The long-lived stau as thermal relic

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in Collaboration with F.D. Steffen and M. Pospelov

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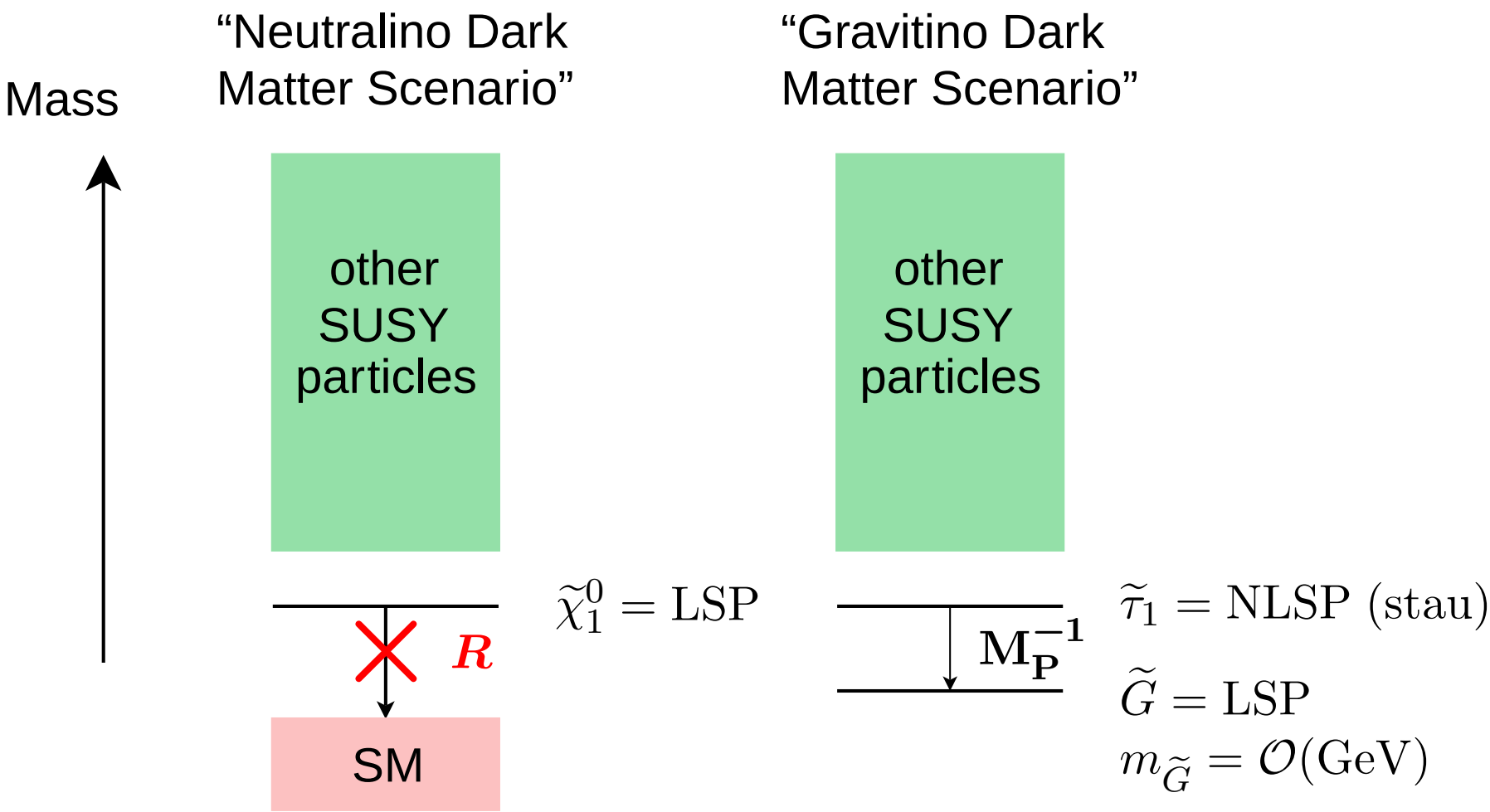
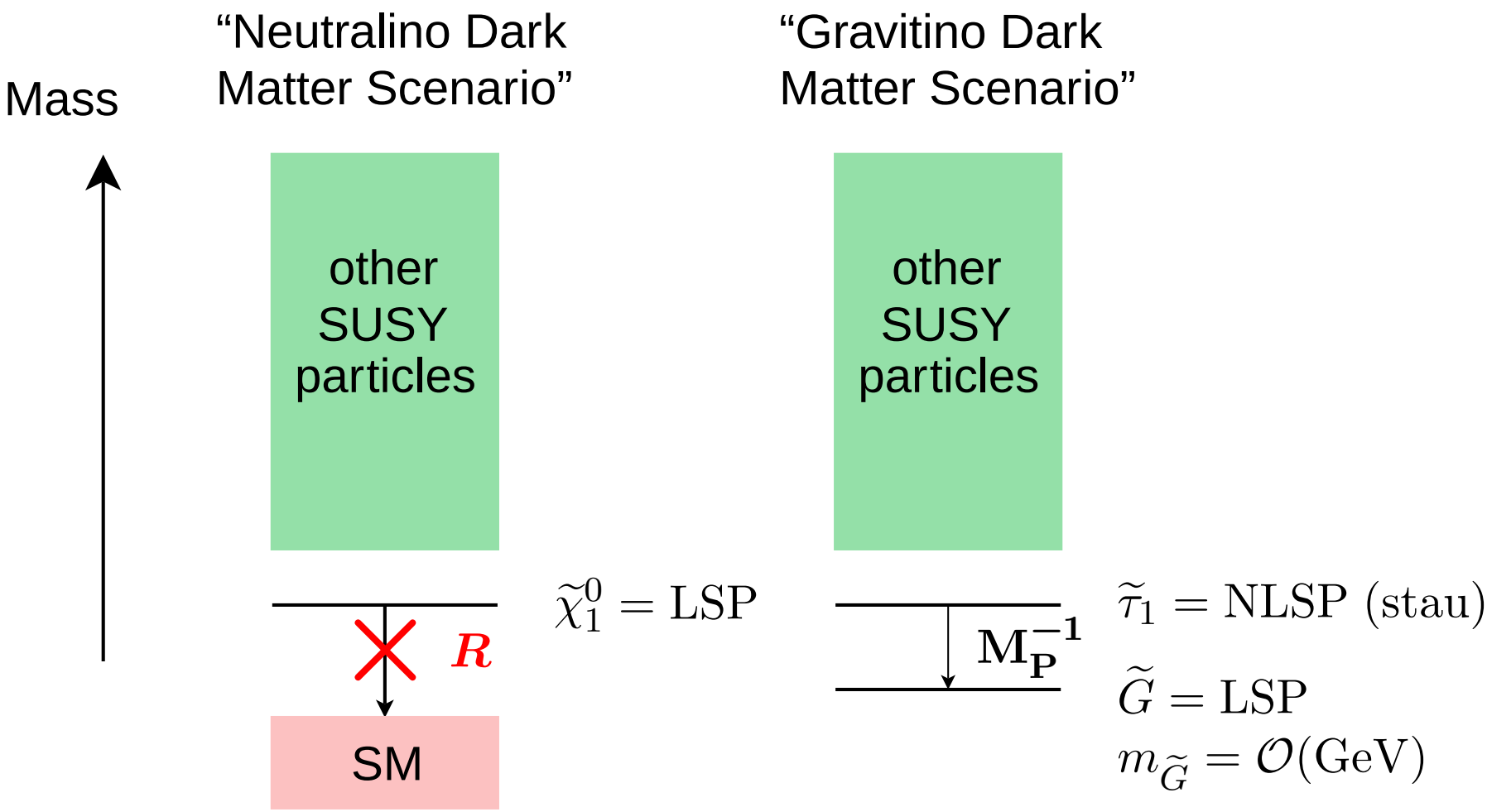
Outline

- How can we have a long-lived stau?
- Small tour through the associated history of the Early Universe
- Primordial decoupling of the stau

