Inflationary Universe
(project A01 status report)

Toward Understanding Physics/Mechanism of Inflation

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10 February, 2018

Inflation: current status

- scalar spectral index: $n_s<1$ at ~ 5σ
- tensor/scalar ratio: $r < 0.1$ implies $E_{inflation} < 10^{16}$ GeV
- simple, canonical models are on verge of extinction ($m^2\phi^2$ model excluded at $> 2\sigma$)
- R^2 (Starobinsky) model seems to fit best. But why?
- f_{NL}^{local} <O(1) suggests (effectively) single-field slow-roll but f_{NL}^{local} =O(1) or scale-dep f_{NL}^{local} =O(10) not excluded

↓

some element of non-canonicality seems necessary

Theories/models? Observational tests/signatures?

research summary

Teruaki Suyama ⇨ talk
Shuichiro Yokoyama ⇨ poster

Tsutomu Kobayashi, Kazunori Nakayama, Misao Sasaki,
Tomo Takahashi, Masahide Yamaguchi, Jun'ichi Yokoyama

76 published papers
(27 for the last year)

Very active!

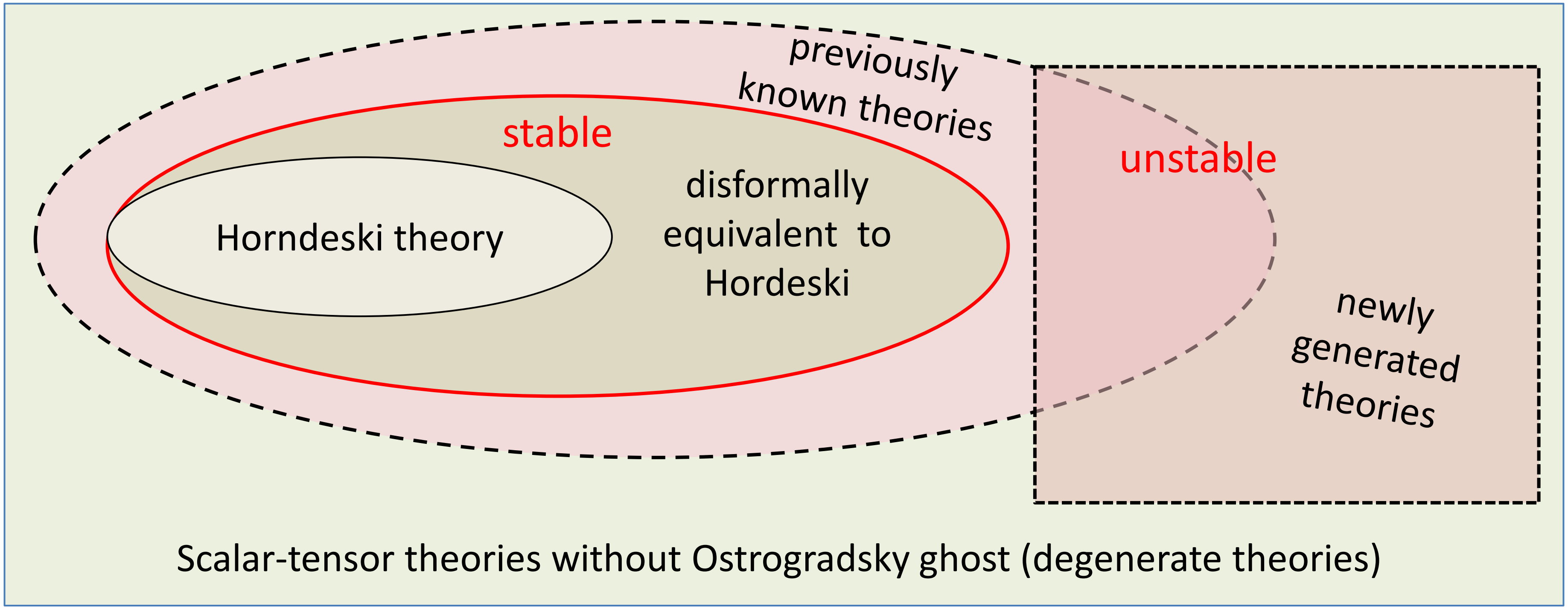
Selected Recent Papers

- ⇨ Observational signatures of the parametric amplification of gravitational waves during reheating after inflation,
  S Kuroyanagi, C Lin, M Sasaki, S Tsujikawa, PRD97 (2018) 023516
- ⇨ Pole inflation in Jordan frame supergravity,
  K Saikawa, M Yamaguchi, Y Yamashita, D Yoshida, JCAP 1801 (2018) 031
- ⇨ Extended mimetic gravity: Hamiltonian analysis and gradient instabilities,
  K Takahashi, T Kobayashi, JCAP 1711 (2017) 038
- Refined Study of Isocurvature Fluctuations in the Curvaton Scenario,
  N Kitajima, D Langlois, T Takahashi, S Yokoyama, JCAP 1712 (2017) 042
- ⇨ Electroweak Vacuum Metastability and Low-scale Inflation
  Y Ema, K Mukaida, K Nakayama, JCAP 1712 (2017) 030
