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

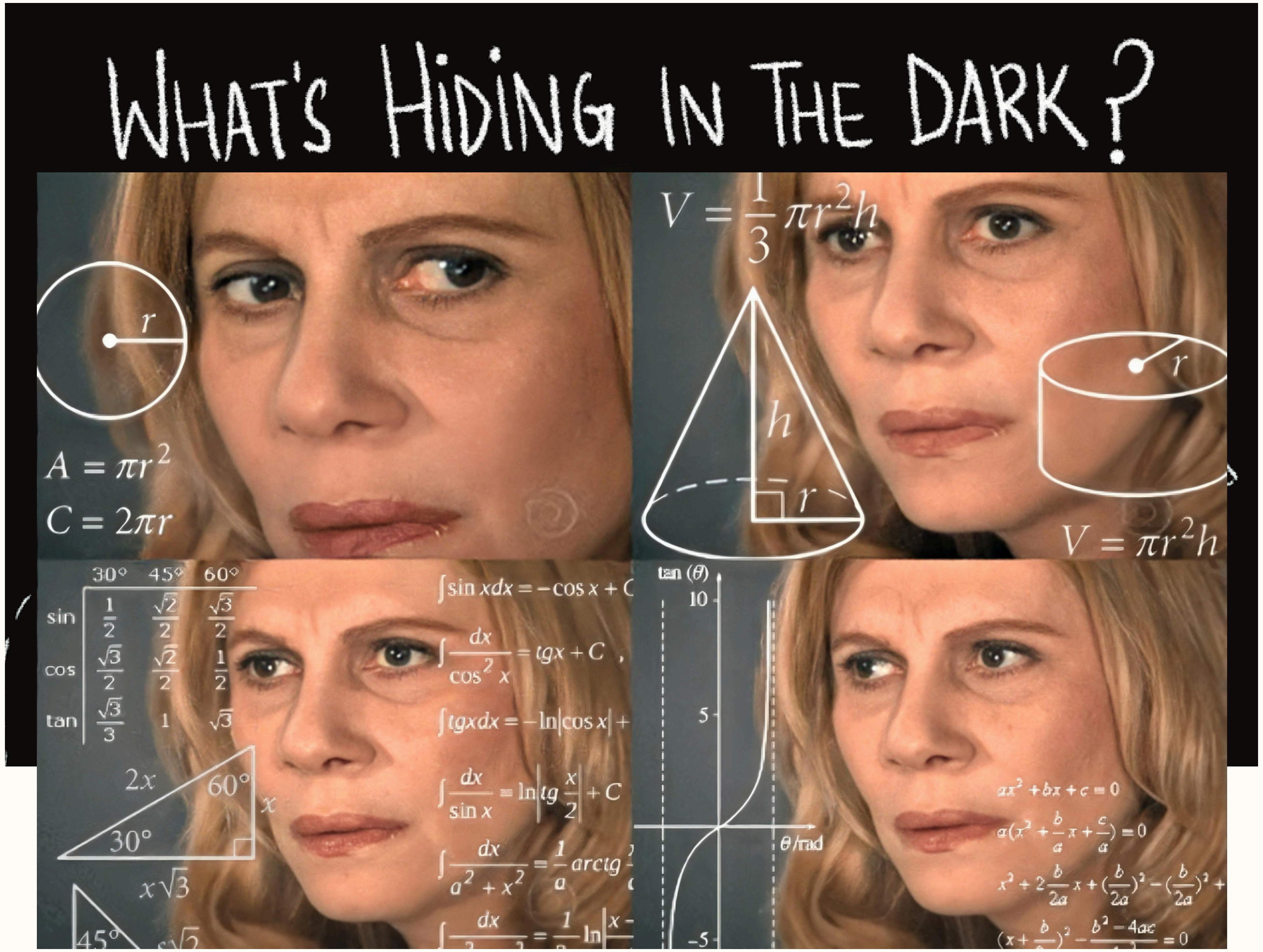
Outline:

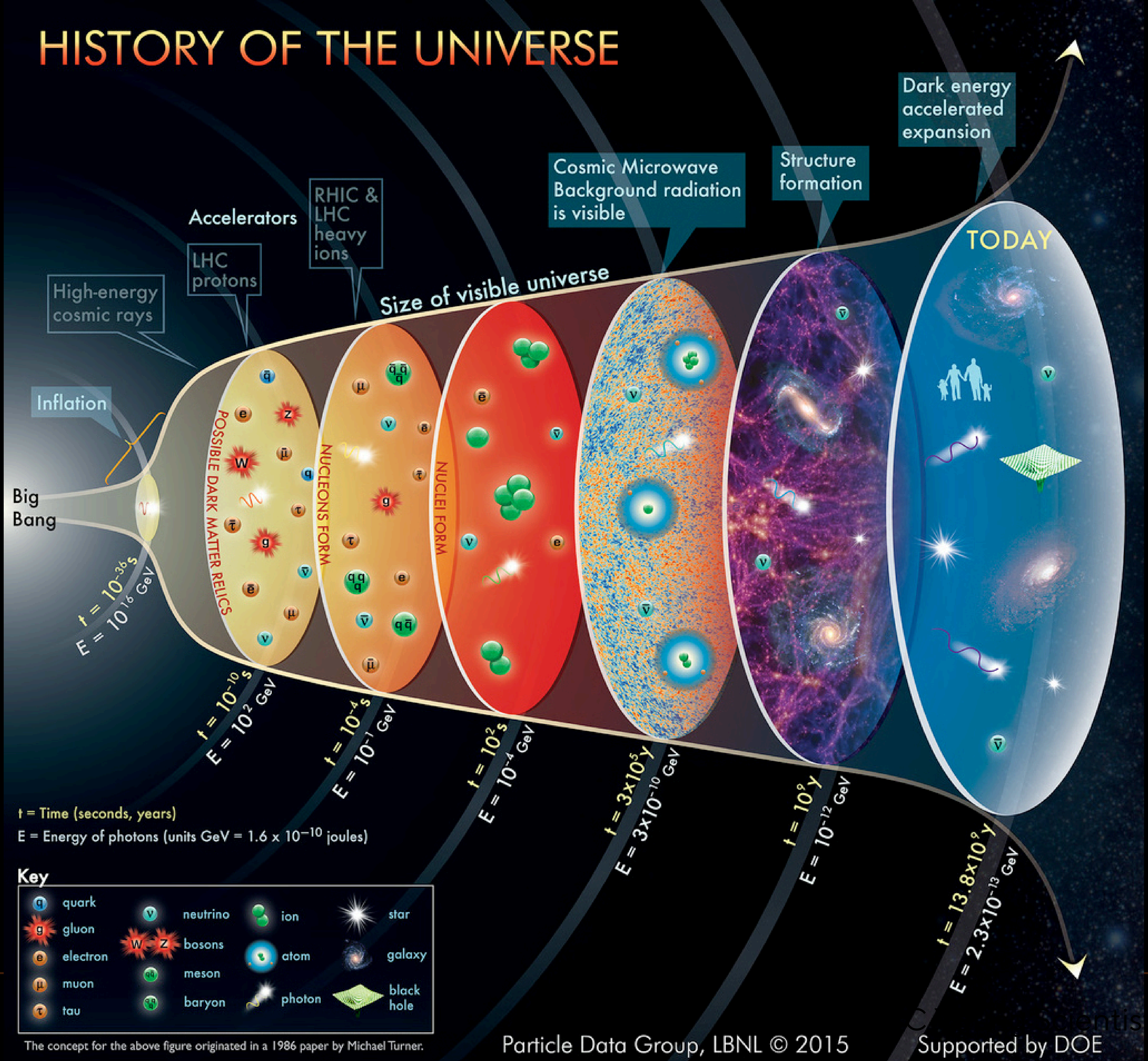
1. Dark matter production in the early Universe
2. UV - dominated Freeze-in
3. The phase-in scenario
4. Results
5. Conclusions

Credit: Saniya Heeba

Outline:

1. Dark matter production in the early Universe
2. UV - dominated Freeze-in
3. The phase-in scenario
4. Results
5. Conclusions

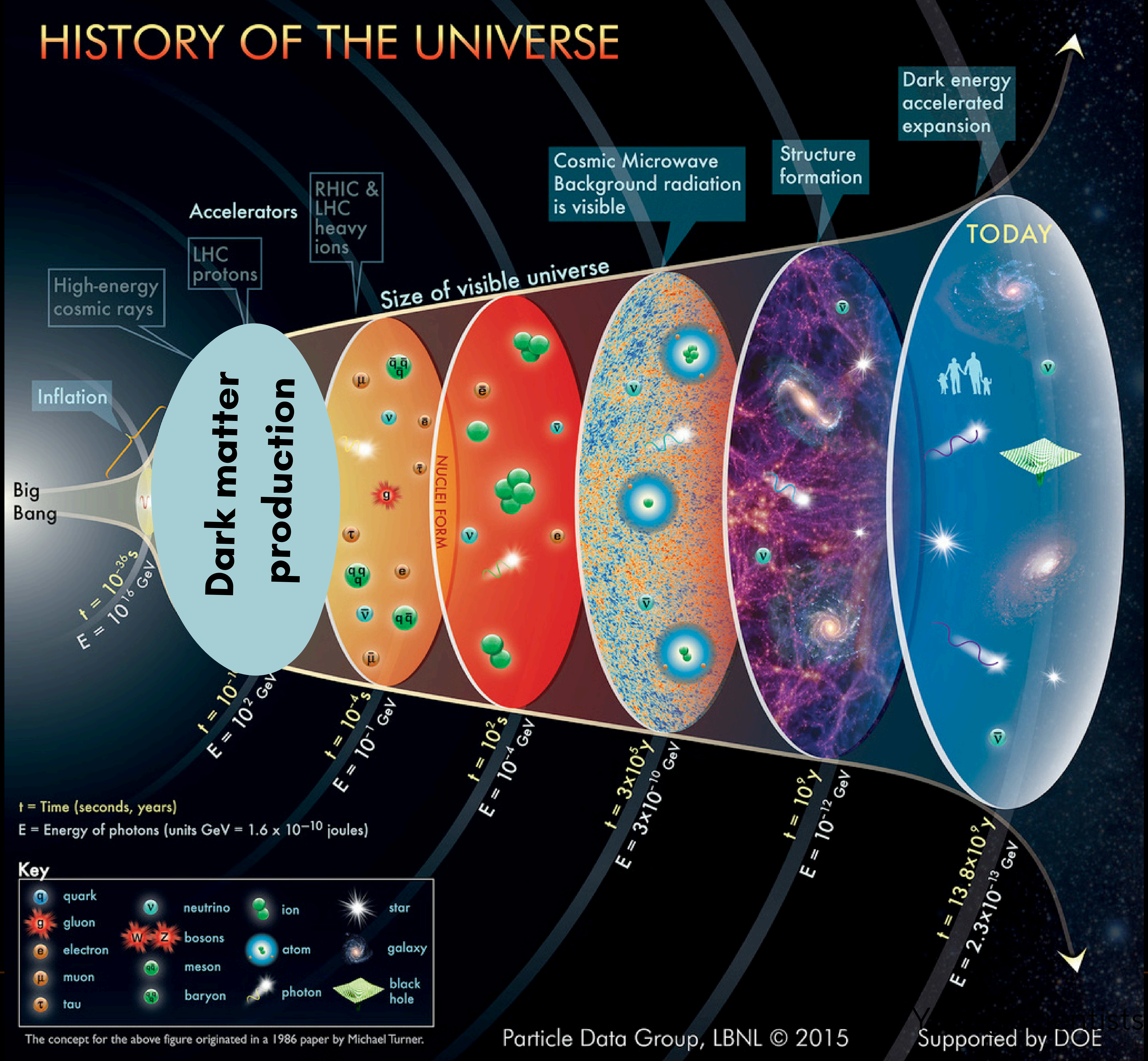



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

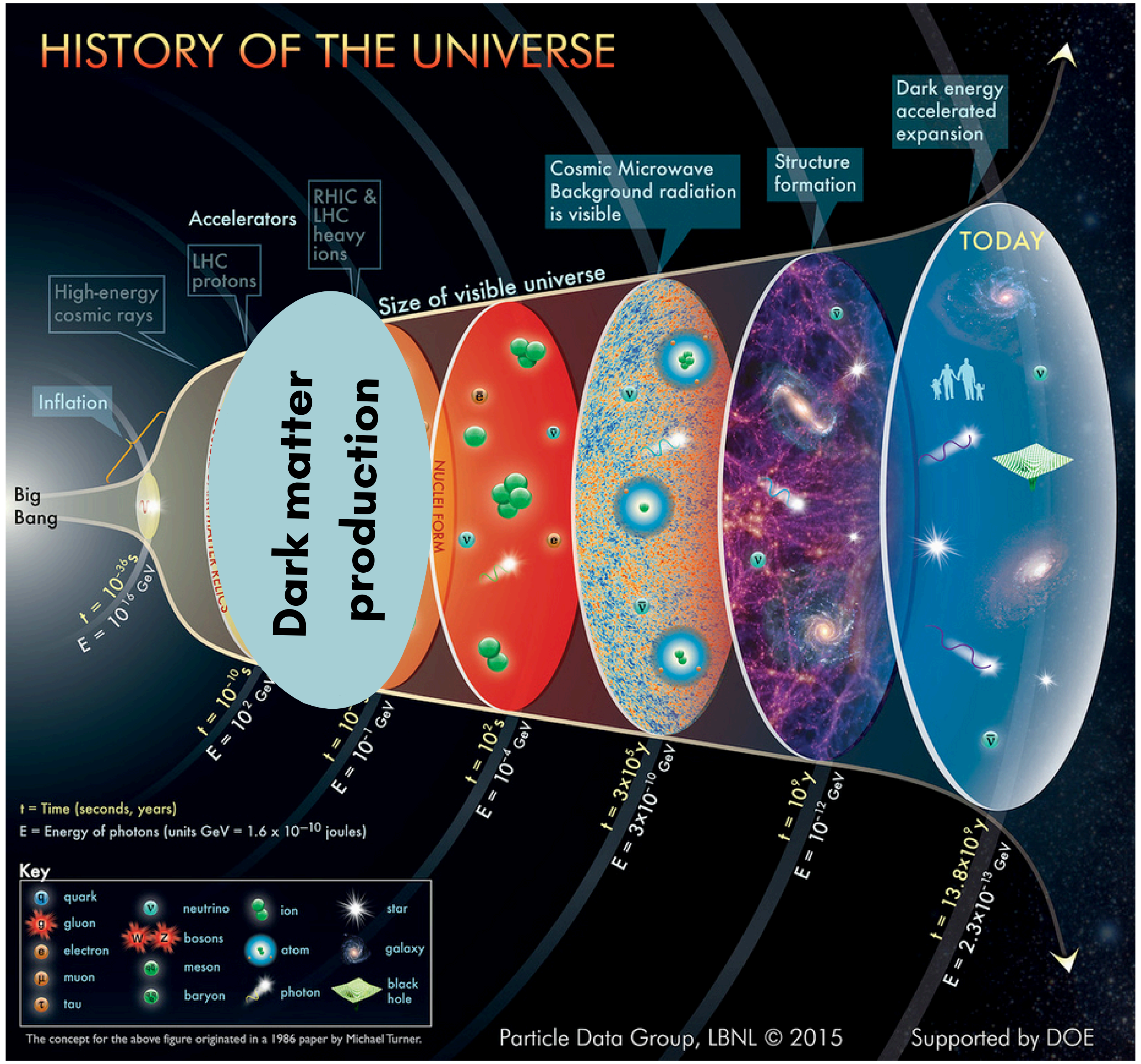
Important in this talk :

