# Resonant Leptogenesis

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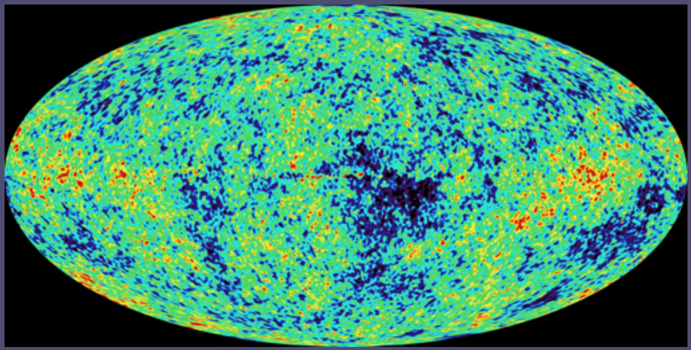
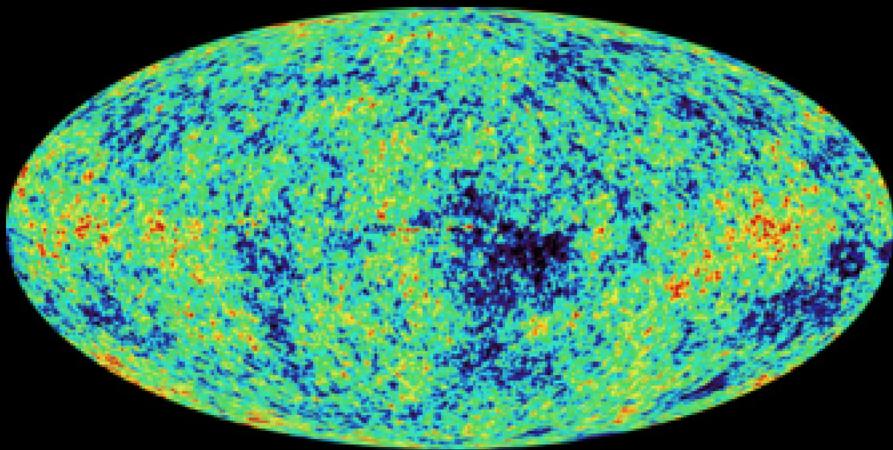


[Image from the WMAP satellite]

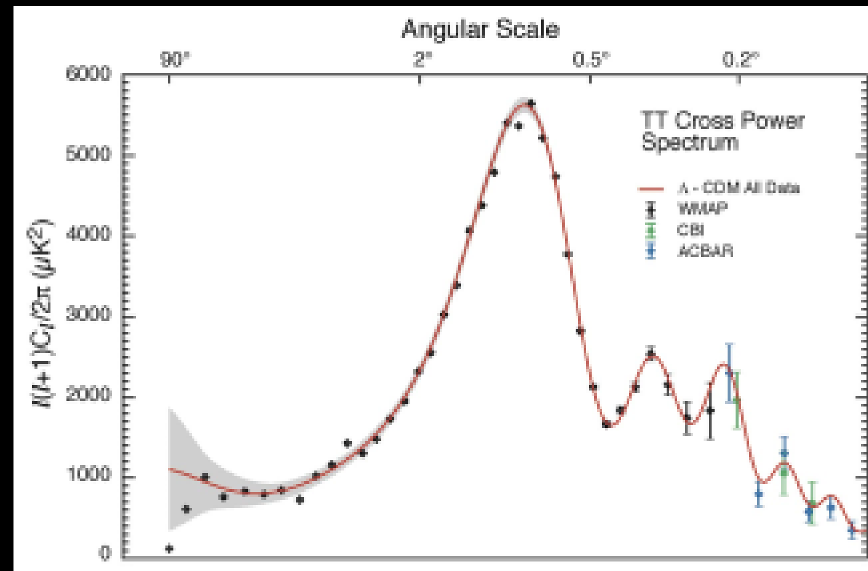
# Introduction

- The baryon asymmetry of the universe
- Neutrino masses and mixings
  - See-saw mechanism & alternatives
- **Leptogenesis**
  - Improved Boltzmann equations
- **Resonant Leptogenesis**
  - TeV scale leptogenesis, no dependence on initial conditions

# Baryon asymmetry



[WMAP science team]




