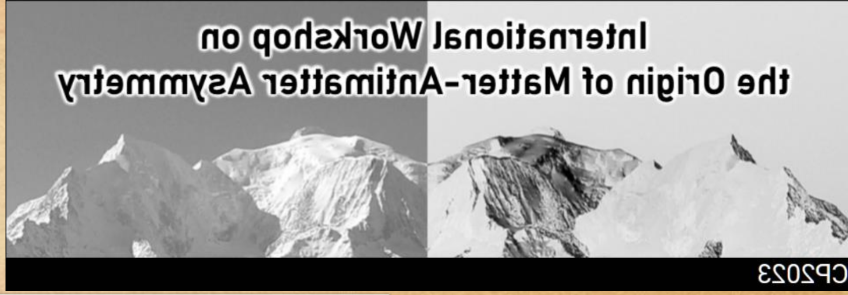

Neutrinos, Cosmological **Phase-Transition** and the **Matter-Antimatter** Asymmetry

ν

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under the supervision of Stéphane Lavignac

- Why is there no anti-workshop at « sehcuoH seL »? (pronunciation is left as an exercise to the reader)

- Almost only particles are observed at all scales (no anti-particles)

- The CMB gives us the ratio baryons/photons:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} = 6.10^{-10} \neq 0$$

→ Need for New Physics: Sterile Neutrinos

Outline

1. Motivating sterile Neutrinos
2. Phase-Transition
3. Tools and Results: Out-of-Equilibrium QFT

1. Motivating sterile Neutrinos: **light neutrinos and asymmetry**

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The Seesaw Mechanism

Light Standard Model neutrinos

Sterile Neutrinos

Figure by Shaaban Khalil

N: sterile Neutrinos
ϕ: Higgs field
l_α: lepton field, can be neutrino ν or electron e
L_{SM}: Lagrangian of the Standard Model

The Neutrinos interact with the Standard Model

Violates **CP symmetry**

$$\boxed{L = L_{SM} + i\bar{N}\gamma^\mu\partial_\mu N - M_I\bar{N}_I^c N_I + Y_{I\alpha}N_i\bar{l}_\alpha\tilde{\phi} + h.c.}$$

Massive Neutrinos
Majorana mass M

Violates **Lepton number**

Sakharov conditions for generation of matter-antimatter asymmetry (1967):

- Baryon/Lepton number violation
- C and CP violation
- Out-of-Equilibrium

Andreï Sakharov

2. **Phase Transition**: going out of equilibrium

$$\boxed{L = L_{SM} + i\bar{N}\gamma^{\mu}\partial_{\mu}N - M_I\bar{N}_I^c N_I + Y_{I\alpha}N_I\bar{l}_{\alpha}\tilde{\phi} + h.c.}$$

$$\Downarrow$$

[Rosauro-Alcaraz (2021)]

[Huang, Xie (2022)]

$$\boxed{L = L_{SM} + L_S + i\bar{N}\gamma^{\mu}\partial_{\mu}N - \lambda_{NS}^{I}\, S\bar{N}_I^c N_I + Y_{I\alpha}N_I\bar{l}_{\alpha}\tilde{\phi} + h.c.}$$

$$M_I = \lambda_{NS}^{I}\, S$$

New interactions, new dynamics for the sterile sector

$$< S > = 0 \quad \rightarrow < S > \neq 0$$

Typically, the scalar field S will experience a **phase-transition**.

A (strongly) **first-order phase-transition** can be more interesting for two reasons:

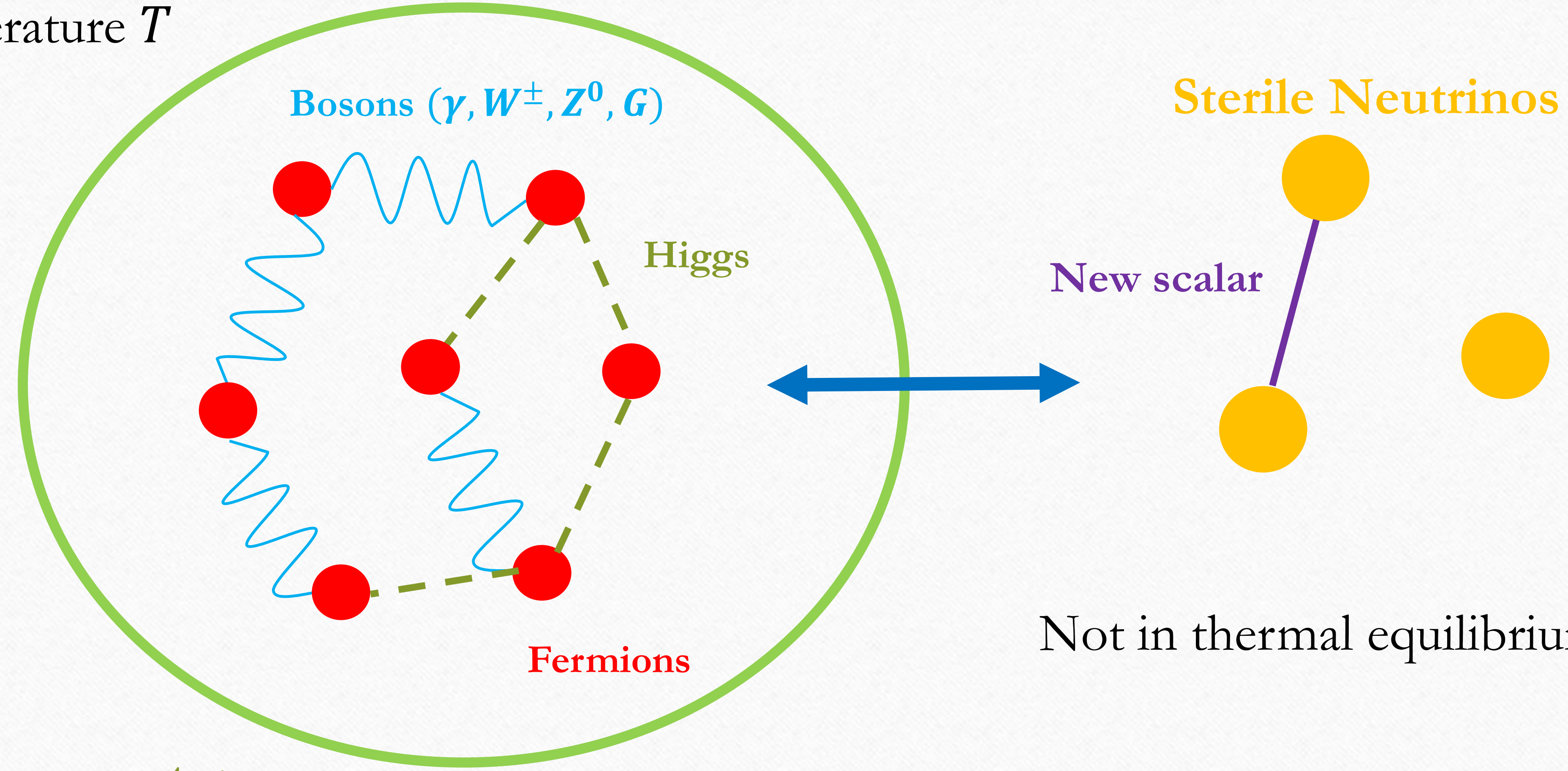
1. Specific **gravitational wave** signature.

