Search for hybrid inflation with the cosmological collider

Yi-Peng Wu

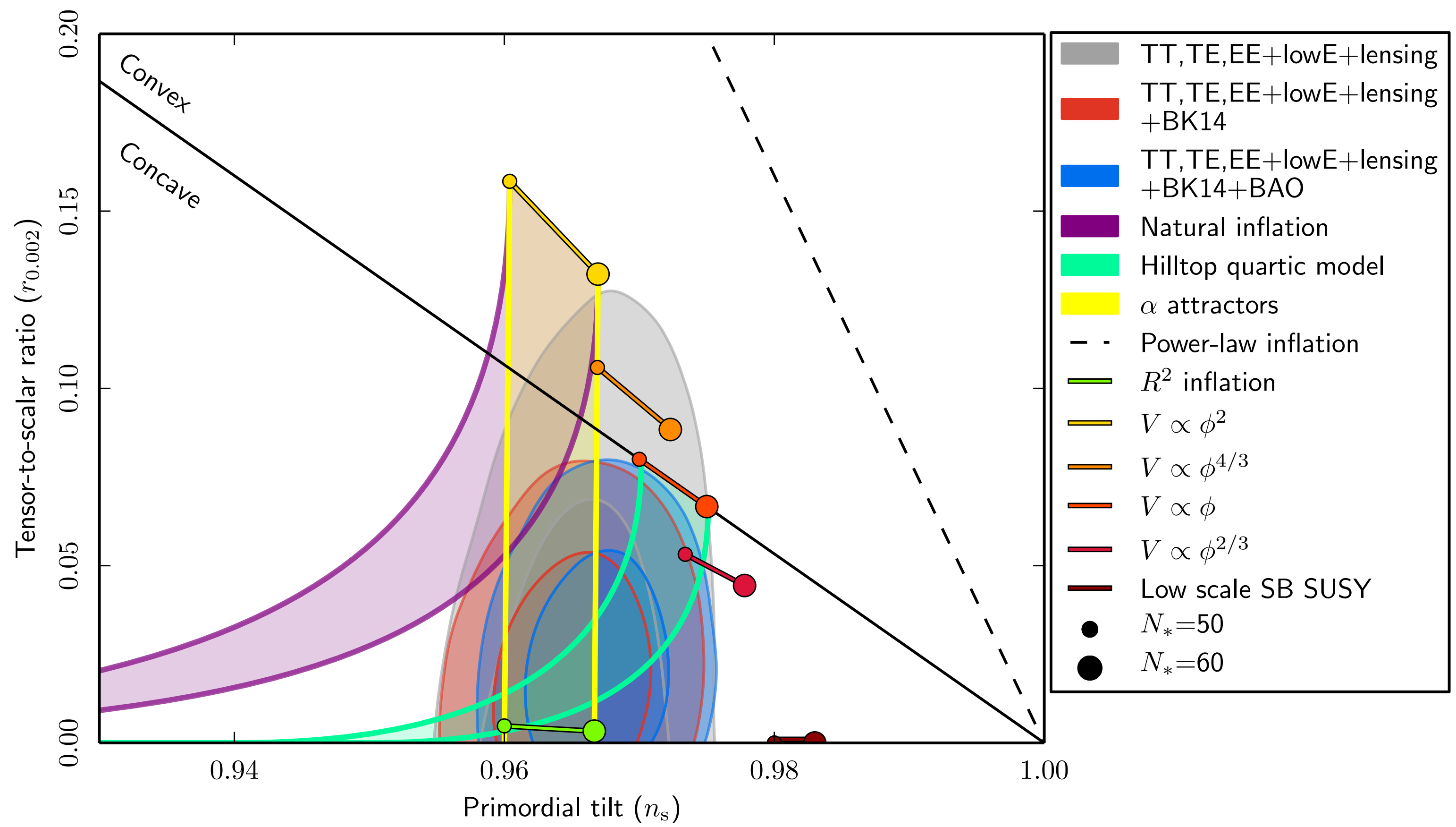
based on JCAP**07** (2018) 068

RESearch Center for the Early Universe (RESCEU)
The University of Tokyo

with Jun'ichi Yokoyama, Yi Wang & Siyi Zhou

Standard single-field inflation with Einstein gravity

PLANCK (2018)



- Ruled out n_s =1 by more than 6 σ level
- No evidence beyond slow-roll (nor feature in the potential)

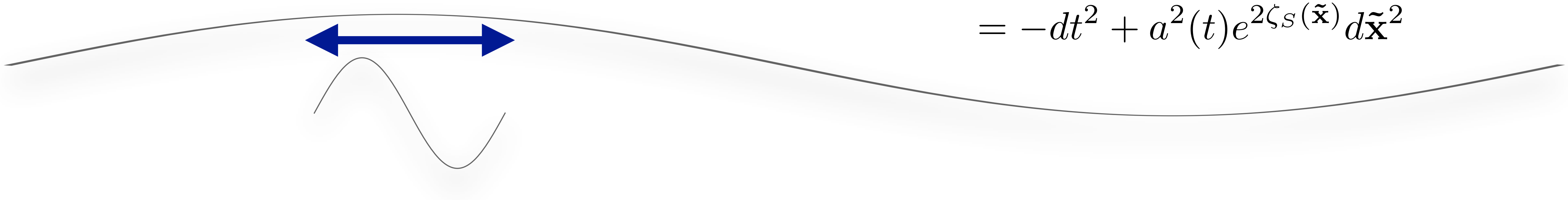
$$n_s = 0.9649 \pm 0.0042 \text{ at } 68\,\% \text{ CL.}$$

➤ We know quantum fluctuations much better than the classical motion.

The single-field consistency relation with slow-roll

Maldacena (2003)

$$ds^2 = -dt^2 + a^2(t)e^{2\zeta_S(\mathbf{x})+2\zeta_L}d\mathbf{x}^2$$
$$= -dt^2 + a^2(t)e^{2\zeta_S(\tilde{\mathbf{x}})}d\tilde{\mathbf{x}}^2$$



de Putter et al. [1610.00785]

The dilatation transformation

$$\langle\zeta(k_1)\zeta(k_2)\rangle_{\zeta_L} = e^{-(n_s-1)\zeta_L}\langle\zeta(\tilde{k}_1)\zeta(\tilde{k}_2)\rangle_0$$

The squeezed bispectrum

$$\lim_{k_3\to 0}\langle\zeta(k_1)\zeta(k_2)\zeta(k_3)\rangle = -(n_s-1)\langle\zeta(k_S)\zeta(k_S)\rangle\langle\zeta(k_L)\zeta(k_L)\rangle$$

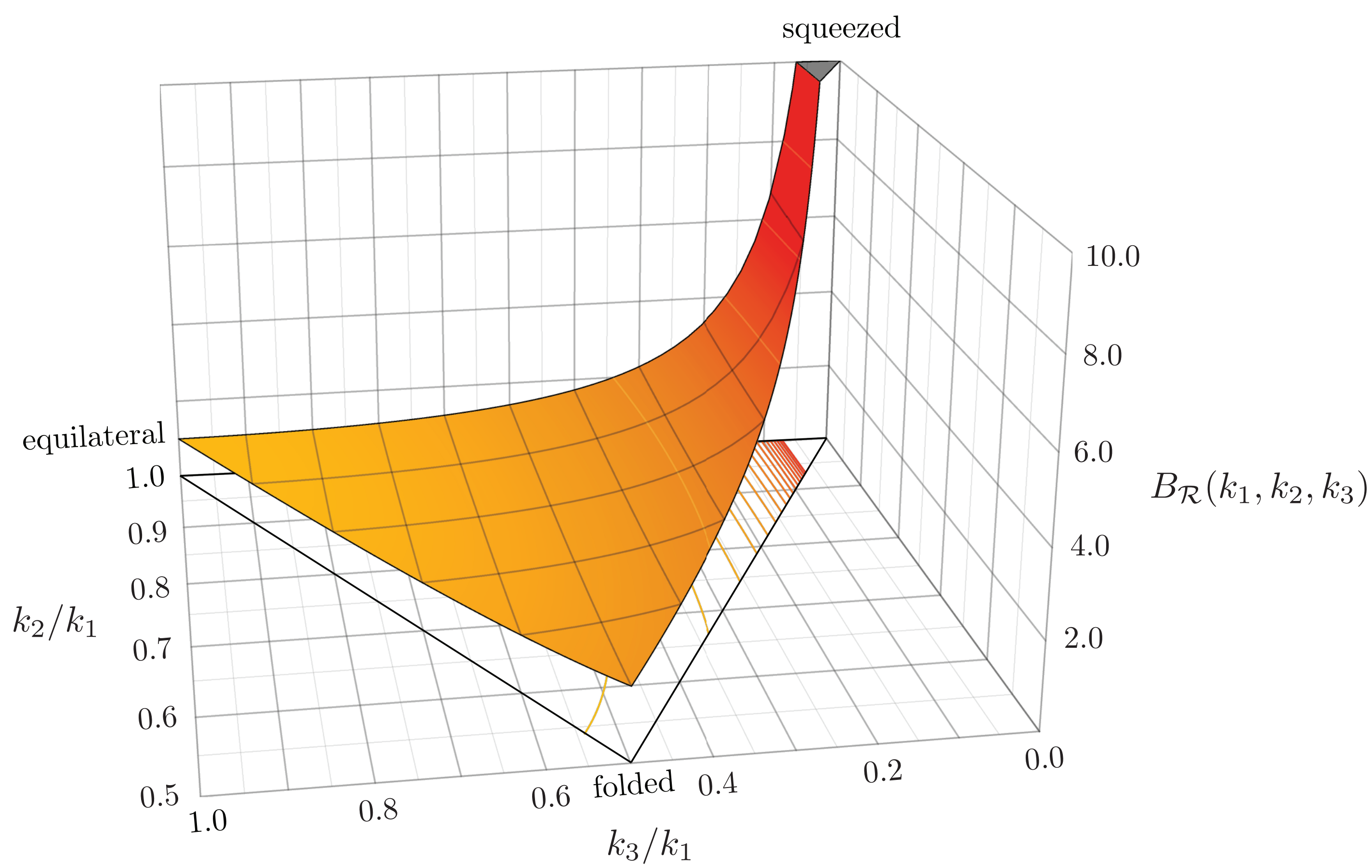
- **The squeezed limit of bispectrum is suppressed by slow-roll conditions.**

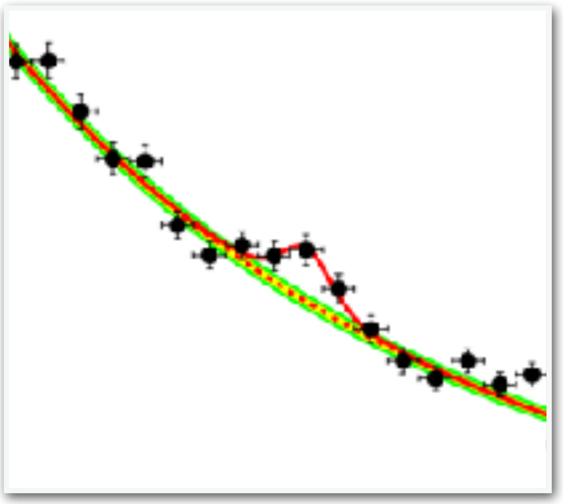
Cosmological collider

— probing new physics during inflation

Assassi, Baumann & Green (2012)

