Nonequilibrium QFT approach to leptogenesis

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INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PTFS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

In collaboration with M. Garny, A. Hohenegger, A. Kartavtsev, and D. Mitrouskas

Baryogenesis via Leptogenesis

- Matter-antimatter asymmetry in the Universe

CMB + BBN $\Rightarrow$

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.2 \pm 0.2)\, 10^{-10}$$

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  $\rightarrow$ 3 Sakharov conditions:
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Leptogenesis

SM + 3 heavy Majorana neutrinos:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\bar{N}_i \left(i\partial\!\!\!/ - M_i\right) N_i - h_{\alpha i}\bar{\ell}_\alpha \tilde{\phi} P_R N_i - h^\dagger_{i\alpha}\bar{N}_i \tilde{\phi}^\dagger P_L \ell_\alpha$$

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3. Expanding Universe + N_i decay

Canonical approach

Generation of an asymmetry:

	production	washout
N_i (inverse)decay	$\mathcal{O}\left(h^4\right)$	$\mathcal{O}\left(h^2\right)$
$\Delta L = 2$ scattering	$\mathcal{O}\left(h^6\right)$	$\mathcal{O}\left(h^4\right)$
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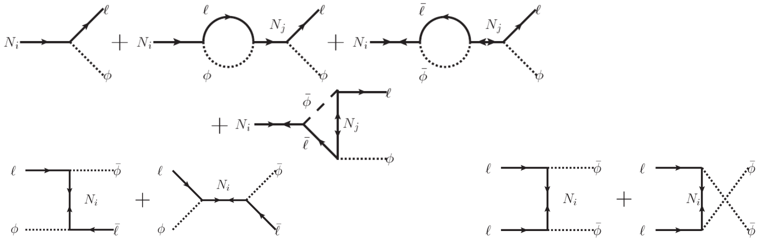
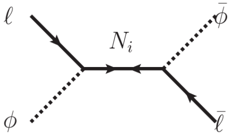


$\Rightarrow$ into the Boltzmann equation for the lepton number!

Canonical approach



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- Double counting problem

  → can be solved if one neglects the quantum statistical factors

  ⇒ Real intermediate state substraction

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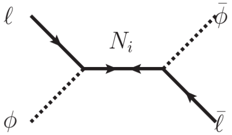

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  - $\rightarrow$ thermal decay width?
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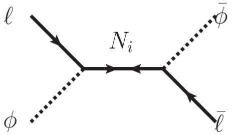

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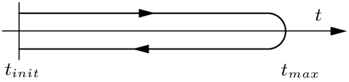
Nonequilibrium Quantum Field Theory approach is needed!!

Basics of nonequilibrium QFT

Right-handed neutrinos propagator on CTP:

$$S_{ij}^{\alpha\beta}(x,y) = < T_{\mathcal{C}} N_i^{\alpha}(x) \bar{N}_j^{\beta}(y) >$$



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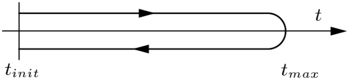
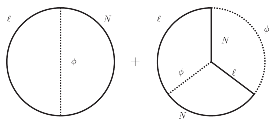


Schwinger-Dyson equation

$$\hat{S}^{-1}(x,y) = \hat{S}_0^{-1}(x,y) - \hat{\Sigma}(x,y) \; , \qquad \Sigma_{ij}^{\alpha\beta}(x,y) = -\frac{\delta i\Gamma_2}{\delta S_{ji}^{\beta\alpha}(y,x)}$$

$\Gamma_2 =$ 2PI effective action $=$



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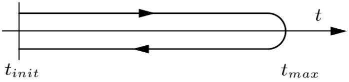

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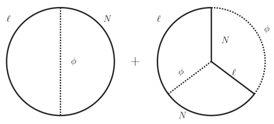

$\rightarrow$ doubling of the d.o.f.: $\hat{S}(x,y) = \underbrace{\hat{S}_F(x,y)}_{\text{statistical}} - \frac{i}{2} \text{sign}_{\mathcal{C}}(x^0 - y^0) \underbrace{\hat{S}_\rho(x,y)}_{\text{spectral}}$

Quantum Boltzmann equation

- **Wigner transform** $\leftrightarrow$ Fourrier transform wrt relative coordinates
- **Gradient expansion** $\leftrightarrow$ Expansion in slow relative to fast time-scales (H/T)
- **Quasiparticle approximation** $\leftrightarrow$ Narrow width approximation
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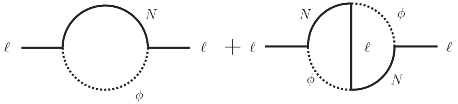
Quantum Boltzmann equation

$$\frac{d}{dt}(n_\ell(t) - n_{\bar{\ell}}(t)) = g_w \int \frac{d^4p}{(2\pi)^4} \text{tr}\Big[\Big(\underbrace{\Sigma_{\ell<}(t,p)(1-f_\ell^p)}_{\text{gain term}} + \underbrace{\Sigma_{\ell>}(t,p) f_\ell^p}_{\text{loss term}}\Big) S_{\ell\rho}(t,p)\Big]$$

