VILA DO CONDE, PORTUGAL, 29-31 MARCH, 2016

11th Iberian Cosmology Meeting

IBERICOS 2016

SOC **ANA ACHÚCARRO** (LEIDEN/BILBAO), **FERNANDO ATRIO-BARANDELA** (SALAMANCA), **MAR BASTERO-GIL** (GRANADA), **JUAN GARCIA--BELLIDO** (MADRID), **RUTH LAZKOZ** (BILBAO), **CARLOS MARTINS** (PORTO), **JOSÉ PEDRO MIMOSO** (LISBON), **DAVID MOTA** (OSLO)

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SERIES OF MEETINGS WHICH AIM TO ENCOURAGE INTERACTIONS AND COLLABORATIONS BETWEEN RESEARCHERS WORKING IN COSMOLOGY AND RELATED AREAS IN PORTUGAL AND SPAIN.

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Little Warm Inflation:

particle physics scenario

João G. Rosa

Universidade de Aveiro

with Mar Bastero-Gil, Arjun Berera and Rudnei O. Ramos

(to appear soon)

11th Iberian Cosmology Meeting, Vila do Conde, Portugal, 29 March 2016

Inflation: a window into high energies

CMB anisotropies require inflation to occur at high energies:

$$V^{1/4} \sim 10^{16} \left(\frac{r}{0.1}\right)^{1/4} \text{ GeV}$$

Can the inflaton be embedded into a fundamental theory?

We need to know how it interacts with other fields!

Warm inflation

[Berera 1995]

Interactions with cosmic plasma induce dissipation:

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

This damps inflaton's motion and sources radiation:

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^2$$

In slow-roll regime:

$$\dot{\phi} \simeq -\frac{V'(\phi)}{3H(1+Q)} \qquad \rho_R \simeq \frac{3}{4}Q\dot{\phi}^2$$

for $Q = \Upsilon/3H$ and $\epsilon_\phi, |\eta_\phi| \ll 1 + Q$.

Warm inflation

Inflation can occur in a warm rather than supercooled regime:

$$\frac{T}{H} \sim Q^{1/4} \left(\frac{\dot{\phi}}{H^2} \right)^{1/2} \gtrsim 1 \quad \Rightarrow \quad H^2 \ll \dot{\phi} \ll \sqrt{V(\phi)} \sim H M_P$$

Main features:

- Extra friction prolongs inflation
- Radiation sub-dominant but can smoothly take over

$$\frac{\rho_R}{V(\phi)} \simeq \frac{1}{2} \frac{\epsilon_\phi}{1+Q} \frac{Q}{1+Q}$$

- Dissipation induces thermal inflaton fluctuations

Warm inflation

Challenges: [Berera, Gleiser & Ramos; Yokoyama & Linde (1998)]

- Coupling the inflaton to light particles is hard:

$$\mathcal{L} = -g\phi\bar{\psi}\psi \qquad \Rightarrow \qquad m_\psi = g\phi \gtrsim T$$

- Light particles induce large thermal mass corrections:

$$\Delta m_\phi^2 \sim g^2 T^2 \gg H^2$$

- Small couplings yield little dissipation…

Can couple indirectly through heavy mediators, but one needs a large number of mediators to sustain the thermal bath!

[Berera & Ramos (2003); Moss & Xiong (2006);Bastero-Gil, Berera, Ramos + JGR (2011-15)]

Little Warm inflation

Consider a U(1) gauge theory spontaneously broken by two complex Higgs fields:

$$\langle \phi_1 \rangle = \langle \phi_2 \rangle \equiv M/\sqrt{2}$$

One Nambu-Goldstone boson is "eaten" by the gauge field, while the other becomes the physical singlet scalar inflaton:

$$\phi_1 = \frac{M}{\sqrt{2}} e^{i\phi/M} \ , \qquad \phi_2 = \frac{M}{\sqrt{2}} e^{-i\phi/M}$$

"Little Higgs"

[Arkani-Hamed, Cohen & Georgi (2001)]

Little Warm inflation

Couple the inflaton to charged and singlet Weyl fermions:

$$
\begin{aligned}
-\mathcal{L}_{\phi\psi} &= \frac{g}{\sqrt{2}}(\phi_1+\phi_2)\bar{\psi}_{1L}\psi_{1R} - i\frac{g}{\sqrt{2}}(\phi_1-\phi_2)\bar{\psi}_{2L}\psi_{2R} + \mathrm{h.c.} \\
&= gM\cos(\phi/M)\bar{\psi}_1\psi_1 + gM\sin(\phi/M)\bar{\psi}_2\psi_2 \ .
\end{aligned}
$$

with interchange symmetry:

$$
\phi_1 \leftrightarrow i\phi_2, \qquad \psi_{1L,R} \leftrightarrow \psi_{2L,R}
$$

Fermion masses are bounded and can be light!

$$
gM \lesssim T \lesssim M
$$

Little Warm inflation

Effective potential at high temperature:

$$V_T \simeq \sum_{i=1,2} \left[-\frac{7\pi^2}{180} T^4 + \frac{m_i^2 T^2}{12} + \frac{m_i^4}{16\pi^2} \left(\log\left(\frac{\mu^2}{T^2}\right) - c_f \right) \right]$$

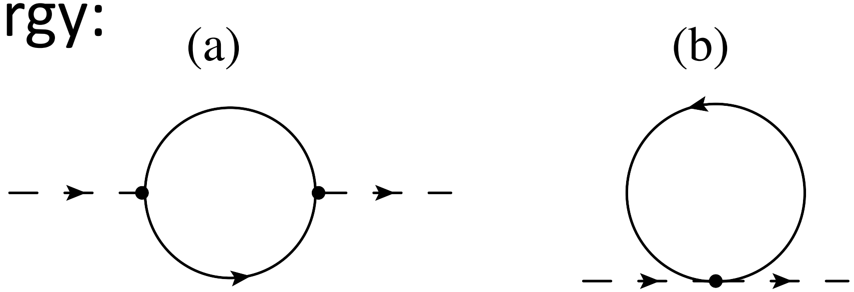
No thermal inflaton masses!