2. Sudden change in the value of the field, which allows for **non-equilibrium** dynamics.

Standard Model

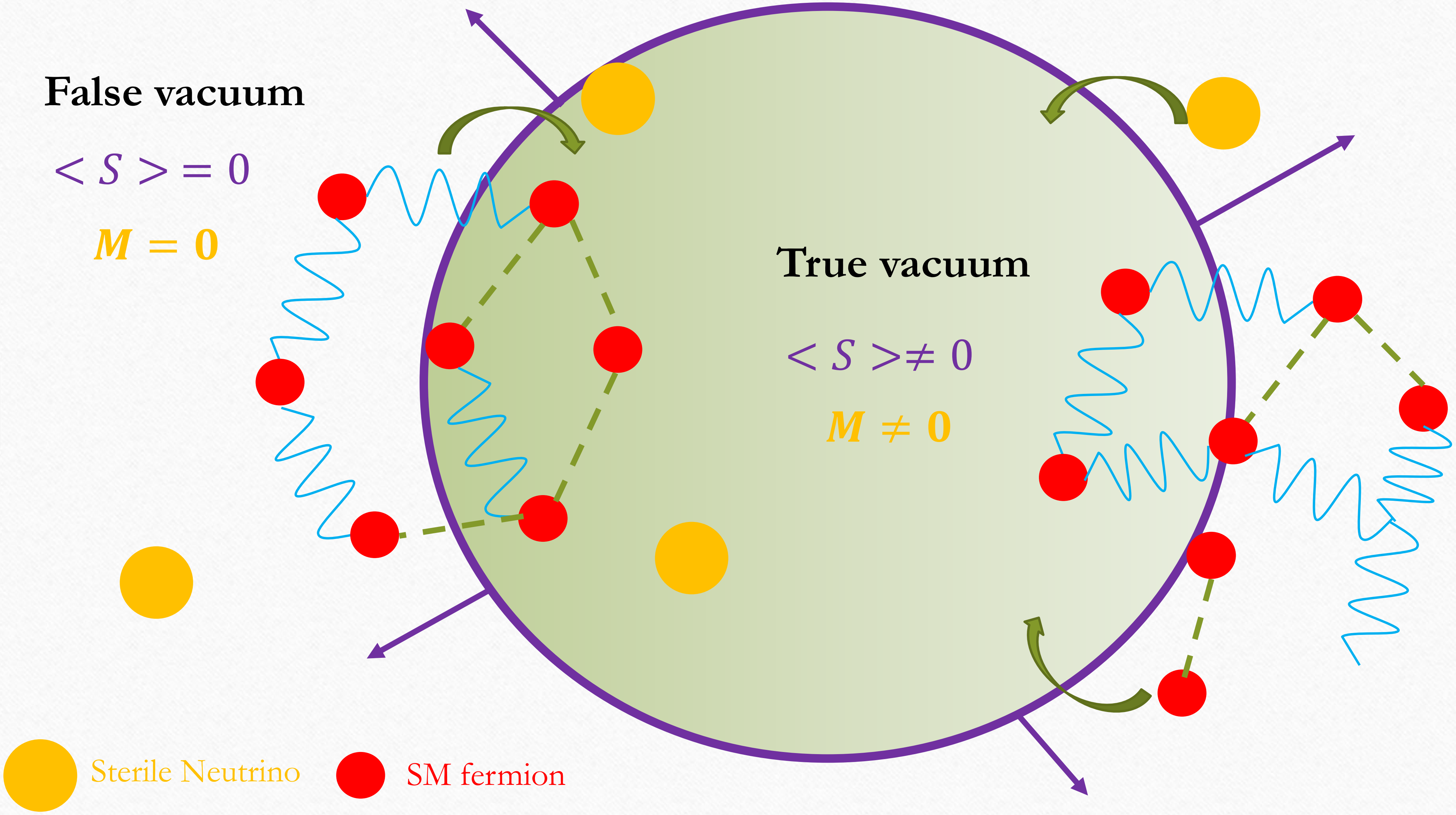
New sector

Temperature T

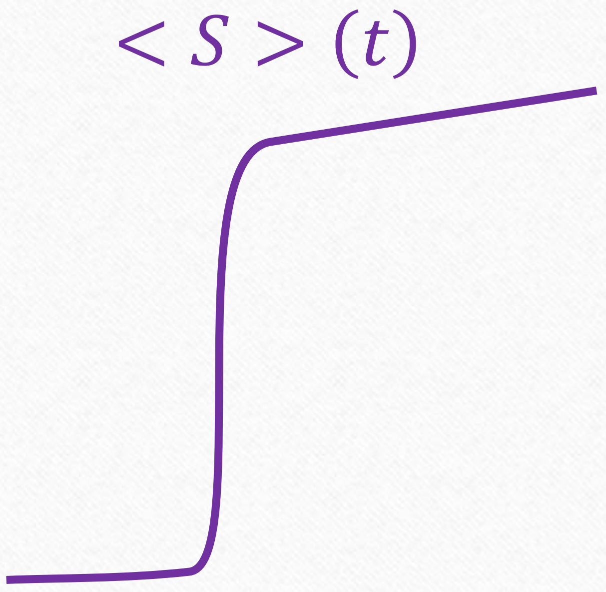


Not in thermal equilibrium

« Active » sector


False vacuum
$< S > = 0$
$M = 0$
True vacuum
$< S > \neq 0$
$M \neq 0$
Sterile Neutrino
SM fermion

During the **phase-transition**, the masses of the Neutrinos are **time-dependent**. All quantities will have an explicit time-dependence along the **wall**.



$$M_I = \lambda_{NS}^{I} < S > (t) = M_I(t)$$

3. Tools and Results: **Out-of-Equilibrium QFT**

Thermal Leptogenesis

[Anisimov, Buchmüller, Drewes, Mendizabal (2010)]

Low-scale Leptogenesis

[Drewes, Garbrecht, Gueter, Klaric (2010)]

Electroweak Baryogenesis

[Lee, Cirigliano, Ramsey-Musolf (2005)]

…

Equilibrium QFT: Schwinger-Dyson Equation

$\Sigma =$ self-energy

Free propagator

$$S^{-1}(x-y) = i\delta(x-y)\gamma^{\mu}\partial_{\mu} - \Sigma(x-y)$$

Full propagator

Deviation due to interactions

$$i\,\gamma^{\mu}\partial_{\mu}S(x-y) - \Sigma \otimes S(x-y) = \delta(x-y)$$

(convolution)

Non-Equilibrium QFT: Schwinger-Dyson Equation

$\Sigma =$ self-energy

$$S^{-1}(x-y,\boldsymbol{t}) = i\delta(x-y)\gamma^{\mu}\partial_{\mu} - \Sigma(x-y,\boldsymbol{t})$$

$$i\,\gamma^{\mu}\partial_{\mu}S(x-y,\boldsymbol{t}) - \Sigma \otimes S(x-y,\boldsymbol{t}) = \delta(x-y)$$

