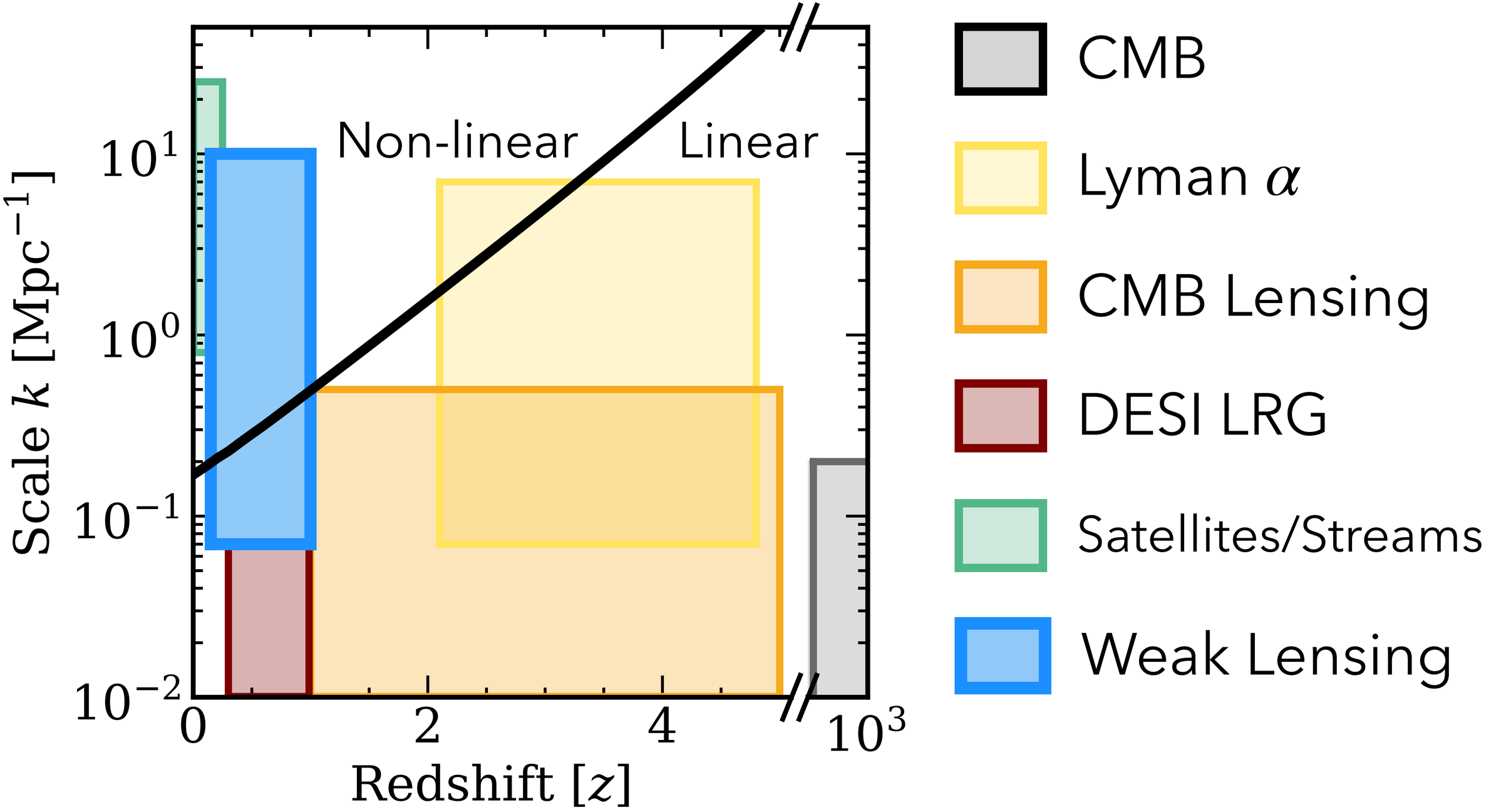
Toward a Complete Picture of Baryon Feedback



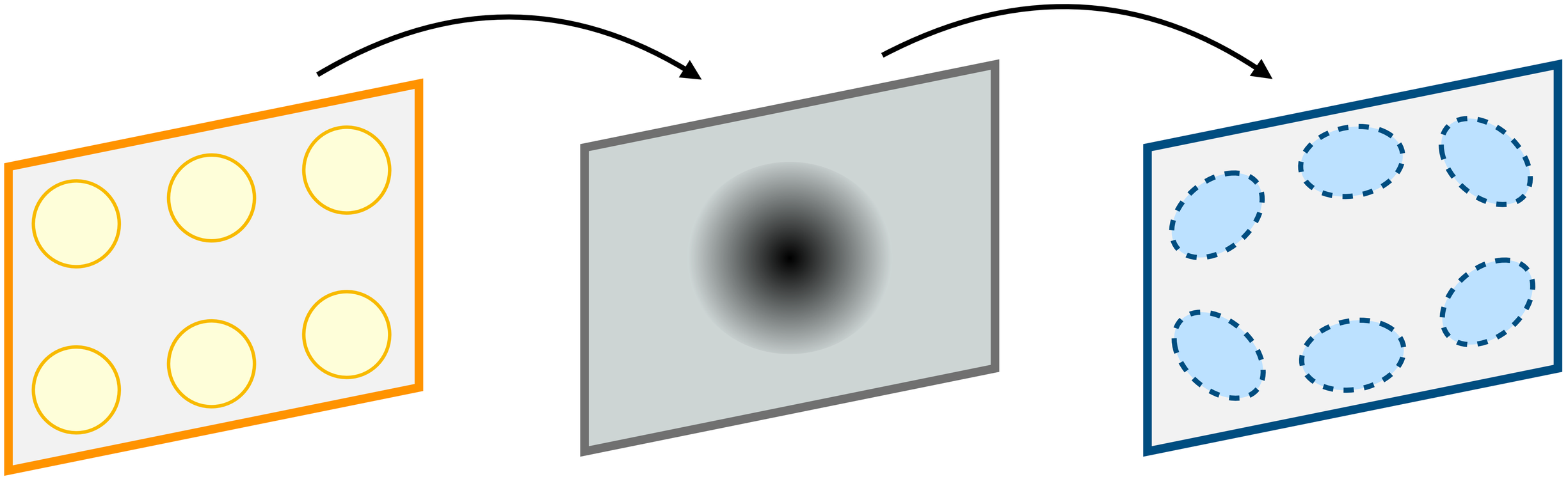
Jared Siegel, Princeton University

Alex Amon, Jenny Greene,
Eliot Quataert and Ian McCarthy




Non-linear
Linear
Scale k [Mpc^{-1}]
10^1
10^0
10^{-1}
10^{-2}
0
2
4
10^3
Redshift [z]
CMB
Lyman α
CMB Lensing
DESI LRG
Satellites/Streams
Weak Lensing

Weak Lensing Cosmology

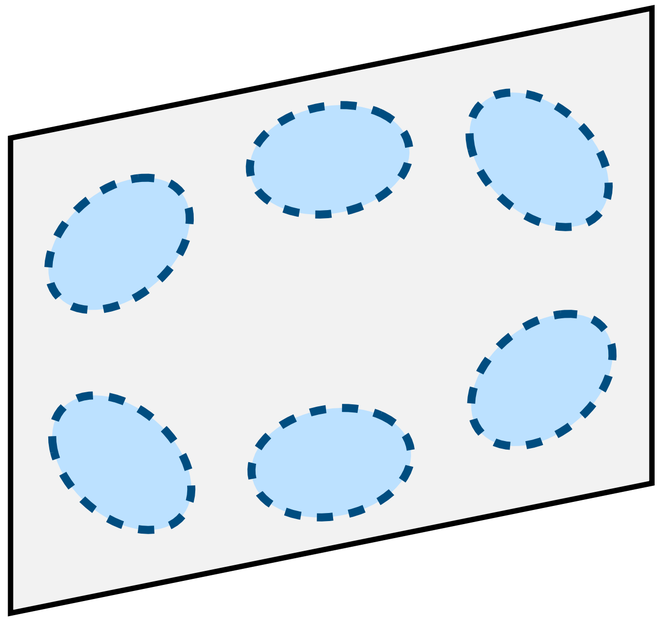


Background Galaxies

Intervening Matter

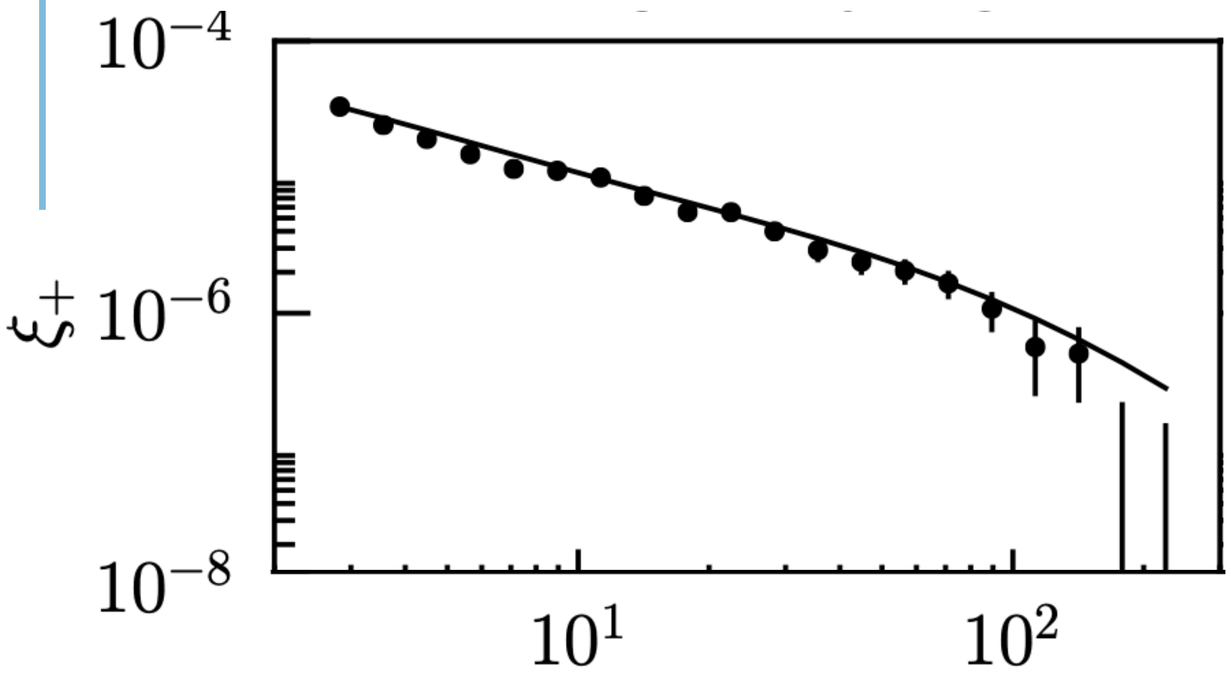
Lensed Galaxy Images

Weak Lensing Cosmology



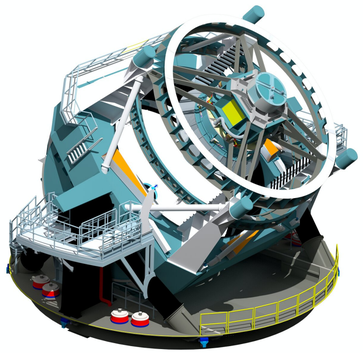
Lensed Galaxy Images

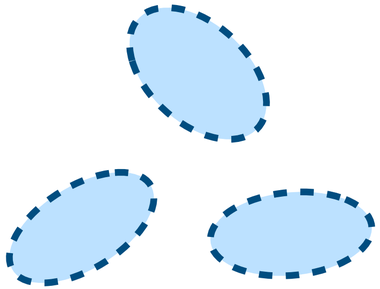
Shear Two-point Correlation

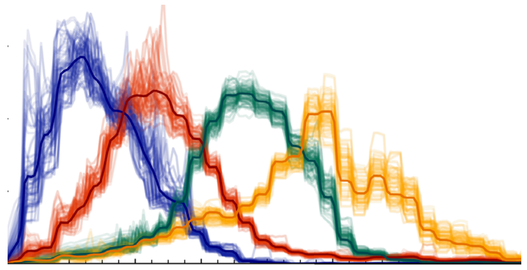


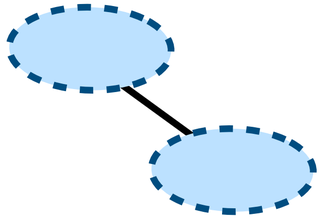
Angular Scale [arcmin]

