New results for thermal axion production in the early Universe

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SUBATECH

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Contents of the presentation

Based on ***K. Bouzoud***, *J. Ghiglieri - Thermal axion production at hard and soft momenta (2404.06113)*

Axion:

- Good dark matter candidate ($m_a \lesssim 10^{-1}\ \mathrm{eV}$ from experimental bounds)
- Solves the "strong CP problem"

Kim-Shifman-Vainshtein-Zakharov (KSVZ) model

$$\mathcal{L}_{\mathrm{int}} = \frac{g_3^2}{32\pi^2}\frac{a}{f_{\mathrm{PQ}}} G\tilde{G} \tag{1}$$

f_{PQ}: energy scale below which the axion exists ($\geq 4 \times 10^8\ \mathrm{GeV}$ from experimental bounds)

The axion only interacts with gluons

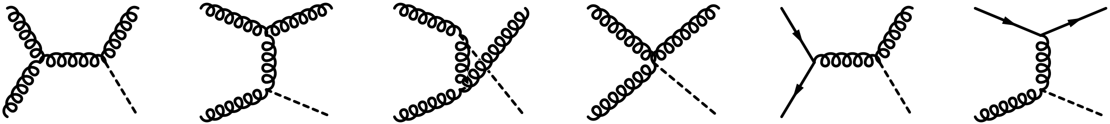


Figure: All tree-level processes in the KSVZ model producing **one** axion in the final state

If $\mathcal{L}_{\text{int}}$ is realized in nature:

- Bose-Einstein condensate axion population $\equiv$ dark matter
- Ultra-relativistic ("hot") axion population $\equiv$ *dark radiation* → focus of this talk

Extra contribution to the effective number of neutrinos

Measure of the contribution of the hot axion population to the energy density of the Universe. Defined as:

$$\Delta N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \left.\frac{e_a}{e_\gamma}\right|_{\text{CMB}} \tag{2}$$

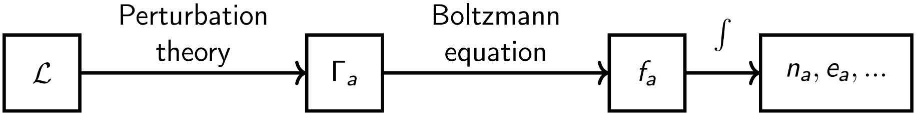


Figure: Phenomenological computation flowchart

Current results

From **Planck** at 2σ: $\Delta N_{\text{eff}} < 0.3$

Future experiments

Expected constraint (at 2σ):

- From **Simons Observatory**: $\Delta N_{\text{eff}} < 0.1$
- From **CMB-S4**: $\Delta N_{\text{eff}} < 0.06$
- From **CMB-HD**: $\Delta N_{\text{eff}} < 0.028$

→ More precise future experiments motivate more precise theoretical computations

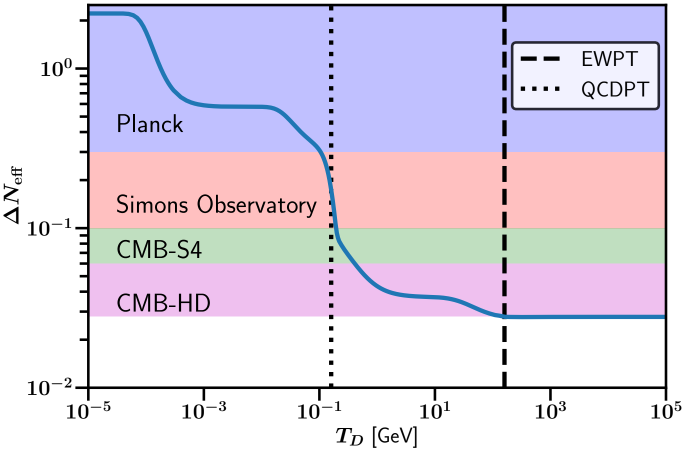


Figure: ΔN_{eff} as a function of the decoupling temperature for a BSM scalar

$$\Gamma_a(k) = \frac{1}{4k} \overbrace{\int \mathrm{d}\Omega_{2\to 2}}^{\text{Phase space integral}} \overbrace{\sum_{A,B,C} |\mathcal{M}_{A+B\to C+a}|^2}^{2\,\to\,2\ \text{scatterings}} \underbrace{\frac{f_A(p_1) f_B(p_2)[1 \pm f_C(k_1)]}{n_B(k)}}_{\text{Thermal distributions}} \tag{3}$$

$f_i \equiv n_B$ or n_F

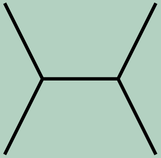


Figure: s channel

$|\mathcal{M}|^2 \propto s^{-1}$. $s \to 0$ limit is not problematic

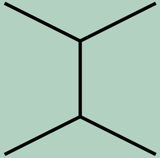


Figure: t channel

$|\mathcal{M}|^2 \propto t^{-1}$. Sensitivity to collective modes in $t \to 0$ limit (bc. $\lambda \to \infty$)

Different methods exist for implementing the collective effects. They converge for small values of g_3 (QCD coupling constants) but become extrapolations at larger g_3.
The "spread" between those methods can be used to quantify the theoretical uncertainty.

