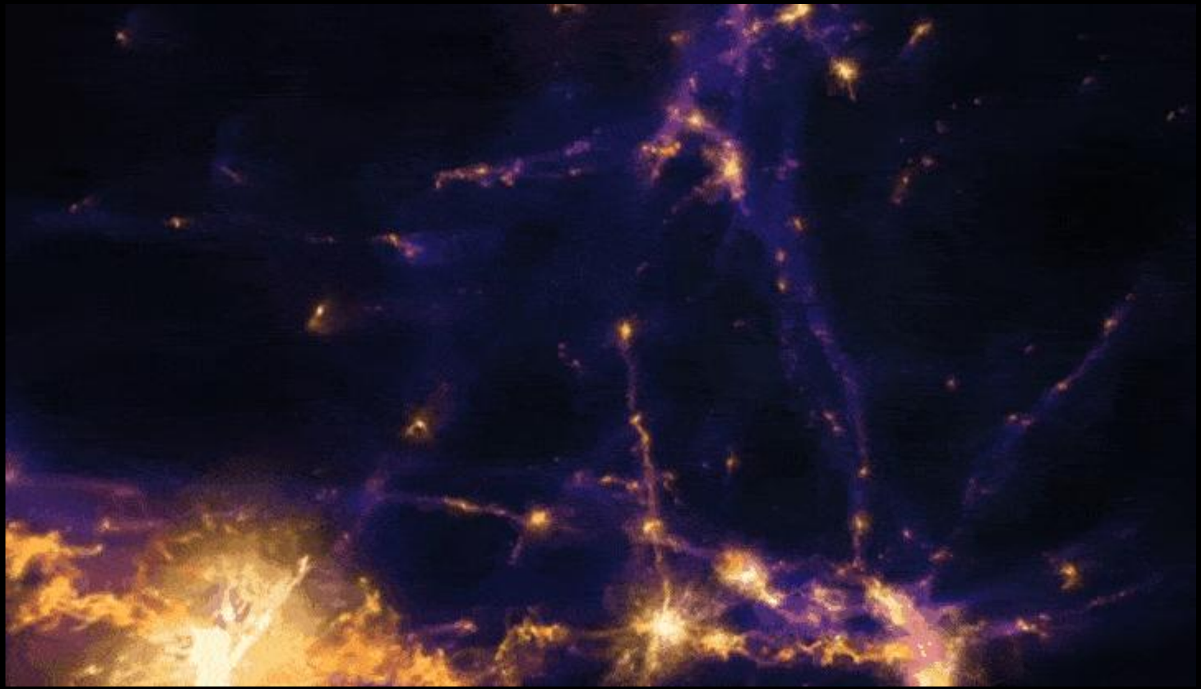


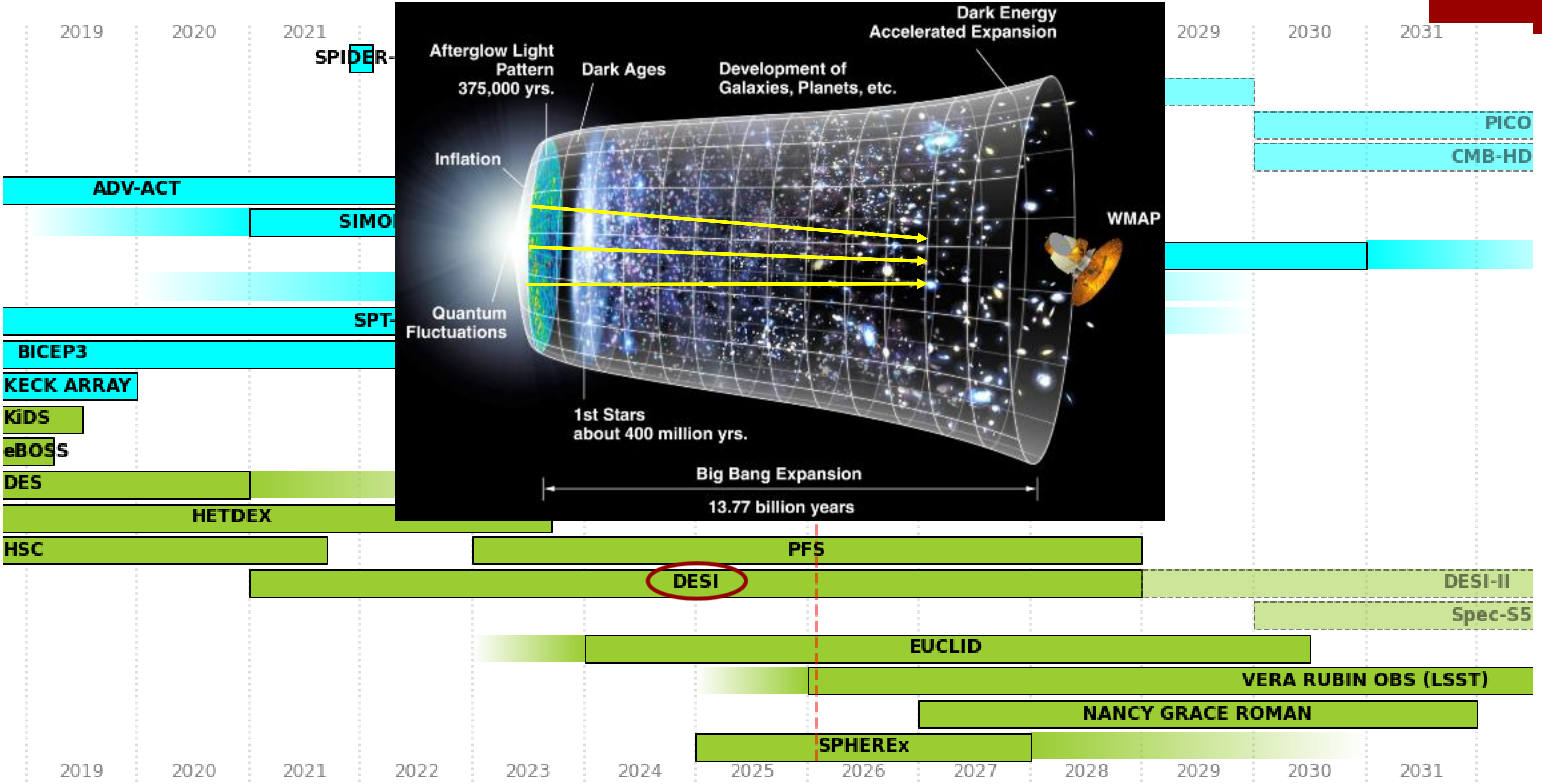
Anchors in the late- and mid-time Universe

Boryana Hadzhiyska
Institute of Astronomy
Assistant Professor

CosmoForward, Tenerife

10/2/2026

Mid- and late-time anchors



Credit: D. Kirkby

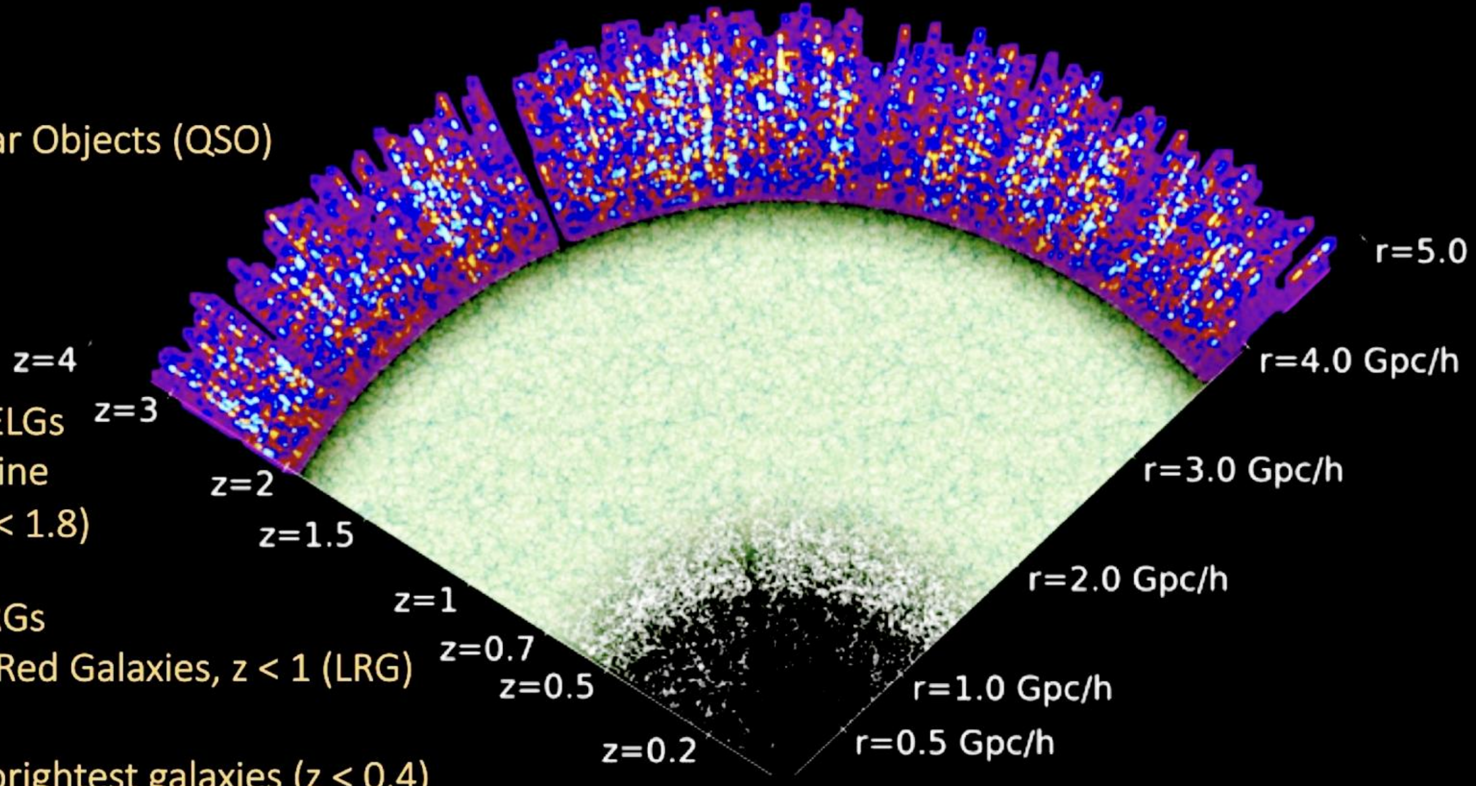
Dark Energy Spectroscopic Instrument (DESI)

≳ **2.7** million
Quasi Stellar Objects (QSO)

≳ **13** million ELGs
(Emission Line
Galaxies, z < 1.8)

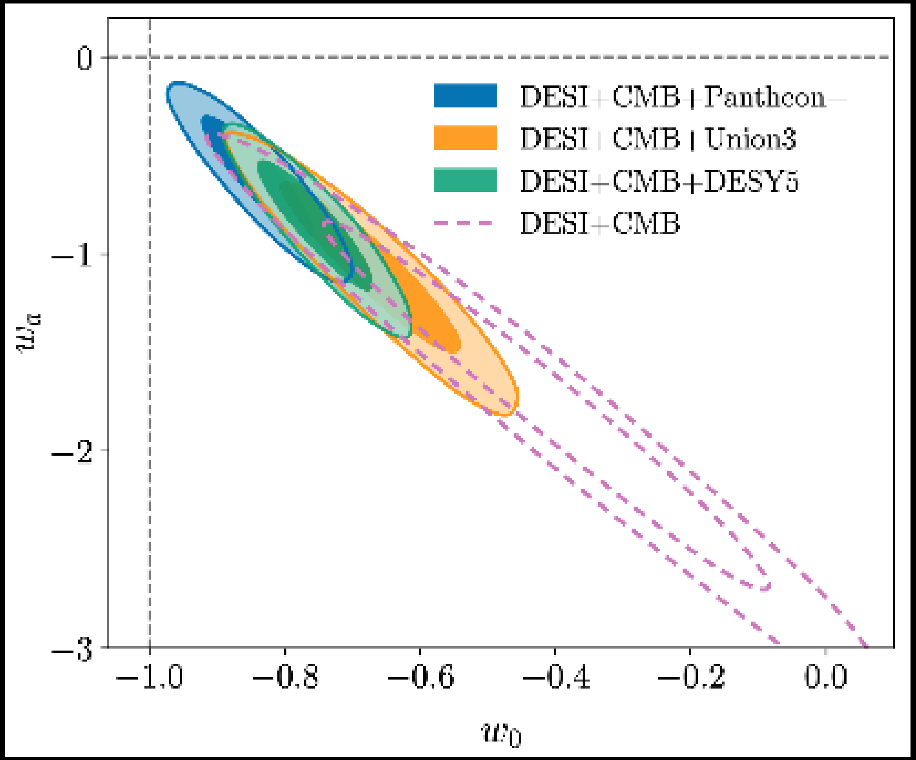
≳ **7.5** million LRGs
(Luminous Red Galaxies, z < 1 (LRG)

≳ **9** million brightest galaxies (z < 0.4)

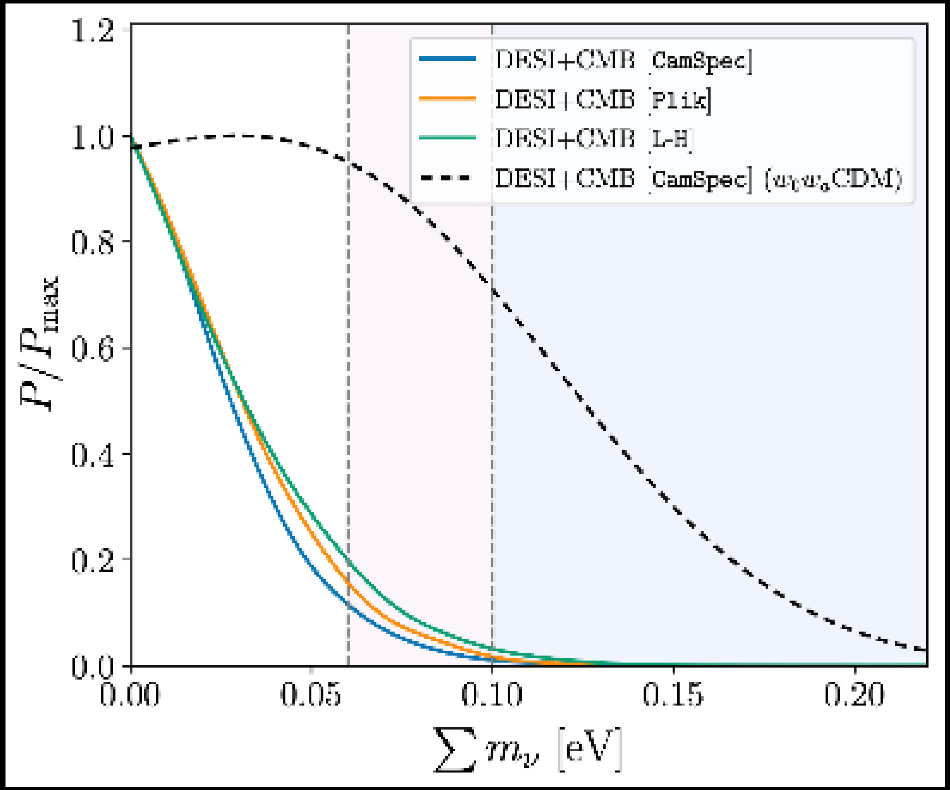


Dark Energy and neutrino masses

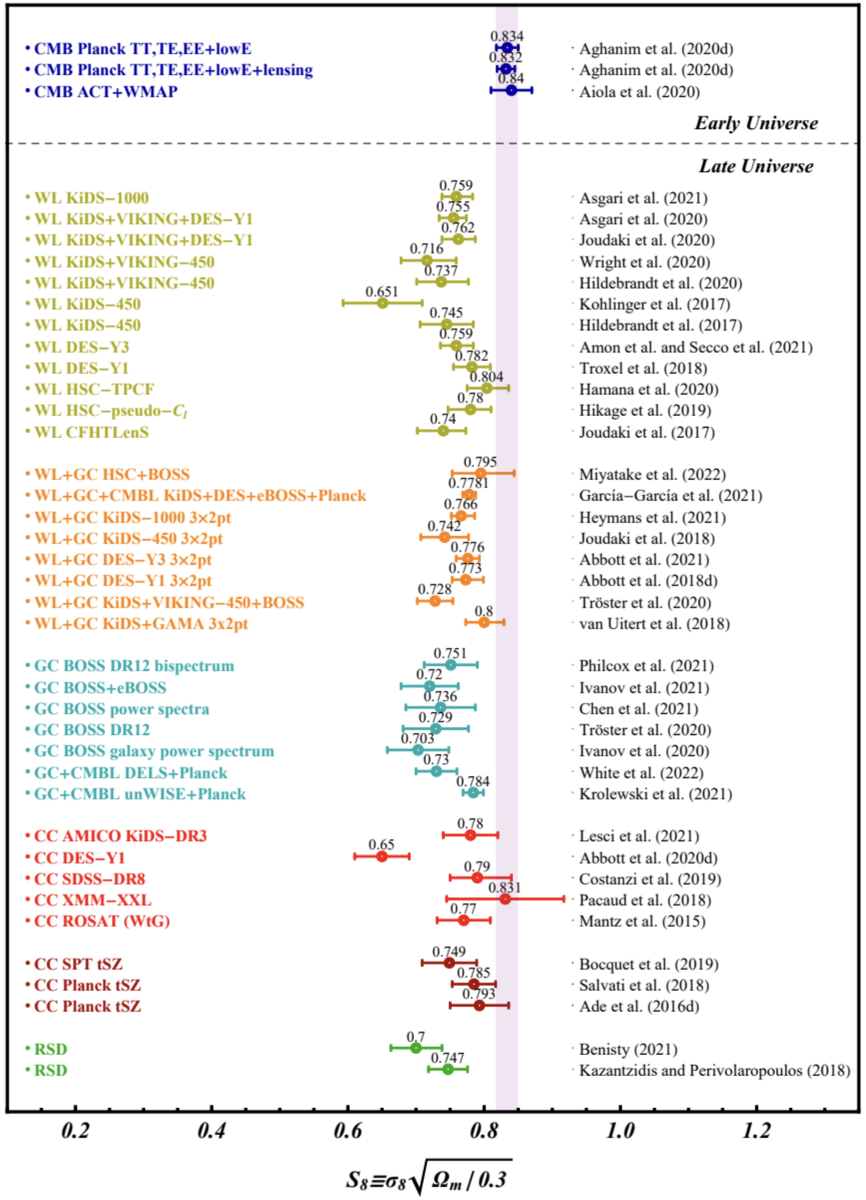
Is dark energy dynamical?



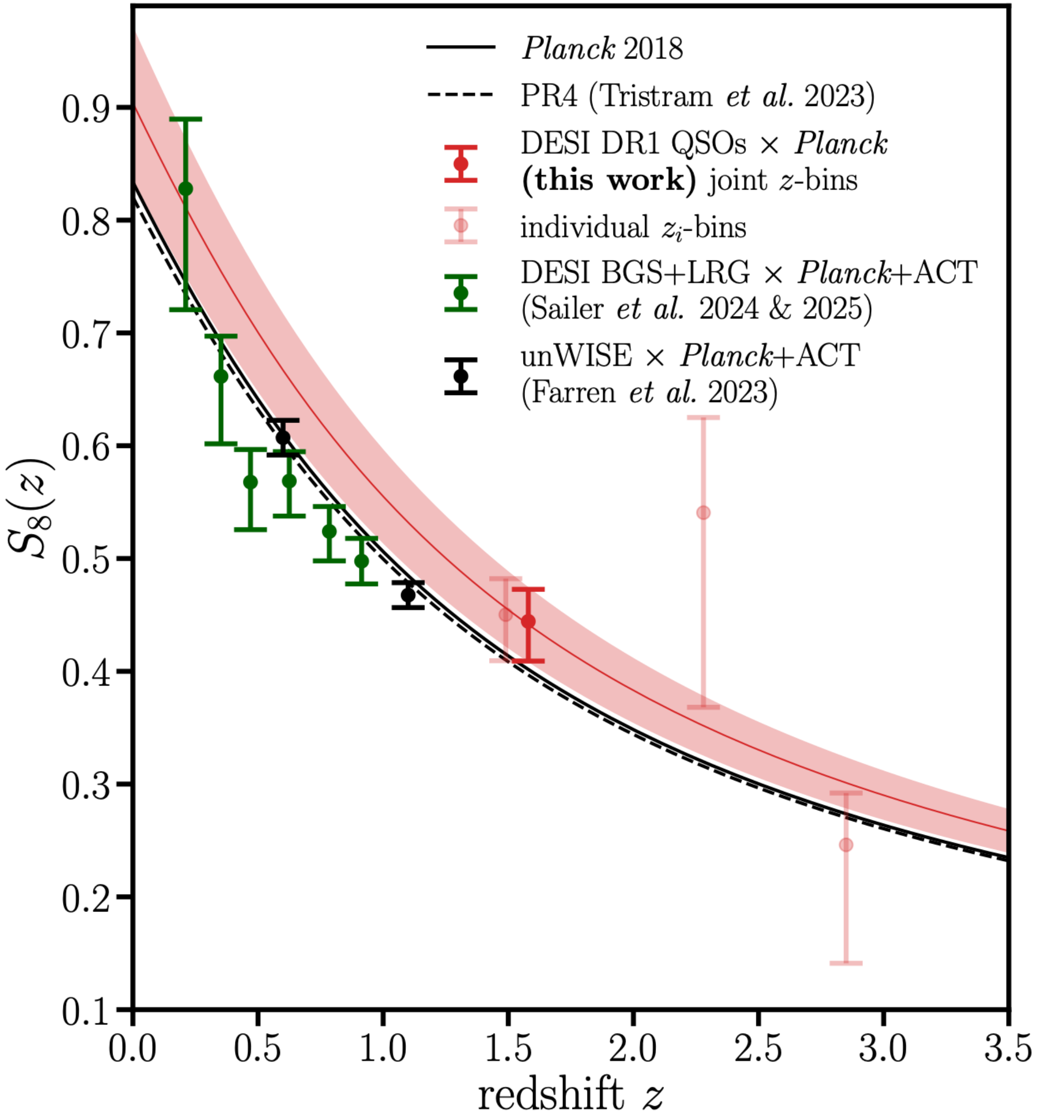
Can we reliably measure neutrino mass?



