Resonant leptogenesis

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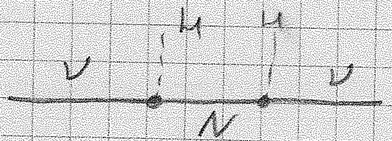
Outline

1. Killing two birds with a stone
2. Experimental tests
3. Thermal resonant leptogenesis
4. Leptogenesis via oscillations
5. A first principles approach
6. Summary

Resonant leptogenesis (MITP talk, 31.07.14)

1. Majorana neutrino – two problems solved at once.

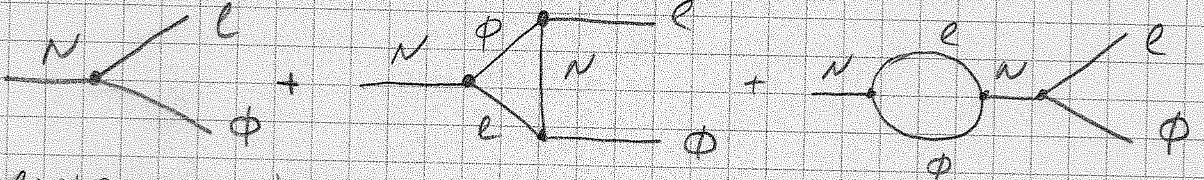
a. Neutrino masses



$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = -\, m_D M_N^{-1} m_D^T$$
$$\hookrightarrow \sim v^2 Y^2 / M_N$$

b. Leptogenesis



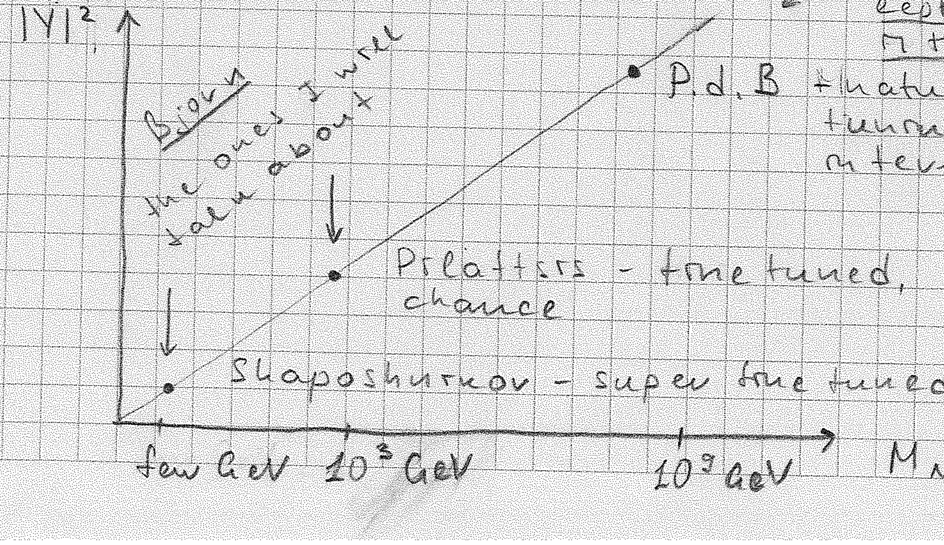
lepton number violation

CP – violation

\+ sphalerons + expansion of the Universe

c. Talks of the others

- see - saw and leptogenesis work in the whole range



Bjorn

the ones I will talk about

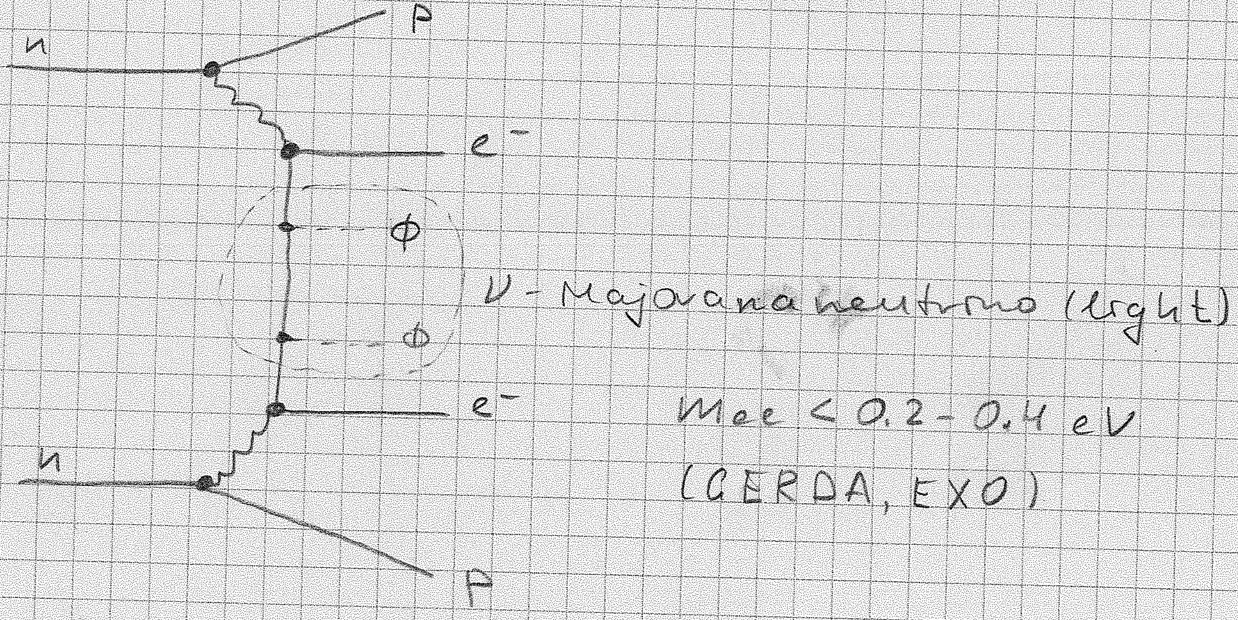
P.d.B – natural, no fine tuning, not testible in terrestrial

Pilaftsis – fine tuned, chance

Shaposhnikov – super fine tuned, explains also dark matter, chance to see in a dedicated experiment.

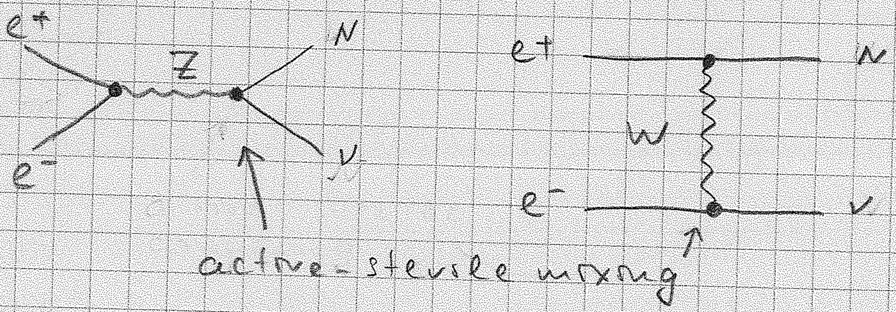
2. Experimental tests beyond neutrino masses and leptogenesis

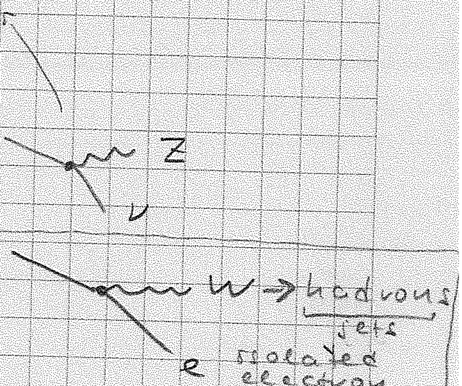
a. Neutrinoless double-beta decay



$m_{ee} < 0.2 - 0.4$ eV
(GERDA, EXO)

b. Majorana neutrinos at LEP



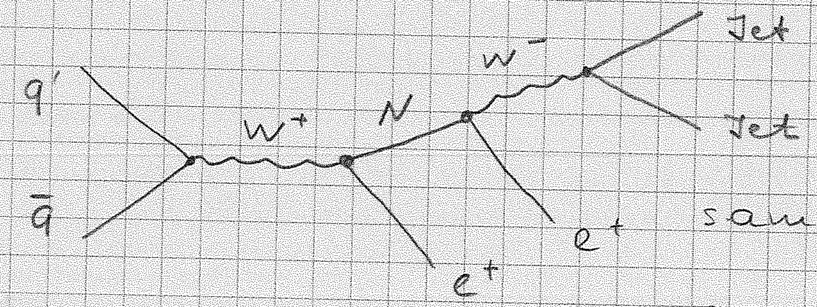


$\boxed{\text{SLIDE 3 (constraints)}}$

$M_N \lesssim 200$ GeV

b. Majorana neutrinos at the LHC

SLIDE 4 (constraints)