We implemented three different methods:

"Strict LO"

Already implemented for the axion case in Peter Graf, Frank Daniel Steffen, *Thermal axion production in the primordial quark-gluon plasma* (1008.4528)

- Leads to large negative values

"Subtraction"

Previously implemented for the neutrino case in J. Ghiglieri, M. Laine, *Neutrino dynamics below the electroweak crossover* (1605.07720)

- Reduces the negativity but does not fix it entirely

"Tuned"

Previously implemented for YM dynamics in M. C. A. York, A. Kurkela, E. Lu, G. D. Moore, *UV Cascade in Classical Yang-Mills via Kinetic Theory* (1401.3751)

- No negative values

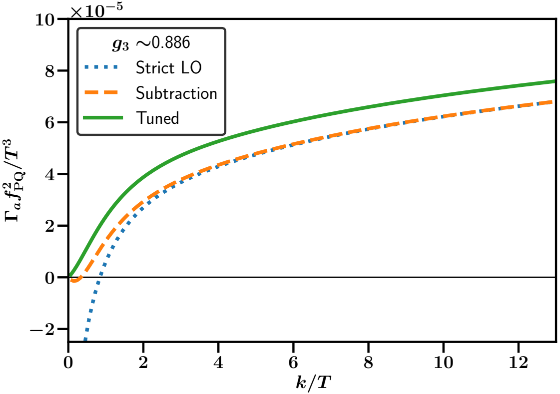


Figure: Axion production rate at $T = 10^4$ GeV

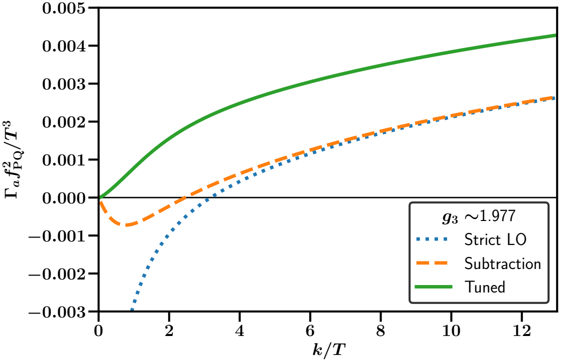
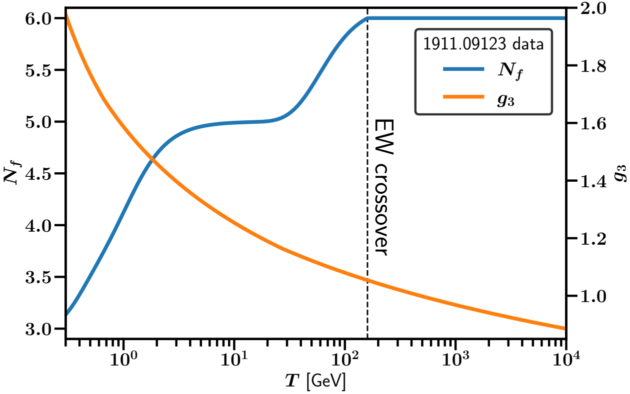


Figure: Axion production rate at $T = 0.3$ GeV

Time/temperature evolution

$$\underbrace{\partial_t f_a}_{} = \Gamma_a \left[n_B - f_a \right] \tag{4}$$

Creation/destruction



- Use $\Gamma_{\rm used} \equiv \max\left(0, \Gamma_{\rm computed}\right)$.
- Initial condition:
  $f_a(T_{\rm max}) = n_B(T_{\rm max})$.

