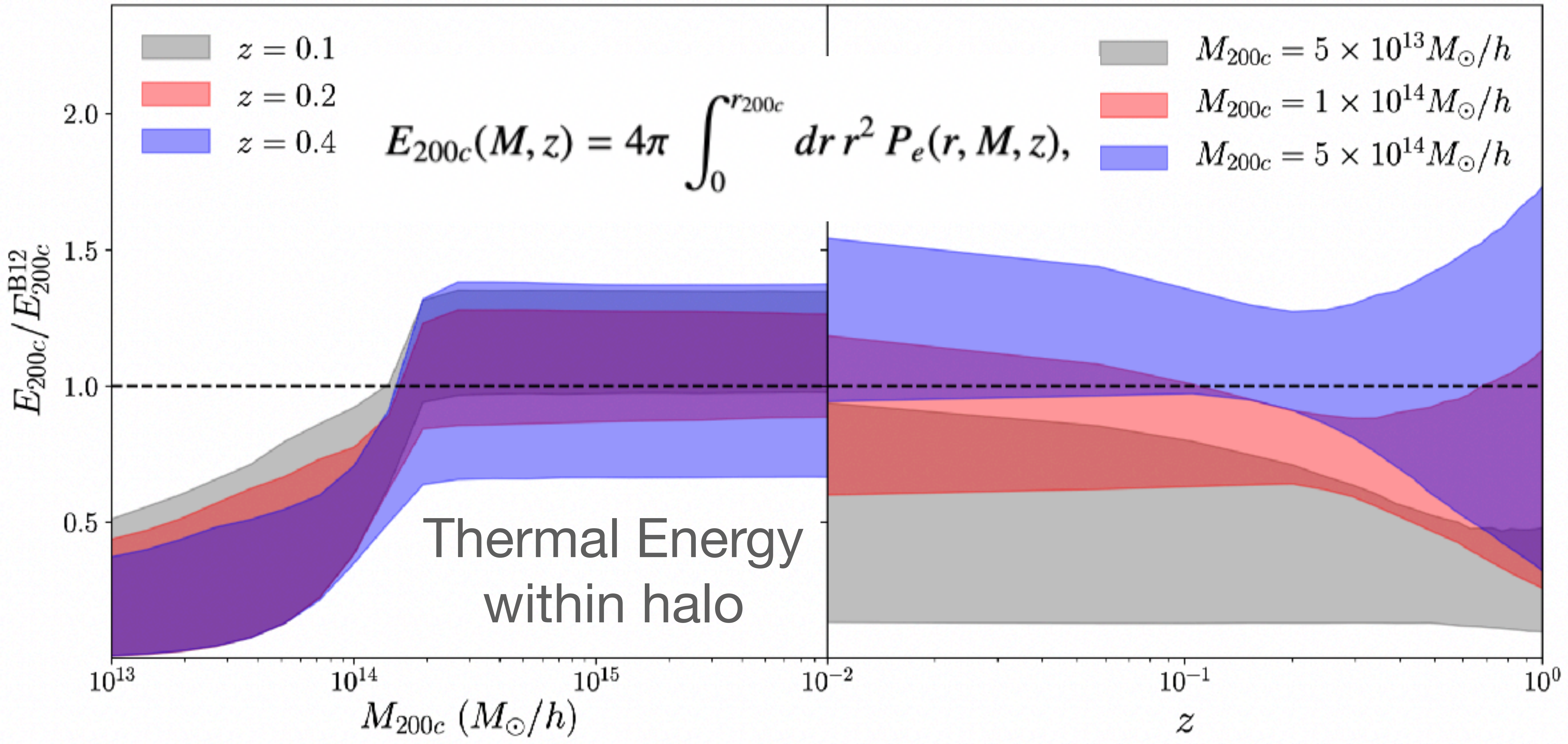
*Amplitude of pressure profile*

*Outer radii slope of profile*

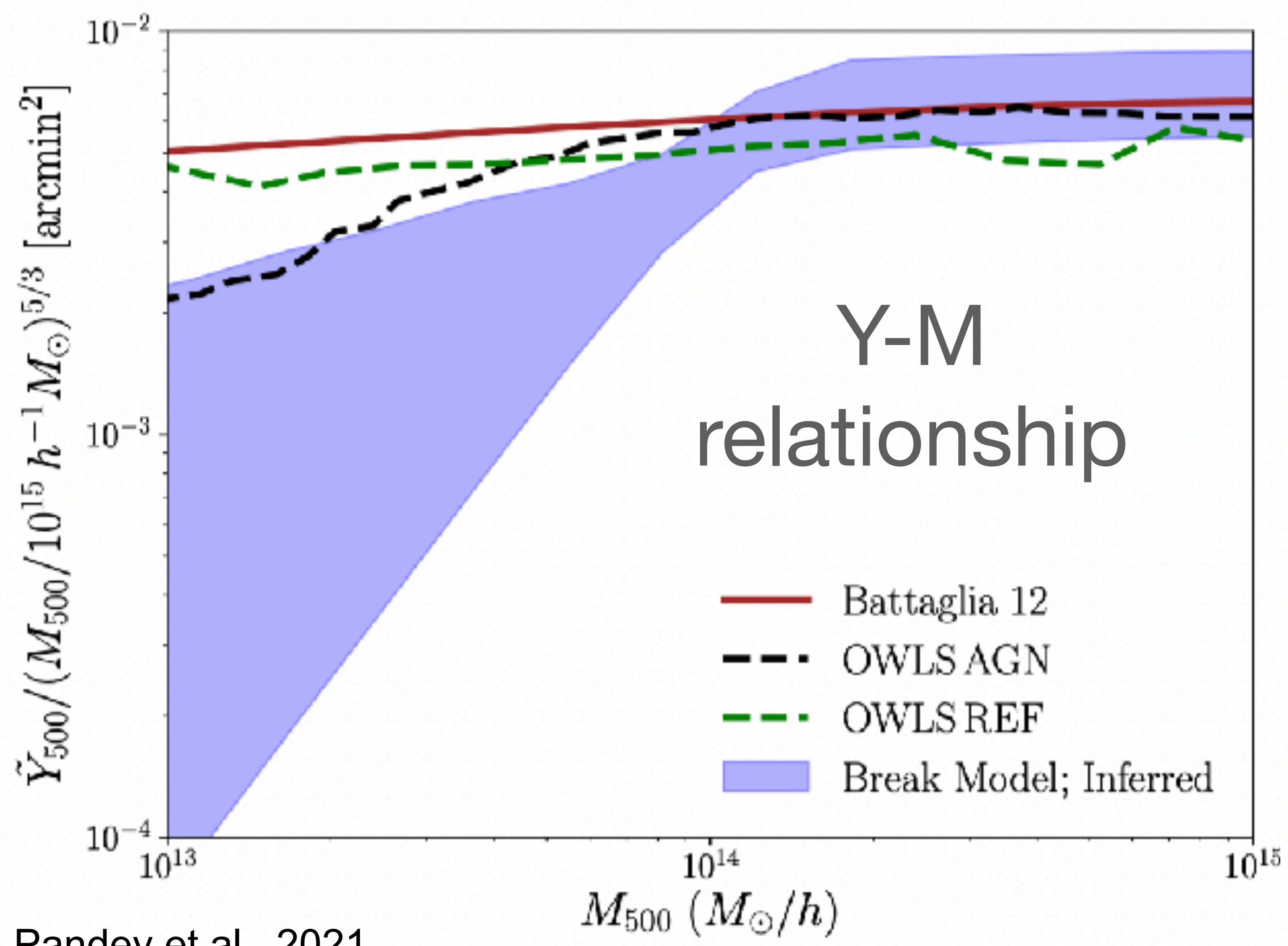
*Evolution of profile with redshift*

*Evolution of profile with mass (for lower masses)*

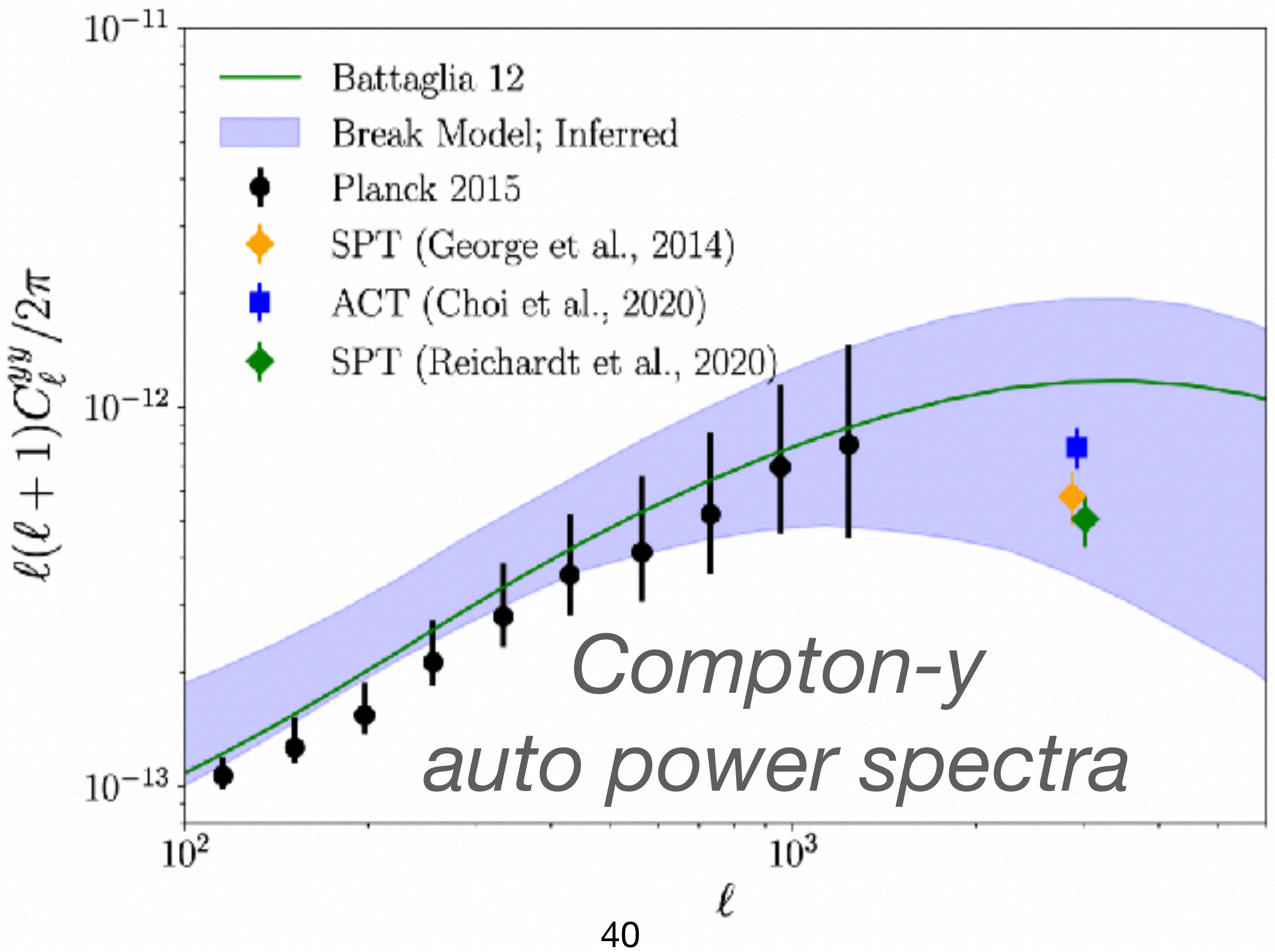
Pandey et al., 2021



Thermal Energy within halo



Y-M relationship



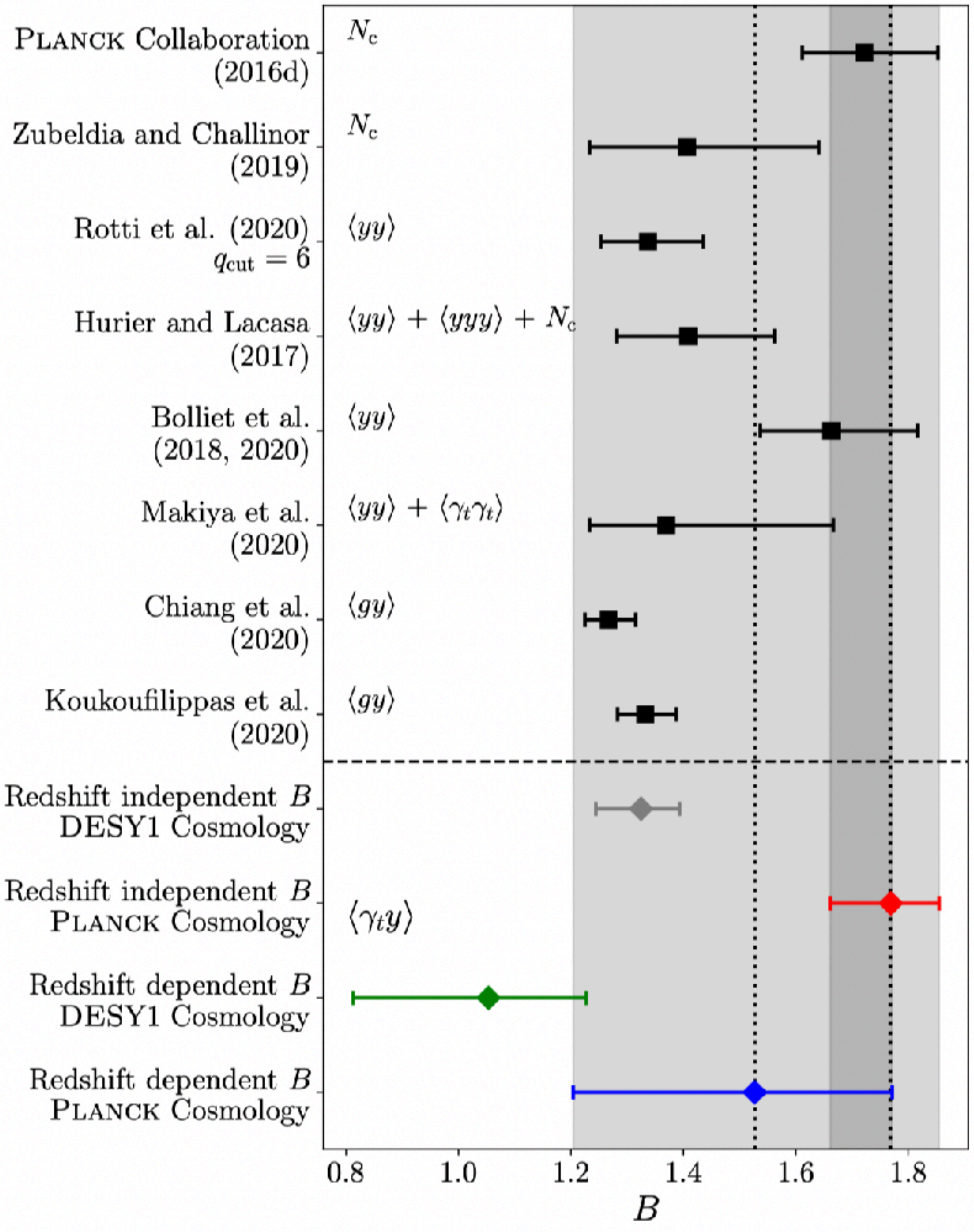
*Compton-y auto power spectra*

- Inferences with constraints shown in previous slides
- Preference for lower pressure or thermal energy in lower mass halos, particularly at higher redshifts.
- Higher mass halos consistent with expectations of halo model (and direct measurements from experiments)

Pandey et al., 2021

# *Arnaud10 Model and mass bias*

- $M_{500c}^{\mathrm{SZ}} = M_{500c}^{\mathrm{true}}/B$
  - If hydrostatic equilibrium is violated, expect B>1 (theoretically expect B~1.2)
- Only one (two) free parameters for redshift independent (dependent) mass bias parameter.
- At Planck cosmology, results consistent with previous studies based on clusters or Compton-y auto power
