# The Effective Quintessence from String Lanscape

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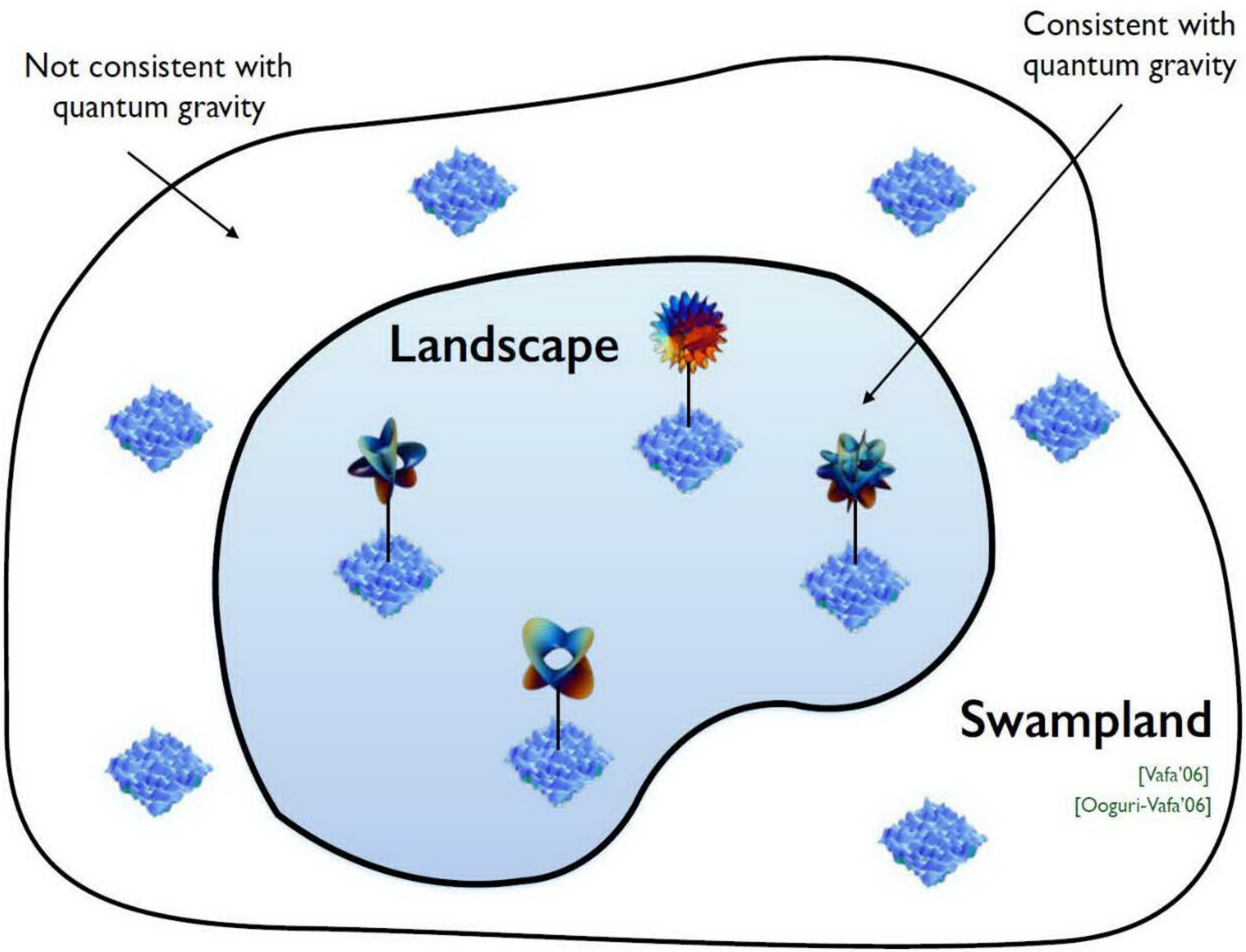
Dec. 30,2018, 5th International Workshop on
Dark Matter, Dark Energy and Matter-Antimatter Asymmetry,
Fo-Guang-Shan, Kaohsiung

# Outline

- 1) The String Swampland and String Landscape
- 2) The origin and sign of Large Scale Lorentz Violation
- 3) The Cosmology with large scale Lorentz Violation in swampland and string landscape
- 4) Summary

- The possible string vacua compactification choice can be of order 10^272000 (in F-theory). Among them, inequivalent ones constitute the string landscape.
- it is likely that any consistent looking lower dimensional effective field theory (EFT) coupled to gravity can arise in some way from a string theory compactication
- the set of all EFT which do not admit a string theory UV completion as the swampland.


Not consistent with
quantum gravity
Consistent with
quantum gravity
Landscape
Swampland
[Vafa'06]
[Ooguri-Vafa'06]

dS space does not exist as a consistent quantum theory of gravity and it belongs to the swamp-land.----1. Metastable dS and 2. Quintessence models, the dS vacuum is completely unstable, and slowly rolling down

