TRI-RESONANT LEPTOGENESIS

Thomas McKelvey

With A. Pilaftsis and D. Karamitros

MANCHESTER 1824

The University of Manchester

OUTLINE

- Introduce TRL Model
- Introduce Relativistic Degrees of Freedom
- Study the Impact of the Relativistic Degrees of Freedom
- Discuss Observation Bounds

MOTIVATION

- WMAP and Planck observatory observe a matter-antimatter asymmetry

$$\eta_B^{CMB} = \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.104 \pm 0.058) \times 10^{-10}$$

- Observations of flavour oscillations in SM neutrinos implies the existence of neutrino masses

- Degrees of freedom are typically ignored in models at higher mass scales

TRL MODEL

- Minimal seesaw extension of the SM with three singlet neutrinos

$$\mathcal{L} \supset h^{\nu}_{i\alpha}\, L_i \widetilde{\Phi} N_\alpha - \frac{1}{2}\overline{N^c_\alpha}\, m_\alpha N_\alpha + H.c.$$

$$h^{\nu} = \begin{pmatrix} a & a\omega & a\omega^2 \\ b & b\omega & b\omega^2 \\ c & c\omega & c\omega^2 \end{pmatrix}$$

$$\Big\downarrow$$

$$m^{\nu} \to 0 \qquad \eta_B \neq 0!$$

- Heavy neutrino mass spectrum has a resonant structure, with mass splittings

$$m_\alpha - m_\beta \sim \frac{1}{2}\Gamma_{\alpha,\beta}$$

- Yukawa symmetry motivated with $\mathbb{Z}_3$ or $\mathbb{Z}_6$ structure.

TRANSPORT EQUATIONS

- We require a set of Quantum Transport Equations with Oscillation and Mixing Phenomena included

- Much of the interesting dynamics occur close to equilibrium, so we introduce the matrices

$$\Delta = \frac{\eta^N}{\eta^N_{eq}} - \mathbb{I} \quad \delta = \frac{\delta\eta^N}{\eta^N_{eq}}$$

- We also require a transport equation for the Lepton asymmetry

TRANSPORT EQUATIONS

$$\frac{d\Delta}{d\ \ln z} = \frac{\delta_h}{H}\left(-\frac{i}{2}[\mathcal{E},\delta] - \frac{1}{2\eta_{eq}^N}\left\{\Delta, \mathcal{R}\left[\gamma_{L\Phi}^N\right]\right\}\right) - \left(\frac{d\ \ln h_{eff}}{d\ \ln z} - \frac{d\ \ln \eta_{eq}^N}{d\ \ln z}\right)(\Delta + \mathbb{I})$$

$$\frac{d\delta}{d\ \ln z} = \frac{\delta_h}{H}\left(-\frac{i}{2}[\mathcal{E},\delta] - \frac{i}{\eta_{eq}^N}\{\Delta, \mathcal{I}[\delta\gamma]\} - \frac{1}{2\eta_{eq}^N}\left\{\delta, \mathcal{R}\left[\gamma_{L\Phi}^N\right]\right\}\right) - \left(\frac{d\ \ln h_{eff}}{d\ \ln z} - \frac{d\ \ln \eta_{eq}^N}{d\ \ln z}\right)\delta$$

TRANSPORT EQUATIONS

$$\frac{d\Delta}{d\ \ln z} = \frac{\boxed{\delta_h}}{H}\left(-\frac{i}{2}[\mathcal{E},\delta] - \frac{1}{2\eta_{eq}^N}\{\Delta, \mathcal{R}[\gamma_{L\Phi}^N]\}\right) - \left(\boxed{\frac{d\ \ln h_{eff}}{d\ \ln z}} - \boxed{\frac{d\ \ln \eta_{eq}^N}{d\ \ln z}}\right)(\Delta + \mathbb{I})$$

$$\frac{d\delta}{d\ \ln z} = \frac{\boxed{\delta_h}}{H}\left(-\frac{i}{2}[\mathcal{E},\delta] - \frac{i}{\eta_{eq}^N}\{\Delta, \mathcal{J}[\delta\gamma]\} - \frac{1}{2\eta_{eq}^N}\{\delta, \mathcal{R}[\gamma_{L\Phi}^N]\}\right) - \left(\boxed{\frac{d\ \ln h_{eff}}{d\ \ln z}} - \boxed{\frac{d\ \ln \eta_{eq}^N}{d\ \ln z}}\right)\delta$$

