Reheating after the supercooled phase transitions with radiative symmetry breaking

Based on JCAP 02 (2026) 021, arXiv: 2507.21215 [hep-ph],FR, Alberto Salvio

Francesco Rescigno

University of Rome "Tor Vergata" & INFN

Hot Topics in Modern Cosmology, Spontaneous Workshop XVIII
September 13rd – 19th, 2026, IESC Cargese, France

INFN
Istituto Nazionale di Fisica Nucleare

TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Table of Contents

First order phase transitions (FOPTs)

Radiative symmetry breaking (RSB) & the Gildener-Weinberg scenario

Reheating after FOPT in Gildner-Weinberg Models: General Properties

Radiative Electroweak Symmetry Breaking (EWRSB)

Preheating after FOPT

Outline

First order phase transitions (FOPTs)

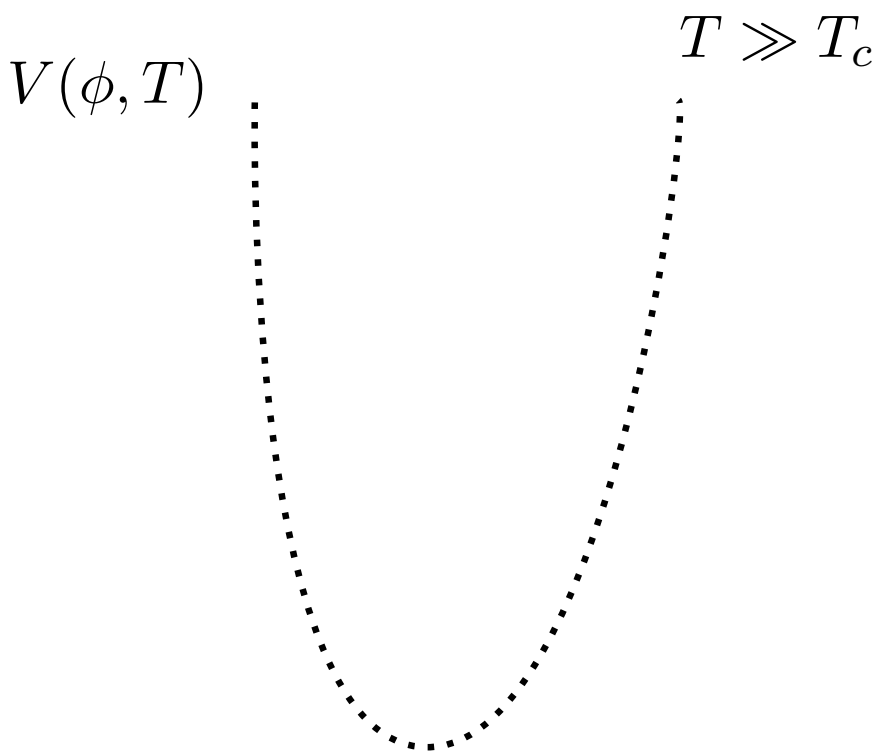
Radiative symmetry breaking (RSB) & the Gildener-Weinberg scenario

Reheating after FOPT in Gildner-Weinberg Models: General Properties

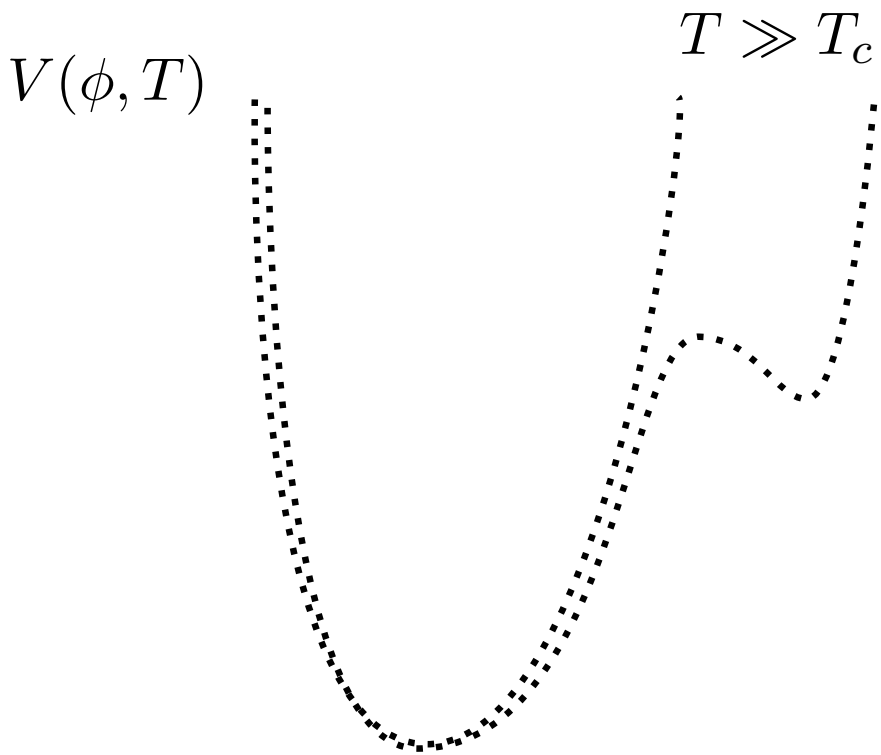
Radiative Electroweak Symmetry Breaking (EWRSB)

Preheating after FOPT

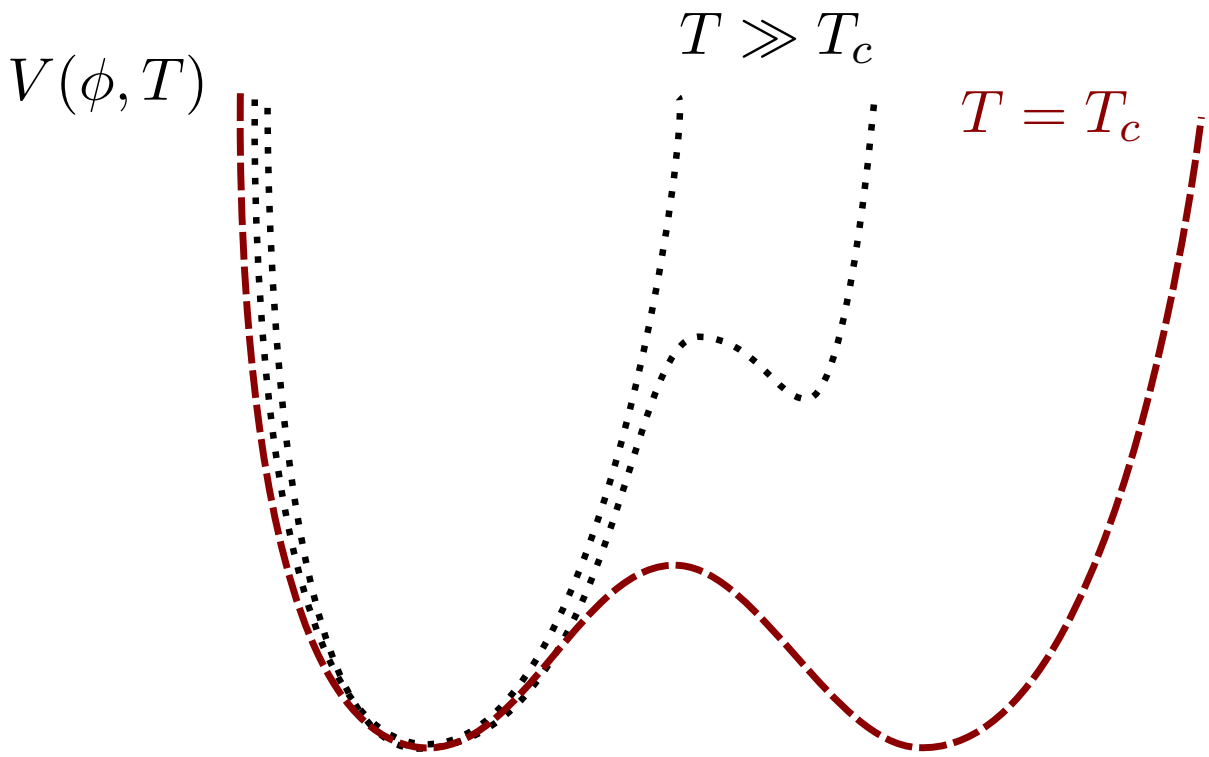
What is a first order phase transition (FOPT)?



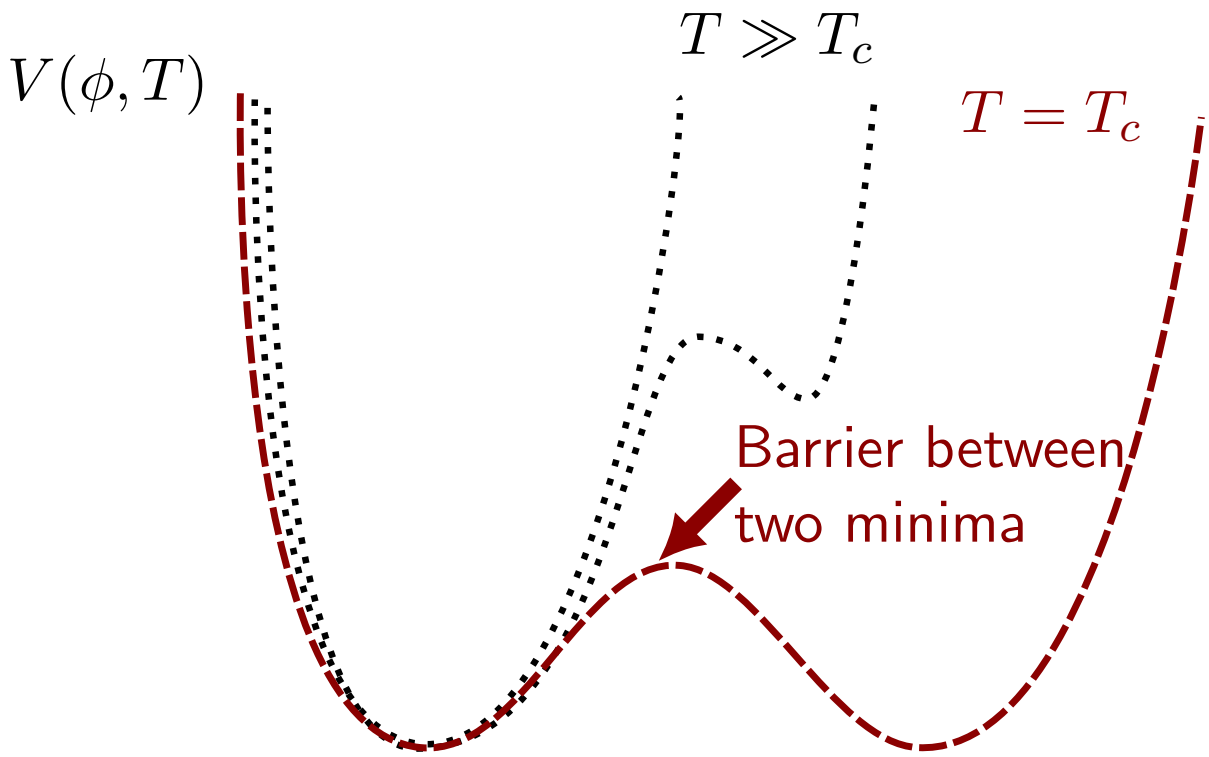
What is a first order phase transition (FOPT)?



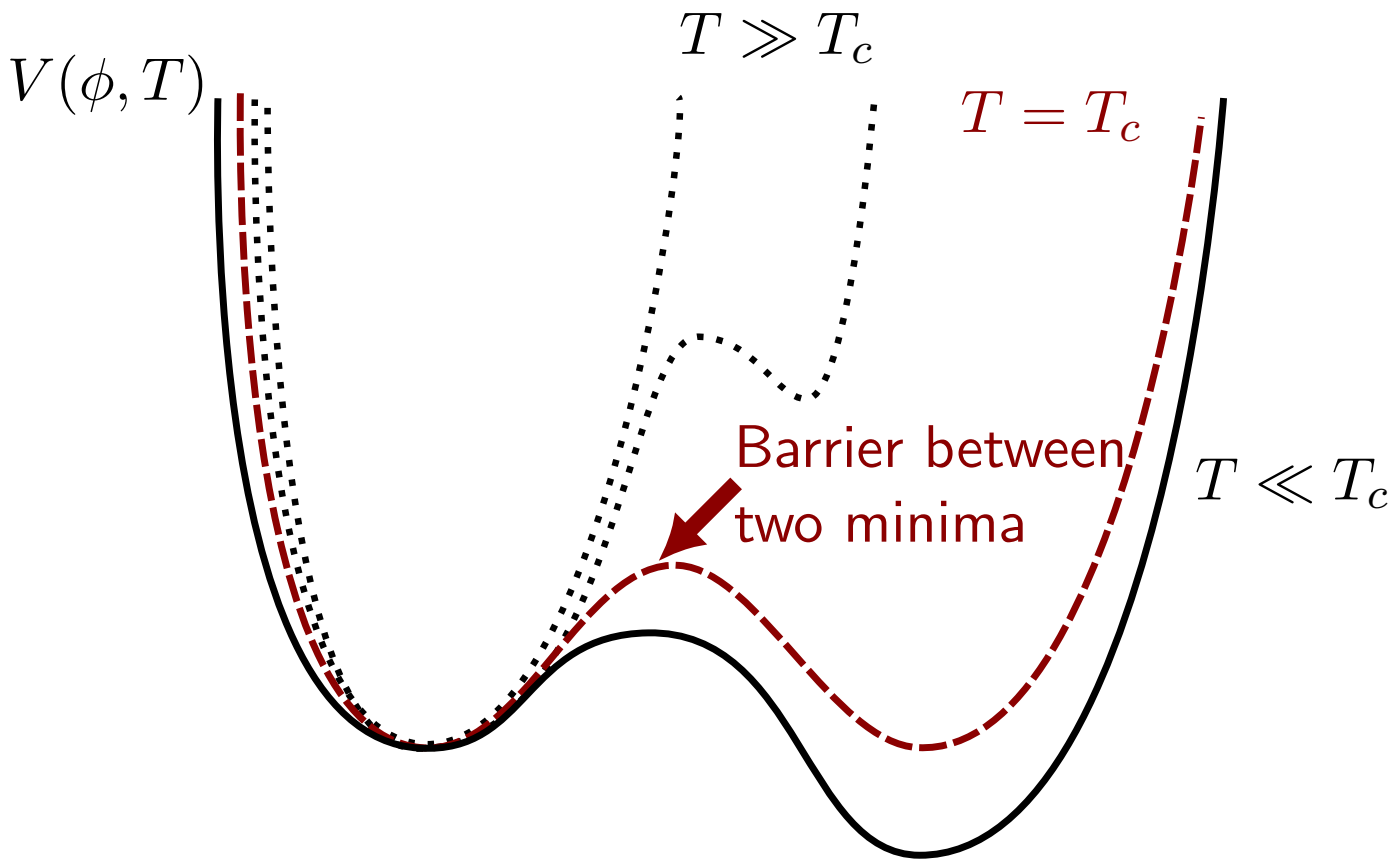
What is a first order phase transition (FOPT)?



