Title: Shapes of non-Gaussianity in warm inflation

Speakers: Mehrdad Mirbabayi

Series: Particle Physics

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Abstract: Sphaleron heating has been recently proposed as a mechanism to realize warm inflation when inflaton is an axion coupled to pure Yang-Mills. As a result of heating, there is a friction coefficient ?\propto T^3 in the equation of motion for the inflaton, and a thermal contribution to cosmological fluctuations. Without the knowledge of the inflaton potential, non-Gaussianity is the most promising way of searching for the signatures of this model. Building on an earlier work by Bastero-Gil, Berera, Moss and Ramos, we compute the scalar three-point correlation function and point out some distinct features in the squeezed and folded limits. As a detection strategy, we show that the combination of the equilateral template and one new template has a large overlap with the shape of non-Gaussianity over the range 0.01 <= ?/? <= 1000 and in this range 0.7<|f_NL|<50.

Zoom link: https://pitp.zoom.us/j/95921707772?pwd=NUNhU1QrRm5HaDJNMEYyaTJXQmZnQT09

Shapes of non-Gaussianity in warm inflation

Mehrdad Mirbabayi

ICTP

based on 2205.13227 with Andrei Gruzinov

PI, Nov 29, 2022

Review of the standard paradigm

- Inflation is a theory of initial condition.
- It erases the pre-existing structures by stretching them to unobservably long λ.
- It makes the inflationary universe classically cold and empty.
- It stretches vacuum fluctuations in the UV to be observed cosmological perturbations.

Warm inflation Fang 80', Moss 85', Yokoyama, Maede 86', Berera,Fang 95',. . .

- Inflation is a theory of initial condition.
- It erases the pre-existing structures by stretching them to unobservably long λ.
- ~~It makes the inflationary universe classically cold and empty.~~
  Repeated particle production keeps the universe warm and populated.
- ~~It Stretches vacuum fluctuations in the UV into the observed cosmological perturbations.~~
  The origin of what we see are the subhorizon thermal fluctuations.

Energy budget

Warm inflation needs a continuous energy transfer

$$\phi \to X \quad \text{(another sector)}$$

such that

$$\frac{\rho_X}{\rho_{\rm tot}} \sim \epsilon \qquad \text{small but approximately fixed.}$$

Assuming thermalization, the temperature can be much greater than H:

$$T \gg H \qquad \text{is compatible with} \qquad T^4 \ll M_{\rm pl}^2 H^2.$$

Background evolution

Particle production back-reacts on the inflaton evolution

$$\ddot{\phi} + (3H + \gamma)\dot{\phi} + V'(\phi) = 0,$$

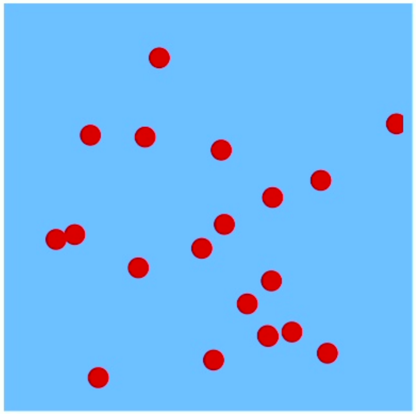
$$\dot{\rho}_X + 4H\rho_X = \gamma\dot{\phi}^2.$$

This can have a warm slow-roll attractor.

Therefore, not only conceptually different but also the predictions of warm inflation for a given $V(\phi)$ are dramatically different from cold inflation. E.g. the number of e-folds.

Origin of perturbations

The transfer of energy $\phi \to X$ is not uniform. It is a random microscopic process.



- This induces large (effectively classical) fluctuations already inside the horizon
$$\delta\phi \gg \delta\phi_{\rm vac}.$$
- By the central theorem the observed spectrum is nearly Gaussian if $T \gg H$.
- But the non-Gaussian features can be distinct from other scenarios. (We are sensitive to $\mathcal{O}(10^{-4})$ deviation from Gaussianity.)

