Axions and saxions from the primordial supersymmetric plasma and extra radiation signatures

[P.G.,Steffen, arXiv:1208.2951]

Peter Graf
Max-Planck-Institut für Physik
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Origin of the saxion

The Strong CP Problem

- The θ-vacuum term is CP-violating

$$\mathcal{L}_{\mathrm{CP}} = \bar{\theta}\,\frac{g^2}{32\pi^2} G^b_{\mu\nu} \widetilde{G}^{b\,\mu\nu}$$

- Prefactor is a sum of two independent quantities

$$\bar{\theta} = \theta_{\mathrm{QCD}} - \arg\det M$$

- Measurements of the electric dipole moment of the neutron yield the constraint

$$|\bar{\theta}| < 10^{-10}$$

The Peccei - Quinn solution

[Peccei,Quinn, '77]

- A global chiral U(1) ensures CP conservation dynamically
- Spontaneous breaking at f_{PQ}
- Resulting Goldstone boson is the axion

$$\mathcal{L}_{\rm PQ} = \frac{g^2}{32\pi^2 f_{\rm PQ}} a G^b_{\mu\nu} \widetilde{G}^{b\,\mu\nu}$$

- Axion acquires mass and restores CP

Supersymmetric version

- Two more particles: axino and saxion
- Saxion mass:
- SUSY requires superpotential to be holomorphic
- Turns real U(1) into a complex symmetry

$$\Phi \to e^{\Lambda}\Phi \qquad \Lambda \in \mathbb{C}$$

- flat direction makes saxion massless

[Kugo, Ojima, Yanagida, '84]

- SUSY breaking gives saxion a mass

Coupling and decay rates

Saxion Couplings

$$A = (\sigma + ia)/\sqrt{2} + \sqrt{2}\theta\tilde{a} + F_A\theta\theta$$

$$\mathcal{L}_{\mathrm{PQ}} = -\frac{\sqrt{2}\alpha_s}{8\pi f_{\mathrm{PQ}}}\int d^2\theta A W^b W^b + \mathrm{h.c.}$$

$$\mathcal{L}_{\mathrm{PQ}}^{\mathrm{int}} = \frac{\alpha_s}{8\pi f_{\mathrm{PQ}}}\Big[\sigma\left(G^{b\,\mu\nu}G^b_{\mu\nu} - 2D^bD^b - 2i\bar{\tilde{g}}^b_M\gamma^\mu D_\mu\tilde{g}^b_M\right)$$
$$+a\left(G^{b\,\mu\nu}\widetilde{G}^b_{\mu\nu} + 2\bar{\tilde{g}}^b_M\gamma^\mu\gamma^5 D_\mu\tilde{g}^b_M\right)$$
$$-i\bar{\tilde{a}}_M\frac{[\gamma^\mu,\gamma^\nu]}{2}\gamma^5\tilde{g}^b_M G^b_{\mu\nu} + 2\bar{\tilde{a}}_M D^b\tilde{g}^b_M\Big]$$

Models of PQ sector

- Focus on hadronic models
- SM-singlet PQ fields ϕ_i with charges q_i and VEVs v_i
- Near the VEVs the scalar part can be written as

$$\phi_i = v_i \exp\left[\frac{q_i(\sigma + ia)}{\sqrt{2}v_{\mathrm{PQ}}}\right]$$

Saxion coupling to axions

$$\mathcal{L}_{\mathrm{PQ}}^{\mathrm{kin}} = \sum_{i=1}^{N} \partial^\mu \phi_i \partial_\mu \phi_i^*$$

$$= \sum_{i=1}^{N} \left(\frac{v_i q_i}{\sqrt{2} v_{\mathrm{PQ}}} \right)^2 \left[(\partial_\mu a)^2 + (\partial_\mu \sigma)^2 \right] \exp\left(\frac{2 q_i \sigma}{\sqrt{2} v_{\mathrm{PQ}}} \right)$$

$$\sim \left(1 + \frac{\sqrt{2} x}{v_{\mathrm{PQ}}} \sigma \right) \left[\frac{1}{2} (\partial_\mu a)^2 + \frac{1}{2} (\partial_\mu \sigma)^2 \right] + \ldots$$

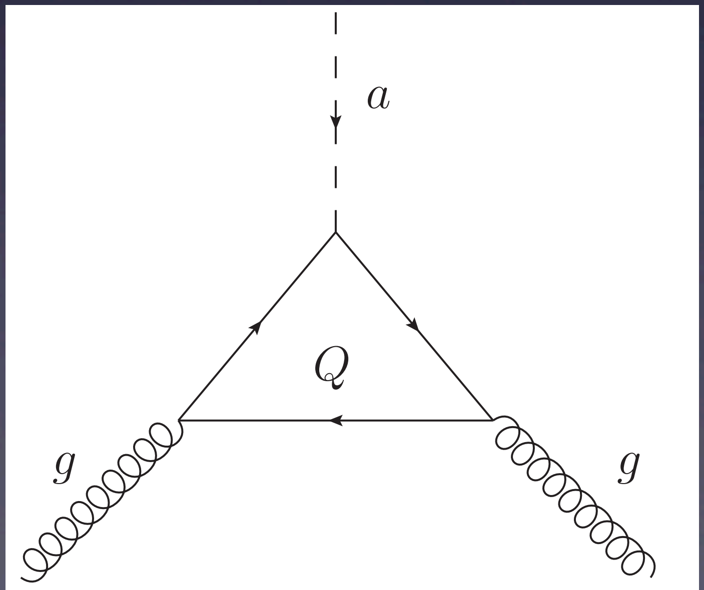
[Chun, Lukas, '95]

$$v_{\mathrm{PQ}} = \sqrt{\sum_i v_i^2 q_i^2} \qquad x = \sum_i \frac{q_i^3 v_i^2}{v_{\mathrm{PQ}}^2}$$