Arkani-Hamed & Maldacena (2015)





From Baumann & McAllister

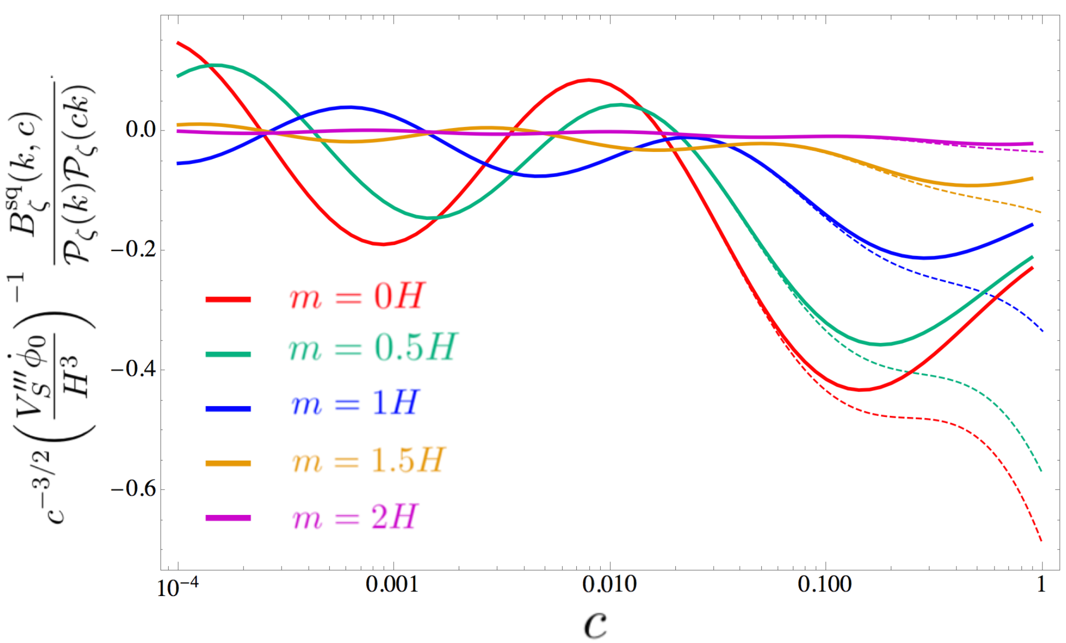
Characteristic signals of heavy particles

Example I. quasi-single field inflation

Chen & Wang (2010)

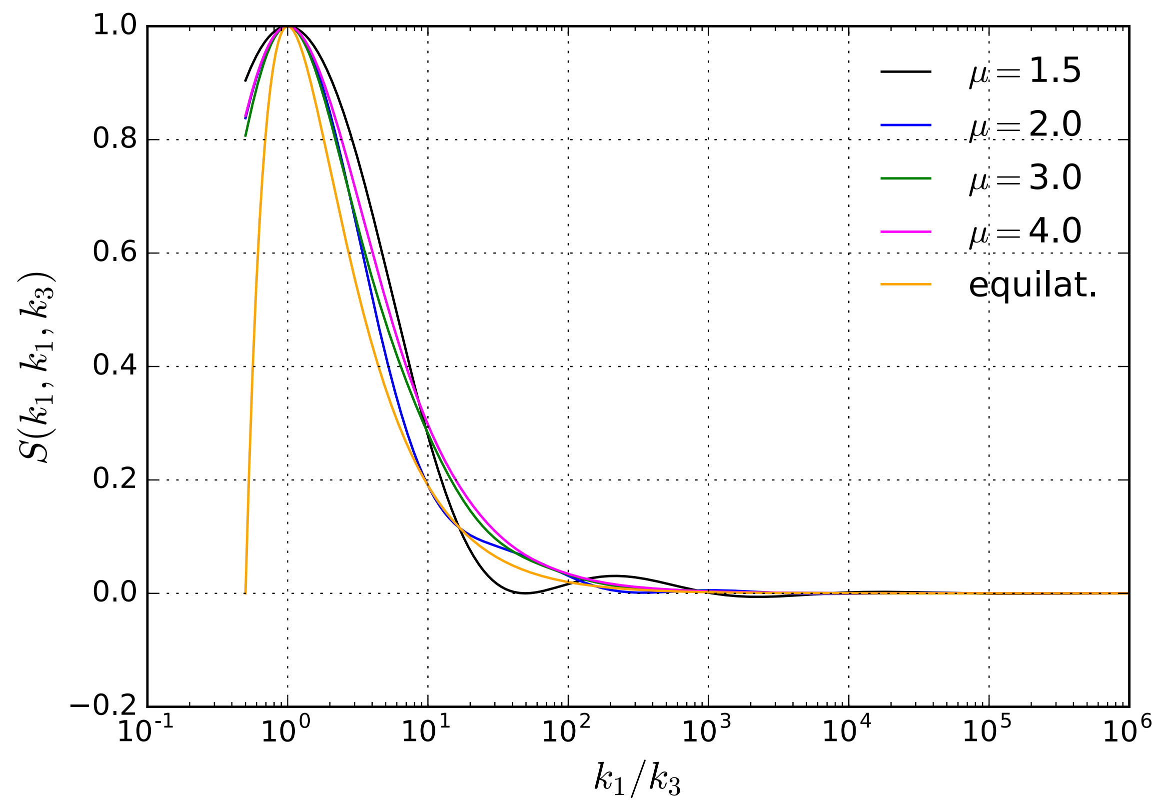
- Signals from a strong coupling

$$\mathcal{L}_I \sim \frac{\rho}{\Lambda}(\partial\phi)^2\sigma$$



An, McAneny, Ridgway & Wise (2017)

- Signals with a large mass $\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$



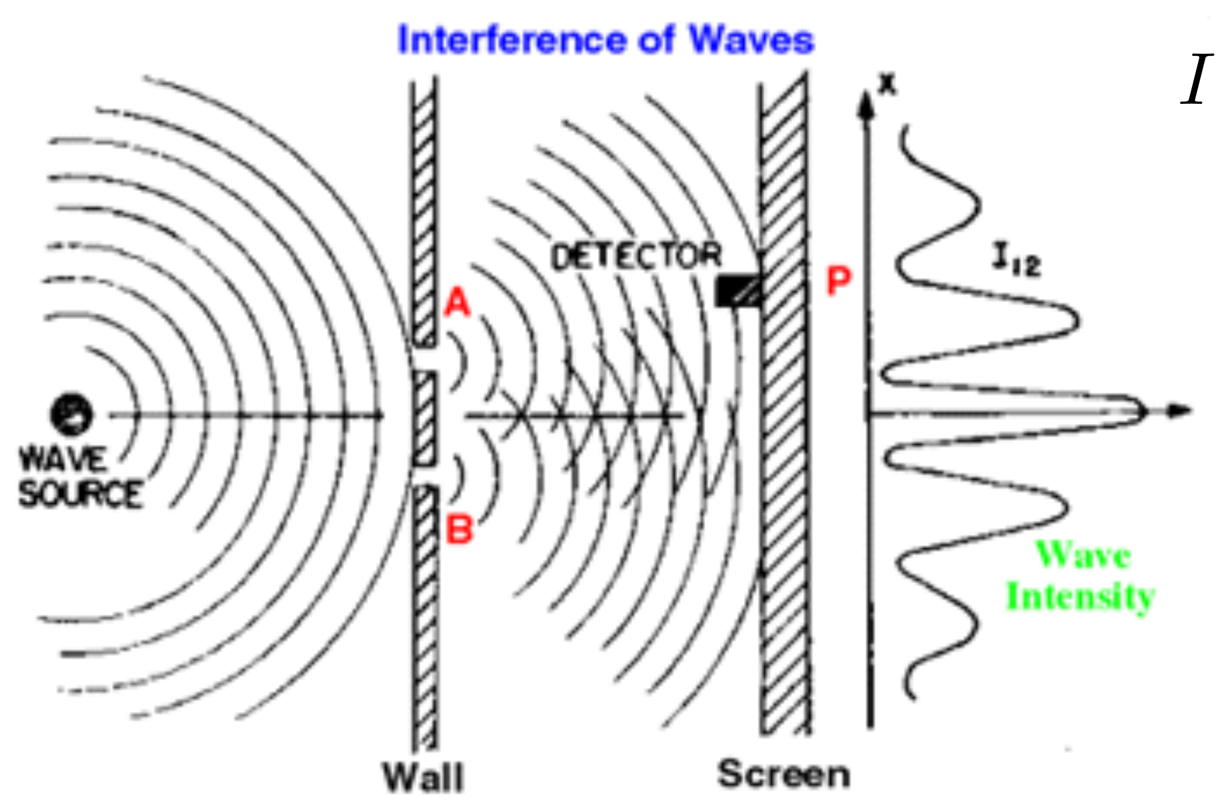
Meerburg et. al. (2016)

wave interference

The source

$$\Psi_1(\vec{r},t) = A_1(\vec{r})e^{-i[\omega t - \alpha_1(\vec{r})]}$$

$$\Psi_2(\vec{r},t) = A_2(\vec{r})e^{-i[\omega t - \alpha_2(\vec{r})]}$$



credit by Quan Bui

The intensity

$$I(\vec{r}) = \int dt \; \Psi\Psi^*$$

$$\sim A_1^2 + A_2^2 + 2A_1A_2\cos[\alpha_1 - \alpha_2]$$

$$\Psi = \Psi_1 + \Psi_2$$

cosmological quantum interference

The two sources

$$\zeta(k,\eta) \sim e^{-ik\eta}$$

analytic waves

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

$$\sigma(k,\eta) \sim \left(\frac{-k\eta}{2}\right)^{2n \pm i\mu}$$

analytic + non-analytic waves

must come from $\boldsymbol{\sigma}$!

