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Dark Radiation in Sequestered String Models

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Based on:

1) "Sequestered dS String Scenarios: Soft terms ", L. Aparicio, M. Cicoli, S. Krippendorf, A. Maharana, FM, F. Quevedo, [1409.1931]

2) "General Analysis of DR in Sequestered String Models ", M. Cicoli, FM, [to appear]

14th String Pheno 2015

Instituto de Fisica Teórica UAM-CSIC

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SEQUESTERED STRING MODELS

M. Cicoli's talk
arXiv:1409.1931

(dS vacua, LVS moduli stabilization, visible sector at singularities)

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SPLIT-SUSY scenario

$$M_a \approx 1 \text{ TeV}$$

$$m_0 \simeq B\hat{\mu} \approx 10^7 \text{ GeV}$$

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- Gravitino mass: $m_{3/2} \simeq 10^{10}\,\text{GeV}$
- Lightest modulus: $m_v \simeq 10^7\,\text{GeV}$

$\boxed{m_{\text{soft}} \ll m_{3/2}}$ (sequestering)

$\boxed{m_v \gg 50 \text{ TeV}}$ (no CMP)

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Q: which kind of cosmology can arise from them?

L. Aparicio's talk
[Aparicio et al., 2015]

Dark Radiation: what is it?

Relativistic particles in the hidden sector

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Relativistic particles in the hidden sector

energy density of relativistic d.o.f. after e^+e^- annihilation

$$\rho_{\rm rel} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff} \right)$$

effective number of neutrino species:

$$N_{\rm eff} = N_{\rm eff,SM} + \Delta N_{\rm eff}$$

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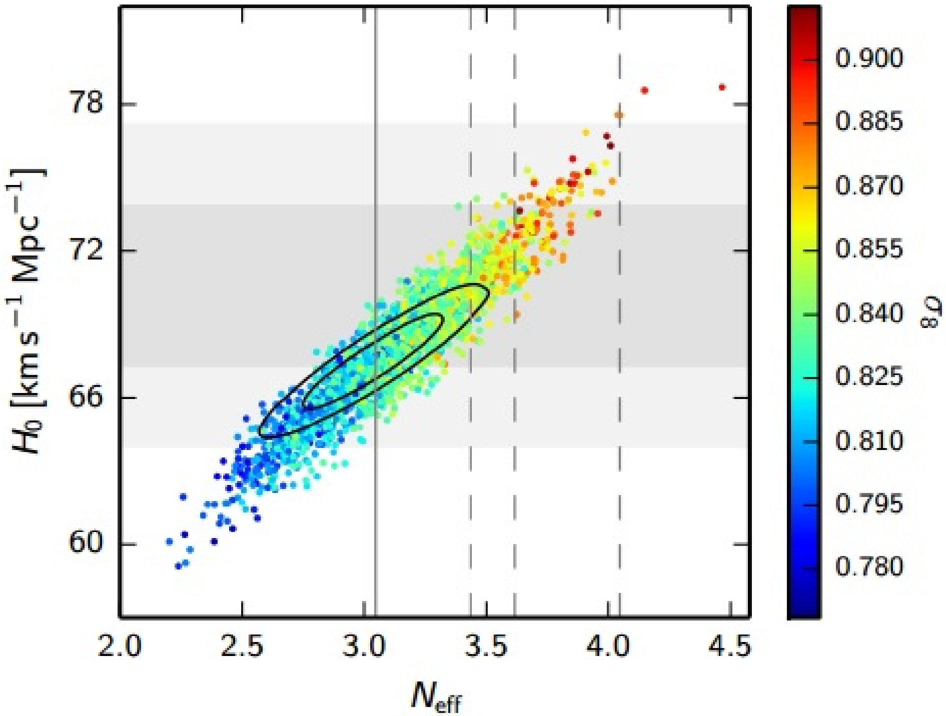
$\Delta N_{eff} > 0 \Rightarrow$ **DARK RADIATION**

experimental constraints coming from BBN and CMB observations:

larger ρ_{rel} $\longrightarrow$ larger H $\longrightarrow$ can modify CMB and BBN predictions

Planck 2015: there is no need for dark radiation.



[Planck collaboration 2015, arXiv:1502.01589]

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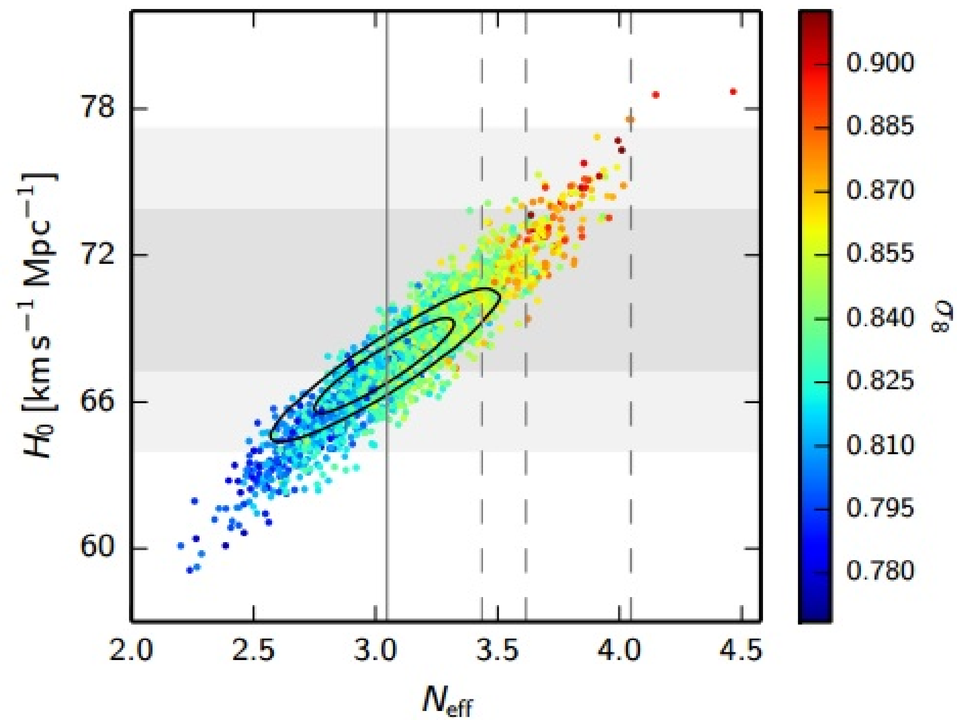

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- There is a positive correlation between H_0 and $\Delta N_{\rm eff}$.
- The value of H_0 used by Planck is in tension with direct measurements by the HST.
- Example reported by Planck: $\Delta N_{\rm eff} = 0.39$.