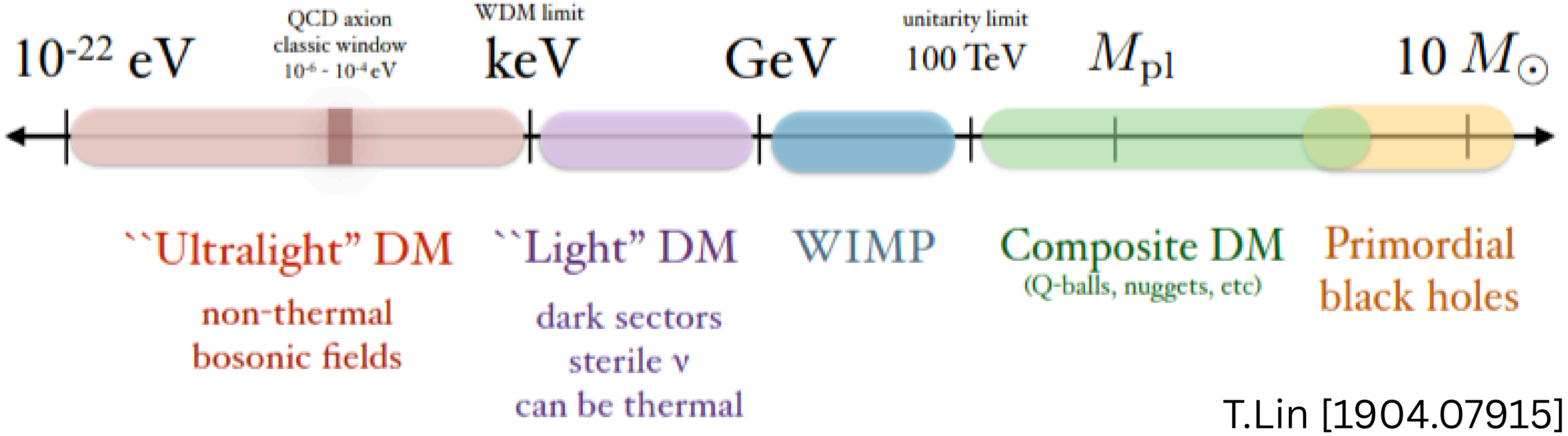
$T_{\rm RH}$:

Temperature of the radiation bath after inflation



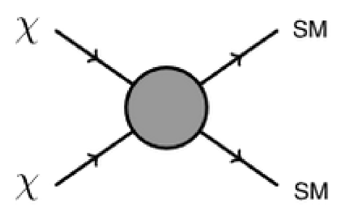
Dark Matter Production





T.Lin [1904.07915]

Assume some interactions with the standard model:



Freeze-out Paradigm in a Nutshell

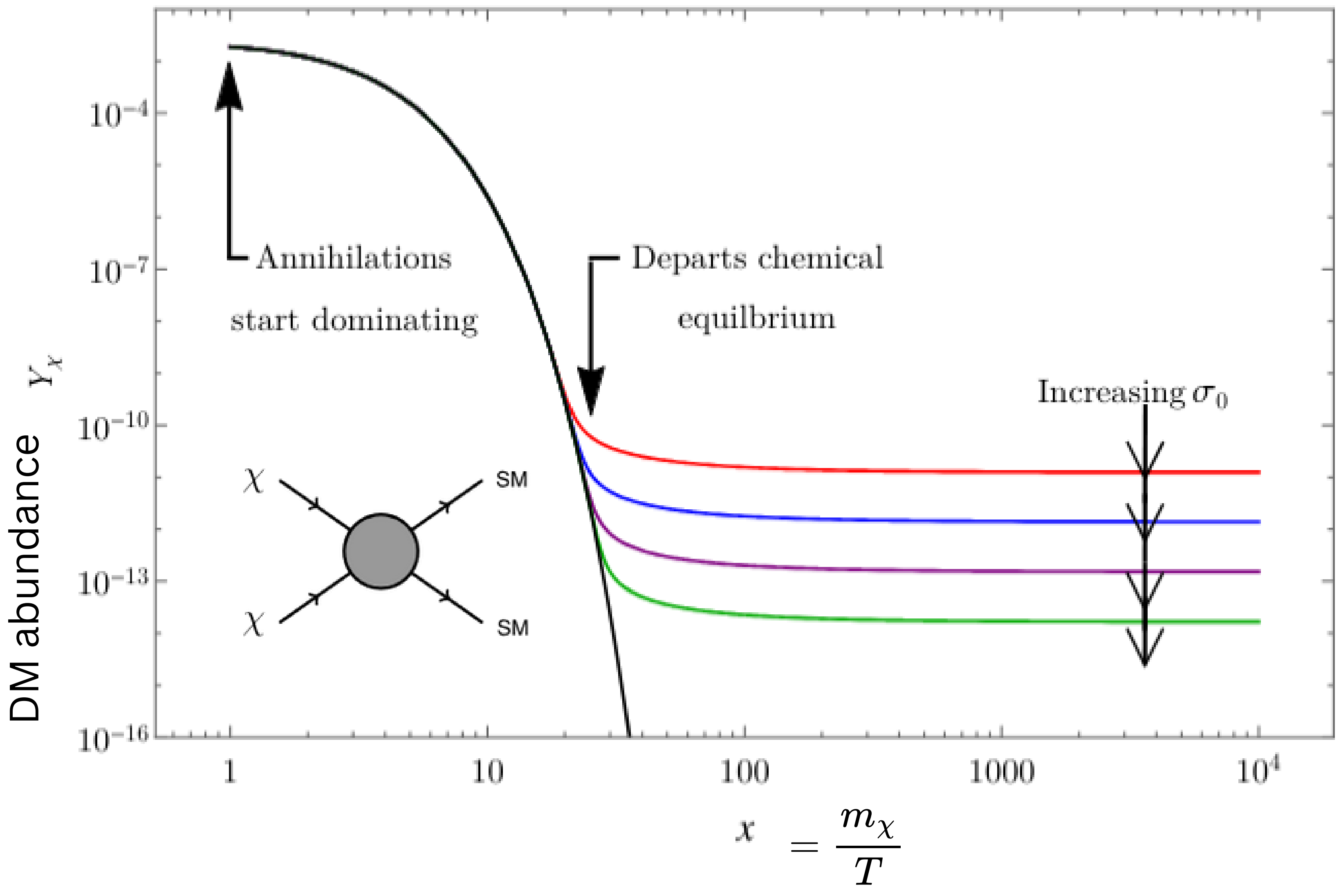
- Thermal dark matter (DM): DM and SM particles were in thermal equilibrium at early times, i.e high temperatures

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - \left(n_\chi^{\rm eq}\right)^2\right)$$

- When the rate of DM annihilation becomes comparable to the Hubble rate, DM decouples

  → Freeze-out

- In basic models: masses 100 TeV - few GeV and "sizable" couplings
- Strong bounds from direct detection experiments



Freeze-out Paradigm in a Nutshell

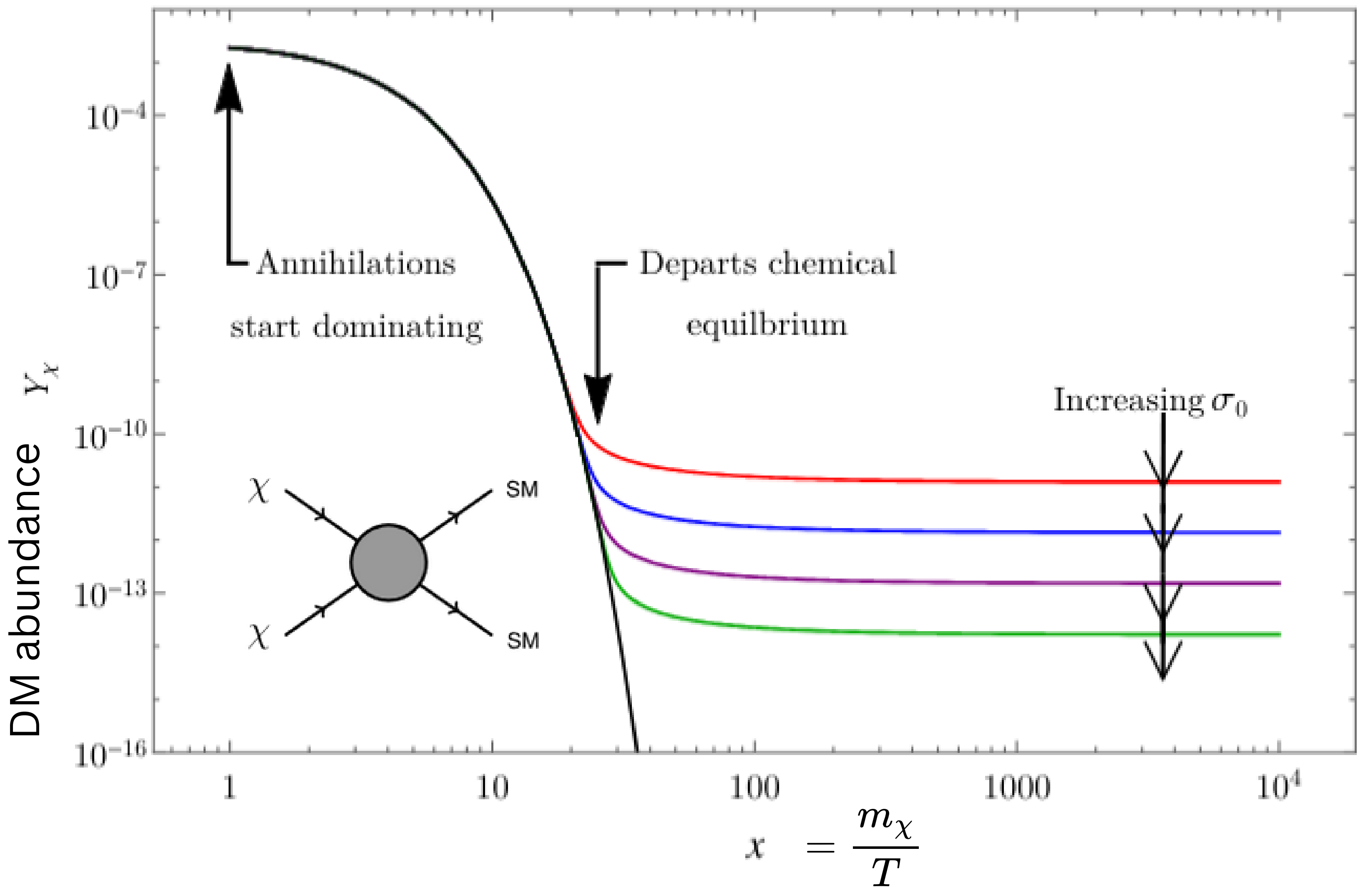
- Thermal dark matter (DM): DM and SM particles were in thermal equilibrium at early times, i.e high temperatures

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - \left(n_\chi^{\text{eq}}\right)^2\right)$$

- When the rate of DM annihilation becomes comparable to the Hubble rate, DM decouples

→ Freeze-out

- In basic models: masses 100 TeV - few GeV and "sizable" couplings
- Strong bounds from direct detection experiments



→ non-thermal production ?