The correlation function

$$\left\langle \hat{Q}[\zeta, \dot{\zeta}, \sigma, \dot{\sigma}] \right\rangle = (\text{non-oscillatory}) + (\text{oscillatory})$$

Cosmological collider

— probing new physics during inflation

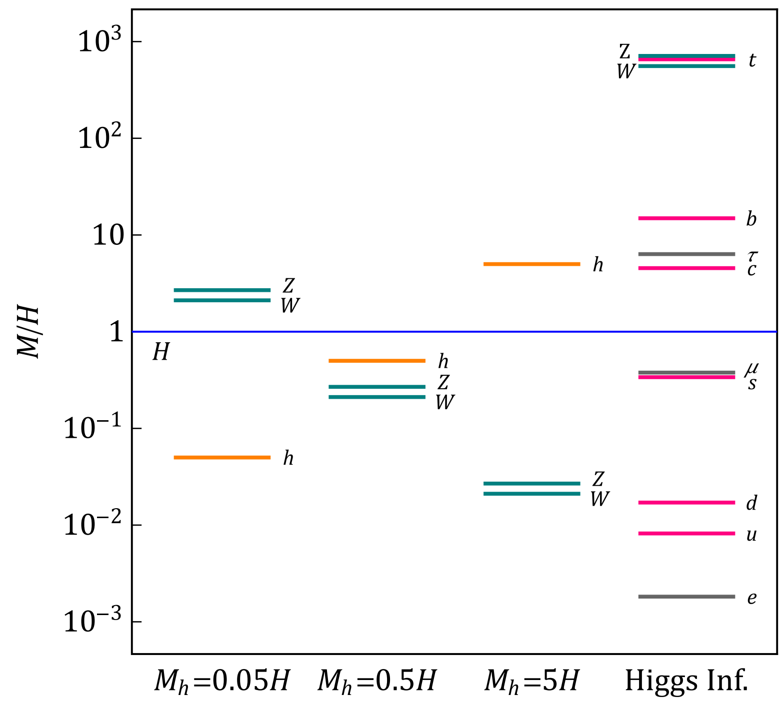
Steps towards new discovery:

Chen, Wang & Xianyu PRL**118** (2017)

Chen, Wang & Xianyu JHEP04 (2017)

1. To work out the background signals during inflation.

Reviewed by Yi Wang



The SM mass spectrum during inflation

The squeezed SM bispectrum:

$$\langle \zeta_{k_1}\zeta_{k_2}\zeta_{k_3}\rangle' \equiv \frac{(2\pi)^4}{(k_1k_2k_3)^2}P_\zeta^2 S(k_1,k_2,k_3),$$

$$S_\alpha = \begin{cases} \mathcal{A}_\alpha\left(\frac{k_L}{k_S}\right)^{a_s-2\mu_s} + (\mu_s \to -\mu_s), & \mu_s \text{ real} \\ 2\mathrm{Re}\left[\mathcal{A}_\alpha\left(\frac{k_L}{k_S}\right)^{a_s-2\mu_s}\right], & \mu_s \text{ complex,} \end{cases}$$

Cosmological collider

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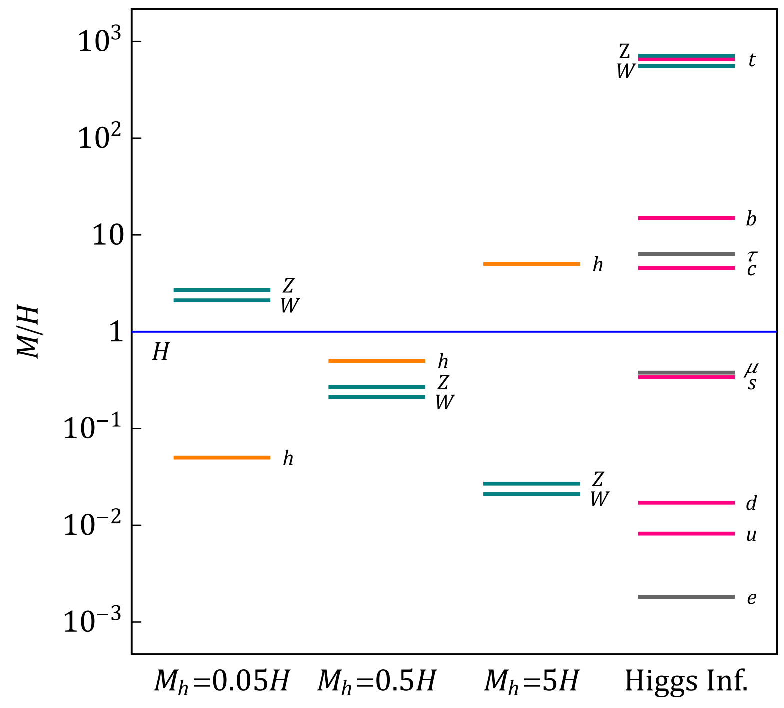


The SM mass spectrum during inflation

➤ **These SM corrections are usually negligible…**

Cosmological collider

— probing signals of massive fields during inflation

Steps towards new discovery:

1. To work out the background signals during inflation.

✔ 2. To figure out how new particles enter the bispectrum.

From Yi Wang's talk

$$f_{NL} \sim P_\zeta^{-1/2} \times \text{couplings} \times \text{suppression factors}$$

Cosmological collider

— probing signals of massive fields during inflation

Steps towards new discovery:

1. To work out the background signals during inflation.
2. To figure out how new particles enter the bispectrum. ✔

From Yi Wang's talk

$$f_{NL} \sim P_\zeta^{-1/2} \times \text{couplings} \times \text{suppression factors}$$

model-dependent

Cosmological collider

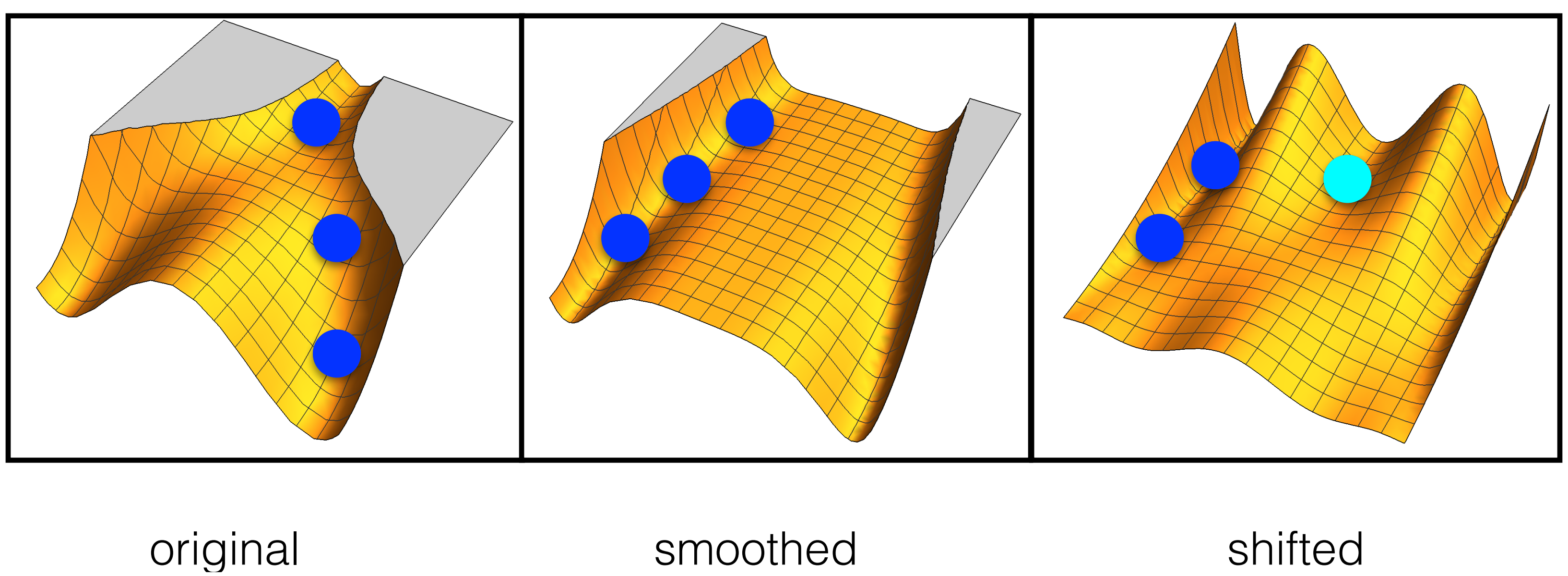
— probing signals of massive fields during inflation

Steps towards new discovery:

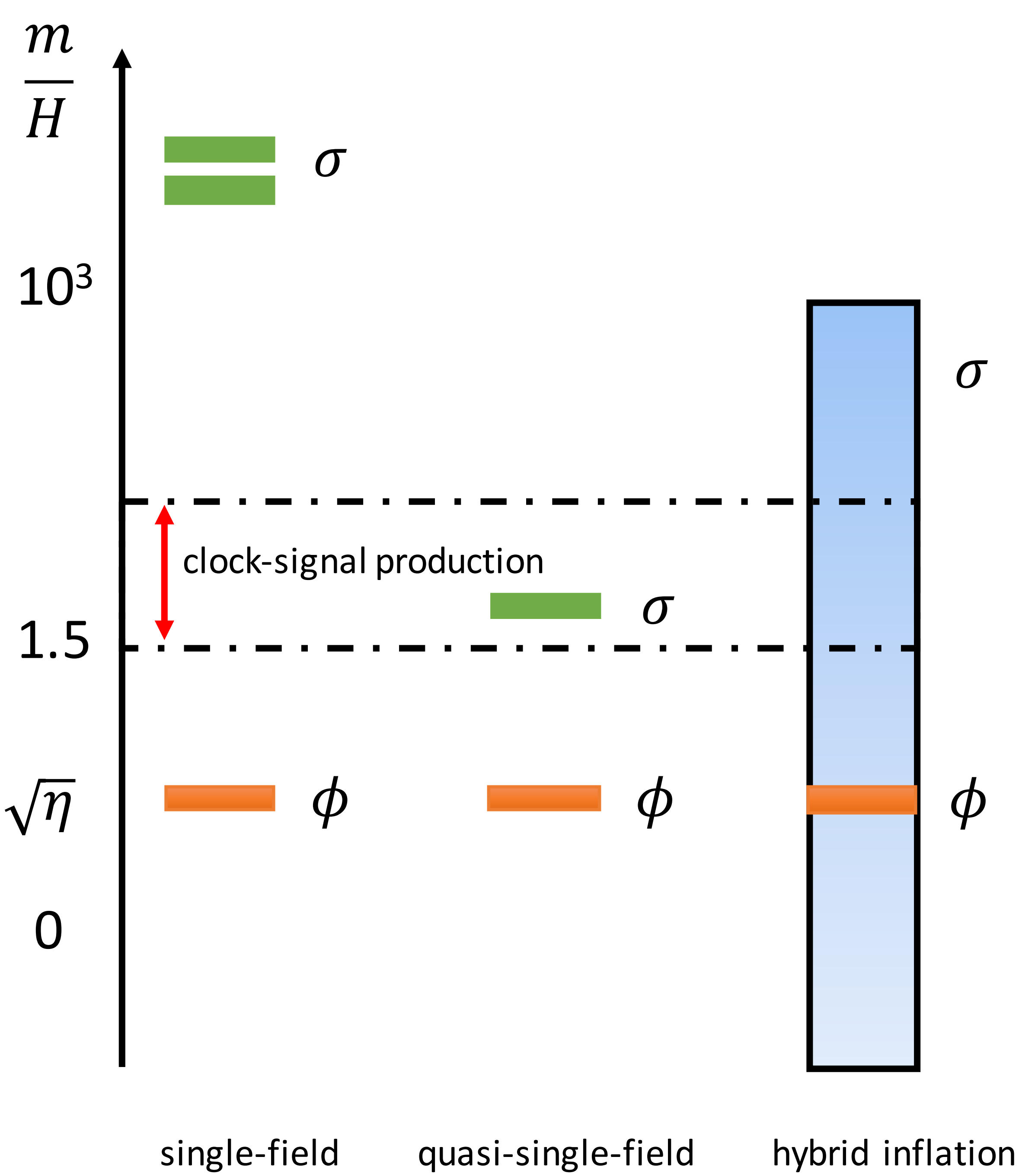
1. To work out the background signals during inflation.

✔ 2. To figure out how new particles enter the bispectrum.

