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LEPTOGENESIS: CONNECTING COSMOLOGY AND PARTICLE PHYSICS

Rémi Faure, IPhT

Moriond conference, March 25th

WHY LEPTOGENESIS (=CREATION OF LEPTONS)?

[Planck2018]

Baryon-to-photon ratio $$\eta_B \equiv \frac{n_B}{n_\gamma} = (6.13 \pm 0.04) \times 10^{-10} \simeq \frac{n_B - \bar{n}_B}{n_\gamma}$$

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→ **Leptogenesis** using **right-handed neutrinos** (also called sterile neutrinos)

1. STANDARD LEPTOGENESIS

Majorona sterile neutrinos can explain neutrino masses in the **Seesaw** model.

$$\boxed{L = L_{SM} + \left(i/2\,\bar{N}_I \gamma^{\mu} \partial_{\mu} N_I \; - 1/2\, M_I \bar{N}_I^c N_I - Y_{I\alpha} \bar{N}_I \tilde{\phi}^{\dagger} l_{\alpha} + h.c.\right)}$$

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Majorana masses M_I

Violates **Lepton number**

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Standard leptogenesis: Thermal leptogenesis → **Decays of (heavy) sterile neutrinos**

$\simeq 10^{15}$ GeV

ARS leptogenesis → **Production of (light) sterile neutrinos**

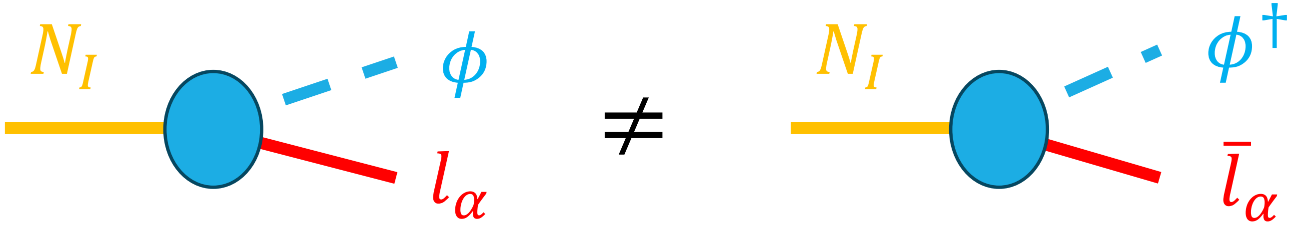
$\simeq 100$ GeV

THERMAL LEPTOGENESIS

[Fukugita, Yanagida, ‘86]

A lepton asymmetry is produced in sterile neutrino **decays** as they get out of equilibrium because of the **Universe expansion.**

$$M_I \simeq 10^{15}\ \text{GeV}$$



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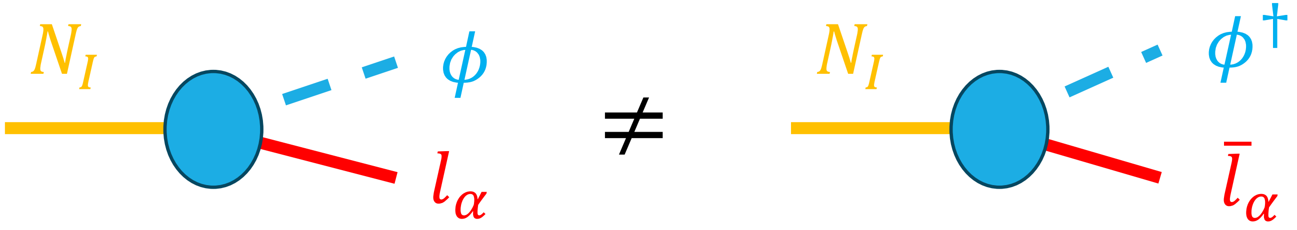

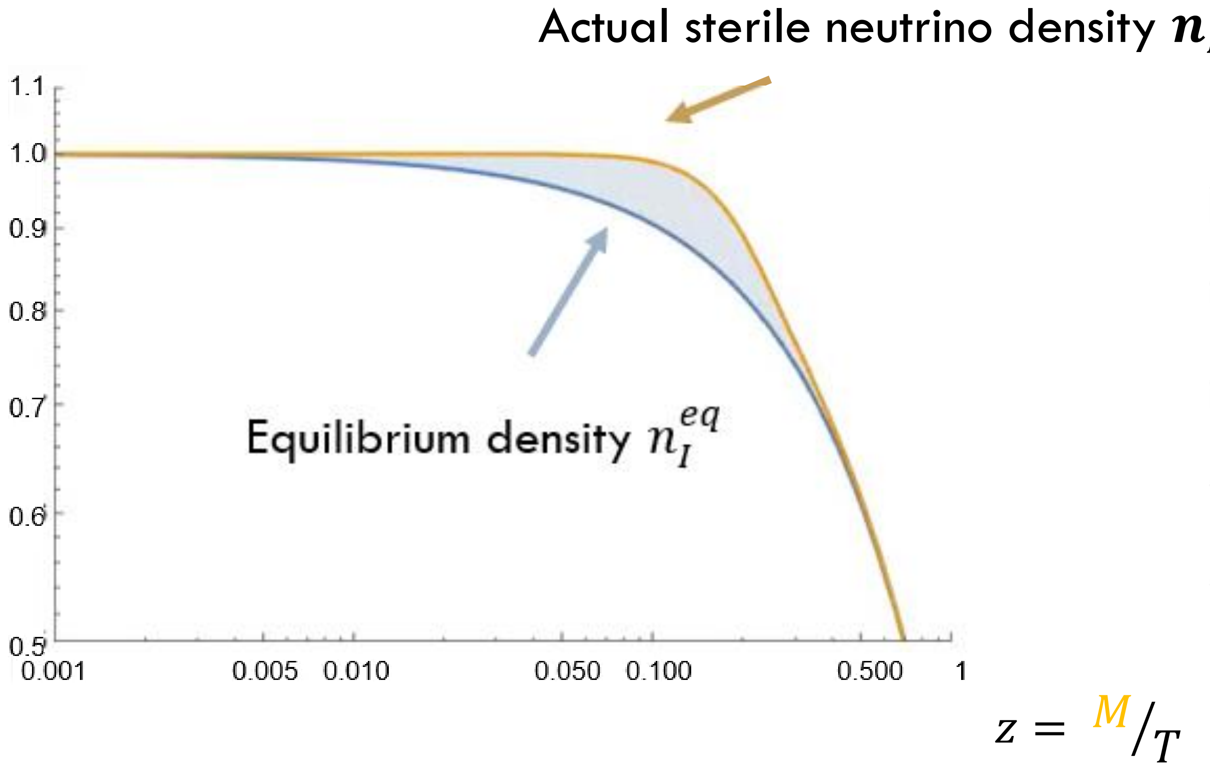

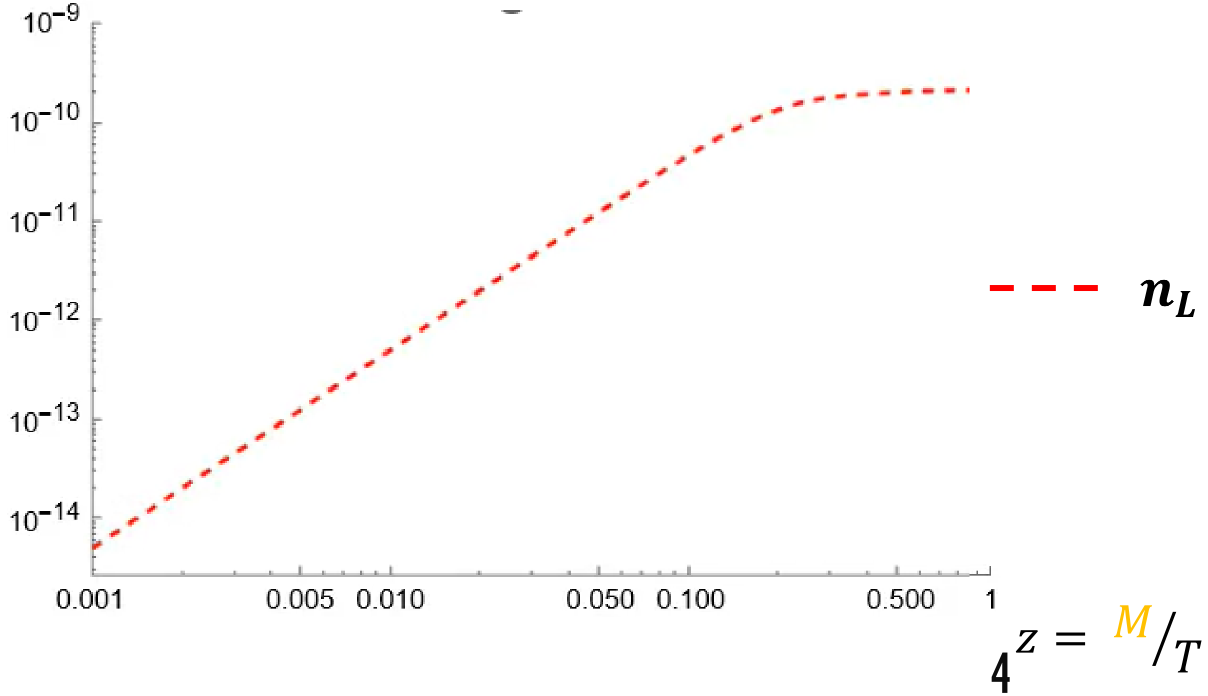

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[Akhmedov, Rubakov, Smirnov, '98]

As they are being **produced in the interaction basis (*Y*)**, sterile neutrinos **oscillate** between **different mass eigenstates (M_I)**.

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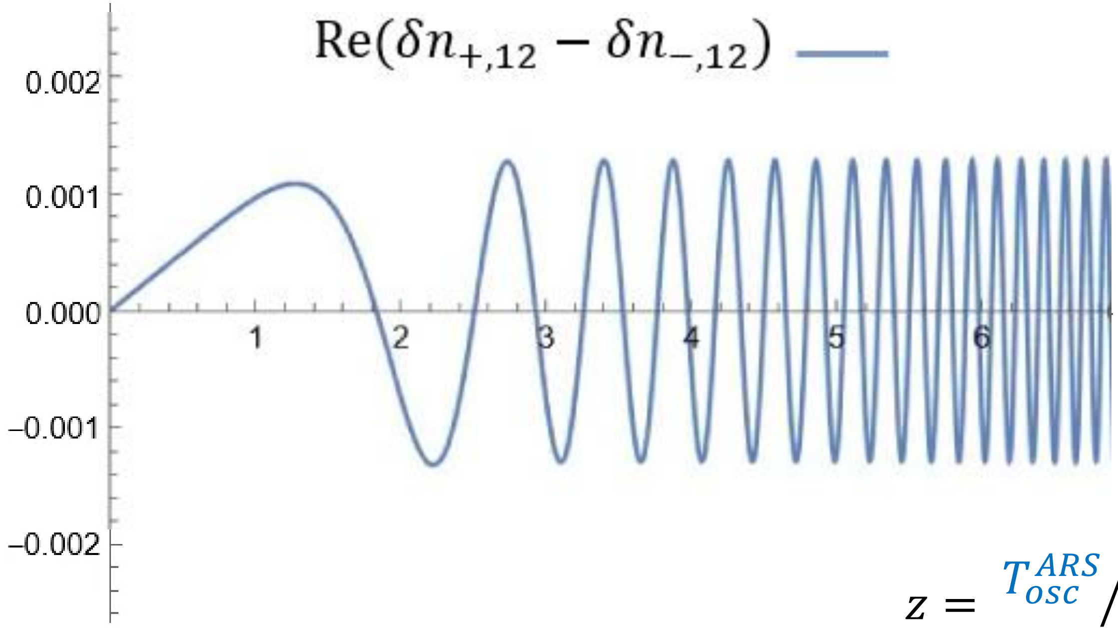
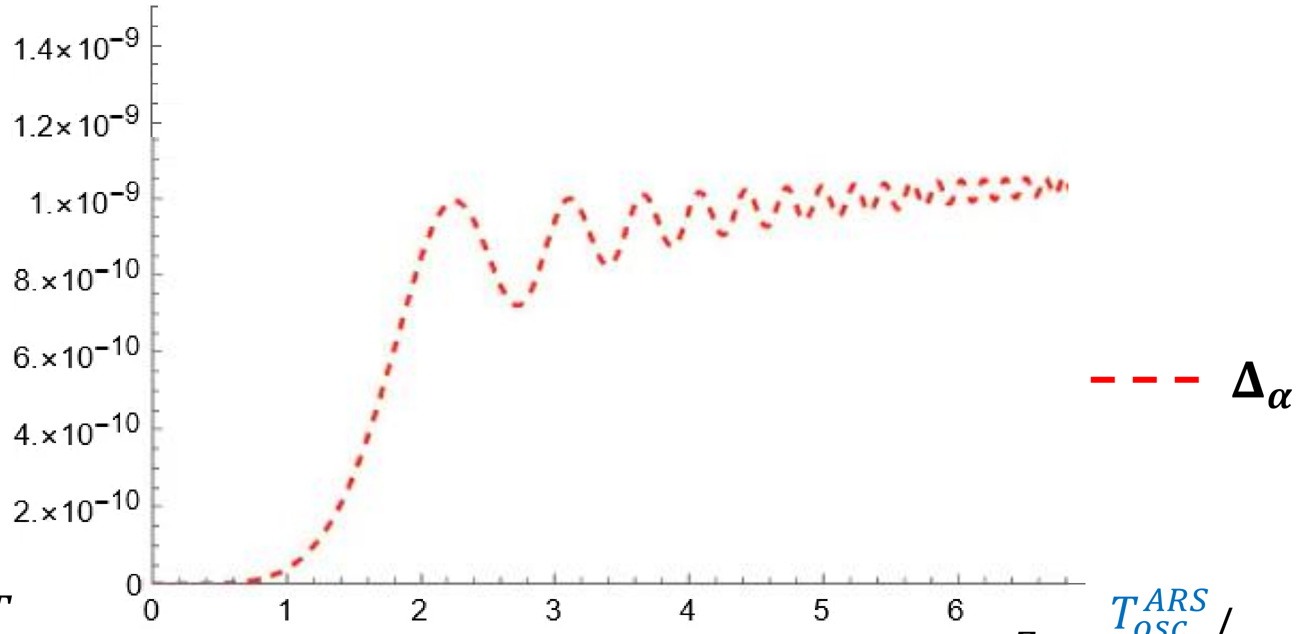


