Title: Cosmology and astrophysics from small scales

Speakers: Shivam Pandey

Series: Cosmology & Gravitation

Date: January 14, 2022 - 3:00 PM

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Abstract:
Complex and poorly understood astrophysics impacts our ability to constrain cosmological and astrophysical models from the large scale structure. Two major sources of systematic errors are galaxy biasing (non-linear mapping between dark matter and galaxies) and baryonic feedback (impact of supernovae or AGN on LSS). In the first part of my talk, I will describe a hybrid perturbation theory model of galaxy biasing and show its validation at sub-percent accuracy. I will then describe the cosmological constraints obtained using this model on the measurements from the first three years of observations of the Dark Energy Survey (DES). In the second part of my talk, I will describe tomographic measurements and analysis of the cross-correlations between thermal Sunyaev-Zel'dovich (tSZ) effect and gravitational lensing. Using data from ACT, Planck, and DES, we obtain the highest significance (20 sigma) measurements to-date and use them to constrain models for the pressure profiles of halos across a wide range of halo mass and redshift. We find evidence for reduced pressure in low mass halos, consistent with predictions for the effects of increased feedback from AGN. Lastly, we also comment on application of this study to the sigma8 tension and hydrostatic mass bias as inferred from the cluster count analysis.

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Perimeter_22_talk

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….)

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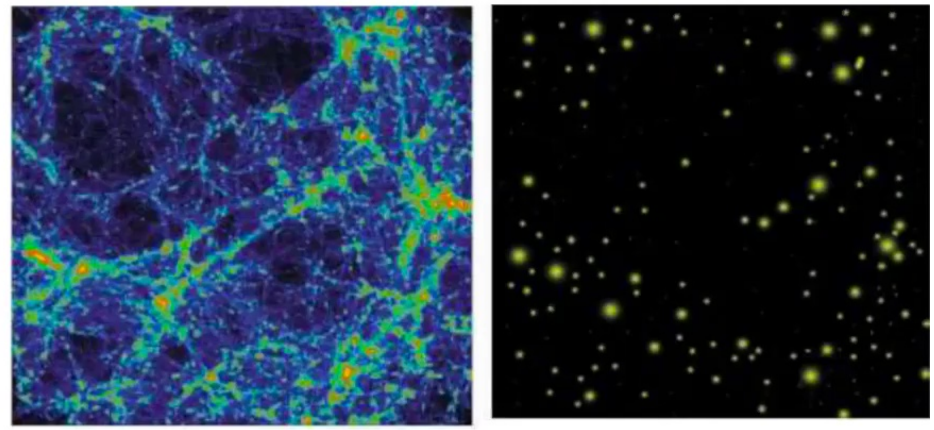
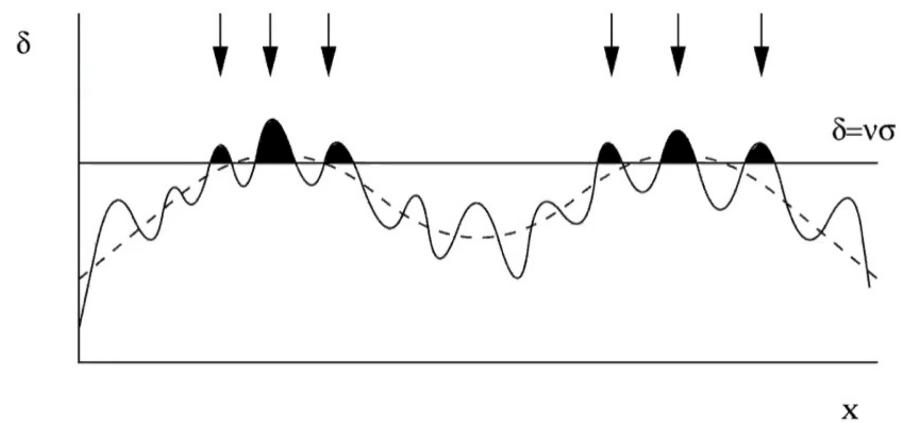
Impact of (g)astrophysics on LSS

- We don't directly 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

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- **S. Pandey**, M. Gatti et al. (arxiv:2108.01601)
- **S. Pandey** et al (in prep.)

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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 δ_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 $\langle \delta_g \delta_m \rangle$:

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

Linear Bias

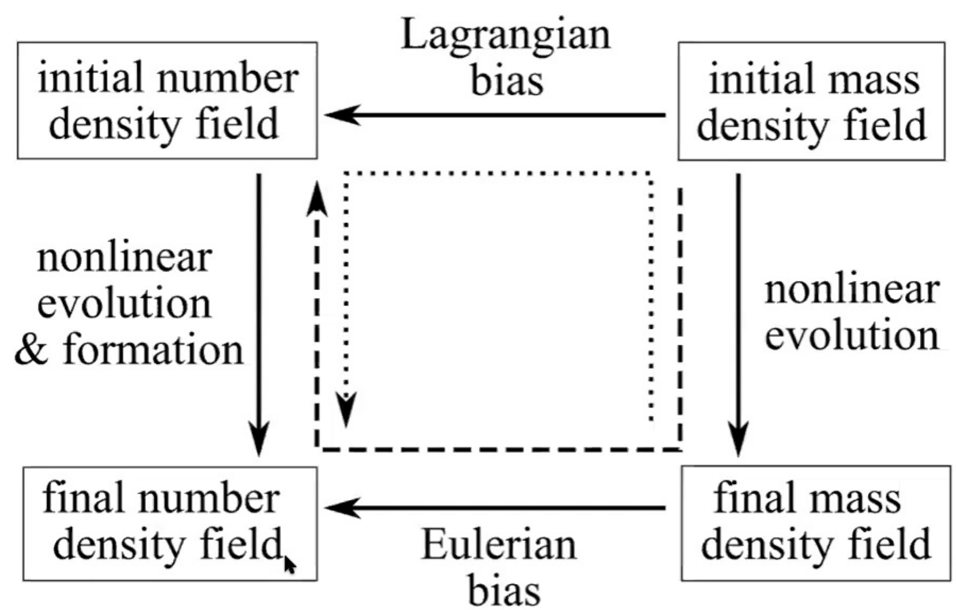
1-Loop PT *(captures gravitational non-locality)*