Alternatively, expand Lagrangian to quadratic order:

$$\mathcal{L}_{\phi\psi} = -\sum_i \left[m_i + g_i \delta\phi + \frac{f_i}{2} \delta\phi^2 + \ldots \right] \bar{\psi}_i \psi_i$$

Little Warm inflation

Inflaton self-energy:



$$\begin{aligned}\Sigma_\phi(0) &= \left[\left(g_1^2 + m_1 f_1\right) + \left(g_2^2 + m_2 f_2\right)\right] I_T \\ &= g^2 \left[-\cos(2\phi/M) + \cos(2\phi/M)\right] I_T = 0\ ,\end{aligned}$$

where $I_T \simeq -(\Lambda^2/2\pi^2) + (T^2/6)$.

Cancellation of quadratic divergences and thermal masses!

Little Warm inflation

Dissipation comes from non-local terms in the effective action, which come only from diagram (a):

No cancellation of dissipative terms!

$$\begin{aligned}\Upsilon &= \int d^4x' \Sigma_R(x,x')\,(t'-t) \\ &= \sum_i 4\frac{g_i^2}{T}\int \frac{d^3p}{(2\pi)^3}\frac{m_i^2}{\Gamma_{\psi_i}\omega_p^2} n_F(\omega_p)\,[1-n_F(\omega_p)]\end{aligned}$$

where $\omega_p = \sqrt{|\mathbf{p}|^2 + m_i^2}$.

[Bastero-Gil, Berera & Ramos (2001)]

Little Warm inflation

Fermion decay from additional Yukawa interactions:

$$\mathcal{L}_{\psi\sigma} = -h\sigma \sum_{i=1,2} \left(\bar{\psi}_{iL}\psi_{\sigma R} + \bar{\psi}_{\sigma L}\psi_{iR}\right)$$

Dissipation coefficient proportional to the temperature:

$$\Upsilon \simeq \alpha(h)\frac{g^2}{h^2}T \; , \qquad \alpha(h) \simeq \frac{3}{1 - 0.34\log(h)}$$

with $m_i^2 \simeq \Delta m_T^2 \simeq h^2 T^2/8$. [c.f. Yokoyama & Linde (1998)]

Summary

- Inflaton is a pseudo-Nambu-Goldtsone boson
- Inflaton is a gauge singlet ➡ arbitrary scalar potential
- Inflaton coupled to light fermions with bounded masses
- Cancellation of thermal masses and quadratic divergences
- No cancellation of dissipative effects: $\Upsilon \propto T$
- Warm inflation with only a few fields!

See Mar Bastero-Gil's talk for dynamics and observational predictions!

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Little Warm Inflation
(observational predictions)

