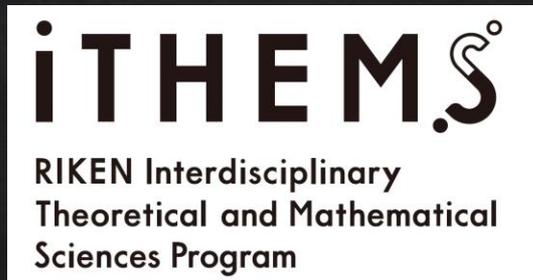


Model building aspects of cosmological collider

Shuntaro Aoki (RIKEN)

Collaboration with A. Ghoshal and A. Strumia, 2408.07069



2025 CAU-IBS BSM workshop
2025/2/21

short summary of Cosmo-Collider

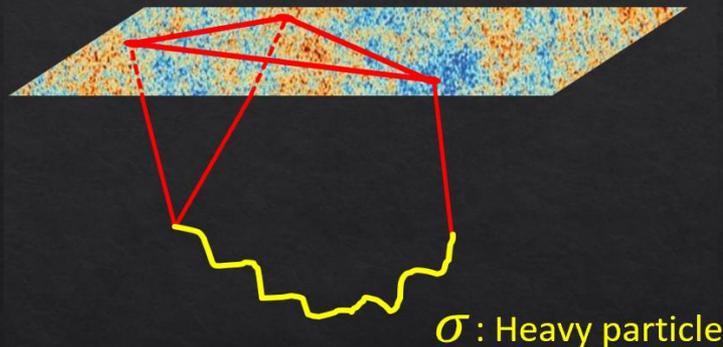
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Chen, Wang, '10
Baumann, Green, '12
Noumi, Yamaguchi, Yokoyama, '13
Arkani-Hamed, Maldacena, '15
...

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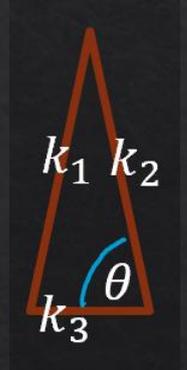
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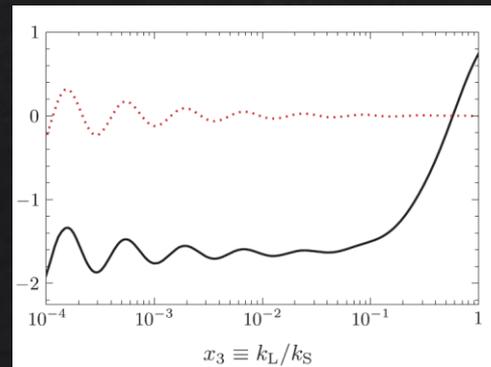
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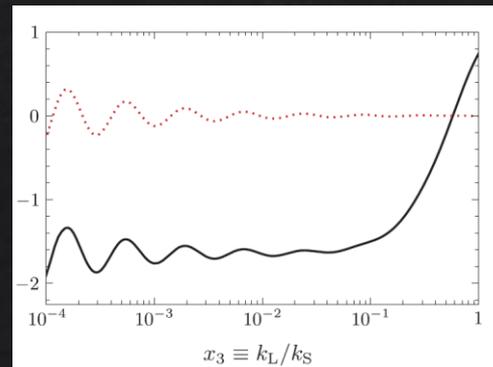


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From TASI Lectures on Primordial Cosmology

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- Specific feature: oscillation = “CC signal”
- Target: $m_\sigma \sim H \sim 10^{13}$ (GeV) \gg ground experiment
- Hubble mass appears naturally in BSM (SUSY, non-minimal coupling to gravity, ...)

Question

- What are the conditions for a large CC signal?
(Obviously, the mass should be $\sim H$, but is that enough?)

Focus

- 3pt. correlator = Bispectrum (f_{NL})

Focus

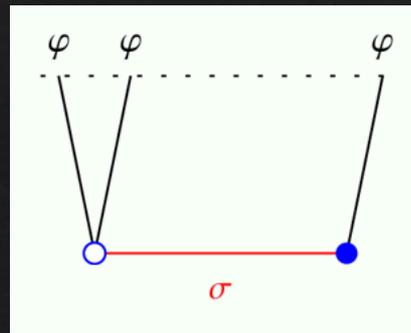
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- inflation scenario (alternatives: curvaton, modulated reheating, ...)
- Tree \gg Loop (exception: chemical potential)
- Scalar exchange (forget fermion & gauge bosons)



Two-scalar action

- inflaton + an extra scalar: ϕ^a ($a = 1, 2$)

$$S = \int d^4x \sqrt{|\det g|} \left[-\frac{\bar{M}_{\text{Pl}}^2}{2} R + \frac{K_{ab}(\phi)}{2} (\partial_\mu \phi^a) (\partial^\mu \phi^b) - V(\phi) \right]$$

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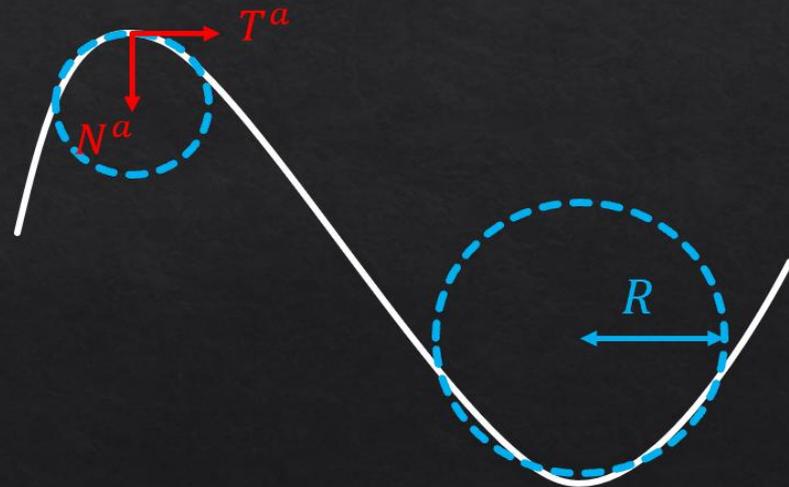
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- Turn: specific to multifield dynamics

$$T^a \equiv \phi_0'^a / \phi_0'$$

$$N_a \equiv \sqrt{\det K} \epsilon_{ab} T^b$$

$$\phi_0'^2 \equiv K_{ab} \phi_0'^a \phi_0'^b$$



Turn rate

- Second SR parameter η^a

$$\eta^a \equiv -\frac{D_{\mathcal{N}}\phi_0'^a}{\phi_0'} = \eta_T T^a + \eta_N N^a, \quad \eta_T = -\frac{\phi_0''}{\phi_0'}, \quad \eta_N \equiv -N_a D_{\mathcal{N}} T^a.$$

