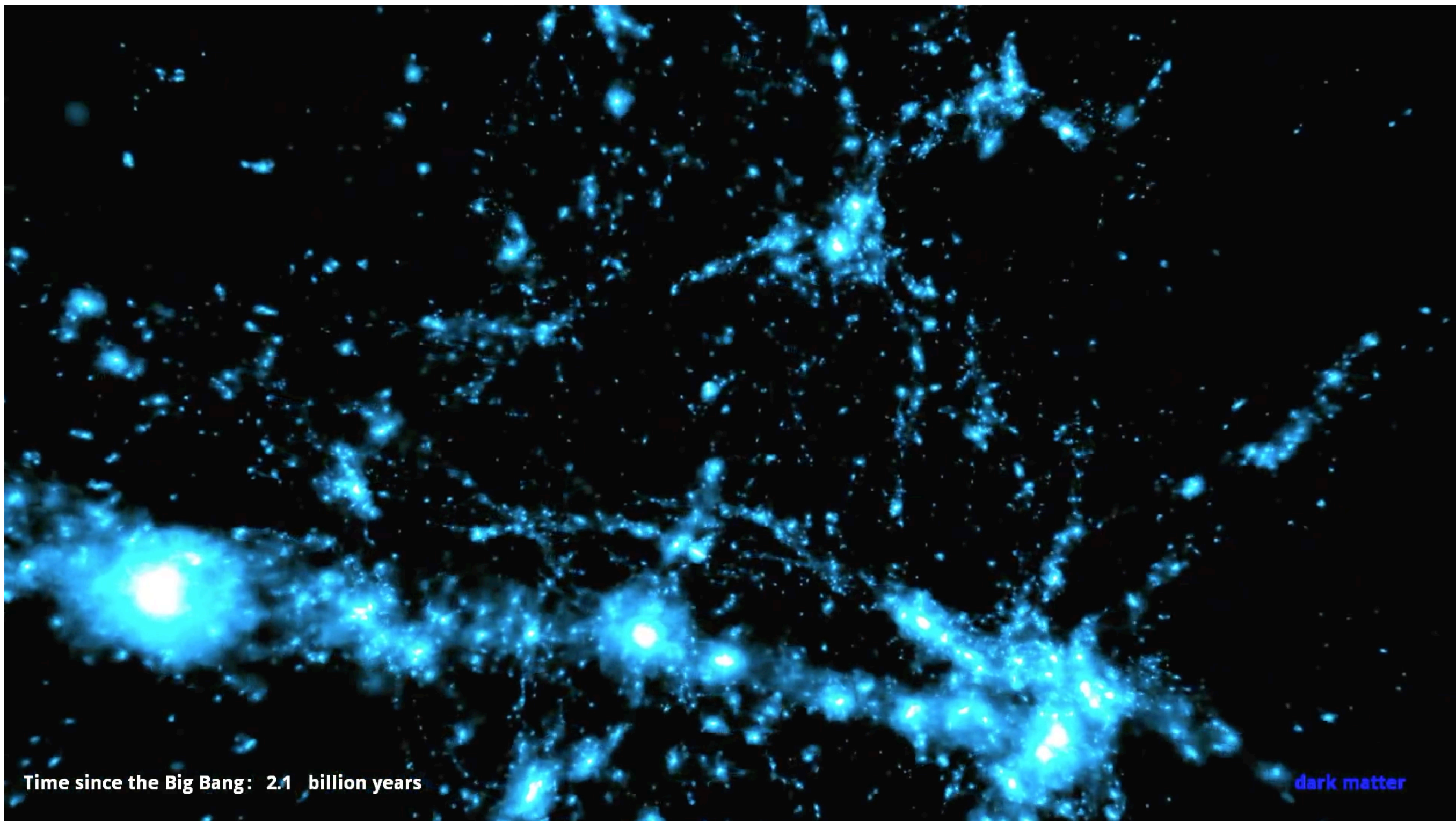


Backlighting the LSS with the CMB

★ Alleviating baryonic uncertainties

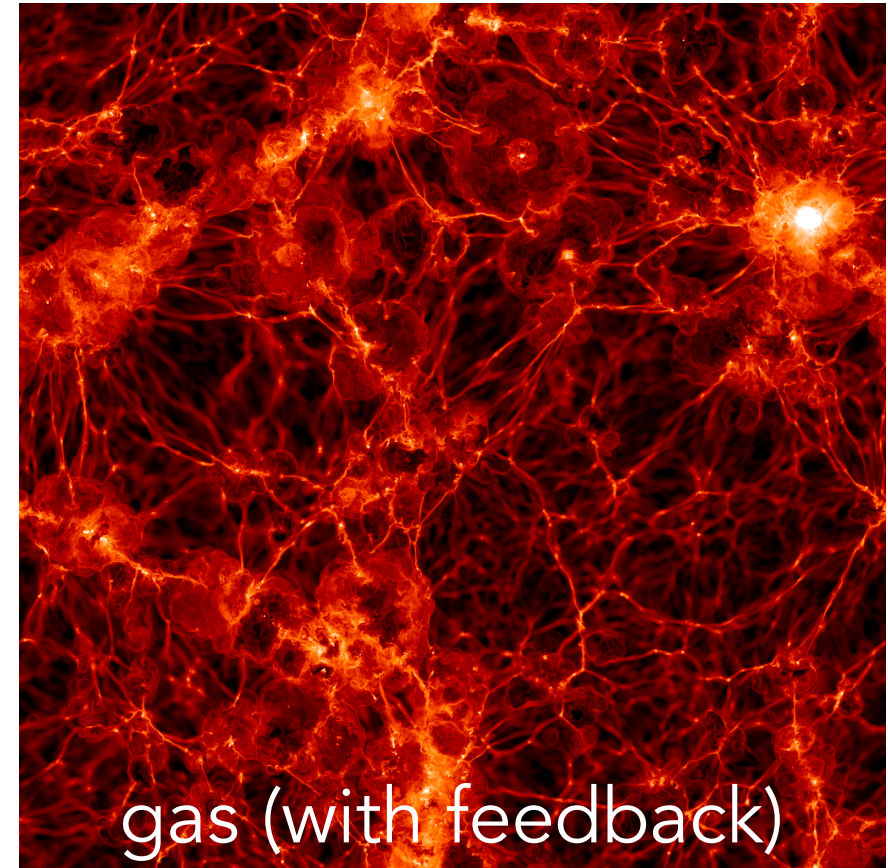
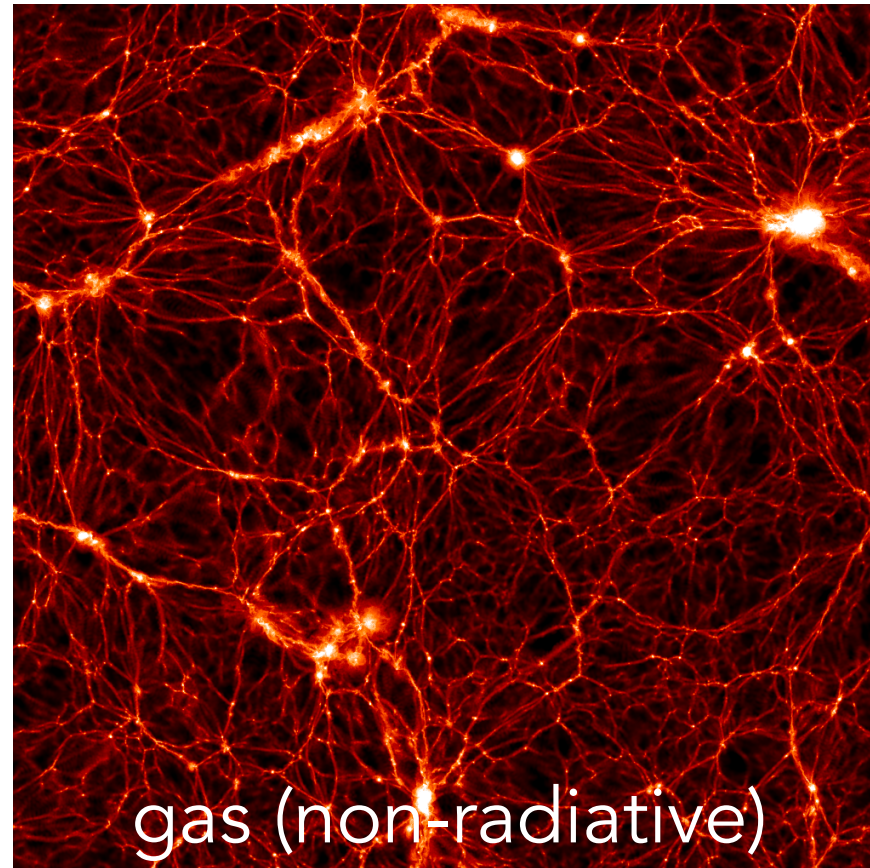
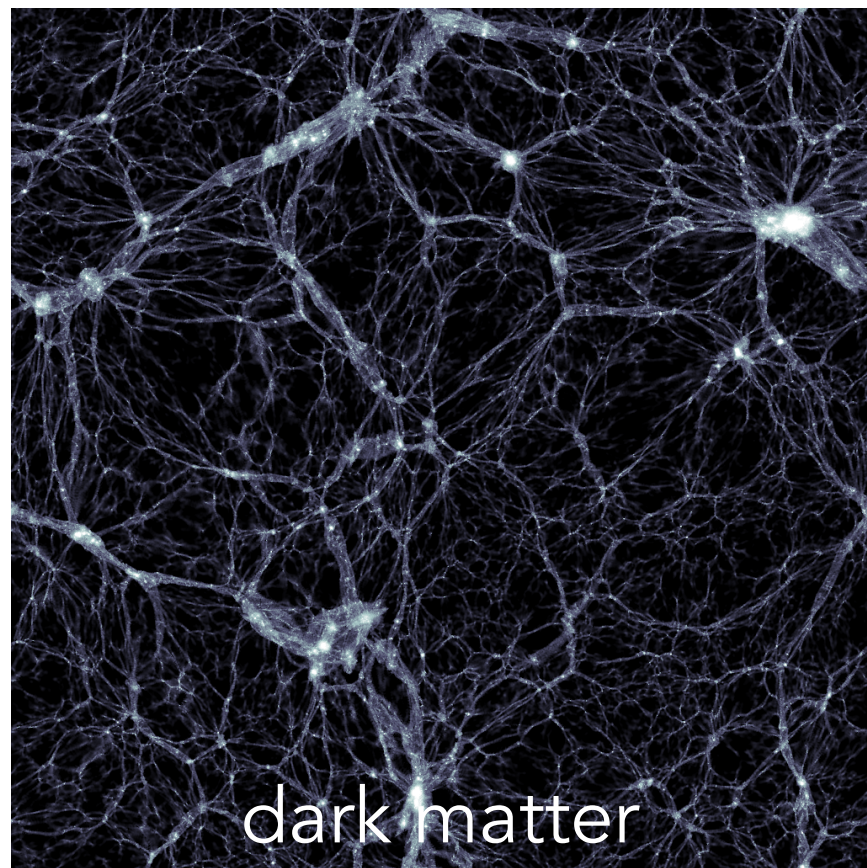
Why care about baryons? Cosmology & Galaxy formation



Supernovae and supermassive black holes regulate galaxy formation
Unknown feedback amplitude
→ **(Missing) baryon problem**

Illustris

(Missing) baryon problem



Haider+16, Illustris simulation

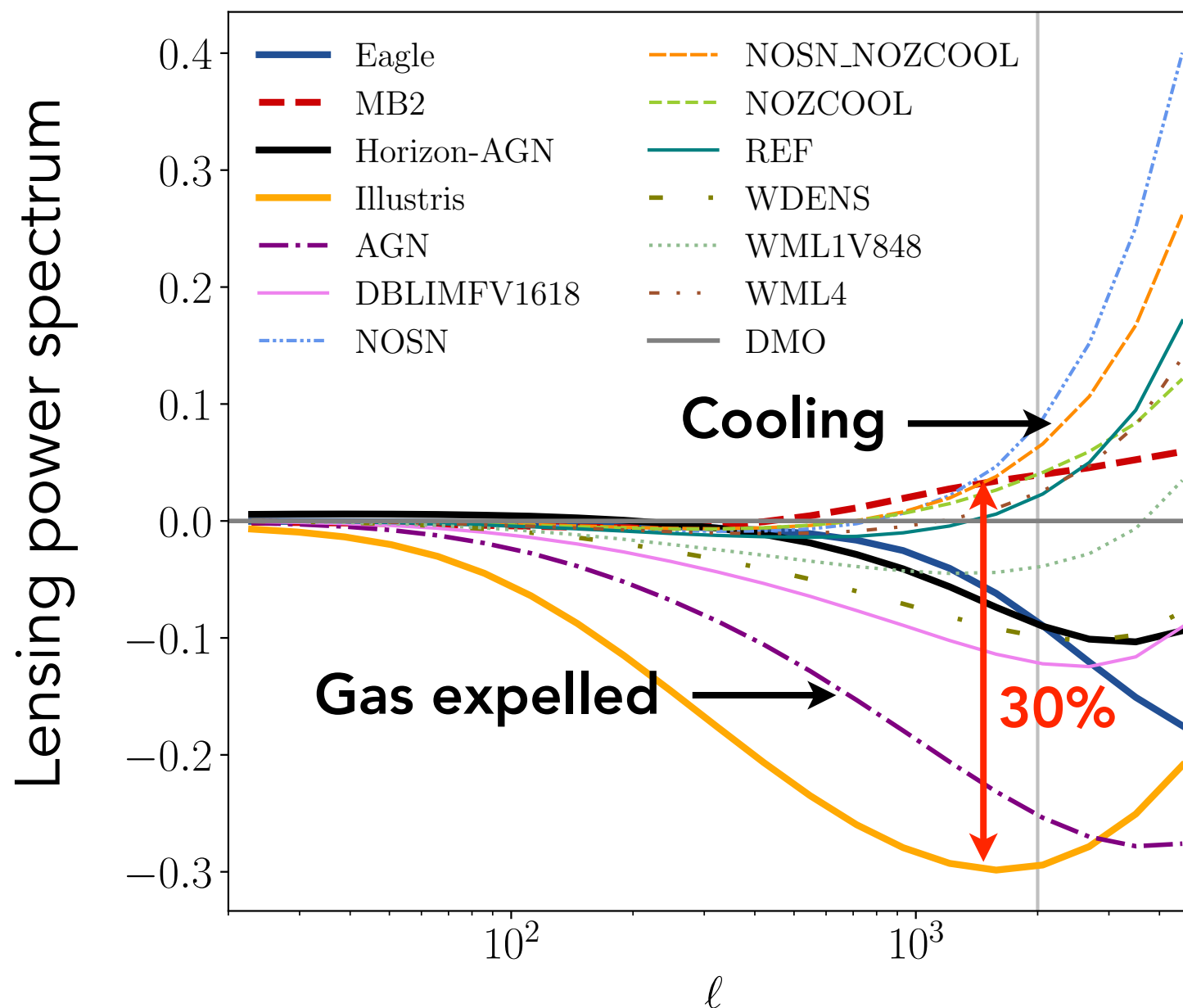
Most baryons in gas (not stars)

Feedback pushes gas outside virial radius

Too faint to detect outside of low mass halos, at high z

→ **Gas profiles tell us about feedback**

Baryons limit weak lensing cosmology



Huang+18

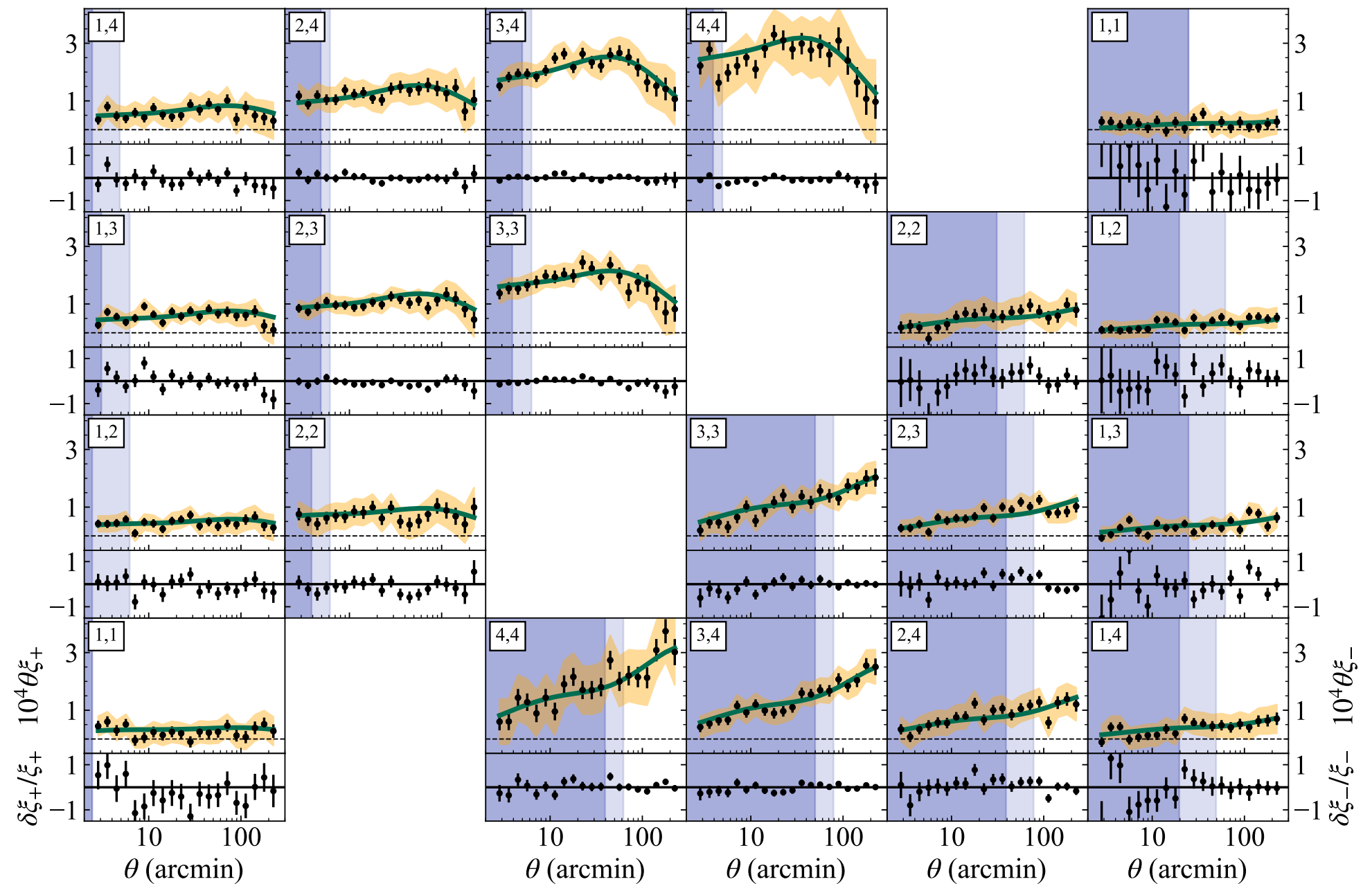
Baryons ~15% total matter, localization is uncertain

→ Largest (30%) uncertainty on the matter power spectrum!

