Collaborative Research Center TRR 257
Particle Physics Phenomenology after the Higgs Discovery

Karlsruher Institut für Technologie

Dark Matter Phase-in

Producing feebly-interacting particles after a first-order phase transition

Presented by Henda Mansour

Based on: [2504.10593] with C. Benso and F. Kahlhoefer

Dark Matter Production in The Early Universe

For now: null results from DM experiments

→ non-thermal production ?

IR freeze-in demands extremely small couplings

[Hall et al. 0911.1120]

UV freeze-in :

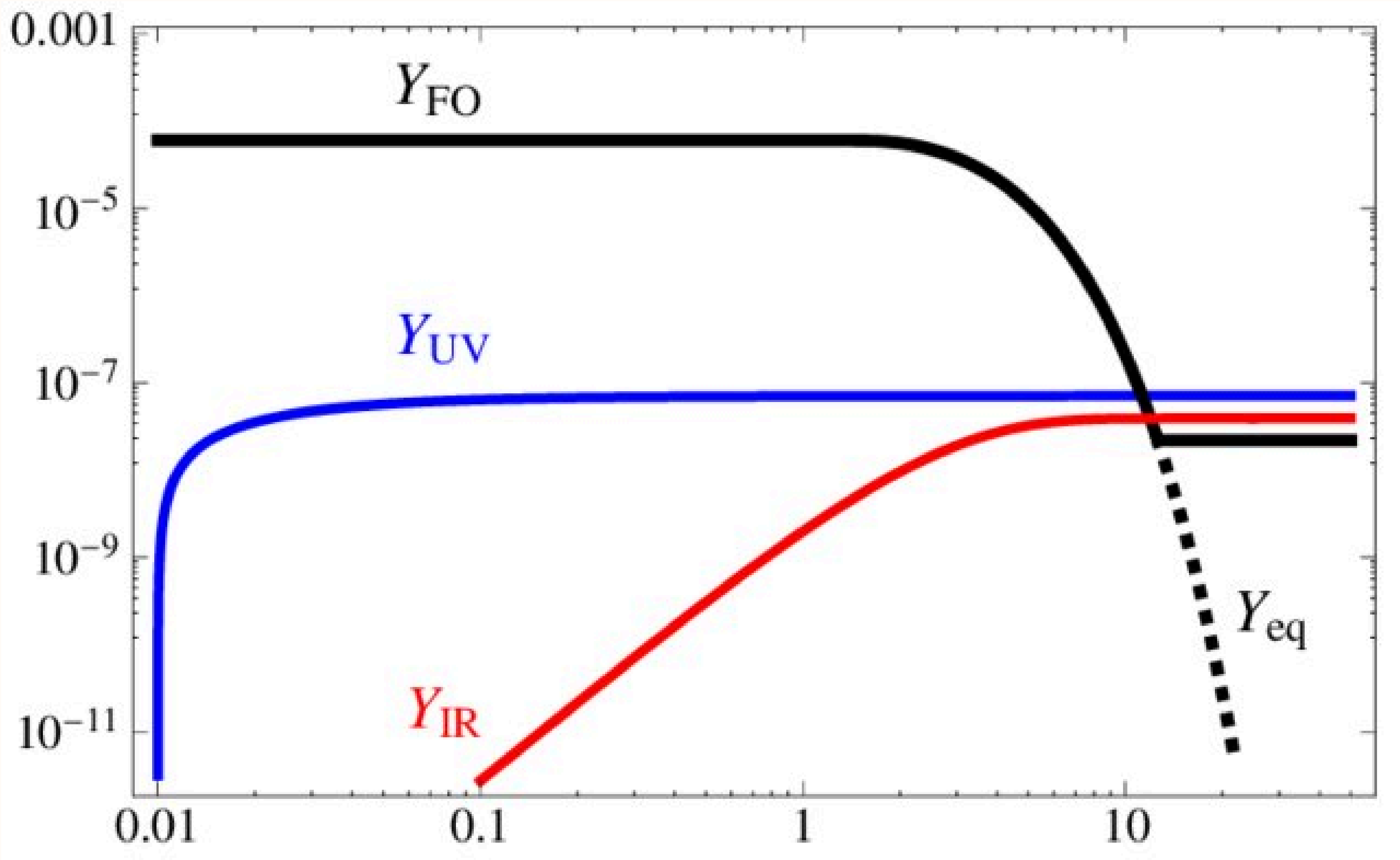
Interactions via non-renormalizable operators with dimension n+4 and thermally averaged crosssection:

$$\langle \sigma v \rangle \propto T^{2(n-1)}/\Lambda^{2n}$$

Problem: sensitivity of the DM yield to the reheating and maximal temperature

[Bernal et al. 1909.07992]

$$Y_{\rm DM} \propto M_{\rm pl} T_{RH}^{2n-1}/\Lambda^{2n}$$



[Elahi et al. 1410.6157]

UV- freeze-in and FOPTs

UV freeze-in :

DM relic density is determined by the reheating/ maximal temperature

$$Y_{\rm DM} \propto M_{\rm pl} T_{RH}^{2n-1}/\Lambda^{2n}$$

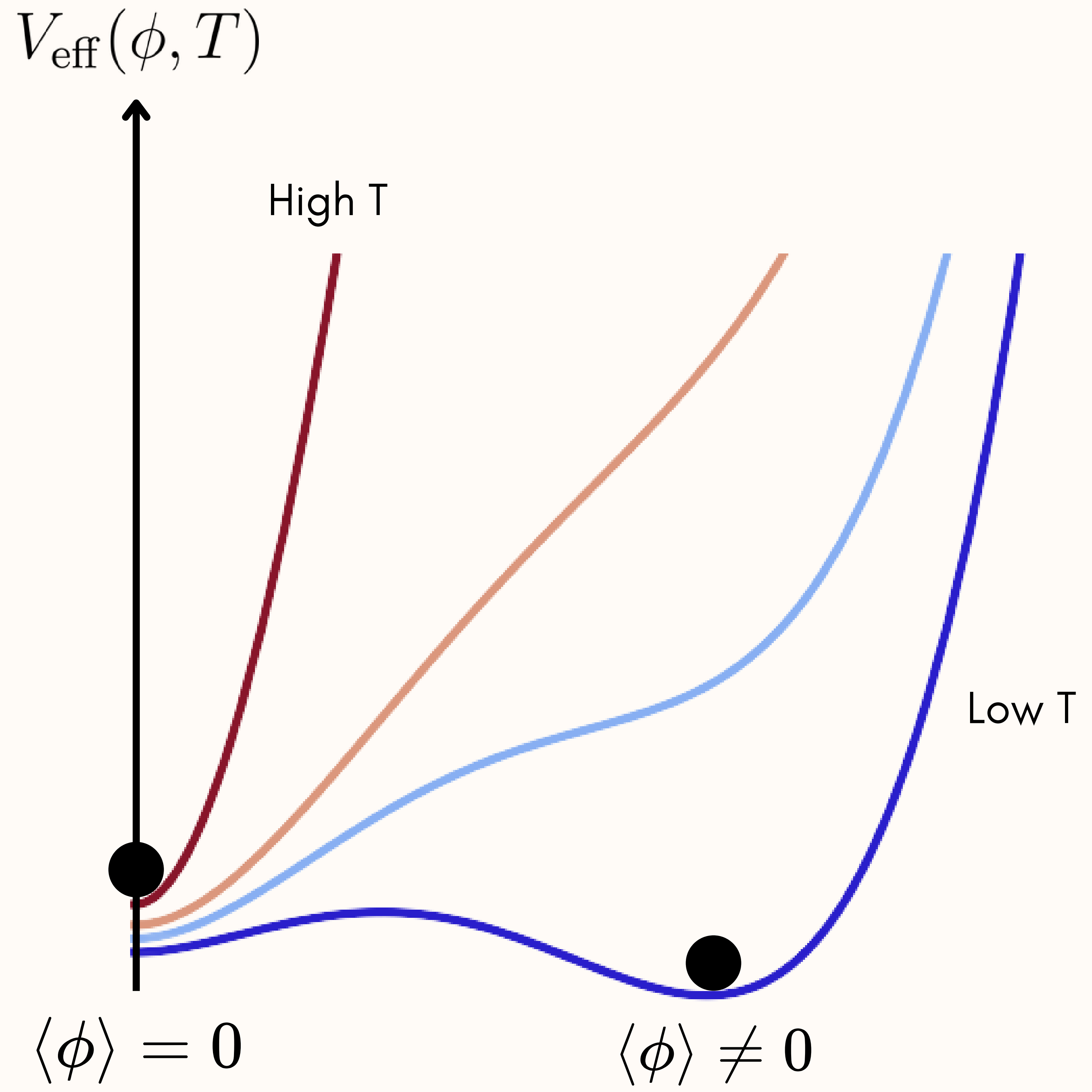
[Elahi et al. 1410.6157]
[Bernal et al. 1909.07992]

First-Order Phase Transition (FOPT):

- Can dilute pre-existing relics if supercooled
- Relevant temperature scale is $T_{\rm PT}$

Question: Under which conditions does $T_{\rm PT}$ become the relevant scale that determines the relic density?

