Interacting dark energy with intricate horizon structure

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PANE 2026

18-21 November, 2026





Reference Article

Journal of Cosmology and Astroparticle Physics

PAPER

Barrow holographic dark energy interacting model in the presence of radiation and matter

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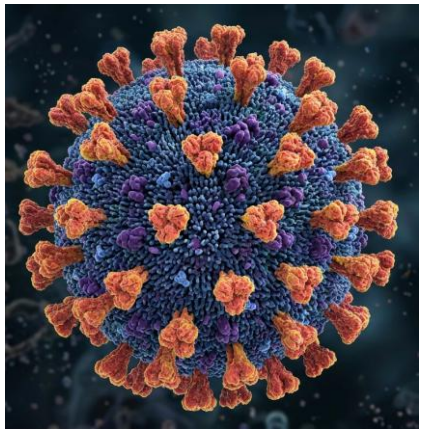
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Journal of Cosmology and Astroparticle Physics, Volume 2025, November 2025

Citation Gopinath Guin *et al* JCAP11(2025)048

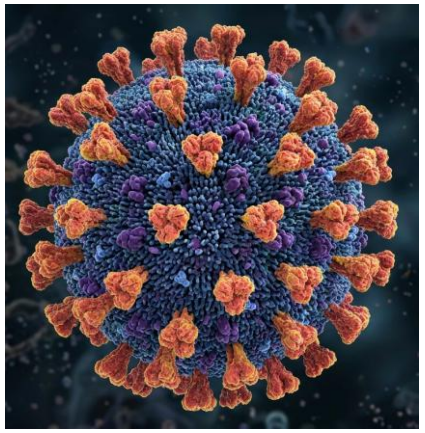
DOI 10.1088/1475-7516/2025/11/048

Covid-19



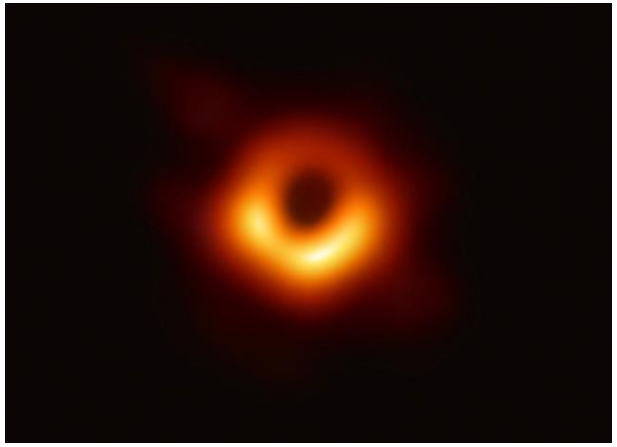
Credit: AI generation by Google Gemini

Covid-19



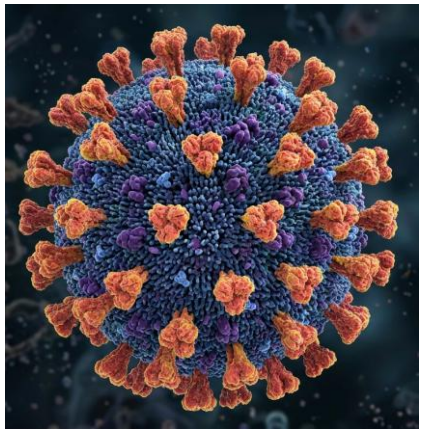
Credit: AI generation by Google Gemini

The first picture of a black hole.



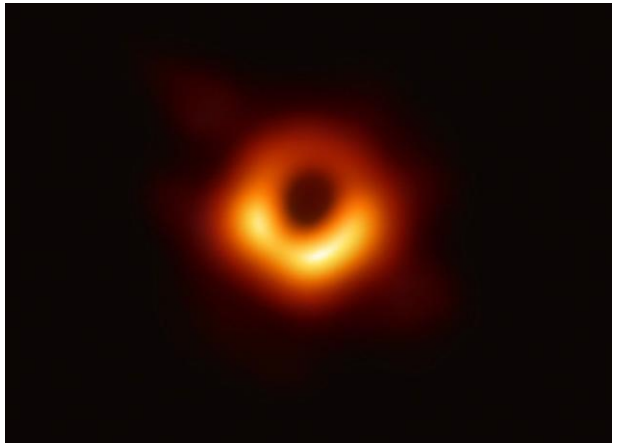
Credit: Event Horizon Telescope Collaboration

Covid-19



What if the boundary of a black hole were not perfectly smooth, but had a fractal-like structure?

