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Viscous dark matter cosmology

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Motivation

- In the standard cosmological description, the DM fluid is considered as perfect but the deviation from the perfect fluid can lead to some interesting consequences.
- It has been argued that the viscous cosmic fluid can lead to early time and late time cosmic acceleration.
  Padmanabhan and Chitre (1987), Cheng (1991), Fabris et. al. (2006)
- Viscous dark matter can reduce the tension between the Planck and local measurements of the Hubble expansion rate.
  Anand et. al. (2017).

Self-interacting dark matter (SIDM)

- The collision-less cold dark matter explain the large scale structure but fails to explain the small scale problems such as the core cusp problem, missing satellite problems etc.
- The problem can be explained by considering the baryonic physics or the DM physics.
- The SIDM may be a possible solution. At small scales, the DM density is large and thus the scattering rate is non-zero.
- At large scales the DM density is low thus the scattering rate goes to zero and SIDM behaves like the non-interacting cold dark matter.

Viscous self interacting dark matter (VSIDM)

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

$$\zeta = \frac{5.9}{9}\left(\frac{m\langle v\rangle^2}{\langle \sigma v\rangle}\right) \quad \text{and} \quad \eta = \frac{1.18}{3}\left(\frac{m\langle v\rangle^2}{\langle \sigma v\rangle}\right) \quad , \tag{1}$$

where $\langle \mathrm{A}\rangle$ represents the thermal average of A.

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Accelerating cosmological expansion from cosmic viscosity

- For viscous DM the deceleration parameter evolve as

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

where, $D=\frac{1}{a^2}\langle\eta[\partial_i v_j\partial_i v_j+\partial_i v_j\partial_j v_i-\frac{2}{3}\partial_i v_i\partial_j v_j]\rangle\rangle+\ \frac{1}{a^2}\langle\zeta[\vec{\nabla}.\vec{v}]^2\rangle$

$$+\ \frac{1}{a}\langle\vec{v}\cdot\vec{\nabla}(p-6\zeta H)\rangle.$$

Here the effective equation of state is related to the total pressure as $\langle P\rangle+\langle\Pi_B\rangle=\hat{w}_{\rm eff}\ \langle\rho_{\rm SIDM}\rangle$.

- Assuming today $\left|\frac{dq}{d\ln a}\right|\ll 1$ and $\hat{w}_{\rm eff}=0$, the above equation simplifies as

$$(q-1)(2q-1)=\frac{4\pi GD}{3H^3} \quad (3)$$

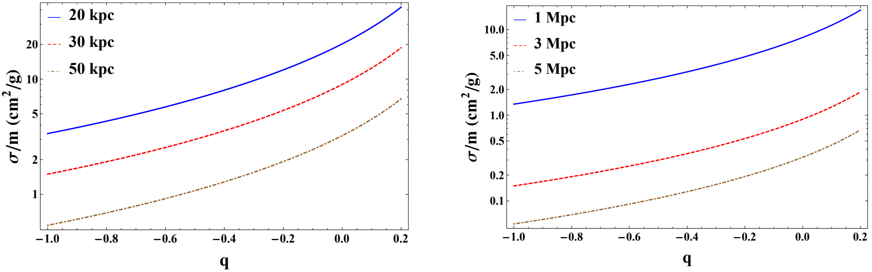
Weidemann et al. PRL 114, 091301 (2015)

Calculation of D

- We assume η, ζ do not vary over the spatial region of our interest.
- Assume $\partial_i \sim 1/L$, where L is scale over which the spatial averaging has to be done.
- We also assume DM is cold, i.e. $\hat{w}_{\text{eff}} = 0$.
- Using the above assumptions, we obtain D term at present, $z = 0$ as

$$D = \frac{16.32\langle v\rangle^4}{9}\left(\frac{m}{\langle\sigma v\rangle}\right)\left(\frac{1}{L}\right)^2. \qquad (4)$$

Viscous SIDM and Cosmic Acceleration



- The plot suggest that the accelerated expansion may be possible at both the galactic and cluster scale.
- But the mean free path calculation suggest that for SIDM particles, the hydrodynamic description will be valid from cluster to larger scale.