First-Order Phase Transitions



- Well motivated in many extensions of the SM or dark sectors.
- Scalar potential + thermal corrections:

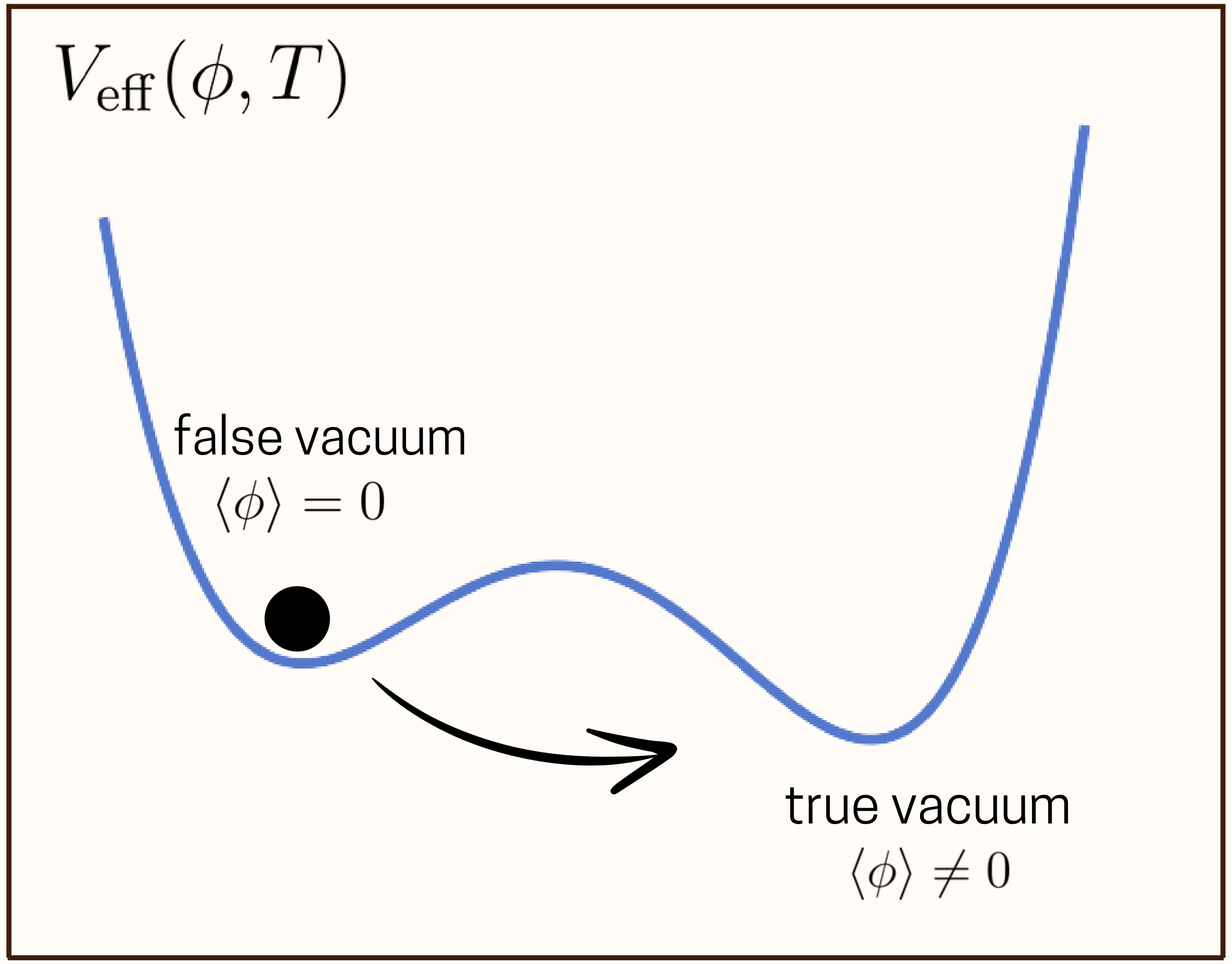
$$V_{\text{eff}}(\phi, T) = V(\phi) + \Delta V(\phi, T)$$

$$V_{\text{eff}}(\phi, T) = \left(-\lambda\nu^2 + \frac{\alpha}{24}T^2\right)\phi^2 - \gamma T\phi^3 + \lambda\phi^4$$

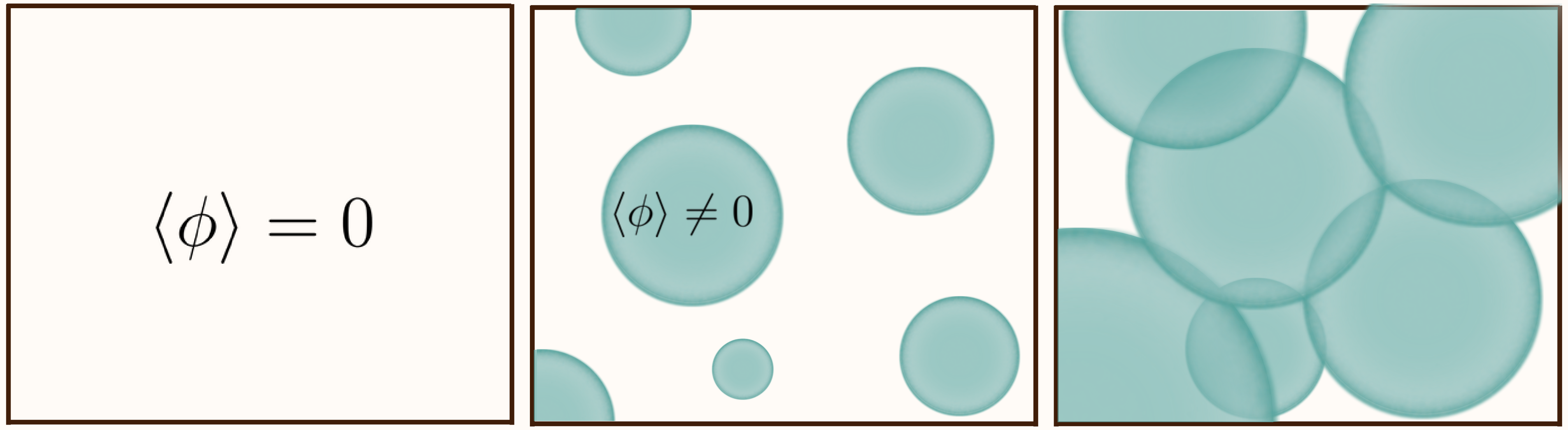
(Example)

- Interesting phenomenology: Gravitational waves, production of primordial black holes .

First-Order Phase Transitions



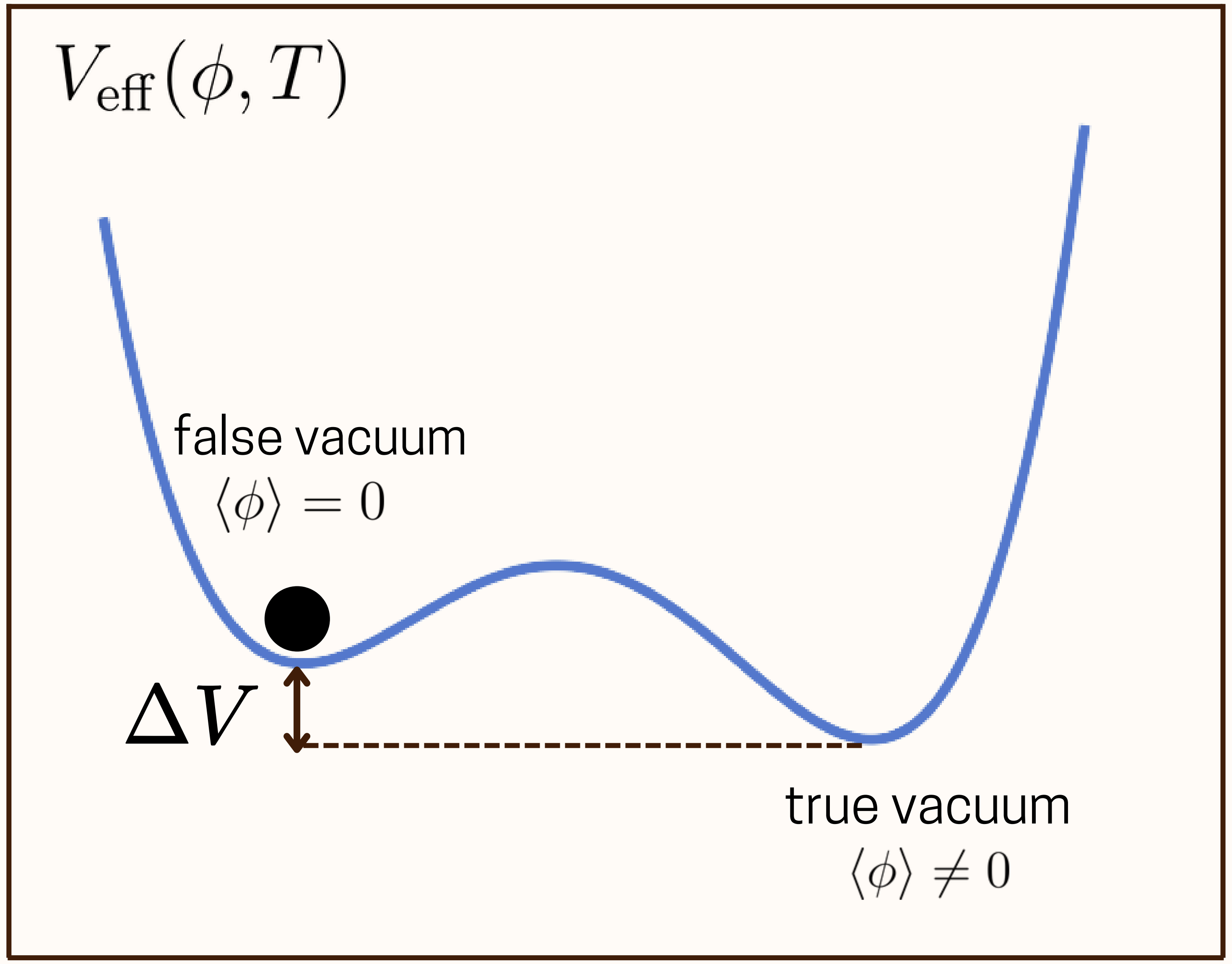
The transition proceeds through bubble nucleation:



$T > T_{\text{nuc}}$

In the following: $T_{\text{PT}} \simeq T_{\text{nuc}} \simeq T_{\text{perc}}$
because $\beta^{-1} \ll H^{-1}$

