SLAC NATIONAL ACCELERATOR LABORATORY

Emmanuel Schaan

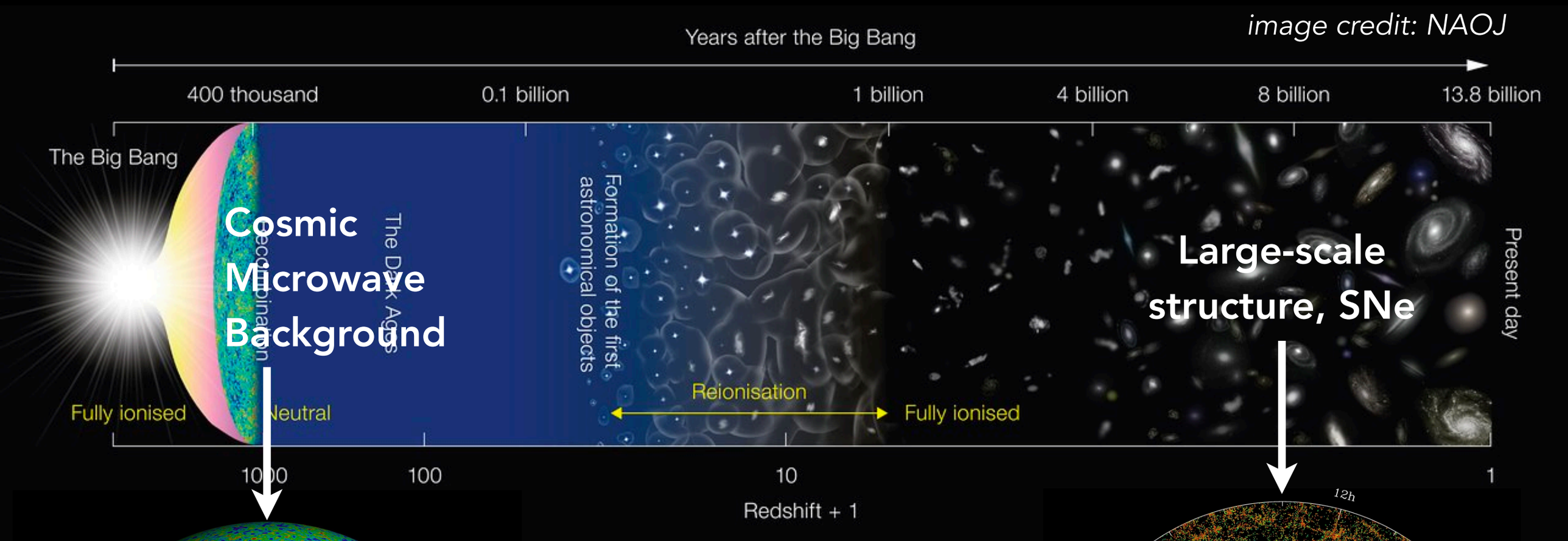
Backlighting the Universe

with the Cosmic Microwave Background

Kristina Armitage

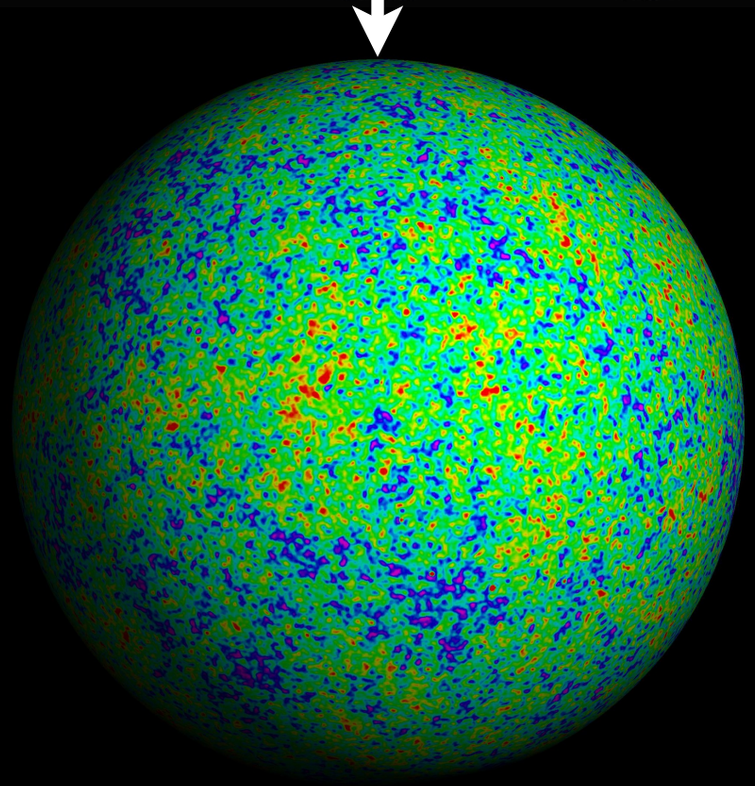
The Universe as a fundamental Physics laboratory

image credit: NAOJ

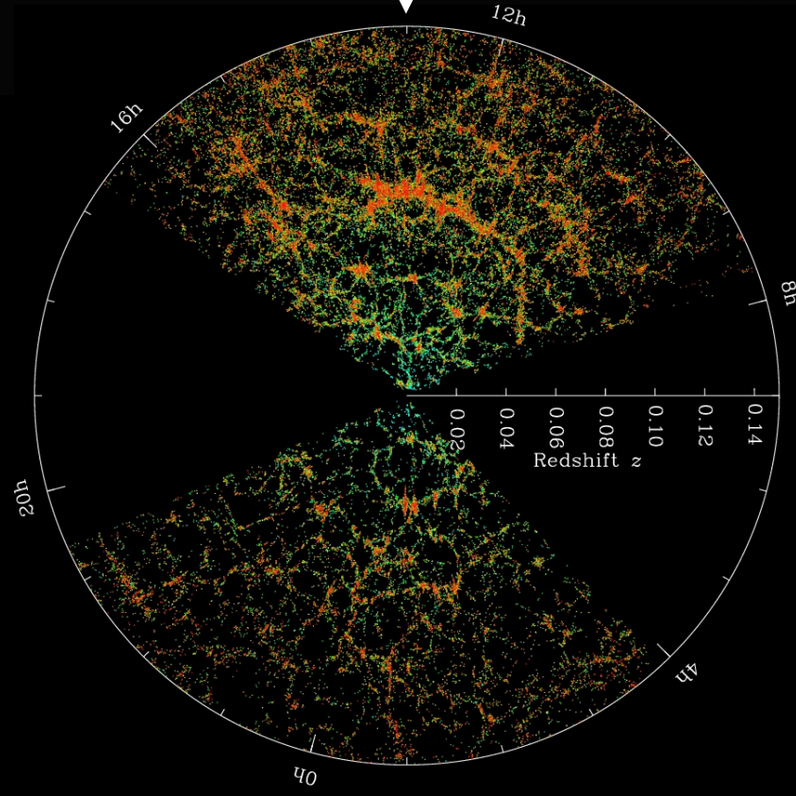


Cosmic Microwave Background

Large-scale structure, SNe



Tegmark, WMAP3



Blanton, SDSS

Dark energy

Energy density, equation of state?

Dark matter

Interactions, temperature?

Inflation

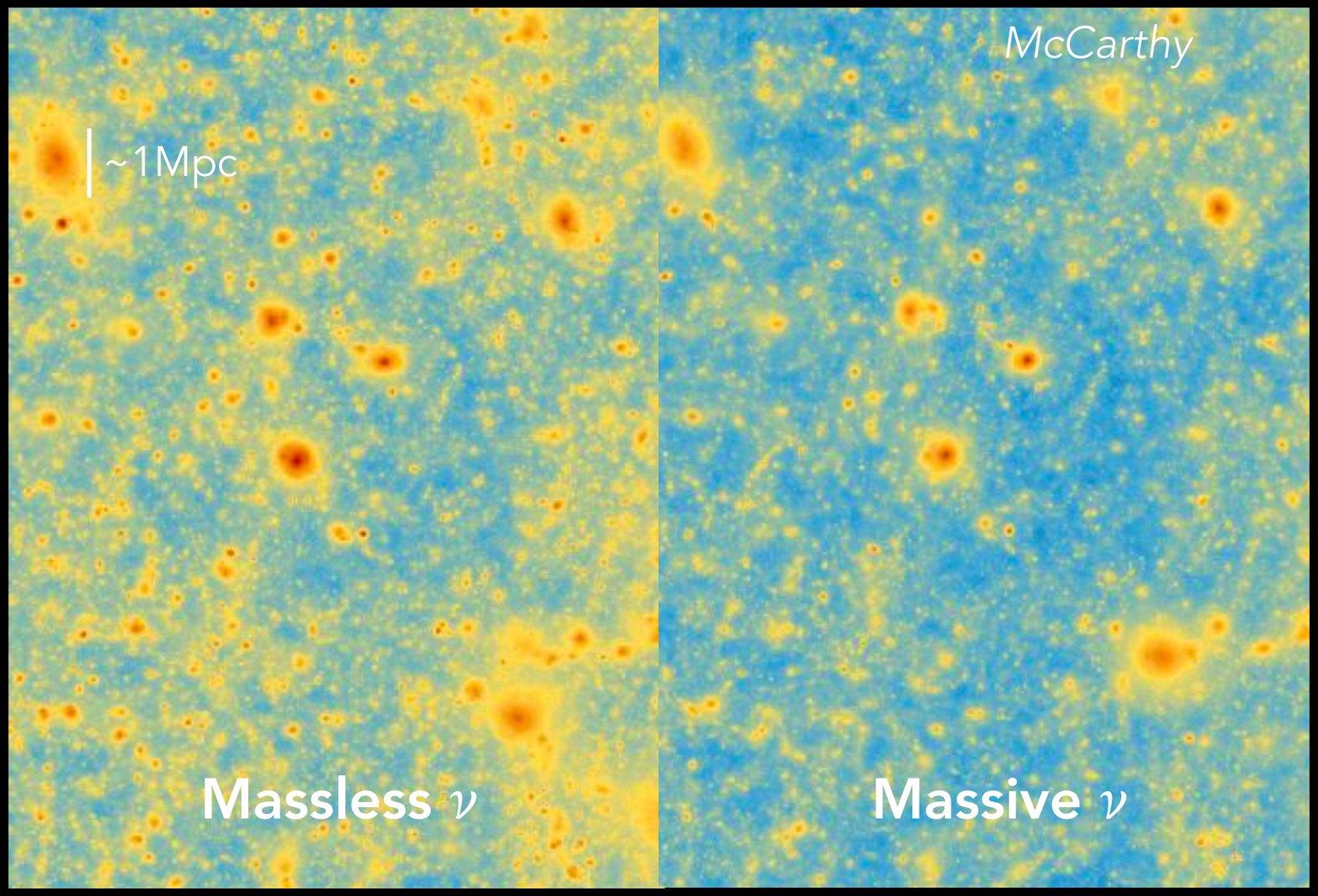
Number of fields, interactions, energy scale?

Neutrinos

Masses? Hierarchy? Dirac/Majorana? Additional sterile neutrinos? CP phase?

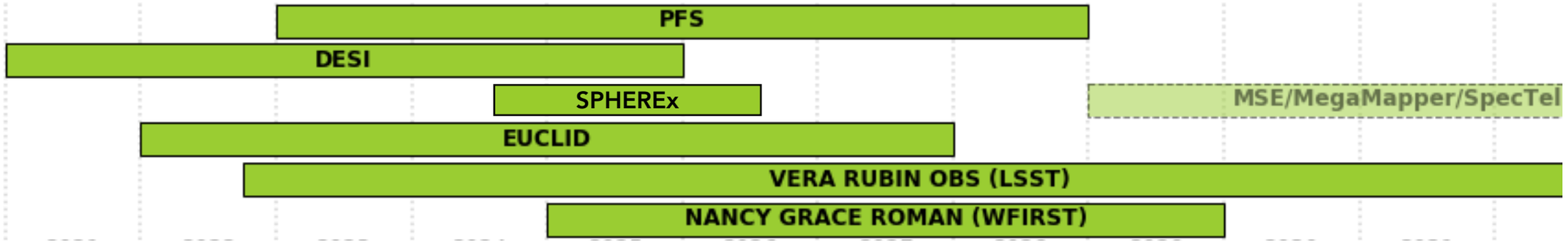
Cosmology can weigh the neutrinos

Neutrinos = 0.5% of all matter, but their gravity suppresses LSS 8-fold = 4%

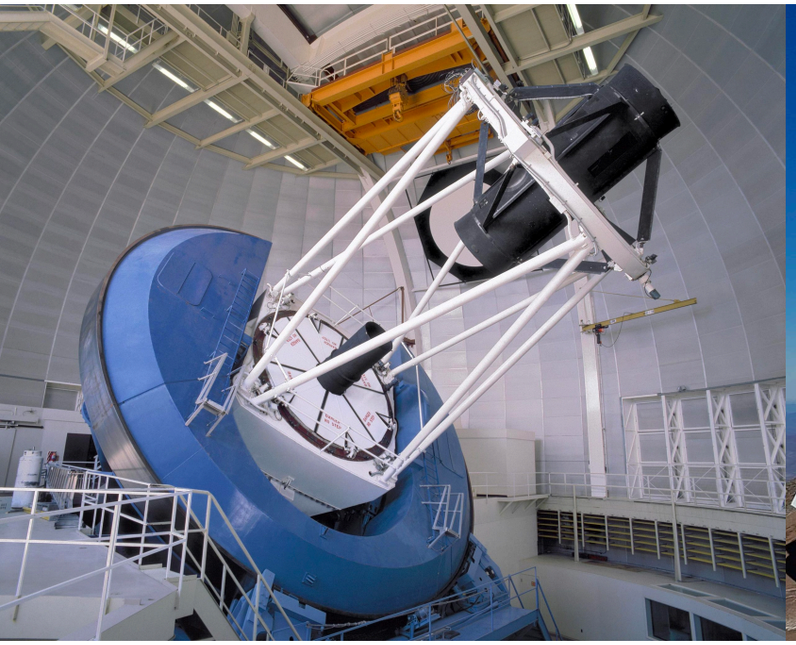


→ CMB & LSS: masses to ~ 20 meV precision

Why now? LSS experiments are probing dark matter, dark energy, neutrinos & the Universe's initial conditions

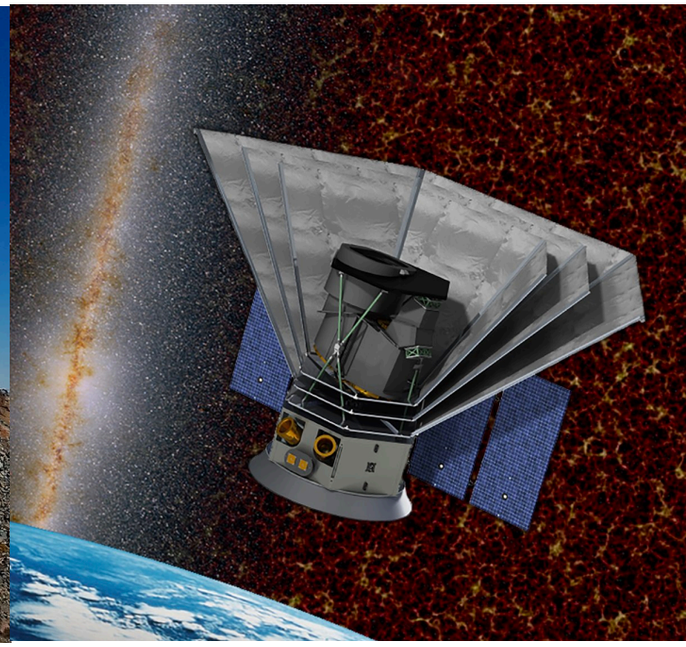


Kirkby



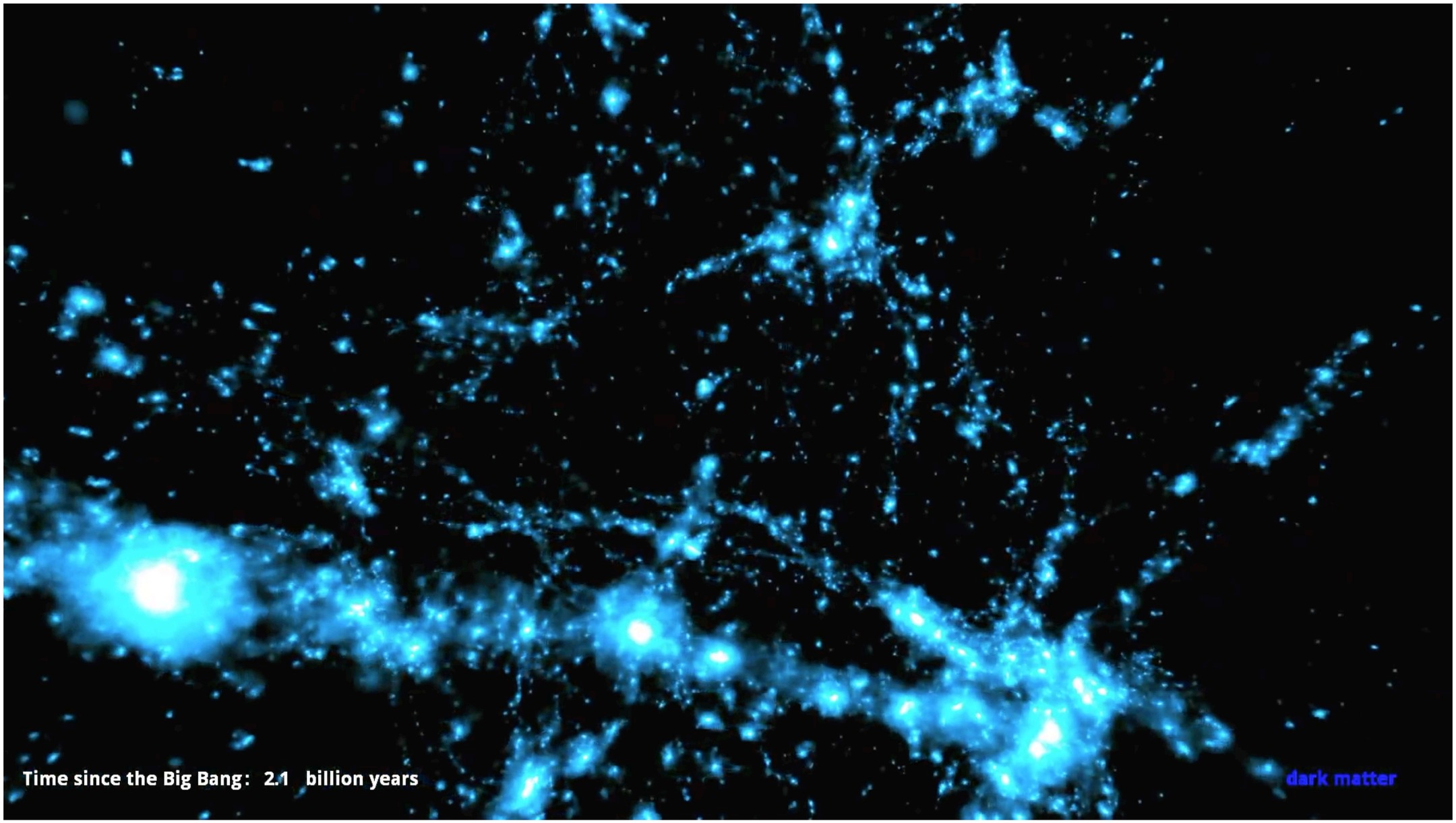
Dark Energy Spectroscopic Instrument

Vera Rubin Observatory LSST



SPHEREx

Why care about baryons? Cosmology & Galaxy formation



Illustris

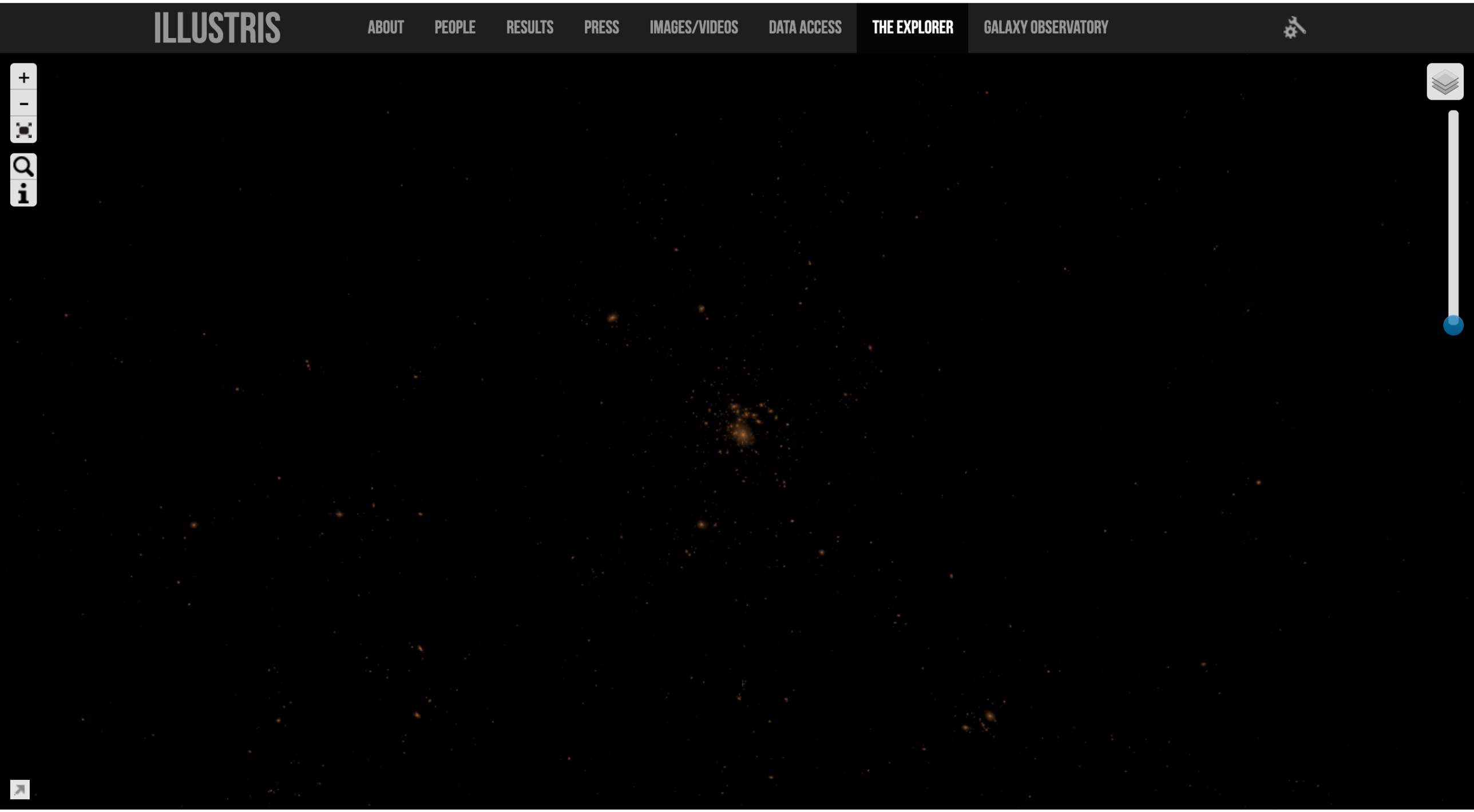
Supernovae and supermassive black holes regulate galaxy formation