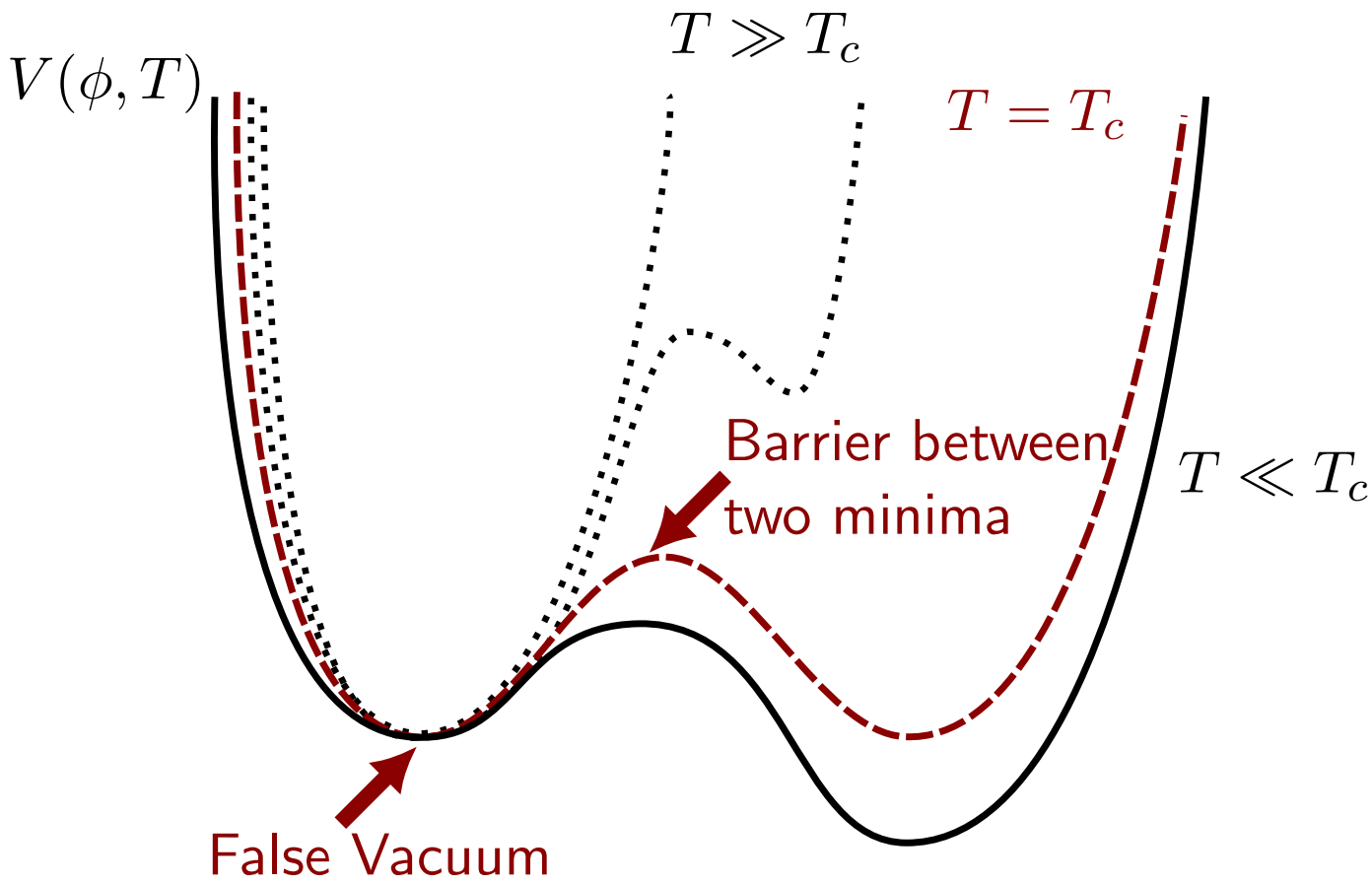
What is a first order phase transition (FOPT)?



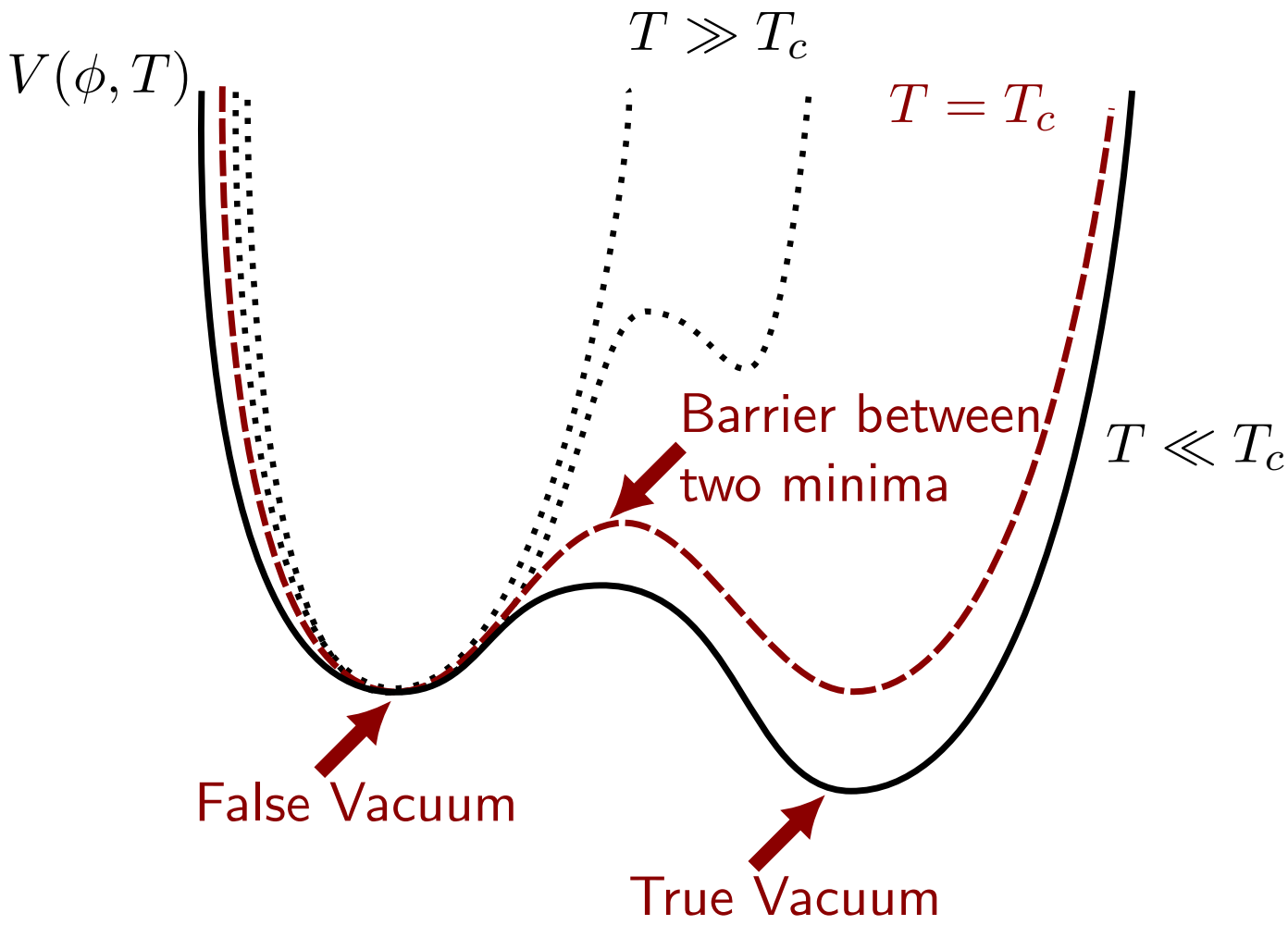
What is a first order phase transition (FOPT)?



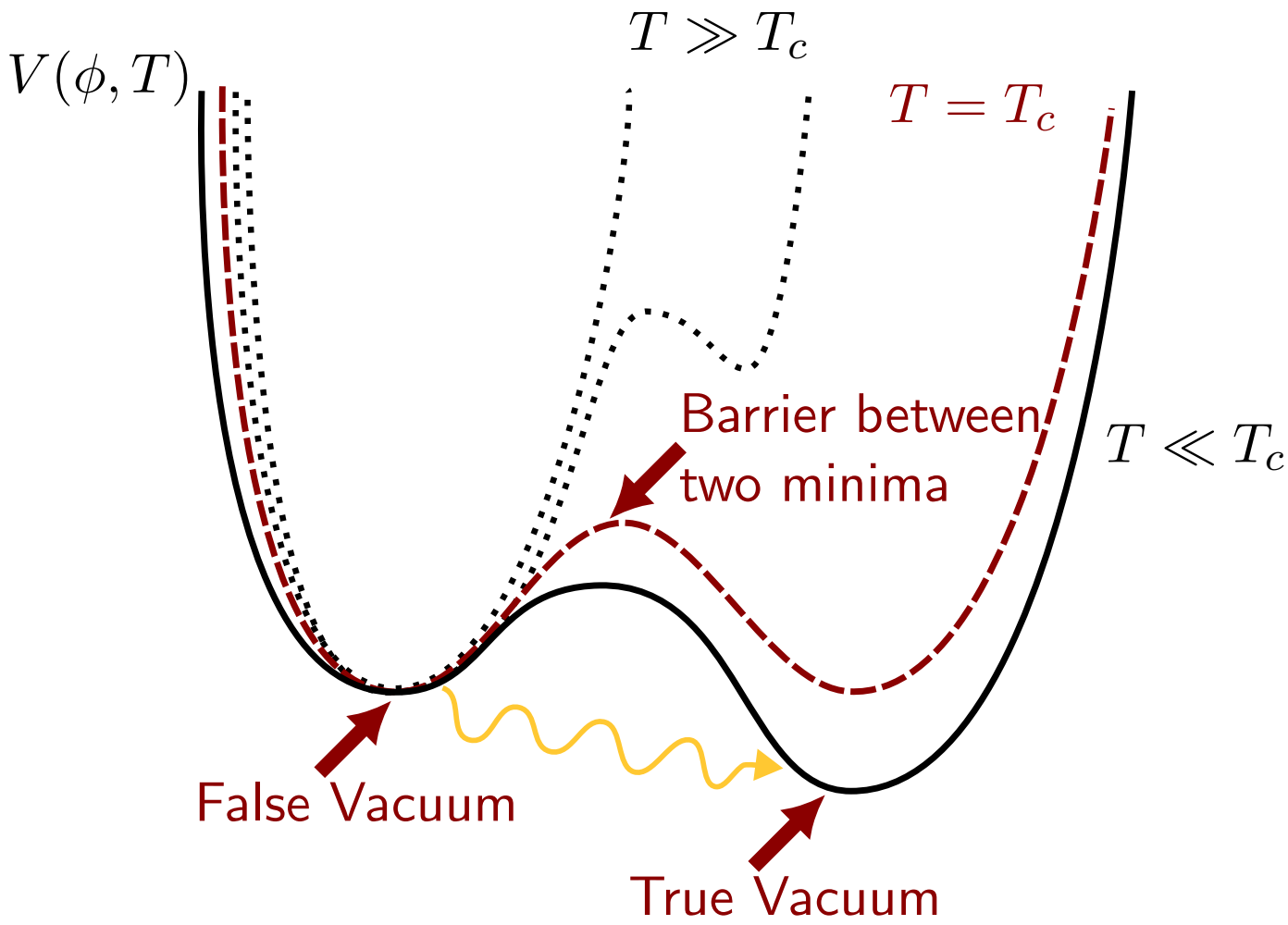
What is a first order phase transition (FOPT)?



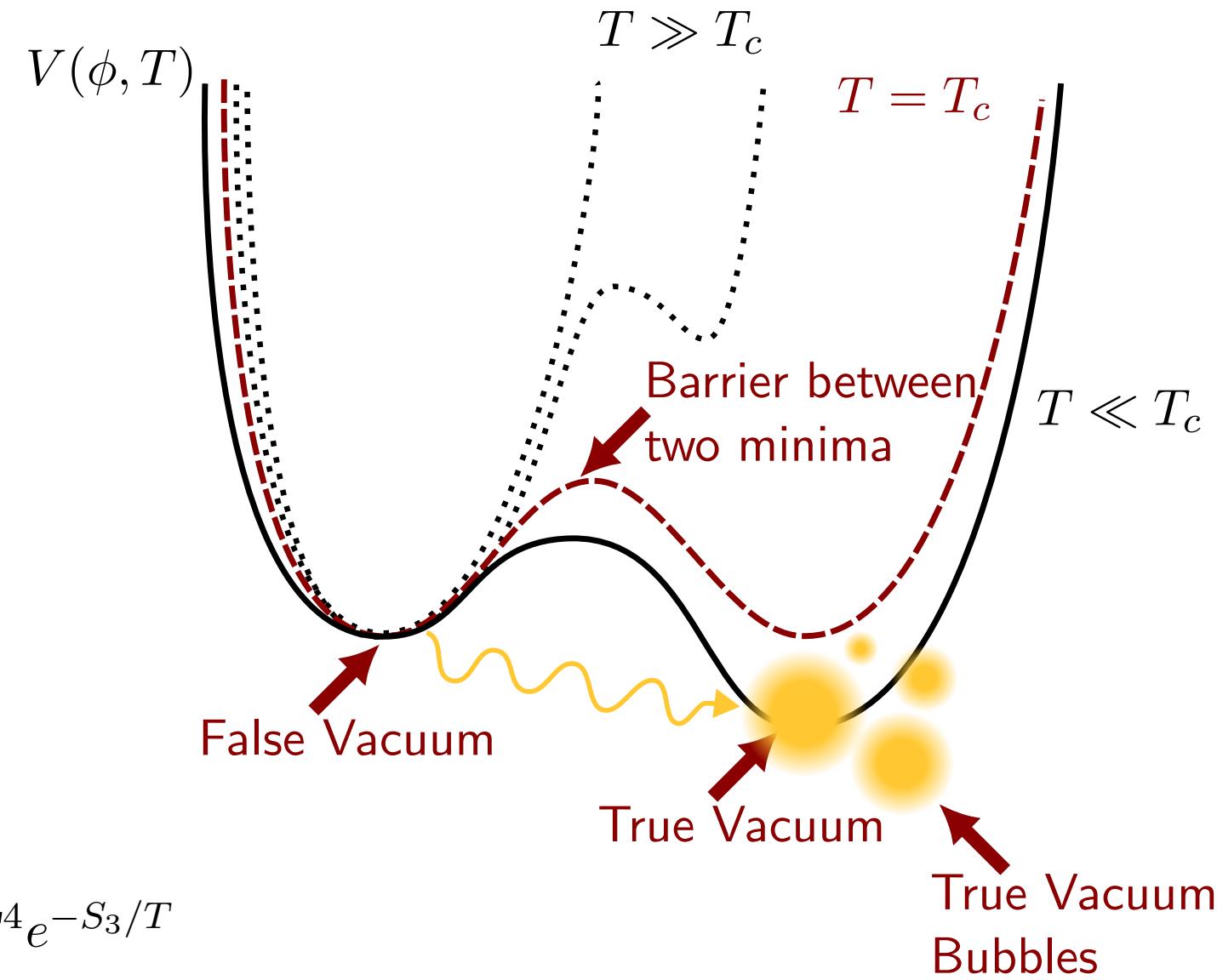
What is a first order phase transition (FOPT)?