First-Order Phase Transitions



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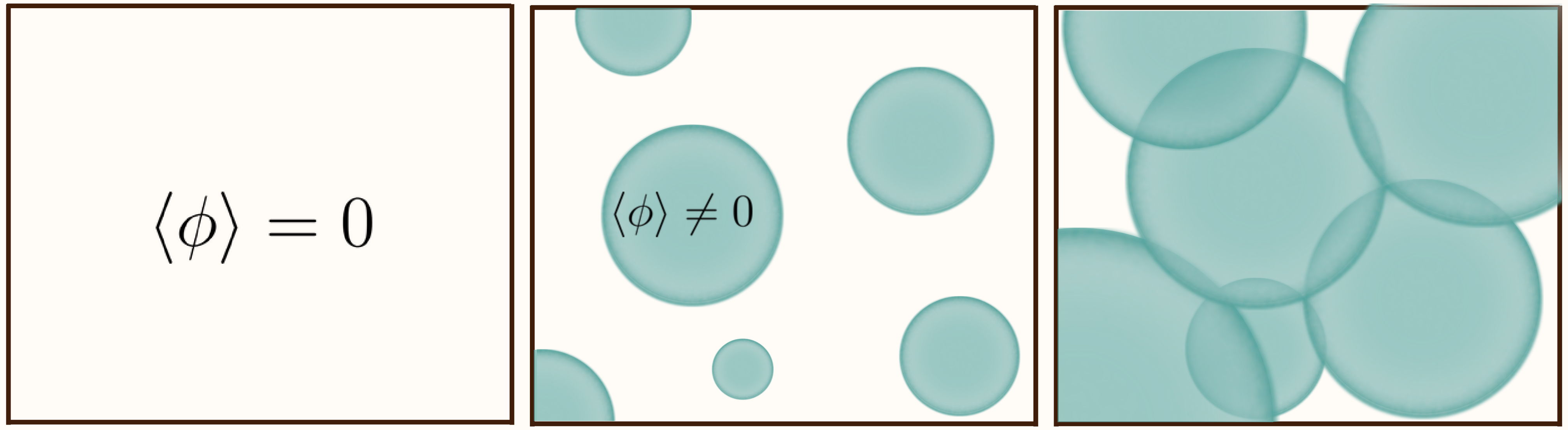
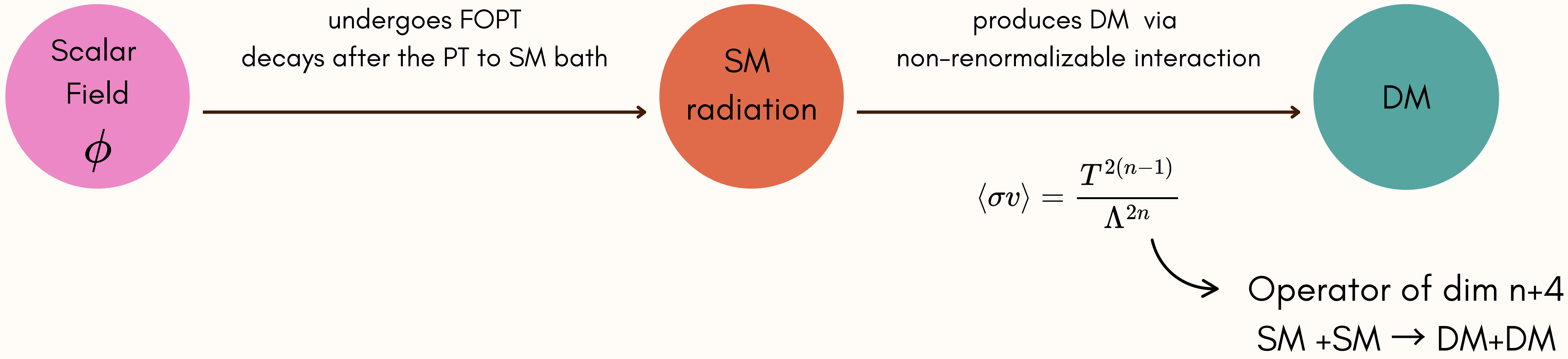


$T > T_{\text{nuc}}$

In the following: $T_{\text{PT}} \simeq T_{\text{nuc}} \simeq T_{\text{perc}}$
because $\beta^{-1} \ll H^{-1}$

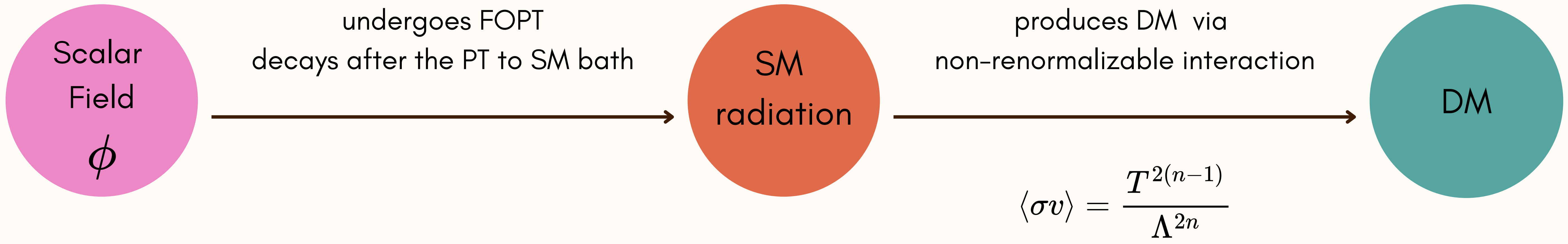
+ The scalar field acts like a cosmological constant before the transition.
  The PT is supercooled if: $\Delta V > \rho_{\text{rad}}(T_{\text{PT}})$
+ Energy injection to the radiation bath after the phase transition

The DM phase-in scenario



$$\langle \sigma v \rangle = \frac{T^{2(n-1)}}{\Lambda^{2n}}$$

The DM phase-in scenario



Boltzmann equations:

$$\frac{\mathrm{d}\rho_\phi}{\mathrm{d}a} = -\frac{3(1+\omega)}{a}\rho_\phi - \frac{\Gamma}{aH}\rho_\phi$$

$$\frac{\mathrm{d}\rho_{\mathrm{SM}}}{\mathrm{d}a} = -\frac{4}{a}\rho_{\mathrm{SM}} + \frac{\Gamma}{aH}\rho_\phi$$

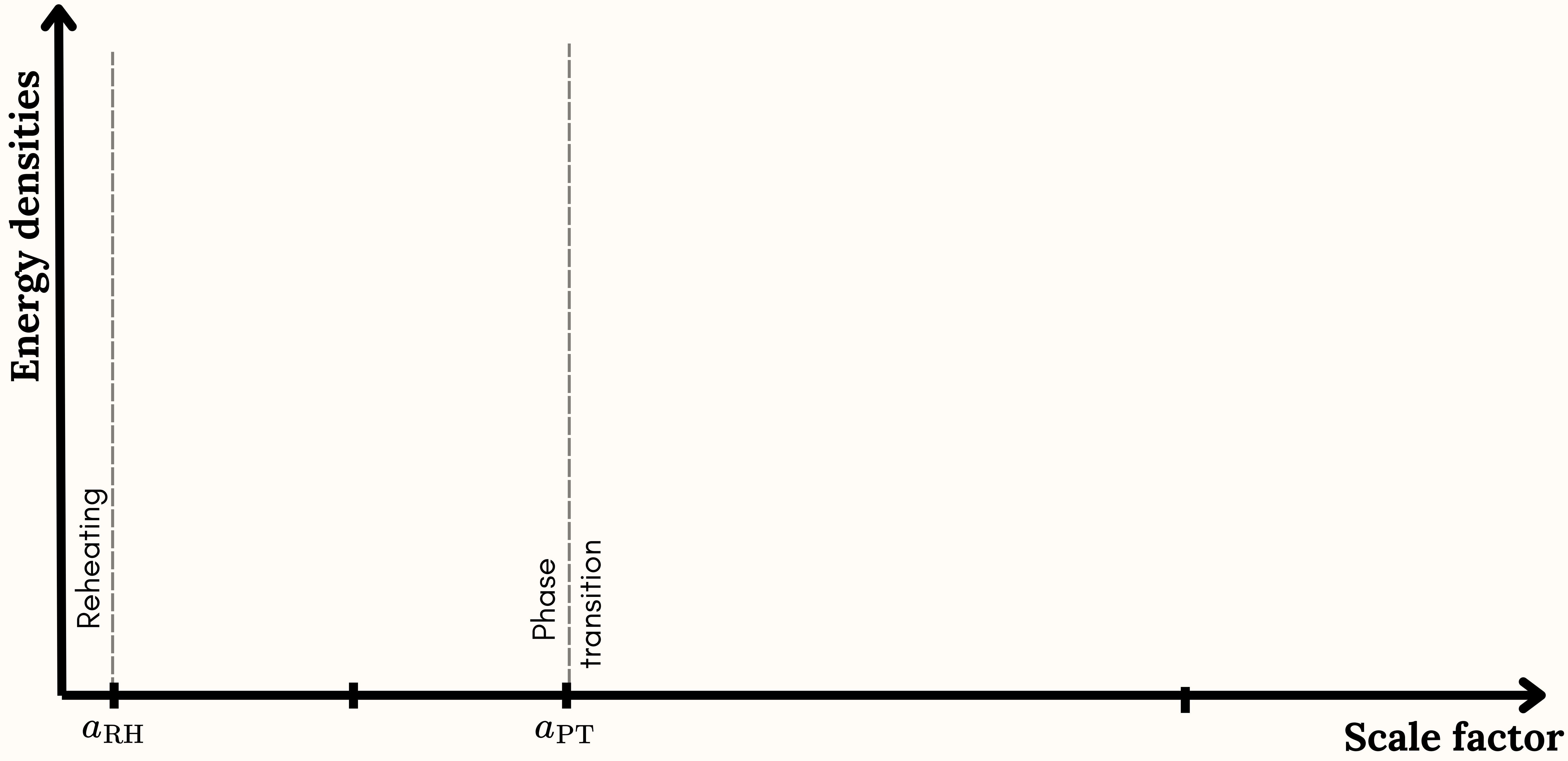
$$\frac{\mathrm{d}n_{\mathrm{DM}}}{\mathrm{d}a} = -\frac{3}{a}n_{\mathrm{DM}} + \frac{\langle \sigma v \rangle}{aH}n_{\mathrm{SM}}^2$$