same-sign dilepton

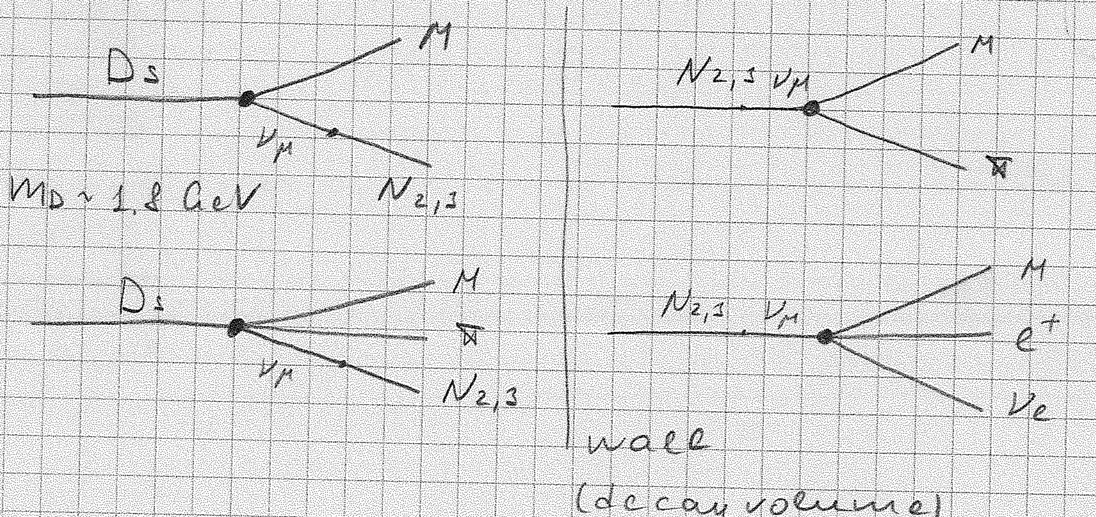
? why electrons, not muons

- Example:

$|U_{eN}|^2 \simeq 5.2\times10^{-3} \to M \lesssim 800$ GeV after $\sqrt{s} \sim 14$ TeV upgrade

↑ leptons are emitted back-to-back - clean signature and excellent background suppression.

c. Majorana neutrinos at SHiP



- Sensitive to $0.5\ \text{GeV} \leq m_N \leq 2\ \text{GeV}$, $10^{-6} \lesssim |U_{\mu N}|^2 \lesssim 10^{-10}$

SLIDE 5 (constraints)

3. Thermal resonant leptogenesis $|M \gtrsim T_{sph}$

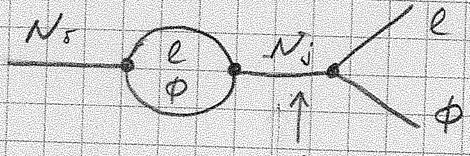
a. Motivation

Washout rate $\propto \frac{\Gamma}{H}$, $H \propto \frac{T^2}{M_{pl}}$ ← radiation dominated, • $M > T_{sph}$ - production of total asymmetry

↳ Majoranas are close to equilibrium at low temperatures, most of the asymmetry is washed out.

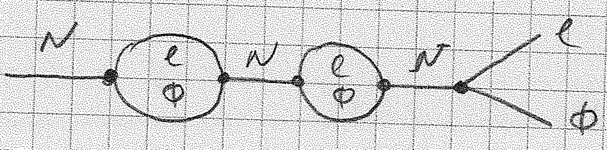
↳ compensate by more efficient production

↳ stronger CP-violation



$\epsilon_i \propto \frac{1}{M_i^2 - M_j^2}$ - resonant enhancement

b. Divergence and resummation



Schwinger - Dyson → generalization to CTP - Kadanoff-Baym equations.

$$\epsilon_i \propto \frac{M_i^2 - M_j^2}{(M_i^2 - M_j^2)^2 + A^2}$$

← $M_i\Gamma_j$ - Pilaftsis

$\frac{M_i\Gamma_i}{\omega_i} - \frac{M_j\Gamma_j}{\omega_j}$ - Anisimov et. al.

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no thermal corrections
double counting persists
these issues are resolved in KB formalism

c. Thermal masses and widths

- External lines acquire effective masses
- Should the masses in the expression for the CP-violating parameter be replaced by the thermal ones - answer this question a bit later.

4. Leptogenesis via oscillations

$M \ll T_{sph}$
total lepton number violation
$\propto M/T \to 0$

- Singlet neutrinos are produced through their Yukawa couplings. The production mechanism conserves CP, i.e. equal number of particles of opposite helicity is created.
- CP-violating oscillations and interactions create an asymmetry in the individual sterile neutrino flavors, their sum $=0$ (because $T \gg M$).
- Singlet neutrinos communicate their asymmetry to neutrinos and charged leptons through their Yukawa couplings.
- Assume that at least one of the steriles comes into equilibrium before sphaleron freezeout (its asymmetry is transferred to the baryon asymmetry) and at least one does not (its asymmetry is 'lost' for baryogenesis).

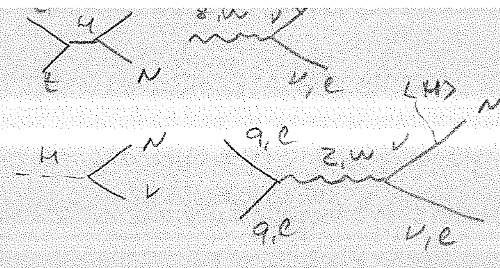
↙ Just like thermal leptogenesis does not have to be resonant!!!

$$i\frac{d\rho}{dt} = [M,\rho] - \frac{i}{2}\{\Gamma,\rho\} + \frac{i}{2}\{\Gamma^{p}, 1-\rho\}$$

↑ heuristic ↑ does not work for a hierarchical spectrum!!!

↑ Pilaftsis - problems with real intermediate states, have to be removed by hands.

↑ should be also used for TeV-scale resonant leptogenesis.



dilation
$\Gamma = \Gamma^0 \langle \frac{M}{E} \rangle_T$

- rates of $1 \leftrightarrow 2$ reactions $\propto M/T$ and suppressed.
- most important are $2 \leftrightarrow 2$ reactions

  $Q_L N_R \leftrightarrow t_R l_a$, $t_R^c N_R \leftrightarrow Q_L l_a$, $l_a N_R \leftrightarrow t_R Q_L$
- The resulting asymmetry is of the order of h^6 (suppressed as compared to thermal lep-s) ?

  ↙ application of the mechanism

b. Thermal history of the Universe in νMSM

$\boxed{\text{SLIDE 6}}$

- Two stages of leptogenesis: first responsible for the baryon asymmetry, second for dark matter.
- For the second $T \sim M$, close to thermal leptogenesis, thermal corrections still important
- For the first $T \gg M$, ARS mechanism, thermal correction's are crucial to achieve resonant enhancement of the asymmetry production.

  ↑ interesting application of all the techniques discussed here; will be partially tested experimentally soon.

  ↑ comparison of the BAU region and the experimentally accessible region.

5. KB approach - simplified setup

a. Solution without backreactions

- Consists of an equilibrium and out-of-equilibrium parts

$\boxed{\text{SLIDE 7}}$

- instantly bring the system out-of-equilibrium at $t=0$.
- The initial conditions are not very realistic, but allow to study quantitatively important effects.
- Encode thermal effects, oscillations, even the memory effects, off-shell effects!

b. Form of the regulator

- Comparing to the Boltzmann approximation

$$\epsilon \propto \frac{M_i M_j (M_i^2 - M_j^2)}{(M_{i_{eff}}^2 - M_{j_{eff}}^2)^2 + (M_{i_{eff}}\Gamma_{i_{eff}} - M_{j_{eff}}\Gamma_{j_{eff}})^2} \times \int (1 + f_\phi - f_e)$$

- Heuristically found $M \to M_{th}$ in the denominator whereas the masses in the numerator are the thermally adjusted masses in the Kadanoff-Baym equations
- We recently performed a more self-consistent analysis and demonstrated analytically that masses in the numerator are mass parameters of the Lagrangian, whereas in the denominator we have the thermal masses.
- This is consistent with fundamental symmetries → CP violating parameter must vanish if the underlying Lagrangian is CP-symmetric.
- Practical recipy for taking thermal effects into account for not too close to resonance situations.

Additionally multiply by $1 + f_\phi - f_e$ to take into account the overall enhancement.

c. Contribution of the off-diagonals

- The off-diagonals give negative contribution to the final asymmetry and effectively reduce CP-violating parameter.

- Stress, that in the regime where the oscillations are important, the notion of a CP-violating parameter to be used in the Boltzmann equation is not very meaningful; Boltzmann can't take oscillations into account.

$\boxed{\text{SLIDE 8}}$

d. Technical problems with going to higher T

- For $T \gg M$ the self-energies acquire a large component proportional to α.

- The propagators acquire a large tensor component, which makes the calculation rather involved.

