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

Outline:

1. Introduction:
   - non-thermal dark matter production
   - first-order phase transitions
2. The phase-in scenario
3. Results
4. Conclusions

Credit: Saniya Heeba

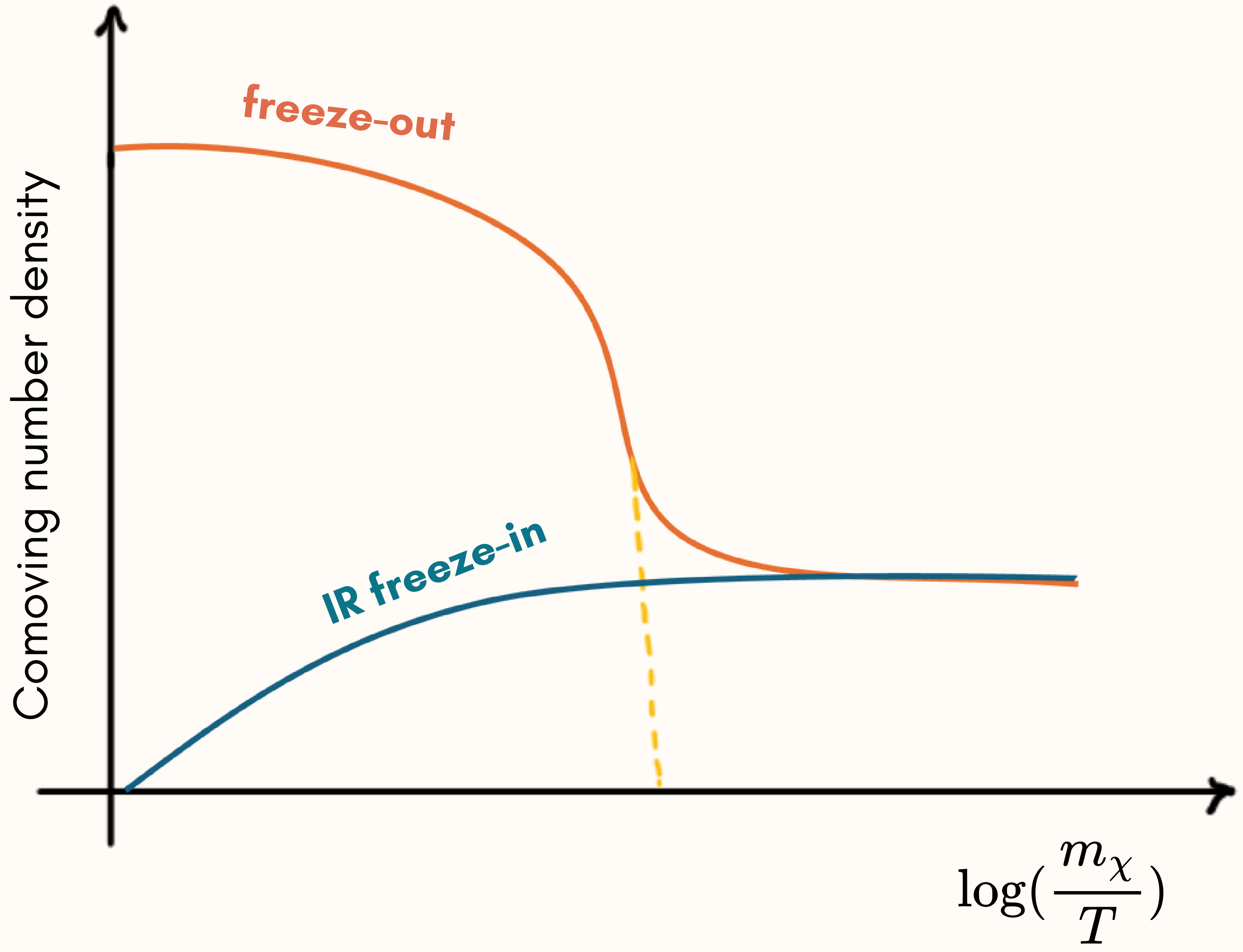
Non-Thermal Dark Matter Production

Strong bounds from direct detection experiments on WIMPs → **non-thermal production ?**

Interactions so feeble that DM and SM were never in thermal equilibrium
→ DM abundance builds up

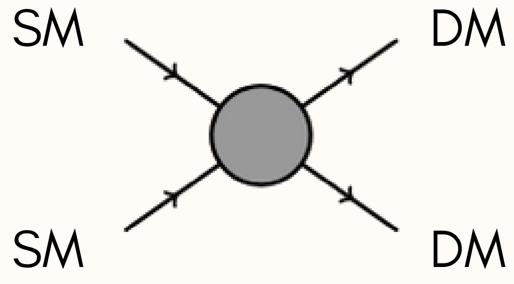
IR freeze-in demands extremely small couplings

[Hall et al. 0911.1120]



Non-Thermal Dark Matter Production

Another realisation of freeze-in:
Interactions via non-renormalizable operators with dimension n+4:

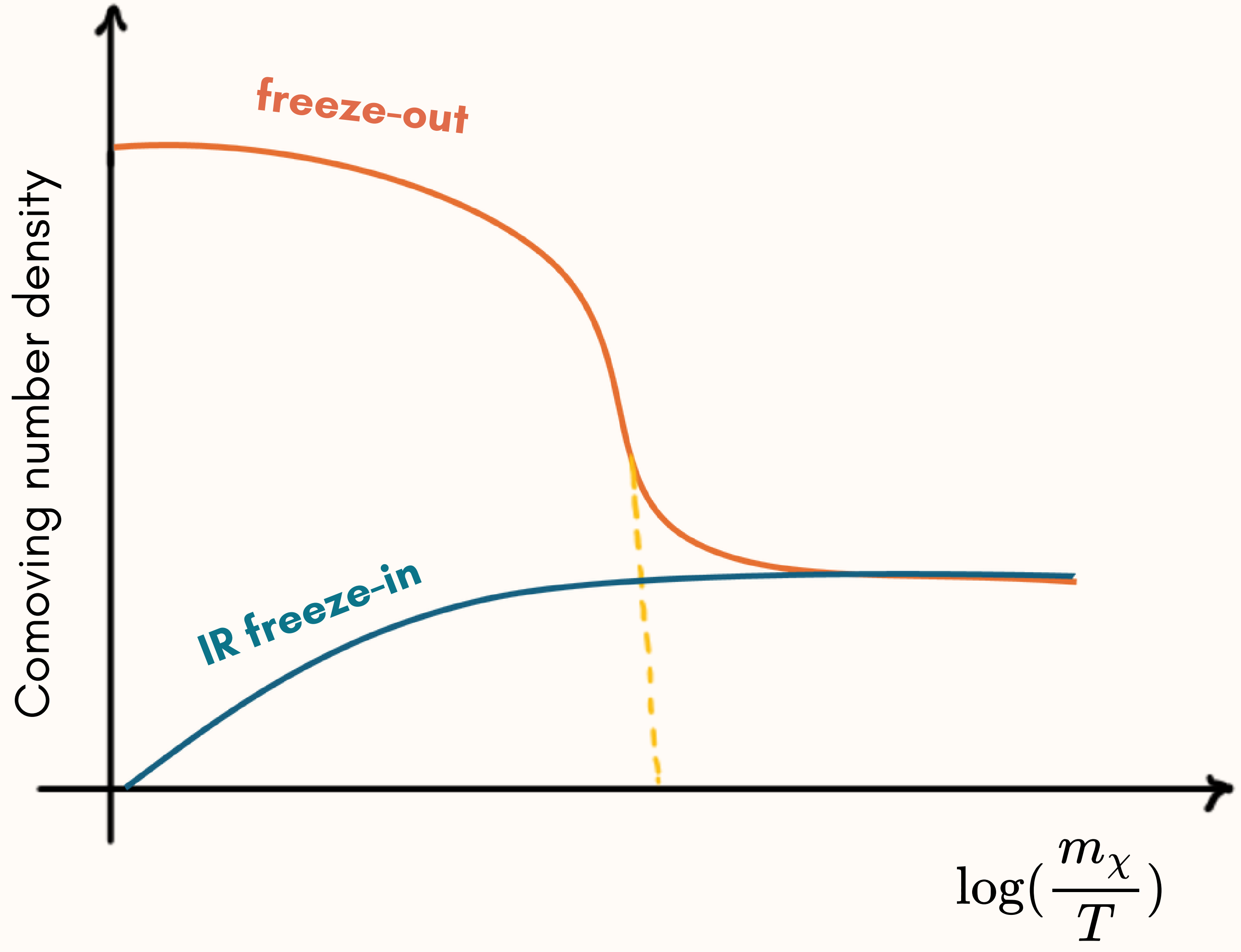


and thermally averaged crosssection:

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

Temperature of SM radiation bath

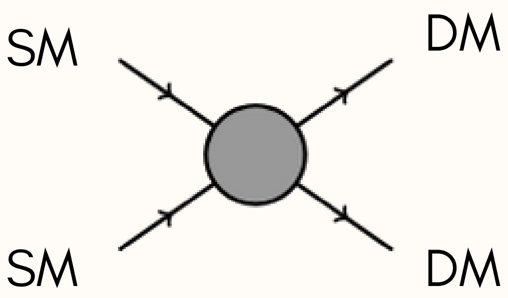
UV-suppression scale



Non-Thermal Dark Matter Production

Another realisation of freeze-in:

Interactions via higher dimensional operators:

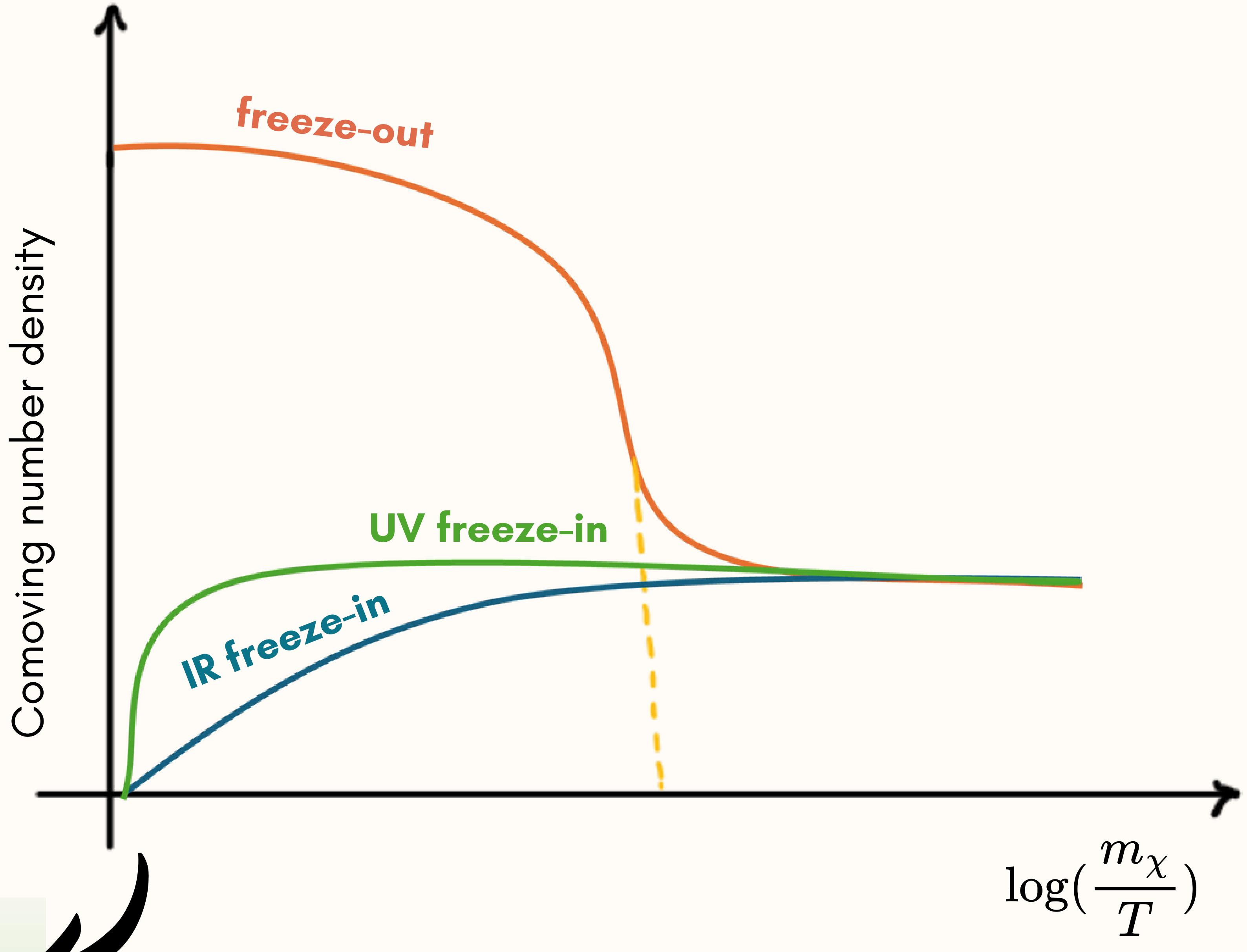


$$\langle \sigma v \rangle \propto \frac{T^{2(n-1)}}{\Lambda^{2n}}$$

Temperature of SM radiation bath (T)

UV-suppression scale (Λ)

→ UV-dominated freeze-in

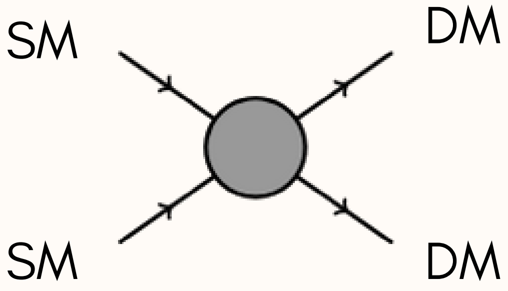


The bulk of DM production is at primordial reheating : $T \sim T_{\rm RH}$

Non-Thermal Dark Matter Production

UV-dominated freeze-in:

Interactions via higher dimensional operators:



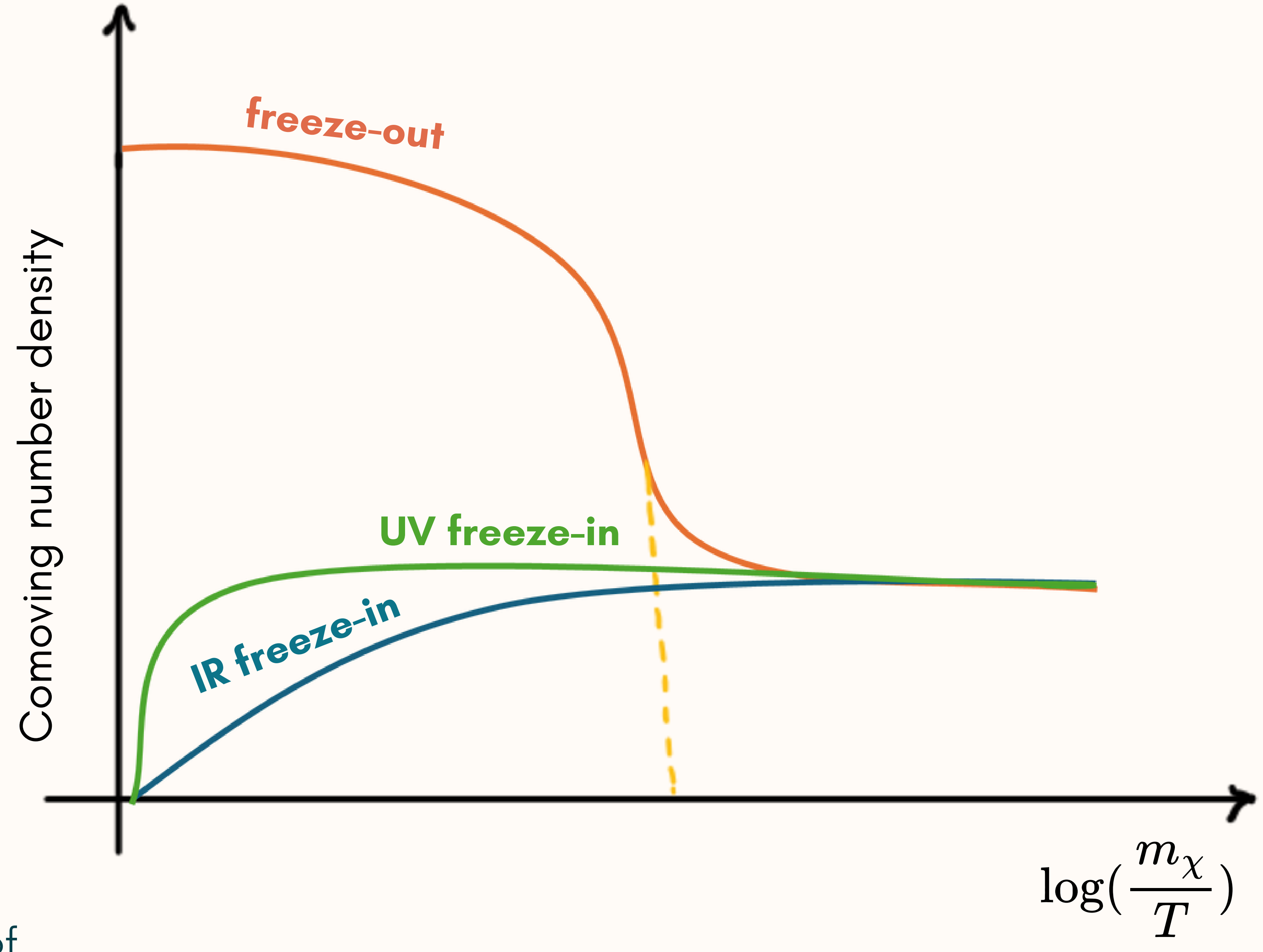
$$\langle \sigma v \rangle \propto \frac{T^{2(n-1)}}{\Lambda^{2n}}$$

Problem: sensitivity of the DM abundance to the reheating and maximal temperature of SM radiation bath:

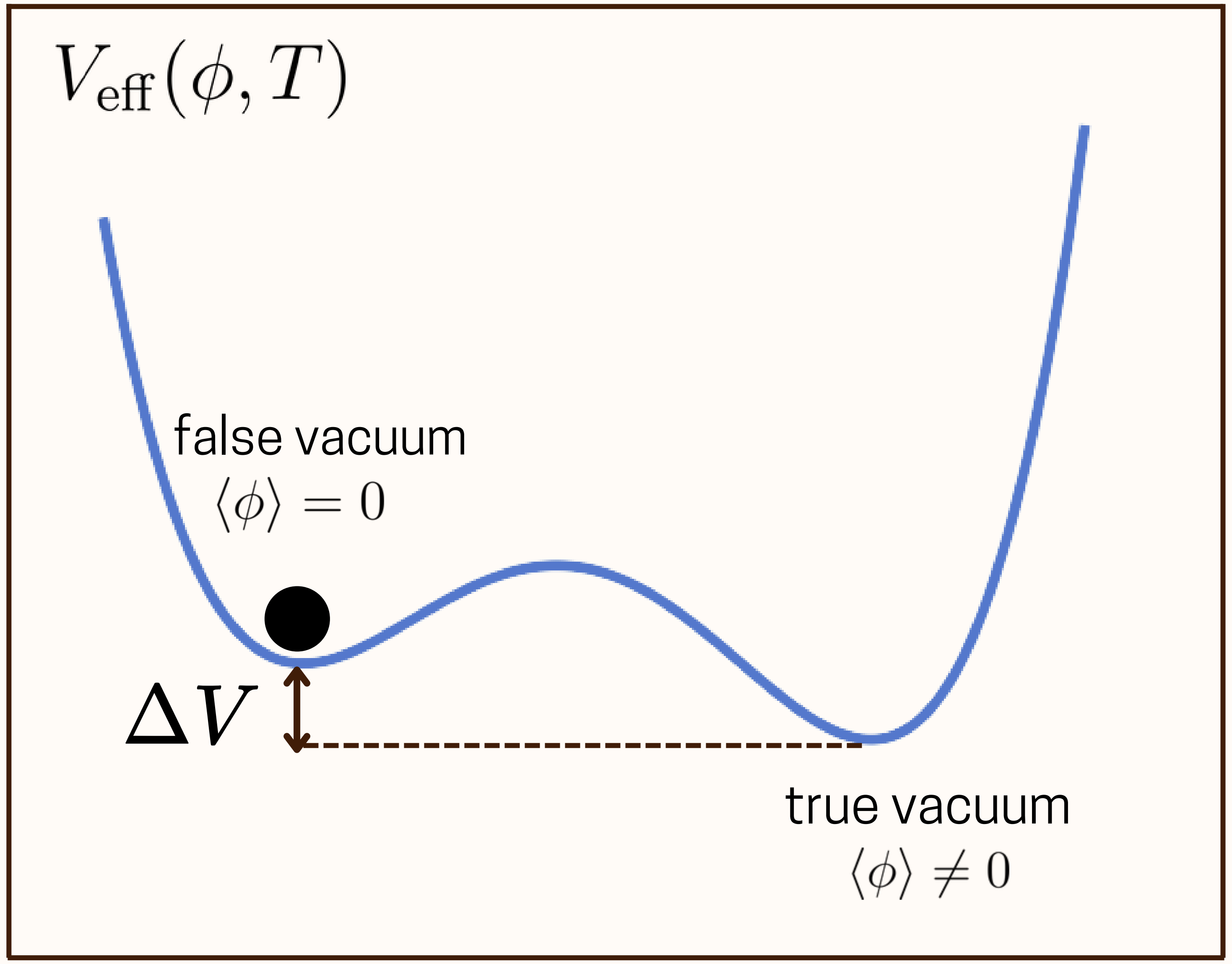
[Bernal et al. 1909.07992]
[Elahi et al. 1410.6157]