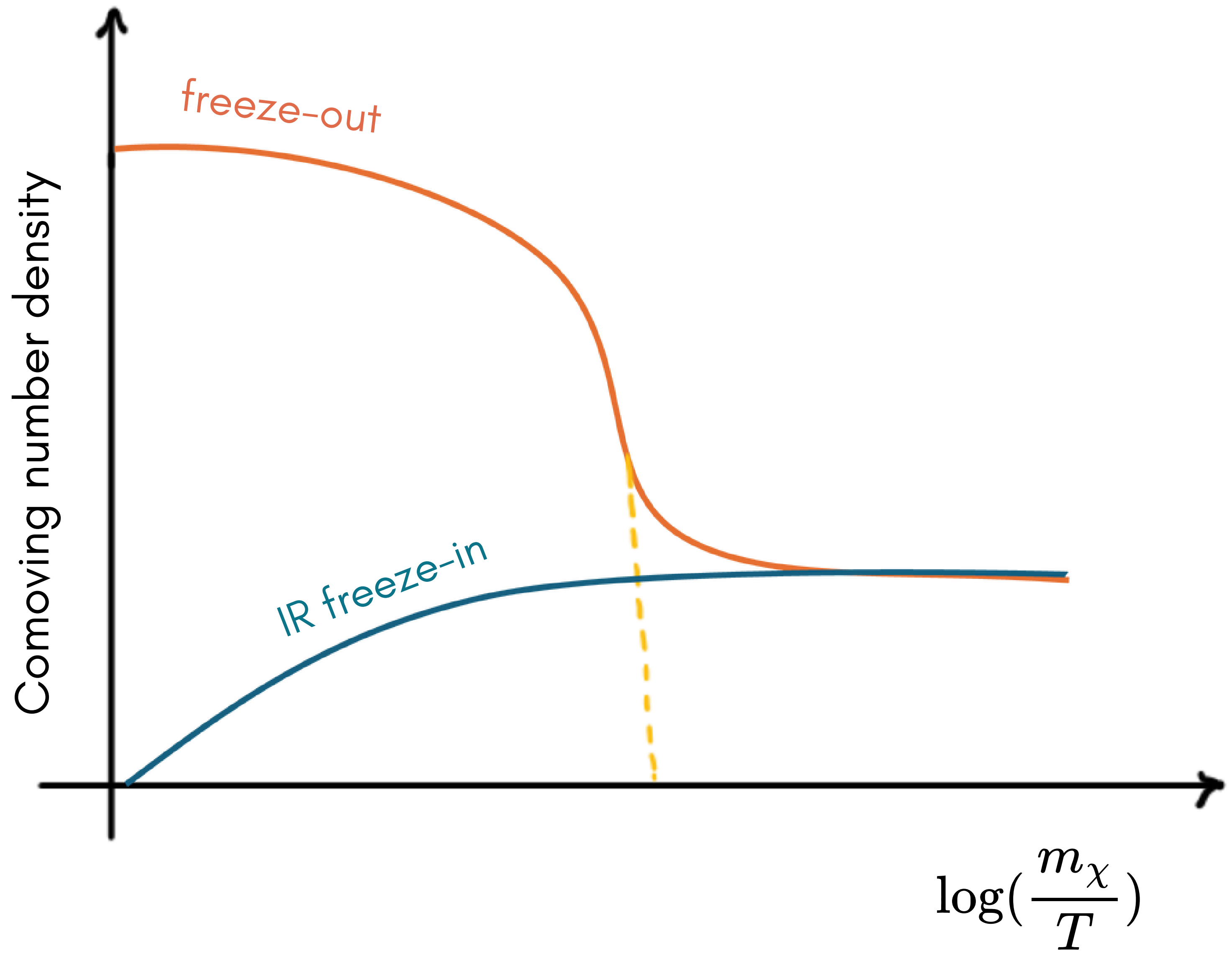
Non-Thermal Dark Matter Production

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

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]

UV freeze-in :

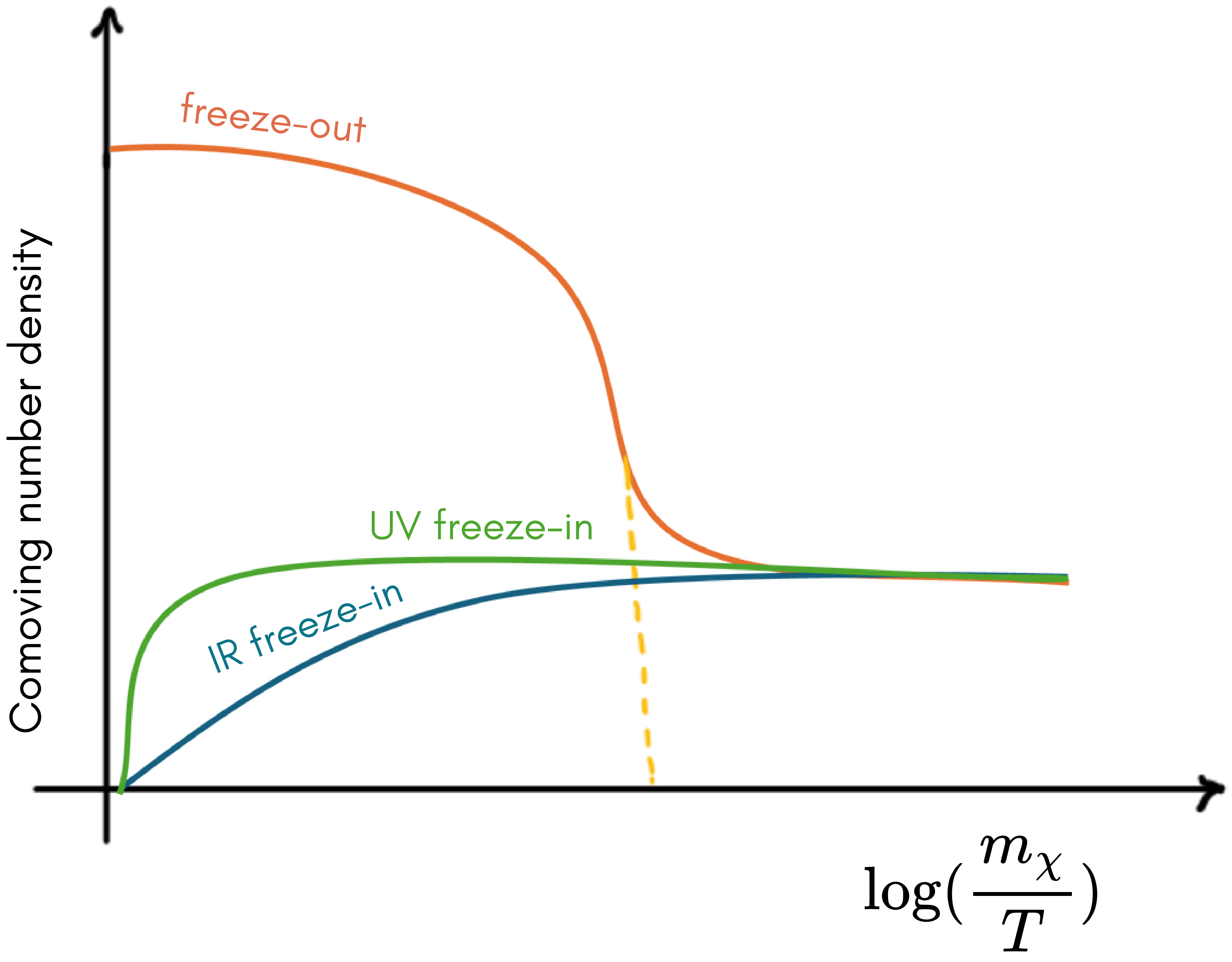
Interactions via non-renormalizable operators with dimension n+4 and thermally averaged crosssection:

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

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

[Bernal et al. 1909.07992]

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



UV- freeze-in and First Order Phase Transitions

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]

UV- freeze-in and First Order Phase Transitions

UV freeze-in :

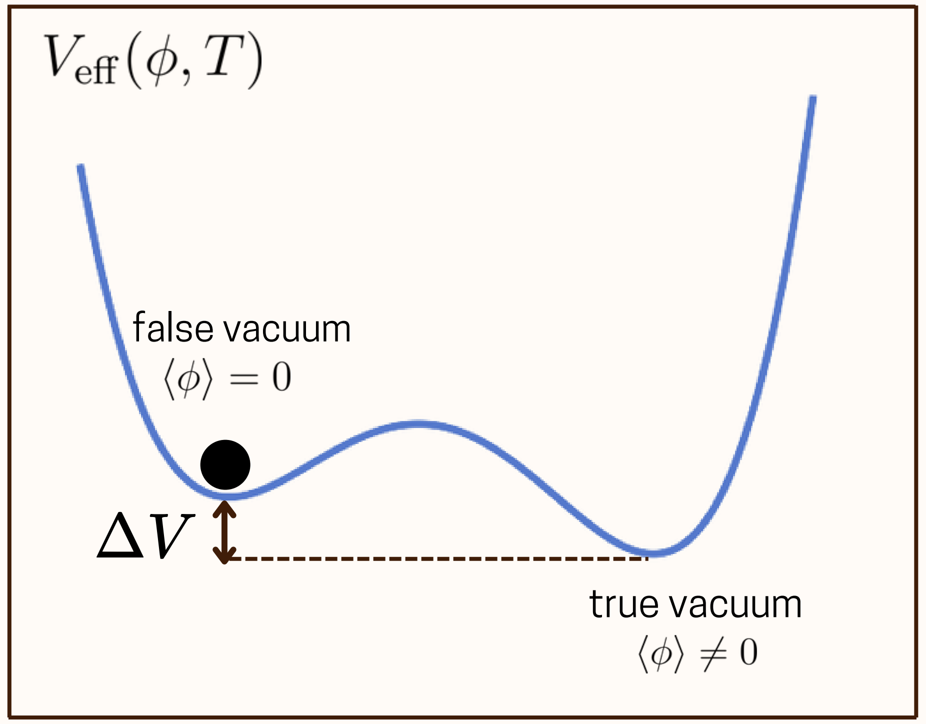
DM relic density is determined by the reheating / maximal temperature $Y_{\rm DM} \propto M_{\rm pl} T_{RH}^{2n-1}/\Lambda^{2n}$

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

First-Order Phase Transition (FOPT):

(Talk by Felix)

- 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 $T_{\rm PT}$



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

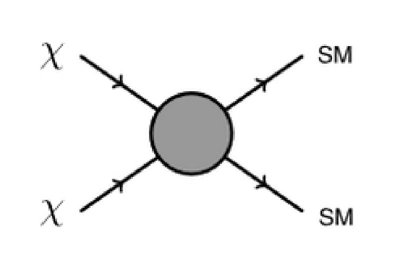
The DM phase-in scenario

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

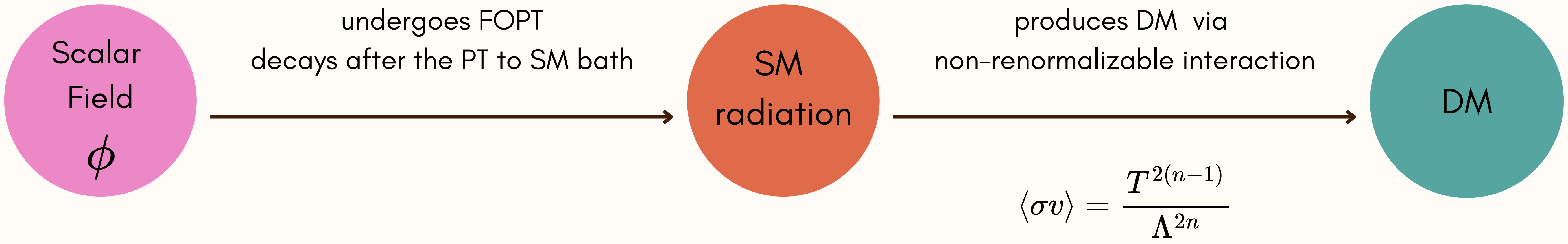
$$\langle \sigma v \rangle = \frac{T^{2(n-1)}}{\Lambda^{2n}}$$

Operator of dim n+4

SM +SM → DM+DM



The DM phase-in scenario



Boltzmann equations for energy/number densities:

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

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

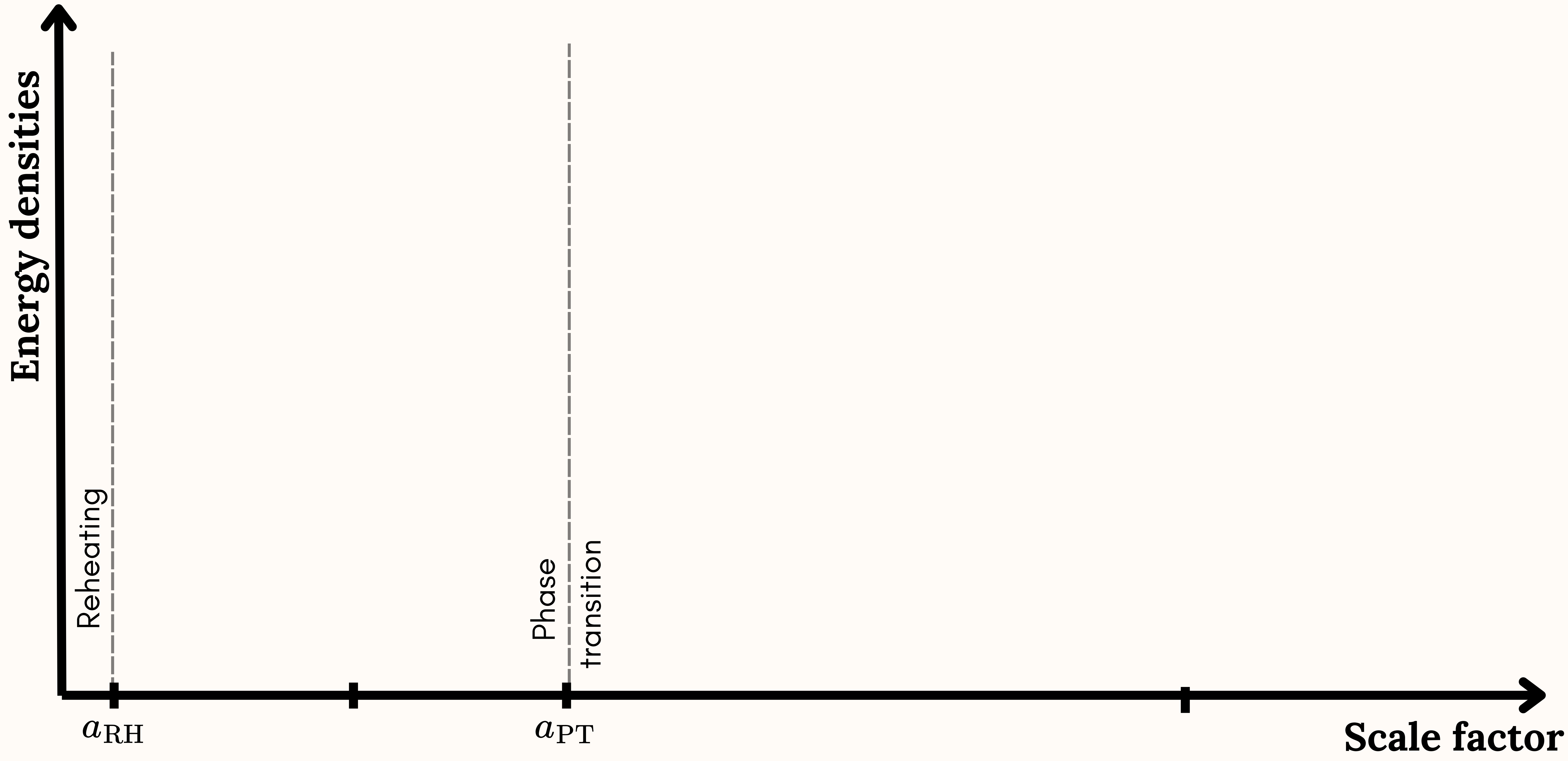
$$\frac{\mathrm{d}n_{\mathrm{DM}}}{\mathrm{d}a} = -\frac{3}{a}n_{\mathrm{DM}} + \frac{\langle \sigma v \rangle}{aH}n_{\mathrm{SM}}^2$$