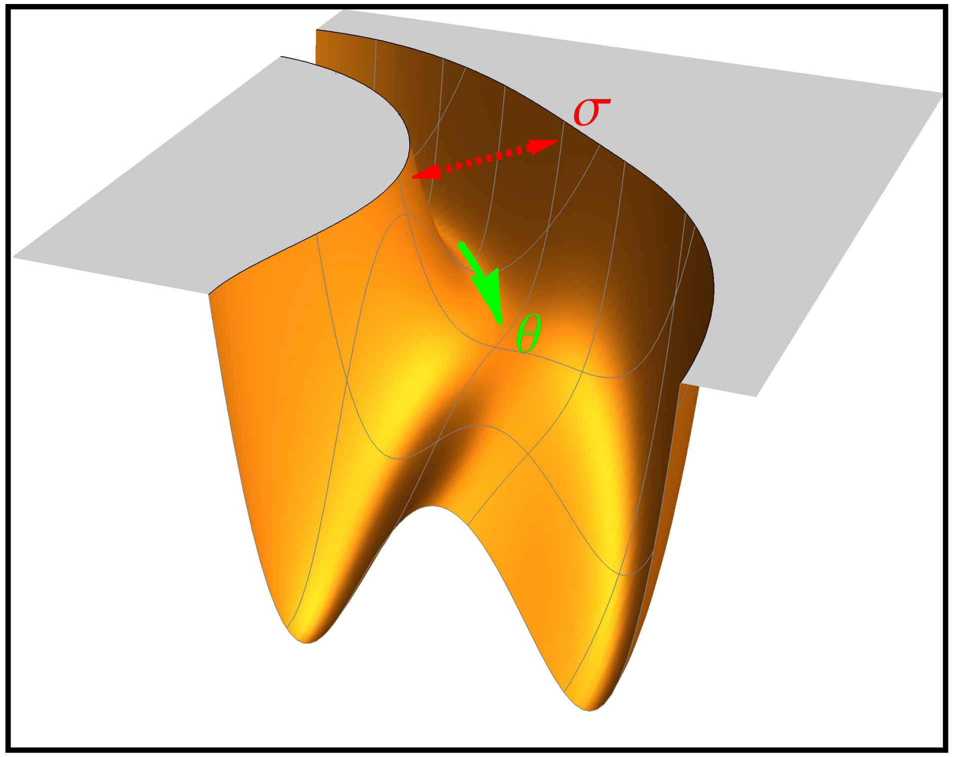
Example II. hybrid inflation (waterfall transition)



Mass spectrum of hybrid inflation



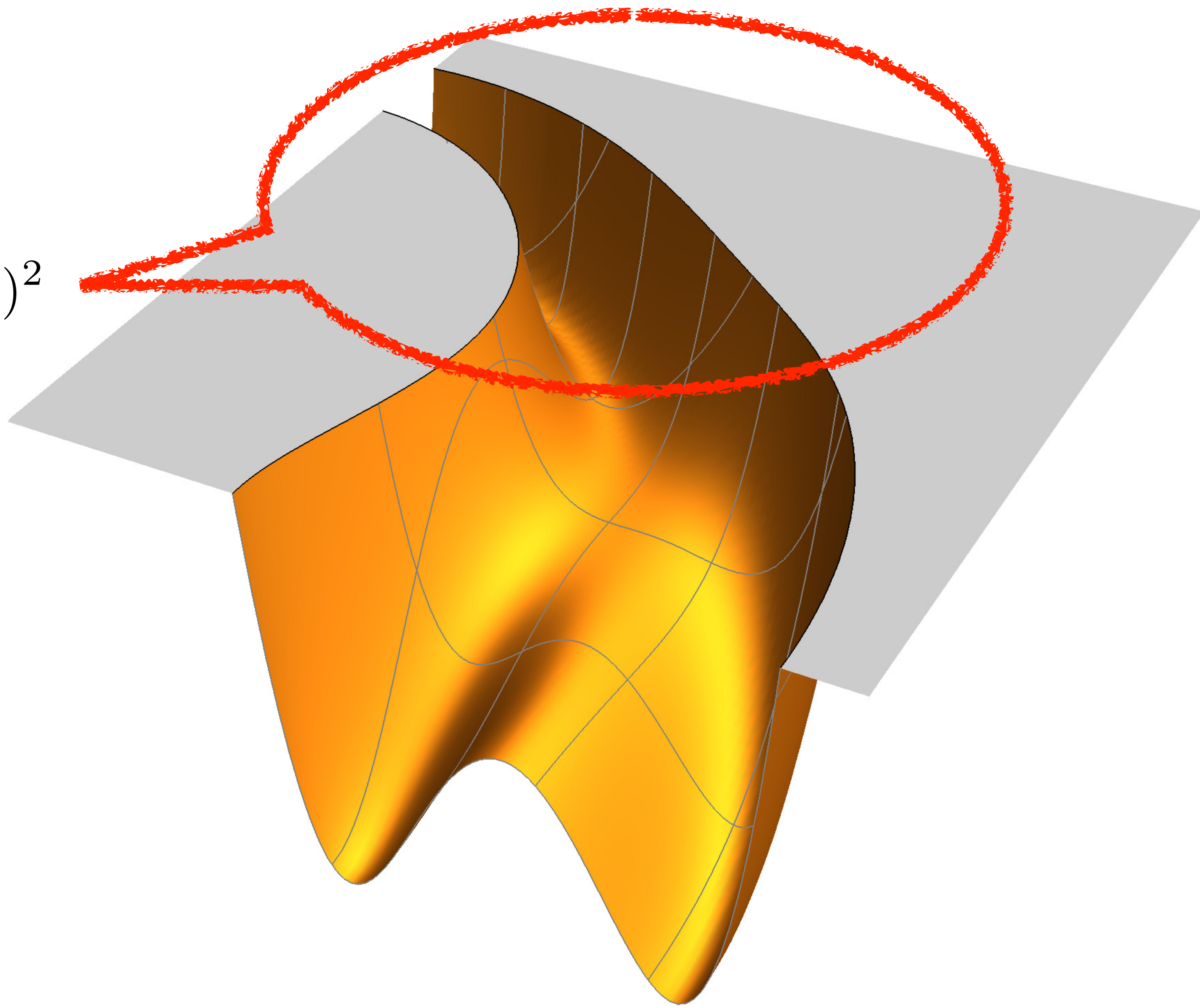
$$\theta = \phi/\Lambda$$



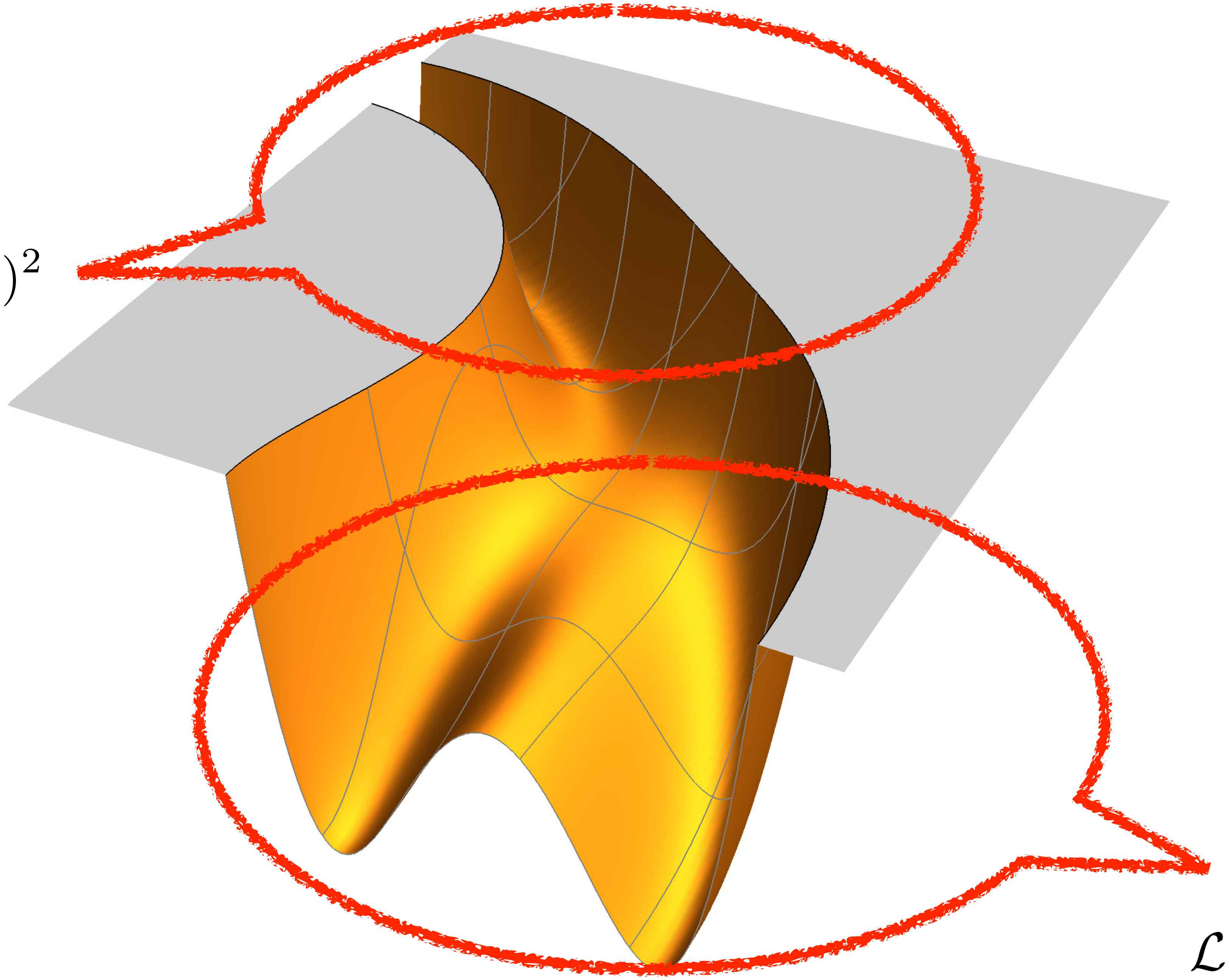
Wang, YPW, Yokoyama & Zhou (2018)

