

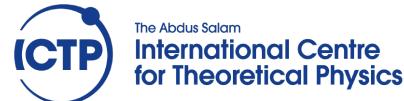


Portorož 2023

April 11 - 14, 2023
Particle Physics from Early Universe to Future Colliders

Improved hot dark matter bound on the QCD axion

Giovanni Villadoro



2211.03799 with A. Notari and F. Rompineve

The (Minimal) QCD Axion

$$\mathcal{L}_{SM}^{\theta=0} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a} \frac{\alpha_s}{8\pi} G\tilde{G} + \dots$$

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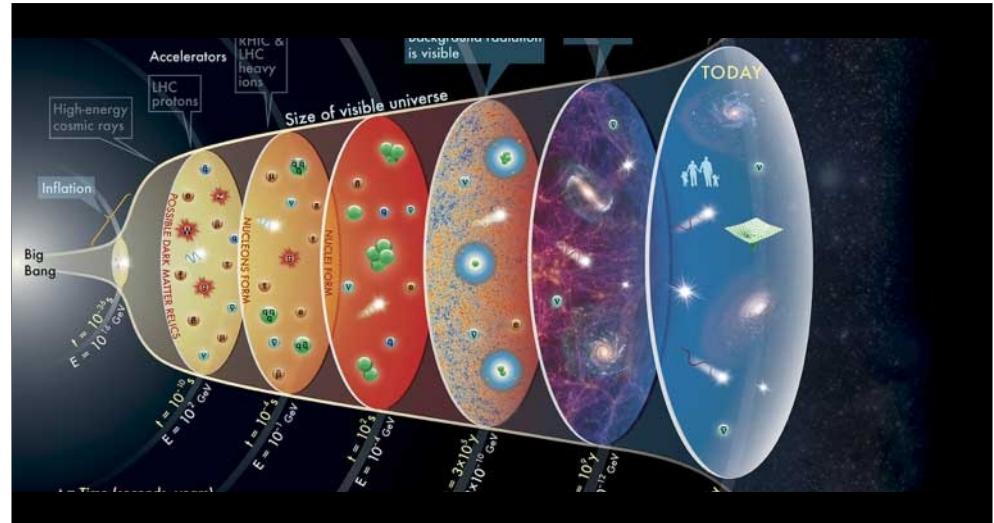
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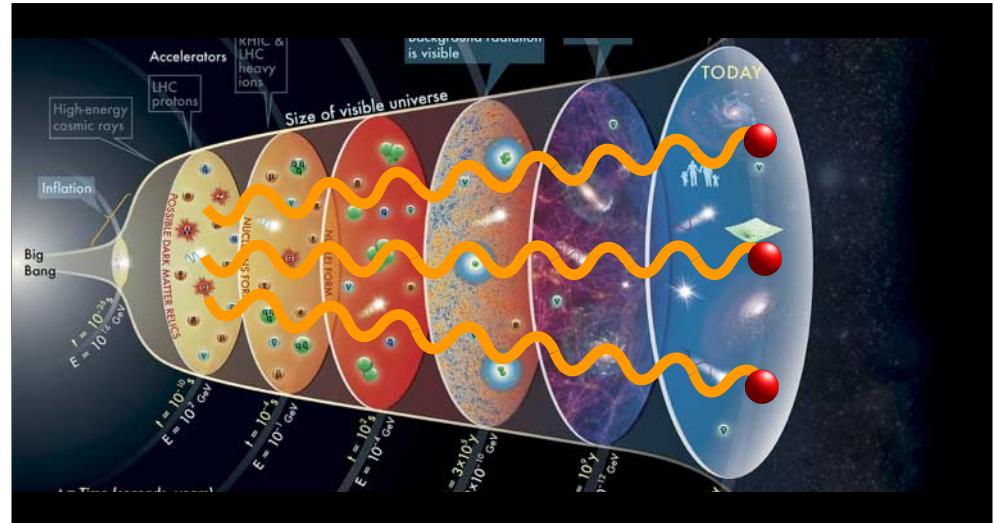
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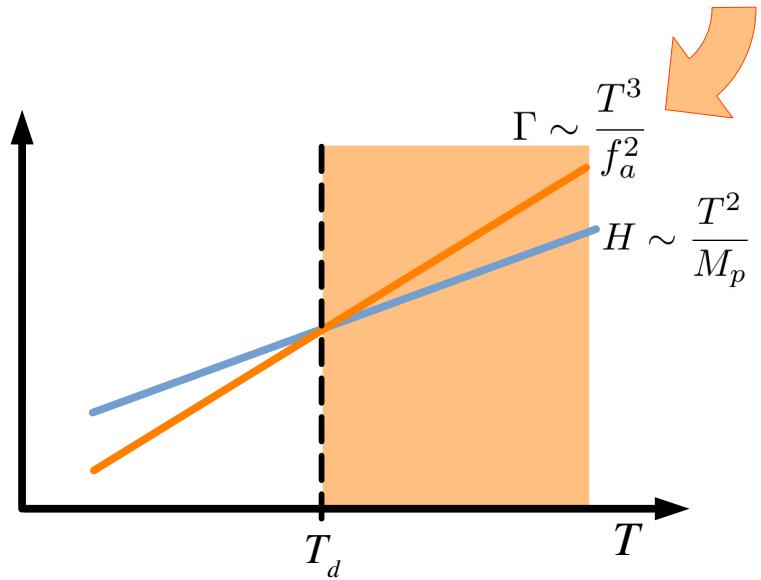
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$$\Gamma \sim \frac{T^3}{f_a^2}$$