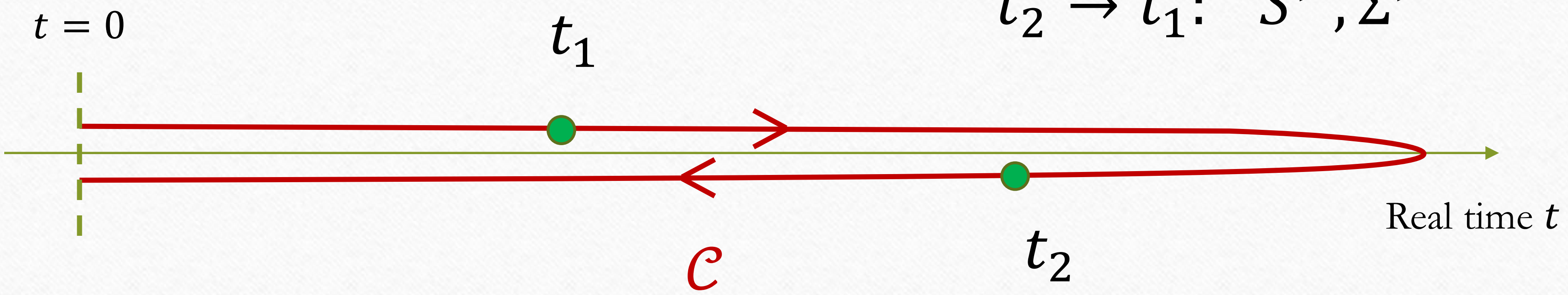
$\boldsymbol{t}$-dependence: no longer time-translation invariant

[Keldysh (1965)]

Keldysh-Schwinger/CTP formalism

$t_1 \to t_2$: $S^<, \Sigma^<$

$t_2 \to t_1$: $S^>, \Sigma^>$



Initial value problem: we know the distribution only at $t = 0$ ($\cancel{< f|S|i >}$)

$$i\,\gamma^{\mu}\partial_{\mu}S(x-y,\boldsymbol{t})-\Sigma\otimes S(x-y,\boldsymbol{t})=\delta(x-y)$$

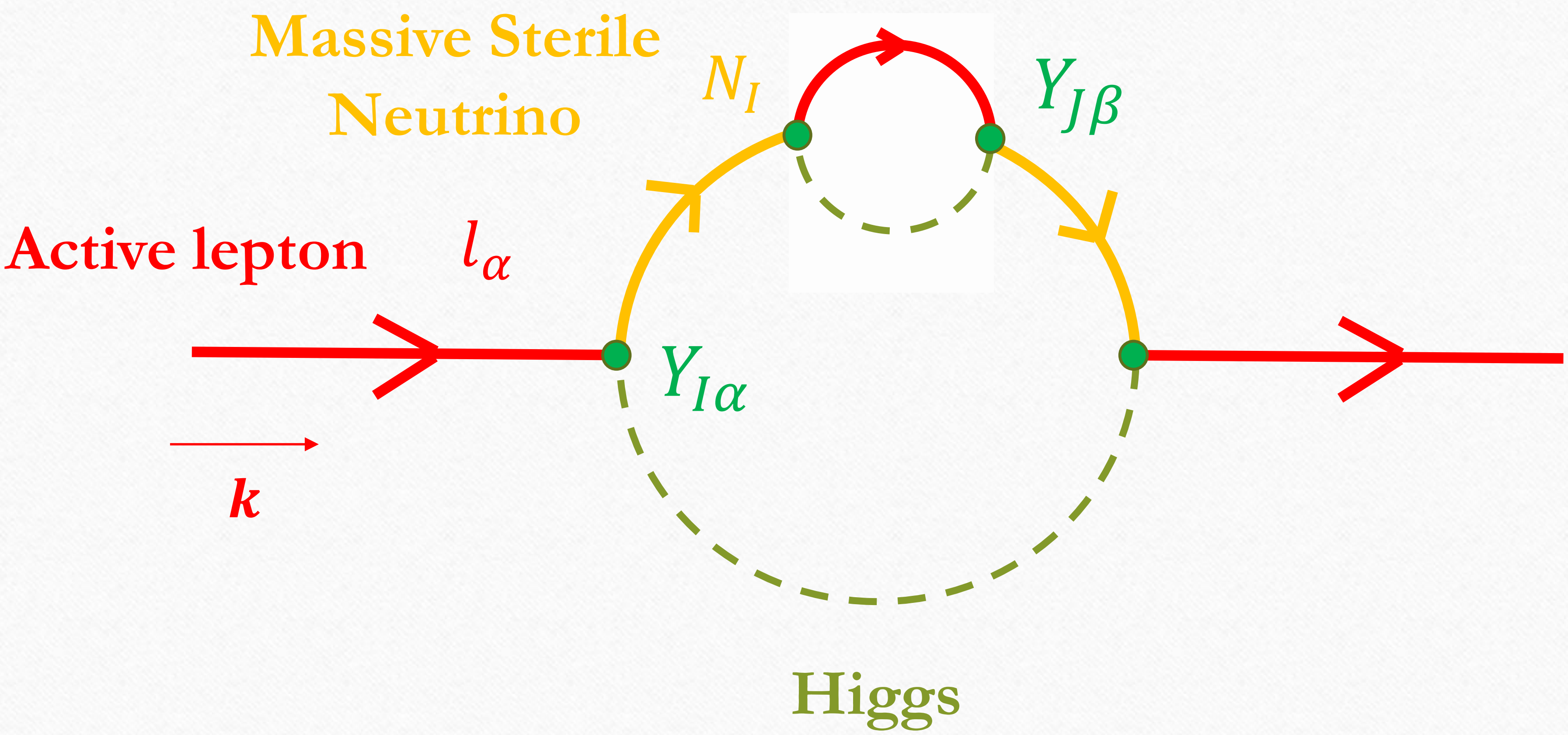
n_L = asymmetry between leptons and anti-leptons = density of lepton number

$j^{\mu}=-\mathrm{Tr}(\gamma^{\mu}S_L)$ = quadri-current associated with the lepton number