Beyond momentum-independent approximation

Solve for multiple momenta **instead of** using integrated *approximate* form giving energy density

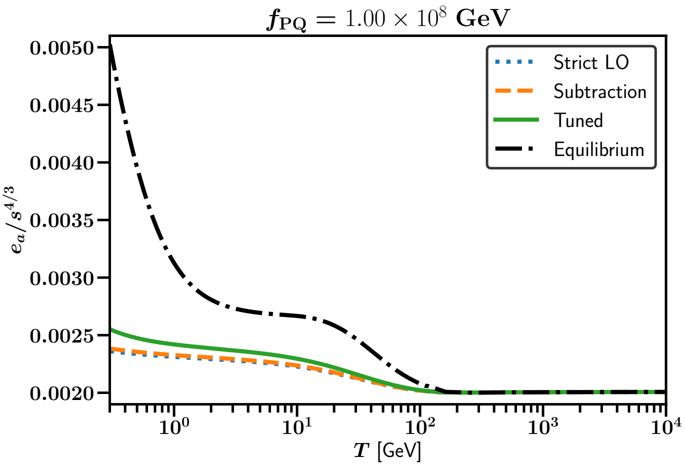
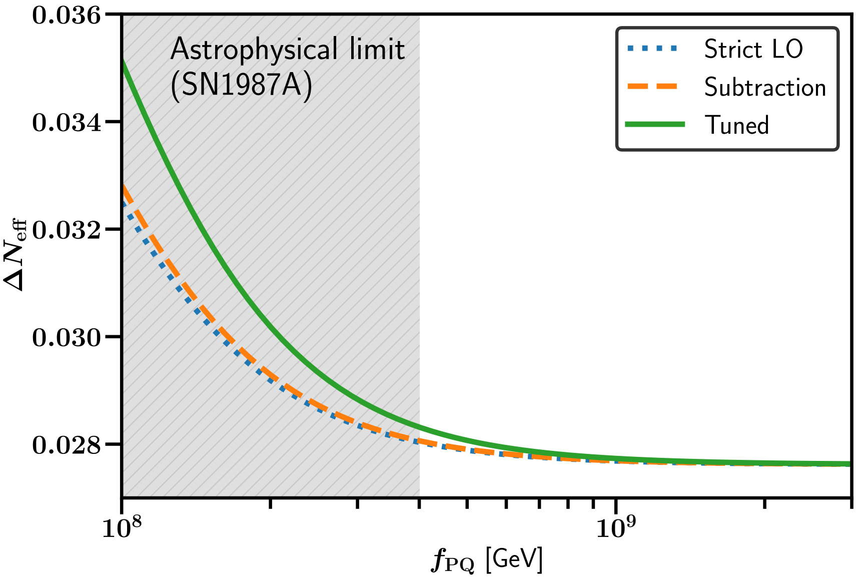


Figure: (Normalized) axion energy density

"Equilibrium" $\equiv$ energy density for $f_a = n_B$


Astrophysical limit
(SN1987A)
Strict LO
Subtraction
Tuned
$\Delta N_{\rm eff}$
0.036
0.034
0.032
0.030
0.028
10^8
10^9
$f_{\rm PQ}$ [GeV]

- Main source of theoretical uncertainty is the choice of production rate computation method (~ 0.002 at most)
- The error due to the momentum-independent approximation is smaller than that (~ 0.0005 at most)
- These conclusions might change if delayed production (at QCD transition or after) happens
- CMB-HD would be more constraining than the current astrophysical limit

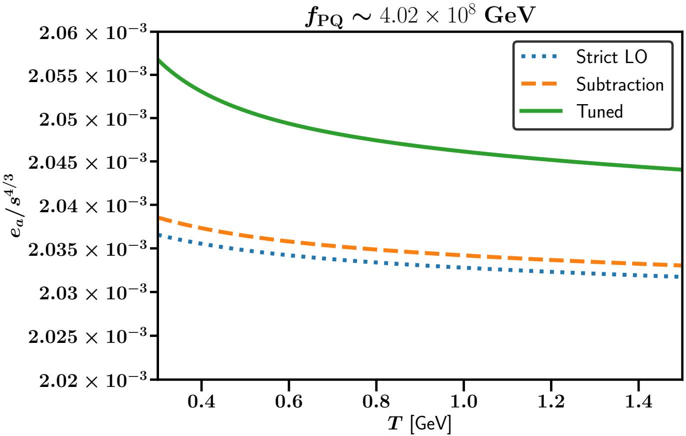


Figure: Normalized axion energy density for f_{PQ} close to the astrophysical limit

Inclusion of QCD transition effects

- Use effective number of colors $N_{C,\mathrm{eff}}$
- Do the same analysis below QCDPT using the χPT Lagrangian and merge the two rates (similar to d'Eramo *et al.* in 2108.05371)

