Leptogenesis

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The Baryon Asymmetry

- Observation

From BBN and CMB!

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

- Sakharov's conditions: SM
  - **B** violation ✔
  - CP violation ✔
  - Departure from thermal equilibrium ✘ In SM: Requires $m_h \lesssim (40 - 80)\ \mathrm{GeV}$

(Strong electroweak phase transition possible
in SM extensions → Stephan Huber's talk thursday)

Leptogenesis

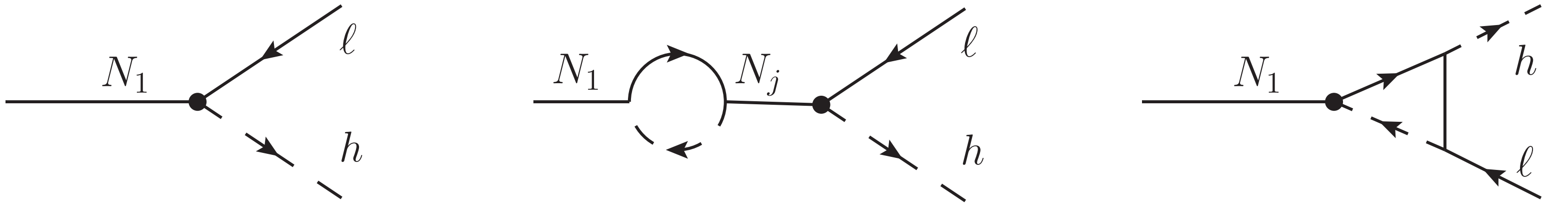
Fukugita, Yanagida, 1986.
Reviews:
Davidson, Nardi, Nir, 2008;
Blanchet, di Bari, 2012.

- Extend SM with right-handed neutrinos:

$$\mathcal{L} \supset -\tfrac{1}{2} M_i \bar{N}_i^c N_i - Y_{i\alpha} \bar{N}_i H \ell_\alpha + \text{h.c.}$$

- Explicit **L** (and **B-L**) violation

- CPV from phases in Y



$$\epsilon = \frac{\Gamma(N_1 \to H\ell) - \Gamma(N_1 \to H^\dagger \bar{\ell})}{\Gamma(N_1 \to H\ell) + \Gamma(N_1 \to H^\dagger \bar{\ell})} \propto \frac{\Im m[(YY^\dagger)^2_{1j}]}{(YY^\dagger)_{11}} \frac{M_1}{M_j}$$

Leptogenesis II

- Departure from thermal equilibrium

$$T > M_1 : \quad Y_{N_1}^{\rm eq} \sim 1 \qquad\qquad T \ll M_1 : \quad Y_{N_1}^{\rm eq} \sim e^{-M_1/T}$$

when $\Gamma(N_1 \to \ell H) \sim H(T = M_1)$

- Neutrino see-saw

$$m_\nu \sim \frac{Y^2 v^2}{M}$$

$$\frac{\Gamma}{H} \approx \frac{M_{\rm pl}}{137\pi}\,\frac{Y^2}{M_1} \overset{!}{=} 1 \qquad \Longleftrightarrow \qquad \boxed{m_\nu \sim \rm meV}$$