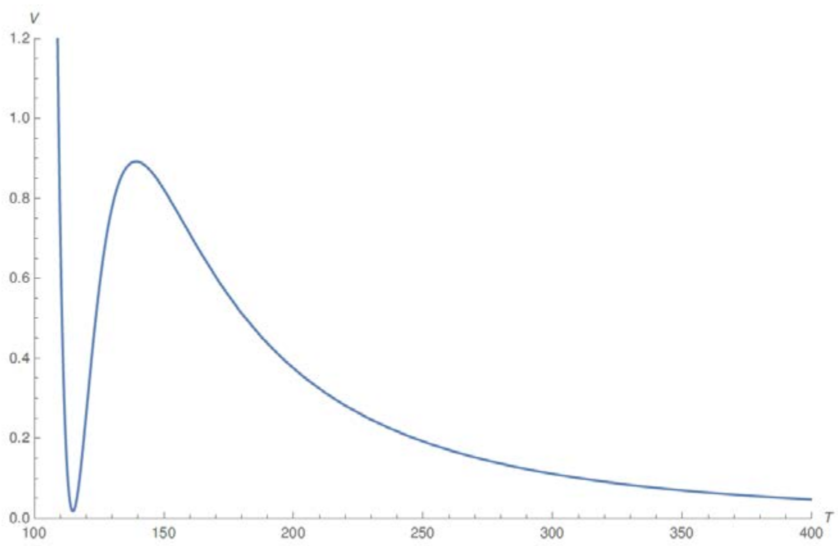



**Figure 7**. The scalar potential for a metastable $dS$.

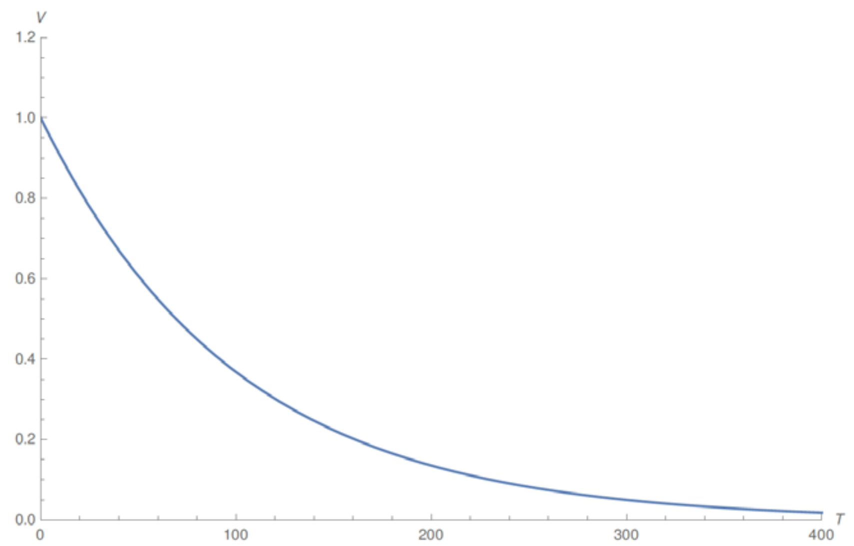



**Figure 8**. The scalar potential for an unstable $dS$.

- dS Swampland Conjecture: Obied, Ooguri, Spodyneiko, Vafa ‘18
- In the dS regime, there exists always a scalar field direction where the potential is sliding with a slope bigger than the gravitational strength
- This excludes all dS stationary solutions (dS local minima, maxima(refined), saddle points), implies any dS state should run away fast enough.
- The dark energy of our Universe can not be a C.C, but is the potential energy of a sliding scalar field Q=quintessence
- Refined dS swampland conjecture: Garg, Krishnan ’18 Ooguri, Palti, Shiu, Vafa ‘18
- All unstable dS stationary points (Higgs & pion maxima) are compatible with the refined dS SC