SUSY setup

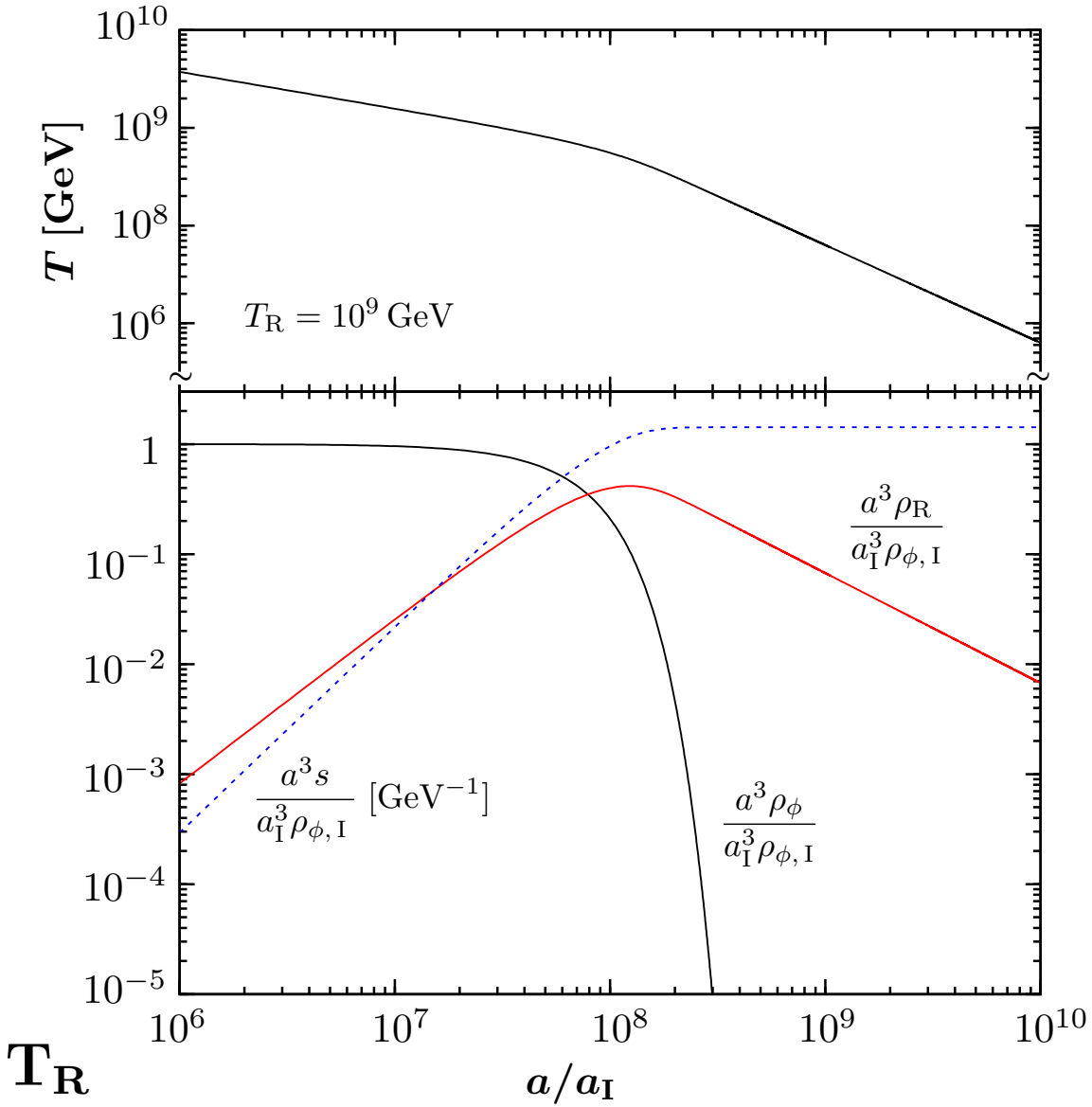

Mass
“Neutralino Dark Matter Scenario”
other SUSY particles
R
SM
$\widetilde{\chi}_1^0 = \mathrm{LSP}$
“Gravitino Dark Matter Scenario”
other SUSY particles
$\mathbf{M_P^{-1}}$
$\widetilde{\tau}_1 = \mathrm{NLSP\ (stau)}$
$\widetilde{G} = \mathrm{LSP}$
$m_{\widetilde{G}} = \mathcal{O}(\mathrm{GeV})$

SUSY setup



- What is the Cosmology associated with the Gravitino-Stau scenario?

'Initial Conditions' - Reheating

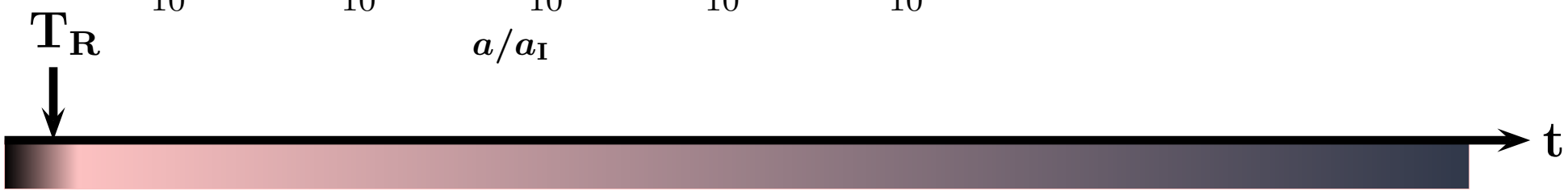


- Inflaton decays

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

- Universe enters radiation dominated epoch at $T_{\rm R}$

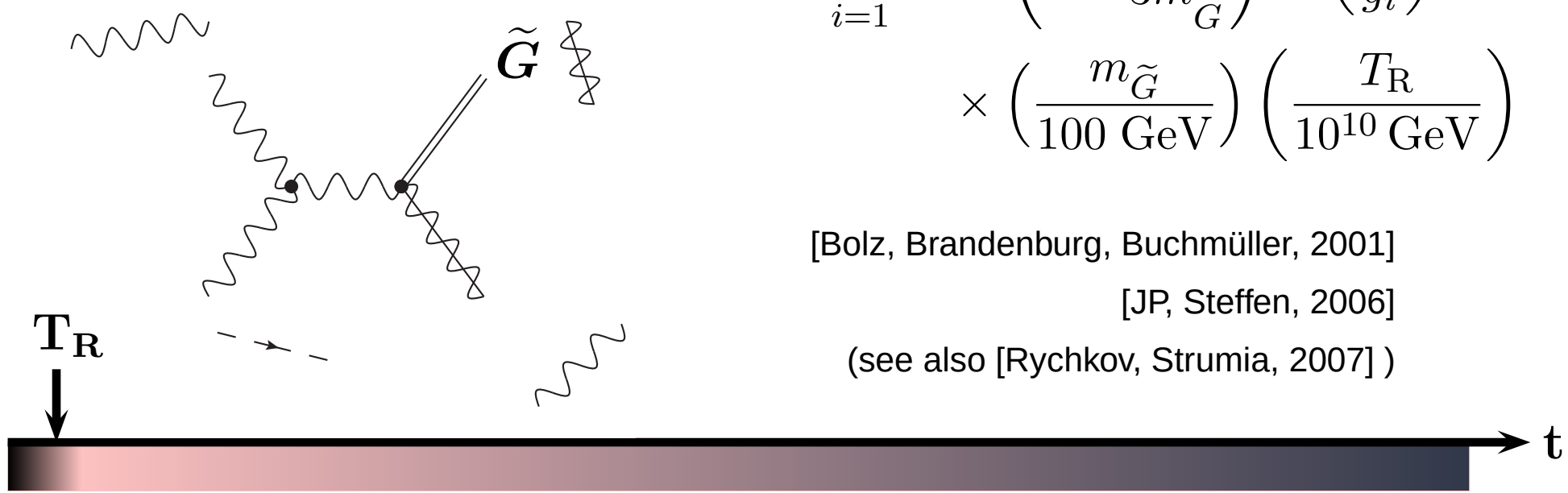
$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_\phi \rho_\phi$$



Thermal Gravitino Production

- For $T_{\rm R} \sim \mathcal{O}(10^6 - 10^{10}\ {\rm GeV}) \rightarrow$ thermal gravitino production can be very efficient
- guaranteed production mechanism $\rightarrow \Omega_{\widetilde{G}}^{\rm TP} \in \Omega_{\rm dm}$
- $\Omega_{\widetilde{G}}^{\rm TP} \leq \Omega_{\rm dm} \sim 0.2 \rightarrow$ one aspect of the 'Gravitino Problem'

$$\Omega_{\widetilde{G}}^{\rm TP} h^2 = \sum_{i=1}^{3} \omega_i \, g_i^2 \left(1 + \frac{M_i^2}{3 m_{\widetilde{G}}^2}\right) \ln\left(\frac{k_i}{g_i}\right) \times \left(\frac{m_{\widetilde{G}}}{100\ {\rm GeV}}\right) \left(\frac{T_{\rm R}}{10^{10}\ {\rm GeV}}\right)$$



[Bolz, Brandenburg, Buchmüller, 2001]

[JP, Steffen, 2006]

(see also [Rychkov, Strumia, 2007])

Stau as thermal relic

- Gravitino Production from Decays: $\widetilde{\tau}_1 \to \widetilde{G} + \tau$
- Lifetime of $\widetilde{\tau}_1$: e.g. take $m_{\widetilde{G}} = 20$ GeV, $m_{\widetilde{\tau}_1} = 100$ GeV $(1$ TeV$)$
  $\to \tau_{\widetilde{\tau}_1} \simeq 46$ weeks $(200$ s$)$

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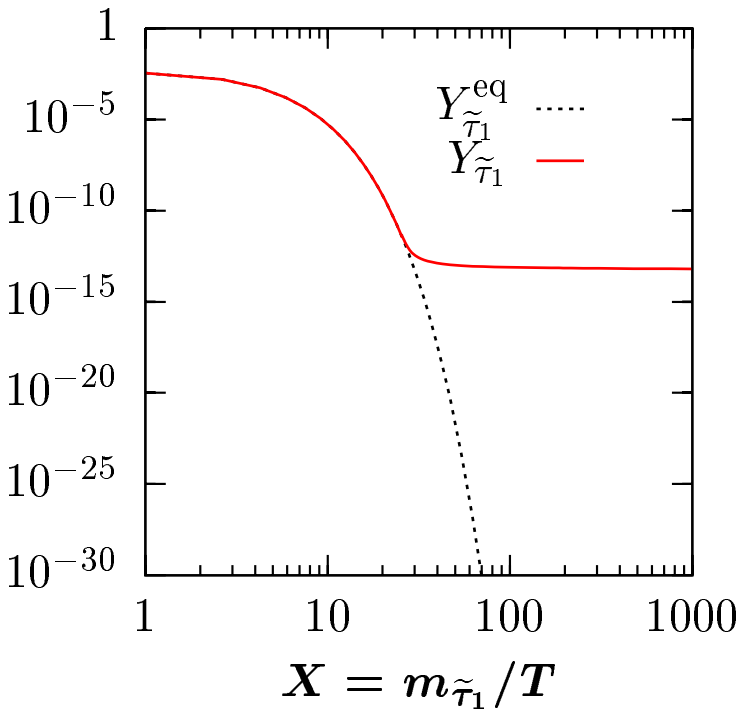
- $\dfrac{dY_{\widetilde{\tau}}}{dt} = -s\langle \boldsymbol{\sigma} v \rangle \left[Y_{\widetilde{\tau}}^2 - (Y_{\widetilde{\tau}}^{\rm eq})^2 \right]$
  $(Y_{\widetilde{\tau}} \equiv n_{\widetilde{\tau}}/s)$