Challenge for warm inflation

Yokoyama, Linde '98

As an example, consider a coupling of the form

$$\Delta\mathcal{L} = \frac{\phi}{f}\mathcal{O}, \quad \mathcal{O} \in X, \qquad T \ll f.$$

This typically generates a thermal mass

$$\delta m_{\rm th}^2 \sim \frac{T^4}{f^2}.$$

The typical friction term is

$$\gamma \sim \frac{T^3}{f^2} \sim \frac{T}{f}\delta m_{\rm th} \ll \delta m_{\rm th}.$$

Minimal warm inflation

Berghaus,Graham,Kaplan '19

Suppose inflaton is an axion coupled to a Yang-Mills plasma at $T > T_c$,

$$\Delta\mathcal{L} = \frac{\phi}{f}\alpha \mathrm{Tr}(G_{\mu\nu}\tilde{G}^{\mu\nu}).$$

- The corrections to the potential come from instantons,

$$\delta m^2 \sim \frac{T^4}{f^2}e^{-\#/\alpha}.$$

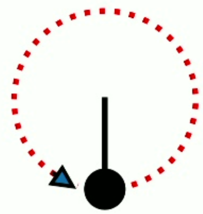
- The dissipation term is much important. *Sphaleron heating* leads to

$$\gamma \sim \frac{\alpha^5 T^3}{f^2}.$$

Grigoriev,Rubakov,Shaposhnikov '89, Arnold,Son,Yaffe '96, Moore,Tassler '10

Sphaleron heating in YM

- In $4d$ YM, there exist real-time field configurations that start and end at the vacuum, but they are not deformable to the trivial configuration.



- At finite T they happen automatically. They are called Sphaleron transitions. Every time the following charge jumps by ± 1

$$Q(t) = \int_0^t \int_V d^3x \alpha \mathrm{Tr} G \tilde{G}.$$

- Therefore $Q(t)$ performs a random walk at long time-scales

$$\langle Q(t) \rangle = 0, \qquad \lim_{t\to\infty} \lim_{V\to\infty} \frac{\langle Q(t)^2 \rangle}{Vt} = \Gamma \approx \alpha^5 T^4.$$

Warm inflation

When $\dot{\phi} \neq 0$ (but $\alpha\dot{\phi}/f \ll T$ for linear response approx.), the jumps are biased (by FDT Laine,Vuorinen '17)

$$\left\langle \alpha \mathrm{Tr} G\tilde{G} \right\rangle = \frac{\Gamma}{2fT}\dot{\phi}.$$

This will fix the $\gamma \simeq \alpha^5 T^3/f^2$ in the background equations ($w_{YM} \approx 1/3$ at $T \gg T_c$)

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which together with $H^2 \approx 8\pi GV/3$ have an *attractor* slow-roll solution if the potential is sufficiently flat. (If $\gamma > H$, then the slow-roll conditions are relaxed.)

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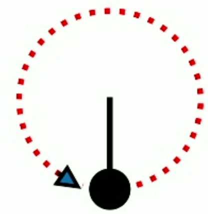

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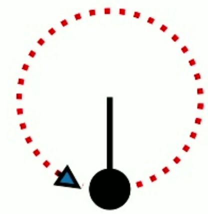

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Perturbations

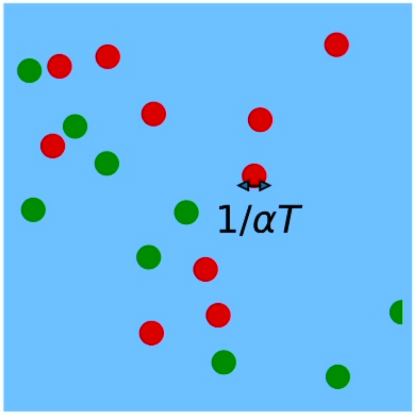
We probe inflation by measuring cosmological perturbations.