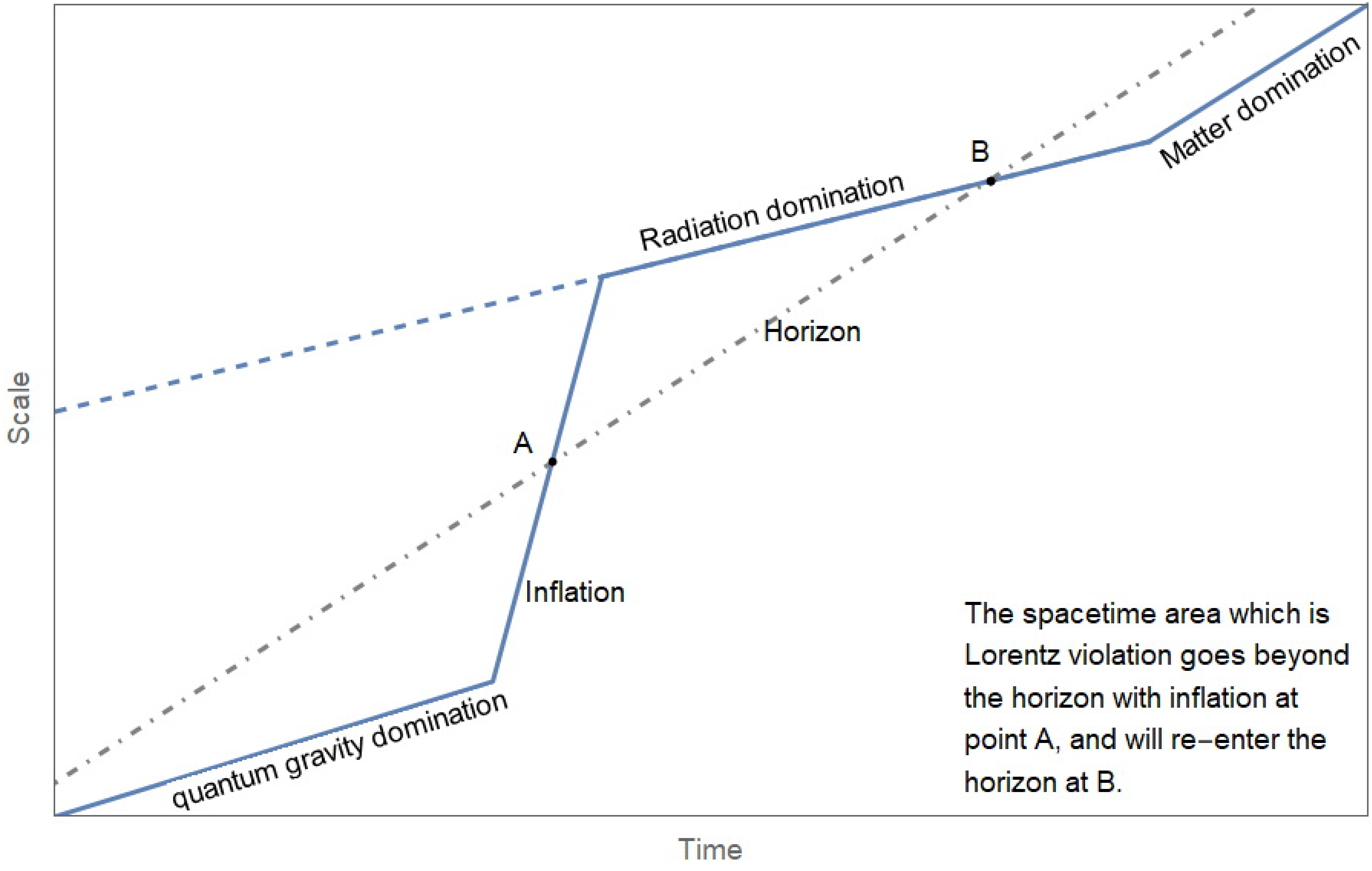
# The $\Lambda$CDM model

- Einstein equation with cosmological constant

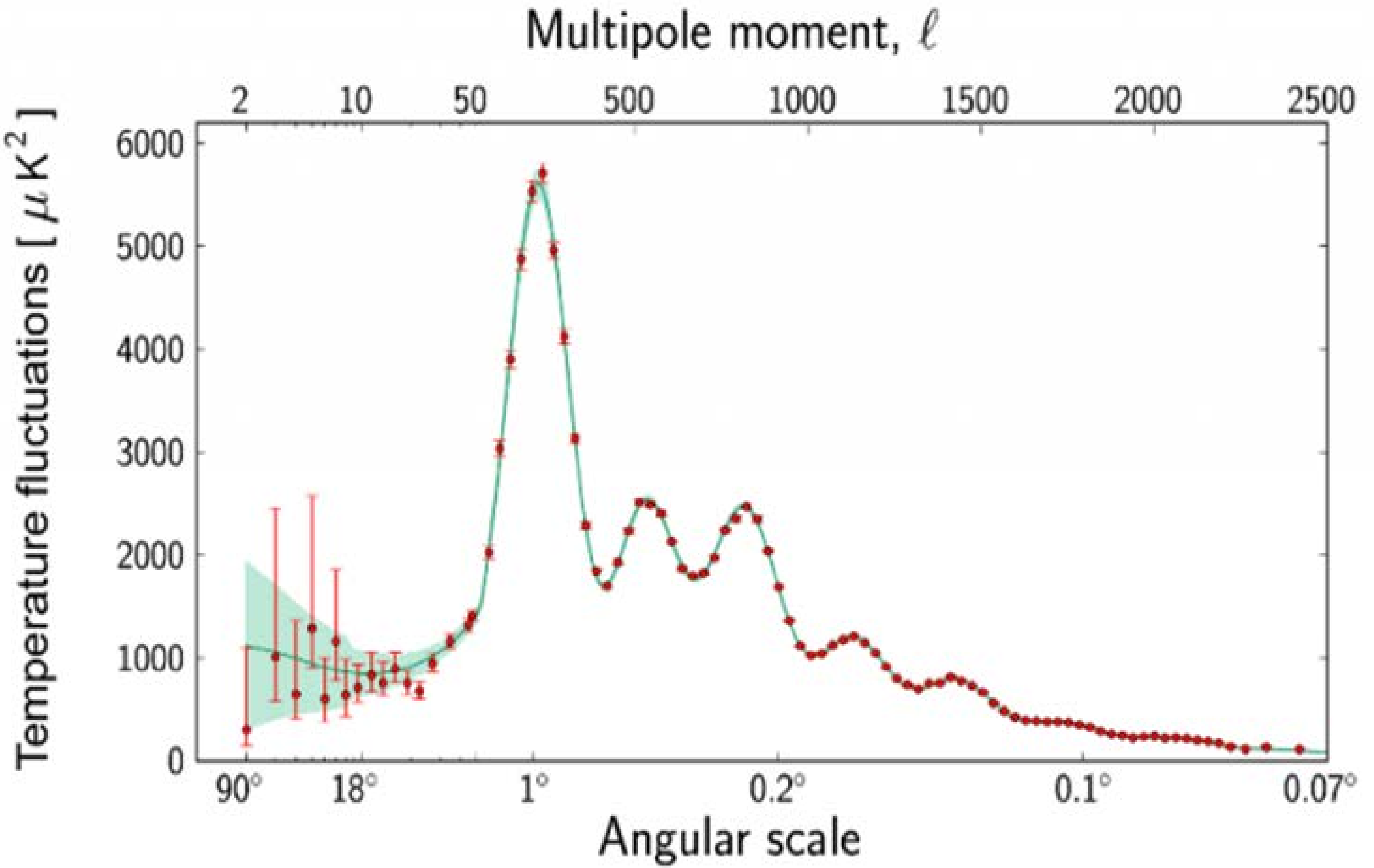
$$S_E = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(R-2\Lambda\right)$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\left(T_M\right)_{\mu\nu}$$

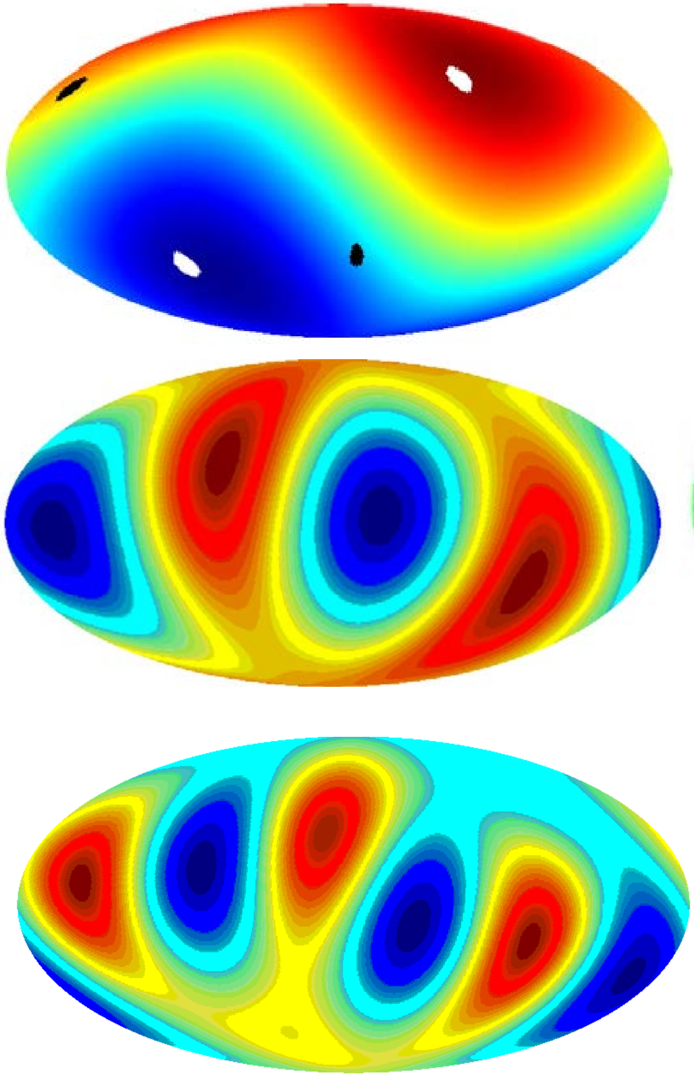
- Difficulty: There is huge dismatch between theoretical prediction and observation of $\Lambda$, ranging from 54 to 112 order of 10