Before the PT: $\Gamma = 0$ and $\omega = -1$

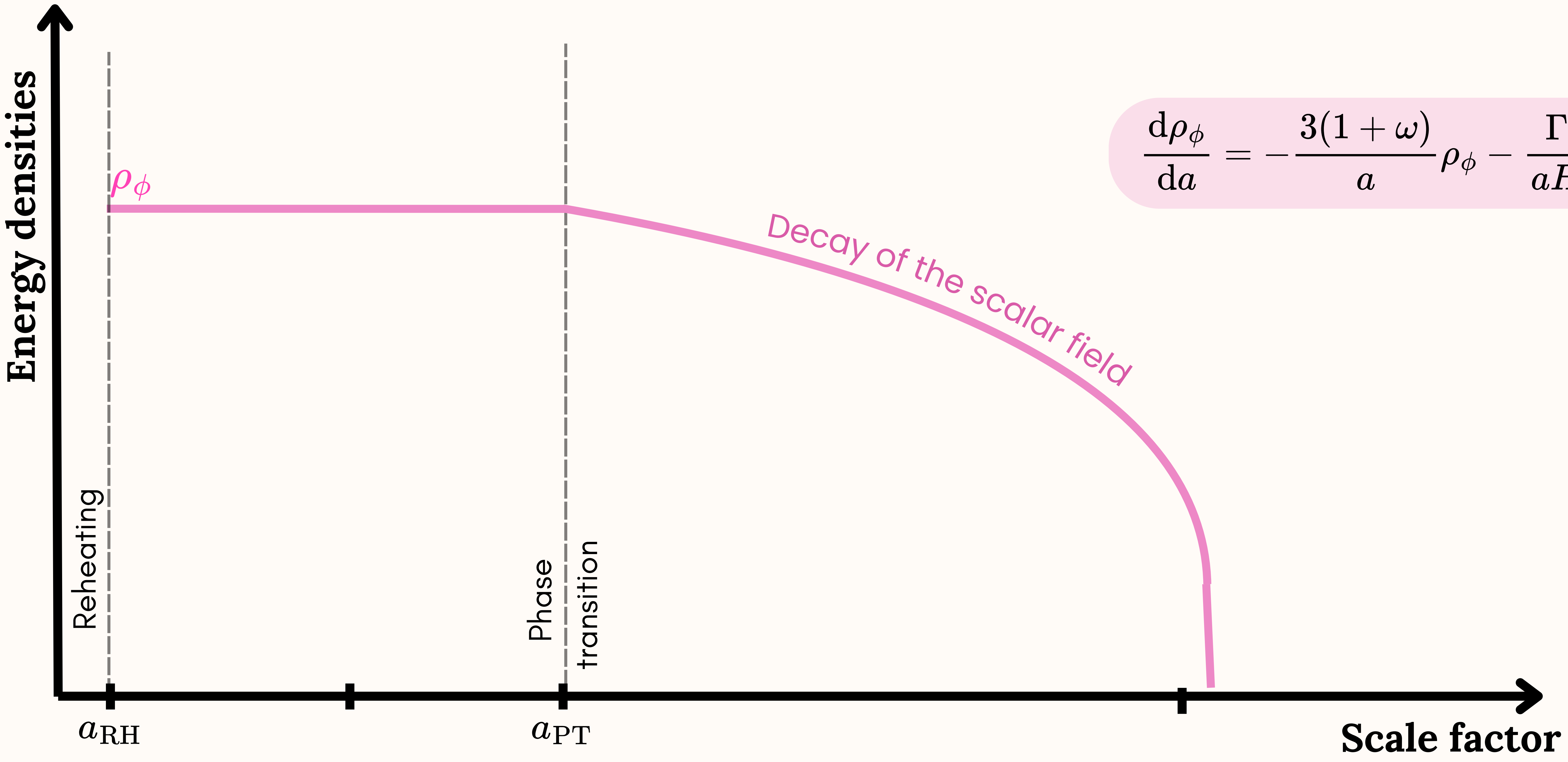
After the PT: $\Gamma = \mathrm{const}$ and $0 \leq \omega \leq 1/3$

Friedmann eq: $H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi}{3M_{\mathrm{Pl}}^2}(\rho_{\mathrm{SM}} + \rho_\phi)}$

The DM phase-in scenario

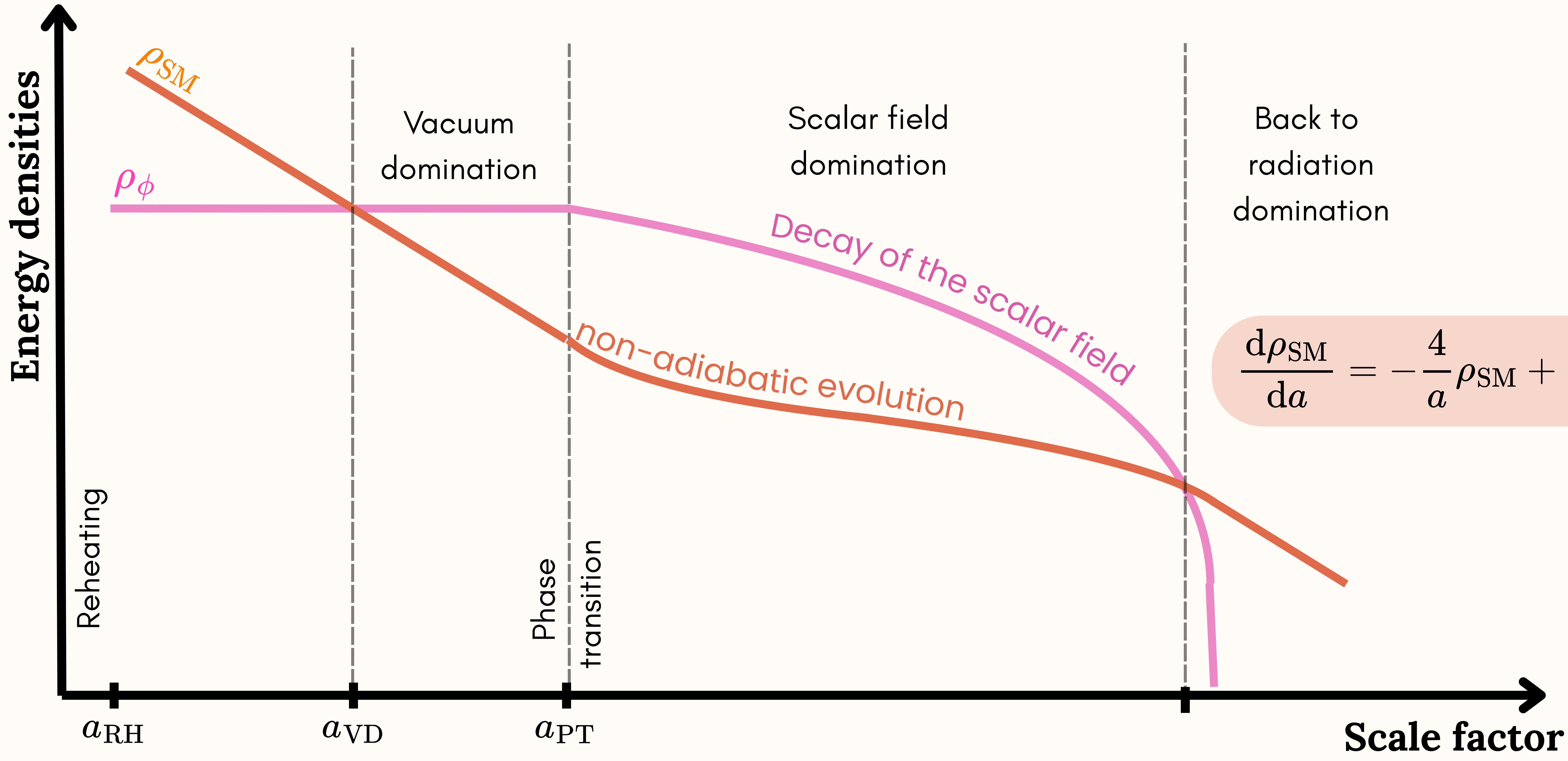


The DM phase-in scenario



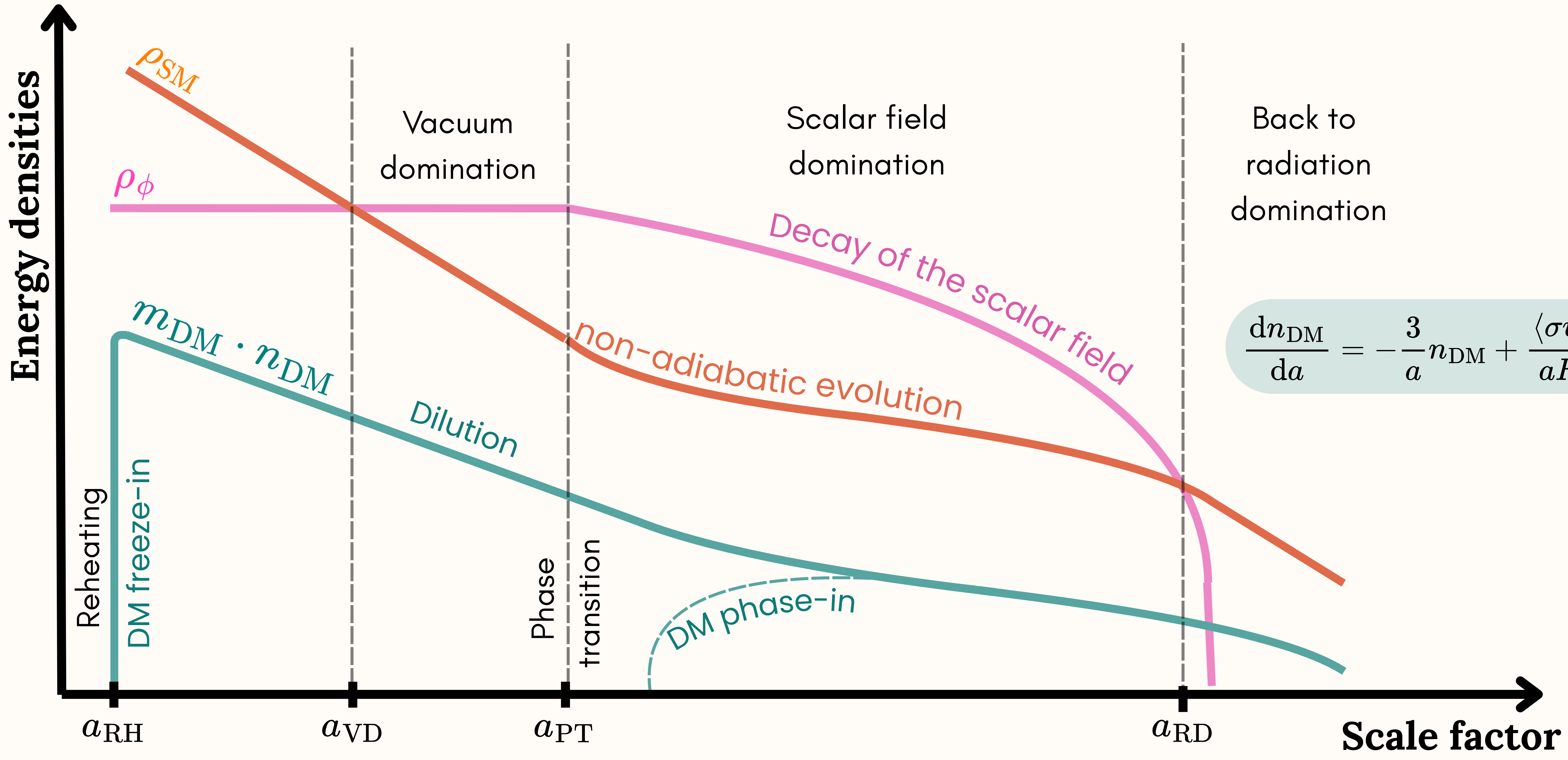
$$\frac{\mathrm{d}\rho_\phi}{\mathrm{d}a} = -\frac{3(1+\omega)}{a}\rho_\phi - \frac{\Gamma}{aH}\rho_\phi$$