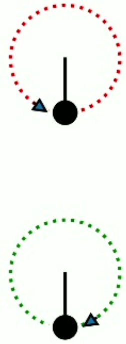
- At $\lambda \gg 1/T$ degrees of freedom of YM plasma are phonons of a radiation fluid
$$T^{YM}_{\mu\nu} = \frac{4}{3}\rho u_\mu u_\nu + \frac{1}{3}\rho g_{\mu\nu},$$
where we neglect $\mathcal{O}(\alpha)$ corrections to EoS and $\mathcal{O}(H/T)$ dissipative corrections.
- However, there is one dissipative term that is essential
$$-\nabla^2\phi + V'(\phi) = \frac{\alpha}{f}\mathrm{Tr}G\tilde{G} = \underbrace{-\gamma(\rho)u^\mu\partial_\mu\phi}_{\langle\rangle\text{on long-}\lambda\text{ bgr}} + \underbrace{\xi}_{\text{noise}}.$$
This couples ϕ to the fluid:
$$\nabla^\nu T^{YM}_{\mu\nu} = \partial_\mu\phi(\gamma u^\mu\partial_\mu\phi - \xi).$$

Bastero-Gil, Berera, Moss, Ramos '14

Noise correlators

- We need the statistics of ξ to find superhorizon correlators of $\zeta \simeq -\frac{H\delta\phi}{\dot{\phi}}$.
- The 2pf in the limit of $k, \omega \to 0$ is $\Gamma/f^2 = 2\gamma T$.
- At low ω, k only sphalerons contribute significantly to the noise correlators. The conventional belief is that sphalerons have a characteristic size $1/(\alpha T)$ and large separation when $\alpha \ll 1$.





Noise correlators

Then ξ can be approximated as the sum of two Poisson distributed quantities at long wavelengths. "Right-handed" sphalerons with rate Γ_+ and "left-handed" ones with rate Γ_- such that

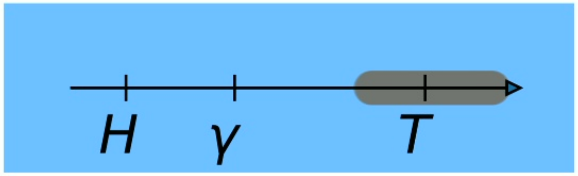
$$\Gamma_+ - \Gamma_- = \frac{\Gamma\dot{\phi}}{2fT}, \qquad \Gamma_+ + \Gamma_- = \Gamma.$$

The odd correlators are proportional to the parity breaking parameter:

$$\langle\xi(x_1)\cdots\xi(x_N)\rangle \approx \frac{\Gamma}{f^N}\left(\prod_{i=2}^{N}\delta^4(x_i - x_1)\right) \times \begin{cases} 1, & N \text{ even}, \\ \frac{u^\mu\partial_\mu\phi}{2fT}, & N \text{ odd}. \end{cases}$$

Predictivity of EFT

During inflation each k mode stretches from UV (unknown) to IR (known)



In our EFT, we have (using $\zeta \simeq -\frac{H\delta\phi}{\dot\phi}$)

$$\left\langle \zeta_{\vec{k}}\zeta_{-\vec{k}} \right\rangle' = \frac{H^2}{\dot\phi^2}\int_{-\infty}^{\infty} dtdt'\, G_{\phi_{\vec{k}}}(\infty, t) G_{\phi_{-\vec{k}}}(\infty, t') \left\langle \xi_{\vec{k}}(t)\xi_{-\vec{k}}(t') \right\rangle .$$

This is predictive if the time-integrals are dominated well after $k/a \sim T$.