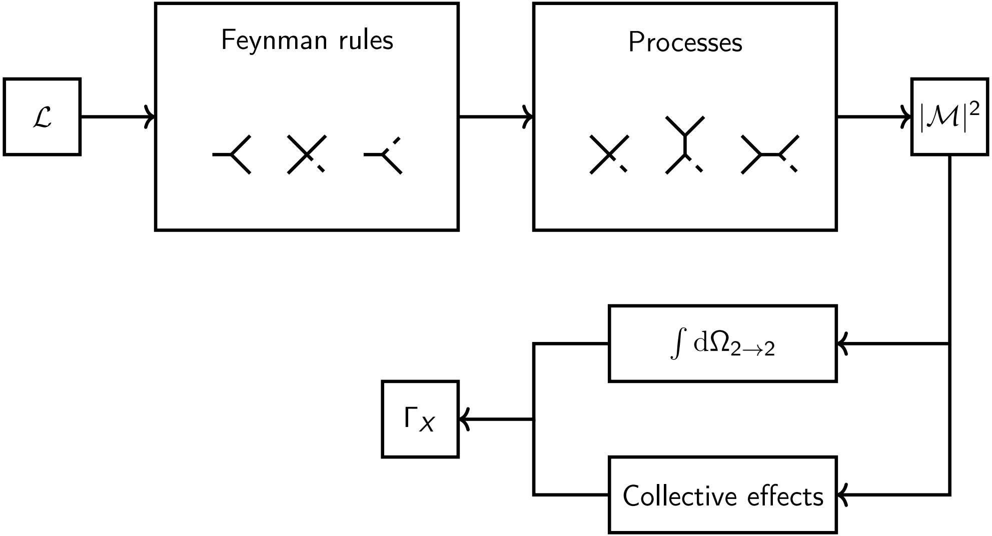
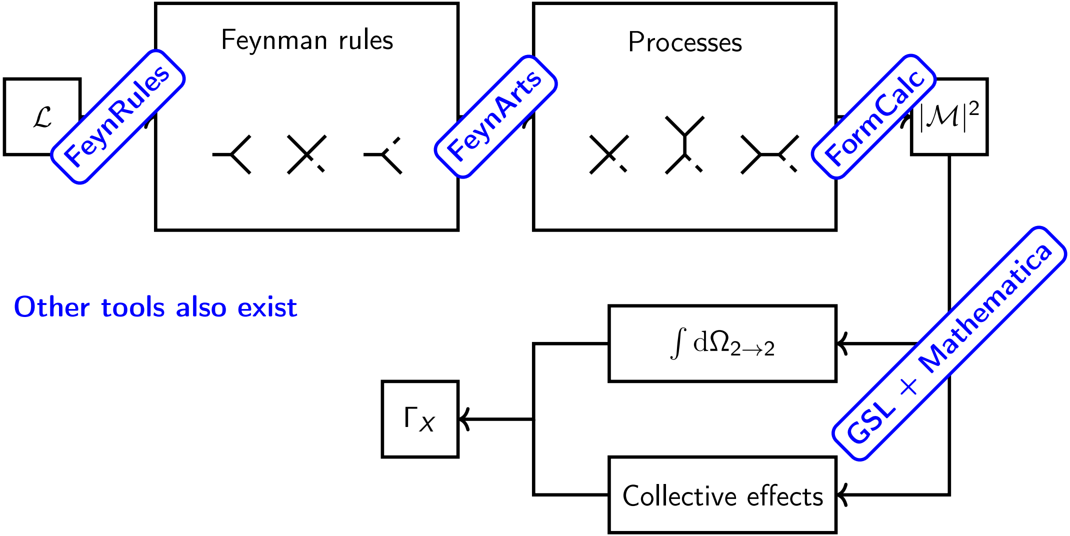