- Lowering the value of $\sigma_8$ (to DES value) or assuming a evolution of mass bias with redshift reconciles with other studies using galaxies and CMB-lensing correlations



# Conclusions

- Cross-correlation of shear and Compton-y is a promising probe that can answer many lingering questions about physics of feedback, without additional complexity.
  - This is of crucial importance to validate our model for cosmological analysis using cosmic-shear 2pt correlations using next generation surveys like LSST, Euclid, Roman etc.
  - We find preference for lower pressure in low-mass halos consistent with increased feedback with DES and ACT/Planck datasets.
- Ongoing and future work:
  - A joint analysis of shear-y cross-correlations and shear-shear auto-correlations is needed to consistently analyze cosmology and pressure profile.
  - An updated halo model frame-work is needed to consistently and coherently modify both dark matter and gas pressure profile
  - Jointly analyze with galaxy x tSZ to probe the evolution of halo pressure profiles in a wide range of halo masses
  - Use the kSZ information by measuring and jointly analyzing with *kSZ x shear* and *kSZ x galaxy* as well as jointly analyze with *tSZ x galaxy*

# Thank you!

# PT intro

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

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

Continuity Equation

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

Euler Equation

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

Poisson Equation

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

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

*encodes gravity*

*encodes cosmology*

- 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

*tidal tensor*

*velocity divergence*

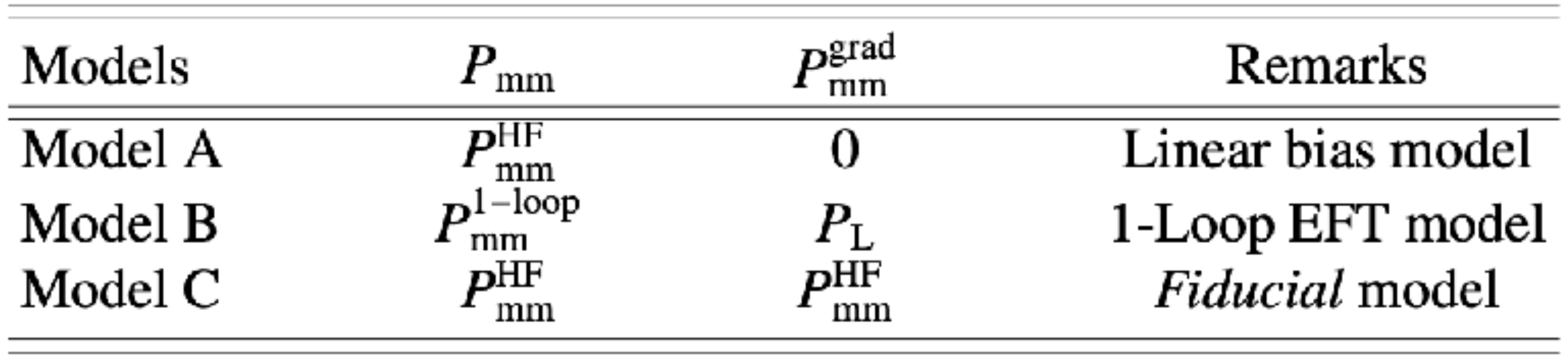
$$\delta_{\mathrm{g}} \sim f(\delta_{\mathrm{m}}, \nabla_i \nabla_j \Phi, \nabla_i v_j) \sim f^{(1)}(\delta_{\mathrm{m}}) + f^{(2)}(\delta_{\mathrm{m}}^2, s^2) + f^{(3)}(\delta_{\mathrm{m}}^3, \delta_{\mathrm{m}} s^2, \psi, st) + \dots \,.$$

