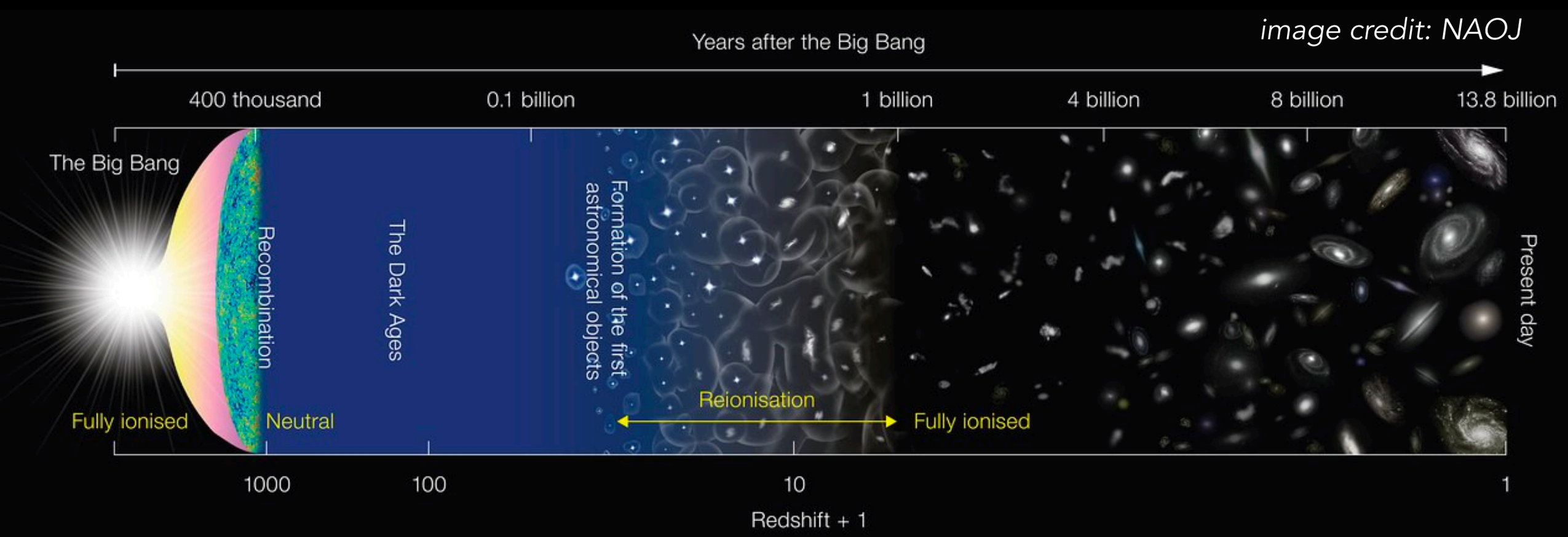
Emmanuel Schaan Chamberlain fellow

Backlighting the Universe

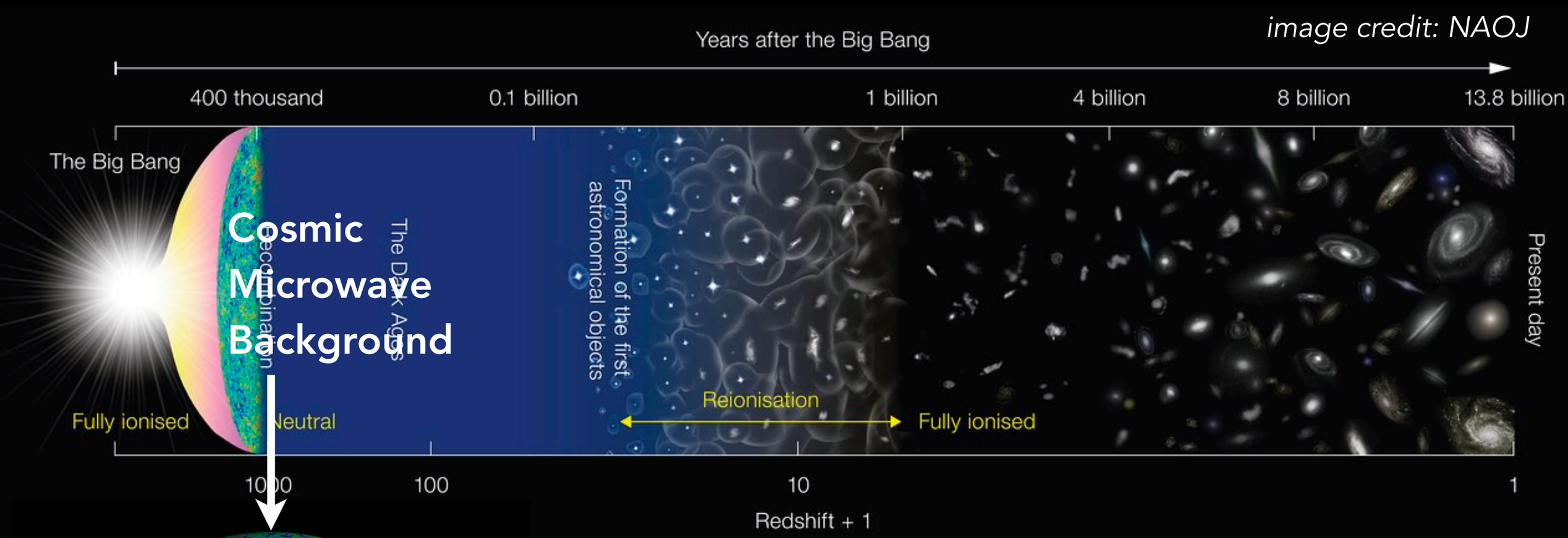
Cosmic Microwave Background Secondary Anisotropies

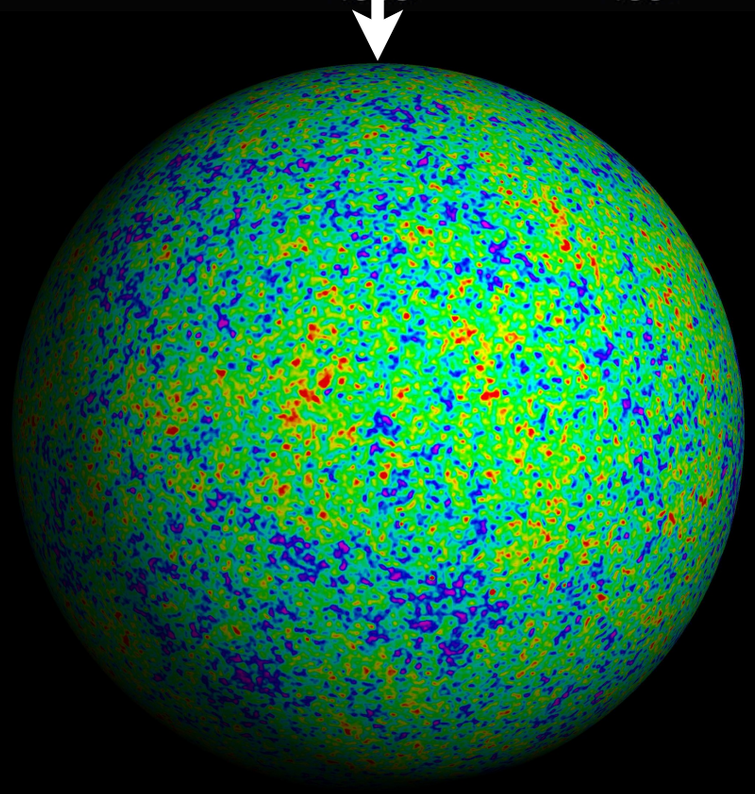
The Universe as a fundamental Physics laboratory



The Universe as a fundamental Physics laboratory

image credit: NAOJ

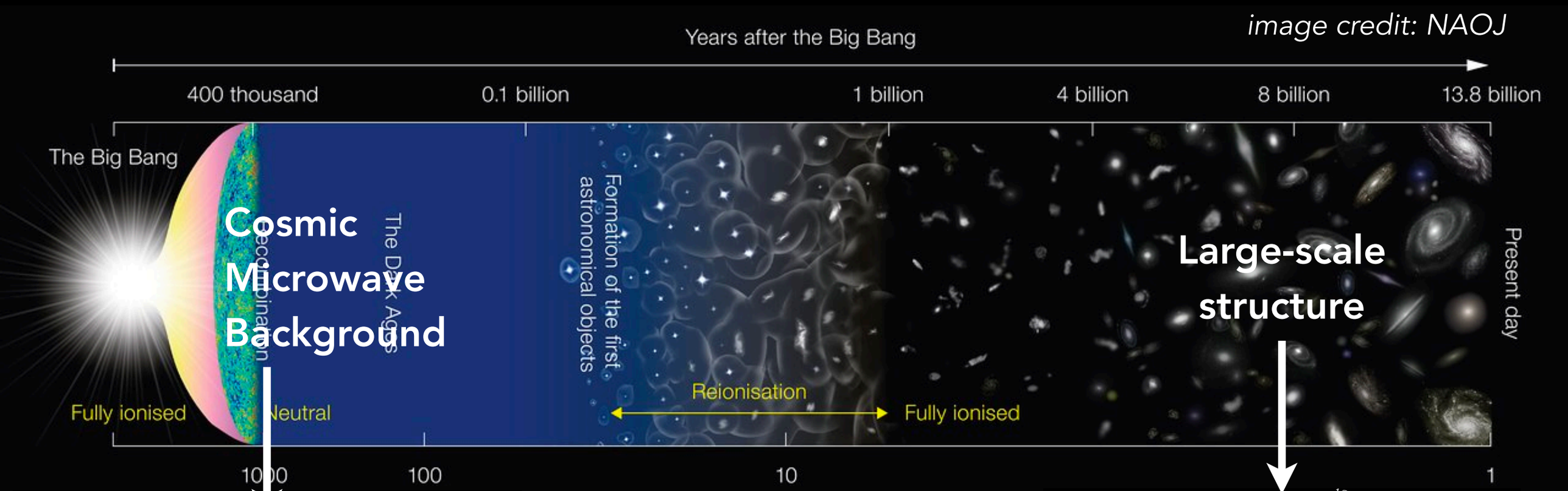


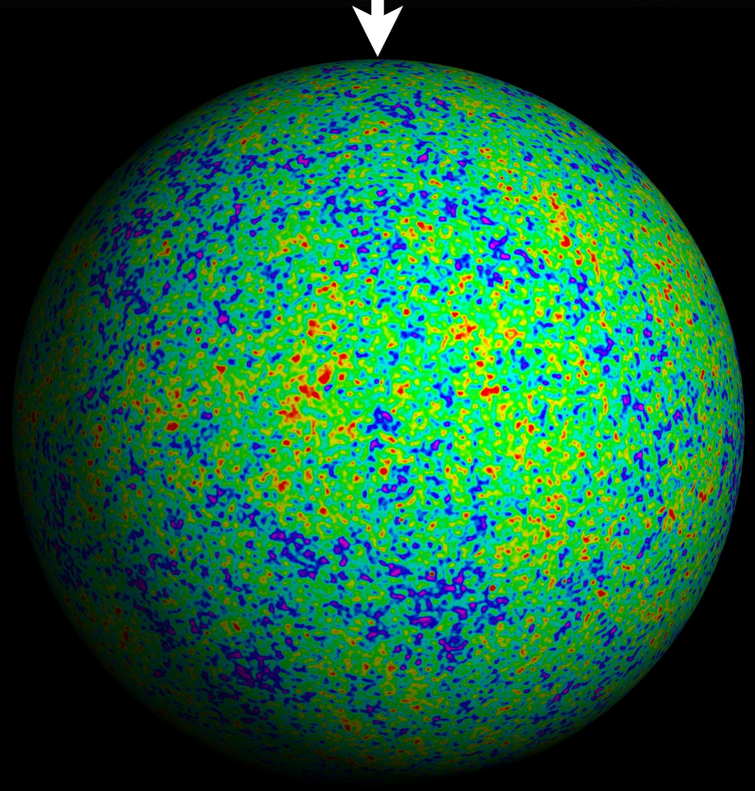


Tegmark, WMAP3

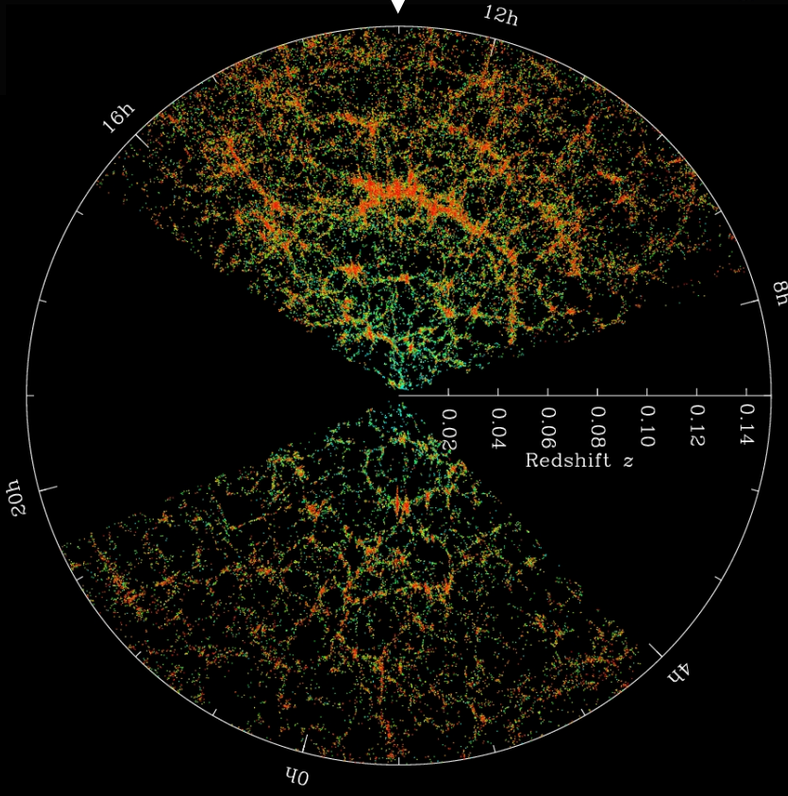
The Universe as a fundamental Physics laboratory