Unknown feedback amplitude

→ **Missing "baryon problem"**

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

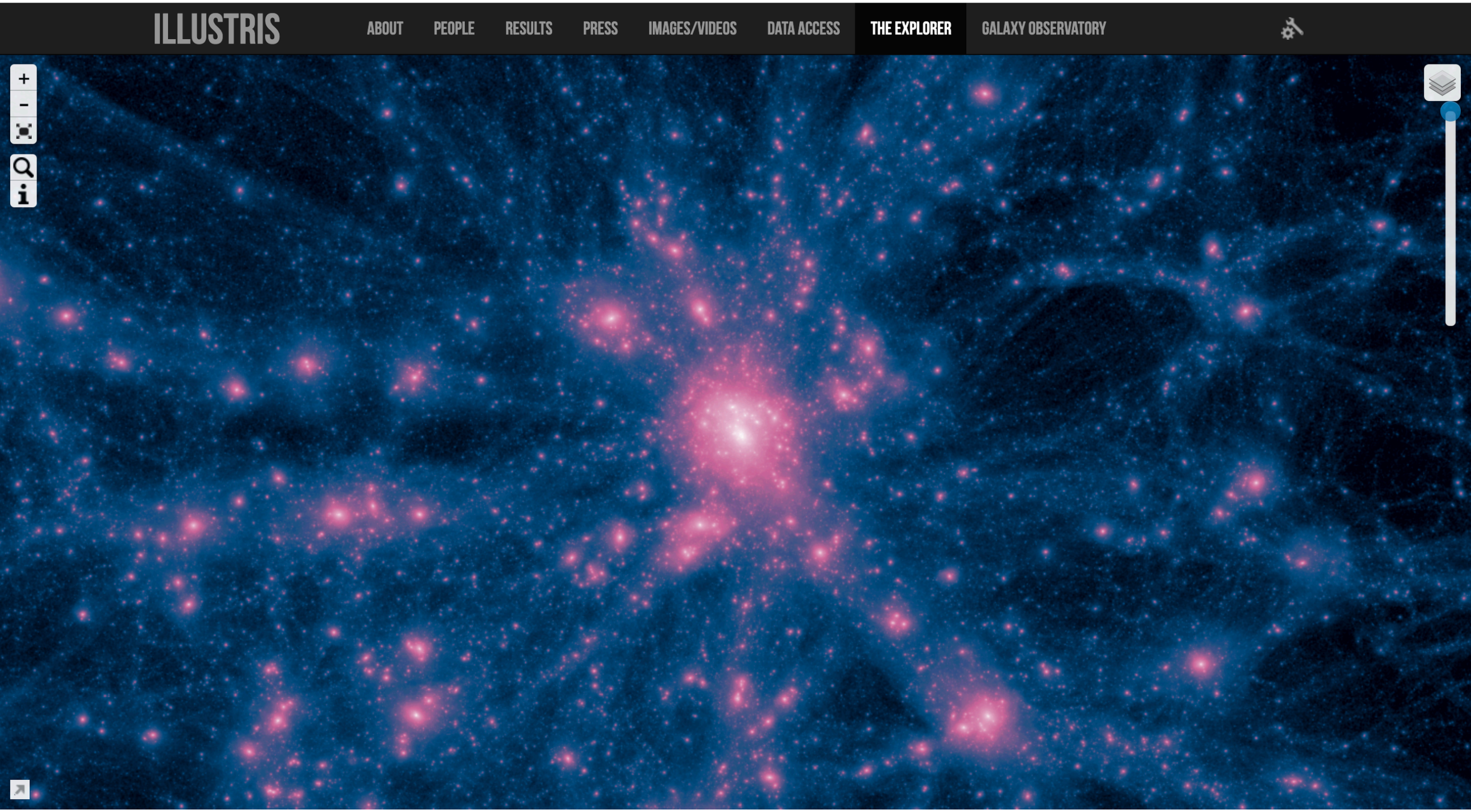
Light is a biased tracer of the mass



Starlight

Illustris simulation explorer

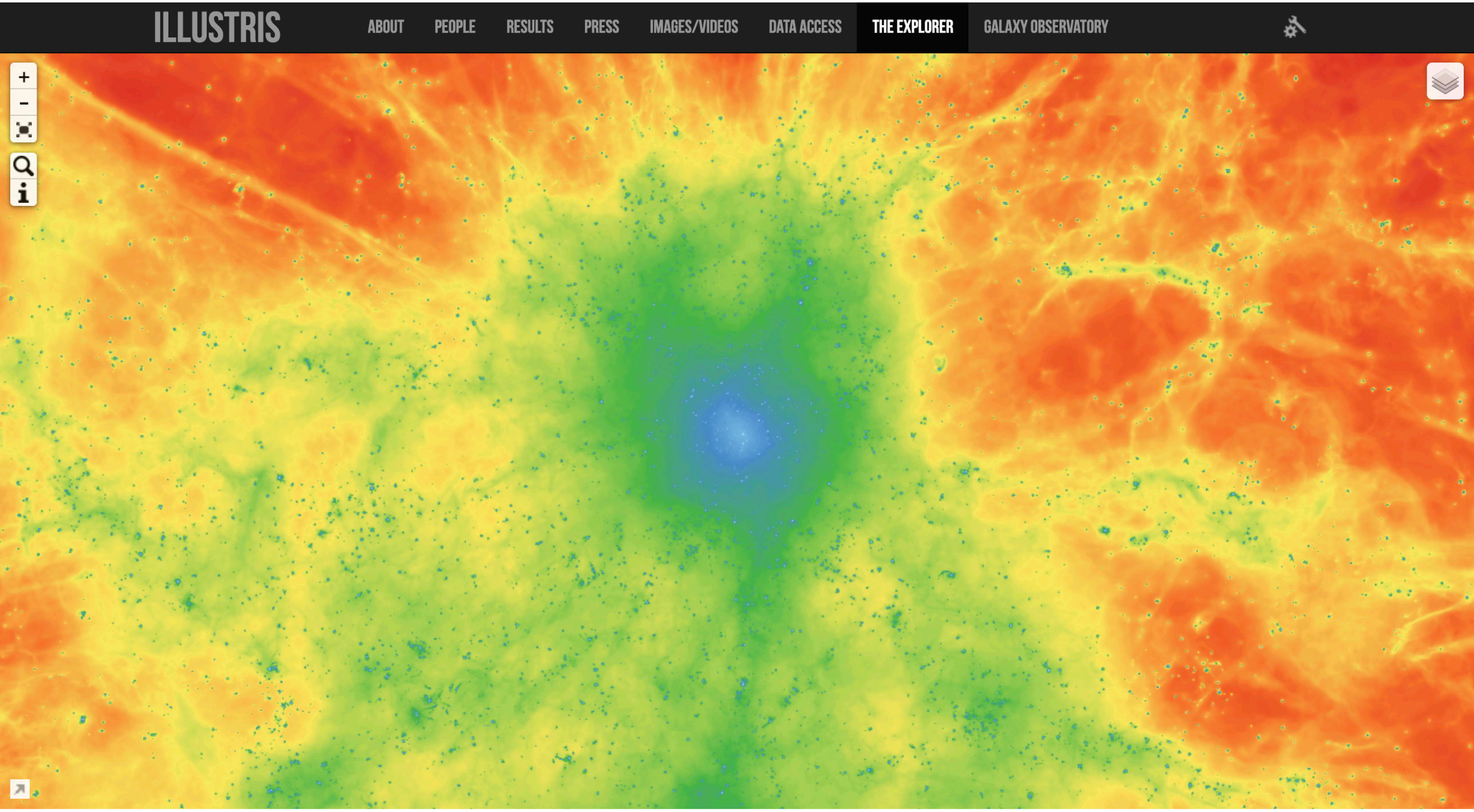
Light is a biased tracer of the mass



Starlight, dark matter

Illustris simulation explorer

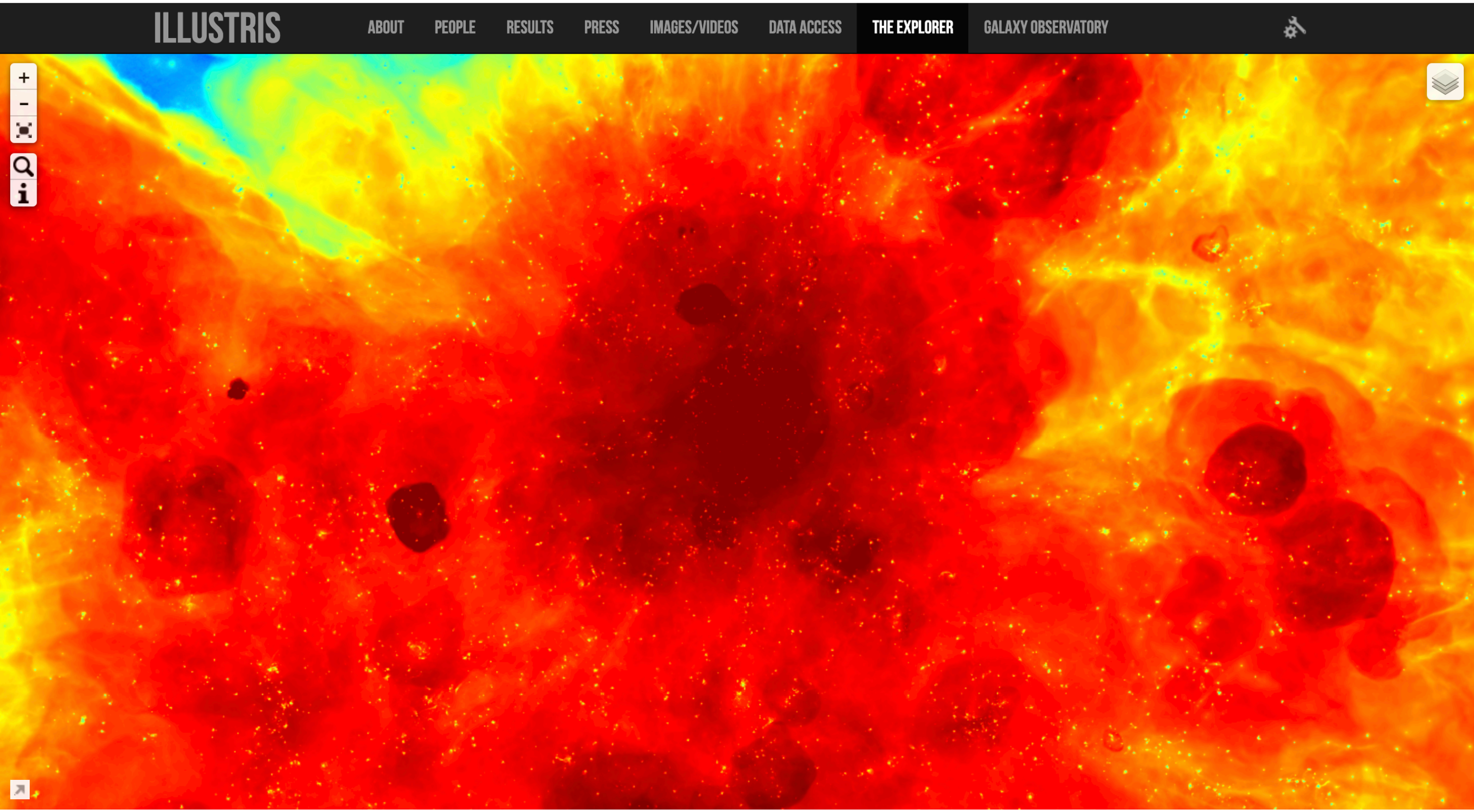
Light is a biased tracer of the mass



Starlight, dark matter, gas density

Illustris simulation explorer

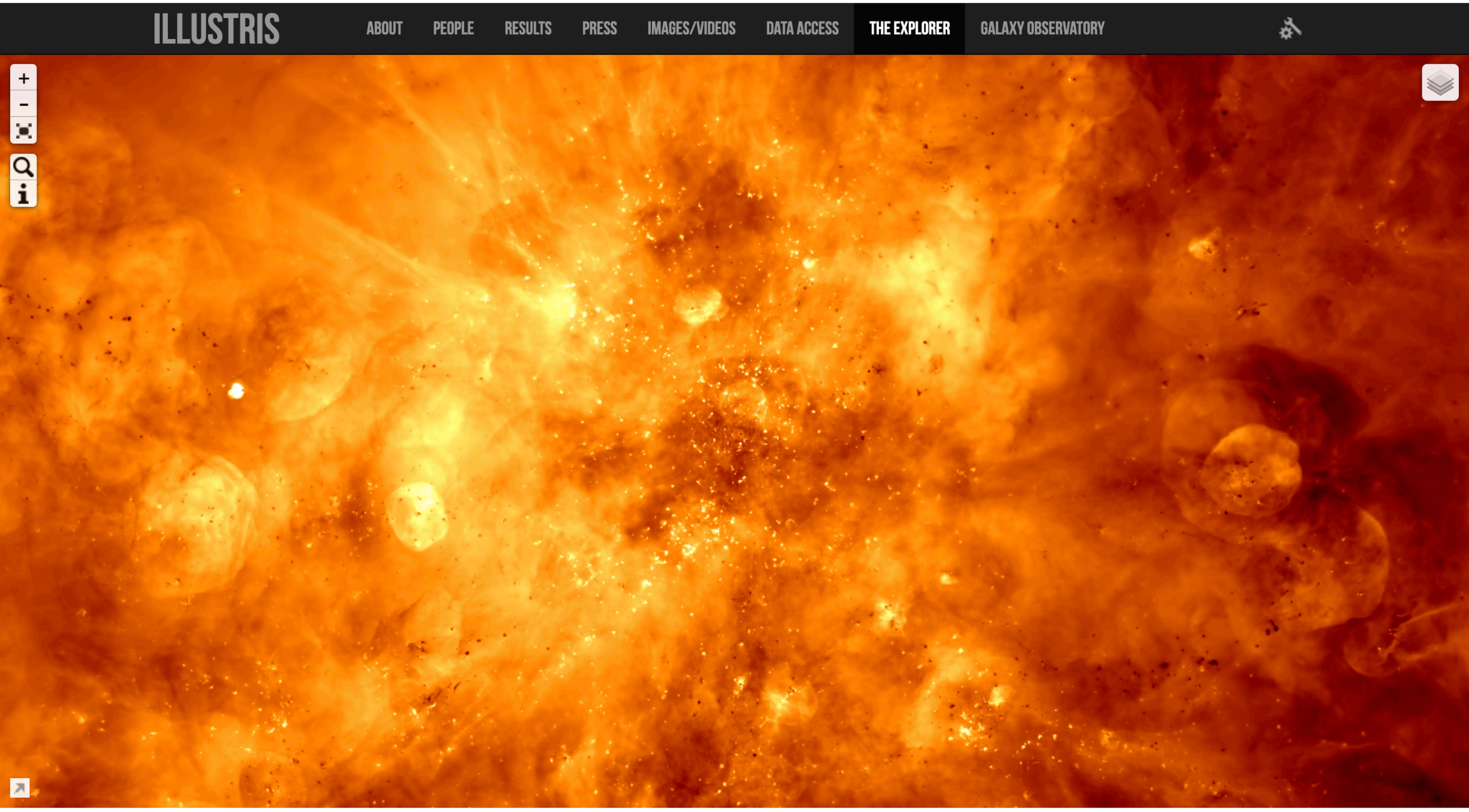
Light is a biased tracer of the mass



Starlight, dark matter, gas density, temperature

Illustris simulation explorer

Light is a biased tracer of the mass



Starlight, dark matter, gas density, temperature, velocity

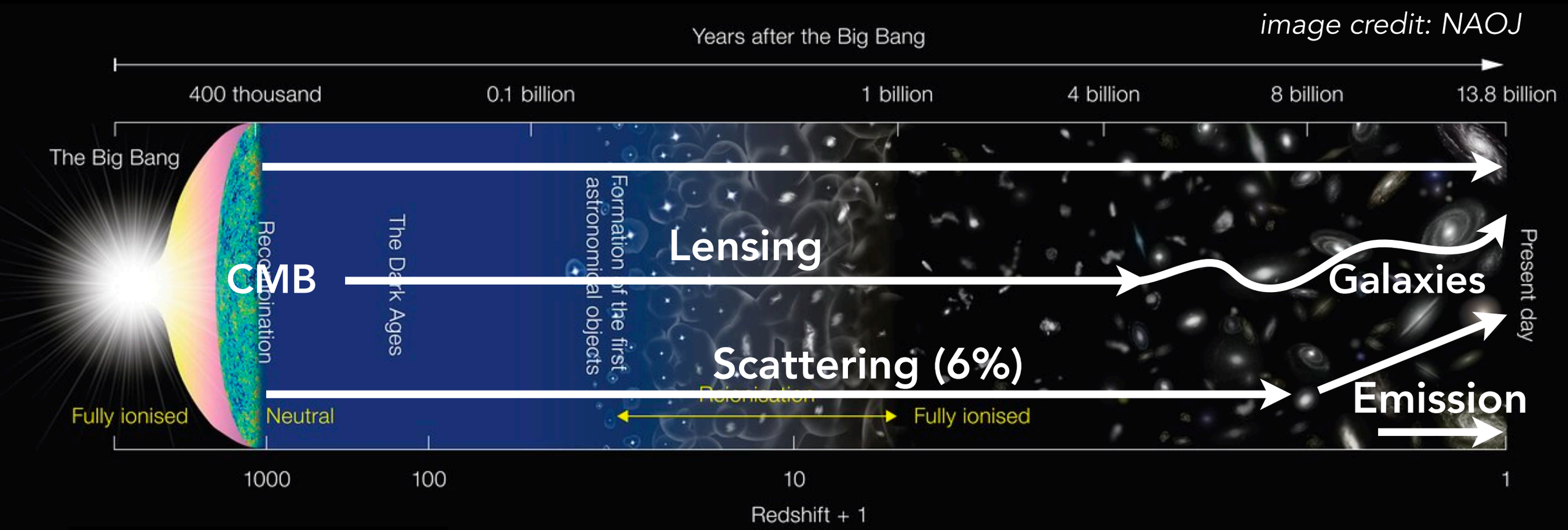
Illustris simulation explorer

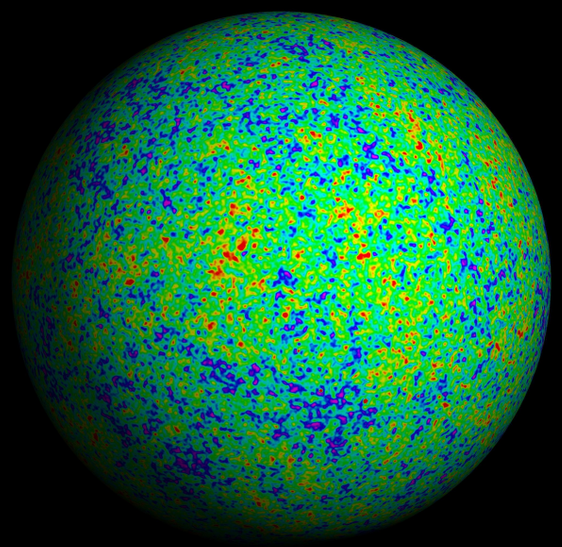
Milky way
(our own galaxy)

Andromeda galaxy

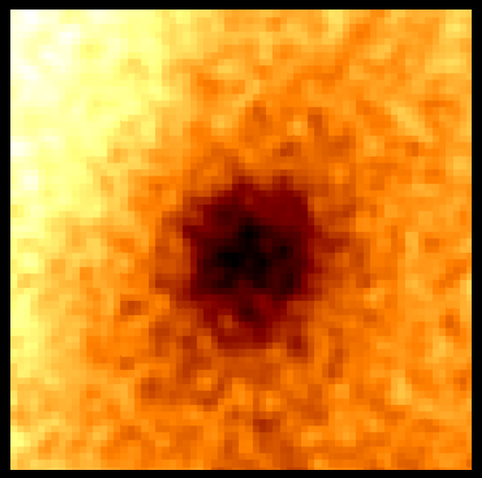
NASA, ESA, DePasquale, Wheatley, Levay: QSO absorption lines

Backlighting the galaxies with the CMB

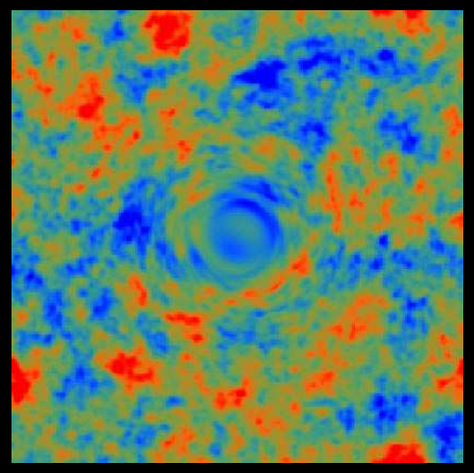




Initial conditions



Scattering:
Gas shadows



Lensing:
Mass shadows

Summary of CMB secondaries

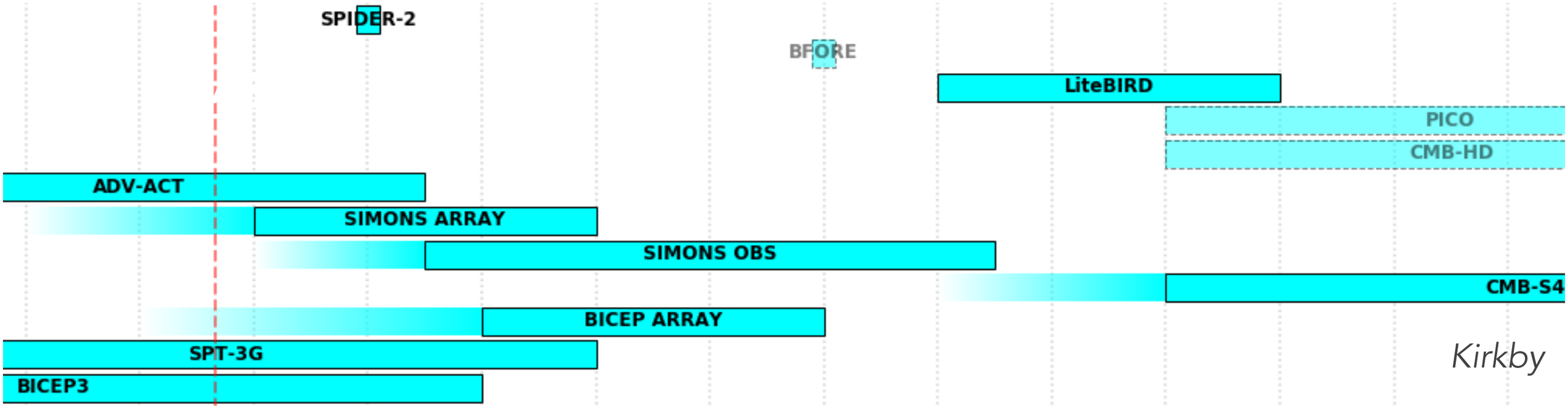
Key parameters:

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

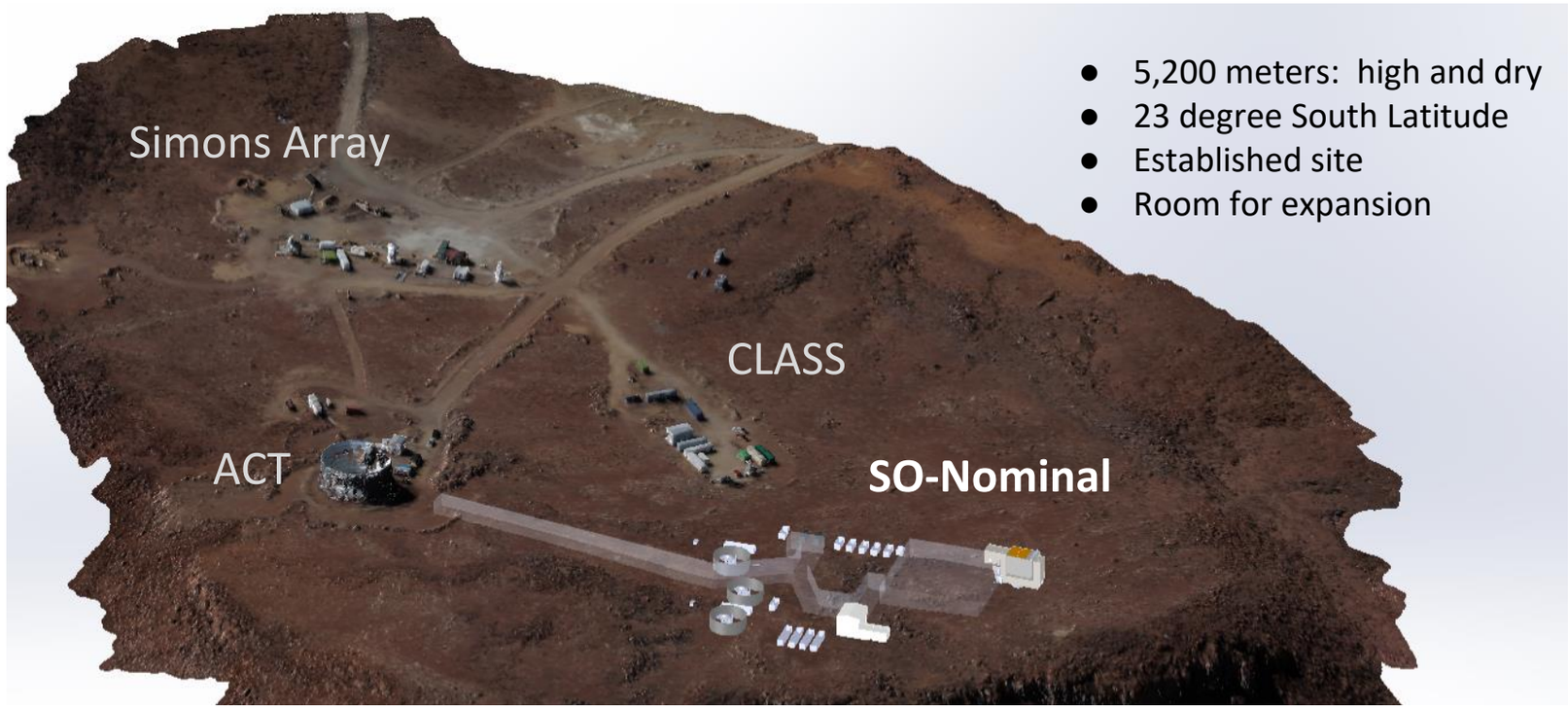
→ Many imprints with complementary information :

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?

