Inflation and Thermal Right-Handed Sneutrino Dark Matter

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Plan of the Talk

- F_D-Term Hybrid Inflation
- Natural Solution to the Gravitino Overabundance Problem
- Right-Handed Sneutrino as Thermal Dark Matter
- Further Cosmological and Particle-Physics Implications
- Conclusions and Future Directions

*Talk based on

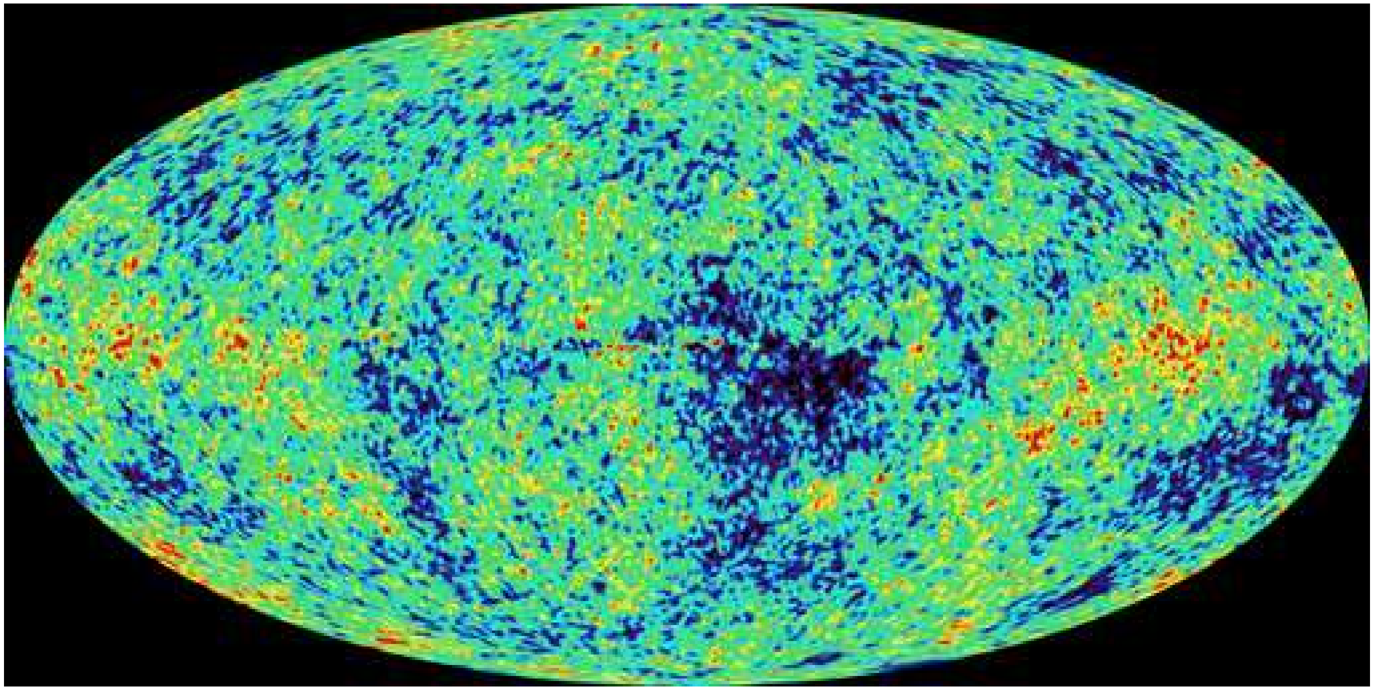
B. Garbrecht and A.P., PL**B636** (2006) 154;

B. Garbrecht, C. Pallis and A. P., JHEP**0612** (2006) 038;

F. Deppisch and A. P., JHEP**10** (2008) 080

• Standard Big-Bang Cosmology and WMAP

Density perturbations as observed by WMAP



$$\frac{\delta T}{T} \sim \frac{\delta\rho}{\rho} \sim 10^{-5}$$

– Inflation Dynamics

Number of e-folds:

$$\mathcal{N}_e \;=\; \int_{t_{\mathcal{N}}}^{t_{\rm end}} dt\; H(t) \;\approx\; \frac{1}{m^2_{\rm Pl}} \int_{\phi_{\rm end}}^{\phi_{\mathcal{N}}} d\phi\, \frac{V}{V_\phi} \;\approx\; 50 - 60$$

Power spectrum of curvature perturbations:

$$P^{1/2}_{\mathcal{R}} \;=\; \frac{1}{2\sqrt{3}\pi m^3_{\rm Pl}}\, \frac{V^{3/2}}{|V_\phi|} \;\approx\; 4.86\times 10^{-5} \qquad (k_0 = 0.002\ \text{Mpc}^{-1})$$

Spectral index:

$$n_s - 1 \;=\; \frac{d\ln P^{1/2}_{\mathcal{R}}}{d\ln k} \;=\; 2\eta - 6\varepsilon \;\approx\; -0.037\,^{+0.015}_{-0.014} \quad (\text{WMAP 5 years data})$$

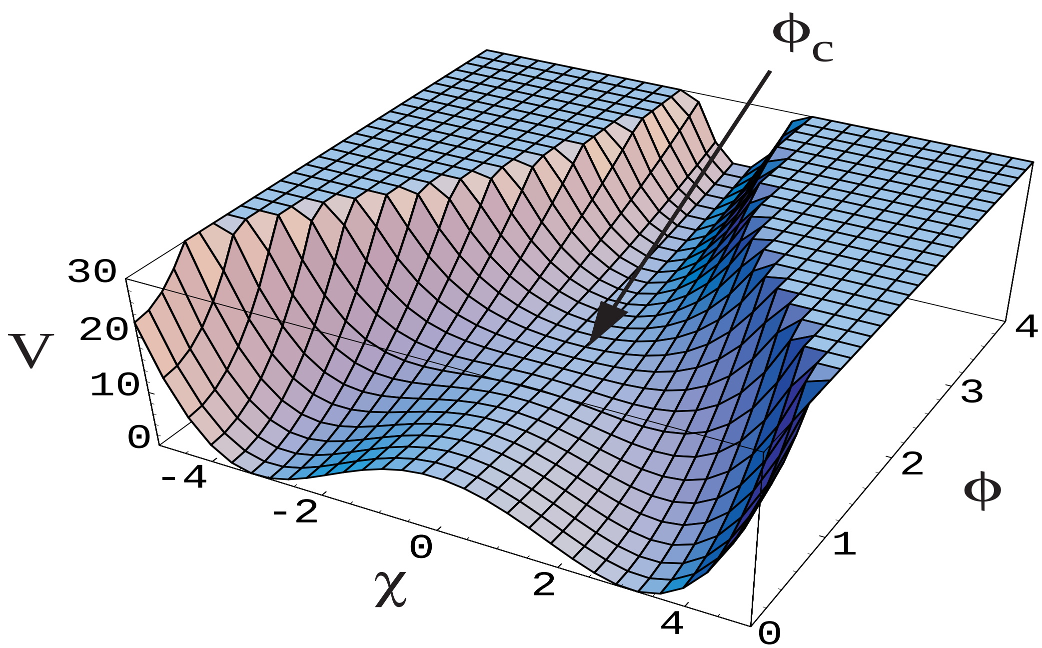
Slow-roll parameters:

$$\varepsilon \;=\; \frac{1}{2}\, m^2_{\rm Pl} \left(\frac{V_\phi}{V}\right)^2 \;\ll\; 1\,, \qquad \eta \;=\; m^2_{\rm Pl}\, \frac{V_{\phi\phi}}{V} \;\ll 1$$

• F_D-Term Hybrid Inflation

– Hybrid Inflation

[A.D. Linde, PLB259 (1991) 38]



$$V = \frac{\lambda}{4}(|\chi|^2 - M^2)^2 + \frac{1}{2} g\,|\chi|^2\,|\phi|^2 + \frac{1}{2} m^2|\phi|^2$$

Inflation starts, when $\phi \gg \phi_c \sim M$, $\chi = 0 \rightarrow \quad V \simeq \frac{\lambda}{4} M^4 + \frac{1}{2} m^2|\phi|^2$

Inflation ends with the so-called **waterfall mechanism**

– F-Term Hybrid Inflation

[E. Copeland, A. Liddle, D. Lyth, E. Stewart, D. Wands, PRD49 (1994) 6410;
G. Dvali, Q. Shafi, R. Schaefer, PRL73 (1994) 1886]

Superpotential:

$$W \;=\; \kappa\,\widehat{S}\,(\widehat{X}_1\,\widehat{X}_2 - M^2)$$

Real Potential determined from F terms:

$$\begin{aligned} V \;&=\; |\partial W/\partial S|^2 \;+\; |\partial W/\partial X_1|^2 \;+\; |\partial W/\partial X_2|^2 \\ &=\; \kappa^2\,|X_1X_2 - M^2|^2 \;+\; \kappa^2|S|^2\,(|X_1|^2 + |X_2|^2) \end{aligned}$$

Start of inflation: $S^{\rm in} \;>\; M$, $X^{\rm in}_{1,2} \;=\; 0$, with $V \;=\; \kappa^2 M^4$.