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- η_N can be large only if $1/R$ (curvature of trajectory) is sub-Planckian

Fluctuations

➤ Expand

$$\phi^a = \phi_0^a + \varphi^a$$

fluctuations



Fluctuations

➤ Expand

$$\phi^a = \phi_0^a + \varphi^a$$

↑
fluctuations

➤ decompose

$$\varphi^a = \varphi T^a + \sigma N^a,$$

↑
 φ (adiabatic)
 $\sim \zeta$ (curvature)

↑
 σ (iso-curvature)

Quadratic action

➤ Quadratic action

$$S^{(2)} = \int d^4x a^3 \left[\left(\frac{\dot{\varphi}^2}{2} - \frac{(\partial_i \varphi)^2}{2a^2} - \frac{m_\varphi^2}{2} \varphi^2 \right) + \left(\frac{\dot{\sigma}^2}{2} - \frac{(\partial_i \sigma)^2}{2a^2} - \frac{m_\sigma^2}{2} \sigma^2 \right) + \mathcal{L}_{\varphi\sigma} \right]$$

free ~massless

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$$m_\sigma^2 = V_{NN} + H^2 \left(\frac{\phi_0'^2}{2} \mathcal{R} - \eta_N^2 \right)$$

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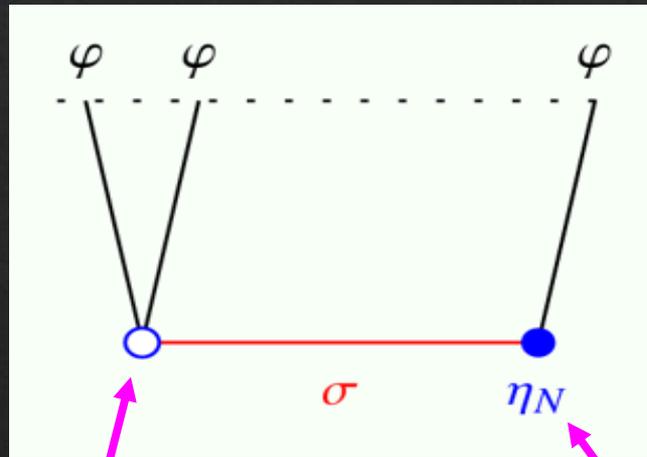
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➤ Transfer vertex

$$\mathcal{L}_{\varphi\sigma} = 2\eta_N H \sigma \dot{\varphi}$$

Turn rate converts $\varphi \leftrightarrow \sigma$

Understanding so far



??

need big turn rate

Cubic interactions

- Many cubic interactions, dominated by potential couplings

$$\mathcal{L}^{(3)} \sim \underbrace{V_{TTT}\varphi^3}_{\text{small}} + V_{NTT}\sigma\varphi^2 + V_{NNT}\sigma^2\varphi + V_{NNN}\sigma^3 + \dots$$

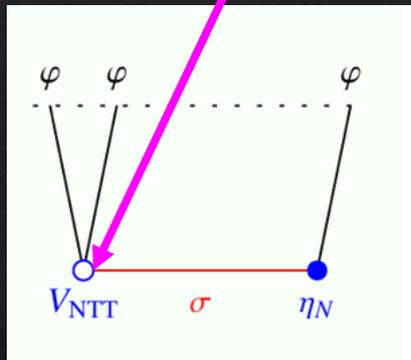
Maldacena '03

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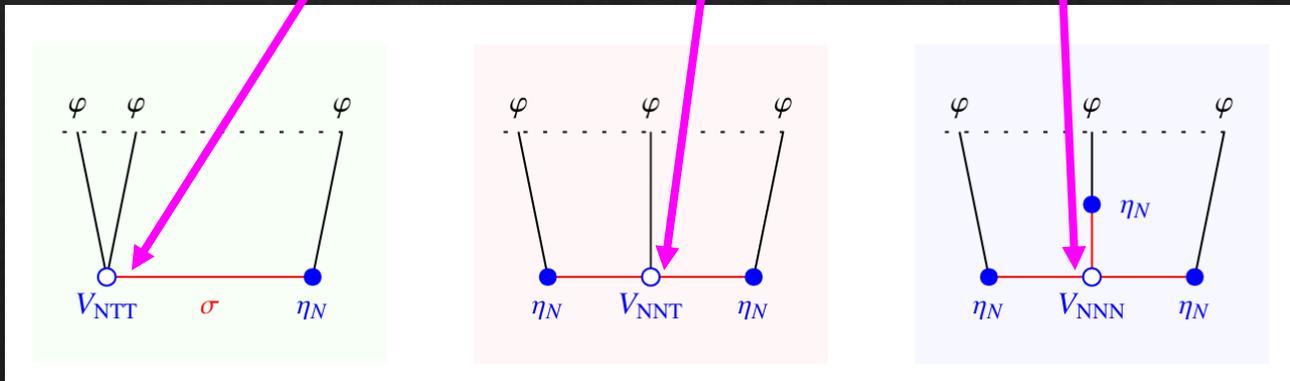
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- Dominant diagrams



Remark

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- ◆ Single σ -exchange

$$V_{NTT}/H \sim \eta_N V_{NN}/H\phi'_0 \sim \eta_N H/\phi'_0 \sim \eta_N \times 10^{-5}$$

$$\uparrow \\ m_\sigma \sim H \text{ for CC}$$

remember

$$m_\sigma^2 = V_{NN} + H^2 \left(\frac{\phi_0'^2}{2} \mathcal{R} - \eta_N^2 \right)$$

