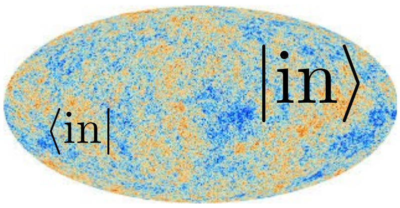
CosPA2017 @ YITP, Kyoto

Inflationary fluctuations with phase transitions



based on [1704.05026]

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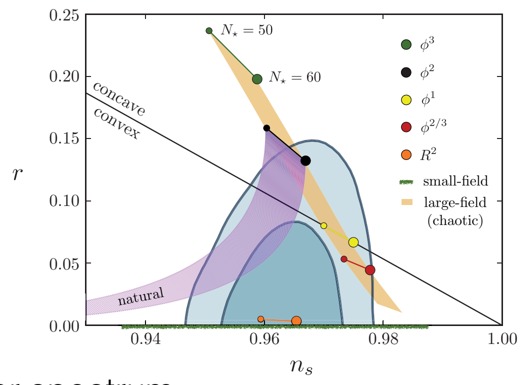
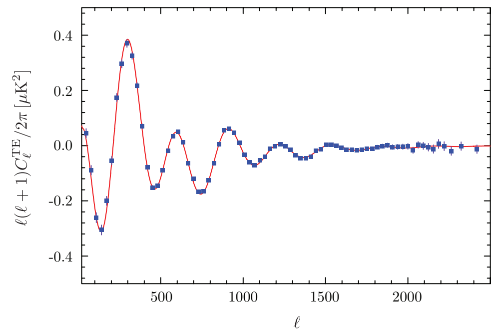
Research Center for the Early Universe

What is inflation all about?

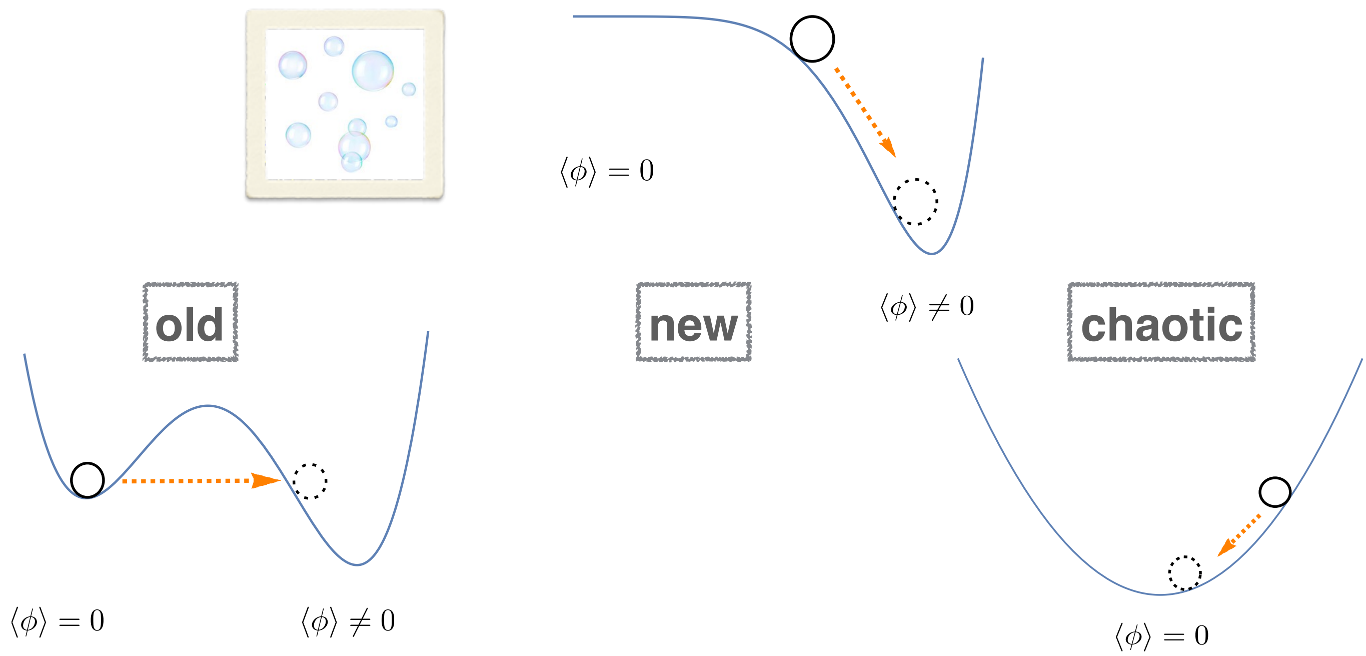
$$a(t) \sim e^{Ht}$$



- The initial conditions of Big Bang cosmology.
- The generation of primordial density fluctuations.
- The small deviation from scale-invariant primordial power spectrum.
- The existence of acoustic oscillation peaks.
- Current status: reported by inflationary speakers!