- Revisiting the oscillations in the CMB angular power spectra at $\ell \sim 120$ in the Planck 2015 data,
  K Horiguchi, K Ichiki, J Yokoyama, PTEP 2017 (2017) 093E01
- New bound on low reheating temperature for dark matter in models with early matter domination,
  KY Choi, T Takahashi, PRD96 (2017) 041301
- Spin Distribution of Primordial Black Holes,
  T Chiba, S Yokoyama, PTEP 2017 (2017) 083E01 9.
- ⇨ Note on Reheating in G-inflation
  HB Moghaddam, R Brandenberger, J Yokoyama, PRD95 (2017) 063529.
- CMB Scale Dependent Non-Gaussianity from Massive Gravity during Inflation,
  G Domenech, T Hiramatsu, C Lin, M Sasaki, JCAP 1705 (2017) 034

1. Modified Gravity

K Takahashi, T Kobayashi, JCAP 1711 (2017) 038 [1708.02951]

- *"Extended mimetic gravity"*
  generated general degenerate higher derivative theories by performing non-invertible conformal transformation and analyzed their cosmological stability.
  - result supports the conjecture "all degenerate scalar-tensor theories that are not equivalent to Horndeski under disformal transformation are unstable"



Modified Gravity (conti.)

S Hirano, T Kobayashi, H Tashiro, S Yokoyama, 1801.07885 [astro-ph.CO] + ...

- *“Matter bispectrum beyond Horndeski” + ongoing work*

GW170817 → GW propagation speed = c → strong constraint on MG

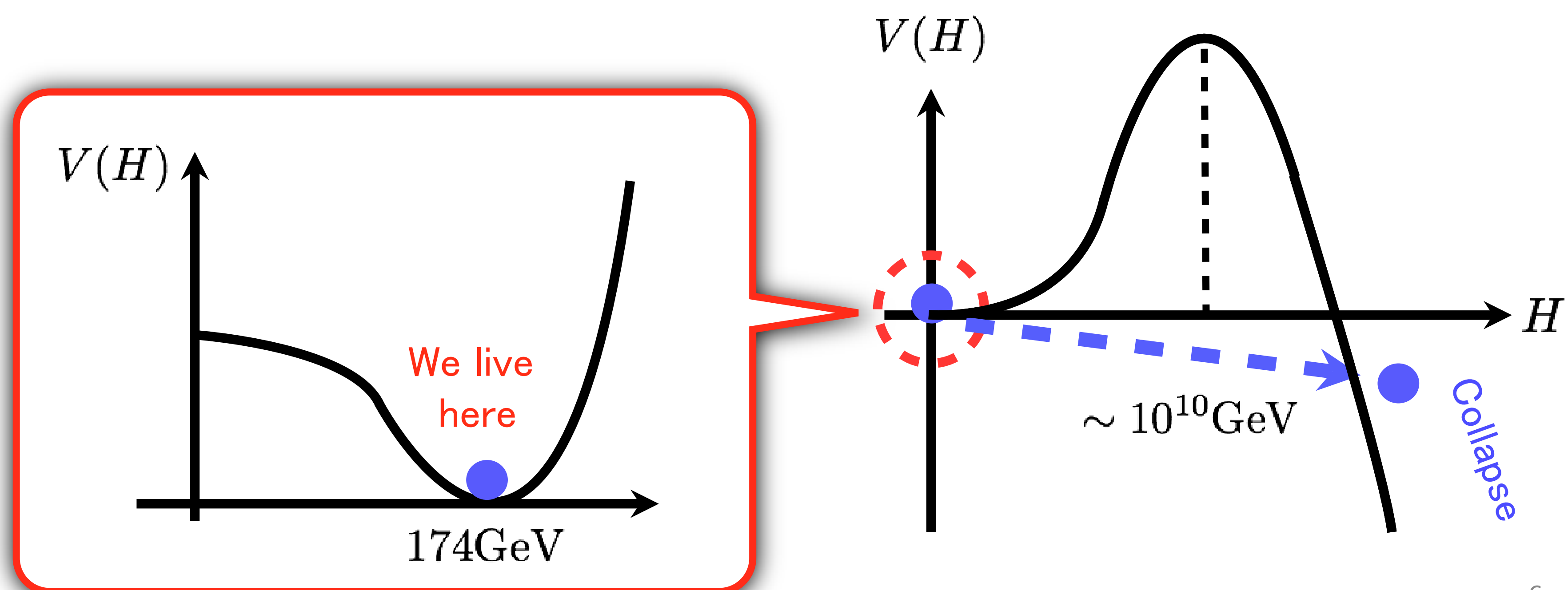
- allowed class of models = DHOST/beyond Horndeski
- any other constraint from, eg, growth rate of density perturbations?

2. EW Vacuum Metastability and Low-scale Inflation

Y Ema, K Mukaida, K Nakayama, JCAP 1712(2017) 030 [1706.08920]

Instability of Electroweak Vacuum

- Current vacuum = broken EW symmetry due to Higgs
- Higgs' mass: 125GeV (LHC) ⟶ Metastable Vacuum
- Why the current Universe can exist?