Why study the growth of structure over time?



Credit: Abdalla (2022)



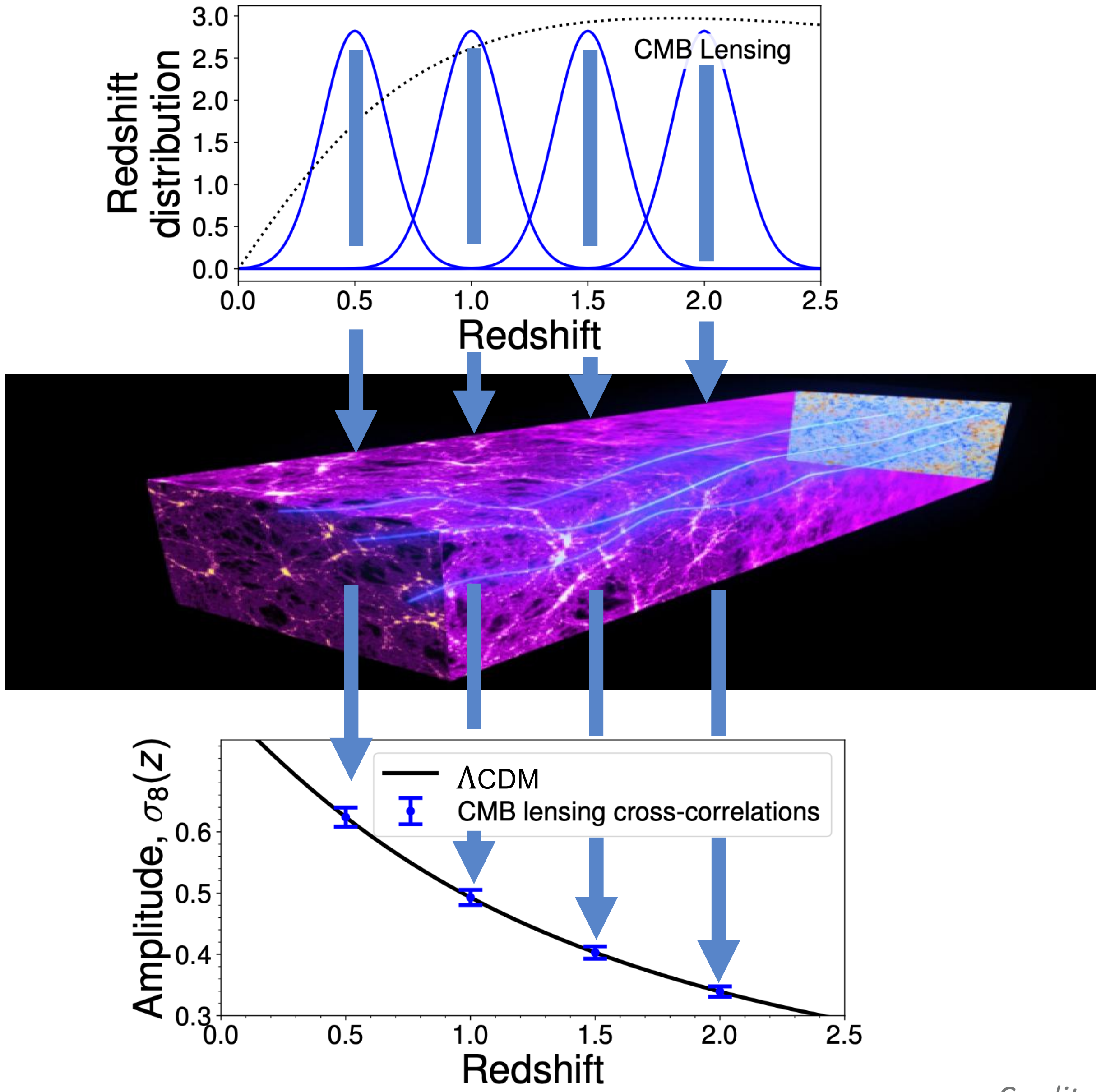
Farren et al. (2023), Sailer et al. (2024, 2025), de Belsubce (2025)

CMB lensing tomography

$$C_\ell^{\kappa g} \propto b_g \sigma_8^2$$
$$C_\ell^{gg} \propto b_g^2 \sigma_8^2$$

$$\sigma_8 \sim \frac{C_\ell^{\kappa g}}{\sqrt{C_\ell^{gg}}}$$

$$\mathrm{S/N}(\sigma_8) = \mathrm{S/N}(C_\ell^{\kappa g})$$



Credit: A. Krolewski

DESI DR2 x CMB lensing analysis

- Coming soon!
- People involved: Alex Krolewski, Anton Baleato, Gerrit Farren, Berni Ried Guachalla, Xinyi Chen, Sofia Chiarenza, Mark Maus, etc.
- Data vector: $P_\ell(k)$, $C_\ell^{\kappa g}$
- Big advance: replace angular power spectrum C_ℓ^{gg} with 3D multipoles $P_\ell(k)$
    - Extra information on $f\sigma_8$ from large-scale RSD
    - $P_\ell(k)$ much less susceptible to angular systematics
- Theoretical model: EFT for galaxy clustering and Hybrid EFT for cross-correlations

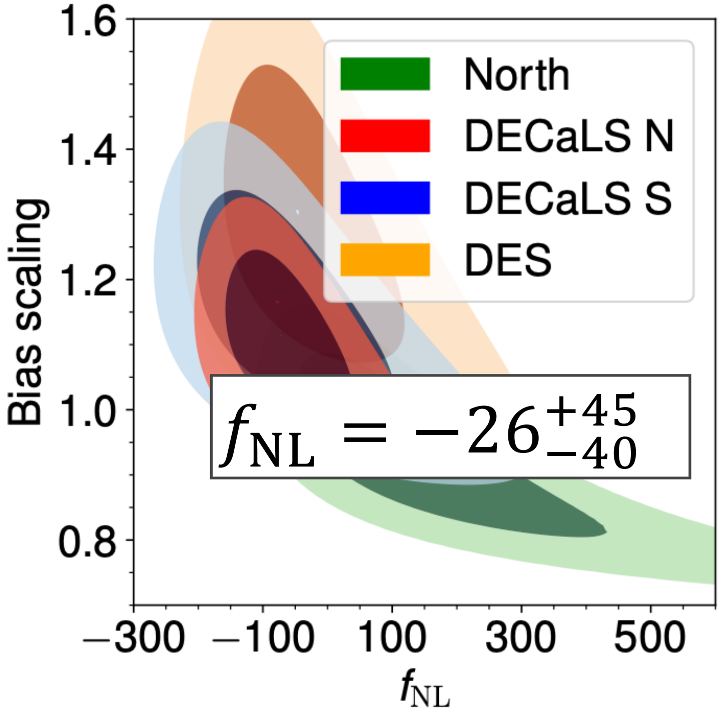
Cross-correlations are clean

Especially important on large scales!

Primordial non-Gaussianity with CMB lensing and large-scale structure

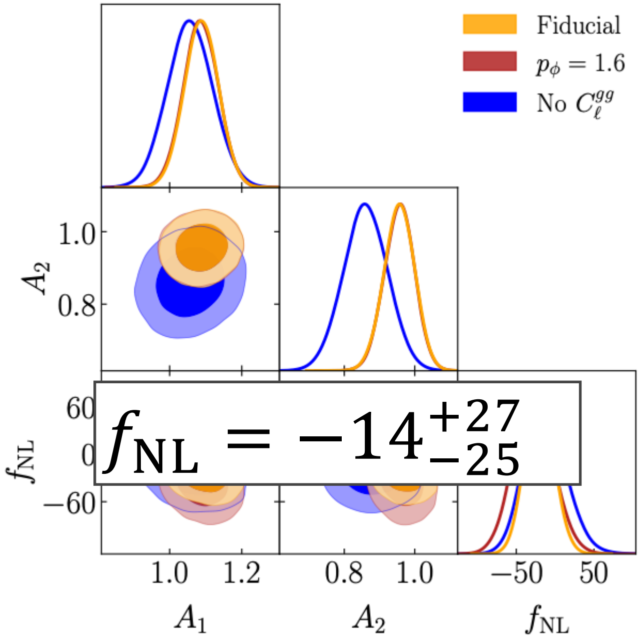
- Quasar targets are difficult: tons of large-scale power even after cleaning
- Cross-correlations are clean: use them to access contaminated modes!

DESI QSO targets x Planck PR3



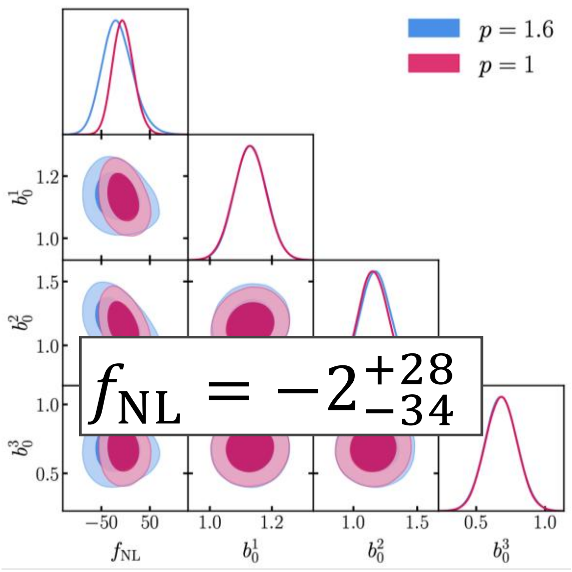
Krolewski et al. (2024)

Quaia x Planck PR4



Fabbian et al. (2024)

DESI DR1 QSO spec x Planck PR4



Chiarenza et al. (2025)

A killer application of cross-correlations to PNG

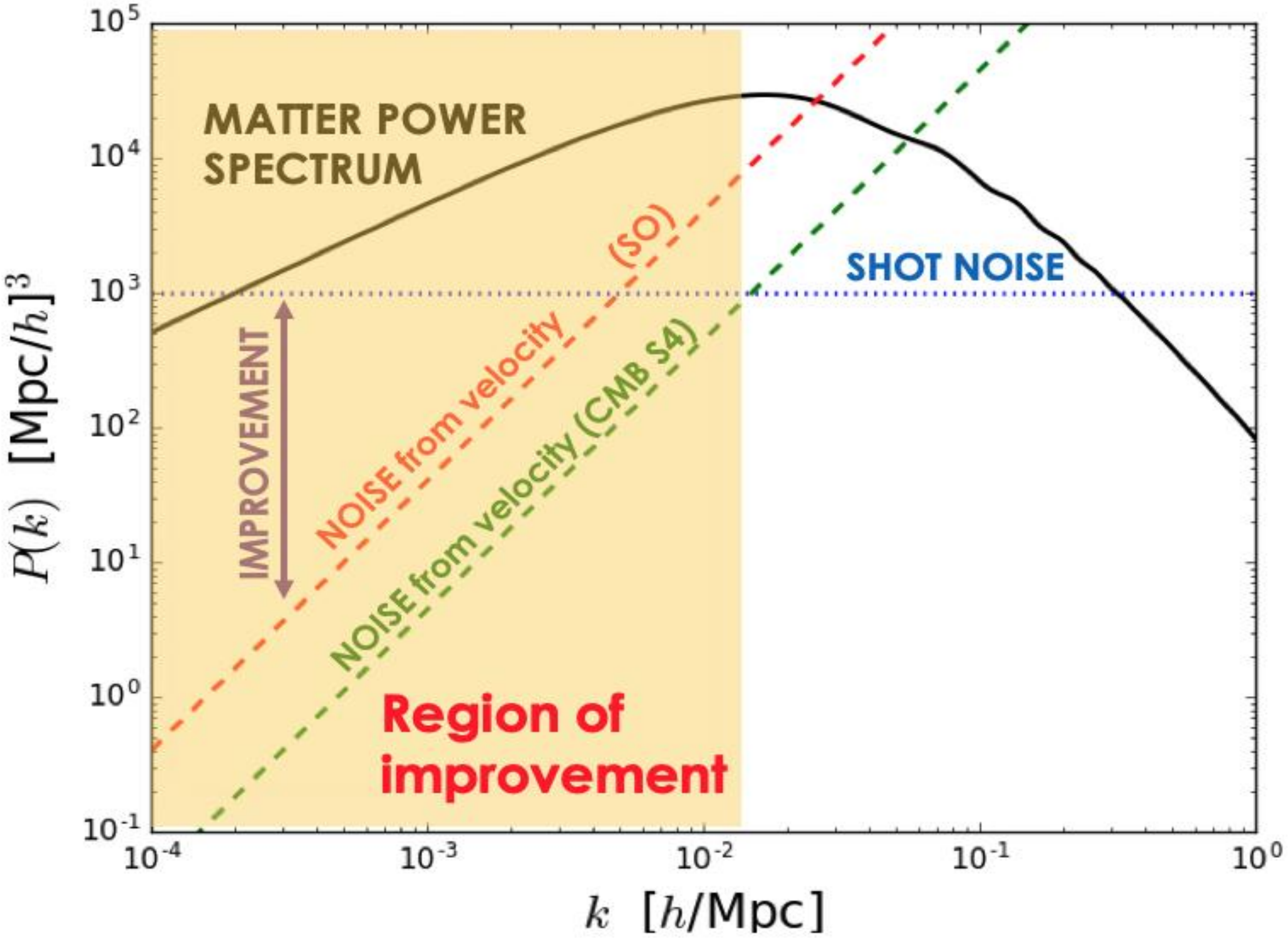
- Radial velocity map can be reconstructed from the kSZ effect

$$\frac{T_{\rm kSZ}}{T_{\rm CMB}} = \tau_{\rm halo} \; \frac{v_{\rm halo}}{c}$$

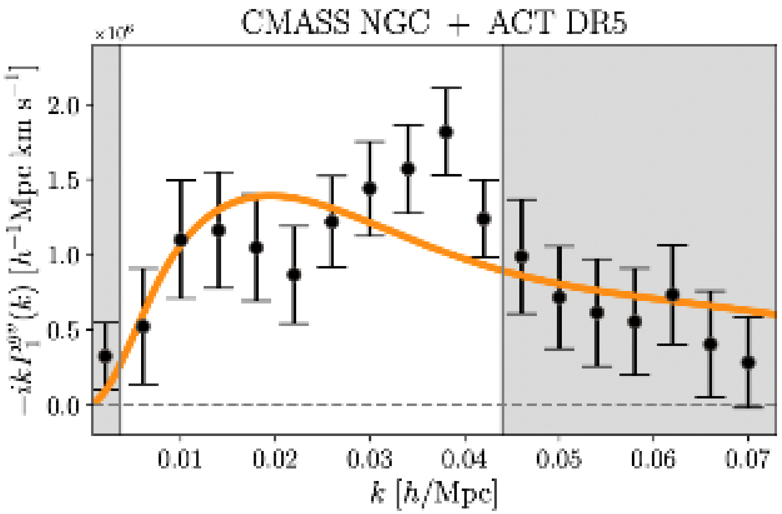
- Reconstruction noise:

$$\text{Recon. noise} \propto k^2$$

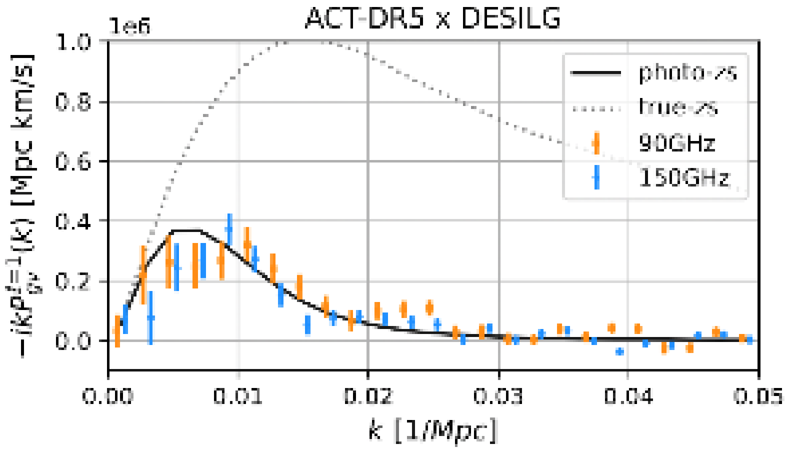
- Perfect for large scales



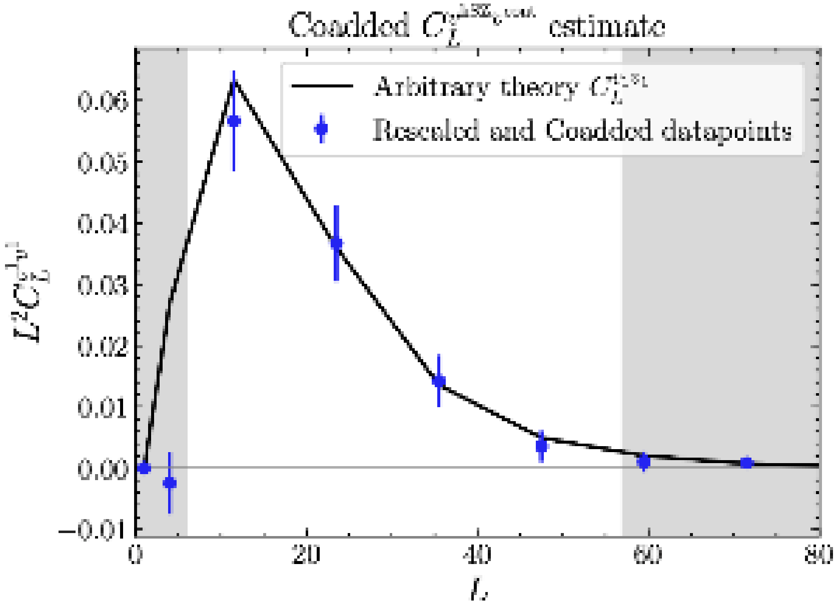
kSZ velocity reconstruction: some recent results



Lague, Madhavacheril++ (PRL, 2025)



Hotinli, Smith, Ferraro (2025)



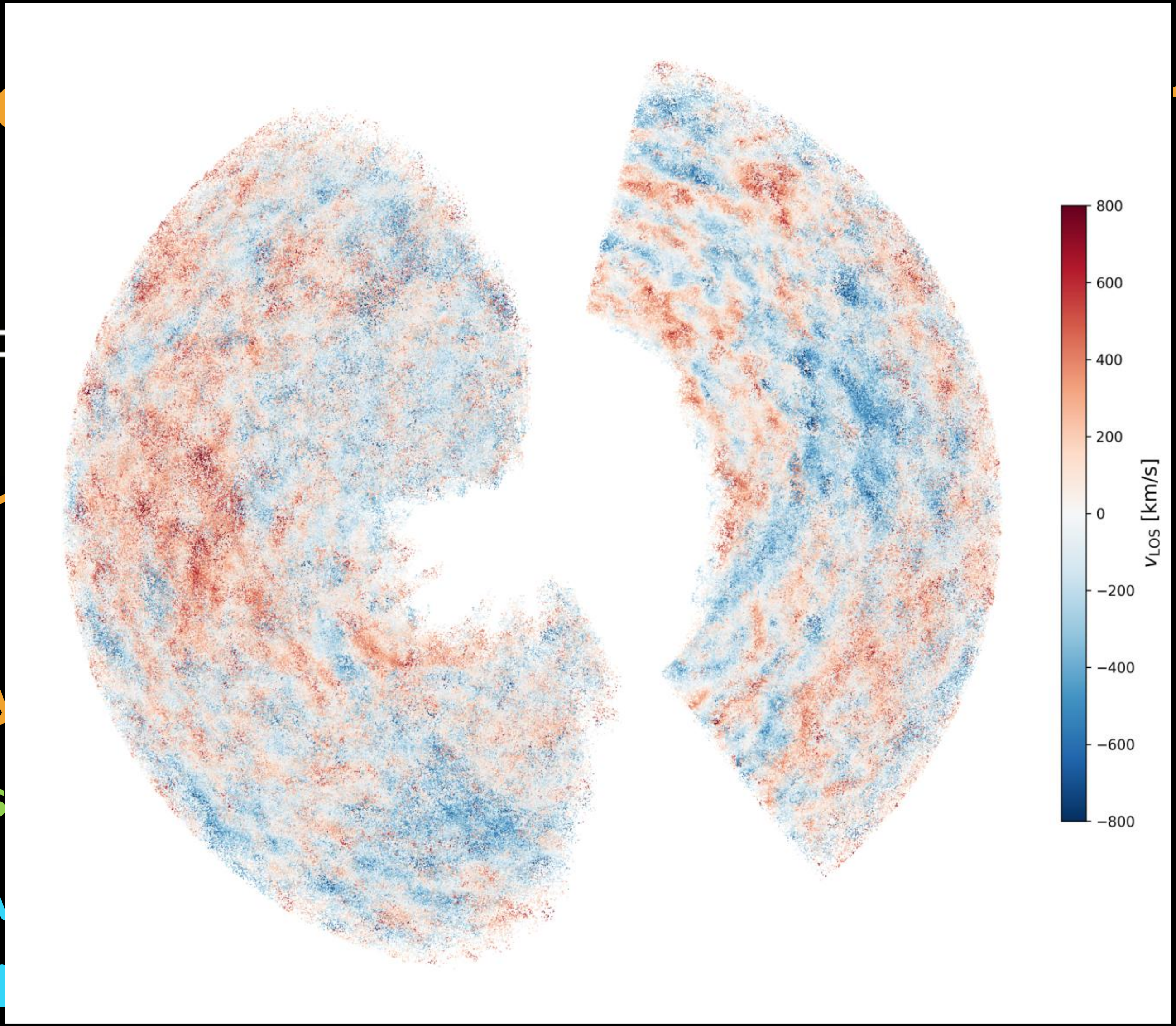
McCarthy++ (2025)

