Constraining reionization with the global 21cm signal and kSZ

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In collaboration with Adrian Liu
and Adelie Gorce

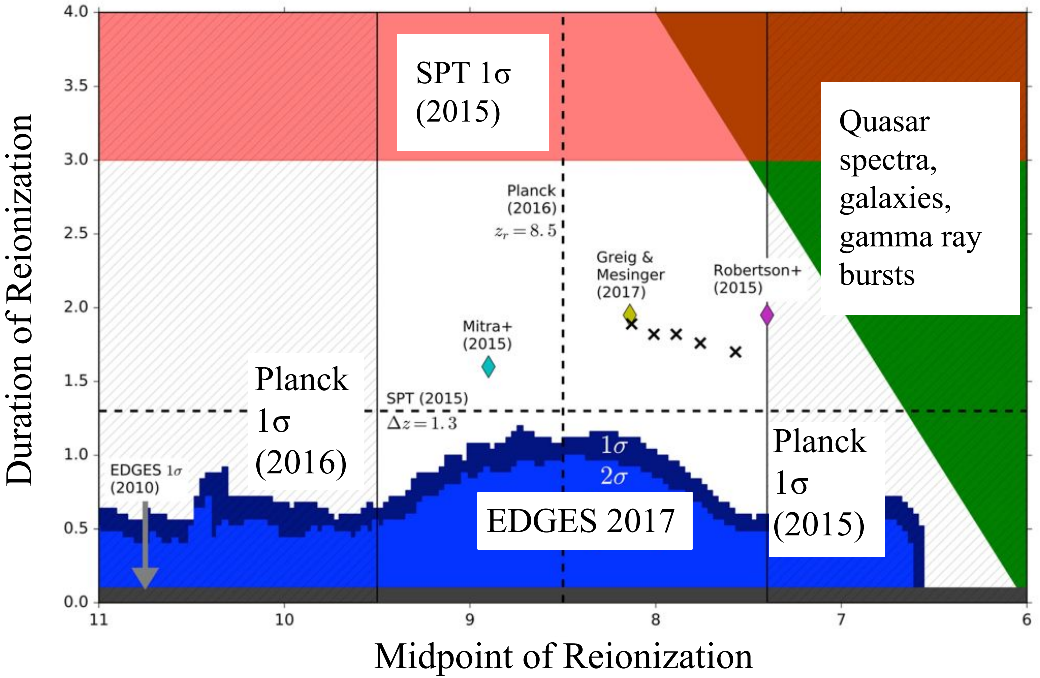
McGill University

Overview

- The global 21cm signal and kinetic Sunyaev Zeldovich effect are **complementary** probes of reionization.
- The **Karhunen-Loeve** basis highlights this complementarity.
- Working in this basis facilitates the **detection and removal of systematics.**

The ionization history

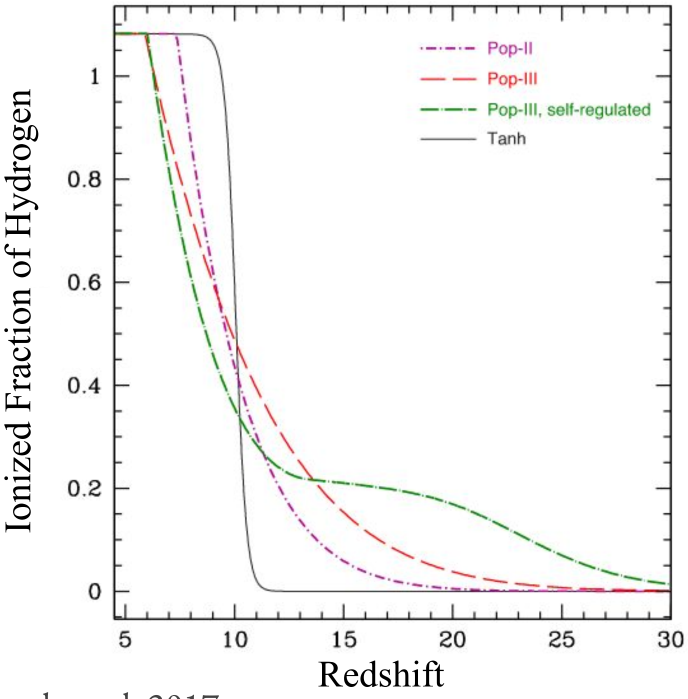
- We have some bounds for its midpoint, end, and duration.



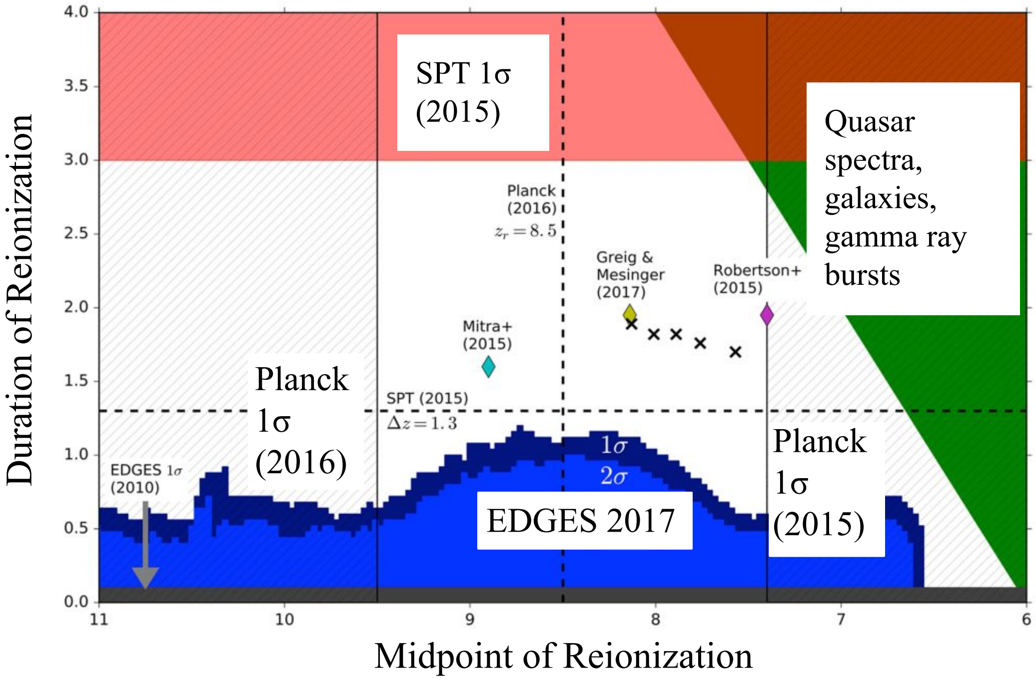
Monsalve et al, 2017

The ionization history

- We have some bounds for its midpoint, end, and duration.
- Few limits on precise shape.



Miranda et al, 2017



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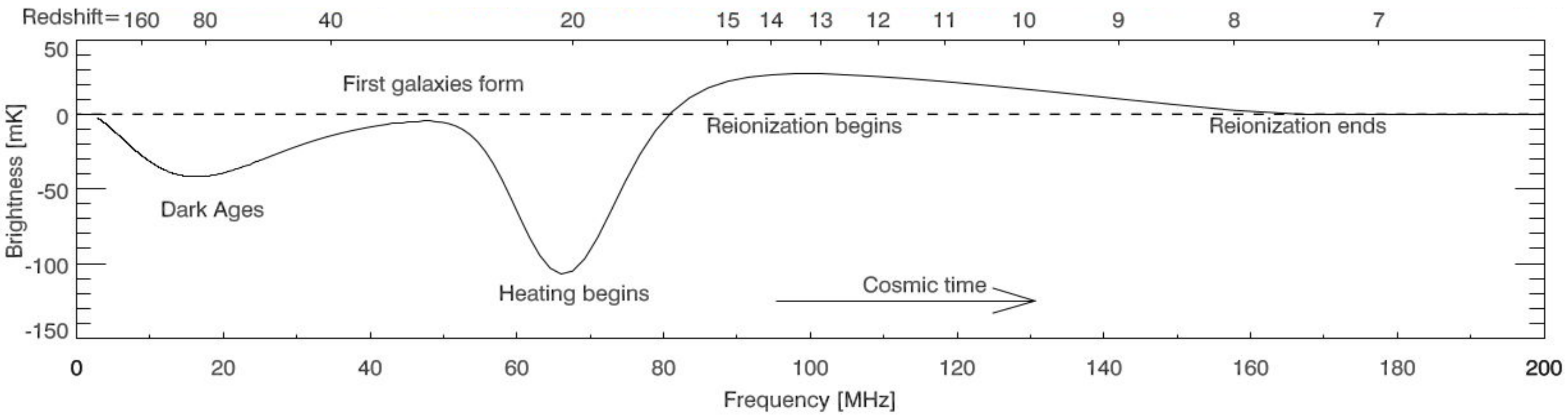
The global 21cm signal



- During reionization, the global signal closely tracks the ionization history

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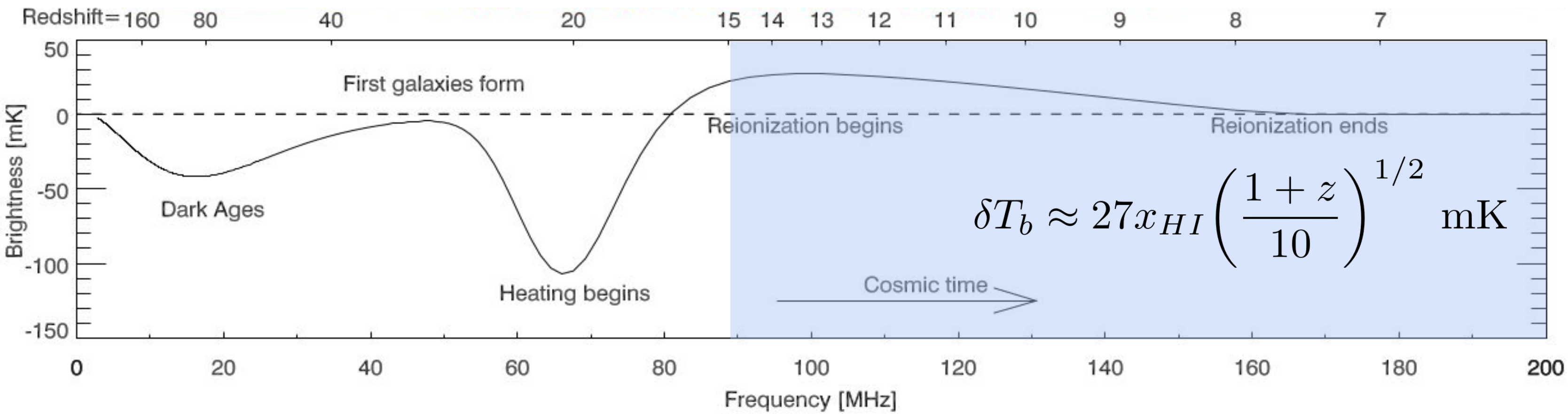