$X_{1,2}$-Mass Matrix:

$$M^2_{X_{1,2}} \;=\; \begin{pmatrix} |\kappa|^2|S|^2 & -\,\kappa^2 M^2 \\ -\,\kappa^{*\,2}M^2 & |\kappa|^2|S|^2 \end{pmatrix}$$

End of inflation: $S < M \;\;\rightarrow\;\; \det M^2_{X_{1,2}} < 0 \;\;\rightarrow$ waterfall mechanism.

– Slope of the Potential

Potential is too flat! $\partial V/\partial S = 0$.

Radiative lifting of the S-flat direction:

$$V_{1-\text{loop}} \;=\; \frac{\kappa^4 M^4}{16\pi^2}\,\ln\left(\frac{|S|^2}{M^2}\right)$$

SUGRA corrections: $V_{\text{SUGRA}} \;=\; -c_H^2 H^2|S|^2 \;+\; \kappa^2 M^4 \frac{|S|^4}{2\,m_{\text{Pl}}^4} \;+\; \ldots$

Number of e-folds:

$$\mathcal{N}_e \;=\; \frac{4\pi^2}{\kappa^2}\,\frac{(S^{\text{in}})^2}{m_{\text{Pl}}^2} \;\approx\; 55$$

For $10^{-3} \lesssim \kappa \lesssim 10^{-2} \longrightarrow S^{\text{in}} \lesssim 10^{-1}\, m_{\text{Pl}} \to$ predictive scenario

Power spectrum: $P_{\mathcal{R}}^{1/2} \;=\; \sqrt{\frac{4\mathcal{N}_e}{3}}\,\left(\frac{M}{m_{\text{Pl}}}\right)^2 \;=\; 5\times 10^{-5} \;\to\; M \sim 10^{16}$ GeV.

M close to the GUT or gauge-coupling unification scale M_X.

Spectral index: $n_s - 1 = -\frac{1}{\mathcal{N}_e} \;\approx -0.02$ (mSUGRA).

– F_D-Term Hybrid Inflation

[B. Garbrecht and A.P., PL**B636** (2006) 154]

$$W \;=\; \kappa\,\widehat{S}\,(\widehat{X}_1\widehat{X}_2 \;-\; M^2) \;+\; \lambda\,\widehat{S}\widehat{H}_u\widehat{H}_d \;+\; \frac{\rho}{2}\,\widehat{S}\,\widehat{N}_i\widehat{N}_i$$
$$+\; h^{\nu}_{ij}\widehat{L}_i\widehat{H}_u\widehat{N}_j \;+\; W^{(\mu=0)}_{\rm MSSM}$$

+ Subdominant FI D-term of U$(1)_X$: $-\frac{g_X}{2}\,m^2_{\rm FI}D_X$

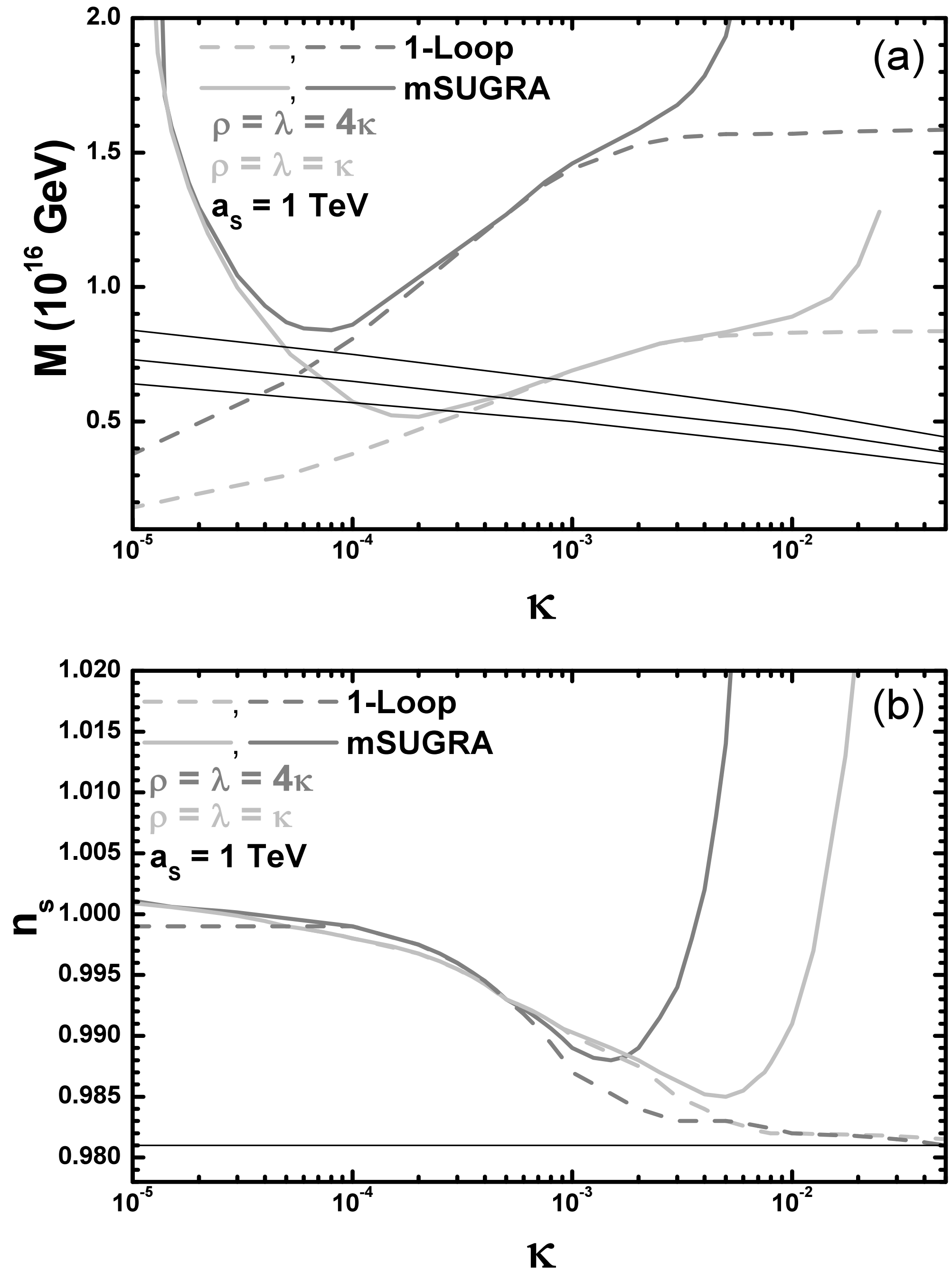
Remarks:

- **Mass scales:** $m_{\rm Pl}$, M, $m_{\rm FI}$ and $M_{\rm SUSY}$.
- $\langle S\rangle \sim \frac{1}{\kappa}\,M_{\rm SUSY}$ sets the Electroweak and the Singlet Majorana scale:

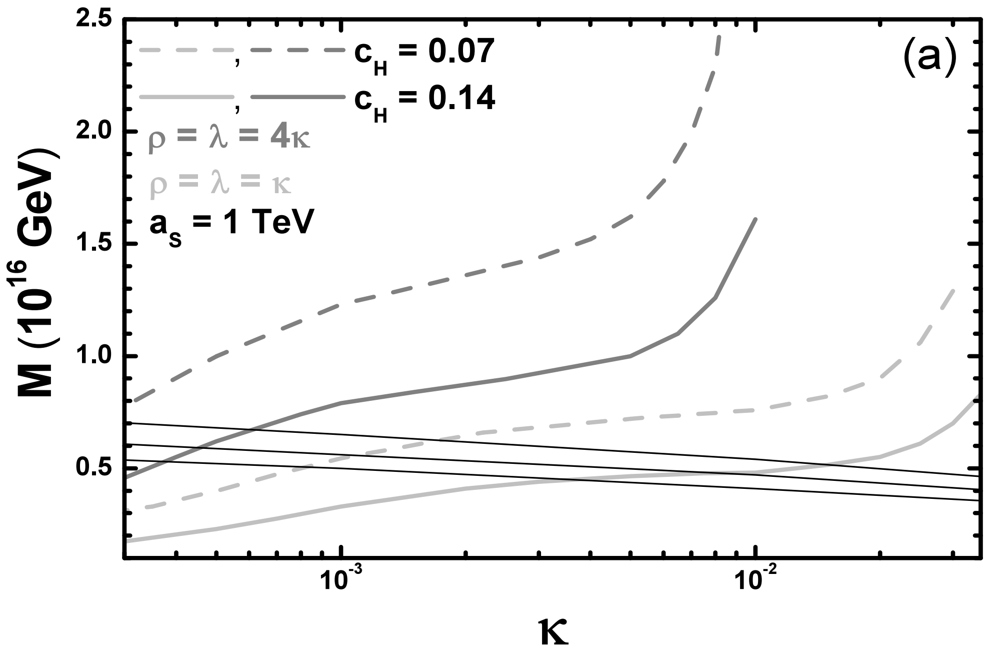
$$\mu \;=\; \lambda\,\langle S\rangle\,, \qquad m_N \;=\; \rho\,\langle S\rangle$$