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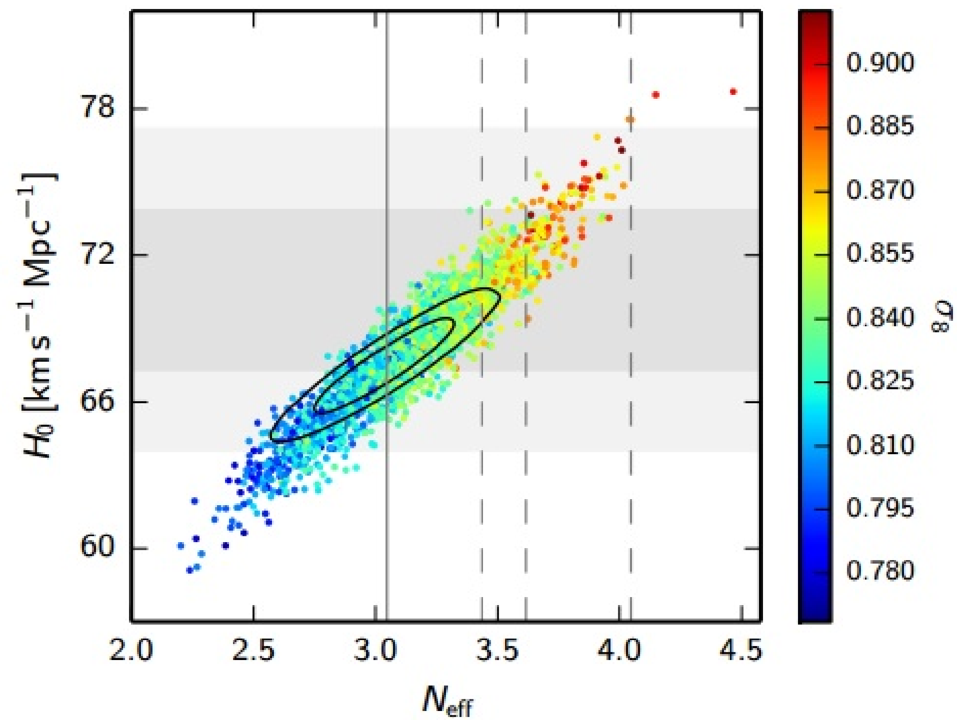

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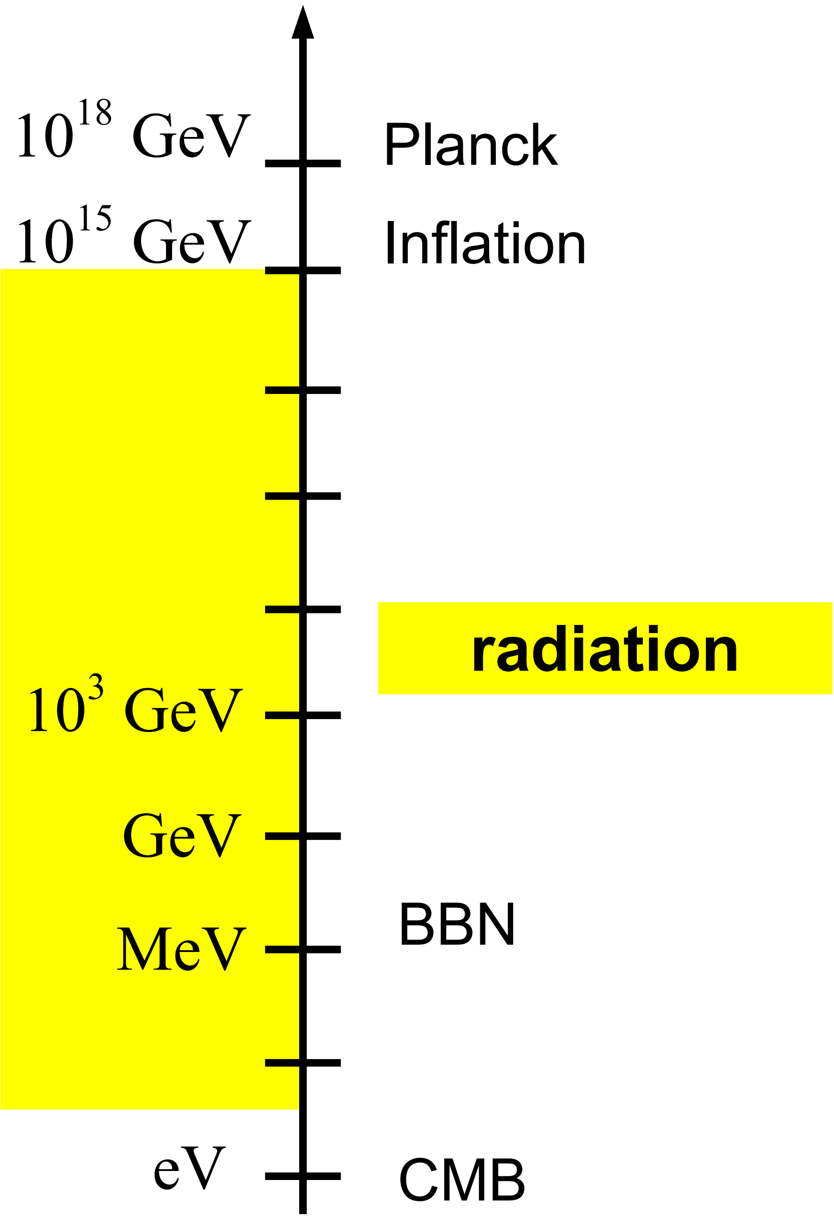
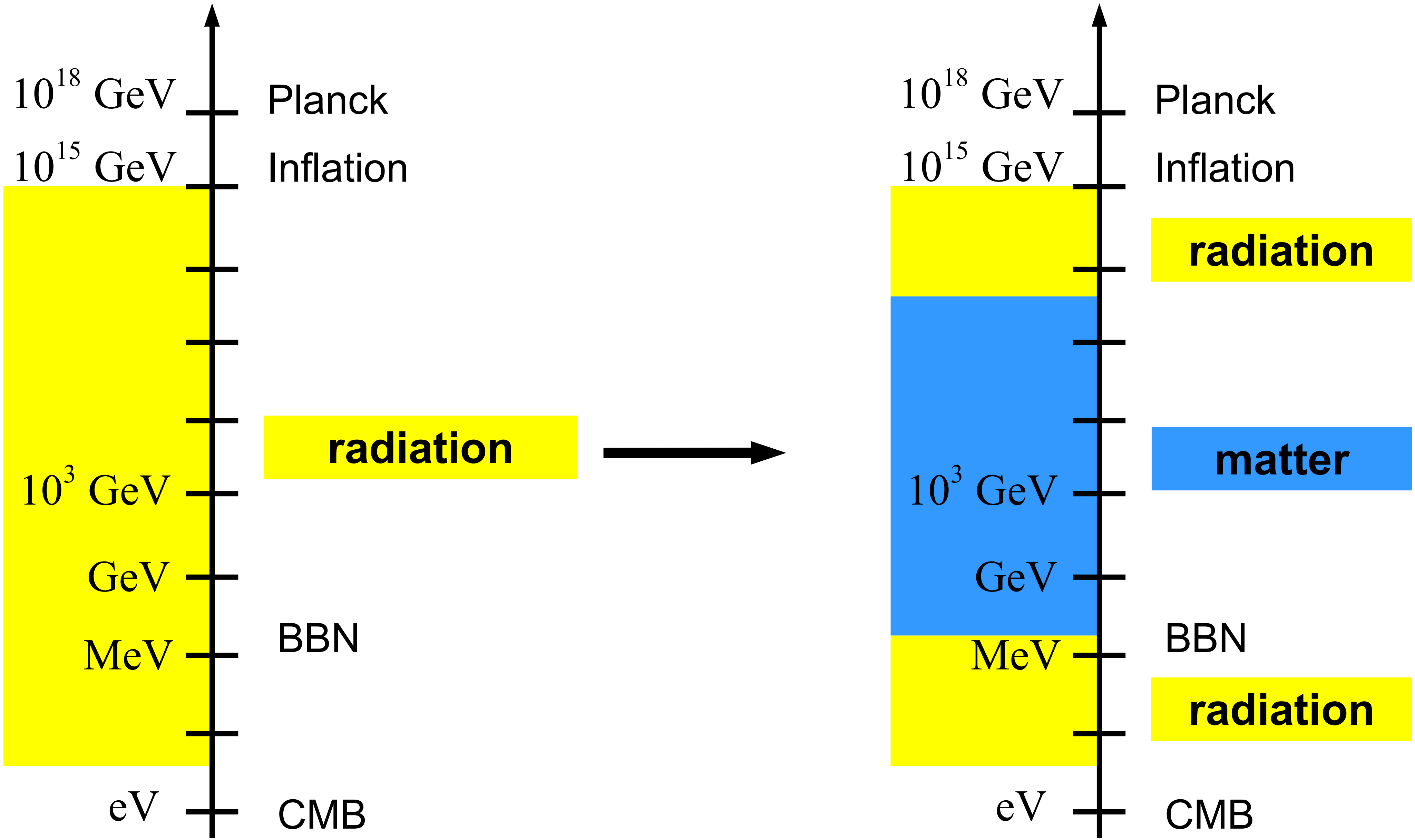
In this talk I will consider $\Delta N_{\mathrm{eff}} \leqslant 0.5$ as a reference upper bound on ΔN_{eff}.

