Title: A skeptic's guide to CMB probes of galaxy formation

Speakers: Emmanuel Schaan

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

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Abstract:

Galaxies and their surroundings imprint shadows on the cosmic microwave background. These shadows contain tantalizing information about galaxy formation: from the baryon density, temperature, pressure, velocities, to the dark matter potential and its time-evolution due to accretion. In this talk, I will review the unique opportunities and challenges in learning about galaxy formation and cosmology from CMB observables.

A skeptic's guide to CMB probes of baryons

Baryons: much information to uncover

Learn about galaxy formation? cosmology?
Feedback on the gas? stars?
→ Immense challenges & opportunities

CMB: unique backlight, reveals galaxy properties like watermark on banknote

Should you trust CMB probes of baryons?
My goal: present subtleties/idiosyncrasies of CMB/kSZ as baryon probe

On this topic:
See talks of Alex, Hiranya, Leah, Jared, Ian, Erwin, Evan, Jonah, Sanskriti, Simone, Will, Gerrit, Boryana & many others!
& Organizers Selim, Nick, Kendrick, Matt, Niayesh+

Summary of CMB secondaries

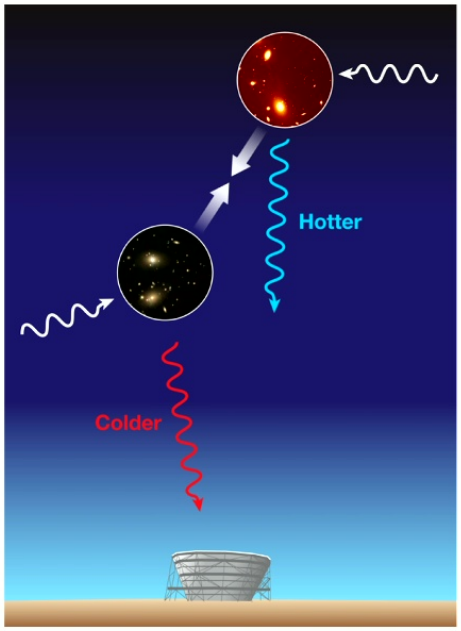
Key parameters:

$$\theta_{\rm lens} \sim 1' \sim 10^{-4},\ \int dt\dot{\Phi} \sim 10^{-4},\ \tau \sim 10^{-3},\ \frac{k_B T_e}{m_e c^2} \sim \left(\frac{v_{\rm th}}{c}\right)^2 \sim 0.01,\ \frac{v_{\rm bulk,rot,turb}}{c} \sim 10^{-3},\ \frac{\delta T_0}{T_0} \sim a_2 \sim 10^{-5}$$

→ **Many imprints with complementary information :**

Potential		
Lensing	$\theta_{\rm lens} \frac{\nabla T_0}{T_0}$	Total mass
ISW, Rees-Sciama	$\int dt\ \dot{\Phi}$	DE, accretion rate
Moving lens	$\theta_{\rm lens} (v_{\rm bulk\ \perp}/c)$	Transverse velocities
Single scattering		
Screening	$\tau\ (\delta T_0/T_0)$	Gas density
kSZ, rot kSZ, turb kSZ	$\tau\ (v_{\rm bulk\ \parallel}/c)$	Gas density, LOS velocities
tSZ, relat tSZ	$\tau\ (v_{\rm th}/c)^{2,4}$	Gas thermal pressure, temperature
Polarized scattering	$\tau\ (v_{\rm bulk\ \perp}/c)^2, \tau\ a_2$	Gas density, Ultra large scales
Multiple scattering		
Smaller by factor τ		Break degeneracies with tau?

Why is kSZ special?