Also Lai, Kvasiuk, Münchmeyer (2025)

- Upcoming exciting results from DESI DR2
- Numerous opportunities with SPHEREx

Kinemati... t

From CMB $\frac{T_{\rm kSZ}}{T_{\rm CMB}} =$

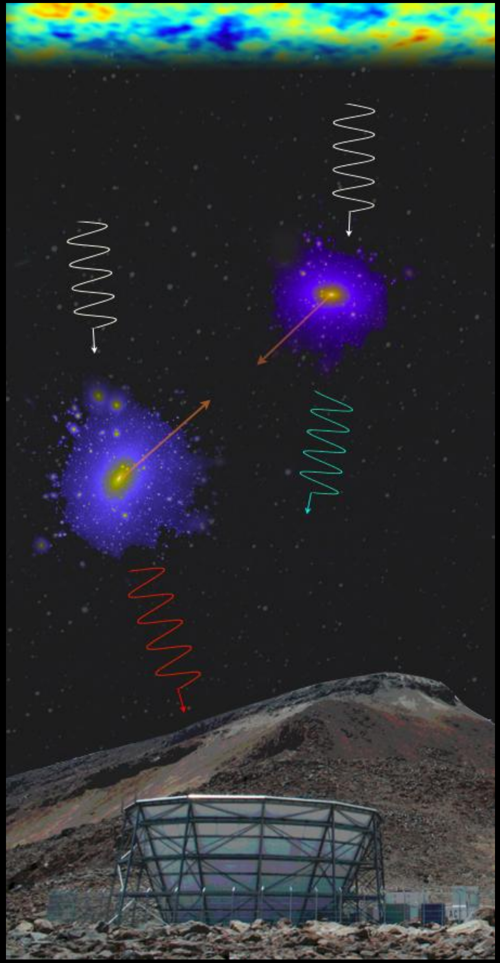


"Optical depth" =
key to gas density

Astrophysics

Robust to additiv

Clean probe of t



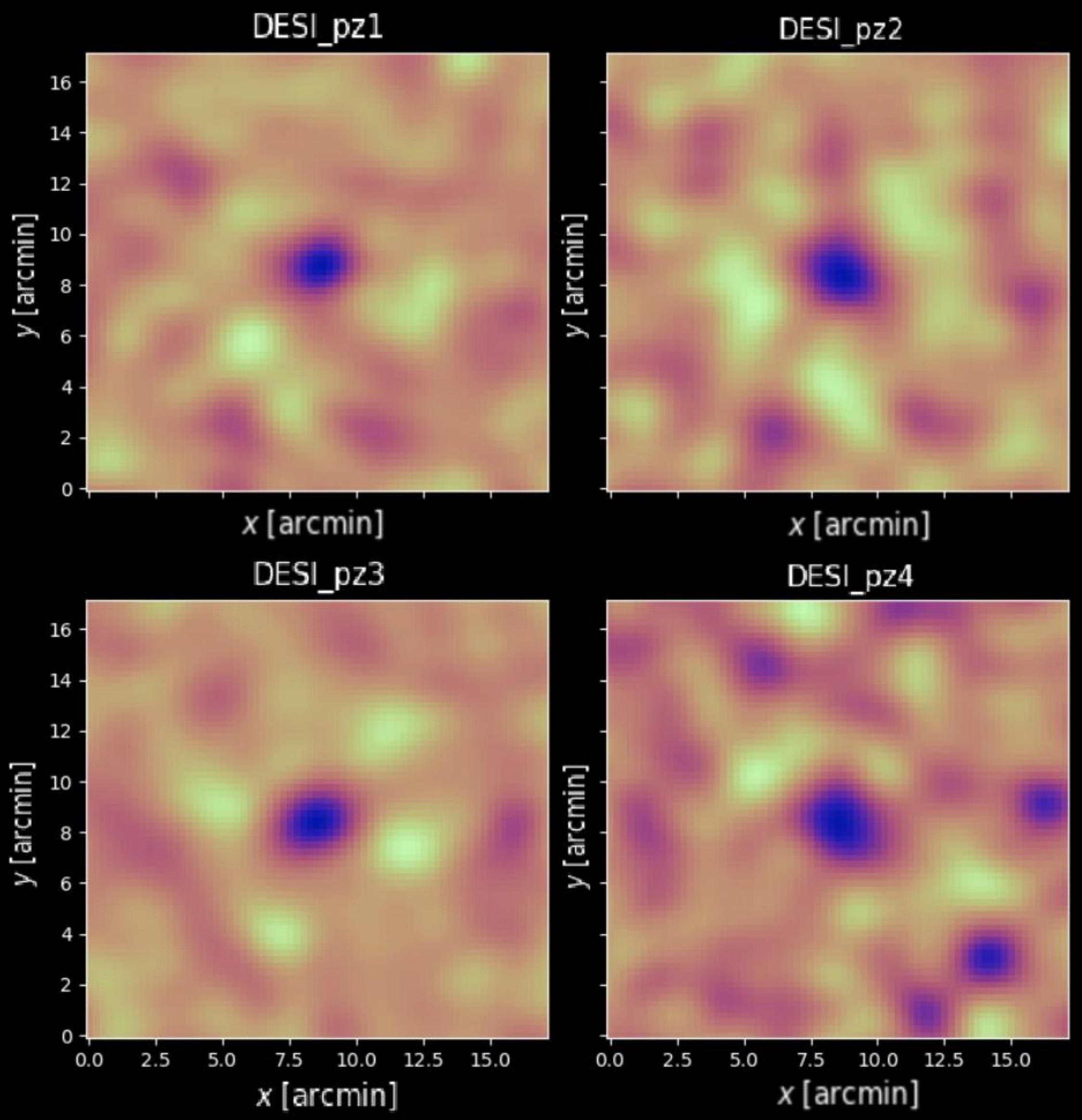
2D stacks of galaxies

CMB map cutouts

$$\hat{T}_{\rm kSZ}(\theta_d) = -\frac{1}{r}\frac{v^{\rm rec}_{\rm rms}}{c}\frac{\sum_i \mathcal{T}_i(\theta_d)(v_{{\rm rec},i}/c)}{\sum_i (v_{{\rm rec},i}/c)^2}$$

60-70% correlation b/n true and reconstructed

Continuity equation velocities

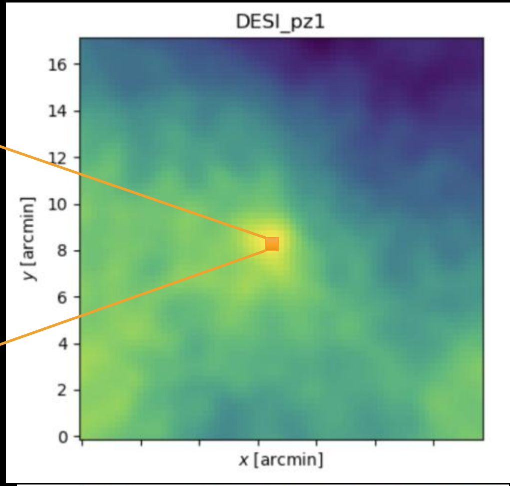


Hadzhiyska+ ACT & DESI 24

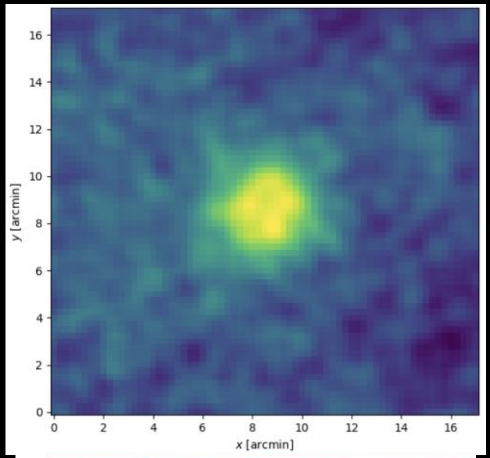
Towards an integrated view of baryons

stars

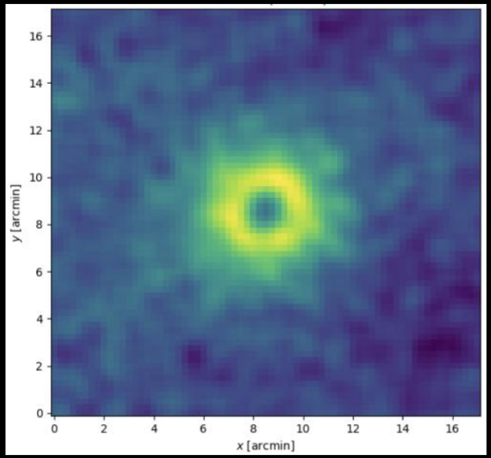
gas density
(kSZ and screening)

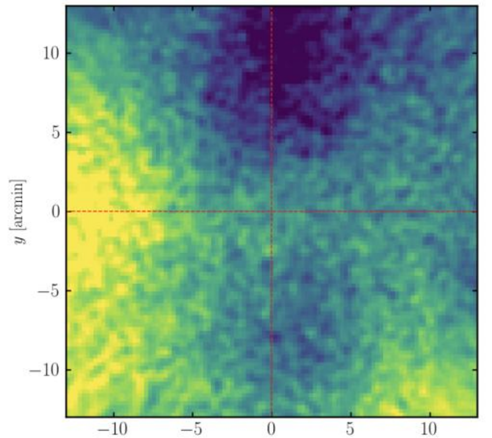


thermal pressure
(tSZ)

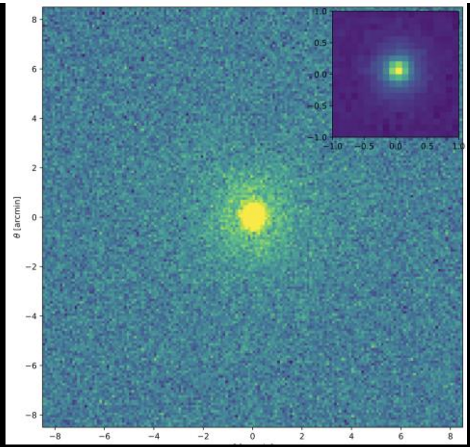


thermal pressure + dust
(tSZ + CIB)

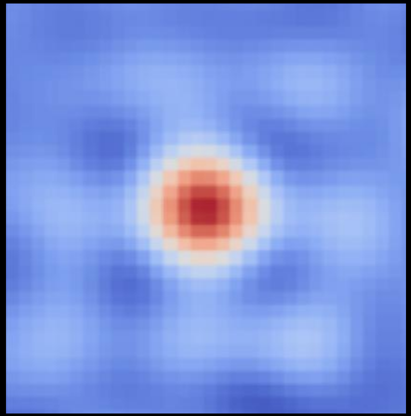




filaments
(kSZ)



hot gas
(X-ray)



mass
(CMB lensing)

How do we measure the gas distribution

Traditionally:

- X-rays $\propto \rho_{\rm gas}^2 \, \Lambda(T, Z) \approx \rho_{\rm gas}^2 \, T^{1/2}$

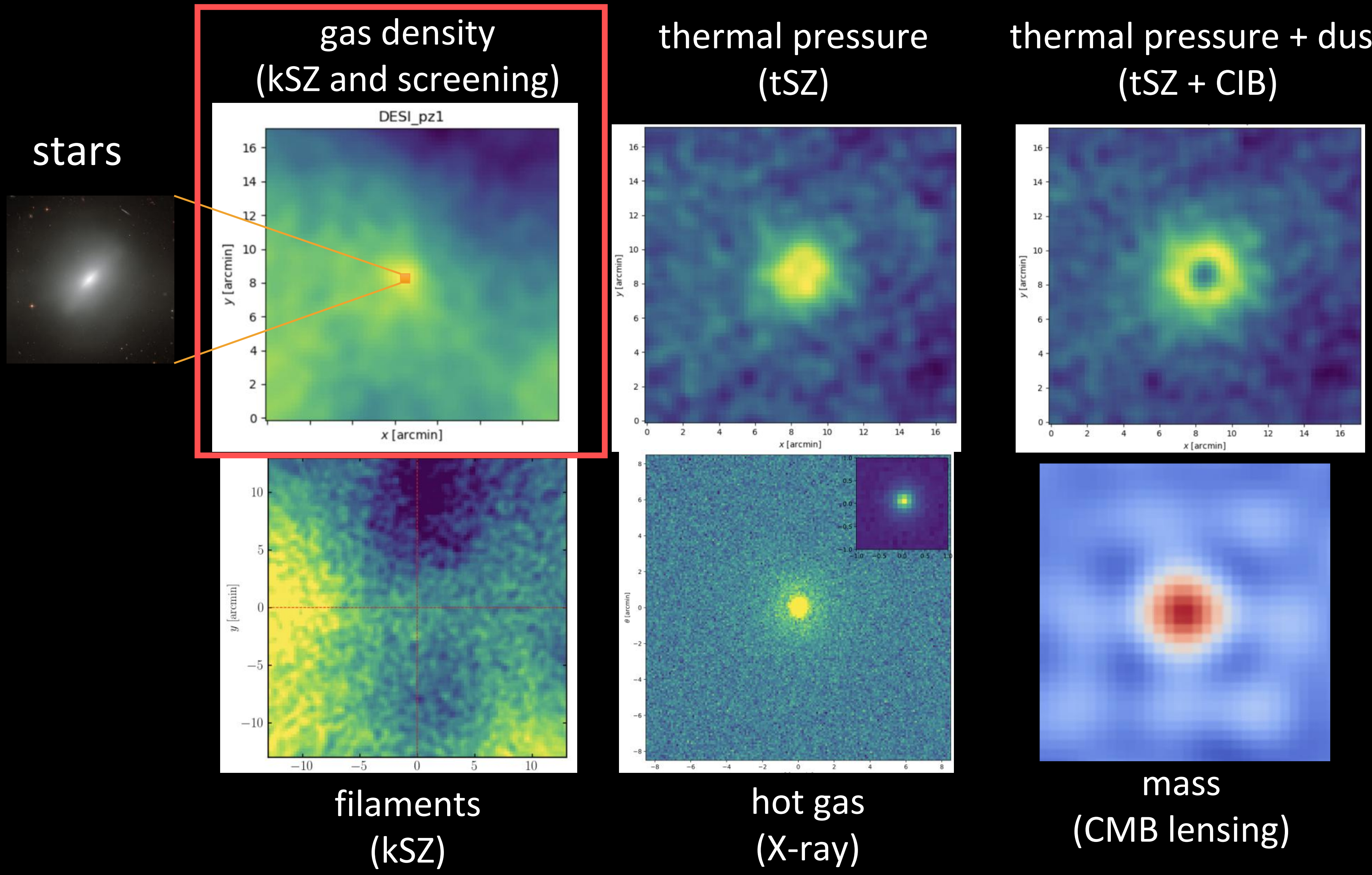
CMB-based probes:

- Kinematic Sunyaev-Zel'dovich $\propto \rho_{\rm gas}$
- Thermal Sunyaev-Zel'dovich $\propto \rho_{\rm gas} \, T$
- Patchy screening $\propto \rho_{\rm gas}$

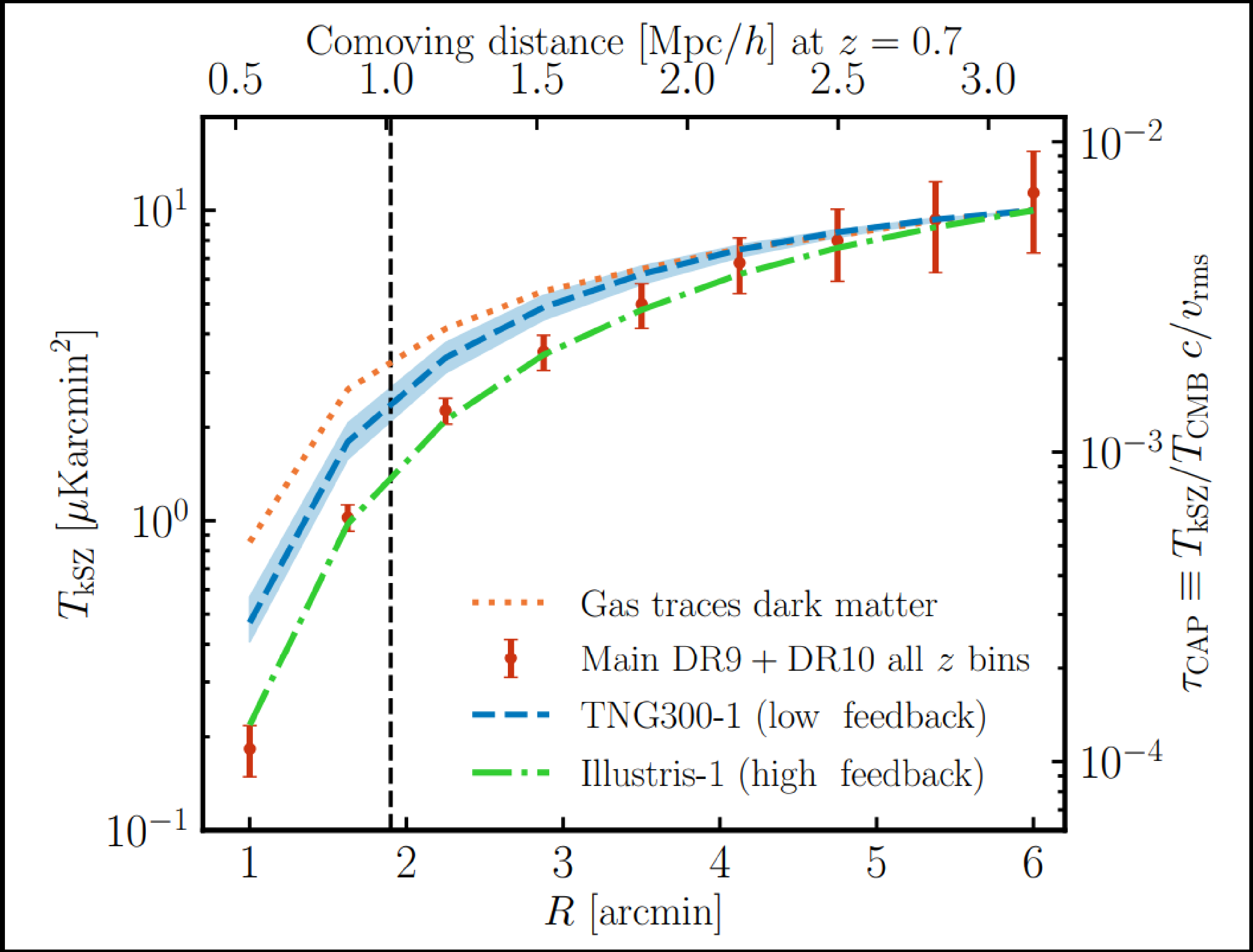
Promising:

- Fast Radio Bursts $\propto \rho_{\rm gas}$
- Absorption/Emission lines $\propto \rho_{\rm gas} \, f(Z)$

Towards an integrated view of baryons



The evidence for large baryonic feedback



Cumulative gas profiles

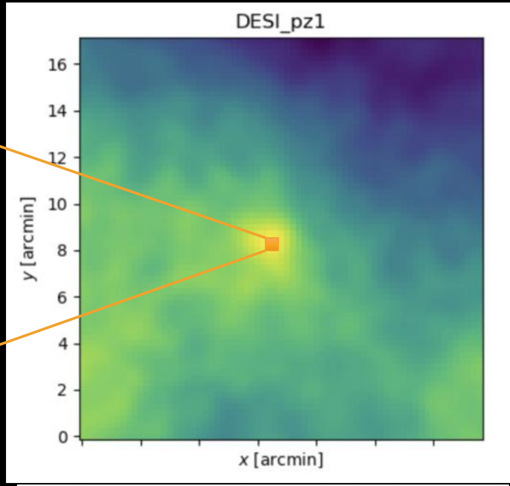
Distance from center [arcmin]

