The Effective Potential originating from Swampland and the non-trivial Brans-Dicke coupling

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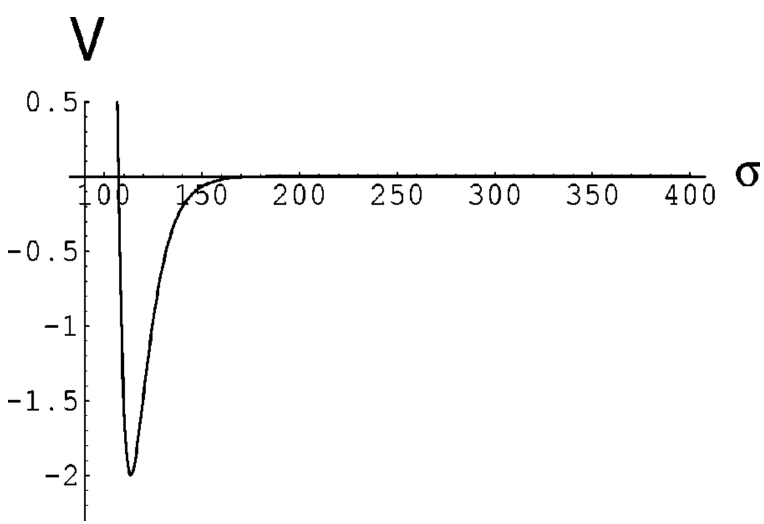
Outline

- 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 10^500. 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 compactification
- the set of all EFT which do not admit a string theory UV completion as the swampland.
- The generic AdS vacuum is SUSY preserving.
- To account the inflation and accelerating expansion one needs to lift the AdS to dS vacuum.

The uplifting the AdS type of vacua to dS ones comes from $\bar{D}_3$ branes tension in a sufficiently warped background, in the presence of quantum corrections, by carefully adding $\bar{D}_3$ branes into the compactification. –KKLT construction Kachru, PRD 03

Shortage: no-go theorems, restrictions on ingredients used in string theory, typically specific combinations of fluxes, D-branes, orientifolds



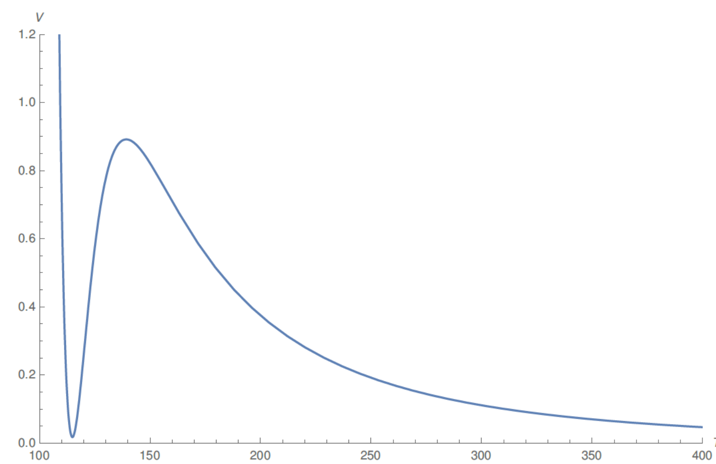


Figure 7. The scalar potential for a metastable dS.

The second criterion of swampland conjecture excludes the EFT with a meta-stable dS vacuum as theory with UV completion. Metastable dS belongs to the swampland.

Quintessence model can satisfy the second criterion.

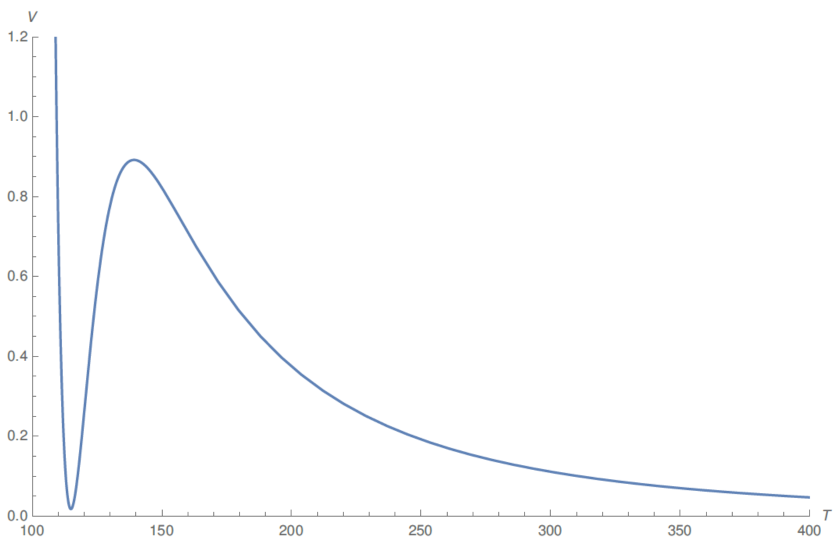


Figure 7. The scalar potential for a metastable dS.

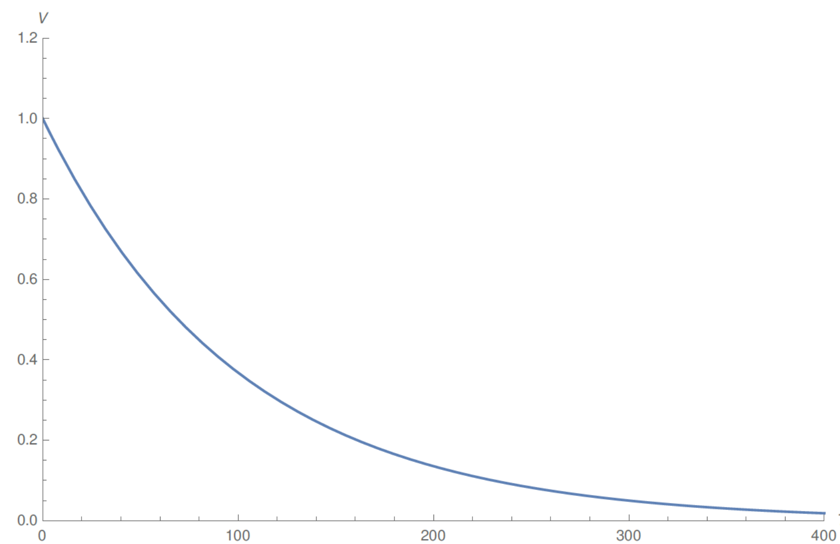
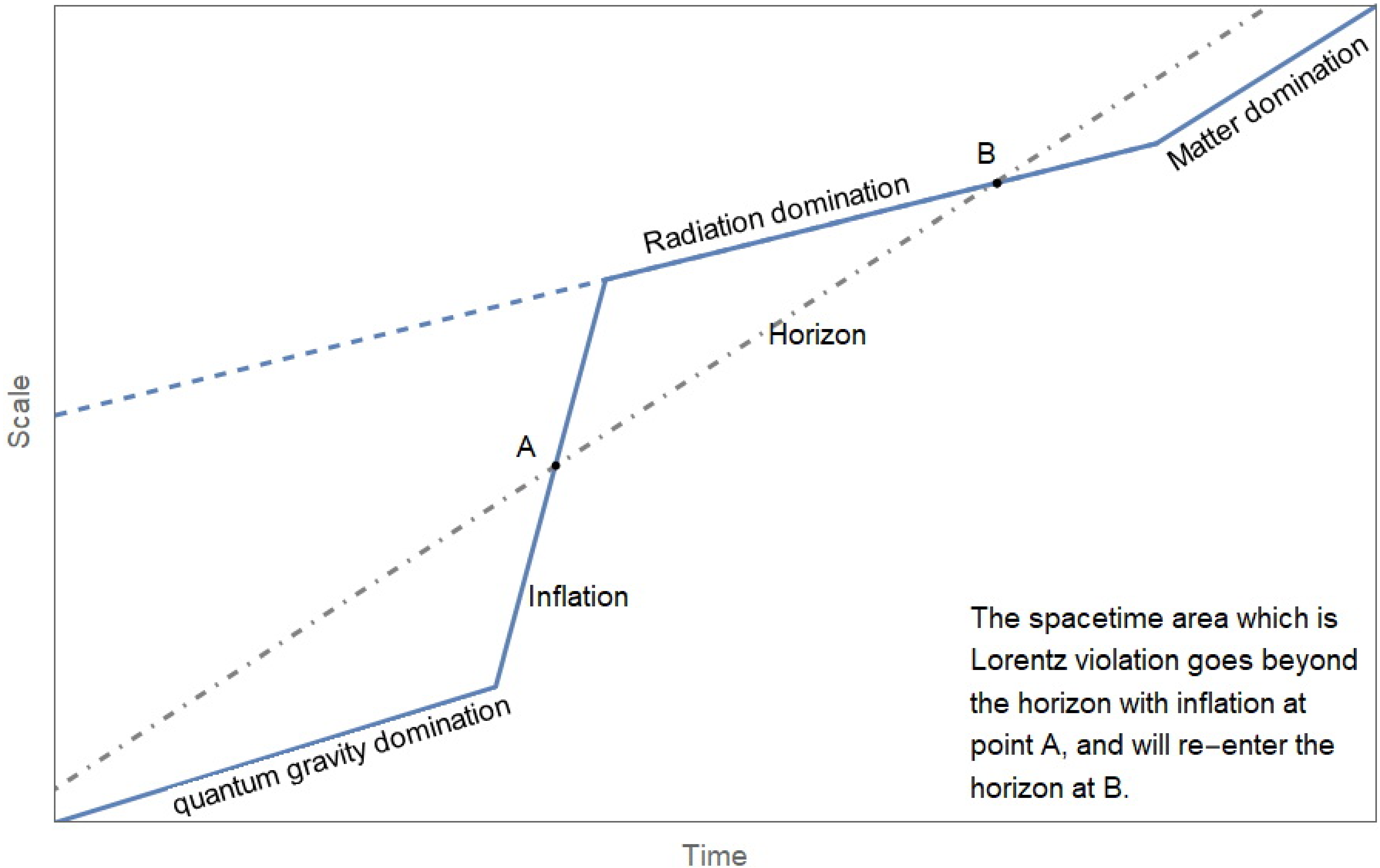
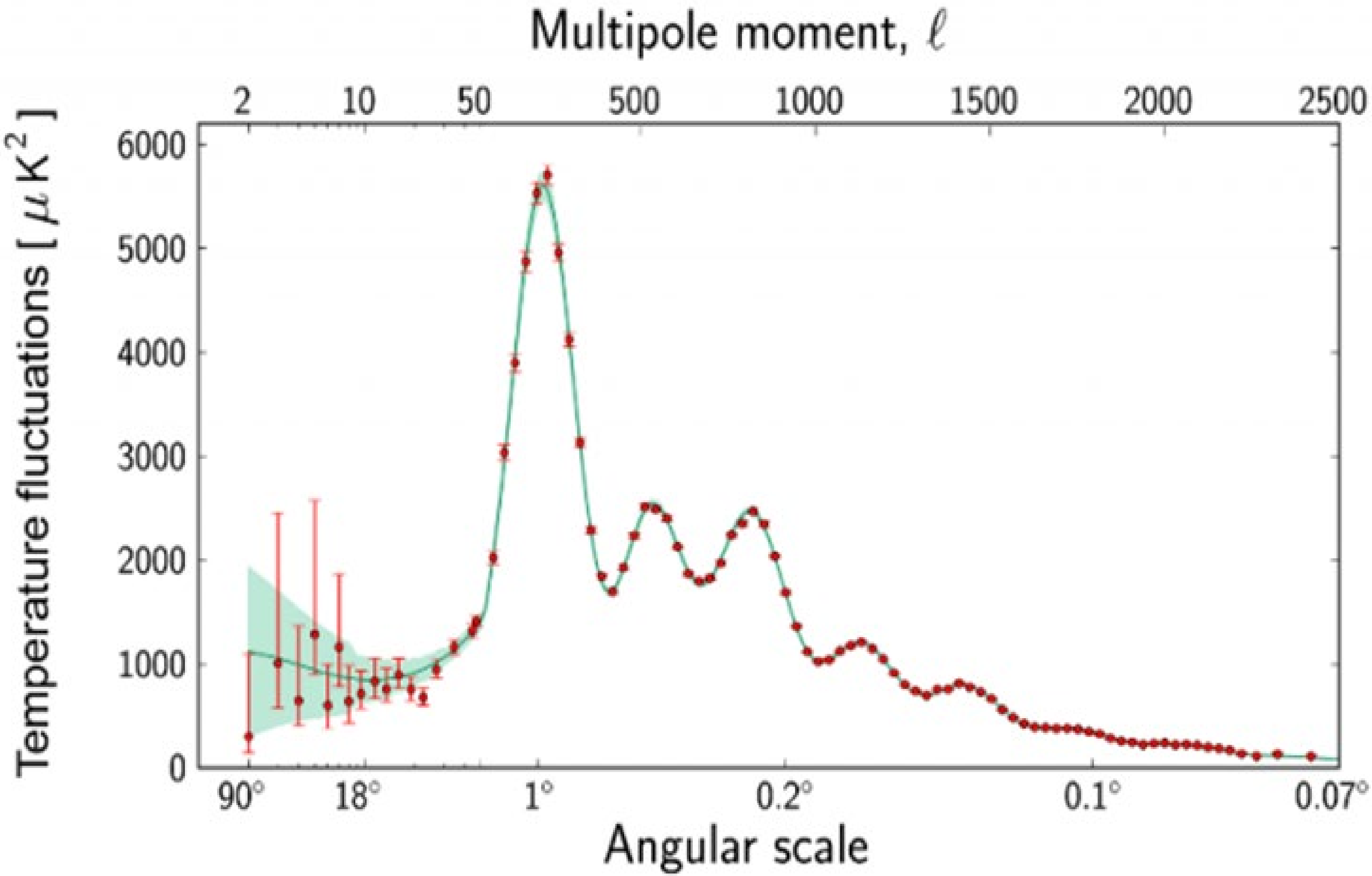