Hand et al 2012

$$\frac{\delta T_{\rm kSZ}}{T_{\rm CMB}} = \tau \frac{v_{\rm bulk}}{c} \quad \propto \; n_e$$

→ Linear in gas density

Ideal for lensing; higher masses possible

Lucie-Smith Peiris Pontzen 24

Low mass halos, high z, far outside the virial radius

Robust to dust contamination

No assumptions about metallicity, temperature, clumping

Complementary with tSZ, absorption lines, X rays, FRBs

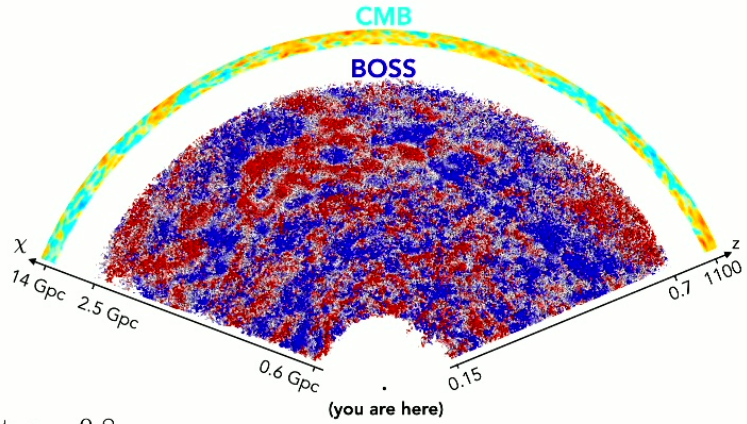
How is kSZ measured?

$$\frac{\delta T_{\rm kSZ}}{T_{\rm CMB}} = \tau \frac{v_{\rm bulk}}{c}$$

Naïve stacking cancels the signal

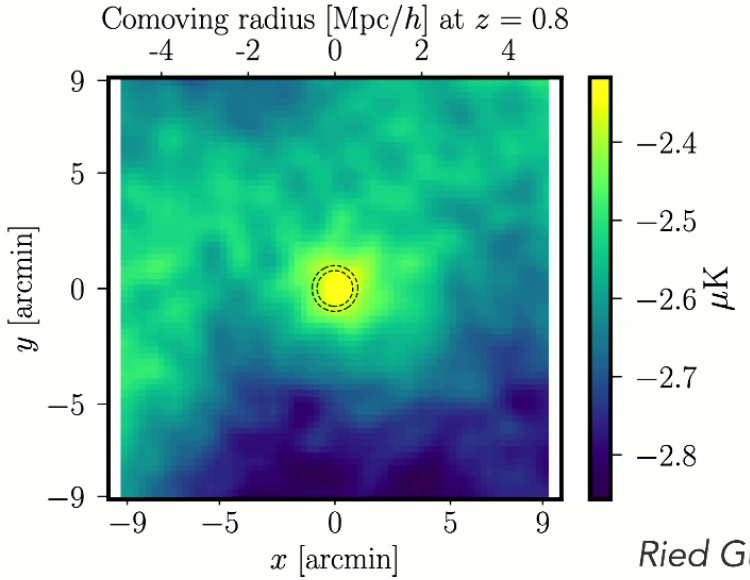
→ **weight by "reconstructed velocities"**

(Other, equivalent approaches *Smith+19)*



Schaan Ferraro+21

→



Ried Guachalla+25

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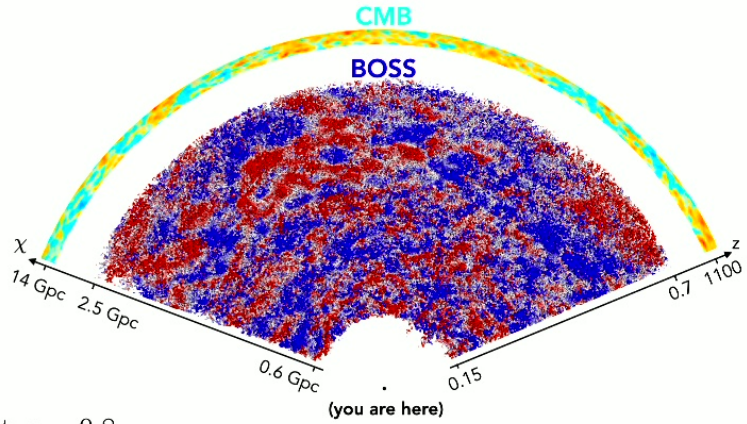