Higher-derivative + EFT *(captures spatial non-locality)*

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

Question we want to answer

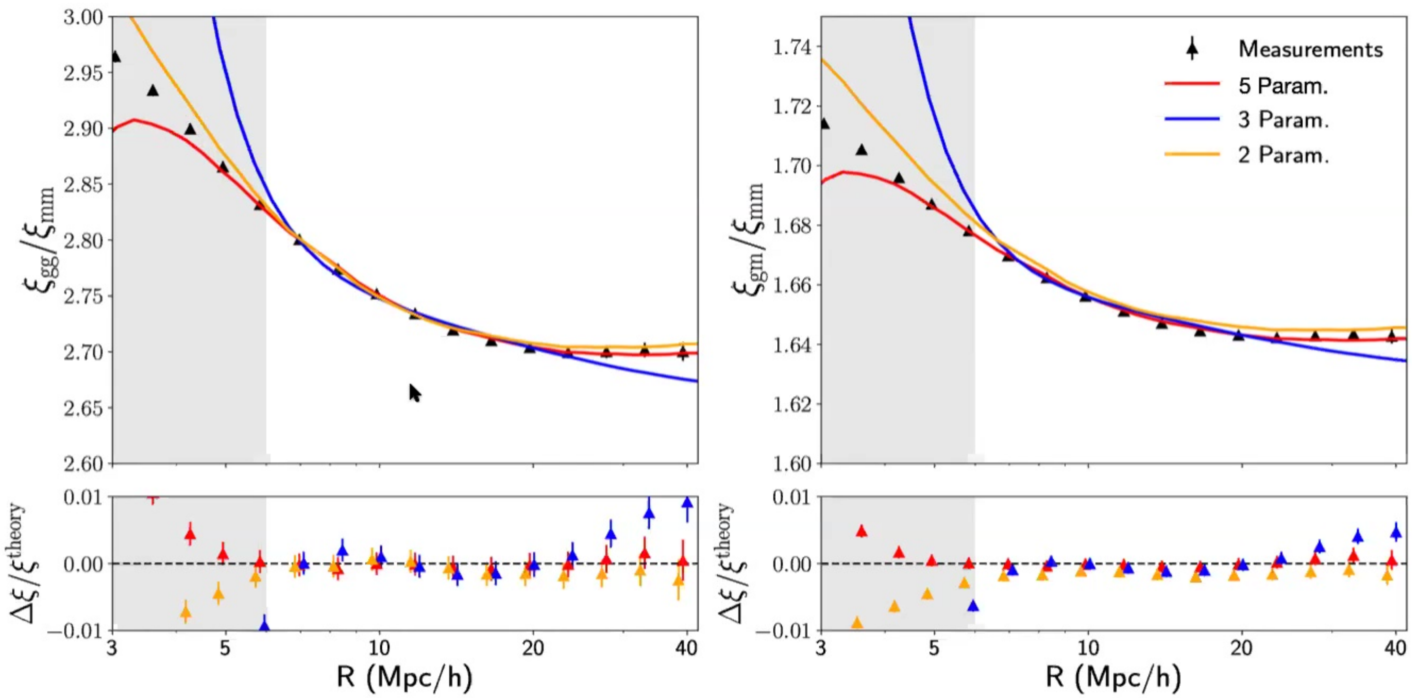
- How many of bias parameters, especially b_s, b_{3nl} and b_k can we fix/remove?
  - Co-evolution values:
    - $b_s = (-4/7) \times (b_1 - 1) + b_s^{Lag}$
    - $b_{3nl} = (b_1 - 1) + b_{3nl}^{Lag}$
    - Assuming spatial locality, $b_k = 0$



Matsubara 2013

Validation on LSST-like sims

- Uses Cosmo-DC2 sims, based on Outer-rim sims. Doing validation at z=1.0 snapshot.
  - 3 Gpc/h box size, ~3e9 $M_\odot$ mass res
- Fits to configuration space with three models
  - *Galaxy sample constructed with conditions $m_r < 23$*



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

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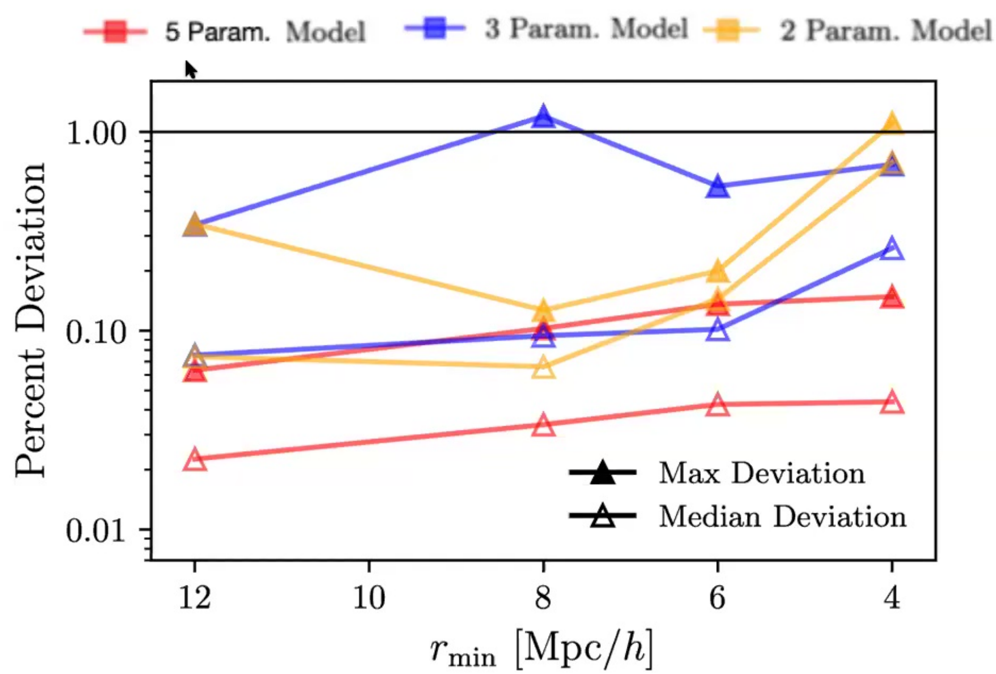
Goldstein, Pandey et al., in prep.

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

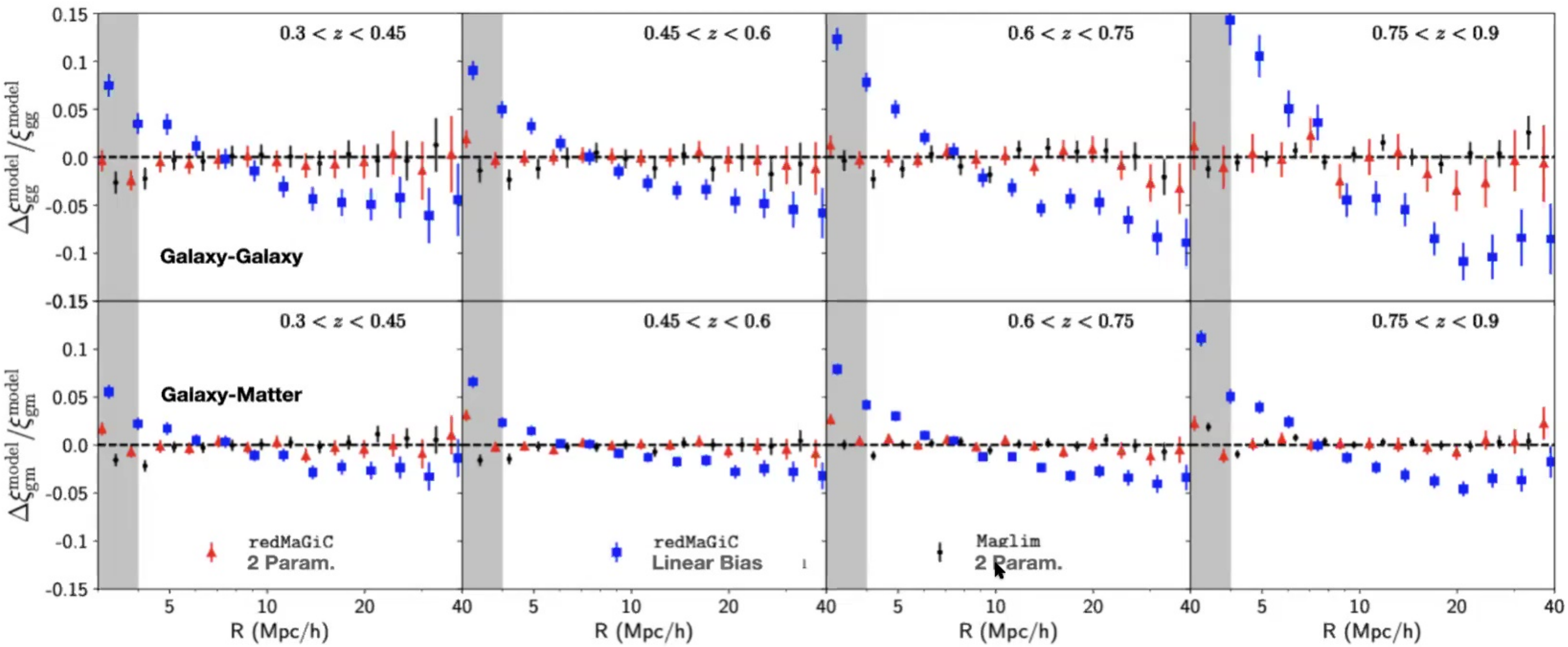
- We find similar results in configuration space
- Fiducial model with 5 free parameters works very well
- We get sub-percent fits with all the models at various scale cuts.
- A 2-parameter model suffices for target accuracy of 1-percent or less down to 4Mpc/h (for $m_r < 23$ sample)
    - Similar conclusions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



Goldstein, Pandey et al., in prep.