Degrees of Freedom Effects

Thermal Leptogenesis Terms

LEPTON ASYMMETRY EQUATION

$$\frac{d(\delta\eta_L)_{ij}}{d\ \ln z} = \frac{\delta_h}{H}\left(\Delta_{\alpha\beta}\ (\delta\gamma)_{i\alpha j\beta} - \delta_{\alpha\beta}\left(\gamma^{N}_{L\Phi}\right)_{i\alpha j\beta}\right) + (2 \to 2) - \left(\frac{d\ \ln h_{eff}}{d\ \ln z}\right)(\delta\eta_L)_{ij}$$

LEPTON ASYMMETRY EQUATION

$$\frac{d(\delta\eta_L)_{ij}}{d\ \ln z} = \frac{\boxed{\delta_h}}{H}\left(\Delta_{\alpha\beta}\,(\delta\gamma)_{i\alpha j\beta} - \delta_{\alpha\beta}\left(\gamma^N_{L\Phi}\right)_{i\alpha j\beta}\right) + (2 \to 2) - \left(\boxed{\frac{d\ \ln h_{eff}}{d\ \ln z}}\right)(\delta\eta_L)_{ij}$$

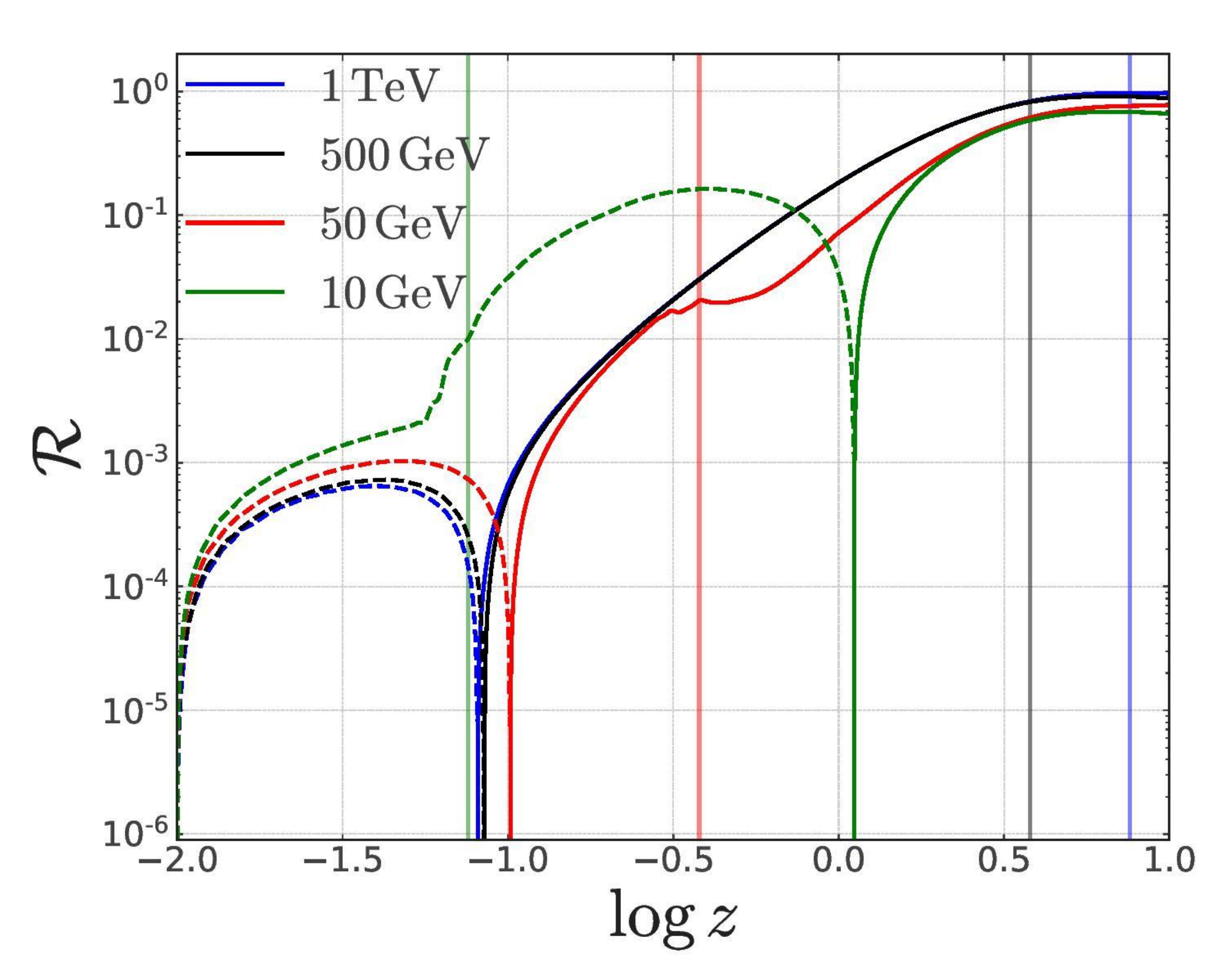
Neutrino evolution feeds into the Lepton asymmetry