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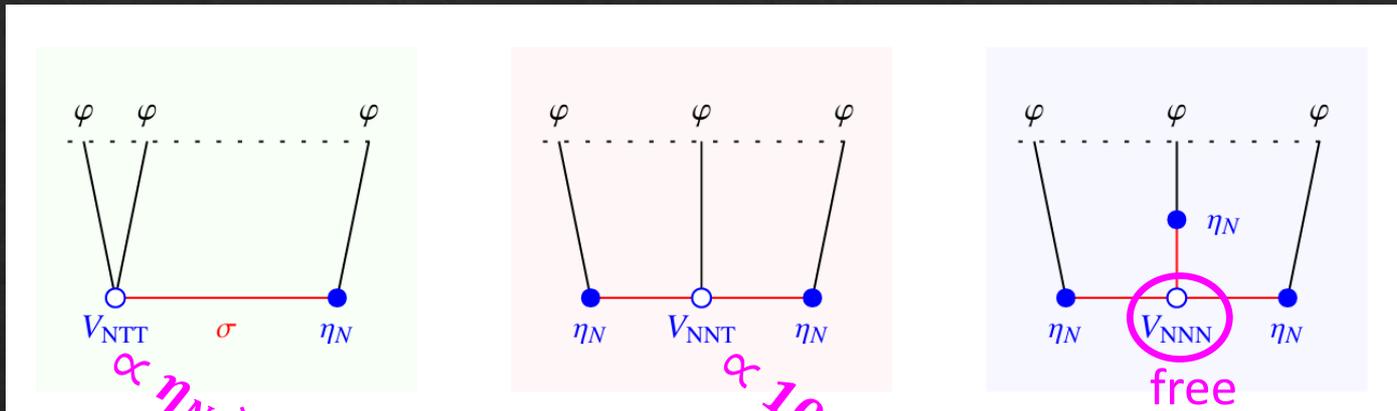
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remember

$$m_\sigma^2 = V_{NN} + H^2 \left(\frac{\phi_0'^2}{2} \mathcal{R} - \eta_N^2 \right)$$

- V_{NNN} is not constrained (free parameter) in general

Turn rate η_N controls almost everything



$\propto \eta_N \times 10^{-5}$

$\propto 10^{-5}$

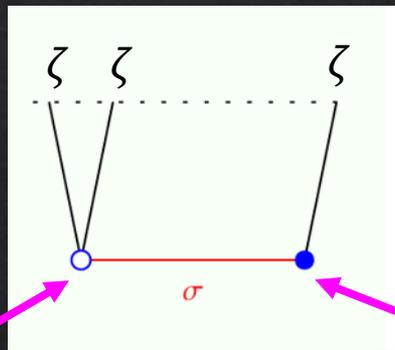
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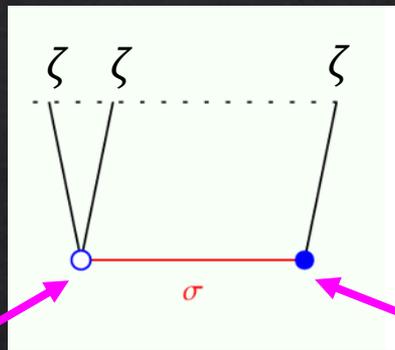
L. Pinol, SA, S. Renaux-Petel, M. Yamaguchi

$$\frac{\dot{\phi}_0 \eta_N}{H} \sigma \left[\dot{\zeta}^2 - \frac{(\partial \zeta)^2}{a^2} \right]$$

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- We confirmed the result is same in both gauge

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- Big turn rate $\eta_N \sim \sqrt{2\epsilon} M_{\text{pl}}/R \Rightarrow$ sub-Plankian physics
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Examples

Motivated models with R^2

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➤ J-frame

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

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➤ E-frame

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

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

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

Interpolate two inflation scenarios

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→ vanishing turn rate
- $V_{\text{J}} \ll f_0^2$: **ϕ -like inflation**. Potential is minimized by $f(\phi) = -\zeta_z z^2$
→ $z = z(\phi)$ → non-zero turn rate

Plankion(dilaton)- R^2

K. Kannike, G. Hutsi, L. Pizza, A. Racioppi, M. Raidal, A. Salvio, A. Strumia, 1502.01334.

- Corresponds to a choice (dimensionless theory):

$$\left\{ \begin{array}{l} f = \xi_s s^2 \\ V_J = \lambda_s(s) s^4 / 4 \end{array} \right. \quad \lambda_s(s) \simeq \frac{b}{8} \ln^2 \frac{s^2}{w^2}$$