Why now? High-res high-sensitivity CMB experiments



Kirkby

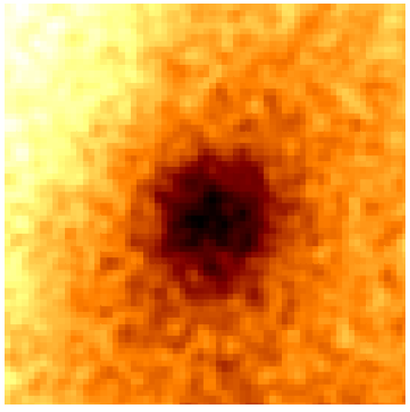


SO Science goals and forecasts 19
Lee+20

Growing interest in the CMB

Outline: Combining CMB & LSS

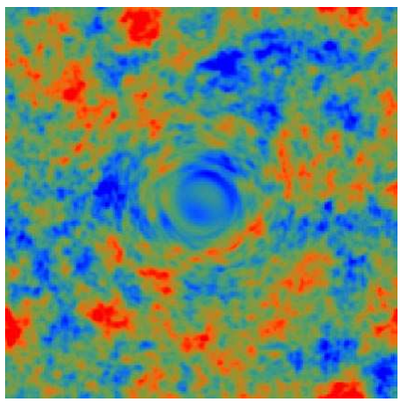
Gas shadows

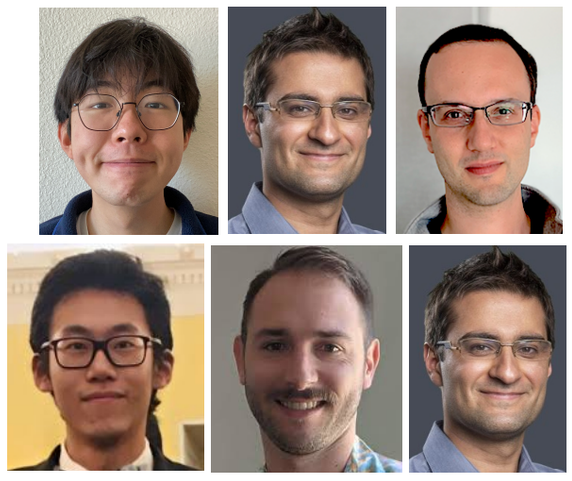


ACT x DESI kSZ & tSZ

Hadzhiyska+23, 24
RiedGuachalla+23, 25
Liu+24

Mass shadows





CMB lensing noise bias avoidance

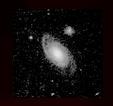
Shen Schaan Ferraro 23

Bayesian lensing bias

from polarized extragalactic foregrounds

Qu Millea Schaan 24

Gas shadows:
Localize the missing baryons



Missing baryon “opportunity”: Cosmology & Galaxy formation

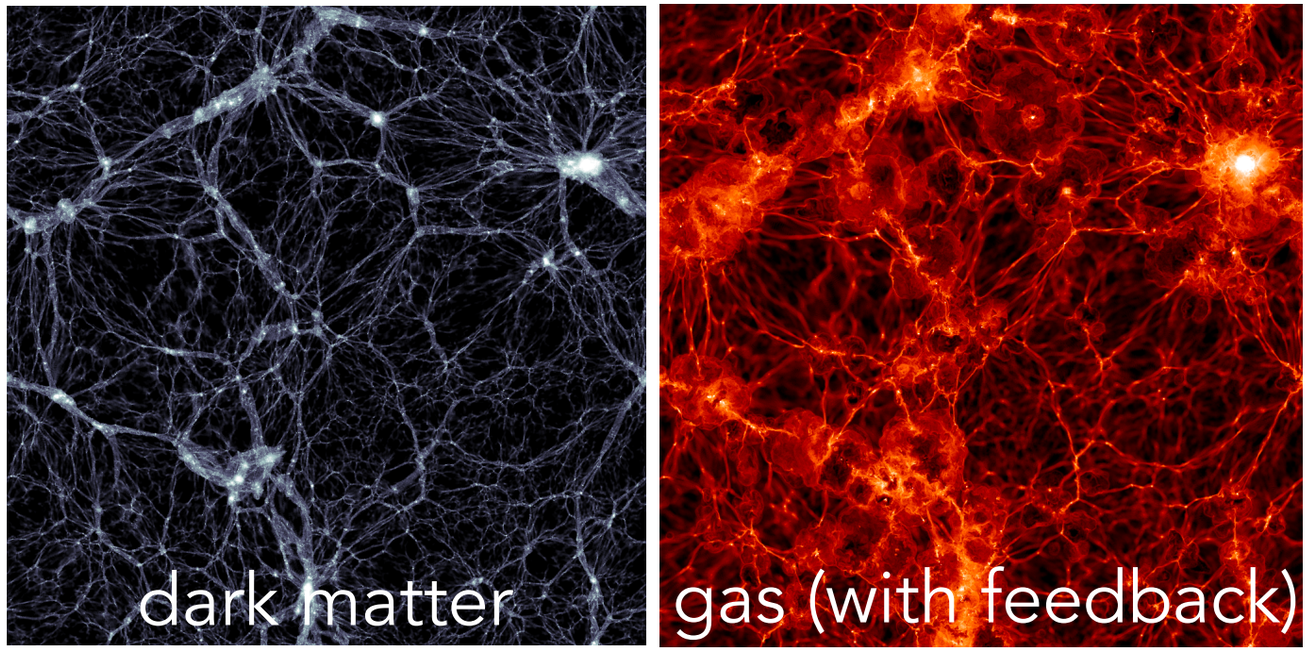
Galaxy formation

Feedback pushes gas outside virial radius

Too faint to detect

→ **Missing baryon problem**

→ **Limits our understanding of galaxy formation**



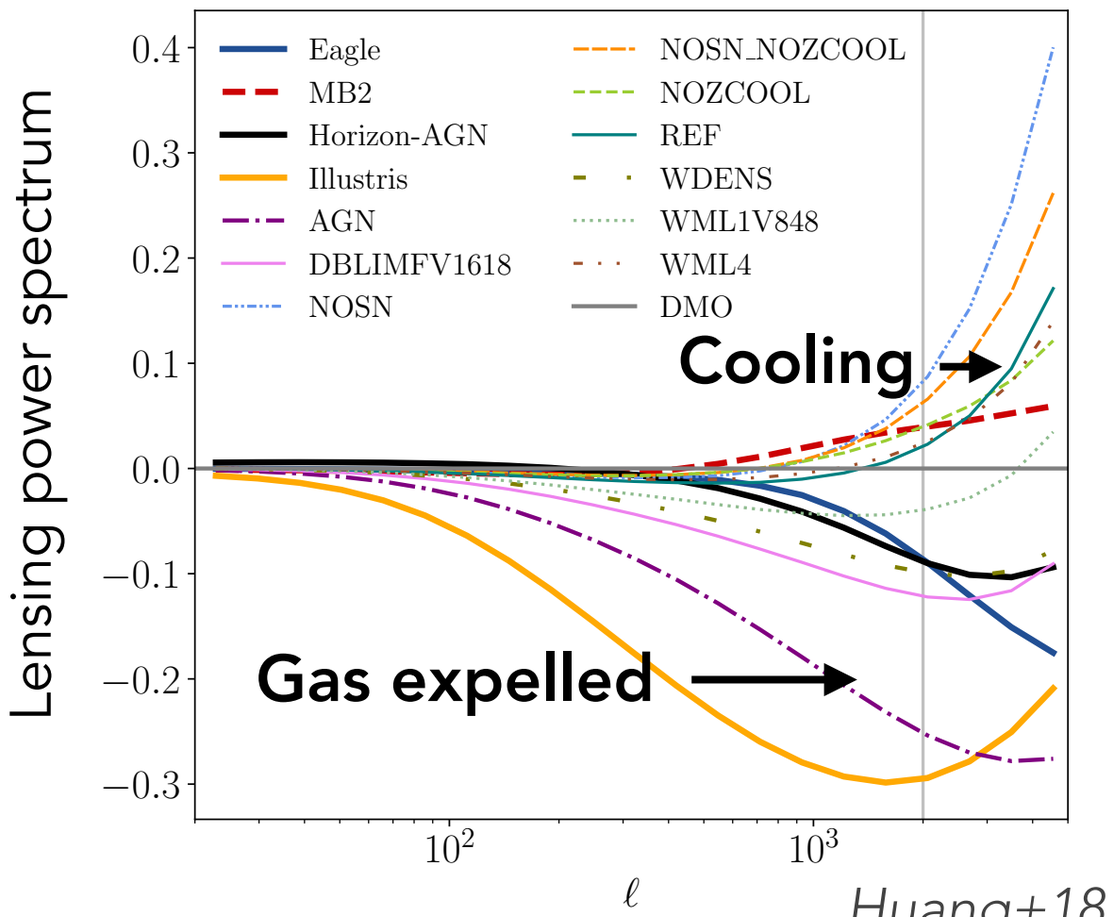
Haider+16, Illustris simulation

Cosmology

Baryons ~15% total matter

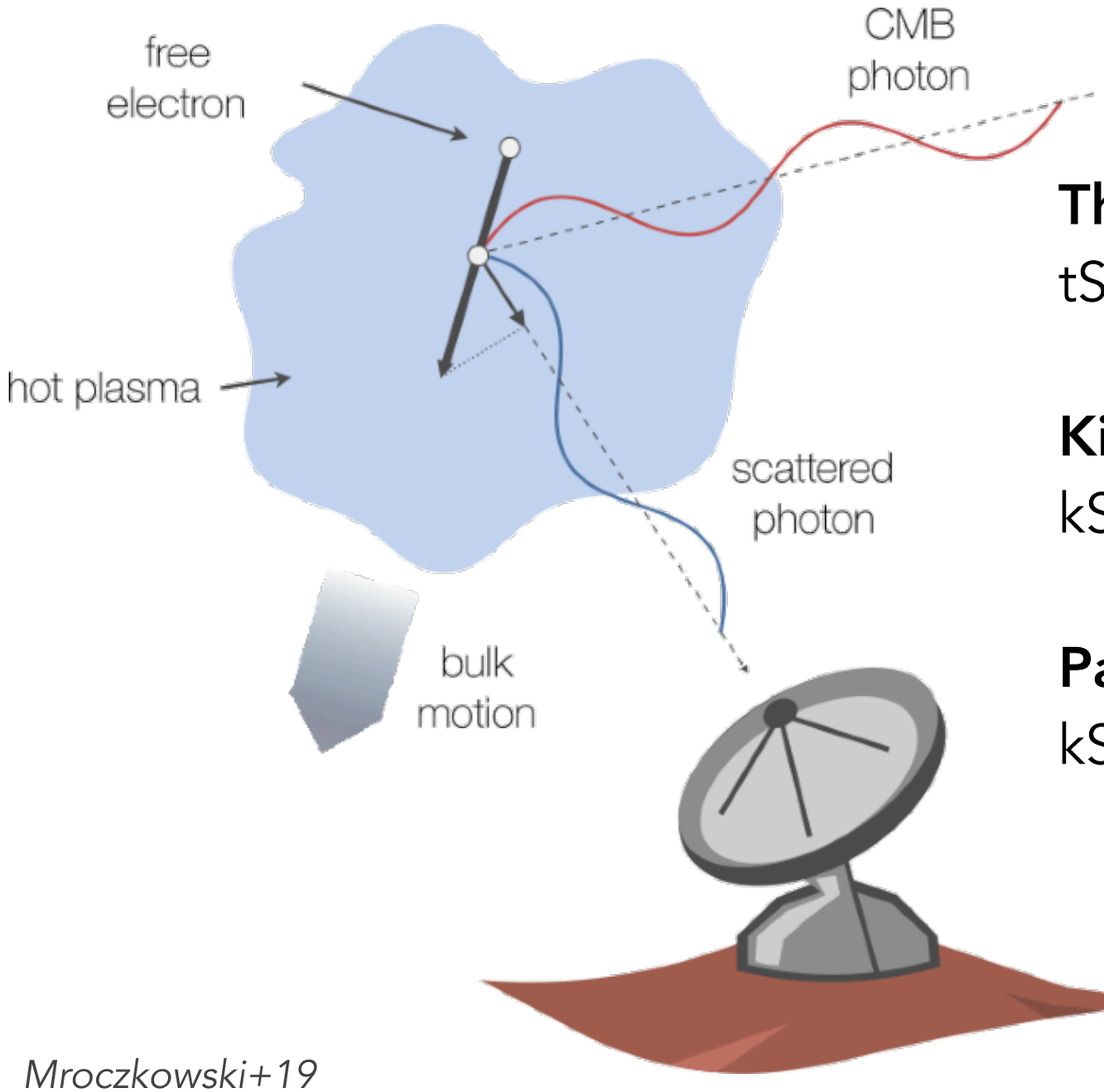
→ **Largest (30%) theoretical uncertainty on matter power spectrum**

→ **Limits cosmology from weak lensing: Rubin, Roman, Euclid**



Huang+18

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

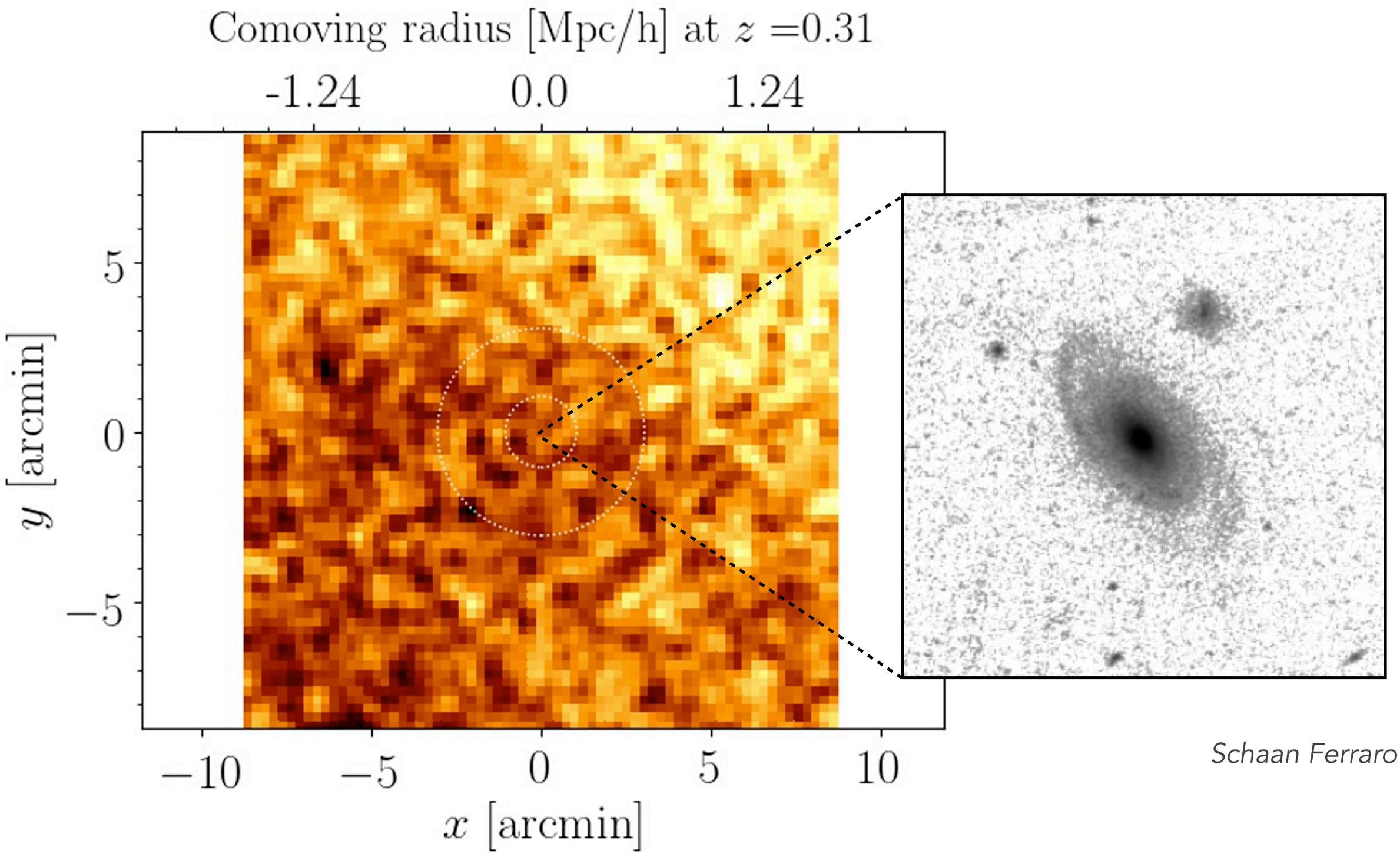
Patchy screening: Doppler Simple scattering

kSZ = gas density * primary CMB

→ Unique probe of missing baryons!

(Looking forward to FRBs too!)

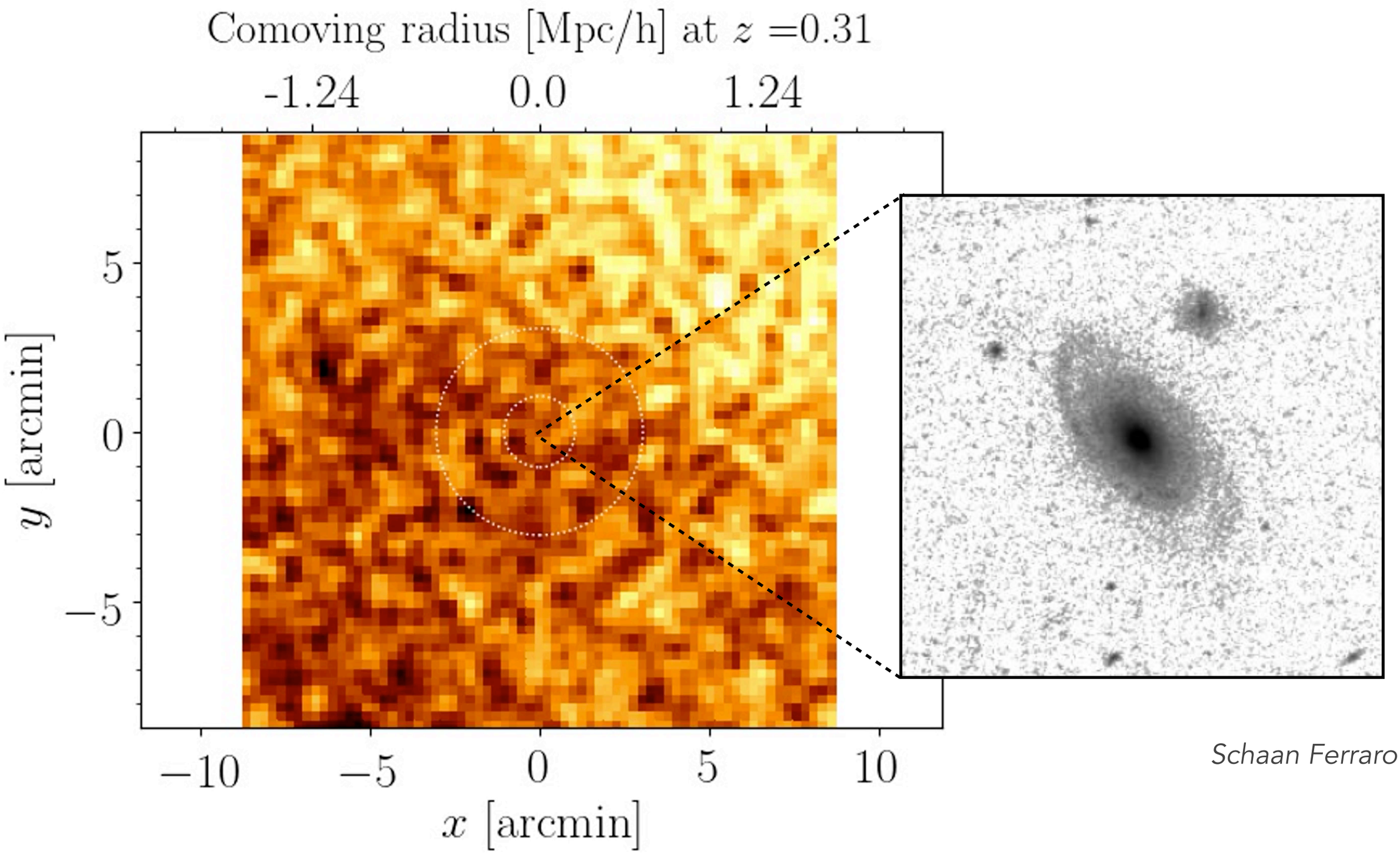
Extracting tSZ: single galaxy



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!

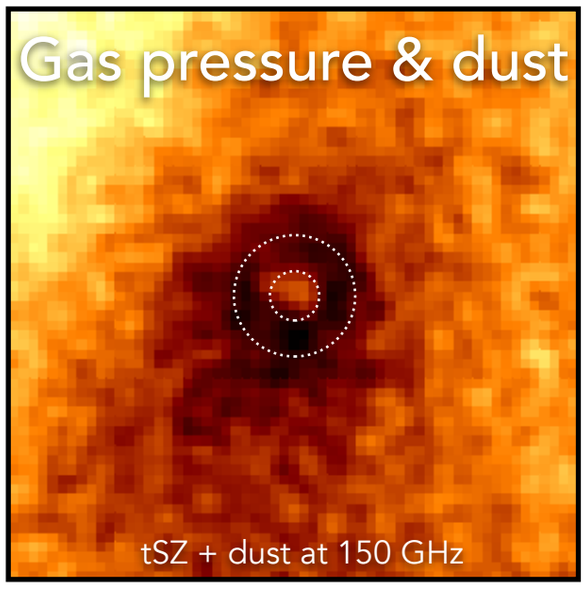
Higher precision tSZ: ACTxDESI

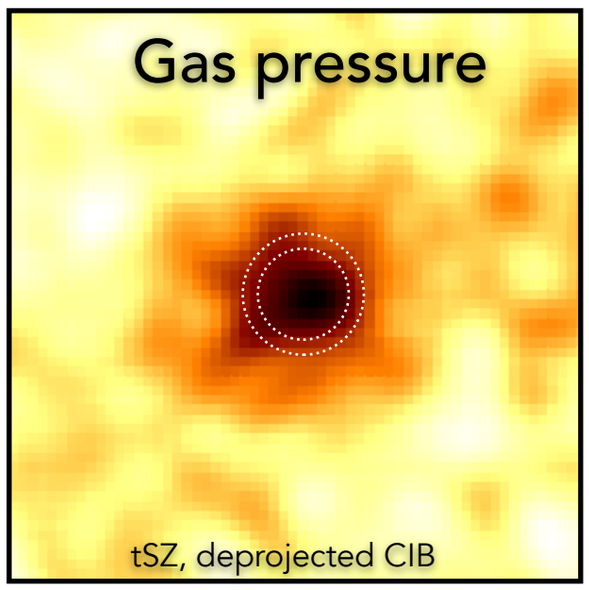
Henry Liu

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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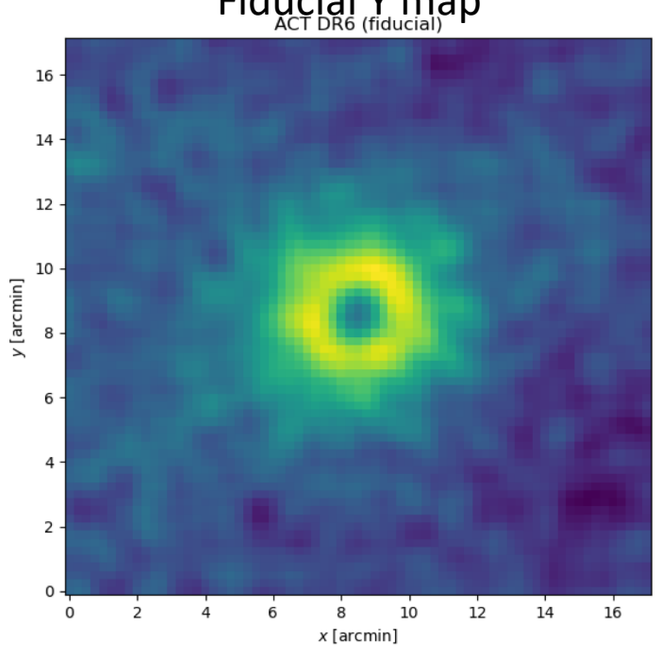
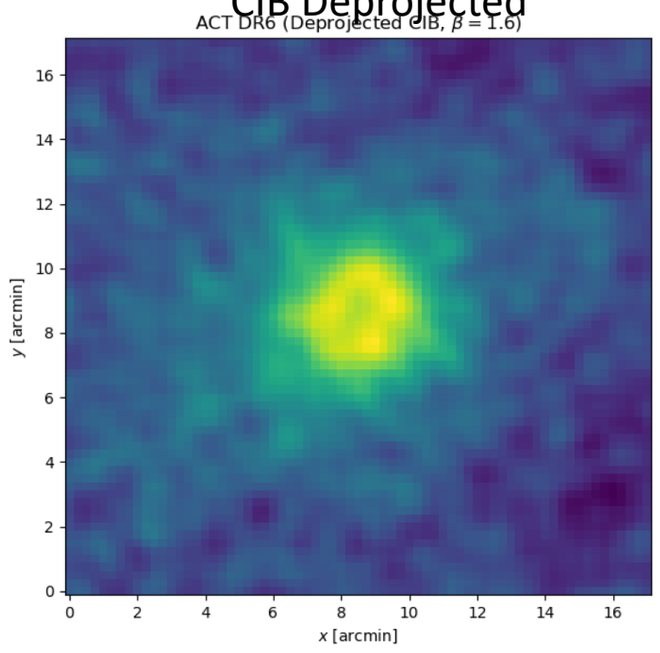
Clean by masking/deprojecting with variable dust SED

Fiducial Y map

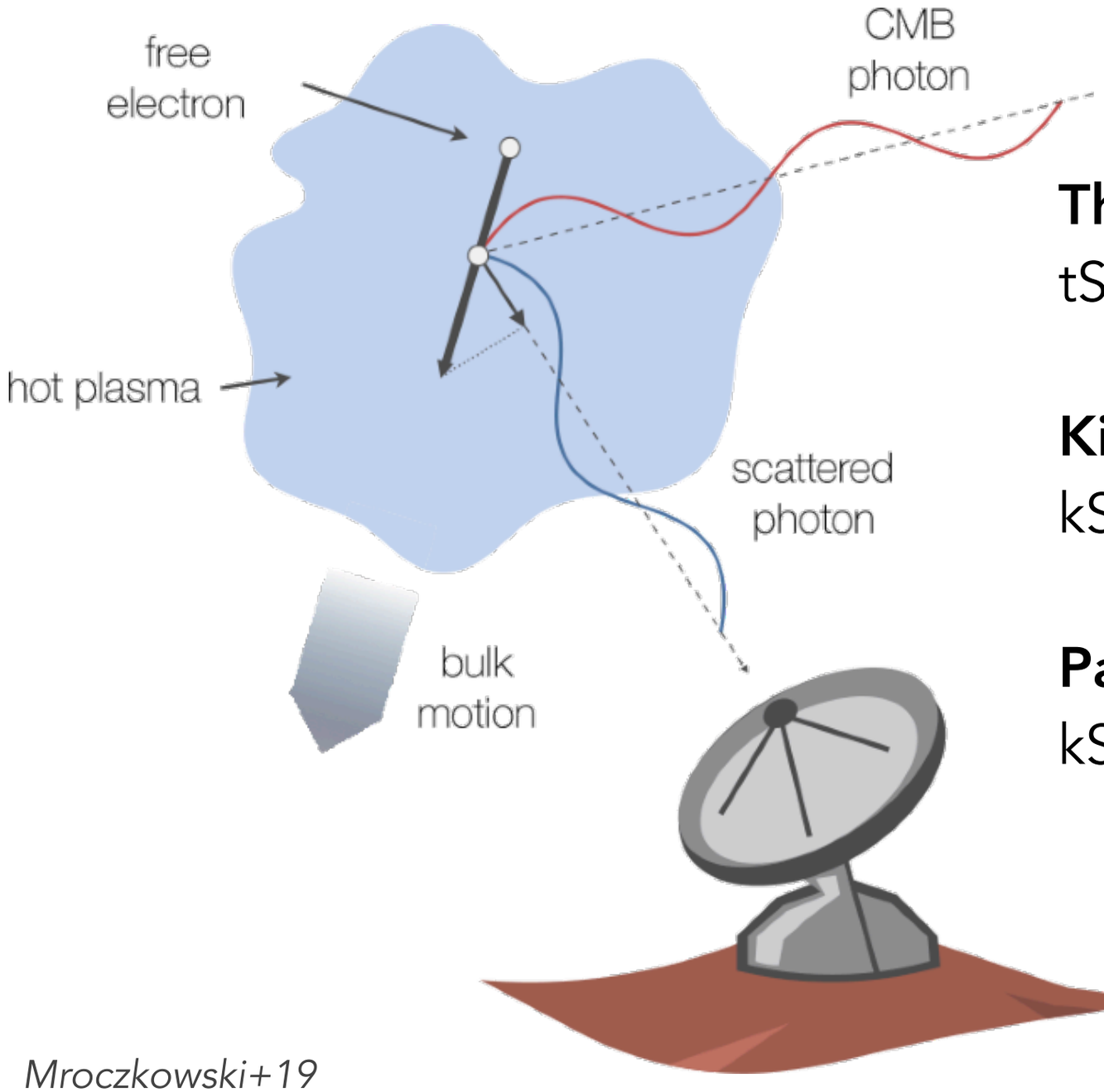


CIB Deprojected



Liu+24

CMB can help: Sunyaev-Zel'dovich effects



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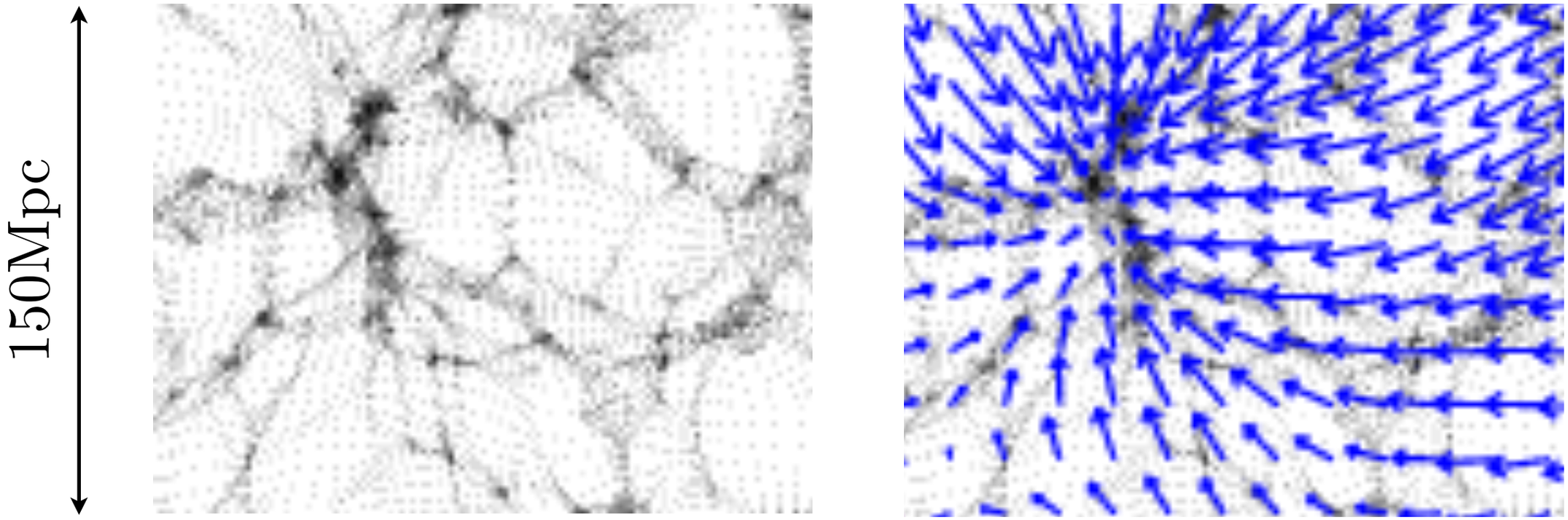
→ Unique probe of missing baryons!