Degrees of freedom are also present

h_{eff} VS. η_{eq}^{N}

- Reduction in the effective degrees of freedom wash-out the number density

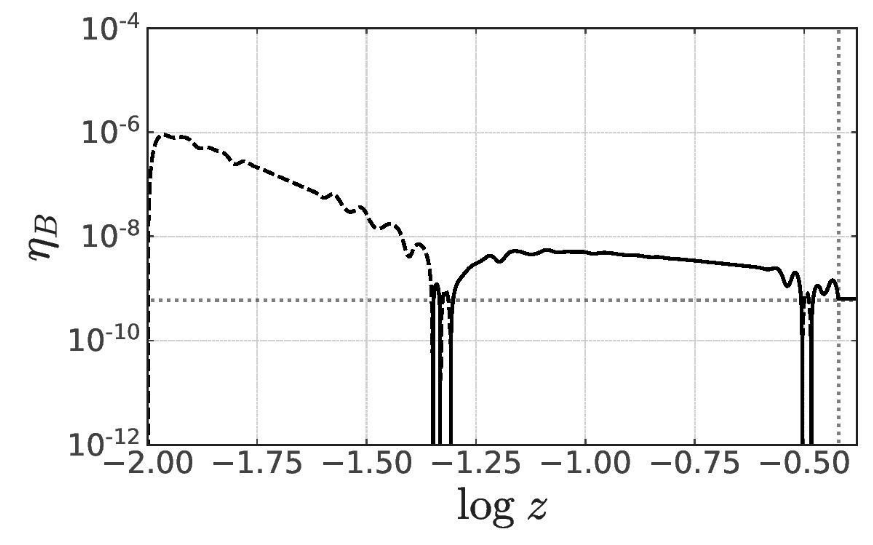
- Cooling of the Universe due to expansion makes the number density over abundant



