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Impact of dynamical radiation–matter interaction on the interacting Barrow holographic dark energy model

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Gopinath Guin, Souvik Paul, Sunandan Gangopadhyay
Email: gopinath.guin@bose.res.in, souvik.paul@bose.res.in, sunandan.gangopadhyay@bose.res.in
Department of Astrophysics and High Energy Physics
S. N. Bose National Centre for Basic Sciences

INTRODUCTION & AIM

- Observations have revealed that the Universe is undergoing accelerated expansion, which led to the introduction of dark energy to explain this phenomenon. Interactions between two or more components of the Universe are possible, and in this work, we also consider the presence of radiation, as its density can influence such interactions.
- Having roughness in the horizon can affect the form of the dark energy and that leads to changes in the dynamics of the universe. In this work we have considered such roughness and have constrained the parameter value for different model.
- We have considered the dependency of the interaction on several types of matter component and have constrained the model parameters and fitted them using more than one dataset.

METHOD

- Barrow Entropy for a black hole with fractal and intricate structure is given as

$$S_B = \left(\frac{A}{A_0}\right)^{1+\frac{\Delta}{2}} . \qquad (1)$$

Where, $A_0 = 4l_p^2$, $0 \leq \Delta \leq 1$.

- From Cohen-Kaplan-Nelson bound, holographic dark energy has an inequality for a cosmic horizon L, $\rho_{de}L^4 \leq S$ and taking holographic dual of the cosmic horizon to blackhole horizon one has

$$\rho_{de}L^4 \sim L^{2+\Delta} \implies \rho_{de} = CL^{-2+\Delta} , \qquad (2)$$

C is a parameter of appropriate dimension. For $\Delta = 0$, $\rho_{de} = 3c^2M_P^2L^{-2}$, this is the standard form of dark energy.

- For a isotropic and homogeneous universe we have a unique metricnamely FLRW metric,

$$ds^2 = -dt^2 + a(t)^2\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega_2^2\right] \qquad (3)$$

- With the choice of perfect fluid's energy momentum tensor $T_{\mu\nu} = (p + \rho)u_\mu u_\nu + pg_{\mu\nu}$ one has from the Einstein equations($G_{\mu\nu} = 8\pi G T_{\mu\nu}$) two independent Friedmann equations

$$3H^2 + \frac{3k}{a^2} = \frac{\rho}{M_P^2}$$
$$\frac{\ddot{a}}{a} = -\frac{1}{6M_P^2}(3p+\rho) \qquad (4)$$

- On the other hand, the divergence free of the $T_{\mu\nu}$ gives,

$$\nabla_\mu T^{\mu\nu}_{\text{Total}} = \nabla_\mu \sum_i T_i^{\mu\nu} = 0 \qquad (5)$$
$$\implies \dot{\rho}_i + 3H(\rho_i + p_i) = \mathcal{Q}_i , \qquad (6)$$

with $\sum_i \mathcal{Q}_i = 0$ and $i \in \{r, m, de\}$

Our Model: Interaction depends on radiation density

- Among various possibilities if we consider the interaction proportional to radiation density only, then defining, $\mathcal{Q}_m = \Gamma r_2 H\rho_{de}$ and $\mathcal{Q}_r = \Gamma\alpha\, r_2 H\rho_{de}$ we get three equations from (6), as

$$\dot{\rho}_m + 3H\rho_m = \mathcal{Q}_m = -\Gamma H\rho_r , \quad \dot{\rho}_r + 3H(\rho_r + p_r) = \mathcal{Q}_r = -\Gamma\alpha H\rho_r , \qquad (7)$$
$$\dot{\rho}_{de} + 3H(\rho_{de} + p_{de}) = \mathcal{Q}_{de} = \Gamma(1+\alpha)\rho_r$$

- Time is not a good measure in cosmology rather scale factor is so if we define a new variable $x = \ln a$, then shifting from time derivative to x derivative and after little bit of calculation we got three coupled differential equation with the definition $y = R_h/a(t)$, R_h is future event horizon.

$$\frac{\Omega'_{de}}{\Omega_{de}(1-\Omega_{de})} = (\Delta - 2)\left(1 - \sqrt{\frac{3M_p^2\Omega_{de}}{C}}L^{\frac{-\Delta}{2}}\cos y\right) - \frac{1}{(1-\Omega_{de})}\left[2(\Omega_{de}+\Omega_m+\Omega_r-1) - \Omega_m(\Gamma\frac{r_2}{r_1}+3) - \Omega_r(\Gamma\alpha+4)\right] \qquad (8)$$