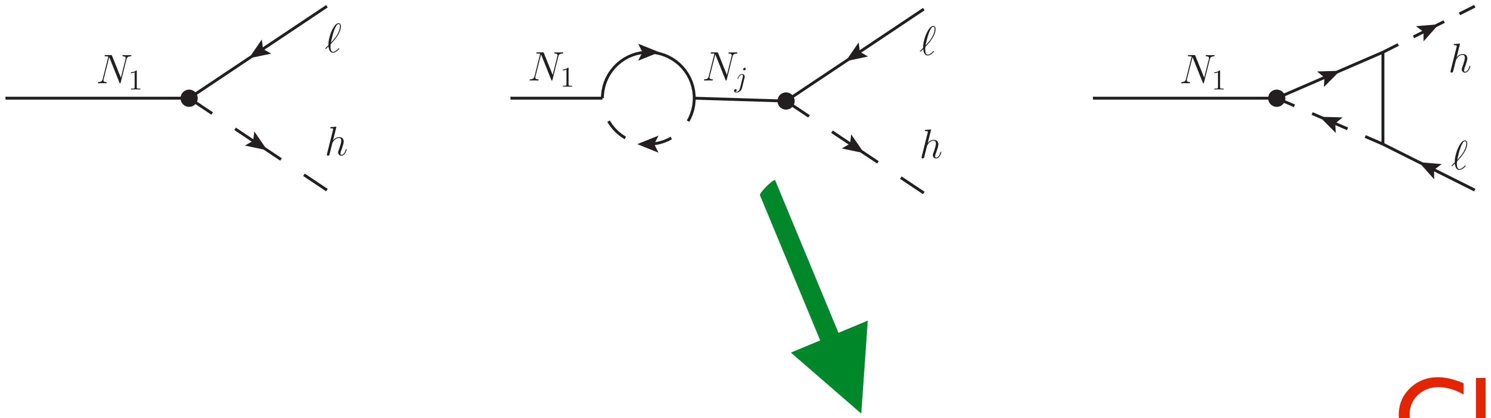
Neutrino mass conspiracy

Rest of this talk

- Theory progress
    - Nonequilibrium QFT
    - flavour effects
    - thermal rates
    - spectator effects
- Some thoughts about testability
    - Light neutrino CP phase, 0νββ
    - Neutrino flavour/mass models

Why NEQFT?

- Classical vs. Quantum Effects



Quantum Effect

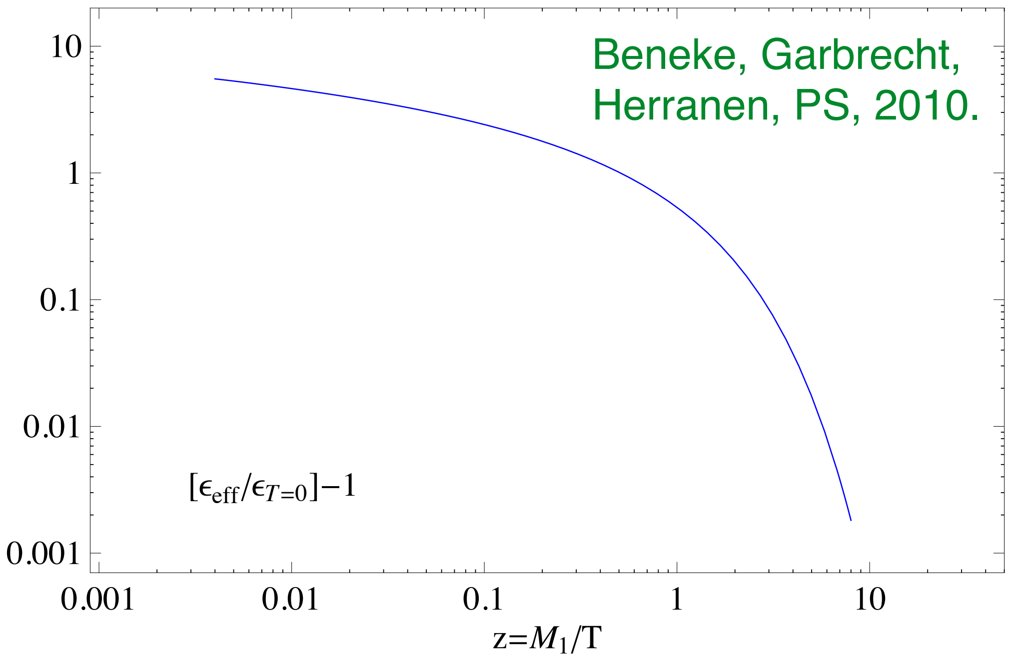
$$\partial_\eta f_{\ell-\bar{\ell}} = C_D[f_{\ell-\bar{\ell}}] + C_S[f_{\ell-\bar{\ell}}]$$