hybrid inflation with a turn

$$\mathcal{L}_I \sim \frac{1}{\Lambda}\sigma\,(\partial\phi)^2$$



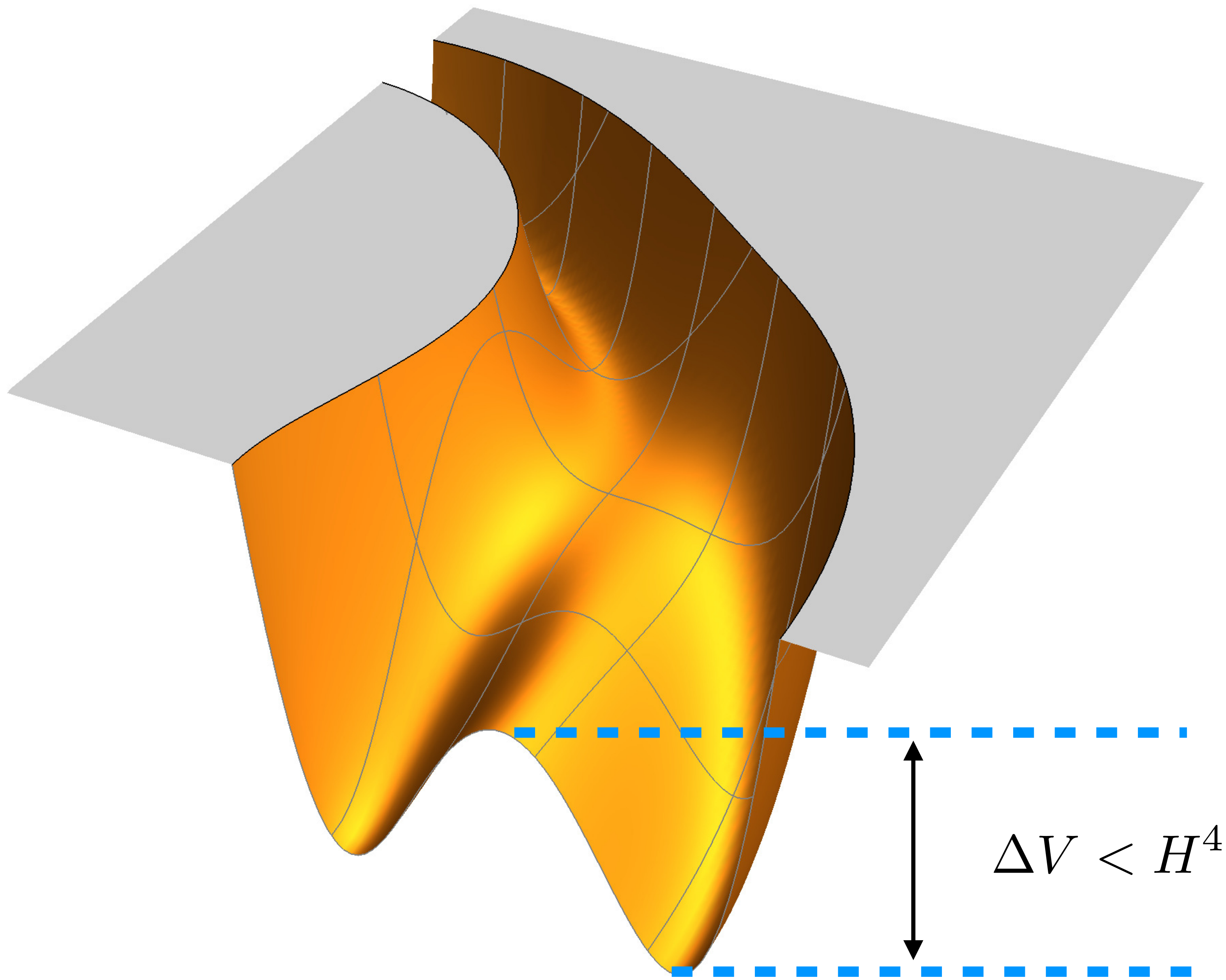
hybrid inflation with a turn



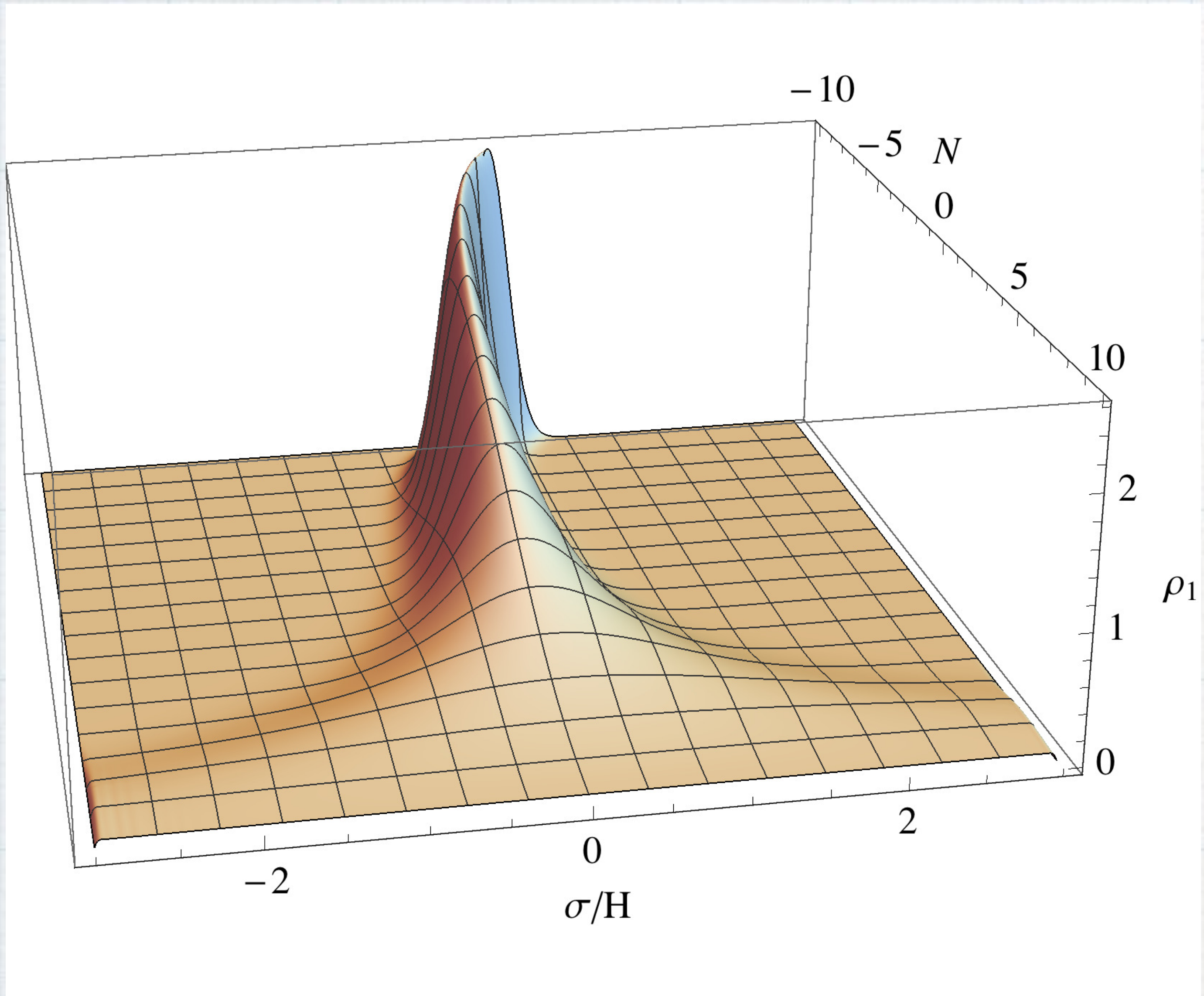
$$\mathcal{L}_I \sim \frac{1}{\Lambda}\sigma\,(\partial\phi)^2$$

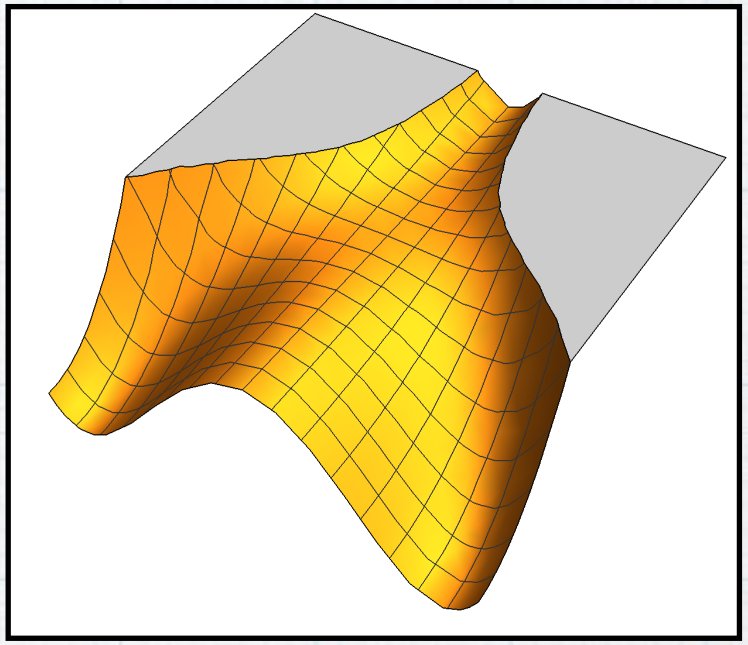
$$\mathcal{L}_I \sim \frac{g^2}{2}\,\phi^2\sigma^2$$