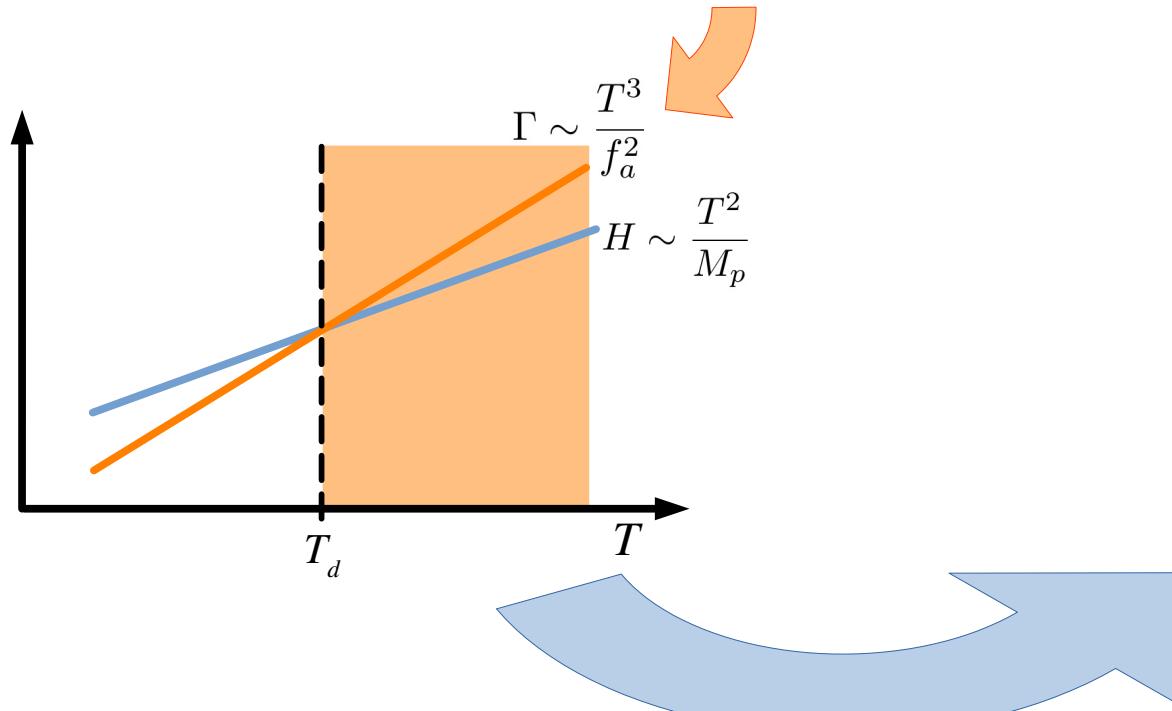
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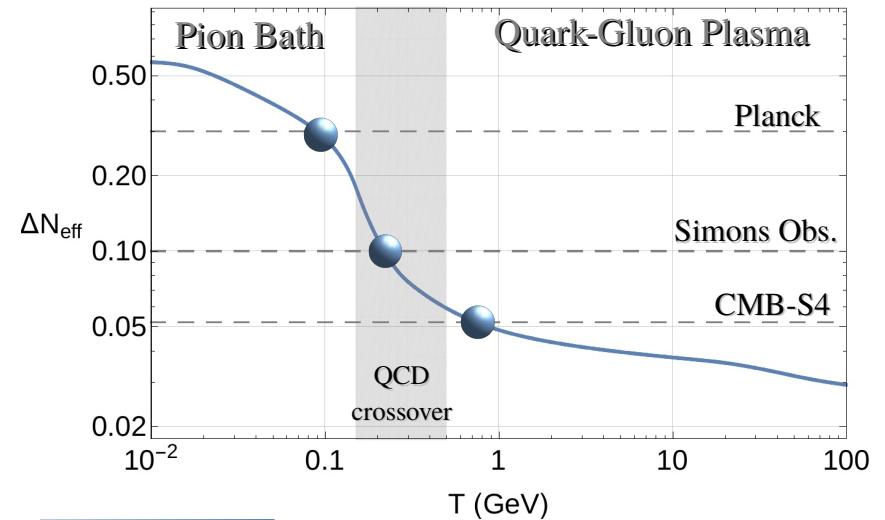
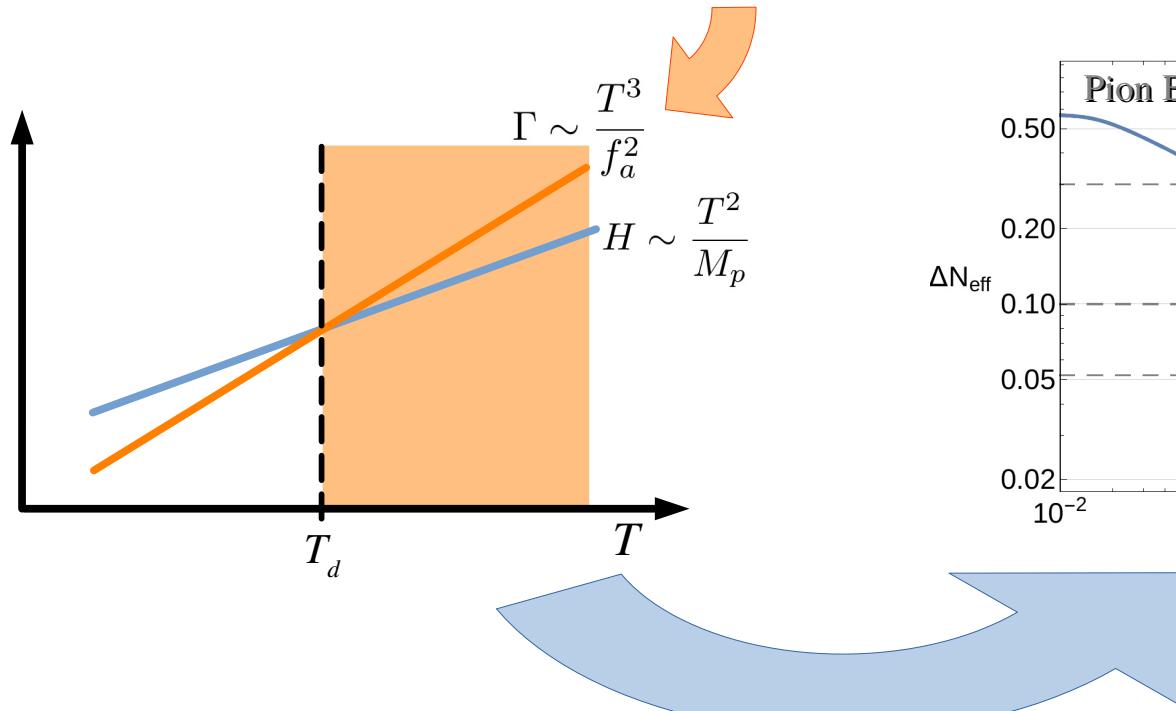
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