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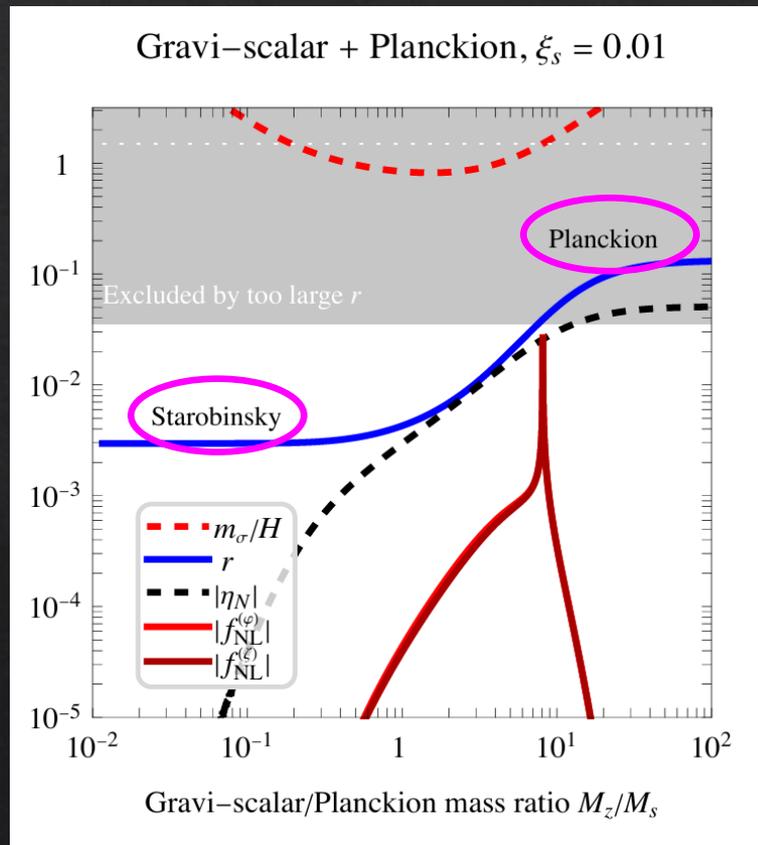
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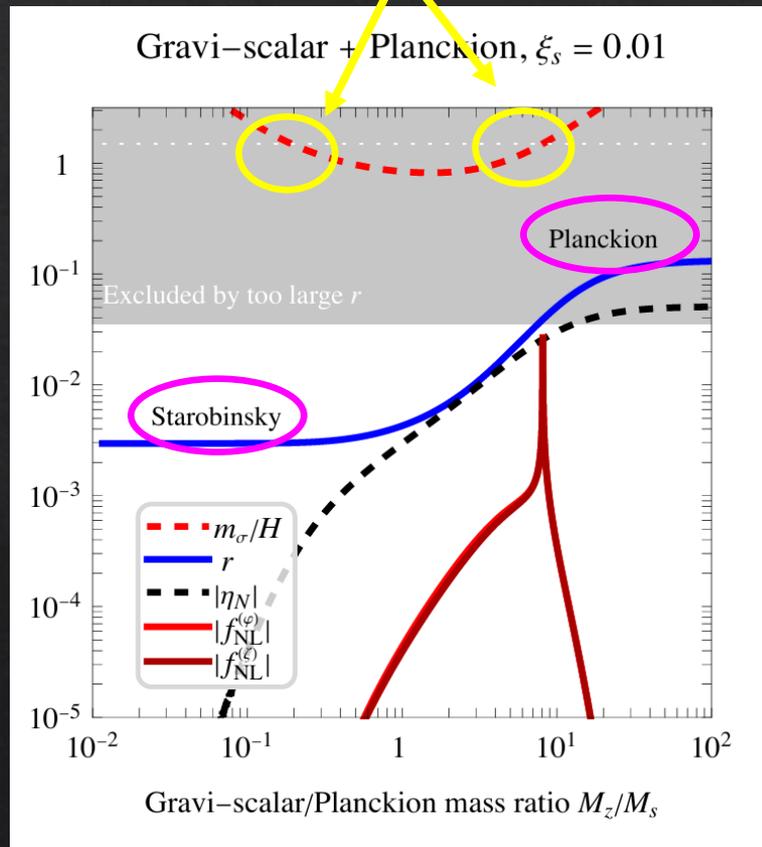
- dimensionful parameter = M_{pl}