Schaan Ferraro+21

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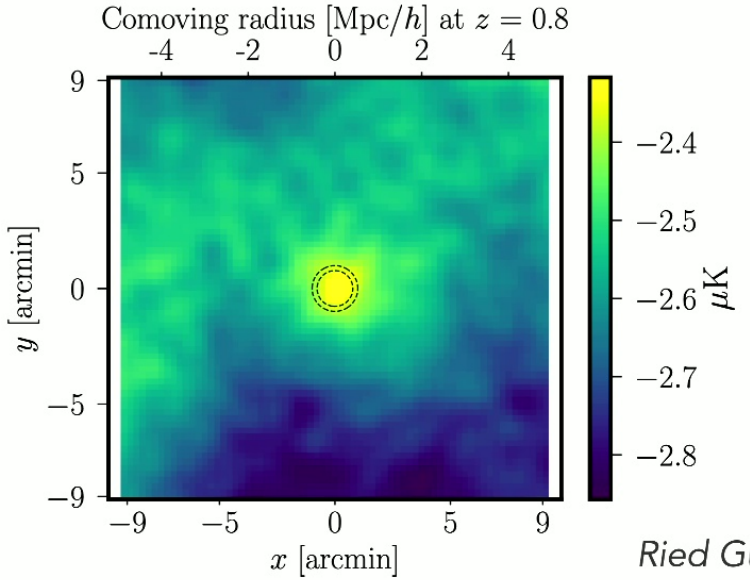
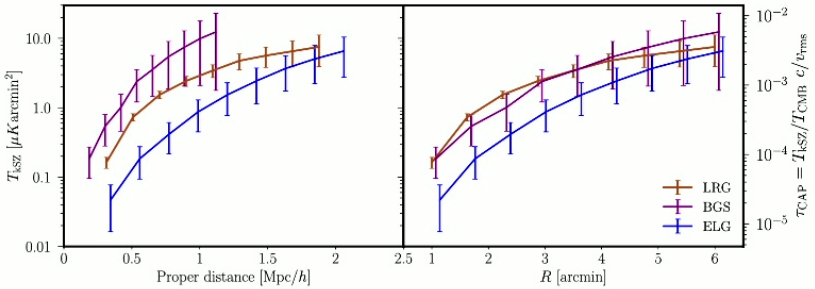


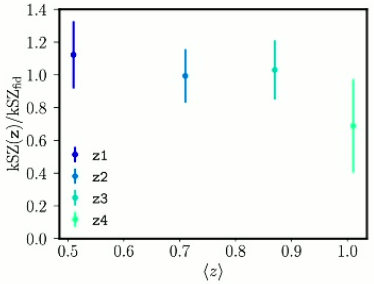
Ried Guachalla+25

Latest stacked kSZ profiles available?

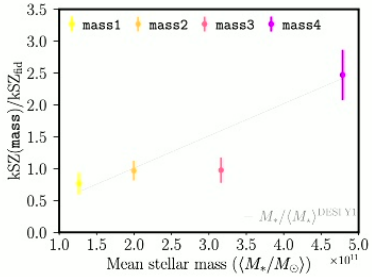
DESI LRG, BGS, ELG
spectro: *Ried Guachalla+25*
photo: *Hadzhiyska+25*



