$f(R)$ gravity with broken Weyl gauge symmetry and its effects on cosmological evolution

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Research highlights

- We construct **Weylian $f(R)$ gravity** and investigate the **spontaneous symmetry breaking(SSB)** of Weyl symmetry in the primordial era.
- SSB induces **a new genuine non-minimal coupling in the perturbational regime** that cannot be expected in standard $f(R)$ gravity.
- **Tensor perturbation** gets **correlated** with the **scalar perturbation, giving deviations in the Integrated-Sachs-Wolfe(ISW) effect.**
- Changes in CMB anisotropy **result in a tighter bound in values of the tensor-to-scalar ratio r.**

Gravity with larger gauge group

Weyl gauge symmetry

Extension of the connection to include more freedom

$\nabla_\alpha g_{\mu\nu} = g_{\mu\nu}\phi_{,\alpha}$

New scale symmetry associated with the field ϕ

$(g_{\mu\nu}, \phi) \to (\Omega^2 g_{\mu\nu}, \phi + 2M_P \ln\Omega)$

Larger diffeomorphism gauge group

$\mathbf{Diff}_{\mathrm{GR}} \subset \mathbf{Diff}_{\mathrm{Weyl}}$

Gauge transformation
$\nabla_\alpha \gamma_{\mu\nu} = 0$
$(\gamma_{\mu\nu} = e^{-\phi/M_P} g_{\mu\nu}, 0)$

The action

$$S = \frac{M_P^2}{2}\int dx^4 \sqrt{-\gamma}\left[R_\gamma - \frac{1}{2}(\nabla\varphi)^2 - V(\varphi)\right]$$

R_γ: Ricci scalar w.r.t. $\gamma_{\mu\nu}$, $\varphi \approx e^{\phi/M_P}$ ($\because$ gauge condition)

Our model

SSB

$$S = \frac{M_P^2}{2}\int dx^4 \sqrt{-\gamma}\left[f(R_\gamma) - \frac{1}{2}(\nabla\varphi)^2 - V_0(\varphi^2 - M_P^2)^2\right]$$

After SSB, we expand $\varphi \approx M_P(1+\delta\varphi)$ and obtain

$$S \supset \frac{M_P^2}{2}\int dx^4 \sqrt{-\gamma}\left[f\left(\gamma^{\mu\nu}(R_g)_{\mu\nu}\right) - 3f'\left(\gamma^{\mu\nu}(R_g)_{\mu\nu}\right) m_{\delta\varphi}^2 \delta\varphi\right]$$

$(R_g)_{\mu\nu}$: Ricci tensor w.r.t. $g_{\mu\nu}$, $m_{\delta\varphi}^2 \equiv 4V_0 M_P^2$: mass of $\delta\varphi$

Equivalent action with non-minimal coupling

Standard $f(R)$ theory

$$S = \frac{M_P^2}{2}\int dx^4 \sqrt{-g} f(R)$$

$$\updownarrow$$

$$S = \int dx^4 \sqrt{-\hat{g}}\left[\frac{M_P^2}{2}R_{\hat{g}} - \frac{1}{2}(\hat{\nabla}\zeta)^2 - V(\zeta)\right]$$

Our model

$$S \supset \frac{M_P^2}{2}\int dx^4 \sqrt{-\gamma}\left[f\left(\gamma^{\mu\nu}(R_g)_{\mu\nu}\right) - 3f'\left(\gamma^{\mu\nu}(R_g)_{\mu\nu}\right) m_{\delta\varphi}^2 \delta\varphi\right]$$

$$\updownarrow$$

$$S = \int dx^4 \sqrt{-\hat{\gamma}}\left[\frac{M_P^2}{2}A(\zeta,\delta\varphi)R_{\hat{\gamma}} - \frac{1}{2}(\hat{\nabla}\zeta)^2 - V(\zeta)\right] + \int dx^4 \sqrt{-\hat{\gamma}}\left[-\frac{1}{2}(\hat{\nabla}\delta\varphi)^2 - \frac{1}{2}m_{\delta\varphi}^2\delta\varphi^2 + \delta V(\zeta,\delta\varphi)\right]$$

