Probes of reheating

after non-Abelian axion-like inflation

S. Procacci[a] with S. Biondini[b], P. Klose[c], H. Kolesova[d], M. Laine[e]
University of [a]Geneva, [b]Basel, [c]Bielefeld, [d]Stavanger, [e]Bern

UNIVERSITÉ DE GENÈVE

goal

Starting from vacuum dominated universe, describe the transition to the advent of Standard Model fields in thermal equilibrium.

framework [1,2]

Embed inflaton φ within a medium,

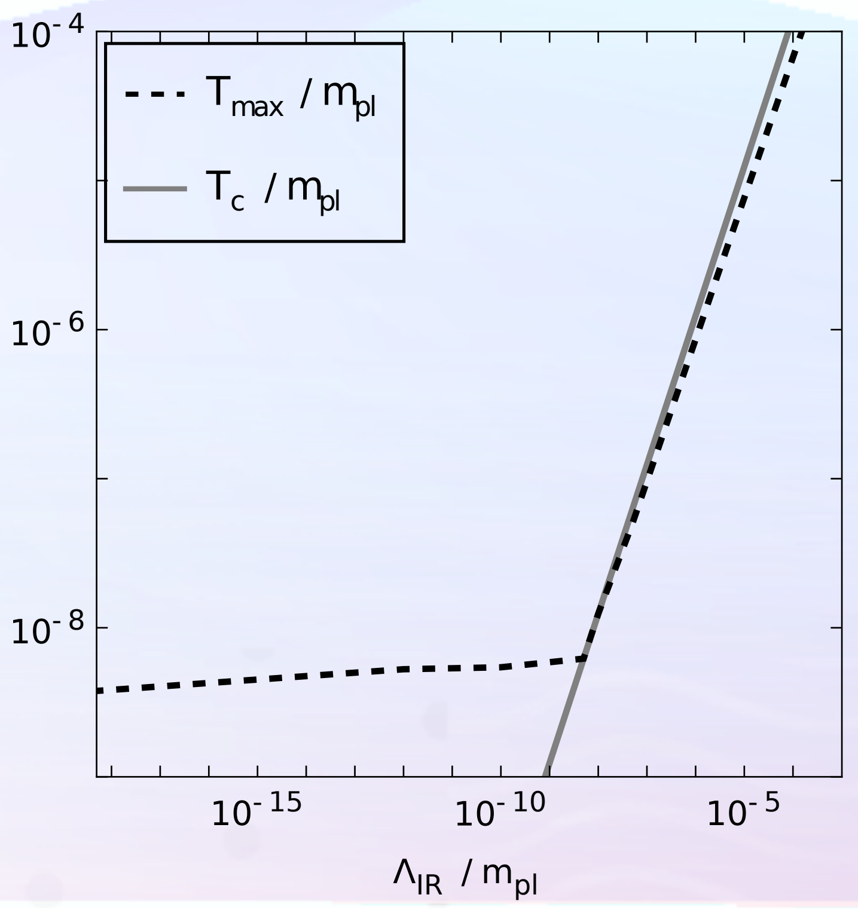
$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \varphi J + \mathcal{L}_{\rm med}\,.$$

Derive weakly-coupled effective equations at the end of inflation,

$$\dot e_\varphi + (\overset{\text{Hubble rate}}{3H} + \overset{\text{friction}}{\Upsilon})(\overset{\text{energy}}{e_\varphi} + \overset{\text{pressure}}{p_\varphi}) = 0\,, \quad (1a)$$

$$\dot e_{\rm med} + 3H(e_{\rm med} + p_{\rm med}) - \Upsilon e_\varphi = 0\,, \quad (1b)$$

asking for $H \gg \Upsilon > 0$ and $V_{\rm eff}(\varphi) \approx V(\varphi)$.