Thermal History



Thermal History

The presence of moduli can modify this standard picture

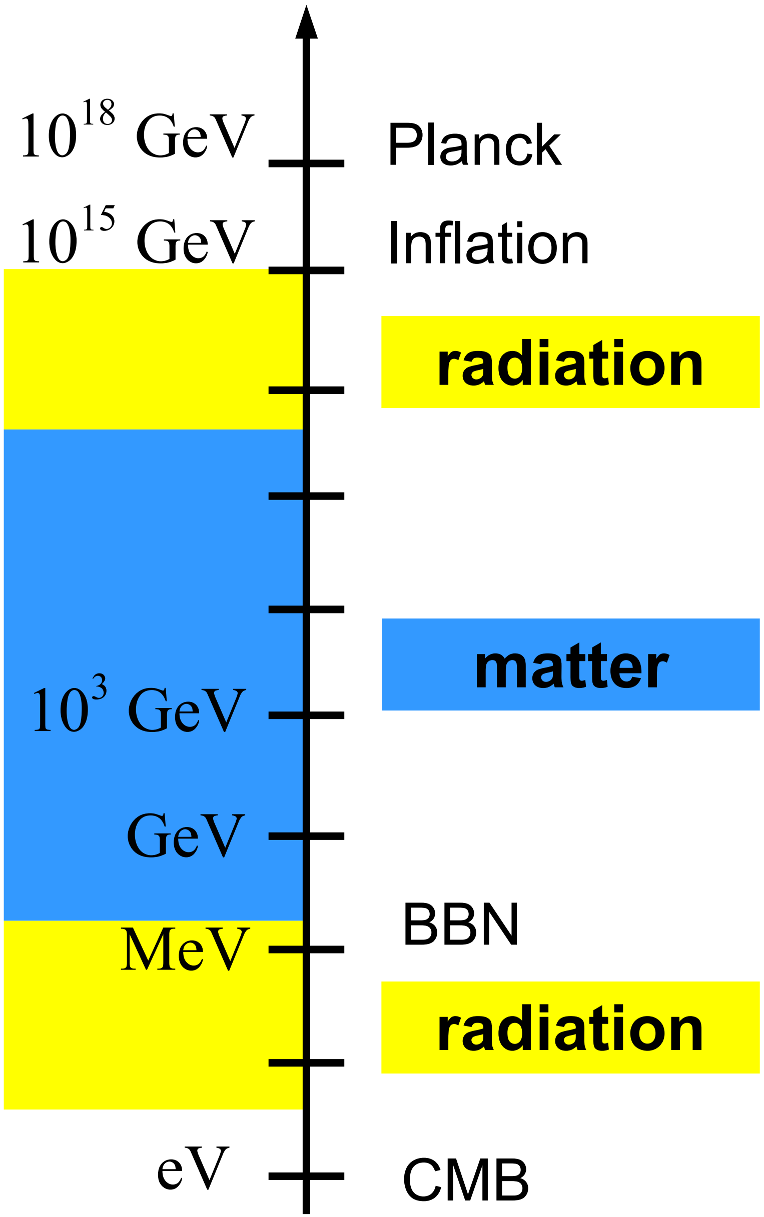


Non-thermal history

- Quantum corrections displace moduli during inflation

$$V = \frac{1}{2} m_\phi^2 \phi^2 + H^2 (\phi - \phi_0)^2 \qquad m_\phi \ll H_{\inf}$$

E.o.m. $$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$



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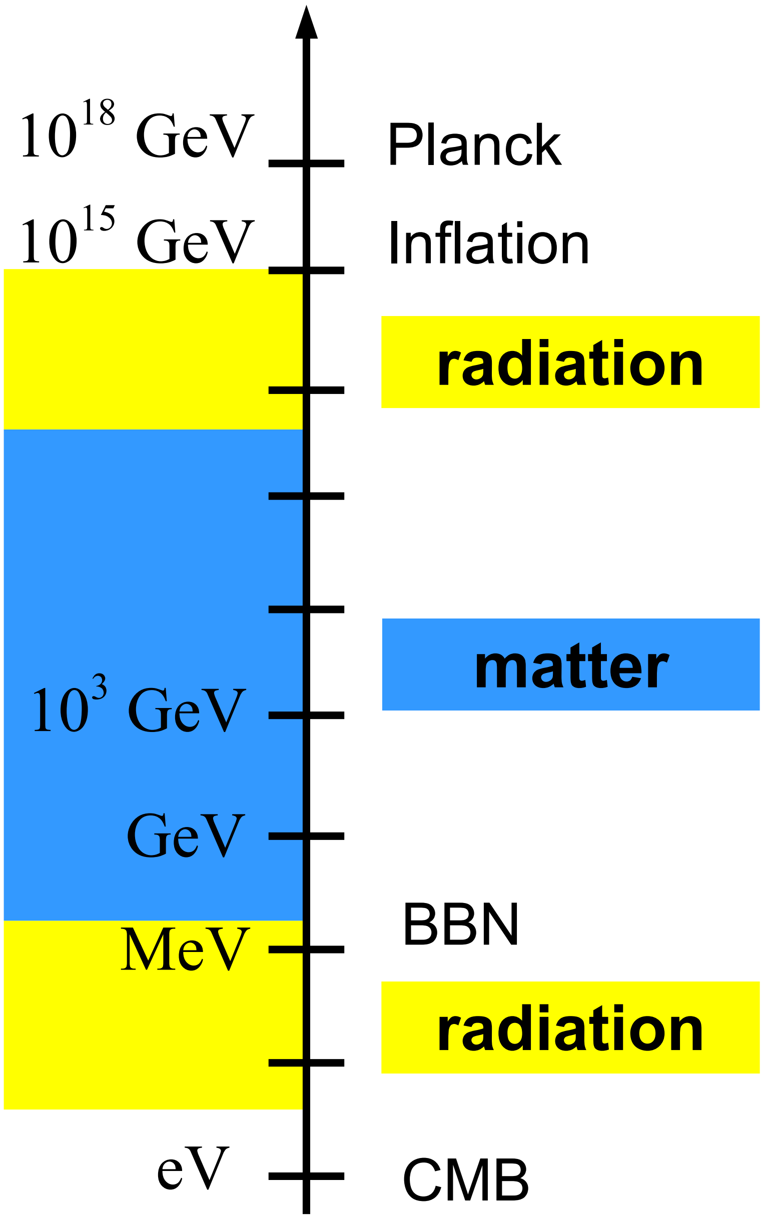

