Model Independent Probes of Dark Sector Physics

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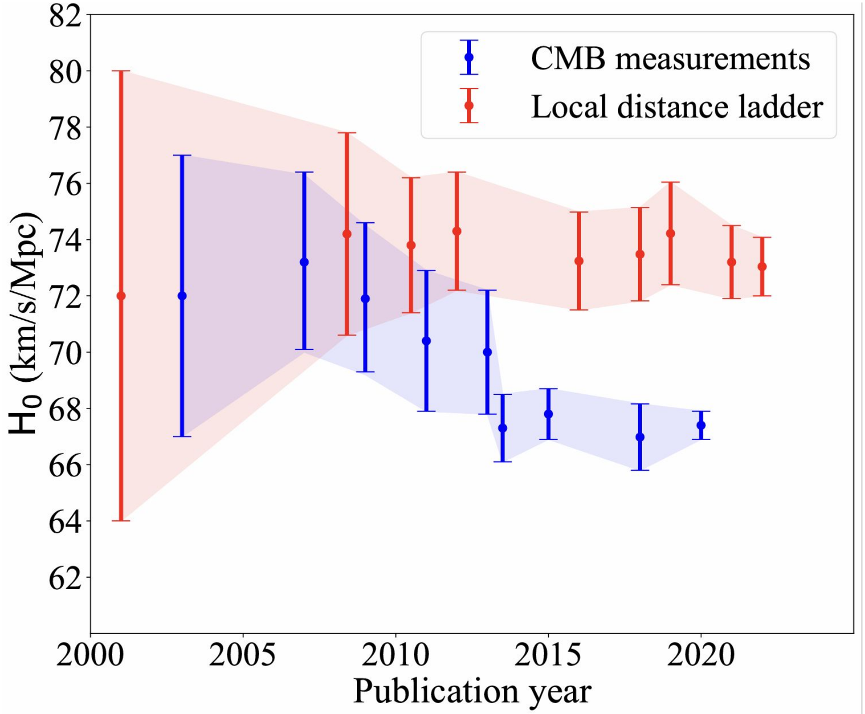
Background and Key Terms

Hubble Tension

- From the Planck data: 67 km/s/Mpc
- From the supernovae: 74 km/s/Mpc
- The tension remains at a level from $4 - 5\sigma$
- Λ-CDM model is challenged by new models [6]



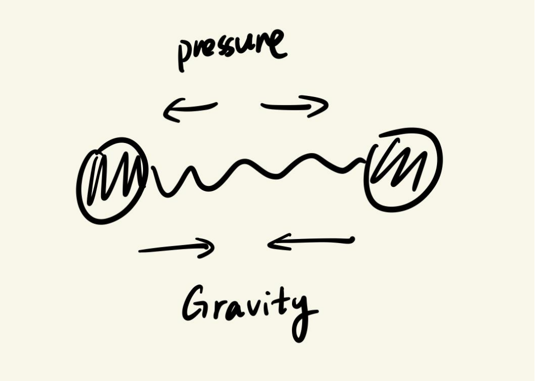
Hubble tension.
Credit to https://www.mdpi.com/2218-1997/9/2/94.

Model Independent Approach

- Wess-Zumino Dark Radiation Model (WZDR) and Chameleon Early Dark Energy Model (CEDE) as benchmark
- Using Generalized Dark Matter (GDM) method and principal component analysis (PCA)
- Project the models onto the principal components
- Obtain constraints to these models by using Planck data

Generalized Dark Matter (GDM)

- Describe the cold dark matter (CDM) and other forms of dark matter like neutrinos, dark radiation and scalar field as a fluid [2] [4]
- Sound speed and equation of state are critical to constrain the GDM
- The equation of state is a dimensionless number that describes the relationship between pressure and density
- The sound speed refers to the oscillation of the cosmic fluid
- In Λ-CDM, cold dark matter (CDM) and neutrinos contribute to the dark fluid



Cartoon for sound speed.