Cold inflation/Warm inflation

Dissipative coefficient: $\Upsilon(T) = C_T T$

Primordial spectrum: Chaotic models $\lambda \varphi^4$, $m_\phi^2 \phi^2$

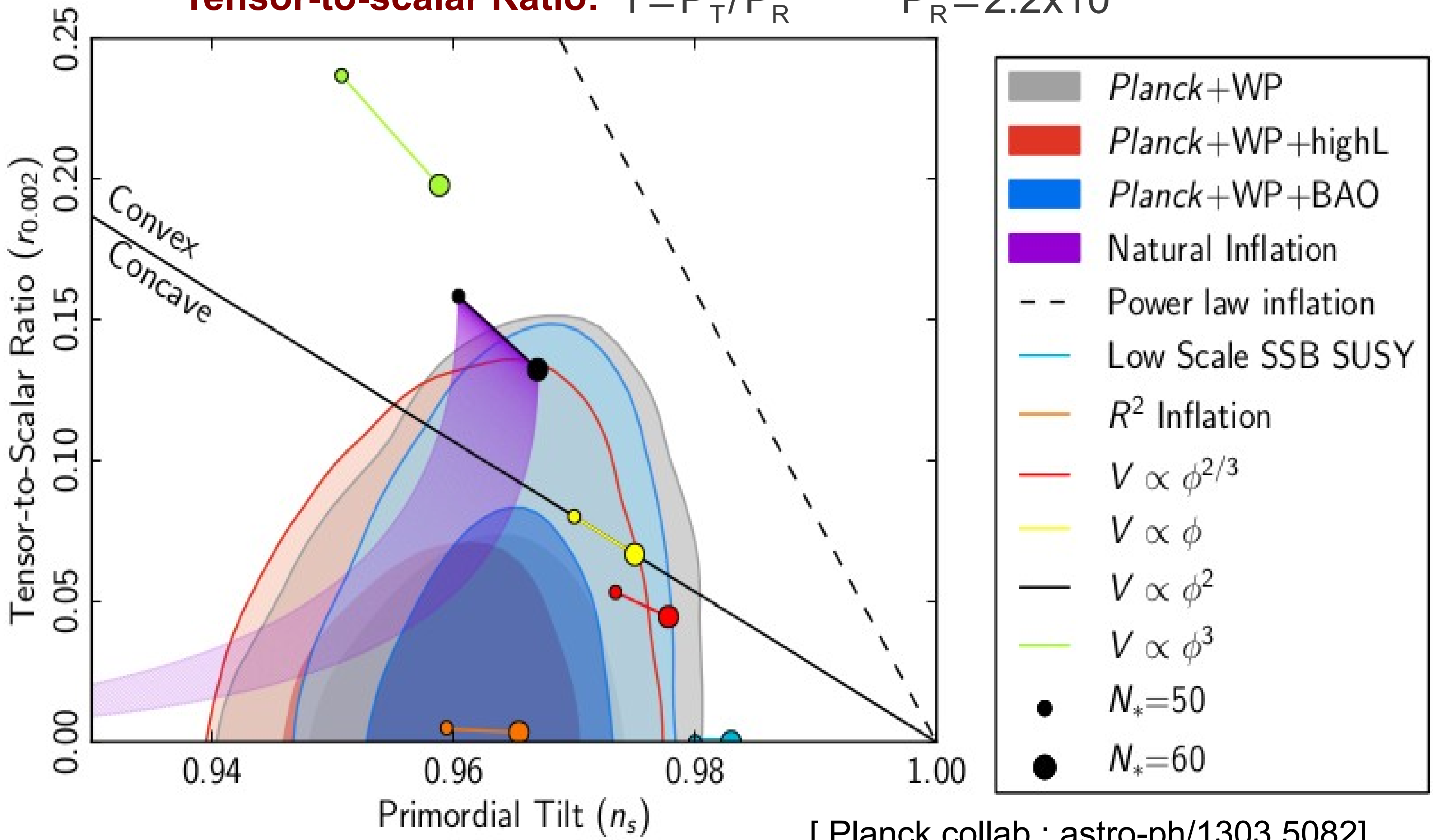
Mar Bastero Gil
University of Granada

Work done in collab with: A. Berera, R. Ramos, J. Rosa

Primordial spectrum: ~adiabatic, ~scale-invariant, gaussian?, tensors?

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s-1} \qquad k_0 = 0.002\,\mathrm{Mpc}^{-1}$

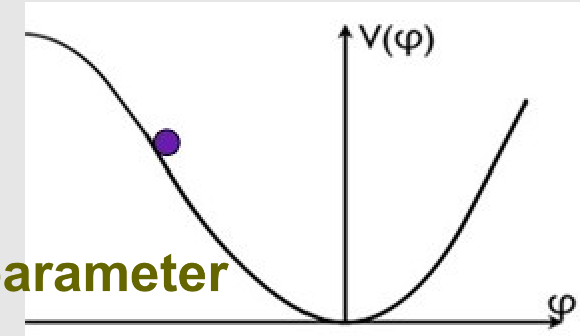
Tensor-to-scalar Ratio: $r = P_T/P_R \qquad P_R = 2.2\mathrm{x}10^{-9}$



[Planck collab.: astro-ph/1303.5082]

Slow Roll Inflation

Scalar field rolling down its (flat) potential



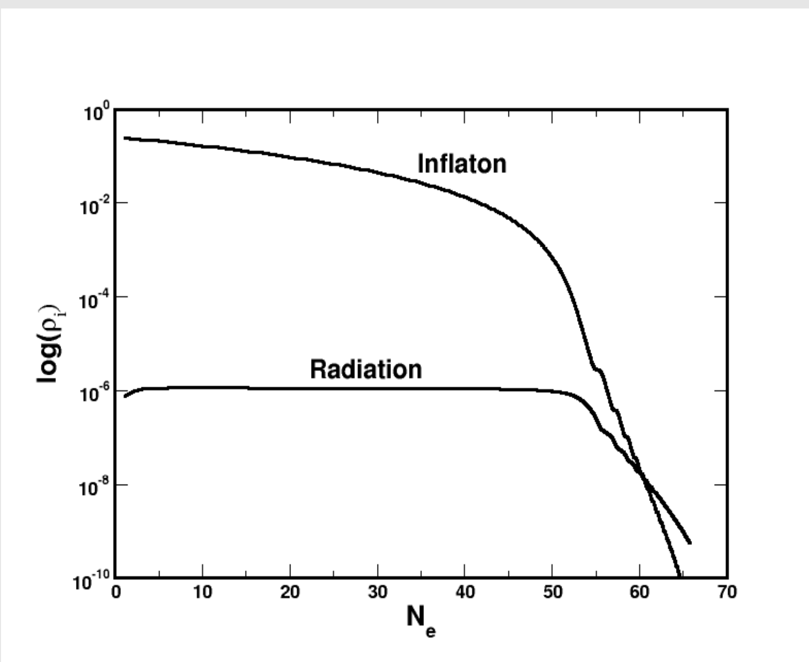
Kinetic energy << potential energy $H^2 \sim V/3m_P^2$ **Hubble parameter**

Inflation → Reheating → Radiation → Matter

Inflaton interacts with other particles

"Cold" inflation: Interactions negligible during Inflation —Reheating→ Radiation

"Warm" inflation: Inflaton decay into light dof —Dissipation→ Radiation



A (small) fraction of the vacuum energy is converted into radiation during inflation

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V_{\phi} = 0$$

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^2 \quad \text{"Source term"}$$

"Decay" into light dof= extra friction

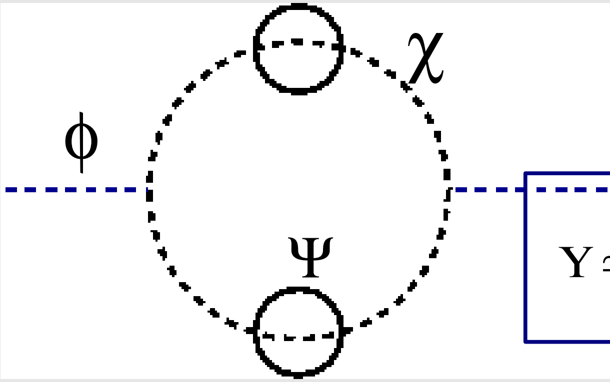
Interactions & Dissipative coefficient

Low T regime:

light fermions

$$L = \cdots - \frac{1}{2} m_\phi^2 \phi^2 - \frac{g^2}{2}\phi^2\chi^2 + h\chi\psi\bar{\psi} + \cdots$$

heavy $m_\chi = g\phi > H, T$



BG, Berera, Ramos & Rosa 2012

$$\Upsilon \simeq \frac{32}{\sqrt{2\pi}} \frac{g^2 N_\chi}{h^2 N_\Upsilon} (m_\chi T)^{1/2} e^{-m_\chi/T} + 0.02\, h^2 N_\Upsilon N_\chi \left(\frac{T^3}{\phi^2}\right) \simeq C_\phi \frac{T^3}{\phi^2}$$