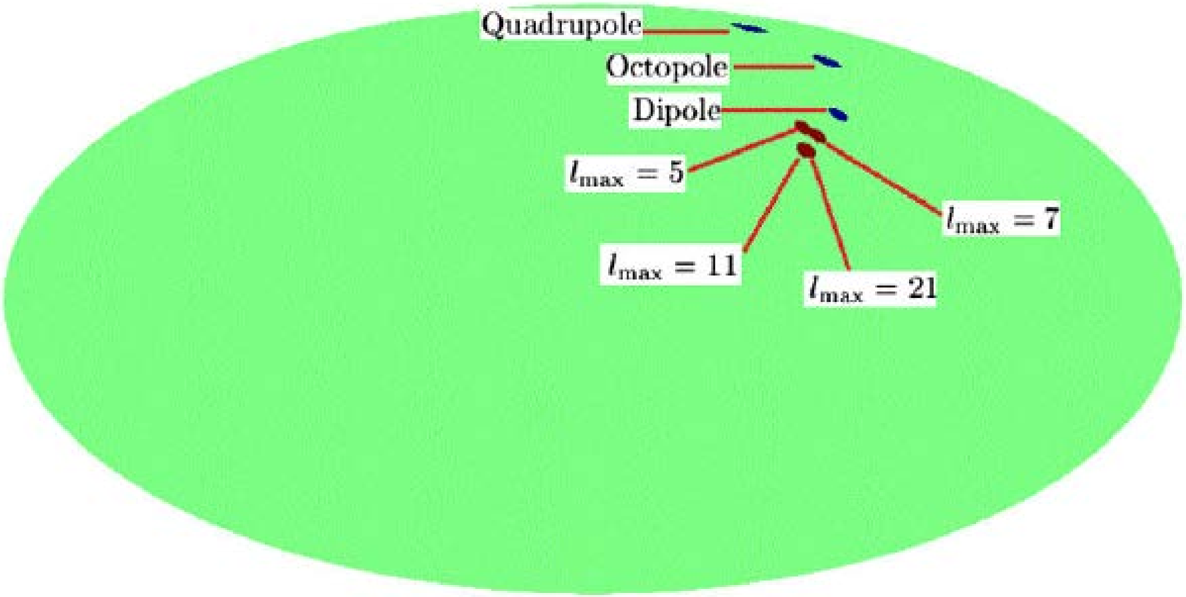

Matter domination
B
Radiation domination
Horizon
Scale
A
Inflation
quantum gravity domination
The spacetime area which is Lorentz violation goes beyond the horizon with inflation at point A, and will re−enter the horizon at B.
Time

# Anistropies of CMB



# Comparing with preferred directions in CMB dipole, quadrupole and octopole





# The Lorentz Violated EFT of Gravity

- The action for a sim(2) gravity

$$S_E = \frac{1}{16\pi G}\int d^4xh\left(R^{ab}{}_{ab} + \lambda_1{}^{\mu}\left(A^{10}{}_{\mu} - A^{31}{}_{\mu}\right) + \lambda_2{}^{\mu}\left(A^{20}{}_{\mu} + A^{23}{}_{\mu}\right)\right)$$

- The Lagrange-multipliers term can be regarded as an effective angular momentum distribution $C_{M\,eff}$

$$\mathcal{D}_\nu\left(h\left(h_a{}^\nu h_b{}^\mu - h_a{}^\mu h_b{}^\nu\right)\right) = 16\pi G\left(C_M + C_{M\,eff}\right)_{ab}{}^{\mu}$$

- Lorentz violation leads to non-trivial distribution of contortion
- The non-trivial effective concribution to the energy-momentum distribution by contortion is expected to be responsible for the dark partner of the matter.

$$\tilde{R}_c{}^a - \frac{1}{2}\delta_c{}^a\tilde{R} = 8\pi G\left(T_{eff} + T_M\right)_c{}^a$$

- The Bianchi Identities imply the conservation of $T_{eff}$

arXiv:1802.03502

# The Modified Constrain for SO(3)

- For SO(3) $\Lambda_0{}^j(x)=0$

$$A'^i{}_{0\mu}=\Lambda^i{}_j(x)A^j{}_{0\mu}\Lambda_0{}^0(x)+\Lambda^i{}_j(x)\partial_\mu\Lambda_0{}^j(x)$$

$$=\Lambda^i{}_j(x)A^j{}_{0\mu}$$

- The Modified Constrain for SO(3) can be

$$S_E=\frac{c^4}{16\pi G}\int d^4xh\left(R-2\Lambda_0+\lambda^u\left(\left(A^0{}_{1u}\right)^2+\left(A^0{}_{2u}\right)^2+\left(A^0{}_{3u}\right)^2-f_u^2\right)\right)$$

- Where $f_\mu$ can be regarded as the measurement of Lorentz violation.

# Accelerating Expansion of the Universe

- To construct the FRW like solution of the model

$$ds^2 = \mathrm{d}t^2 - a(t)^2\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta\mathrm{d}\varphi^2\right)$$

- The naïve commoving tetrad can be chosen as

$$h^0 = \mathrm{d}t,\ h^1 = \frac{a(t)}{\sqrt{1-kr^2}}\mathrm{d}r,\ h^2 = ra(t)\mathrm{d}\theta,\ h^3 = r\sin\theta a(t)\mathrm{d}\varphi$$

- And

$$h_0 = \frac{\partial}{\partial t},\ h_1 = \frac{\sqrt{1-kr^2}}{a(t)}\frac{\partial}{\partial r},\ h_2 = \frac{1}{ra(t)}\frac{\partial}{\partial\theta},\ h_3 = \frac{1}{r\sin\theta a(t)}\frac{\partial}{\partial\varphi}$$

# Accelerating Expansion of the Universe

- The field eqn for the tetrad field by $\dfrac{\delta S}{\delta h^{a}{}_{\mu}}$

$$G^{a}{}_{b} \equiv R^{a}{}_{b} - \frac{1}{2} R \delta^{a}{}_{b} + \Lambda_{0} \delta^{a}{}_{b} = \frac{8\pi G}{c^{4}} T^{a}{}_{b}$$

# Cosmic solution of contortion

- The ideal fluid of cosmic media demands

$$G^1{}_1 = G^2{}_2 = G^3{}_3$$

- With decomposition of connections, $A^a{}_{b\mu} = \Gamma^a{}_{b\mu} + K^a{}_{b\mu}$ a simple solution can be chosen as

$$K^0{}_{11} = K^0{}_{22} = K^0{}_{33} = \mathcal{K}(t)$$

- With other contortion components vanish.
- And the relation with $f_\mu(x)$ is

$$\left( f_t, f_r, f_\theta, f_\varphi \right) = \left( a(t)\mathcal{K}(t) + \dot{a}(t) \right) \cdot \left( 0, \frac{1}{\sqrt{1-kr^2}}, r, r\sin\theta \right)$$

- The degree of freedom of $f_\mu(x)$ is actually 4, which hide in the choice of frames by Lorentz boost.