The DM phase-in scenario



$$\frac{{\rm d}\rho_{\rm SM}}{{\rm d}a} = -\frac{4}{a}\rho_{\rm SM} + \frac{\Gamma}{aH}\rho_\phi$$

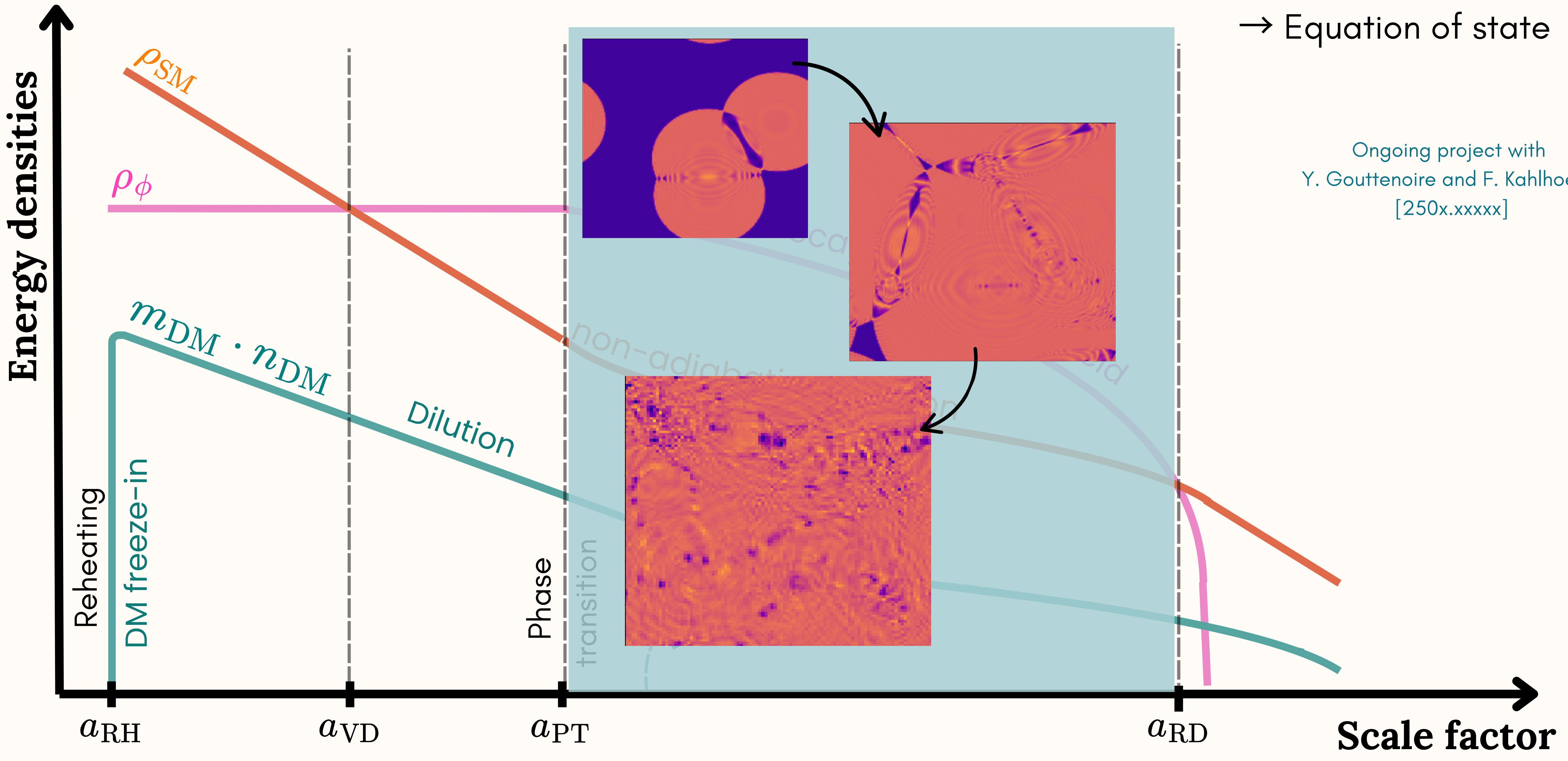
The DM phase-in scenario



$$\frac{\mathrm{d}n_{DM}}{\mathrm{d}a} = -\frac{3}{a} n_{DM} + \frac{\langle \sigma v \rangle}{aH} n_{SM}^2$$

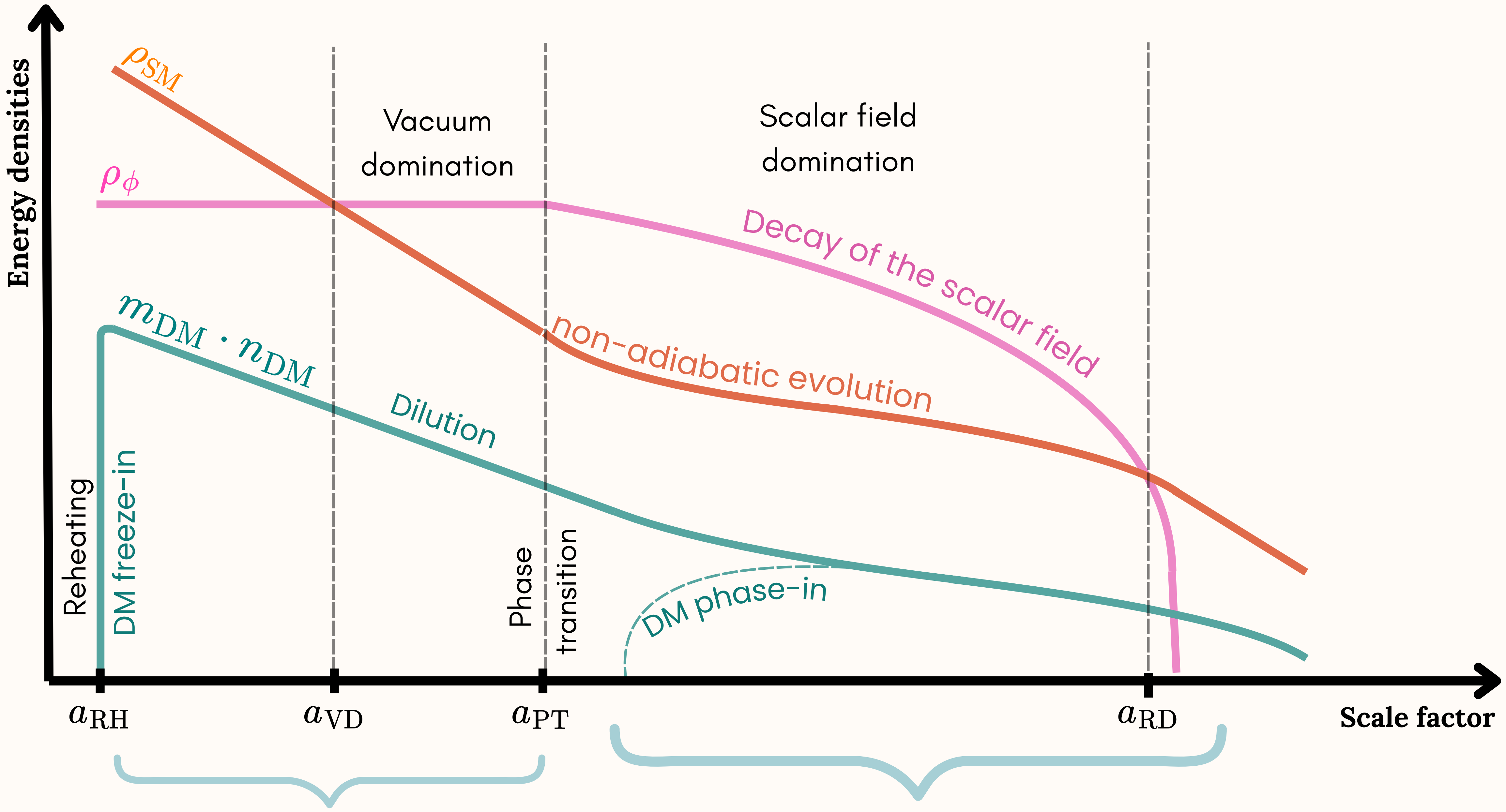
The DM phase-in scenario

Highly inhomogeneous scalar field
→ Equation of state $\omega \neq 0$



Ongoing project with
Y. Gouttenoire and F. Kahlhoefer
[250x.xxxxx]

Phase-in condition



Dark matter is produced in different phases.