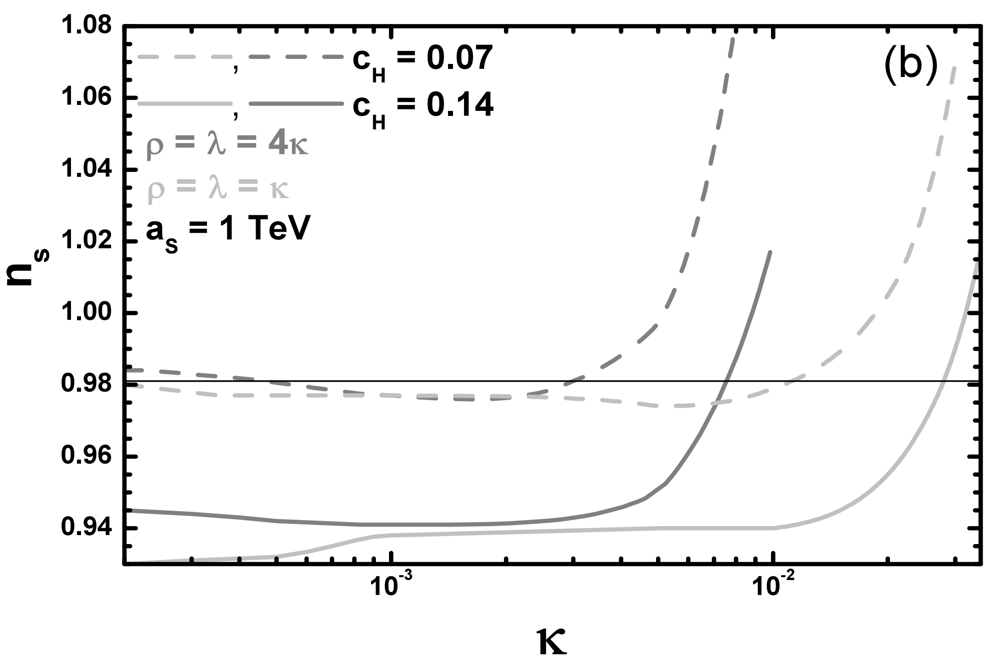
- Lepton Number Violation mediated by right-handed neutrinos N_i occurs at the EW scale $\mu \sim m_N$.
  $\rightarrow$ BAU may be explained by thermal EW-scale resonant leptogenesis.

[B. Garbrecht, C. Pallis, A.P., JHEP**0612** (2006) 038]



Next-to-mSUGRA with $-c_H^2\, H^2 S^2$ [B. Garbrecht, C. Pallis, A.P., JHEP**0612** (2006) 038]





$$n_{\rm s} - 1 \;\approx\; -\frac{1}{\mathcal{N}_e} \;-\; c_H^2$$

– Post-inflationary Dynamics

$$X_\pm \;=\; \frac{1}{\sqrt{2}}\,(X_1 \pm X_2) \;=\; \langle X_\pm\rangle \;+\; \frac{1}{\sqrt{2}}\,(R_\pm \;+\; iI_\pm),$$

with $\langle X_+\rangle = \sqrt{2}M$ and $\langle X_-\rangle = \frac{v}{\sqrt{2}} = \frac{m^2_{\rm FI}}{2\sqrt{2}M}$

Sector	Boson	Fermion	Mass	D-parity
Inflaton (κ-sector)	$S,\ R_+,\ I_+$	$\psi_\kappa = \begin{pmatrix} \psi_{X_+} \\ \psi_S^\dagger \end{pmatrix}$	$\sqrt{2}\kappa M$	$+$
U(1)$_X$ Gauge (g-sector)	$V_\mu\ [I_-],\ R_-$	$\psi_g = \begin{pmatrix} \psi_{X_-} \\ -i\lambda^\dagger \end{pmatrix}$	gM	$-$

$$\Gamma_\kappa \;=\; \frac{1}{32\pi}\,(4\lambda^2 + 3\rho^2)m_\kappa, \qquad \Gamma_g \;=\; \frac{g^2}{128\pi}\,\frac{m^4_{\rm FI}}{M^4}\,m_g.$$

– Reheat Temperature and Gravitino Constraint

Inflaton decays reheat the Universe, when $\Gamma_\kappa \gtrsim H(T_\kappa^{\rm reh})$:

$$T_\kappa^{\rm reh} \;=\; \left(\frac{90}{\pi^2 g_*}\right)^{1/4}\,\sqrt{\Gamma_\kappa\, m_{\rm Pl}}$$

Generic Gravitino constraint ($T_\kappa^{\rm reh} \lesssim 10^9$ GeV) implies

$$\kappa\left(\lambda^2 + \frac{3}{4}\rho^2\right) \;\lesssim\; 3\cdot 10^{-15}\times\left(\frac{T_\kappa^{\rm reh}}{10^9\ {\rm GeV}}\right)^2\left(\frac{10^{16}\ {\rm GeV}}{M}\right)$$

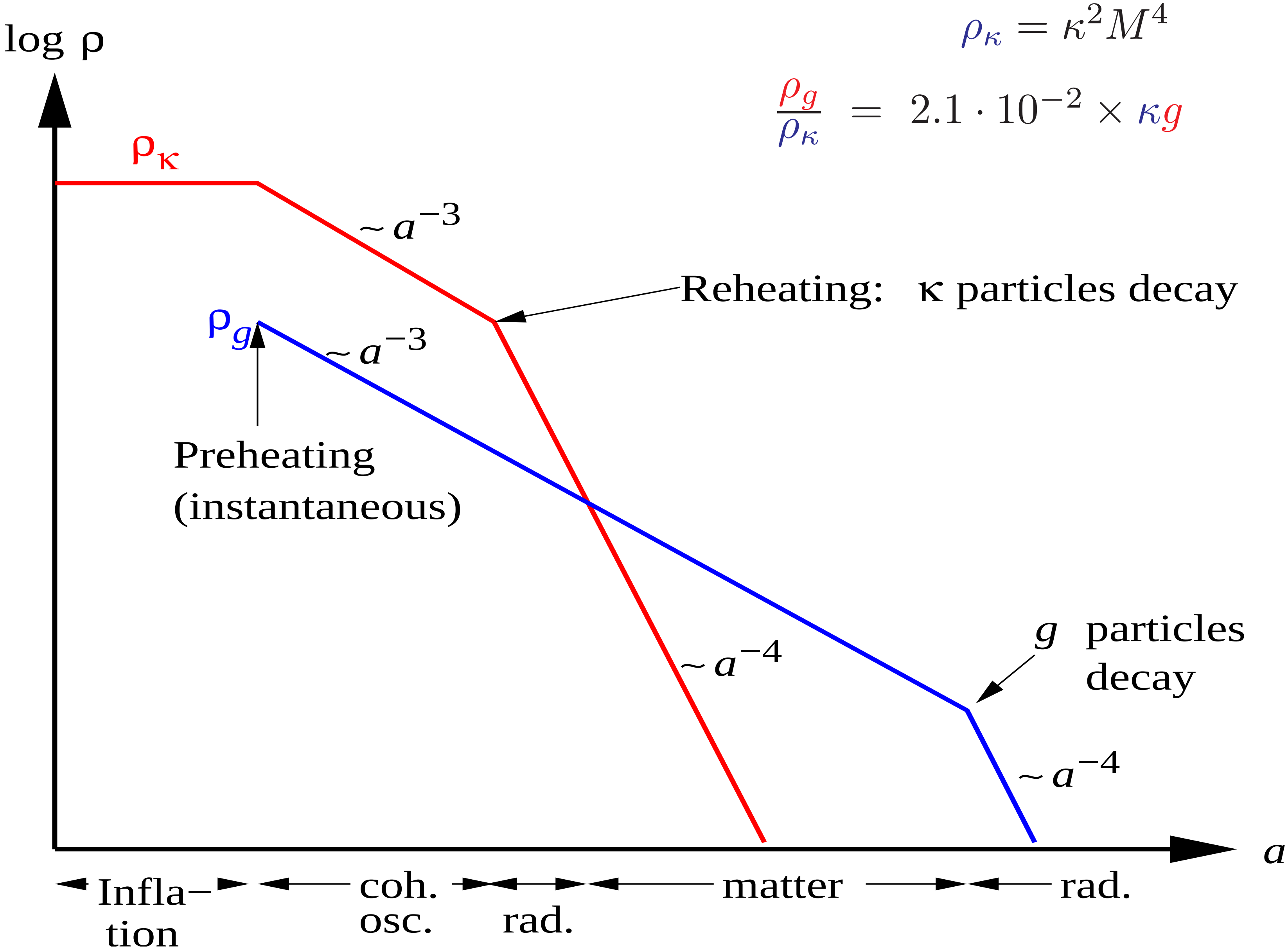
For $\kappa \approx \lambda \approx \rho \quad \to \quad \kappa,\ \lambda,\ \rho\ \lesssim\ 10^{-5}$

