Gravitino and axino dark matter with low reheating temperature

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Introduction

- What is the nature of dark matter (DM)?

  $\Rightarrow$ Lightest Supersymmetric Particle(?)

- if we find SUSY at the LHC and no sign of DM in upcoming experiments $\Rightarrow$ maybe hint for supersymmetric DM with very tiny interaction rates: gravitino or axino

- gravitino $\widetilde{G}$ is a superpartner of graviton
- QCD – strong CP problem $\Rightarrow$ axion (Peccei-Quinn)
- axino $\tilde{a}$ is a fermionic superpartner of axion
- $\widetilde{G}$ and $\tilde{a}$ are extremely weakly interacting massive particle (EWIMP) – interaction rates suppressed by $M_{\rm Pl}$ or $f_a \sim 10^{11}$ GeV
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How to produce relic supersymmetric EWIMPs?

Assumption: after inflation maximum temperature too low for EWIMPs to be in thermal equilibrium. We consider then two main mechanism of production:

$$\Omega_{\rm EWIMP} h^2 = \Omega^{\rm NTP}_{\rm EWIMP} h^2 + \Omega^{\rm TP}_{\rm EWIMP} h^2$$

Non-Thermal Production
late decays of the next-to-LSP

- possible electromagnetic and hadronic cascades that destroy light nuclei in the early Universe

→ this alters predictions of the Big Bang Nucleosynthesis (BBN)

- late-time injection of light (fast) particles may cause problem with the Large Scale Structure (LSS) formation

→ too warm dark matter (WDM)

- T_R-dependent only for low T_R

Thermal production
scatterings of superparticles in the thermal plasma

- depends on T_R

→ generally larger T_R ⇒ larger yield $Y^{\rm TP} = n^{\rm TP}/s$

- different dependence on the $m_{\rm EWIMP}$ for the axino and the gravitino

$$\Omega^{\rm TP}_{\rm EWIMP} h^2 \propto m_{\rm EWIMP}\, Y^{\rm TP} \propto \begin{cases} T_R/m_{\tilde{G}} \\ T_R\, m_{\tilde{a}} \end{cases}$$

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$$\Omega_{\rm EWIMP}^{\rm NTP} h^2 = \frac{m_{\rm EWIMP}}{m_\chi} \Omega_\chi h^2$$

$\chi \to \mathrm{EWIMP} + \ldots$

- in the early Universe χ remained in thermal equilibrium
- when temperature T dropped down $\Rightarrow$ freeze-out of χ

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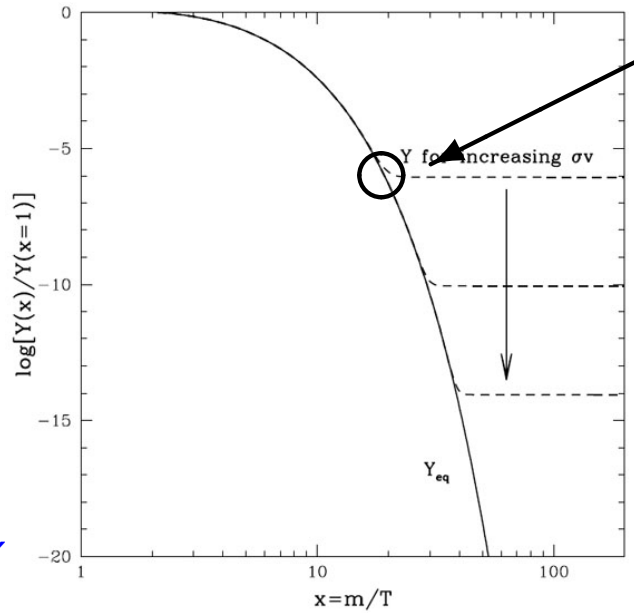
high T_R



$\log Y$

$Y = \frac{n_\chi}{s} \sim$ comoving number density

$x = m_\chi / T$ grows with time

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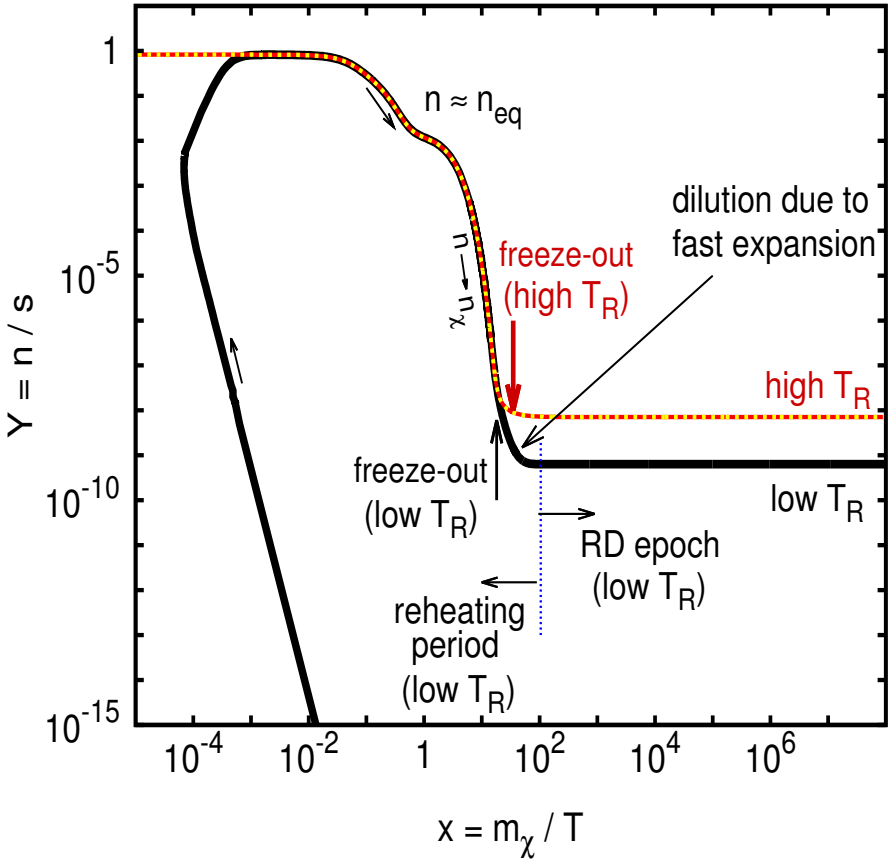