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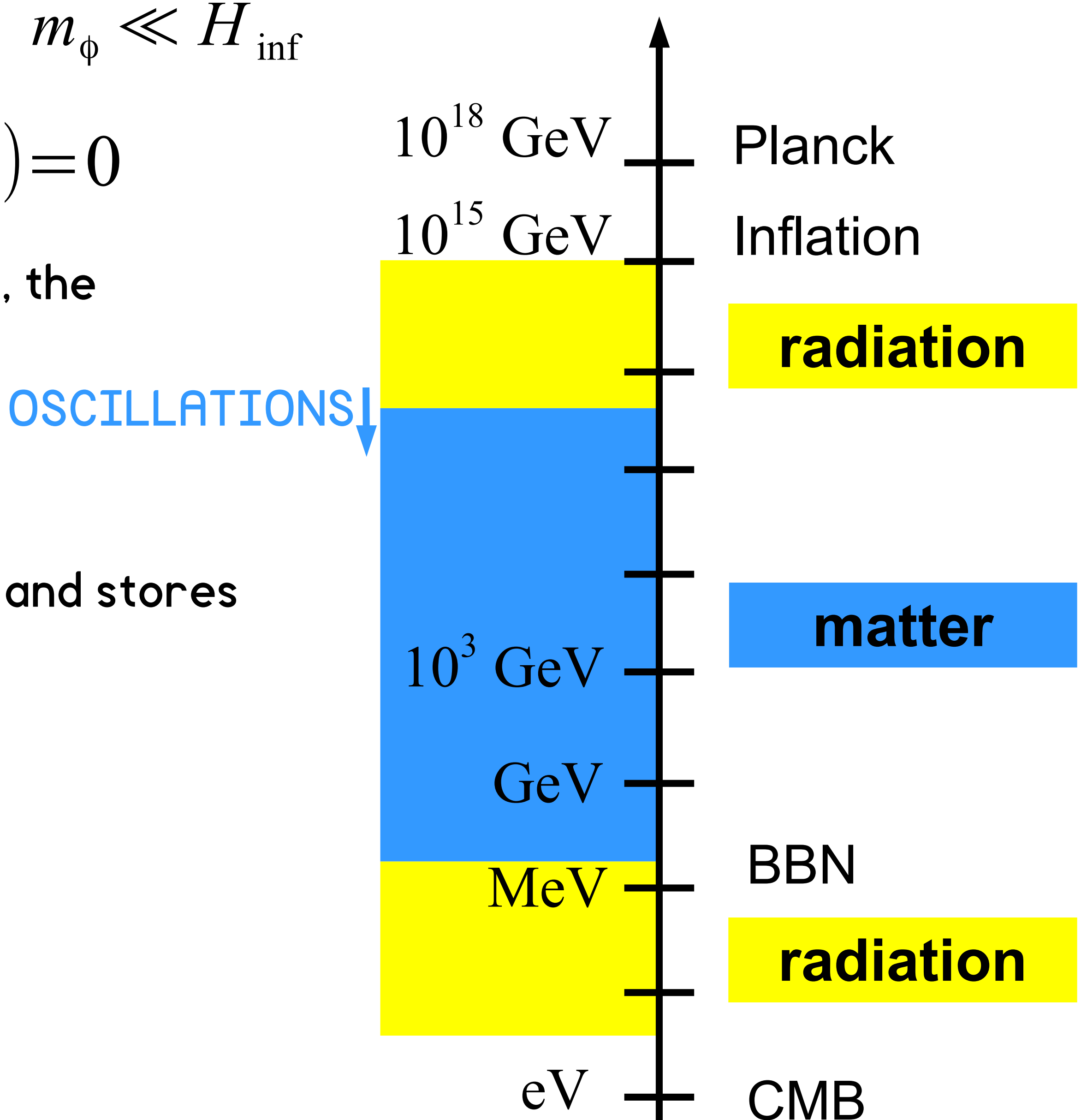

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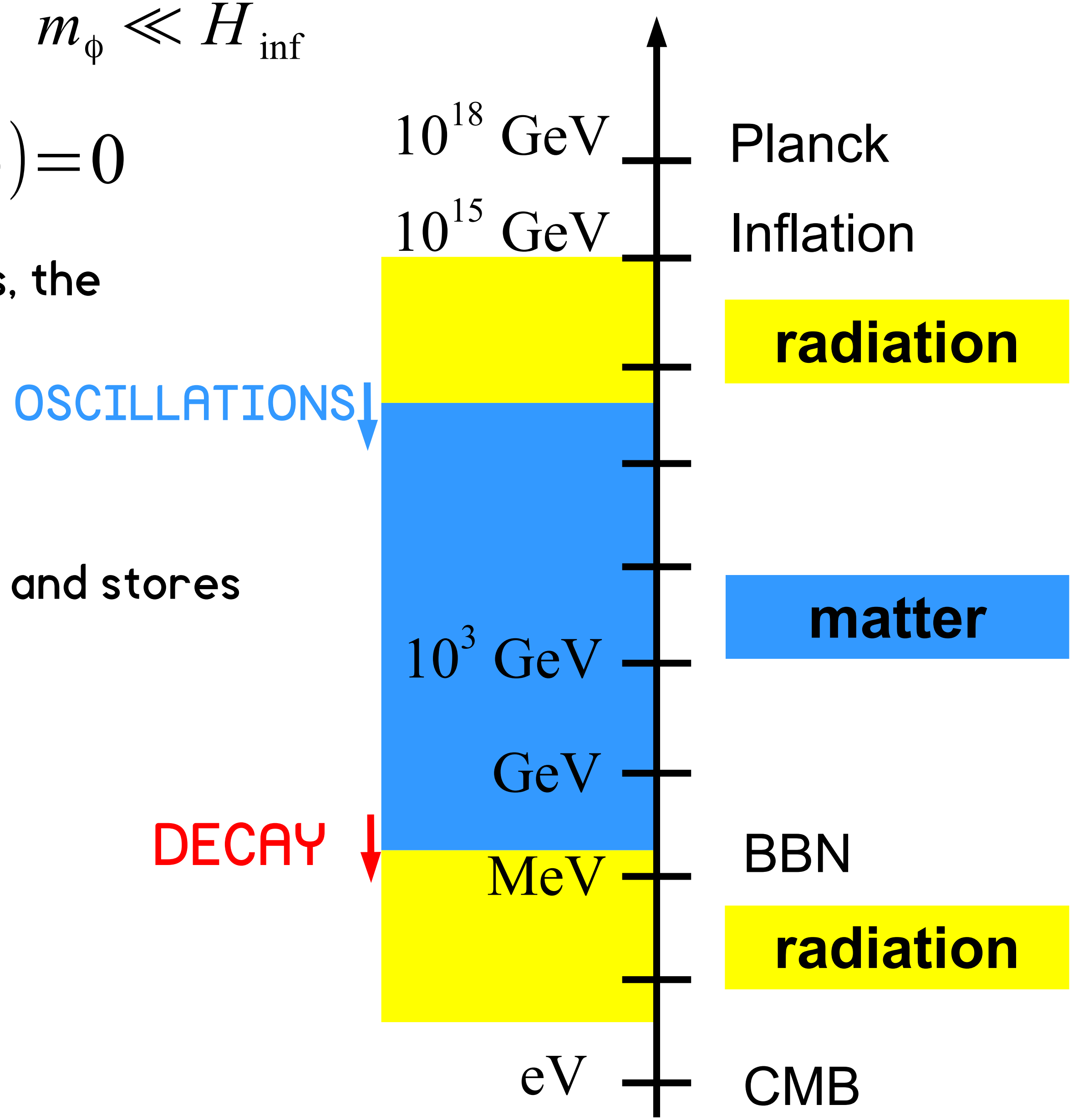
- Decay when: $H \approx \Gamma \approx \frac{m_\phi^3}{M_p^2}$