- Denoting $\tilde{G}^a_c$ the Einstein tensor of Levi-Civita Connection

$$G^a{}_c = \tilde{G}^a_c + 2\left(\tilde{\nabla}_{[c}K^{ab}{}_{b]} + K^a{}_{e[c}K^{eb}{}_{b]} - \frac{1}{2}\left(\tilde{\nabla}_d K^{db}{}_b + K^d{}_{e[d}K^{eb}{}_{b]}\right)\delta^a{}_c\right) + \Lambda_0\delta^a{}_c$$

- The gravitation field equation

$$\tilde{R}^a{}_c - \frac{1}{2}\tilde{R}\delta^a{}_c = 8\pi G\left(T + T_\Lambda\right)^a{}_c, \quad T_\Lambda{}^a{}_c = \frac{1}{8\pi G}\Lambda^a{}_c = \frac{1}{8\pi G}\left(\tilde{G}^a_c - G^a{}_c\right)$$

- The gravitation field equations for the naïve tetrad of RW metric of $k = 0$

$$3\left(\mathscr{K} + \frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{c^4}\left(\rho + \Lambda_0\right)$$

$$\left(\mathscr{K} + \frac{\dot{a}}{a}\right)^2 + 2\left(\dot{\mathscr{K}} + \frac{\dot{a}\mathscr{K}}{a} + \frac{\ddot{a}}{a}\right) = \frac{8\pi G}{c^4}\left(-p + \Lambda_0\right)$$

- And

$$[T_\Lambda]^a{}_c = Diag(\rho_\Lambda, -p_\Lambda, -p_\Lambda, -p_\Lambda)$$

$$\rho_\Lambda = -\frac{c^4}{8\pi G}\left(3\mathscr{K}^2 + 6\mathscr{K}\frac{\dot{a}}{a} - \Lambda_0\right)$$

$$p_\Lambda = \frac{c^4}{8\pi G}\left(\mathscr{K}^2 + 4\mathscr{K}\frac{\dot{a}}{a} + 2\dot{\mathscr{K}} - \Lambda_0\right)$$

- Denote $\Lambda_0$ as the cosmological constant in our Lorentz violating model, Λ as the observed one and take the geometrical unit $\frac{8\pi G}{c^4}=1$ and $x=\frac{\Lambda_0}{\Lambda}$
- the modified Friedmann Equation

$$\left(\mathscr{K}+\frac{\dot{a}}{a}\right)^2=\frac{1}{3}(\rho+\Lambda_0)$$

$$\ddot{a}=-\frac{a}{2}\left(p+\frac{\rho}{3}\right)+\frac{1}{3}\left(a\Lambda_0-3\frac{d}{dt}(a\mathscr{K})\right)$$

- The Friedmann Eqns in ΛCDM

$$\left(\frac{\dot{a}}{a}\right)^2-\frac{\Lambda}{3}=\frac{\rho}{3}$$

$$\ddot{a}=-\frac{a}{2}\left(p+\frac{\rho}{3}\right)+\frac{1}{3}a\Lambda$$

- Accelerating expansion condition:

$$\frac{a}{2}\left(p+\frac{\rho}{3}-\frac{2}{3}\Lambda_0\right)+\frac{d}{dt}\left(a\mathcal{K}\right)<0$$

- the modified Friedmann Equation with the Eq of States for cosmic media p=wρ

$$\dot{H}(t)+\dot{\mathscr{K}}(t)+H(t)\left(H(t)+\mathscr{K}(t)\right)+\frac{3w+1}{2}\left(H(t)+\mathscr{K}(t)\right)^2-\frac{(w+1)}{2}\Lambda_0=0$$

- And w≈0 for matter dominated period
- Define the Effective Cosmological Constant

$$\Lambda_{eff}(t)=\Lambda_0-3\left(\mathscr{K}(t)^2+2\mathscr{K}(t)\frac{\dot{a}(t)}{a(t)}\right)$$

- Initial conditions: $$\mathcal{K}(t_0)^2 + 2\mathcal{K}(t_0)\frac{\dot{a}(t_0)}{a(t_0)} = \frac{\Lambda_0}{3} - \frac{\Lambda}{3}$$

$$\mathcal{K}(t_0) = H_0\left(\pm\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0}}-1\right) \rightarrow \Lambda_0 \geq -(3H_0-\Lambda) \approx -\frac{2}{5}\Lambda$$

- Three cases of approximation
- Case A: $\frac{\mathrm{d}}{\mathrm{d}t}(a\mathcal{K}) = -\frac{1}{3}a(\Lambda-\Lambda_0)$
- Or

$$H(t)\mathscr{K}(t) + \dot{\mathscr{K}}(t) = \frac{1}{3}(\Lambda_0 - \Lambda)$$

- Case B:

$$\dot{\mathscr{K}}(t)+(3w+2)H(t)\mathscr{K}(t)+\frac{3w+1}{2}\mathscr{K}^2(t)=\frac{w+1}{2}(\Lambda_0-\Lambda)$$

- Case C:

$$[T_\Lambda]^a{}_c = Diag(\rho_\Lambda, -p_\Lambda, -p_\Lambda, -p_\Lambda)$$

$$p_\Lambda = w_0\rho_\Lambda$$

$$(3w_0+1)\mathscr{K}^2+(6w_0+4)H\mathscr{K}+2\dot{\mathscr{K}}-(w_0+1)\Lambda_0=0$$

$$\dot{H}+\dot{\mathscr{K}}+H(H+\mathscr{K})+\frac{3w+1}{2}(H+\mathscr{K})^2-\frac{(w+1)}{2}\Lambda_0=0$$