$\Omega_{\rm DM,FI}$

↓

Determined by reheating temperature

$n_{\rm DM,FI} \propto T_{\rm RH}^{2n-1}$

$\Omega_{\rm DM,PI}$

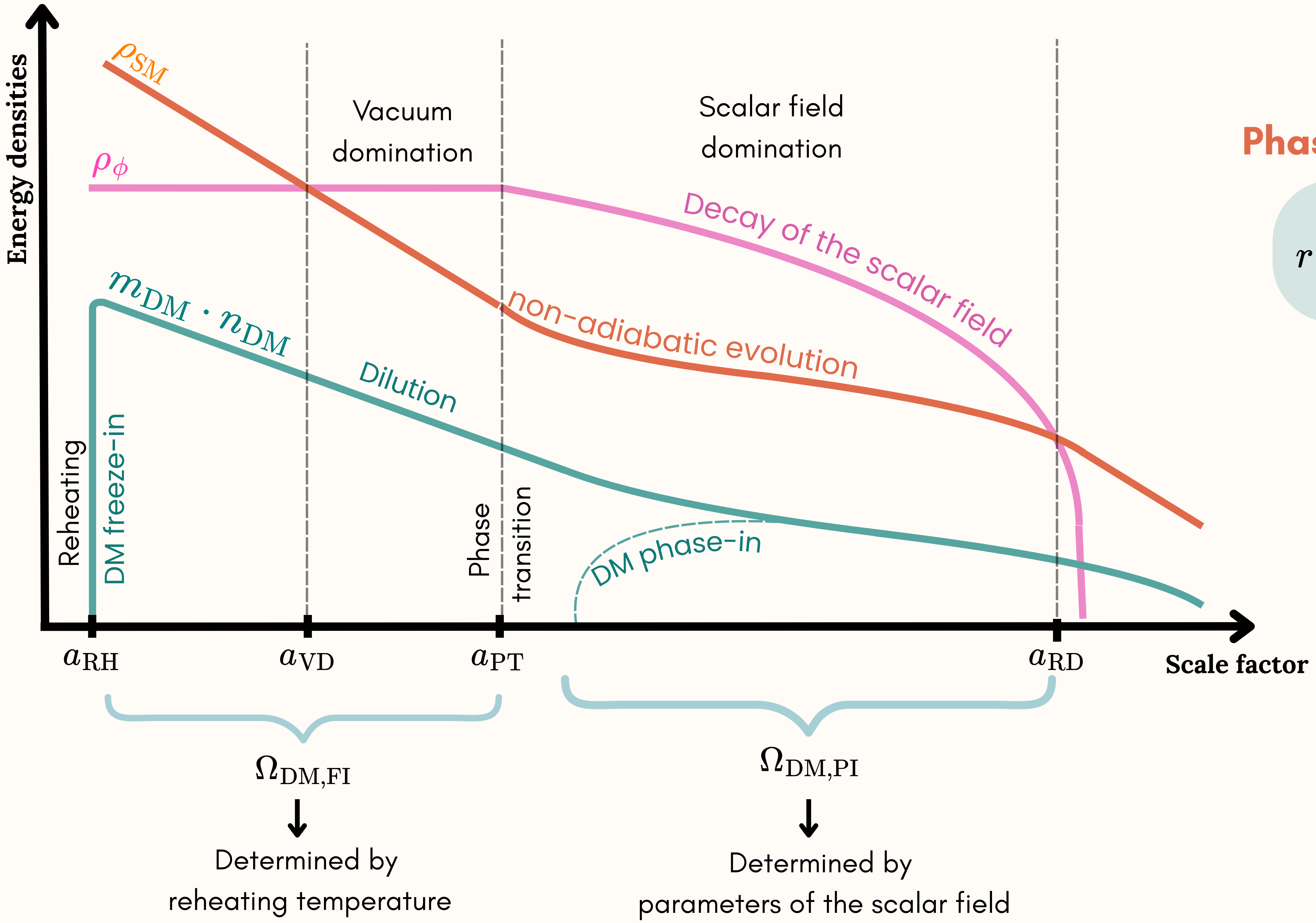
↓

Determined by parameters of the scalar field

Sensitive to the radiation bath temperature after the decay: $T_{\rm RD}$

$n_{\rm DM,PI} \propto T_{\rm RD}^{2n-1}$

Phase-in condition



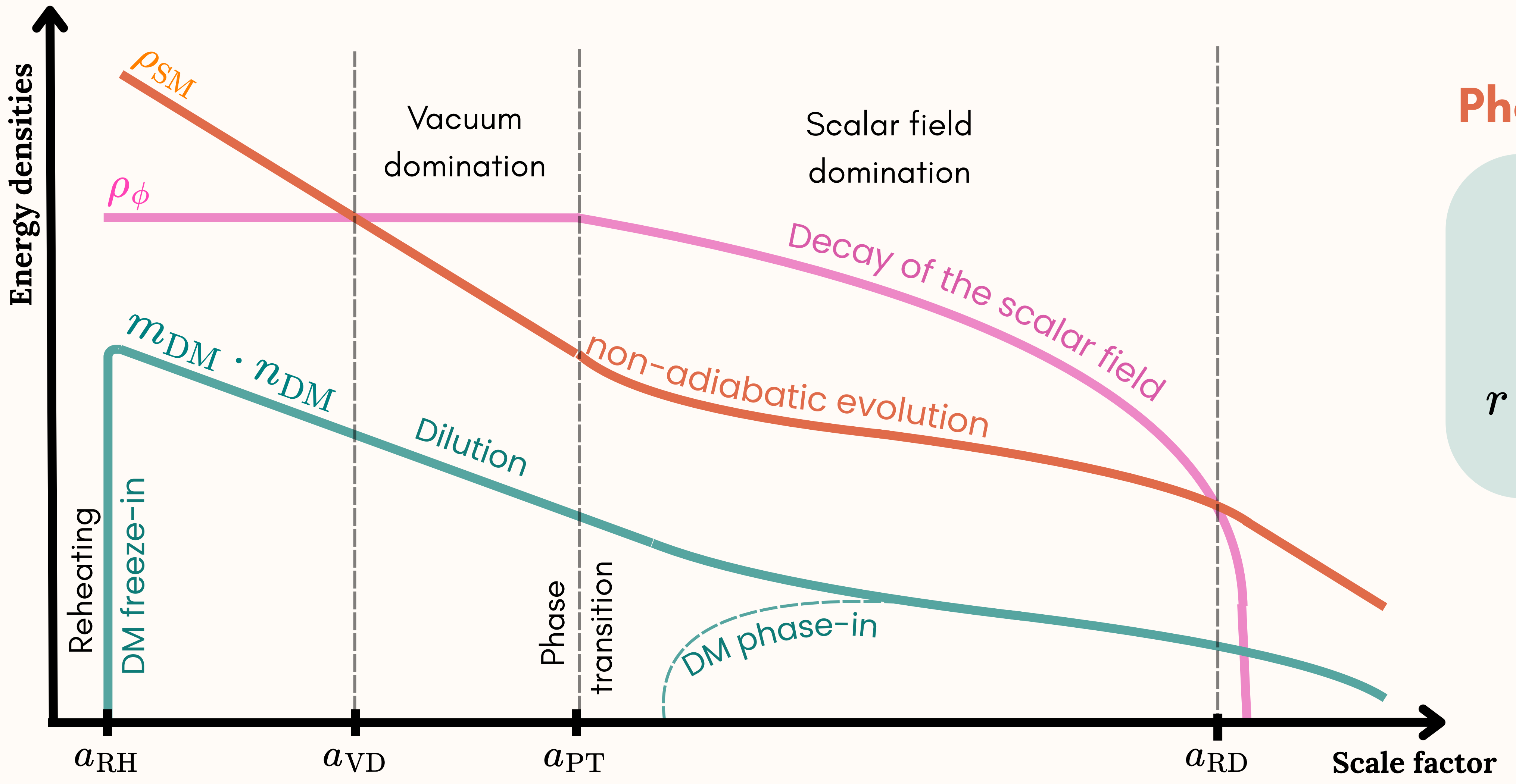
Phase-in condition:

$$r(T_{RH}, T_{PT}, \Delta V, \Gamma, \omega, n) > 1 \quad \text{with:} \quad r = \frac{\Omega_{DM,PI}}{\Omega_{DM,FI}}$$

Parameters of the problem:

- T_{RH} : Reheating temperature
- T_{PT} : Phase transition temperature
- ΔV : Potential energy/ latent heat
- Γ : Decay rate of the scalar field
- ω : Equation of state parameter
- n : Dimensions of operator (-4)

Phase-in condition



Phase-in condition:

$$r(T_{RH}, T_{PT}, \Delta V, \Gamma, \omega, n) > 1 \quad \text{with: } r = \frac{\Omega_{DM,PI}}{\Omega_{DM,FI}} = \frac{\text{phase}-\text{in}}{\text{freeze}-\text{in}}$$

$$r \approx T_{RH}^{-2n+1} T_{PT}^{-3} \Delta V^{\frac{n+1}{2}} g_\star^{-(n+1)/2} \left(\frac{\sqrt{\Delta V}}{M_{Pl}\Gamma} + \sqrt{\frac{3}{8\pi}} \right)^{\frac{2}{1+w}-1-n}$$

Parameters of the problem:

- T_{RH} : Reheating temperature
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- n : Dimensions of operator (-4)

Analytical estimate:

$$n_{DM}^{tot}(T) = \frac{1}{D}\left[n_{DM}^{I}(a_{VD}) \left(\frac{T}{T_{VD}}\right)^3 + n_{DM}^{II}(a_{PT}) \left(\frac{T}{T_{PT}}\right)^3 \right] + n_{DM}^{III}(a_{RD}) \left(\frac{T}{T_{RD}}\right)^3 + n_{DM}^{IV}(T)$$