GDM Fluid Described by 3 EoMs

Continuity equation (think about EM):

$$\dot{\delta}_d = -(1+w_d)(\theta_d + \frac{\dot{h}}{2}) - 3\frac{\dot{a}}{a}\left(\frac{\delta P_d}{\delta \rho_d} - w_d\right)\delta_d$$

Euler equation (think about F = ma):

$$\dot{\theta}_d = -\frac{\dot{a}}{a}(1-3w_d)\theta_d - \frac{\dot{w}_d}{1+w_d}\theta_d + \frac{\delta P_d/\delta\rho_d}{1+w_d}k^2\delta_d - k^2\sigma_d$$

Dilution of energy change depends on equation of state:

$$\frac{\dot{\rho}_d}{\rho_d} = -3(1+w_d)\frac{\dot{a}}{a}.$$

Equation of State and The Effective Sound Speed

$$w_d = \frac{P_d}{\rho_d}$$

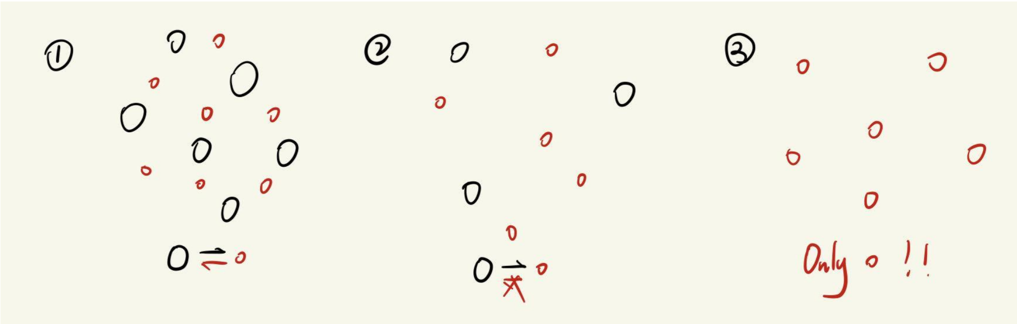
$$c_d^2(k,a) = \frac{\delta P_d}{\delta \rho_d}$$

$$c_{d,\mathrm{eff}}^2 = \frac{k^2 c_d^2 \delta_d + 3(w_d - \frac{1}{3}\frac{\dot{w}_d}{1+w_d}\left(\frac{\dot{a}}{a}\right)^{-1})\frac{\dot{a}}{a}(1+w_d)\theta_d}{k^2\delta_d + 3\frac{\dot{a}}{a}(1+w_d)\theta_d}$$

for rel matter $w = \frac{1}{3}$
mild $0 < w < \frac{1}{3}$
non-rel $w \approx 0$
dark energy $w < -\frac{1}{3}$

WZDR Model

- Cold dark matter (CDM)
- Neutrinos
- Assumes the existence of two additional dark species: one is massless and the other is massive: 3 major phases
- Interactive dark matter (IDM)
- Reduces Hubble tension to around 2.7σ [1] [6]



Cartoon for WZDR model.

CEDE Model

- Dark matter
- Neutrinos
- Added a scalar field with a mass to the early universe around matter-radiation equality
- Conformally coupled with dark matter
- Diluted in the later universe [3]

Principal Component Analysis (PCA)

- A powerful tool to reduce the dimensionality of high dimensional data
- Obtain principal components from cosmic linear perturbation theory and Fisher matrix (first equation)
- Diagonalize the Fisher matrix to get eigenvectors (V) and eigenvalues (D) (second equation)
- Represent equation of state and sound speed as a linear combination of PCs
- Help us constrain the models

$$F_{ij} = \sum_{\ell} f_{\text{sky}} \left(\frac{2\ell+1}{2} \right) \frac{\partial \mathbf{C}_\ell}{\partial \theta_i} \mathbf{\Sigma}_l^{-1} \frac{\partial \mathbf{C}_\ell}{\partial \theta_j}$$

$$\theta = \{\mathbf{p}, \mathbf{q}\}$$

θ in our case is w(z) for various z and $c_d^2(k,a)$ for various k and a.

$$\mathbf{F} = \mathbf{V}\mathbf{D}\mathbf{V}^\top$$

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Methods

Cosmic Linear Anisotropy Solving System (CLASS)

- A Boltzmann code
- Simulate the linear perturbation of the universe and compute large structure observables [5]
- Different versions of the CLASS code for different models
- Compute equation of state and sound speed by using the code

Projection

- Now we have principal components and sound speed/equation of state
- Rewrite the sound speed/equation of state into the linear combination of principal components
- Test the models by using CMB data (in the future)