Validation on DES-like simulations (full lightcone)

- We use DES-like simulation and fit the 3D correlation functions at fixed cosmology
  - Two different galaxy catalogs, split into *four redshift bins*, 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



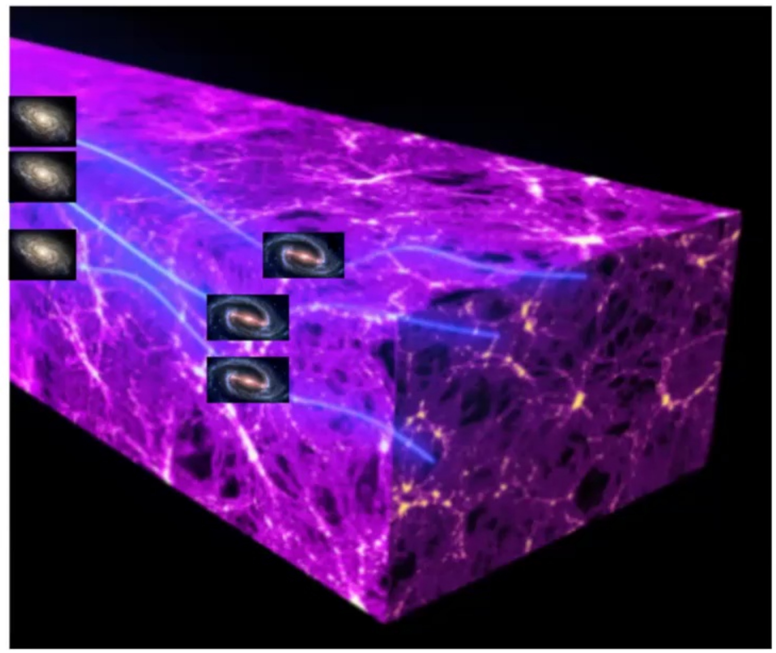
Pandey et al. 2021

Application to DES-Y3 data

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

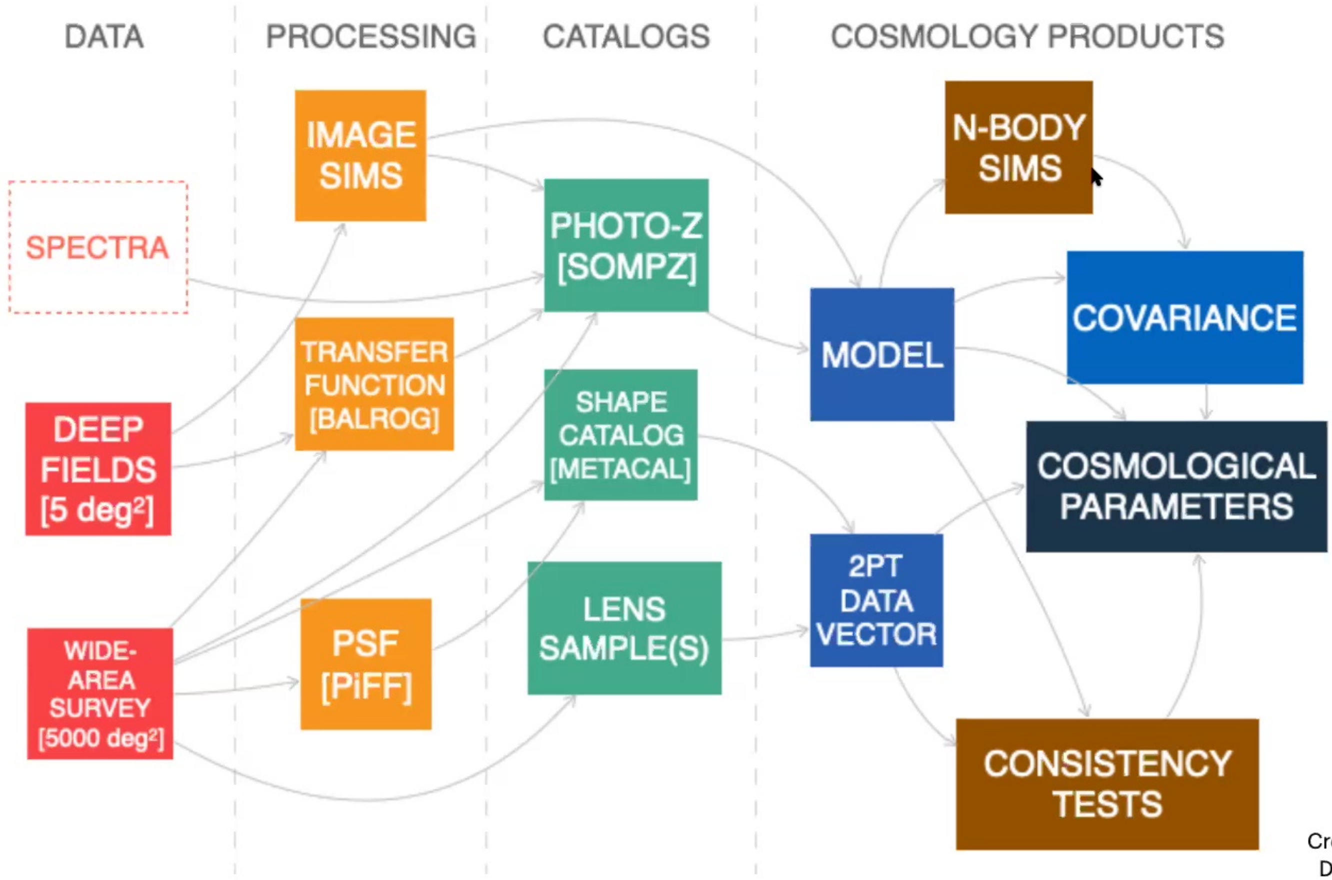
- DES extracts positions and shapes of galaxies from images.
- Intrinsic shape of galaxies get distorted by weak lensing caused by all the matter between us and the galaxy.
- From *position* (foreground lens = = L) and *shapes* (background source = = S) of the galaxies, we construct three 2-pt functions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

  (LL and LS together: $2 \times 2\,\text{pt}$)