- $\widetilde{\tau}_1$ freeze out: $T_{\rm dec} \simeq$ few GeV
  $(t_{\rm dec} = \mathcal{O}(ns))$

- $\to$ $\widetilde{\tau}_1$ is thermal relic



BBN as a probe for new physics

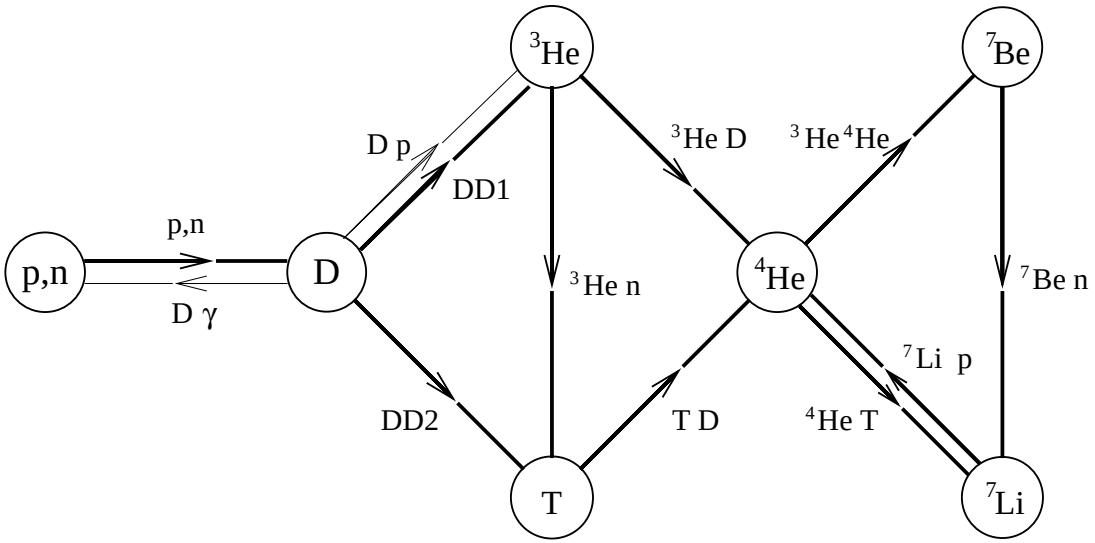


Fig. from [Mukhanov, 2004]

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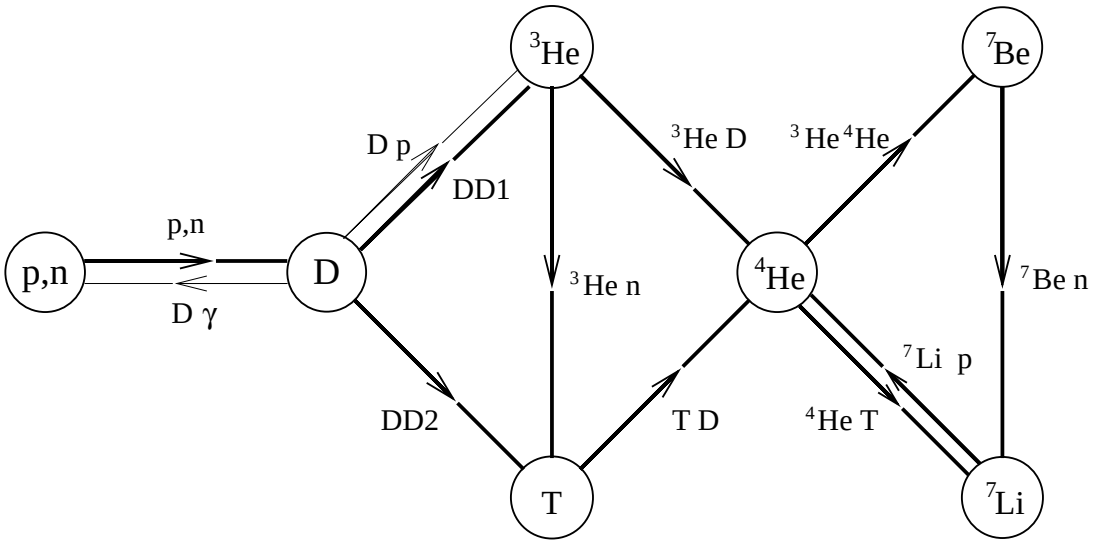

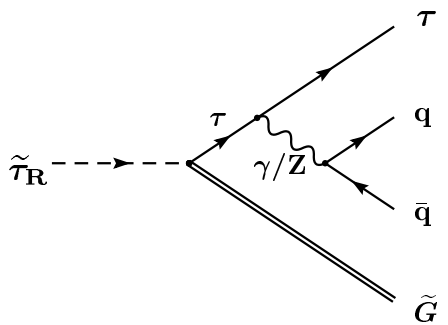

- $\tilde{\tau}_1$ can decay during/after BBN, leading to

Fig. from [Steffen, 2006]

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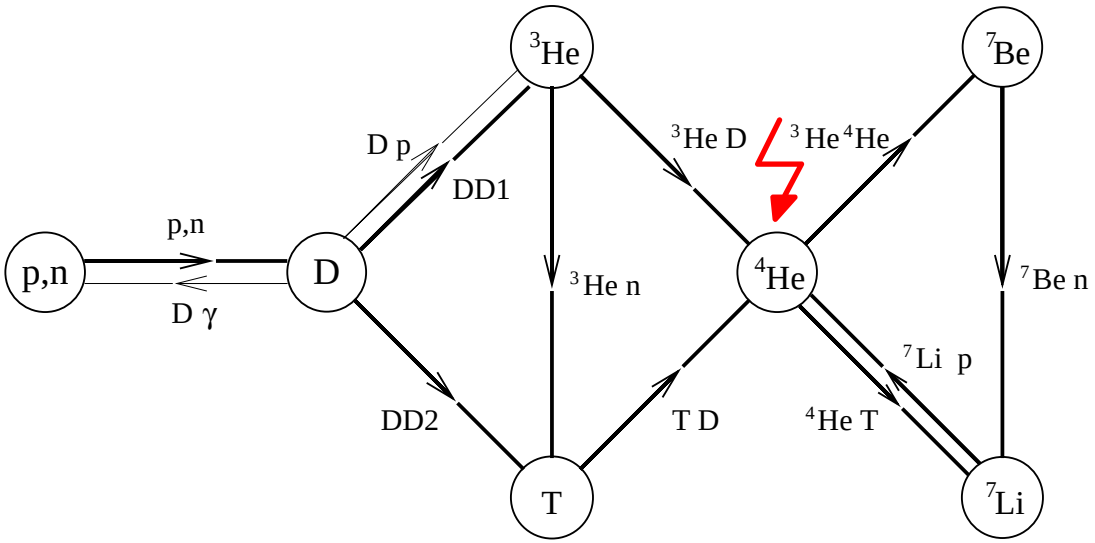


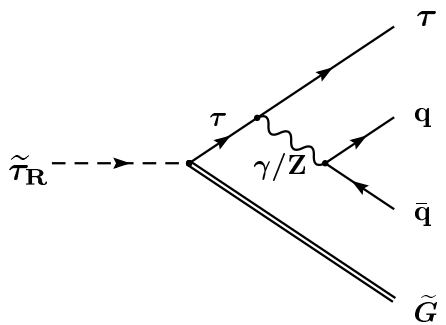


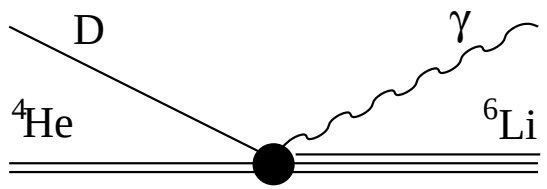
Fig. from [Steffen, 2006]

- $\tilde{\tau}_1$ can decay during/after BBN, leading to
- electromagnetic and hadronic energy release from decay products can spoil successful predictions of BBN
- another aspect of the Gravitino Problem