Classical Boltzmann Equation

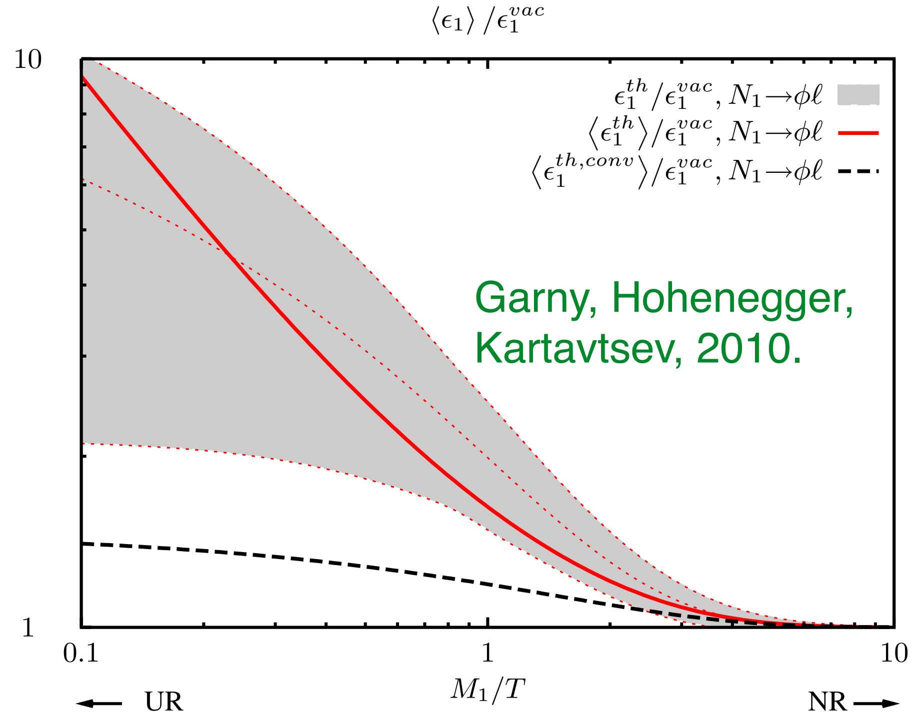
- Early universe not empty: hot thermal plasma
  - NEQFT allows more systematic study of thermal effects
  - More control over approximations

NEQFT applications

- Thermal corrections to CPV



Beneke, Garbrecht, Herranen, PS, 2010.



Garny, Hohenegger, Kartavtsev, 2010.

also Anisimov, Buchmuller, Drewes, Medizabal, 2010;
and earlier work by Riotto, de Simone, 2007; Giudice, Notari et al, 2004; Covi et al, 1997.

- Resonant LG Pilaftsis, Underwood, 2003.
  - Interplay of heavy and light flavours
  - Choice of regulator

Garbrecht, Herranen, 2011;
Garny, Hohenegger, Kartavtsev, 2011;
Iso, Shimada, Yamanaka, 2013, 2014;
Hohenegger, Kartavtsev, 2014;
Dev, Millington, Pilaftsis, Teresi, 2014;
Garbrecht, Gautier, Klaric, 2014;