Weak Lensing Cosmology







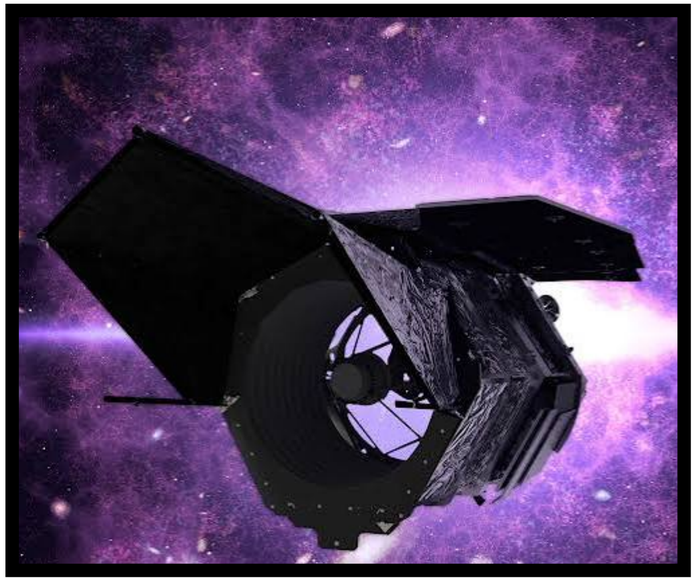


Shape Catalog | Redshift bins | 2-point statistics | Cosmology

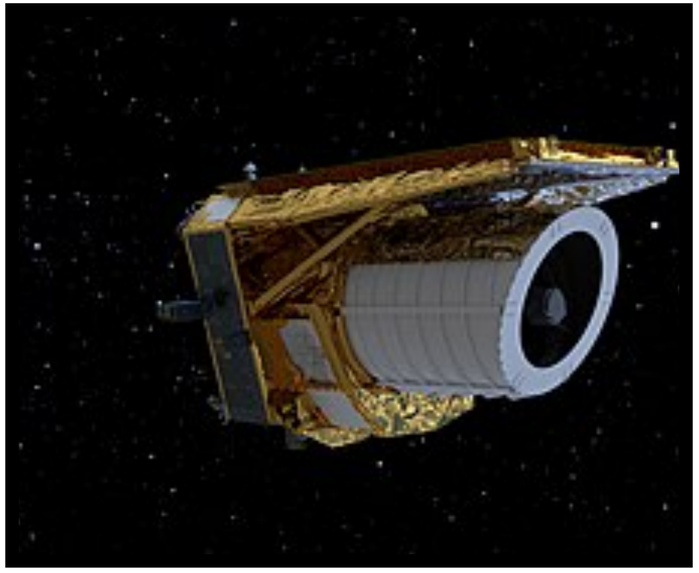
Weak Lensing Cosmology



Rubin LSST



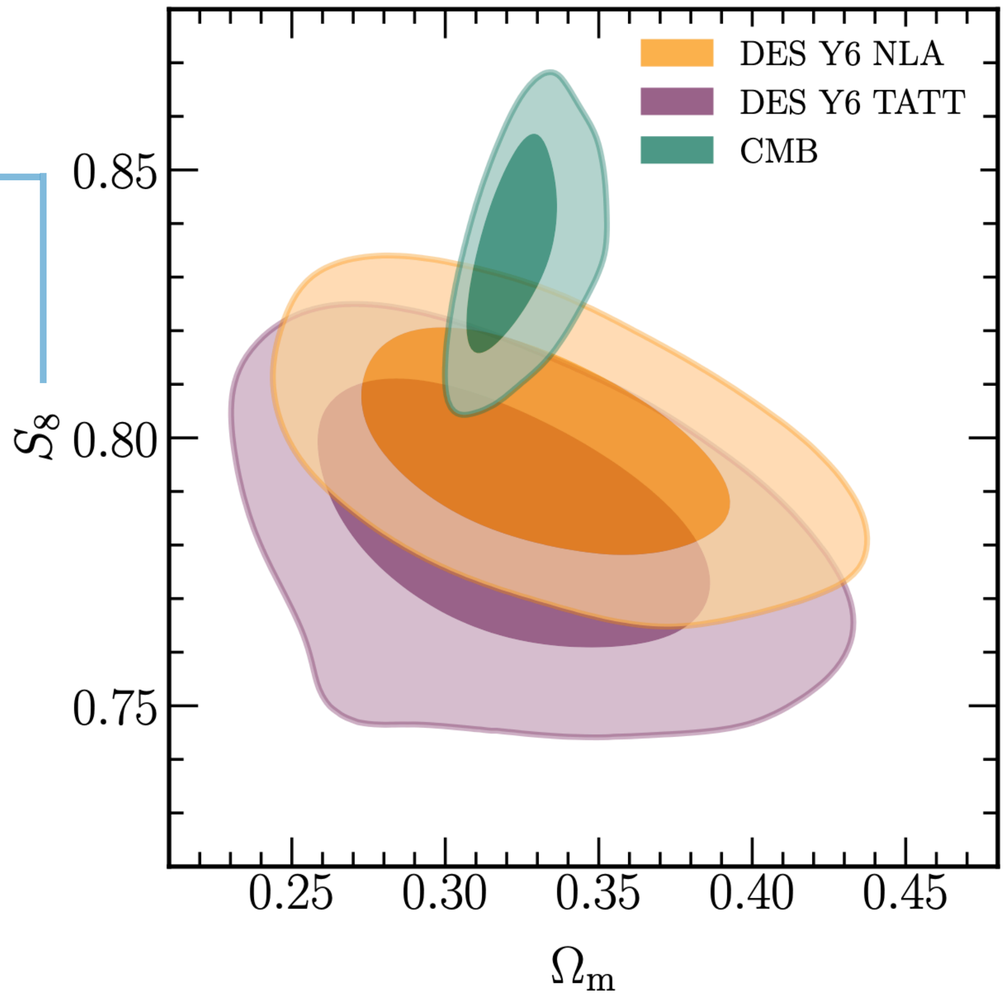
Roman



Euclid

Weak Lensing Cosmology

$$S_8 = \sigma_8 \sqrt{\Omega_\mathrm{m}/0.3}$$

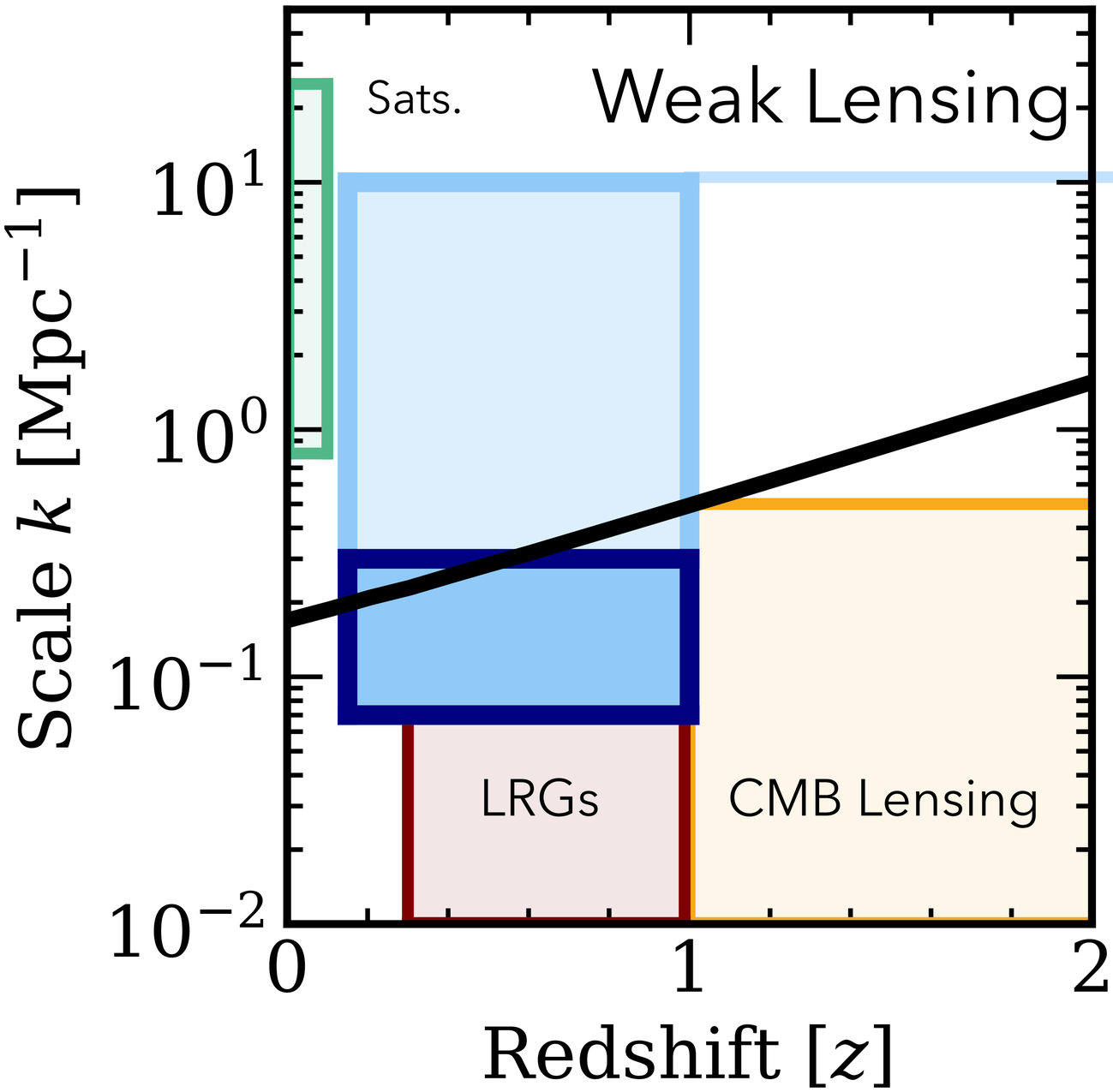


Planck + ACT + SPT

Dark Energy Survey Y6

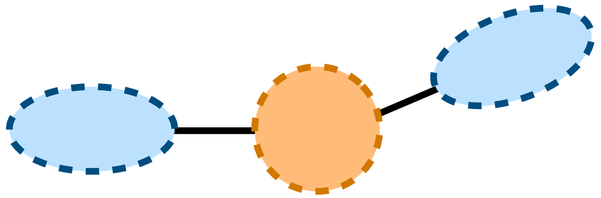
140 million galaxies

DES Y6 Cosmic Shear



Astrophysical Effects

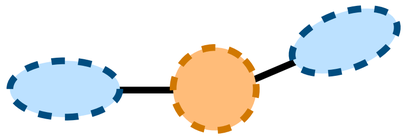
Intrinsic Alignments



Baryonic Feedback



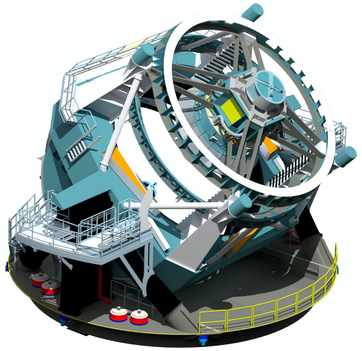
Toward Small Scale Weak Lensing

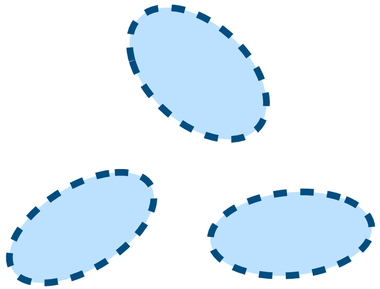


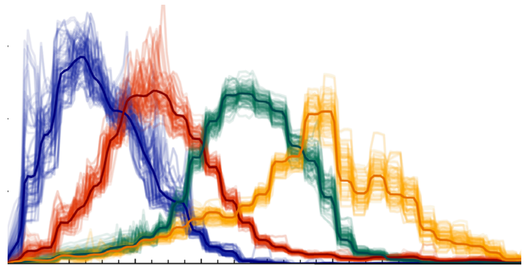


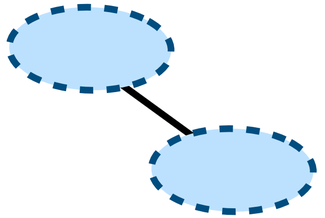
Intrinsic Alignments

Baryon Feedback









Shape Catalog

Redshift bins

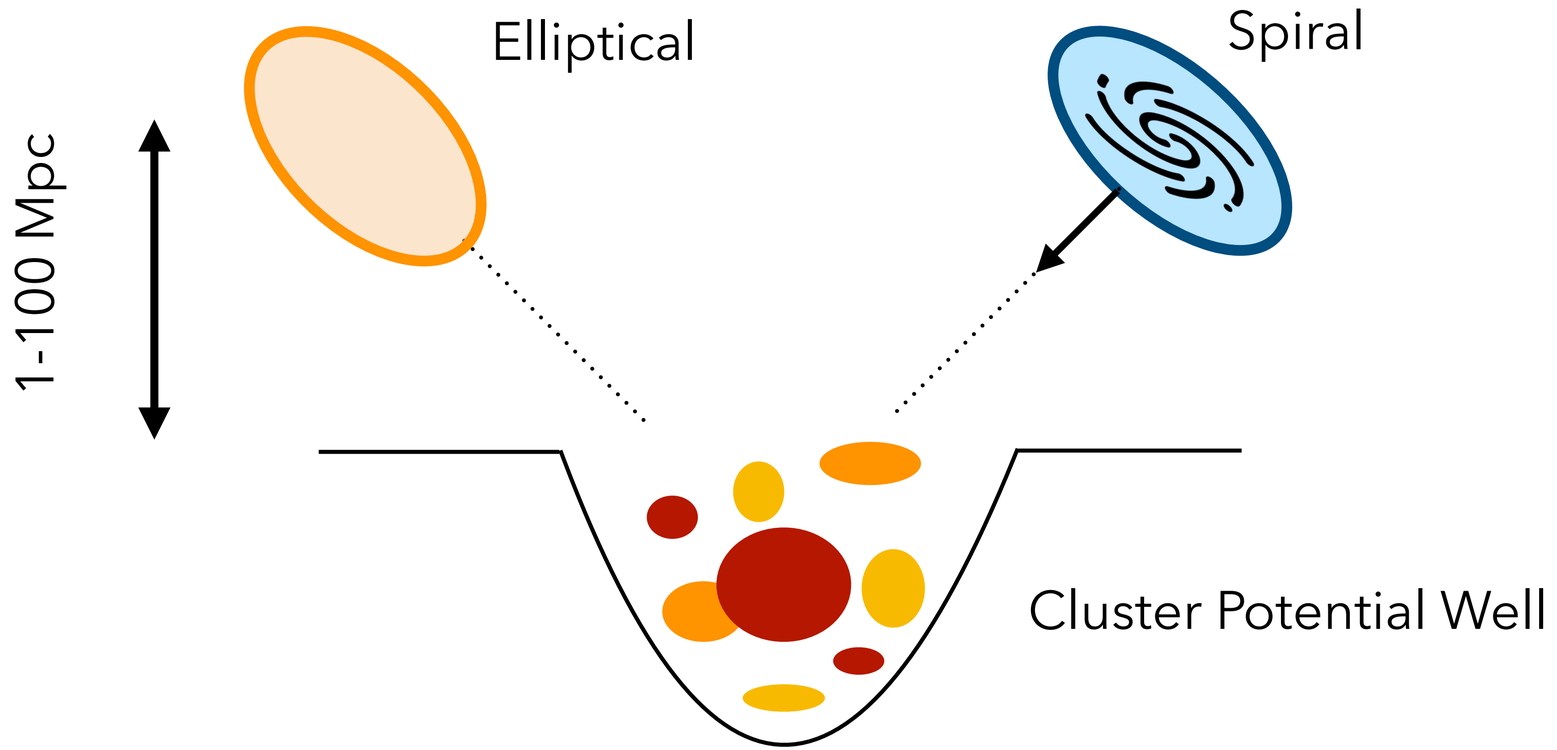
2-point statistics

Cosmology

Intrinsic Alignments

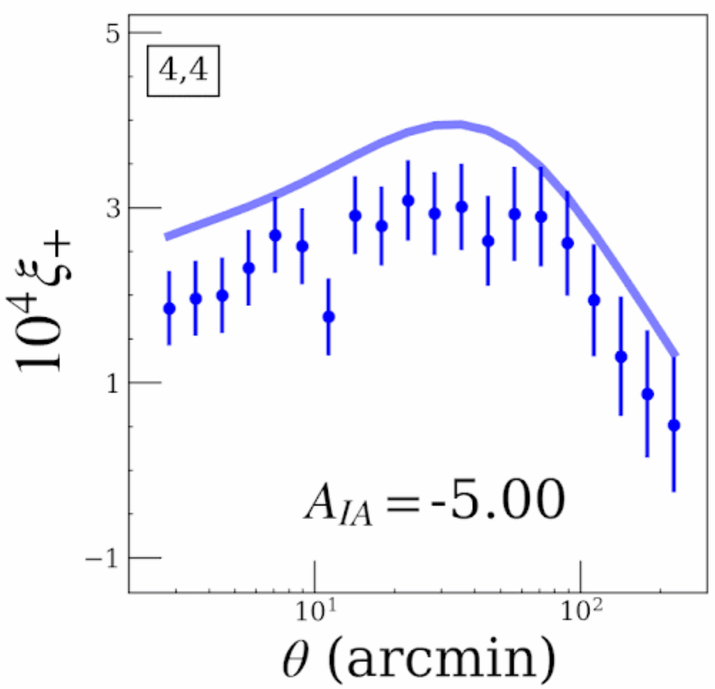
Correlations between galaxy shapes

and their local environments

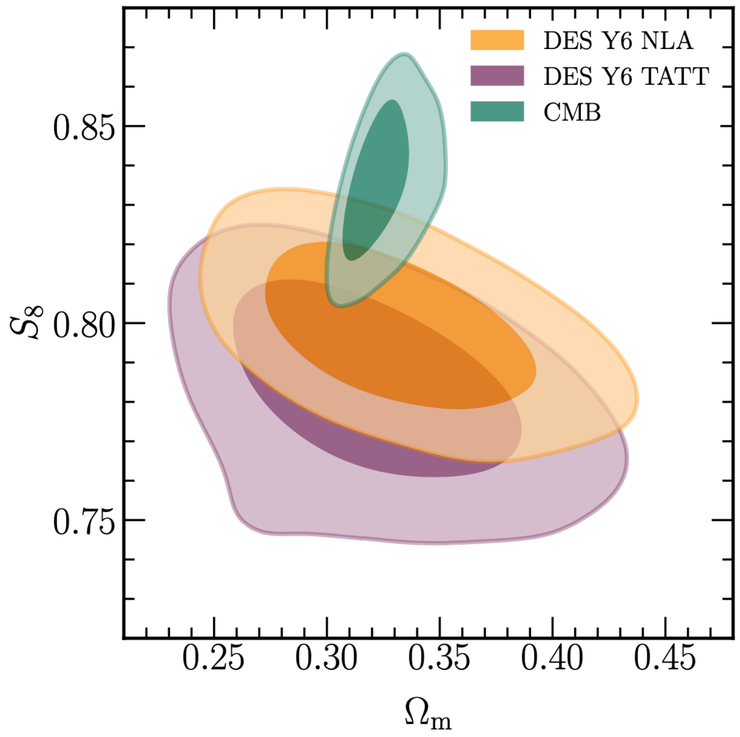


Intrinsic Alignments

Alignments are a source of uncertainty and potential bias



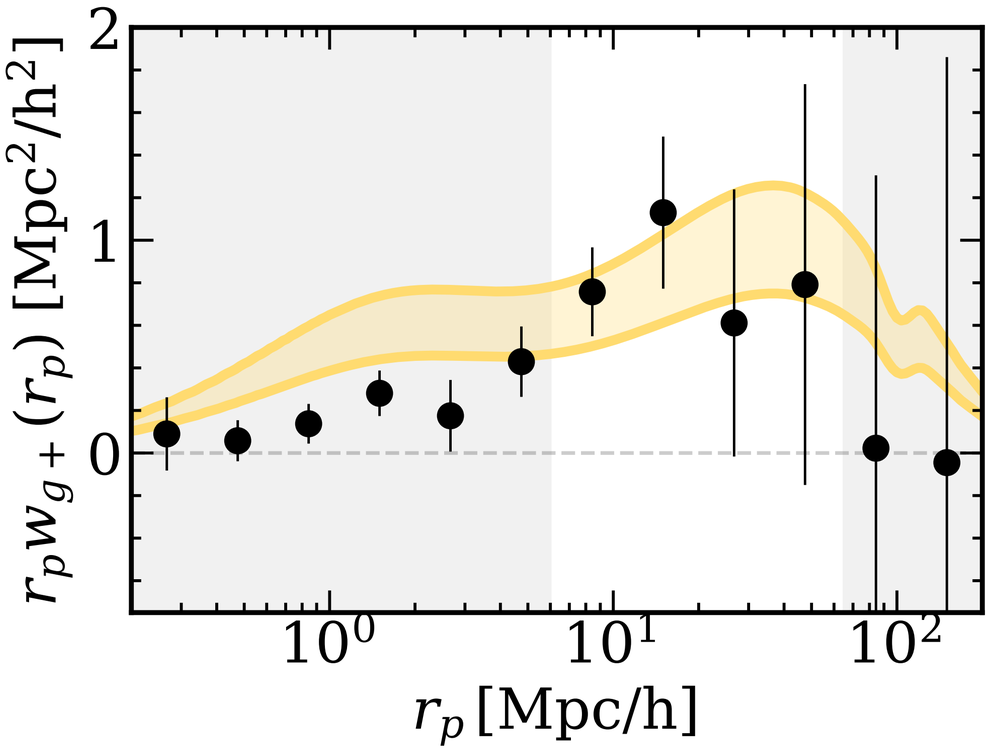
Courtesy of Jamie McCullough



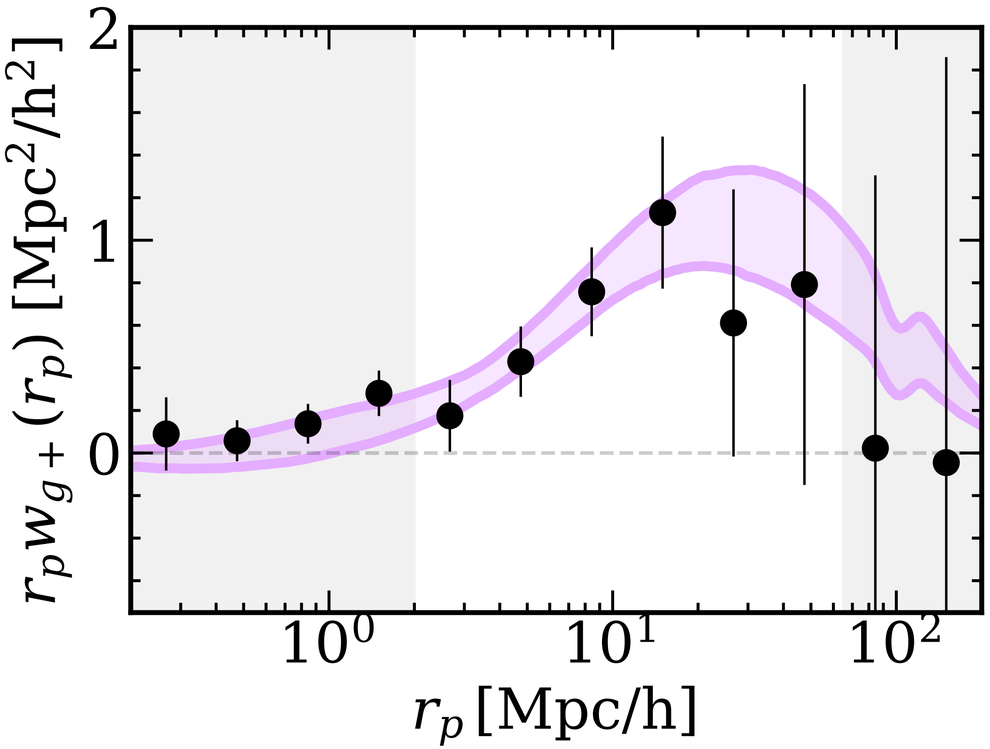
DES Y6 Cosmic Shear

Intrinsic Alignments: Modeling

Non-linear Linear Alignment



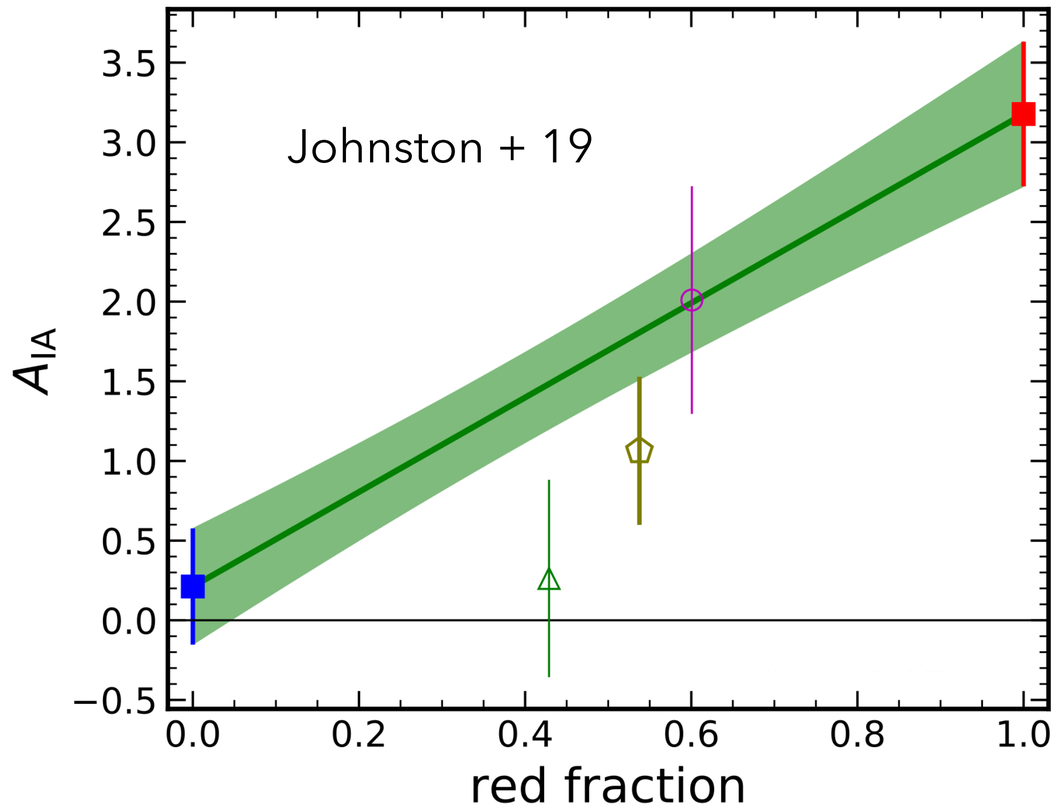
Tidal Alignment and Tidal Torquing



See Lamman+24 & Blazek+25

Intrinsic Alignments: Demographics

Direct measurements reveal how IA depends on galaxy type



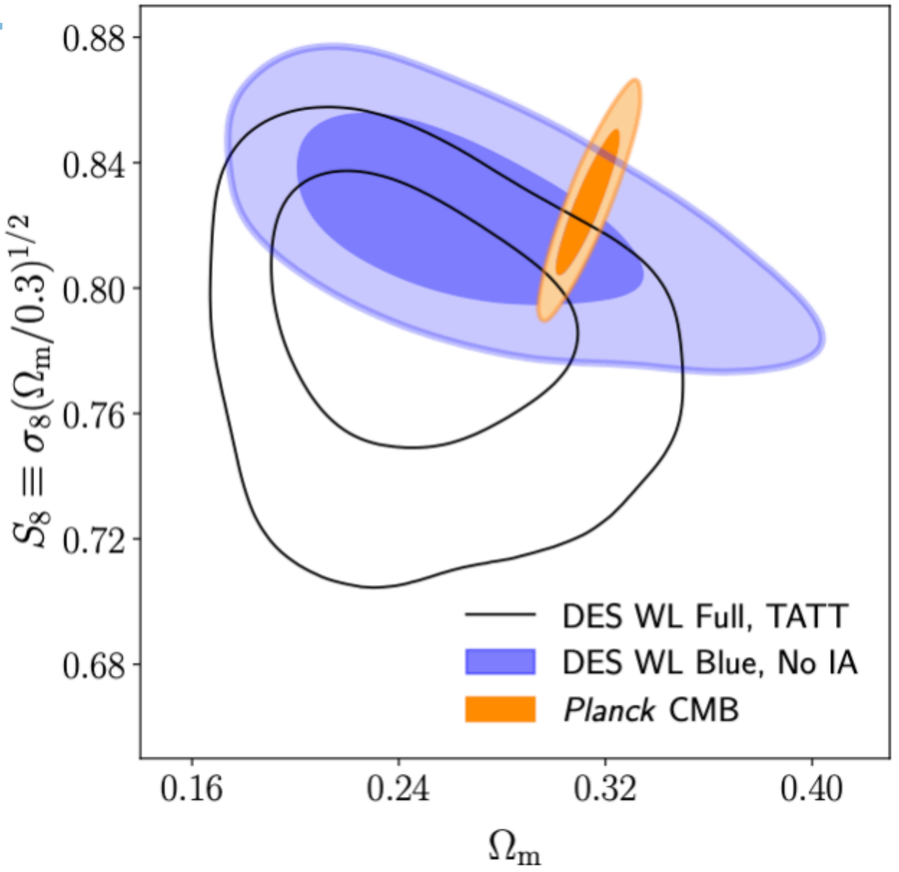
Tailored IA



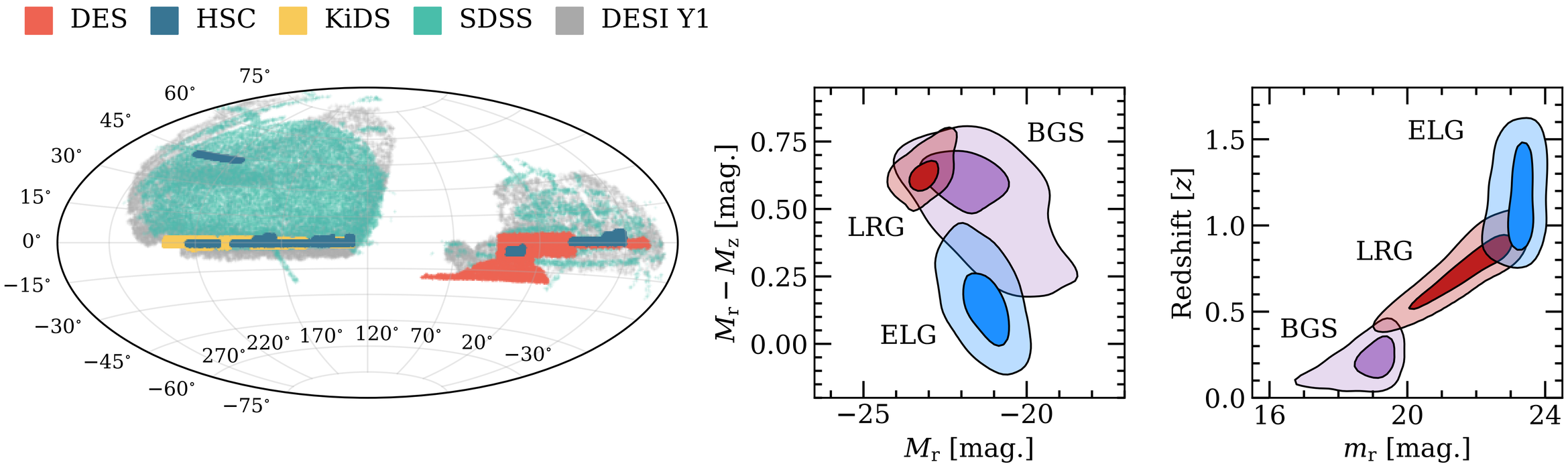
Blue Shear

DES Y3 reanalysis using a pure star forming shape catalog (70% of galaxies)

McCullough + 24



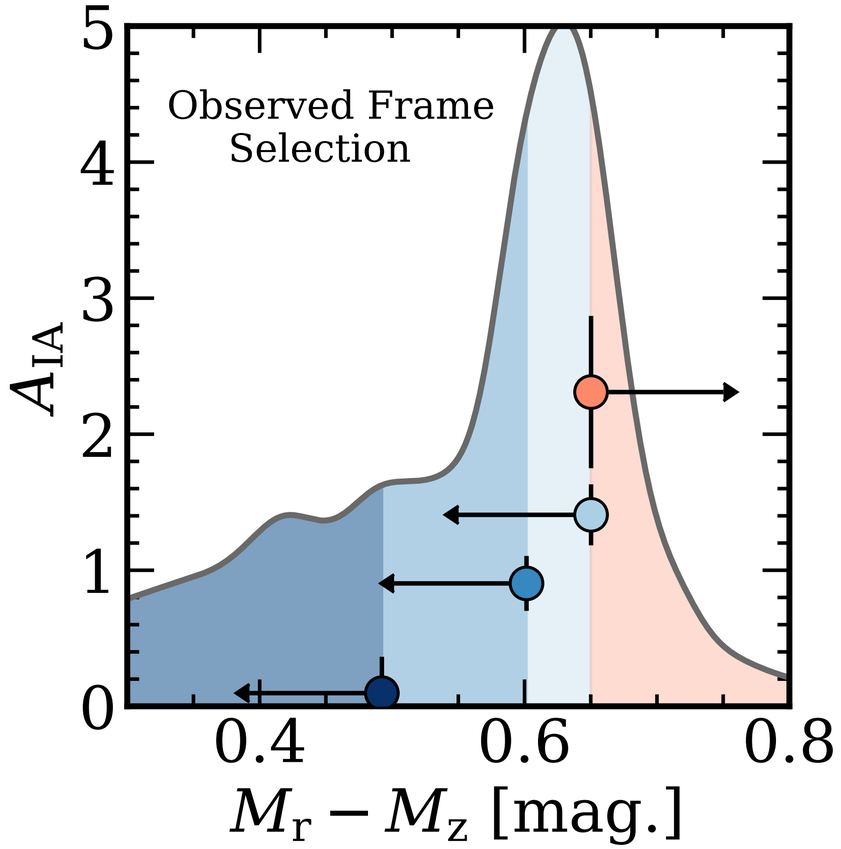
Direct Measurements with DESI

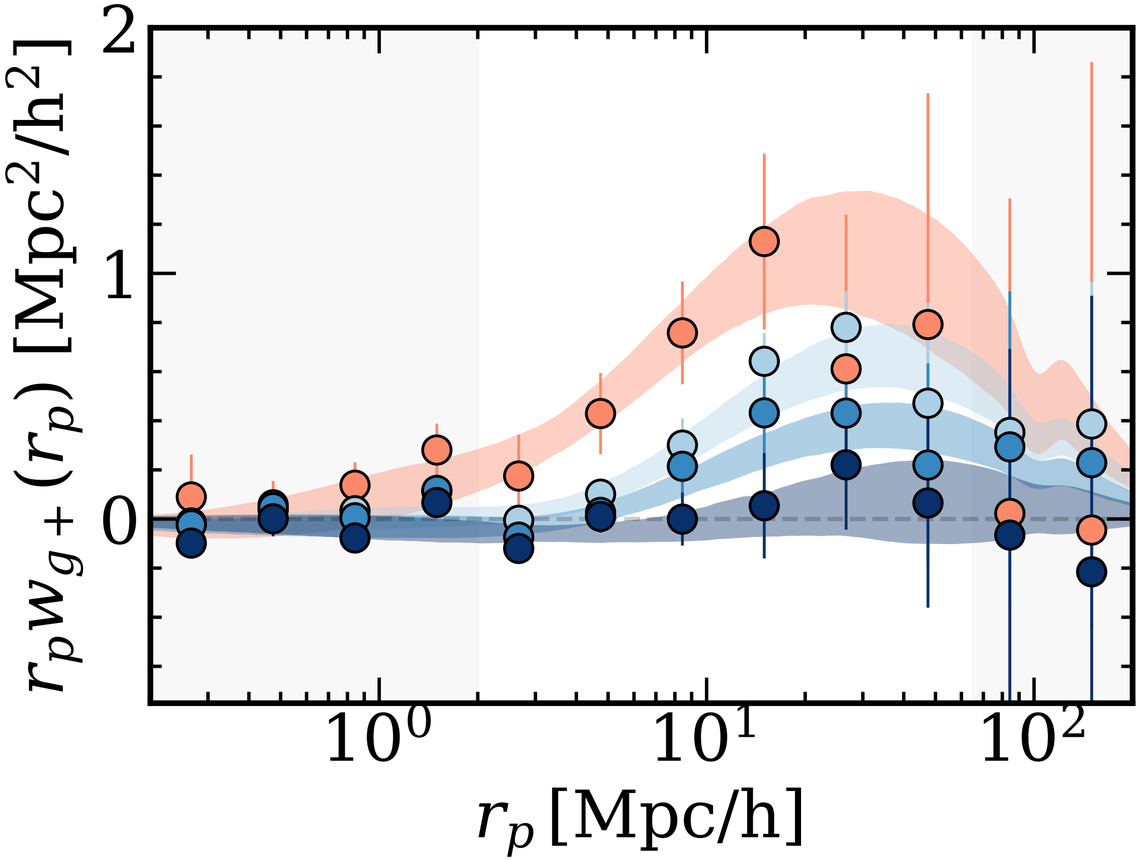


How does alignment depend on galaxy type, mass, and redshift?

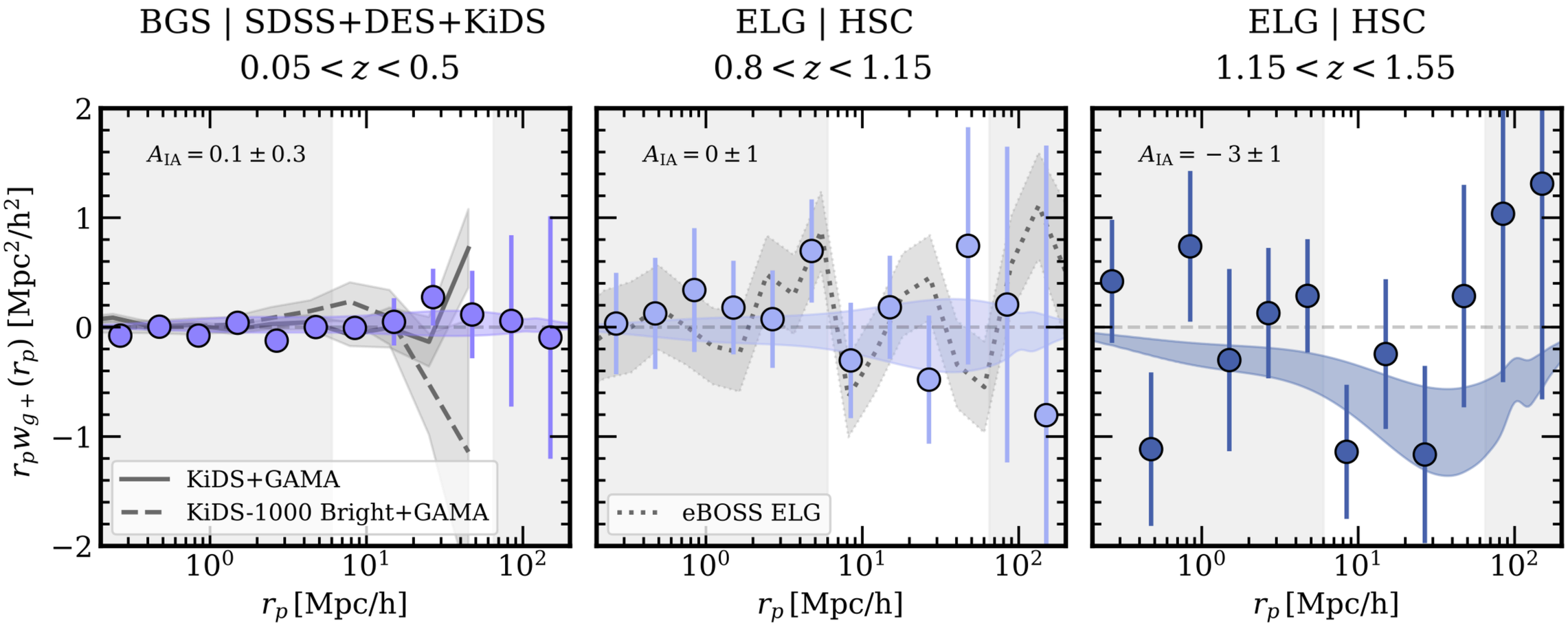
Intrinsic Alignments: DESI DR1

Blue star forming galaxies are minimally aligned





Intrinsic Alignments: DESI DR1

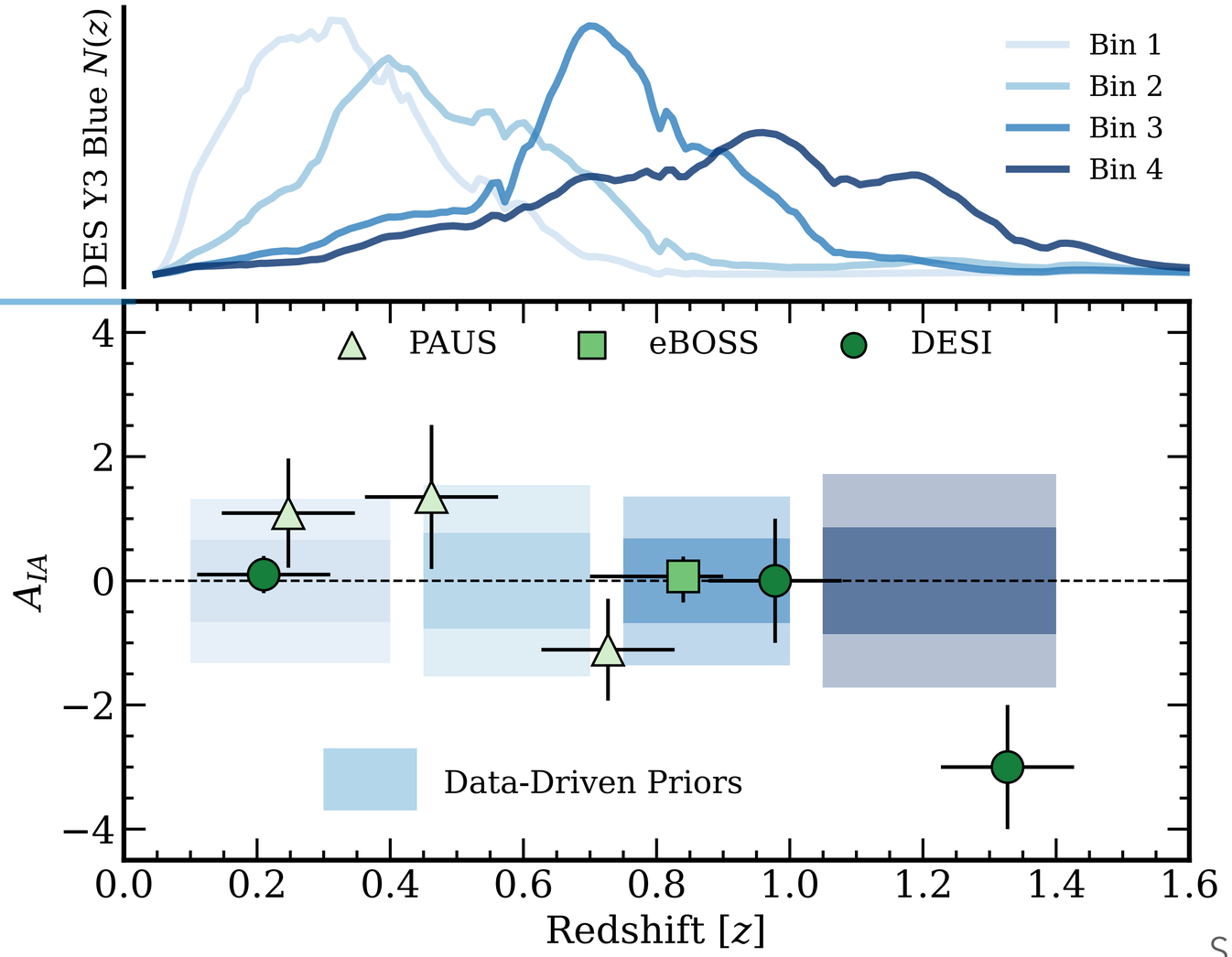


Tailored IA

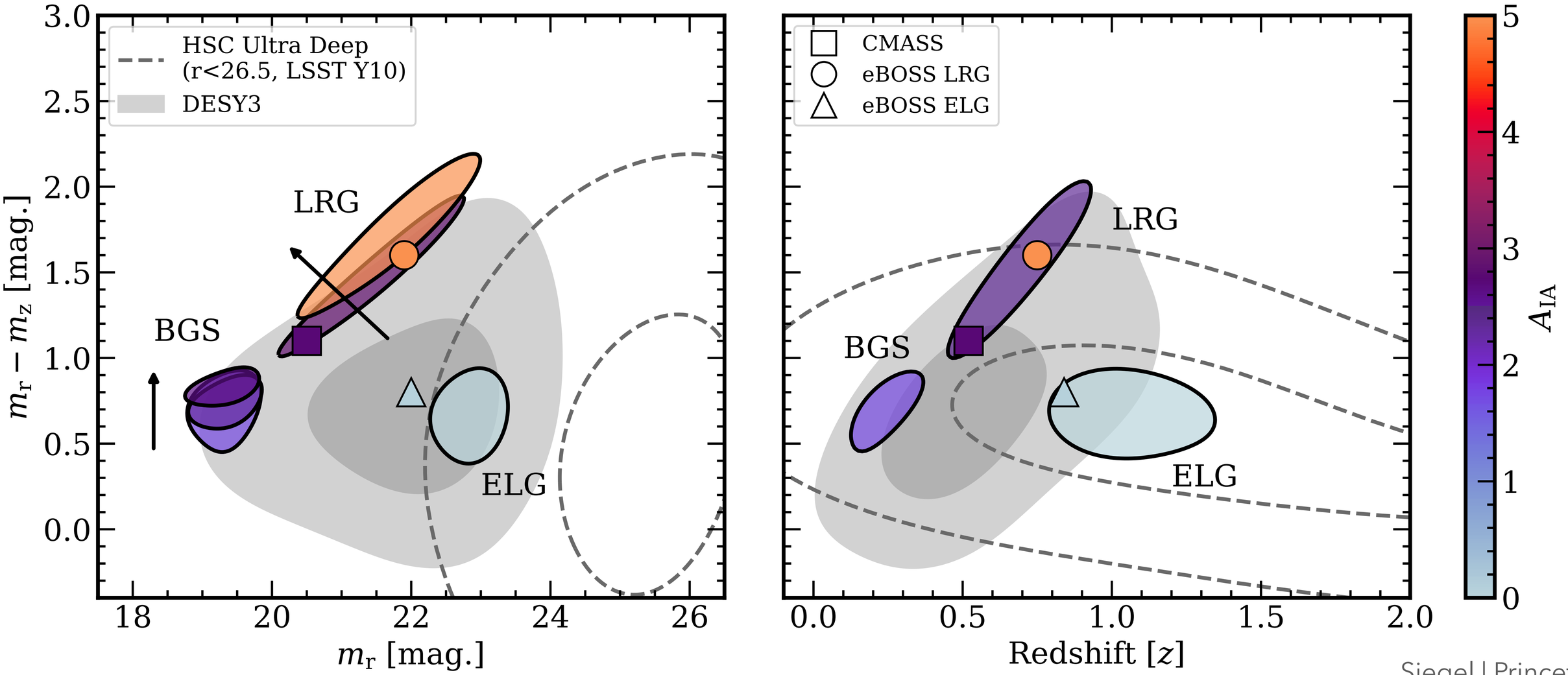


Priors

McCullough, Siegel + in prep



Tailored IA


HSC Ultra Deep
(r<26.5, LSST Y10)
DESY3
LRG
BGS
ELG
$m_r - m_z$ [mag.]
m_r [mag.]
CMASS
eBOSS LRG
eBOSS ELG
Redshift [z]
A_{IA}

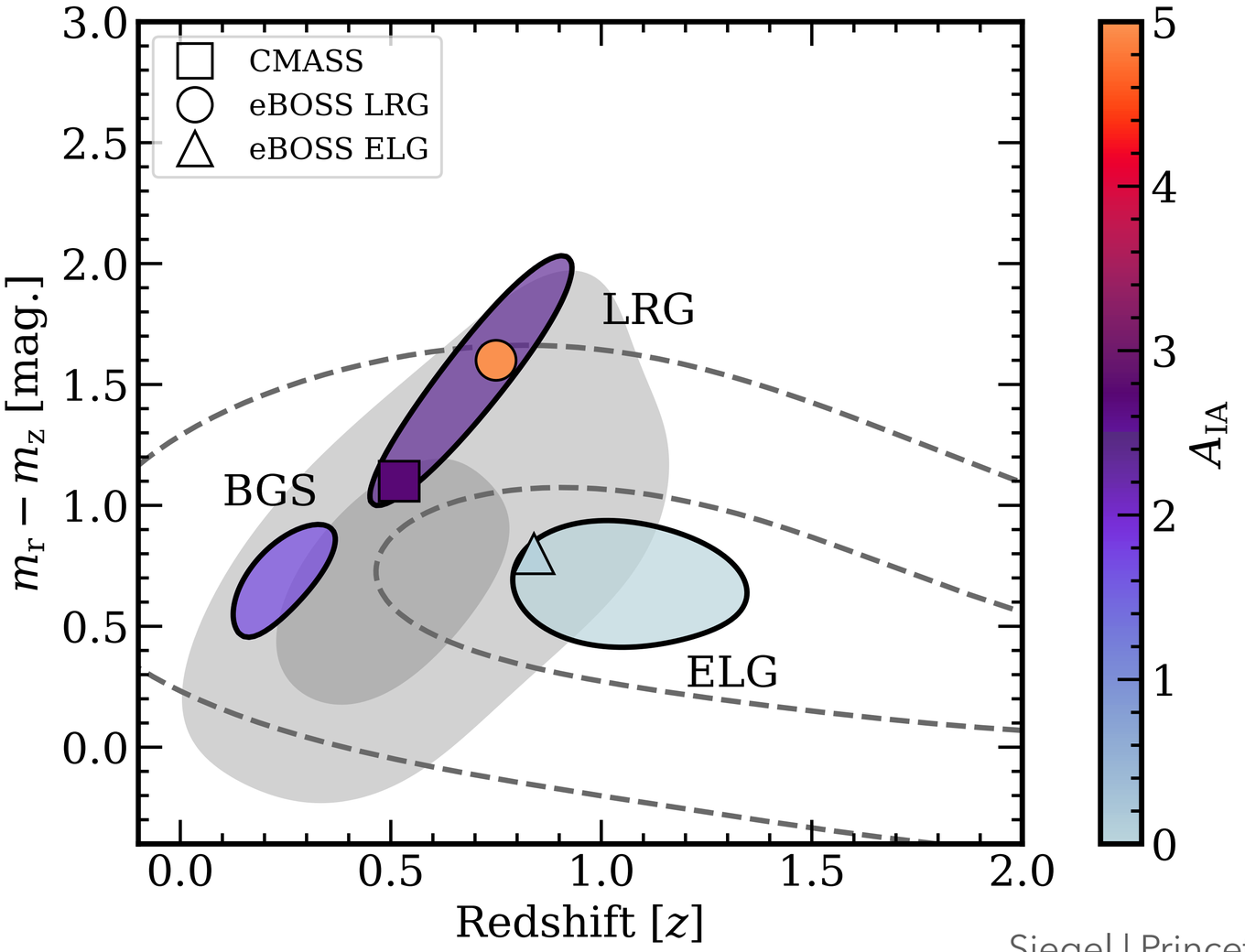
Tailored IA

What's next?