Adiabatic approximation:

$$T > H$$

$$\dot{\phi}/\phi, \quad H < \Gamma_\chi \simeq h^2 m_\chi / (8\pi)$$

Macroscopic Microscopic

- Easy to fulfill for not too small values of h
- Thermal corrections under control (inflaton coupled to heavy fields) + susy to control T=0 corrections

$$\frac{\Gamma_\chi}{\dot{\phi}/\phi} > \frac{\Gamma_\chi}{H} > \left(\frac{\Gamma_\chi}{m_\chi}\right)\left(\frac{m_\chi}{T}\right)\left(\frac{T}{H}\right) > 1$$

Getting 50-60 e-fold of inflation typically requires $C_\phi \sim 10^6$

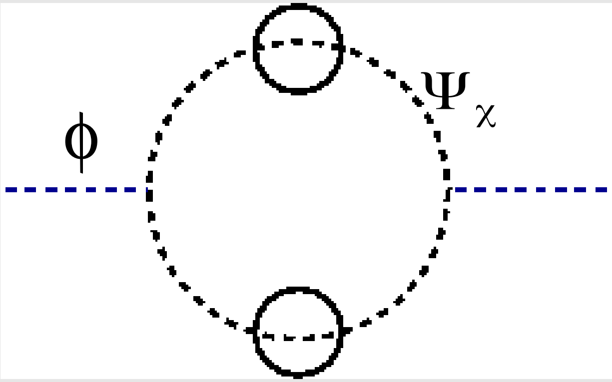
Interactions & Dissipative coefficient

High T regime:

light scalar

$$L = \cdots - \frac{1}{2} m_\phi^2 \phi^2 - g \phi \bar{\psi}_\chi \psi_\chi - h \sigma \bar{\psi}_\chi \psi_\chi + \cdots$$

light $m_\Psi = g\phi > H, T, g \ll 1$



$$\Upsilon \simeq \frac{3}{1 - 0.34 \log h} \frac{g^2}{h^2} T$$

Linear T coefficient

Adiabatic approximation:

$$T > H$$

$$\dot{\phi}/\phi, \quad H < \Gamma_\chi \simeq \frac{\pi}{512} h^4 \left(\frac{T}{H}\right)$$

Macroscopic   Microscopic

- Small g coupling to keep fermions light
- Not too small h because of adiabatic condition
- How to avoid thermal corrections to inflaton potential due to light fields?

Berera, Gleiser &Ramos PRD'98; Yokoyama & Linde PRD '98

Interactions & Dissipative coefficient

High T regime:

Inflaton a PNGB of a broken U(1) symmetry + pair of fermions + exchange sym.

$$L = \cdots - gM\cos(\phi/M)\,\bar{\psi}_1\psi_1 - gM\sin(\phi/M)\,\bar{\psi}_2\psi_2 - h\sigma\sum_{i=1,2}(\bar{\psi}_i\psi_\sigma + \bar{\psi}_\sigma\psi_i) + \cdots$$

light Ψ: $gM < T < M$, $g \ll 1$

Thermal potential:

$$\Delta V_T = -\frac{\pi^2}{90} g_R T^4 + \frac{g^2 M^2}{12} T^2 + \frac{g^4(\phi) M^4}{16\pi^2}\left(\log\frac{\mu^2}{T^2} - c_f\right)$$

Light dof

No thermal mass for the inflaton

Total energy density:

$$\rho_T = \frac{1}{2}\dot{\phi}^2 + V(\phi) + \Delta V_T - T\frac{d\Delta V_T}{dT}$$

$$\rho_R = \frac{\pi^2}{30} g_R(\phi, T) T^4$$

Effective no. of dof:

$$g_R(\phi, T) \simeq g_R - \frac{5}{2\pi^2}\left(\frac{gM}{T}\right)^2 + \frac{15}{16\pi^4}\left(\frac{gM}{T}\right)^4\left(3 + \cos\left(\frac{4\phi}{M}\right)\right)$$

Fluctuations & primordial spectrum: coupled system

Field EOM: $$\delta\ddot{\phi}_k^{GI} + (3H+\Upsilon)\delta\dot{\phi}_k^{GI} + \dot{\phi}\,\delta\Upsilon^{GI} + \left(\frac{k^2}{a^2} + V_{\phi\phi}\right)\delta\phi_k^{GI} \simeq (2\Upsilon T)^{1/2}\hat{\xi}_k$$

fluctuation force ξ

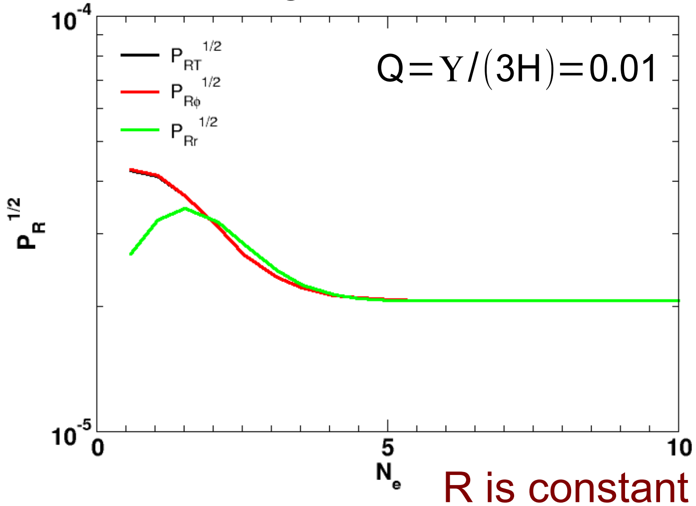
(light d. of f.)