image credit: NAOJ



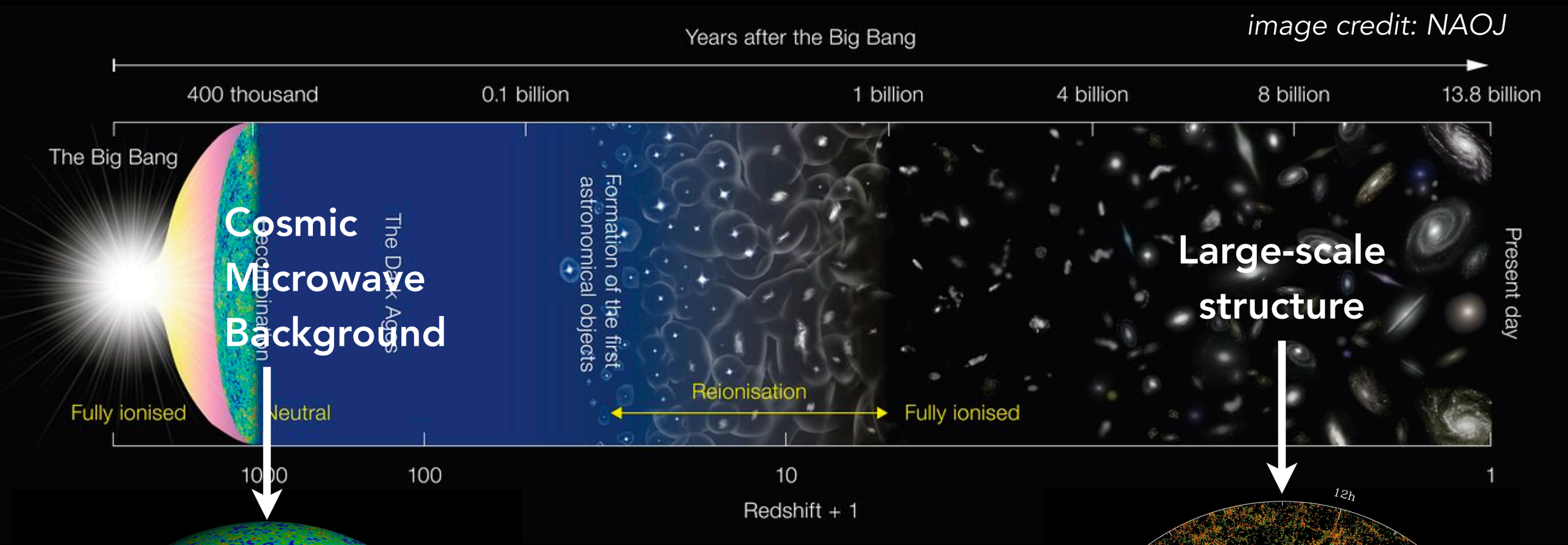


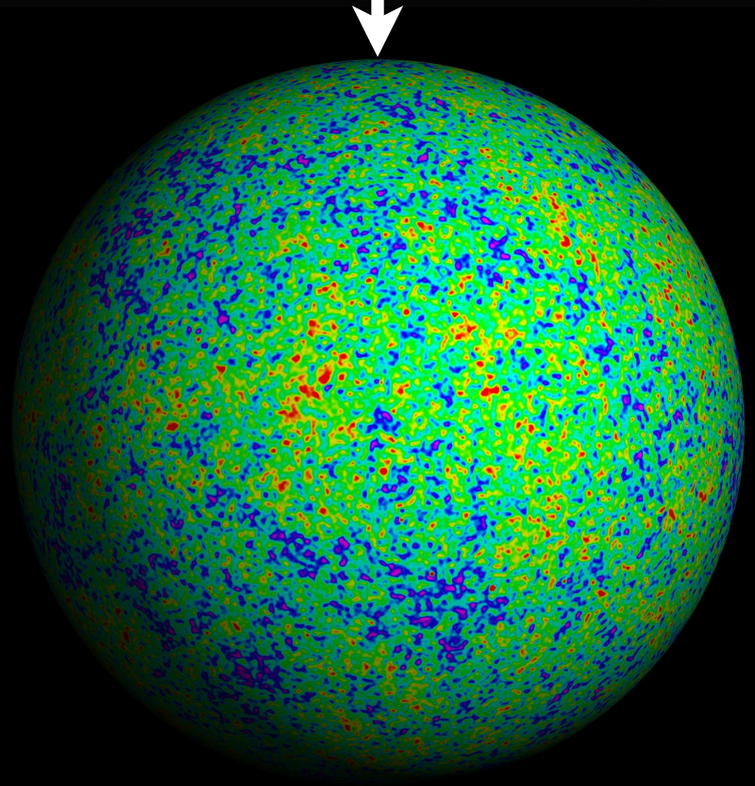
Tegmark, WMAP3



Blanton, SDSS

The Universe as a fundamental Physics laboratory



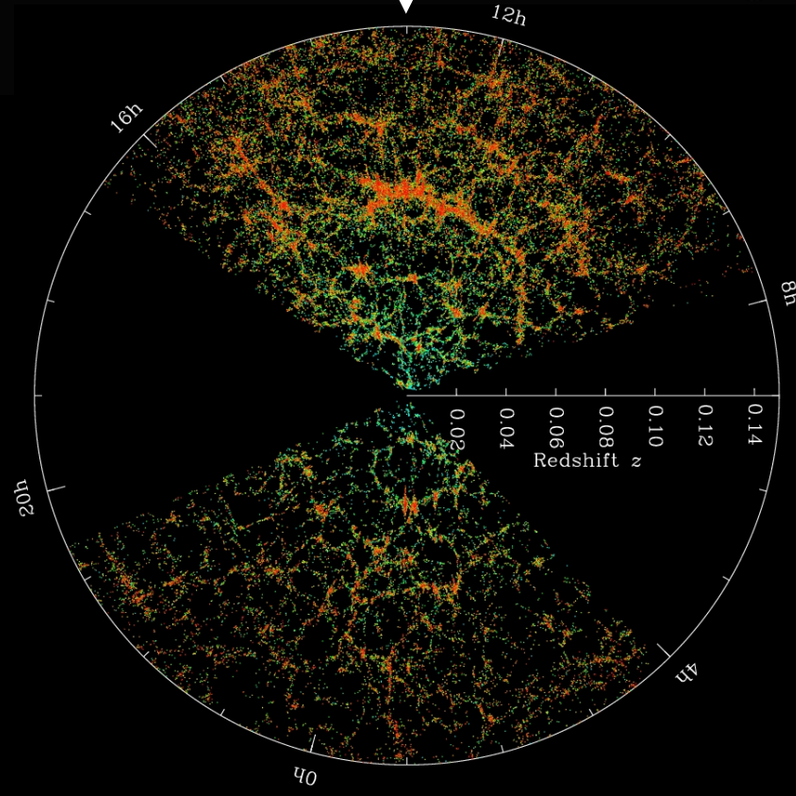


Tegmark, WMAP3

Dark energy

Dark matter

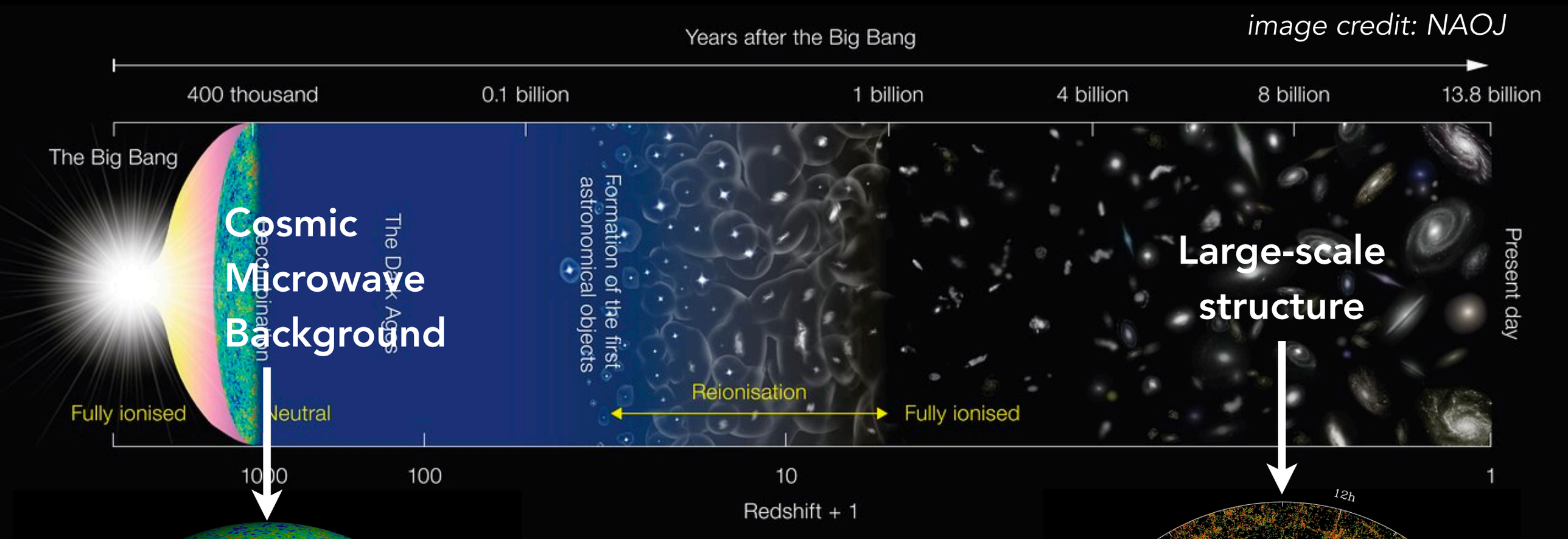
Inflation

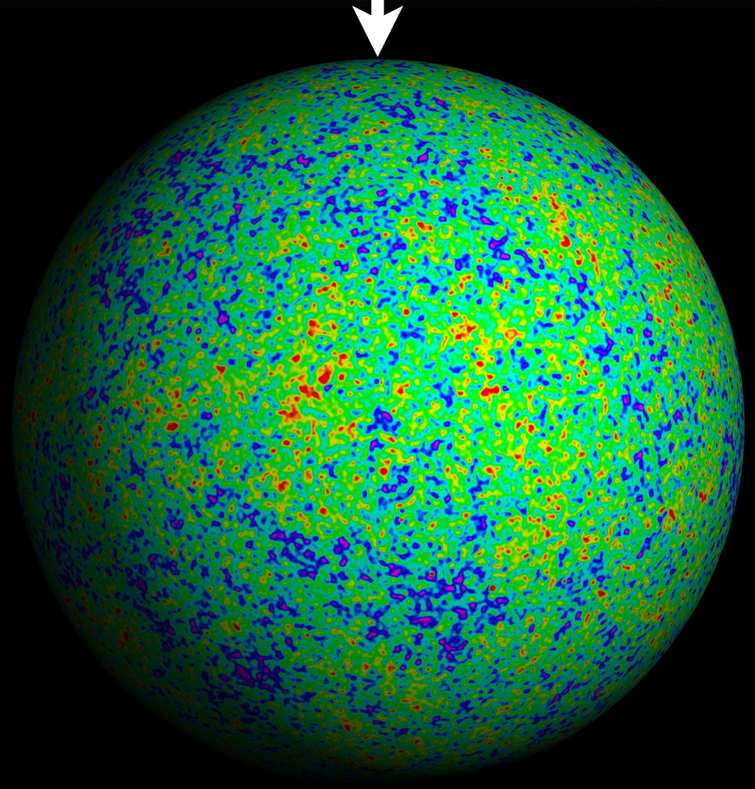


Blanton, SDSS

The Universe as a fundamental Physics laboratory

image credit: NAOJ





Tegmark, WMAP3

Dark energy

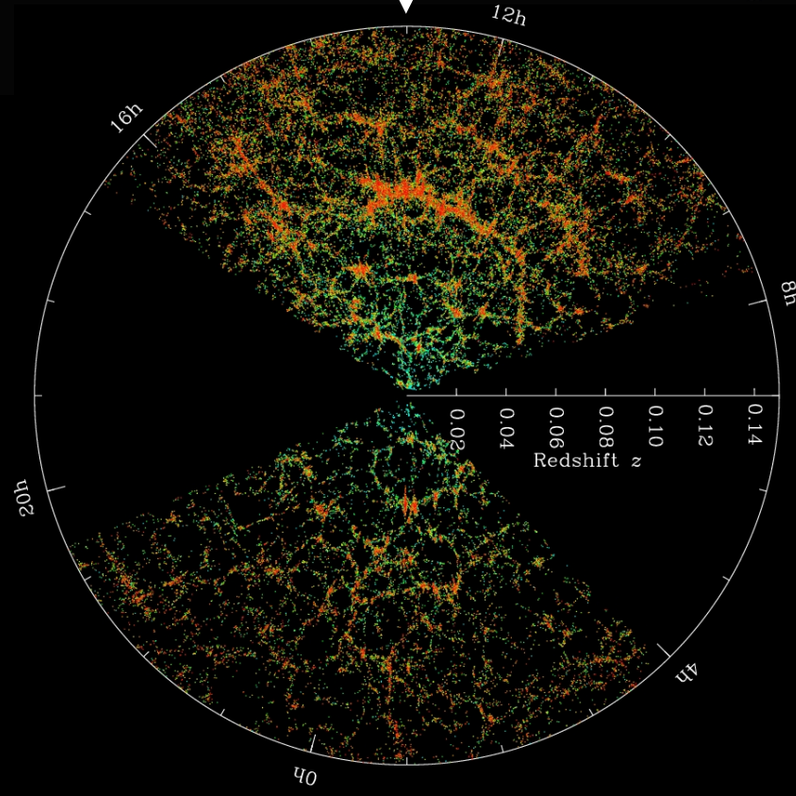
Energy density, equation of state?

Dark matter

Interactions, temperature?

Inflation

Number of fields, interactions, energy scale?



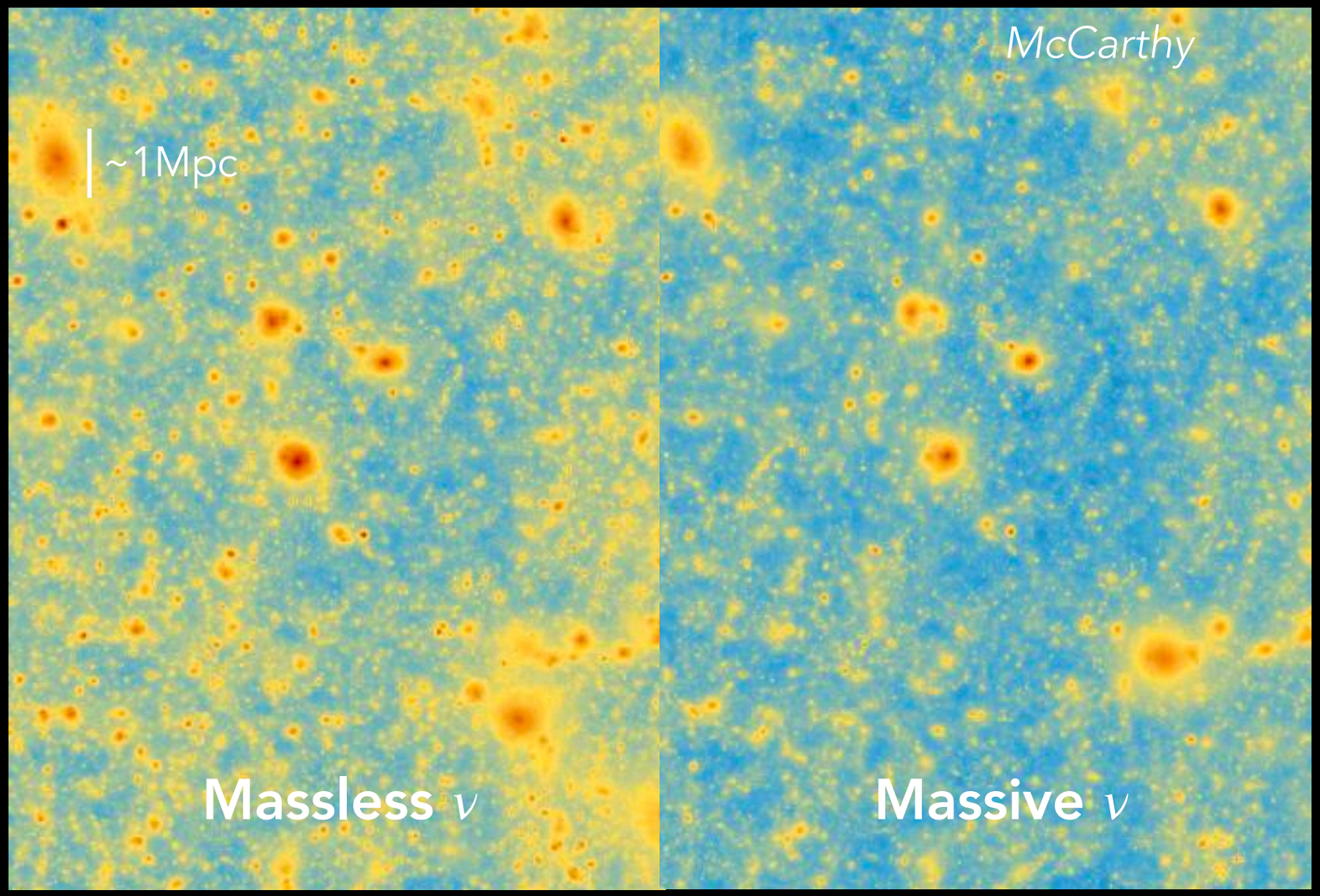
Blanton, SDSS

Neutrinos

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

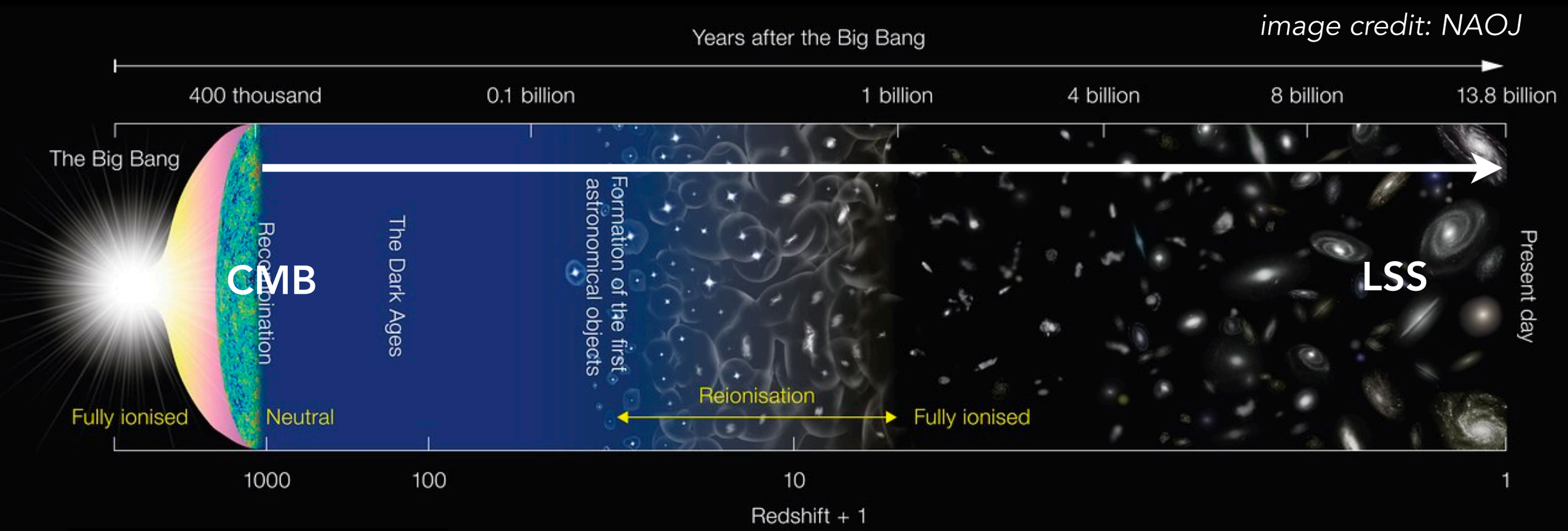
Cosmology can weigh the neutrinos

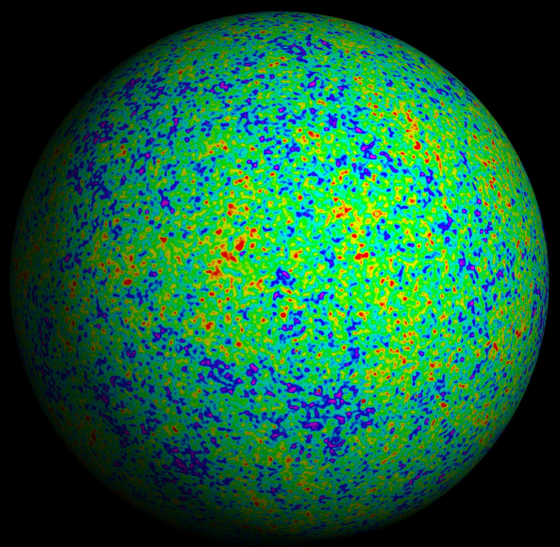
Neutrinos = 0.5% of all matter, but their gravity suppresses LSS 8-fold = 4%



→ CMB & LSS: masses to ~ 20 meV precision

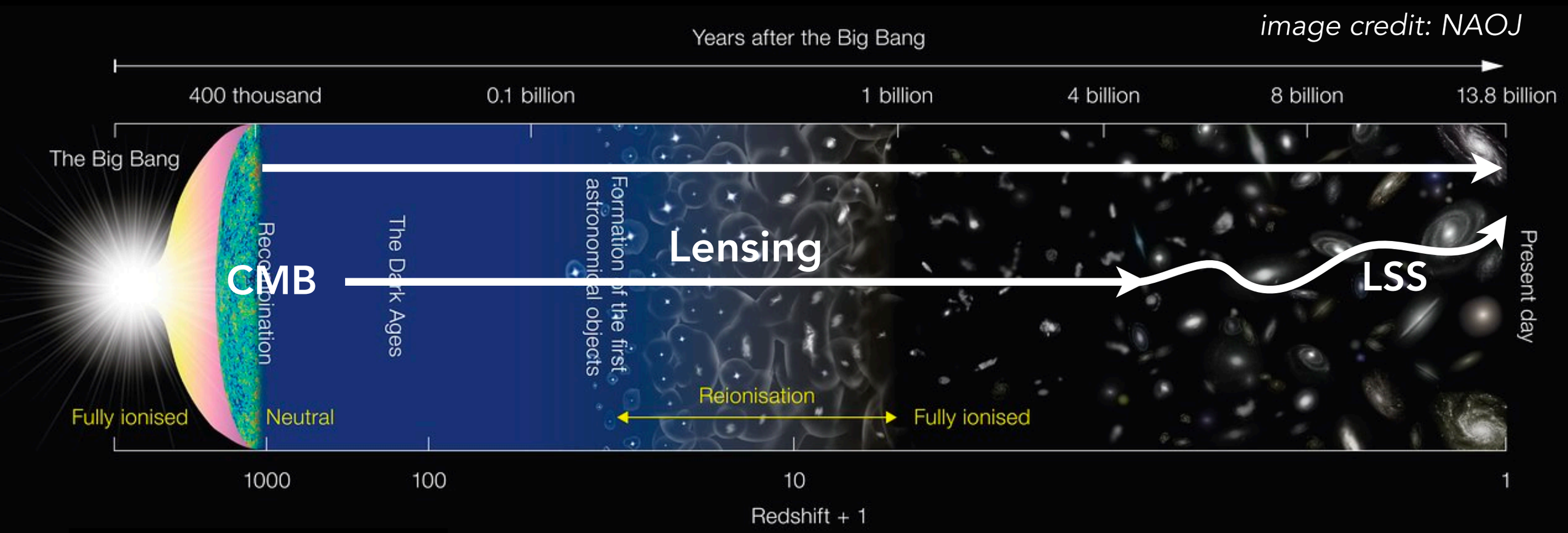
How? CMB *is* an LSS probe

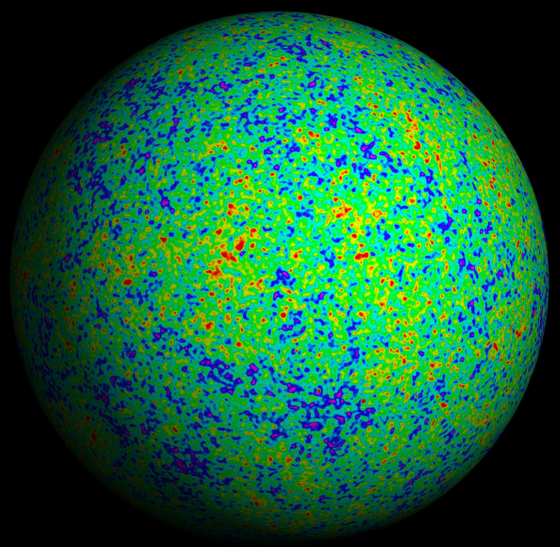




Initial conditions

How? CMB *is* an LSS probe





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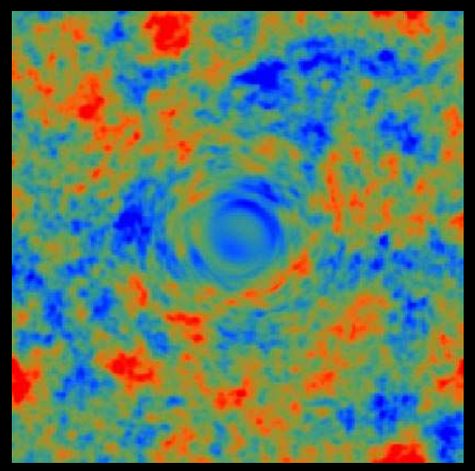
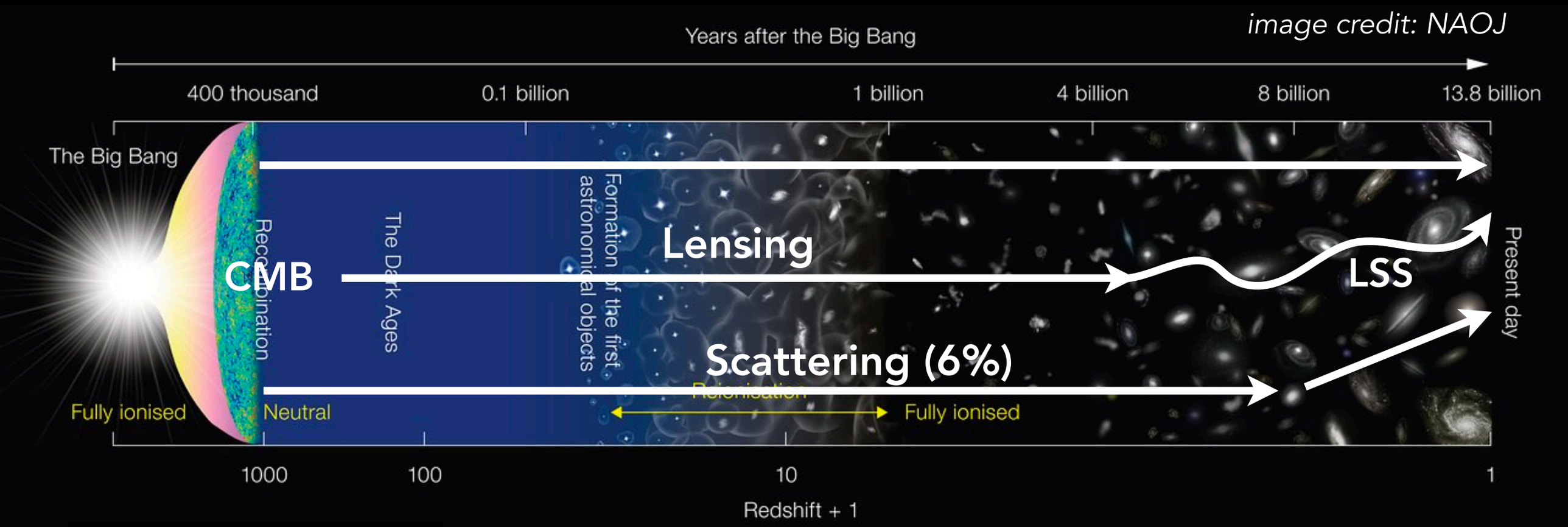
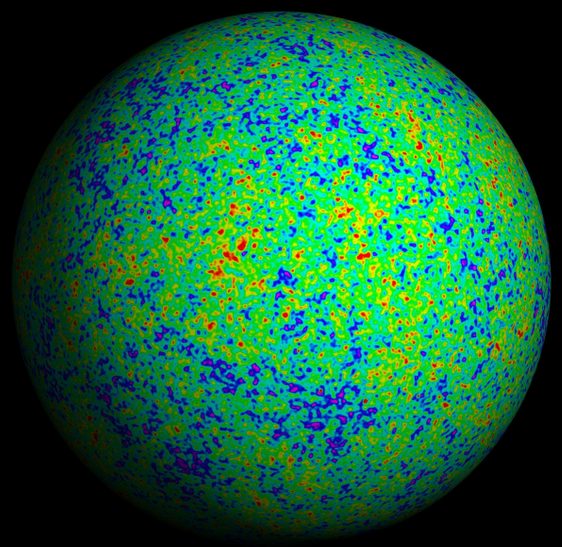


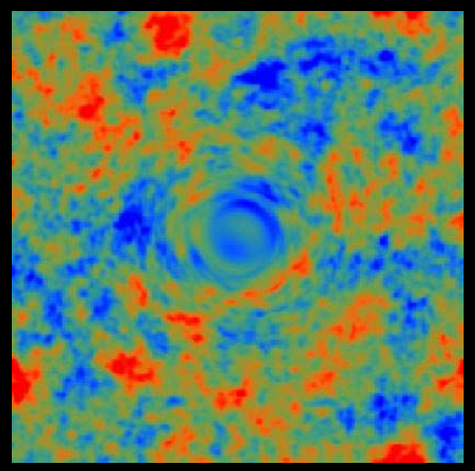
Lensing:
Mass shadows

How? CMB *is* an LSS probe





Initial conditions



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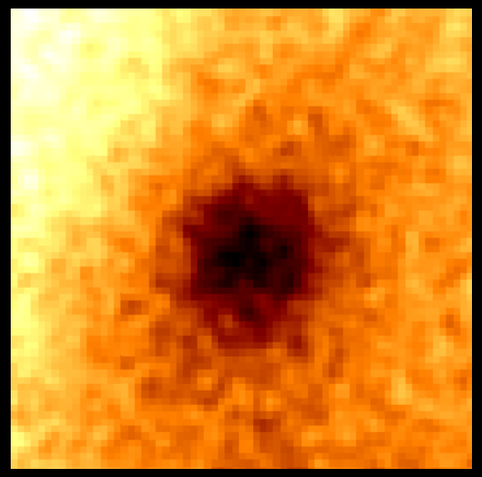

Scattering:
Gas shadows

LSS imprints on the CMB

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	$\theta_{\rm lens}$	Total mass
ISW, Rees-Sciama	$\int dt\ \dot{\Phi}$	Accretion rate, DE
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?