DESI DR2

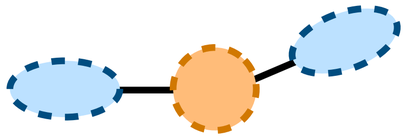
LSST DP2

DESI II



Toward Small Scale Weak Lensing



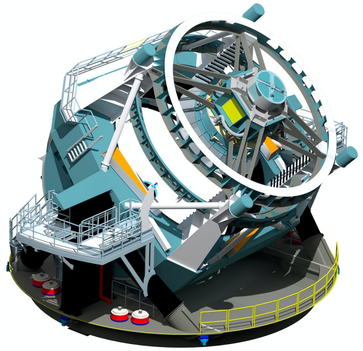


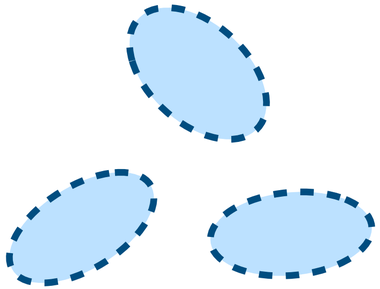


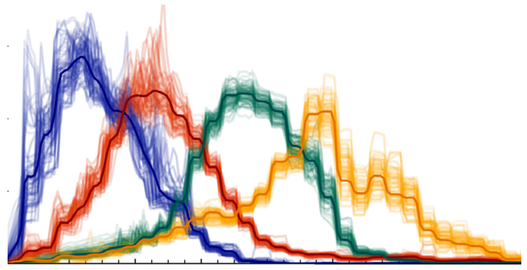


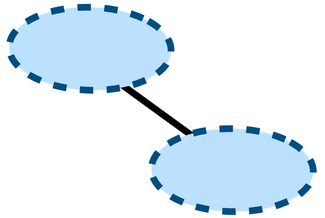
Intrinsic Alignments

Baryon Feedback









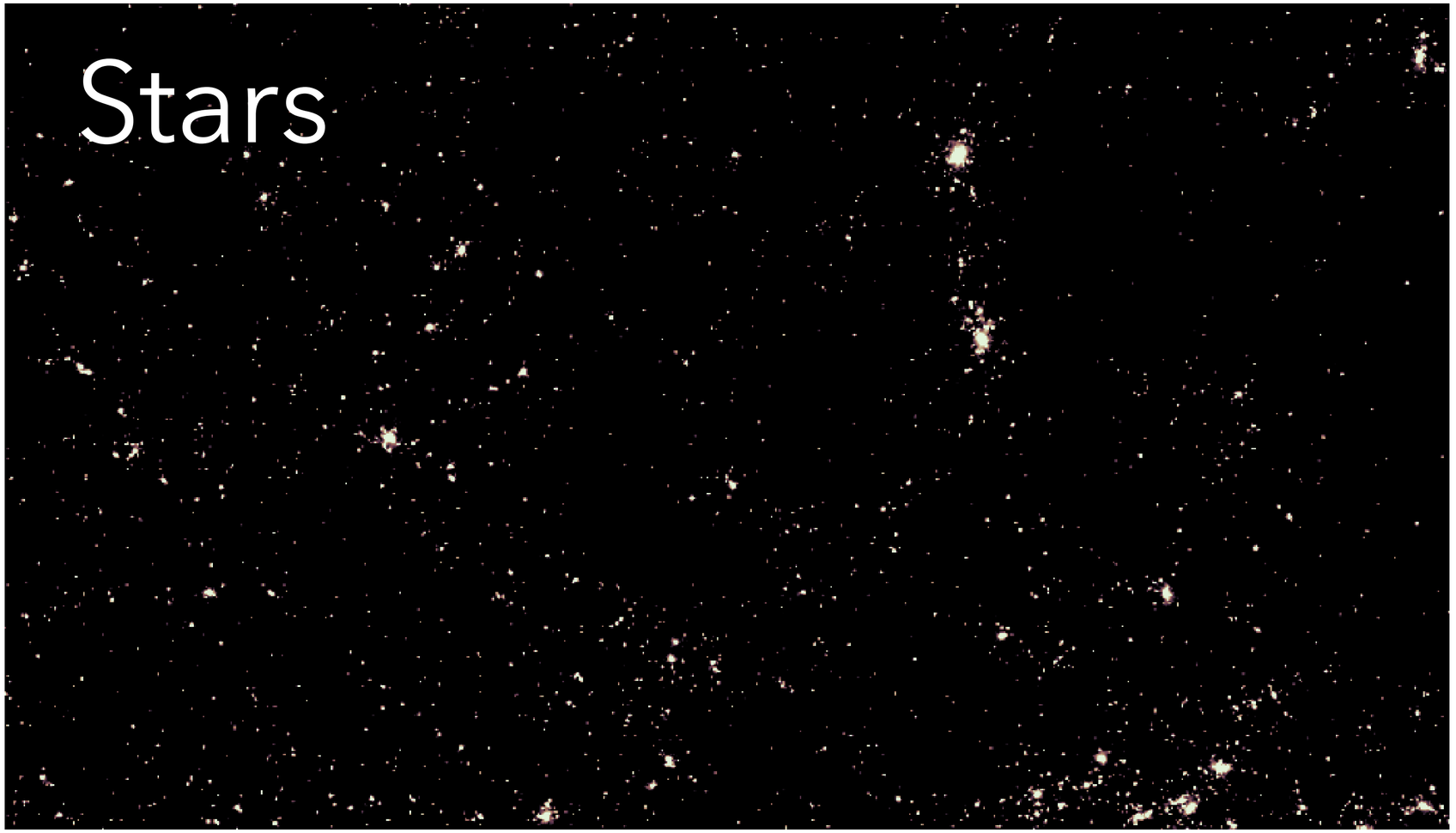
Shape Catalog

Redshift bins

2-point statistics

Cosmology

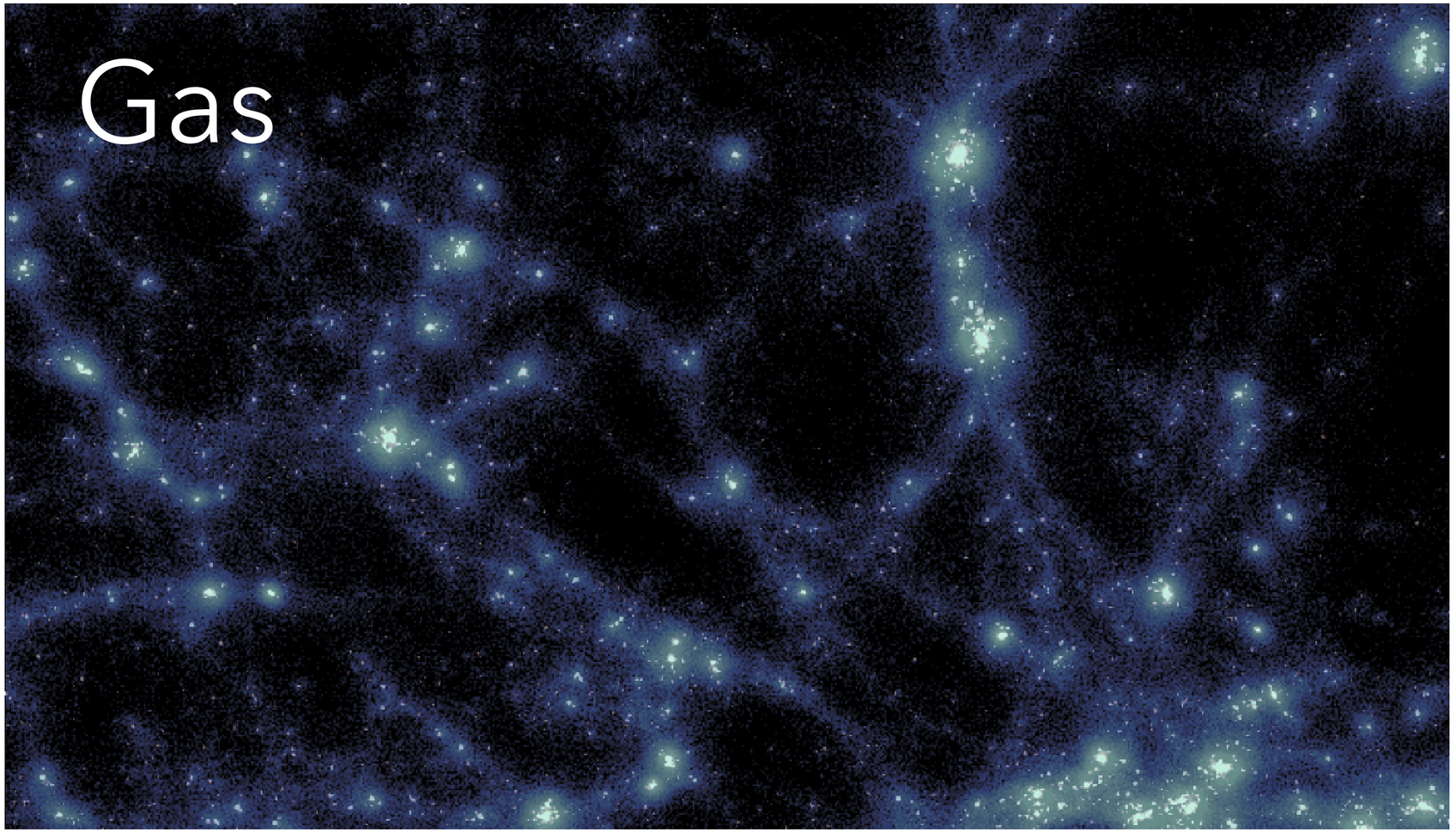
Baryon Feedback



100 Mpc

Schaye et al. 2023

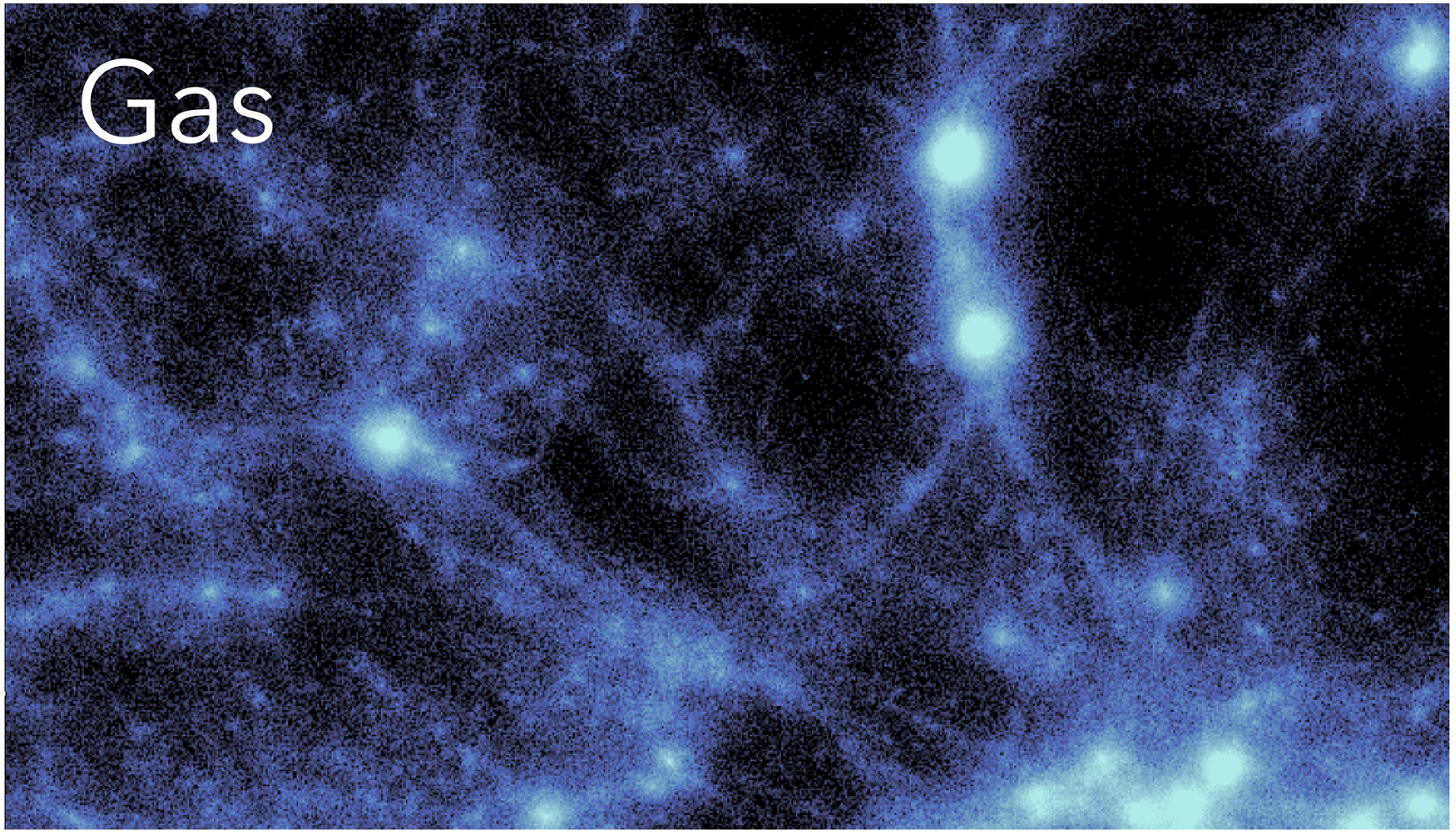
Baryon Feedback



100 Mpc

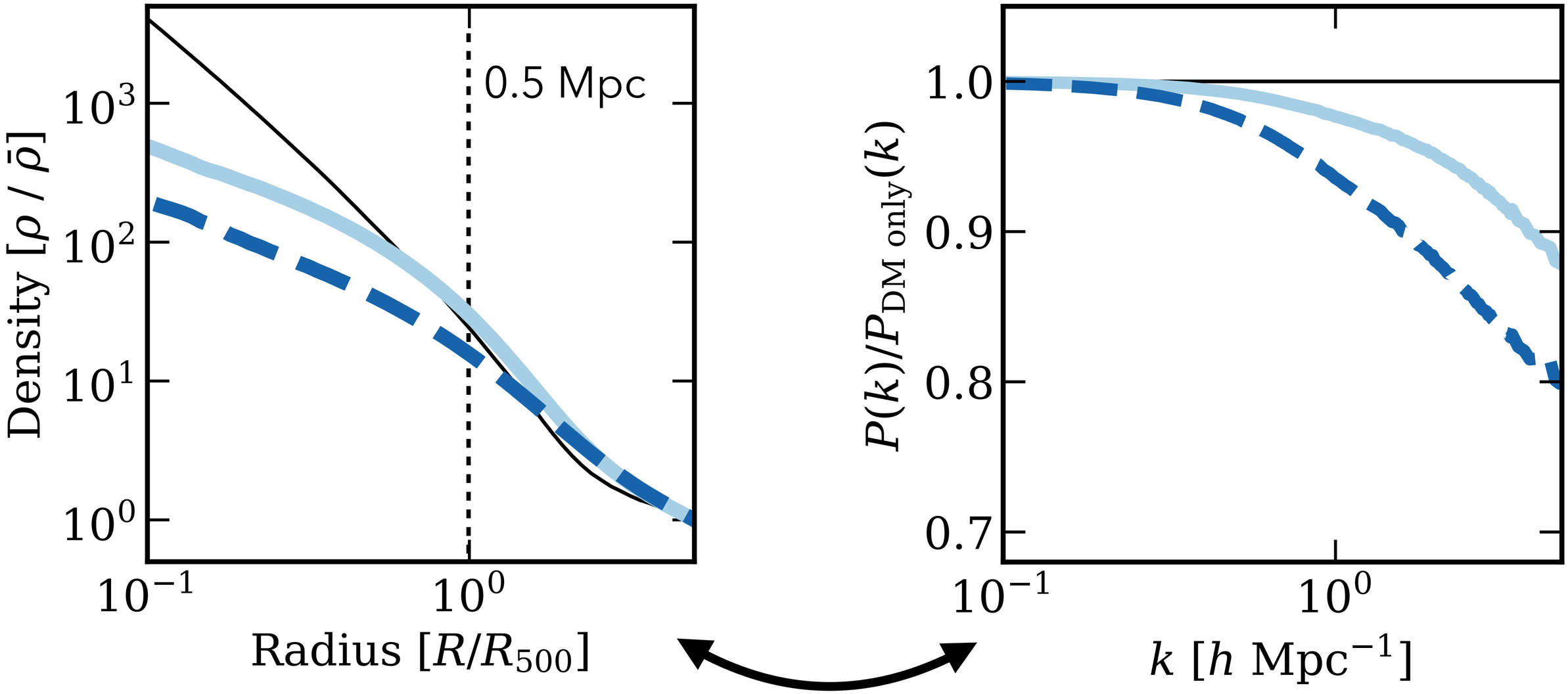
Schaye et al. 2023

Baryon Feedback



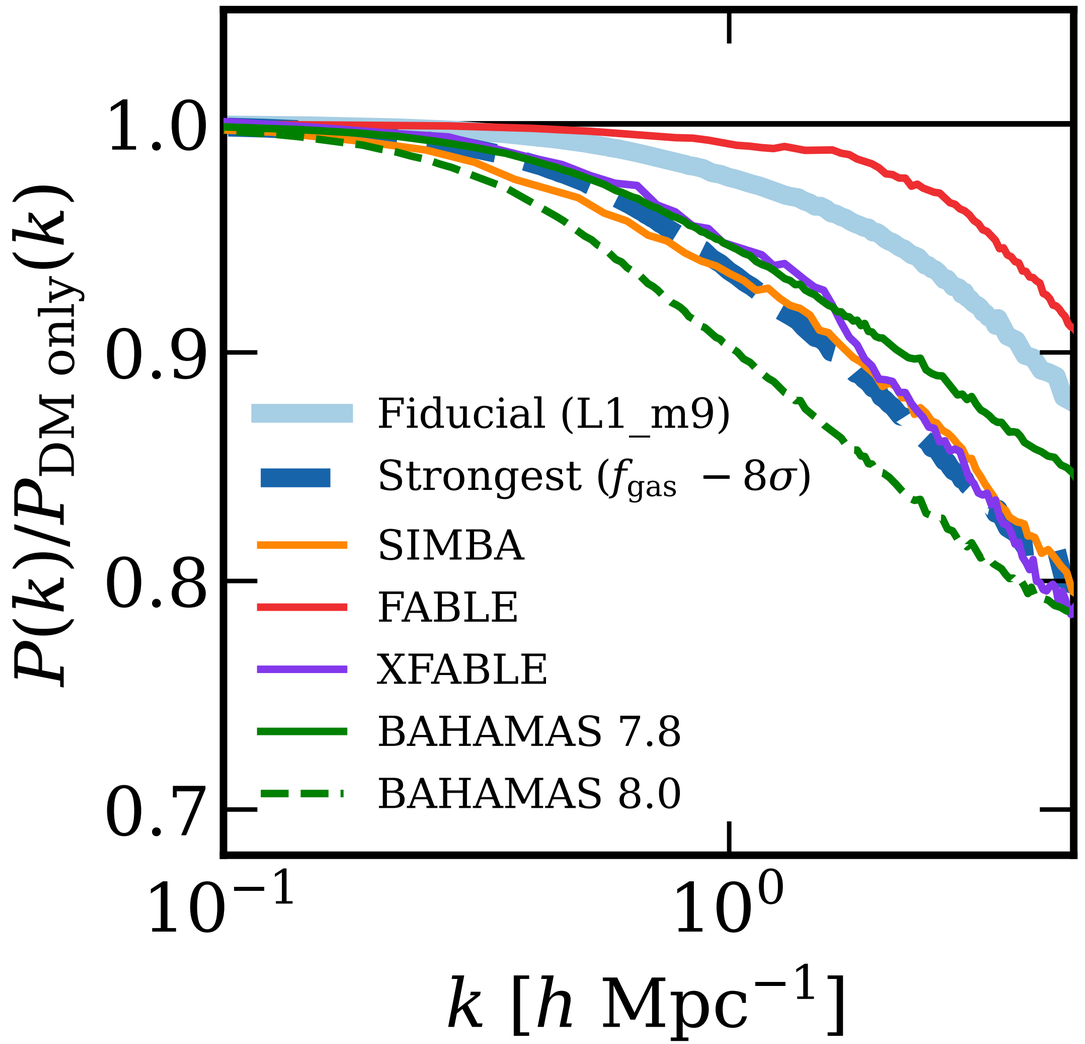
Schaye et al. 2023

Baryon Feedback



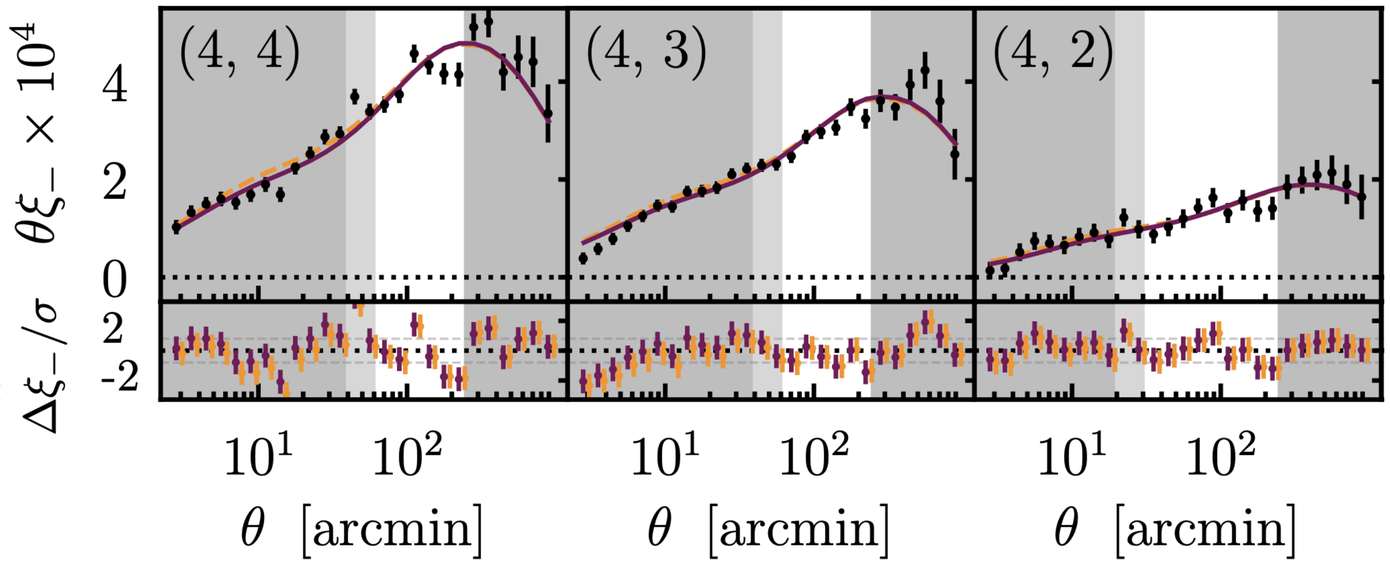
Baryon Feedback

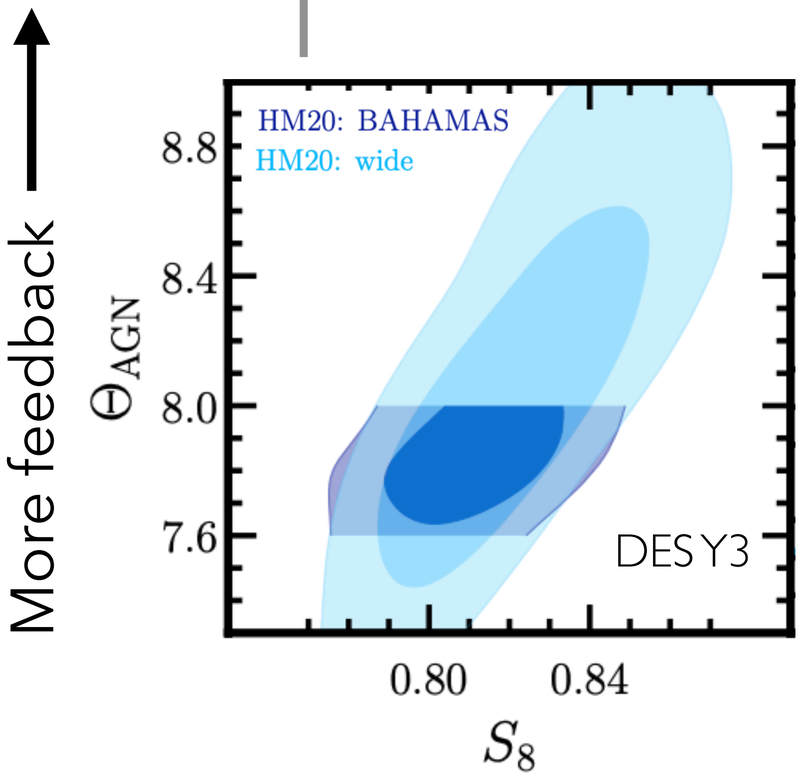
Simulation Predictions



Baryon Feedback

Baryon feedback is a source of **uncertainty** and a potential **bias** for cosmic shear

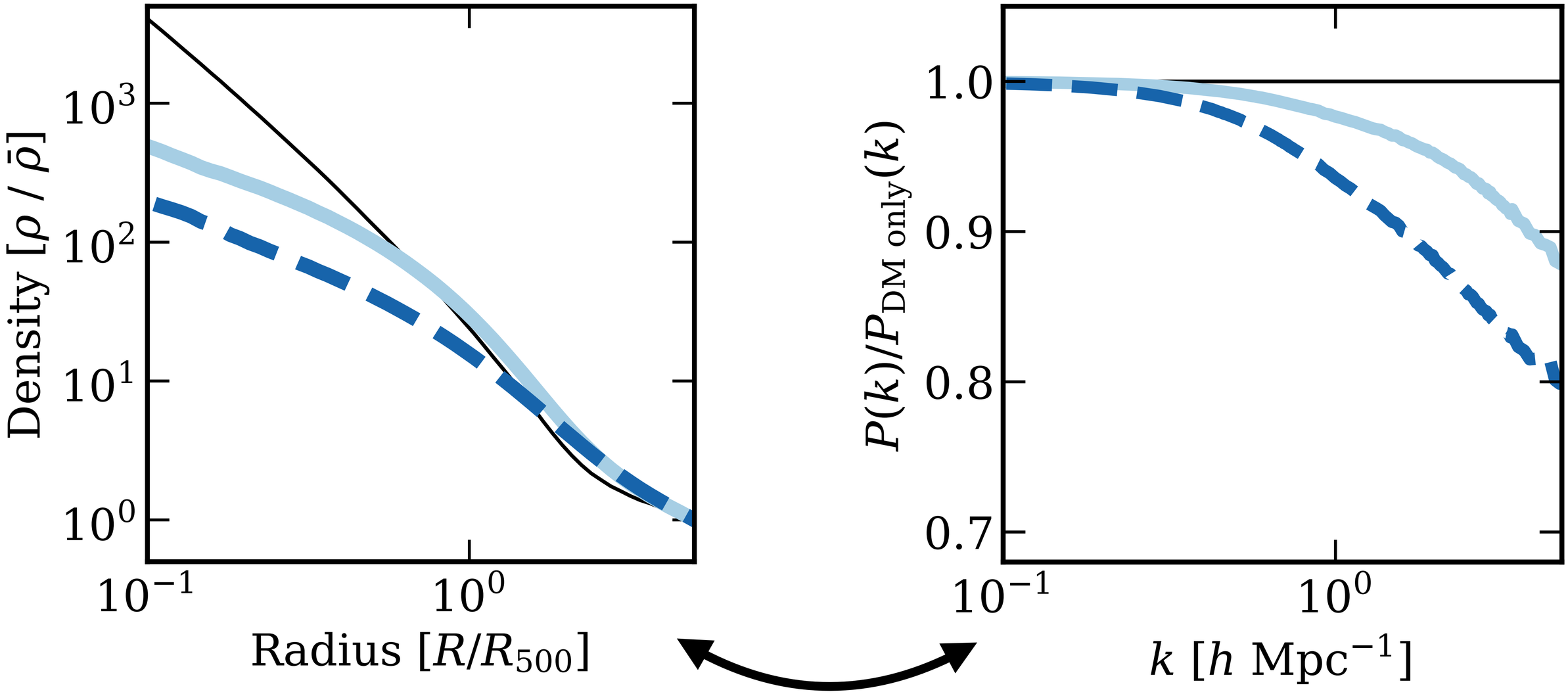


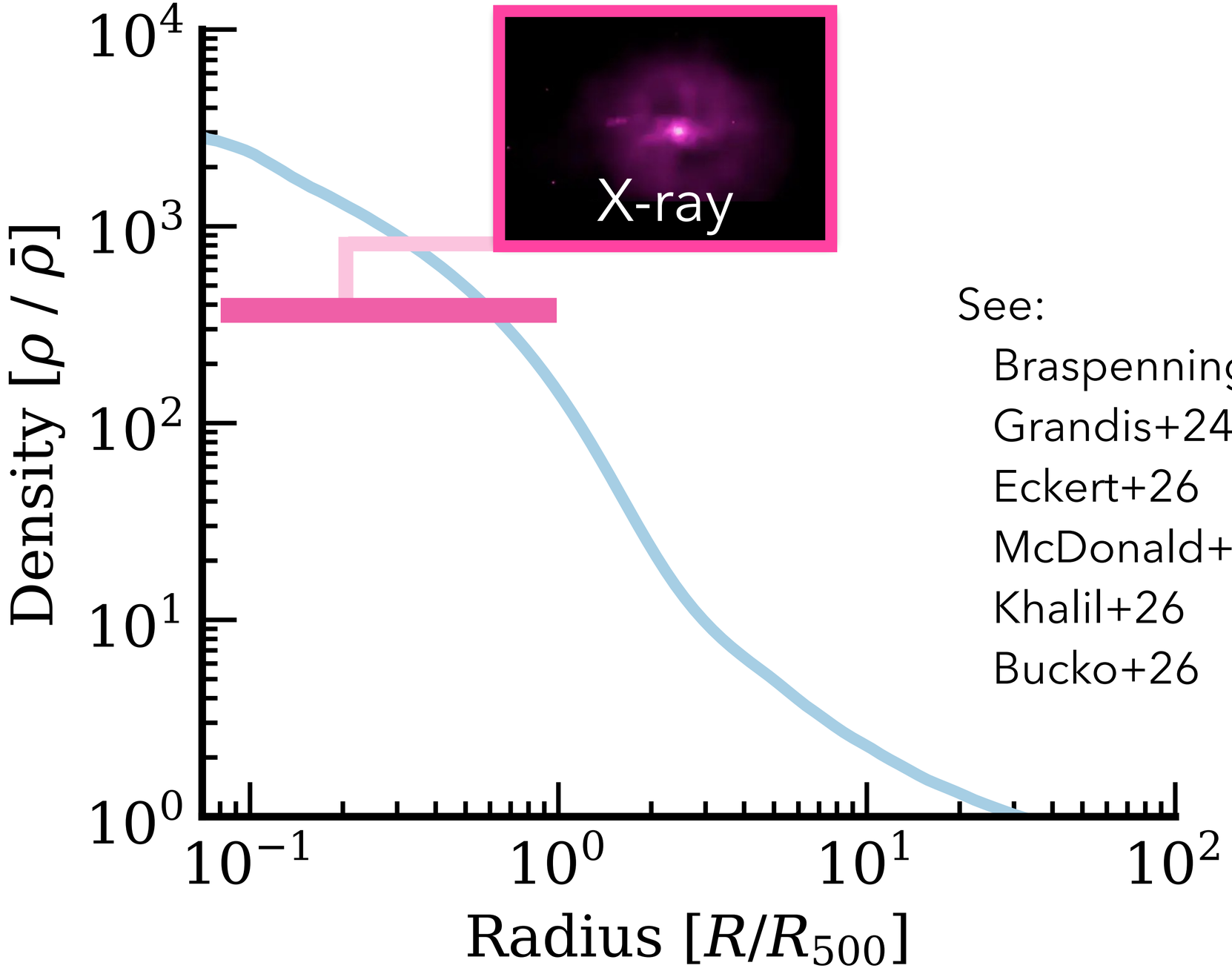


DES Y6 Cosmic Shear

Bigwood+24

Baryon Feedback





See:

Braspenning+24

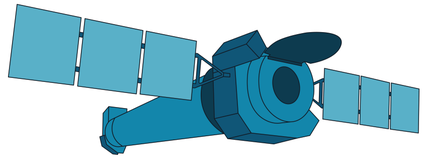
Grandis+24

Eckert+26

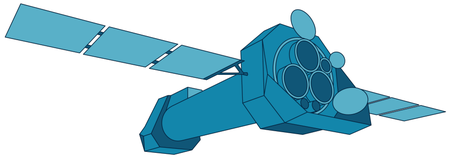
McDonald+26

Khalil+26

Bucko+26

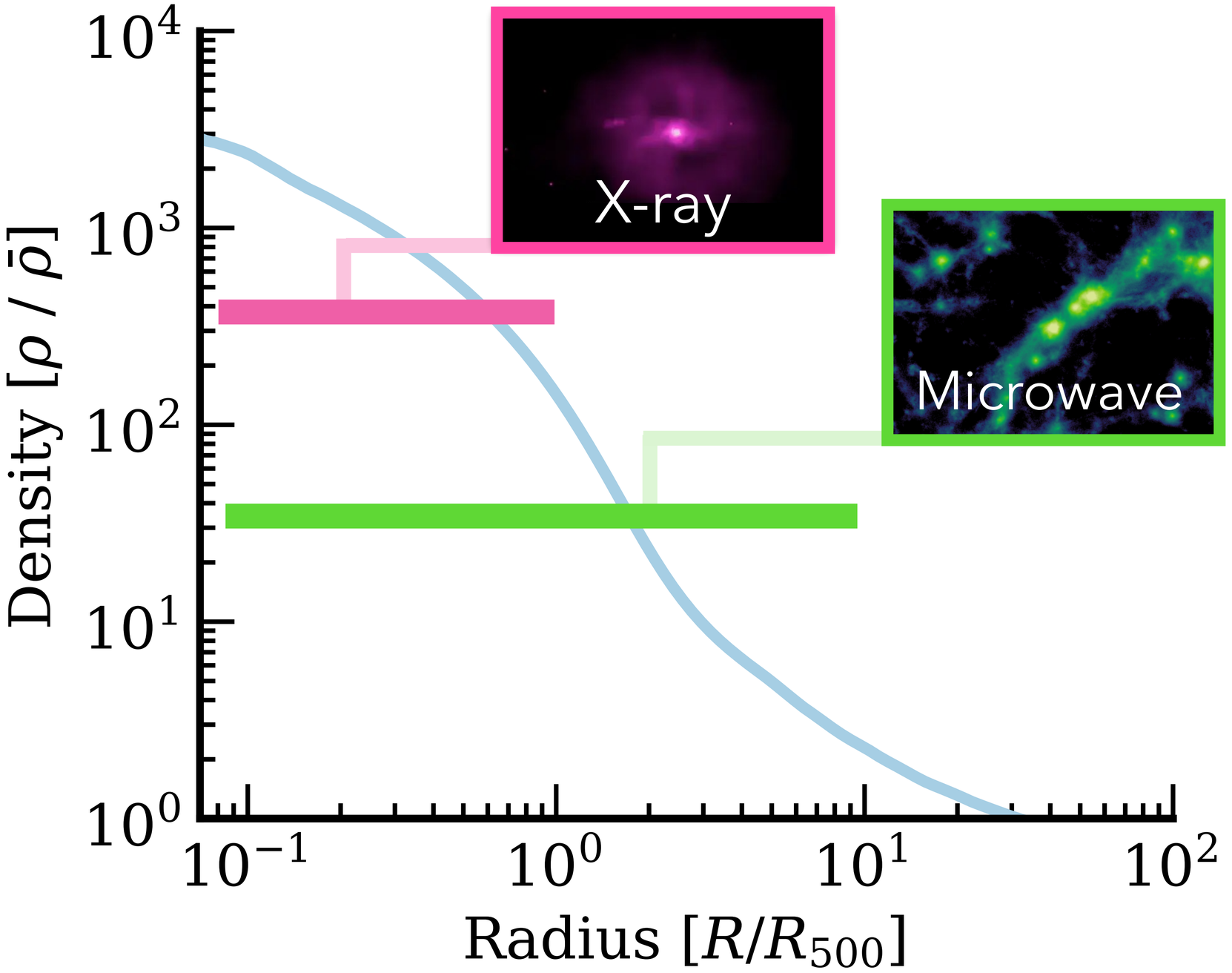


Chandra



XMM-Newton

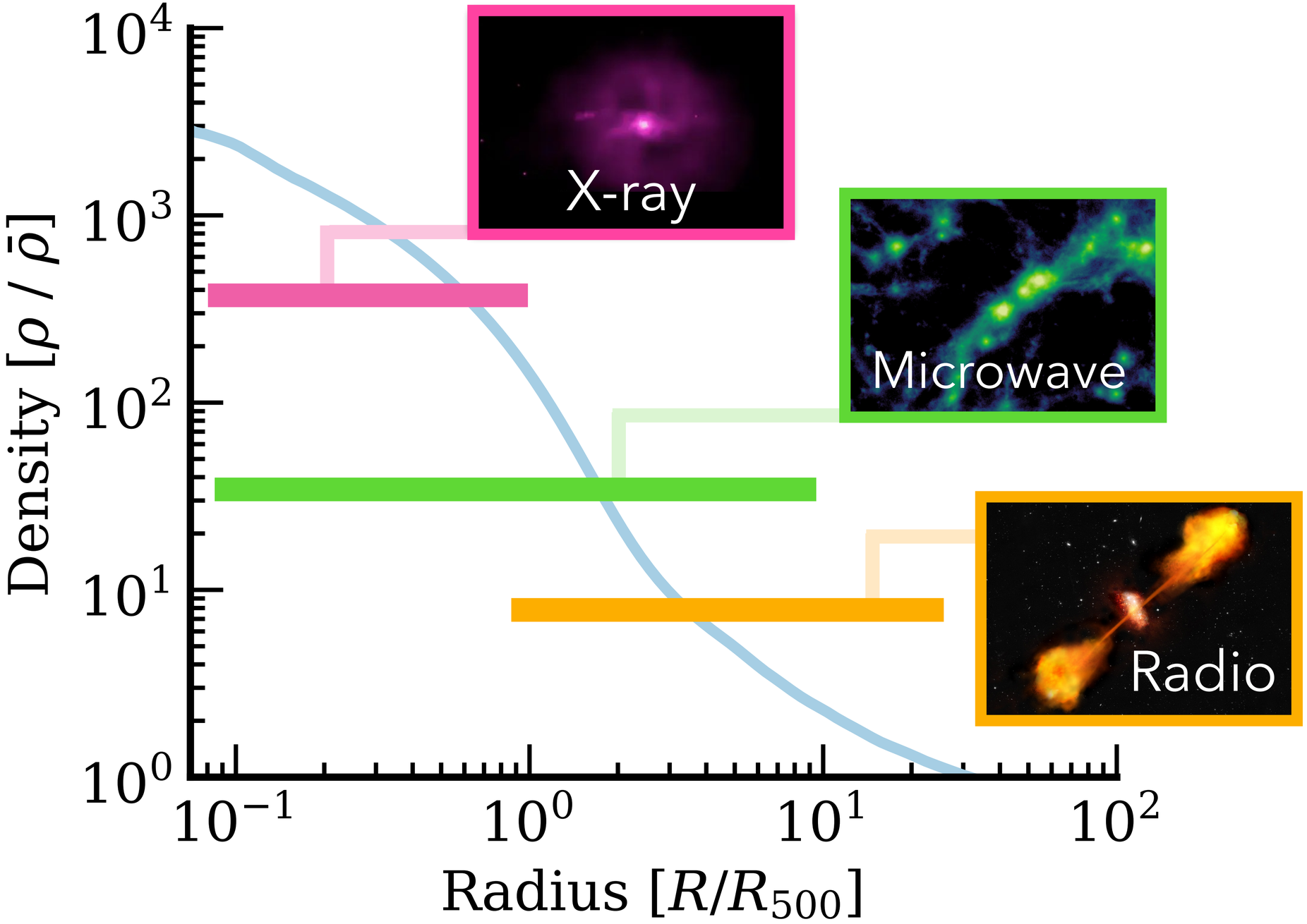
eROSITA



SDSS

DESI

ACT







See:

Sharma+26

McCarty+26

Reischke+26

Leung+25

How do we use these new observations?