Relation of two PQ scales

- Kinetic term defines v_{PQ}
- Effective interaction defines f_{PQ}
- Relation via quark loop from superpotential:

$$h\Phi_1 Q_L \bar{Q}_R$$



$$\mathcal{L}^{\rm int} = \frac{h v_1 \alpha_s}{8\pi\sqrt{2} m_Q v_{\rm PQ}} a G^{b\,\mu\nu} \widetilde{G}^b_{\mu\nu}$$

$$f_{\rm PQ} = \sqrt{2} v_{\rm PQ}$$

[P.G., Steffen, arXiv:1208.2951]

Saxion Decay

- The saxion is unstable with decay width

$$\Gamma_\sigma \propto \frac{m_\sigma^3}{f_{\rm PQ}^2}$$

- Decay into axions may be dominant

$$\Gamma_{\sigma\to aa} = \frac{x^2 m_\sigma^3}{64\pi v_{\rm PQ}^2} = \frac{x^2 m_\sigma^3}{32\pi f_{\rm PQ}^2}$$

- Decay into gluons

$$\Gamma_{\sigma\to gg} = \frac{\alpha_s^2 m_\sigma^3}{16\pi^3 f_{\rm PQ}^2}$$

Additional radiation from saxion decay

Additional radiation

- Radiation content of the Universe:

$$\rho_{\rm rad}(T) = \left[1 + \frac{7}{8} N_{\rm eff} \left(\frac{T_\nu}{T}\right)^4\right] \rho_\gamma(T)$$

- Extra radiation parametrized by

$$N_{\rm eff} = 3 + \Delta N_{\rm eff} \qquad T \gtrsim T_\nu^{\rm dec}$$

$$N_{\rm eff} = 3.046 + \Delta N_{\rm eff} \qquad T \lesssim T_\nu^{\rm dec}$$

Axions from saxion decay

- If all of extra rad are non-thermal axions ...

$$\Delta N_{\rm eff}(T) = \frac{120}{7\pi^2 T_\nu^4}\,\rho_{\rm a}^{\rm NTP}(T)$$

- ... that come from saxion decays:

$$\rho_{\rm a}^{\rm NTP}(T) = \frac{m_\sigma}{2}\left[\frac{g_{*S}(T)}{g_{*S}(T_\sigma)}\right]^{1/3}\frac{T}{T_\sigma}\,2Y_\sigma^{\rm eq/TP}\,s(T)$$

[Chang, Kim, '96;
Takahashi et al. '07;
Kawasaki et al., '08;]

Thermal Saxions

Thermal Saxions

- Saxions may reach thermal equilibrium (depends on T_R and f_{PQ})

$$Y_\sigma^{\mathrm{eq}} = \frac{n^{\mathrm{eq}}}{s} \simeq 1.2 \times 10^{-3}$$

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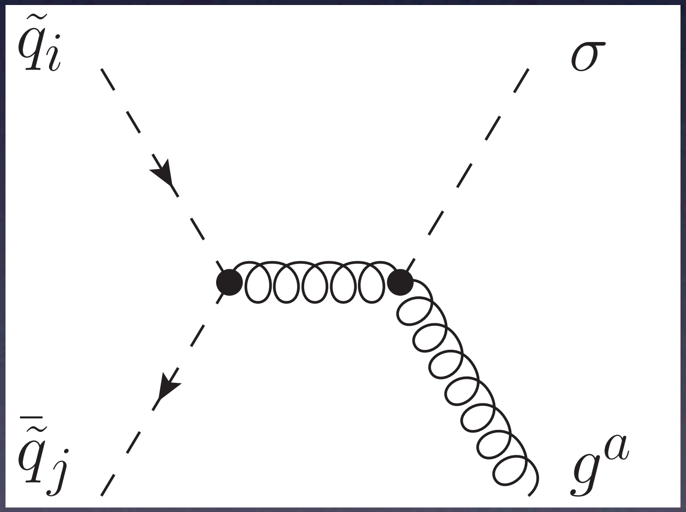
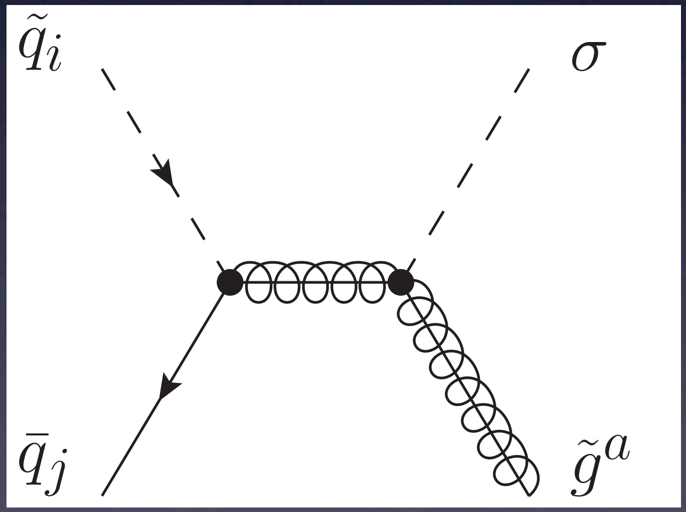
- If they do not, still production via scattering





$$Y_\sigma^{\mathrm{TP}} \simeq 1.33 \times 10^{-3} g_s^6 \ln\left(\frac{1.01}{g_s}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{f_{\mathrm{PQ}}}\right)^2\left(\frac{T_{\mathrm{R}}}{10^8\,\mathrm{GeV}}\right)$$