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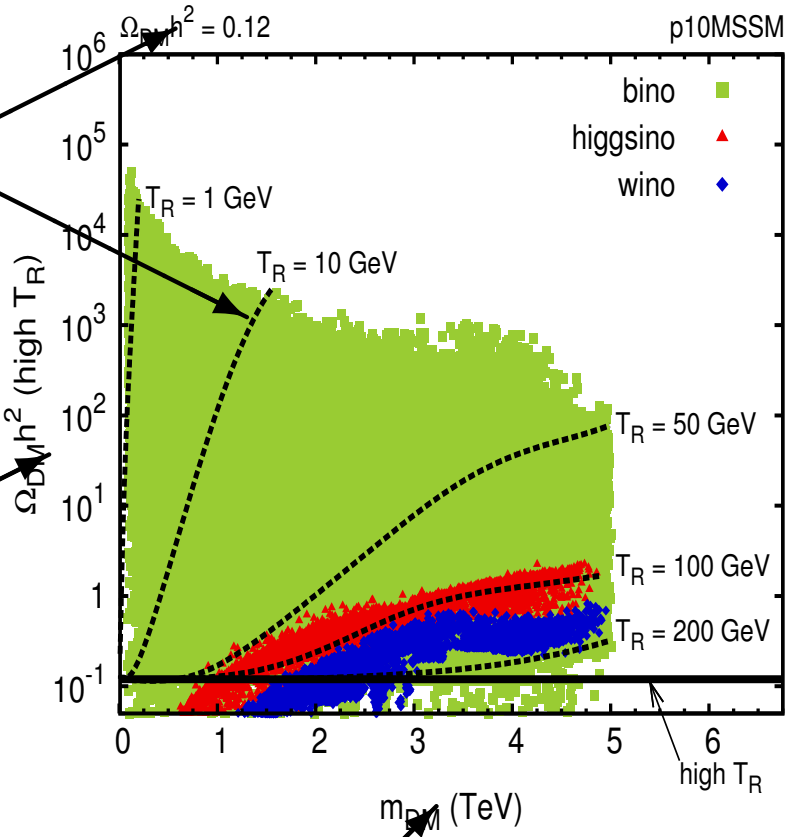
$\Omega_\chi h^2(\mathbf{low}\ T_R) \simeq 0.12$
along the lines of constant T_R

$\Omega_\chi h^2(\mathbf{high}\ T_R)$



m_χ

Gravitino DM – low T_R

$\Rightarrow$ NTP dominates for not very light $\widetilde{G}$

$$\Omega_{\widetilde{G}} h^2 = \frac{m_{\widetilde{G}}}{m_{\rm LOSP}} \Omega_{\rm LOSP} h^2$$

more general notation

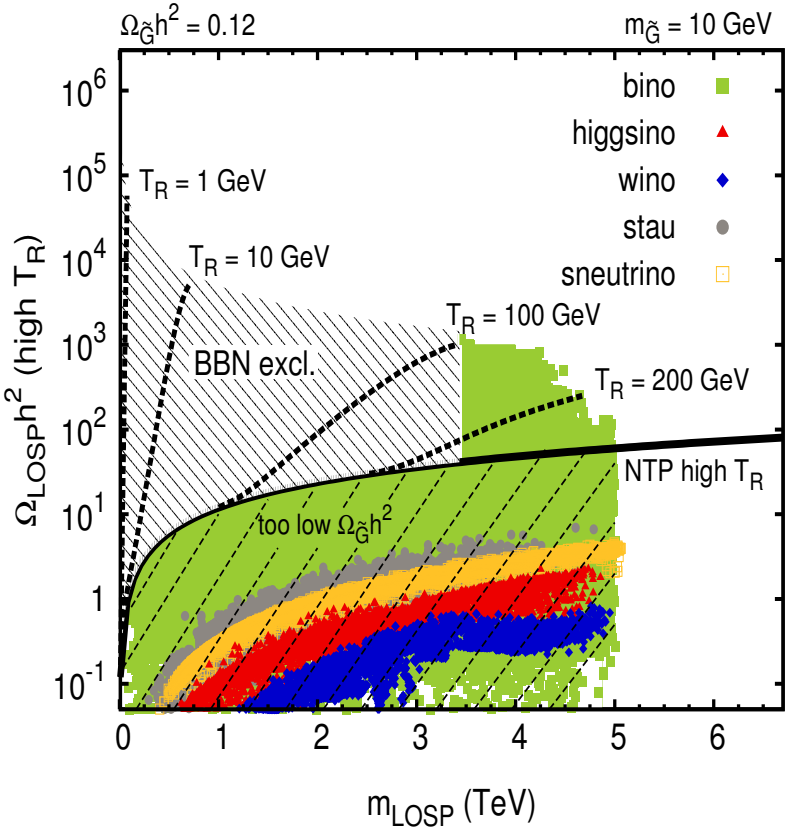
$\chi \to$ LOSP

lightest ordinary supersymmetric particle

Bino LOSP

- $B_h \gtrsim 0.1$
- $\tau \sim \frac{m_{\widetilde{G}}^2}{m_{\widetilde{B}}^5}$ for $m_{\widetilde{B}} \gg m_{\widetilde{G}}$
- BBN requires $\tau \lesssim 0.1$ s

$$\Rightarrow \quad m_{\widetilde{B}} \gtrsim 1.4 \left(\frac{m_{\widetilde{G}}}{\rm GeV}\right)^{2/5} {\rm TeV}$$



