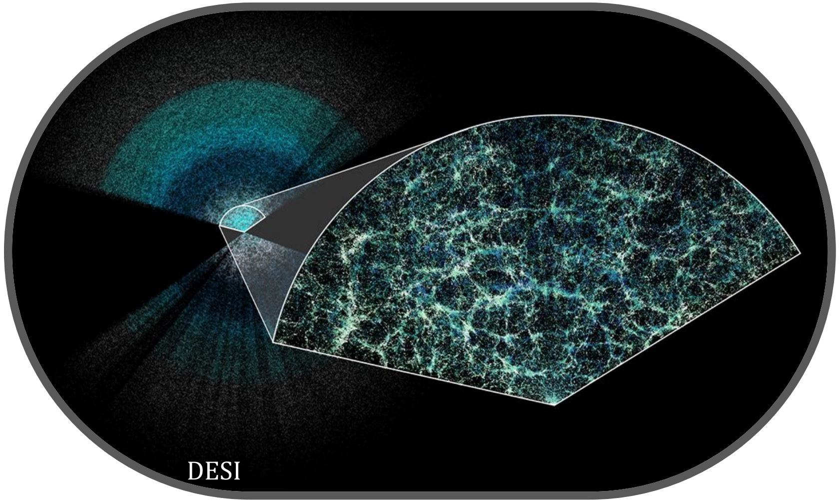
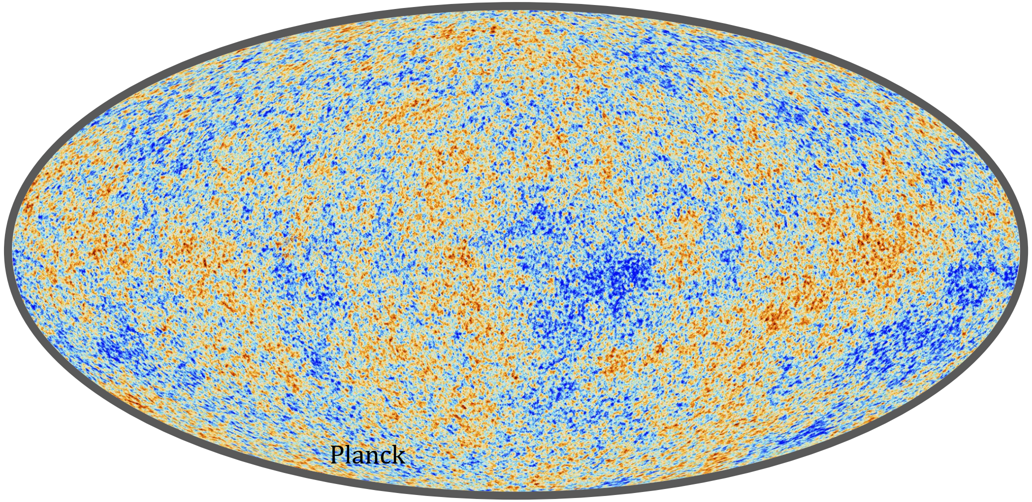
SYNERGIES WITH CMB

Selim C. Hotinli





Spec S5
LBNL
07/05/2024

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Imprints of LSS on the CMB

CMB x LSS cross-correlations: help maximize the information content from CMB and LSS

Sourced by gravitational potentials:

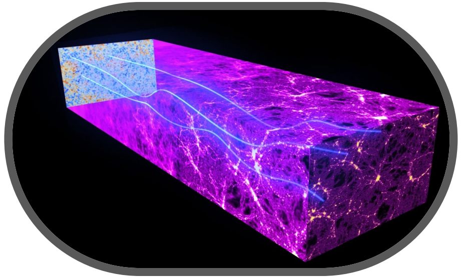
	Lensing,	$\propto \vec{\theta}_{\rm lens} \cdot \vec{\nabla} T$
	ISW,	$\propto \dot{\Phi}$
	Rees-Sciama,	
E. Pierpaoli's [next] talk ←	Moving Lens	$\propto \vec{v}_{\perp} \cdot \vec{\nabla} \Phi$

Sourced by Thomson scattering:

J. Huang's talk ←	Screening,	$\propto e^{-\tau}\, T$
	kinetic SZ,	$\propto v_{\|\|}\, \tau$
	rotational kSZ, turbulent SZ	$\propto v_{\rm rot}\, \tau$, $v_{\rm therm}\, \tau$
	thermal SZ, relativistic SZ	$\propto f(z)\, y_{\rm compt}$
	polarized SZ,	$\propto \tau\, a^{T}_{2m}$
	kinetic polarized SZ	$\propto \tau\, v_{\perp}^2$

Sourced by Dust:

Cosmic infrared background $\propto I_{\nu}$



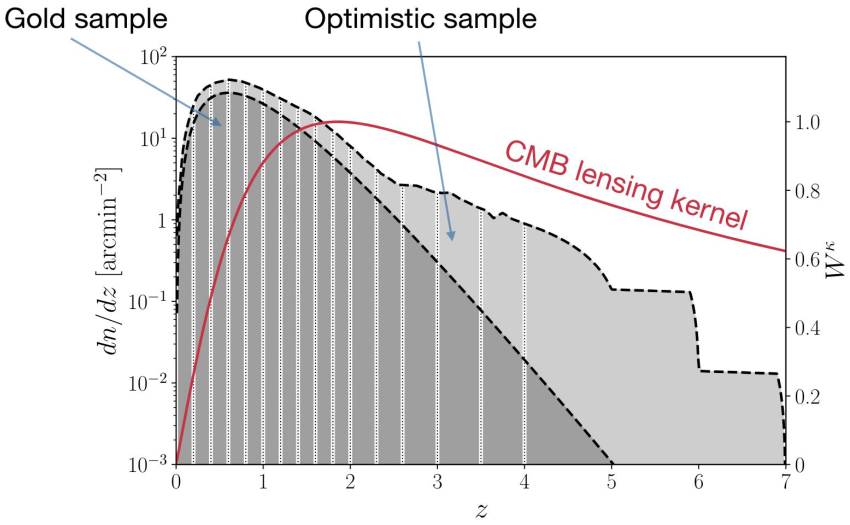
LSS x CMB lensing

- Powerful probe of underlying dark matter structure
- Not sensitive to galaxy bias
- CMB lensing maps are **projected LOS**

CMB lensing – galaxy x-correlations:

- (redshift slices) **tomographic analysis**

Lensing has a broad redshift kernel with significant contribution from 2<*z*<5.



Related works: S. Chen, M. White, J. DeRose, N. Kokron (2022), N. Sailer, E. Castorina, S. Ferraro, and M. White (2021), B. Yu, S. Ferraro, Z. Knight, L. Knox, and B. Sherwin (2021), M. Wilson and M. White (2019), B. Yu, R. Knight, B. Sherwin, S. Ferraro, L. Knox, and M. Schmittfull (2018), C. Modi, M. White, and Z. Vlah (2017), M. Schmittfull and U. Seljak (2017), ++

LSS x CMB lensing

- Powerful probe of underlying dark matter structure
- Not sensitive to galaxy bias
- CMB lensing maps are **projected LOS**

CMB lensing – galaxy x-correlations:

- (redshift slices) **tomographic analysis**
- Relation between luminous matter and dark matter
- Breaking the degeneracy with galaxy bias

$$P_{mm}(k) \sim \frac{\left[C_{\ell=k\chi}^{mg}\right]^2}{C_{\ell=k\chi}^{gg}}$$

More robust against:

- Details of selection functions
- Spatially inhomogeneous noise

(that could add spurious power to auto-correlations)

- Intrinsic alignments
- Non-linear baryonic effects
- Assumptions about CMB experiment