Hadzhiyska+ 24 see also Amodeo+ 21, McCarthy+ 24, Bigwood+ 24,25

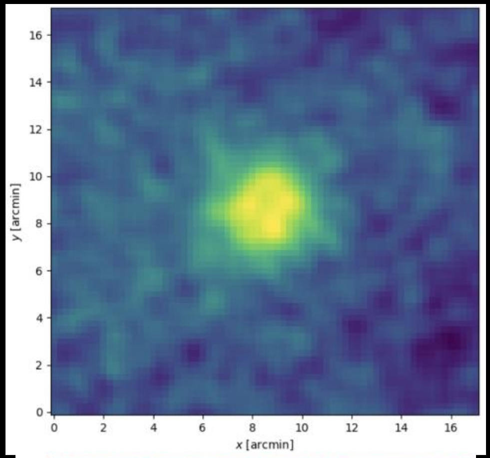
Towards an integrated view of baryons

stars

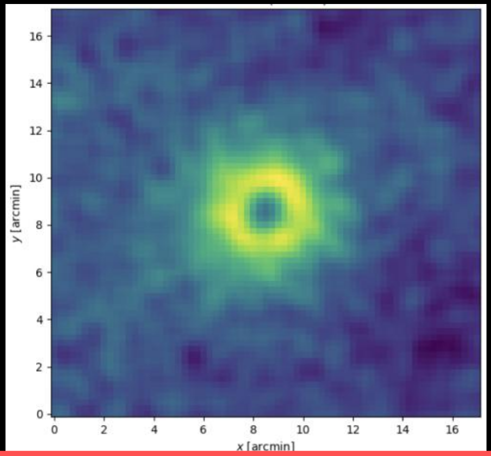
gas density
(kSZ and screening)

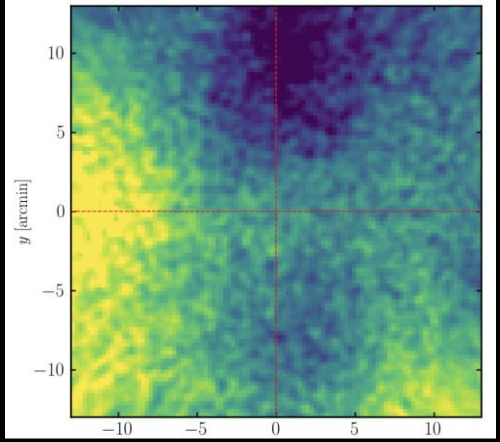


thermal pressure
(tSZ)

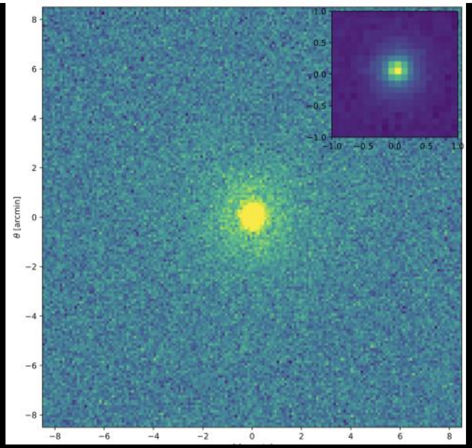


thermal pressure + dust
(tSZ + CIB)

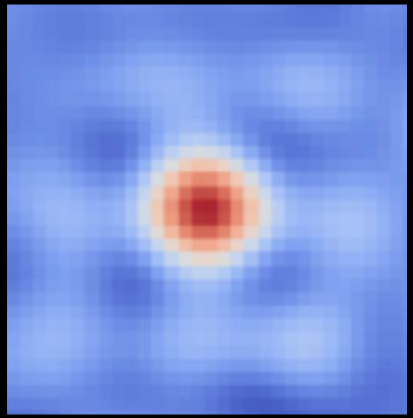




filaments
(kSZ)



hot gas
(X-ray)

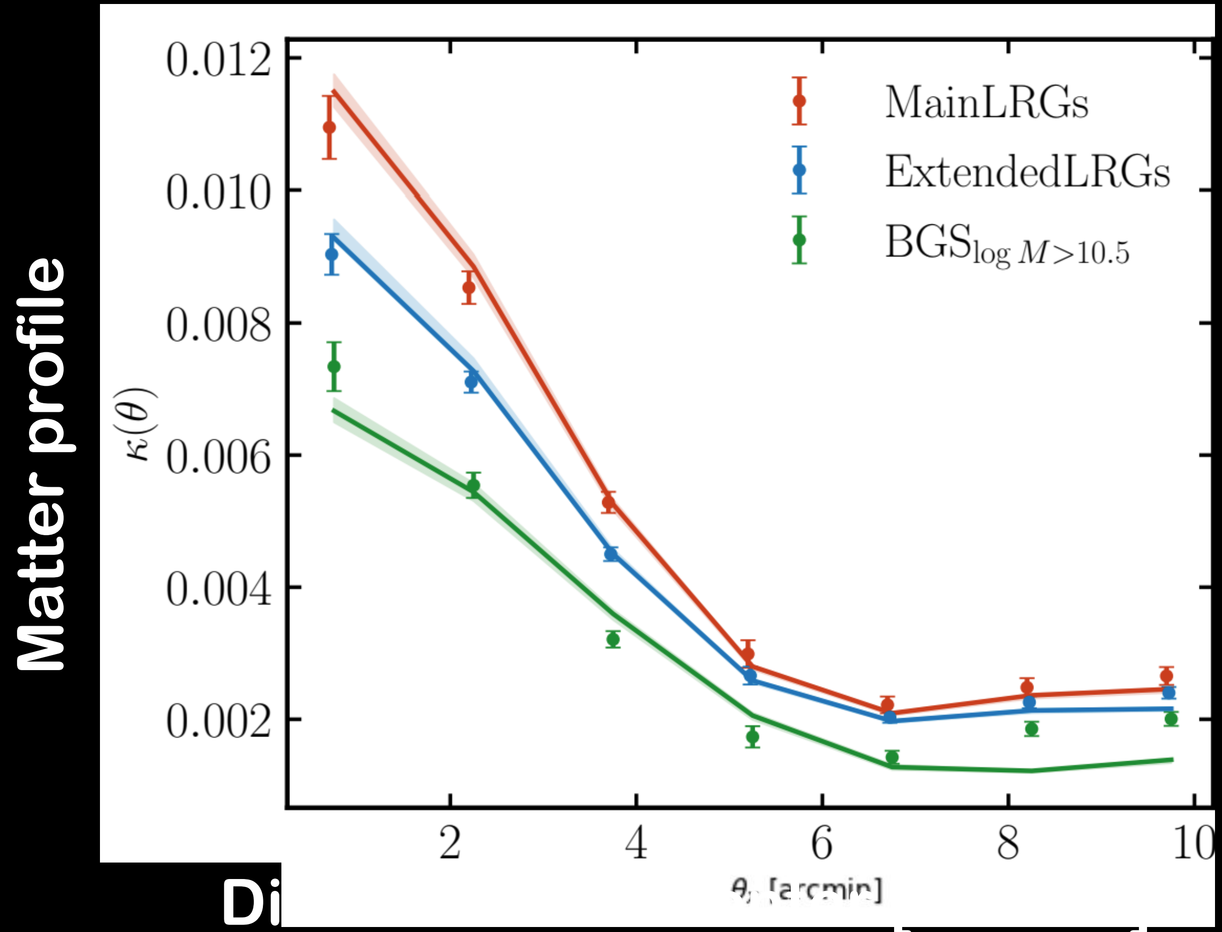


mass
(CMB lensing)

CMB lensing

$$\kappa \propto \rho_{\text{total}}$$

- **High significance** (>30σ) measurement of total matter profile (ACT DR6, Qu+ 24)
- **Self-consistent** galaxy selection (stacking on same LRG sample)

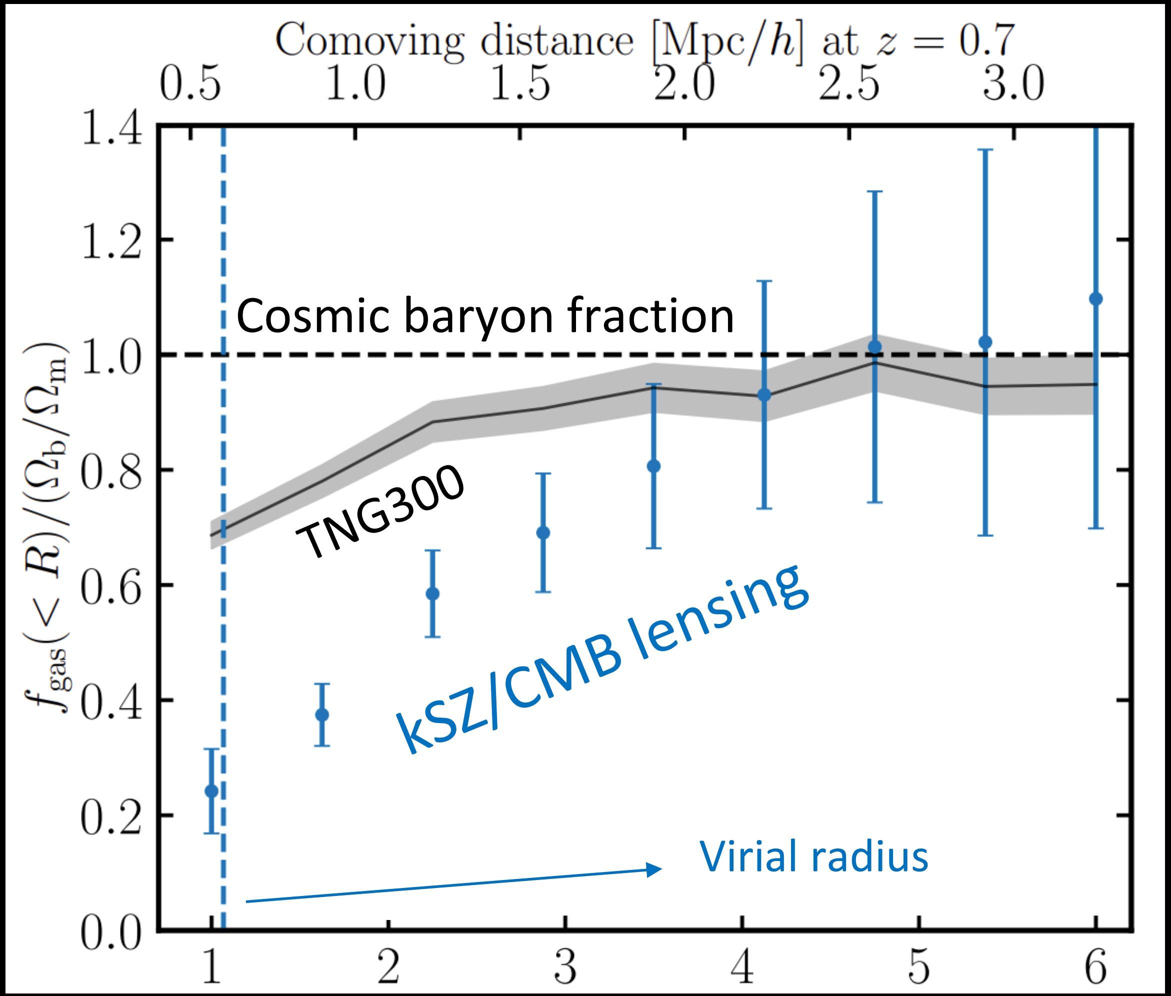


Apples-to-apples comparison!

Hadzhiyska+ 25, see also Lucie-Smith+ 25, Sunseri+ 25, Siegel+ 25

Powerful combination of kSZ and CMB lensing

- Ratio of kSZ and CMB lensing: gas fraction
- ~5σ lower gas fractions compared with TNG
- Data prefers stronger feedback!



Gas fraction

Distance from center [arcmin]

Preliminary results from DESI DR2 and ACT

Luminous red galaxies

- Sample Size: ~2.4 million
- Redshift Range: $0.4 < z < 1.1$

FJQ,Ried Guachalla,Schaan++ (in prep 2026)

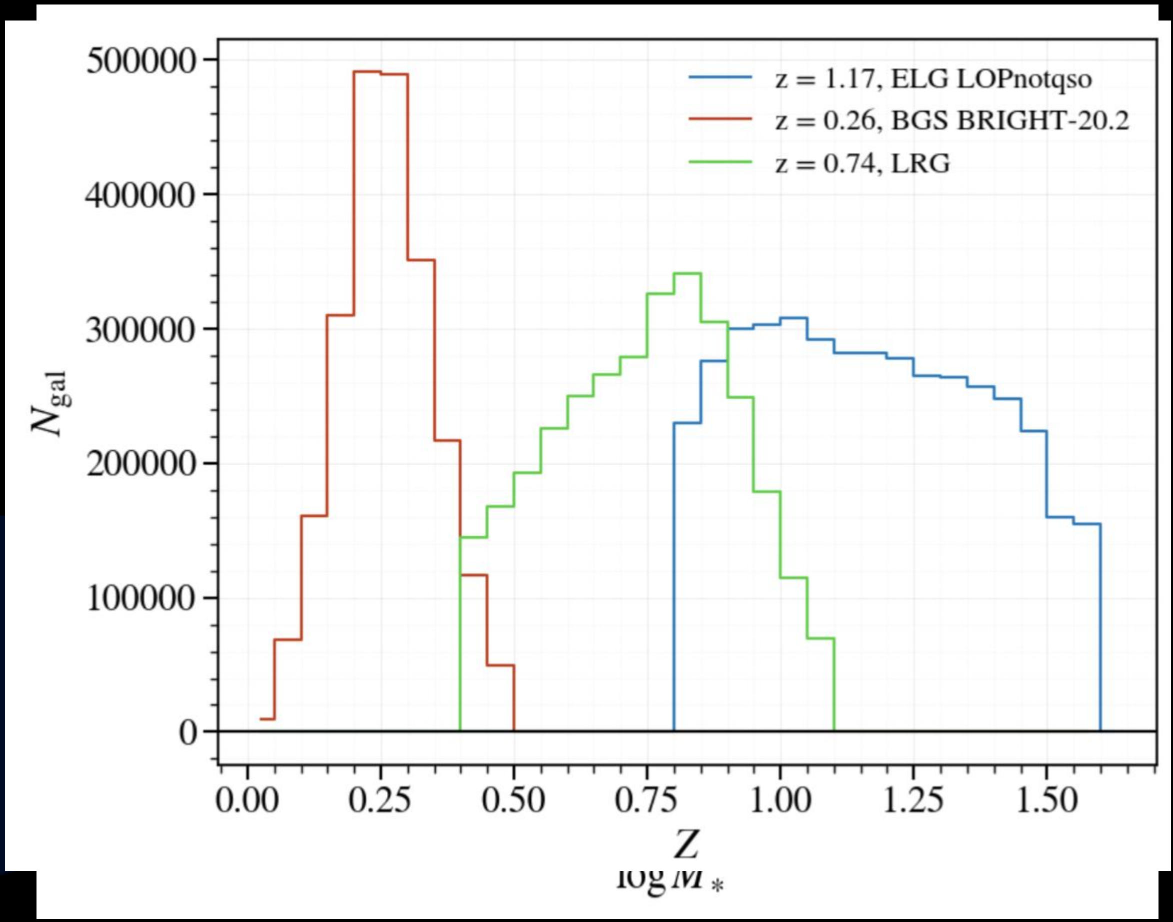
Bright galaxy survey

- Sample Size: ~2.3 million
- Concentrated at lower redshifts $\bar{z} = 0.26$

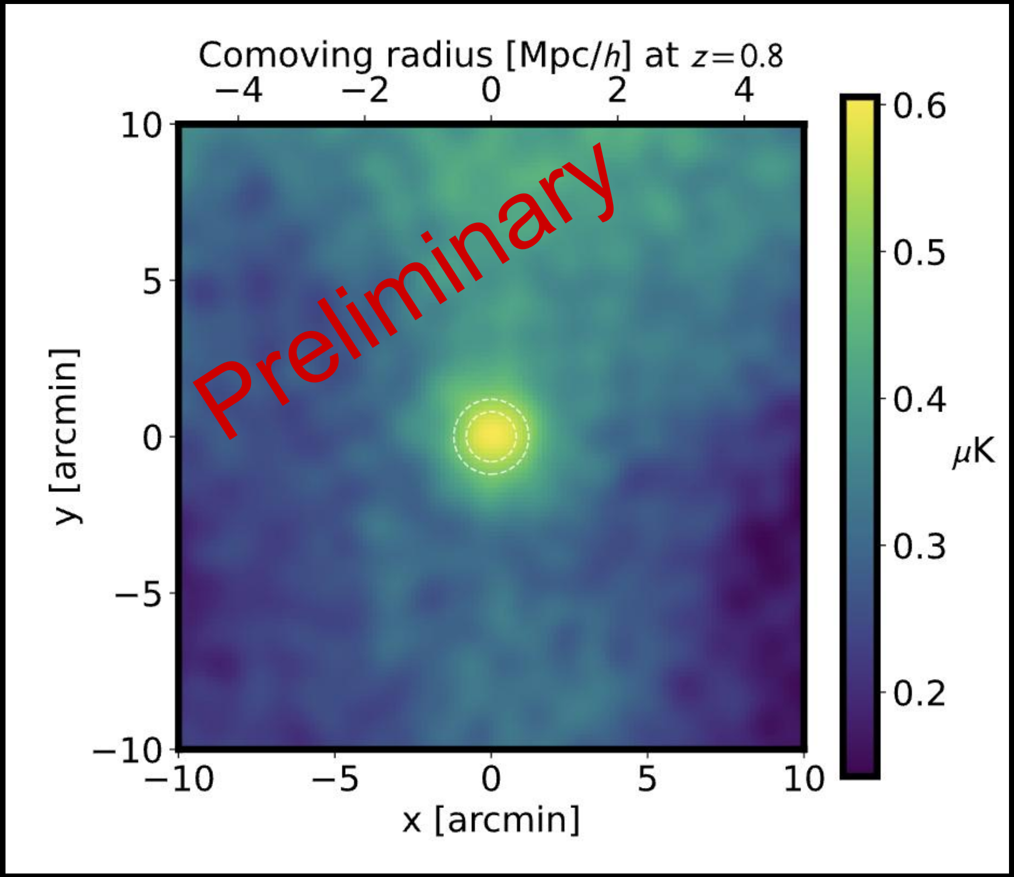
Emission-Line galaxies

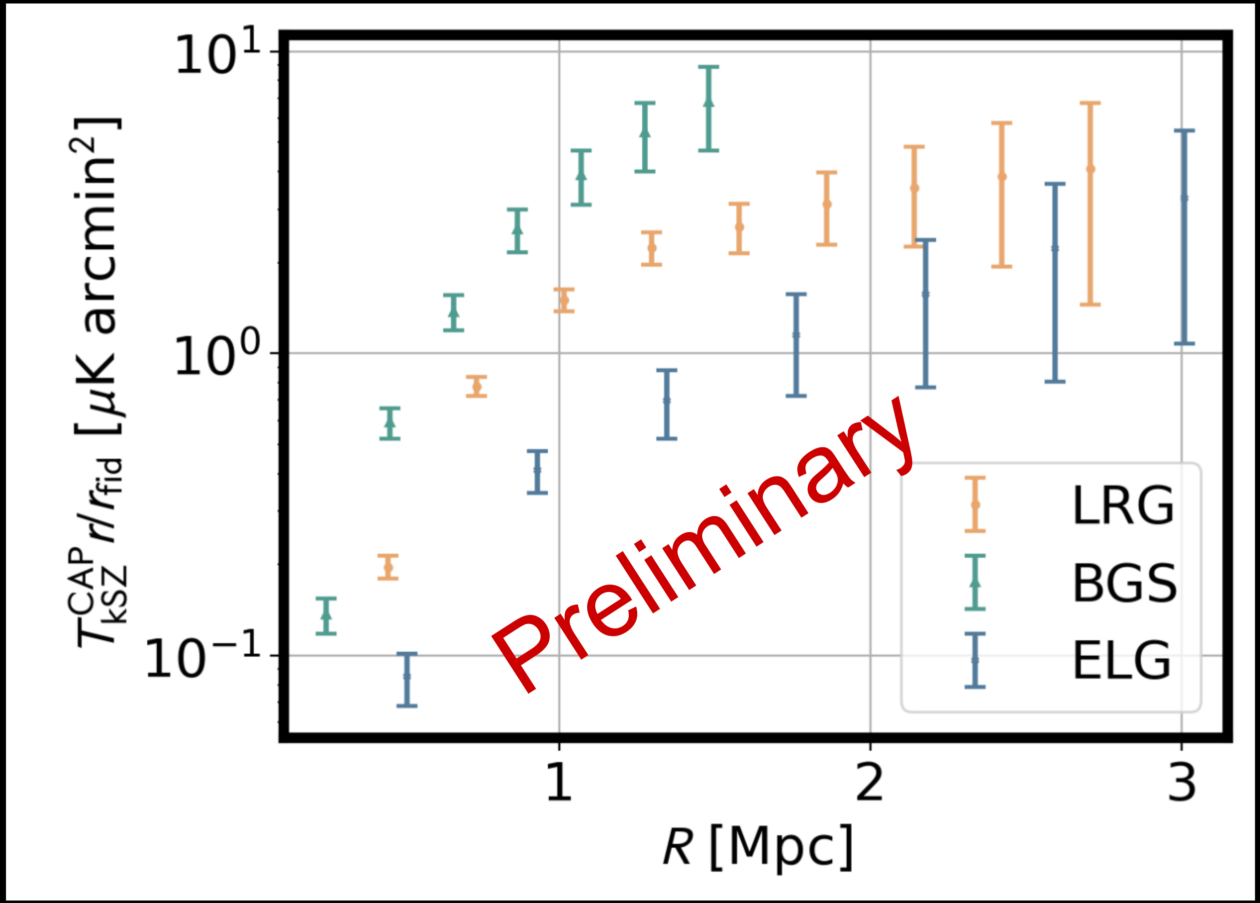
- Sample Size: ~4.1 million
- Extend up to $z \sim 1.17$

Hadzhiyska,Ferraro, FJQ++ (in prep 2026)