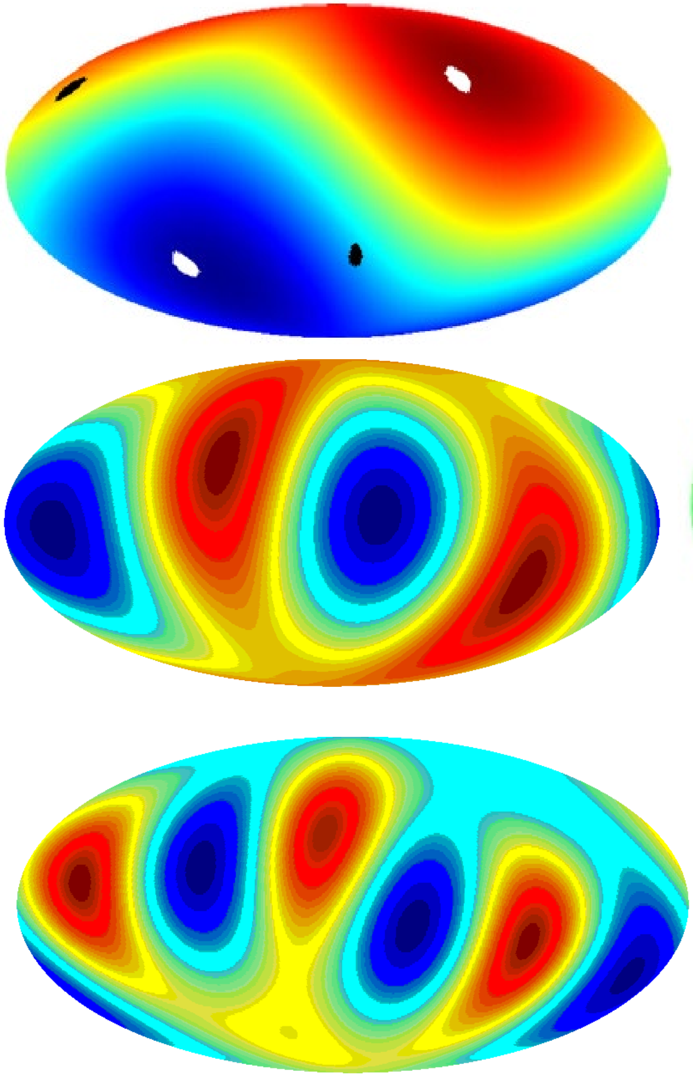
Figure 8. The scalar potential for an unstable dS.

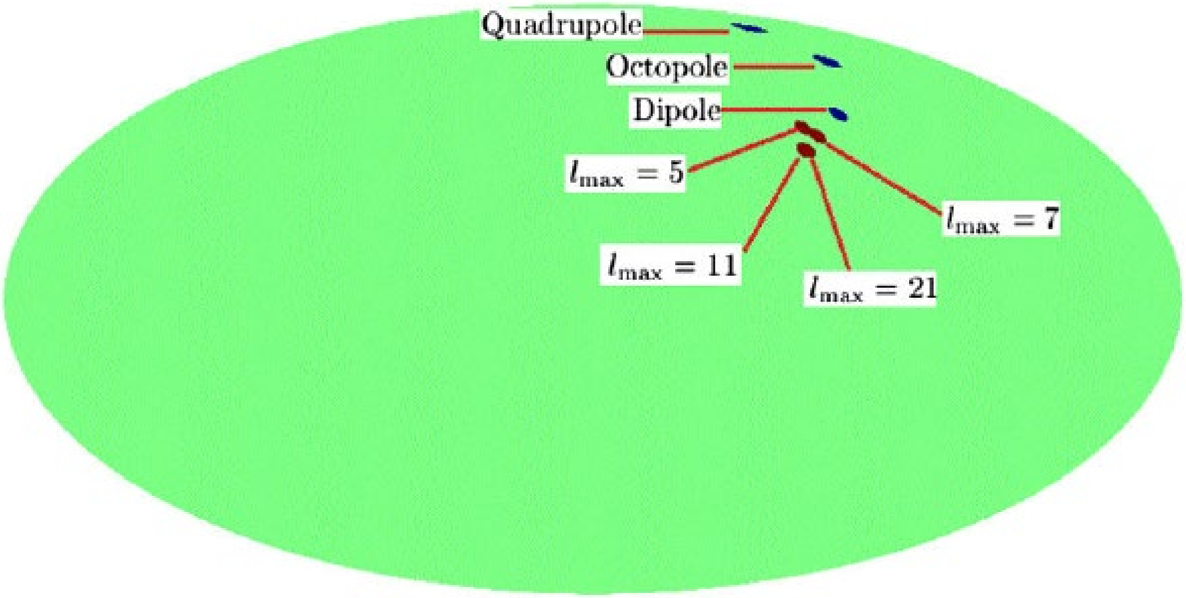

Scale
Time
B
Matter domination
Radiation domination
Horizon
A
Inflation
quantum gravity domination
The spacetime area which is Lorentz violation goes beyond the horizon with inflation at point A, and will re-enter the horizon at B.