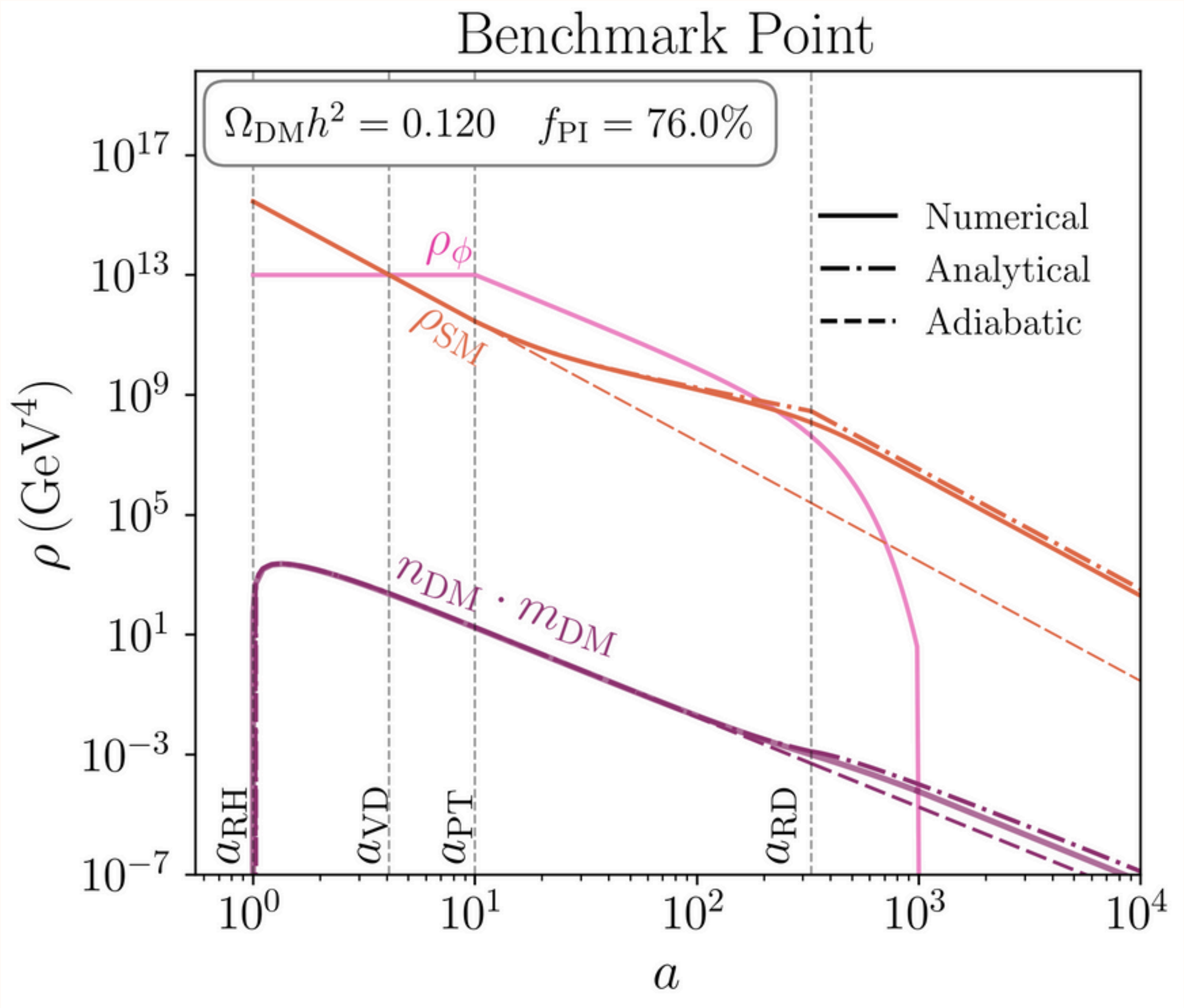
Dilution factor: $D = \frac{S_{RD}}{S_{PT}} = \left(\frac{T_{RD}a_{RD}}{T_{PT}a_{PT}}\right)^3$

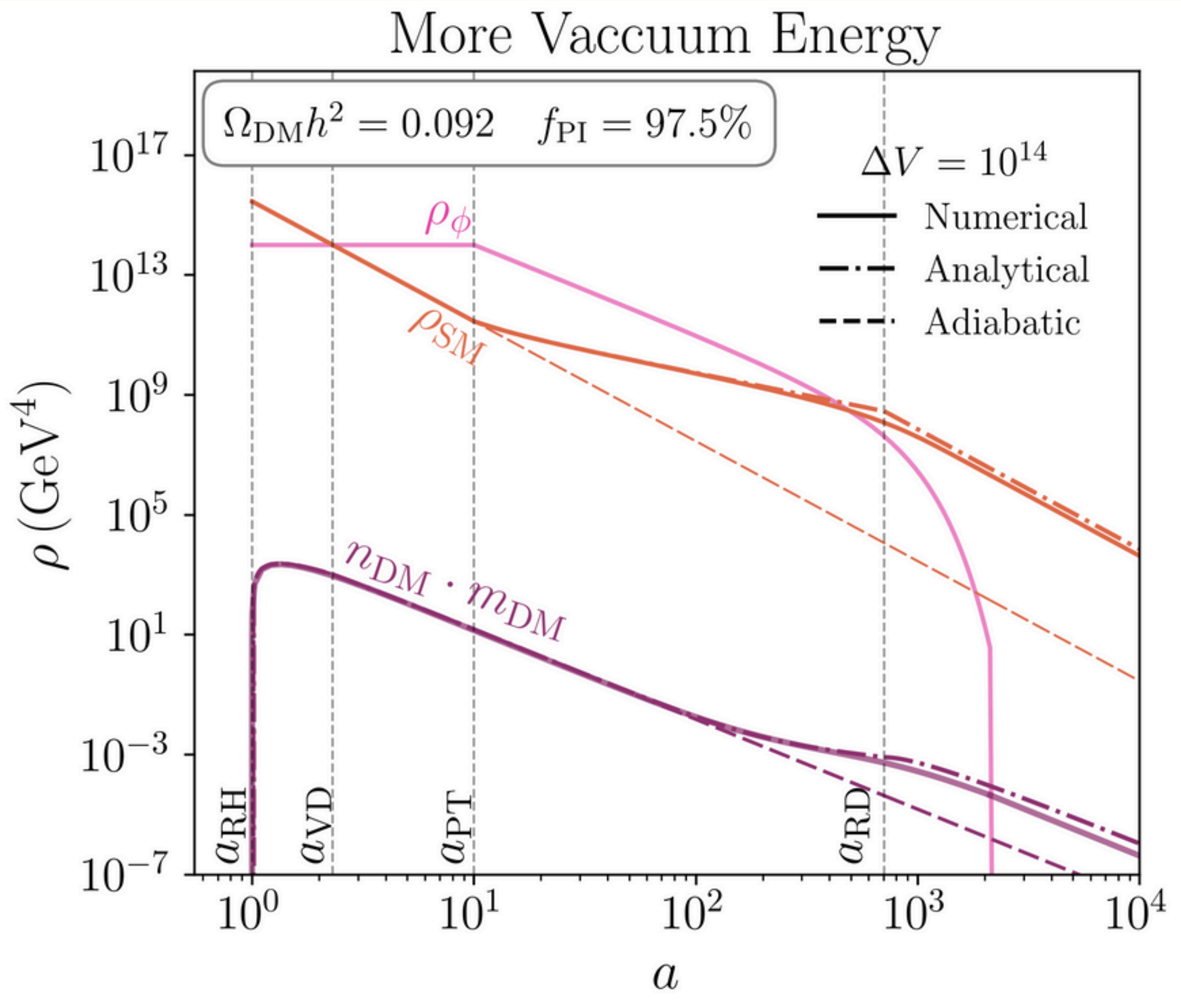
Some examples

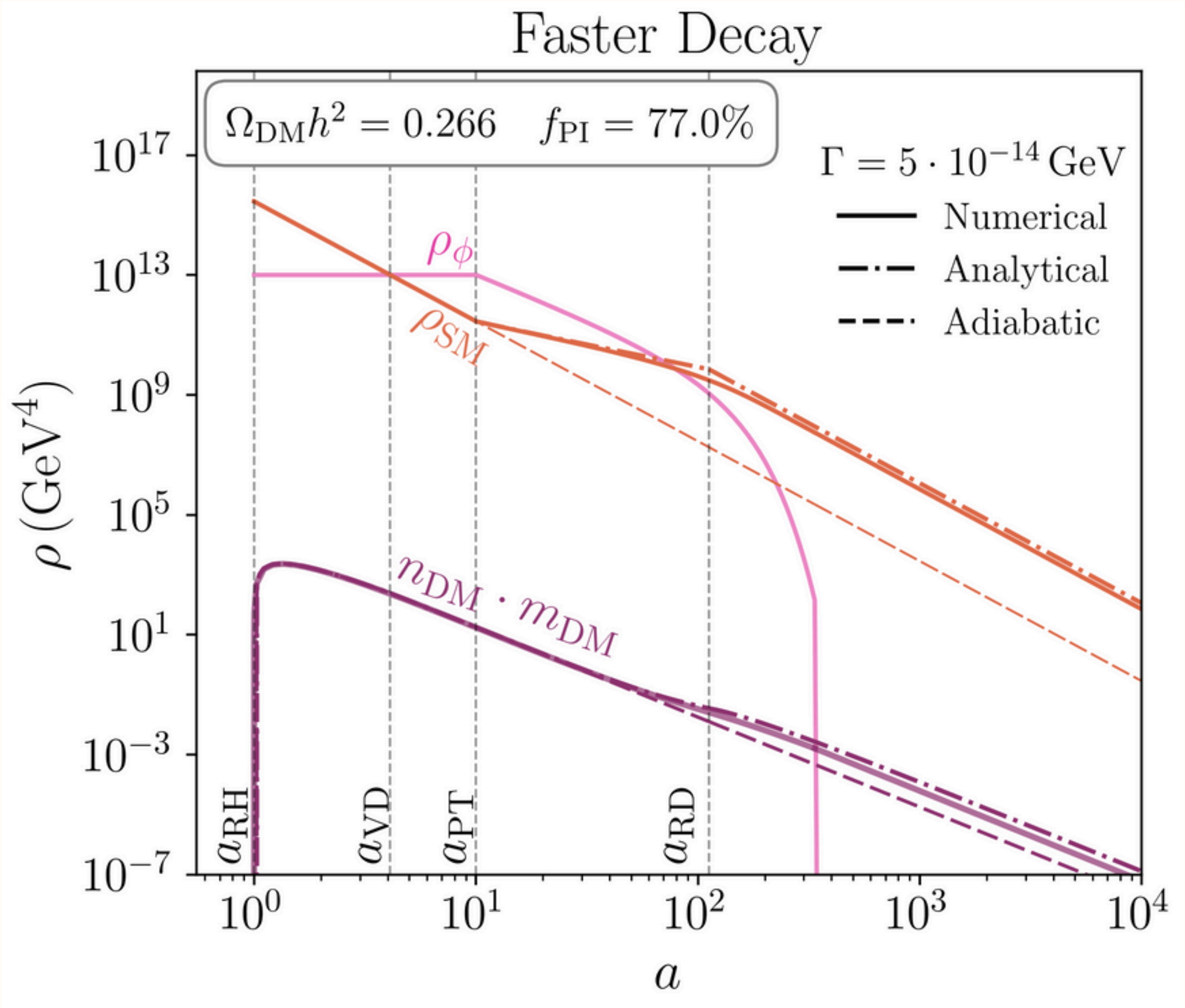
Phase-in condition

$$r \approx T_{\rm RH}^{-2n+1} T_{\rm PT}^{-3} \Delta V^{\frac{n+1}{2}} g_\star^{-(n+1)/2} \left(\frac{\sqrt{\Delta V}}{M_{\rm Pl}\Gamma} + \sqrt{\frac{3}{8\pi}} \right)^{\frac{2}{1+w}-1-n} > 1 \quad \text{with:} \quad r = \frac{\Omega_{\rm DM,PI}}{\Omega_{\rm DM,FI}} = \frac{\text{phase-in}}{\text{freeze-in}}$$

For : $n = 1$ and $\omega = 0$ (i.e Dim 5 operator and assuming matter domination during the decay).