The first picture of a black hole.



- The entropy for smooth (Horizon) black hole scales as $S = \frac{A}{4G} = \frac{A}{A_0} \propto L^2$
- If fractal-structure introduces then the scaling changes : $S \propto L^{2+\Delta}, \quad 0 \leq \Delta < 1,$ Δ measures the fractalness.
- Holographic dark energy follows an inequality: $\rho_{de} L^4 < S \Longrightarrow \rho_{\mathrm{de}} = C L^{-2+\Delta}, C = 3c^2 M_P^2$

Credit: AI generation by Google Gemini

Credit: Event Horizon Telescope Collaboration

Basics of Cosmology in a Slide

❖ **The FLRW Metric**

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

❖ **Perfect fluid stress energy tensor**

$$T_{\mu\nu} = (\rho + p)u_\mu u_\nu + p g_{\mu\nu}$$

❖ **Einstein Equation**

$$G_{\mu\nu} = \frac{1}{M_{Pl}^2} T_{\mu\nu}, \quad \text{where } \mu, \nu = t, r, \theta, \phi$$

❖ Friedmann Equations

$$3H^2 + \frac{3k}{a^2} = \frac{\rho}{M_P^2}$$

$$\Longrightarrow 3H^2 = \frac{1}{M_P^2}(\rho + \rho_k),\ \rho_k = -\frac{3kM_P^2}{a^2}$$

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

Here, $\mathrm{H} = \frac{\dot{\mathrm{a}}}{\mathrm{a}}$ is the Hubble parameter.

Defining, $\Omega_i \equiv \frac{\rho_i}{3H^2 M_p^2}$, we get

$$1 = \sum_j \Omega_j, \qquad j = de, m, r, k$$

Stress energy tensor is divergence free:

$$\nabla_\mu T^{\mu\nu}_{\text{total}} = 0 = \nabla_\mu \sum_i T_i^{\mu\nu}$$

$$\nabla_\mu T_i^{\mu\nu} = 0$$

$$\nabla_\mu T_i^{\mu\nu} = Q_i \quad \text{with} \quad \sum_i Q_i = 0$$

Introducing Interaction

What is the form of Q ?

$\nabla_\mu T_i^{\mu\nu} = Q_i$ can be written

$$\dot{\rho}_i + 3H\rho_i(1+\omega_i) = Q_i\,, \quad \omega_i \equiv \frac{p_i}{\rho_i}$$

Component-wise the above equation reads

$$\dot{\rho}_m + 3H\rho_m(1+\omega_m) = Q$$
$$\dot{\rho}_r + 3H\rho_r(1+\omega_m) = \alpha Q$$
$$\dot{\rho}_{de} + 3H\rho_{de}(1+\omega_{de}) = -(1+\alpha)Q$$

One can ask

We take a new form :

$$Q = -\Gamma H\rho_r = -\Gamma H r_2 \rho_{de}, \quad r_2 = \frac{\rho_r}{\rho_{de}}$$

Divergence of the EM tensor finally takes the form:

$$\dot{\rho}_m + 3H\rho_m = Q_m = -\Gamma H\, r_2\, \rho_{de},$$
$$\dot{\rho}_r + 3H(\rho_r + p_r) = Q_r = -\Gamma\alpha\, r_2 H\rho_{de},$$
$$\dot{\rho}_{de} + 3H\rho_{de}(1+\omega_{de}) = (1+\alpha)\Gamma r_2 H\rho_{de}$$

In cosmology time is not a direct observable rather scale factor is (through the redshift).
So, by introducing a new variable $x \equiv \ln a$, we get

Governing Equations

$$\frac{d}{dx}[\ln(\rho_{de})] = \frac{\rho_{\mathrm{de}}{}'}{\rho_{\mathrm{de}}} = \Gamma(1+\alpha)r_2 - 3(1+\omega_{de})$$

$$\frac{\rho_m{}'}{\rho_m} = -\left(3 + \frac{\Gamma}{r_1}\right), \quad r_1 \equiv \rho_m/\rho_{de}$$

$$\frac{\rho_r{}'}{\rho_r} = -\left(4 + \frac{\Gamma\alpha}{r_2}\right)$$

We have $$\frac{d}{dx}[\ln(\rho_{de})] = \frac{\rho_{\mathrm{de}}{}'}{\rho_{\mathrm{de}}} = \Gamma(1+\alpha)r_2 - 3(1+\omega_{de})$$