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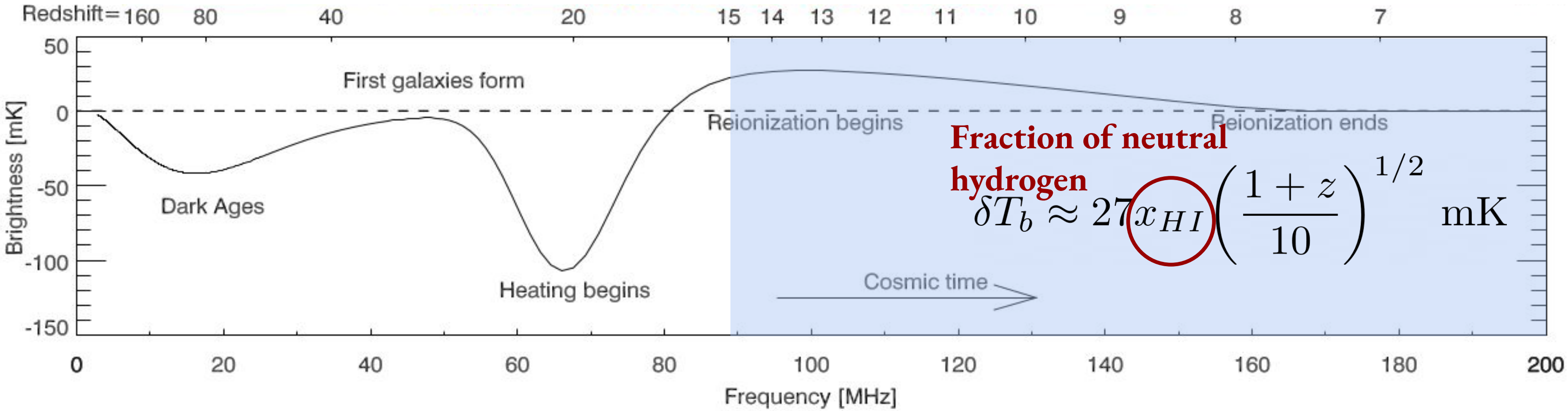

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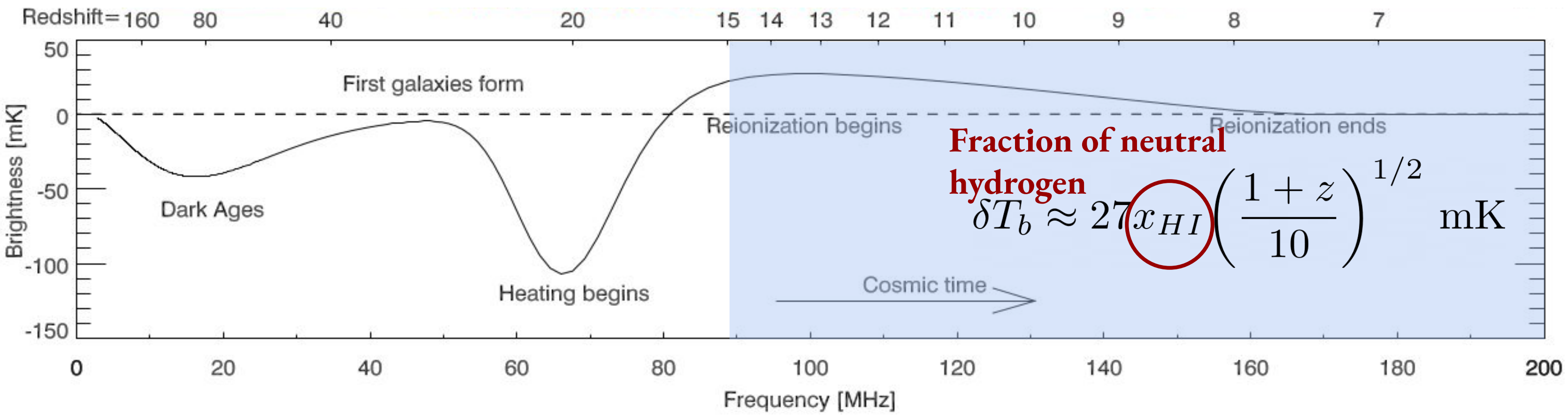
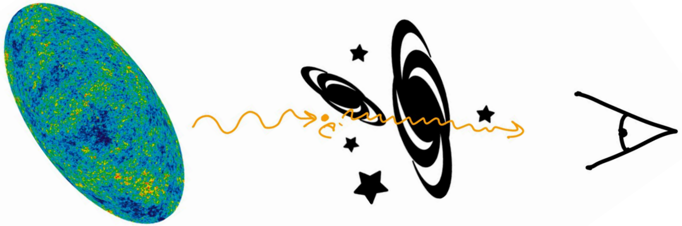


- During reionization, the global signal closely tracks the ionization history
- The global signal is **most sensitive to rapidly evolving reionization histories** due to spectrally smooth foregrounds

The kinetic Sunyaev-Zeldovich effect (kSZ)

- CMB photons scattering off of energetic electrons with bulk relative velocity



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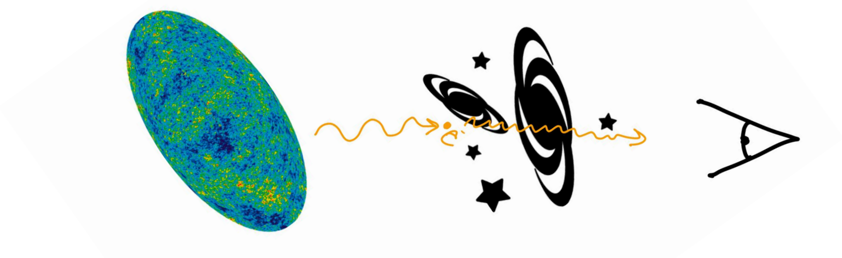
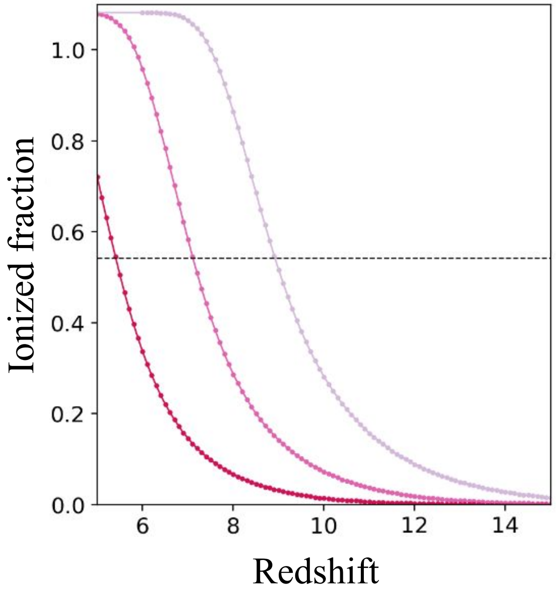
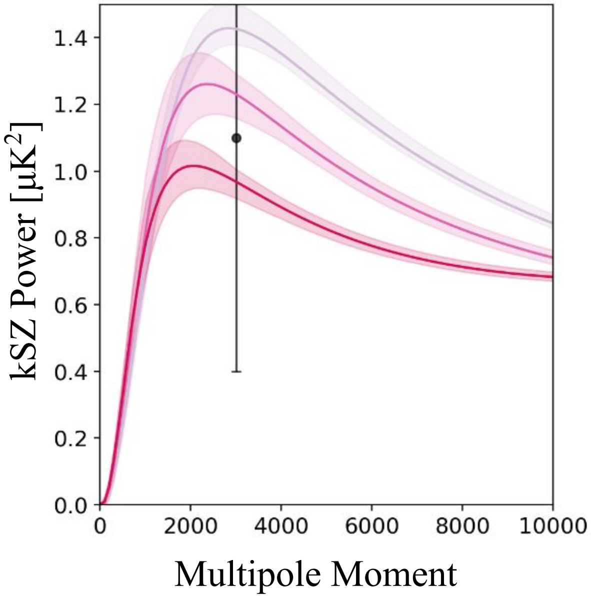


- Power spectrum changes with midpoint, duration, morphology of reionization





Gorce et al, 2020

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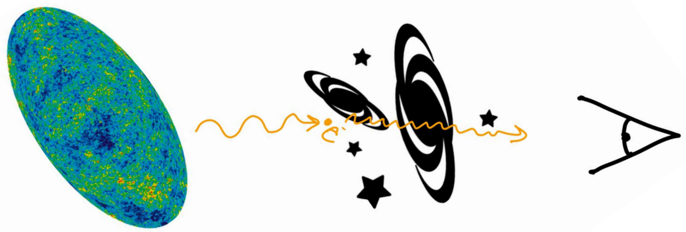
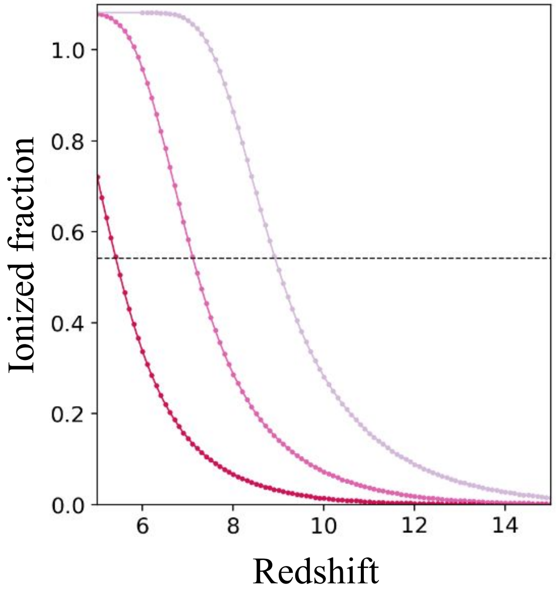
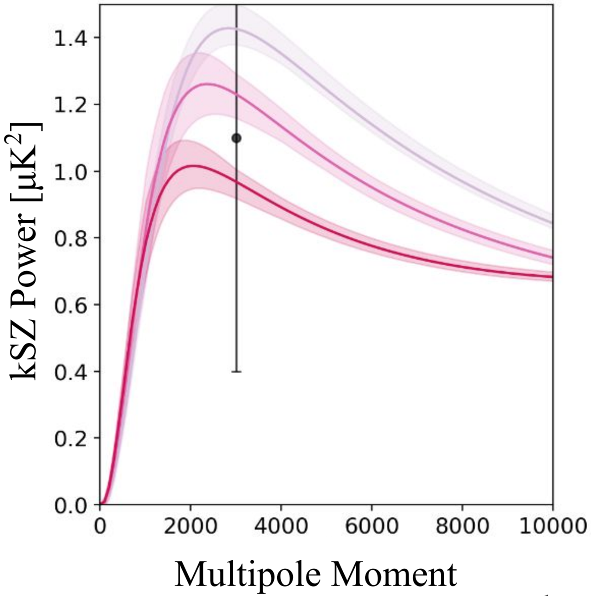


- Power spectrum changes with midpoint, duration, morphology of reionization
- Sensitive to extended ionization histories.





Gorce et al, 2020

The global signal is sensitive to **rapidly evolving** ionization histories, the kSZ to **extended** ionization histories.

The Karhunen-Loeve (KL) Transform

- A transformation whose eigenvalues represent the ratio of two signals.
- Familiar example: signal-to-noise analysis and data compression.