Credits : Wikipedia

Schematic of DES analysis pipeline



Credits: Cyrille Doux
DES Collaboration

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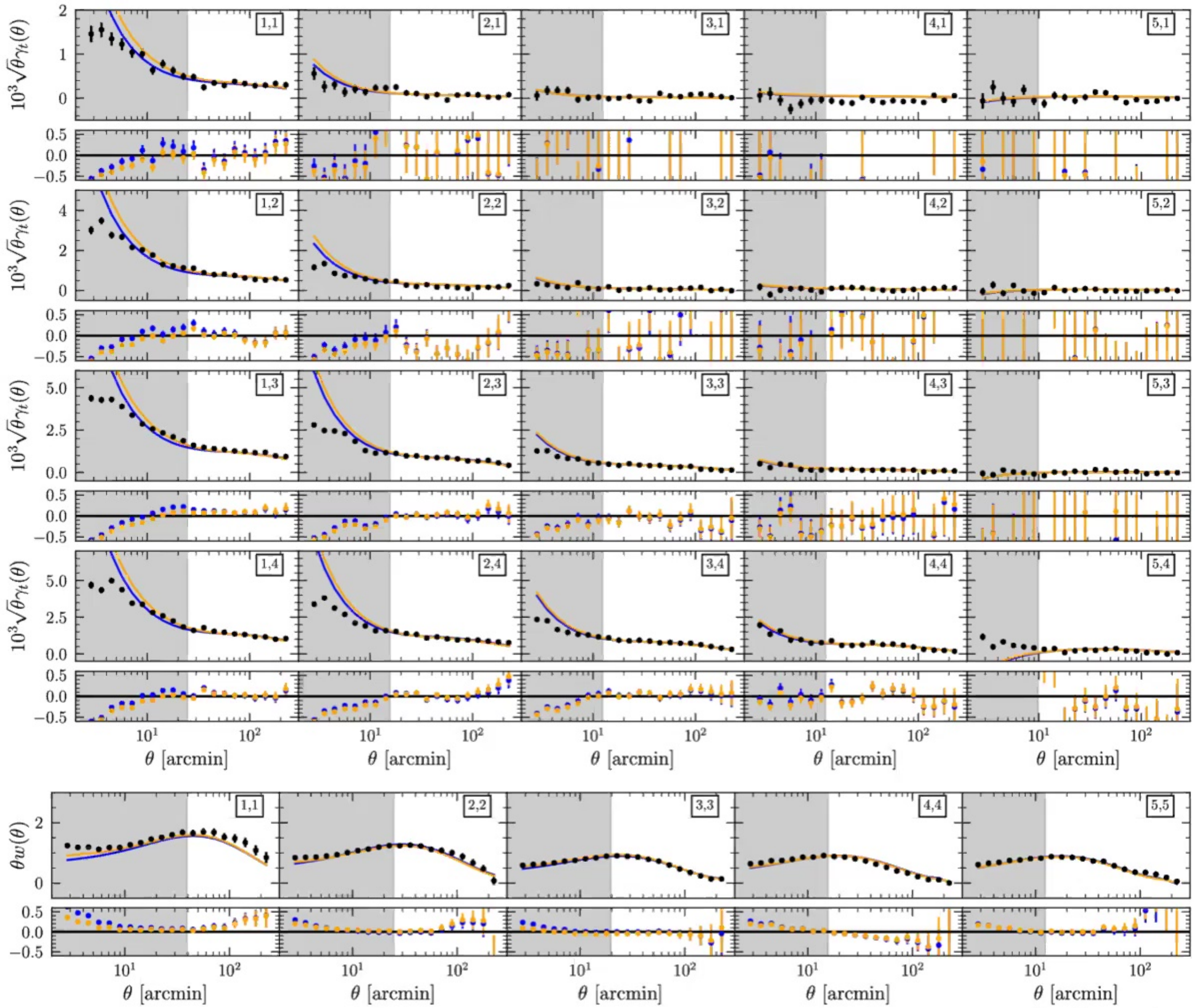
Final measurements

(redMaGiC sample here)

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



Pandey et al.

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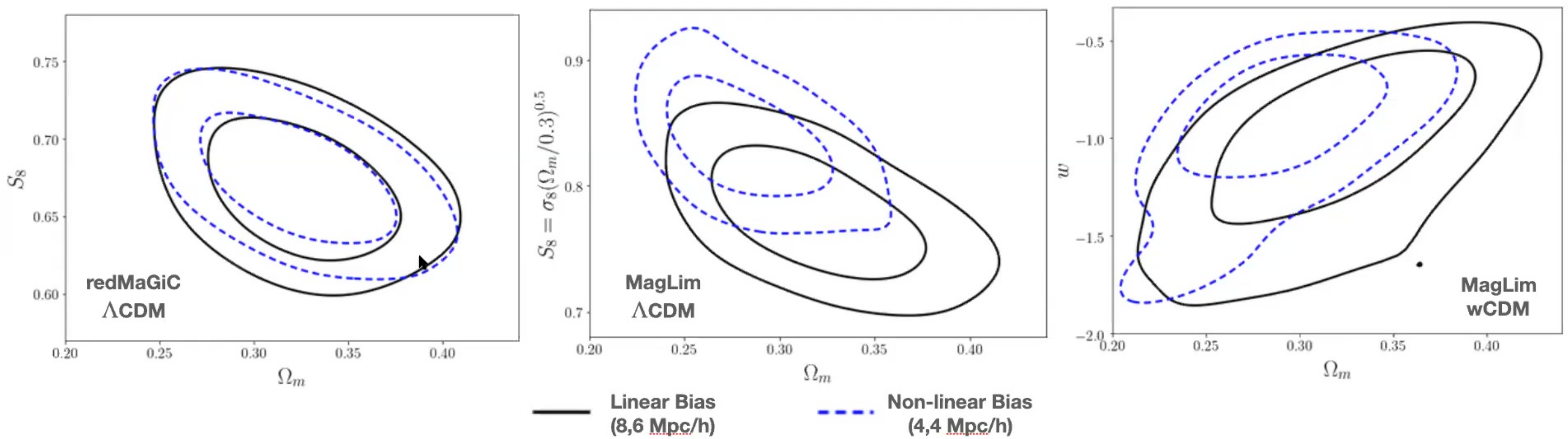
Result on data using $w(\theta) + \gamma_t(\theta)$

- Results with two different lens samples. **Using NL bias model at smaller scales results in 25-40% gain in cosmological constraints**



Pandey et al. 2021

Porredon, ... 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.

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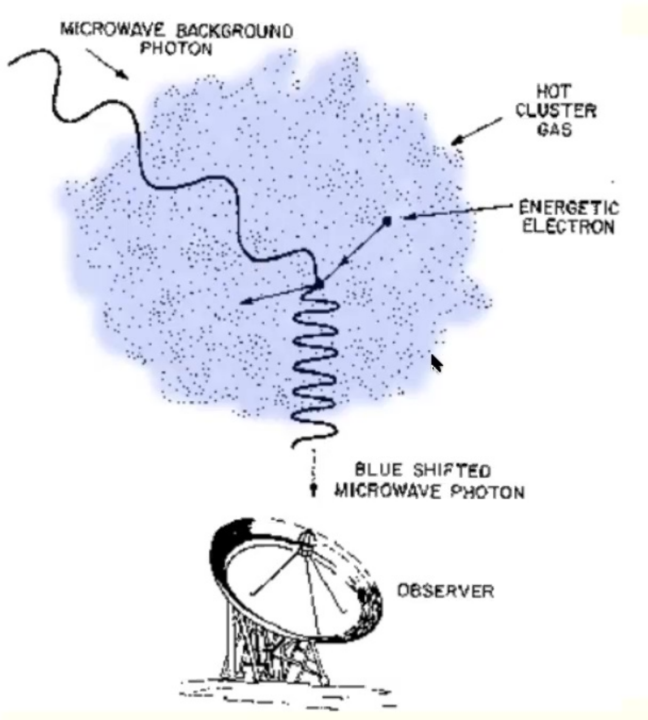
tSZ and shear : *tracers of LSS*

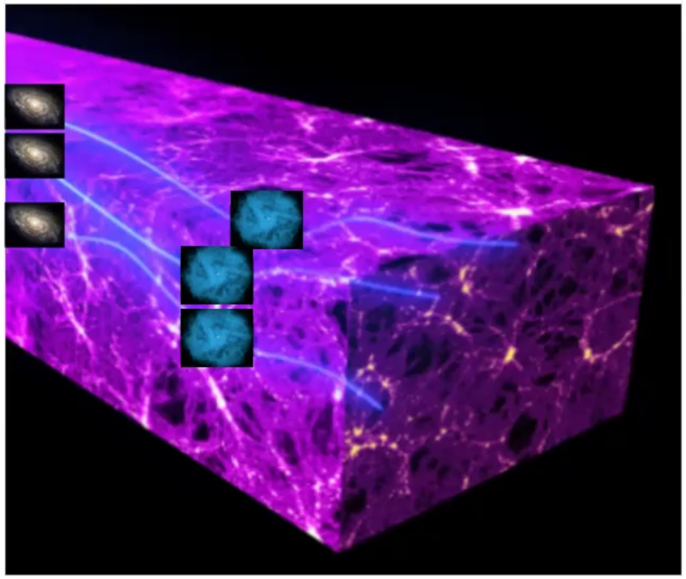
1. Compton-y parameter derived from CMB distortion is sensitive the integrated pressure (and hence to thermal energy of hot gas)

2. Cosmic shear measures coherent distortion in galaxy shape because of weak gravitational lensing by the foreground matter

3. Cross-correlation with other tracers, e.g., shear, can isolate the importance of the feedback in different redshifts, different halo masses and different environment conditions.



