Dynamical equilibration of dark matter and baryon energy densities

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UNIVERSITY OF MARYLAND

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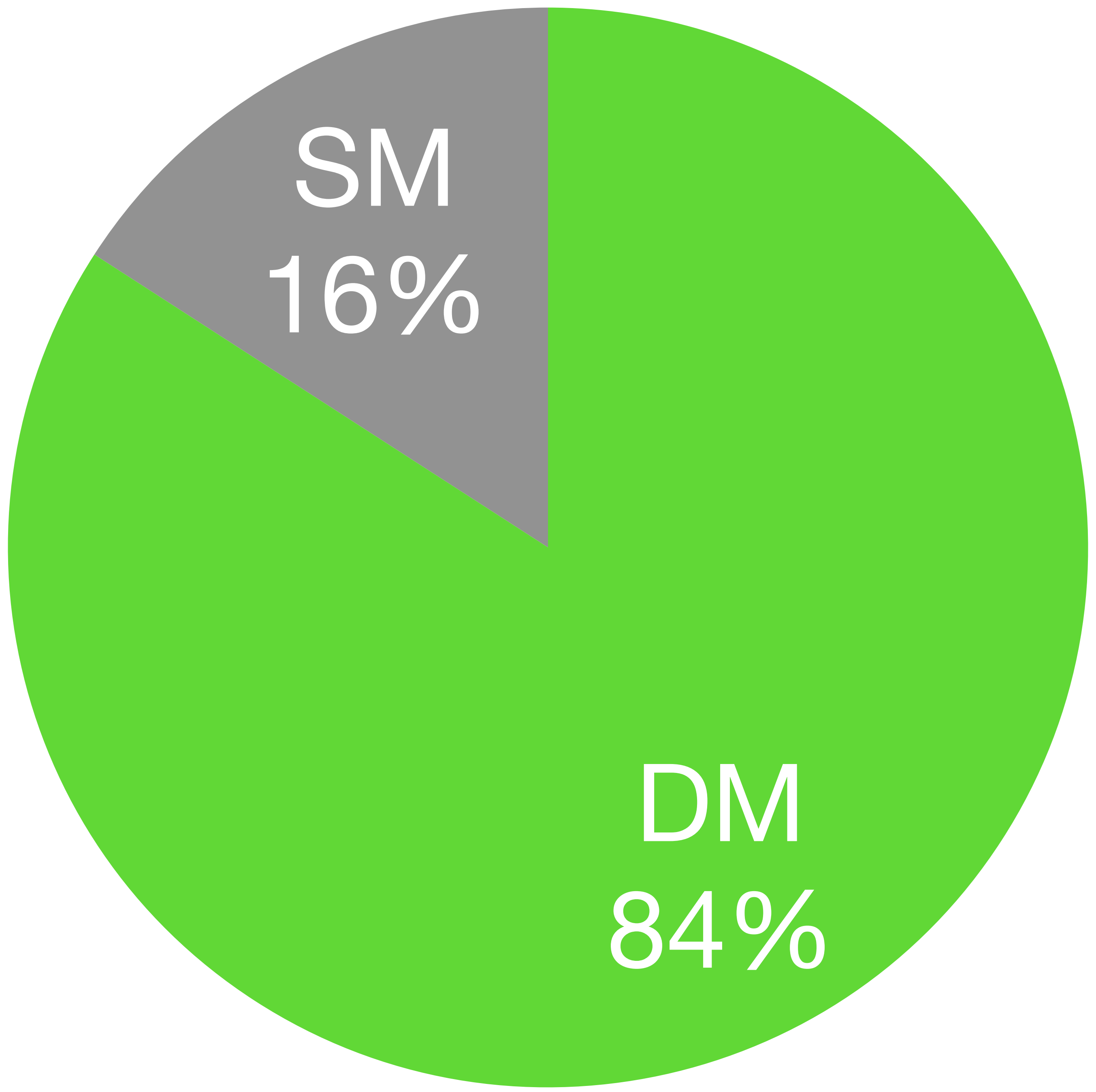
Matter content of the universe

DM makes up the majority of matter content of the universe

When discussing DM we usually try to find a viable production mechanism that explains observed abundance