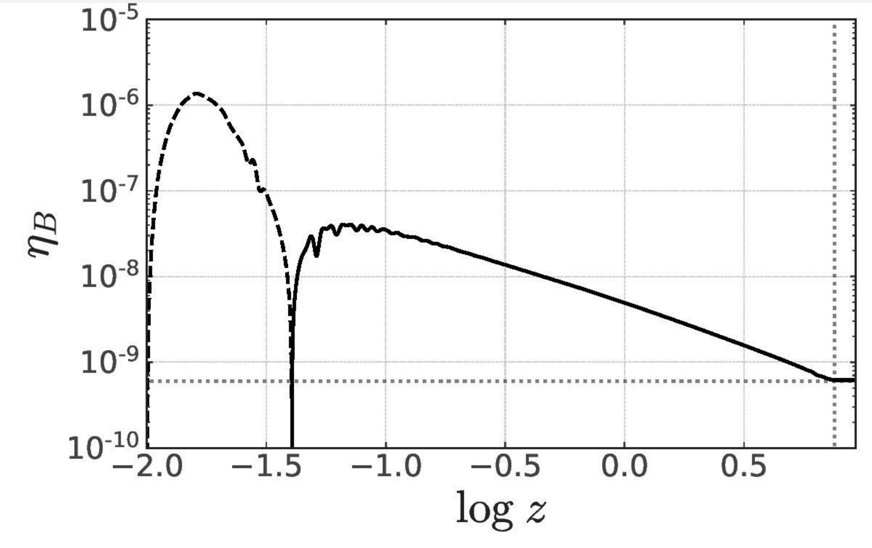
$$\mathcal{R} = \frac{h_{eff}(z)}{h_{eff}(z_0)} - \frac{\eta_{eq}^{N}(z)}{\eta_{eq}^{N}(z_0)}$$

EVOLUTION OF THE BAU

50 GEV



I TEV



EVOLUTION OF THE BAU

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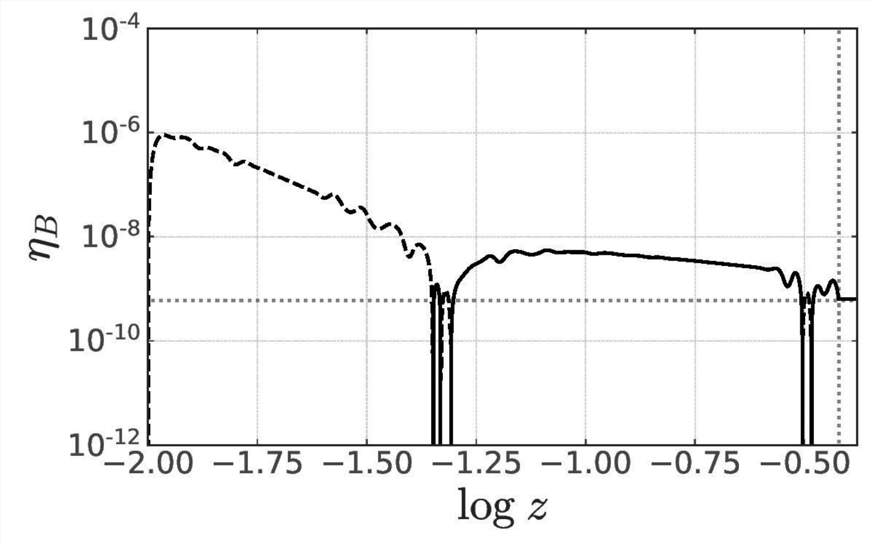
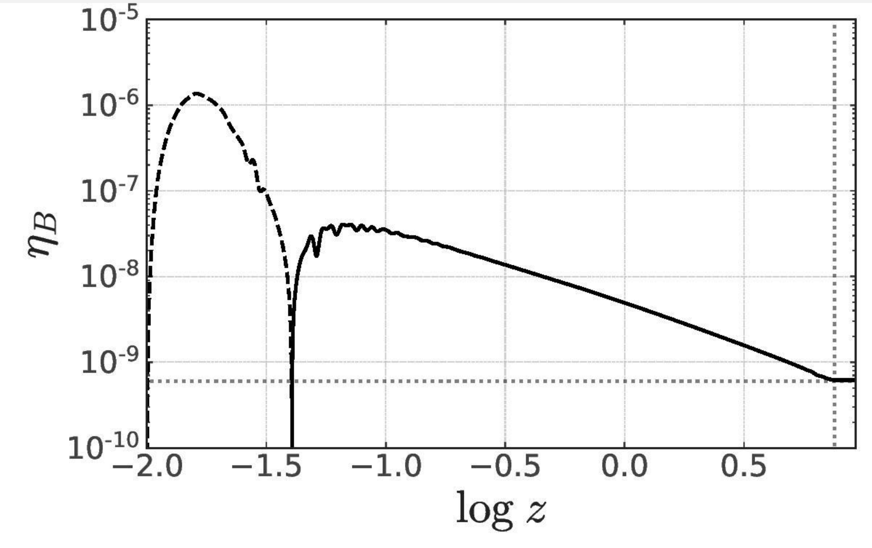


