Probing New Physics through the Cosmological Collider

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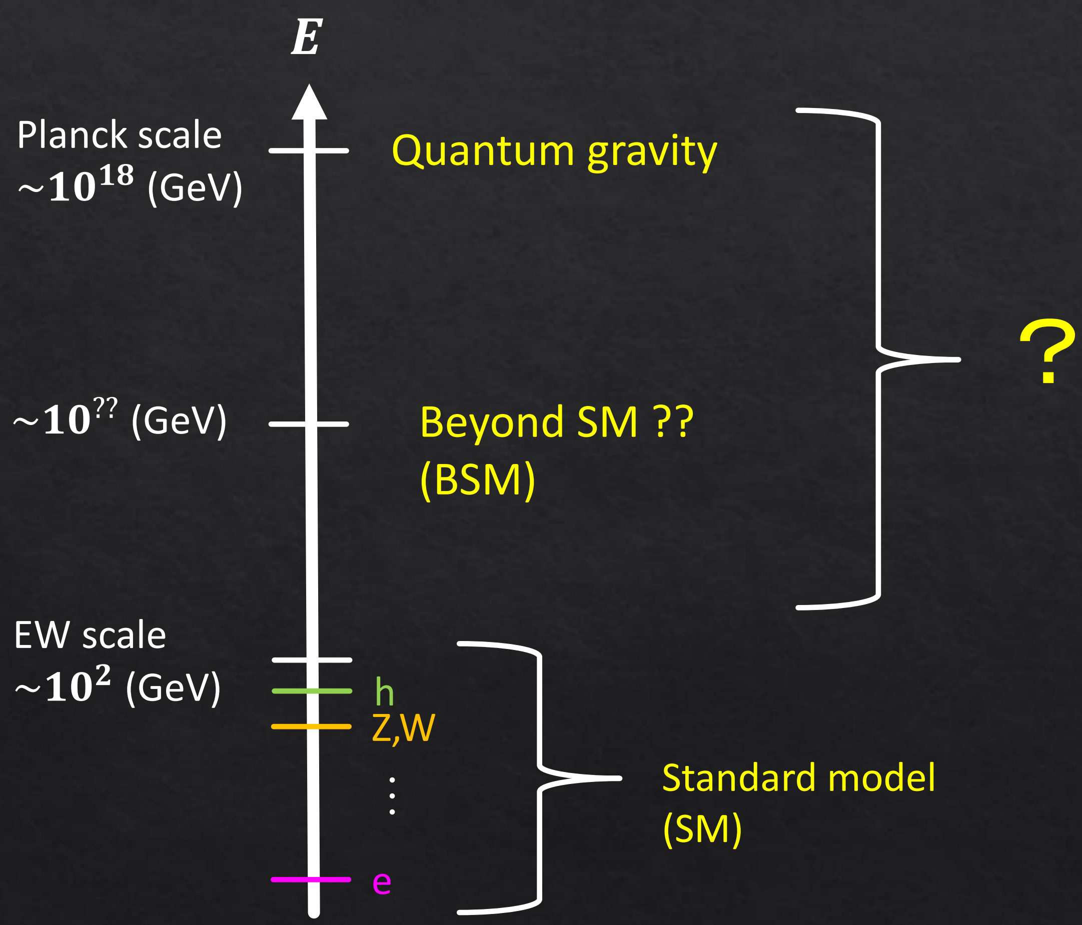
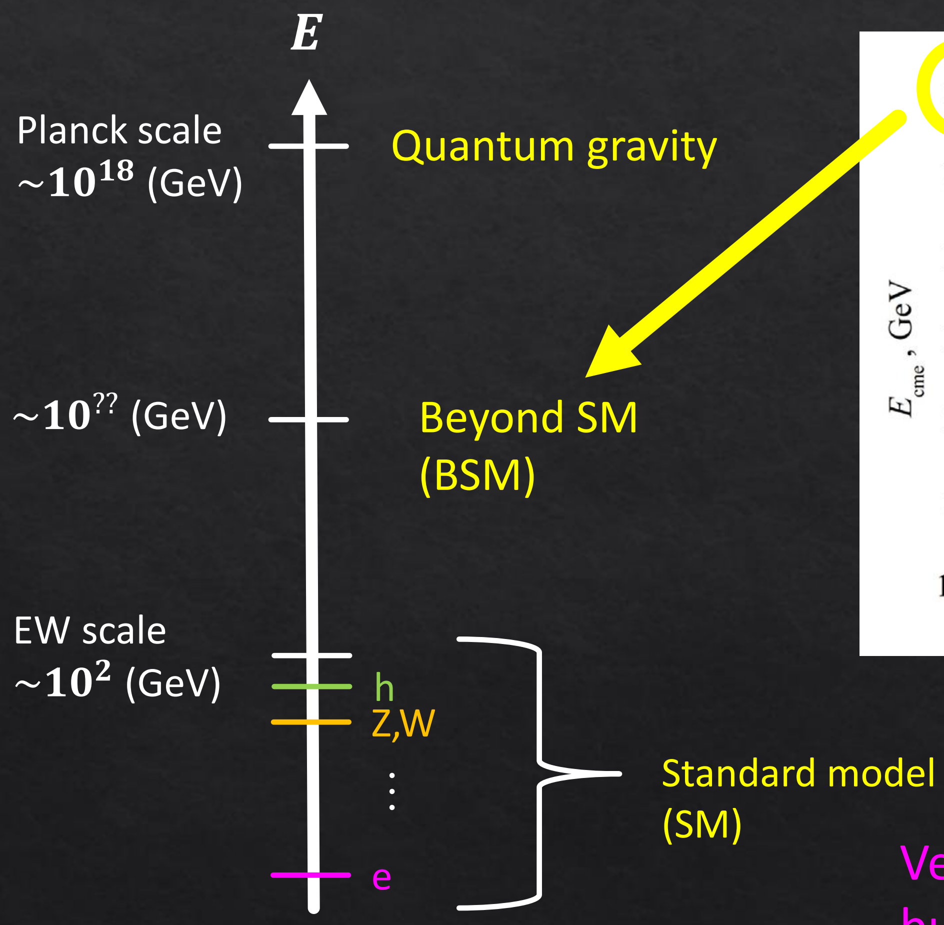
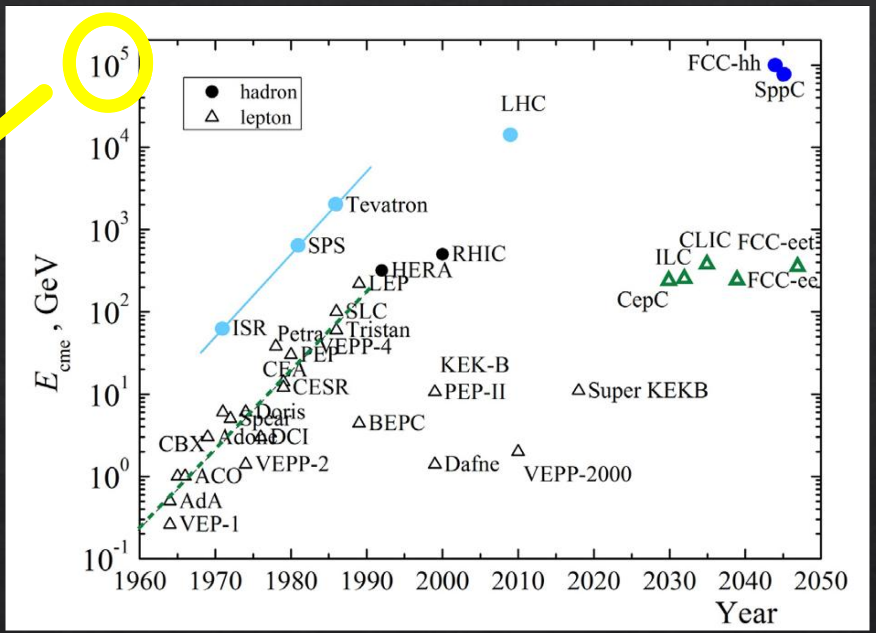
Introduction



