JOHNS HOPKINS
KRIEGER SCHOOL
of ARTS & SCIENCES

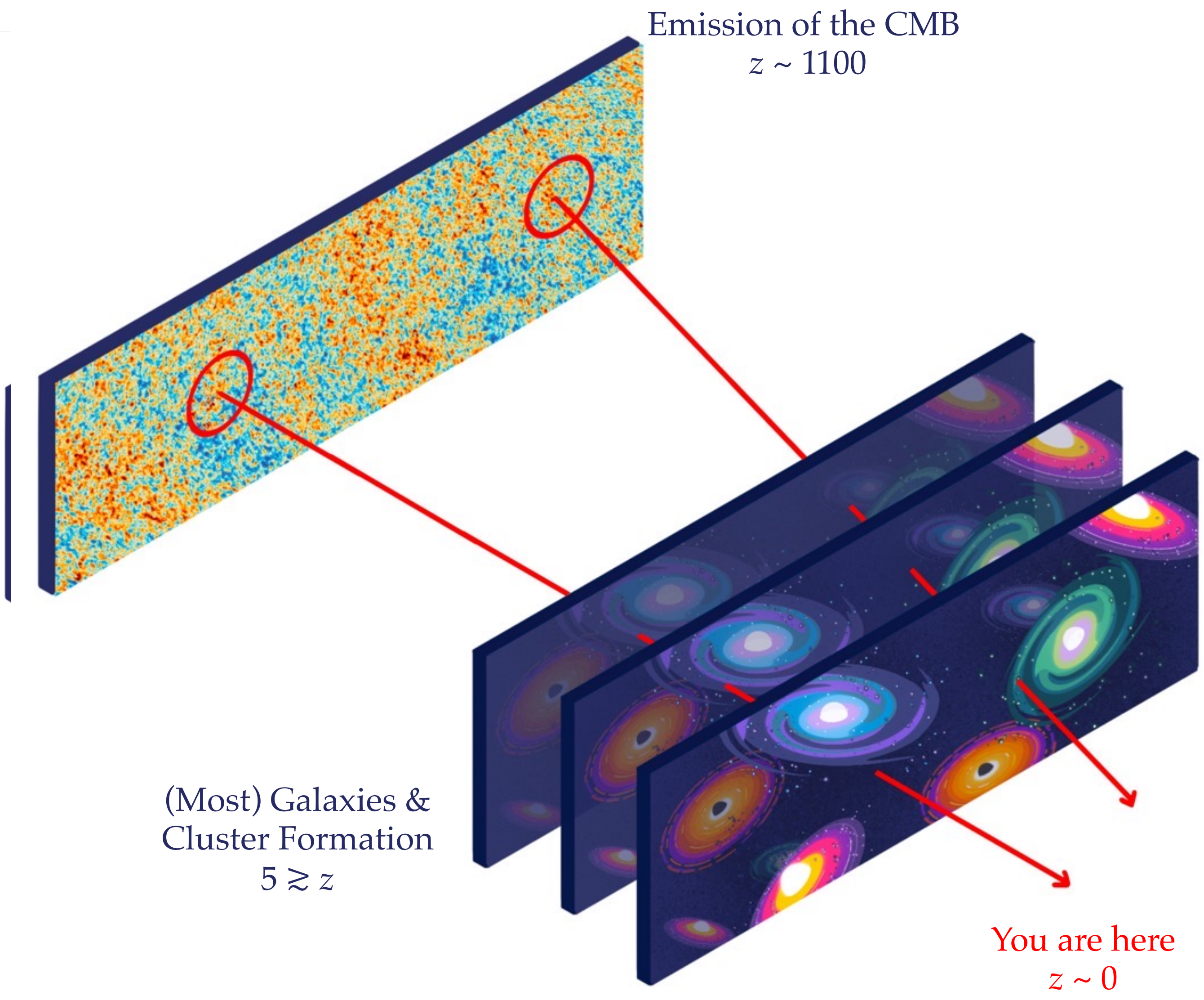
Cosmology from Cross-Correlations: kSZ & Galaxy Surveys

Neha Anil Kumar [α]

TAC Seminar: Monday, November 10th, 2025

[α] nanilku1@jhu.edu

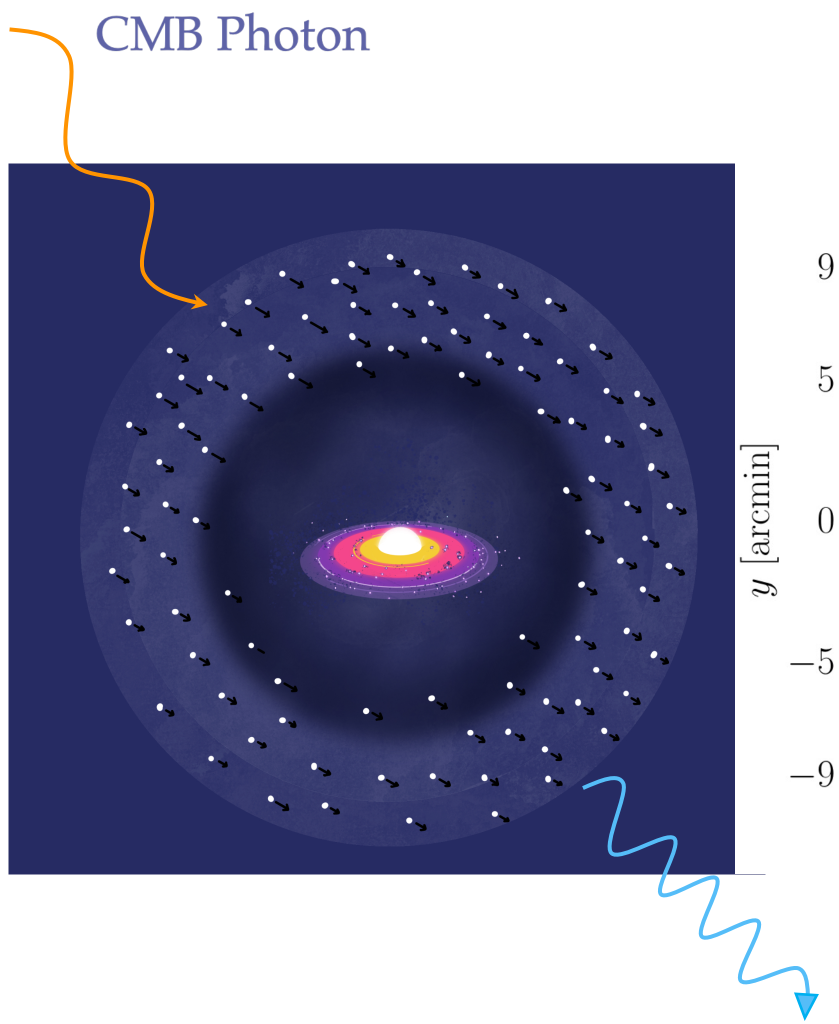
CMB Secondaries

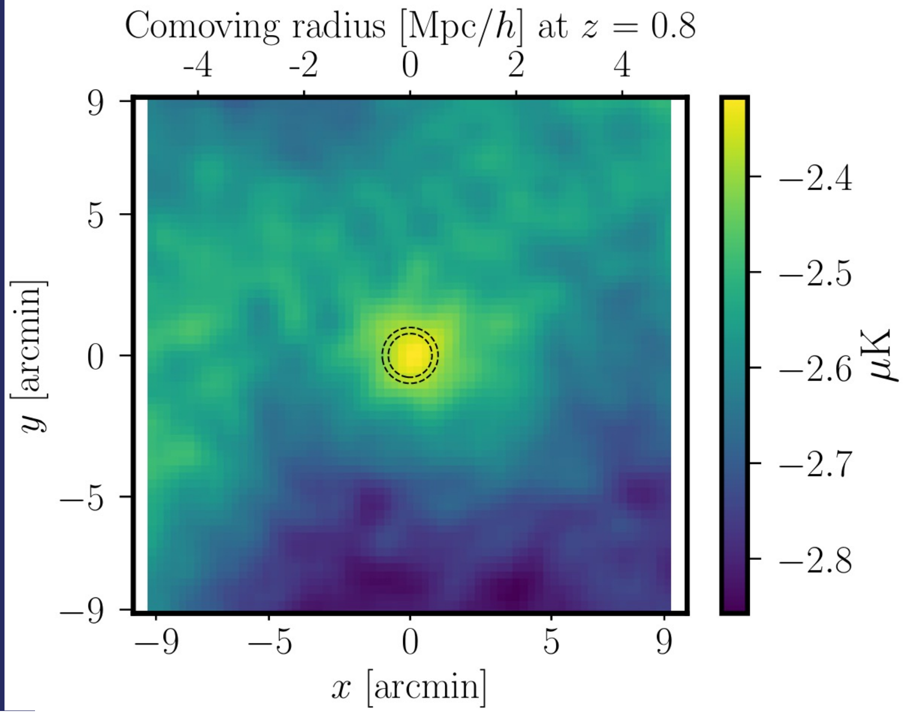


- Line of sight interactions between CMB photons and intervening matter
  - **Electro-magnetic:**
    Thermal SZ, Kinetic SZ, Scattering …
  - **Gravitational:**
    Lensing, Sachs-Wolf …
- Different lines of sight experience different fluctuations
- Cumulative effect is measured

Galaxies & some of these secondary effects are independent tracers of the same underlying fields & distributions

The Kinetic Sunyaev-Zel'dovich Effect



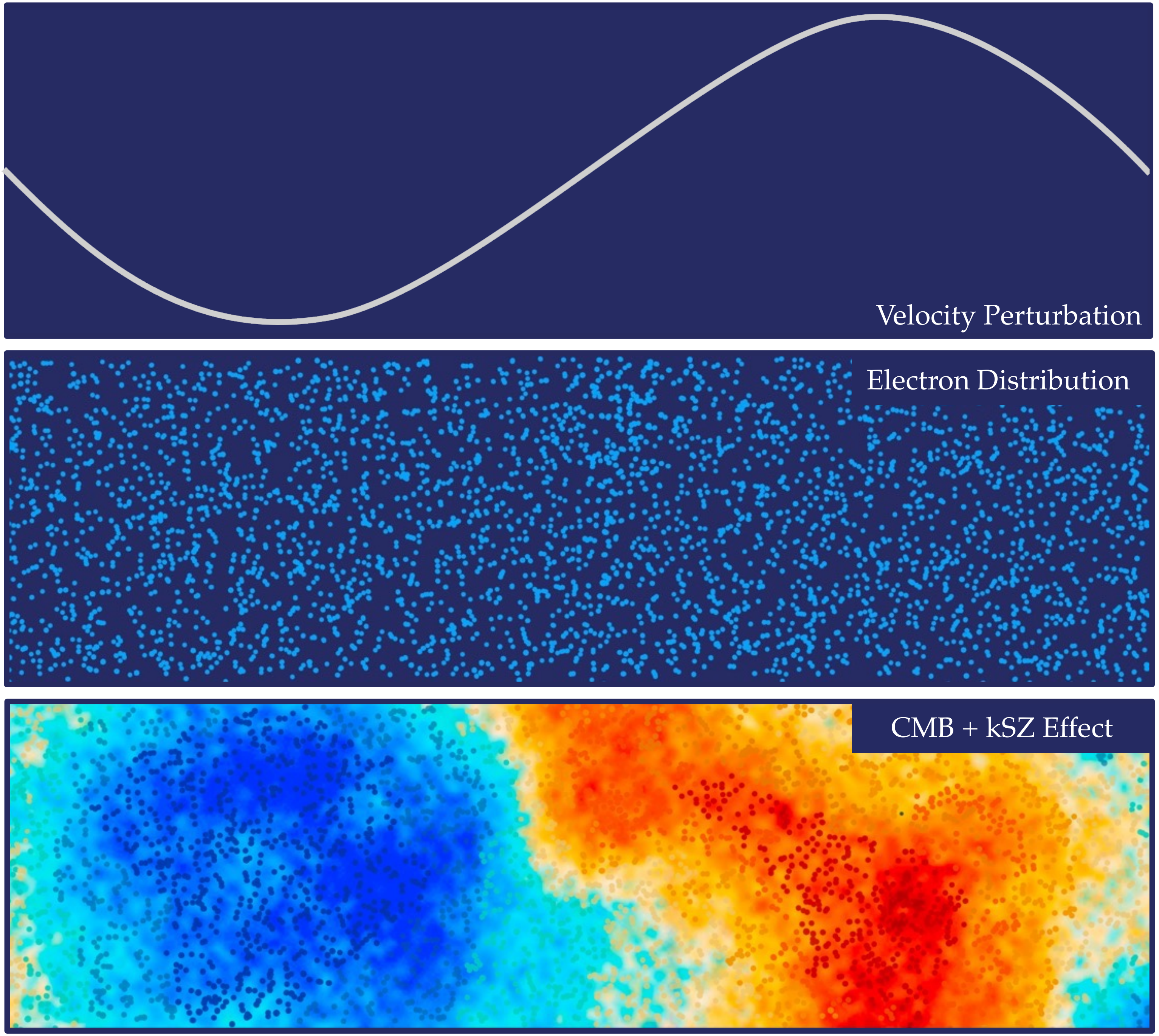


Ried Guachalla et al. [2503.19870]