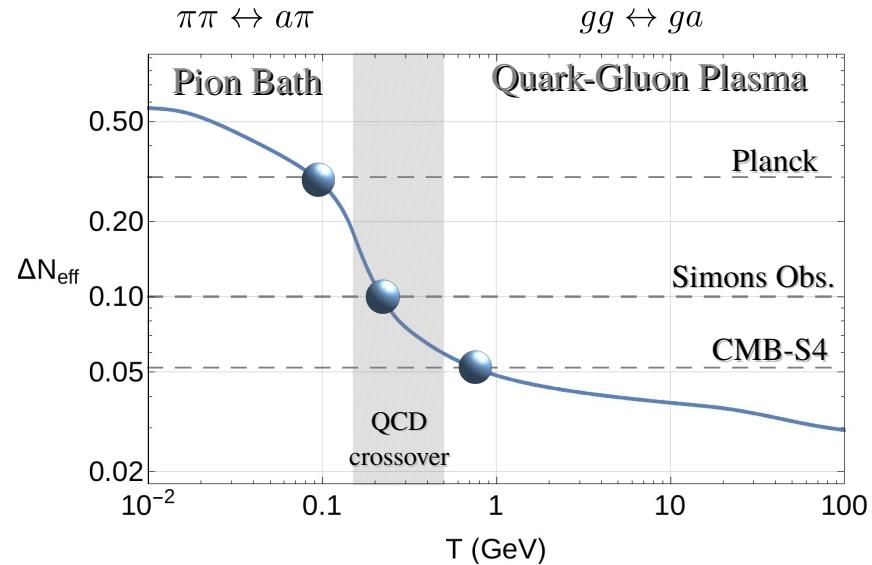
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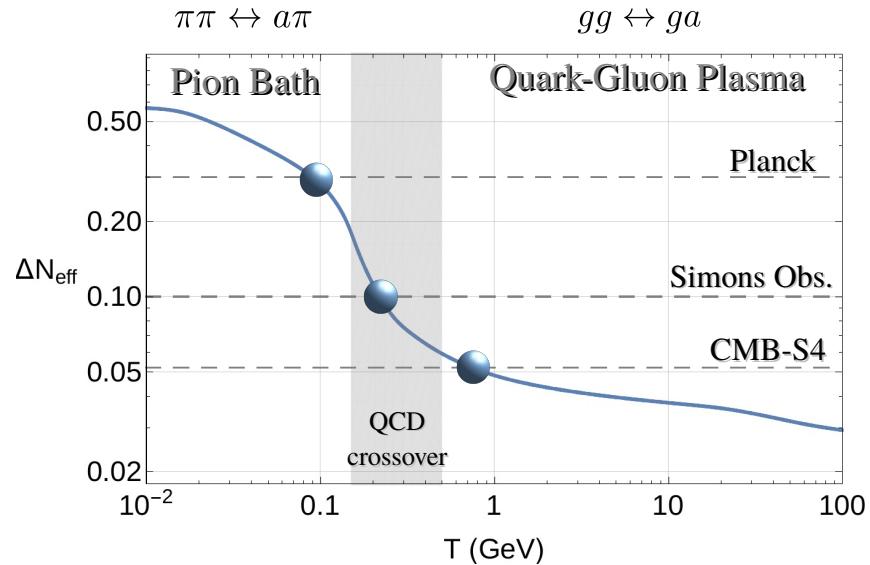
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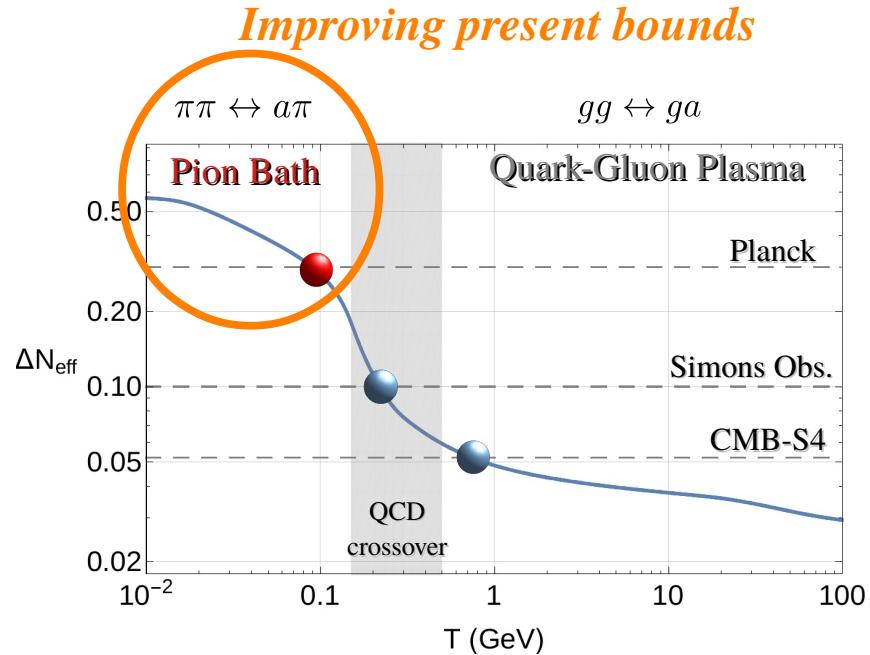