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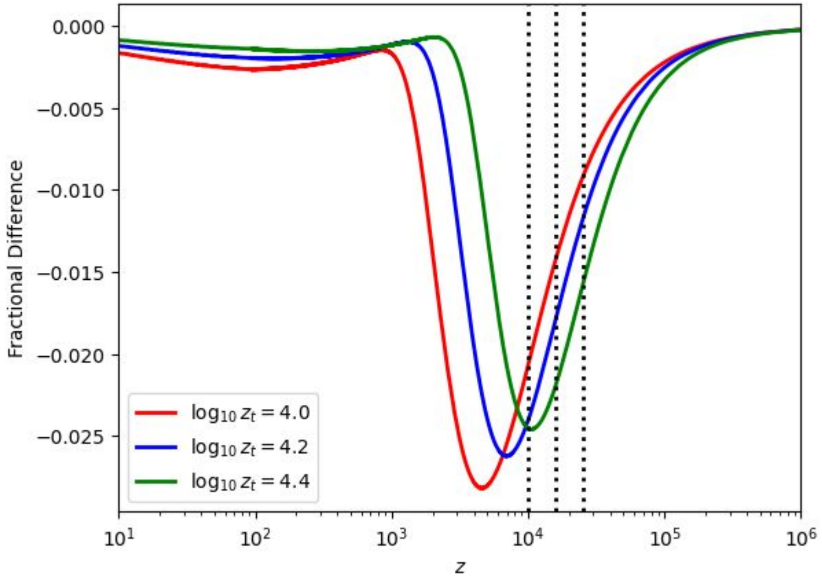
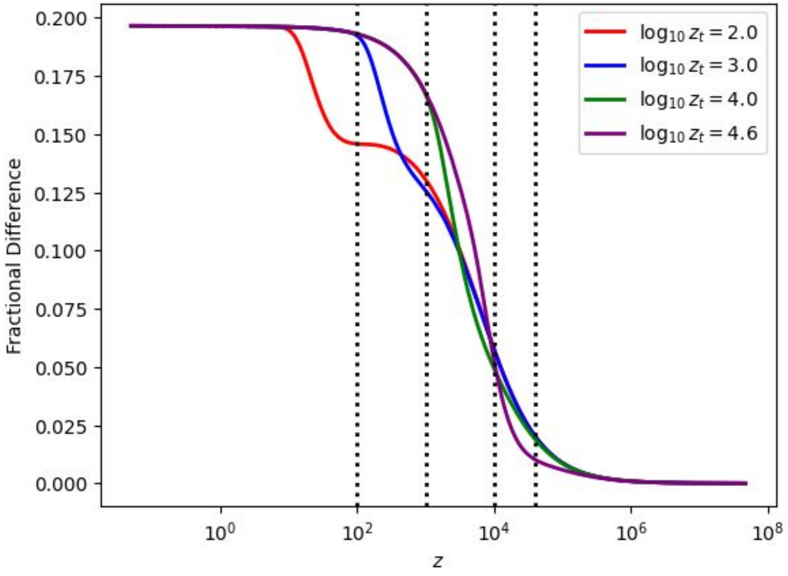
Results

Equation of State



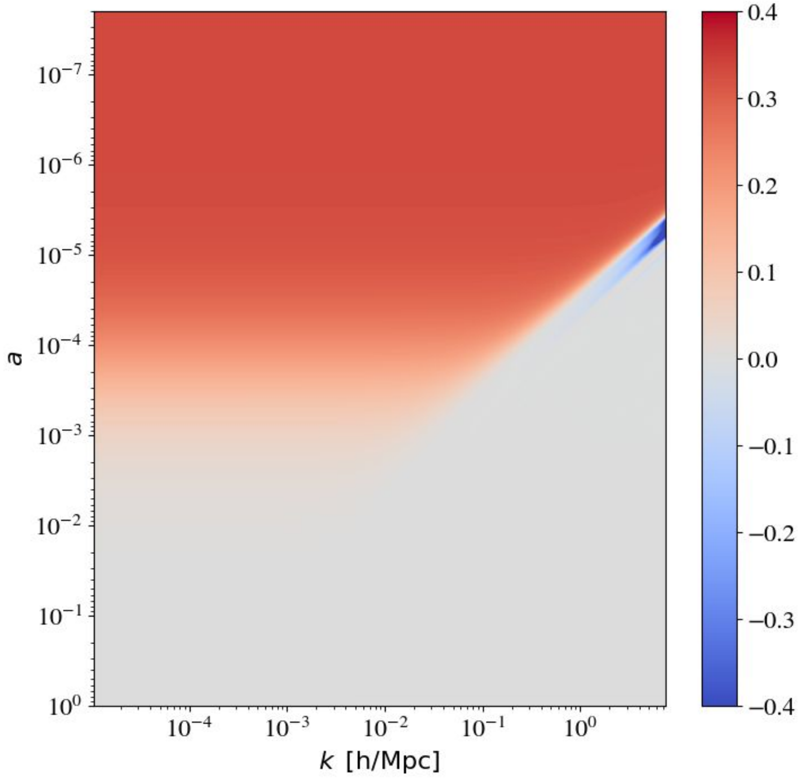
Fractional difference of equation of state for WZDR model between low z_t and high z_t.