LSS imprints on the CMB

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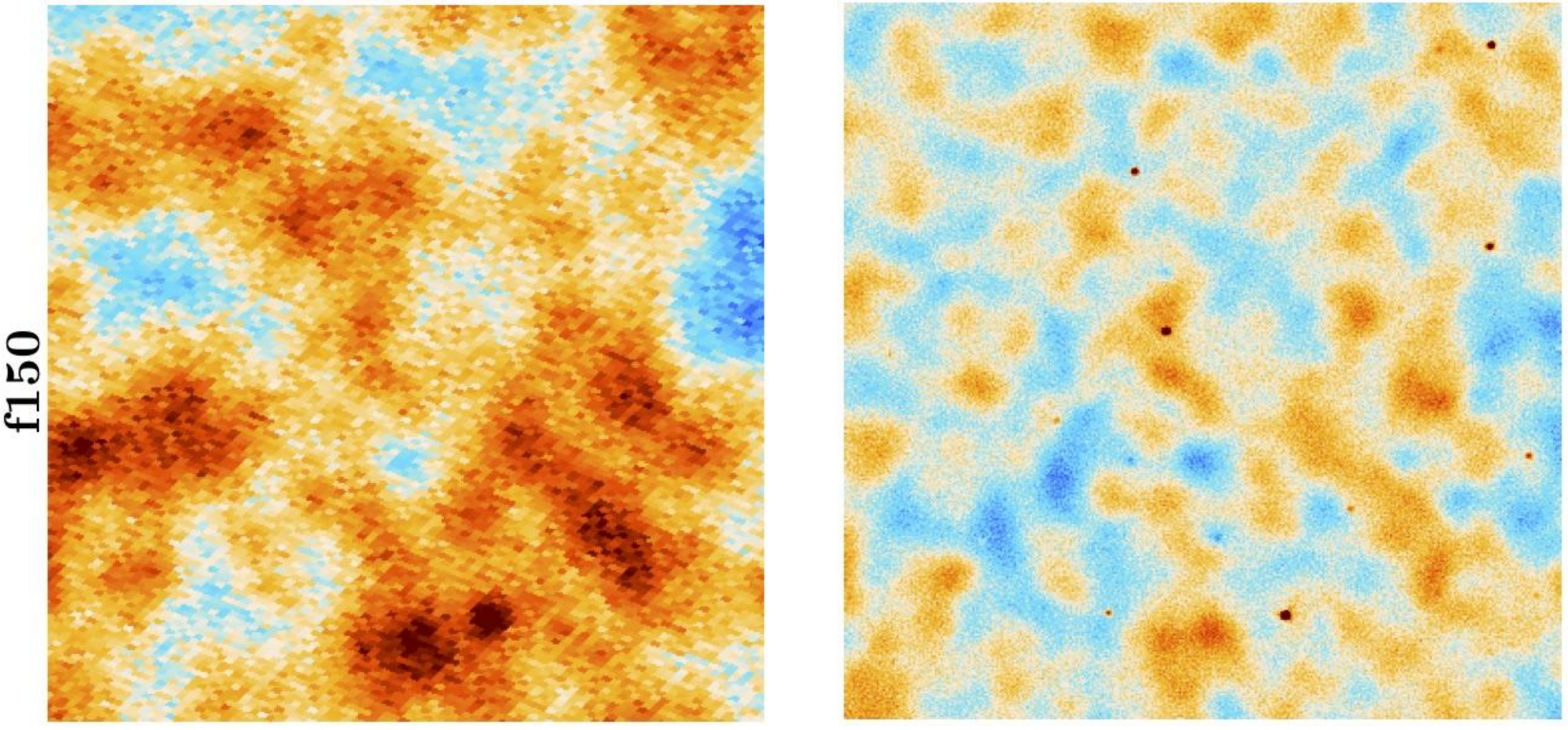
CMB can help: it *is* an LSS probe

Planck

ACT



~1deg

Naess+20

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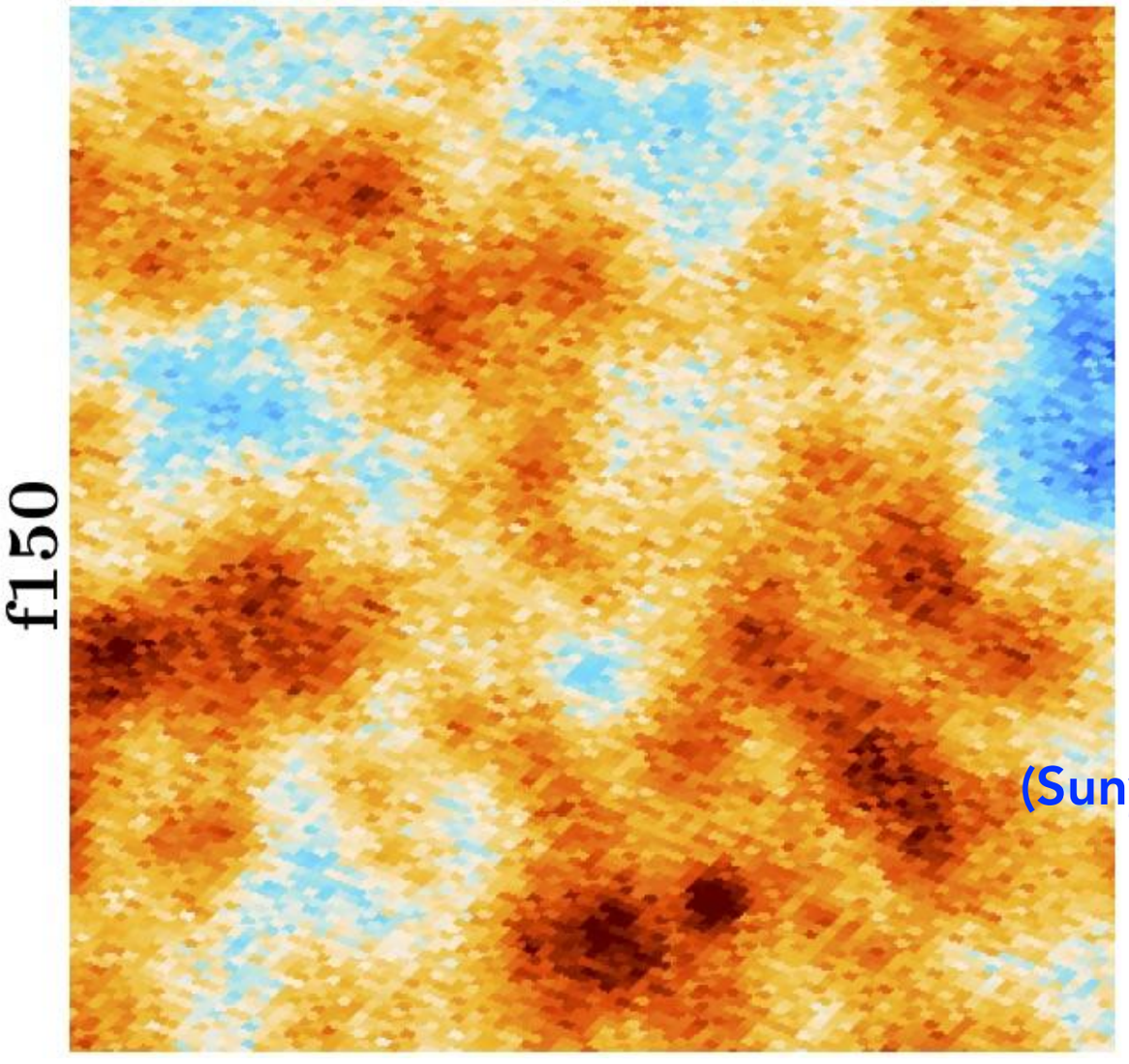
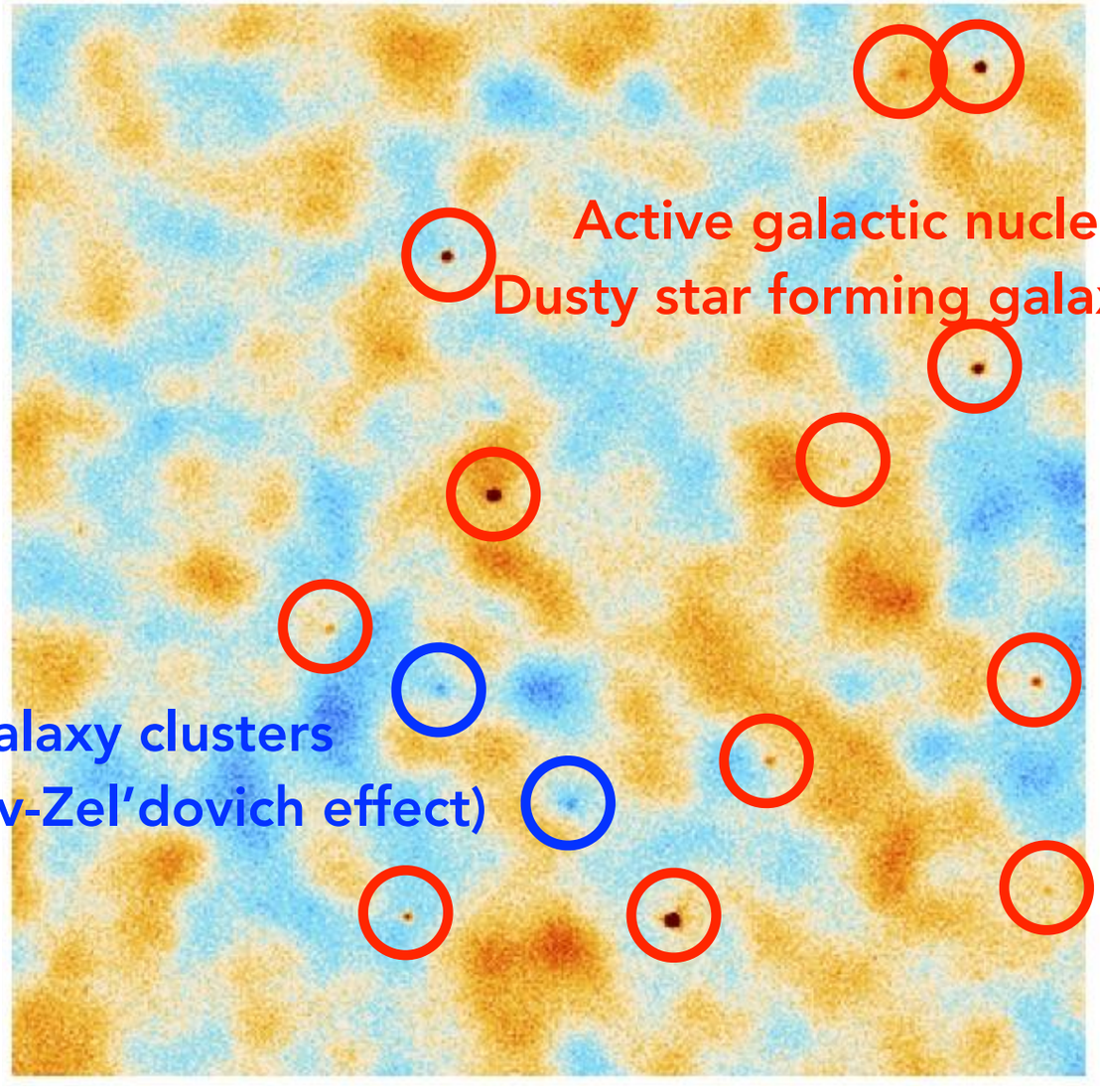
ACT





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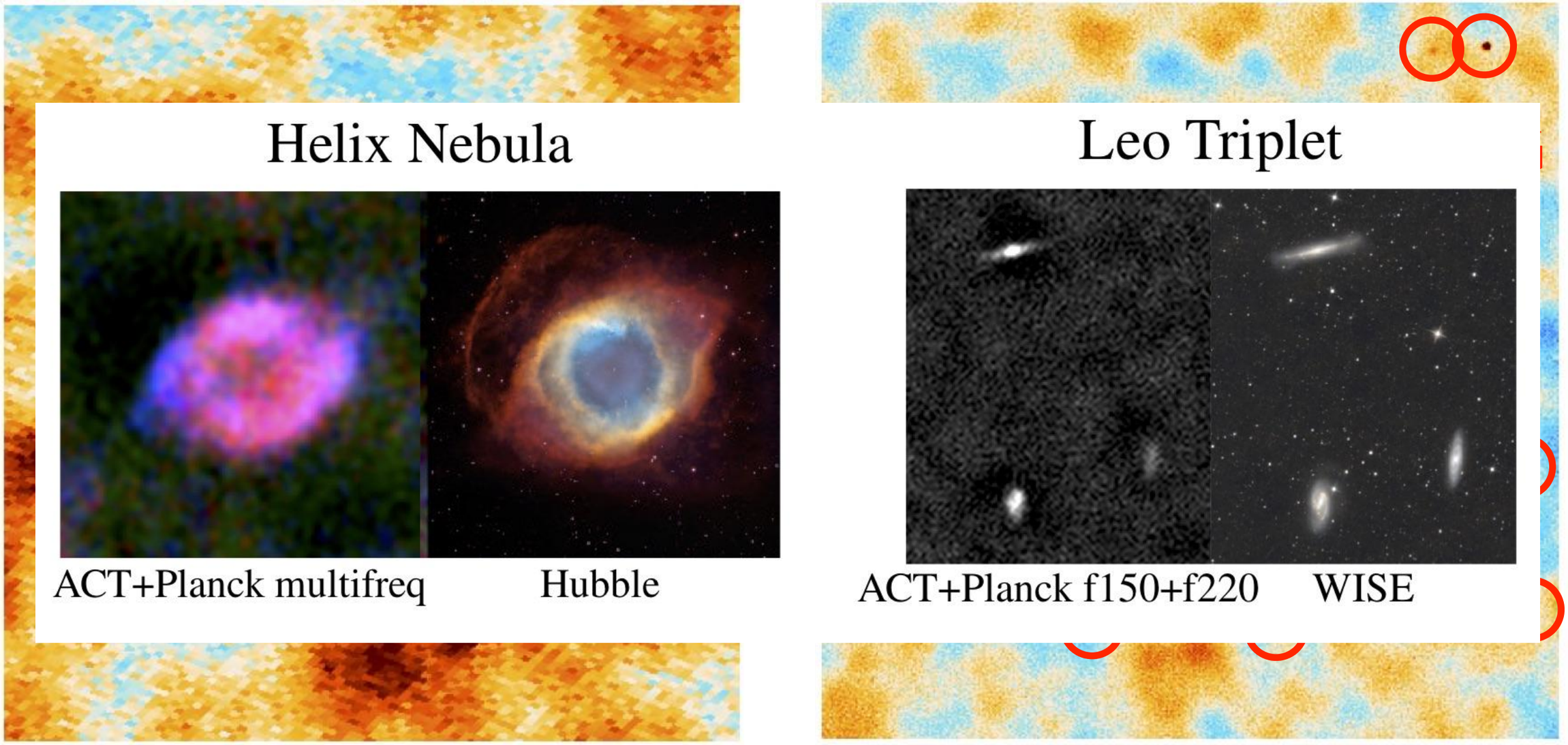
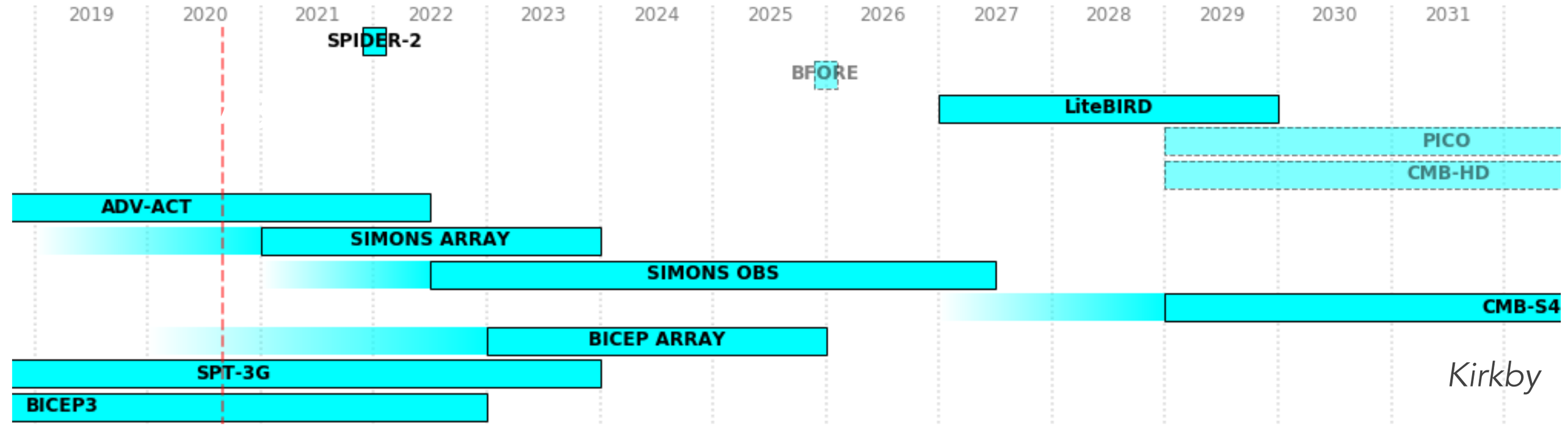