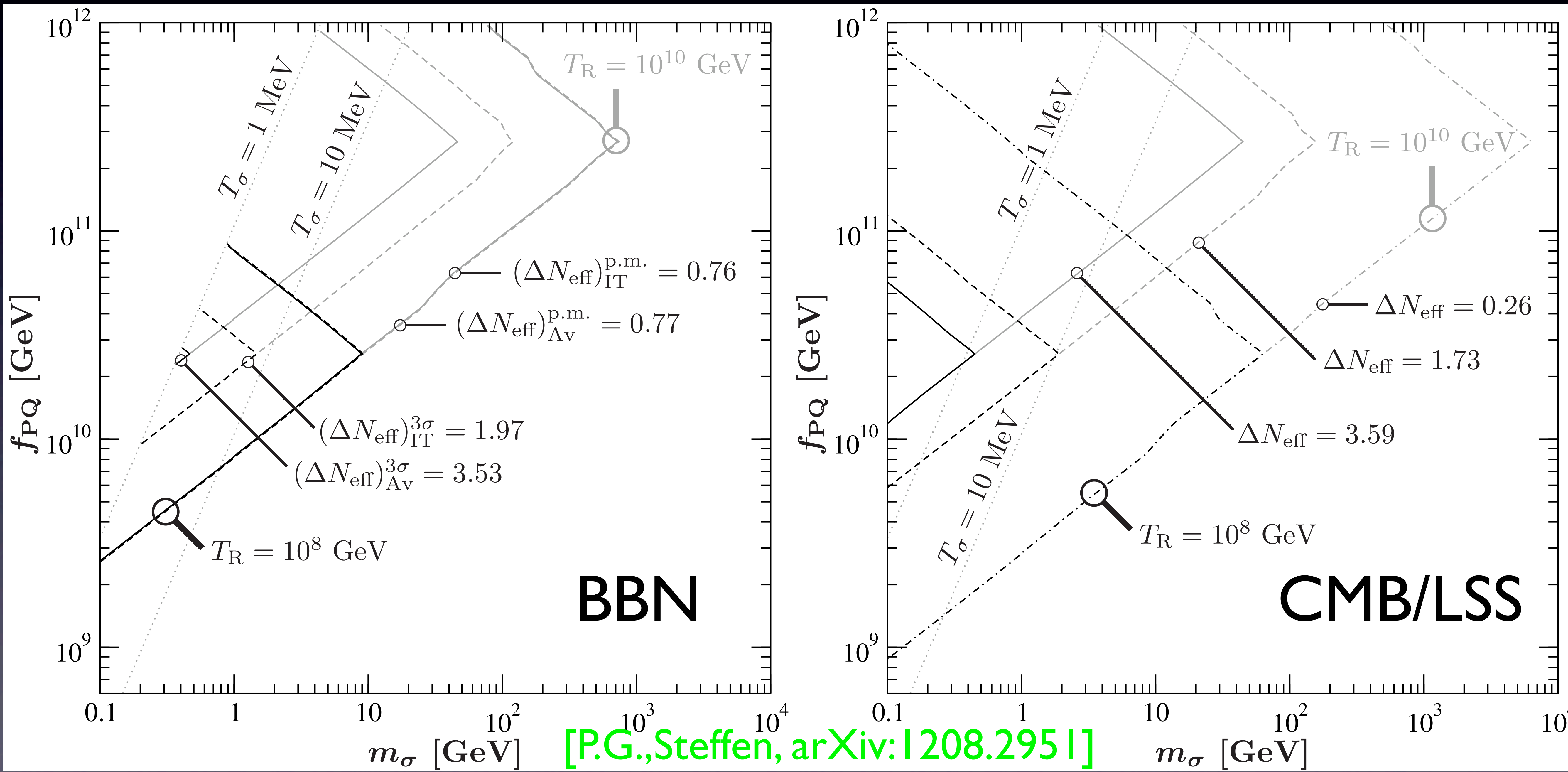
[P.G., Steffen, arXiv:1208.2951]

Additional radiation at BBN and CMB/LSS

Theoretical BBN prediction done with PArthENoPE

Data	p.m./mean	upper limit
$Y_\mathrm{p} + [\mathrm{D/H}]_\mathrm{p}$ [Izotov, Thuan, '10; Pettini et al., '08]	0.76	$< 1.97\ (3\sigma)$
$Y_\mathrm{p} + [\mathrm{D/H}]_\mathrm{p}$ [Aver et al., '10; Pettini et al., '08]	0.77	$< 3.53\ (3\sigma)$
$\mathrm{CMB} + \mathrm{HPS} + \mathrm{HST}$ [Hamann et al., '10]	1.73	$< 3.59\ (2\sigma)$