CC signal

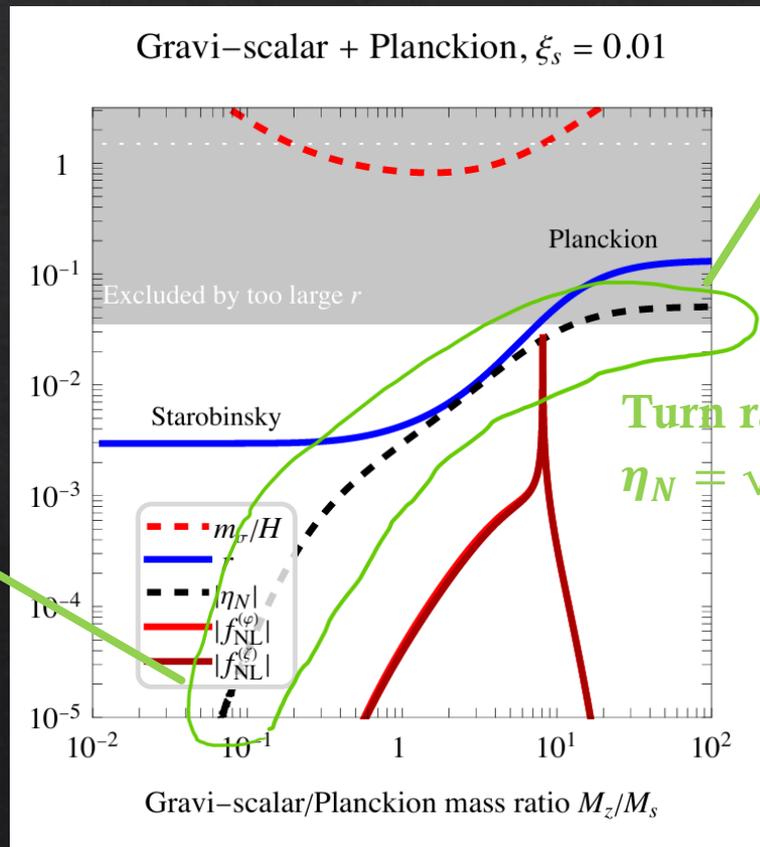


CC signal

$$m_\sigma \sim H$$



CC signal

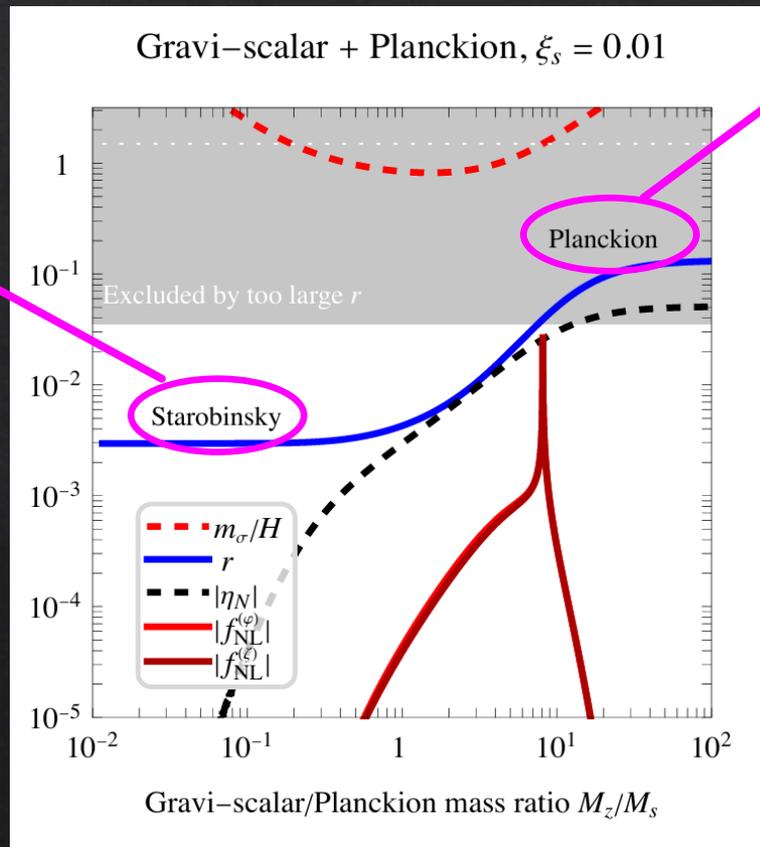


non-zero turn
 with $R \sim M_{\text{pl}}$
 $\Rightarrow \eta_N \sim \sqrt{\epsilon}$

almost zero turn
 $R \sim \infty \Rightarrow \eta_N \sim 0$

CC signal

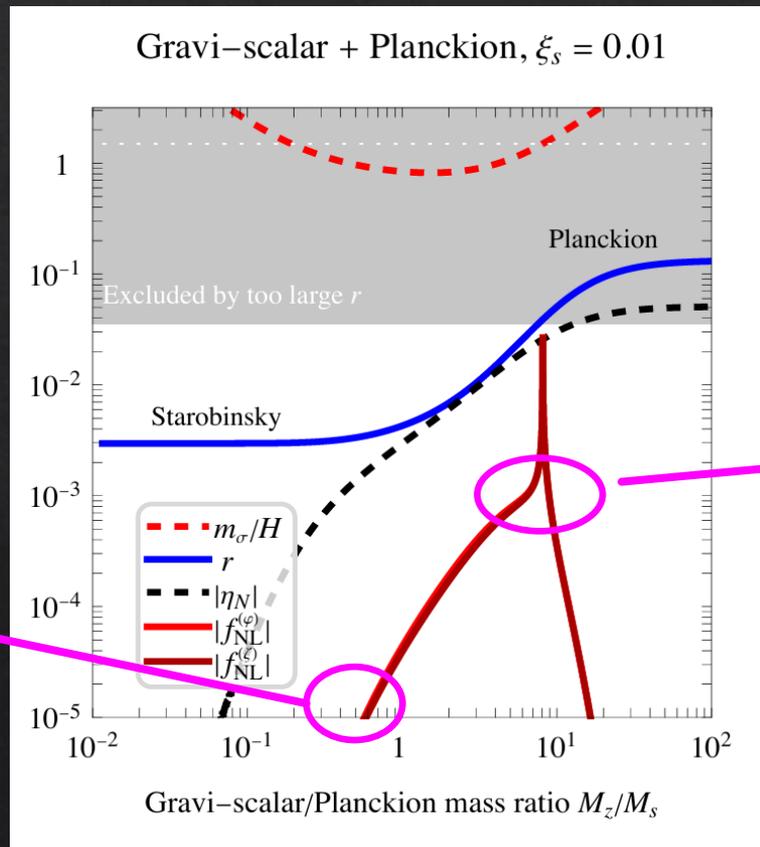
Small r



quadratic potential
 \Rightarrow Large r

CC signal

$f_{\text{NL}} \sim 0$



$f_{\text{NL}} \sim \epsilon$

For large turn rate

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➤ Bigger ϵ ?? → difficult: $r \approx 16\epsilon < 0.033$...

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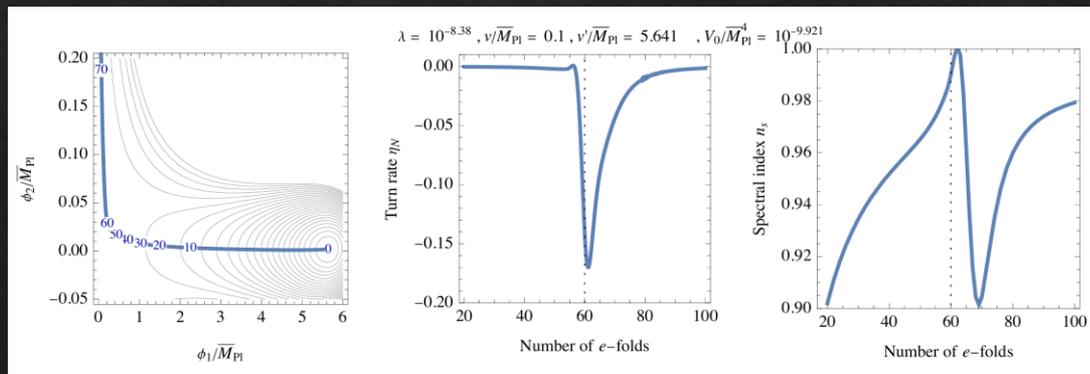
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- Bigger ϵ ?? \rightarrow difficult: $r \approx 16\epsilon < 0.033 \dots$
- Smaller R (sub-Planckian physics)
- But sudden turn has a risk of disrupting n_s

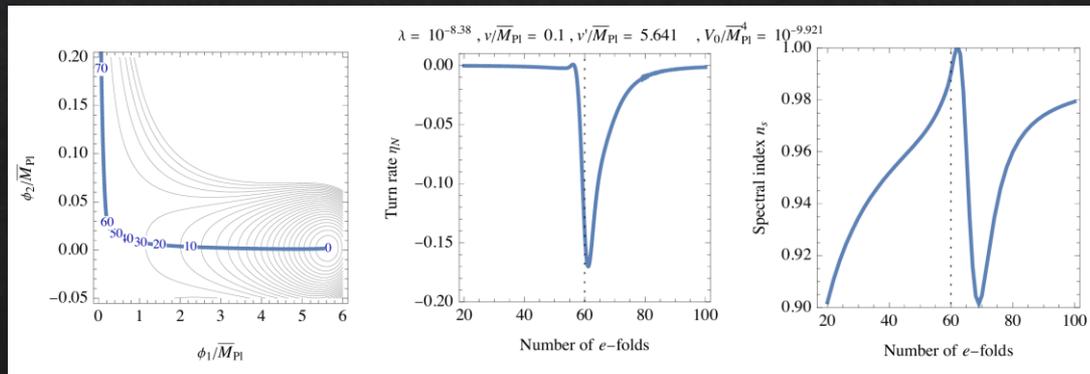


discussed a lot in PBH context

For large turn rate

$$\eta_N = \frac{d\phi_0}{dN} \times \frac{1}{R} = \sqrt{2\epsilon} M_{\text{pl}} \times \frac{1}{R}$$