(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 $r(v_{true}, v_{rec})$

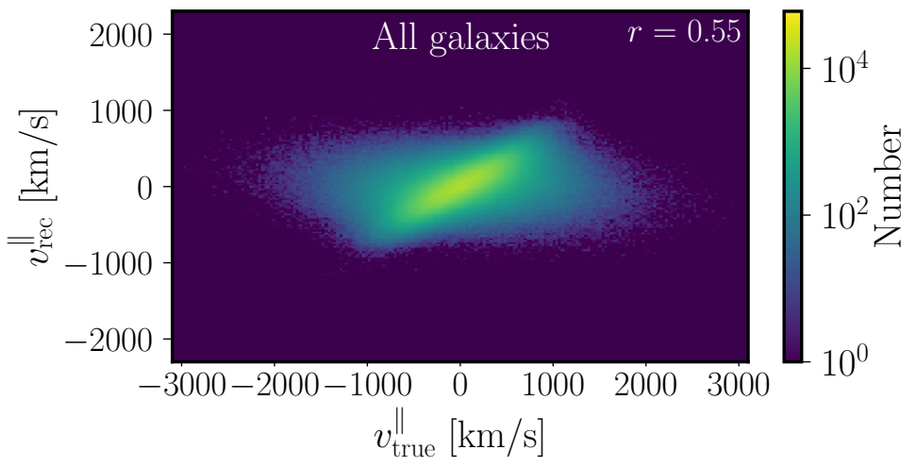
→ Quantify from sims

Velocity reconstruction via continuity equation: assessment

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




Hadzhiyska+23, Ried Guachalla+23



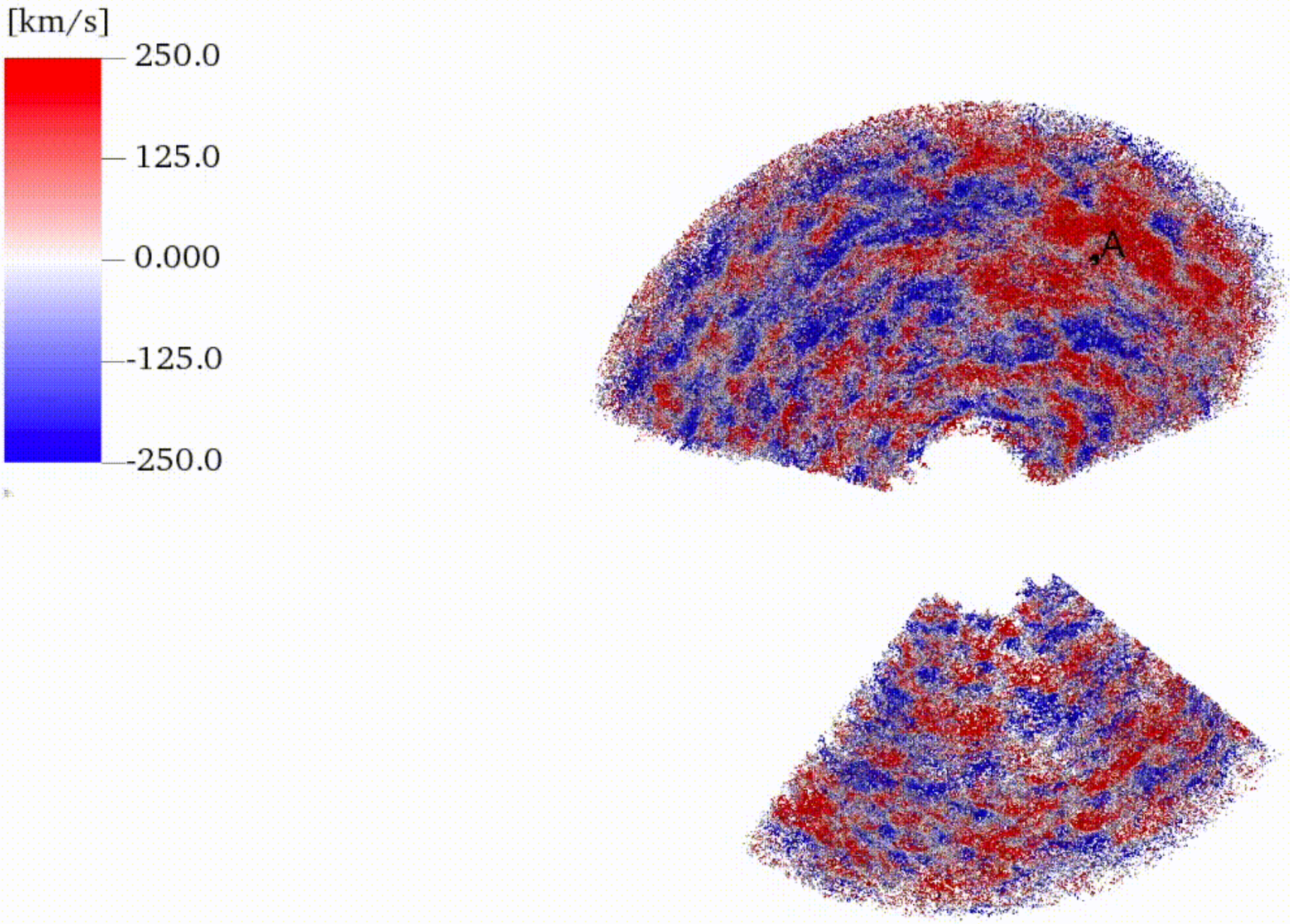
Key results

- 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



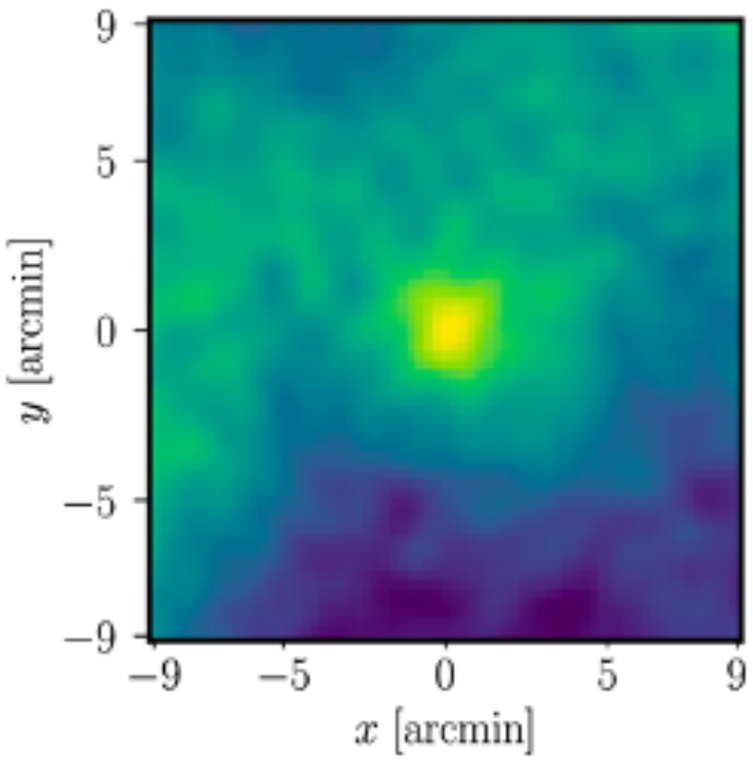
BOSS (CMASS AND LOWZ)

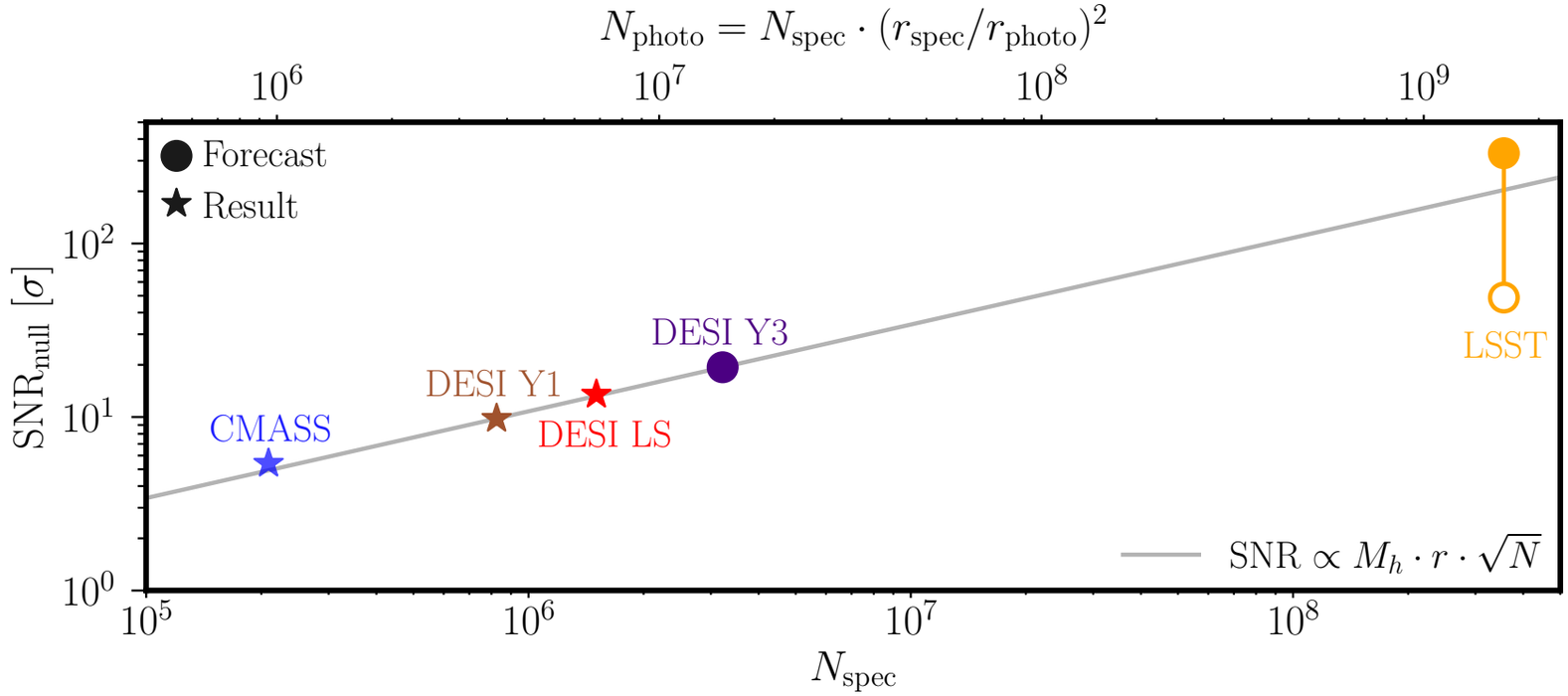
Ried Guachalla

Higher precision kSZ: ACTxDESI

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

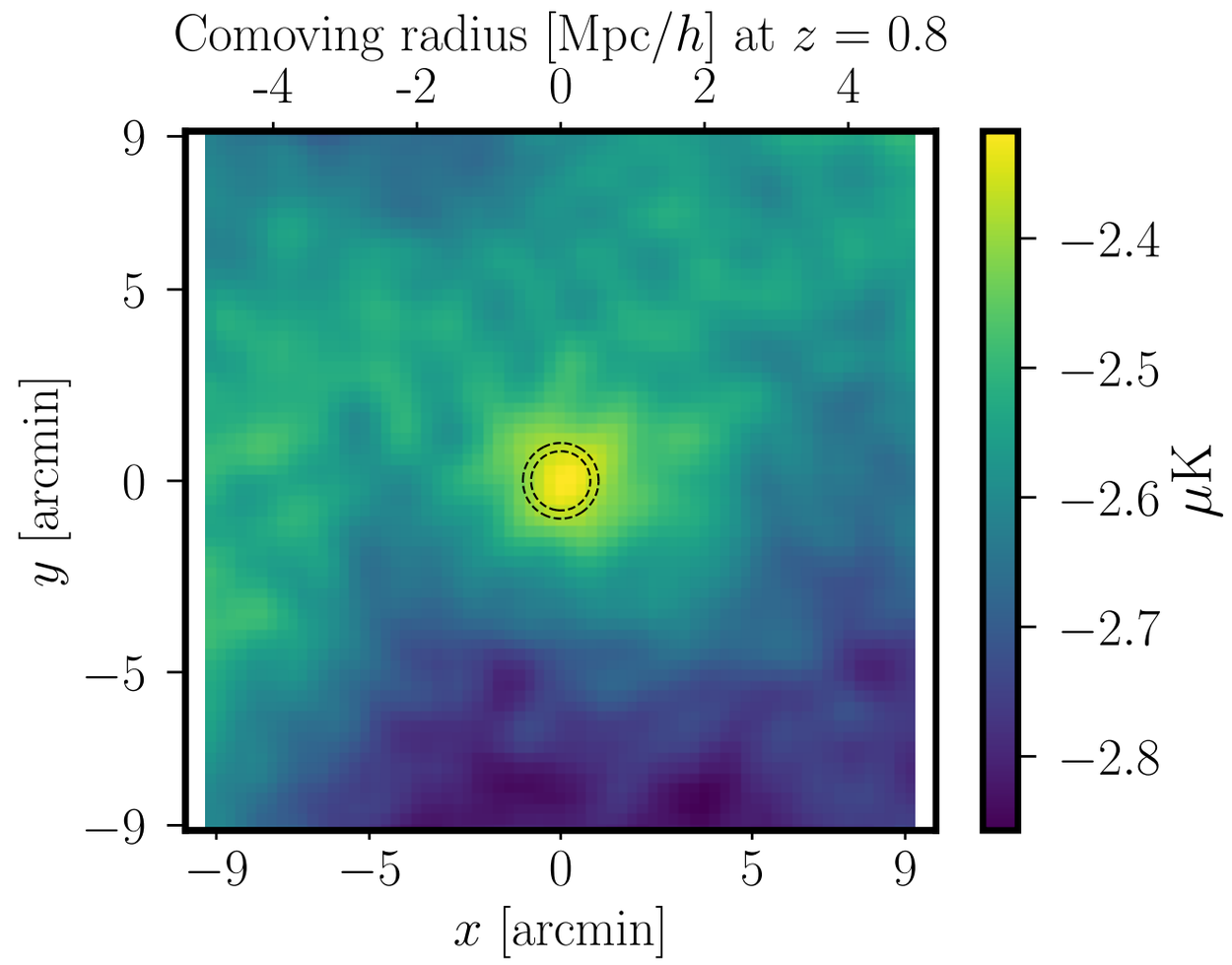
High precision stacked kSZ
Compare photo & spectro samples
Explore dependence on M, z, L
Confirm gas more extended than DM
Matches Illustris (large feedback),
not Illustris TNG





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!

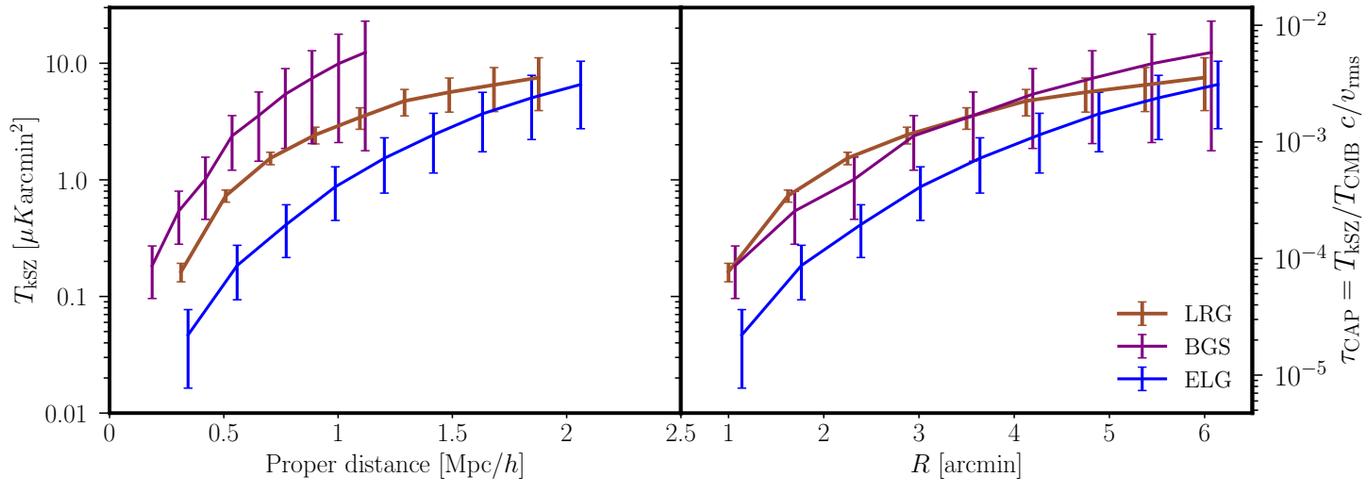
kSZ unique probe of outskirts of galaxy groups and clusters
→ Complementary with X-ray & tSZ, which probe cluster centers best

Latest stacked kSZ profiles available?

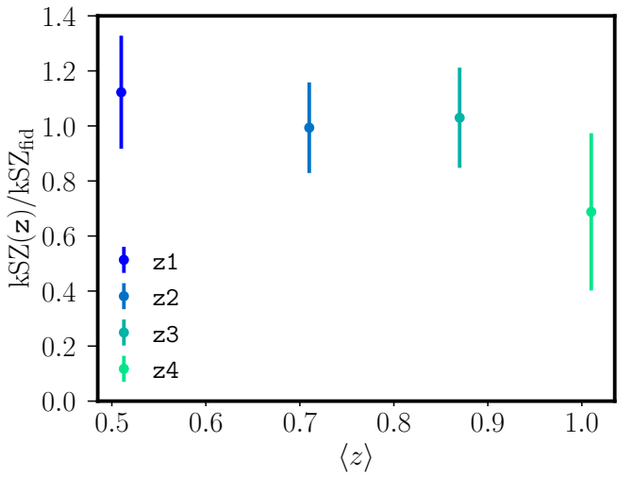
DESI LRG, BGS, ELG

spectro: *Ried Guachalla+25*

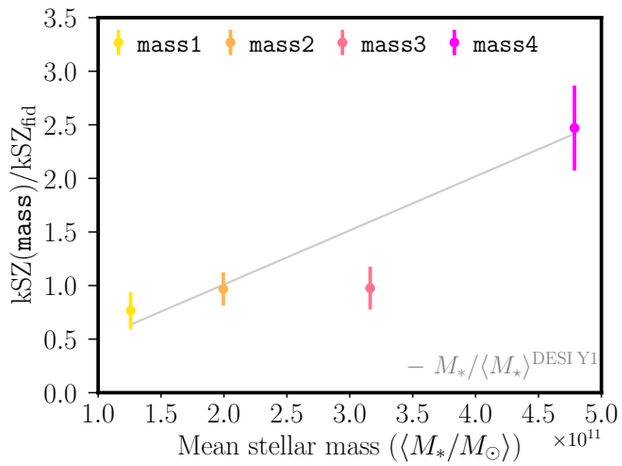
photo: *Hadzhiyska+25*



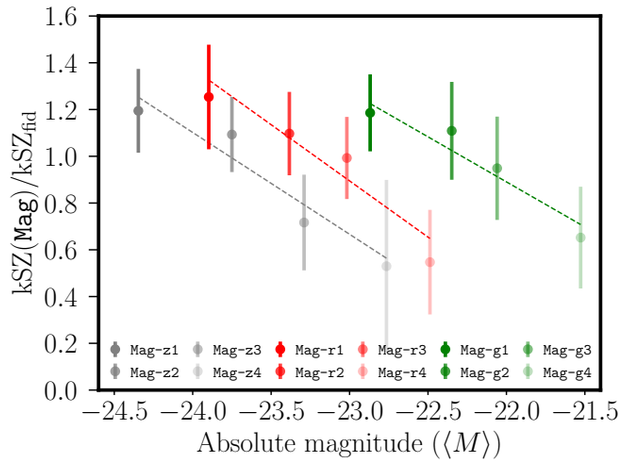
Also splits by redshift,



stellar mass,

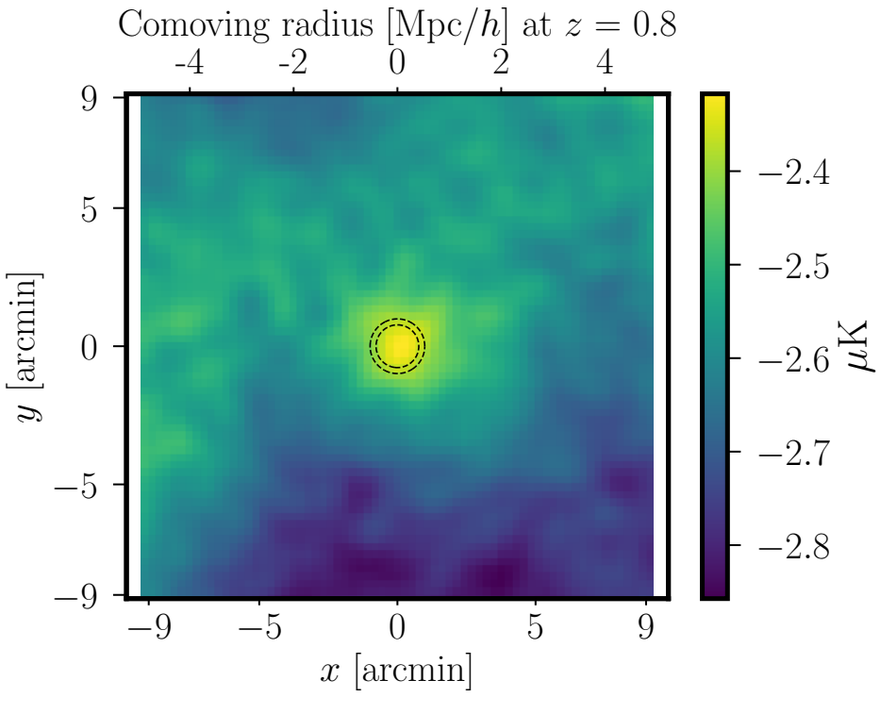


absolute magnitude



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

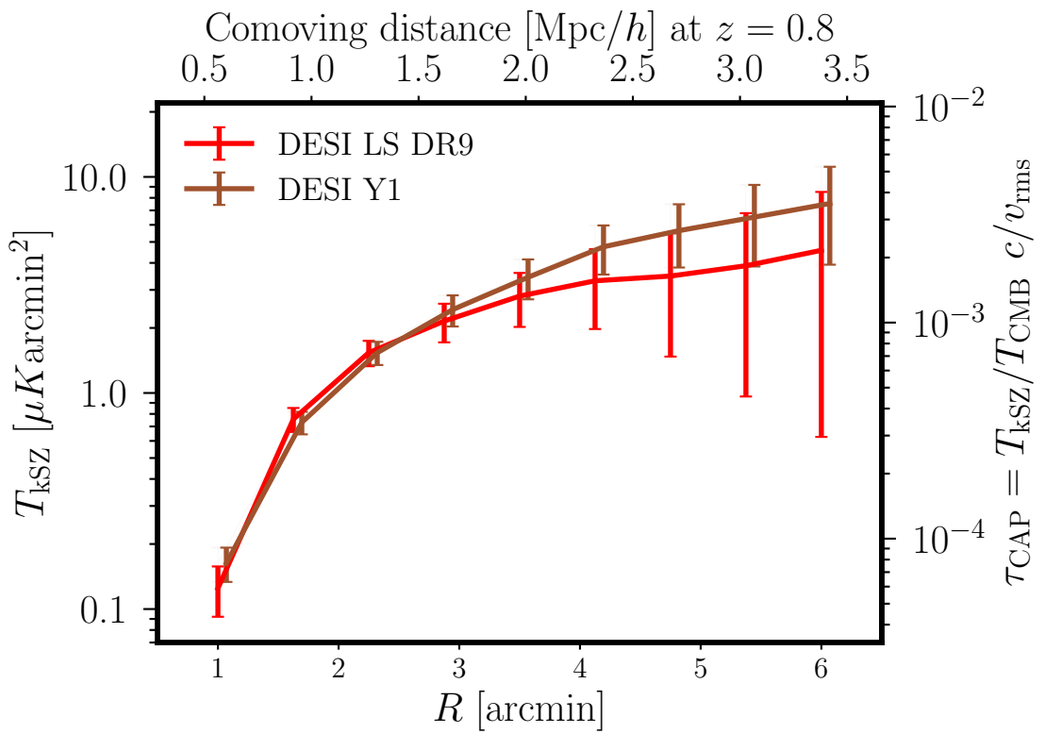
Large-scale noise: profile slope VS M_{gas}

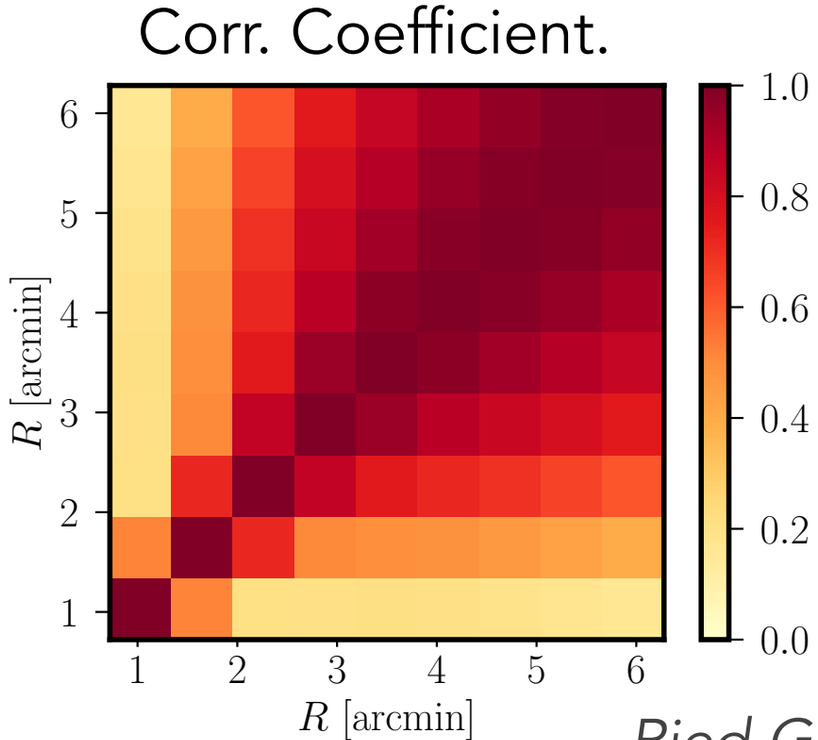


Primary CMB (~degree) dominates noise on larger scales

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

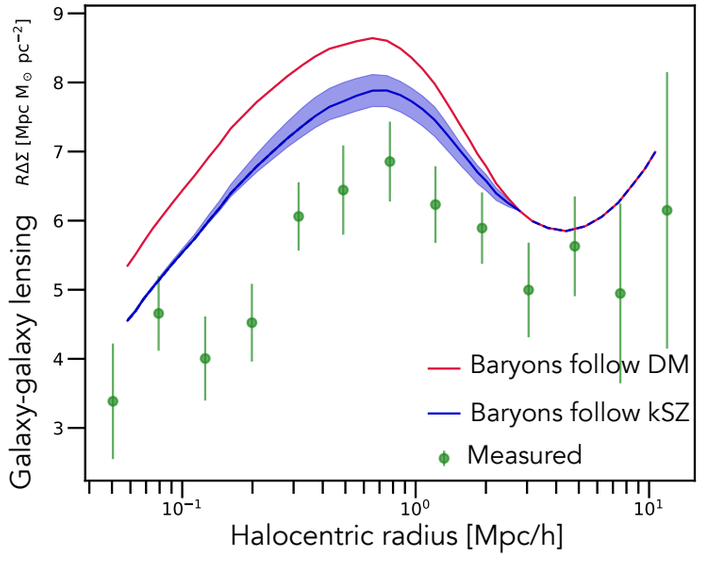
CAP filter avoids displaying constant CMB mode, but is not required.
Fourier measurements simplify this



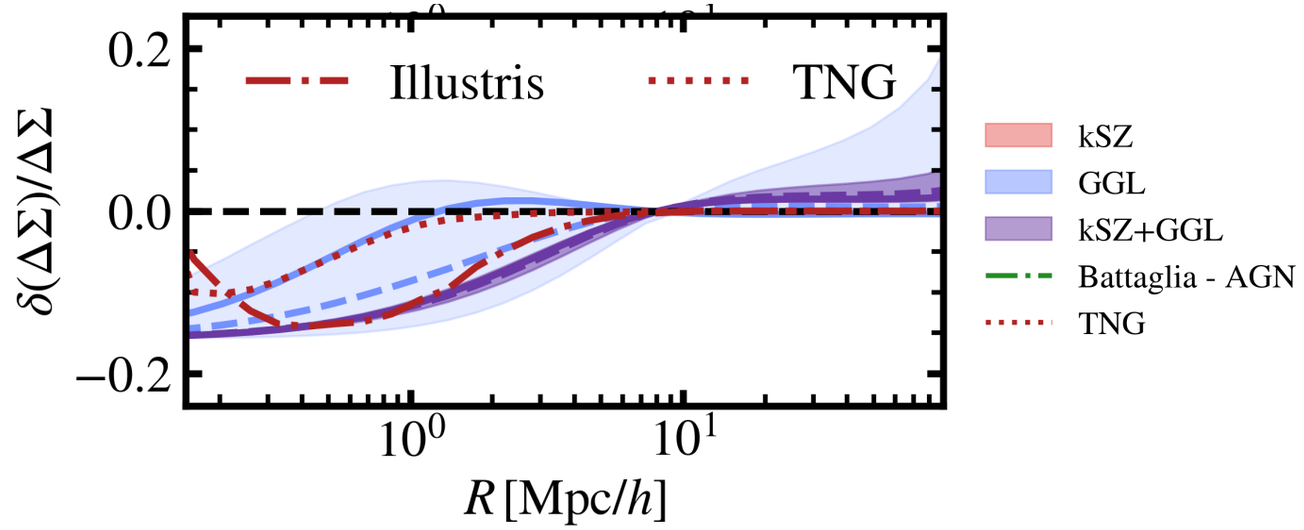


Ried Guachalla+25

kSZ is faint. Is precision enough for lensing?