A working example is the one of a non-Abelian gauge plasma [3], coupled to φ via an axion-like term,

$$J = \frac{\overset{\text{YM coupling}}{\alpha(\Lambda_{\rm IR})}}{16\pi\,\underset{\text{decay cst of }\varphi}{f_a}}\,\epsilon^{\mu\nu\rho\sigma}\,\underset{\substack{\text{YM field strength}\\ c\in\{1,\ldots,N_c\}}}{F^c_{\mu\nu}F^c_{\rho\sigma}}\,.$$

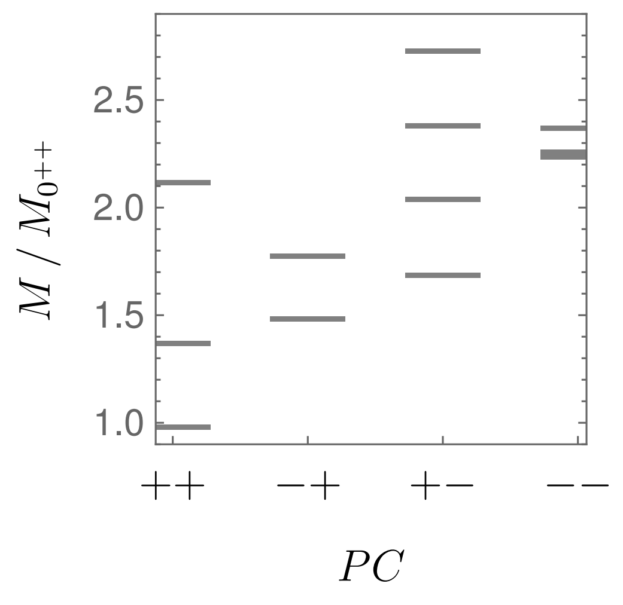
Then the medium thermalizes quickly [4], and its self-interactions become strong as $T \to T_c{}^+(\Lambda_{\rm IR})$. In the following $N_c = 3$ [5].

glueball dark matter [6,7]

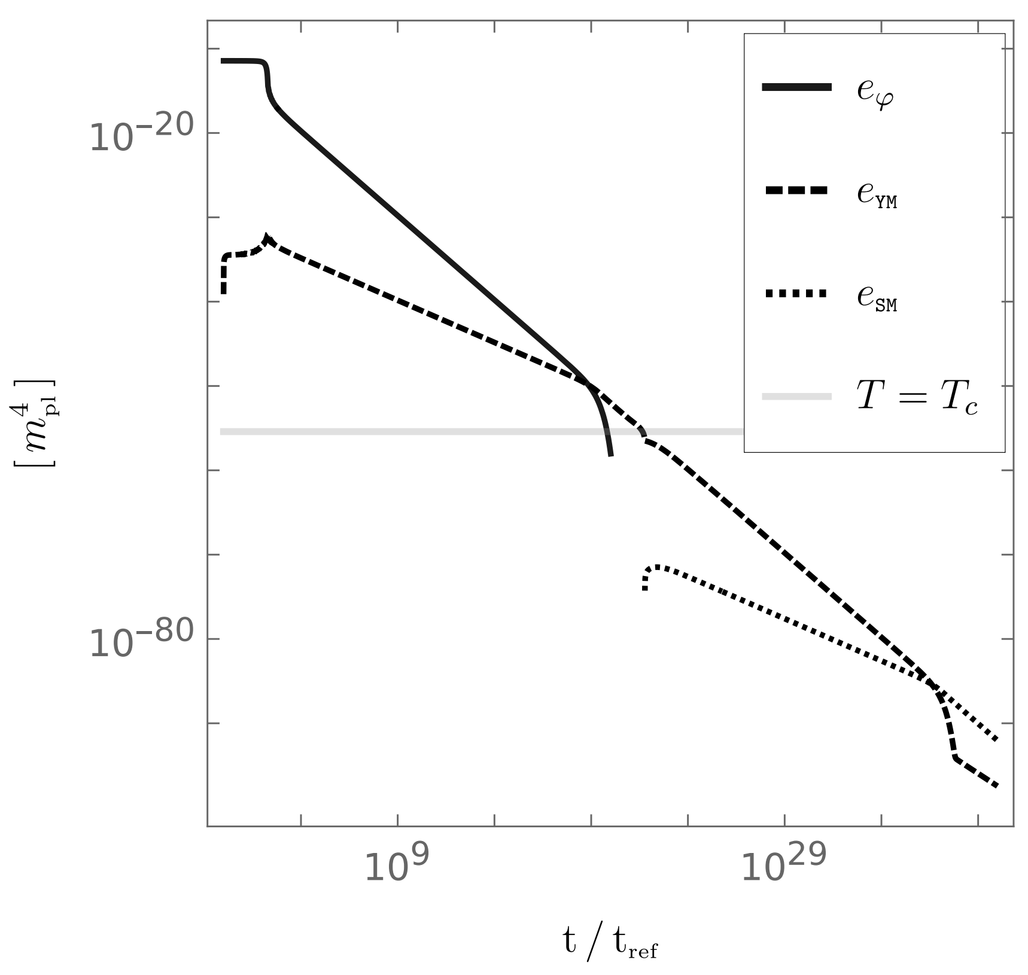
If $\Lambda_{\rm IR} \lesssim H(t_{\rm ref})$, the energy released by φ heats up the Yang-Mills sector to lower $T_{\rm max} \gg \Lambda_{\rm IR}$, implying a phase transition later on.