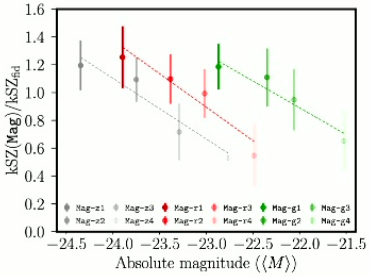
Also splits by redshift,



stellar mass,

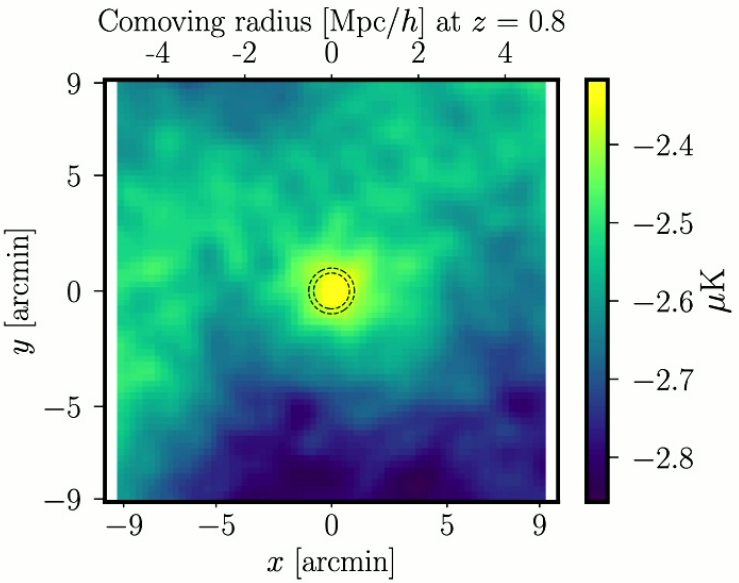


absolute magnitude



→ All publicly available. Don't hesitate to use them & ask questions!

Aren't CMB experiments too low resolution?

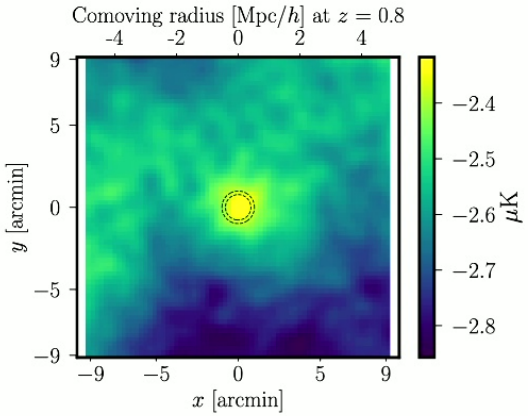


Ried Guachalla+25

Virial radius of galaxy groups ~ 1', and gas extends several R_{vir}
→ Well matched to CMB data!

kSZ unique probe of outskirts of galaxy groups and clusters
→ Complementary with X-ray & tSZ, which probe cluster centers best

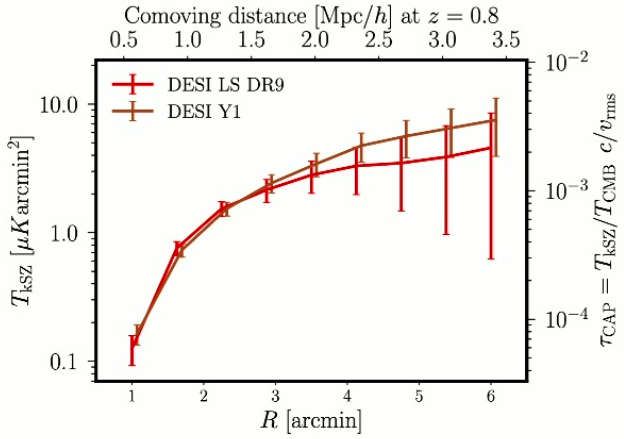
Large-scale noise: profile slope VS M_{gas}

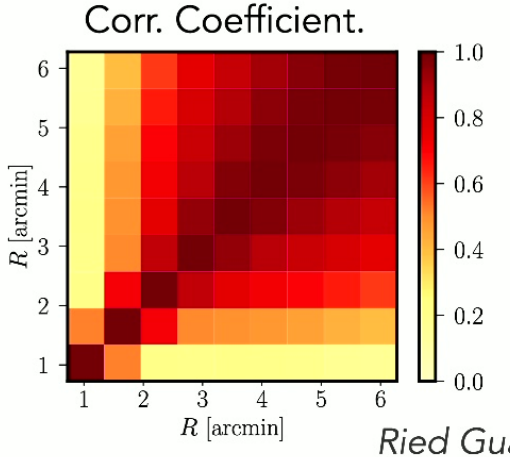


Primary CMB (~degree) dominates noise on larger scales

→ kSZ measures profile shape/slope better than its integral (M_{gas})