How to analyze 1% precision LSS data when baryons (15% of matter) are missing?

Baryons: much information to recover!

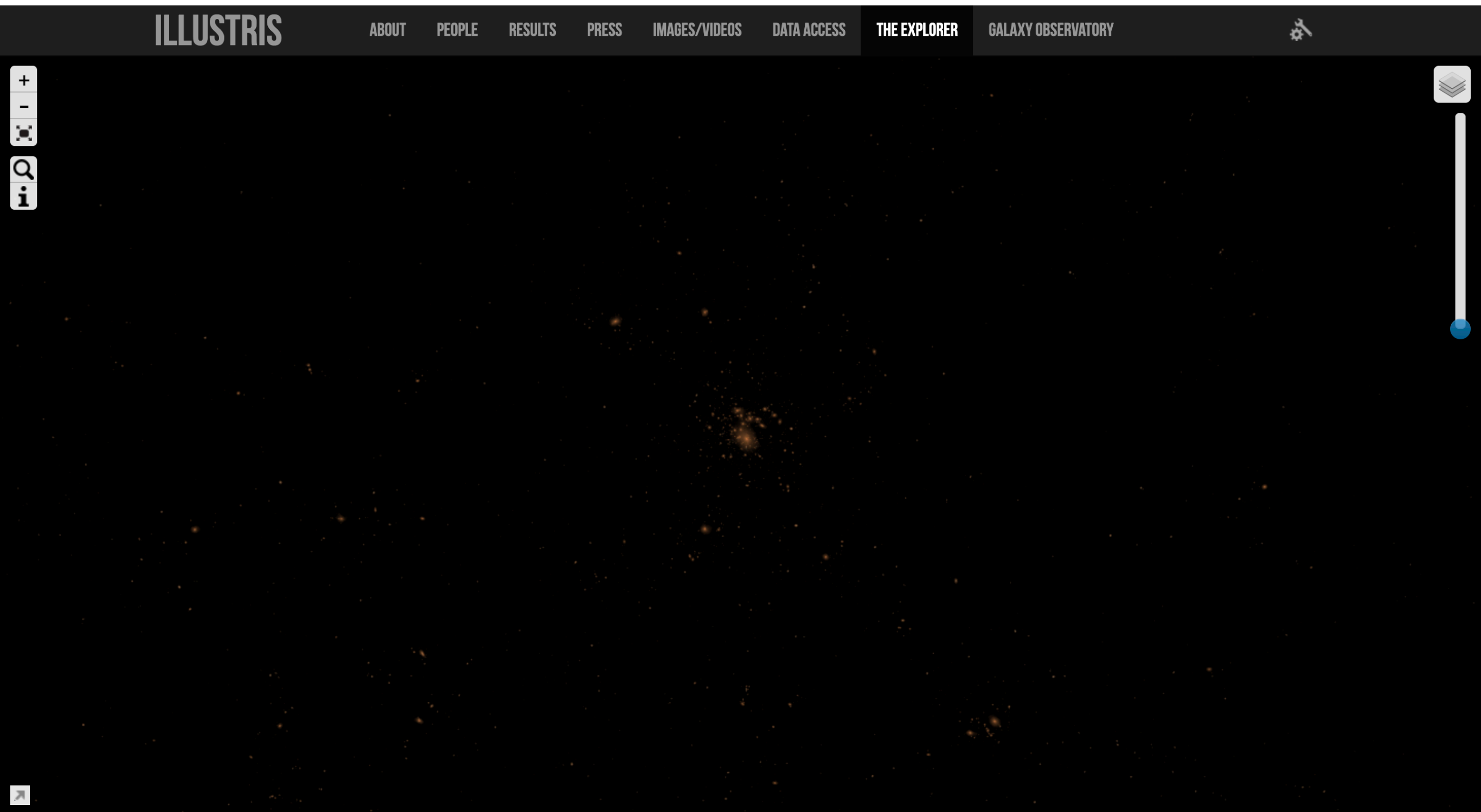
Shaded
=
Discarded



DES Y3 Amon+22

Localizing the baryons would unleash the constraining power of LSST/Euclid

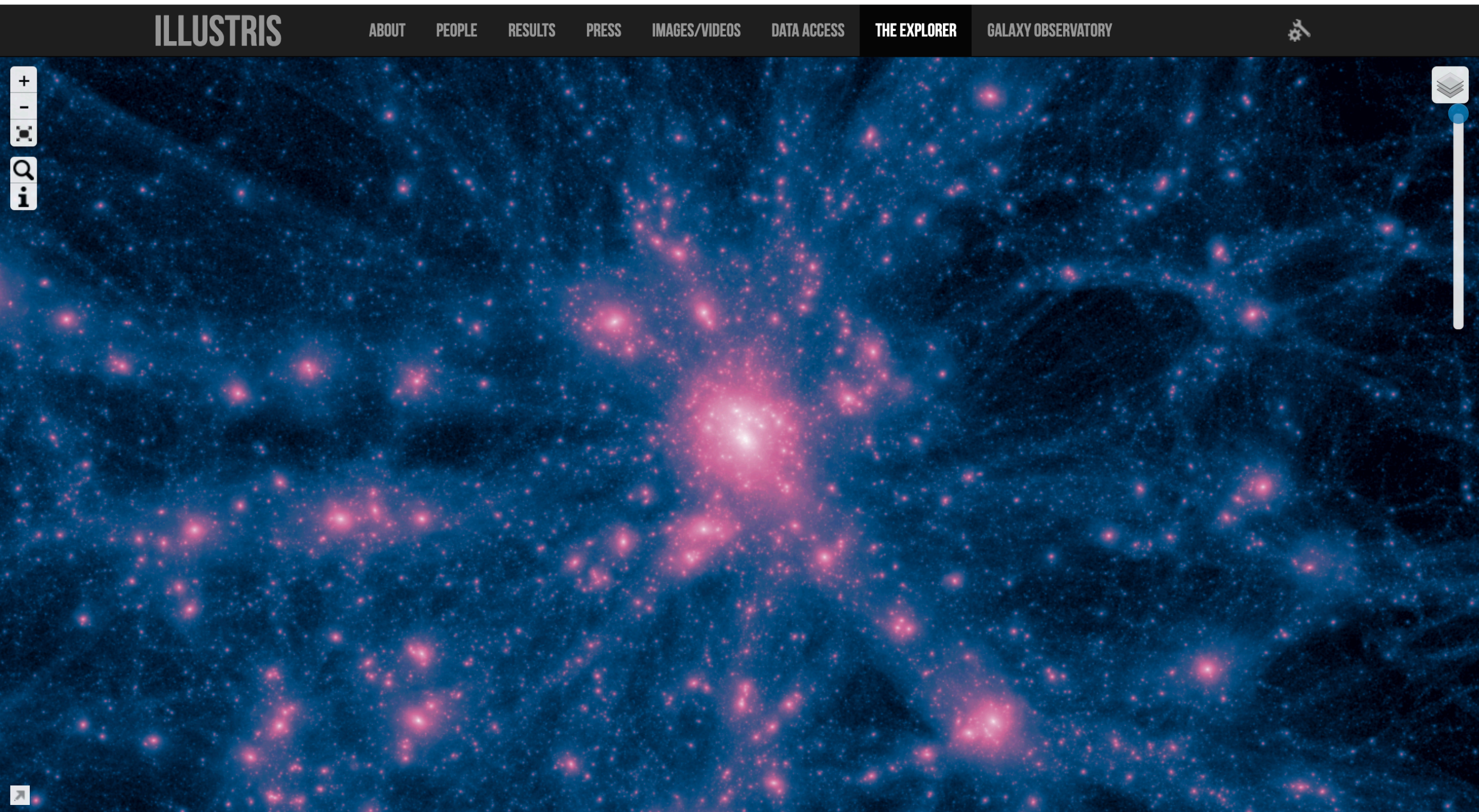
Light is a biased tracer of the mass



Starlight

Illustris simulation explorer

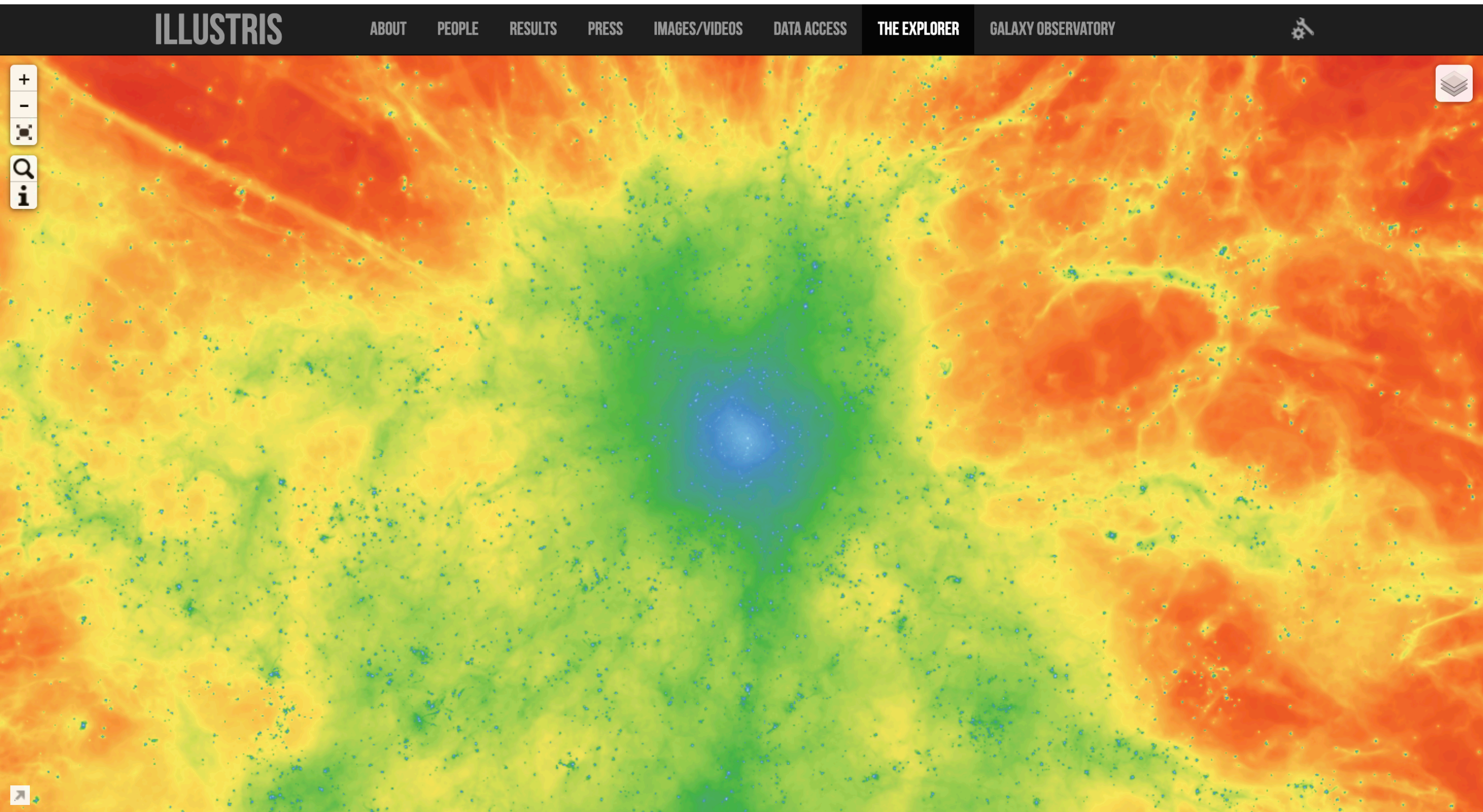
Light is a biased tracer of the mass



Starlight, dark matter

Illustris simulation explorer

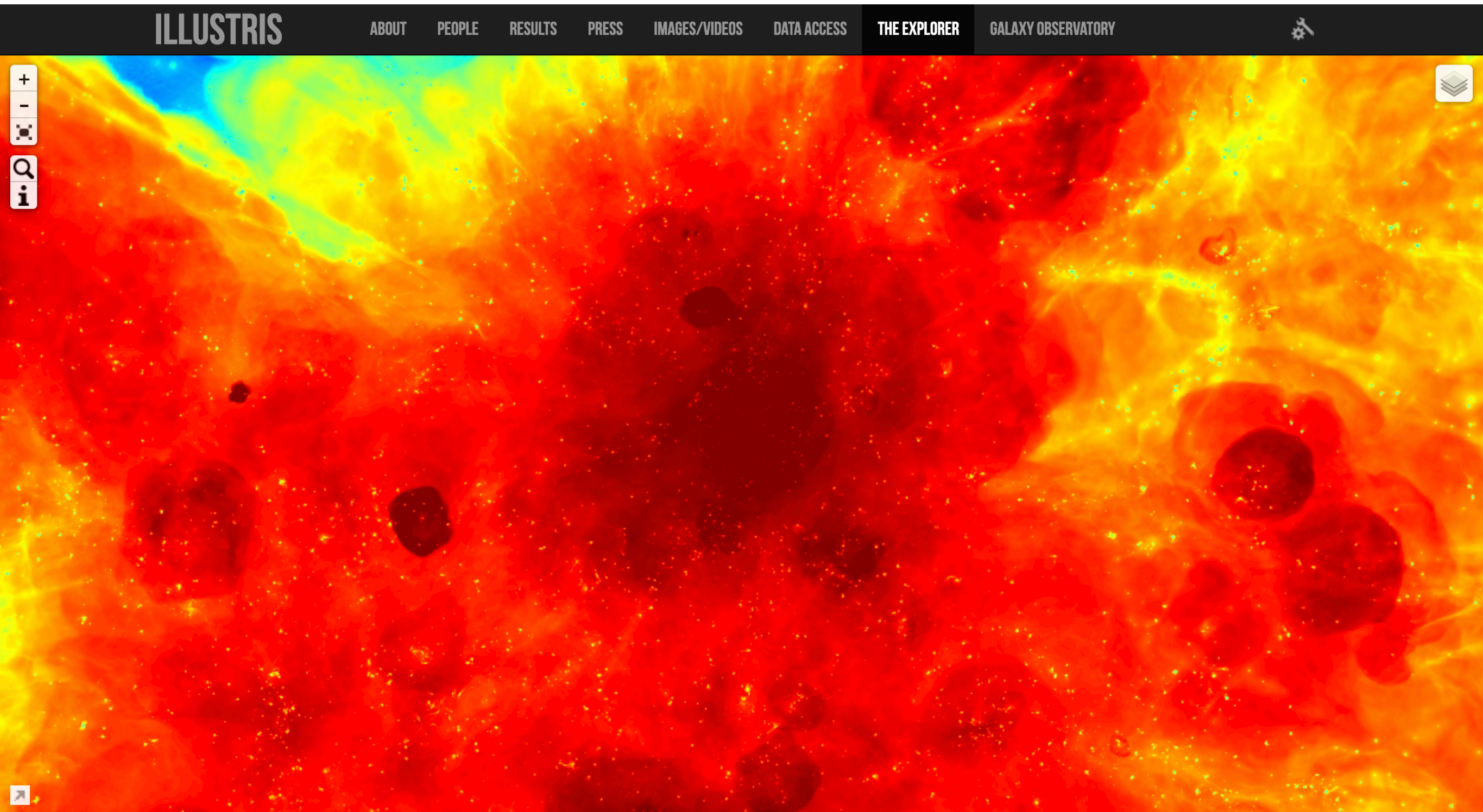
Light is a biased tracer of the mass



Starlight, dark matter, gas density

Illustris simulation explorer

Light is a biased tracer of the mass



Starlight, dark matter, gas density, temperature

Illustris simulation explorer

Light is a biased tracer of the mass

ILLUSTRIS

ABOUT

PEOPLE

RESULTS

PRESS

IMAGES/VIDEOS

DATA ACCESS

THE EXPLORER

GALAXY OBSERVATORY



Starlight, dark matter, gas density, temperature, velocity

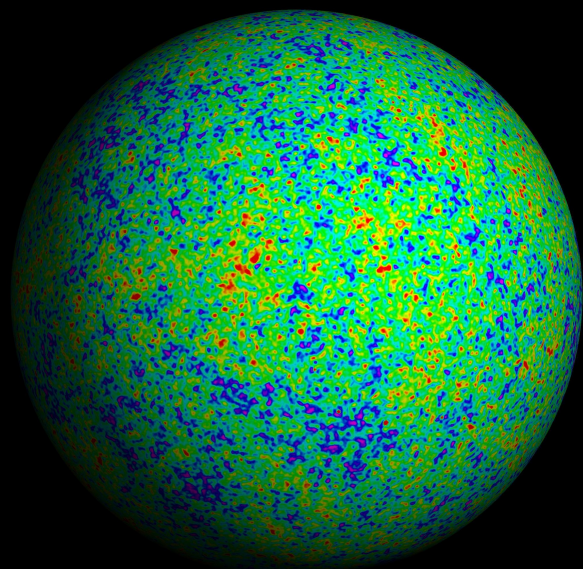
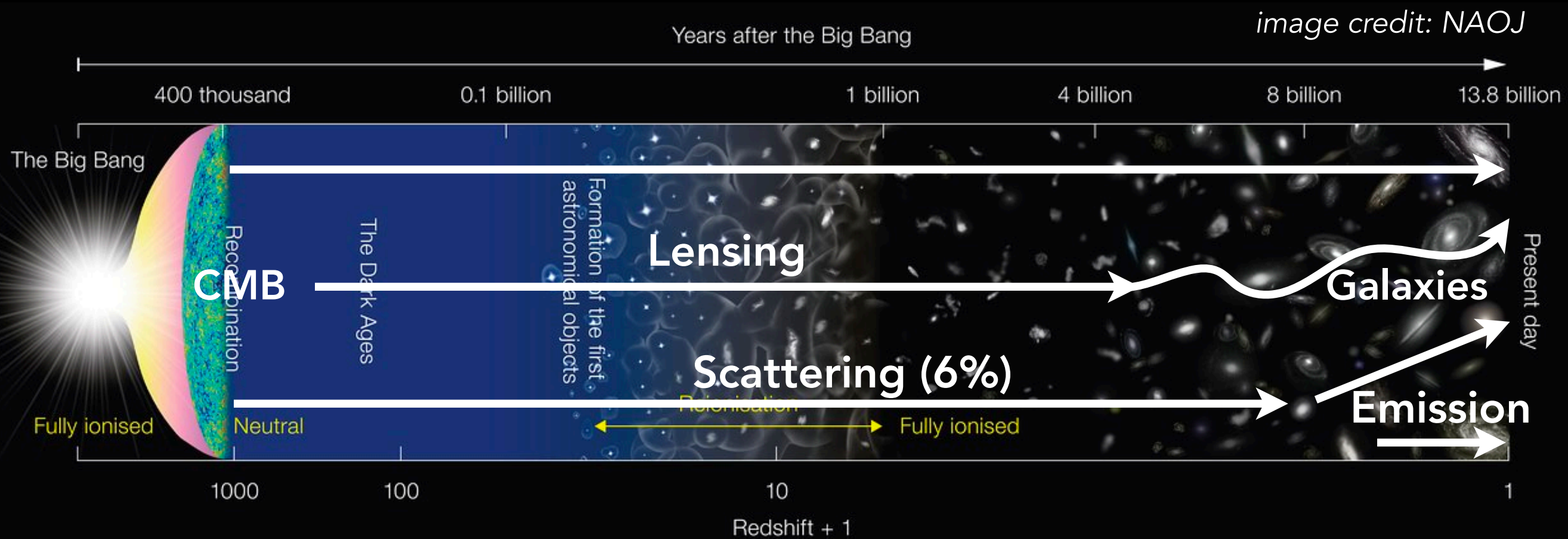
Illustris simulation explorer



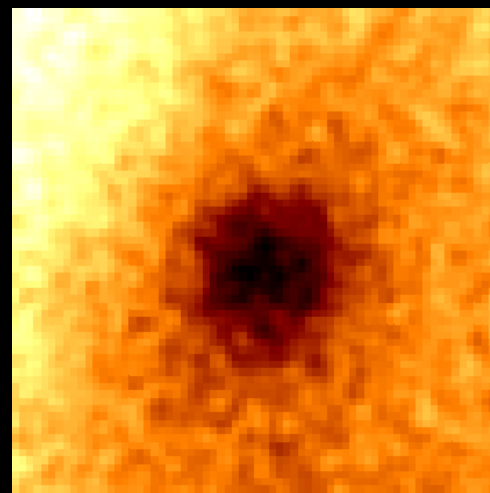
Milky way
(our own galaxy)

Andromeda galaxy

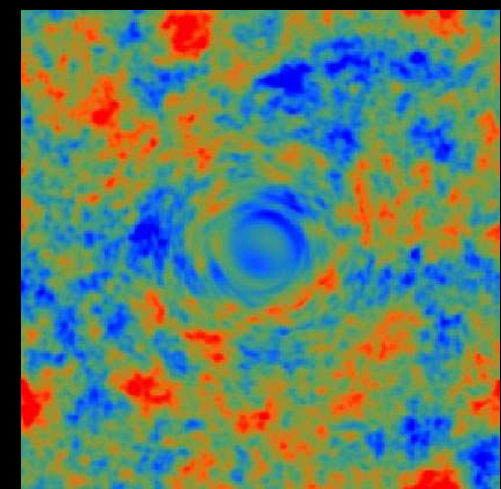
Backlighting the galaxies with the CMB



Initial conditions



Scattering:
Gas shadows



Lensing:
Mass shadows

Summary of CMB secondaries

Key parameters:

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

→ Many imprints with complementary information :

Potential

Lensing

ISW, Rees-Sciama

Moving lens

$$\theta_{\text{lens}} \frac{\nabla T_0}{T_0} \quad \text{Total mass}$$

$$\int dt \dot{\Phi} \quad \text{DE, accretion rate}$$

$$\theta_{\text{lens}} (v_{\text{bulk} \perp} / c) \quad \text{Transverse velocities}$$

Single scattering

Screening

kSZ, rot kSZ, turb kSZ

tSZ, relat tSZ

Polarized scattering

$$\tau (\delta T_0 / T_0) \quad \text{Gas density}$$

$$\tau (v_{\text{bulk} \parallel} / c) \quad \text{Gas density, LOS velocities}$$

$$\tau (v_{\text{th}} / c)^{2,4} \quad \text{Gas thermal pressure, temperature}$$

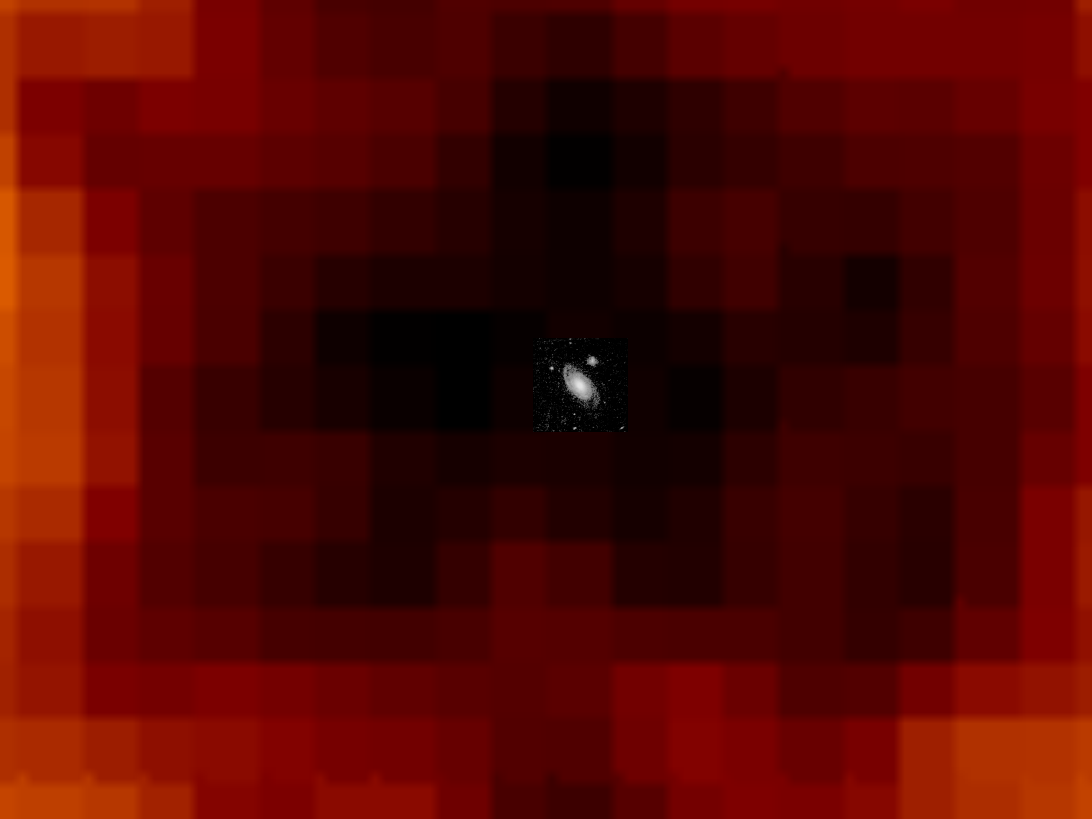
$$\tau (v_{\text{bulk} \perp} / c)^2, \tau a_2 \quad \text{Gas density, Ultra large scales}$$

Multiple scattering

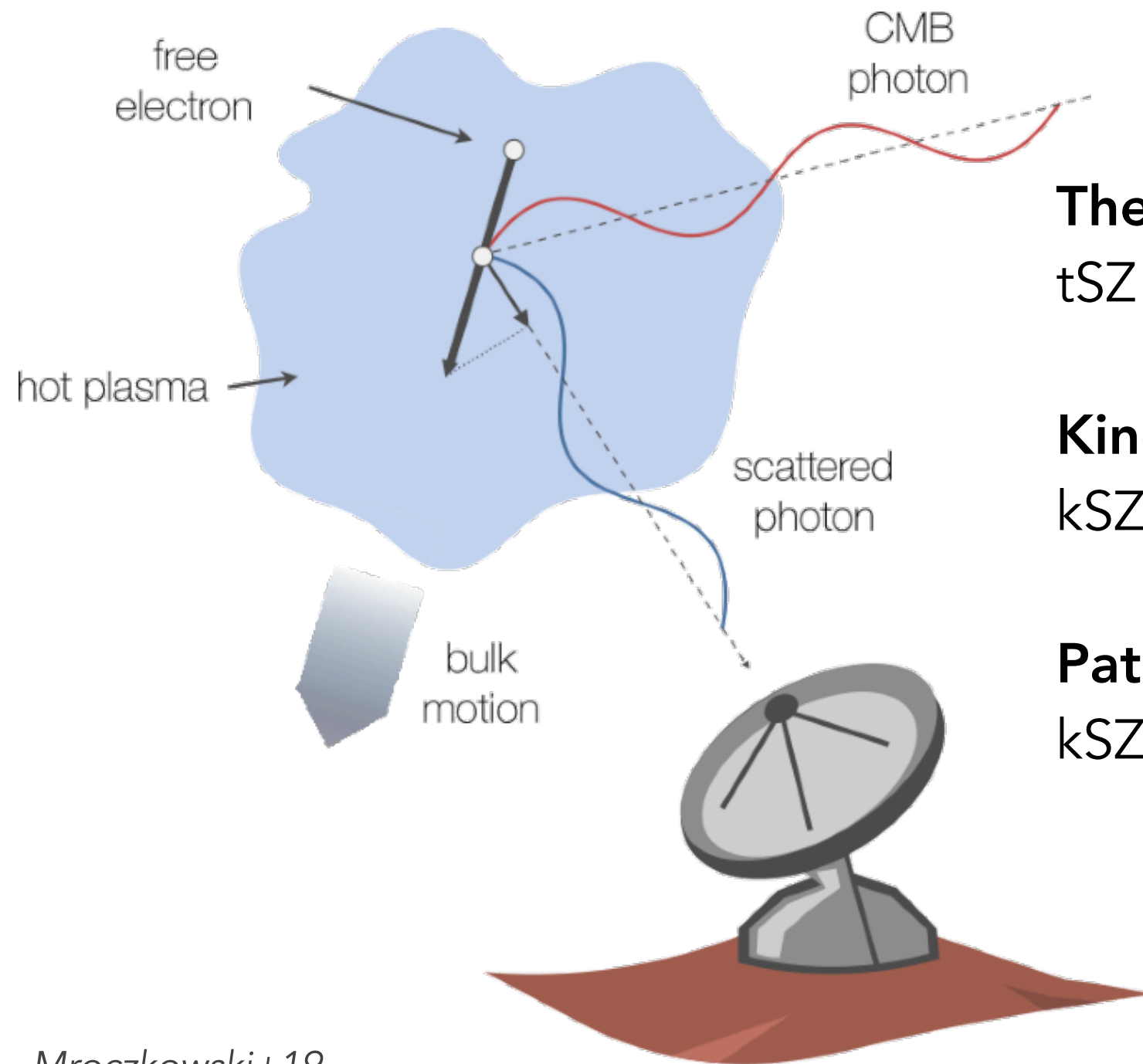
Smaller by factor τ

Break degeneracies with tau?

Gas shadows:
Localize the "missing" baryons



CMB can help: Sunyaev-Zel'dovich effects



Thermal SZ: Doppler from thermal motions
 $tSZ = \text{gas density} * \text{temperature}$

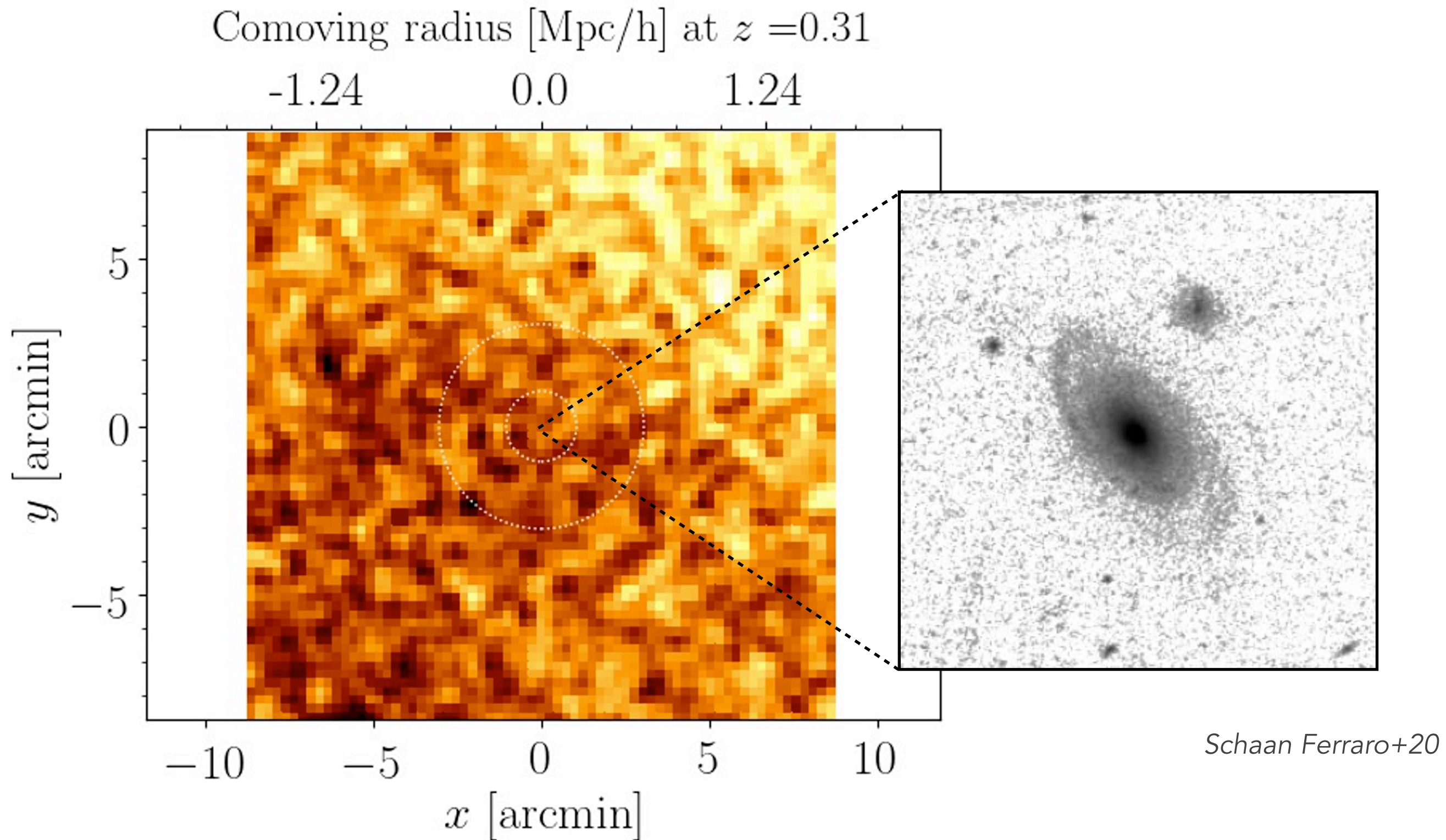
Kinematic SZ: Doppler from bulk motion
 $kSZ = \text{gas density} * \text{bulk velocity}$

Patchy screening: Doppler Simple scattering
 $kSZ = \text{gas density} * \text{primary CMB}$

Mroczkowski+19

→ Unique probe of missing baryons!
(Looking forward to FRBs too!)

