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Viscous Self-Interacting Dark Matter and Accelerated Expansion of the Universe

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Energy budget of the Universe

- Observations show that we see only 4.9% of the Universe, and the rest of the 95.1% is invisible.
- Dark sectors: dark matter and dark energy.
- We do not know the nature of dark matter and dark energy.
- It is natural to ask a question whether the two dark sectors are related or not?

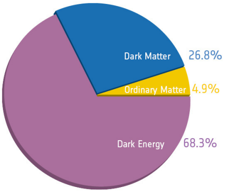


Figure: Energy budget (ESA/Planck)

The motivation of viscous cosmology

- In the standard cosmological description, the cosmic fluid is considered perfect, but since Universe is made from real fluids, one should consider the dissipative processes into account.
- In a homogeneous and isotropic background, directional dissipative process (shear and heat conduction) cannot play a significant role in the cosmic expansion.
- However, at the late time when structures become non-linear and inhomogeneous at a small scale, the shear viscosity may also play an important role in cosmic evolution.
  Weidemann et al. 2015

- In the presence of the cosmic bulk viscosity and using the FLRW metric, the Freedman equations become

$$H^2 = \frac{8\pi G}{3}\rho \quad \text{and} \quad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left[\rho + 3(P - 3\zeta H)\right] \qquad (1)$$

- A cosmic fluid with large bulk viscosity can lead to early time and late cosmic acceleration.
  Padmanabhan and chitre (1987), Cheng (1991), Febris et al. (2006)
- The DM viscous energy dissipation may lead to photon generation, which can explain the reported EDGES anomaly.
  A. K. Mishra (JCAP 05 (2020) 034)
- The viscous DM can ameliorate the tension between the Planck and local measurements. Anand et al. 2017.

Self-interacting dark matter (SIDM)

- The collisionless cold dark matter (CCDM) explain the large scale structure very well, but it faces the problems like core cusp problem, missing satellite problem, etc. on a small scale. S. Tulin and Yu (2018)
- SIDM may provide a consistent solution to the small scale issues faced with the CCDM. Spergel and Steinhardt (2000)
- At small scales, the DM density is large, and thus the scattering rate is non-zero, and SIDM behaves like the interacting particles.
- At large scales, the DM density is low; thus, the scattering rate goes to zero, and SIDM behaves like the non-interacting particles.

Mean free path and validity of the fluid approximation

In the dilute gas approximation, the mean free path of the SIDM particle is given by

$$\lambda_{\rm SIDM} \sim 3 \times 10^9 \left(\frac{m/\sigma}{\rm gm/cm^2}\right)\left(\frac{\rm M_\odot kpc^{-3}}{\rho}\right) \quad {\rm kpc}\ . \qquad (2)$$

- For dwarf galaxies, $\sigma/m = 1$ cm^2/g and $\rho \sim 10^8$ M$_\odot$kpc^{-3}, so $\lambda_{\rm SIDM} \sim 15$ kpc, but the typical sizes are smaller than 10 kpc.
- For cluster scale, $\sigma/m = 0.1$ cm^2/g and $\rho \sim 2 \times 10^7 {\rm M_\odot kpc^{-3}}$, $\lambda_{\rm SIDM} \sim$ Mpc, which is order of the typical cluster scale.
- It implies that the cluster scale is the smallest scale to apply the fluid picture of the SIDM particles.

Oh et. al. 2011, Tulin et al.(2016), Kaplinghat et. al. 2015, Newman et. al. 2012

Viscous self interacting dark matter (VSIDM)

- The self-interaction between the dark matter thermalizes the inner region of the halo. The momentum transfer between the fluid elements may lead to viscous effects.
- We calculate the viscous coefficients of SIDM from the kinetic theory using the relaxation time approximation.
- Using the Maxwellian distribution in the non-relativistic limit of the dark matter particles, the shear and bulk viscosity are obtained as

$$\eta = \frac{m}{\langle \sigma v \rangle}\left(\frac{T}{m}\right) , \tag{3}$$

$$\zeta = \frac{m}{\langle \sigma v \rangle}\frac{T}{m}\left[\frac{5}{3}\left(1+\frac{9}{4}C_n^4\right) - 2C_n^2\left(1-\frac{3}{2}C_n^2\right)\left(\frac{m}{T}\right) + C_n^4\left(\frac{m}{T}\right)^2\right] \tag{4}$$