- Why should that be interesting - corrections to the effective masses are of the order of the decay widths. In the resonant region the mass-difference is also of the order of the width → $\Delta M_{therm} \sim \Delta M_{vac}$. Does that have any implications?

$$M_1 \simeq M(0) + \Gamma\, c(T/M)^2, \quad \Delta M \simeq \Delta M(0) + (\Gamma_2 - \Gamma_1)\, c\, (T/\bar{M})^2$$

6. Toy-model - KB approach

a. Lagrangian $\boxed{\text{SLIDE 9}}$

b. Effective masses

- explicitly take into account and study effects related to medium induced corrections to the masses.

- Masses are defined as zeroes of det of inverse retarded or advanced propagator.
- Effective masses can run away - mass difference increases with T SLIDE 10
- Effective masses can cross - mass difference initially decreases, reaches zero and then begin increasing again. SLIDE 11

c. Crossing or avoided crossing. In neutrino physics spectrum follows from Hamiltonian, which is a hermitean matrix. Σ^R is not hermitean - masses can cross.

The result for physical observables does not depend on definition. It is just convenient to use definitions that allow to write the results in a particularly simple way.

7. Leptogenesis discussion slide

- Conceptual issues have been resolved. We are in "precision leptogenesis era"
- Should pay attention not only to the production and washout rates, but also to the quality of the used approximation for the kinetic equations.

8. Boltzmann approximation

a. Initial conditions SLIDE 12

- Translate KB solution to Boltzmann solution by integrating interpreting Wigner-transform of the former as KB ansatz

- The "spectral function" oscillates and only effectively, in the integral sense reproduces smooth result in the late-time limit → ambiguity in the comparison of the two approaches

b. Spurious peak SLIDE 13

- Get a strong enhancement around $R \approx 1$ because effective masses in the denominator vanish

9. Density matrix approximation.

a. Initial conditions. SLIDE 14

- The same problem. The Wigner-trafo can be interpreted as density matrix only if one really wants it.

b. Numerical result SLIDE 15

- No spurious peak, smoth everywhere.

10. Comparison with KB

compare only the source term.

SLIDE 16

- Boltzmann approximation is good at large R (hierarchical spectrum)
- Density matrix is good at very small R, including $R = 1$ (resonant regime)
- In between both deviate from the "exact" result - some room for improvement
- Keep in mind that we simply compare KB solution, with two translated KB solutions!

- Work on the independent solution of the density matrix and Boltzmann is underway

- Preliminary, the usual density matrix equations are pretty good, especially if the additional $[\Pi_h, \rho]$ term is taken into account.

10. Additional off-shell effects.

SLIDE 17, 18

- KB results that I have presented rely on approximate integration in the vicinity of the mass shell (Breit-Wigner approximation used in the existing works)

- With scalars we can integrate numerically over the whole region of p^0 and quantify the quality of Breit-Wigner approximation.

- Example for $T=1$. The difference is below 5% in the whole range of R → good news for the approximation schemes. SLIDE 19

11. Summary

SLIDE 20

- See-saw I can be experimentally tested only for $M_N \sim 1$ TeV and $M_N \sim 1$ GeV masses.

- For this masses leptogenesis proceeds in very different ways, but with two neutrinos we need maximal resonance to reproduce the observed baryon asymmetry of the Universe

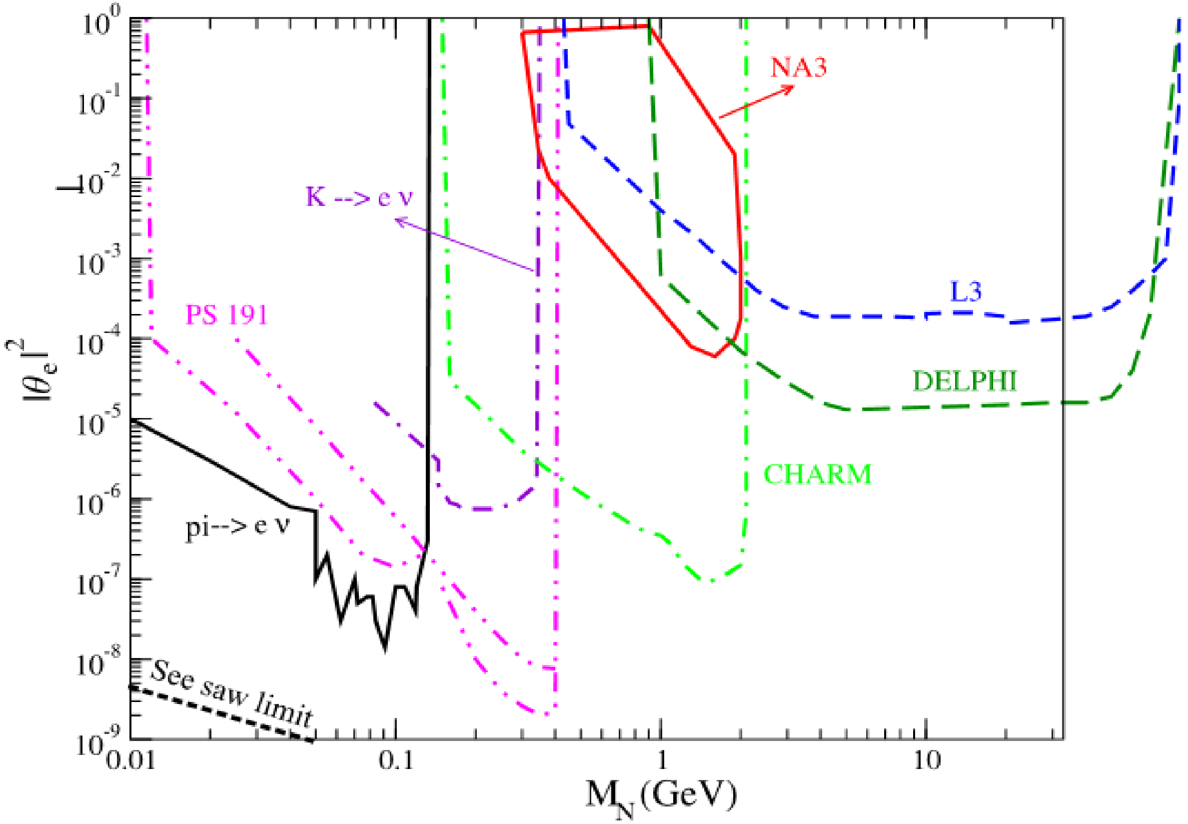
- Boltzmann is a questionable appr-n. If you want to use it beware that you only get an order of magnitude estimate anyway. Can in principle neglect thermal corrections

- Density matrix is a much better approximation.

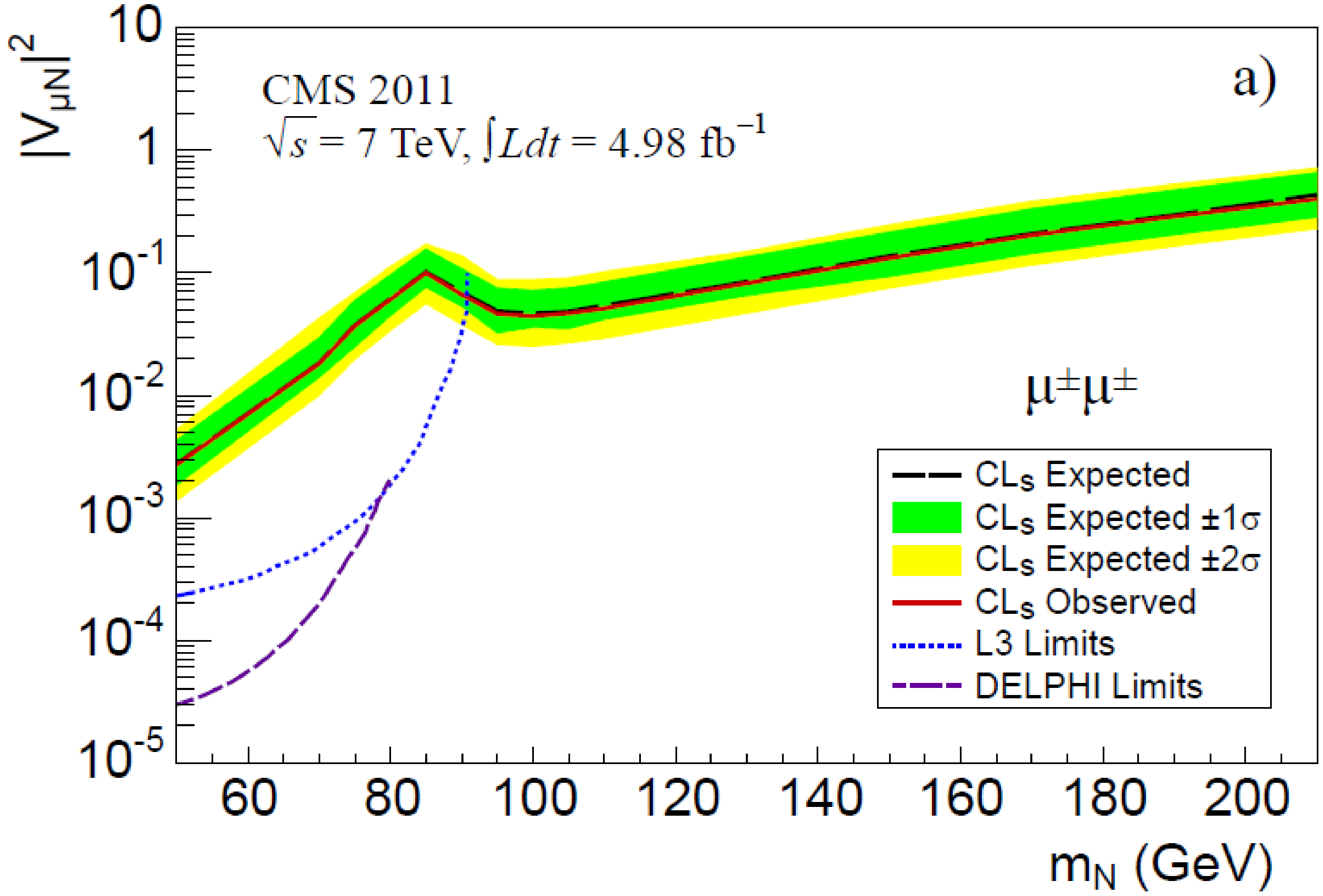
Taking thermal effects is important to get quantitative results.