Significant Impact on BAU from degrees of freedom at low-scale

1 TEV

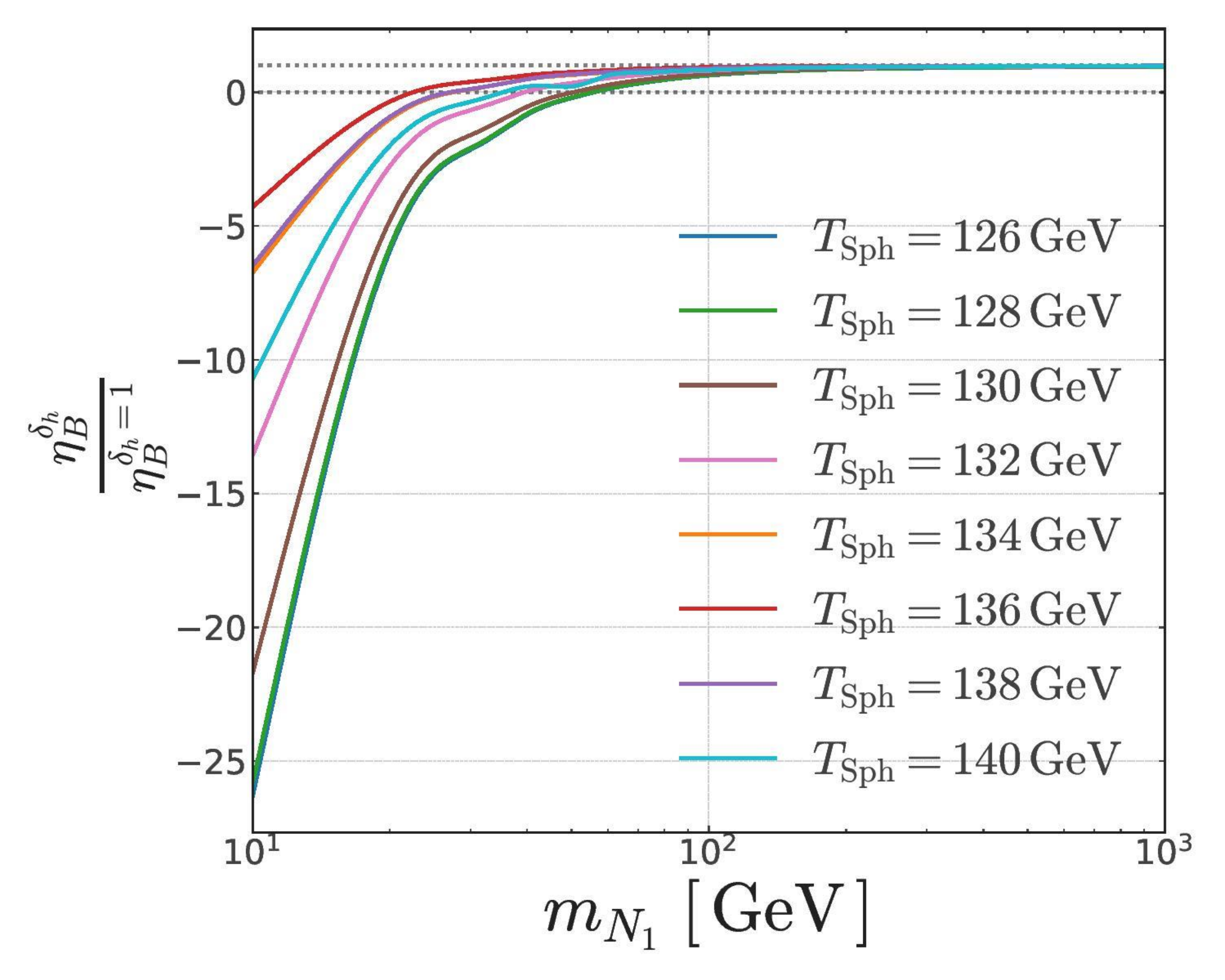


High scale is largely protected from variations in the degrees of freedom