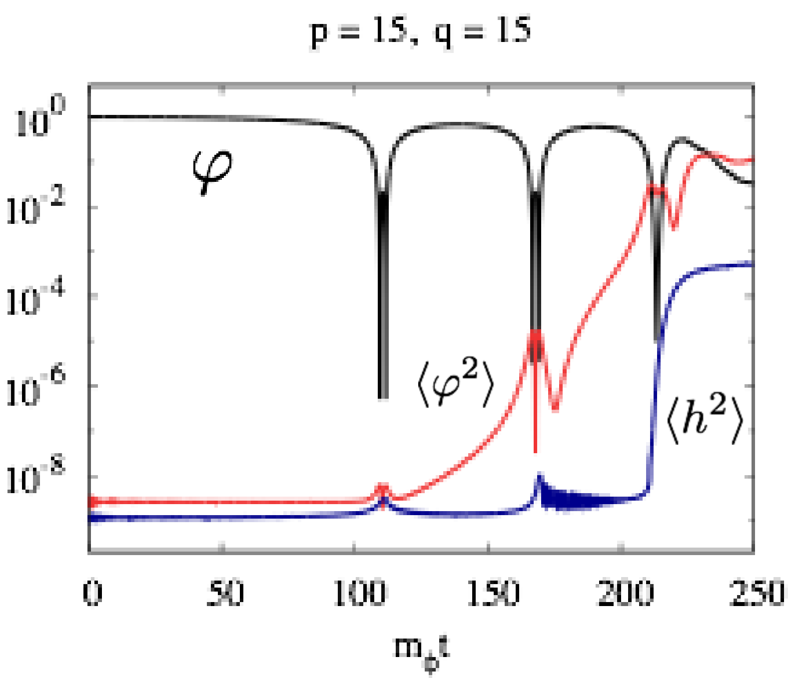


Low-scale Inflation

$$\mathcal{L} = \frac{M_{\rm Pl}^2}{2} R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}(\partial h)^2 - U(\phi, h) \qquad V(\phi) = \Lambda^4 \left[1 - \left(\frac{\phi}{v_\phi}\right)^n\right]^2$$

Inflaton-Higgs coupling: $$U(\phi, h) = V(\phi) + \frac{\tilde{\sigma}_{\phi h}}{2}\phi h^2 + \frac{\lambda_{\phi h}}{2}\phi^2 h^2 + \frac{m_h^2}{2} h^2 + \frac{\lambda_h}{4} h^4$$

Higgs fluctuations amplify due to parametric resonance



initial value at the onset of oscillations

$$p \equiv \frac{2\sigma_{\phi h}\varphi_{\rm ini}}{m_\phi^2}, \quad q \equiv \frac{\lambda_{\phi h}\varphi_{\rm ini}^2}{m_\phi^2}$$

stability constraint:

$$|p|, q \lesssim \mathcal{O}(1)$$

3. Probing multi-field inflation models with CMB spectral distortion

K Kainulainen, J Leskinen, S Nurmi, T Takahashi, JCAP1711 (2017) 002 [1707.01300]

- CMB μ distortion can probe primordial power spectrum on small scales.

$$\mu = \int_{z_1}^{z_2} dz e^{-z^2/z_{\rm DC}^2} \left[- \int \frac{dk^3}{(2\pi)^3} A \mathcal{P}_\zeta(k) \frac{d}{dz} \left(\frac{3c_s^2}{\sqrt{2} e^{-k^2/k_D^2}} \right) \right]$$

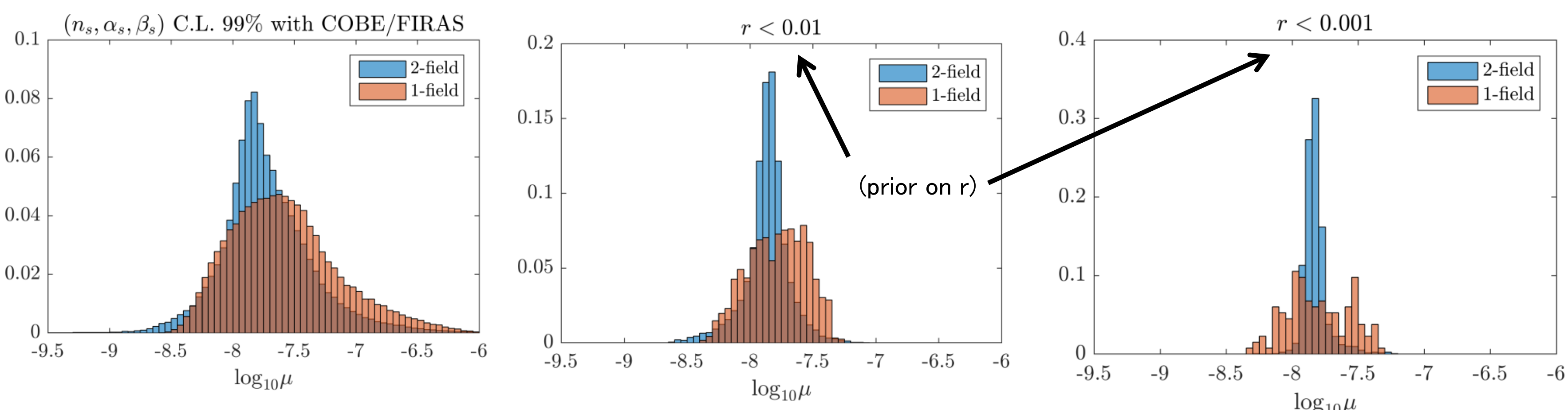
- Scales of 50/Mpc < k < 10^4 /Mpc can be probed.