What is a first order phase transition (FOPT)?



What is a first order phase transition (FOPT)?

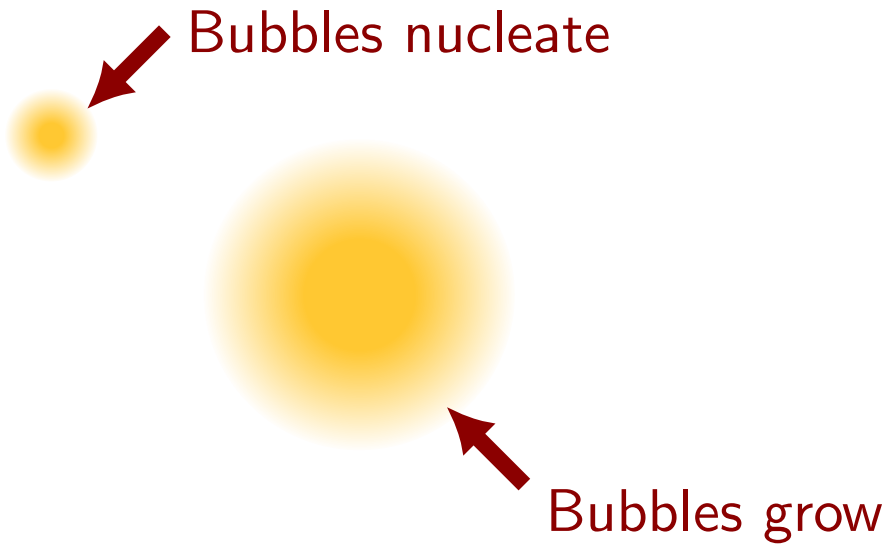


$$\Gamma \sim T^4 e^{-S_3/T}$$

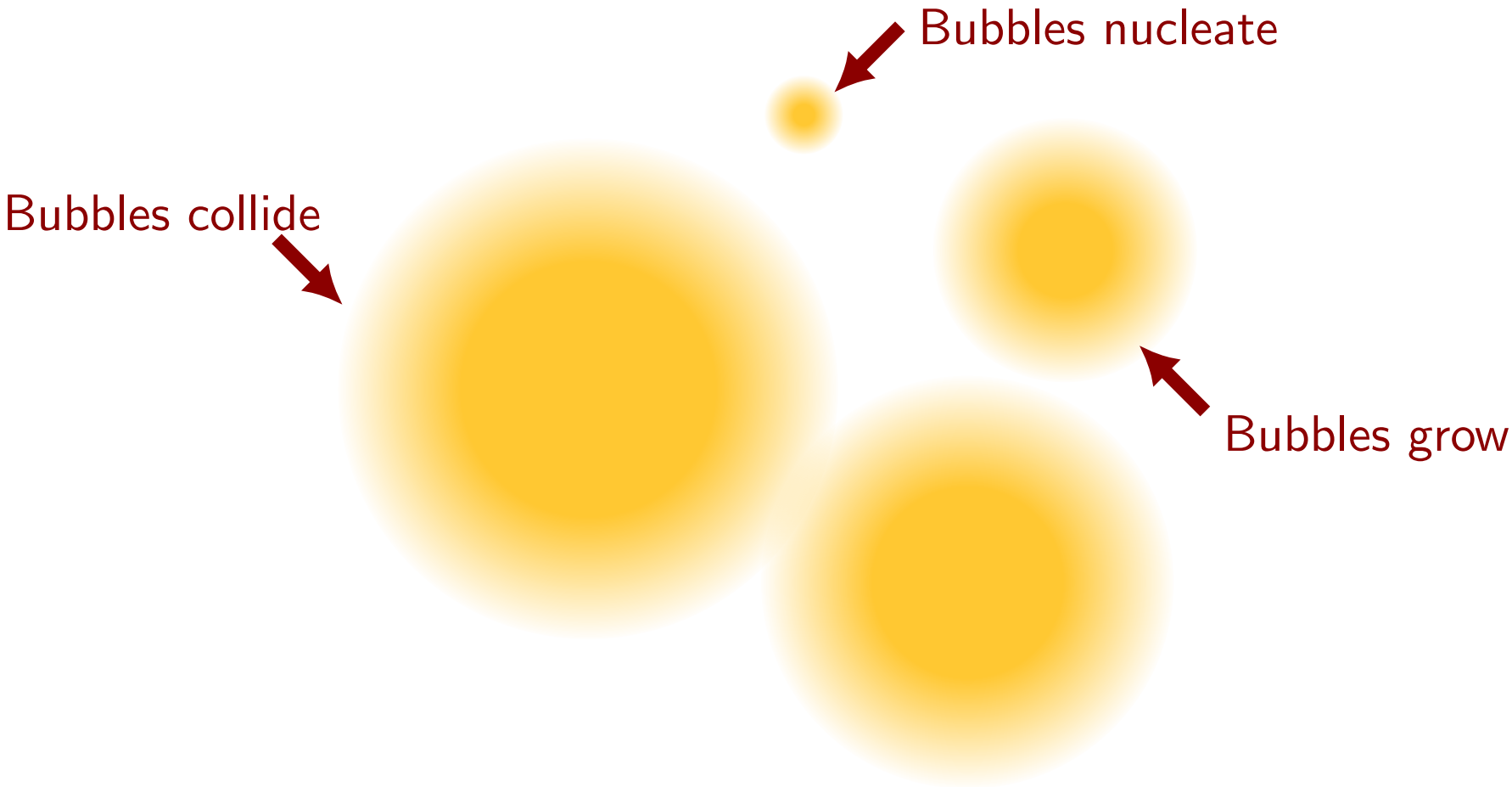
FOPT Evolution



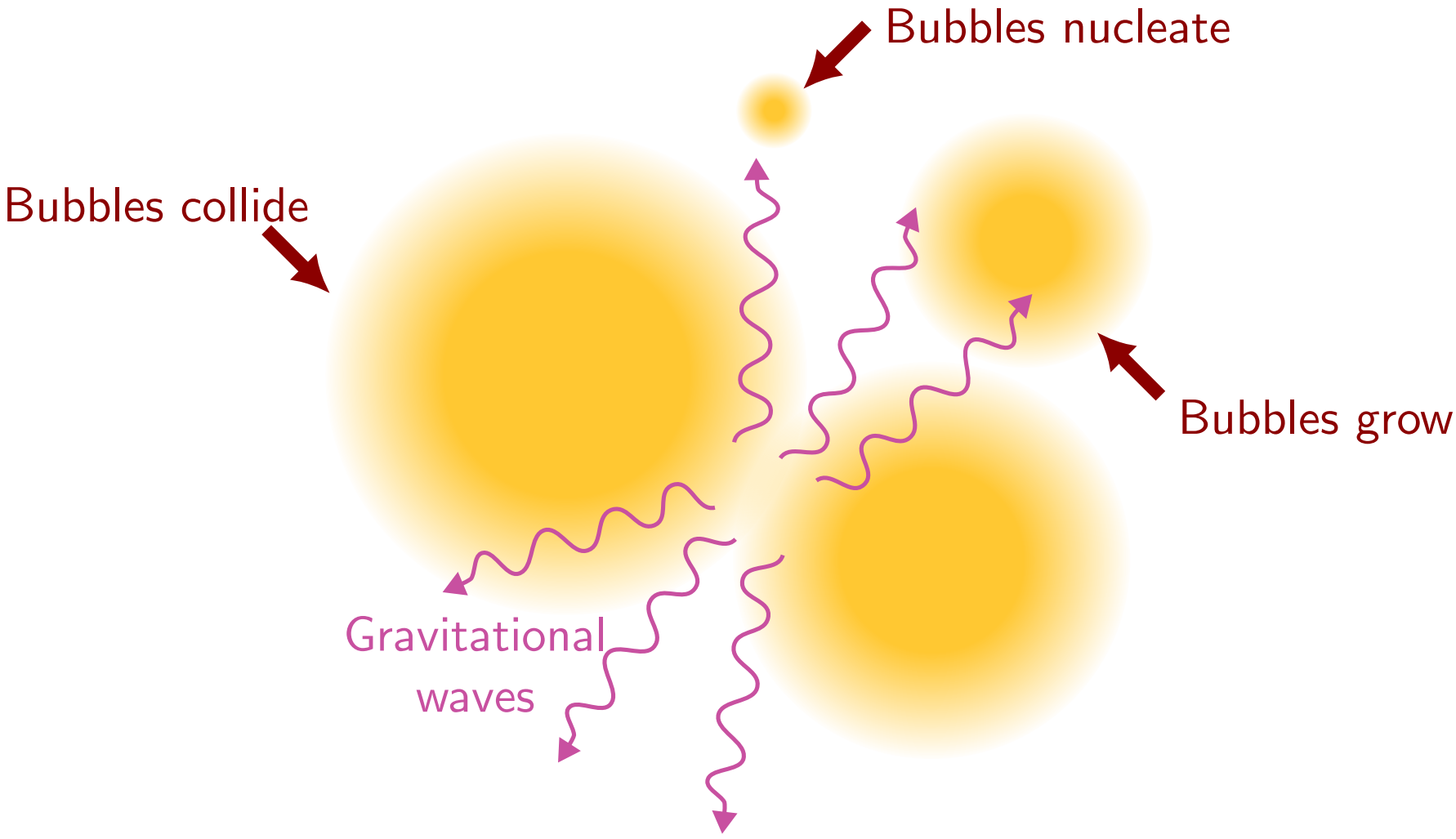
FOPT Evolution



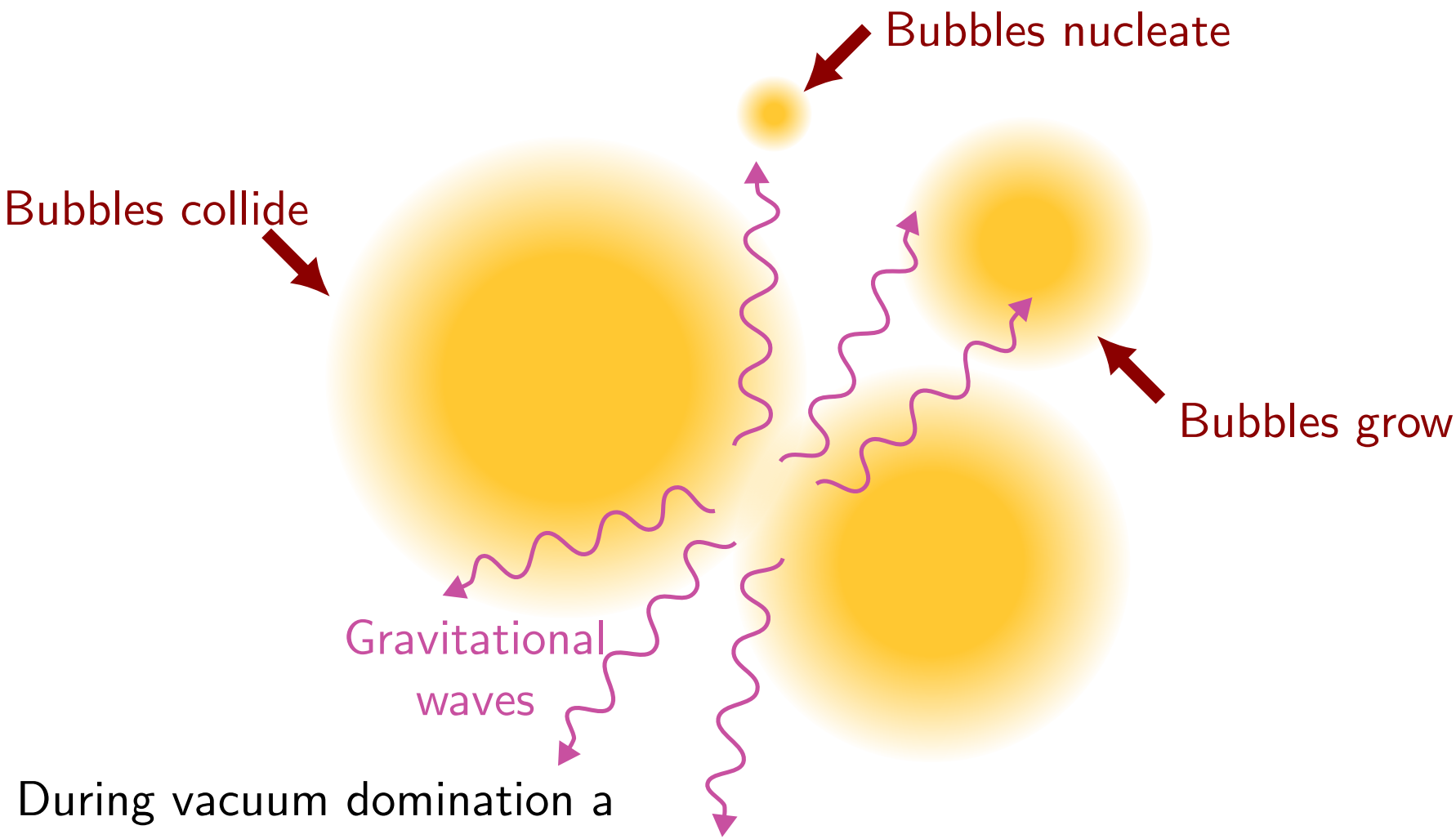
FOPT Evolution



FOPT Evolution

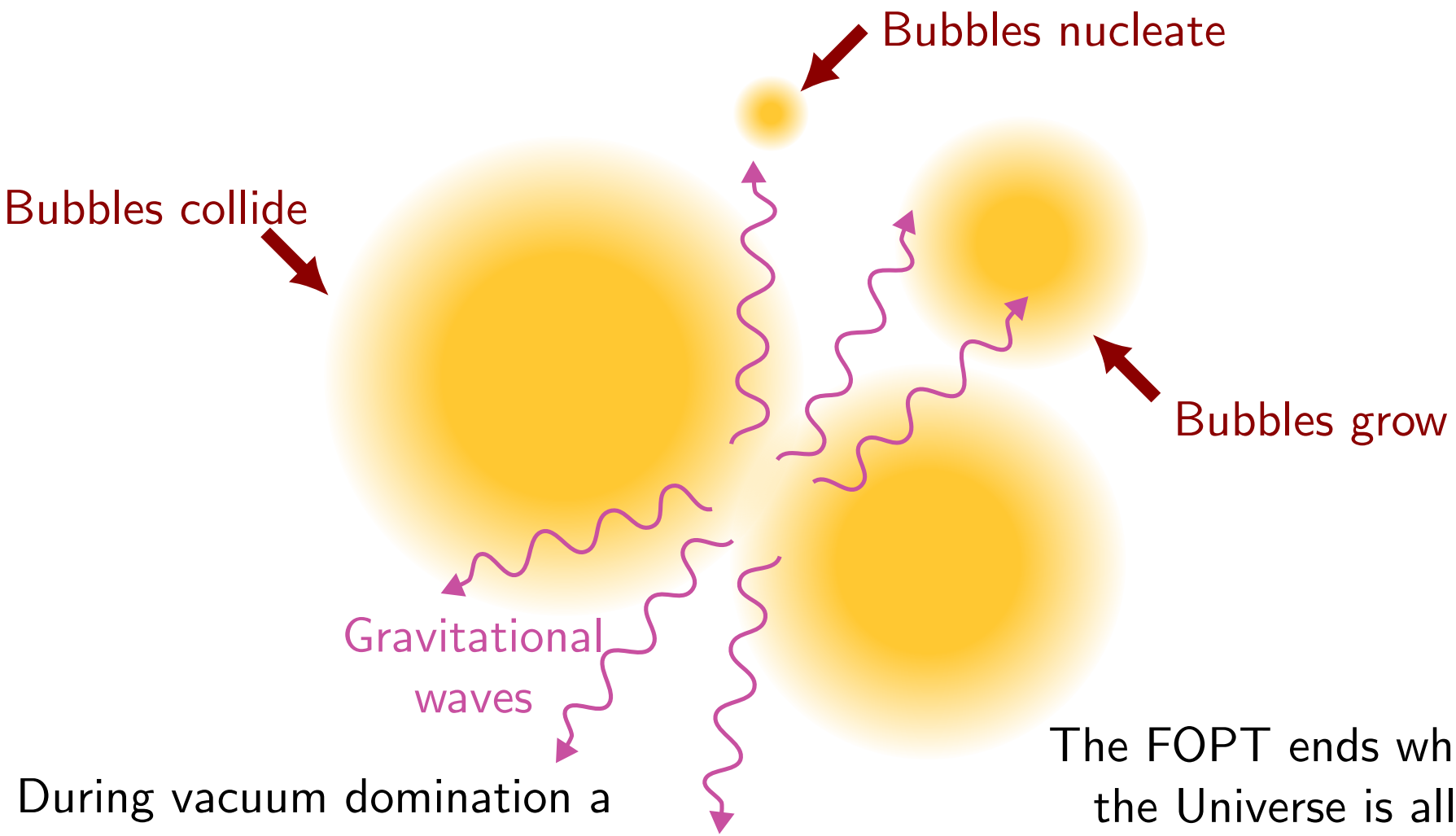


FOPT Evolution



During vacuum domination a stage of **thermal inflation** occurs

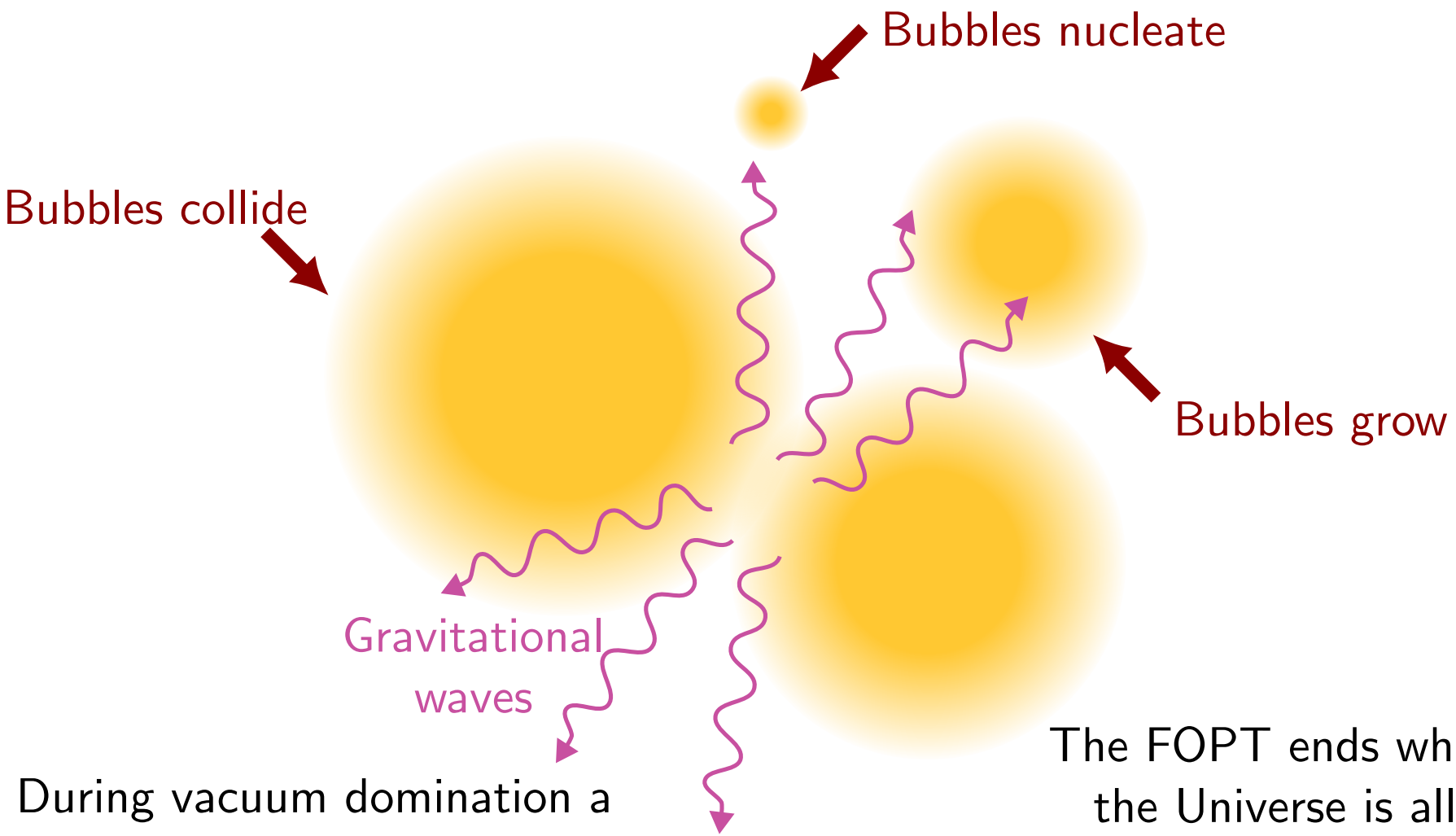
FOPT Evolution



During vacuum domination a stage of **thermal inflation** occurs

The FOPT ends when the Universe is all in the true vacuum

FOPT Evolution



During vacuum domination a stage of **thermal inflation** occurs

The FOPT ends when the Universe is all in the true vacuum

After thermal inflation the Universe must be **reheated**

Outline

First order phase transitions (FOPTs)

Radiative symmetry breaking (RSB) & the Gildener-Weinberg scenario

Reheating after FOPT in Gildner-Weinberg Models: General Properties

Radiative Electroweak Symmetry Breaking (EWRSB)

Preheating after FOPT

General setup of the Gildener-Weinberg scenario

We start from the most general no-scale Lagrangian:

$$\mathcal{L}_{\rm ns} = -\tfrac{1}{4}F^A_{\mu\nu}F^{\mu\nu}_A + \tfrac{1}{2}D_\mu\phi_a D^\mu\phi_a + \bar{\psi}_j i\not{D}\psi_j - \tfrac{1}{2}(Y^a_{ij}\psi_i\psi_j\phi_a + \text{h.c.}) - V_{\rm ns}(\phi),$$

$$D_\mu\phi_a = \partial_\mu\phi_a + i\theta^A_{ab}V^A_\mu\phi_b, \qquad D_\mu\psi_j = \partial_\mu\psi_j + it^A_{jk}V^A_\mu\psi_k,$$

$$V_{\rm ns}(\phi) = \frac{\lambda_{abcd}}{4!}\phi_a\phi_b\phi_c\phi_d.$$

General setup of the Gildener-Weinberg scenario

At quantum level the couplings depend on the RG energy μ, there may be some specific value $\mu = \tilde{\mu}$ at which the potential $V_{\rm ns}(\phi)$ develops a flat direction parametrized as $\phi_a = \chi \nu_a$:

$$V(\chi) = \frac{\lambda_\chi(\mu)}{4}\chi^4, \qquad \lambda_\chi(\mu) \equiv \frac{1}{3!}\lambda_{abcd}(\mu)\nu_a\nu_b\nu_c\nu_d,$$

such that $\lambda_\chi(\tilde{\mu}) = 0$, $\lambda_{ijkl}(\tilde{\mu})\nu_i\nu_j\nu_k = 0$ (flat direction).

General setup of the Gildener-Weinberg scenario

At quantum level the couplings depend on the RG energy μ, there may be some specific value $\mu = \tilde{\mu}$ at which the potential $V_{\rm ns}(\phi)$ develops a flat direction parametrized as $\phi_a = \chi \nu_a$:

$$V(\chi) = \frac{\lambda_\chi(\mu)}{4}\chi^4, \qquad \lambda_\chi(\mu) \equiv \frac{1}{3!}\lambda_{abcd}(\mu)\nu_a\nu_b\nu_c\nu_d,$$