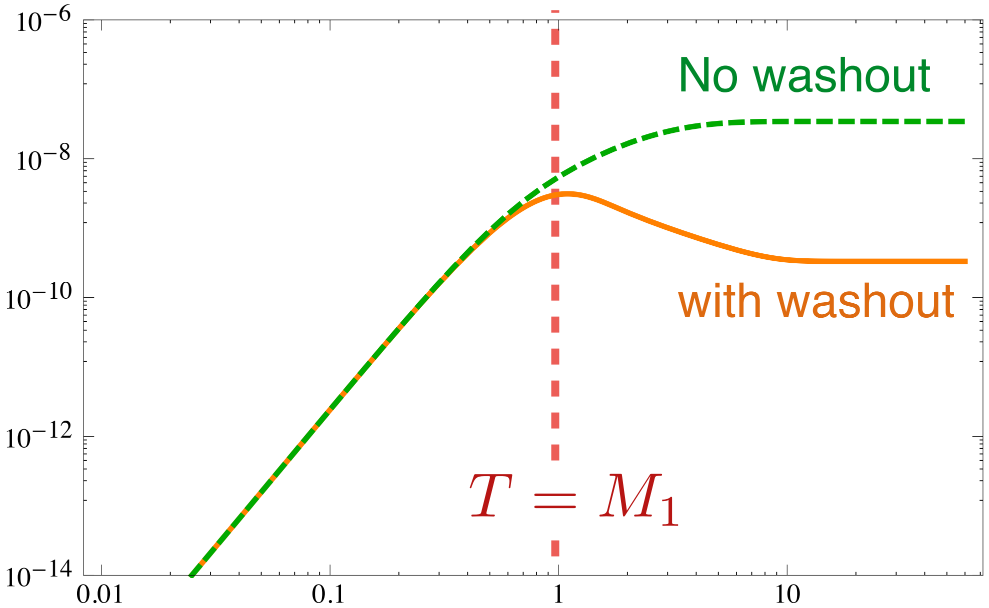
Flavour effects

Barbieri et al, 2000; Endoh et al, 2004;
Abada et al, 2006; Nardi et al, 2006;

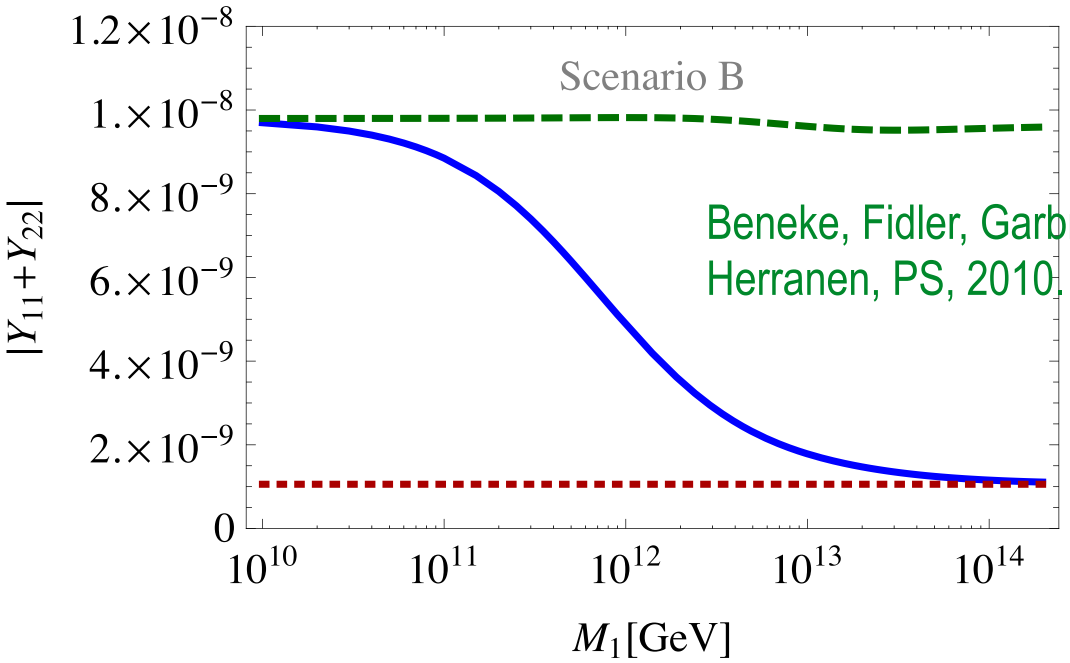
- Boltzmann equation

$$\frac{d}{dt}Y_\ell = S - W\left(Y_\ell + \tfrac{1}{2}Y_H\right)$$

washout is important!



- For $T \lesssim 10^{12}\ \mathrm{GeV}$: Tau Yukawa in equilibrium
  - Different washout for different flavours, increase final asymmetry
  - No oscillations!