Introduction

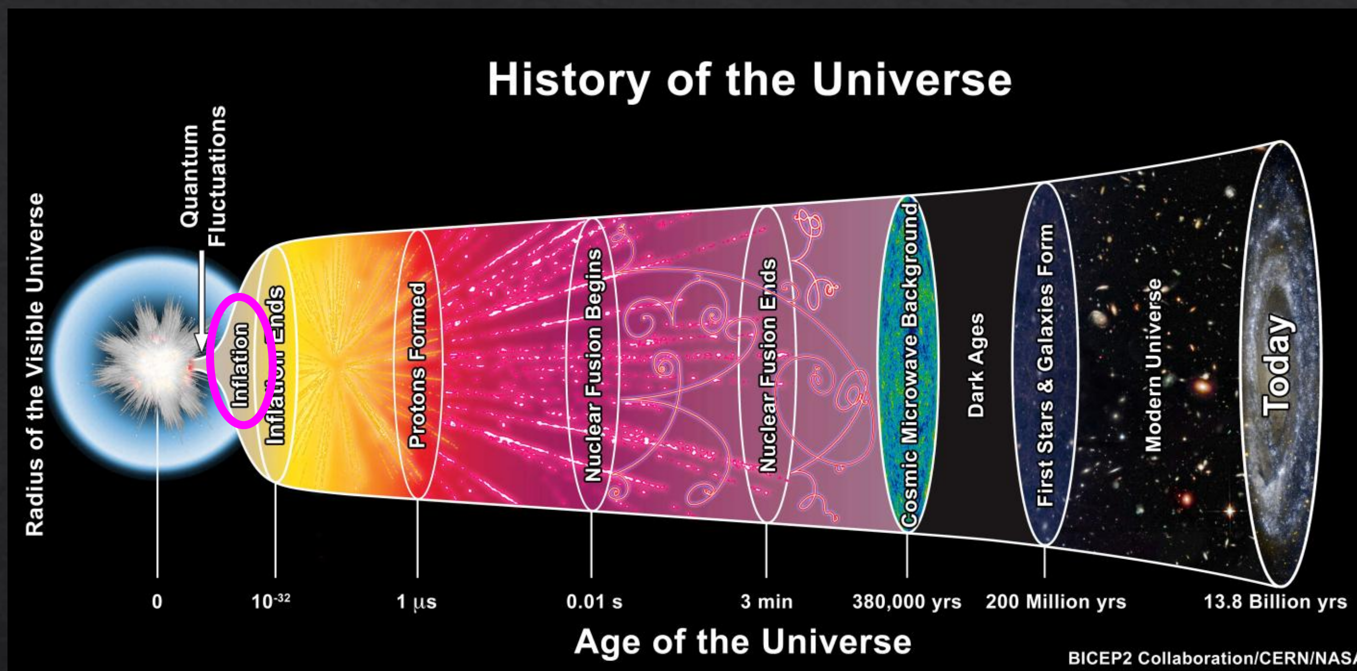


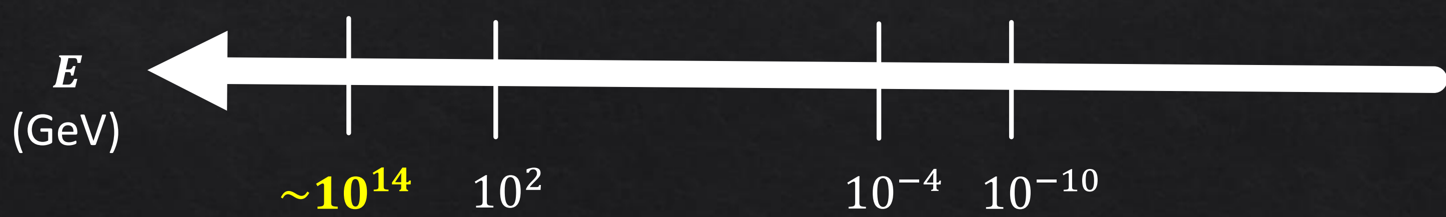


Gray, Future colliders for the high-energy frontier

Very important,
but BSM might appear at higher scale
⇒ Another approach?