CAP filter avoids displaying constant CMB mode, but is not required. Fourier measurements simplify this



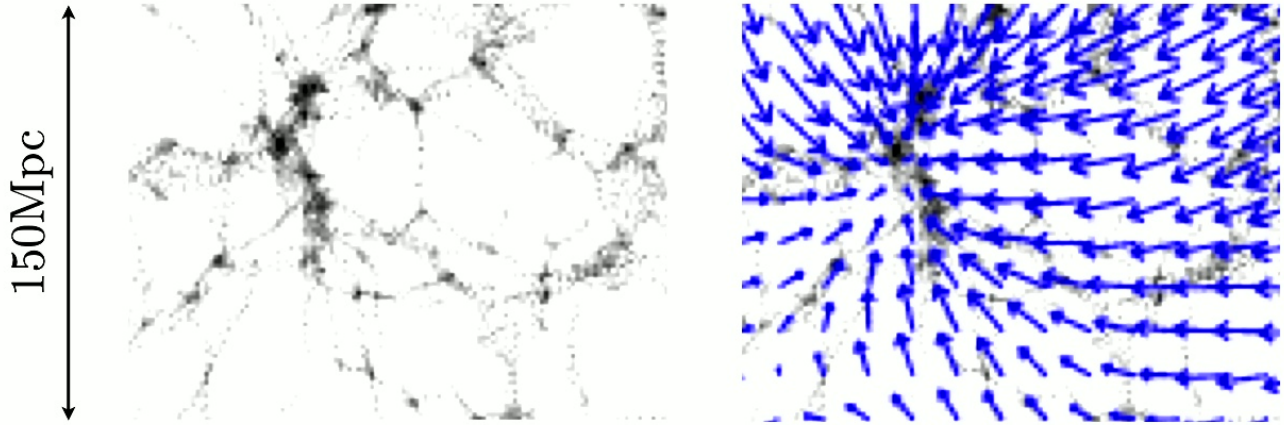


Ried Guachalla+25

Are velocities a problem?

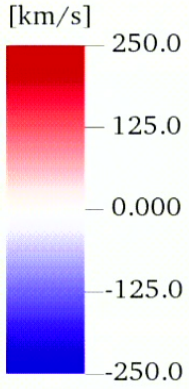
Mass conservation + linear approx.

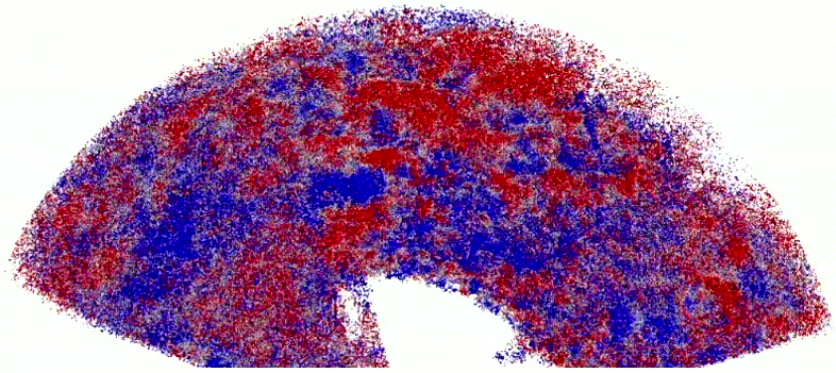
$$\dot{\delta} + \vec{\nabla} \cdot \vec{v} = 0 \quad \Rightarrow \quad \vec{v} = -aHf \; \vec{\nabla}\Delta^{-1}\delta$$



Eisenstein+07, Padmanabhan+12,14

Are velocities a problem?