Using

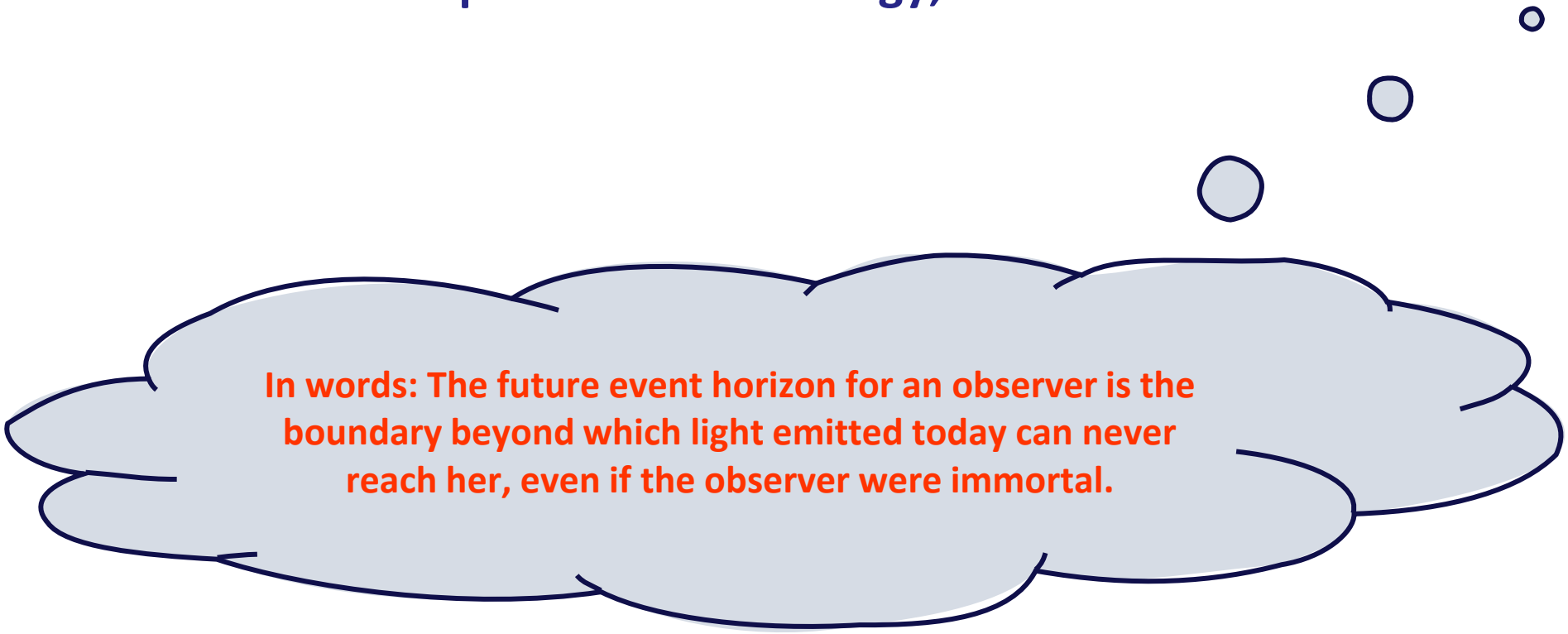
$$\rho_{de} = \Omega_{de}\frac{\rho_r + \rho_m + \rho_k}{\Omega_r + \Omega_m + \Omega_k} = \Omega_{de}\frac{\rho_r + \rho_m + \rho_k}{1 - \Omega_{de}}$$

We can write

$$\frac{d}{dx}\ln(\rho_{de}) = \frac{\Omega_{de}{}'}{\Omega_{de}(1-\Omega_{de})} + \frac{1}{\rho_m+\rho_r+\rho_k}(\rho_m{}' + \rho_r{}' - 2\rho_k) = \Gamma(1+\alpha)r_2 - 3(1+\omega_{de})$$

Cosmic horizon

There are several horizons present in cosmology; here we choose the future event horizon.



Cosmic horizon

There are several horizons present in cosmology; here we choose the future event horizon.

