Constraints on running vacuum model with $H(z)$ and $f\sigma_8$

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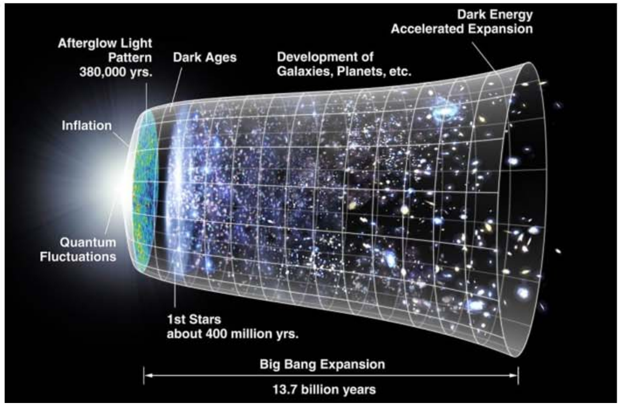
Based on:
Chao-Qiang Geng, Chung-Chi Lee and Lu Yin, JCAP 1708, 032 (2017)

Outline

- Motivation and background
- Introduce the running vacuum model(RVM)
- Observational constraints on RVM
- Summary

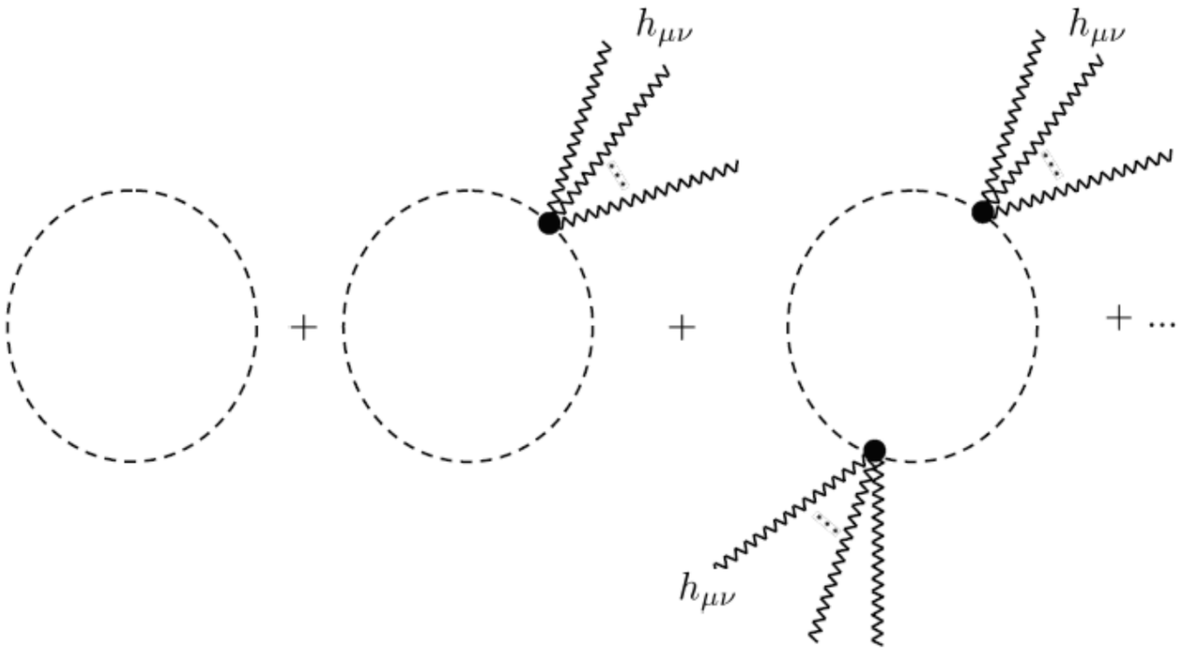
Motivation and Background



- Cosmomc accelerate expantion ➡ Λ
- Problems:
  - Nonzero but tiny
  - coincidence problem
- 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



the corresponding determinant in the action:

$$\sqrt{-g} = 1 + \frac{1}{2}\,h + \mathcal{O}\left(h^2\right) + \mathcal{O}\left(h_{\mu\nu}\,h^{\mu\nu}\right) + \ldots$$