- Most precise measurement provided by WMAP

$$\frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10}$$

  – Previous constraints from nucleosynthesis

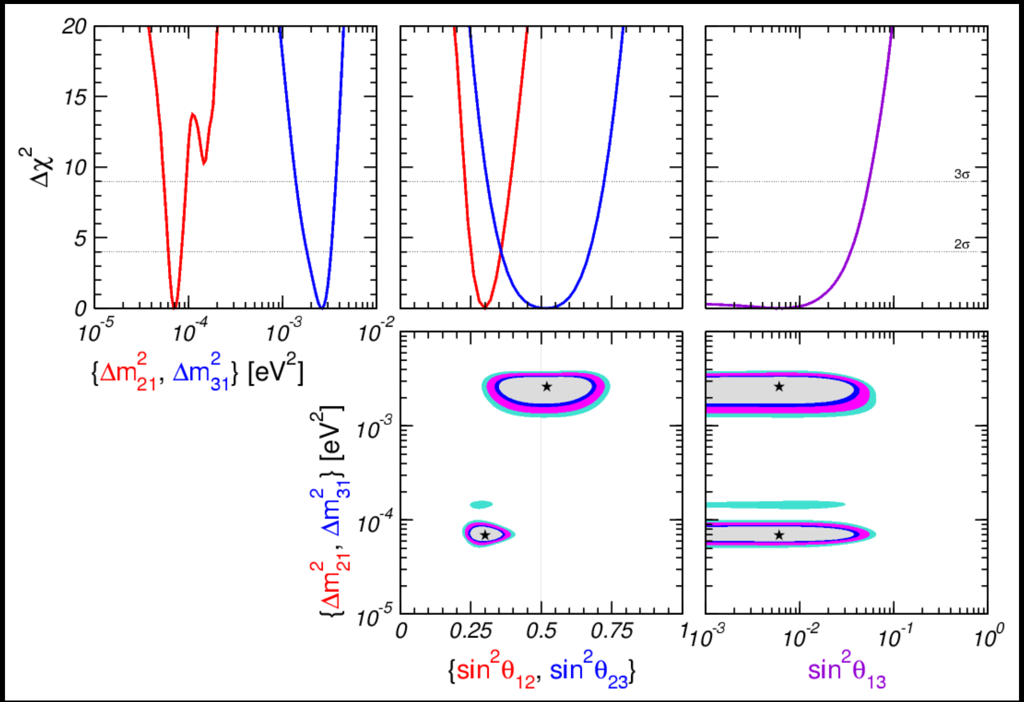
# Neutrino mass differences and mixings

– Data from a global fit, including SNO-salt data

[M. Maltoni, T. Schwetz,

M. A. Tortola,

J. W. F. Valle PRD **68** 113010]




$$\Delta m^2_{\rm atm} = m_3^2 - m_1^2$$

$$\Delta m^2_{\rm sol} = m_2^2 - m_1^2$$

$3\sigma$ limits:

$$1.4 \times 10^{-3} < \Delta m^2_{\rm atm}\,[\mathrm{eV}^2] < 3.7 \times 10^{-3}$$

$$5.4 \times 10^{-5} < \Delta m^2_{\rm sol}\,[\mathrm{eV}^2] < 9.5 \times 10^{-5}$$

- Add one SM gauge singlet right handed neutrino per generation

$$L_l \equiv \begin{pmatrix} \nu_{iL} \\ l_{iL} \end{pmatrix} \qquad l_{iR} \qquad \nu_{iR}$$

$$\mathcal{L}_{\text{mass}} \sim (\bar{\nu}_L \,,\, \bar{\nu}_R^C) \begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix} \begin{pmatrix} \nu_L^C \\ \nu_R \end{pmatrix} + \text{h.c.}$$

  – where $m_D = \frac{1}{\sqrt{2}} h^\nu \, v$

- If $m_D \ll m_M$

$$m_\nu^{\text{light}} \sim -m_D \frac{1}{m_M} m_D^T$$

$$m_N^{\text{heavy}} \sim m_M$$

# Baryogenesis

- Conditions for successful baryogenesis, Sakharov 1967
  - **Baryon number violation**
  - **C and CP violation**
  - **Conditions out of thermal equilibrium**

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- GUT Baryogenesis
  - B and CP violation occurs during the out of equilibrium interactions of very heavy ‘X’ particles [M. Yoshimura PRL**41**(1978)281, S. Dimopoulos, L. Susskind PRD**18**(1978)4500]

- Electroweak baryogenesis
  - B+L is violated at high temperatures in SM, baryogenesis occurs at the electroweak phase transition

    [V. A. Kuzmin, V. A. Rubakov M. E. Shaposhnikov PLB**155**(1985)36]

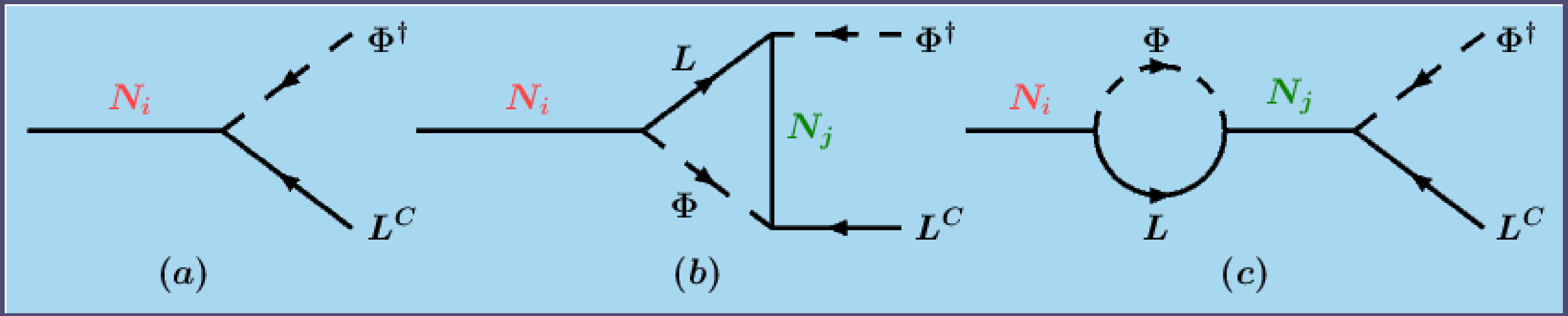
- **Baryogenesis through leptogenesis**
  - [M. Fukugita, T. Yanagida PLB**174**(1986)45]