Anistropies of CMB

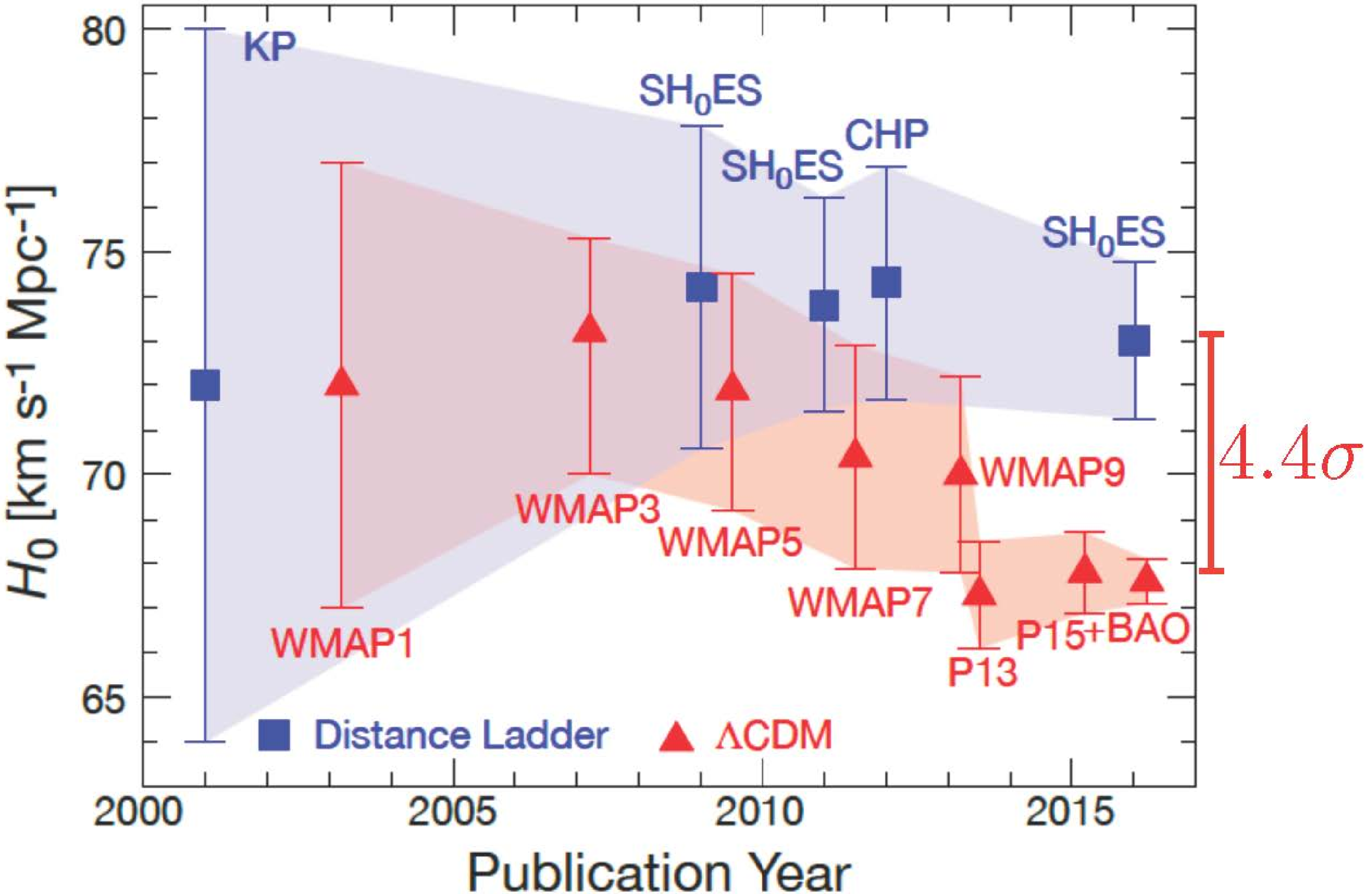


Comparing with preferred directions in CMB dipole, quadrupole and octopole





HST Key Project PI [Freedman Nature Astro 2017]



The Lorentz Violated EFT of Gravity

- The action for a sim(2) gravity

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

- 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_μ 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

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

Cosmic solution of contortion

- The perfect 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

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

- With other contortion components vanish.
- Expand the field eq. with quantities with "~" in Levi-Civita connection

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

$$\left[T_\Lambda\right]^a{}_c = Diag(\rho_\Lambda, -p_\Lambda, -p_\Lambda, -p_\Lambda), \quad \rho_\Lambda = -\frac{c^4}{8\pi G}\left(3\mathscr{K}^2 + 6\mathscr{K}\frac{\dot{a}}{a} - \Lambda_0\right)$$

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

- Denote Λ_0 as the bare cosmological constant in our Lorentz violating model from vacuum energy density, 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:

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

- 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

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

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

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

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

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

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

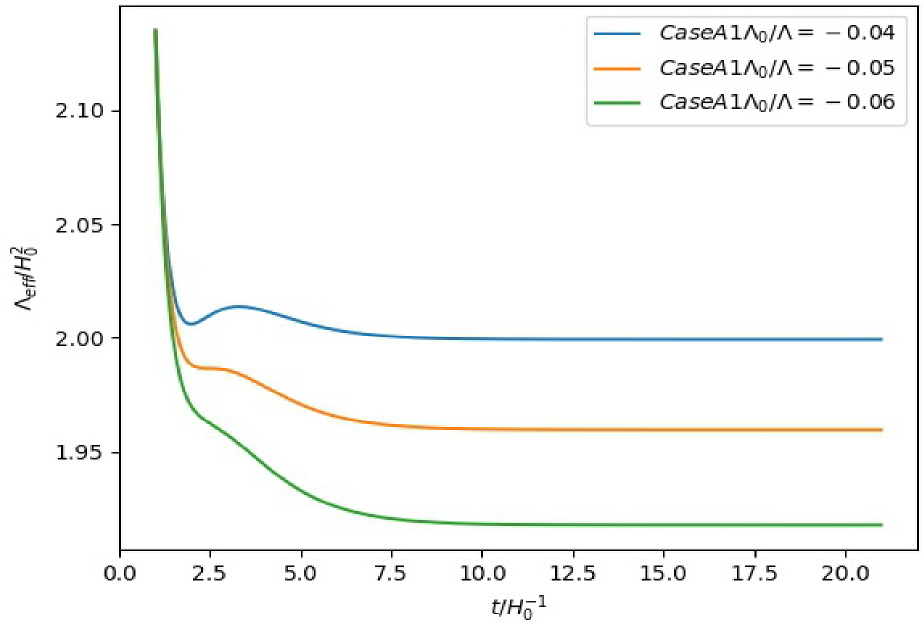
$$\dot{H}+\dot{\mathscr{K}}+H(H+\mathscr{K})+\frac{3w+1}{2}(H+\mathscr{K})^2-\frac{(w+1)}{2}\Lambda_0=0$$

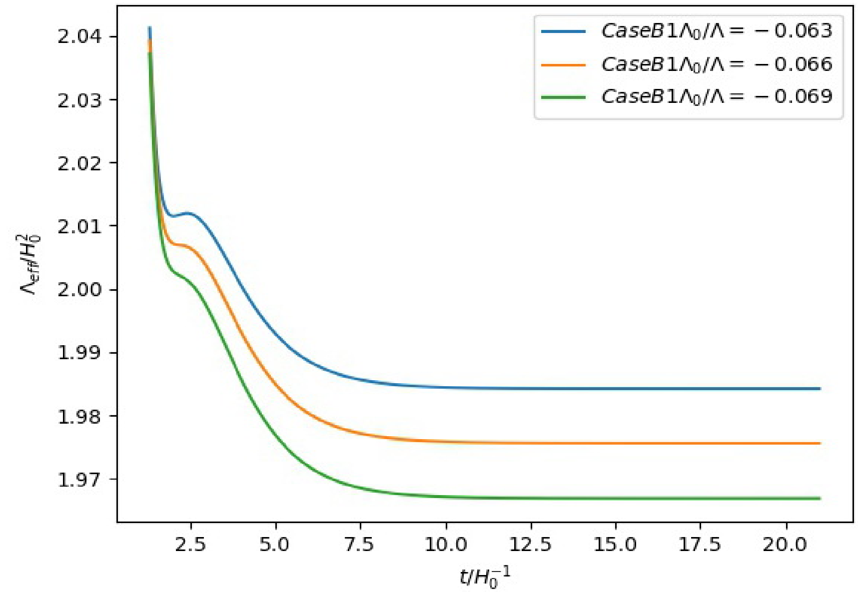
$$\mathscr{K}(t_0)=H_0\left(\pm\sqrt{1-\frac{\Lambda-\Lambda_0}{3H_0{}^2}}-1\right),\quad H_0=H(t_0)$$

- Define the Effective Cosmological Constant which really responsible to the accelerating expansion

$$\Lambda_{eff}\left(t\right)=\Lambda_{0}-3\left(\mathscr{K}\left(t\right)^{2}+2\mathscr{K}\left(t\right)\frac{\dot{a}\left(t\right)}{a\left(t\right)}\right)$$

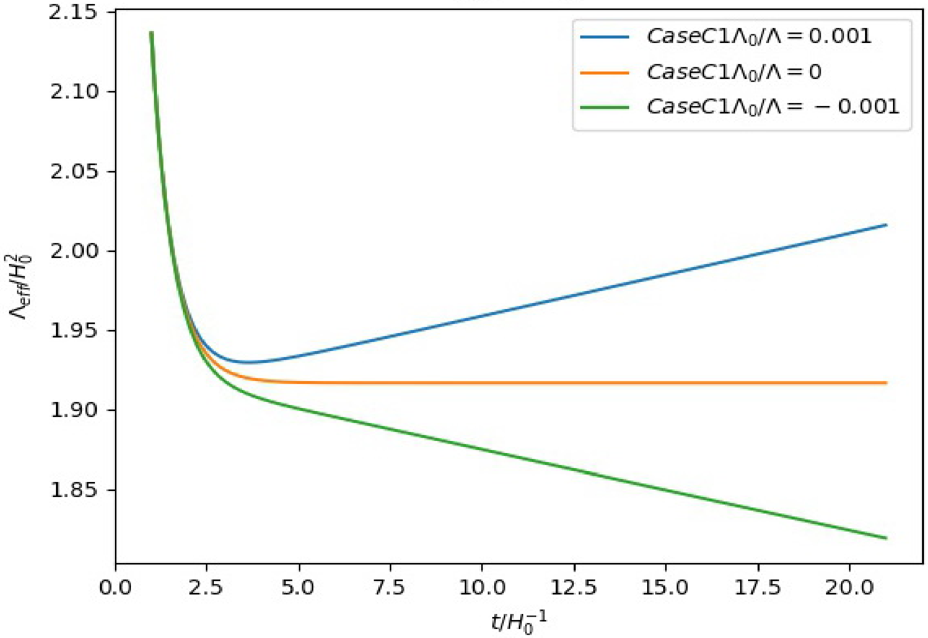
- the cirtical value for Λ_0 which symbolizes the transformation from a monotonically quintessence like $\Lambda_{eff}\left(t\right)$ to the metastable dS potential can be solved for all of the case of approximations. The critical value Λ_{0-crit} centers around $\Lambda_{0-crit}=0$. It can be conjectured the deviation of Λ_{0-crit} from 0 is caused by the approximations. In a more elaborated model, it should have $\Lambda_{0-crit}=0$.