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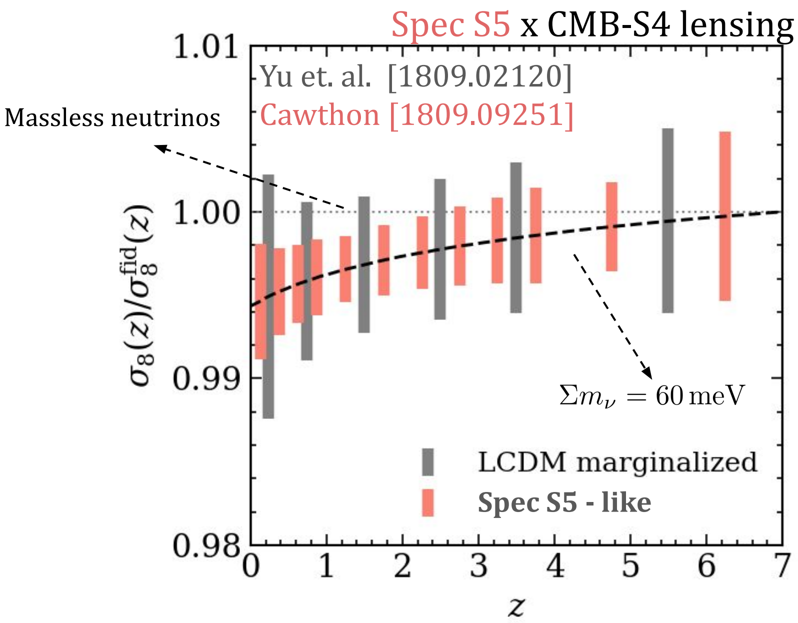
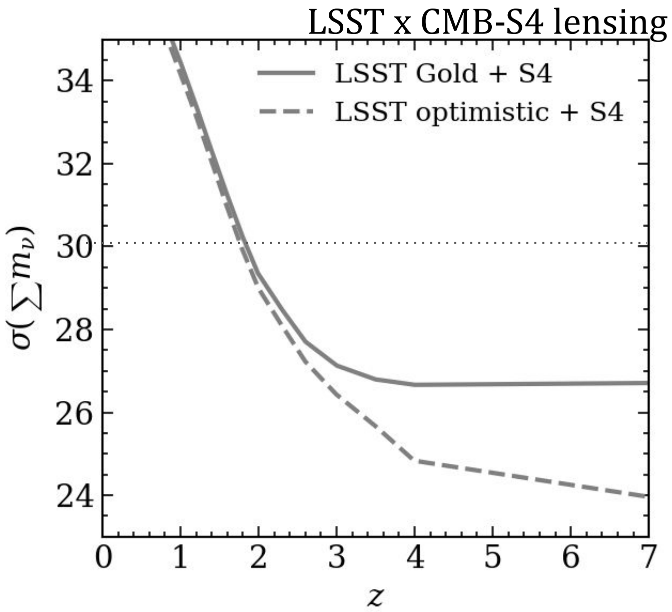
LSS x CMB lensing

Growth of structure:



Massive neutrinos suppress the growth of density fluctuations

Neutrino masses:



Beyond 2σ constraints on neutrino mass.
(or high-significance implication of new physics e.g. → Craig et al. 2405.00836)

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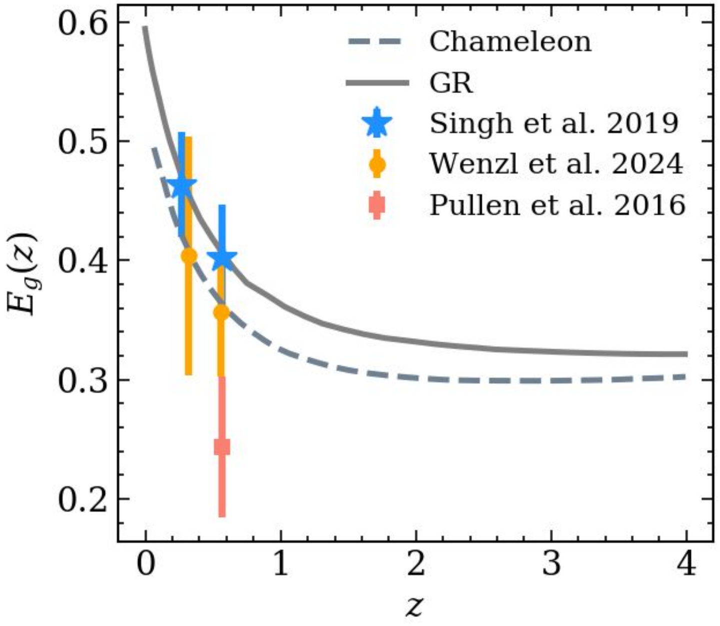
LSS x CMB lensing

Probing general relativity:

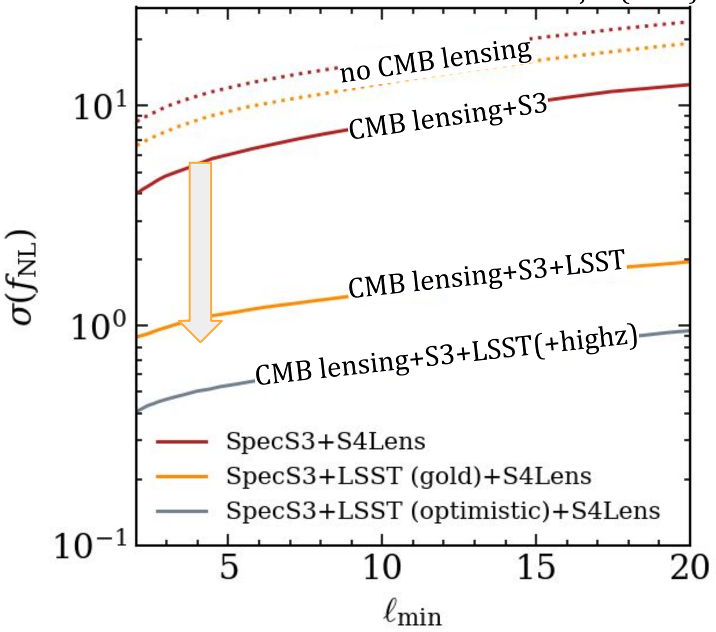


E_G: A consistency check on GR, sensitive to the ratio of Newtonian potential and curvature potential

(Zhang et al, 07)

Probing non-Gaussianity on large-scales:

M. Schmittfull and U. Seljak (2017)



Around an order-or-magnitude increase for the constraints on f_{NL} from CMB lensing x LSS

(more on this later)

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Sunyaev Zel'dovich effects

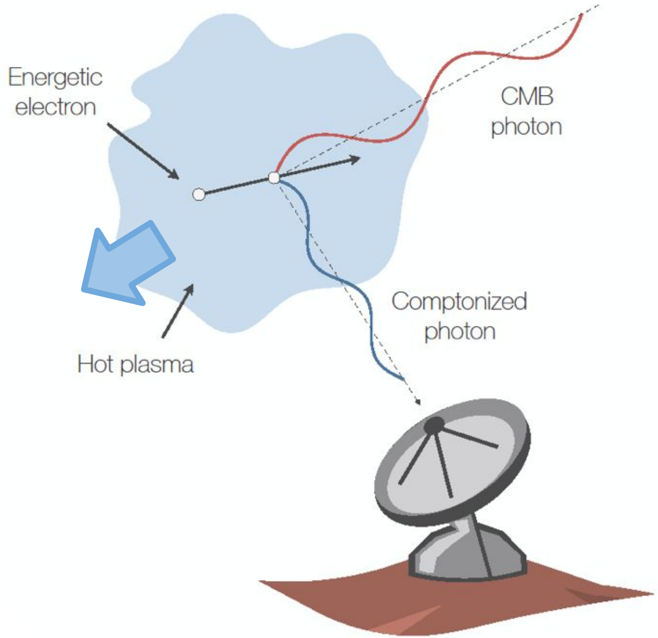
Inverse Compton scattering of CMB photons with free electrons in the late-time Universe
These effects probe diffuse ionized gas.