Extra radiation: limits on saxions



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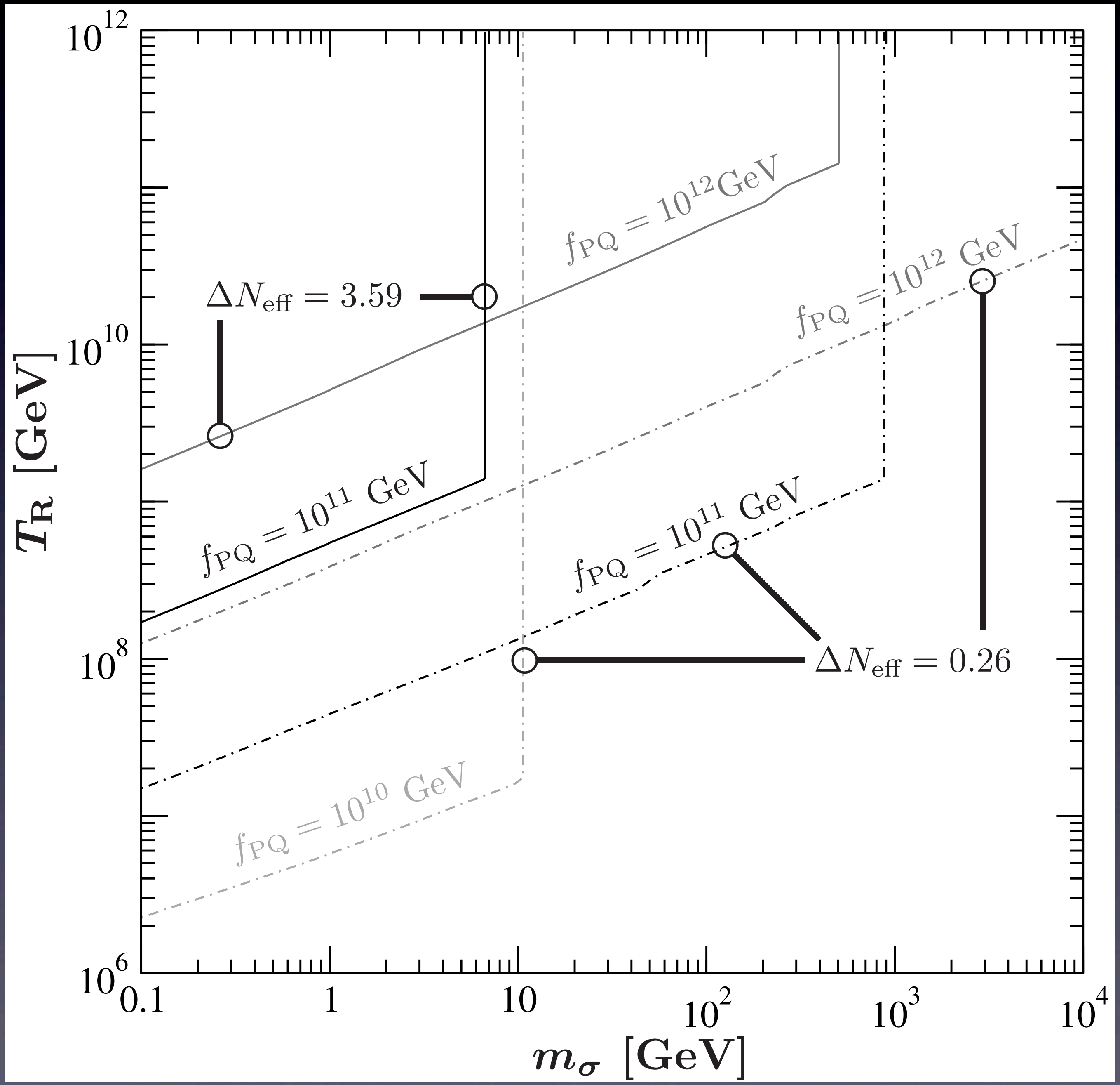