Simulation forward modeling

Siegel+25a arXiv:2509.10455

Semi-analytic modeling

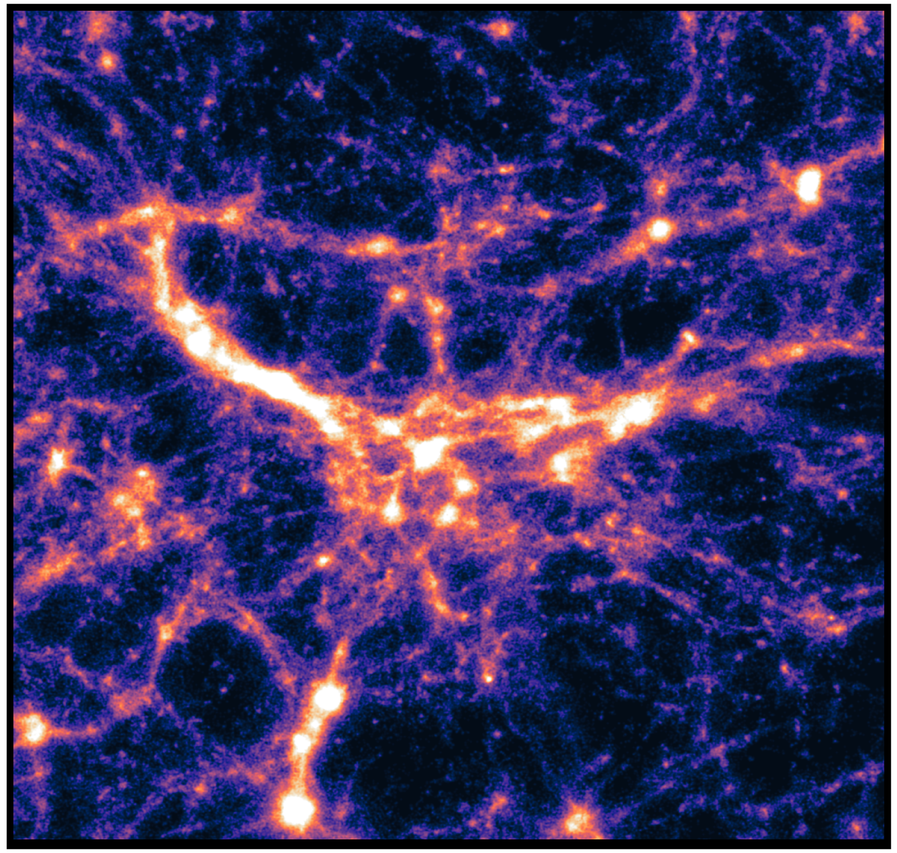
Siegel+25b arXiv:2512.02954

FLAMINGO simulations

$1\ \mathrm{Gpc}^3$ boxes

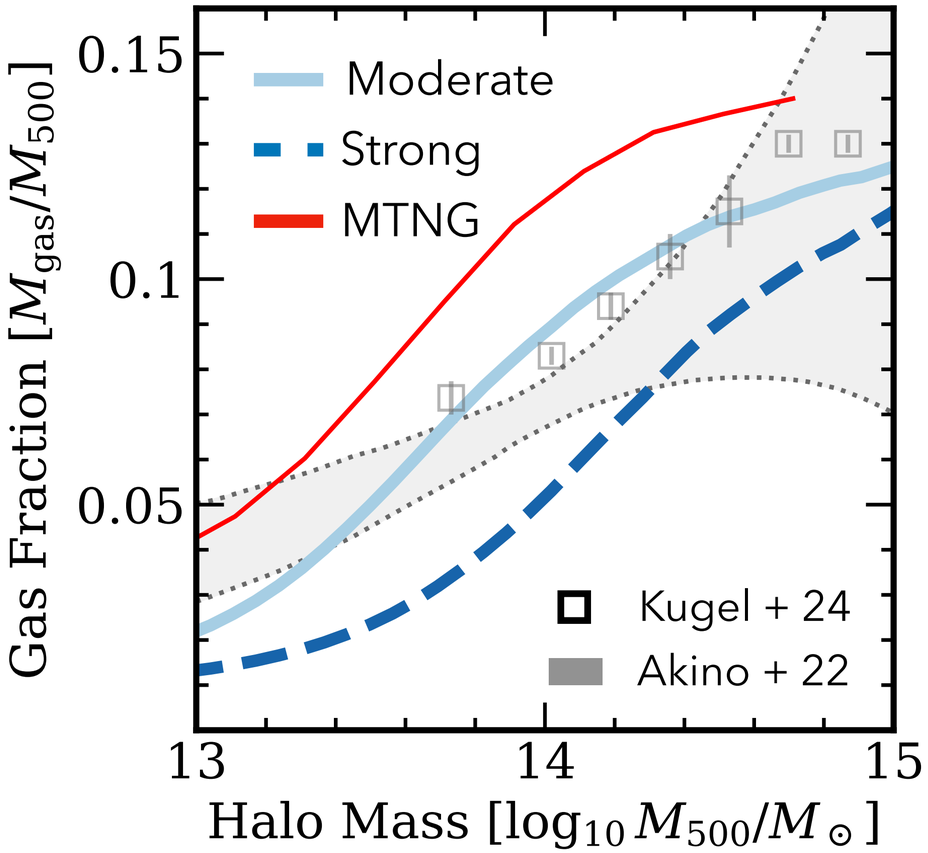
Calibrated to SHMR &
group and cluster gas fractions

8 different feedback variants

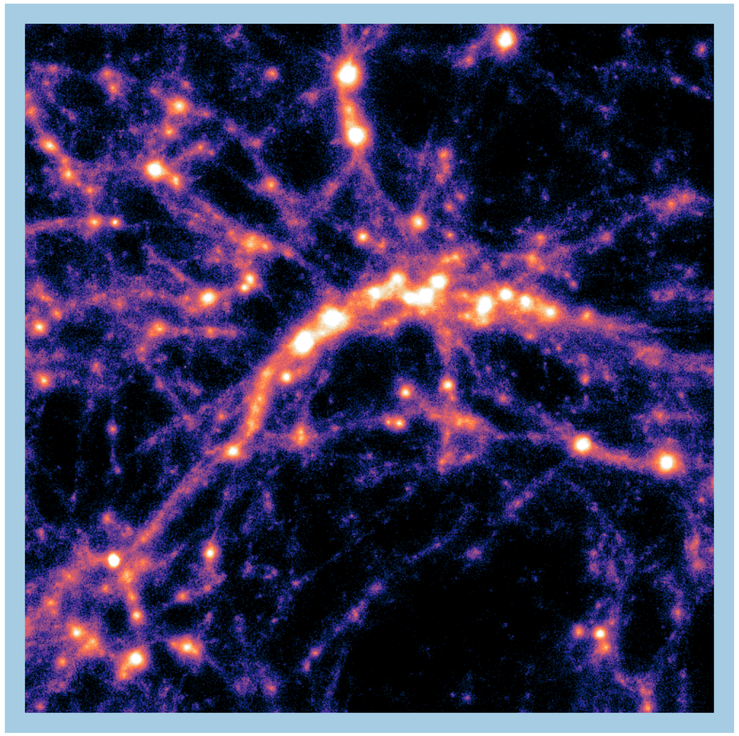


Schaye et al. 2023

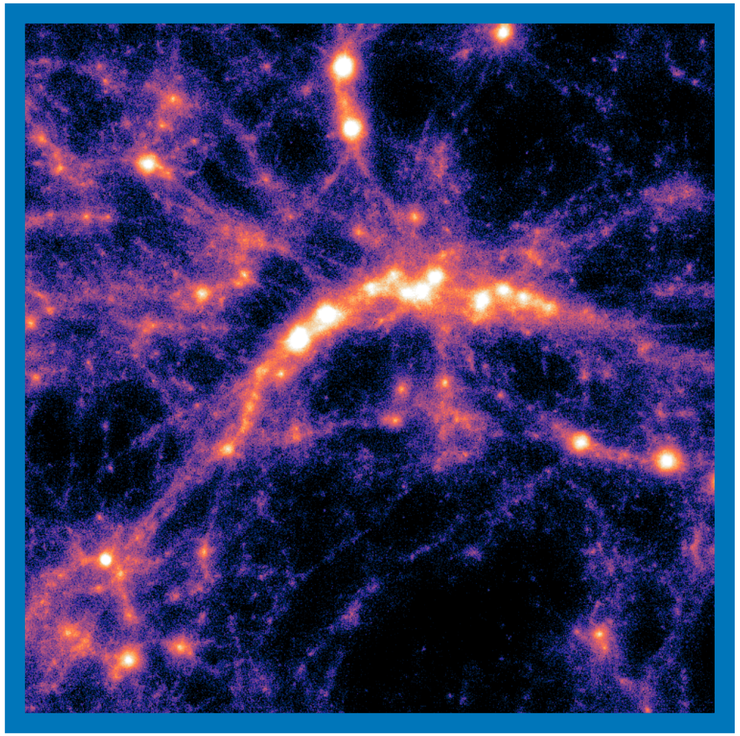
FLAMINGO simulations



Moderate Feedback

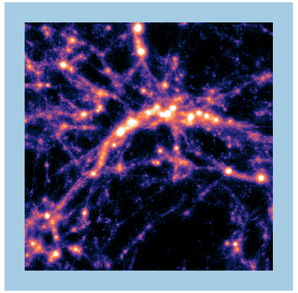


Strong Feedback



100 Mpc

The Many Faces of FLAMINGO

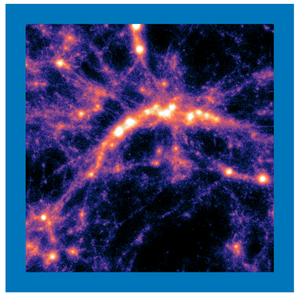


Moderate Feedback

X-ray L-T: Braspenning+25

Diffuse X-ray: McDonald+26

$\Delta\Sigma$ Filtered kSZ: Liu+26



Strong Feedback

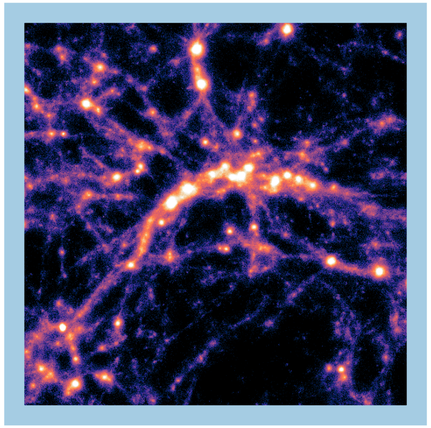
CAP kSZ: McCarthy+25

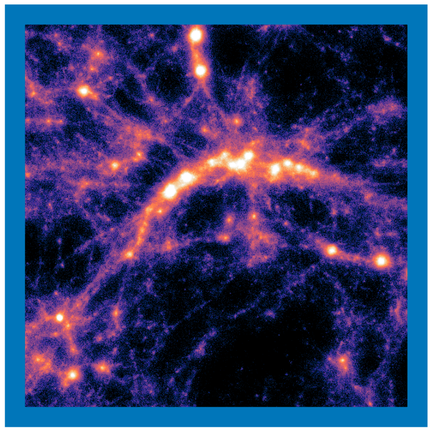
FRB Cross-correlations: McCarthy+26

eROSTIA X-ray: Bucko+26

Mulit-probe Emulator

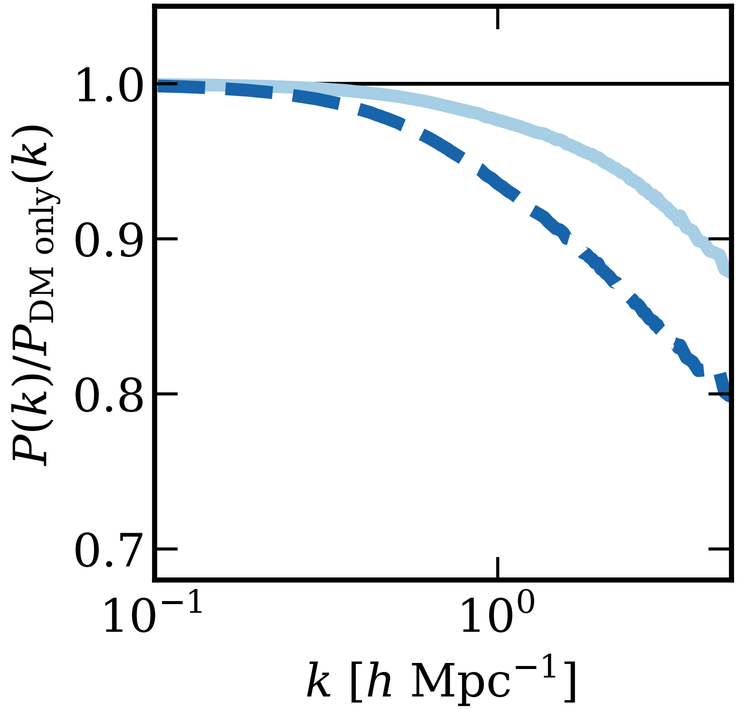






Observables

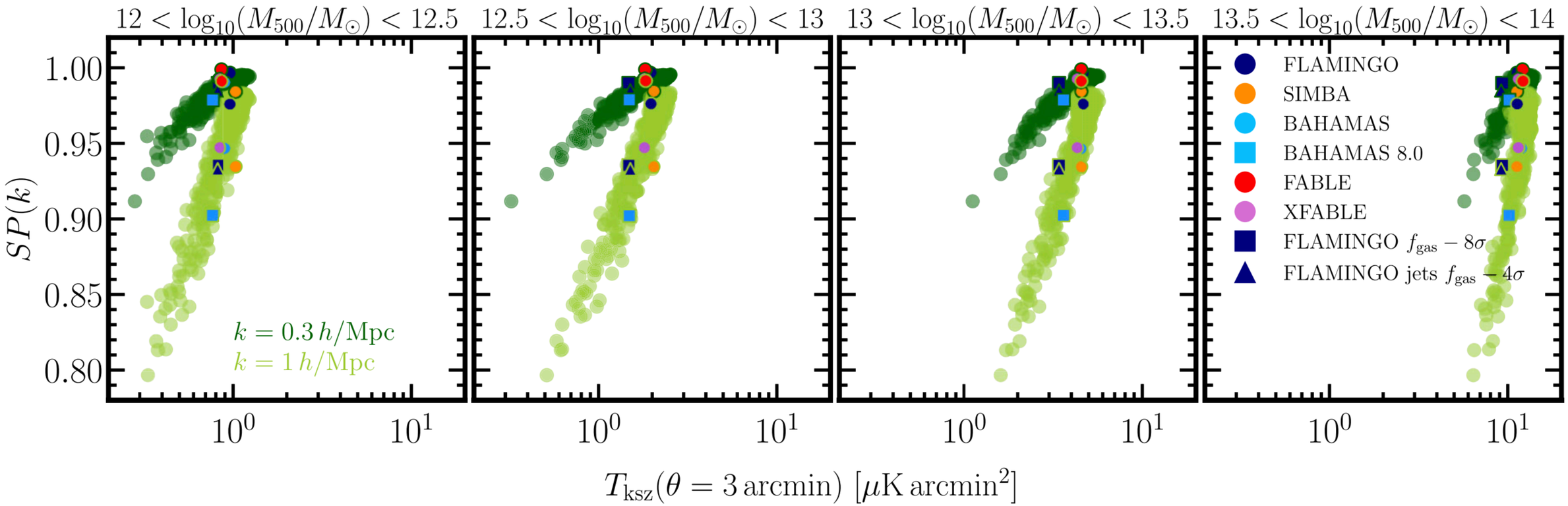
X-ray
+
kSZ
+
FRB
+
GGL
+
Clustering



From Observables to P(k)



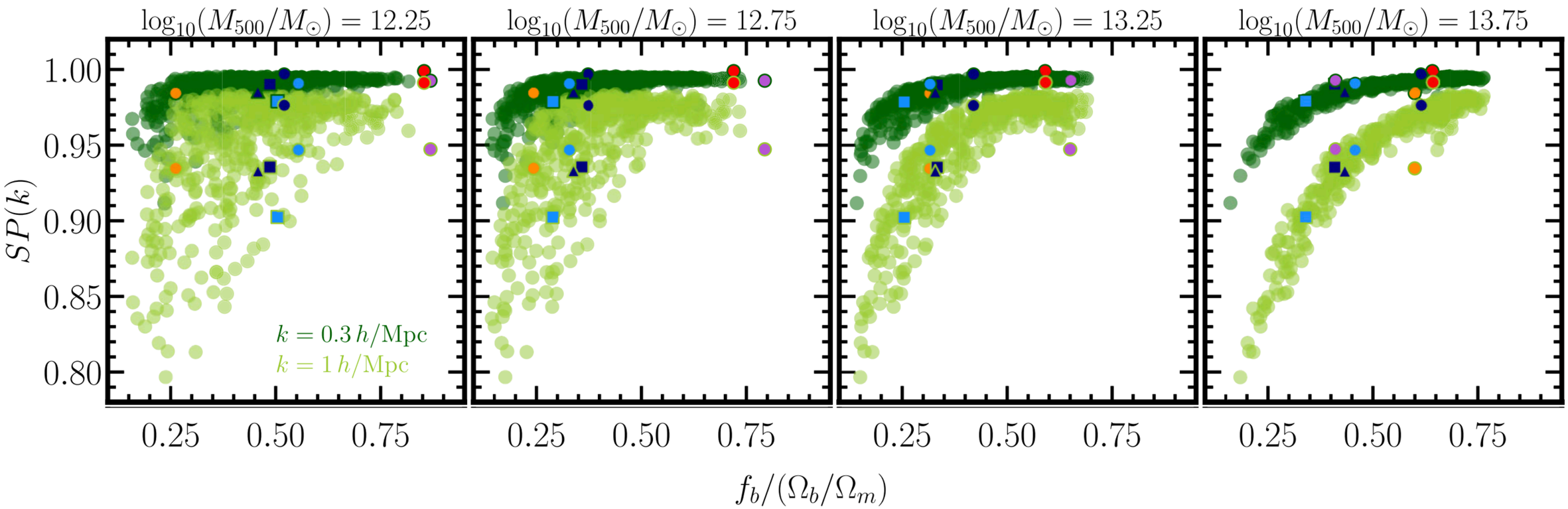
Bigwood, Yamamoto, Siegel+25



From Observables to P(k)

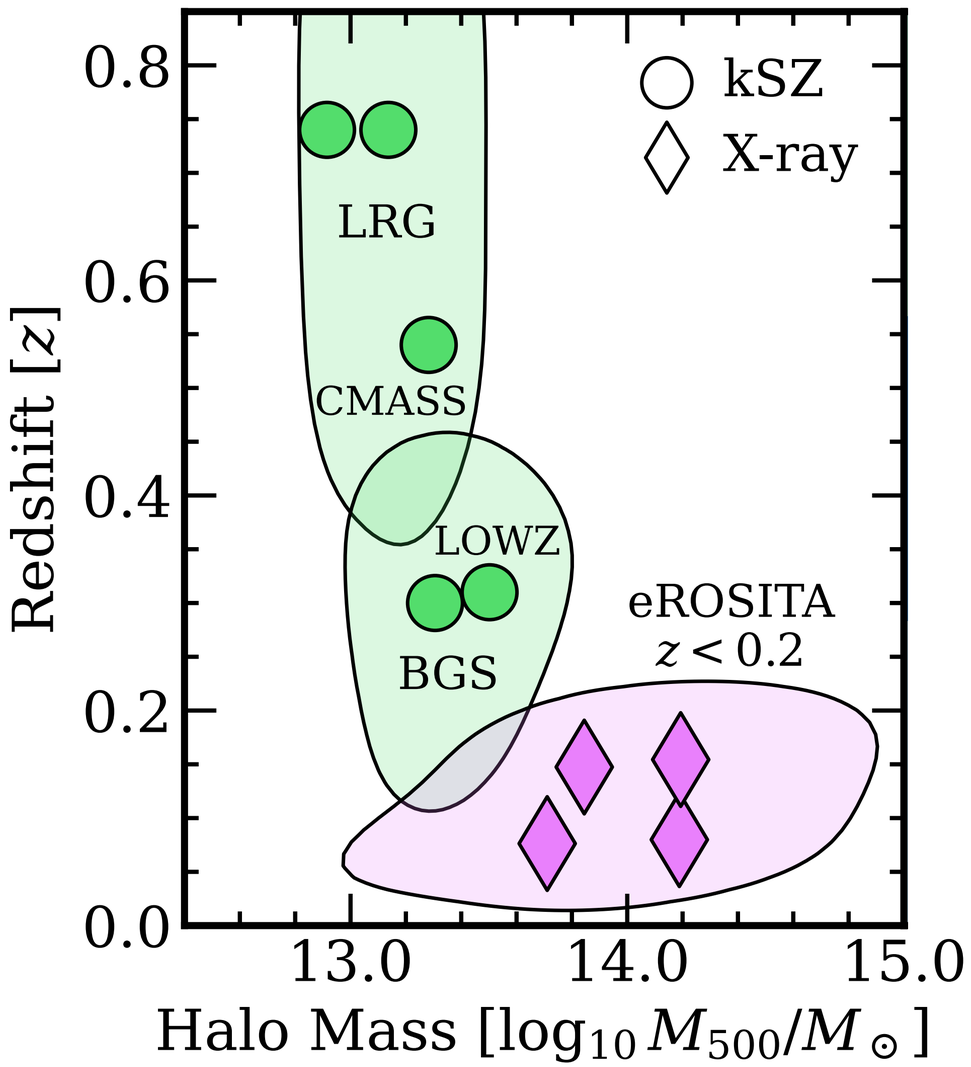


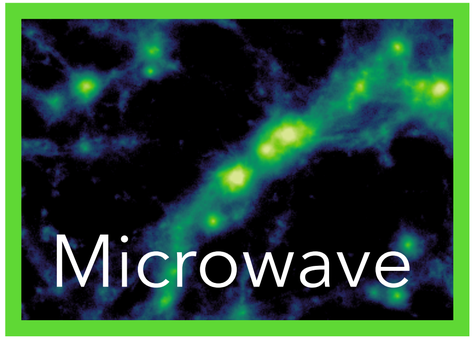
Bigwood, Yamamoto, Siegel+25



Also see: van Daalen+20, Salcido+23, van Daalen+26

Building a Complete Picture



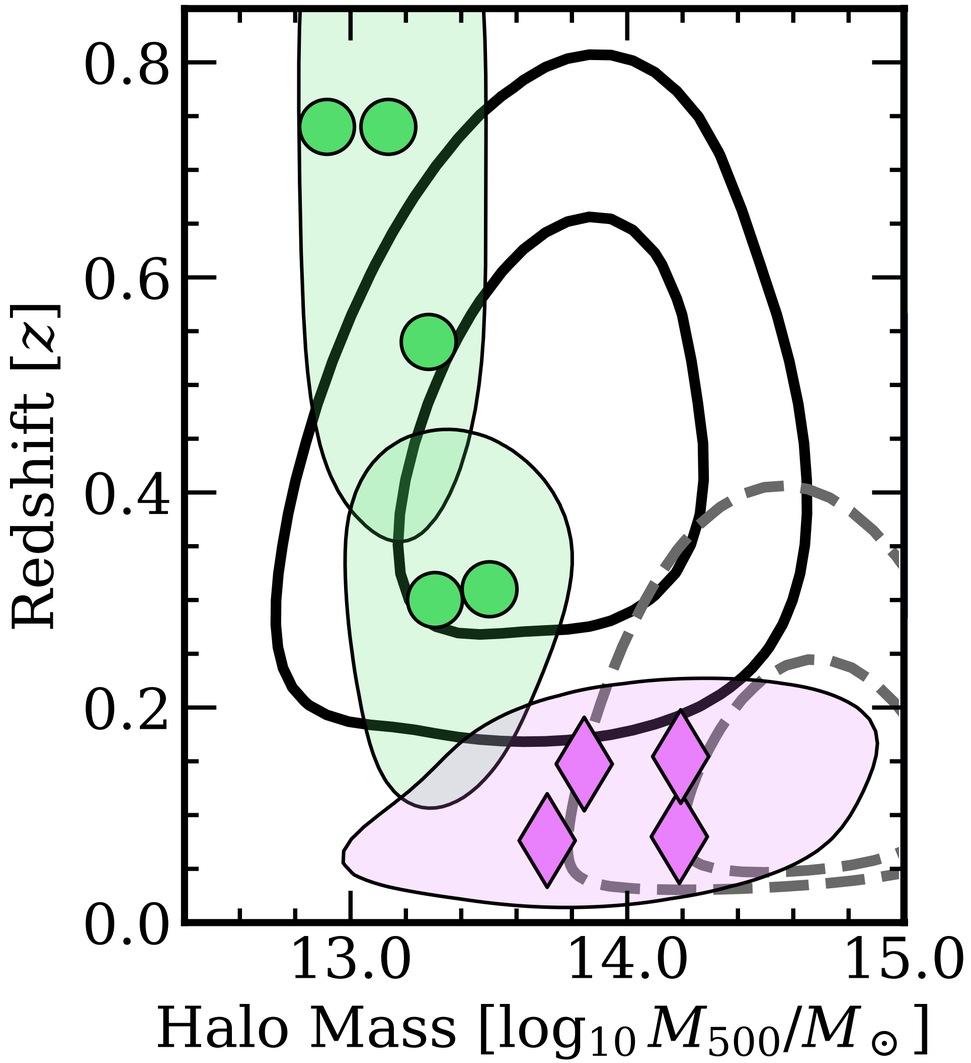


Schaan et al. 2021
Hadzhiyska et al. 2024
Reid Guachalla et al. 2025



Vikhlinin et al. 2006
Sun et al. 2009
Lovsari et al. 2015
Eckert et al. 2016
Akino et al. 2022
Bulbul et al. 2024