In the action :

$$S[\phi, g_{\mu\nu}] = \int d^4x\,\sqrt{-g(x)}\,\left[\frac{1}{2}\,g^{\mu\nu}\,\partial_\mu\phi\,\partial_\nu\phi + \frac{1}{2}\,\xi\,\phi^2\,R - V_c(\phi)\right]$$

of the scalar field, which we take as a free field here

$$V(\phi) = (1/2)\,m^2\,\phi^2$$

Introduce the running vacuum model

• 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

$$\boxed{\Lambda = 3\nu H^2 + \Lambda_0}$$

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

Background evolution

- 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

- $Q_{m,r}$ 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

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

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

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 $\theta_{m,r} = ik_i v^i_{m,r}$.

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

Added Hubble parameter

- In the RVM, due to the background evolution of the Hubble parameter, one has

$$\frac{H^2}{H_0^2} = \frac{\Omega_{\mathrm{m}} a^{-3\xi} + \Omega_{\mathrm{r}} a^{-4\xi} + \Omega_\Lambda - \nu}{1-\nu}$$

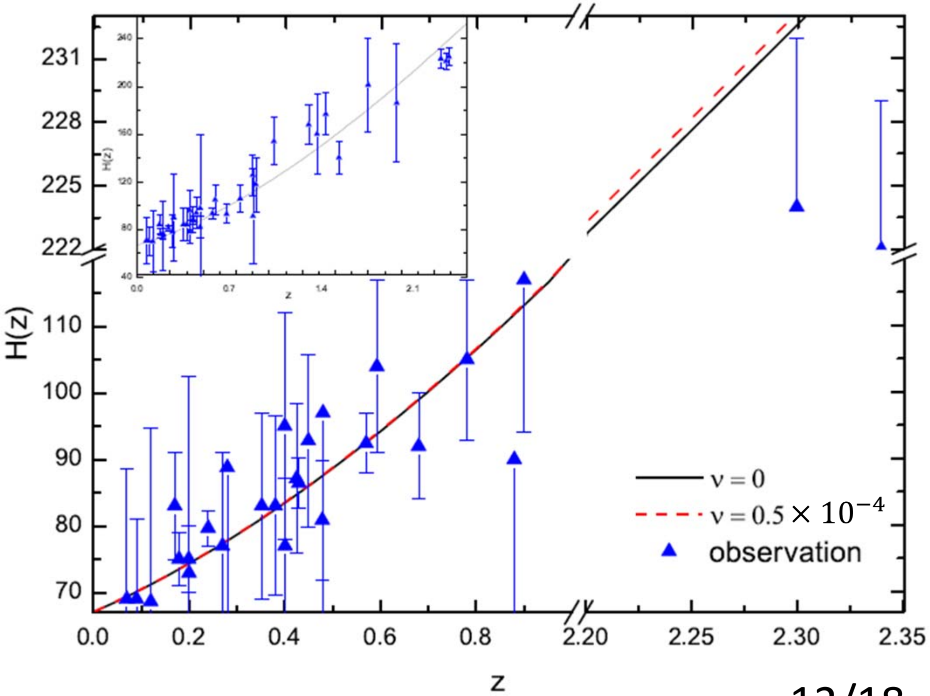
where $\xi = 1 - \nu$, $\Omega_{\mathrm{m(r)}} = \rho_{m(r)}^{(0)} / 3H_0^2$, $\Omega_\Lambda - \nu = \rho_\Lambda^{(z=0)} / 3H_0^2 - \nu$

and $\Omega_{\mathrm{m}} + \Omega_{\mathrm{r}} + \Omega_\Lambda = 1$.

As discussed by J.Sola

[arxiv:1605.06104]

The lager ν is, the smaller $H(z)$ behaves in the high redshift regime



The weighted linear growth fσ_8

- The spectrum of the cosmic matter fluctuations can give important constraints on models about the structure formation.