- Next thing to do is of course a careful evaluation of the production and washout rates including gauge corrections

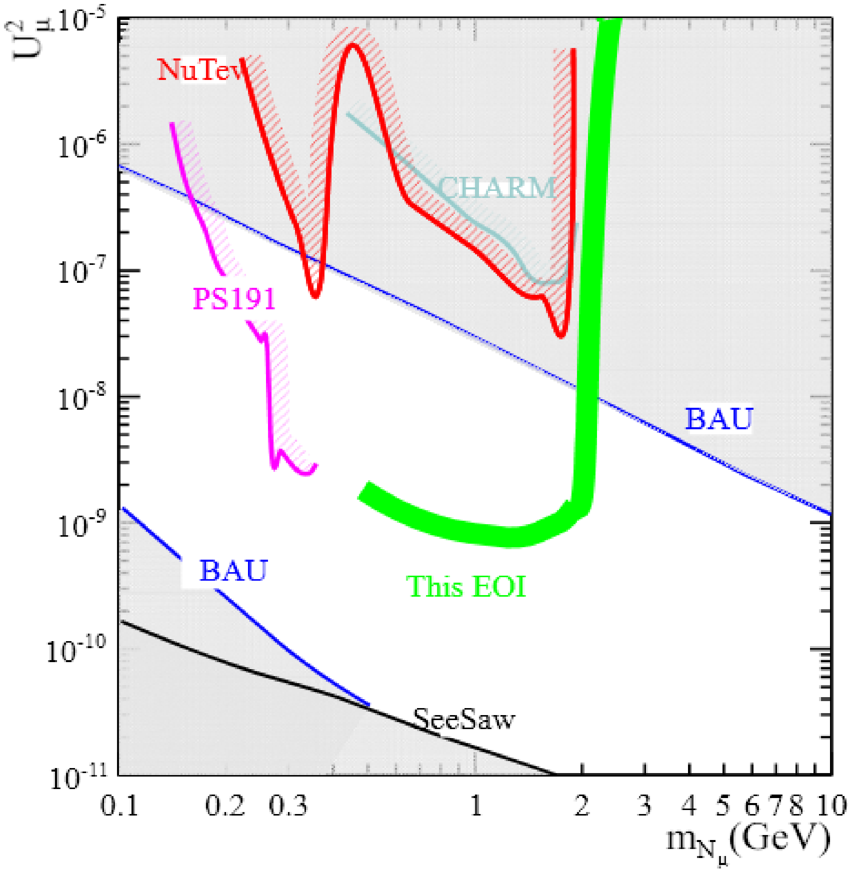
Bounds on sterile neutrinos



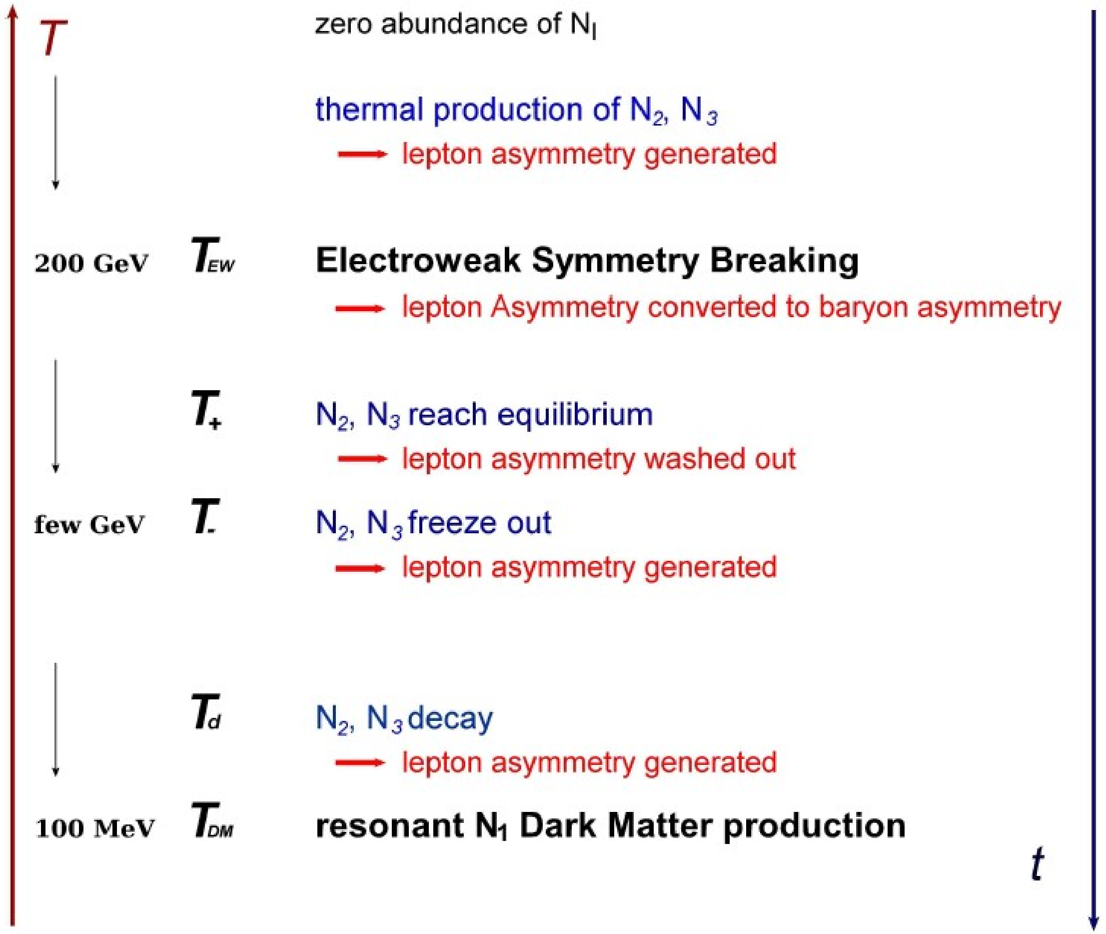
CMS constraints



Expected sensitivity



Thermal history in the vMSM



T

zero abundance of N_I

thermal production of N_2, N_3

→ lepton asymmetry generated

200 GeV T_{EW} **Electroweak Symmetry Breaking**

→ lepton Asymmetry converted to baryon asymmetry

T_+ N_2, N_3 reach equilibrium

→ lepton asymmetry washed out

few GeV T_- N_2, N_3 freeze out

→ lepton asymmetry generated

T_d N_2, N_3 decay

→ lepton asymmetry generated

100 MeV T_{DM} **resonant N_1 Dark Matter production**

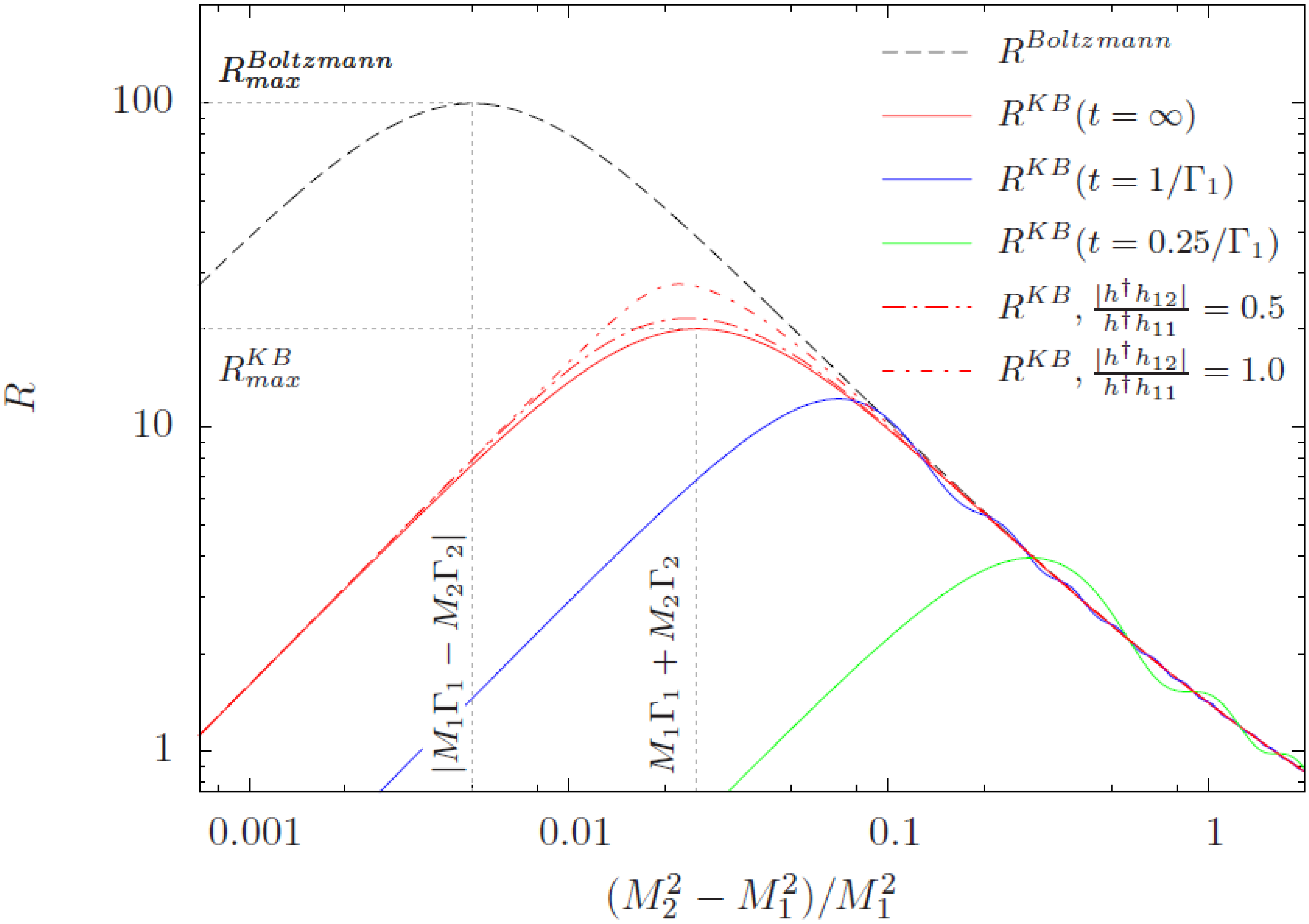
t

From
1208.4607

Test solution of KB equations

$$\begin{aligned} S^{ij}_{F\,\mathbf{p}}(t,t') &= S^{ij\,th}_{F\,\mathbf{p}}(t-t') \\ &\quad - S^{ik}_{R\,\mathbf{p}}(t)i\gamma_0\Delta S^{kl}_{F\,\mathbf{p}}(0,0)i\gamma_0 S^{lj}_{A\,\mathbf{p}}(-t') \end{aligned}$$