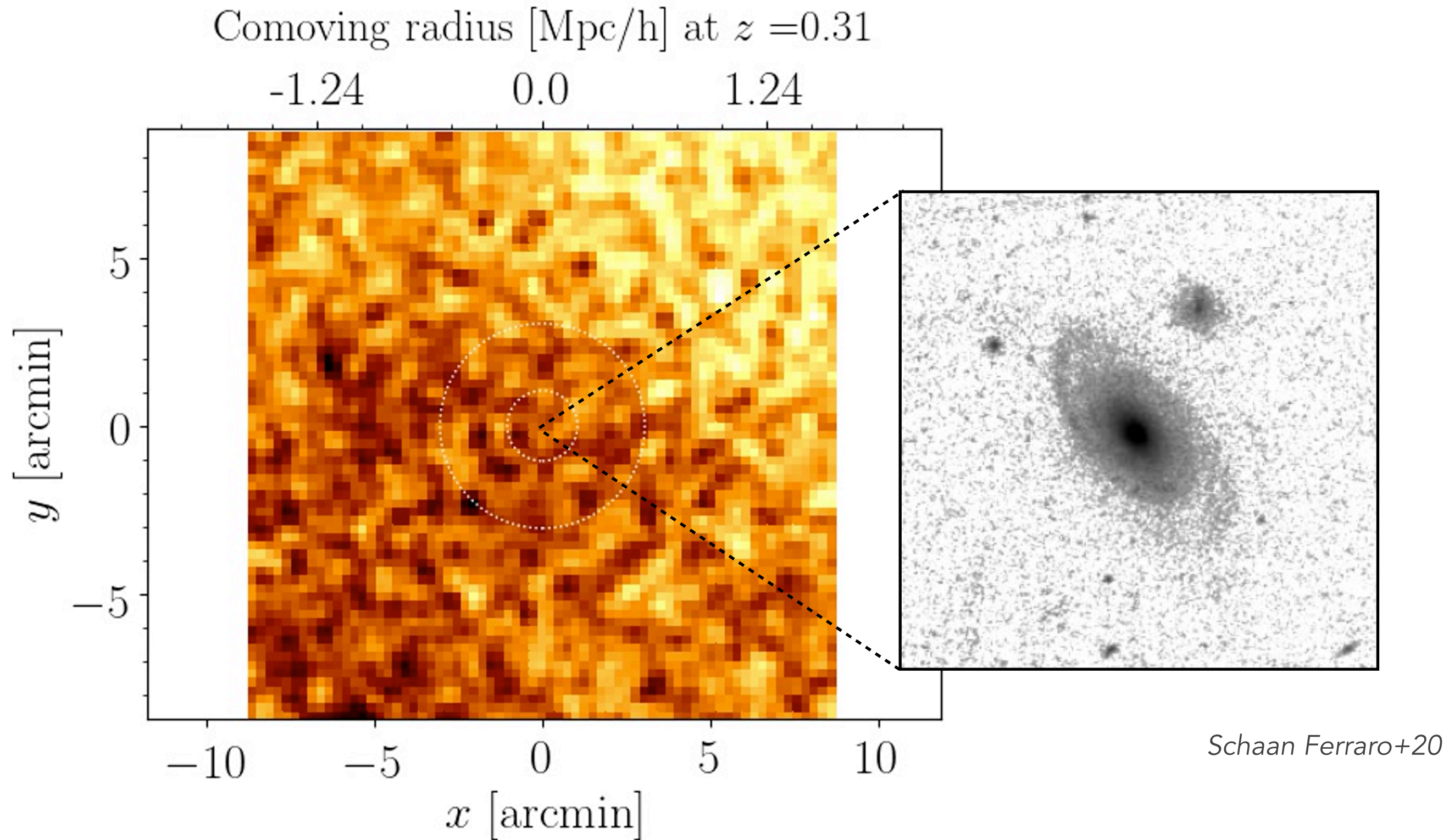
Extracting tSZ: single galaxy



Schaan Ferraro+20

SNR per galaxy is too low to detect!

Extracting tSZ: 400,000 galaxies



Extended tSZ profile is well resolved!

Higher precision tSZ: ACTxDESI

Henry
Liu



Simone
Ferraro



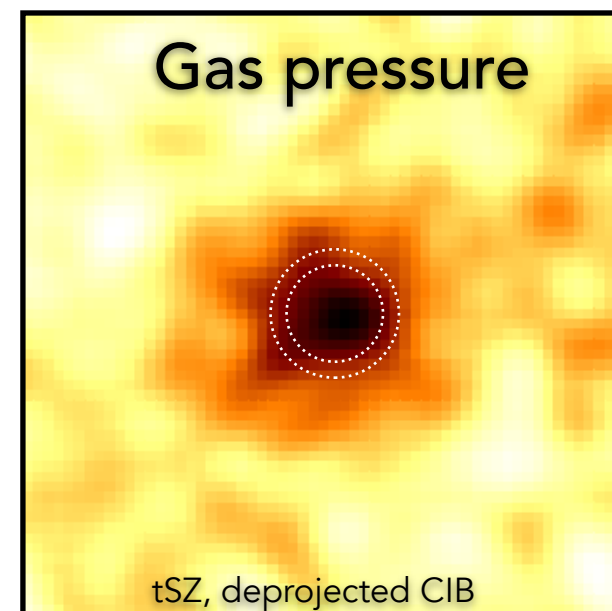
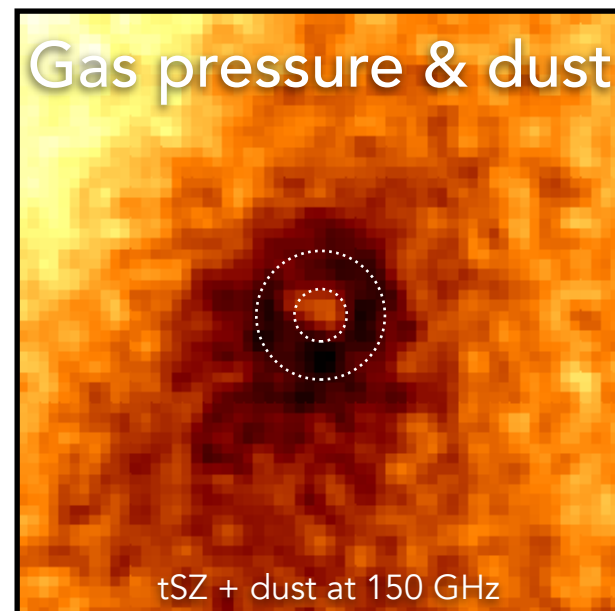
Emmanuel
Schaan



High precision stacked tSZ

Significant dust bias

Clean by masking/deprojecting with variable
dust SED



Schaan Ferraro+20

Higher precision tSZ: ACTxDESI

Henry
Liu



Simone
Ferraro



Emmanuel
Schaan



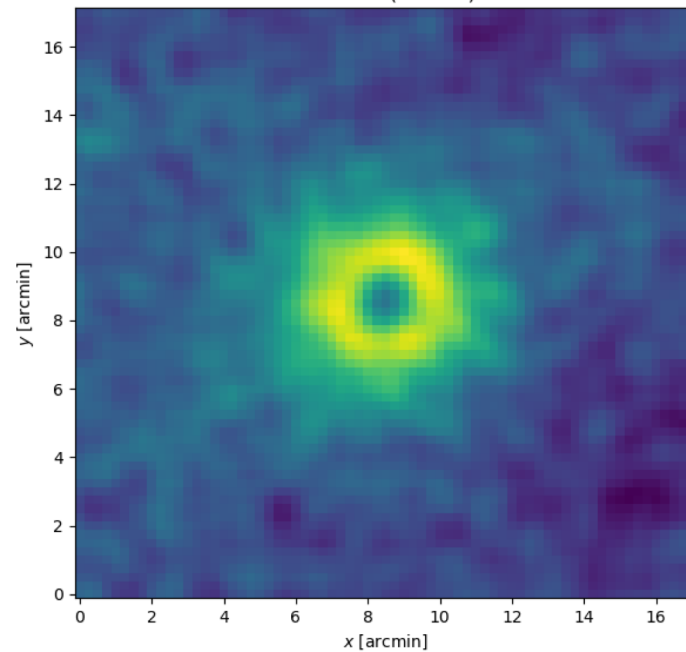
High precision stacked tSZ

Significant dust bias

Clean by masking/deprojecting with variable
dust SED

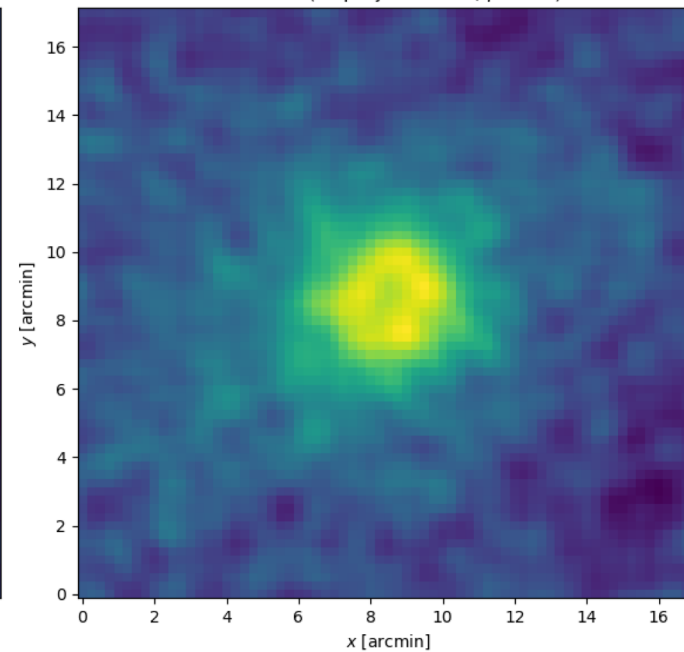
Fiducial Y map

ACT DR6 (fiducial)



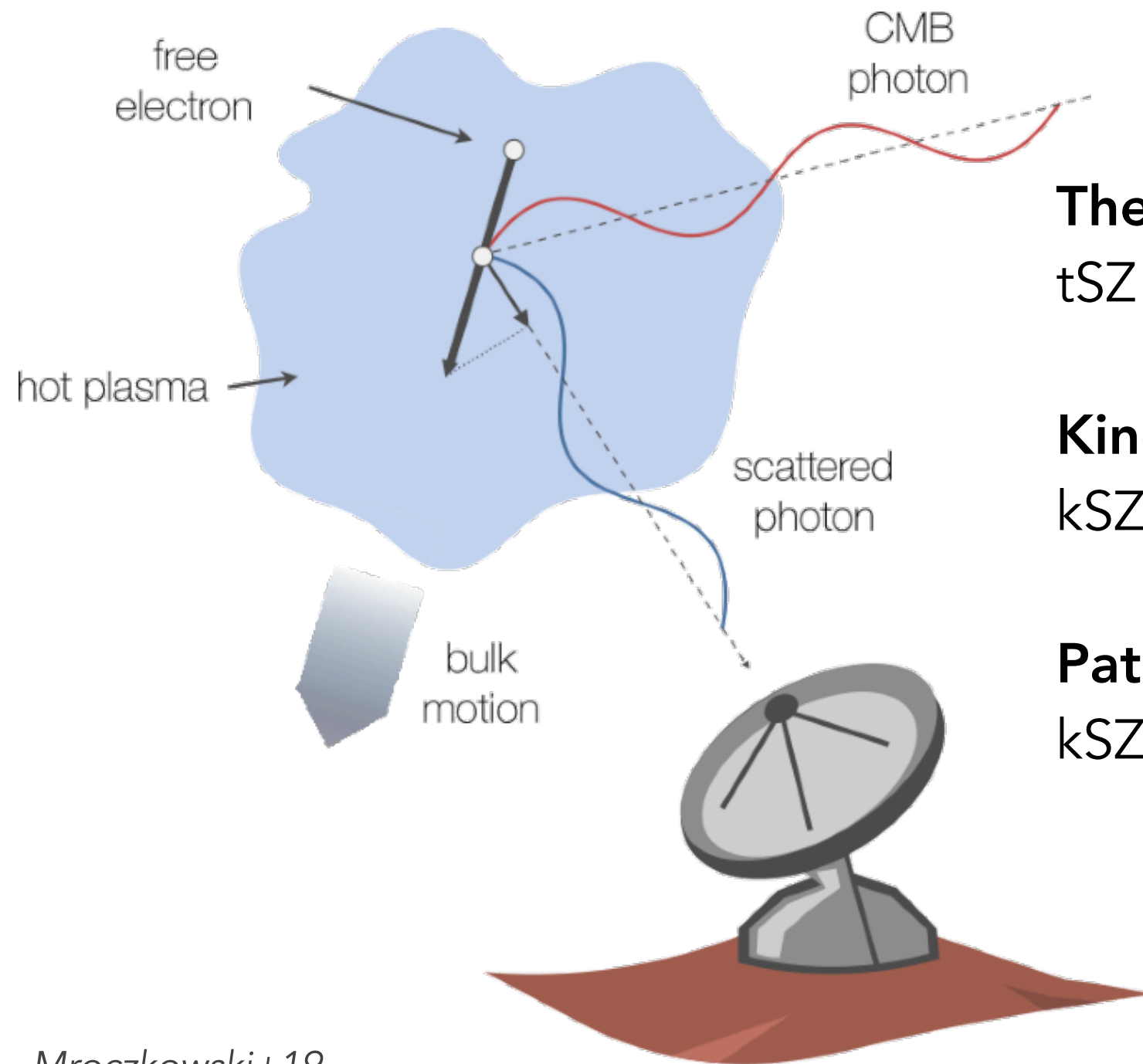
CIB Deprojected

ACT DR6 (Deprojected CIB, $\beta = 1.6$)



Liu+24

CMB can help: Sunyaev-Zel'dovich effects



Thermal SZ: Doppler from thermal motions
 $tSZ = \text{gas density} * \text{temperature}$

Kinematic SZ: Doppler from bulk motion
 $kSZ = \text{gas density} * \text{bulk velocity}$

Patchy screening: Doppler Simple scattering
 $kSZ = \text{gas density} * \text{primary CMB}$

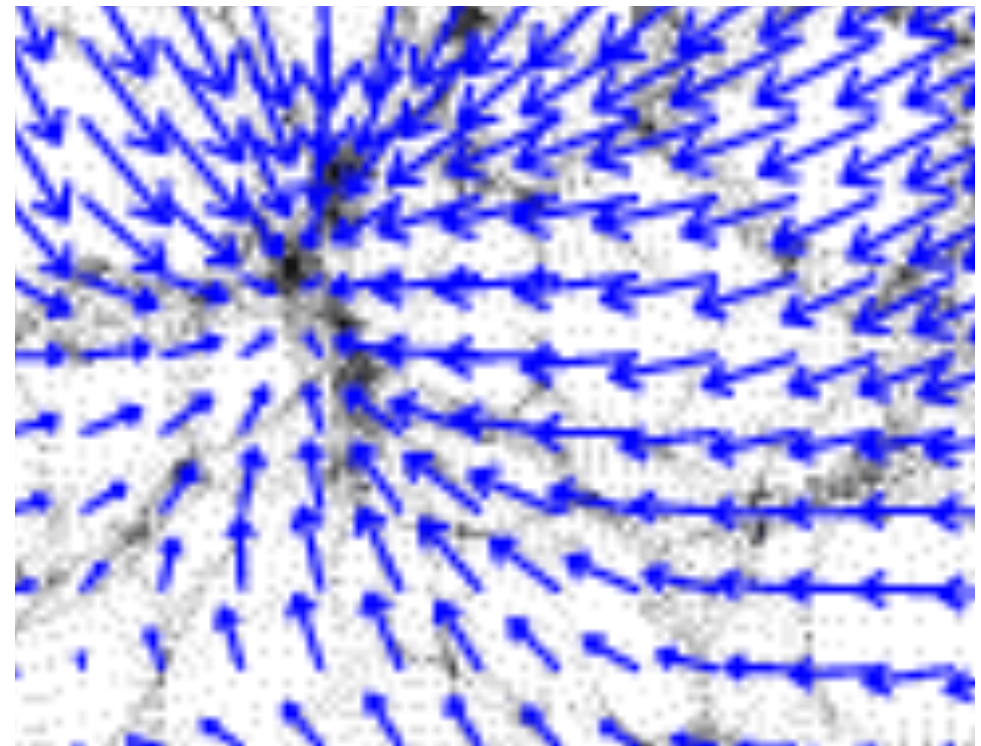
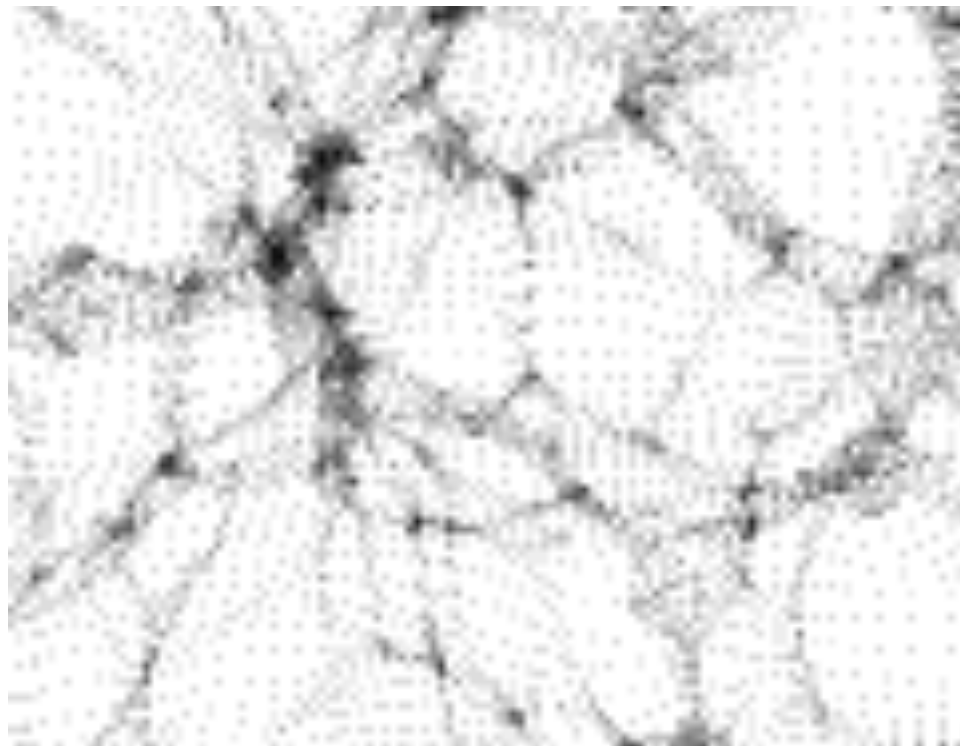
Mroczkowski+19

→ Unique probe of missing baryons!
(Looking forward to FRBs too!)

