Running vacuum model in non-flat universe

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Outline

- Motivation
- Running vacuum model (RVM) in non-flat universe
- Numerical results for RVM
  - Theoretical CMB power spectra
  - Global fitting of cosmological parameters with observational data
- Conclusion

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Spatially-flat models

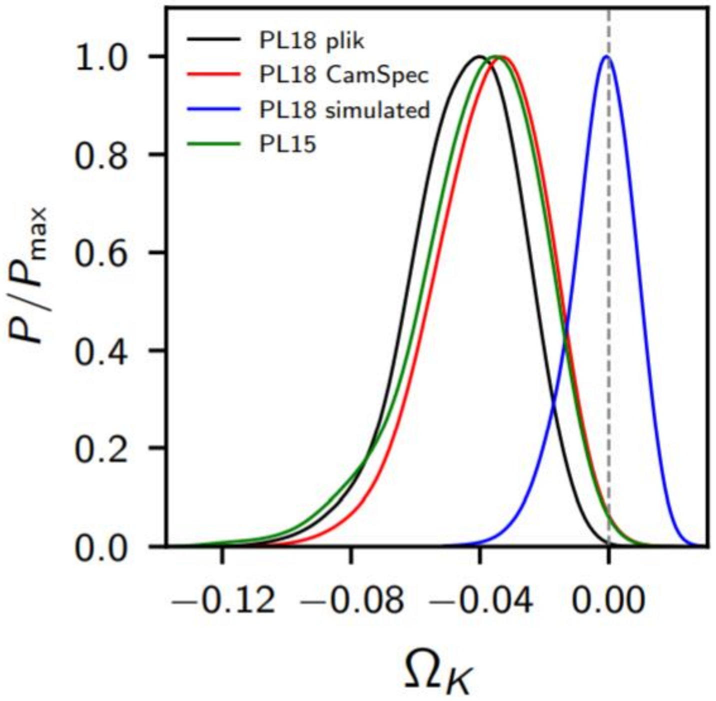
- ΛCDM model
  - Fine-tunning problem
  - Coincidence problem

- Dynamical dark energy models
  - ρ_Λ varies with time

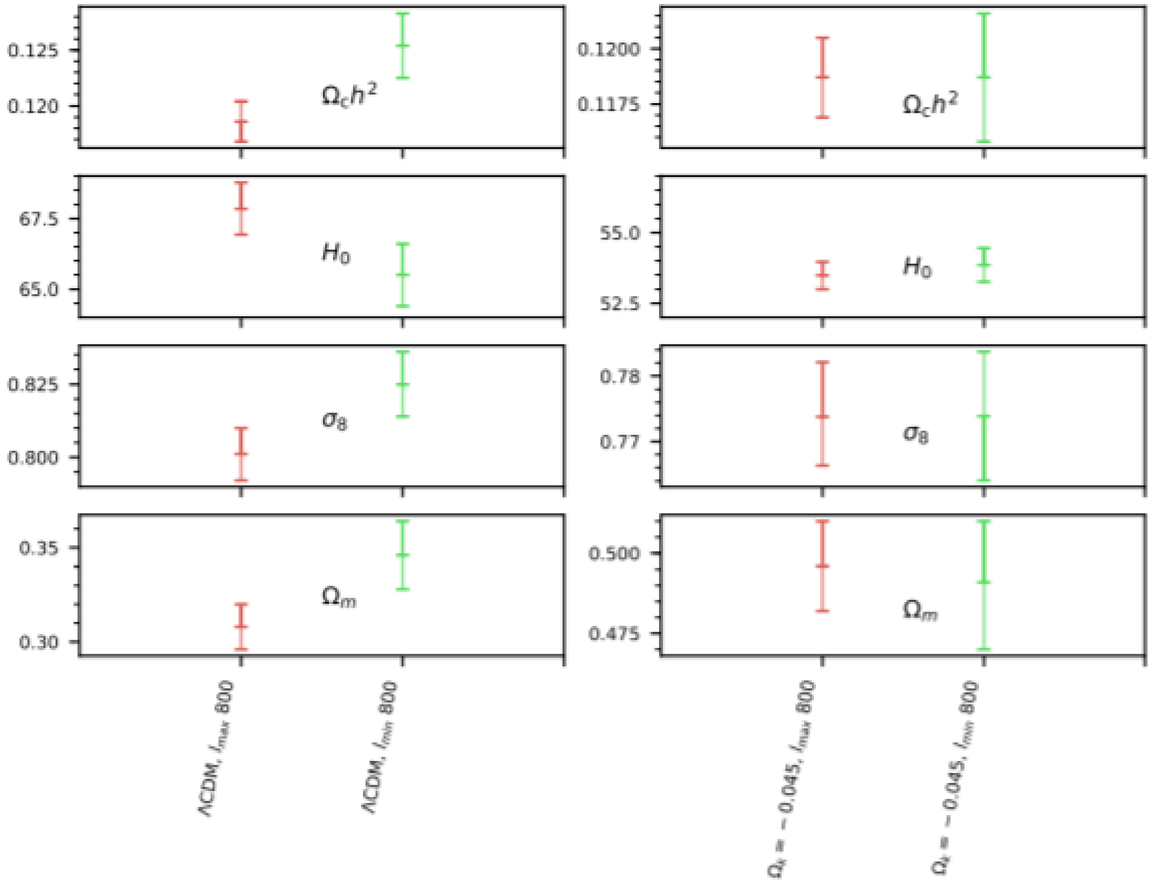
- Alleviate Hubble tension and σ_8 tension