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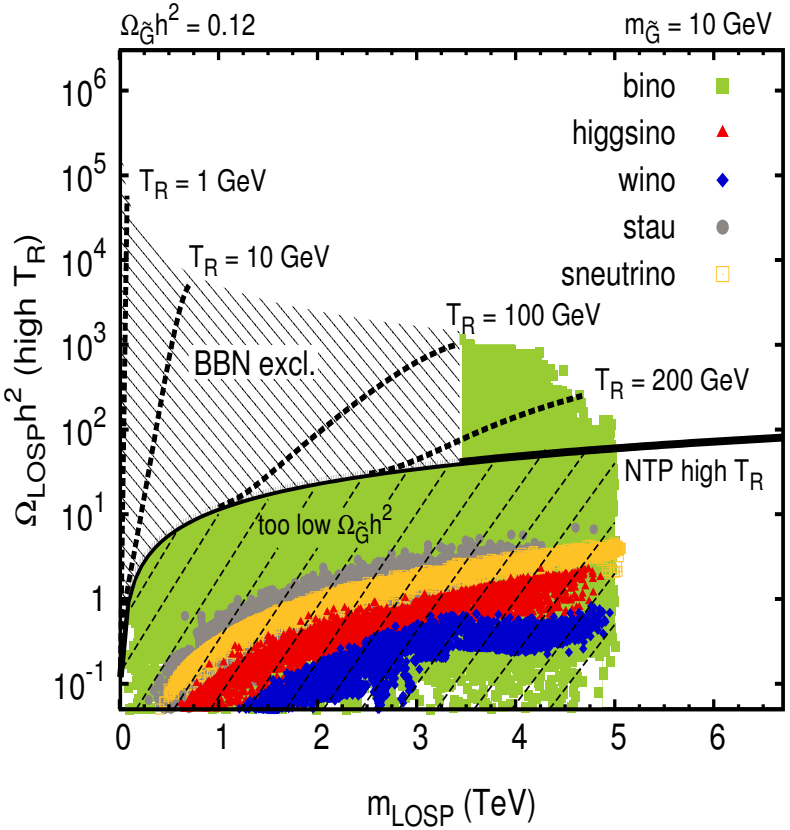
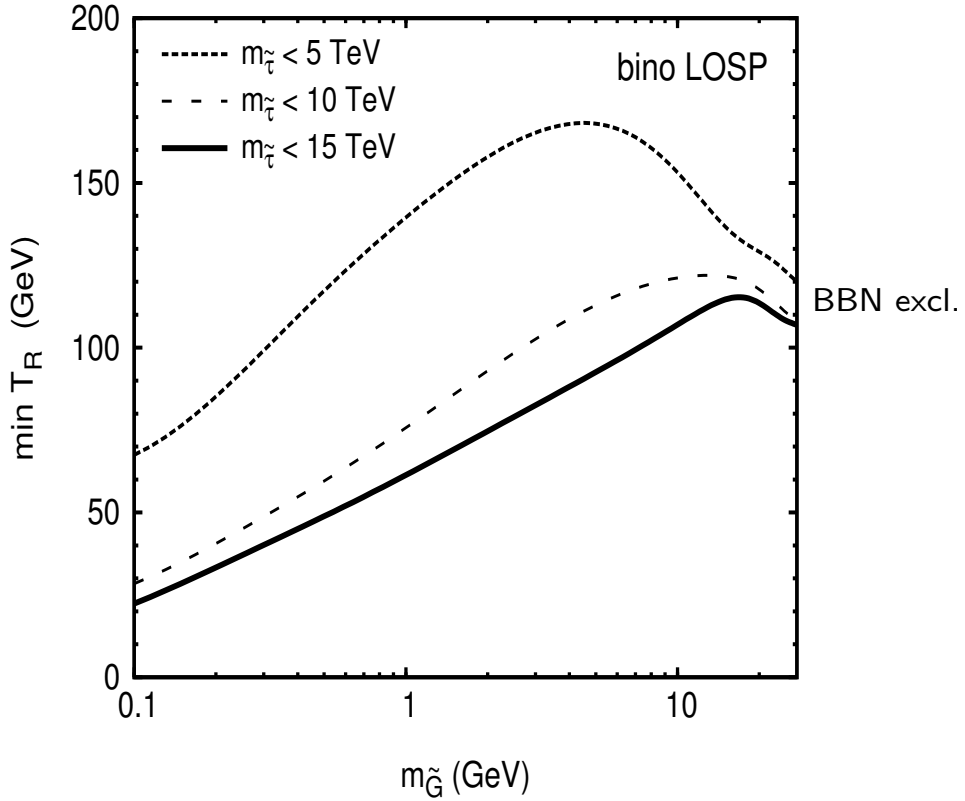
BBN + relic density constraints

$\Rightarrow$ lower limit on T_R

min $T_R \sim \mathcal{O}(100\,{\rm GeV})$





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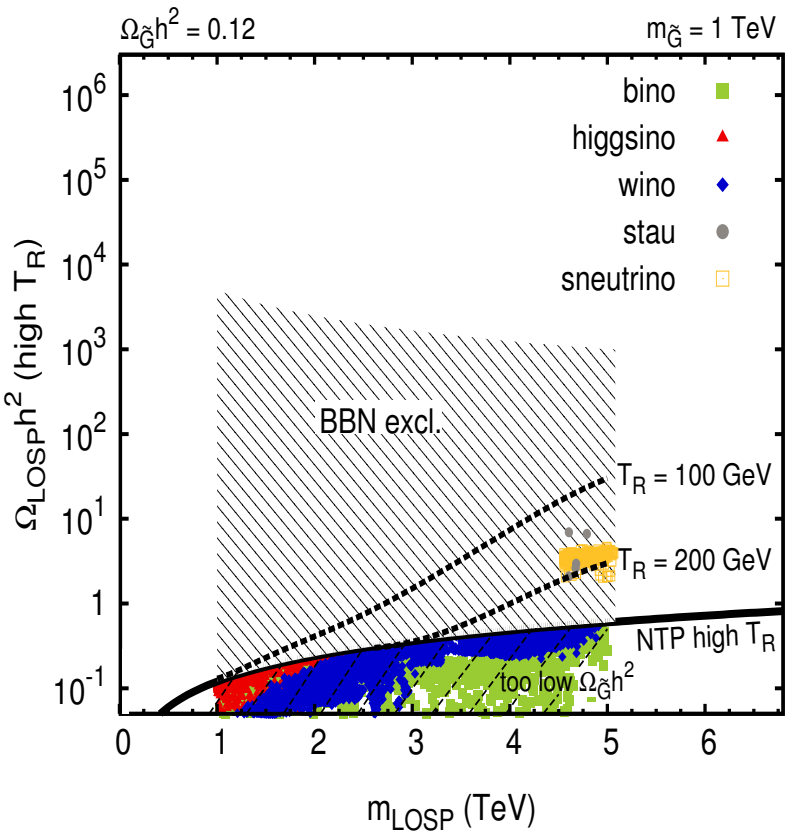
Slepton LOSP

- lower $\Omega_{\widetilde{l}} h^2 \Rightarrow$ larger $m_{\widetilde{G}}$
- low B_h
- $\tau \sim \frac{m_{\widetilde{G}}^2}{m_{\widetilde{l}}^5} \left(1 - \frac{m_{\widetilde{G}}^2}{m_{\widetilde{l}}^2}\right)^{-4}$



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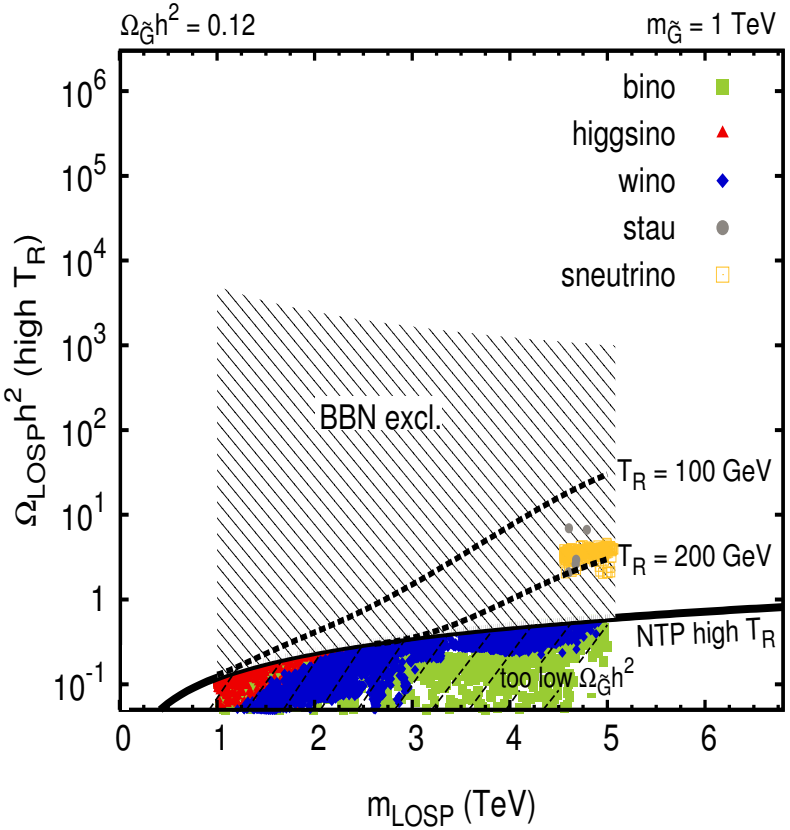