Figure: Flowchart of the production rate computation process



$\mathcal{L}$

FeynRules

Feynman rules

FeynArts

Processes

FormCalc

$|\mathcal{M}|^2$

GSL + Mathematica

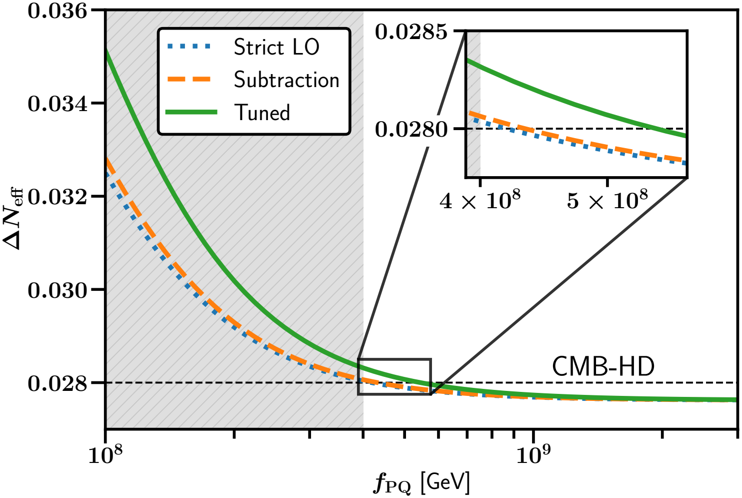
$\int \mathrm{d}\Omega_{2\to 2}$

Collective effects

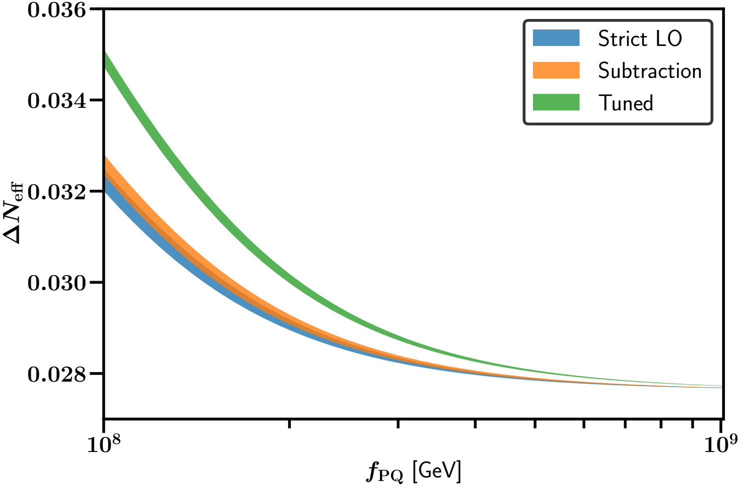
Γ_X

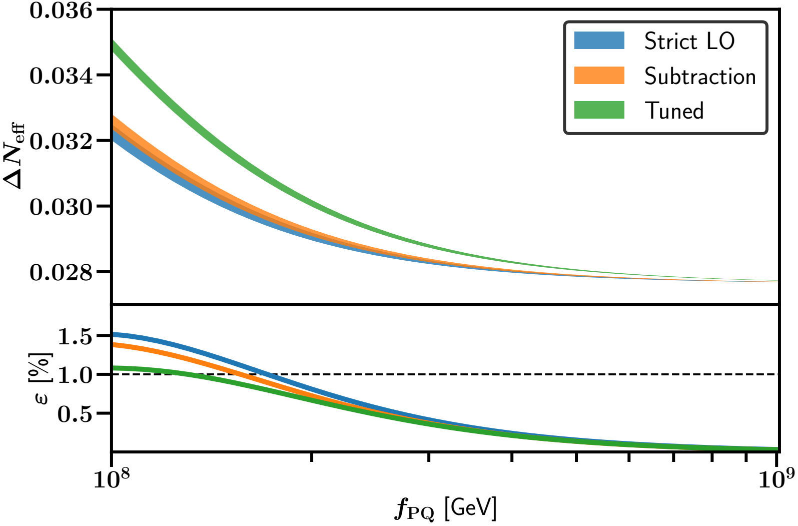
Other tools also exist

Figure: Flowchart of the production rate computation process


Strict LO
Subtraction
Tuned
0.036
0.034
0.032
0.030
0.028
ΔN_{eff}
10^8
10^9
f_{PQ} [GeV]
CMB-HD
0.0285
0.0280
4×10^8
5×10^8

Momentum-dependent method vs. momentum-averaged approximation





Relative error

$$\varepsilon = \frac{|\mathrm{dep} - \mathrm{avg}|}{\mathrm{dep}} \quad (5)$$

- Planck Collaboration, *Planck 2018 results. VI. Cosmological Parameters* (1807.06209)
- Simons Observatory Collaboration, *The Simons Observatory: Science goals and forecasts* (1808.07445)
- CMB-S4 Collaboration, *Snowmass 2021 CMB-S4 White Paper* (2203.08024)
- CMB-HD Collaboration, *Snowmass 2021 CMB-HD White Paper* (2203.05728)
- Jihn E. Kim, *Weak-Interaction Singlet and Strong CP Invariance* (Phys. Rev. Lett. 43, 103)
- Mikhail A. Shifman, A.I. Vainshtein, Valentin I. Zakharov, *Can Confinement Ensure Natural CP Invariance of Strong Interactions* (Nucl. Phys. B 166)
- Pierluca Carenza, Tobias Fischer, Maurizio Giannotti, Gang Duo, Gabriel Matrinez-Pinedo, Alessandro Mirizzi, *Improved axion emissivity from a supernova via nucleon-nucleon bremsstrahlung* (1906.11844)