Minimal F_D-Term Hybrid Inflation ruled out by $n_s - 1 < 0$,
unless . . . there is an extra source of entropy release

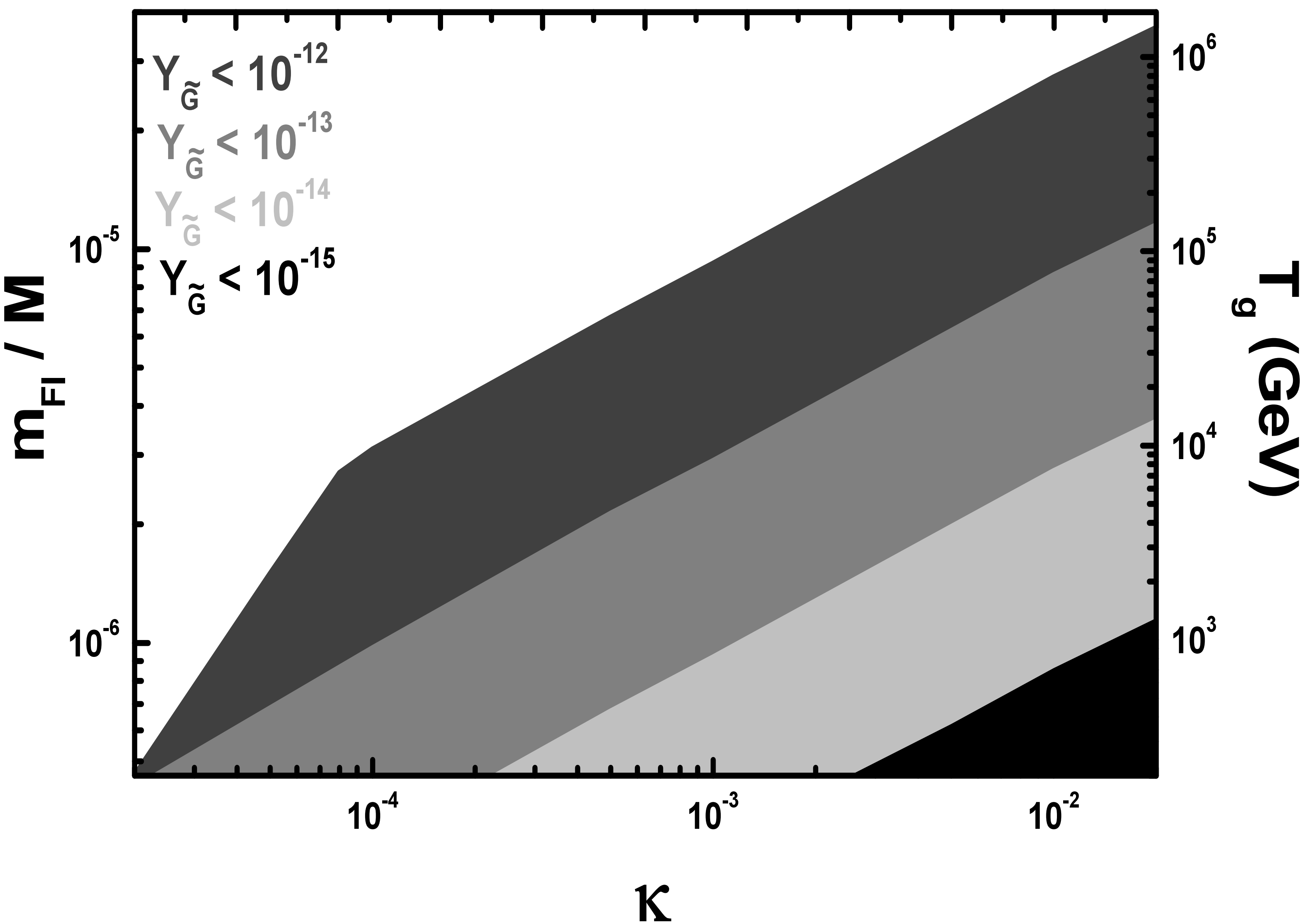
– Thermal History of the Universe

$$\rho_\kappa = \kappa^2 M^4$$

$$\frac{\rho_g}{\rho_\kappa} = 2.1 \cdot 10^{-2} \times \kappa g$$



[B. Garbrecht, C. Pallis, A.P., JHEP**0612** (2006) 038]



• Right-Handed Sneutrino as Thermal Dark Matter

Related considerations:

- D. Hooper, J. March-Russell and S. M. West, PLB605 (2005) 228.
- C. Arina and N. Fornengo, JHEP0711 (2007) 029.
- C. Arina, F. Bazzocchi, N. Fornengo, J. C. Romao and J. W. F. Valle, PRL101 (2008) 161802.

⋮

But all with significant Left-Handed Sneutrino component!

– Right-Handed Sneutrinos in the F_D-Term Hybrid Model

$\Delta(B-L) = 0$ or $2 \quad \longrightarrow \quad R$-Parity Conservation.

Right-handed sneutrino mass matrix:

$$\mathcal{M}^2_{\widetilde{N}} = \begin{pmatrix} \rho^2 v_S^2 + M^2_{\widetilde{N}} & \rho A_\rho v_S + \rho\lambda v_u v_d \\ \rho A^*_\rho v_S + \rho\lambda v_u v_d & \rho^2 v_S^2 + M^2_{\widetilde{N}} \end{pmatrix}$$

$$\longrightarrow \quad m^2_{\widetilde{N}_{\rm LSP}} = \rho^2 v_S^2 + M^2_{\widetilde{N}} - (\rho A_\rho v_S + \rho\lambda v_u v_d).$$

New LSP interaction:

[B. Garbrecht, C. Pallis and A. P., JHEP**0612** (2006) 038]

$$\mathcal{L}^{\rm LSP}_{\rm int} = \frac{1}{2}\lambda\rho\, \widetilde{N}^*_i \widetilde{N}^*_i H_u H_d \quad + \quad {\rm H.c.}$$

SUSY version of the Higgs-Portal scenario.

[V. Silveira and A. Zee, PLB161 (1985) 136; J. McDonald, PRD50 (1994) 3637.]

Process: $\widetilde{N}_{\rm LSP}\widetilde{N}_{\rm LSP} \to \langle H_u \rangle \, H_d \to W^+W^- \; (m_{\widetilde{N}_{\rm LSP}} > M_W)$

$$\Omega_{\rm DM}\, h^2 \;\sim\; \left(\frac{10^{-4}}{\rho^2\lambda^2}\right) \left(\frac{\tan\beta\, M_H}{g_w\, M_W}\right)^2 \quad \longrightarrow \quad \lambda\,,\rho \;\gtrsim\; 0.1$$

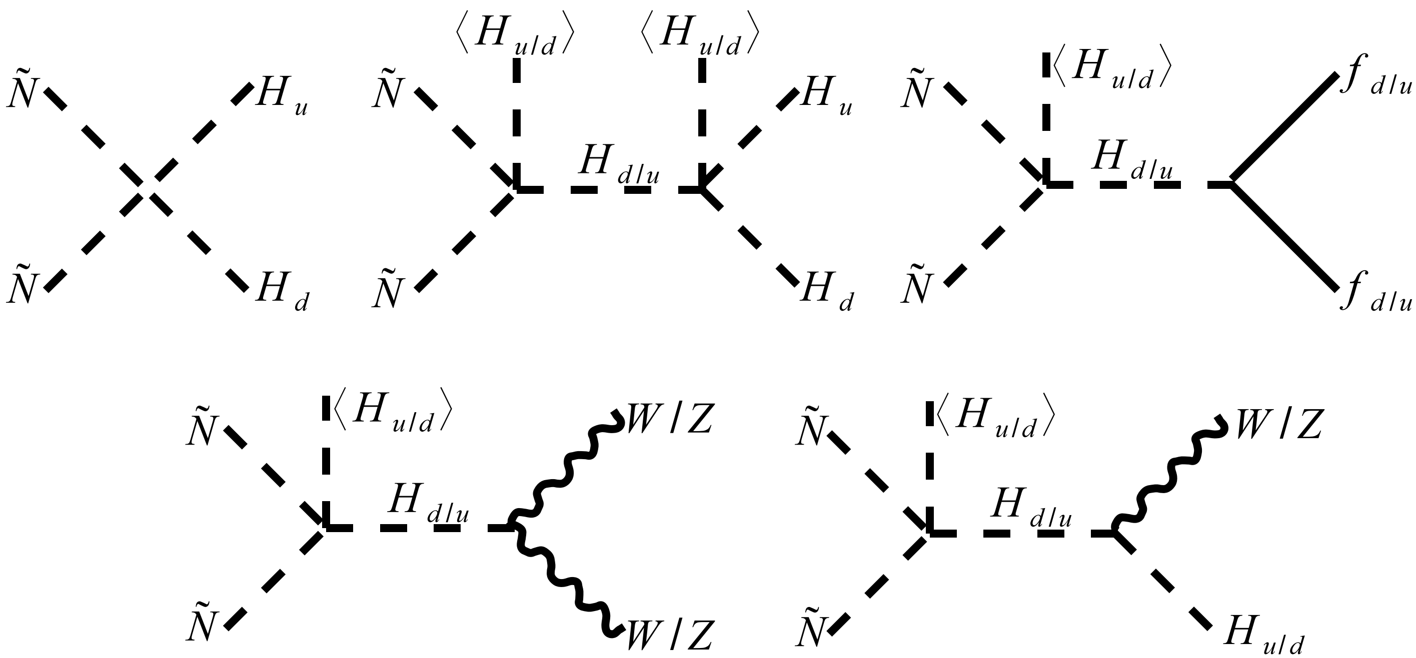
Process: $\widetilde{N}_{\rm LSP}\widetilde{N}_{\rm LSP} \to \langle H_u \rangle \, H_d \to b\bar{b} \quad (M_{H_d} \approx 2m_{\widetilde{N}_{\rm LSP}} < 2M_W)$