<u>The thermal SZ (tSZ) effect</u>:
CMB photons scatter off on energetic electrons (an energy boost)

- Sensitive to electron gas pressure.

<u>kinematic SZ (kSZ) effect</u>:
Electron non-zero **bulk velocity** with respect to the CMB frame.

- Sensitive to electron column density.



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- Sensitive to electron gas pressure.

$$\frac{\delta T_{\rm tSZ}(\hat{\boldsymbol{n}})}{T_{\rm CMB}} = f_{\rm tSZ}(\nu)\, y(\hat{\boldsymbol{n}})$$

Compton-y

<u>kinematic SZ (kSZ) effect</u>:
Electron non-zero **bulk velocity** with respect to the CMB frame.

- Sensitive to electron column density.

$$\frac{\delta T_{\rm kSZ}(\hat{\boldsymbol{n}})}{T_{\rm CMB}} \propto N_e(\boldsymbol{\theta})\, \frac{v_r}{c}$$

Column density of electrons

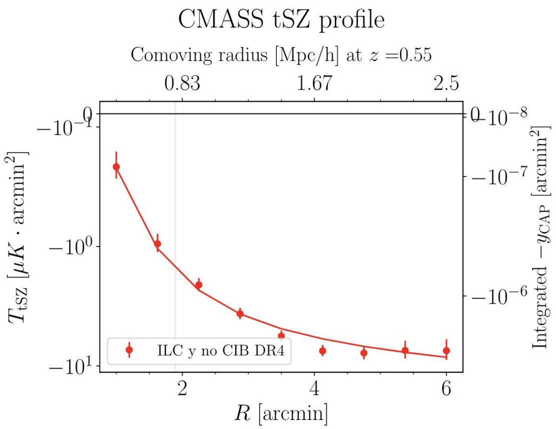
Radial velocity

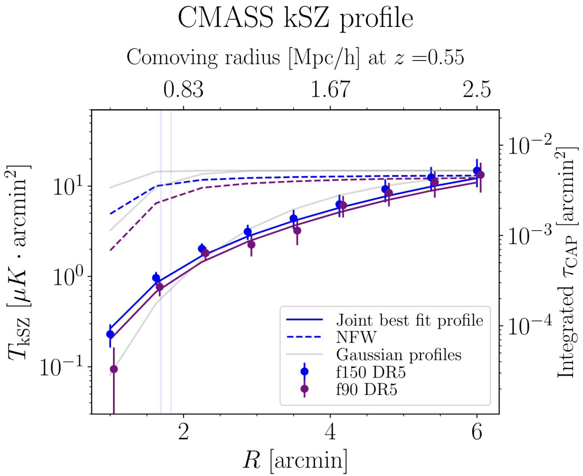
Cross-correlations of CMB & LSS:
$\rightarrow$ redshift dependent **distribution**, **thermal state**, and **dynamics** of <u>baryons</u>.

Can be used to **improve cosmological constraints**.

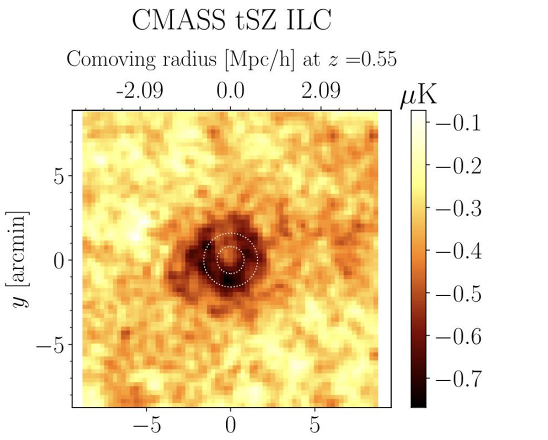
Sunyaev Zel'dovich effects

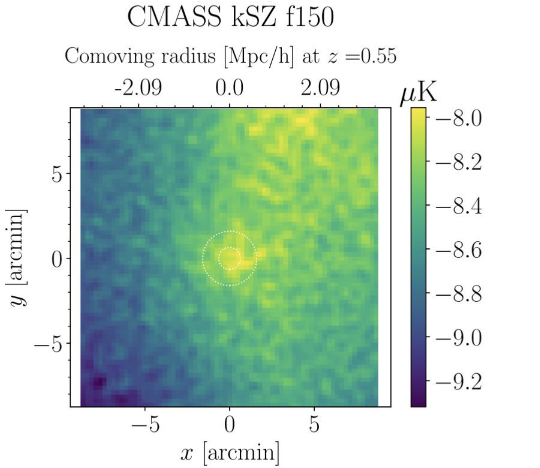
Measurement of profiles:





Stacking tSZ and kSZ patches on galaxies:





These signals can be used to determine the full thermodynamic information of the halo

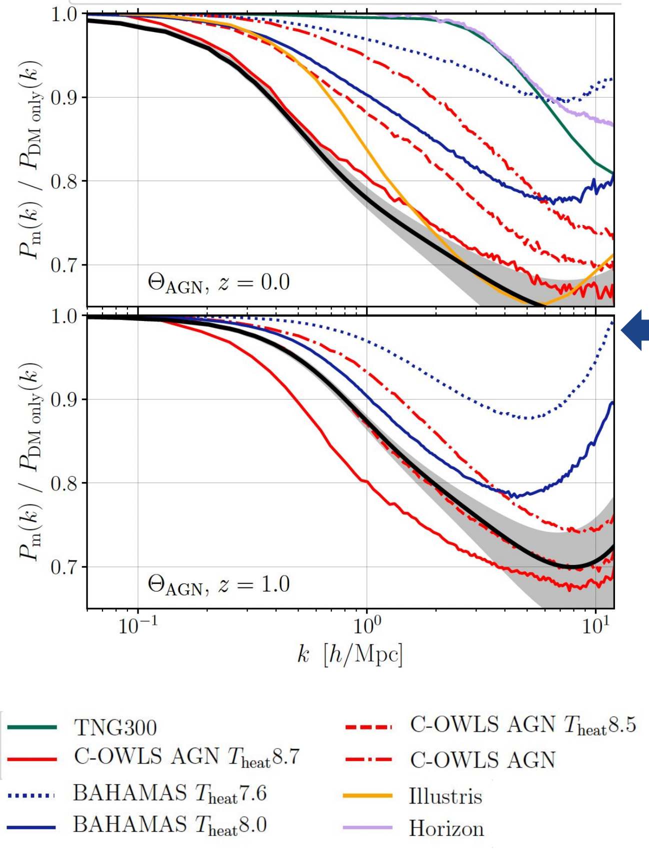
- Electron profiles,
- Fraction of non-thermal pressure,
- Temperature profiles, etc.
- Amount of baryonic feedback