- CMB photons scatter off free e⁻ in profiles with bulk velocity
  - Doppler shift

$$\frac{\Delta T}{T_{\mathrm{CMB}}}(\hat{n}) \propto n_e(\hat{n}, z)\vec{v} \cdot \hat{n}$$

- Sensitive to
  - ionized baryon profiles
  - large-scale velocity field
    - **Shared by system**



The kSZ Effect

- CMB photons scatter off free e^- in profiles with bulk velocity
  - Doppler shift

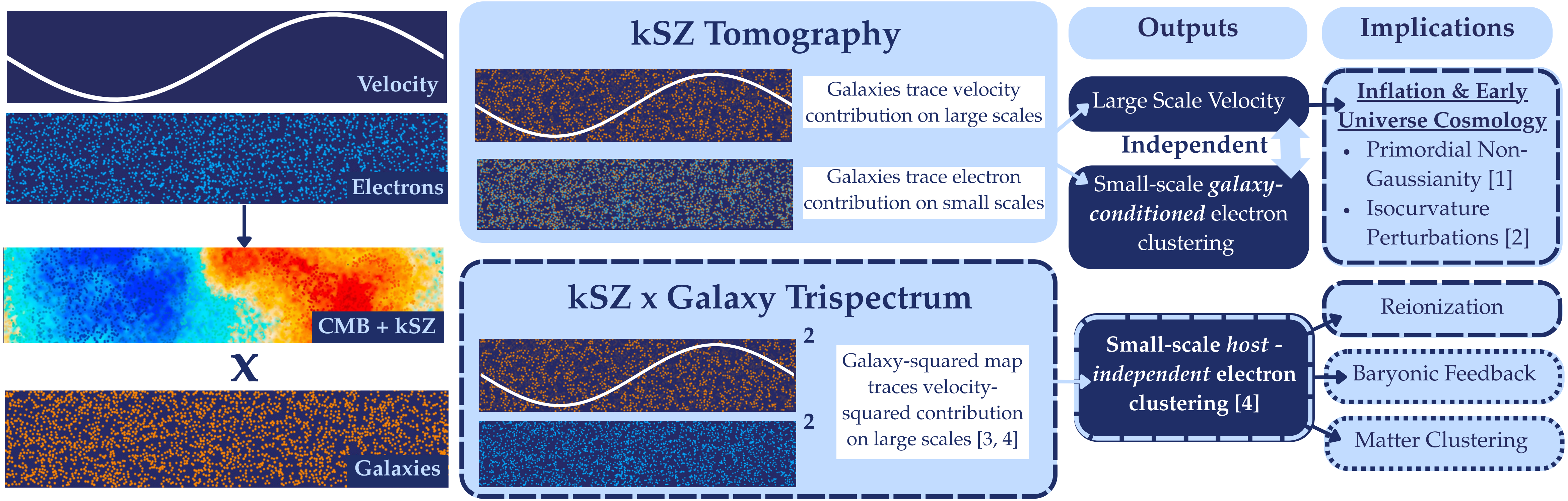
$$\frac{\Delta T}{T_{\rm CMB}}(\hat{n}) \propto n_e(\hat{n}, z)\vec{v}\cdot\hat{n}$$

- Sensitive to
  - Free-electron distributions
    - Sensitive to astrophysics
  - large-scale velocity field
    - Sensitive to cosmology

Cross-correlations:

- **Isolate the contributions**
- **Tomographic measurement**

Summary of my kSZ Work



[0] Review on kSZ tomography statistic: K. Smith et al. (2018) [1810.13423]
[1] **Neha Anil Kumar**, Gabriela Sato-Polito, Marc Kamionkowski, Selim C. Hotinli [2205.03423]
[2] **Neha Anil Kumar**, Selim C. Hotinli, and M. Kamionkowski [2208.02829]
[3] **Neha Anil Kumar**, Mesut Çalışkan, Selim Hotinli, Marc Kamionkowski, Simone Ferraro, Kendrick Smith [2506.11188]
[4] **Neha Anil Kumar**, Mesut Çalışkan, Selim Hotinli, Kendrick Smith, Marc Kamionkowski [2509.18249]

New kSZ x Galaxy Four-Point Cross Correlation

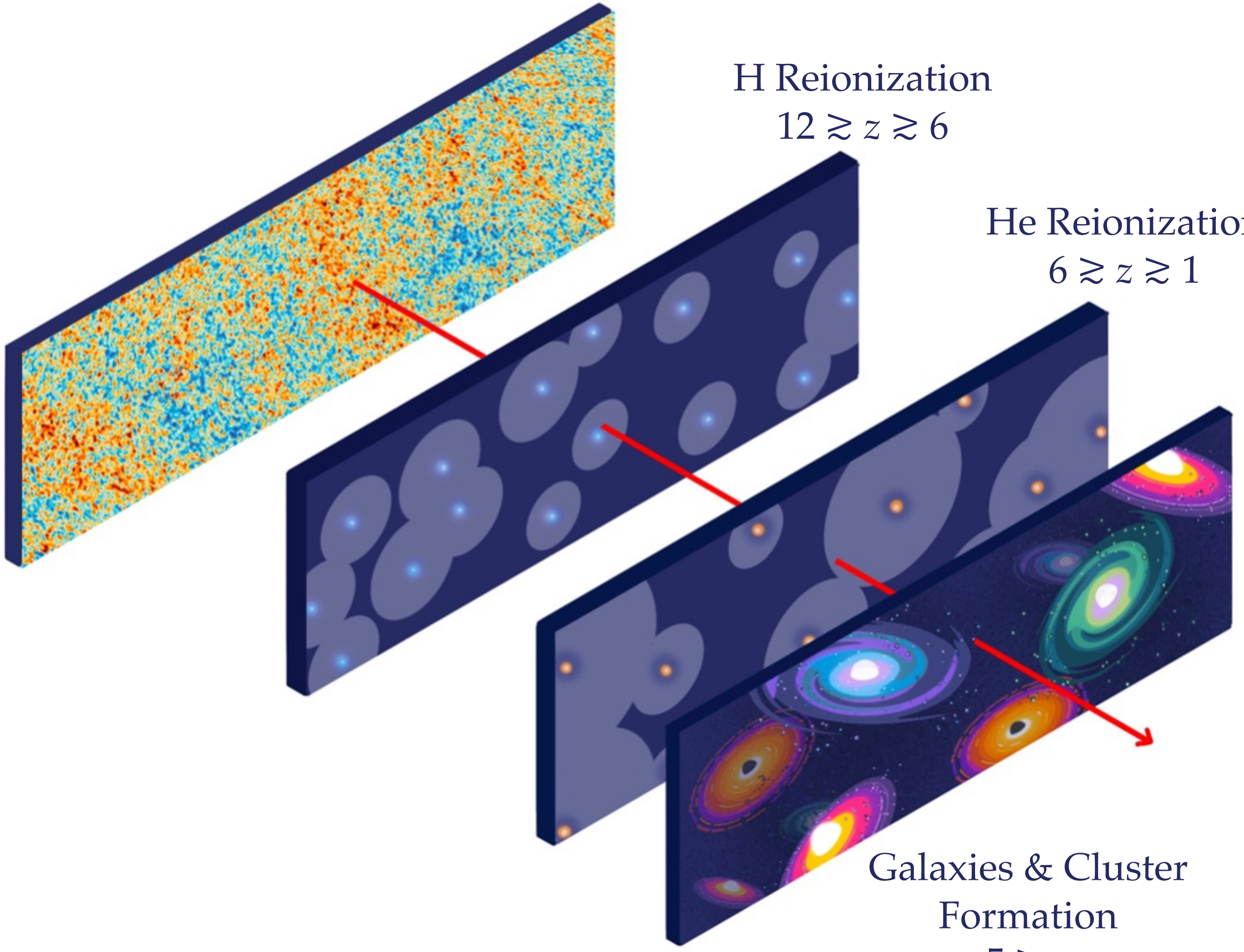
Application I:

Reionization from Cross-Correlations

Neha Anil Kumar, Mesut Çalışkan, Selim Hotinli, Marc Kamionkowski, Simone Ferraro, Kendrick Smith

*arXiv: 2506.11188

CMB Secondaries & Reionization



Hydrogen Reionization:

- H is initially neutral
- Gradual and finite increase in free e^-
- Sourced by first stars

$$E_\gamma \geq 13.6 \text{ eV}$$

He Reionization:

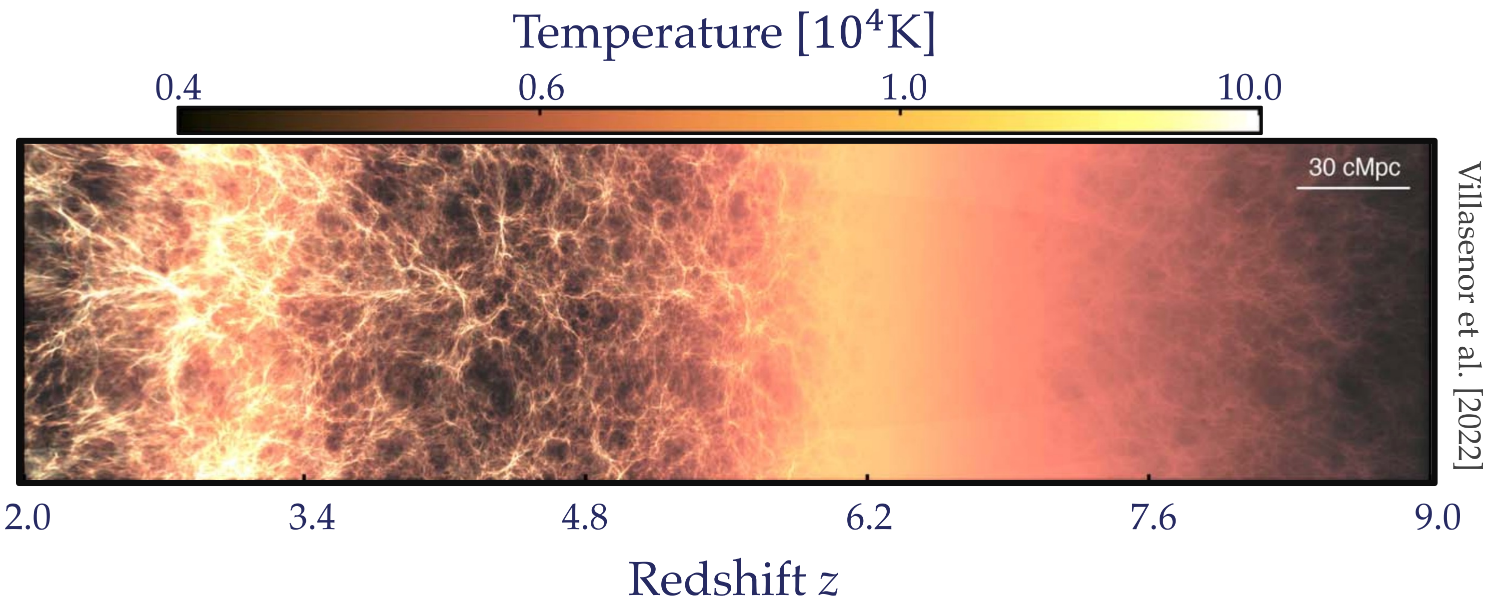
- He is singly ionized
- Relative abundance of 8%
- Sourced by early quasars