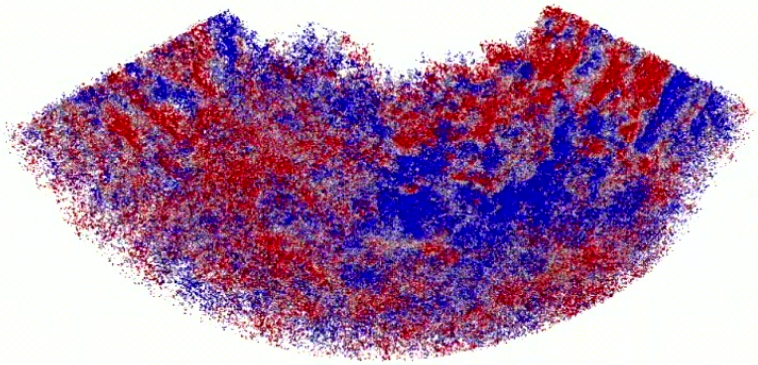




Velocities correlated on very large scales ~100 cMpc

→ Challenge for small-box sims

→ But makes velocity reconstruction simpler (linear theory)

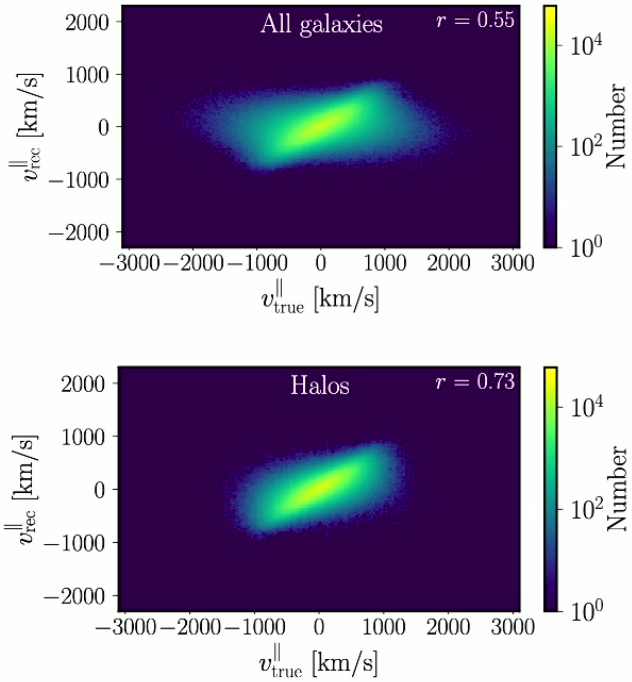


DESI Y1

Ried Guachalla

Are velocities a problem?

Assessed performance of velocity reconstruction *Ried Guachalla+23, Hadzhiyska+23*



Key results

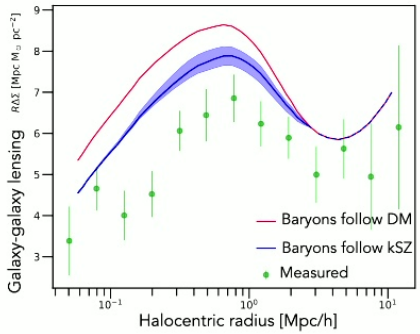
- Reconstruct halo (not galaxy) velocities → good for kSZ!
- Photo samples extremely powerful (DESI LS, DES, HSC, LSST)
- Naïve hybrid photo-spectro reconstruction worse than photo-only