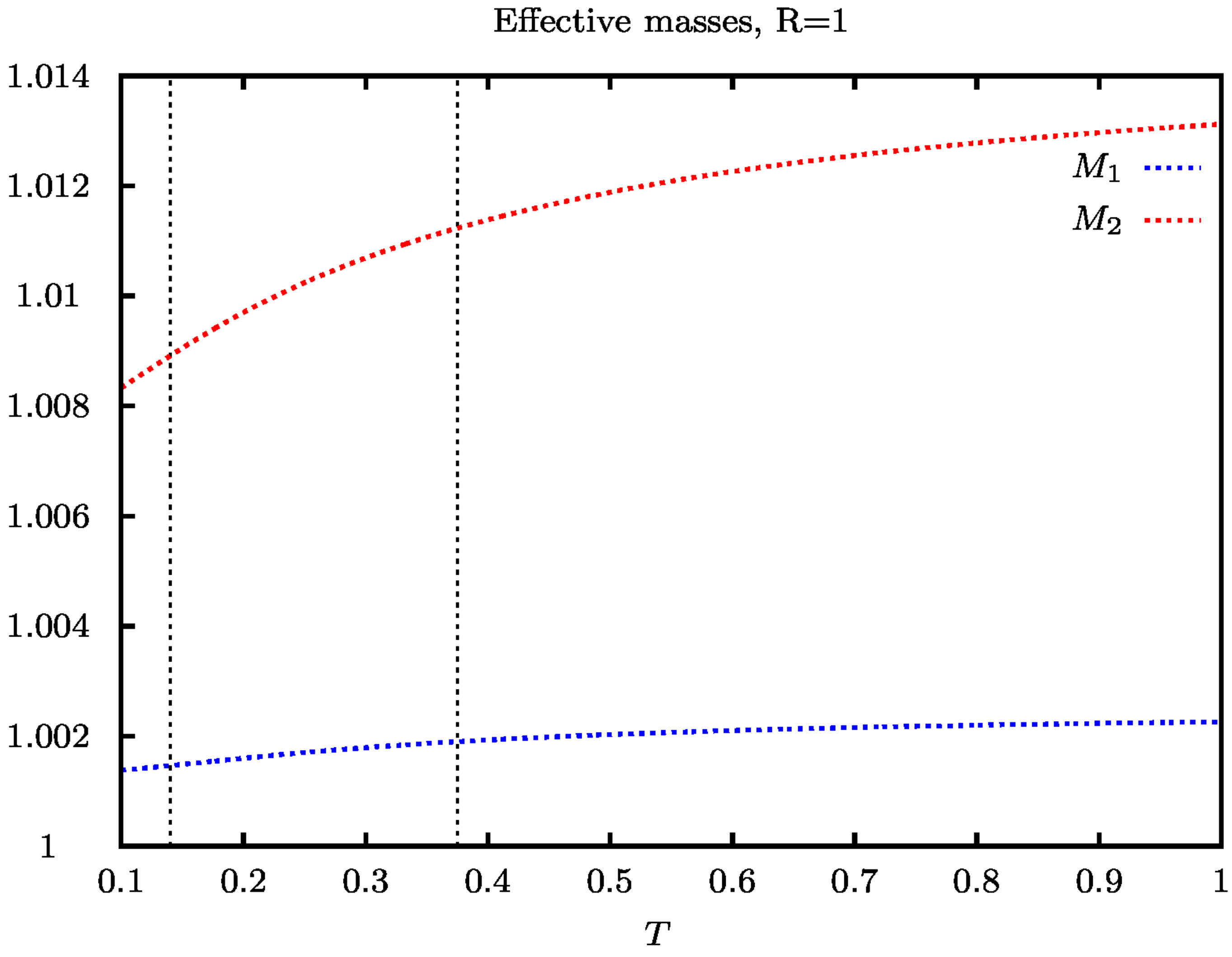
Contribution of oscillations



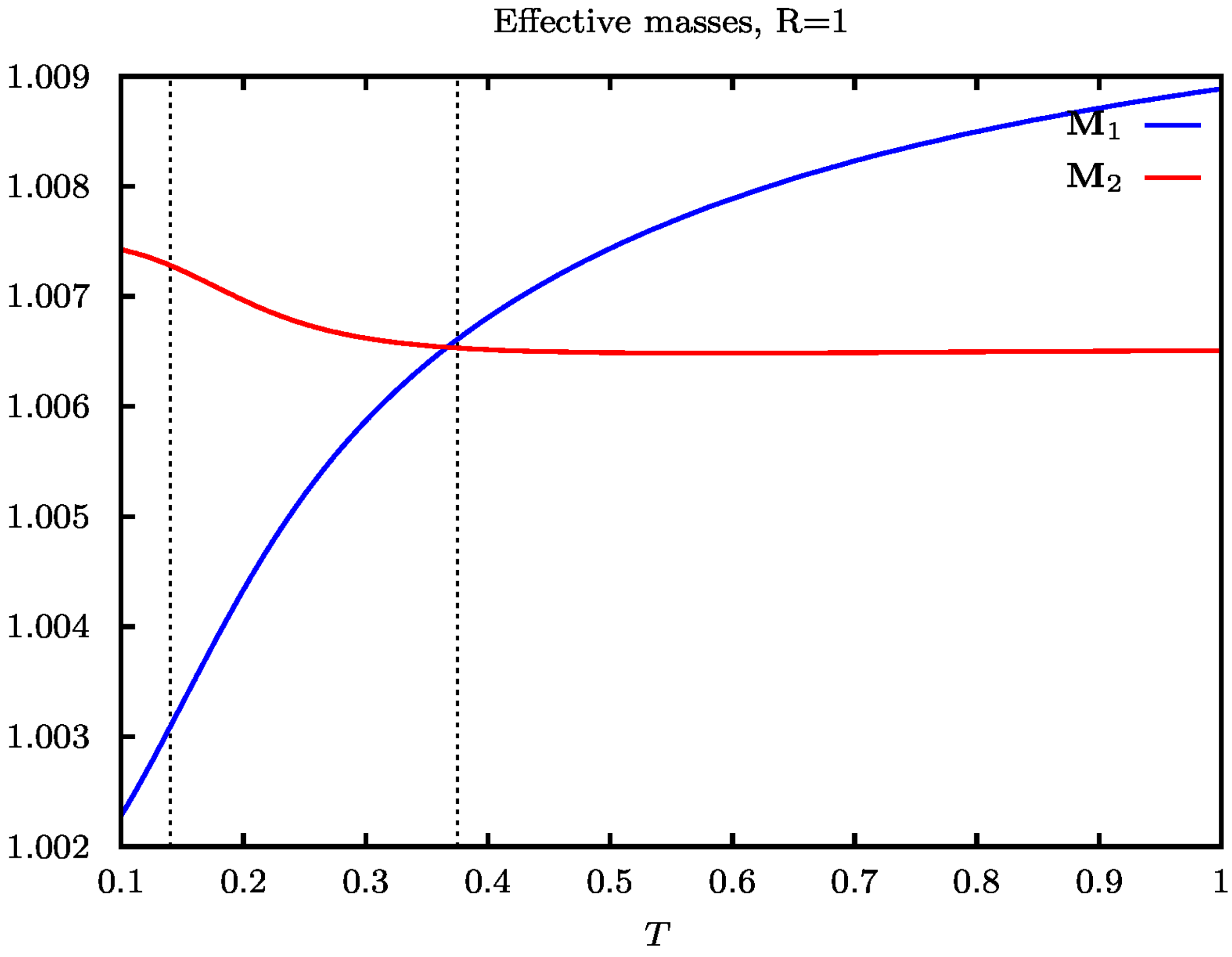
Toy model

$$
\begin{aligned}
\mathcal{L} = & \frac{1}{2}\partial^\mu\psi_i\partial_\mu\psi_i - \frac{1}{2}\psi_i M^2_{ij}\psi_j \\
& + \partial^\mu\bar{b}\partial_\mu b - m^2\,\bar{b}b \\
& - \frac{\lambda}{2!2!}(\bar{b}b)^2 - \frac{h_i}{2!}\psi_i bb - \frac{h_i^*}{2!}\psi_i\bar{b}\bar{b}