Boltzmann Eq.

$$\frac{dY}{d \log x} = (Y^{\text{eq}} - Y) \frac{\bar{\Gamma}}{H} \left(1 - \frac{1}{3} \frac{d \log g_{*,S}}{d \log x} \right)$$

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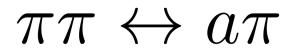


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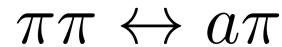
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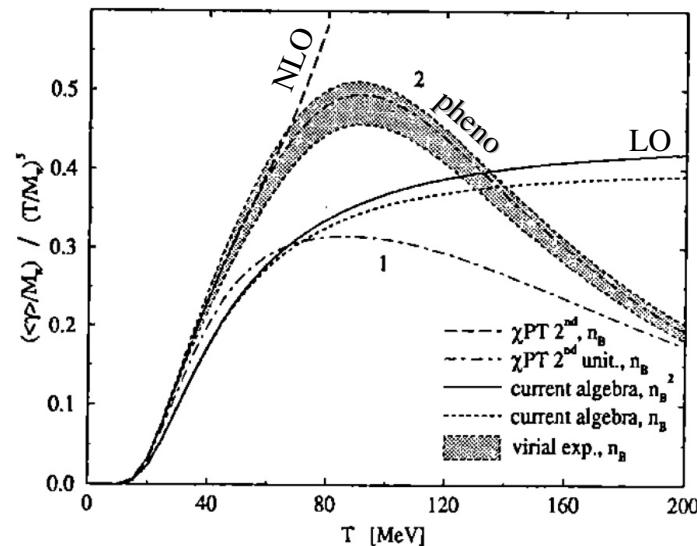
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Schenk '94