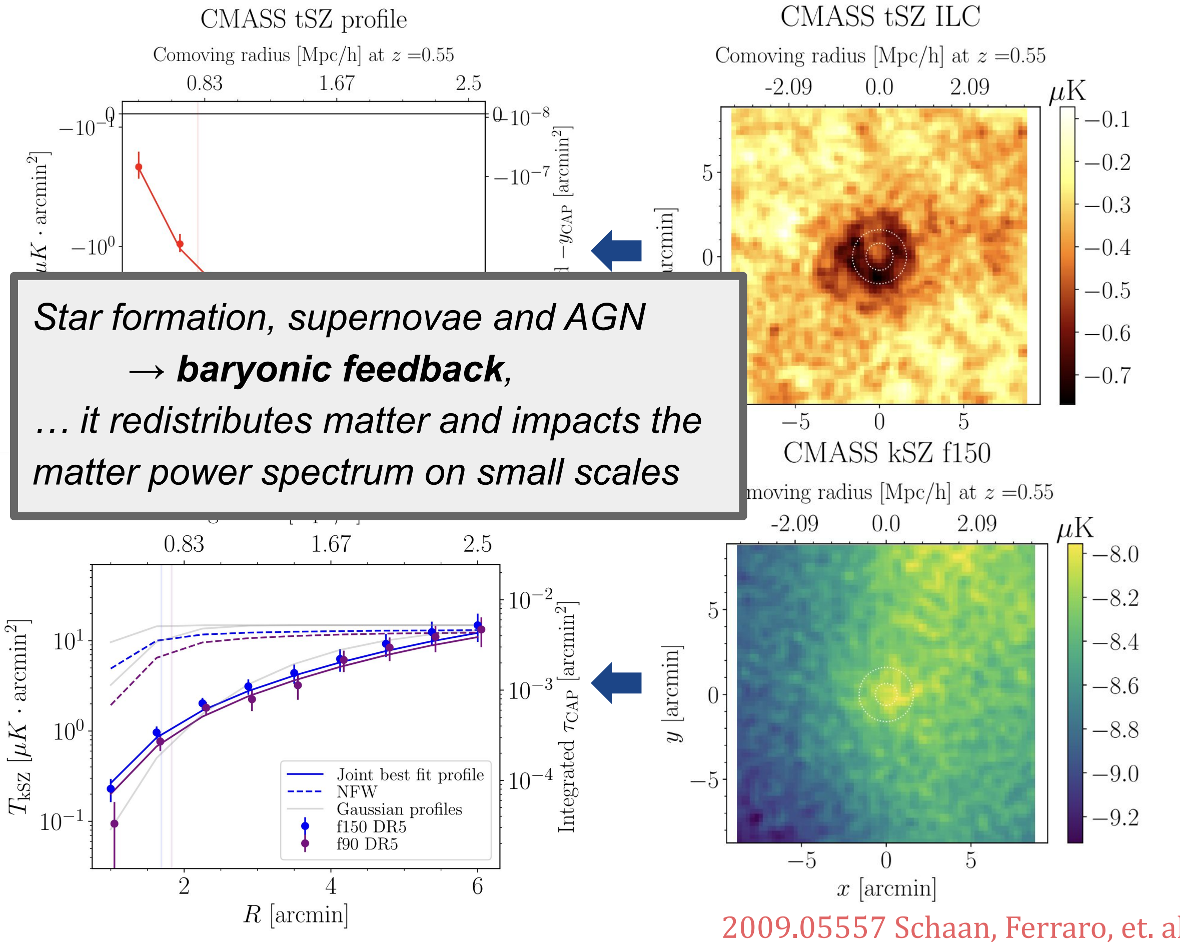
Access to gas properties

→ baryonic effects in the matter power spectrum and weak lensing.

2009.05557 Schaan, Ferraro, et. al.

Sunyaev Zel'dovich effects





Star formation, supernovae and AGN
→ ***baryonic feedback****,*
… it redistributes matter and impacts the matter power spectrum on small scales

2009.05557 Schaan, Ferraro, et. al.

kinetic SZ

SZ effects are probes of cosmology as well.

$$\frac{\delta T_{\rm kSZ}(\hat{\boldsymbol{n}})}{T_{\rm CMB}} \propto N_e(\boldsymbol{\theta}) \frac{v_r}{c}$$

= cosmology

Column density of electrons

Radial velocity

kinetic SZ

Measurements in isolation are subject to a **large null condition**

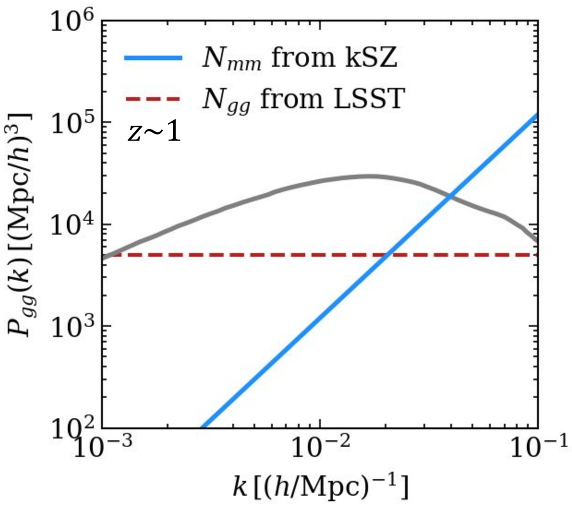
$$P_{gg}(k) = b_g^2 \underline{P_{mm}(k)}$$

Cross-correlations removes this dependence

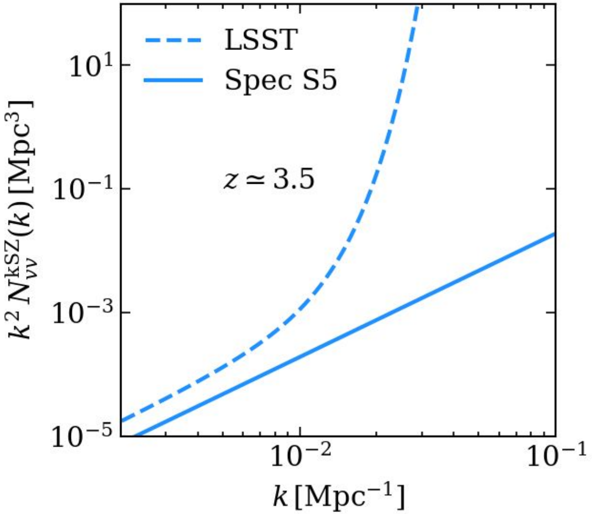
$$\frac{P_{gg}(k)}{P_{gv}(k)} = b_g \left(\frac{faH}{k}\right)^{-1} \frac{P_{mm}(k)}{P_{mm}(k)}$$

The reconstruction **noise** scales like **velocity**

$$N_{mm}(k,\mu) \propto k^2 N_{vv}(k,\mu)$$



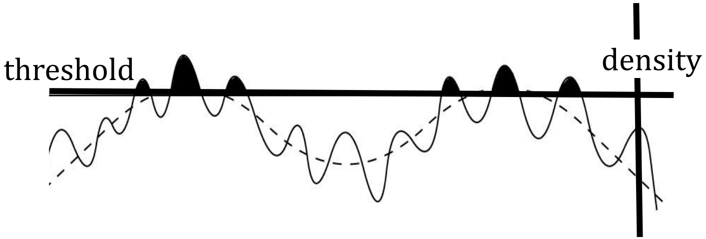
Redshifts improve reconstruction significantly, including at **high z**

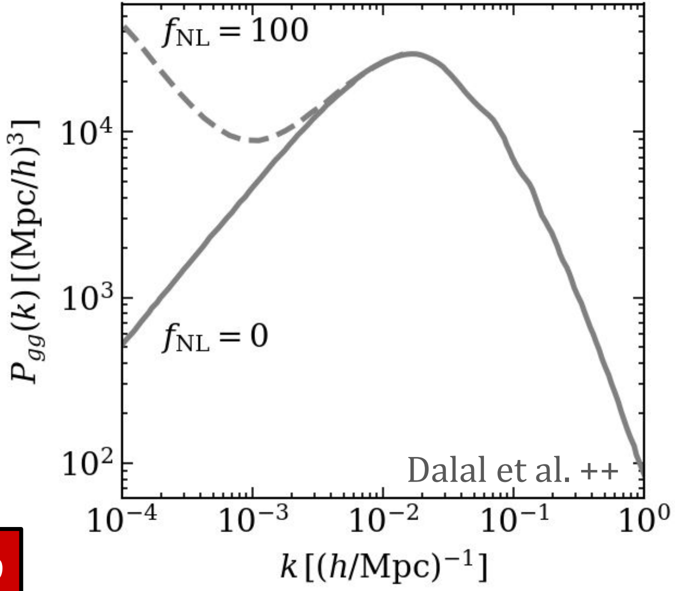


Related works: AS Deutsch, Dimastrogiovanni, M Johnson, M Münchmeyer, and A Terrana (2018) K Smith, M Madhavacheril, M Münchmeyer, S Ferraro, U Giri, M Johnson (2018) J Cayuso, M Johnson, J Mertens (2018), J Cayuso, R Bloch, SC Hotinli, M Johnson, F McCarthy (2021) D Contreras, F McCarthy, MC Johnson (2022) U Giri, K Smith (2020)M Münchmeyer, MS Madhavacheril, S Ferraro, MC Johnson, K Smith (2018) NA Kumar, G Sato-Polito, M Kamionkowski, SC Hotinli (2022) ++

