Constraints on Running Vacuum Model with H(z) and $f\sigma_8$

Lu Yin
National Tsing Hua University

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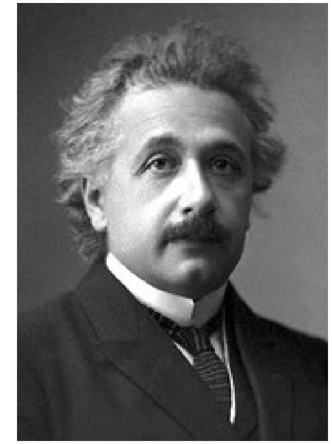
NTHU

Outline

- The history of Λ in Estein's Equations
- Introduce the running vacuum model(RVM)
  (Based on:Chao-Qiang Geng, Chung-Chi Lee and Lu Yin, JCAP 1708, 032 (2017))
- Observational constraints on RVM
- Summary and conclusion

Einstein's Equations



1915 *The field equations of gravitation*

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{g_{\mu\nu}}{2} R + R_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Static universe

1917 *Cosmological considerations on the general relativity theory*

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \qquad (13a)$$

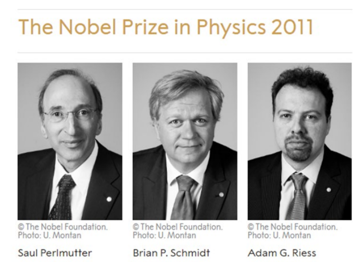
Λ appears

1929 Hubble's law shows the expanding universe.

1931 To the cosmological problem of the general relativity theory

Λ disappears ("Einstein's blunder")

1998 Accelerated expanding universe was found



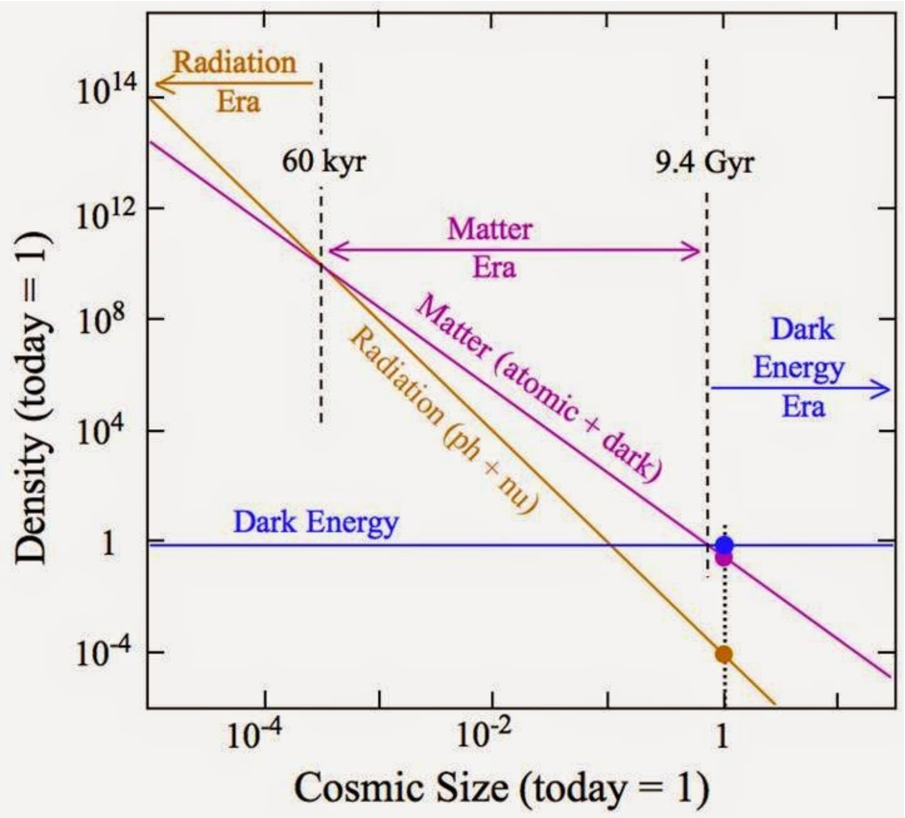
Now the Einstein equation is given by

$$R_{\mu\nu} - \frac{g_{\mu\nu}}{2} R + \Lambda g_{\mu\nu} = 8\pi G T^{M}_{\mu\nu}$$

set $R = g^{\mu\nu} R_{\mu\nu}$ is the Ricci scalar， and $T^{M}_{\mu\nu}$ is the energy-momentum tensor of matter and radiation.

