Dark matter, Dark energy and CMB

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Outline

- What is the problem?
- Decaying vacuum energy as the dark energy
- A new proposal
- Discussion

What is the problem?

- Observation shows that the universe has accelerating expansion
- Ordinary matter give rises to the decelerating expansion
- Accelerating expansion needs strange form of the matter which is called dark energy

$$\frac{\dot{a}}{a} = \frac{8\pi G}{3}\rho, \qquad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

Accelerating expansion $\longrightarrow$ $(\rho + 3p) < 0$

What is the problem?

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$\downarrow$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi\left(T_{\mu\nu} - \frac{\Lambda}{8\pi}g_{\mu\nu}\right) = 8\pi\tilde{T}_{\mu\nu}$$

$$\tilde{T}_{\mu\nu} = (\tilde{\rho} + \tilde{p})u_\mu u_\nu + \tilde{p}g_{\mu\nu}, \qquad \tilde{\rho} = \rho + \frac{\Lambda}{8\pi}, \quad \tilde{p} = p - \frac{\Lambda}{8\pi}$$

$$\begin{cases} \rho_\Lambda = \frac{\Lambda}{8\pi G} \\ p_\Lambda = -\frac{\Lambda}{8\pi G} \end{cases} \longrightarrow \quad \rho_\Lambda + 3p_\Lambda = -\frac{\Lambda}{4\pi G} < 0$$

What is the problem?

- Vacuum energy of quantum fields can be origin of ρ_Λ
- Vacuum energy is given by $\rho_v = \frac{k_c^4}{16\pi^2}$
- $k_c \sim M_p \quad \longrightarrow \quad \rho_v \simeq 10^{70}(\mathrm{GeV})^4$
- Observation gives $\rho_\Lambda \simeq 10^{-47}(\mathrm{GeV})^4$
- There is a discrepancy to 123 order of magnitude

Decaying vacuum energy

- $\Lambda = At^{-l}$ — t is the cosmic time
- $\Lambda = Ba^{-m}$ — $m = 4 \rightarrow$ Radiation like
- $\Lambda = CH^{n}$ — Holographic dark energy
- $\Lambda = Dq^{p}$ — q is deceleration parameter

Vacuum energy decays to the matter

$$\dot{\rho} + 3H(\rho + p) = 0$$

$$\downarrow$$

$$\underbrace{\dot{\rho}_m + 3H(\rho_m + p_m)}_{\text{matter part}} + \underbrace{\dot{\rho}_\Lambda + 3H(\rho_\Lambda + p_\Lambda)}_{\text{vacuum part}} = 0$$

$$\downarrow$$

$$\dot{\rho}_m + 3H\rho_m = -\dot{\rho}_\Lambda$$

- If $\dot{\rho}_\Lambda = 0 \longrightarrow \rho_m = \rho_{0m} a^{-3}$
- If $\dot{\rho}_\Lambda \neq 0 \longrightarrow \rho_m = \rho_{0m} a^{-3+\epsilon}$

A new proposal

The model is based on the four assumptions

- The universe composition: $\begin{cases} \text{radiation(CMB and CNB)} \\ \text{matter(dark and baryonic)} \\ \text{dark energy} \end{cases}$
- Primordial black holes(PBHs) are as the dark matter
- Zero-point energy of one quantum scalar field is the dark energy
- CMB and PBHs are in thermal equilibrium

S. Zeynizadeh and M. Nouri-Zonoz 2012, arxiv:1212.6770

Order of magnitude computation (SI)

$$T_{\text{CMB}} = T_{\text{PBH}}$$

$$2.725 = \frac{\hbar c^3}{8\pi G k_B M_{\text{PBH}}}$$

$$\downarrow$$

$$M_{\text{PBH}} \simeq 0.45 \times 10^{26}\text{gr}$$

$$r_{\text{PBH}} = \frac{2G}{c^2} M_{\text{PBH}} \quad \longrightarrow \quad r_{\text{PBH}} \simeq 6.68 \times 10^{-2}\text{mm}$$

Order of magnitude computation (SI)