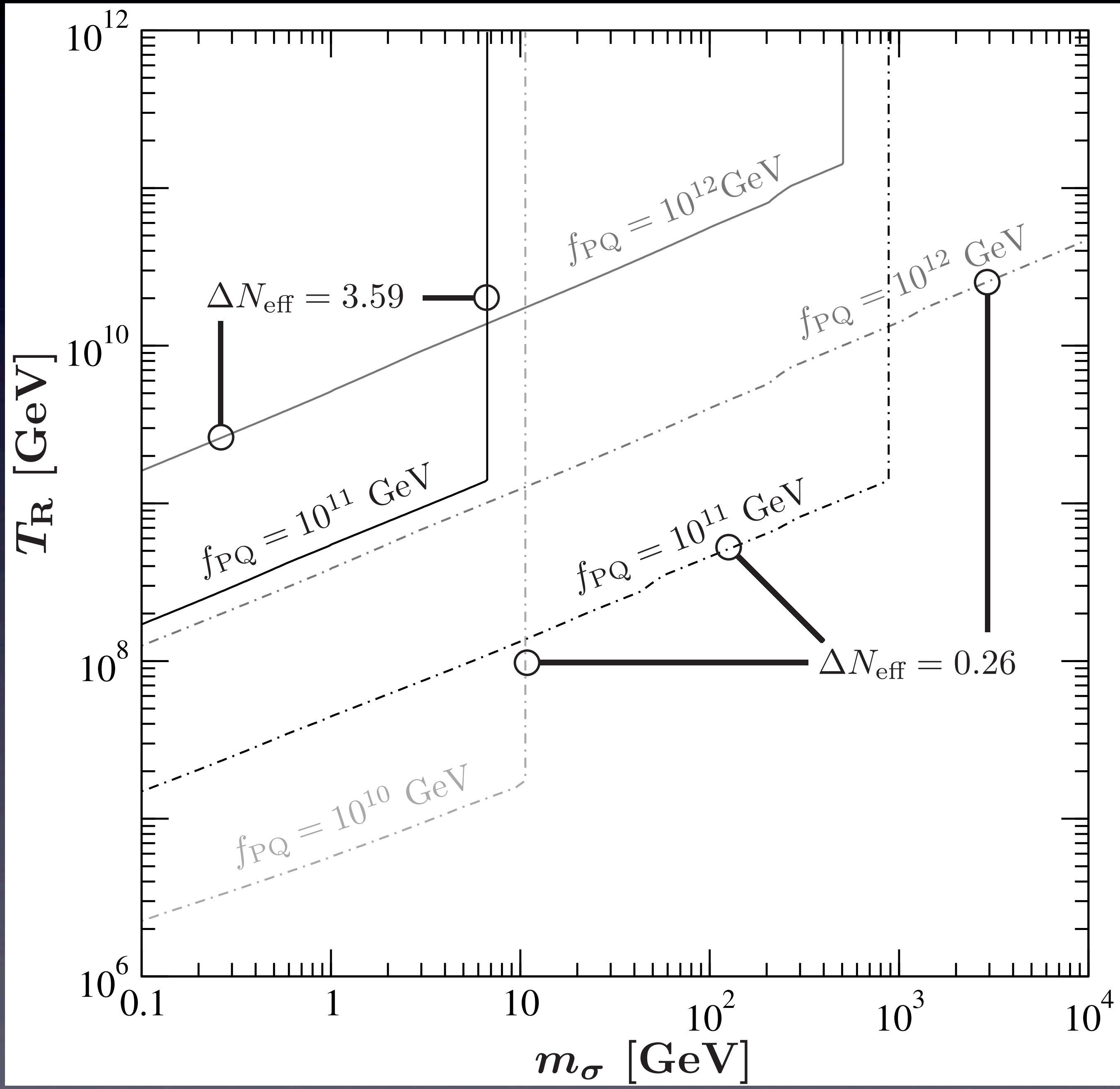
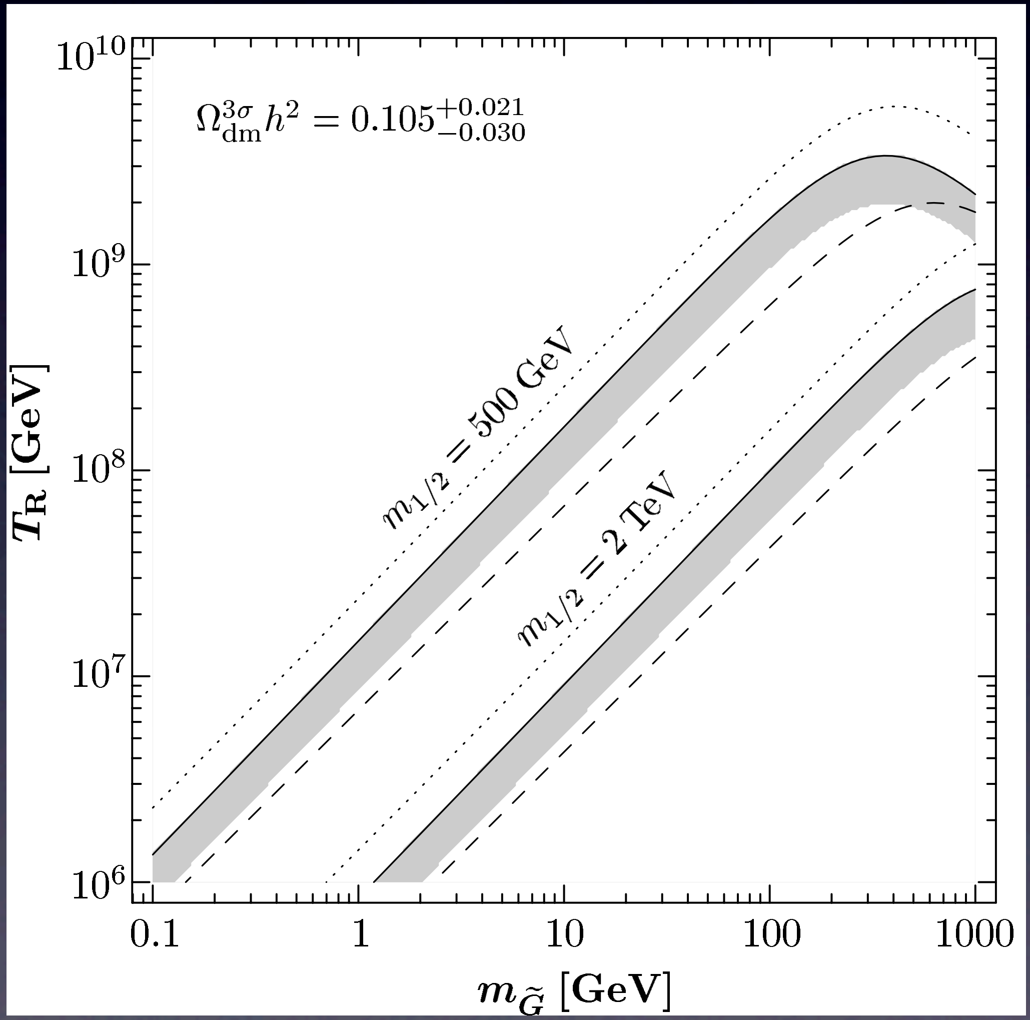
T_R upper limits