$$\Omega_{\rm DM}\, h^2 \;\sim\; 10^{-4}\times B^{-1}(H_d \to \widetilde{N}_{\rm LSP}\widetilde{N}_{\rm LSP}) \times \left(\frac{M_H}{100~{\rm GeV}}\right)^2 \quad \longrightarrow \quad \lambda\,,\rho \;\gtrsim\; 10^{-2}$$

Limits from Cosmological Inflation:

$$\begin{aligned} \lambda(M_{\rm SUSY})\,\rho(M_{\rm SUSY}) \;&\lesssim\; 2.3\times 10^{-4} \quad (\text{mSUGRA}) \\ &\lesssim\; 5.8\times 10^{-4} \quad (\text{nmSUGRA}) \end{aligned}$$

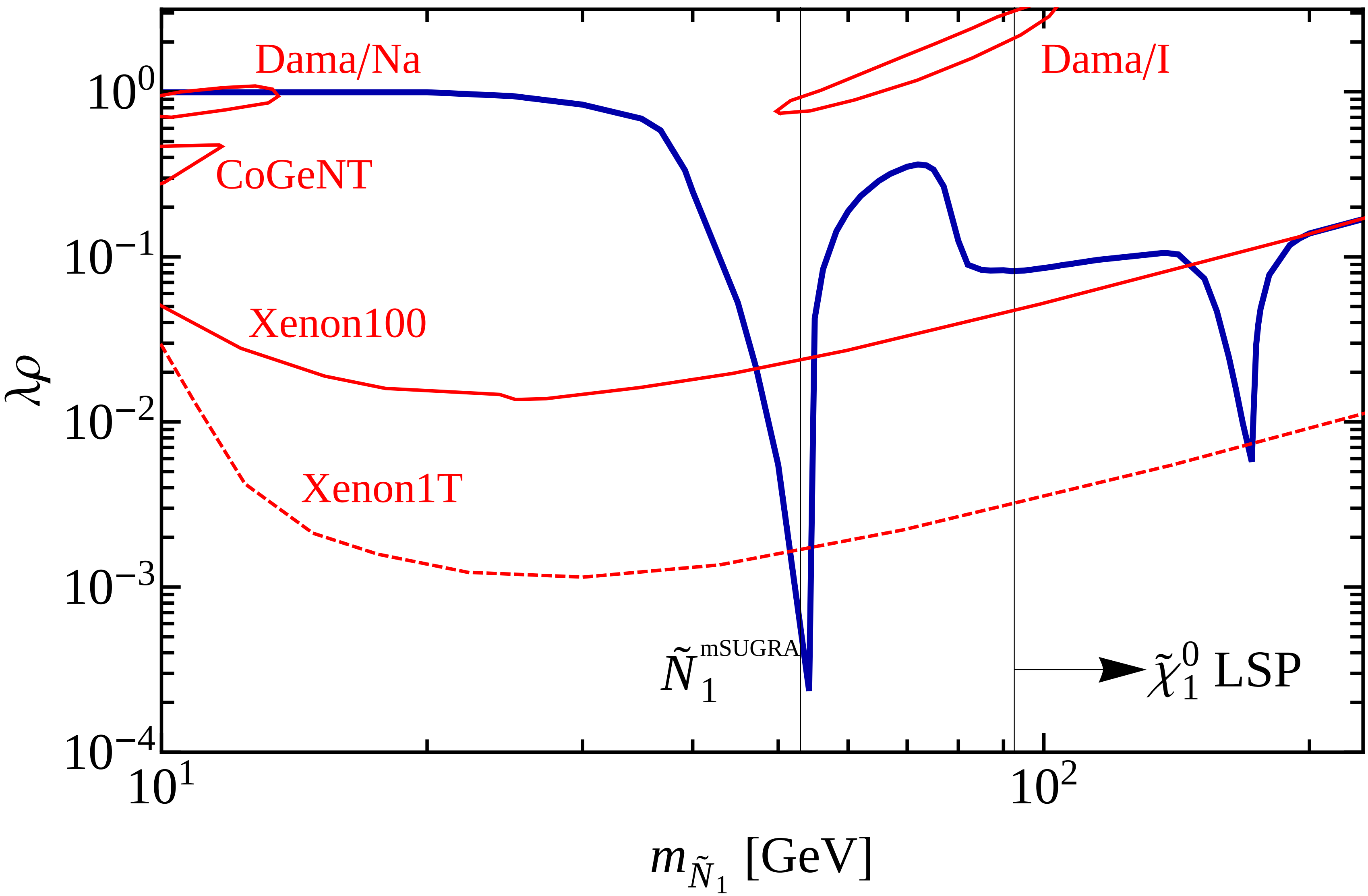
[F. Deppisch, A.P., JHEP**10** (2008) 080]



Numerical estimate assisted by **CPsuperH2.0**

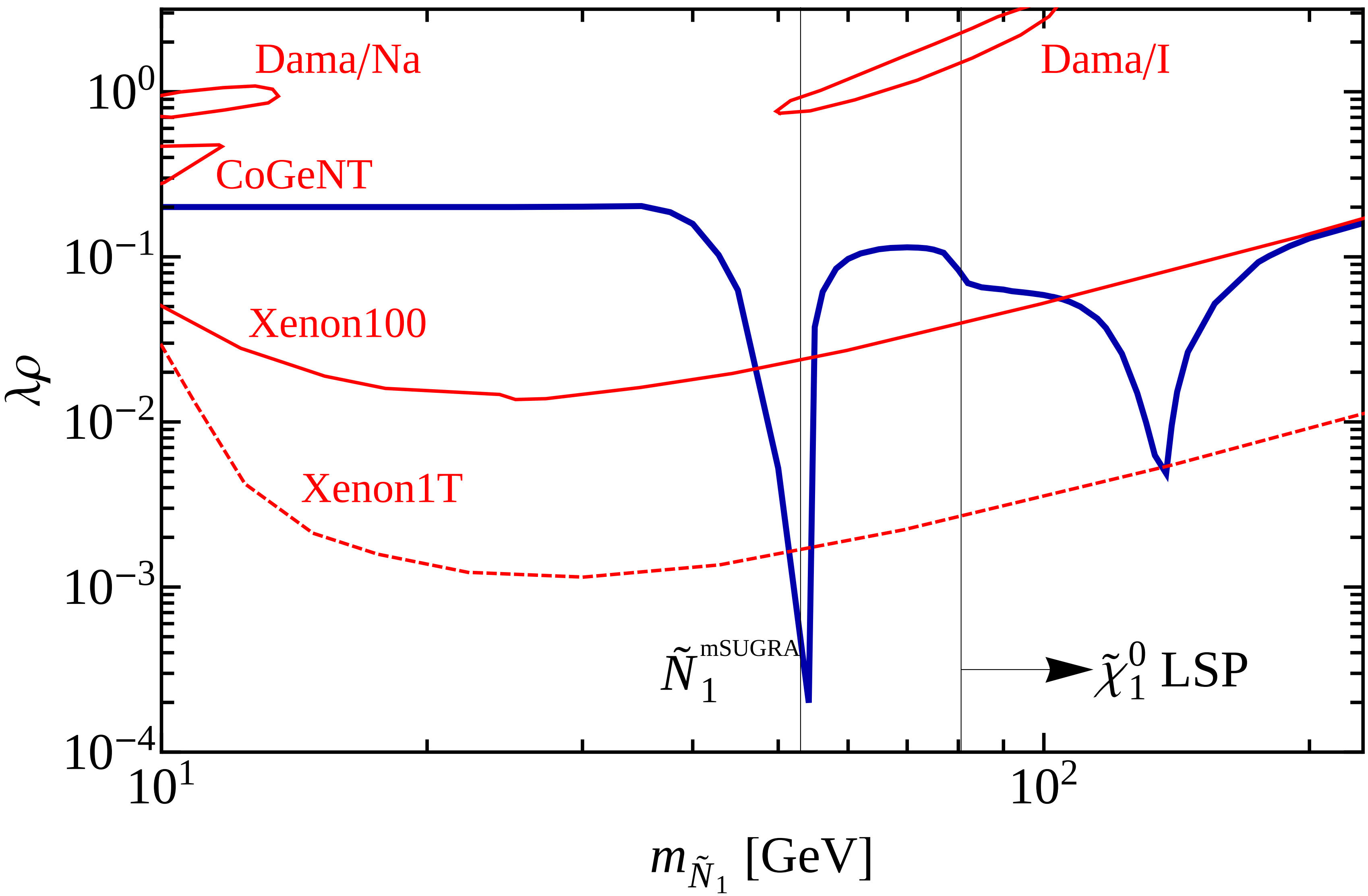
[J. S. Lee, M. Carena, J. Ellis, A. P., C. E. M. Wagner, arXiv:0712.2360 [hep-ph].]