DR in type IIB

[Allahaverdi et al., 2014]

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- Type IIB: $T_b = \tau_b + i\,\psi_b$ (volume modulus)
- LVS stabilization
  1) τ_b perturbative: $m_{\tau_b} \simeq M_p / V^{3/2}$
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- $$K \supset -3 \log\left(T_b + \bar{T}_b\right)$$

  $$\mathcal{L}_{\text{int}} \supset -\sqrt{\frac{2}{3}}\,\delta\Phi\,\partial_\mu a_b\,\partial^\mu a_b$$

  CN: $\Phi = \sqrt{\frac{3}{2}} \log \tau_b \qquad a_b = \sqrt{\frac{3}{2}} \frac{\psi_b}{\langle \tau_b \rangle}$

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→ Decay width $\Phi \to a_b\, a_b$:

$$\Gamma = \frac{1}{48\pi} \frac{m_\Phi^3}{M_p^2} \equiv \Gamma_0$$

Decay channels into the visible sector

- Decay into visible gauge bosons
  $\Phi \to A\,A$

$$\Gamma_{\Phi \to AA} = \left(\frac{\alpha_{\mathrm{SM}}}{4\pi}\right)^2 \Gamma_0 \ll \Gamma_0$$

always loop suppressed

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  (mass-terms)

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- Higgs fields

$$\Gamma_{\Phi\to HH} \simeq f\left(Z, m_H, B\hat{\mu}\right)\Gamma_0$$

$\Phi \to H_u H_d$ ($B\hat{\mu}$-term, GM-term Z)

$\Phi \to H_{u/d} \bar{H}_{u/d}$ (mass-terms)

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Total decay rate: $\quad \Gamma_{\rm tot} = \left(1 + c_{\rm vis}\right)\Gamma_0$

Sequestered CMSSM

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$$\longrightarrow \quad \boxed{c_{\text{vis}} = 2Z^2}$$

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- DR produced: $\Delta N_{\text{eff}} = \frac{43}{7}\frac{1}{c_{\text{vis}}}\left[\frac{g(T_{\text{dec}})}{g(T_{\text{reheat}})}\right]^{1/3}$

$$g(T_{\text{dec}}) \simeq 10.75$$

$$g(T_{\text{reheat}}) \simeq 86.25$$

$$0.7 \text{ GeV} \leq T_{\text{reheat}} \leq 13 \text{ GeV}$$

$$\xrightarrow[Z=1]{} 1.63 \leq \Delta N_{\text{eff}} \leq 1.74$$

[Cicoli, Conlon, Quevedo, 2012]

[Higaki, Takahashi, 2012]

[Angus, Conlon et al., 2013]

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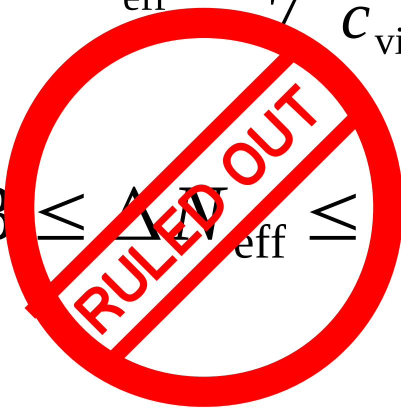

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Decay channels:

$\Phi \to C\bar{C}$ $\Phi \to H_{u/d}\bar{H}_{u/d}$	mass terms	$\Phi \to H_u H_d$	GM & $B\hat{\mu}$-terms

Sketch of the computation:

- Lagrangian depends on Φ : $\mathscr{L}(\Phi) = \mathscr{L}_{\text{kin}}(\Phi) - V(\Phi)$
- Idea: expand around the volume minimum: $\Phi = \langle \Phi \rangle + \delta\Phi$
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- Start from the Kähler potential which determines the kinetic terms:

$$K=-2\log\mathcal{V}+\frac{2}{T_b+\bar{T}_b}\sum_{\alpha}C^{\alpha}\bar{C}^{\alpha}+\left(\frac{2Z}{T_b+\bar{T}_b}H_u H_d+\text{h.c.}\right)\longrightarrow\mathscr{L}_{\text{kin}}(\Phi)$$

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- Consider canonically normalized fields:

$$h_1 = \frac{\Re H_u^+}{\sqrt{\langle \tau_b \rangle}} \qquad h_2 = \Re \frac{H_u^0}{\sqrt{\langle \tau_b \rangle}} \qquad \ldots \qquad \sigma_\alpha = \frac{\Re C^\alpha}{\langle \tau_b \rangle} \qquad \chi_\alpha = \frac{\Im C^\alpha}{\sqrt{\langle \tau_b \rangle}}$$

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- The scalar potential takes the form:

$$V = V_{\text{LVS}} + \frac{m_0^2}{2}\sum_\alpha\left(\sigma^{\alpha\,2} + \chi^{\alpha\,2}\right) + \frac{1}{2}\left(\hat{\mu}^2 + m_0^2\right)\sum_{i=1}^{8} h_i^2 + B\hat{\mu}\left(h_1 h_4 - h_2 h_3 + h_6 h_7 - h_5 h_8\right)$$

- Expand the soft-terms which depend on the volume,

for example: $$m_0^2(\Phi) = m_0^2\left(1 - \frac{9}{2}\sqrt{\frac{2}{3}}\,\delta\Phi\right)$$

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- The total decay rate into the visible sector is given by:

$$B\hat{\mu} = Z\,m_0^2 \qquad c = \frac{m_0}{m_\Phi}$$

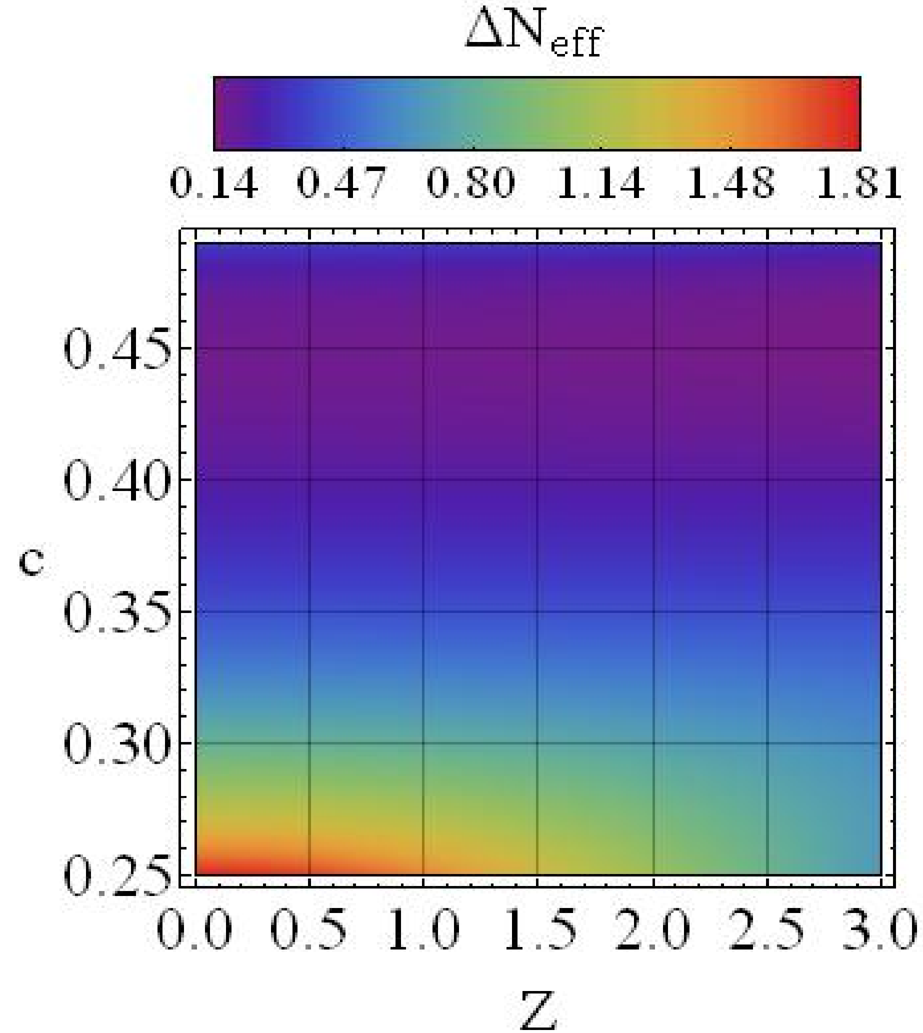
$$c_{\mathrm{vis}} = \left[2Z^2\left(7c^2-1\right)^2 + 49c^4\left(1+\frac{2N}{4}\right)\right]\sqrt{1-4c^2}$$

$2N = 90$ squarks and sleptons d.o.f. in the MSSM

Results

- A large region of the parameter space admits values of $\Delta N_{\mathrm{eff}} \leqslant 0.5$.

- Most of the suppression is due to the decay into scalars.



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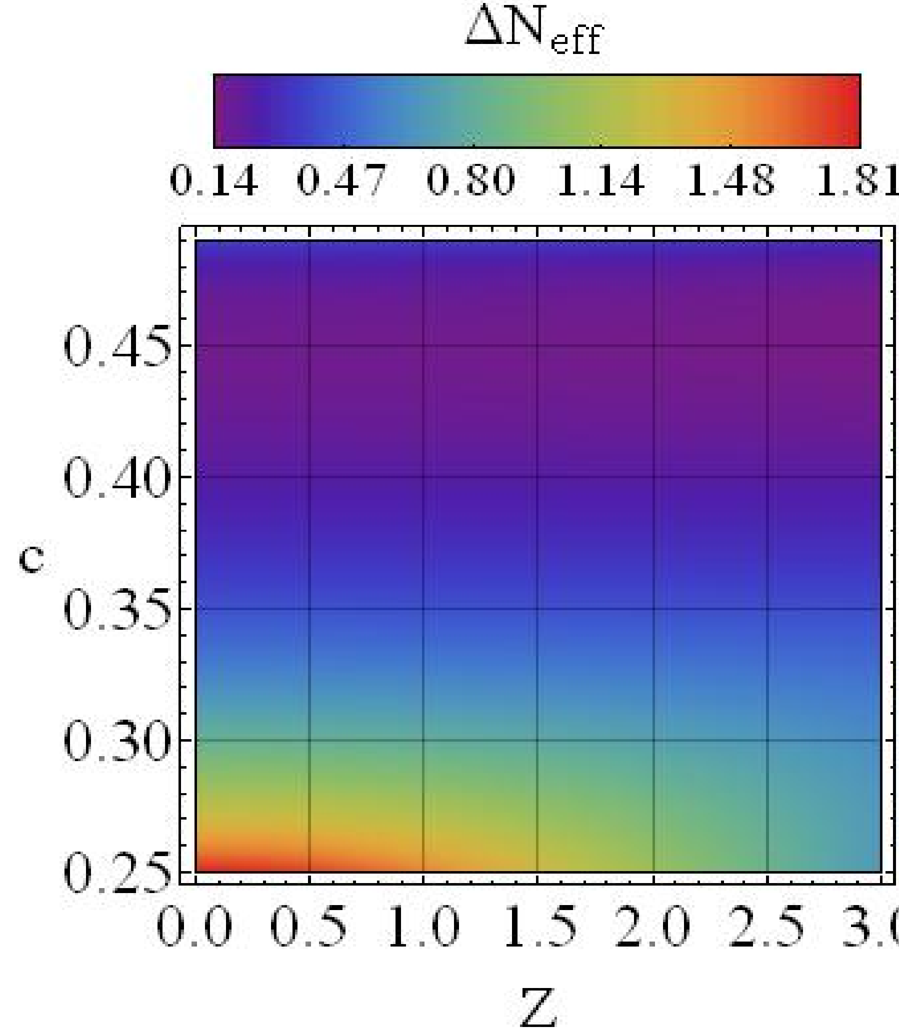
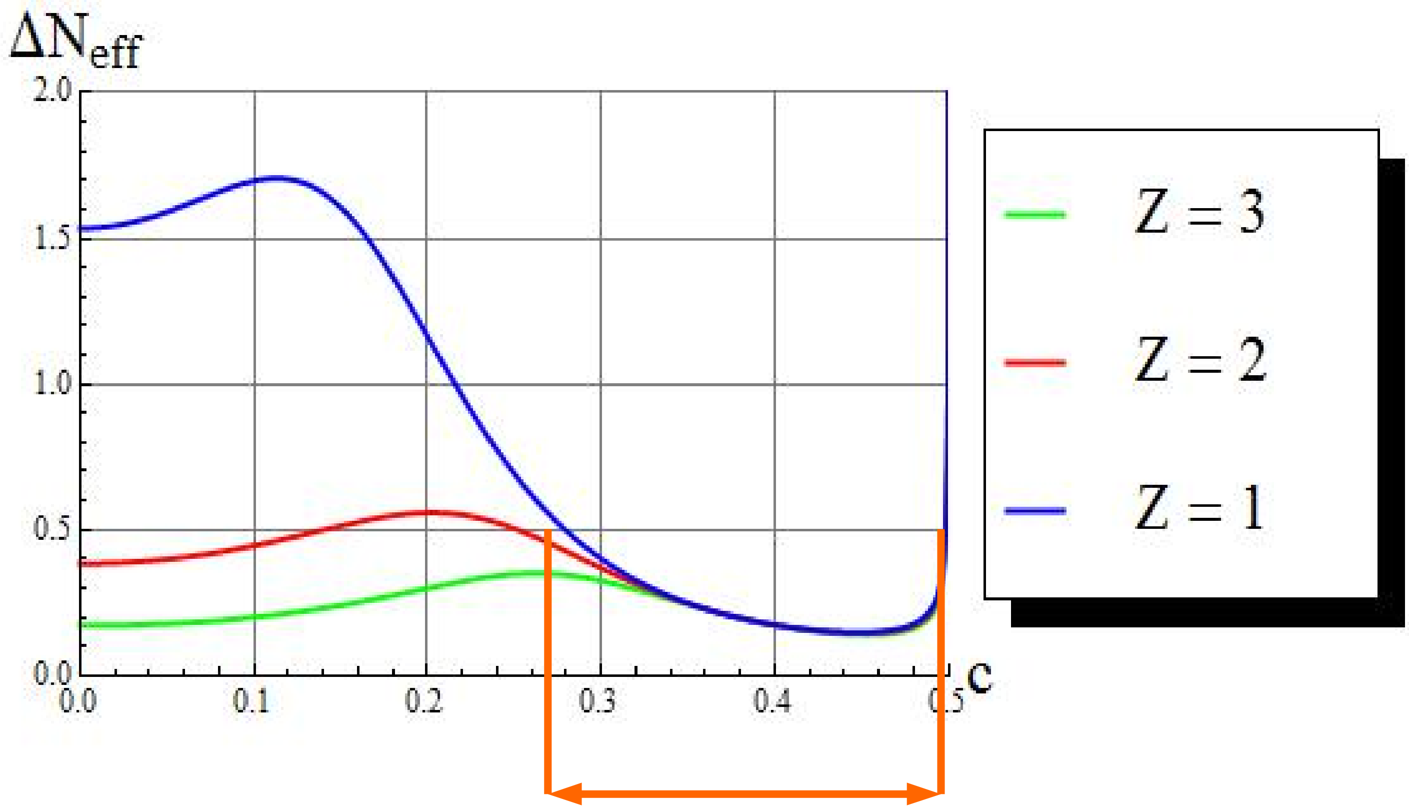