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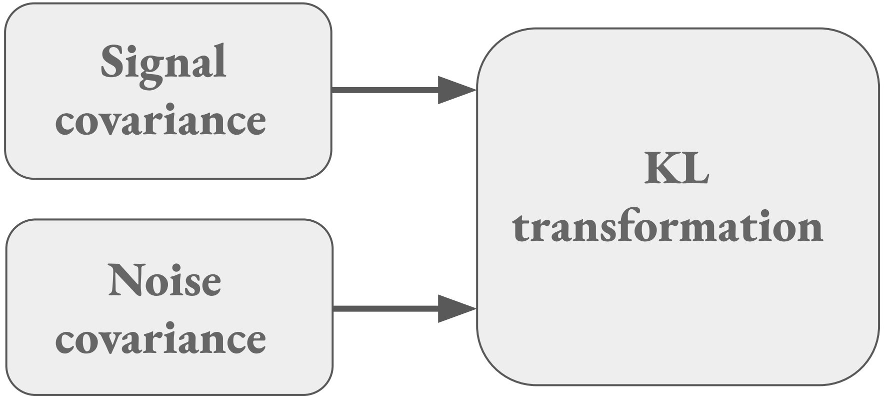

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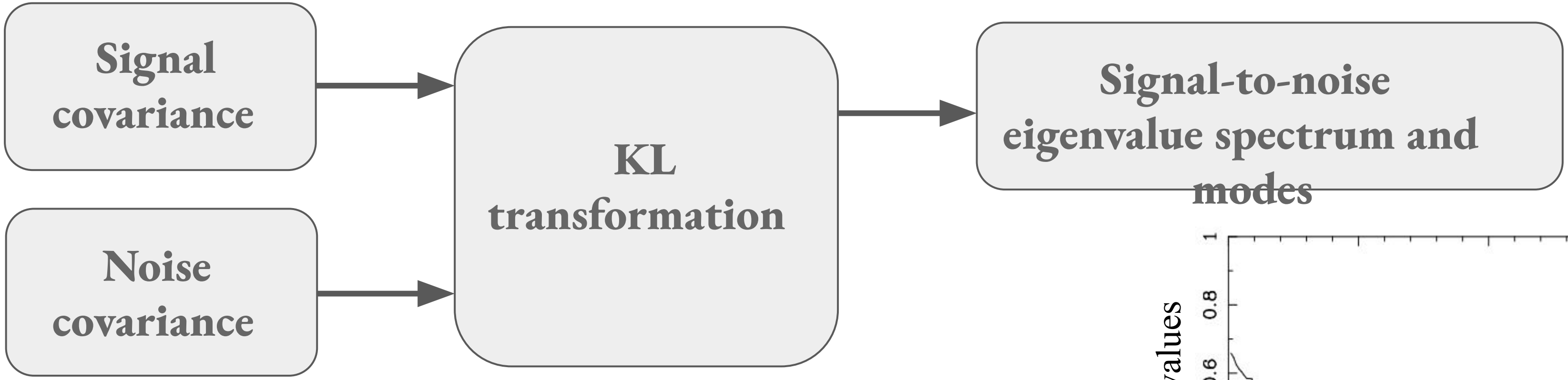

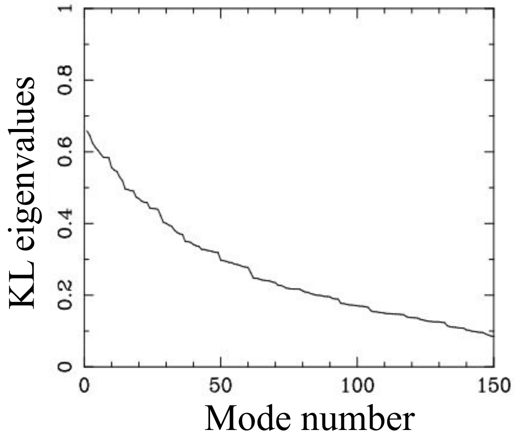

Tegmark,Taylor & Heavens (1996)

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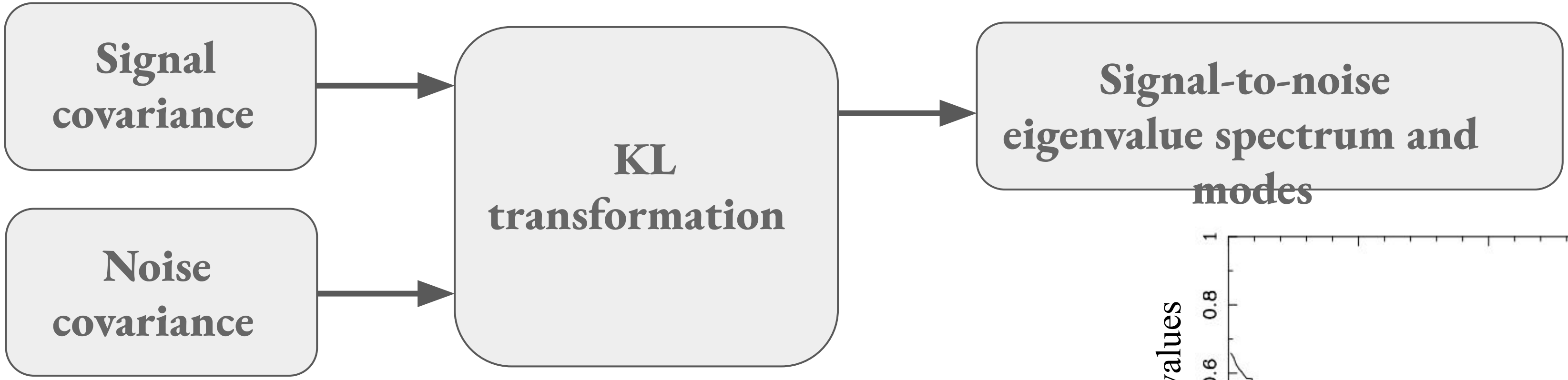

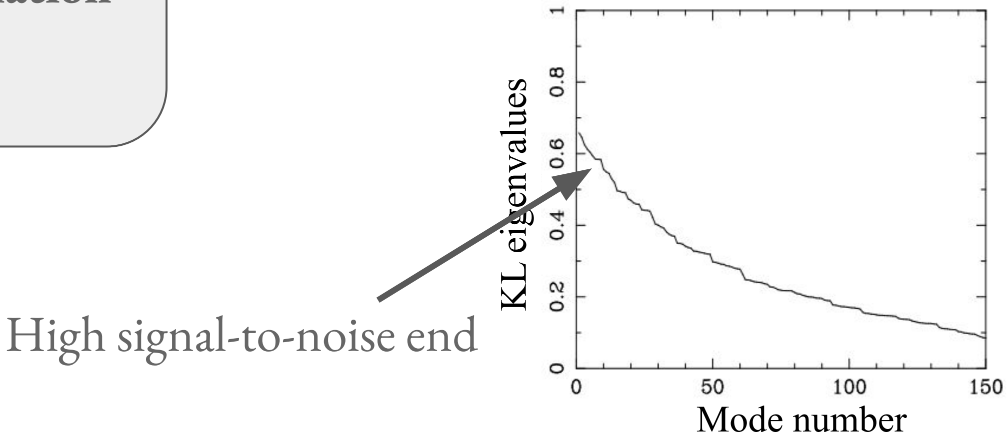

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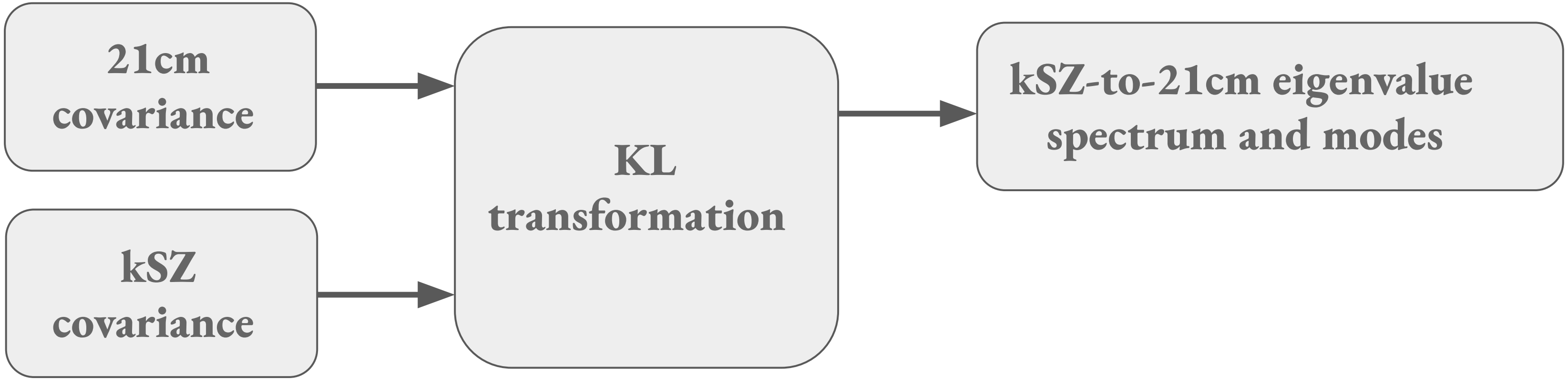
- In our case: kSZ-to-21cm analysis



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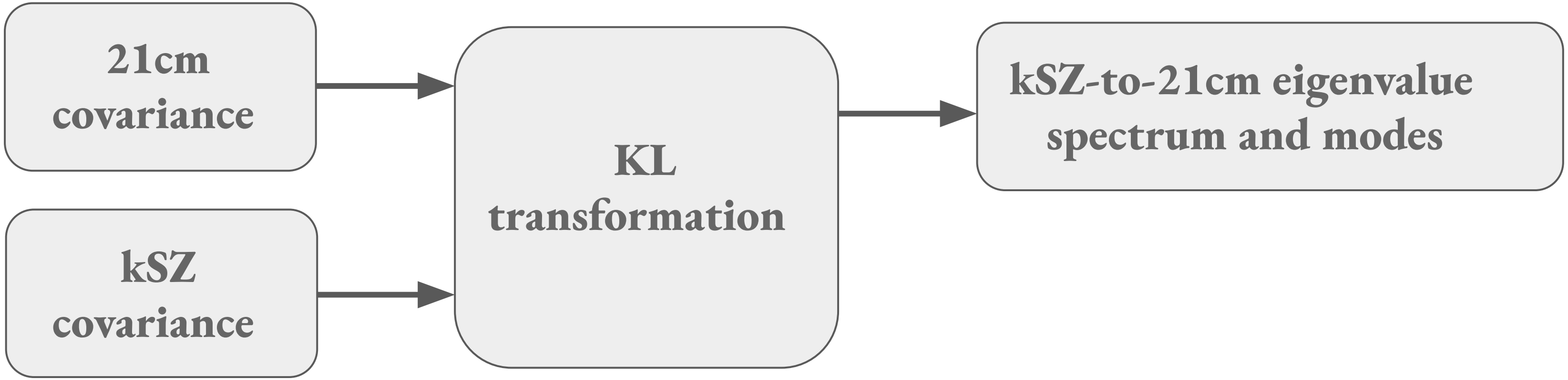
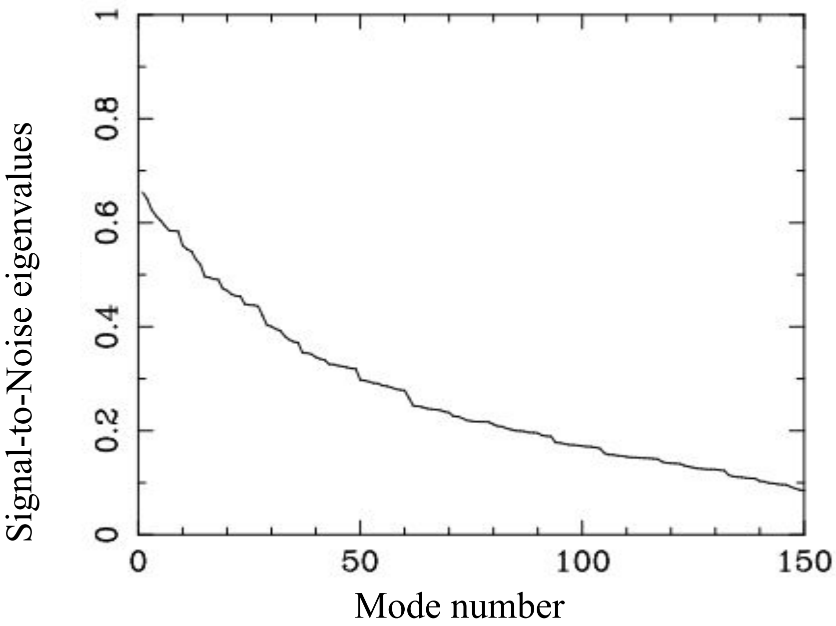