$$\frac{\delta\Upsilon^{GI}}{\Upsilon} = \frac{1}{4}\frac{\delta\rho_r^{GI}}{\rho_r} = \frac{\delta T}{T}$$

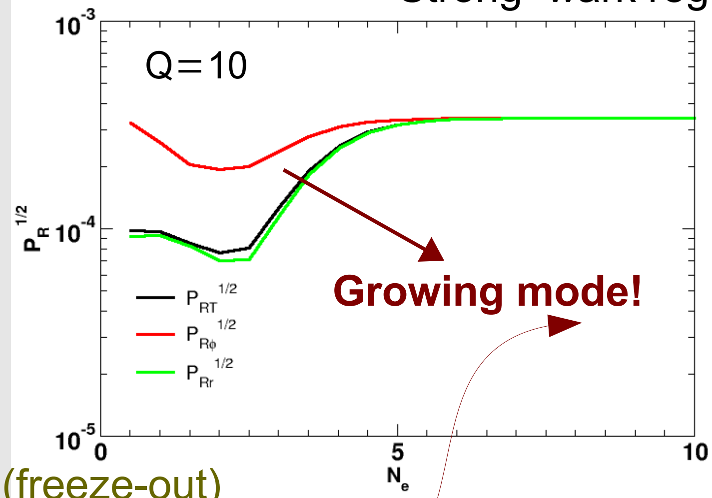
→ Coupled system inflaton-radiation

$$P_R = \frac{h_\phi}{h_T}P_{R_\phi} + \frac{h_r}{h_T}P_{R_r} \simeq P_{R_r} \simeq P_{R_\phi}, \qquad (h_i = \rho_i + p_i)$$

Weak wark regime



Strong wark regime



R is constant after horizon crossing (freeze-out)

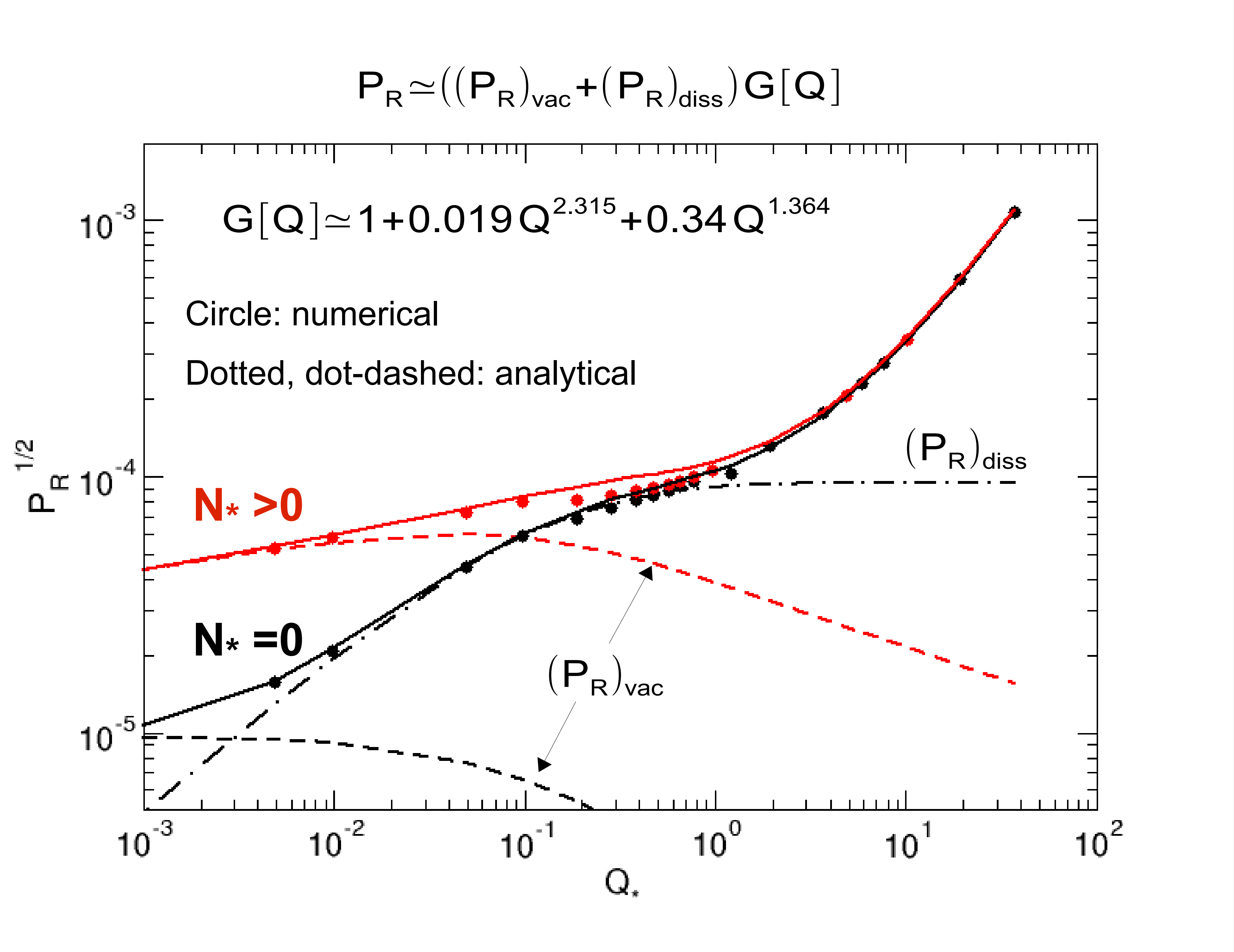
$$P_R \simeq \left(\frac{H}{\dot{\phi}}\right)^2 \left(\frac{H}{2\pi}\right)^2 \left(1 + 2\mathcal{N} + \frac{T}{H}\frac{4\pi Q}{\sqrt{1+4\pi Q/3}}\right) \times G[Q], \qquad Q = \Upsilon/(3H)$$