A. Atreya, J. R. Bhatt, **A. K. Mishra**, JCAP 02(2018),024

Effect of the DM viscosity on the cosmic evolution

- For the viscous DM, the deceleration parameter evolve as

$$-\frac{dq}{d\ln a} + (q-1)\left(2q - (1+3\hat{w}_{\rm eff})\right) = \frac{4\pi G D}{3H^3}(1-3\hat{w}_{\rm eff}) \quad (5)$$

$$D = \frac{1}{a^2}\langle \eta[\partial_i v_j \partial_i v_j + \partial_i v_j \partial_j v_i - \tfrac{2}{3}\partial_i v_i \partial_j v_j]\rangle_s + \frac{1}{a^2}\langle \zeta[\vec{\nabla}.\vec{v}]^2\rangle_s + \frac{1}{a}\langle \vec{v}\cdot\vec{\nabla}(P - 6\zeta H)\rangle_s .$$

where, $\langle P\rangle_s + \langle \Pi_B\rangle_s = \hat{w}_{\rm eff}\ \langle \rho_{\rm SIDM}\rangle_s$

- Assuming $|dq/d\ln a| \ll 1$ and $\hat{w}_{\rm eff} = 0$, the present accelerated expansion of the Universe ($q \approx -0.6$) requires

$$\frac{4\pi G D}{3H^3} \approx 3.5 \quad (6)$$

Weidemann et al. 2015

Estimation of dissipation term

- A lower limit of the spatial average is defined on the scale from which the DM fluid description starts, i.e., 3 Mpc and the upper scale is considered to homogeneity scale, i.e.,$\sim$ 100 Mpc.
- We assume that η, ζ are do not vary over the spatial region, therefore we assume i.e, $\langle\eta\rangle_s = \eta$ and $\langle\zeta\rangle_s = \zeta$.
- We assume, $\hat{w}_{\mathrm{eff}} = 0$.
- We replace the spatial averages of the velocity gradient by its average value between the fluid element scale to homogeneity scale. Therefore we approximate $\langle\vec{\nabla}\cdot\vec{v}\rangle_s \sim v_0/L$.

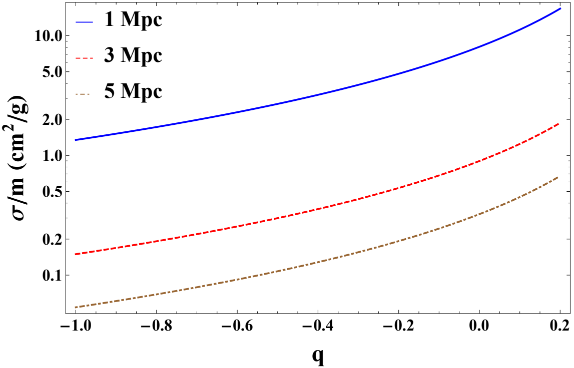
Properties of the dissipation term

Using the above approximations, we get

$$D = (1+z)^2 \left(\frac{v_0}{L}\right)^2 \left[\frac{4}{3}\eta + 2\zeta\right] \tag{7}$$

- The contribution from the smaller scale (where the Universe is inhomogeneous) is large, whereas the contribution from the larger scale (where Universe is more or less homogeneous) is small.
- For very large averaging length scale or vanishing bulk and shear viscosity ($\eta = \zeta = 0$), D term vanishes and the VSIDM fluid behaves like a dissipationless fluid.

VSIDM and present cosmic acceleration



- The present cosmic acceleration, i.e., $q \approx -0.6$ requires $\sigma/m \approx 0.1$ cm^2/g. The same constraint on SIDM parameter is also reported from cluster scale observations. Tulin et al.(2016)
- It suggests that SIDM viscosity may account for the current accelerated expansion of the Universe.