[F. Deppisch, A.P., JHEP**10** (2008) 080]



$$m_0 = 70 \text{ GeV}, \ m_{1/2} = 243 \text{ GeV}, \ A_0 = 300 \text{ GeV}, \ \tan\beta = 10, \ \mu = 303 \text{ GeV} .$$

[F. Deppisch, A.P., JHEP**10** (2008) 080]

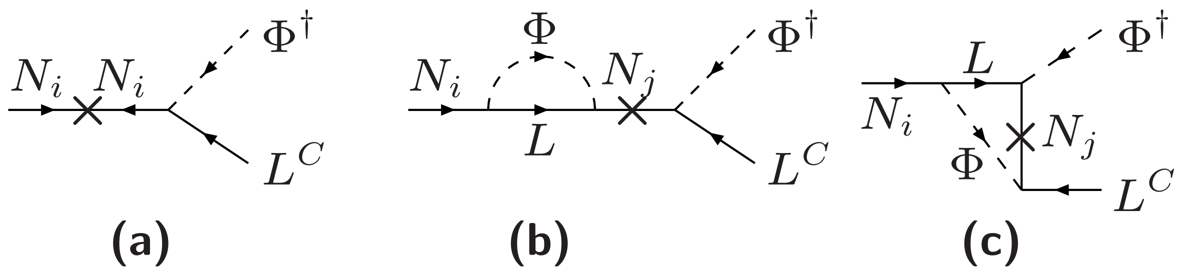


$$m_0 = 125 \text{ GeV},\ m_{1/2} = 212 \text{ GeV}, A_0 = 300 \text{ GeV},\ \tan\beta = 30,\ \mu = 263 \text{ GeV}\ .$$

• Baryogenesis through Leptogenesis

Out-of-equilibrium L-violating decays of heavy Majorana neutrinos produce a net lepton asymmetry, converted into the BAU through $(B+L)$-violating sphaleron interactions.

[M. Fukugita, T. Yanagida, PLB174 (1986) 45.]



• Importance of the self-energy effects, for $|m_{N_1} - m_{N_2}| \ll m_{N_{1,2}}$

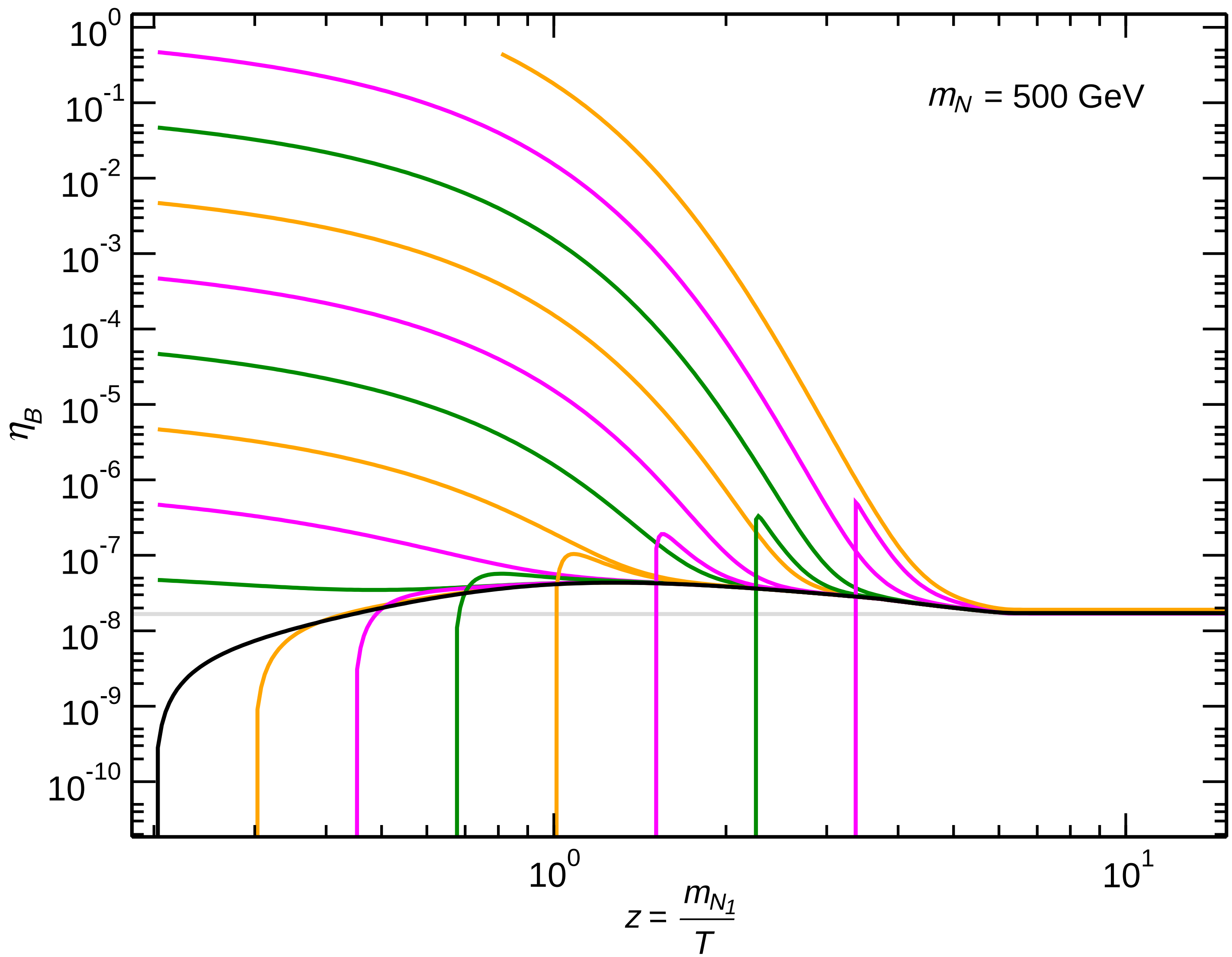
[J. Liu, G. Segré, PRD48 (1993) 4609;
M. Flanz, E. Paschos, U. Sarkar, PLB345 (1995) 248;
L. Covi, E. Roulet, F. Vissani, PLB384 (1996) 169.]

• Resonant Leptogenesis (the importance of $\Gamma_{N_{1,2}}$ width effects)