$$\mathbf{C}_{kSZ}\mathbf{v} = \lambda \mathbf{C}_{21}\mathbf{v}$$

21cm-to-kSZ eigenvalues and modes



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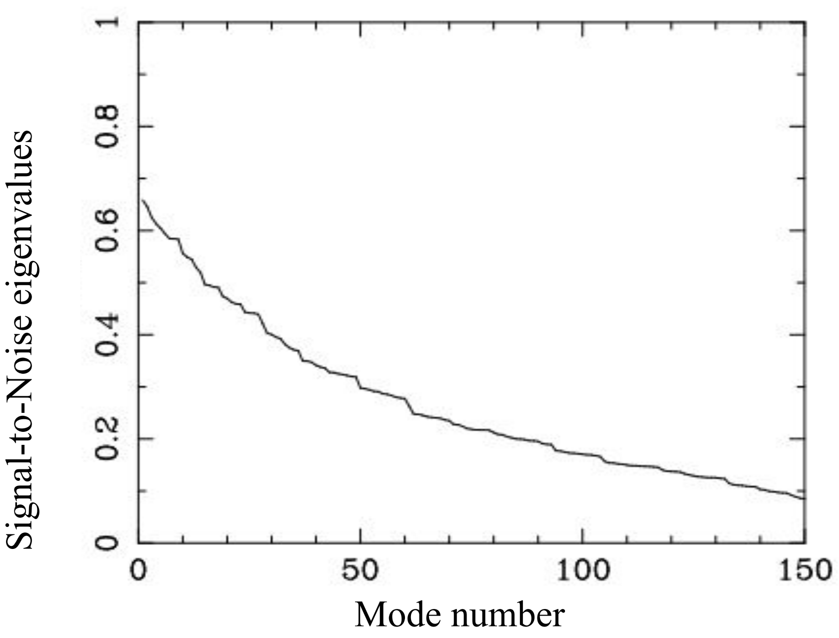

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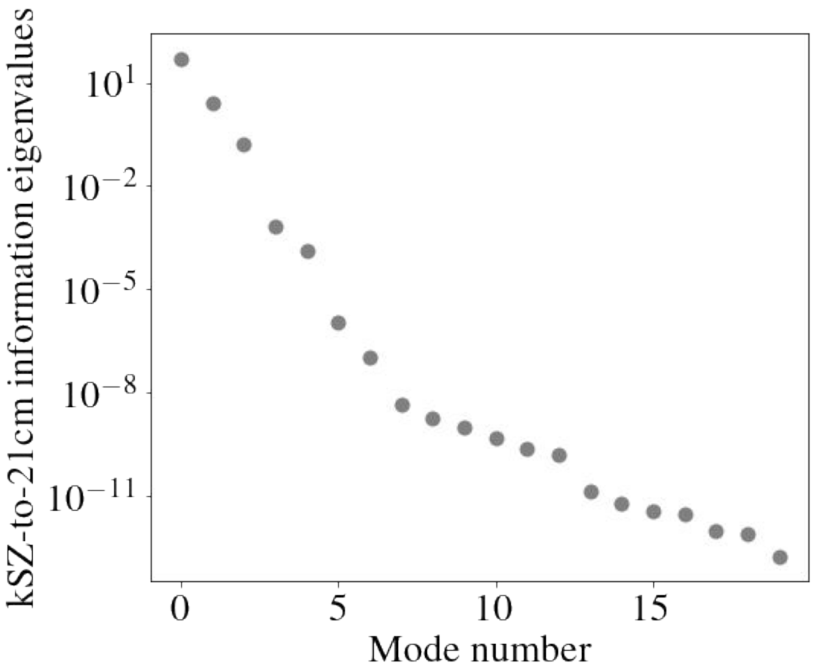

Begin, Liu & Gorce (in prep)

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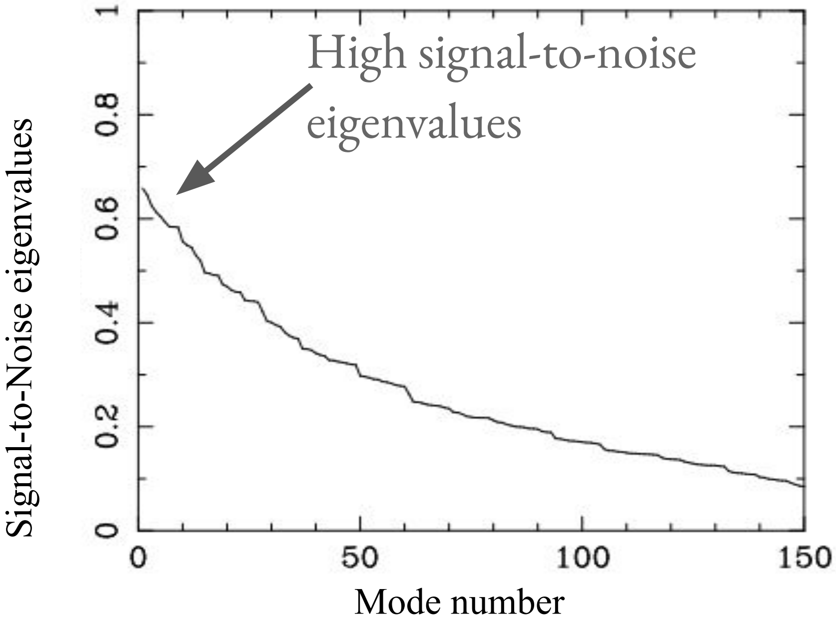

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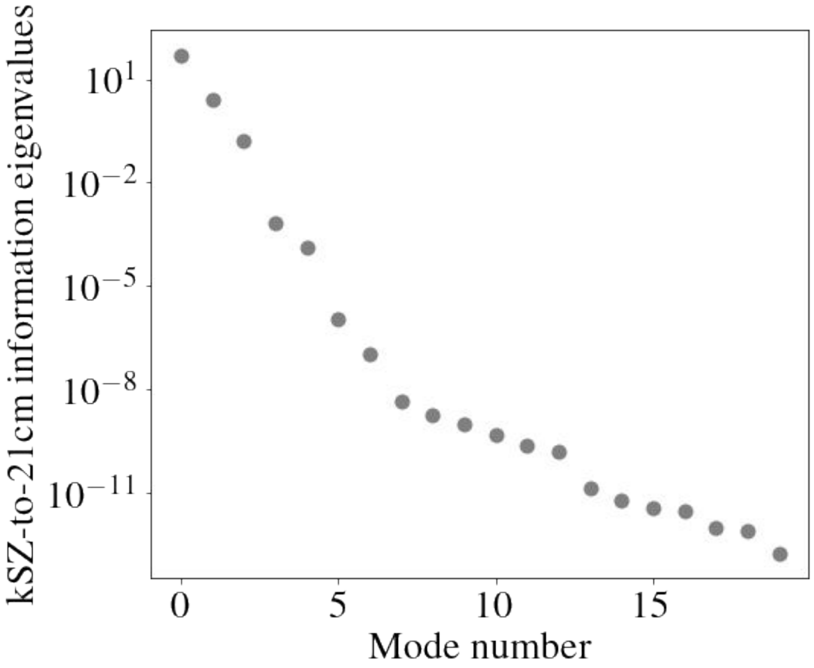

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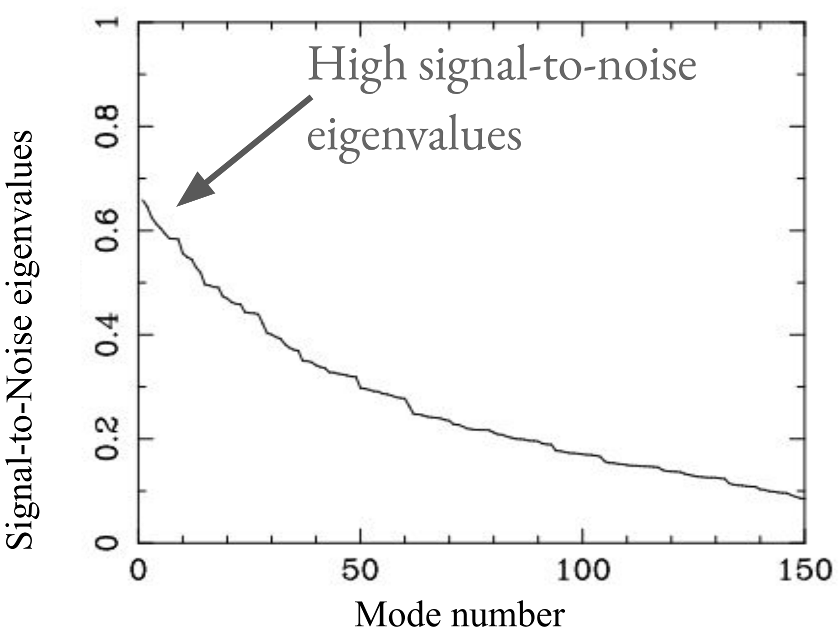

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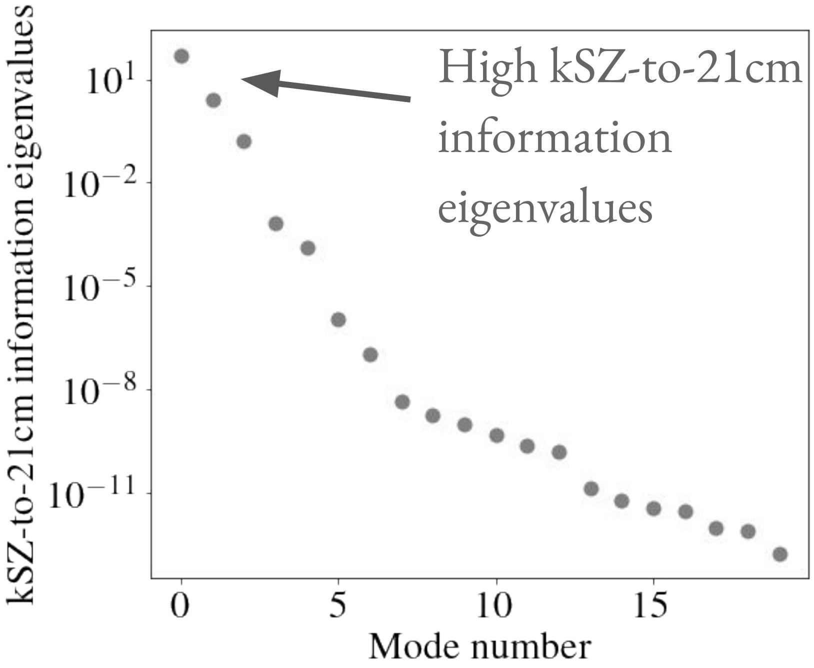