- Bigger ϵ ?? \rightarrow difficult: $r \approx 16\epsilon < 0.033 \dots$
- Smaller R (sub-Planckian physics)
- But sudden turn has a risk of disrupting n_s



discussed a lot in PBH context

- Multiple constant turn

Large turn rate during all inflation

- Examples of inflationary potential

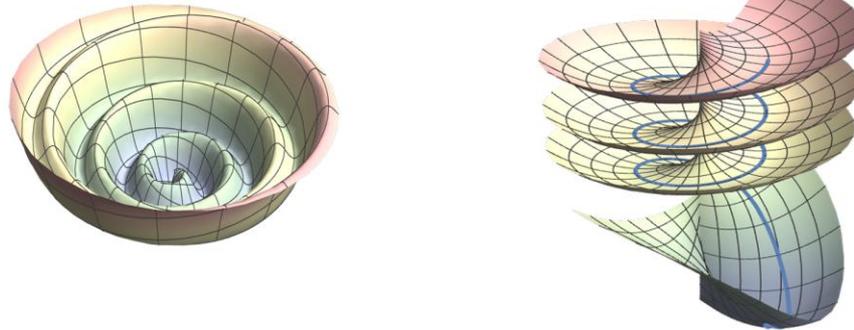
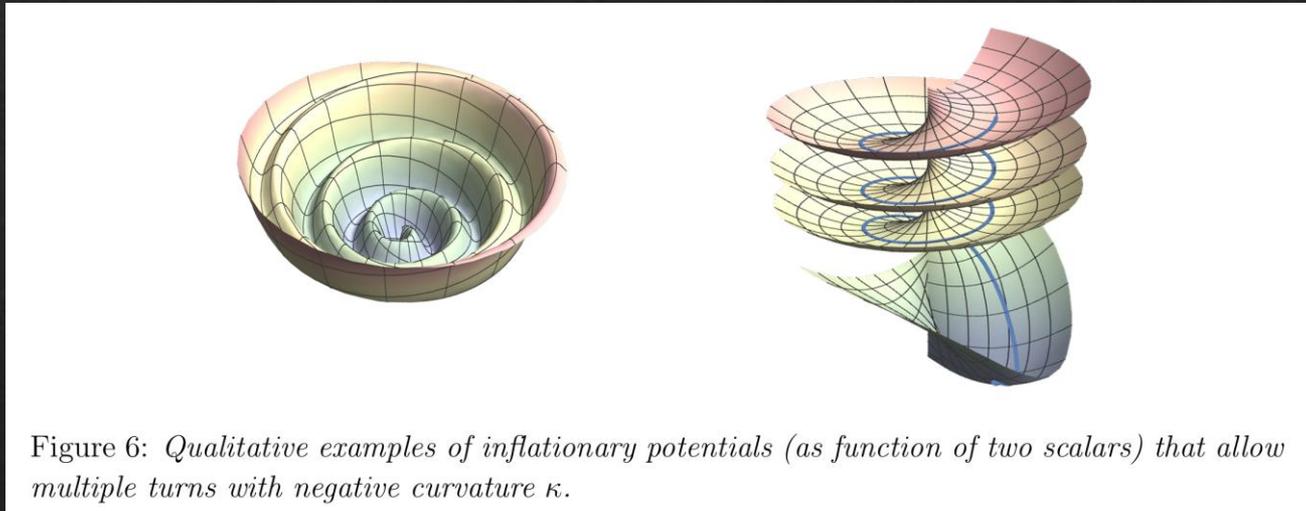


Figure 6: *Qualitative examples of inflationary potentials (as function of two scalars) that allow multiple turns with negative curvature κ .*

Large turn rate during all inflation

- Examples of inflationary potential



- Can they be derived from a well-motivated theory? (work in progress)

Summary

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- **Cosmological Collider** \supset mass & spin of new particles
- Not clear under what condition a large signal can be obtained, sometimes incorrectly estimated
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 - Inflation models with Planck-scale physics predict $f_{\text{NL}} \sim \epsilon$
 - Confirmed by motivated models: Plankion- R^2 & Higgs- R^2
 - For large signal, big turn rate (sub-Planckian physics) and/or big V_{NNN}

Thank you!!