such that $\lambda_\chi(\tilde{\mu}) = 0$, $\lambda_{ijkl}(\tilde{\mu})\nu_i\nu_j\nu_k = 0$ (flat direction).

The one-loop effective potential at zero temperature is:

$$V_q(\chi) = \frac{\lambda_\chi(\mu)}{4}\chi^4 + \frac{\beta_{\lambda_\chi}}{4}\left(\log\frac{\chi}{\mu} - \frac{1}{4}\right)\chi^4, \qquad \beta_{\lambda_\chi} \equiv \mu\frac{d\lambda_\chi}{d\mu}.$$

General setup of the Gildener-Weinberg model

Setting $\mu = \tilde{\mu}$ we obtain $\lambda_\chi = 0$, i.e.

$$V_q(\chi) = \frac{\bar{\beta}}{4}\left(\log\frac{\chi}{\chi_0} - \frac{1}{4}\right)\chi^4,$$

$$\bar{\beta} \equiv [\beta_{\lambda_\chi}]_{\mu=\tilde{\mu}}, \qquad \chi_0 \equiv \frac{\tilde{\mu}}{e^{1/4+a_s}}.$$

General setup of the Gildener-Weinberg model

Setting $\mu = \tilde{\mu}$ we obtain $\lambda_\chi = 0$, i.e.

$$V_q(\chi) = \frac{\bar{\beta}}{4}\left(\log\frac{\chi}{\chi_0} - \frac{1}{4}\right)\chi^4,$$

$$\bar{\beta} \equiv [\beta_{\lambda_\chi}]_{\mu=\tilde{\mu}}, \qquad \chi_0 \equiv \frac{\tilde{\mu}}{e^{1/4+a_s}}.$$

When the conditions,

$$\begin{cases} \lambda_\chi(\tilde{\mu}) = 0 & \text{(flat direction)} \\ \beta_{\lambda_\chi}(\tilde{\mu}) > 0 & \text{(minimum condition)} \end{cases}$$

are fulfilled χ_0 is the zero temperature vacuum-expectation value of χ and is the new absolute minima of $V(\chi)$.

General setup of the Gildener-Weinberg model

Setting $\mu = \tilde{\mu}$ we obtain $\lambda_\chi = 0$, i.e.

$$V_q(\chi) = \frac{\bar{\beta}}{4}\left(\log\frac{\chi}{\chi_0} - \frac{1}{4}\right)\chi^4,$$

$$\bar{\beta} \equiv [\beta_{\lambda_\chi}]_{\mu=\tilde{\mu}}, \qquad \chi_0 \equiv \frac{\tilde{\mu}}{e^{1/4+a_S}}.$$

When the conditions,

$$\begin{cases} \lambda_\chi(\tilde{\mu}) = 0 & \text{(flat direction)} \\ \beta_{\lambda_\chi}(\tilde{\mu}) > 0 & \text{(minimum condition)} \end{cases}$$

are fulfilled χ_0 is the zero temperature vacuum-expectation value of χ and is the new absolute minima of $V(\chi)$.

The fluctuation around χ_0 has mass $m_\chi^2 = \bar{\beta}\chi_0^2$.

Properties of Phase Transition in RSB models

Phase Transitions in RSB models are **always FOPT**.

JCAP **04** (2023), 051 [arXiv:2302.10212 [hep-ph]] A. Salvio.

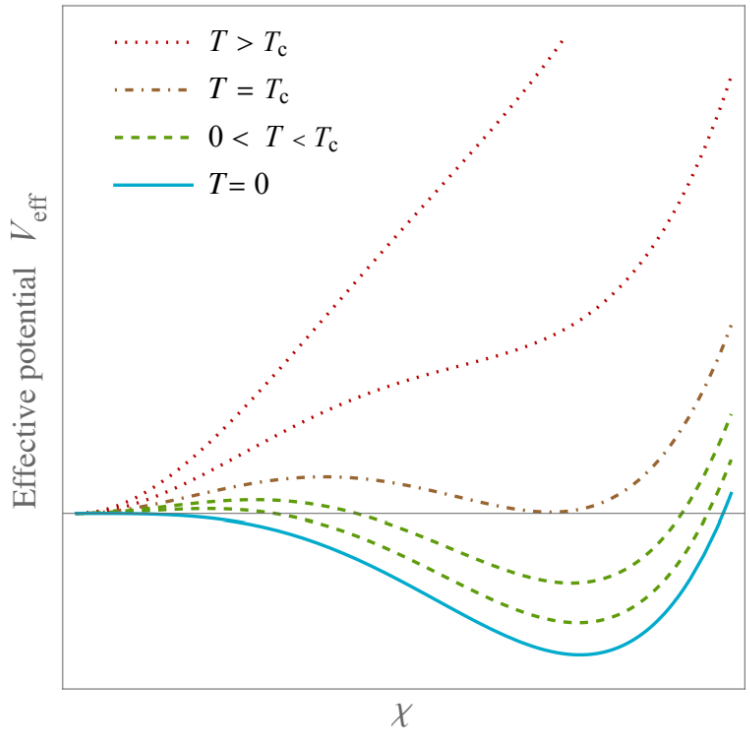


Image from JCAP **04** (2023), 051 [arXiv:2302.10212 [hep-ph]], A. Salvio

Properties of Phase Transition in RSB models

Phase Transitions in RSB models are **always FOPT**.
JCAP **04** (2023), 051 [arXiv:2302.10212 [hep-ph]] A. Salvio.

FOPTs in RSB feature always a **super-cooling phase**, i.e. the temperature drops much below T_c before the bubble nucleation became effective. This is accompanied by a period of **thermal inflation**.