A : non-minimal coupling mediated by $\delta\varphi$

δV: interaction potential

Example: Starobinsky inflation

Effective Planck and cosmological constants

$$(M_P^2)_{\mathrm{eff}} = (M_P^2)_{\mathrm{bare}} \times A(\zeta,\delta\varphi)$$
$$\Lambda_{\mathrm{eff}} = \Lambda_{\mathrm{bare}} + (M_P^{-2})_{\mathrm{eff}} \times \delta V(\zeta,\delta\varphi)$$

Starobinsky inflation: $f(R) = R + R^2/6M$

After the inflation, the gravity sector of the action becomes

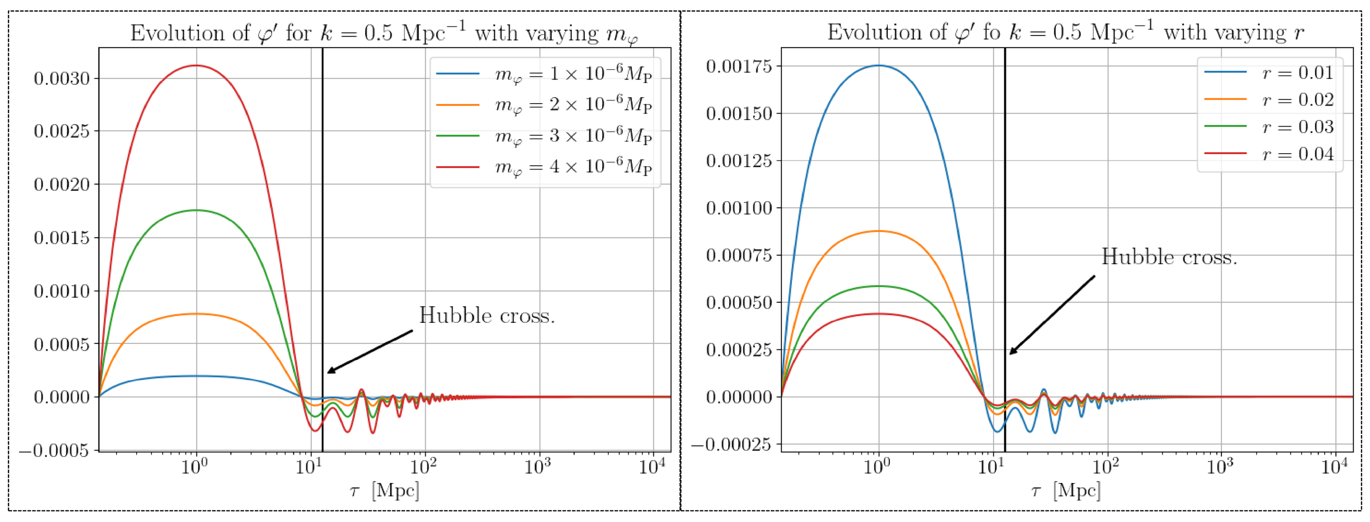
$$S \supset \frac{M_P^2}{2}\int dx^4 \sqrt{-\gamma}\left[\left\{1 - \left(\frac{m_{\delta\varphi}}{M}\right)^2 \delta\varphi\right\}R_\gamma\right] \qquad (\delta V = 0)$$