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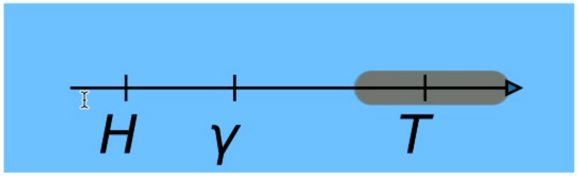

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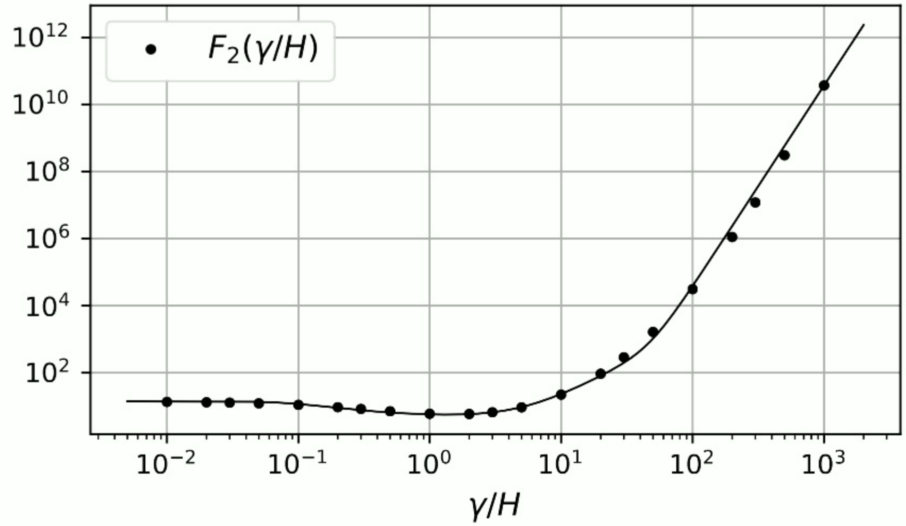
Power spectrum

Thermal fluctuations $\gg$ vacuum fluctuations

$$k^3 \left\langle \zeta_{\vec{k}} \zeta_{-\vec{k}} \right\rangle' = \frac{H^2}{\dot{\phi}^2} 2\gamma T \; F_2(\gamma/H)$$

$$F_2(\gamma/H) = k^3 \int_{-\infty}^{\infty} \frac{dt}{a(t)^3} G(t)^2$$



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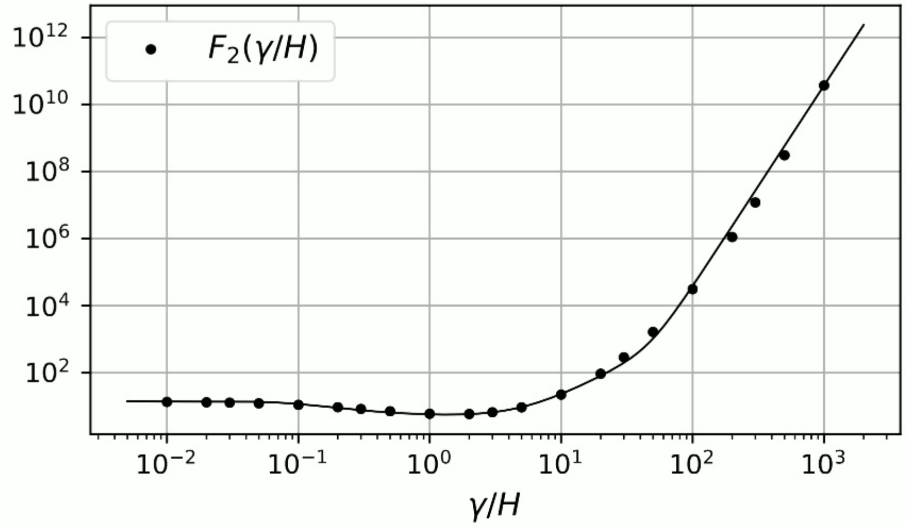