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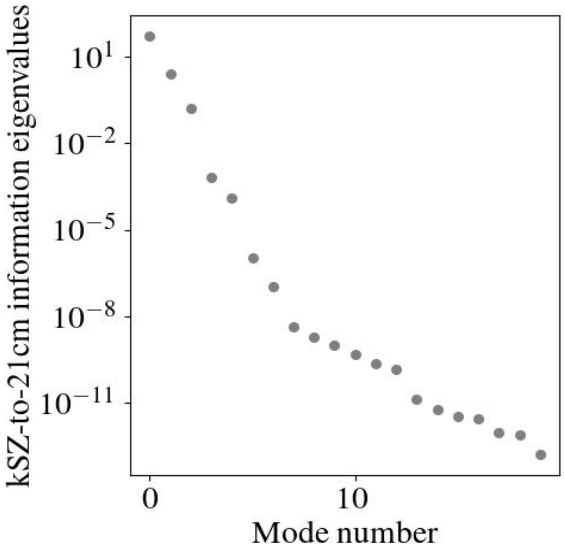

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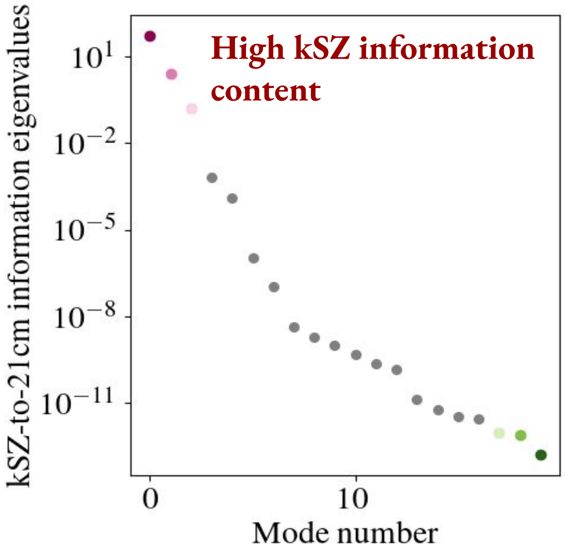

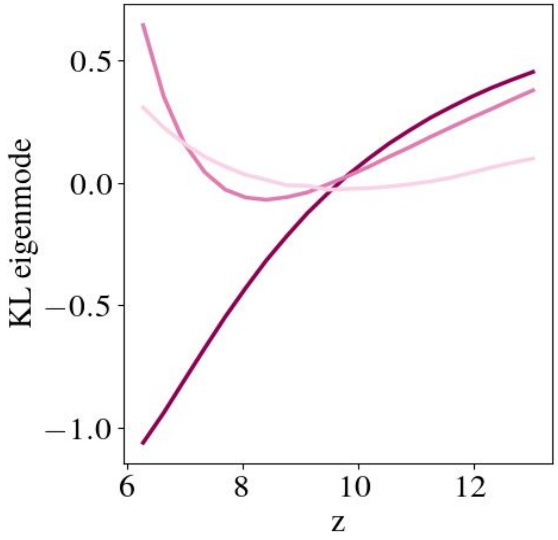

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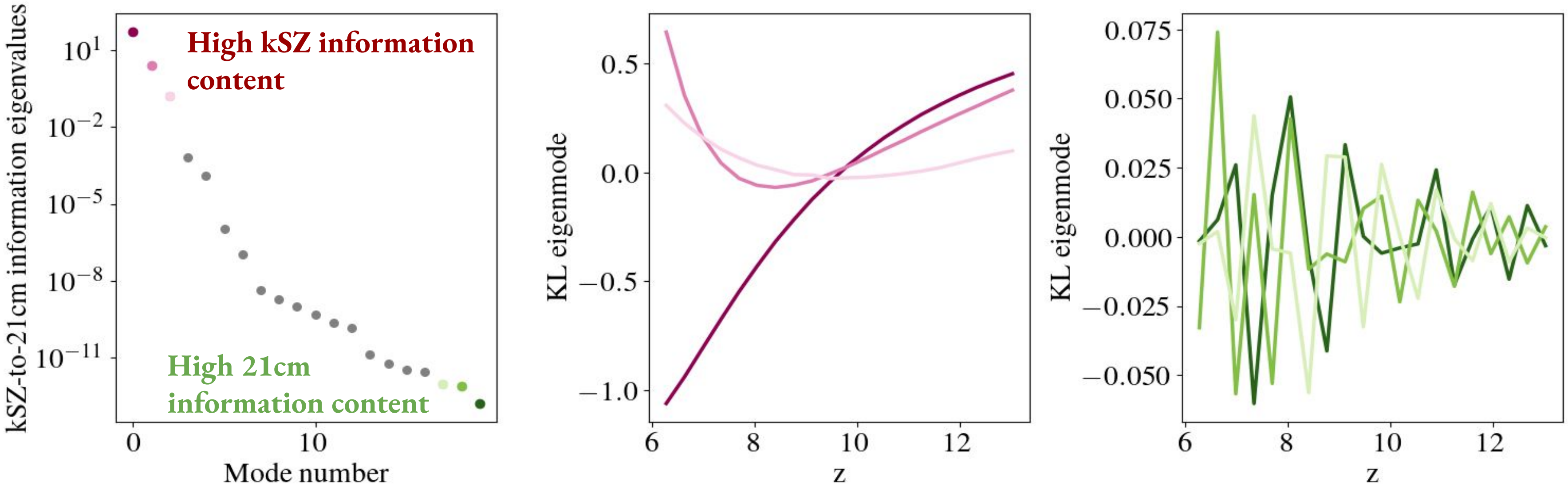

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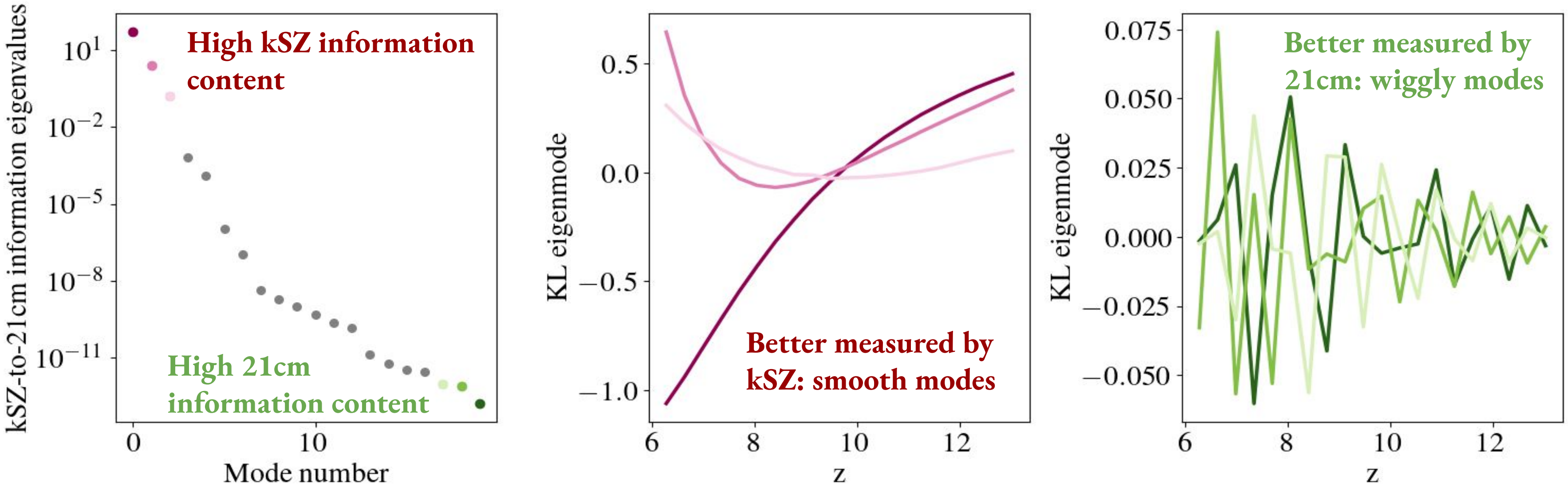
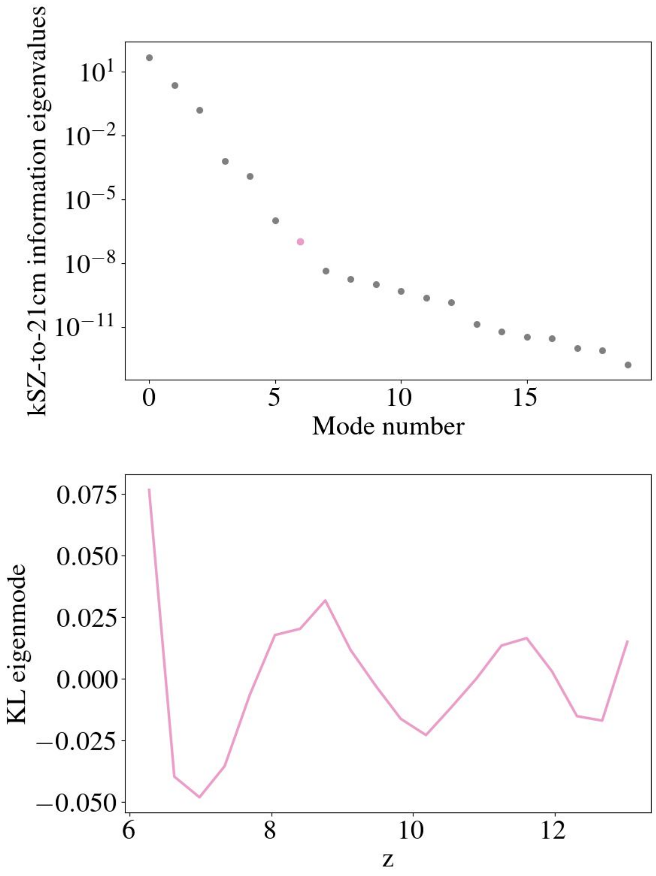
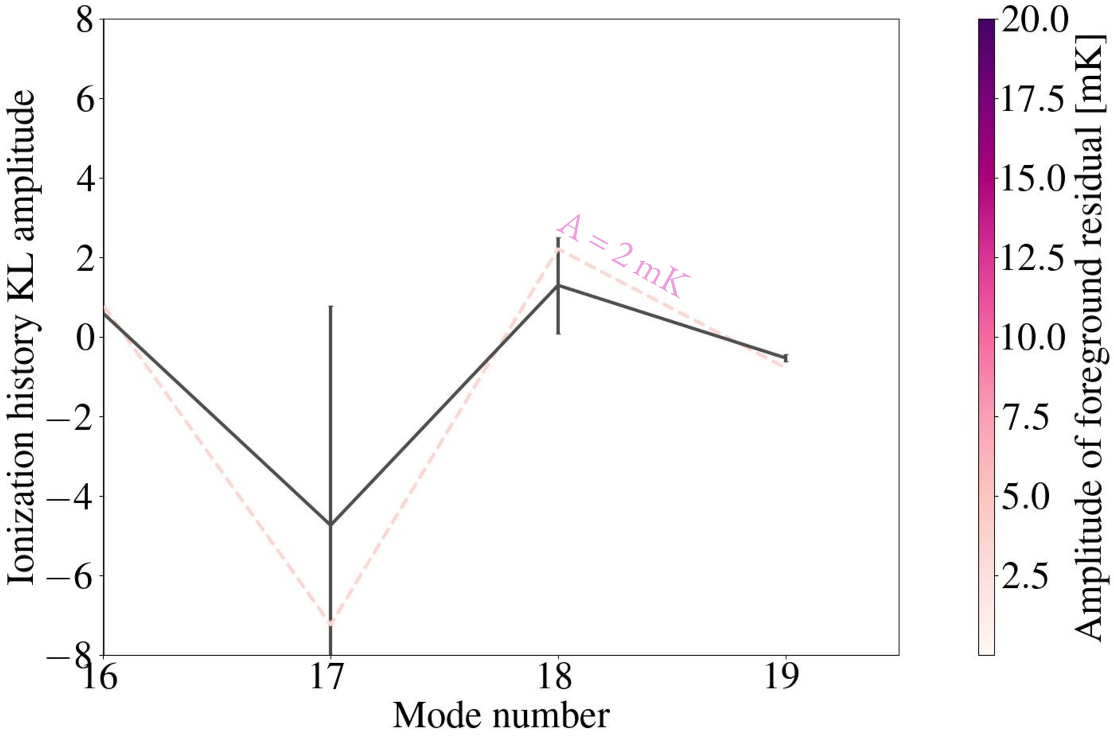


Overlap modes

- Some modes are well measured by both signals
- We can use these common modes to perform **consistency checks**, allowing us detect and project out systematics



How do systematics perturb data in the KL basis?