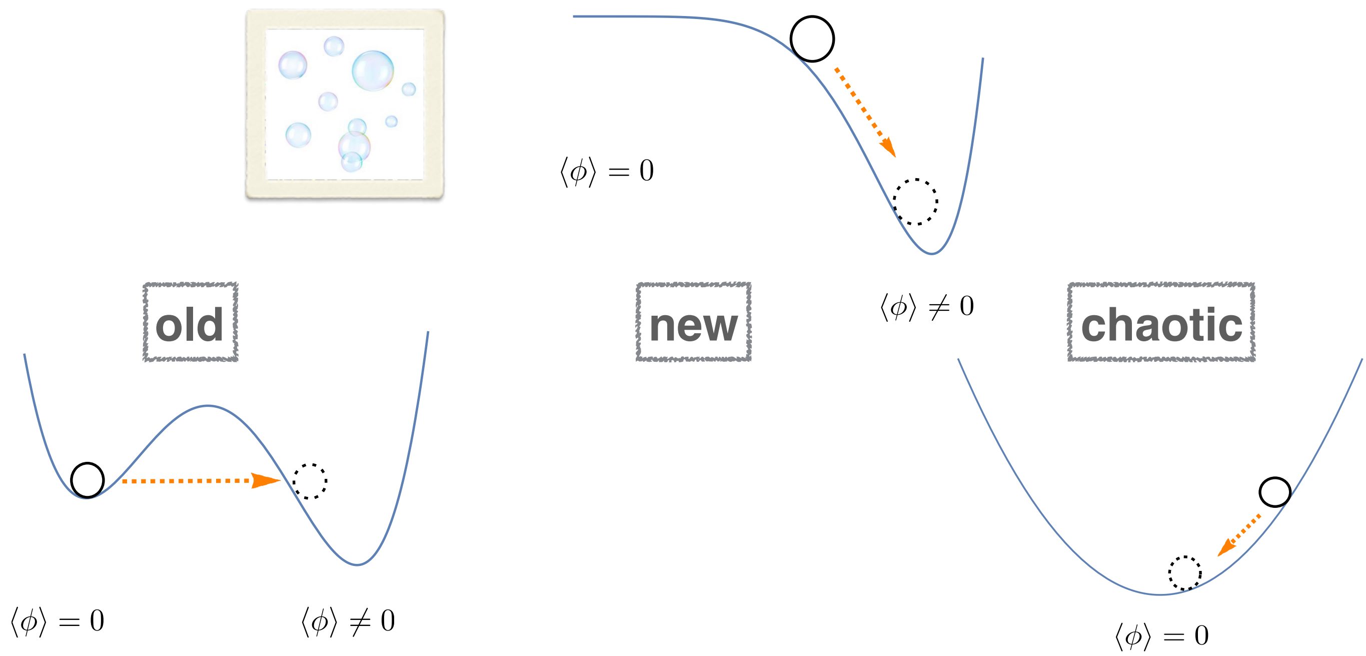


What is inflation all about?



What is inflation all about?

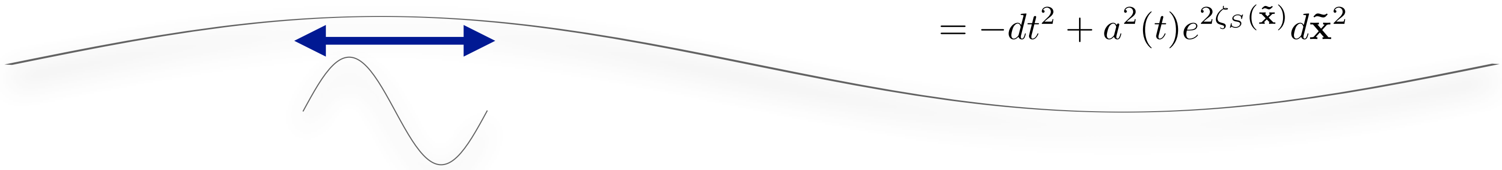
- ➤ The transition of **vev** plays a fundamental role in all inflation scenarios.



The single-field consistency relation

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]

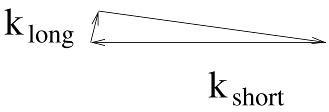
The dilatation transformation $\langle\zeta(k_1)\zeta(k_2)\rangle_{\zeta_L} = e^{-(n_s-1)\zeta_L}\langle\zeta(\tilde{k}_1)\zeta(\tilde{k}_2)\rangle_0$

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 curvature perturbation in single-clock inflation is conserved.
- The squeezed limit of bispectrum is suppressed by spacetime symmetry.