$$\alpha_s \equiv \left. \frac{{\rm d}n_s}{{\rm d}\ln(k)} \right|_{k=k_{\rm ref}}$$

$$\beta_s \equiv \left. \frac{{\rm d}^2 n_s}{{\rm d}\ln(k)^2} \right|_{k=k_{\rm ref}}$$

<u>Histogram of prediction for the distribution of μ</u>

(all configurations are compatible with Planck constraints on n_s, α, β)



4. Pole inflation in Jordan frame supergravity

K Saikawa, M Yamaguchi, Y Yamashita, D Yoshida, JCAP 1801 (2018) 031 [1709.03440].

- **The models favored by the current observations (Starobinsky model, Higgs inflation, αattractor) can be understood in a unified way as pole inflation.**
- **The non-minimal coupling to gravity (R) may (easily) lead to this kind of pole structure of kinetic term after conformal transformation to Einstein frame.**
- **We simply impose the canonical kinetic term of a scalar field in the Jordan frame like Ferrara et al. (dubbed FKLMP model).**
- **We have shown that, in the FKLMP model, the relation between the Kahler potential and the frame function is uniquely determined by imposing that a scalar field has the canonical kinetic term and that a frame function consists only of a holomorphic term for symmetry breaking terms.**
- **We have relaxed this latter condition and discussed a wider class of models.**

Pole inflation

(Galante et al., Broy et al., Terada.)

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}K(\rho)g^{\mu\nu}\partial_\mu\rho\partial_\nu\rho - V(\rho)\right]$$

- K(ρ) has a pole at ρ= 0 in Laurent series :

$$K(\rho) = \frac{a_p}{\rho^p} + \cdots,$$

Canonically normalized field φ

$$\rho \simeq \begin{cases} \rho_0 e^{-\frac{\varphi}{\sqrt{a_2}}} & \text{for } p=2 \\ \left(\frac{(2-p)}{2\sqrt{a_2}}\varphi\right) & \text{for } p>2 \end{cases}$$

- V(ρ) is regular at ρ= 0 :

$$V(\rho) = V_0(1 - \rho + \cdots)$$

$$V(\varphi) \simeq \begin{cases} V_0\left[1 - \rho_0 e^{-\frac{\varphi}{\sqrt{a_2}}}\right] & \text{for } p=2 \\ V_0\left[1 - \left(\frac{(2-p)}{2\sqrt{a_2}}\varphi\right)^{\frac{2}{2-p}}\right] & \text{for } p>2 \end{cases}$$

(asymptotically flat)

By canonically normalizing a field, the potential is effectively stretched.

Primordial perturbations :

$$n_s - 1 \simeq -\frac{p}{p-1}\frac{1}{N},$$

$$r \simeq \frac{8}{a_p}\left[\frac{a_p}{(p-1)N}\right]^{\frac{p}{p-1}}.$$

α attractors ⇔ p=2, $a_2 = 3\alpha/2$

a_p dependence appears only in r.

Though subleading terms yield higher order corrections, the leading order predictions do not depend on the details.

FKLMP model and its extension

(Ferrara, Kallosh, Linde, Marrani, Van Proeyen 2010)

Inflation models in Jordan frame supergravity with the canonical kinetic term

Kahler potential: $\mathcal{K}(z,\bar{z}) = -3\log\left(-\frac{1}{3}\Phi(z,\bar{z})\right)$.

(special relation between K & Φ)

Equivalent under imposing the canonical kinetic term

Frame function: $\Phi(z,\bar{z}) = -3 + \delta_{\alpha\bar{\beta}} z^{\alpha}\bar{z}^{\bar{\beta}} + J(z) + \bar{J}(\bar{z})$,

holomorphic

with $\Phi_{\alpha}\hat{\partial}_{\mu}z^{\alpha} - \Phi_{\bar{\beta}}\hat{\partial}_{\mu}\bar{z}^{\bar{\beta}} = 0$

$$\mathcal{L}_{\mathrm{FKLMP}} = \sqrt{-g_J}\left[-\frac{1}{6}\Phi\mathcal{R}_J - \delta_{\alpha\bar{\beta}}\hat{\partial}_{\mu}z^{\alpha}\hat{\partial}_{\nu}\bar{z}^{\bar{\beta}}g_J^{\mu\nu} - V_J\right].$$

We extend

$$J(z,\bar{z})$$

with keeping the canonical kinetic term in Jordan frame

5. Reheating after G-inflation

HB Moghaddam, R Brandenberger, J Yokoyama, PRD95 (2017) 063529 [1612.00998].