Credits : L. Van Speybroeck



Credits : Wikipedia

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

2. Baryonic feedback with tSZ xcorr

Using DES, ACT and Planck

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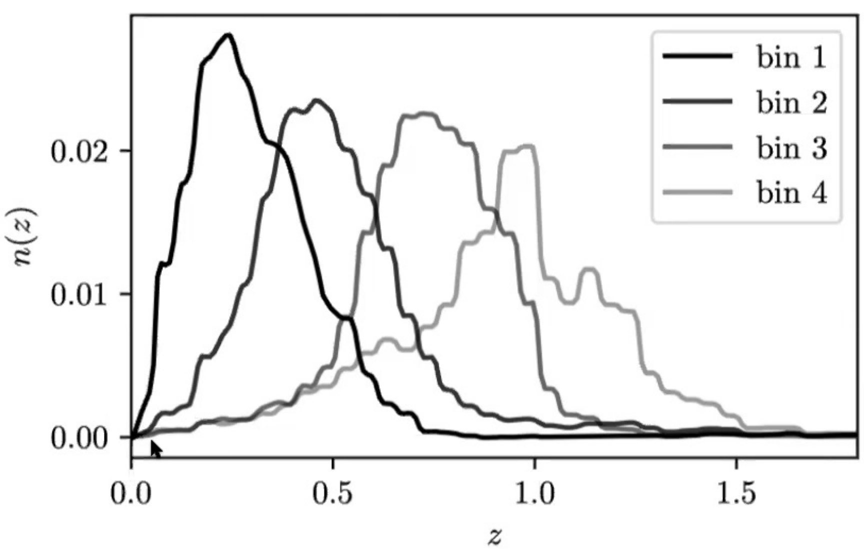
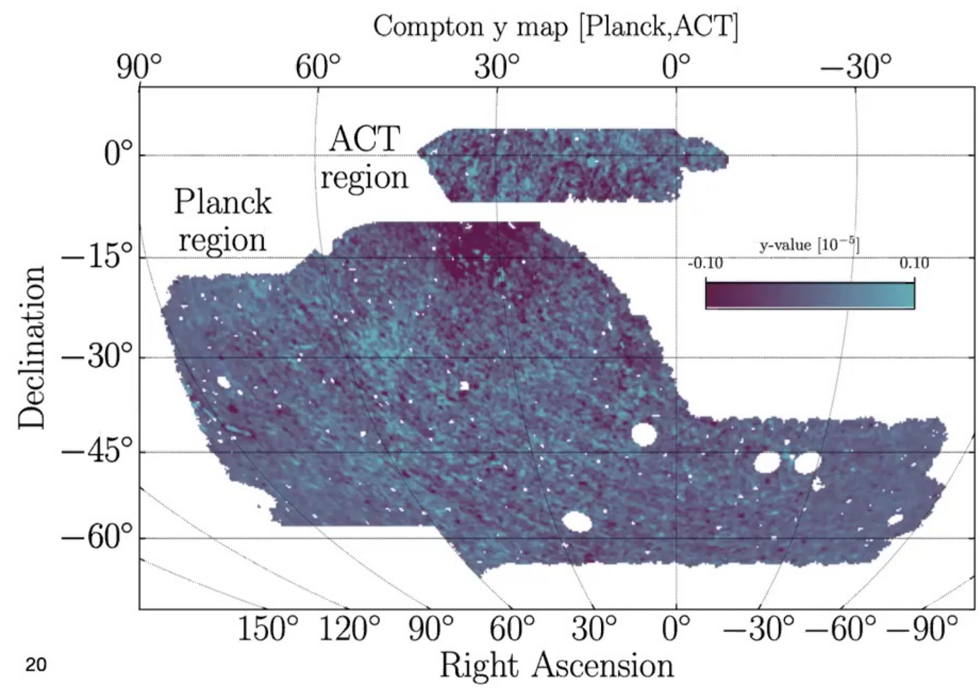
Sky and redshift coverage of dataset

- 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, Pandey et al., 2021



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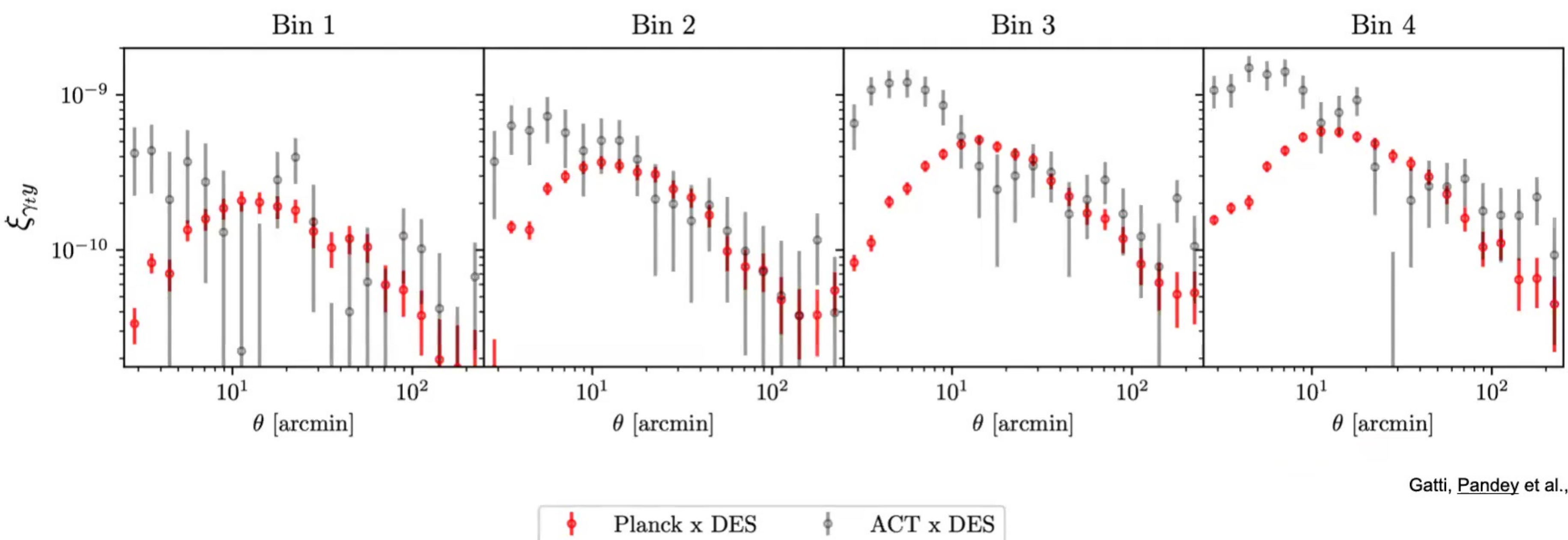
Final tomographic measurements