Amodeo+21



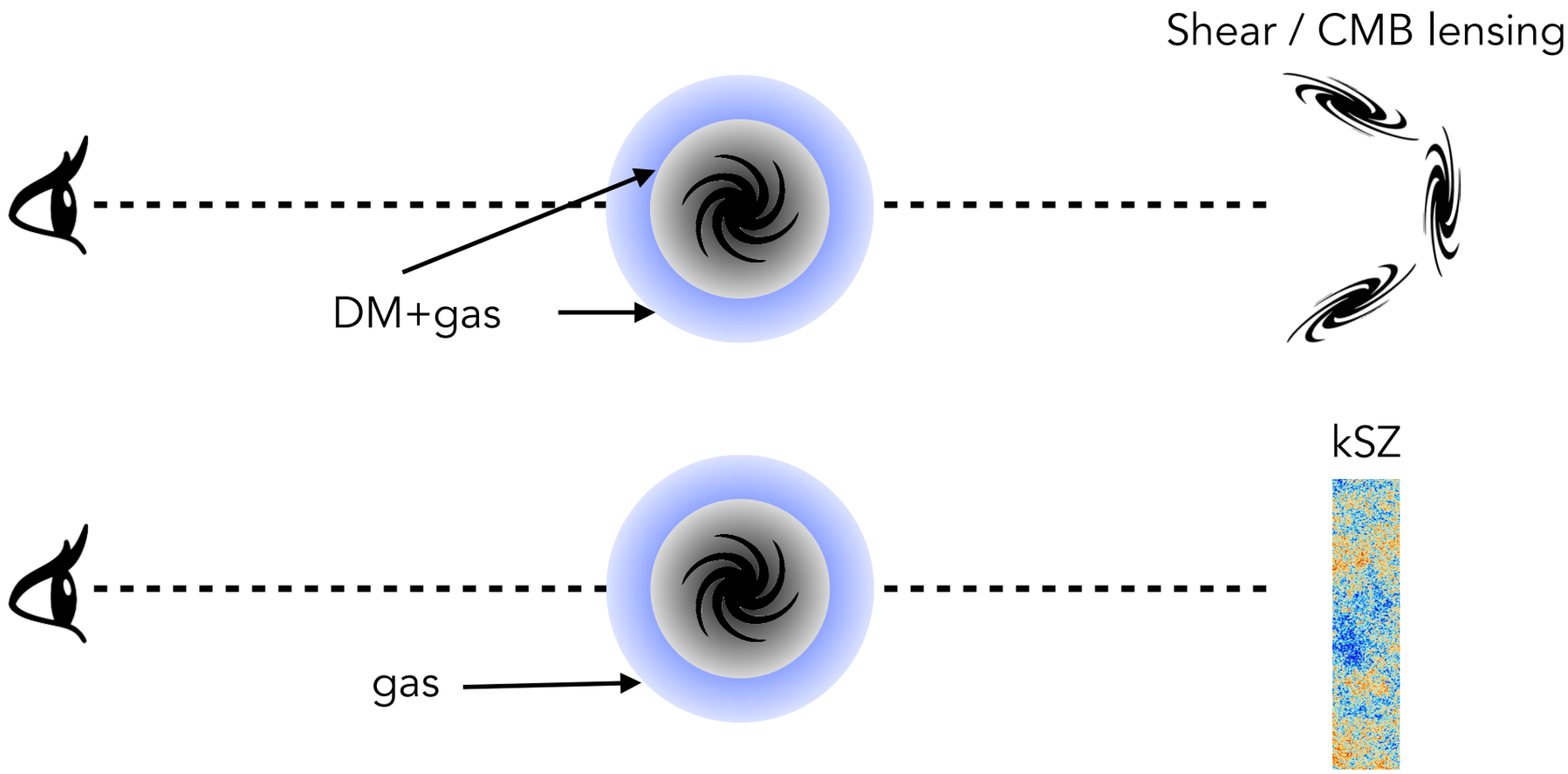
Sunseri+25

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**

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)*

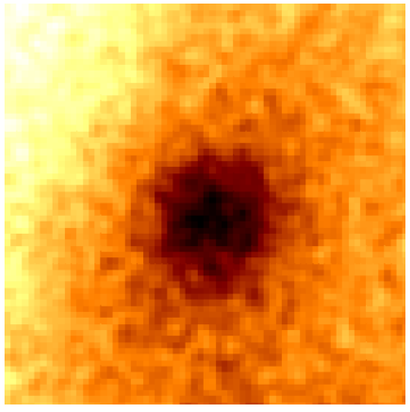
Universality of matter power suppression? (*Van Daalen+20, Joop's talk*)
→ would help!

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

Outline: Combining CMB & LSS

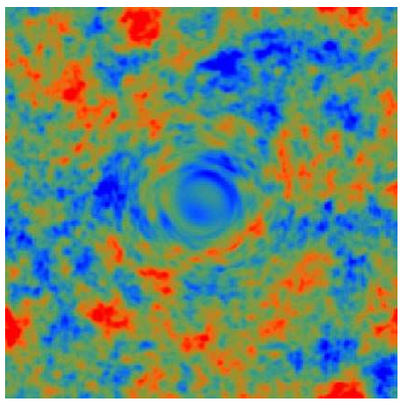
Gas shadows

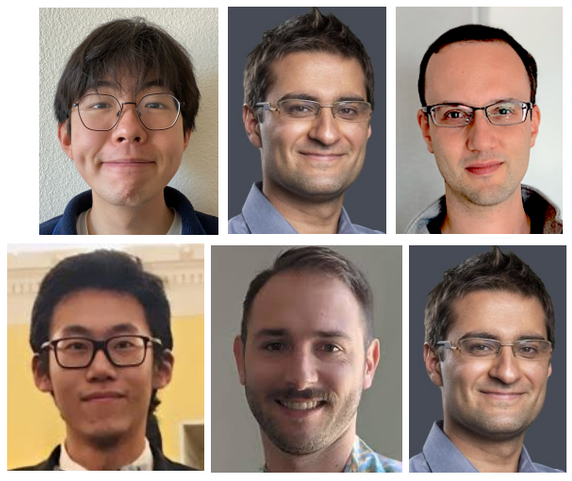


ACT x DESI kSZ & tSZ

Hadzhiyska+23, 24
RiedGuachalla+23, 25
Liu+24

Mass shadows





CMB lensing noise bias avoidance

Shen Schaan Ferraro 23

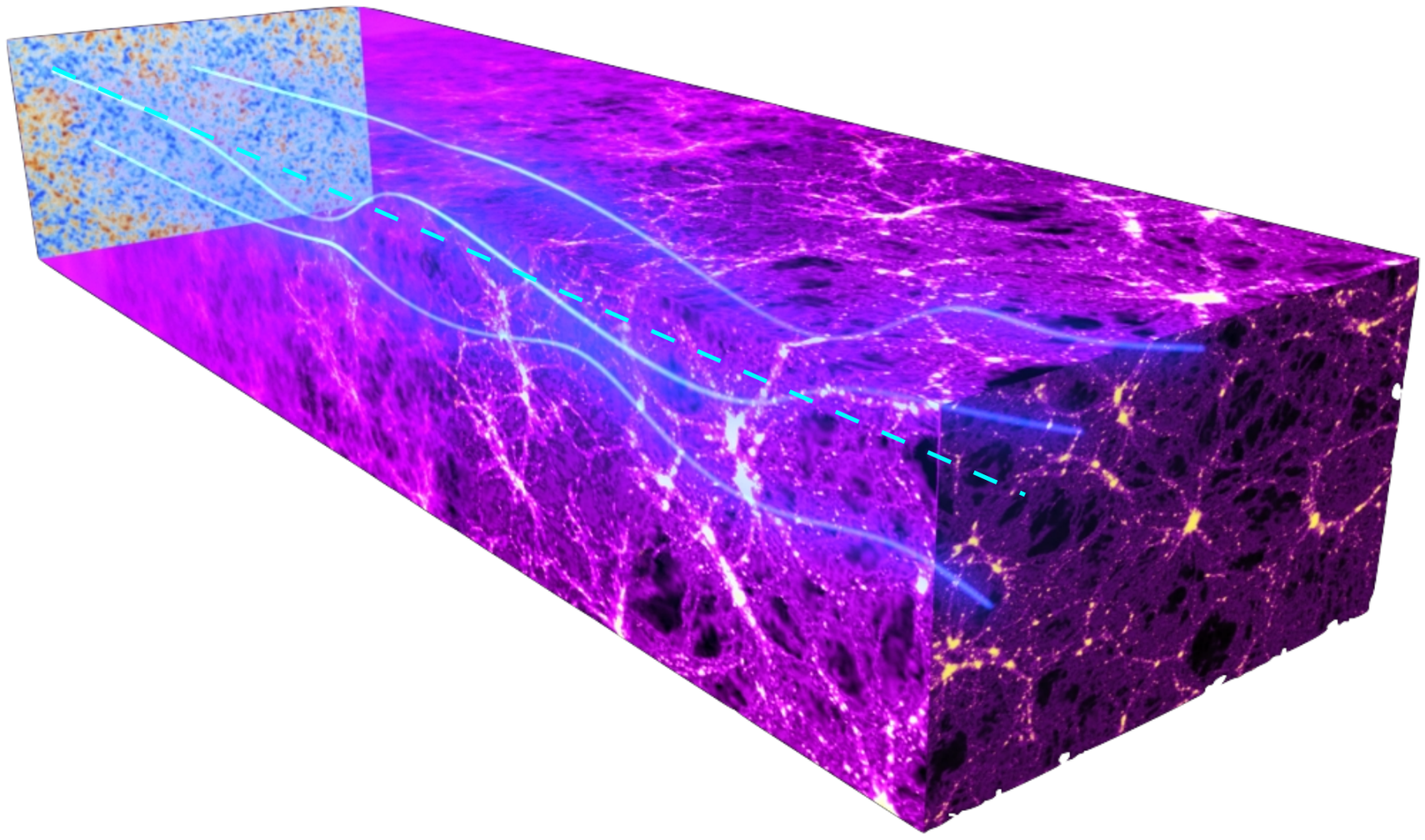
Bayesian lensing bias

from polarized extragalactic foregrounds

Qu Millea Schaan 24

Mass shadows:
Improving CMB lensing estimators

CMB lensing: overview

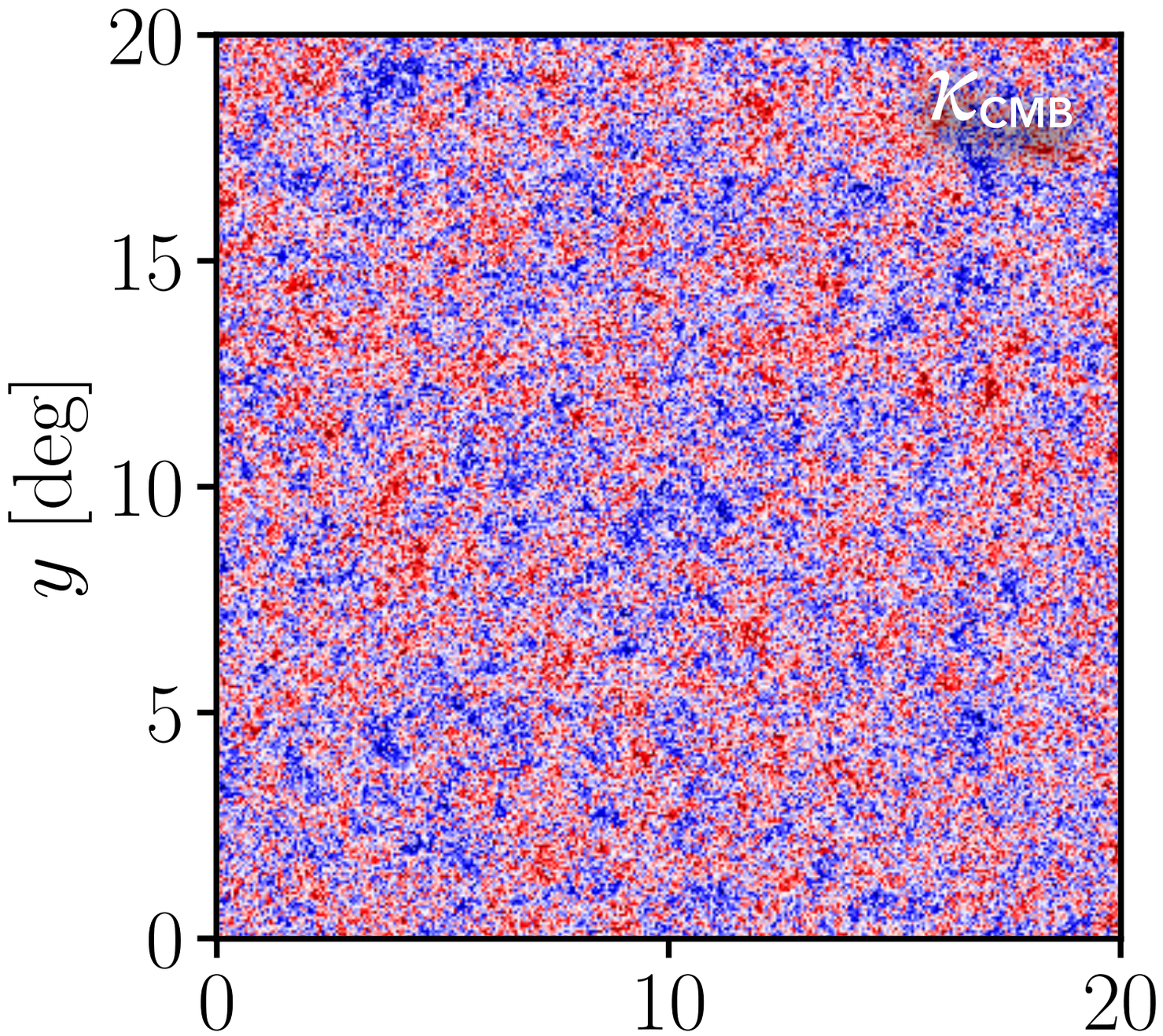


~2′ deflections, coherent on degree scale

Surface brightness: $T(\mathbf{x}) = T^0(\mathbf{x} - \mathbf{d}_{(\mathbf{x})})$

Born approximation: $\mathbf{d} = \nabla\phi = 2\nabla\Delta^{-1}\kappa$

CMB lensing: overview



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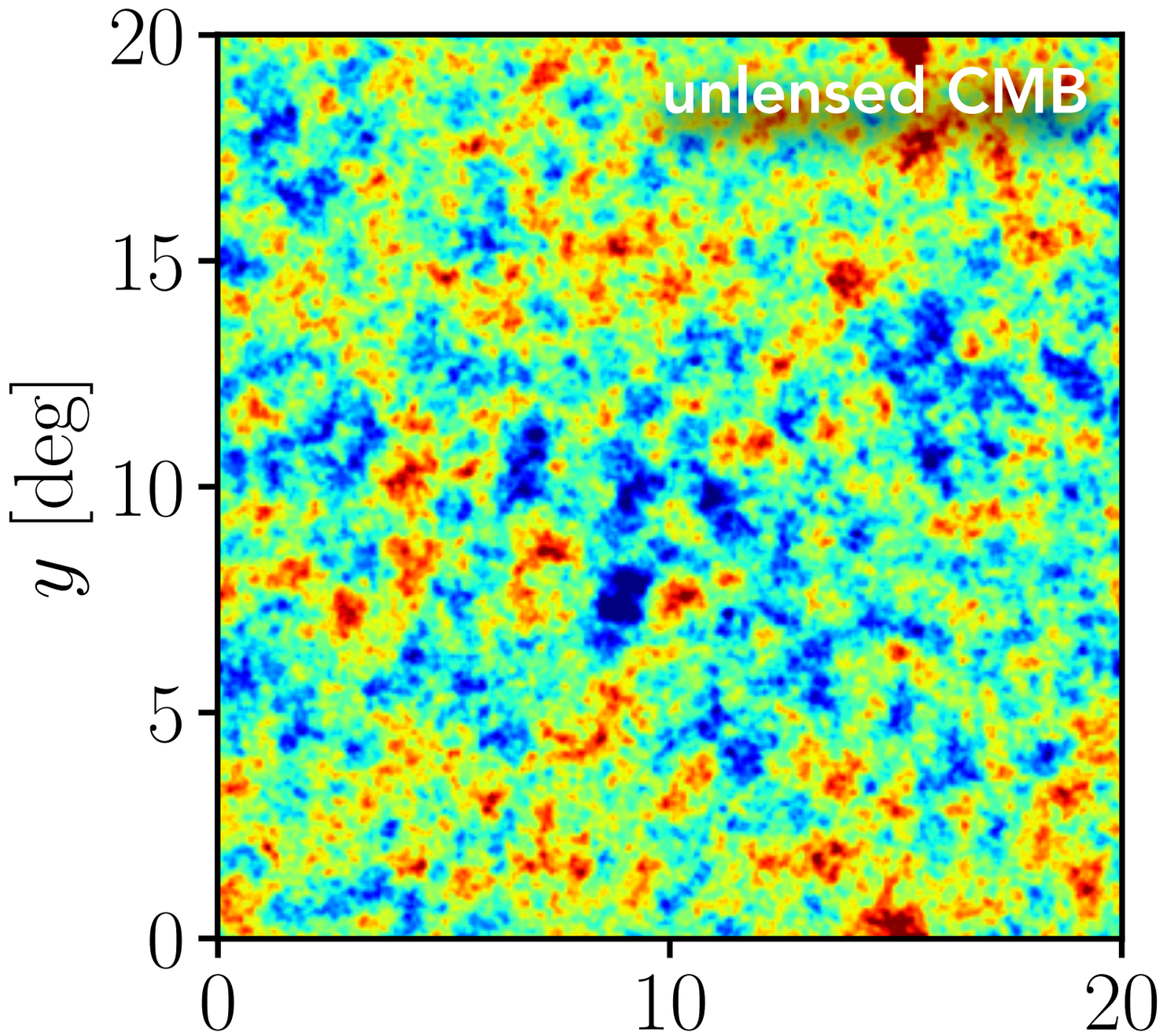
CMB lensing: overview



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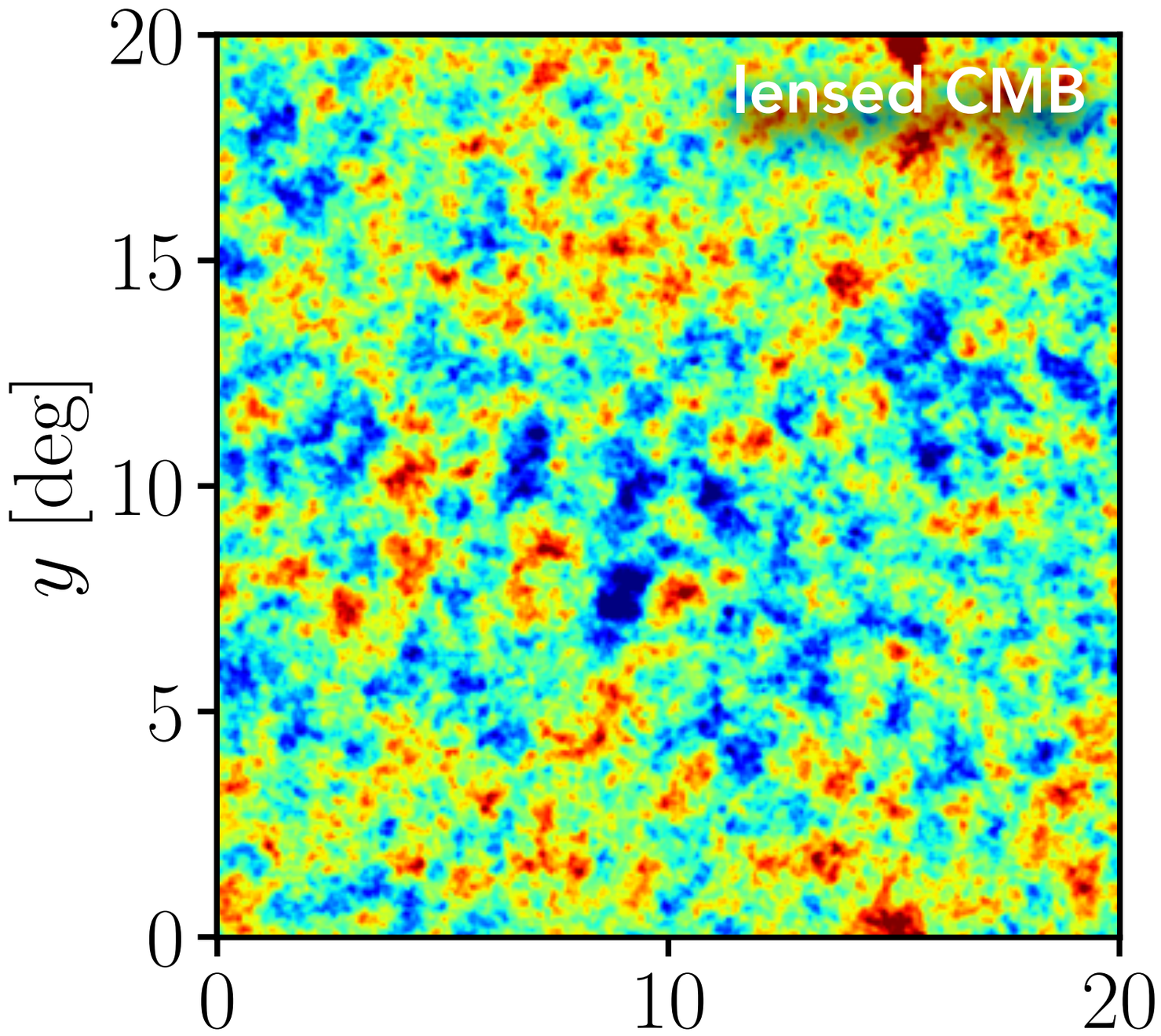
CMB lensing: overview