Let the YM sector be dark and assume that its degrees of freedom in the confined phase transform under Parity and Charge conjugation [8]:

- C-odd glueballs are stable, $\Gamma_s \sim \Lambda_{\rm IR}^9/M_{\rm new}^8$, and form the relic dark matter,
- C-even glueballs are unstable, $\Gamma_u \sim \Lambda_{\rm IR}^5/M_{\rm new}^4$, and "reheat" the visible sector.



$\Lambda_{\rm IR} \sim 0.2 \times 10^6\,{\rm GeV}, \quad \Gamma_u \sim 2. \times 10^{-23}\,{\rm GeV}$



At $T < T_c(\Lambda_{\rm IR})$ the evolution eqs. (1) are coupled to SM dynamics and glueball interactions described by Boltzmann equations.

$$\dot e_{\rm YM} + 3H\overbrace{(e_{\rm YM} + p_{\rm YM})}^{\sum e^{\rm (i)}_{u,s}} = \Upsilon e_\varphi - e_u\Gamma_u$$

$$\dot e_{\rm SM} + 4He_{\rm SM} = e_u\Gamma_u$$

$$\dot n^{\rm (i)}_u + (3H + \Gamma_u)n^{\rm (i)}_u = \ldots$$

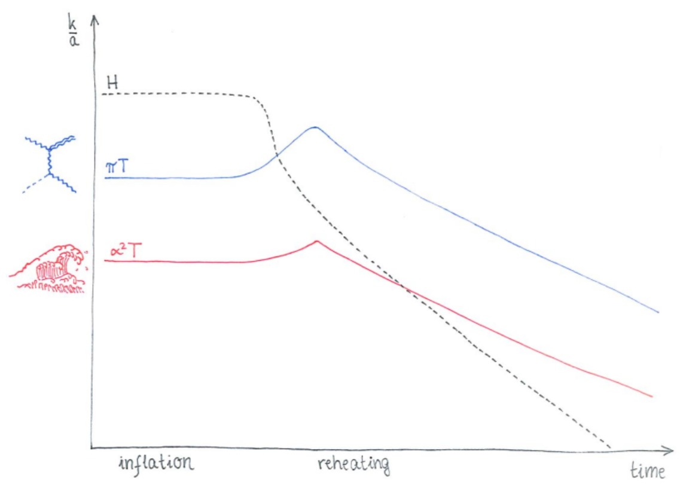
$$\dot n^{\rm (i)}_s + 3Hn^{\rm (i)}_s = \ldots$$

gravitational waves [9,10]