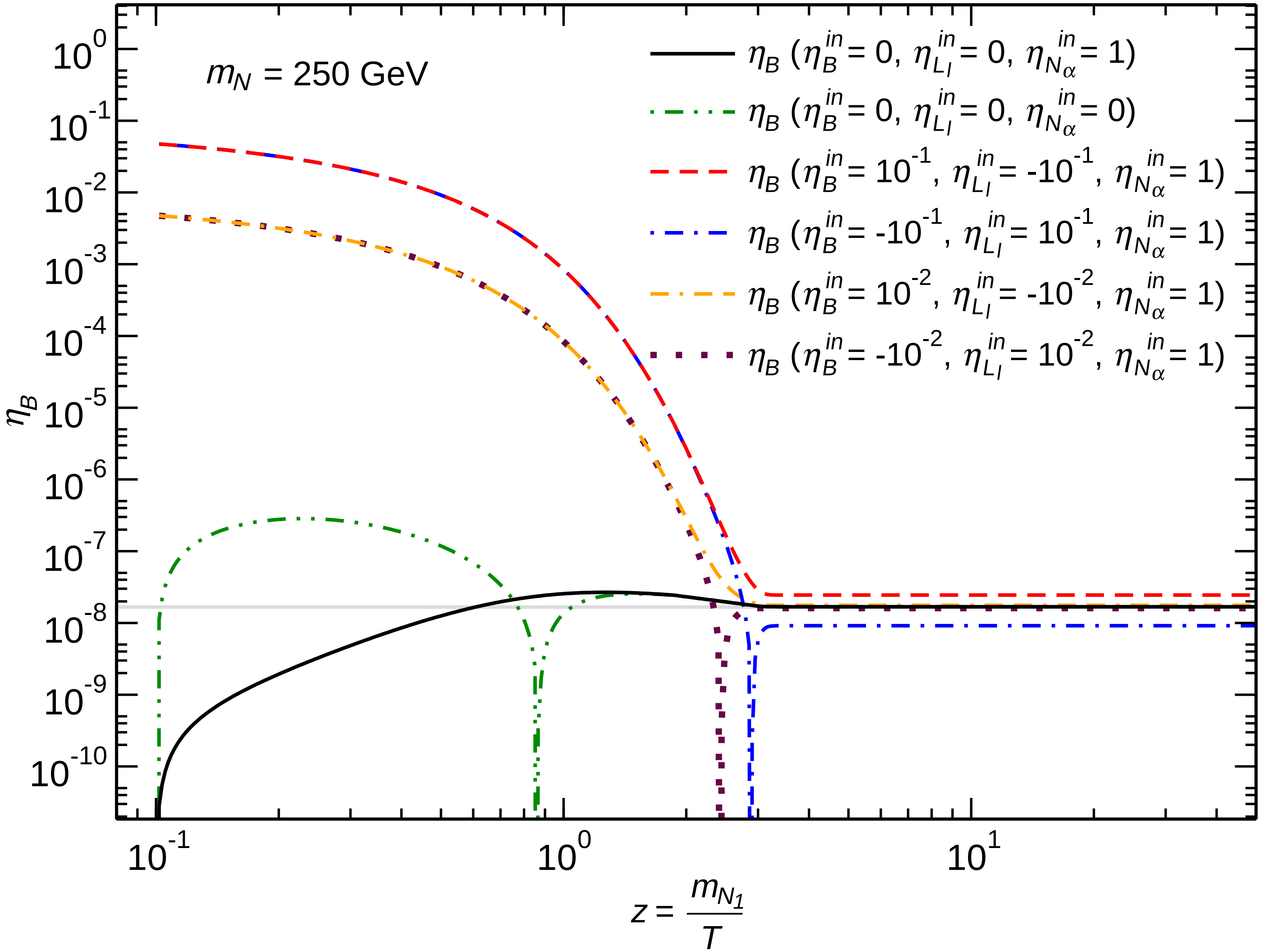
[A.P., PRD56 (1997) 5431; A.P. and T. Underwood, NPB692 (2004) 303.]

– Resonant τ-Leptogenesis with Observable Lepton Flavour Violation

[A.P., PRL95 (2005) 081602; A.P. and T. Underwood, PRD72 (2005) 113001]

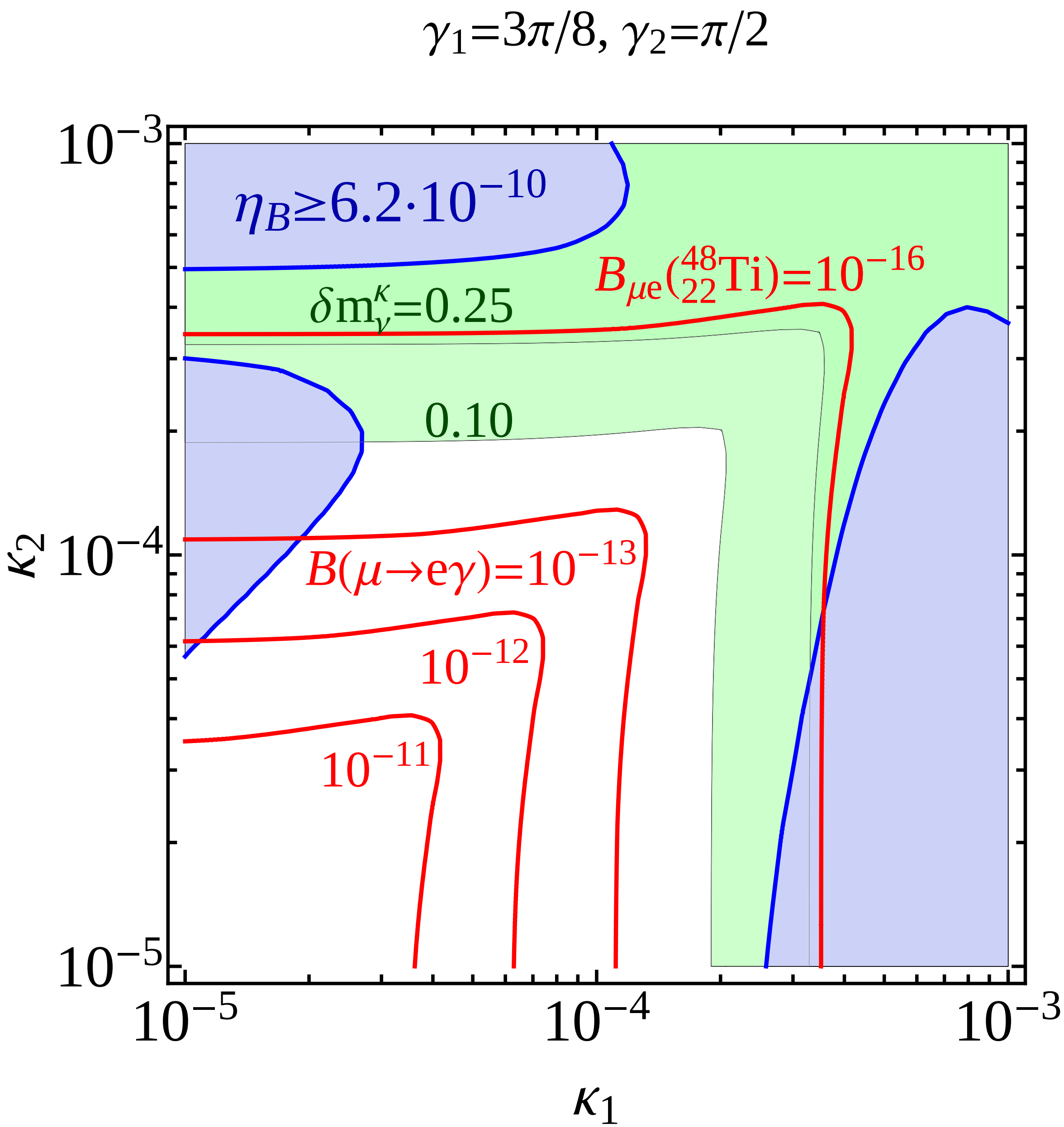


[A.P. and T. Underwood, PRD72 (2005) 113001]



• **LFV and Minimal RL**

[F. Deppisch, A.P., PRD83 (2011) 076007.]



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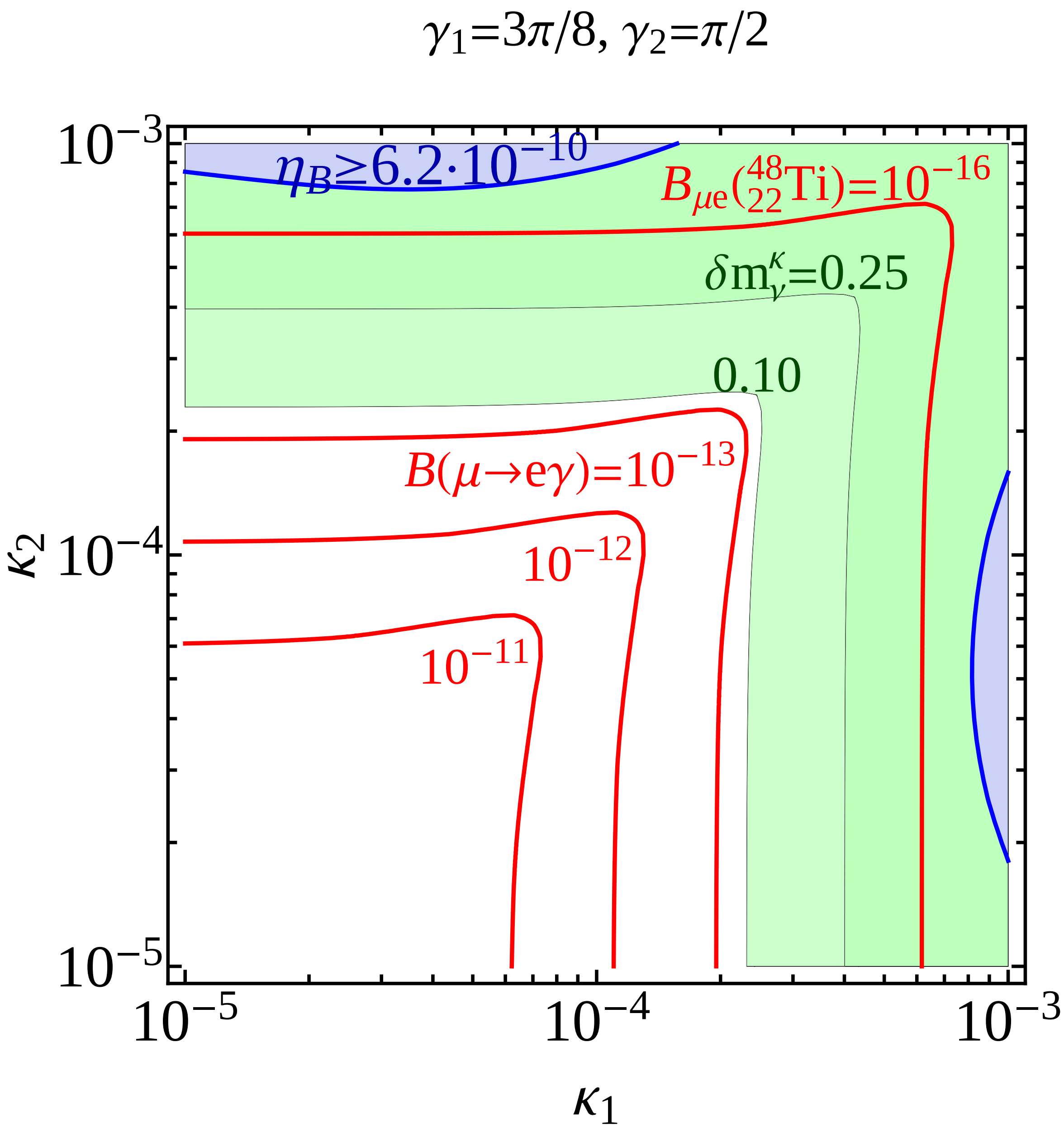