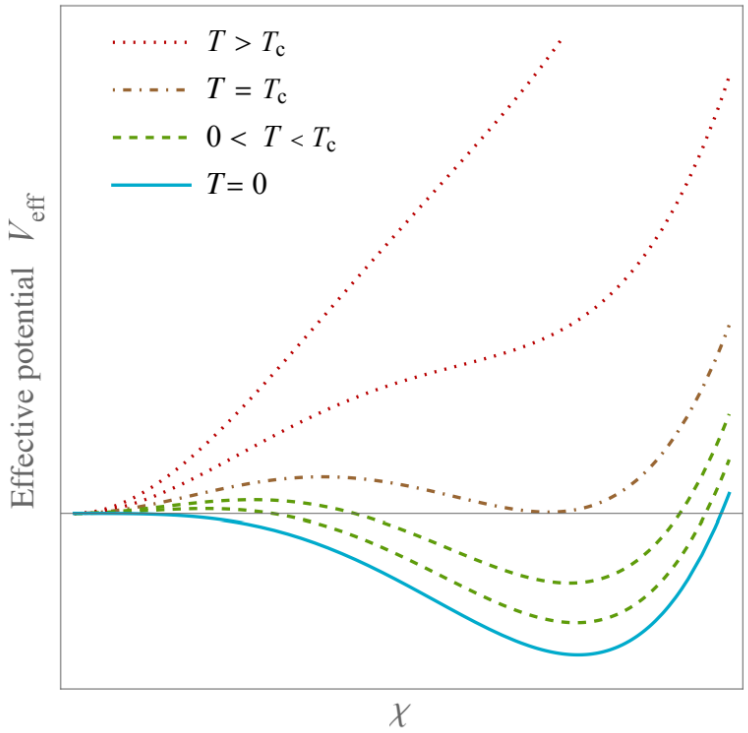


Image from JCAP **04** (2023), 051 [arXiv:2302.10212 [hep-ph]], A. Salvio

Properties of Phase Transition in RSB models

Phase Transitions in RSB models are **always FOPT**.
JCAP **04** (2023), 051 [arXiv:2302.10212 [hep-ph]] A. Salvio.

FOPTs in RSB feature always a **super-cooling phase**, i.e. the temperature drops much below T_c before the bubble nucleation became effective. This is accompanied by a period of **thermal inflation**.

FOPT in RSB models are always **strong**, the PT releases a large amount of energy.

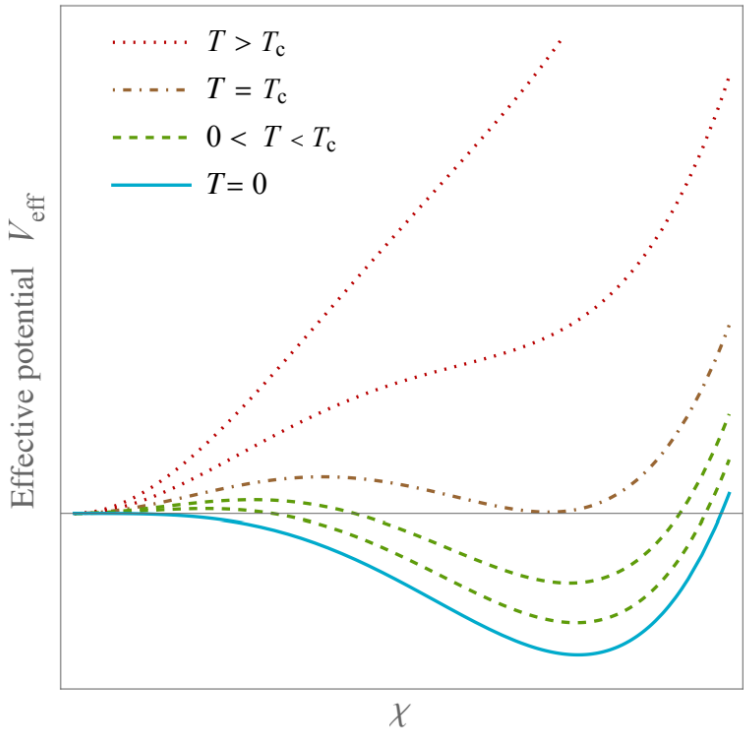


Image from JCAP **04** (2023), 051 [arXiv:2302.10212 [hep-ph]], A. Salvio

Supercool Expansion

Supercool expansion allows to study the FOPT in a **simple**, **model-independent** way

Supercool Expansion

Supercool expansion allows to study the FOPT in a **simple**, **model-independent** way

$$\epsilon = \frac{g^4}{6\bar{\beta}\log\frac{\chi_0}{T}}$$

Supercool Expansion

Supercool expansion allows to study the FOPT in a **simple**, **model-independent** way

$$g^2 \equiv \sum_b n_b m_b^2(\chi)/\chi + \sum_f m_f^2(\chi)/\chi^2$$

$$\epsilon = \frac{g^4}{6\bar{\beta}\log\frac{\chi_0}{T}}$$

Supercool Expansion

Supercool expansion allows to study the FOPT in a **simple**, **model-independent** way

$$g^2 \equiv \sum_b n_b m_b^2(\chi)/\chi + \sum_f m_f^2(\chi)/\chi^2$$

$$\epsilon = \frac{g^4}{6\bar{\beta}\log\frac{\chi_0}{T}}$$

JCAP 04 (2023) 051, arXiv:2302.10212[hep-ph], A. Salvio

Supercool expansion (LO)

$\epsilon < 1$

$\bar{V}_{\rm LO}(\chi, T) \approx \frac{m^2(T)}{2}\chi^2 - \frac{\lambda(T)}{4}\chi^4,$

$m^2(T) \equiv \frac{g^2T^2}{12},$

$\lambda(T) \equiv \bar{\beta}\log\frac{\chi_0}{T}$

$S_3 \approx c_3\frac{m}{\lambda}$, $c_3 = 18.897\cdots$

FOPT parameters such as T_n, β/H_n...

expressed in terms of **three parameters**

$$(\chi_0, \bar{\beta}, g)$$

Supercool Expansion

Supercool expansion allows to study the FOPT in a **simple**, **model-independent** way

$$\epsilon = \frac{g^4}{6\bar{\beta}\log\frac{\chi_0}{T}}$$

$$g^2 \equiv \sum_b n_b m_b^2(\chi)/\chi + \sum_f m_f^2(\chi)/\chi^2$$

$$\tilde{g}^3 \equiv \sum_b n_b m_b^3(\chi)/\chi^3$$

JCAP 04 (2023) 051, arXiv:2302.10212[hep-ph], A. Salvio JCAP 12 (2023) 046, arXiv: 2307.04694 [hep-ph], A. Salvio

Supercool expansion (LO)

$\epsilon < 1$

$$\bar{V}_{\rm LO}(\chi,T) \approx \frac{m^2(T)}{2}\chi^2 - \frac{\lambda(T)}{4}\chi^4,$$

$$m^2(T) \equiv \frac{g^2T^2}{12},$$

$$\lambda(T) \equiv \bar{\beta}\log\frac{\chi_0}{T}$$

$$S_3 \approx c_3\frac{m}{\lambda},\ c_3 = 18.897\cdots$$

FOPT parameters such as T_n, β/H_n... expressed in terms of **three parameters**

$$(\chi_0, \bar{\beta}, g)$$

Improved Supercool expansion (LO)

$\epsilon \sim 1$

$$\bar{V}_{\rm LO}(\chi,T) \approx \frac{m^2(T)}{2}\chi^2 - \frac{k(T)}{3}\chi^3 - \frac{\lambda(T)}{4}\chi^4,$$

$$k(T) \equiv \frac{\tilde{g}^3T}{4\pi},$$

JHEP 02 (2023) 125, arXiv:2212.08085,N. Levi, T. Opferkuch, D. Redigolo

$$S_3 \approx 27\pi m^3\frac{1+\exp\left(-k/(m\sqrt{\lambda})\right)}{2k^2+9\lambda m^2},$$

FOPT parameters expressed in terms of **four parameters**

$$(\chi_0, \bar{\beta}, g, \tilde{g})$$

Outline

First order phase transitions (FOPTs)

Radiative symmetry breaking (RSB) & the Gildener-Weinberg scenario

Reheating after FOPT in Gildner-Weinberg Models: General Properties

Radiative Electroweak Symmetry Breaking (EWRSB)

Preheating after FOPT

...but after the FOPT?

After **thermal inflation** the Universe must be reheated.

...but after the FOPT?

After **thermal inflation** the Universe must be reheated.

The field χ starts oscillating around the minimum of the potential in analogy with the inflaton field after the cosmic inflation.

...but after the FOPT?

After **thermal inflation** the Universe must be reheated.

The field χ starts oscillating around the minimum of the potential in analogy with the inflaton field after the cosmic inflation.

In analogy with the cosmic inflation the Universe is reheated through:

- **Perturbative reheating**: decay of the field χ into SM particles. Efficient when the SM is **embedded** in the RSB sector.

- **Preheating**: particle production through parametric resonance. Important when the SM is coupled to the RSB sector **through a portal**.

Reheating after FOPT in Gildner-Weinberg (GW) models

We start from the most general GW lagrangian

$$\mathcal{L}_{\rm ns} = -\tfrac{1}{4}F^A_{\mu\nu}F^{\mu\nu}_A + \tfrac{1}{2}D_\mu\phi_a D^\mu\phi_a + \bar{\psi}_j i\not{D}\psi_j - \tfrac{1}{2}(Y^a_{ij}\psi_i\psi_j\phi_a + \text{h.c.}) - V_{\rm ns}(\phi).$$

Reheating after FOPT in Gildner-Weinberg (GW) models

We start from the most general GW lagrangian

$$\mathcal{L}_{\rm ns} = -\tfrac{1}{4}F^A_{\mu\nu}F^{\mu\nu}_A + \tfrac{1}{2}D_\mu\phi_a D^\mu\phi_a + \bar{\psi}_j i\not{D}\psi_j - \tfrac{1}{2}(Y^a_{ij}\psi_i\psi_j\phi_a + \text{h.c.}) - V_{\rm ns}(\phi).$$

After RSB, putting $\chi = \chi_0 + \delta\chi$, rotating the generators such that the vector are in mass basis

$$\theta'^N = \mathcal{M}_{NM}\theta^M,$$

we want to divide the vector mass spectrum in massive gauge boson B^N_μ and massless gauge bosons A^N_μ.

Reheating after FOPT in Gildner-Weinberg (GW) models

We start from the most general GW lagrangian

$$\mathcal{L}_{\rm ns} = -\tfrac{1}{4}F^A_{\mu\nu}F^{\mu\nu}_A + \tfrac{1}{2}D_\mu\phi_a D^\mu\phi_a + \bar{\psi}_j i\not{D}\psi_j - \tfrac{1}{2}(Y^a_{ij}\psi_i\psi_j\phi_a + \text{h.c.}) - V_{\rm ns}(\phi).$$

After RSB, putting $\chi = \chi_0 + \delta\chi$, rotating the generators such that the vector are in mass basis

$$\theta'^N = \mathcal{M}_{NM}\theta^M,$$

we want to divide the vector mass spectrum in massive gauge boson B^N_μ and massless gauge bosons A^N_μ.

We also rotate the scalar and fermion fields to the mass basis, imposing the **unitary gauge** $\phi_a\bar{\theta}^N_{ab}\nu_b = \phi_a\bar{T}^N_a = 0$ for all the broken generators $\bar{\theta}$ where $\bar{T}^N_a$ are the goldstone directions.

Reheating after FOPT in Gildner-Weinberg (GW) models

We get the following interaction lagrangian related to the decay of $\delta\chi$

$$\mathcal{L}^{V}_{\rm int} = -(\bar{T}^{N})^{2}\chi_{0}\delta\chi B^{N}_{\mu}B^{N\mu} - \bar{T}^{N}_{a}\bar{\theta'}^{N}_{an}\mathcal{O}^{T}_{nc}\delta\chi\phi'_{c}B^{N}_{\mu}B^{N\mu},$$

Reheating after FOPT in Gildner-Weinberg (GW) models

We get the following interaction lagrangian related to the decay of $\delta\chi$

$$\mathcal{L}^V_{\rm int} = -(\bar{T}^N)^2\chi_0\delta\chi B^N_\mu B^{N\mu} - \bar{T}^N_a \bar{\theta'}^N_{an}\mathcal{O}^T_{nc}\delta\chi\phi'_c B^N_\mu B^{N\mu},$$

$$\mathcal{L}^S_{\rm int} = -\lambda_a\chi_0\delta\chi\phi'_a\phi'_a - \tfrac{1}{3!}\lambda_{mnl}\mathcal{O}^T_{ma}\mathcal{O}^T_{nb}\mathcal{O}^T_{lc}\delta\chi\phi'_a\phi'_b\phi'_c,$$

$$\lambda_{mnl} \equiv \tfrac{1}{3!}\lambda_{mnld}(\tilde{\mu})\nu^d,$$

Reheating after FOPT in Gildner-Weinberg (GW) models

We get the following interaction lagrangian related to the decay of $\delta\chi$

$$\mathcal{L}^V_{\rm int} = -(\bar{T}^N)^2\chi_0\delta\chi B^N_\mu B^{N\mu} - \bar{T}^N_a \bar{\theta'}^N_{an}\mathcal{O}^T_{nc}\delta\chi\phi'_c B^N_\mu B^{N\mu},$$

$$\mathcal{L}^S_{\rm int} = -\lambda_a\chi_0\delta\chi\phi'_a\phi'_a - \tfrac{1}{3!}\lambda_{mnl}\mathcal{O}^T_{ma}\mathcal{O}^T_{nb}\mathcal{O}^T_{lc}\delta\chi\phi'_a\phi'_b\phi'_c,$$

$$\lambda_{mnl} \equiv \tfrac{1}{3!}\lambda_{mnld}(\tilde{\mu})\nu^d,$$

$$\mathcal{L}^F_{\rm int} = -y_a\delta\chi\psi_a\bar{\psi}_a + \text{h.c.} \qquad (\psi = \bar{\psi} \text{ for Majorana fermions}),$$