Previously, in kinetically driven G-inflation (as well as k-inflation) Reheating was thought to occur through gravitational particle production due to the change of the geometry because there is no inflaton oscillation after inflation.

$$a(t) \propto e^{H_{\rm inf} t} \longrightarrow a(t) \propto t^{\frac{1}{3}}$$

This process is known to be inefficient with the reheating temperature given by

$$T_R = \frac{3N^{\frac{3}{4}}}{(32\pi^2)^{\frac{3}{4}}}\left(\frac{30}{\pi^2 g_*}\right)^{\frac{1}{4}}\frac{H_{\rm inf}^2}{M_G} \simeq 3.9\times 10^6 N^{\frac{3}{4}}\left(\frac{g_*}{106.75}\right)^{-\frac{1}{4}}\left(\frac{r}{0.01}\right)\,{\rm GeV}.$$

(Ford 1987, Kunimitsu & JY 2014)

Here N is the number of light bosonic degree of freedom (minimal coupling to gravity assumed) and r is the tensor-to-scalar ratio.

We studied effect of direct interaction with the inflaton ϕ and another scalar χ which preserves the shift symmetry of the former.

$$\mathcal{L}_{int} = \frac{1}{2M^2}(\partial\phi)^2\chi^2 = -\frac{1}{2M^2}\dot{\phi}^2\chi^2$$

Mode function satisfies

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left(\frac{k^2}{a^2} + M^{-2}\dot{\phi}^2\right)\chi_k = 0$$

$$X_k \equiv a^{-1}\chi_k \qquad dt = a(t)d\tau$$

$$X_k'' + \left(k^2 + M^{-2}\dot{\phi}^2 a^2 - \frac{a''}{a}\right)X_k = 0$$

$$M^{-2}\dot{\phi}^2 a^2 - \frac{a''}{a} \equiv -V(\tau)$$

$$\rho_r(\tau) = \frac{-1}{32\pi^2 a^4} \int_{-\infty}^{\tau} d\tau_1 d\tau_2 \ln(\mu |(\tau_1 - \tau_2)|) V'(\tau_1) V'(\tau_2)$$

$$\simeq \frac{H_{\inf}^4}{128\pi^2 a^4} \left[5\frac{M_G^4}{M^4} + 12\ln\left(\frac{1}{H_{\inf}\Delta t}\right) \right]$$

M_G : reduced Planck scale

direct interaction | gravitational particle production

★ If $M \leq M_G$ the direct interaction is more important than gravitational particle production and realizes a higher reheating temperature.

★ The reheating temperature can be much higher when direct interaction is dominant.

$$T_R = \frac{5H_{\inf}^2 M_G^2}{32\pi^2 (3g_*)^{1/4} M^3} = 1.2\times 10^{13} \left(\frac{g_*}{106.75}\right)^{-\frac{1}{4}} \left(\frac{r}{0.01}\right) \left(\frac{M}{10^{16}\,\mathrm{GeV}}\right)^{-3} \mathrm{GeV}$$

6. Inflationary Massive Gravity

S Kuroyanagi, C Lin, M Sasaki , S Tsujikawa, PRD97 (2018) 023516 [1710.06789]

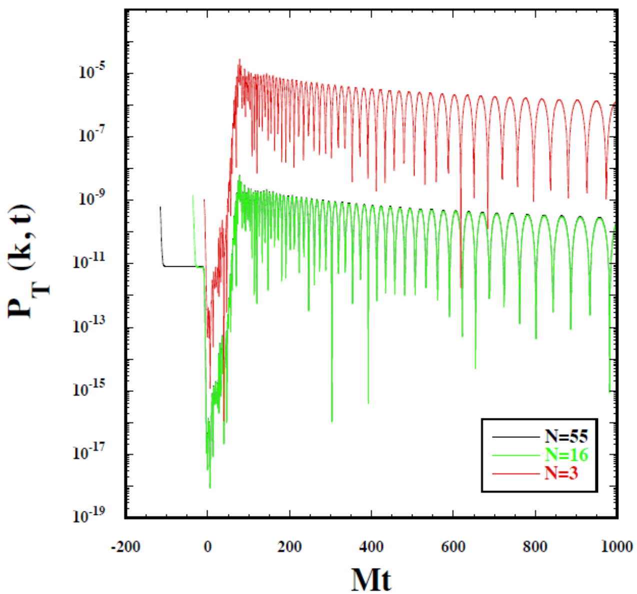
$$S = \int d^4x \left[\frac{M_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{9}{8} M_P^2 m_g^2(\phi) \frac{\delta Z^{ij} \delta Z^{ij}}{Z^2} \right]$$