BAU DEVIATIONS

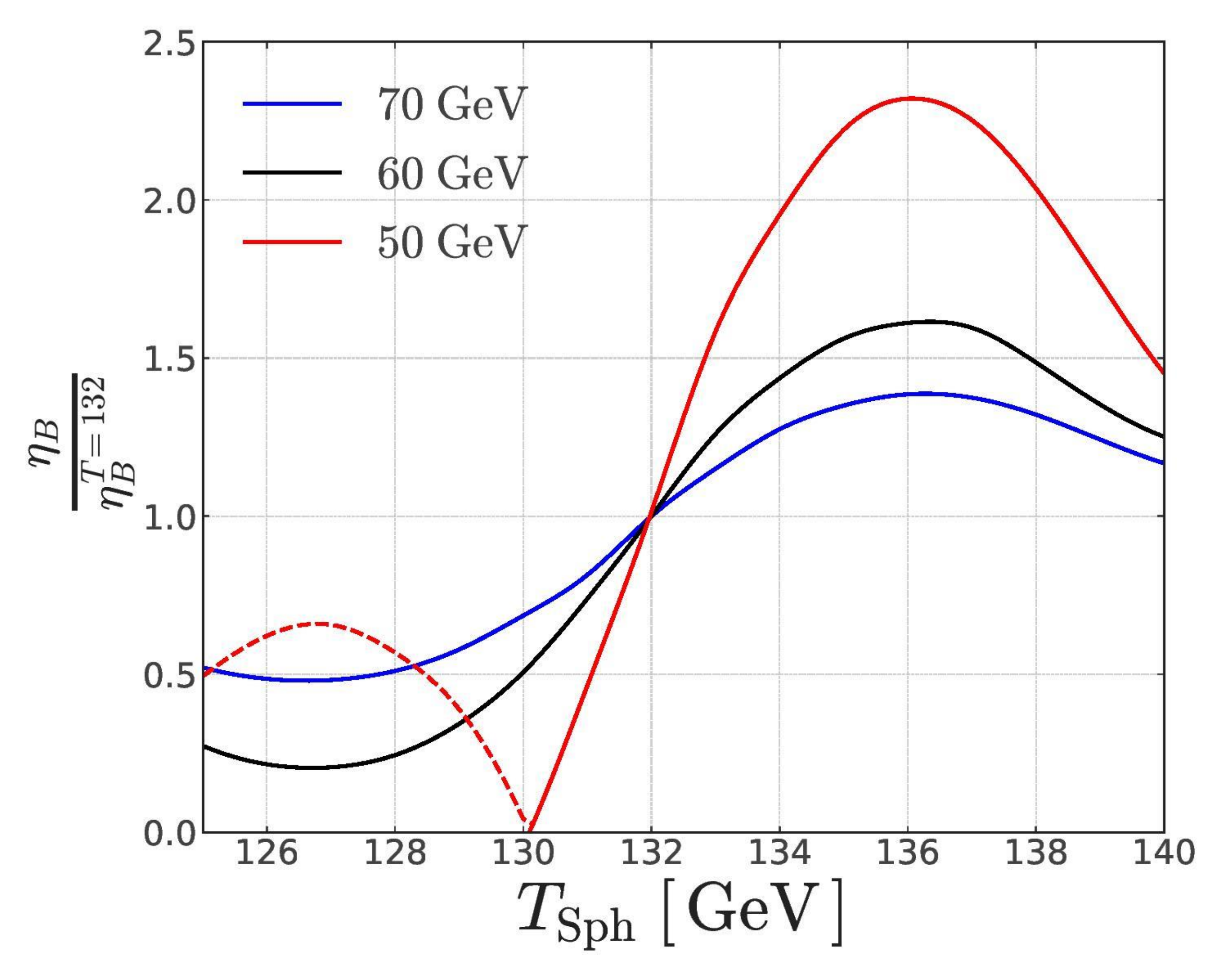
- Above 100 GeV the deviations are small – degrees of freedom are of low significance