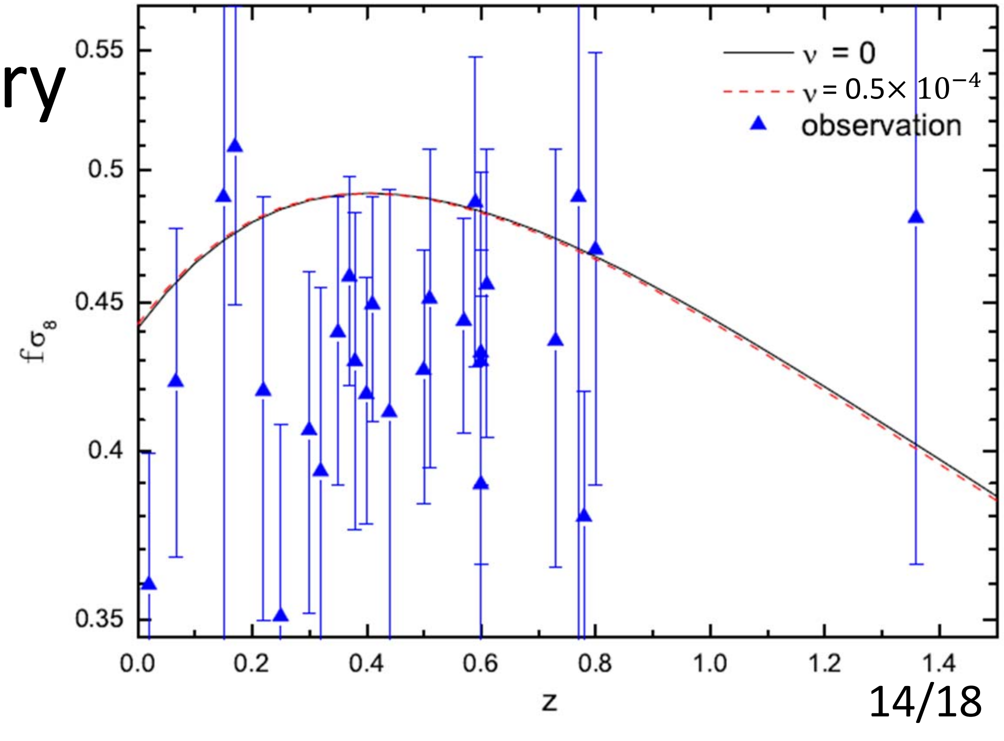
- These fluctuations can be described by the weighted linear growth $f(z)\sigma_8(z)$.