$\Sigma_\ell =$



Lepton asymmetry

Free (thermal-) propagators into the lepton self-energy:

$$S_{\ell F} = (\tfrac{1}{2} - f_\ell^p) P_L \not{p}\, \mathrm{sign}(p^0)(2\pi)\delta(p^2 - m_\ell^2) \quad \Delta_{\phi F} = (\tfrac{1}{2} + f_\phi^k)\mathrm{sgn}(k^0)(2\pi)\delta(k^2 - m_\phi^2)$$

$$S_{NF}^{ij} = \delta^{ij}(\tfrac{1}{2} - f_{N_i}^q)(\not{q} + M_i)\mathrm{sign}(q^0)(2\pi)\delta(q^2 - M_i^2)$$

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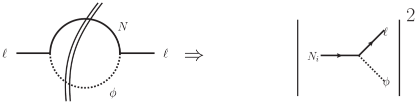

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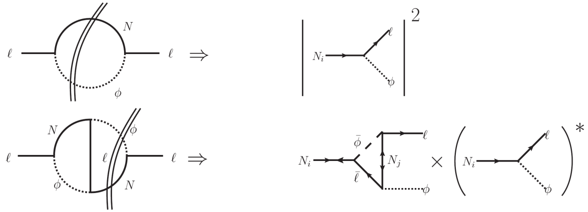

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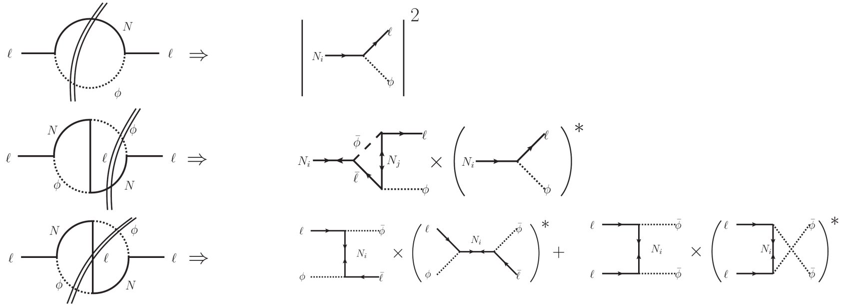

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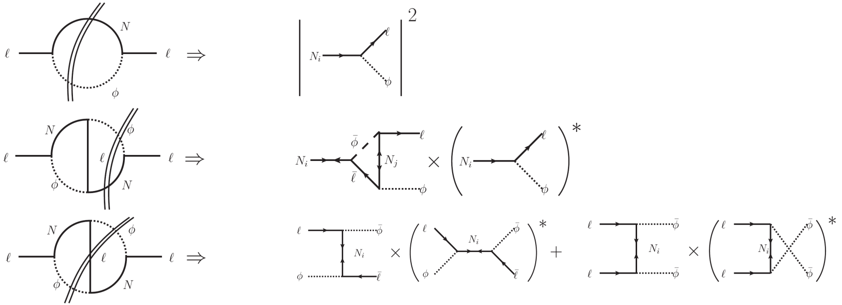

The amplitudes incorporate thermal masses and thermal widths but,

→ Self-energy contribution to the decay rate is missing !

→ $s \times s$ and $t \times t$ channels of the scattering processes are missing!

⇒ need to go **beyond** the free propagator approximation!

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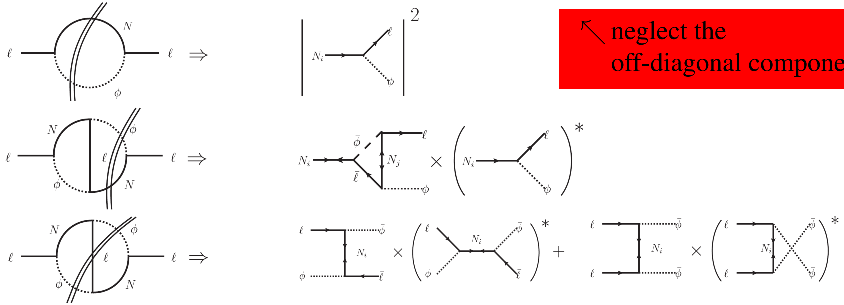

↖ neglect the off-diagonal components

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Resummation and extended QP approximation