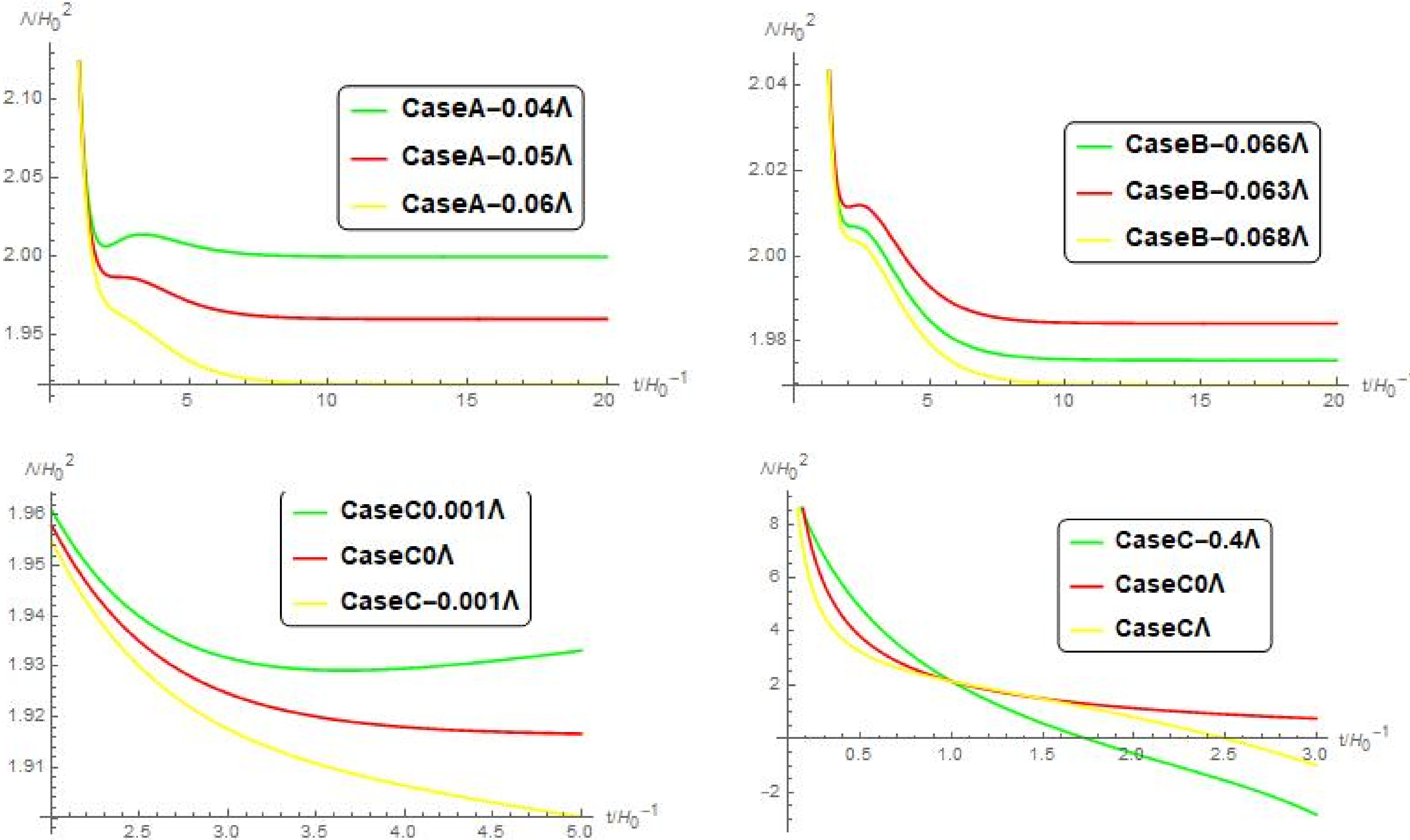
$$\mathscr{K}(t_0)=H_0\left(\pm\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0{}^2}}-1\right),\quad H_0=H(t_0)$$

- the cirtical value for $\Lambda_0$ which symbolizes the transformation from a monotonically quintessence like $\Lambda_{eff}(t)$ to the metastable dS potential can be solved for all of the case of approximations. The critical value $\Lambda_{0-crit}$ centers around $\Lambda_{0-crit}=0$ . It can be conjectured the deviation of $\Lambda_{0-crit}$ from 0 is caused by the approximations. In a more elaborated model, it should have $\Lambda_{0-crit}=0$ .

| | The initial value $\mathscr{K}(t_0)$ | The critical value for $\Lambda_0$ |
|---|---|---|
| CaseA | $\mathscr{K}(t_0)=H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}-1\right)$<br>$\mathscr{K}(t_0)=-H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}+1\right)$ | -0.05Λ<br>-0.187Λ |
| CaseB | $\mathscr{K}(t_0)=H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}-1\right)$<br>$\mathscr{K}(t_0)=-H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}+1\right)$ | -0.066Λ<br>-0.2144Λ |
| CaseC($w_0$=-1) | $\mathscr{K}(t_0)=H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}-1\right)$<br>$\mathscr{K}(t_0)=-H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}+1\right)$ | 0.00001<br>0.00001 |
| CaseC( $w_0$=-8/9) | $\mathscr{K}(t_0)=H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}-1\right)$<br>$\mathscr{K}(t_0)=-H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}+1\right)$ | 0.119Λ<br>0.075Λ |

