Axion Inflation with Dissipation and Thermalization

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[1] In collaboration with Ricardo Z.Ferreira, and Konrad Tywoniuk

Inflation

- Inflation is the best candidate for initial conditions of our Universe
- Can explain:
  - Observed small spatial curvature Ω_k (“flatness problem").
  - Why Universe causally connected on large scales (“horizon problem").
  - In addition: provides the seeds for observed cosmological density fluctuations.

Inflation

- In FLRW metric, expansion described by $a(t)$

$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2$$

- $a(t) \simeq e^{Ht}$
- Need $N = Ht \gtrsim 60$
- Need fluid with $p \sim -\rho$ dominating energy density

Standard slow-roll Inflation

- Simple approach: a new scalar field

$$\rho = V(\phi) + \frac{\dot{\phi}^2}{2} \qquad p = -V(\phi) + \frac{\dot{\phi}^2}{2} \tag{1}$$

$(\dot{\phi}^2/2 \ll V)$

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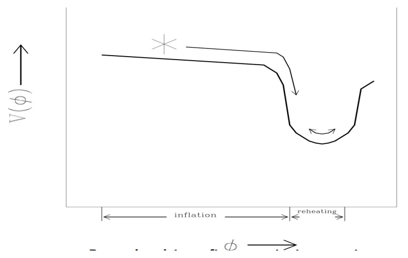
- $\Rightarrow$ Slowly rolls for $\left(\frac{a_I}{a_F}\right) = e^N \gtrsim e^{60}$

Slow-roll



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- Quantum fluctuations ⇒ Density fluctuations

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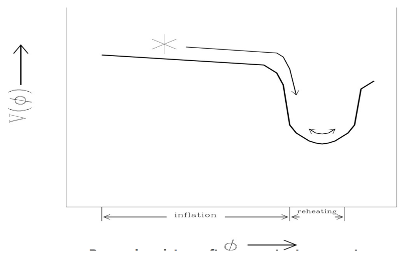

- Slow-roll: “Vacuum" state
- Quantum fluctuations ⇒ Density fluctuations
- Then fast roll and create particles, thermalization ("Reheating")

Slow-roll Inflation: simple but...

- Which V?
- Why unusually flat V?
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- Not many observables, beyond cosmological density perturbations (A, n_s, r, perhaps f_{NL}...)

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  - Temperature already during inflation
  - Strong Dissipation during inflation (friction?)

Inflation with Axial coupling

- ϕ coupled to U(1) gauge fields, “axion-like":

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + V(\phi) + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\phi}{4f_\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$

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- Derivative coupling $\Longrightarrow$ No corrections to $V(\phi)$

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- In a time dependent ϕ and in FLRW (conformal time $ad\tau = dt$, $\pm$ positive (negative) helicity) :

$$A''_{\pm} + \left(k^2 \mp \frac{k\phi'}{f}\right) A_{\pm} = 0\,,$$

(*e.g.* I. Tkachev, Pisma Astron.Zh. 12 (1986))

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- One helicity is unstable: gauge fields become quickly large

Constant $\dot{\phi}$ and de Sitter

- (Sorbo & Anber '09) assumed: $\dot{\phi} = const$ in de Sitter
  $a(t) = -\frac{1}{H\tau}$

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- Solution at $\tau \to 0^-$ (future):

$$A_+ \approx \frac{1}{\sqrt{2k}} \left(\frac{k|\tau|}{2\xi}\right)^{1/4} e^{\pi\xi - 2\sqrt{2\xi k|\tau|}}$$

Consequences

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$$\frac{\langle F\tilde{F}\rangle}{4} = \frac{1}{2a^4}\int \frac{d^3k}{(2\pi)^3}\, k\, \frac{d\left[|A_+|^2 - |A_-|^2\right]}{d\tau} \approx \left(\frac{H}{\xi}\right)^4 e^{2\pi\xi}$$