➢ The problems of Λ:

- coincidence problem
- Nonzero but tiny



➢ One solution to coincidence problem is

$$\rho_\Lambda(H) = \rho_\Lambda^0 + \frac{3\nu}{8\pi} M_P^2 \left(H^2 - H_0^2\right).$$

J. Sola, J. Phys. Conf. Ser. 453 (2013) 012015

Introduce the running vacuum model

To explain the accelerated expansion of the universe, we consider $\Lambda = \Lambda(H)$ is the time-dependent parameter

- Quadratic model:
  - $\Lambda \propto H^2$

    J. C. Carvalho, J. A. S. Lima and I. Waga, Phys. Rev. D **46**, 2404 (1992)
  - $\Lambda = \Lambda_0 + \nu H^2$

    I. L. Shapiro and J. Sola, Phys. Lett. B **475**, 236 (2000)
  - $\Lambda = C_0 + C_{\dot{H}} \dot{H} + C_H H^2$

    S. Basilakos, D. Polarski and J. Sola, Phys. Rev. D **86**, 043010 (2012)
- Linear model: $\Lambda = \sigma H$

  R. Schutzhold, Phys. Rev. Lett. **89**, 081302 (2002)
- Power series models:
  - $\Lambda = n_0 + n_1 H + n_2 H^2$

    S. Basilakos, M. Plionis and J. Sola, Phys. Rev. D **80**, 083511 (2009)

- We consider $\Lambda = \Lambda(H)$ is the time-dependent parameter to explain the accelerated expansion of the universe.

We obtain the Friedmann equations

$$H^2 = \frac{a^2}{3}(\rho_M + \rho_\Lambda)$$

$$\dot{H} = -\frac{a^2}{6}(\rho_M + 3P_M + \rho_\Lambda + 3P_\Lambda)$$

where $H = da/(a\,d\tau)$, τ is the conformal time

$\rho_M = \rho_m + \rho_r$ and $P_M = P_m + P_r = P_r$

The equations of state(EoS) are given by

$$\omega_{r,m,\Lambda} = \frac{P_{r,m,\Lambda}}{\rho_{r,m,\Lambda}} = \frac{1}{3}, 0, -1$$

- We consider Λ to be a function of the Hubble parameter

$$\Lambda = 3\nu H^2 + \Lambda_0$$

where ν and Λ_0 are two free parameters, $\nu \geq 0$

Background evolution of RVM

- From the conservation equation $\nabla^{\mu}(T^{M}_{\mu\nu} + T^{\Lambda}_{\mu\nu}) = 0$

we have

$$\dot{\rho}_{tot} + 3H(1+\omega)\rho_{tot} = 0$$

$$\dot{\rho}_{\Lambda} + 3H(1+\omega_{\Lambda})\rho_{\Lambda} = 6\nu H\dot{H} \neq 0$$

resulting in that dark energy unavoidably couples to matter and radiation , given by

$$\dot{\rho}_{m,r} + 3H(1+\omega_{m,r})\rho_{m,r} = Q_{m,r}$$

↑ Energy transform

Background evolution of RVM

- $Q_{m,r}$ is the decay rate of the dark energy taken to be

$$Q_{m,r} = -\frac{\dot{\rho}_\Lambda(\rho_{m,r} + P_{m,r})}{\rho_M} = 3\nu H(1 + \omega_{m,r})\rho_{m,r}$$

- Then we get $\rho_{m,r} = \rho_{m,r}^{(0)} a^{-3(1+\omega_{m,r})\xi}$

where $\xi = 1 - \nu$ and $\rho_{m,r}^{(0)}$ are the energy densitys of matter or radiation at $z = 0$.