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Motivation

Naively ρ_{DM} can have any value, most models allow wide range of DM abundance

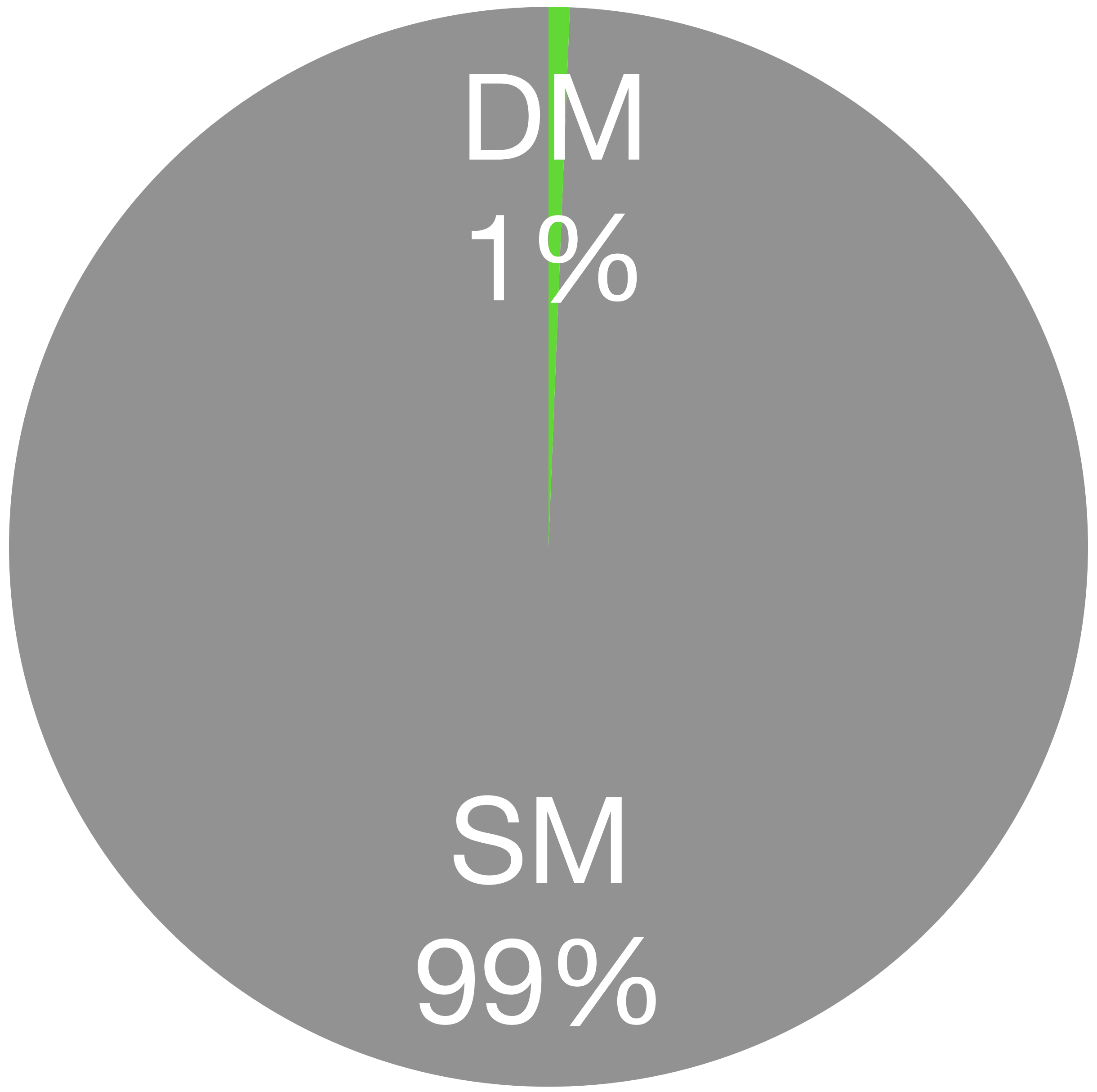
Similarly ρ_B is exponentially sensitive to α_{QCD} through dimensional transmutation