hybrid inflation with a turn



The domain wall problem

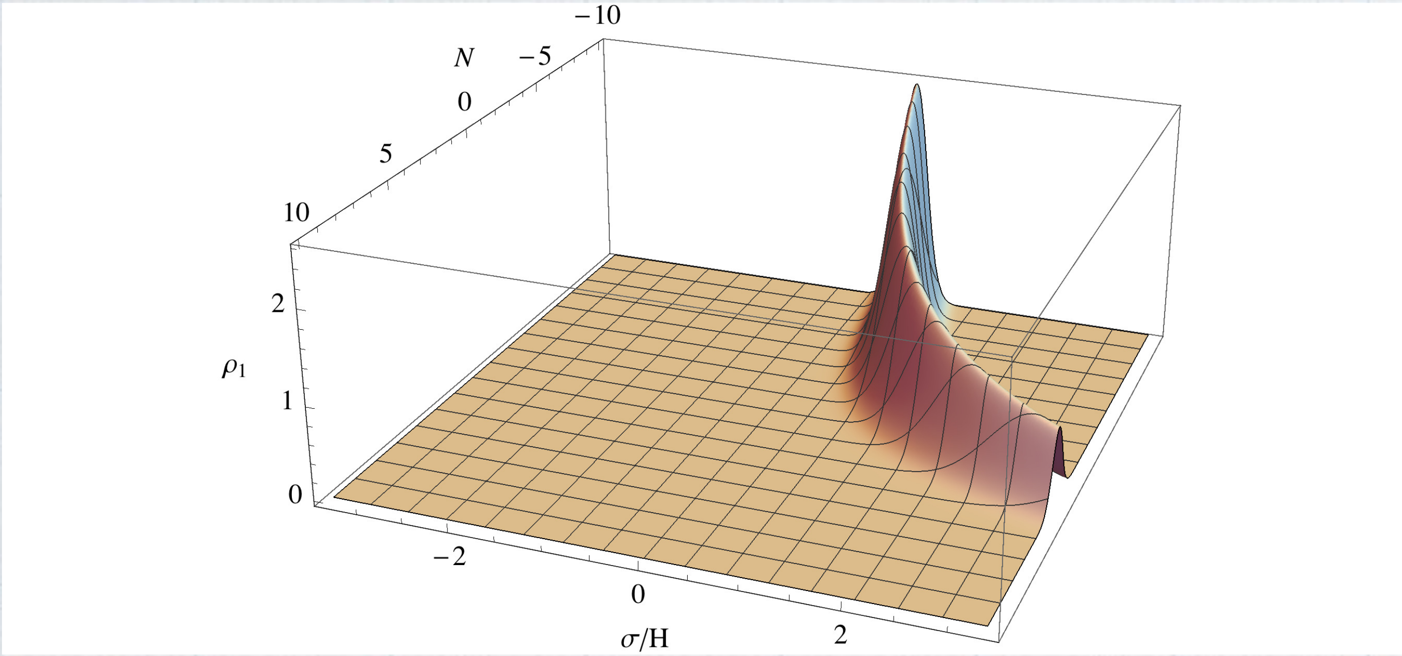


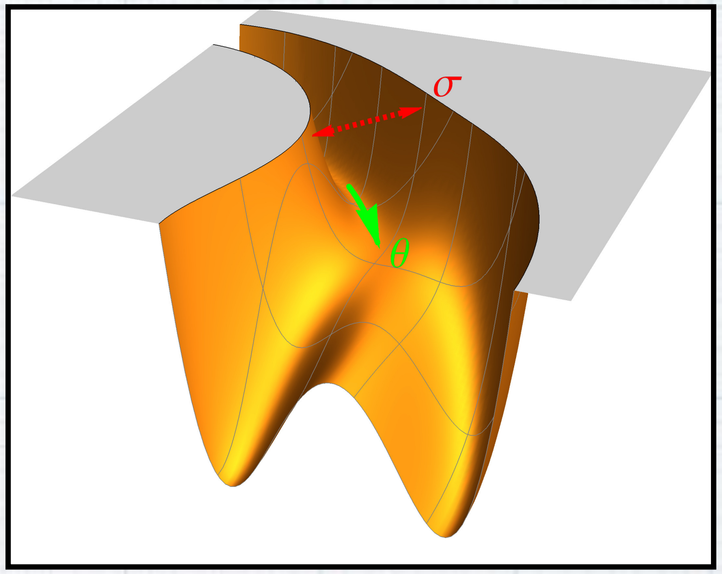


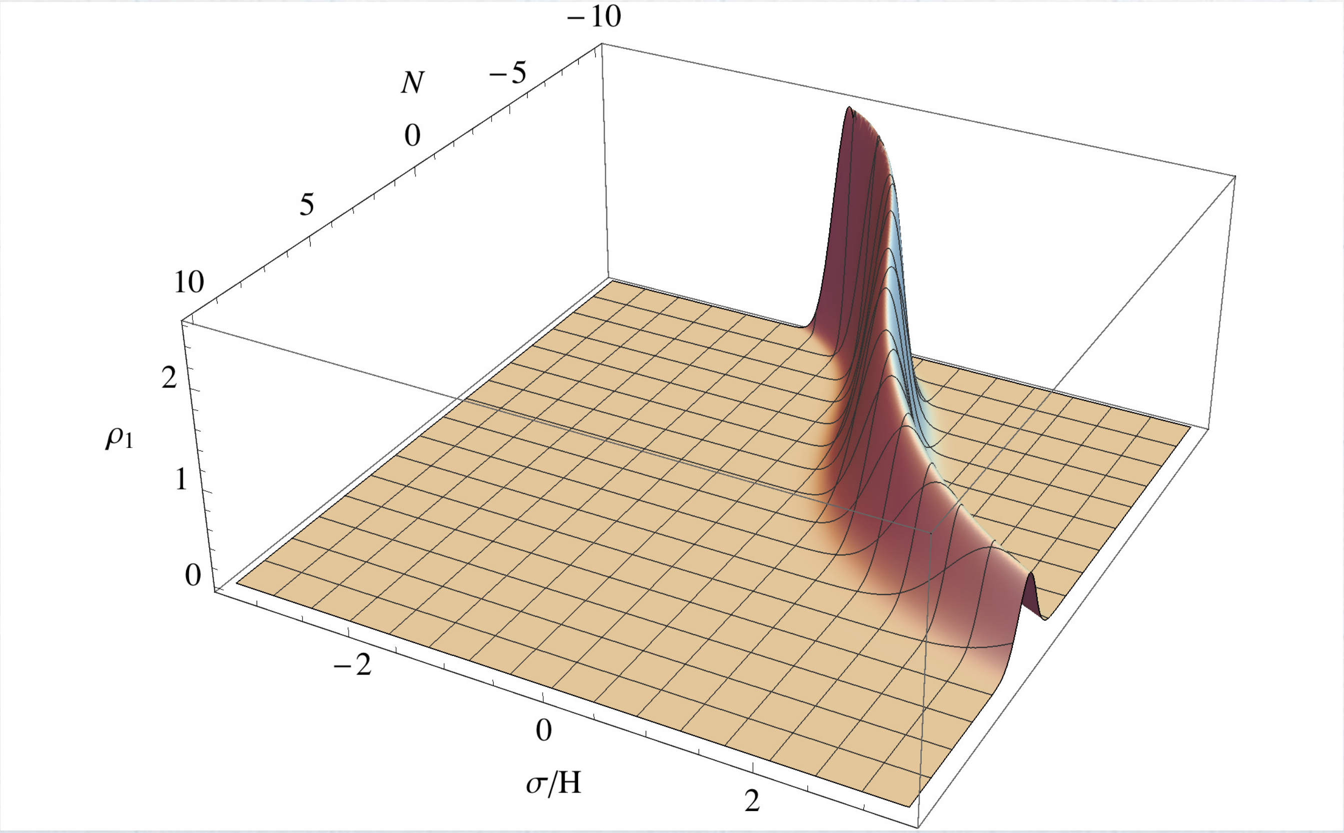
Linde (1993)

ρ_1 : one-point probability distribution function

The domain wall problem







The DW formation rate is controlled by model parameters.

Characteristic signals of heavy particles

Example I. quasi-single field inflation

Reviewed in Baumann's talk

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

analytic	non-analytic
$1/\mu^2$	$e^{-\pi\mu}$
EFT	**particle production**

Lee, Baumann & Pimentel (2016)

Chen, Namjoo & Wang (2016)

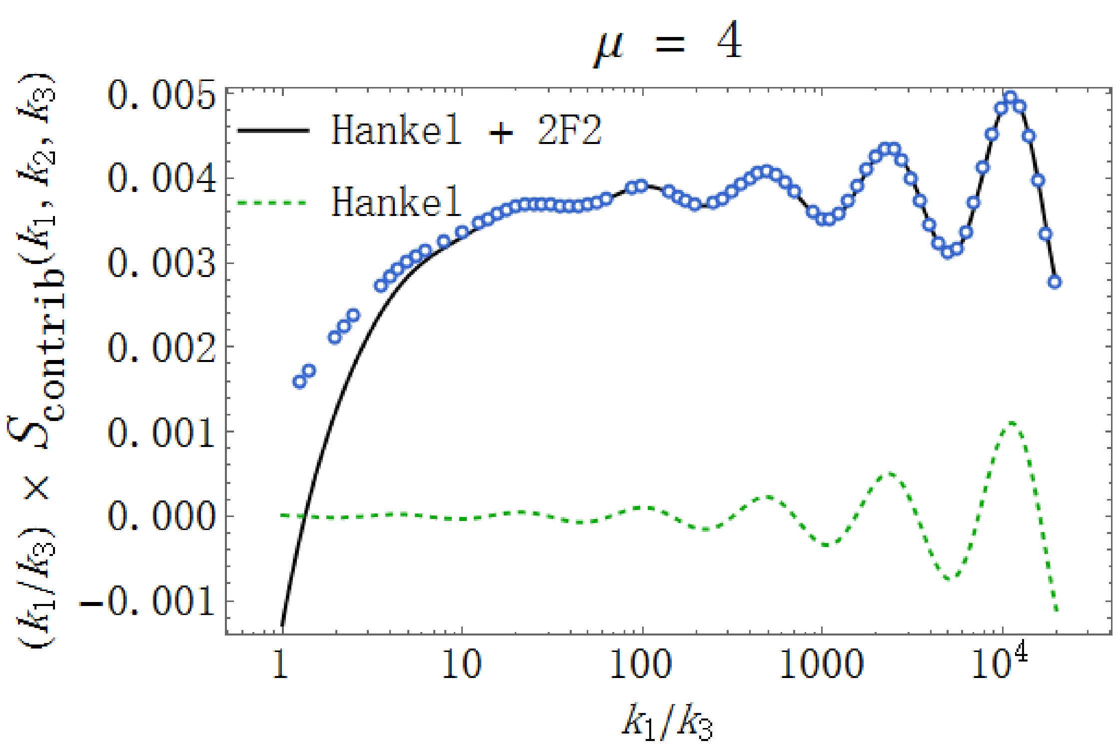
Iyer et. al (2018)

Characteristic signals of heavy particles

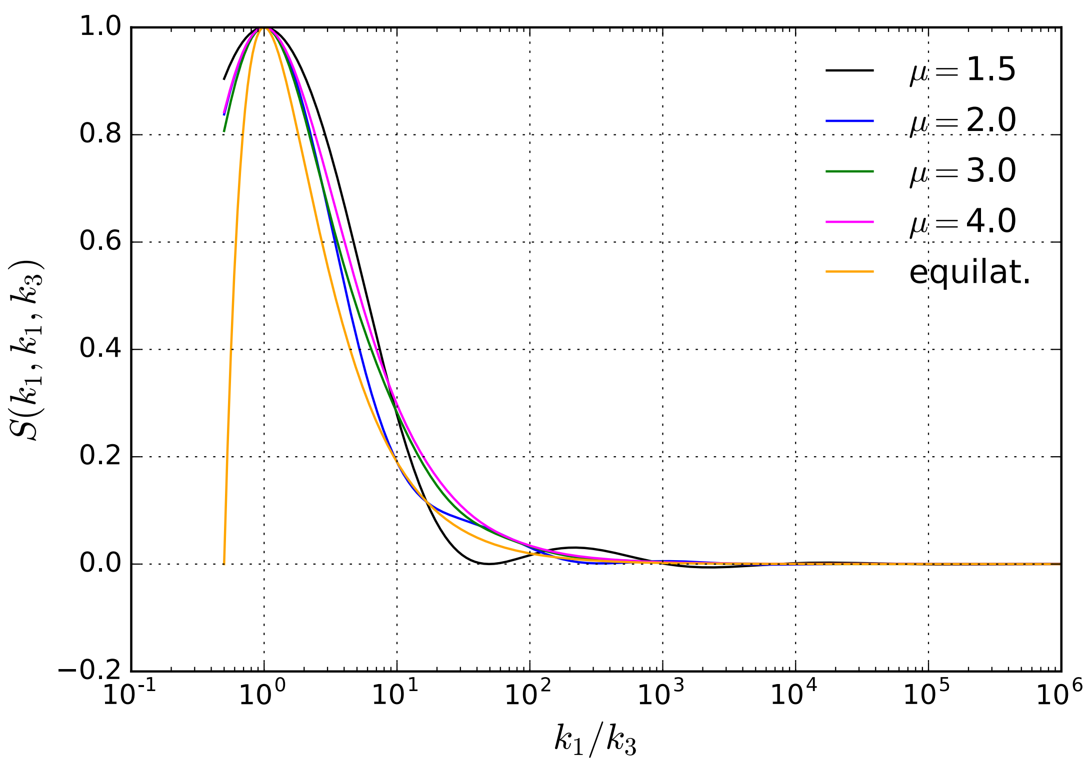
Example I. quasi-single field inflation

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

analytic v.s. non-analytic



Chen, Namjoo & Wang (2016)