Dissipative processes may maintain a non-trivial distribution of inflaton particles:

$$\mathcal{N} \simeq n_{BE} = (e^{k/aT} - 1)^{-1}$$

Ramos, da Silva, 1302.3544; BG, Berera, Moss & Ramos, 1401.1149

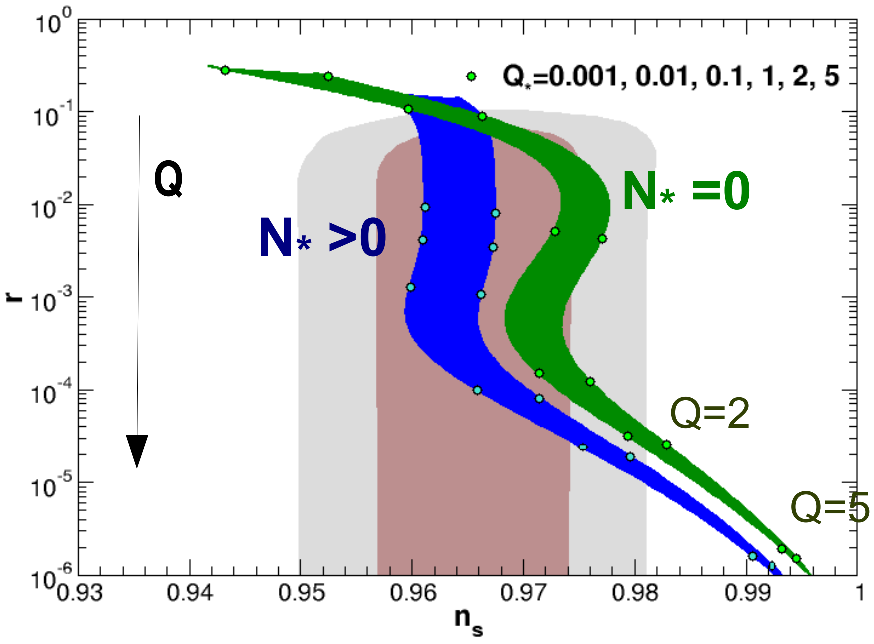
Primordial spectrum



Chaotic model: $V(\phi) = \lambda \phi^4 / 4, \quad \lambda = 10^{-14}, \quad N_e = 50$

Primordial spectrum: quartic chaotic model

$$V(\phi)=V_0\left(\frac{\phi}{m_P}\right)^{4}, \quad N_e=50-60$$



$$n_s-1=\frac{d\ln P_R}{dN_e}=(n_s-1)_N+(n_s-1)_{diss}+(n_s-1)_G, \quad (n_s-1)_G>0$$

$$r\simeq\frac{16\,\epsilon_\varphi}{(1+2\mathcal{N}+\Delta_Q)\,G[Q]}\leq 16\,\epsilon_\phi$$

Quartic:

$$\mathcal{N}\neq 0, Q<1: \; n_s\simeq 1-2/N_e, \quad r\simeq 16\,\epsilon_\phi\left(\frac{H}{T}\right)\ll 0.1$$

Warm inflation &Non-gaussiantiy : T dependent diss. coefficient

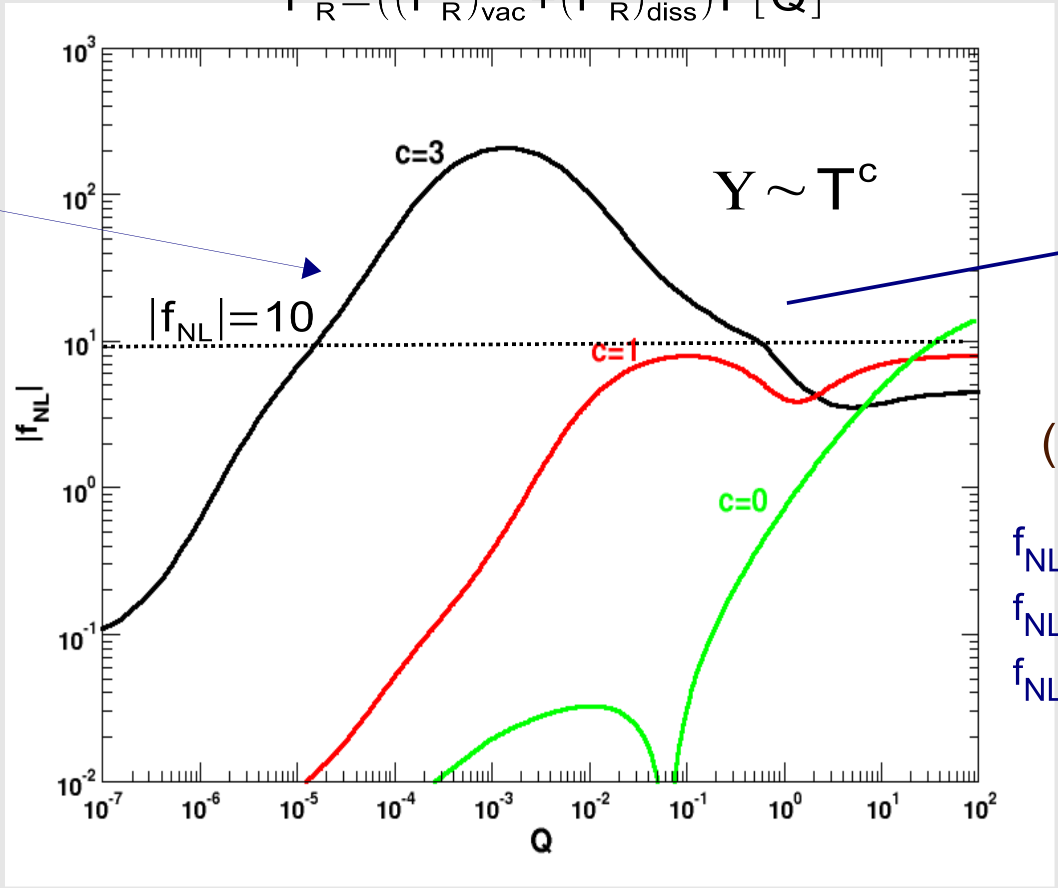
- **Bispectrum:** $B_R(k_1, k_2, k_3) = \sum_{cyc} \langle R_1(k_1) R_1(k_2) R_2(k_3) \rangle = A_B(k) \bar{B}(k_1, k_2, k_3)$