kinetic SZ

Clustering is sensitive to large-scale fluctuations

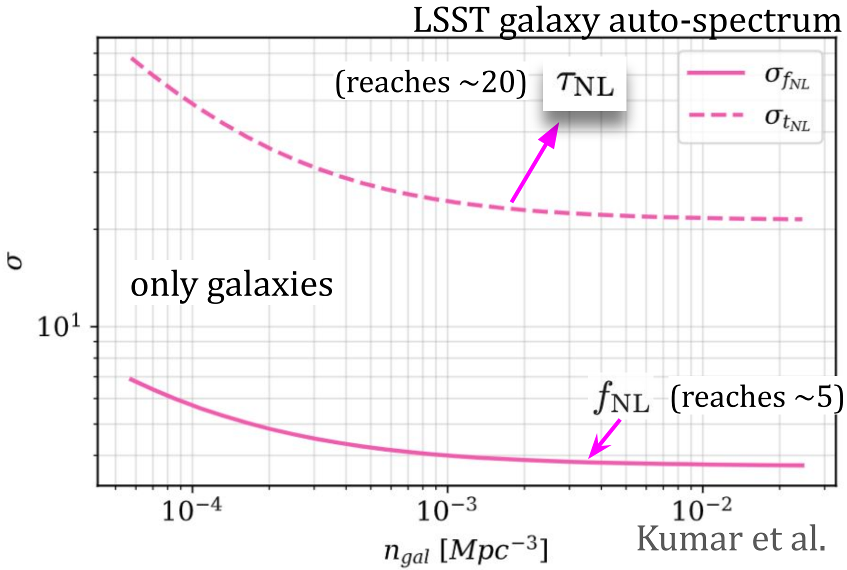




Spectra from galaxies gain scale dependence in the presence of primordial non-Gaussianity

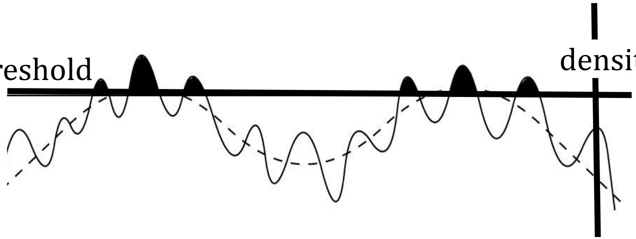
$$P_{gg}(k,\mu) = \left[b_g^2 + \triangle \; f_{\rm NL} + \diamond \; \tau_{\rm NL} \right] P_{mm}(k)$$

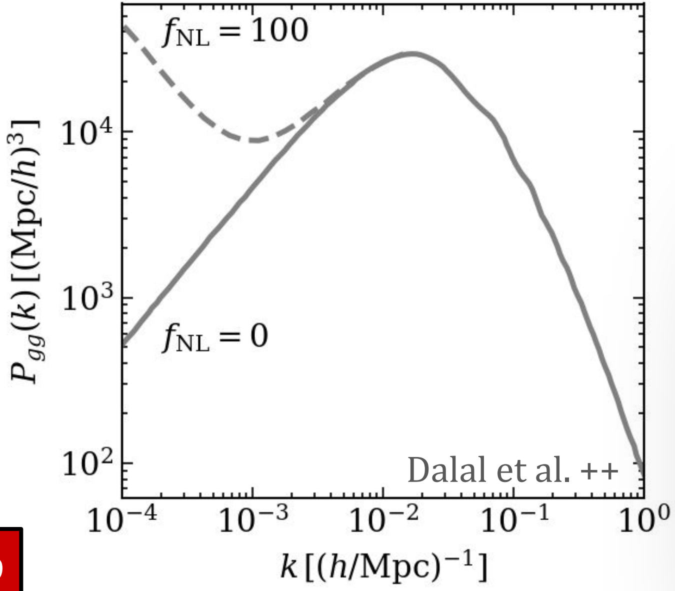
Single-field slow roll: $\tau_{NL} \equiv (6/5 f_{\rm NL})^2$



kSZ tomography (or velocity reconstruction)

Clustering is sensitive to large-scale fluctuations



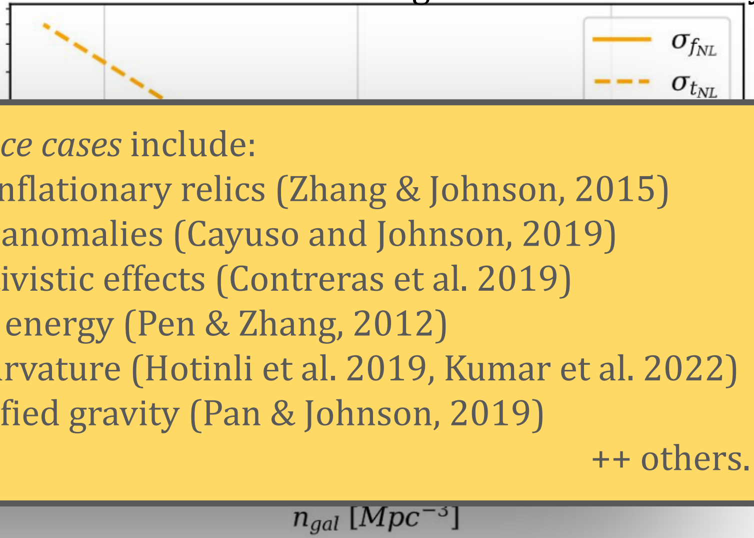


Spectra from galaxies gain scale dependence in the presence of primordial non-Gaussianity

$$P_{gg}(k,\mu) = \left[b_g^2 + \quad f_{\rm NL} + \quad \tau_{\rm NL} \right] P_{mm}(k)$$

kSZ reconstructed large-scale velocities help probing this effect beyond the cosmic variance.

LSST galaxies + kSZ velocity

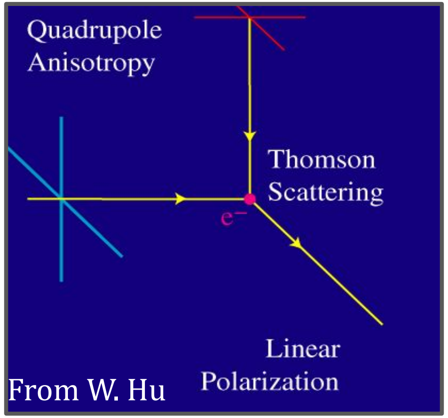


Science cases include:
Pre-inflationary relics (Zhang & Johnson, 2015)
CMB anomalies (Cayuso and Johnson, 2019)
Relativistic effects (Contreras et al. 2019)
Dark energy (Pen & Zhang, 2012)
Isocurvature (Hotinli et al. 2019, Kumar et al. 2022)
Modified gravity (Pan & Johnson, 2019)
++ others.

polarized SZ

pSZ tomography (or quadrupole reconstruction)

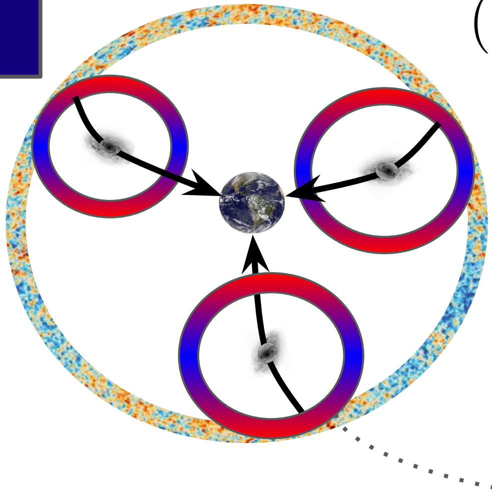
$$\langle TBg \rangle, \ \langle TEg \rangle, \ \langle EBg \rangle, \ \langle EEg \rangle, \ \ldots$$