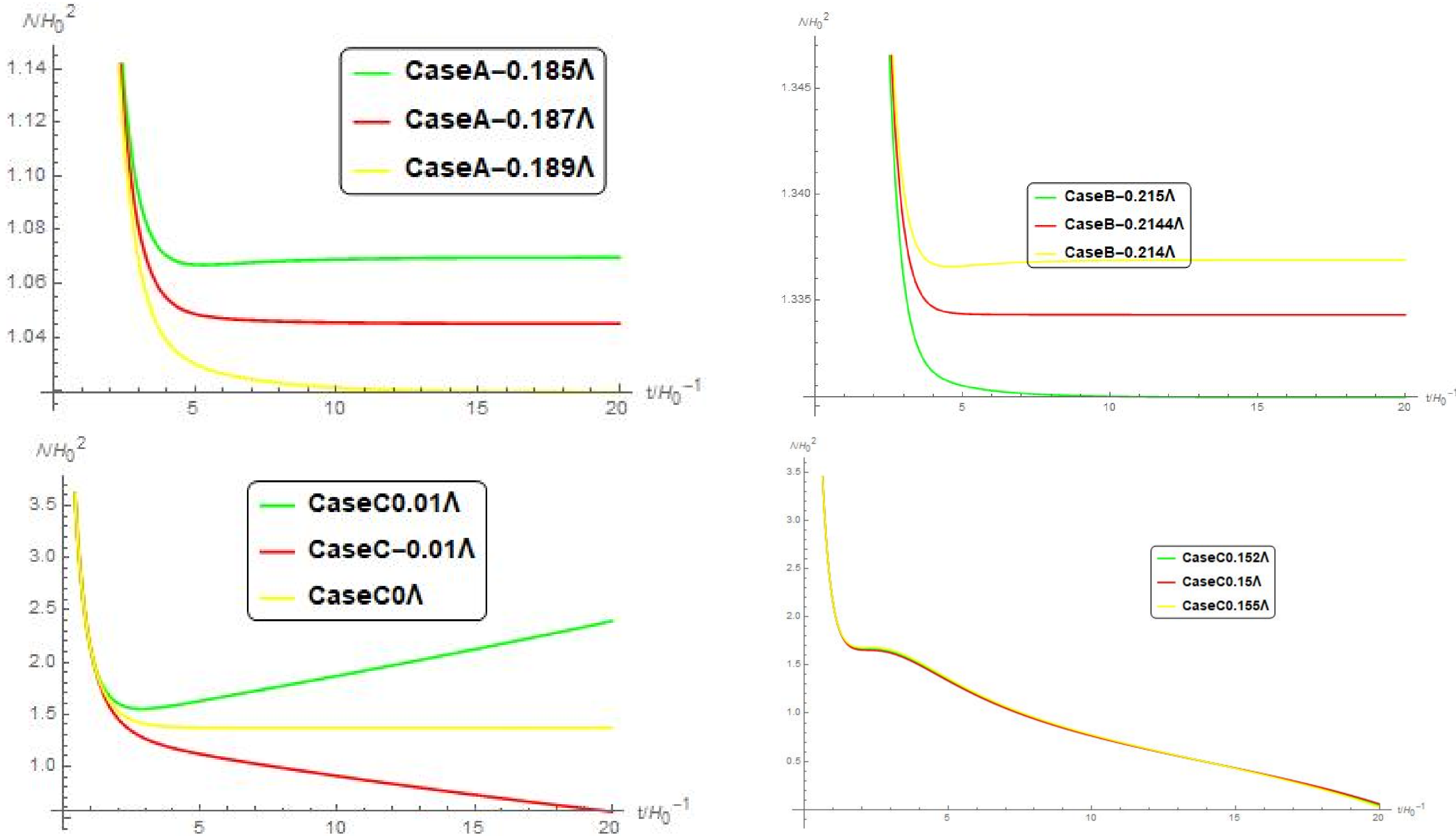
- For Case C, when $w_0 > -8/9$ there doesn't exist a solution of the critical value for $\Lambda_0$ which signs the transformation from a monotonically quintessence potential to a metastable dS potential

| | | |
|---|---|---|
| CaseC( $w_0$=-7/9) | $\mathscr{K}(t_0) = H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\,2}}}-1\right)$ <br> $\mathscr{K}(t_0) = -H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\,2}}}+1\right)$ | Monotonic for all $\Lambda_0$ <br> 0.152Λ |
| CaseC( $w_0$=-1/2) | $\mathscr{K}(t_0) = H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\,2}}}-1\right)$ <br> $\mathscr{K}(t_0) = -H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\,2}}}+1\right)$ | Monotonic for all $\Lambda_0$ <br> 0.321Λ |
| CaseC( $w_0$=-1/3) | $\mathscr{K}(t_0) = H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\,2}}}-1\right)$ <br> $\mathscr{K}(t_0) = -H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\,2}}}+1\right)$ | Monotonic for all $\Lambda_0$ <br> 0.397Λ |




- The transformation from quintessence to dS

- $\mathscr{K}(t_0)=H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\,2}}}-1\right)$ and $w_0=-1,-7/9$ for Case C




- The transformation from quintessence to dS
- $\mathscr{K}(t_0) = -H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{2}}}+1\right)$ and $w_0 = -1, -7/9$ for Case C

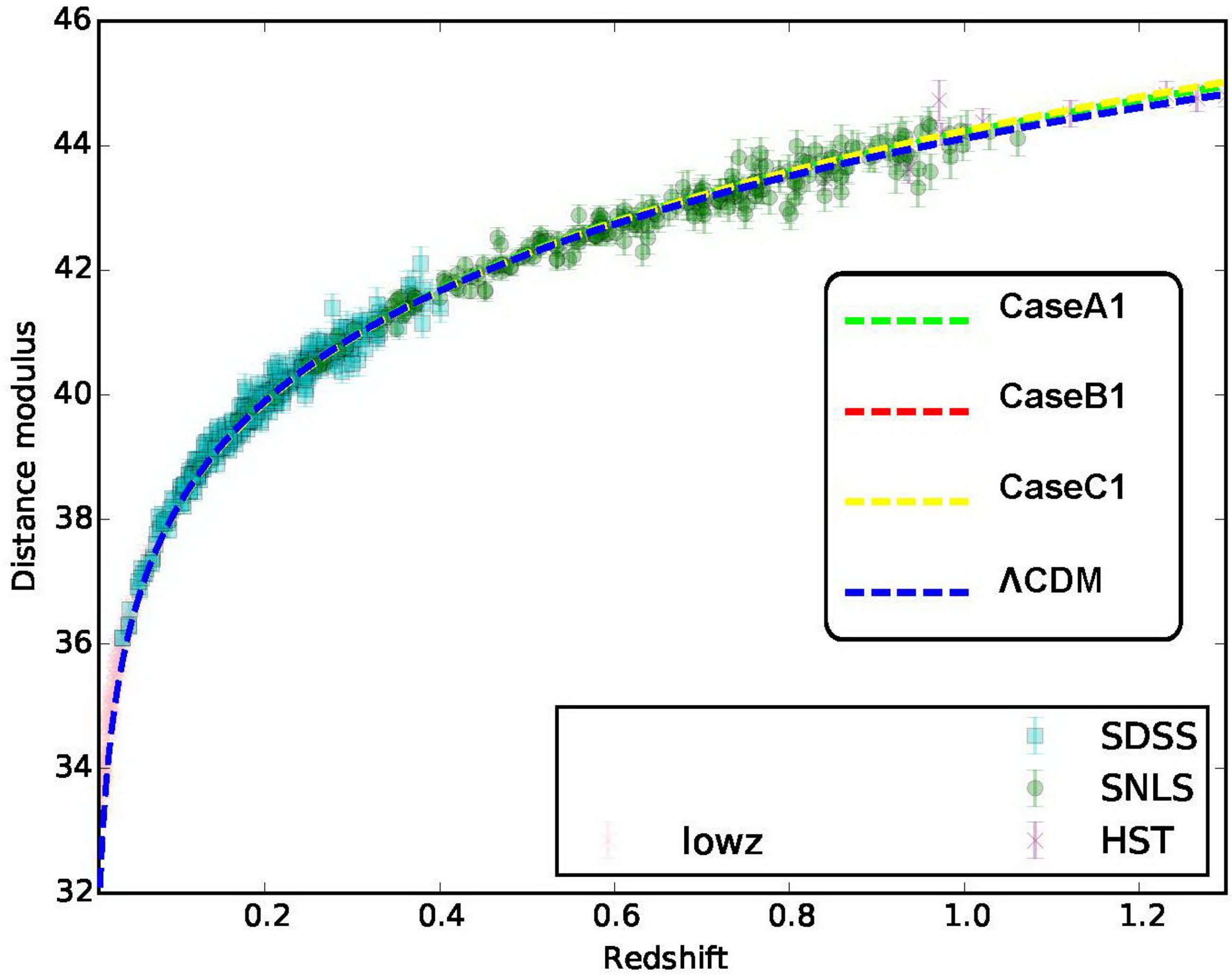
- Actually Case C approximation is not a good one from the comparition of Hubble constant vs t and the luminant distance vs redshift z.
- The reason may be we use a fixed w_0 in the equation of state of dark partner part. Ignore the case w_0>-8/9 (excluded by observation of luminosity distance with redshift relation),we can make the conclusion:
- Quintessence is generated from string landscape effectively.
- The critical value of cosmological constant separating quintessence from metastable dS is approximately zero