shape

$$f_{NL} = \frac{18}{5} \frac{A_B(k)}{P_R(k)^2}$$ Non-linear parameter

$P_R \simeq ((P_R)_{vac} + (P_R)_{diss}) F[Q]$

$(P_R)_{vac} > (P_R)_{diss}$



$(P_R)_{vac} < (P_R)_{diss}$

(Planck: f_{NL} <~O(10))

f_{NL}^{local} = 2.7 +- 5.8 ($k_3 << k_1 \sim k_2$)

f_{NL}^{equil} =-42 +- 75 ($k_3 \sim k_1 \sim k_2$)

f_{NL}^{warm} = 4 +- 33

[BG, Berera, Moss, Ramos '14]

Summary

- Dissipative effects due to decaying fields can be relevant during inflation, and modify the inflationary predictions

- "Low T" regime for dissipation (massive scalar χ decaying into light dof): thermal corrections under control, but required large number of fields $N_\chi \sim 10^6$

- "High T" regime for dissipation (light fermion ψ decaying into light dof): $\Upsilon = C_T T$

Inflaton a PNGB of a broken U(1) symmetry + pair of fermions + exchange sym.

Light fermions: $gM < T$ + thermal corrections under control + minimal matter content

$\lambda\phi^4$ compatible with data, $Q^* \sim 0.01-1$, $r \sim 0.1-10^{-4}$

- For a T dependent dissipative coefficient, the field and radiation perturbation EOM form a coupled system: Field fluctuations are amplified before freeze-out ($Q < 1$)

Blue-tilted spectrum for $Q >> 1$

- Non-gaussianity compatible with observations for both weak and strong dissipative regime, with a characteristic shape

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Synthetic Tensor Modes

Ricardo Zambujal Ferreira

[1] CP^3-Origins
University of Southern Denmark

Ingredient 1: Tensor Modes

- Detection of tensor modes (gravitational waves) by LIGO opened a new and unique window to all the gravitational phenomena in the Universe

- Strong experimental effort to observe tensor modes in different frequency bands (LIGO, eLISA, BICEP, CMB-Pol, etc.) motivates a deeper study of all possible sources:
  - **Short scales**: Astrophysical, Phase transitions in the early universe, defects, etc.
  - **Large scales** (> 1Mpc):
    - Are tensor modes the smoking gun of inflation?
    - Do they tell us the energy scale of inflation?
    - Are there other mechanisms (synthetic tensor modes)?

Ingredient 2: Axion-like Particles

Axion-like particles (pseudo-scalars) (ϕ) appear in many different contexts (CP problem, String Theory, BSM, etc.):

- Pseudo Goldstone boson of an (explicitly) broken global symmetry.
- Interesting inflaton candidate (protected to radiative corrections, Natural Inflation)

  [Freese, Frieman and Olinto '90]

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right], \qquad f \equiv \text{axion decay constant.}$$

- Axions (ϕ) couple with gauge fields through the axial coupling

$$\mathcal{L}_{\text{int}} = -\frac{\alpha\phi}{4f} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

Axial Coupling with gauge fields

- Axial Coupling induces an instability in the equation of motion: [Anber and Sorbo 06']

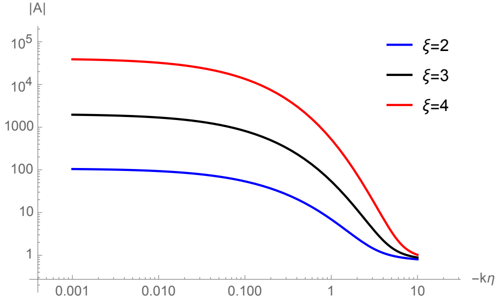
$$A_\pm(\tau,k)'' + \left(k^2 \pm \frac{2k\xi}{\tau}\right) A_\pm(\tau,k) = 0,$$

where $\xi \equiv \frac{\alpha\dot{\phi}}{2fH}$.