Reheating after FOPT in Gildner-Weinberg (GW) models

General decay rates (two body)

$$\Gamma^{(2S)} = \sum_a \frac{\lambda_a^2 \chi_0}{8\pi\sqrt{\bar{\beta}}} \sqrt{1 - \frac{4\lambda_a}{\bar{\beta}}}\, \Theta\left(\sqrt{\bar{\beta}} - 2\sqrt{\lambda_i}\right) \equiv \sum_a \Gamma(\delta\chi \to \phi_a' \phi_a'),$$

$$\Gamma^{(2F)} = \sum_i \frac{s_i y_i^2 \chi_0}{8\pi} \sqrt{\bar{\beta}} \left(1 - \frac{4y_i^2}{\bar{\beta}}\right)^{3/2} \Theta\left(\sqrt{\bar{\beta}} - 2y_i\right) \equiv \sum_i \Gamma(\delta\chi \to \psi_i' \psi_i'),$$

$$\Gamma^{(2V)} = \sum_N \frac{g_N^4 \chi_0}{32\pi\sqrt{\bar{\beta}}} \left(12 + \frac{\bar{\beta}^2}{g_N^4} - 4\frac{\bar{\beta}}{g_N^2}\right) \sqrt{1 - \frac{4g_N^2}{\bar{\beta}}}\, \Theta\left(\sqrt{\bar{\beta}} - 2g_N\right)$$

$$\equiv \sum_N \Gamma(\delta\chi \to B_N B_N),$$

where

$$g_N^2 \equiv -(\bar{T}^N)^2.$$

Reheating after FOPT in Gildner-Weinberg (GW) models

Using the definitions

$$\zeta_{Sa} \equiv \frac{4m_a^2}{m_\chi^2} = \frac{4\lambda_a}{\bar{\beta}}, \qquad \zeta_{Fi} \equiv \frac{4m_i^2}{m_\chi^2} = \frac{4y_i^2}{\bar{\beta}}, \qquad \zeta_{VN} \equiv \frac{4m_N^2}{m_\chi^2} = \frac{4g_N^2}{\bar{\beta}}.$$

we can write the two-body decay rates in a simpler form

Reheating after FOPT in Gildner-Weinberg (GW) models

Using the definitions

$$\zeta_{Sa} \equiv \frac{4m_a^2}{m_\chi^2} = \frac{4\lambda_a}{\bar{\beta}}, \qquad \zeta_{Fi} \equiv \frac{4m_i^2}{m_\chi^2} = \frac{4y_i^2}{\bar{\beta}}, \qquad \zeta_{VN} \equiv \frac{4m_N^2}{m_\chi^2} = \frac{4g_N^2}{\bar{\beta}}.$$

we can write the two-body decay rates in a simpler form

General decay rates (two-body, ζ-form)

$$\Gamma^{(2S)}(\bar{\beta}, \zeta_S) = \frac{\bar{\beta}^{3/2}}{32\pi}\zeta_S\chi_0, \quad \Gamma^{(2F)}(\bar{\beta}, \zeta_F) = \frac{\bar{\beta}^{3/2}}{32\pi}\zeta_F\chi_0, \quad \Gamma^{(2V)}(\bar{\beta}, \zeta_V) = \frac{\bar{\beta}^{3/2}}{32\pi}\zeta_V\chi_0,$$

$$\zeta_S \equiv \frac{1}{4}\sum_a \zeta_{Sa}^2\sqrt{1-\zeta_{Sa}}\Theta\left(1-\zeta_{Sa}\right), \qquad \zeta_F \equiv \sum_i s_i\zeta_{Fi}(1-\zeta_{Fi})^{3/2}\Theta\left(1-\zeta_{Fi}\right),$$

$$\zeta_V \equiv \sum_N \left(1-\zeta_{VN}+\frac{3}{4}\zeta_{VN}^2\right)\sqrt{1-\zeta_{VN}}\Theta\left(1-\zeta_{VN}\right).$$

Reheating after FOPT in Gildner-Weinberg (GW) models

We can expand these expressions in the limit of small ζ

Reheating after FOPT in Gildner-Weinberg (GW) models

We can expand these expressions in the limit of small ζ

General decay rates (two-body small ζ limit)

$$\Gamma^{(2S)}(\bar{\beta},\zeta_S)=\frac{\bar{\beta}^{3/2}}{32\pi}\zeta_S\chi_0,\quad \Gamma^{(2F)}(\bar{\beta},\zeta_F)=\frac{\bar{\beta}^{3/2}}{32\pi}\zeta_F\chi_0,\quad \Gamma^{(2V)}(\bar{\beta},\zeta_V)=\frac{\bar{\beta}^{3/2}}{32\pi}\zeta_V\chi_0,$$

$$\zeta_S=\frac{1}{4}\sum_a\zeta_{Sa}^2+O(\zeta_{Sa}^3),\qquad \zeta_F=\sum_i s_i\left(\zeta_{Fi}-\frac{3}{2}\zeta_{Fi}^2\right)+O(\zeta_{Fi}^3),$$

$$\zeta_V=N_{bg}-\sum_N\left(\frac{3}{2}\zeta_{VN}-\frac{9}{8}\zeta_{VN}^2\right)+O(\zeta_{VN}^3).$$

Reheating after FOPT in Gildner-Weinberg (GW) models

General decay rates (three body)

$$\Gamma^{(3S)} = \sum_{a,b,c} \frac{S\chi_0}{64\pi^5\sqrt{\bar{\beta}}}(\lambda'_{abc})^2\omega_3\left(\bar{\beta}, \sqrt{\lambda_a}, \sqrt{\lambda_b}, \sqrt{\lambda_c}\right)\Theta\left(\sqrt{\bar{\beta}} - \sqrt{\lambda_a} - \sqrt{\lambda_b} - \sqrt{\lambda_c}\right)$$

$$\Gamma^{(SV)} = \sum_{N,c} \frac{(G_c^N)^4\chi_0}{32\pi^5\sqrt{\bar{\beta}}}\left(2\omega_3\left(\bar{\beta}, g_N, g_N, \sqrt{\lambda_c}\right) + \frac{1}{g_N^4}\omega_3^{(4)}\left(\bar{\beta}, g_N, \sqrt{\lambda_c}\right)\right)$$
$$\times\,\Theta\left(\sqrt{\bar{\beta}} - \sqrt{\lambda_c} - 2g_N\right),$$

where

$$\lambda'_{abc} \equiv \lambda_{mnl}\mathcal{O}^T_{ma}\mathcal{O}^T_{nb}\mathcal{O}^T_{lc}, \qquad (G_c^N)^4 \equiv (\bar{T}_a^N\bar{\theta}'^N_{an}\mathcal{O}^T_{nc})^2.$$

and ω_3 and $\omega_3^{(4)}$ are adimensionalized phase space integrals.

Reheating temperature $T_{\rm rh}$ and instantaneous reheating

If $\delta\chi$ decays into some SM particles with width $\Gamma_{\delta\chi}$ the reheating temperature $T_{\rm rh}$ is at least

$$T_{\rm rh} \gtrsim \min\left(\left(\frac{45\Gamma_{\delta\chi}^2\bar{M}_p^2}{4\pi^3 g_*(T_{\rm rh})}\right)^{1/4}, \left(\frac{30\Delta V}{\pi^2 g_*(T_{\rm rh})}\right)^{1/4}\right),$$

Reheating temperature $T_{\rm rh}$ and instantaneous reheating

If $\delta\chi$ decays into some SM particles with width $\Gamma_{\delta\chi}$ the reheating temperature $T_{\rm rh}$ is at least

$$T_{\rm rh} \gtrsim \min\left(\left(\frac{45\Gamma_{\delta\chi}^2\bar{M}_p^2}{4\pi^3 g_*(T_{\rm rh})}\right)^{1/4}, \left(\frac{30\Delta V}{\pi^2 g_*(T_{\rm rh})}\right)^{1/4}\right),$$

given vacuum energy density and equivalence expressed as temperature

$$\Delta V = \frac{\bar{\beta}\chi_0^4}{16}, \qquad \frac{\pi^2}{30} g_*(T_{\rm eq}) T_{\rm eq}^4 \equiv \Delta V,$$

$$T_{\rm eq}^4 = \frac{15\bar{\beta}\chi_0^4}{8\pi^2 g_*(T_{\rm eq})}.$$

Reheating temperature $T_{\rm rh}$ and instantaneous reheating

We can express the **instantaneous reheating** condition

$$T_{\rm rh} \approx T_{\rm eq},$$

in a general form for GW models (including only two-body decays)

$$\zeta^2_{\rm tot} \gtrsim \frac{512\pi^3}{3\bar{\beta}^2}\frac{\chi_0^2}{\bar{M}_P^2},$$

Reheating temperature $T_{\rm rh}$ and instantaneous reheating

We can express the **instantaneous reheating** condition

$$T_{\rm rh} \approx T_{\rm eq},$$

in a general form for GW models (including only two-body decays)

$$\zeta_{\rm tot}^2 \gtrsim \frac{512\pi^3}{3\bar{\beta}^2}\frac{\chi_0^2}{\bar{M}_P^2},$$

where we defined

$$\Gamma_{\rm tot}(\bar{\beta},\zeta_S,\zeta_F,\zeta_V) \equiv \Gamma^{(2S)}(\bar{\beta},\zeta_S) + \Gamma^{(2F)}(\bar{\beta},\zeta_F) + \Gamma^{(2V)}(\bar{\beta},\zeta_V) = \frac{\bar{\beta}^{3/2}}{32\pi}\zeta_{\rm tot}\chi_0,$$

$$\zeta_{\rm tot} = \zeta_S + \zeta_F + \zeta_V.$$

Reheating temperature $T_{\rm rh}$ and instantaneous reheating

We can express the **instantaneous reheating** condition

$$T_{\rm rh} \approx T_{\rm eq},$$

in a general form for GW models (including only two-body decays)

$$\zeta_{\rm tot}^2 \gtrsim \frac{512\pi^3}{3\bar{\beta}^2}\frac{\chi_0^2}{\bar{M}_P^2},$$

where we defined

$$\Gamma_{\rm tot}(\bar{\beta},\zeta_S,\zeta_F,\zeta_V) \equiv \Gamma^{(2S)}(\bar{\beta},\zeta_S) + \Gamma^{(2F)}(\bar{\beta},\zeta_F) + \Gamma^{(2V)}(\bar{\beta},\zeta_V) = \frac{\bar{\beta}^{3/2}}{32\pi}\zeta_{\rm tot}\chi_0,$$

$$\zeta_{\rm tot} = \zeta_S + \zeta_F + \zeta_V.$$

Using the small ζ expansion we obtain the condition

$$N_{bg}^2 \gtrsim \frac{512\pi^3}{3\bar{\beta}^2}\frac{\chi_0^2}{\bar{M}_P^2}.$$

Reheating temperature $T_{\rm rh}$ and instantaneous reheating

We can express the **instantaneous reheating** condition

$$T_{\rm rh} \approx T_{\rm eq},$$

in a general form for GW models (including only two-body decays)

$$\zeta_{\rm tot}^2 \gtrsim \frac{512\pi^3}{3\bar{\beta}^2}\frac{\chi_0^2}{\bar{M}_P^2},$$

where we defined

$$\Gamma_{\rm tot}(\bar{\beta},\zeta_S,\zeta_F,\zeta_V) \equiv \Gamma^{(2S)}(\bar{\beta},\zeta_S) + \Gamma^{(2F)}(\bar{\beta},\zeta_F) + \Gamma^{(2V)}(\bar{\beta},\zeta_V) = \frac{\bar{\beta}^{3/2}}{32\pi}\zeta_{\rm tot}\chi_0,$$

$$\zeta_{\rm tot} = \zeta_S + \zeta_F + \zeta_V.$$

Using the small ζ expansion we obtain the condition

$$N_{bg}^2 \gtrsim \frac{512\pi^3}{3\bar{\beta}^2}\frac{\chi_0^2}{\bar{M}_P^2}.$$

Adding the three-body decay contributions make the reheating even faster.

Outline

First order phase transitions (FOPTs)

Radiative symmetry breaking (RSB) & the Gildener-Weinberg scenario

Reheating after FOPT in Gildner-Weinberg Models: General Properties

Radiative Electroweak Symmetry Breaking (EWRSB)

Preheating after FOPT

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

We start from the **conformal SM**, replacing

$$\mathcal{L}_h = \mu^2 |\mathcal{H}|^2 \longrightarrow \mathcal{L}_{\phi h} = \tfrac{1}{2}\lambda_{ab}\phi_a\phi_b|\mathcal{H}|^2,$$

where

$$\mathcal{H} = \tfrac{1}{\sqrt{2}} \begin{pmatrix} \eta_1 + i\eta_2 \\ h + i\eta_3 \end{pmatrix}.$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

We start from the **conformal SM**, replacing

$$\mathcal{L}_h = \mu^2 |\mathcal{H}|^2 \longrightarrow \mathcal{L}_{\phi h} = \tfrac{1}{2}\lambda_{ab}\phi_a\phi_b|\mathcal{H}|^2,$$

where

$$\mathcal{H} = \tfrac{1}{\sqrt{2}}\begin{pmatrix}\eta_1 + i\eta_2 \\ h + i\eta_3\end{pmatrix}.$$

We add a real scalar ϕ_h with a $\mathbb{Z}_2$ symmetry $\phi_h \to -\phi_h$. The scalar potential is then

$$V(h,\phi_h) = \tfrac{1}{4}\lambda_h h^4 + \tfrac{1}{4}\lambda_\phi \phi_h^4 - \tfrac{1}{4}\lambda_{\phi h} h^2\phi_h^2$$

$$= \tfrac{1}{4}\left(\sqrt{\lambda_h}h^2 - \sqrt{\lambda_\phi}\phi_h^2\right)^2 + \tfrac{1}{2}\sqrt{\lambda_h}\sqrt{\lambda_\phi}h^2\phi_h^2 - \tfrac{1}{4}\lambda_{\phi h}h^2\phi_h^2.$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

At the renormalization scale $\tilde{\mu}$ the classical potential vanishes along the **flat direction**, and couplings and fields satisfy

$$\sqrt{\lambda_h} h^2 = \sqrt{\lambda_\phi}\phi_h^2 \quad \text{(flat direction)}, \qquad \lambda_{\phi h} = 2\sqrt{\lambda_h}\sqrt{\lambda_\phi}.$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

At the renormalization scale $\tilde{\mu}$ the classical potential vanishes along the **flat direction**, and couplings and fields satisfy

$$\sqrt{\lambda_h} h^2 = \sqrt{\lambda_\phi}\phi_h^2 \quad \text{(flat direction)}, \qquad \lambda_{\phi h} = 2\sqrt{\lambda_h}\sqrt{\lambda_\phi}.$$

We rotate the fields so that the flat-direction field χ appears manifestly in the Lagrangian,

$$\begin{cases} \phi_h = \chi \cos\alpha - H \sin\alpha, \\ h = \chi \sin\alpha + H \cos\alpha, \end{cases}$$

where the mixing angle α is defined by

$$\tan\alpha \equiv \sqrt{\frac{\lambda_{\phi h}}{2\lambda_h}}.$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

Including the 1-loop contribution along the flat direction and expanding $\chi = \chi_0 + \delta\chi$, we get

$$v = \chi_0 \sin\alpha = \chi_0 \sqrt{\frac{\lambda_{\phi h}}{\lambda_{\phi h} + 2\lambda_h}},$$

relating the RSB scale to the Higgs VEV, so that

$$h = v + \delta\chi \sin\alpha + H \cos\alpha.$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

Including the 1-loop contribution along the flat direction and expanding $\chi = \chi_0 + \delta\chi$, we get

$$v = \chi_0 \sin\alpha = \chi_0 \sqrt{\frac{\lambda_{\phi h}}{\lambda_{\phi h} + 2\lambda_h}},$$

relating the RSB scale to the Higgs VEV, so that

$$h = v + \delta\chi \sin\alpha + H \cos\alpha.$$

This gives the **effective 1-loop potential**

$$\begin{aligned} V_{1-\text{loop}}(H, \delta\chi) =& \frac{\lambda_{\phi h}\chi_0^2}{2} H^2 + \frac{4\lambda_h^2 - \lambda_{\phi h}^2}{2\sqrt{2}\lambda_h} \sqrt{\frac{\lambda_{\phi h}\lambda_h}{(\lambda_{\phi h} + 2\lambda_h)^2}}\, \chi_0 H^3 + \frac{(\lambda_{\phi h} - 2\lambda_h)^2}{16\lambda_h} H^4 \\ &+ \lambda_{\phi h}\chi_0 \delta\chi H^2 + \frac{\lambda_{\phi h}}{2} \delta\chi^2 H^2 + \frac{4\lambda_h^2 - \lambda_{\phi h}^2}{2\sqrt{2}\lambda_h} \sqrt{\frac{\lambda_{\phi h}\lambda_h}{(\lambda_{\phi h} + 2\lambda_h)^2}}\, \delta\chi H^3 \\ &+ \frac{\bar{\beta}}{2} \chi_0^2 \delta\chi^2 + \delta\chi \text{ self-interactions}, \qquad M_h = \sqrt{\lambda_{\phi h}}\chi_0. \end{aligned}$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

The EW gauge bosons and SM fermions develop a coupling with $\delta\chi$. For the W bosons, the interaction Lagrangian with h is

$$\mathcal{L}_{hWW} = \frac{1}{4} g_2^2 h^2 W_\mu^+ W^{-\mu}$$

$$= \frac{1}{4} g_2^2 \chi_0^2 \sin^2\alpha\, W_\mu^+ W^{-\mu} + \frac{1}{4} g_2^2 H^2 W_\mu^+ W^{-\mu} \cos^2\alpha + \frac{1}{2} g_2^2 \chi_0 \cos\alpha\, \sin\alpha\, H W_\mu^+ W^{-\mu}$$
$$+ \frac{1}{2} g_2^2 \chi_0 \sin^2\alpha\, \delta\chi W_\mu^+ W^{-\mu} + \frac{1}{4} g_2^2 \sin^2\alpha\, \delta\chi^2 W_\mu^+ W^{-\mu} + \frac{1}{2} g_2^2 \cos\alpha\, \sin\alpha\, \delta\chi H W_\mu^+ W^{-\mu},$$

where g_1 and g_2 are the gauge couplings of $SU(2)$ and $U(1)$.