Perturbation

- The metric perturbations are given by

$$ds^2 = a^2(\tau)\left[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j\right]$$

$$h_{ij} = \int d^3k e^{i\vec{k}\cdot\vec{x}}\left[\widehat{k}_i\widehat{k}_j h(\widehat{k},\tau) + 6(\widehat{k}_i\widehat{k}_j - \frac{1}{3}\delta_{ij})\eta(\widehat{k},\tau)\right]$$

i,j=1,2,3 h and η are two scalar perturbations in the synchronous gauge.

- The matter and radiation density perturbations

$$\dot{\delta}_{m,r} = -(1+\omega_{m,r})\left(\theta_{m,r} + \frac{\dot{h}}{2}\right) - 3H\left(\frac{\delta P_{m,r}}{\delta\rho_{m,r}} - \omega_{m,r}\right)\delta_{m,r} - \boxed{\frac{Q_{m,r}}{\rho_{m,r}}\delta_{m,r}}$$

$$\dot{\theta}_{m,r} = -H(1-3\omega_{m,r})\theta_{m,r} + \frac{\delta P_{m,r}/\delta\rho_{m,r}}{1+\omega_{m,r}}\frac{k^2}{a^2}\delta_{m,r} - \boxed{\frac{Q_{m,r}}{\rho_{m,r}}\theta_{m,r}}$$

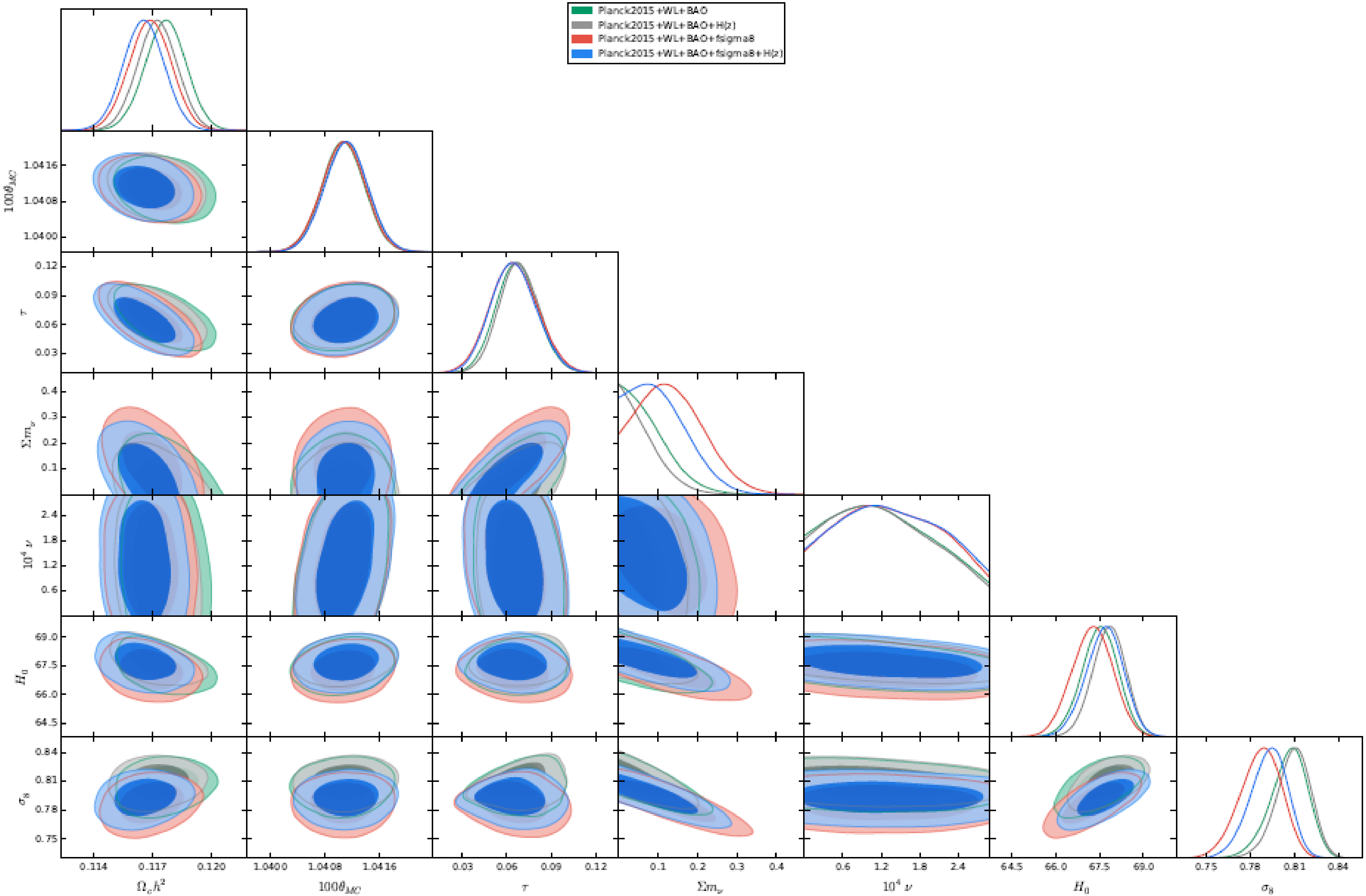
where $\delta_{m,r} \equiv \delta\rho_{m,r}/\rho_{m,r}$ and $\theta_{m,r} = ik_i\upsilon^i_{m,r}$.