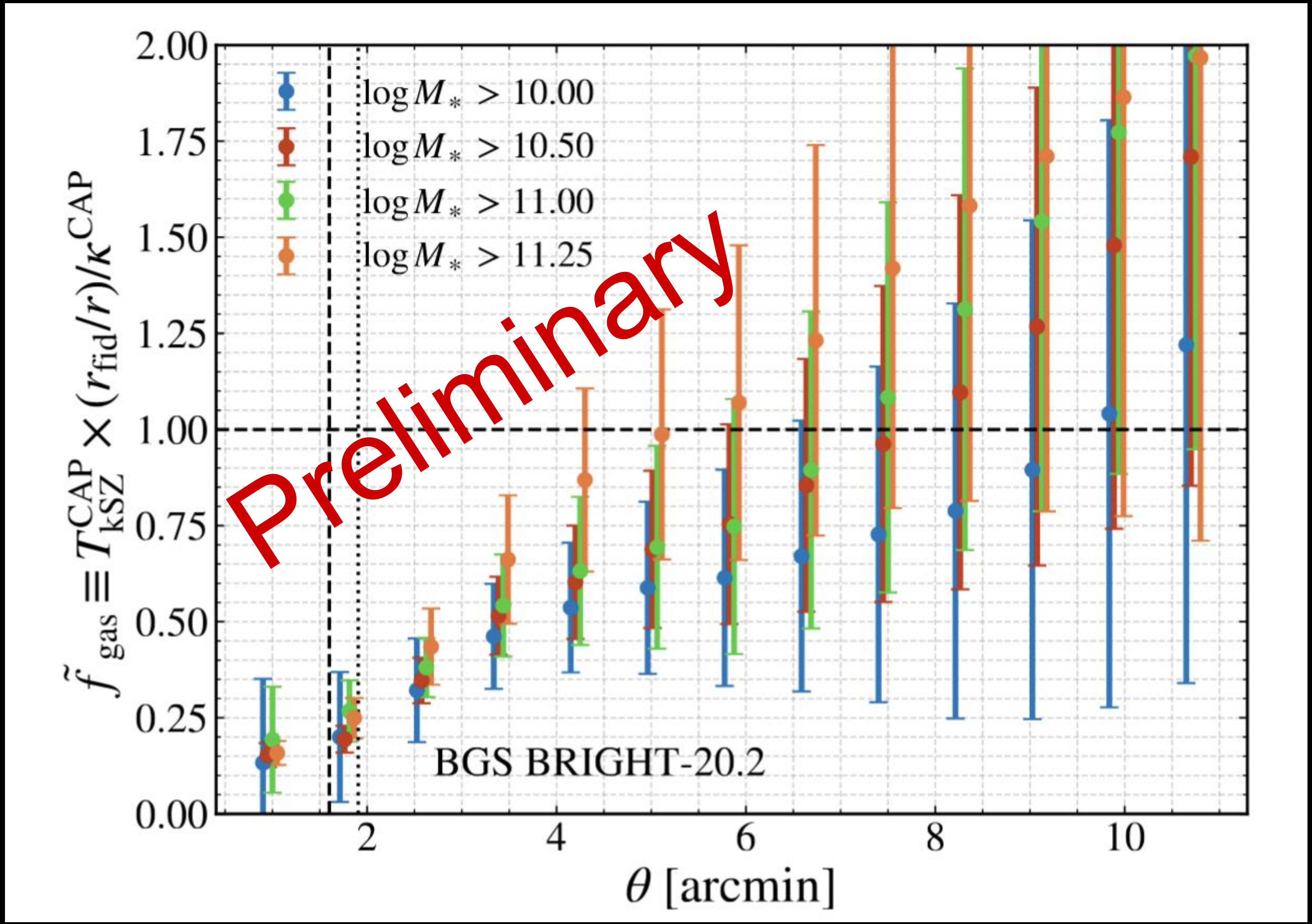


Lever arm in mass and redshift





Gas fractions from CMB lensing and kSZ

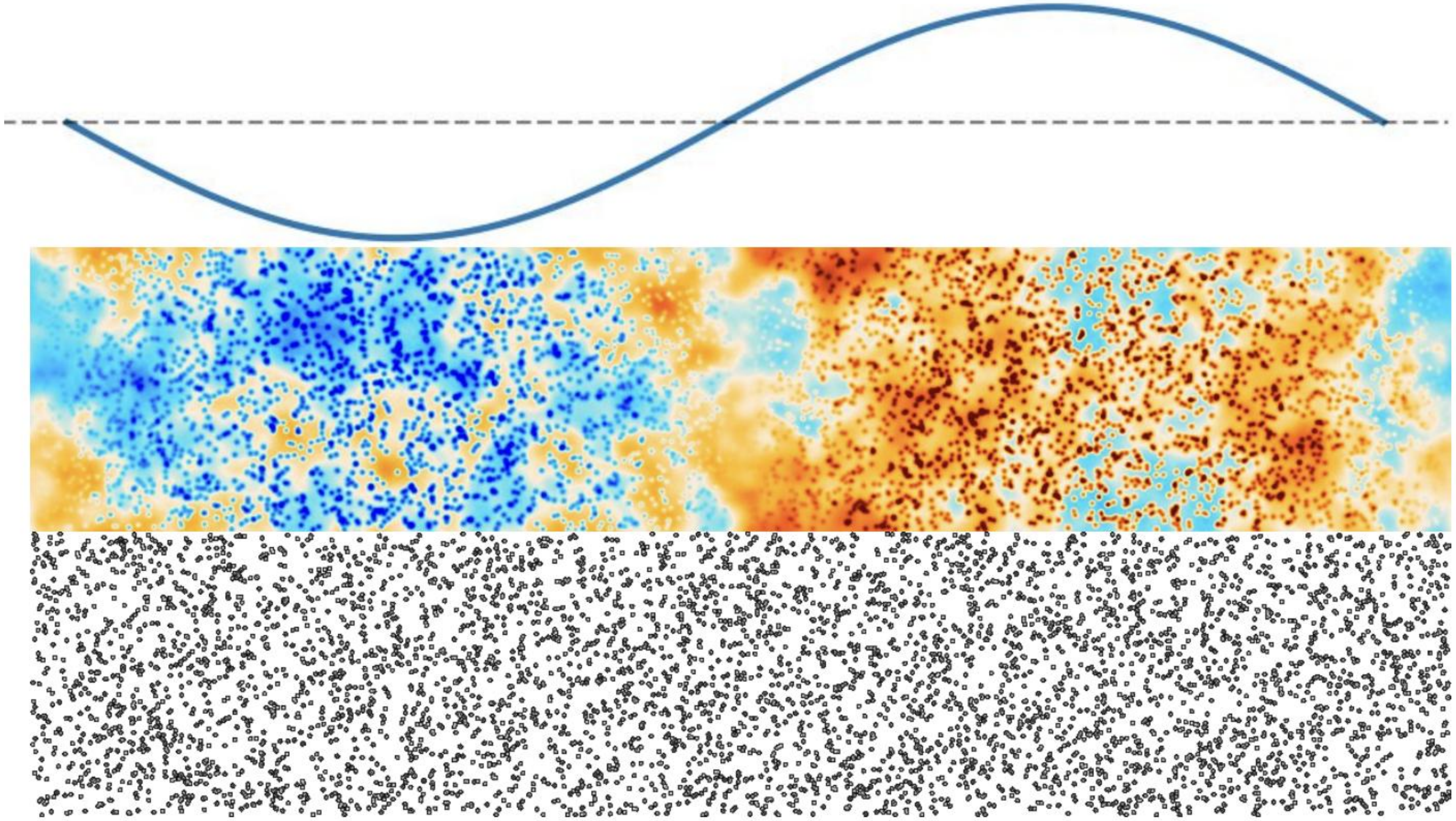


HARMONIC SPACE ESTIMATORS

Large scale velocity mode

Small scale CMB

Galaxy position



Credit Mat Madhavacheril

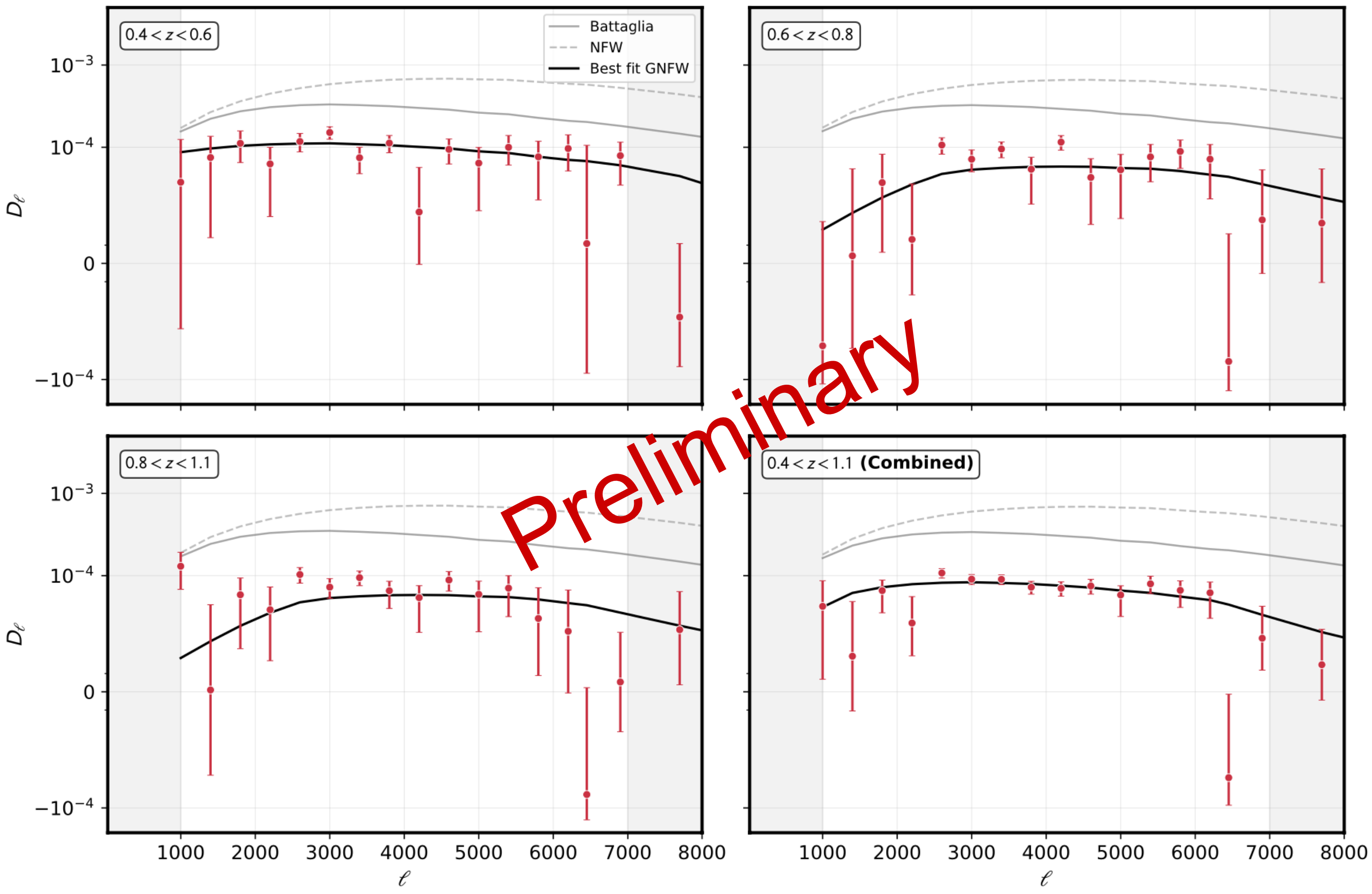
HARMONIC SPACE ESTIMATORS

We also provide GNFW fits and comparison with Battaglia profiles

$$\tilde{\hat{C}}_\ell^{\pi\times T_{CMB}} = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}\pi_{\ell m}\Theta^*_{\ell m}$$

$$\hat{C}_\ell^{\pi x T} = -r\sigma_{\rm true}\sigma_{\rm rec}C_\ell^{\tau g}$$

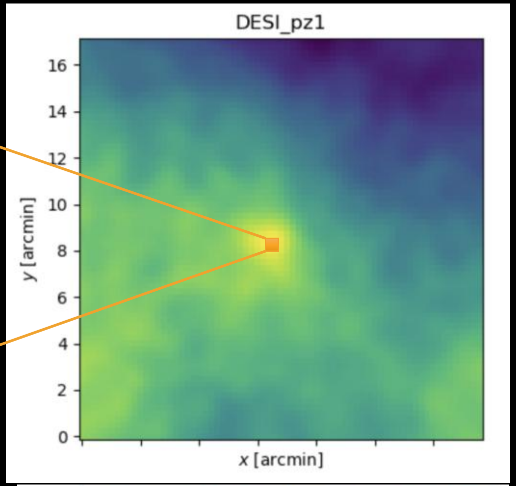
See also Harscouet+ 2025



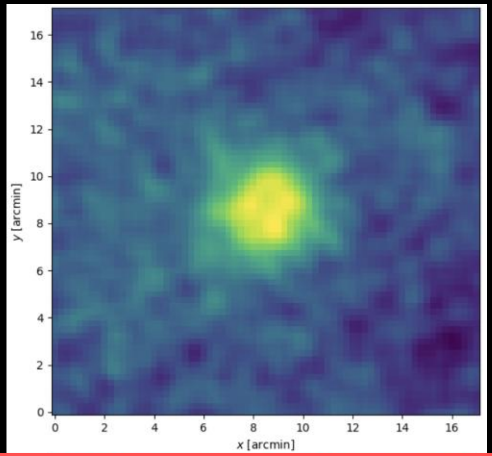
Towards an integrated view of baryons

stars

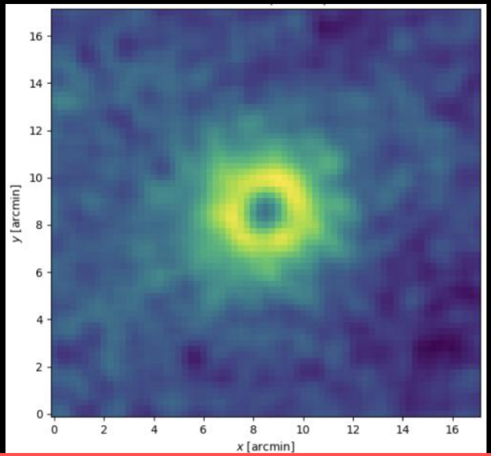
gas density
(kSZ and screening)

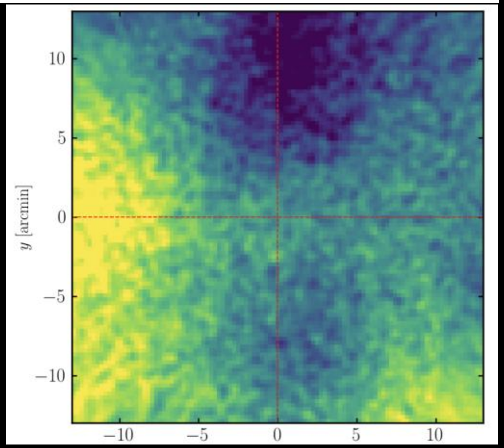


thermal pressure
(tSZ)

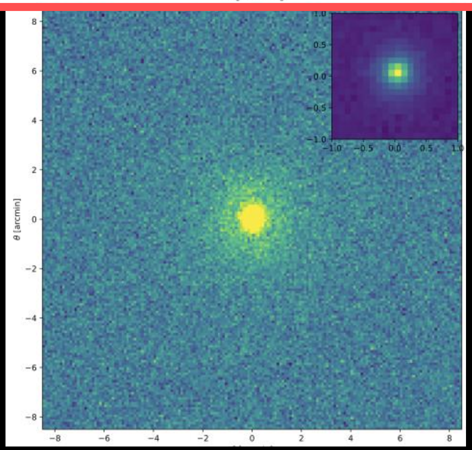


thermal pressure + dust
(tSZ + CIB)

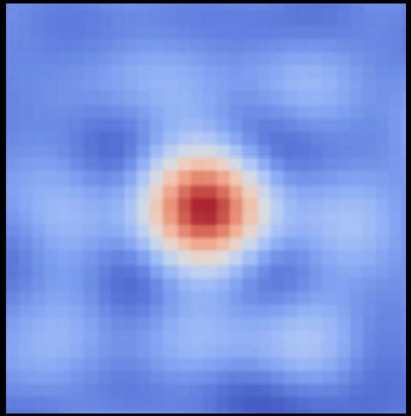




filaments
(kSZ)



hot gas
(X-ray)



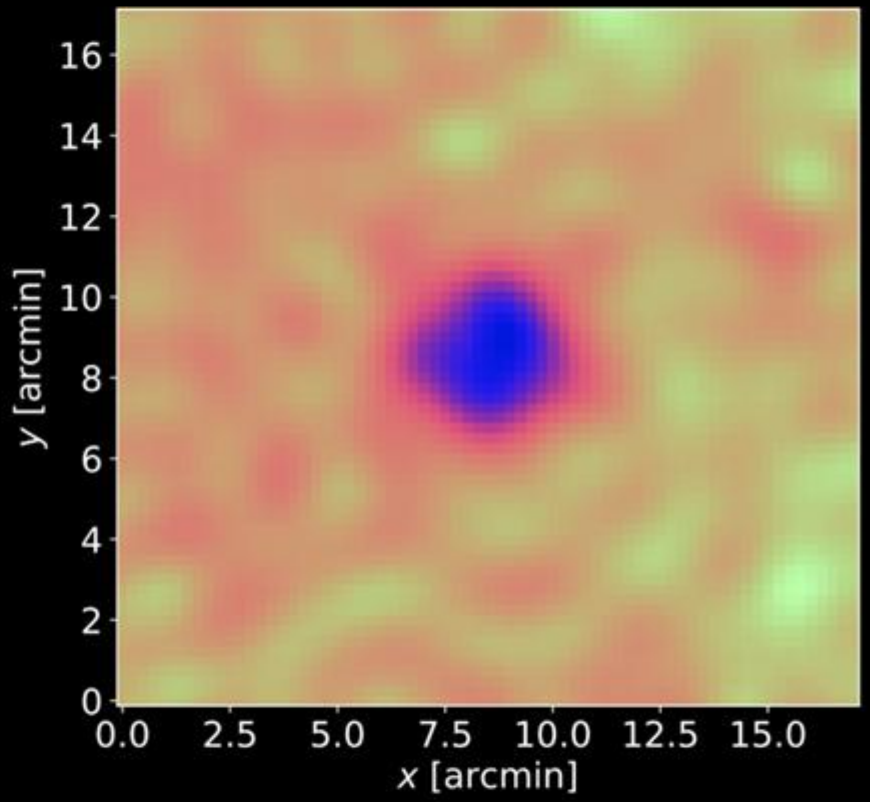
mass
(CMB lensing)

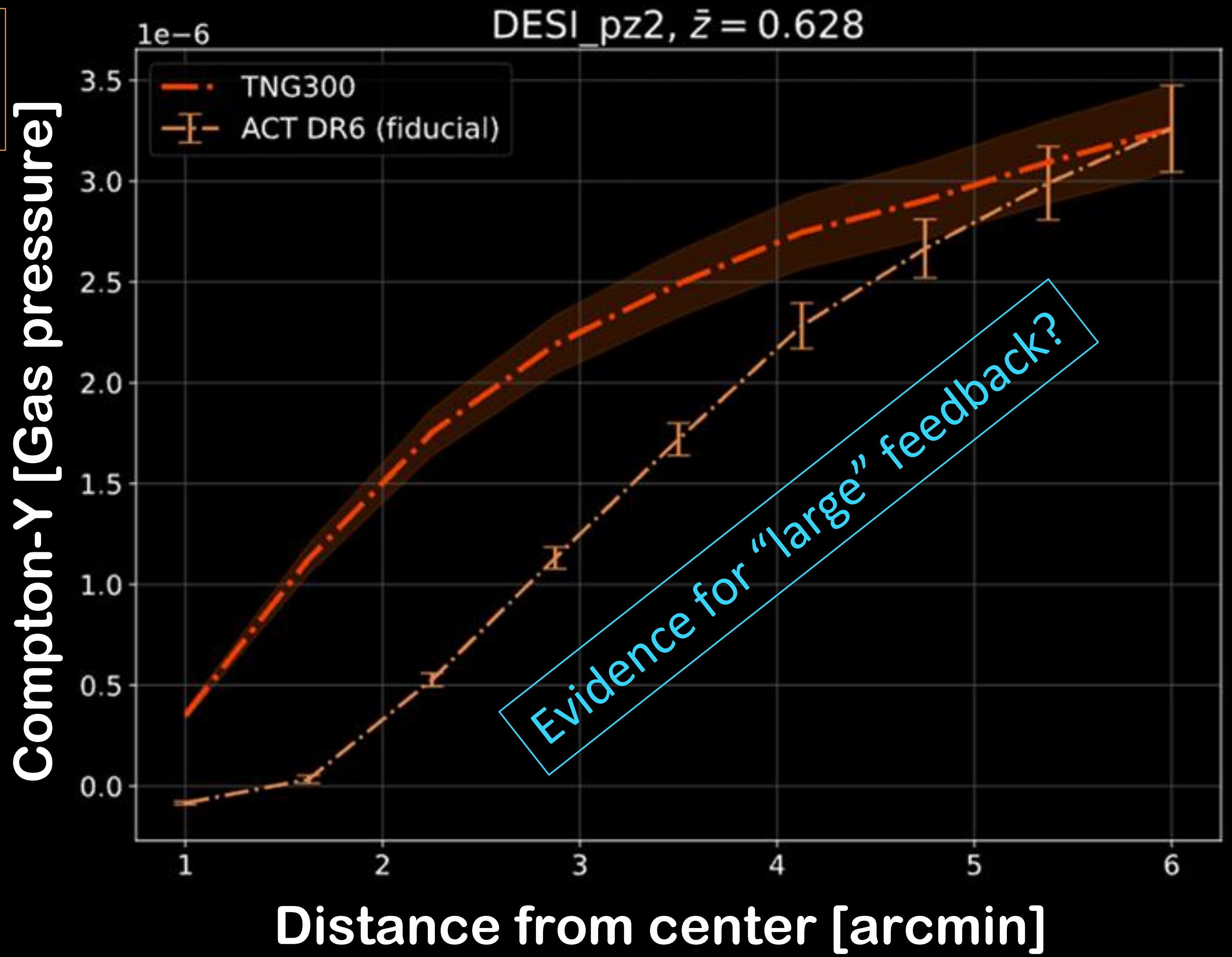
Henry Liu

Also see
Hill+ 2013,
Vavagiakis+ 2021,
McCarthy+ 2024,
Dalal+ 2025,

The thermal SZ effect (tSZ)

$$\frac{T_{\mathrm{tSZ}}}{T_{\mathrm{CMB}}} \propto \rho_{\mathrm{gas}}\, T_{\mathrm{gas}}$$