- In case a spatial non-locality exists
  - Effective field theory:
    - Smooth $\delta$ to make it actually small
    - Truncate integrals due to UV divergences

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

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

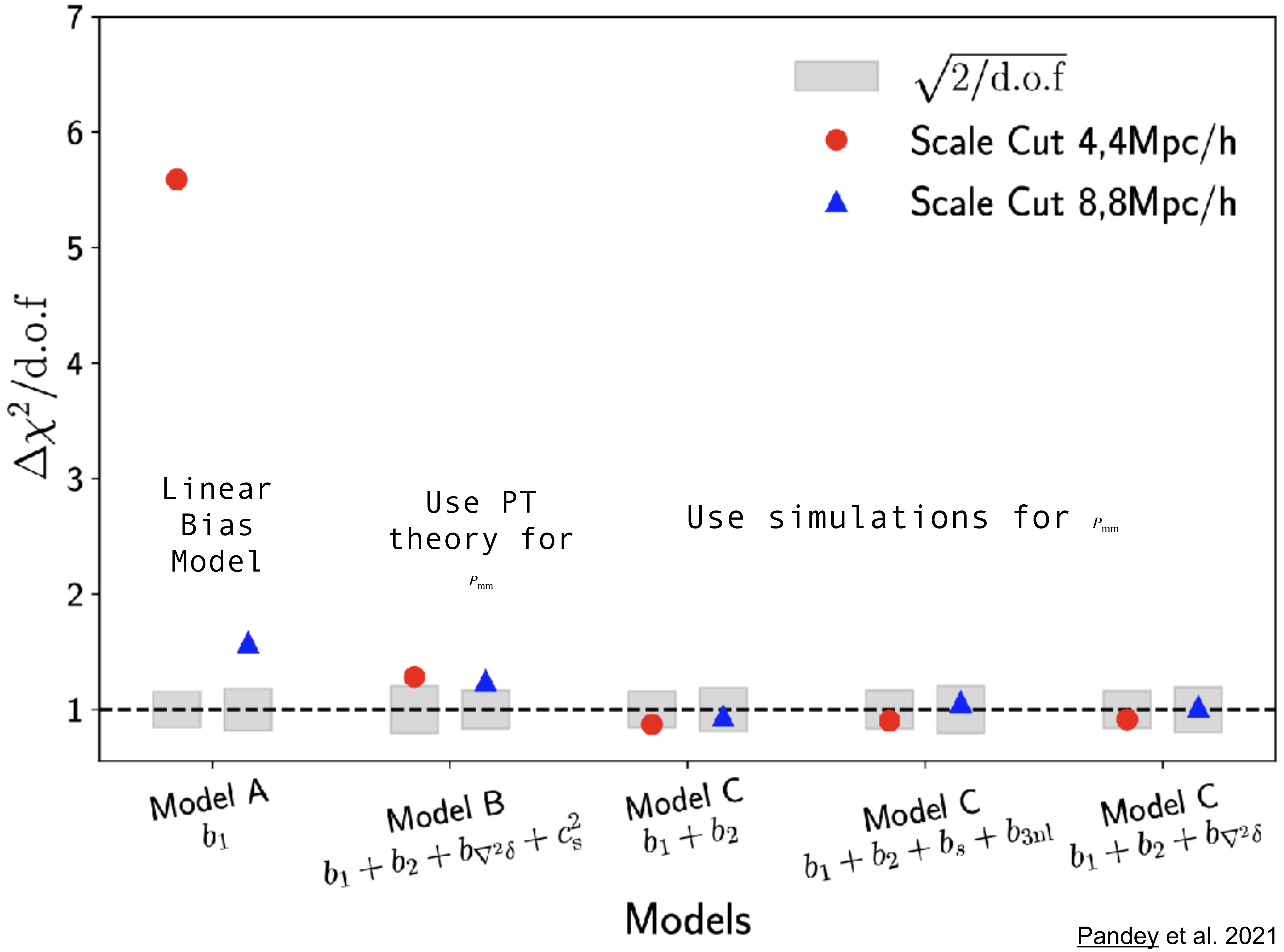
# Minimizing the degrees of freedom



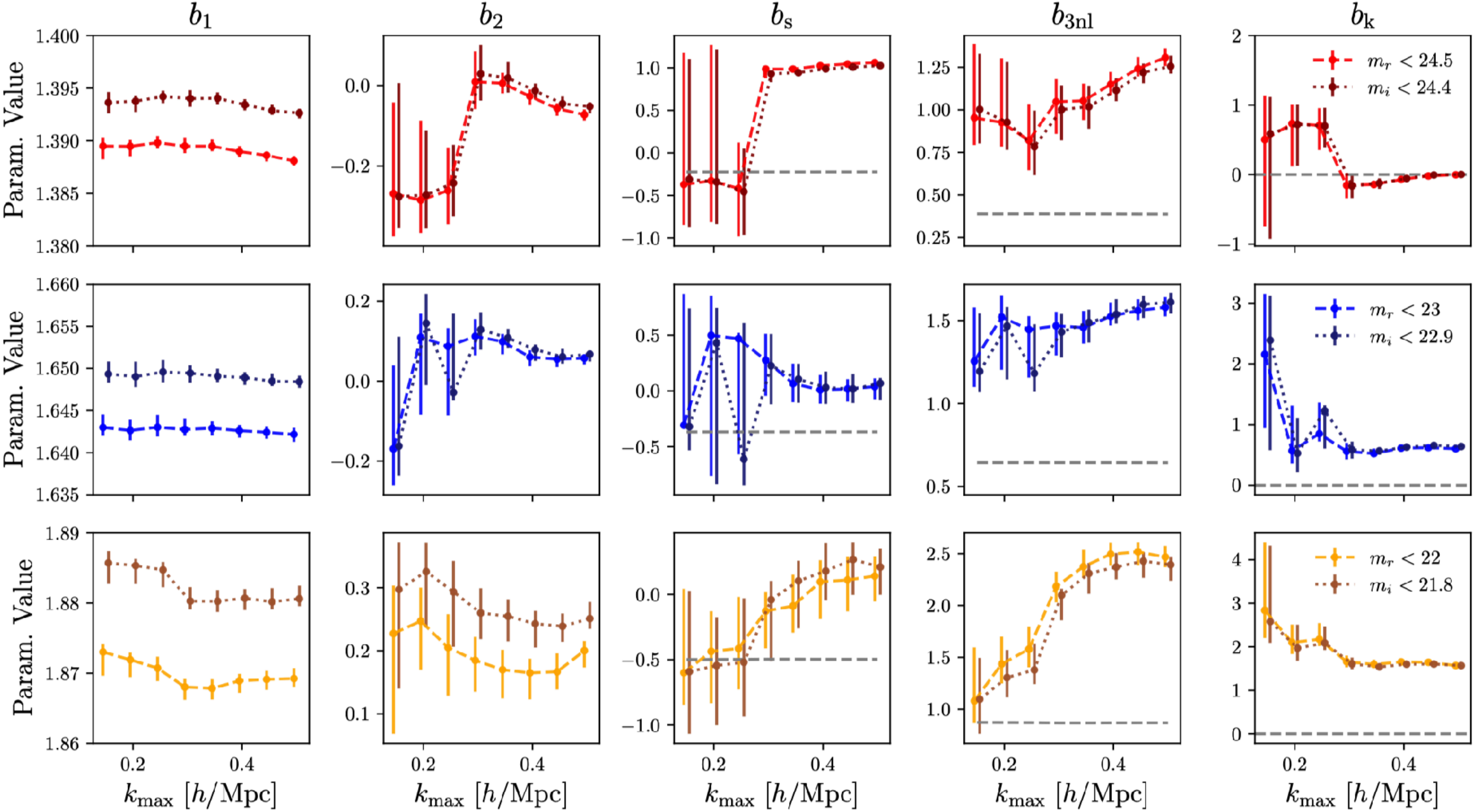