Universe as a gigantic accelerator



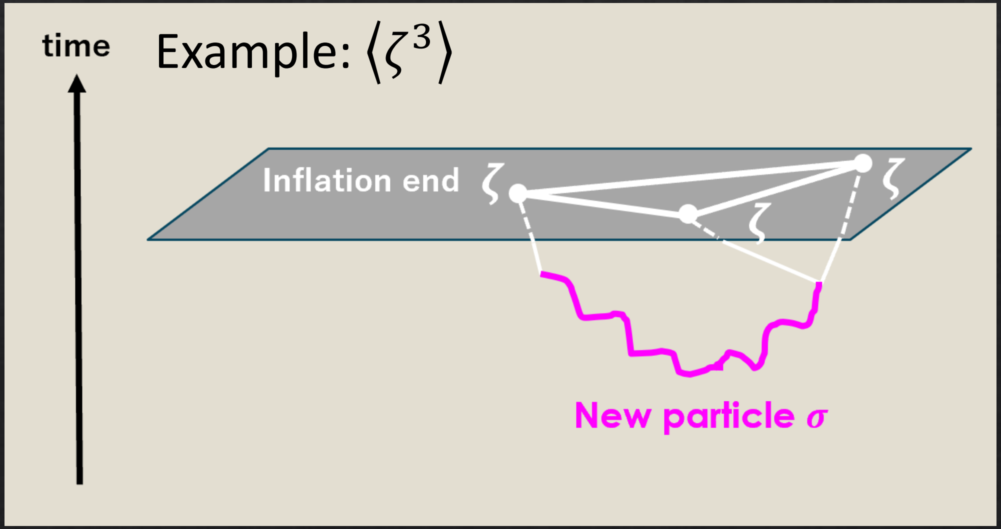


Idea: probing new physics with inflation energy

Cosmological Collider

Chen, Wang, '10
Baumann, Green, '12
Noumi, Yamaguchi, Yokoyama, '13
Arkani-Hamed, Maldacena, '15

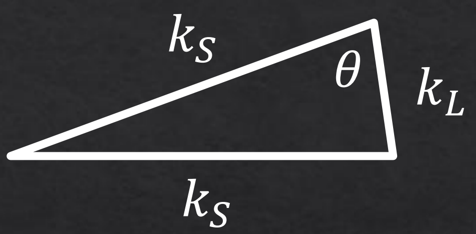
- $\langle \zeta^n \rangle$ can contain information of heavy (new) particle σ



Cosmic expansion creates σ with mass $\sim H$

Cosmological Collider

- Clear signal in squeezed limit of triangle $k_S \gg k_L$



- σ leaves specific imprint on $\langle \zeta^3 \rangle$

$$\langle \zeta^3 \rangle \big|_{k_L \ll k_S} \sim e^{-\pi\mu} \left(\frac{k_L}{k_s} \right)^{\frac{3}{2}} \cos \left[\mu \log \left(\frac{k_L}{k_s} \right) + \delta(\mu) \right] P_s(\cos\theta)$$

Boltzmann suppression

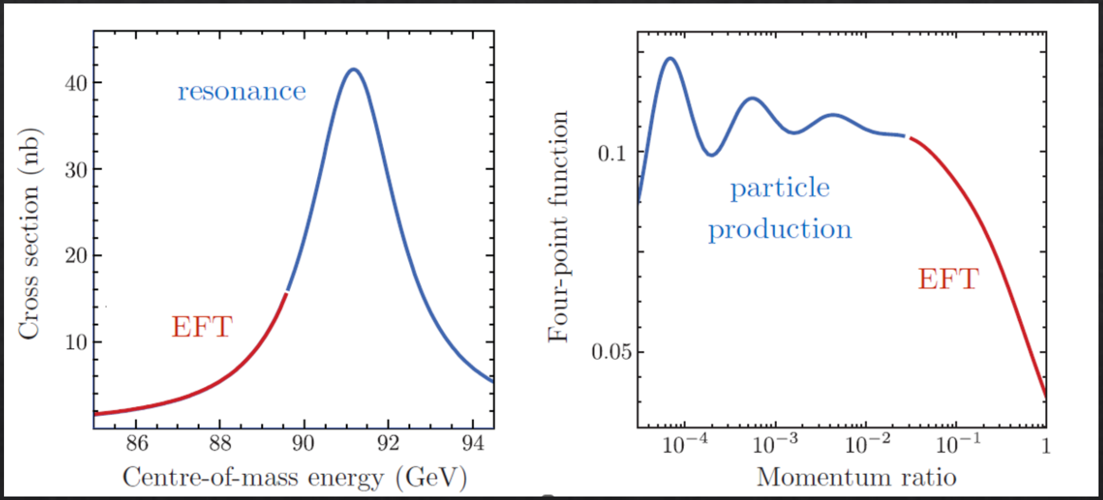
dilution

$\mu \sim m_\sigma / H$: mass

spin

Cosmological Collider

- Particle physics analogy

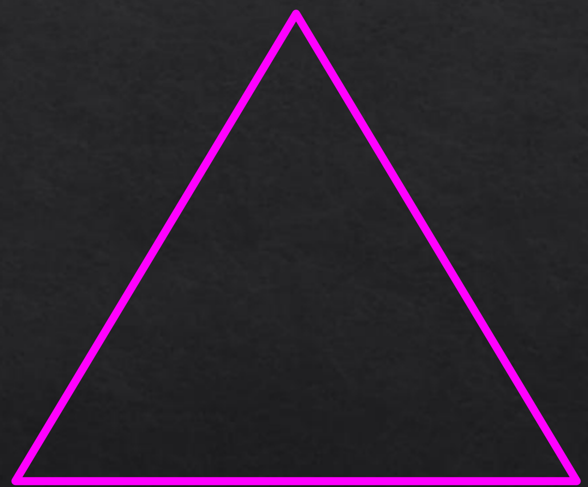


Baumann, Lectures on The Cosmological Bootstrap

- $m_\sigma \sim H_{\rm inf} \sim 10^{14}$(GeV) $\gg\gg\gg 10^{4,5}$(GeV) ~ collider on earth

Several directions

Understand
structure of correlators
(→ Xianyu's talk)



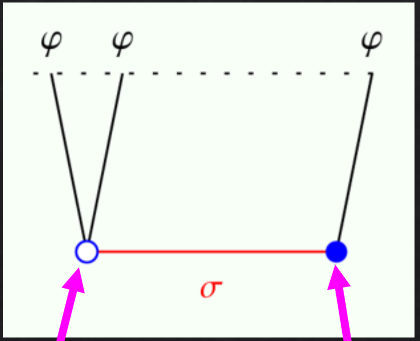
Comparison with
Observation
(→ Zhong's talk)

Application to BSM
(model building aspects)
(→ My talk)

Condition for large CC signal??

$$\langle \zeta^3 \rangle \big|_{k_L \ll k_s} \sim e^{-\pi\mu} \left(\frac{k_L}{k_s}\right)^{\frac{3}{2}} \cos\left[\mu \log\left(\frac{k_L}{k_s}\right) + \delta(\mu)\right] P_s(\cos\theta)$$

??



