SLAC NATIONAL ACCELERATOR LABORATORY

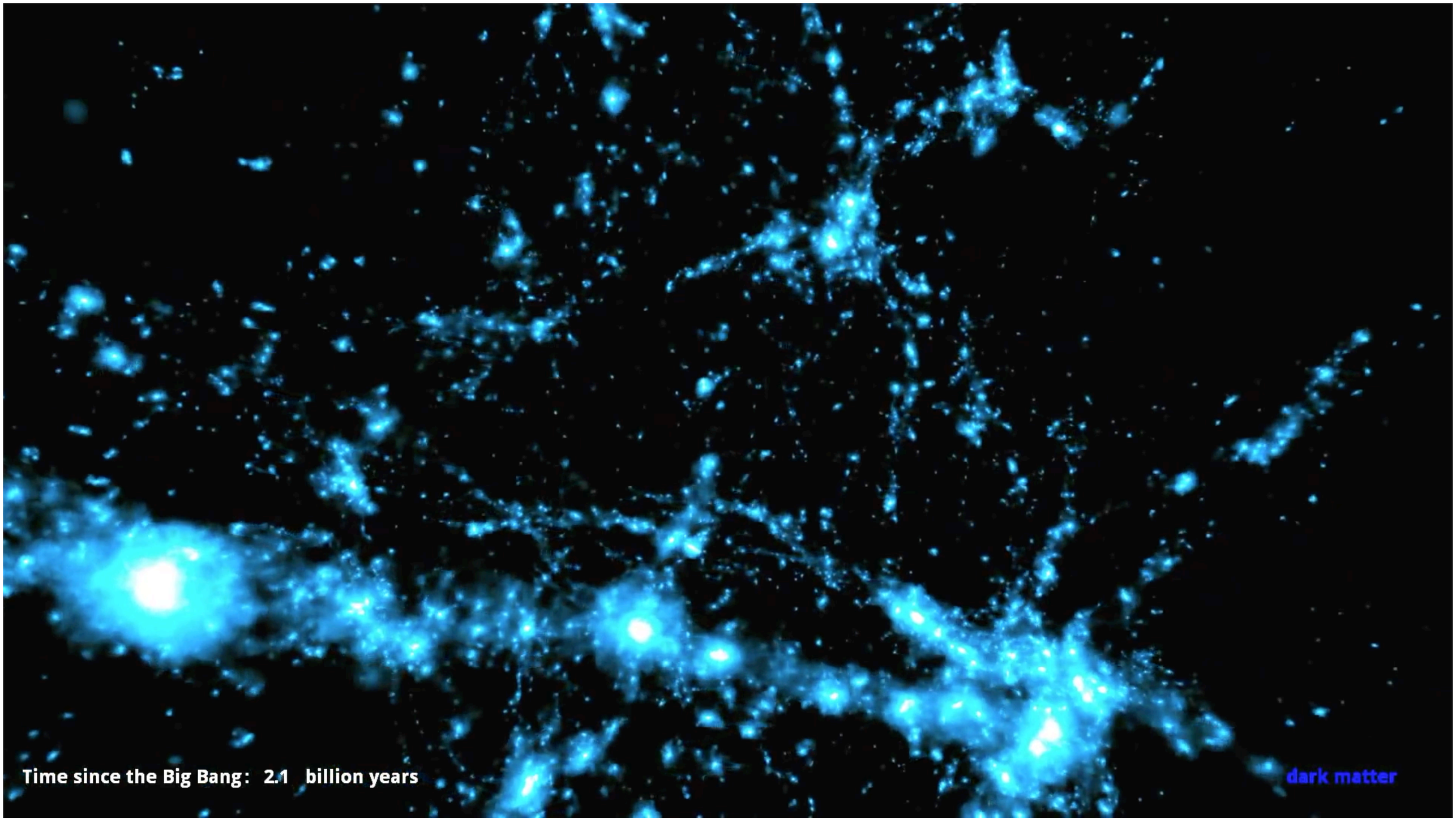
Emmanuel Schaan

Backlighting the LSS with the CMB

Alleviating baryonic uncertainties

Kristina Armitage

Why care about baryons? Cosmology & Galaxy formation



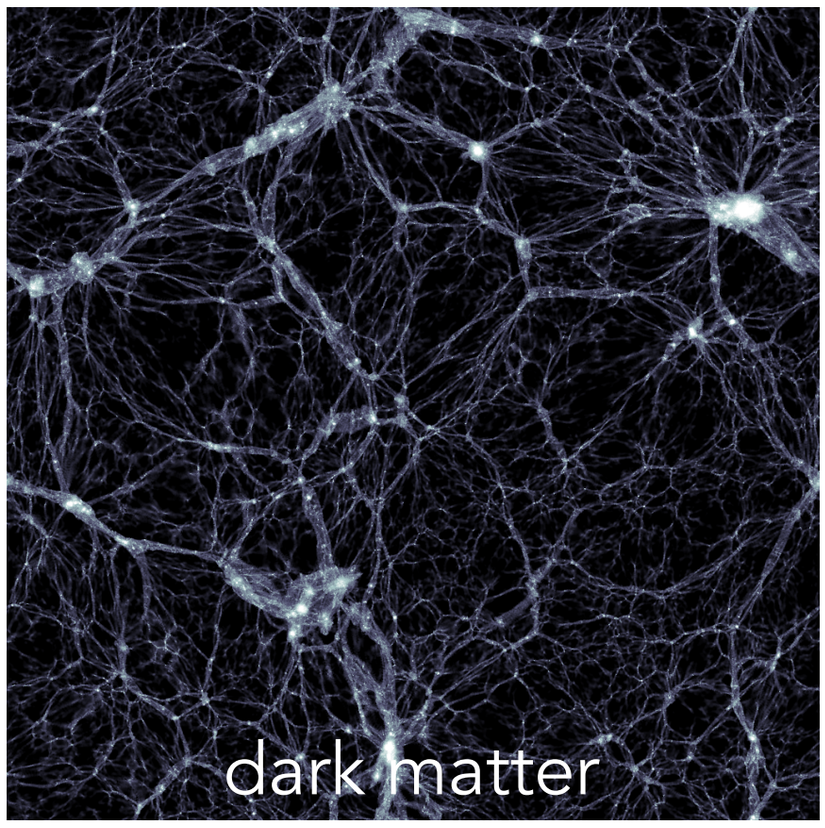
Illustris

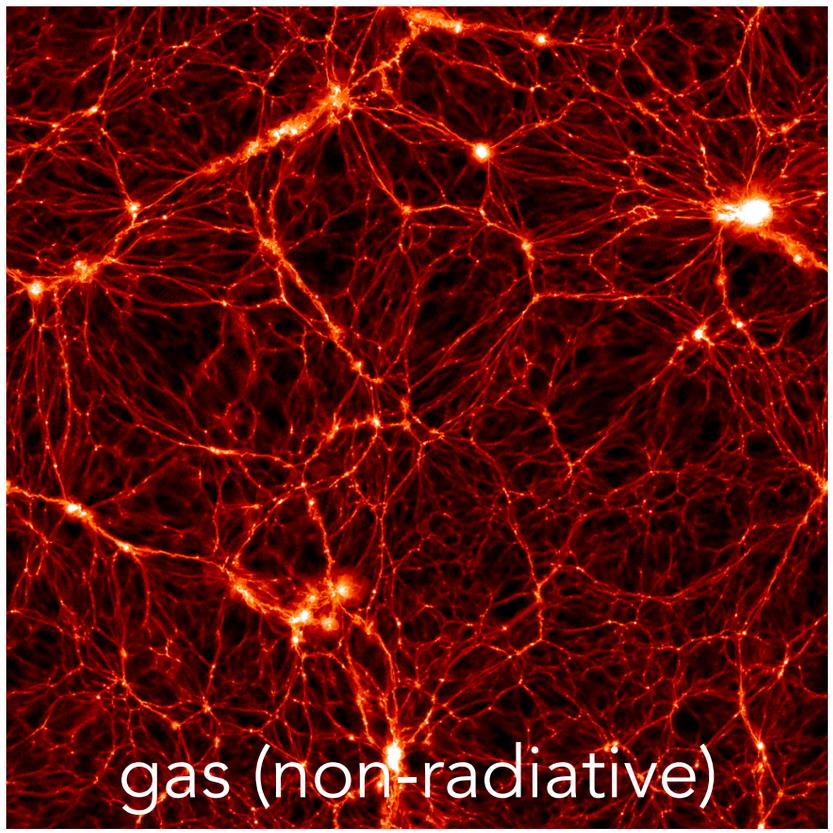
Supernovae and supermassive black holes regulate galaxy formation

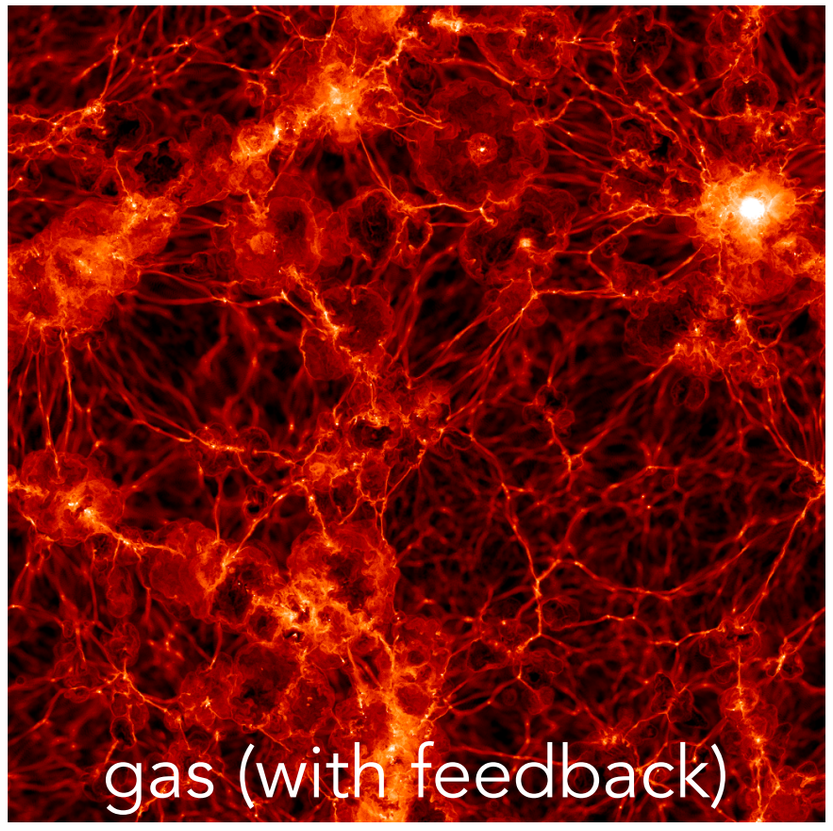
Unknown feedback amplitude

→ (Missing) baryon problem

(Missing) baryon problem







Haider+16, Illustris simulation

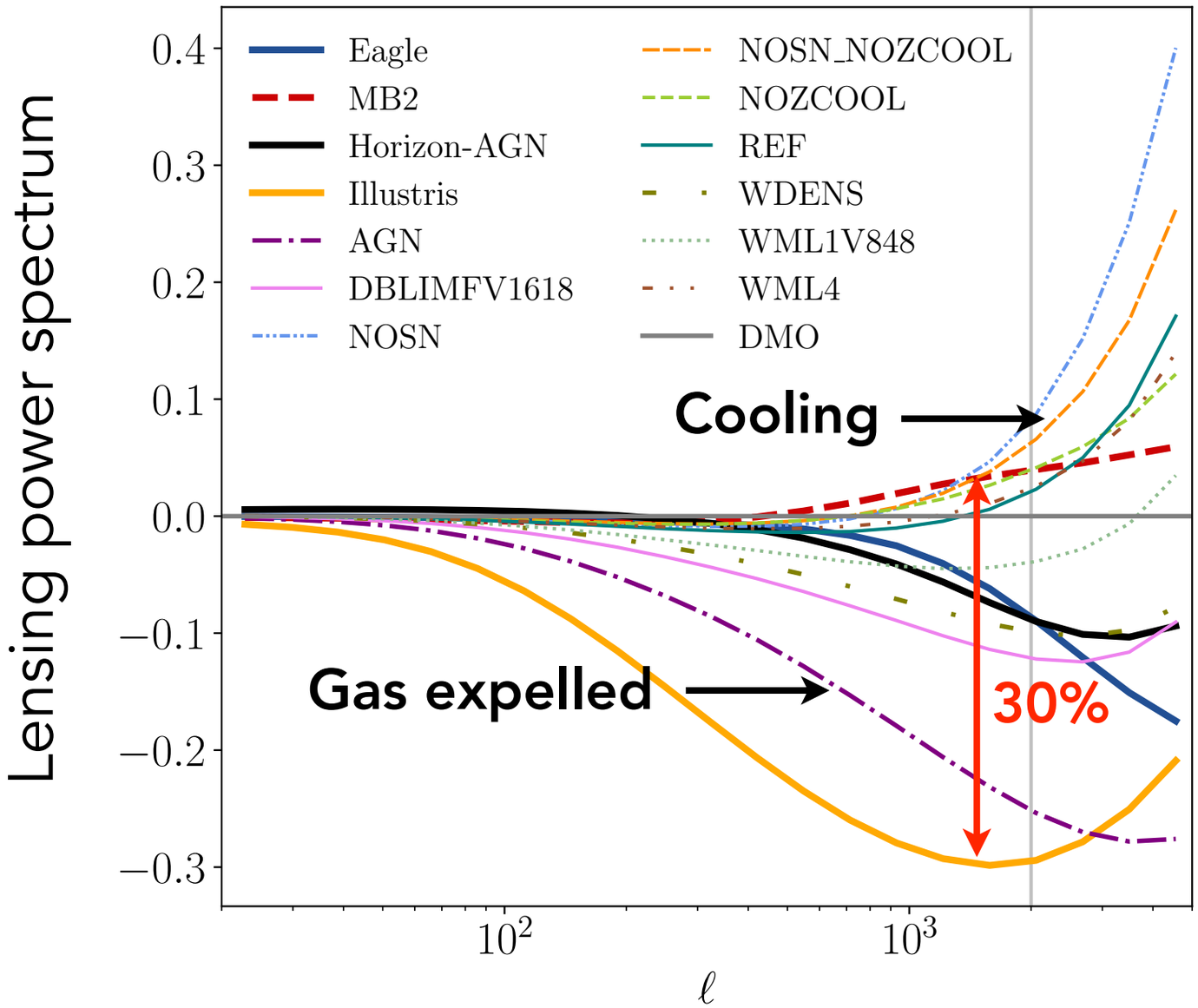
Most baryons in gas (not stars)

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

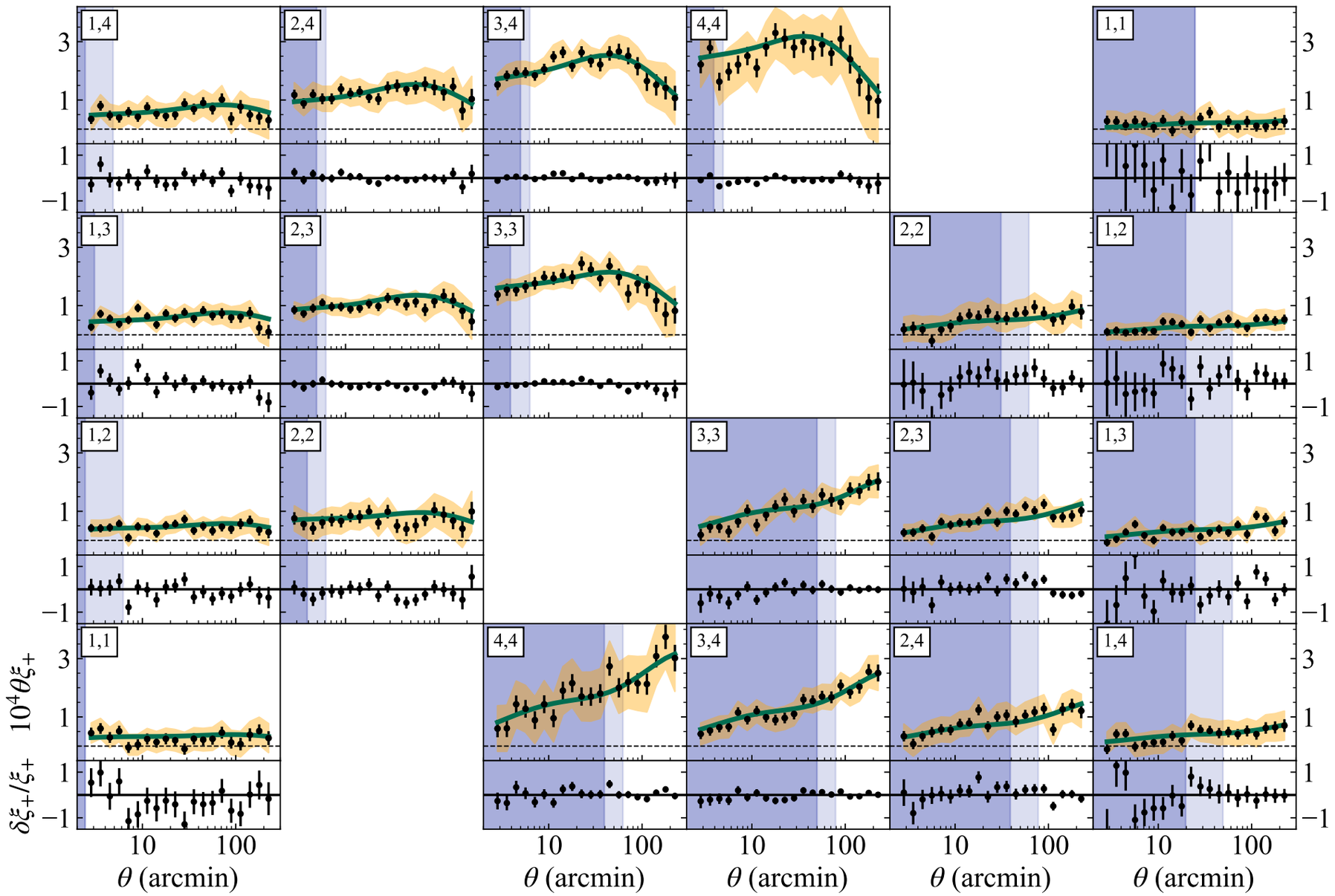
Baryons ~15% total matter, localization is uncertain

→ 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!