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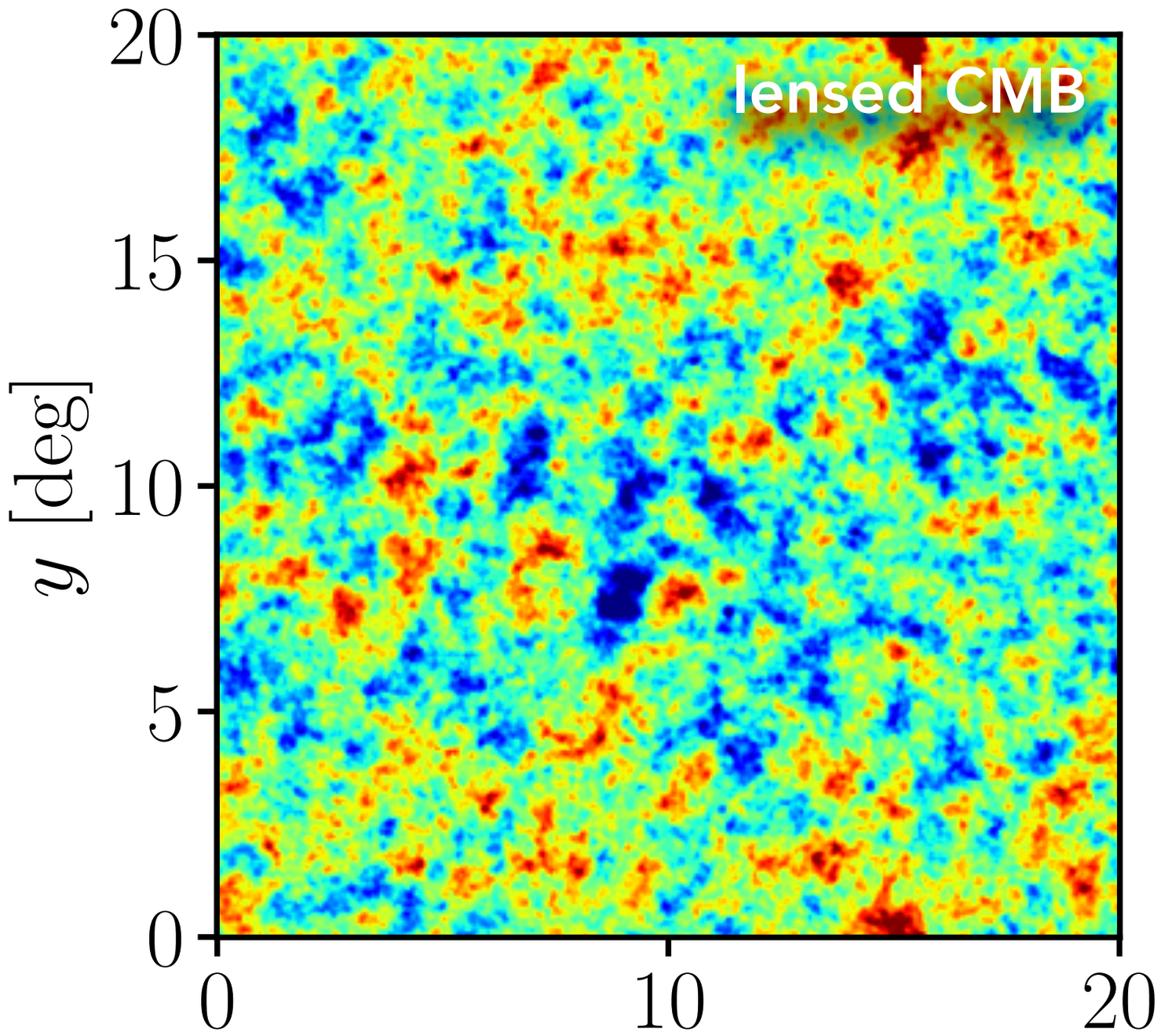
CMB lensing: overview



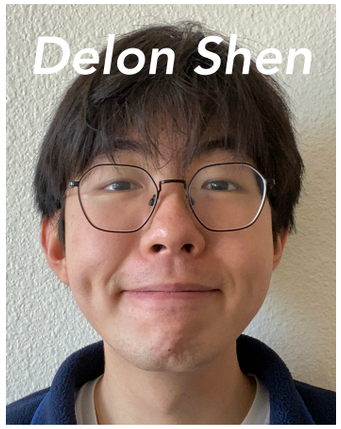
Lensing breaks the statistical isotropy of the CMB by coupling small and large scales

→ **Reconstruct with a quadratic estimator**

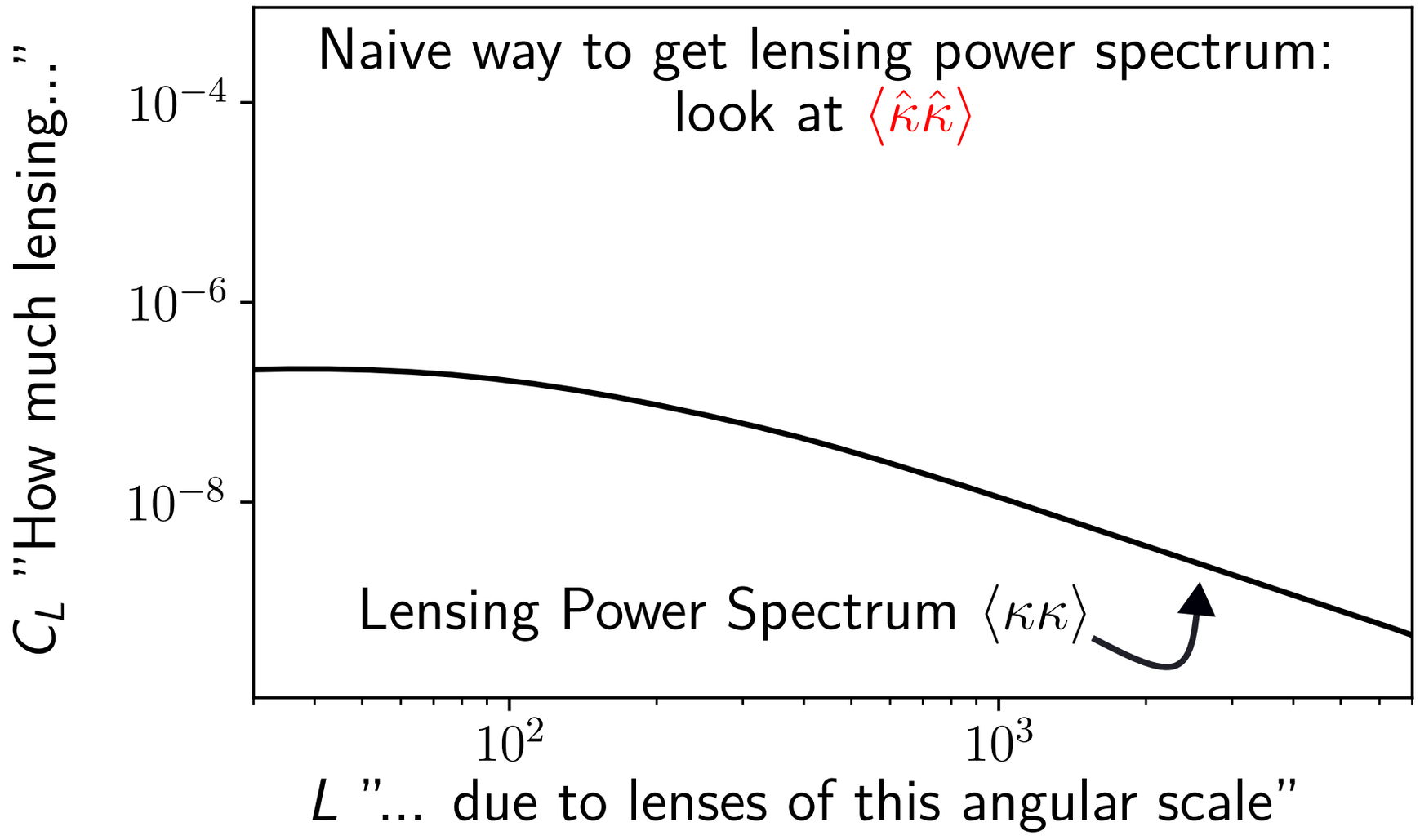
CMB lensing noise bias avoidance

Shen Schaan Ferraro 2024

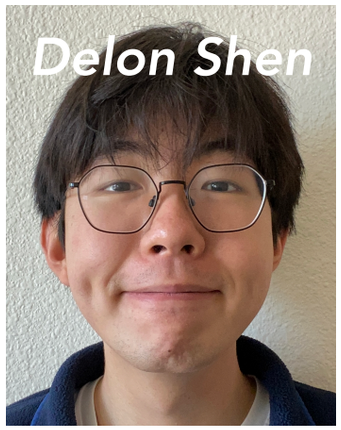
Slides adapted from Delon Shen



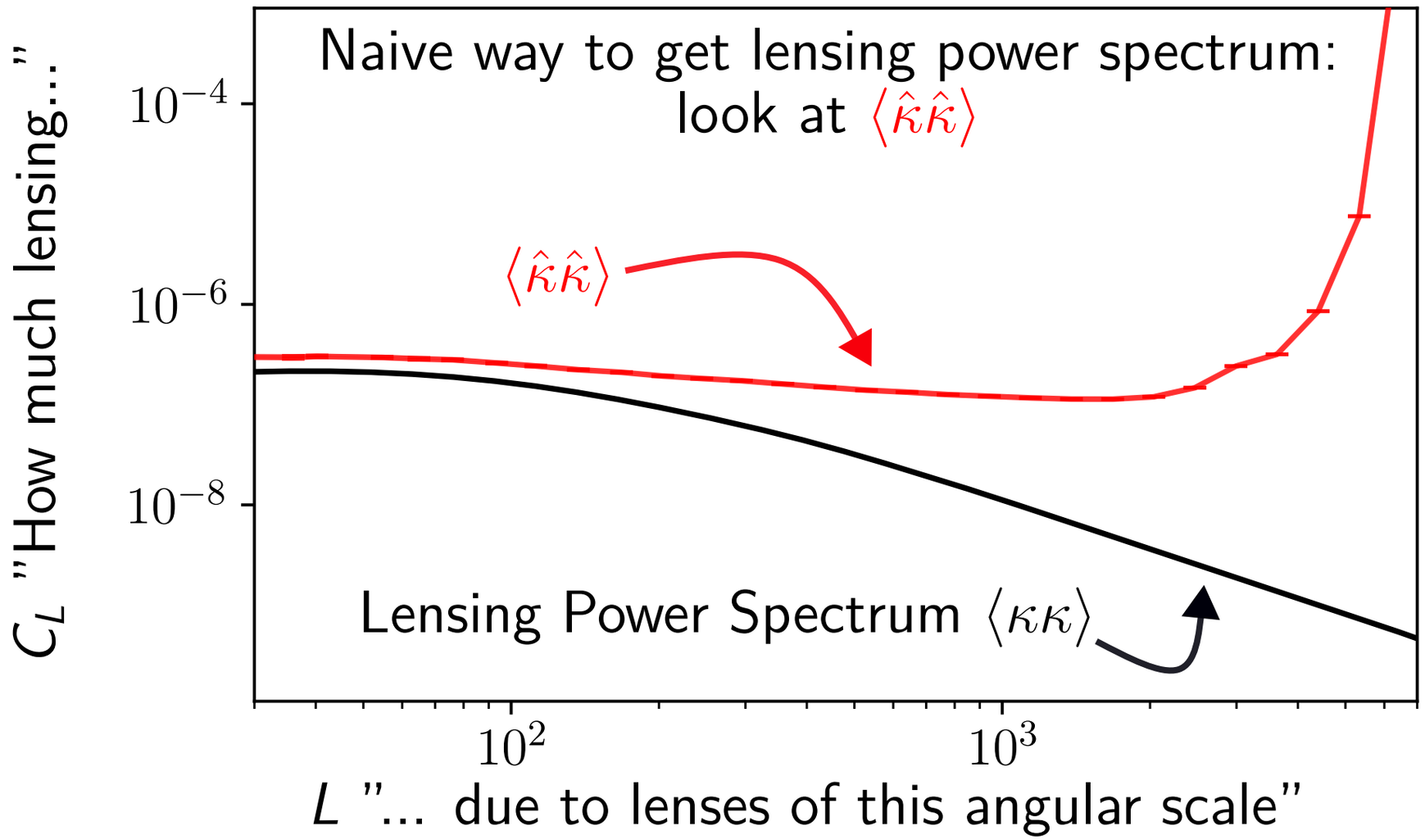
Gaussian noise bias subtraction is limiting on small scales



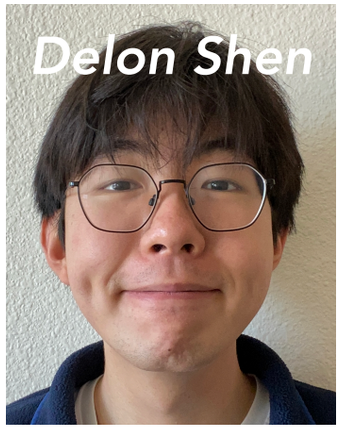
Shen Schaan Ferraro 2024



Gaussian noise bias subtraction is limiting on small scales



Shen Schaan Ferraro 2024



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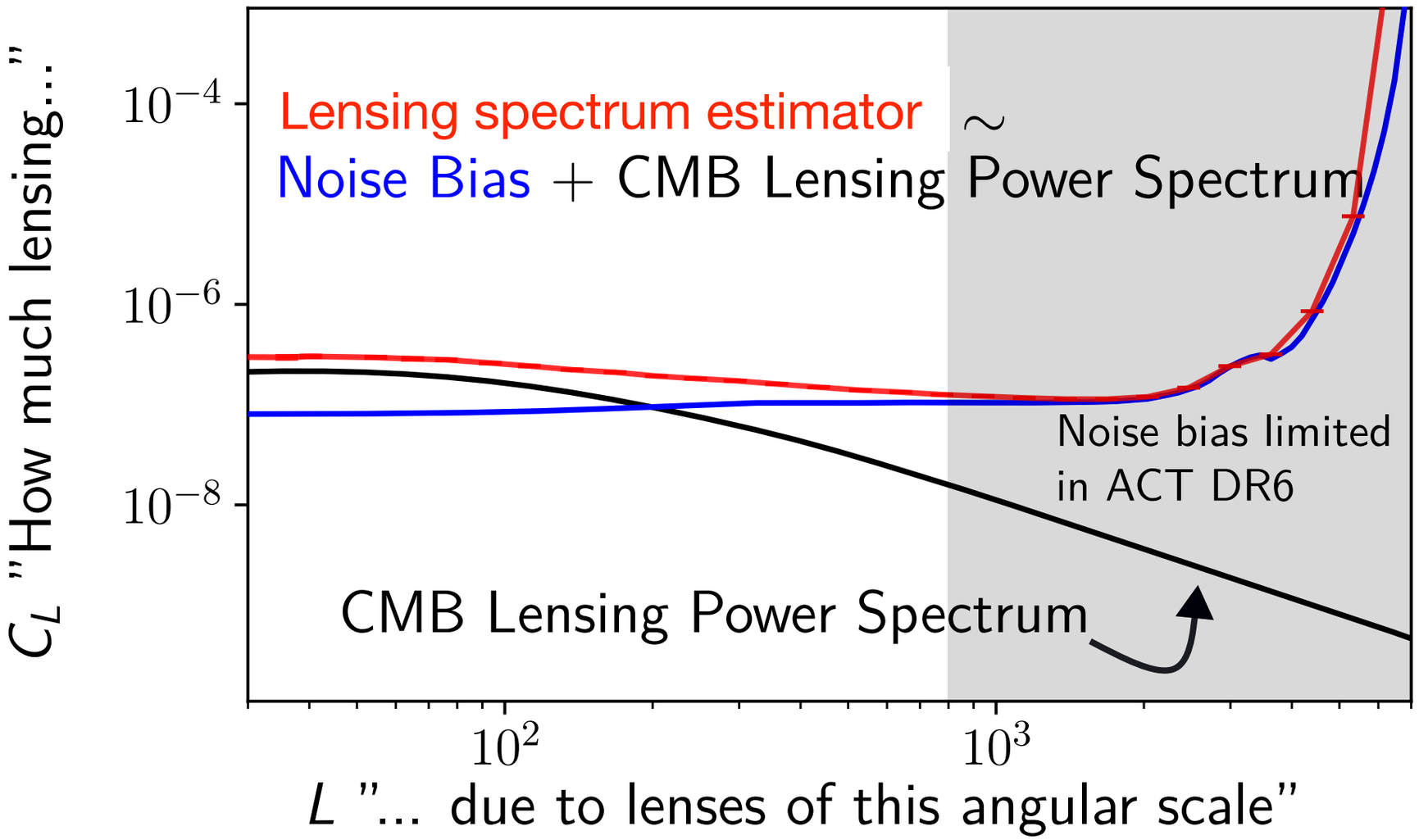
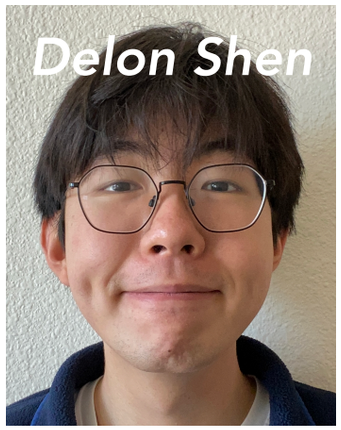


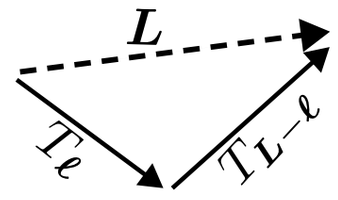
Noise bias present even without lensing → Subtract it!

Shen Schaan Ferraro 2024

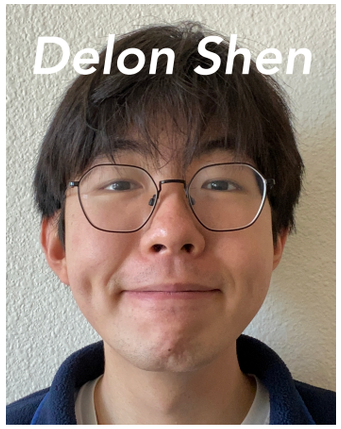


"Auto from crosses": avoid noise bias

Recall $\hat{\kappa}_{\boldsymbol{L}} \sim \int_{\boldsymbol{\ell}} T_{\boldsymbol{\ell}} T_{\boldsymbol{L}-\boldsymbol{\ell}} \sim$



Sherwin Das 10, Smith+15, Shen Schaan Ferraro 2024



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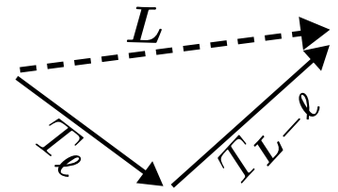
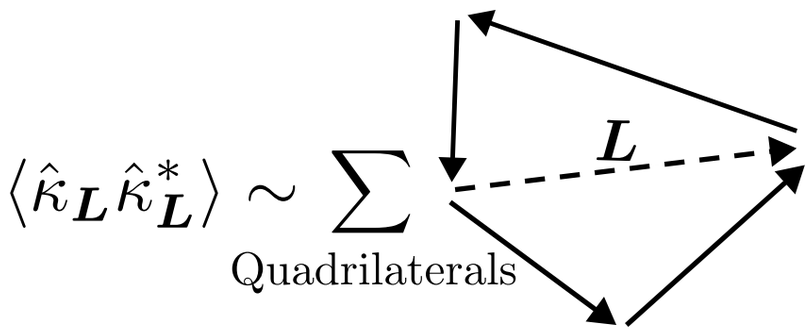
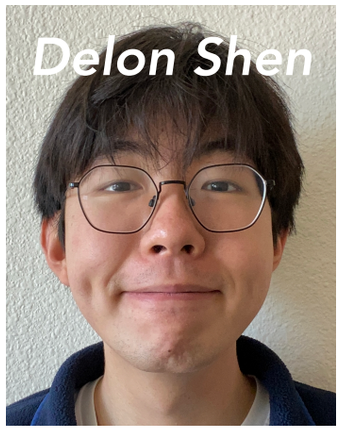


$\langle \hat{\kappa}_{\boldsymbol{L}} \hat{\kappa}^*_{\boldsymbol{L}} \rangle \sim$

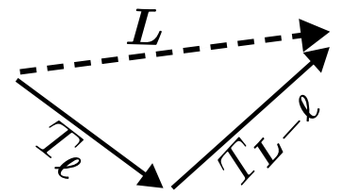


Sherwin Das 10, Smith+15, Shen Schaan Ferraro 2024

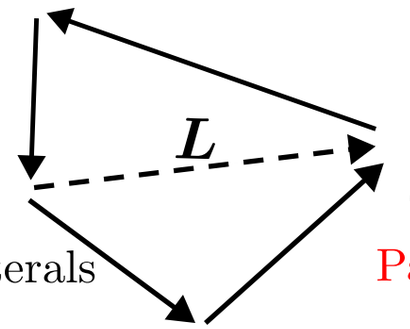


"Auto from crosses": avoid noise bias

Recall $\hat{\kappa}_{\boldsymbol{L}} \sim \int_{\boldsymbol{\ell}} T_{\boldsymbol{\ell}} T_{\boldsymbol{L}-\boldsymbol{\ell}} \sim \sum_{\boldsymbol{\ell}}$

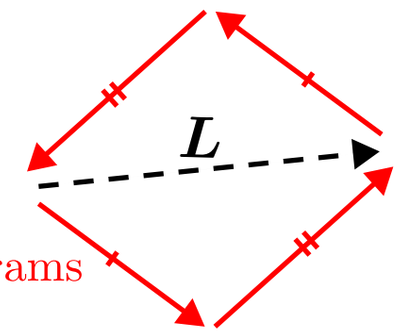


$\langle \hat{\kappa}_{\boldsymbol{L}} \hat{\kappa}^*_{\boldsymbol{L}} \rangle \sim \sum$



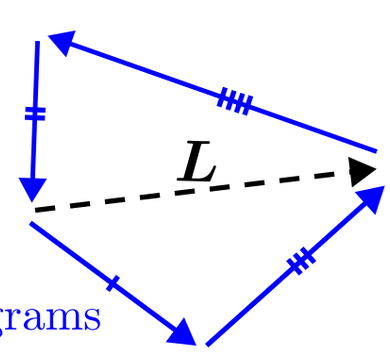
Quadrilaterals

$\sim \sum$



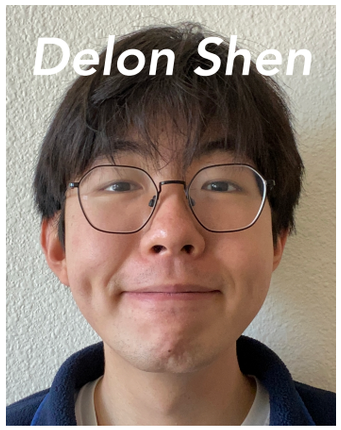
Parallelograms

$+ \sum$



Non-Parallelograms

Sherwin Das 10, Smith+15, Shen Schaan Ferraro 2024



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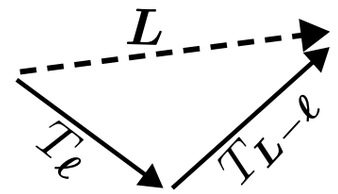
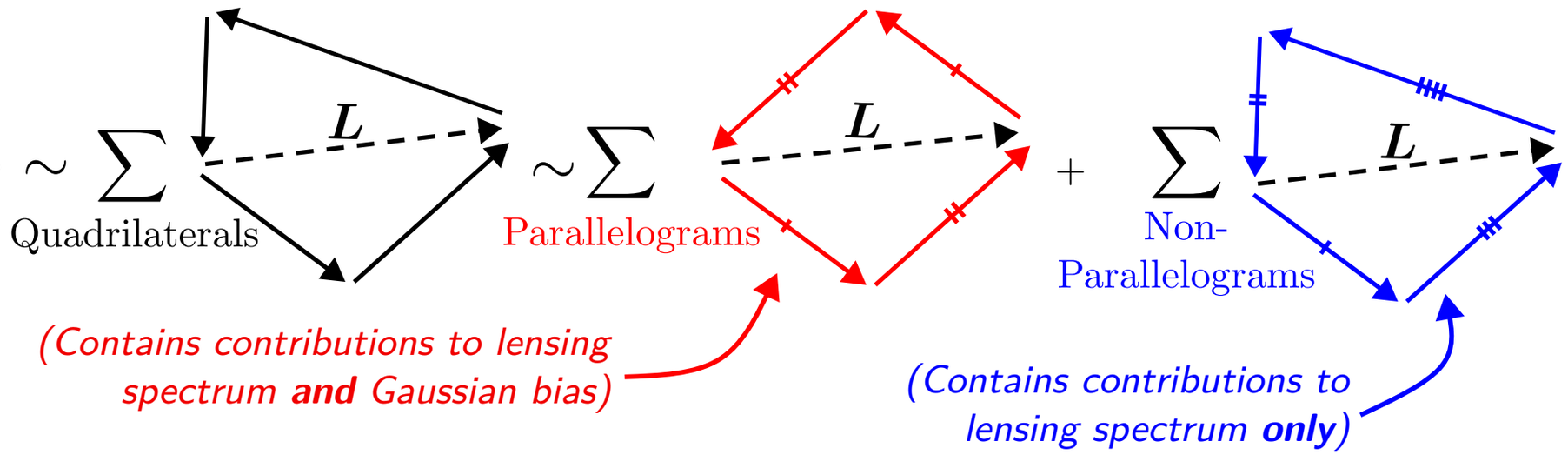


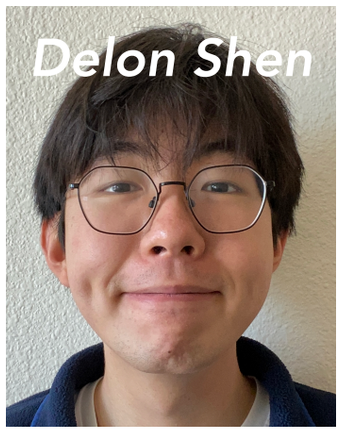
$\langle \hat{\kappa}_{\boldsymbol{L}} \hat{\kappa}^*_{\boldsymbol{L}} \rangle \sim$



*(Contains contributions to lensing spectrum **and** Gaussian bias)*

*(Contains contributions to lensing spectrum **only**)*

Sherwin Das 10, Smith+15, Shen Schaan Ferraro 2024



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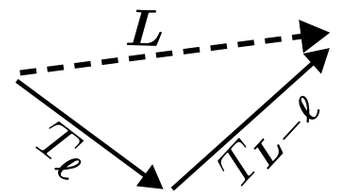
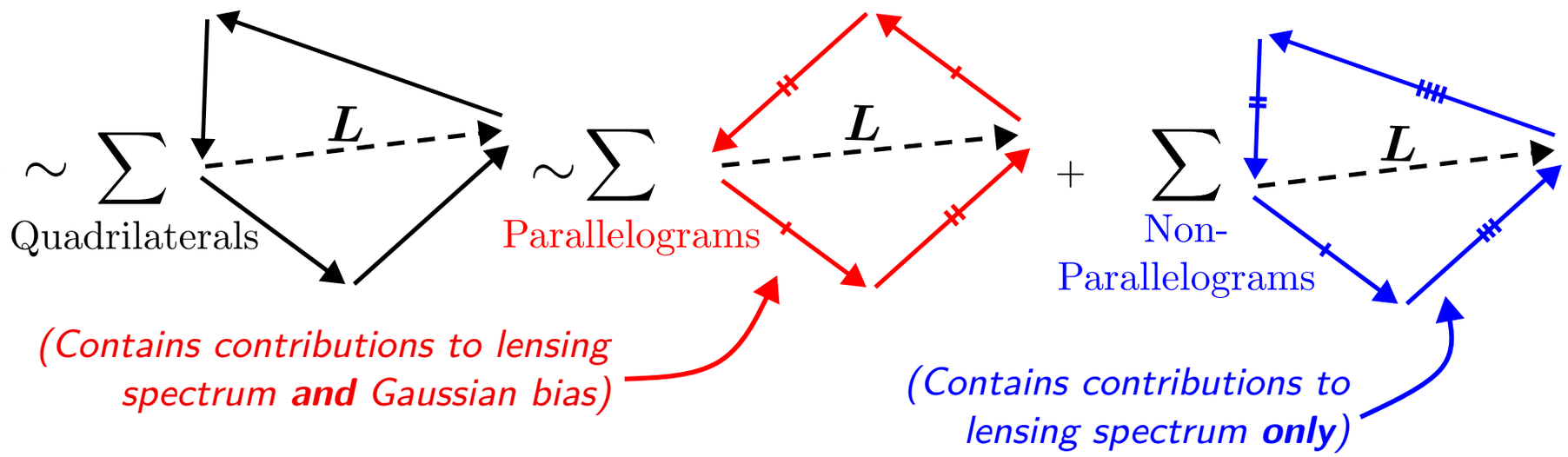
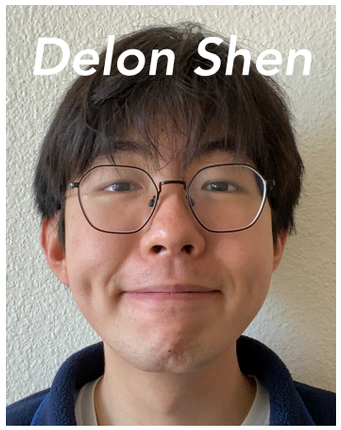