Assess impact of

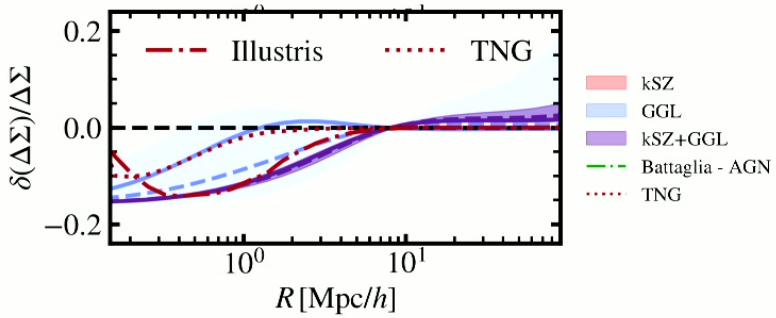
- satellite fraction
- number density
- smoothing
- cosmology

Subtleties about overall amplitude remain: see Alex, Leah, Jared's talks
Doppler term subtraction

kSZ is faint. Is precision enough for lensing?



Amodeo+21



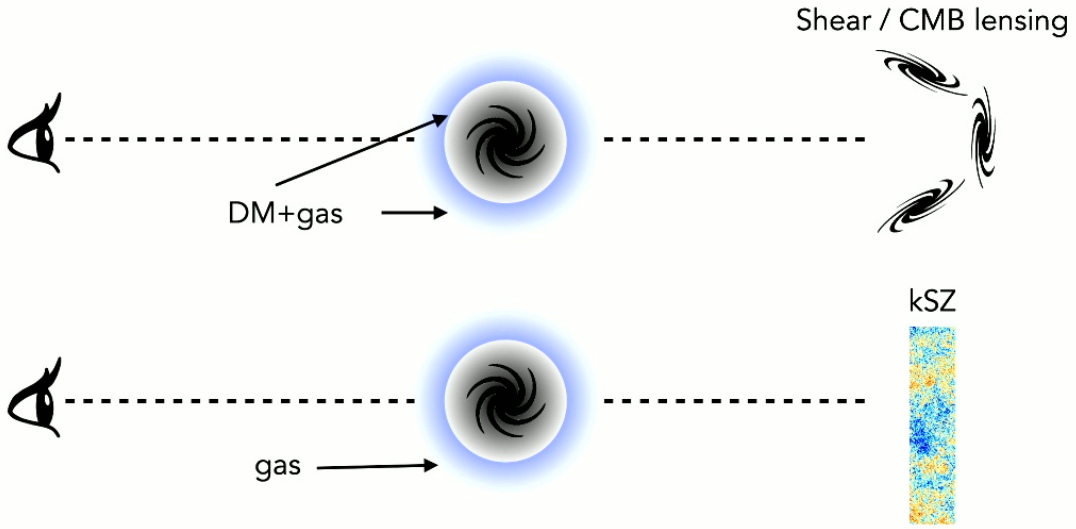
Sunseri+25

Precision already informative in 2021, now much better & improving

Baryons are 15% of the matter.
For 1%-precision lensing, only 7%-precision kSZ needed
→ **statistics will not be limiting**

→ **Modeling is the challenge**

Subtracting baryons from galaxy-galaxy lensing is a well-posed problem



→ **Directly subtract the baryonic contribution!**

Same halos, HOD, weighting (linear in mass, VS tSZ or Xray), angular scales

Hadzhiyska+25, Sunseri+25, McCarthy+25

Galaxy formation & Cosmic shear: trickier!

kSZ only measured around some halos at some z
Cosmic shear = sum over halo masses & z
→ **Extrapolation needed** (*Lucie-Smith+25)*

Universality of matter power suppression? (*Van Daalen+20, Joop's talk*)
→ would help!

Comparison with simulation requires matching the galaxy sample
mass (stellar or halo? mean or distribution?)
satellite fraction & miscentering
HOD?
→ **All "large feedback" claims hinge on this**

Great progress being made
Bigwood+24, Sunseri+25, McCarthy+25

Conclusions

CMB probes many baryons & dark matter properties

New measurements available & upcoming,
function of mass, redshift, etc

Unique opportunity to learn about galaxy formation & lensing
once interpretation challenges are met!

More CMB imprints will soon be usable: screening, rotational kSZ