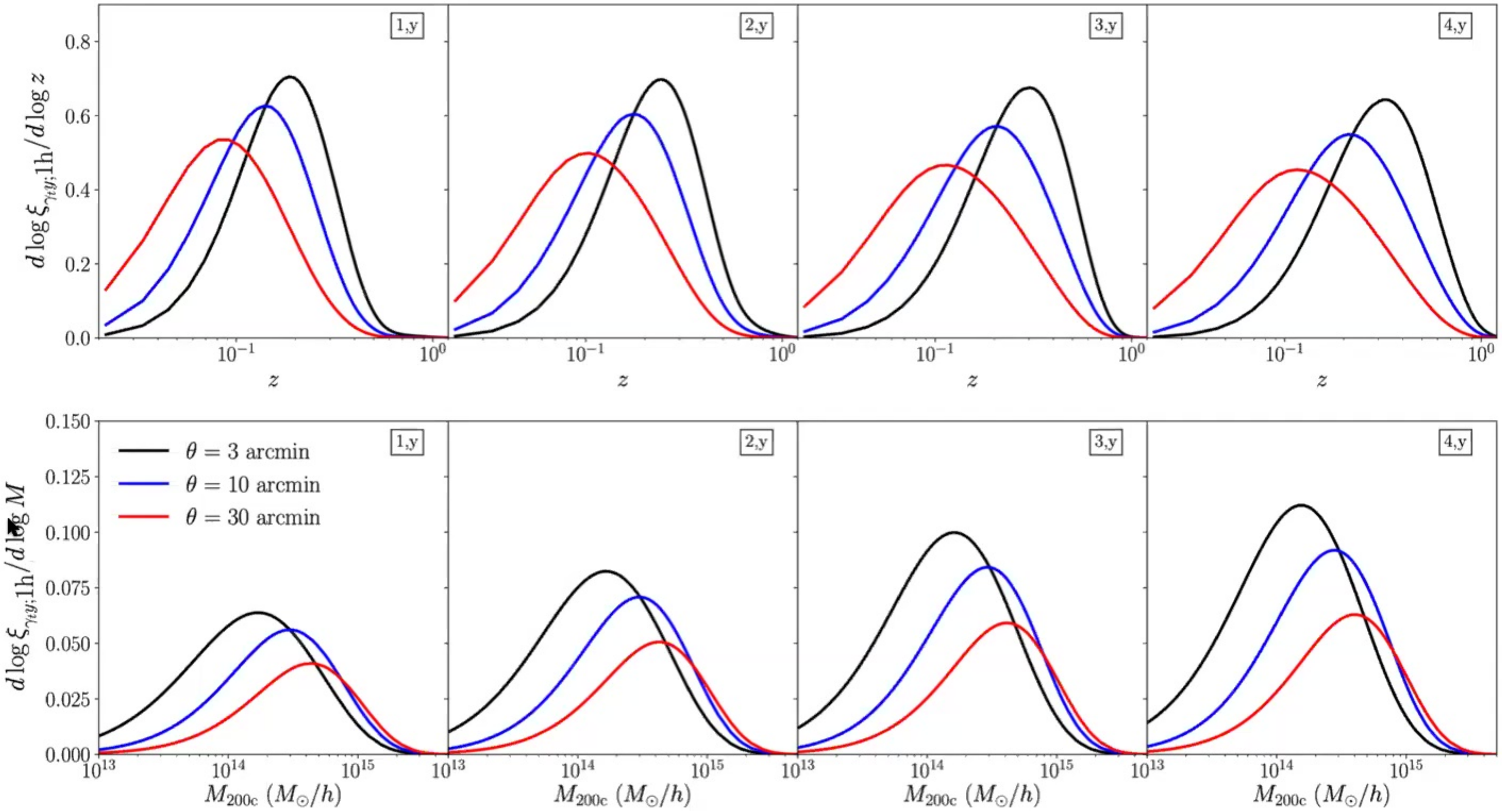


Gatti, Pandey et al., 2021

- ~*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

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Measurement and theory robustness tests

Validate the scales used to get cosmological and astrophysical conclusions

- Compton-y
  - Leakage of Cosmic infrared background (CIB)
    - We find and correct for CIB leakage in the Planck y-map
  - Leakage of radio sources
    - We find radio source contamination to be negligible
- 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
    - Forward model the intrinsic alignment and include in the theory predictions

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Astrophysics and Cosmology from the measurements

- We model the signal with halo model framework:
  $\langle \gamma_t y \rangle = \text{1-halo} + \text{2-halo} + \langle \text{IA} \times y \rangle \sim f(\text{cosmology}) \times g(\text{pressure-profile})$
- 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)

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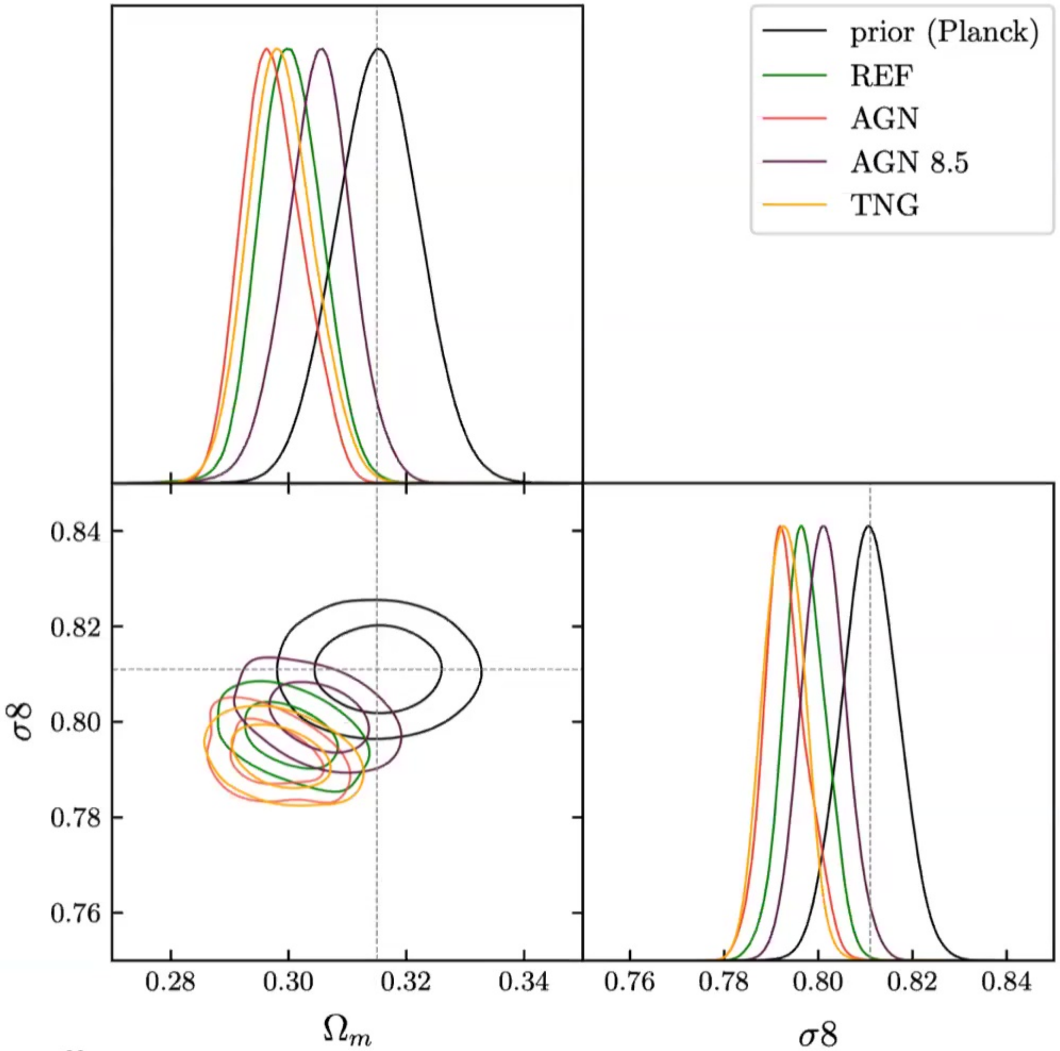
1. Aggressive

- Rescale shear profile without additional freedom

$$\bar{\kappa}_{\ell}(M,z) \rightarrow \bar{\kappa}_{\ell}(M,z)\sqrt{\frac{P_{\rm DM+baryons}(k,z)}{P_{\rm DM}(k,z)}},$$