- Below 100 GeV the BAU is suppressed and may even fall below zero.



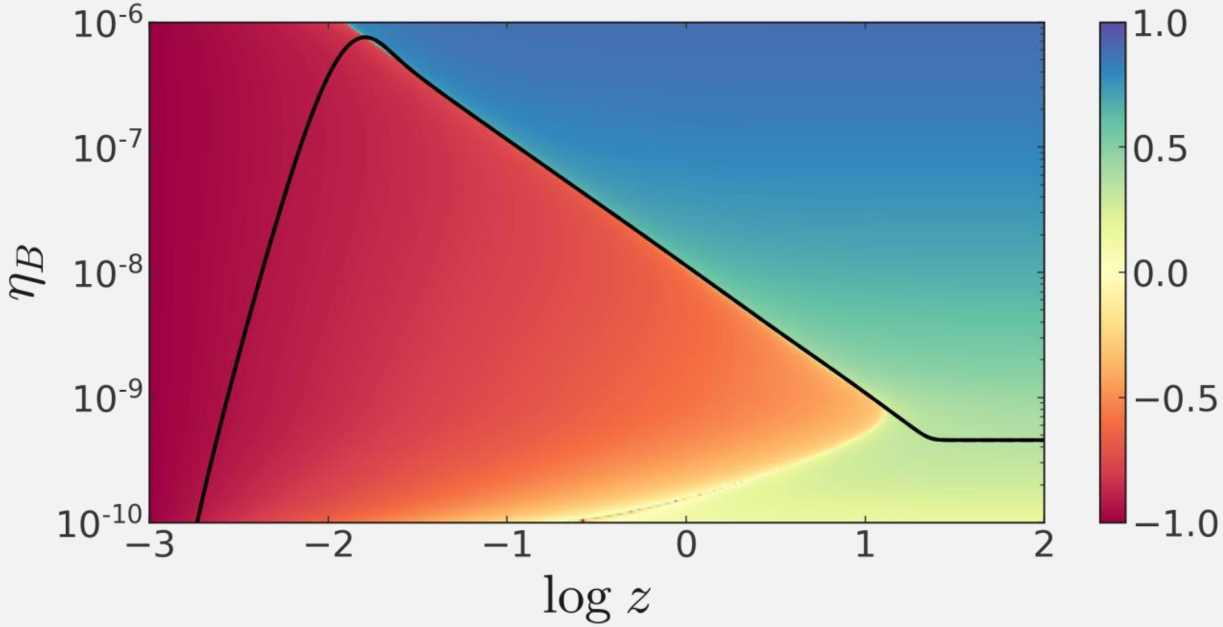
SPHALERON TEMPERATURE DEPENDENCE

- Inclusion of degrees of freedom induces large dependence on T_{Sph} at low heavy neutrino mass scales
- Deviations increase as the mass scales decrease