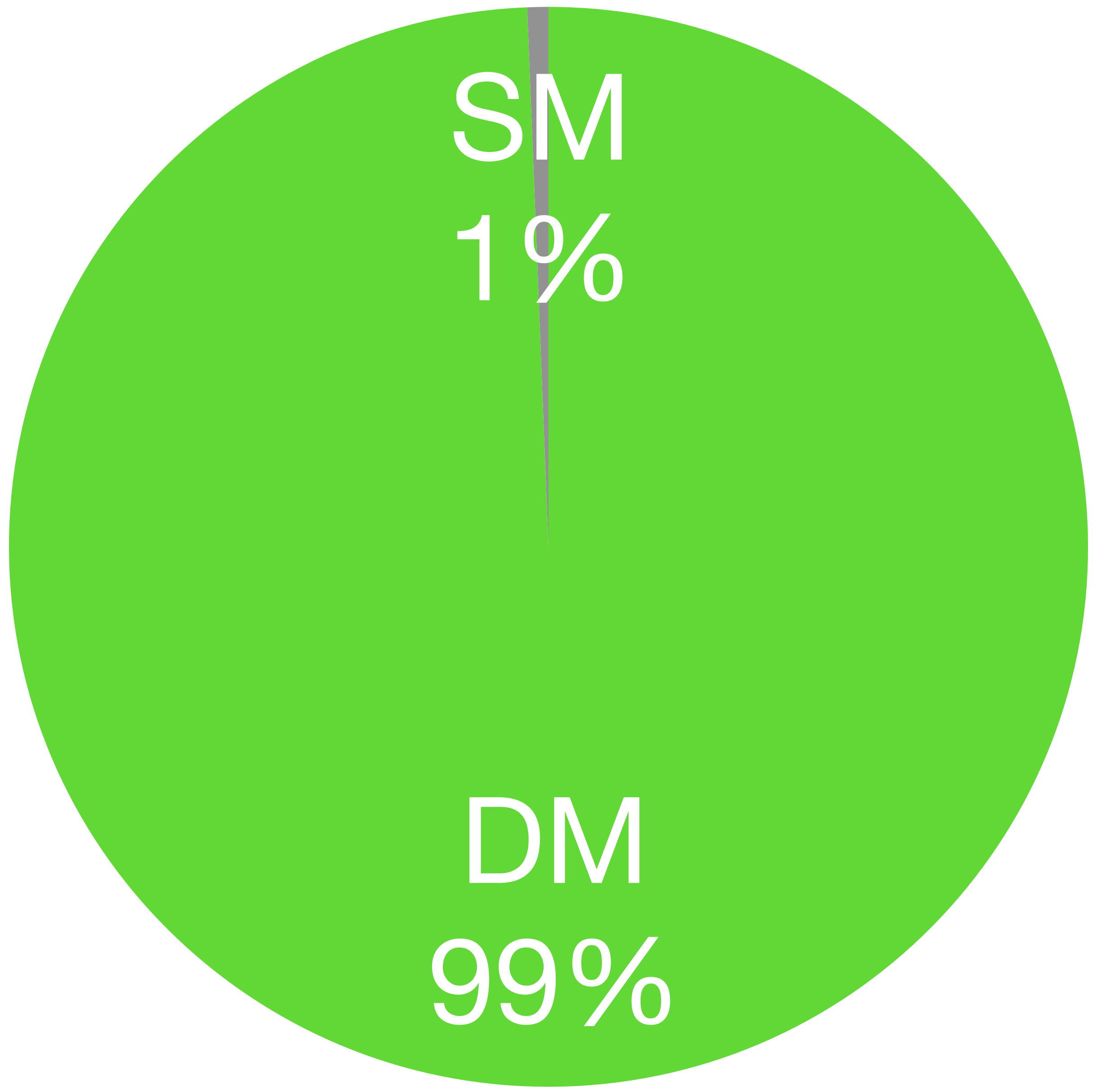
$$\rho_B \propto m_p \propto \Lambda_{QCD} \propto e^{-\frac{\#}{g^2}}$$

Motivation

The fact that $\rho_{DM}/\rho_B \approx 5$ seems very accidental

Like axions explain why $\bar{\theta} \approx 0$, perhaps there is a mechanism that prefers $\rho_B \sim \rho_{DM}$