| Models | $P_{\rm mm}$ | $P_{\rm mm}^{\rm grad}$ | Remarks |
|---|---|---|---|
| Model A | $P_{\rm mm}^{\rm HF}$ | 0 | Linear bias model |
| Model B | $P_{\rm mm}^{\rm 1-loop}$ | $P_{\rm L}$ | 1-Loop EFT model |
| Model C | $P_{\rm mm}^{\rm HF}$ | $P_{\rm mm}^{\rm HF}$ | *Fiducial* model |

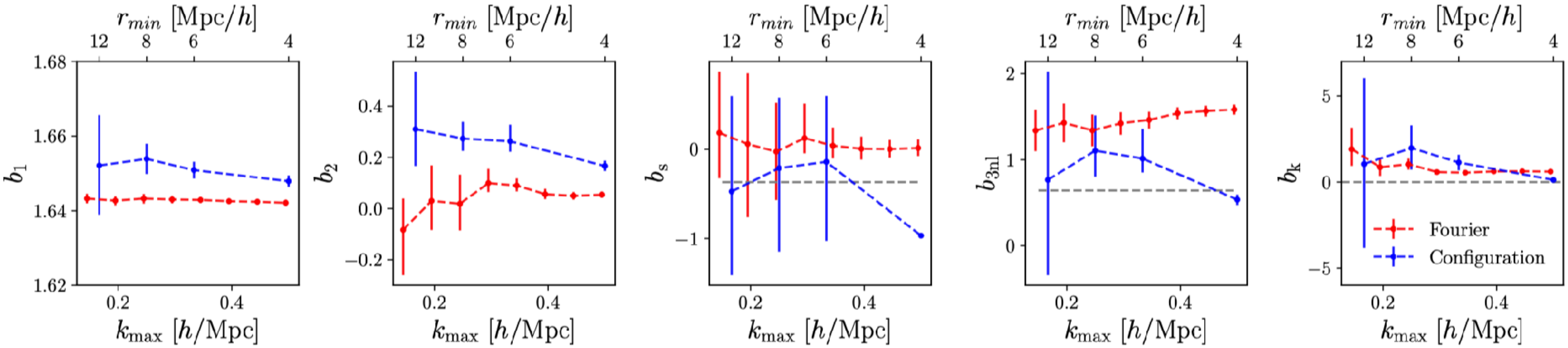
Results for the redMagic sample:

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

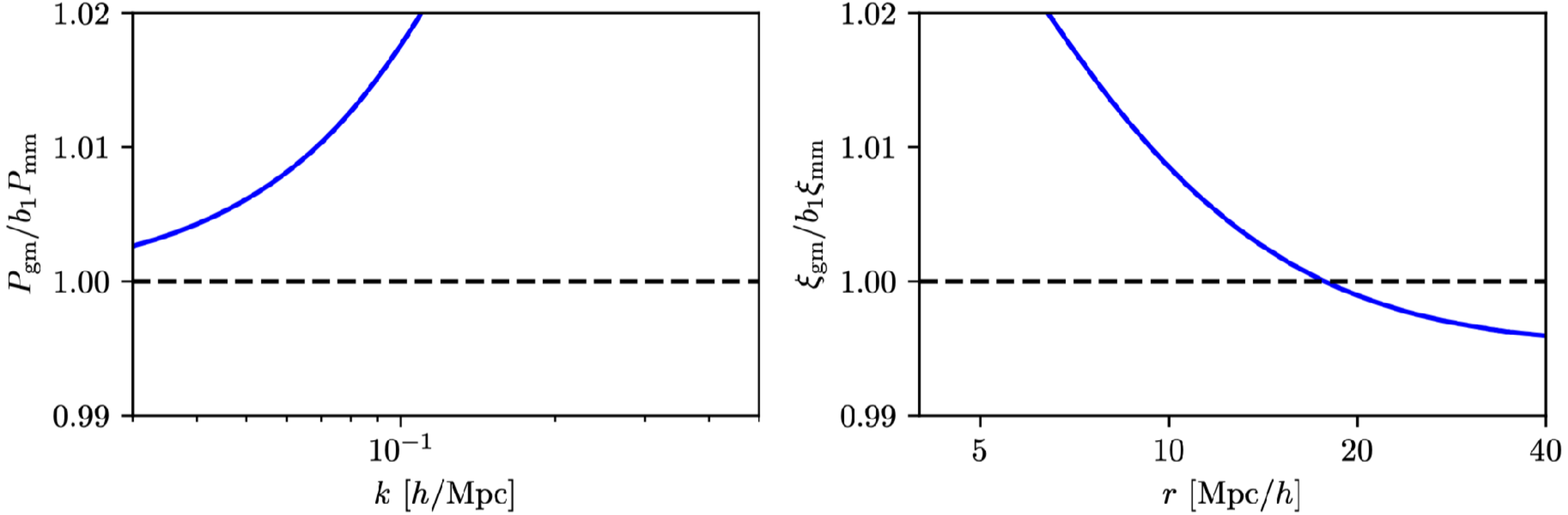


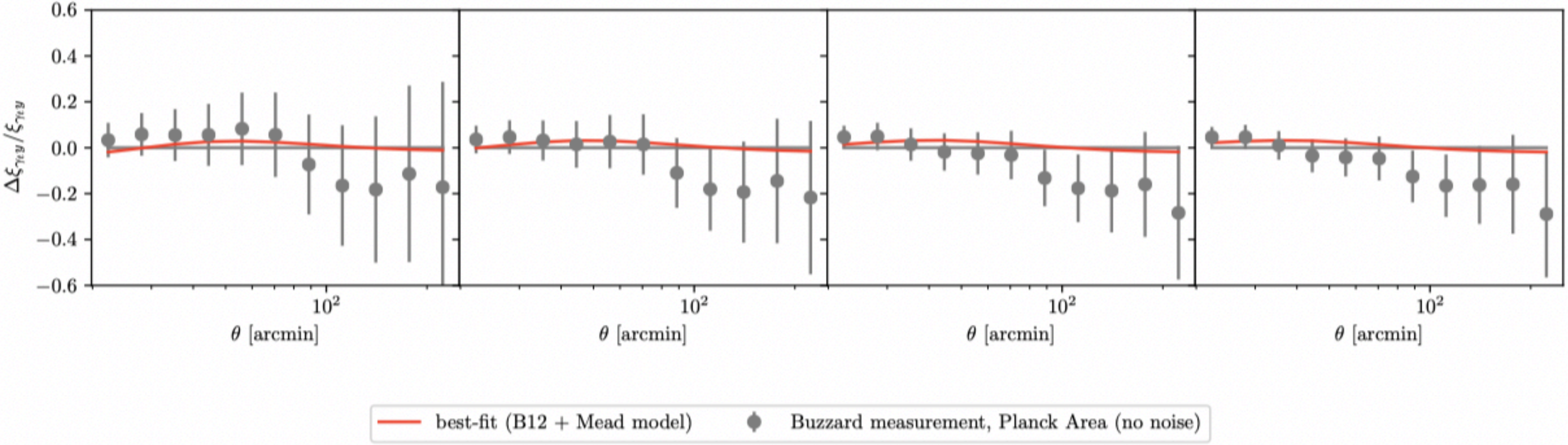
Pandey et al. 2021

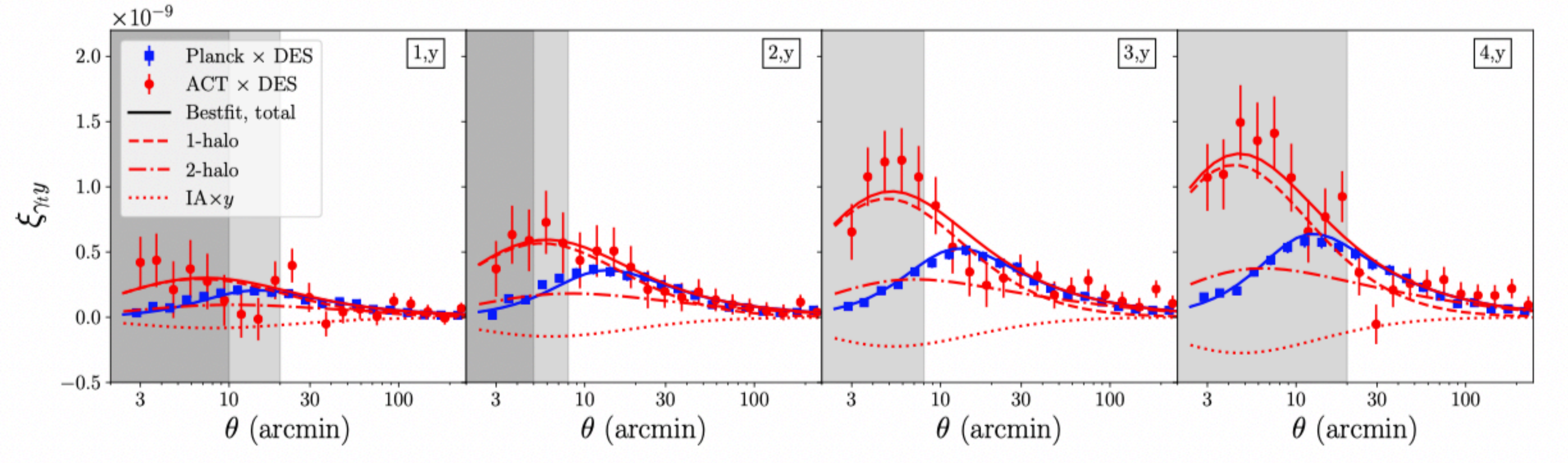

$b_1$
$b_2$
$b_s$
$b_{3nl}$
$b_k$
Param. Value
Param. Value
Param. Value
$m_r < 24.5$
$m_i < 24.4$
$m_r < 23$
$m_i < 22.9$
$m_r < 22$
$m_i < 21.8$
1.400
1.395
1.390
1.385
1.380
1.660
1.655
1.650
1.645
1.640
1.635
1.89
1.88
1.87
1.86
0.0
−0.2
0.2
0.0
−0.2
0.3
0.2
0.1
1.0
0.5
0.0
−0.5
−1.0
0.5
0.0
−0.5
0.0
−0.5
−1.0
1.25
1.00
0.75
0.50
0.25
1.5
1.0
0.5
2.5
2.0
1.5
1.0
2
1
0
−1
3
2
1
0
4
3
2
1
0
0.2
0.4
$k_{\rm max}$ [$h$/Mpc]