Definition of future event horizon:

$$R_h \equiv a(t)\int_t^\infty \frac{d\tau}{a(\tau)} = a(t)\int_0^{r_h} \frac{d\tilde{r}}{\sqrt{1-\tilde{r}^2}} = a(t)\sin^{-1}(r_h)$$

Again, we can write

$$R_h \equiv a(t)\int_t^\infty \frac{d\tau}{a(\tau)} = \int_{a(t)}^\infty \frac{d\tilde{a}}{\tilde{a}^2 H} = \int_x^\infty \frac{d\tilde{x}}{a(\tilde{x})H(\tilde{x})}$$

Comoving horizon radius: $r_h = \sin\left(\frac{R_h}{a(t)}\right) = sin(y)$

Areal length: $L = ar_h = a\sin(y)$

$$\Rightarrow \dot{L} = \dot{a}\sin(y) + a\dot{y}\cos(y)$$

$$\Rightarrow \frac{\dot{L}}{L} = H\left(1 - \frac{\cos(y)}{HL}\right)$$

$$\rho_{de} = CL^{\Delta-2}$$

$$\dot{\rho}_{de} = \rho_{de}(\Delta-2)\frac{\dot{L}}{L} = (\Delta-2)H\rho_{de}\left(1-\frac{\cos(y)}{HL}\right)$$

Inserting this in the continuity equation we have

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

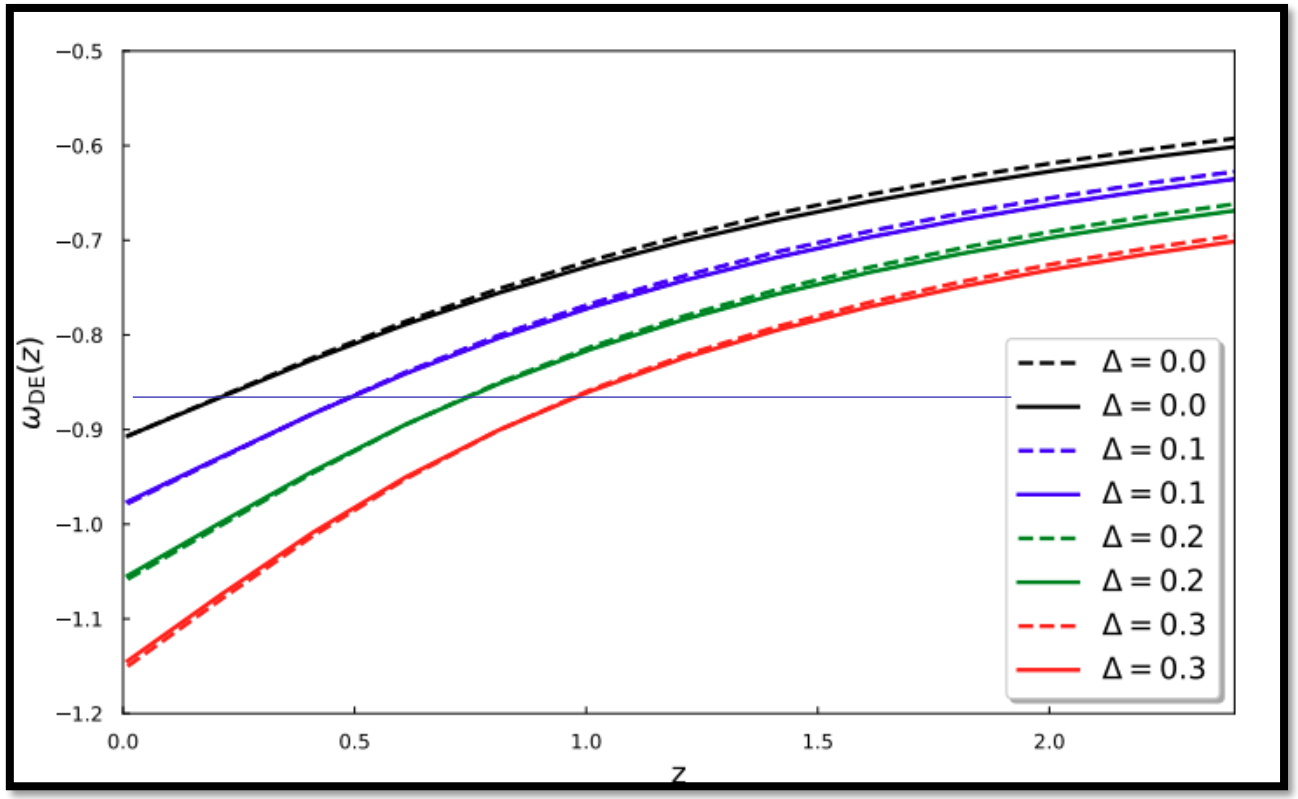
$$\frac{\Omega'_{de}}{\Omega_{de}(1-\Omega_{de})} = (\Delta-2)\left(1-\sqrt{\frac{3M_p^2\Omega_{de}}{C}}\,L^{-\frac{\Delta}{2}}\cos y\right) - \frac{1}{1-\Omega_{de}}\left[2(\Omega_{de}+\Omega_m+\Omega_r-1)-\Omega_m\left(\Gamma\frac{r_2}{r_1}+3\right)-\Omega_r(\Gamma\alpha+4)\right]$$