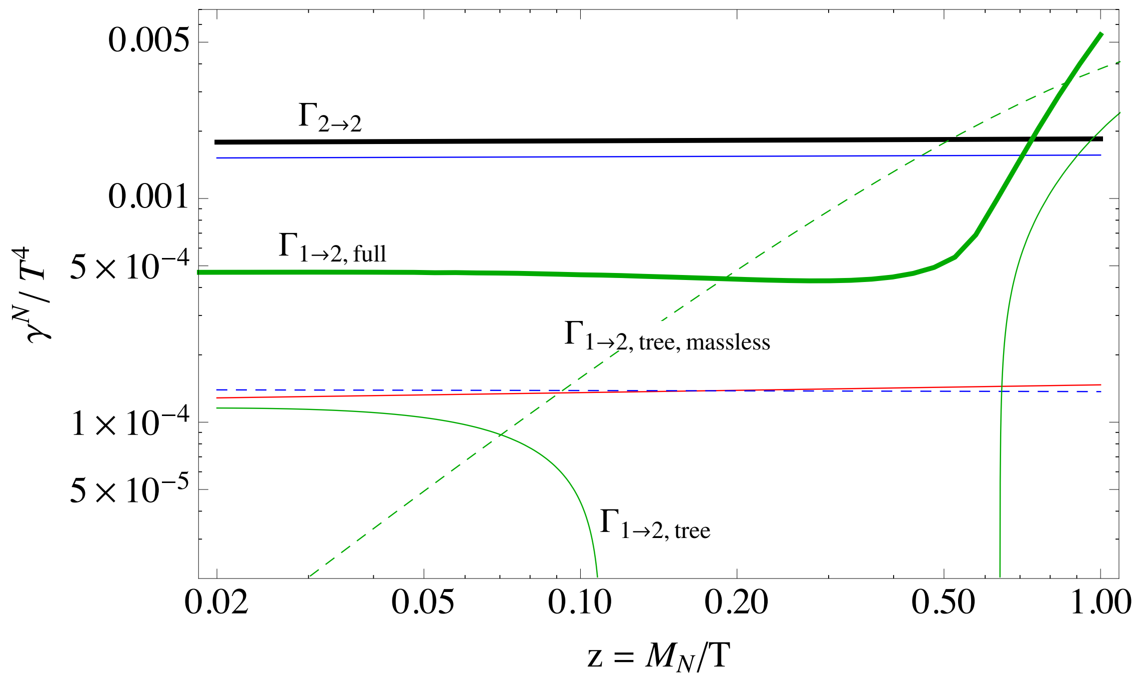
Beneke, Fidler, Garbrecht, Herranen, PS, 2010

Scattering rates

- N1 production rate

from Garbrecht, Glowna, PS, NPB 2013

see also:
Salvio, Lodone, Strumia, 2011;
Anisimov, Besak, Bodeker, 2010, 2012;
M. Laine, 2013;