Extracting kSZ: Velocity reconstruction

Mass conservation: $\vec{v} \propto \vec{\nabla} \Delta^{-1} \delta$

150Mpc



Eisenstein+07, Padmanabhan+12,14

kSZ amplitude $\propto \langle \mathbf{v}_{\text{true}} \mathbf{v}_{\text{rec}} \rangle$ or $r(\mathbf{v}_{\text{true}}, \mathbf{v}_{\text{rec}})$

→ Quantify from sims

Velocity reconstruction via continuity equation: assessment

Bernardita Boryana Simone Emmanuel

Ried Guachalla Hadzhiyska Ferraro Schaan



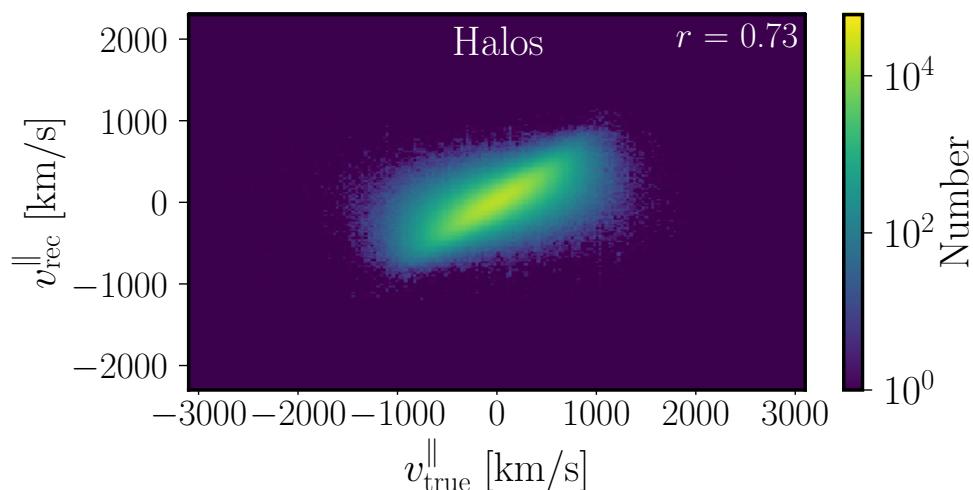
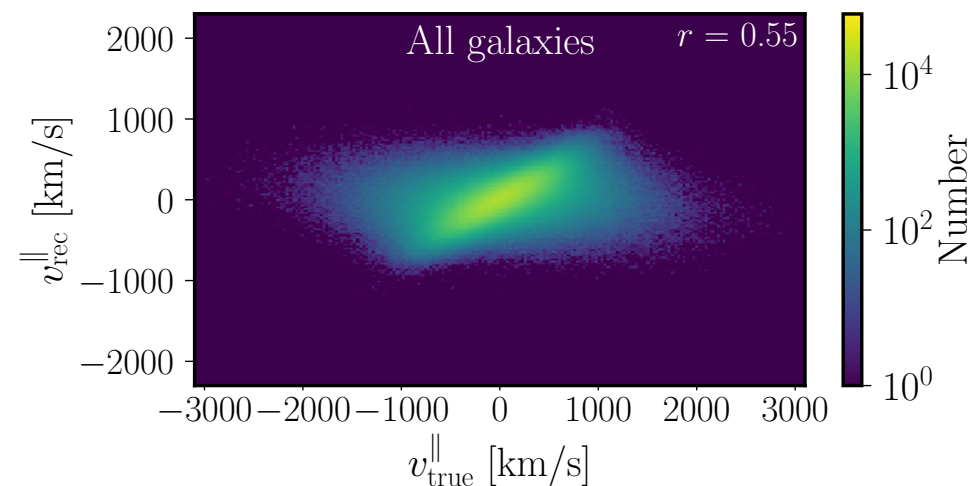
Hadzhiyska+23, Ried Guachalla+23

Key results

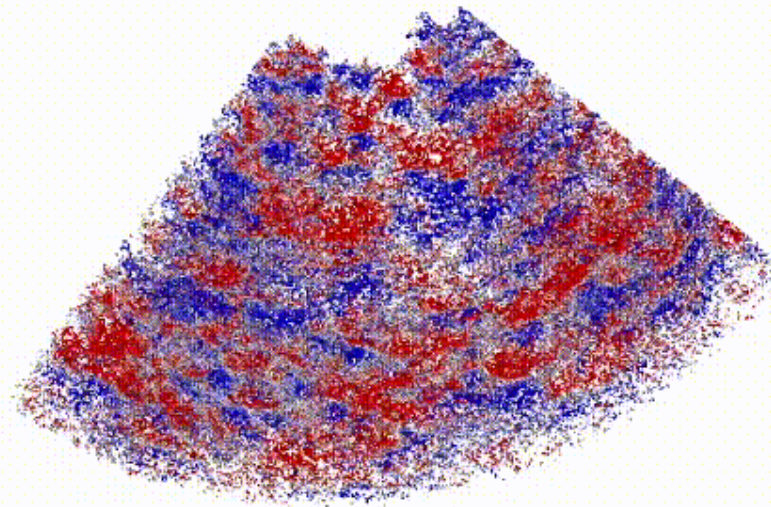
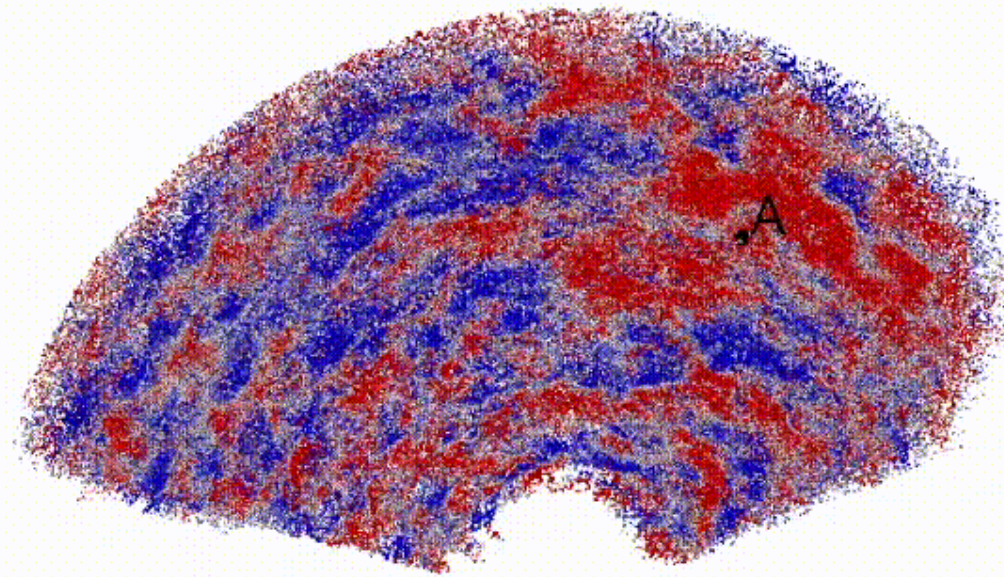
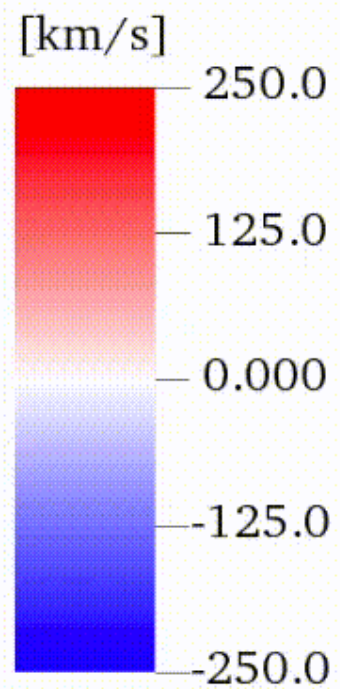
- Reconstruct halo (not galaxy) velocities
→ good for kSZ!
- Photo samples extremely powerful
(DESI LS, DES, HSC, LSST)
- Naïve hybrid photo-spectro reconstruction
worse than photo-only

Assess impact of

- satellite fraction
- number density
- smoothing
- cosmology



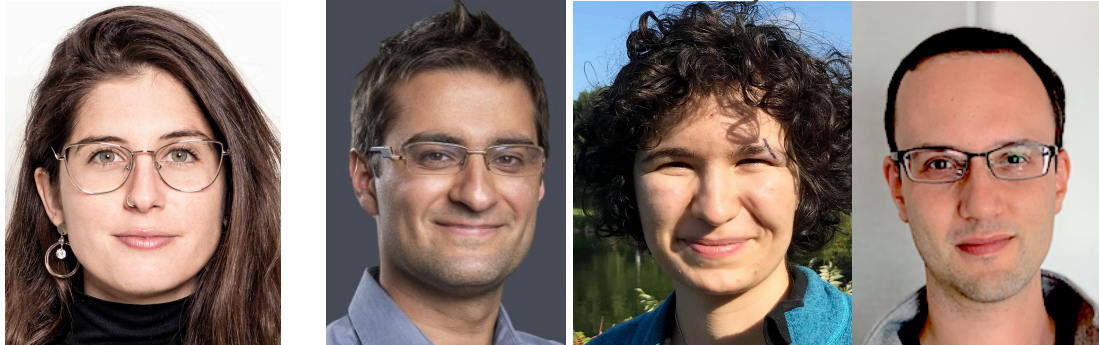
Higher precision measurements: ACTxDESI



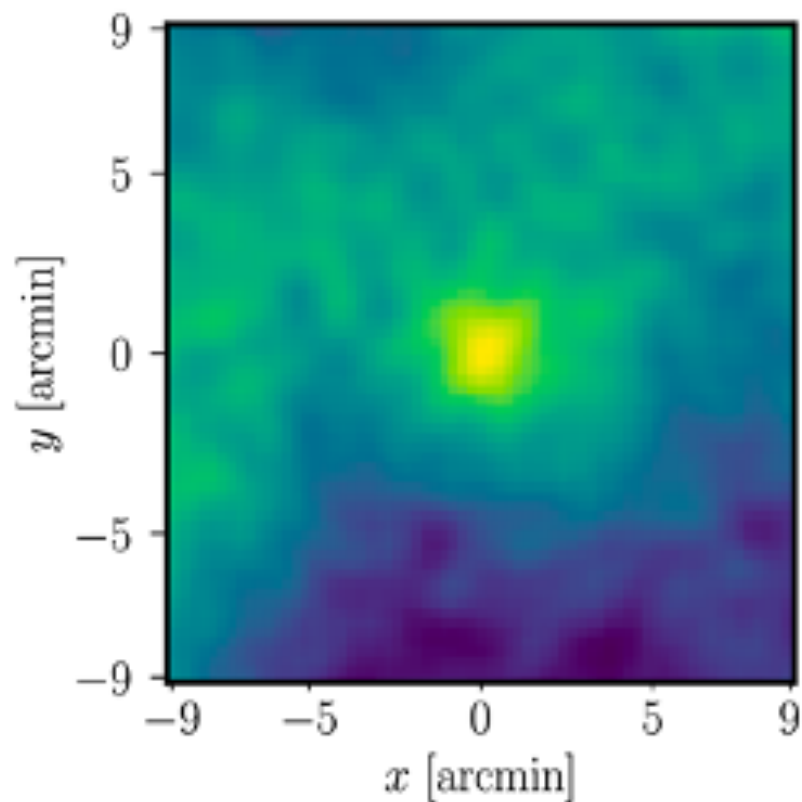
BOSS (CMASS AND LOWZ)

Higher precision kSZ: ACTxDES

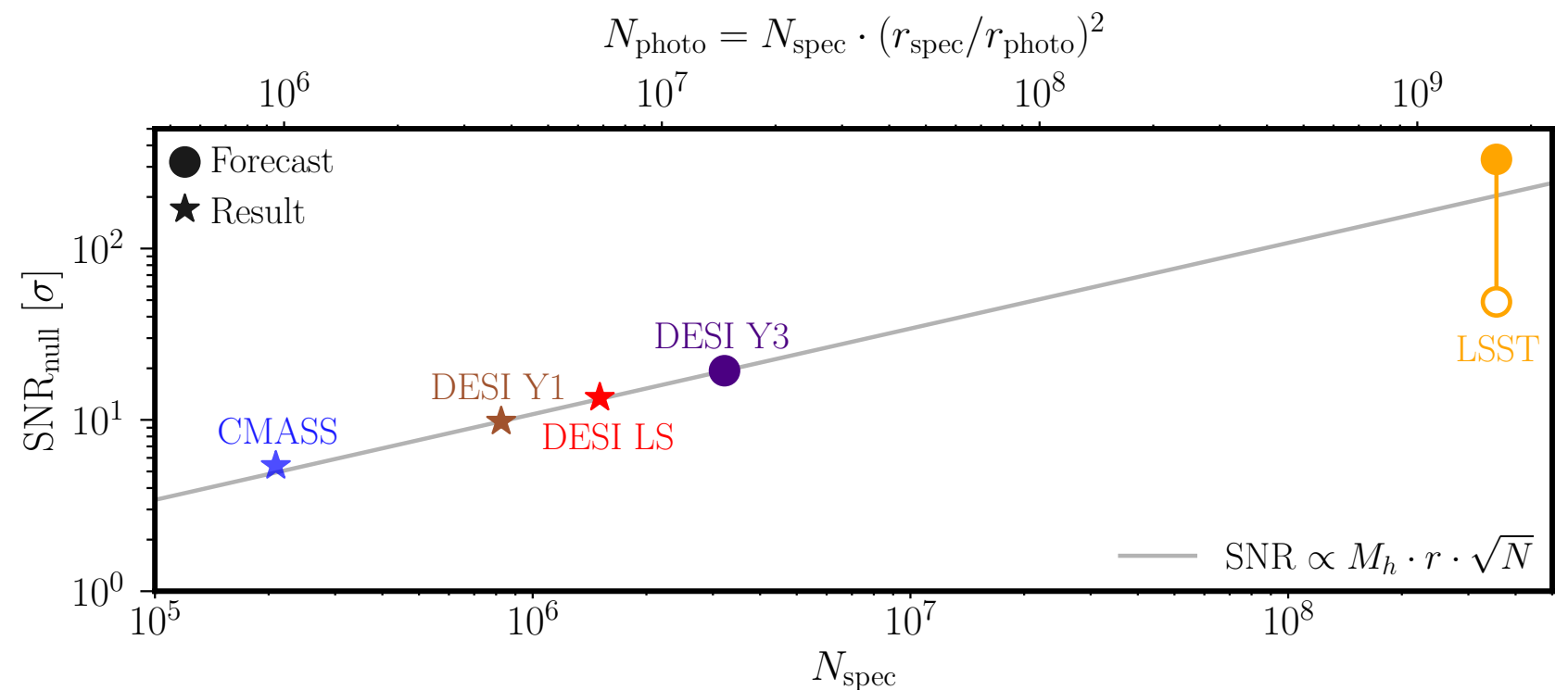
Bernardita Ried Guachalla Emmanuel Schaan Boryana Hadzhiyska Simone Ferraro



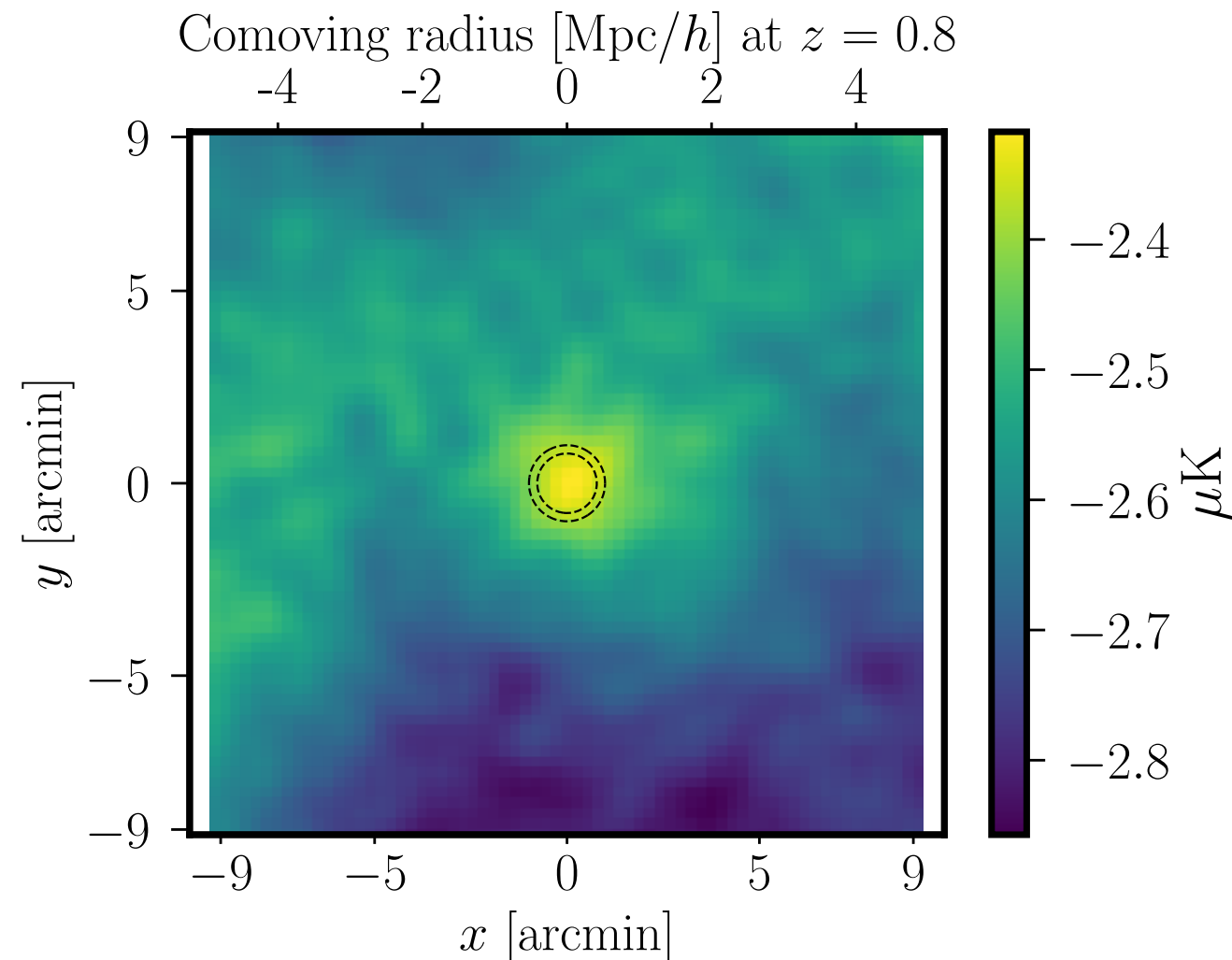
High precision stacked kSZ
Compare photo & spectro samples
Explore dependence on M , z , L
Confirm gas more extended than DM
Matches Illustris (large feedback),
not Illustris TNG



Ried Guachalla+25



Aren't CMB experiments too low resolution?