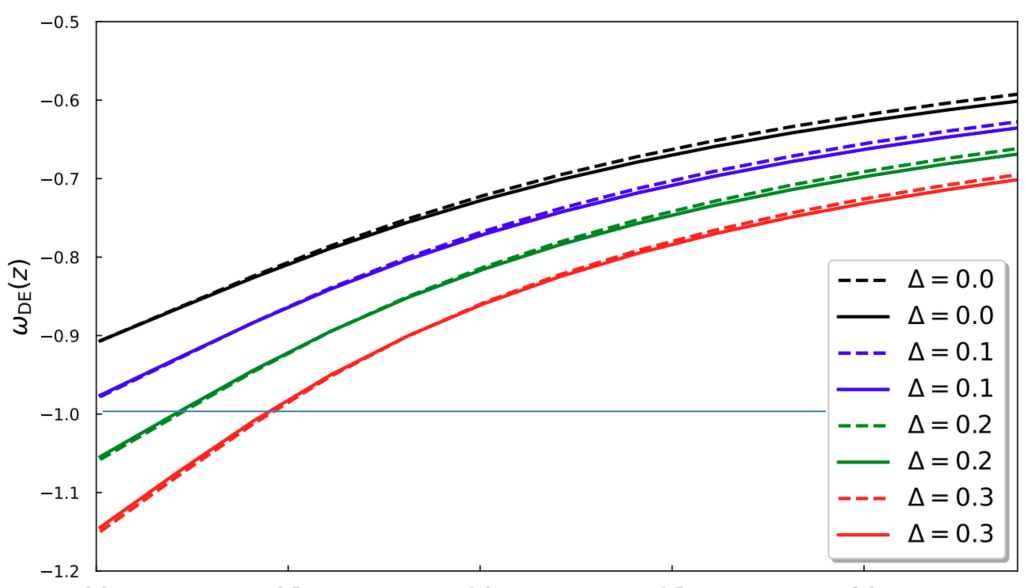
$$\frac{\Omega'_m}{\Omega_m} = -\left(\Gamma\frac{r_2}{r_1}+3\right) - (\Delta-2)\left(1 - \sqrt{\frac{3M_p^2\Omega_{de}}{C}}L^{\frac{-\Delta}{2}}\cos y\right)\Omega_{de} - \left[2(\Omega_{de}+\Omega_m+\Omega_r-1) - \Omega_m\left(\Gamma\frac{r_2}{r_1}+3\right) - \Omega_r(\Gamma\alpha+4)\right] \qquad (9)$$

$$\frac{\Omega'_r}{\Omega_r} = -\left(\Gamma\alpha+4\right) - (\Delta-2)\left(1 - \sqrt{\frac{3M_p^2\Omega_{de}}{C}}L^{\frac{-\Delta}{2}}\cos y\right)\Omega_{de} - \left[2(\Omega_{de}+\Omega_m+\Omega_r-1) - \Omega_m\left(\Gamma\frac{r_2}{r_1}+3\right) - \Omega_r(\Gamma\alpha+4)\right] \qquad (10)$$

Also we got the equation of state for dark energy

$$\omega_{de} = \frac{\Gamma(1+\alpha)r_2}{3} - \left(\frac{\Delta+1}{3}\right) + \left(\frac{\Delta-2}{3}\right)cosy\sqrt{\frac{3M_p^2\Omega_{de}}{C}}L^{\frac{-\Delta}{2}}$$

RESULTS & DISCUSSION



ω_{de} vs z plot. $(\Omega_{de,0}, \Omega_{m,0}, \Omega_{r,0}, \Omega_{k,0}) = (0.75, 0.26, 10^{-4}, -0.0101)$ for the closed universe and $(0.73, 0.26, 10^{-4}, 0.0099)$ for the open universe, with $\Gamma = 10^{-4}$ and $\alpha = 10^{-1}$

Parameter	$k = +1$	$k = -1$
H_0	$70.8523^{+3.9370}_{-2.7438}$	$71.1084^{+2.6118}_{-2.0095}$
$\Omega_{m,0}$	$0.2674^{+0.0271}_{-0.0271}$	$0.2189^{+0.0232}_{-0.0234}$
$\Omega_{r,0}$	$1.49^{+1.00}_{-0.99} \times 10^{-4}$	$1.47^{+1.00}_{-1.00} \times 10^{-4}$
$\Omega_{k,0}$	$-6.09^{+3.63}_{-2.81} \times 10^{-3}$	$3.50^{+3.20}_{-2.77} \times 10^{-3}$
Γ	$0.2810^{+0.1519}_{-0.1489}$	$0.2029^{+0.1895}_{-0.1467}$
Δ	$0.1697^{+0.0967}_{-0.0742}$	$0.0697^{+0.0742}_{-0.0809}$
α	$0.6027^{+0.2890}_{-0.4233}$	$0.4189^{+0.3682}_{-0.3120}$

Best fit parameters after running MCMC for CC+BAO dataset.

Statistical comparison

Model	K	AIC	BIC	Δ AIC	Δ BIC
ΛCDM	+1	35.2321	45.3129	0.000	0.000
	−1	34.4625	44.6146	0.000	0.000
$Q = -\Gamma H\rho_r$	+1	36.2800	48.5383	1.0479	3.2254
	−1	36.2550	48.5133	1.7925	3.8987

CONCLUSION

Higher Barrow exponents drive dark energy into the phantom regime, consistent with MCMC results. Separate priors for open vs. closed universes were required to satisfy $\sum\Omega_i = 1$. Among tested interactions ($Q \propto \rho_m$, ρ_{de} , $\rho_{de} + \rho_m + \rho_r$), $Q \propto \rho_r$ best competes with ΛCDM.

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