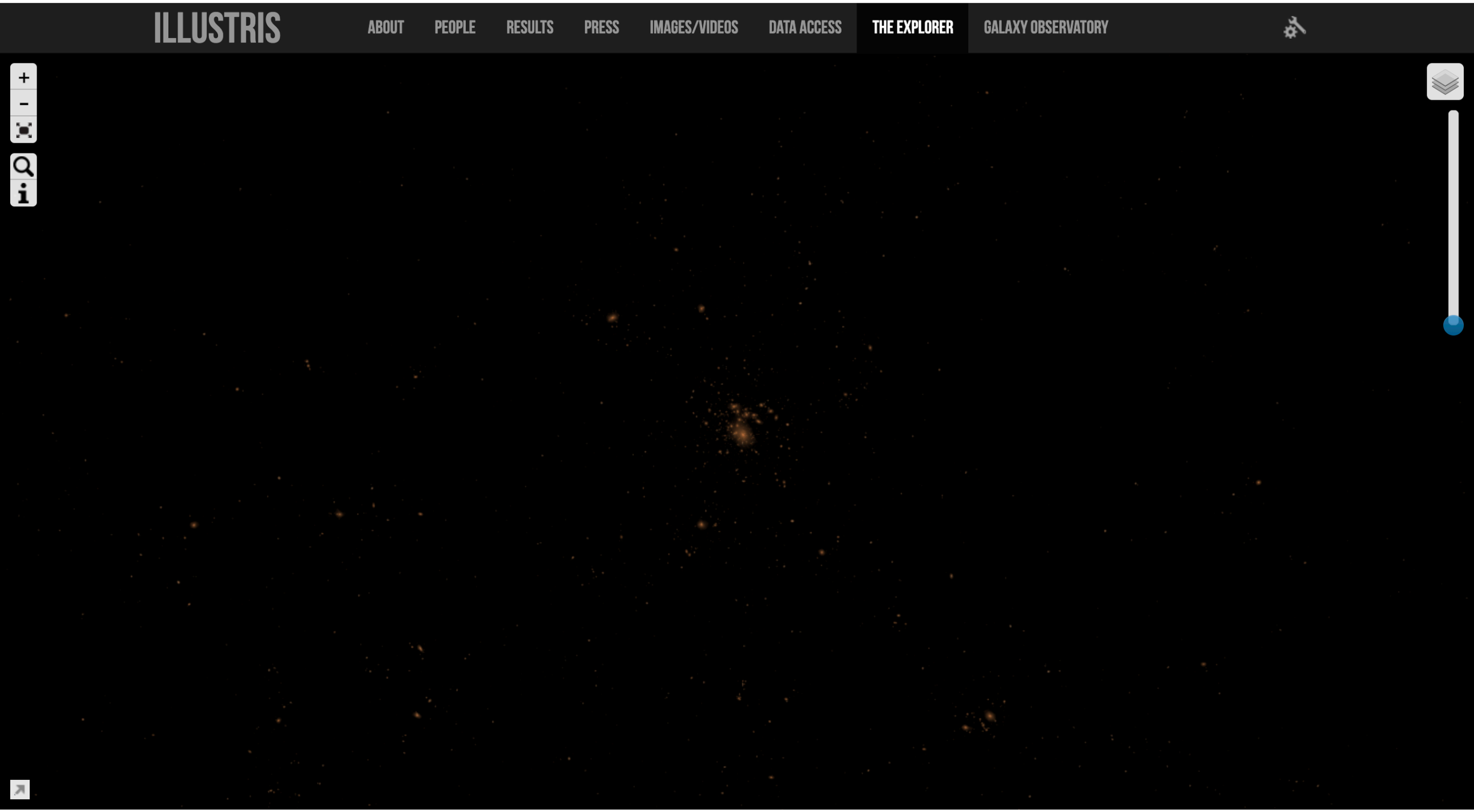
Shaded = Discarded



DES Y3 Amon+22

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

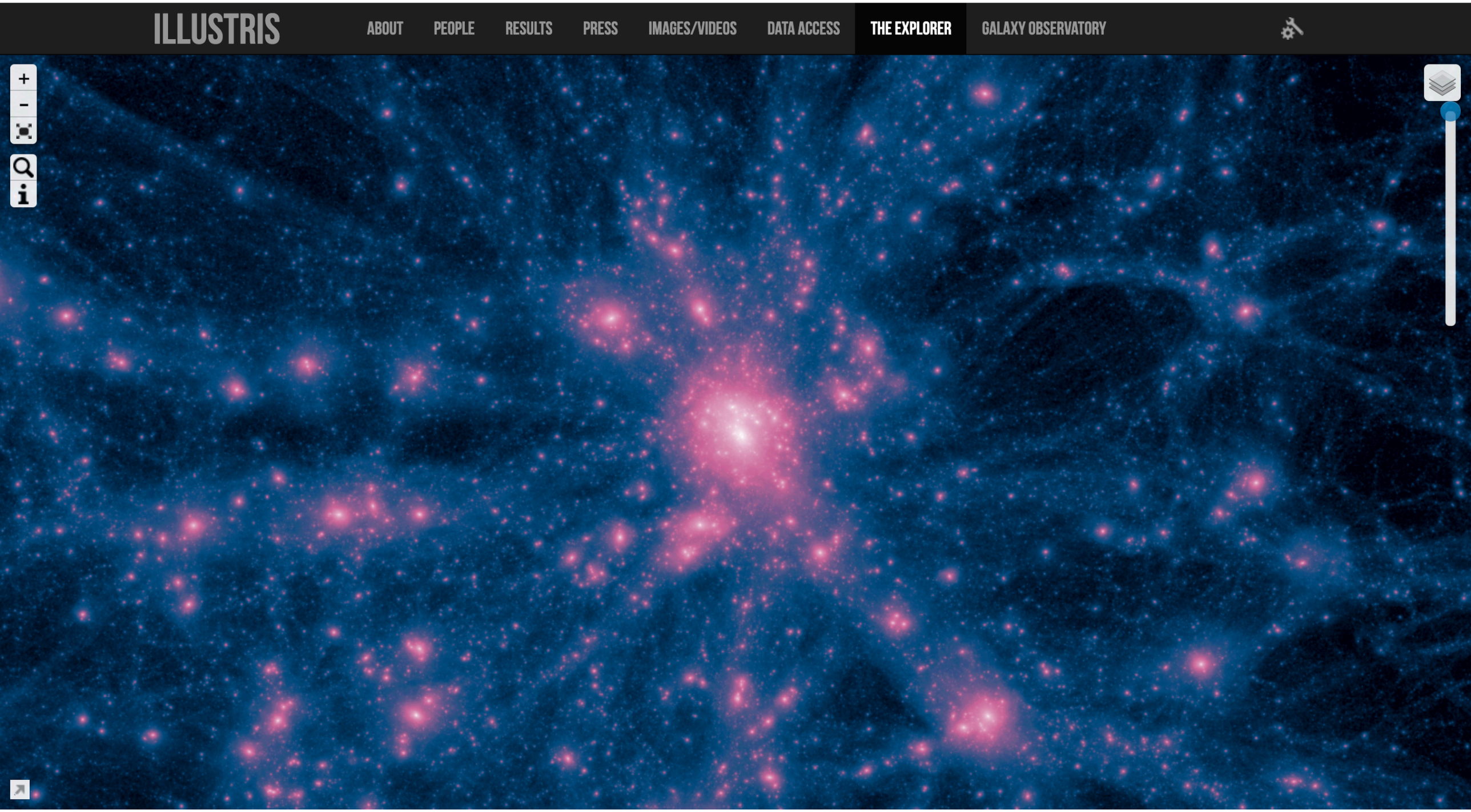
Light is a biased tracer of the mass



Starlight

Illustris simulation explorer

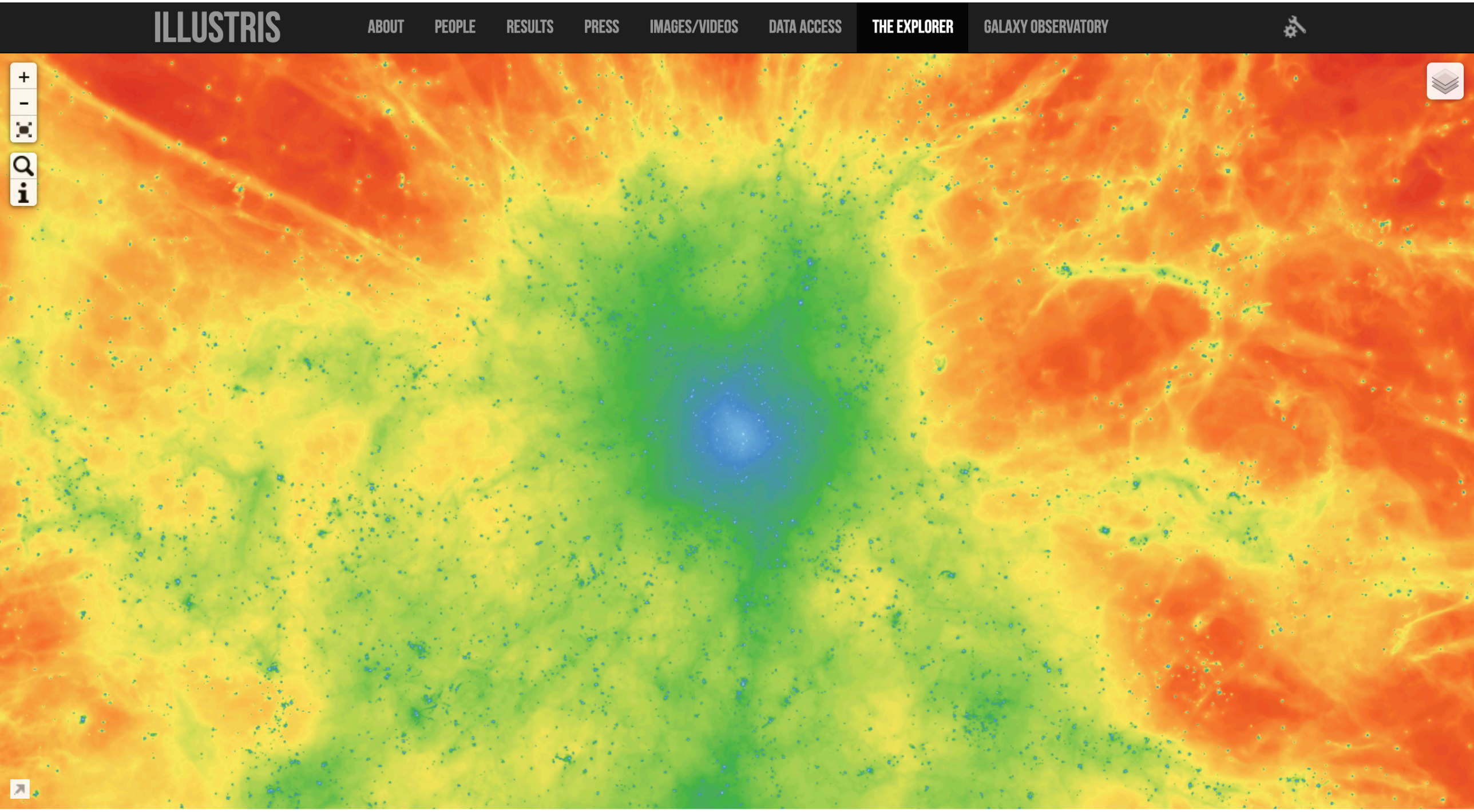
Light is a biased tracer of the mass



Starlight, dark matter

Illustris simulation explorer

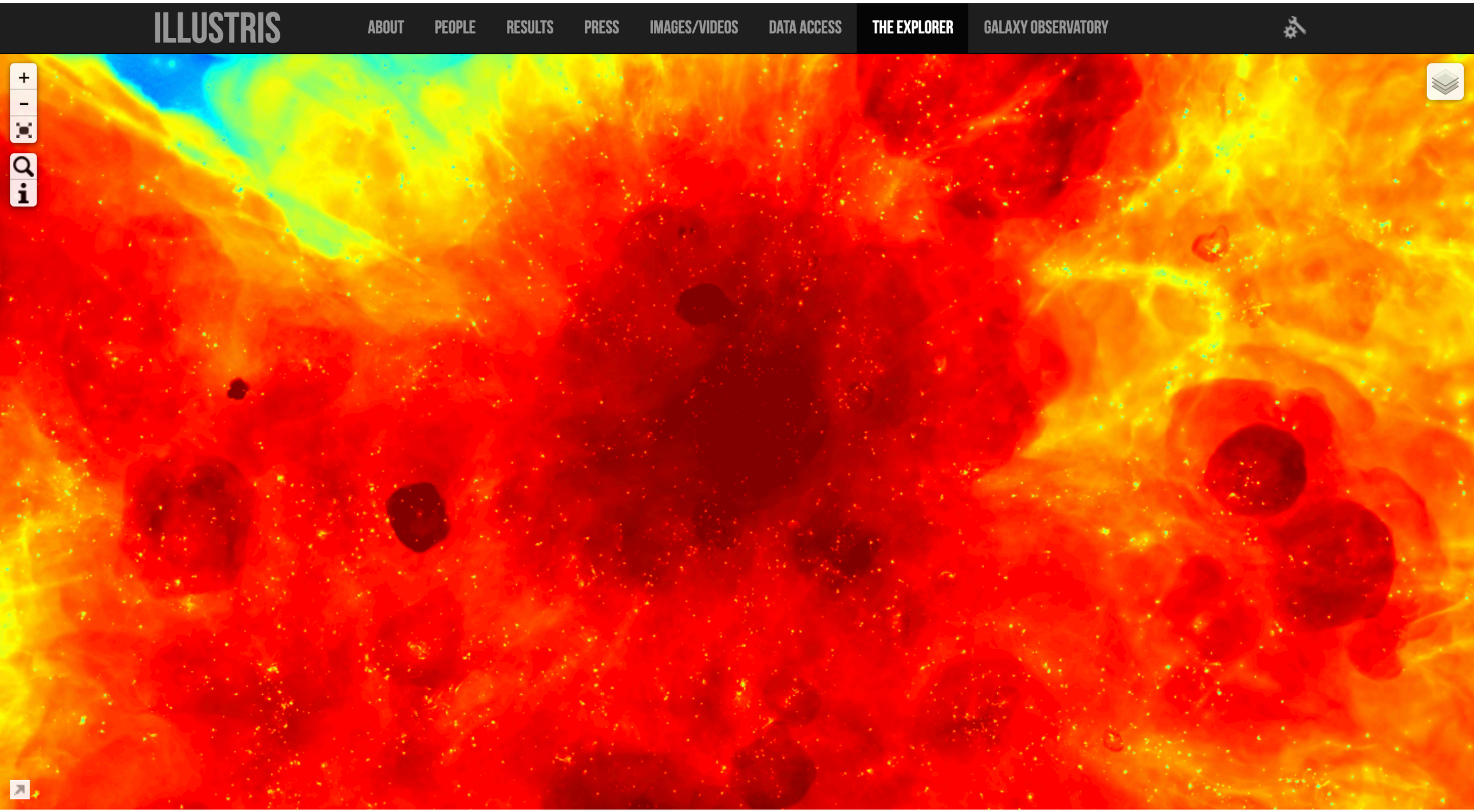
Light is a biased tracer of the mass



Starlight, dark matter, gas density

Illustris simulation explorer

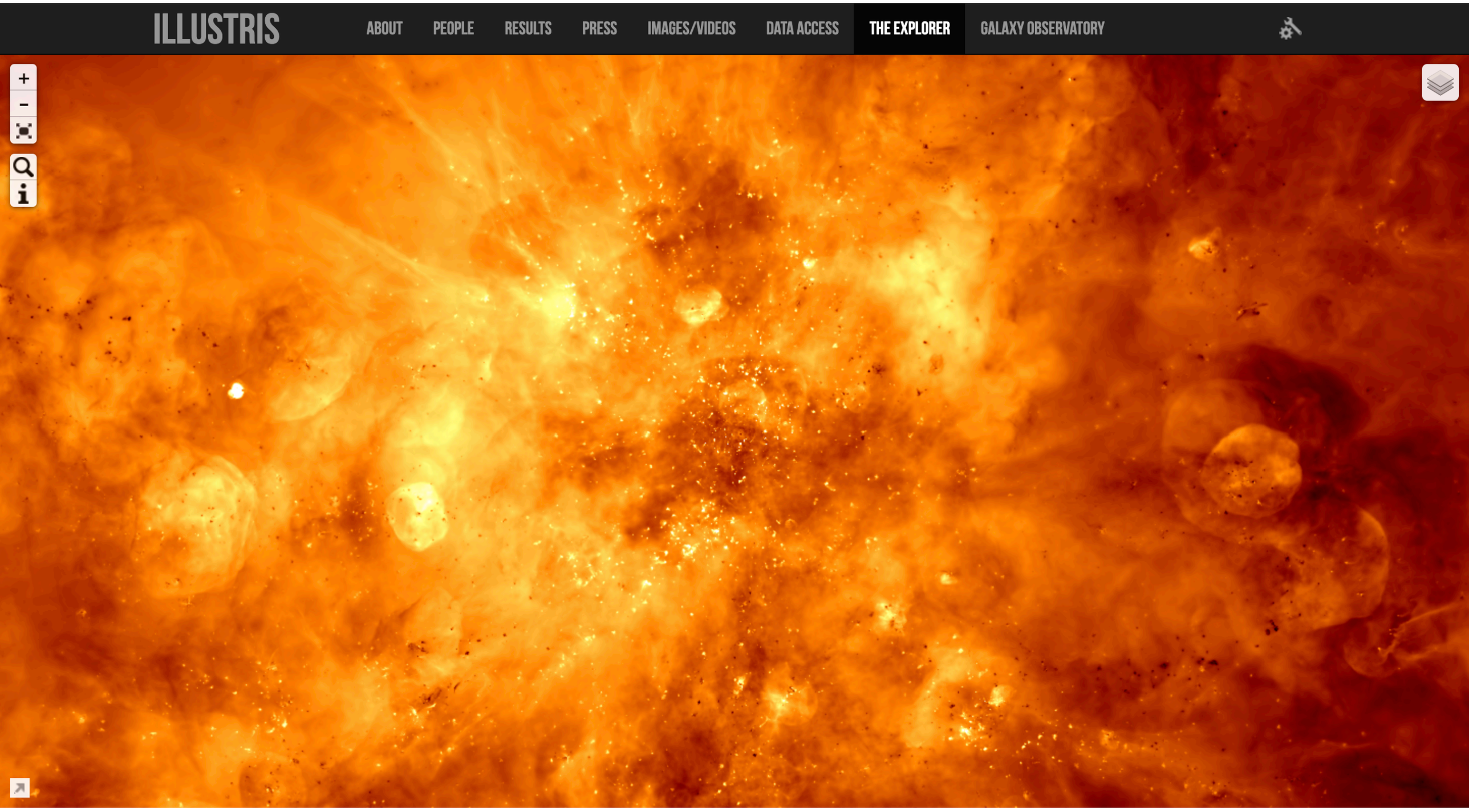
Light is a biased tracer of the mass



Starlight, dark matter, gas density, temperature

Illustris simulation explorer

Light is a biased tracer of the mass



Starlight, dark matter, gas density, temperature, velocity

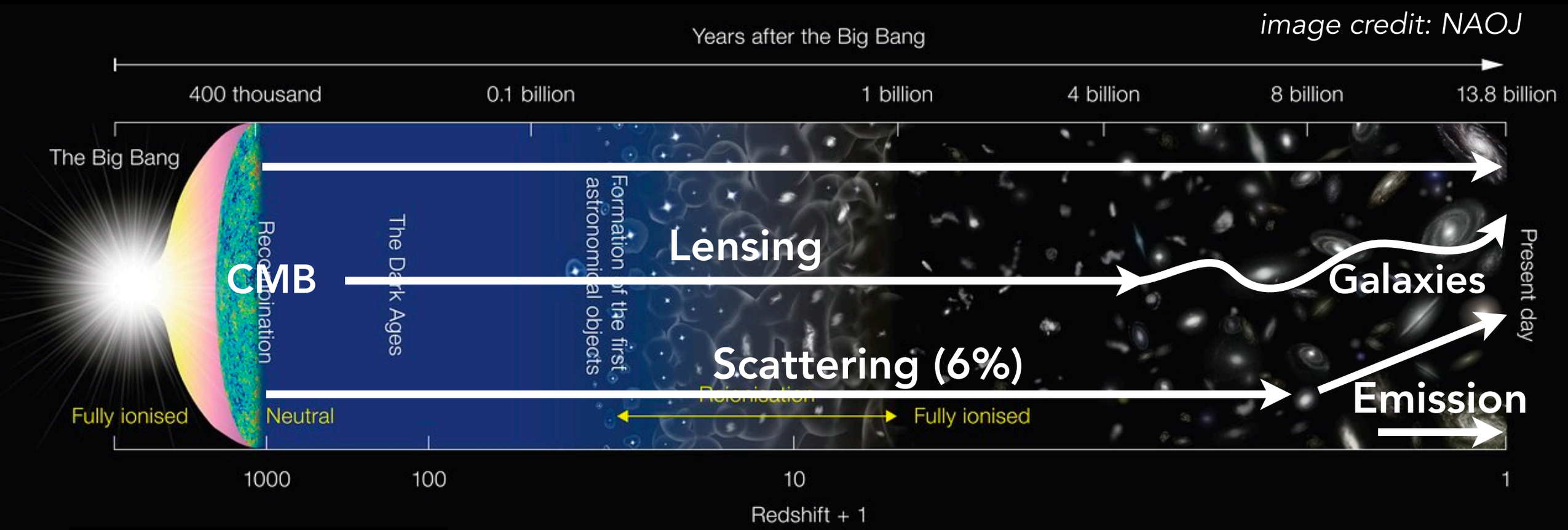
Illustris simulation explorer

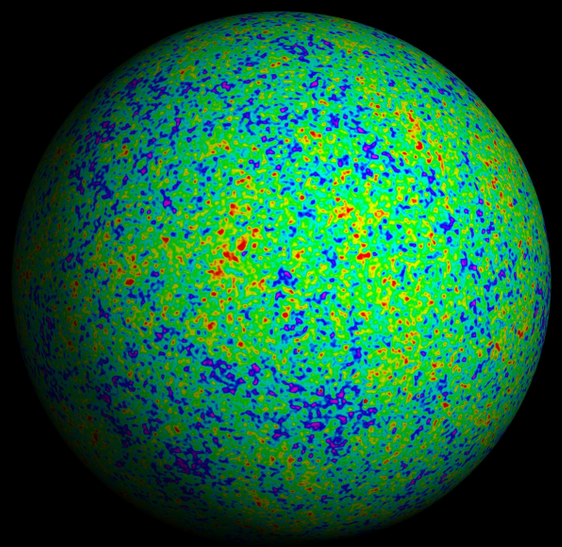
Milky way
(our own galaxy)

Andromeda galaxy

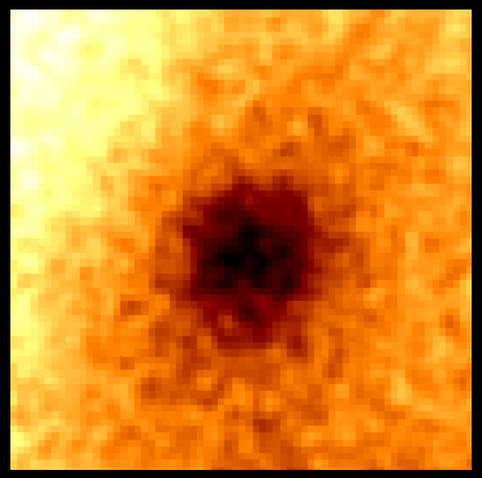
