Model-independent Probes of Dark Sector Physics

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Introduction

Hubble Tension:
- The difference for **Hubble constant** measurement;
- Remained at a level ranging from $\mathbf{4-6\sigma}$ [2];
- The standard dark matter model: **Λ-CDM model**
- Cosmologists are exploring new models;

Model-independent Approach:
- Studied **Wess-Zumino Dark Radiation (WZDR) Model** and **Chameleon Early Dark Energy (CEDE) Model** as a benchmark;
- Tested the models using the **generalized dark matter (GDM) methods** [3] and **principal component analysis (PCA)**;
- Studied the **equation of state (w)** and the **effective sound speed ($c^2_{d,\mathrm{eff}}$)** to describe **GDM fluids**;
- The **dark matter fluid** includes elements only interact with photons and baryons through **gravitational interactions**;
- PCA reduces the dimensionality of high-dimensional data to a small number of dominant templates, known as **principal components (PCs)**;
- New models represented by **linear combinations** of PCs.

Methods

- Described the system with 3 **equations of motion**.
- Found the equation of state by definition: $w_d = \frac{P_d}{\rho_d}$.
- Obtained the expression of effective sound speed based on the definition of the sound speed: $c_d^2(k,a) = \frac{\delta P_d}{\delta \rho_d}$.
- Programmed these equations and other basic parameters of the universe in **CLASS code** [6];
- Projected the effective sound speed onto the **PCs**;
- Applied **cosmic microwave background (CMB)** data to this method to obtain **constraints** of these models.

WZDR Model Description

- In **Λ-CDM**, the **cold dark matter (CDM)** and **neutrinos** form the dark fluid;
- **WZDR model** assumes the existence of two additional dark species: one is **massless (ϕ)** and the other is **massive (ξ)** [7];
- 3 major phases:
  1. Thermal and chemical **equilibrium**;
  2. The universe expands and the temperature drops. ξ decays to ϕ becomes dominant. This happens at the **transition redshift (z_t)**.
  3. ξ becomes negligible, and ϕ becomes **dominant**.
- Reduces Hubble tension to around $\mathbf{2.7\sigma}$ [1].

Outputs

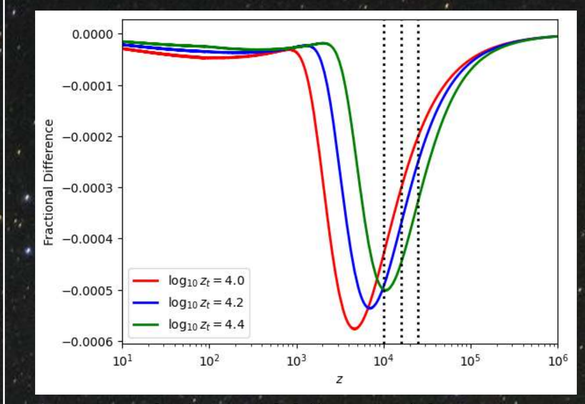

Figure 1: The fractional difference of the equation of state between various z_t.

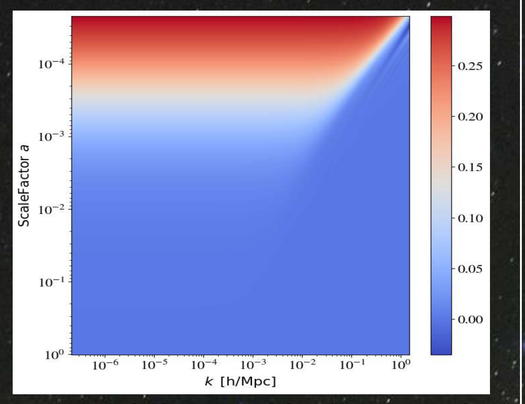

Figure 2: The heatmap of the effective sound speed of the WZDR model.

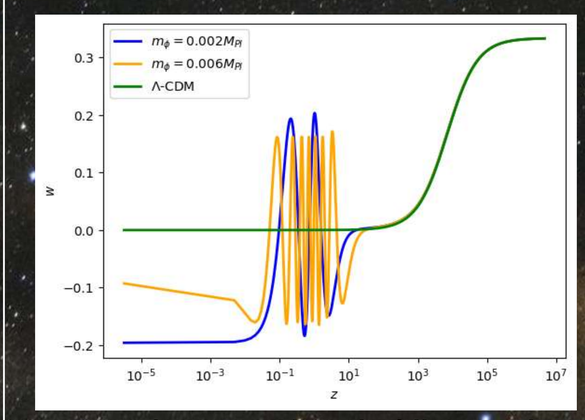

Figure 3: The equation of state for different m_ϕ for the CEDE model and the Λ-CDM model.

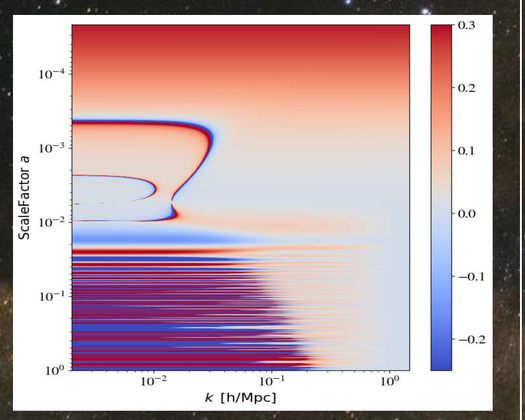

Figure 4: The heatmap of the effective sound speed of the CEDE model.

CEDE Model Description

- Added a **scalar field (ϕ)** with a mass (m_ϕ) to the early universe around **matter-radiation equality** [8];
- Conformally **coupled** with dark matter;
- **Diluted** in the later universe;

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Take Away!

- **Analyzed the dark matter models to ease Hubble tension;**
- **Used the generalized dark matter methods and principal component analysis.**

Analysis of Output

WZDR Model:
- For w, the transition happens around z_t;
- Relativistic to non-relativistic to relativistic;
- $c^2_{d,\mathrm{eff}}$ is similar to the Λ-CDM model;
- Has subtle difference at high k and low a.

CEDE Model:
- For w, there are oscillatory structures differed from the Λ-CDM model;
- $c^2_{d,\mathrm{eff}}$ shows similar oscillatory structures like w.

Current Work and Next Step

- Generated PCs from the **Fisher Matrix** and **CMB perturbation theory**;
- Project $c^2_{d,\mathrm{eff}}$ onto the PCs;
- Plot the coefficients versus the PCs;
- Consider the effects of uncertainties to coefficients;
- Project real CMB data to obtain constraints to these models.

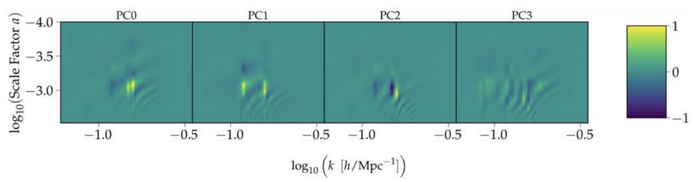

Figure 5: An example of generated PCs.

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