Bounce in GR and higher-order derivative operators

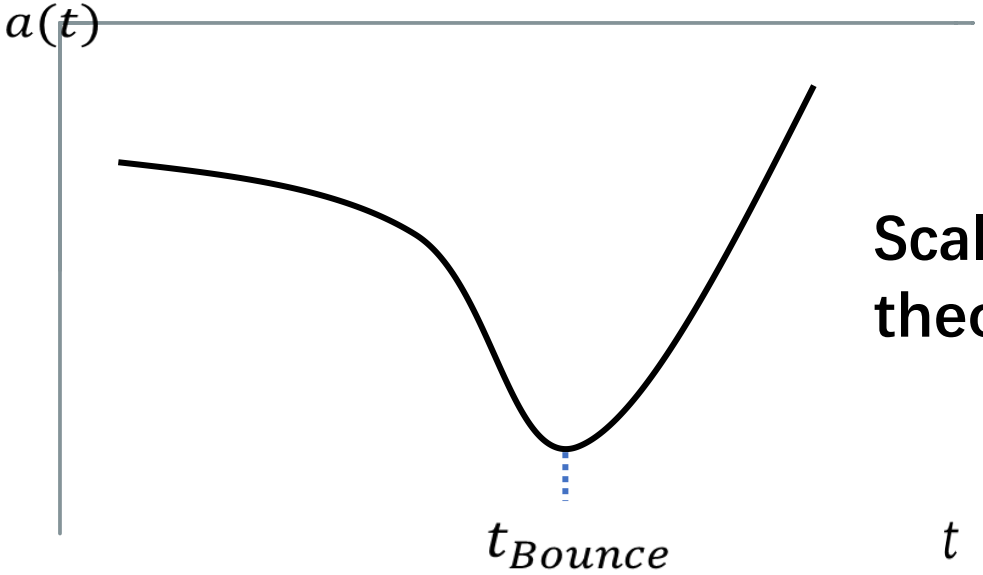
By: Gen Ye

G. Ye and Y.S. Piao, Commun. Theor. Phys. **71**, 427 (2019)

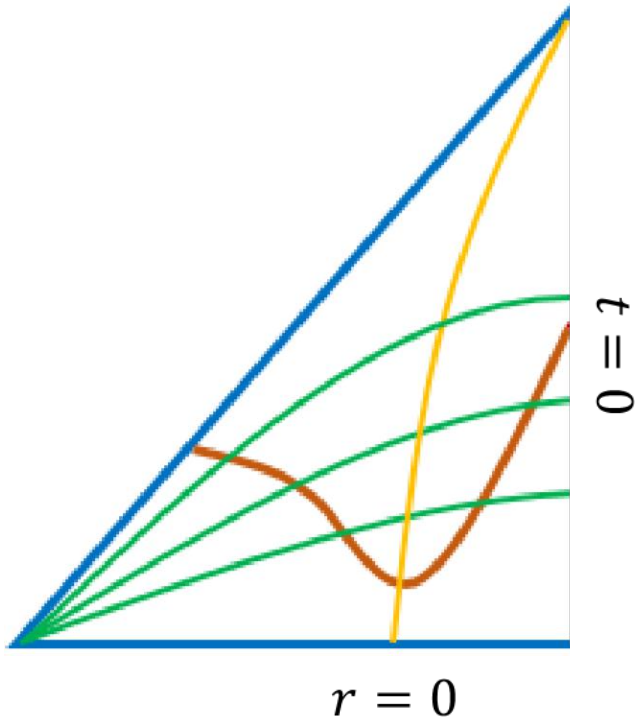
G. Ye and Y.S. Piao, Phys. Rev. D **99**, 084019 (2019)

Bounce cosmology

- Singularity problem in inflation[1]: geodesically incomplete
  - Why BD vacuum?
- Avoid singularity: classical bounce
  - Violate Null Energy Condition (NEC)



Scalar-tensor theories



[1] S. W. Hawking and R. Penrose, Proc. R. Soc. A 314 (1970) 529
A. Borde, A. H. Guth, and A. Vilenkin, Phys. Rev. Lett. 90 (2003) 151301

Stability of cosmological bounce

- Extensively studied[1][2], various instabilities noticed
- **The No-go Theorem**[3][4]: stable, nonsingular cosmologies are prohibited within the *Horndeski theory* (2nd order EOM)

$$\xi(t_2) - \xi(t_1) = \int_{t_1}^{t_2} a(t) \left(\mathcal{F}_\mathcal{T} + \mathcal{F}_\mathcal{S}\right) \mathrm{d}t$$

- Evade the No-go: going beyond Horndeski
  - Cai, Y., Wan, Y., Li, HG. et al. J. High Energ. Phys. (2017) 2017: 90

[1] Y.-F. Cai, D.A. Easson and R. Brandenberger, J*CAP* 08 (2012) 020
[2] Qiu, T. & Wang, YT. J. High Energ. Phys. (2015) 2015: 130
[3] M. Libanov, S. Mironov, and V. Rubakov, J. Cosmol. Astropart. Phys. 08 (2016) 037
[4] T. Kobayashi, Phys. Rev. D 94, 043511 (2016).

Implication of GW170817

G. Ye and Y.S. Piao, Commun. Theor. Phys. 71, 427 (2019)

- Generalize the $c_T = 1$ constraint to the early universe

beyond-Horndeski

$$\mathcal{L}^{DHOST}_{c_T=1} = N\sqrt{h}L^{DHOST}_{c_T=1} = N\sqrt{h}\left[P + QK + A(\mathcal{R} - \mathcal{K}_2) - \frac{3AB^2}{2N^2}N'^2 - \frac{2AB}{N}N'K\right.$$

$$\mathcal{K}_2 \equiv K^2 - K_{ij}K^{ij} \qquad \left. + \frac{B}{a^2}\left(2\frac{A}{N} + 2A_N - \frac{AB}{2}\right)(\partial N)^2\right],$$

- Will the the $c_T = 1$ constraint destabilize bounce?
- Will the B-terms destabilize bounce?

NO

- The inverse method[1] EOM: $\mathcal{F}(P, Q, A, B, \partial \mid N, H, t, \partial) = 0$

[1] Anna Ijjas and Paul J. Steinhardt, Phys. Rev. Lett. 117, 121304

The EFT point of view

G. Ye and Y.S. Piao, Phys. Rev. D 99, 084019 (2019)

- Exploit the B-terms as EFT operators

$$L = \frac{M_P^2}{2}{}^{(4)}R + P(\phi, X) - \left(B + \frac{X^2B^2}{4M_P^2}\right)\phi^\mu\phi_{\mu\nu}\phi_\lambda\phi^{\lambda\nu}$$
$$+ B\phi^\mu\phi^\nu\phi_{\mu\nu}\Box\phi + \frac{XB^2}{M_P^2}(\phi_\mu\phi^{\mu\nu}\phi_\nu)^2,$$

- Evade the no-go: from A to B

$c_T = 1$ Beyond-Horndeski

$$\boldsymbol{A(X,\phi)}$$

$$P + QK + A(\mathcal{R} - \mathcal{K}_2)$$

$c_T = 1$ DHOST

$$\boldsymbol{B(X,\phi)}$$

Bounce in General relativity

Outlook

- Pre-inflationary bounce
- Blackhole/Wormhole
- Quantum corrections
- Initial value problem
- …

Thanks for your attention