Building a Complete Picture



Fiducial DES Y6 Scale Cut

$\xi_-(\theta = 40')$

Small Scale Lensing

$\xi_-(\theta = 2.5')$

Also see Lucie-Smith+25

Galaxy-Galaxy Lensing



DES



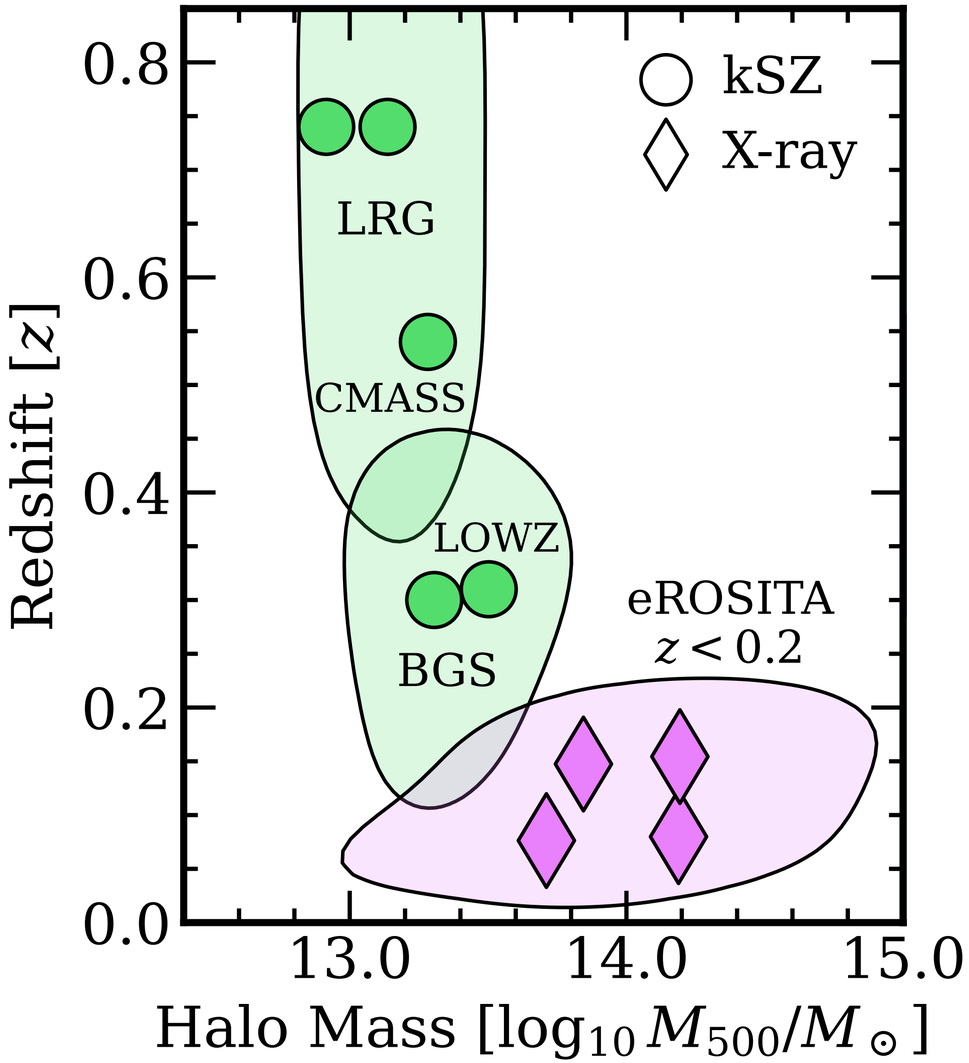
KiDS

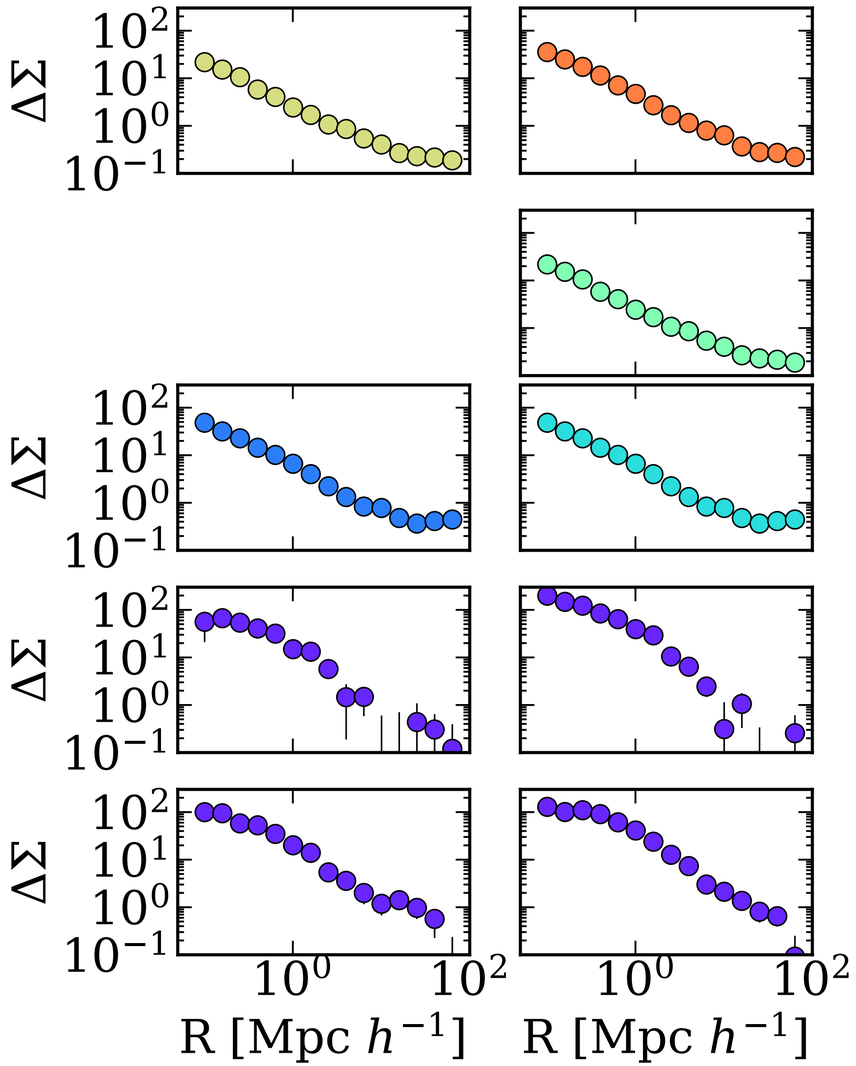


HSC



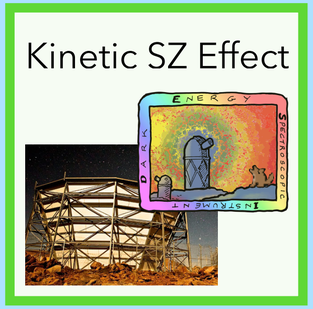
Building a Complete Picture





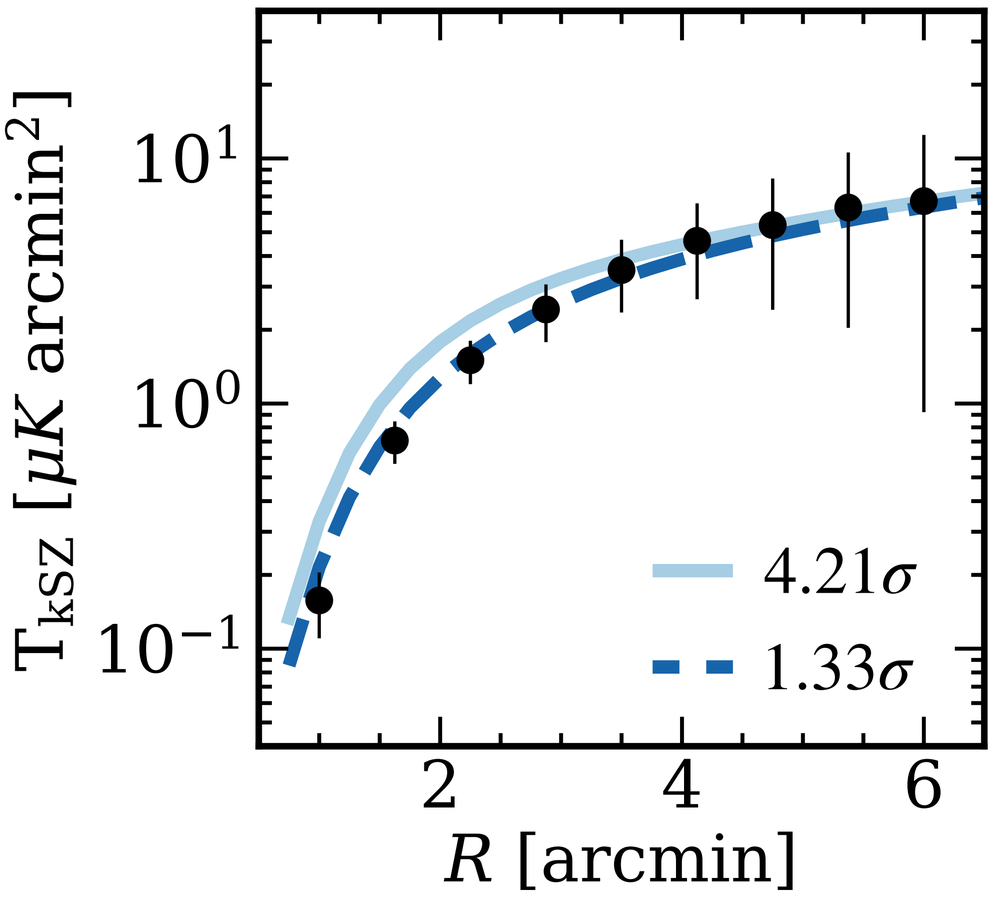
Amon+23

Siegel+25

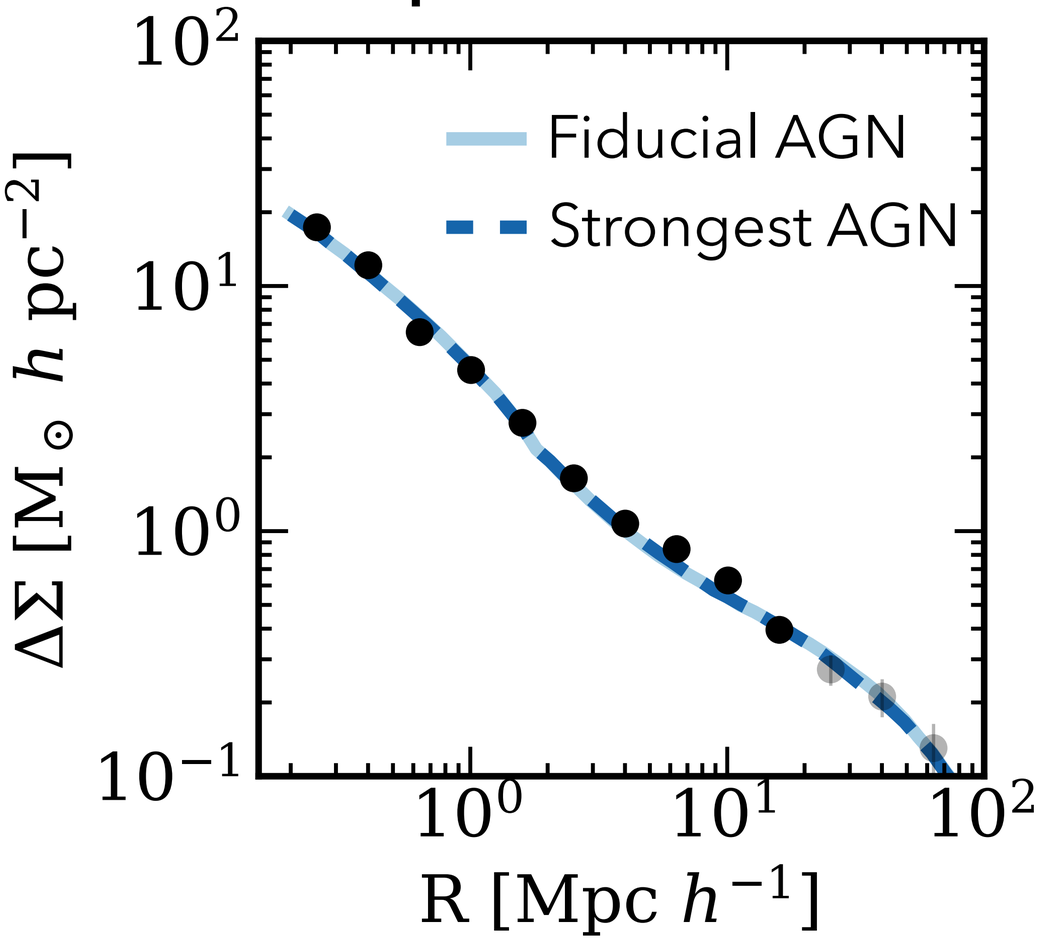


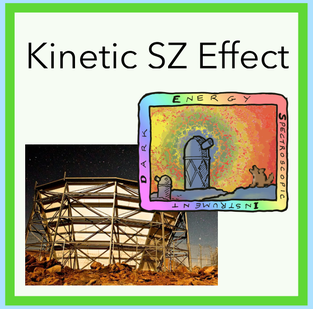
Like-with-like kSZ Analysis

Ried Guachalla + 25



Siegel + 25

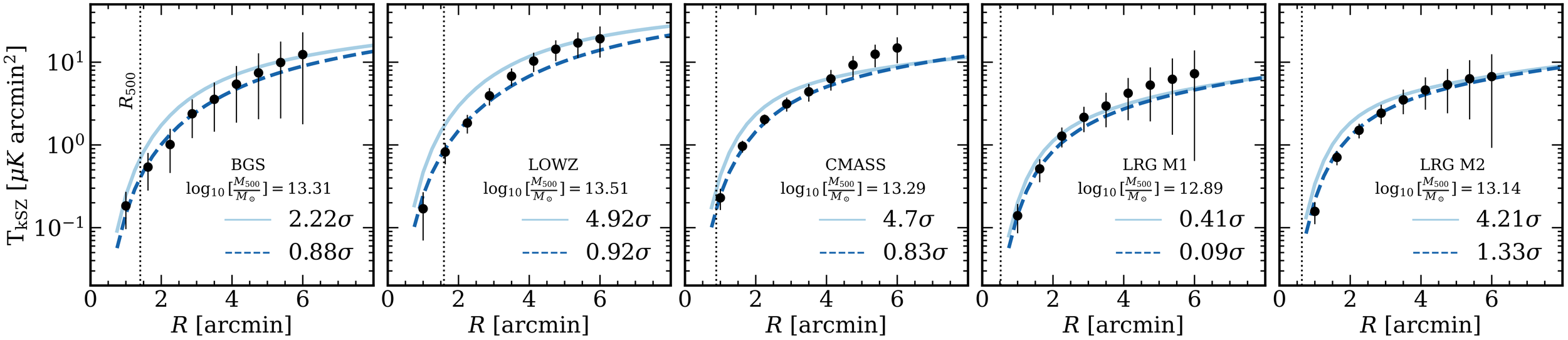




SDSS/DESI+ACT kSZ

kSZ data: Schaan + 21, Ried Guachalla + 25

GGL data: Amon + 23, Siegel + 25



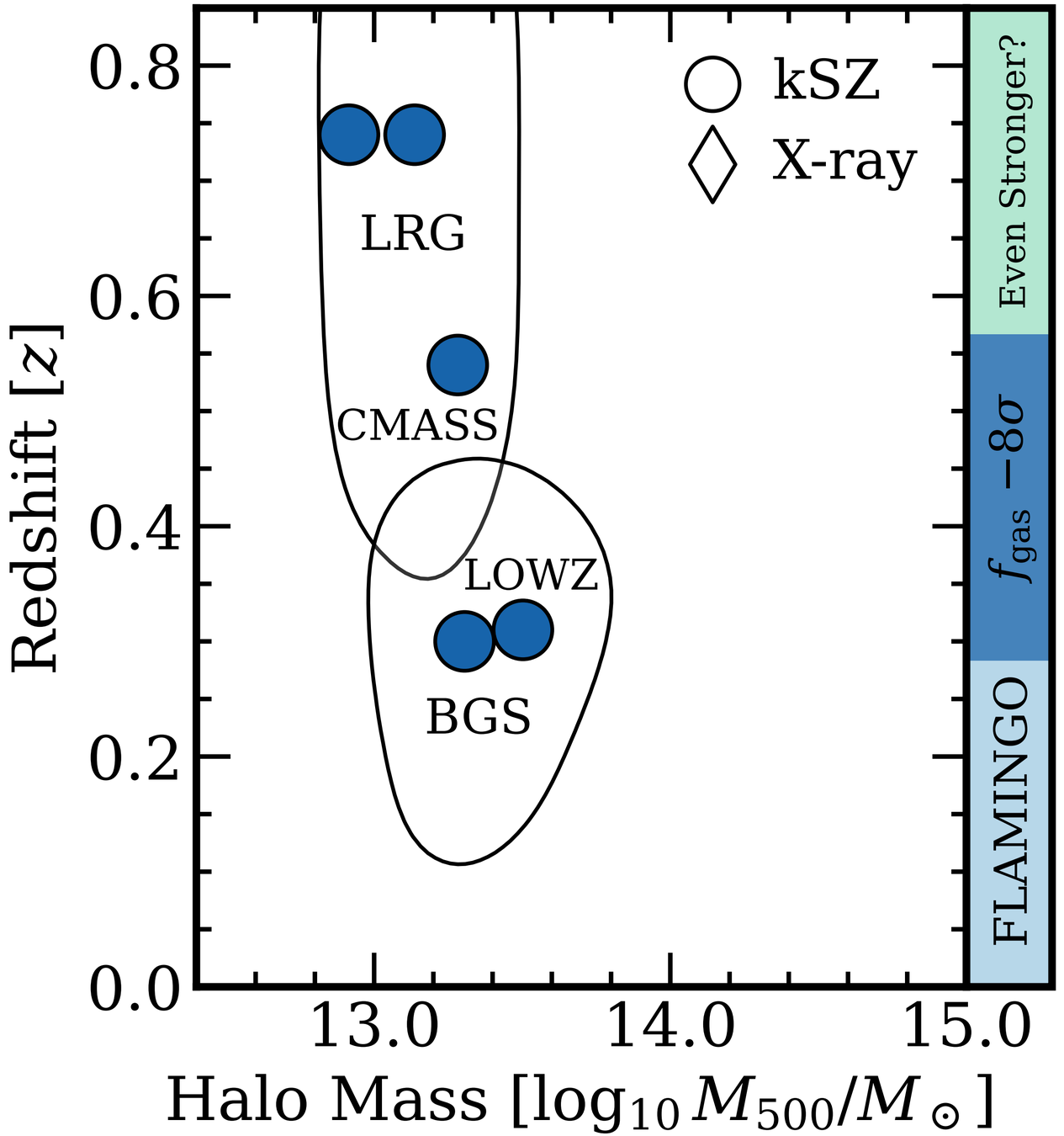
McCarthy+24

Siegel+25

Also see: Hadzhiyska+24

Ried Guachalla + 25

Landscape of Feedback



McCarthy+24 arXiv:2410.19905

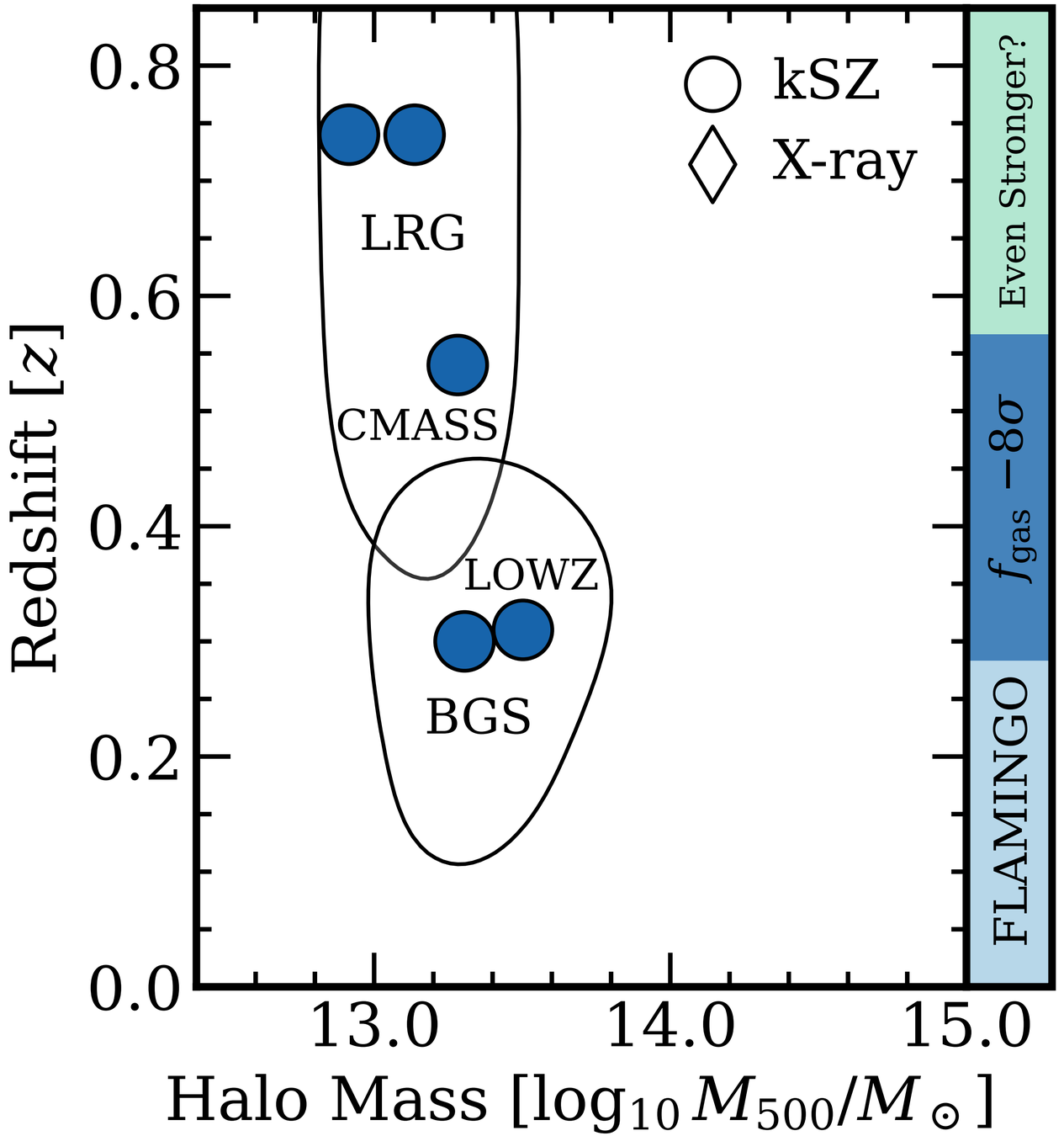
Siegel+25 arXiv:2509.10455

Landscape of Feedback

Bigwood, Yamamoto, Siegel+25
FABLE, SIMBA, BAHAMAS

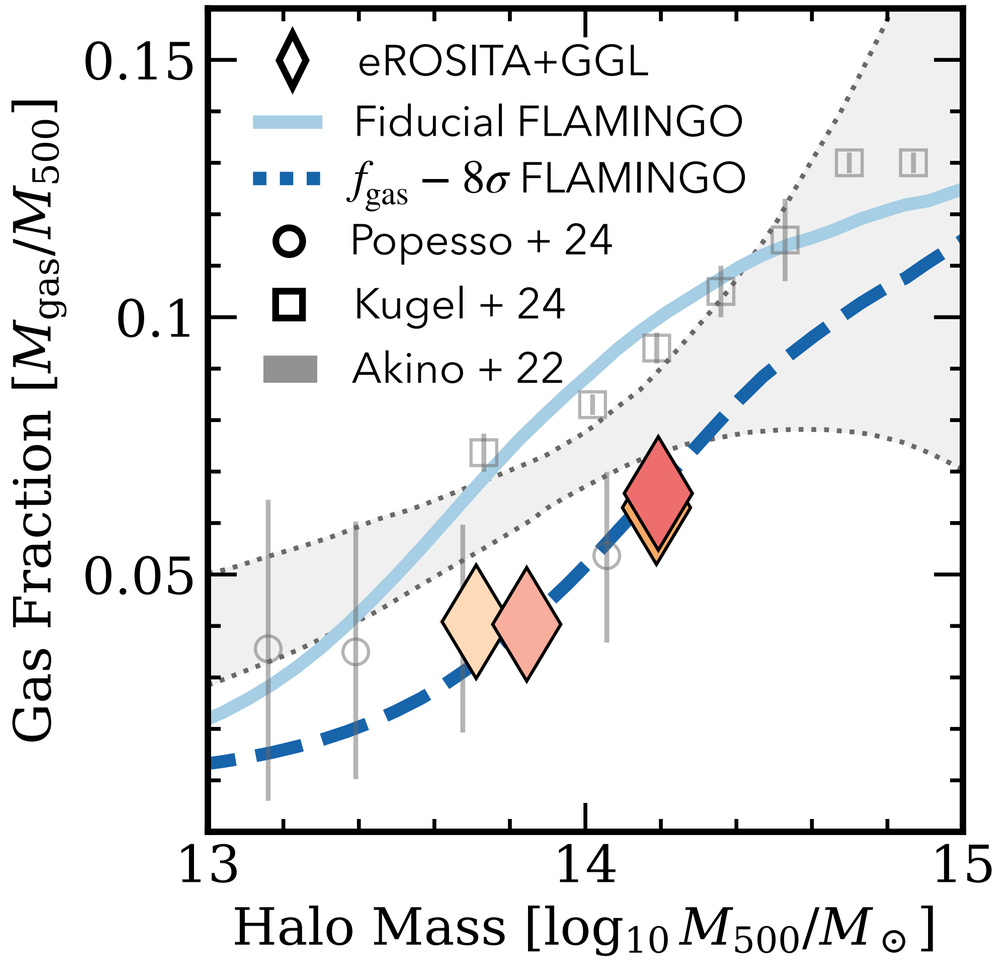






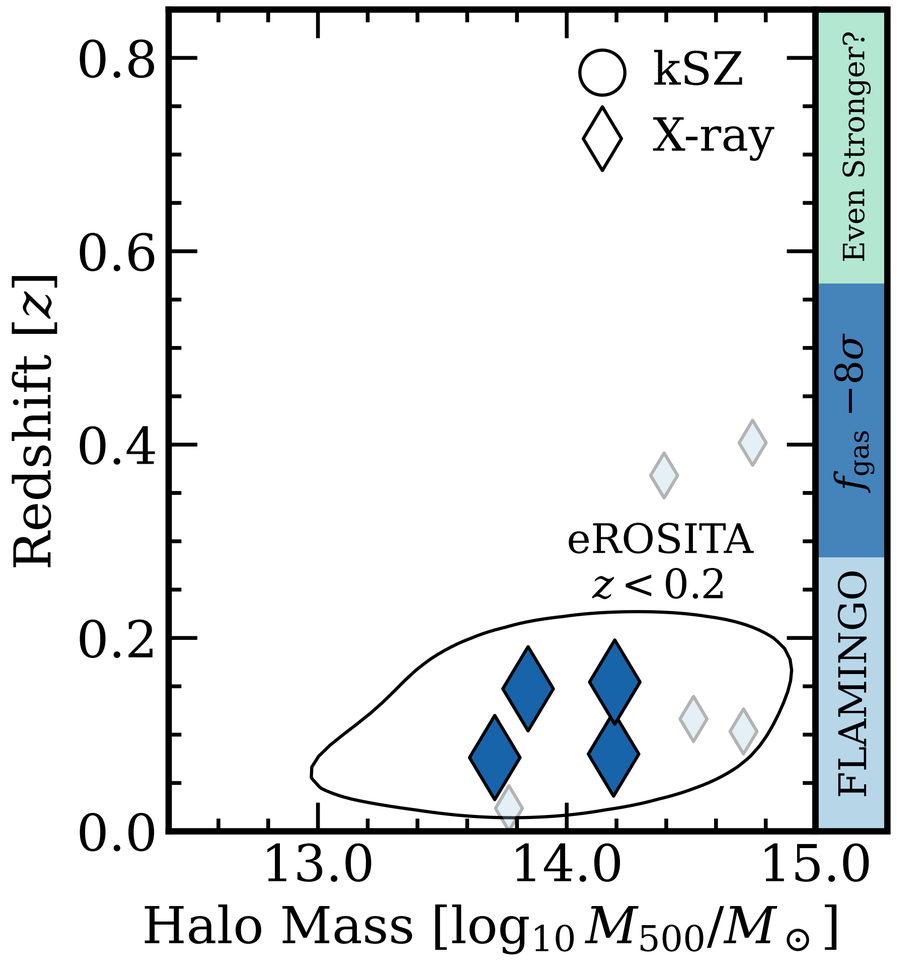
X-ray Gas Fraction

eROSITA+WL Gas Fractions

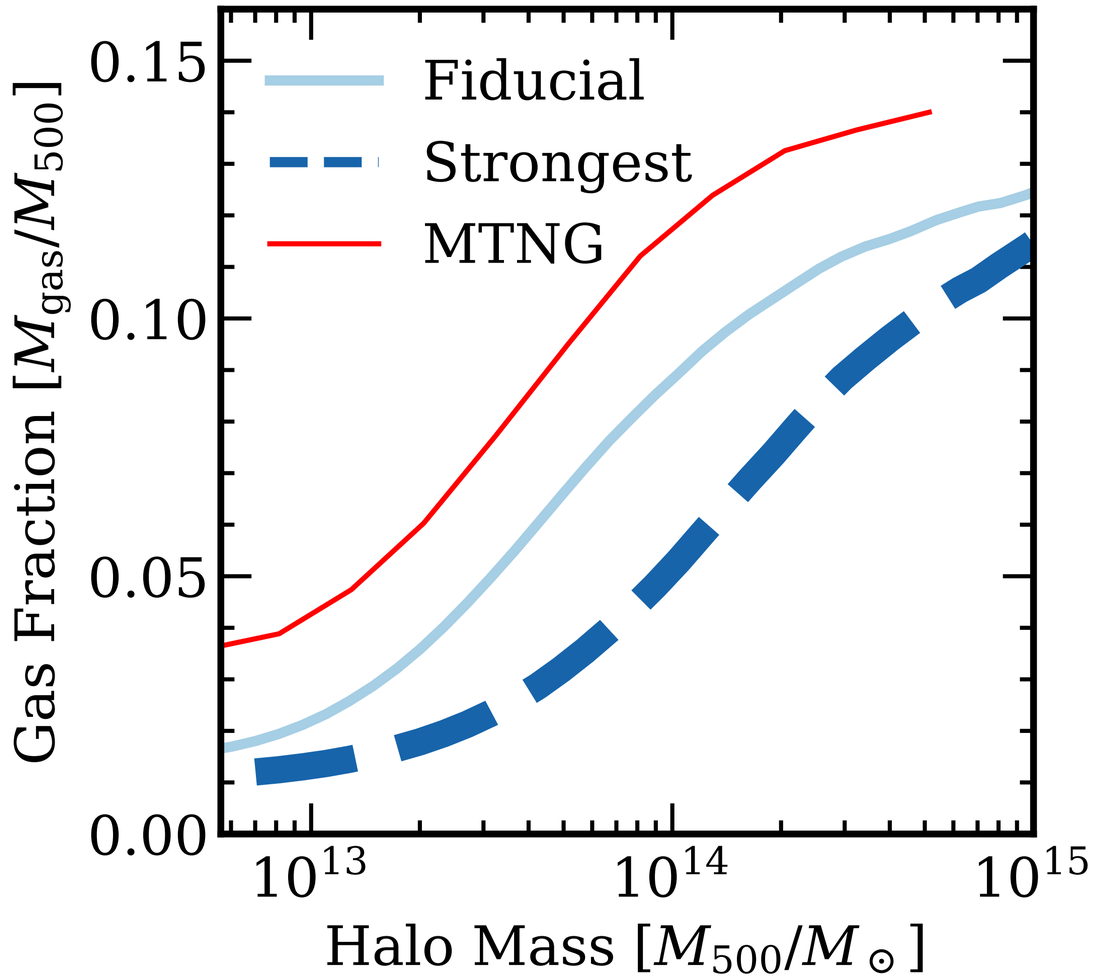


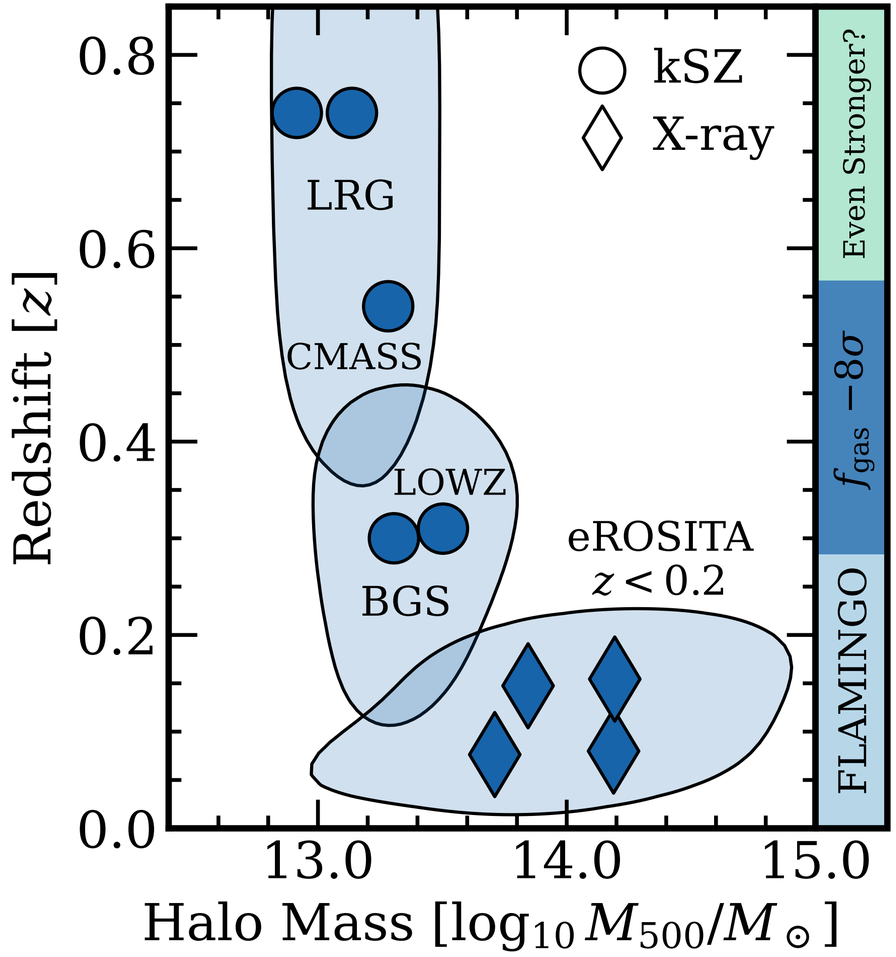
Also see:

- Seppi+22
- Popesso+24
- Marini+24
- Seppi+26
- Khalil+26
- Bucko+26
- Ding+in prep



Landscape of Feedback





How do we use these new observations?