Non-flat universe

- ➢Planck 2018 data favor closed universe at more than 99% confidence level.



$\Omega_K = 0$ $\qquad$ $\Omega_K = -0.0045$



[E. D. Valentino et al. , Nat. Astron. (2019)]

Non-flat models

- Ω_K is also dynamical.
  - There is degeneracy between Ω_K and other parameters.

- Motivate us to study on dynamical dark energy models in non-flat universe and find constraints of cosmological parameters.

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Friedmann equations

- Einstein's equation is reduced to Friedmann equations in homogeneous and isotropic universe.

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_r + \rho_\Lambda) - \frac{K}{a^2}\,,$$

$$\dot{H} = -4\pi G(\rho_m + \rho_r + \rho_\Lambda + P_m + P_r + P_\Lambda) + \frac{K}{a^2}$$

- Density parameters

$$\Omega_m = \frac{8\pi G\rho_m}{3H^2},\quad \Omega_r = \frac{8\pi G\rho_r}{3H^2},\quad \Omega_\Lambda = \frac{8\pi G\rho_\Lambda}{3H^2},\quad \Omega_K = \frac{-K}{a^2H^2}$$

- Equation of state in RVM

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

Running vacuum model (RVM)

- Running vacuum model (RVM)
  - ρ_Λ is defined as a function of the Hubble parameter
  - ρ_Λ transfer energy to matter and radiation as the evolution of the universe
- RVM in flat universe

$$\rho_\Lambda = \frac{1}{8\pi G}\left\{3\nu H^2 + \Lambda_0\right\}$$

- RVM in non-flat universe

$$\rho_\Lambda = \frac{1}{8\pi G}\left\{3\nu(H^2 - H_0^2) + 3\nu(\frac{K}{a^2} - K) + \Lambda_0\right\}$$

Running vacuum model (RVM)

- Energy exchanges between components

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

$$\dot{\rho}_{\Lambda} + 3H(1 + w_{\Lambda})\rho_{\Lambda} = -Q \,,$$

- Evolutions of energy densities

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

$$\rho_{m,r} = \rho_{m,r}^{(0)} a^{-3(1+w_{m,r})(1-\nu)}$$

$$\rho_{\Lambda} = \rho_{\Lambda}^{(0)} + \frac{\nu}{1-\nu}\left\{\rho_m^{(0)}\left[a^{-3(1-\nu)} - 1\right] + \rho_r^{(0)}\left[a^{-4(1-\nu)} - 1\right]\right\}$$