$z = T_{osc}^{ARS}/T$



$z = T_{osc}^{ARS}/T$

$$\boldsymbol{\delta n_h} = \begin{pmatrix} \boldsymbol{n_{1,h}} - n_1^{eq} & \delta n_{h,12} \\ \delta n_{h,12}^* & \boldsymbol{n_{2,h}} - n_2^{eq} \end{pmatrix}$$

$$T_{osc}^{ARS} \equiv \left(a_R\left(M_2^2 - M_1^2\right)\right)^{1/3}$$

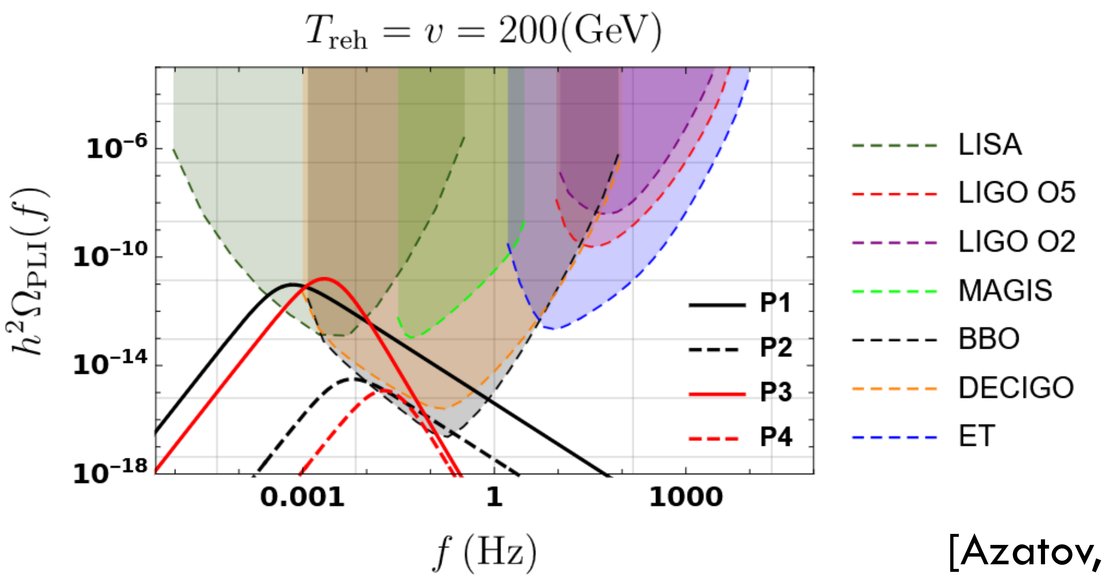
$a_R \simeq 7 \times 10^{17}\text{GeV}$

2. STERILE NEUTRINOS AND PHASE TRANSITION

WHY COSMOLOGICAL PHASE TRANSITIONS?

- Naturally appear in GUTs or conformal models (extra scalar fields)

- Produce **Gravitational Waves** (GW) that can be detected



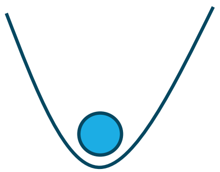
P1,P2: phase transitions with fast-accelerating bubbles
P3,P4: phase transitions with finite velocity bubbles

[Azatov, Vanvlasselaer, Yin, 21']

Phase transition in leptogenesis:

$$M_I \bar{N}_I^c N_I \to \lambda_I \, S \, \bar{N}_I^c N_I$$

At some temperature T_n:



$< S > = 0$

$\boldsymbol{M = 0}$

$< S > \neq 0$

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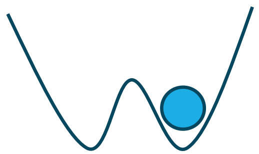

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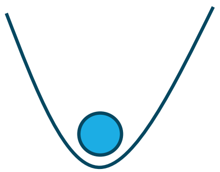

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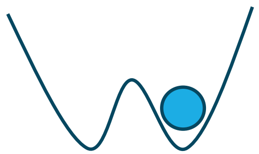
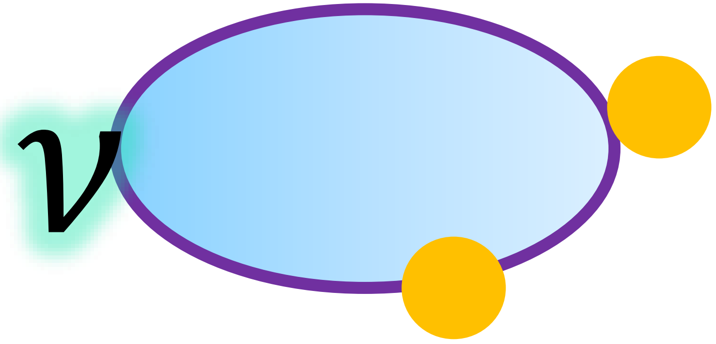


Question

How does a **phase transition** modify standard **leptogenesis** (with sterile neutrinos)?

3. STERILE NEUTRINOS WITH **TIME-DEPENDENT MASSES**



« THERMAL-LIKE »: MASS GAIN MECHANISM

[Baldes et al., '21]
[Huang, Xie, '22]
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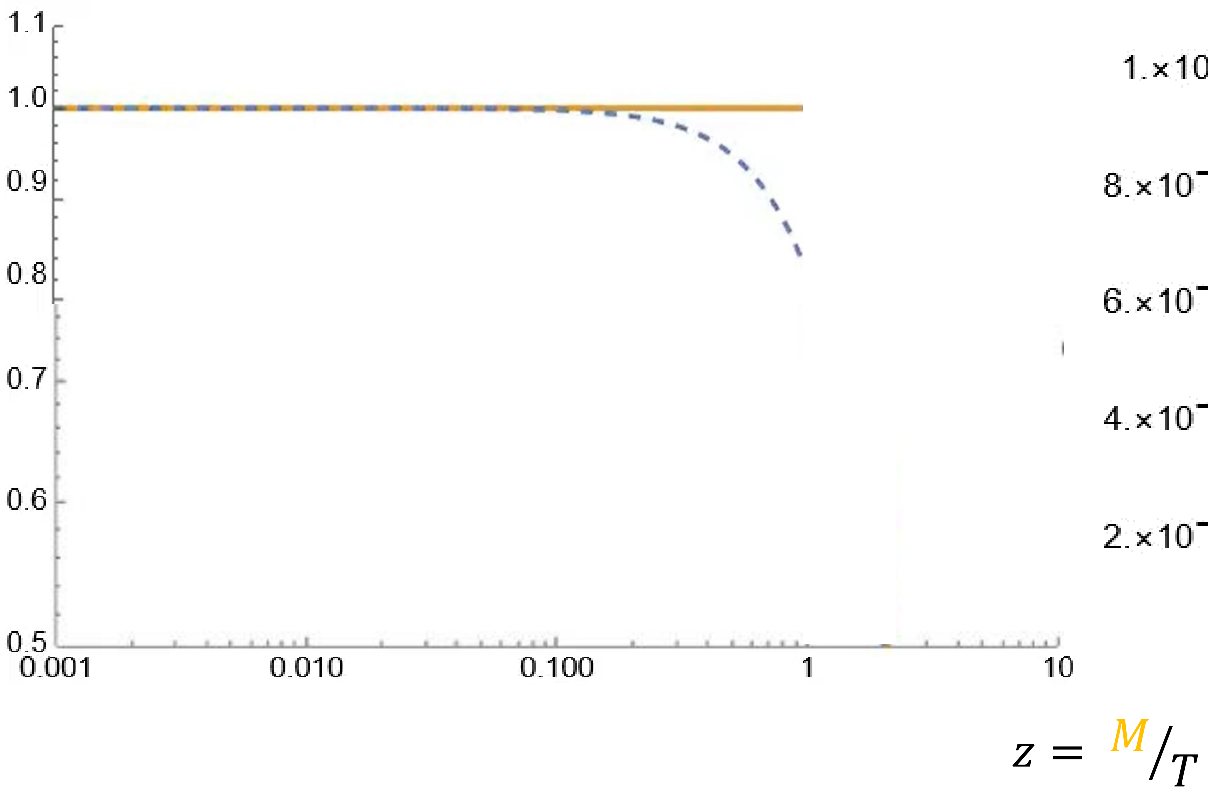
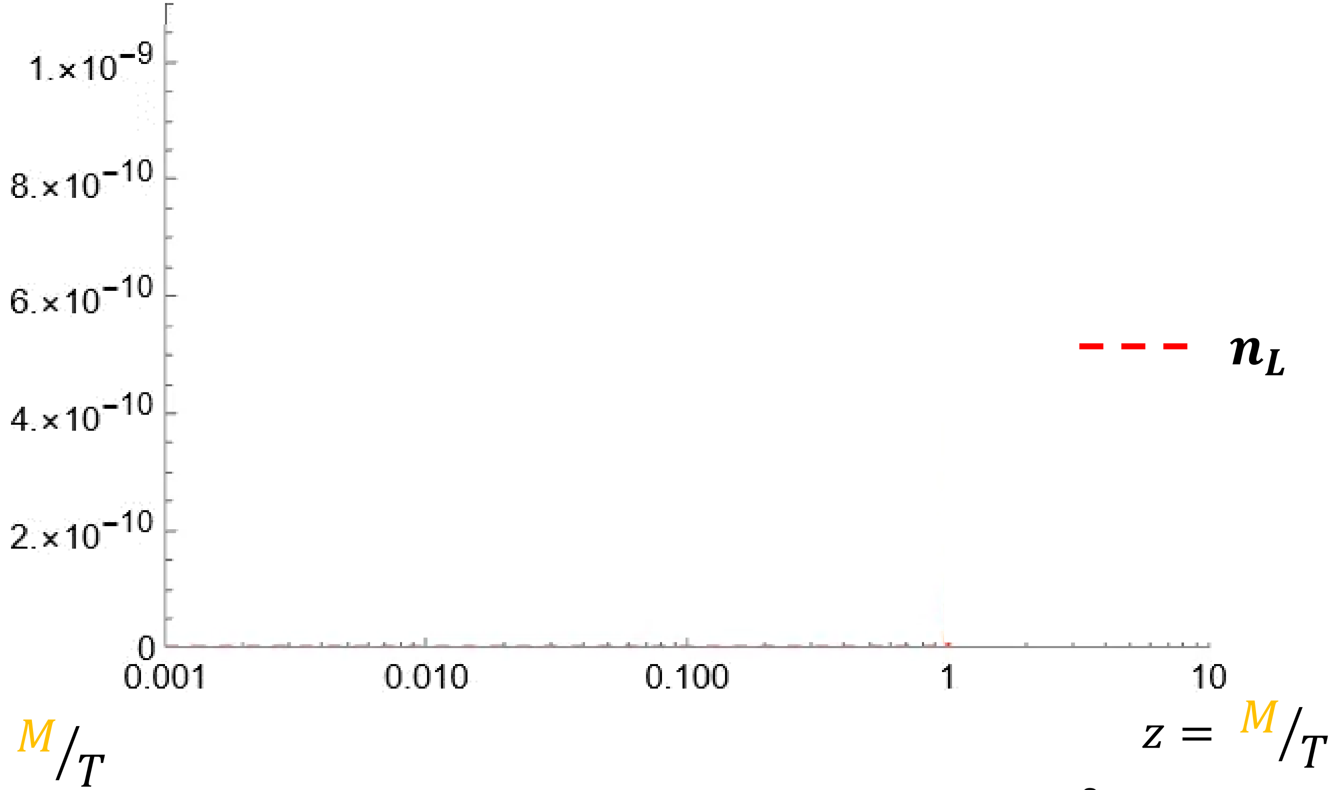
After the phase transition, sterile neutrinos become **very massive** ($M \gg T_n$), are (suddenly) out-of-equilibrium and **quickly decay**.