The tensor power spectrum of the Starobinsky inflation is

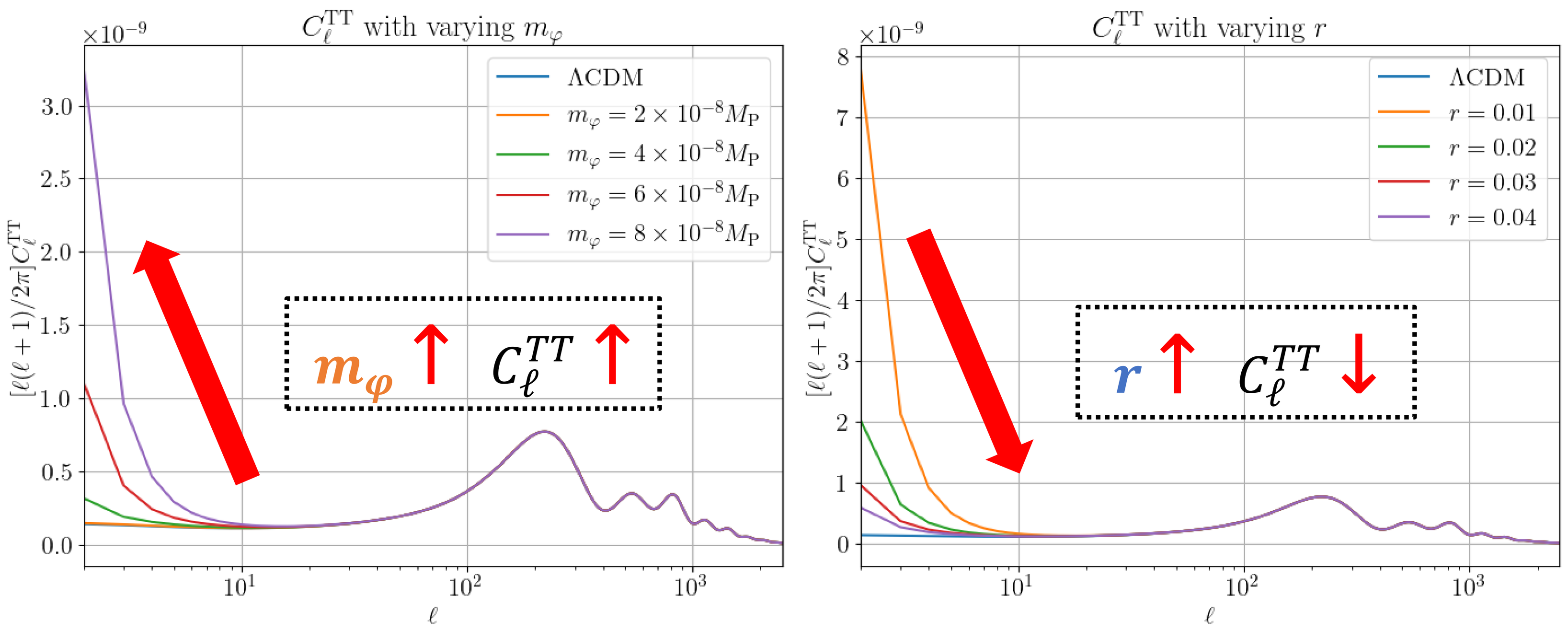
$\mathcal{P}_T \approx 4\pi^{-1}(M/M_P)^2 \to r$**: tensor-to-scalar ratio**

ISW effect makes bigger r more preferable

Deviation in ISW effect: $\Delta I^{\mathrm{ISW}} = \left[1 - \left(\frac{m_{\delta\varphi}}{M}\right)^2\right]\int_{\eta_*}^{\eta_0} d\eta\, \delta\varphi' j_\ell[k(\eta_0 - \eta)]$



CMB temperature anisotropy



Best-fit values of r and their 68% and 95% confidence bounds

	ΛCDM		Our model	
Planck	68%	95%	68%	95%
	< 0.0505	< 0.107	$\mathbf{0.055^{+0.017}_{-0.049}}$	$\mathbf{< 0.127}$
Planck +BICEP /Keck	68%	95%	68%	95%
	$0.0161^{+0.0061}_{-0.013}$	< 0.0348	$\mathbf{0.0196^{+0.0076}_{-0.012}}$	$\mathbf{0.020^{+0.020}_{-0.019}}$

Weyl symmetry breaking yields more probability for bigger r!

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