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@ all orders in χ PT

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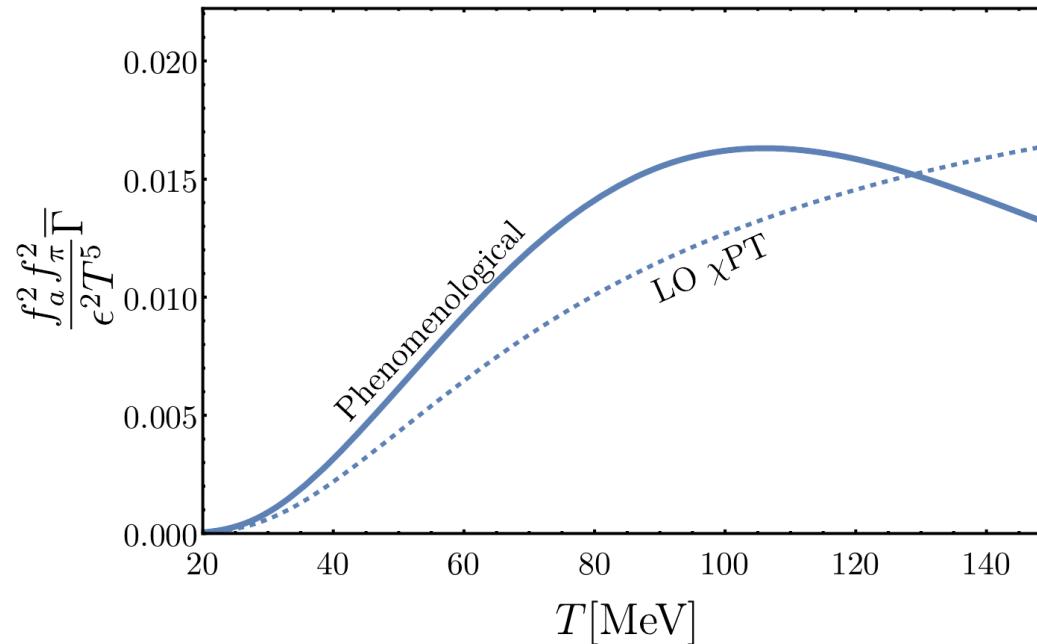
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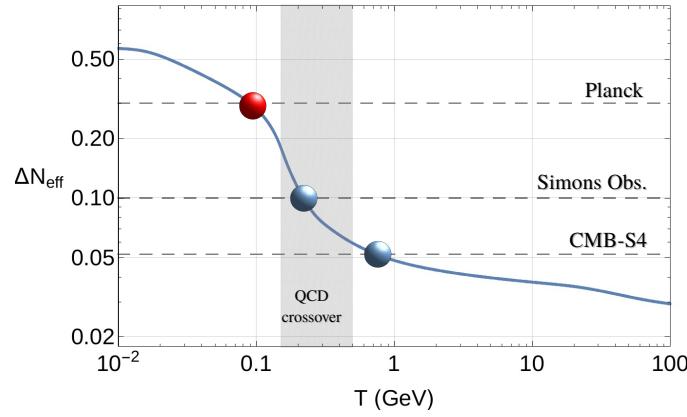
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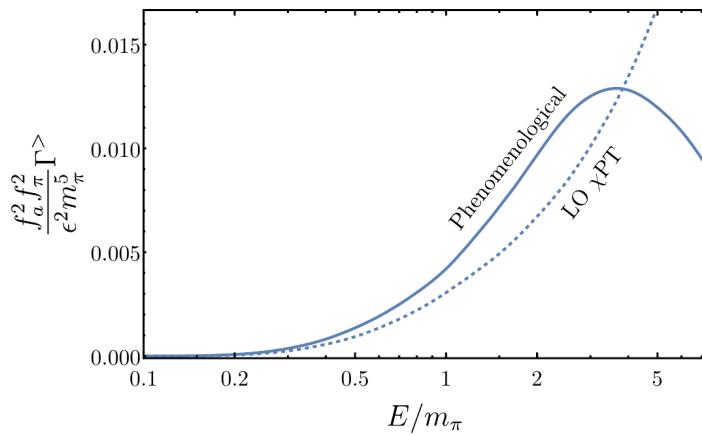
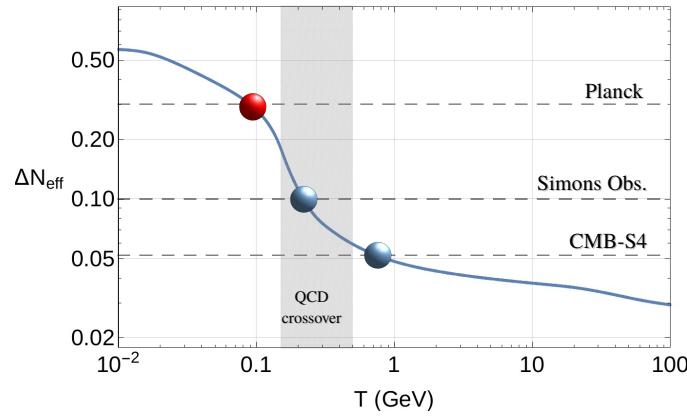
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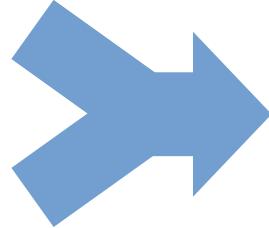
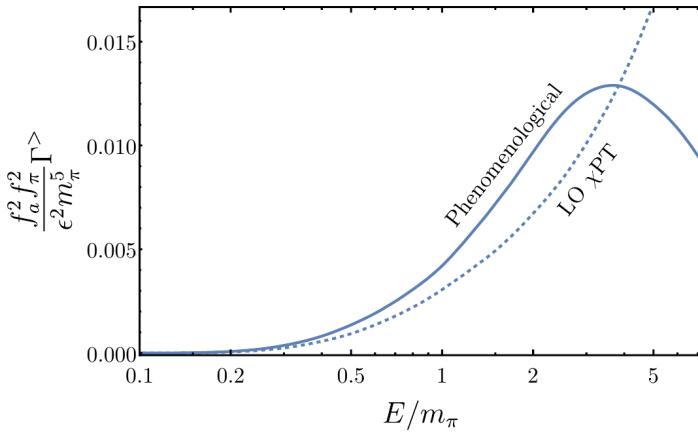
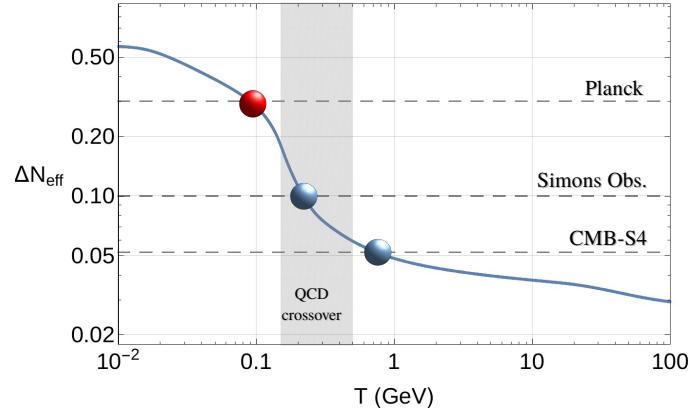
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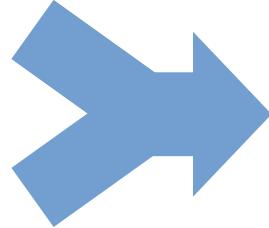
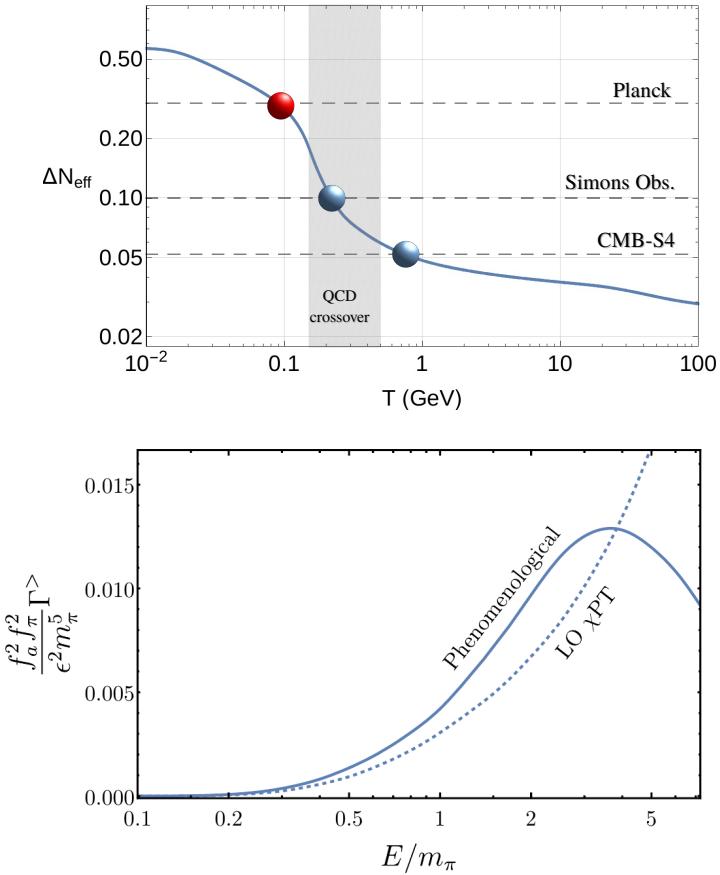
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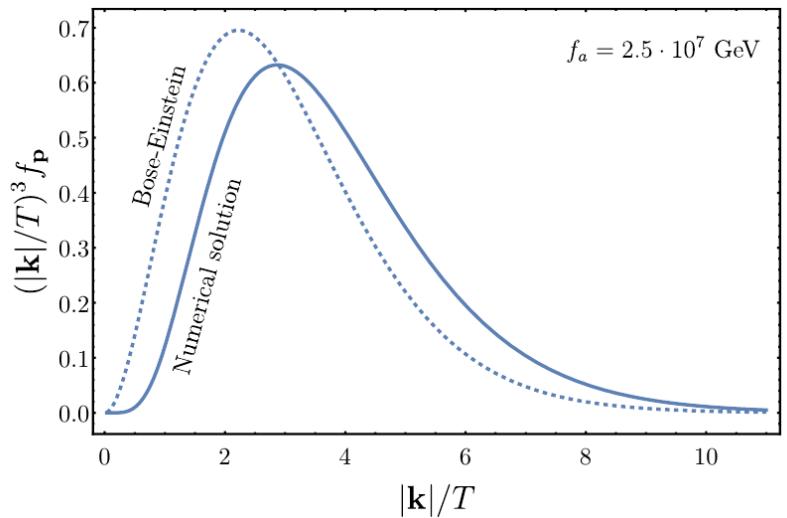
$$\frac{df_p}{dt} = (1 + f_p) \Gamma^< - f_p \Gamma^>$$