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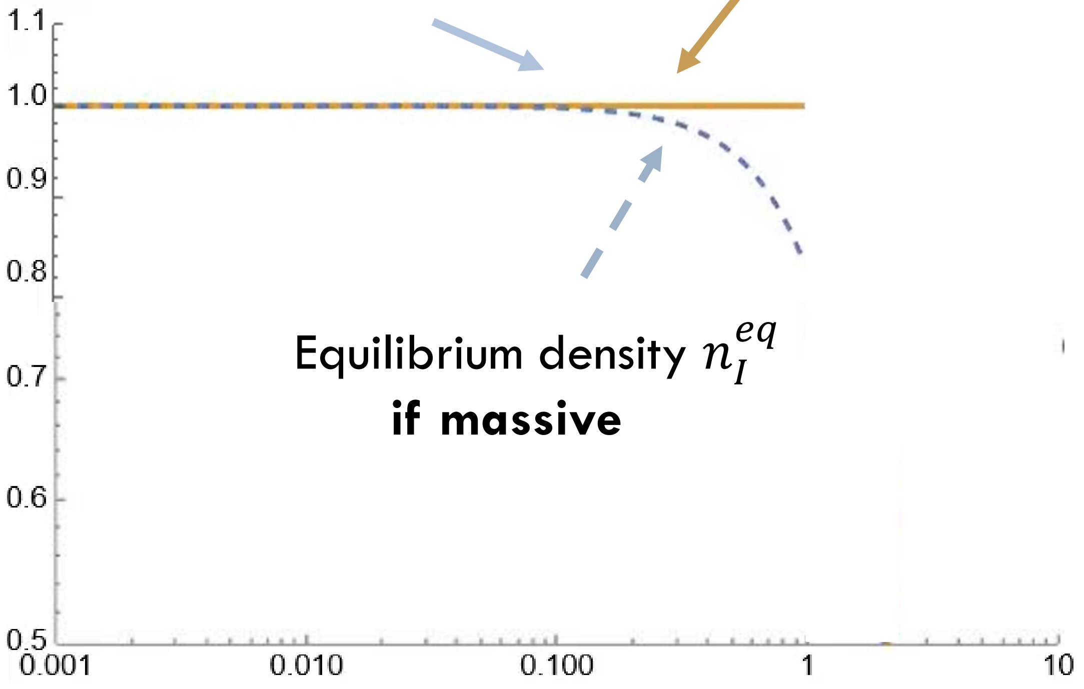
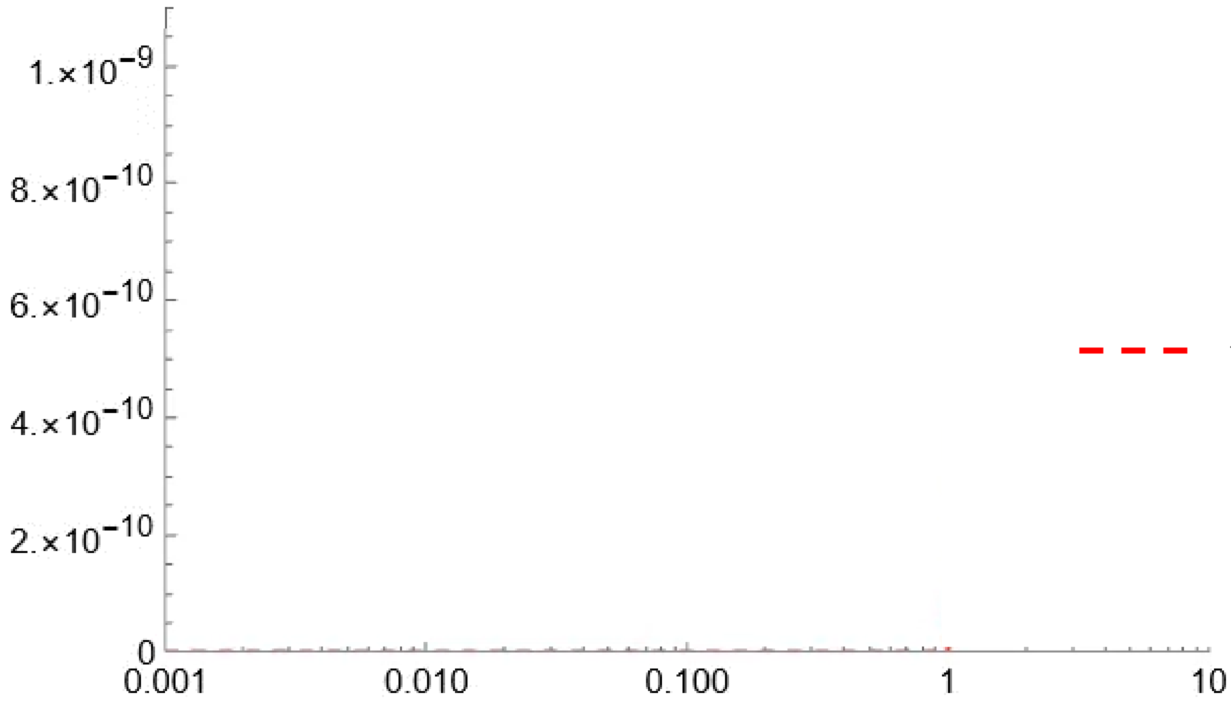
massless equilibrium n_I^{eq} = Actual sterile neutrino density $\boldsymbol{n_I}$



Equilibrium density n_I^{eq} **if massive**

$z = M/T$



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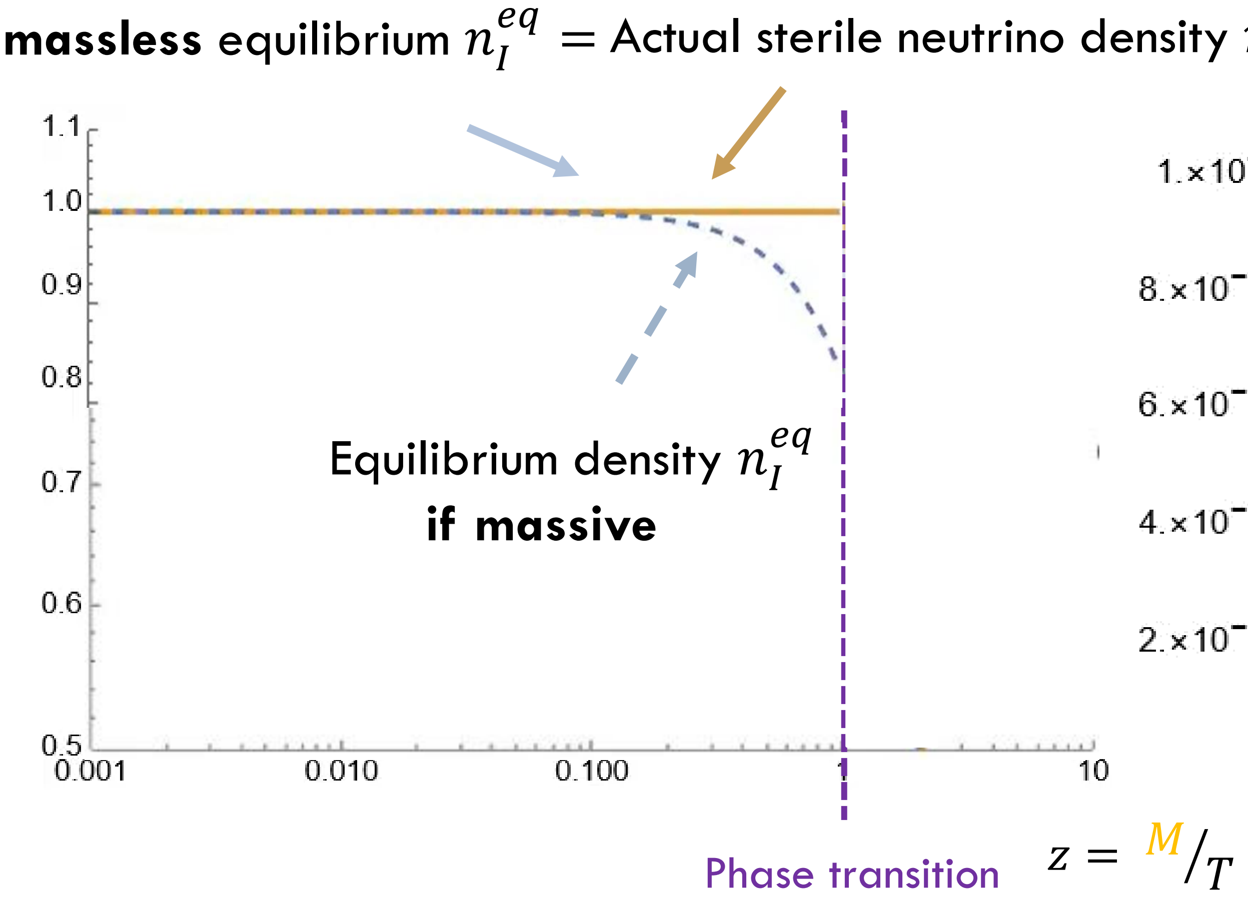