- The component of ρ_{Λ} in RVM is the same in flat and non-flat universe

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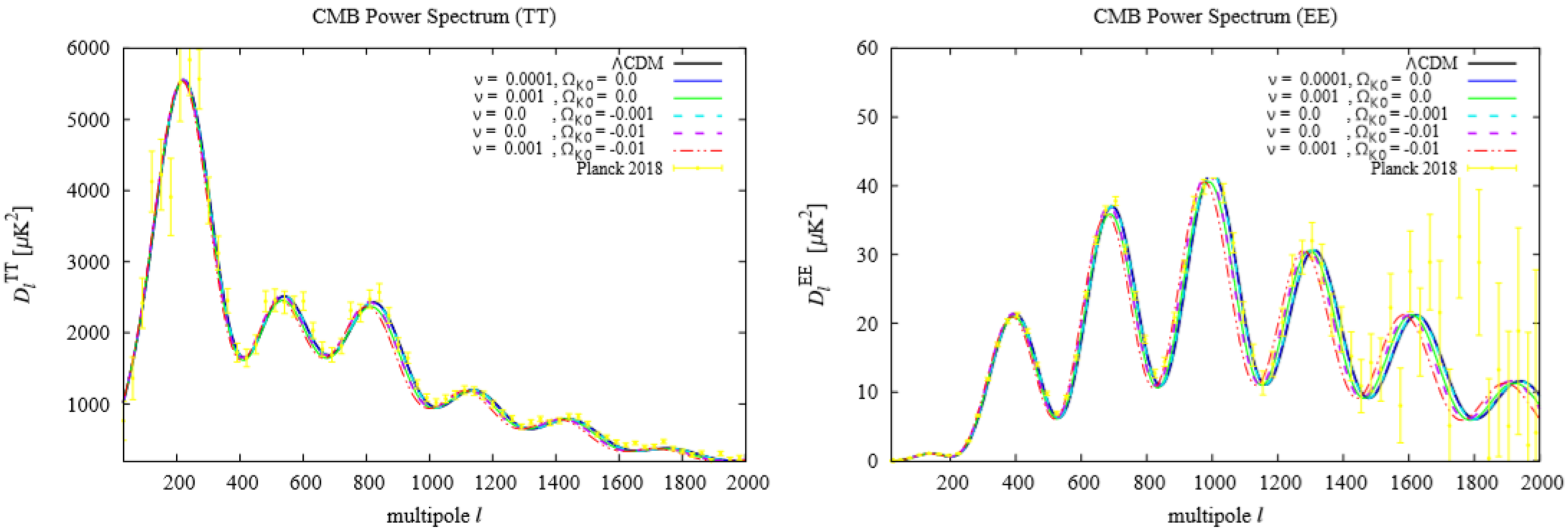
Method to find constraints