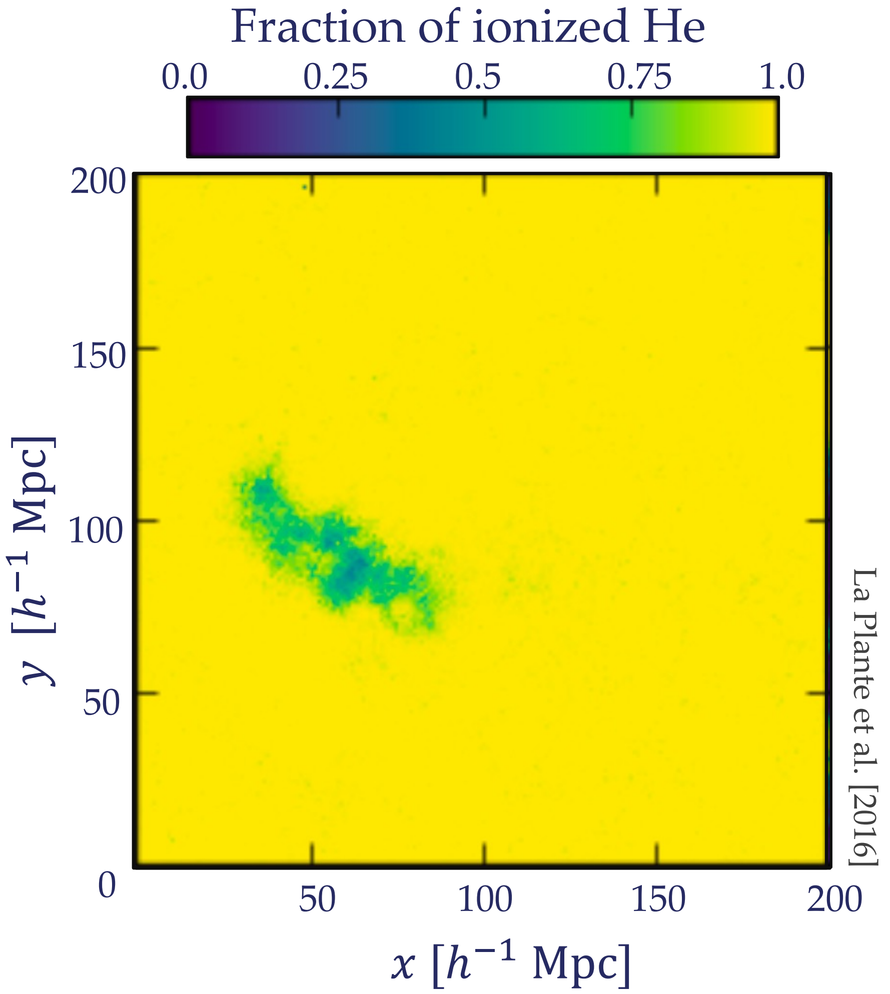
$$E_\gamma \geq 54.4 \text{ eV}$$

CMB Secondaries:

- Electromagnetic
- Thermal SZ, kinetic SZ, screening.....
- Gravitational
  - Lensing, Sachs-Wolf...

Helium Reionization





$5.0 \gtrsim z \gtrsim 2.5$

<u>Morphology:</u>

⇢ Increase in temperature of inter-stellar medium

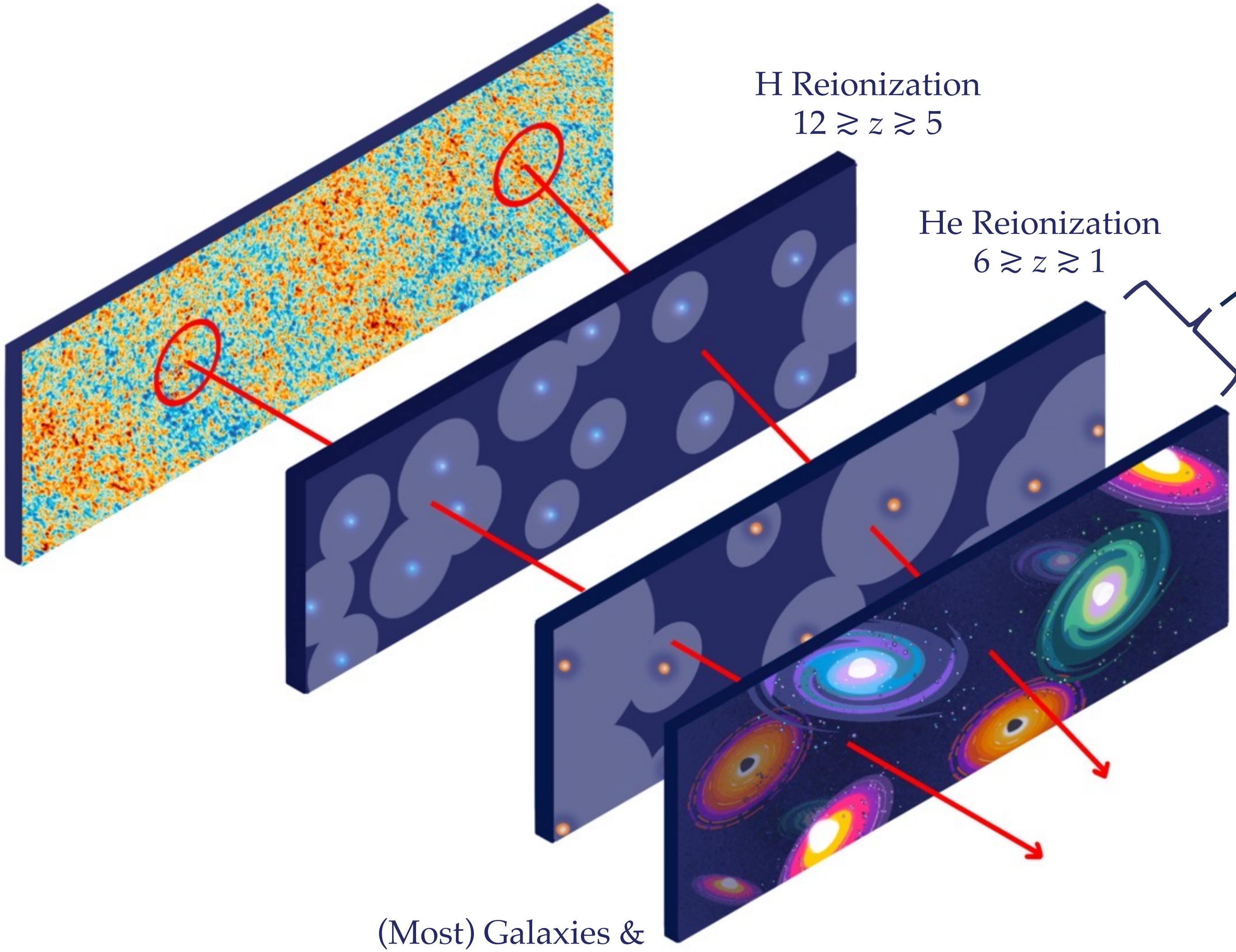
⇢ Gradual and finite increase in free e^- ⇢ **'patchy'**

⇢ spherical bubbles

⇢ 'Patchiness' ⇢ Clustering of sources

⇢ Quasar luminosity function, lifetimes & clustering

Reionization from CMB & Galaxies



⇢ Different lines of sight will experience different fluctuations

- ⇢ CMB ⇢ Morphology of reionization
- ⇢ Bubble distribution, time, duration etc.

How do we disentangle the line-of-sight effects?

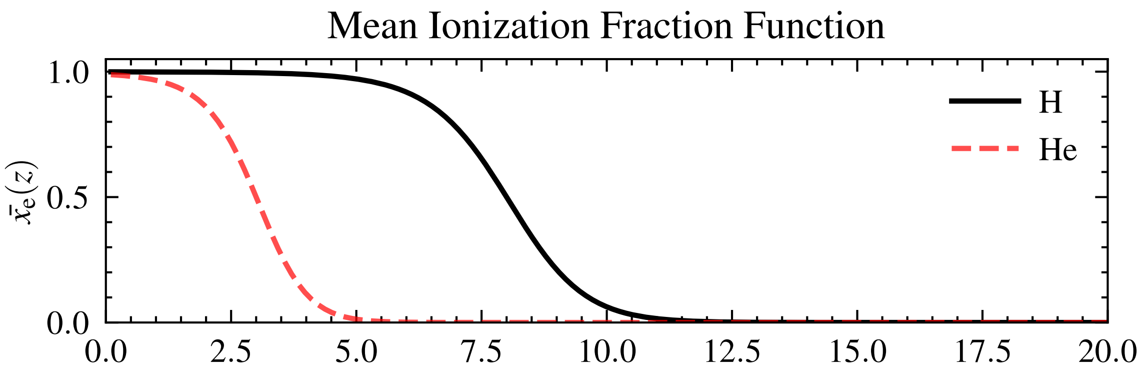
→ He bubbles overlap with early Galaxy distributions!

- ⇢ Observationally accessible

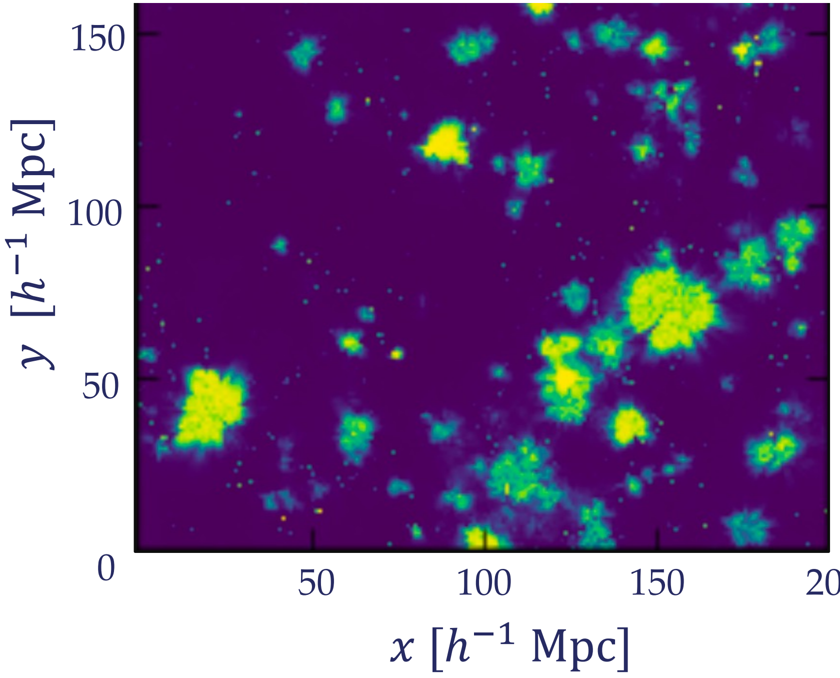
Cross-correlate to tomographically pick-up He reionization signal!

He Reionization Forecasts [1] using CIB, galaxies & kSZ S.C. Hotinli (2023) [2] kSZ Tomography S.C. Hotinli et al. (2022)

Morphology of Reionization



Çalışkan, **NAK**, et al [2023]



La Plante et al. [2016]

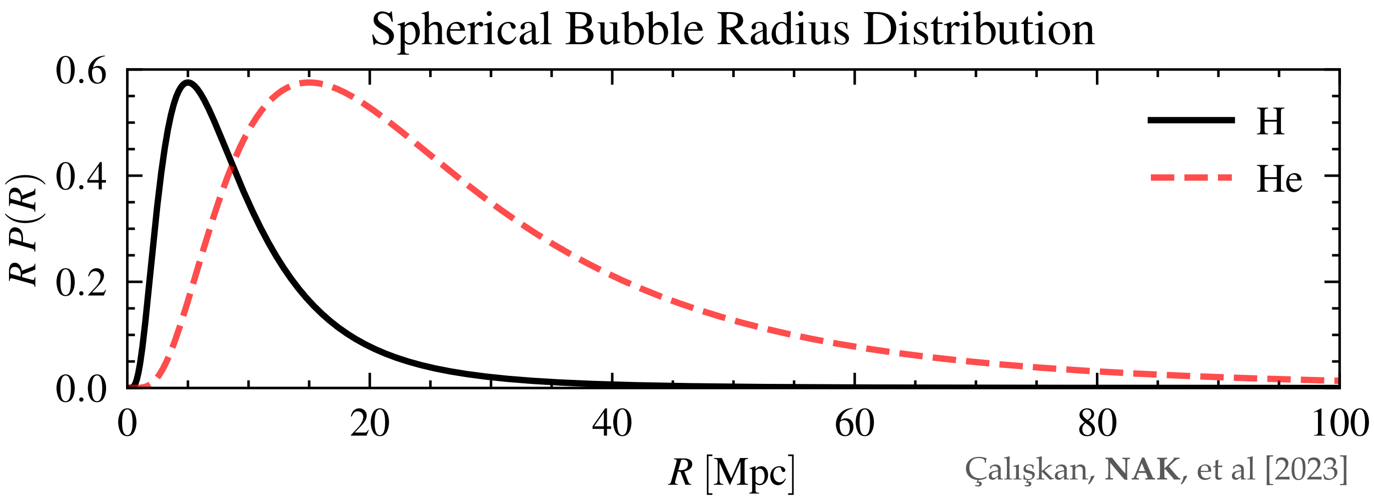
<u>Analytical Model for Reionization</u>:

⇢ Changing Ionization Fraction $\{y_{\rm re},\ \Delta_y\}$

⇢ Bubble Radius Distribution $\{\bar{R},\ \sigma_{\ln R}\}$

⇢ Bubble bias b

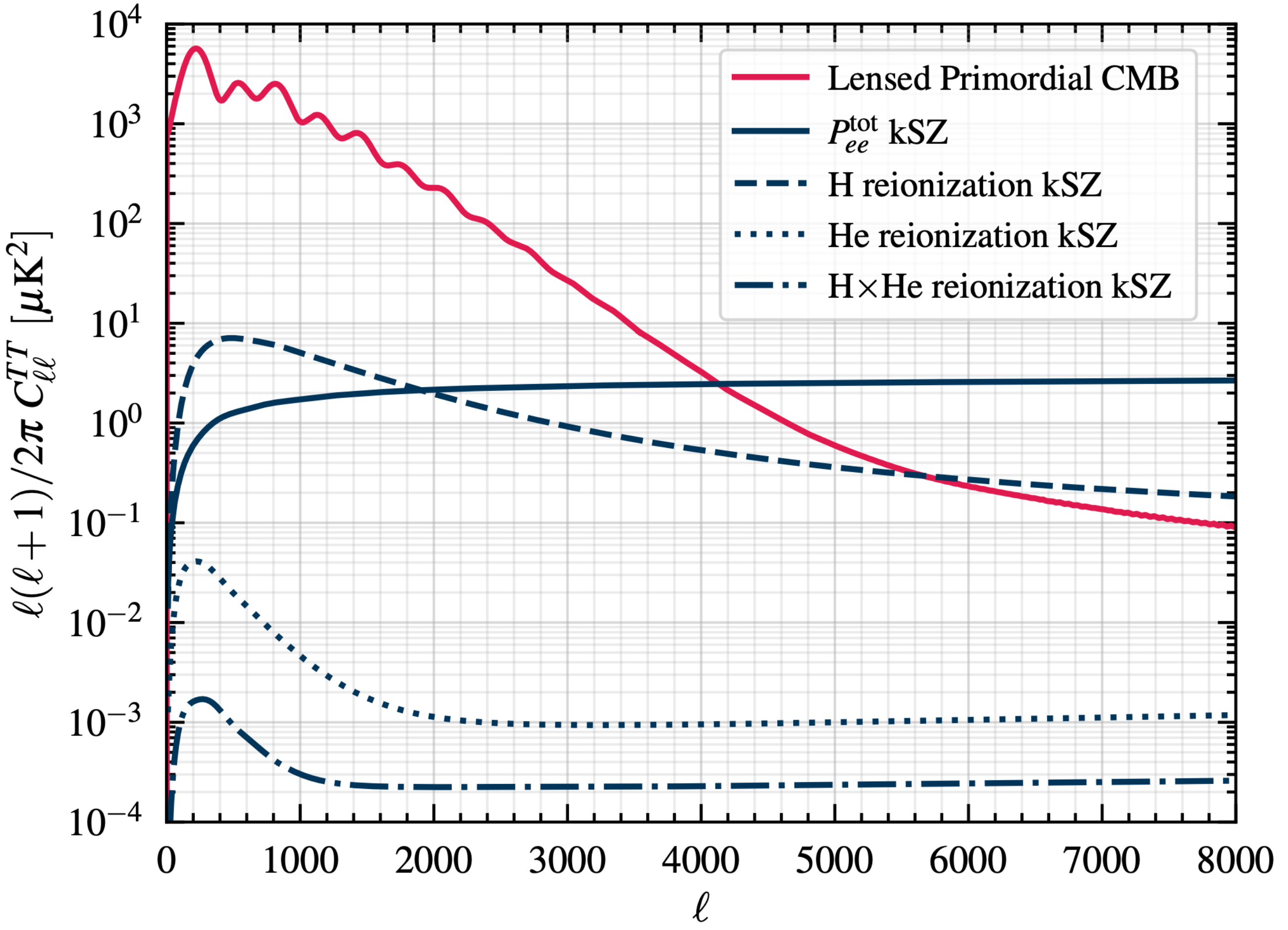
⇢ Assuming bubbles trace matter distribution



Çalışkan, **NAK**, et al [2023]

H reionization modelling from Dvorkin & Smith [2009]

kSZ from Reionization



Formation
$5 \gtrsim z$

- ⇢ kSZ is line-of-sight effect
  - ⇢ Multiple contributions to account for!
- ⇢ But signal offers no shape information

How do we disentangle the separate effects?

- ⇢ Devise a new field that picks up small scales

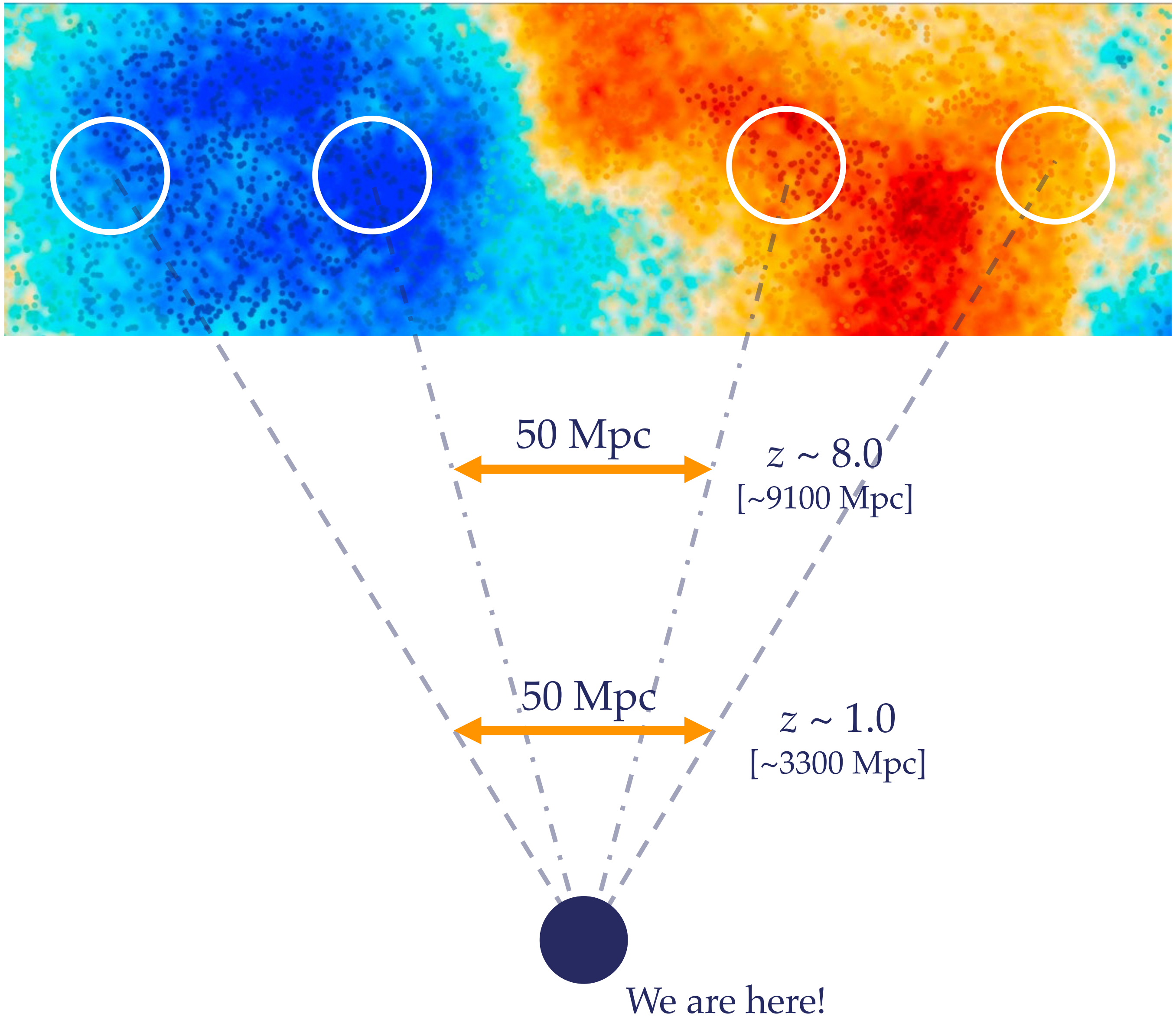
$$K(\hat{n}) = T_S(\hat{n})^2$$

- ⇢ The average power in this statistic:

$$\bar{K} \equiv \langle K(\hat{n}) \rangle$$

Recent forecasts involving patchy kSZ from HeReionization / kSZ Trispectrum [1] I. Methodology (2023) [2] K. Smith & S. Ferraro et al. **(2016)**

Effect on the CMB: kSZ Signal



$$K(\hat{n}) = T_S(\hat{n})^2$$

On scales larger than the local 'patch':

⇢ Assume that variations come from velocity

$$K(\hat{n}) = \int dz \, \frac{d\bar{K}}{dz} \frac{v_r(\hat{n}, z)^2}{\langle v_r(z)^2 \rangle}$$

↳ Perturbations have a characteristic length

⇢ Different redshifts induce correlations on different angular scales

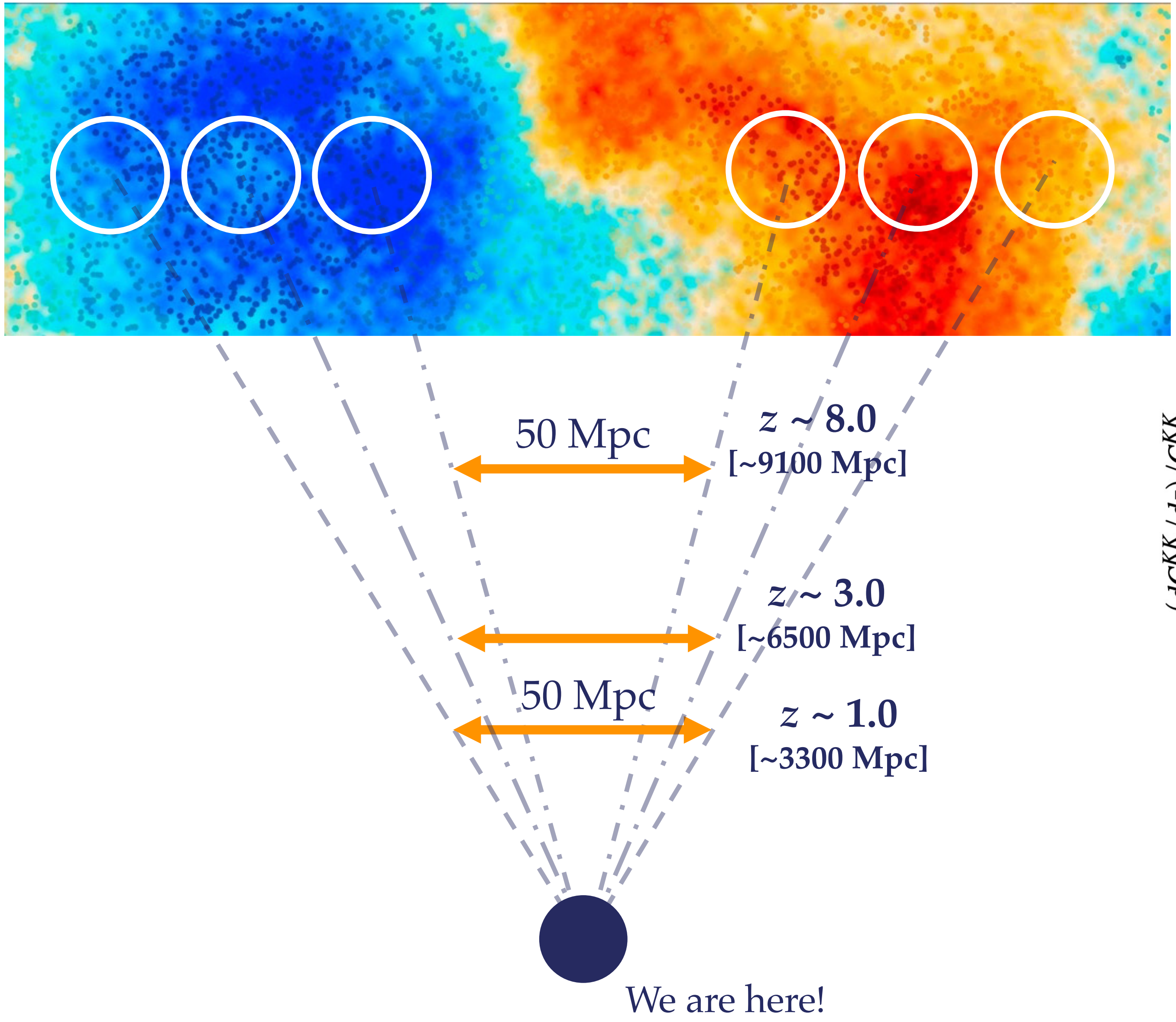
⇢ Construct power spectrum:

$$C_L^{KK} \propto \langle K(\vec{L}) K^*(\vec{L}) \rangle$$

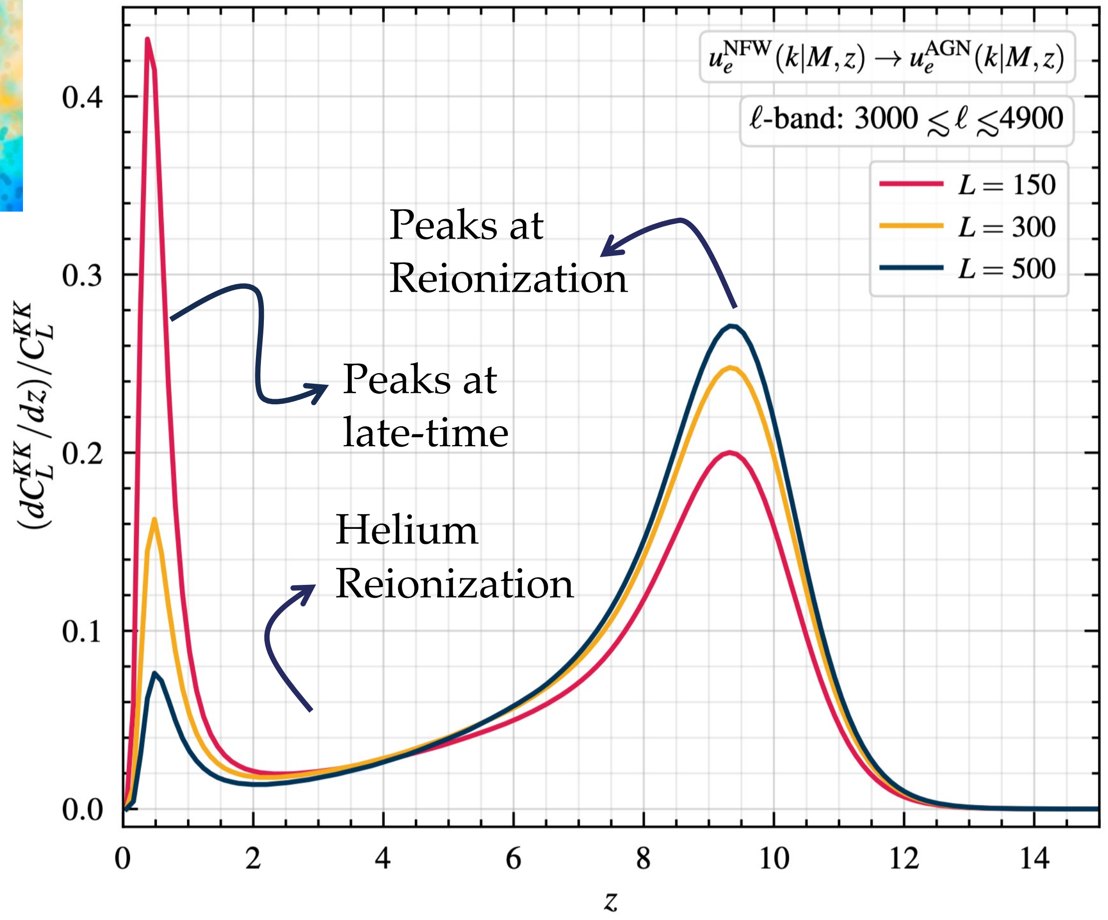
↳ Shape of power spectrum separates kSZ contributions!

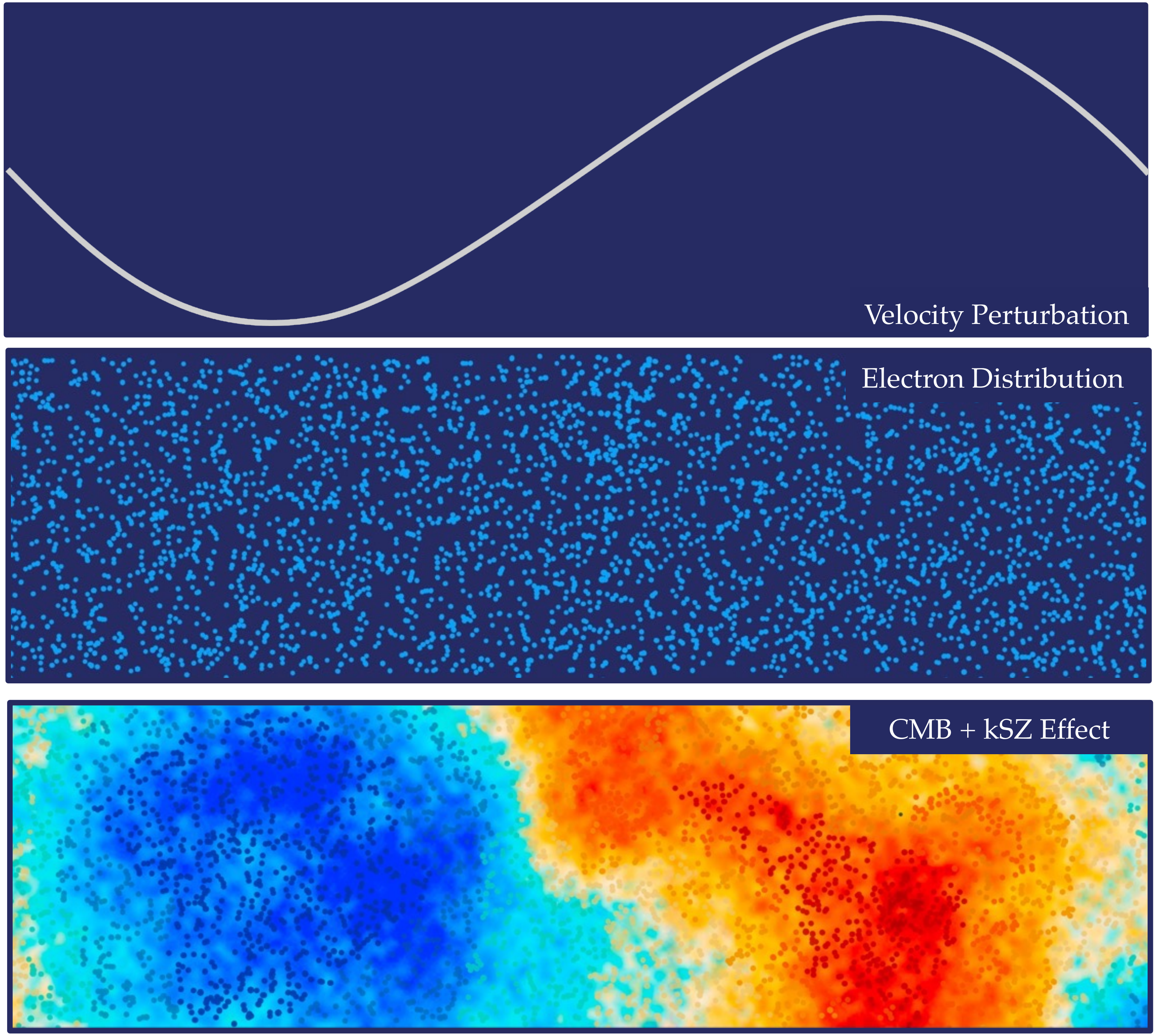
kSZ Trispectrum Methodology [1] K. Smith & S. Ferraro (2018) ;
Application [2] Raghunathan et. al. (2024) [3] N. MacCrann et al. (2024)

Effect on the CMB: the C_L^{KK} Signal



Redshift Contribution at Different Scales





Cross-Correlation

$$K(\hat{n}) = \int dz \, \frac{d\bar{K}}{dz} \frac{v_r(\hat{n}, z)^2}{\langle v_r(z)^2 \rangle}$$

Ionized electron distribution

$\eta(\hat{n}, z) \propto$ Large-scale velocity field²

$$v_r(\vec{k}, z) = \mu \frac{faH}{k} \delta_m(\vec{k}, z)$$

LCDM + geometry

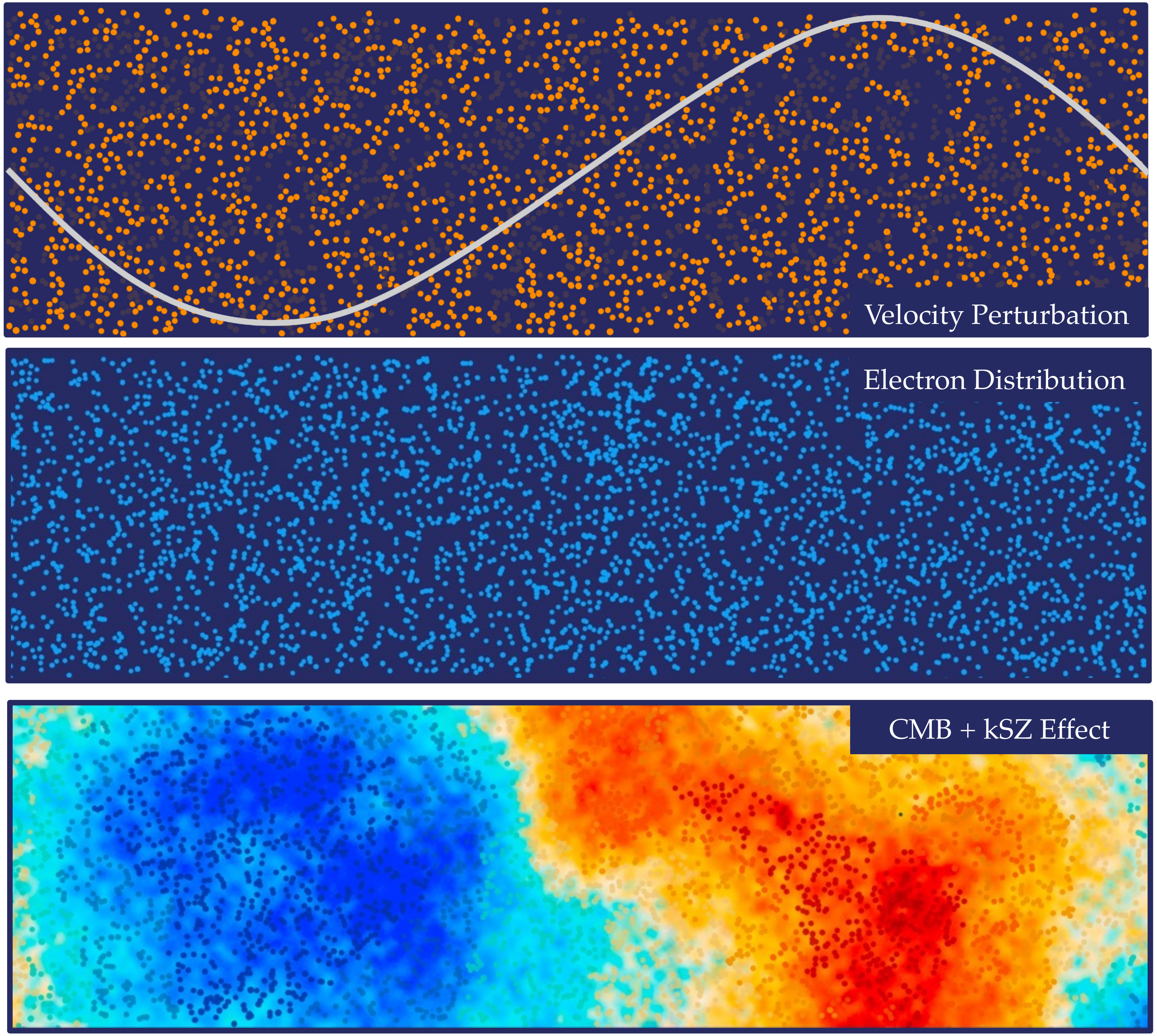
Matter Over Density Field:

$$\delta_m(\vec{x}) = \frac{\rho_m(\vec{x}) - \bar{\rho}_m}{\bar{\rho}_m}$$

Also traced by galaxies!

$$\delta_g(\vec{x}) \equiv \frac{n_g(\vec{x}) - \bar{n}_g}{\bar{n}_g}$$

$$\delta_g(\vec{k}, z) \overset{k \to 0}{=} b_g(z) \delta_m(\vec{k}, z)$$



Galaxy Correlations

⇢ Signal Probes:

$$K(\hat{n}) = \int dz \, \frac{d\bar{K}}{dz} \frac{v_r(\hat{n}, z)^2}{\langle v_r(z)^2 \rangle}$$

Ionized electron distribution [reionization]