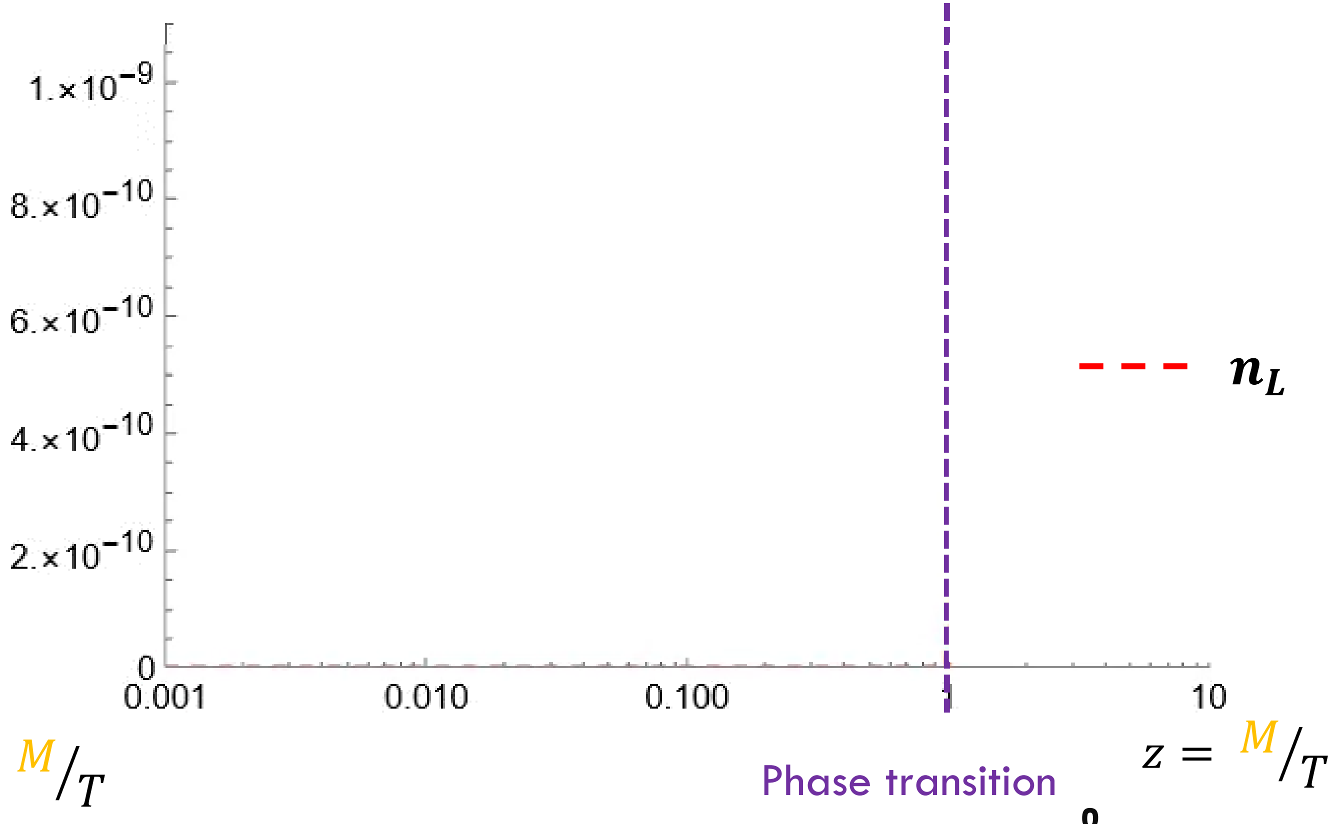

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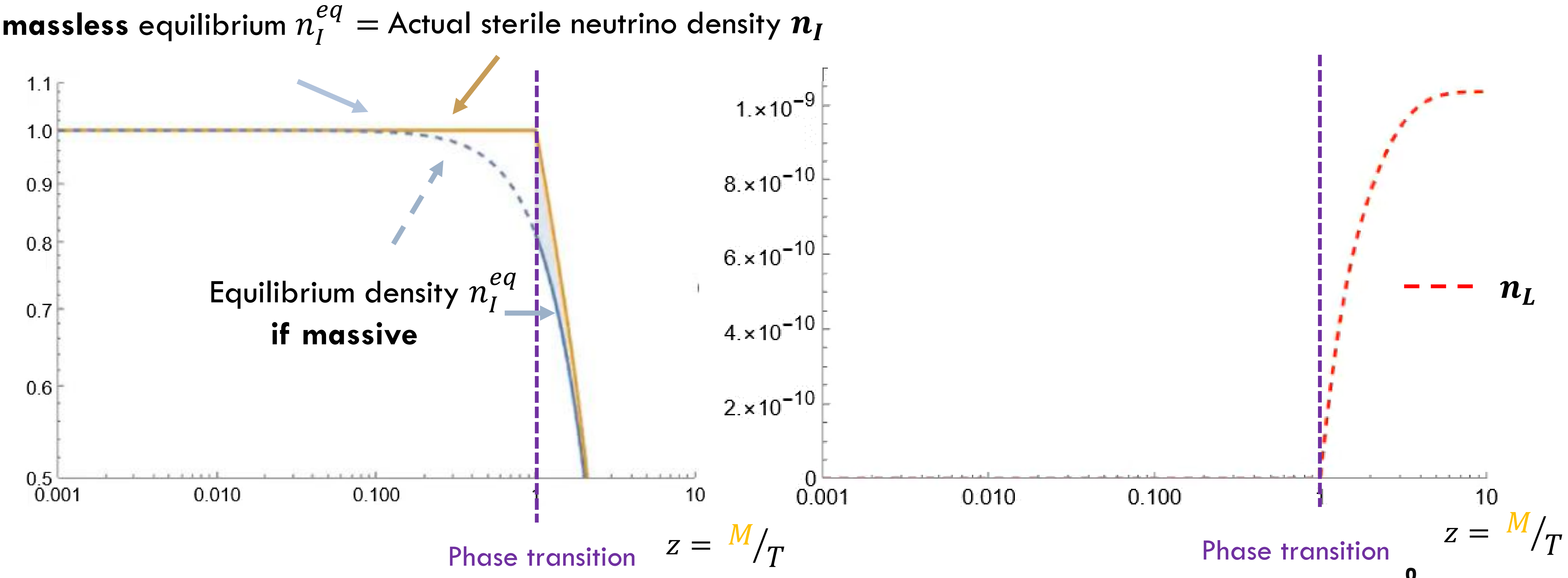
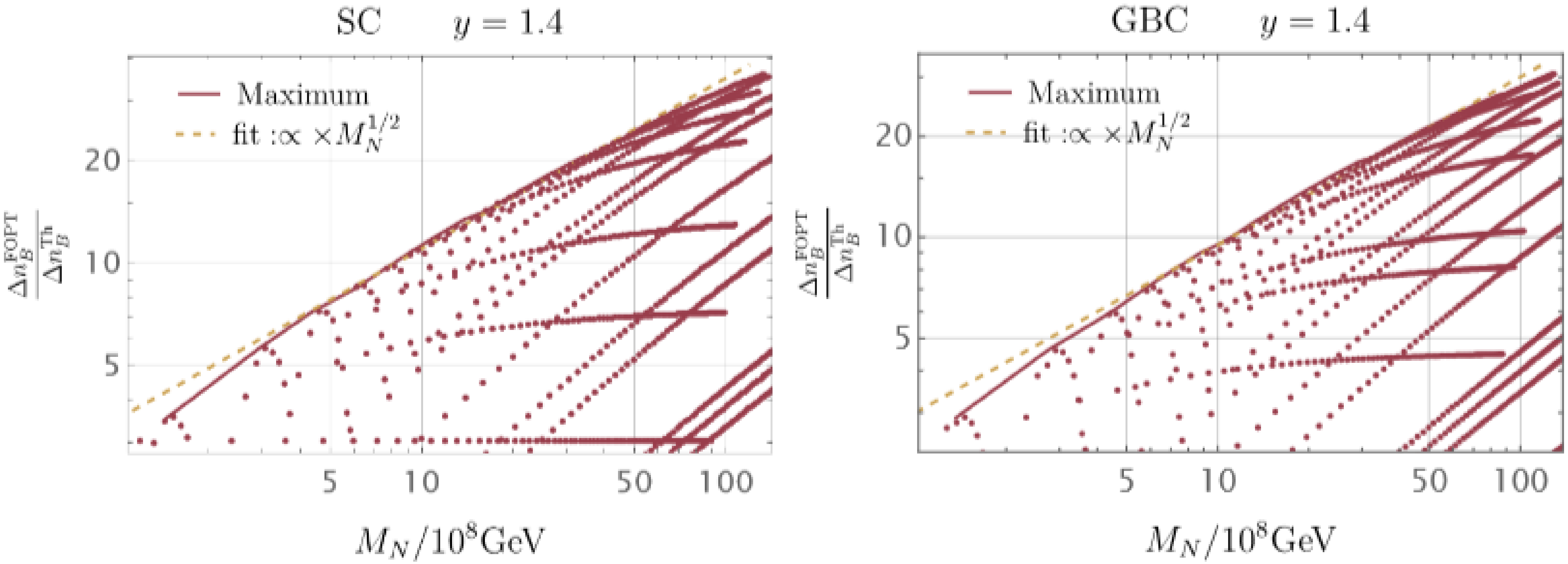


Comparison of thermal leptogenesis with/without a phase transition



Adapted from
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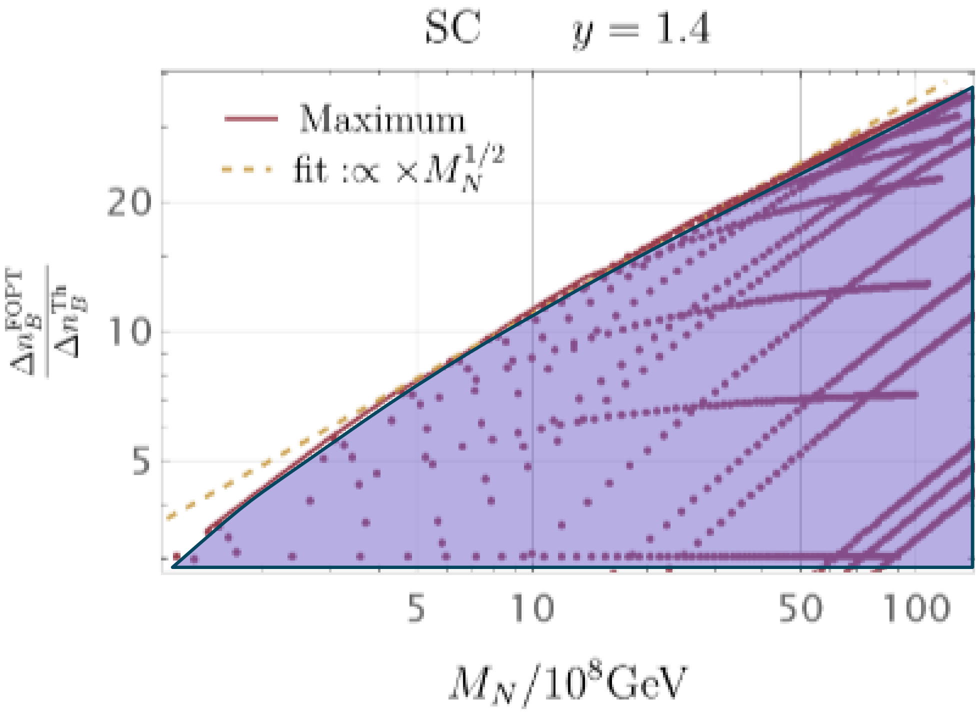
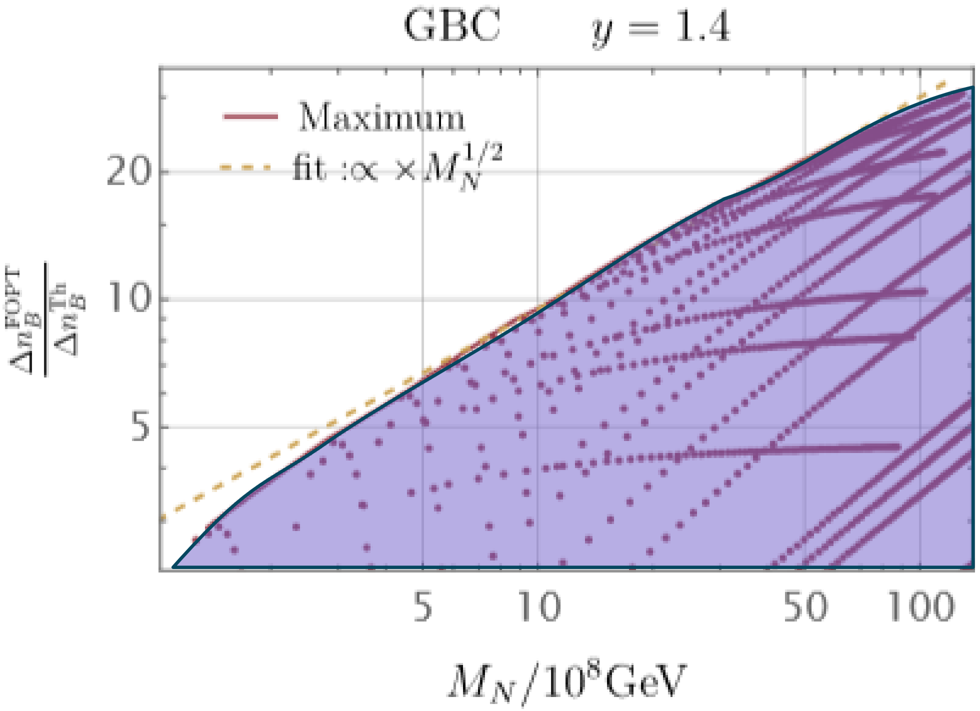




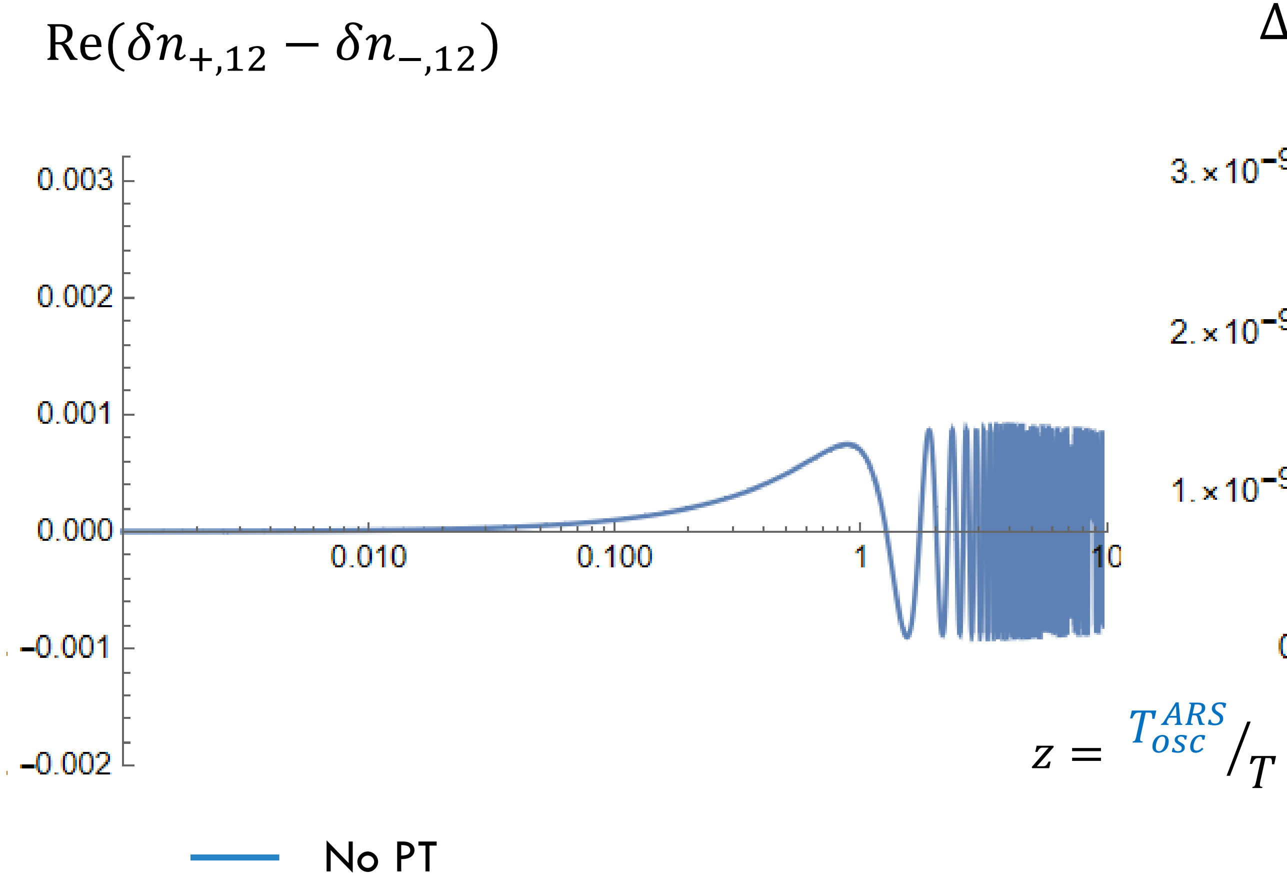
More asymmetry produced in the phase transition scenario for $M_N > 10^8$ GeV