Zero-point energy:

$$\rho_v = \frac{1}{16\pi^2}\frac{\hbar}{c}\left(\frac{2\pi}{\lambda_c}\right)^4$$

key assumption:

$$\lambda_c \sim r_{\mathrm{PBH}} \qquad \longrightarrow \qquad \rho_v \simeq 17.4 \times 10^{-29}\,\frac{\mathrm{gr}}{\mathrm{cm}^3}$$

Which is very close to $\rho_c \simeq 10^{-29}\,\frac{\mathrm{gr}}{\mathrm{cm}^3}$

Two important question

- Can be PBH in stable equilibrium with its surrounding?

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- Can be PBH in stable equilibrium with its surrounding?
- Can we write equilibrium condition with respect to infinite observer?

black hole enclosed by thermal bath

Hawking temperature at r

$$T(r) = \frac{1}{8\pi GM}\left(1 - \frac{2GM}{r}\right)^{-\frac{1}{2}}$$

$$\downarrow$$

$$M^3 + 2rG(4\pi)^2 T^2 M^2 = \frac{r}{2G}$$

$$\downarrow$$

$$M_1 \simeq \frac{1}{8\pi GT}\left(1 + \frac{1}{8\pi rT}\right), \quad M_2 \simeq \frac{r}{2G}\left(1 - \frac{1}{(4\pi rT)^2}\right)$$

J. York, Phys.Rev.D 1986

black hole enclosed by thermal bath

$$E = \left(\frac{\partial I}{\partial \beta}\right)_A = r - r\left(1 - \frac{2GM}{r}\right)^{\frac{1}{2}},$$

$$C_A = \left(\frac{\partial E}{\partial T}\right)_A = 8\pi G M^2 \left(1 - \frac{2GM}{r}\right)\left(\frac{3GM}{r} - 1\right)^{-1}$$

I is Euclidean action and C_A is heat capacity

for $2GM < r < 3GM$, C_A is positive for M_2 and there is thermal stability

CMB as thermal bath

$$r = xGM, \qquad M \simeq \frac{r}{2G}\left(1 - \frac{1}{(4\pi r T)^2}\right), \qquad 2 < x < 3$$

$$\downarrow$$

$$T = \frac{1}{4\pi G M \sqrt{x^2 - 2x}}$$

$$x = \text{constant} \quad \longrightarrow \quad M \sim \frac{1}{T} \quad \longrightarrow \quad M \sim a$$

$$x = x(T) \quad \longrightarrow \quad M \nsim \frac{1}{T} \quad \longrightarrow \quad M \nsim a$$

$$\downarrow$$

$$M = M(a)$$

Vacuum energy as a function of PBH mass

$$\rho_\Lambda = \frac{1}{16\pi^2}\left(\frac{2\pi}{\lambda_c}\right)^4, \quad \lambda_c \sim r, \quad r = 2GM$$

$$\downarrow$$

$$\rho_\Lambda = \frac{\pi^2}{16G^4}\frac{1}{M^4}$$

$$\begin{cases} \rho_M = M(a)n(a) \\ \rho_\Lambda = \frac{\pi^2}{16G^4}\frac{1}{M(a)^4} \\ \dot{\rho} + 3H(\rho + p) = 0 \\ p_\Lambda = w\rho_\Lambda \end{cases} \xrightarrow{w=-1} M(a) = \left(\frac{\pi^2}{4G^4 n_0}\right)^{\frac{1}{5}} a^{\frac{3}{5}}$$

$$\rho_M = n_0^{\frac{4}{5}}\left(\frac{\pi^2}{4G^4}\right)^{\frac{1}{5}} a^{-\frac{12}{5}}, \qquad \rho_\Lambda = \frac{1}{4}n_0^{\frac{4}{5}}\left(\frac{\pi^2}{4G^4}\right)^{\frac{1}{5}} a^{-\frac{12}{5}}$$