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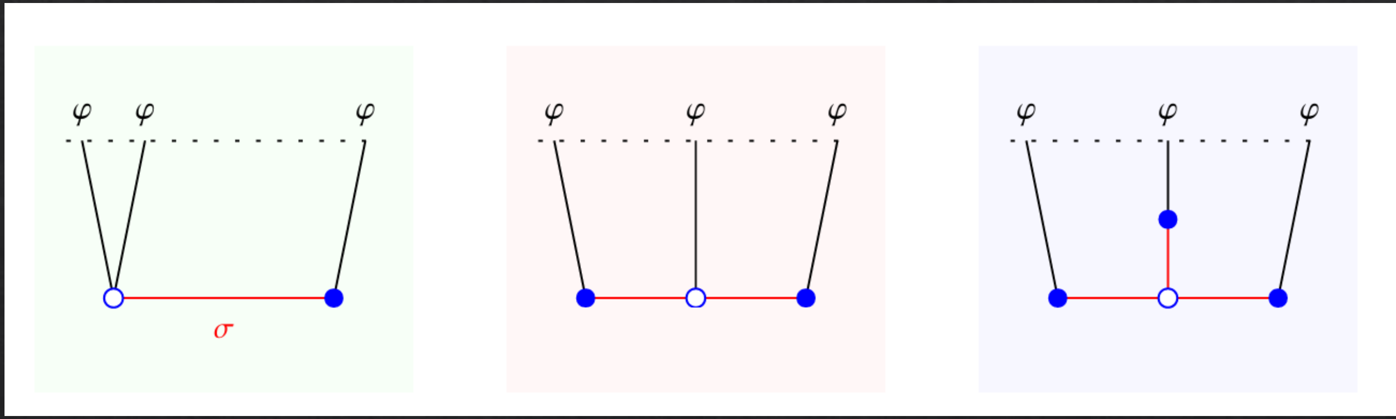
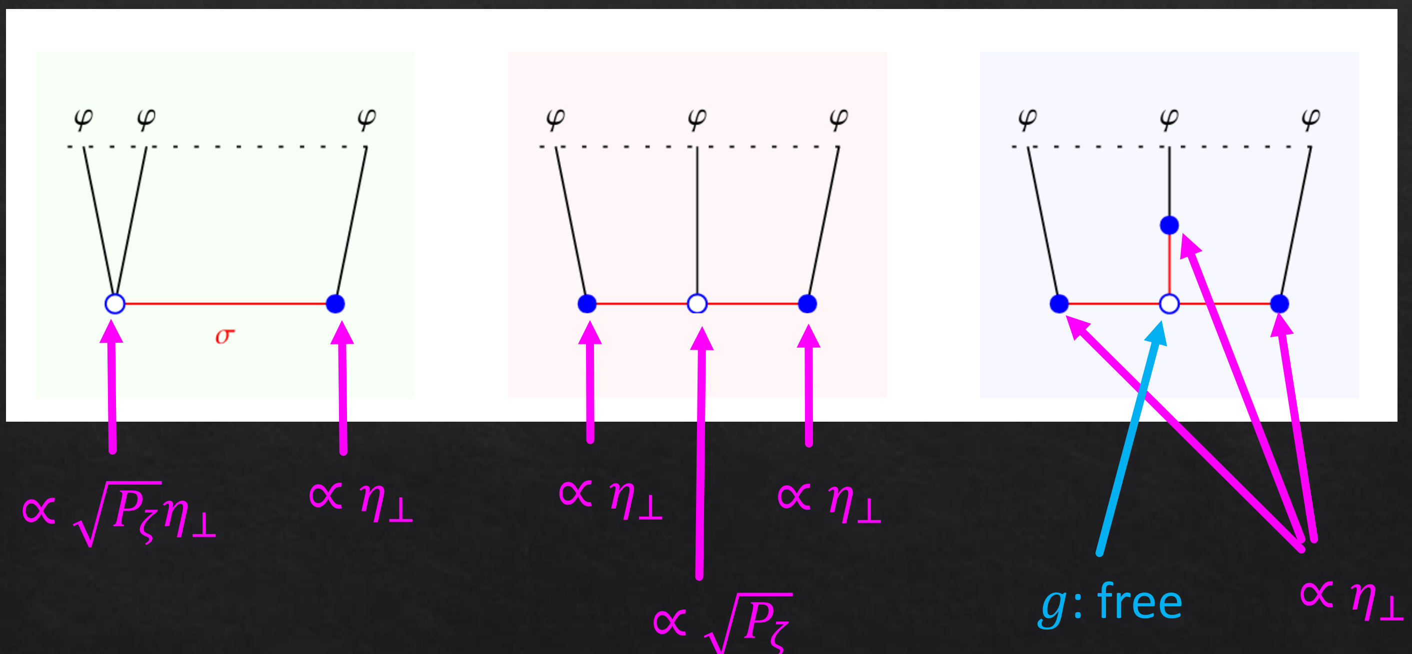
Summary:
3 dominant diagram for $\langle \zeta^3 \rangle$



Summary:
3 dominant diagram for $\langle \zeta^3 \rangle$

Assume $m_\sigma \sim H$ (w/o fine-tuning)