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VSIDM cosmology at low redshift

- Assuming the cluster to be virialized at $z \sim 2.5$ and peculiar velocity varying like power law form as

$$\langle \partial v \rangle_s \sim \frac{v_0}{L} \left(\frac{1}{1+z} \right)^n \,, \tag{5}$$

the evolution equation for deceleration parameter is given by

$$\frac{dq}{dz} + \frac{(q-1)(2q-1)}{(1+z)} = \beta \left(\frac{1+z}{\bar{H}^3} \right) . \tag{6}$$

Here, $\bar{H} = H/H_0$ and the dissipation parameter is defined as

$$\beta = \frac{4\pi G}{3H_0^3} \left(\frac{4}{3}\eta + 2\zeta \right) \left(\frac{v_0}{L(1+z)^n} \right) . \tag{7}$$

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Contraining the model parameters of VSIDM

- The evolution of the Hubble rate is given as

$$\frac{d\bar{H}}{dz} = \frac{(q+1)}{(1+z)}\ \bar{H}. \tag{8}$$

- The Hubble expansion rate and deceleration parameter are obtained by solving the coupled differential equations (6) and (8).
- Using χ^2 analysis, we obtain the best fit values of the viscosity parameters, $n = 0.57$ and $L = 20.12$ Mpc.

Results

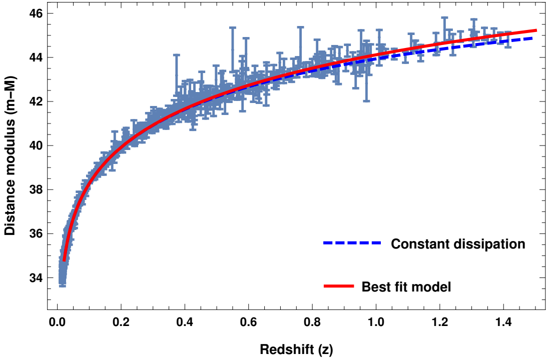
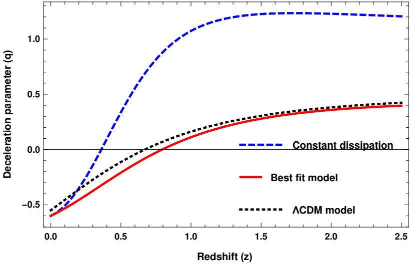
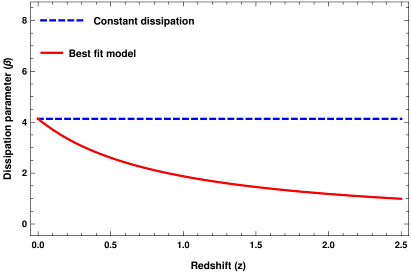


Figure: VSIDM model fit the supernovae data well.





- The viscous dissipation is small at earlier time (at large redshift) and increases at late time (at large redshift).
- The decreasing viscous dissipation at earlier time explain the low redshift data well but the constant dissipation fails to do so.

Viscous dark matter cosmology

- Here we will study the effect of the DM viscosity in redshift interval, $15 \leq z \leq 1300$.
- We consider a power law form of the DM bulk viscosity as (Velten et. al. 2013)

$$\zeta_\chi(z) = \zeta_0 \left(\frac{\rho_\chi(z)}{\rho_\chi(0)} \right)^\alpha \quad . \tag{9}$$

- The heat energy density per unit time dissipated by the viscous DM is given by (S. Weinberg, 1972)

$$\frac{dQ_{\rm v}}{dVdt} = 9\zeta H^2. \tag{10}$$

DM temperature in presence of the viscosity

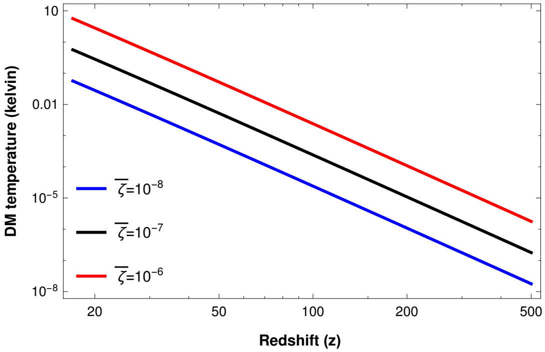
- In presence of the viscosity the DM temperature evolves as

$$T_\chi(z) = A(1+z)^2 - \frac{4.2}{24\pi} \left(\frac{H_0^2 \; m_{\rm Pl}^2}{\rho_c}\right) \left(\frac{m_\chi \; \bar{\zeta}}{\alpha - 1.16}\right) \left[1+z\right]^{3(\alpha - \frac{1}{2})} \quad , \tag{11}$$

  where $\bar{\zeta} = \frac{24\pi G \zeta_0}{H_0}$ is dimensionless viscosity parameter.

- To evaluate the constant of integration A, we consider the initial condition at $z = 1300$ such that $T_\chi(1300) = 0$.