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

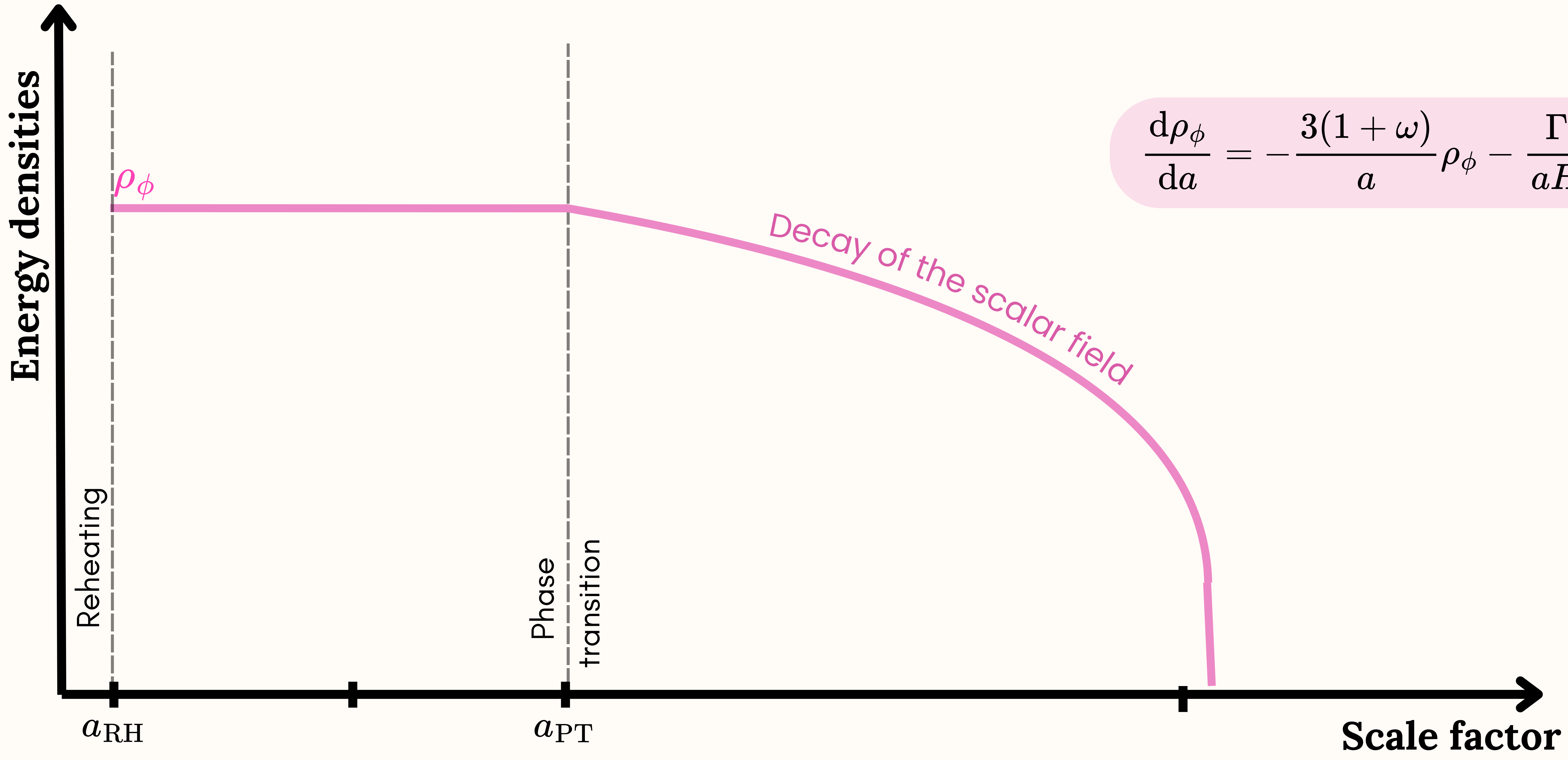
After the PT: $\Gamma = \mathrm{const}$ and $0 \leq \omega \leq 1/3$

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

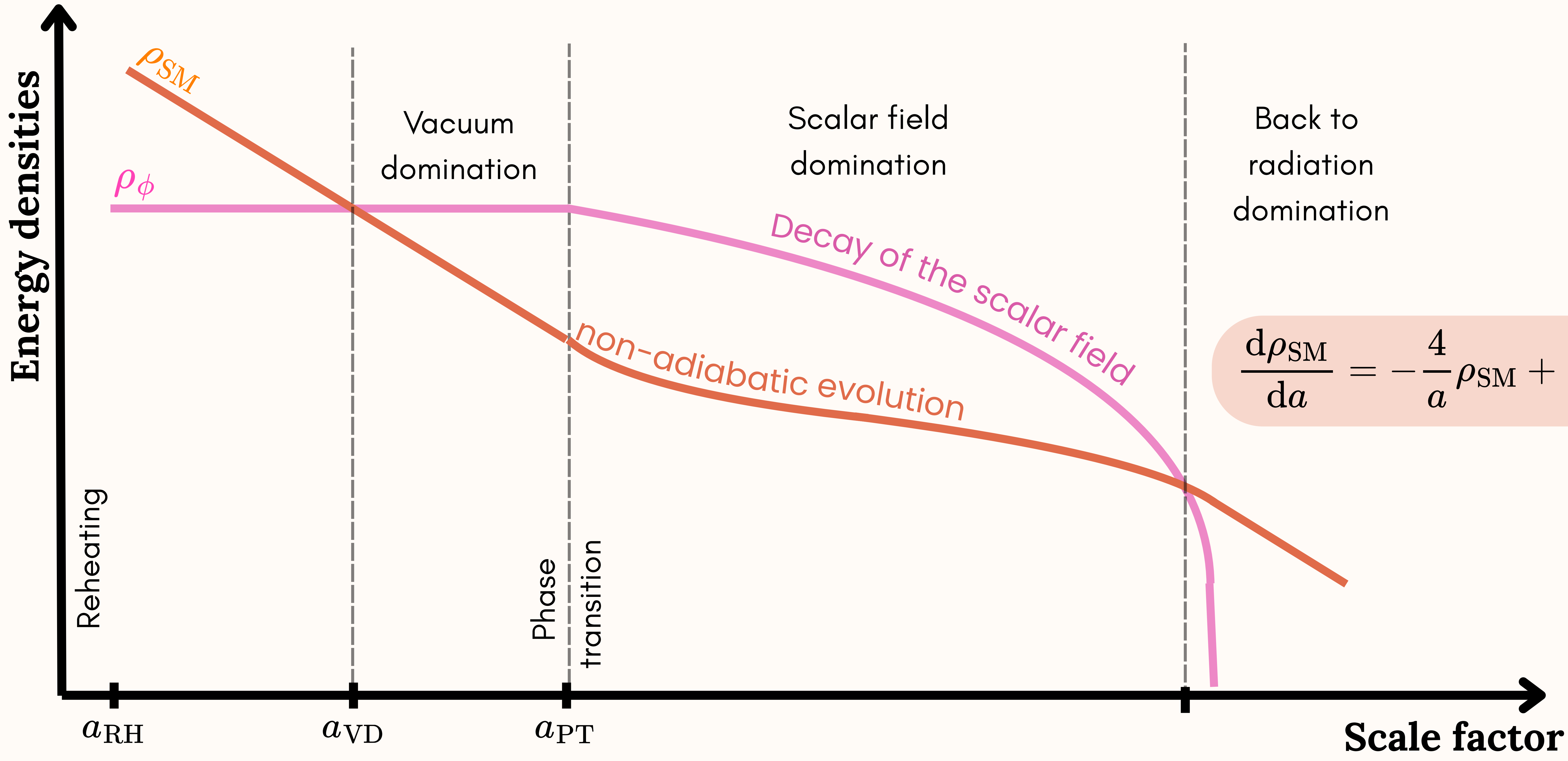


The DM phase-in scenario



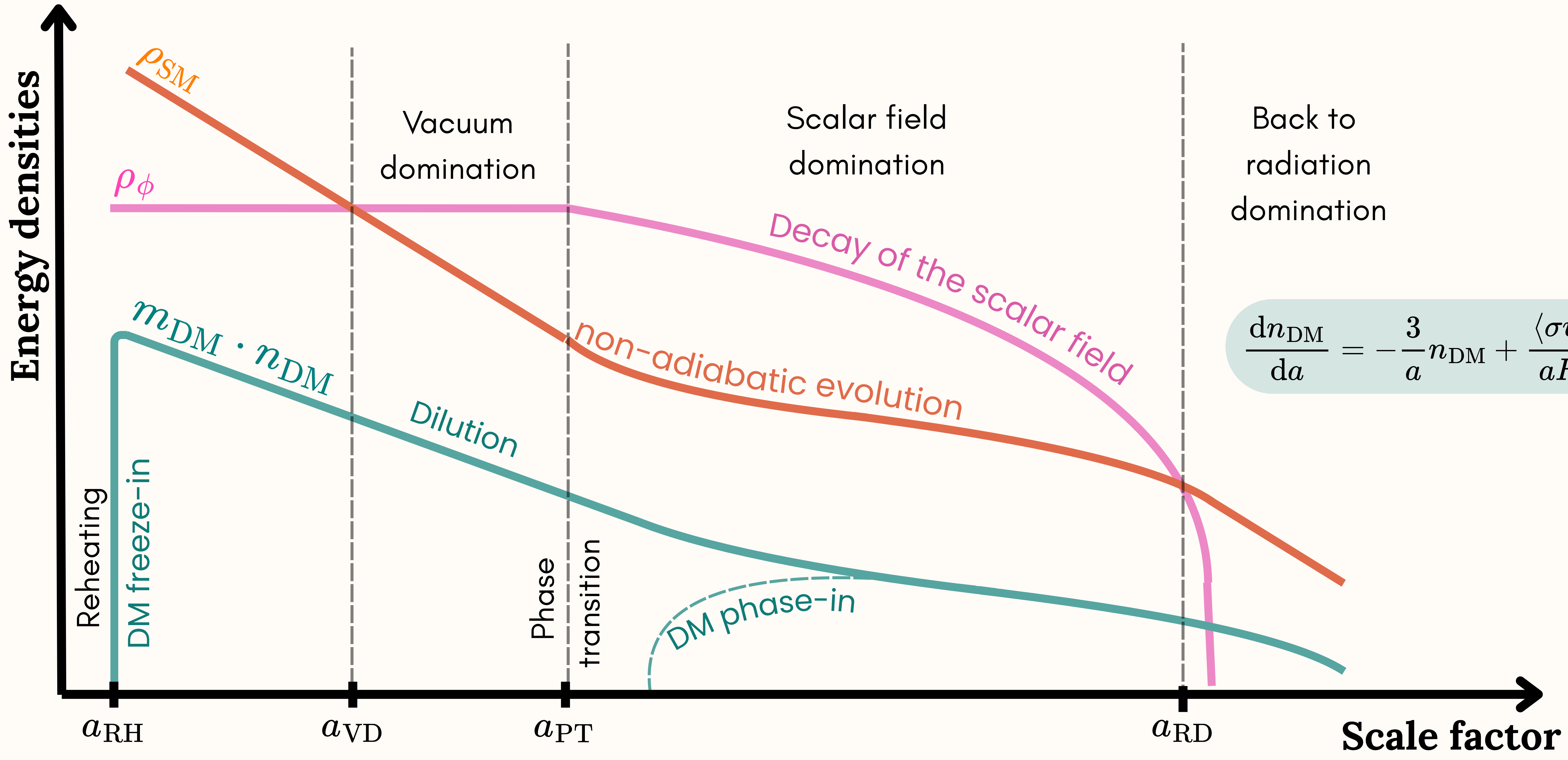
$$\frac{d\rho_\phi}{da} = -\frac{3(1+\omega)}{a}\rho_\phi - \frac{\Gamma}{aH}\rho_\phi$$