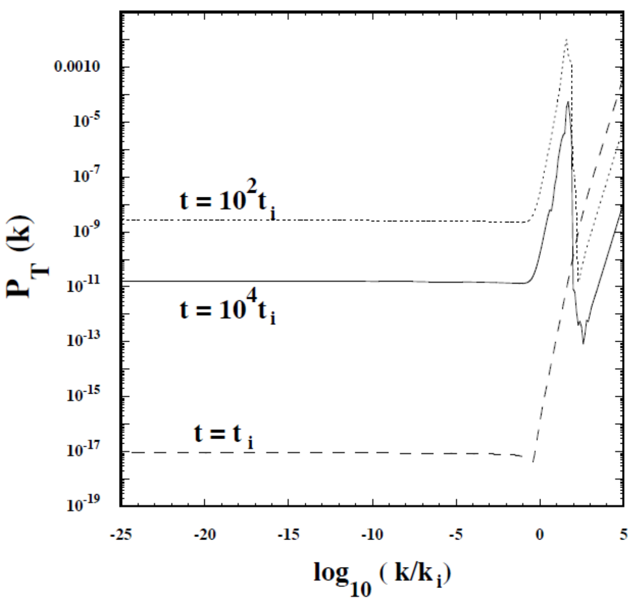
$$\delta Z^{ij} = Z^{ij} - 3 \frac{Z^{ik} Z^{kj}}{Z}; \quad Z = Z^{ii}$$

$$Z^{ij} = g^{\mu\nu} \partial_\mu \varphi^i \partial_\nu \varphi^j - \frac{g^{\mu\alpha} \partial_\mu \varphi^0 \partial_\alpha \varphi^i g^{\nu\alpha} \partial_\nu \varphi^0 \partial_\beta \varphi^j}{X} = h^{ij}$$

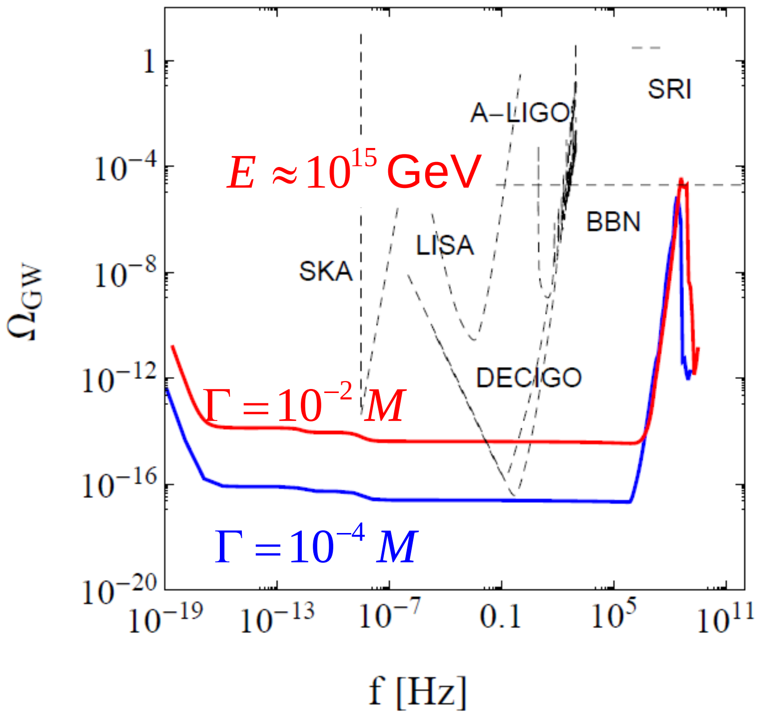
m_g^2 oscillates during reheating ⇨ parametric amp of tensor modes

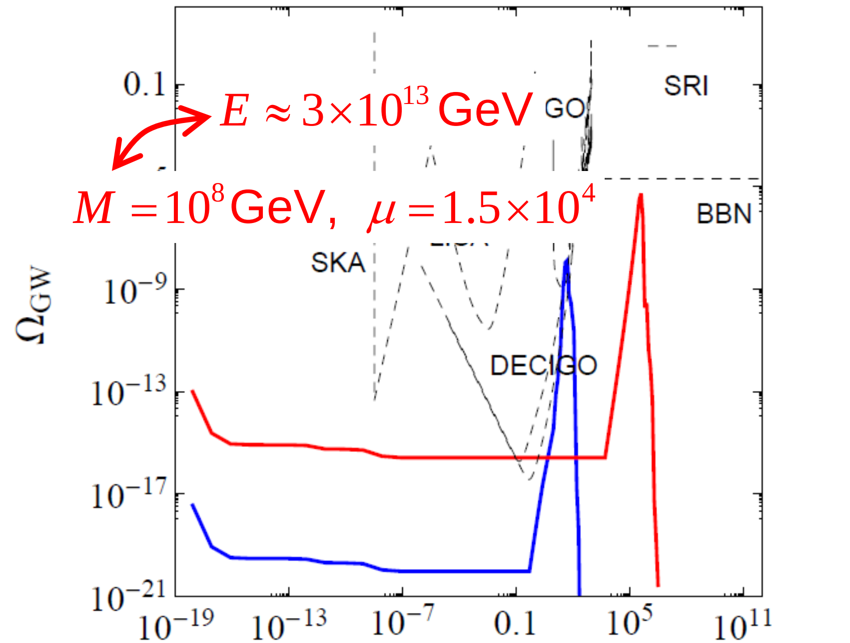
Lin & MS (2015)