# Baryogenesis through leptogenesis

- **Lepton number and CP violation occurs during the out of equilibrium decay of a heavy Majorana neutrino.**

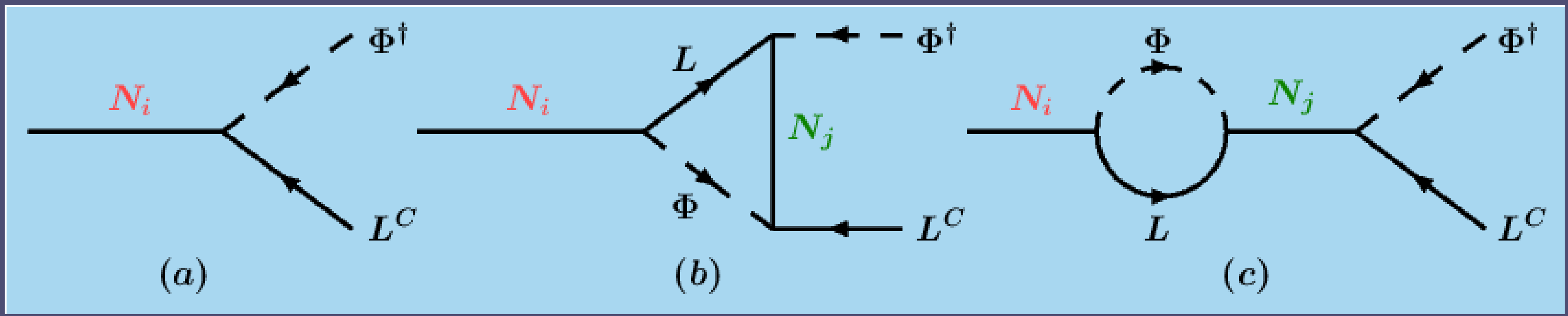
- The lepton-antilepton asymmetry is partially converted to a baryon asymmetry by the Standard Model $B + L$ violating ($B - L$ conserving) *sphaleron* process.

- The typical mass of a heavy Majorana neutrino is $\gtrsim 10^9\,\mathrm{GeV}$




- Interference between tree level **(a)** and 1 loop vertex **(b)** graphs is the origin of the CP asymmetry in conventional leptogenesis ($\varepsilon'$-type CP violation).

# Resonant leptogenesis




- **If $M_{N_i} - M_{N_j} \ll M_{N_i}$ the self-energy ($\varepsilon$-type) contribution to the CP asymmetry becomes dominant.**

- **Resonant leptogenesis** occurs when $M_{N_i} - M_{N_j} \sim \Gamma_{N_i}$, in this case the CP asymmetry can become very large (even order 1).

- The $\varepsilon$-type CP asymmetry,

$$\varepsilon_{N_i} = \frac{\mathrm{Im}(h^{\nu\dagger}\, h^{\nu})^2_{ij}}{(h^{\nu\dagger}\, h^{\nu})_{ii}(h^{\nu\dagger}\, h^{\nu})_{jj}} \frac{(m^2_{N_i} - m^2_{N_j}) m_{N_i} \Gamma^{(0)}_{N_j}}{(m^2_{N_i} - m^2_{N_j})^2 + m^2_{N_i} \Gamma^{(0)\,2}_{N_j}}$$

- Order 1 CP asymmetries are possible when,

$$m_{N_2} - m_{N_1} \sim \frac{1}{2} \Gamma^{(0)}_{N_{1,2}}$$

$$\frac{\mathrm{Im}(h^{\nu\dagger}\, h^{\nu})^2_{ij}}{(h^{\nu\dagger}\, h^{\nu})_{ii}(h^{\nu\dagger}\, h^{\nu})_{jj}} \sim 1$$

[A. Pilaftsis PRD**56**(1997)5431]

# Models

- The conditions for resonant leptogenesis can be met in several ways e.g.

$$\mathcal{L}_{\rm mass} = -\sum_{i,j=1}^{3}\Big( h^{\nu}_{ij}\,\bar{L}_i\,\widetilde{\Phi}\,P_R\,N_j + \frac{1}{2}\,\overline{N}_i\,\widehat{M}_{S\,ij}\,P_R\,N_j + \mathrm{h.c.}\Big)$$