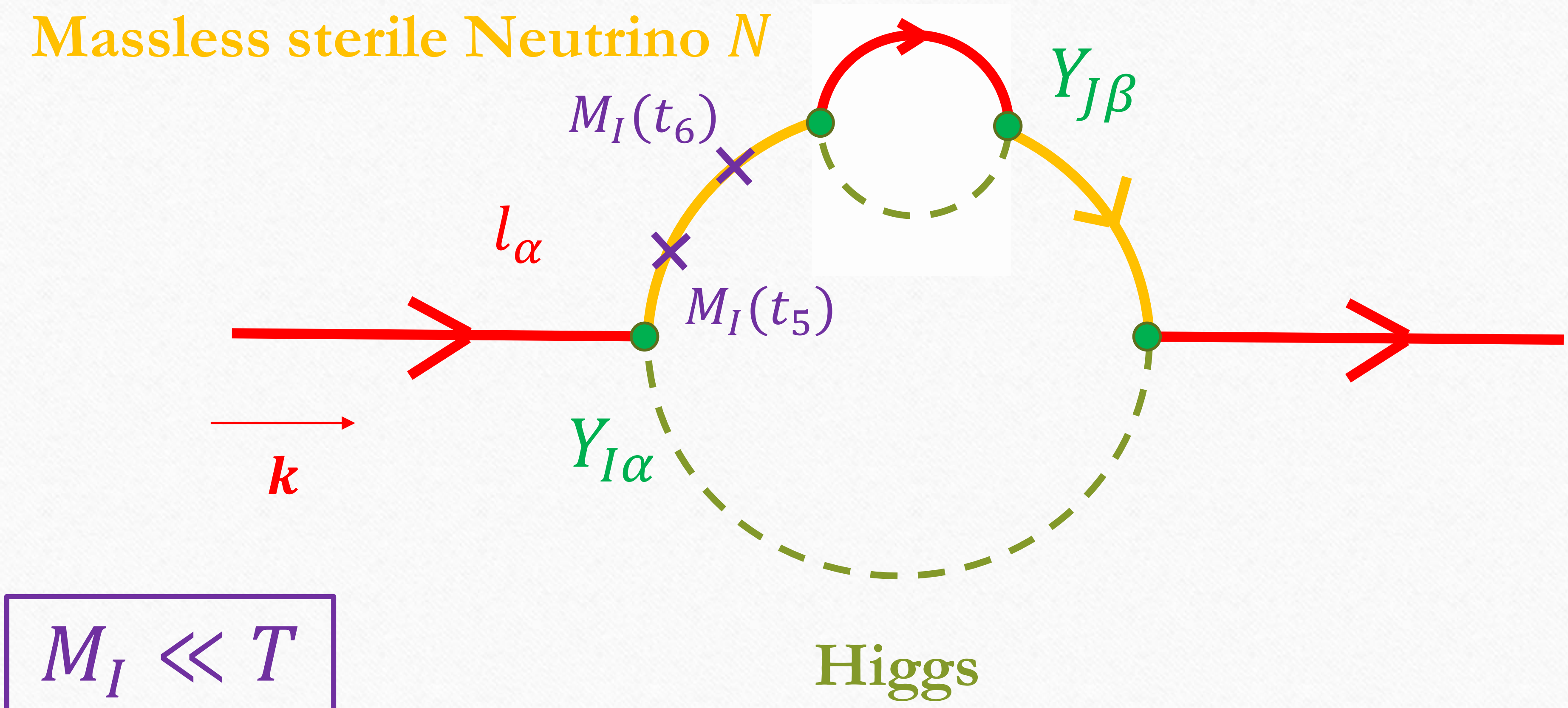
$$n_L=\mathrm{j}^0=-\mathrm{Tr}(\gamma^0 S_L)=i\int \mathrm{d}t_1\,\mathrm{Tr}(i\,\gamma^0\partial_0 S_L)$$

$$=-\int \mathrm{d}t_1\mathrm{d}t_2(\mathrm{Tr}(\Sigma^{>}(t_1,t_2)S_L^{<}(t_2,t_1))-\mathrm{Tr}(\Sigma^{<}S_L^{>}))$$

[1]. « Quantum Leptogenesis I », Anisimov, Buchmuller, Drewes, Mendizabal https://arxiv.org/abs/1012.5821



Two-loop self-energy Σ_{k}



$\boxed{M_I \ll T}$

(expansion in M)

Two-loop self-energy $\Sigma_{\mathbf{k}}$

Final (comoving) asymmetry

Majorana masses of the heavy Neutrino states (violate **lepton number**)

$$Y_L^\alpha = \frac{n_L^\alpha}{s} \propto \sum_{I,J} \frac{\mathrm{Im}\left(Y_{I\alpha} Y_{J\alpha}^* \left(YY^\dagger\right)_{JI}\right)}{\left(YY^\dagger\right)_{II}\left(YY^\dagger\right)_{JJ}} \frac{M_I^2}{T^2} \times \text{phase space}$$

CP-violating term (differenciates particles and anti-particles)

Temperature of the phase transition (**out-of-equilibrium** process)

Casas-Ibarra parametrization

[Casas, Ibarra (2001)]

$$Y \equiv \sqrt{M}\,\boldsymbol{R}\,\underbrace{\sqrt{m}\,U^{\dagger}_{PMNS}}_{\text{Observable at low-energy}}$$

$$\boldsymbol{R} = \begin{pmatrix} \cos(\boldsymbol{\omega}) & \sin(\boldsymbol{\omega}) & 0 \\ -\sin(\boldsymbol{\omega}) & \cos(\boldsymbol{\omega}) & 0 \end{pmatrix}$$

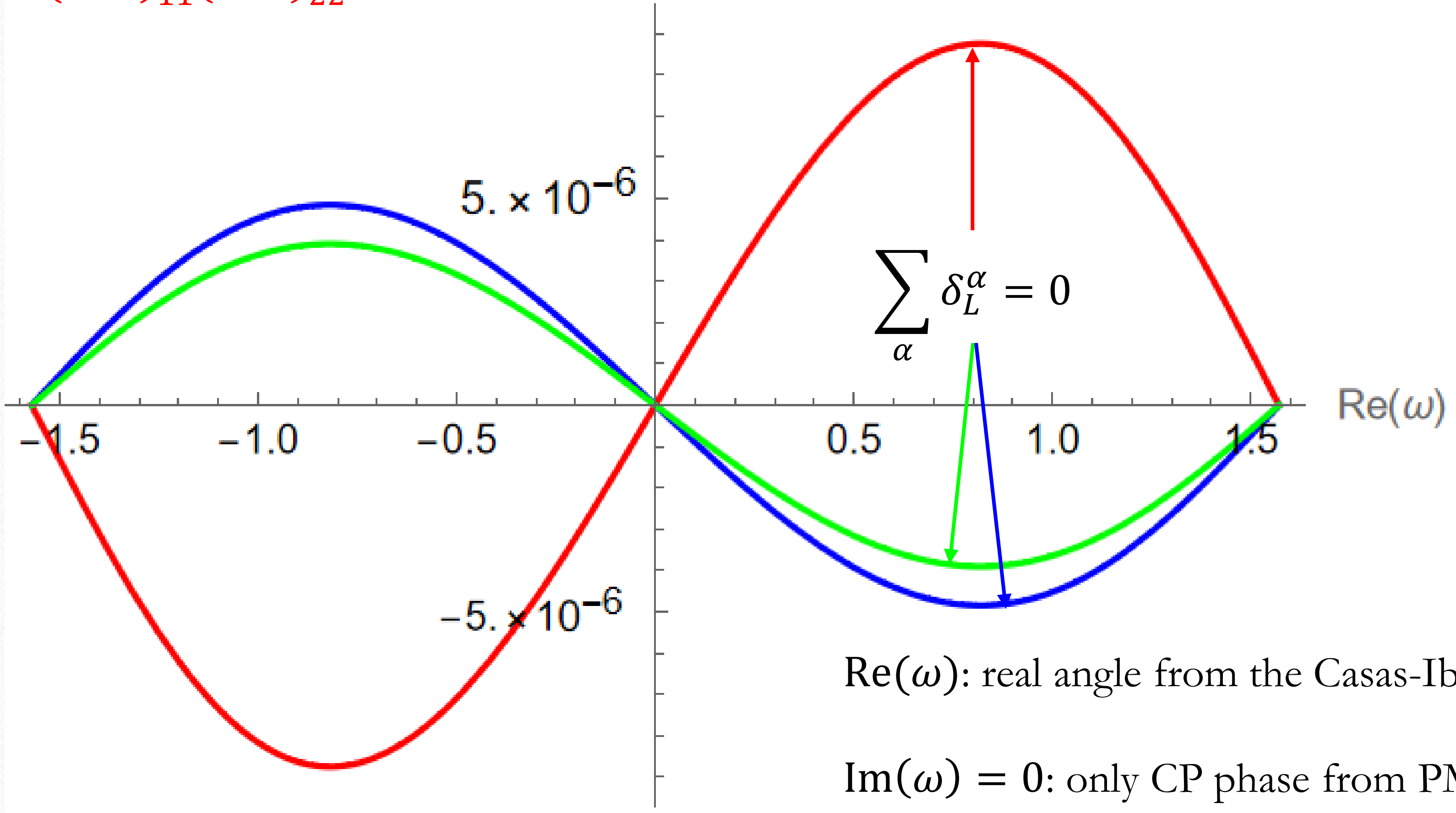
$$m = \begin{pmatrix} m_3 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_1 \end{pmatrix} \simeq \begin{pmatrix} |\Delta m_{atm}| & 0 & 0 \\ 0 & |\Delta m_{sol}| & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