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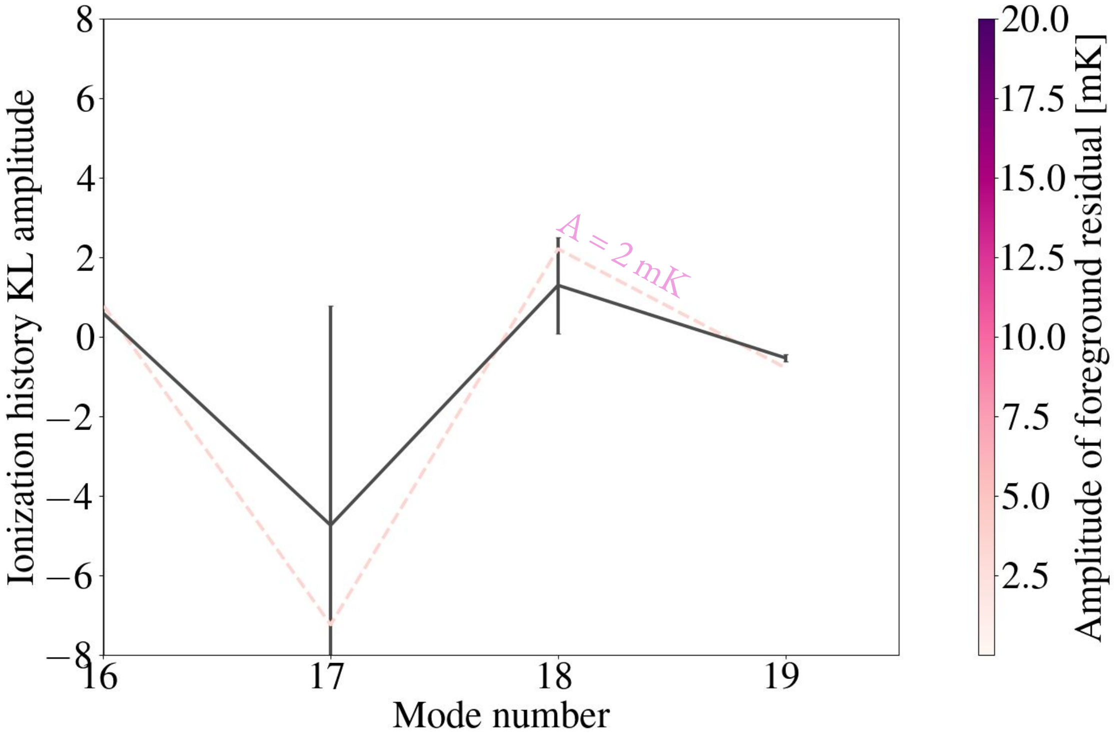
$$x_{HI}(z) = \sum_i a_i \phi_i(z)$$

KL modes



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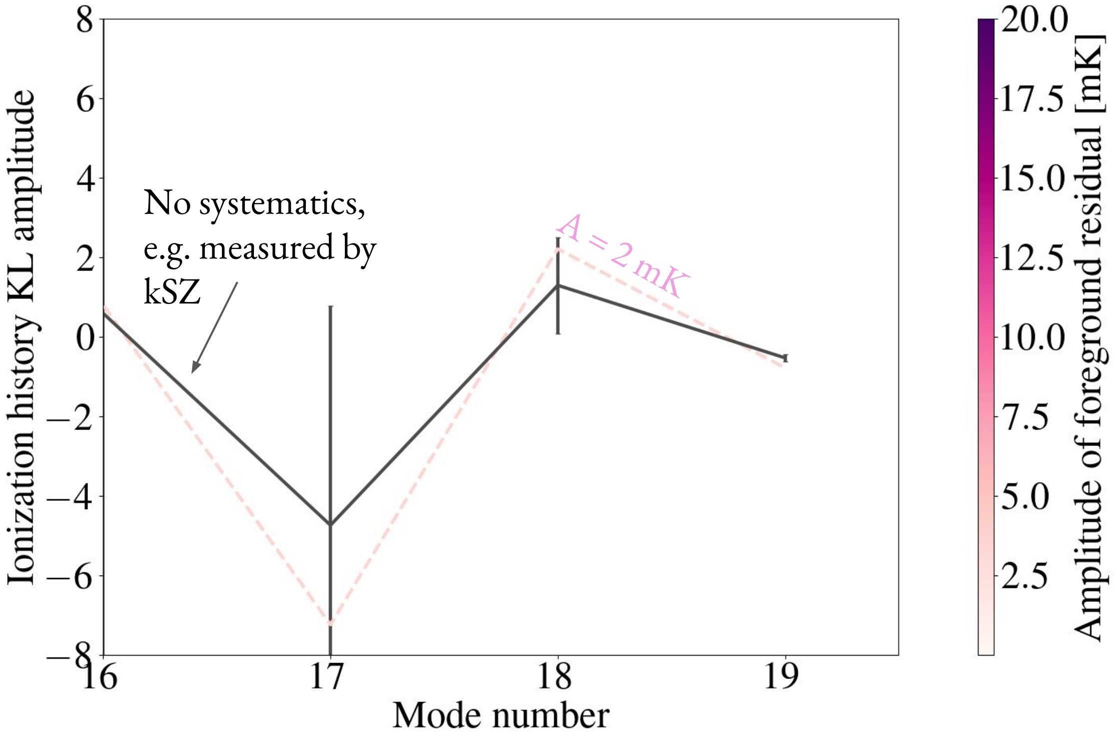


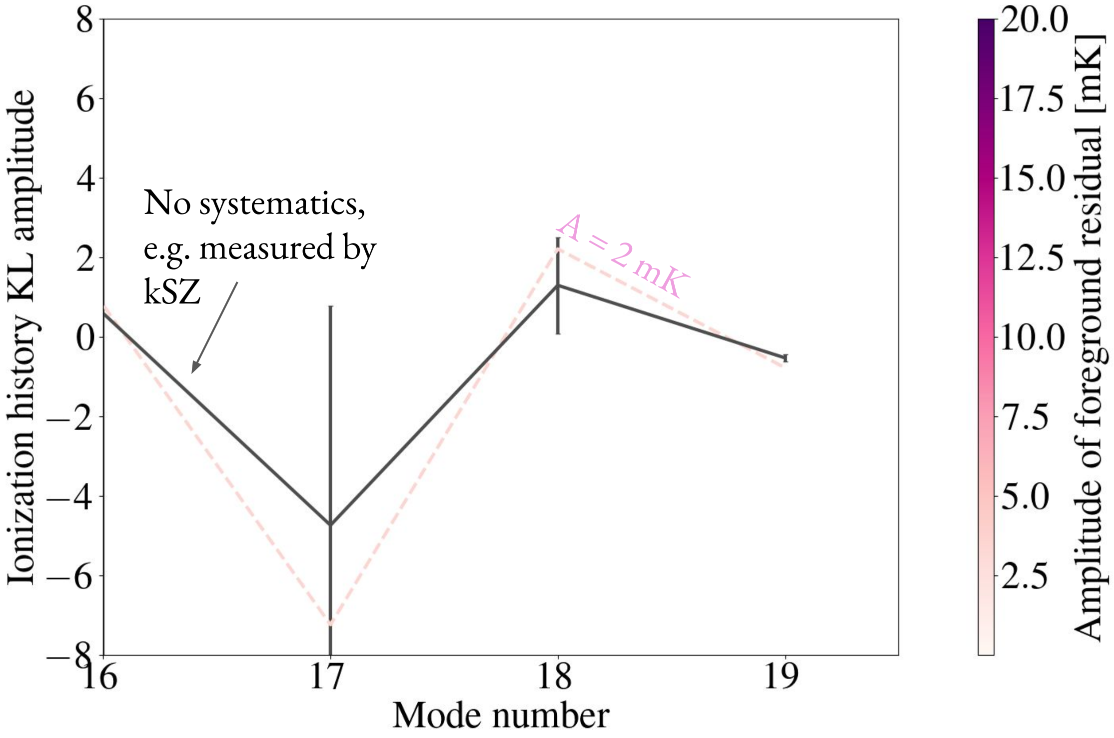
How do systematics perturb data in the KL basis?

- Model foregrounds as power law

$$T_{fg} = A\left(\frac{\nu}{\nu_\star}\right)^{\alpha}$$

- Add to ionization history, do KL transform

$$KL(x_{HI} + x_{fg})$$



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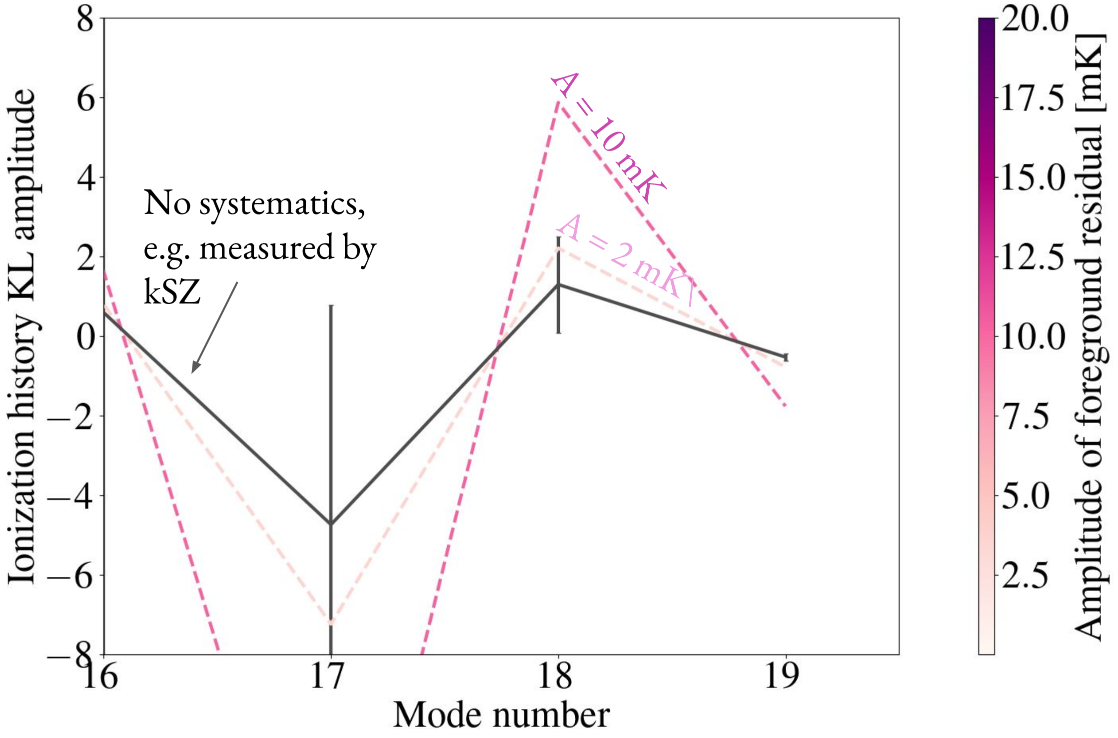