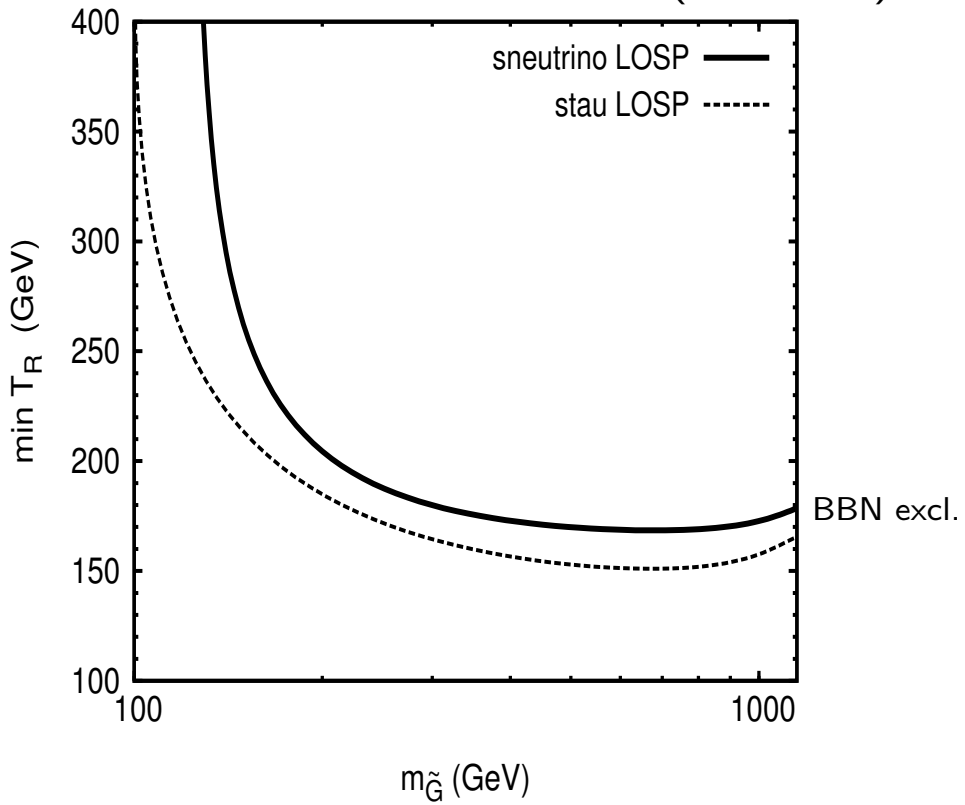

Axino DM – low T_R

Non-thermal production– analogous to the case of gravitino DM, but...

$\rightarrow$ BBN constraints become milder (shorter lifetime) if $\boldsymbol{\chi \rightarrow \tilde{a}\gamma}$ decays are allowed, .i.e., if $\mathbf{C_{aYY} \neq 0}$ where $\mathcal{L}_{\tilde{a}}^{\rm eff} \supset i\,\frac{\alpha_Y\, C_{aYY}}{16\pi\, f_a}\,\bar{\tilde{a}}\,\gamma_5\,[\gamma^\mu,\gamma^\nu]\,\widetilde{B}\,B_{\mu\nu}$

$\Rightarrow$ if $C_{aYY} \neq 0$ BBN constraints become mild

$\rightarrow$ if $\mathbf{C_{aYY} = 0}$, decays to $\tilde{a}\gamma$ are suppressed, while $\boldsymbol{\chi \rightarrow \tilde{a}q\bar{q}}$ becomes dominant with hadronic branching fraction $\mathbf{B_h = 1}$ and larger lifetime

$$\tau_{\widetilde{\rm B}} \approx 120\,{\rm sec}\left(\frac{100\,{\rm GeV}}{{\rm m}_{\widetilde{\rm B}}}\right)^5\left(\frac{{\rm m}_{\tilde{\rm q}}}{1\,{\rm TeV}}\right)^4\left(\frac{1\,{\rm TeV}}{{\rm m}_{\tilde{\rm g}}}\right)^2\left(\frac{{\rm f}_{\tilde{\rm a}}}{10^{11}\,{\rm GeV}}\right)^2 . \qquad (1)$$

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Thermal production– can be non-negligible even for $T_R \sim 100\,\mathrm{GeV}$

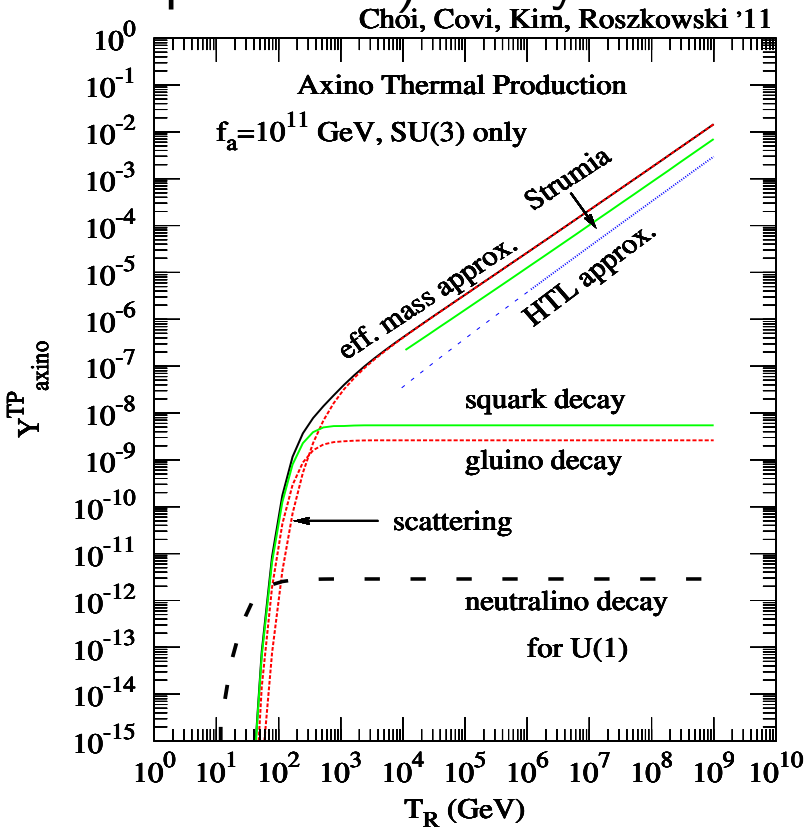
$\rightarrow$ axino couplings are suppressed by $1/f_a$ with $f_a \sim 10^9 - 10^{12}\,GeV \ll M_{\rm Pl}$