[P.G.,Steffen, arXiv:1208.2951; compare to: Kawasaki et al., '08]

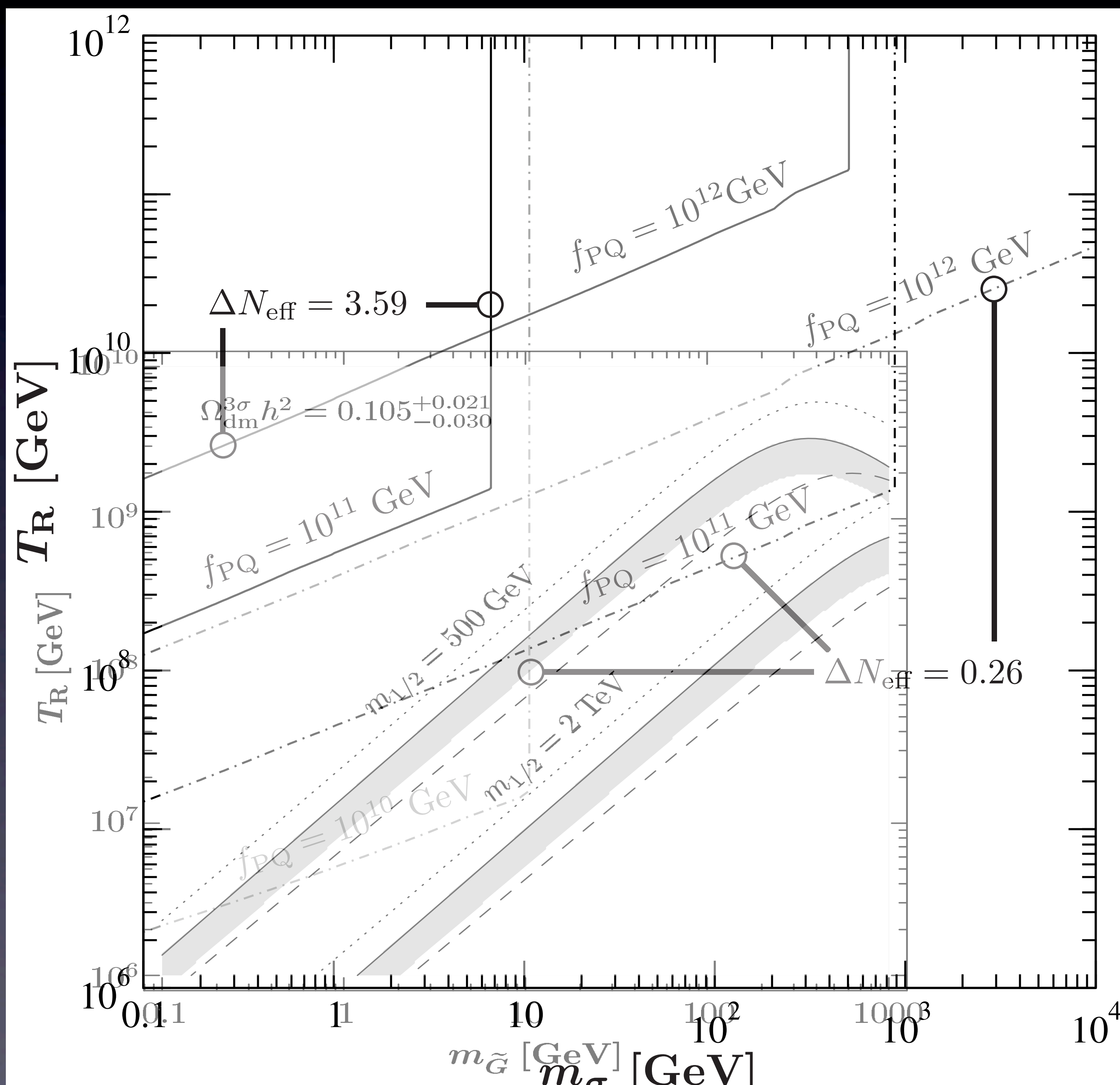
T_R limits (gravitino LSP)