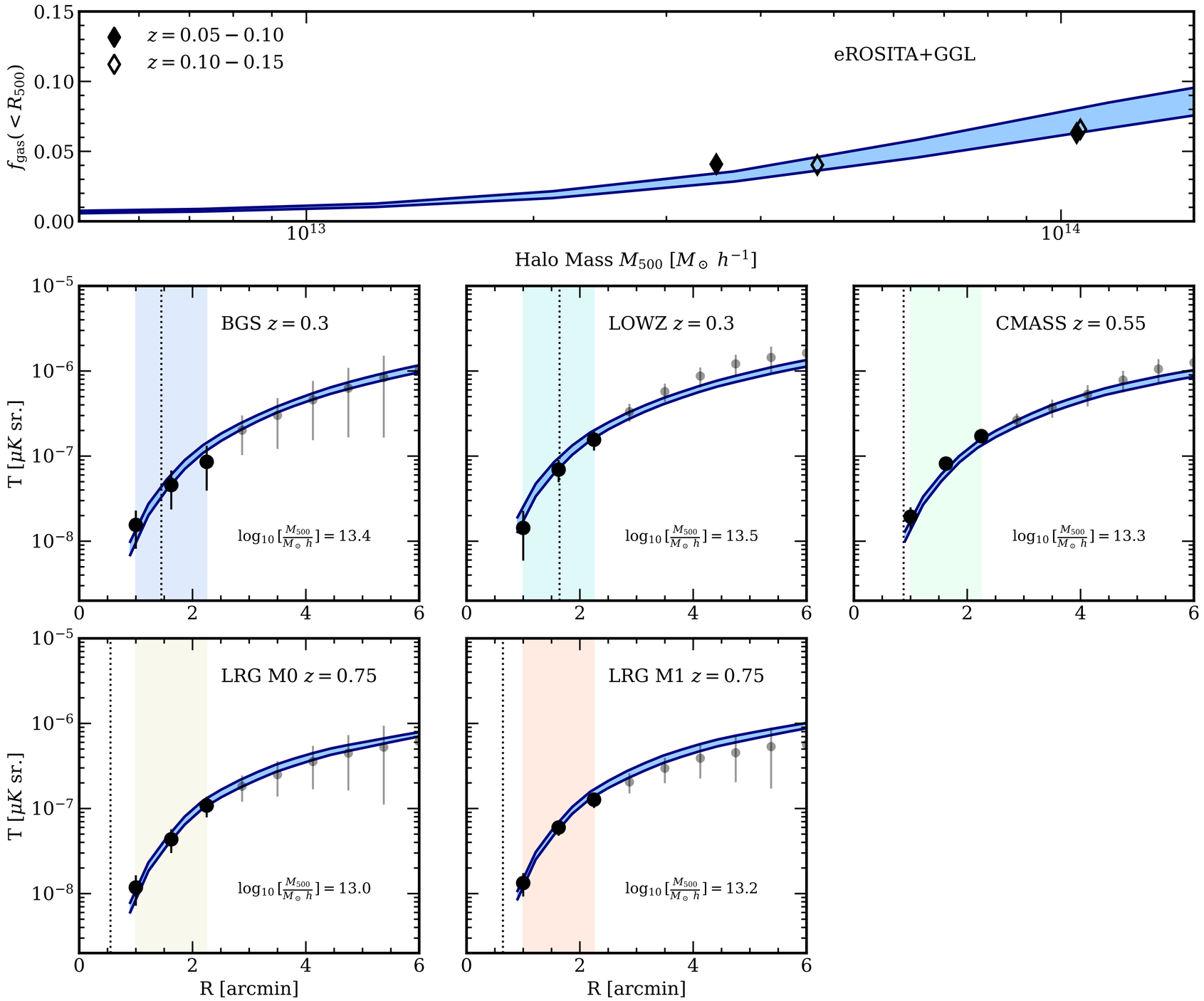
Simulation forward modeling

Siegel+25a arXiv:2509.10455

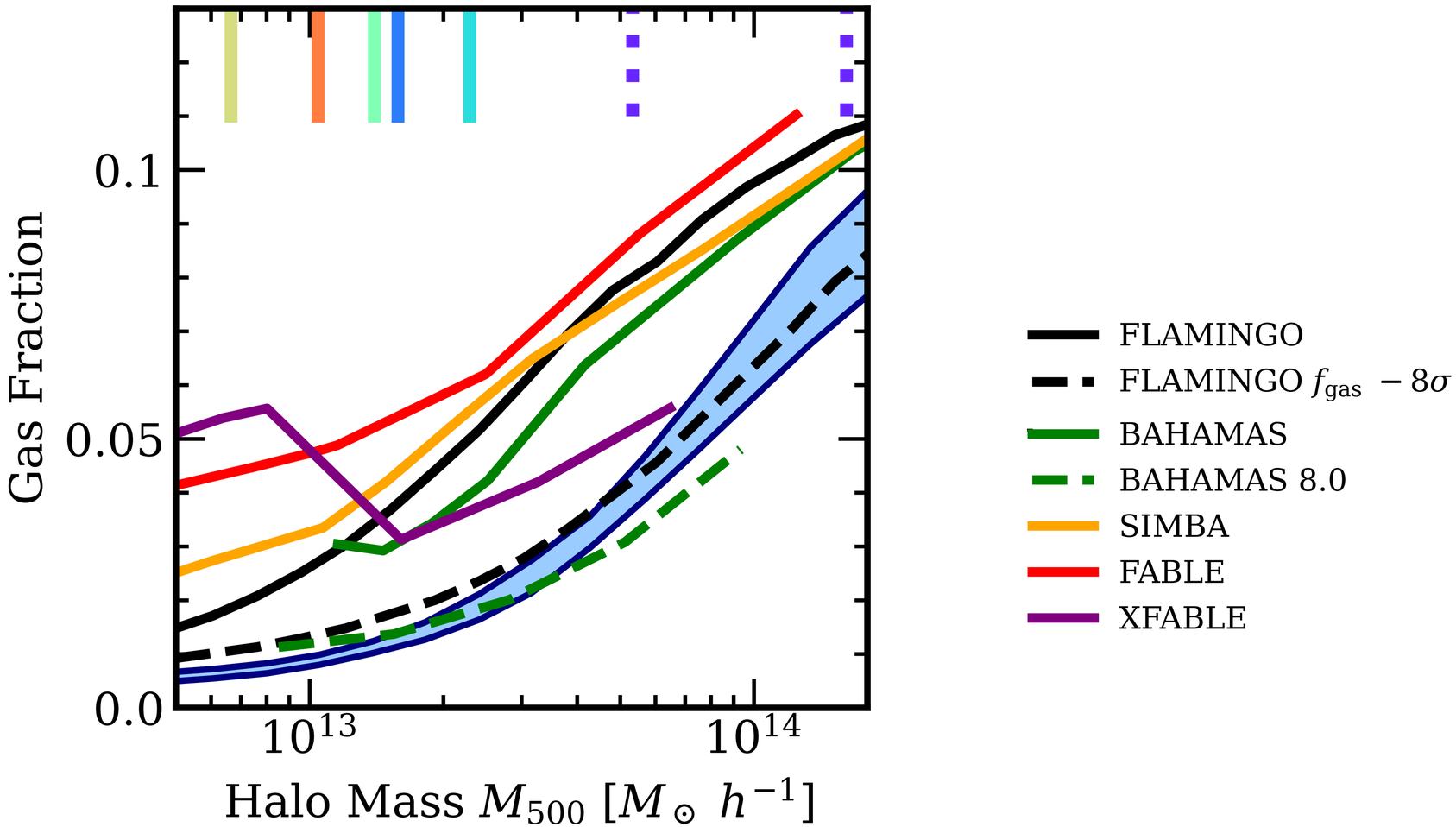
Semi-analytic modeling

Siegel+25b arXiv:2512.02954

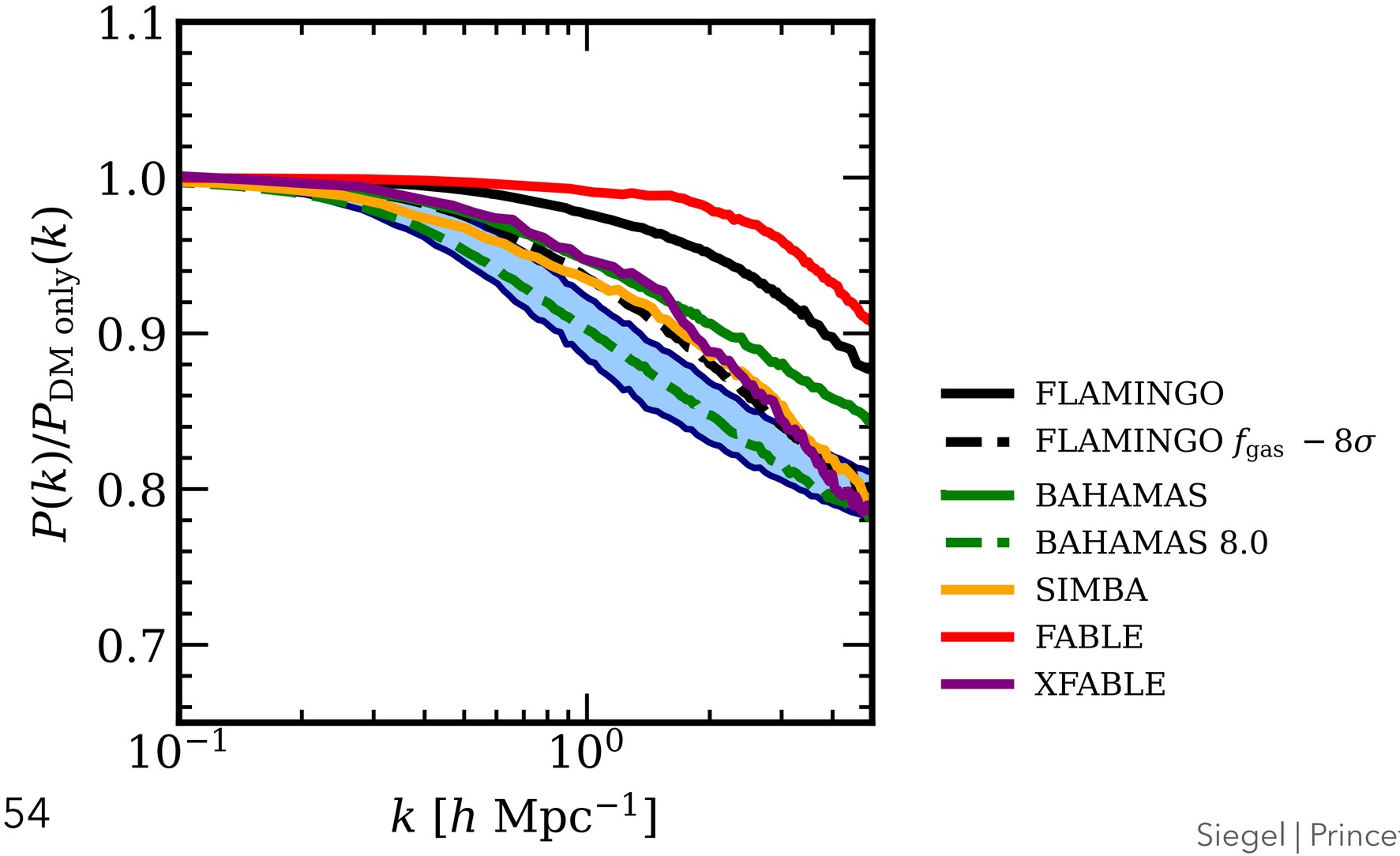
X-ray & kSZ Joint Fit



Building a Complete Picture



Building a Complete Picture

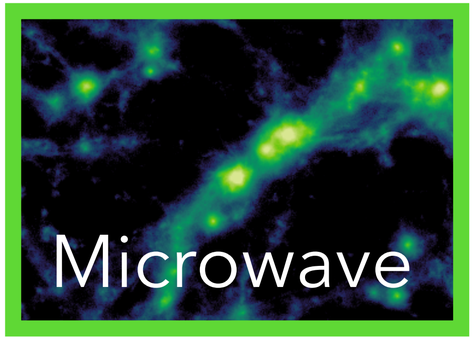


Siegel+25b arXiv:2512.02954

Building a Complete Picture



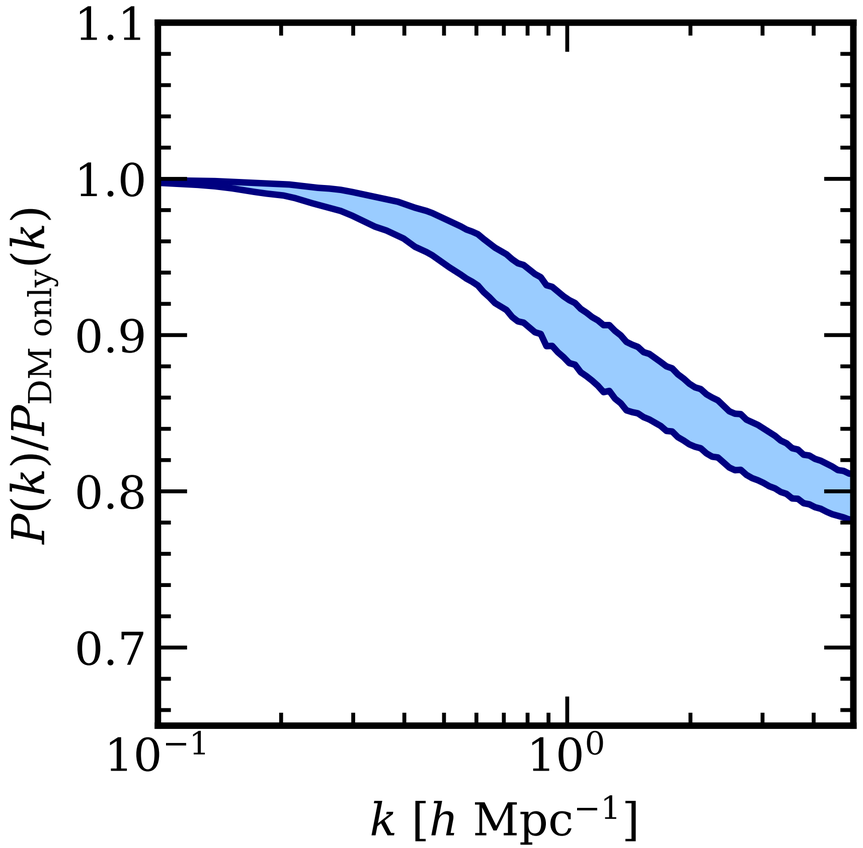




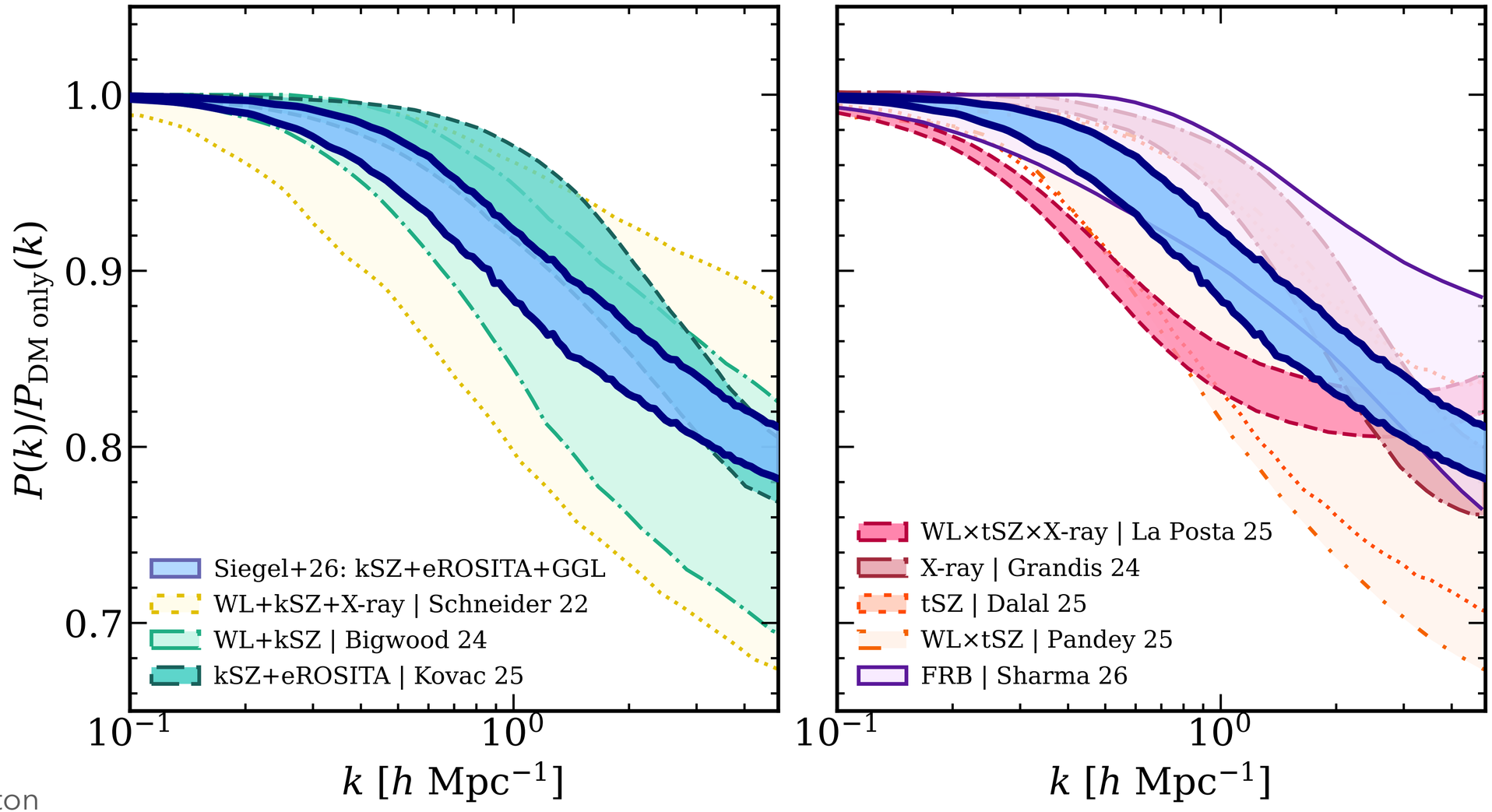
Simulation forward modeling

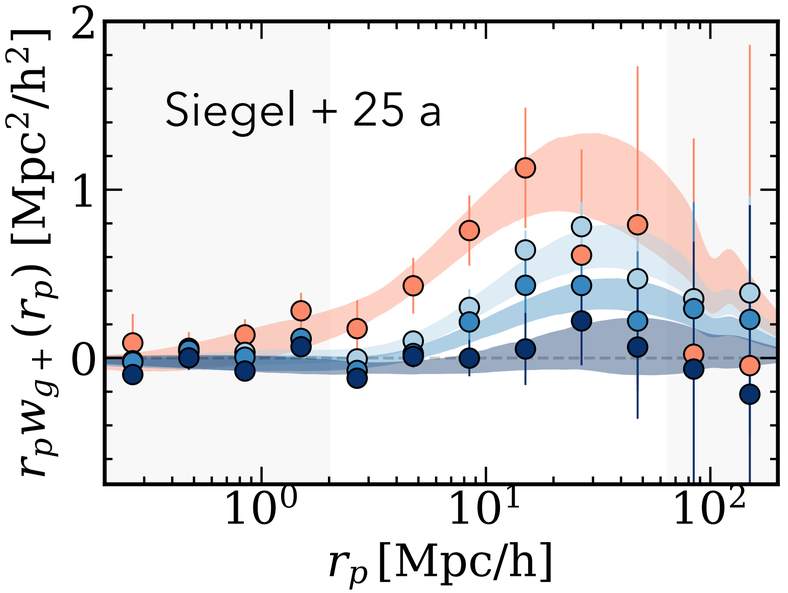
+

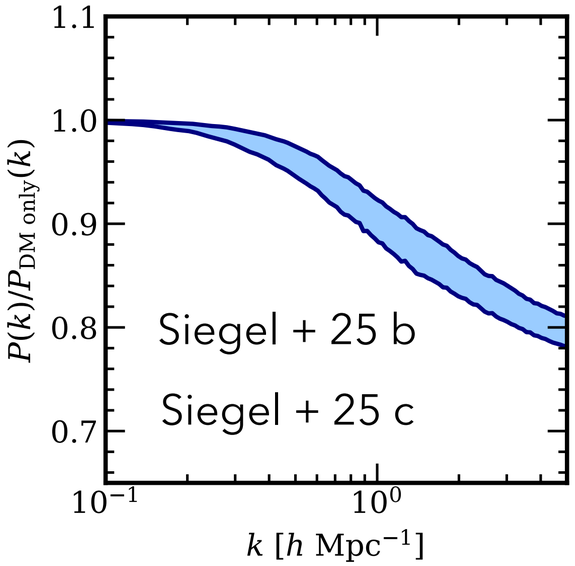
Semi-analytic modeling



Landscape of Feedback Measurements

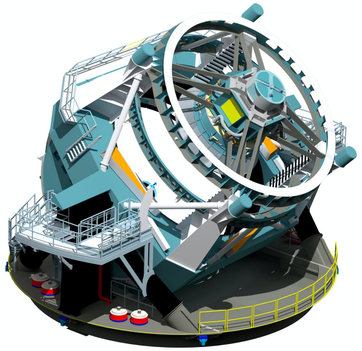


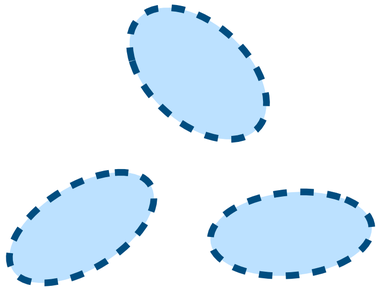


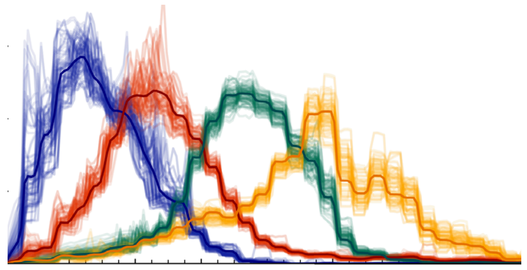


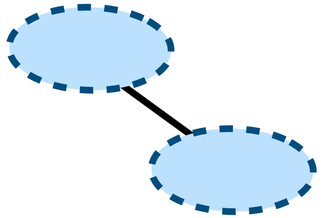
Intrinsic Alignments

Baryon Feedback









Shape Catalog

Redshift bins

2-point statistics

Cosmology

Data-driven Lensing



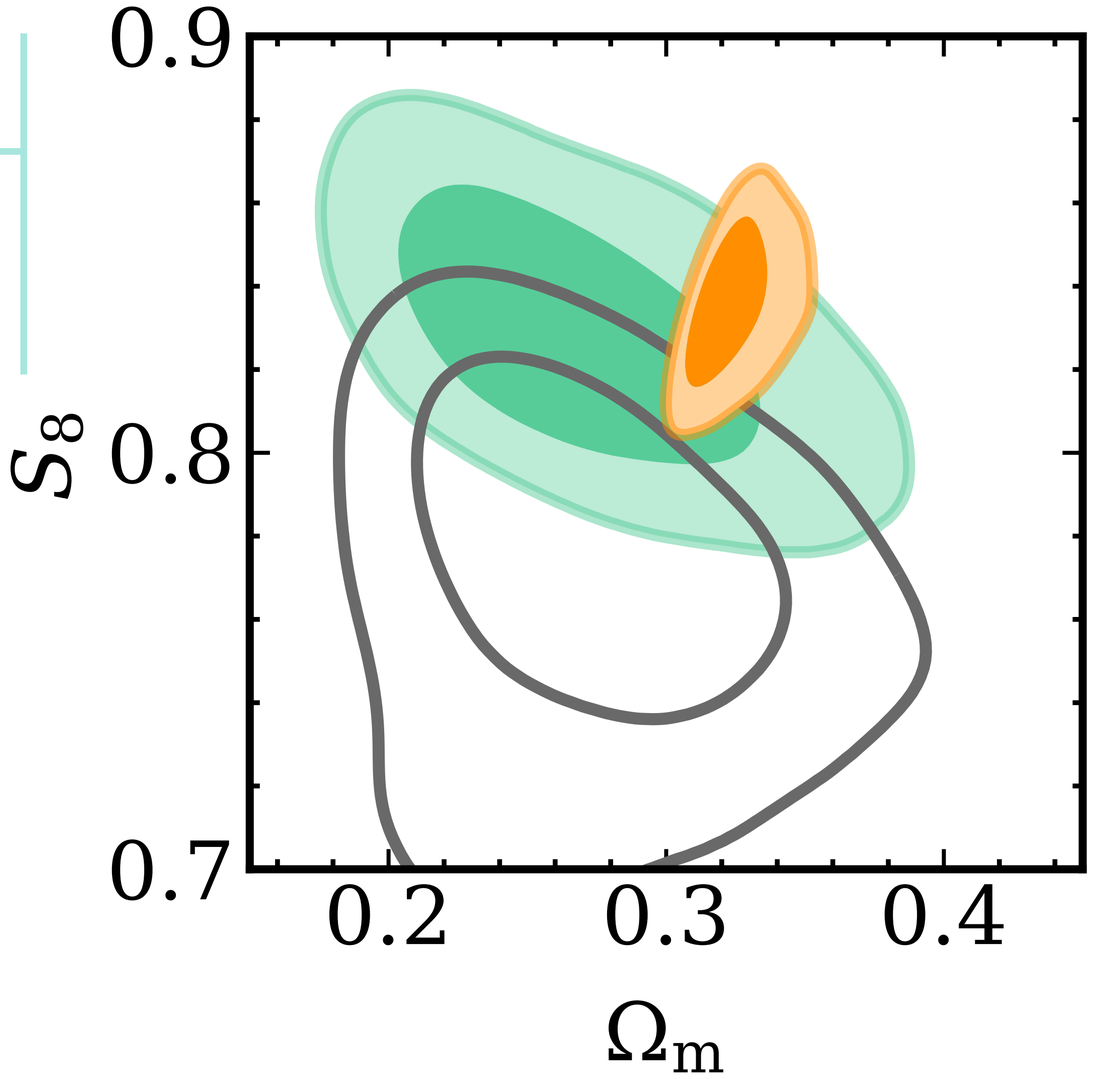


DES Y3 Small Scales

Blue galaxy sample

IA priors

Feedback priors



ACT + SPT + Planck

Louis + 25

DES Y3

Amon + 22

Data-driven Lensing

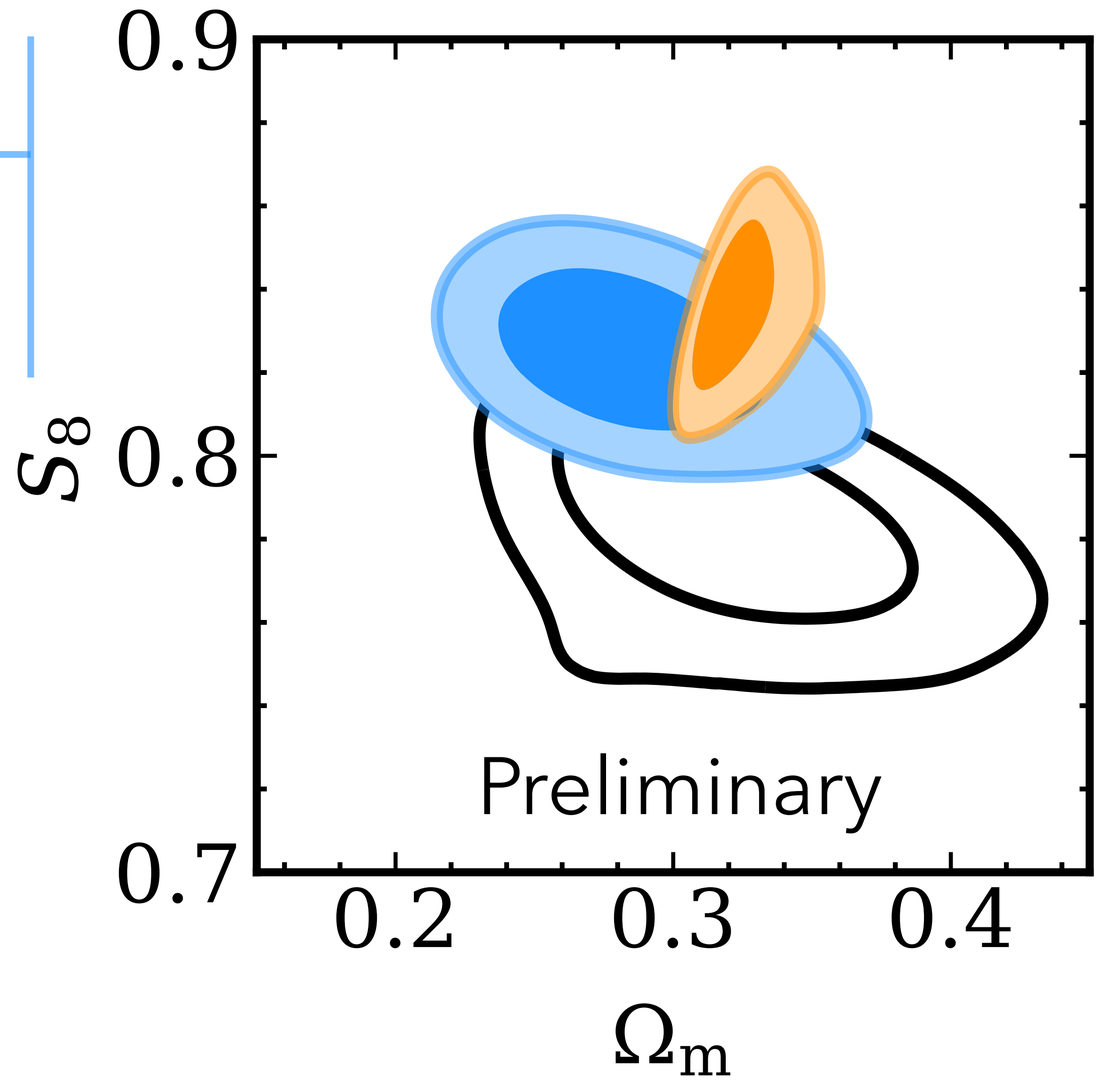
DES Y6 Small Scales

Blue shear:

Yin + in prep

Small Scales:

Siegel + in prep



ACT + SPT + Planck

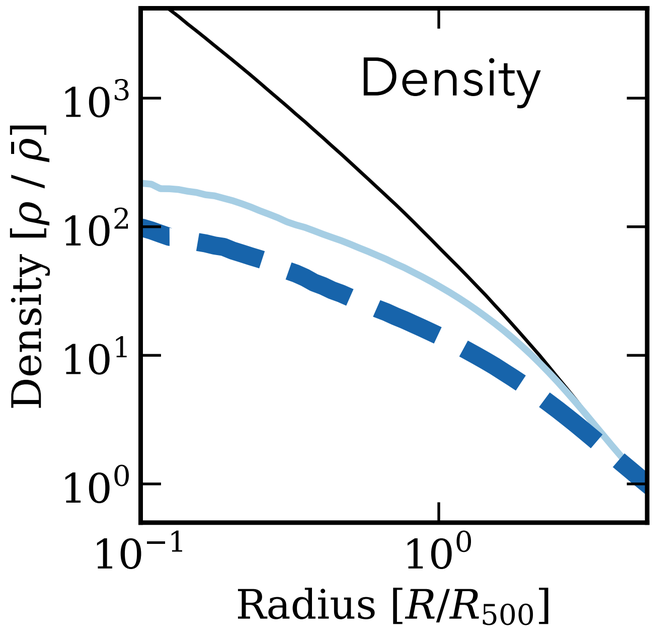
Louis + 25

DES Y6

DES + 26

Implications: Physics of Feedback

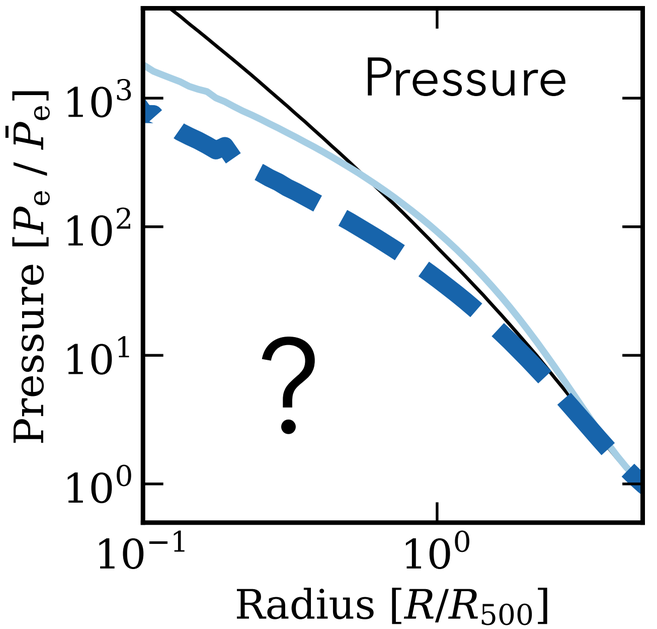
Where is the gas?



Siegel+25a arXiv:2509.10455

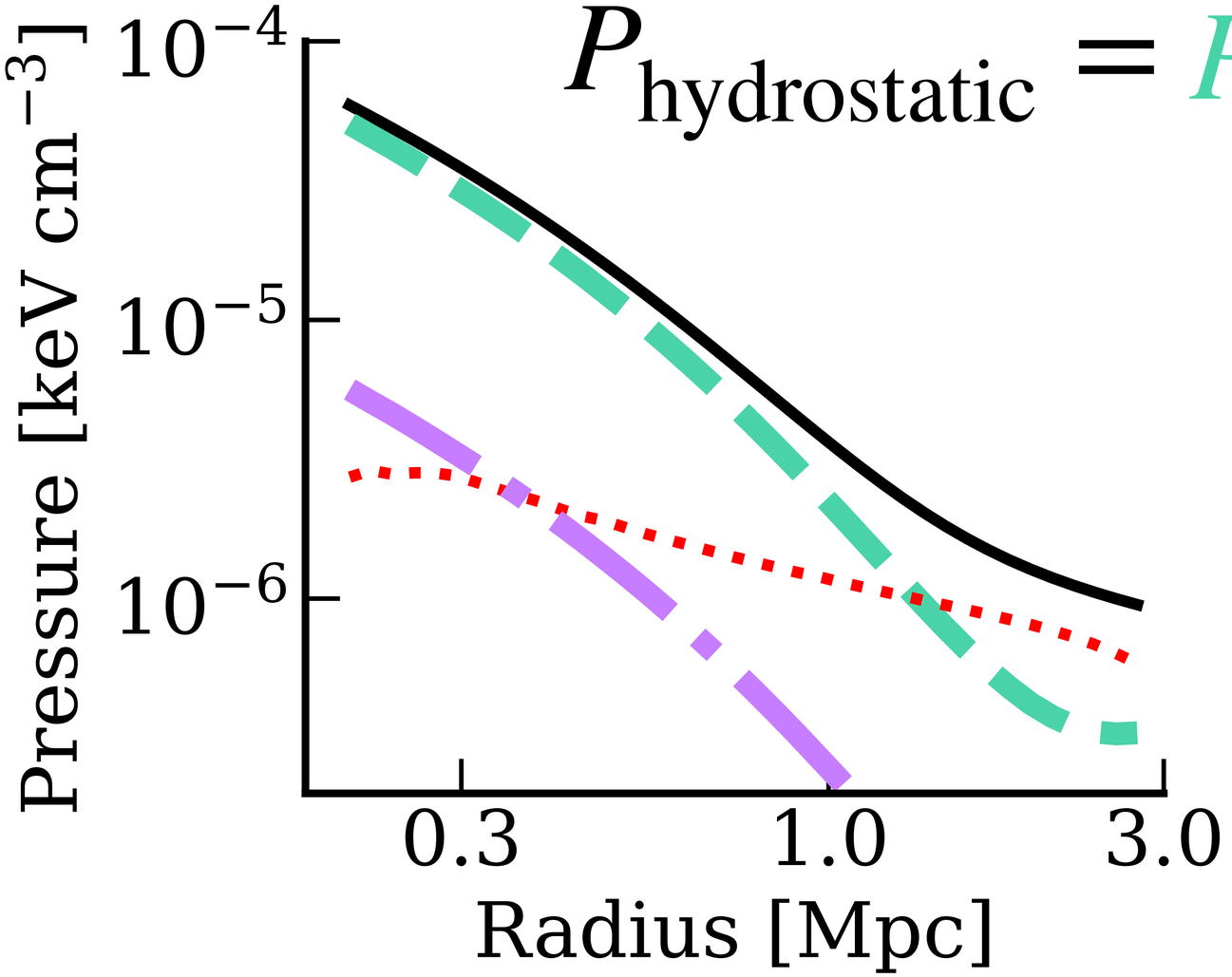
Siegel+25b arXiv:2512.02954

What is its state?