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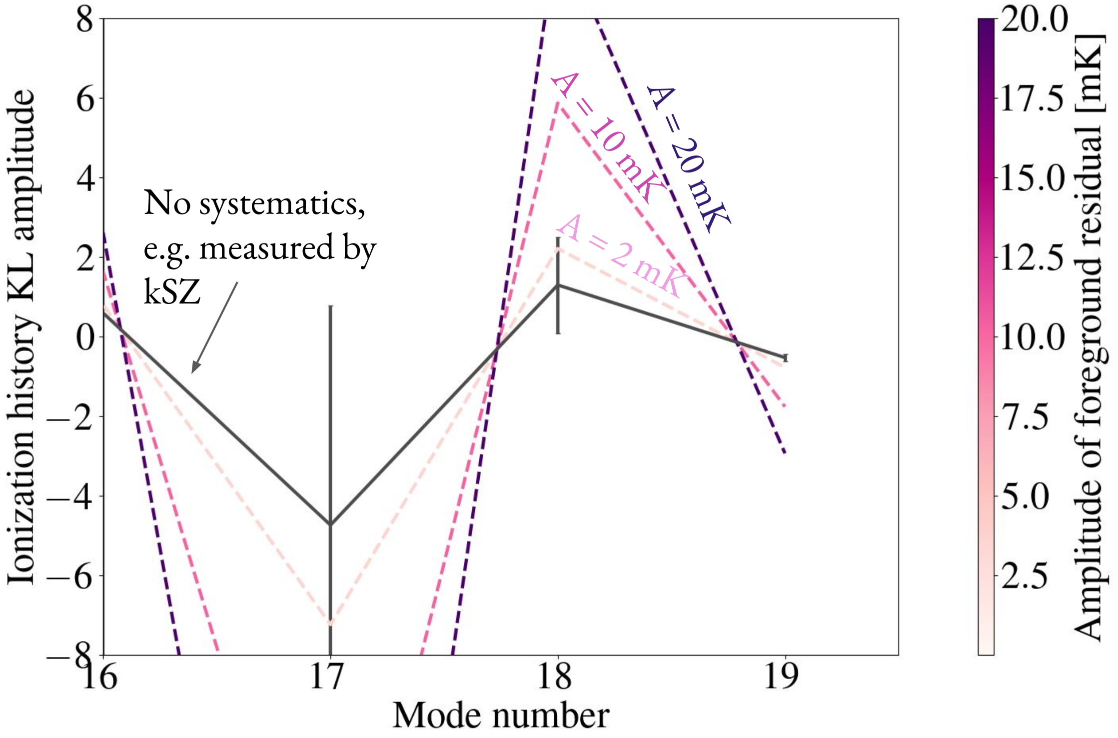

The Linear Matched Filter

- Used to detect presence of template shape in data

$$\nu = \sqrt{\frac{(\mathbf{s}^T \mathbf{\Sigma}^{-1} \mathbf{z})^2}{\mathbf{s}^T \mathbf{\Sigma} \mathbf{s}}}$$

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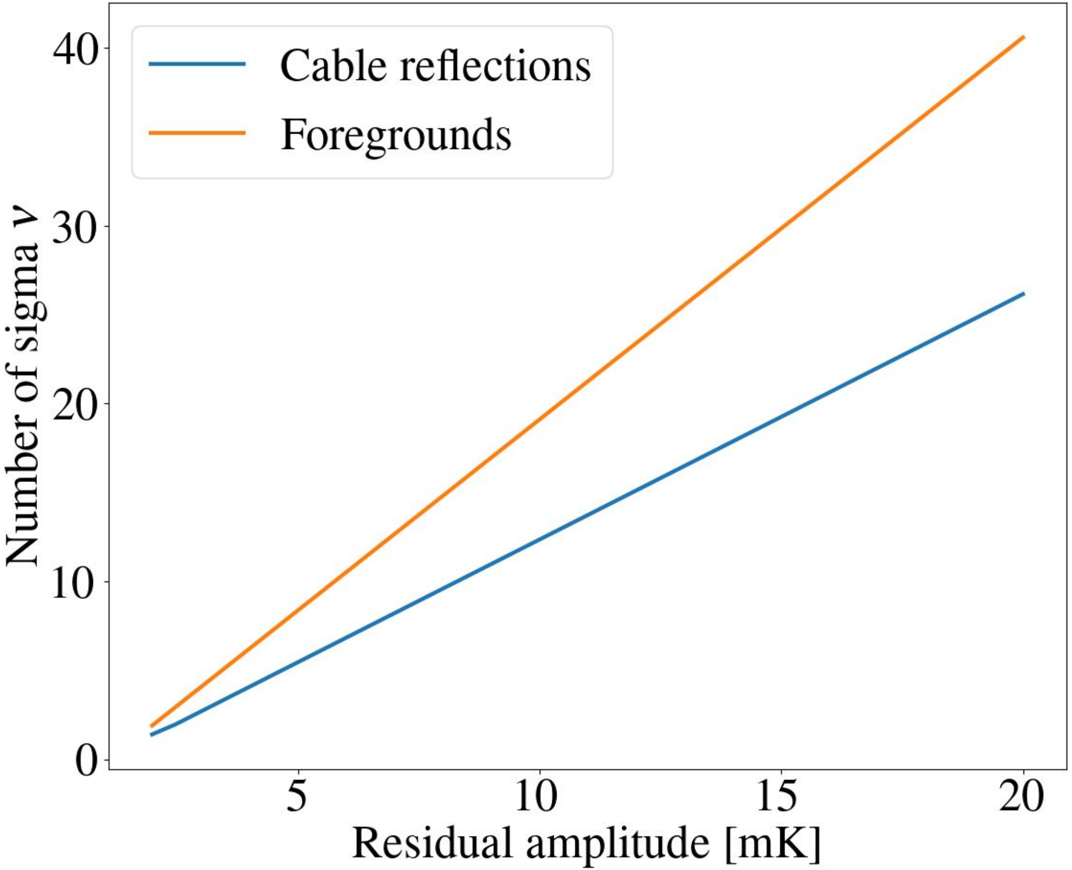
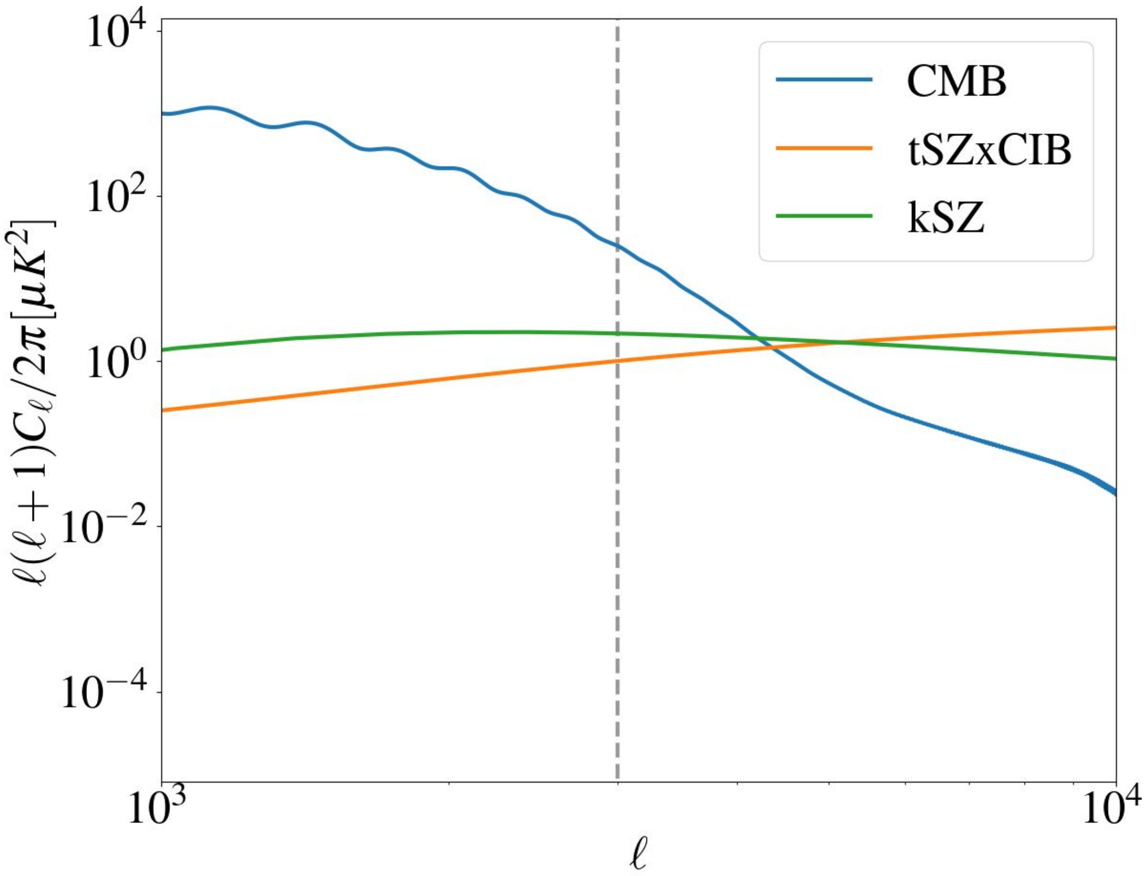
Number of sigma with which we claim detection of systematic in data

Systematic shape template

Cable reflection and foreground systematics



CMB and tSZxCIB residuals



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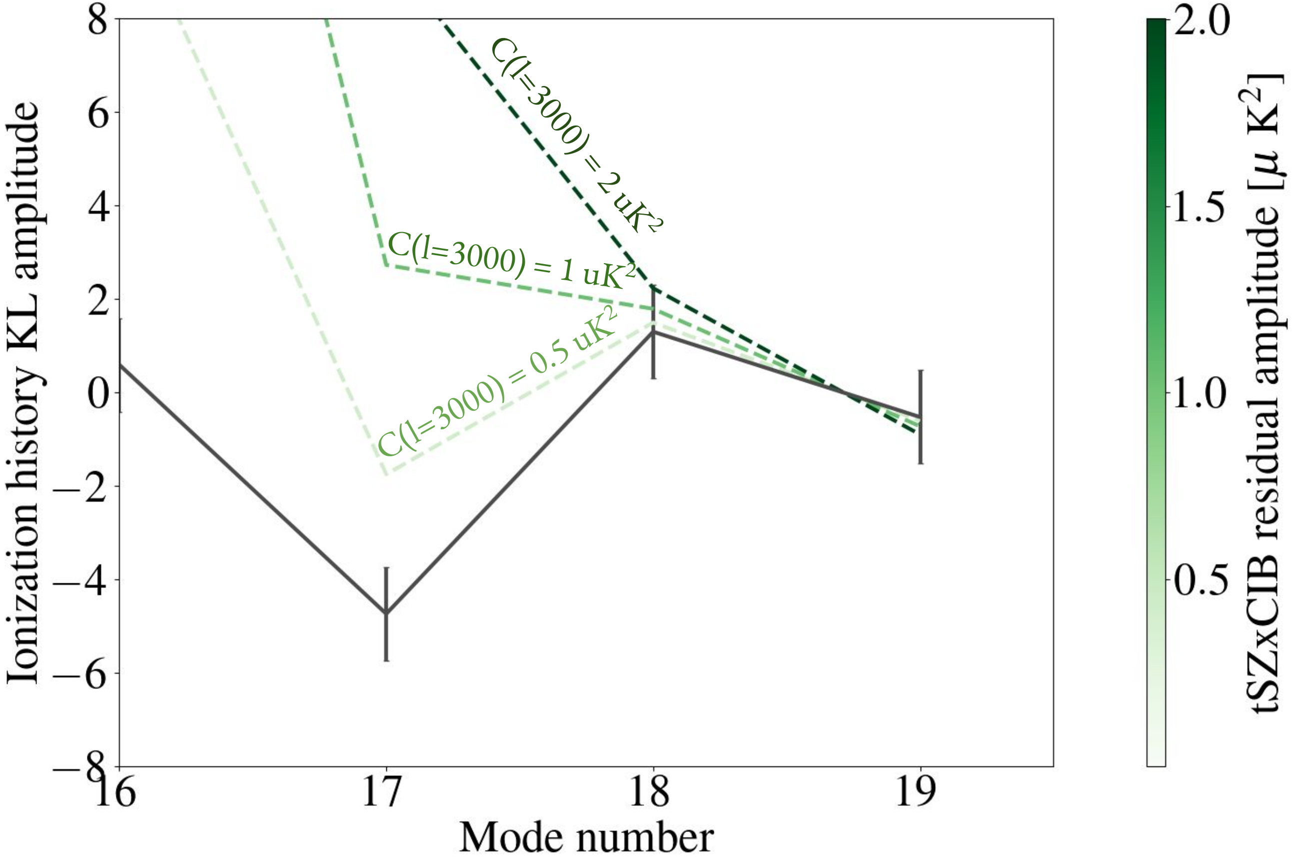