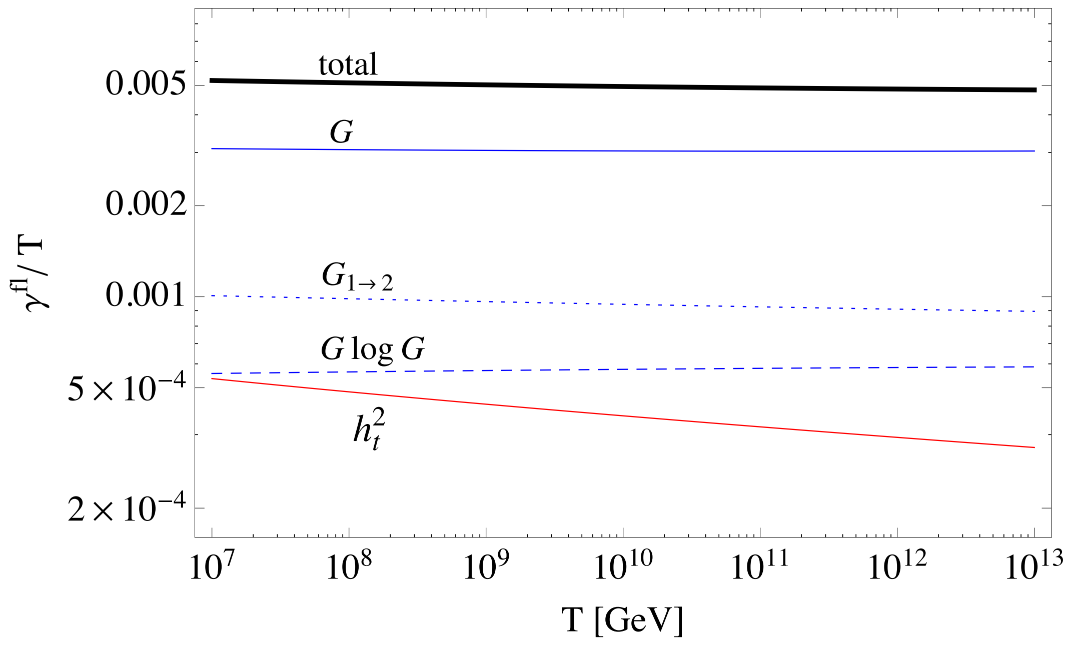


- Flavour equilibration rate

$$\Gamma^{\text{fl}}_\alpha \approx 5\times10^{-3}|h_\alpha|^2 T$$

compare with $(3-17)\times10^{-3}$ in literature

Garbrecht, Glowna, PS, NPB 2013.



Spectator effects

- Return to Boltzmann Equation

$$\frac{d}{dt}Y_\ell = S - W\left(Y_\ell + \tfrac{1}{2}Y_H\right)$$

- In principle $Y_H = Y_\ell$ from hyper-charge neutrality
  - Y_H also modified by (top) Yukawa interactions, Y_ℓ by electroweak spalerons: spectator effects
- Solution so far: $$\frac{d}{dt}Y_{B-L} = -S + W(c_\ell + c_H)Y_{B-L}$$
  - Find c_ℓ , c_H using chem. equilibrium relations, assuming that spectators are either fully equilibrated or inactive