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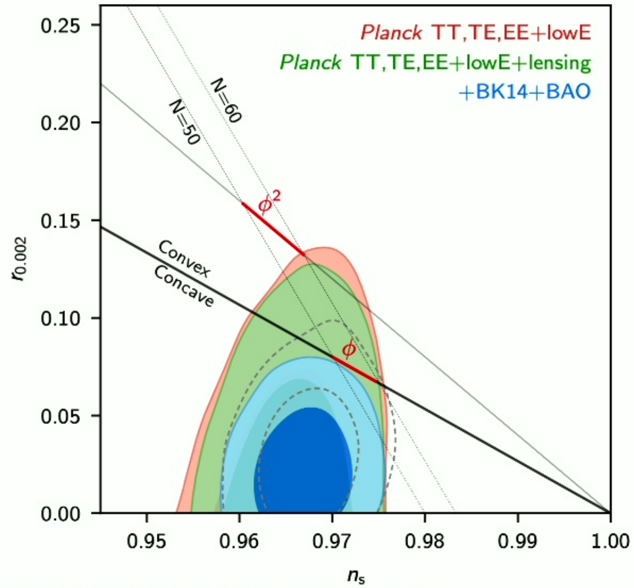
Bastero-Gil, Berera, Moss, Ramos '14

Warm ϕ^4 inflation (ϕ^2 can't be saved)

$$N_e = 55, \qquad \phi \approx 11.6 M_{\rm pl}, \qquad 1 - n_s \approx 0.0337, \qquad \gamma \approx 5.34 H.$$

For $SU(2)$ gauge group

$$\frac{T}{H} \approx 1200, \qquad r \approx 4.7 \times 10^{-7}.$$



Non-Gaussianity

Without the knowledge of $V(\phi)$, NG is the best way to detect/rule-out warm inflation.

- NG is usually more visible in the 3pf than higher $n$pfs. It's common to normalize it as

$$f_{NL}(k_1, k_2, k_3) = \frac{5\left\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\right\rangle'}{6\sum_{\rm perms}\left\langle \zeta_{\vec{k}_i}\zeta_{-\vec{k}_i}\right\rangle'\left\langle \zeta_{\vec{k}_i}\zeta_{-\vec{k}_i}\right\rangle'}.$$

- One source of NG is the Poisson stat. of the noise (B_{sn})

$$f_{NL}\zeta \propto \underbrace{\frac{1}{N^{1/2}}}_{\text{central limit th.}} \times \underbrace{\frac{\dot{\phi}}{fT}}_{\text{parity}} < \frac{H^2}{T^2},$$

where $N \sim T^4/H^4$ is the number of sphalerons contributing to a given perturbation.

Nonlinear evolution

Another source is the hydro nonlinearities

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Second order perturbations will cause 3-point NG

$$B_{211} = -\frac{H^3}{\dot{\phi}^3}\lim_{t\to\infty}\left\langle \phi^{(2)}_{\vec{k}_1}(t)\phi^{(1)}_{\vec{k}_2}(t)\phi^{(1)}_{\vec{k}_3}(t)\right\rangle + \text{permrs.}$$

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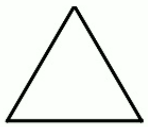
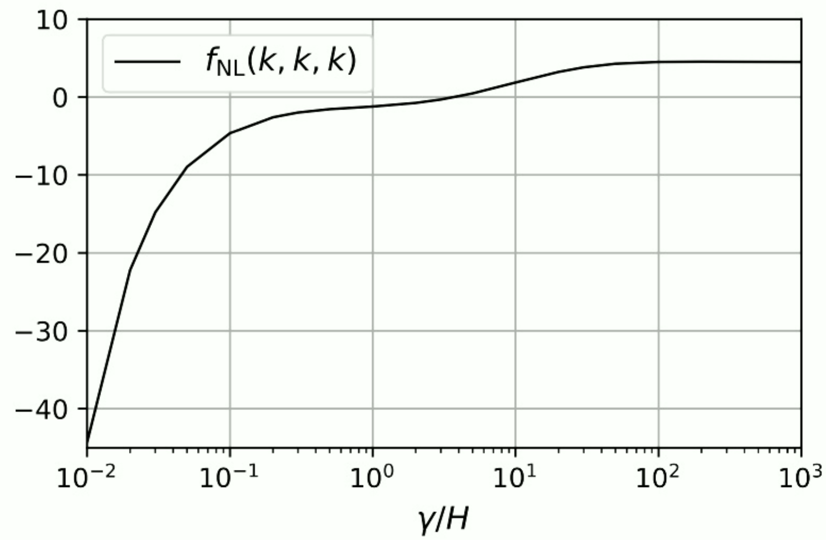
Equilateral configuration