(normal ordering)

Non-observable complex angle ω (parameter)

$$\frac{\mathrm{Im}\left(Y_{1\alpha}Y_{2\alpha}^{*}(YY^{\dagger})_{21}\right)}{(YY^{\dagger})_{11}(YY^{\dagger})_{22}}\,\frac{M_2^2-M_1^2}{T^2}\equiv\delta_L{}^{\alpha}$$

$M_1 = 100$ GeV
$M_2 = 110$ GeV
$T = 10^6$GeV



$\mathrm{Re}(\omega)$: real angle from the Casas-Ibarra parametrization

$\mathrm{Im}(\omega) = 0$: only CP phase from PMNS, $\delta = 3\pi/2$

This work can be compared to a work by Pascoli, Turner and Zhou, who derived a lepton asymmetry from a **varying Weinberg operator**.

The coefficient of the operator is driven by a **phase-transition**.

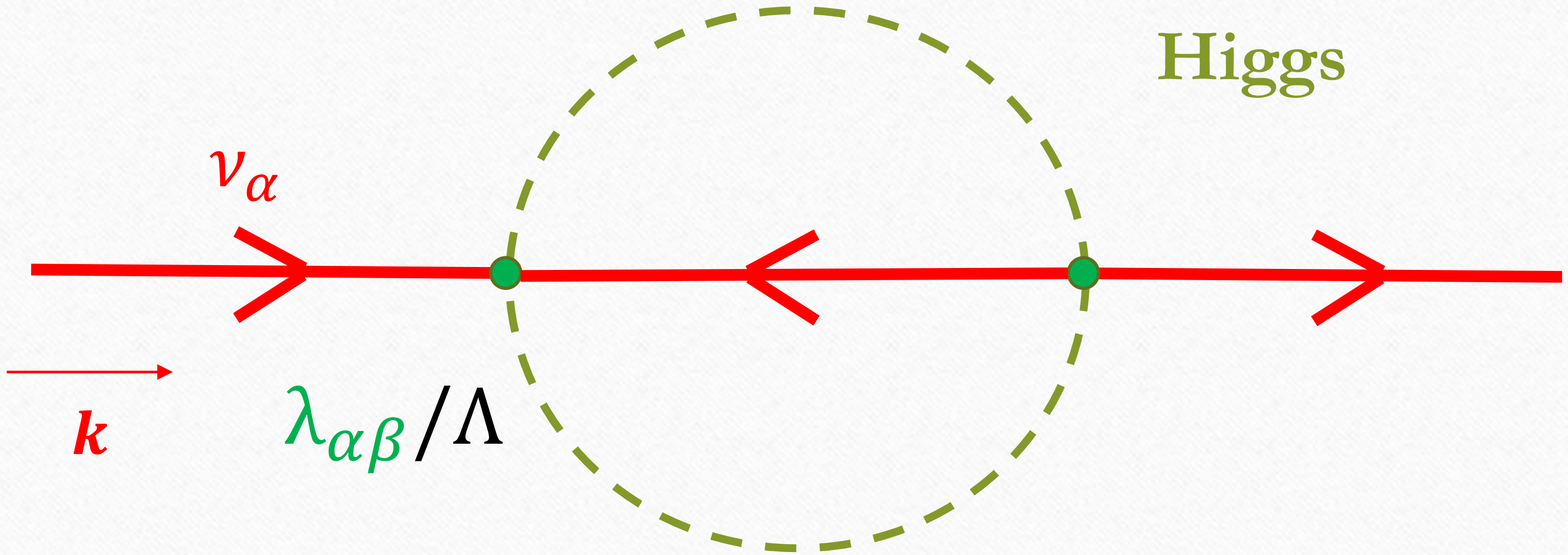
$$L = L_{SM} + \frac{\lambda_{\alpha\beta}}{\Lambda} l_\alpha H\, C l_\beta H + h.c. = L_{SM} + \frac{\lambda_{\alpha\beta}(S)}{\Lambda} l_\alpha H\, C l_\beta H + h.c.$$

$$\lambda^0 \to \lambda\,, \quad m_\nu^0 \to m_\nu$$

(Active neutrino mass matrix)

[Pascoli, Turner, Zhou (2018)]

$$L = L_{SM} + \frac{\lambda_{\alpha\beta}}{\Lambda} l_\alpha H\, C l_\beta H + h.c. = L_{SM} + \frac{\lambda_{\alpha\beta}(S)}{\Lambda} l_\alpha H\, C l_\beta H + h.c.$$



Two-loop self-energy Σ_k

[2]. « Leptogenesis via Varying Weinberg Operator: the CTP Approach», Turner, Zhou, https://arxiv.org/abs/1808.00470v2

(Active) neutrino mass matrix before and after the PT (**CP and Lepton Number violation**)

v_H: Higgs vev
m_ν^0: (active) neutrino mass matrix **before** PT (parameter)
m_ν: (active) neutrino mass matrix **after** PT (measurable)

$$Y_L \propto \frac{\mathrm{Im}\left(\mathrm{Tr}\left(m_\nu^0 m_\nu^*\right)\right)}{v_H^4} T^2 \times \text{phase space}$$

Final (comoving) asymmetry

Temperature of the phase transition (**out-of-equilibrium** process)