- Model based on the Froggatt-Nielsen mechanism
  - Introduce two fields, $\Sigma$ and $\overline{\Sigma}$
  - $U(1)_{\rm FN}$ charges :

| | $\Sigma$ | $\overline{\Sigma}$ | $\nu_{1R}$ | $\nu_{2R}$ | $\nu_{3R}$ |
|---|---|---|---|---|---|
| $Q_{\rm FN}$ | $+1$ | $-1$ | $-1$ | $+1$ | $0$ |

[A. Pilaftsis, T.U. hep-ph/0309342]

- The singlet mass matrix takes the form

$$M_S \sim M \begin{pmatrix} \varepsilon^2 & 1 & \varepsilon \\ 1 & \bar{\varepsilon}^2 & \bar{\varepsilon} \\ \varepsilon & \bar{\varepsilon} & M_X/M \end{pmatrix}$$

  – where $\varepsilon = \langle \Sigma \rangle / M_{\mathrm{GUT}}$ and $\bar{\varepsilon} = \langle \overline{\Sigma} \rangle / M_{\mathrm{GUT}}$

- The Dirac neutrino mass matrix has the form

$$m_D \equiv \frac{v}{\sqrt{2}} h \sim \frac{v}{\sqrt{2}} \begin{pmatrix} \varepsilon & \bar{\varepsilon} & 1 \\ \varepsilon & \bar{\varepsilon} & 1 \\ \varepsilon & \bar{\varepsilon} & 1 \end{pmatrix}$$

[A. Pilaftsis, T.U. hep-ph/0309342]

- If $\langle\Sigma\rangle \sim \langle\overline{\Sigma}\rangle \sim \sqrt{M\, M_{\mathrm{GUT}}}$ and $M_X \sim M_{\mathrm{GUT}}$ then we have
  - One very heavy Majorana neutrino, $m_{N_3} \sim M_{\mathrm{GUT}}$
  - Two nearly degenerate heavy Majorana neutrinos, $m_{N_{1,2}} \sim M$ with a mass difference $m_{N_1} - m_{N_2} \sim \varepsilon^2 M \sim \Gamma^{(0)}_{N_1}$

- Other models with nearly degenerate heavy Majorana neutrinos possible, see e.g. SO(10) with a type III see-saw [C. H. Albright, S. M. Barr, hep-ph/0312224]
  Neutrino mass from SUSY breaking [T. Hambye, J. March-Russell, S. West, hep-ph/0403183]

# Constraints from the out of equilibrium condition

- The decay of heavy Majorana neutrinos must occur out of thermal equilibrium (Sakharov) for successful leptogenesis.
- Define $K_i = \Gamma^{(0)}_{N_i}/H(T = m_{N_i})$
- $K_i$ should be smaller than a certain value $K^{\max}$
- Can express this constraint in terms of effective light neutrino masses, $\widetilde{m}_i$,

$$\widetilde{m}_i \equiv \frac{v^2 \, (h^{\nu\dagger} h^{\nu})_{ii}}{2\, m_{N_i}} \lesssim 10^{-3}\, K_i^{\rm max}\ {\rm eV}\,.$$

- Hierarchical thermal leptogenesis has $K^{\rm max} \sim 1$
- Resonant leptogenesis can be successful with $K^{\rm max}$ larger than 1000.
- If a 'large' $\gtrsim 0.2\,{\rm eV}$ effective Majorana mass was seen in $0\nu\beta\beta$ decay it could be naturally accommodated with resonant leptogenesis.

– Hierarchical thermal leptogenesis would be strongly disfavoured in this case.

[Buchmuller, Di Bari, Plumacher,PLB**575**75]

- An estimate for the baryon to photon ratio may be obtained from,

$$\eta_B \sim -\sum_{i=1,2,3} \frac{\delta_{N_i}}{200\,K_i} \approx -\sum_{i=1,2,3} \frac{1}{200} \left( \frac{10^{-3}\ \mathrm{eV}}{\widetilde{m}_i} \right) \delta_{N_i}\,,$$