For $Z = 1$, $m_0 = 10^7$ GeV and $c = 0.45$ we get $\Delta N_{\rm eff} = 0.14$

It is not a fine-tuned result!



For $Z = 1$ all these values of c: $0.28 < c < 0.49$

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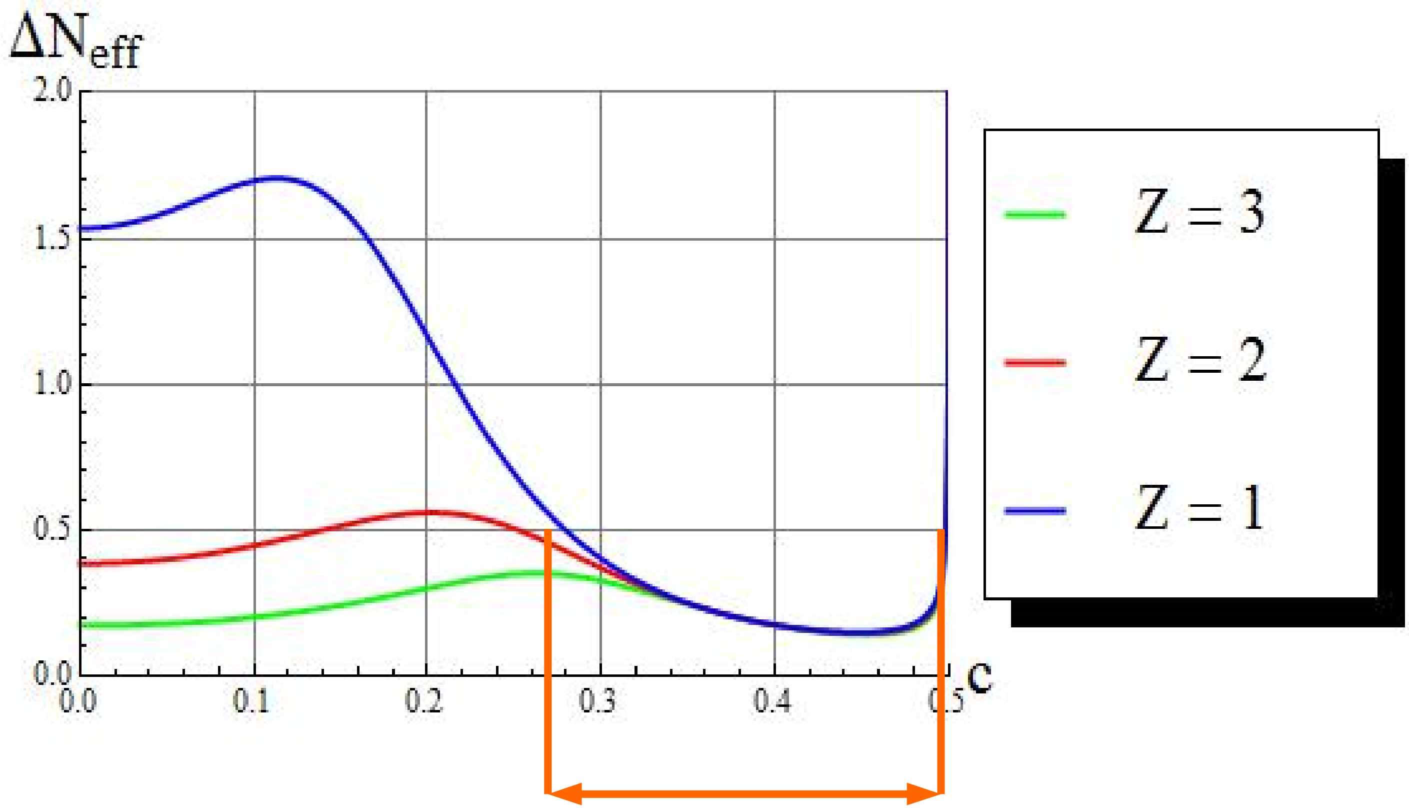

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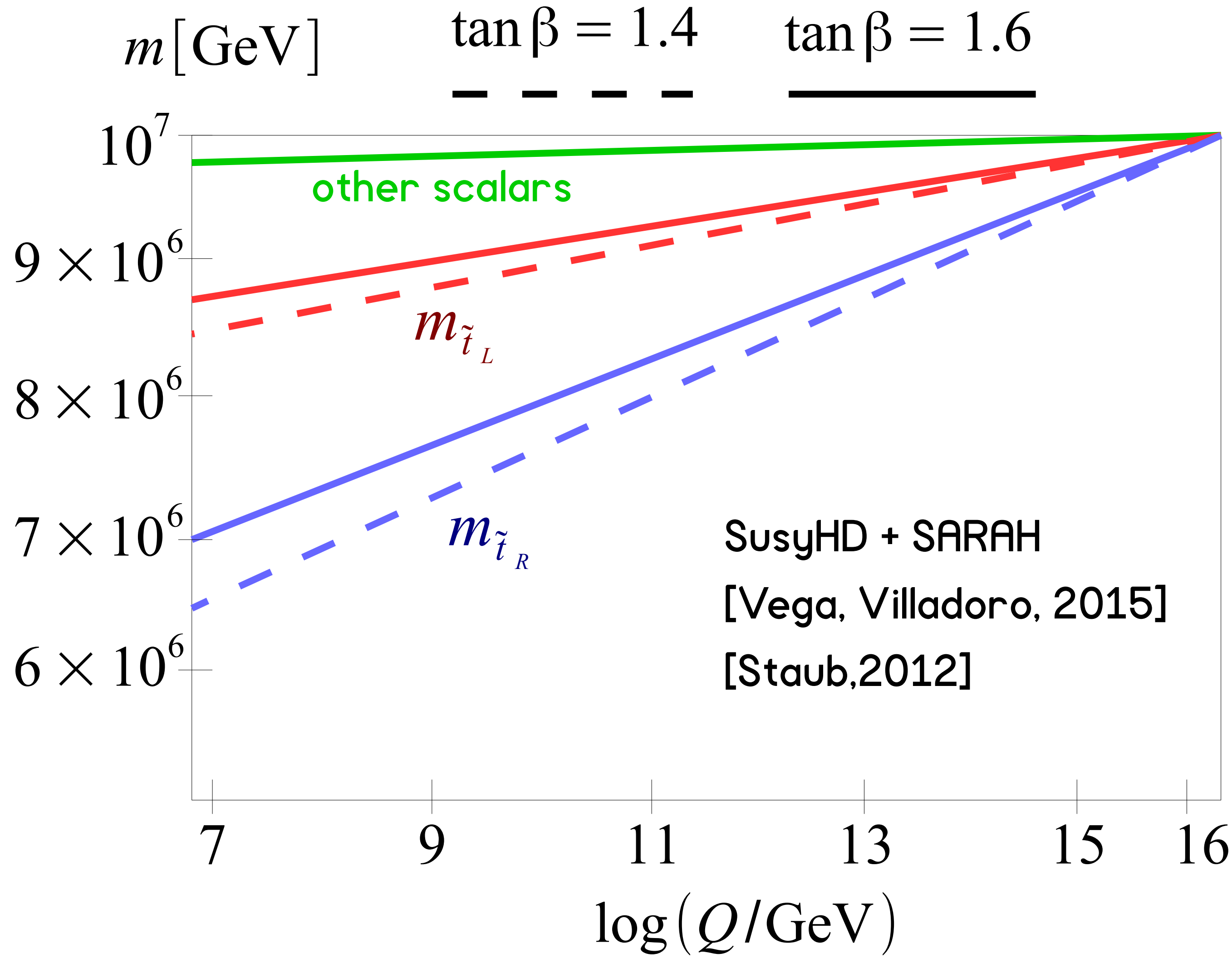
Q: is the result modified by taking into account the RG flow?