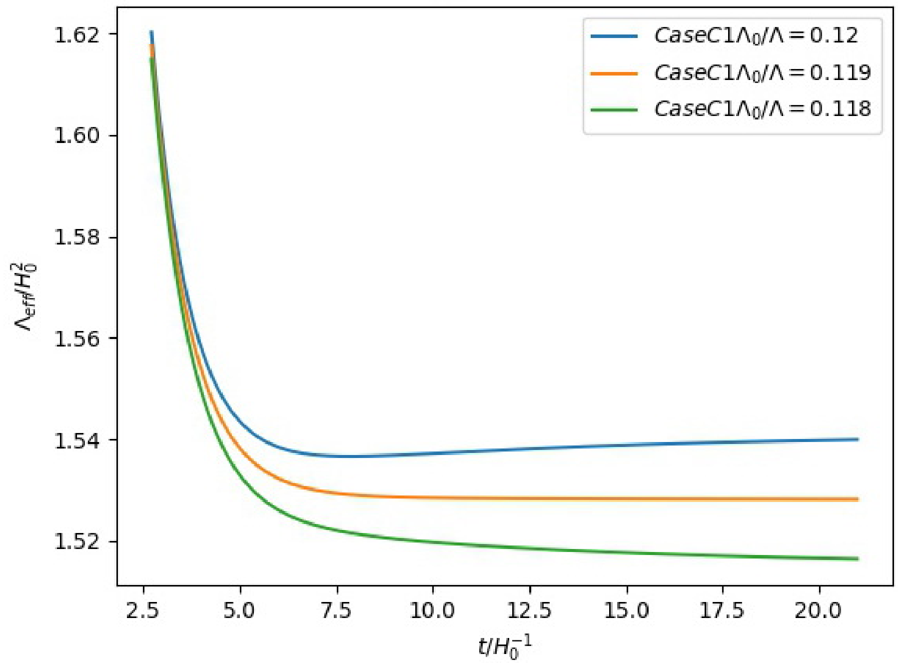




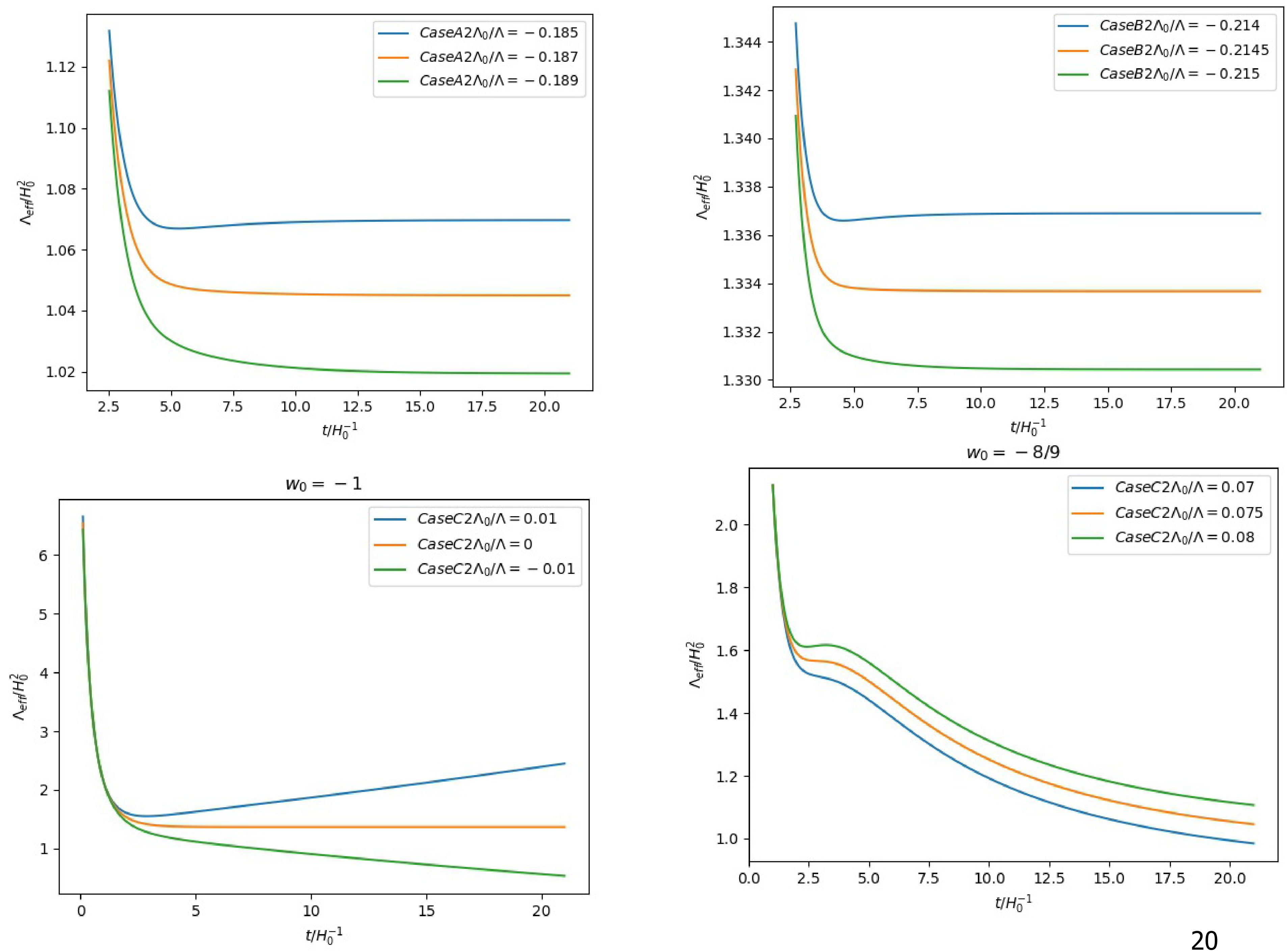
$w_0 = -1$

$w_0 = -8/9$





- The transformation from quintessence to dS


$Case A2 \Lambda_0/\Lambda = -0.185$
$Case A2 \Lambda_0/\Lambda = -0.187$
$Case A2 \Lambda_0/\Lambda = -0.189$
Λ_{eff}/H_0^2
t/H_0^{-1}
$Case B2 \Lambda_0/\Lambda = -0.214$
$Case B2 \Lambda_0/\Lambda = -0.2145$
$Case B2 \Lambda_0/\Lambda = -0.215$
Λ_{eff}/H_0^2
t/H_0^{-1}
$w_0 = -1$
$Case C2 \Lambda_0/\Lambda = 0.01$
$Case C2 \Lambda_0/\Lambda = 0$
$Case C2 \Lambda_0/\Lambda = -0.01$
Λ_{eff}/H_0^2
t/H_0^{-1}
$w_0 = -8/9$
$Case C2 \Lambda_0/\Lambda = 0.07$
$Case C2 \Lambda_0/\Lambda = 0.075$
$Case C2 \Lambda_0/\Lambda = 0.08$
Λ_{eff}/H_0^2
t/H_0^{-1}

- Phenomenological, the Λ_{eff} can be regarded as the energy density produced by some auxiliary fields which responsible for the accelerating expansion such as quintessence field etc. e.g.

$$S_q = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{pl}^2 R\left(1+\xi\phi\right)-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

$$R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R = 8\pi G\frac{T_{\mu\nu}}{1+\xi\phi},\quad \ddot{\phi}+3H\dot{\phi}+V_{,\phi}-\frac{1}{2}M_{pl}^2 R\xi = 0$$

$$\Lambda_{eff} = \frac{\frac{\dot{\phi}^2}{2}+V\left(\phi\left(t\right)\right)}{1+\xi\phi},\quad \dot{\Lambda}_{eff} = \dot{\phi}\frac{\left(\frac{1}{2}M_{pl}^2 R-\Lambda_{eff}\right)\xi - 3H\dot{\phi}}{1+\xi\phi}$$

$$V\left(\phi\left(t\right)\right) = \Lambda_{eff}\left(1+\xi\phi\right)-\frac{\dot{\phi}^2}{2}$$

- the cirtical value for Λ_0 which symbolizes the transformation from a monotonically quintessence like $V(\phi(t))$ to the metastable dS potential is almost the same as one for Λ_{eff} in most cases esp in the case of landscape when