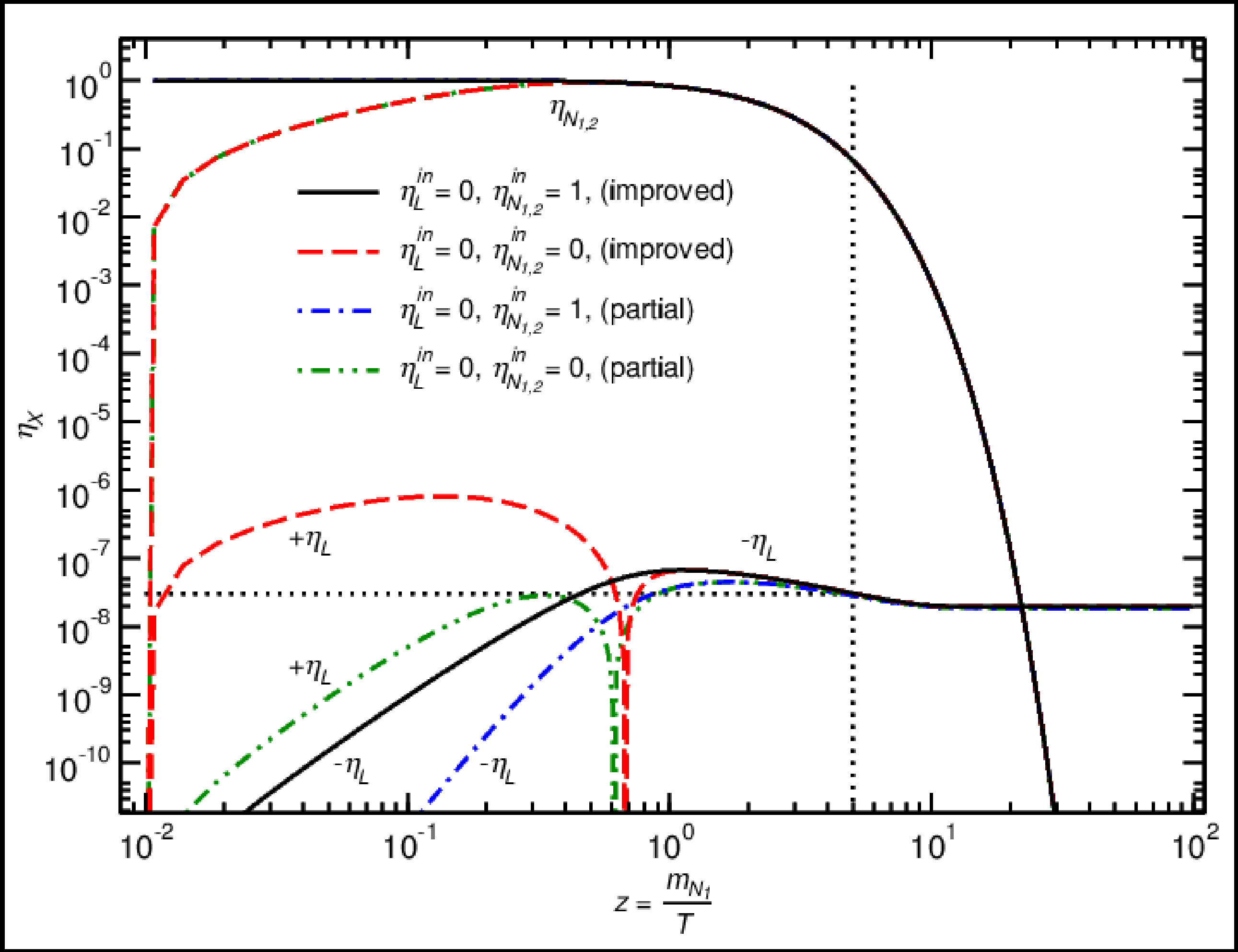
– where $\delta_{N_i}$ is the CP asymmetry in the decay of $N_i$.

[A. Pilaftsis, T.U. hep-ph/0309342]

