Axion Inflation: Naturally thermal

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Axions in inflation

- Appealing way of realizing inflation; mass is protected by the (discrete) shift symmetry. E.g.: Natural Inflation [Freese, Frieman and Olinto '90]

$$\mathcal{L}_\phi = (\partial_\mu \phi)^2 + \Lambda^4 (1 + \cos(\phi/f))$$

- Axions (ϕ) are expected to couple to gauge fields through an axial coupling

$$\frac{\phi}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}, \qquad \tilde{F}^{\mu\nu} \equiv \frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{-g}} F_{\alpha\beta}$$

where f is the axion decay constant. Moreover, the universe has to reheat. This coupling is an efficient and safe way to do it.

- When ϕ develops a VEV, parity is broken and the eom for the massless gauge field ($A_\pm$) during inflation becomes [Tkachev 86', Anber&Sorbo 06']

$$A''_\pm(\tau, k) + \left(k^2 \pm \frac{2k\xi}{\tau}\right) A_\pm(\tau, k) = 0, \qquad \xi = \frac{\dot{\phi}}{2fH}$$

- Instability band: $(8\xi)^{-1}H < k/a < 2\xi H$. If $\xi \simeq$ constant: [Anber and Sorbo 06']

$$A_k(\tau) \simeq \frac{1}{\sqrt{2k}} e^{-ik\tau}, \qquad \text{subhorizon}$$
$$A_k(\tau) \simeq \frac{1}{2\sqrt{\pi k \xi}} e^{\pi\xi}, \qquad \text{superhorizon}$$

- Phenomenology:
    - Large loop corrections to ζ induced through the coupling $2\xi\zeta F\tilde{F}$

$$\text{2-point function}: \quad P^{\zeta}_{\text{1-loop}} = \mathcal{O}(10^{-4}) P^2_{\text{obs}} e^{4\pi\xi}$$
$$\text{non-Gaussianity}: \quad f^{\text{equi}}_{NL}|_{\text{1-loop}} = \mathcal{O}(10^{-7}) P_{\text{obs}} e^{6\pi\xi}$$

    - Large tensor modes, flatenning of the potential by backreaction, preheating, ...
    - Non-Gaussianity constraints $\xi \lesssim 2.5$ ($\xi < 2.2$) on CMB scales which imposes a lower bound on f and excludes some of the interesting phenomenology.

[Anber&Sorbo 09', Sorbo 11', Barnaby&Peloso 11', Linde et al. 13', Bartolo et al. 14', Mukohyama et al. 14', **RZF**&Sloth 14', Adshead et al. 15', Planck 15', **RZF** et. al 15', ...]

Particle production and thermalization [RZF&Notari 1706.00373]

- But what happens when $\xi \gg 1$?
- Instability band covers subhorizon modes where particle interpretation is meaningfull.

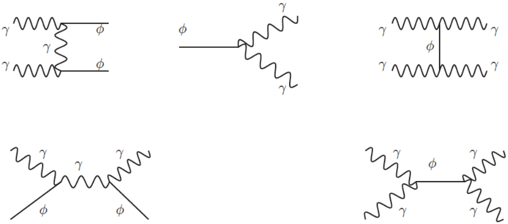
Instability $\Rightarrow$ particle production of modes

- Gauge field effective particle number (N_γ) per mode k:

$$\frac{1}{2} + N_\gamma(k) = \frac{\rho_\gamma(k)}{k} = \sum_{\text{pol}} \frac{A_k'^2 + k^2 A_k^2}{2k} \quad \Rightarrow \quad \begin{cases} N_\gamma(k) \simeq 0, & k/a \gg H \\ N_\gamma(k) \simeq \frac{e^{2\pi\xi}}{8\pi\xi}, & k/a \ll H \end{cases}$$

What happens when there are many particles around...?

If gauge field is Abelian (e.g. photons) interactions are



For example, the scatering rate of $\gamma\gamma \to \gamma\gamma$

$$S_{\gamma\gamma\to\gamma\gamma} = \frac{1}{E_1}\int \prod_{i=2}^{4}\left(\frac{d^3 p_i}{(2\pi)^3 (2E_i)}\right)|M_n|^2 \times$$
$$\times B_{\gamma\gamma\to\gamma\gamma}(k,p_2,p_3,p_4)(2\pi)^4 \delta^{(4)}\left(k^\mu + p_2^\mu - p_3^\mu - p_4^\mu\right)$$

where $B_{\gamma\gamma\to\gamma\gamma}(p_1,p_2,p_3,p_4)$ contains the phase space factors given by

$$B_{\gamma\gamma\to\gamma\gamma}(p_1,p_2,p_3,p_4) = N_\gamma(p_1)N_\gamma(p_2)\left[1+N_\gamma(p_3)\right]\left[1+N_\gamma(p_4)\right] - (p_1 \leftrightarrow p_3, p_2 \leftrightarrow p_4).$$

which is $\propto N_\gamma^3$.

