Leptogenesis, Inflation and the Maximal Temperature of the Universe

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arXiv: 1305.3392, 1309.7788, 1404.1832

Planck 2014, Paris

I. Leptogenesis & Supersymmetry

Leptogenesis is a successful theory for baryogenesis, and therefore a promising guide for extrapolations beyond the Standard Model:

- consistent with neutrino masses and mixings
- naturally embedded in grand unification (this talk; other versions also possible)
- (qualitative & quantitative) constraints on dark matter, when combined with supersymmetry [standard MSSM neutralino DM inconsistent!]
- favours small field models of inflation (hybrid), but also consistent with large field models

Leptogenesis & gravitinos

For large temperatures danger of gravitino overproduction; but for thermal leptogenesis and typical superparticle masses, observed amount of dark matter possible:

$$\Omega_{3/2}h^2 = C\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2 \;, \quad C \sim 0.5$$

$\Omega_{3/2}h^2 \sim 0.1$ is natural value; but why is reheating temperature close to minimal LG temperature $T_L \gtrsim 10^9\mathrm{GeV}$?

Simple observation: heavy neutrino decay width (for typical LG parameters)

$$\Gamma_{N_1} = \frac{\widetilde{m}_1}{8\pi}\left(\frac{M_1}{v_{\mathrm{F}}}\right)^2 \sim 10^3\ \mathrm{GeV}\;, \quad \widetilde{m}_1 \sim 0.01\ \mathrm{eV}\;, \quad M_1 \sim 10^{10}\ \mathrm{GeV}$$

yields reheating temperature (for gas of decaying heavy neutrinos)

$$T_R \sim 0.2 \cdot \sqrt{\Gamma^0_{N_1} M_P} \sim 10^{10}\ \mathrm{GeV}$$

wanted for gravitino DM. *Intriguing hint or misleading coincidence?*

Spontaneous B-L breaking & false vacuum decay

Supersymmetric SM with right-handed neutrinos:

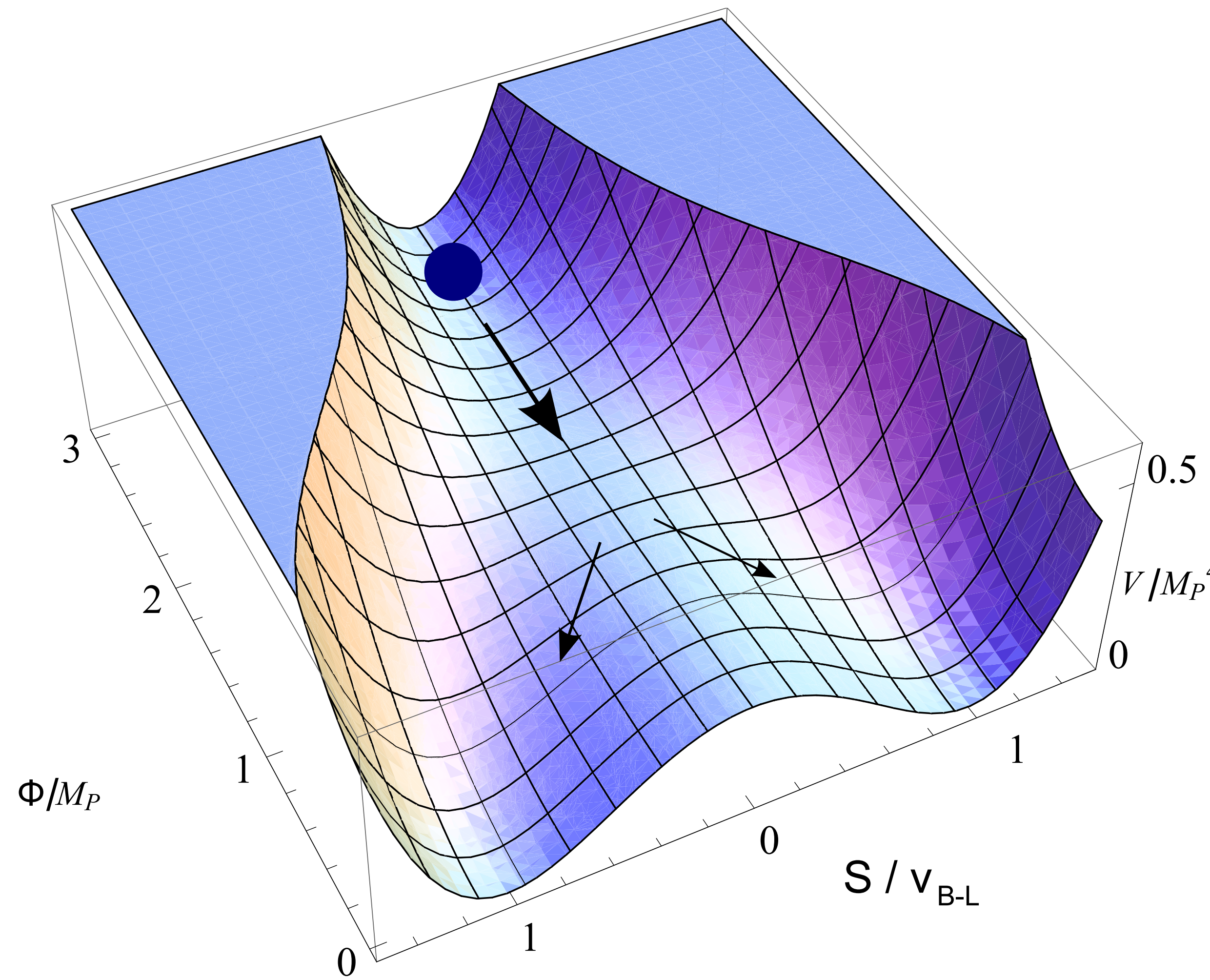
$$W_M = h^u_{ij} \mathbf{10}_i \mathbf{10}_j H_u + h^d_{ij} \mathbf{5}^*_i \mathbf{10}_j H_d + h^\nu_{ij} \mathbf{5}^*_i n^c_j H_u + h^n_i n^c_i n^c_i S_1$$

in SU(5) notation: $\mathbf{10} \supset (q, u^c, e^c),\ \mathbf{5}^* \supset (d^c, l),\ n^c \supset (\nu^c)$; B-L breaking:

$$W_{B-L} = \lambda \Phi \left(\frac{1}{2} v^2_{B-L} - S_1 S_2 \right)$$

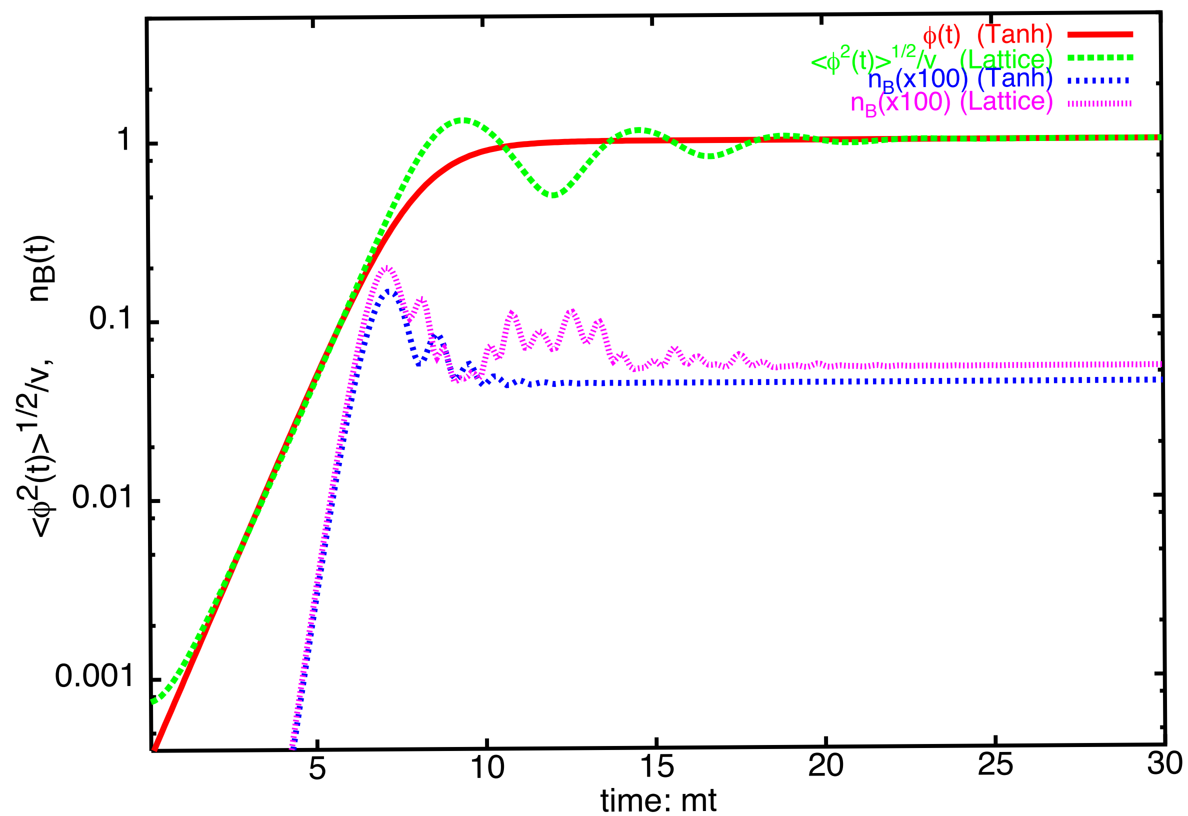
$\langle S_{1,2} \rangle = v_{B-L}/\sqrt{2}$ yields heavy neutrino masses.

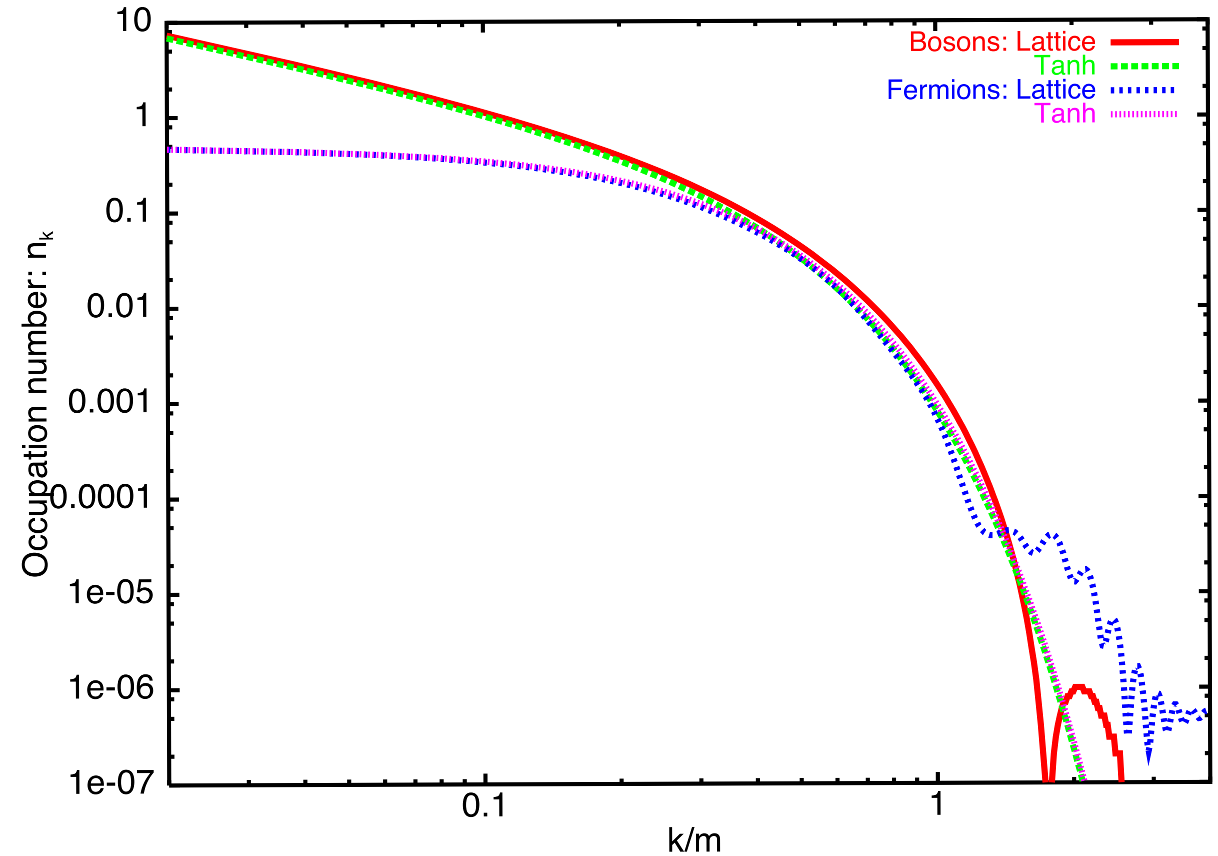
Lagrangian is determined by low energy physics: quark, lepton, neutrino masses etc, but it *contains all ingredients wanted in cosmology*: inflation, leptogenesis, dark matter, ..., all related! [hybrid inflation: Copeland et al. '94, Dvali et al. '94].
Technically: Abelian Higgs model in unitary gauge; inflation ends with phase transition ("tachyonic preheating", "spinodal decomposition")