NASA, ESA, DePasquale, Wheatley, Levay: QSO absorption lines

Backlighting the galaxies with the CMB

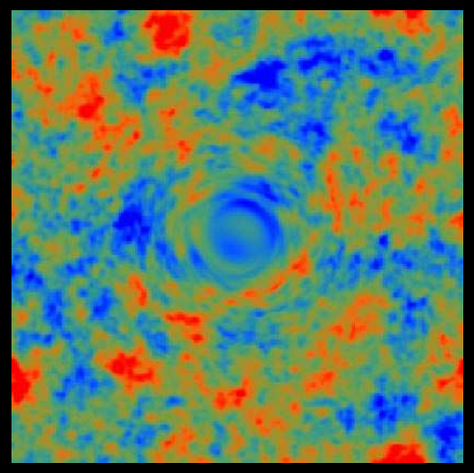




Initial conditions



Scattering:
Gas shadows



Lensing:
Mass shadows

Summary of CMB secondaries

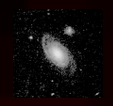
Key parameters:

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

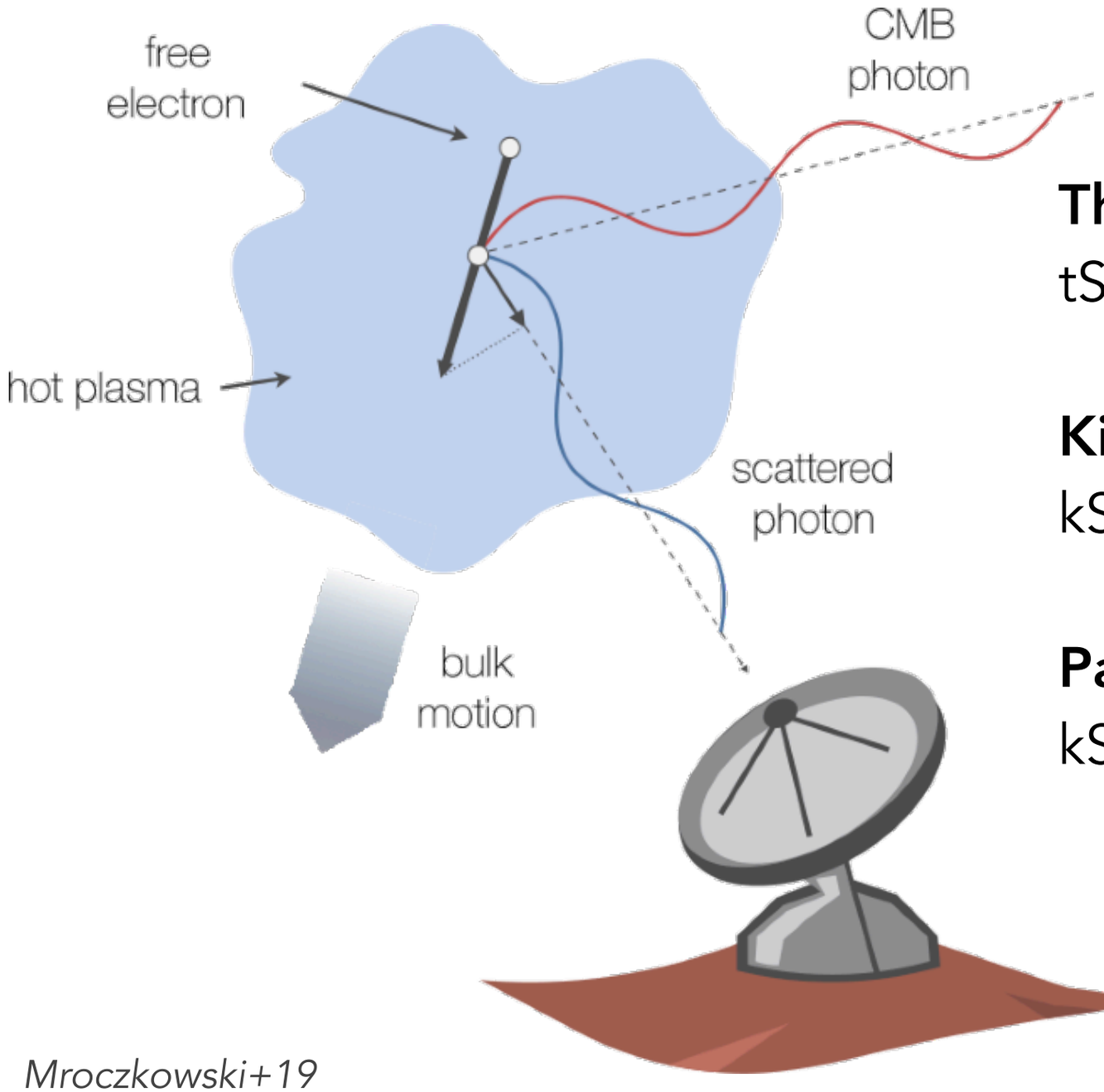
→ Many imprints with complementary information :

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	$\tau\ \left(v_{\rm bulk\ \parallel}/c\right)$	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?

Gas shadows:
Localize the missing baryons



CMB can help: Sunyaev-Zel'dovich effects



Mroczkowski+19

Thermal SZ: Doppler from thermal motions

tSZ = gas density * temperature

Kinematic SZ: Doppler from bulk motion

kSZ = gas density * bulk velocity

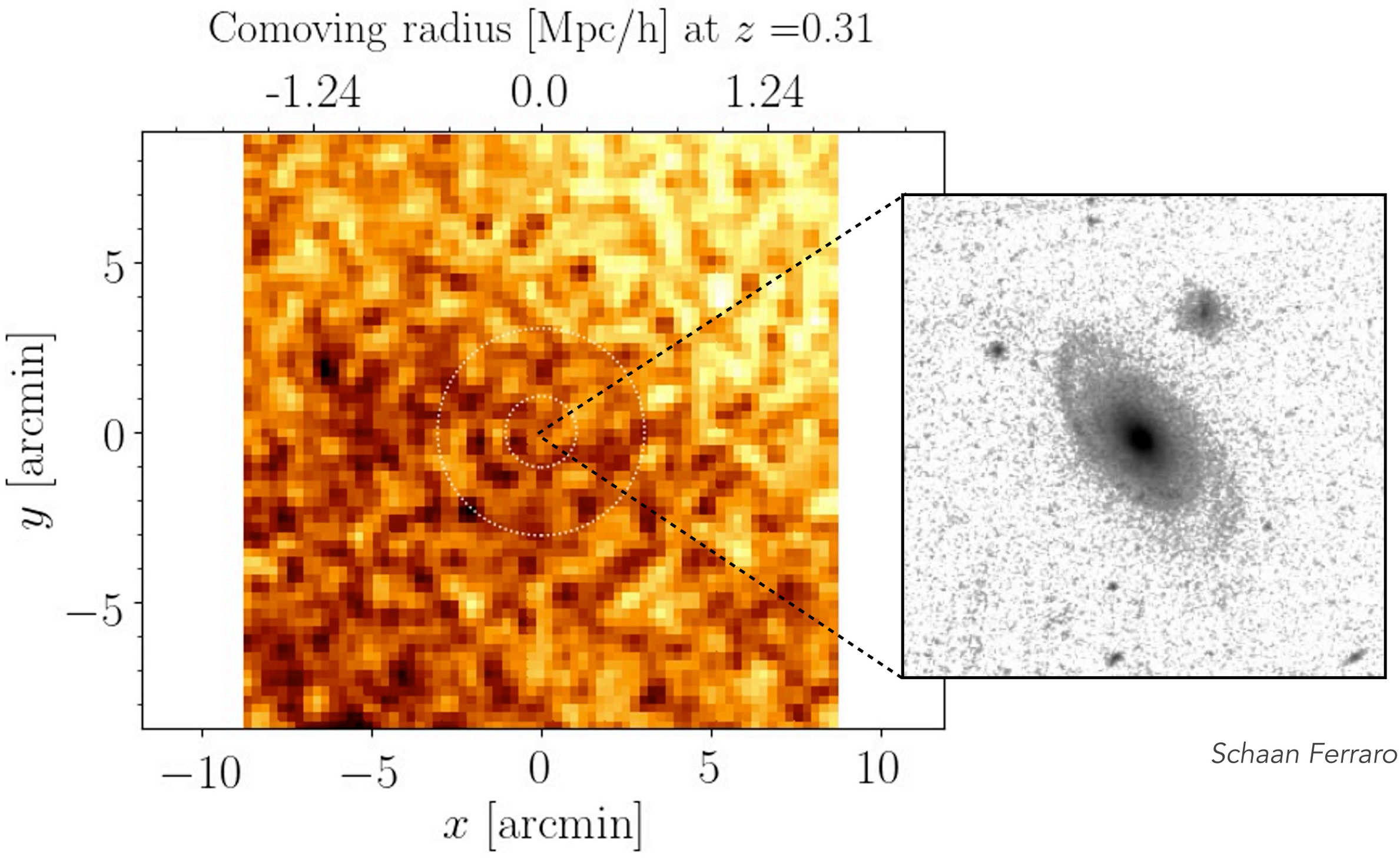
Patchy screening: Doppler Simple scattering

kSZ = gas density * primary CMB

→ Unique probe of missing baryons!