The DM phase-in scenario



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

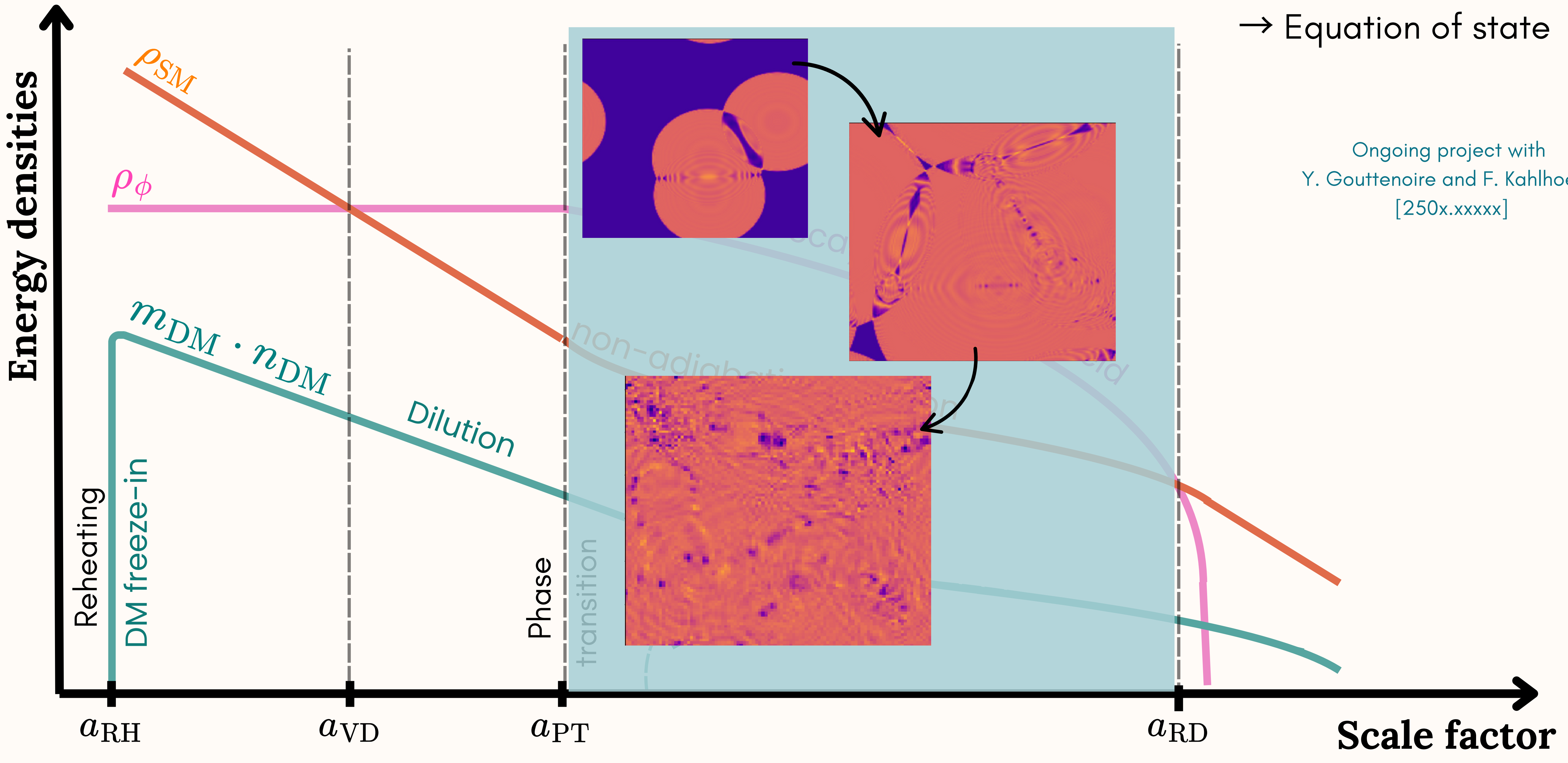
The DM phase-in scenario



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

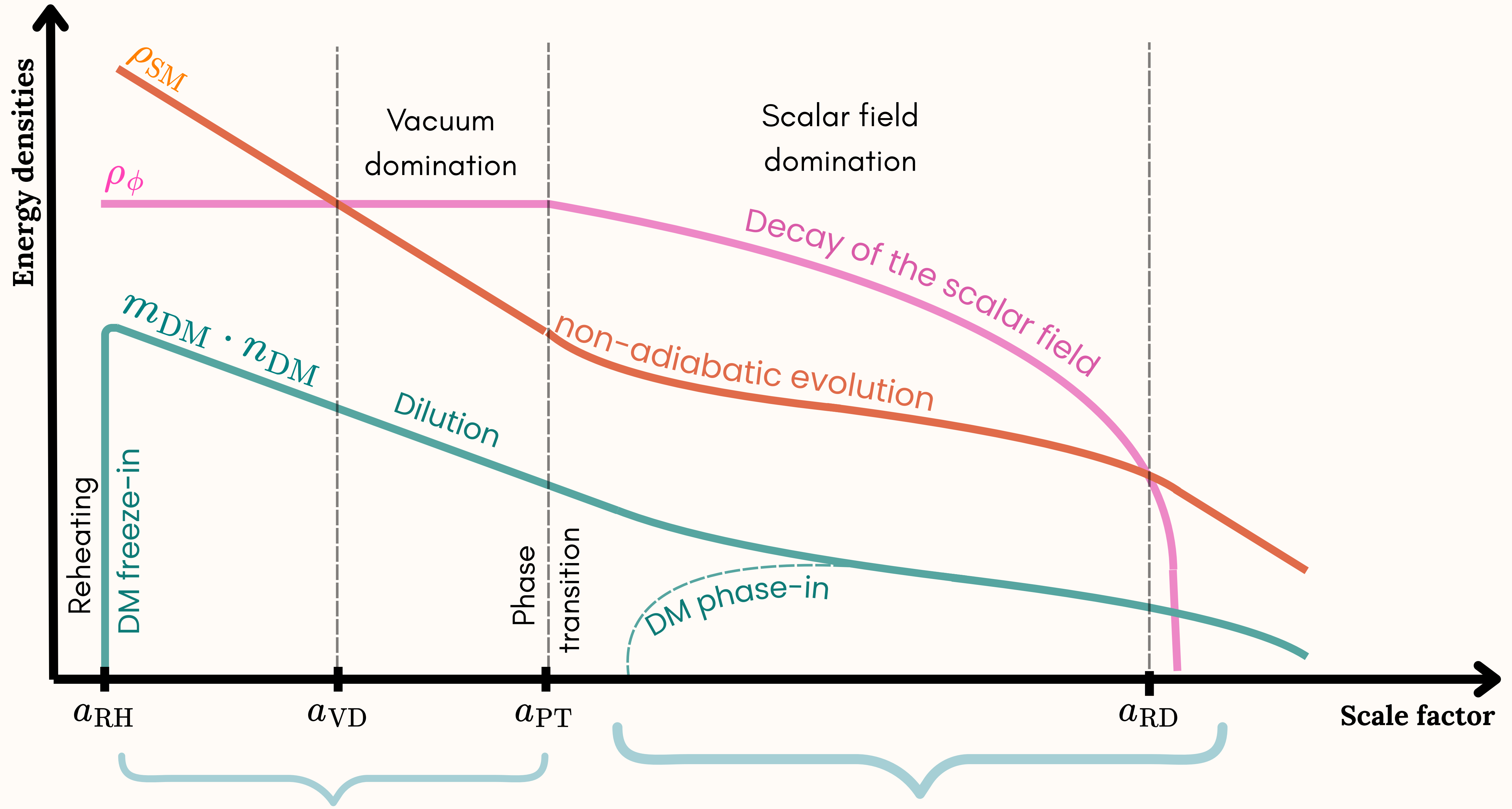
The DM phase-in scenario

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



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

Phase-in condition



$\Omega_{DM,FI}$

↓

Determined by reheating temperature

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

$\Omega_{DM,PI}$

↓

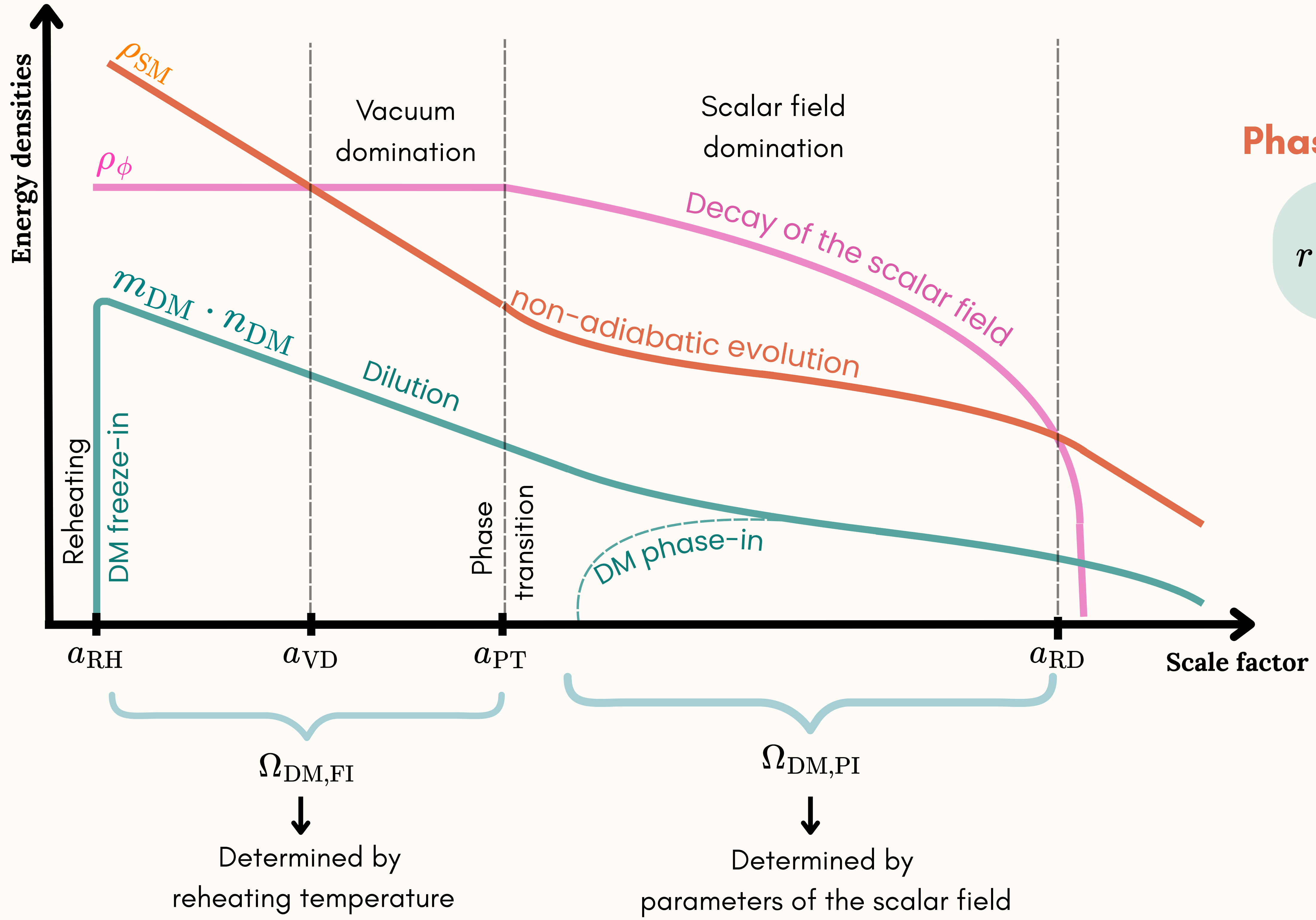
Determined by parameters of the scalar field

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

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

Dark matter is produced in different phases.

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)