examples





Starobinsky model $\left(\varepsilon_{\rm inf} = -\frac{\dot H}{H^2} \simeq 2.5\times10^{-4}\right)$

$$V = \frac{3}{4} M^2 M_{pl}^2 \left[1 - \exp\left(-\frac{\sqrt{6}\phi}{3M_{pl}}\right)\right]^2$$

with $m_g^2 = \lambda\phi^2 \exp[-2(\phi / M_{pl})^2]$

$\lambda = 4.8\times10^{-7}$

low-scale model $\left(\varepsilon_{\rm inf} \ll 10^{-4}\right)$

$$V = \frac{1}{2} M^2\phi^2, \quad H_{\rm end} = \frac{2}{3} M, \quad \Gamma = 10^{-3} M$$

with $m_g^2 = \mu \frac{\dot\phi^2}{M_{pl}^2}$

Big-Bang Nucleosynthesis (BBN) gives stringent constraints

7. Scalaron from R^2-inflation as a Heavy Field

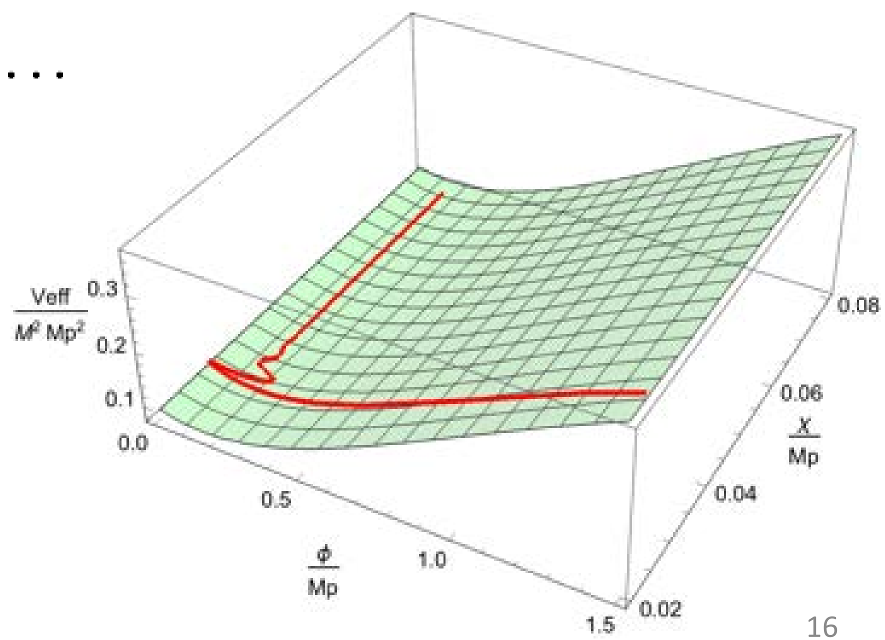
S Pi, YL Zhang, QG Huang, M Sasaki, [1712.09896].

- We propose the Lagrangian as the Starobinsky R^2 gravity plus a scalar field χ, nonminimally coupled to gravity

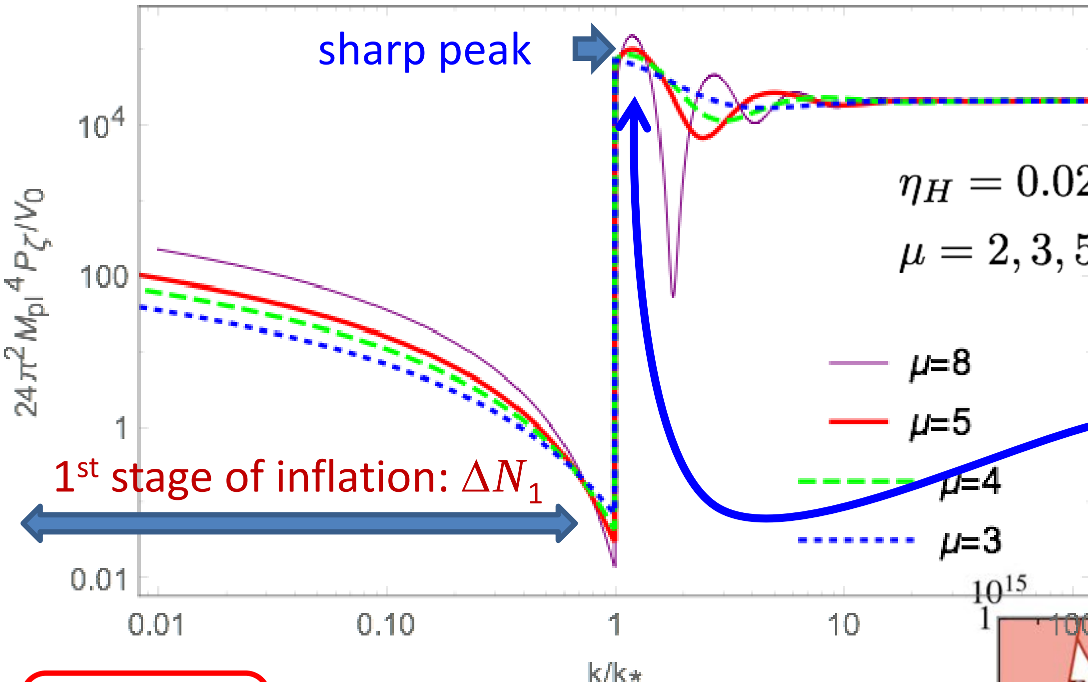
$$S_J = \int d^4x\sqrt{-g}\left\{\frac{M_{\rm Pl}^2}{2}\left(R+\frac{R^2}{6M^2}\right) - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi) - \frac{1}{2}\xi R\chi^2\right\}.$$