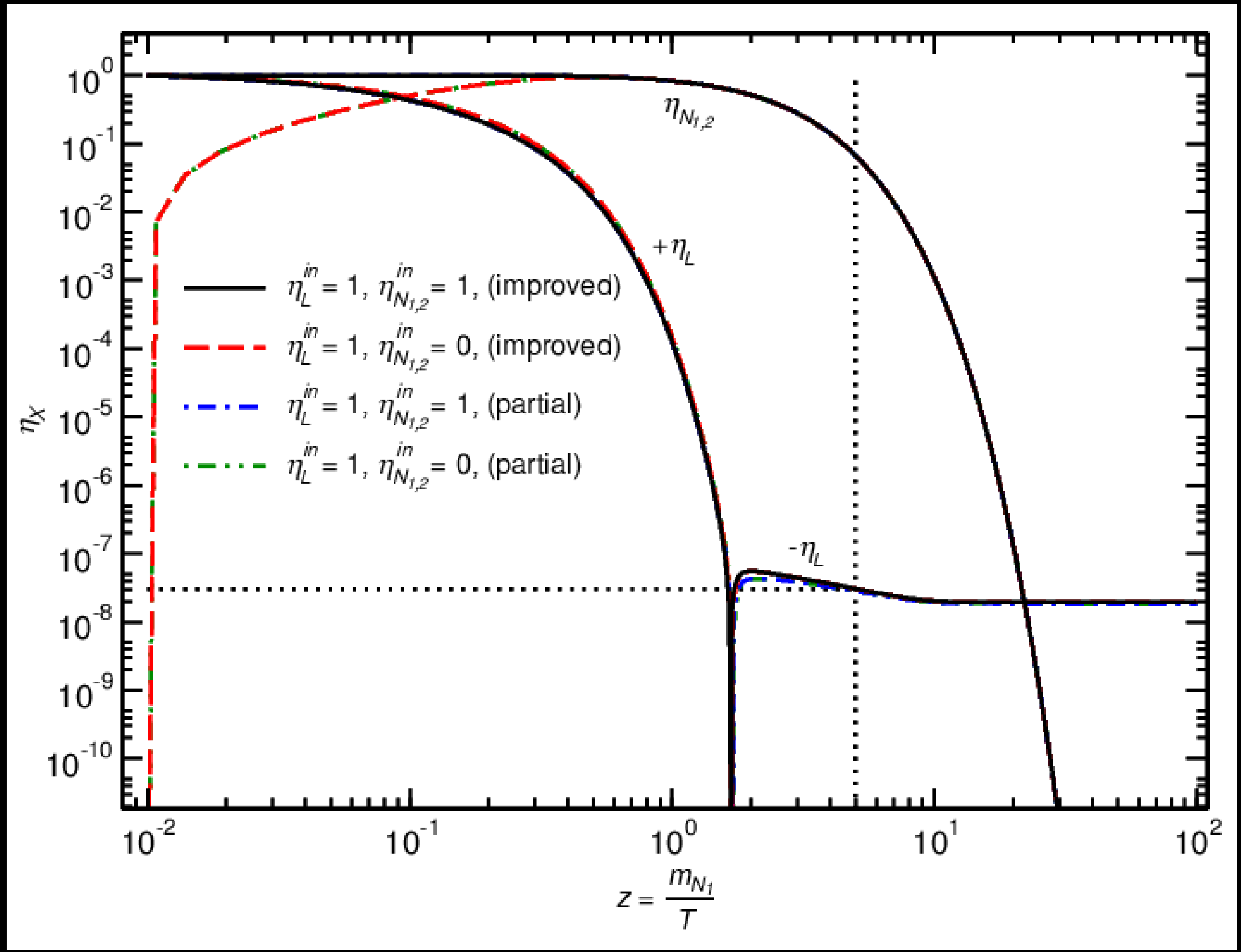
# Boltzmann equations

- **Reliable calculation of the baryon asymmetry requires the numerical solution of the Boltzmann equations.**
  - They track the abundance of a particle species as the universe evolves

- Recent improvements,
  - inclusion of gauge scattering terms
  - inclusion of CP violating scattering terms




$$m_{N_1} = 1\,\mathrm{TeV},\ x_N \equiv \frac{m_{N_2}}{m_{N_1}} - 1 = 7.7 \times 10^{-10}$$