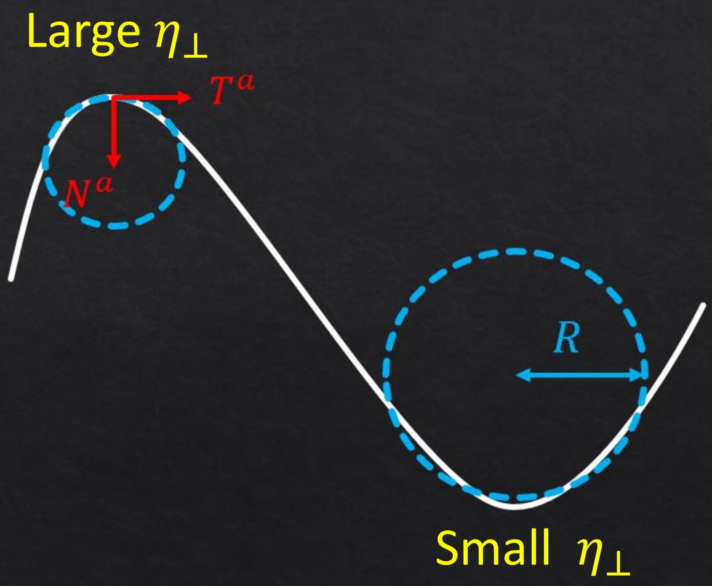
$\sqrt{P_\zeta} \sim 10^{-5}$: const



"Quasi single field inflation"
Chen, Wang, '10

Turn

- Turn rate: $\eta_\perp = \frac{d\phi}{d\mathcal{N}} \times \kappa$ (similar to $\omega = v/R$ in Newtonian mechanics)



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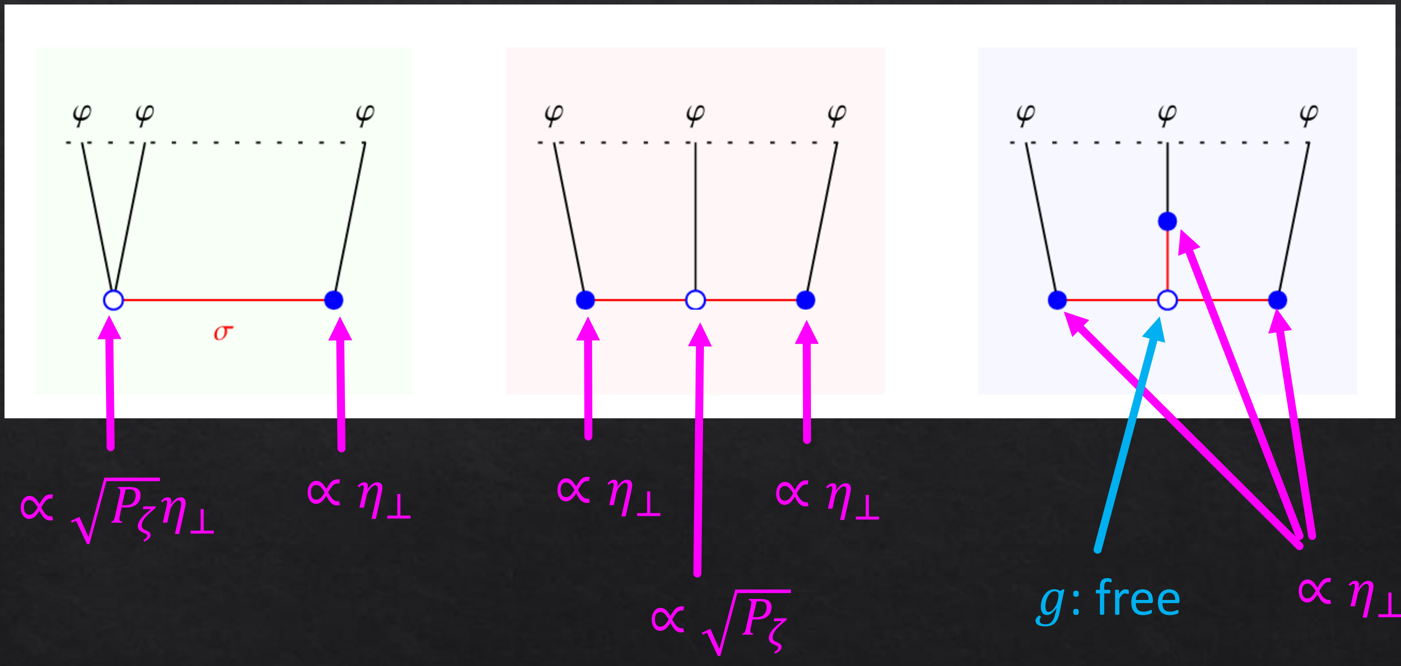


CC signal $\propto \eta_\perp^2$(× oscillation ×BF)	$\propto \eta_\perp^2$	$\propto \eta_\perp^3 \times g/H\sqrt{P_\zeta}$

Conditions for large signal

- Large turn rate $\eta_\perp$. Remember $\eta_\perp = \frac{d\phi}{d\mathcal{N}} \times \kappa = \sqrt{2\epsilon} M_{\mathrm{PL}} \times \kappa$
  $\Rightarrow$ Large κ $\Rightarrow$ sub-Planckian scale

- Large cubic σ^3 (triple exchange)

Check by concrete model

- ϕ (Higgs or dilaton) + R^2 (Scalaron) Small CC signal $\sim O(\epsilon)$

  SA, A. Ghoshal and A. Strumia, 2408.07069

- Multifield α-attractor

  SA, Roest, Werth, in progress

- Monodromy

  SA, Otsuka, Yanagita, 2509.06739

(Multifield α-attractor and Monodromy:) Large $\sim O(1)$

Scalar ϕ + R^2

SA, A. Ghoshal and A. Strumia, 2408.07069

- J-frame

$$S = \int d^4x \sqrt{|\det g|}\left[-\frac{1}{2}f(\phi)R + \frac{R^2}{6f_0^2} + \sum_\phi \frac{(D_\mu\phi)(D^\mu\phi)}{2} - V_J(\phi)\right]$$

  - ϕ: some scalars (specified later)
  - R^2 gives an additional scalar z (scalaron)

- E-frame

$$S = \int d^4x \sqrt{|\det g|}\left[-\frac{\bar{M}_{\rm Pl}^2}{2}R + \frac{6\bar{M}_{\rm Pl}^2}{z^2}\frac{(\partial_\mu z)^2 + \sum_\phi (D_\mu\phi)^2}{2} - V(\phi, z)\right]$$

$$V = \left(\frac{6\bar{M}_{\rm Pl}^2}{z^2}\right)^2\left[V_J(\phi) + \frac{3}{8}f_0^2\left(f + \xi_z z^2\right)^2\right].$$

$$\xi_z = -1/6,$$

Include two important models

- ϕ = Dilaton : $f = \xi\phi^2, V_J = \lambda(\phi)\phi^4/4$ Kannike et al, '15,…