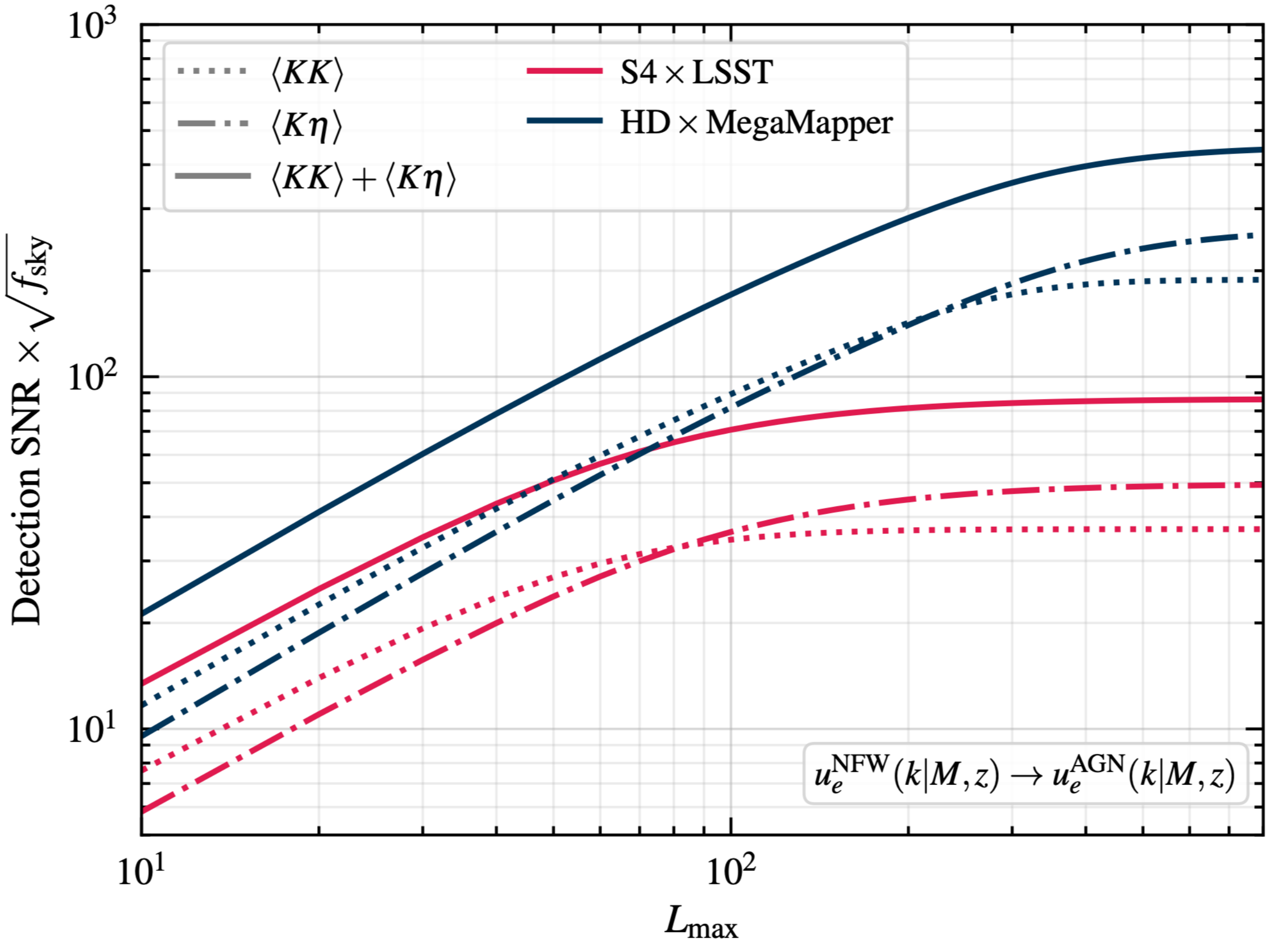
$\eta(\hat{n}, z) \propto$ Large-scale velocity field (squared) [standard cosmology]

Also traced by galaxies!

Construct tomographic $\{\langle K(\hat{n})\eta(\hat{n}, z)\rangle\}$

Velocity reconstruction from galaxies [1] B. Ried Guchalla et. al. (2024) [2] Hadzhiyska et. al. (2024)

Galaxy Correlations: SNR Improvement



$$C_L^{KK}\propto\langle K(\vec{L})K^*(\vec{L})\rangle$$

⇢ Note that this is $\propto\langle T(\vec{\ell}_1)T(\vec{\ell}_2)T(\vec{\ell}_3)T(\vec{\ell}_4)\rangle$

$$K(\hat{n})=\int dz\,\frac{d\bar{K}}{dz}\,\frac{v_r(\hat{n},z)^2}{\langle v_r(z)^2\rangle}$$

Ionization electrons distribution [reionization]

$\eta(\hat{n},z)\propto$ Large-scale velocity field (squared) [standard cosmology]

Also traced by galaxies!

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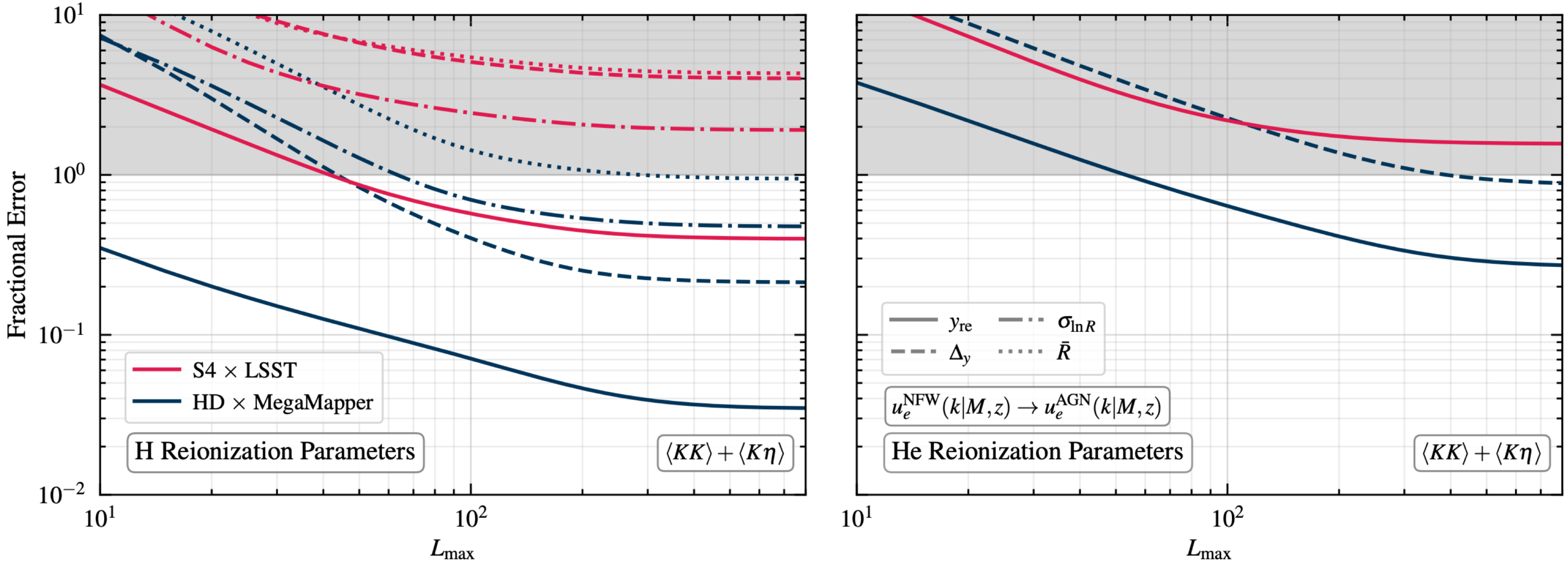
Galaxy Correlations: Parameter Error Improvement



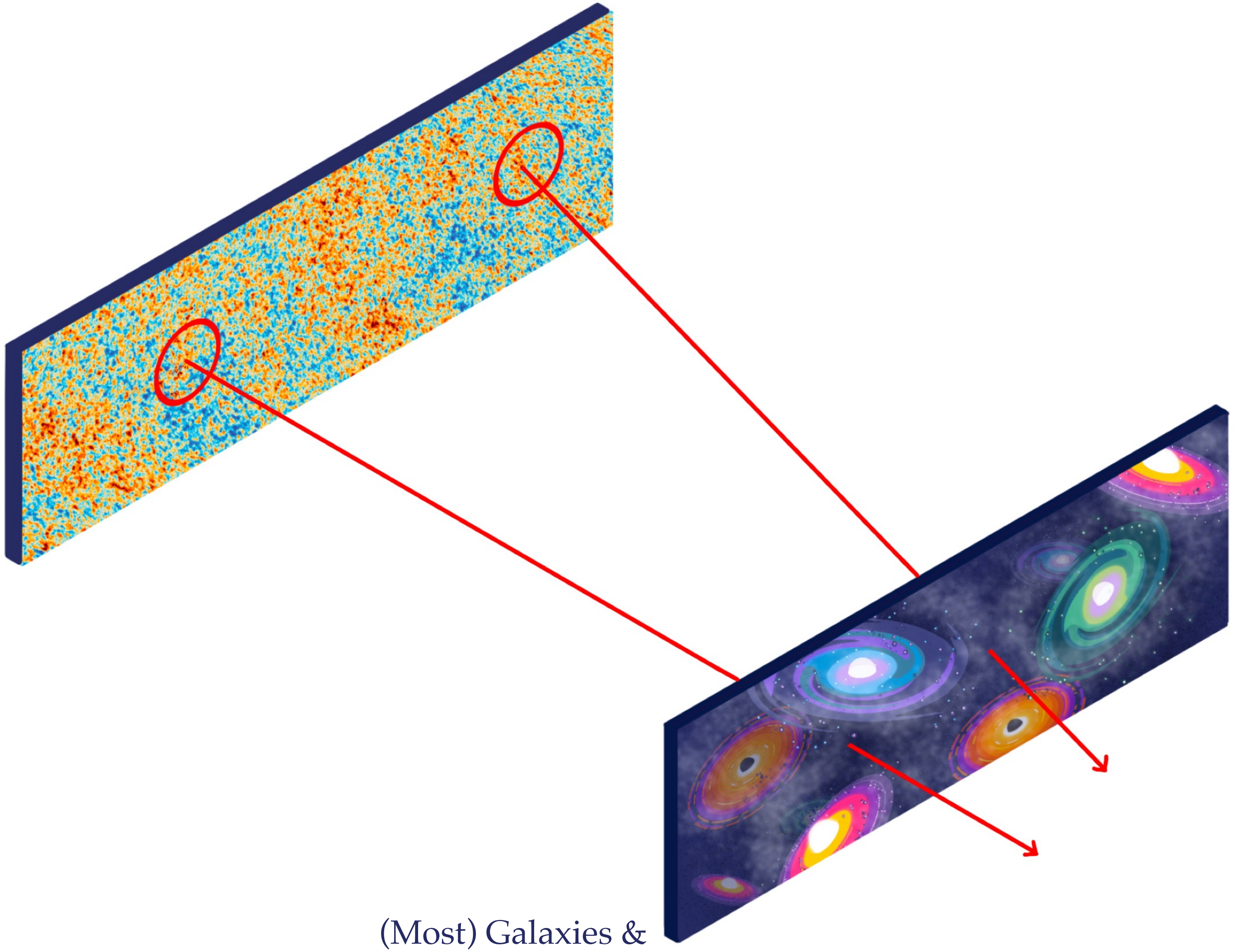
New kSZ x Galaxy Four-Point Cross Correlation

Application II:
'Electrons Everywhere, All at once'

Neha Anil Kumar, Mesut Çalışkan, Selim Hotinli, Kendrick Smith, Marc Kamionkowski