(Looking forward to FRBs too!)

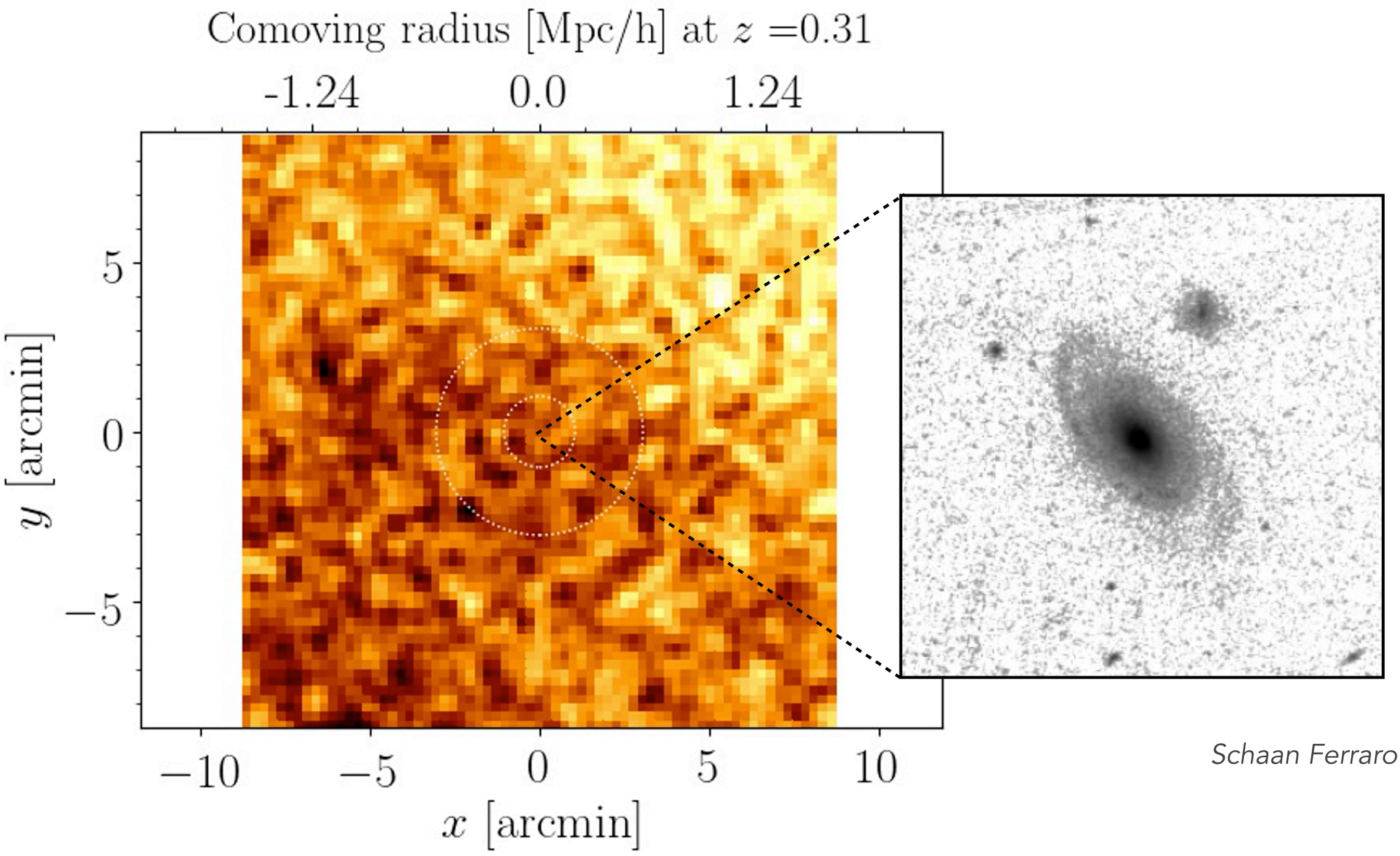
Extracting tSZ: single galaxy



Schaan Ferraro+20

SNR per galaxy is too low to detect!

Extracting tSZ: 400,000 galaxies



Schaan Ferraro+20

Extended tSZ profile is well resolved!

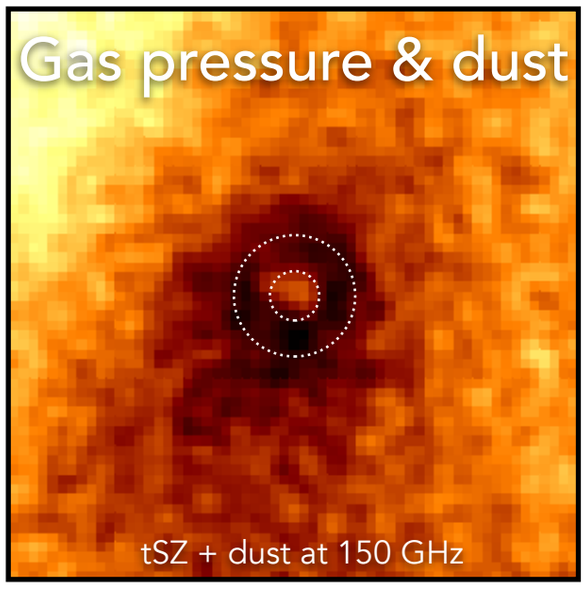
Higher precision tSZ: ACTxDESI

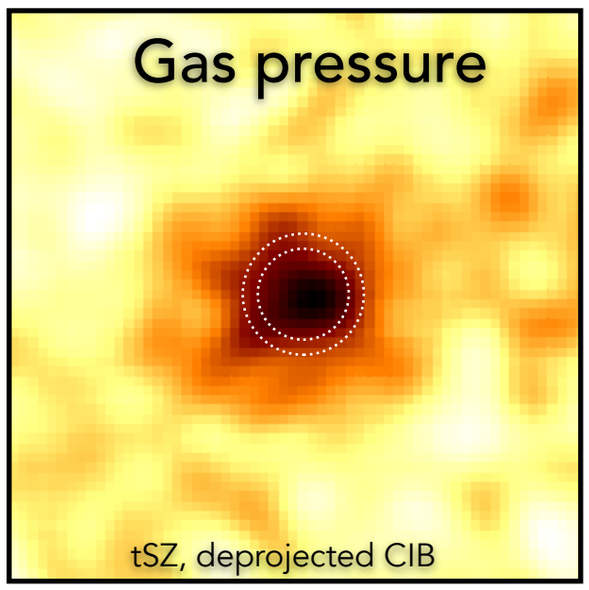
Henry Liu

Simone Ferraro

Emmanuel Schaan

High precision stacked tSZ
Significant dust bias
Clean by masking/deprojecting with variable dust SED





Schaan Ferraro+20

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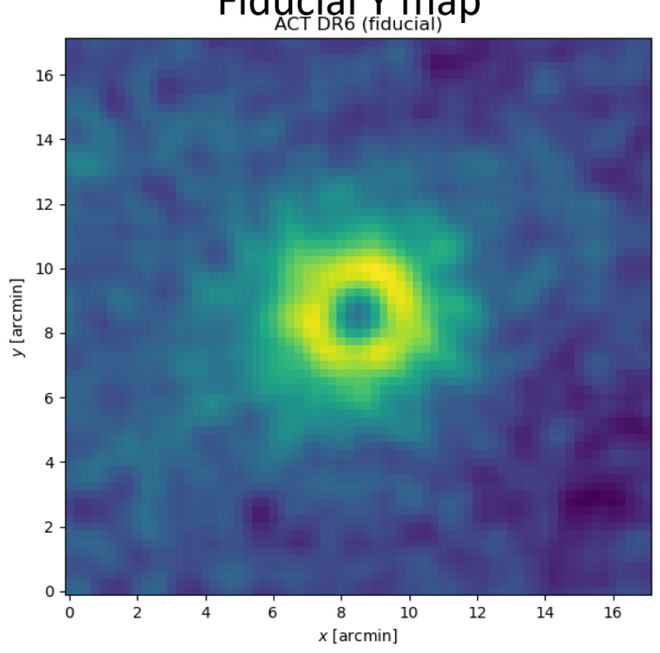
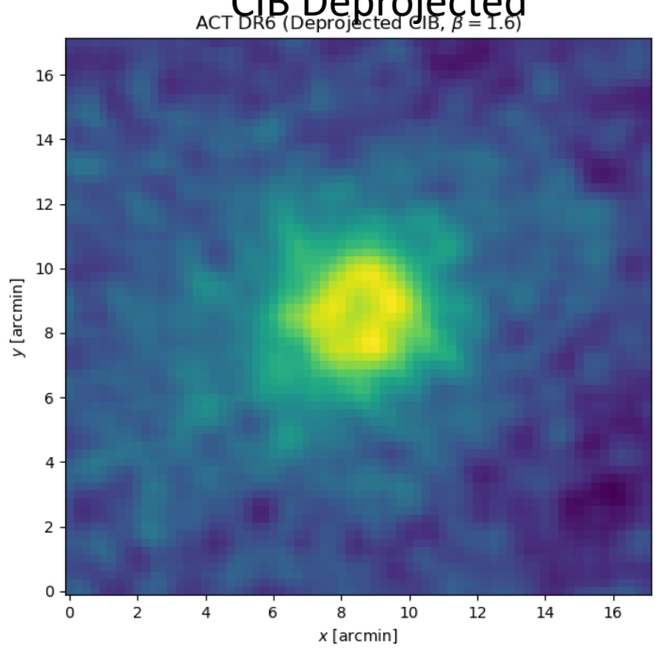
Fiducial Y map

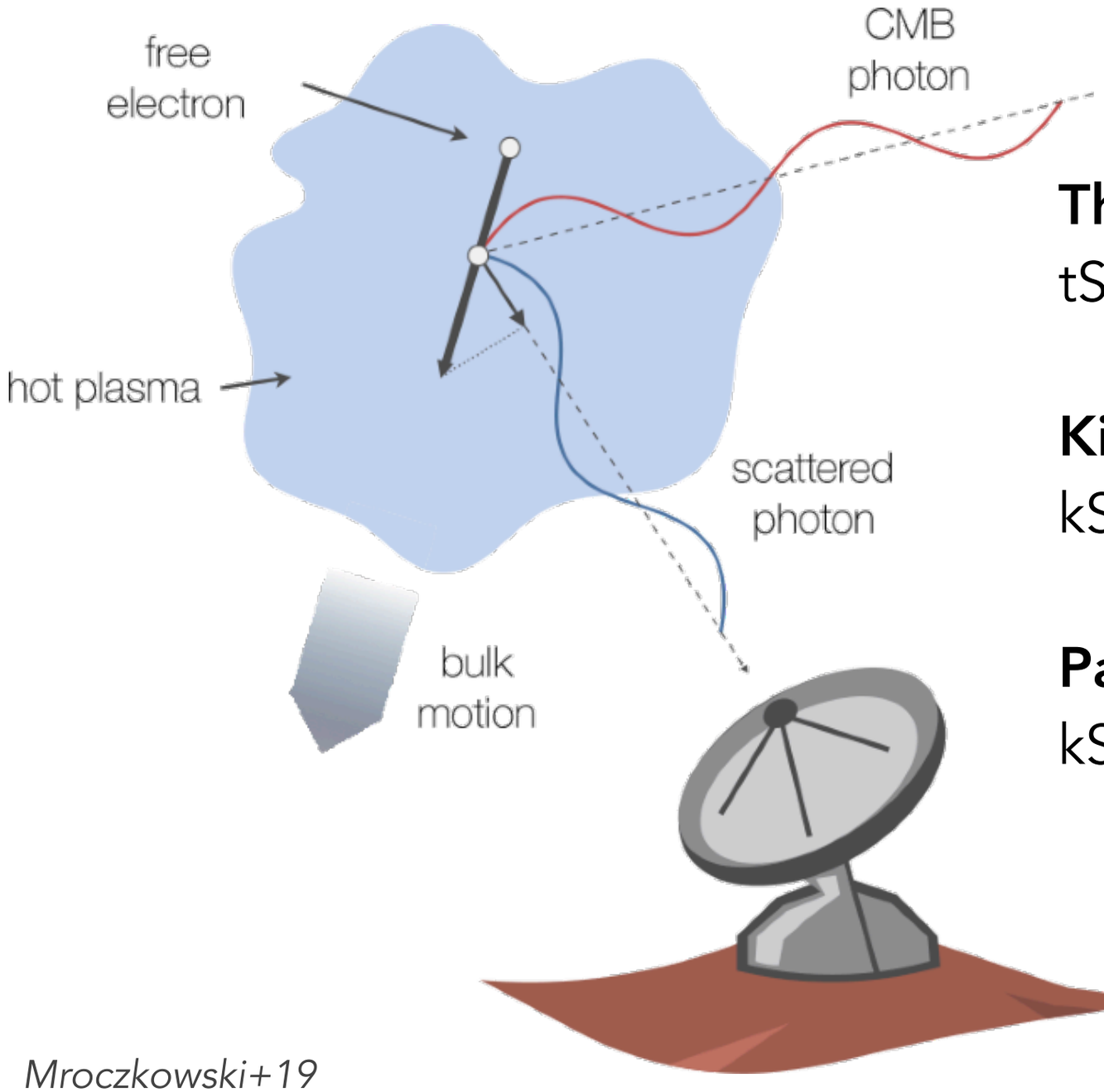


CIB Deprojected



Liu+24

CMB can help: Sunyaev-Zel'dovich effects



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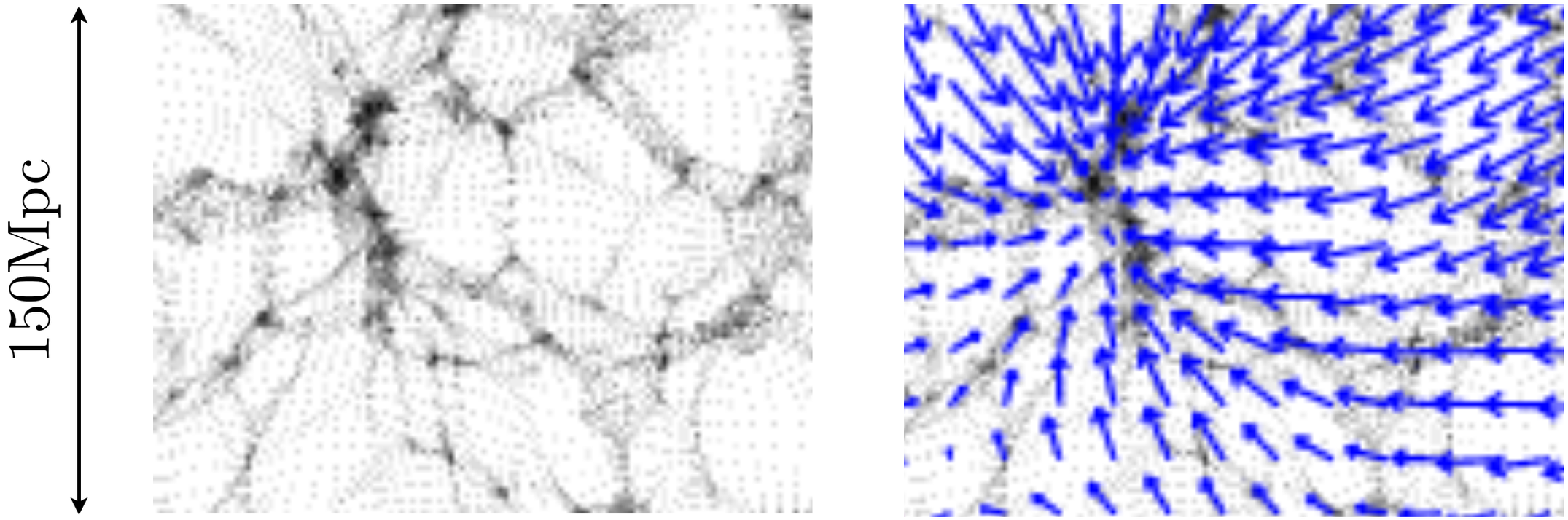
→ Unique probe of missing baryons!