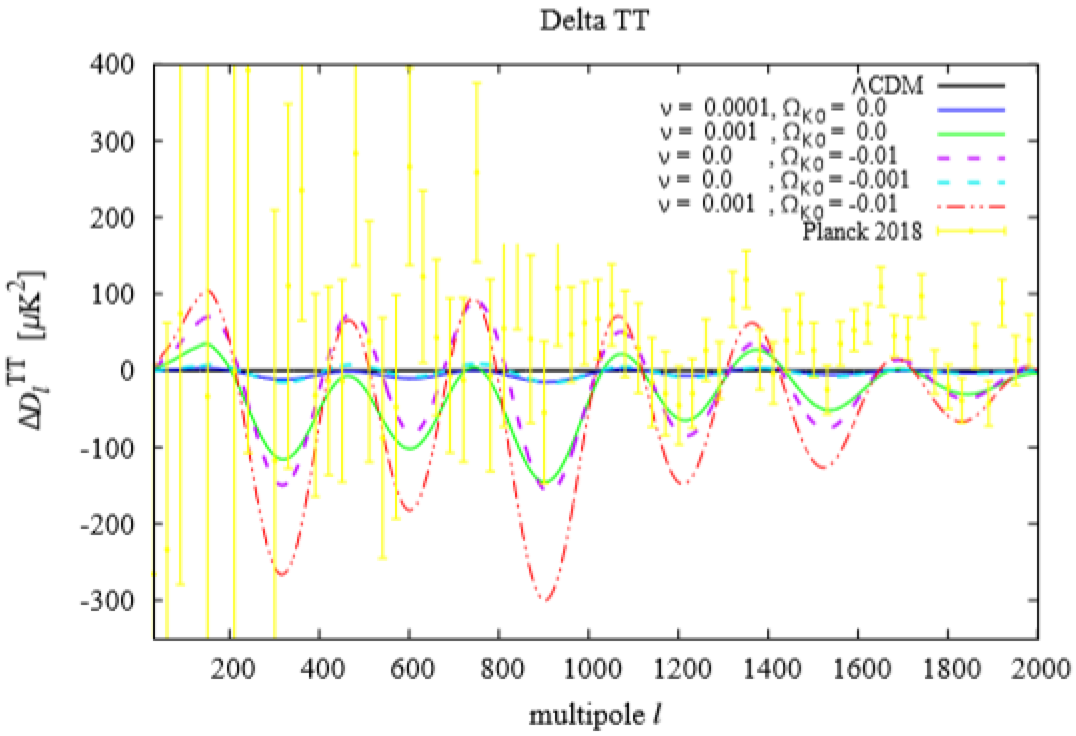
- CAMB package (by Antony Lewis) :
  - Code for Anisotropies in the Microwave Background
  - Solve Boltzmann equations and compute theoretical CMB power spectra and matter power spectrum with a given set of cosmological parameters.
  - We modify the background density evolutions and evolution of the density perturbation.

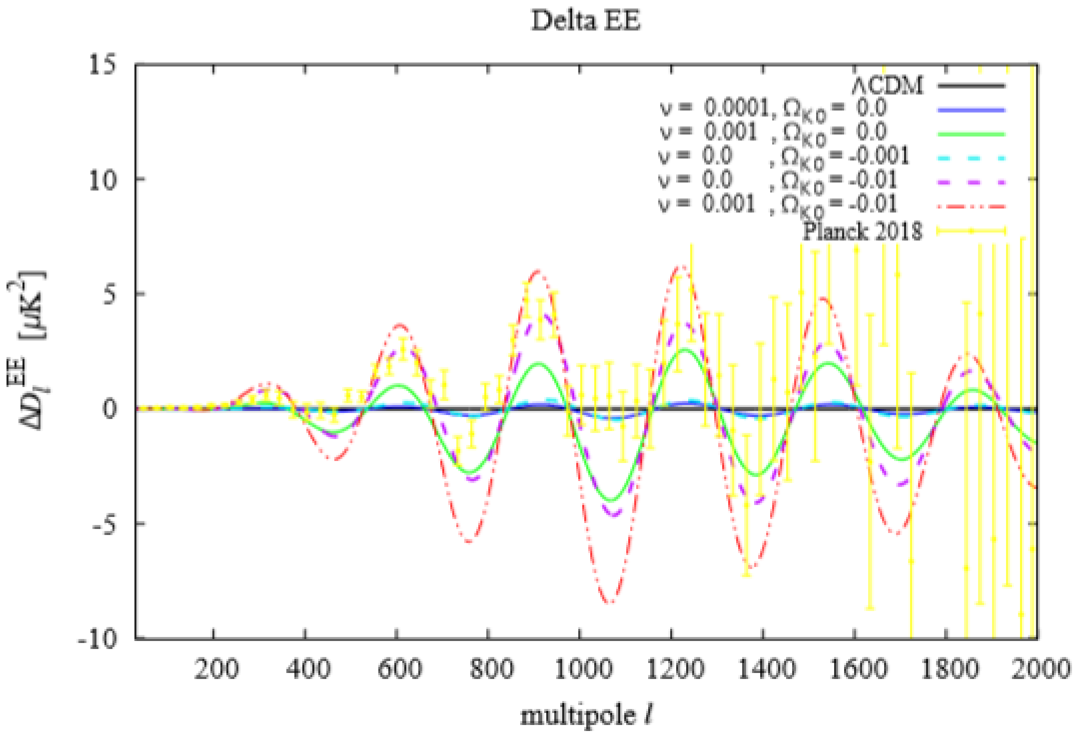
Theoretical CMB power spectra



- ➢ RVM will reduce to ΛCDM when $\upsilon = 0$ and $\Omega_K = 0$.
- ➢ $0.0 < \upsilon < 0.001$ and $0.0 > \Omega_K > -0.01$ fit well to Planck 2018 data.