\end{aligned}
$$

Effective masses (runaway)



Effective masses (crossing)

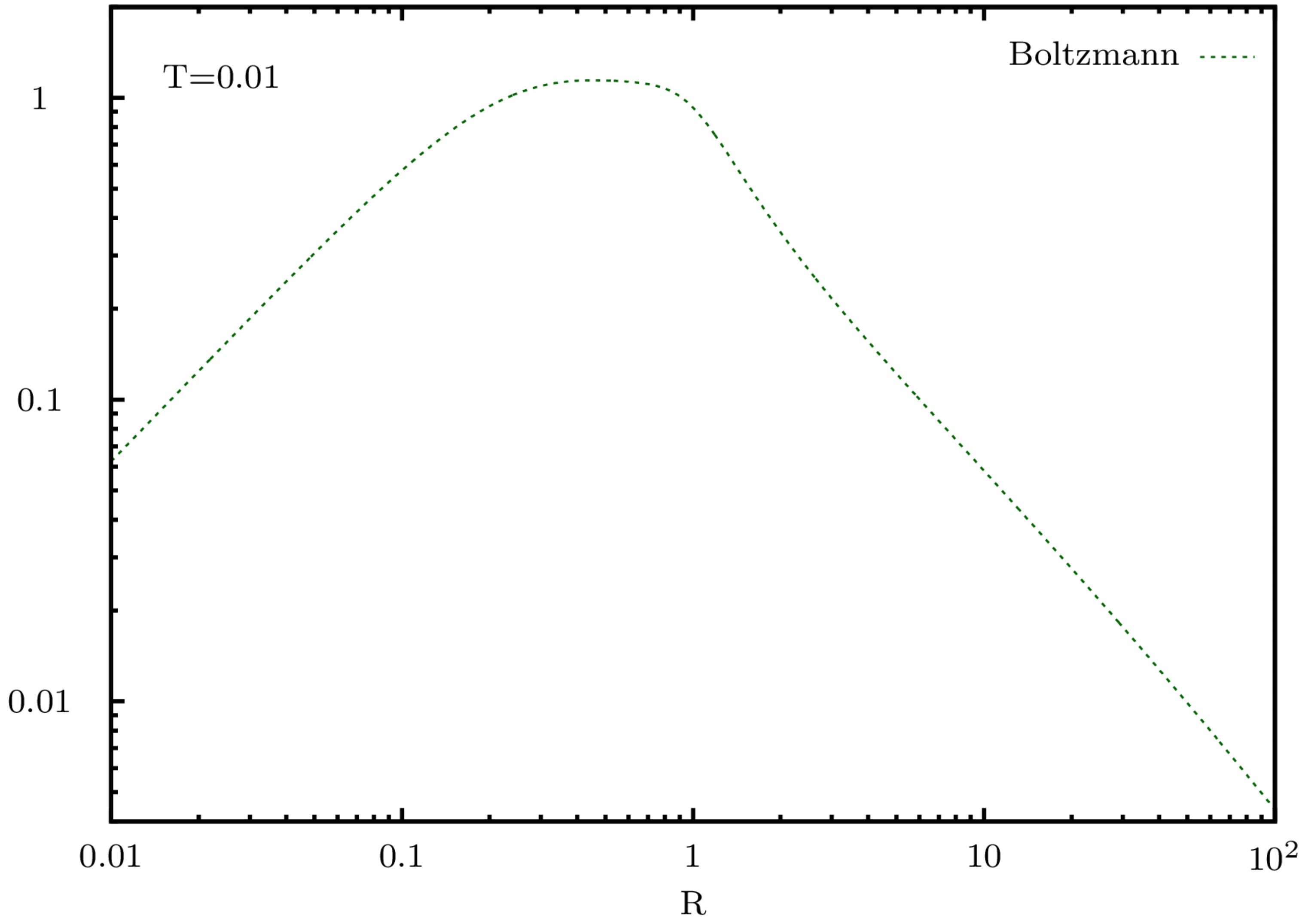


“Translation” to Boltzmann

$$\Delta G_F^{ii}(\tau, q_0, \vec{q}) \approx \frac{\sin[2(q_0 - \omega_i)\tau]}{q_0(q_0 - \omega_i)} \cdot \Delta f_i(\tau, \vec{q})$$

$$\Delta f_i(\tau, \vec{q}) \equiv -\frac{\Delta_F^{ii}(\vec{q})}{2\omega_i}\theta(\tau)e^{-\Gamma_i\tau}$$