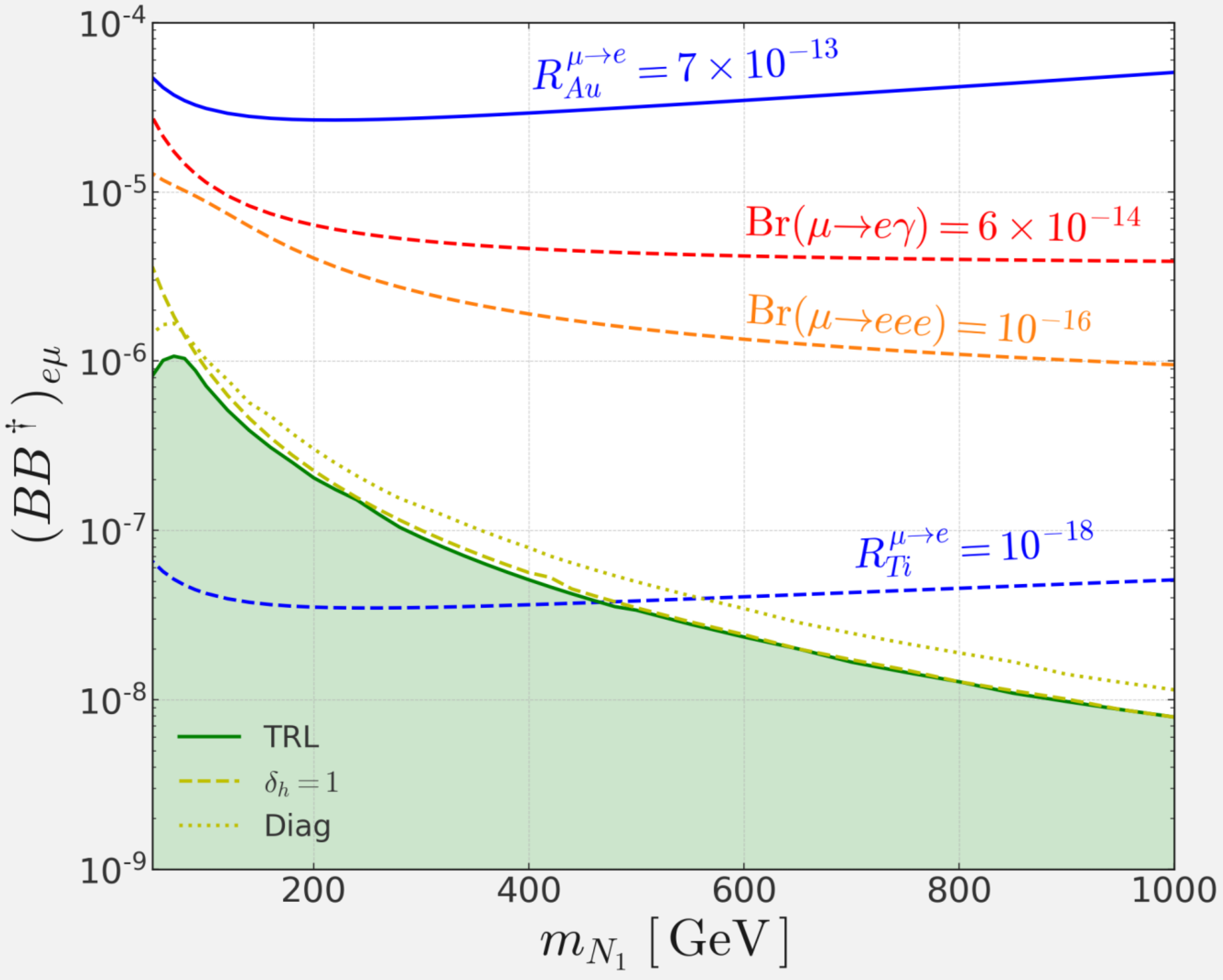
ATTRACTOR PROPERTIES

- The transport equations we use exhibit attractor properties
- Provides independence from initial conditions
- Impact of degrees of freedom are present regardless of initial conditions.



OBSERVATION LIMITS

- Suppression of the mixing due to the impact of the degrees of freedom.
- Much of the parameter space is out of the range of current experiments
- Possible observations at PRISM



SUMMARY

- We accounted for the variations in the relativistic degrees of freedom in Leptogenesis models

- Showed that the inclusion of the degrees of freedom can have a significant impact for models with sub-100 GeV heavy neutrinos

- Identified that the inclusion of degrees of freedom effects can induce large dependence on T_{Sph}.

- Discussed the observation limits at current and projected experiments