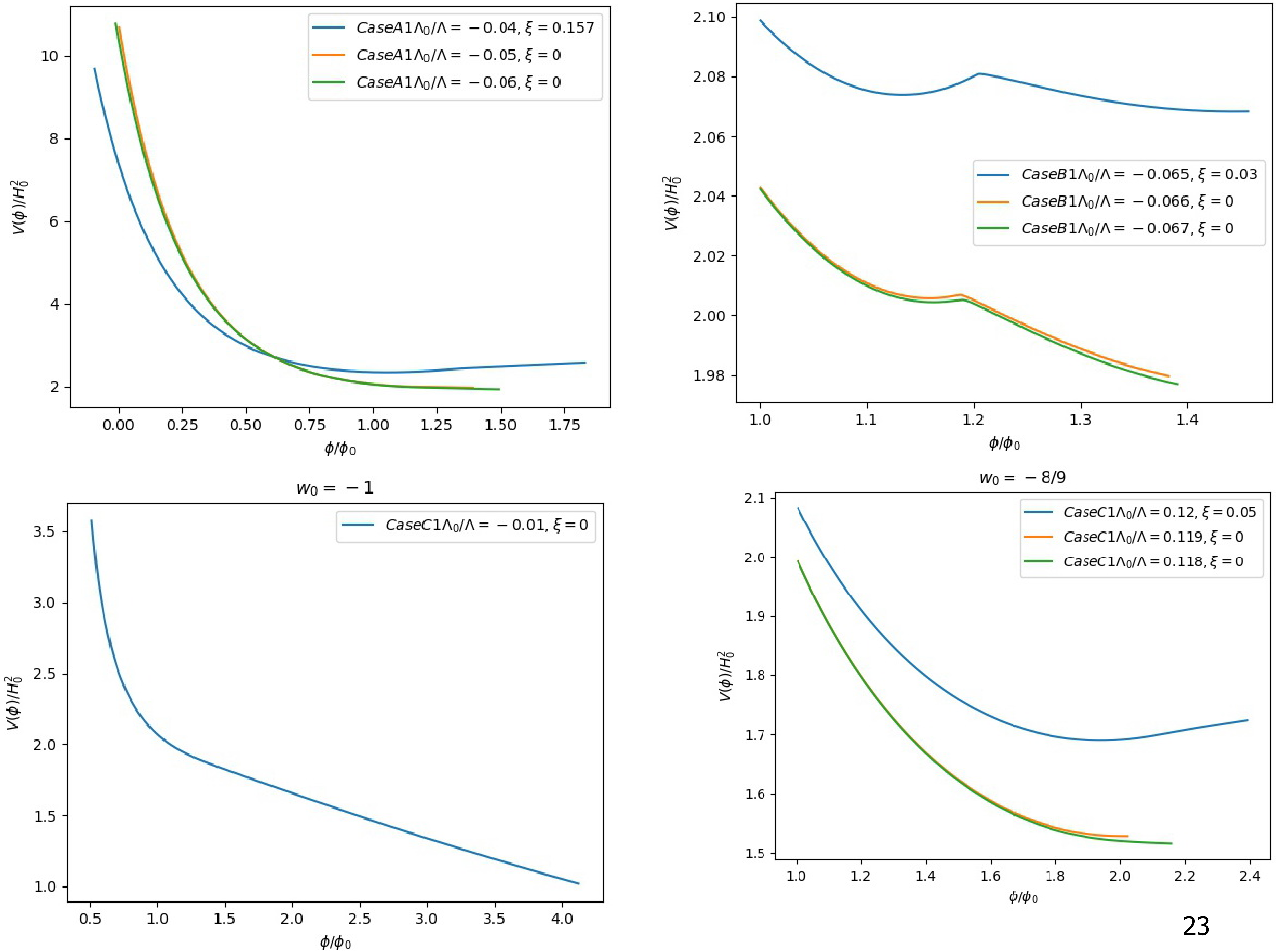
$\Lambda_0 < \Lambda_{0-crit}$

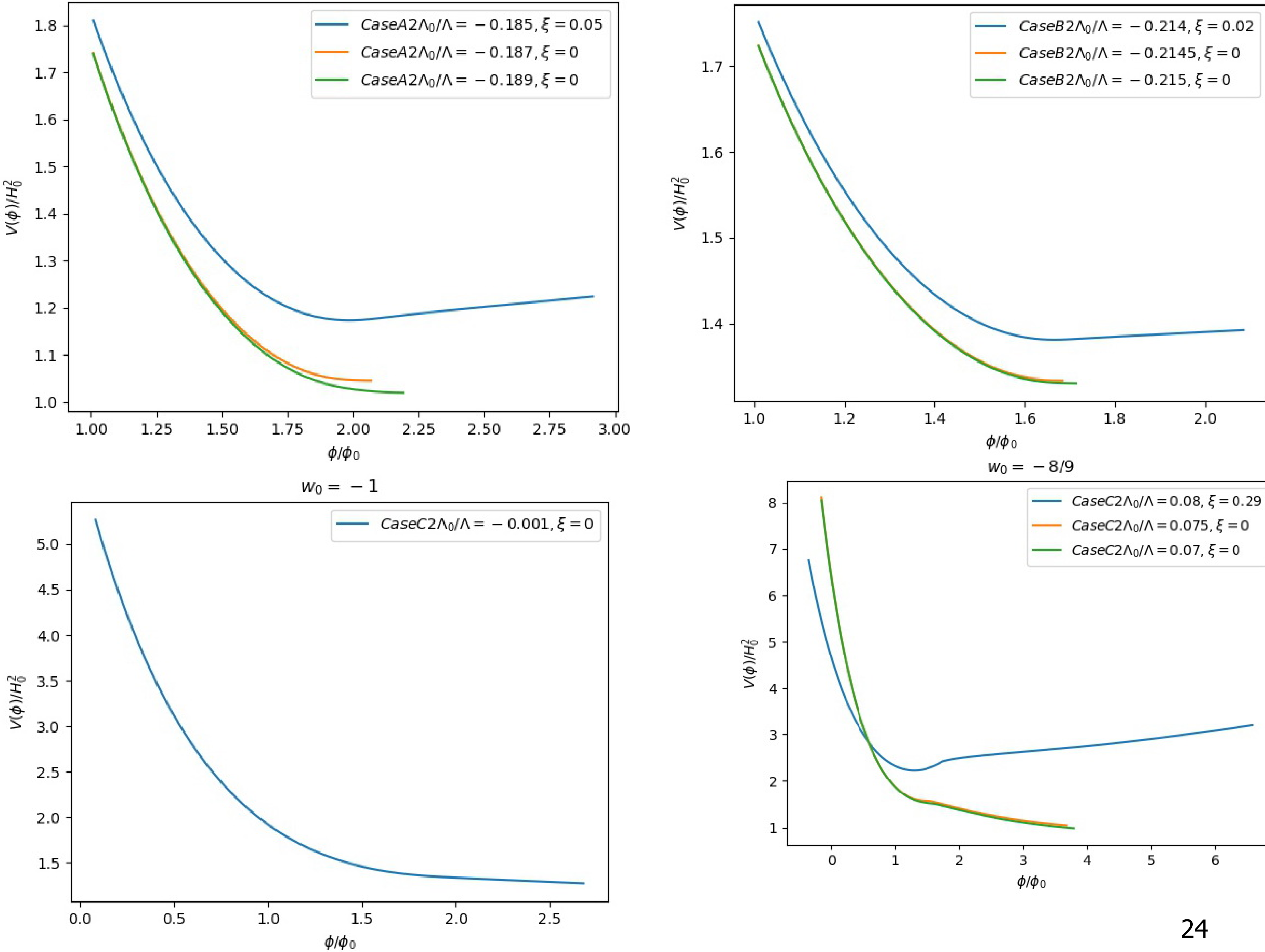
- However, when $\Lambda_0 > \Lambda_{0-crit}$ the non-trivial Brans-Dicke type of coupling $\xi_{\min} > 0$ is required

$$\dot{\phi} = \xi \frac{3\left(\dot{H} + 2H^2\right) - \Lambda_{eff}}{6H} \pm \sqrt{\left[\frac{3\left(\dot{H} + 2H^2\right) - \Lambda_{eff}}{6H}\right]^2 \xi^2 - \frac{\dot{\Lambda}_{eff}}{3H}\left(1 + \xi\phi\right)}$$

- The restriction on ξ

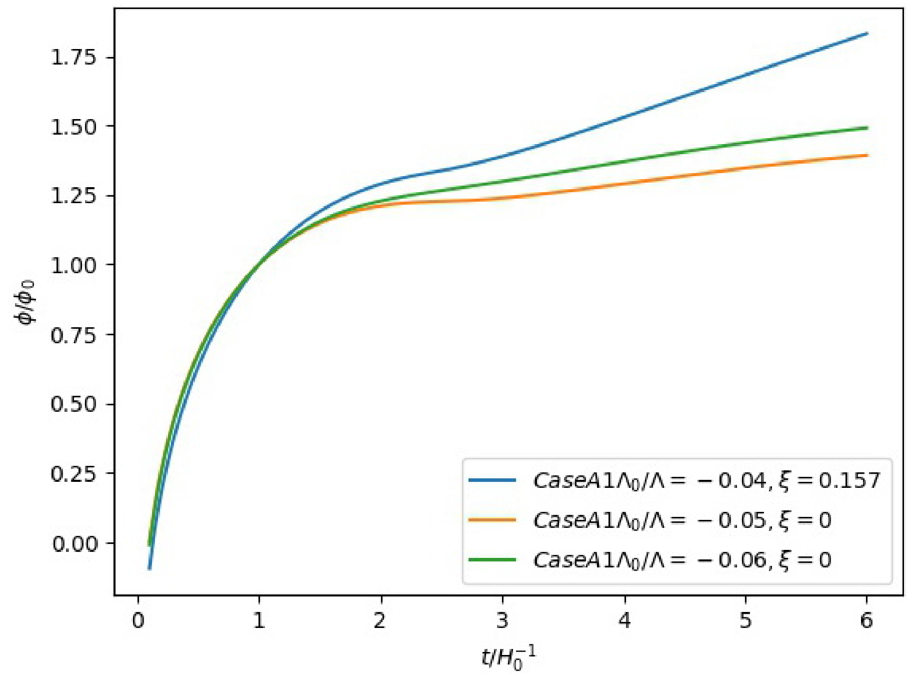
$$\left[3\left(\dot{H} + 2H^2\right) - \Lambda_{eff}\right]^2 \xi^2 - 12H\dot{\Lambda}_{eff}\left(1 + \xi\phi\right) \geq 0$$

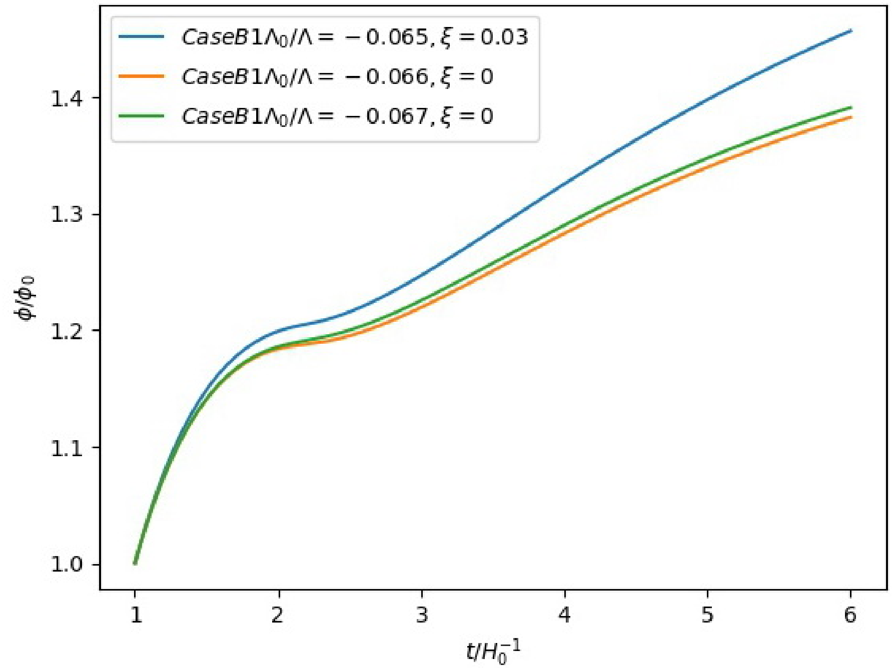

CaseA1Λ0/Λ = −0.04, ξ = 0.157
CaseA1Λ0/Λ = −0.05, ξ = 0
CaseA1Λ0/Λ = −0.06, ξ = 0
V(ϕ)/H0^2
ϕ/ϕ0
CaseB1Λ0/Λ = −0.065, ξ = 0.03
CaseB1Λ0/Λ = −0.066, ξ = 0
CaseB1Λ0/Λ = −0.067, ξ = 0
V(ϕ)/H0^2
ϕ/ϕ0
w0 = −1
CaseC1Λ0/Λ = −0.01, ξ = 0
V(ϕ)/H0^2
ϕ/ϕ0
w0 = −8/9
CaseC1Λ0/Λ = 0.12, ξ = 0.05
CaseC1Λ0/Λ = 0.119, ξ = 0
CaseC1Λ0/Λ = 0.118, ξ = 0
V(ϕ)/H0^2
ϕ/ϕ0