The result is essentially independent of the RG running.

- Scalars don't run, except for $m_{\tilde{t}_L}$ and $m_{\tilde{t}_R}$.
- We take the running of $B\hat{\mu}$ and Z into account.
- We didn't study the EWSB so far.



For $m_\Phi = 2.2\times10^7\ \mathrm{GeV}$ we get $\Delta N_{\mathrm{eff}} \simeq 0.16$

Conclusions and next steps

We have shown that the the amount of DR produced in Split-SUSY, LVS sequestered string models with all moduli stabilized and dS vacua is generically within the current experimental bounds, if the decay into scalar fields is kinematically allowed.

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We have shown that the the amount of DR produced in Split-SUSY, LVS sequestered string models with all moduli stabilized and dS vacua is generically within the current experimental bounds, if the decay into scalar fields is kinematically allowed.

- EWSB has to be analyzed carefully.
- Correlation with DM production.

Thank you!

Yukawas: $\hat{Y}_{\alpha\beta\gamma} = e^{K/2} \dfrac{Y_{\alpha\beta\gamma}}{\sqrt{\tilde{K}_\alpha \tilde{K}_\beta \tilde{K}_\gamma}}$

Locality of Yukawa couplings requires: $\tilde{K} = e^{K/3}$

We parameterize the Kähler matter metric $\tilde{K} = \dfrac{f_\alpha}{\mathcal{V}^{2/3}}\left(1 - c_s \dfrac{\xi s^{3/2}}{\mathcal{V}}\right)$

Scalar masses: $m_0^2 = \dfrac{15}{2}\left(c_s - \dfrac{1}{3}\right)\dfrac{m_{3/2}^2 \tau_s^{3/2}}{\mathcal{V}}$ $\qquad c_s \neq \dfrac{1}{3}$

Volume modulus mass: $m_\Phi^2 = \# \dfrac{m_{3/2}^2 \tau_s^{1/2}}{\mathcal{V}}$

In LVS: $\tau_s \simeq \log\left(\dfrac{\mathcal{V}}{W_0}\right) \gg 1$ $\Longrightarrow$ Tipically: $\dfrac{m_0^2}{m_\Phi^2} > \dfrac{1}{4}$

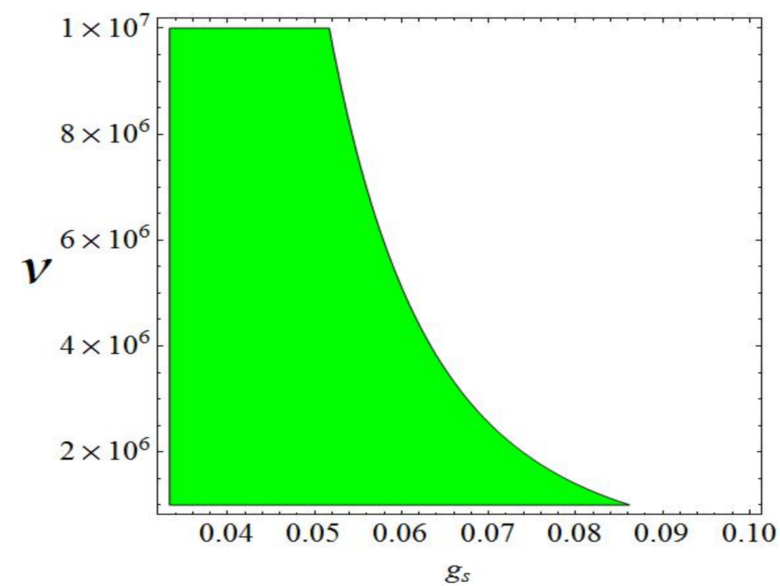
Introduce SL corrections into the Kähler potential: $\delta K_{\text{loop}} = \frac{g_s}{\mathcal{V}^{2/3}}$

Matter metric gets modified: $\tilde{K} = \frac{1}{\mathcal{V}^{2/3}}\left(1 - c_s \frac{\xi s^{3/2}}{\mathcal{V}} - \frac{c_{\text{loop}} g_s}{\mathcal{V}^{2/3}}\right)$

Scalar masses take the form:

$$m_0^2 = \left(\frac{15}{2}\left(c_s - \frac{1}{3}\right)\frac{\tau_s^{3/2}}{\mathcal{V}} - \left(c_{\text{loop}} - \frac{1}{3}\right)\frac{2 g_s}{\mathcal{V}^{2/3}}\right) m_{3/2}^2 \qquad \tau_s = \left(\frac{\xi}{2}\right)^{2/3}\frac{1}{g_s}$$

$\longrightarrow$ Enlarge the region of the parameter space where the decay is possible: i.e. for $c_s = 1/3$ and $c_{\text{loop}} = 0$



Canonically normalized fields:

$$h_1 = \frac{\Re\, H_u^+}{\sqrt{\langle \tau_b \rangle}} \qquad h_2 = \Re \frac{H_u^0}{\sqrt{\langle \tau_b \rangle}} \qquad h_3 = \Re \frac{H_d^0}{\sqrt{\langle \tau_b \rangle}} \qquad h_4 = \Re \frac{H_d^-}{\sqrt{\langle \tau_b \rangle}}$$

$$h_5 = \Im \frac{H_u^+}{\sqrt{\langle \tau_b \rangle}} \qquad h_6 = \Im \frac{H_u^0}{\sqrt{\langle \tau_b \rangle}} \qquad h_7 = \Im \frac{H_d^0}{\sqrt{\langle \tau_b \rangle}} \qquad h_8 = \Im \frac{H_d^-}{\sqrt{\langle \tau_b \rangle}}$$

$$\sigma_\alpha = \frac{\Re\, C^\alpha}{\langle \tau_b \rangle} \qquad \chi_\alpha = \frac{\Im\, C^\alpha}{\sqrt{\langle \tau_b \rangle}}$$