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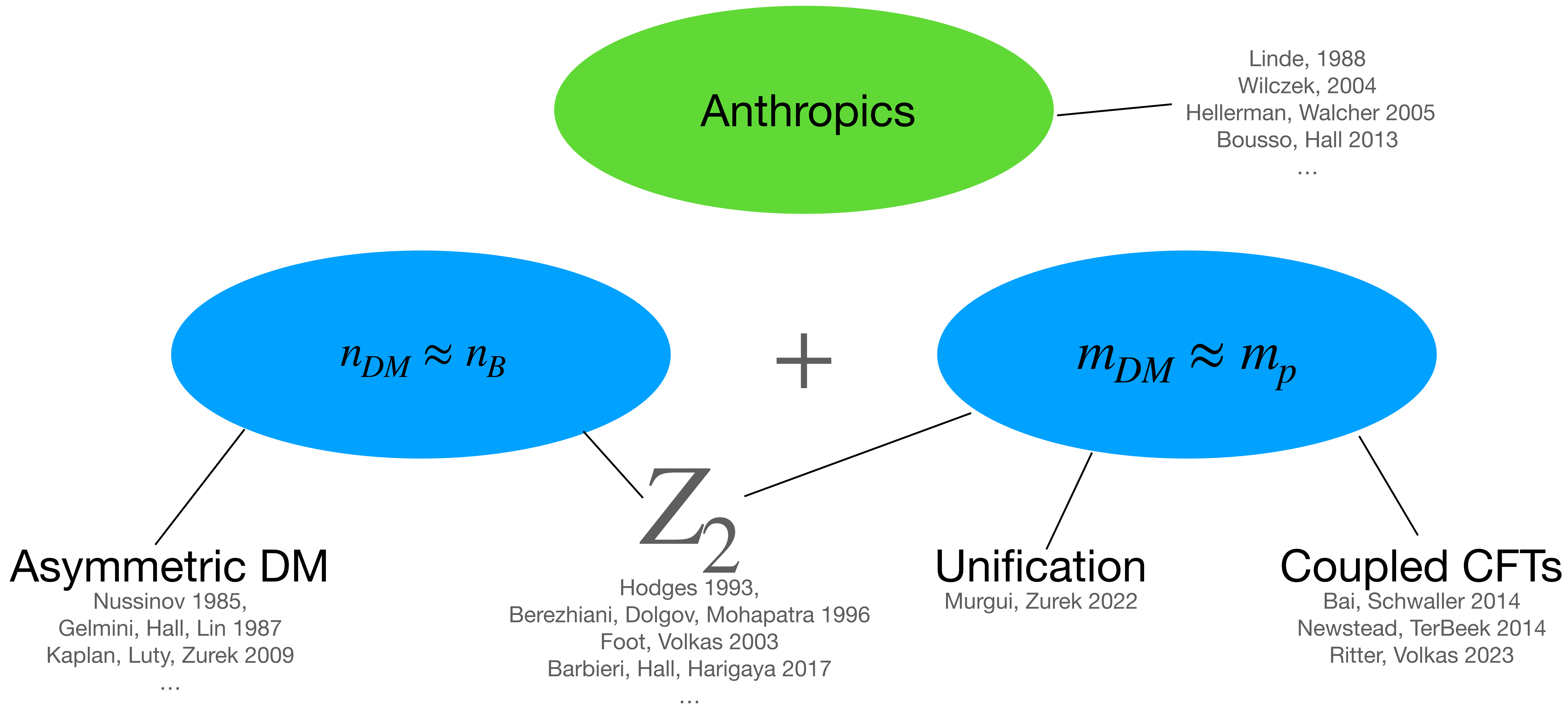
$\rho_{DM} \approx 5\rho_B$: current approaches



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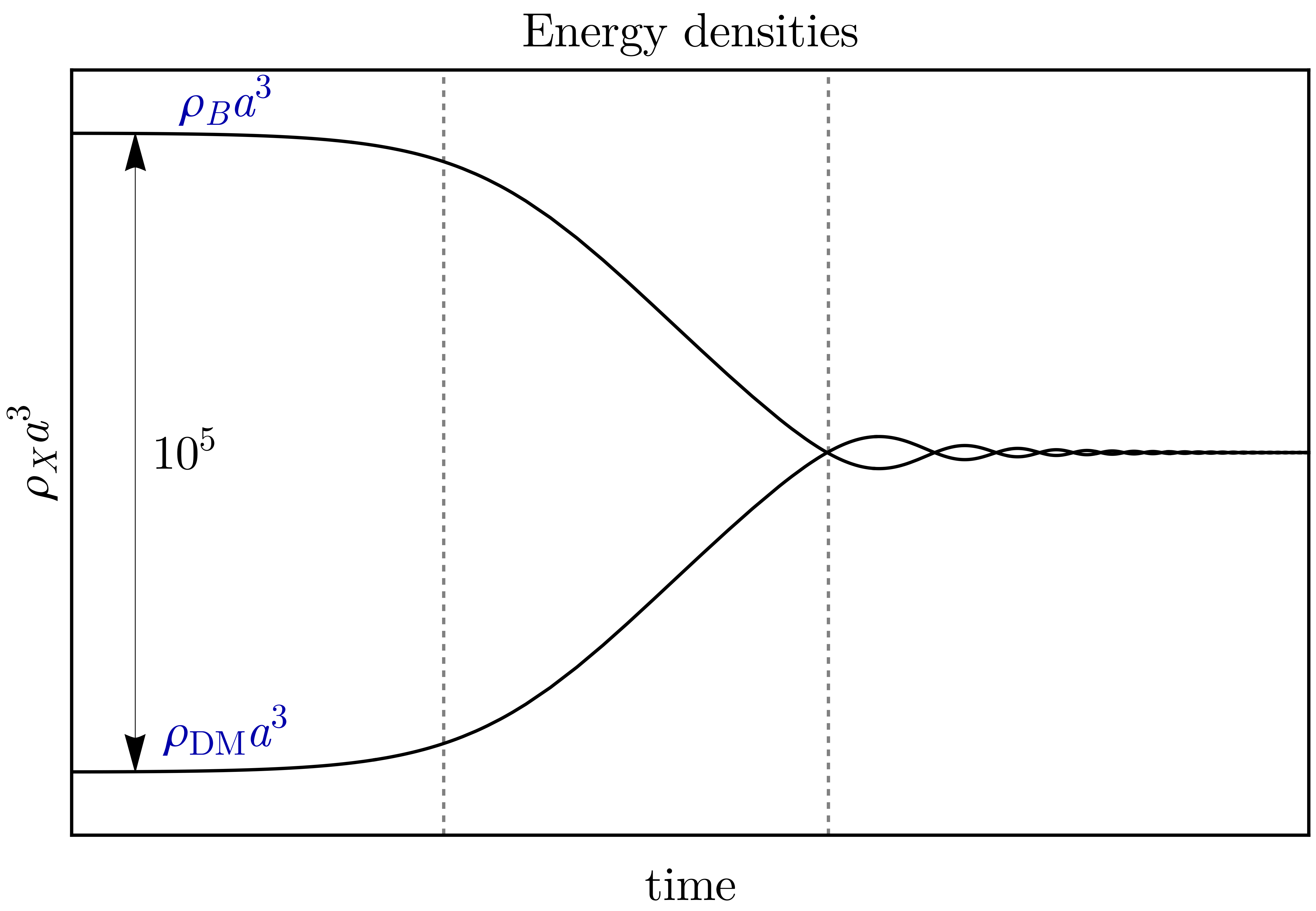
The goal