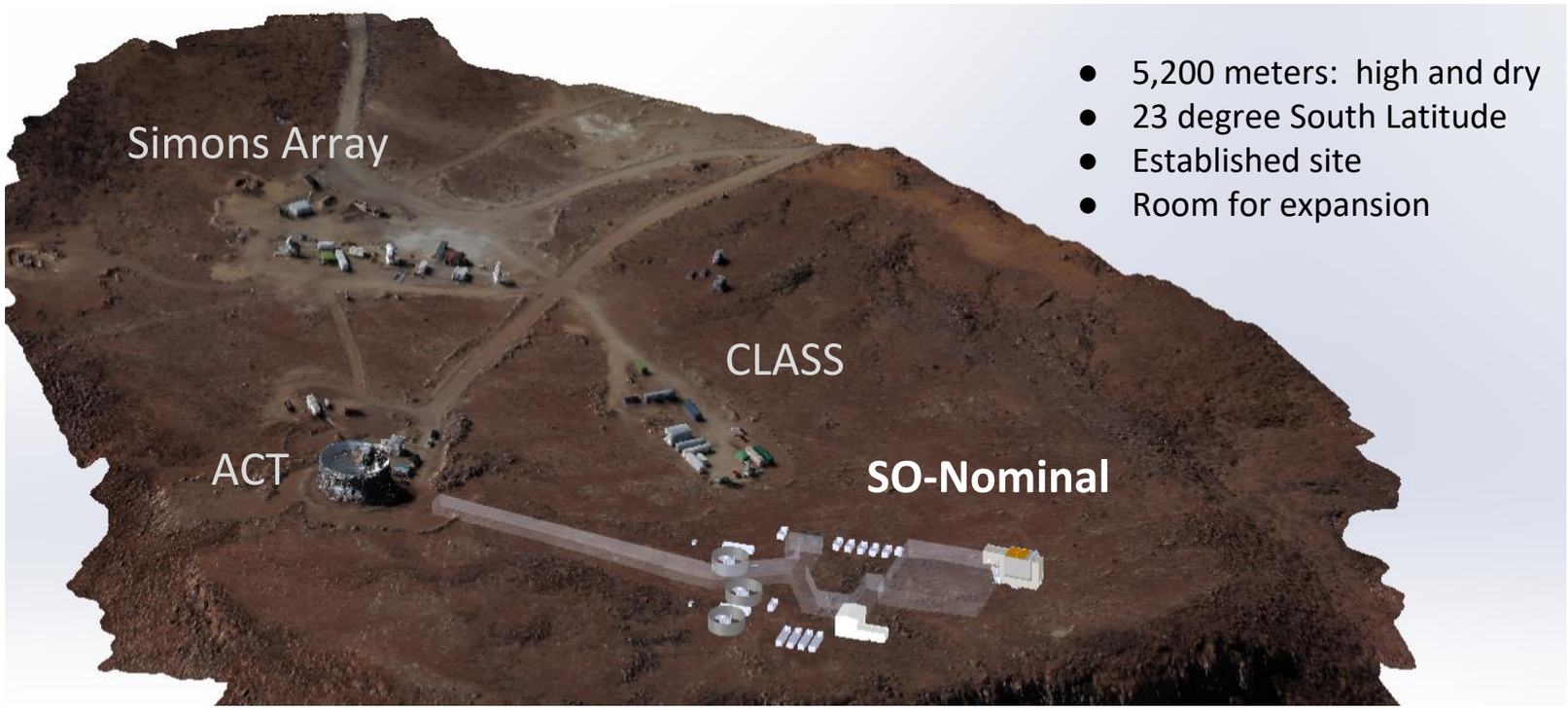
~1deg

Naess+20

Why now? High-res high-sensitivity CMB experiments



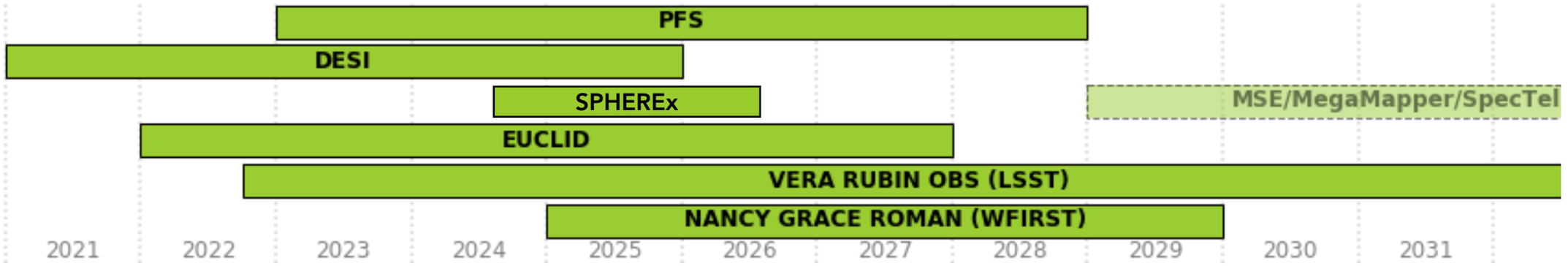
Kirkby



SO Science goals and forecasts (inc. Schaan) 19
Lee+Schaan+20

CMB-S4 Science book (inc. Schaan)
16, 19a, 19b, 20

Why now? Gigantic LSS surveys



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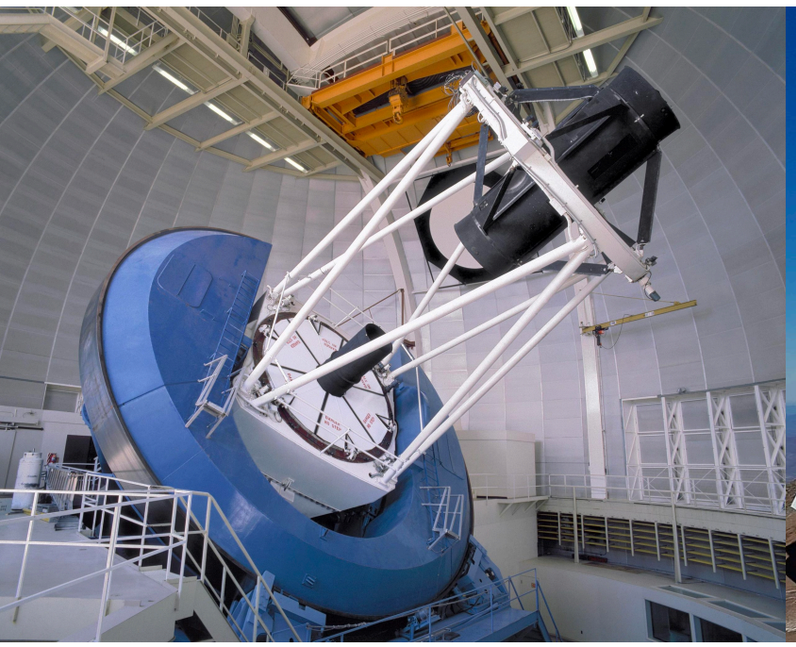
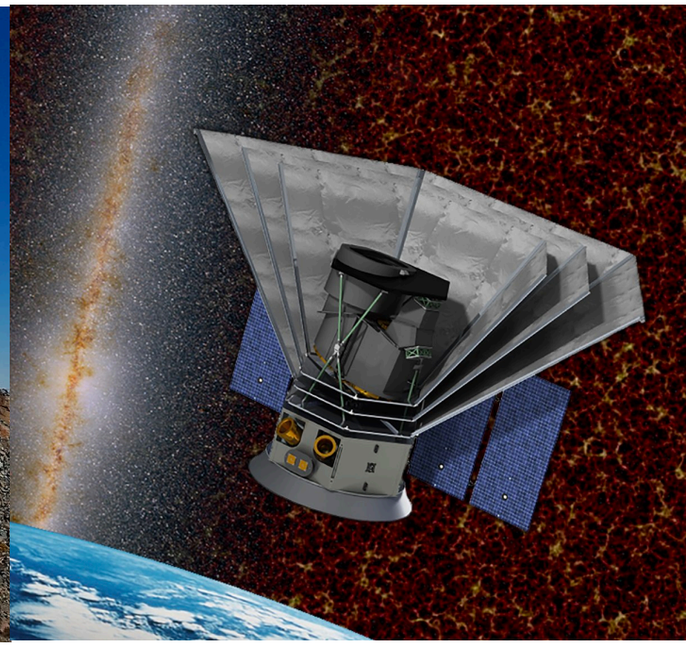


Dark Energy Spectroscopic Instrument

Vera Rubin Observatory LSST

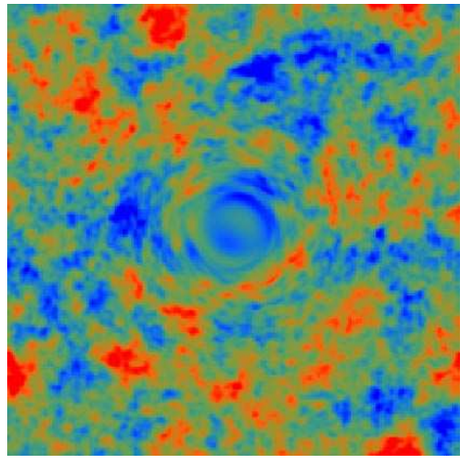
Fang Eifler Schaan+21
Schaan+20, 16



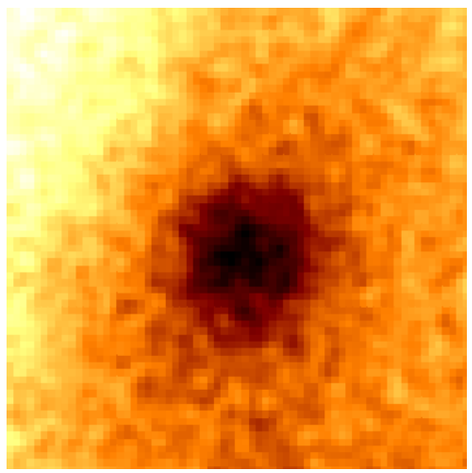
SPHEREx

Doré+Schaan+16, 18

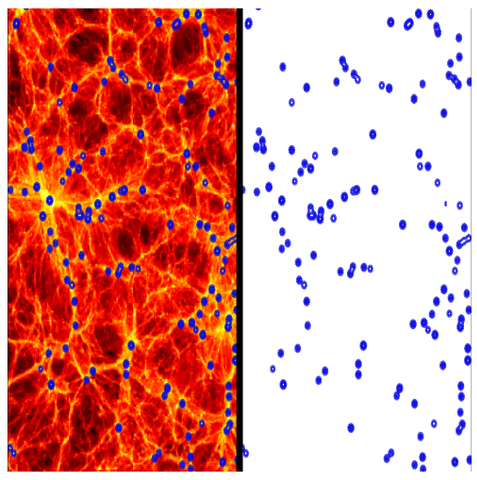
Outline: Combining CMB & LSS



Mass shadows



Gas shadows

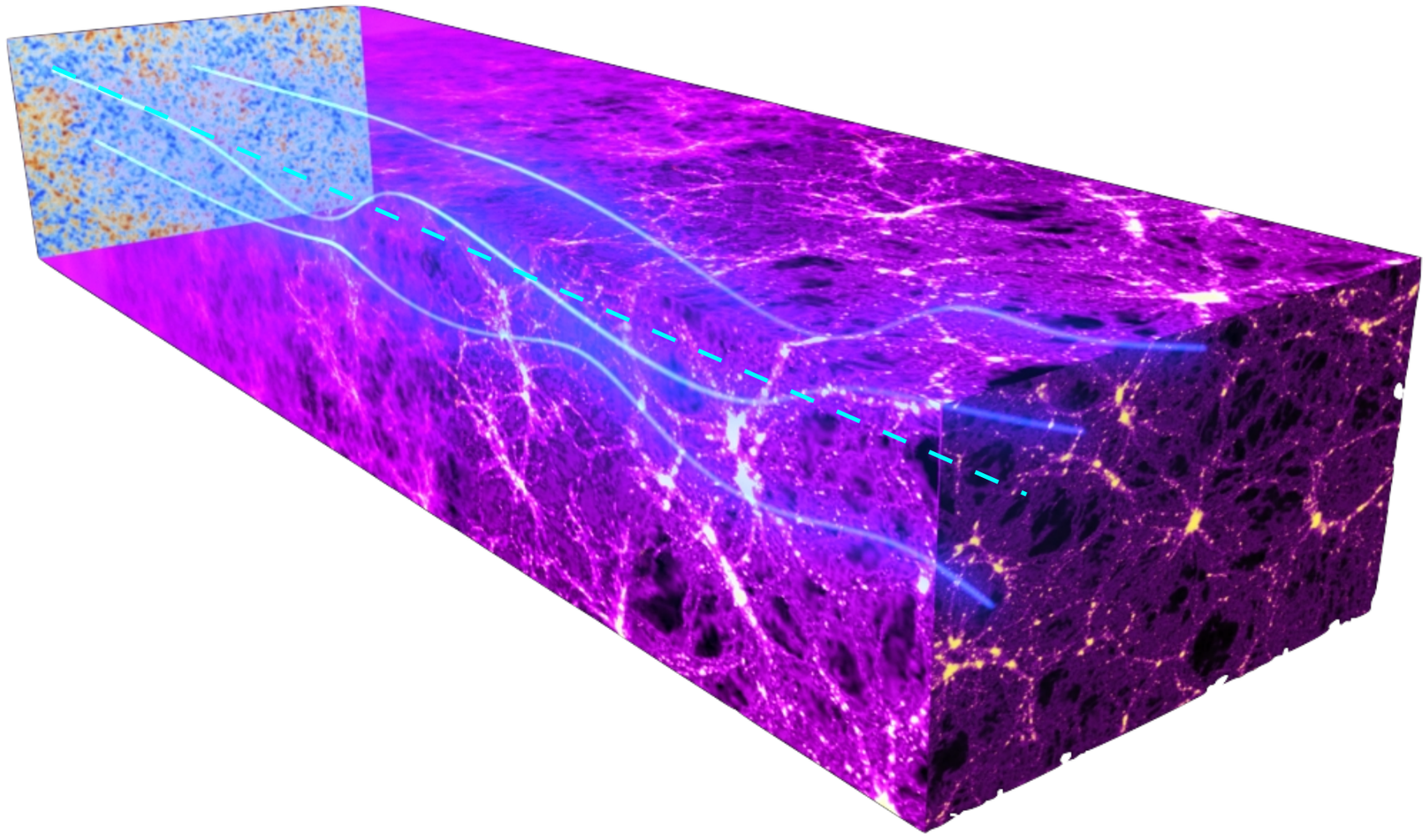


Future

Mass shadows:
Analogy CMB-galaxy lensing

Hu Okamoto 02

CMB lensing: overview

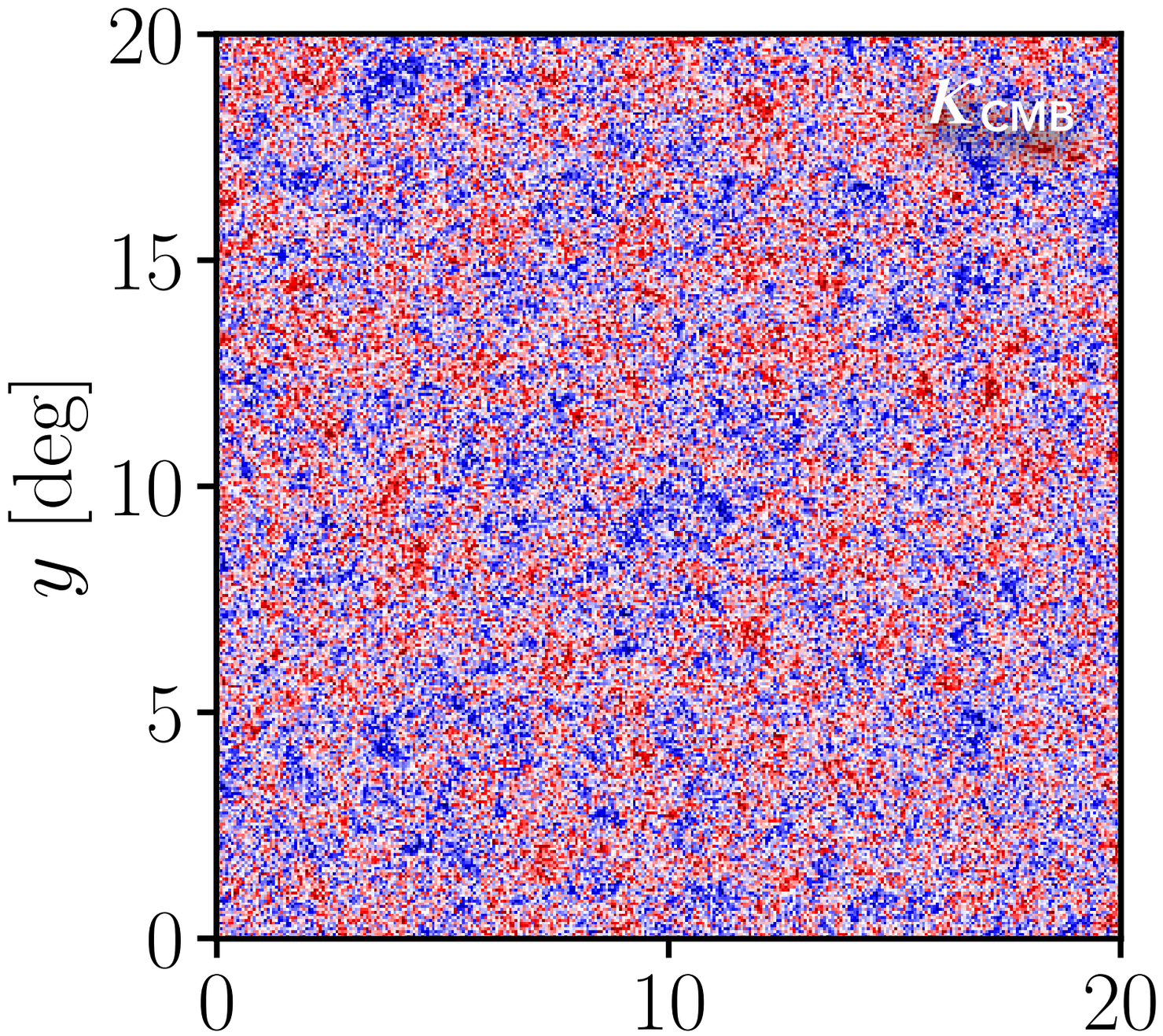


~2′ deflections, coherent on degree scale

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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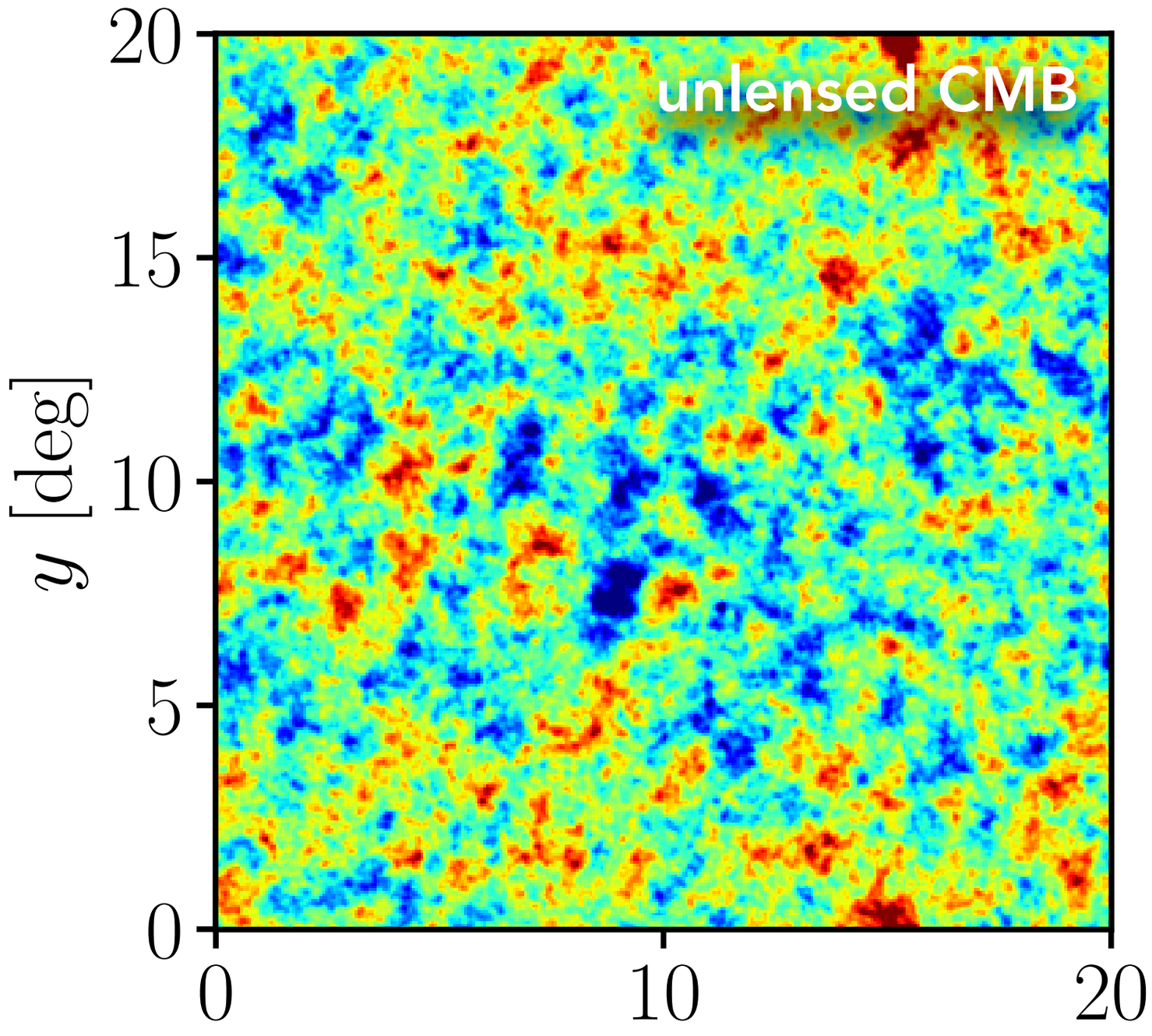

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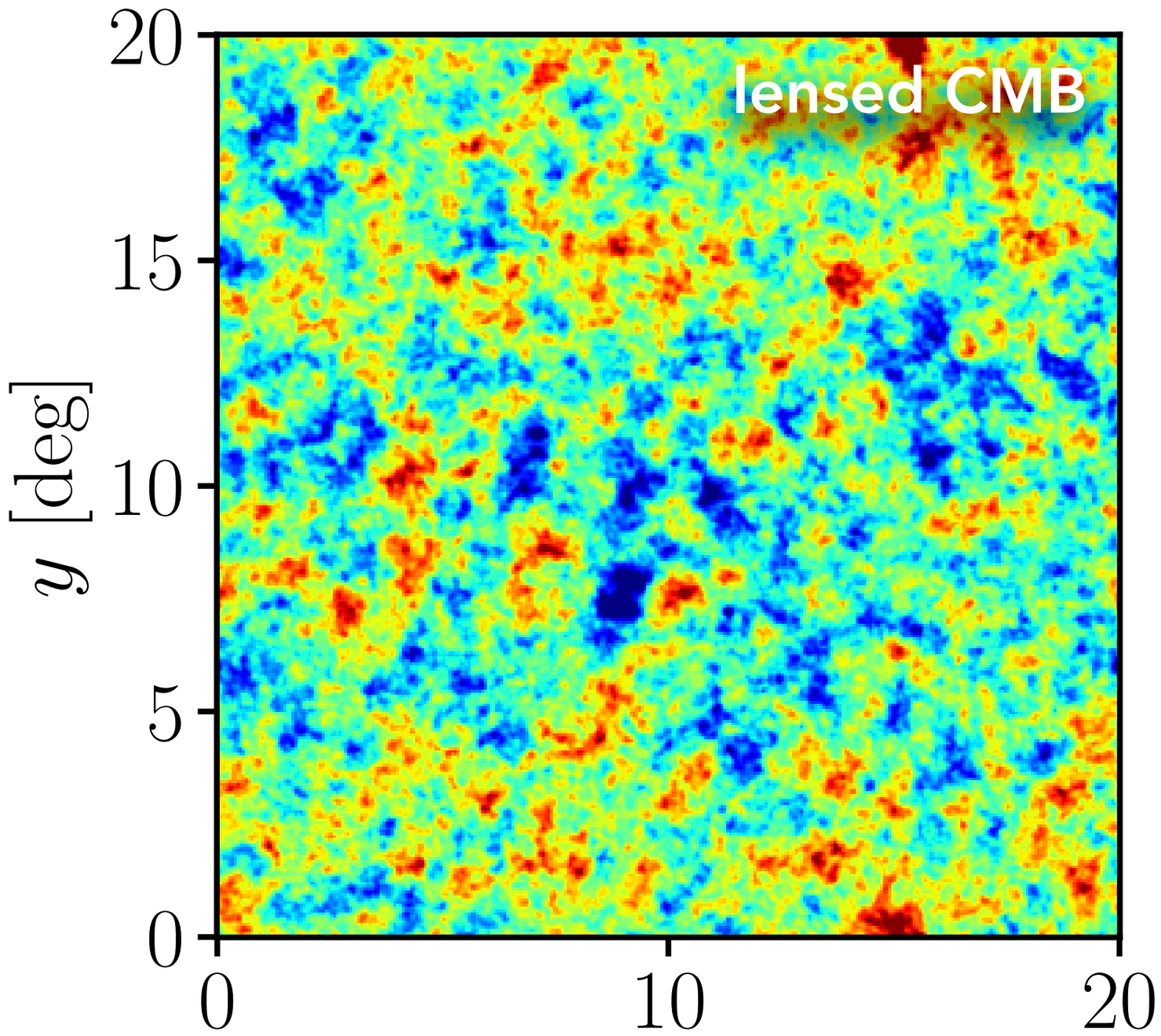