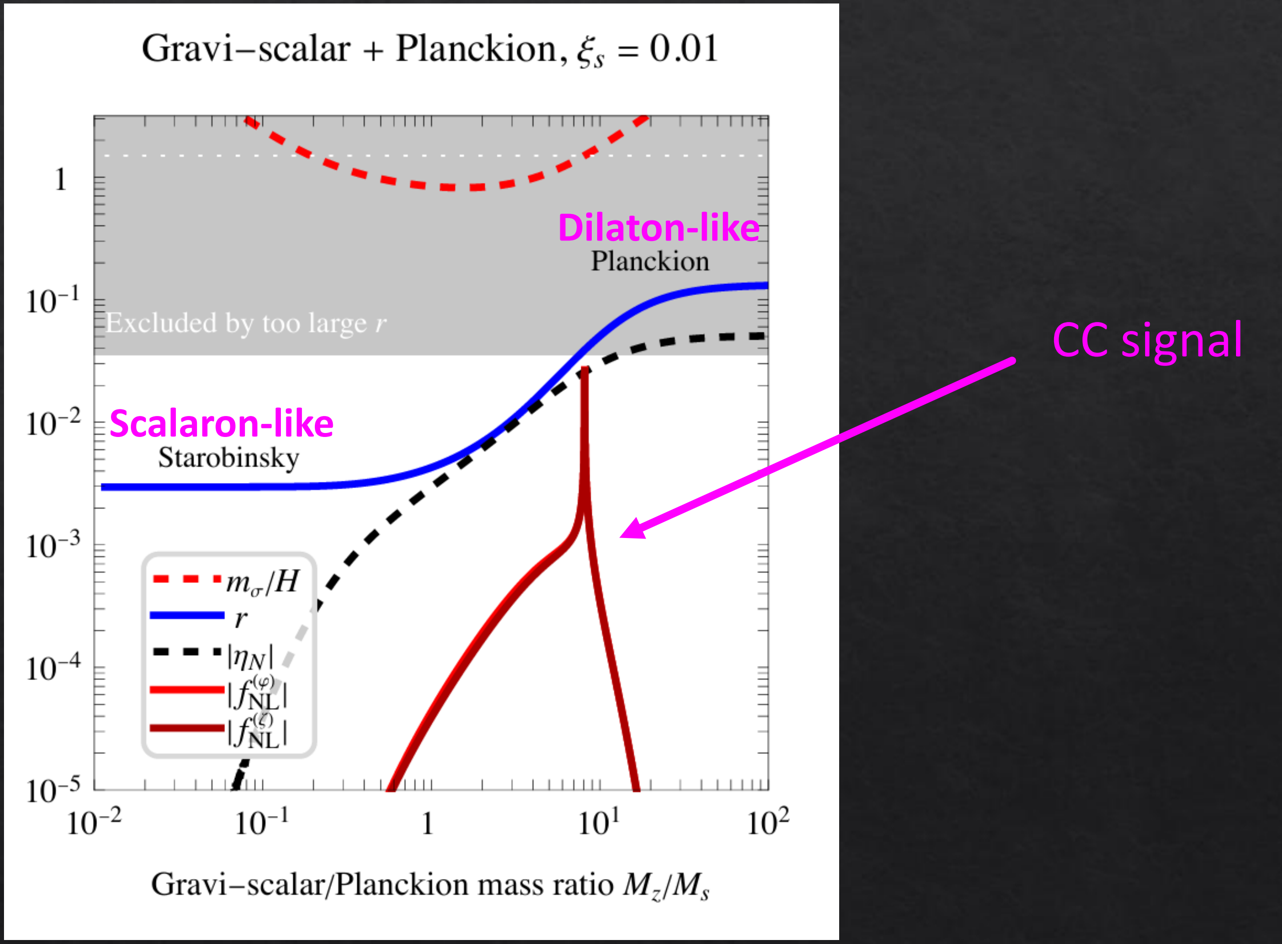
←Planck scale is induced by $\langle\phi^2\rangle = M_{\rm pl}^2/\xi_s$

- ϕ = Higgs : $f = M_{\rm PL}^2 + \xi\phi^2, V_J = \lambda\phi^4/4$ Salvio, Mazumdar '15, Ema '17, ...

← Unitarizing Higgs inflation $\xi f_0^2 \sim O(1)$

Only scale $\sim M_{\rm PL}$ for natural parameter choice
$\Rightarrow \kappa \propto 1/M_{\rm Pl} \Rightarrow \eta_{\rm N} \propto \sqrt{\epsilon}$: Small turn !!

CC signal from dilaton+R^2



Multifield α-attractor

- Two field generalization of α-attractor (α, $R_m \equiv m_\chi^2/m_\phi^2$)

$$G_{IJ} = \frac{6\alpha}{(1-\phi^2-\chi^2)^2}\delta_{IJ}\,.$$

$$V(\phi,\chi) = \frac{\alpha}{2}\left(m_\phi^2\phi^2 + m_\chi^2\chi^2\right)\,,$$

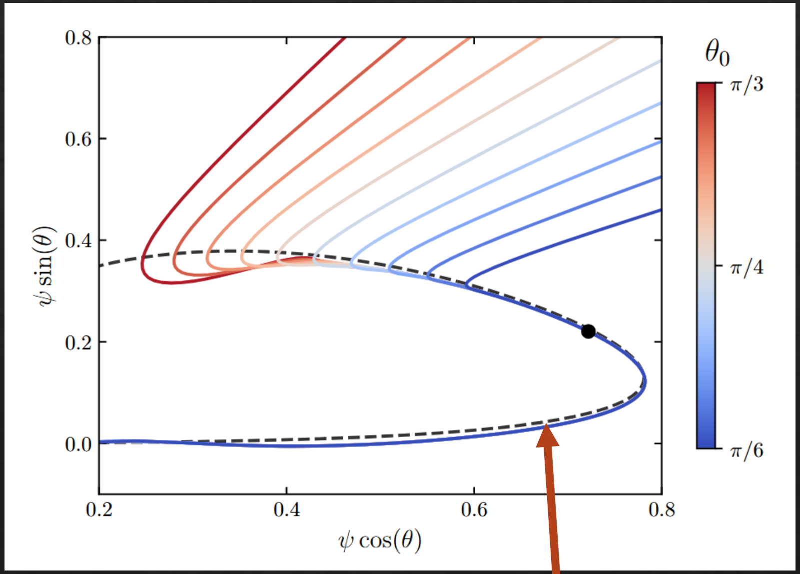
- $\phi = r\cos\theta, \chi = r\sin\theta$
  - radial (r) inflation for $\alpha \gg 1$ (~single α-attractor)