- All the scatterings are enhanced by powers of N_γ.
  Therefore, when N_γ reaches a given threshold

$$t_{\text{scatterings, decays}} \ll H^{-1} \quad \Rightarrow \quad \text{thermalization}$$

- To estimate the conditions for thermalization we derive, from the eom, Boltzmann-like eqs. for $N_{\gamma_+}(k)$, $N_{\gamma_-}(k)$ and $N_\phi(k)$:

$$\begin{aligned} N'_{\gamma_+}(k,\tau) &= -\frac{4k\xi}{\tau}\frac{\text{Re}\left[g(k,\tau)\right]}{|g(k,\tau)|^2+k^2}\left(N_{\gamma_+}(k,\tau)+1/2\right) \\ N'_{\gamma_-}(k,\tau) &\simeq N'_\phi(k,\tau) \simeq 0 \end{aligned}$$

where $g(k,\tau) = A'(k,\tau)/A(k,\tau)$. Then, add the scatterings and decays

$$N'_{\gamma_+}(k) = -\frac{4k\xi}{\tau}\frac{\text{Re}[g_A(k,\tau)]}{|g_A(k,\tau)|^2+k^2}\left(N_{\gamma_+}(k)+1/2\right) + S^{++} + S^{+\phi} + D^{+\phi} + S^{+-} \quad ,$$

$$N'_{\gamma_-}(k) = -S^{+-}\,, \qquad N'_\phi(k) = -S^{+\phi} - D^{+\phi} \quad ,$$

- Numerically we verify that and verify that the distribution of particles approaches a Bose-Einstein distribution when

$$\xi \gtrsim 0.44 \log\left(\frac{f}{H}\right) + 3.4 \quad \underset{\text{Observational Constraint } (P_\zeta^{\text{obs}})}{\Longrightarrow} \quad \xi \gtrsim 5.8$$

In the backreacting and non-perturbative regime $\Rightarrow$ unclear.

- But if gauge fields belong to the SM thermalization is much more efficient
    - Many ($\gamma\psi$, gg), fixed and unsuppressed interactions (more predictive). More realistic, inflaton has to couple to SM.
    - For example, $\gamma\psi$ scatterings or gluon self-interactions thermalization requires

$$\begin{cases} \left(\frac{\pi\alpha_{EM}}{2}\right)^2 \left(\frac{H}{k_*}\right)^2 H N^2_{\gamma\gamma\to e^-e^+} \gg N_{\gamma\gamma\to e^-e^+} H \quad \Rightarrow \quad \xi \gtrsim 2.9 \\ \left(\frac{9\pi\alpha_S}{32}\right)^2 \left(\frac{H}{k_*}\right)^2 H N^3_{gg\to gg} \gg N_{gg\to gg} H \quad \Rightarrow \quad \xi \gtrsim 2.9 \end{cases}$$

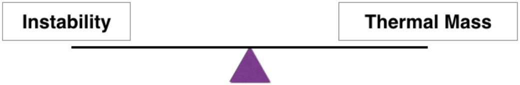
Under control !

What happens next?

- After thermalization gauge field develops a thermal mass $m_T = \bar{g}\,T$

$$A''_\pm + \omega_T^2(k) A_\pm = 0, \qquad \omega_T^2(k) = \left(k^2 \pm \frac{2k\xi}{\tau} + \frac{m_T^2}{H^2\tau^2}\right).$$

- If $m_T > \xi H$ the instability disappears and thermal bath redshifts. However, if $T \lesssim H$ the thermal mass disappears and the instability restarts



- Therefore, the system should reach an equilibrium (or oscillate around it) which balances the two terms:

$$\omega_T^2(k) \gtrsim 0 \qquad \Rightarrow \qquad T_{eq} \simeq \frac{\xi H}{\bar{g}}$$

The equilibrium temperature is linear in ξ and thus all predictions are changed!

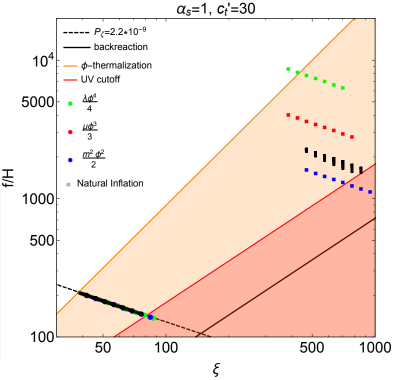
Can we also thermalize the inflaton?