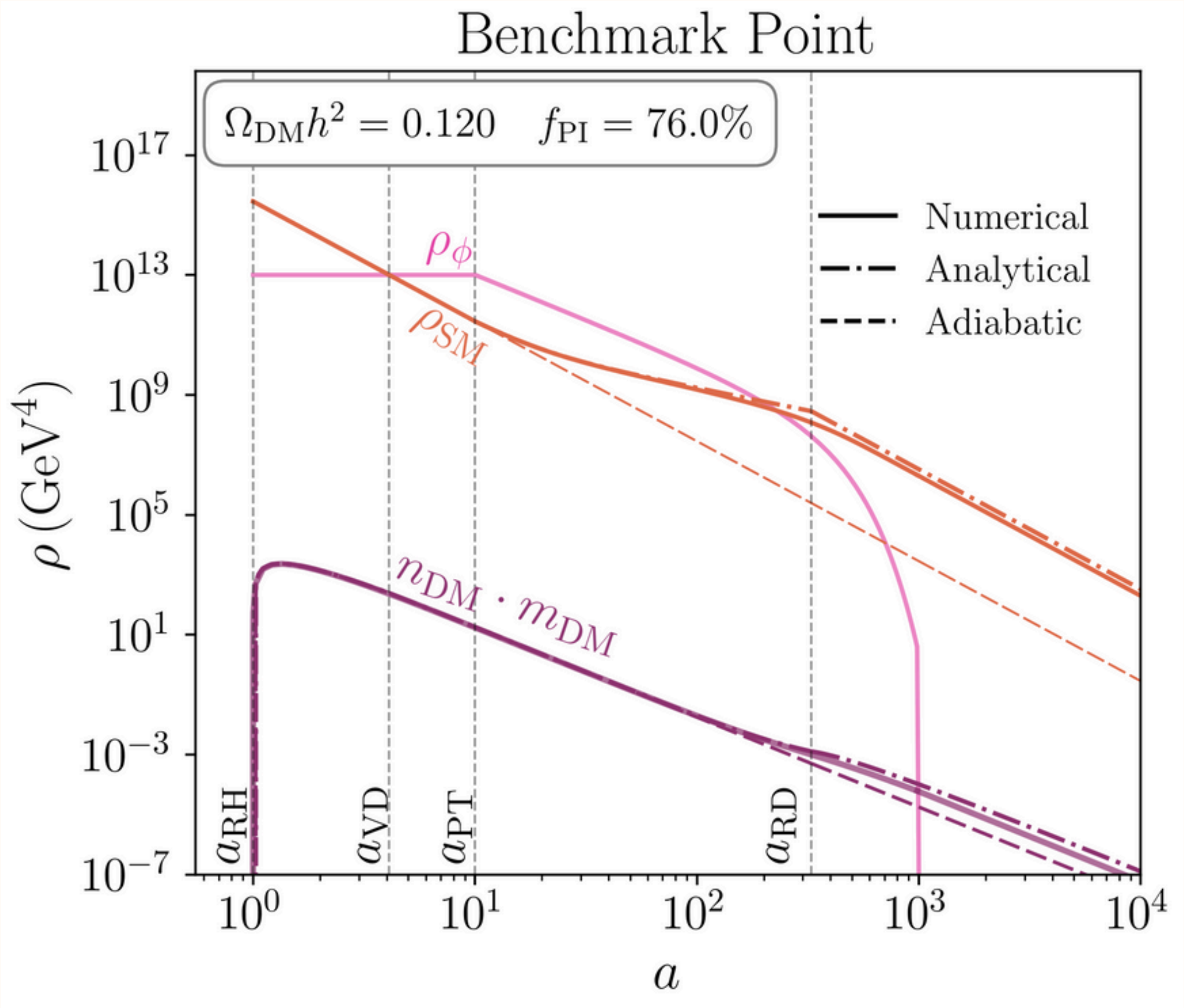
Some examples

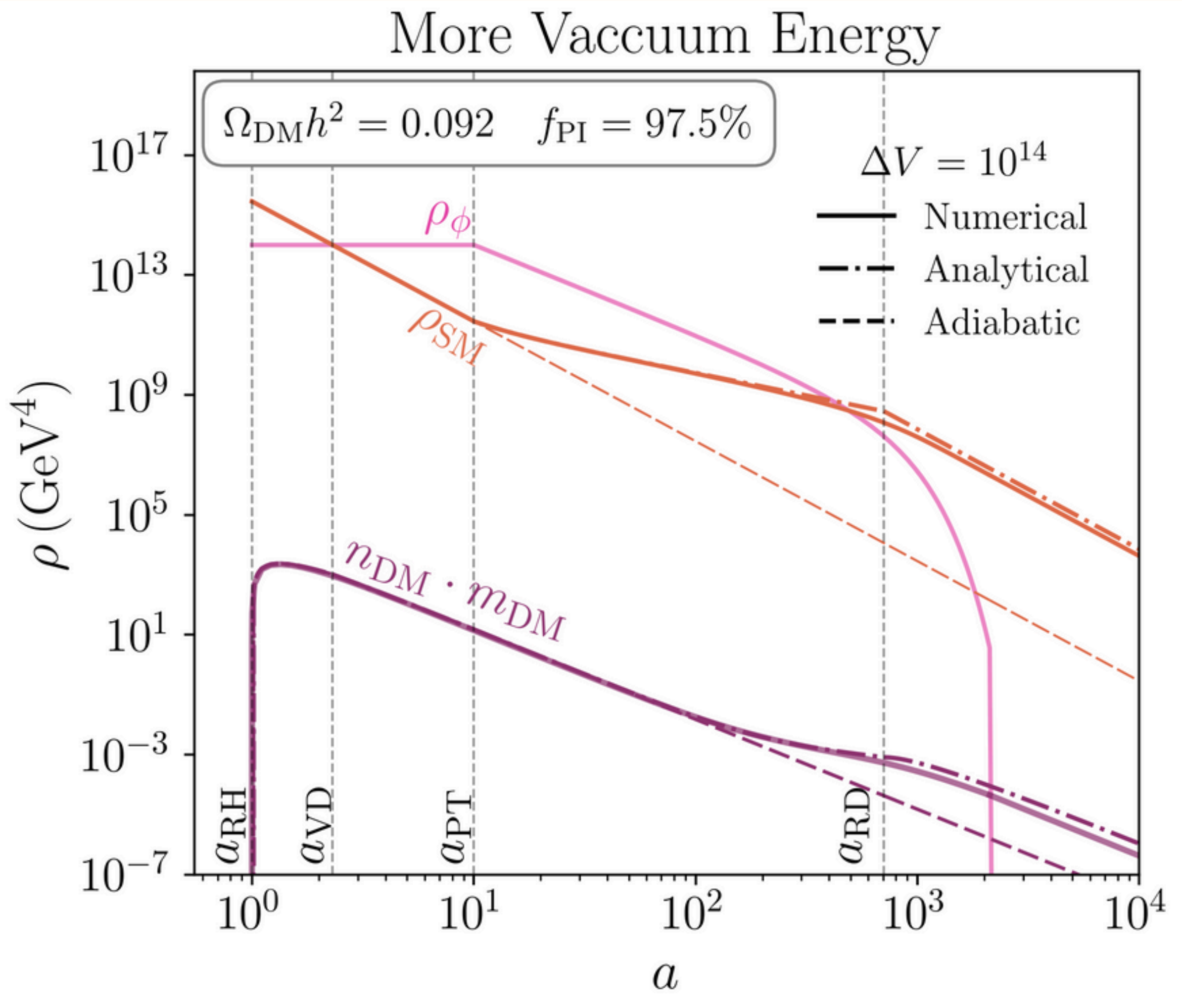
Phase-in condition

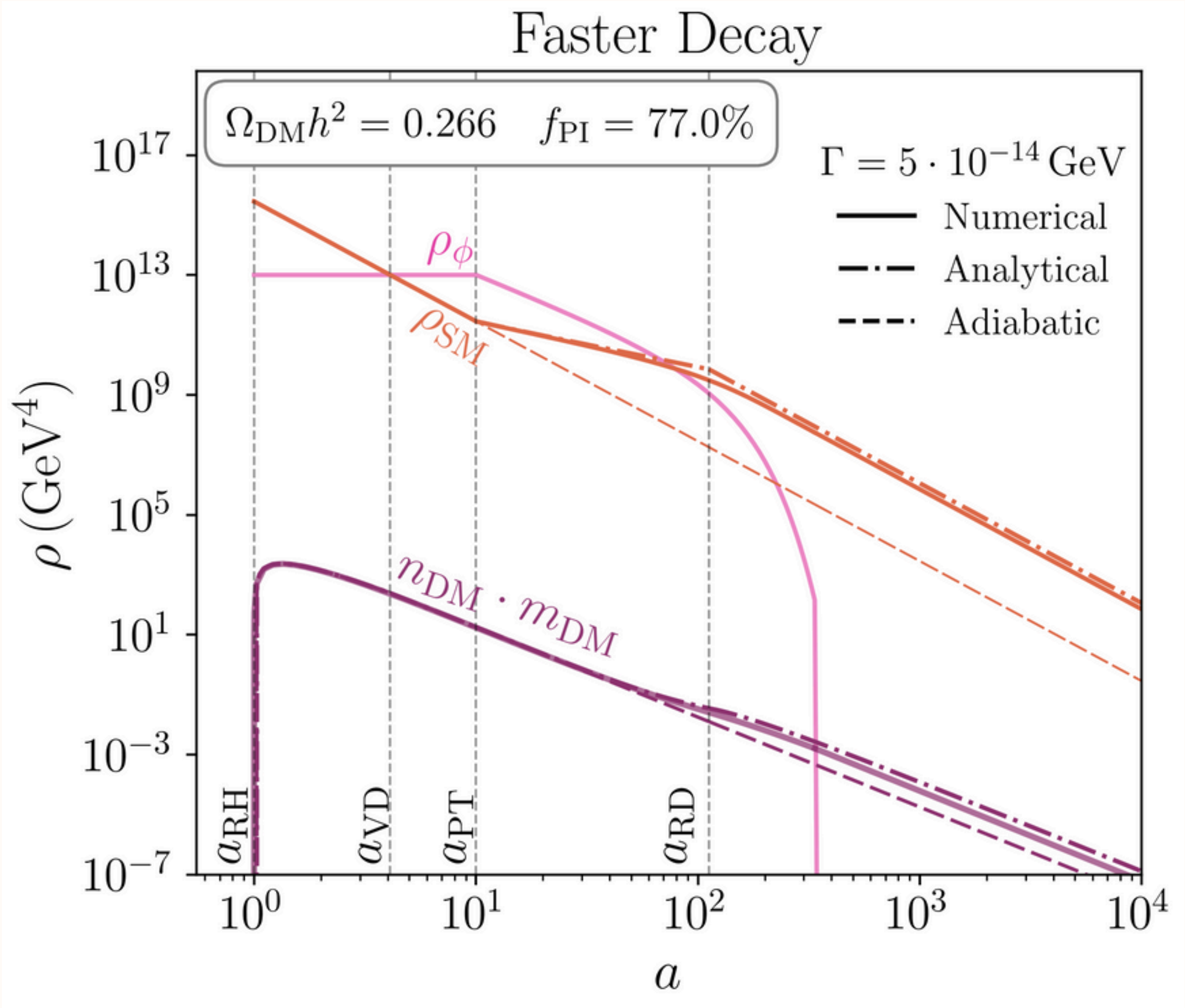
$$r \approx T_{\rm RH}^{-2n+1} T_{\rm PT}^{-3} \Delta V^{\frac{n+1}{2}} g_\star^{-(n+1)/2} \left(\frac{\sqrt{\Delta V}}{M_{\rm Pl}\Gamma} + \sqrt{\frac{3}{8\pi}} \right)^{\frac{2}{1+w}-1-n} > 1$$

with: $r = \frac{\Omega_{\rm DM,PI}}{\Omega_{\rm DM,FI}} = \frac{\text{phase} - \text{in}}{\text{freeze} - \text{in}}$

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







Benchmark values

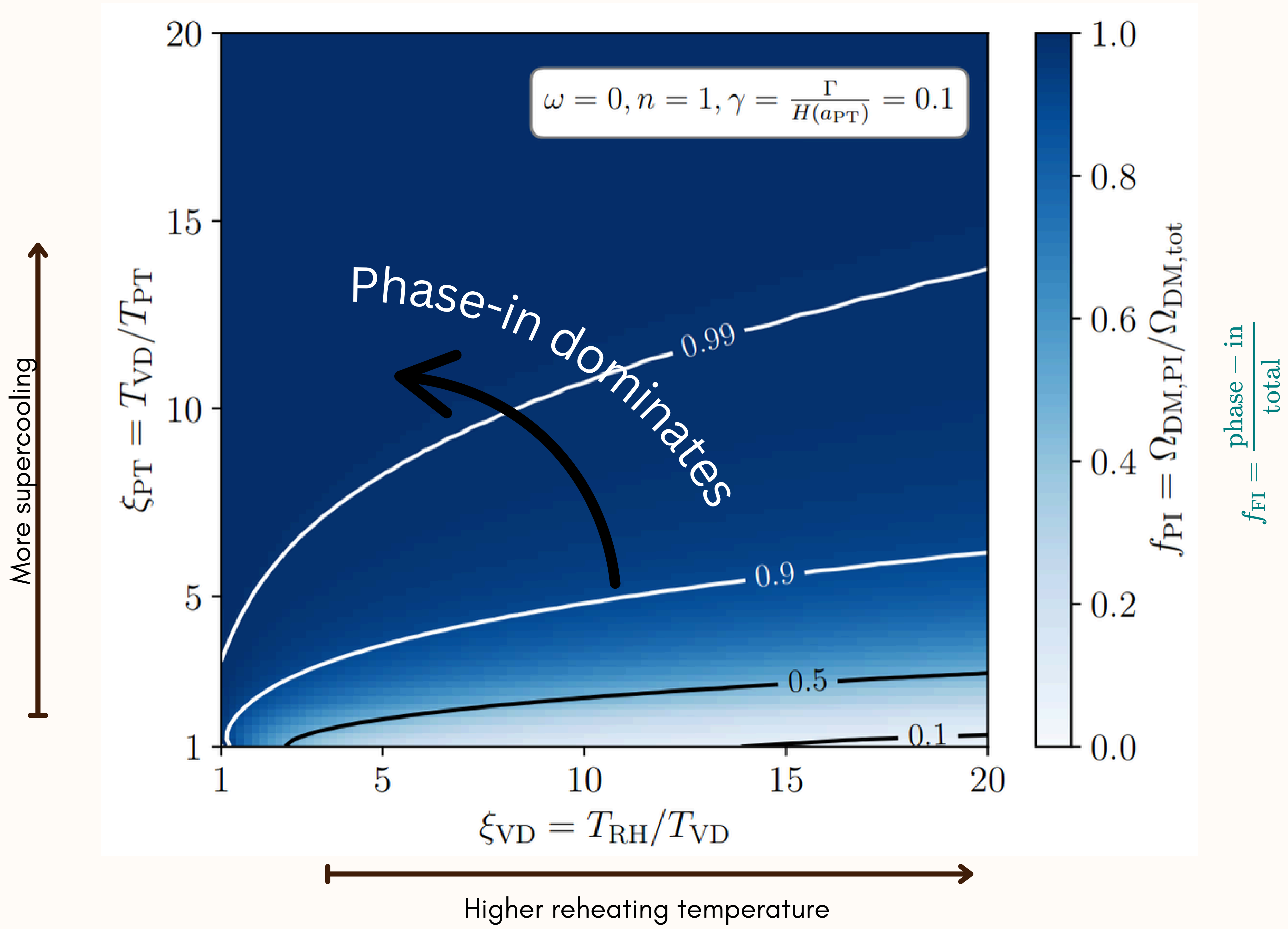
$m_{\rm DM} = 1\,\text{MeV},\ T_{\rm RH} = 3 \cdot 10^3\,\text{GeV}$