$$f(z) = -(1+z)\frac{d\ln\delta_m}{dz}$$

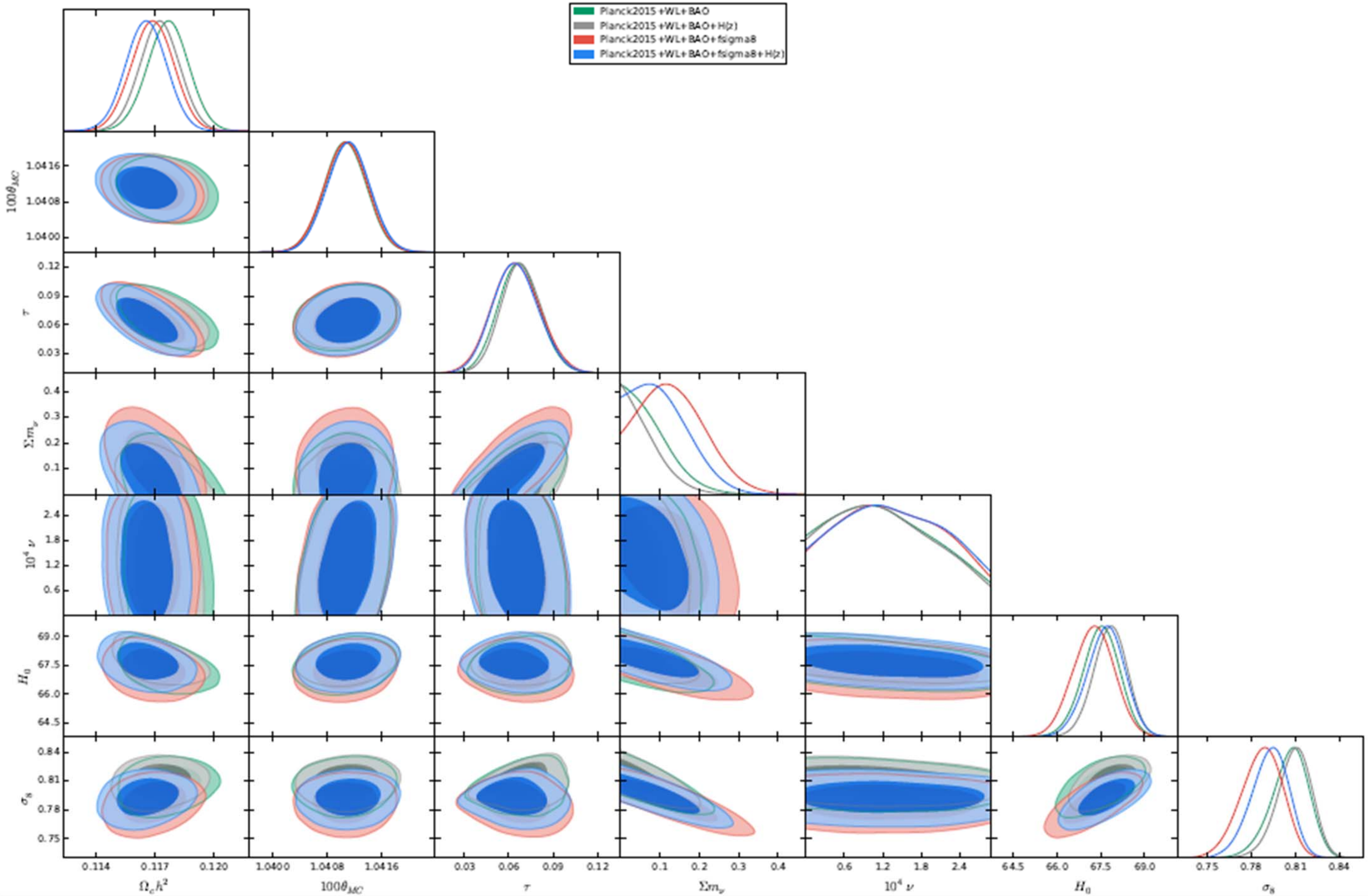
And σ_8 is the root-mean-square matter fluctuation amplitude on the scale of $R_8 = 8h^{-1}$ Mpc at the redshift z, given by

$$\sigma_8(z) = \delta_m^2(z) \int \frac{d^3k}{(2\pi)^3} P(k, \vec{p}) W^2(kR_8)$$

With $P(k, \vec{p})$ the ordinary linear matter power spectrum and $W^2(kR_8)$ the top-hat smoothing function.