These models work only if $m_{DM} \sim$ GeV

Our goal was to find a dynamical mechanism that works for arbitrary DM mass.

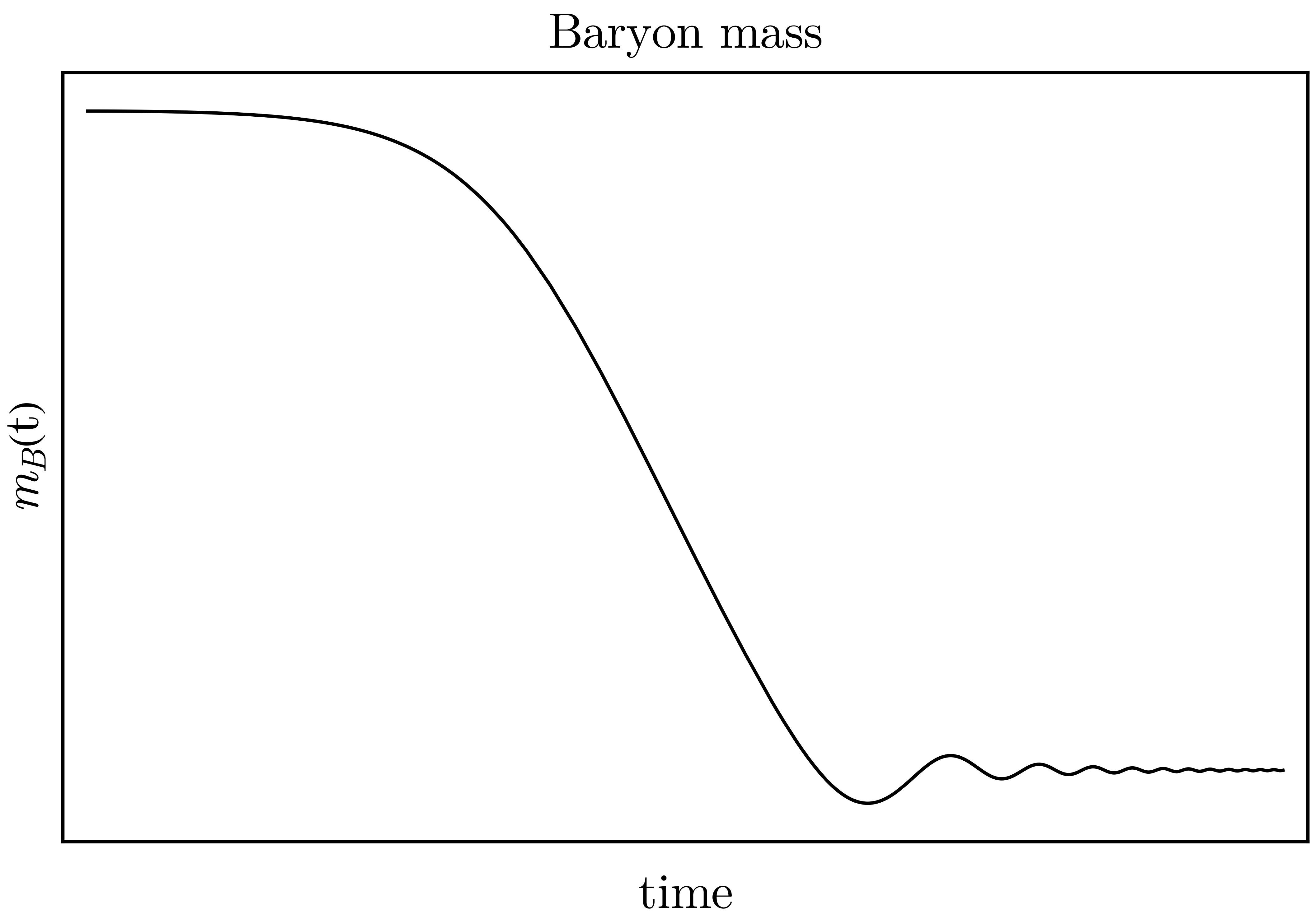
Here, energy densities of DM and B can be vastly different. Then as the relaxation happens they become comparable.