- The formula for the redshift remains unchanged as in the Lorentzian invariant case. $1+z=\frac{a_0}{a}$
- The dependence of luminosity distance $d_L$ with redshift and Hubble constant.

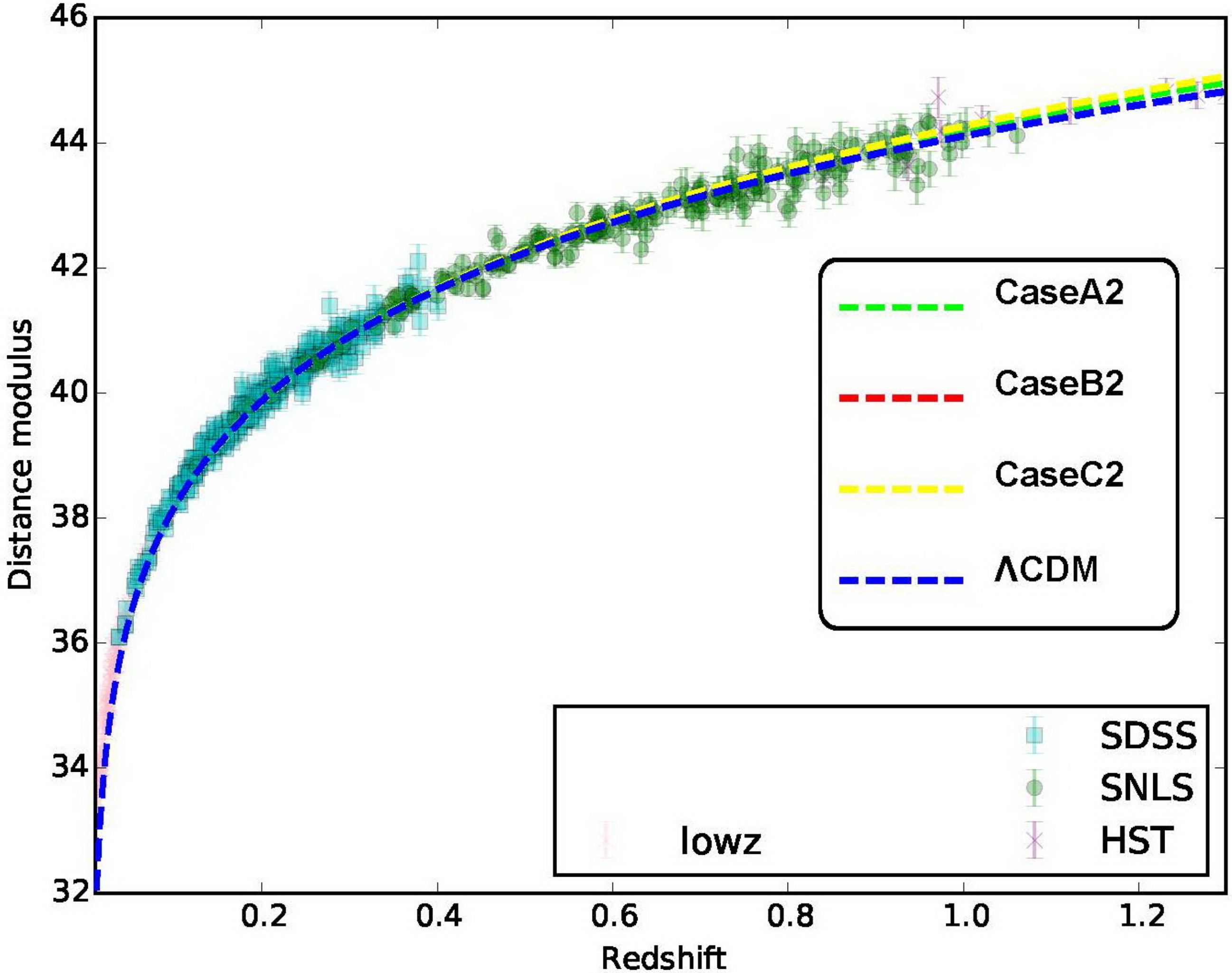
$$H(z)=\left(\frac{\mathrm{d}}{\mathrm{d}z}\frac{d_L}{1+z}\right)^{-1}, \qquad \frac{\mathrm{d}t}{\mathrm{d}z}=-\frac{1}{1+z}\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{d_L}{1+z}\right)$$

- The distance modulus is defined as

$$\mu=25+5\log_{10}\left(d_L / Mpc\right)$$




- Comparation of distance magnitudes. $\Lambda_0 = -0.4\Lambda$
- $\mathscr{K}(t_0) = H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}-1\right)$ and $w_0 = -0.88$ for Case C




- Comparation of distance magnitudes vs z, $\Lambda_0 = -0.4\Lambda$
- $\mathscr{K}(t_0) = -H_0\left(\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0^{\ 2}}}+1\right)$ and $w_0 = -8/9$ for Case C

# Summary

- For string landscape with $\Lambda_0 > -\left(3H_0 - \Lambda\right) \approx -\frac{2}{5}\Lambda$ ,the effective cosmological constant naturally give a quintessence like potential which satisfies the dS Swampland conjecture
- The string swampland is not necessary for late accelerating expansion
- Accelerating expansion of our universe can be consistent with quantum gravity
- For string swampland with positive cosmological constant for most reasonally approximation, the effective cosmological constant behaves like a metastable dS potential rather than the quintessence like one when the large scale Lorentz violation is taken into account.
- the scenario prefers approximately zero cosmological constant $\Lambda_{0-crit} = 0$ as a separation of effective quintessence from meta-stable dS

# THANKS!