$\rightarrow$ for non-instantaneous reheating larger temperatures are attainable than in the radiation dominated epoch

$\Rightarrow$ modified $Y^{\rm TP}$

Axino TP with non-instantaneous reheating

- for high T_R – $SU(3)_c$ scatterings dominate
- for $T_R \lesssim 10^3\ GeV$ – squark and gluino decays become dominant
- for $T_R \lesssim 100\,\mathrm{GeV}$ – neutralino (being still in thermal equilibrium) decays to axino may dominate



K. Y. Choi, L. Covi, J. E. Kim and L. Roszkowski, JHEP 1204 (2012) 106

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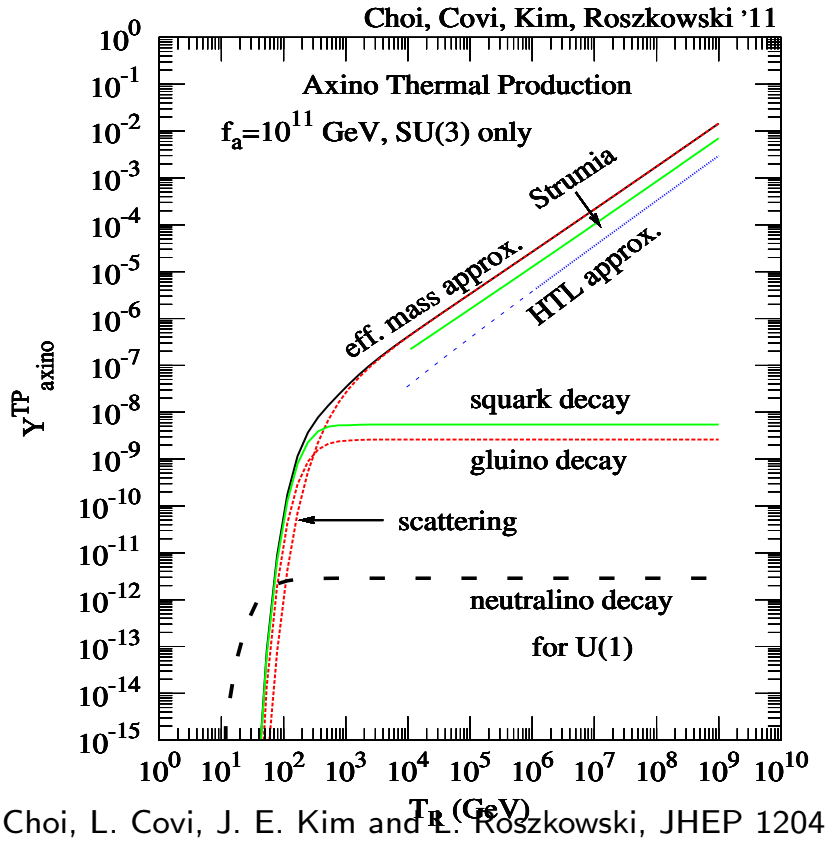

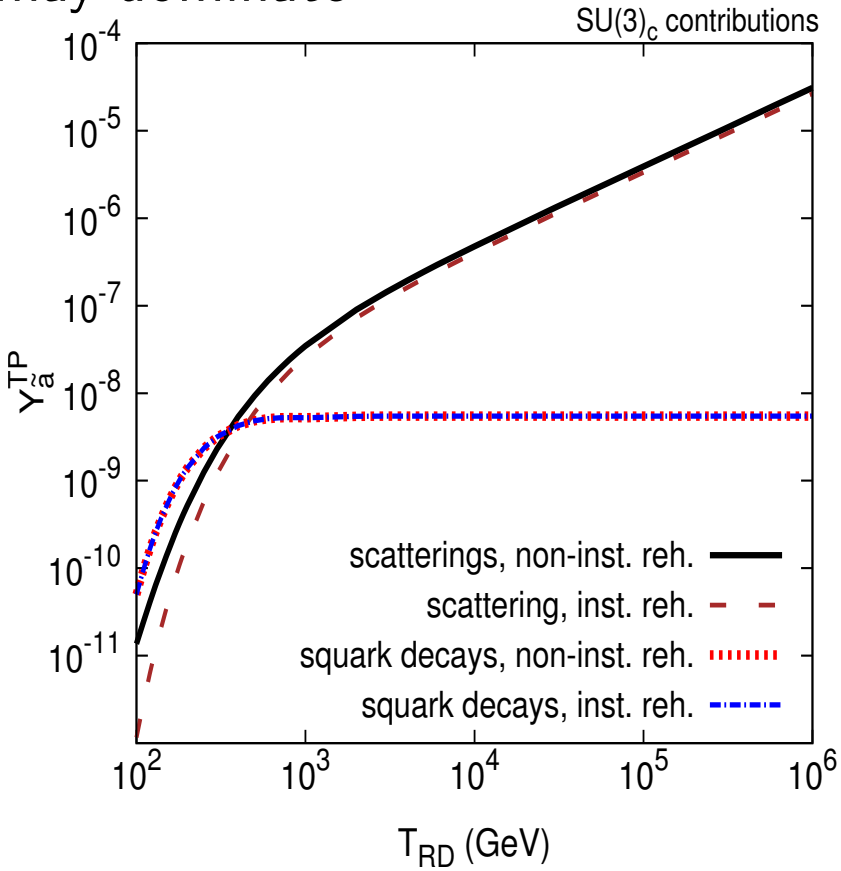

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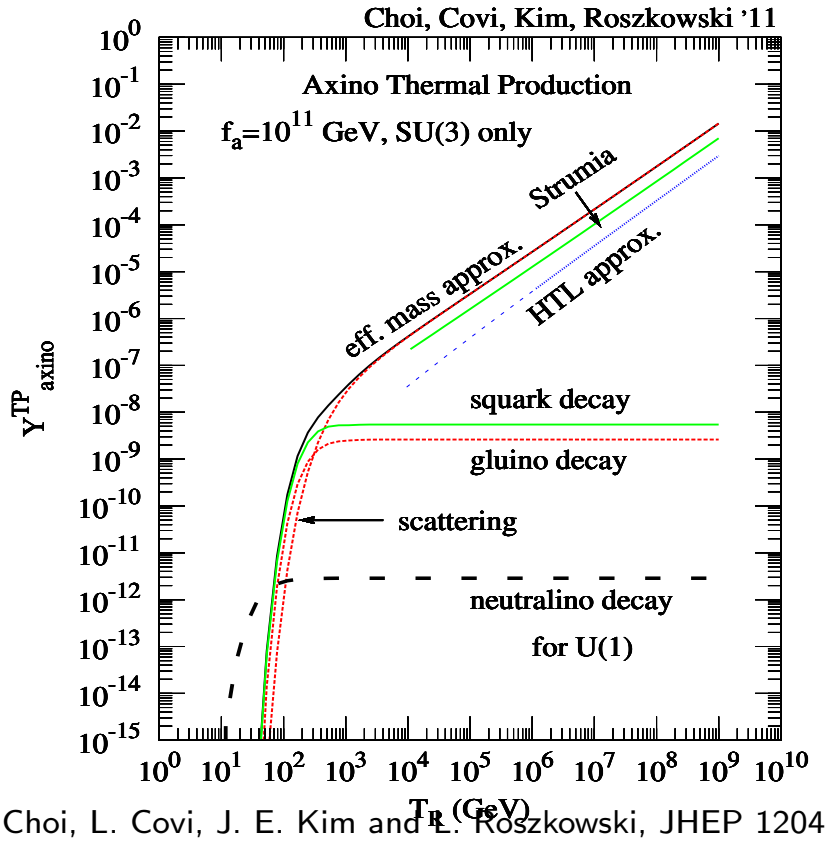