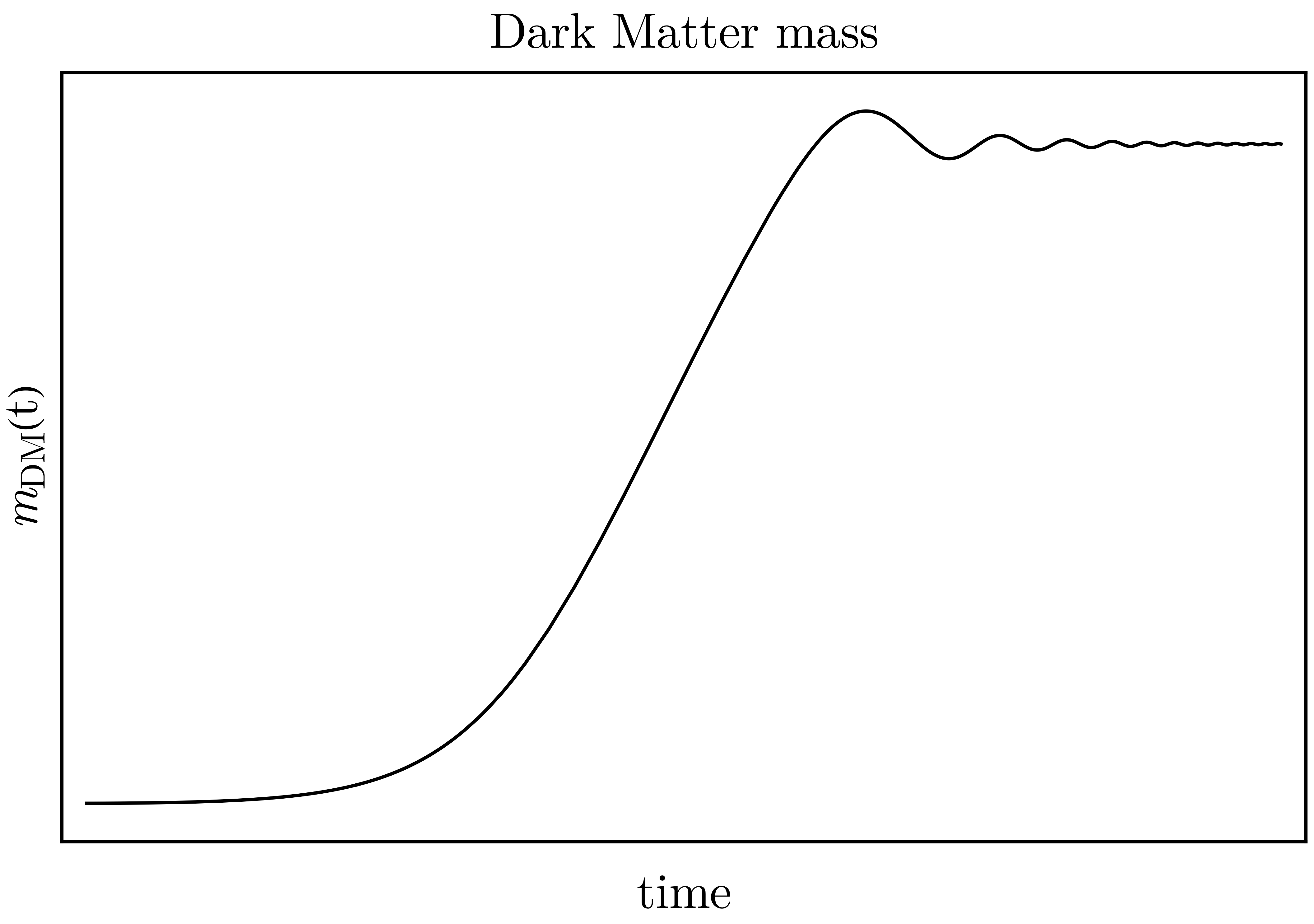
Checklist

- Toy model
- More realistic model
- Example
- Bounds and signals

The mechanism

We achieve this by introducing a scalar that controls masses of Baryons and Dark Matter. If Baryon mass decreases, the DM mass goes up and vice versa.