Ried Guachalla+25

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

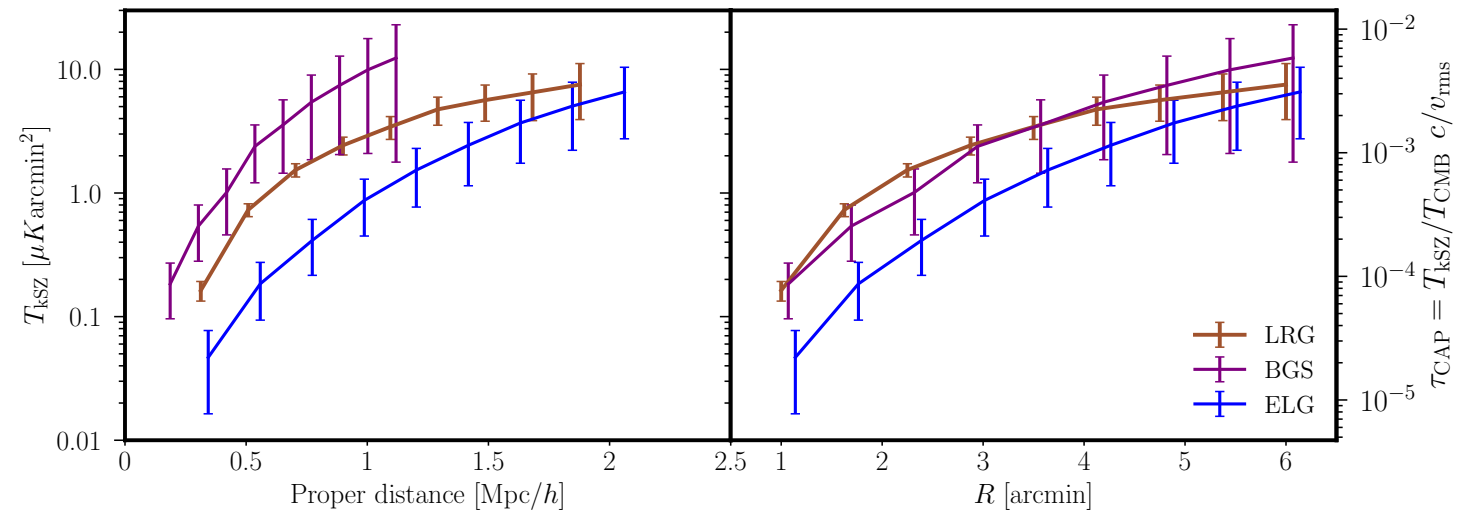
kSZ unique probe of outskirts of galaxy groups and clusters
→ Complementary with X-ray & tSZ, which probe cluster centers best

Latest stacked kSZ profiles available?

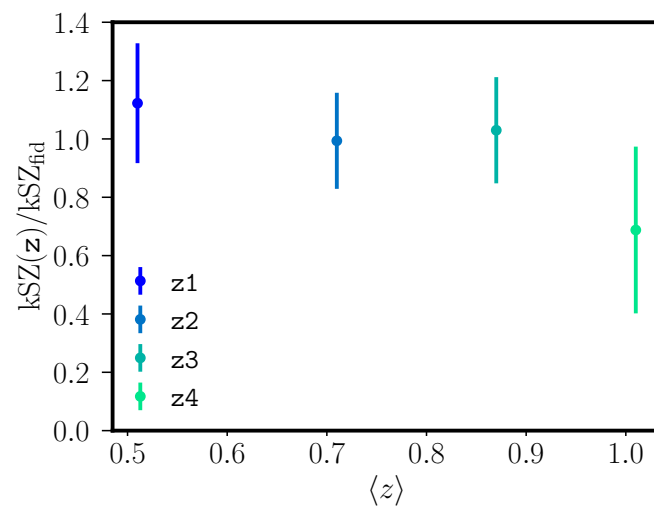
DESI Y1 LRG, BGS, ELG

spectro: *Ried Guachalla+25*

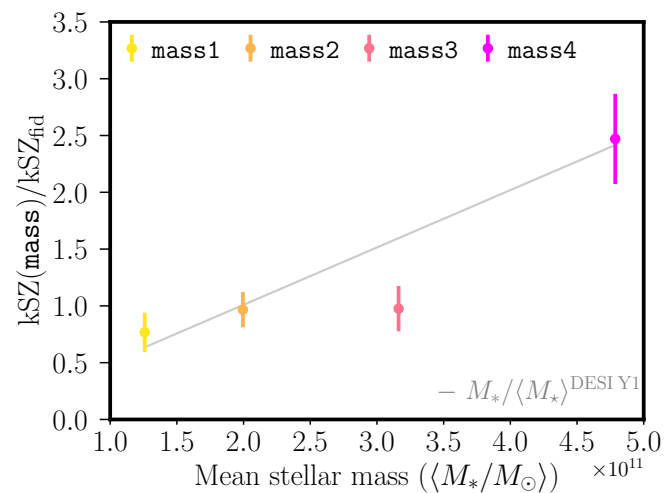
photo: *Hadzhiyska+25*



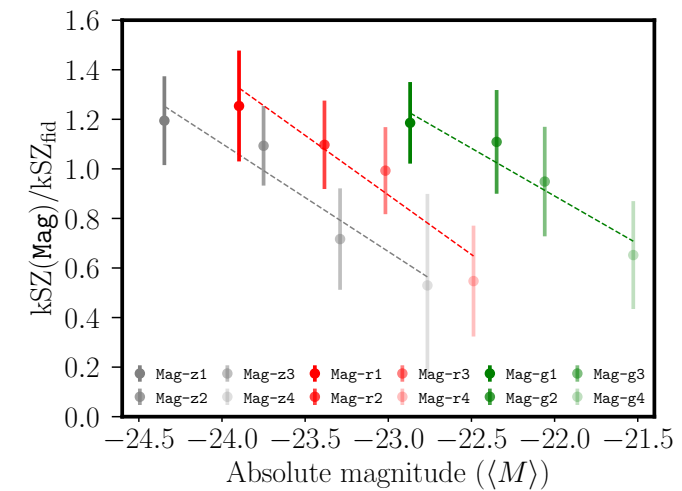
Also splits by redshift,



stellar mass,

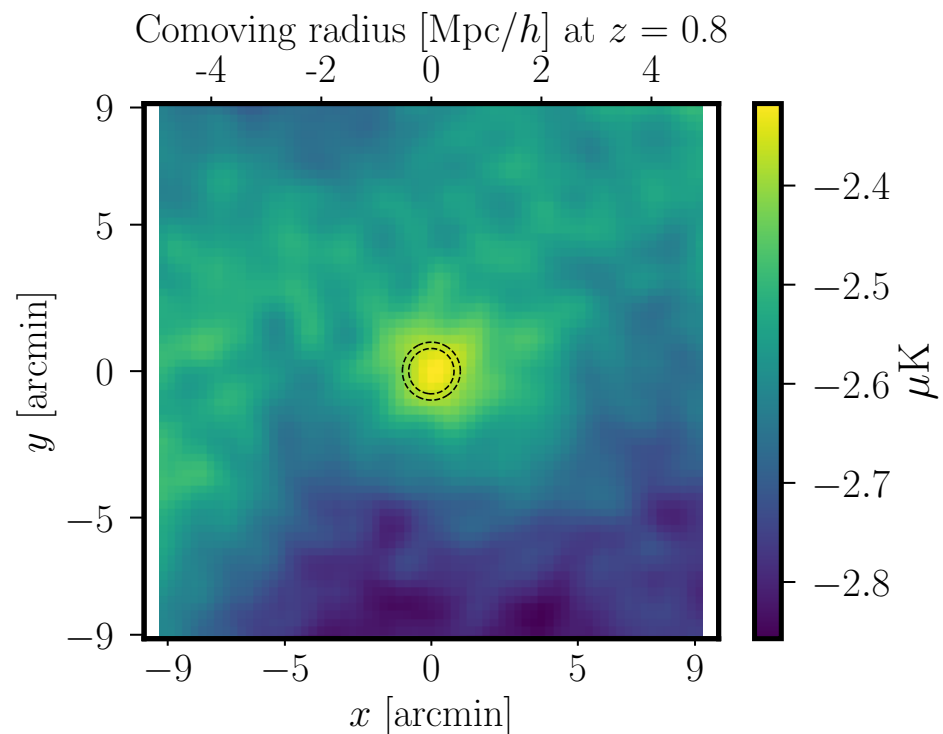


absolute magnitude



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

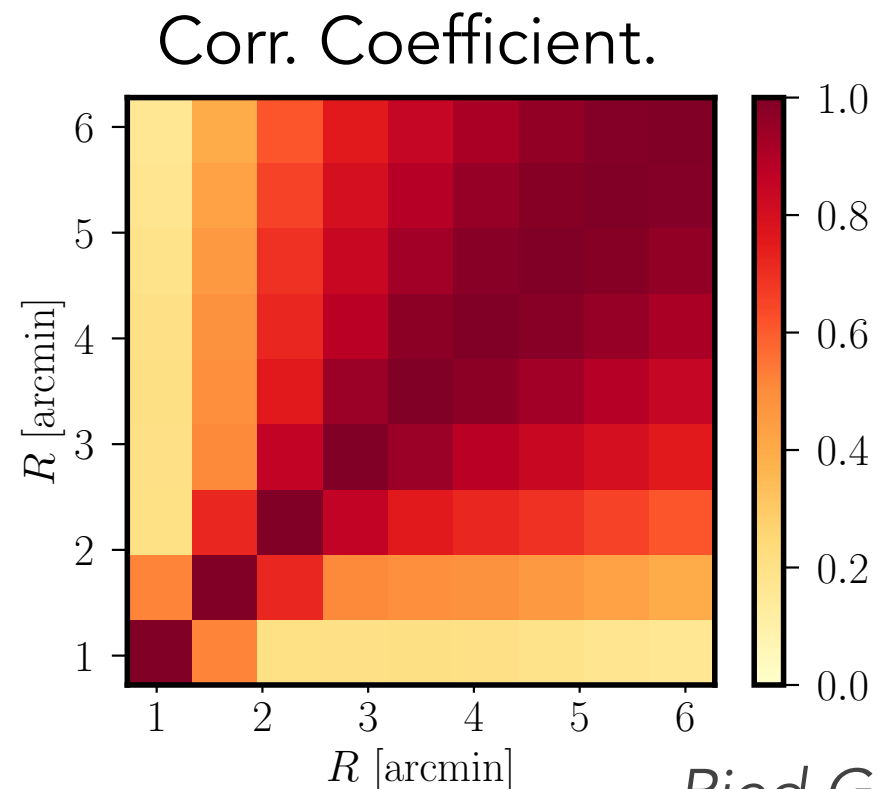
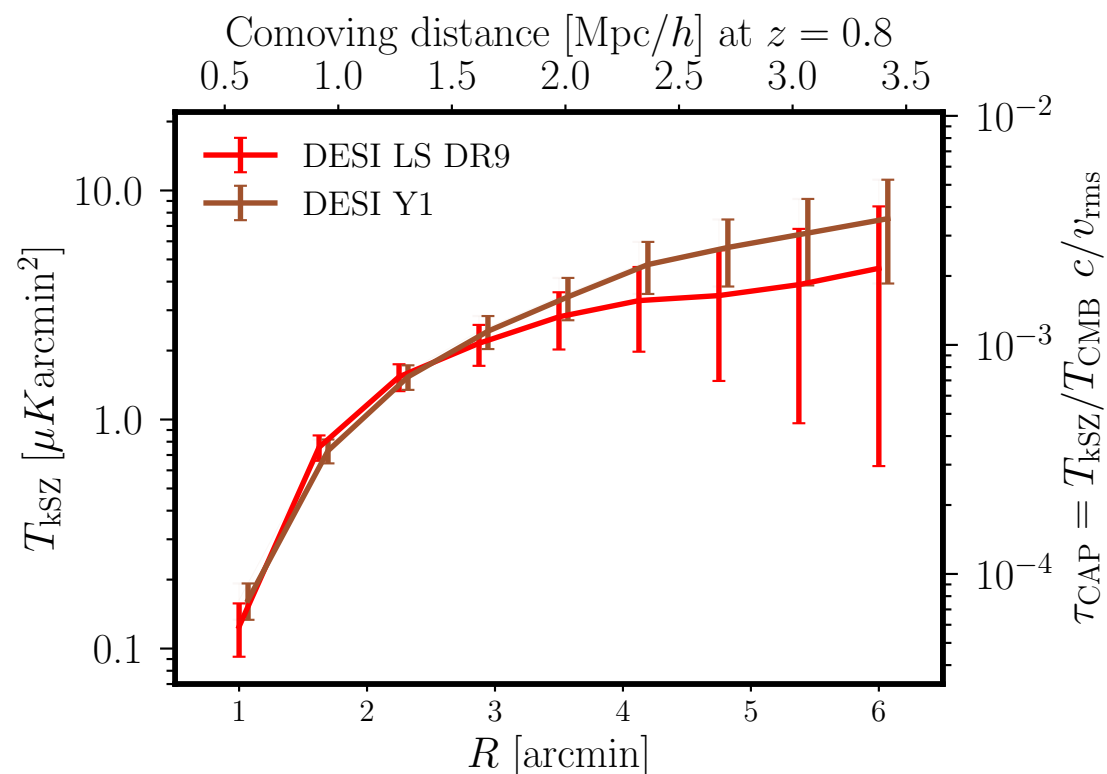
Large-scale noise: profile slope VS M_{gas}



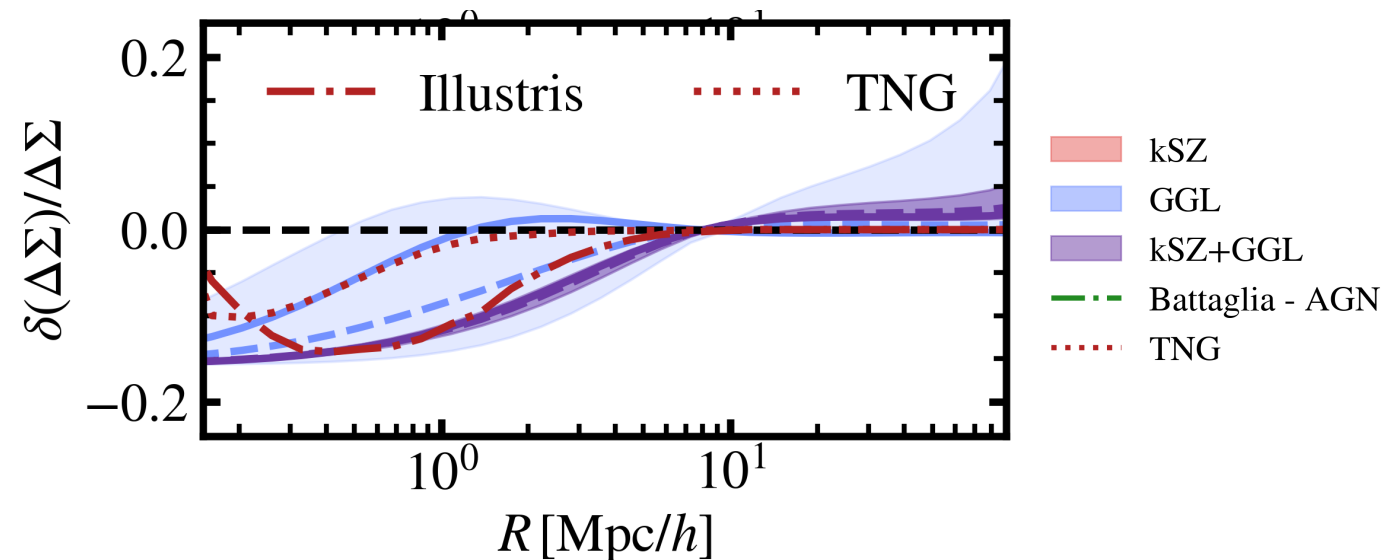
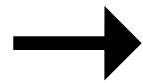
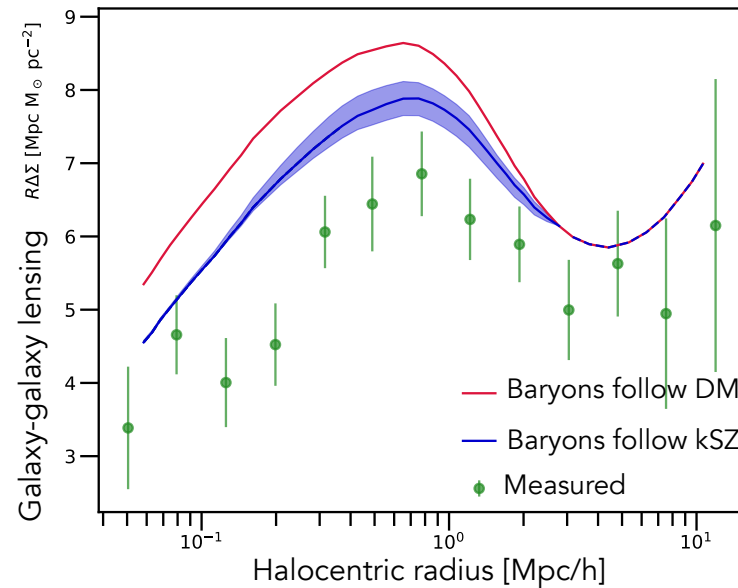
Primary CMB ($\sim$ degree) dominates noise on larger scales

→ 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



kSZ is faint. Is precision enough for lensing?