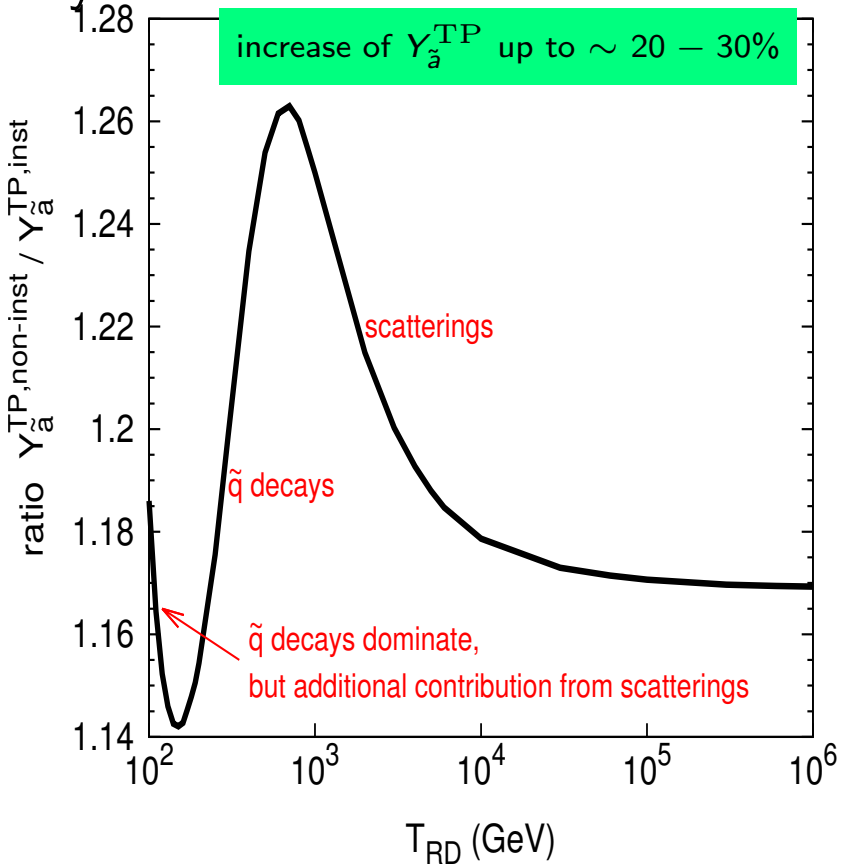

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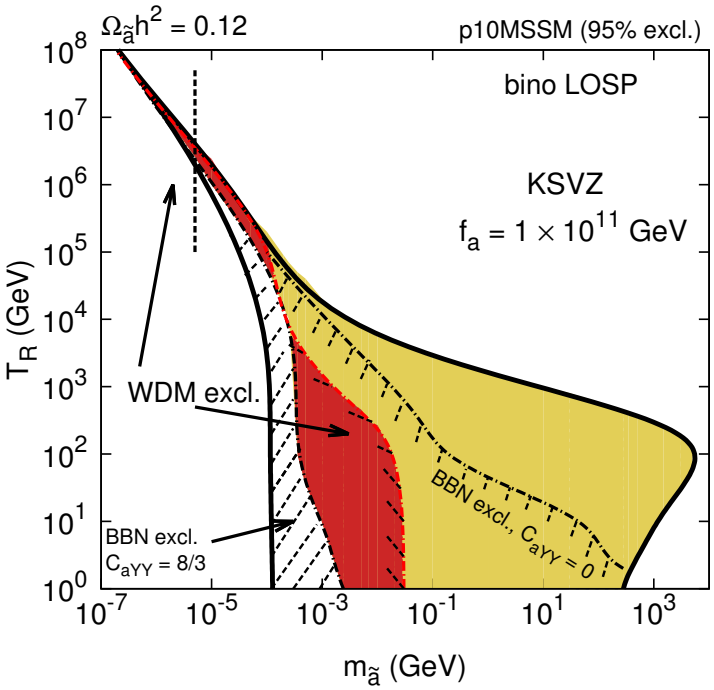
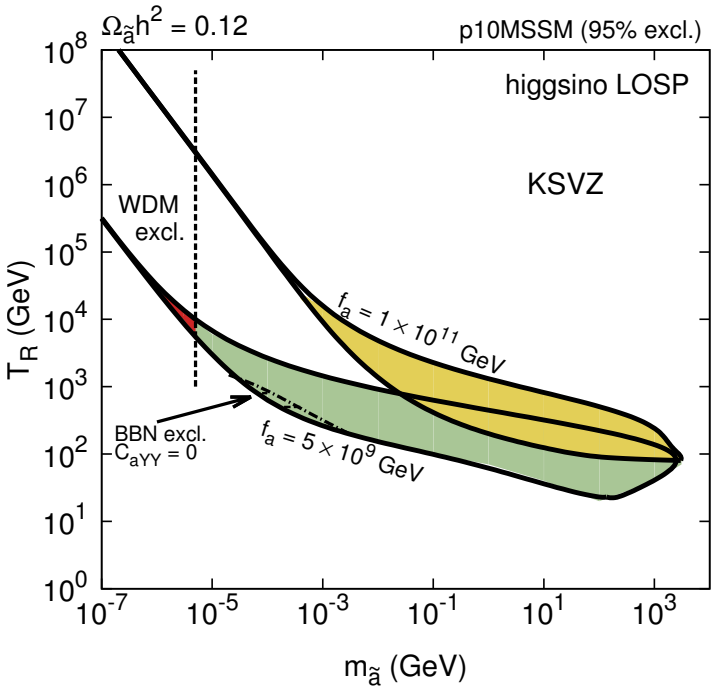
Axino DM with neutralino LOSP

- T_R-dependent upper bound on $m_{\tilde{a}}$
- max $m_{\tilde{a}}$ for narrow range of $T_R \sim \mathcal{O}(100\,\mathrm{GeV})$
- lower limit on T_R for higgsino LOSP ($T_R \sim \mathcal{O}(10\,\mathrm{GeV})$) and bino LOSP with $C_{aYY} = 0$ ($T_R \sim \mathcal{O}(1\,\mathrm{GeV})$)