Siegel+26 arXiv:2608.00164

What is the pressure of the gas?



$$P_{\text{hydrostatic}} = P_{\text{thermal}} + P_{\text{kinetic}} + P_{\text{nt}} \; ?$$

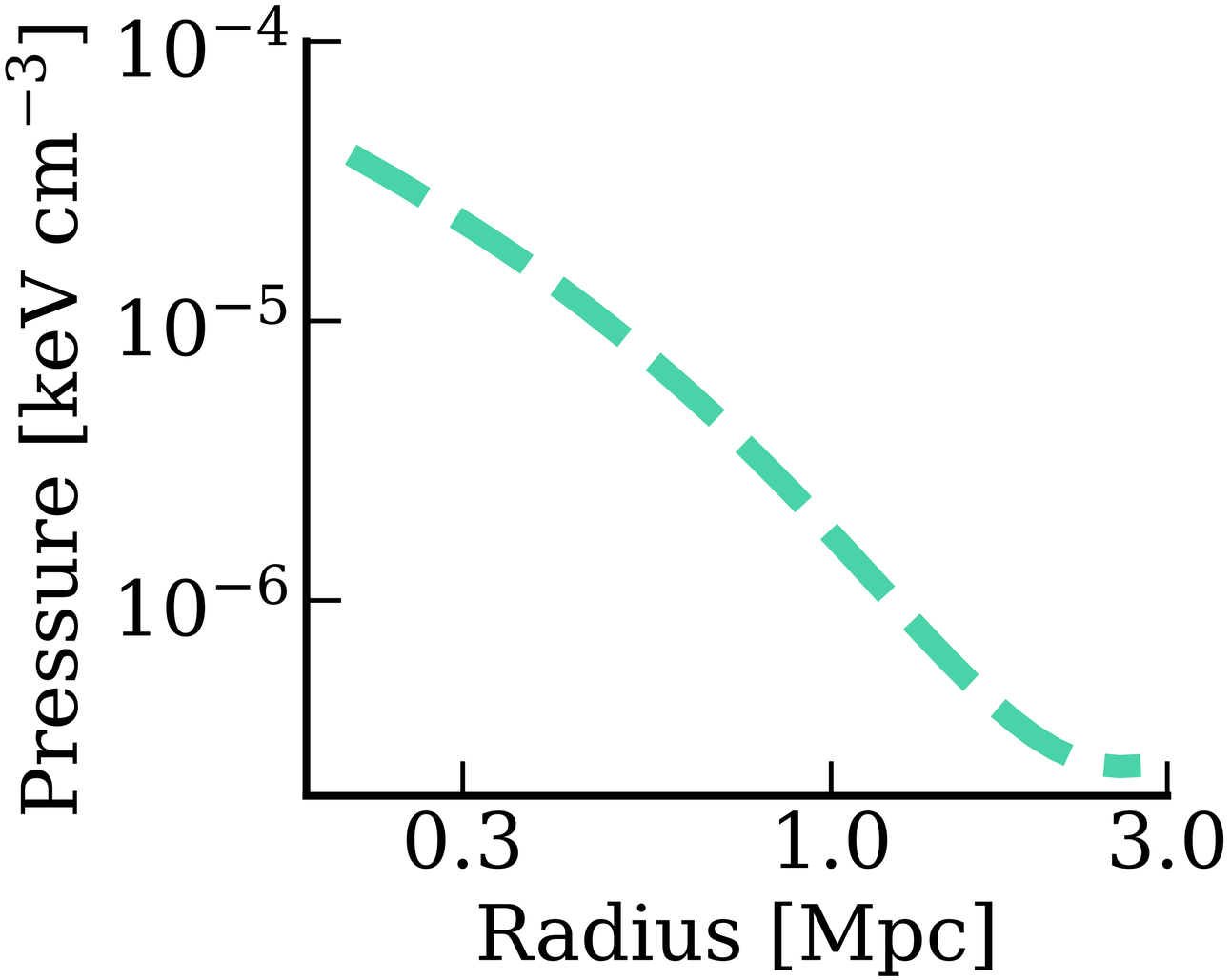
Non-equilibrium electrons?

Cosmic ray pressure support?

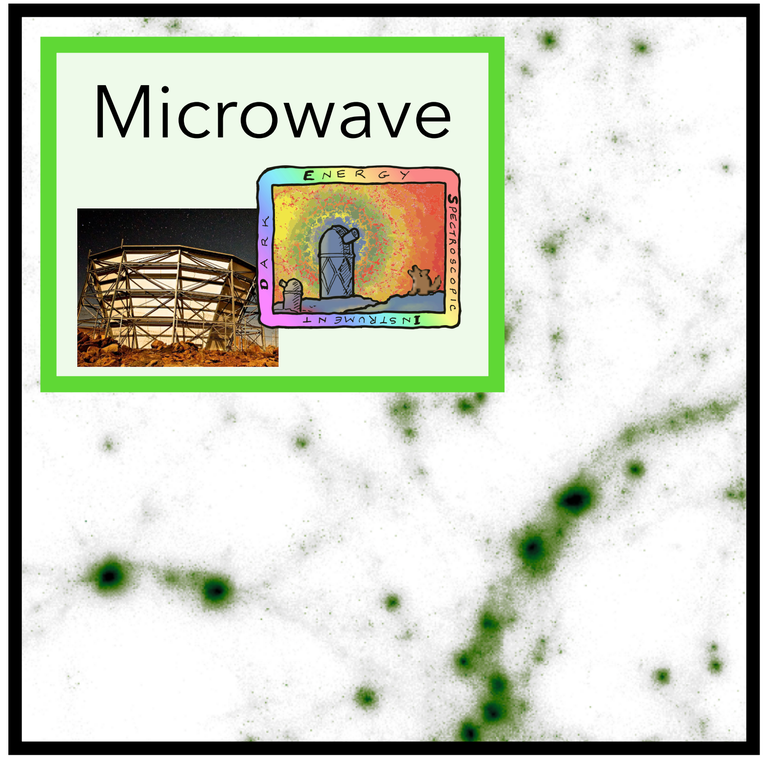
Quataert & Hopkins (2025)

Ponnada et al. 2026

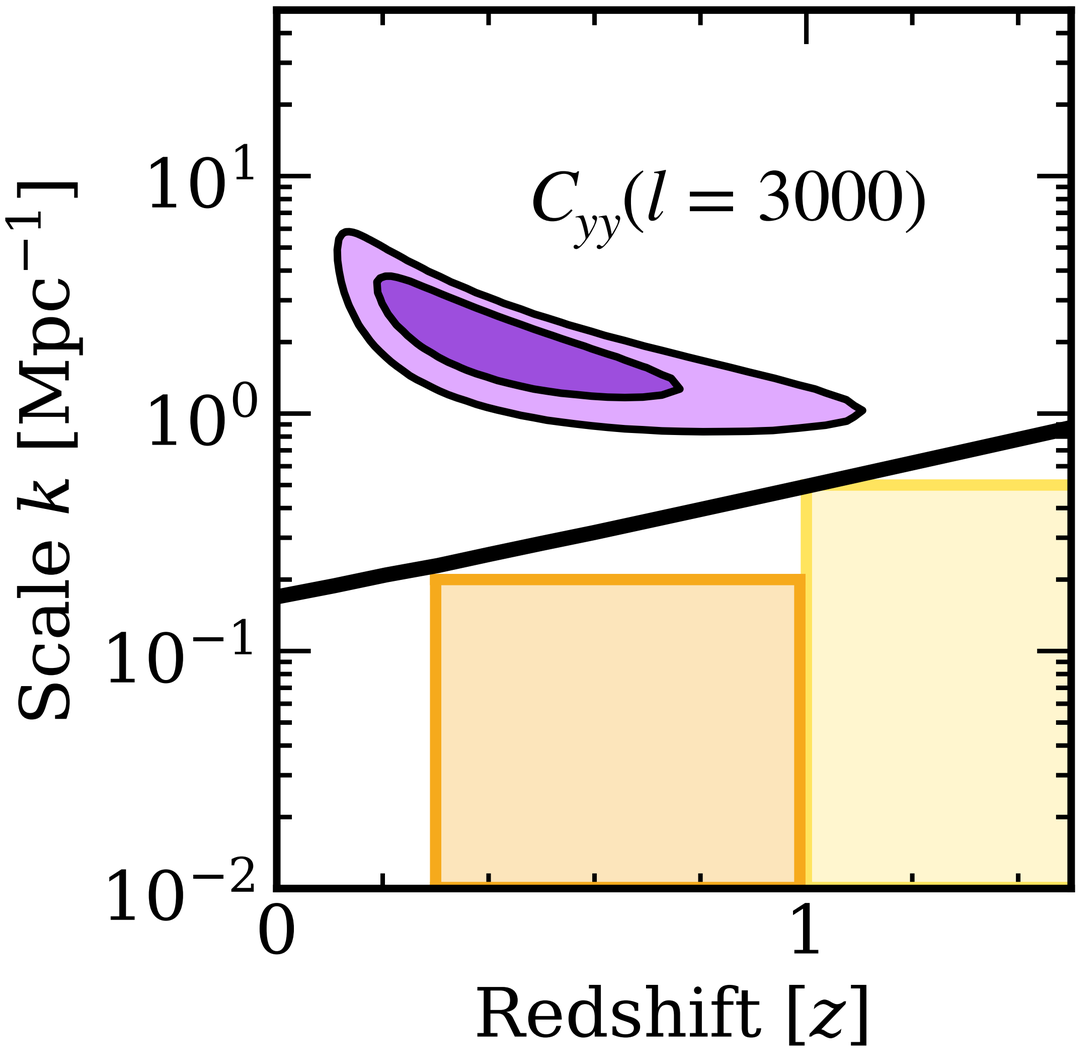
Thermal SZ Effect

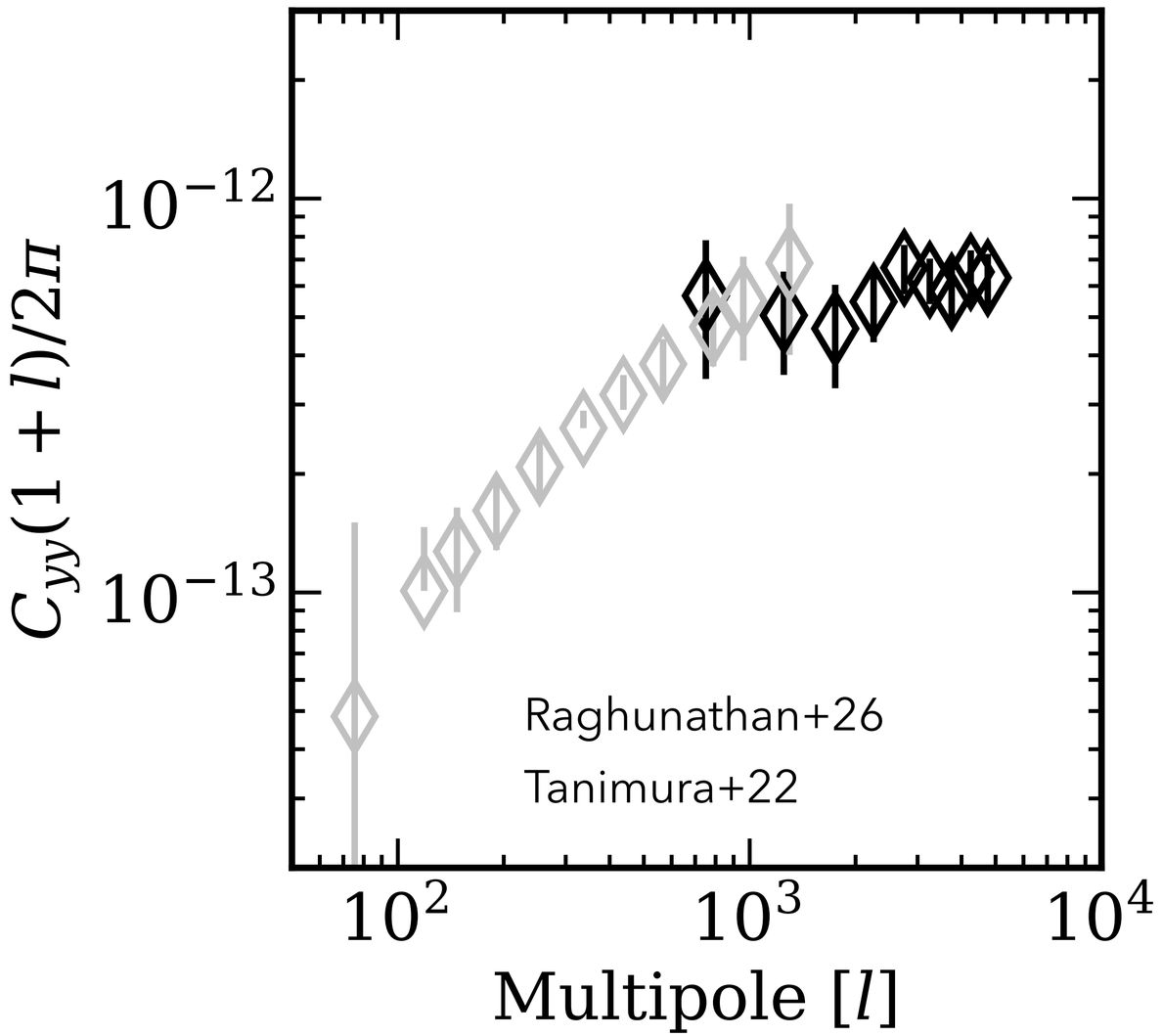


Thermal Sunyaev Zeldovich

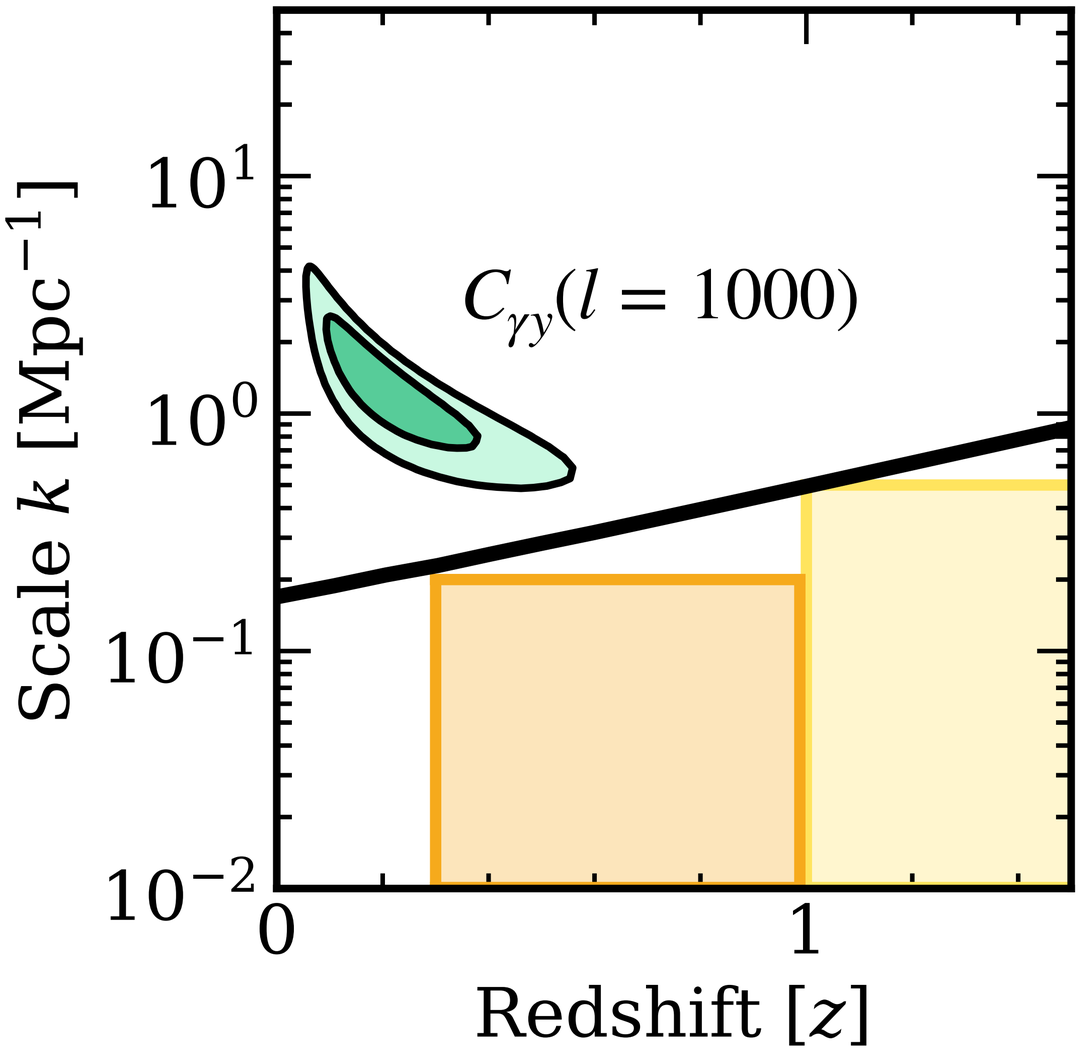


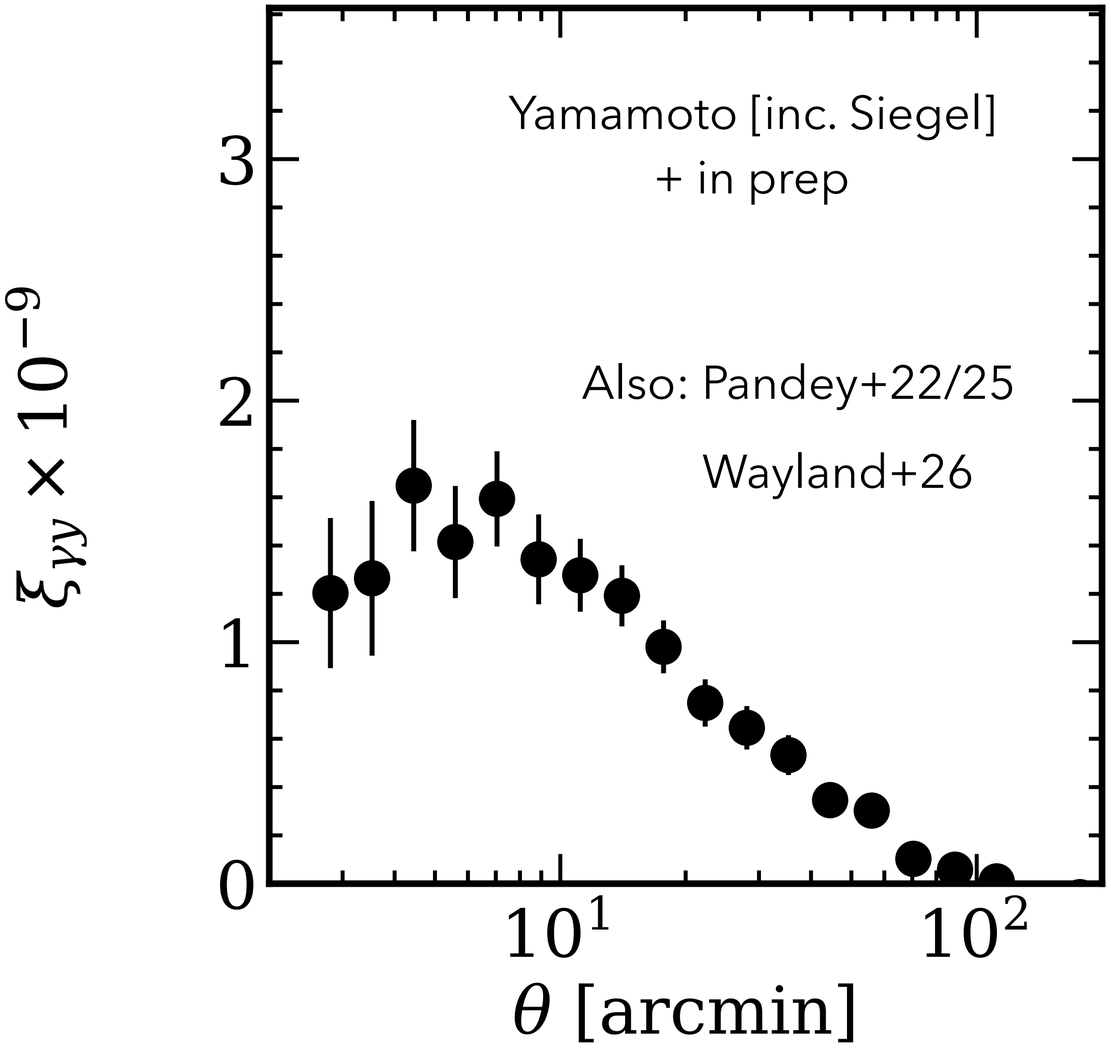
Implications: Non-linear Probes



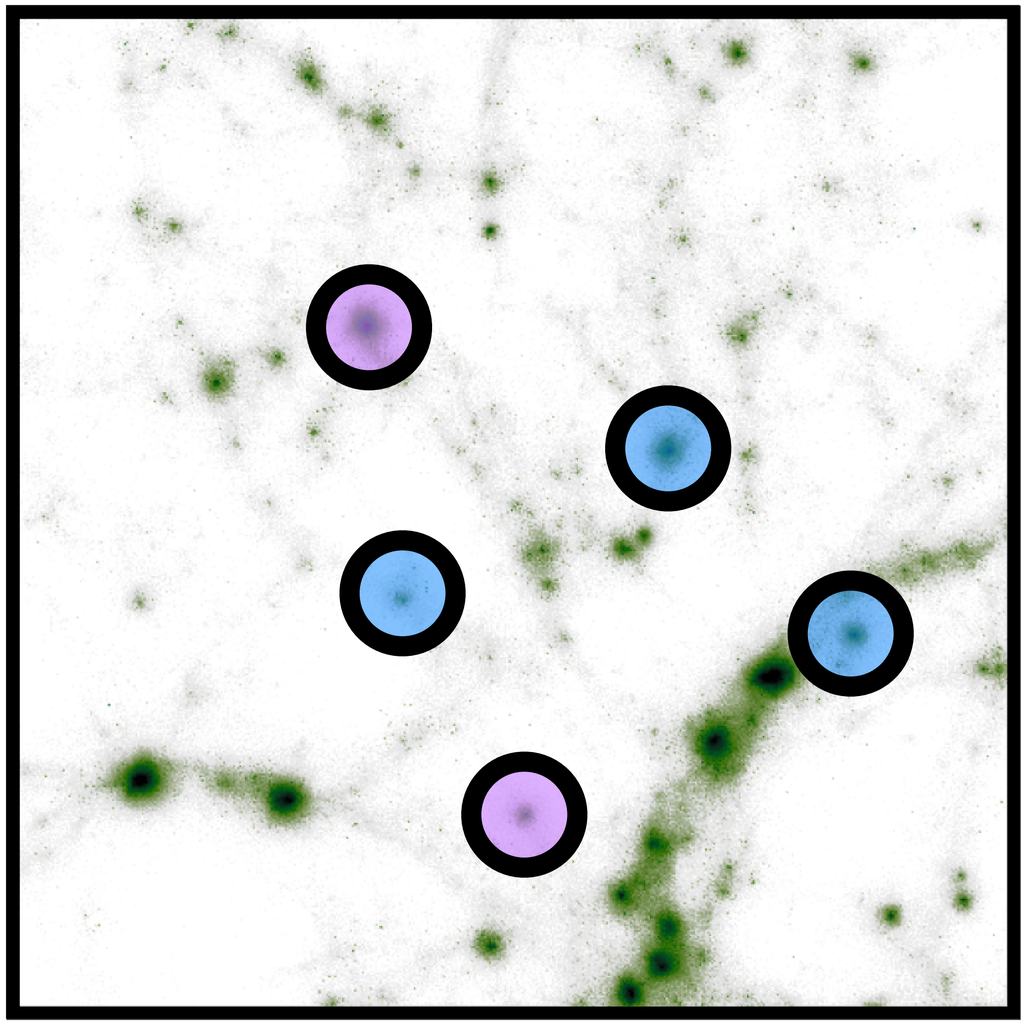


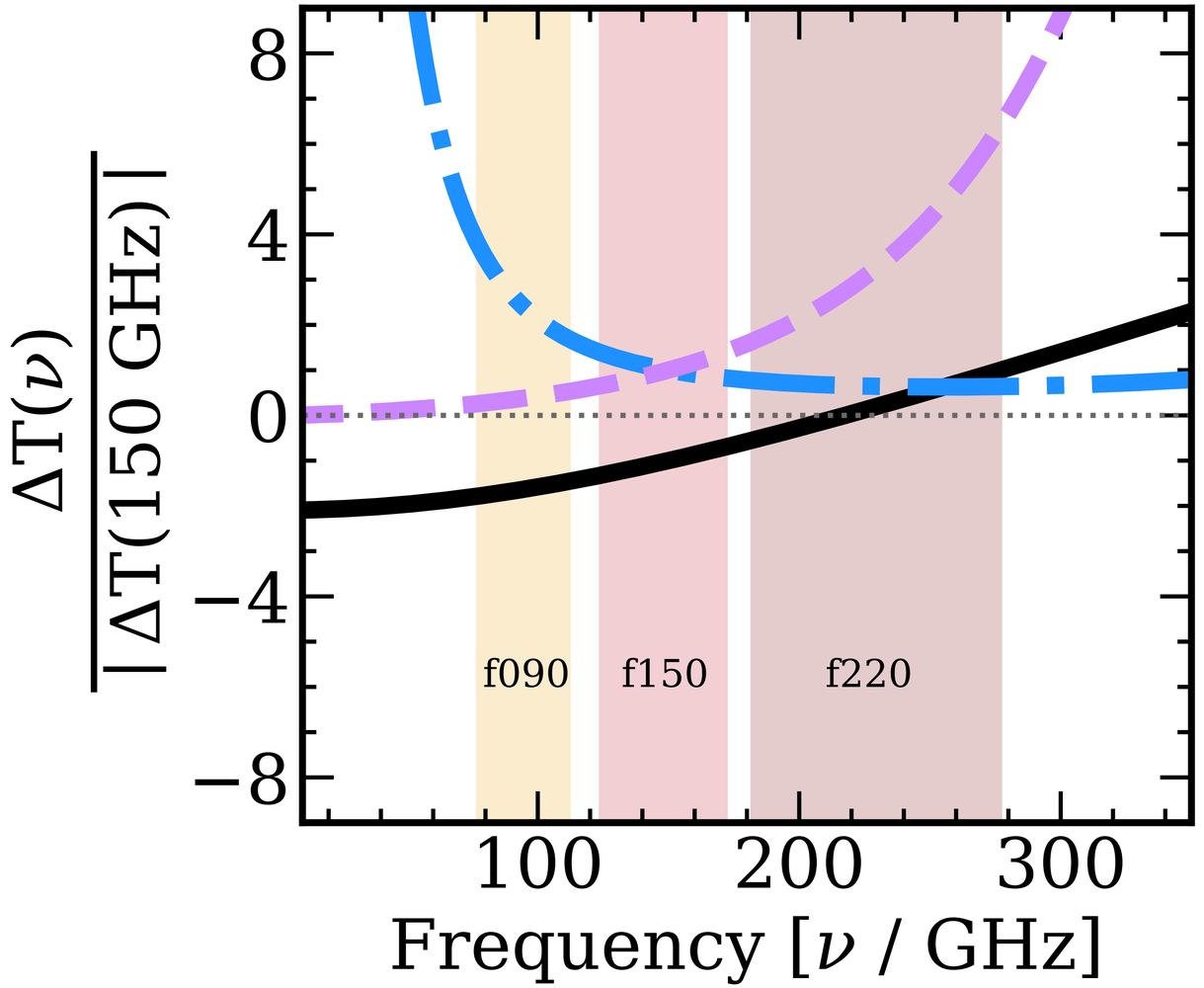
Implications: Non-linear Probes



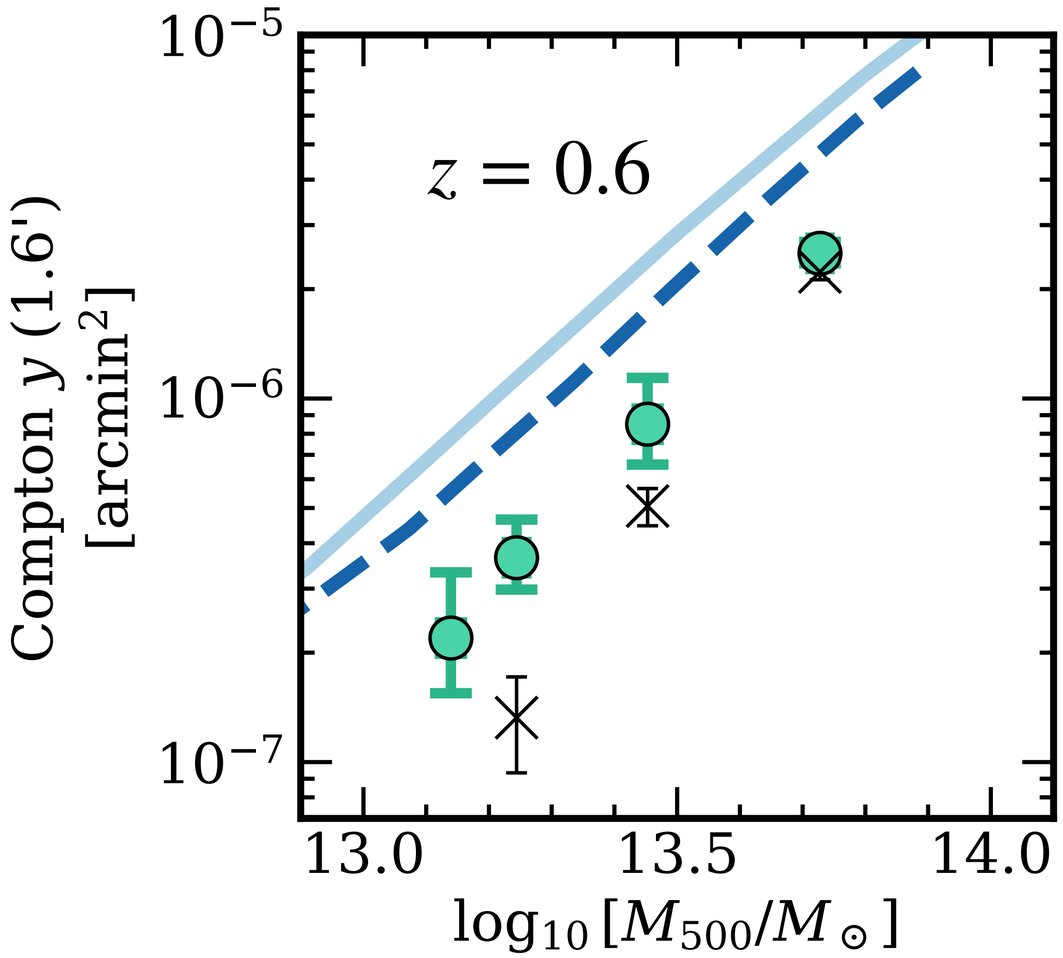


Thermal SZ Effect





New Thermal SZ Measurements



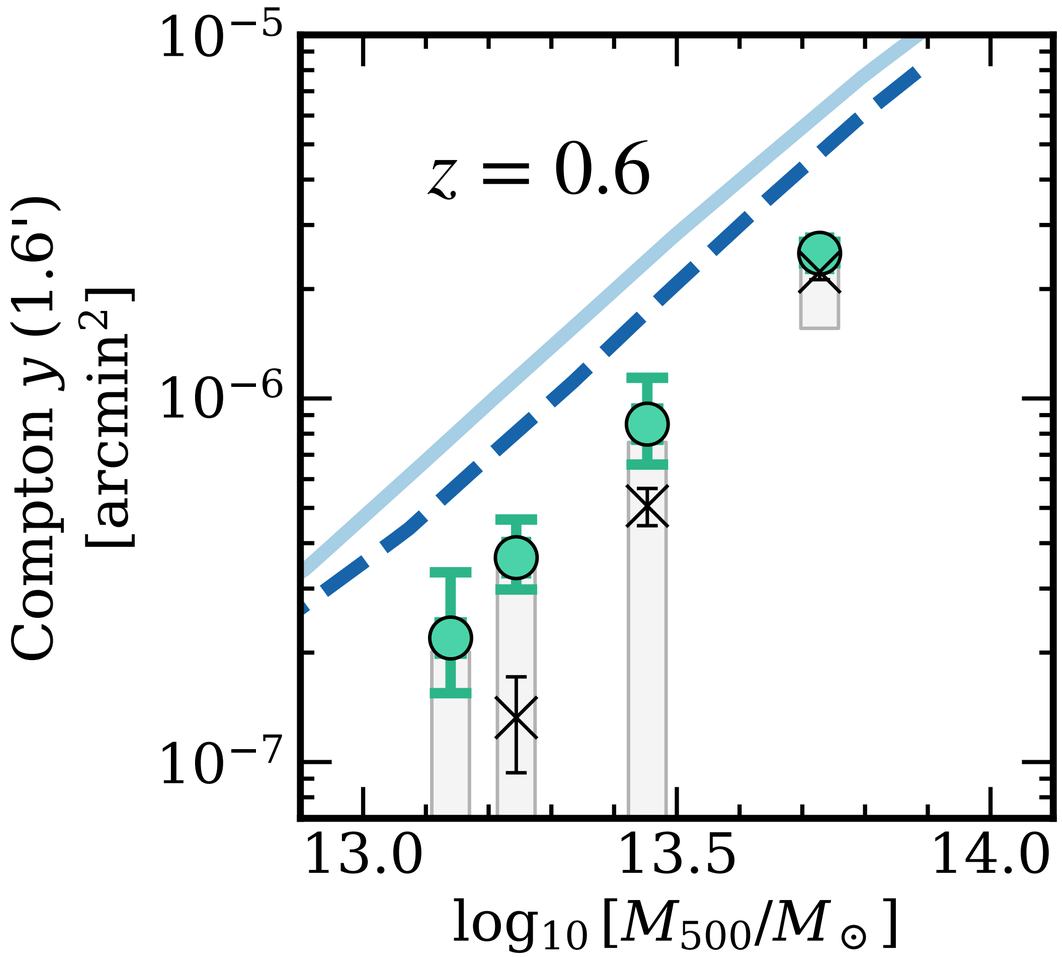
This Work (Dust+Radio model)

No Corrections

Fiducial FLAMINGO

Strongest FLAMINGO

New Thermal SZ Measurements



This Work (Dust+Radio model)