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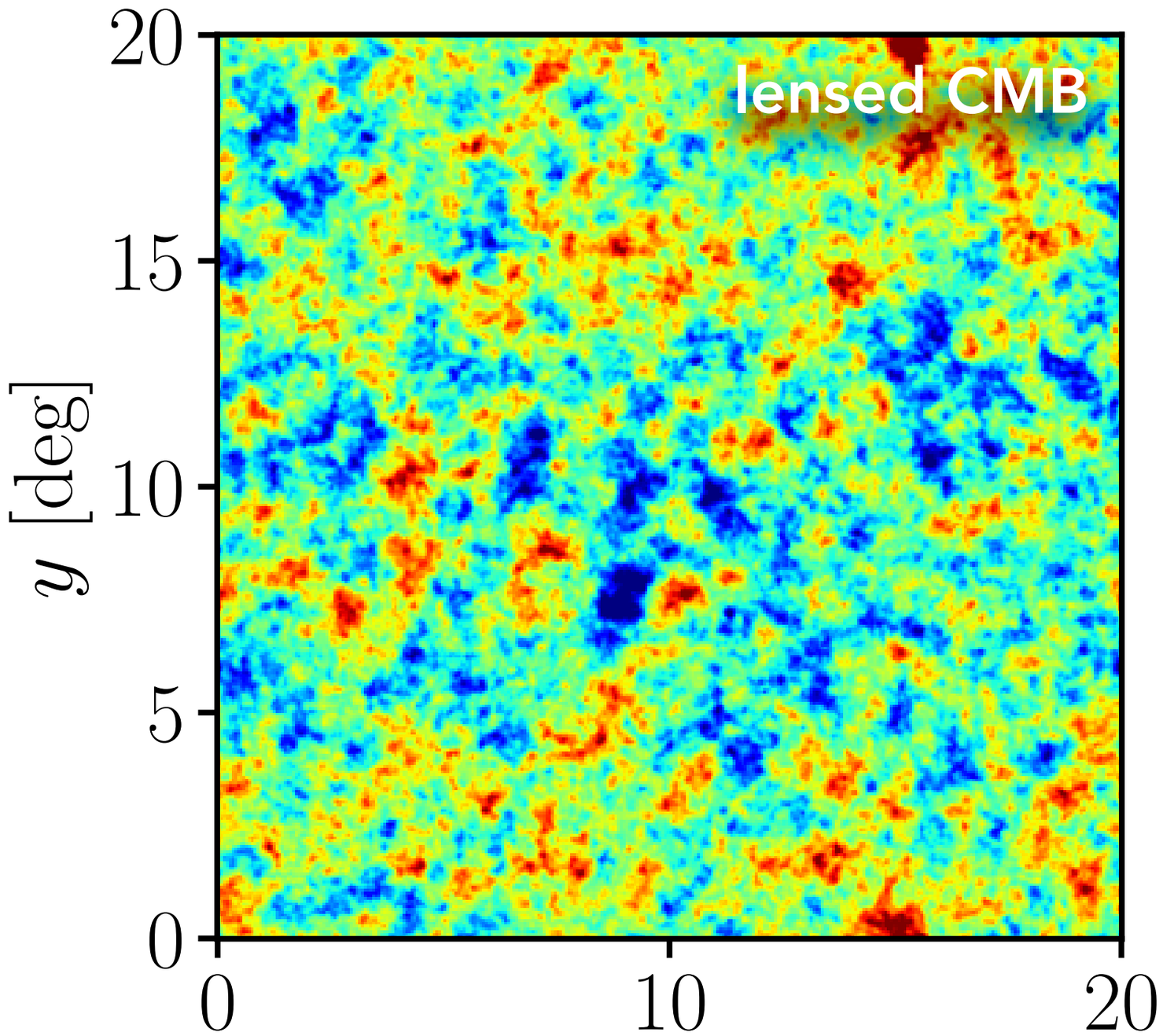

Lensing breaks the statistical isotropy of the CMB by coupling small and large scales

→ **Reconstruct with a quadratic estimator**

Lensing is crucial for CMB science

Title	Parameter	Projected precision	Current[a]	SO Method
Primordial fluctuations	r	**0.002**	0.03	BB
	P(k=0.2 /Mpc)	**0.4%**	6%	T/E/k
	f_{NL}	**1**	5	kSZ+LSST
		1		kk+LSST
Relativistic Species	N_{eff}	**0.05**	0.2	T/E
Neutrino mass	Σm_ν (eV)	**0.03**	0.1	kk+DESI
		0.03		tSZ-N+LSST
		0.04		tSZ-Y+DESI
Dark Energy	σ_8(z=1-2)	**1%**	7%	kk+LSST
		1%		tSZ+LSST/k
	H_0 (LCDM)	**0.3**	0.7	T/E
Galaxy Evolution	feedback efficiency in massive halos	**2%**	50-100%	tSZ+kSZ
	non-thermal pressure in massive halos	**5%**	50-100%	tSZ+kSZ
Reionization	duration Δz	**0.3**	1.4	T/E (kSZ)

SO Science paper

Lensing is crucial for CMB science

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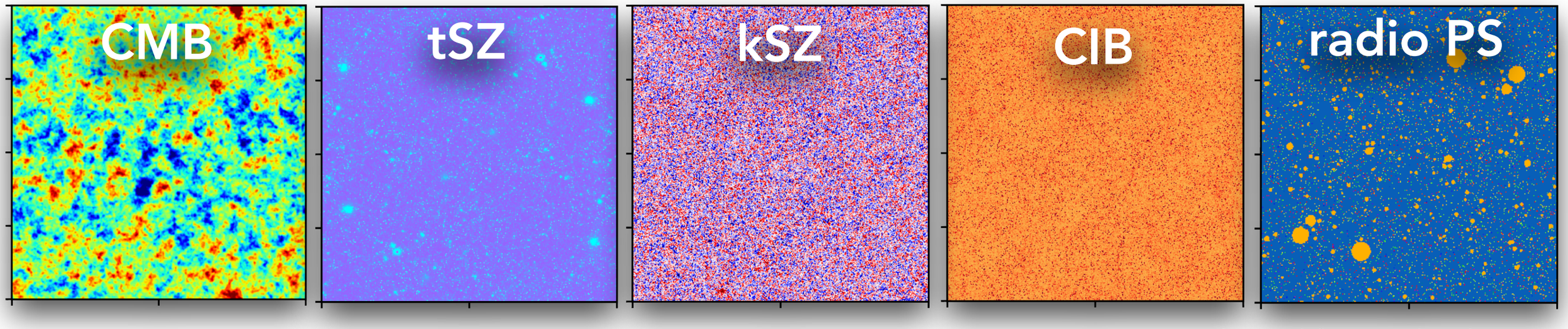
Reionization	duration Δz	**0.3**	1.4	T/E (kSZ)

SO Science paper

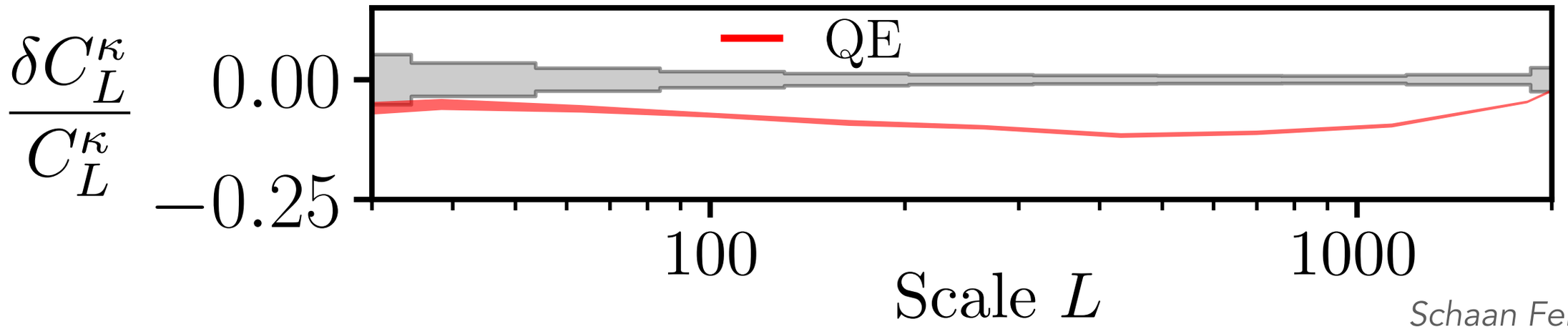
→ CMB lensing is crucial

Key hurdle: extragalactic foregrounds



adapted from Sehgal+09

Highly significant bias to lensing

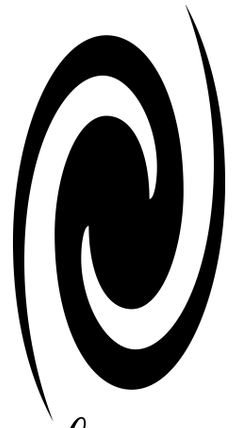


Schaan Ferraro 18

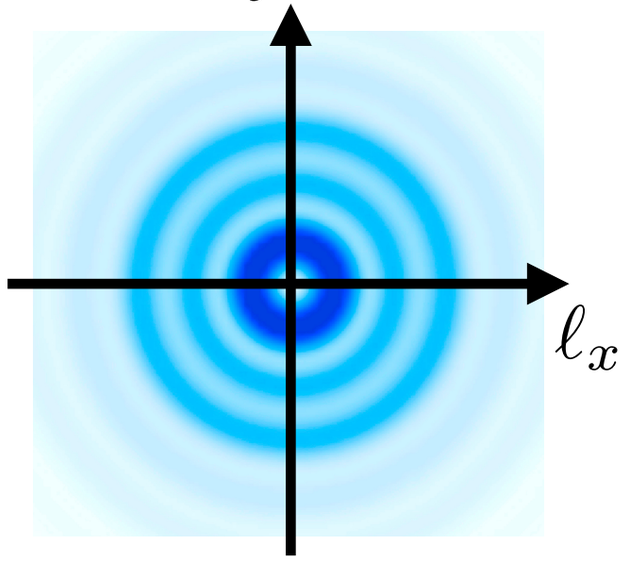
Analogy CMB ↔ galaxies

Lensing ≈ Magnification + Shear

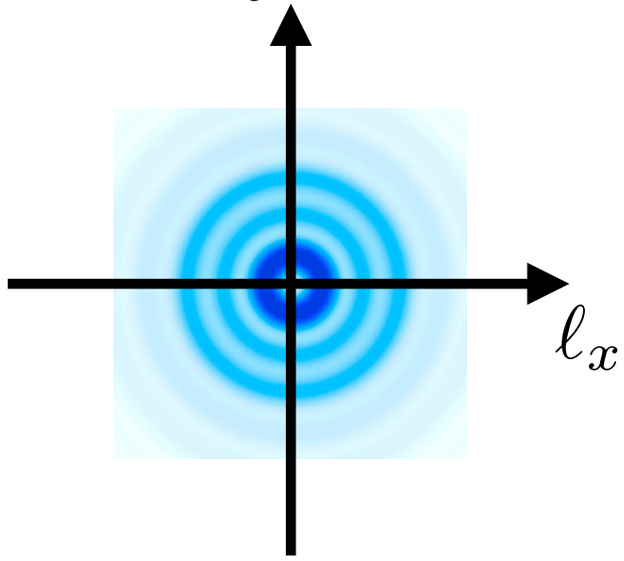
Galaxies:



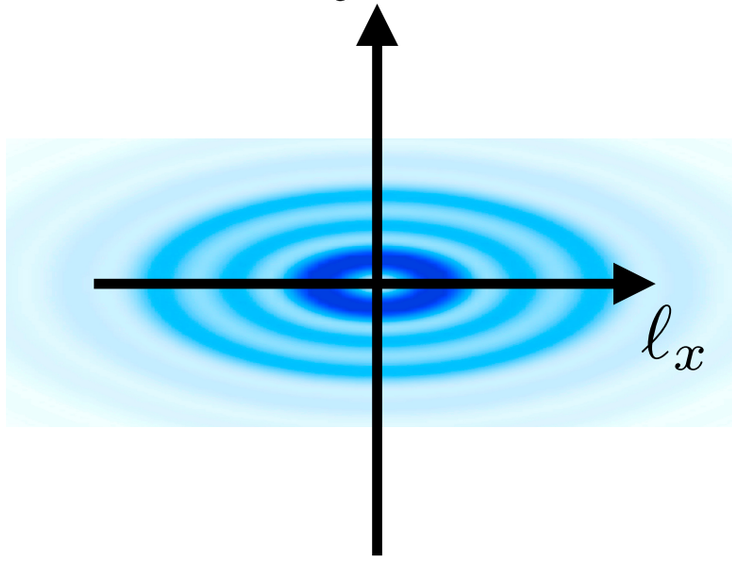
CMB:



Unlensed



Magnified
→ monopole



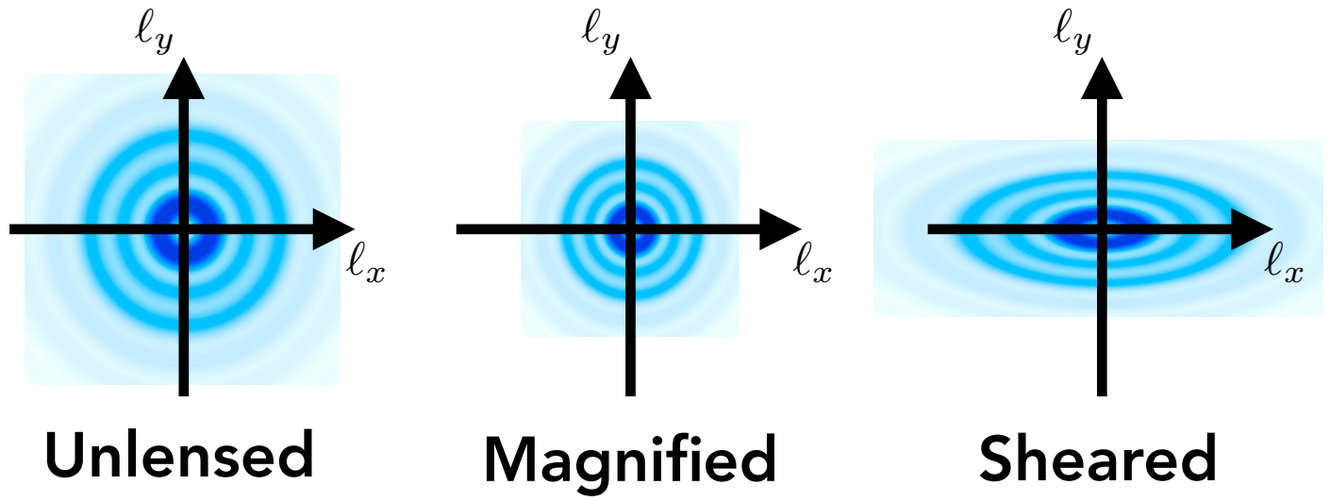
Sheared
→ quadrupole

Zaldarriaga Seljak 98, Lu Pen 08, Bucher+10, Prince+17, ***Schaan Ferraro 18***

Symmetries: lensing VS foregrounds

CMB lensing

→ Monopole & quadrupole

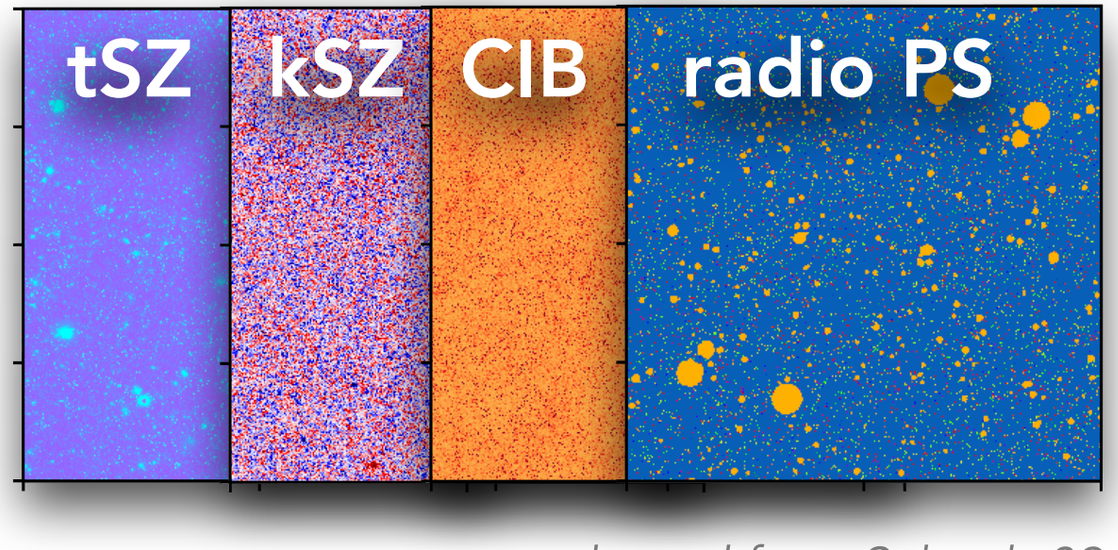


Schaan Ferraro 18

Extragalactic foregrounds

~Spherical halos/pointlike galaxies

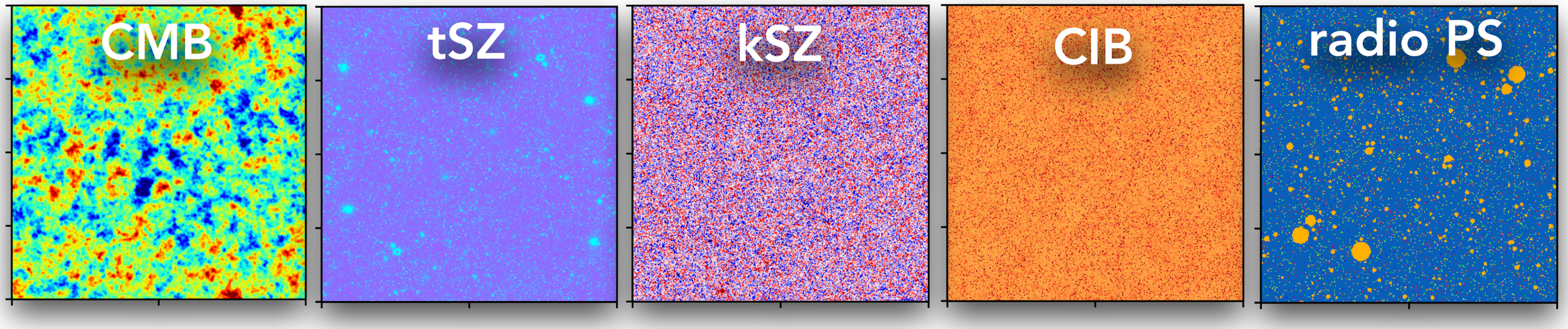
→ Monopole only



adapted from Sehgal+09

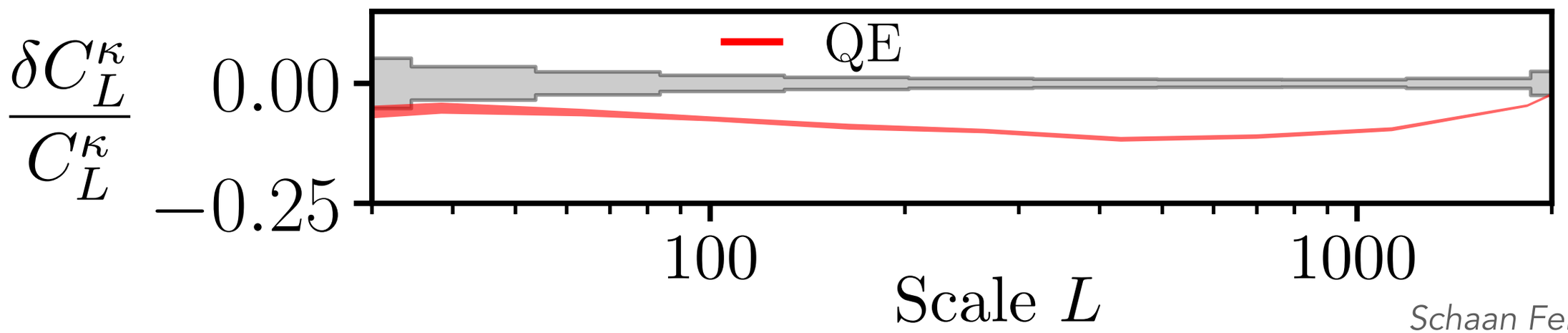
→ Foregrounds should not affect shear!