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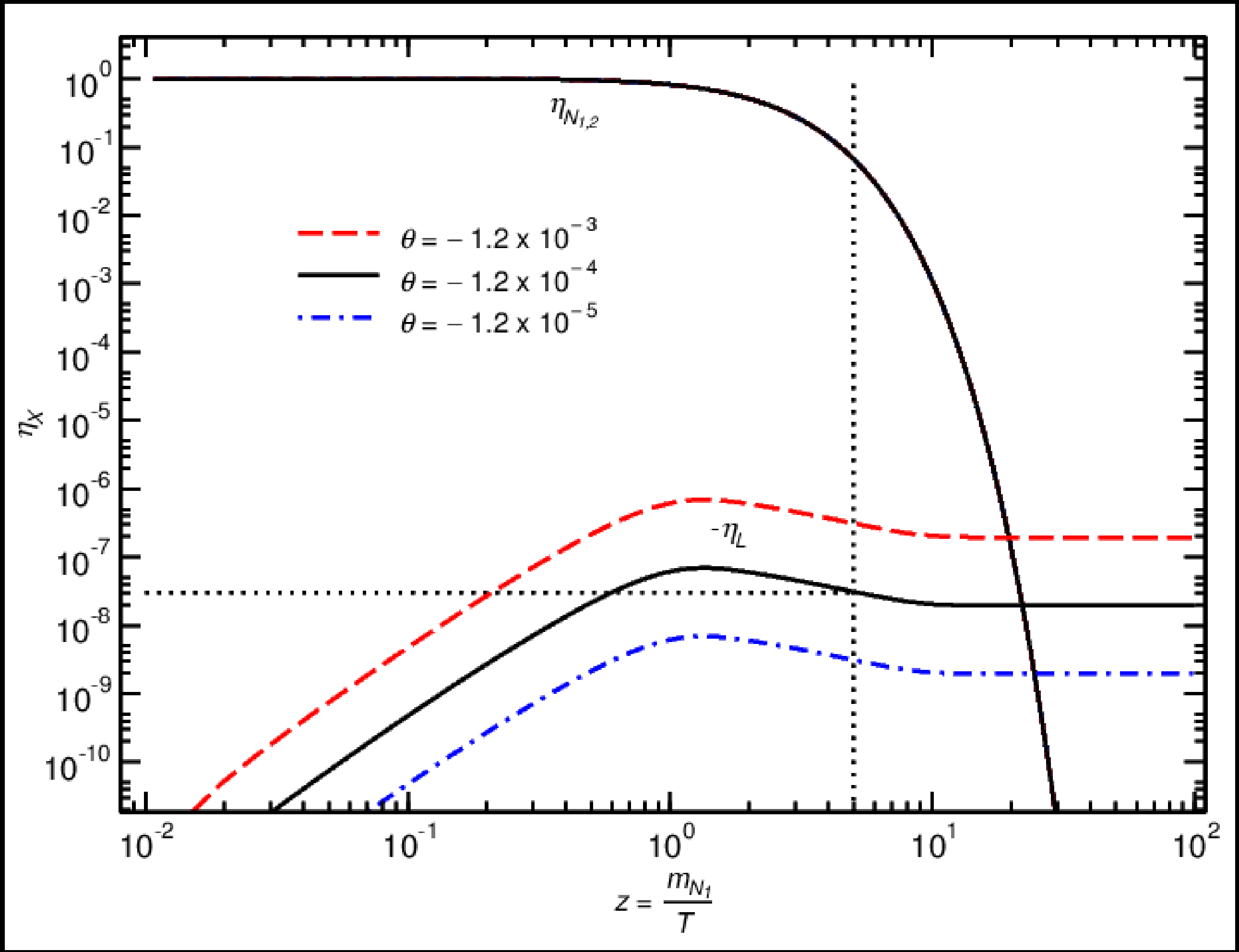
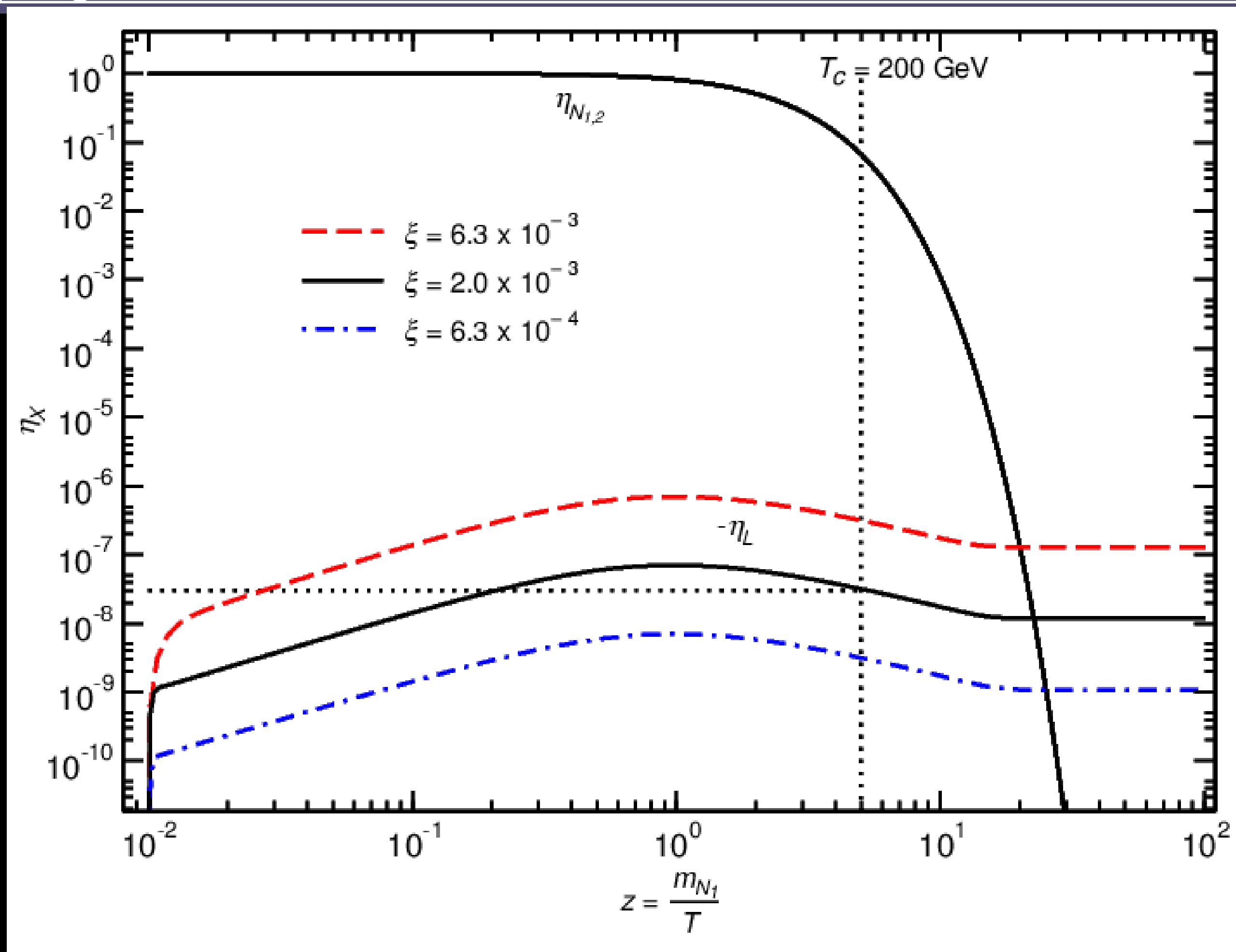