$T_{\rm PT} = 300\,\text{GeV},\ \Delta V = 10^{13}\,\text{GeV}^4$

$\Gamma = 10^{-14}\,\text{GeV},\ \Lambda = 1.88 \cdot 10^{13}\,\text{GeV}$

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

Numerical results

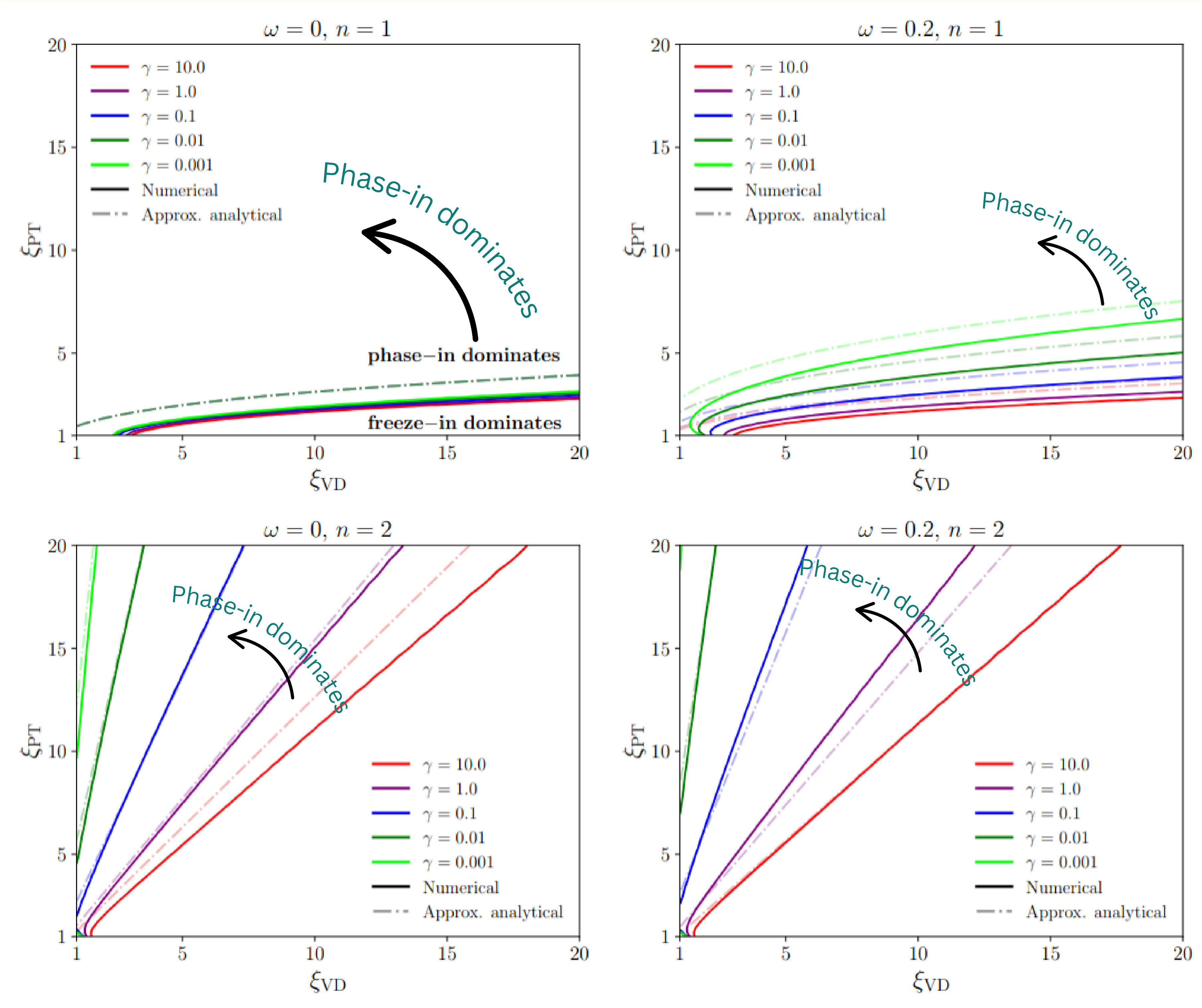


Phase-in condition : results

matter dom. | modified cosmology

Dim 5 operator

Dim 6 operator



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

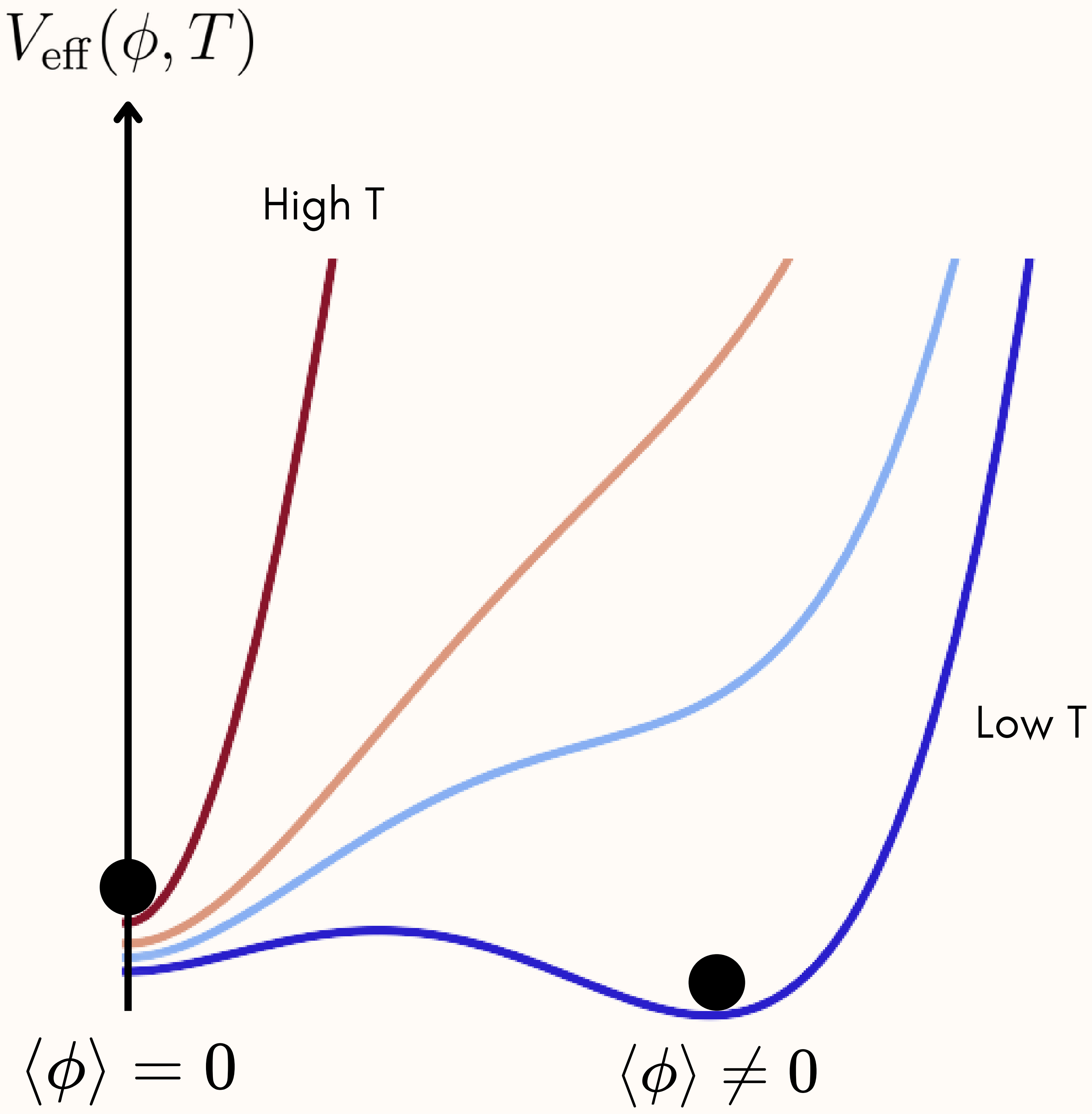
$$f_{\rm peak} \propto T_{\rm RD}$$

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])

First-Order Phase Transitions



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

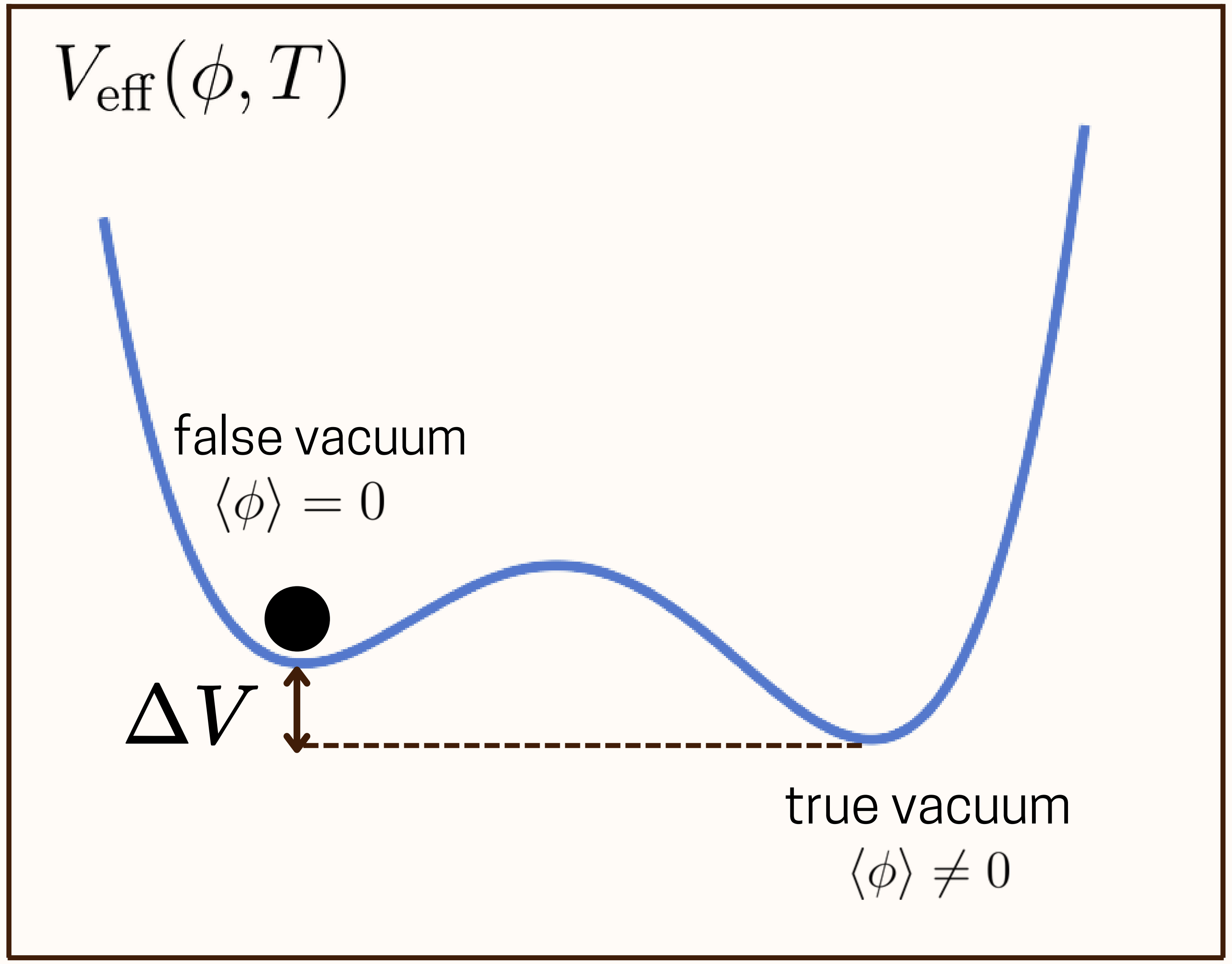
$$V_{\text{eff}}(\phi, T) = V(\phi) + \Delta V(\phi, T)$$

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

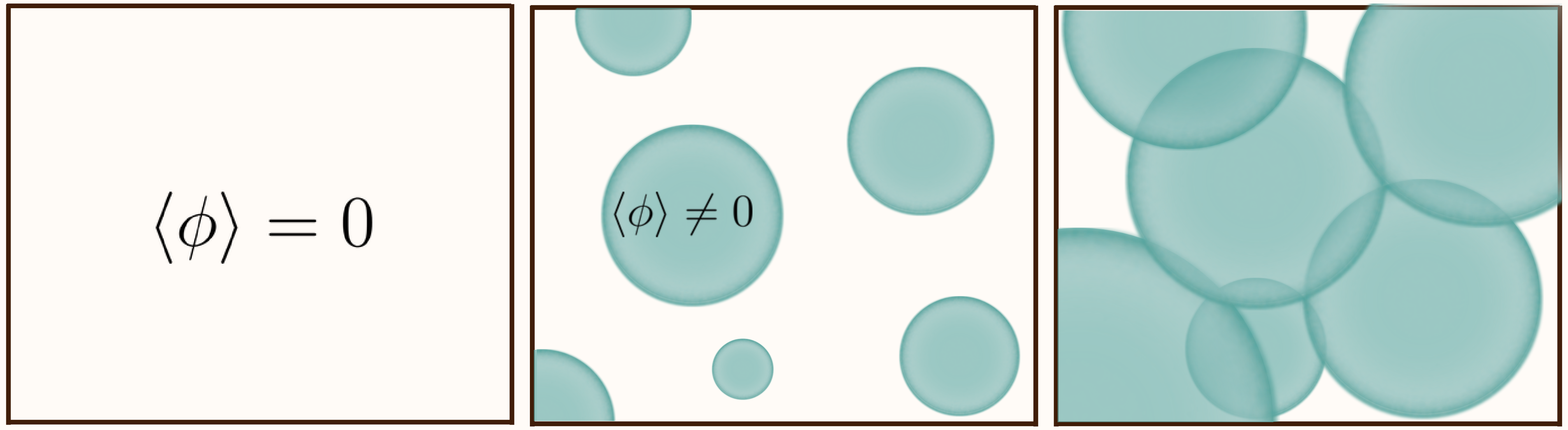
(Example)

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

First-Order Phase Transitions



The transition proceeds through bubble nucleation:

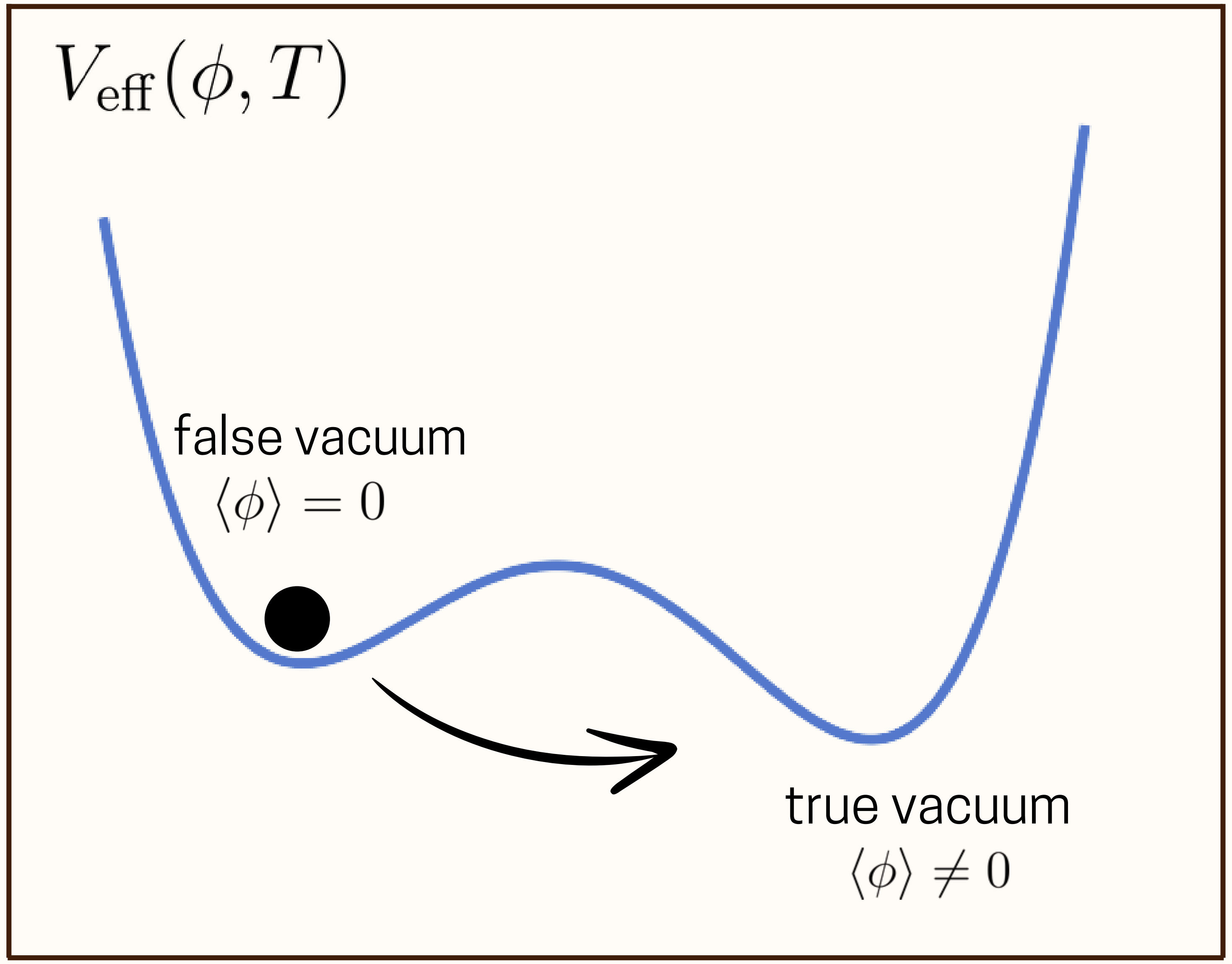


$T > T_{\text{nuc}}$

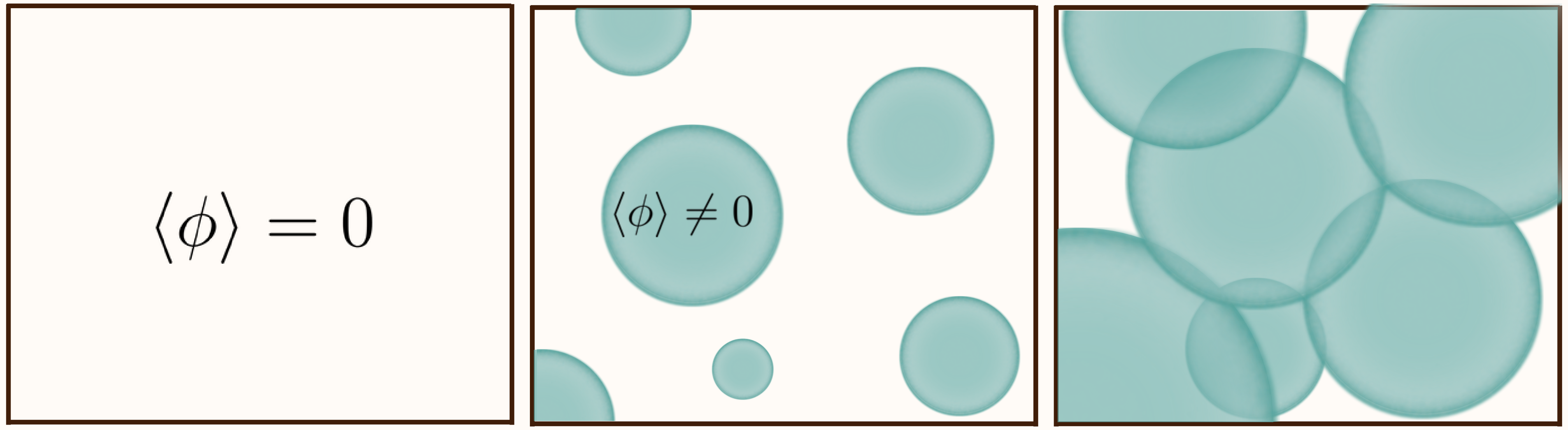
In the following: $T_{\text{PT}} \simeq T_{\text{nuc}} \simeq T_{\text{perc}}$
because $\beta^{-1} \ll H^{-1}$

+ 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

First-Order Phase Transitions



The transition proceeds through bubble nucleation:

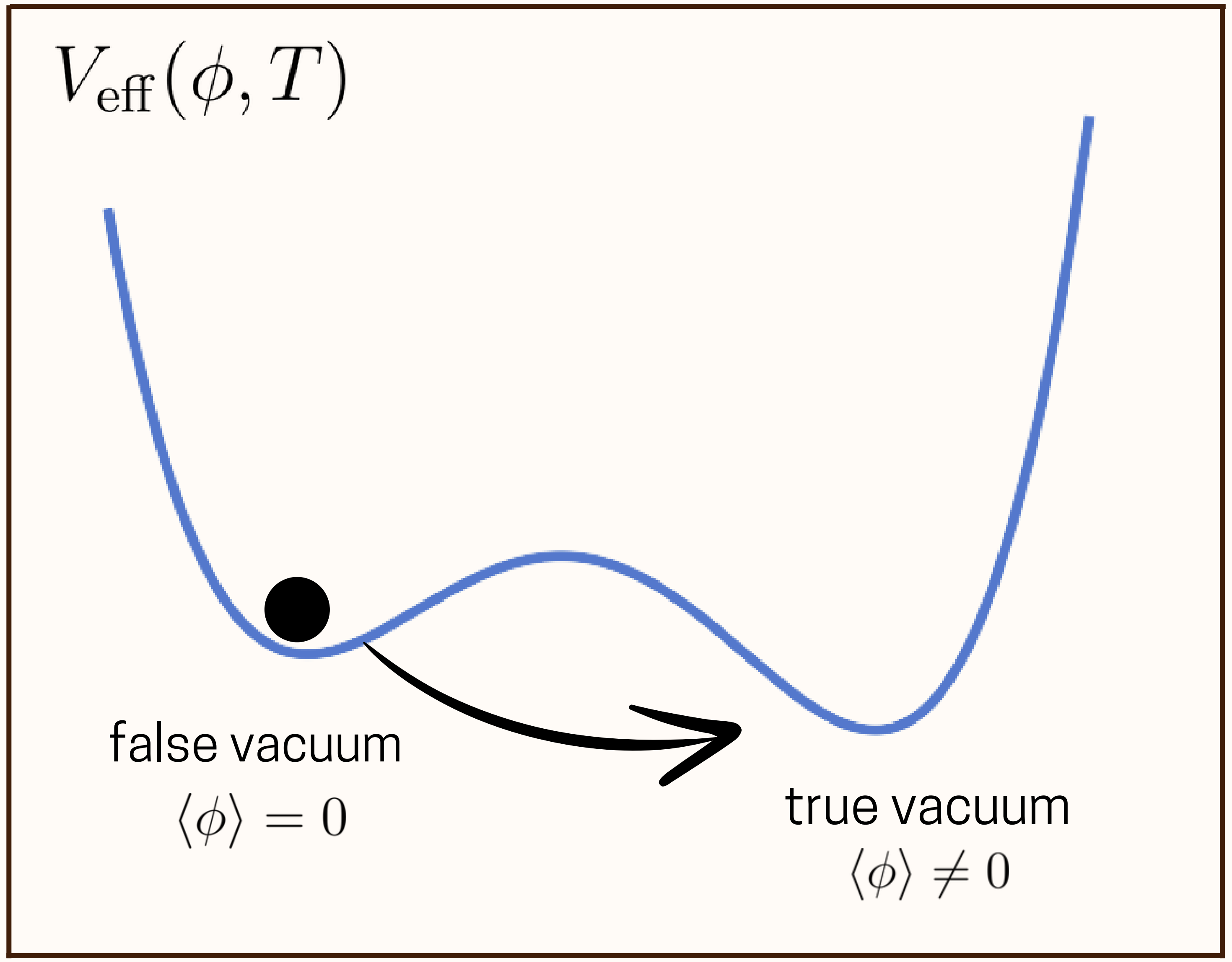


$T > T_{\text{nuc}}$

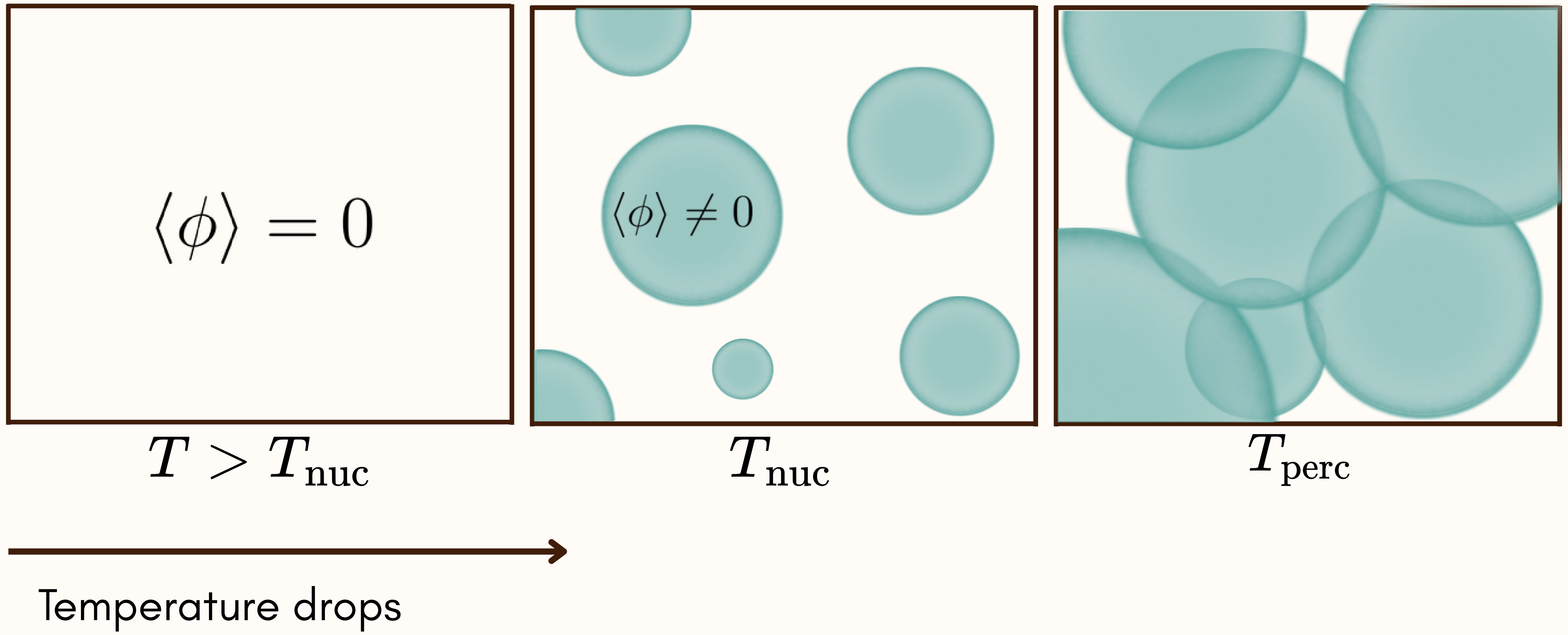
In the following: $T_{\text{PT}} \simeq T_{\text{nuc}} \simeq T_{\text{perc}}$

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

First-Order Phase Transitions



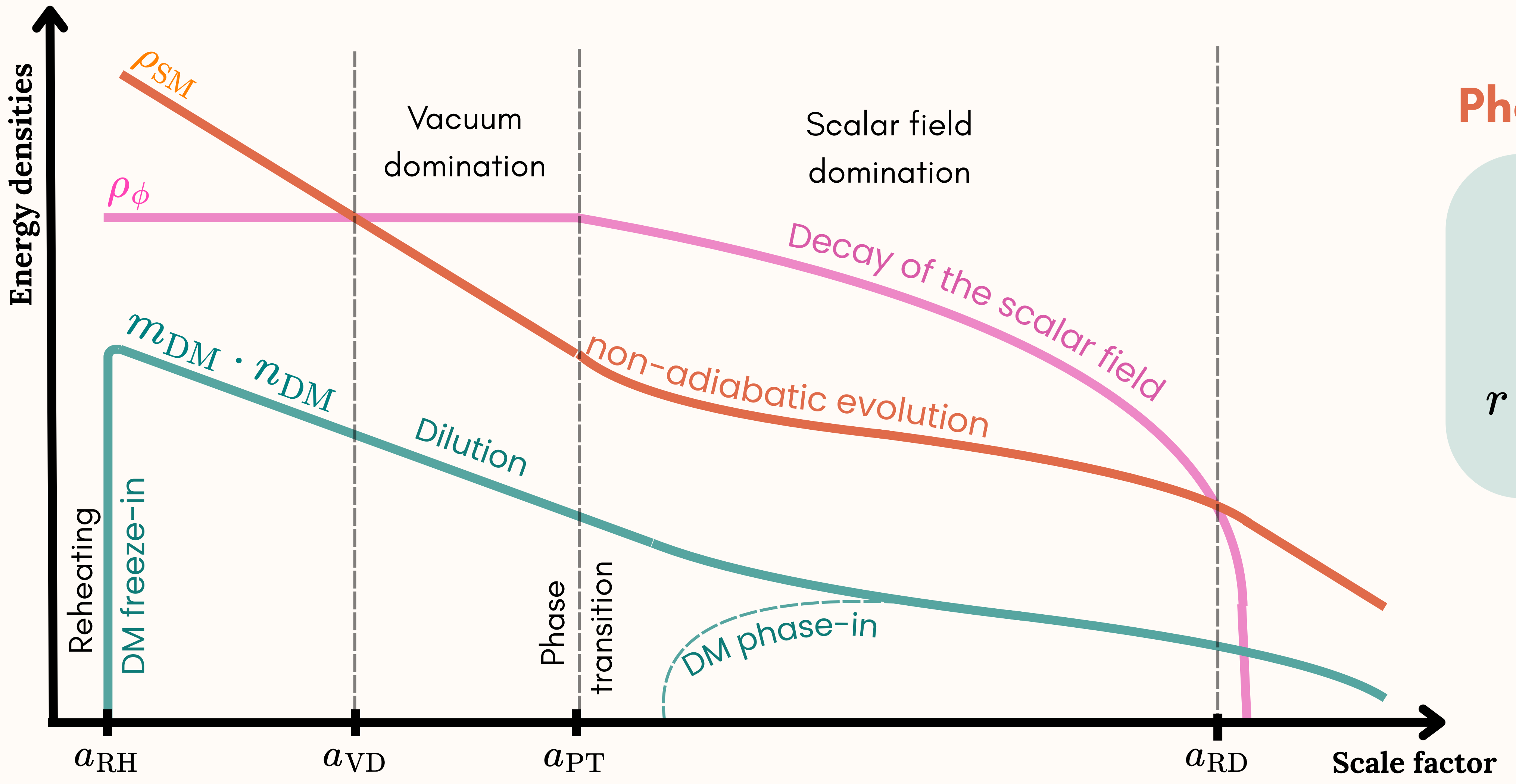
Bubble nucleation:



In the following: $T_{\text{PT}} \simeq T_{\text{nuc}} \simeq T_{\text{perc}}$

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

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
- 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)

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