$r_{min}$ [Mpc/$h$]
12
8
6
4
$b_1$
1.68
1.66
1.64
1.62
$b_2$
0.4
0.2
0.0
−0.2
$b_s$
0
−1
$b_{3nl}$
2
1
0
$b_k$
5
0
−5
0.2
0.4
$k_{max}$ [$h$/Mpc]
Fourier
Configuration


$P_{\rm gm}/b_1P_{\rm mm}$
1.02
1.01
1.00
0.99
$10^{-1}$
$k$ [$h$/Mpc]
$\xi_{\rm gm}/b_1\xi_{\rm mm}$
1.02
1.01
1.00
0.99
5
10
20
40
$r$ [Mpc/$h$]


0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
$\Delta\xi_{\gamma y}/\xi_{\gamma y}$
$10^2$
$\theta$ [arcmin]
best-fit (B12 + Mead model)
Buzzard measurement, Planck Area (no noise)

$\times 10^{-9}$
2.0
1.5
1.0
0.5
0.0
−0.5
$\xi_{\gamma_t y}$
Planck × DES
ACT × DES
Bestfit, total
1-halo
2-halo
IA×$y$
1,y
2,y
3,y
4,y
3
10
30
100
$\theta$ (arcmin)

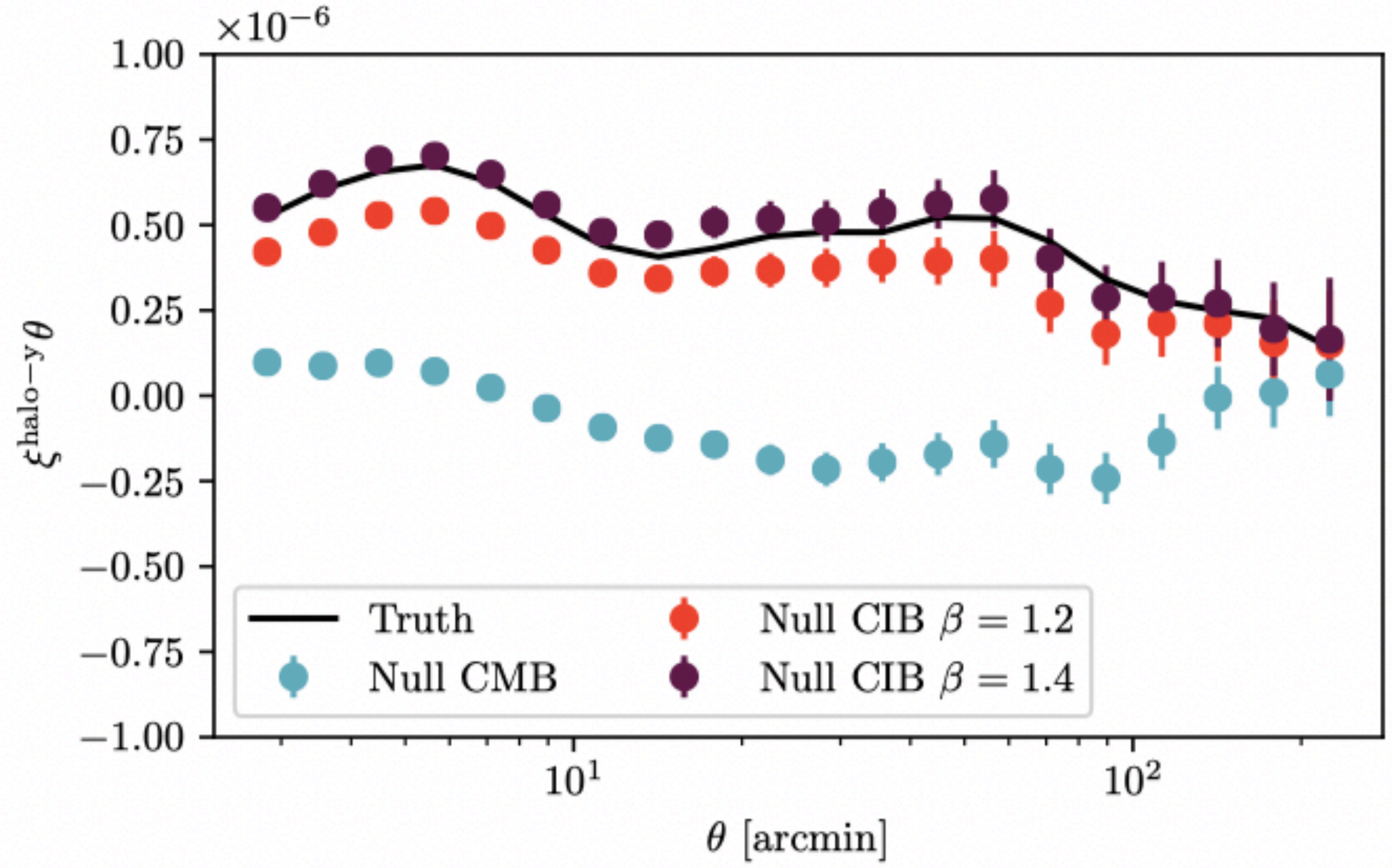
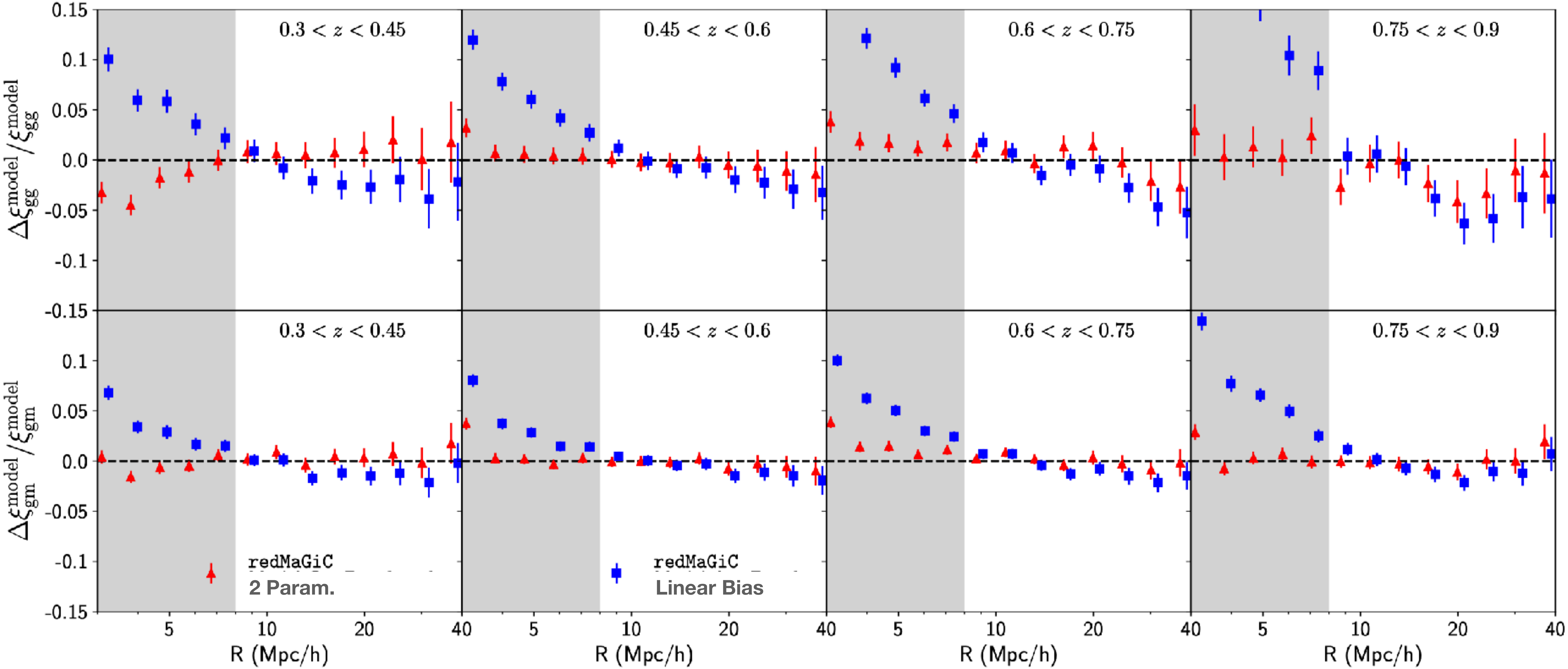