Remote quadrupole seen by electrons

$$(Q \pm iU)^{(e)}(\hat{\boldsymbol{n}}) = N_e(\boldsymbol{\theta}) \pm p(\hat{\boldsymbol{n}})$$

Column density of electrons



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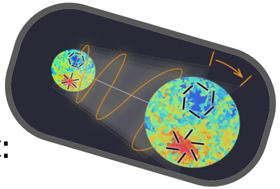
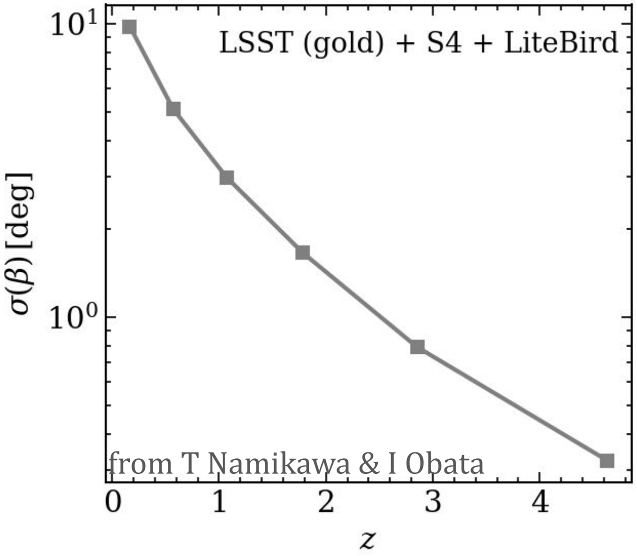
polarized SZ

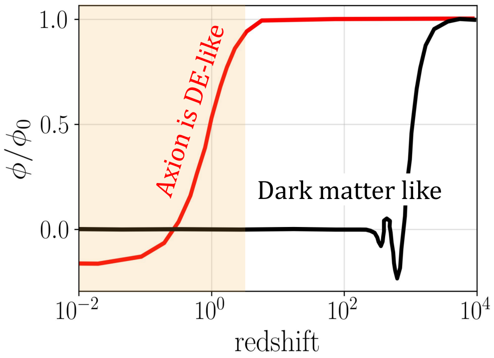
(As possible follow-ups of break-through measurements.)

Tomographic measurement of the pSZ effect allows probing cosmic birefringence as a function of redshift:





Axion dark matter
or dark energy?



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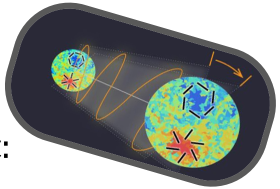

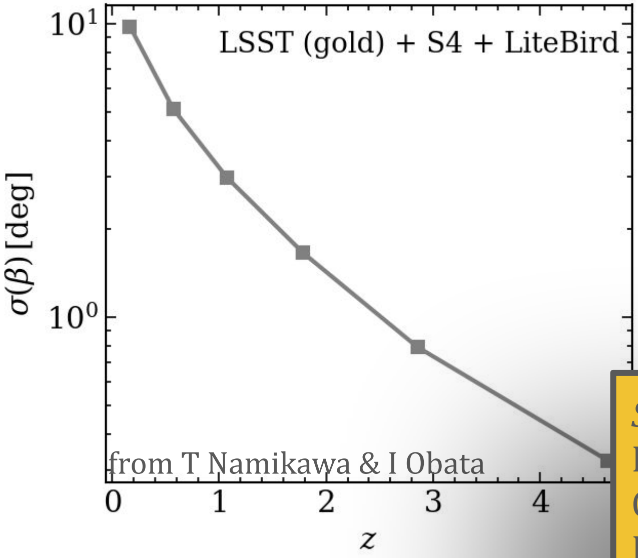

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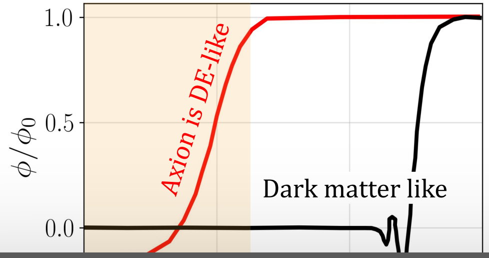
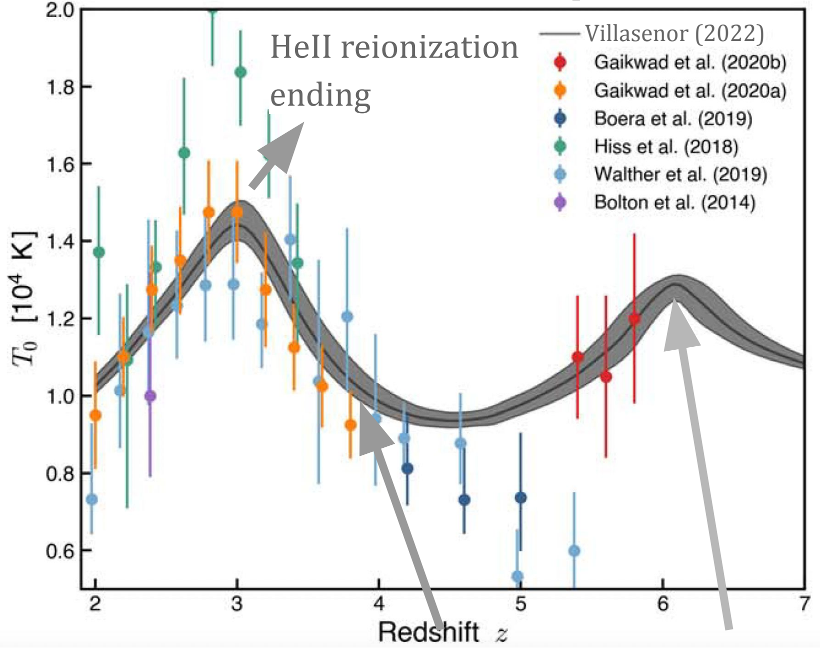


Science cases include:
Primordial tensor fluctuations (2203.05728)
CMB anomalies (Cayuso and Johnson, 2019)
Primordial non-Gaussianity (Hotinli et al. 2022)
Optical depth to reionization (Meyers et al. 2017)
++ others.

Related works: M Kamionkowski, A Loeb (97) E Alizadeh, C M. Hirata (2012) … (2017)
AS Deutsch, MC Johnson, M Münchmeyer, A Terrana (2017) J Meyers, PD Me … SC
Hotinli, GP Holder, MC Johnson, M Kamionkowski (2022) H Nakatsuka, Y Namikawa, E Komatsu (2022) T Namikawa, I Obata (2023), ++

HeII reionization with Spec S5 x CMB (ionization of the second electron in He, ~54 eV)

Redshift evolution of IGM temperature



HeII reionization starting

HI reionization ending

Data points: Lyman-alpha measurements.

Gray line: Hydro simulation (fitted)

Data shows a clear suggestion for the **existence** of HeII reionization **starting** around z~4 and ending around z~3.

Note that these data points are model dependent.

Simulate a range of thermal histories, fit the best matching Lyman-alpha flux power and take the corresponding temperature.

Additional probes of this epoch may help validate and inform other observations.

Related *works:* e.g. Miralda-Escudé, Rees (1994) Sokasian, Abel, Hernquist (2001,02), Hui, Haiman (2003), Faucher-Giguère, Lidz, Zaldarriaga, Hernquist (2008,09), Furlanetto, Oh (2007,08), Dixon, Furlanetto, Mesinger (2013), Worseck, Prochaska, Hennawi, McQuinn (2014), Compostella, Cantalupo, Porciani (2014), La Plante, Trac, Croft, Cen (2017), and others.