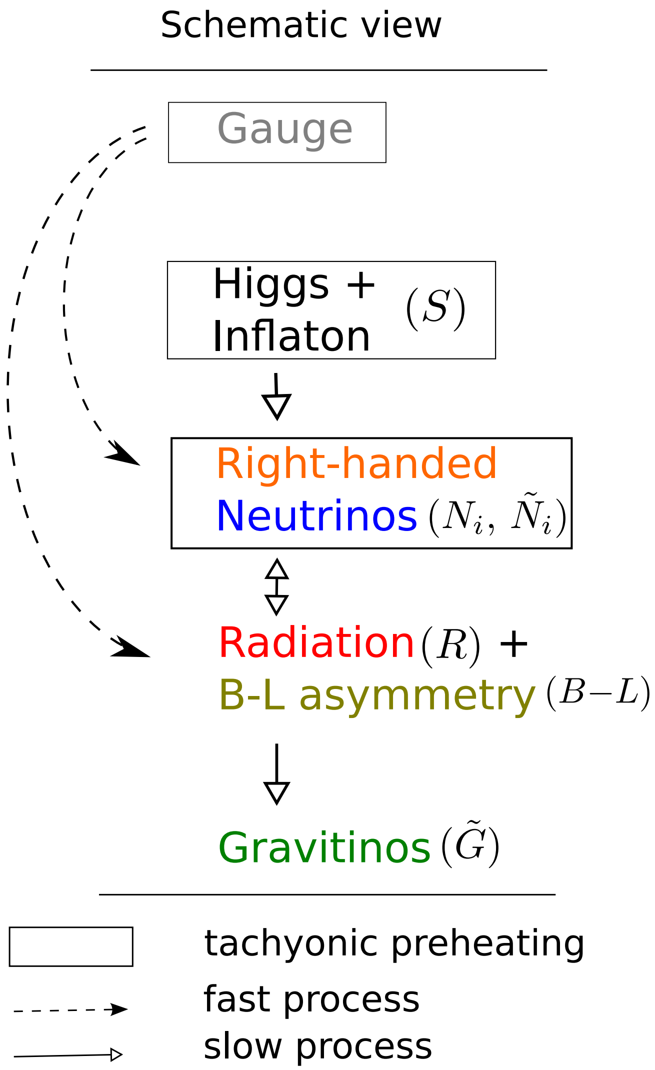
time-dependent masses of B-L Higgs, inflaton, heavy neutrinos ... (bosons and fermions):

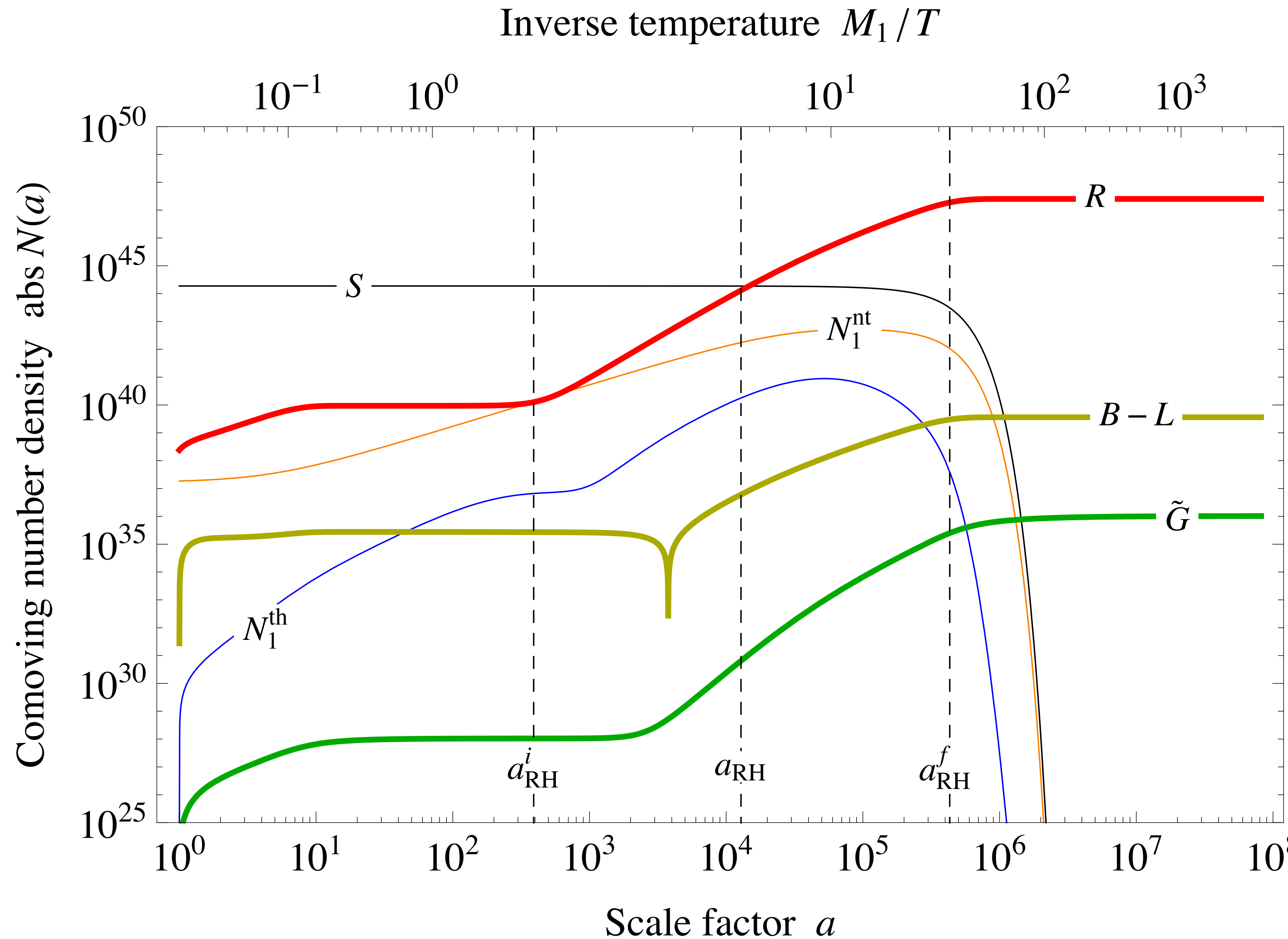
$$m_\sigma^2 = \frac{1}{2}\lambda(3v^2(t) - v_{B-L}^2)\ , \quad m_\phi^2 = \lambda v^2(t)\ , \quad M_i^2 = (h_i^n)^2 v^2(t)\ \ldots$$





Rapid transition from false to true vacuum by fluctuations of 'waterfall' B-L Higgs field; production of low momentum Higgs bosons (contain most energy), also other bosons and fermions coupled to B-L Higgs field (Garcia-Bellido, Morales '02), production of cosmic strings: initial conditions for reheating

