Perturbation Theory in Bulk Viscous Cosmology

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Contents

Why viscosity?

- Bulk viscosity has been proposed as a potential solution to cosmic tensions and has shown some promise
- Natural extension to the perfect fluid model
- Existence of dissipative processes in astrophysics and cosmology

Competing viscosity models

Eckart Theory

- Classical irreversible thermodynamics
- Transport equation for the viscosity:

$$\Pi = -\zeta\theta, \quad \text{with} \quad \theta = \nabla_\mu u^\mu \tag{1}$$

Müller-Israel-Stewart Theory

- Extensive irreversible thermodynamics
- Advantage: Causal theory → important for any physical theory
- Transport equation for viscosity:

$$\tau\dot{\Pi} + \Pi = -\zeta\theta - \frac{\epsilon}{2}\Pi\tau\left(\theta + \frac{\dot{\tau}}{\tau} + \frac{\dot{T}}{T} + \frac{\dot{\zeta}}{\zeta}\right) \tag{2}$$

- in truncated form:

$$\tau\dot{\Pi} + \Pi = -\zeta\theta \tag{3}$$

Basics of perturbation theory

- Perturb the Einstein equations: $\delta G_{\mu\nu} = \delta T_{\mu\nu}$
- $(P, \rho, \Pi, \Phi) \rightarrow (P + \delta P, \rho + \delta\rho, \Pi + \delta\Pi, \Phi + \delta\Phi)$
- Set of differential equations that describe the evolution of matter and gravity perturbations
- Can be done in Newtonian framework and in the full relativistic theory

Exploring the parameter space I

Parameters in question

The relevant set of parameters:

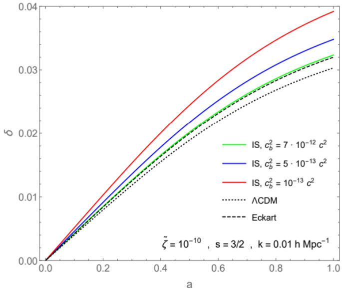
$$\text{Viscosity coefficient: } \zeta = \zeta_0 \left(\frac{\rho}{\rho_0}\right)^s, \zeta_0 = \frac{H_0}{24\pi G}\tilde{\zeta} \tag{4a}$$

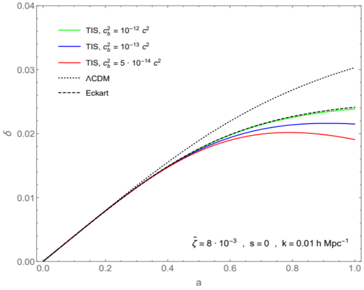
$$\text{viscosity index: } s \tag{4b}$$

$$\text{relaxation time: } c_b^2 = \frac{\zeta}{(\rho + p)\,\tau} \tag{4c}$$

Exploring the parameter space II

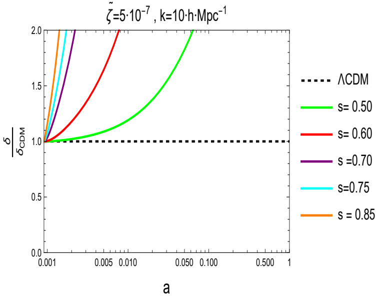
- Results from Acquaviva *et al* has shown some interesting results.
- Certain parameters lead to enhanced growth of perturbations.

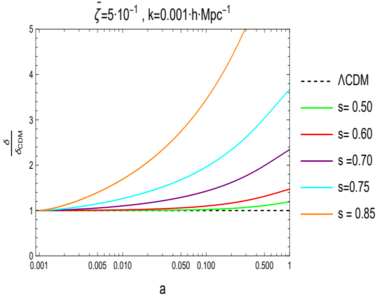




Exploring the parameter space III

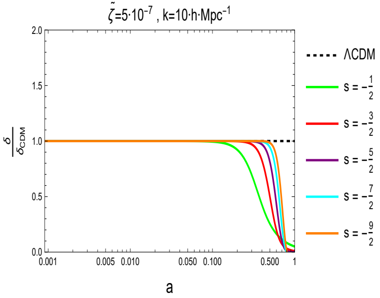
- We test the sensitivity with regards to the positive s values on different scales.

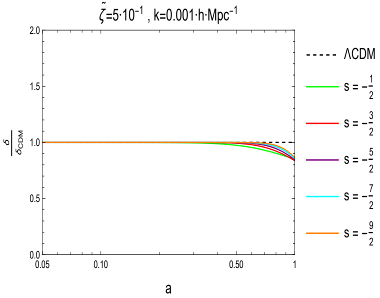




Exploring the parameter space IV

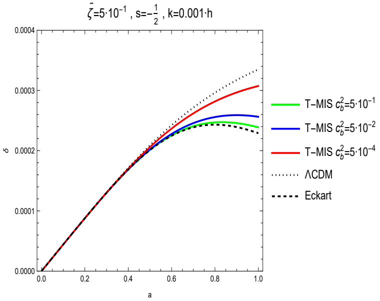
- One can do the same for the negative s values.

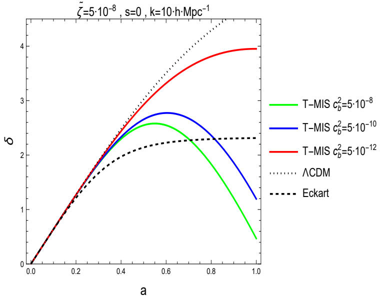




Exploring the parameter space V

- TMIS theory seems to lie somewhere in between ΛCDM and Eckart.





Conclusion and future work

- Conclusion:
  - Introduction of viscosity has observable changes to the evolution of matter perturbations.
  - Perturbations are sensitive to certain choices of parameters.
- Future work:
  - Introduce the full MIS theory into governing equations for both matter and metric perturbations
  - Computational work which will allow for testing of theories.

Thank you

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