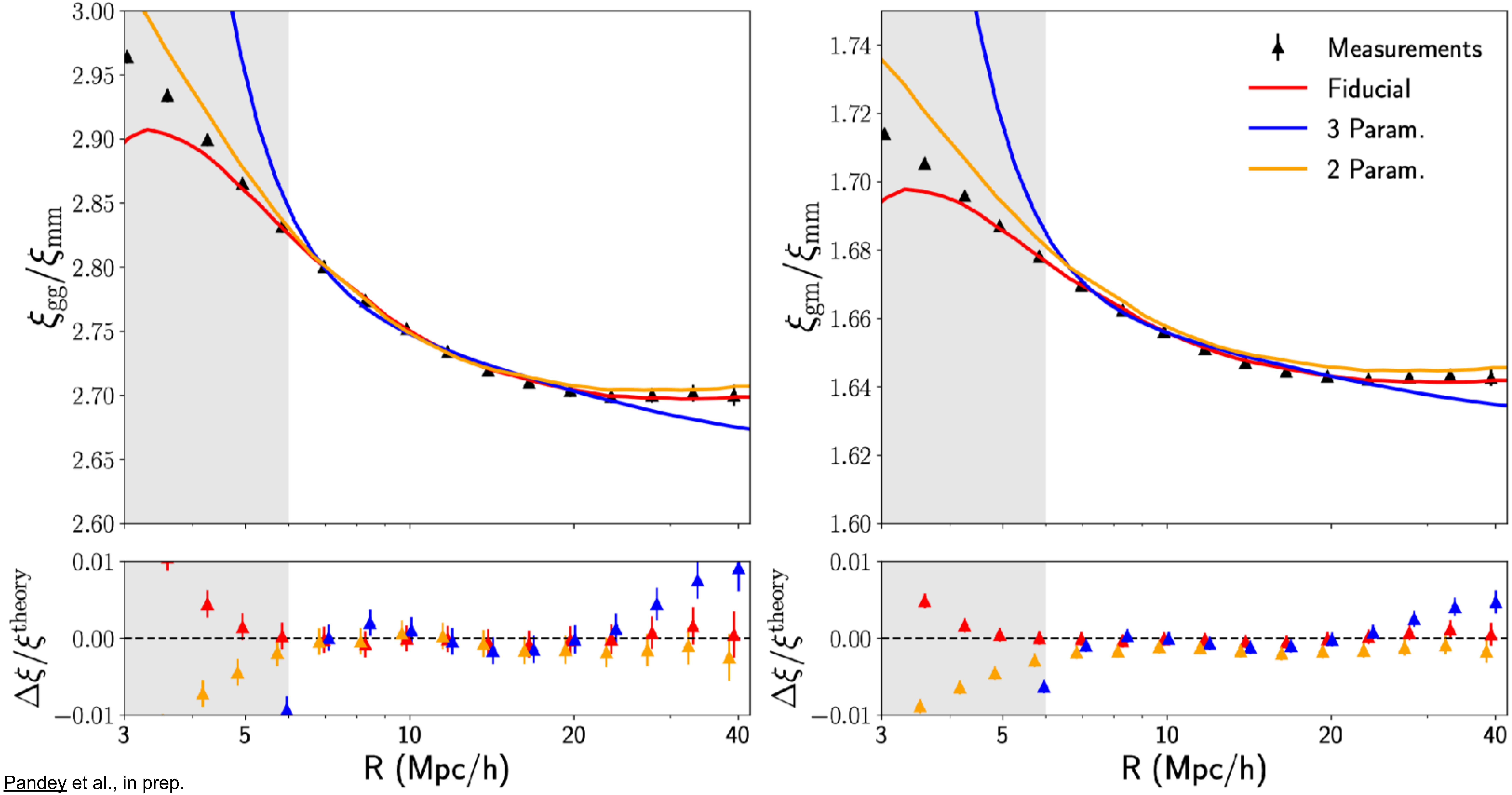
Figure 16. Halo-Compton-*y* correlation from Websky mocks. The three different measurements use three different versions of the Compton-*y* maps. The black line refers to the case where the Compton-*y* map is created starting from frequency channels without CIB contamination, whereas the two other measurements have been obtained using frequency channels contaminated by a fiducial CIB signal, with or without CIB de-projection at the map-making level.

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



Pandey et al. 2021

# Fitting in configuration space ($m_r < 23$)



Goldstein, Pandey et al., in prep.