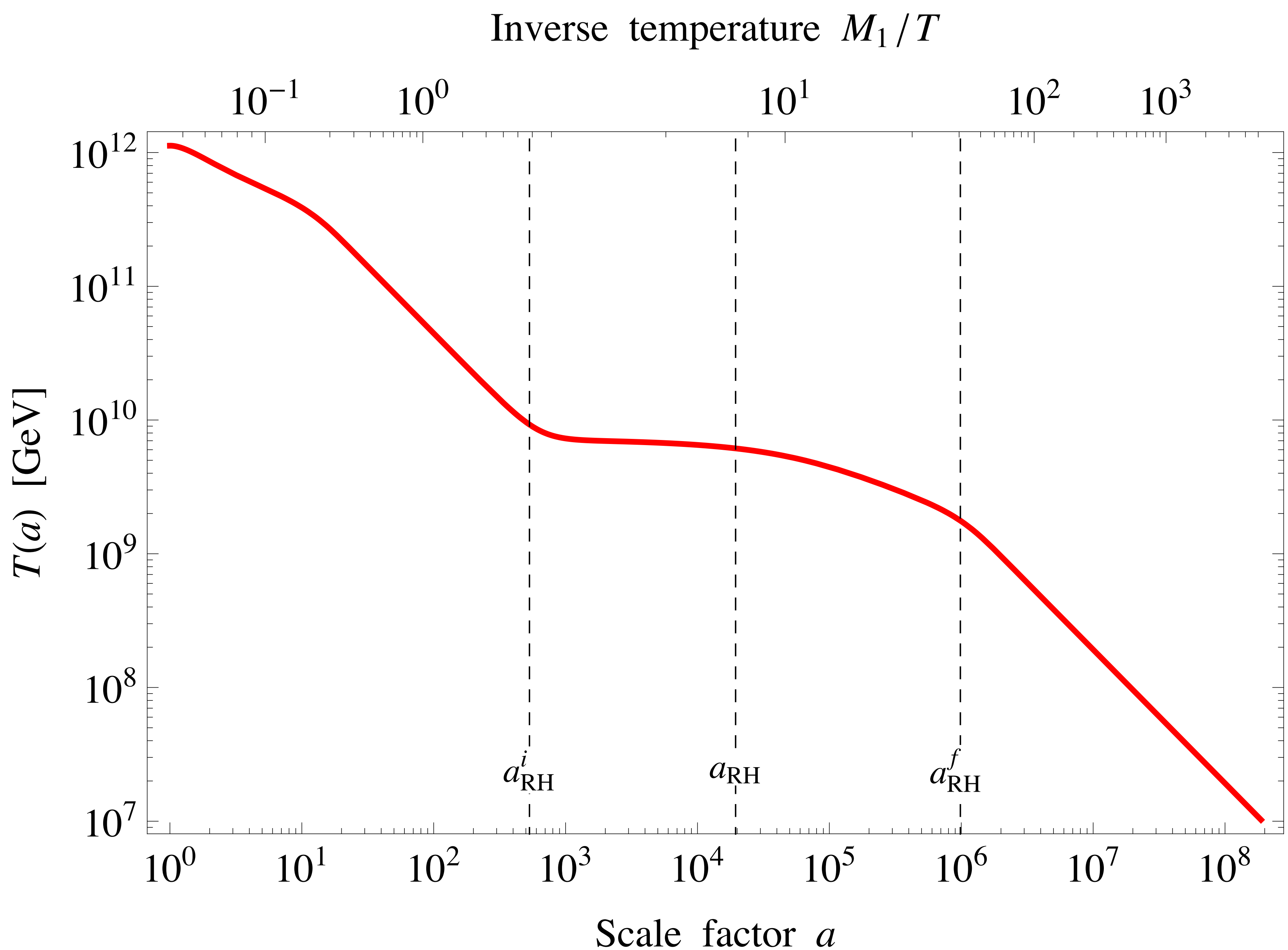




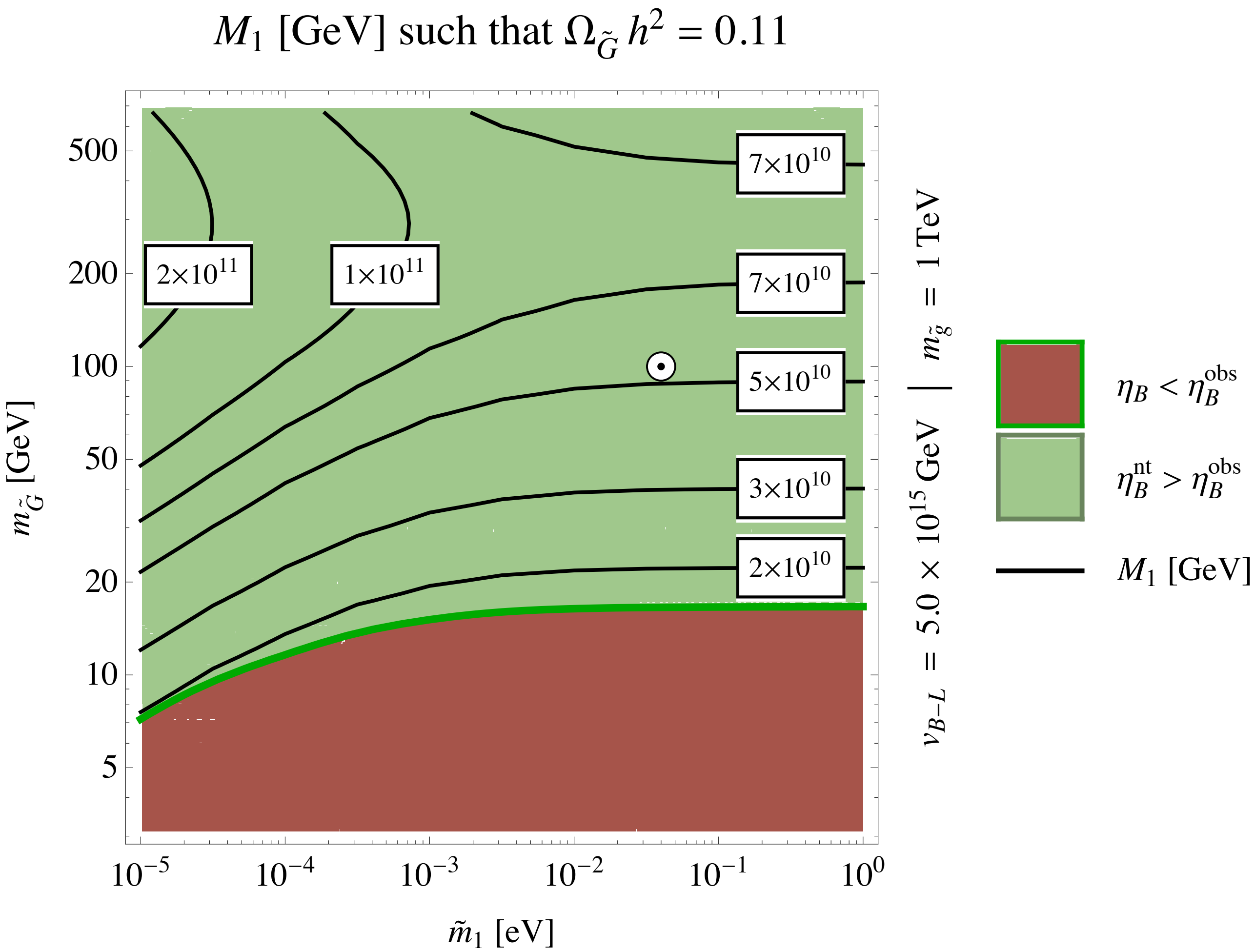
Transition from end of inflation to hot early universe (typical parameters), calculated by means of Boltzmann equations:

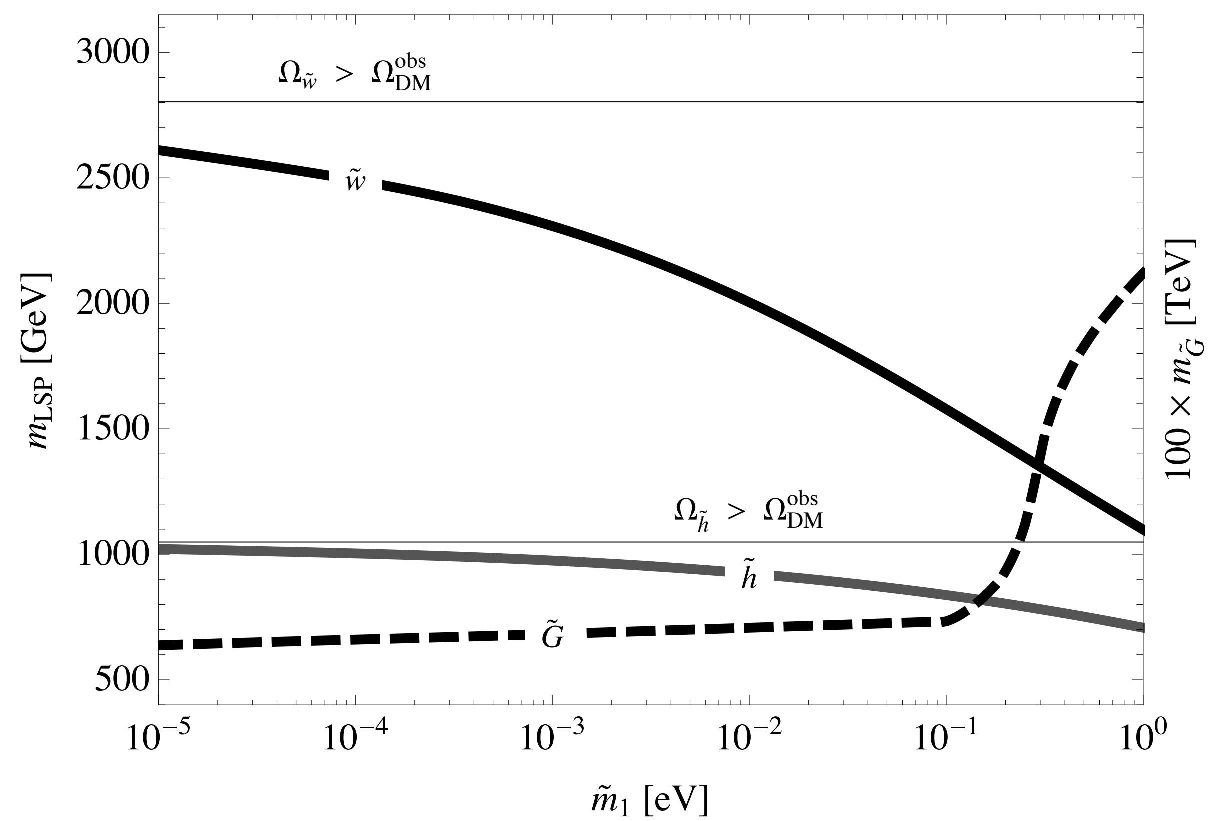
$$E\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_X(t,p) = \sum_{i'j'..}\sum_{ij..} C_X(Xi'j'.. \leftrightarrow ij..)$$

yields correct baryon asymmetry and dark matter abundance



Time evolution of temperature: intermediate plateau (“maximal temperature”), determined by neutrino properties! Yields gravitino abundance when combined with ‘standard formula’





parameter scans: successful leptogenesis and gravitino DM (*left*) or neutralino DM (*right*) [non-thermally produced in decays of thermally produced gravitinos] constrains neutrino and superparticle masses; can be tested at LHC!

II. Gravitational Waves

Relic gravitational waves are window to very early universe; contributions from inflation, preheating & cosmic strings (see Maggiore '07, Dufaux et al '10, Hindmarsh '11); cosmological B-L breaking: prediction of GW spectrum with all contributions! Perturbations in flat FRW background:

$$ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu \ , \quad \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h^\rho_\rho$$

determined by linearized Einstein equations,

$$\bar{h}''_{\mu\nu}(\mathbf{x},\tau) + 2\frac{a'}{a}\bar{h}'_{\mu\nu}(\mathbf{x},\tau) - \nabla^2_{\mathbf{x}}\bar{h}_{\mu\nu}(\mathbf{x},\tau) = 16\pi G T_{\mu\nu}(\mathbf{x},\tau)$$

yields spectrum of GW background:

$$\Omega_{GW}(k,\tau) = \frac{1}{\rho_c}\frac{\partial\rho_{GW}(k,\tau)}{\partial\ln k} \ ,$$

$$\int_{-\infty}^{\infty} d\ln k \frac{\partial\rho_{GW}(k,\tau)}{\partial\ln k} = \frac{1}{32\pi G}\left\langle \dot{h}_{ij}(\mathbf{x},\tau)\,\dot{h}^{ij}(\mathbf{x},\tau)\right\rangle$$

Gravitational waves from cosmic strings

Differential energy density in terms of stress-energy tensor of source:

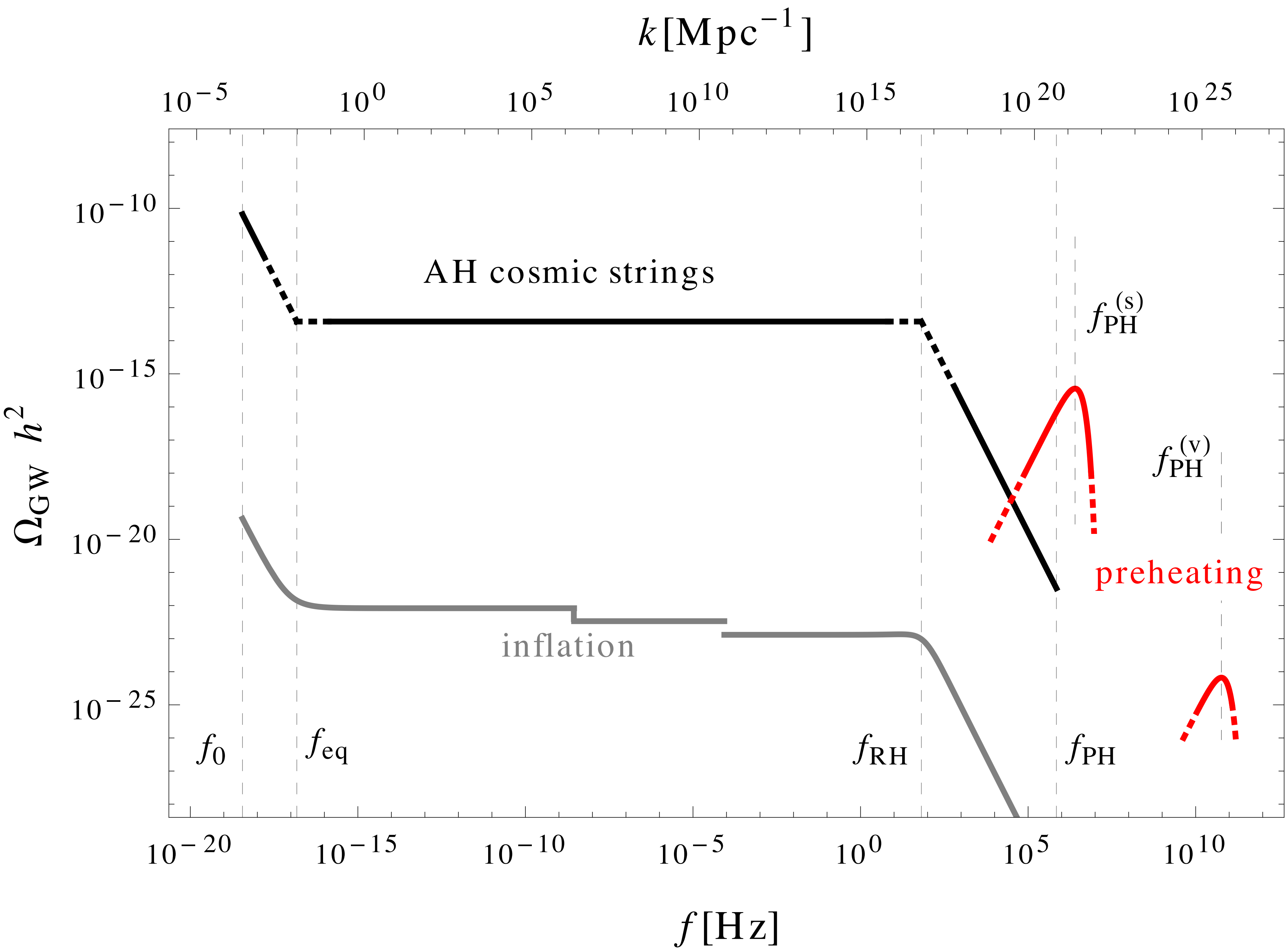
$$\frac{\partial \rho_{\rm GW}(k,\tau)}{\partial \ln k} = \frac{2G}{\pi}\frac{k^3}{a^4(\tau)}\int_{\tau_i}^{\tau} d\tau_1 \int_{\tau_i}^{\tau} d\tau_2 \, a(\tau_1)\, a(\tau_2)\, \cos(k(\tau_1-\tau_2))\, \Pi^2(k,\tau_1,\tau_2)$$