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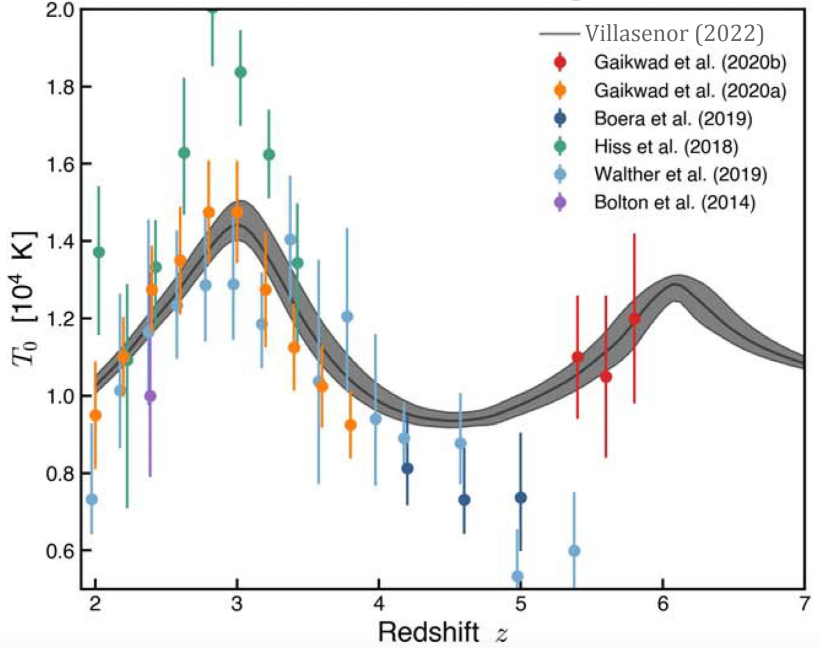
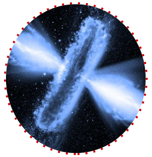


Helium reionization depends on AGN:



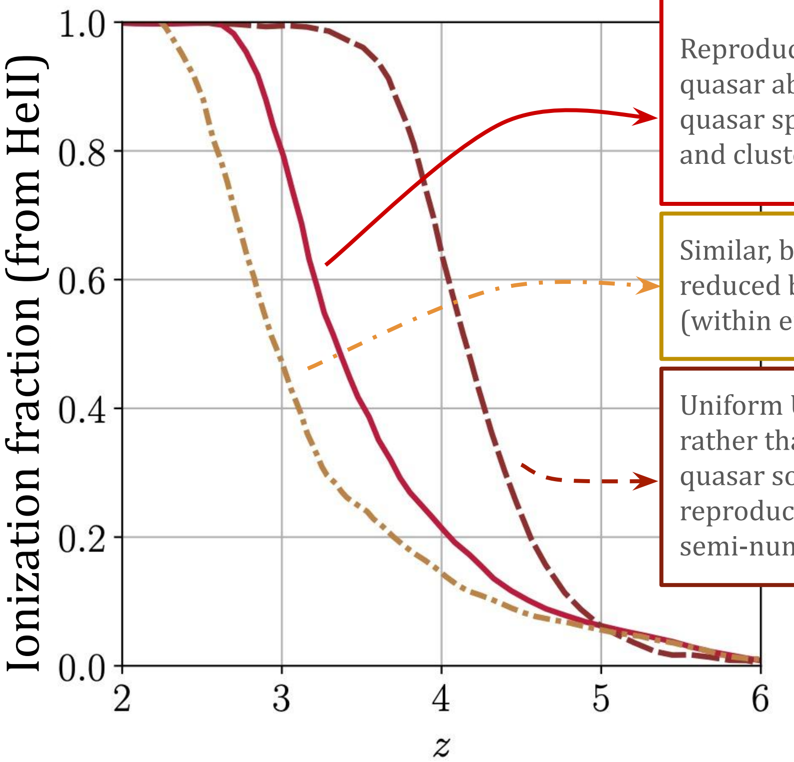
- Properties of quasars
  - Quasar luminosity functions
  - Accretion mechanisms
  - Clustering
  - Variability
  - Lifetimes
- Growth and evolution of supermassive black holes.

Related *works:* e.g. Miralda-Escudé, Rees (1994) Sokasian, Abel, Hernquist (2001,02), Hui, Haiman (2003), Faucher-Giguère, Lidz, Zaldarriaga, Hernquist (2008,09), Furlanetto, Oh (2007,08), Dixon, Furlanetto, Mesinger (2013), Worseck, Prochaska, Hennawi, McQuinn (2014), Compostella, Cantalupo, Porciani (2014), La Plante, Trac, Croft, Cen (2017), and others.

HeII reionization with Spec S5 x CMB

(ionization of the second electron in He, ~54 eV)

(Hydro simulation) La Plante et al. [1710.03286]



Reproduces measured quasar abundance (SDSS), quasar spectrum (HST), and clustering (BOSS)

Similar, but abundance reduced by factor of 2 (within error bars)

Uniform UV background rather than explicit quasar sources, reproduces the semi-numeric models

Ionization fraction during this time is highly sensitive to quasar abundance, spectra and clustering.

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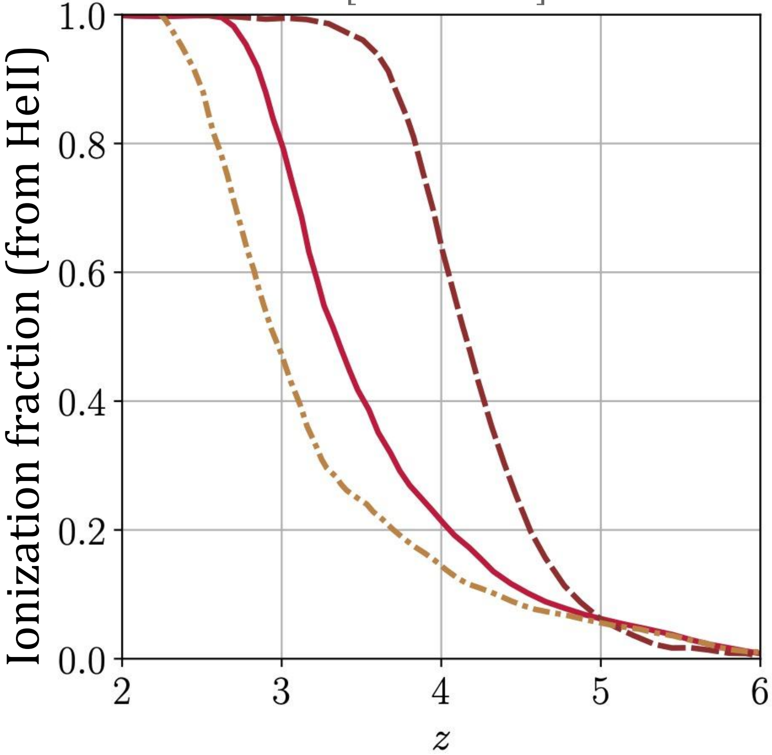


SZ effects in CMB are sensitive to the ionization fraction

$$\frac{\delta T_{\rm kSZ}(\hat{\boldsymbol{n}})}{T_{\rm CMB}} \propto N_e(\boldsymbol{\theta}) \frac{v_r}{c}$$