- If the axion is light ($\xi \simeq$ const.) solution is can be expressed in terms of Coulomb functions:

$$A_+(\tau,k) = \frac{1}{2k}\left(G_0(\xi,-k\tau) + iF_0(\xi,-k\tau)\right)$$

- Gauge field dynamics: oscillates inside the horizon, is resonantly produced at horizon crossing and freezes outside the horizon



Solution is exponentially dependent on ξ

$$A_+ \underset{-k\tau\to 0}{\propto} e^{\pi\xi}$$

CMB Anisotropies

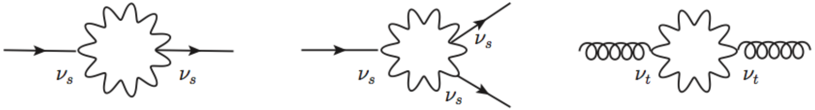
- Leading interactions with scalar and tensor modes [Barnaby and Peloso 11']

$$\mathcal{L}_{\text{int}} = \frac{\alpha\delta\phi}{4f} F_{\mu\nu}\tilde{F}^{\mu\nu} + T^{\text{EM}}_{\mu\nu}\delta g^{\mu\nu} \ .$$

- If the axion is the inflaton then curvature perturbation ($\zeta = -H\delta\phi/\dot{\phi}$, in the flat gauge) interacts directly with gauge-fields

$$\mathcal{L}^{\text{scalar}}_{\text{int}} = \frac{\xi}{2}\zeta\, F_{\mu\nu}\tilde{F}^{\mu\nu} .$$

Interaction is parametrically stronger than the gravitational coupling.



Loop effects - Axion is the inflaton

- Power spectrum: is changed to (γ_α are "small" numerical coefficients)

$$P_\zeta \simeq \mathcal{P}\left(1+\gamma_s \frac{\mathcal{P}}{\xi^6} e^{4\pi\xi}\right), \qquad \mathcal{P}^{1/2} = \frac{H^2}{2\pi\dot{\phi}}$$

$$P_{\rm GW} \simeq 16\epsilon\mathcal{P}\left(1+\gamma_t \frac{\epsilon\mathcal{P}}{\xi^6} e^{4\pi\xi}\right); \qquad \epsilon \text{ suppressed}$$

- 3-point function (non-gaussianities):

$$\langle \zeta_{k_1}\zeta_{k_2}\zeta_{k_3}\rangle^{\text{one-loop}} = (2\pi)^3\delta^{(3)}(\sum_i \vec{k}_i) f(k_1,k_2,k_3)\frac{\mathcal{P}^3}{\xi^9}e^{6\pi\xi};$$

Peaks on the equilateral configuration $(k_1 = k_2 = k_3)$ [Barnaby et al. 11']

$$f_{NL}^{\rm equi} = \gamma_{NG}\frac{\mathcal{P}}{\xi^9}e^{6\pi\xi}$$

Axion **Not** the inflaton

What if the pseudo-scalar (σ) in the axial coupling is not the inflaton?

[Barnaby et al. 12', Shiraishi et al. 13', Cook , Sorbo 13', Mukohyama et al. 14', **RZF**, Sloth 14']

$$\mathcal{L}_{\text{int}} = -\frac{\alpha\sigma}{4f} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- There is no direct coupling with the inflaton, apart from the gravitational, so are non-gaussianities suppressed?
  - Mechanism for generating GW larger than the vacuum? Observation of tensor modes would not tell us the energy scale of inflation.

- Problem: $\delta\sigma$ is not gauge invariant. When rewriting in terms of gauge-invariant quantities the coupling with gravity is universal [**RZF**, Sloth 14']

$$\mathcal{L}_{\text{int}} = -\frac{\xi}{2}\left(\zeta + \mathcal{S}_{\sigma\phi}\right) F_{\mu\nu}\tilde{F}^{\mu\nu}.$$

Superhorizon Evolution of Curvature Perturbations

However, constraints on the model depend on what happens to the axion afterwards:

- Axion does not decay during inflation:
  - Non-gaussianity is not suppressed.
- Axion becomes massive and decays during inflation: [Mukohyama et al. 14']
  - Curvature and isocurvature perturbation cancel each other. Leading correction is ϵ suppressed and comes from the superhorizon enhancement [**RZF**, Sloth 14']

$$\zeta(\tau) = \zeta_* + \left(\frac{\dot{\sigma}_*}{\dot{\phi}_*}\right)^2 \zeta_\sigma^* \left[\Delta N \left(2\epsilon_\phi - \lambda_2\right) + \frac{\epsilon_\phi}{6}\right]$$

where $\Delta N = \log\left(\tau^*/\tau_{osc}\right)$ is the duration, in e-folds, from horizon crossing until the decay of the axion.

Perturbativity constraints

- Production of tensor modes is exponential sensitive to ξ. Is perturbation theory in trouble? [**RZF**, Ganc, Noreña, Sloth '15]
  - Higher order diagrams (in the in-in formalism) scale as

$$10^{-2}\xi^2 e^{2\pi\xi} P_\zeta$$

    Perturbativity requires $\xi \lesssim 3.5$.

  - For non-abelian gauge fields ($SU(N)$) there is an extra perturbative constraint due to the self-interactions:

$$10^{-2} g^2 N^3 e^{4\pi\xi} P_\zeta \lesssim 1, \qquad g \equiv \text{coupling constant}$$

Implications and Conclusions

- Axions are natural in many frameworks. Axial coupling with gauge fields triggers an instability which can generate large anisotropies.
    - What are the cosmological signals if the instability occurs at late times (Axion dark matter, quintessence)?

- Universal constraint on ξ during inflation translates into a lower bound on the decay constant of all axions:

$$\xi \lesssim 3 \quad \Rightarrow \quad f_i \gtrsim \frac{\alpha_i}{6} \frac{\dot{\phi}_i}{H} M_p \quad \forall i$$

    - For natural inflation, each decay constant should satisfy this bound (separately).

    - If the axion decays during inflation bound on ξ is relaxed but perturbativity constraints close the window for large synthetic tensor modes on the largest scales (small are less constrained)

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