    Kallosh, Linde, Roest, 1311.0472
  - Angular (θ) inflation for $\alpha \ll 1$

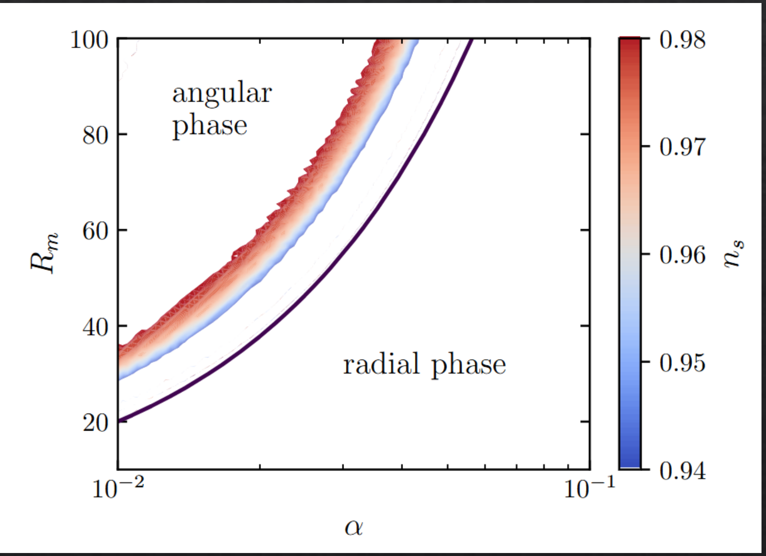
    Christodoulidis, Roest, Sfakianakis, 1803.09841

Multifield α-attractor

Trajectory (attractor)



Parameter space



$$1 - r^2(\theta) \approx \frac{9\alpha(\cot\theta + R_m \tan\theta)^2}{2(R_m - 1)^2}$$

Multifield α-attractor

- Large turn rate: $\eta_\perp \sim 1$ for $\alpha \sim \epsilon \ll 1$ (curvature of trajectory $\kappa \propto 1/\alpha M_{\rm Pl}$)

SA, Roest, Werth, in progress

$$\eta_\perp^2 \simeq \frac{4\epsilon}{3\alpha}$$

- isocurvature mass

$$m_{\sigma,\rm eff}^2 = \eta_\perp^2 H^2$$

$m_{\sigma,\rm eff} \sim H$ for $\eta_\perp \sim 1$
$\Rightarrow O(1)$ CC signal

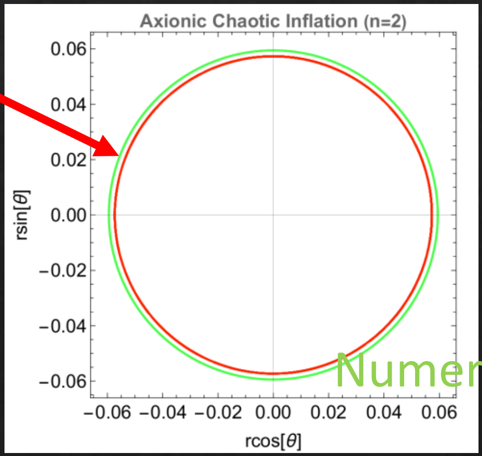
Monodromy

SA, Otsuka, Yanagita, 2509.06739

Flat target space $G_{IJ} = \mathrm{diag}\,(1, r^2)$

$$V(r,\theta) = \alpha\theta^n + \frac{M^2}{2}(r-R)^2\,,$$

Trajectory with $\frac{R}{r} \ll 1$: $\frac{n^2\alpha^2\theta^{2n-2}}{r^4} \simeq 3m^2\left(m^2r^2 + \alpha\theta^n\right)$



Turn rate: $\eta_\perp^2 \simeq \frac{2\epsilon M_{\rm Pl}^2}{r^2}$

curvature $\kappa \propto 1/r$

$\Rightarrow$ large $\eta_\perp$ $\Rightarrow$ large CC

iso mass: $m^2 = \frac{M^2 R}{r}\,.$

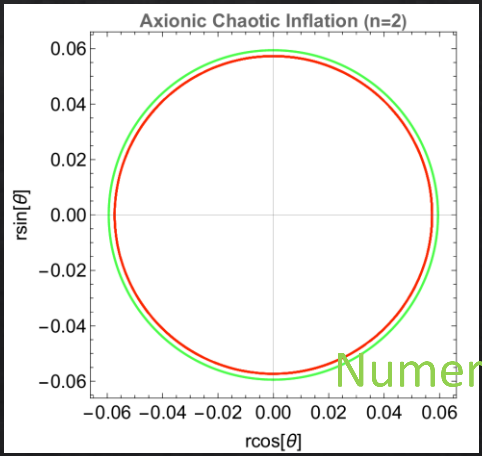
Monodromy

SA, Otsuka, Yanagita, 2509.06739

Flat target space $G_{IJ} = \text{diag}\,(1, r^2)$

$$V(r,\theta) = \alpha\theta^n + \frac{M^2}{2}(r-R)^2\,,$$

Parameters: (n, α, M, R)	n_s	r	$\lvert\eta_\perp\rvert \equiv \lvert\rho\rvert/(2H)$	m/H
$\left(\frac{1}{2}, 2.7\times10^{-11}, 3\times10^{-4}, 4\times10^{-4}\right)$	0.98	0.03	16.2	4.77
$(1, 6.1\times10^{-13}, 1.5\times10^{-4}, 4\times10^{-4})$	0.975	0.018	10.5	2.15
$(2, 1\times10^{-14}, 3.5\times10^{-5}, 8\times10^{-4})$	0.967	0.022	2.16	0.85



Numerical

Summary

- Model building aspects of CC with tree scalar exchange (conditions for large signal, explicit models)