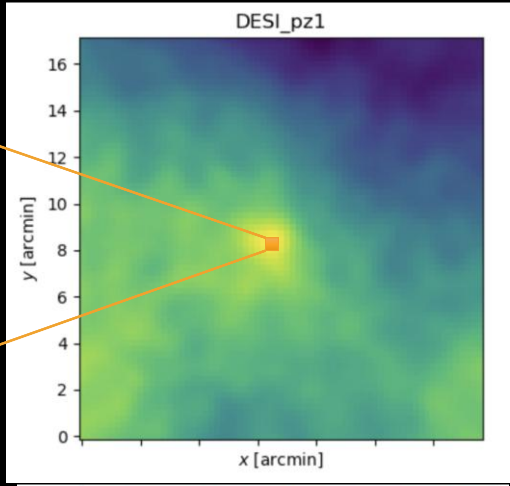


Liu+ (2025, ACT + DESI), see also Efsthatiou, McCarthy (2025)

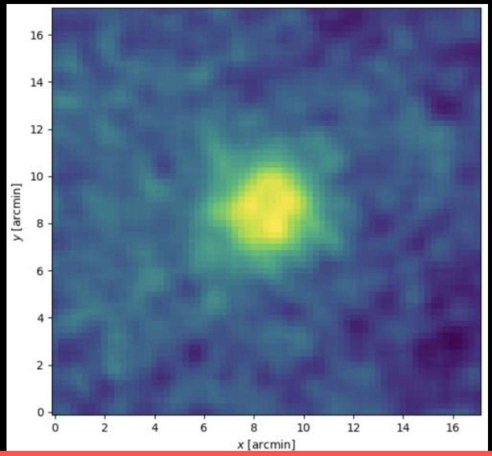
Towards an integrated view of baryons

stars

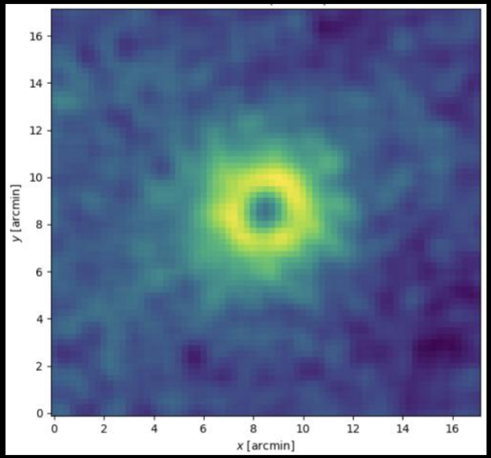
gas density
(kSZ and screening)

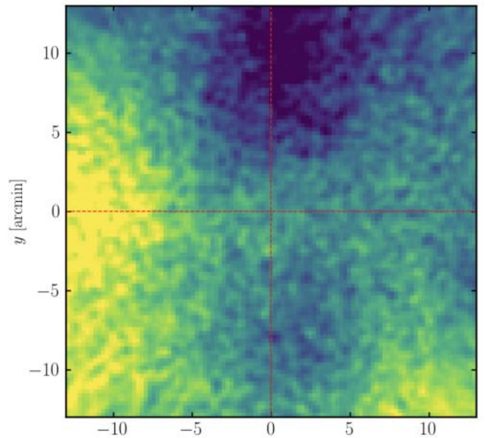


thermal pressure
(tSZ)

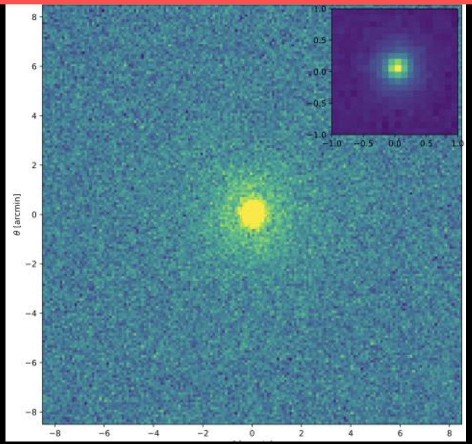


thermal pressure + dust
(tSZ + CIB)

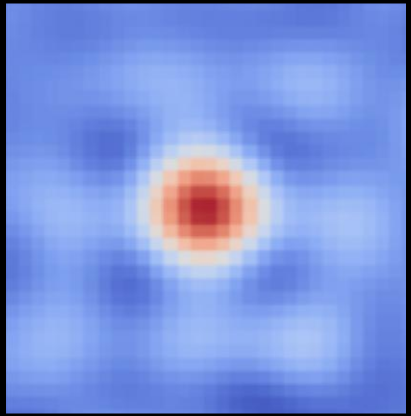




filaments
(kSZ)



hot gas
(X-ray)



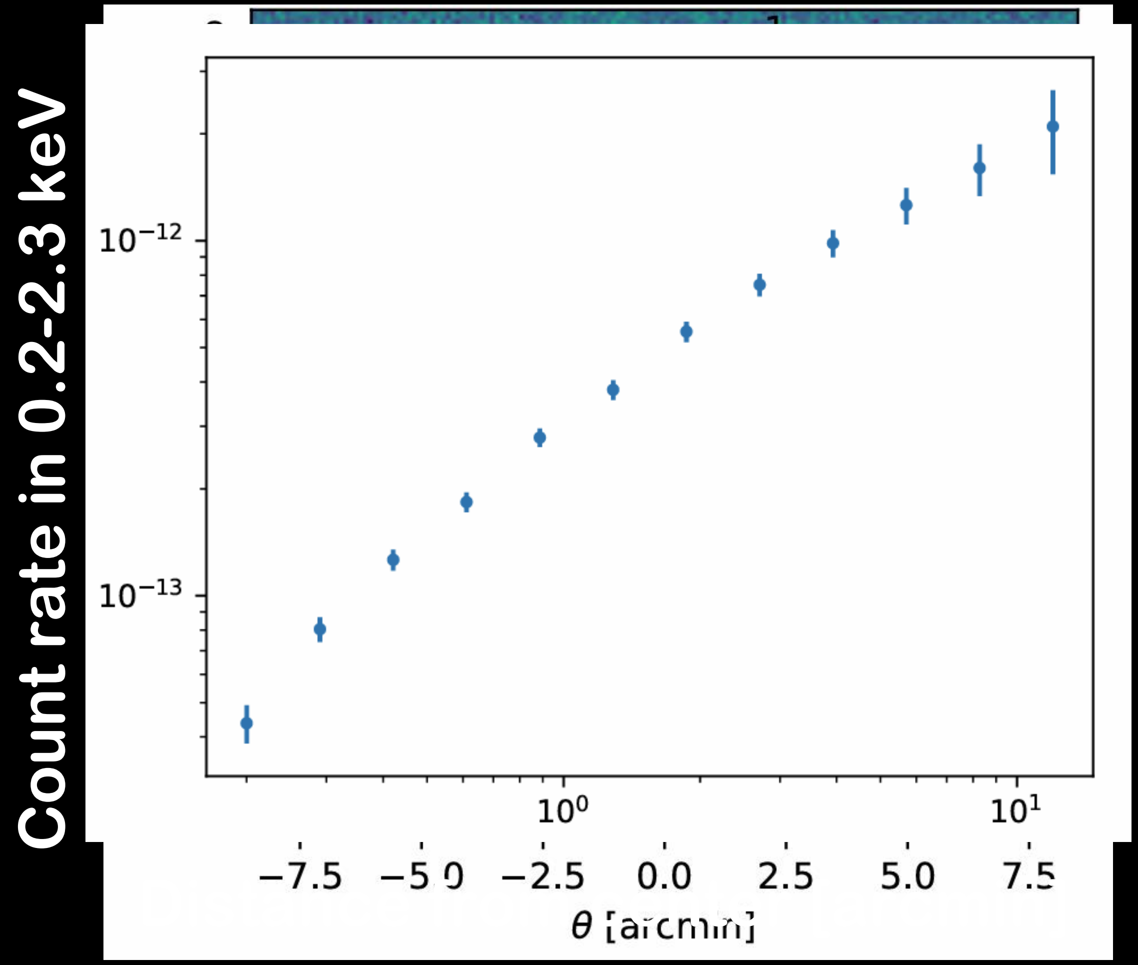
mass
(CMB lensing)

Gerrit Farren

Also see
Bahar+ 2021
Popesso+ 2024,
Ferreira+ 2024,
La Posta+ 2024

eROSITA X-ray stacks of the DESI LRGs

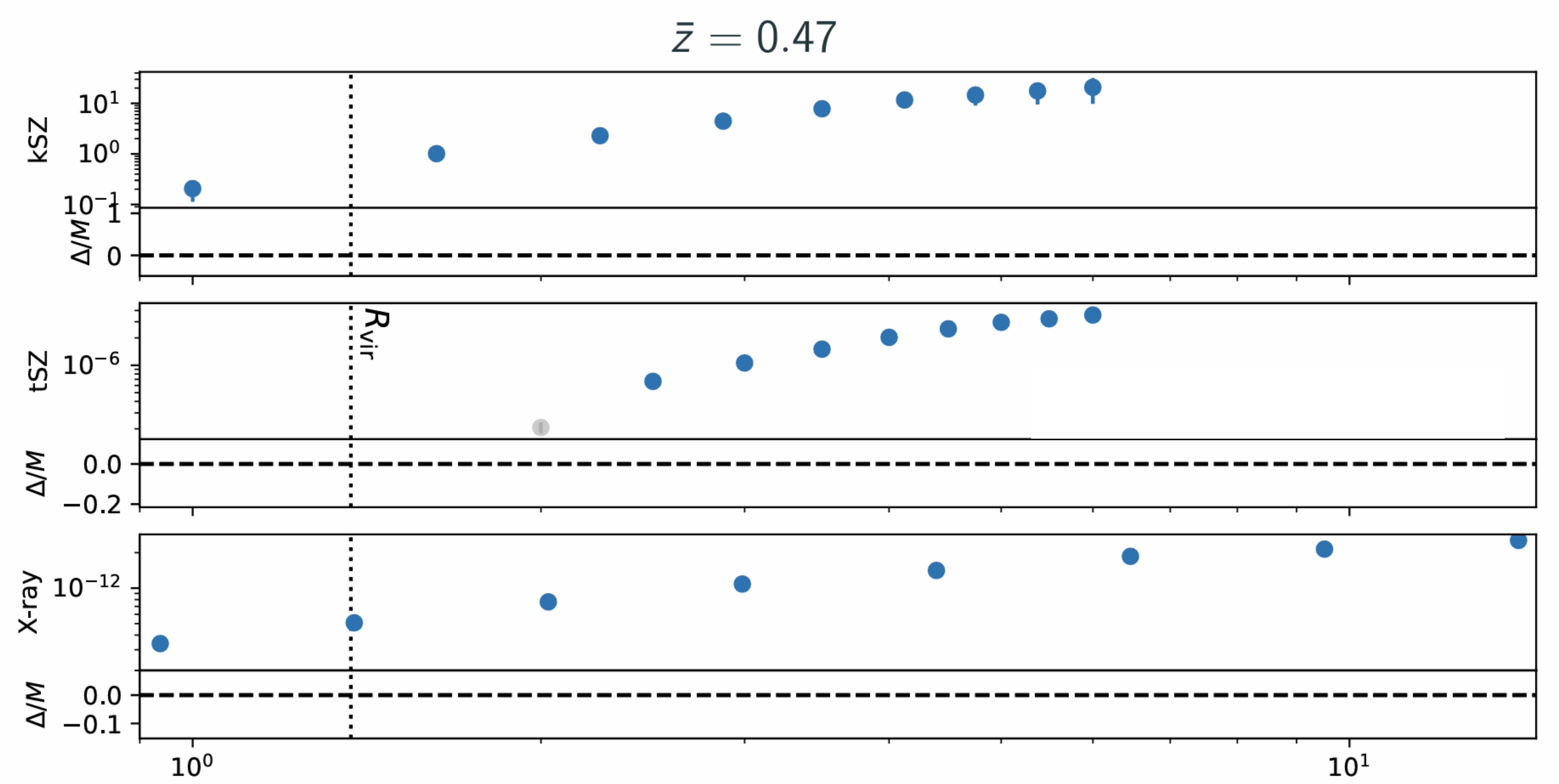
Stacked count rates



$$\text{X-ray} \propto \rho_{\rm gas}^2\, \Lambda(T,Z) \approx \rho_{\rm gas}^2\, T^{1/2}$$

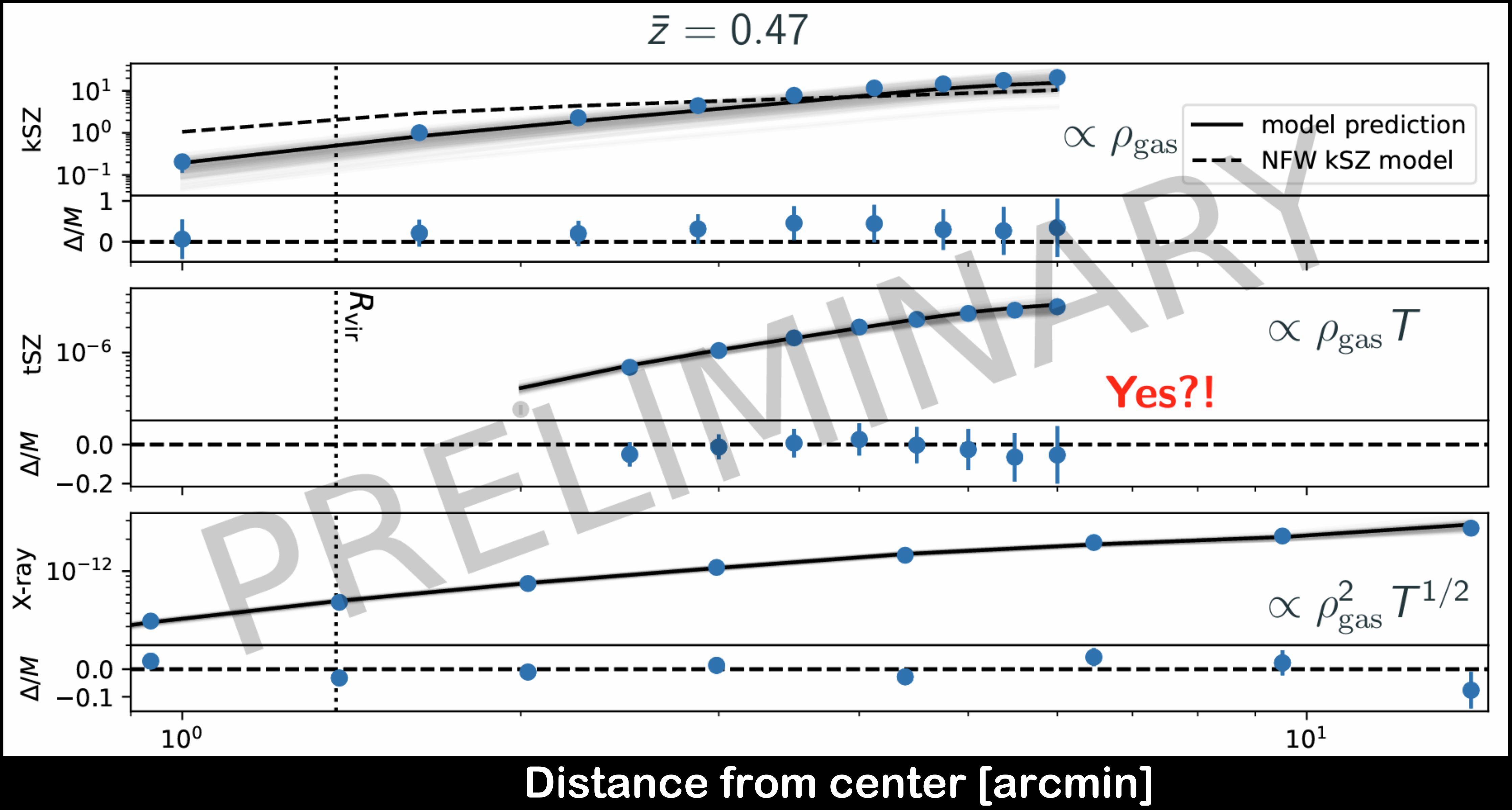
- Adopt DESI LRG sample (same as kSZ, tSZ, etc.) for consistent comparison!
- Mask X-ray point sources
- Stack count rates in the eROSITA 0.2 – 2.3 keV band
- SNR ~ 150!!

Let's put kSZ, tSZ and X-rays together!



Distance from center [arcmin]

Does a simple model fit all probes?