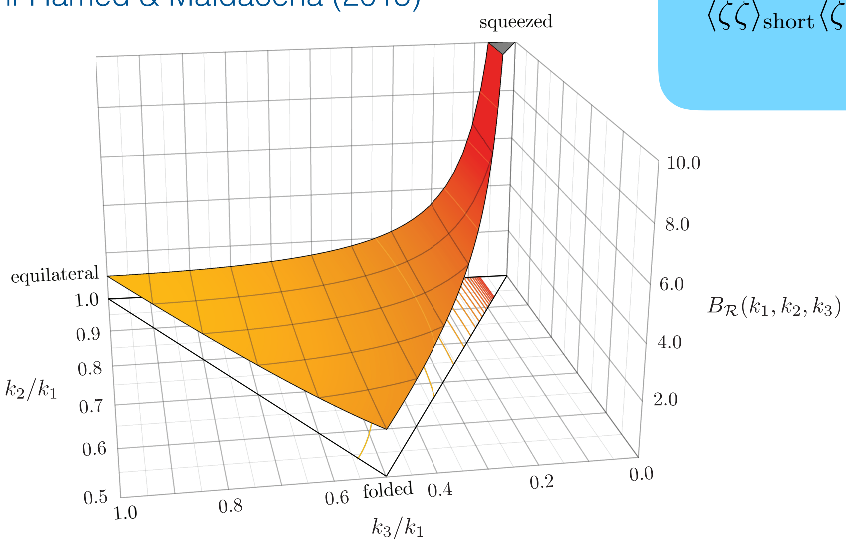
Cosmological collider

— probing signals of massive fields during inflation



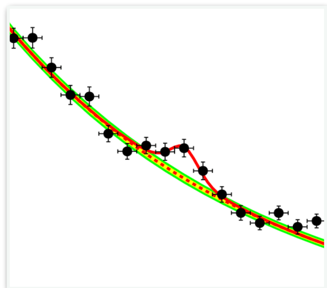
Assassi, Baumann & Green (2012)

Arkani-Hamed & Maldacena (2015)



The squeezed bispectrum

$$\frac{\langle \zeta\zeta\zeta \rangle}{\langle \zeta\zeta \rangle_{\rm short} \langle \zeta\zeta \rangle_{\rm long}} \sim \epsilon \sum_i w_i \left(\frac{k_{\rm long}}{k_{\rm short}} \right)^{\Delta_i}$$



More in Yi Wang's talk!

Cosmological collider

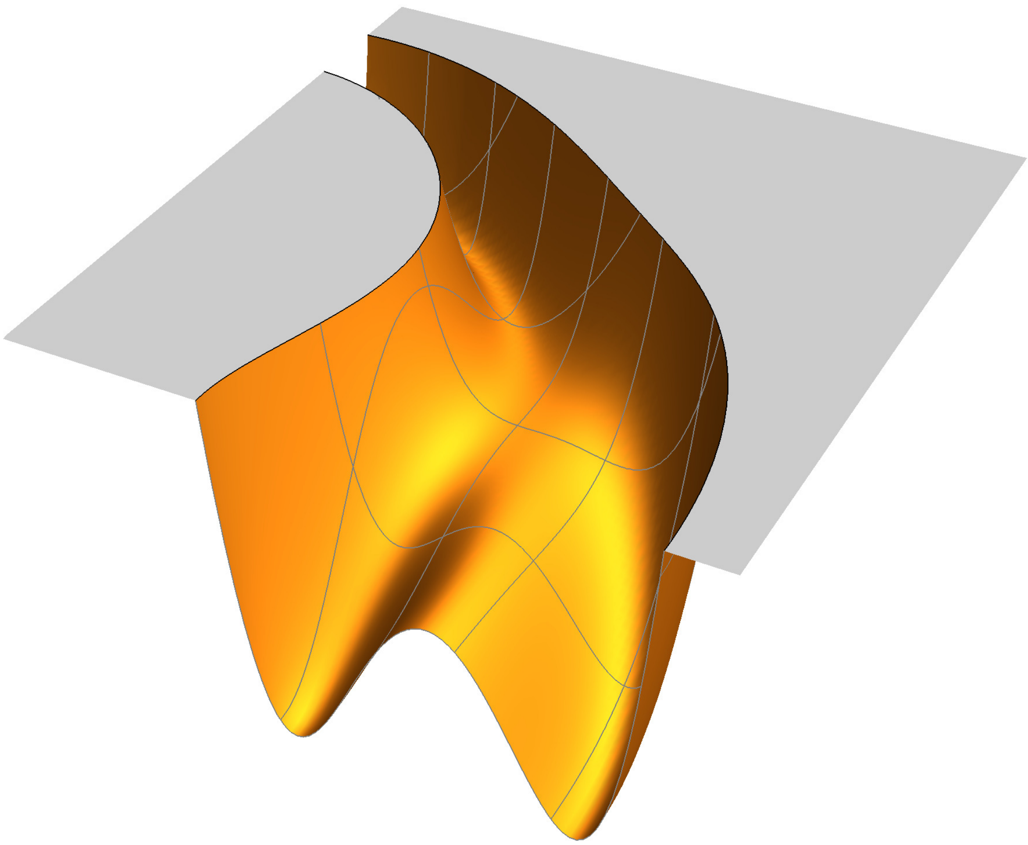
— probing signals of massive fields during inflation

Steps towards new discovery: Chen, Wang & Xianyu (2016,2017a,b)