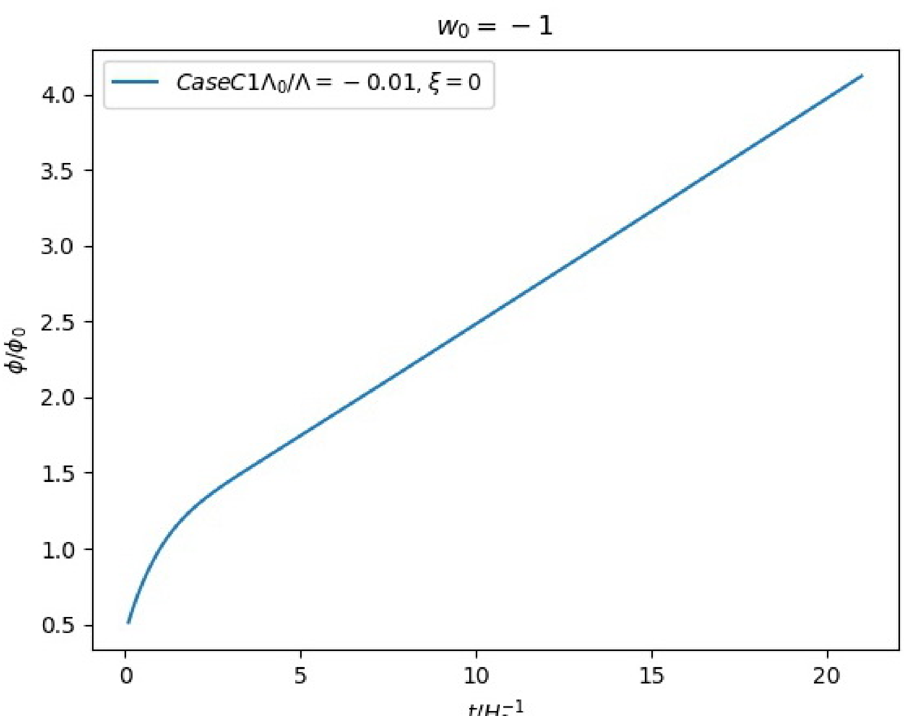


CaseA2Λ0/Λ = −0.185, ξ = 0.05
CaseA2Λ0/Λ = −0.187, ξ = 0
CaseA2Λ0/Λ = −0.189, ξ = 0
V(ϕ)/H0²
ϕ/ϕ0
CaseB2Λ0/Λ = −0.214, ξ = 0.02
CaseB2Λ0/Λ = −0.2145, ξ = 0
CaseB2Λ0/Λ = −0.215, ξ = 0
V(ϕ)/H0²
ϕ/ϕ0
w0 = −1
CaseC2Λ0/Λ = −0.001, ξ = 0
V(ϕ)/H0²
ϕ/ϕ0
w0 = −8/9
CaseC2Λ0/Λ = 0.08, ξ = 0.29
CaseC2Λ0/Λ = 0.075, ξ = 0
CaseC2Λ0/Λ = 0.07, ξ = 0
V(ϕ)/H0²
ϕ/ϕ0

- For Case C, when $w_0 > -8/9$ there doesn't exist a solution of the critical value for Λ_0 which signs the transformation from a monotonically quintessence potential to a dS potential
- The ϕ evolution versus t is monotonical which may be regarded as an intrinsic time for the evolution of the universe.


$CaseA1 \Lambda_0/\Lambda = -0.04, \xi = 0.157$
$CaseA1 \Lambda_0/\Lambda = -0.05, \xi = 0$
$CaseA1 \Lambda_0/\Lambda = -0.06, \xi = 0$
ϕ/ϕ_0
t/H_0^{-1}


$CaseB1 \Lambda_0/\Lambda = -0.065, \xi = 0.03$
$CaseB1 \Lambda_0/\Lambda = -0.066, \xi = 0$
$CaseB1 \Lambda_0/\Lambda = -0.067, \xi = 0$
ϕ/ϕ_0
t/H_0^{-1}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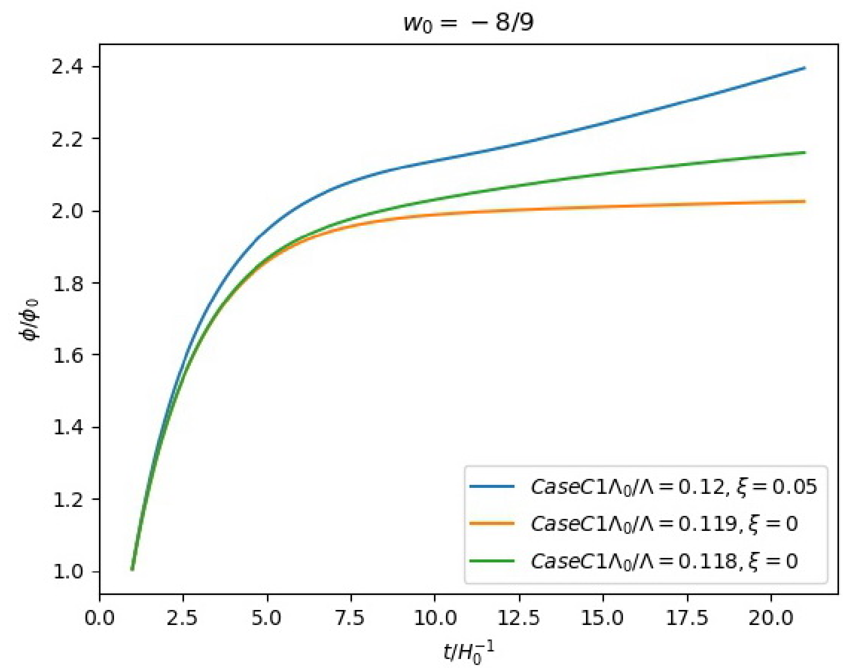
$CaseC1 \Lambda_0/\Lambda = -0.01, \xi = 0$
ϕ/ϕ_0
t/H_0^{-1}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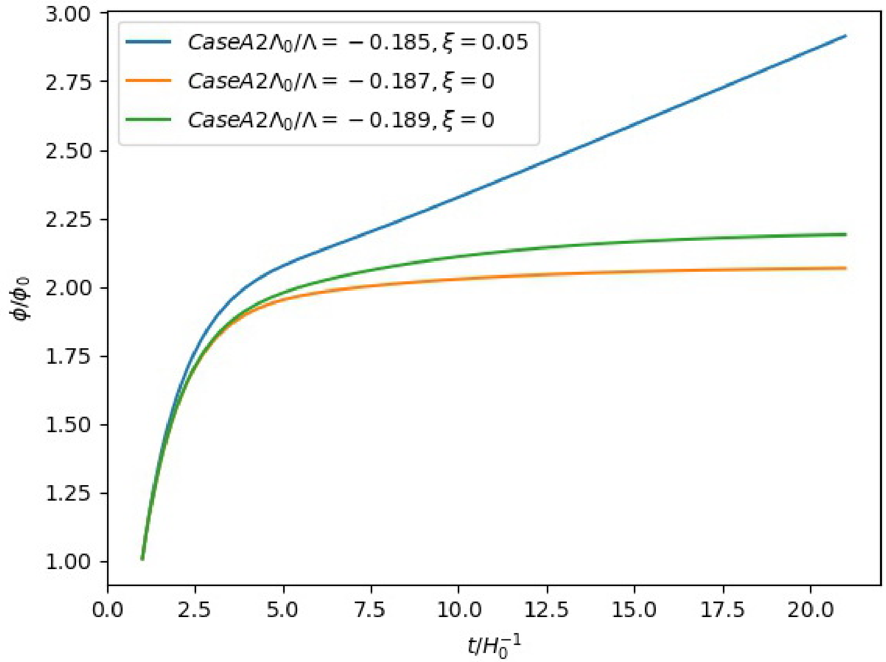
ϕ/ϕ_0
t/H_0^{-1}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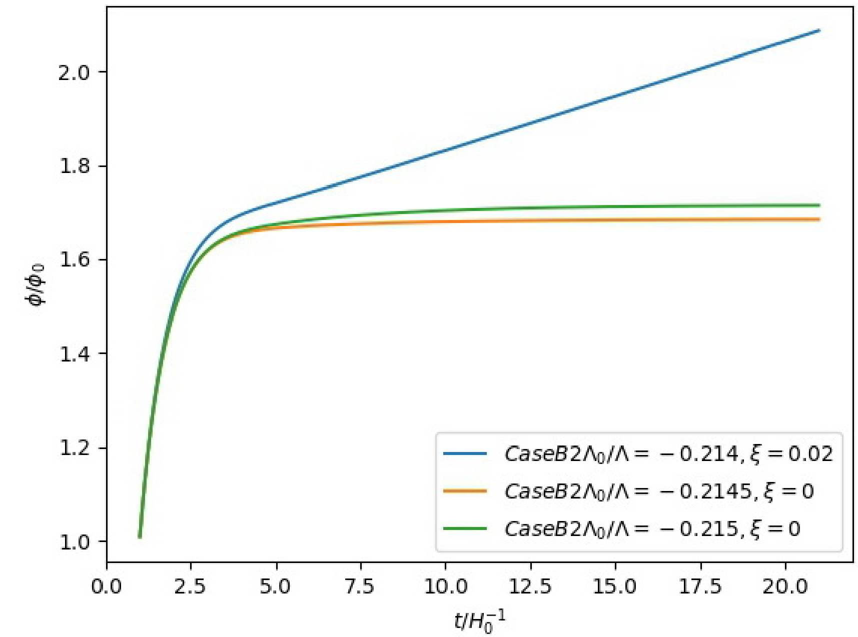
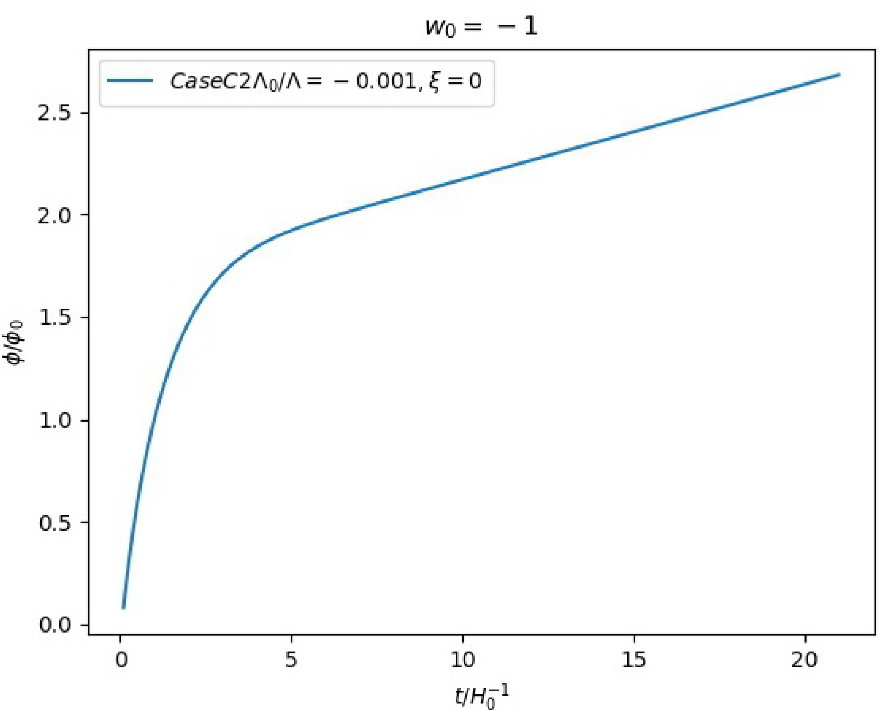
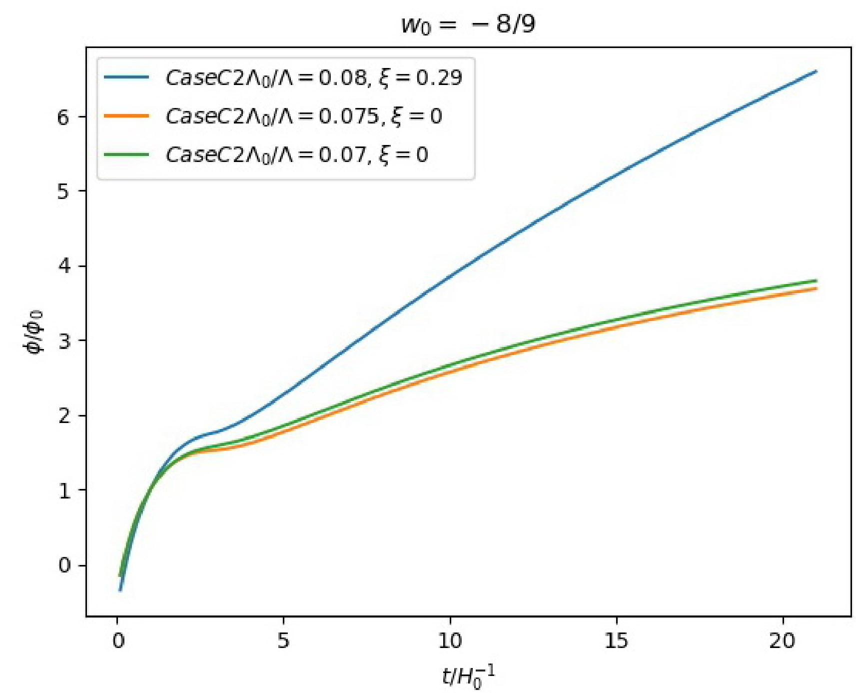
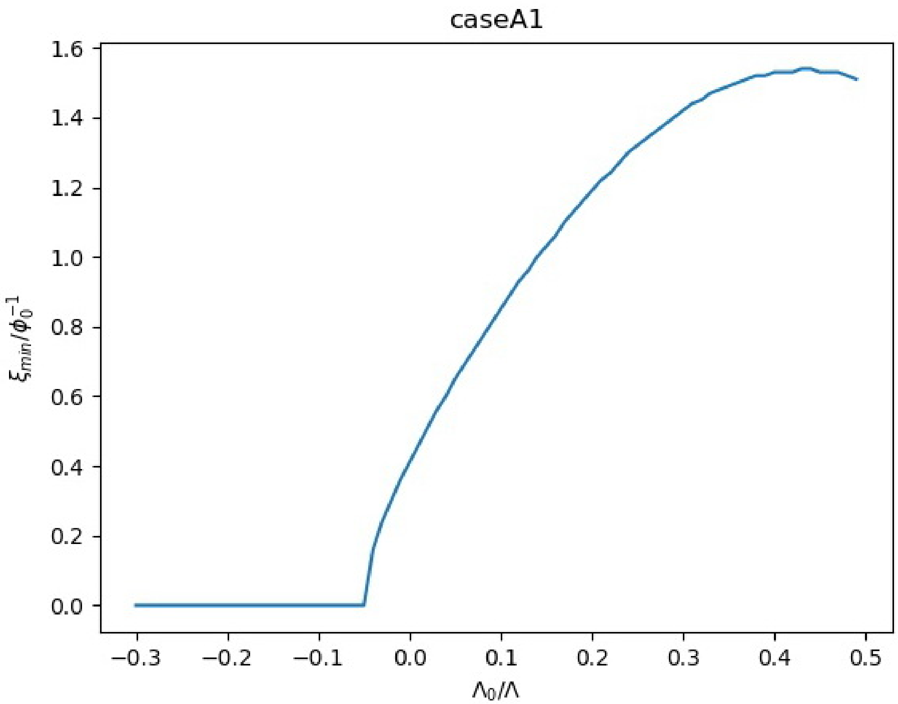
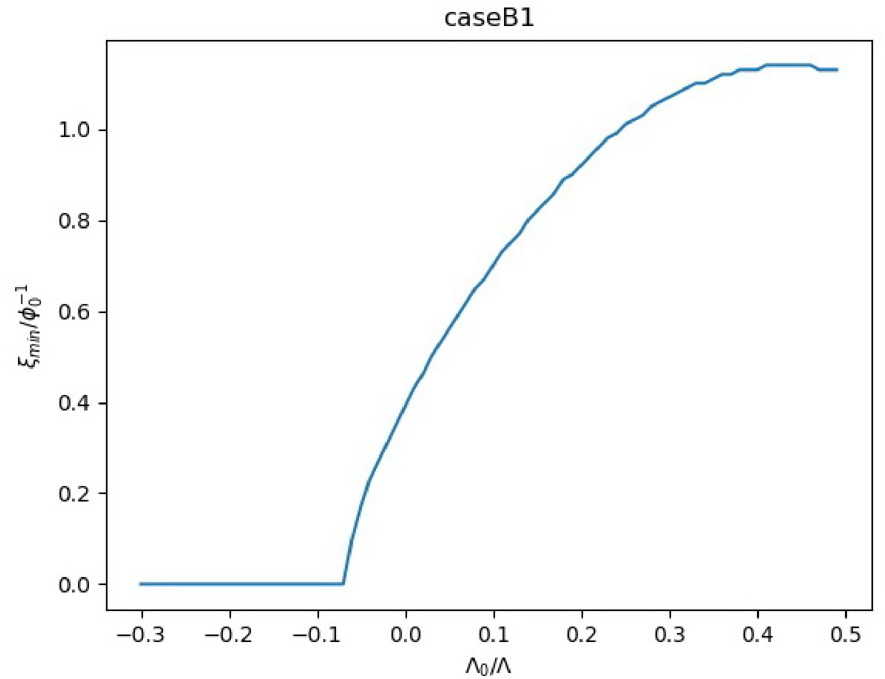
$CaseA2\Lambda_0/\Lambda = -0.189, \xi = 0$
ϕ/ϕ_0
t/H_0^{-1}