Catalyzed BBN as a probe for new physics

- The presence of $\widetilde{\tau}_1^- = X^-$ during BBN leads to bound-state formation of X^- with light elements
- e.g. for production of $^6\mathrm{Li}$ [Pospelov, 2006]

standard BBN:
$\rightarrow \langle \sigma_S v \rangle$



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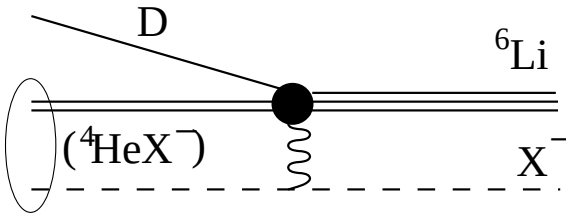
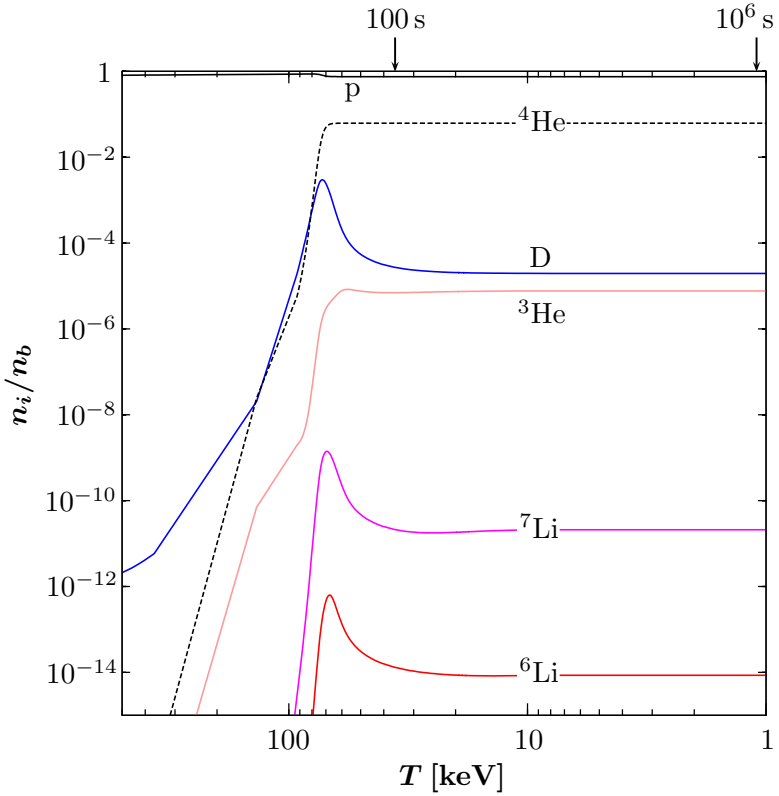
$\rightarrow \langle \sigma_C v \rangle$



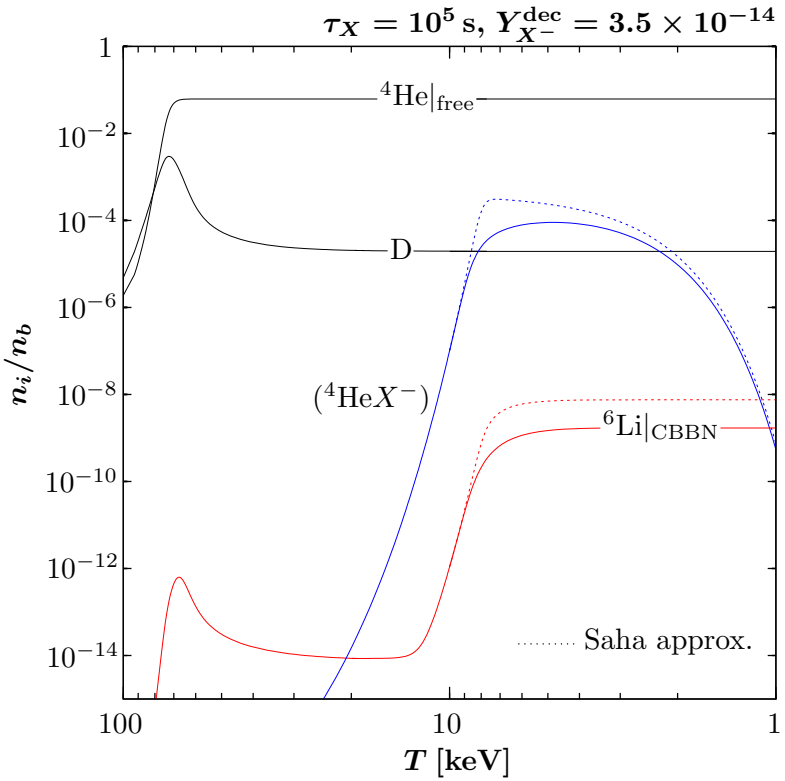
cross-section enhanced by 7 orders of magnitude

Catalyzed BBN as a probe for new physics

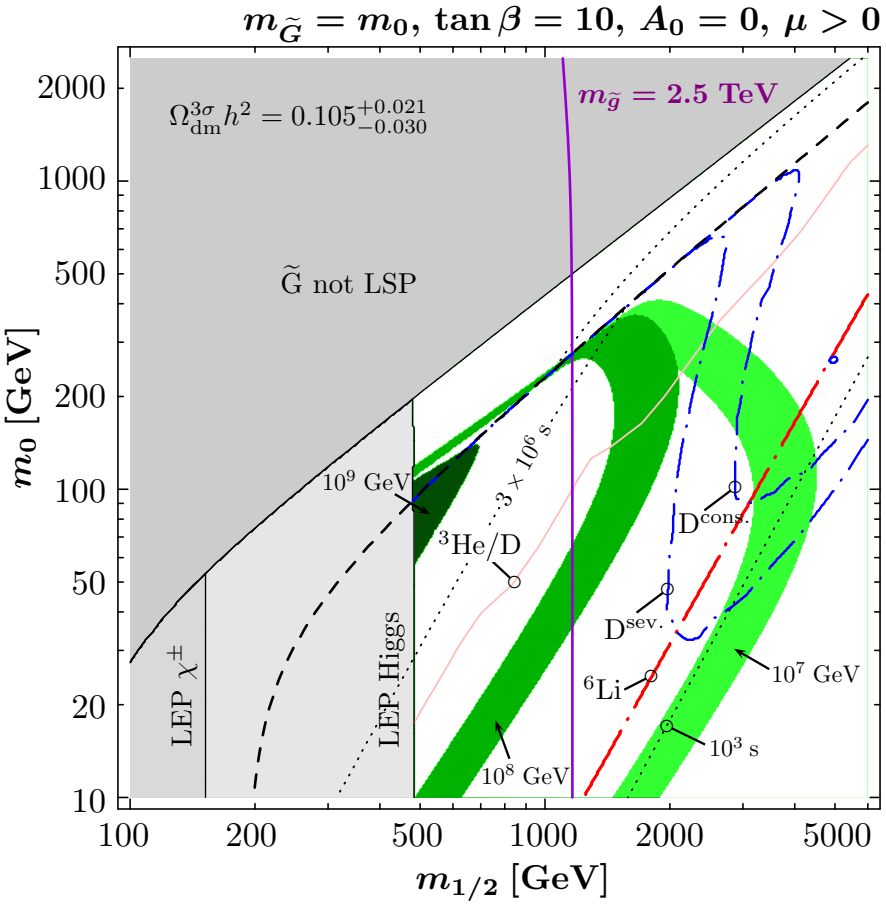
Standard BBN:



Catalyzed BBN:



Cosmological constraints in the Gravitino - Stau scenario



[JP, Steffen, 2007 & 2008]

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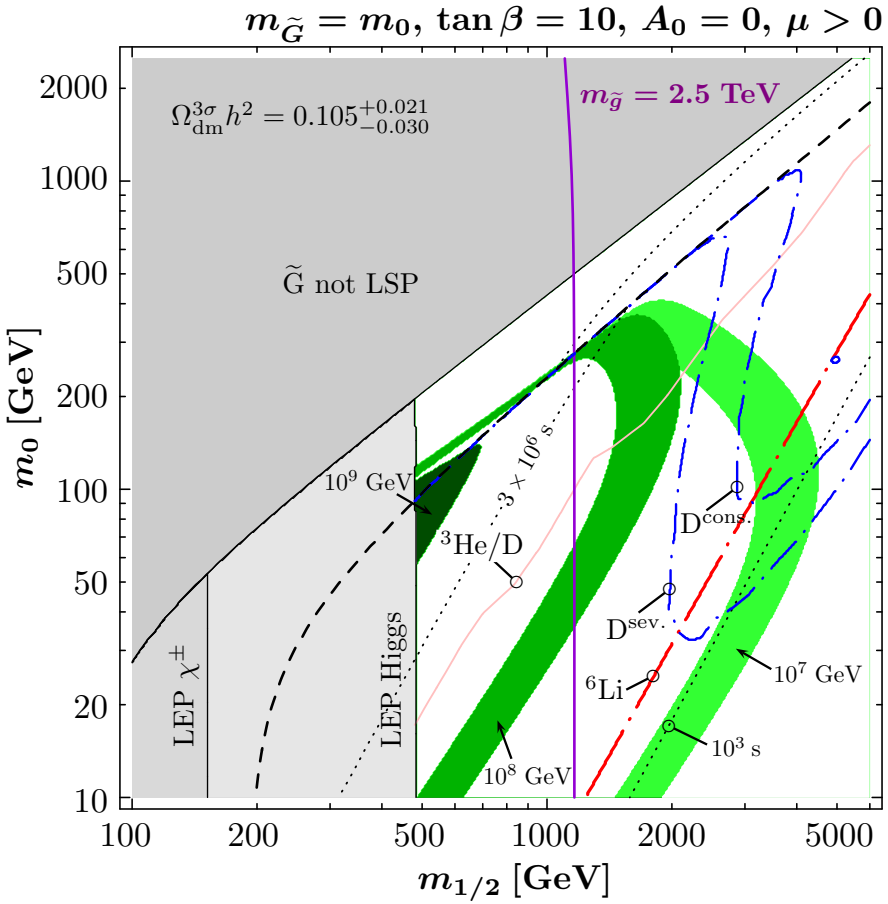