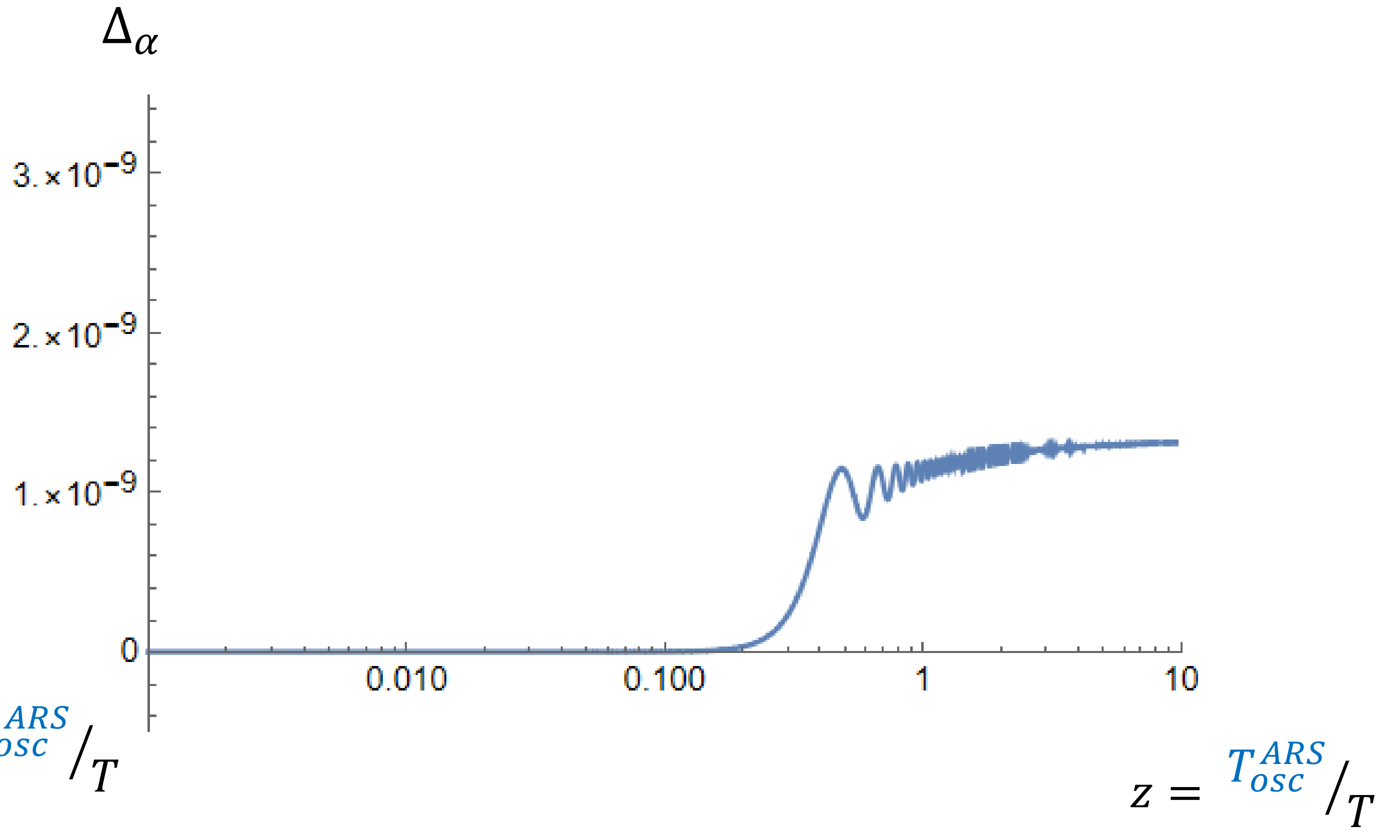
Adapted from [Chun, Dutka, Jung, Nagels, Vanvlasselaer, '23]

« ARS-LIKE »: STERILE NEUTRINO **OSCILLATIONS**

[RF, Lavignac, 2504.XXXXX]

Initially, sterile neutrinos are **absent** in the plasma and **massless.** They **cannot undergo vacuum oscillations**, before the PT: oscillations are frustrated.





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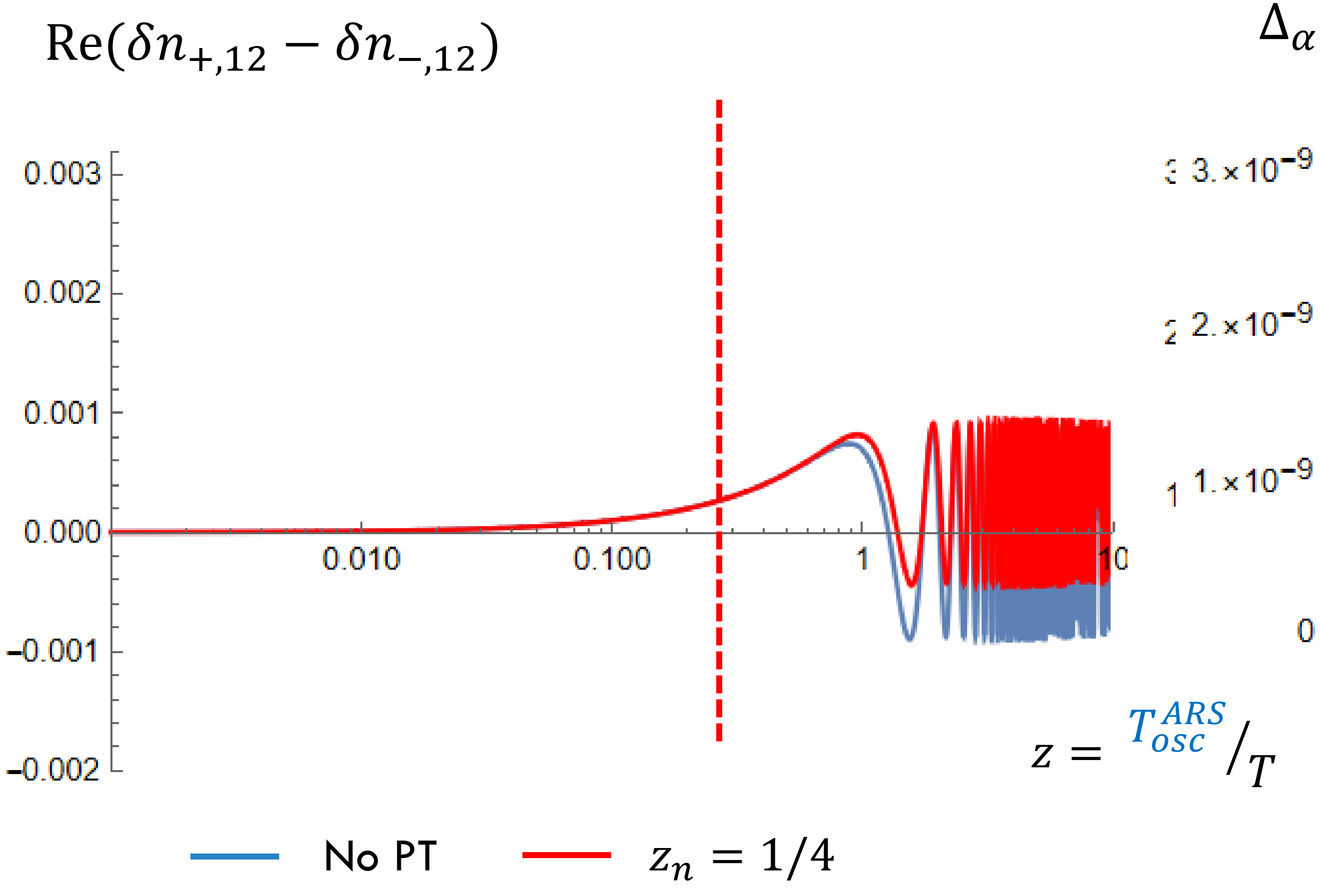