Key hurdle: extragalactic foregrounds



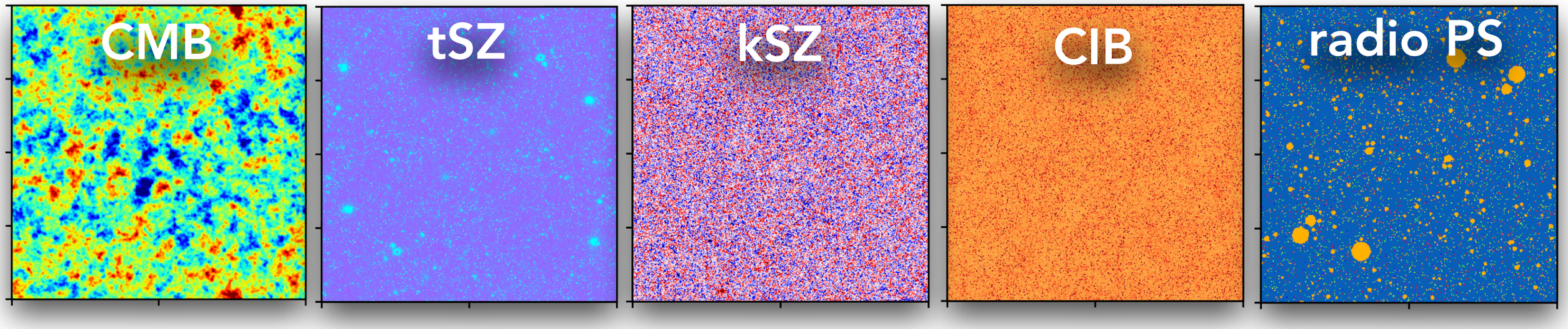
adapted from Sehgal+09

Highly significant bias to lensing



Schaan Ferraro 18

Key hurdle: extragalactic foregrounds



adapted from Sehgal+09

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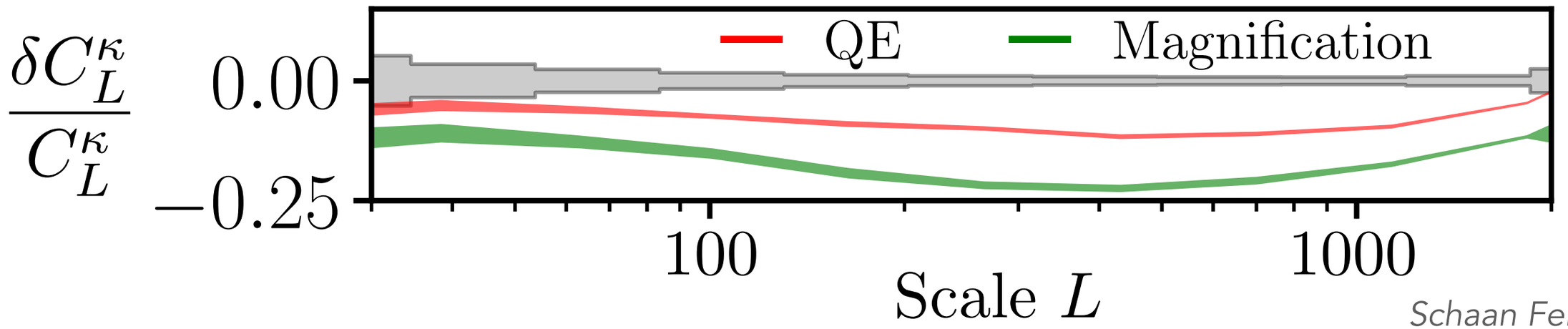
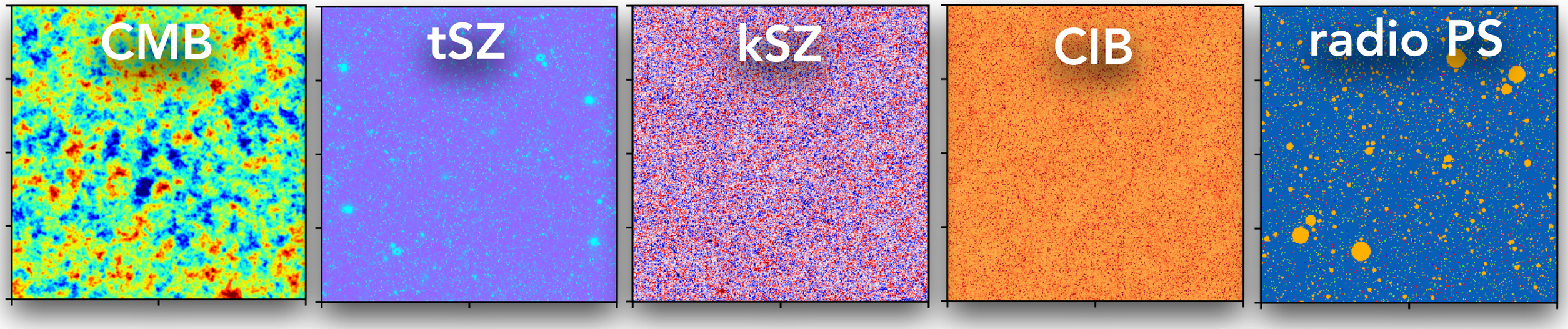


Schaan Ferraro 18

Key hurdle: extragalactic foregrounds



adapted from Sehgal+09

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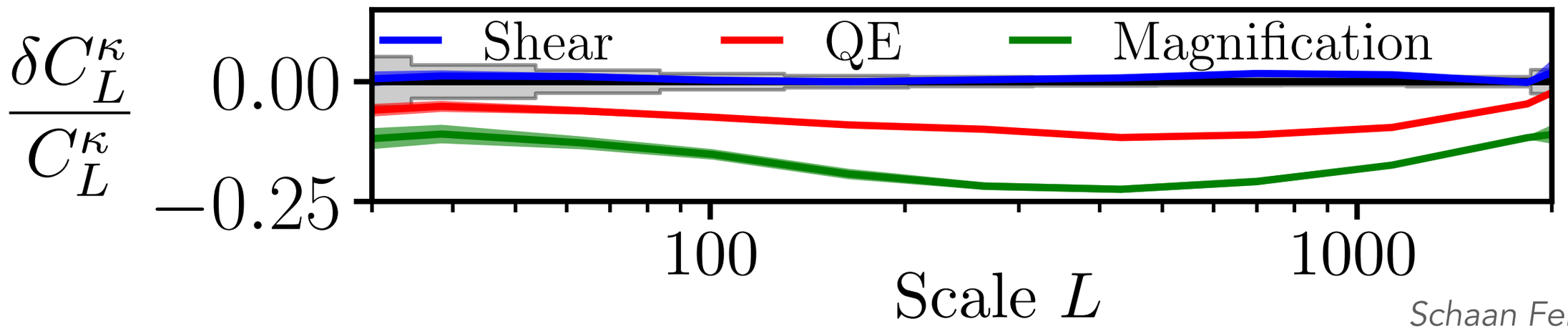
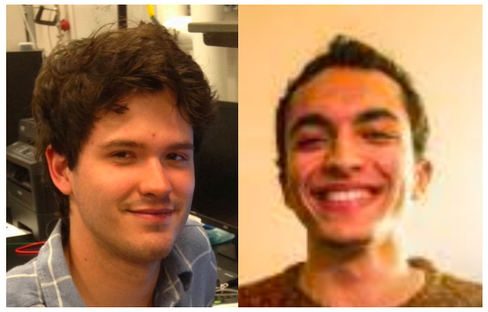


Schaan Ferraro 18

Works for all extragalactic foregrounds!

Nulls bias and increases signal-to-noise

Many recent & upcoming projects!



Bias-hardening
Best multifrequency cleaning
Best combination of estimators

Schaan Ferraro 18
Sailer Schaan Ferraro 20
Sailer Schaan Ferraro Darwish Sherwin 21
Darwish Sherwin Sailer Schaan Ferraro 21

First calculation:
Foregrounds are themselves lensed

Mishra Schaan 19

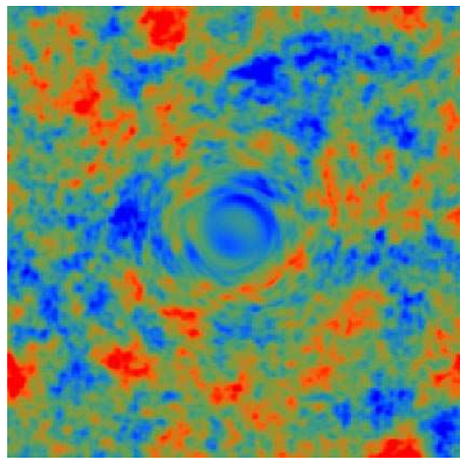
Measuring lensing from intensity maps
New estimator avoids interloper bias
& extracts high-z signal

Maniyar Schaan Pullen 21
Schaan+18

First calculation:
Polarized extragalactic foreground bias

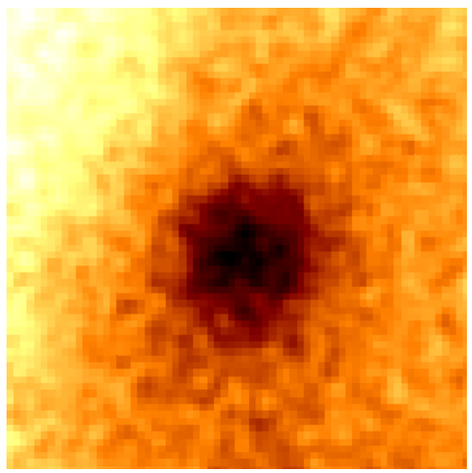
Schaan Millea in prep

Outline: Combining CMB & LSS

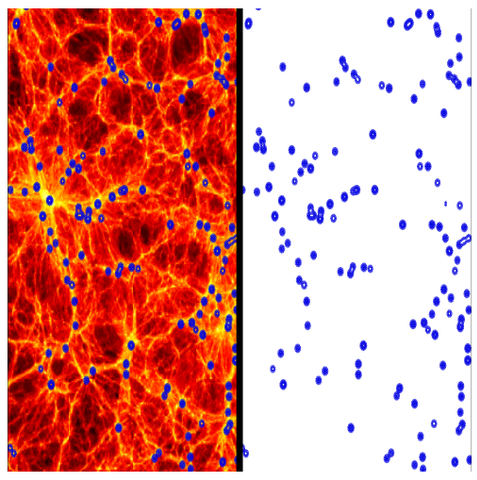


Mass shadows: Analogy CMB-galaxy lensing

Improved CMB lensing

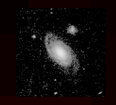


Gas shadows



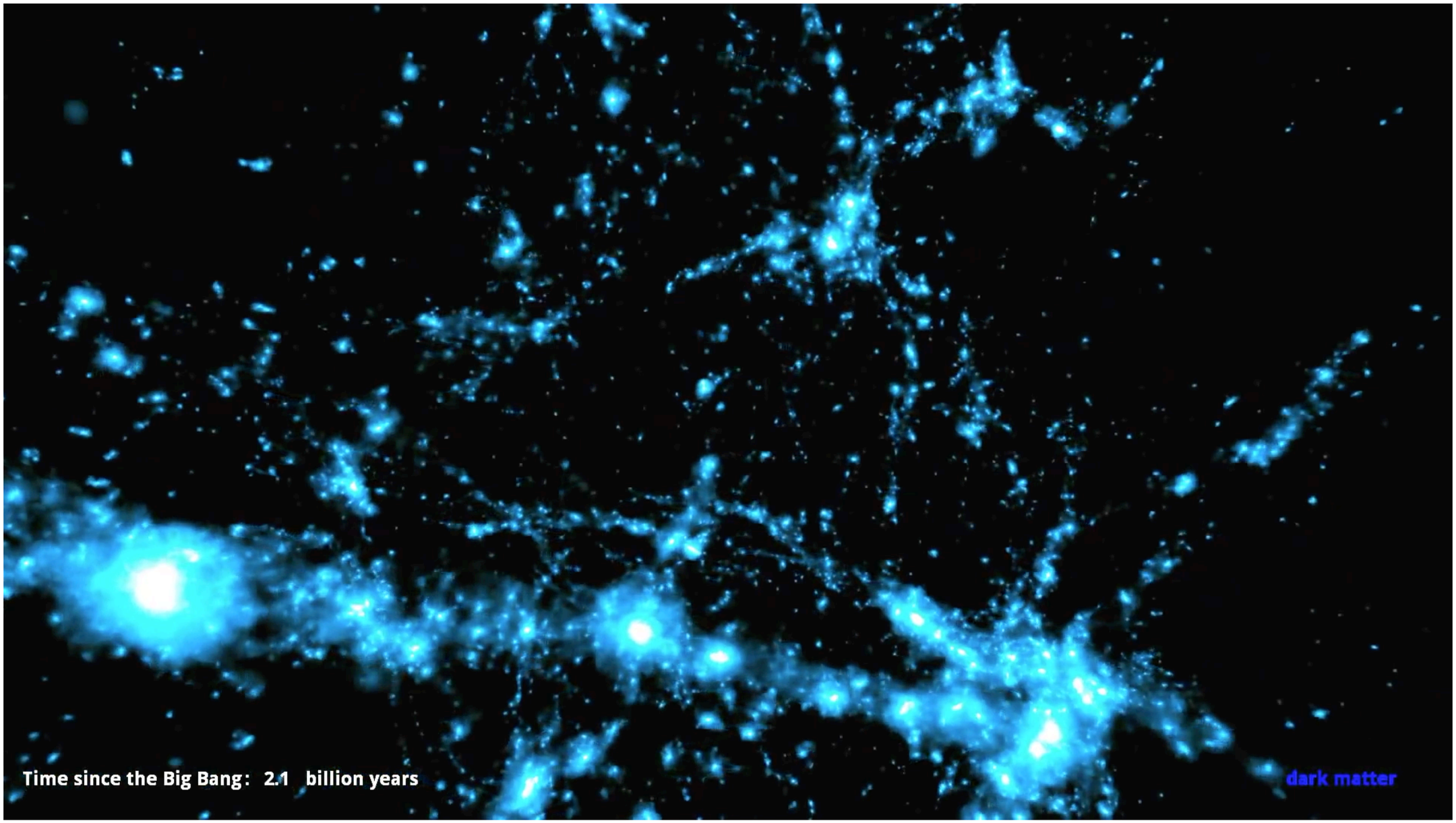
Future

Gas shadows:
Localize the missing baryons



Schaan+20

Why care? Cosmology & Galaxy formation



Illustris

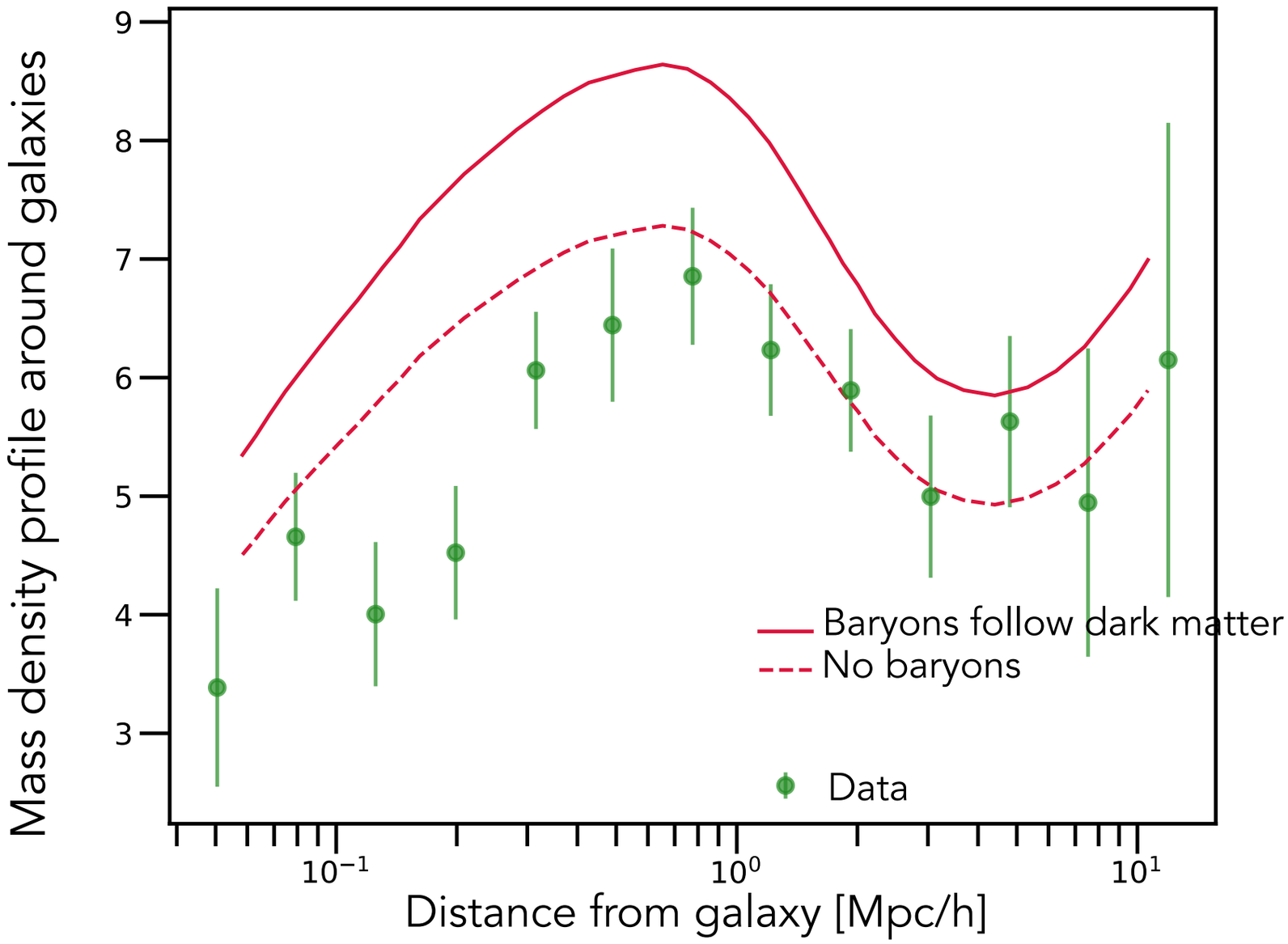
Supernovae and supermassive black holes regulate galaxy formation

Unknown “feedback” amplitude

→ **Missing baryon problem**

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

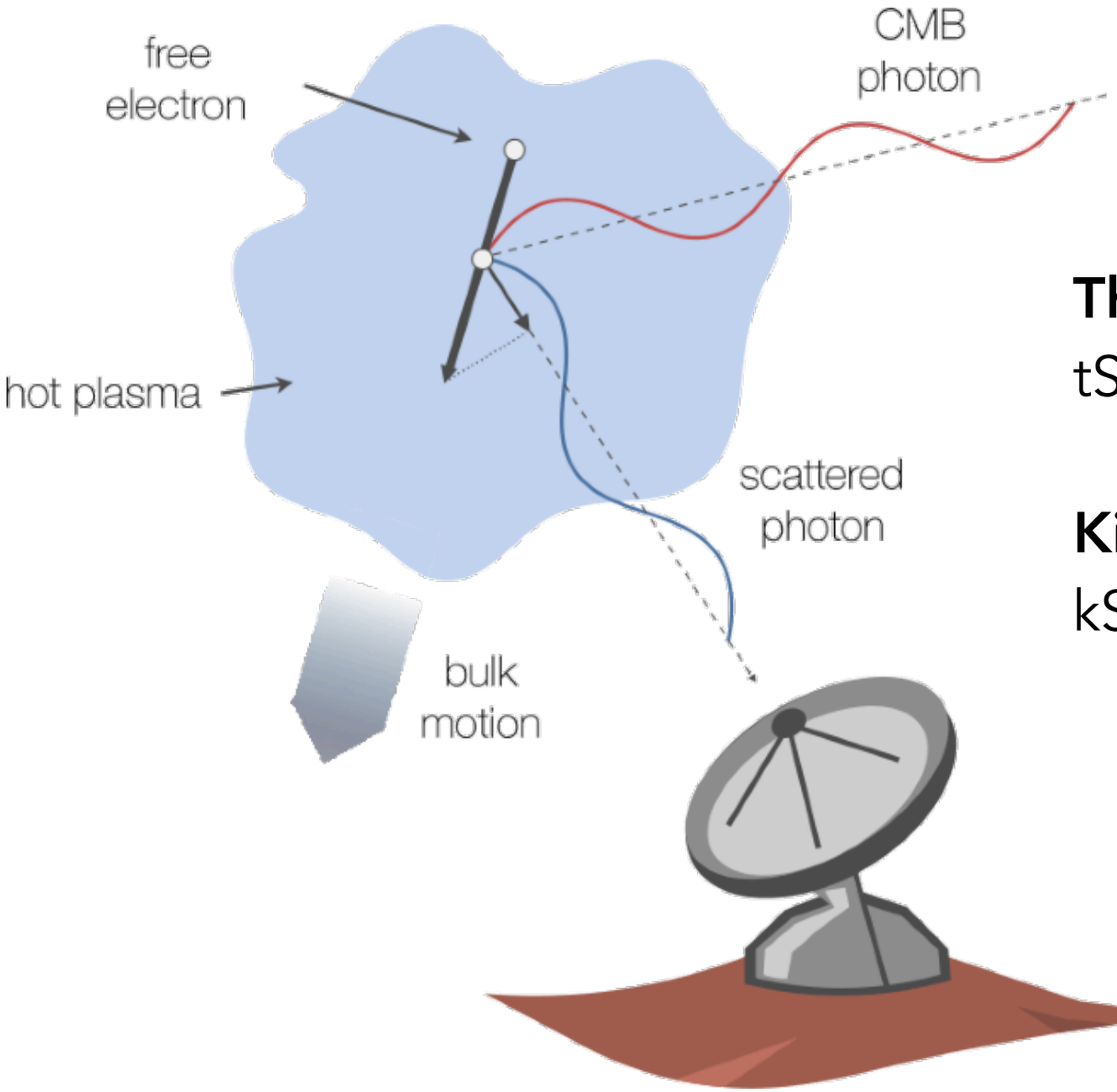
LSS tension: “lensing is low”



Amodeo Battaglia Schaan Ferraro & ACT 20

How much of this tension is due to baryons?