The result



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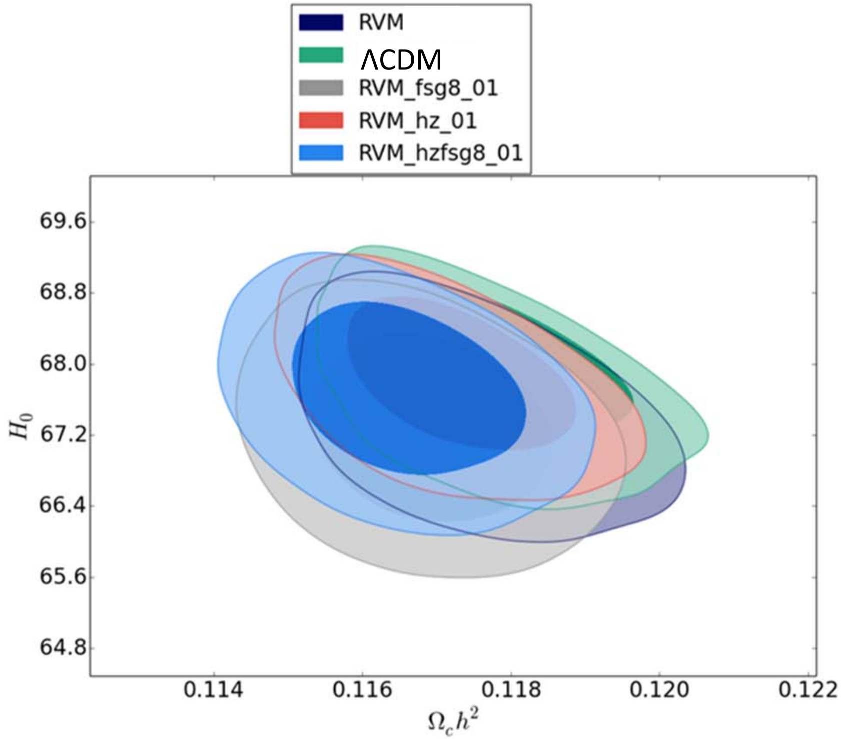
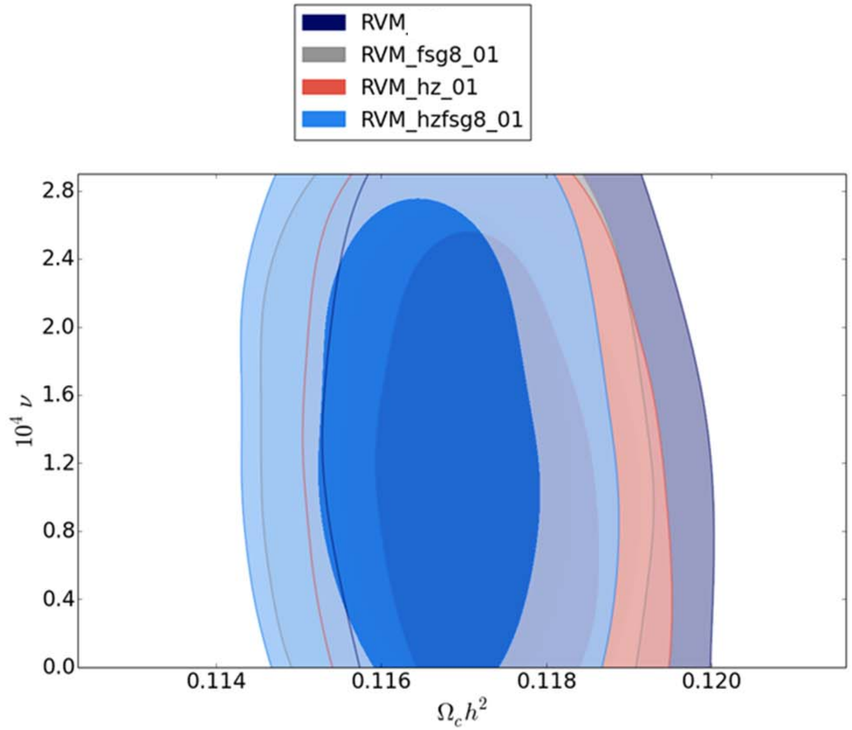
The result


RVM
ΛCDM
RVM_fsg8_01
RVM_hz_01
RVM_hzfsg8_01
69.6
68.8
68.0
67.2
66.4
65.6
64.8
H_0
0.114
0.116
0.118
0.120
0.122
$\Omega_c h^2$


RVM
RVM_fsg8_01
RVM_hz_01
RVM_hzfsg8_01
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
$10^4\,\nu$
0.114
0.116
0.118
0.120
$\Omega_c h^2$

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)

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Summary

- The running vacuum model scenario is suitable to describe the late-time accelerating universe at the background level.
- By calculating the pertubation and performing the global fit to the observational data, we have obtained that $\chi^2_{\mathrm{RVM}} < \chi^2_{\Lambda\mathrm{CDM}}$, implying that the current data prefers RVM.

Thank you