Amodeo+21

Sunseri+25

Precision already informative in 2021, now much better & improving

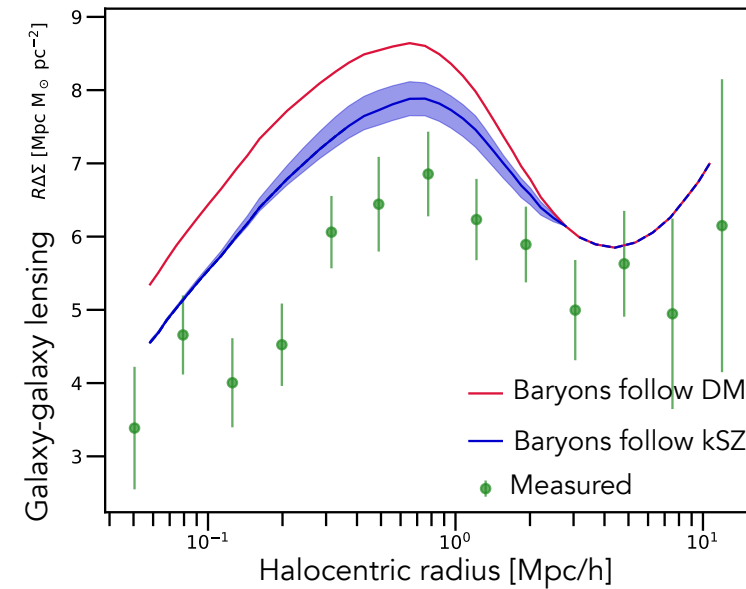
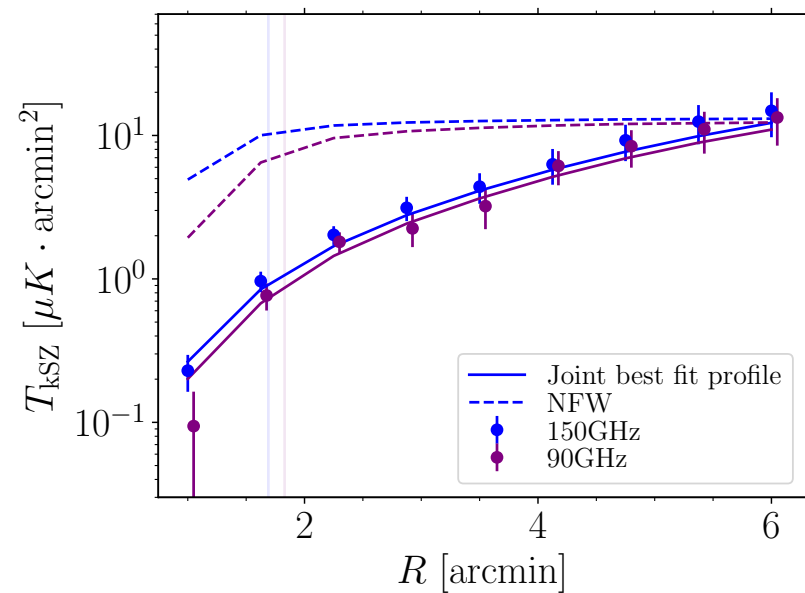
Baryons are 15% of the matter.

For 1%-precision lensing, only 7%-precision kSZ needed

→ **statistics will not be limiting**

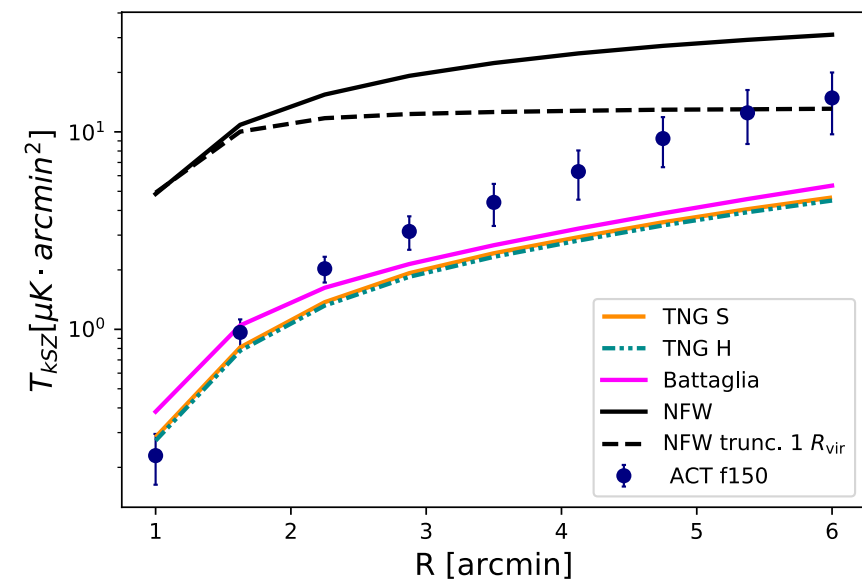
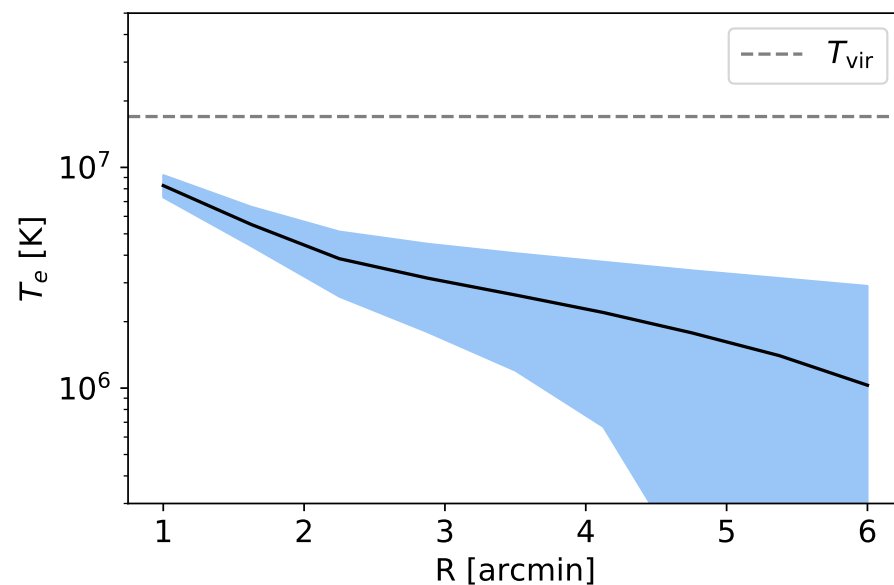
→ **Modeling is the challenge**

What we learned: galaxy formation & lensing



Gas is more extended than dark matter

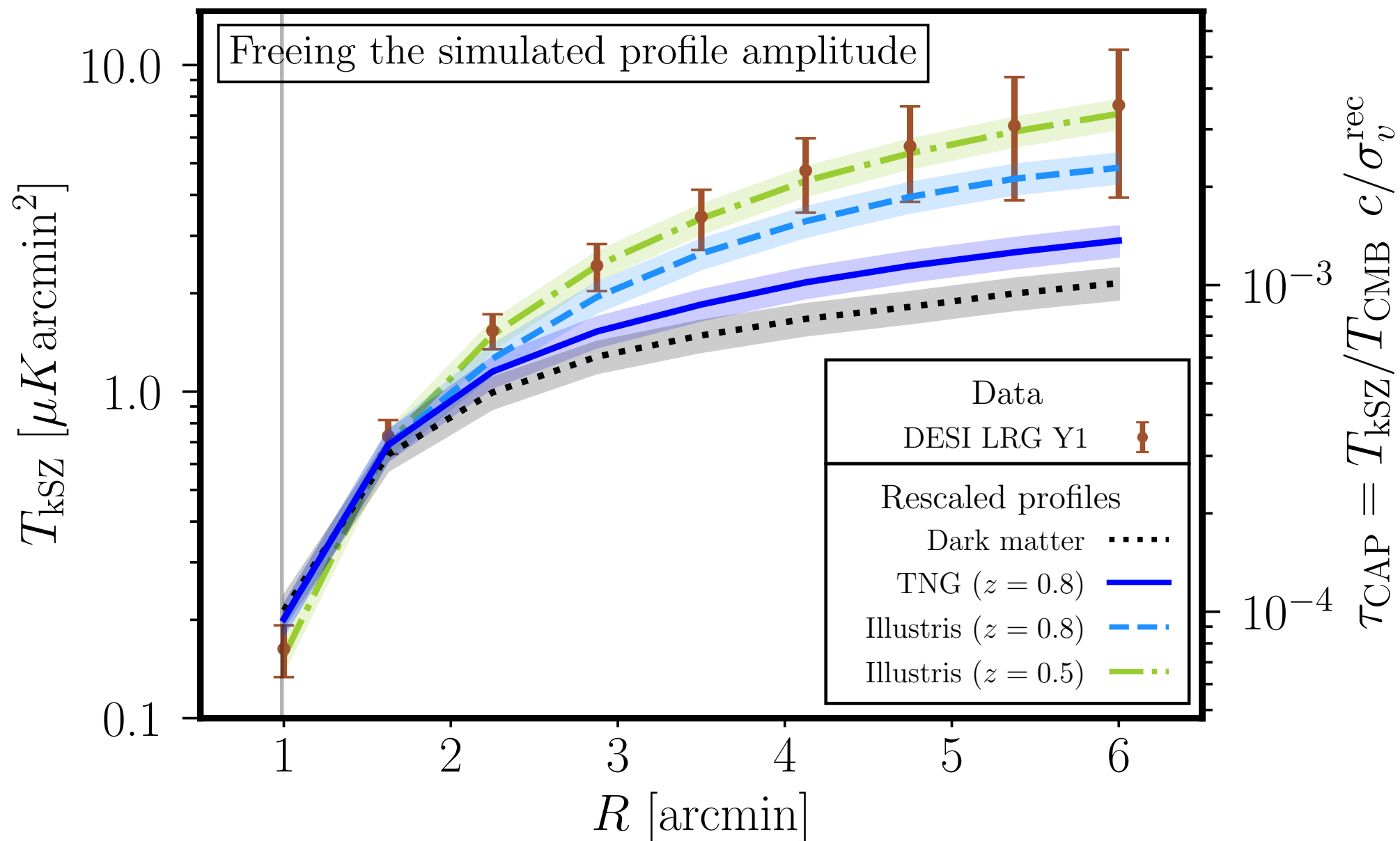
This explains half of the low lensing tension



Combining kSZ & tSZ yields
the gas temperature
far outside the virial radius

New input to galaxy formation models:
feedback needs to push and heat more
gas to the halo outskirts?

Tentative conclusions on feedback

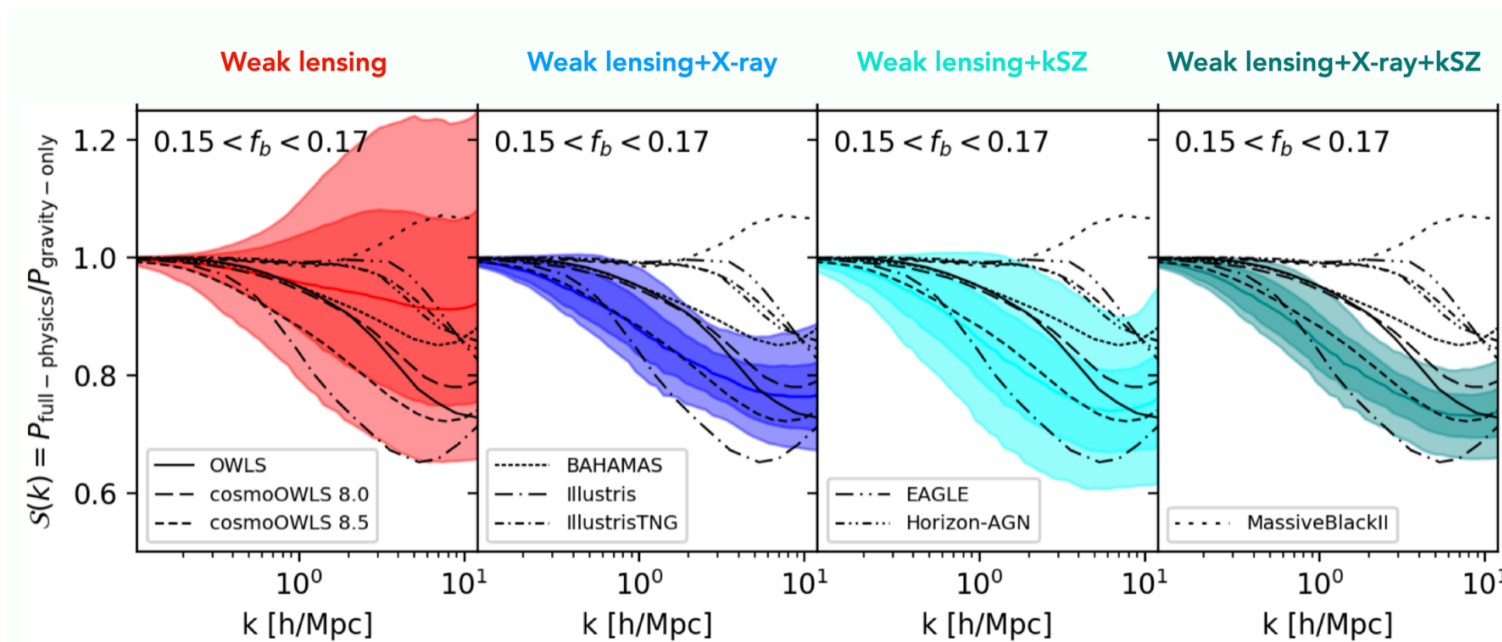


Gas appears pushed farther out than in hydro sims?