$\langle \hat{\kappa}_{\boldsymbol{L}} \hat{\kappa}^*_{\boldsymbol{L}} \rangle \sim$

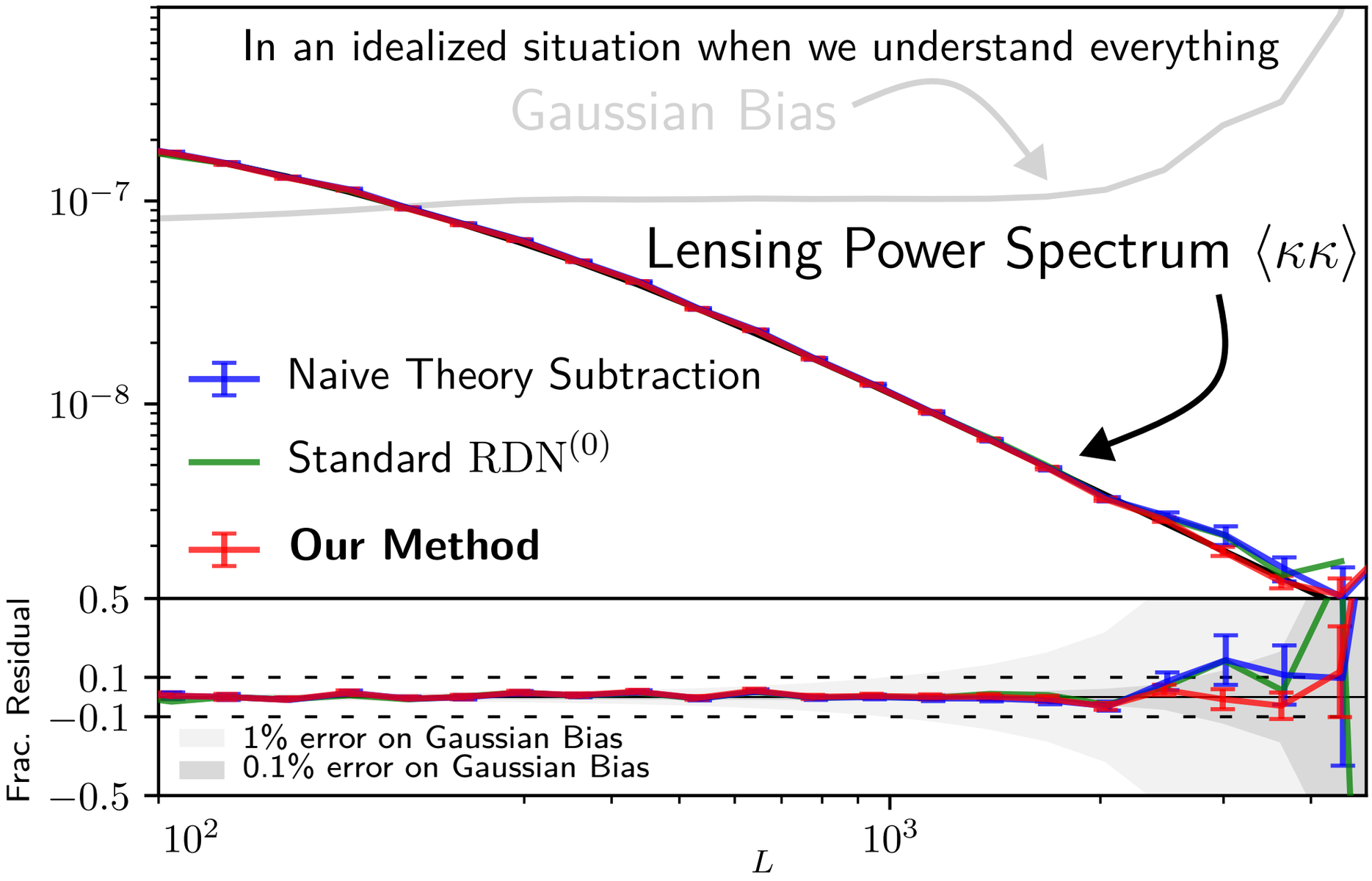


Idea: ignore all the quadrilaterals that **do** contribute to the Gaussian bias, the parallelograms

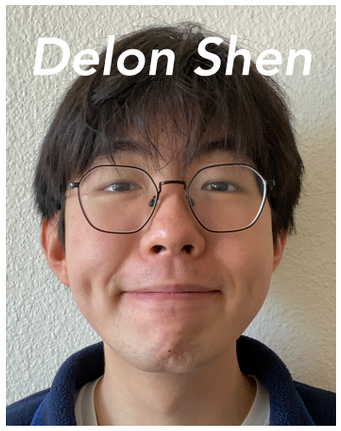
Sherwin Das 10, Smith+15, Shen Schaan Ferraro 2024



Useful with mask & noise anisotropy



Shen Schaan Ferraro 2024



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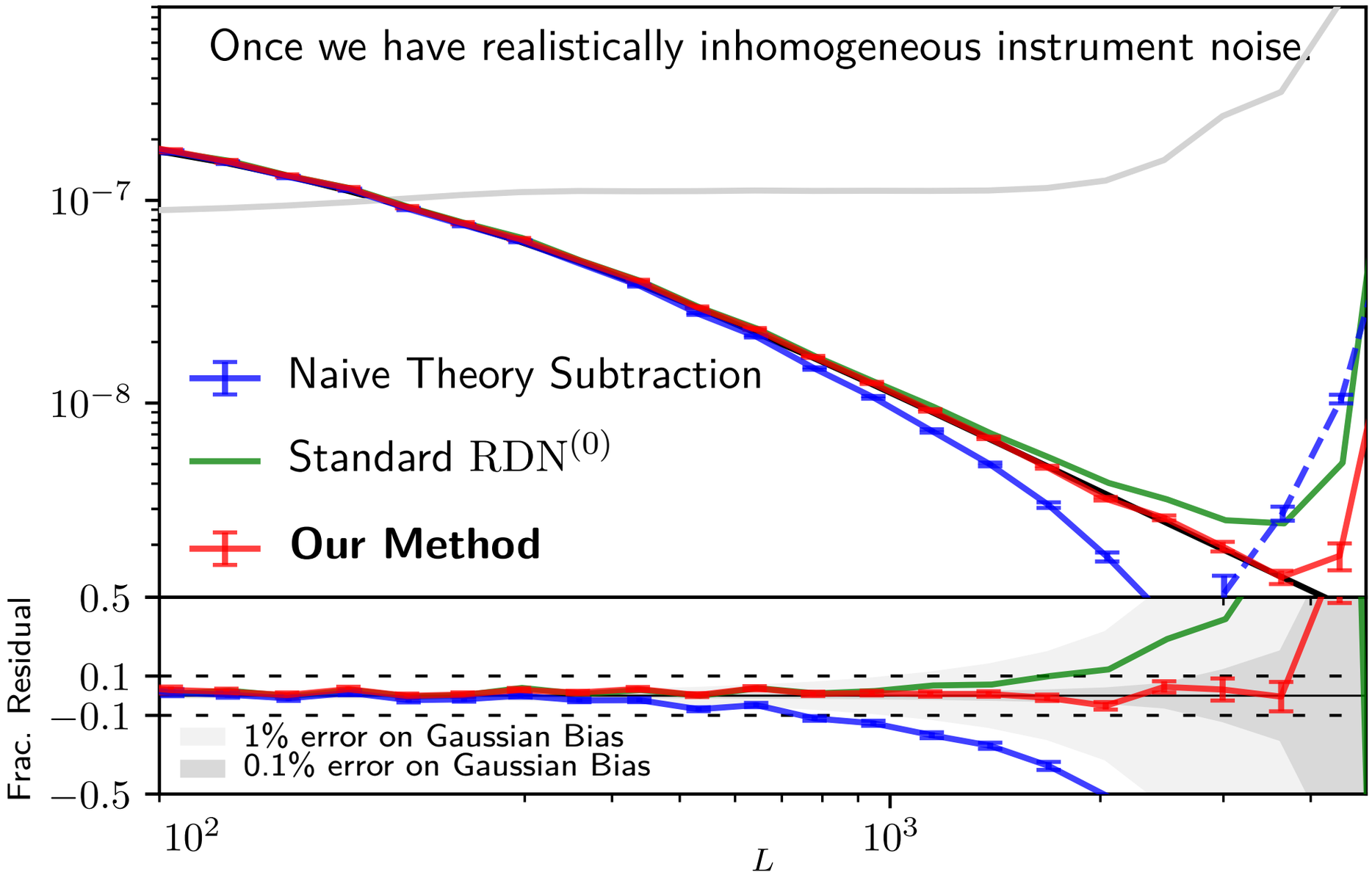


Useful even for realistic inhomogeneous noise

No computational cost

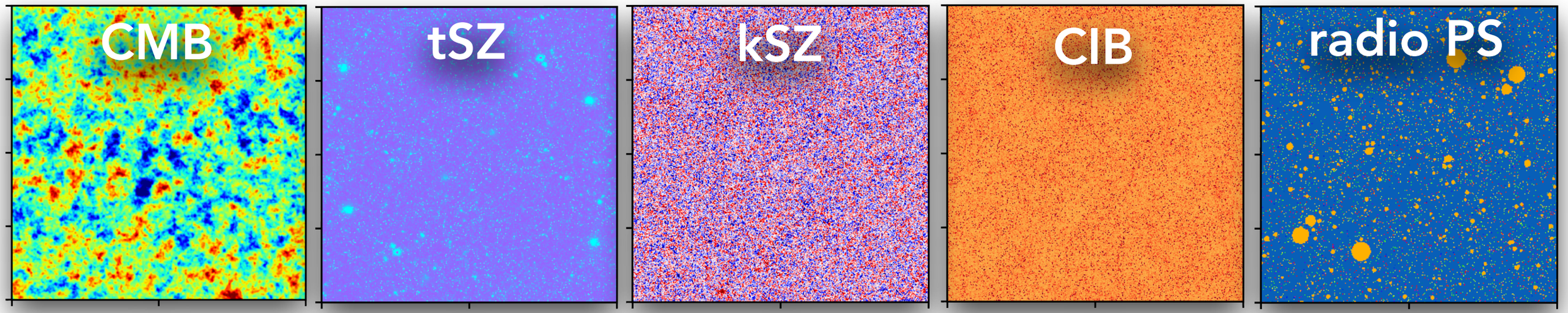
No statistical cost

Shen Schaan Ferraro 2024

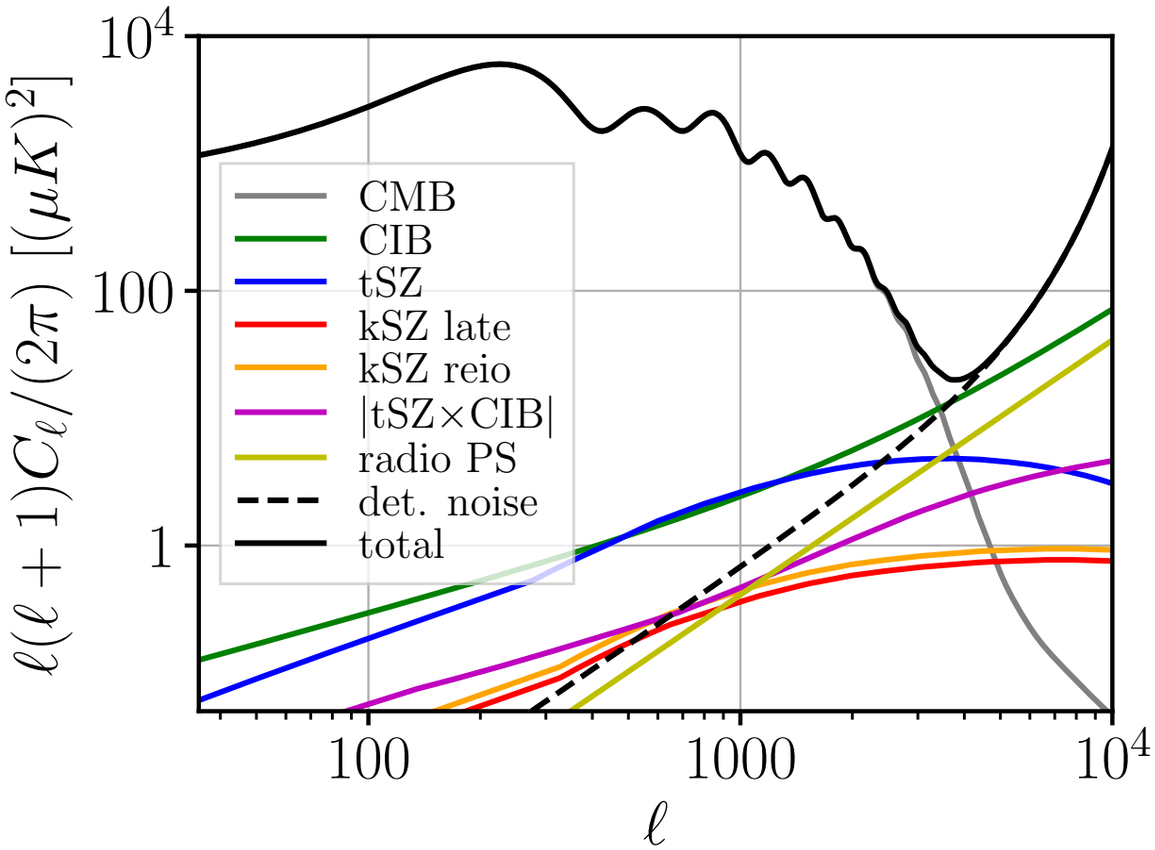
Bayesian lensing bias is robust
to polarized extragalactic foregrounds
&
Bayesian analog of point source hardening

Qu Milllea Schaan 2024

Extragalactic foregrounds: Temperature



adapted from Sehgal+09



Power dominant on small scales

→ extra noise

Statistics is non-Gaussian, uncertain and correlated with $\kappa_{\rm CMB}$

→ Several percent bias (bispec.+trispec.)

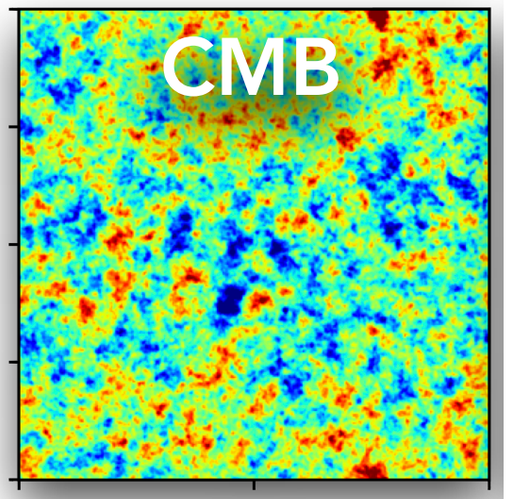
Schaan Ferraro 18

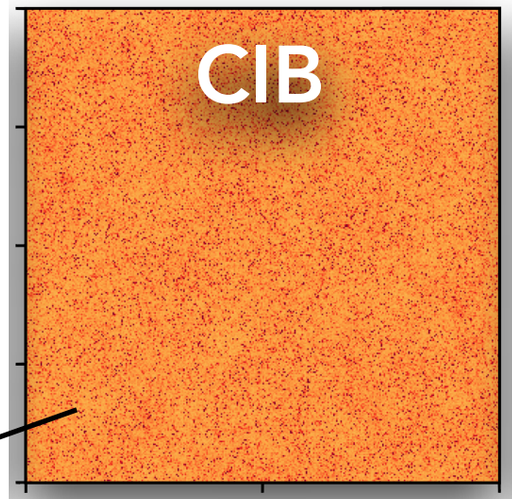
→ limits $\ell_{\rm max}$≃3000 for SO and S4

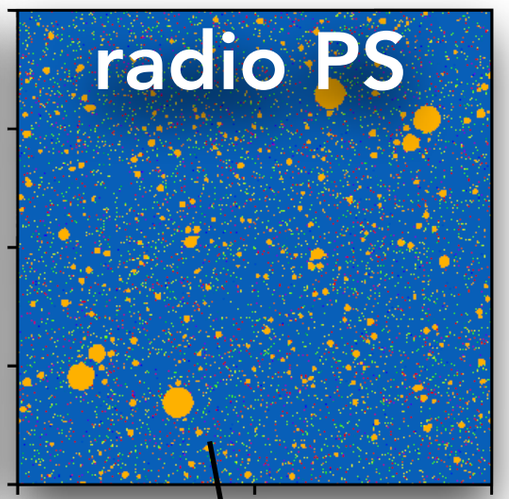
Point source/profile hardening, shear, asymmetric QE help

Sailer+21, 23, Darwish+23, Madhavacheril Hill 18 & many more

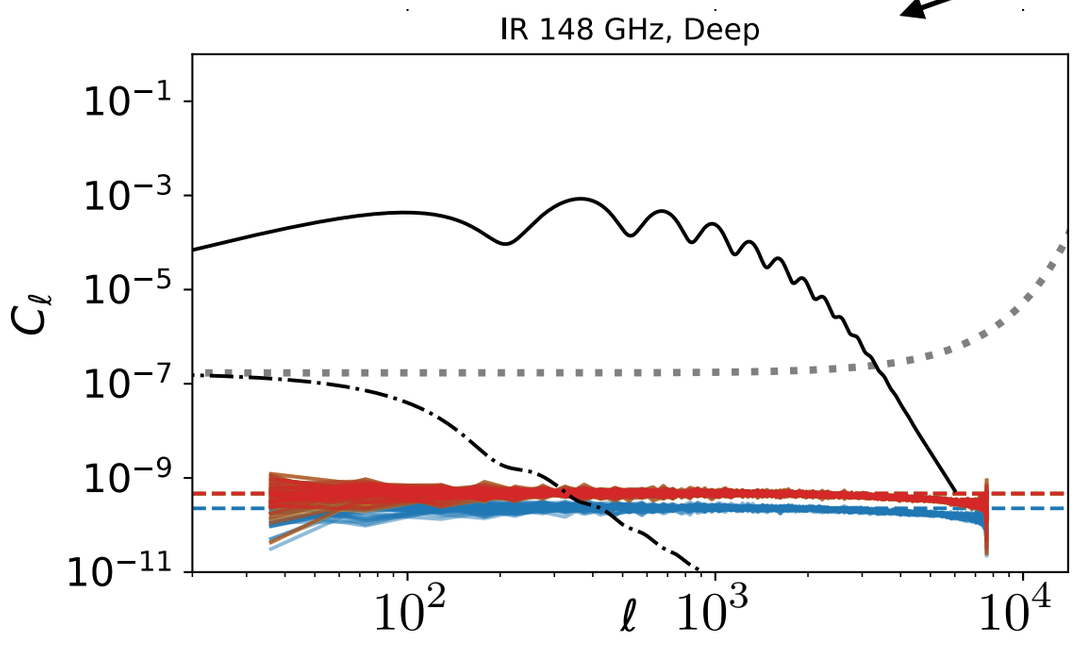
Extragalactic foregrounds: Polarization

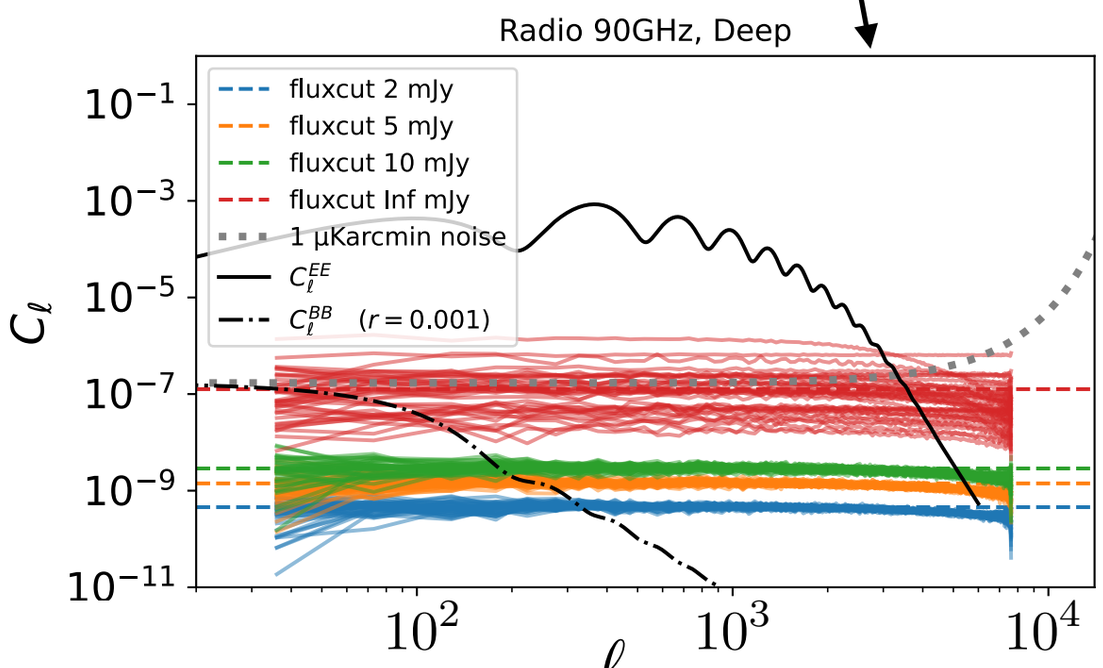






adapted from Sehgal+09





Fewer foregrounds, smaller power, simpler statistics (Poisson)

Radio power scales as sensitivity after masking point sources

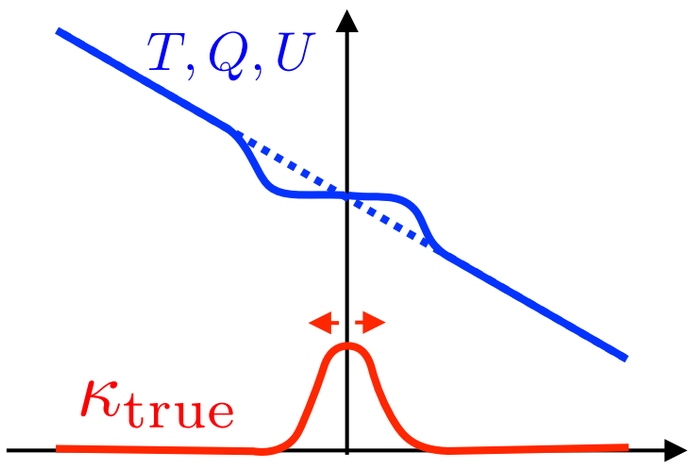
Optimal methods outperform QE in polarization

→ Sensitivity to foregrounds? Analog of point source hardening?