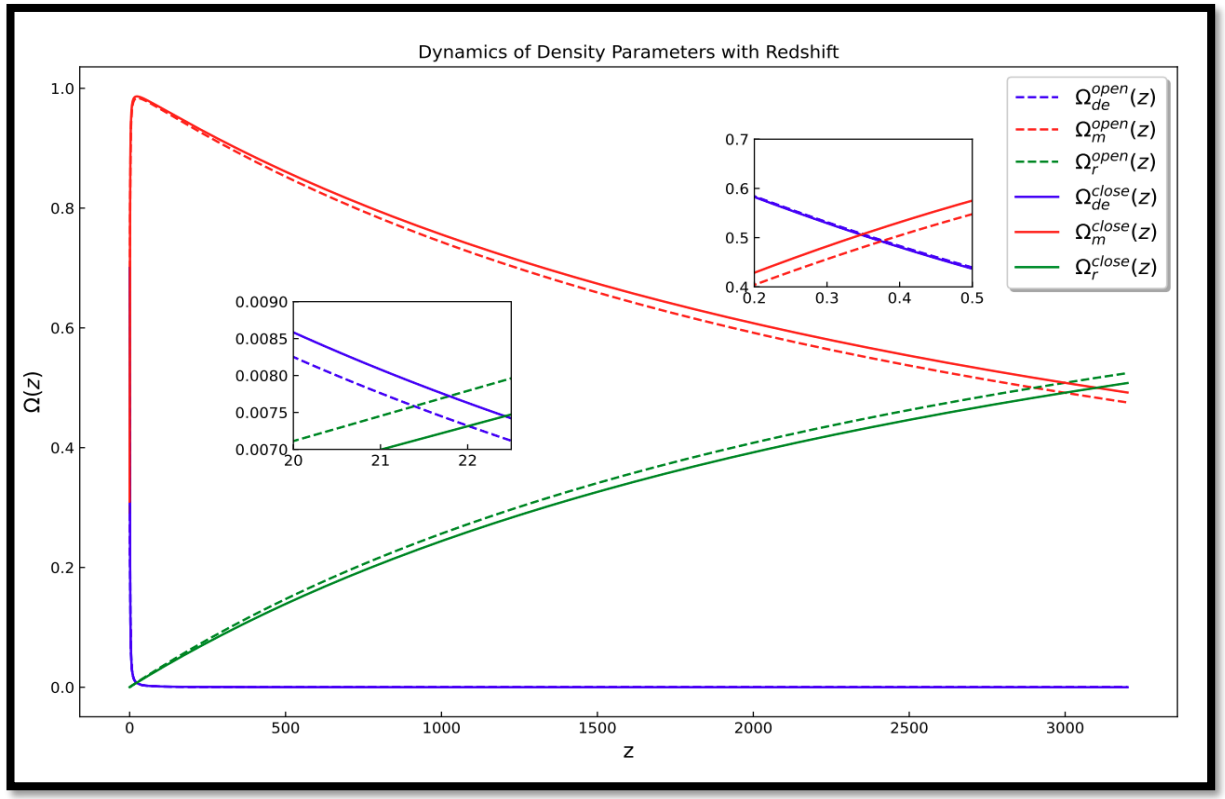
$$\frac{\Omega_m{}'}{\Omega_m} = -\left(\Gamma\frac{r_2}{r_1}+3\right)-(\Delta-2)\left(1-\sqrt{\frac{3M_p^2\Omega_{de}}{C}}L^{\frac{-\Delta}{2}}\cos y\right)\Omega_{de}-\left[2(\Omega_{de}+\Omega_m+\Omega_r-1)-\Omega_m\left(\Gamma\frac{r_2}{r_1}+3\right)-\Omega_r(\Gamma\alpha+4)\right]$$