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

We correctly reproduce the **mass term** for the W boson

$$M_W = \frac{1}{2} g_2 \chi_0 \sin\alpha = \frac{1}{2} g_2 v.$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

We correctly reproduce the **mass term** for the W boson

$$M_W = \frac{1}{2} g_2 \chi_0 \sin\alpha = \frac{1}{2} g_2 v.$$

The same happens for the Z boson; its interaction Lagrangian with h is

$$\mathcal{L}_{hZZ} = \frac{1}{8} g_Z^2 h^2 Z_\mu Z^\mu$$

$$= \frac{1}{8} g_Z^2 \chi_0^2 \sin^2\alpha \, Z_\mu Z^\mu + \frac{1}{8} g_Z^2 H^2 Z_\mu Z^\mu \cos^2\alpha + \frac{1}{4} g_Z^2 \chi_0 \cos\alpha \, \sin\alpha \, H Z_\mu Z^\mu$$

$$+ \frac{1}{4} g_Z^2 \chi_0 \sin^2\alpha \, \delta\chi Z_\mu Z^\mu + \frac{1}{8} g_Z^2 \sin^2\alpha \, \delta\chi^2 Z_\mu Z^\mu + \frac{1}{4} g_Z^2 \cos\alpha \, \sin\alpha \, \delta\chi H Z_\mu Z^\mu,$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

We correctly reproduce the **mass term** for the W boson

$$M_W = \frac{1}{2} g_2 \chi_0 \sin\alpha = \frac{1}{2} g_2 v.$$

The same happens for the Z boson; its interaction Lagrangian with h is

$$\mathcal{L}_{hZZ} = \frac{1}{8} g_Z^2 h^2 Z_\mu Z^\mu$$

$$= \frac{1}{8} g_Z^2 \chi_0^2 \sin^2\alpha \, Z_\mu Z^\mu + \frac{1}{8} g_Z^2 H^2 Z_\mu Z^\mu \cos^2\alpha + \frac{1}{4} g_Z^2 \chi_0 \cos\alpha \, \sin\alpha \, H Z_\mu Z^\mu$$

$$+ \frac{1}{4} g_Z^2 \chi_0 \sin^2\alpha \, \delta\chi Z_\mu Z^\mu + \frac{1}{8} g_Z^2 \sin^2\alpha \, \delta\chi^2 Z_\mu Z^\mu + \frac{1}{4} g_Z^2 \cos\alpha \, \sin\alpha \, \delta\chi H Z_\mu Z^\mu,$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

We correctly reproduce the **mass term** for the W boson

$$M_W = \frac{1}{2} g_2 \chi_0 \sin\alpha = \frac{1}{2} g_2 v.$$

The same happens for the Z boson; its interaction Lagrangian with h is

$$\mathcal{L}_{hZZ} = \frac{1}{8} g_Z^2 h^2 Z_\mu Z^\mu$$

$$= \frac{1}{8} g_Z^2 \chi_0^2 \sin^2\alpha \, Z_\mu Z^\mu + \frac{1}{8} g_Z^2 H^2 Z_\mu Z^\mu \cos^2\alpha + \frac{1}{4} g_Z^2 \chi_0 \cos\alpha \, \sin\alpha \, H Z_\mu Z^\mu$$
$$+ \frac{1}{4} g_Z^2 \chi_0 \sin^2\alpha \, \delta\chi Z_\mu Z^\mu + \frac{1}{8} g_Z^2 \sin^2\alpha \, \delta\chi^2 Z_\mu Z^\mu + \frac{1}{4} g_Z^2 \cos\alpha \, \sin\alpha \, \delta\chi H Z_\mu Z^\mu,$$

$$M_Z = \frac{1}{2} g_Z \, \chi_0 \sin\alpha = \frac{1}{2} g_Z \, v, \qquad g_Z \equiv \sqrt{g_1^2 + g_2^2}.$$

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

The mixing angle α must be **small** to respect experimental constraints, so to generate the SM VEV v we need $\chi_0 \gg v$.

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

The mixing angle α must be **small** to respect experimental constraints, so to generate the SM VEV v we need $\chi_0 \gg v$.

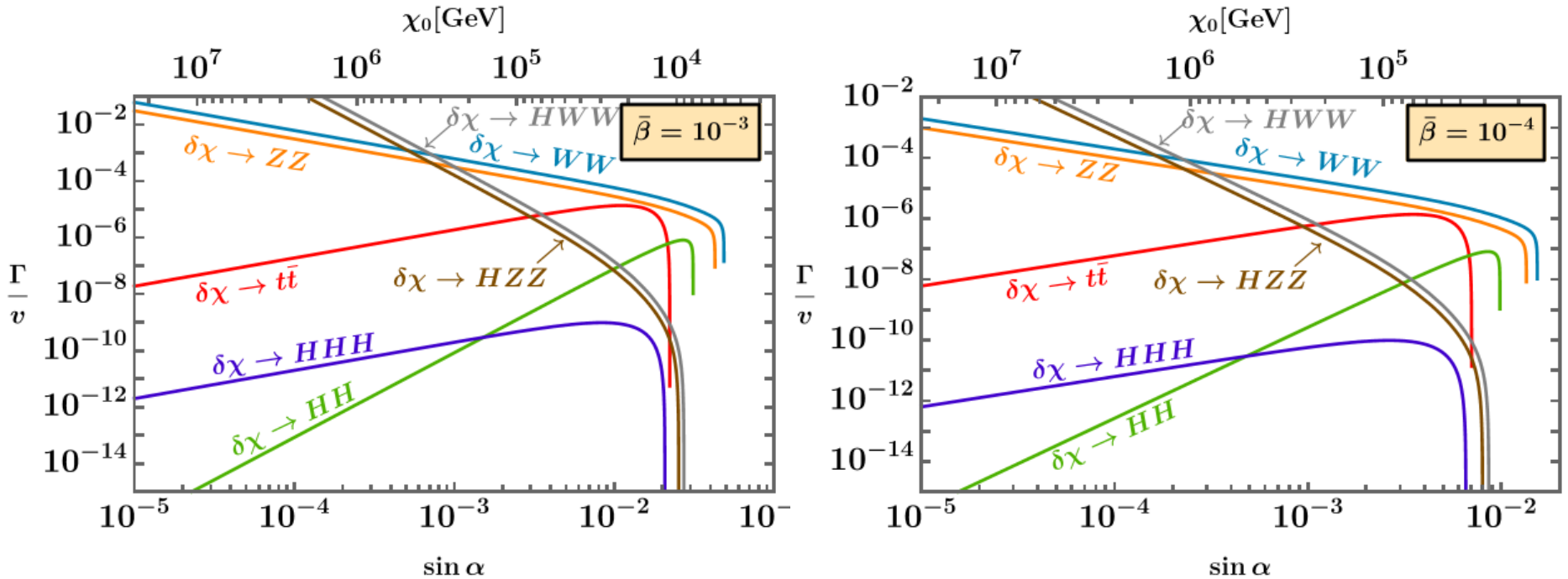


Figure taken from JCAP 02 (2026) 021 arXiv:2507.21215 [hep-ph], FR, A. Salvio

Radiative Electroweak Symmetry Breaking (EWRSB): General Properties

The mixing angle α must be **small** to respect experimental constraints, so to generate the SM VEV v we need $\chi_0 \gg v$.

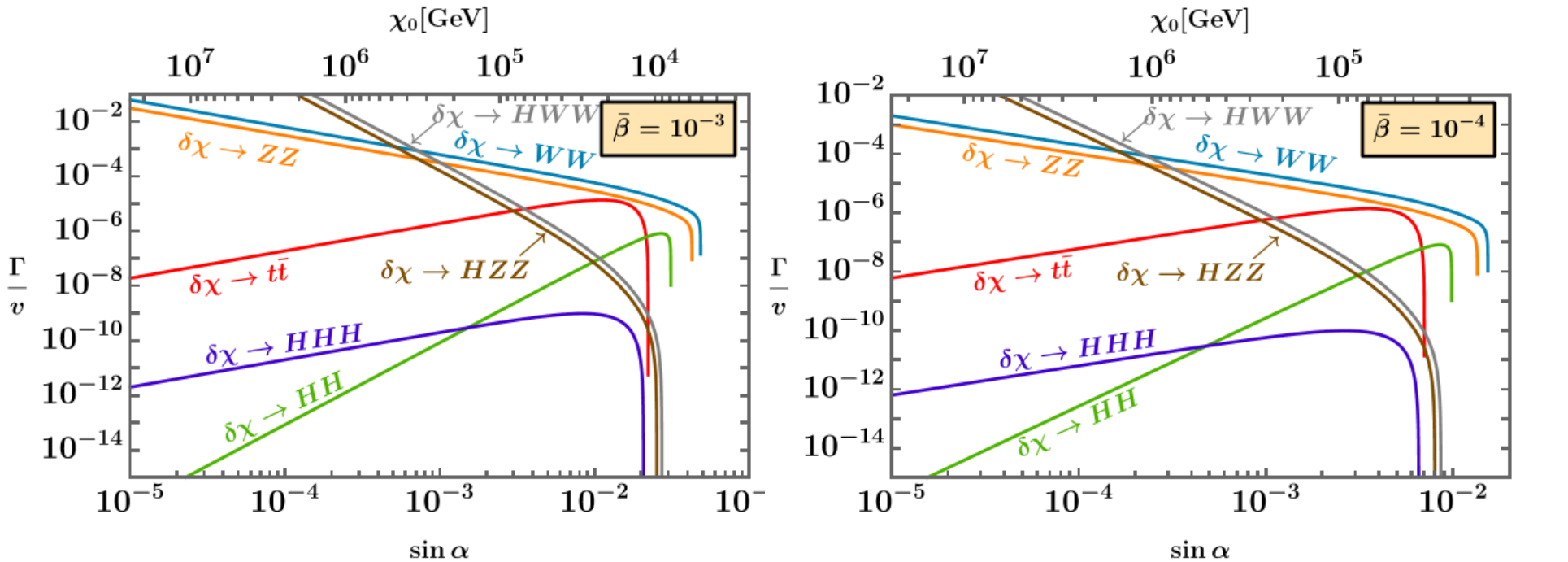


Figure taken from JCAP 02 (2026) 021 arXiv:2507.21215 [hep-ph], FR, A. Salvio

The condition for **instantaneous reheating** takes the form

$$\zeta_{\rm tot}^2 \sin^2\alpha \gtrsim \frac{512\pi^3}{3\bar{\beta}^2}\frac{v^2}{\bar{M}_P^2}, \quad N_{bg}^2 \sin^2\alpha \gtrsim \frac{512\pi^3}{3\bar{\beta}^2}\frac{v^2}{\bar{M}_P^2}.$$

Concrete case: B-L and DM production

Starting from the following Lagrangian

$$\mathcal{L}^{\rm ns}_{\rm matter} = \mathcal{L}^{\rm ns}_{\rm SM} + D_\mu A^\dagger D^\mu A + \bar{N}_j i \not{D} N_j - \tfrac{1}{4} B'_{\mu\nu} B'^{\mu\nu}$$

$$+ \left(Y_{ij} L_i \mathcal{H} N_j + \tfrac{1}{2} y_{ij} A N_i N_j + \text{h.c.}\right) - \lambda_a |A|^4 + \lambda_{ah} |A|^2 |\mathcal{H}|^2,$$

Concrete case: B-L and DM production

Starting from the following Lagrangian

$$\mathcal{L}^{\rm ns}_{\rm matter} = \mathcal{L}^{\rm ns}_{\rm SM} + D_\mu A^\dagger D^\mu A + \bar{N}_j i \not{D} N_j - \tfrac{1}{4} B'_{\mu\nu} B'^{\mu\nu}$$

$$+ \left(Y_{ij} L_i \mathcal{H} N_j + \tfrac{1}{2} y_{ij} A N_i N_j + \text{h.c.}\right) - \lambda_a |A|^4 + \lambda_{ah} |A|^2 |\mathcal{H}|^2,$$

where

$$A \equiv \frac{1}{\sqrt{2}}(a + i\eta_4),$$

$$D_\mu = \partial_\mu + i g_3 T^\alpha G^\alpha_\mu + i g_2 T^a W^a_\mu + i g_Y \mathcal{Y} B_\mu + i[g_m \mathcal{Y} + g'_1 (B - L)] B'_\mu.$$