No Corrections

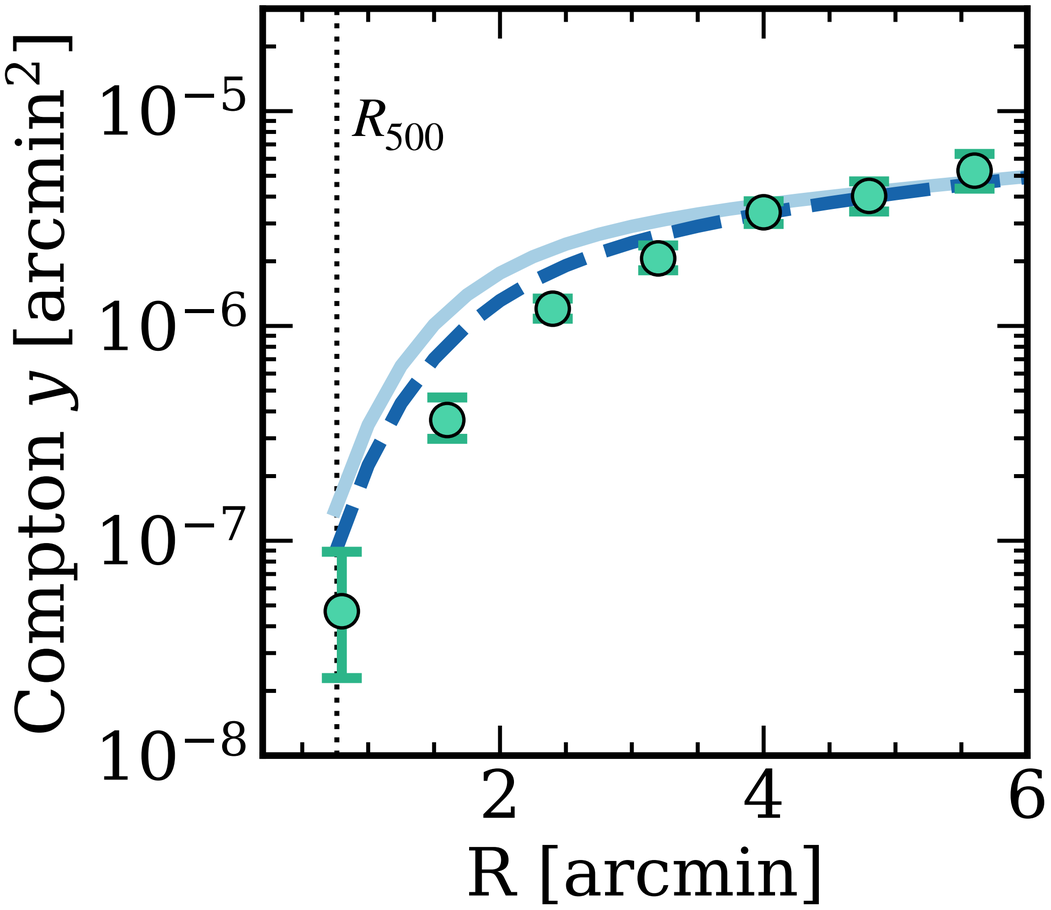
Fiducial FLAMINGO

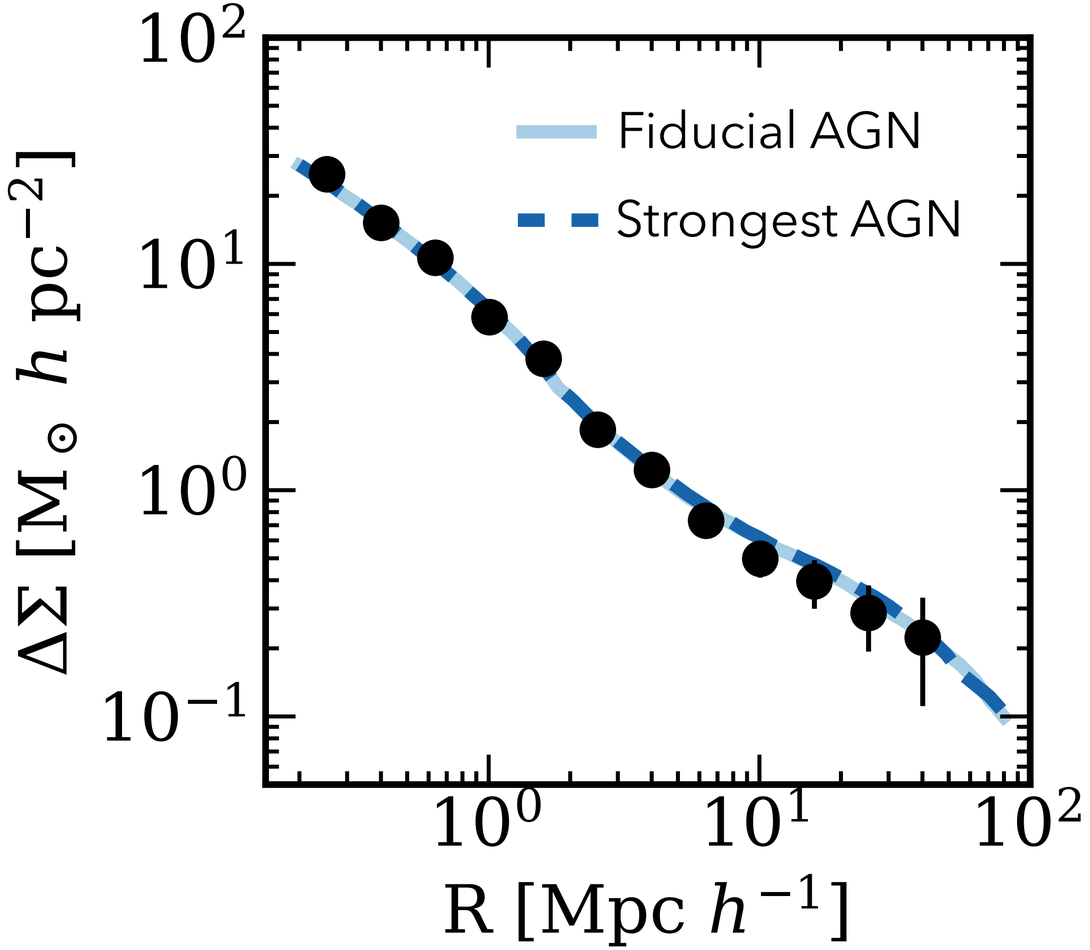
Strongest FLAMINGO

ACT+Planck CIB+$d\beta$ deprojections (Coulton+24)

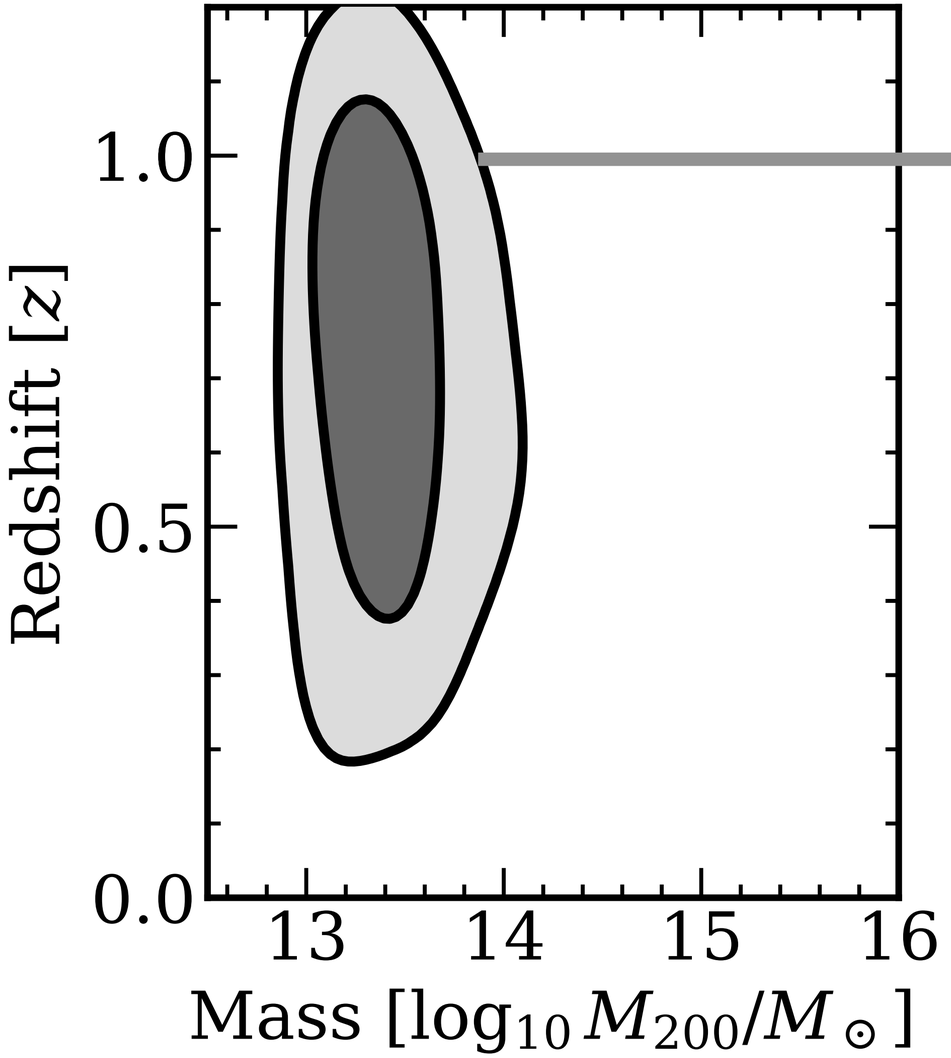
Also see Liu + 25, Das + 25/26

New Thermal SZ Measurements

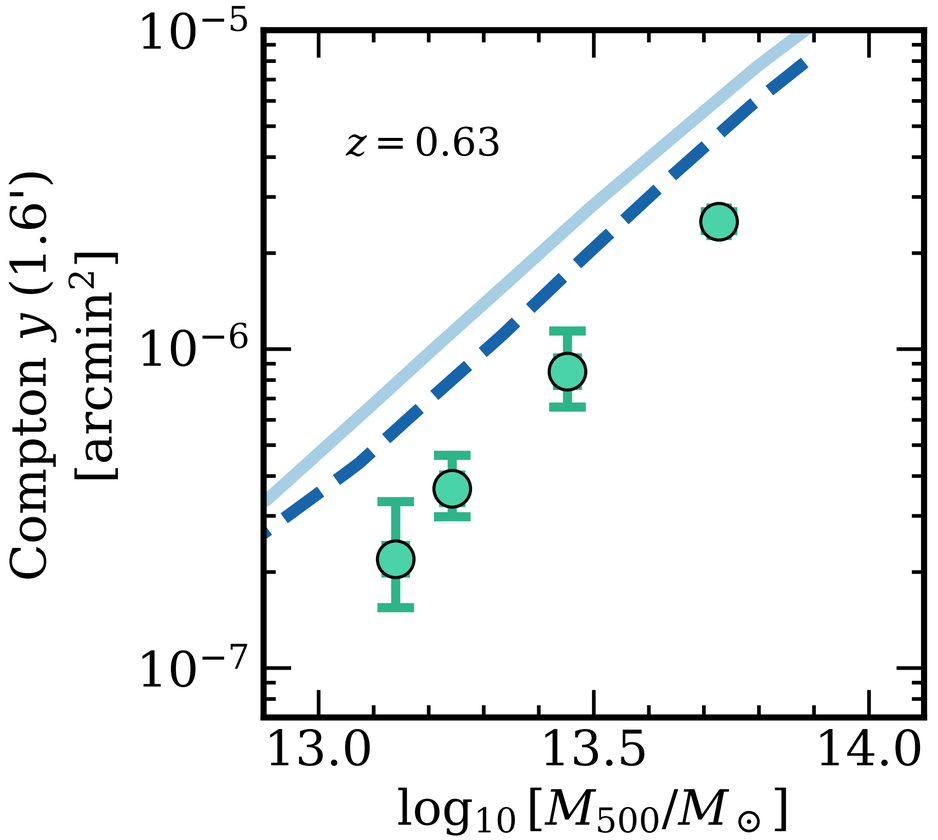




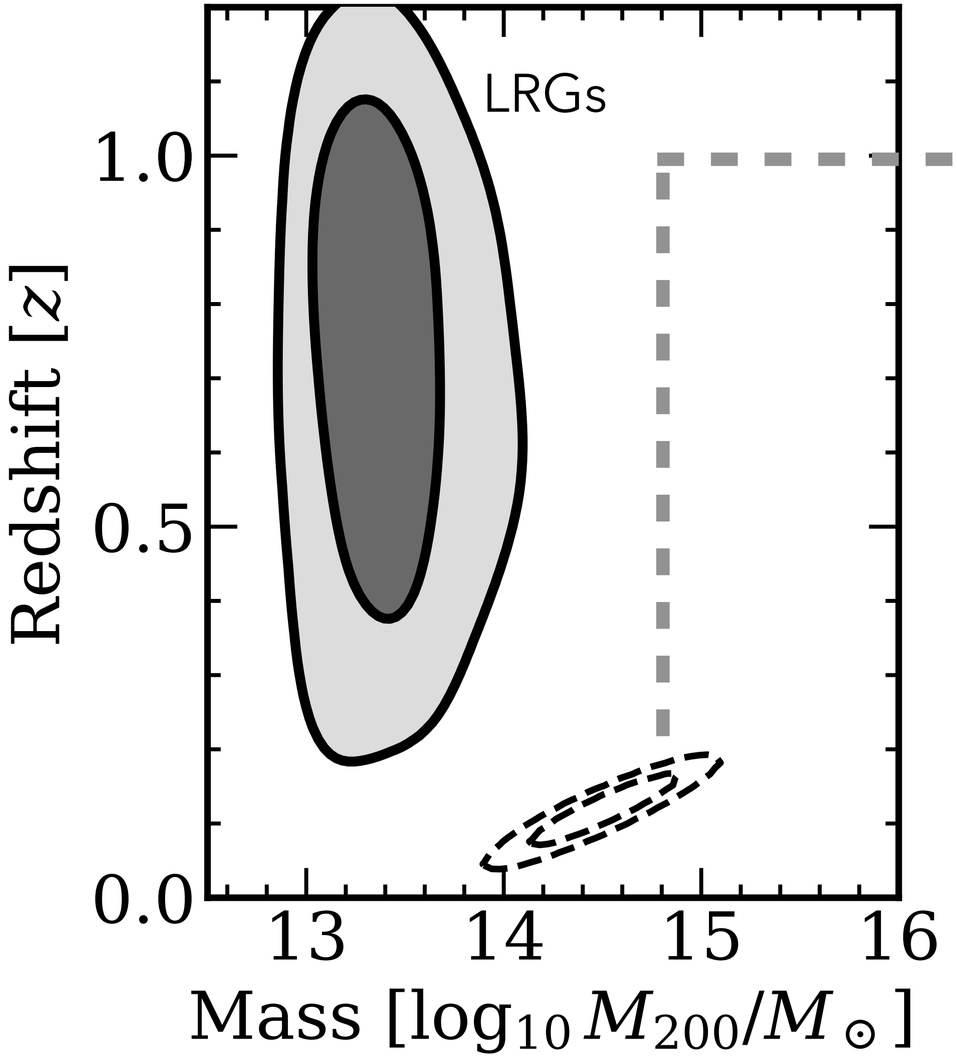
Landscape of Thermal Pressure



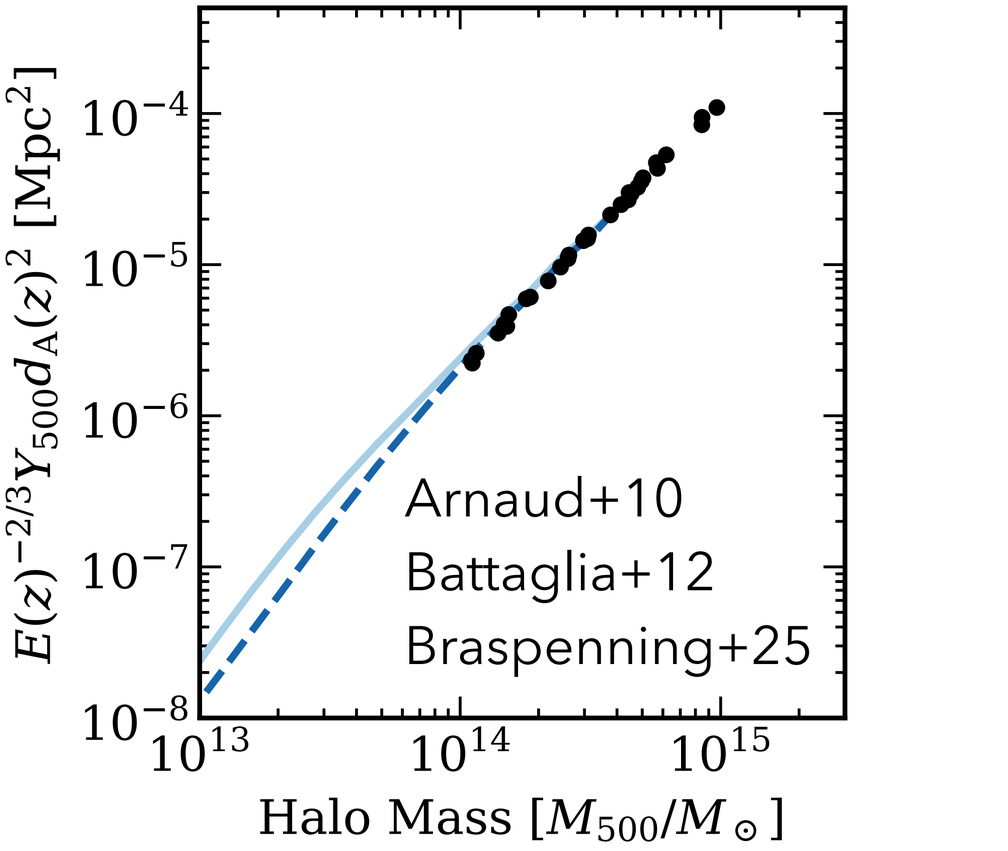
DESI LRGs



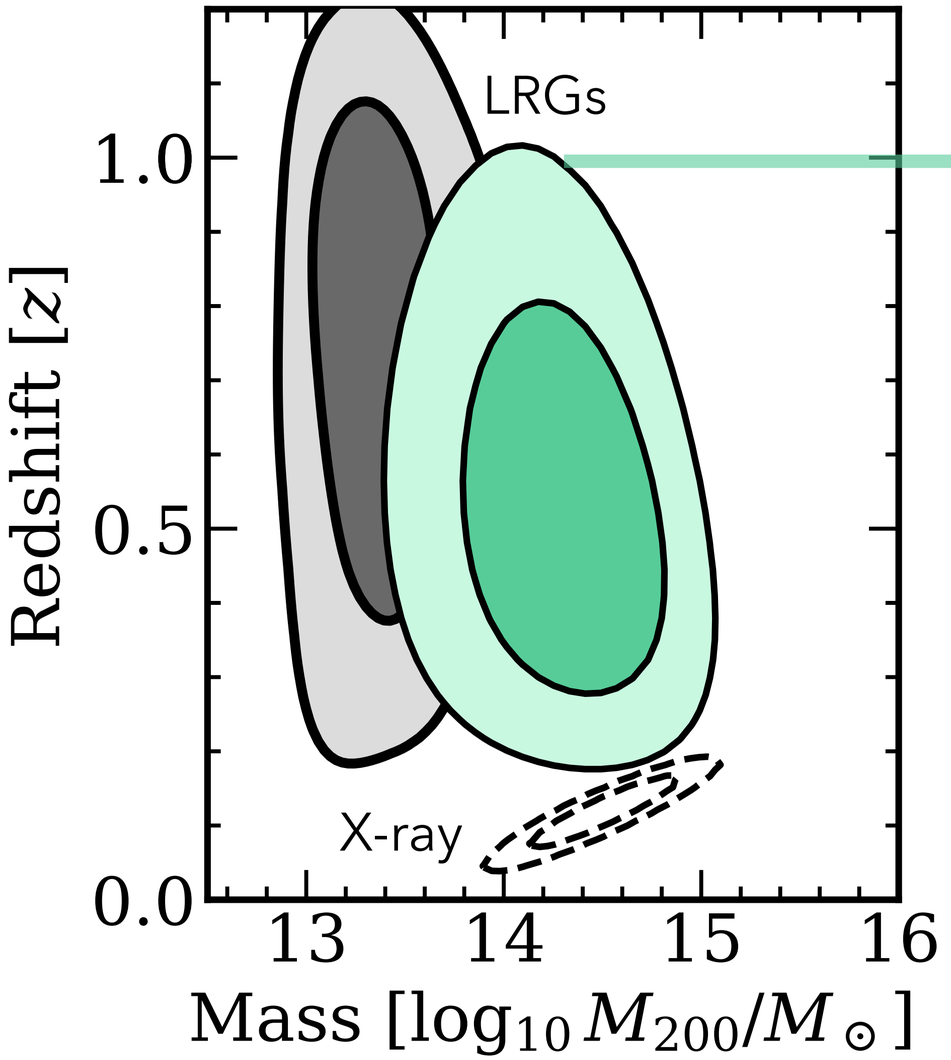
Landscape of Thermal Pressure



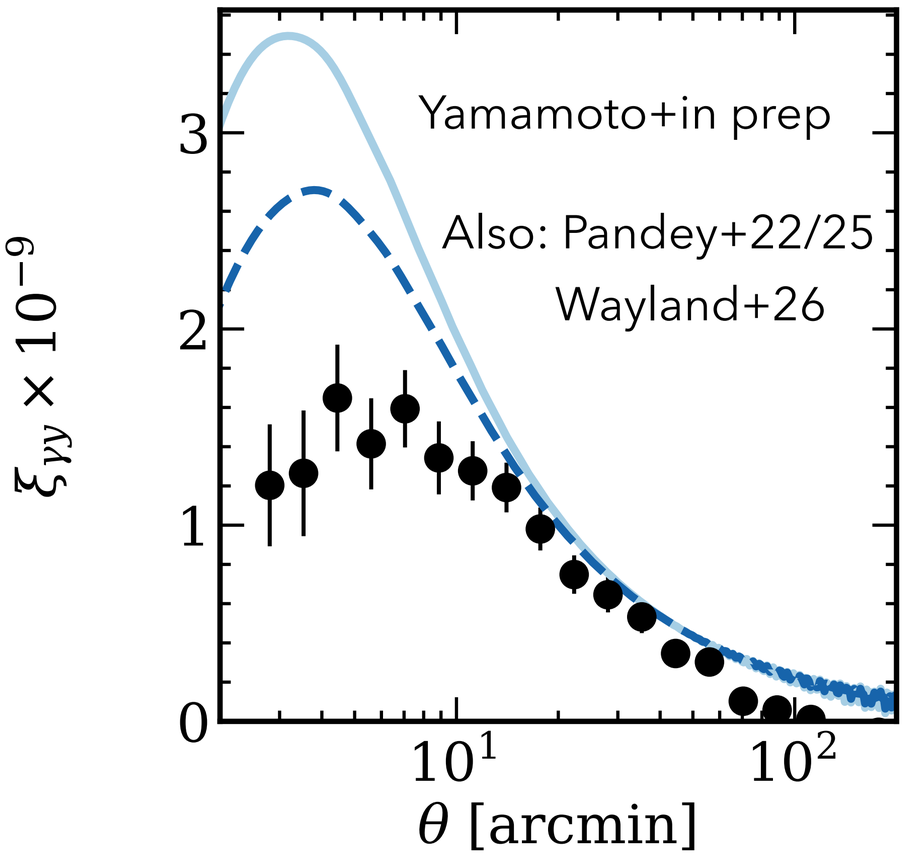
REXCESS X-ray Sample



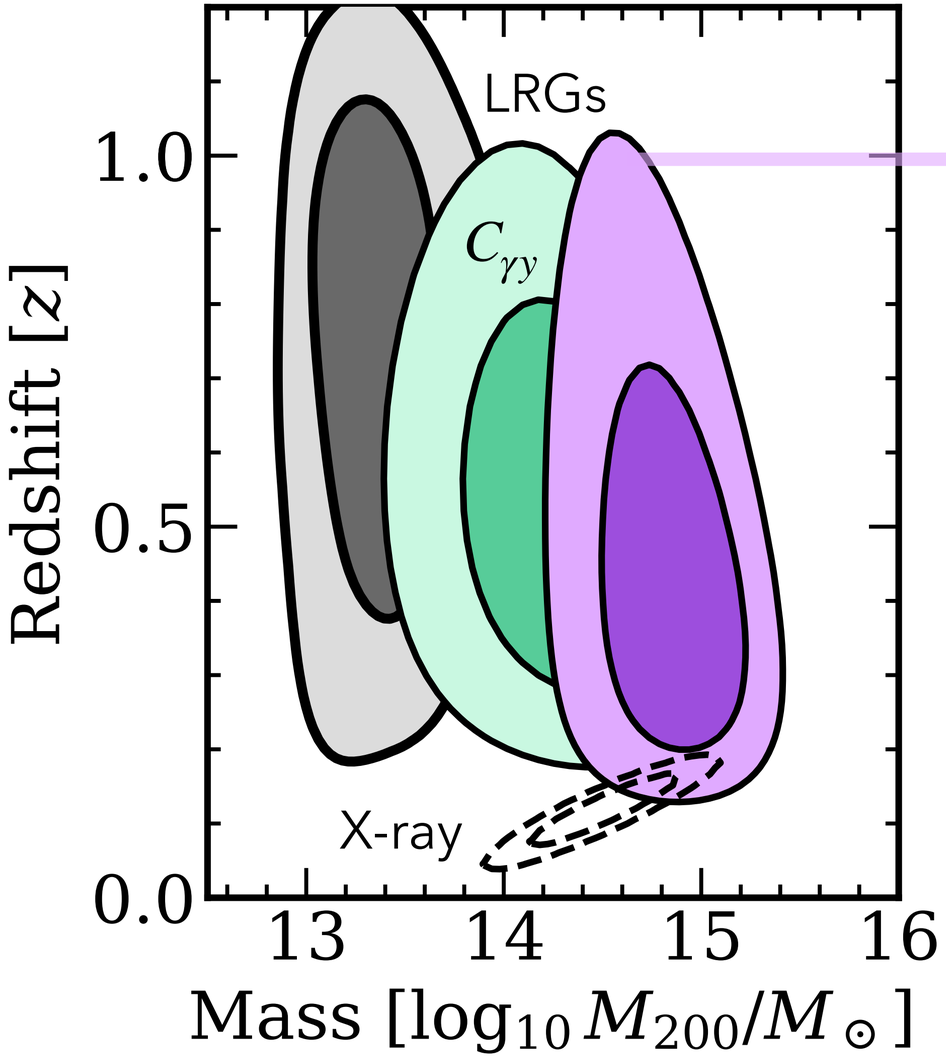
Landscape of Thermal Pressure



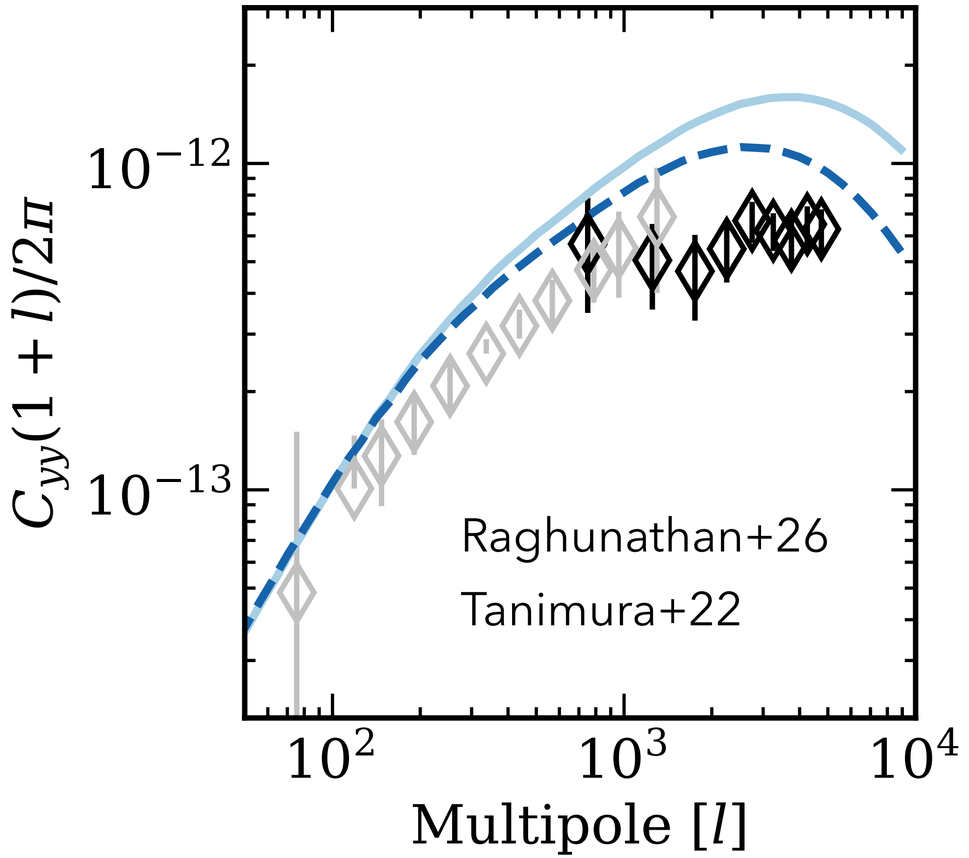
tSZ x Shear



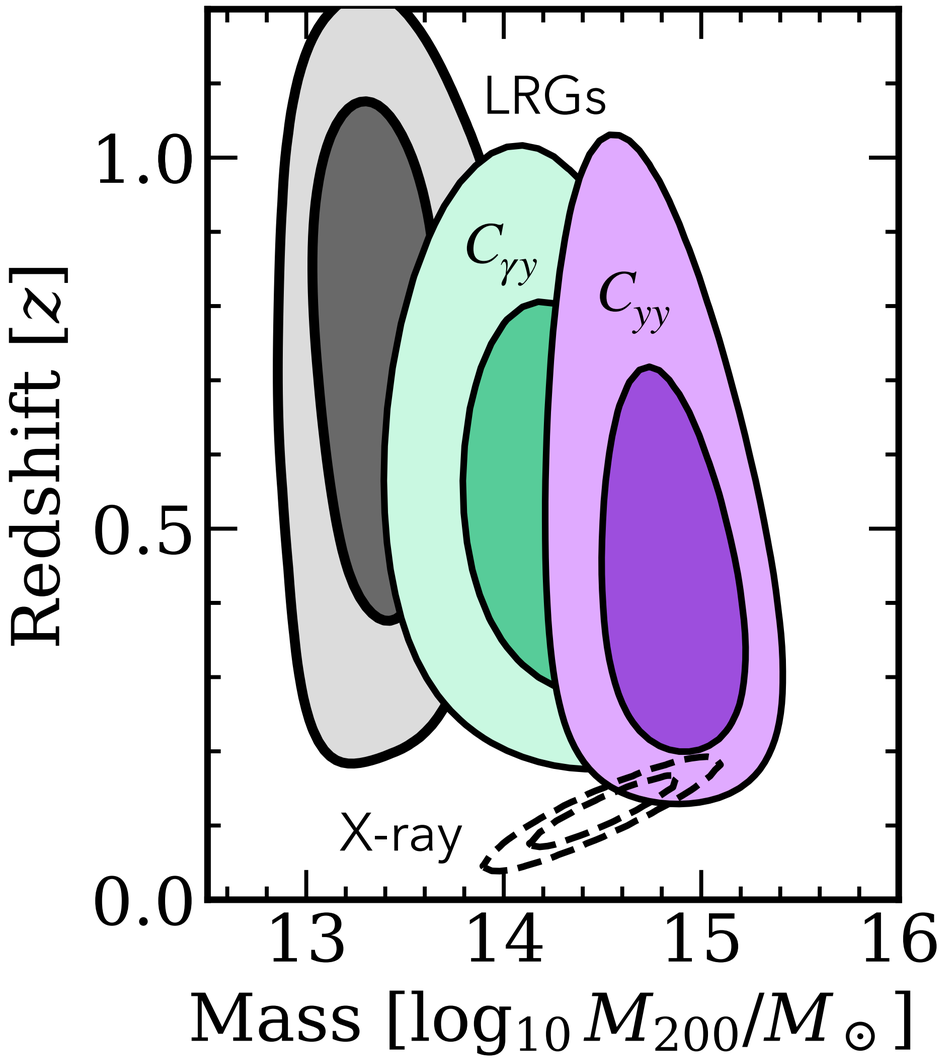
Landscape of Thermal Pressure



tSZ Autopower



Landscape of Thermal Pressure



- Cosmic ray pressure support?

  Quataert & Hopkins (2025)
  Ponnada et al. 2026

- History of energy injection

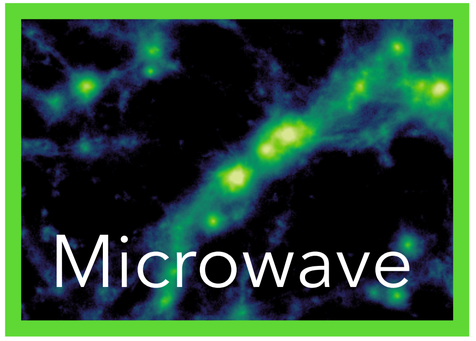
- Intrinsic scatter in gas properties

Also see Pandey+22/25, La Posta+25, Wayland+26

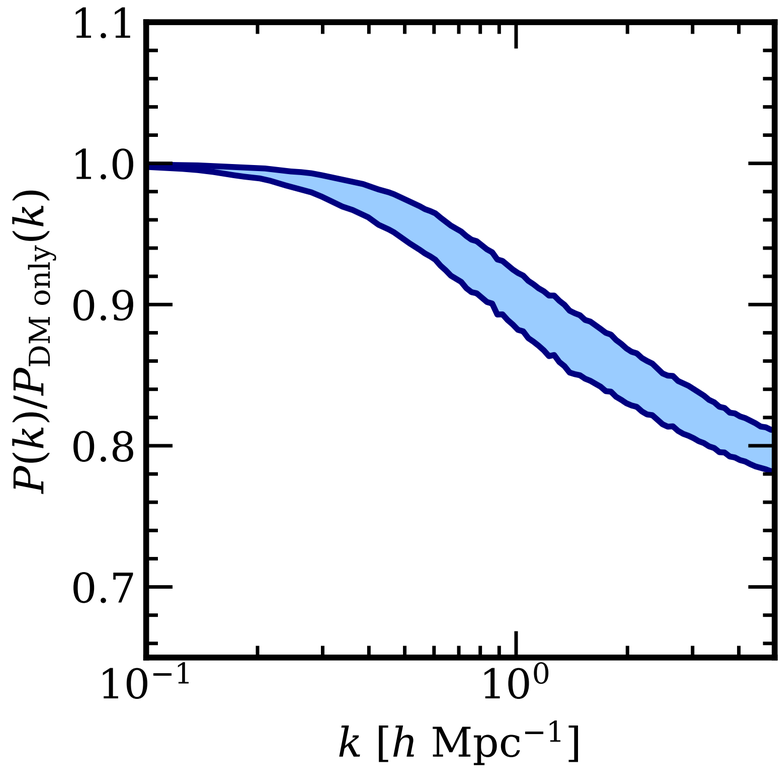
Building a Complete Picture







Where is the gas?



What is its state?