Buchmuller, Plumacher, 2001
Nardi, Nir, Racker, Roulet, 2006

Partial tau Yukawa equilibration

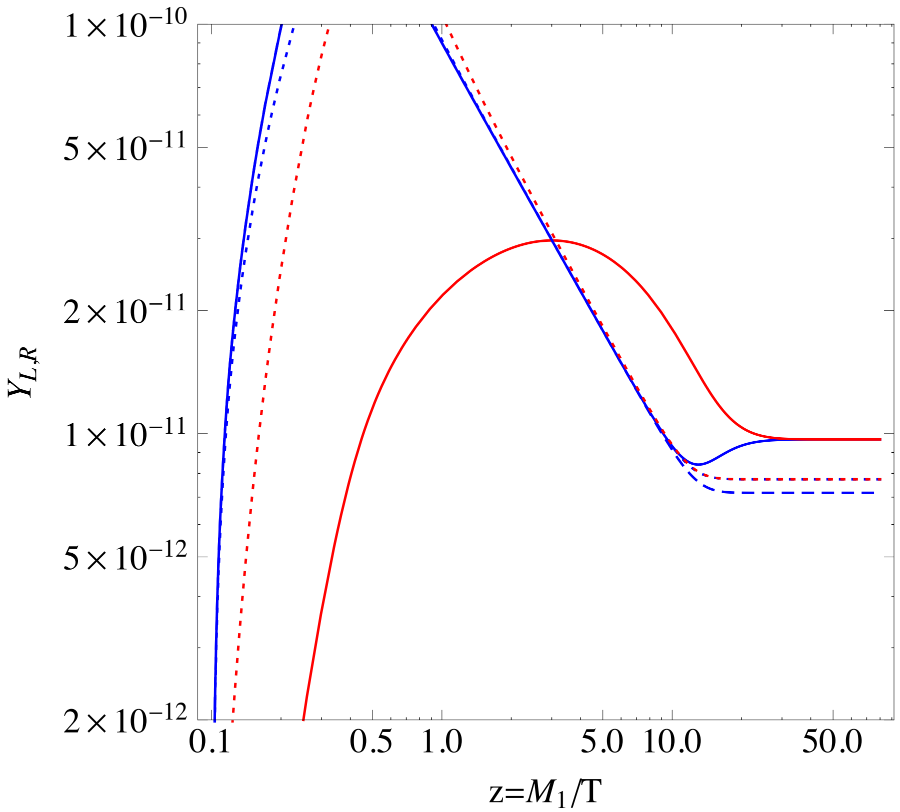
Garbrecht, PS, 1404.2915

- Evolution equations

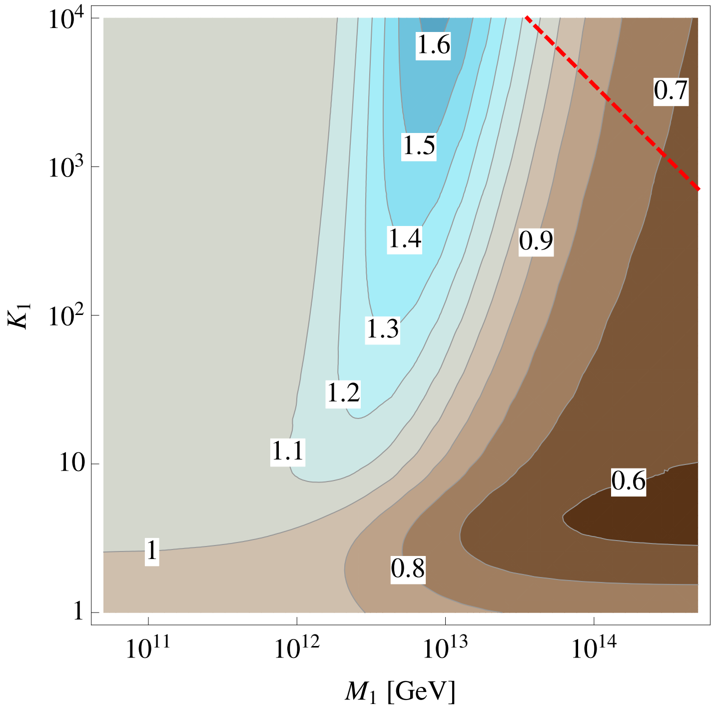
$$\frac{d}{dt}Y_\ell = S - WY_\ell - \gamma^{\rm fl} h_\tau^2 (Y_\ell - Y_R)$$