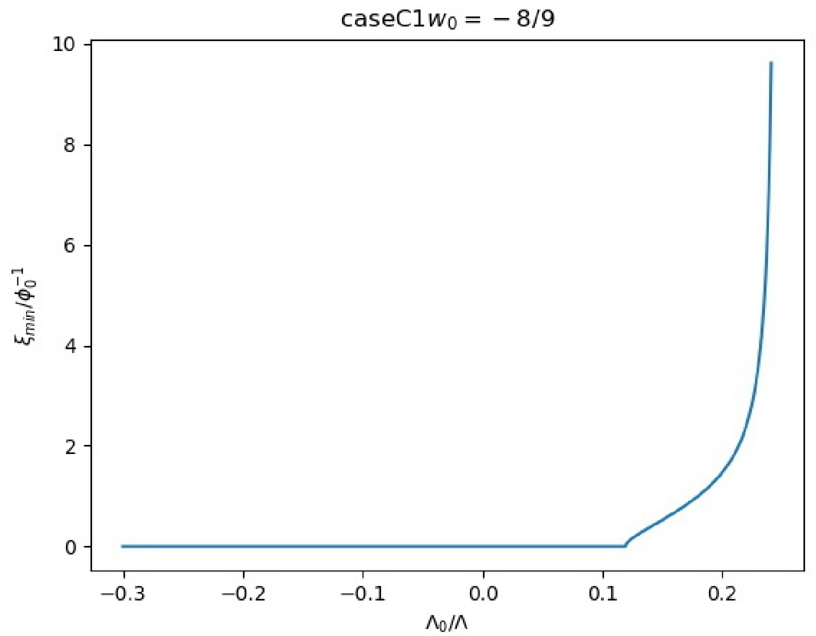

$CaseB2\Lambda_0/\Lambda = -0.214, \xi = 0.02$
$CaseB2\Lambda_0/\Lambda = -0.2145, \xi = 0$
$CaseB2\Lambda_0/\Lambda = -0.215, \xi = 0$
ϕ/ϕ_0
t/H_0^{-1}


$w_0 = -1$
$CaseC2\Lambda_0/\Lambda = -0.001, \xi = 0$
ϕ/ϕ_0
t/H_0^{-1}

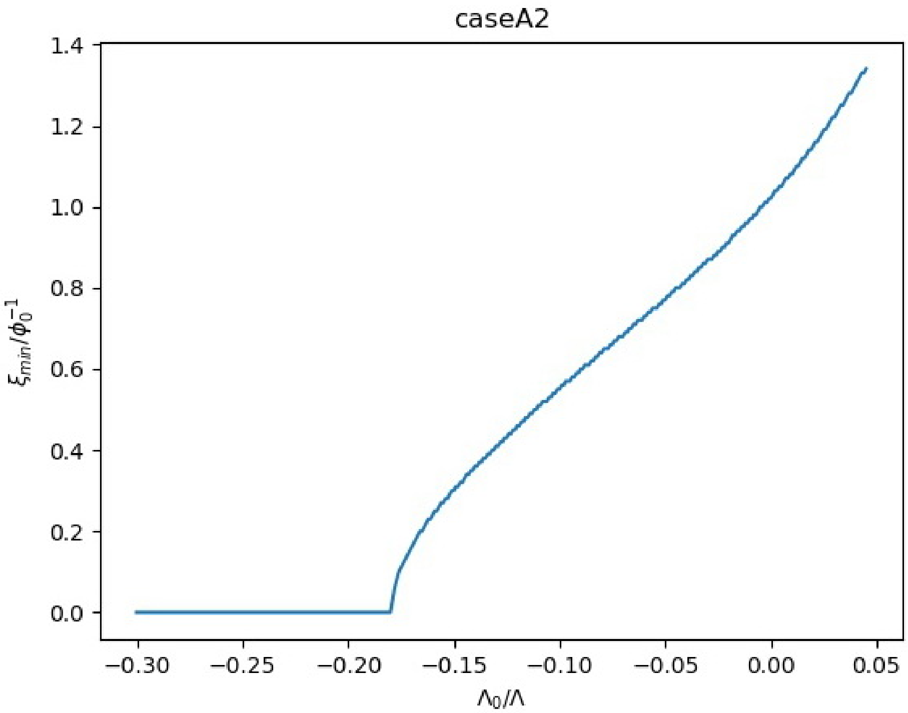

$w_0 = -8/9$
$CaseC2\Lambda_0/\Lambda = 0.08, \xi = 0.29$
$CaseC2\Lambda_0/\Lambda = 0.075, \xi = 0$
$CaseC2\Lambda_0/\Lambda = 0.07, \xi = 0$
ϕ/ϕ_0
t/H_0^{-1}