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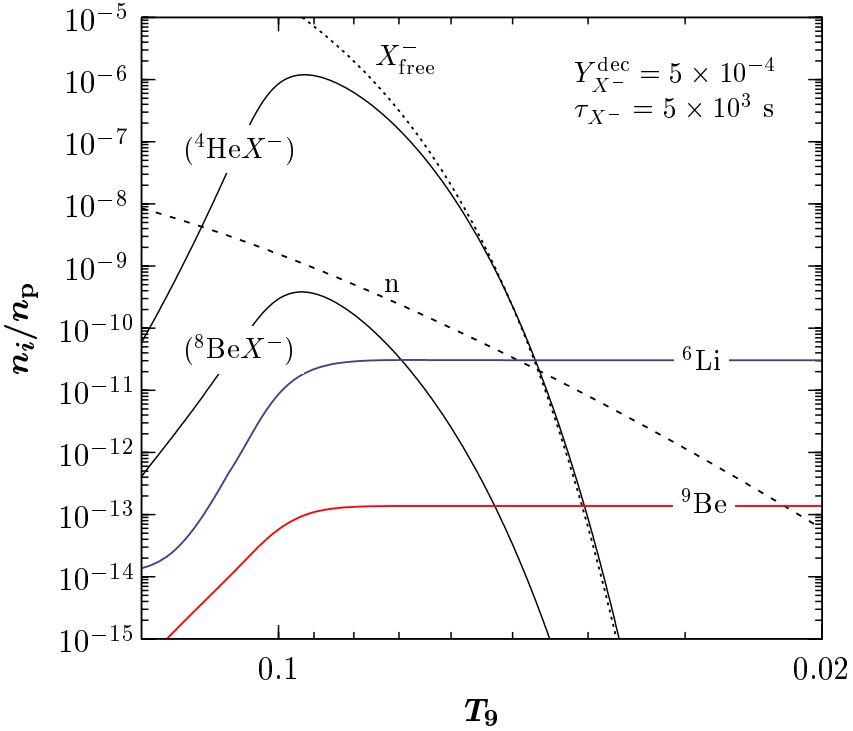

[Pospelov, JP, Steffen, 2008]

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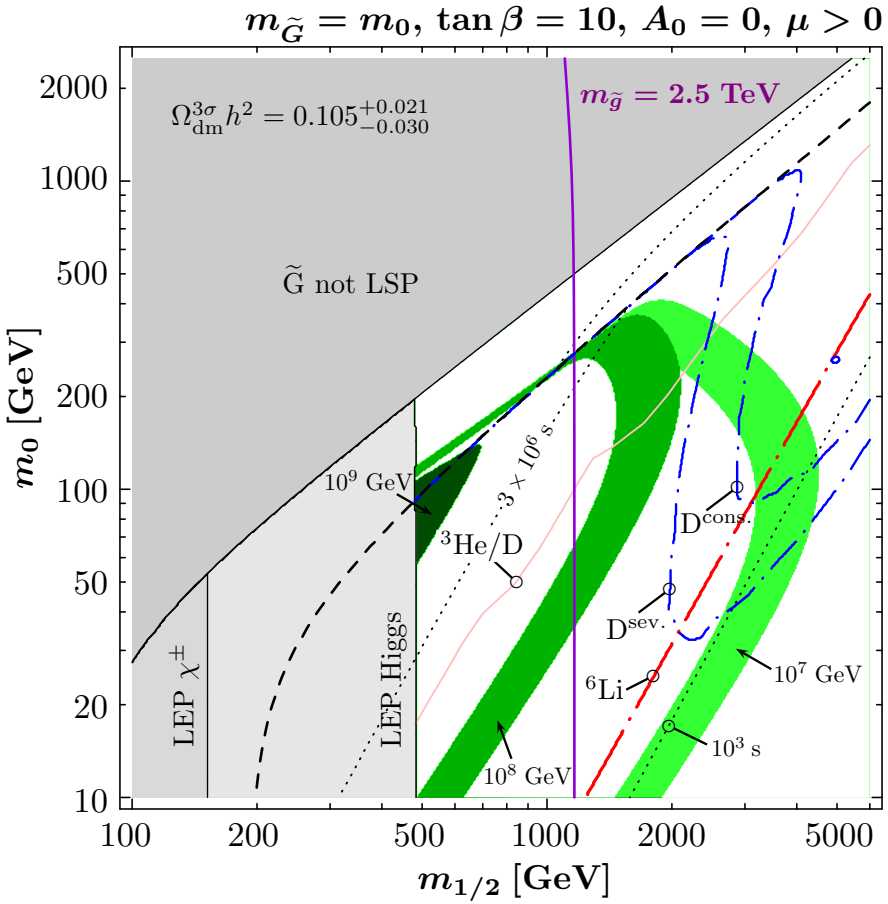

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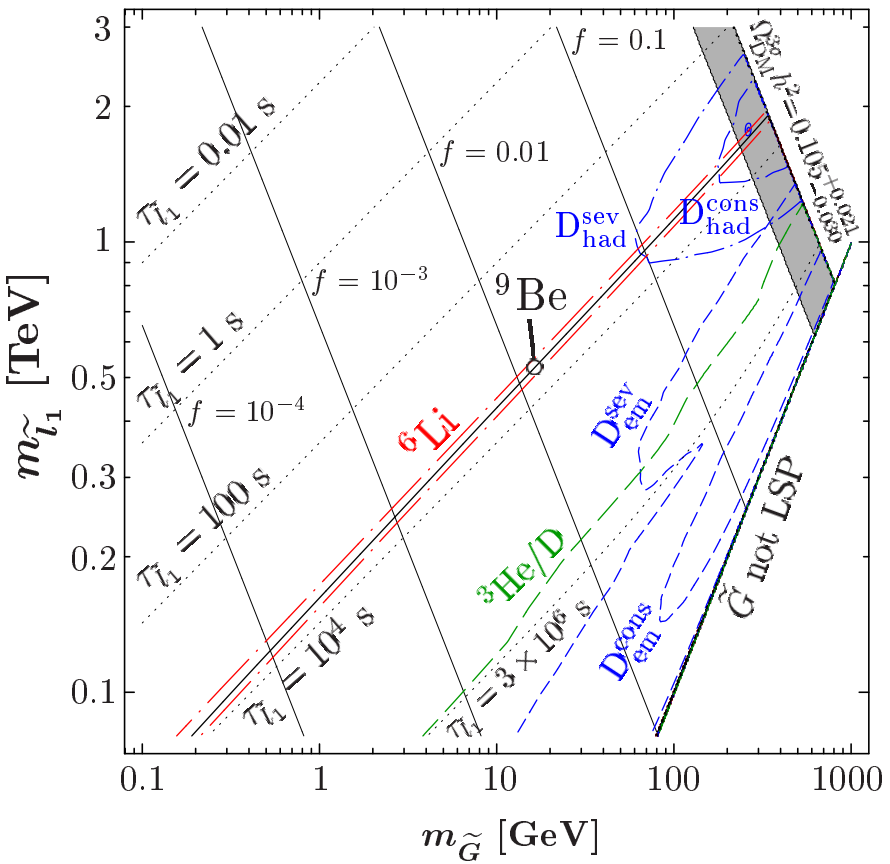