*arXiv: 2509.18249

The Problem: Baryon Gas at Low z

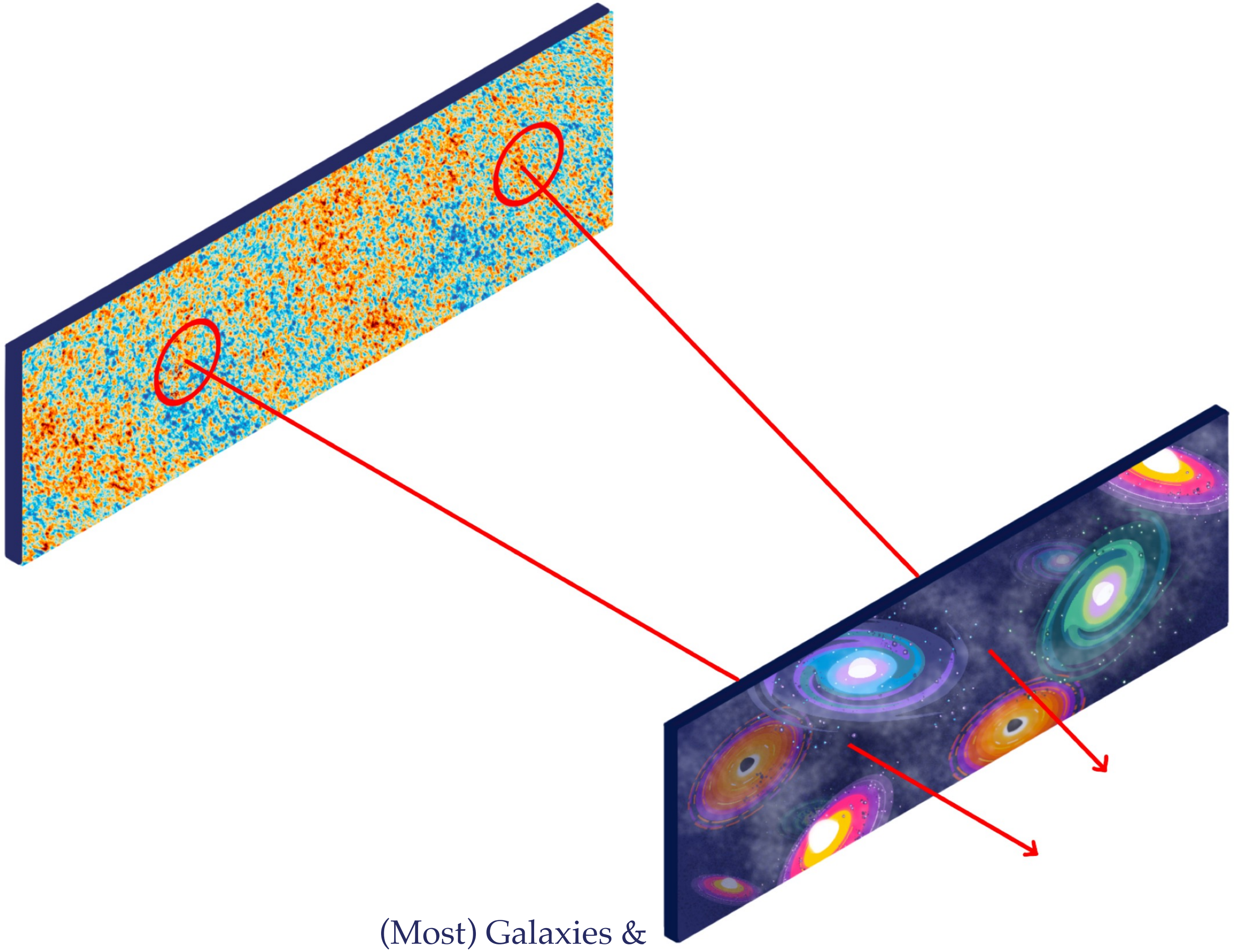


(Most) Galaxies &
Cluster Formation
$5 \gtrsim z$

<u>Where are the baryons?</u>

- ⇢ Total mass in stars only account for 10% of total baryon budget
- ⇢ Only 15-20% exists as hot/ cold gas within galaxies and clusters
- ⇢ Remaining extends far beyond $R_{\rm vir}$

Setting Goals: Baryon Gas at Low z



(Most) Galaxies &
Cluster Formation
$5 \gtrsim z$

Quantifying Gas Clustering:

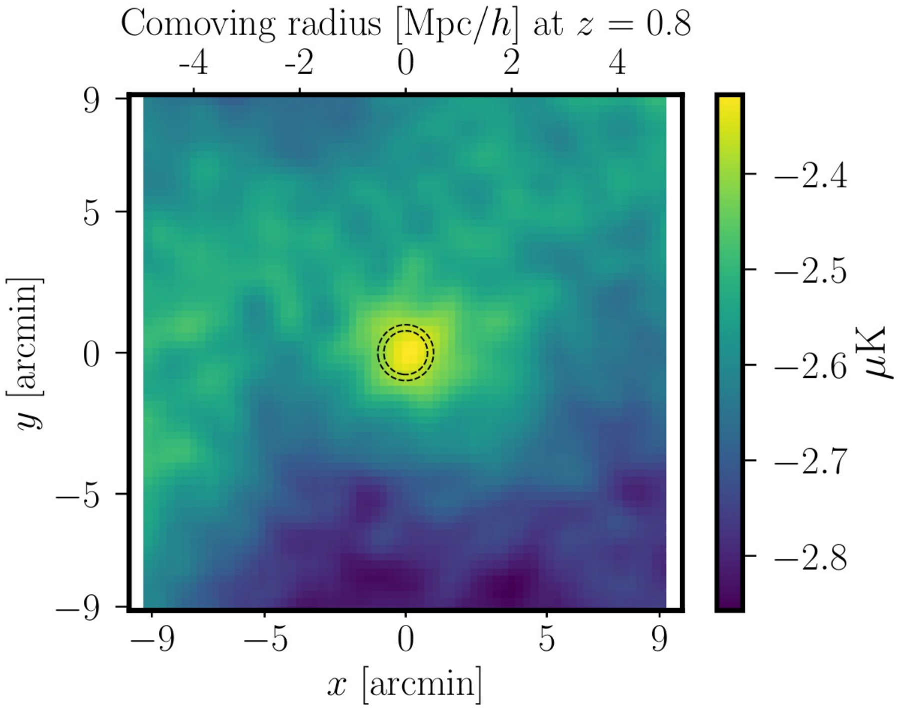
$$\delta_e(\vec{x}) = \frac{n_e(\vec{x}) - \bar{n}_e}{\bar{n}_e}$$

⇢ **Two-point clustering statistics**

⇢ ***Purely*** interested in how baryonic gas is distributed / clustered?

$$\langle \delta_e(\vec{k})\delta_e(\vec{k}') \rangle \equiv (2\pi)^3 P_{ee}(k)\delta^3(\vec{k} - \vec{k}')$$

Existing Probes: Baryon Gas at Low z



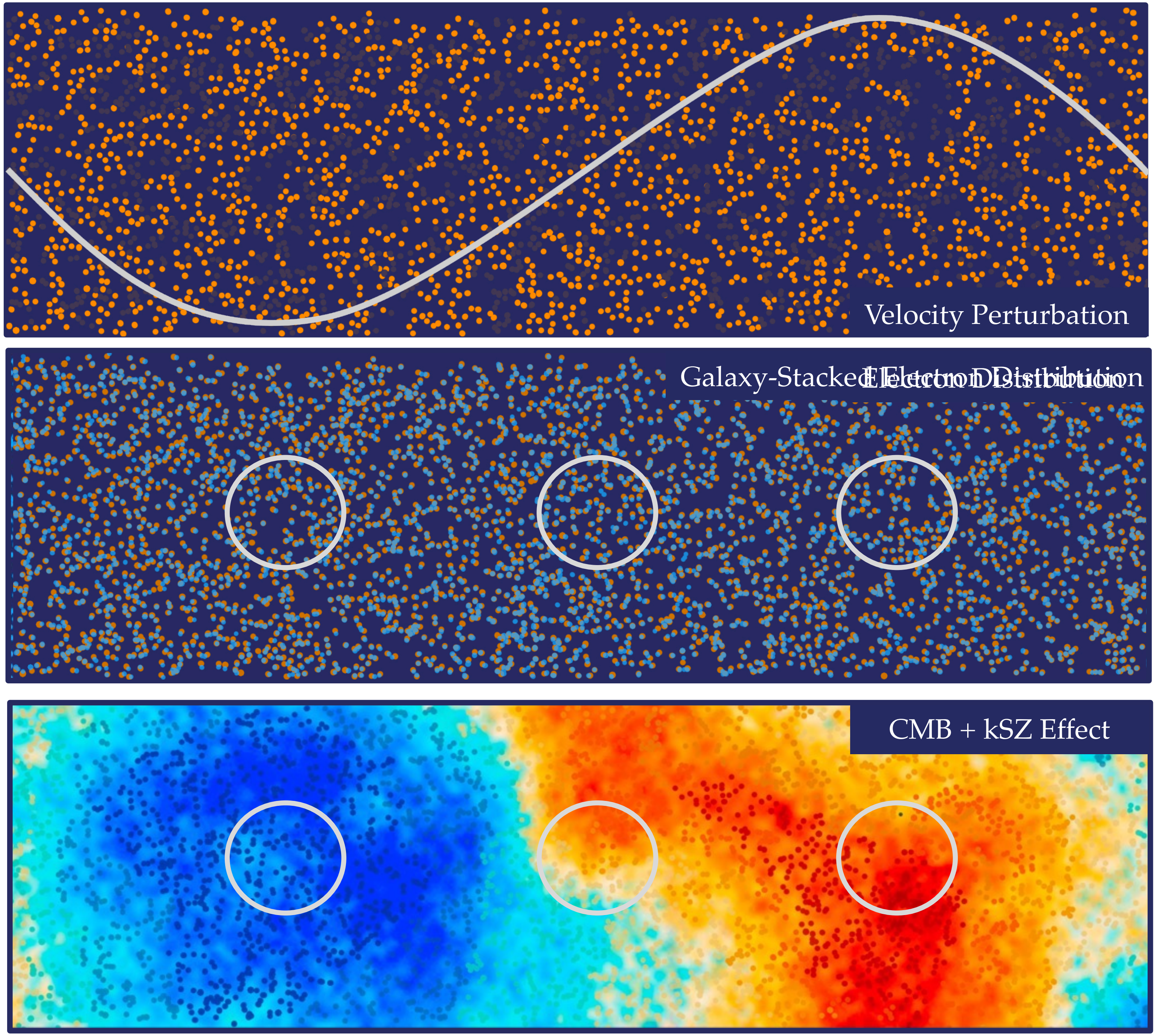
Ried Guachalla et al. [2503.19870]

Existing Probes:

⇢ Observations of X-rays, thermal SZ, **kSZ Tomography/ stacking**

kSZ Analyses: Hadzhiyska et. al. [2407.07152] ; Hadzhiyska et. Al. [2507.14136] (lensing + kSZ); Schaan et. al. [2009.05557] (thermal + kinetic SZ); Amodeo et. al. [2009.05558] (thermal + kinetic SZ)

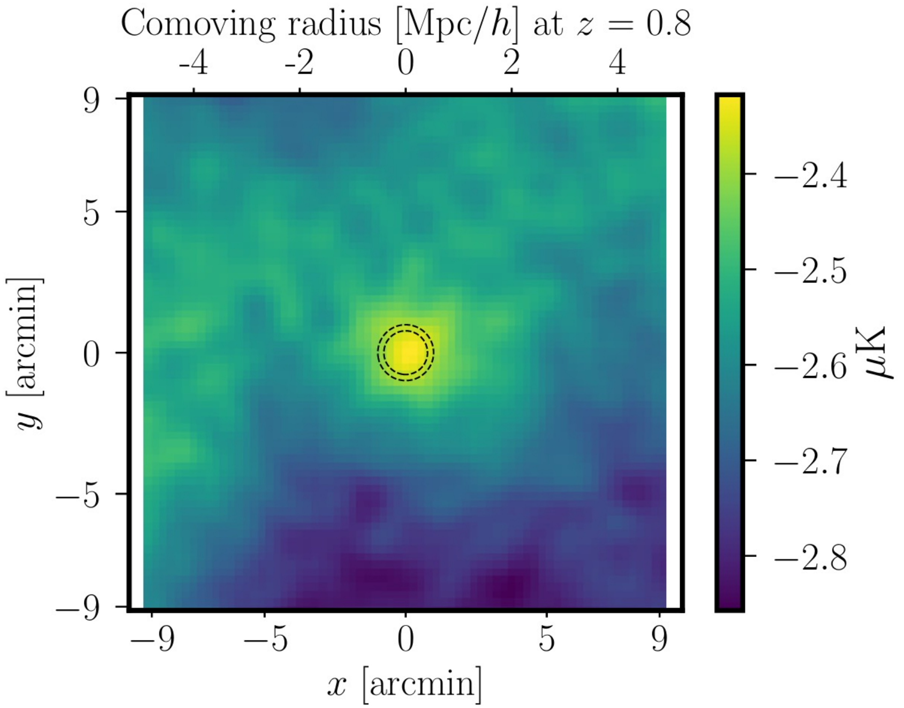
kSZ Stacking



$$\langle T(\vec{\ell})\delta_g(\vec{k}_1)\delta_g(\vec{k}_2)\rangle_{k_1 \ll \{\ell_1, k_2\}}$$

- ⇢ Large-scale galaxy modes are used to reconstruct velocities
- ⇢ kSZ is then stacked over *bright* galaxies
  - ⇢ Includes velocity weighting from above reconstruction
- ⇢ Measure integrated gas profile, *conditioned on* galaxy positions

Existing Probes: Baryon Gas at Low z



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Existing Probes:

- Observations of X-rays, thermal SZ, **kSZ Tomography**
- Measure integrated gas profile, *conditioned on* galaxy positions

$$\delta_g(\vec{x}) \equiv \frac{n_g(\vec{x}) - \bar{n}_g}{\bar{n}_g} \qquad \delta_e(\vec{x}) = \frac{n_e(\vec{x}) - \bar{n}_e}{\bar{n}_e}$$

$$\langle \delta_e(\vec{k})\delta_g(\vec{k}') \rangle \equiv (2\pi)^3 P_{ge}(k)\delta^3(\vec{k} - \vec{k}')$$

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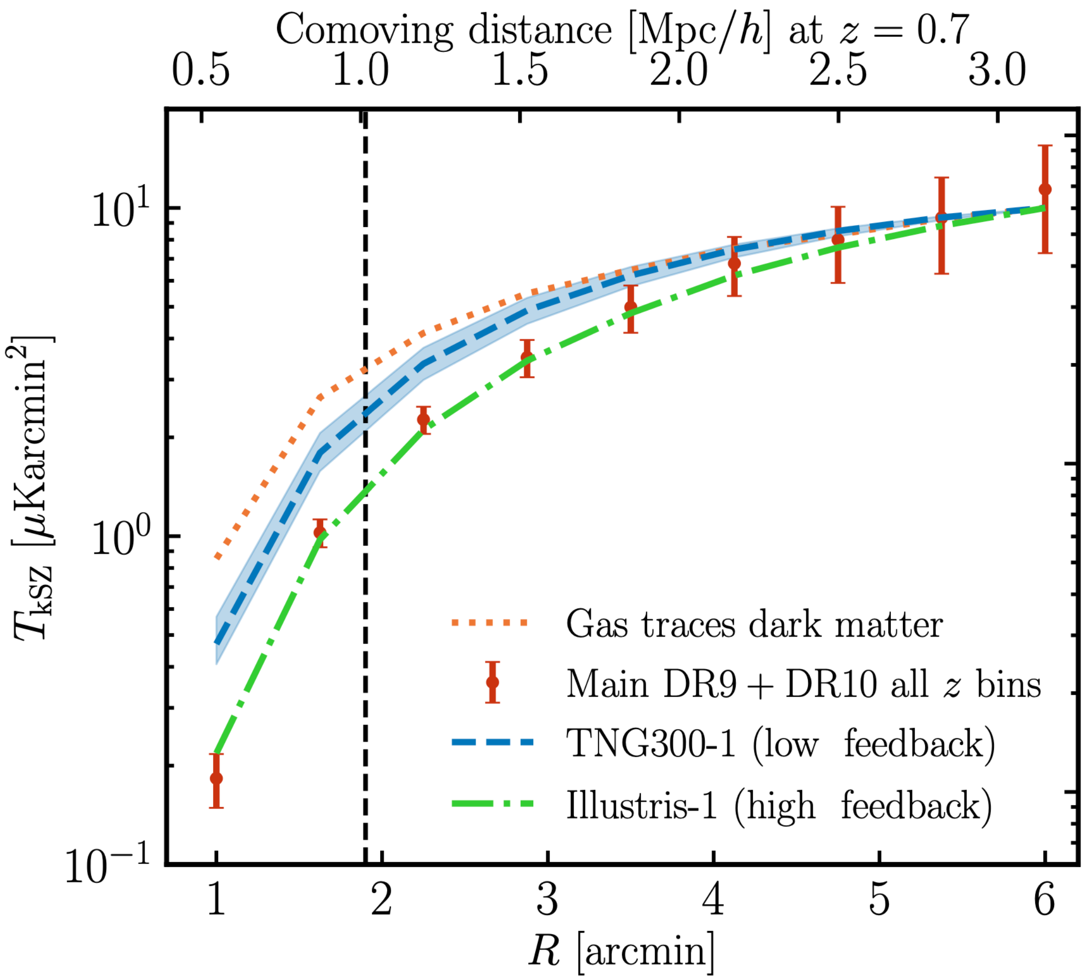
Recent kSZ Measurements: Baryon Gas at Low z

ACT x DESI 'Main LRG' sample, $z \in [0.4, 1.0]$



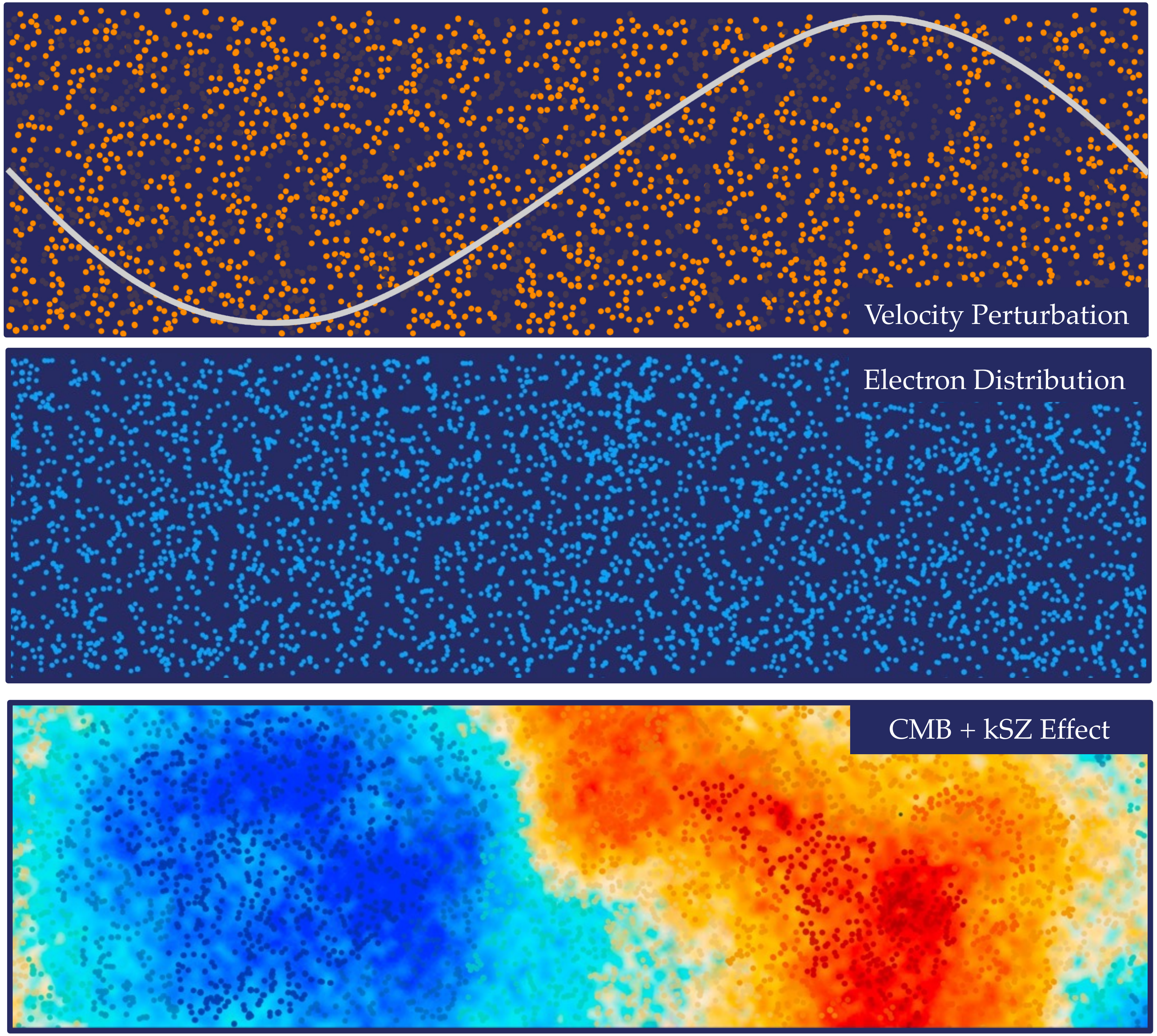
Hadzhiyska et. al. [2407.07152]

- Measurement:
  - High-feedback models are preferred
- Implications:
  - Baryonic feedback, S_8 tension (Lange et. al. [1906.08680])
- **Biased by small-scale galaxy clustering**

$$\delta_g(\vec{x}) \equiv \frac{n_g(\vec{x}) - \bar{n}_g}{\bar{n}_g} \qquad \delta_e(\vec{x}) = \frac{n_e(\vec{x}) - \bar{n}_e}{\bar{n}_e}$$

$$\langle \delta_e(\vec{k}) \delta_g(\vec{k}') \rangle \equiv (2\pi)^3 P_{ge}(k) \delta^3(\vec{k} - \vec{k}')$$

Recent Analyses: Hadzhiyska et. al. [2407.07152] ; Hadzhiyska et. Al. [2507.14136] (lensing + kSZ); Schaan et. al. [2009.05557] (thermal + kinetic SZ); Amodeo et. al. [2009.05558] (thermal + kinetic SZ)



kSZ x Galaxy Trispectrum

$$K(\hat{n}) = \int dz \, \frac{d\bar{K}}{dz} \frac{v_r(\hat{n}, z)^2}{\langle v_r(z)^2 \rangle}$$

Ionized electron distribution

$\eta(\hat{n}, z) \propto$ Large-scale velocity field (squared)

1. Use galaxies for 3D template of $\eta(\hat{n}, z)$
2. Cross-correlate to obtain tomographic

$$\langle K(\vec{L})\eta(\vec{k}, z_*)\rangle \propto \frac{d\bar{K}}{dz} P^{\perp}_{\eta\eta}(k, z_*)\delta^3(\vec{L}/\chi_* - \vec{k})$$

Cosmology in linear regime

Directly sensitive to $P_{ee}(k, z_*)$ in a fixed k-bin!

⇢ Note that this is

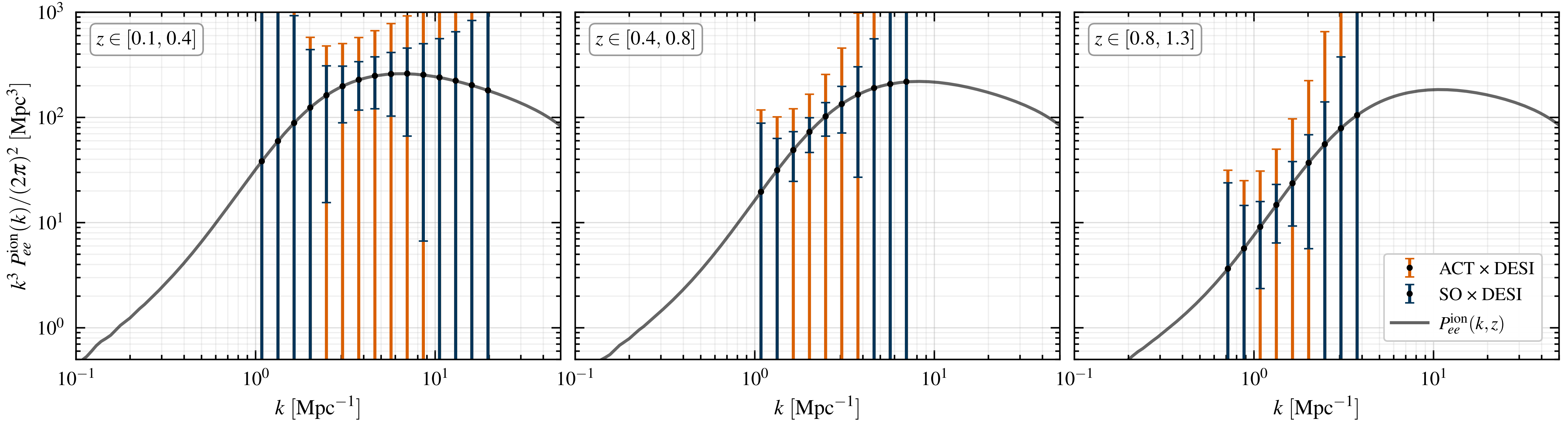
$$\langle T(\vec{\ell}_1)T(\vec{\ell}_2)\delta_g(\vec{k}_1)\delta_g(\vec{k}_2)\rangle_{\{k_1,k_2\}\ll\{\ell_1,\ell_2\}}$$

Forecasts on Electron Power Spectrum

Total Measurement SNR Forecast

ACT x DESI: ~ 3

Simons Observatory x DESI: ~13



Conclusions & Future Directions

Here's what else to look forward to on upcoming project(s):

- On electron power-spectrum constraints:
  - Foreground modeling and testing removal strategies (informed by existing framework for kSZ trispectrum)
  - Pipeline for detection using ACT/ SO
- On reionization
  - Full patchy $\langle TTg \rangle$ exploration

Concluding Remarks:

- A lot of new constraints on cosmology will likely be driven by innovative cross-correlation statistics
  - Primordial non-Gaussianity, isocurvature perturbations, non-linear distributions of electrons at low redshifts etc.

Other stuff I am excited to chat about:

- Stochastic gravitational background forecasts & measurement strategies for PTAs [check out 2311.14159!], LISA, astrometry