1. To work out the background signals during inflation.

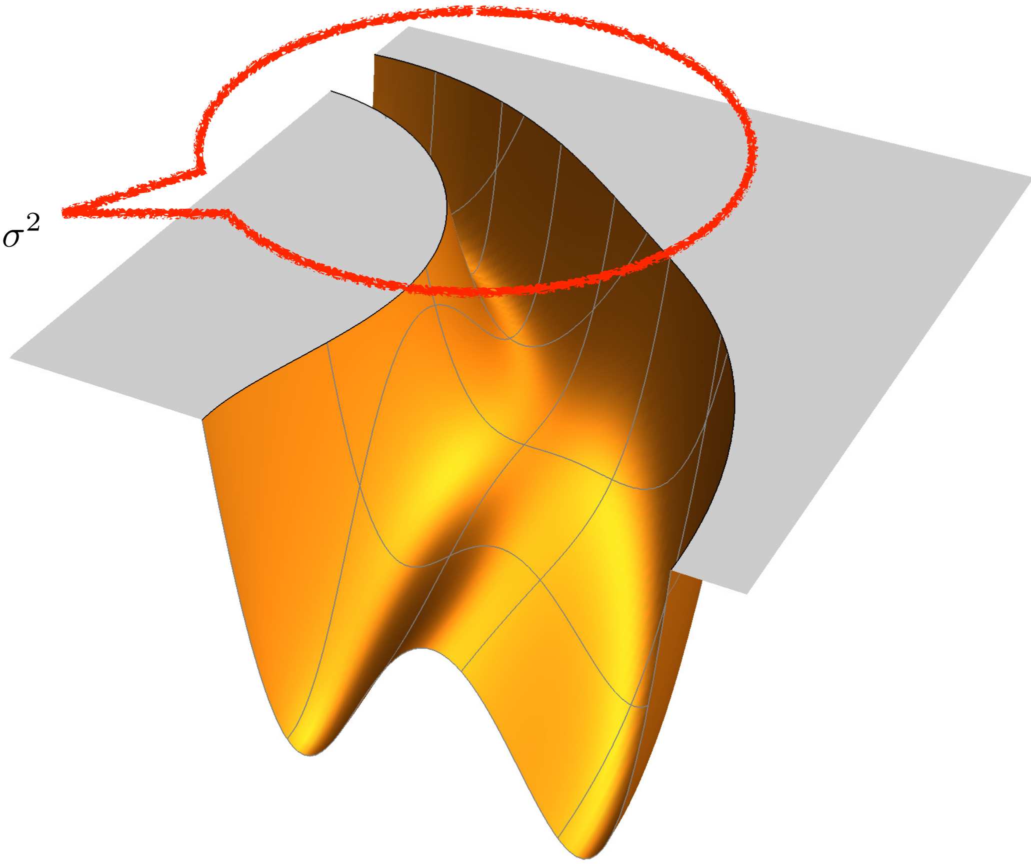
✔ 2. To figure out how new particles enter the bispectrum.

Inflation with phase transitions



Inflation with phase transitions

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



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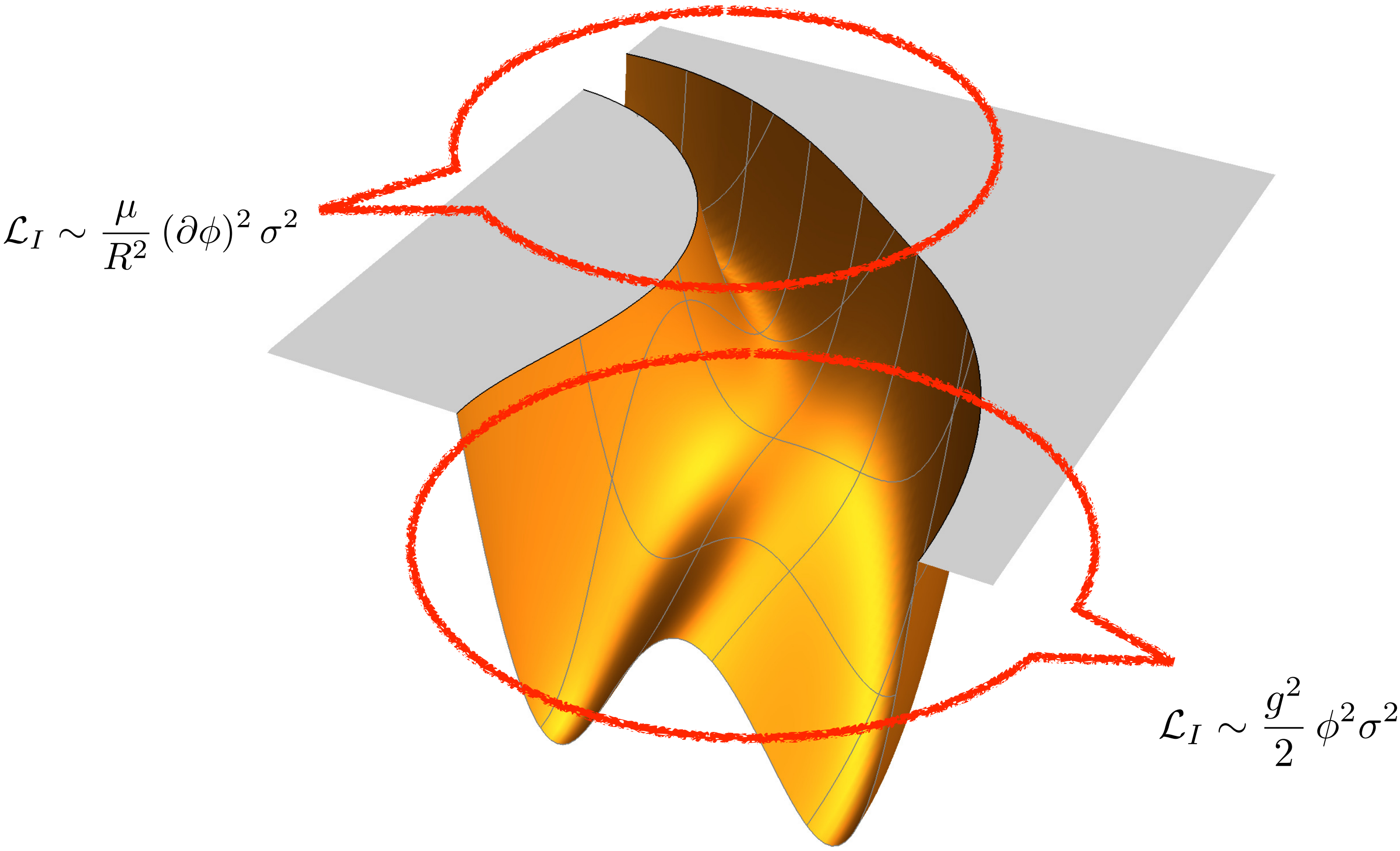