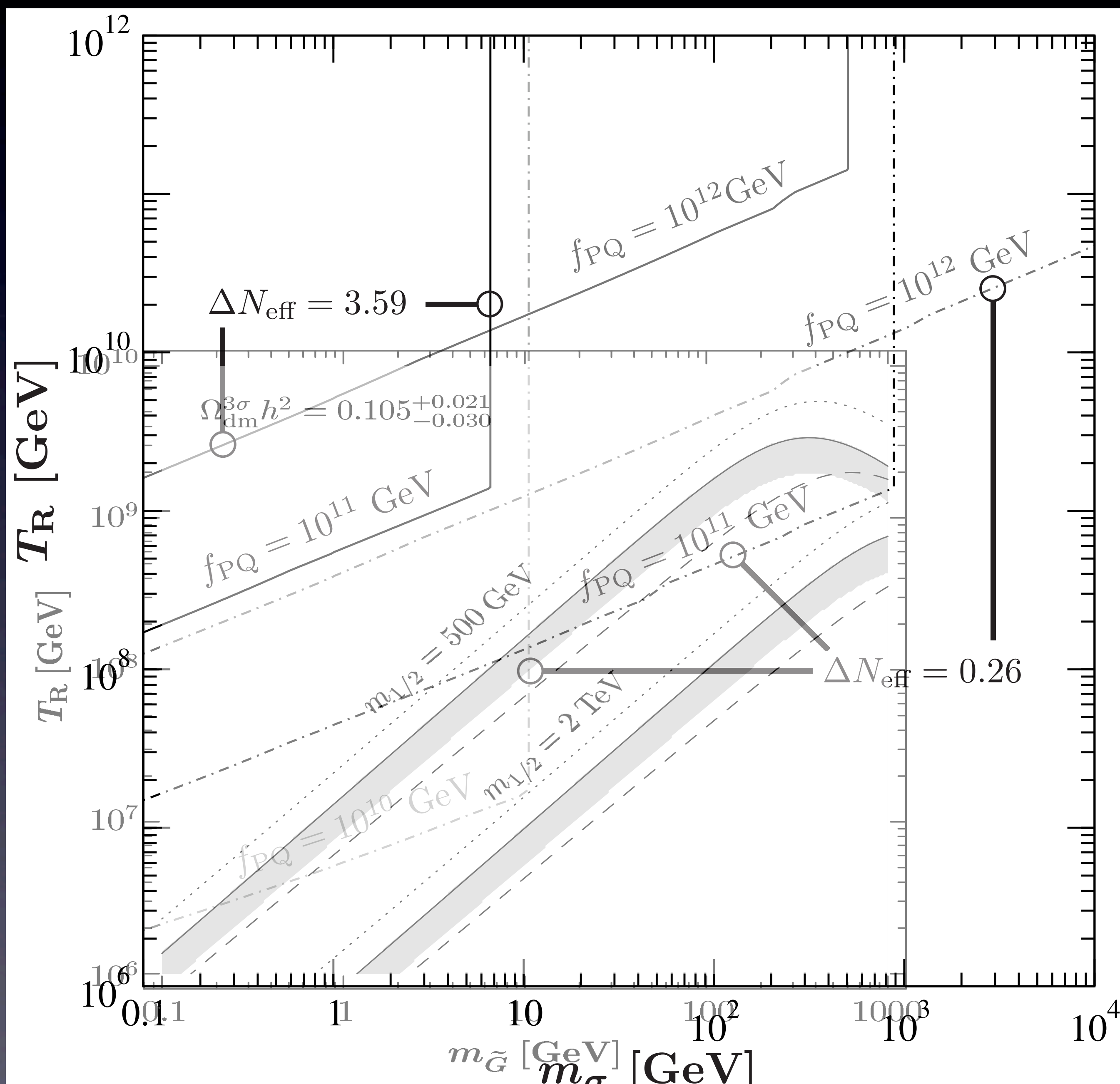


[Pradler, Steffen, '07]

T_R limits (gravitino LSP)

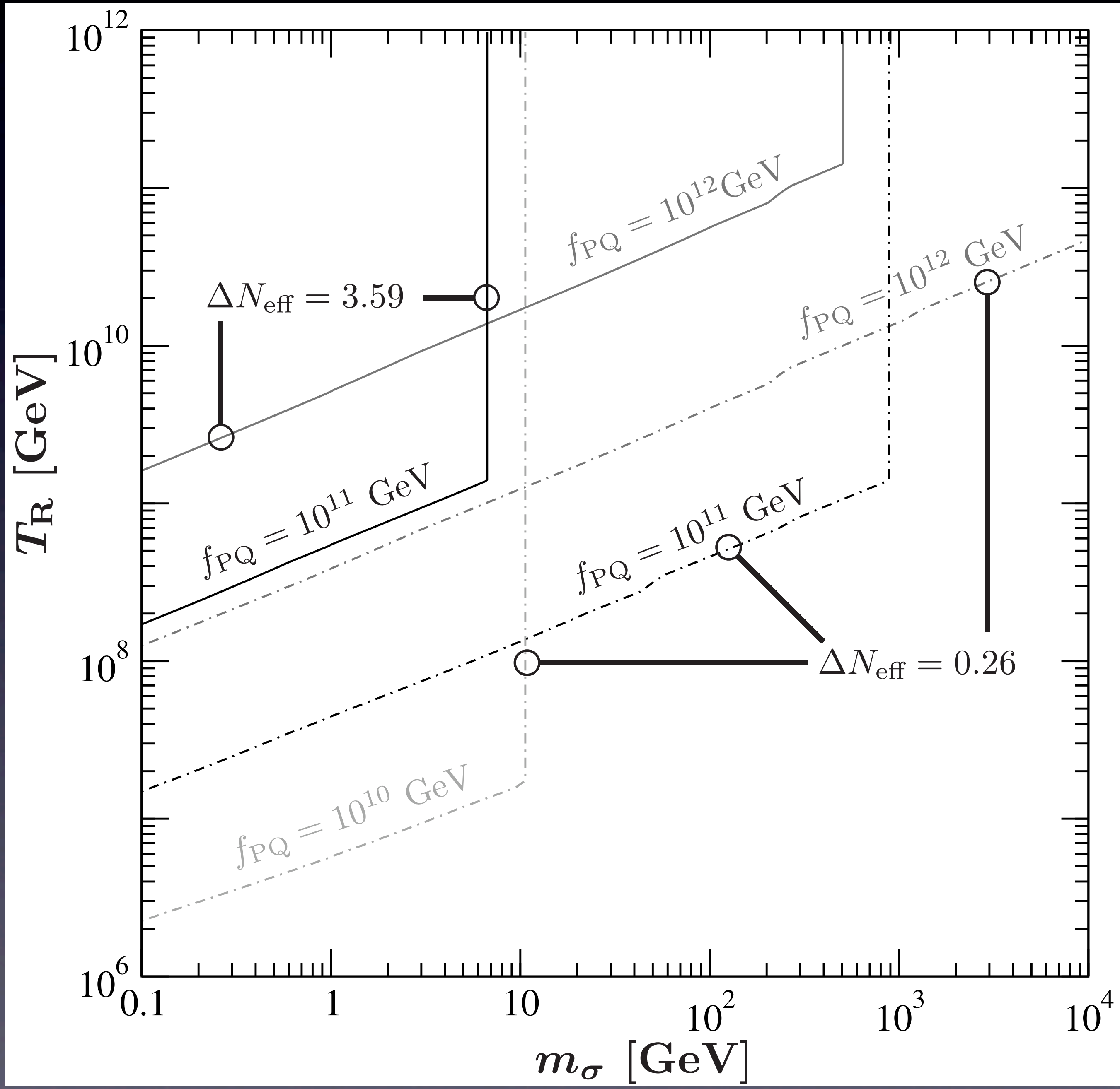


T_R limits (gravitino LSP)



- Gravitino LSP constraints are severe
- For $m_G \simeq 10$ GeV, $T_R \simeq 10^8$ GeV, $f_{PQ} \simeq 3 \cdot 10^{10}$ GeV: $\Delta N_{\text{eff}} \simeq 1$