CMB can help: Sunyaev-Zel'dovich effects



Thermal SZ: Doppler from thermal motions

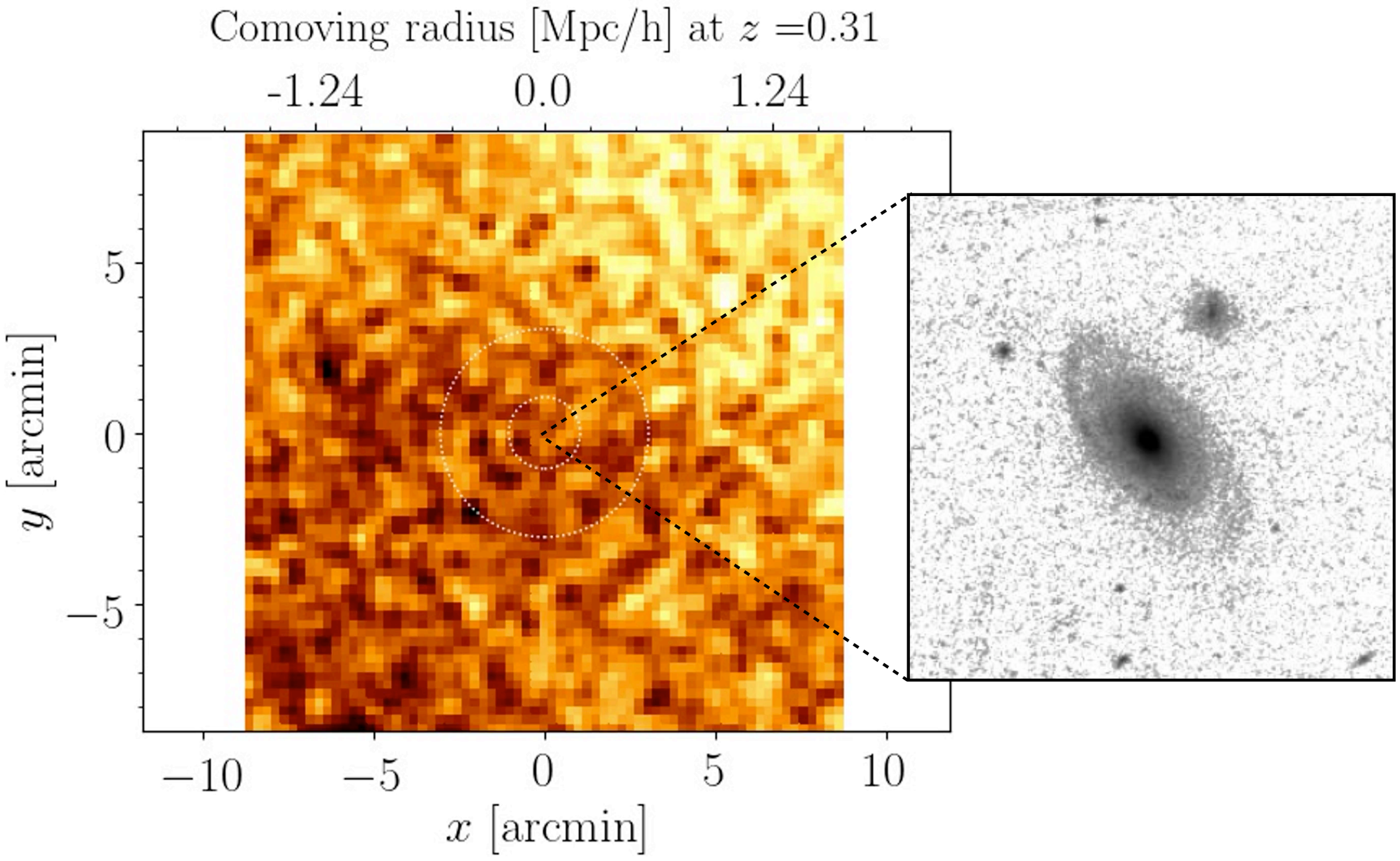
tSZ = gas density * temperature

Kinematic SZ: Doppler from bulk motion

kSZ = gas density * bulk velocity

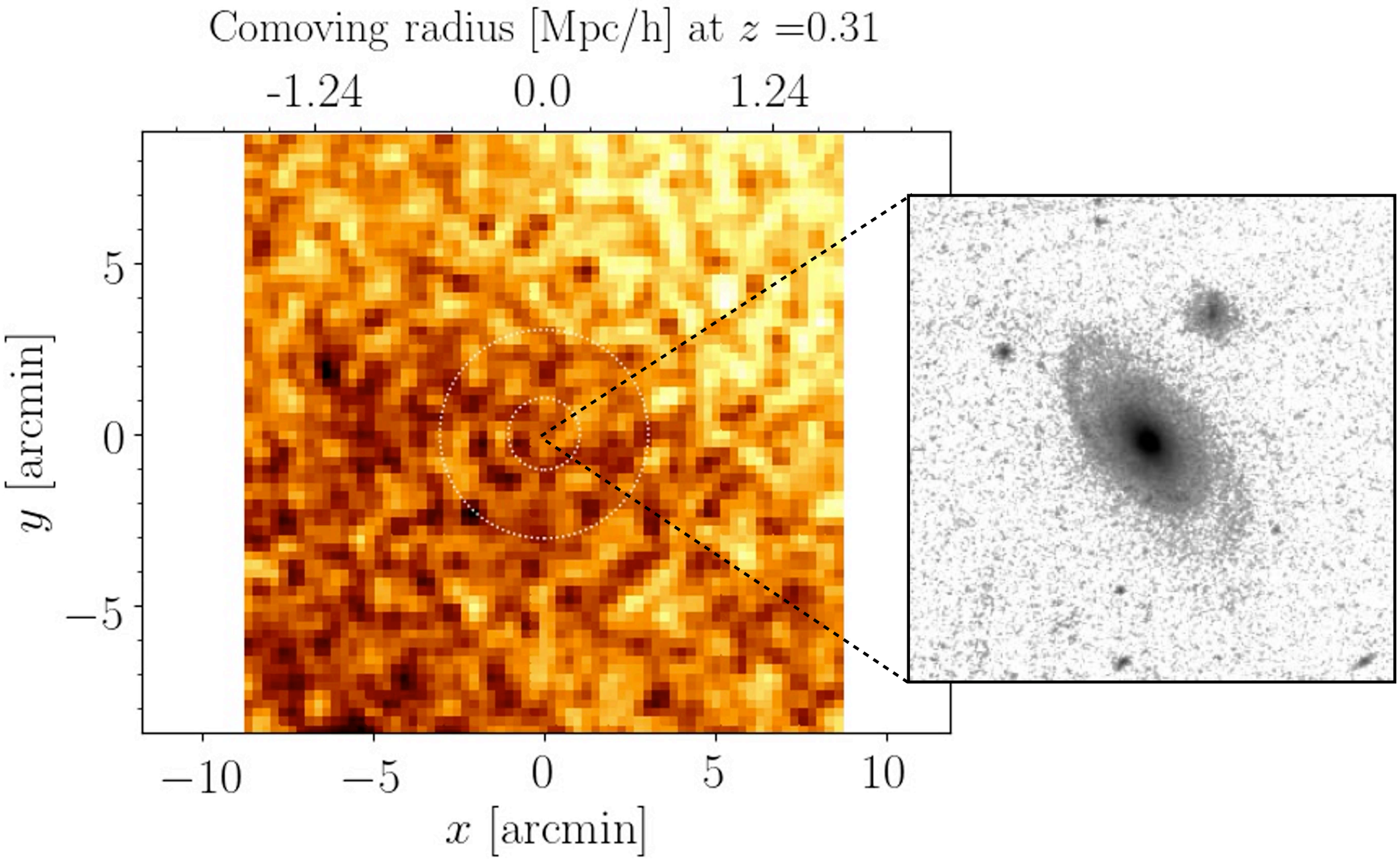
→ Unique probe of missing baryons!

Extracting tSZ: single galaxy



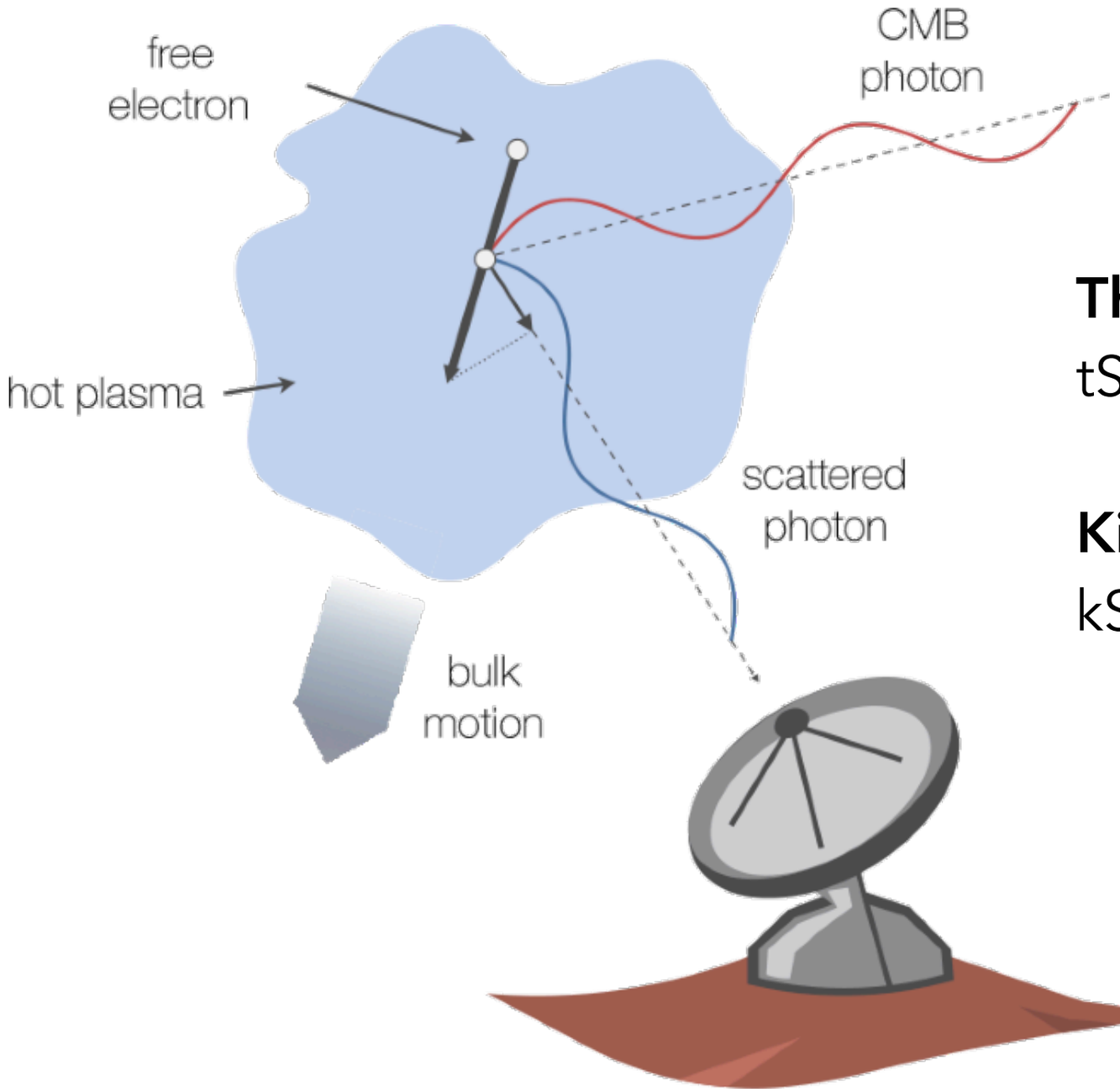
SNR per galaxy is too low to detect!

Extracting tSZ: 400,000 galaxies



Extended tSZ profile is well resolved!

CMB can help: Sunyaev-Zel'dovich effects



Thermal SZ: Doppler from thermal motions

tSZ = gas density * temperature

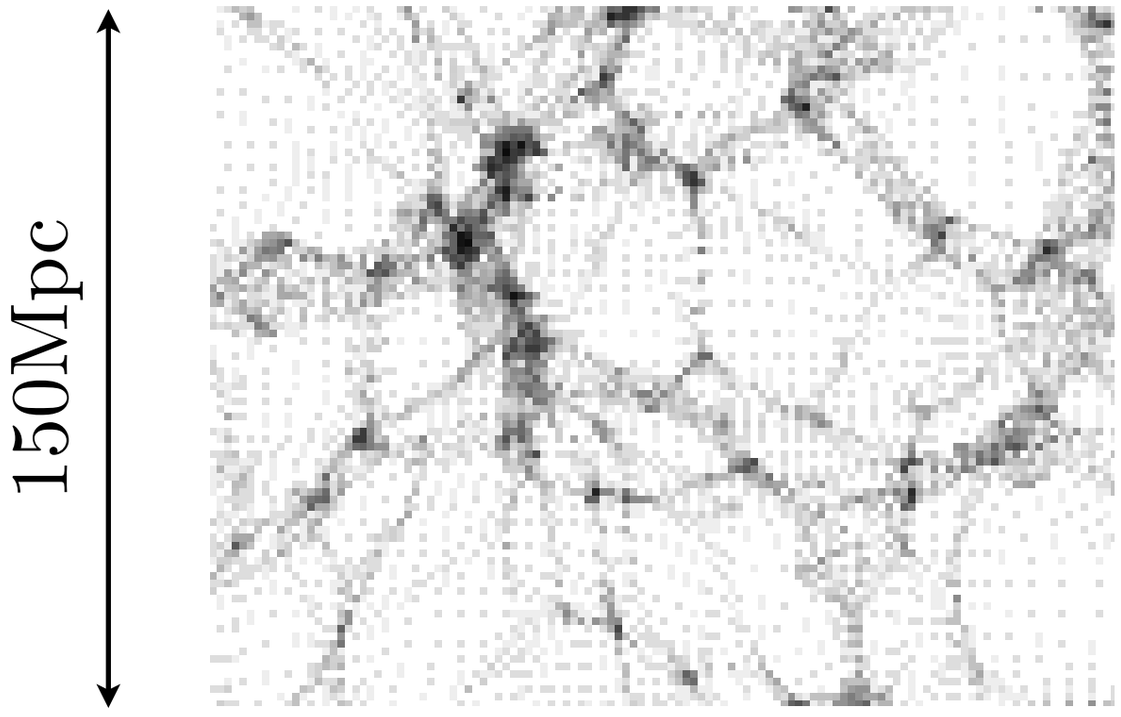
Kinematic SZ: Doppler from bulk motion

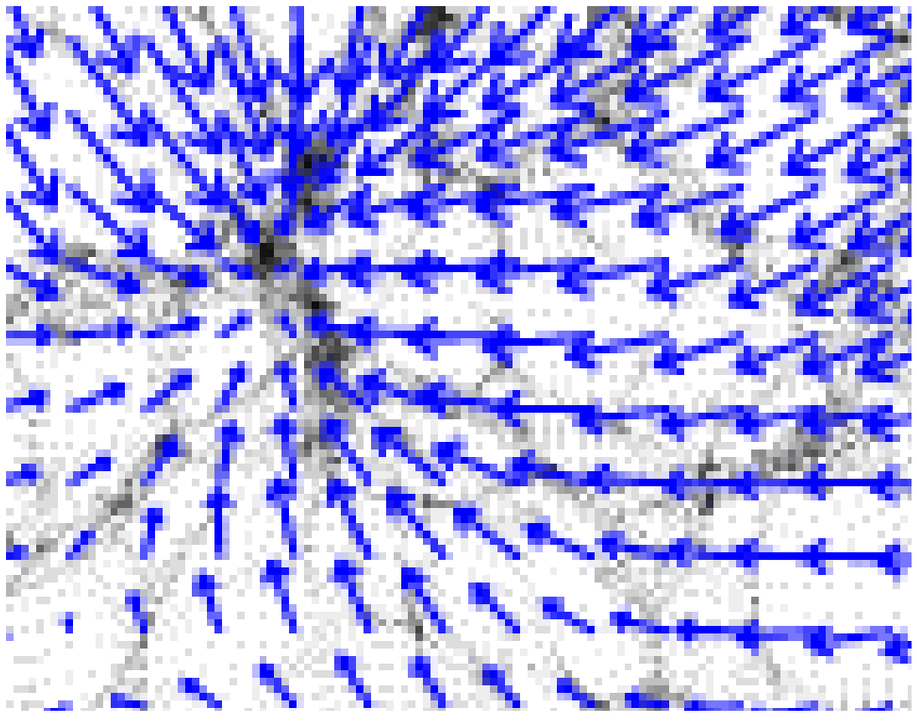
kSZ = gas density * bulk velocity

→ Unique probe of missing baryons!

Extracting kSZ: Velocity reconstruction

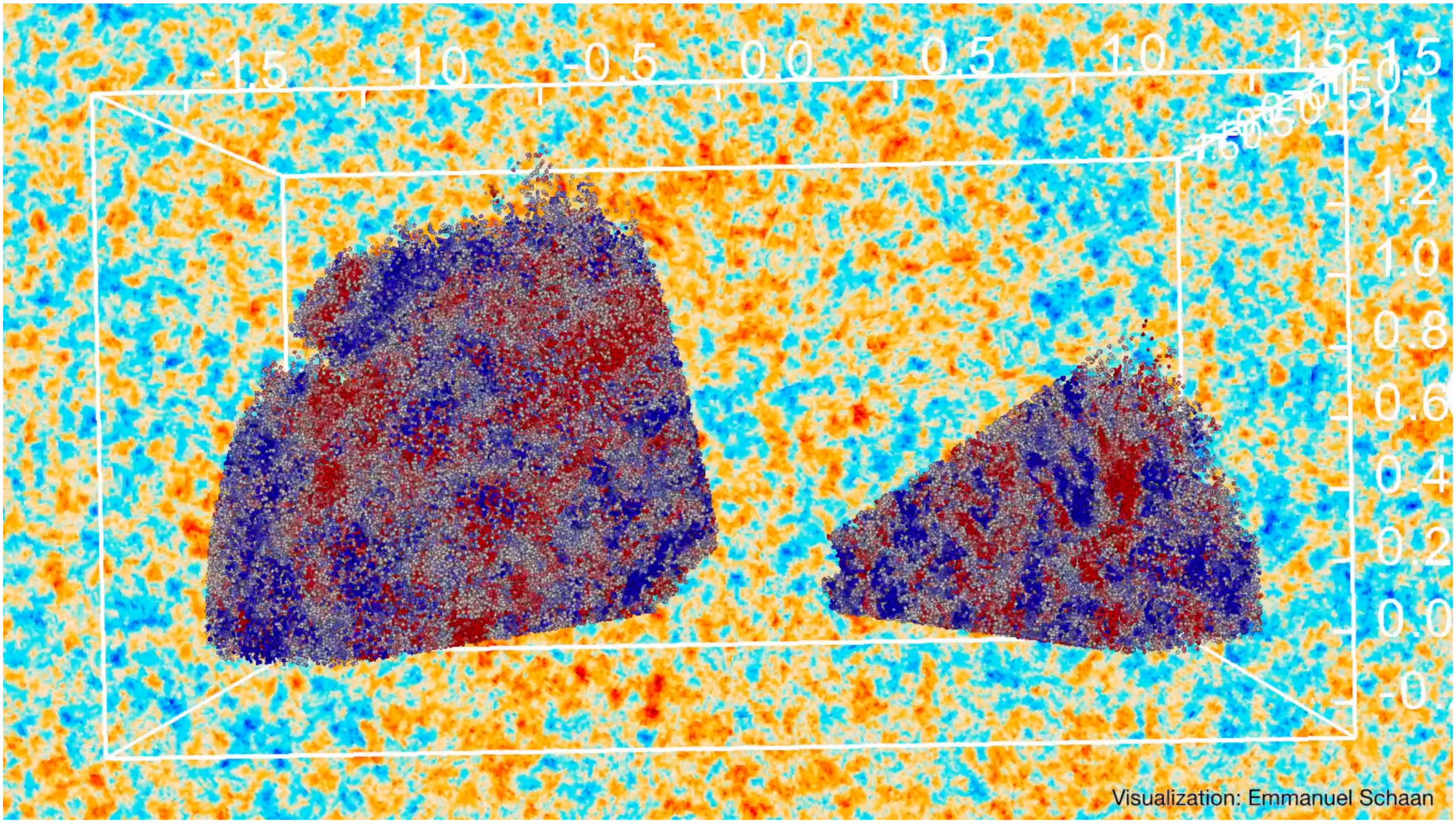
Mass conservation: $\vec{v} \propto \vec{\nabla}\Delta^{-1}\delta$





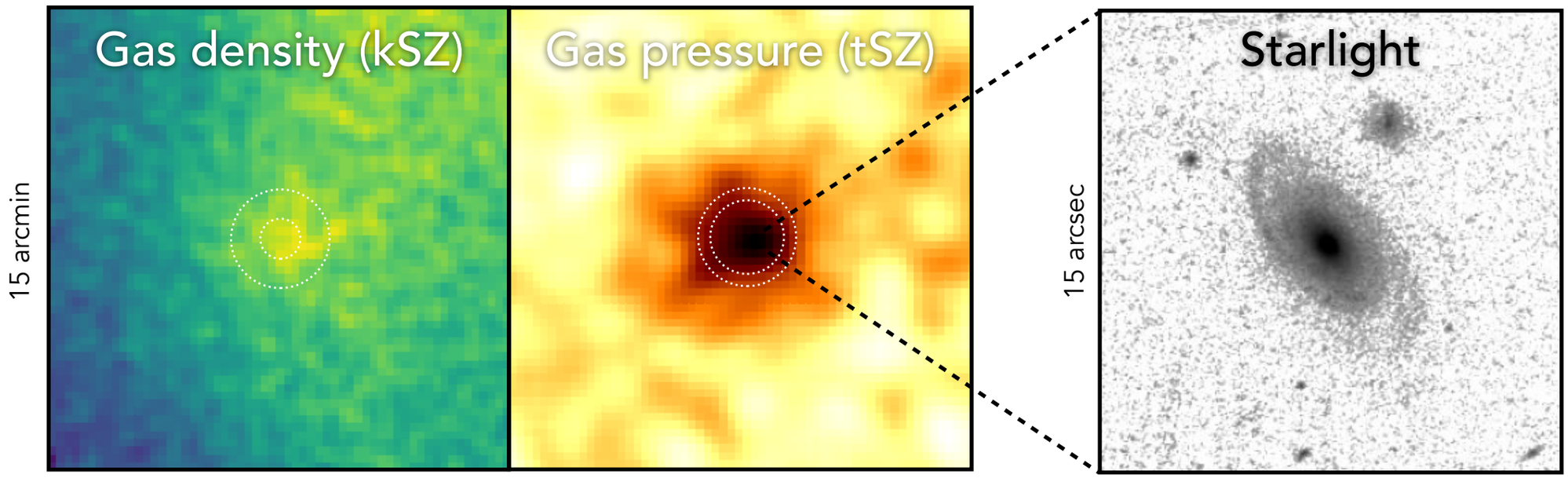
Eisenstein+07, Padmanabhan+12,14

Extracting kSZ: Velocity reconstruction



Velocity data from Smith, Vargas-Magaña, Ho; visualization by Schaan

Mapping baryons & their thermodynamics



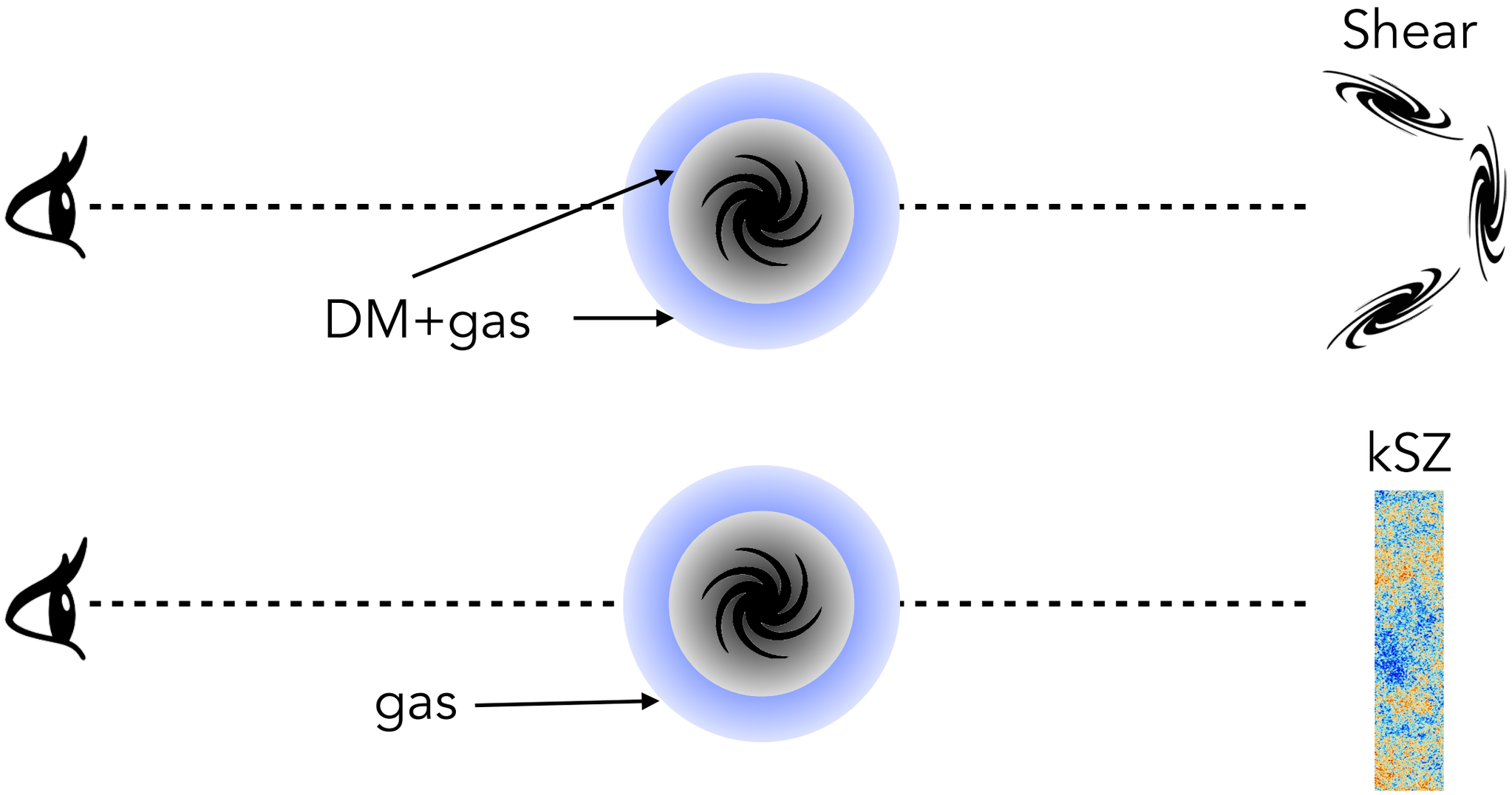
Schaan et al 2020

Highest significance kSZ detection (6-8σ)