- Need big turn rate and/or big σ^3 for large signal

  ↓

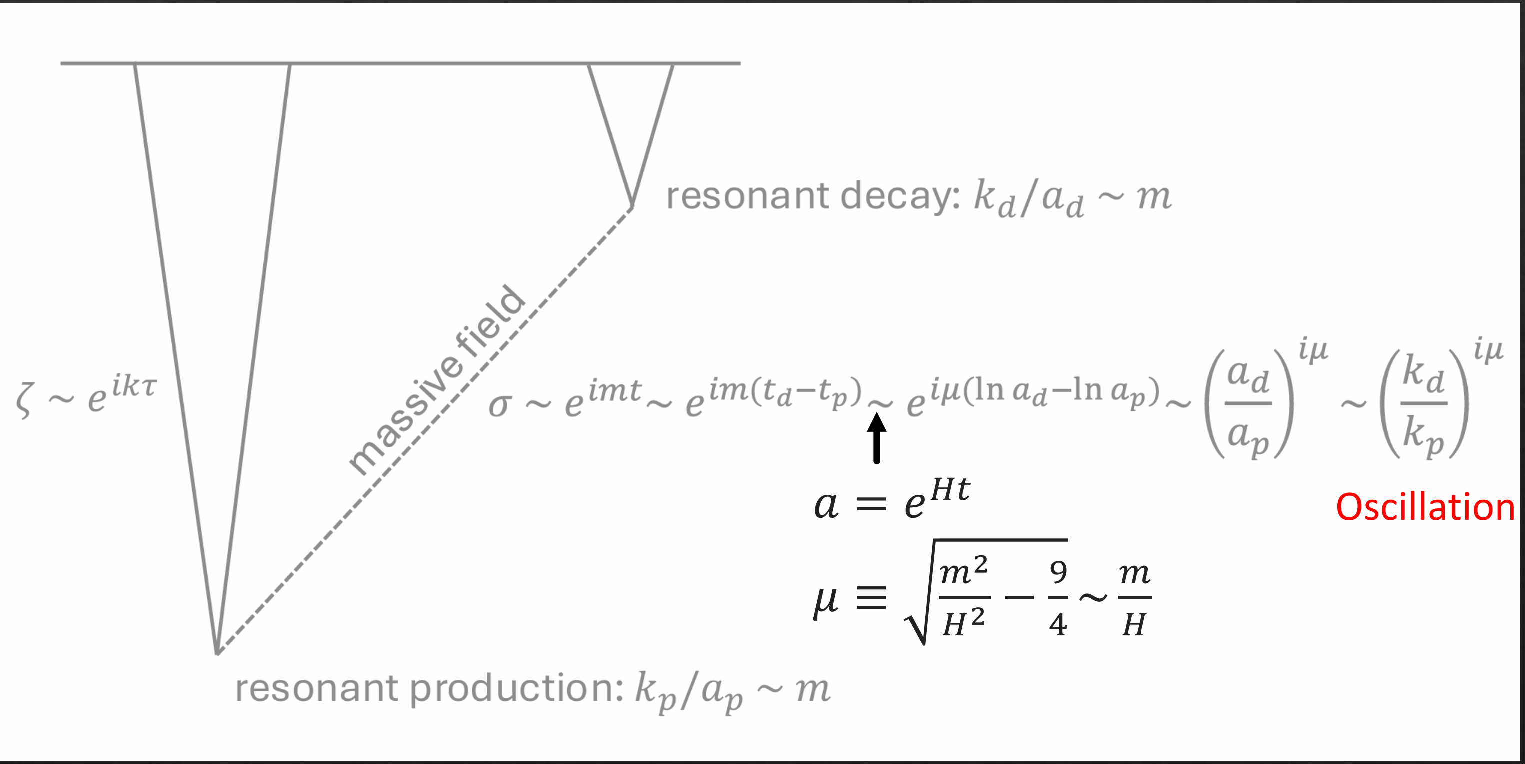
  $\eta_\perp = \sqrt{2\epsilon} M_{\mathrm{PL}} \times \kappa \Rightarrow$ Large κ

- Three models

  - $\phi + R^2 \Rightarrow \kappa \propto 1/M_{\mathrm{Pl}}$
  - Multifield α-attractor $\Rightarrow \kappa \propto 1/\alpha M_{\mathrm{Pl}}$
  - Monodromy $\Rightarrow \kappa \propto 1/r$

Thank you!!

Why oscillation??



From Yi Wang's slide

Target & Assumption

- $\langle \zeta^3 \rangle$
- Inflation scenario
- Tree >> Loop
- Scalar exchange without chemical potential

Many interesting possibilities if relax assumptions

Modulated reheating (Lu, Wang, Xianyu, 1907.07390)
Curvaton (Kumar, Sundrum, 1908.11378)
Chemical potential (Bodas, Kumar, Sundrum, 2010.04727)
Non-BD vacuum (Yin, 2309.05244)
…

From J to E-frame

- J-frame

$$S = \int d^4x \sqrt{|\det g|} \left[-\frac{1}{2} f(\phi) R + \frac{R^2}{6 f_0^2} + \sum_\phi \frac{(D_\mu \phi)(D^\mu \phi)}{2} - V_{\rm J}(\phi) \right]$$

- Add 0 (χ: auxiliary field) $-(R + 3 f_0^2 \chi/2)^2 / 6 f_0^2$ which cancels R^2
- Do Weyl rescaling $g_{\mu\nu}^{\rm E} = g_{\mu\nu}(f + \chi)/\bar{M}_{\rm Pl}^2$
- χ becomes dynamical, define $z \equiv \sqrt{6(f + \chi)}$

- E-frame

$$S = \int d^4x \sqrt{|\det g|} \left[-\frac{\bar{M}_{\rm Pl}^2}{2} R + \frac{6 \bar{M}_{\rm Pl}^2}{z^2} \frac{(\partial_\mu z)^2 + \sum_\phi (D_\mu \phi)^2}{2} - V(\phi, z) \right]$$

$$V = \left(\frac{6 \bar{M}_{\rm Pl}^2}{z^2} \right)^2 \left[V_{\rm J}(\phi) + \frac{3}{8} f_0^2 \left(f + \xi_z z^2 \right)^2 \right].$$

$\xi_z = -1/6,$