Theoretical CMB power spectra





- Residues with respect to ΛCDM in flat universe.
- Degeneracy between $\upsilon = 0.001\,, \Omega_K = 0.0$ (green solid line) and $\upsilon = 0.0\,, \Omega_K = -0.01$ (purple dashed line).

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Method to find constraints

- CosmoMC package (by Antony Lewis) :
  - Markov-Chain Monte-Carlo (MCMC) engine
  - Fit the model from the observational data and give the constraints on cosmological parameters.

Method to find constraints

- Data sets
  - CMB: Planck 2015
    (TT, TE, EE, lowTEB, low-l polarization from SMICA)
  - BAO: baryon acoustic oscillation data from 6dF Galaxy Survey and BOSS
  - SN: supernovae data from (JLA) compilation
  - WL: weak lensing data form CFHTLenS
  - $f\sigma_8$ data

Global fitting in non-flat universe

Parameter	CMB+BAO+SN		CMB+BAO+SN +WL+$f\sigma_8$	
Model	RVM	ΛCDM	RVM	ΛCDM
$100\Omega_b h^2$	2.22 ± 0.05	2.24 ± 0.05	2.21 ± 0.05	2.22 ± 0.05
$100\Omega_c h^2$	11.8 ± 0.4	11.8 ± 0.4	11.8 ± 0.4	11.8 ± 0.4
100τ	$11.6^{+5.5}_{-5.7}$	$12.3^{+5.3}_{-5.9}$	$9.0^{+6.4}_{-7.1}$	$10.8^{+6.1}_{-7.2}$
$10^3\Omega_K$	$1.68^{+7.75}_{-6.97}$	$0.32^{+6.99}_{-6.39}$	$7.02^{+7.80}_{-9.04}$	$7.03^{+6.84}_{-7.87}$
Σm_ν	< 0.434	< 0.395	$0.416^{+0.311}_{-0.407}$	$0.497^{+0.335}_{-0.387}$
$10^4\nu$	< 1.50	$-$	< 1.65	$-$
H_0	$67.6^{+1.5}_{-1.4}$	$67.8^{+1.4}_{-1.5}$	$67.6^{+1.5}_{-1.4}$	$67.7^{+1.4}_{-1.5}$
σ_8	$0.836^{+0.054}_{-0.062}$	$0.843^{+0.052}_{-0.059}$	0.759 ± 0.039	$0.756^{+0.040}_{-0.037}$
$\chi^2_{best-fit}$	2039.18	2038.45	2089.66	2089.66

Constraint at 99% C.L. (ν constraint in 68% C.L.)

- In non-flat universe, RVM and ΛCDM are in consistent with χ^2 fitting.
- The σ_8 tension between data sets is alleviated in RVM.