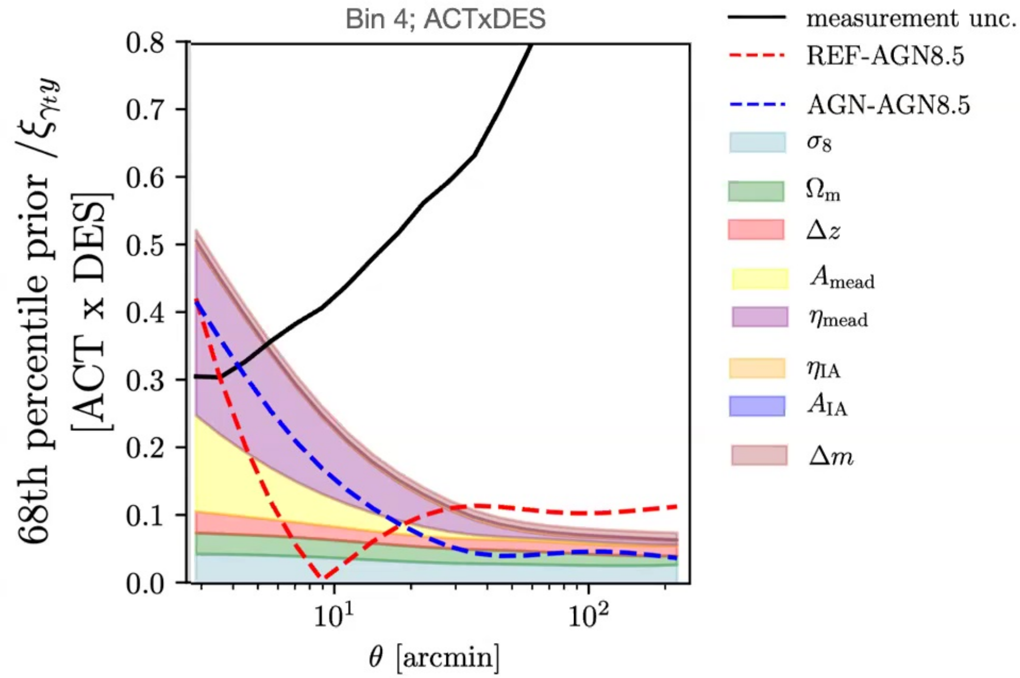
Planck prior (NFW re-scaling)					
	B12	**AGN**	**AGN 8.5**	**REF**	**TNG**
$\chi^2/d.o.f.$	-	172/119	158/119	189/119	198/119
UDM tension	-	4.5 σ	2.2 σ	3.3 σ	4.3 σ

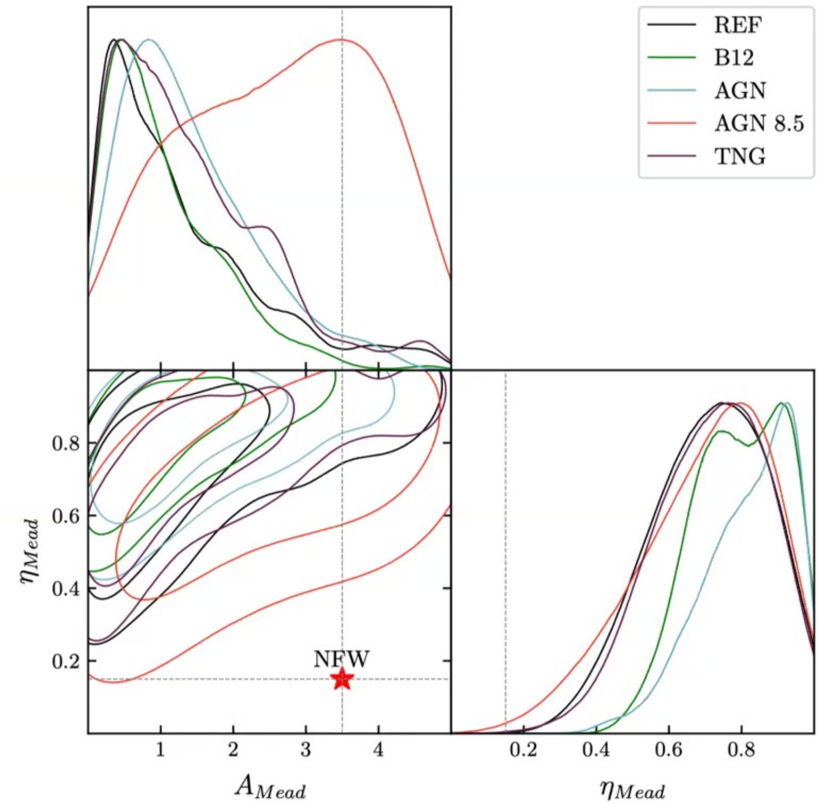
- AGN-8.5 is preferred at Planck cosmology priors



Gatti, Pandey et al., 2021

2. Conservative (parameterize change in DM profile)





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

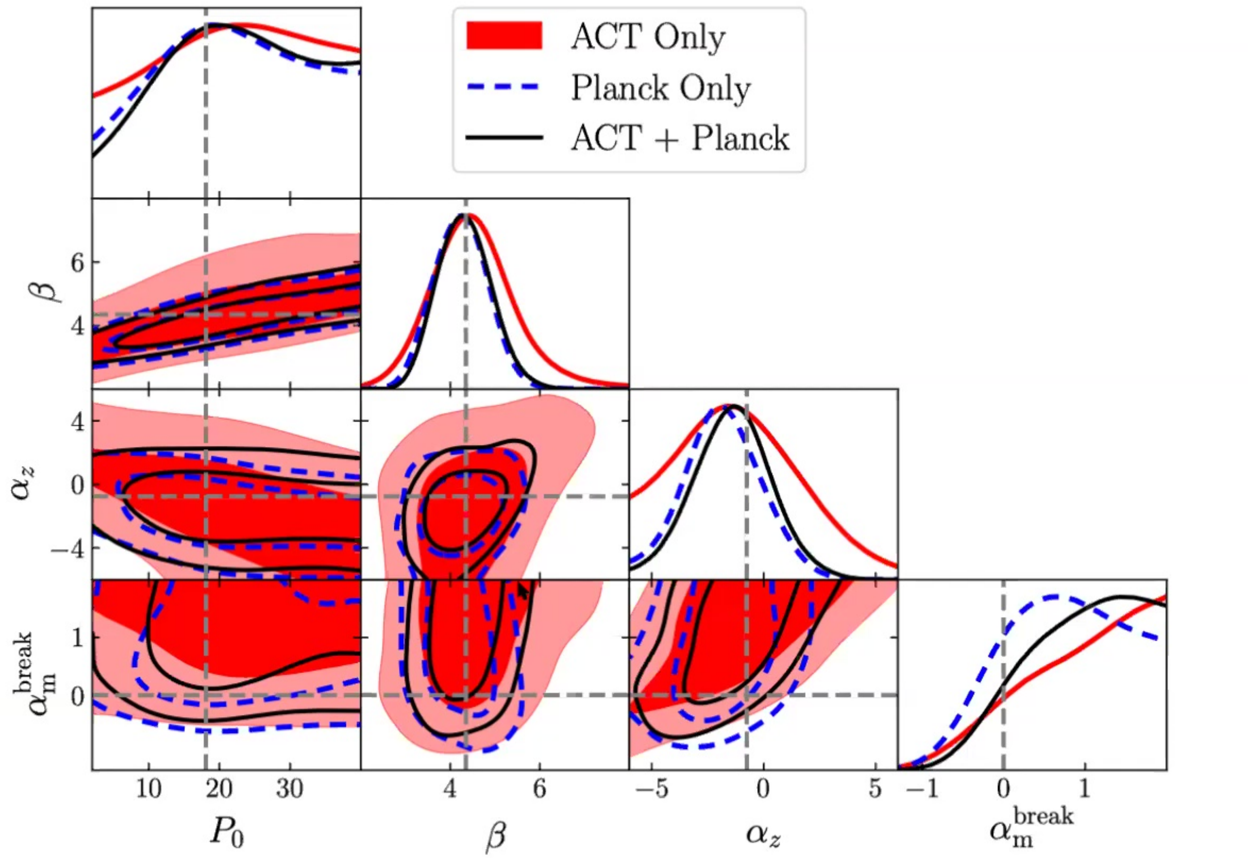
Planck prior (free $A_{\rm Mead}$, $\eta_{\rm Mead}$)					
	B12	**AGN**	**AGN 8.5**	**REF**	**TNG**
$\chi^2/d.o.f.$	154/118	155/118	154/118	155/118	154/118
UDM tension	0.7 σ	1.5 σ	1.4 σ	0.5 σ	0.3 σ

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)