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

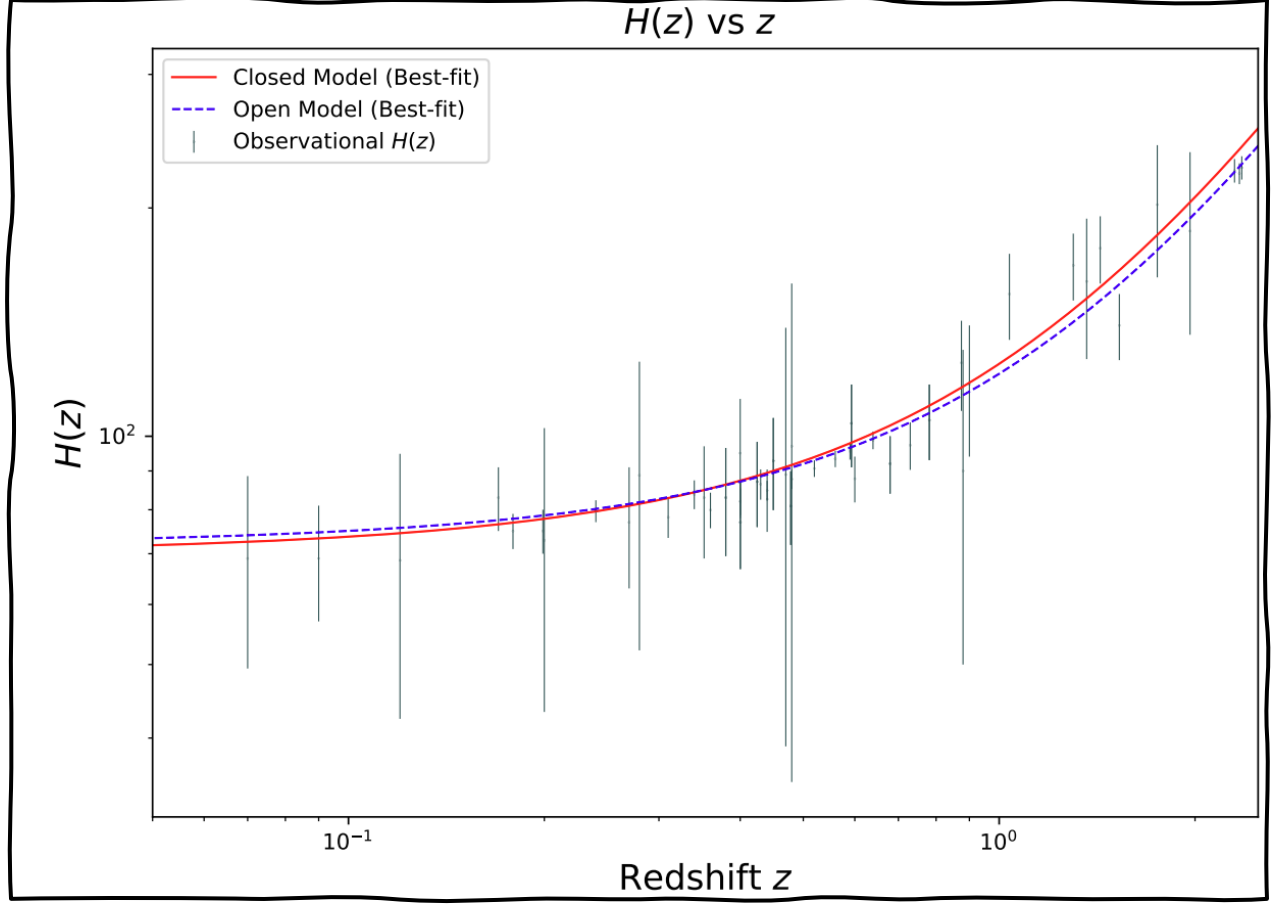
$\rho_{\mathrm{de}} = CL^{-2+\Delta}$ also $\rho_{de} = 3HM_p^2\Omega_{de} \Longrightarrow L = \left[\frac{\Omega_{de}H_0^2(1-\Omega_{de0}-\Omega_{m0}-\Omega_{r0})(1+z)^2}{c^2(1-\Omega_{de}-\Omega_m-\Omega_r)}\right]^{\frac{1}{\Delta-2}}$.