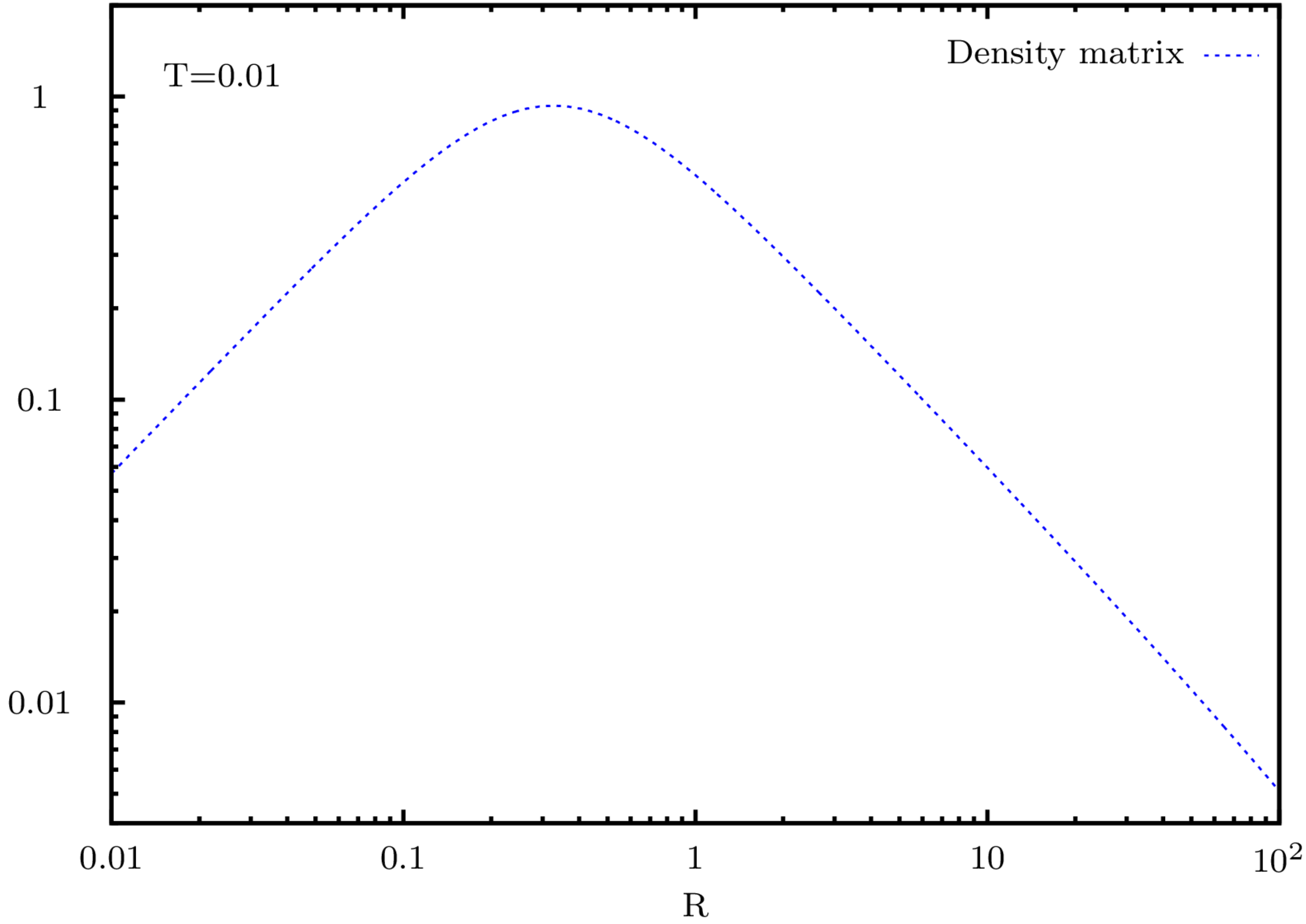
Boltzmann approximation



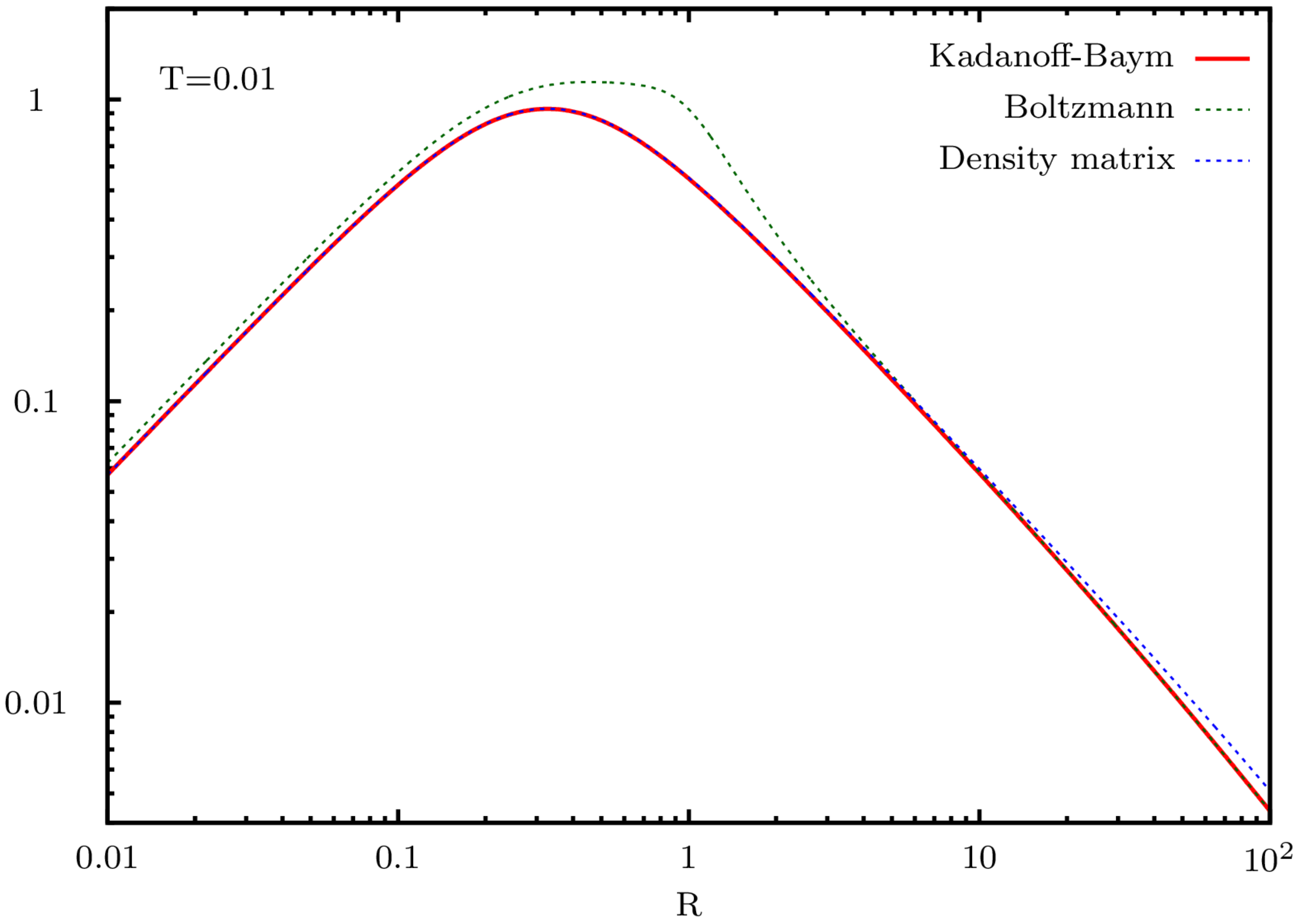
“Translation” to density matrix

$$\Delta G_F^{ij}(\tau, q_0, \mathbf{q}) \approx i\Delta_F(\mathbf{q}) \frac{1}{M_i^2 - M_j^2} \frac{\Pi_\rho^{ij}(\bar{\omega}, \mathbf{q})}{(2\bar{\omega})^2} \times \left[\sum_k \frac{\sin[2(q_0 - \omega_k)\tau]}{q_0 - \omega_k} e^{-\Gamma_k \tau} - 2i \frac{\sin[2(q_0 - \bar{\omega})\tau]}{q_0 - \bar{\omega}} e^{-i(\omega_i - \omega_j)\tau} e^{-\frac{1}{2}(\Gamma_i + \Gamma_j)\tau} \right]$$