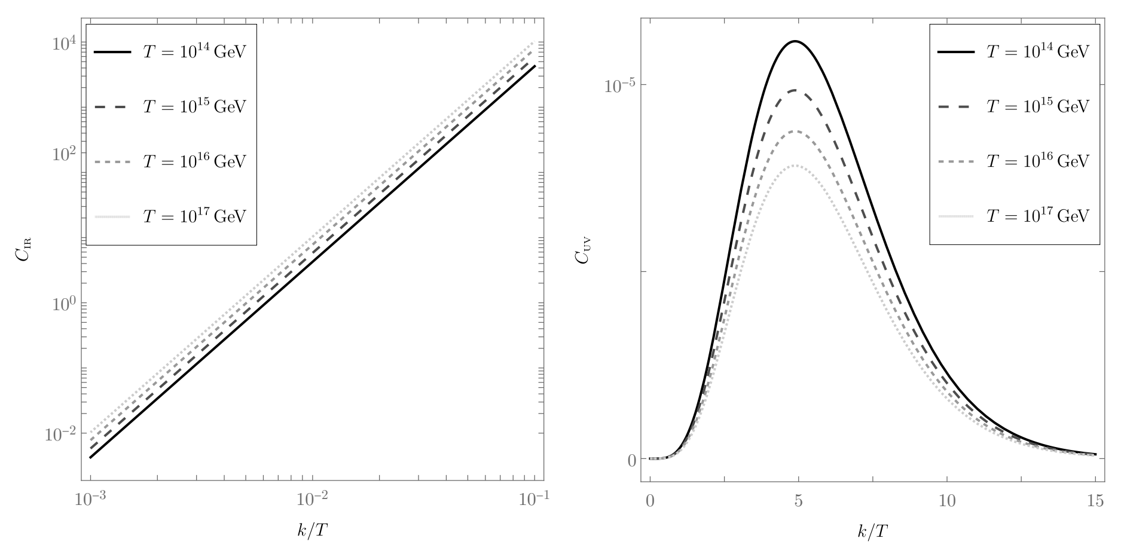
If $\Lambda_{\rm IR} \gg H(t_{\rm ref})$, the energy released by φ heats up the Yang-Mills sector to higher $T_{\rm max} \lesssim \Lambda_{\rm IR}$, inducing large anisotropies in the medium. In turn, these source large tensor perturbations,

$$\left(\partial_t^2 + 3H\partial_t + \frac{k^2}{a^2}\right) h_\pm(t,\mathbf{k}) = \frac{8\pi}{m^2_{\rm pl}}\epsilon^\pm_{ij}(\mathbf{k})\,\delta T^{\rm tt}_{ij}(t,\mathbf{k})\,.$$

Compute the gravitational wave production rate assuming thermal equilibrium, $k/a \gtrsim \alpha^2 T > H$,



$$\frac{{\rm d}e_{\rm GW}}{{\rm d}t\,{\rm d}\ln k} \approx \overbrace{\underbrace{C_{\rm IR}\left(\frac{k}{T}\right)}_{k/a \ll \pi T}\frac{f_a^2T^5}{m^2_{\rm pl}} + \underbrace{C_{\rm UV}\left(\frac{k}{T}\right)}_{k/a \sim \pi T}\frac{T^9}{f_a^2 m^2_{\rm pl}}}^{\text{from }\varphi\text{-medium interactions}} + \underbrace{C_{\rm SM}\left(\frac{k}{T}\right)\frac{T^7}{m^2_{\rm pl}}}_{\substack{\text{SM contribution [10,11],}\\ \text{same IR+UV shapes but}\\ \text{many more channels:}}}\,.$$