[2]. « Leptogenesis via Varying Weinberg Operator: the CTP Approach», Turner, Zhou, https://arxiv.org/abs/1808.00470v2

Comparison of both models

- Asymmetry produced **during** the phase-transition (not via decay afterwards)
- Right-handed Neutrinos are **not** decoupled in our scenario
- Dependence on **low-energy observables**

Summary and conclusion

Work achieved

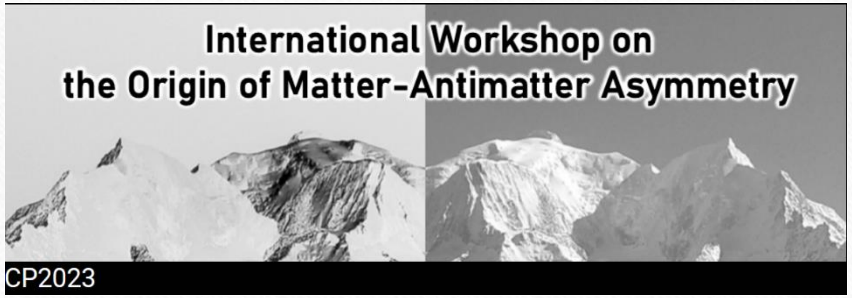
- We consider an original scenario where the Majorana Neutrinos acquire their mass and produce an asymmetry during a single phase-transition.

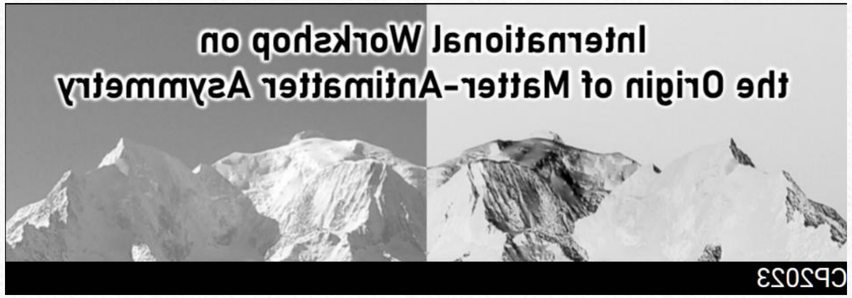
- We computed the asymmetry from first-principles (numerical work on progress).

True vacuum

ν

Thanks for your attention!





[Akhmedov, Rubakov, Smirnov (1998)]

Leptogenesis via neutrino oscillations **(ARS)**

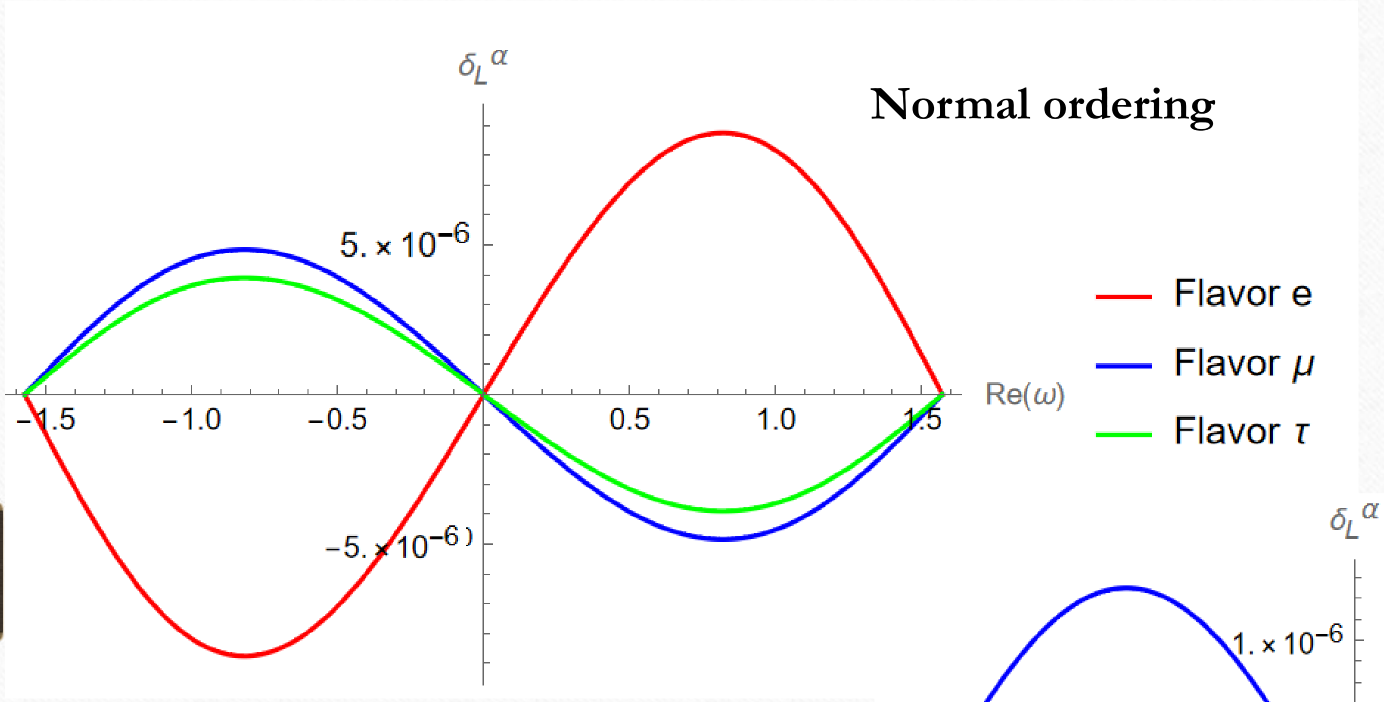
[See for example
Drewes, Garbrecht,
Gueter, Klaric (2010)]

$$T_{osc} \equiv \left(M_{Pl}\Delta M^2_{2,1}\right)^{1/3}$$

$M_{Pl} \simeq 7 \times 10^{17}\text{GeV}$
is the Planck Mass

$$T_{osc} = \left(7 \times 10^{17} \times (110^2 - 100^2)\right)^{1/3}\text{GeV} \simeq 10^7\text{GeV} > T_{PT}$$