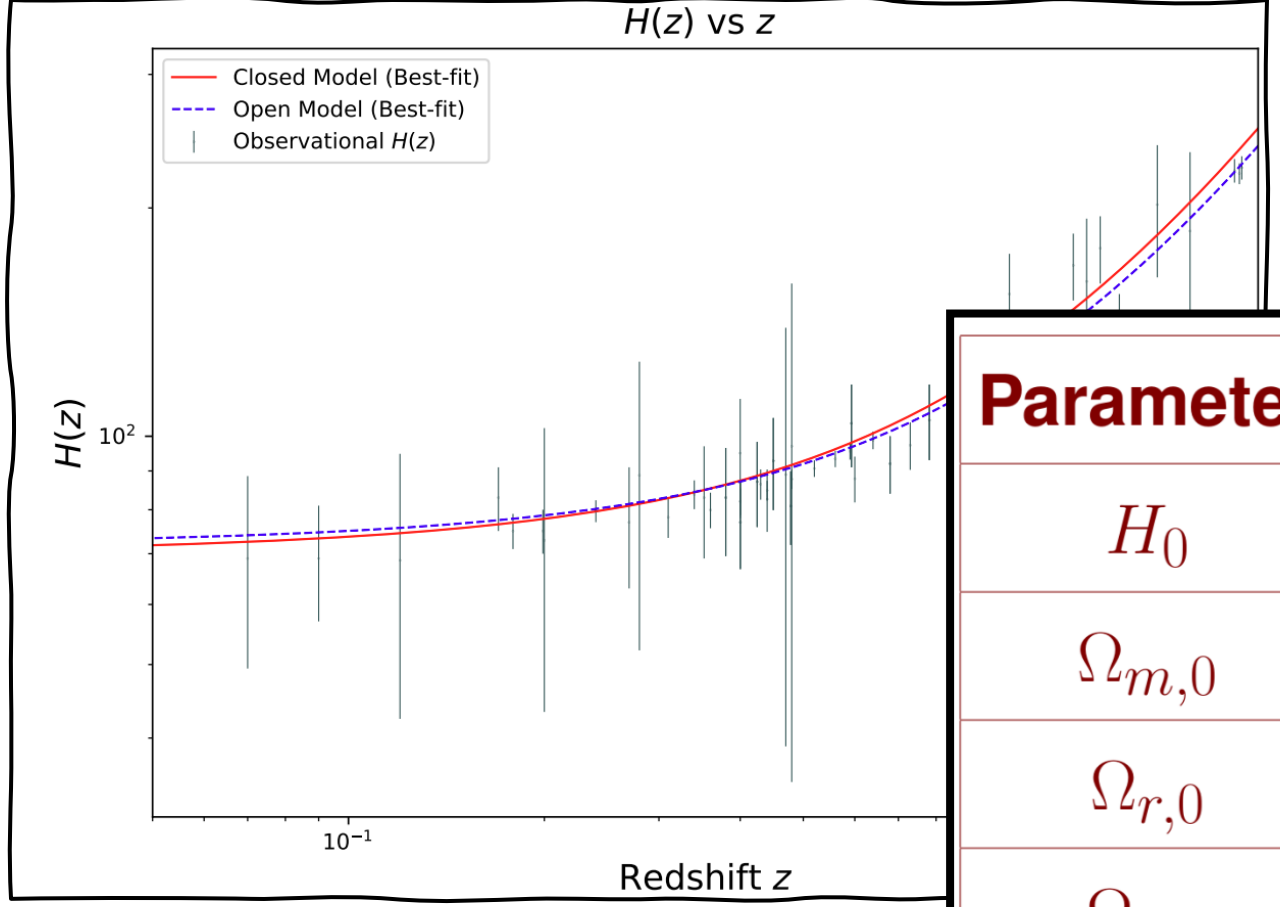
Equation of state and Density Parameters





Evolution of the equation-of-state parameter $w(z)$ for the interaction $Q = -\Gamma H \rho_r$, in open (dashed) and closed (solid) universes. Curves correspond to Barrow exponent $\Delta = 0,\ 0.1,\ 0.2,\ 0.3$(blue, green, red, purple). We adopt $\left(\Omega_{de,0}, \Omega_{m,0}, \Omega_{r,0}, \Omega_{k,0}\right) = (0.75, 0.26, 10^{-4}, -0.0101)$ for the closed universe and $(0.73, 0.26, 10^{-4}, 0.0099)$for the open universe, with $\Gamma = 10^{-4}$.