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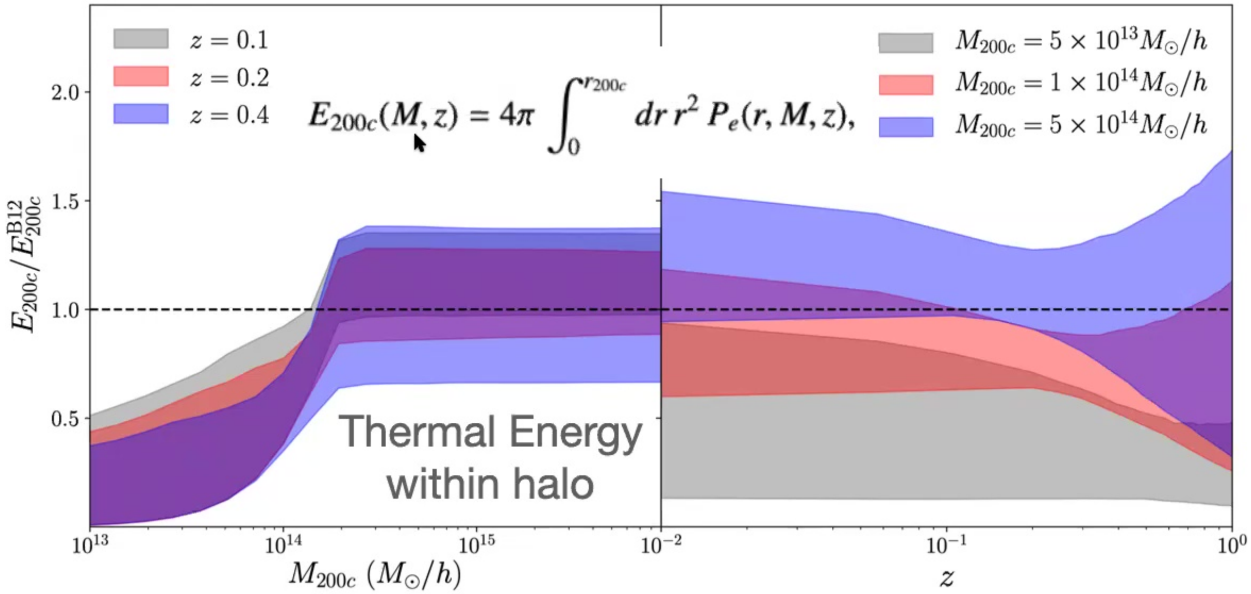
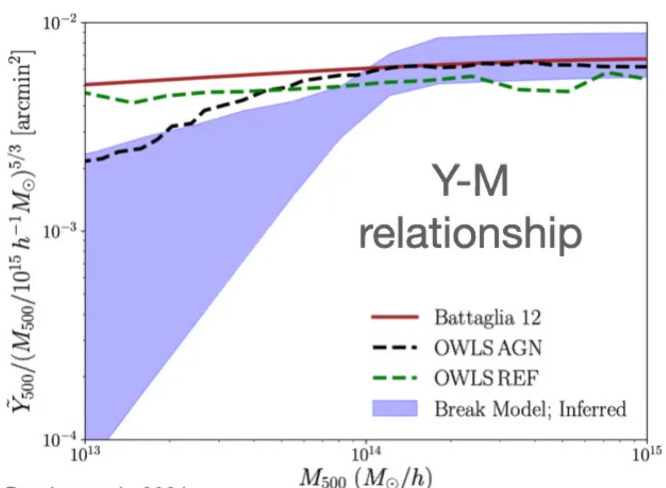
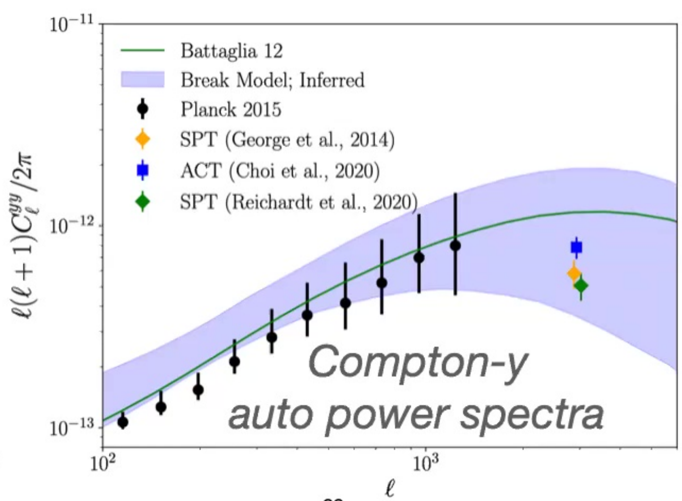


- Inferences with constraints shown in previous slides
- Preference for lower pressure or thermal energy in lower mass halos, particularly at higher redshifts.
- Higher mass halos consistent with expectations of halo model (and direct measurements from experiments)





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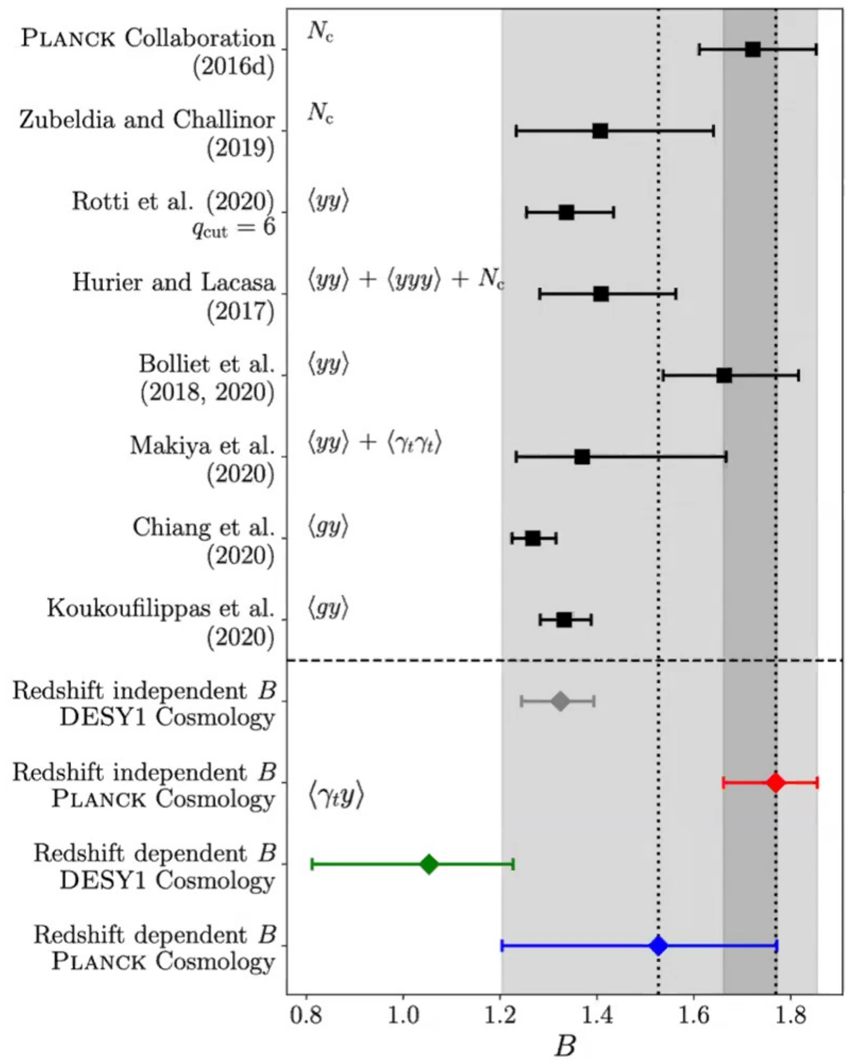
Arnaud10 Model and mass bias

- $M_{500c}^{SZ} = M_{500c}^{true}/B$
  - 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 σ_8 (to DES value) or assuming a evolution of mass bias with redshift reconciles with other studies using galaxies and CMB-lensing correlations



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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*