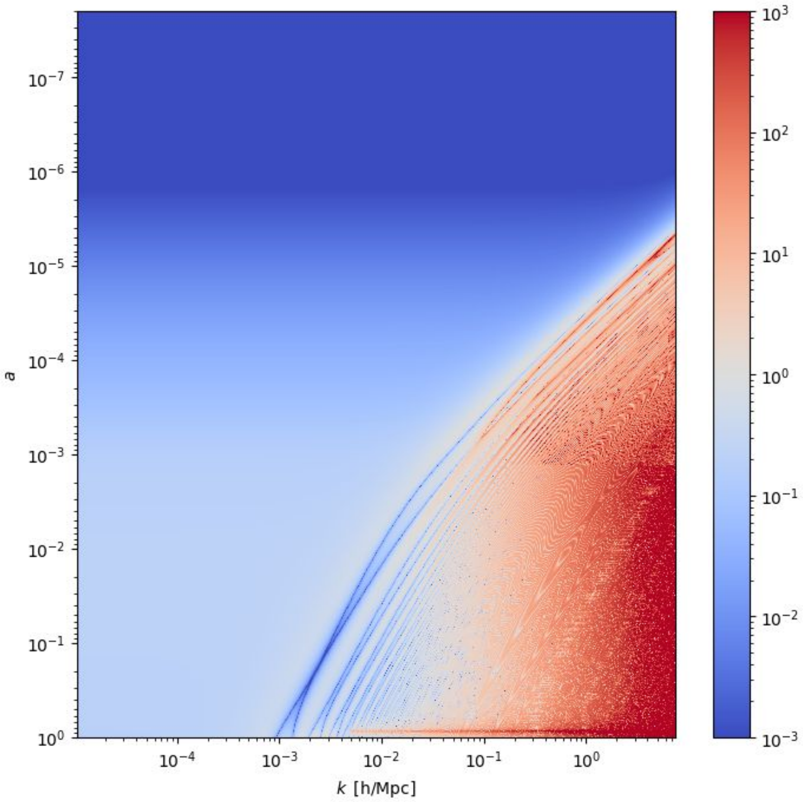
Fractional difference of equation of state between WZDR and Λ-CDM model.

Massive	R	→	NR	→	0
Massless	R	→	R	→	R
Fluid	R	→	NR	→	R

Effective Sound Speed

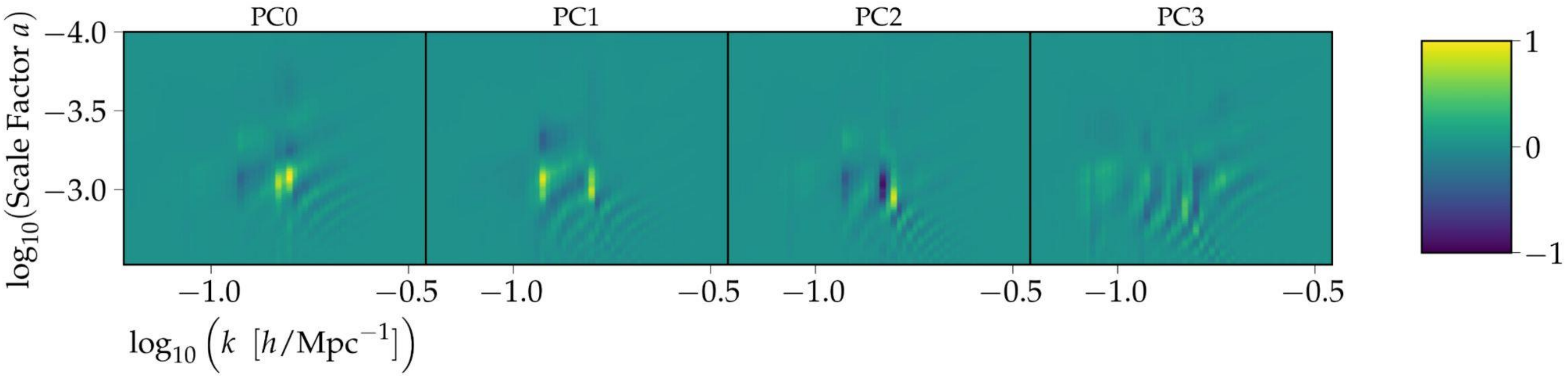


Sound speed for WZDR model.