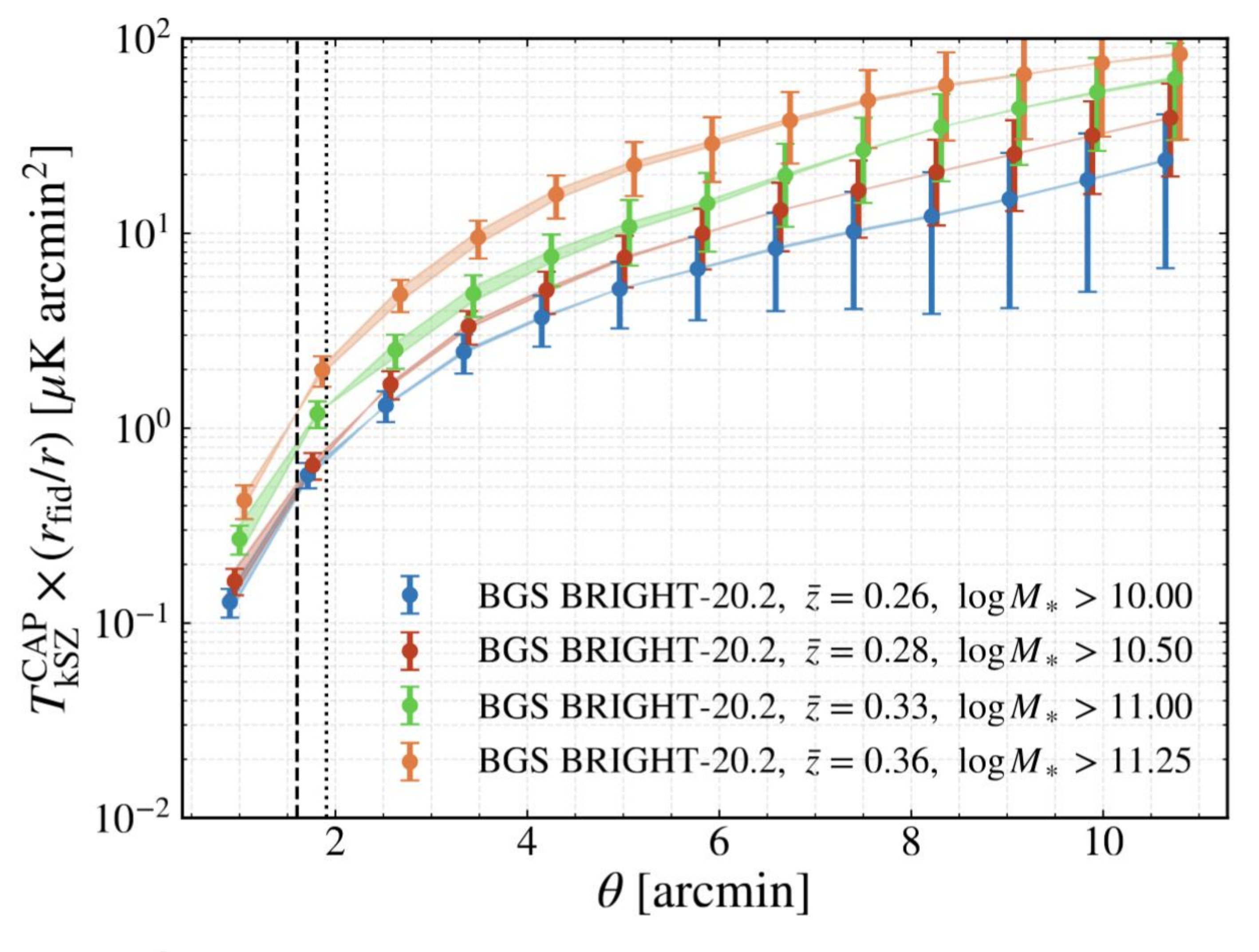


Conclusions

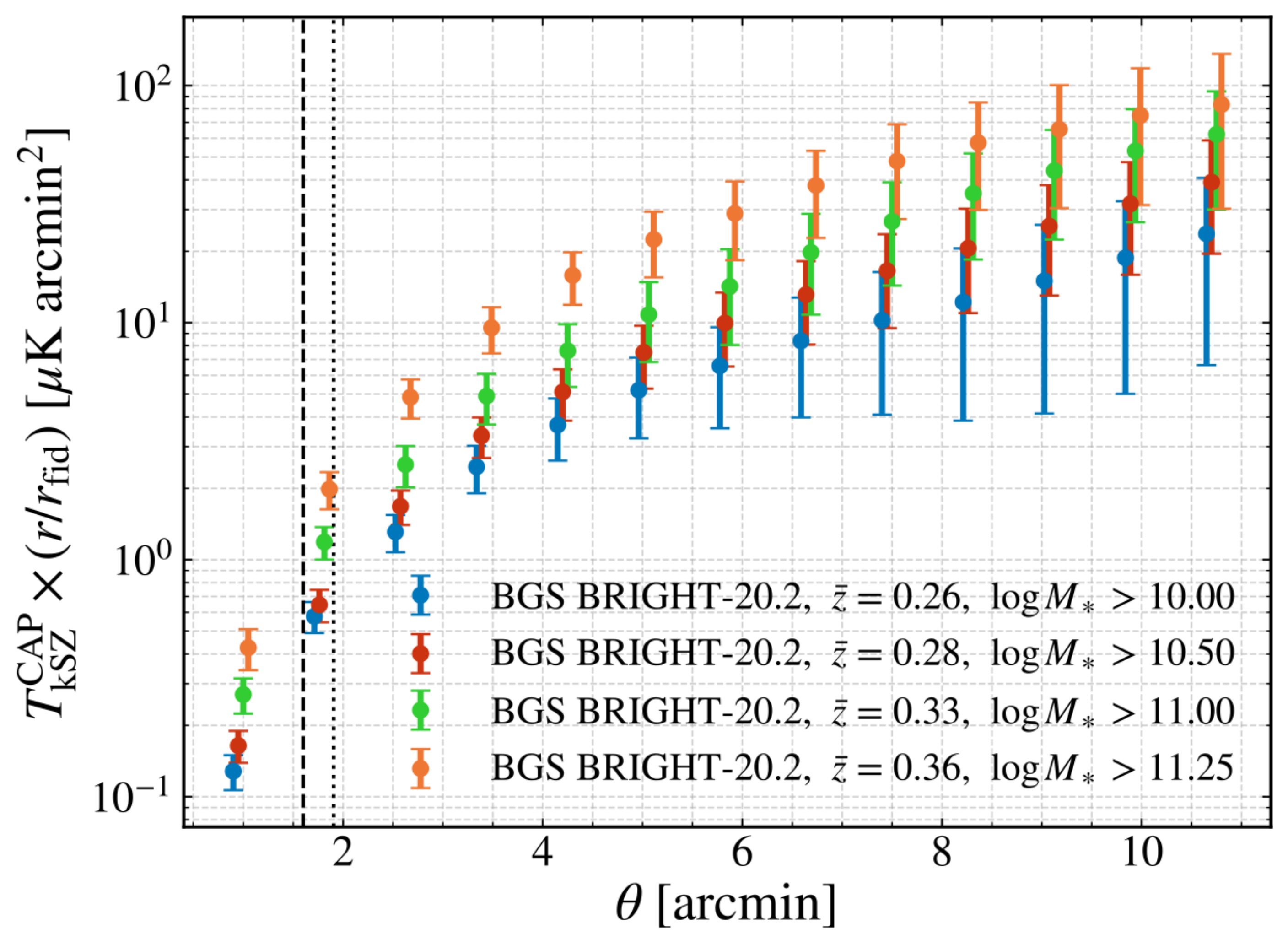
- Cross-correlations offer cleaner measurements (ideal for PNG)
- Multi-frequency observations of the same galaxies (DESI LRGs)!
  - Kinematic Sunyaev-Zel'dovich
  - Thermal Sunyaev-Zel'dovich
  - Patchy screening
  - CMB lensing
  - X-rays
- Probes appear to be empirically consistent with each other
- All point at evidence for large baryonic feedback!

Backup slides

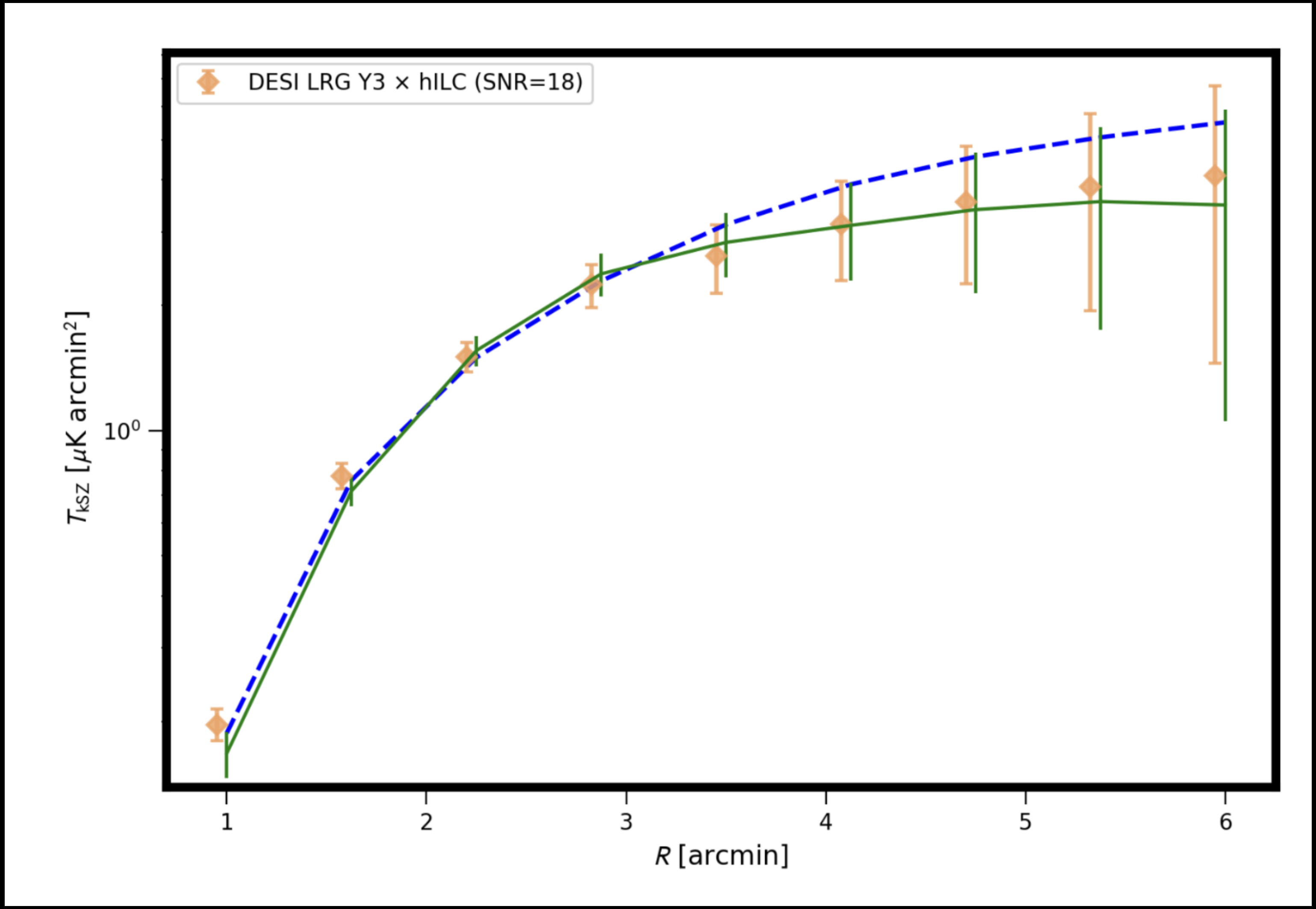
Null tests


$T_{\rm kSZ}^{\rm CAP} \times (r_{\rm fid}/r)$ [μK arcmin^2]
θ [arcmin]
10^2
10^1
10^0
10^{-1}
10^{-2}
2
4
6
8
10
BGS BRIGHT-20.2, $\bar{z} = 0.26$, $\log M_* > 10.00$
BGS BRIGHT-20.2, $\bar{z} = 0.28$, $\log M_* > 10.50$
BGS BRIGHT-20.2, $\bar{z} = 0.33$, $\log M_* > 11.00$
BGS BRIGHT-20.2, $\bar{z} = 0.36$, $\log M_* > 11.25$

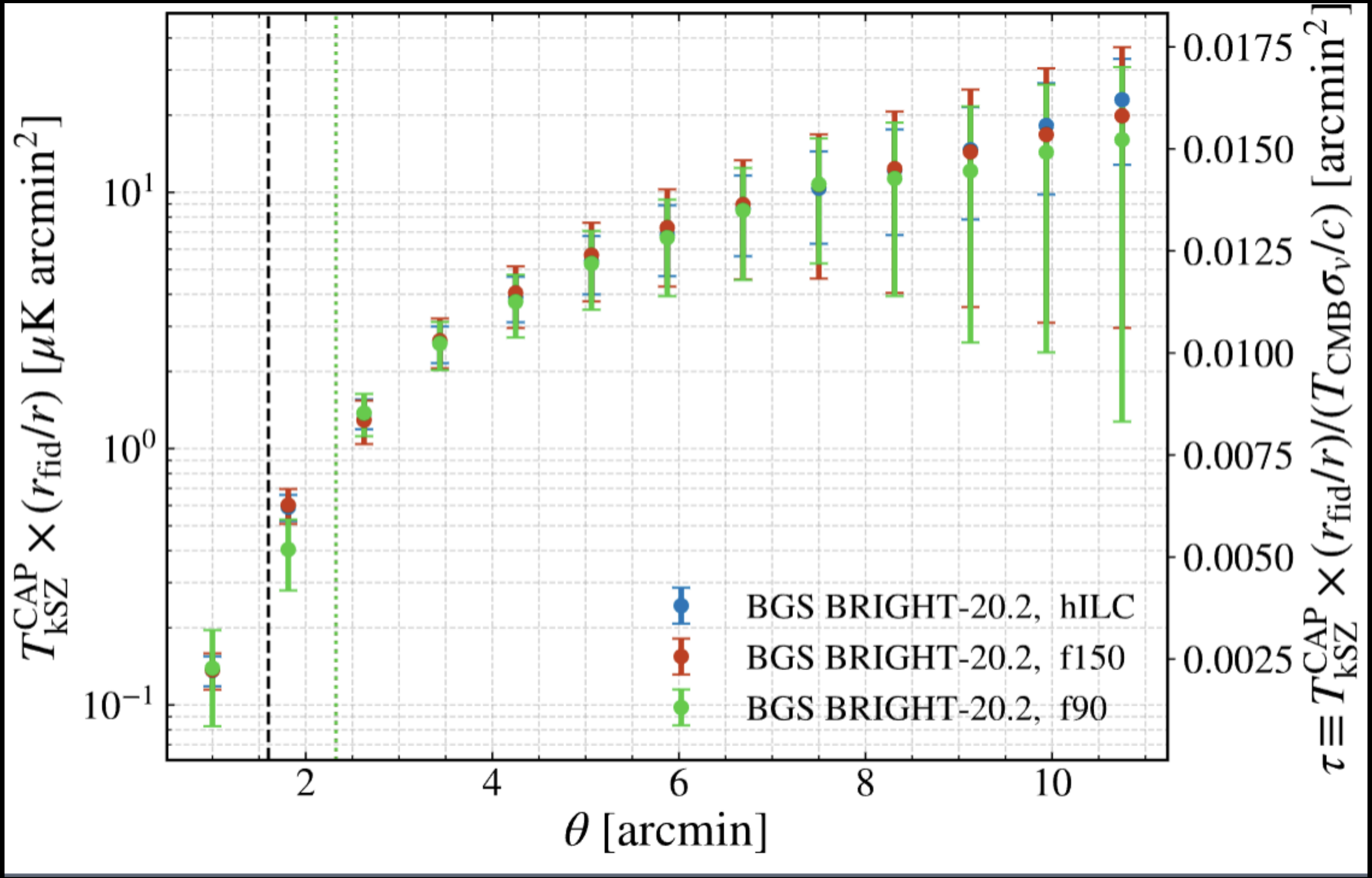
Mass evolution



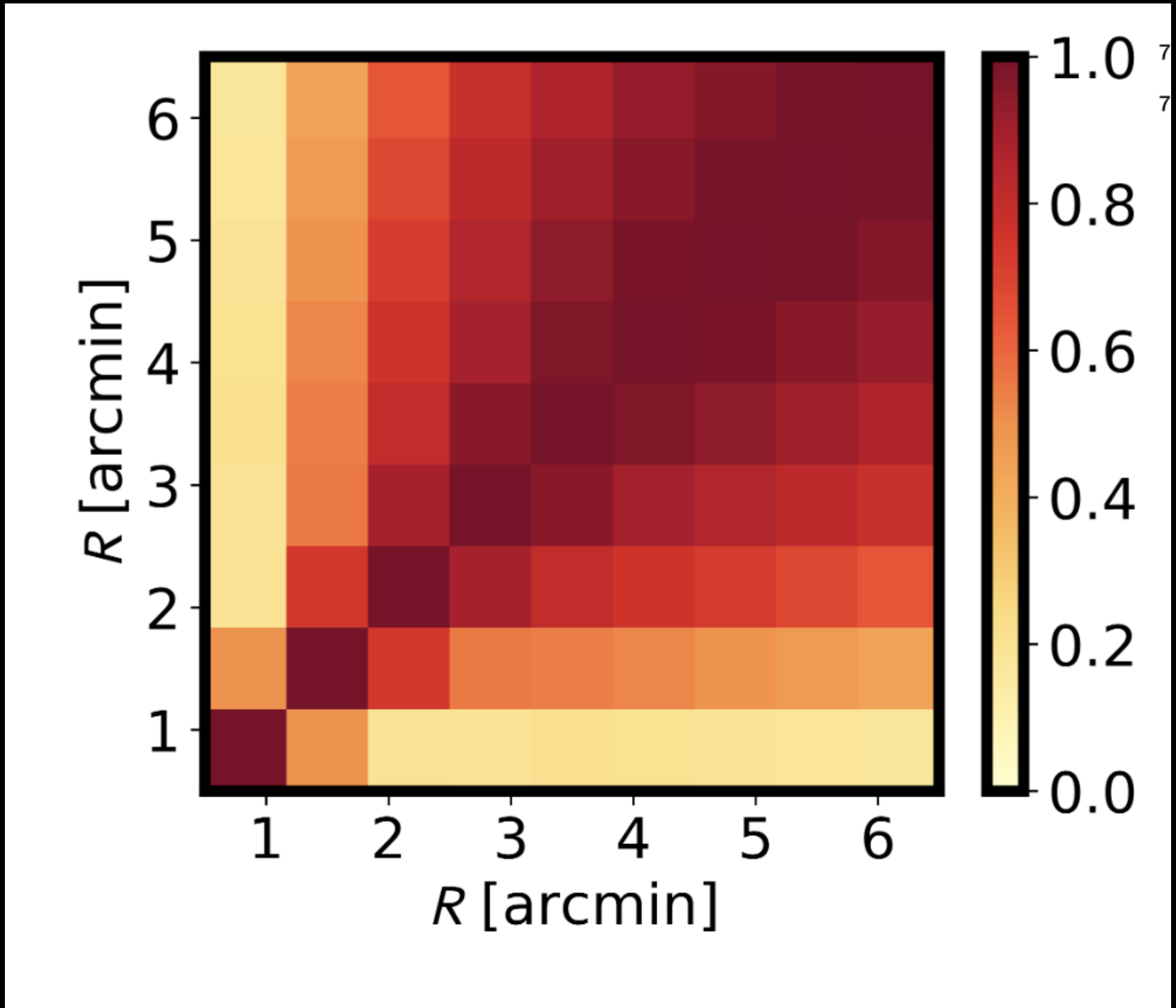
Equivalence between real and harmonic space



Frequency tests



Covariance



in Eq. 11 results in

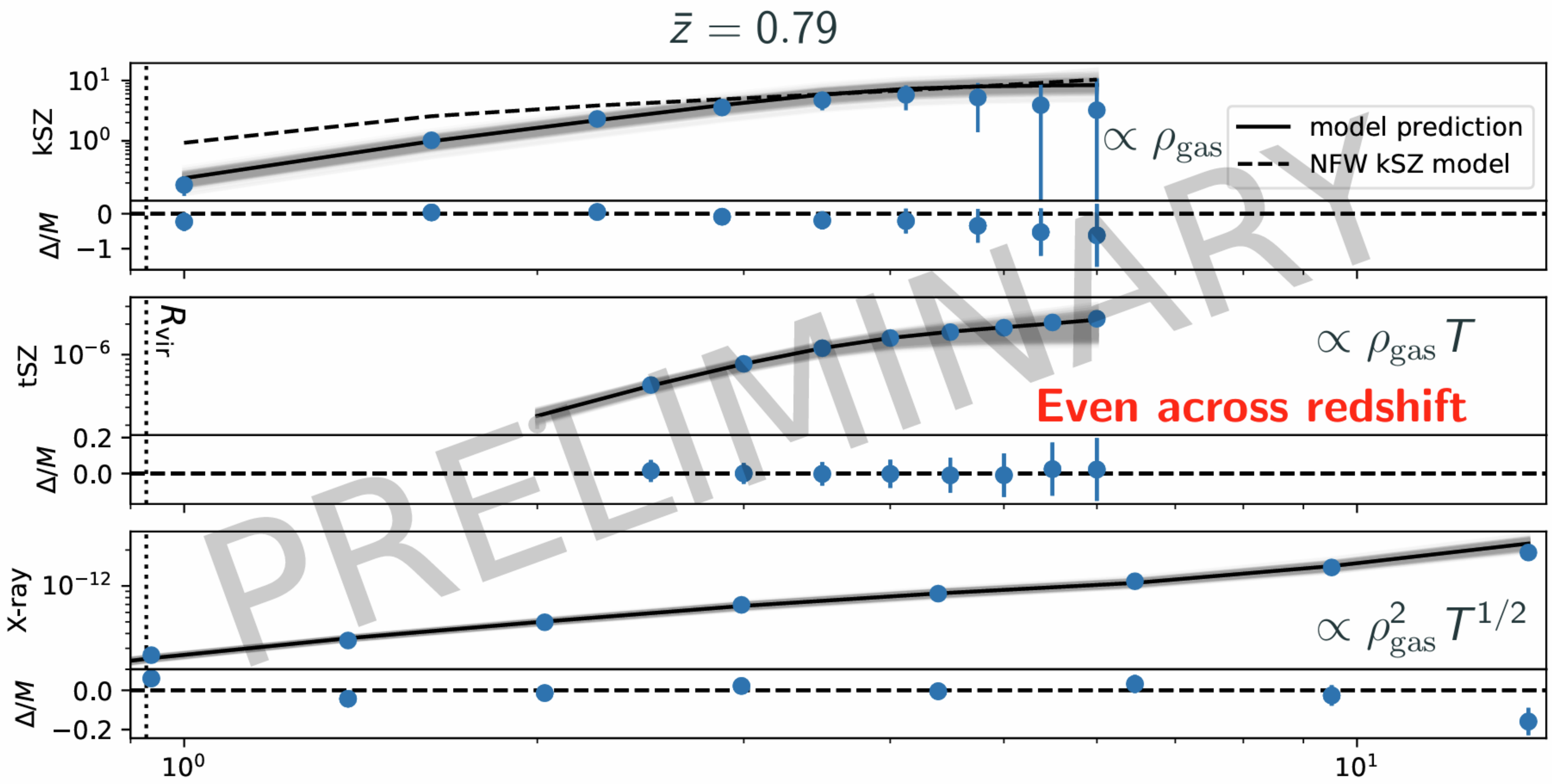
$$C_\ell^{\hat{\pi}\times T_{CMB}} = -\frac{\sigma_T}{c^2}\int d\chi\,\frac{a^{-2}(\chi)}{\chi^2}\,\bar{n}_e(\chi)\,\frac{dp}{d\chi} \times P_{\delta_e v_r,\,\delta_g v_r}\left(k=\frac{\ell+1/2}{\chi},\,\chi\right). \tag{20}$$

Analogous to the treatment in the Ostriker–Vishniac limit for kSZ [53–55], we can simplify $P_{\delta_e v_r,\,\delta_g v_r}$ into an expression involving P_{eg}.

$$\begin{aligned} P_{\delta_e v_r,\,\delta_g v_r}(k,\chi) &\simeq \int \frac{d^3\boldsymbol{k}'}{(2\pi)^3}\,P_{v_r\hat{v}_r}(|\boldsymbol{k}'|)\,P_{eg}(k,\chi) \\ &= r\sigma_{\rm true}\sigma_{\rm rec}P_{eg}(k,\chi) \end{aligned} \tag{21}$$

In Eq. 21, σ denotes the velocity dispersion of

A unified gas profile: preliminary joint model



Caveats and future directions

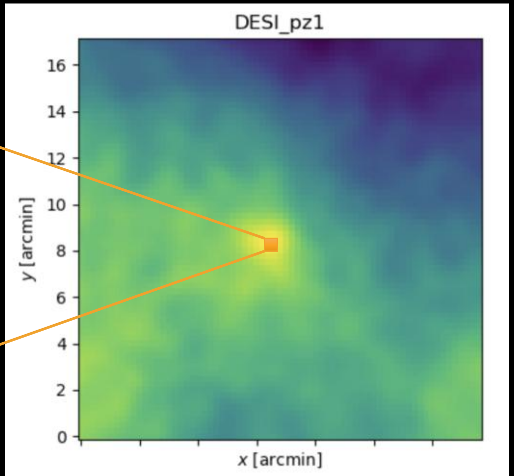
- free parameter $A_{\mathrm{X-ray}}$ relating $\rho_{\mathrm{gas}}^2 T^{1/2}$ to n_{counts} → relate count rates more principally
- $\Lambda_c \neq T^{1/2}$ → include cooling function and eROSITA bandpass
- $\langle \rho_{\mathrm{gas}}^2 \rangle \neq \langle \rho_{\mathrm{gas}} \rangle^2$ → Can we detect clumping?