H(z) vs z
Closed Model (Best-fit)
Open Model (Best-fit)
Observational H(z)
H(z)
10^2
10^-1
10^0
Redshift z



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	$0.6027^{+0.2890}_{-0.4233}$	$0.4189^{+0.3682}_{-0.3120}$

AIC and BIC

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

Maximum log likelihood

No. of free parameters

$$AIC \simeq -2\ln(\mathscr{L}_{\max}) + 2k$$

$$BIC = -2\ln(\mathscr{L}_{\max}) + k\ln(N)$$

No. of dataset points

$$\Delta AIC = AIC_{\text{model}} - AIC_{\Lambda CDM}$$

Discussion

➢ In this presentation, I discussed the Barrow holographic dark energy model in which different sectors of the energy density interact, with the interaction term proportional to the radiation density.

➢ The roughness of the horizon modifies the dark energy sector, and this modification can be interpreted as a quantum-gravity–motivated correction encoded by the Barrow exponent Δ.

➢ All major components of the cosmic energy budget—dark energy, dark matter, and radiation—are included, and their coupled dynamics are studied self-consistently.

➢ The model preserves the standard thermal history of the universe, with consistent radiation–matter and matter–dark energy equality epochs.

➢ The dark energy equation of state becomes dynamical and exhibits a quintessence-to-phantom transition for sufficiently large values of Δ, which is reasonable since Δrepresents a small quantum-gravity correction.

➢ Using late-time observational data, the model prefers slightly lower values of H_0compared to ΛCDM. A detailed analysis with high-redshift data may help clarify the Hubble tension.

➢ From statistical comparison we got that ΛCDM is better among all the interaction model with Barrow correction, if not any of the variable suppressed or ignored. Although interaction proportional to the radiation density is still competes with the ΛCDM far better than all the other model.

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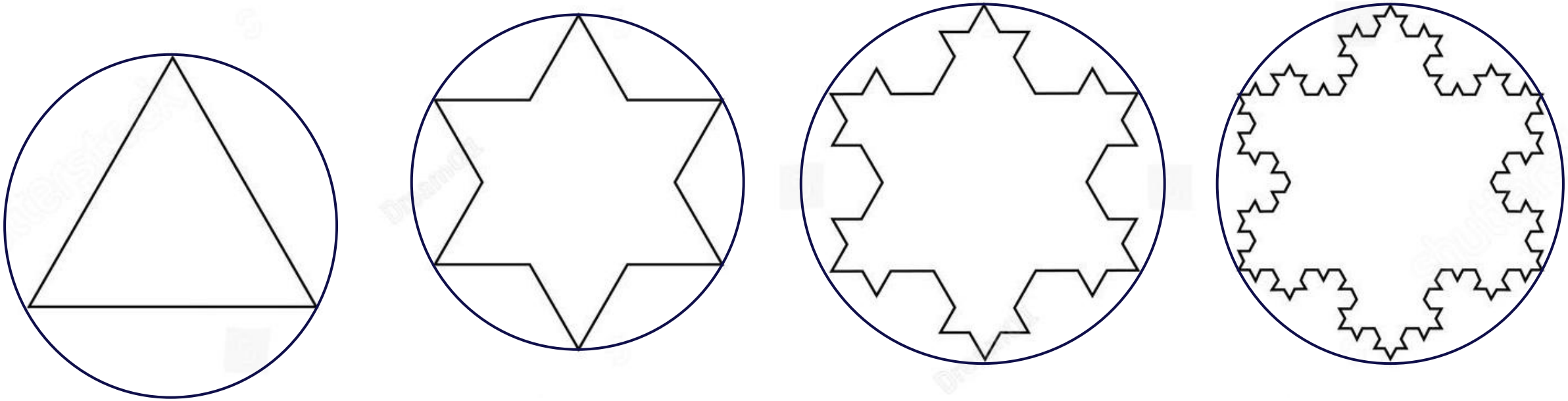
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Thank You!

Fractal Structure and Effective Dimension



Fractal dimension $=\lim_{\epsilon \to 0} \frac{\ln(N(\epsilon))}{\ln(1/\epsilon)} = \ln 4/\ln 3 \approx 1.26$