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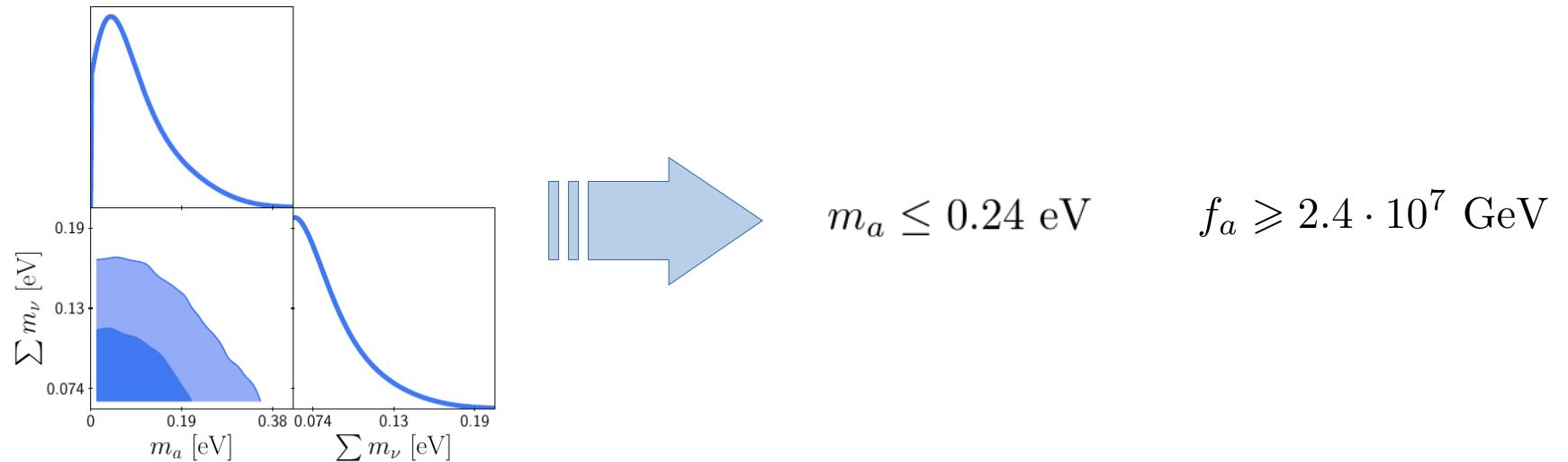
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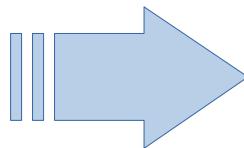
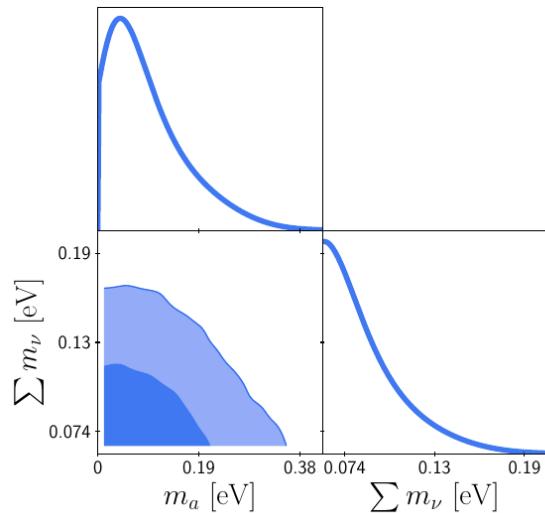
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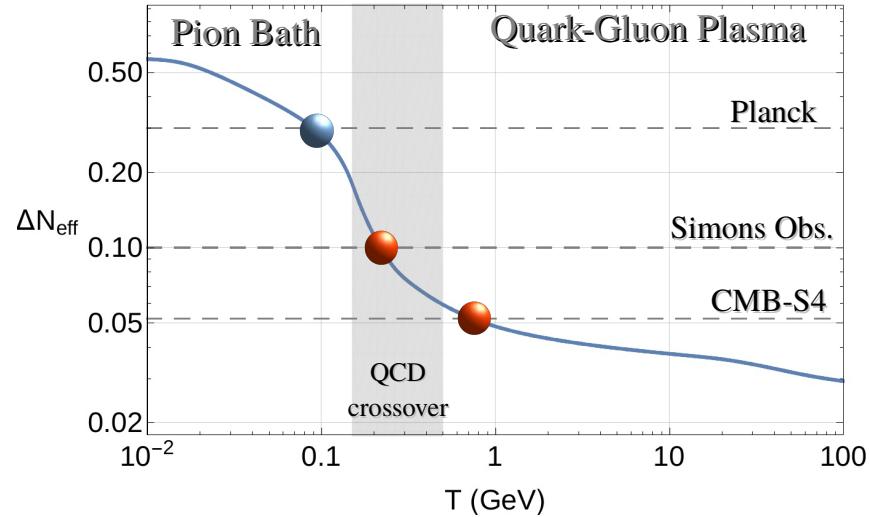
$$m_a \leq 0.24 \text{ eV} \quad f_a \geq 2.4 \cdot 10^7 \text{ GeV}$$