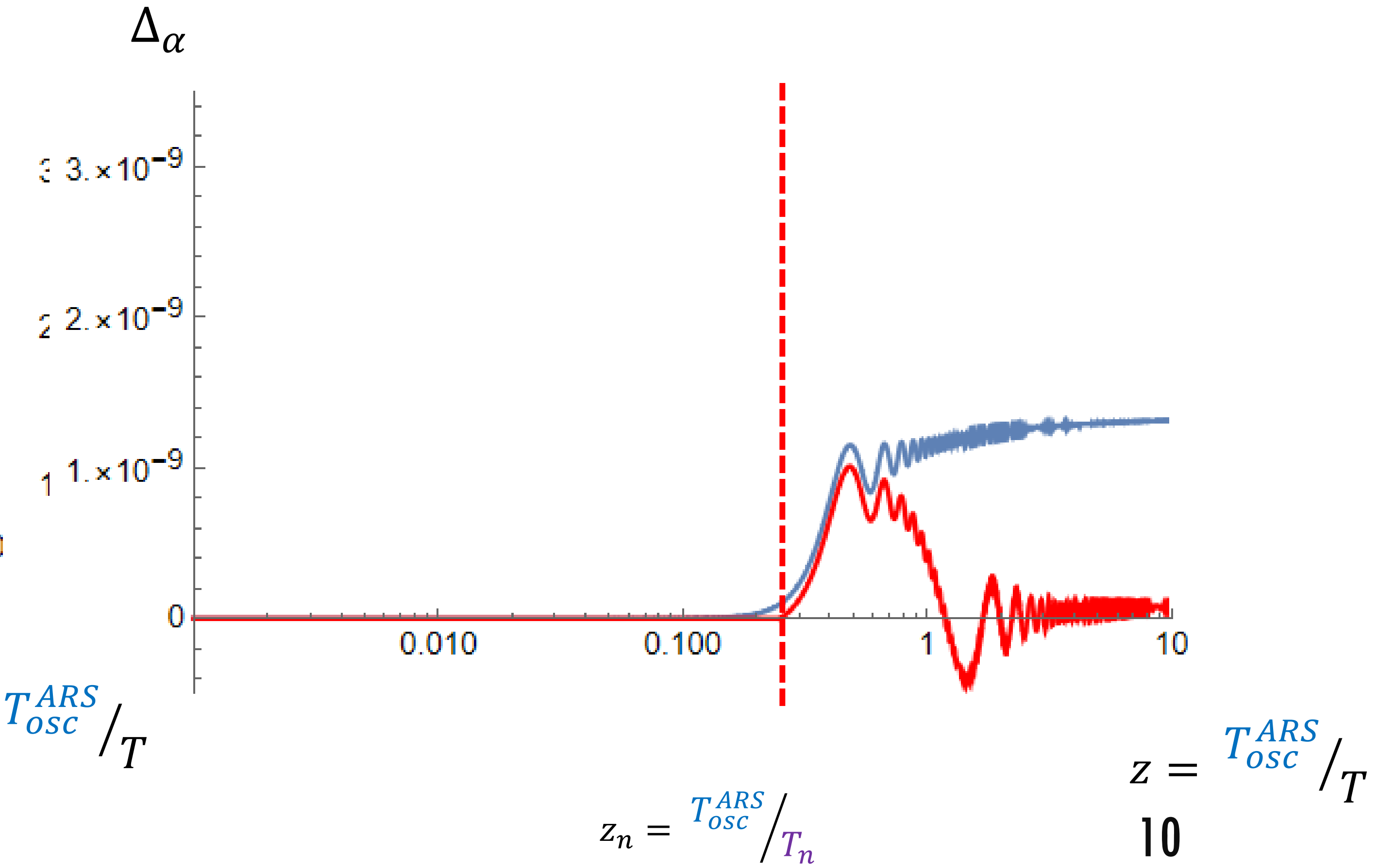

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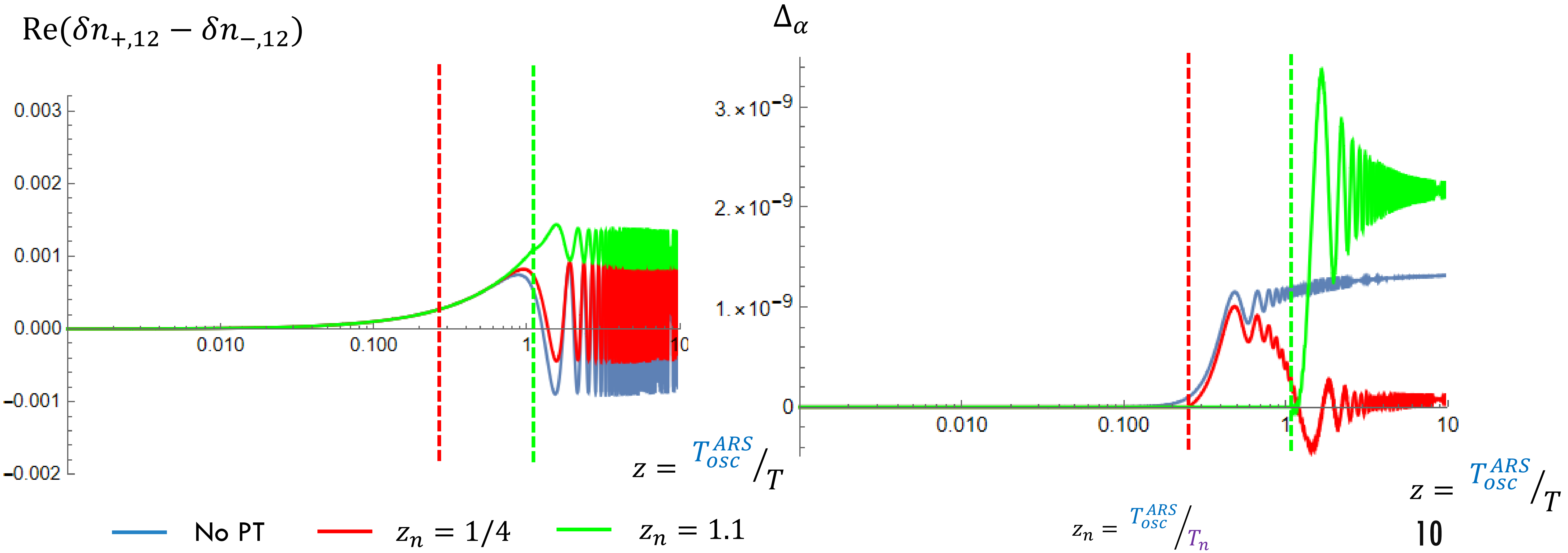

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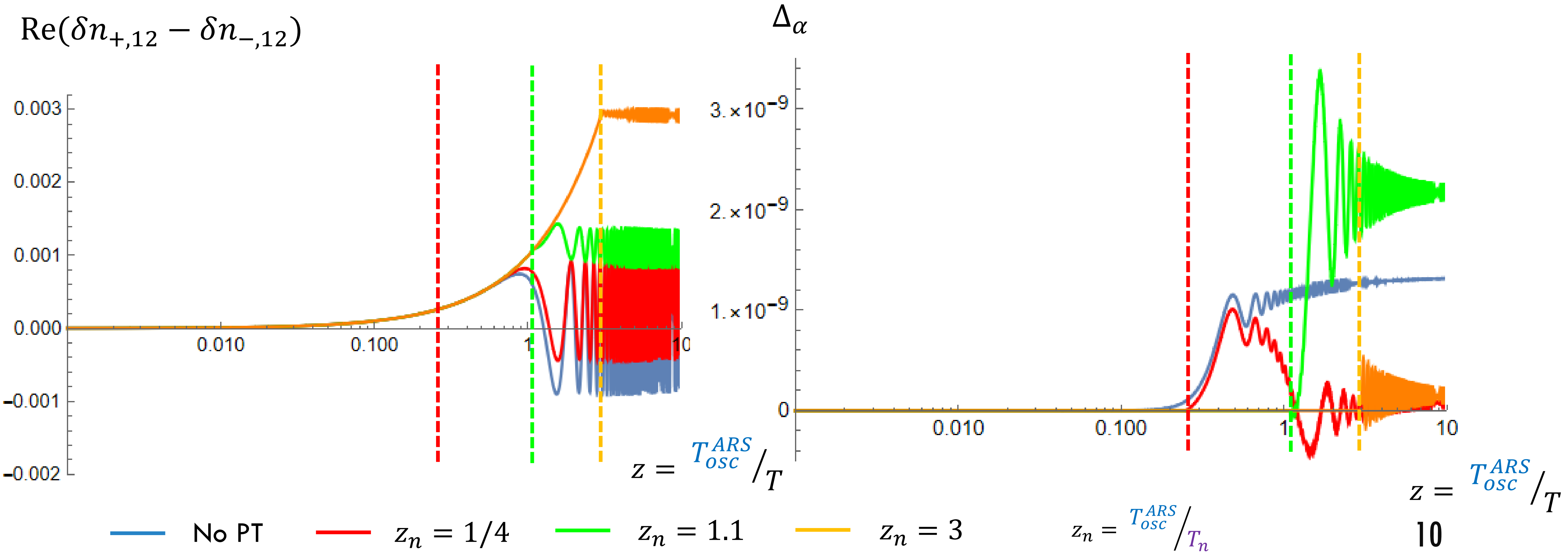
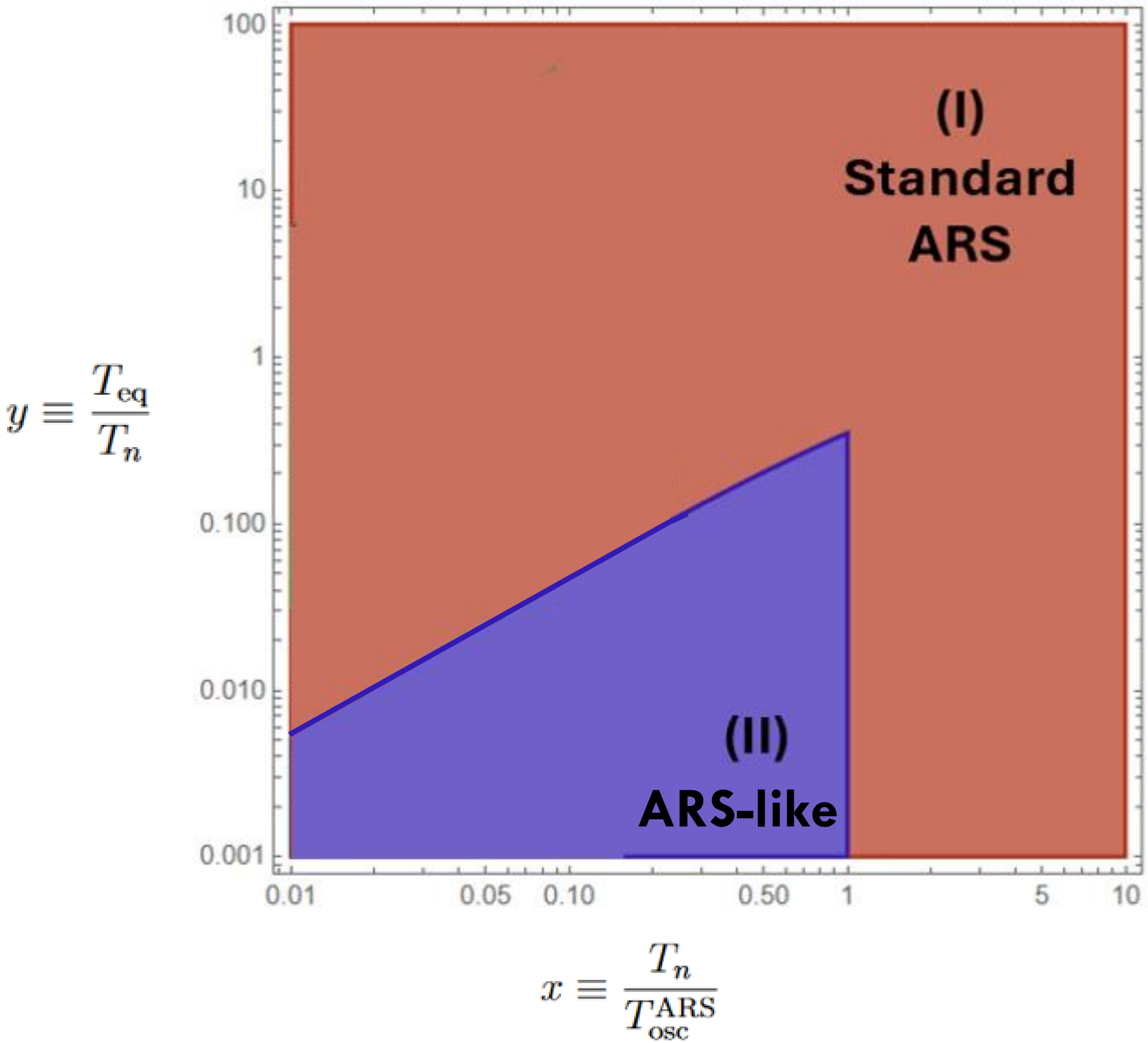


Comparison of ARS without (I) and with (II) a phase transition



T_{osc}^{ARS} = oscillation temperature

$$\equiv \left(a_R (M_2^2 - M_1^2)\right)^{1/3}$$

$a_R \simeq 7 \times 10^{17}\,\mathrm{GeV}$

T_{eq} = equilibration temperature

$$\equiv \Gamma^{-1} = \left(a_R \gamma_+ (YY^\dagger)\right)^{-1}$$

$\gamma_+ \simeq 0.012$

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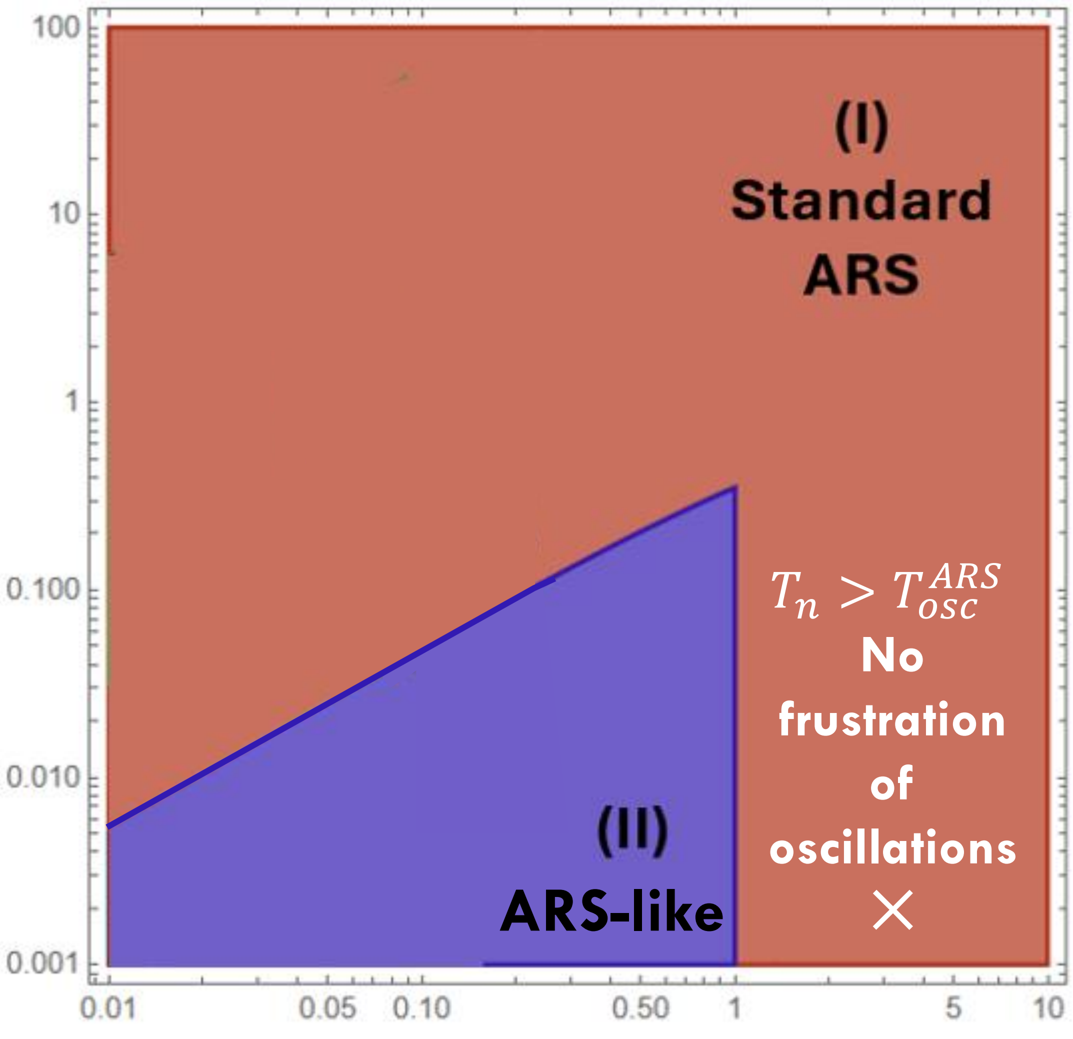