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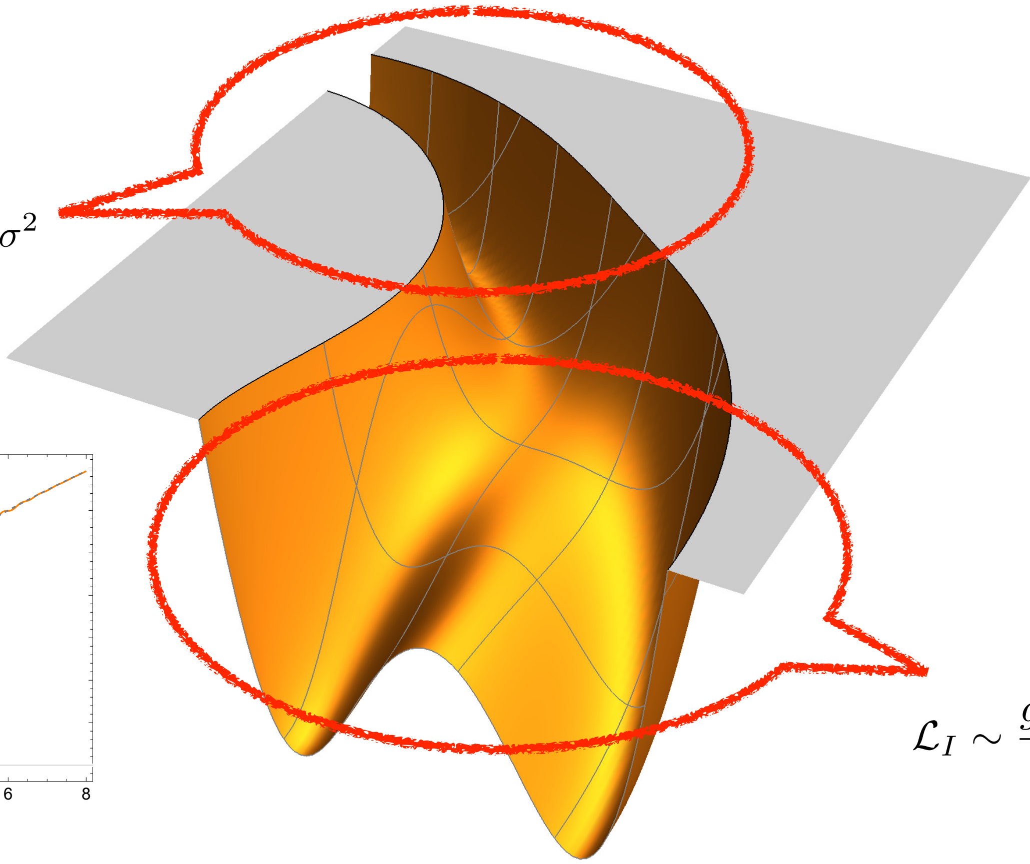
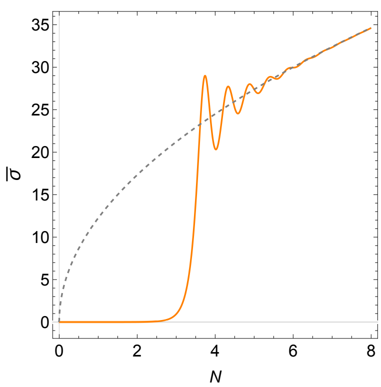