Conclusions

- The Karhunen-Loève basis highlights the complementary relation between the kSZ and 21cm global signal.
- By performing statistical tests on modes that are well measured by both probes, we can detect to the presence of systematics.
- This is a general framework that can be **generalized to any two probes**.

BACKUP SLIDES

Simulating covariances: global 21cm signal

- We use the Fisher information matrix formalism

$$\mathbf{F}^{21}_{\alpha\beta} = \sum_i \frac{\partial T_{21}(z_i)}{\partial x_{HI}(z_\alpha)} \mathbf{\Pi}_{\alpha\beta} \frac{\partial T_{21}(z_i)}{\partial x_{HI}(z_\beta)}$$

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Derivative of global signal with respect to neutral fraction

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Noise covariance

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Simulating covariances: global 21cm signal

- We use the Fisher information matrix formalism
- Entries of Fisher matrix tell us how good 21cm signal is at constraining the ionized fraction in a redshift bin

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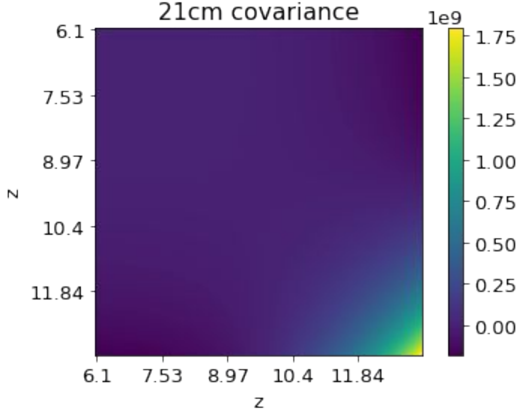

Instrument noise + foregrounds

Simulating covariances: kSZ

$$(\mathbf{C}^{kSZ}_{\alpha\beta})^{-1} \approx \mathbf{F}^{kSZ}_{\alpha\beta} = \sum_i \frac{\partial C_\ell(\ell_i)}{\partial x_{HI}(z_\alpha)} \mathbf{\Pi}_{\alpha\beta} \frac{\partial C_\ell(\ell_i)}{\partial x_{HI}(z_\beta)}$$

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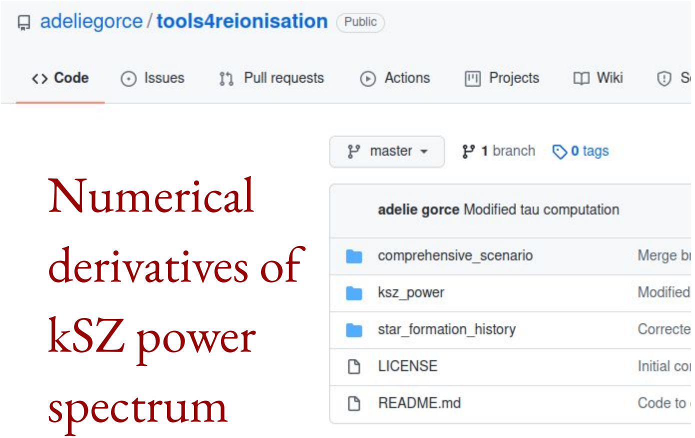
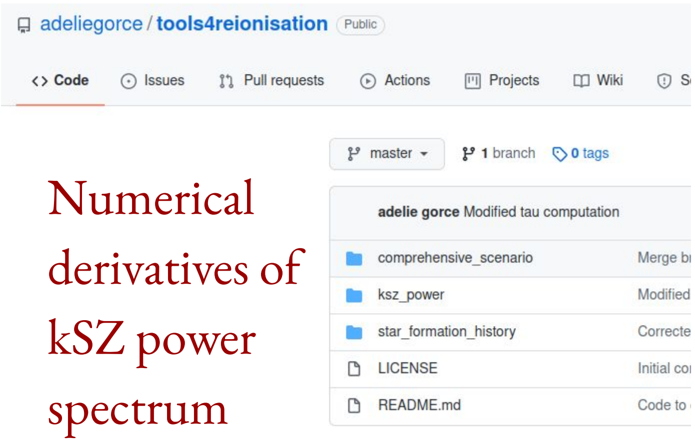
Numerical derivatives of kSZ power spectrum

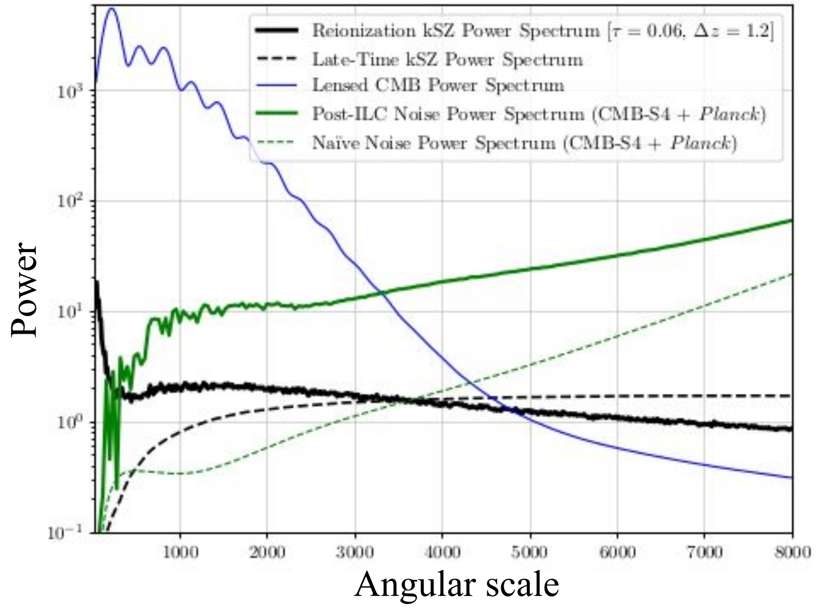


Simulating covariances: kSZ

$$\left(\mathbf{C}^{kSZ}_{\alpha\beta}\right)^{-1} \approx \mathbf{F}^{kSZ}_{\alpha\beta} = \sum_i \frac{\partial C_\ell(\ell_i)}{\partial x_{HI}(z_\alpha)} \mathbf{\Pi}_{\alpha\beta} \frac{\partial C_\ell(\ell_i)}{\partial x_{HI}(z_\beta)}$$

Numerical derivatives of kSZ power spectrum





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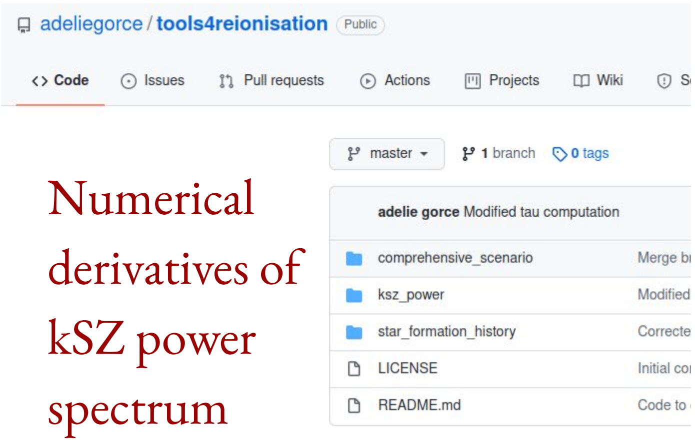
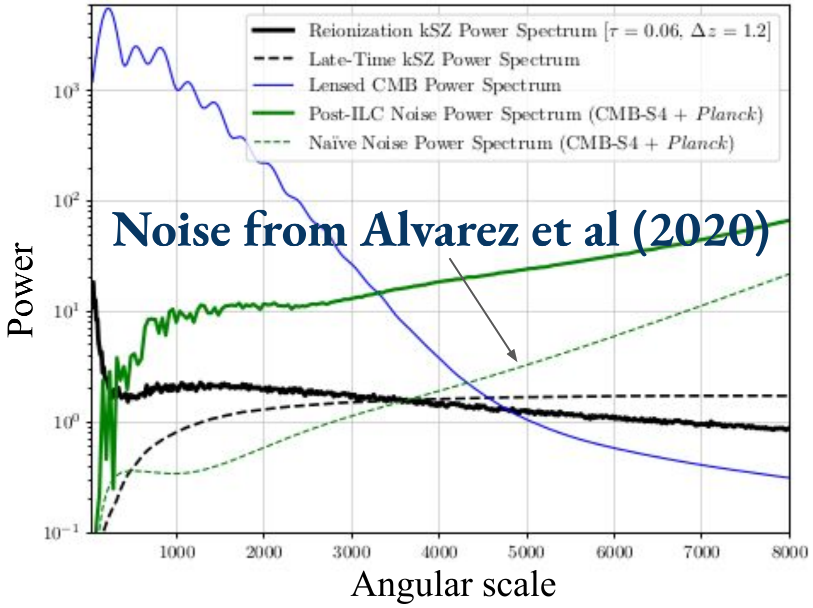


Noise from Alvarez et al (2020)



$$\overline{\mathbf{C}}_{kSZ} = \mathbf{\Psi}^T \mathbf{L}_{21}^{-1} \mathbf{C}_{kSZ} \mathbf{L}_{21}^{-T} \mathbf{\Psi} = \mathbf{\Psi}^T \mathbf{G} \mathbf{\Psi} = \mathbf{\Lambda}$$

$$\overline{\mathbf{C}}_{21} = \mathbf{\Psi}^T \mathbf{L}_{21}^{-1} \mathbf{C}_{21} \mathbf{L}_{21}^{-T} \mathbf{\Psi} = \mathbf{\Psi}^T \mathbf{\Psi} = \mathbf{I}$$

$$\mathbf{L}_{21}^{-1} \mathbf{C}_{kSZ} \mathbf{L}_{21}^{T} \mathbf{v} = \lambda \mathbf{L}_{21}^{T} \mathbf{v}.$$

$$\mathbf{C}_{kSZ} \mathbf{v} = \lambda \mathbf{C}_{21} \mathbf{v}.$$