(Looking forward to FRBs too!)

Extracting kSZ: Velocity reconstruction

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



Eisenstein+07, Padmanabhan+12,14

kSZ amplitude ∝ $\langle v_{true}\, v_{rec}\rangle$ or $r(v_{true}, v_{rec})$

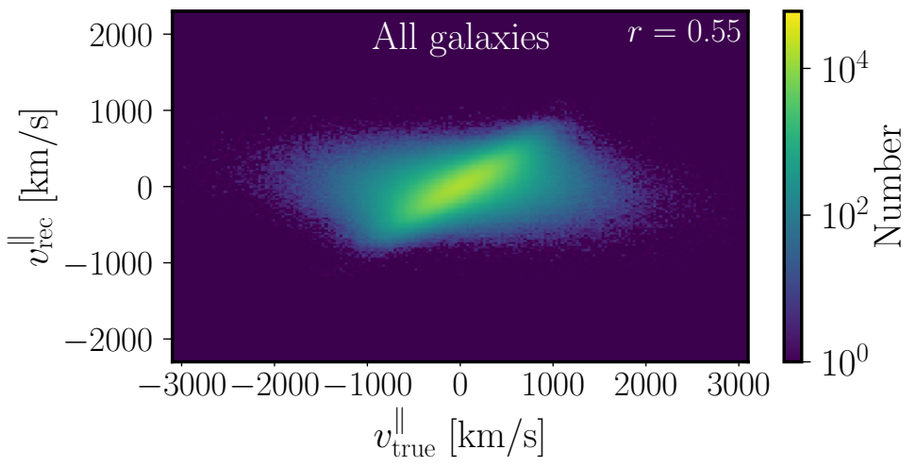
→ Quantify from sims

Velocity reconstruction via continuity equation: assessment

Bernardita Ried Guachalla *Boryana Hadzhiyska* *Simone Ferraro* *Emmanuel Schaan*




Hadzhiyska+23, Ried Guachalla+23



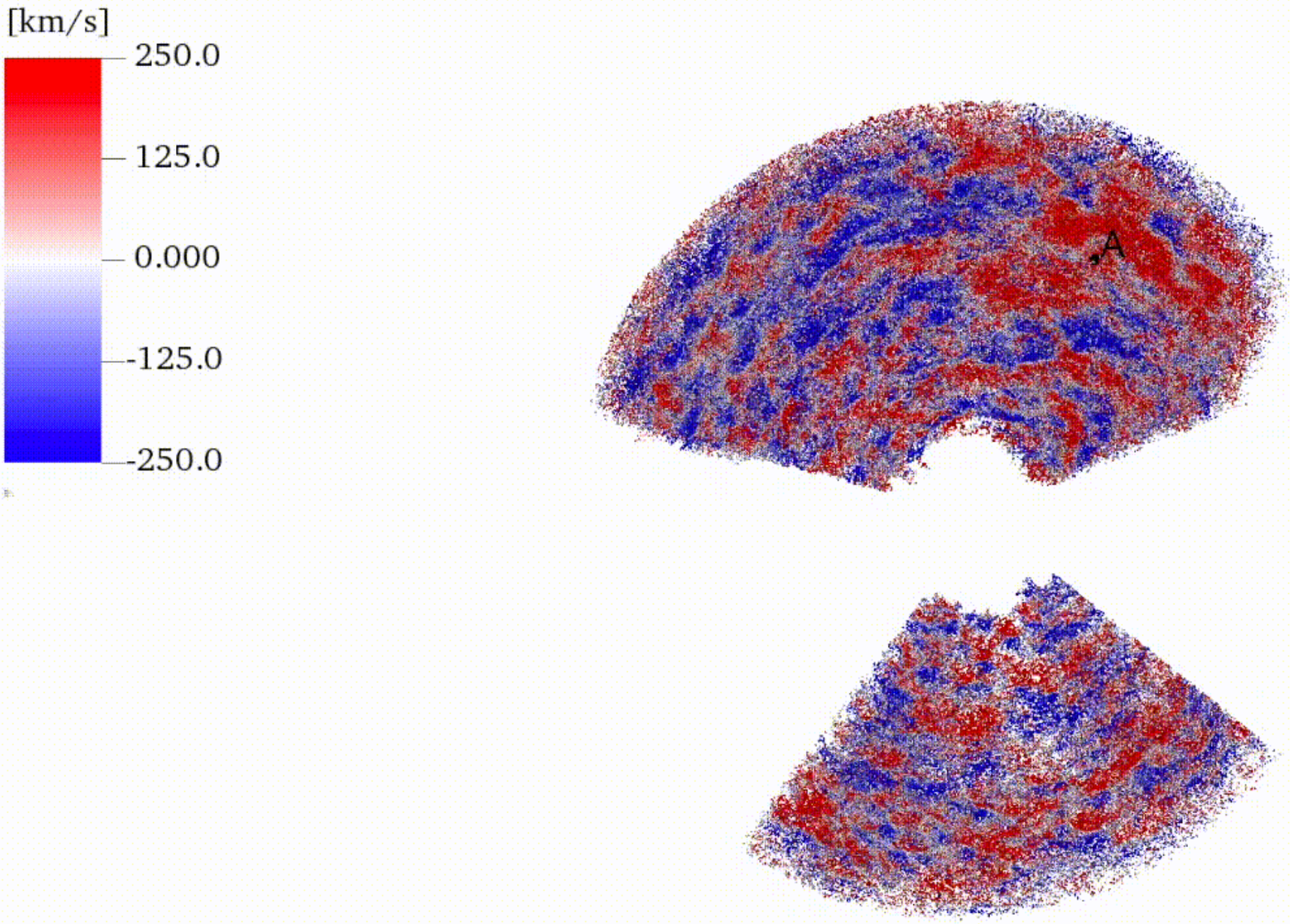
Key results

- 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



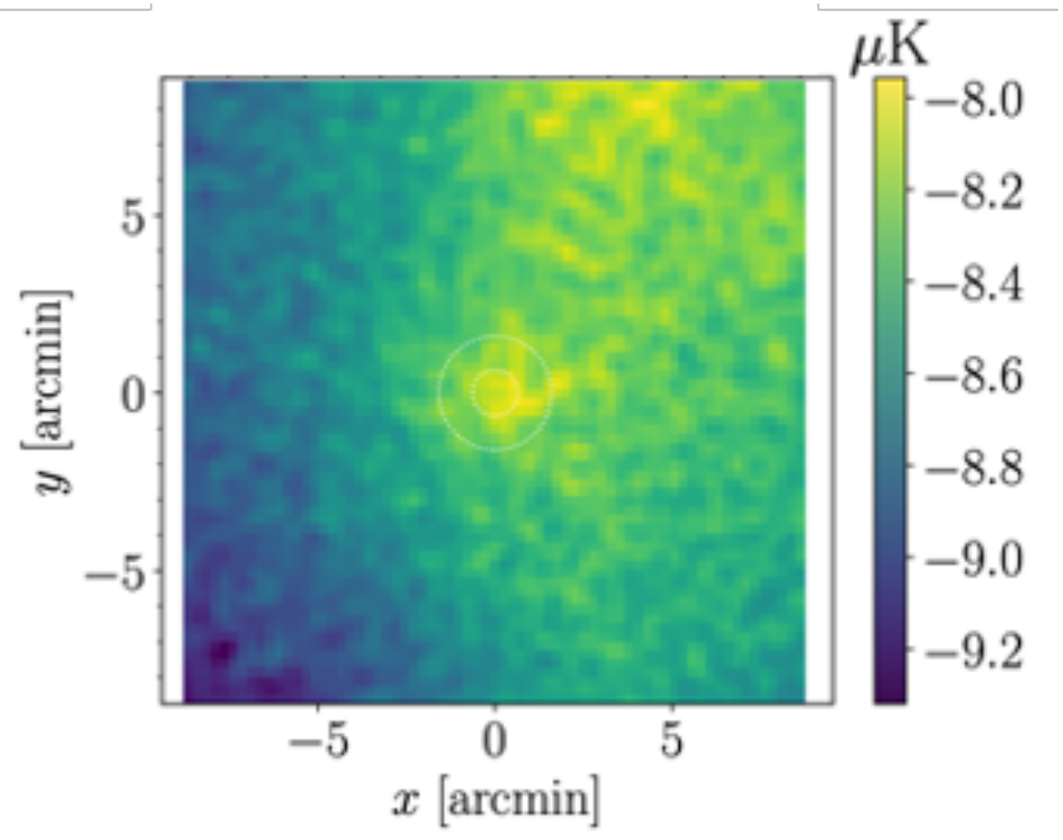
BOSS (CMASS AND LOWZ)

Ried Guachalla

Higher precision kSZ: ACTxDESI

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



Schaan Ferraro+20

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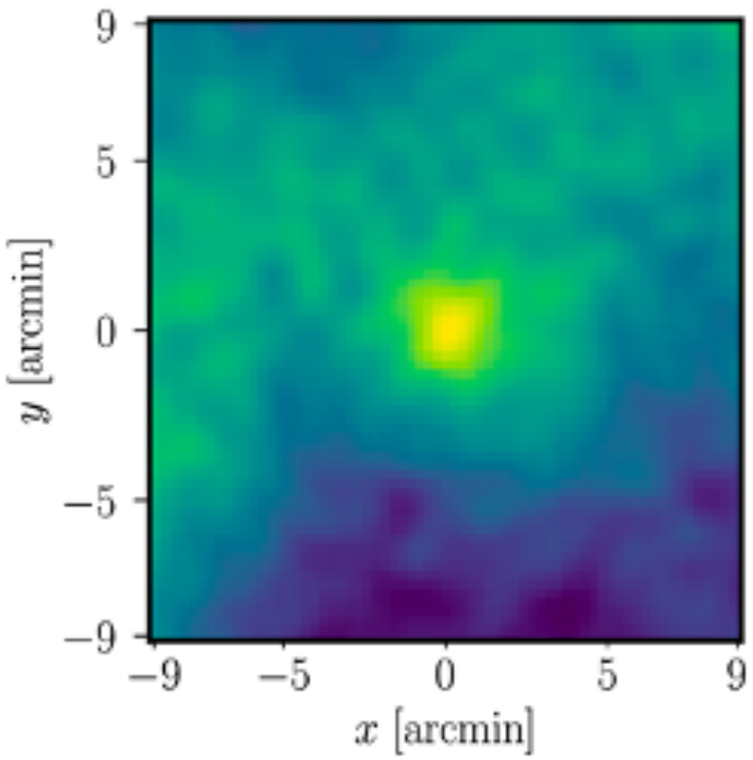
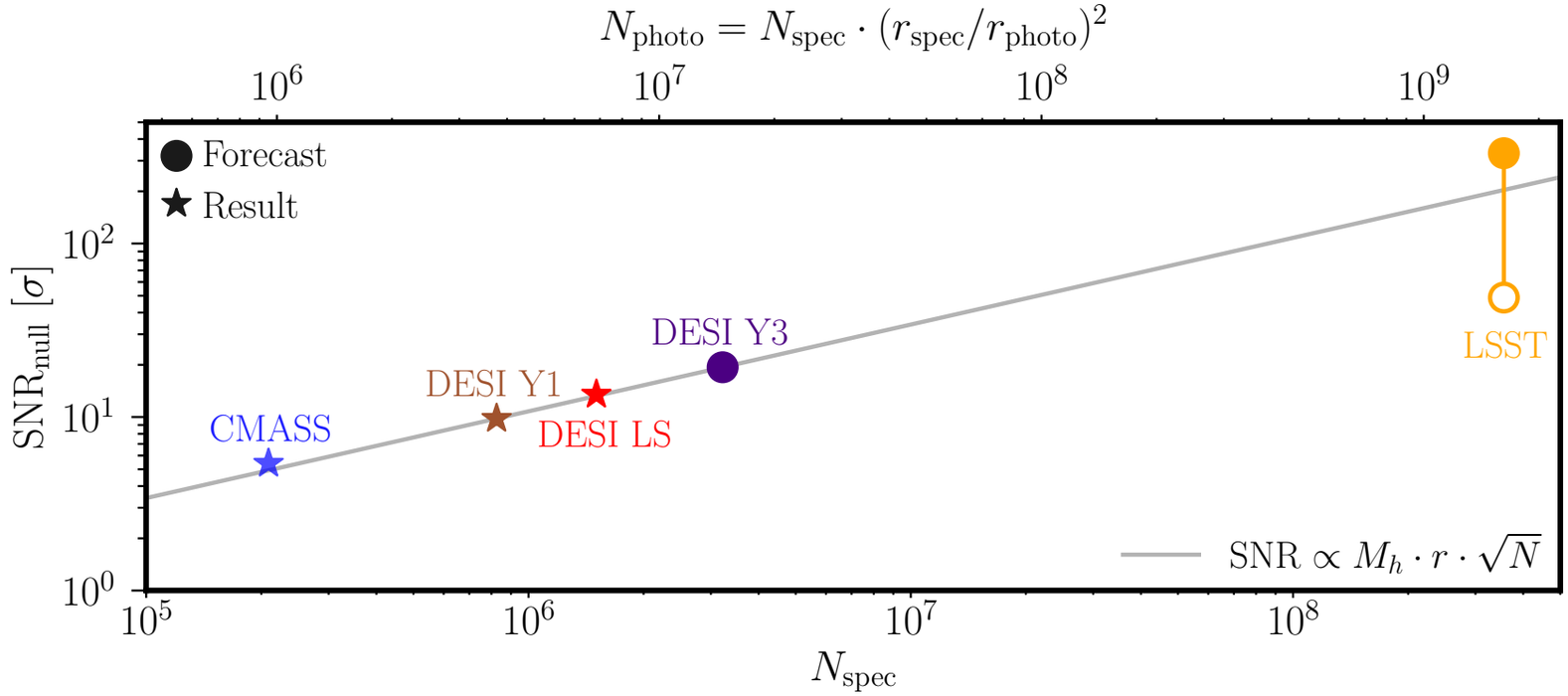
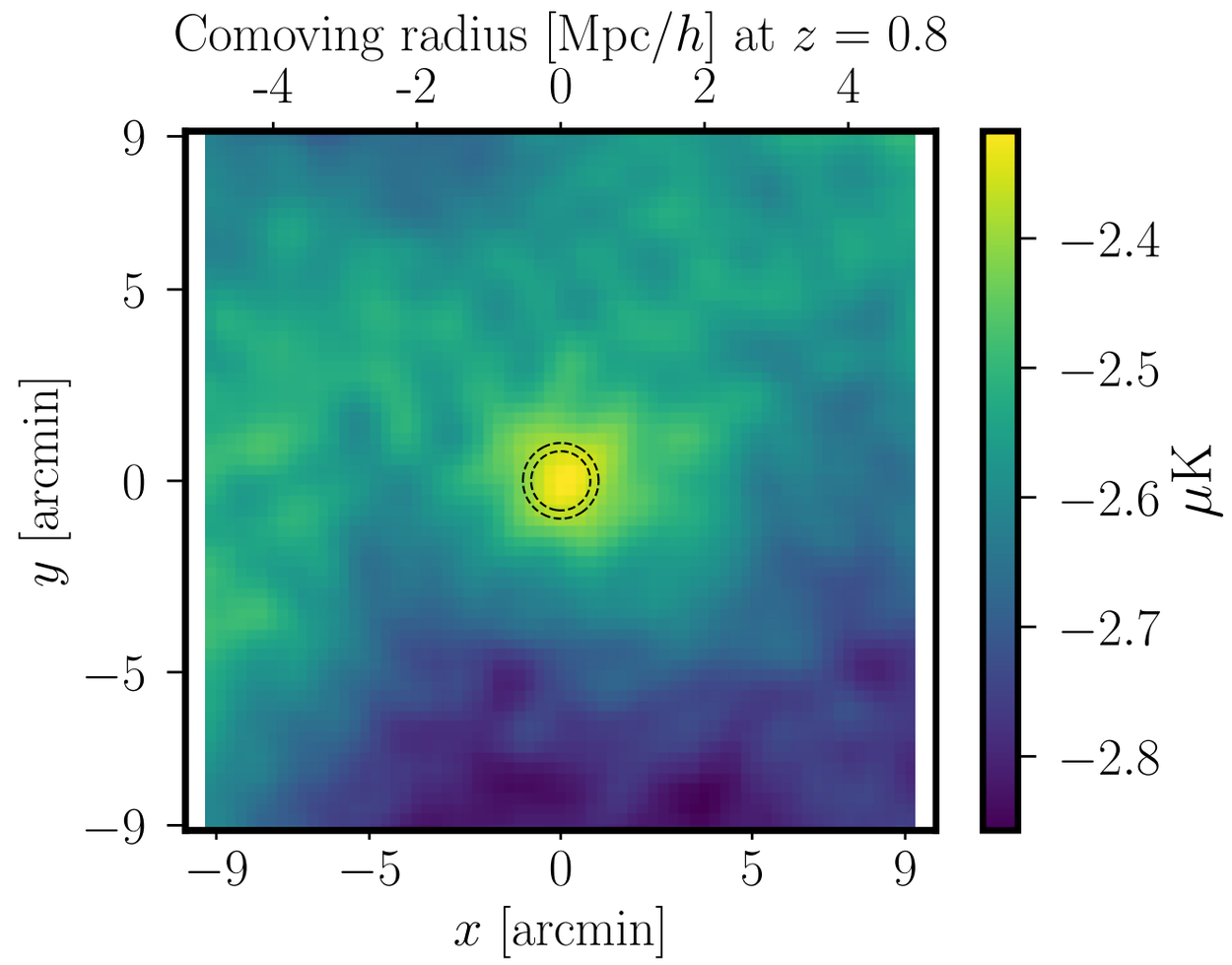




Ried Guachalla+25

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!