Recent determination of normalization for Abelian Higgs strings by means of lattice simulations [Figueroa, Hindmarsh, Urrestilla '13]. Final result:

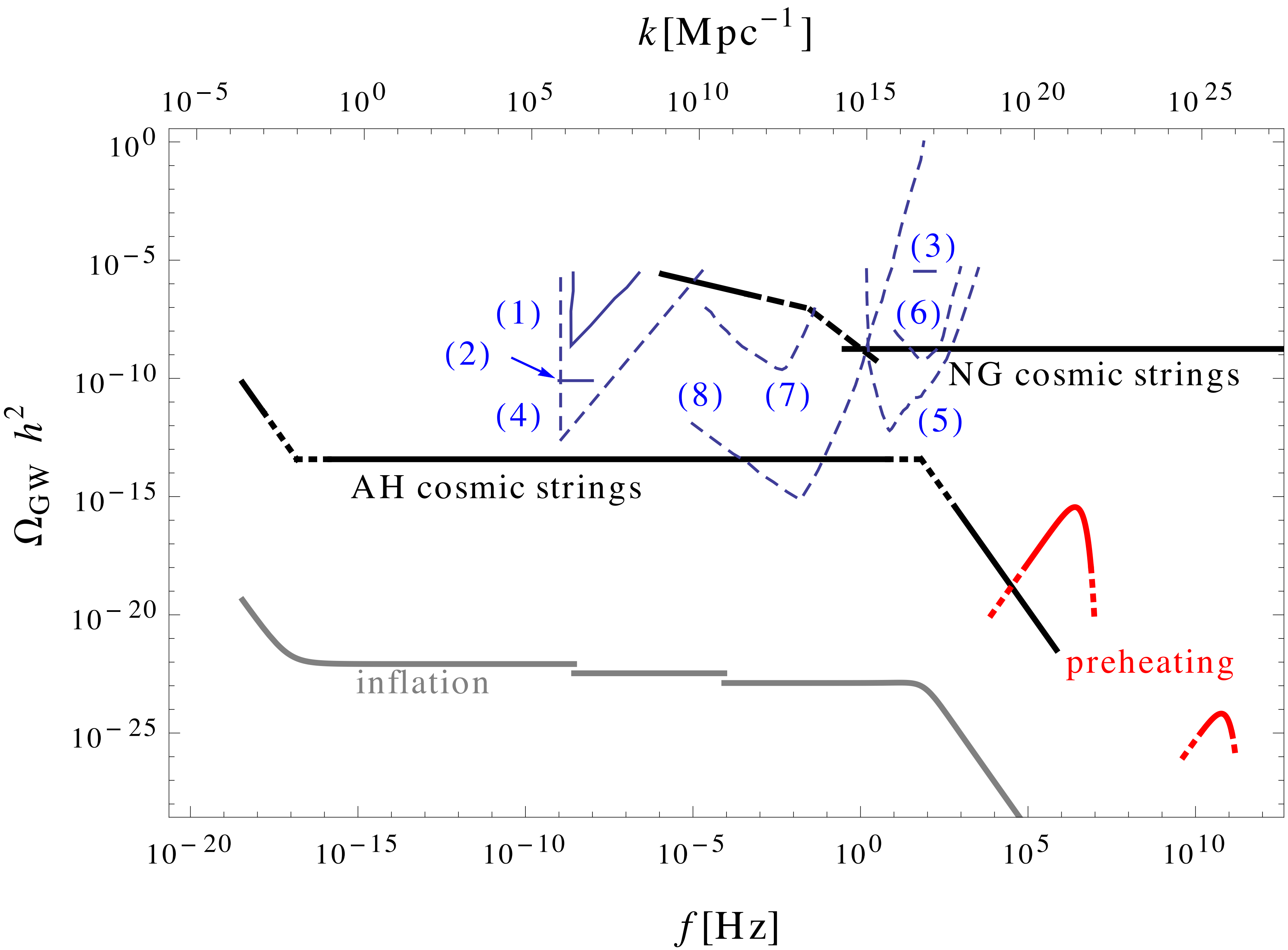
$$\Omega_{\rm GW}(k) \simeq \Omega^{\rm pl}_{\rm GW} \times \begin{cases} (k_{\rm eq}/k)^2, & k_0 \ll k \ll k_{\rm eq} \\ 1, & k_{\rm eq} \ll k \ll k_{\rm RH} \\ (k_{\rm RH}/k)^2, & k_{\rm RH} \ll k \ll k_{\rm PH} \end{cases}$$

$$\Omega^{\rm pl}_{\rm GW} h^2 = 4.0 \times 10^{-14}\, \frac{F^r}{F^r_{\rm FHU}} \left(\frac{v_{B-L}}{5\times 10^{15}{\rm GeV}}\right)^4 \left(\frac{\Omega_r h^2}{4.2\times 10^{-5}}\right)$$

similar to contribution from inflation, but different normalization (lattice); qualitatively different from computation with Nambu-Goto strings



Result: GWs from inflation, preheating and cosmic strings (Abelian Higgs), for typical parameters consistent with leptogenesis and dark matter; test of complete reheating history! Determination of *leptogenesis temperature*!