Efficient direct/cascade decays of the inflaton field to DM

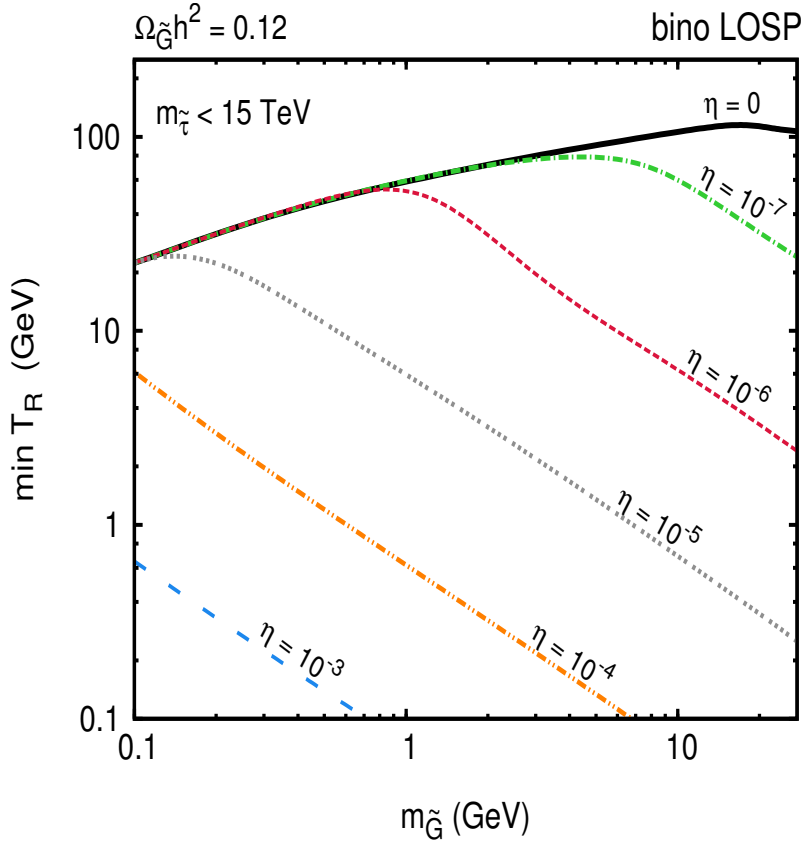
- for low enough temperatures (after χ freezes-out) direct and/or cascade decays of the inflaton field can work as an additional source of χ
- this requires low T_R
- one may then obtain even $\Omega_\chi h^2(\text{low } T_R) > \Omega_\chi h^2(\text{high } T_R)$ depending on

$$\boldsymbol{\eta = \mathrm{b}\,\frac{100\ \mathrm{TeV}}{\mathrm{m}_\phi}}$$

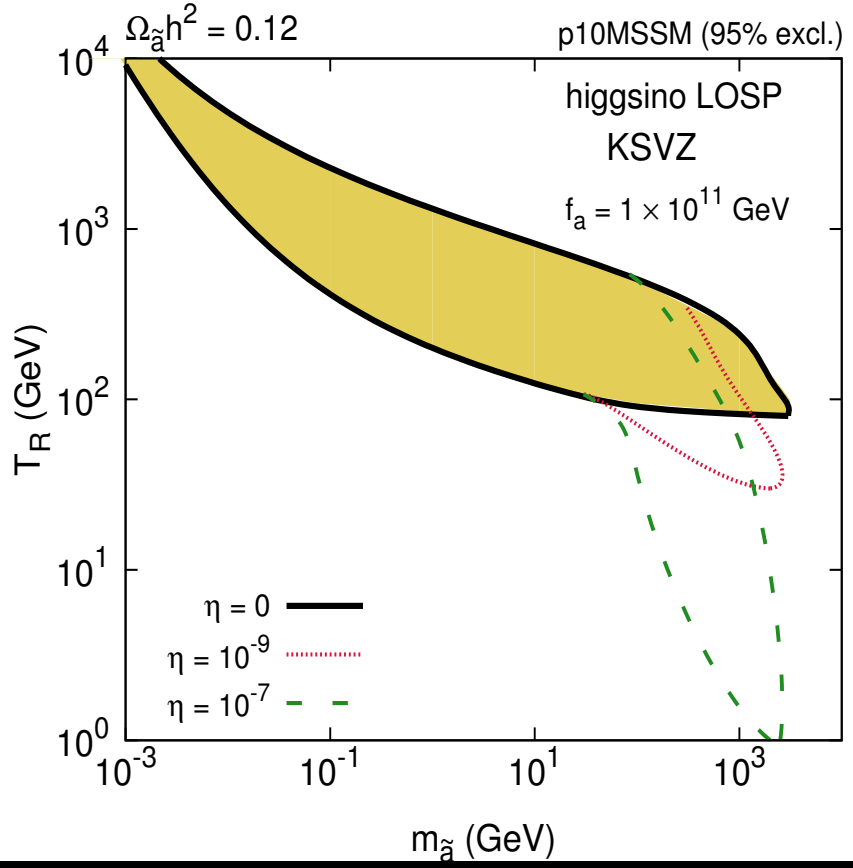
b - average number of χ particles produced per inflaton decay

m_ϕ - inflaton mass

Gravitino DM



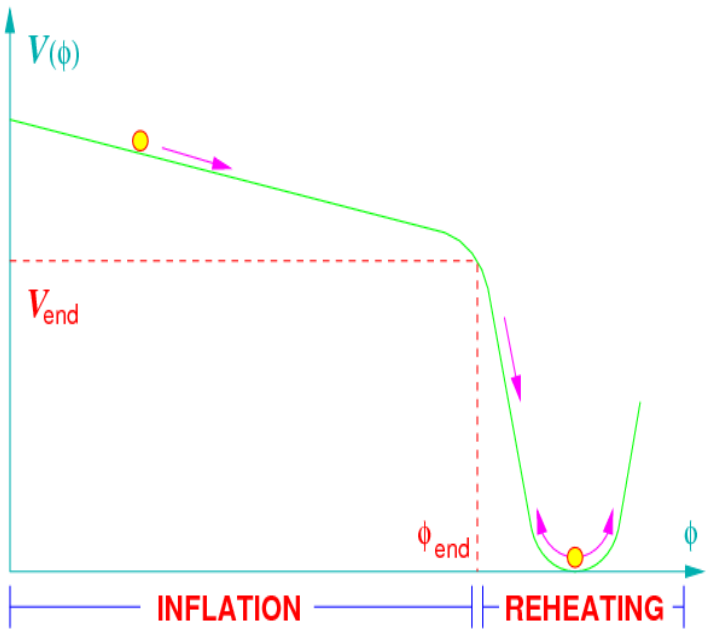
Axino DM



Conclusions

- BBN and relic density constraints in case of gravitino DM introduce lower limit min $T_R \gtrsim 100$ GeV
- it can be relaxed if for efficient direct/cascade decays of the inflaton to DM
- axino DM thermal production yield for non-instantaneous reheating increases up to $\sim 20 - 30\%$ with respect to an instantaneous reheating scenario
- taking into account non-instantaneous reheating leads to corrected T_R-dependent upper limit on the axino DM mass
- for axino DM min $T_R \gtrsim \mathcal{O}(1 - 10\,\mathrm{GeV})$ or even lower for bino LOSP and efficient decays $\widetilde{B} \to \tilde{a}\gamma$