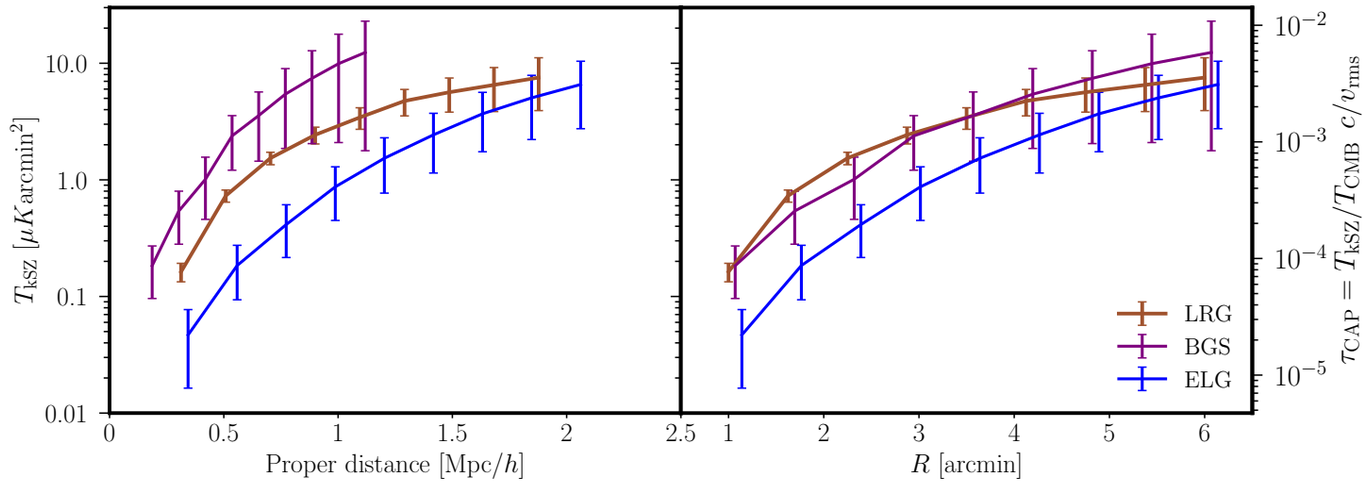
kSZ unique probe of outskirts of galaxy groups and clusters
→ Complementary with X-ray & tSZ, which probe cluster centers best

Latest stacked kSZ profiles available?

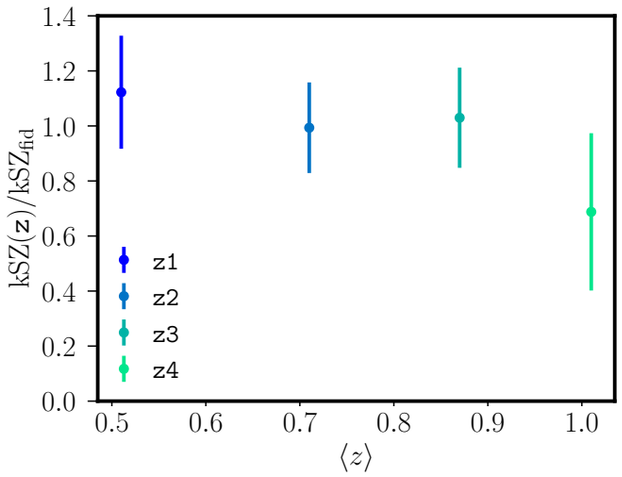
DESI LRG, BGS, ELG

spectro: *Ried Guachalla+25*

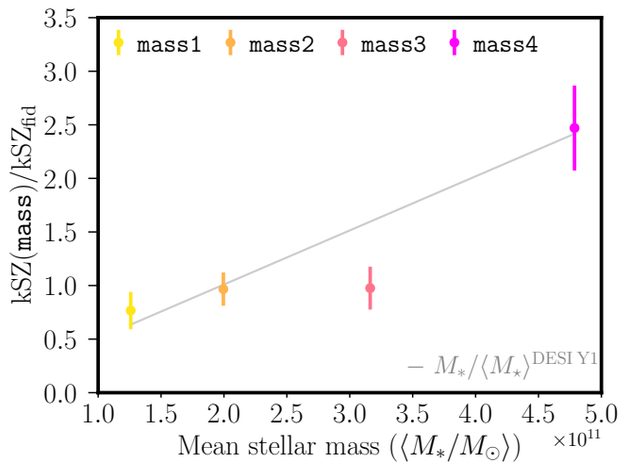
photo: *Hadzhiyska+25*



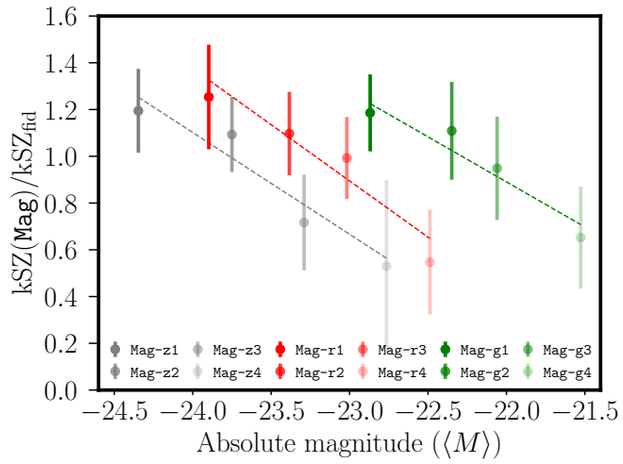
Also splits by redshift,



stellar mass,

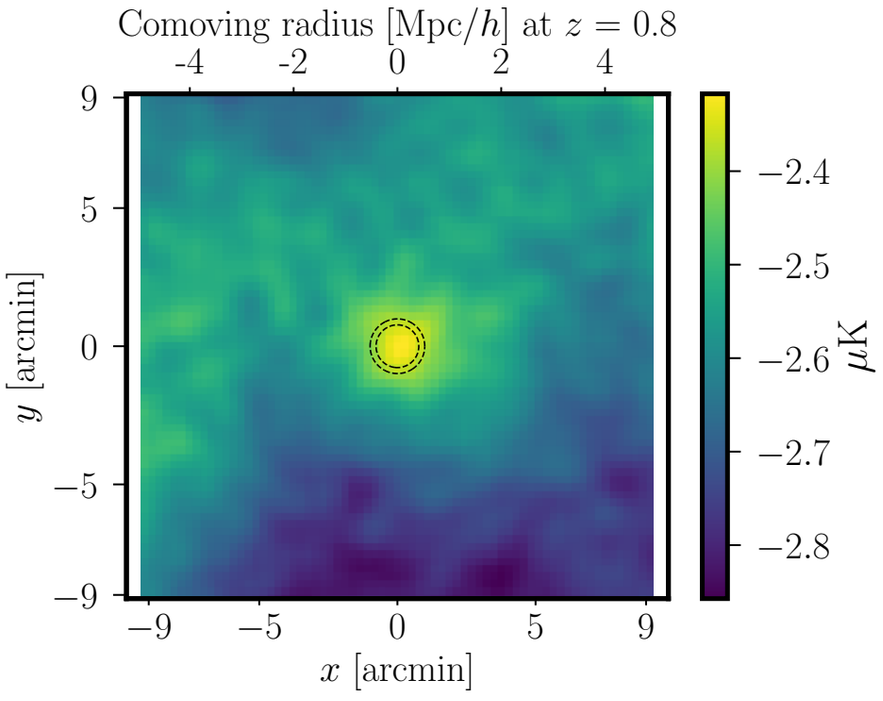


absolute magnitude



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

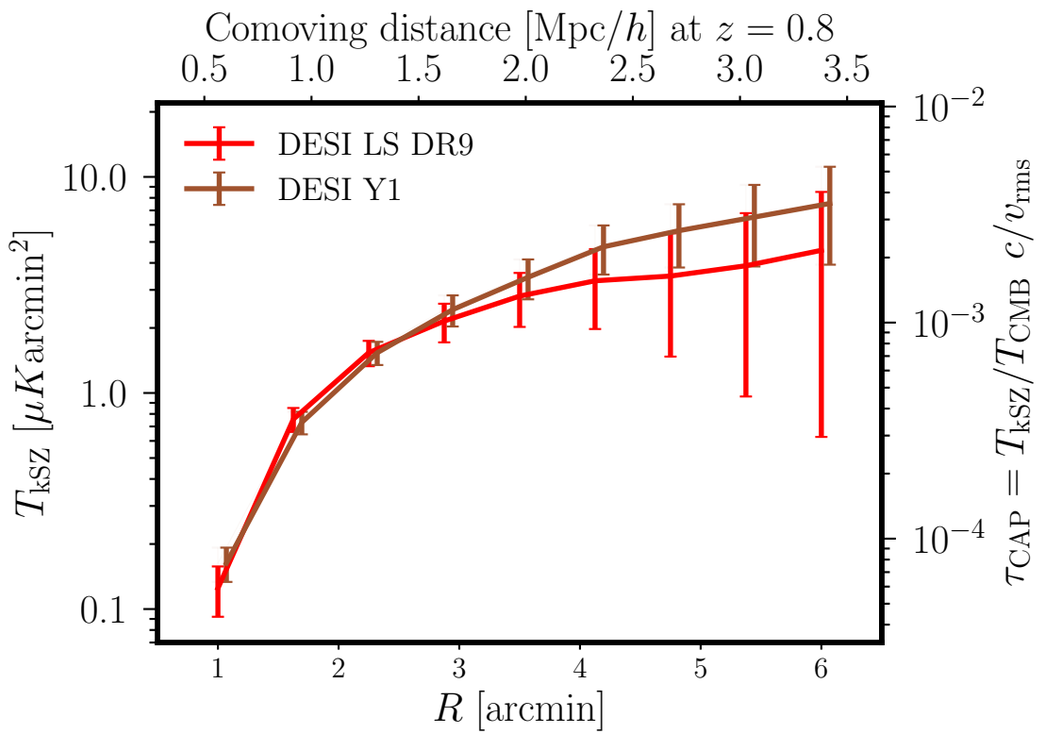
Large-scale noise: profile slope VS M_{gas}

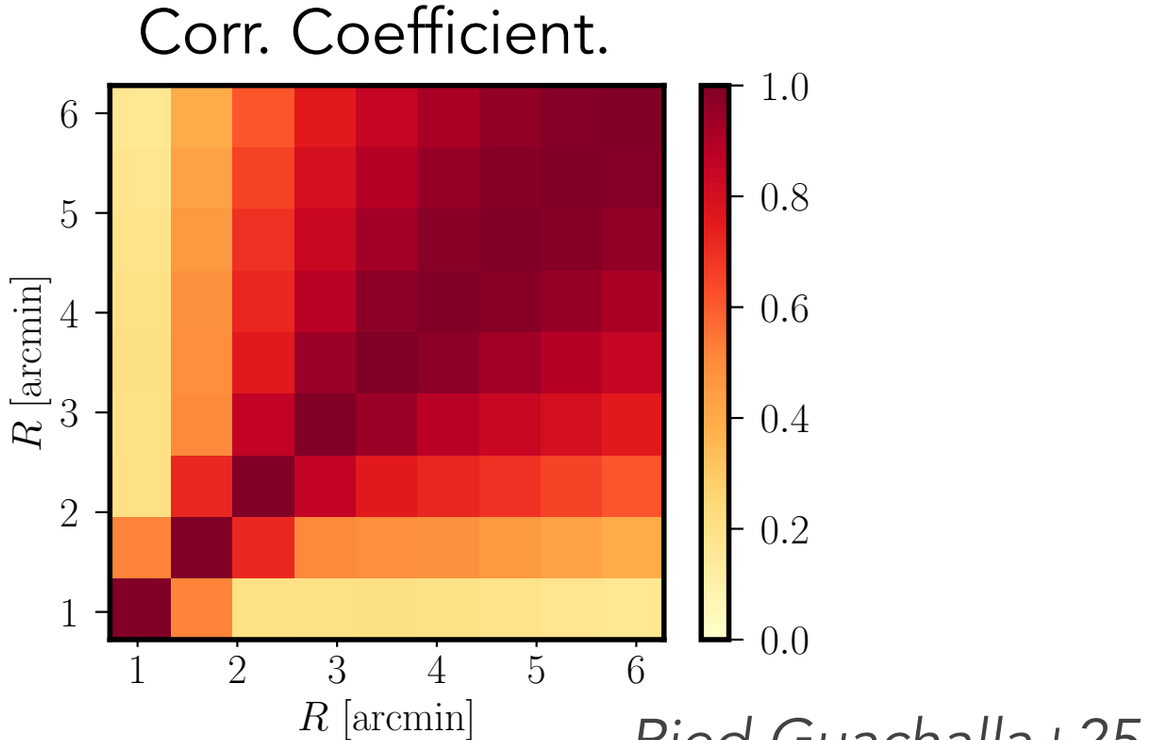


Primary CMB (~degree) dominates noise on larger scales

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

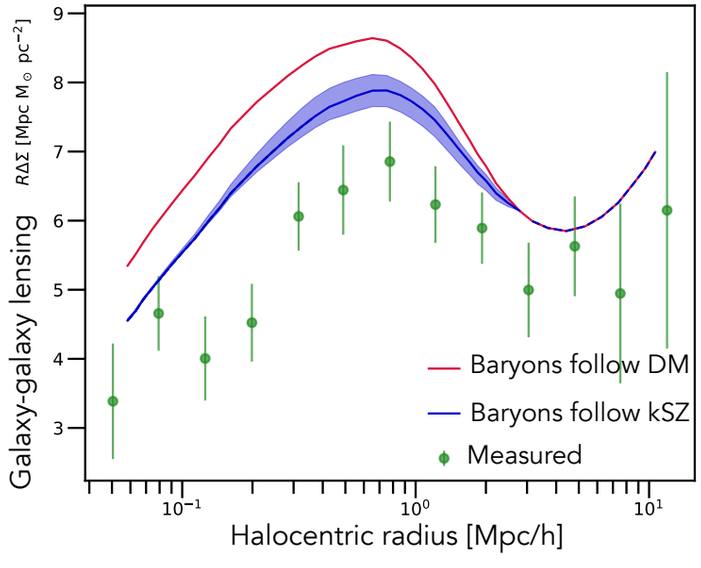
CAP filter avoids displaying constant CMB mode, but is not required.
Fourier measurements simplify this



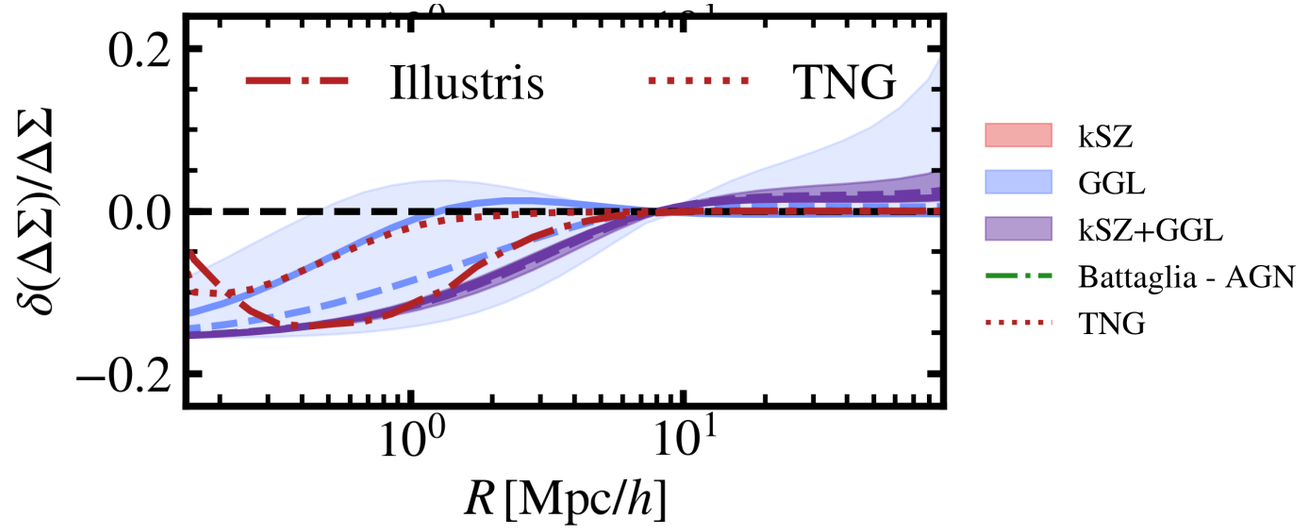


Ried Guachalla+25

kSZ is faint. Is precision enough for lensing?