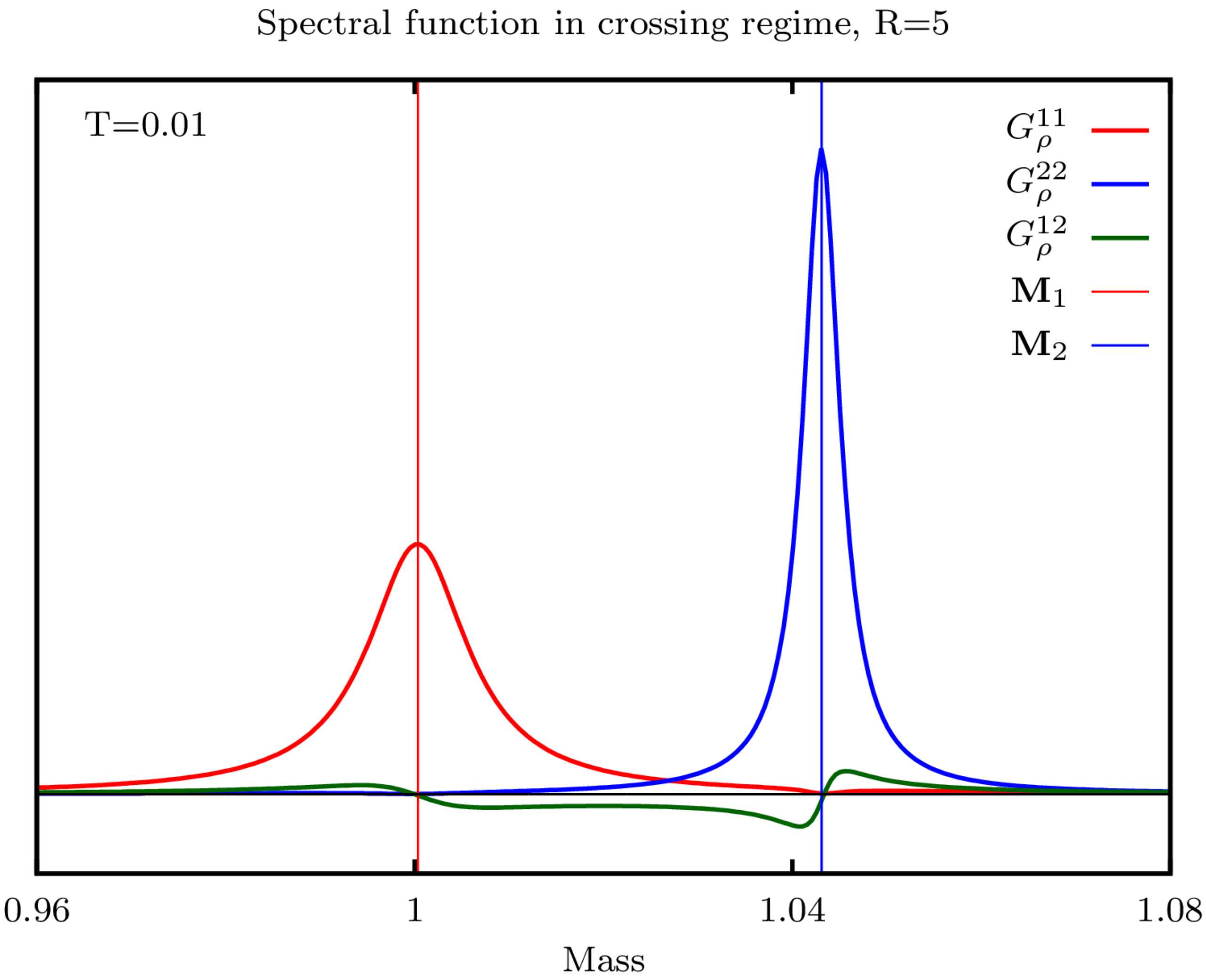
Density matrix approximation



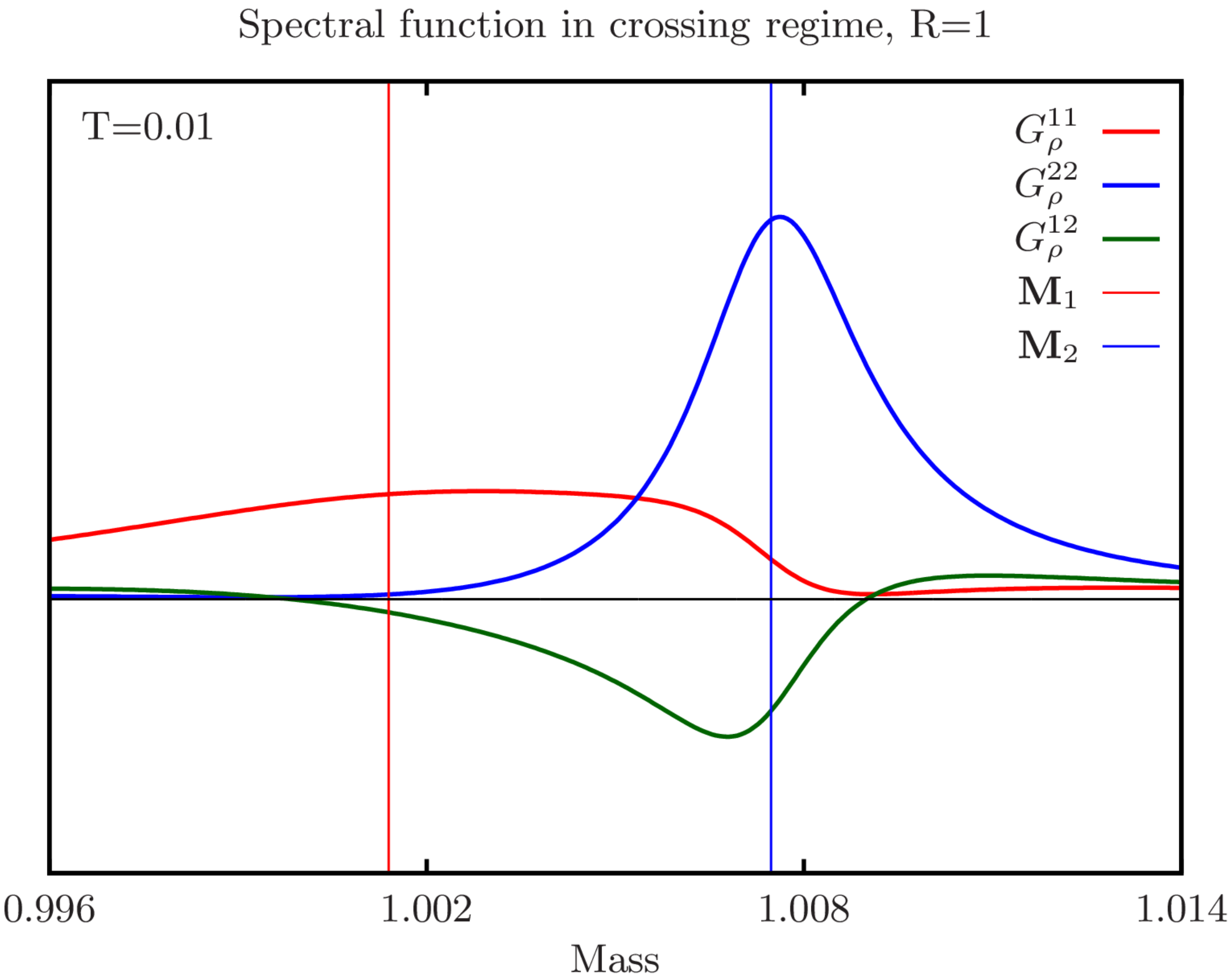
Kadanoff-Baym (effective M & Γ)



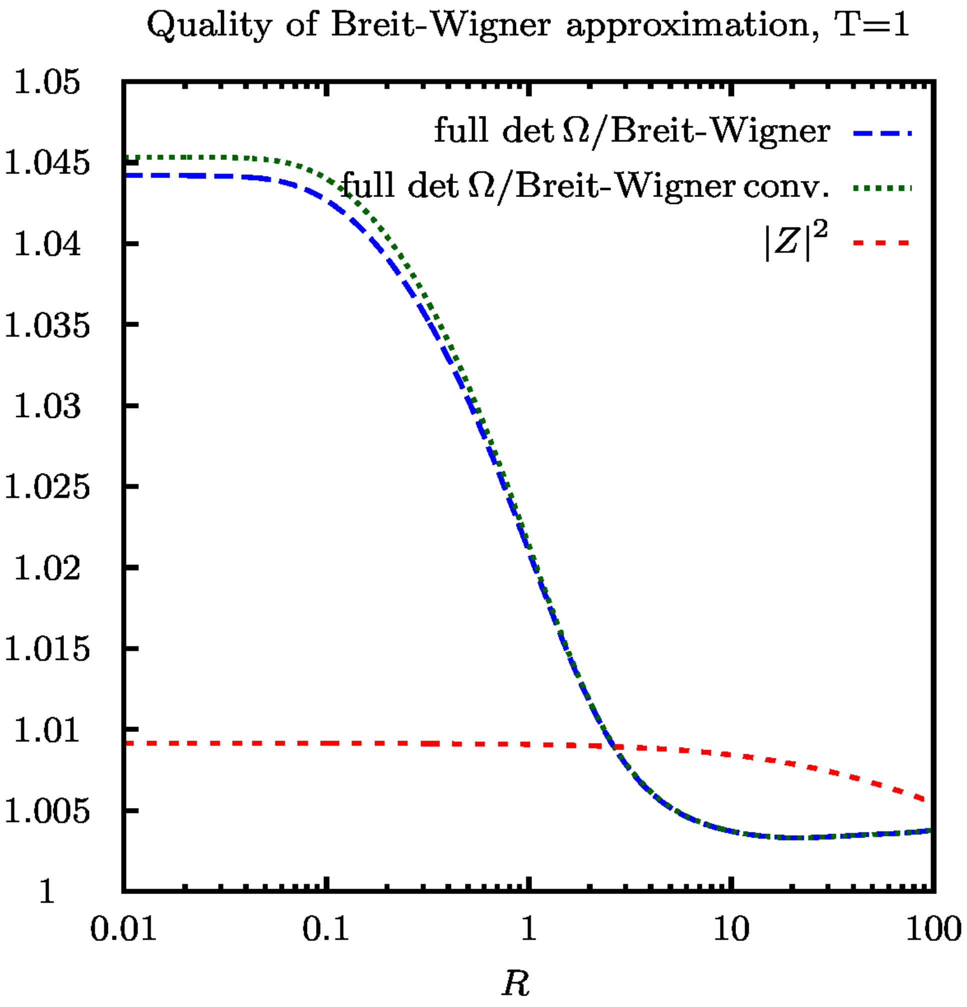
Spectral function



Spectral function



Additional off-shell effects



Summary

1. Possible direct detection only for M ~ 1 TeV and a few GeV
2. With two neutrinos need resonance in both cases
3. Boltzmann is a questionable approximation
4. Density matrix is a very good approximation
5. Want precise CP-violating and washout rates