Reheating period in the evolution of the Universe



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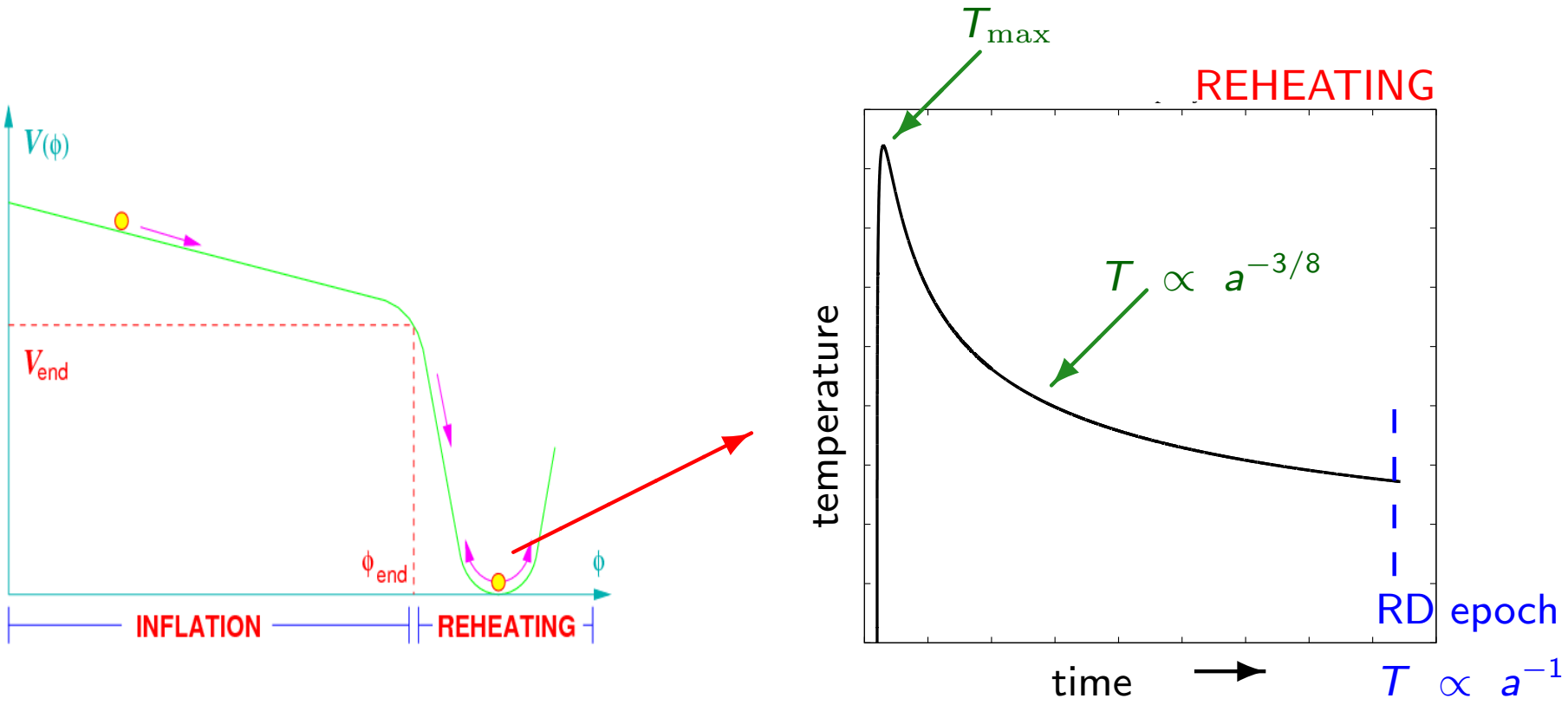

Reheating period in the evolution of the Universe (2)

At the end of a period of cosmological inflation:

- $T \approx 0$
- large potential energy of the inflaton field ϕ is transformed into the kinetic energy of recreated particles
- then $T \nearrow$ (reheating)

If instantaneous reheating: $\Gamma_\phi = H = \sqrt{\frac{8\pi}{3M_{Pl}^2}\rho_\phi}$ and $\rho_\phi = \rho_{rad}(T_R) \sim T_R^4$

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_*(T_R)}{45}}\frac{{T_R}^2}{M_{Pl}} \quad \text{defines reheating temperature } T_R$$

If non-instantaneous reheating – Boltzmann equations:

G. F. Giudice, E. W. Kolb, A. Riotto hep-ph/0005123, G. Gelmini *et al.* hep-ph/0602230

$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi\rho_\phi \qquad \text{inflaton field}$$

$$\frac{d\rho_R}{dt} = -4H\rho_R + \Gamma_\phi\rho_\phi + \langle\sigma v\rangle_{\rm eff}\langle E_X\rangle\left[n_X^2 - (n_X^{eq})^2\right] \qquad \text{radiation}$$

$$\frac{dn_X}{dt} = -3Hn_X - \langle\sigma v\rangle_{\rm eff}\left[n_X^2 - (n_X^{eq})^2\right] \quad \left(+\frac{b}{m_\phi}\Gamma_\phi\rho_\phi\right) \quad \text{dark matter}$$

Radiation dominated (RD) epoch begins when $T \sim T_R$,

before – the reheating period

Reheating period in the evolution of the Universe (2)

At the end of a period of cosmological inflation:

- $T \approx 0$
- large potential energy of the inflaton field ϕ is transformed into the kinetic energy of recreated particles
- then $T \nearrow$ (reheating)

If instantaneous reheating: $\Gamma_\phi = H = \sqrt{\frac{8\pi}{3M_{Pl}^2}\rho_\phi}$ and $\rho_\phi = \rho_{rad}(T_R) \sim T_R^4$

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_*(T_R)}{45}}\,\frac{{T_R}^2}{M_{Pl}} \quad \text{defines reheating temperature } T_R$$

If non-instantaneous reheating – Boltzmann equations:

G. F. Giudice, E. W. Kolb, A. Riotto hep-ph/0005123, G. Gelmini *et al.* hep-ph/0602230

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Direct and cascade decays of the inflaton field into DM with low T_R

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- additional non-thermal DM production in the reheating period after freeze-out
- possible increase of the relic density $\Omega_\chi h^2 \nearrow$

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$$\eta = \mathbf{b}\,\frac{\mathbf{100\ TeV}}{\mathbf{m}_\phi}$$

- possible increase of the relic density $\Omega_\chi h^2$ ↗