Details

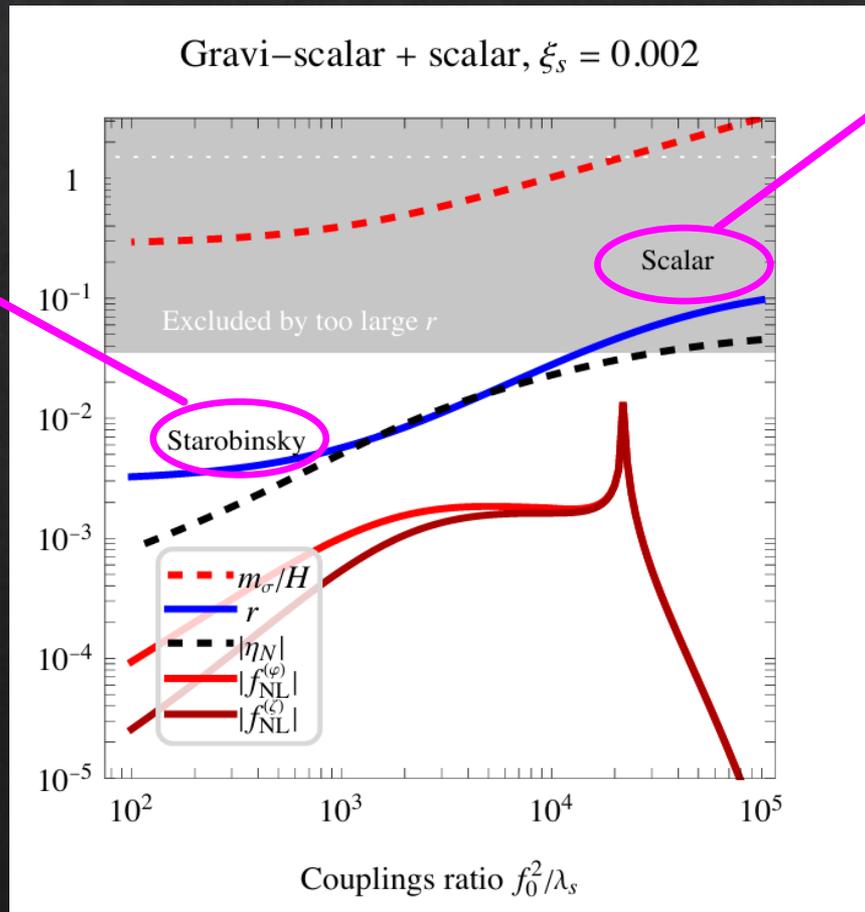
Model2: Higgs- R^2

Salvio, Mazumdar '15, Ema '17, Gorbunov, Tokareva '18, Gundhi, Steinwachs '18, ...

- corresponds to a choice:
$$\left\{ \begin{array}{l} f = \bar{M}_{\text{Pl}}^2 + \xi_s s^2 \\ V_{\text{J}}(s) = \frac{\lambda_s}{4} s^4 \end{array} \right.$$
- s : Higgs in unitary gauge
- Motivated as a UV completion of Higgs inflation
- Interpolate Higgs inflation ($\lambda_s/\xi_s^2 \ll f_0^2$) and Starobinsky inflation ($\lambda_s/\xi_s^2 \gg f_0^2$)
- M_{pl} is the only scale

CC signal

- almost zero turn
- $f_{\text{NL}} \sim 0$
- Small r



- non-zero turn
- $f_{\text{NL}} \sim \epsilon$
- Large r

CC signal

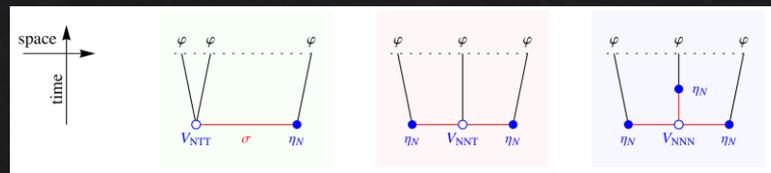
- Bispectrum (shape function S) in squeezed limit $k_3 \equiv k_L \ll k_{1,2} \equiv k_S$.

$$S \simeq \frac{9}{10} \left[f_{\text{NL}}(\nu) \left(\frac{k_L}{k_S} \right)^{1/2-\nu} + f_{\text{NL}}(-\nu) \left(\frac{k_L}{k_S} \right)^{1/2+\nu} \right] \quad \text{where} \quad \nu = \sqrt{\frac{9}{4} - \frac{m_\sigma^2}{H^2}}.$$

Scaling if $m_\sigma < \frac{3}{2}H$. Oscillatory if $m_\sigma > \frac{3}{2}H$.

- Size = f_{NL}

$$f_{\text{NL}} = \frac{10}{9\sqrt{P_\zeta}} \left[\eta_N C_{NTT} \frac{V_{NTT}}{H} + \eta_N^2 C_{NNT} \frac{V_{NNT}}{H} + \eta_N^3 C_{NNN} \frac{V_{NNN}}{H} \right]$$



Background

- EOMs for spatially homogeneous fields $\phi_0^a(t)$

$$\frac{D_{\mathcal{N}}\phi_0'^{ia}}{3 - \epsilon_H} + \phi_0'^{ia} + \bar{M}_{\text{Pl}}^2 \frac{K^{ab}V_b}{V} = 0, \quad H^2 = \frac{V}{\bar{M}_{\text{Pl}}^2(3 - \epsilon_H)}$$

$$D_{\mathcal{N}}\phi_0'^{ia} = \phi_0''^{ia} + \Gamma_{bc}^a \phi_0'^{ib} \phi_0'^{ic}$$

$$\epsilon_H \equiv -\frac{H'}{H} = \frac{K_{ab}\phi_0'^{ia}\phi_0'^{ib}}{2\bar{M}_{\text{Pl}}^2} = \frac{\phi_0'^2}{2\bar{M}_{\text{Pl}}^2}$$

define “total speed”

Quadratic action

$$S^{(2)} = \int d^4x a^3 \left[\left(\frac{\dot{\varphi}^2}{2} - \frac{(\partial_i \varphi)^2}{2a^2} - \frac{m_\varphi^2}{2} \varphi^2 \right) + \left(\frac{\dot{\sigma}^2}{2} - \frac{(\partial_i \sigma)^2}{2a^2} - \frac{m_\sigma^2}{2} \sigma^2 \right) + \mathcal{L}_{\varphi\sigma} \right],$$

$$\mathcal{L}_{\varphi\sigma} = \eta_N H (\sigma \dot{\varphi} - \dot{\sigma} \varphi) - (V_{NT} + 2\epsilon_H H^2 \eta_N) \sigma \varphi = 2\eta_N (H \sigma \dot{\varphi} + \eta_H H^2 \sigma \varphi).$$

$$m_\sigma^2 = M_{NN}^2 - H^2 \eta_N^2 = V_{NN} + H^2 \left(\frac{\phi_0'^2}{2} \mathcal{R} - \eta_N^2 \right),$$

$$m_\varphi^2 = M_{TT}^2 - H^2 \eta_N^2 = V_{TT} + 2\epsilon_H H^2 (3 - \epsilon_H) + 4\epsilon_H H V_T / \dot{\phi}_0 - H^2 \eta_N^2.$$

$$V_{TT} \equiv T^a T^b V_{ab} = H^2 [\epsilon_H (6 - 2\epsilon_H - 5\eta_H) + \eta_H (3 - \eta_H + \eta_{H2}) + \eta_N^2],$$