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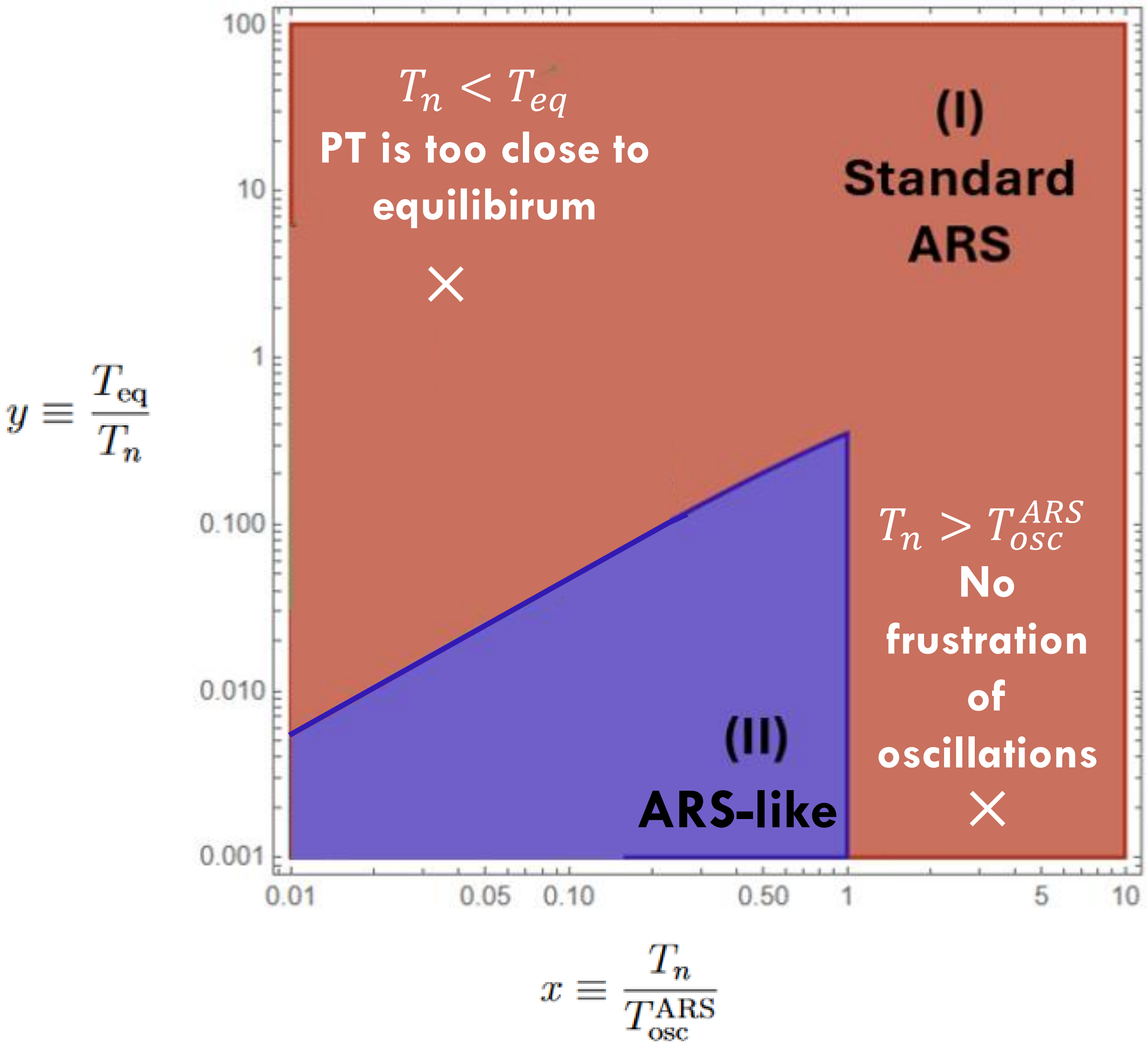

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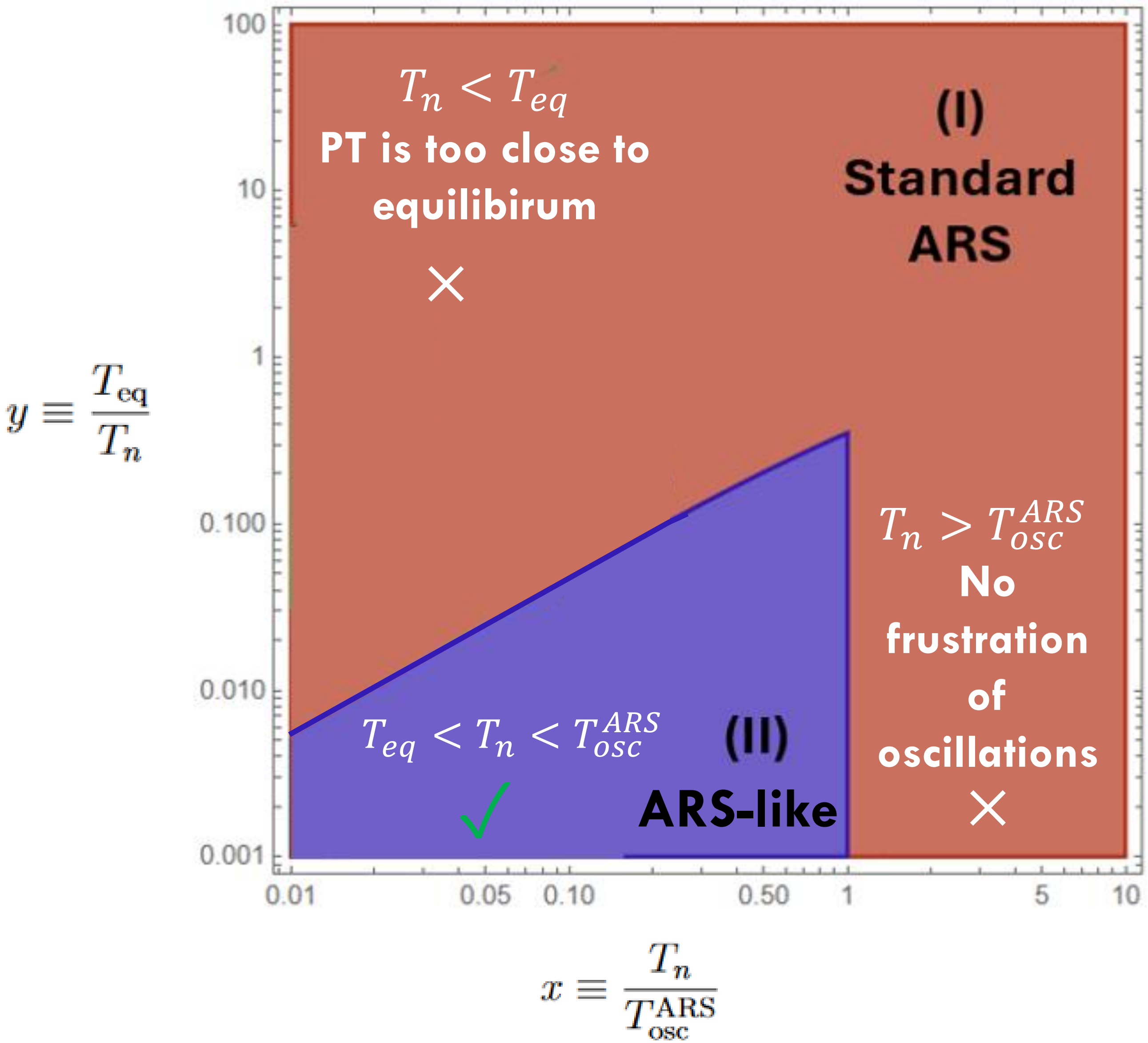

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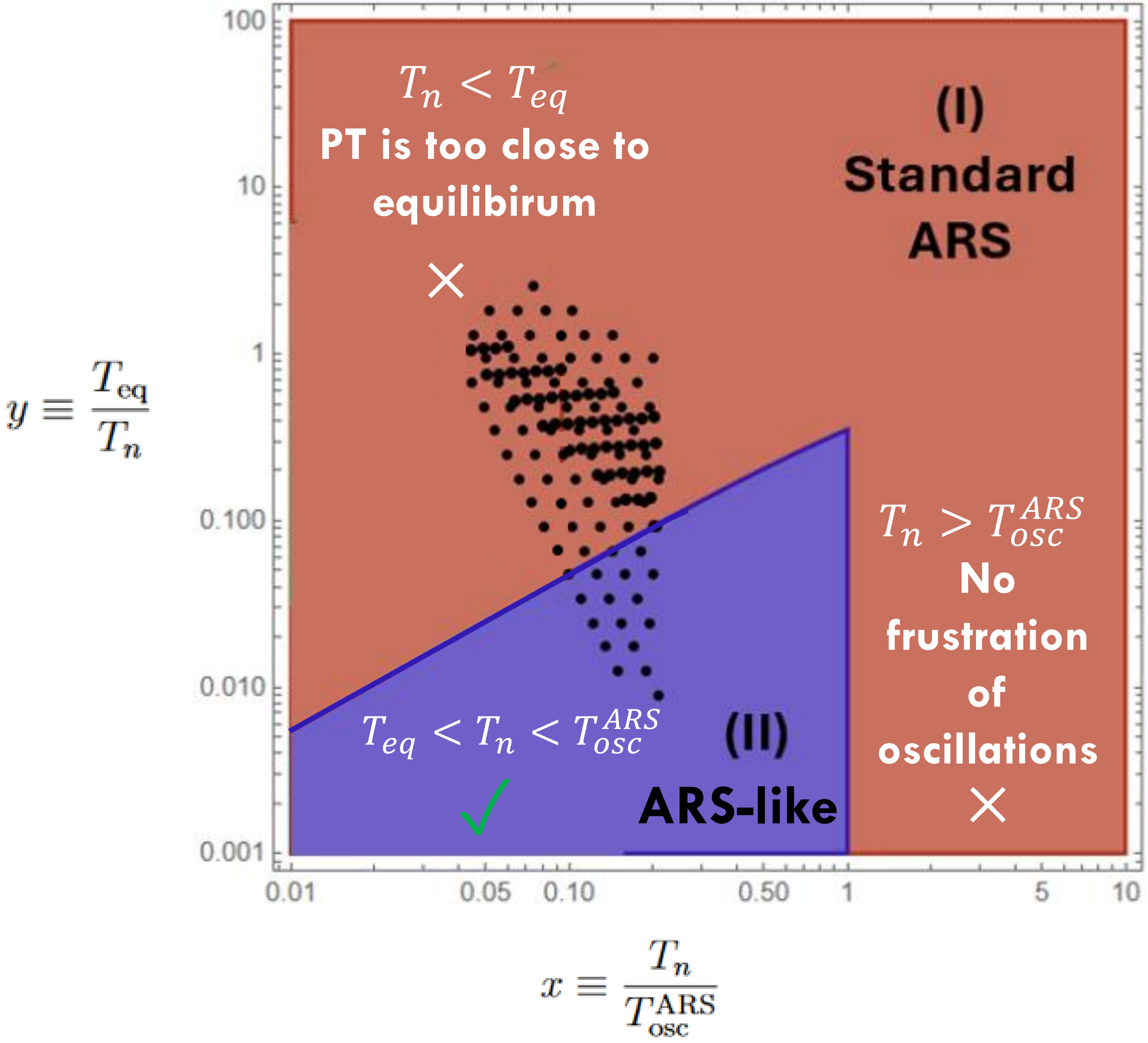

- Successful leptogenesis (full numerical study **with** a PT)

$$T_{osc}^{ARS} = \text{oscillation temperature}$$

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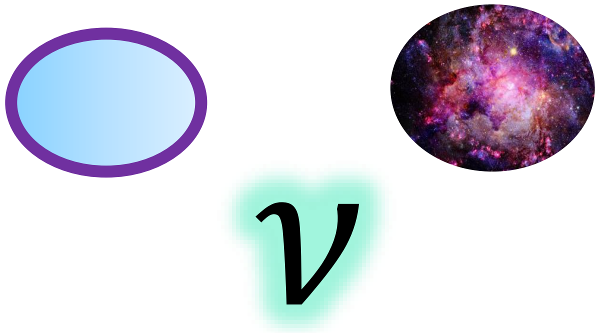
SUMMARY AND CONCLUSION



Question

- Leptogenesis: relates cosmological observations $\eta_B \equiv \frac{n_B}{n_\gamma}$ to properties of particles (sterile neutrinos)

- Connects to Gravitational Waves detection if involves a phase transition

- Phase transitions can enhance the asymmetry production and allow a larger parameter space

True vacuum

ν

Thank you for your attention!