NG depends only on the shape of the triangle formed by $\vec{k}_1, \vec{k}_2, \vec{k}_3$.

$$f_{211}(\gamma \ll H) \sim \frac{H}{\gamma}, \qquad f_{211}(\gamma \gg H) \sim 1.$$





Factorizable templates

- It is useful to have factorizable templates that have large correlation with the actual shapes.
- Define the basis

$$F_{ab} = A^2 k_1^{-a} k_2^{-b} k_3^{-6+a+b} + 5 \text{ perms.}$$

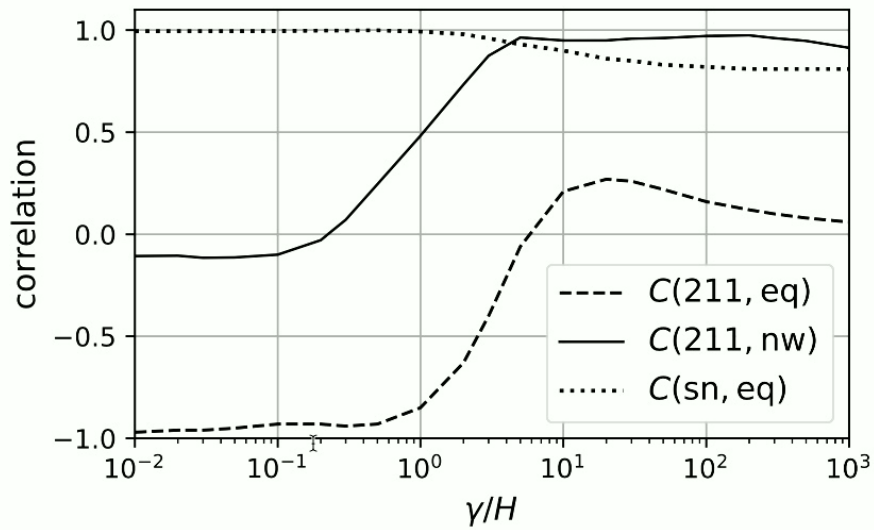
where A is the normalization of the power spectrum for the Newtonian potential. Then, the "equilateral template"

$$F^{\rm eq} = 6F_{32} - 3F_{33} - 2F_{22}.$$

works well for $\gamma < H$ and the "new-warm template" for $\gamma \geq H$:

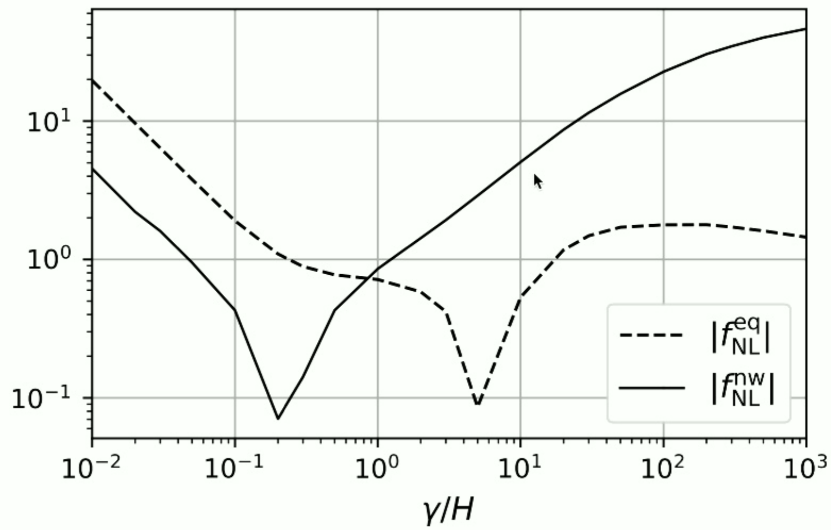
$$F^{\rm nw} = 2F_{43} + F_{42} - F_{44} - F_{33} - F_{41} + 0.08F^{\rm eq}.$$

Templates

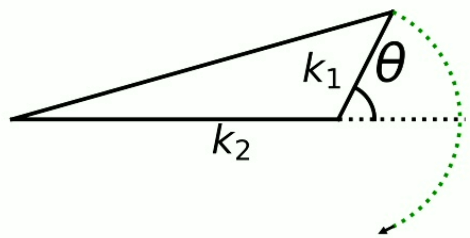


$$C(B_1, B_2) \equiv \frac{B_1 \cdot B_2}{\sqrt{(B_1 \cdot B_1)(B_2 \cdot B_2)}},$$

Warm inflation at the verge of discovery!



Squeezed limit



Since the background is an attractor

$$\lim_{k_1 \to 0} f_{211}(k_1, k_2, k_3) = 0.$$

But the limit is approached differently than single field inflation (where $f_{NL} \propto k_1^2/k_2^2$)

Squeezed limit

- In the $\gamma \ll H$ regime, because of a hydro mode that decays as $1/a$ at super-horizon scales

$$f_{211}(k_1 \ll k_2) \propto \frac{k_1}{k_2}$$

- In the $\gamma \gg H$ regime, perturbations are excited at $k/a \sim \sqrt{H\gamma}$ and then grow until horizon-crossing. As a result

$$f_{211} = f_0 + f_2(\hat{k}_1 \cdot \hat{k}_2)^2, \qquad 1 \ll \frac{k_2}{k_1} \ll \sqrt{\gamma/H},$$

with $f_0 \sim f_2 \sim 1$, slowly varying functions of k_1/k_2.

Squeezed limit

- In the $\gamma \ll H$ regime, because of a hydro mode that decays as $1/a$ at super-horizon scales

$$f_{211}(k_1 \ll k_2) \propto \frac{k_1}{k_2}$$

- In the $\gamma \gg H$ regime, perturbations are excited at $k/a \sim \sqrt{H\gamma}$ and then grow until horizon-crossing. As a result

$$f_{211} = f_0 + f_2(\hat{k}_1 \cdot \hat{k}_2)^2, \qquad 1 \ll \frac{k_2}{k_1} \ll \sqrt{\gamma/H},$$