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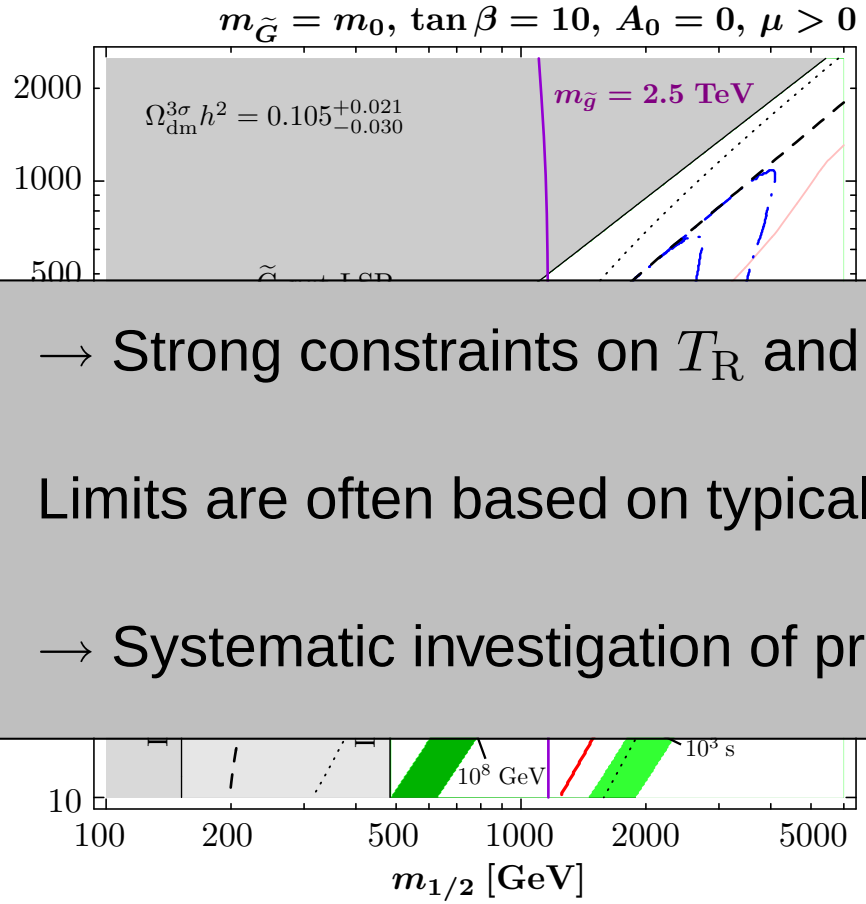
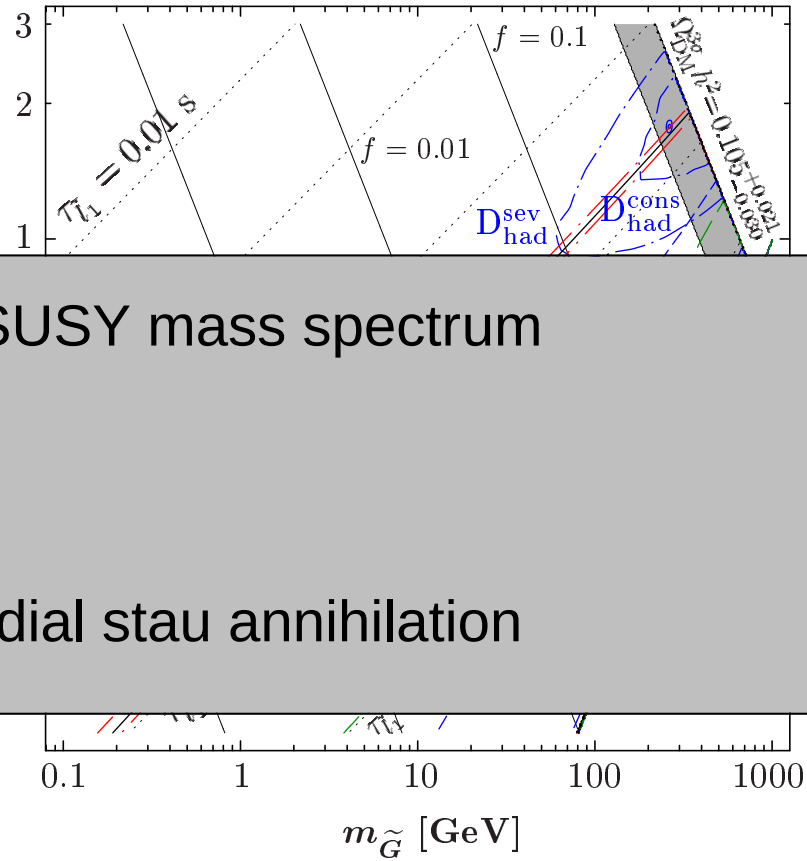




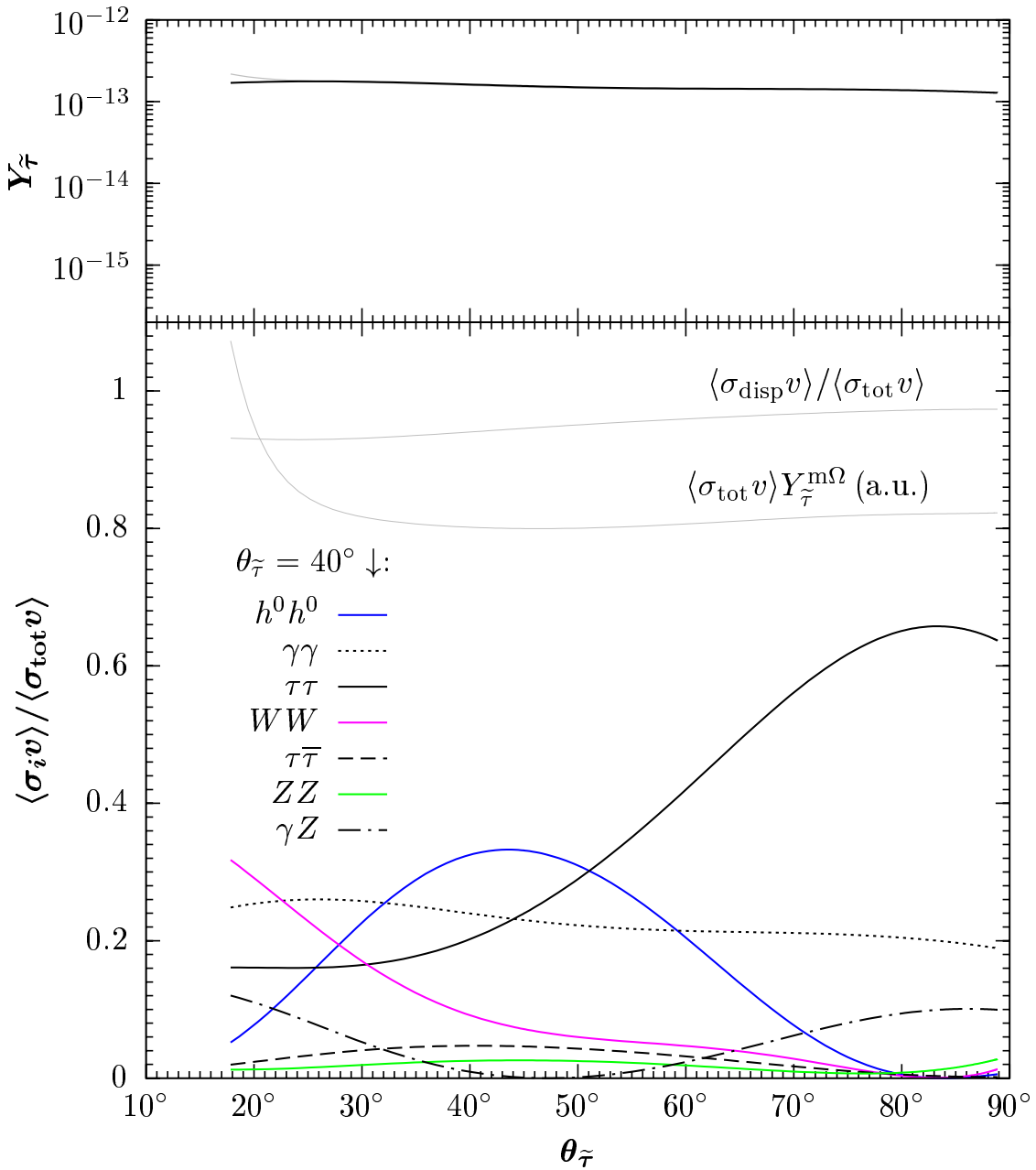
- $\rightarrow$ Strong constraints on $T_{\rm R}$ and on SUSY mass spectrum
- Limits are often based on typical $Y_{\widetilde{\tau}}$!
- $\rightarrow$ Systematic investigation of primordial stau annihilation

[JP, Steffen, 2007 & 2008]

[Pospelov, JP, Steffen, 2008]

Dependence of $Y_{\tilde{\tau}}$ on $\theta_{\tilde{\tau}}$

- Set up own full-fledged relic density calculation
- Typical scenario: $\langle \sigma_{\rm tot} v \rangle$ at $T_{\rm dec}$ only varies within a factor of ~ 1.5
  $\rightarrow \quad Y_{\tilde{\tau}} \sim \text{const}$



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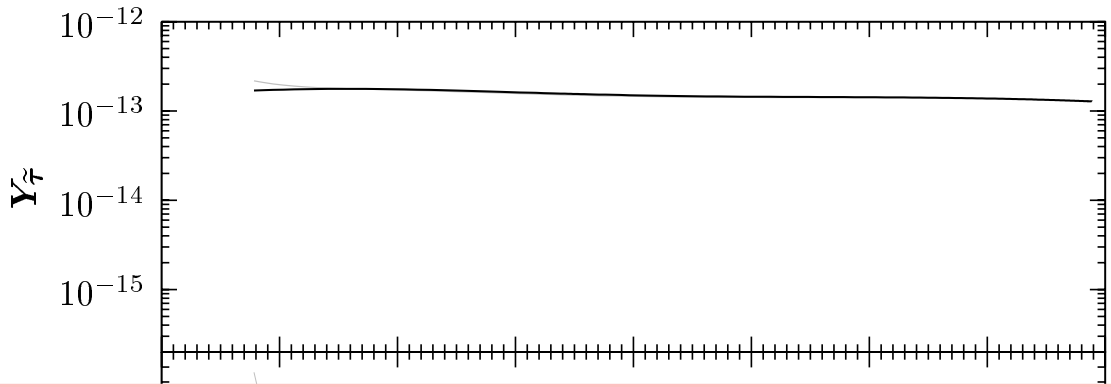


Scalar nature of $\widetilde{\tau}_1$:

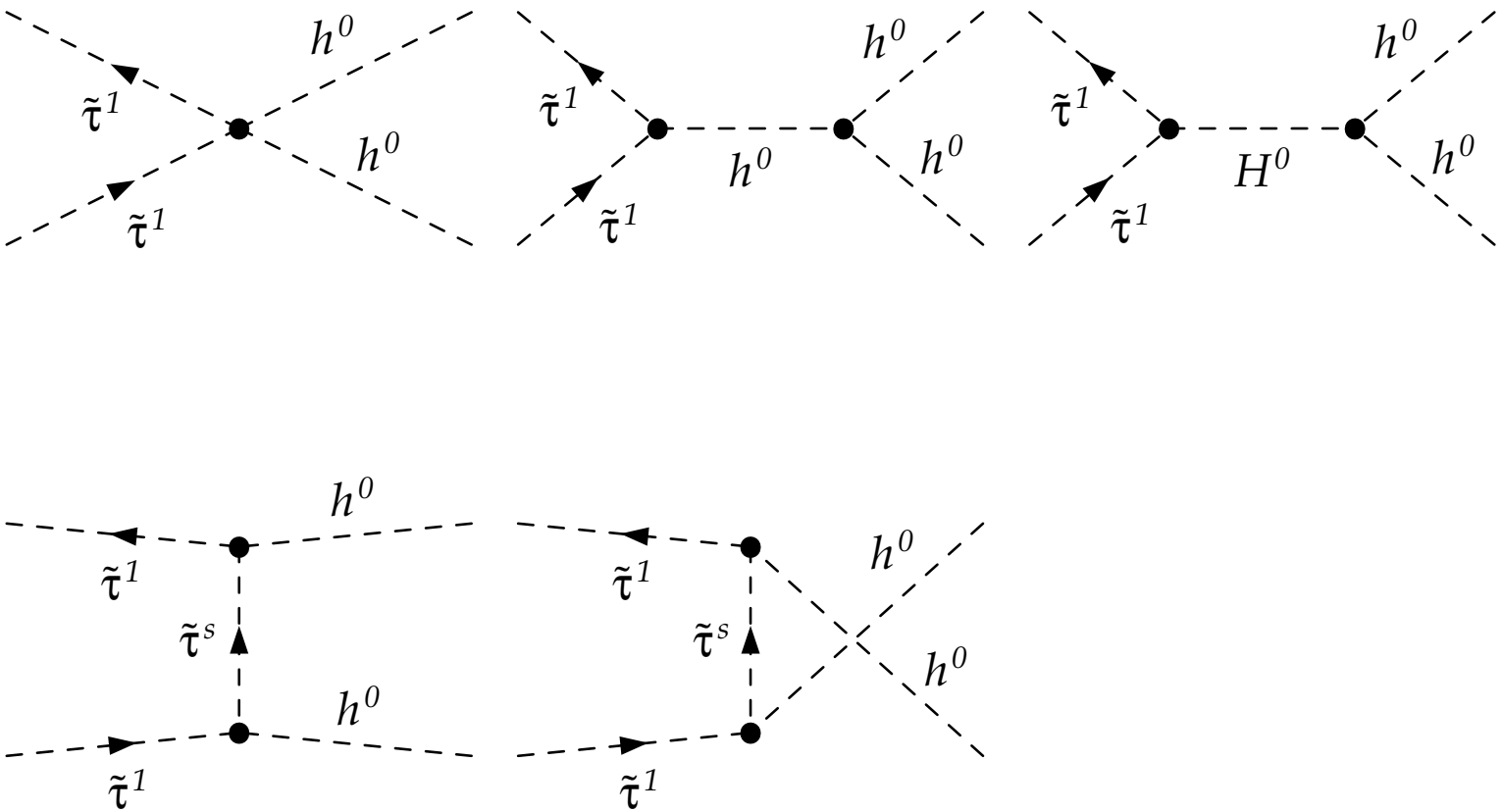
- couples to the (potentially $\tan\beta$-enhanced) dimensionful parameters A_τ and μ via $\mathrm{h}^0, \mathrm{H}^0$ [Ratz et al., 2008; JP, Steffen, 2008]

- in the decoupling limit $(m_{A^0} \gg M_\mathrm{Z})$ simple picture, e.g.:

$$\mathcal{L} \propto \left[\frac{g}{2M_\mathrm{W}} m_\tau (A_\tau - \mu \tan\beta) \sin 2\theta_{\widetilde{\tau}}\right] \widetilde{\tau}_1^* \widetilde{\tau}_1 h^0$$

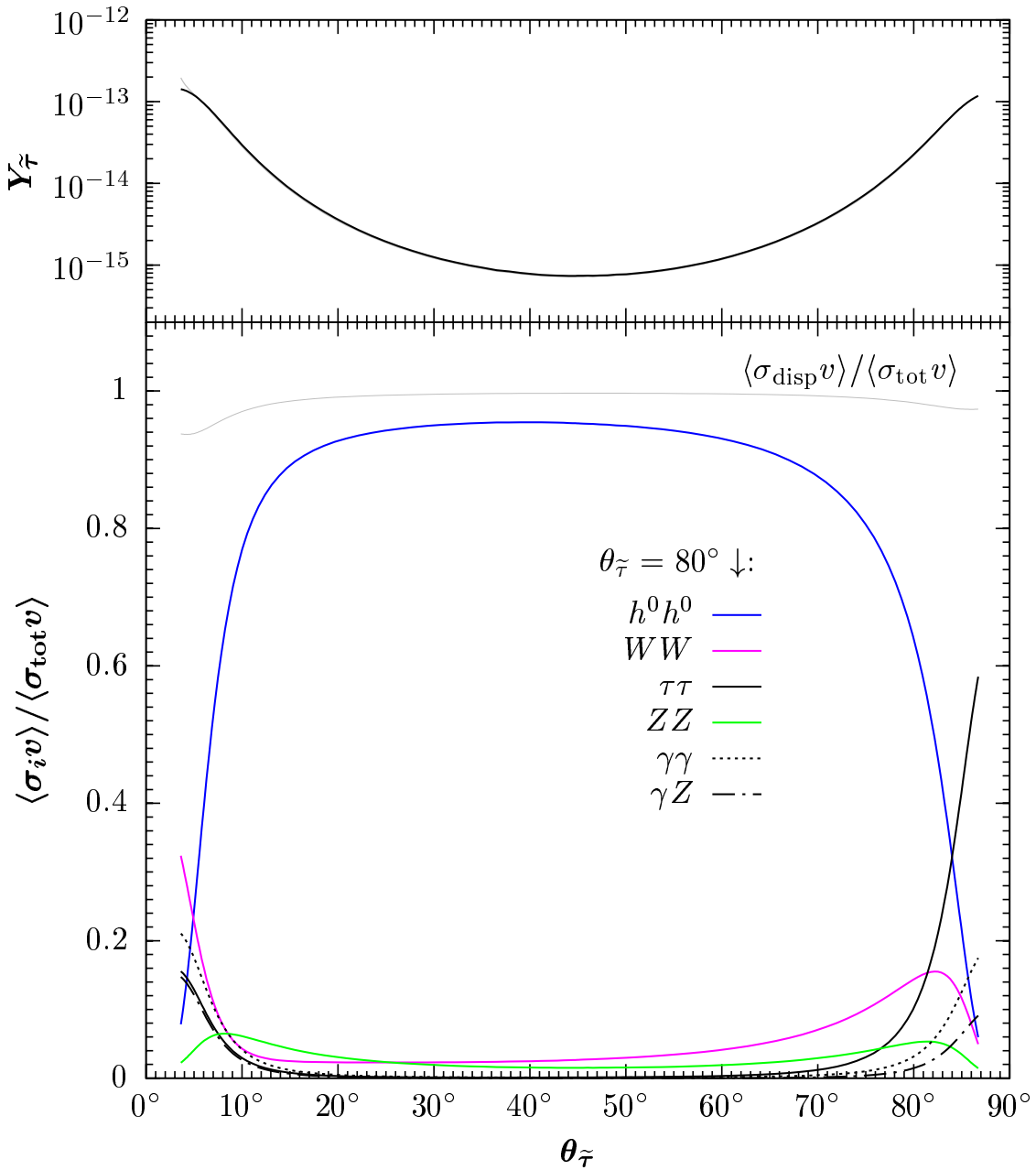
Enhanced annihilation into Higgses

$$\tilde{\tau}^1 \quad \tilde{\tau}^1 \quad \rightarrow \quad h^0 \quad h^0$$



Enhanced annihilation into Higgses

- $\tan\beta = 50$
- e.g. “decoupling limit” ($m_{A^0} \gg M_Z$): only annihilation into h^0 allowed
- Here: $Y_{\tilde{\tau}}^{\min} \simeq 7 \times 10^{-16}$