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Potential

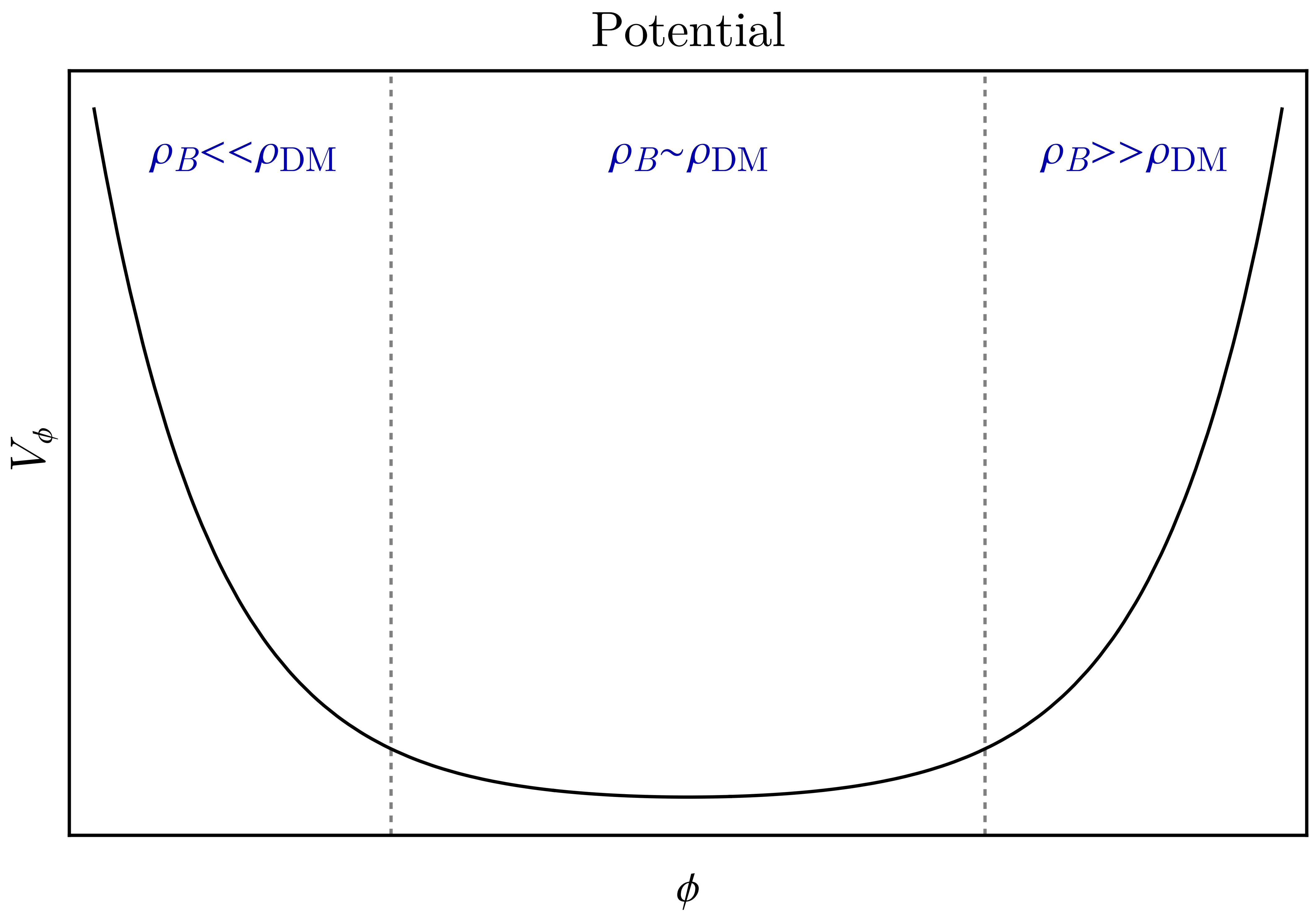
We require baryons and dark matter to be non-relativistic and the evolution of the scalar to be governed by a finite density effective potential

$$V = m_B(\phi)n_B + m_{DM}(\phi)n_{DM}$$

$$m_X = m_X(0)e^{\pm c\phi/f}$$

$$fV'(\phi) = c_B\rho_B(\phi) - c_D\rho_{DM}(\phi) = 0$$

$$\rho_{DM}/\rho_B = c_B/c_D \sim O(1)$$



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EFT

For simplicity we assume that DM is an ALP of the dark sector

$$\mathscr{L} \supset \frac{\phi}{f}\frac{c_B\beta_B}{32\pi^2}G_B^2 - \frac{c_D\beta_D}{64\pi^2}G_D^2, \text{ where } \beta = \frac{11}{3}N_c - \frac{2}{3}N_f$$

$$\frac{1}{g_B^2} \to \frac{1}{g_B^2} - \frac{c_B\beta_B}{8\pi^2}\frac{\phi}{f}$$