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    - Contribution to 2-point function $\langle\delta\phi\delta\phi\rangle_{loop}$
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    - Contribution to tensors (gravitational waves)
  - At large ξ: Backreaction on ϕ dynamics

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Outline

Thermalized Axion Inflation

- Include scattering of gauge bosons [3]:
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  - $\implies$ Thermalization during Inflation, with $T > H$

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    $k/a \sim T$, more inside the horizon
  - Expect: suppression of fluctuations in $\langle\delta\phi\delta\phi\rangle_{loop}$, $\langle\delta\phi\delta\phi\delta\phi\rangle_{loop}$ at Hubble scale (IR)

Particle production and thermalization

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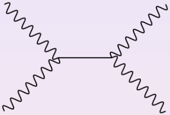
$$\begin{cases} N_\gamma(k) \simeq \quad 0, & k/a \gg H \\ N_\gamma(k) \simeq \frac{e^{2\pi\xi}}{8\pi\xi}, & k/a \ll H \end{cases}$$

Scatterings

Scatterings are enhanced by powers of N_γ



$$\frac{dN_\gamma(k)}{d\tau} = S(k)$$

$$S = \frac{1}{\omega(k)} \int \prod_{i=2}^{4} \left(\frac{d^3 p_i}{(2\pi)^3 (2E_i)} \right) |M_n|^2 (2\pi)^4 \delta^{(4)} \left(k^\mu + p_2^\mu - p_3^\mu - p_4^\mu \right) \cdot$$

$$\cdot N_\gamma(k) N_\gamma(p_2) \left[1 + N_\gamma(p_3)\right] \left[1 + N_\gamma(p_4)\right]$$

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$$N_+ \gg 10^2 \sqrt{\frac{Hf^4}{\omega^5}} \quad \xRightarrow[\omega \approx H]{} \quad \xi \gtrsim 0.45 \ln\left(\frac{f}{H}\right) + 2.7\,,$$

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- Expectation: thermal bath of photons with temperature

$$T \approx \rho_{\gamma,\text{initial}}^{1/4} \approx He^{\pi\xi/2}$$

Boltzmann-like equations

- We rewrite the eom as a Boltzmann-like eq. $(g \equiv A'_+(k,\tau)/A_+(k,\tau))$:

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- Full system $(\gamma_+, \gamma_-, \phi)$

$$\begin{cases} N'_+ = -\frac{4k\xi}{\tau}\frac{\mathrm{Re}[g]}{|g|^2+k^2}\left(N_+ + \frac{1}{2}\right) + S^{++} + S^{+\phi} + D^{+\phi} + S^{+-}\,, \\ N'_\phi = -S^{+\phi} - D^{+\phi}\,, \\ N'_- = -S^{+-}\,, \end{cases}$$

Numerical results

- Discretize: $\mathcal{O}(10)$ modes of comoving momentum: $k \in [1, \mathcal{O}(10)]H$.
- Duration of simulation: $\mathcal{O}(1)$ e-fold, $\{\tau_0 = -2, \tau_f = -1\}$

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- Duration of simulation: $\mathcal{O}(1)$ e-fold, $\{\tau_0 = -2, \tau_f = -1\}$
- Distribution of particles approaches Bose-Einstein distribution at ξ, f in agreement with estimations.

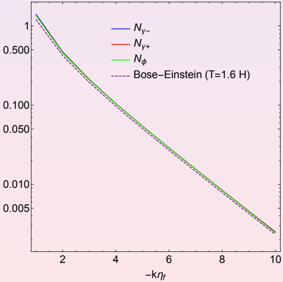
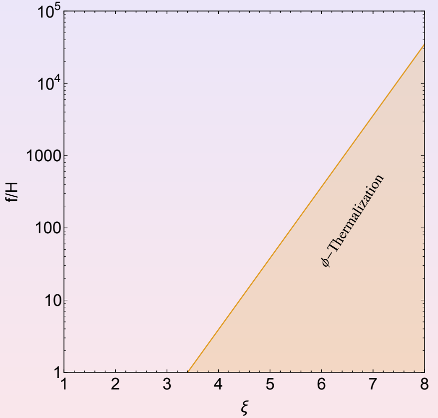