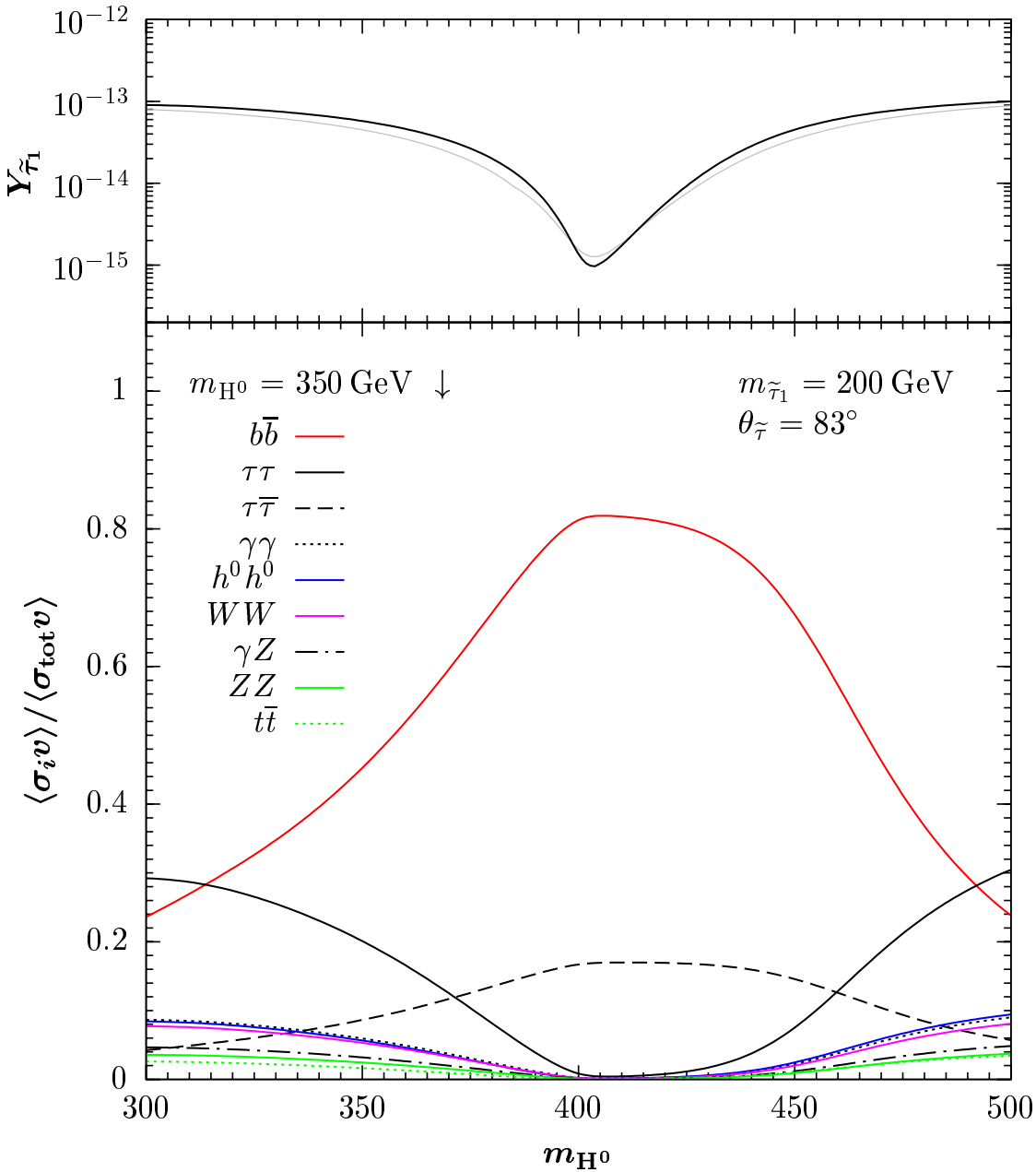


Resonant stau annihilation

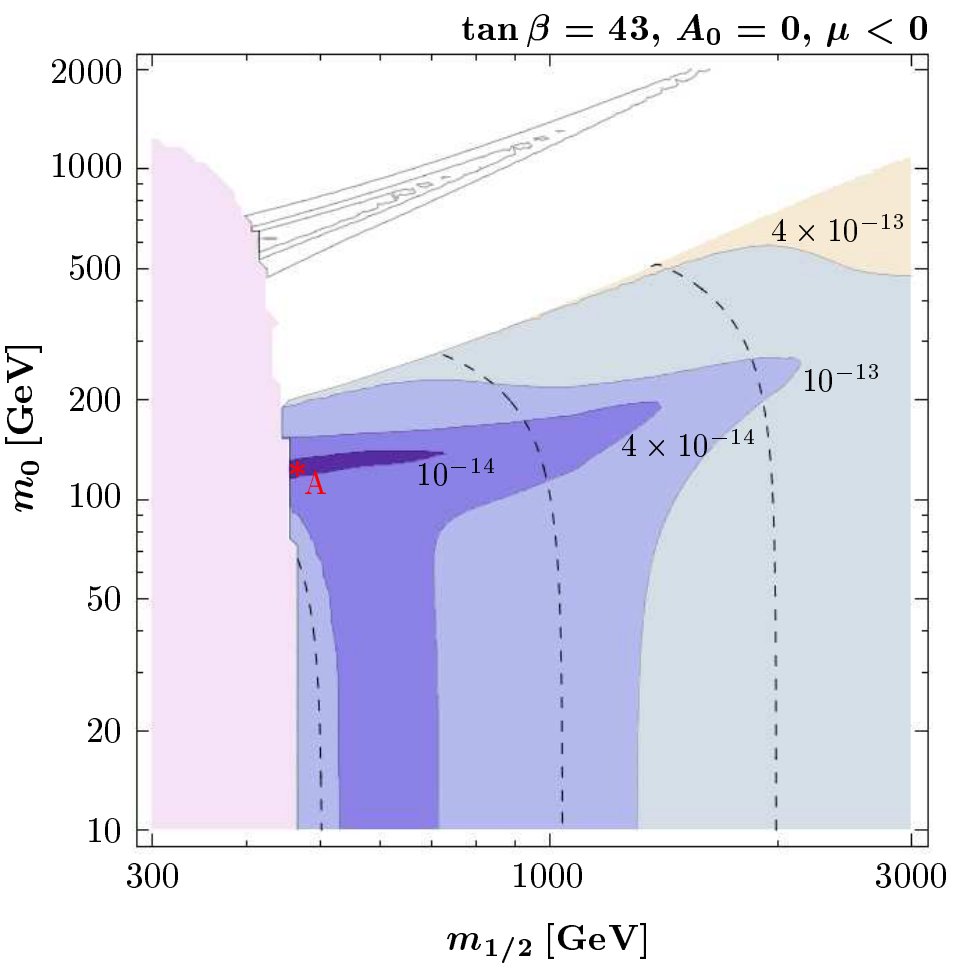
- Annihilation via resonant H^0 production:

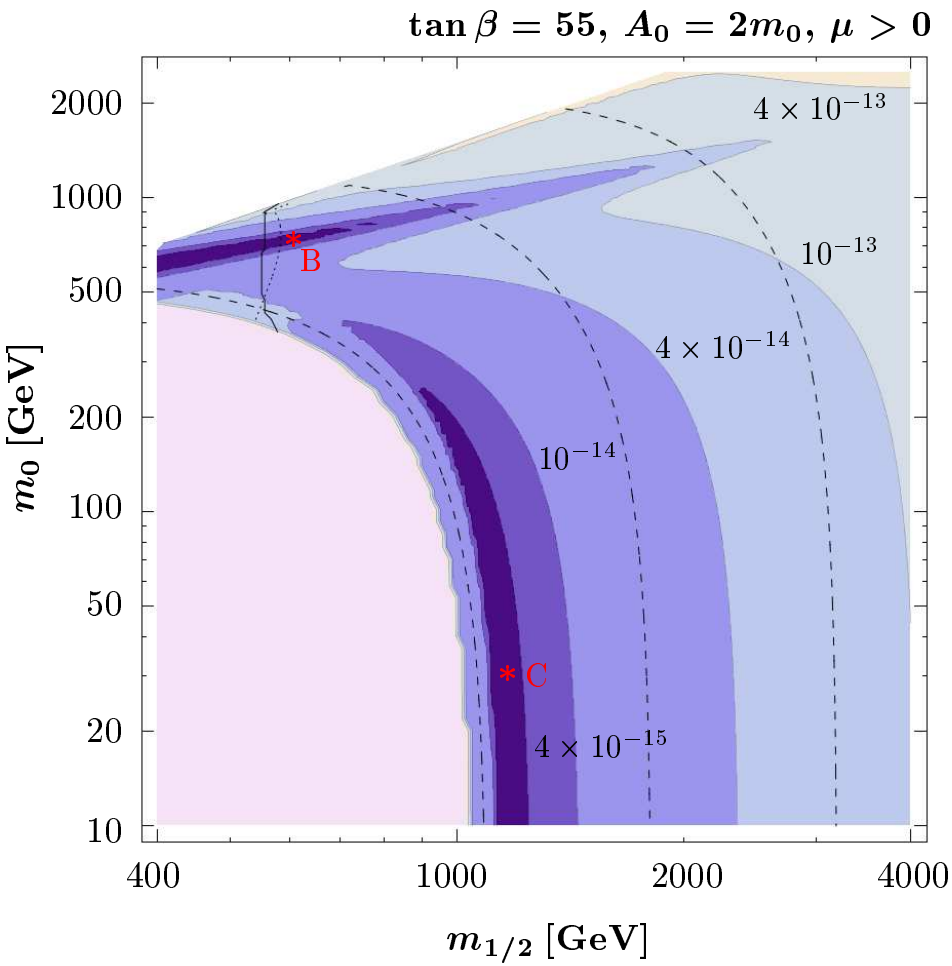
  $\widetilde{\tau}_1\widetilde{\tau}_1 \to H^0 \to \mathrm{SM}$

- MSSM with real parameters: no $\widetilde{\tau}_1\widetilde{\tau}_1 A^0$ coupling $\to$ $\to$ no A^0 resonance
- Here: $Y_{\widetilde{\tau}}^{\min} \simeq 10^{-16}$



Back to the “vanilla Modell”. . . CMSSM





Conclusions

- long-lived stau as thermal relic severely constrained by (C)BBN
- cosmological constraints sensitively depend on $Y_{\widetilde{\tau}}$ which can be substantially depleted

Thermal Relic Abundances of Long-Lived Staus
JP and F. D. Steffen, Nucl. Phys. B 809, 318 (2009)

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Thank you and Merry Christmas!