What can we learn about the underlying matter and temperature profiles?

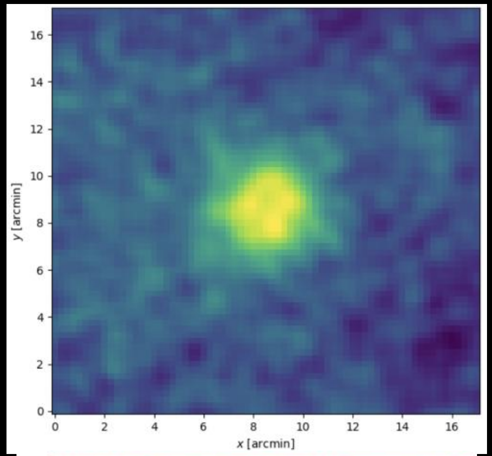
Towards an integrated view of baryons

stars

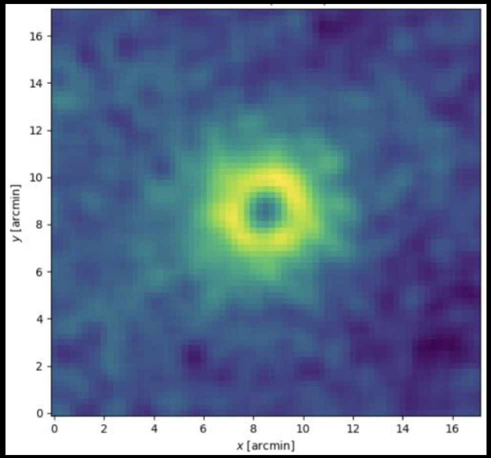
gas density
(kSZ and screening)

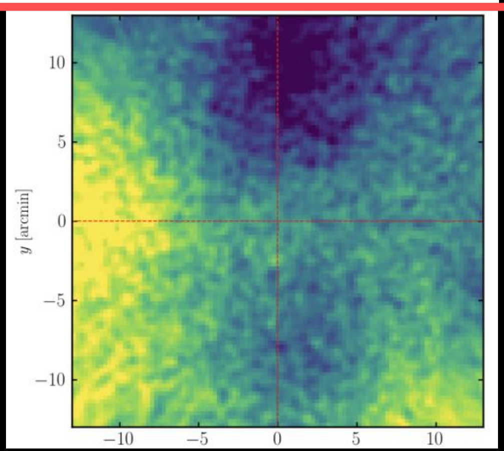


thermal pressure
(tSZ)

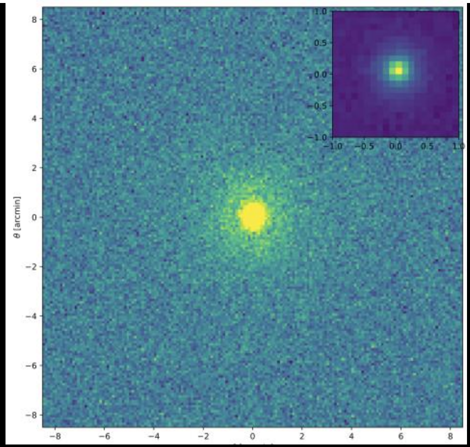


thermal pressure + dust
(tSZ + CIB)

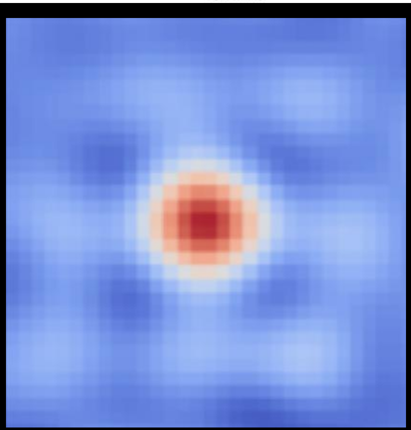




filaments
(kSZ)



hot gas
(X-ray)



mass
(CMB lensing)

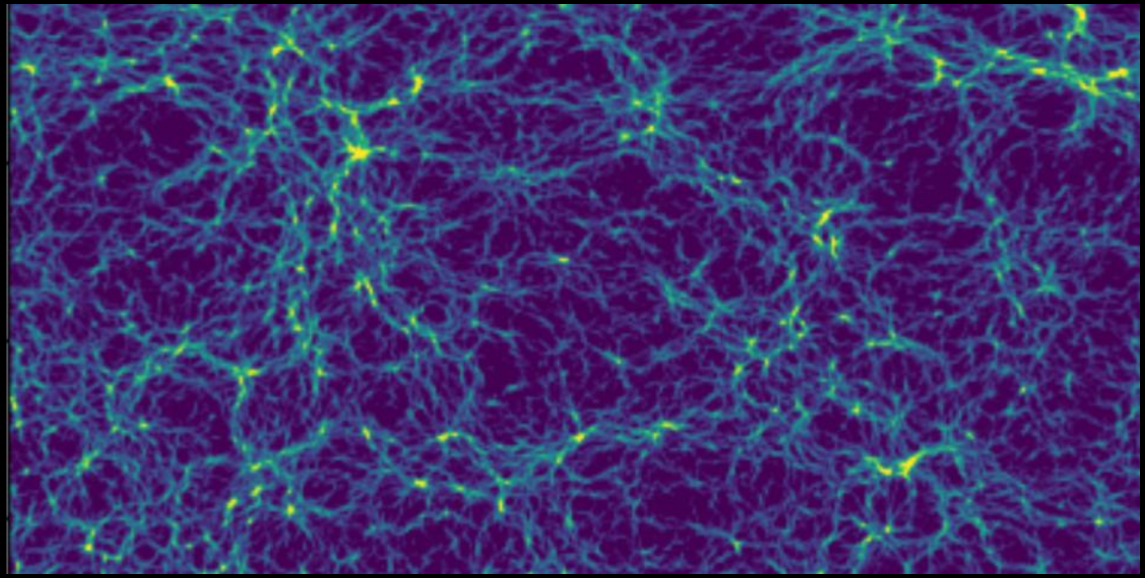
Identifying cosmic filaments in DESI

- Compute tidal tensor, i.e. Hessian of the gravitational potential in 2D:

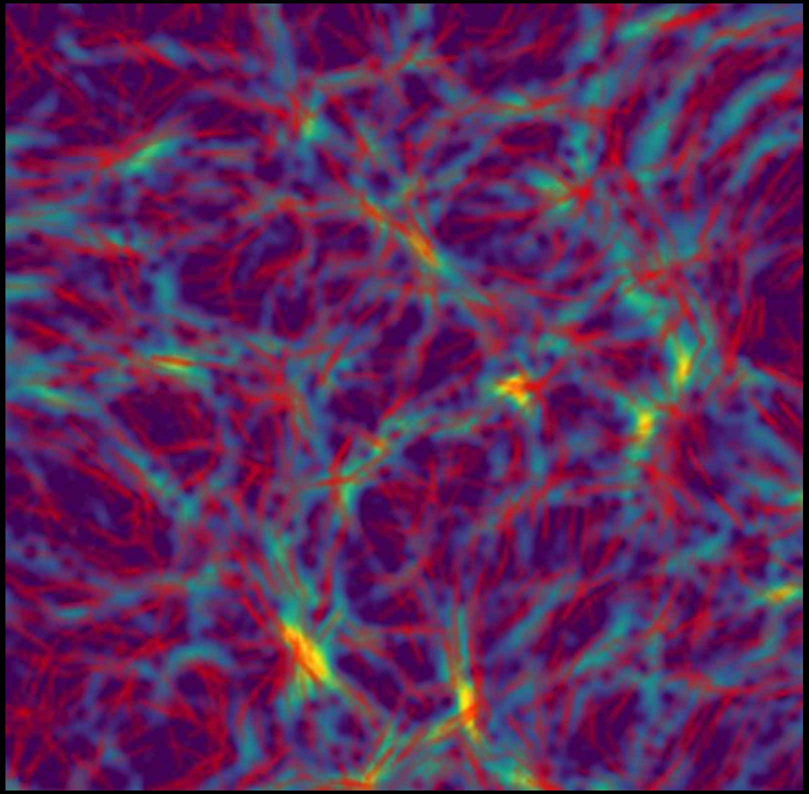
$$t_{ab} \equiv H_{ab}\,\phi$$

- Diagonalize it to obtain evals → smallest evec gives filament direction

Eigenvalue map of DESI BGS



Filament map of DESI BGS

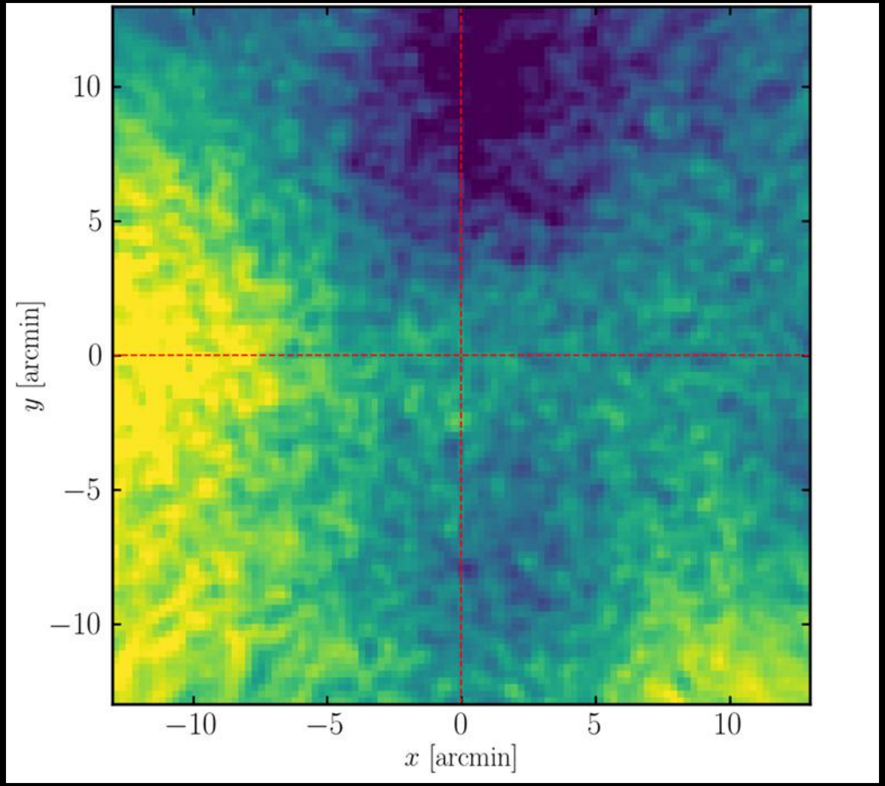


Hadzhiyska+ 24

Alignment of the gas with the filaments

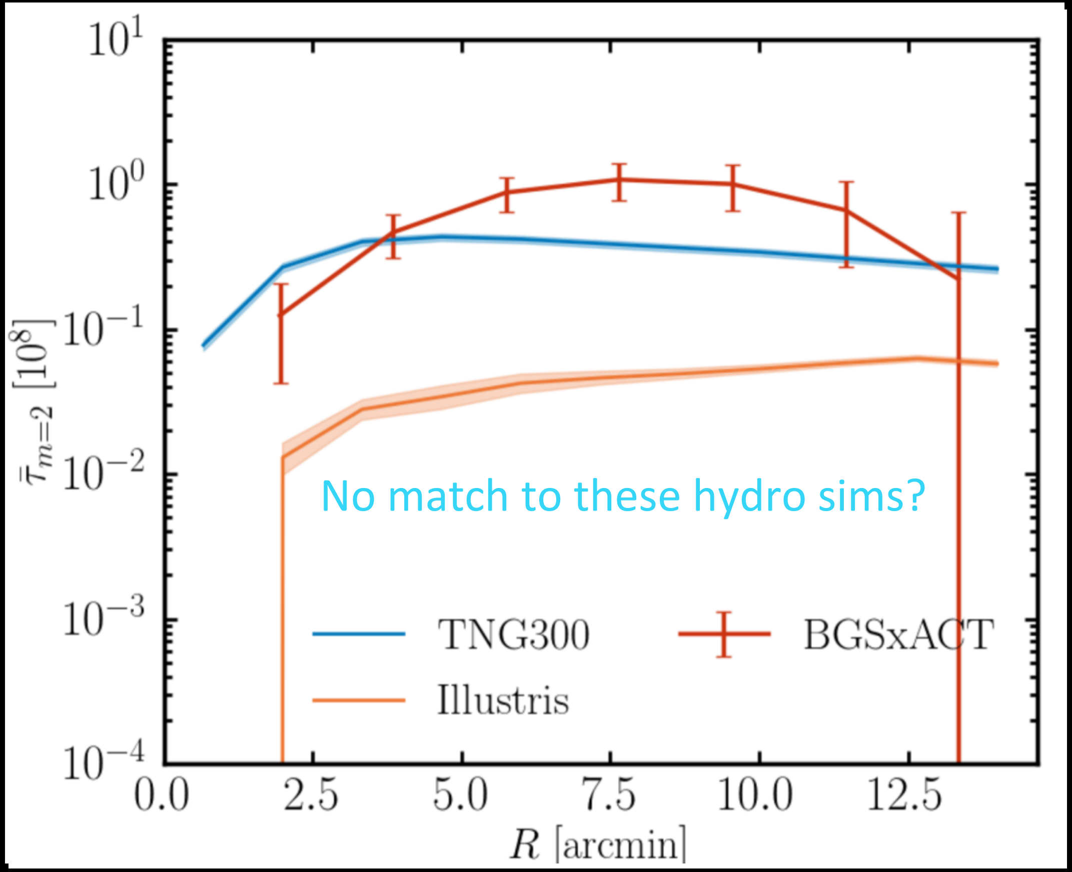
- We find an alignment of gas along the filaments (SNR = 4σ):

Stacked image of DESI BGS



Comparison with hydro sims

Amplitude of alignment



Distance from center

Photons interact with matter!

CMB lensing $$\left(\frac{\Delta T}{T}\right)_{\mathrm{lensing}} \propto \nabla\phi(\boldsymbol{\theta}) \cdot \nabla \left(\frac{\Delta T(\boldsymbol{\theta})}{T}\right)_{\mathrm{primary}}$$

kinematic SZ $$\left(\frac{\Delta T}{T}\right)_{\mathrm{kSZ}} \propto \boxed{N_e(\boldsymbol{\theta})}\, \frac{v_r}{c}$$

column density of electrons

radial velocity

thermal SZ $$\left(\frac{\Delta T}{T}\right)_{\mathrm{tSZ}} \propto N_e(\boldsymbol{\theta}) T_e(\boldsymbol{\theta})$$

patchy screening $$\left(\frac{\Delta T}{T}\right)_{\mathrm{bSZ}} \propto N_e(\boldsymbol{\theta}) \left(\frac{\Delta T(\boldsymbol{\theta})}{T}\right)_{\mathrm{primary}}$$

our team

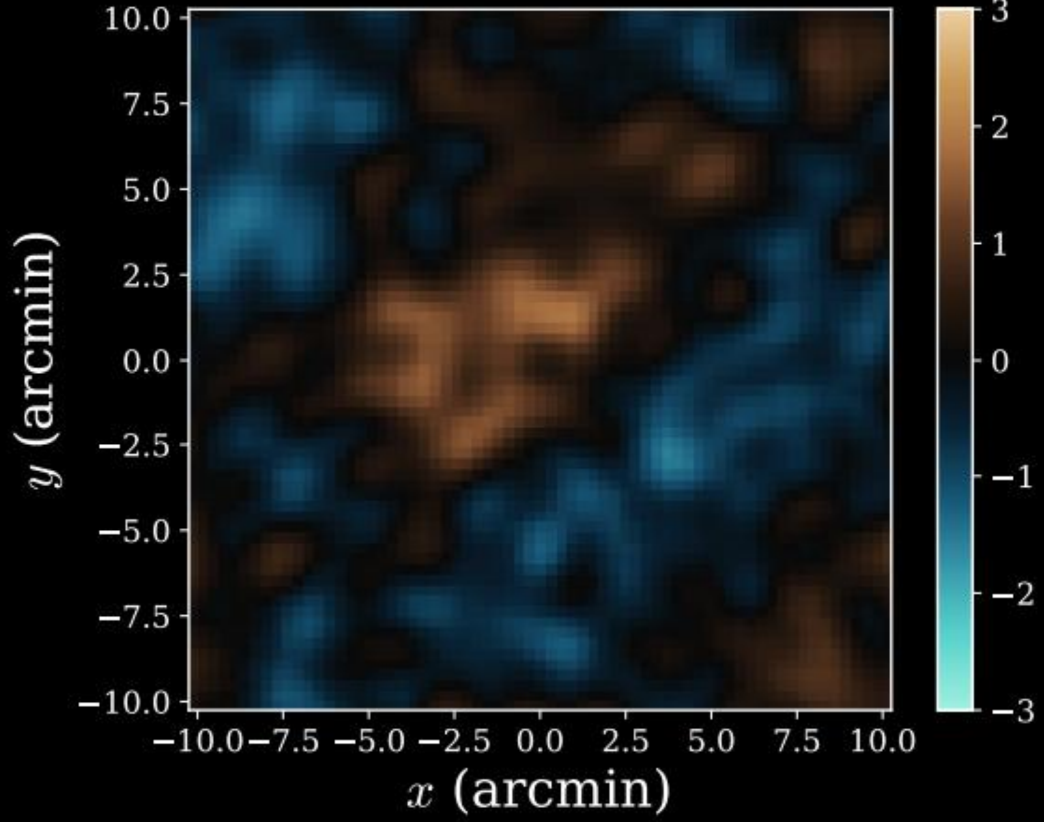
Ried Guachalla, Liu, Hadzhiyska, Schaan, Ferraro

Noah Sailer

Gerrit Farren

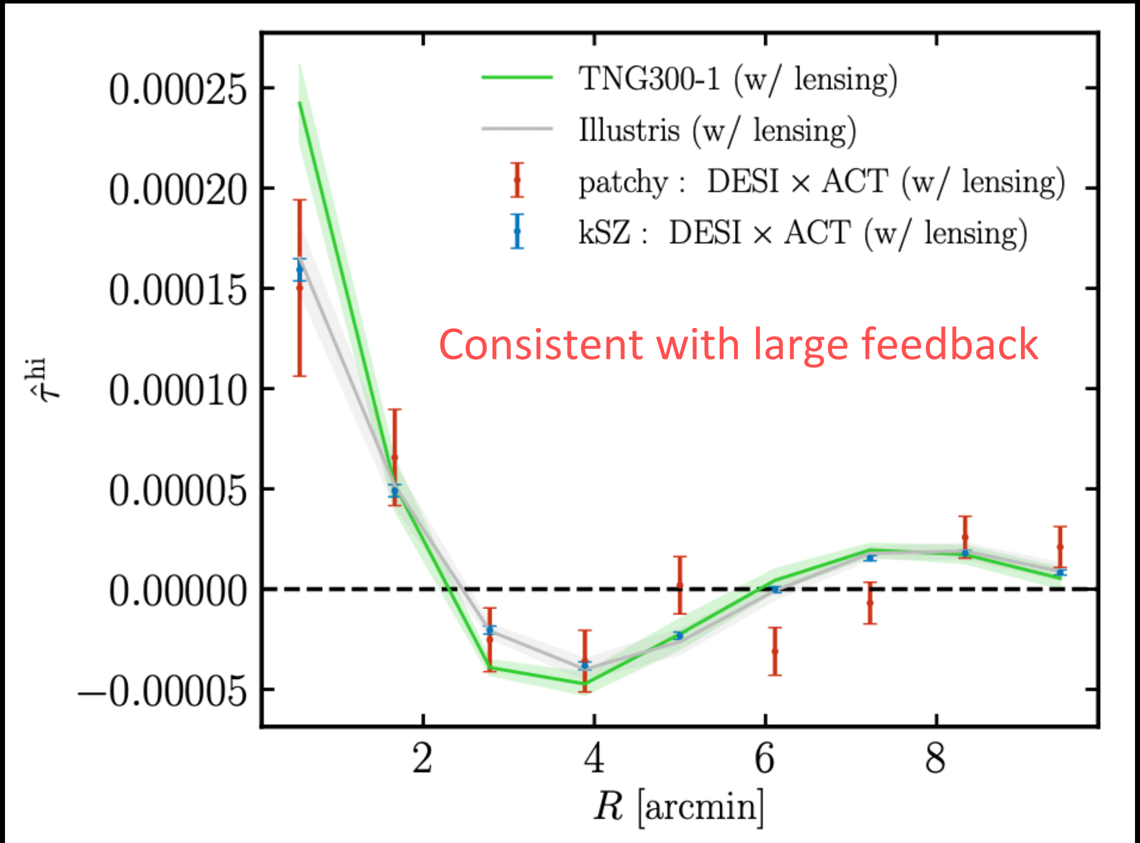
Patchy (or anisotropic) screening

$$T_{\text{patchy}} \propto \rho_{\text{gas}}$$



Noah Sailer

Promising in the future with Rubin-LSST!



Coulton+ 25, Schutt+ 24, Hadzhiyska+ 25, Sailer+ 25

Dark Energy Spectroscopic Instrument (DESI)