Concrete case: B-L and DM production

The new massive gauge boson and $\delta\chi$ have masses

$$m_Z'^2 = 4g'^2\chi_0^2, \qquad m_\chi^2 = \bar{\beta}\chi_0^2,$$

$$\bar{\beta} = \frac{96g_1'^4}{(4\pi)^2} = \frac{8(4\pi)^2}{3\zeta_{Z'}^2}.$$

Concrete case: B-L and DM production

The new massive gauge boson and $\delta\chi$ have masses

$$m_Z'^2 = 4g'^2\chi_0^2, \qquad m_\chi^2 = \bar{\beta}\chi_0^2,$$

$$\bar{\beta} = \frac{96 g_1'^4}{(4\pi)^2} = \frac{8(4\pi)^2}{3\zeta_{Z'}^2}.$$

Dark matter abundance (Right-handed Neutrino)

$$\Omega_{\rm DM} \equiv \frac{\rho_{\rm DM}}{\rho_{cr}} = \frac{s_0 m_{N_1}}{3H_0^2/8\pi G_N}\mathsf{BR}(\delta\chi \to \mathsf{DM}) \approx \frac{0.110}{h^2} \times \frac{m_{N_1}}{0.40\,\mathsf{eV}}\mathsf{BR}(\delta\chi \to N_1 N_1).$$

2406.01705, M. Cirelli, A. Strumia, J. Zupan

Concrete case: B-L and DM production

So in our specific case

$$\Omega_{\rm DM}h^2 \approx 0.110 \times \frac{\chi_0}{0.40\,\text{eV}} \frac{\sqrt{\bar{\beta}\zeta_{N1}}}{4} \frac{\zeta_{N1}(1-\zeta_{N1})^{3/2}}{3}.$$

Concrete case: B-L and DM production

So in our specific case

$$\Omega_{\rm DM}h^2 \approx 0.110 \times \frac{\chi_0}{0.40\,\text{eV}} \frac{\sqrt{\bar{\beta}\zeta_{N1}}}{4} \frac{\zeta_{N1}(1-\zeta_{N1})^{3/2}}{3}.$$

We used the **improved supercool expansion** to calculate the FOPT parameters

JCAP 04 (2023) 051

arXiv:2302.10212 [hep-ph],

A. Salvio

JCAP 12 (2023) 046

arXiv:2307.04694 [hep-ph]

A. Salvio

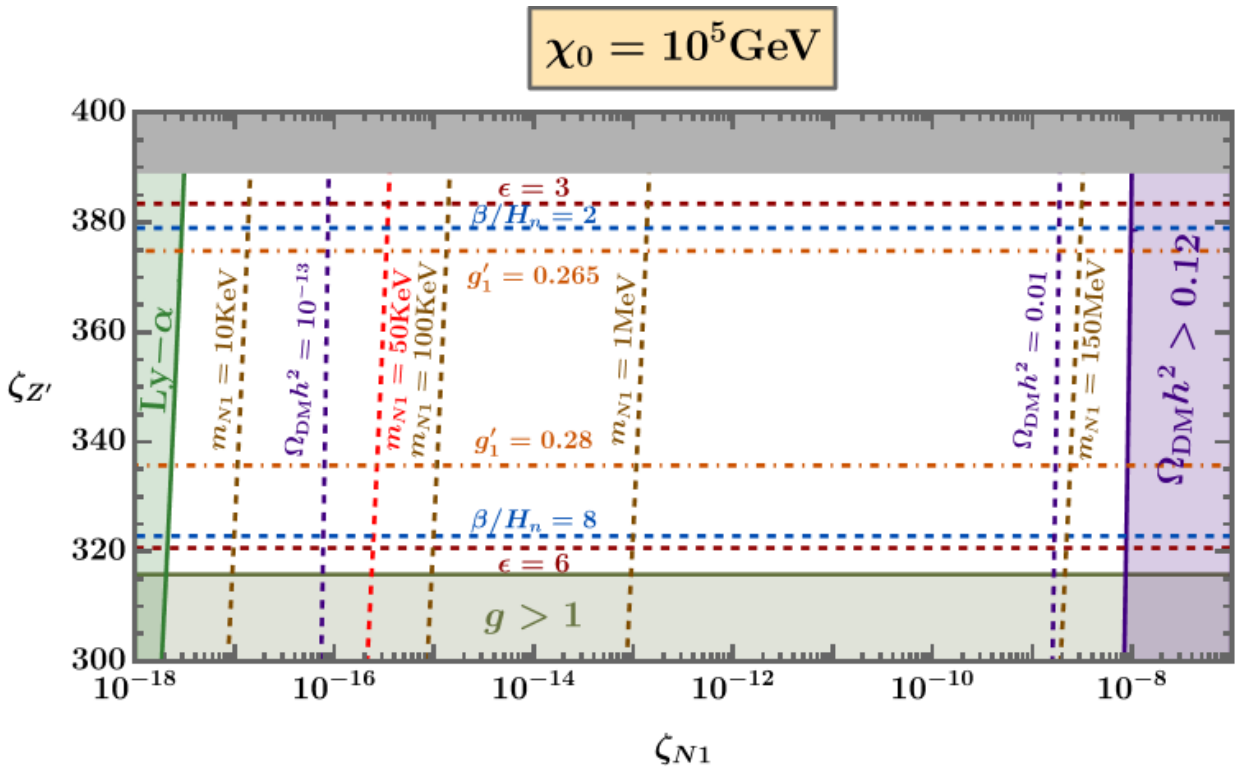


Figure taken from JCAP 02 (2026) 021 arXiv:2507.21215 [hep-ph], FR, A. Salvio

Outline

First order phase transitions (FOPTs)

Radiative symmetry breaking (RSB) & the Gildener-Weinberg scenario

Reheating after FOPT in Gildner-Weinberg Models: General Properties

Radiative Electroweak Symmetry Breaking (EWRSB)

Preheating after FOPT

Preheating: the dark photon model

There are cases when reheating is not very efficient: typically when the **RSB is a dark sector** (feeble interaction with the SM).

Preheating: the dark photon model

There are cases when reheating is not very efficient: typically when the **RSB is a dark sector** (feeble interaction with the SM).

The **dark sector** is described by the Lagrangian

$$\mathcal{L}_{\rm DP} = -\tfrac{1}{4}\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu} - \tfrac{\eta}{2}\mathcal{A}_{\mu\nu}\mathcal{F}^{\mu\nu} + \tfrac{1}{2}(D_\mu\phi)_a(D^\mu\phi)_a - V_{\rm ns}(\phi),$$

equipped with a $U(1)_D$ gauge symmetry.

Preheating: the dark photon model

There are cases when reheating is not very efficient: typically when the **RSB is a dark sector** (feeble interaction with the SM).

The **dark sector** is described by the Lagrangian

$$\mathcal{L}_{\rm DP} = -\tfrac{1}{4}\mathcal{A}_{\mu\nu}\mathcal{A}^{\mu\nu} - \tfrac{\eta}{2}\mathcal{A}_{\mu\nu}\mathcal{F}^{\mu\nu} + \tfrac{1}{2}(D_\mu\phi)_a(D^\mu\phi)_a - V_{\rm ns}(\phi),$$

equipped with a $U(1)_D$ gauge symmetry.

The dark sector is coupled to the Standard Model via

$$\mathcal{L}_{\chi h} = \frac{\lambda_{\chi h}}{2}\chi^2|\mathcal{H}|^2.$$

Preheating: the dark photon model

We allow for EWSB in the SM sector, while **RSB only occurs in the dark sector**. It must then be

$$v \gg \chi_0 \qquad \longrightarrow \qquad m_d, m_h \gg m_\chi.$$

Preheating: the dark photon model

We allow for EWSB in the SM sector, while **RSB only occurs in the dark sector**. It must then be

$$v \gg \chi_0 \qquad \longrightarrow \qquad m_d, m_h \gg m_\chi.$$

Perturbative reheating can only occur through

$$\delta\chi \to A'A'/hh \to 4 \text{ fermions}$$

suppressed by 4-body phase space.

Preheating: the dark photon model

At some stage χ undergoes small oscillations around χ_0,

$$\chi(t) = \chi_0 + \Phi \sin(m_\chi t).$$

Preheating: the dark photon model

At some stage χ undergoes small oscillations around χ_0,

$$\chi(t) = \chi_0 + \Phi \sin(m_\chi t).$$

Resonant production of dark photons can occur,

$$\frac{d^2 A'_k}{dz^2} + (a_k - 2q\cos(2z))A'_k = 0,$$

Preheating: the dark photon model

At some stage χ undergoes small oscillations around χ_0,

$$\chi(t) = \chi_0 + \Phi \sin(m_\chi t).$$

Resonant production of dark photons can occur,

$$\frac{d^2 A'_k}{dz^2} + (a_k - 2q\cos(2z))A'_k = 0,$$

where

$$a_k \equiv \frac{4(k^2 + e_d^2\chi_0^2)}{\bar{\beta}\chi_0^2}, \qquad q_i \equiv \frac{4e_d^2\Phi}{\bar{\beta}\chi_0}, \qquad z \equiv \frac{\sqrt{\bar{\beta}}\,\chi_0 t}{2} + \frac{\pi}{4}.$$

Preheating: the dark photon model

The decay of A' into fermions can **reheat the Universe**

$$\Gamma(A' \to 2 \text{ leptons}) = \frac{(\eta e)^2 m_d}{12\pi} \sqrt{1 - \left(\frac{2m_l}{m_d}\right)^2} \left(1 + \frac{2m_l^2}{m_d^2}\right) \Theta(m_d - 2m_l),$$

$$\Gamma(A' \to \text{hadrons}) = \frac{(\eta e)^2 m_d}{12\pi} \sqrt{1 - \left(\frac{2m_\mu}{m_d}\right)^2} \left(1 + \frac{2m_\mu^2}{m_d^2}\right) R\left(\sqrt{s} = m_d\right),$$

where $R\left(\sqrt{s^2}\right) \equiv \sigma(e^+e^- \to \text{hadrons}, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$.

Preheating: the dark photon model

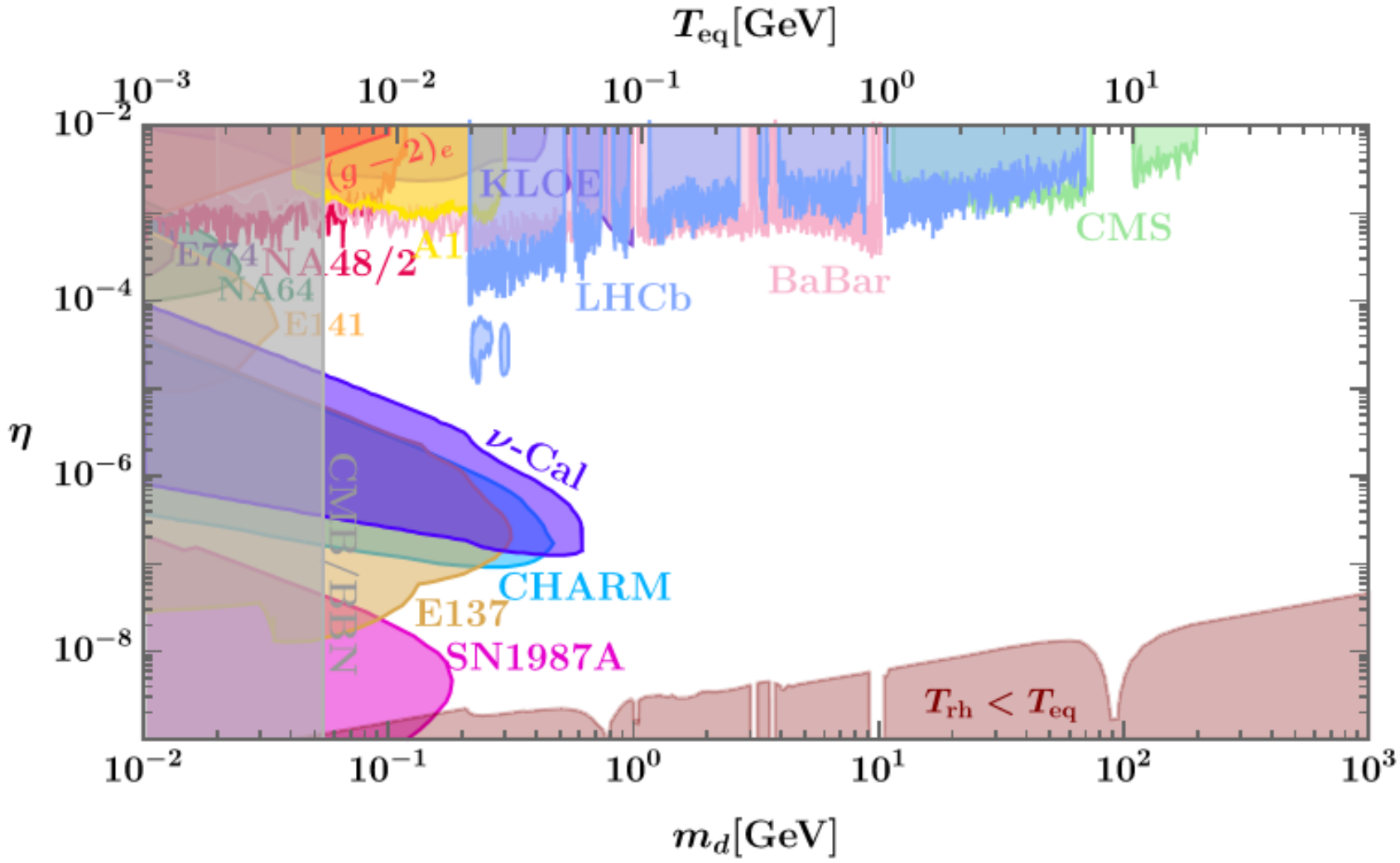


Figure taken from JCAP 02 (2026) 021 arXiv:2507.21215 [hep-ph], FR, A. Salvio

Conclusions

Reheating after FOPT is **not a simple process** (several contributions: bubble collision, reheating, preheating...).

Conclusions

Reheating after FOPT is **not a simple process** (several contributions: bubble collision, reheating, preheating...).

We studied the **perturbative reheating** that occurs after FOPT in GW models where the SM is embedded in the RSB sector...

Conclusions

Reheating after FOPT is **not a simple process** (several contributions: bubble collision, reheating, preheating...).

We studied the **perturbative reheating** that occurs after FOPT in GW models where the SM is embedded in the RSB sector...

...and the **preheating** in the case the RSB sector is hidden.

Conclusions

Reheating after FOPT is **not a simple process** (several contributions: bubble collision, reheating, preheating...).

We studied the **perturbative reheating** that occurs after FOPT in GW models where the SM is embedded in the RSB sector...

...and the **preheating** in the case the RSB sector is hidden.

But this picture of reheating (especially preheating) can be improved!

Conclusions

Reheating after FOPT is **not a simple process** (several contributions: bubble collision, reheating, preheating...).

We studied the **perturbative reheating** that occurs after FOPT in GW models where the SM is embedded in the RSB sector...

...and the **preheating** in the case the RSB sector is hidden.

But this picture of reheating (especially preheating) can be improved!

Interesting phenomenology to explore: dark matter production, gravitational wave production...

Conclusions

Reheating after FOPT is **not a simple process** (several contributions: bubble collision, reheating, preheating...).

We studied the **perturbative reheating** that occurs after FOPT in GW models where the SM is embedded in the RSB sector...

...and the **preheating** in the case the RSB sector is hidden.

But this picture of reheating (especially preheating) can be improved!

Interesting phenomenology to explore: dark matter production, gravitational wave production...

Thank you for your attention !