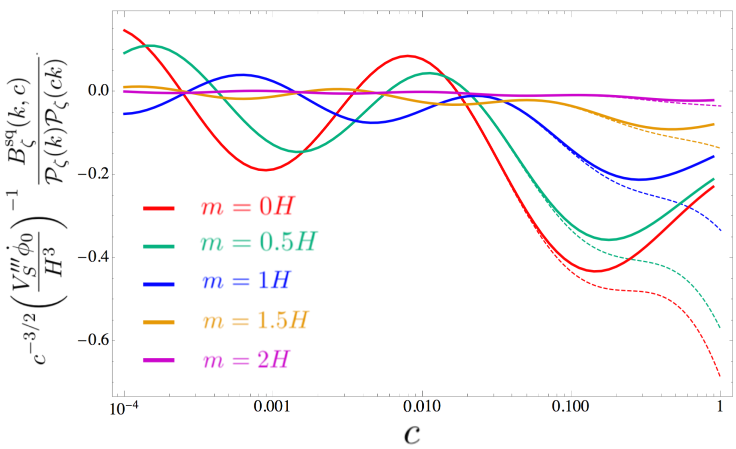


$$\mathcal{L}_I \sim \frac{g^2}{2}\,\phi^2\sigma^2$$

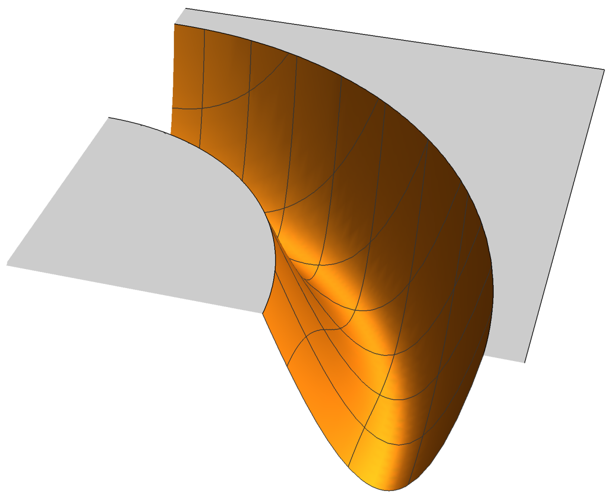
Inflation with a turn

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

- Signals of massive fields in squeezed bi-spectrum



Chen & Wang (2009)



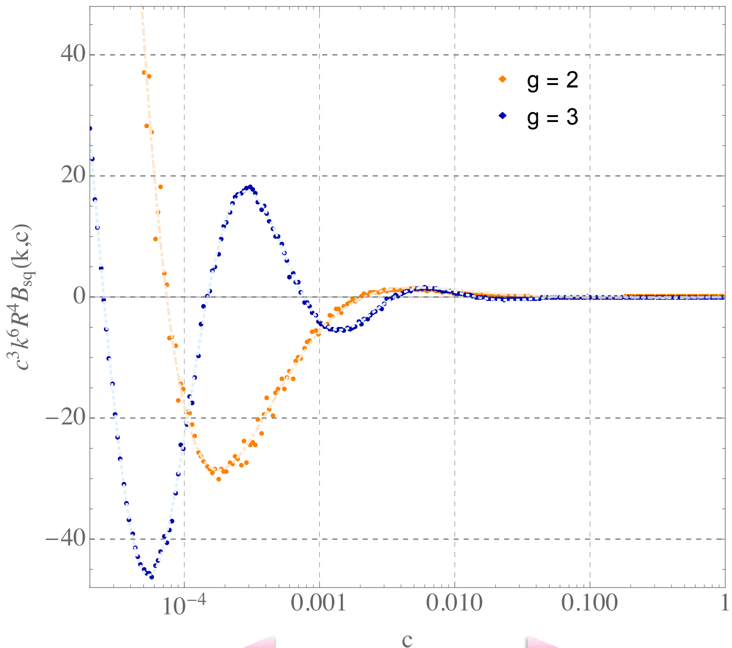
An, McAneny, Ridgway & Wise [1706.09971]

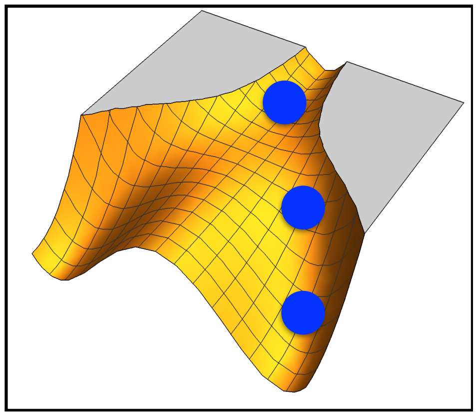
Inflation with a waterfall

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

Linde (1993)

Gong & Sasaki (2010)





Wang, YPW, Yokoyama & Zhou [in preparation]

squeezed ⟷ **equilateral**

$$c = k/k_c$$

- Methods -

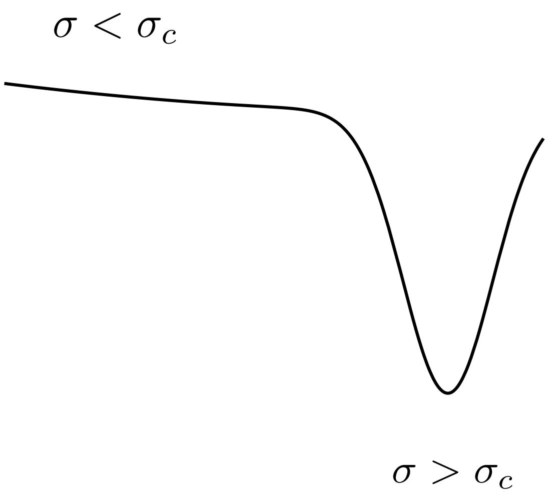
- **Cosmological in-in formalism:**
  - Perturbative interactions (gravitational or derivative couplings)
  - Standard initial states (the Bunch-Davies vacuum)
- **Effective field theory (equation-of-motion approach):**
  - Non-perturbative regime
  - Mixed initial vacuum states