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

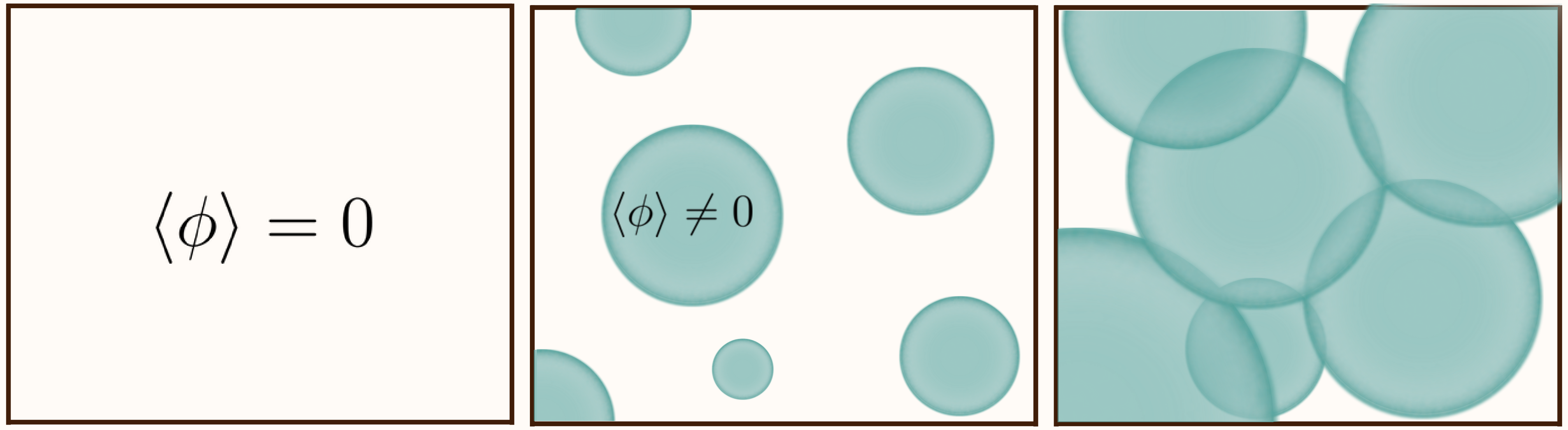
Reheating Temperature of SM radiation bath



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 $\beta^{-1} \ll H^{-1}$

+ 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 $\rightarrow$ Dilution of pre-existing abundance

UV- freeze-in and First Order Phase Transitions

UV freeze-in :

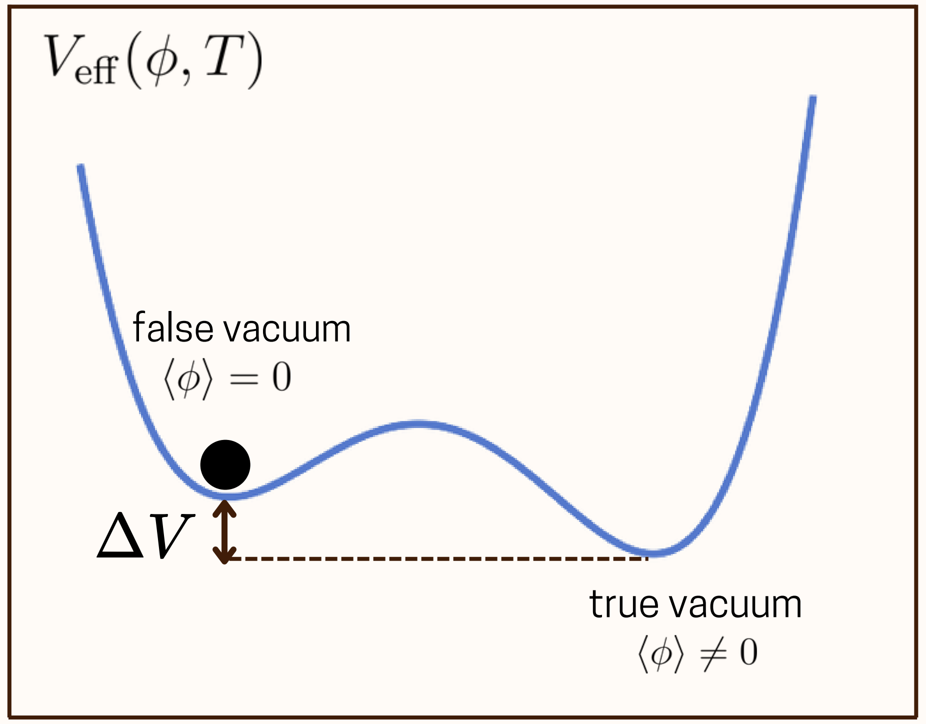
DM relic density is determined by the reheating / maximal temperature

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

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

First-Order Phase Transition (FOPT):

- The scalar field acts like a cosmological constant before the transition.
- Energy injection to the radiation bath after the phase transition : Can dilute pre-existing relics if supercooled.
- Relevant temperature scale is T_{PT}



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

The DM phase-in scenario

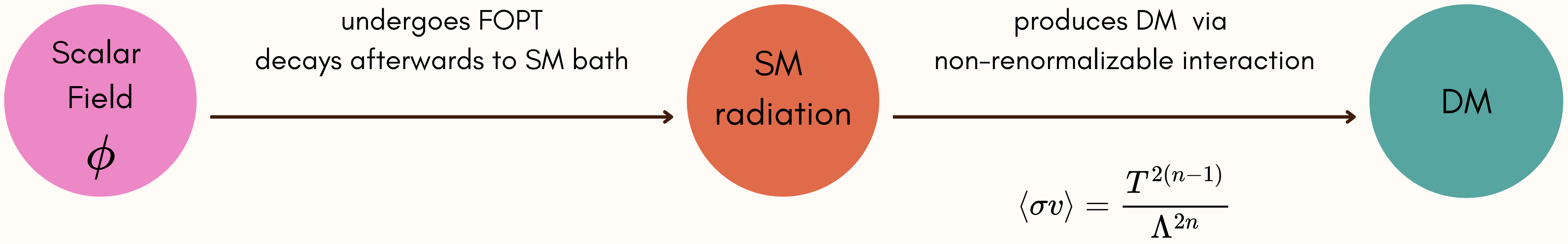
Scalar Field ϕ → (undergoes FOPT, decays afterwards to SM bath) → SM radiation → (produces DM via non-renormalizable interaction) → DM

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

→ Operator of dim n+4

SM +SM → DM+DM

The DM phase-in scenario



Boltzmann equations for energy/number densities:

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

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

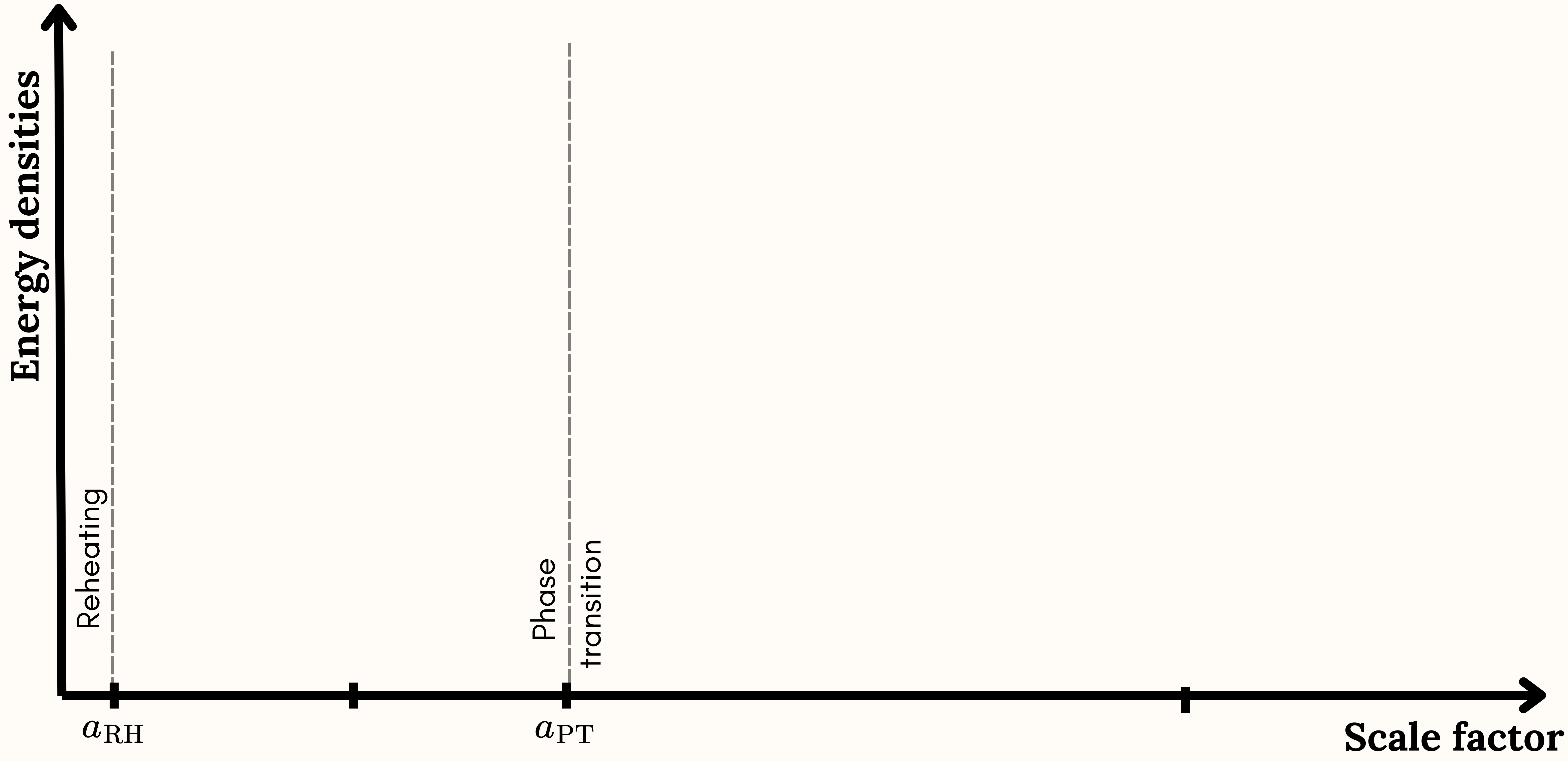
$$\frac{\mathrm{d}n_{\mathrm{DM}}}{\mathrm{d}a} = -\frac{3}{a}n_{\mathrm{DM}} + \frac{\langle \sigma v \rangle}{aH}n_{\mathrm{SM}}^2$$

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

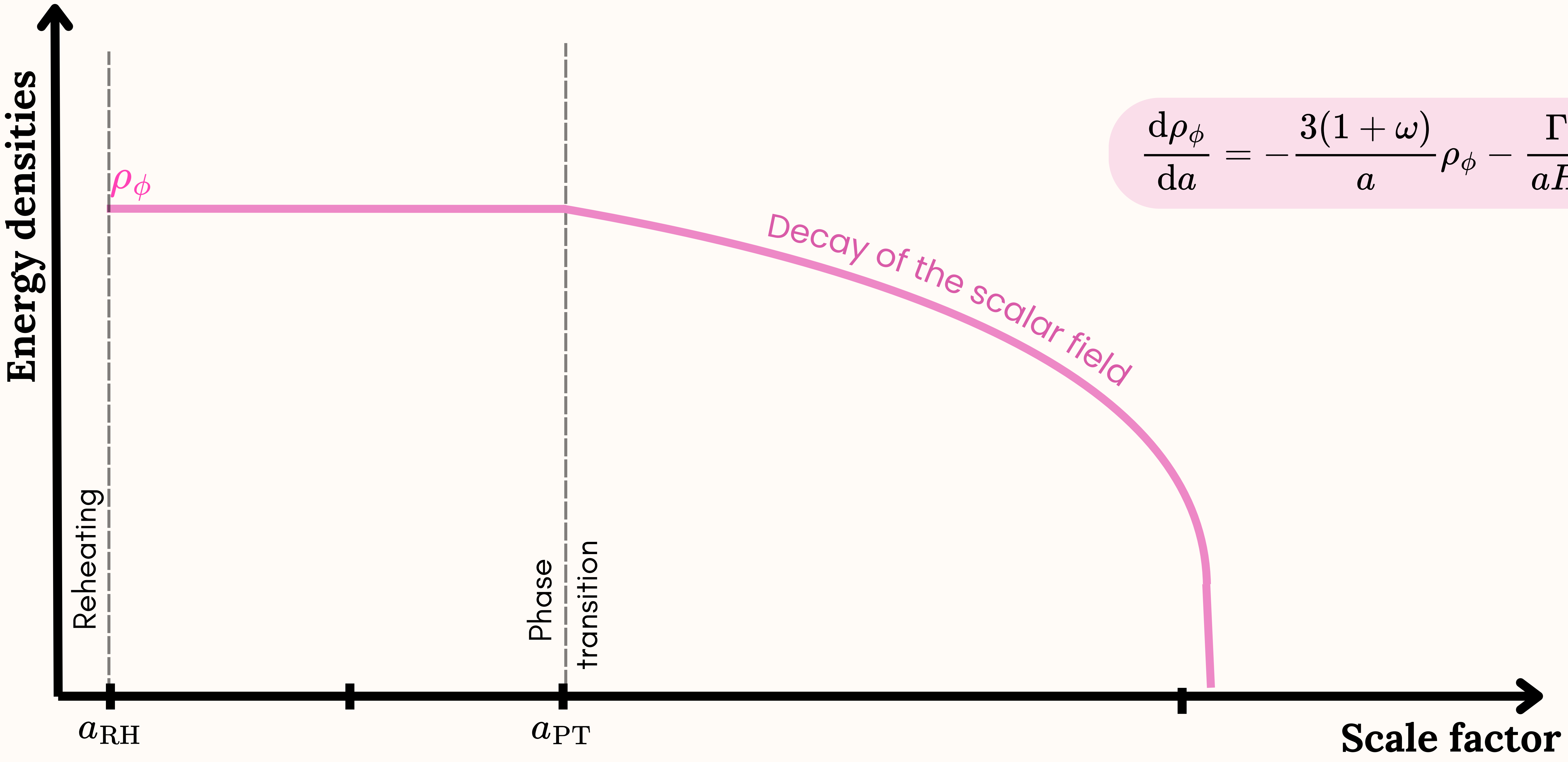
After the PT: $\Gamma = \mathrm{const}$ and $0 \leq \omega \leq 1/3$