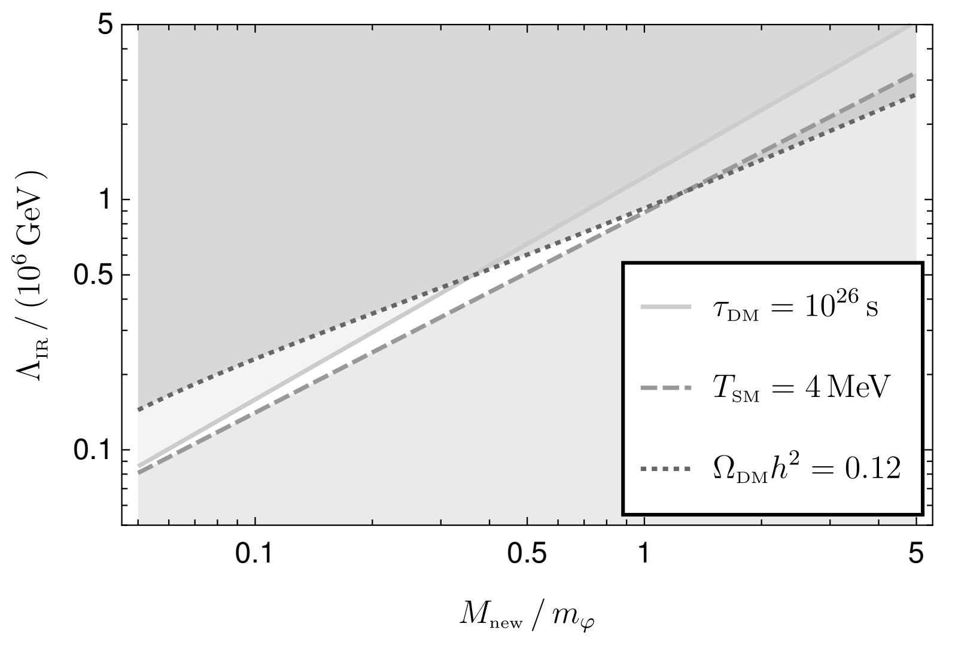


$C_{\rm SM}/C_{\rm UV}|^{\rm peak} \sim \mathcal{O}(10^3)$

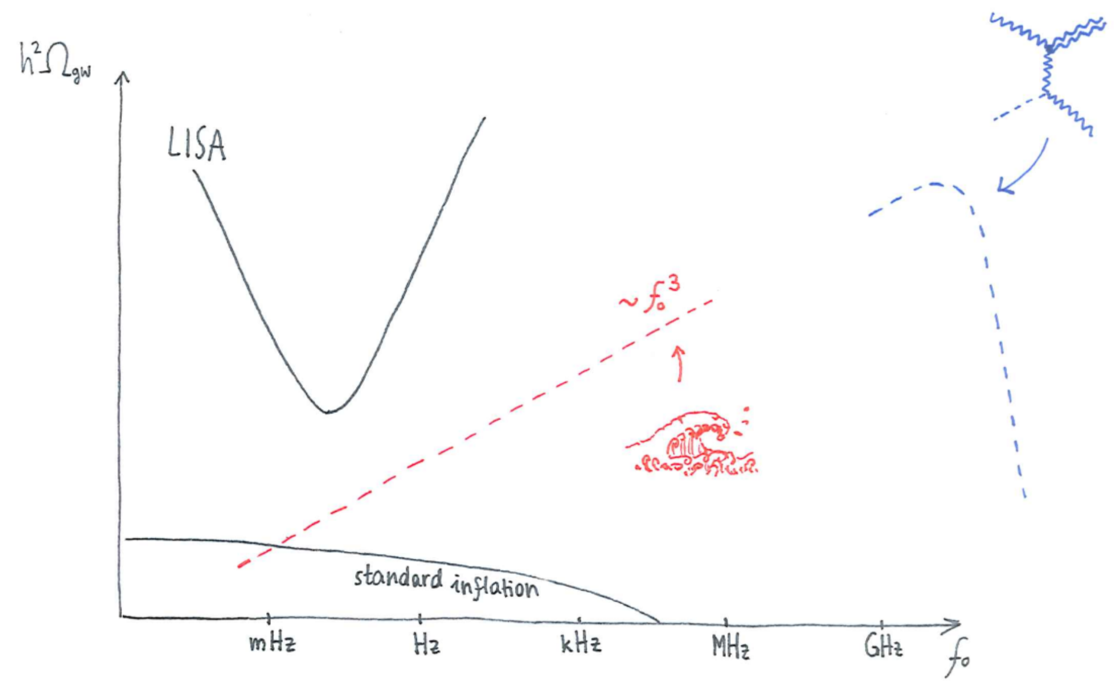
constraints from $\Omega_{\rm DM}$, $\tau_{\rm DM}$ and $T_{\rm SM}$ [6]

$\Omega_{\rm DM}$ depends on $\Lambda_{\rm IR}$ via the time at which confinement occurs, while $T_{\rm SM}$ only depends on the YM→SM portal. Imposing also indirect detection bounds on Γ_s^{-1} yields stringent predictions, $M_{\rm new} \sim 10^{12}\,{\rm GeV}$ and $\Lambda_{\rm IR} \sim 10^5\,{\rm GeV}$.

preliminary results for the parameter space



constraints from $\Omega_{\rm GW}$ and $\Delta N_{\rm eff}$ [9,11]



While the spectral shape is model-independent, peak position and amplitude of $\Omega_{\rm GW}$ depend on $T_{\rm max}$, and thus on $\Lambda_{\rm IR}$. The dominating SM contribution saturates $\Delta N_{\rm eff}$ for $T_{\rm max} > 10^{16}\,{\rm GeV}$ [11], possibly implying $\Lambda_{\rm IR} < 10^{16}\,{\rm GeV}$.

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