Figure: $\xi = 2$, $f/H = 0.1$

Thermalization



$$\Gamma_s \gg H \qquad \Longrightarrow \qquad \xi \gtrsim 0.45 \ln\left(\frac{f}{H}\right) + 2.7\,,$$

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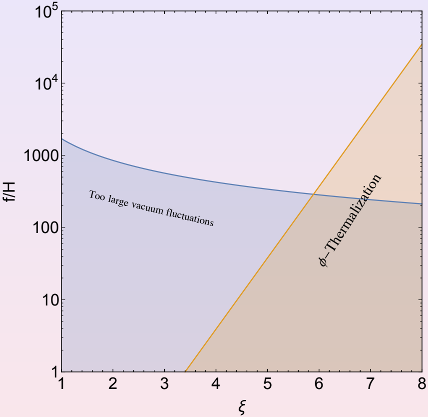

Vacuum fluctuations:

$$P_\zeta^{\rm vac} = \frac{H_*^4}{4\pi^2\dot{\phi}_*^2} = \frac{H^2}{16\pi^2 f^2 \xi^2} \le 2.2 \times 10^{-9} \qquad \Longrightarrow \qquad \frac{f}{H} \gtrsim \frac{2\times 10^3}{\xi}\,.$$

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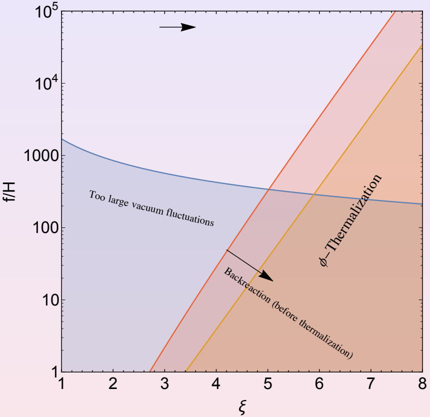

Backreaction on ϕ (before reaching thermalization):

$$\frac{\langle F\tilde{F}\rangle}{f} \gtrsim V'(\phi) \simeq 3H\dot{\phi} \qquad \Longrightarrow \qquad f/H \lesssim 4\times 10^{-3} e^{\pi\xi}/\xi^{5/2}.$$

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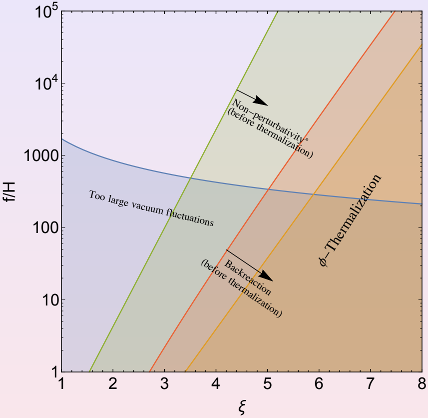

* Requiring perturbativity on loop expansion for cosmological correlators, in absence of thermalization (Ferreira *et al.*,JCAP 1604 (2016)):

$$\frac{H^2}{f^2}\,\frac{e^{2\pi\xi}}{16\pi^2 I} < 1,$$

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  Requirement for thermalization ($\Gamma_s \gg H$) :

$$N_\gamma H \ll \frac{\alpha_{EM}^2}{\omega^2} \cdot H^3 N_\gamma^2 \qquad \Longrightarrow \qquad \xi \gtrsim 2.9$$

SM Thermalization

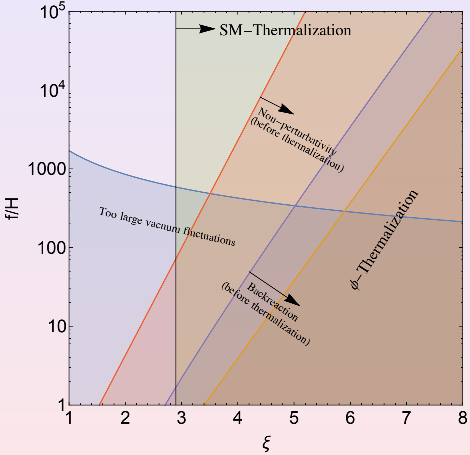

Figure: Summing over all $U_Y(1)$ charged particles in SM.