Optimal lensing fits point sources as convergence dipoles

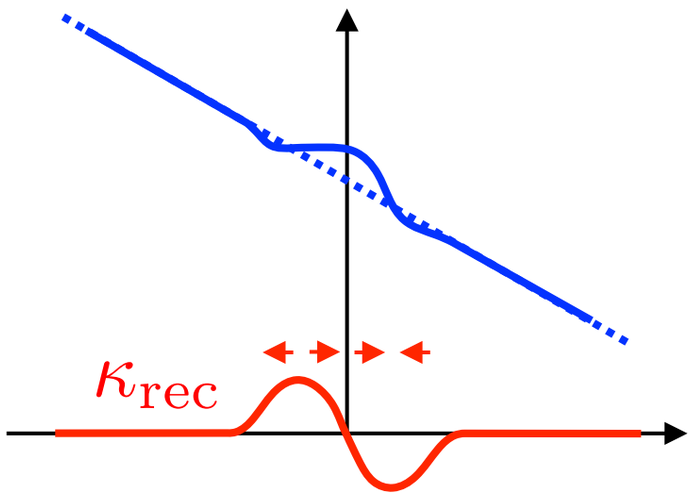
Point source in $\kappa_{\rm true}$

$\implies$ dipole in T, Q, U

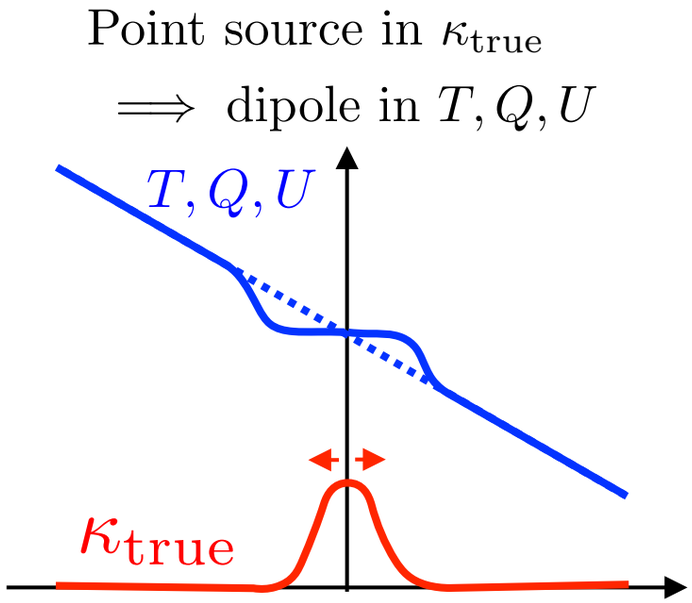


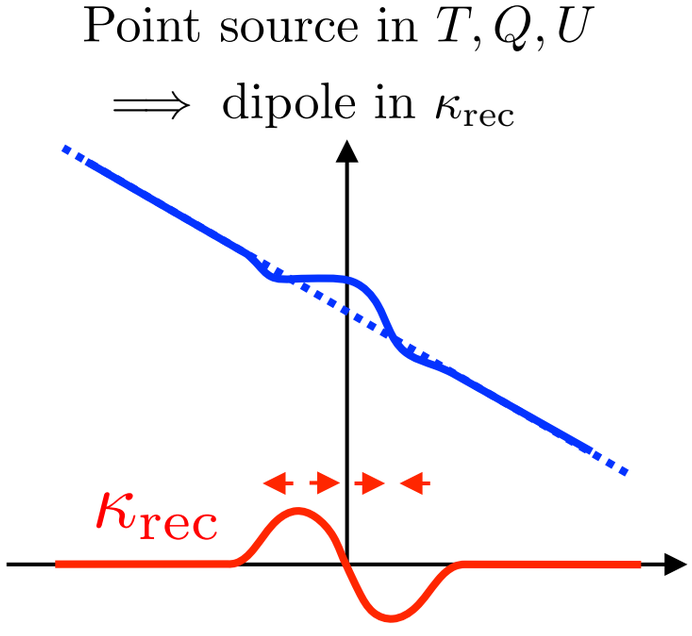
Point source in T, Q, U

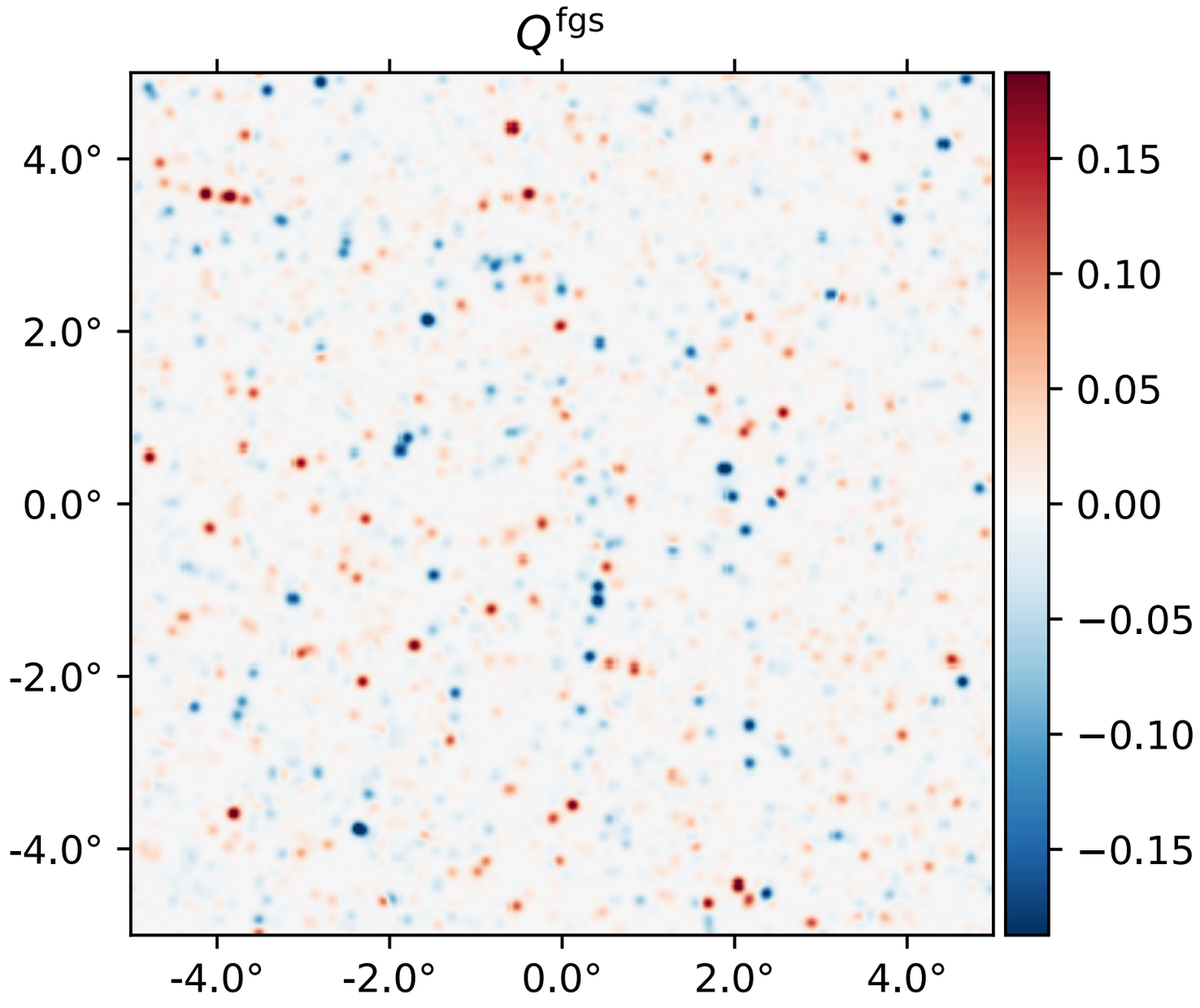
$\implies$ dipole in $\kappa_{\rm rec}$



Optimal lensing fits point sources as convergence dipoles







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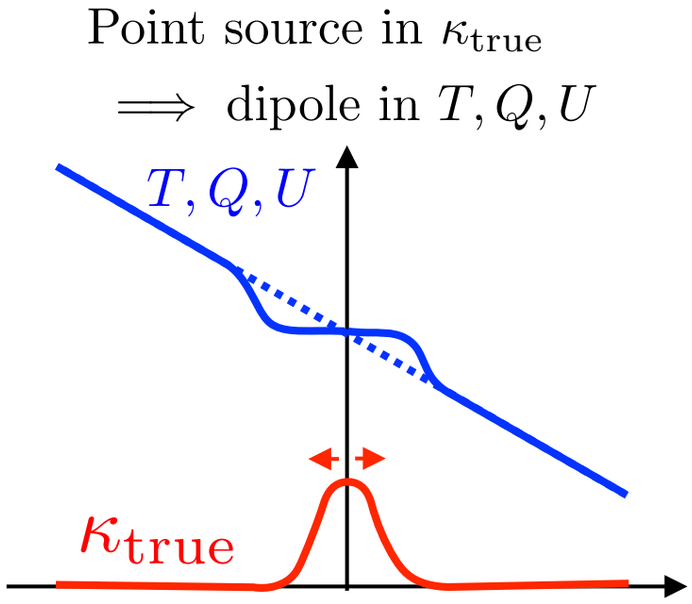
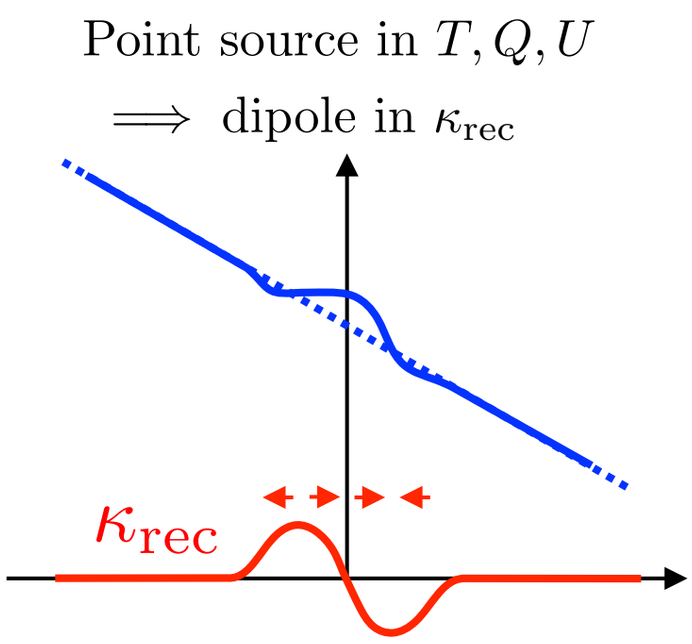
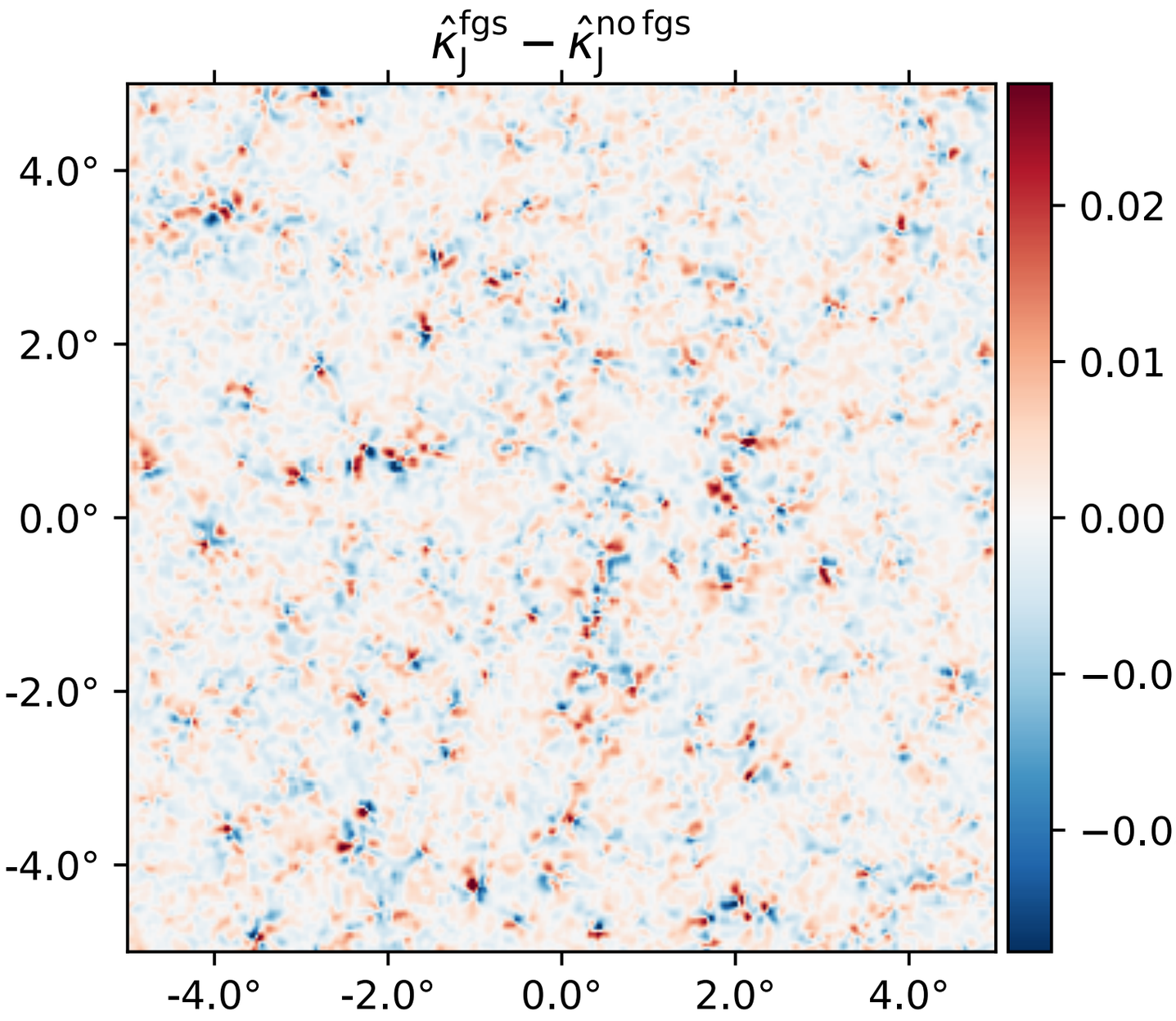
Optimal lensing fits point sources as convergence dipoles







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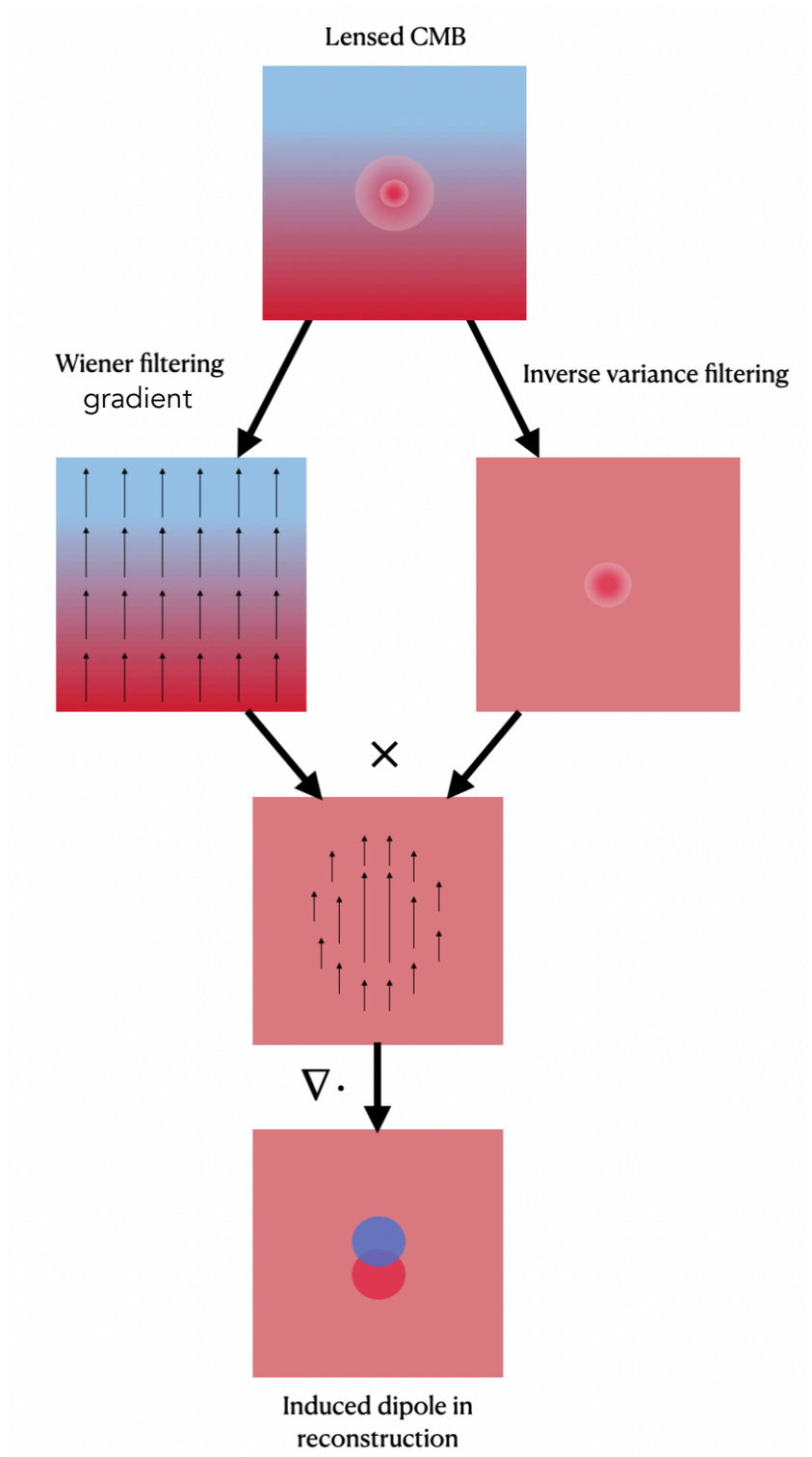
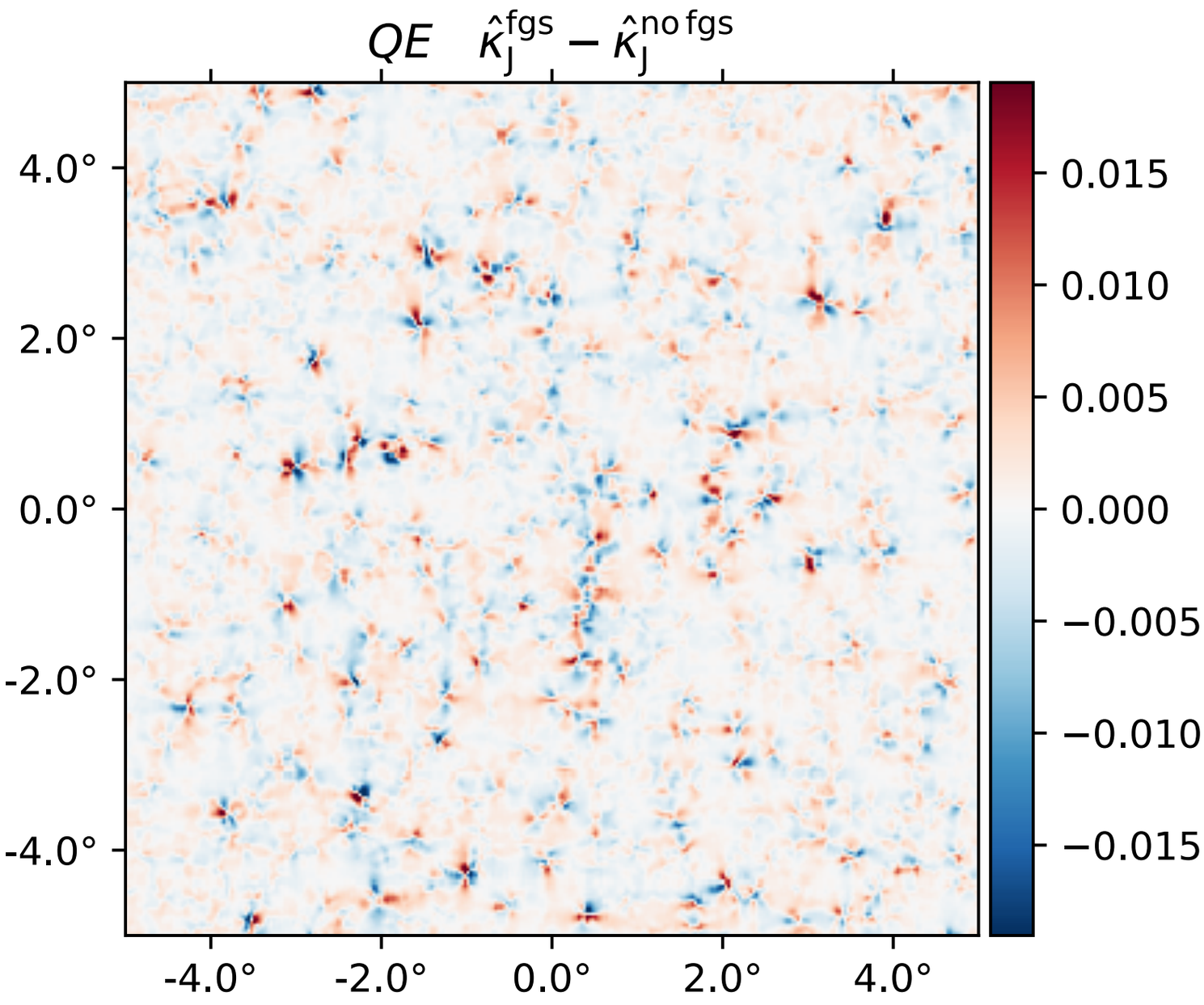
QE too!





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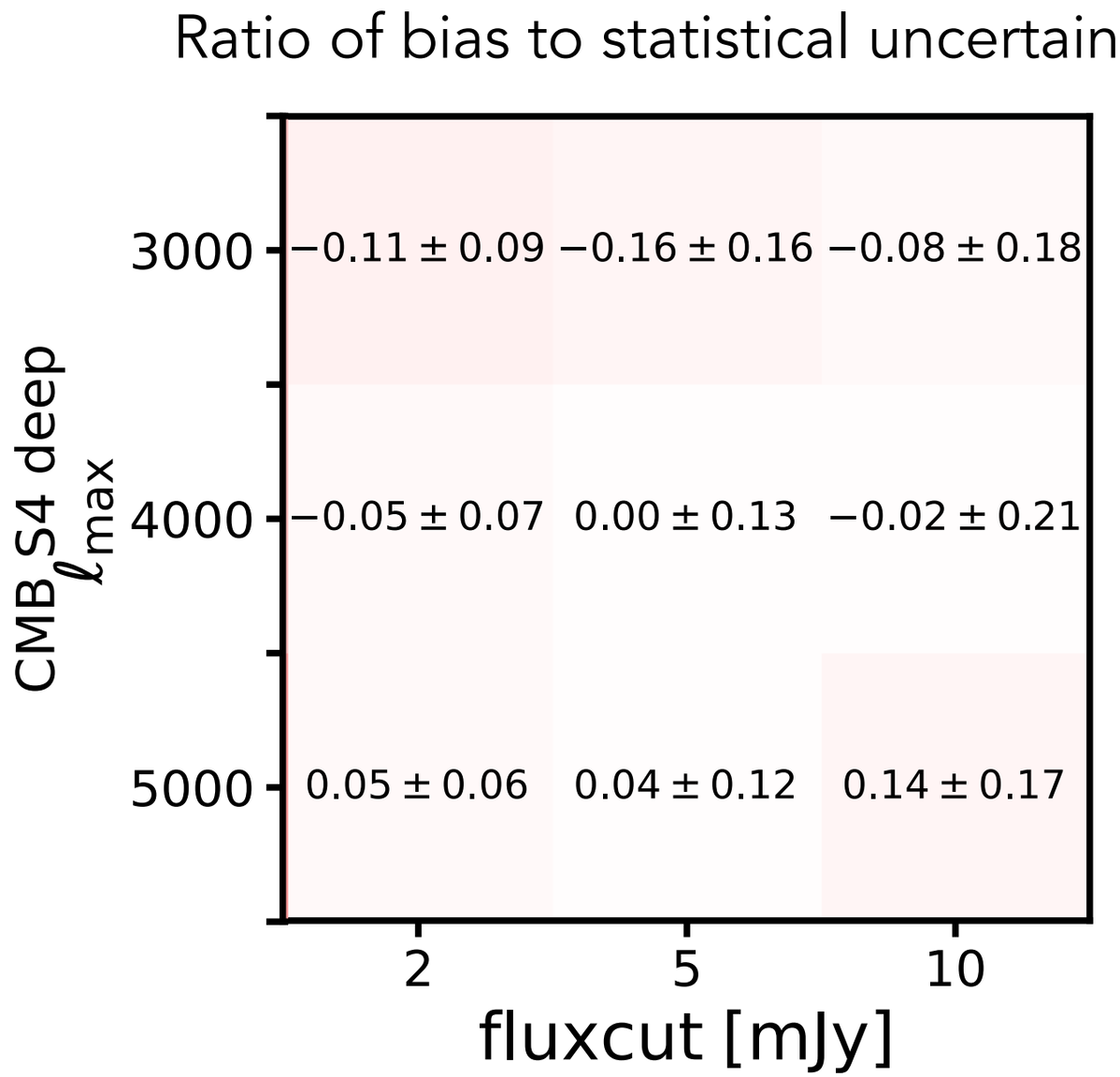
Bias to Bayesian lensing is small for CMB-S4



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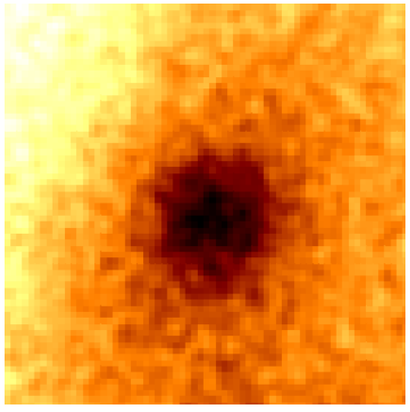
For futuristic experiments where the bias may be important,
we derive an analog to point source hardening

Outline: Combining CMB & LSS

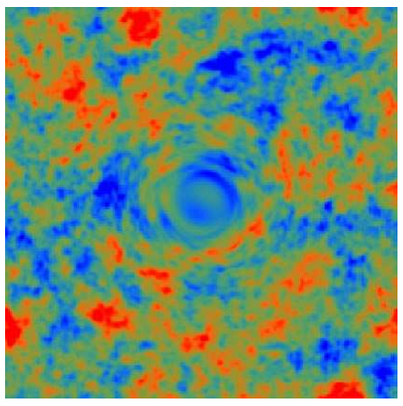
Gas shadows

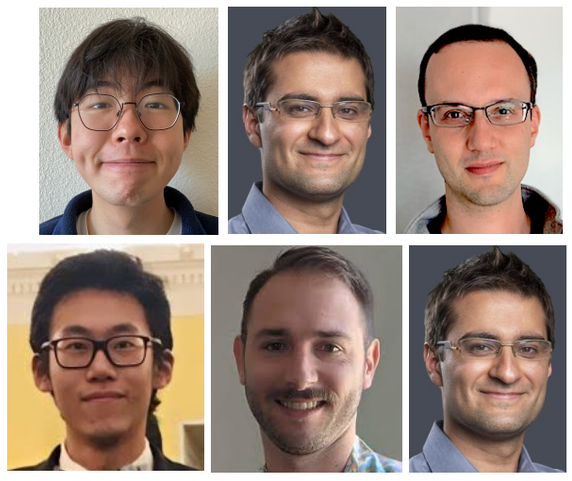


ACT x DESI kSZ & tSZ

Hadzhiyska+23, 24
RiedGuachalla+23, 25
Liu+24

Mass shadows





CMB lensing noise bias avoidance

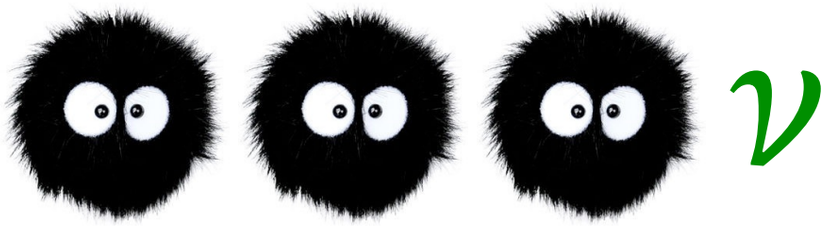
Shen Schaan Ferraro 23

Bayesian lensing bias

from polarized extragalactic foregrounds

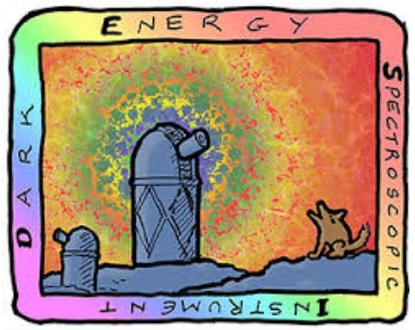
Qu Millea Schaan 24

Conclusions



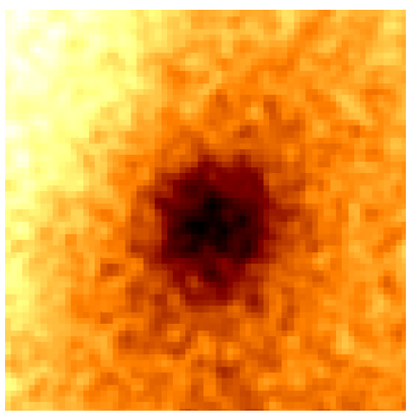
Key Astrophysics & BSM physics

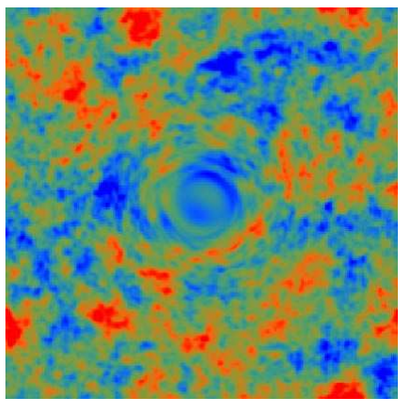
Galaxy formation, dark energy, dark matter, inflation, neutrinos



Key new experiments coming along

DESI, Rubin LSST, Simons Observatory





CMB is a large-scale structure probe

Useful insights from combining CMB & LSS

Thank you!