Column density of electrons

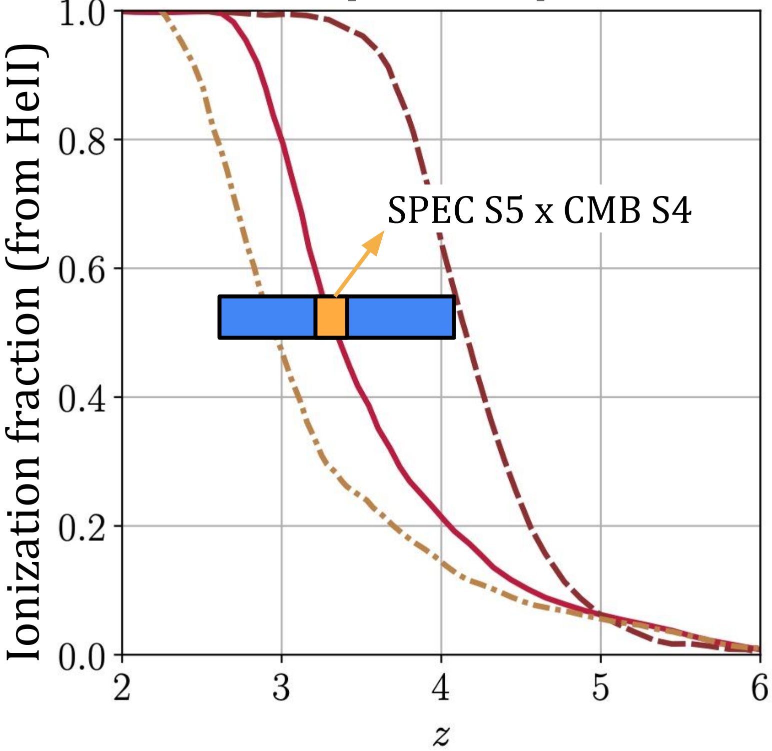
=sensitive to ionization fraction

Radial velocity

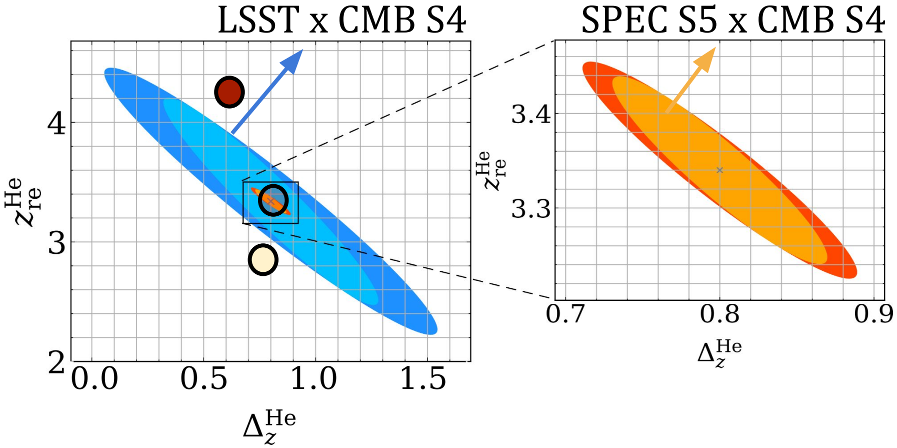
Related *works:* e.g. Miralda-Escudé, Rees (1994) Sokasian, Abel, Hernquist (2001,02), Hui, Haiman (2003), Faucher-Giguère, Lidz, Zaldarriaga, Hernquist (2008,09), Furlanetto, Oh (2007,08), Dixon, Furlanetto, Mesinger (2013), Worseck, Prochaska, Hennawi, McQuinn (2014), Compostella, Cantalupo, Porciani (2014), La Plante, Trac, Croft, Cen (2017), and others.

HeII reionization with Spec S5 x CMB (ionization of the second electron in He, ~54 eV)

La Plante et al. [1710.03286]



$$\langle T_{\rm kSZ}\, g\, g\rangle \propto x_e(z)$$



Hotinli, S Ferraro, G Holder, M Johnson,
M Ka
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kSZ tomography with a Spec S5 survey could provide to be the *most powerful probe* of HeII reionization

Related *works:* e.g. Miralda-Escudé, Rees (1994) Sokasian, Abel, Hernquist (2001,02) ... rnquist (2008,09), Furlanetto, Oh (2007,08), Dixon, Furlanetto, Mesinger (2013), Worseck, P ... o, Porciani (2014), La Plante, Trac, Croft, Cen (2017), and others.

Selim Hotinli (shotinli@perimeterinstitute.ca)

Conclusions

Scientific programs involving **joint-analyses** of different tracers of large-scale structure (**LSS**) and **CMB** are increasingly gaining attention.

They increase the prospects to detect and characterise new signals by reducing systematics, cancelling cosmic variance and breaking degeneracies.

Using the CMB as a **back-light**; observing the scattering and gravitational lensing effects on the CMB by the intervening cosmological structure will provide the most precise tests of **initial conditions**

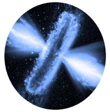
…and has the potential to open *new and unique* windows into unexplored epochs of structure formation like the epoch of **helium reionization**

These methods do not require new experiments other than those being built or proposed.

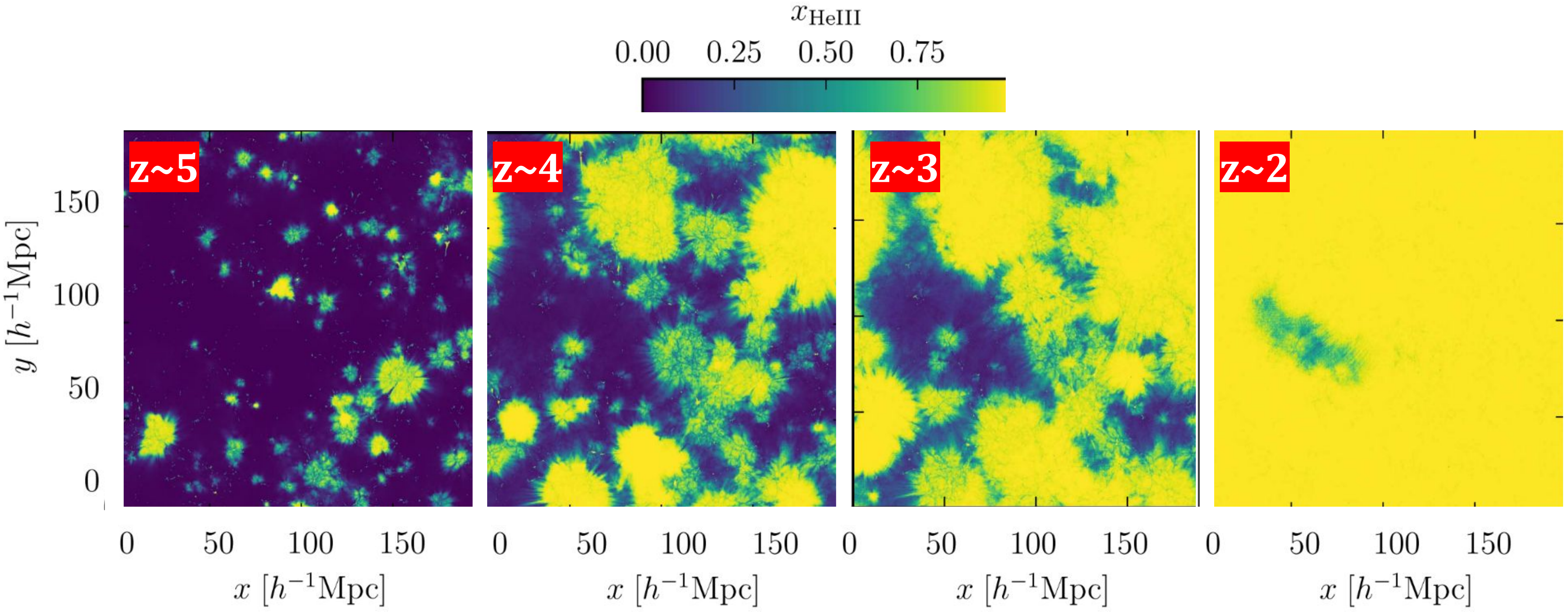
CMB lensing x LSS

kSZ & pSZ tomography

Helium Reionization



HeII reionization with Spec S5 x CMB (ionization of the second electron in He, ~54 eV)



Similar to hydrogen reionization, HeII reionization is also `patchy'.

A Spec S5 survey will have the sensitivity to probe this `patchiness'. (ongoing work)