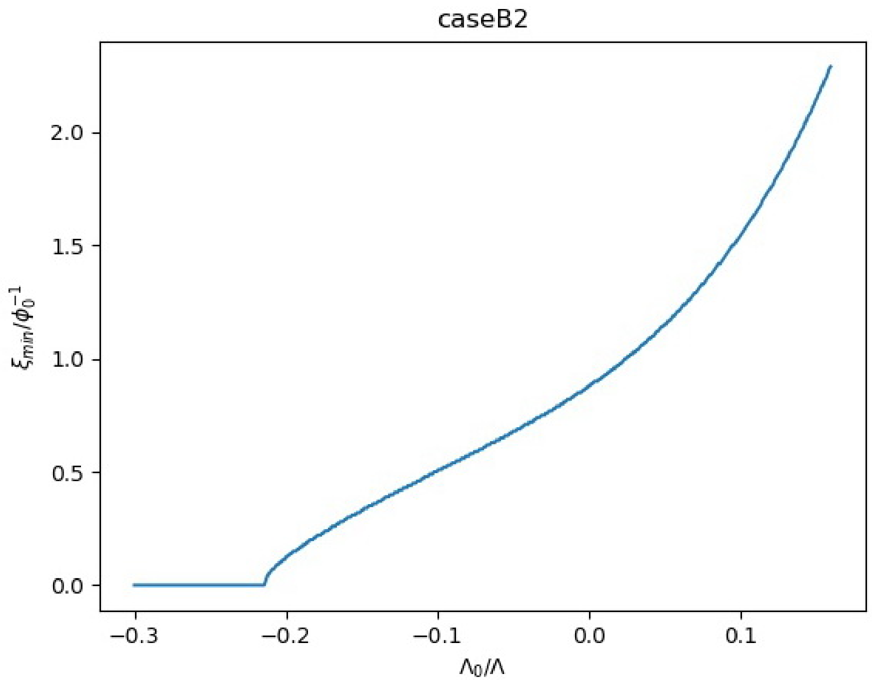


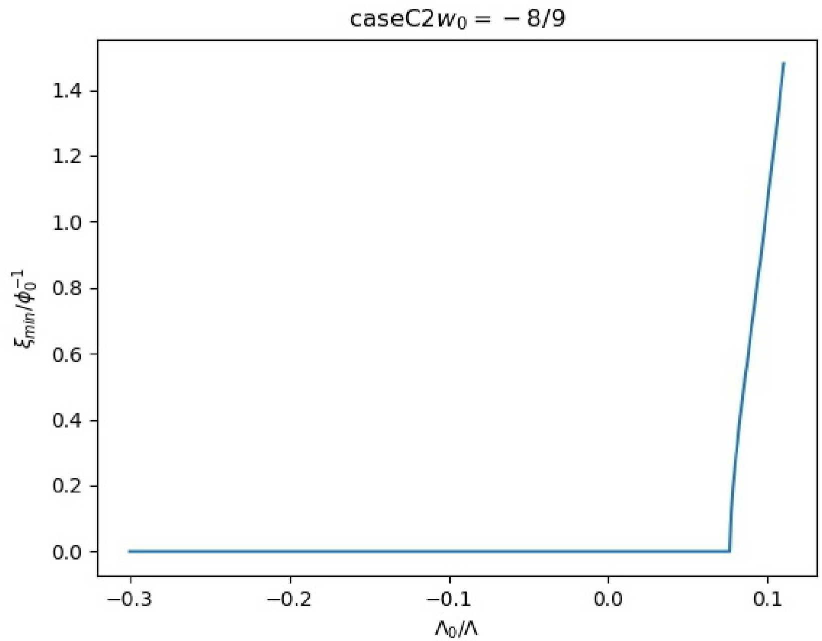




- The restrictions on ξ . The minimal ξ line.







- The restrictions on ξ . The minimal ξ line.

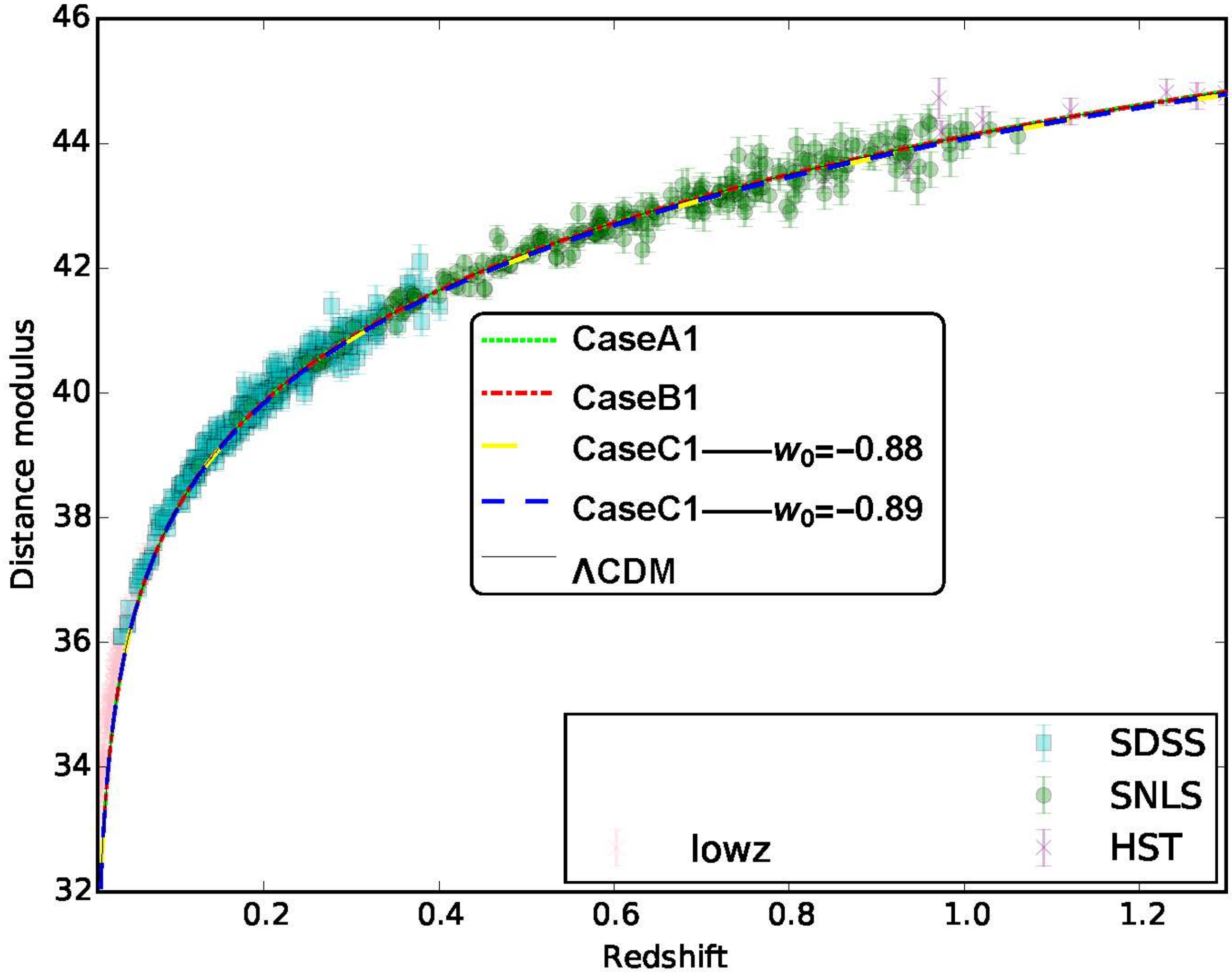
- Actually Case C approximation is not a good one from the comparison between Hubble constant vs t and the luminosity distance vs redshift z.
- The reason may be we use a fixed w_0 in the equation of state of dark partner part. Ignore the case $w_0>-8/9$ (excluded by observation of luminosity distance with redshift relation),we can make the conclusion:
- Quintessence potential is generated from string landscape AdS vacuum effectively.
- The critical value of cosmological constant separating quintessence from metastable dS is approximately zero
- The metastable dS potential needs non-trivial coupling between quintessence field and gravitation. The $w_0=-1$ dS potential is actually stable but metastable and the non-trivial ξ coupling is divergent in this case.

- The metastable dS potential needs non-trivial Brans-Dicke coupling between quintessence field and gravitation. The w_0=-1 dS potential is actually stable but metastable and the non-trivial ξ coupling does not exist in this case.

$$\dot{\Lambda}_{eff} = \dot{\phi}\frac{\left(\frac{1}{2}M_{pl}^2 R - \Lambda_{eff}\right)\xi - 3H\dot{\phi}}{1+\xi\phi}, \quad \left(\frac{1}{2}M_{pl}^2 R - \Lambda_{eff}\right)\xi - 3H\dot{\phi} > 0$$

$$\frac{1}{2}M_{pl}^2 R - \Lambda_{eff} > 0, \quad \xi > \frac{3H\dot{\phi}}{\frac{1}{2}M_{pl}^2 R - \Lambda_{eff}}$$

- If Λ_{eff} grows too large to make $\frac{1}{2}M_{pl}^2 R - \Lambda_{eff}$ from positive to negative. ξ would have no solution.
- The effective description of large scale Lorentz violation effect by quintessence is failed in the case.



- Comparation of distance modulus for $\Lambda_0 = 0.2\Lambda$

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

Summary

- For string landscape with $\Lambda_0 > -(3H_0 - \Lambda) \approx -\frac{2}{5}\Lambda$,the effective cosmological constant naturally give a quintessence like potential which satisfies the dS Swampland conjecture
- The uplifting of AdS to a positive effective consmological constant by frozen large scale Lorentz violation mechanism avoids the meta-stable dS swampland puzzle and have a quantum gravity origin
- For string swampland with positive cosmological constant for most reasonably approximation, the effective quintessence potential behaves as a metastable dS potential and the non-trivial Brans-Dicke type of coupling is required.
- For the stable dS type behavior, there is no solution for ξ and the effective potential approach is failed.

THANKS!