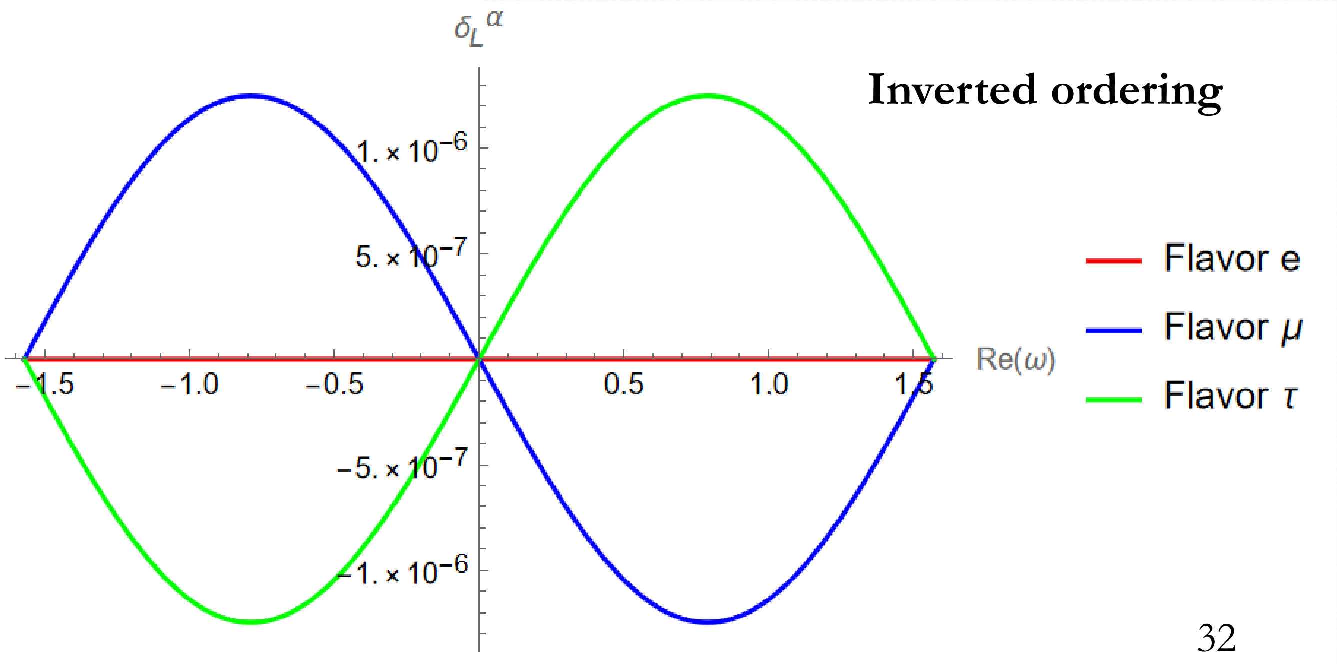
$M_1 = 100\text{ GeV}$ $M_2 = 110\text{ GeV}$ $T_{PT} = 10^6\text{GeV}$



$$\alpha_{21} = 0$$

$$\alpha_{31} = 2\,\pi$$

$$\delta = 3\,\pi/2$$



Further prospects

- Reflection of Sterile Neutrinos on the wall of the bubbles
- (ARS) Leptogenesis without Phase-transition with initial asymmetries – Washout of the asymmetries

The Weinberg operator could be derived from **right-handed Neutrinos**, if they decouple below some energy scale. The value of the Weinberg coefficient depends on the mass of these Neutrinos.

$$\lambda^0/\Lambda = Y^T\, M_{N0}^{-1} Y$$

$$\lambda/\Lambda = Y^T\, (M_{N0} + \lambda_{NS} v_S)^{-1} Y = Y^T\, M_N^{-1} Y$$

$$\Sigma^{<}_{k,\alpha}(\mathrm{t}_1,\mathrm{t}_2)=\int_{c}\mathrm{d}t_5\int_{c}\mathrm{d}t_6 M_I(t_5)M_I(t_6)\times Y_{I\alpha}(Y^{*}_{I\beta}Y_{J\beta})Y^{*}_{J\alpha}$$

$$\times\int_p\int_q\int_{c}\mathrm{d}t_3\mathrm{d}t_4\, S_{N,p}(t_1,t_3)S_{L,k}(t_3,t_4)S_{N,p}(t_4,t_2)\times\Delta_H\Delta_H$$

Propagators for the Higgs field

$$n_L^{\alpha}=-\int dt_1dt_2(\mathrm{Tr}(\Sigma^{>}_{\alpha}S^{<}_{L})-\mathrm{Tr}(\Sigma^{<}_{\alpha}S^{>}_{L}))$$

$$\sim-\iiint_{k,p,q}\int dt_1dt_2\left(\mathrm{Tr}\left(\Sigma^{>}_{k,\alpha}S^{<}_{L,k}\right)-\mathrm{Tr}\left(\Sigma^{>}_{k,\alpha}S^{<}_{L,k}\right)^{*}\right)$$

« phase space » = six-dimensional time-integrals
+ three momentum-integrations

$$I = \int_0^\infty \mathrm{d}t_1 \dots \int_0^\infty \mathrm{d}t_6 \, e^{-\gamma|t_1-t_2|} \dots e^{-\gamma|t_6-t_1|} \, e^{-\Gamma(t_1-t_2)} \dots e^{-\Gamma(t_6-t_1)}$$
$$\times \cos(k(t_1-t_2)) \dots \cos(p(t_6-t_1))$$

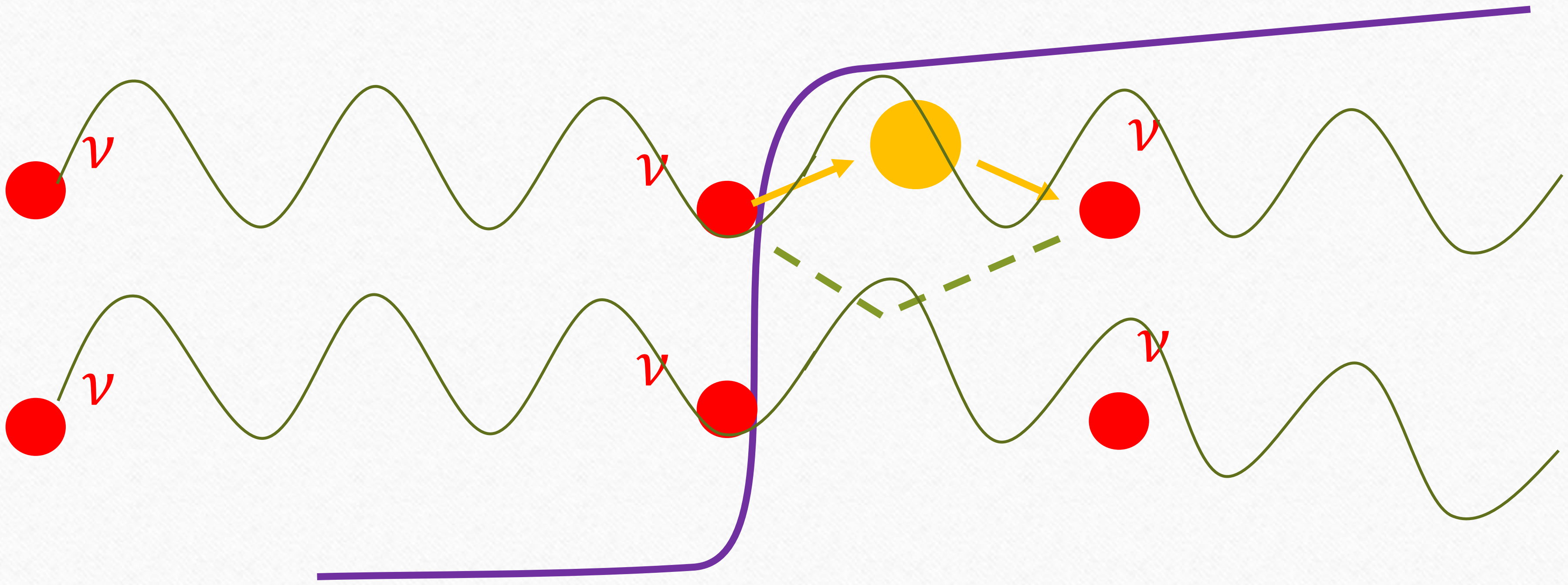
$$= \int_0^\infty \mathrm{d}t_1 \int_{-t_1}^\infty \mathrm{d}y_1 \dots \int_{-(t_1+y_1+\cdots)}^\infty \mathrm{d}y_5 \, e^{-\gamma|y_1|} \dots e^{-\gamma|y_5|} \, e^{-\Gamma y_1} \dots e^{-\Gamma y_5}$$
$$\times \cos(k y_1) \dots \cos(p y_5)$$