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

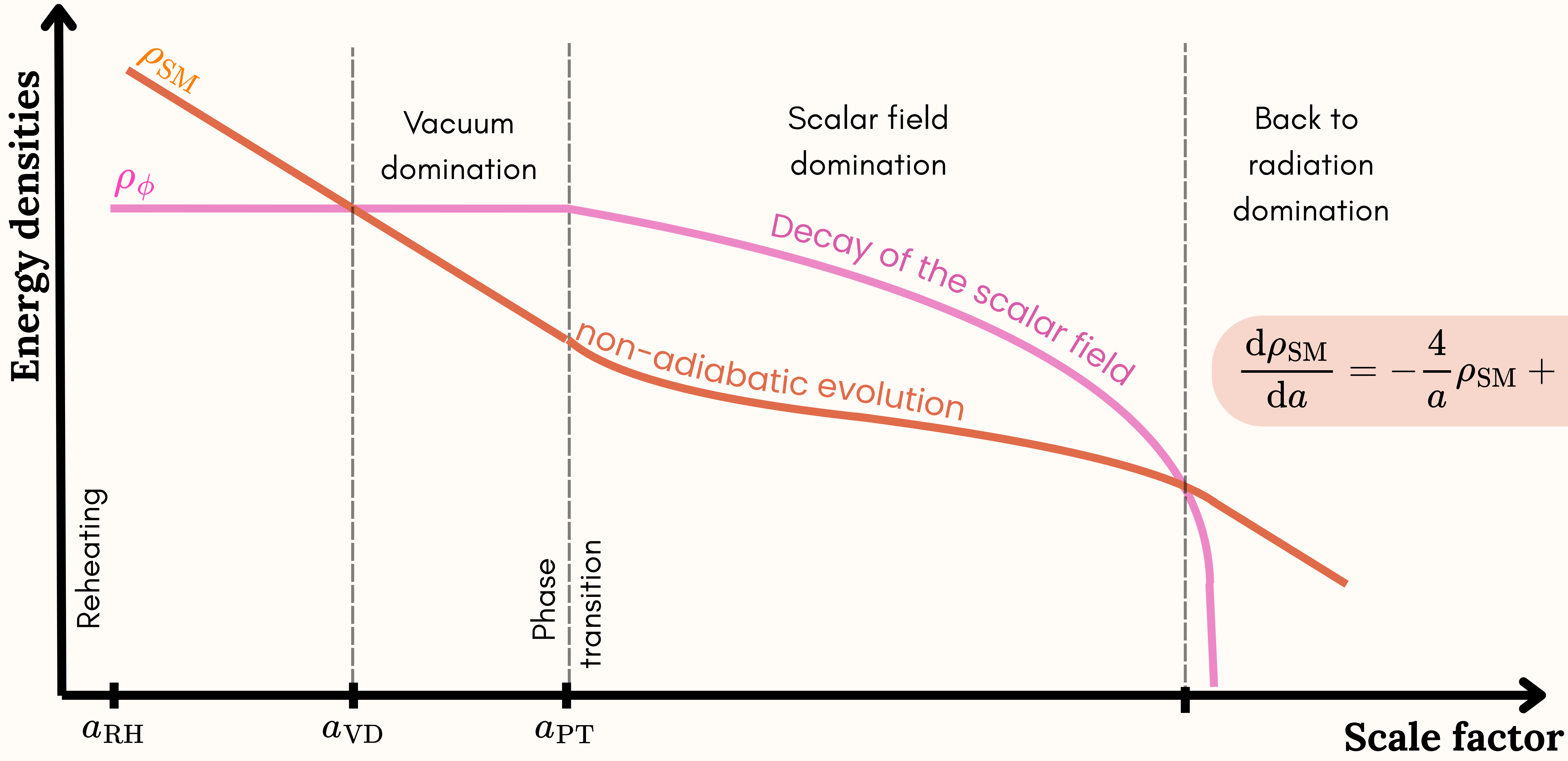


The DM phase-in scenario



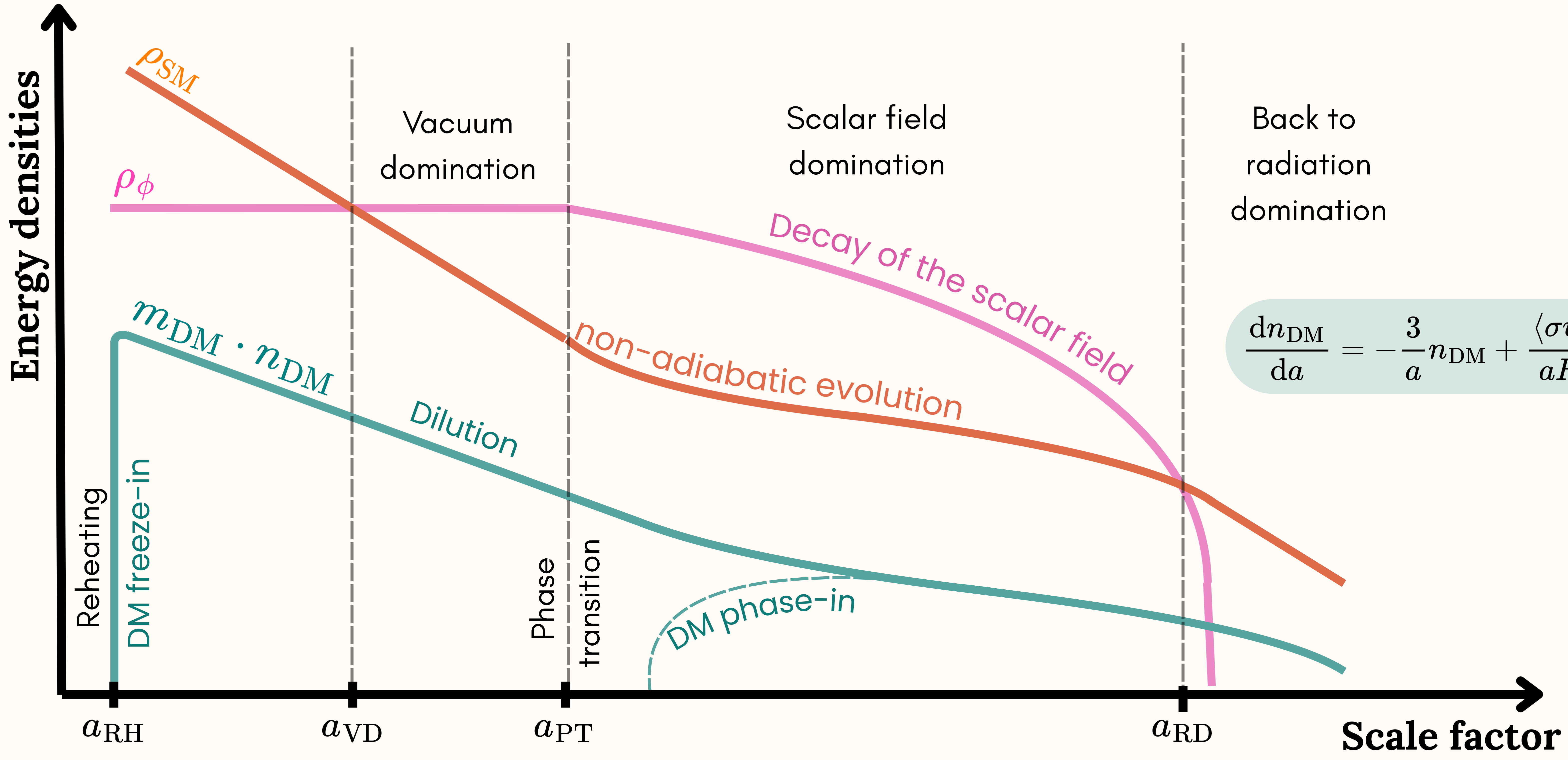
$$\frac{\mathrm{d}\rho_\phi}{\mathrm{d}a} = -\frac{3(1+\omega)}{a}\rho_\phi - \frac{\Gamma}{aH}\rho_\phi$$

The DM phase-in scenario



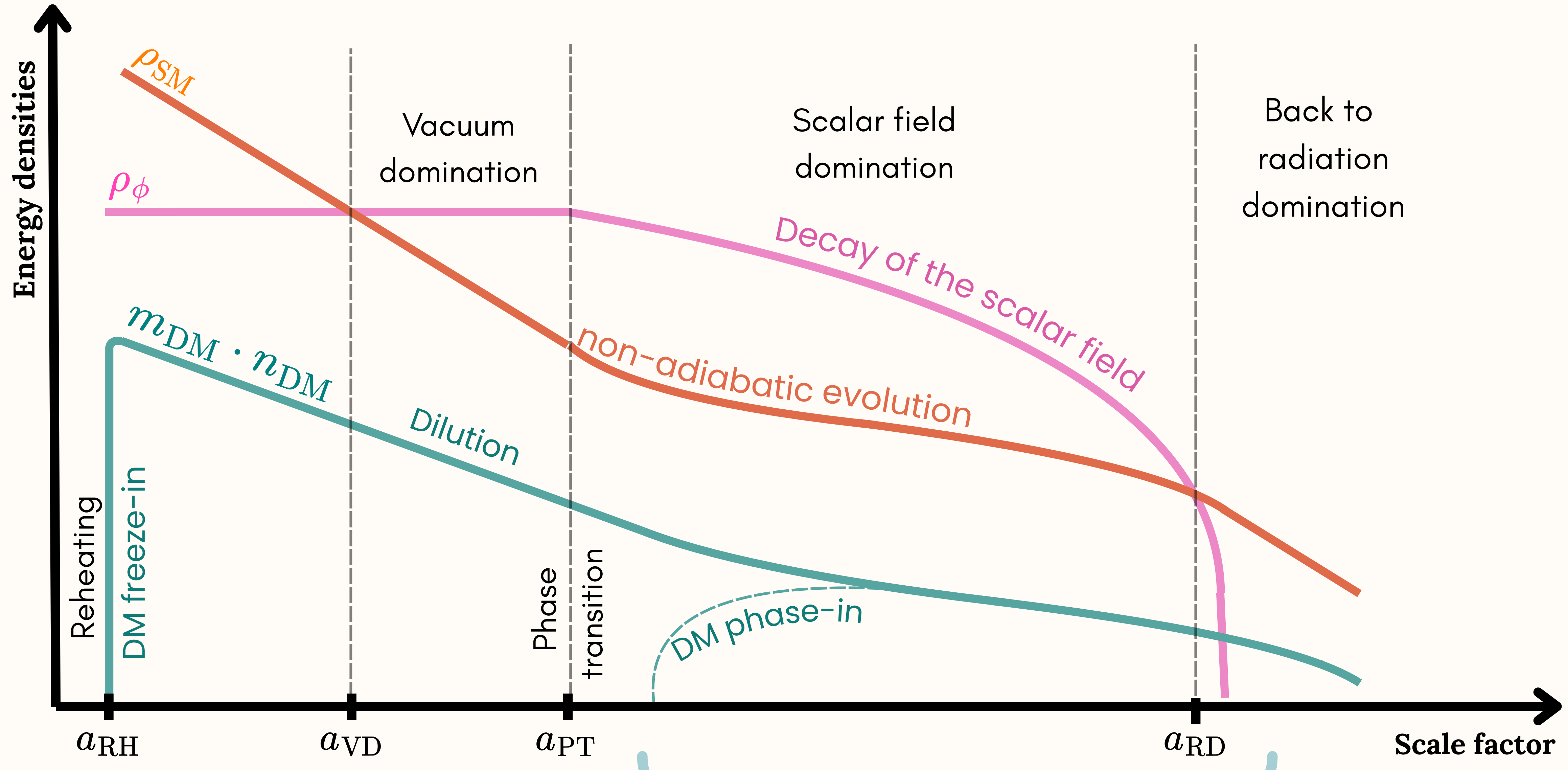
$$\frac{\mathrm{d}\rho_{\rm SM}}{\mathrm{d}a} = -\frac{4}{a}\rho_{\rm SM} + \frac{\Gamma}{aH}\rho_\phi$$

The DM phase-in scenario



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

Phase-in condition



Dark matter is produced in different phases.