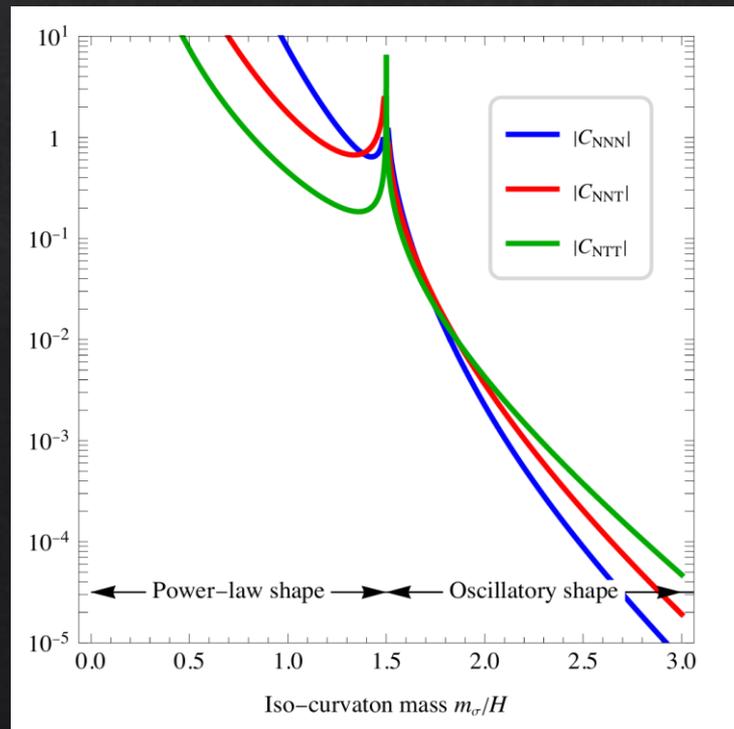
$$V_{NT} \equiv N^a T^b V_{ab} = H^2 \eta_N (3 - 3\epsilon_H - 2\eta_H + \eta_{N2}).$$

$$\epsilon_H = -\frac{d \ln H}{d\mathcal{N}}, \quad \eta_H = -\frac{1}{2} \frac{d \ln \epsilon_H}{d\mathcal{N}}, \quad \eta_{H2} = \frac{d \ln \eta_H}{d\mathcal{N}}, \quad \eta_{N2} = \frac{d \ln \eta_N}{d\mathcal{N}}.$$

Mass dependent coefficients

- Boltzmann suppressed for heavy mass

$$C_{NTT}(\nu) = \frac{2^{2\nu-4}(2\nu-5)}{\sqrt{\pi}(3+2\nu)} \Gamma(\nu) \Gamma\left(\frac{1}{2}-\nu\right) \tan\left[\frac{\pi}{4}(1-2\nu)\right] \sim e^{-\pi m_\sigma/H} \text{ for } m_\sigma \gg H$$



Detail on Plankion- R^2

- In the limit $f_0^2 \ll \lambda_s$ the inflaton is the gravi-scalar z while $s \simeq w$ sits around its minimum, giving Starobinsky inflation with $f_0 \approx 10^{-5}$, small r and negligible turn rate.
- In the opposite limit $\lambda_s \ll f_0^2$ one gets Plankion inflation along the trajectory $z^2 \simeq 6\xi_s s^2$ such that the inflationary potential and V_{NN} are

$$\lambda \sim \left(\frac{H}{M_{\text{Pl}}} \right)^2 \xleftarrow{\text{EoM}} V \simeq \frac{\lambda_s(s) \bar{M}_{\text{Pl}}^4}{4\xi_s^2}, \quad \frac{V_{NN}}{H^2} \simeq \frac{6f_0^2 \xi_s^2}{\lambda_s(s)} (1 + 6\xi_s). \xrightarrow[\text{regime } V_{NN}/H^2 \sim 1]{\lambda \sim f_0^2} \quad (55)$$

The turn rate is $\eta_N \sim \sqrt{\epsilon_H}$ and the dominant cubics are

$$\frac{V_{NNN}}{H} \simeq \frac{f_0^2 \xi_s}{\sqrt{\lambda_s(s)}} 3\sqrt{2}(1 + 3\xi_s)\sqrt{1 + 6\xi_s}, \quad \frac{V_{NTT}}{H} \simeq \frac{f_0^2 \xi_s}{\sqrt{2\lambda_s(s)}} \sqrt{1 + 6\xi_s}. \quad (56)$$

Cosmo-collider signals arise in the quasi-single field regime where the Plankion s is the inflaton, and the gravi-scalar z has Hubble mass, $V_{NN}/H^2 \sim 1$ at $\mathcal{N} \approx 60$ e -folds of inflation. Eq. (56) shows that potential cubics get small in such regime,

$$V_{NTT, NNN}/H \sim f_0 \sim H/\bar{M}_{\text{Pl}}. \quad (57)$$

Detail on Higgs- R^2

We first consider a scalar with $M_s, V_{sss} \simeq 0$ and constant quartic λ_s . Such a scalar is sometimes dubbed ‘Higgs’, but improperly: cosmo-collider signals arise at $m_\sigma \sim H$, when $\lambda_s \sim f_0^2$ is much smaller than the typical Higgs quartic. More precisely, the iso-curvaton mass at inflationary values $z \gg \bar{M}_{\text{Pl}}/\sqrt{\xi_s}$ is

$$\frac{m_\sigma^2}{H^2} \simeq 24\xi_s \left[1 + \frac{f_0^2 \xi_s}{4\lambda_s} (1 + 6\xi_s) \right] - \eta_N^2 \quad (62)$$

showing that a mildly small ξ_s is also needed to have $m_\sigma \simeq 3H/2$. In this model inflationary trajectories again have Planckian curvature $|\kappa| \sim 1/\bar{M}_{\text{Pl}}$, giving a turn rate again suppressed by the slow-roll parameter as in eq. (10), and the typical small cosmo-collider signal of this class of models, $f_{\text{NL}} \sim 0.01$. This is confirmed by the numerical result in the left panel of fig. 5.⁷