- In order to thermalize ϕ in a controllable regime, we need to consider a more efficient interaction $c_t \frac{\partial_\mu \phi}{f} \bar{t}\gamma^\mu \gamma^5 t$.
  (For the QCD axion this interaction can leave to observable N_{eff} [RZF&Notari 1801.06090])

If ϕ thermalizes the spectrum of perturbations is

[Morikawa&Sasaki 84', Berera 95', ...]

$$P_\zeta = 2P_\zeta^{\text{vac}} \left[\frac{1}{2} + N_{\text{Bose-Einstein}}\right]\Bigg|_{\text{h.c}} \simeq P_\zeta^{\text{vac}}\left[1 + \frac{2T}{H}\right]$$



Predictions specific to the model ($T_{eq} = \xi H/\bar{g}$):

$$\begin{aligned} n_s - 1 &= -6\epsilon_H + 2\eta + \frac{\dot{\xi}}{H\xi} = -4\epsilon_H + \eta \\ r &= 16\epsilon\frac{H}{2T} = 8\epsilon\frac{\bar{g}}{\xi} \end{aligned}$$

Predictions for several models in the ThAI regime [RZF&Notari 17']

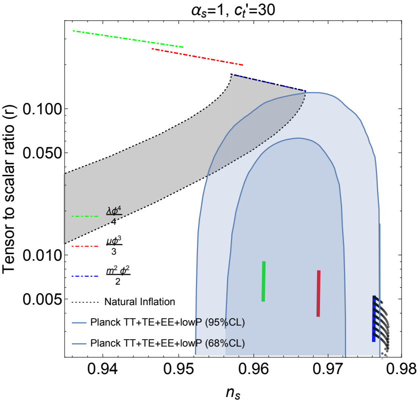
Important point: no thermal mass corrections to the potential

Because all the interactions with the inflaton are shift symmetric

- Lower tensor to scalar ratio, r is suppressed by $H/(2T)$ and spectral tilt slightly bluer
- Monomial potentials become more compatible with data and still with r possibly measured by future surveys.
- Reheating is instantaneous in the presence of these couplings. Therefore, for a given $V(\phi)$, number of e-folds is fixed.
- Non-Gaussianity estimated to be

$$f_{NL}^{\text{thermal}} \approx \mathcal{O}\left(\xi^4 P_\zeta^{\text{vac}} \left(\frac{T}{H}\right)^5\right)$$

$$\Rightarrow \quad \xi < \mathcal{O}(20-100),$$



Conclusions & Future Work

- Controlled and natural setup where a thermal bath can be sustained during inflation by the instability in the gauge fields.
- Couplings with ϕ are shift symmetric so no thermal mass is generated. Coupling to quarks is needed to have thermalization under control.
- Interesting predictions: thermal spectrum, lower tensor to scalar ratio, bluer spectral tilt, reheating history fixed, ...

Can inflation be ThAI?

Future work:

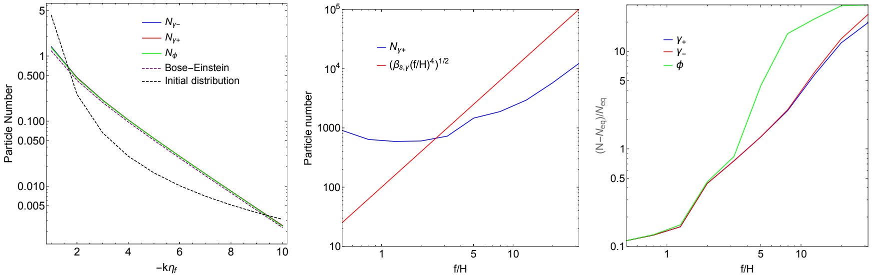
- Better characterization of the equilibrium regime.
- Improve non-Gaussianity calculations to derive more precise constraints on ξ.
- Is the backreacting regime more controllable in the thermal case?

Extra slides

Numerical results

- Box with $\mathcal{O}(10)$ modes of comoving momentum: $k \in [1, \mathcal{O}(10)]H$.
  Duration of simulation: $\simeq 1$ e-fold, $\{\eta_0 = -2, \eta_f = -1\}$
- Checking thermalization by looking at the average difference to a BE distribution

$$\frac{\Delta N}{N} \equiv \frac{1}{N_{\text{tot}}} \sum_k \frac{N^{\text{norm}}(k) - N^{\text{eq}}(k,T)}{N^{\text{eq}}(k,T)} \,,$$



Left: Change in the particle numbers after thermalization for $f = 0.1H$, $\xi = 2$. Center: Final particle number vs f/H for $\xi = 3.9$ Right: Average difference to Bose-Einstein distribution vs f/H for $\xi = 3.9$.