\Leftrightarrow

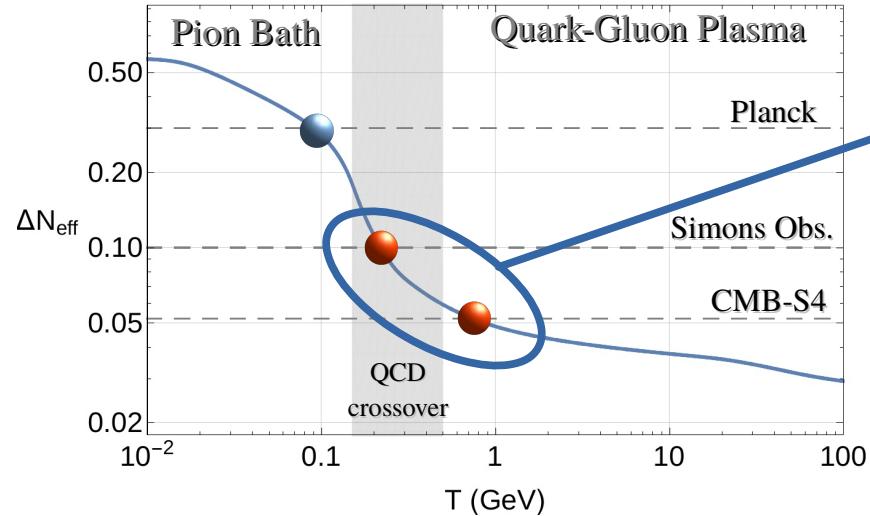
$$\Delta N_{\text{eff}} \lesssim 0.19$$

finite mass effect
 $\sim 40\%$ enhancement

Future Reach



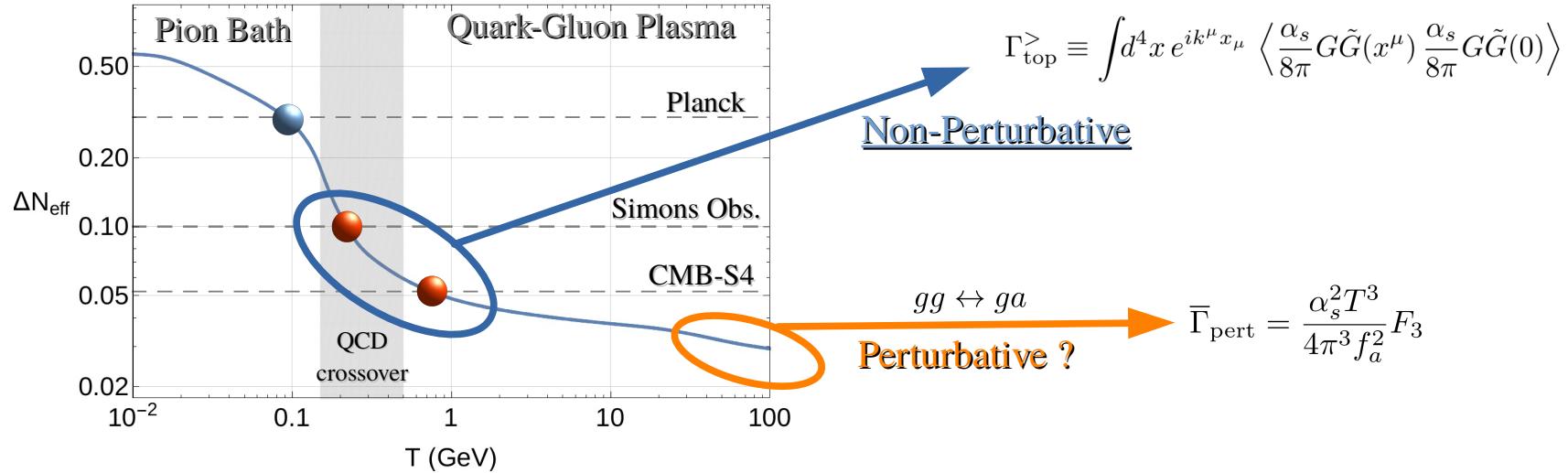
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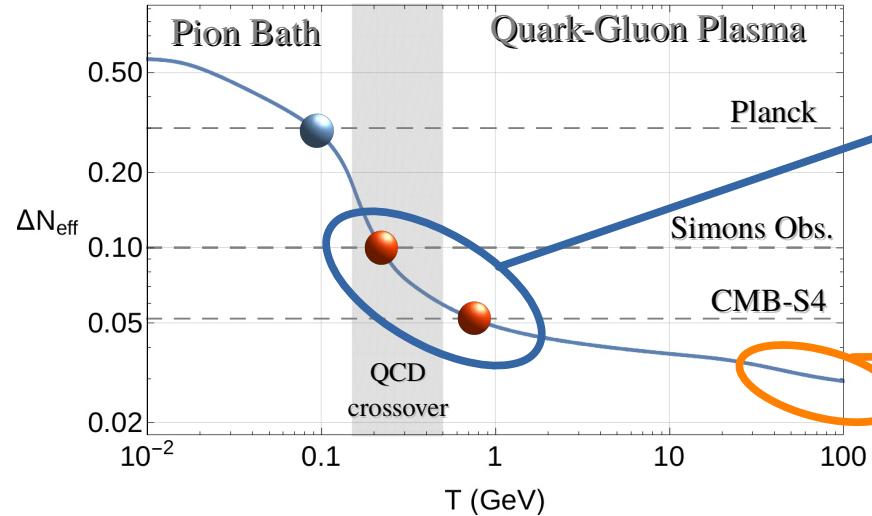
$$\Gamma_{\text{top}}^> \equiv \int d^4x e^{ik^\mu x_\mu} \left\langle \frac{\alpha_s}{8\pi} G\tilde{G}(x^\mu) \frac{\alpha_s}{8\pi} G\tilde{G}(0) \right\rangle$$

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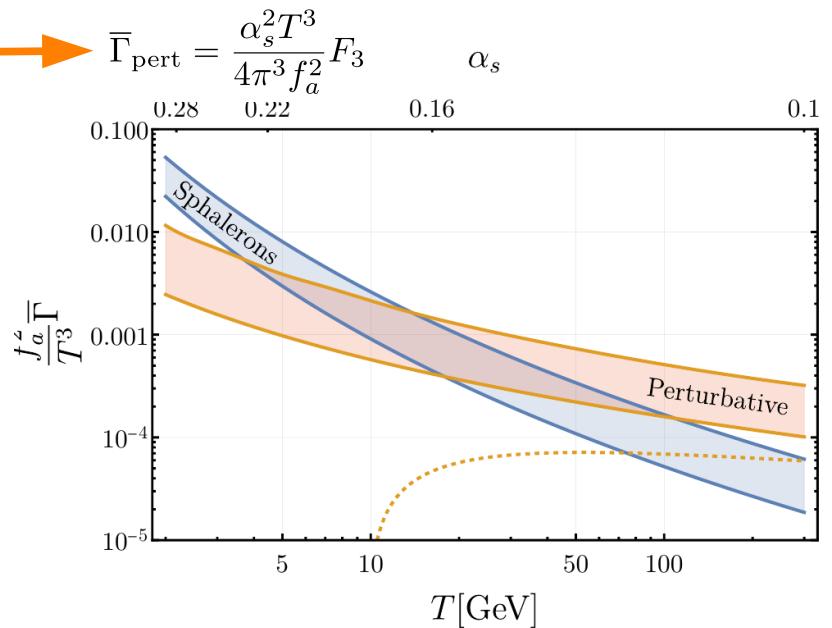