Amodeo+21



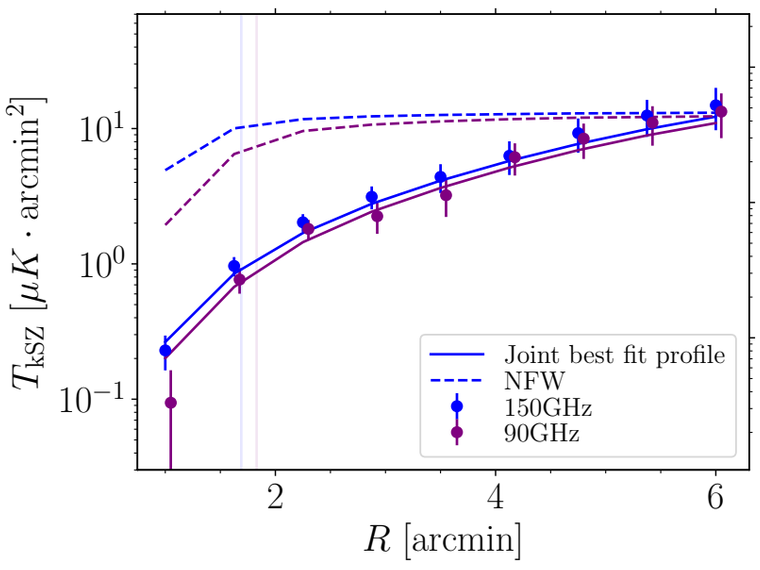
Sunseri+25

Precision already informative in 2021, now much better & improving

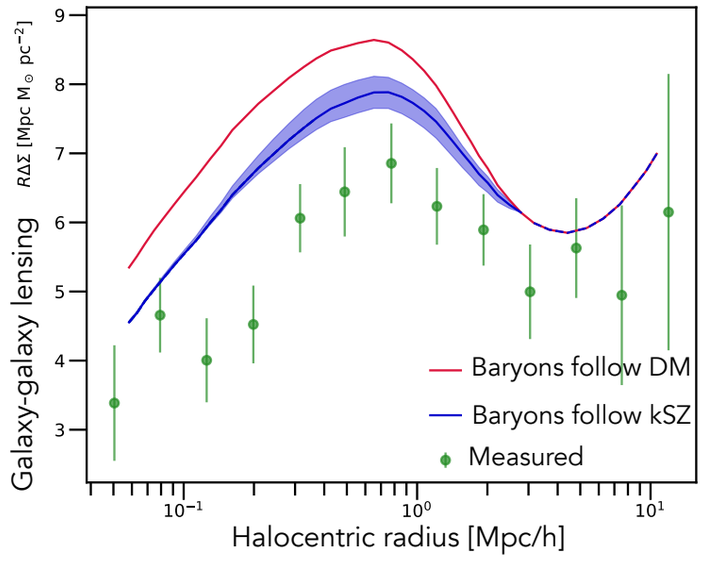
Baryons are 15% of the matter.
For 1%-precision lensing, only 7%-precision kSZ needed
→ **statistics will not be limiting**

→ **Modeling is the challenge**

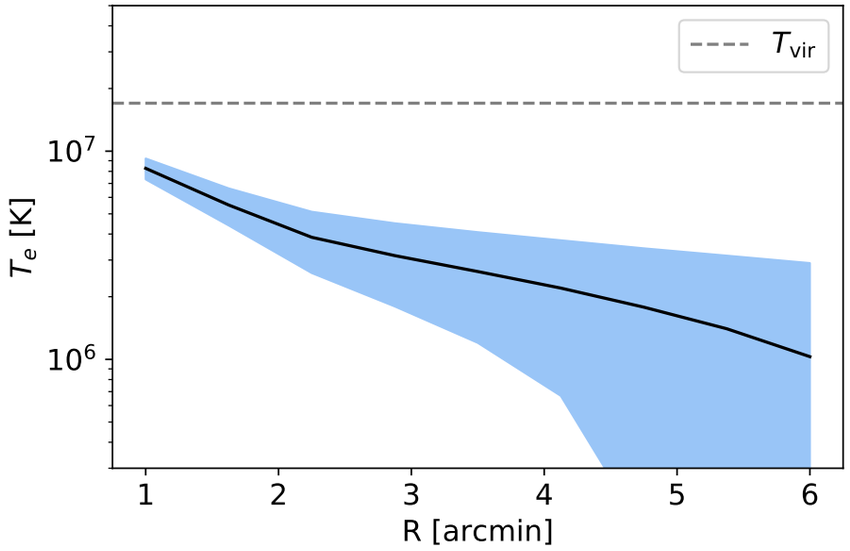
What we learned: galaxy formation & lensing



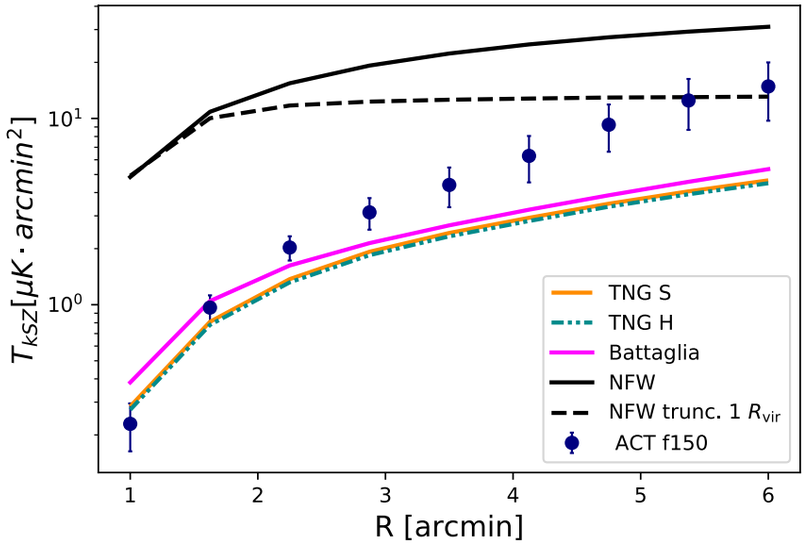
Gas is more extended than dark matter



This explains half of the low lensing tension



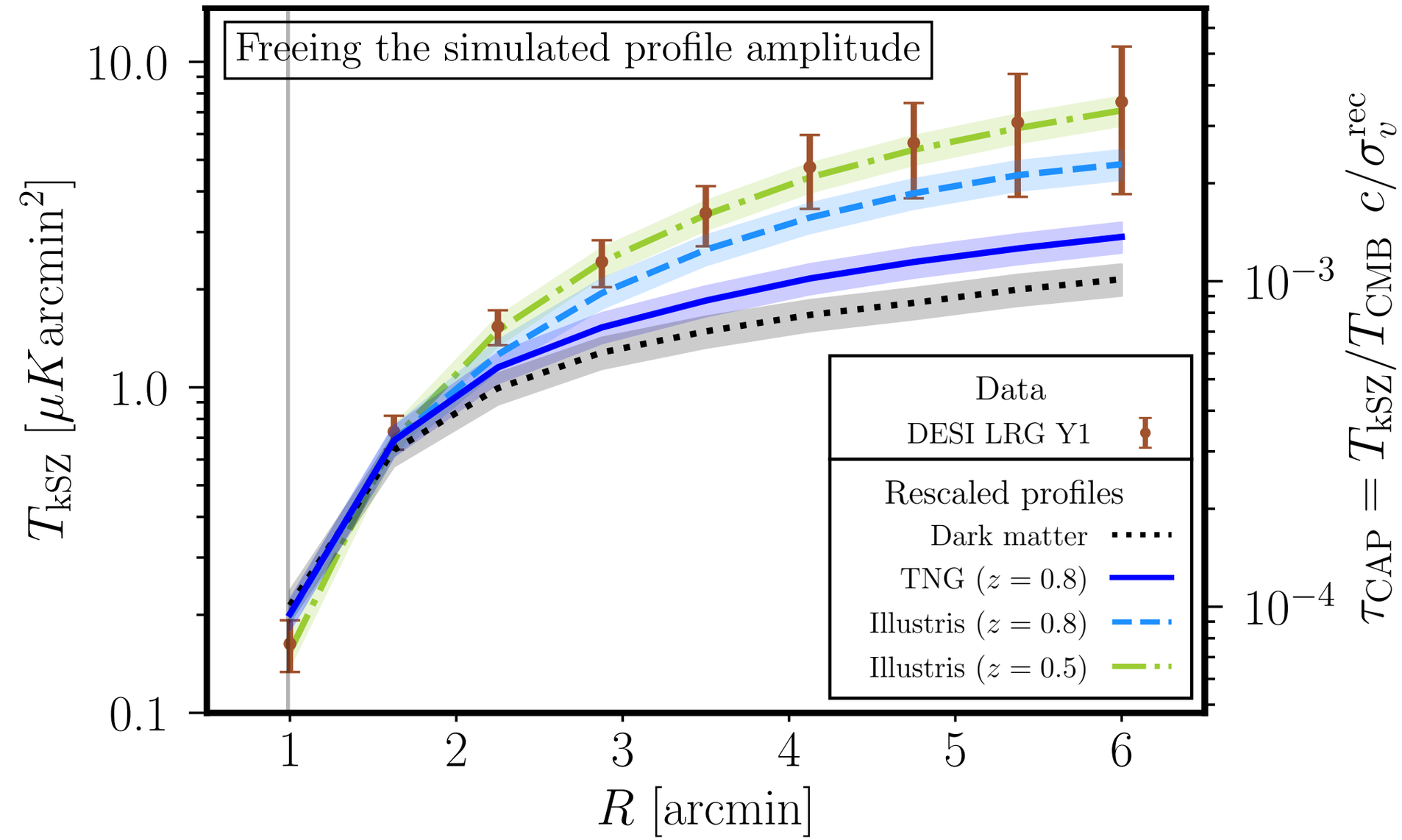
Combining kSZ & tSZ yields
the gas temperature
far outside the virial radius



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

Amodeo Battaglia Schaan Ferraro & ACT 20

Tentative conclusions on feedback

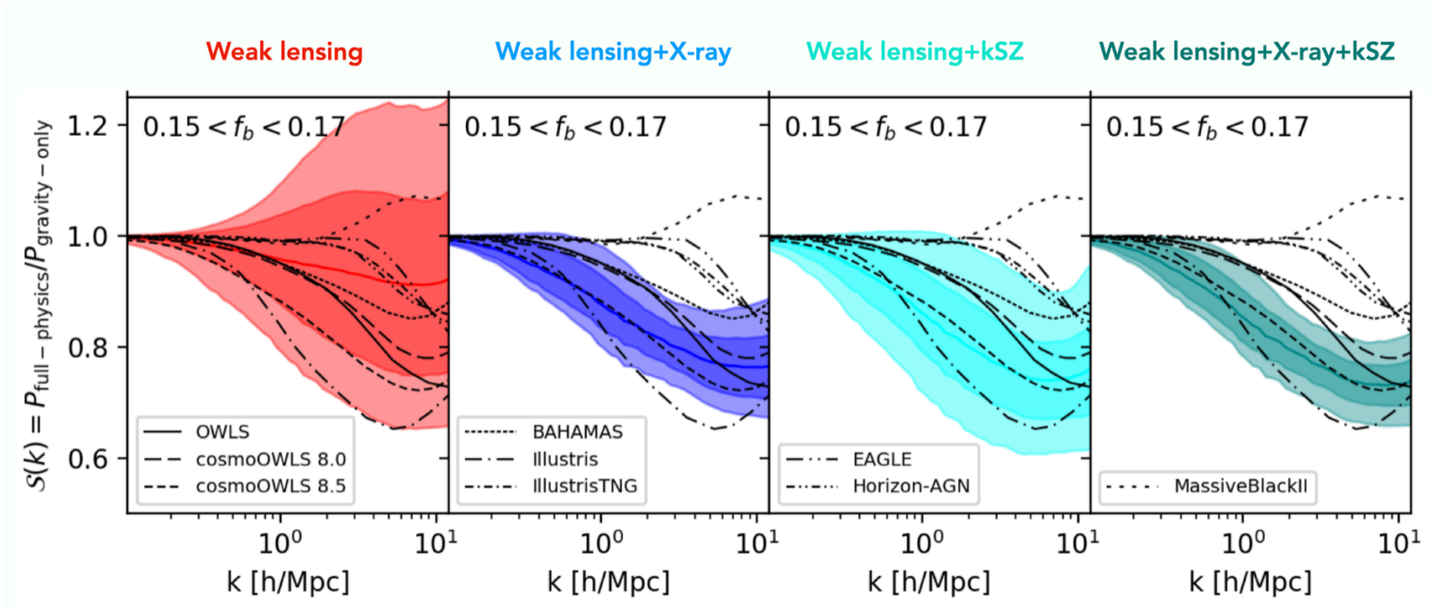


Gas appears pushed farther out than in hydro sims?