$\Omega_{DM,FI}$

↓

Determined by reheating temperature

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

$\Omega_{DM,PI}$

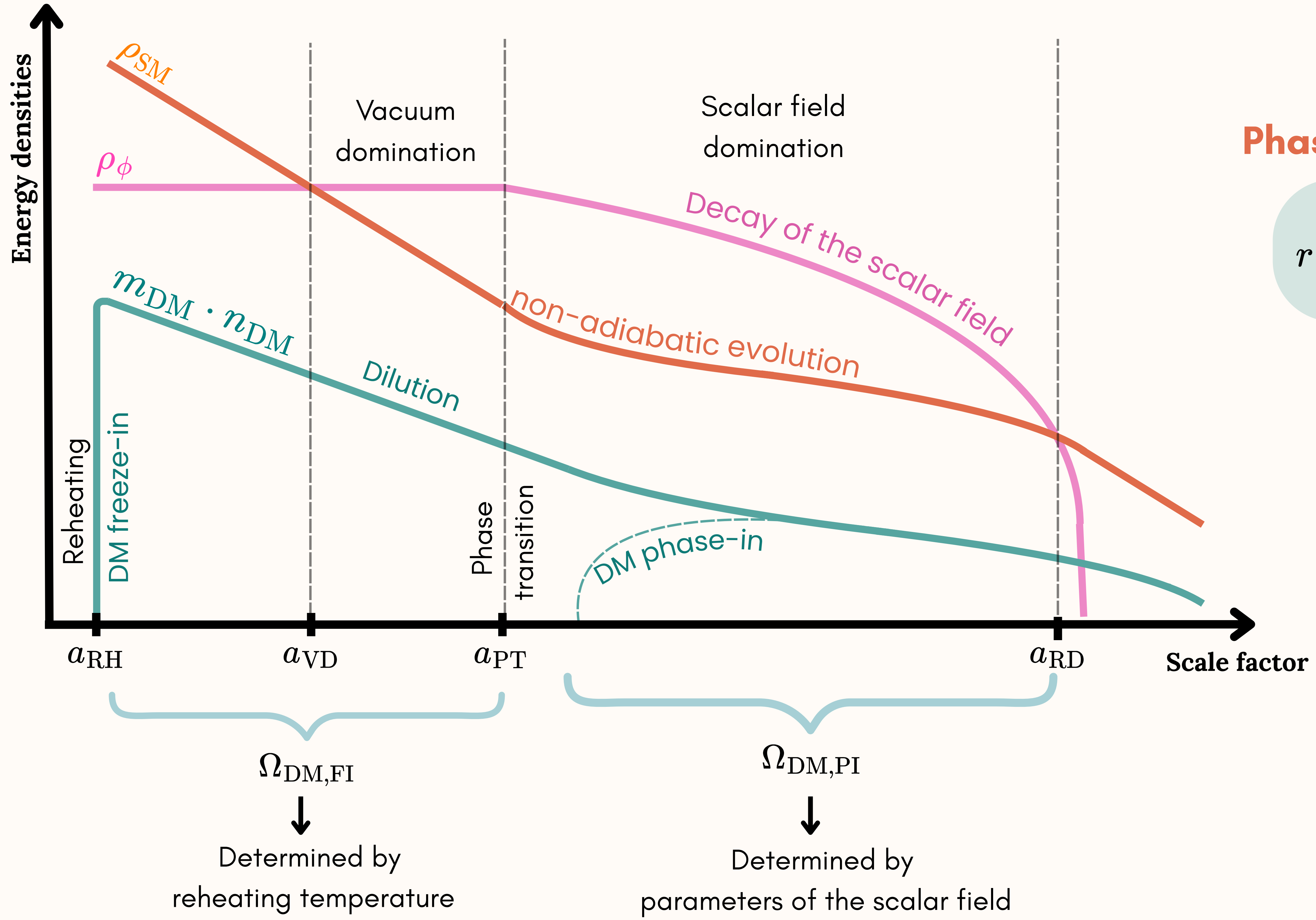
↓

Determined by parameters of the scalar field

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

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

Phase-in condition



Phase-in condition:

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

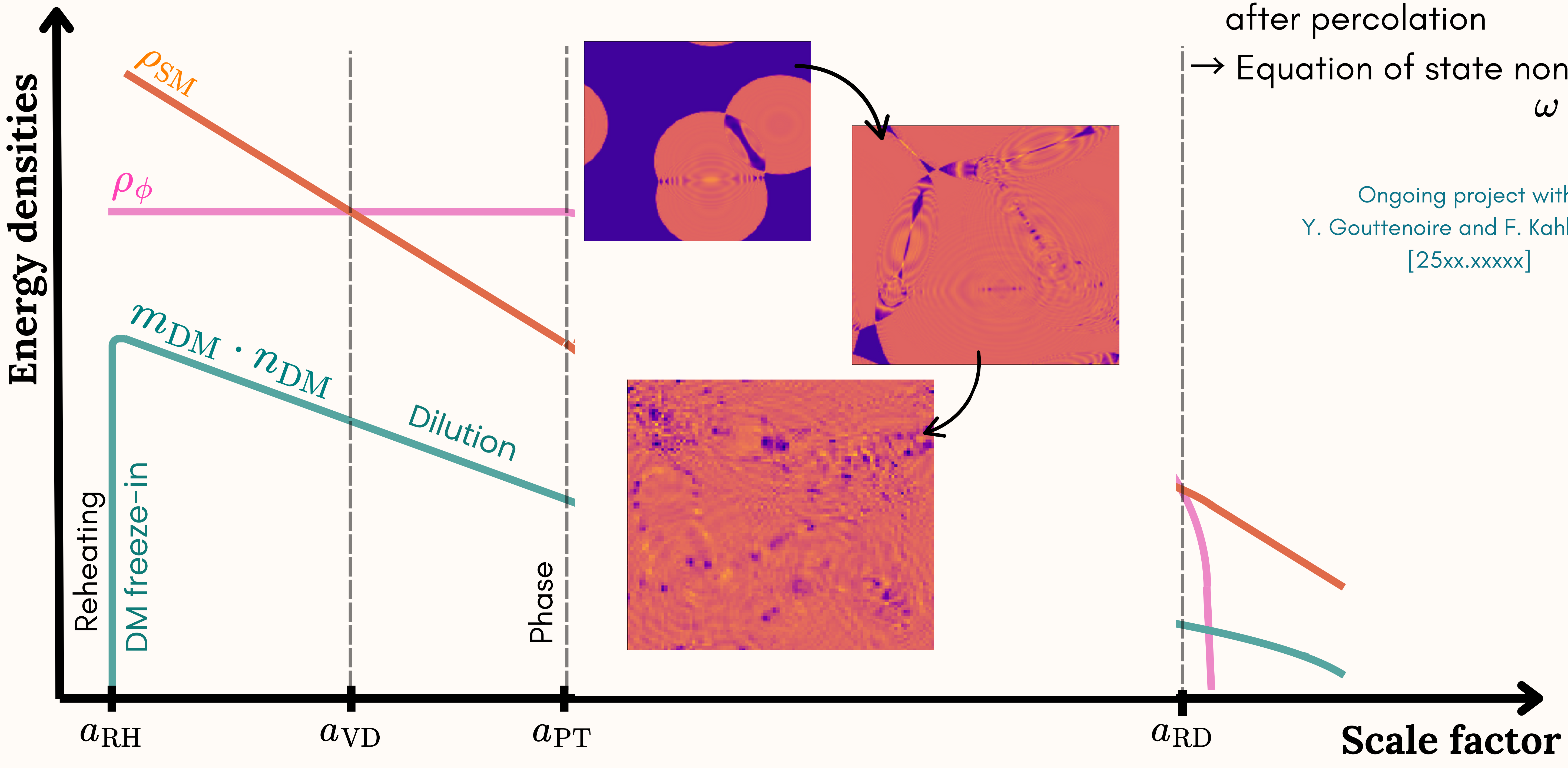
Parameters of the problem:

- 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)

Stage III: scalar field domination

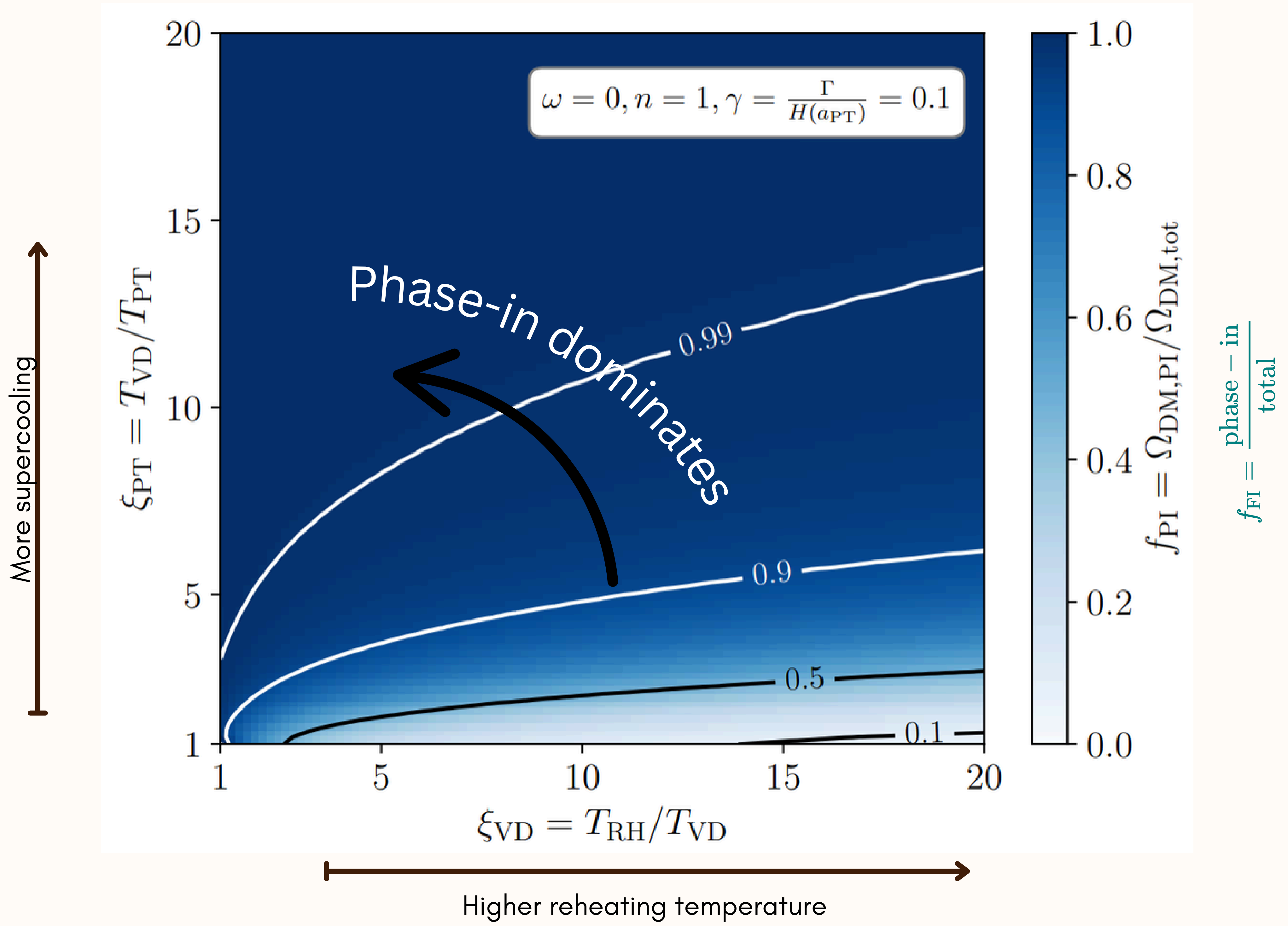
Highly inhomogeneous scalar field configurations after percolation

→ Equation of state non-trivial $\omega \neq 0$?