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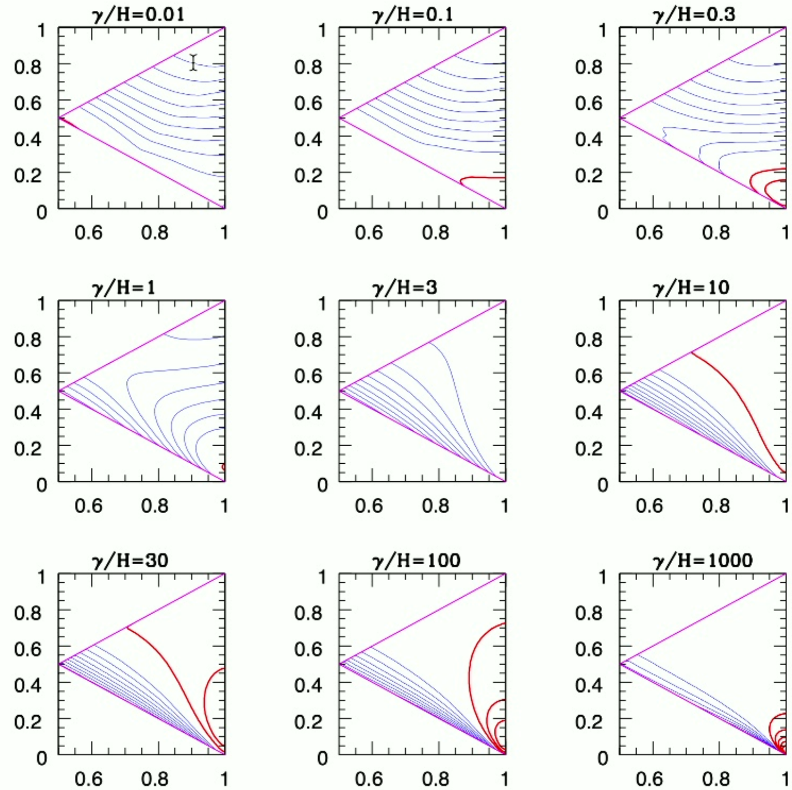
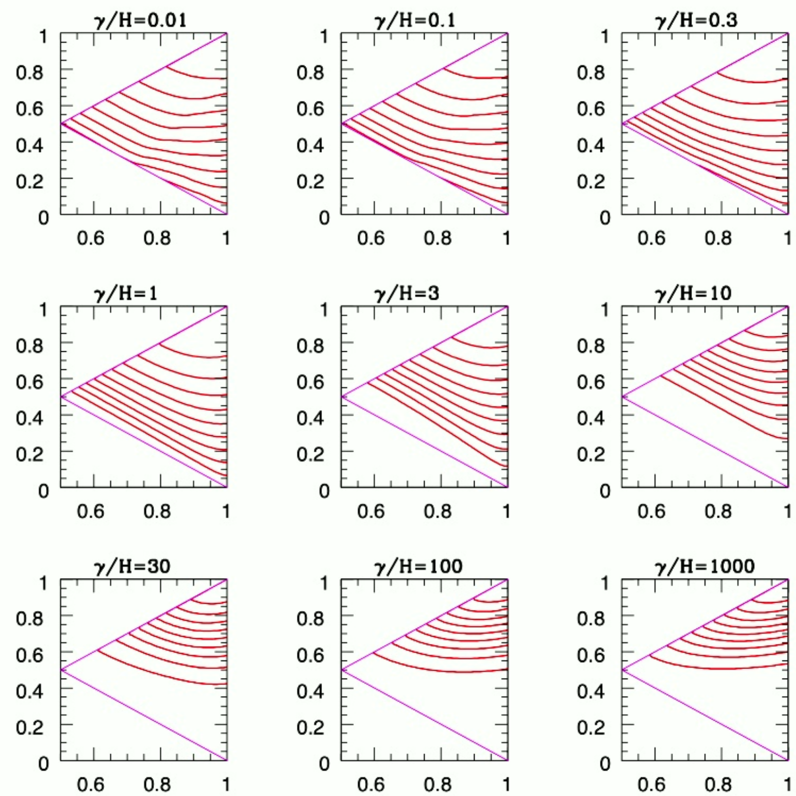
211



Mehrdad Mirbabayi (ICTP) Warm Inflation

Shot-noise



Conclusions and outlook

- Warm inflation can be realized using sphaleron heating.
- It always predicts $f_{NL} \sim 1$ or larger. Hence it is a promising target for NG searches.
- There are similarities, but also qualitative differences with other known scenarios with particle production.

Some open questions:

- Can thermalization also be realized successfully in those scenarios?
- How big is the basin of attraction of minimal warm inflation?
- Reheating into SM.

Thank You!