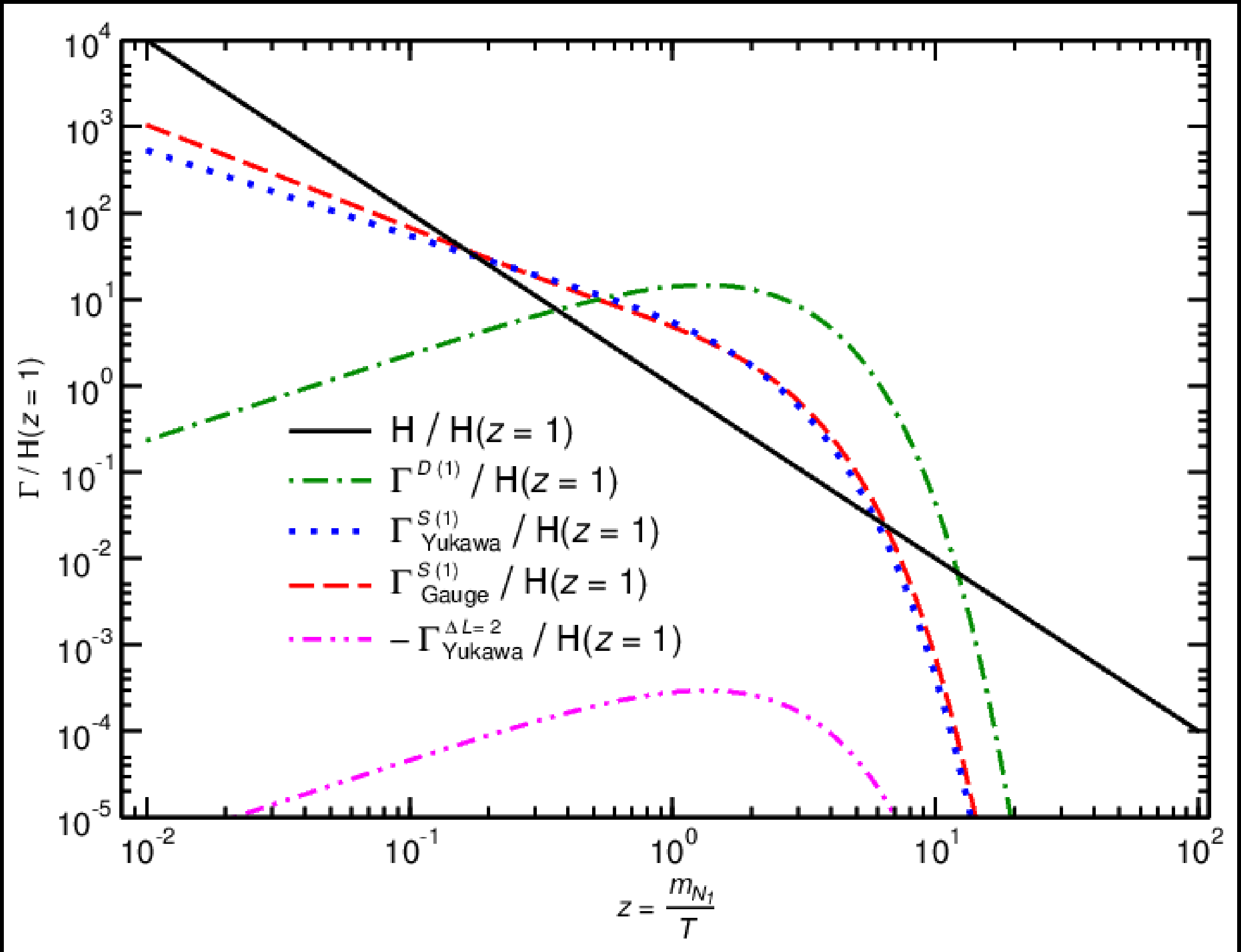

$$x_N = \varepsilon^2,\ \bar{\varepsilon} = e^{i\theta}\,\varepsilon,\ \varepsilon = 4.3 \times 10^{-7}$$

## Resonant Leptogenesis




$$\bar{\varepsilon} = i\xi\,\varepsilon,\ |\varepsilon\bar{\varepsilon}| = 1.9 \times 10^{-13},$$
$$\delta_{N_1} = \delta_{N_2} = -3 \times 10^{-4},\ K_1 = K_2 = 6570$$

# Resonant Leptogenesis



# What's this good for ?

- Low (**1 TeV**) scale leptogenesis
  - **'Heavy' Majorana neutrinos of 1 TeV can provide successful leptogenesis, and be completely consistent with all neutrino data.**

- No dependence on initial conditions – **the final baryon asymmetry is only dependent on the mechanism**

# Conclusions

- **Leptogenesis is an attractive mechanism for explaining the baryon asymmetry of the universe.**

- **In resonant leptogenesis an enhancement of the CP asymmetry allows the scale to be lowered to TeV energies.**

- **Using improved Boltzmann equations, we have showed this is possible with 'real' models, in complete agreement with current neutrino data**

[A. Pilaftsis, T.U. hep-ph/0309342]