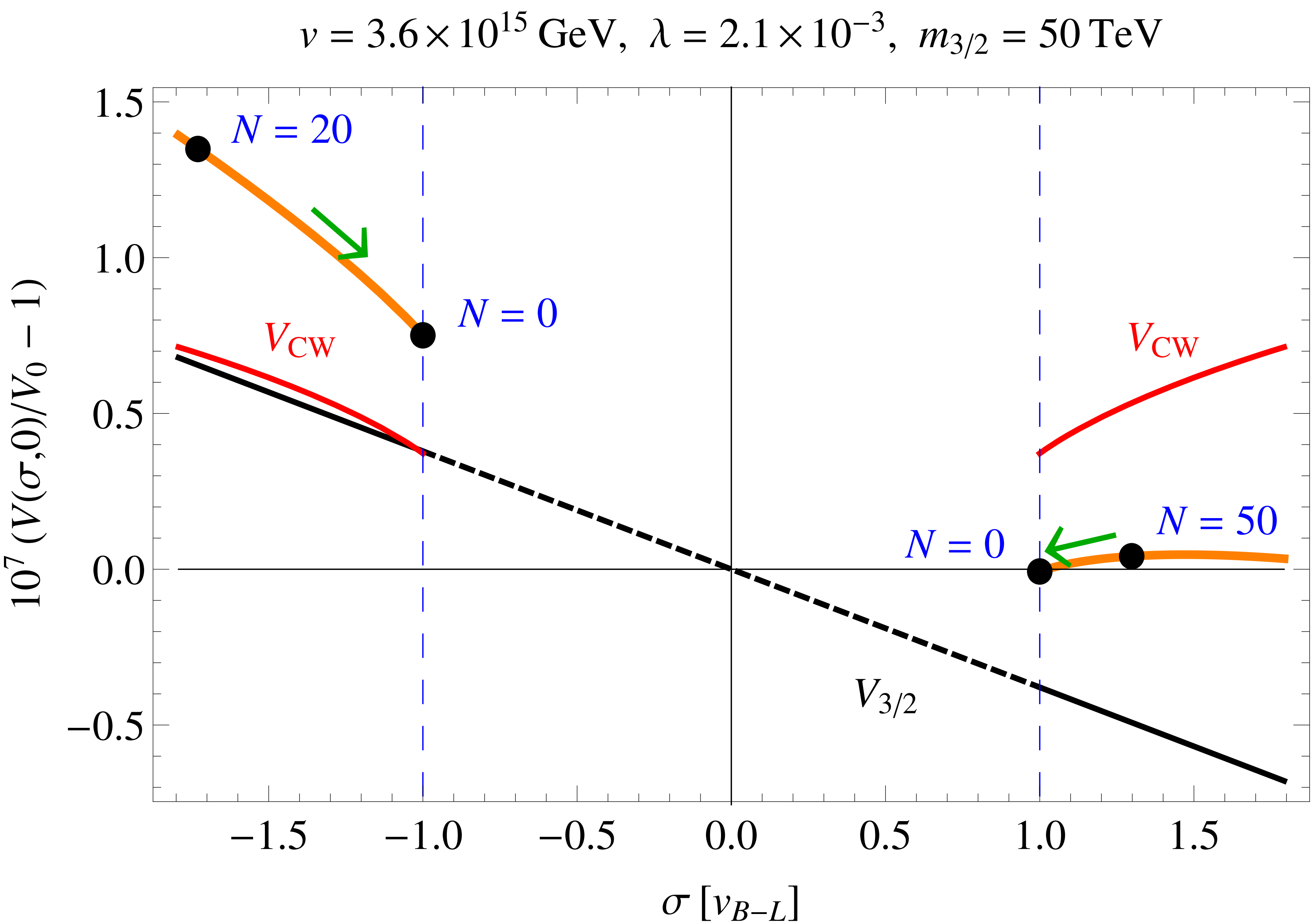
Observational prospects (for typical parameters); 'soon': Advanced Ligo (6) [100 Hz], eLISA [0.01 Hz]; 'later': Einstein Telescope [100 Hz], BBO/DECIGO [0.01 Hz]; eventually determination of reheating temperature (leptogenesis)?!

III. Hybrid Inflation in the Complex Plane

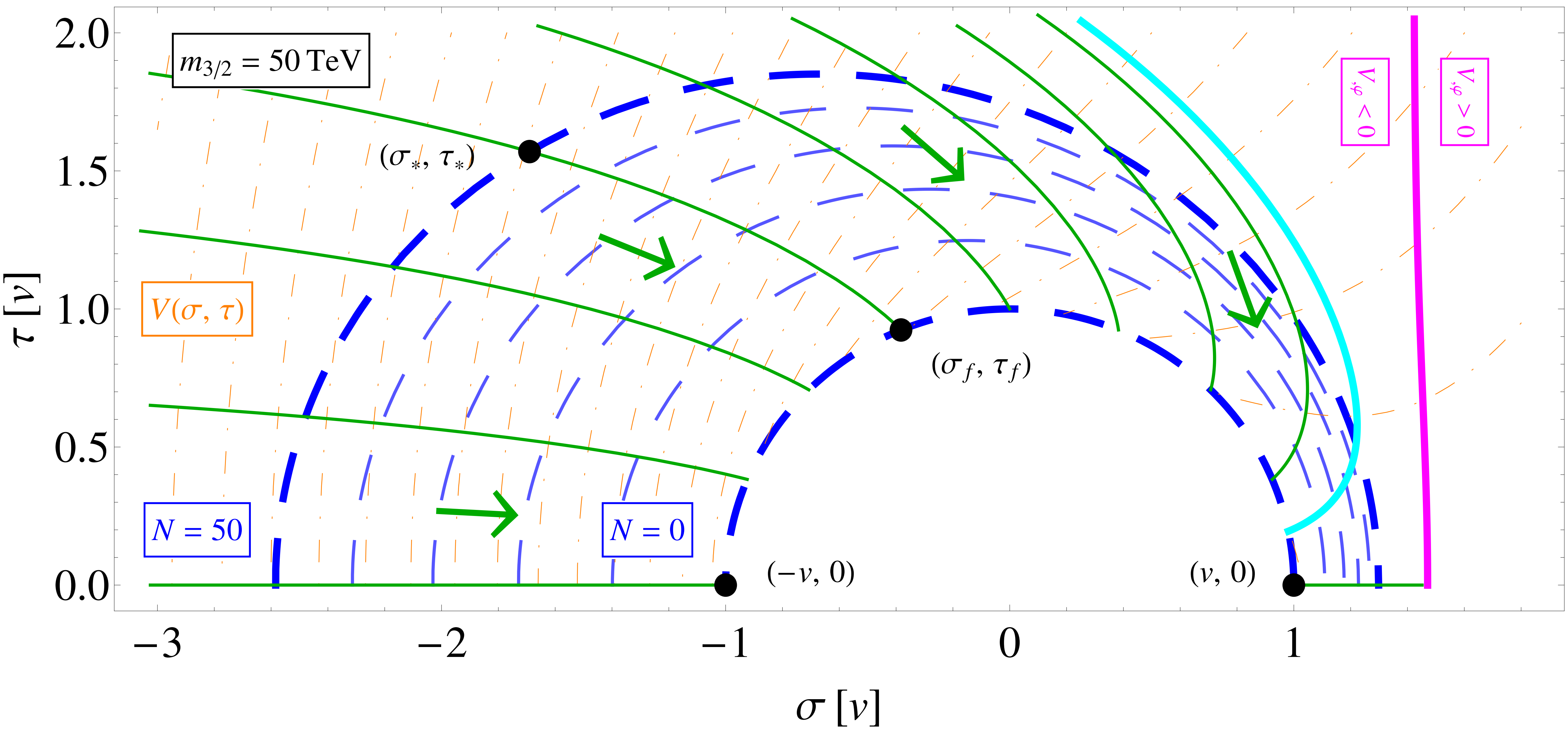
Inflationary potential can be strongly affected by supersymmetry breaking (supergravity correction yields linear term: WB, Covi, Delepine ’00):