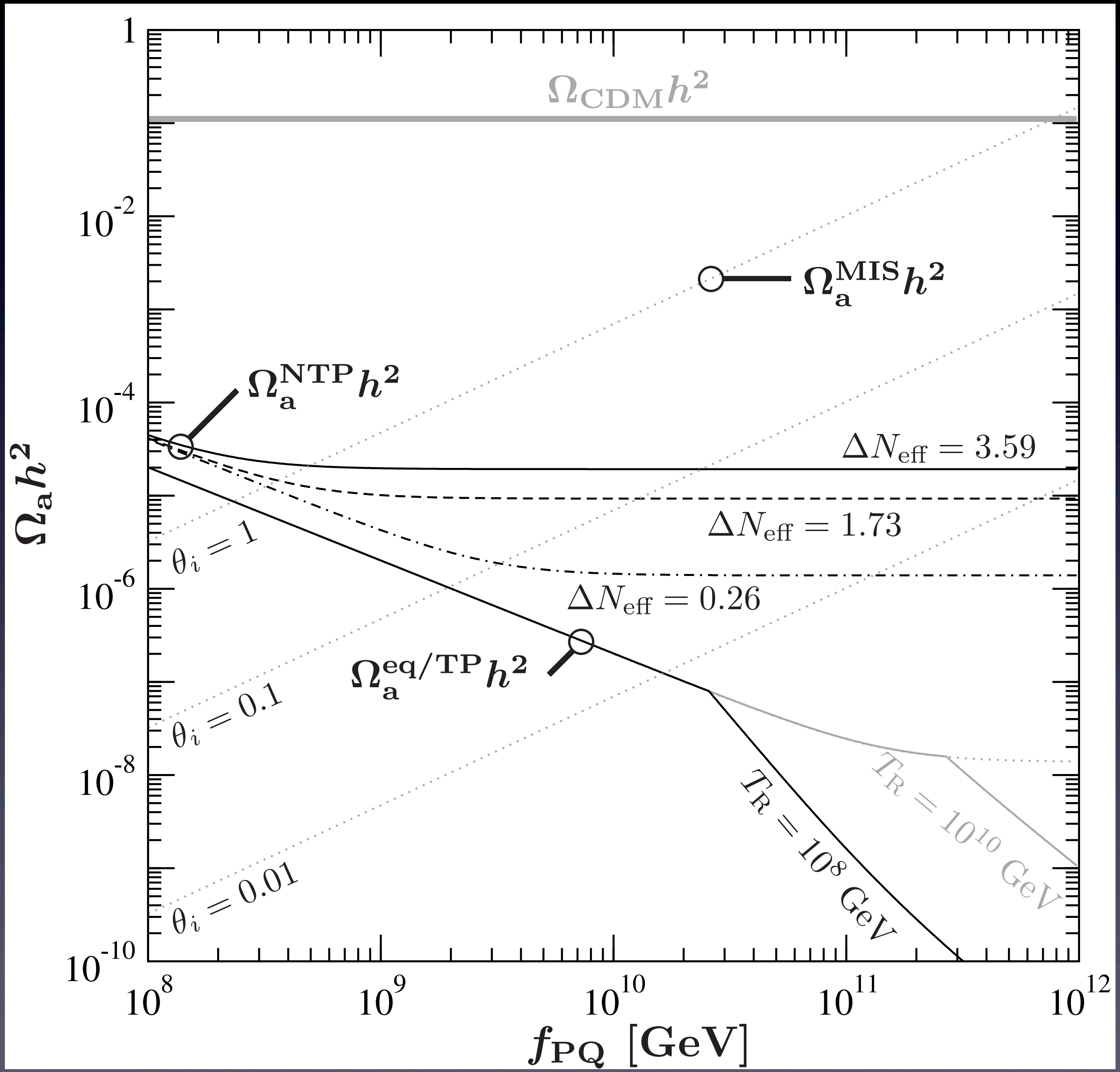
T_R limits (gravitino NLSP)



- Light axino LSP
- For $m_G \simeq$ 100 GeV, $T_R \simeq 10^{10}$ GeV, $f_{PQ} \simeq 10^{12}$ GeV: $\Delta N_{eff} \simeq$ 1 (saxions) $\Delta N_{eff} \simeq$ 0.6 (gravitino) [Hasenkamp, '12]
- Axion CDM

Axion energy density

- Three different populations:
- Thermally produced / thermal relics
- Non-thermal from saxion decay
- Misalignment



[P.G.,Steffen, arXiv:1208.2951]

Conclusions

- PQ mechanism introduces the axion
- SUSY provides flat direction for the saxion
- Production via scattering processes
- Axions from saxion decay constitute extra radiation
- Extra radiation might be hint towards saxions
- Planck results will help to clarify

Saxions non-relativistic at decay?

- Saxions are non-relativistic, if

$$\langle p(T_\sigma)\rangle = \langle p(T_{\mathrm{D}})\rangle \left[\frac{g_{*S}(T_\sigma)}{g_{*S}(T_{\mathrm{D}})}\right]^{1/3} \frac{T_\sigma}{T_{\mathrm{D}}} \ll m_\sigma$$

- This translates into

$$\frac{f_{\mathrm{PQ}}}{x} \gg 8.4 \times 10^7\,\mathrm{GeV} \left(\frac{m_\sigma}{1\ \mathrm{GeV}}\right)^{1/2} \frac{g_{*S}(T_\sigma)^{1/3}}{g_*(T_\sigma)^{1/4}}$$

Saxions decoupled at decay?

- Compare decay temp to decoupling temp

$$T_\sigma \ll T_{\rm D}$$

- upper limit on f_{PQ}

$$f_{\rm PQ} \gg \frac{7.1 \times 10^7\,{\rm GeV}}{x^{1/3}} \left(\frac{m_\sigma}{100\ {\rm GeV}}\right)^{1/2} \left[\frac{232.5}{g_*(T_\sigma)}\right]^{1/12}$$

Saxion yield