Ongoing project with
Y. Gouttenoire and F. Kahlhoefer
[25xx.xxxxx]

Phase-in condition : results

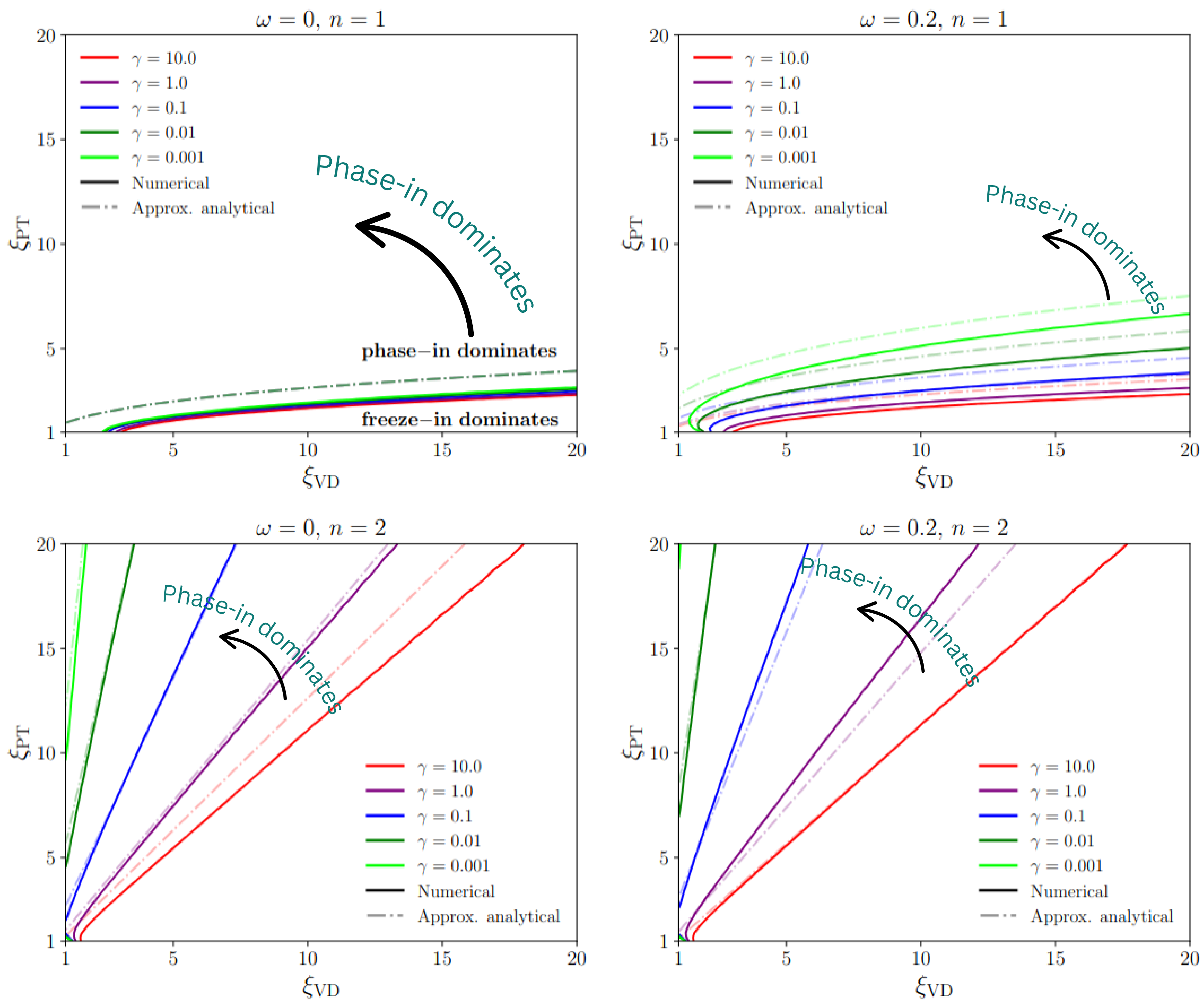


Phase-in condition : results

matter dom. | **modified cosmology**

Dim 5 operator

Dim 6 operator



with:

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

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

$$\gamma = \frac{\Gamma}{H(a_{\rm PT})}$$ (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:

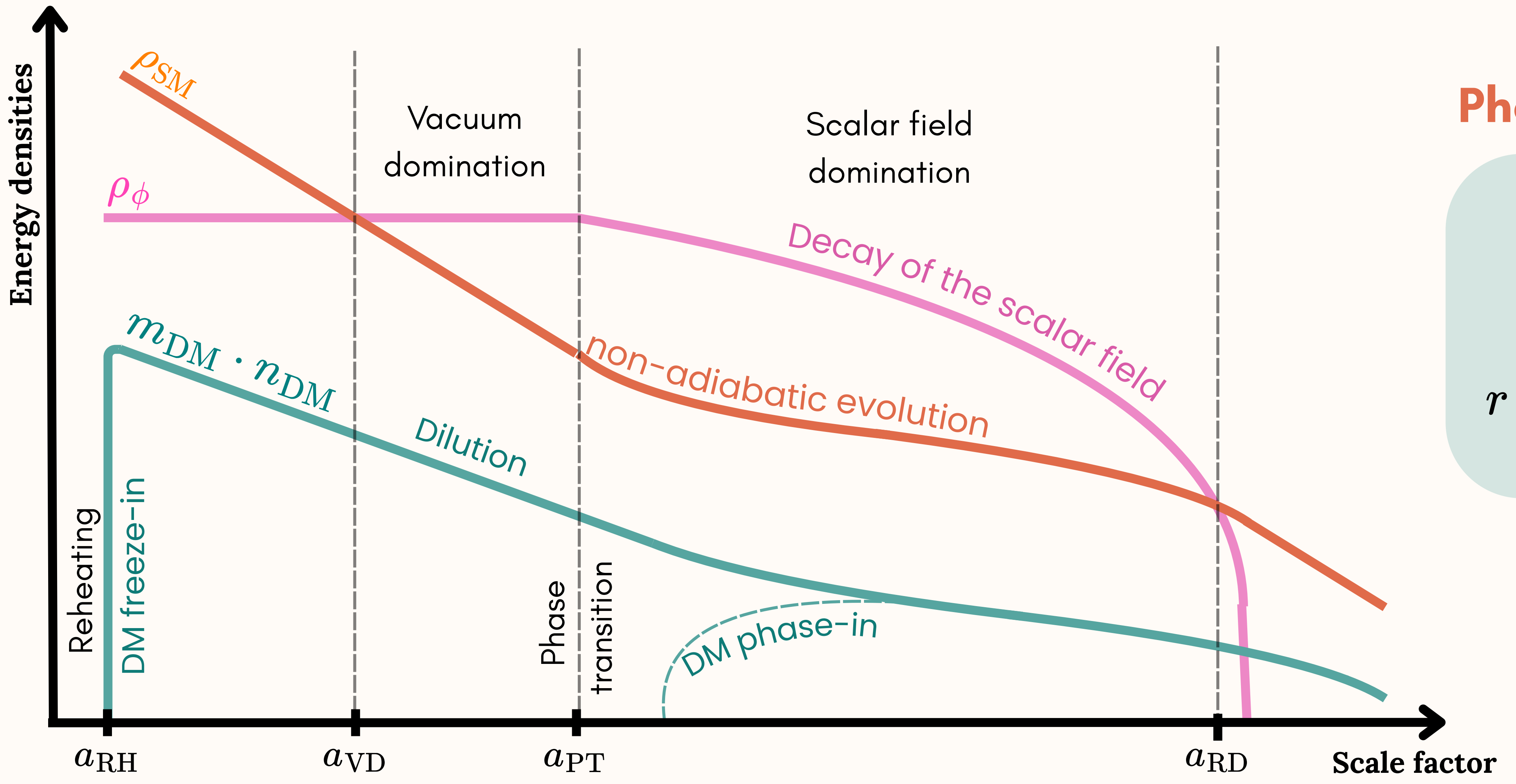
Peak frequency of GW signal → $$f_{\rm peak} \propto T_{\rm RD}$$ ← Temperature after the PT

- 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])

Back-up Slides

Phase-in condition



Phase-in condition:

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

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

Parameters of the problem:

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

Analytical estimate:

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

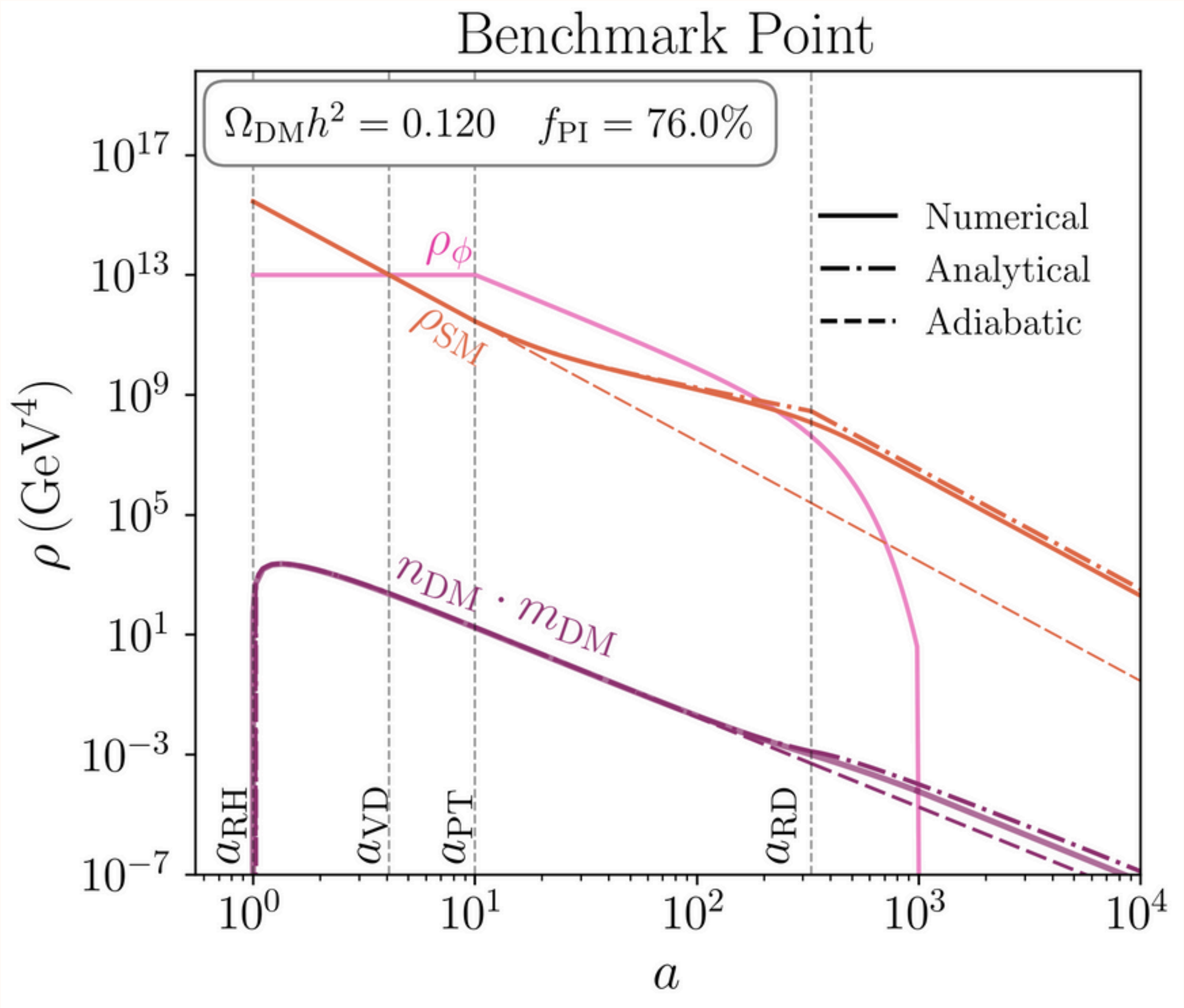
Dilution factor: $D = \frac{S_{RD}}{S_{PT}} = \left(\frac{T_{RD}a_{RD}}{T_{PT}a_{PT}}\right)^3$

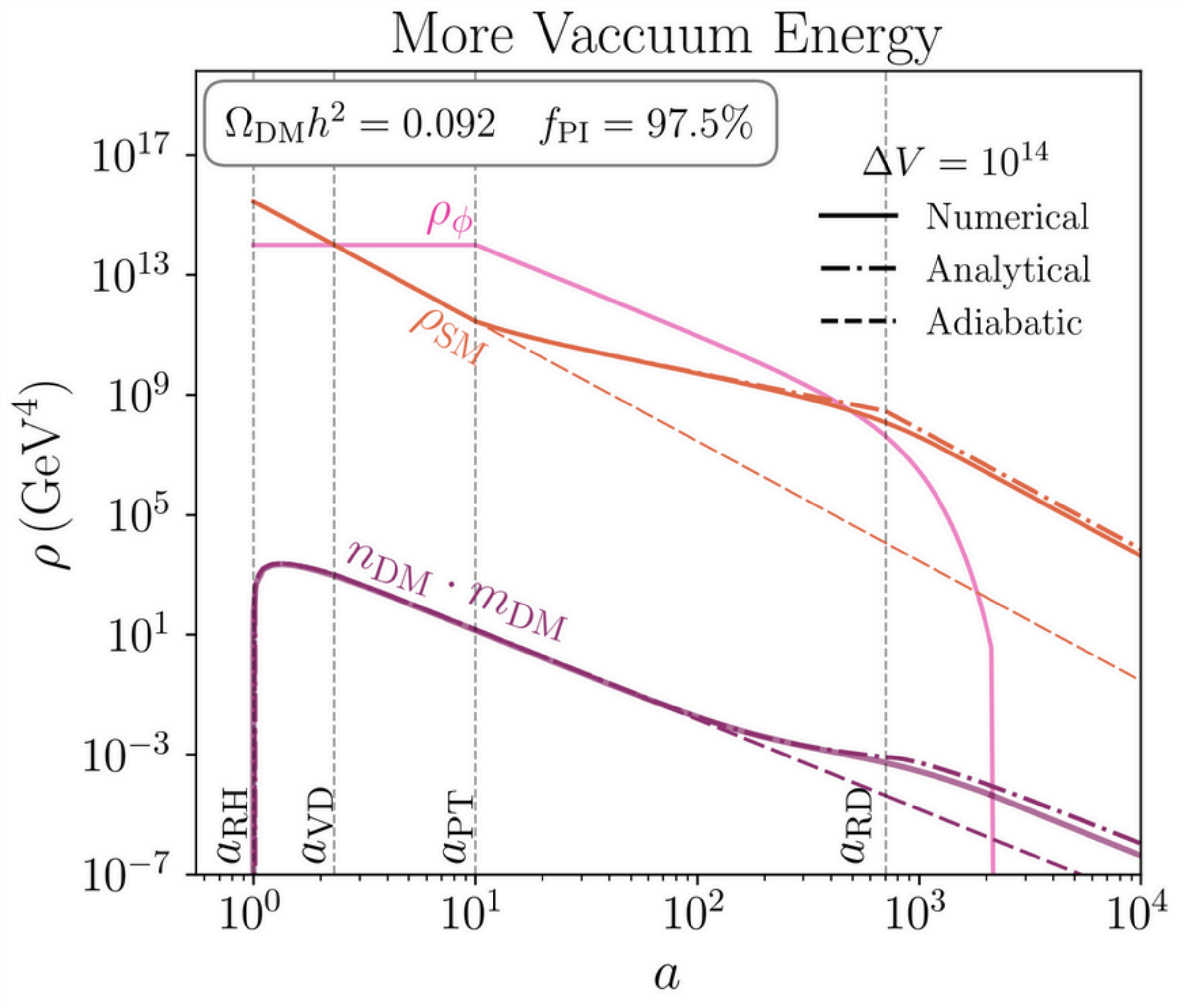
Some examples

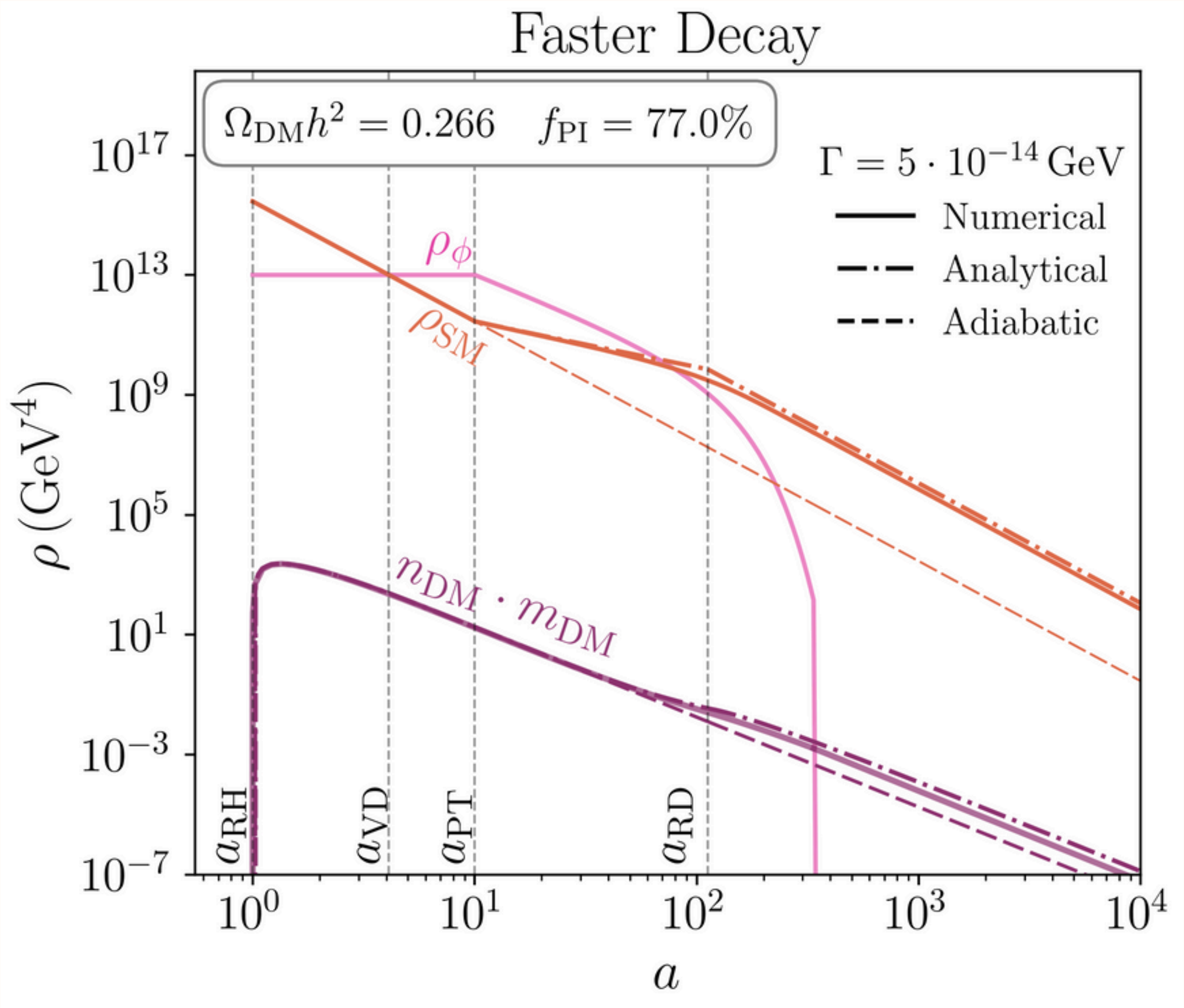
Phase-in condition

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

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