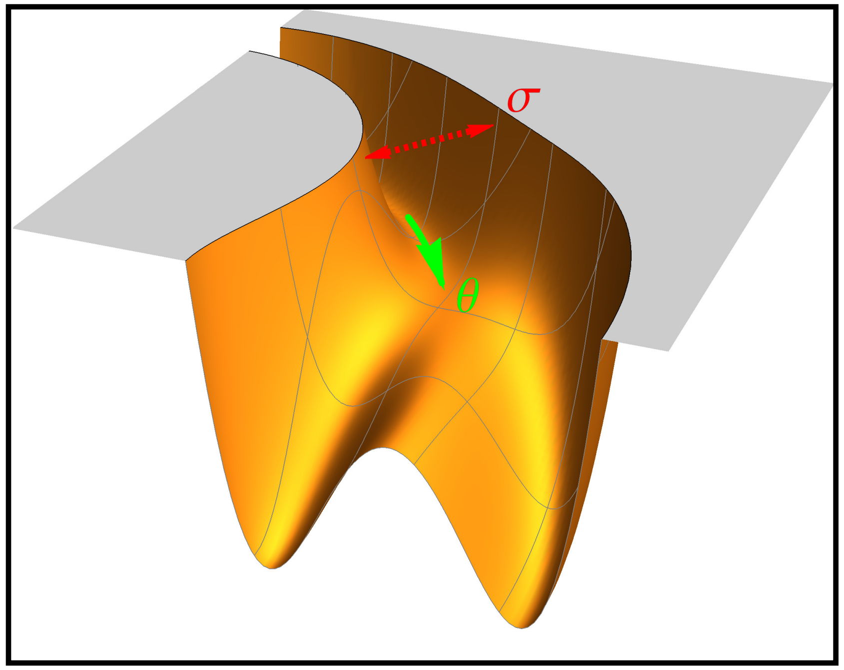


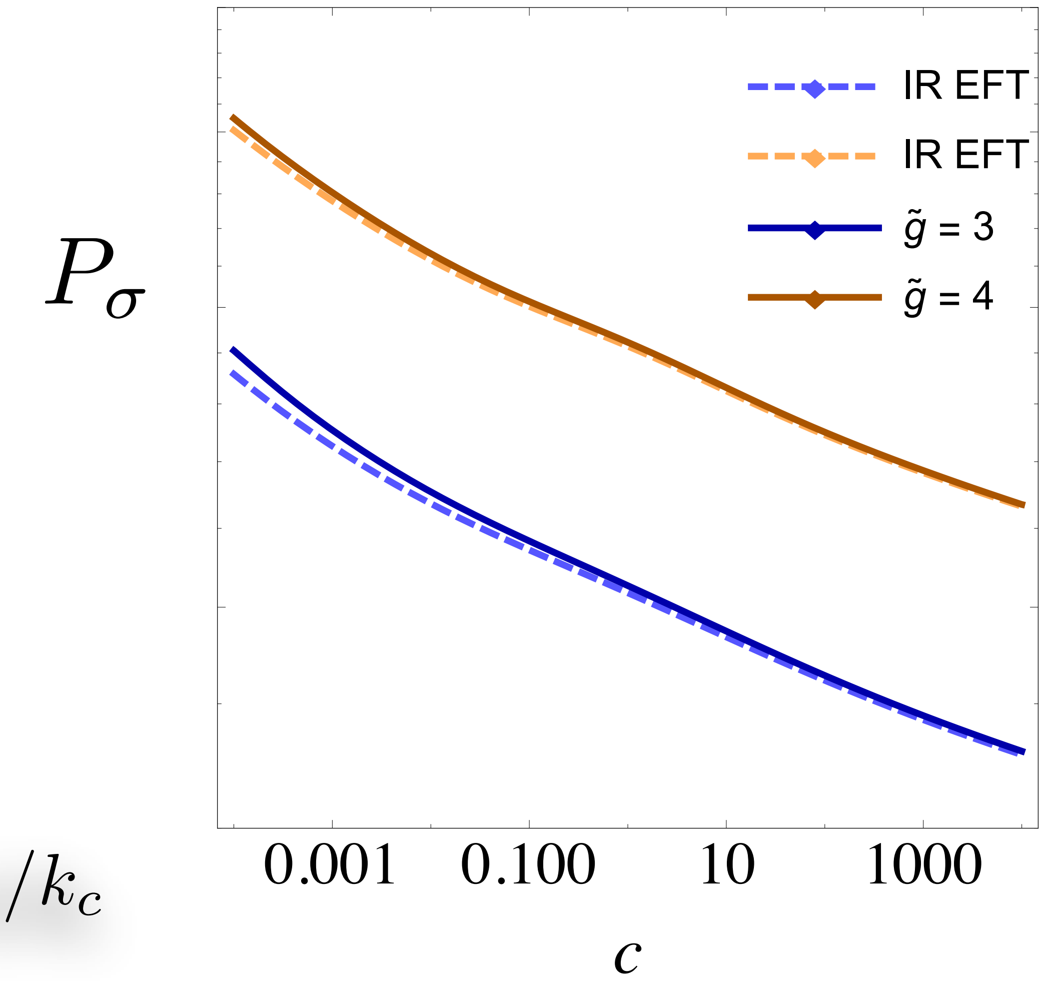
Meerburg et. al. (2016)

Characteristic signals of hybrid inflation

Wang, YPW, Yokoyama & Zhou (2018)

$$V(\theta,\sigma) = V_{\rm sr}(\theta) + \frac{\lambda}{4}\left[(\sigma-\sigma_0^*)^2 - v^2\right]^2 + \frac{g^2}{2}\theta^2(\sigma-\sigma_0^*)^2,$$





$c = k/k_c$

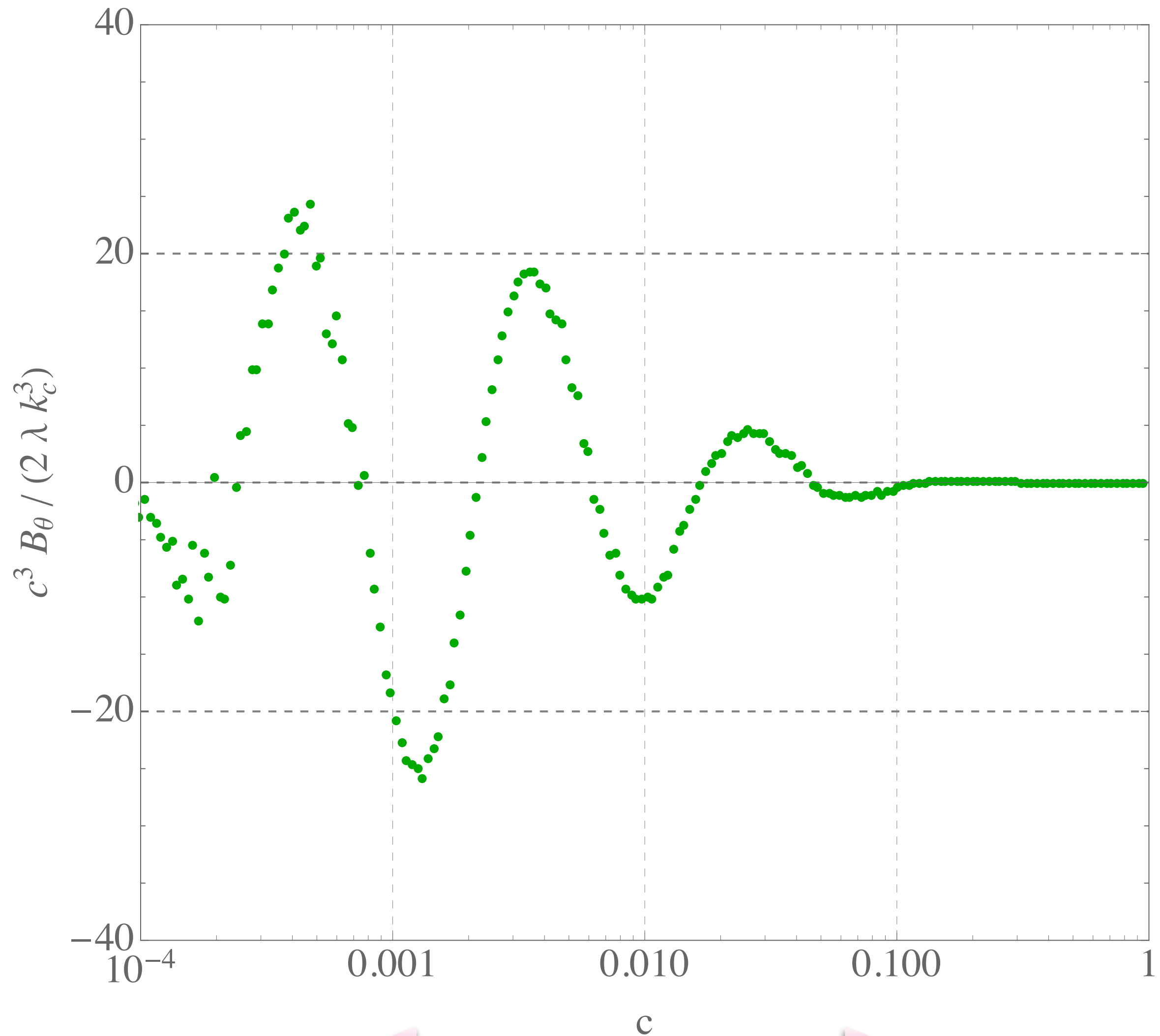
EFT at late-time

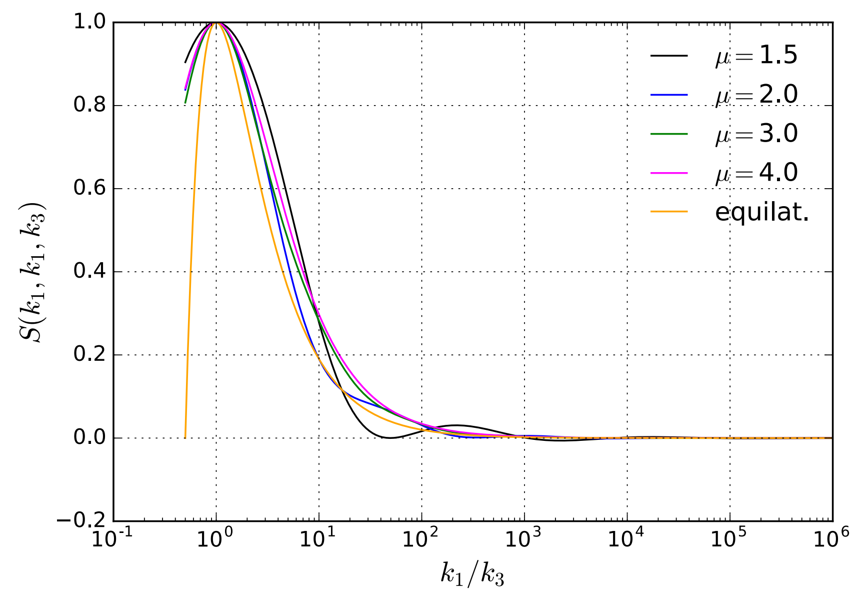
$$\delta\bar{\sigma}^{\rm IR} \approx -2\frac{g^2}{H^2}\theta_c\frac{\bar{\sigma}_{\rm min}}{M_\sigma^2}\delta\theta^{\rm IR}.$$

Characteristic signals of hybrid inflation

$$\mathcal{L}_3 = -\frac{1}{6}a^3R^3V_{\sigma\sigma\sigma}\delta\sigma^3$$

$$\langle\delta\theta_{\mathbf{k_1}}(z)\delta\theta_{\mathbf{k_2}}(z)\delta\theta_{\mathbf{k_3}}(z)\rangle \equiv (2\pi)^4\delta^3(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})B_\theta(\mathbf{k_1},\mathbf{k_2},\mathbf{k_3}).$$





Wang, YPW, Yokoyama & Zhou (2018)