$$\frac{d}{dt}Y_R = -\gamma^{\rm fl} h_\tau^2 (Y_R - Y_\ell)$$

- Asymmetry hidden in Y_R



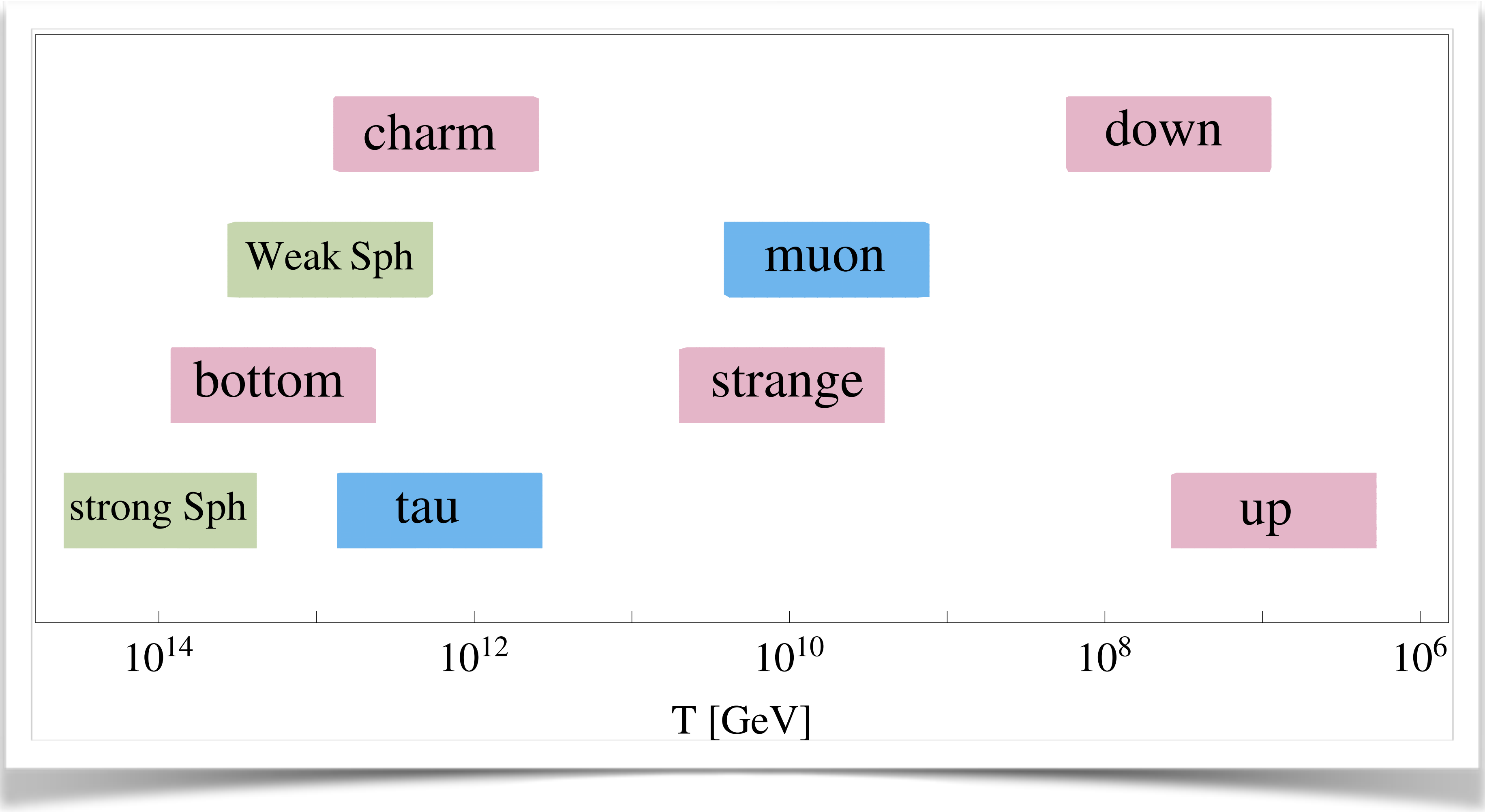
$K_1 = \frac{\Gamma_{N1}}{H}$



- Up to 60% enhancement compared to old approach
- $\Gamma_\tau^{\rm fl}/H = 1$ at $T_\tau \approx 3.7\times10^{11}$ GeV

(Just for illustration! Other spectators, and flavour effects neglected)

Temperature ranges



- There is (almost) always a spectator!
- Can induce new dependence on initial conditions!

Many free parameters

High scale physics

What can we probe?

Neutrino CP phase

- Casas-Ibarra: $Y = \frac{1}{v} D_{\sqrt{M}} R D_{\sqrt{m}} U^{\dagger}_{\mathrm{PMNS}}$
- CP asymmetry:

$$\epsilon_1 \simeq -\frac{3}{8\pi}\frac{M_1}{\langle H_u^0\rangle^2}\frac{\sum_j m_j^2\,\mathrm{Im}(R_{1j}^2)}{\sum_j m_j |R_{1j}|^2}$$

independent of U_{PMNS}

  - Also lower bound on $M_1 \gtrsim 10^9\ \mathrm{GeV}$

Davidson, Ibarra, 2002.

- Not true if flavour effects are included!
- However: vanilla LG can work for any value of the low energy neutrino parameters

Davidson, Garayoa, Palorini, Rius, 2007.

  - Need additional constraints from model building!

Testability?

- Things that could have disfavoured Leptogenesis
  - No Higgs boson/composite Higgs
  - Breakdown of vacuum stability
  - Discovery of BSM consistent with weak scale BG
- 0νββ could prove Majorana nature
- Mixing patterns that point to unique UV model (unlikely!)
- Alternative: GeV-scale Leptogenesis
  - Possible but requires tuning!

see e.g.
Asaka, Shaposhnikov, 2005;
Shuve, Yavin, 2014;
Canetti, Drewes, Garbrecht, 2014;

Conclusions

- Leptogenesis can explain baryon asymmetry of the universe over wide range of parameters, consistent with observed small neutrino masses

- Lots of progress in theoretical description - some work still to do, sizeable effects can still appear in some parameter regions, but predictions are getting more solid!

- Maybe best candidate theory to explain baryon asymmetry. Possible connection with neutrino CP phase, neutrinoless double beta decay, but a full test seems very difficult