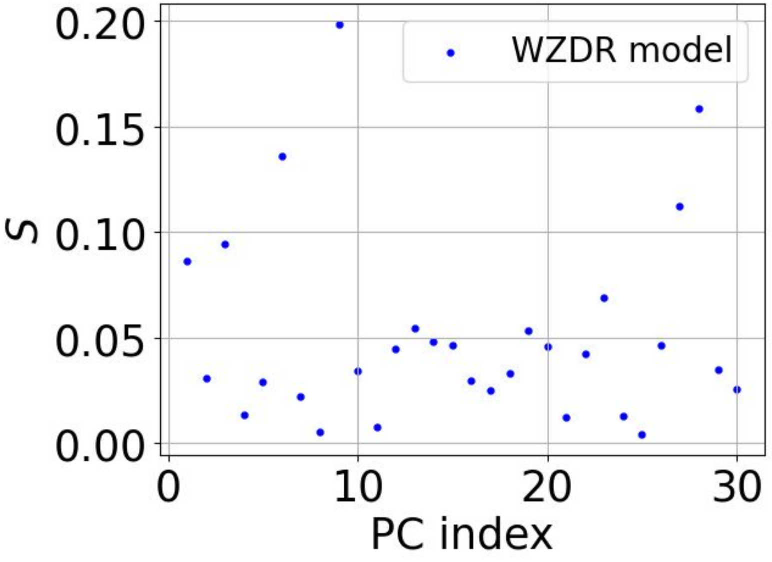
Fractional difference of sound speed between WZDR and Λ-CDM model.

Principal Components Mapping

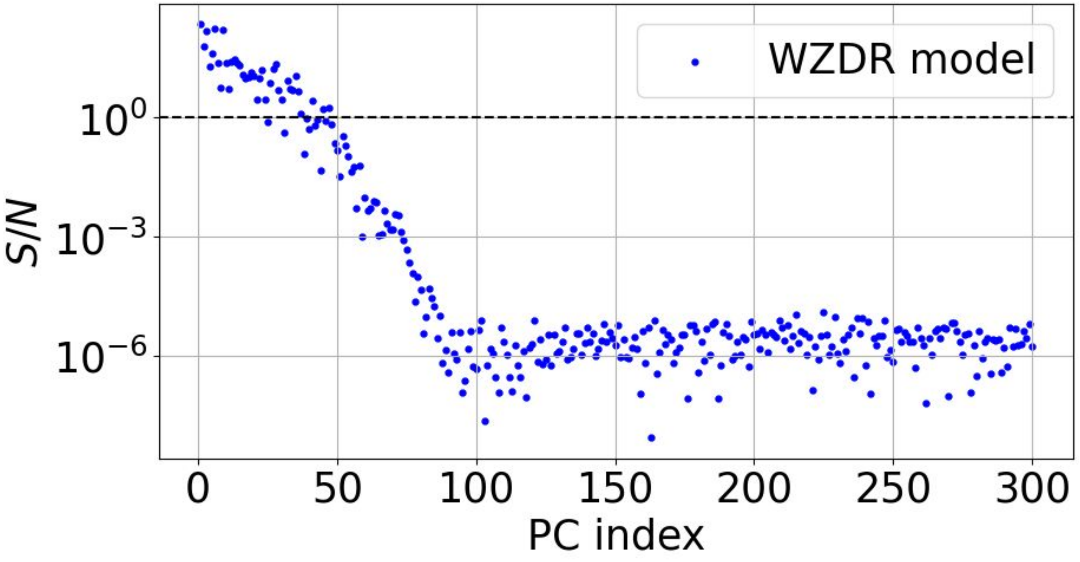


First four PCs for sound speed.