Arvind Kumar Mishra, arXiv:1907:04238



- Viscous DM temperature increases as its viscosity increases.
- The viscosity becomes important for late time of cosmic evolution.

Viscous energy dissipation and photon production

- We assume that the Viscous DM dissipates in the dark radiation (DR), which are in thermal equilibrium with the DM.
- The DR can further convert into the photons via a kinetic mixing.

$$\mathcal{L}_{\mathcal{A}'\mathcal{A}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu} \quad . \tag{12}$$

- Thus the number density of the photon produced via viscous dissipation is given as

$$\frac{dn_{A'\to A}}{d\omega} = \frac{dn_{A'}}{d\omega}\ P_{A'\to A} \tag{13}$$

- In the small frequency limit, i.e. $\omega = \omega_{\rm max}$, the number of the photons generated via viscous dissipation, $n_{A' \to A}$

$$= \frac{\epsilon^2 m_{A'}^2 T_\chi}{\pi} \left[\sqrt{\omega_{\rm max}^2 - m_{A'}^2} + m_{A'} \tan^{-1} \left(\frac{m_{A'}}{\sqrt{\omega_{\rm max}^2 - m_{A'}^2}} \right) - \frac{\pi m_{A'}}{2} \right]$$

$$\times \left| (1+z)\, H(z)\, \frac{dm_A^2}{dz} \right|^{-1}_{z=z_{res}} \tag{14}$$

Arvind Kumar Mishra, arXiv:1907:04238

21-cm signal and EDGES anomaly

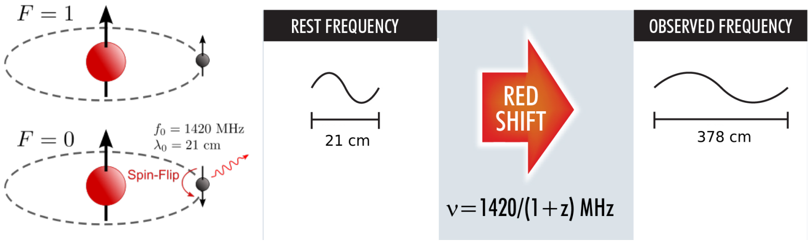
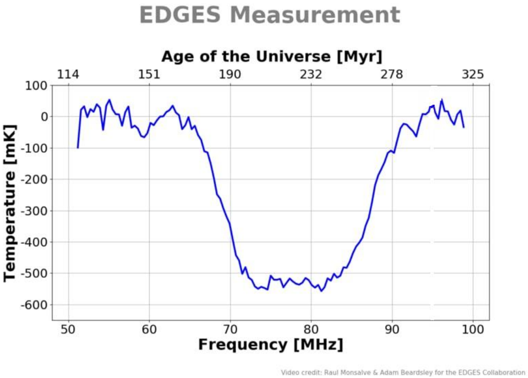


Figure: 21 cm signal

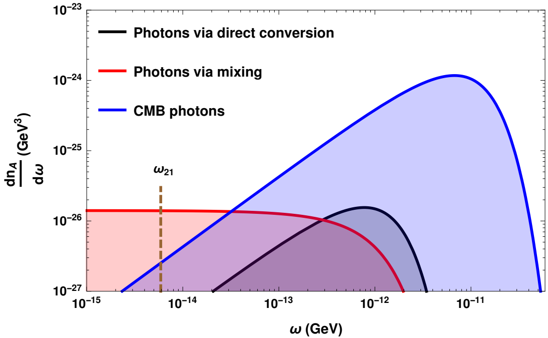
The useful quantity for the 21-cm observation is the differential brightness temperature, T_{21}.



The EDGES observation gives $T_{21}^{EDGES} \approx -500^{+200}_{-500}$ mK but the standard cosmology predicts $T_{21}^{S}(17) \simeq -209$ mK .

Nature **555**, no. 7694, 67 (2018).

Viscous Dissipation into photons explain EDGES Anomaly



- The photons obtained from the viscous dissipation populate the low energy CMB photons, hence it can explain the EDGES anomaly.

Arvind Kumar Mishra, arXiv:1907:04238

Summary

- We find that the self interacting dark matter viscosity is strong enough to explain the late time cosmic acceleration.
- If the viscous dissipation becomes prominent at late time of cosmic evolution, it can also explain the low redshift observations.
- The viscosity in DM fluid can increase its temperature via viscous energy dissipation.
- We argue that viscous dissipation may lead to photon production. These photons can increase the low energy photons of CMB radiation and can explain the EDGES anomaly.

Thank you