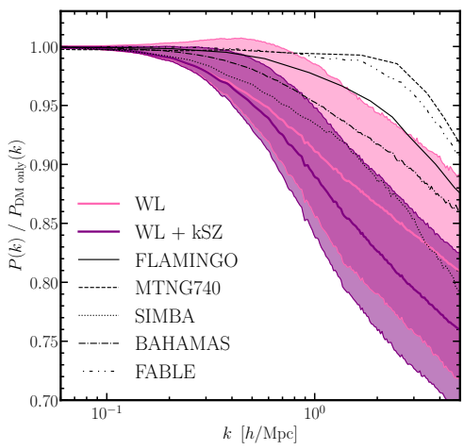
→ **Suggests large effect of feedback on gas?**

Valid *if* galaxies selected in sims match reality

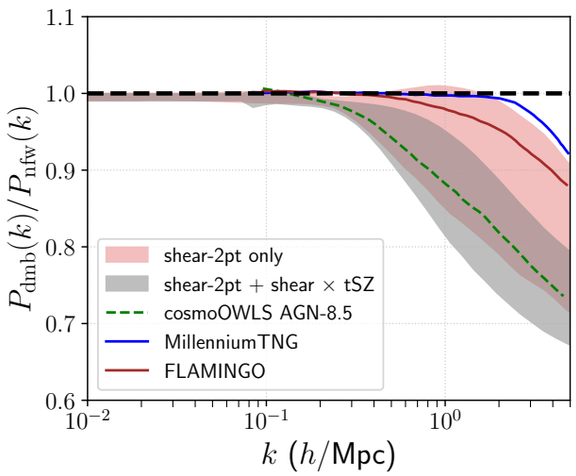
Joint analyses: lensing + baryon info



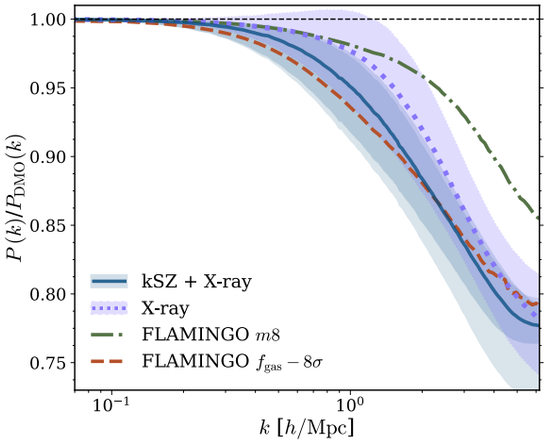
Cosmic shear & "baryons"
Schneider+22



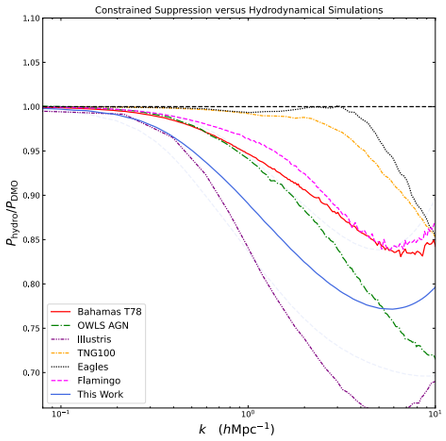
Cosmic shear & kSZ
Bigwood+24, 25



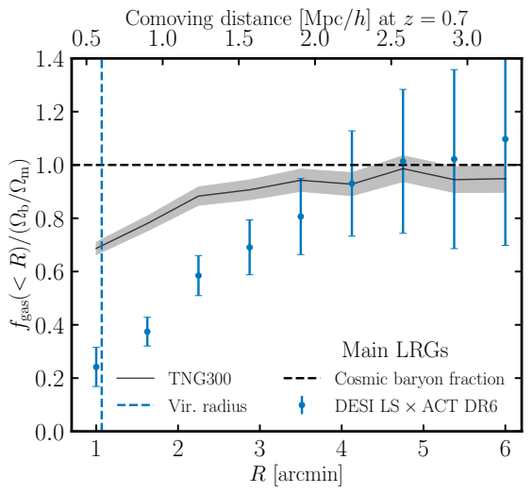
Cosmic shear & shear x tSZ
Pandey+25



kSZ & X-ray
Kovac+25

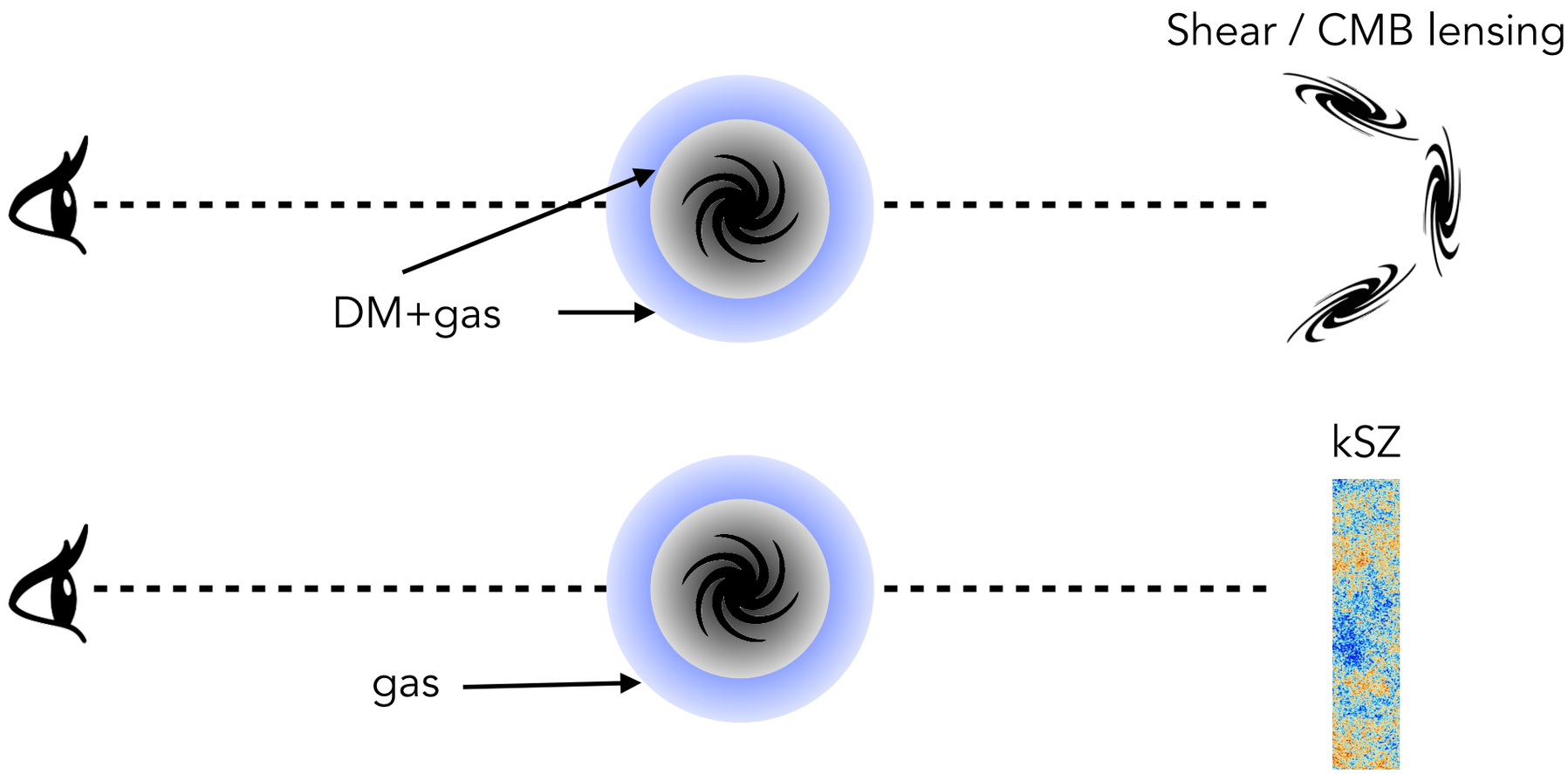


cluster tSZ & cluster lensing
Dalal+25



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)*

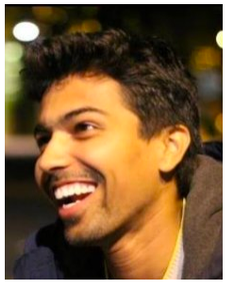
Universality of matter power suppression? (*Van Daalen+20, Joop's talk*)
→ would help!

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

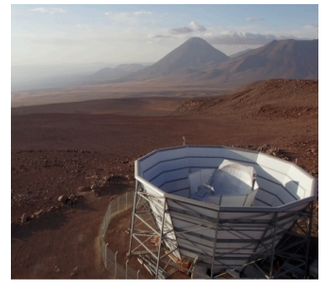
Great progress being made in modeling
Bigwood+24, Sunseri+25, McCarthy+25

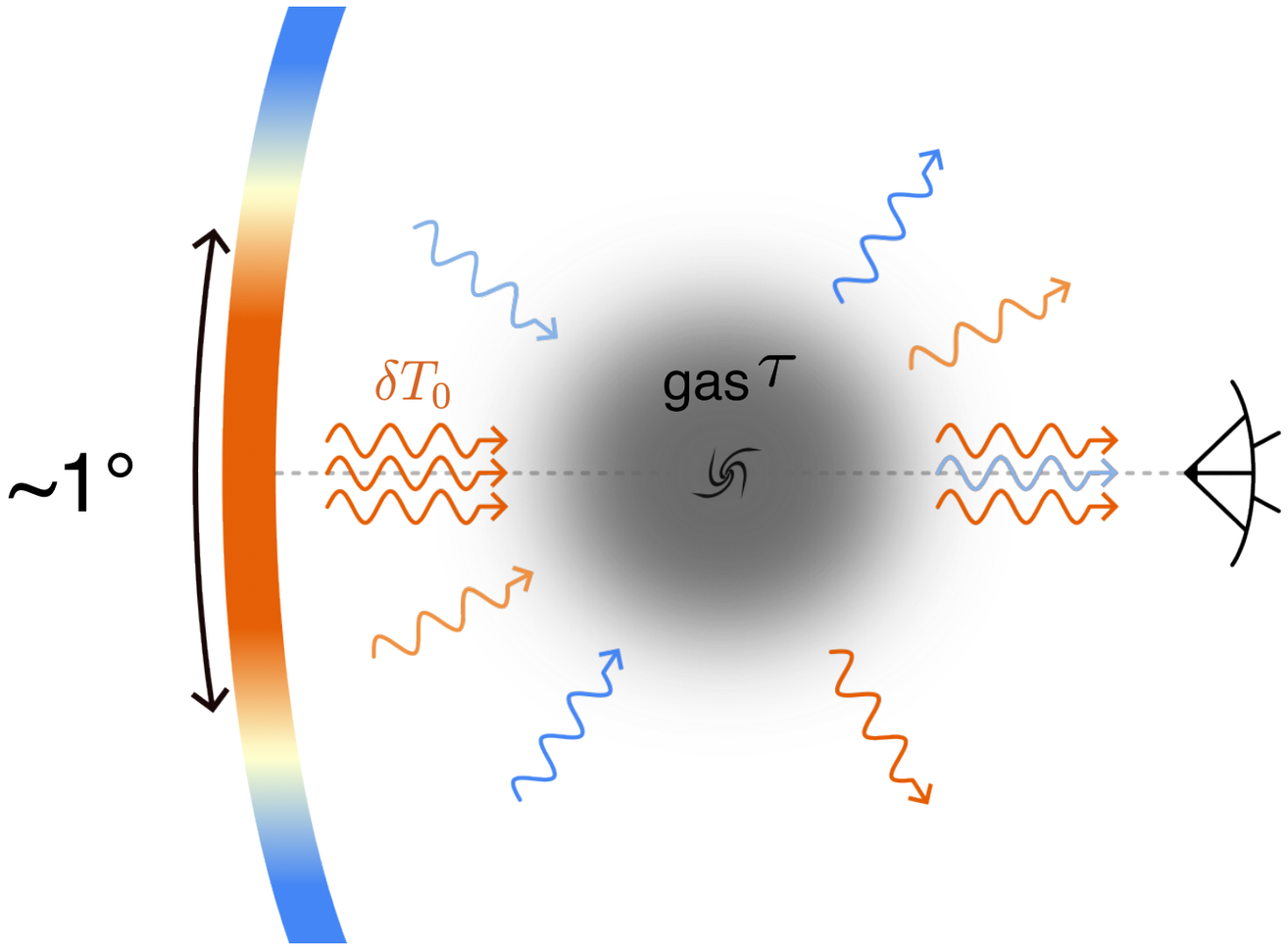
CMB Screening by ionized gas around galaxies

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







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

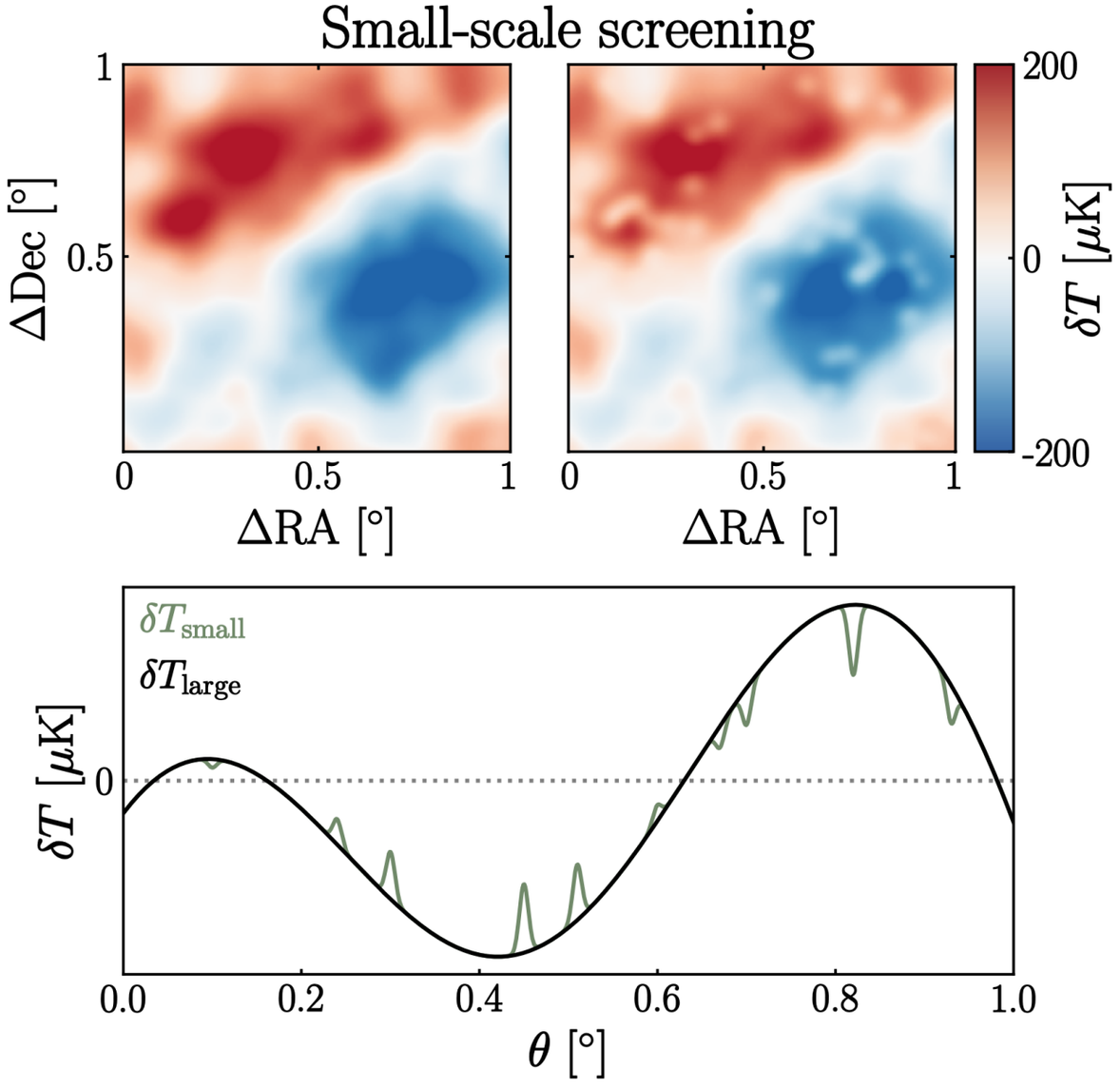
$$\delta T_{\rm obs} = \delta T_{\rm true}\ e^{-\tau}$$

→ Probes diffuse gas around galaxies

Schutt Maniyar Schaan Coulton Mishra 24, Coulton Schutt Maniyar Schaan & ACT 24
Hadzhiyska Sailer Ferraro 25, Sailer Hadzhiyska Ferraro 25

CMB Screening by ionized gas around galaxies

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



Screening changes sign with primary temperature

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

Horowitz Ferraro Sherwin 19, Hadzhiyska Sherwin Madhavacheril Ferraro 19

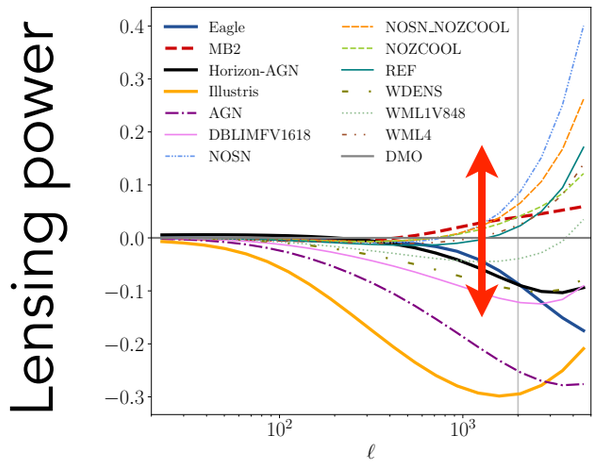
$$\hat{\tau}^{\rm TI}(\boldsymbol{x}) = -\frac{\widehat{\delta T}_{\rm small}(\boldsymbol{x})}{\widehat{\delta T}_{\rm large}(\boldsymbol{x})}$$

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

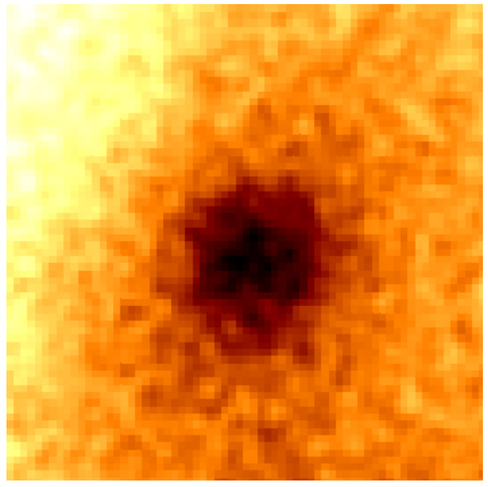
Hadzhiyska Sailer Ferraro 25
Sailer Hadzhiyska Ferraro 25

Schutt Maniyar Schaan Coulton Mishra 24
Coulton Schutt Maniyar Schaan & ACT 24

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!