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- When $m_T \geq \xi H$ completely shields the instability band ($\omega^2 > 0$)

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- New regime: linear in ξ not exponential: $T_{eq} \ll e^{\frac{\pi\xi}{2}} H$!

At equilibrium temperature

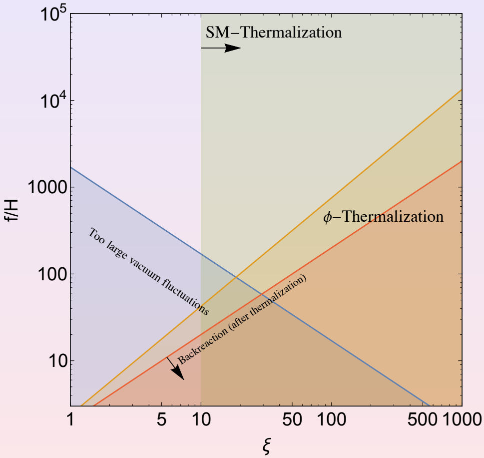

Figure: Using $T_{eq} \approx \frac{\xi H}{g}$, with $g = 0.5$.

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$$\begin{cases} P_\zeta^{\text{therm}} = \frac{\xi}{\bar{g}} \frac{H_*^4}{2\pi^2 \dot{\phi}_*^2} = \frac{H^2}{8\pi^2 f^2 \bar{g} \xi}, \\ n_s - 1 \equiv = -6\epsilon_H + 2\eta + \frac{\dot{\xi}}{H\xi} = -4\epsilon_H + \eta. \end{cases}$$

New regime at T_{eq}

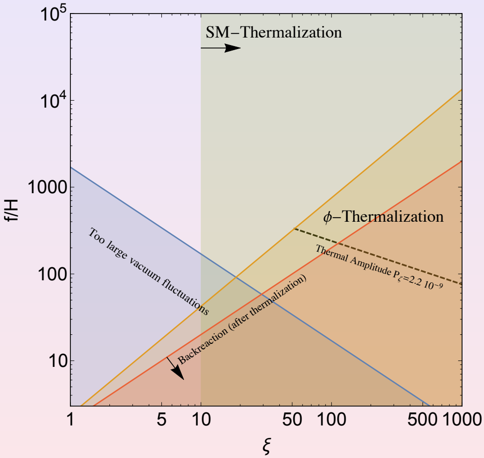

Figure: $P_\zeta = P_\zeta^{vac} \cdot \frac{2T_*}{H_*} = P_\zeta^{vac} \cdot \frac{2\xi}{g}$, $(g = 0.5.)$

Phenomenology in the thermal regime

- Loop effects on ζ drastically modified!
- Thermalization shifts gauge fields from horizon size to UV. At horizon crossing N_γ is reduced.
- We expect (work in progress) much smaller $\langle\zeta\zeta\zeta\rangle_{\rm loop}$
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  - Instead of non-thermal case: $f_{NL} \propto e^{4\pi\xi}$!
  - Constraints on ξ become weaker and (maybe) allow for the backreacting regime? (Work in progress)

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$$r \equiv \frac{P_T}{P_\zeta^{\text{therm}}} = 16\,\epsilon \frac{H_*}{2T_*}\,.$$

- Suppressed by $\frac{H_*}{2T_*} = \frac{g}{2\xi}$
- At least $\mathcal{O}(10^{-2})$ suppression.
- $r \lesssim 10^{-4}$

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- *Work in progress*:
  - Inclusion of Thermal masses (expect T_{eq})
  - Non-gaussianity (expect reduction)
  - Backreaction (Large friction without flat potential: maybe phenomenologically possible?)