- $V(\chi)$ is potential for χ, which we pick for the small-field form: $V(\chi) = V_0 - \frac{1}{2}m^2\chi^2 + \cdots$

- ξ-term is the non-minimally coupled term to solve the initial condition problem. Another version of SSB in χ direction.



PBH as CDM from the transition stage

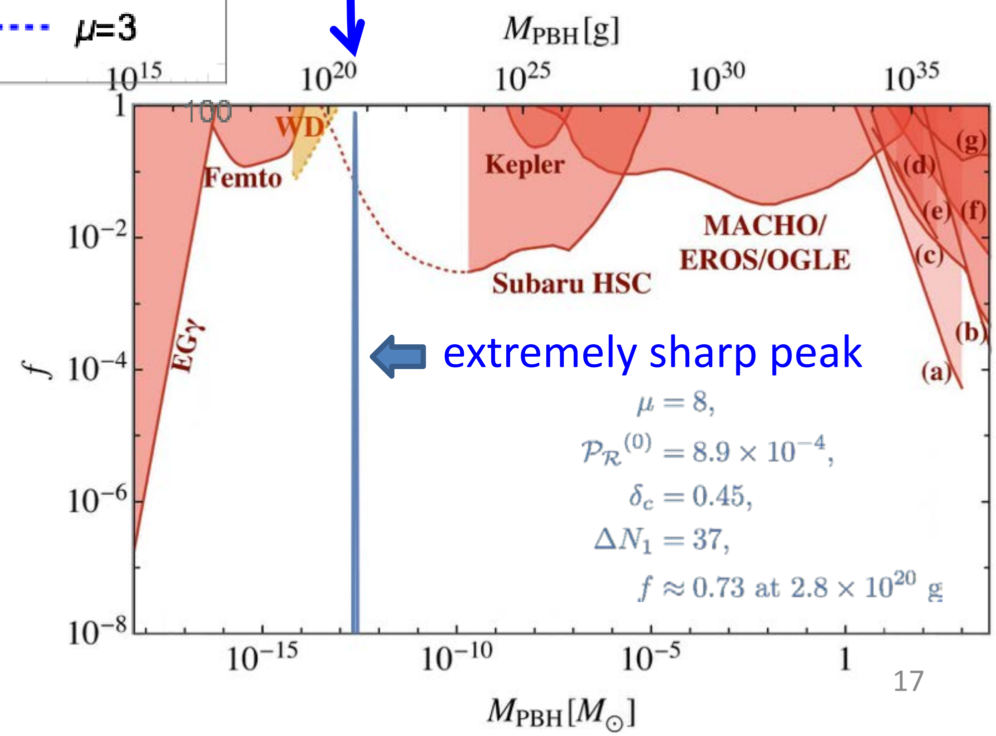


$$\eta_H = 0.02, \quad \chi_*/M_{\rm Pl} = 0.1,$$
$$\mu = 2, 3, 5, 8$$

$$\eta_H \equiv \frac{2m^2 M_{\rm Pl}^2}{V_0}$$

$$\mu^2 \equiv \frac{3M^2 M_{\rm Pl}^2}{V_0},$$

monocromatic
PBH mass spectrum



critical
amplitude

$$f(M_{PBH}) \propto \exp\left(-\frac{\delta_c}{\sqrt{2}\sigma(M_H)}\right)$$

$$\sigma(M_H) = \sqrt{\mathcal{P}(k_*)}$$

$$M_{PBH} = \gamma M_H \sim \frac{M_{\rm Pl}^2}{H} = \frac{M_{\rm Pl}^2}{k_* a} = \frac{M_{\rm Pl}^2}{H_*} e^{2(60-\Delta N_1)}$$

$H_* = k_* a_*$ during inflation

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  ($m^2\phi^2$ model excluded at $> 2\sigma$)
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  but f_{NL}^{local} =O(1) or scale-dep f_{NL}^{local} =O(10) not excluded

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Theories/models? Observational tests/signatures?

Tensor modes to be detected ⟺ multi-band GW astronomy!