Interferences between loops and the tree-level allow for a **distinction between particles and anti-particles** in the **probabilities** (square of the amplitude).

$$|\mathcal{M}|^2 = |\mathcal{M}_0 + \mathcal{M}_1|^2 = \left|\mathcal{M}_0 + \mathcal{M}_1^{odd} + \mathcal{M}_1^{even}\right|^2$$
$$= |\mathcal{M}_0|^2 + |\mathcal{M}_1|^2 + \mathcal{M}_0\mathcal{M}_1^{odd*} + \mathcal{M}_0\mathcal{M}_1^{even*} + c.c.$$

CP conjugation

$$|\overline{\mathcal{M}}|^2 = |\overline{\mathcal{M}_0} + \overline{\mathcal{M}_1}|^2 = \left|\mathcal{M}_0^* - \mathcal{M}_1^{odd*} + \mathcal{M}_1^{even*}\right|^2$$
$$= |\mathcal{M}_0|^2 + |\overline{\mathcal{M}_1}|^2 - \mathcal{M}_0\mathcal{M}_1^{odd*} + \mathcal{M}_0\mathcal{M}_1^{even*} + c.c.$$



Quantum Interference

Mass of the sterile Neutrino $M = 0$ $M \neq 0$

General scheme

- Asymmetry in the **active** sector (Δ_α) is originally very small.
- Solve for the sterile sector only (**no « backreaction »**)
- Compute the source term.

Homogeneous and isotropic Universe

$$\boxed{ds^2 = dt^2 - a(t)^2 d\vec{x}^2}$$

Scale factor = « Size » of the Universe

Its evolution is driven by the **matter content**

$$f_h(\vec{p},\vec{x},t) = f_h(\vec{p},t) \qquad n_h = \int d^3\vec{p}\, f_h(\vec{p},t) = n_h(t) = n^{eq} + \delta n_h$$

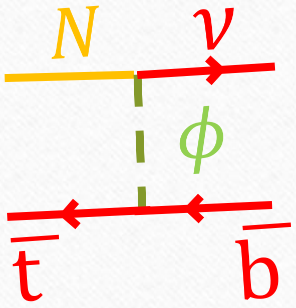
Quantum Boltzmann Equation

Hamiltonian: oscillations between different flavors

« Backreaction » of the asymmetry in active sector

$$\frac{d\delta n_h}{dt} = -\frac{i}{2}\left[H_{vac} + H_{th}, \delta n_h\right] - \frac{1}{2}\{\Gamma_h, \delta n_h\} + \frac{1}{2}\tilde{\Gamma}_\alpha \mathcal{A}_{\alpha\beta}\Delta_\beta$$

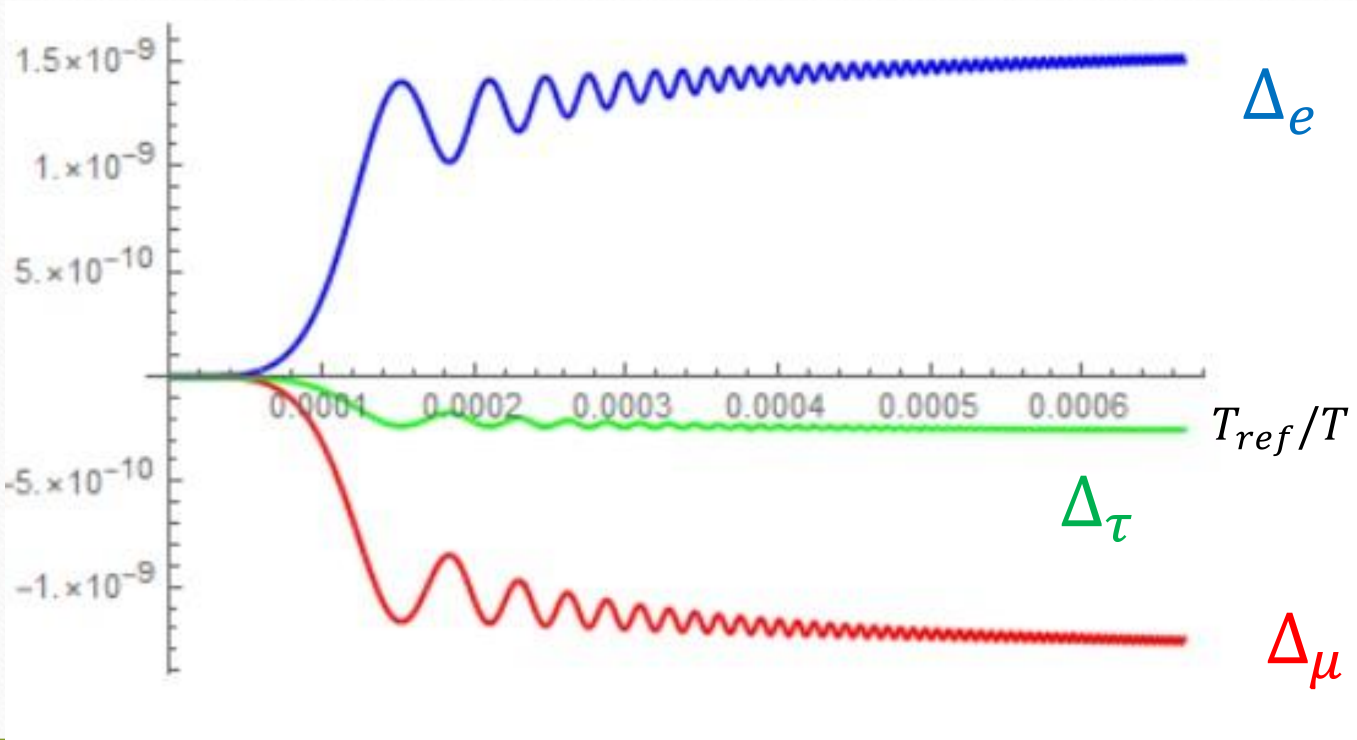
Decay rate: scattering that suppresses Neutrinos



Δ_β = asymmetry in the active sector for each flavor

$\mathcal{A}_{\alpha\beta}$= linear coefficients

Example of an evolution of the asymmetry



$M_1 = 50\ GeV$

$M_2 = M_1 + 10^{-3} GeV$