Gas is well resolved

Gas extends far outside the dark matter (feedback)

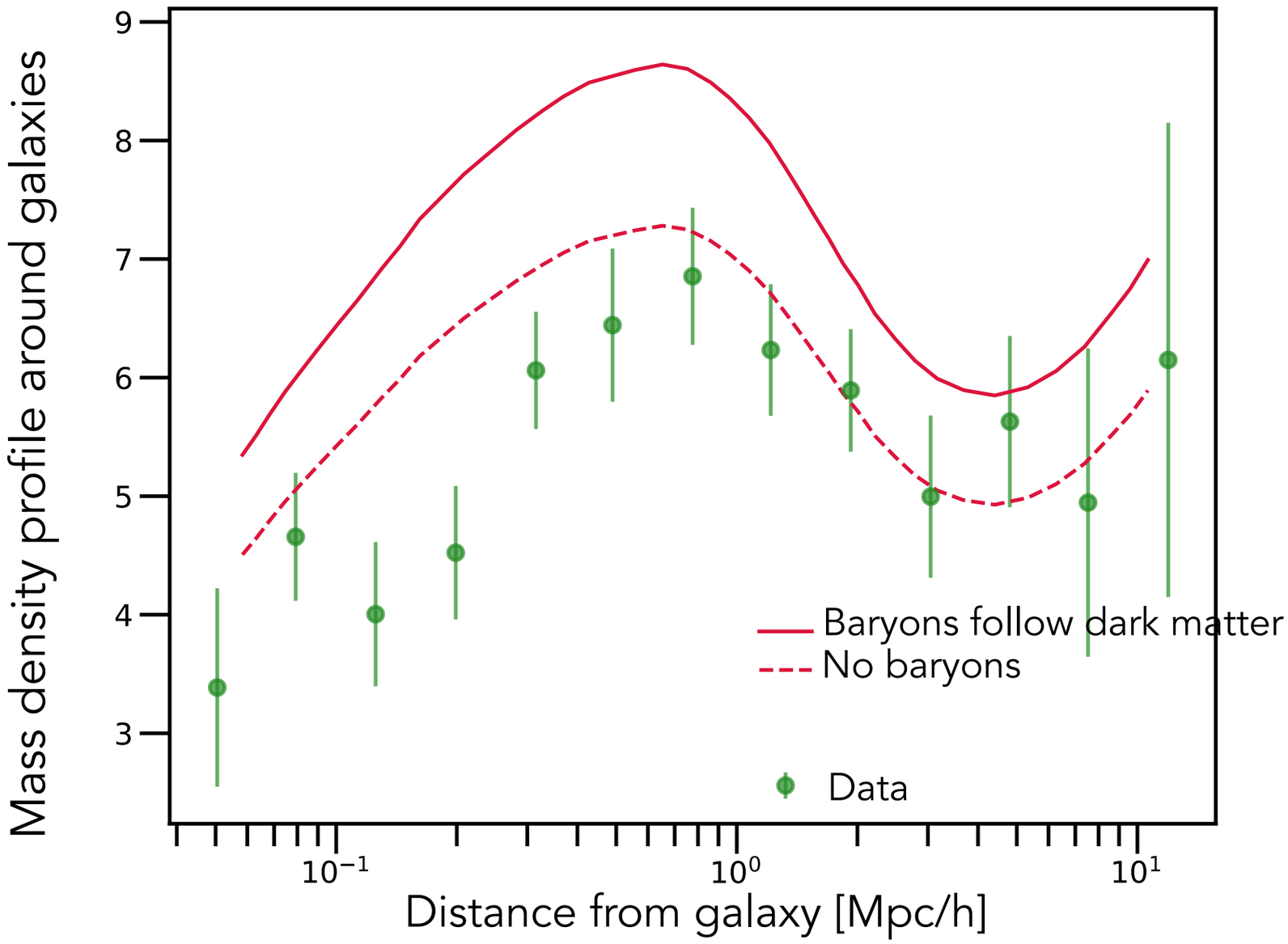
LSS tension: “lensing is low”



→ Directly subtract the baryonic contribution!

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

LSS tension: “lensing is low”



Amodeo Battaglia Schaan Ferraro & ACT 20

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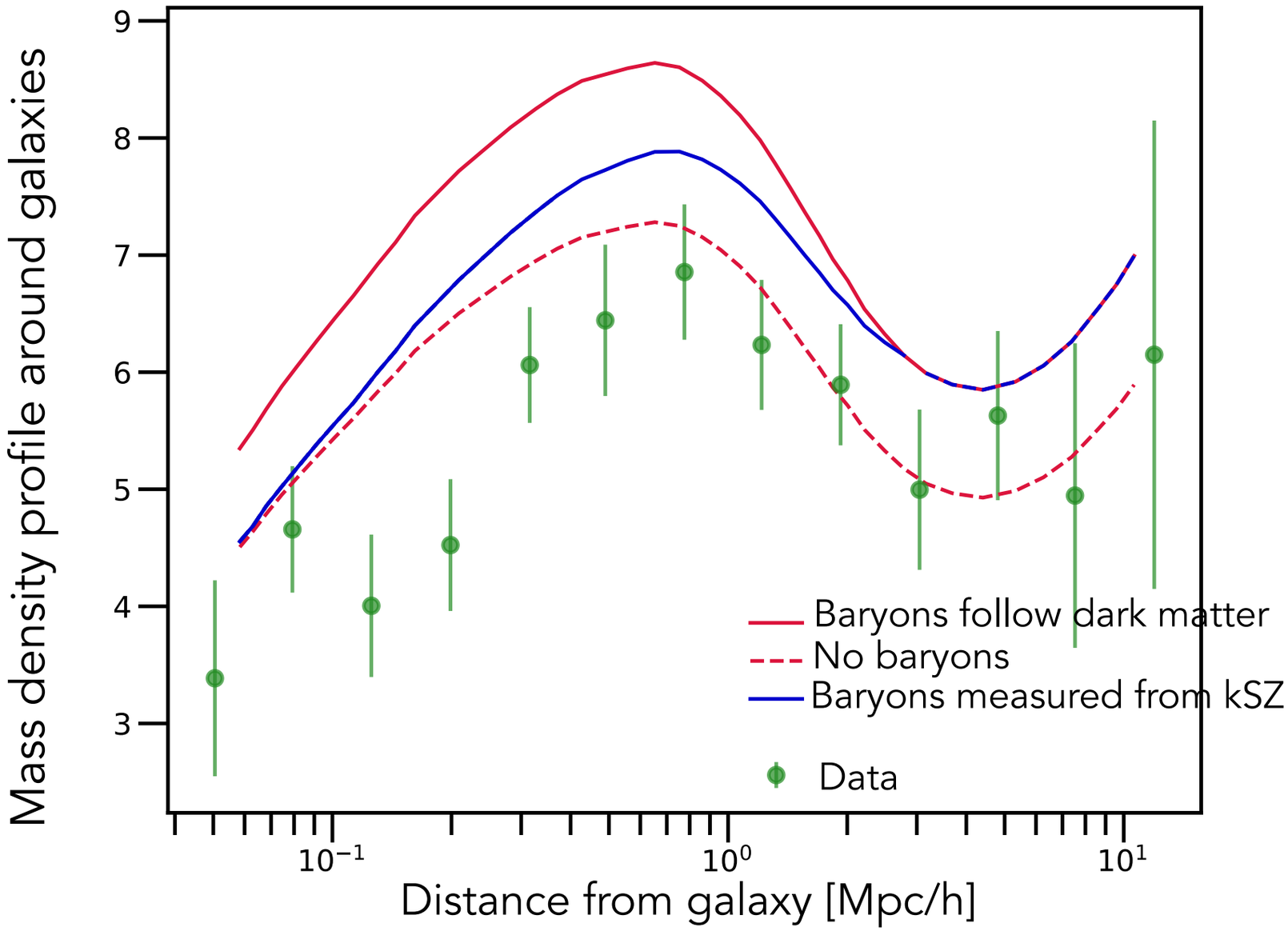


Amodeo Battaglia Schaan Ferraro & ACT 20

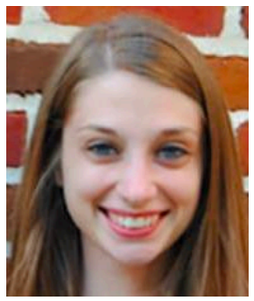
Baryons explain ~half the tension!

KSZ precision sufficient for current lensing data

Many recent & upcoming projects!

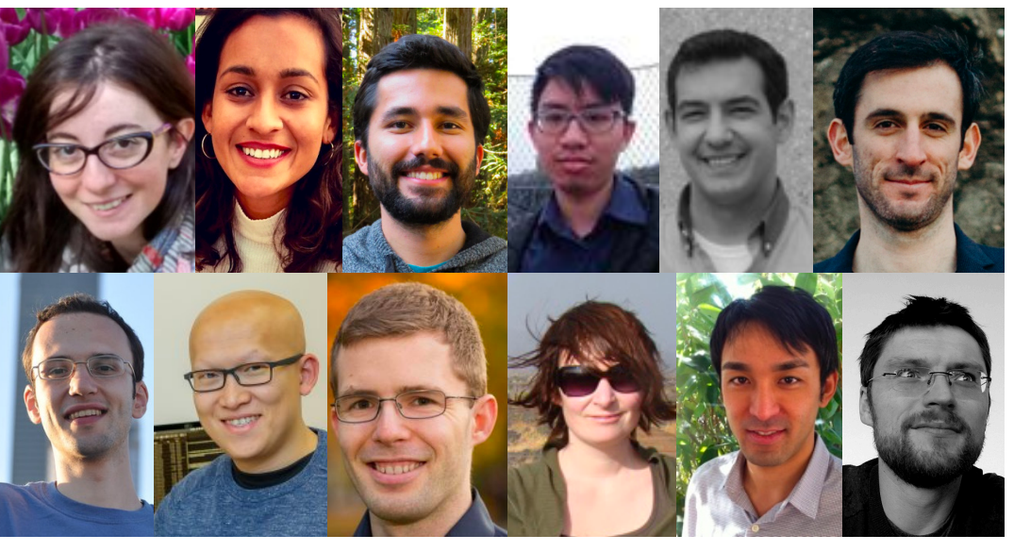
Gas more extended than dark matter
Temperature profile around galaxies
Solves most limiting systematics in current galaxy lensing

Amodeo Battaglia Schaan Ferraro & ACT 20



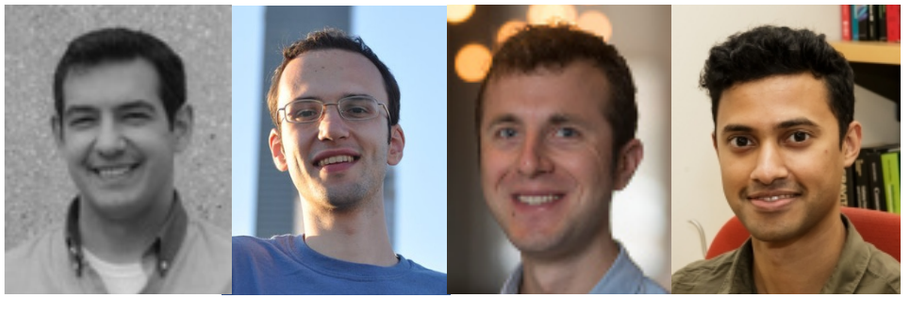
Constraining feedback in galaxy formation

Moser Amodeo Battaglia Alvarez Ferraro Schaan+21



SZ + lensing matter profiles + redshift-space distortions

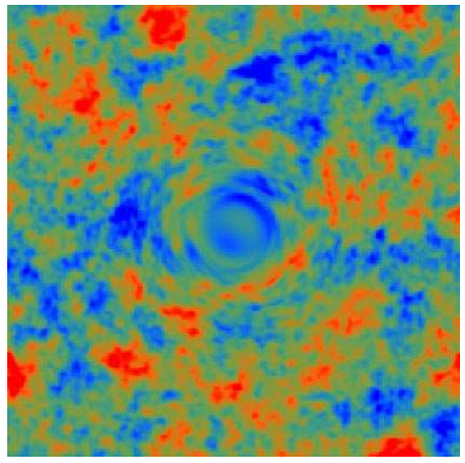
with Amodeo, Amon, Ardila, Aung, Battaglia, deRose, Ferraro, Huang, Lange, Leauthaud, Nagai, Schneider & ACT



SZ + cosmic shear, matter power spectrum

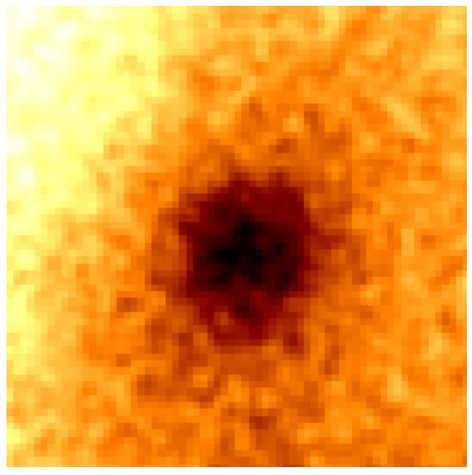
with Battaglia, Ferraro, Hill, Madhavacheril

Outline: Combining CMB & LSS



Mass shadows: Analogy CMB-galaxy lensing

Improved CMB lensing

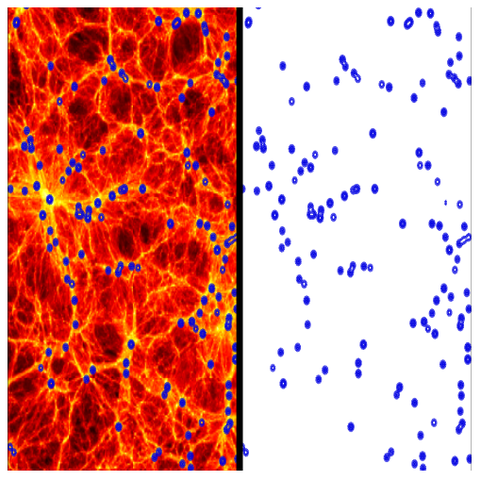


Gas shadows: Localize the missing baryons

Cosmology: solve baryonic uncertainty in lensing

Galaxy formation: feedback

Inflation: primordial non-Gaussianity

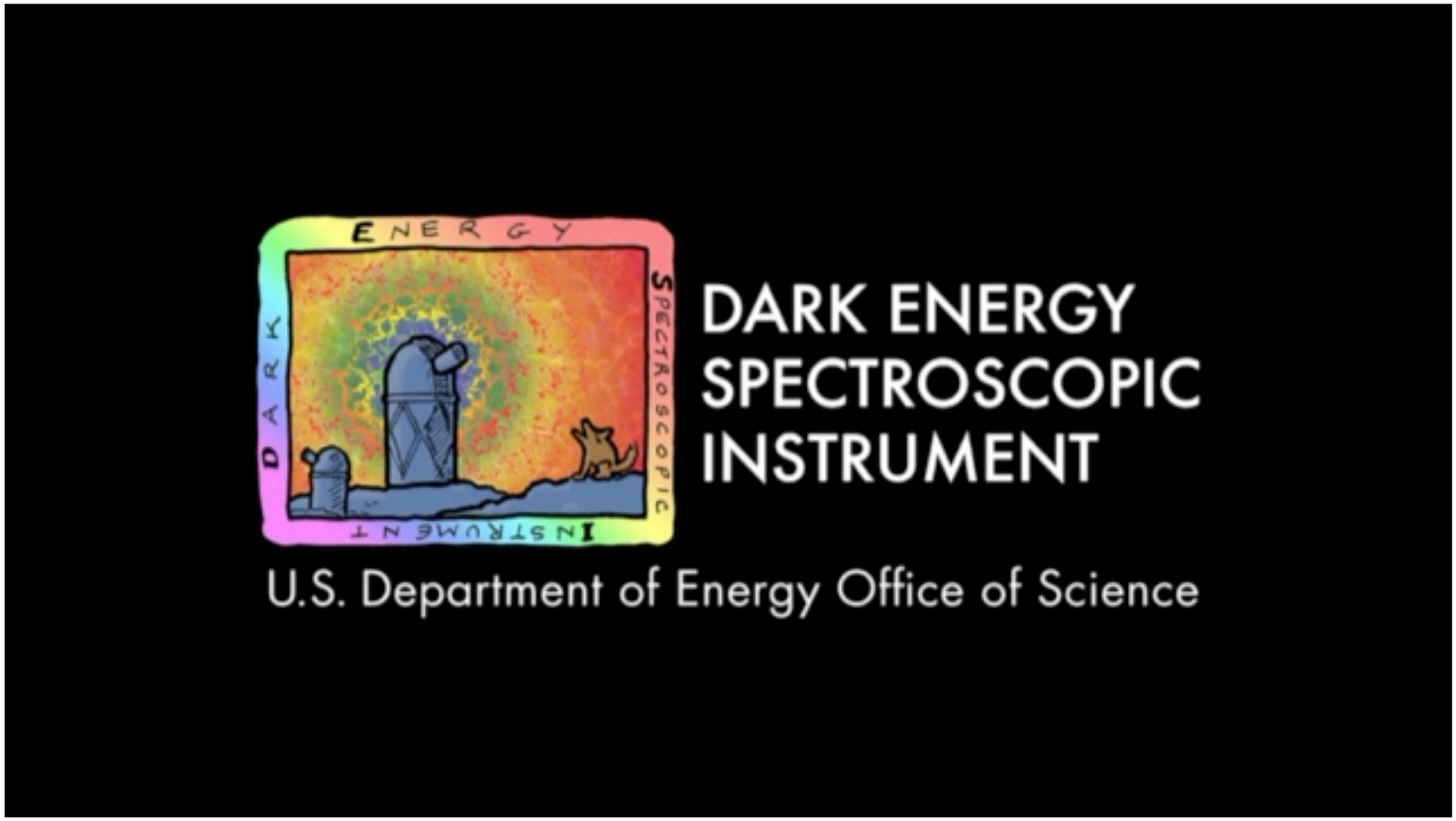


Future

Future Directions

Doré+15

KSZ from DESI: Revolution



Order of magnitude more galaxies

→ Solve baryonic uncertainty for lensing from Rubin

→ Transform galaxy formation

Inflation: primordial non-Gaussianity

→ number of fields, interactions

Summary: CMB secondary anisotropies

Fundamental physics, cosmology & astrophysics

Neutrino masses	20meV precision
Dark energy	density & equation of state (~1%)
Inflation	number of fields, interactions, energy scale
Dark matter	interactions, temperature
Galaxy formation	feedback

Unprecedented LSS & CMB datasets coming online

The CMB *is* an LSS probe

Unique redshift range, large sky coverage

Reveal the invisible Universe (missing baryons & DM)

Independent systematics, analogies with galaxies & LIM

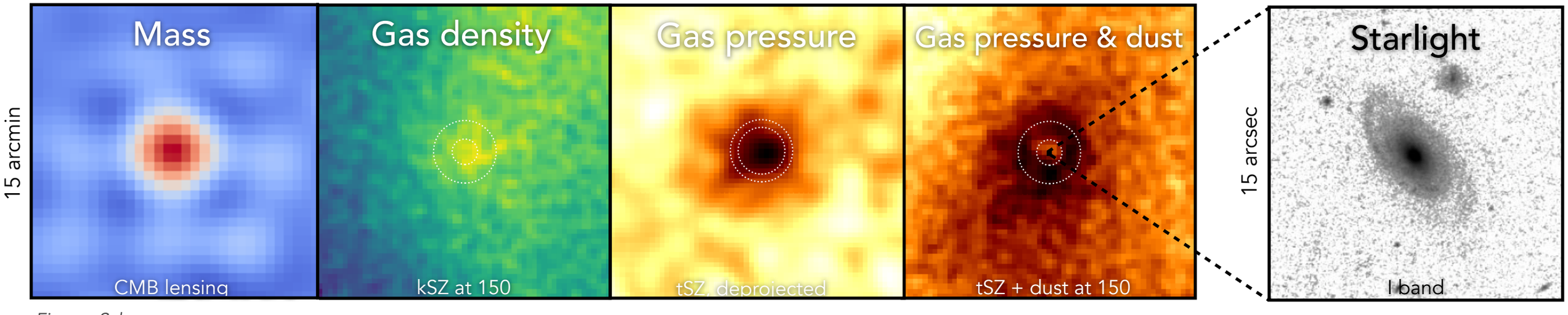


Figure: Schaan

ACT lensing: Madhavacheril, ACT+Planck kSZ & tSZ: Schaan+20, Amodeo+20. HST ACS I band image: Masters+11.