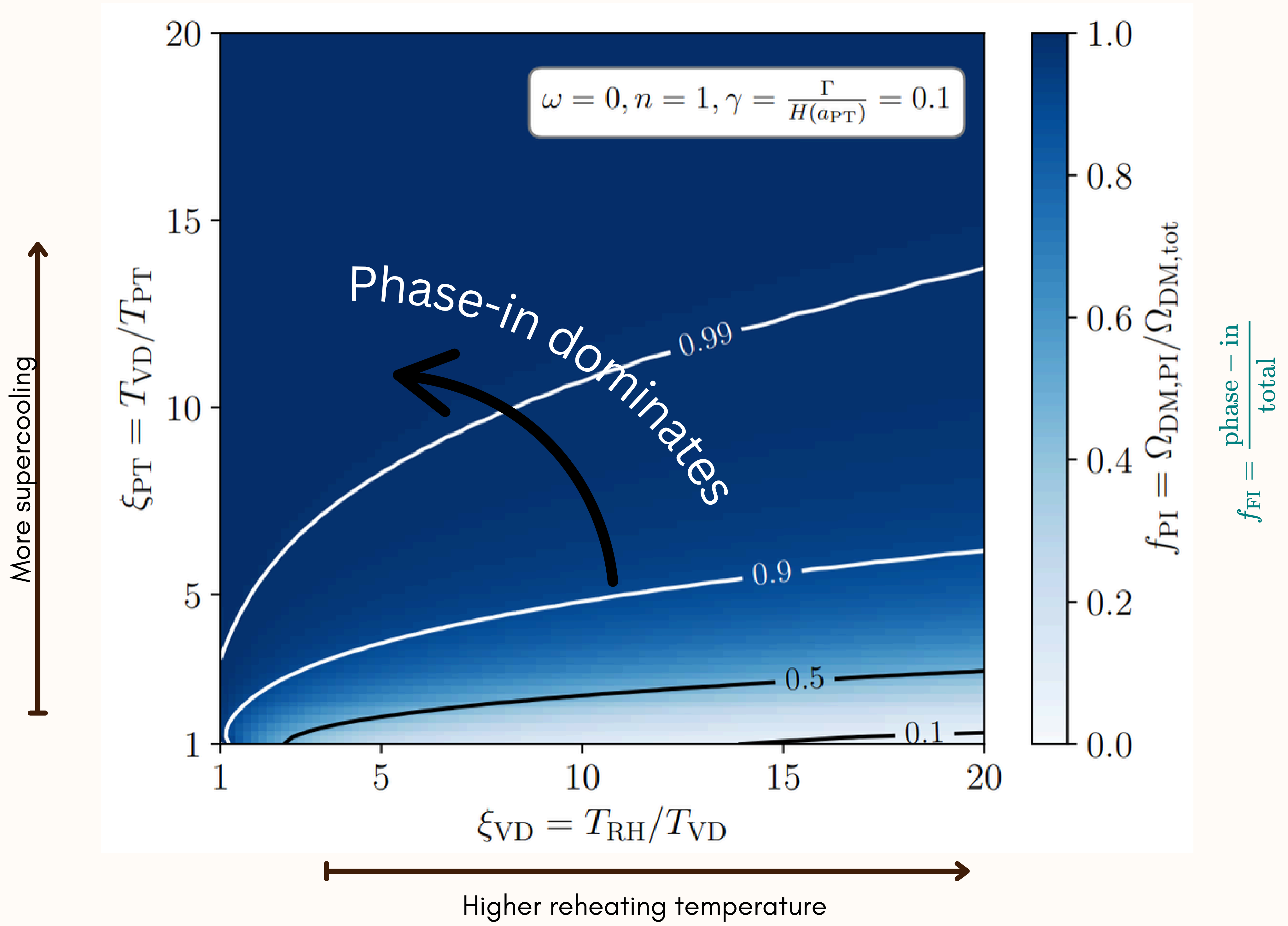


Benchmark values

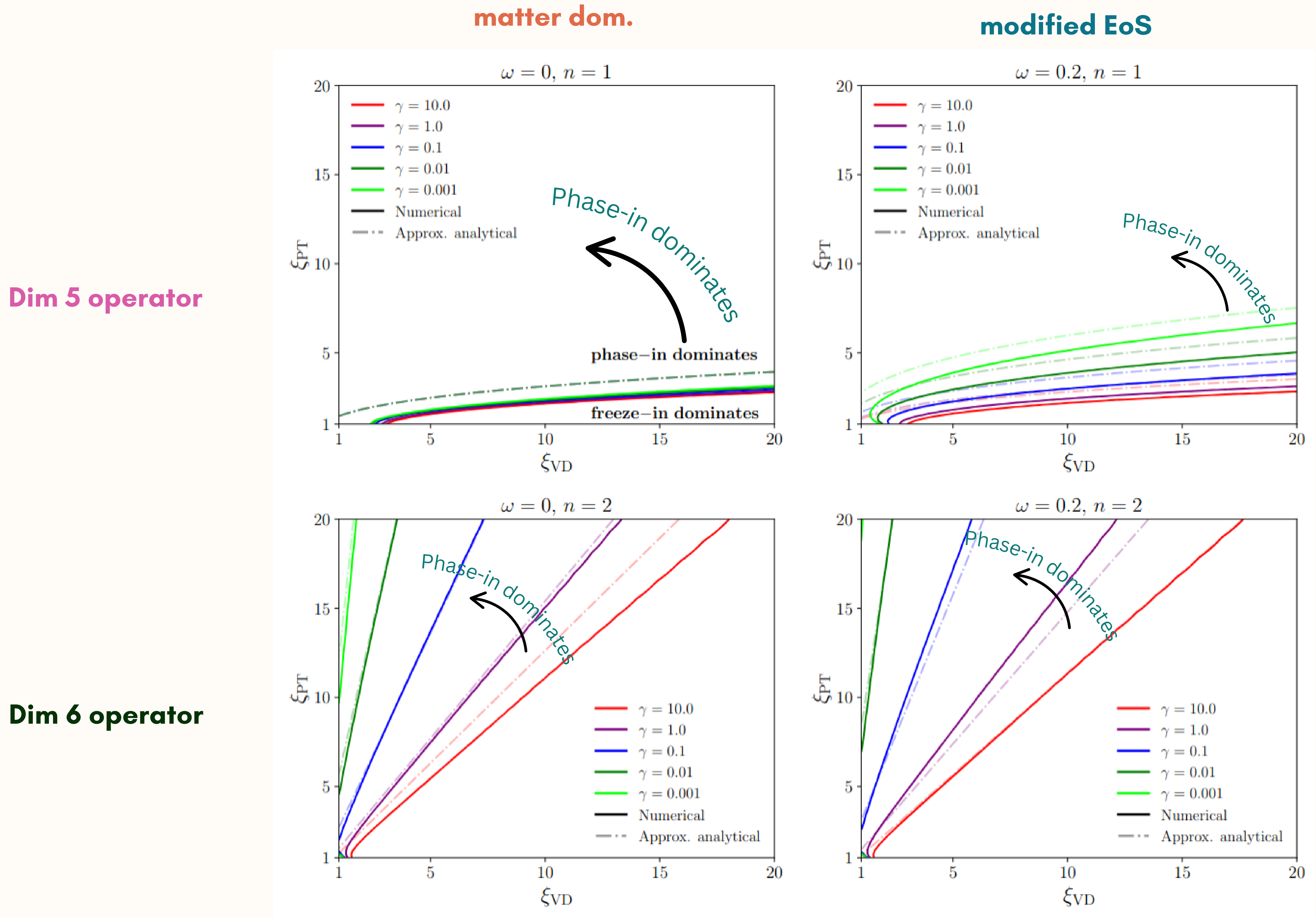
$$m_{\rm DM} = 1\,{\rm MeV},\ T_{\rm RH} = 3 \cdot 10^3\,{\rm GeV}$$
$$T_{\rm PT} = 300\,{\rm GeV},\ \Delta V = 10^{13}\,{\rm GeV}^4$$
$$\Gamma = 10^{-14}\,{\rm GeV},\ \Lambda = 1.88 \cdot 10^{13}\,{\rm GeV}$$

with: $f_{\rm PI} = \dfrac{\Omega_{\rm DM,PI}}{\Omega_{\rm DM,tot}} = \dfrac{\text{phase-in}}{\text{total}}$

Numerical results



Phase-in condition : results



with:

$$\xi_{PT} = \frac{T_{VD}}{T_{PT}} \quad \text{(amount of supercooling)}$$

$$\xi_{VD} = \frac{T_{RH}}{T_{VD}} \quad \text{(high/low reheating temp.)}$$

$$\gamma = \frac{\Gamma}{H(a_{\rm PT})} \quad \text{(speed of the decay)}$$

Phase-in is easier to achieve when the scalar field decays instantaneously.

Conclusions and Implications

- Phase-in is feasible in many scenarios. In this case, the DM relic density becomes mostly sensitive to the temperature of the radiation after the PT and not as much to the reheating temperature.
- While the reheating temperature is challenging to determine from cosmological data, the temperature of the thermal bath after a strong cosmological 1rst order PT is more “accessible” through the expected gravitational waves background:

Peak frequency of GW signal → $$f_{\rm peak} \propto T_{\rm RD}$$ ← Temperature after the PT

- Since, DM production would happen at different times in the evolution, the later produced DM could contribute via a WDM component

(more details in [2504.10593])