Observational constraints on RVM

- We use the **CosmoMC** program to perform the global fitting for the RVM
- Dataset:
  - CMB : Planck 2015

    (TT, TE, EE, lowTEB, low-l polarization and lensing from SMICA)
  - BAO : Baryon acoustic oscillation data from BOSS
  - Weak lensing
  - $H(z)$ data and $f\sigma_8$ data

The result



CQ Geng *et al.*, JCAP 1708, 032 (2017)

The result

Fitting results for the RVM with $\Lambda = 3\nu H^2 + \Lambda_0$

Parameter	(A) *Planck* + WL + BAO	(B) *Planck* + WL + BAO + $f\sigma_8$	(C) *Planck* + WL + BAO + $H(z)$	(D) *Planck* + WL+ BAO + $f\sigma_8$ + $H(z)$
Model parameter $10^4\nu$	< 1.83	< 2.09	< 1.80	< 2.09
Baryon density $100\Omega_b h^2$	2.23 ± 0.03 (2.23)	$2.23^{+0.04}_{-0.03}$ (2.24)	$2.23^{+0.02}_{-0.03}$ (2.23)	2.22 ± 0.03 (2.24)
CDM density $100\Omega_c h^2$	11.8 ± 0.2 (11.8)	11.7 ± 0.2 (11.7)	11.7 ± 0.2 (11.7)	$11.7^{+0.2}_{-0.3}$ (11.7)
Optical depth 100τ	$6.67^{+2.83}_{-2.70}$ (6.96)	$6.48^{+3.23}_{-3.03}$ (6.99)	$6.84^{+2.76}_{-2.61}$ (7.13)	$6.49^{+3.08}_{-2.91}$ (6.96)
σ_8	$0.806^{+0.025}_{-0.026}$ (0.810)	$0.787^{+0.027}_{-0.028}$ (0.788)	$0.809^{+0.023}_{-0.024}$ (0.812)	$0.792^{+0.025}_{-0.026}$ (0.793)
Neutrino mass $\Sigma m_\nu/\mathrm{eV}$	< 0.188 (< 0.198)	< 0.278 (< 0.301)	< 0.161(< 0.176)	< 0.235 (< 0.262)
$\chi^2_{best-fit}$	13487.7 (13488.9)	13509.9 (13512.2)	13511.3 (13512.8)	13531.2 (13534.7)

CQ Geng *et al.*, JCAP 1708, 032 (2017)

Summary and conclusion

- We have calculated the perturbation of RVM.
- We have obtained that $\chi^2_{\rm RVM} < \chi^2_{\Lambda\rm CDM}$, implying that the current data prefers RVM.
- We have a good solution to σ_8 problem with *H(z)* and $f\sigma_8$ dataset.

Thank you!