Signal Versus PCs



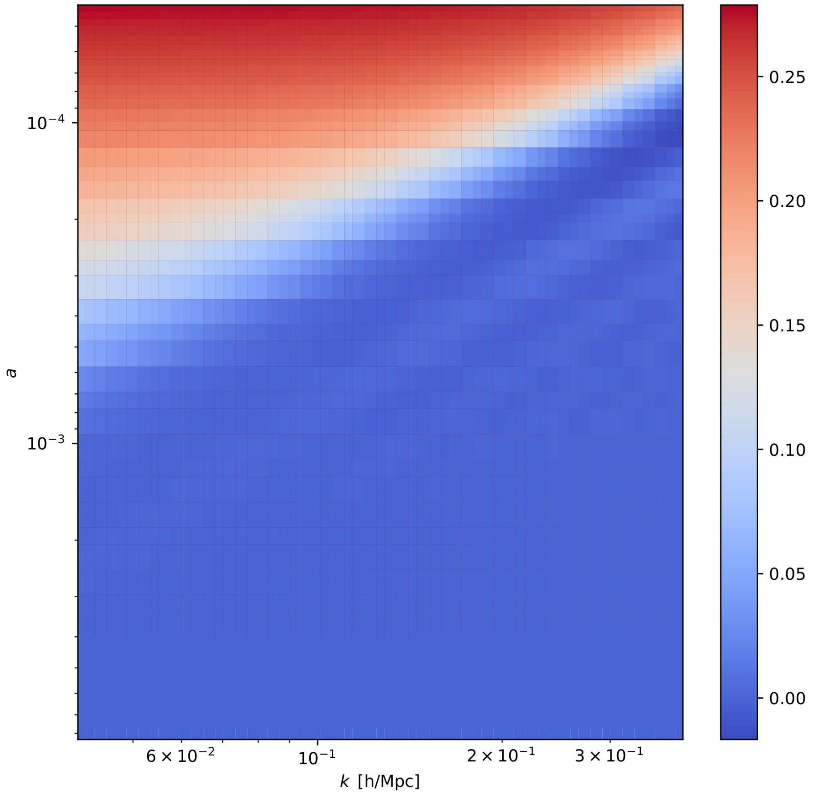
S versus PC index.



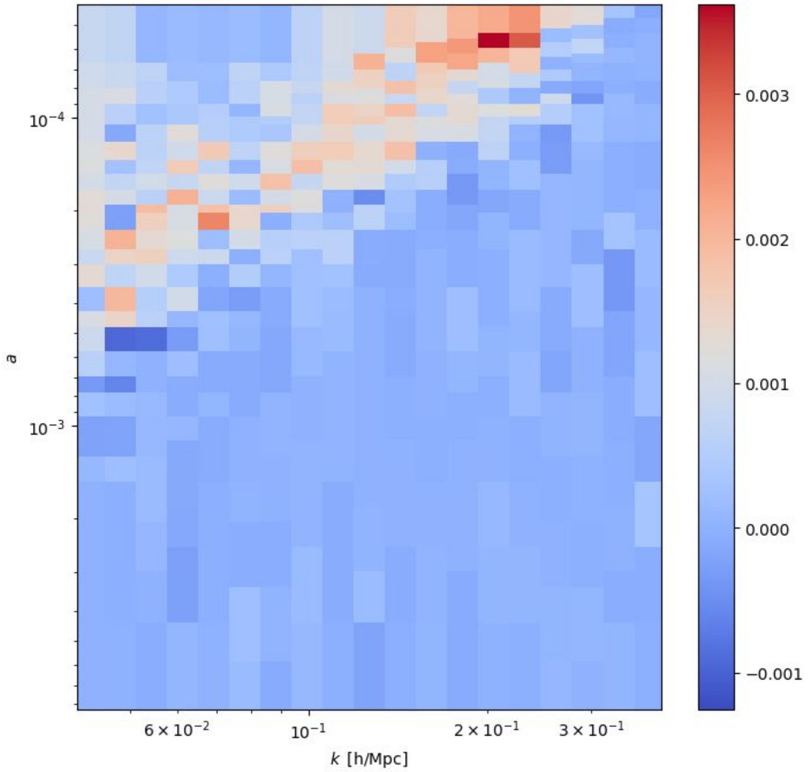
S/N versus PC index.

Signal/Noise Formula: $\Delta C_i = \frac{1}{\sqrt{\lambda_i}}$ $\quad C_i' = \frac{C_i}{\Delta C_i} = \frac{C_i}{\sqrt{\lambda_i}}$

Interesting Test



Coarsified sound speed for WZDR model.



Rebuild sound speed from PCs.

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Conclusion and Reference

Conclusion and Future Work

- Build a good understanding on WZDR
- Finish up the PCA coding
- Refine our understanding to CEDE
- Constrain the GDM by using equation of state and sound speed, and obtain constraints of models by using CMB data

We could finally get our method tested and could generalized to more models!

References and Acknowledgements

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