BACK-UP SLIDES

Baryon-to-photon ratio $\eta_B \equiv \frac{n_B}{n_\gamma} = (6.13 \pm 0.04) \times 10^{-10} \simeq \frac{n_B - \bar{n}_B}{n_\gamma}$

[Planck2018]

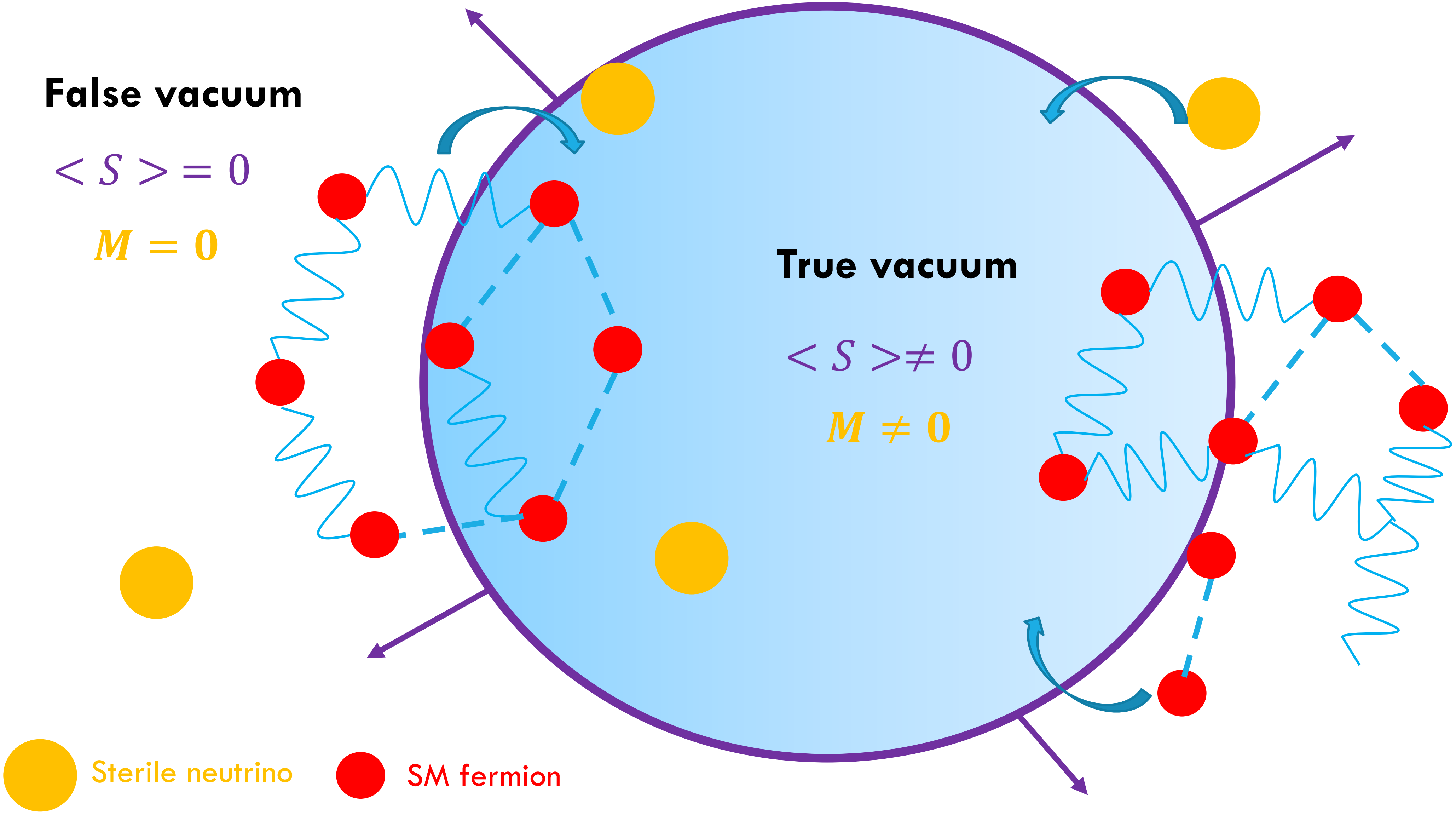
Sakharov conditions for generation of matter-antimatter asymmetry (1967):

- **Baryon/Lepton number violation**
- **C (Charge) and CP (Charge-Parity) violation**
- **Out of Equilibrium**

Andreï Sakharov

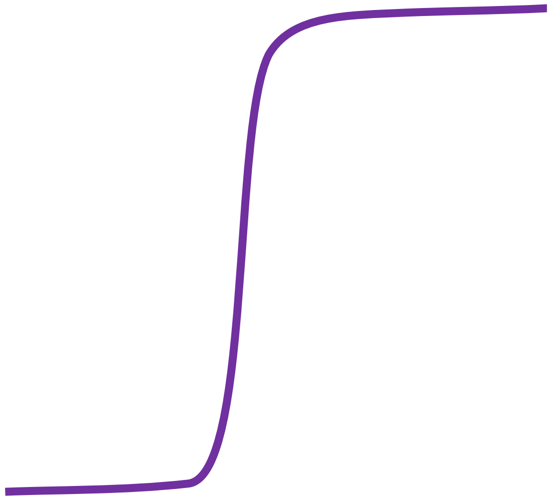
$$M_I \overline{N}_I^c N_I \rightarrow \lambda_I \, S \, \overline{N}_I^c N_I$$

At the nucleation temperature T_n



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

$< S > (t)$



$$M_I = \lambda^I_{NS} < S > (t) = M_I(t)$$

Aside: parameter space $\quad -1/2\, M_I \bar{N}_I^c N_I - Y_{I\alpha} \bar{N}_I \tilde{\phi}^\dagger l_\alpha$

- **Sterile neutrinos**

Casas-Ibarra parametrization: $$Y \equiv \frac{i\sqrt{2}}{v} \underbrace{\sqrt{\mathcal{M}}\boldsymbol{R}}_{\text{Parameters}} \overbrace{\sqrt{m}U_{PMNS}^\dagger}^{\text{Observable at low-energy}}$$

+ fix $\delta_{CP} = \frac{3\pi}{2}, \alpha = 0$

$m_1 = 0$ (normal ordering)

[Casas, Ibarra, '01]

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}$$

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

$$\boxed{M \equiv \frac{M_1 + M_2}{2}, \Delta M = M_2 - M_1}$$

complex angle $\hat{\boldsymbol{z}}$

- **Phase transition** $\quad$ Nucleation temperature T_n

ADVANTAGES OF A PHASE TRANSITION

Nonequilibrium dynamics

$$< S > = < S > (t)$$

$$M_I = M_I(t)$$

(3rd Sakharov condition)

Different sterile neutrino constraints

$$M_I^{\text{High } T} \neq M_I^{\text{Low } T}$$

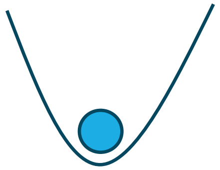
Gives the baryon asymmetry

Related to neutrino data by the Seesaw

$$L = L_{SM} + (i/2\, \bar{N}_I \gamma^\mu \partial_\mu N_I \; - 1/2\, M_I \bar{N}_I^c N_I - Y_{I\alpha} \bar{N}_I \tilde{\phi}^\dagger l_\alpha + h.c.)$$

$$L = L_{SM} + L_S + (i/2\, \bar{N}_I \gamma^\mu \partial_\mu N_I - 1/2\, \lambda_{NS}^I\, S \bar{N}_I^c N_I - Y_{I\alpha} \bar{N}_I \tilde{\phi}^\dagger l_\alpha + h.c.)$$

$M_I = \lambda_{NS}^I < S >$ New dynamics for the sterile sector: **Phase Transition (PT)**

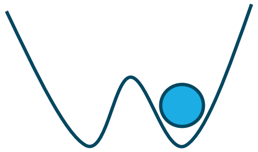


$< S > = 0$

$\boldsymbol{M = 0}$

$< S > \neq 0$

$\boldsymbol{M \neq 0}$



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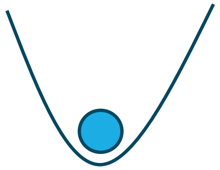

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$\Rightarrow$

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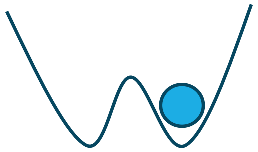
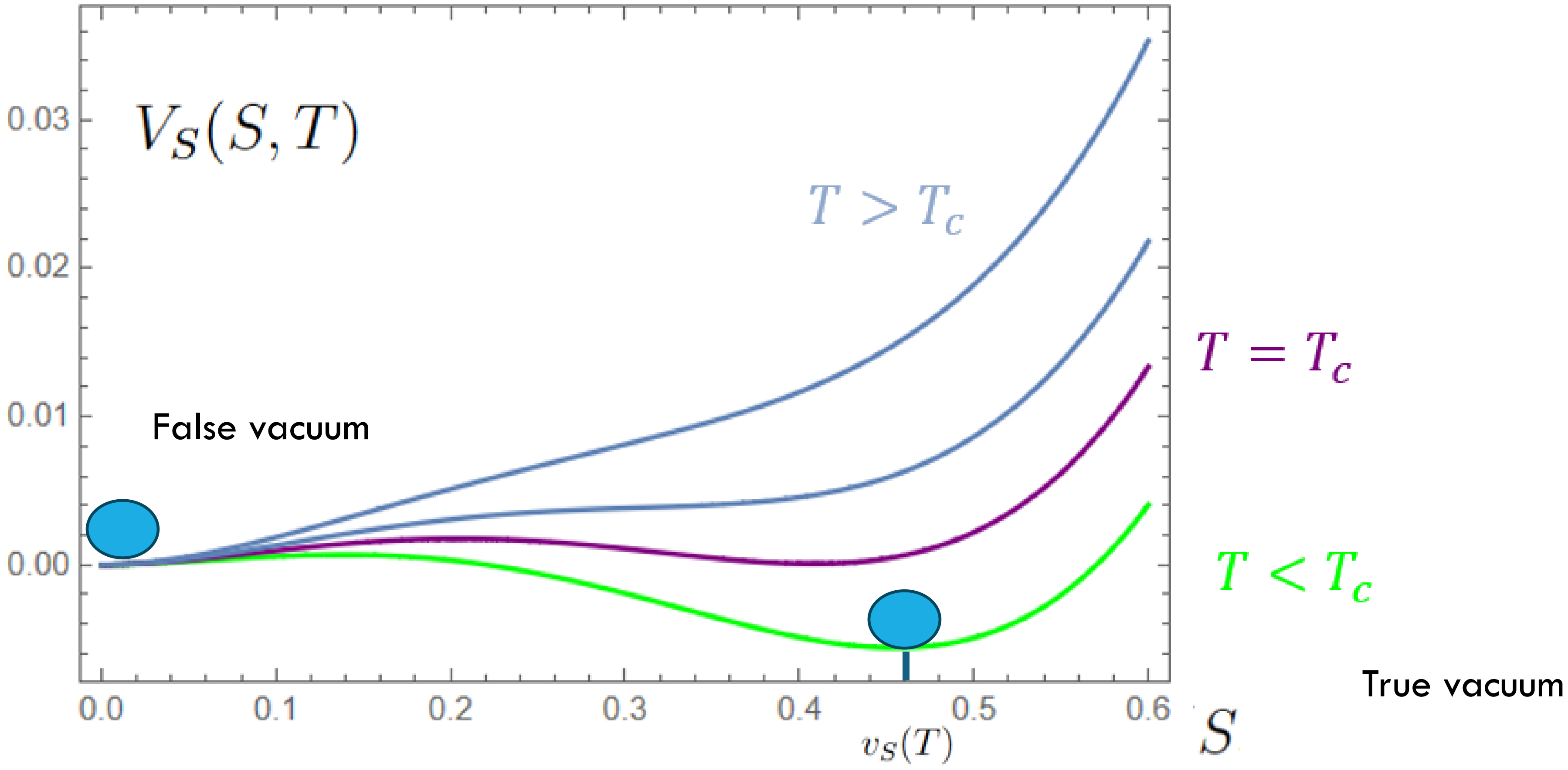


A **(first-order) phase transition** happens through the nucleation of bubbles of true vacuum, at a certain **nucleation temperature** T_n.

$L_S = (\partial S)^2 - V_S(S,T)$ Scalar potential V_S is responsible for the phase transition



Transition happens through the nucleation of bubbles of true vacuum, at a certain **nucleation temperature T_n**.