• Conclusions

- F_D-Term Hybrid Inflation provides an interesting framework for building a Minimal Particle Physics and Cosmology Model.

- The μ-parameter of the MSSM is tied to a universal Majorana mass m_N, via the VEV of the inflaton field.

- The entropy release from the late D-tadpole-induced decays of the g-sector particles offers a simple solution to the gravitino problem.

- Right-Handed Sneutrinos could be the Thermal Dark Matter

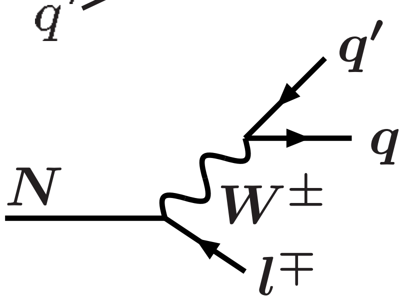
- Baryon Asymmetry in the Universe can be explained by thermal Electroweak-Scale Resonant Leptogenesis, independently of any pre-existing lepton or baryon-number abundance.

- **Further Particle-Physics Implications**:
  - Invisible Higgs Decays: $H \to \widetilde{N}_{\rm LSP}\widetilde{N}_{\rm LSP}$.
  - Observable Signatures: $B(\mu \to e\gamma) \sim 10^{-13}$, $B(\mu \to eee) \sim 10^{-14}$, $B(\mu \to e) \sim 10^{-13}$.

    [A. Ilakovac and A.P., NPB437 (1995) 491; PRD80 (2009) 091902]

  - EW-Scale Heavy Neutrinos and LNV/LFV at the LHC.

    [A. Datta, M. Guchait, A. P., PRD50 (1994) 3195; S. Bray, J.-S. Lee, A.P., NPB786 (2007) 95; J. Kersten, A. Y. Smirnov, PRD76 (2007) 073005; T. Han, B. Zhang, PRL97 (2006) 171804; F. del Aguila, J.A. Aguilar-Saavedra, R. Pittau, JHEP10 (2007) 95; A. Atre, T. Han, S. Pascoli, B. Zhang, JHEP 0905 (2009) 030.]



Signal: 2 leptons + 2 jets + no $\not{p}_T$

• Future Directions

- Further improvements in the theory of the (pre-inflationary), inflationary and post-inflationary dynamics.

- Further connections between inflation, leptogenesis, CDM, neutrino-mass parameters, Higgs physics and other laboratory observables in constrained minimal versions of the F_D-Term Hybrid Model.

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- Possible realizations of the F_D-Term Hybrid Model in GUTs.
  [e.g. $E(7) \to SU(2)_X \otimes SO(12) \to SU(2)_X \otimes SO(10) \otimes U(1)$]

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- **Model-building constraints from a natural solution to the cosmological constant problem.**

- **Back-up Slides**

– The Non-Seesaw Paradigm

[F. Deppisch and A.P., PRD83 (2011) 076007;
based on A.P., ZPC55 (1992) 275;
D. Wyler, L. Wolfenstein, NPB218 (1983) 205;
R.N. Mohapatra, J.W.F. Valle, PRD34 (1986) 1642.]

Break SO(3) and $\mathsf{U(1)}_l$ flavour symmetries:

$$\mathsf{SO(3)} \quad \stackrel{\sim h_\tau}{\longrightarrow} \quad \mathsf{SO(2)} \simeq \mathsf{U(1)}_l \quad \stackrel{\sim h_e}{\longrightarrow} \quad \mathbf{I}$$

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[F. Deppisch and A.P., PRD83 (2011) 076007;
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Break SO(3) and U(1)$_l$ flavour symmetries:

$$\mathrm{SO(3)} \xrightarrow{\sim h_\tau} \mathrm{SO(2)} \simeq \mathrm{U(1)}_l \xrightarrow{\sim h_e} \mathbf{I}$$

U$_l$(1)-broken Yukawa sector:

$$\mathbf{m}_D = \frac{v_{\rm SM}}{\sqrt{2}} \begin{pmatrix} \varepsilon_e & a\, e^{-i\pi/4} & a\, e^{i\pi/4} \\ \varepsilon_\mu & b\, e^{-i\pi/4} & b\, e^{i\pi/4} \\ \varepsilon_\tau & \kappa_1\, e^{-i(\pi/4-\gamma_1)} & \kappa_2\, e^{i(\pi/4-\gamma_2)} \end{pmatrix},$$

with $a \sim b \sim 10^{-2} \sim h_\tau$, $\kappa_{1,2} \lesssim 10^{-3}$ & $|\varepsilon_l| \sim 10^{-7} \sim h_e$.

$$\Longrightarrow \quad \mathbf{m}_\nu^{\rm light} \sim \frac{\varepsilon_l^2\, v_{\rm SM}^2}{m_N} \sim 0.1\ \mathrm{eV} \quad \Longrightarrow \quad m_N \sim 100 - 500\ \mathrm{GeV}$$

$\Longrightarrow$ 3 nearly degenerate heavy Majorana neutrinos.

Light neutrino-mass spectrum:

[A.P., T. Underwood, PRD72 (2005) 113001; F. Deppisch and A.P., PRD83 (2011) 076007]

$$m_\nu^{\rm light} \approx \frac{v^2}{2m_N} \begin{pmatrix} \frac{\Delta m_N}{m_N} a^2 - \varepsilon_e^2 & \frac{\Delta m_N}{m_N} ab - \varepsilon_e \varepsilon_\mu & -\varepsilon_e\varepsilon_\tau \\ \frac{\Delta m_N}{m_N} ab - \varepsilon_e\varepsilon_\mu & \frac{\Delta m_N}{m_N} b^2 - \varepsilon_\mu^2 & -\varepsilon_\mu\varepsilon_\tau \\ -\varepsilon_e\varepsilon_\tau & -\varepsilon_\mu\varepsilon_\tau & -\varepsilon_\tau^2 \end{pmatrix} ,$$

where

$$\Delta m_N \;=\; 2(\Delta m_M)_{23} + i[(\Delta m_M)_{33} - (\Delta m_M)_{22}] \;.$$

$$a^2 \;=\; \frac{2m_N}{v^2}\, \frac{8\pi^2}{\ln(M_X/m_N)}\, \Big(m^\nu_{11} - \frac{(m^\nu_{13})^2}{m^\nu_{33}}\Big)\, \big[2\kappa_1\kappa_2 \sin(\gamma_1+\gamma_2) + i(\kappa_2^2 - \kappa_1^2)\big]^{-1} ,$$

$$b^2 \;=\; \frac{2m_N}{v^2}\, \frac{8\pi^2}{\ln(M_X/m_N)}\, \Big(m^\nu_{22} - \frac{(m^\nu_{23})^2}{m^\nu_{33}}\Big)\, \big[2\kappa_1\kappa_2 \sin(\gamma_1+\gamma_2) + i(\kappa_2^2 - \kappa_1^2)\big]^{-1} ,$$

$$\epsilon_e^2 \;=\; \frac{2m_N}{v^2}\, \frac{(m^\nu_{13})^2}{m^\nu_{33}} , \qquad \epsilon_\mu^2 \;=\; \frac{2m_N}{v^2}\, \frac{(m^\nu_{23})^2}{m^\nu_{33}} , \qquad \epsilon_\tau^2 \;=\; \frac{2m_N}{v^2}\, m^\nu_{33} \;.$$