In **equilibrium** the *full* statistical propagator $\hat{S}_F$ can be expressed in terms of the flavor diagonal propagators $\hat{\mathcal{S}}$ and flavor off-diagonal self-energy $\hat{\Sigma}^{od}$:

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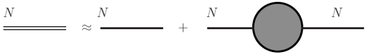

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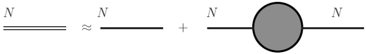

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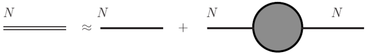

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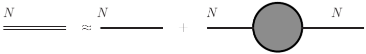

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$\rightarrow$ assume to be valid **out of equilibrium**

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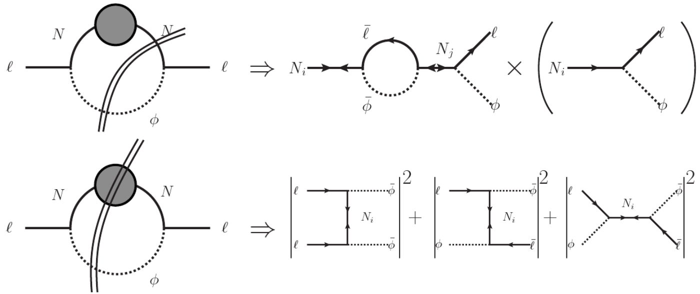
→ insert the resummed Majorana propagator into the one-loop lepton self-energy:



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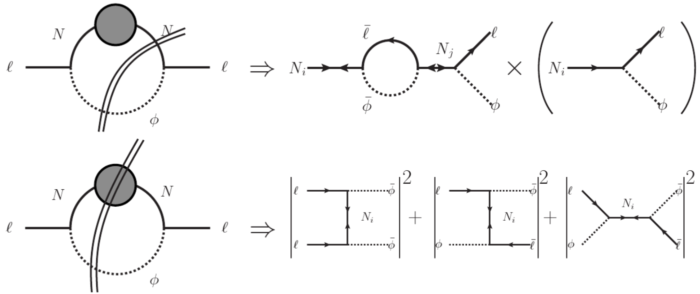

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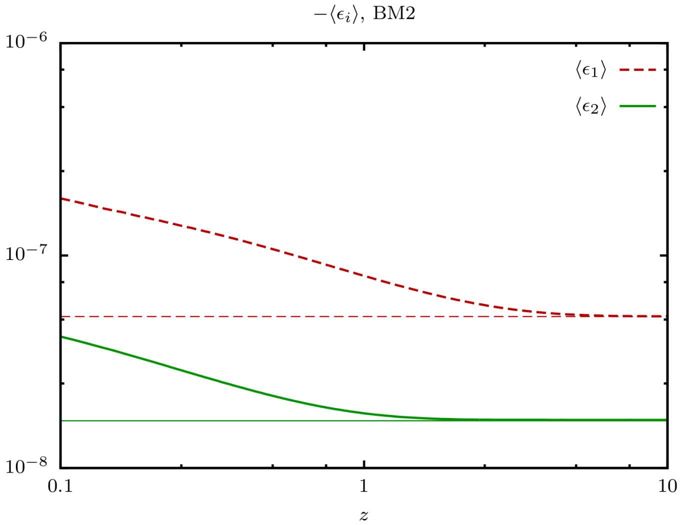
The internal Majorana propagators are automatically RIS-subtracted
⇒ don't need to neglect the quantum statistical factors!

Numerical comparison with canonical approach



$$M_2 = \sqrt{10} M_1$$

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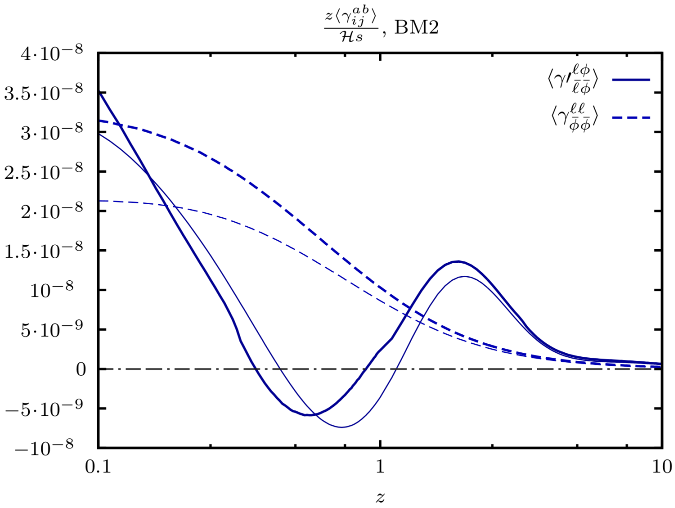

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- reproduce all vacuum diagrams

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Thank you!