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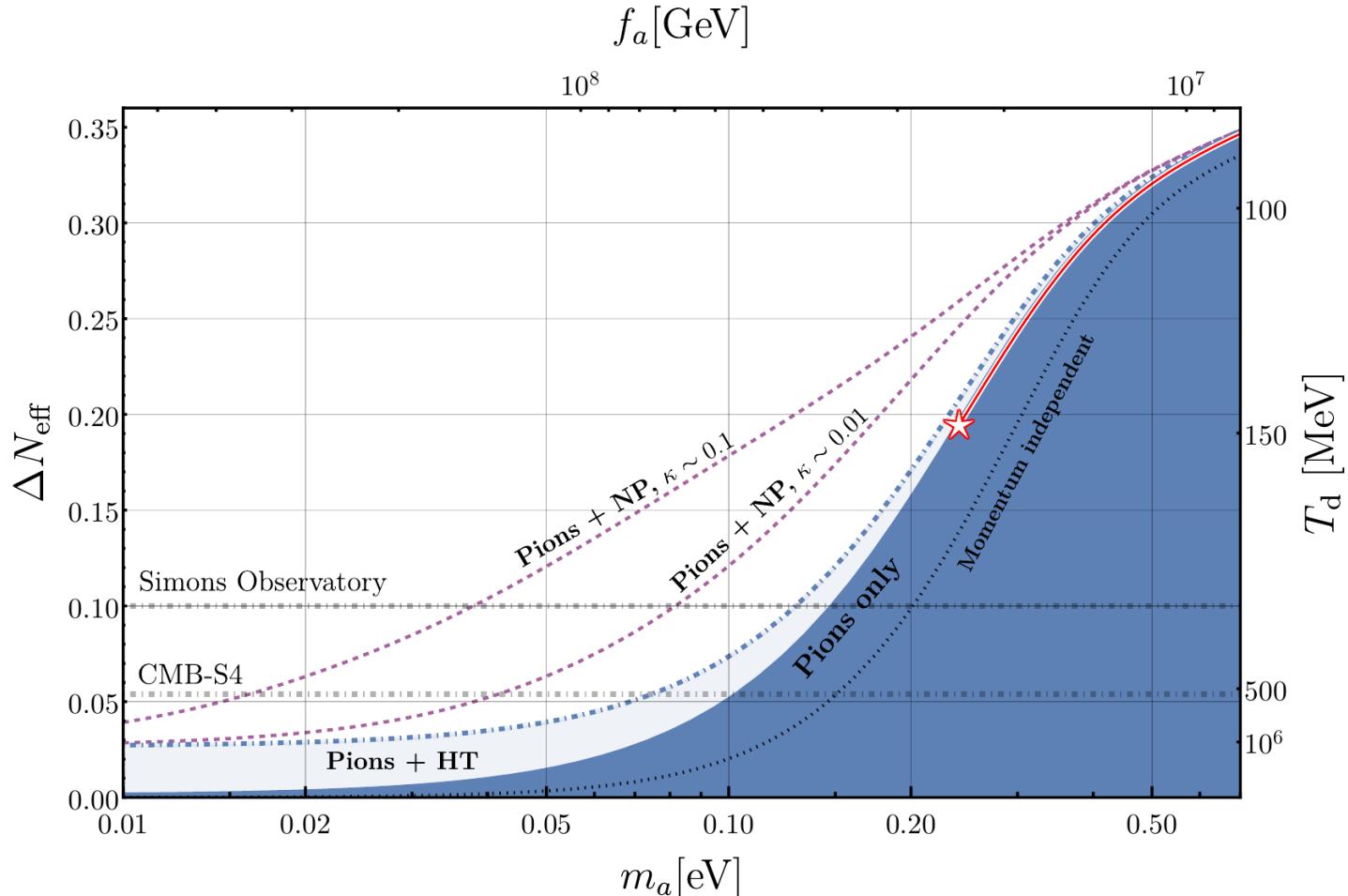
Non-Perturbative

$gg \leftrightarrow ga$

Perturbative ?



Future Reach



Thanks!

Back Up

Momentum dependent Boltzmann Equations

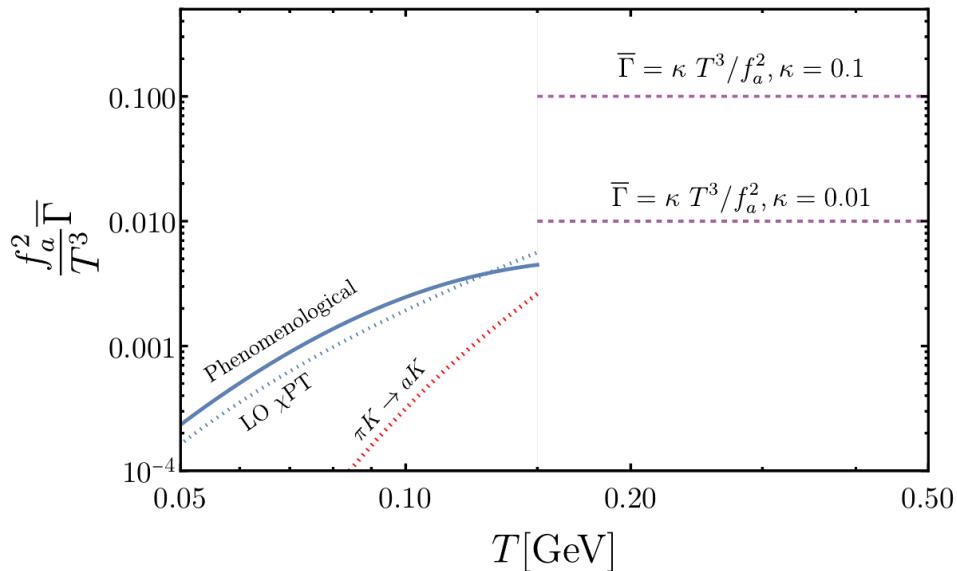
$$\frac{df_{\mathbf{p}}}{dt} = (1 + f_{\mathbf{p}}) \Gamma^< - f_{\mathbf{p}} \Gamma^>$$

$$\Gamma^> = e^{\frac{E}{T}} \Gamma^< = \frac{\Gamma_{\text{top}}^>}{2E f_a^2}, \quad \quad \Gamma_{\text{top}}^> \equiv \int d^4x e^{ik^\mu x_\mu} \left\langle \frac{\alpha_s}{8\pi} G \tilde{G}(x^\mu) \frac{\alpha_s}{8\pi} G \tilde{G}(0) \right\rangle$$

$$\Gamma^< = \frac{1}{2E} \int \left(\prod_{i=1}^3 \frac{d^3 \mathbf{k}_i}{(2\pi)^3 2E_i} \right) f_1^{\text{eq}} f_2^{\text{eq}} (1 + f_3^{\text{eq}}) (2\pi)^4 \delta^{(4)}(k_1^\mu + k_2^\mu - k_3^\mu - k^\mu) |\mathcal{M}|^2$$

Strong Sphaleron-like contribution to Axion rate

$$\bar{\Gamma}_{\text{sphal}} = \frac{1}{n^{\text{eq}}} \int \frac{d^3\mathbf{k}}{(2\pi)^3 2E} \frac{\Gamma_{\text{sphal}}}{f_a^2} e^{-E/T} = \frac{(N_c \alpha_s)^5 T^3}{4\zeta_3 f_a^2} \left(1 - \left(1 + \frac{|\mathbf{k}_s|}{T} \right) e^{-|\mathbf{k}_s|/T} \right)$$



$$\begin{aligned}\Gamma_{\text{top}}^>(E = |\mathbf{k}| < |\mathbf{k}_s|) &\simeq \Gamma_{\text{sphal}} \simeq (N_c \alpha_s)^5 T^4 \\ |\mathbf{k}_s| &\sim N_c \alpha_s T\end{aligned}$$