Global fitting in non-flat universe

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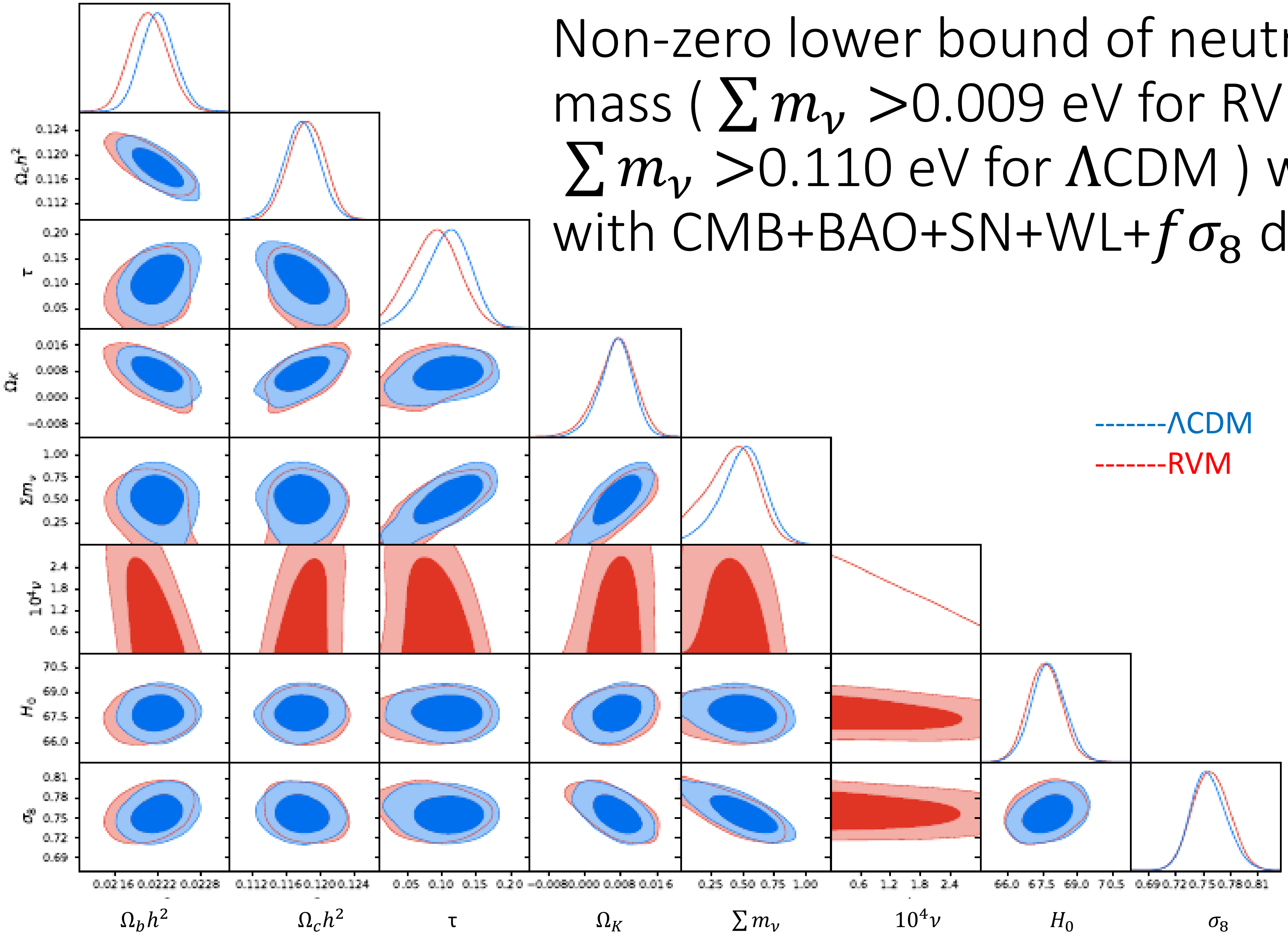
Constraint at 99% C.L. (ν constraint in 68% C.L.)

- We constraint $\nu \le O(10^{-4})$ and $|\Omega_K| \le O(10^{-2})$ for RVM in non-flat universe.
- Compare with RVM in flat universe in previous work:
  - The constraints of ν and $\sum m_\nu$ is relaxed in non-flat universe.
  - The constraints of ν and $\sum m_\nu$ is of the same order as in flat universe.

Non-zero lower bound of neutrino mass ($\sum m_\nu$ >0.009 eV for RVM and $\sum m_\nu$ >0.110 eV for ΛCDM) when fit with CMB+BAO+SN+WL+$f\sigma_8$ data



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Conclusion

- In non-flat universe, RVM and ΛCDM are in consistent with χ^2 fitting.
- The constraints of ν in RVM does not broaden significantly when curvature is involved.
- Involvement of curvature provide us a chance to get non-zero lower bound of neutrino mass in cosmological models.

THANK YOU