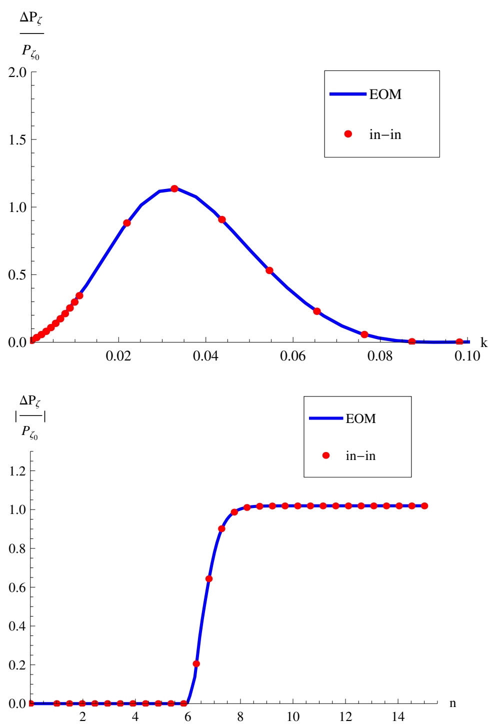
Phase transition triggered by slow-rolling

Chen, Namjoo & Wang [1505.03955]

A modified potential:

$$V(\phi,\sigma) = V_{\mathrm{slow-roll}}(\phi) + V_0\left[1 - e^{-\sigma^2/\sigma_c^2}\right] + \frac{1}{2}m_0^2\,\sigma^2$$





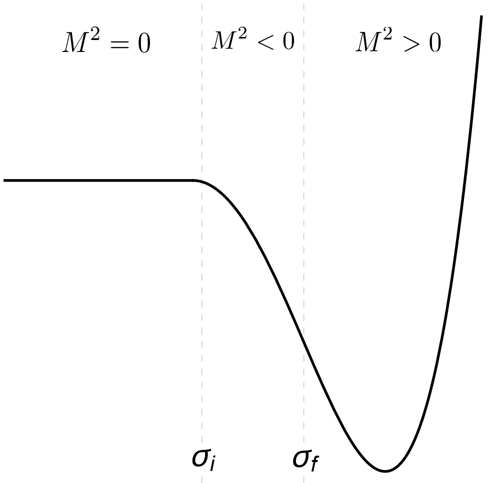
The two approaches matched at tree level.

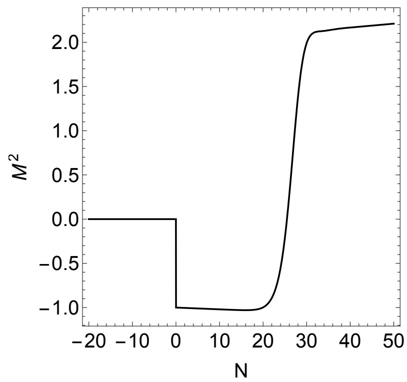
Phase transition triggered by quantum fluctuations

YPW & Yokoyama [1704.05026]

A step potential:
$$V_1(\sigma) = \frac{\lambda}{4} v^4, \qquad \sigma < 0,$$
$$= \frac{\lambda}{4}(\sigma^2 - v^2)^2 \qquad \sigma \geq 0,$$

$$M^2 = \frac{1}{H^2}\frac{\partial^2 V(\sigma)}{\partial \sigma^2}$$





The critical value of classical evolution: $\sigma_i \geq 3H_i^3/(2\pi\lambda v^2)$

The duration of the growing phase:

$$\Delta N = N_f - N_i = \frac{3}{M^2}\ln\left(\frac{2\pi}{3\sqrt{3\lambda}}M^3\right) \qquad \text{classical}$$

$$\Delta N = \frac{3}{2M^2}\ln\left[\frac{M^6(2+4\pi^2/\lambda)}{27+2M^6}\right] \qquad \text{stochastic}$$

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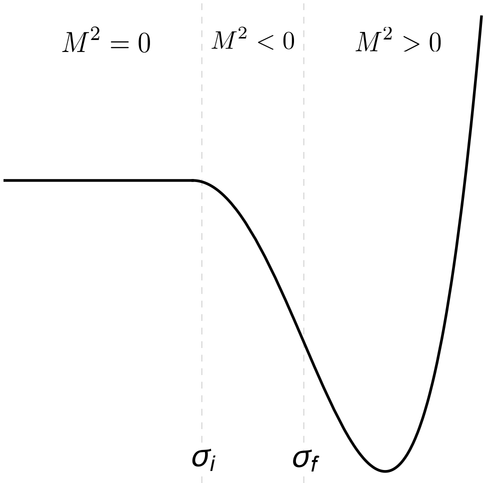
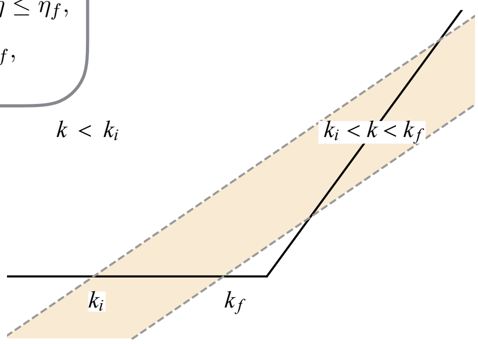


$$u_k'' + \left(k^2 - \frac{l^2 - 1/4}{\eta^2}\right) u_k = 0,$$

$$l = \begin{cases} 3/2, & \eta \leq \eta_i, \\ \sqrt{9/4 + M_-^2}, & \eta_i < \eta \leq \eta_f, \\ \sqrt{9/4 - M_+^2}, & \eta > \eta_f, \end{cases}$$