Equation of state in presence of interaction

$$Z = N \int_{\text{periodic}} [d\phi] \exp\left(\int_0^\beta d\tau \int d^3x L \right)$$

$$\ln Z = V \int \frac{d^3p}{(2\pi)^3} \left[-\frac{1}{2}\beta\omega - \ln(1 - e^{-\beta\omega}) \right], \qquad \beta = \frac{1}{T}$$

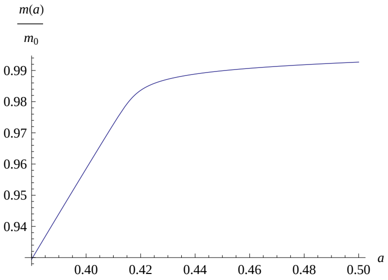
$$\begin{cases} \rho = \frac{1}{V}\frac{\partial \ln Z}{\partial \beta} \\ p = \frac{1}{\beta}\frac{\partial \ln Z}{\partial \beta} \\ w = \frac{p}{\rho} \end{cases} \xrightarrow{T = T_{\text{CMB}}} \qquad w \simeq -0.9995$$

Evolution of PBH mass

$$w \neq -1, \qquad \dot{\rho} + 3H(\rho + p) = 0$$

$$\downarrow$$

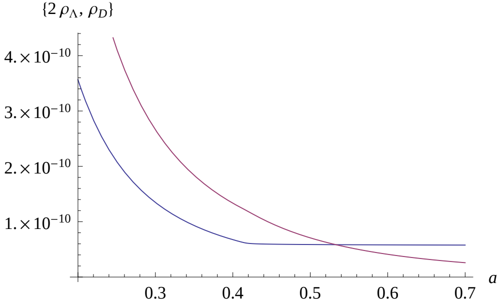
$$M'(a)\left(n_0 a^{-3} - \frac{\pi^2}{4G^4 M(a)^5}\right) + \frac{3}{a}(1+w)\rho_\Lambda = 0$$



Evolution of ρ_Λ and ρ_M

$$\ddot{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$$\ddot{a} = 0 \quad \longrightarrow \quad \rho_M = 2\rho_\Lambda$$



$a \simeq 0.55$ is transition point for deceleration to acceleration

Discussion

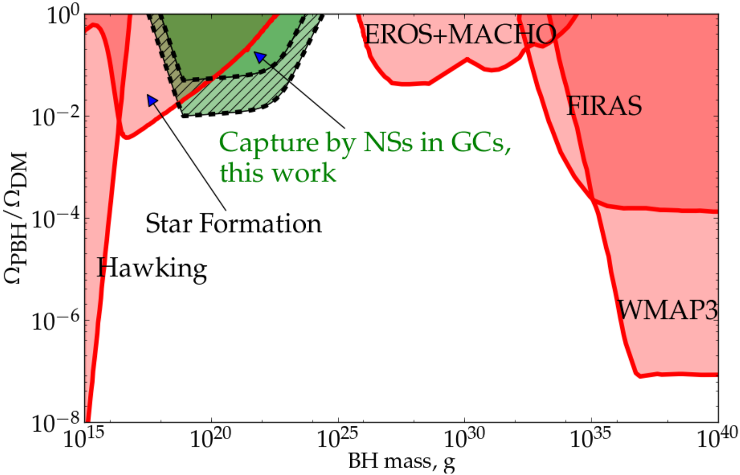
$$\rho_{0\Lambda} = 0.7\rho_c, \quad \rho_\Lambda = \frac{\pi^2}{16G^4}\frac{1}{M^4} \longrightarrow M_0 \simeq 10^{26}\text{gr}$$

$$T = \frac{1}{4\pi GM\sqrt{x^2 - 2x}} : \begin{cases} T = 2.725, x = 3, \longrightarrow M \simeq 0.5 \times 10^{26} \\ T = 2.725, x = 2, \longrightarrow M \to \infty \end{cases}$$

$$M_0 \in (0.5 \times 10^{26}, \infty)$$

M. A. Abramowicz et al. 2009, arXiv:0810.3140

N. Seto and A.Cooray, 2007 arXiv: astro-ph/0702586



Capela, et. al. 2013, arXiv:1301.4984

Thank you