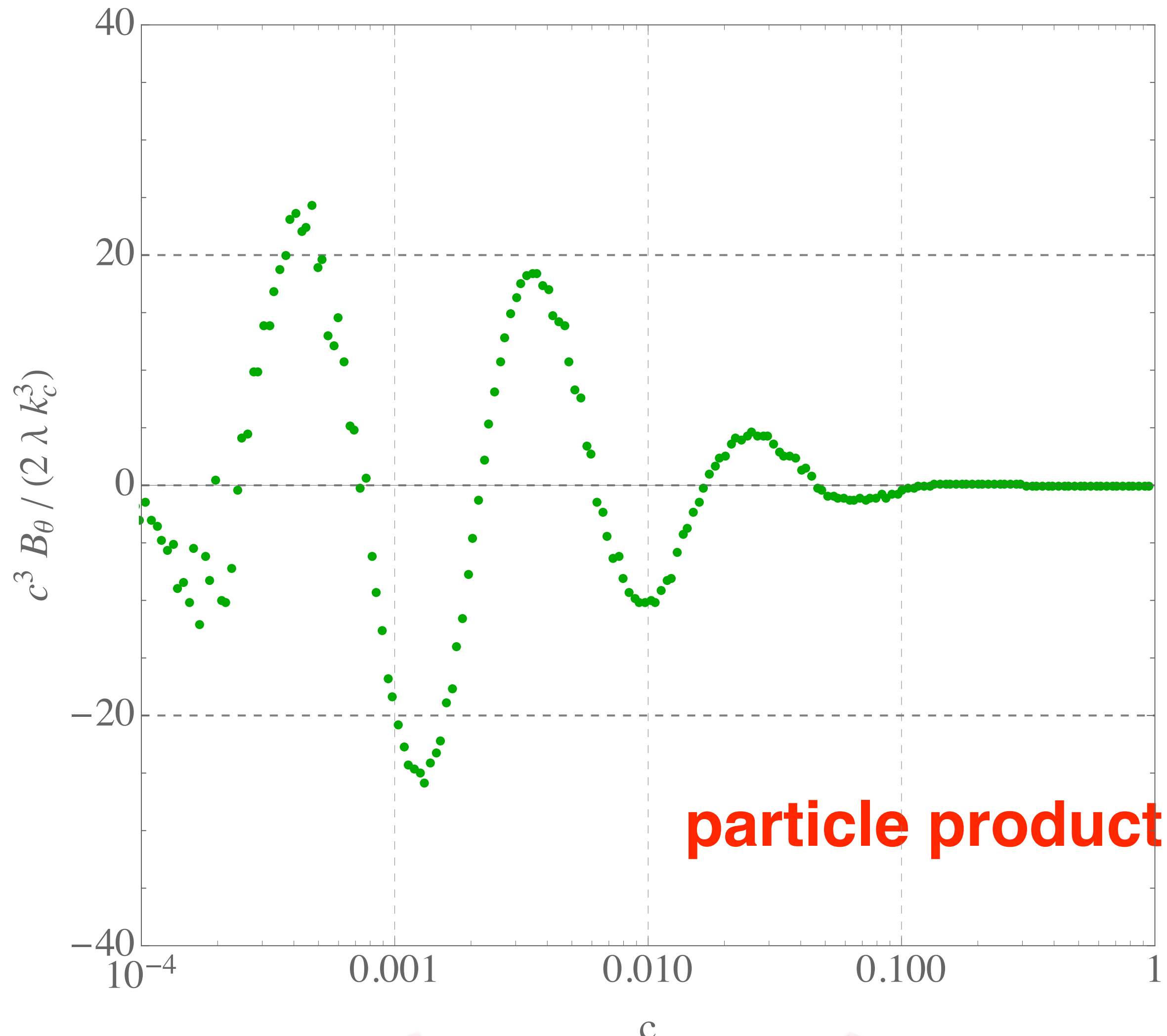
squeezed ⟷ **equilateral**

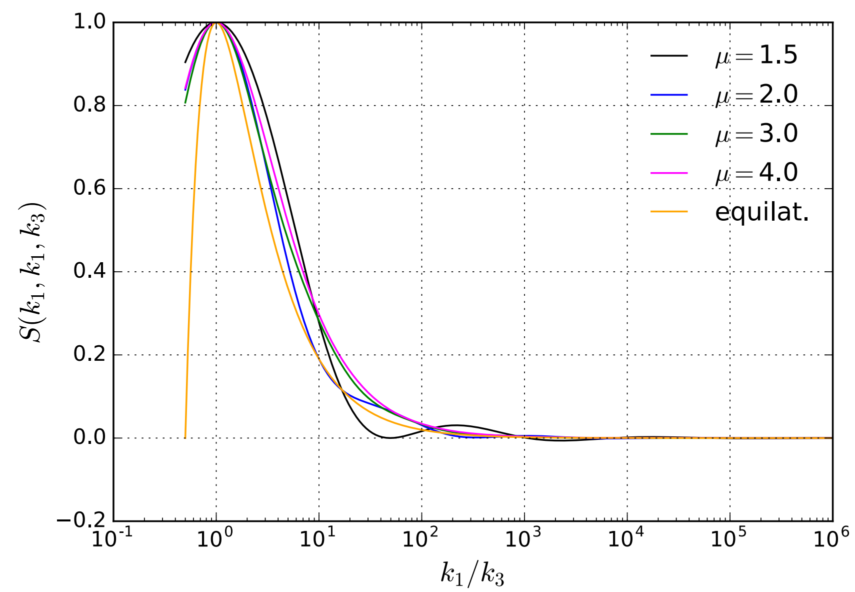
$$c = k/k_c$$

Characteristic signals of hybrid inflation

$$\mathcal{L}_3 = -\frac{1}{6} a^3 R^3 V_{\sigma\sigma\sigma} \delta\sigma^3$$

$$\langle \delta\theta_{\mathbf{k_1}}(z) \delta\theta_{\mathbf{k_2}}(z) \delta\theta_{\mathbf{k_3}}(z) \rangle \equiv (2\pi)^4 \delta^3(\mathbf{k_1} + \mathbf{k_2} + \mathbf{k_3}) B_\theta(\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3}).$$





particle production become more efficient!

Wang, YPW, Yokoyama & Zhou (2018)

squeezed ⟷ **equilateral**

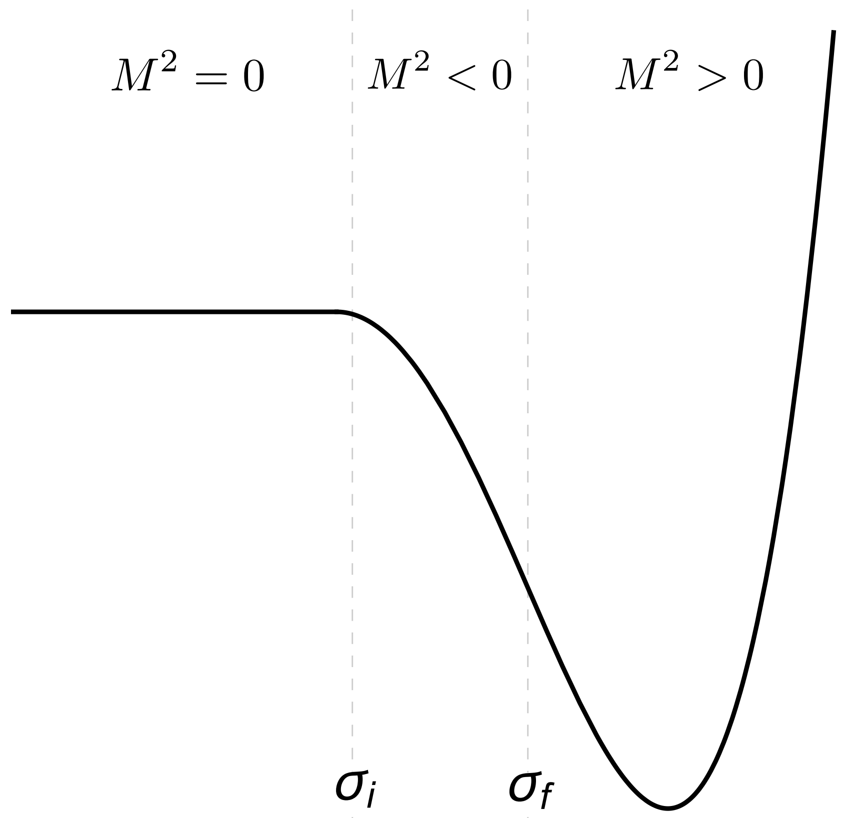
$$c = k/k_c$$

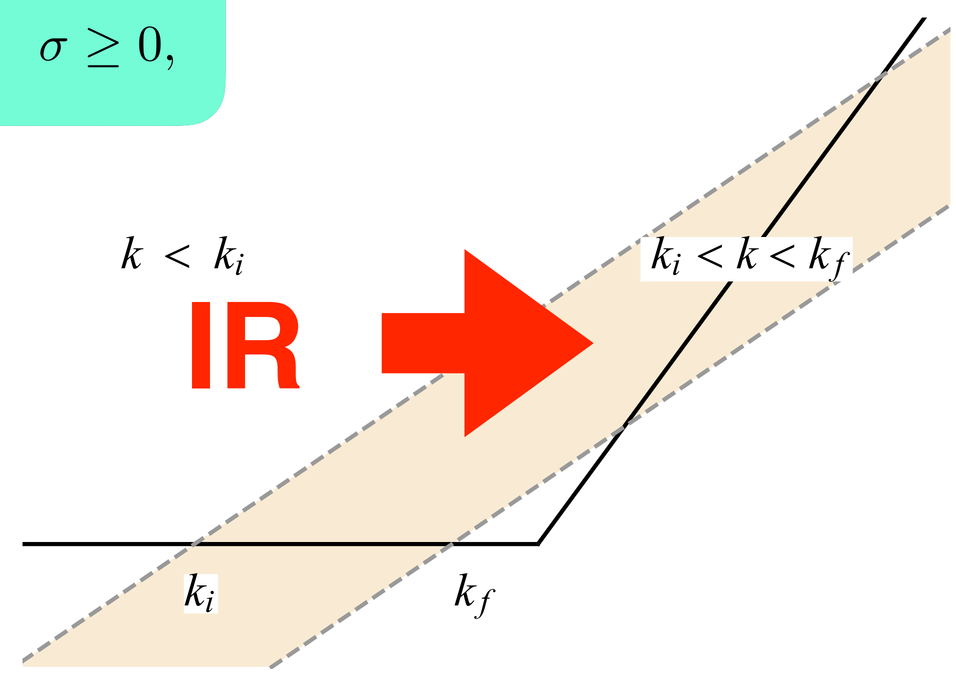
quantum fluctuations with waterfall

A step potential:

$$V_1(\sigma) = \frac{\lambda}{4} v^4, \qquad \sigma < 0,$$

$$= \frac{\lambda}{4}(\sigma^2 - v^2)^2 \qquad \sigma \geq 0,$$





- **analytic mode functions are enhanced due to tachyonic instability**
- **non-analytic contributions are converted from enhanced analytic functions in the new (true) vacuum state**

YPW & Yokoyama JCAP 05(2018) 009

Messages

- Particles with $m > 3H/2$ generate oscillatory features in the squeezed bispectrum (a main target for the cosmological collider research).
- Oscillatory signals are non-analytic (non-local) effects, which are not captured by single-field EFT (integrating out heavy modes).
- A waterfall phase transition can break the scale-invariance, and leads to enhanced non-analytic (oscillatory) signals with arbitrary peaks in between the equilateral and squeezed limits (signature of hybrid inflation).