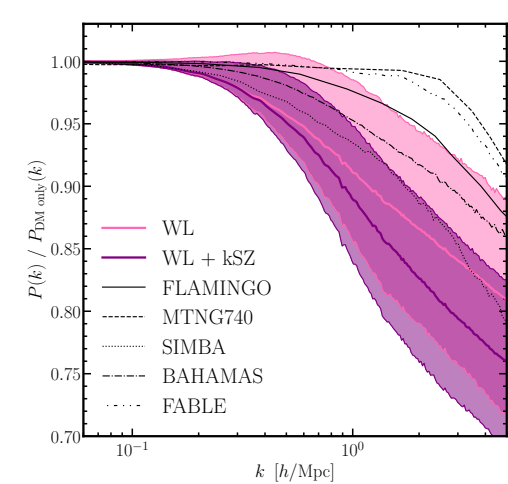
→ **Suggests large effect of feedback on gas?**

Valid *if* galaxies selected in sims match reality

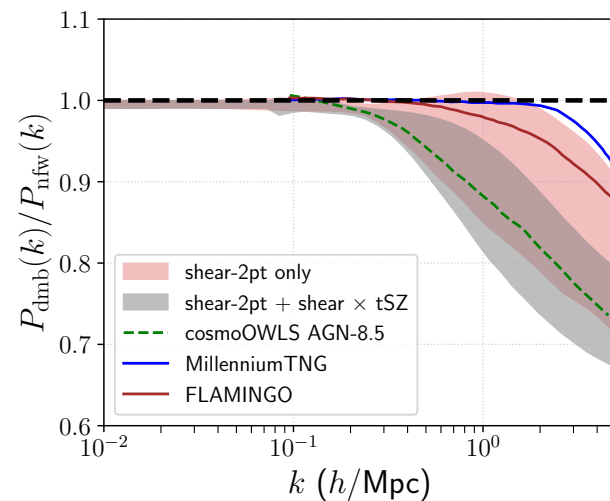
Towards joint analyses: lensing + baryon info



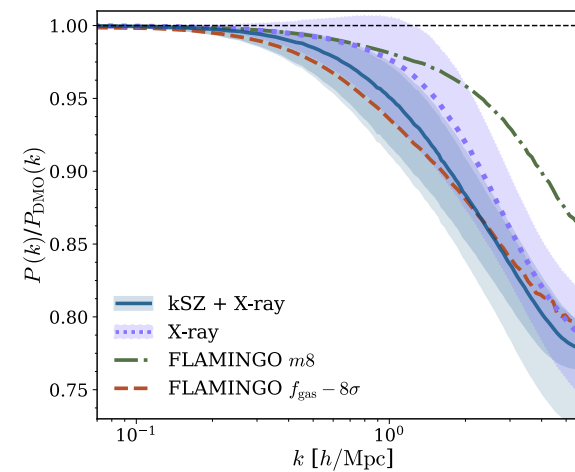
Cosmic shear & "baryons"
Schneider+22



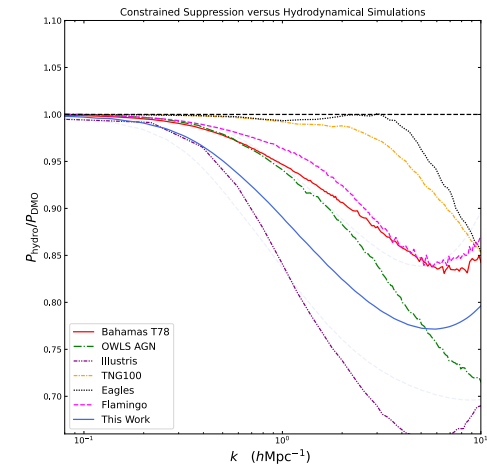
Cosmic shear & kSZ
Bigwood+24, 25



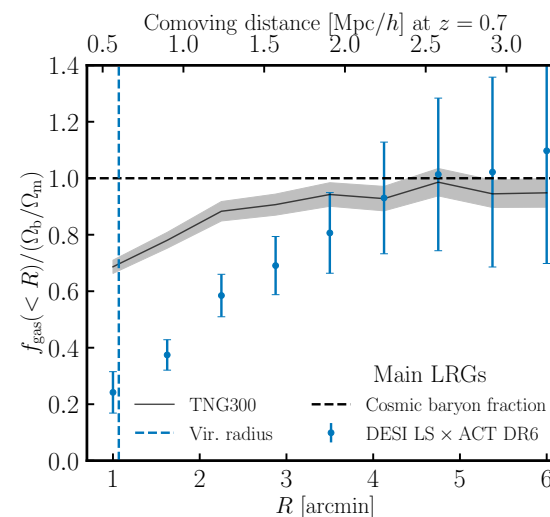
Cosmic shear
& shear x tSZ
Pandey+25



kSZ & X-ray
Kovac+25

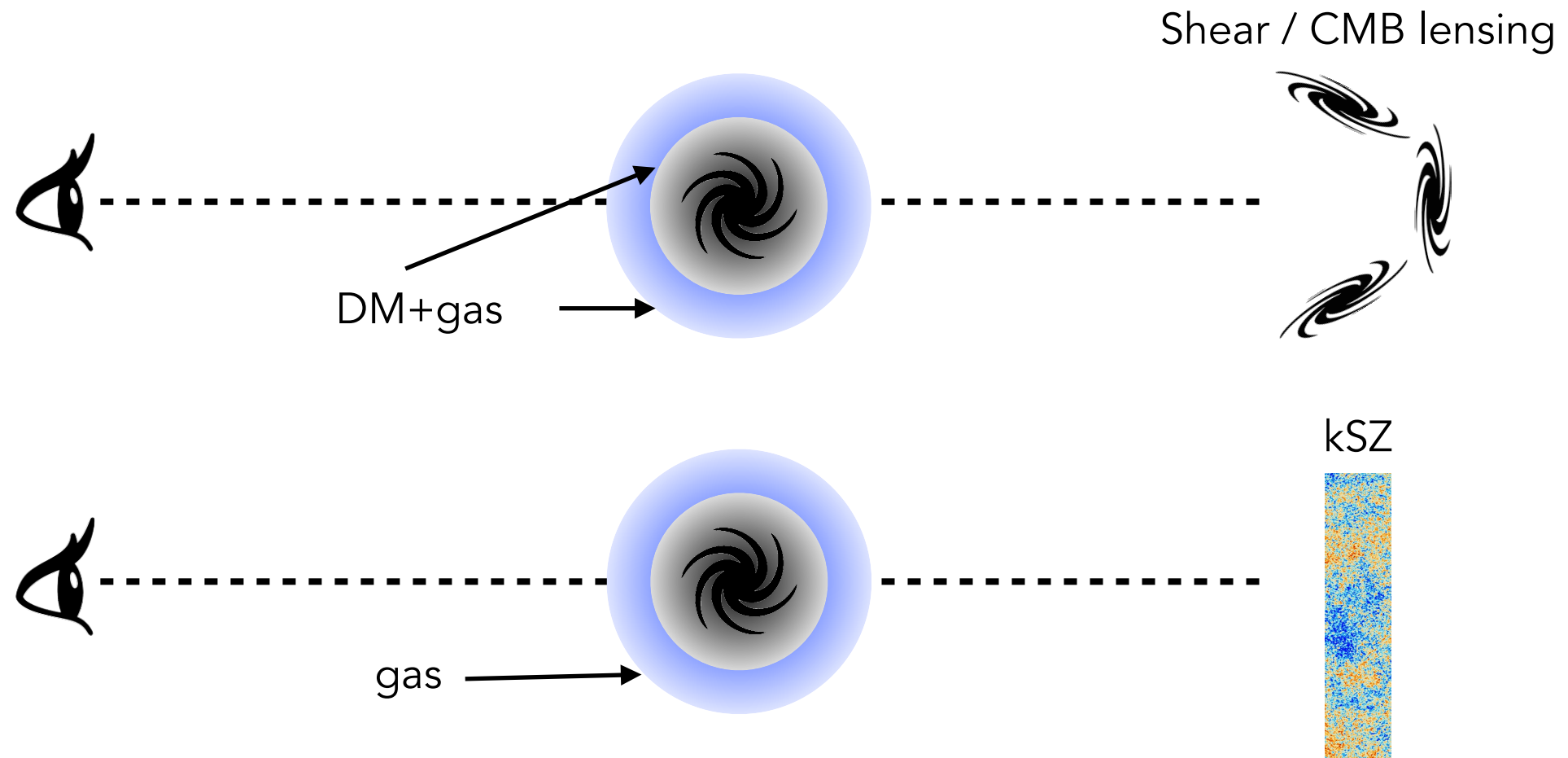


cluster tSZ & cluster lensing
Dalal+25



Galaxy x CMB lensing & galaxy x kSZ
Schneider+22

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 galaxy sample

mass (stellar or halo? mean or distribution?)

satellite fraction & miscentering

HOD?

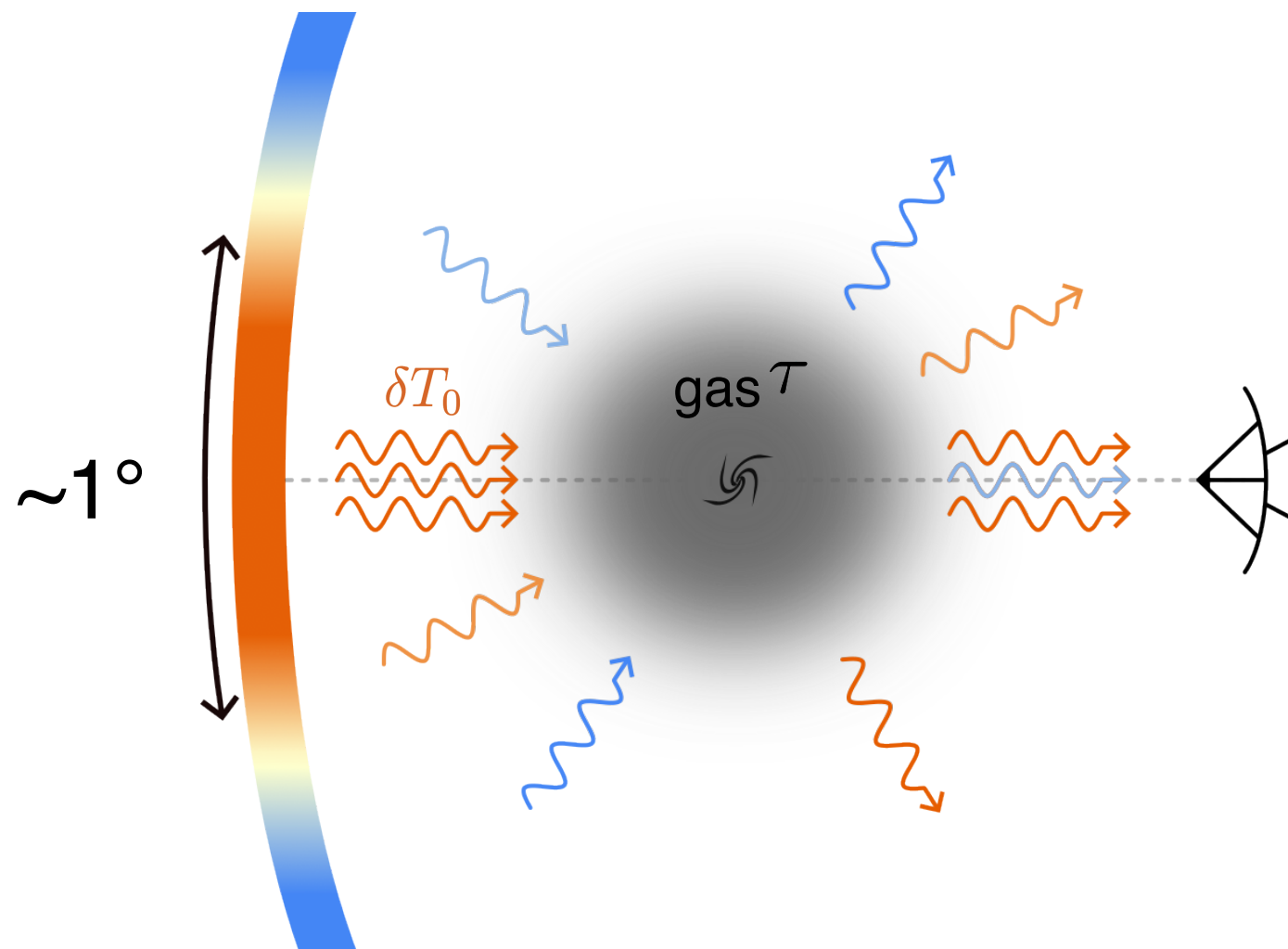
→ **All "large feedback" claims hinge on this**

Great progress being made in modeling

Bigwood+24, Sunseri+25, McCarthy+25

CMB Screening by ionized gas around galaxies

Theo Schutt, Abhishek Maniyar, Will Coulton, Nishant Mishra, Emmanuel Schaan & ACT



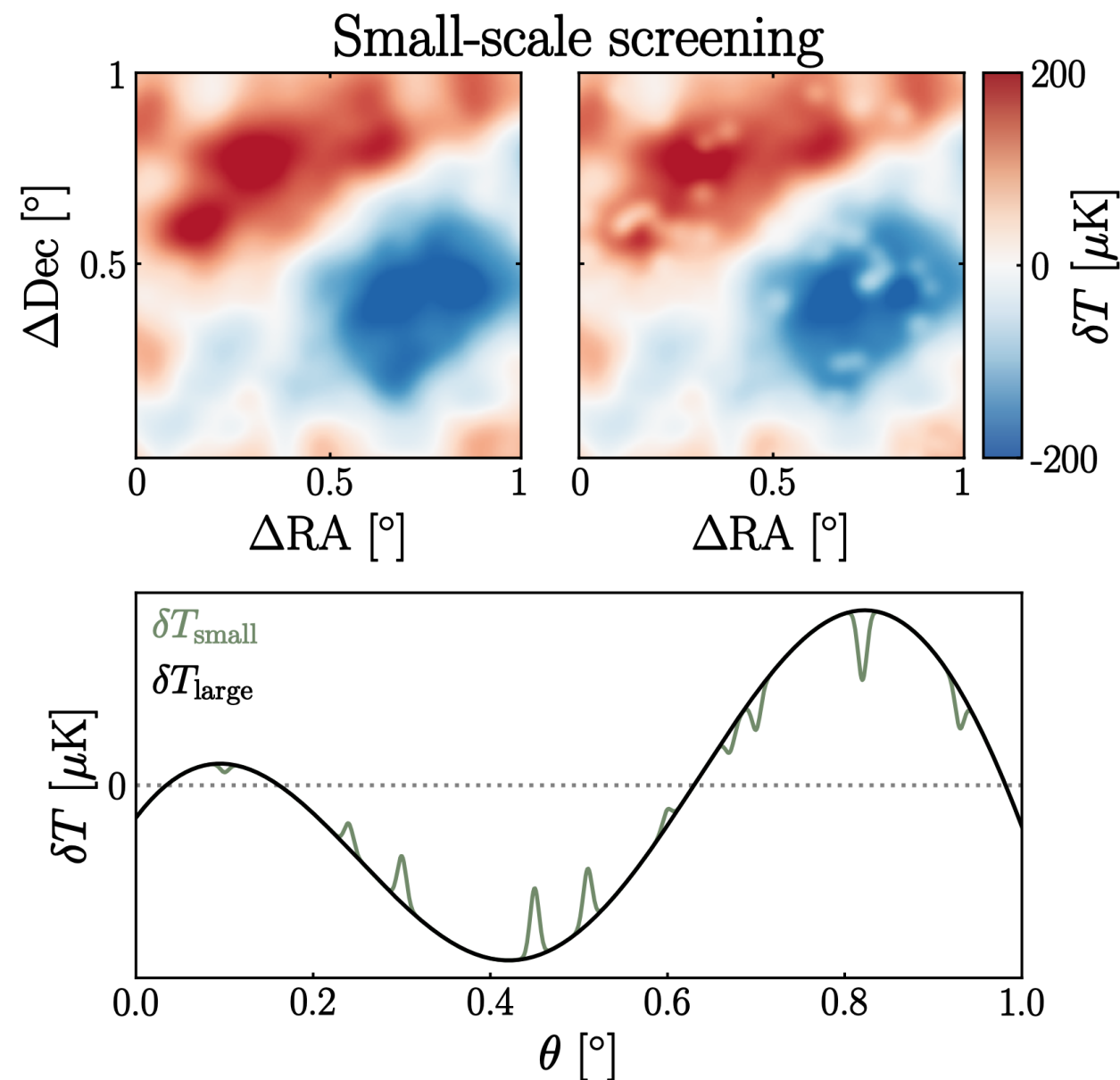
Screening replaces a fraction of CMB photons with "average" CMB photons

$$\delta T_{\text{obs}} = \delta T_{\text{true}} e^{-\tau}$$

→ Probes diffuse gas around galaxies

CMB Screening by ionized gas around galaxies

$$\delta T_{\text{obs}} = \delta T_{\text{true}} e^{-\tau}$$



Screening changes sign
with primary temperature

→ **New "temperature inversion" estimator** analogous to lensing

Horowitz Ferraro Sherwin 19, Hadzhiyska Sherwin Madhavacheril Ferraro 19

$$\hat{\tau}^{\text{TI}}(\mathbf{x}) = -\frac{\widehat{\delta T}_{\text{small}}(\mathbf{x})}{\widehat{\delta T}_{\text{large}}(\mathbf{x})}$$

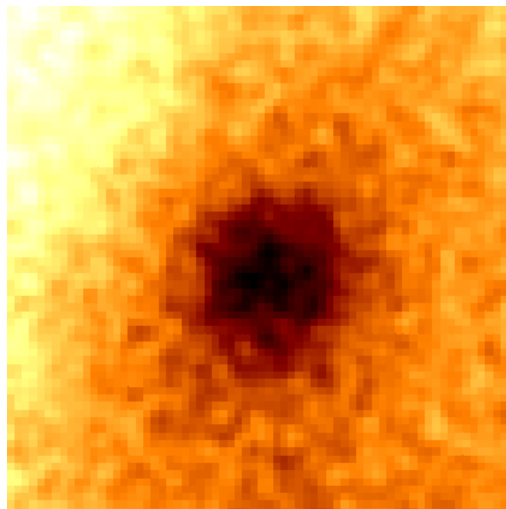
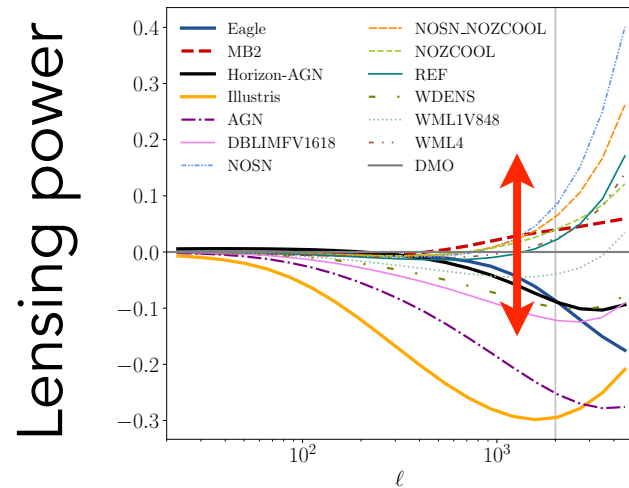
But... large lensing bias needs avoiding/subtracting!

Hadzhiyska Sailer Ferraro 25

Sailer Hadzhiyska Ferraro 25

Conclusions

The uncertain astrophysics of galaxy formation limits our small-scale reach.



CMB can localize the baryons

→ Unleash our ability to learn new Physics from LSS

Thank you!