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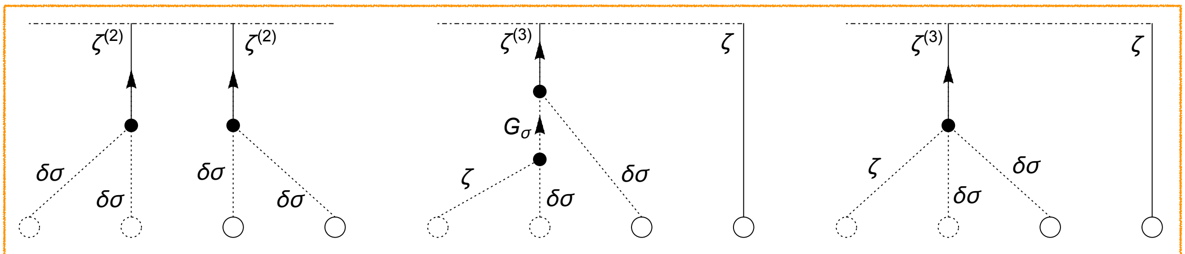
One-loop channels:

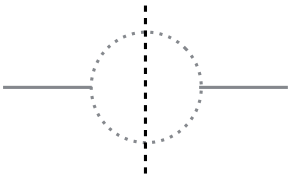
$$\langle\zeta^2\rangle_{\rm CIM} = -\int^{\eta} d\eta_1 \int^{\eta} d\tilde{\eta}_1 \left\langle \left[H_I^{(3)}(\eta_1), \zeta(\eta)\right] \left(\left[H_I^{(3)}(\tilde{\eta}_1), \zeta(\eta)\right]\right)^{\dagger} \right\rangle,$$

$$\langle\zeta^2\rangle_{\rm CIS,1} = -2\,{\rm Re}\left[\int^{\eta} d\eta_2 \int_{2}^{\eta} d\eta_1 \left\langle \left[H_I^{(3)}(\eta_1), \left[H_I^{(3)}(\eta_2), \zeta(\eta)\right]\right] \zeta(\eta) \right\rangle\right],$$

$$\langle\zeta^2\rangle_{\rm CIS,2} = -2\,{\rm Im}\left[\int^{\eta} d\eta_1 \left\langle \left[H_I^{(4)}(\eta_1), \zeta(\eta)\right] \zeta(\eta) \right\rangle\right].$$



(a) CIM (b) CIS,1 (c) CIS,2



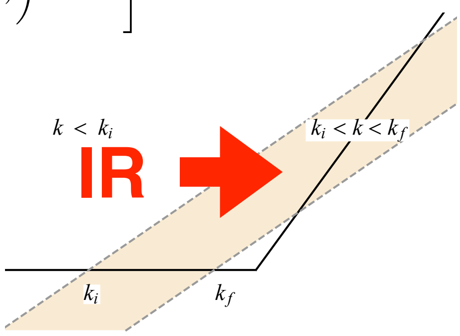
$M^2 < 0$

➤ The dominant decay channel changed!

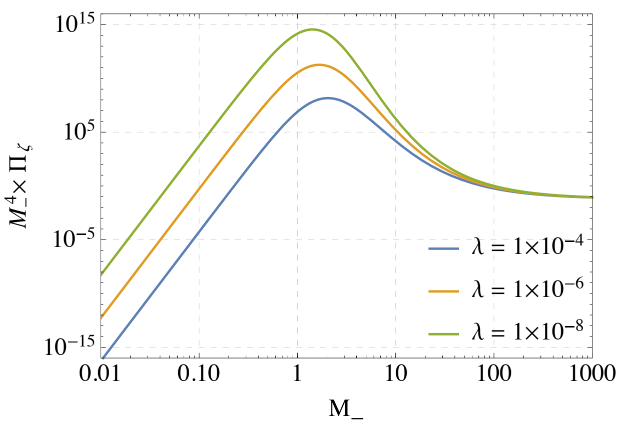
Results of bilinear correlators

Loop corrections from phase transitions:

$$\langle \zeta^2 \rangle \sim \frac{H^2}{\epsilon M_p^2}\left[1 + c_* \frac{H^2}{\epsilon M_p^2}\epsilon^2 M^4 \Pi_\zeta(a) + \left(c_* \frac{H^2}{\epsilon M_p^2}\epsilon^2 M^4 \Pi_\zeta(a)\right)^2 + \dots\right]$$



YPW & Yokoyama [1704.05026]



Loop corrections from spectator fields may be more important than the previous conclusion!

Messages (for the moment)

- The transition of vacuum expectation values (**vev**s) of scalar fields play a fundamental role in all inflation scenarios.
- Primordial signals of massive fields in the cosmological collider are enhanced by a waterfall phase transition.
- Loop corrections from spectator fields are never large, if they always stay in one stable vacuum during inflation.
- IR loop corrections are enhanced by phase transition with a growing **vev** (a tachyonic phase).