$$
\begin{aligned}
V(\phi) &= V_0 + V_{\mathrm{CW}}(\phi) + V_{\mathrm{SUGRA}}(\phi) + V_{3/2}(\phi) \ , \\
V_0 &= \frac{\lambda^2 v^4}{4} \ , \\
V_{\mathrm{CW}}(\phi) &= \frac{\lambda^4 v^4}{32\pi^2} \ln\left(\frac{|\phi|}{v/\sqrt{2}}\right) + \ldots \ , \\
V_{\mathrm{SUGRA}}(\phi) &= \frac{\lambda^2 v^4}{8 M_{\mathrm{P}}^4} |\phi|^4 + \ldots \ , \\
V_{3/2}(\phi) &= -\lambda v^2 m_{3/2}(\phi + \phi^*) + \ldots
\end{aligned}
$$

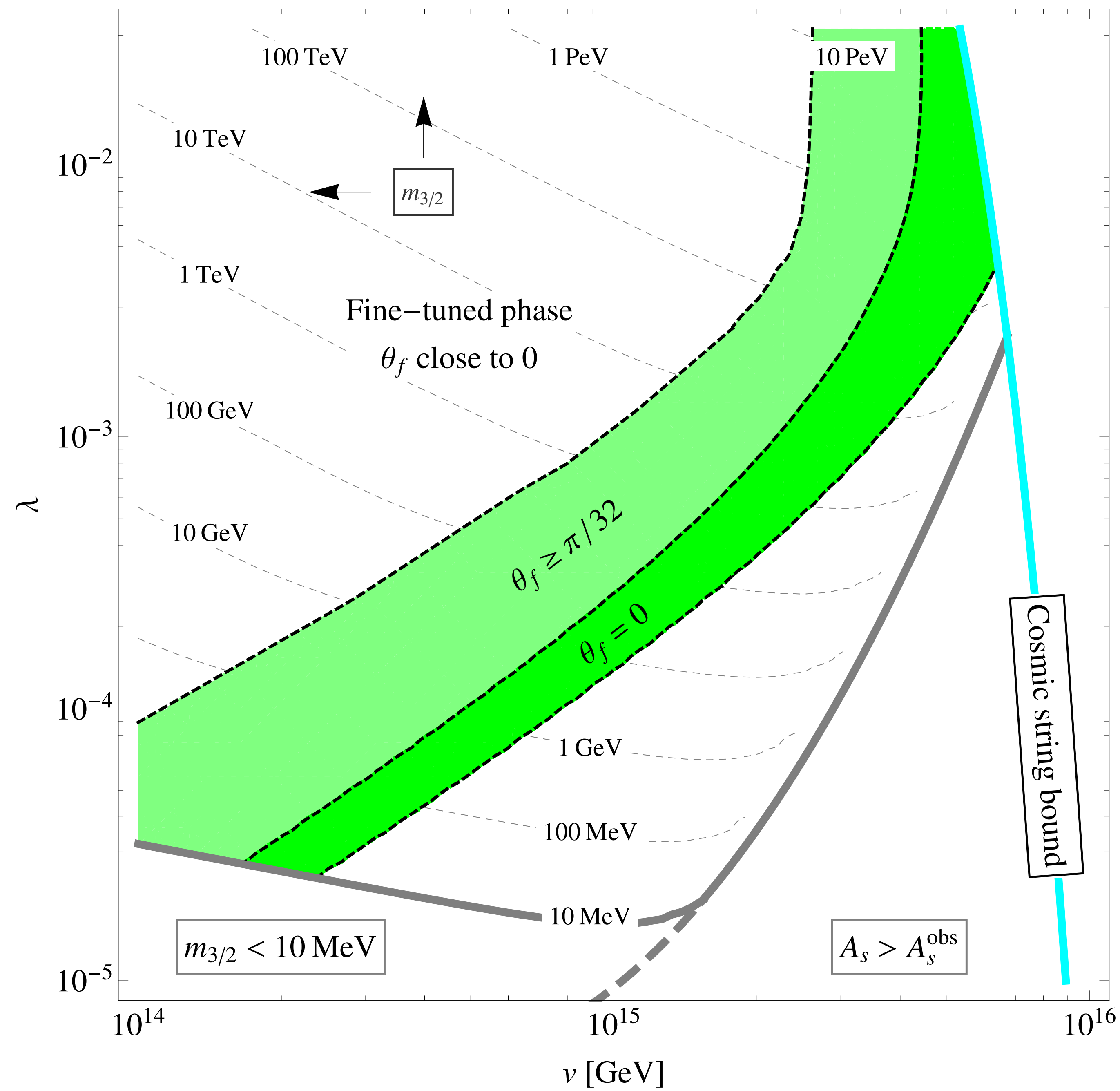
linear term turns hybrid inflation into two-field model in complex plane; strong effect on inflationary observables, now dependent on trajectory, i.e. initial conditions! Inflation consistent with Planck data now possible (otherwise very difficult)



Linear term leads to new 'hill-top' regime of inflaton potential (Pallis & Shafi '13); allows smaller spectral index than ordinary hybrid inflation



Two-field dynamics of complex inflaton in field space; all trajectories provide enough e-folds of expansion but only one yields the correct spectral index $n_s \simeq 0.96$



Parameter scan: relations between scale of B-L breaking, gravitino mass and scalar spectral index (no problem!) cosmic string bound automatically fulfilled!

Comments on BICEP2 results

Prediction of hybrid inflation model for tensor-scalar ratio:

$$r \lesssim 2 \times 10^{-6}$$

Planck data: $r < 0.11$

recent BICEP2 data: $r \simeq 0.2$

Hybrid inflation is inconsistent with BICEP2. Is BICEP2 correct? (recent rumors: more dust than expected ... ?!)

The BICEP2 result is very exciting, it would give evidence for the grand unification energy scale during inflation! This is welcome for leptogenesis. The discussed reheating mechanism can also be combined with 'modified' hybrid inflation, consistent with BICEP2 (see Brummer, Domcke, Sanz 1405.4868; Carpenter, Raby 1405.6143; Pallis, Shafi 1405.7645 and work in progress).

Conclusions

Leptogenesis is attractive mechanism to explain cosmological baryon asymmetry, consistent with neutrino masses

In supersymmetric theories leptogenesis favours gravitino (induced) dark matter in LHC range (no WIMP freeze-out!)

The initial conditions of the hot early universe can be provided by decays of heavy Majorana neutrinos

This reheating mechanism is compatible with different realizations of inflation (work in progress); crucial test: gravitational waves

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