VSIDM cosmology at low redshift

- We assume that on a low redshift interval ($0 \leq z \leq 2.5$), the peculiar velocity gradient varies like a power-law form

$$\langle \partial v \rangle_s \sim \frac{v_0}{L} \left(\frac{1}{1+z} \right)^n \ . \tag{8}$$

- The evolution equation for deceleration parameter is given by

$$\frac{dq}{dz} + \frac{(q-1)(2q-1)}{(1+z)} = \beta \left(\frac{1+z}{\bar{H}^3} \right) \ , \tag{9}$$

$$\text{where,} \quad \beta = \frac{4\pi G}{3H_0^3} \left(\frac{4}{3}\eta + 2\zeta \right) \left(\frac{v_0}{L(1+z)^n} \right) . \tag{10}$$

- The evolution of the Hubble rate is given as

$$\frac{d\bar{H}}{dz} = \frac{(q+1)}{(1+z)} \bar{H}, \quad \text{where} \quad \bar{H} = \frac{H}{H_0} . \tag{11}$$

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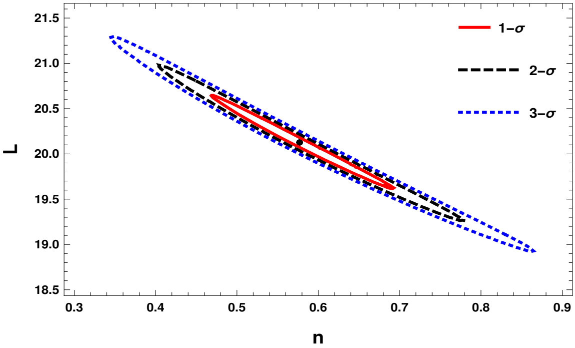
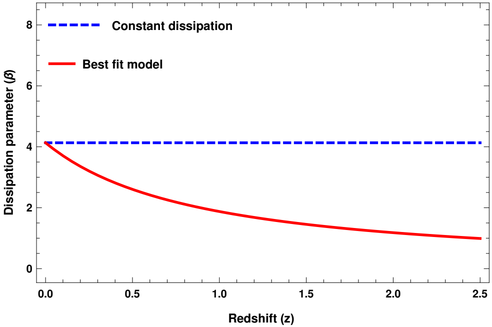
Constraining the model parameters of VSIDM

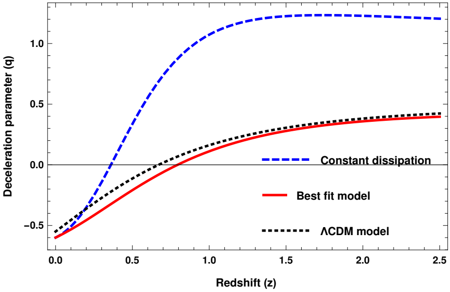


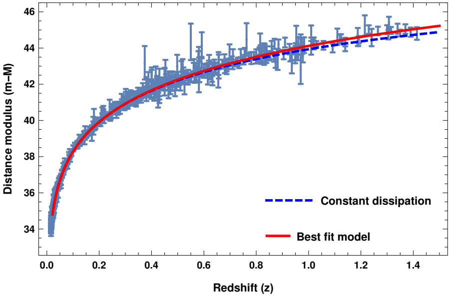
- Using χ^2 analysis, we obtain the best fit values of the viscosity parameters, $n = 0.57$ and $L = 20.12$ Mpc.

Evolution of the dissipation parameter



- The viscous dissipation is small at an earlier time (at high redshift) and increases at the late time (at low redshift).





- The decreasing viscous dissipation at an earlier time explains the low redshift data, but the constant dissipation fails to do so.

Summary and conclusion

- The self-interacting dark matter viscosity is strong enough to explain the late-time cosmic acceleration.
- If the viscous dissipation becomes prominent at the late time of cosmic evolution and decreases early, it can also explain the low redshift observations.
- However in order to study the effect of SIDM viscosity on the cosmological scale, one needs to consider the realistic model for the viscosities and velocities.

Thank You