Dimensional transmutation $m_p \propto \Lambda_{QCD} \propto e^{-\frac{8\pi^2}{\beta g^2}} \propto e^{\frac{c_B\phi}{f}}$

Similarly, $m_{DM} \propto \Lambda_D^2 \propto e^{-\frac{16\pi^2}{\beta_D g_D^2}} \propto e^{-\frac{c_D\phi}{f}}$

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Evolution

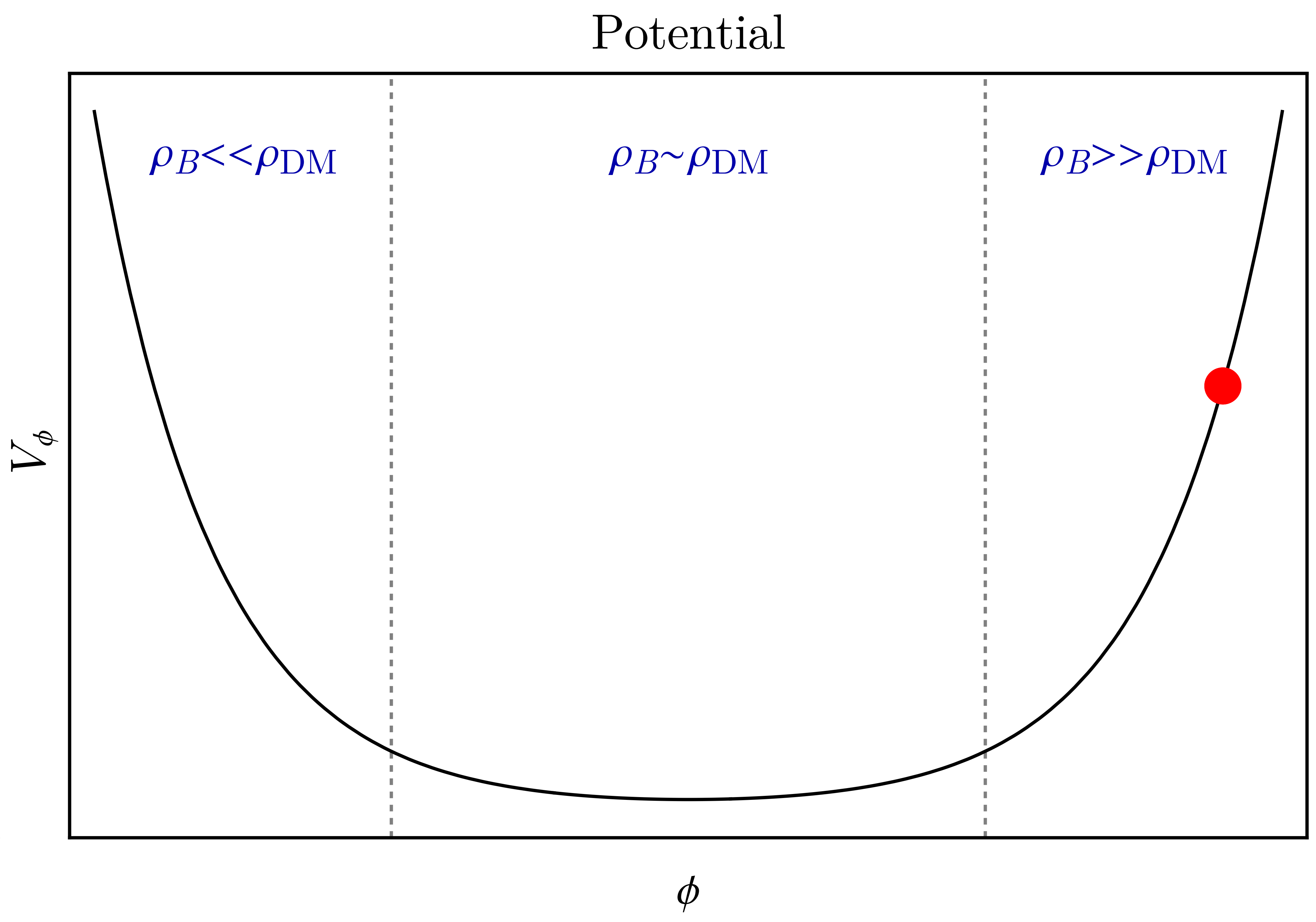
We focus on scenario when initially $\rho_B \gg \rho_{DM}$ and the universe is in RD

Then, the early evolution is dictated by baryons

$$\ddot{\phi} + 3H\dot{\phi} + \frac{c_B \rho_B(0)}{f} e^{c_B \phi/f} = 0$$

$$m_\phi^2 = \frac{c_B^2 \rho_B(0)}{f^2} e^{c_B \phi/f}$$

We have two distinct regimes that depend on the initial value of m_ϕ / H



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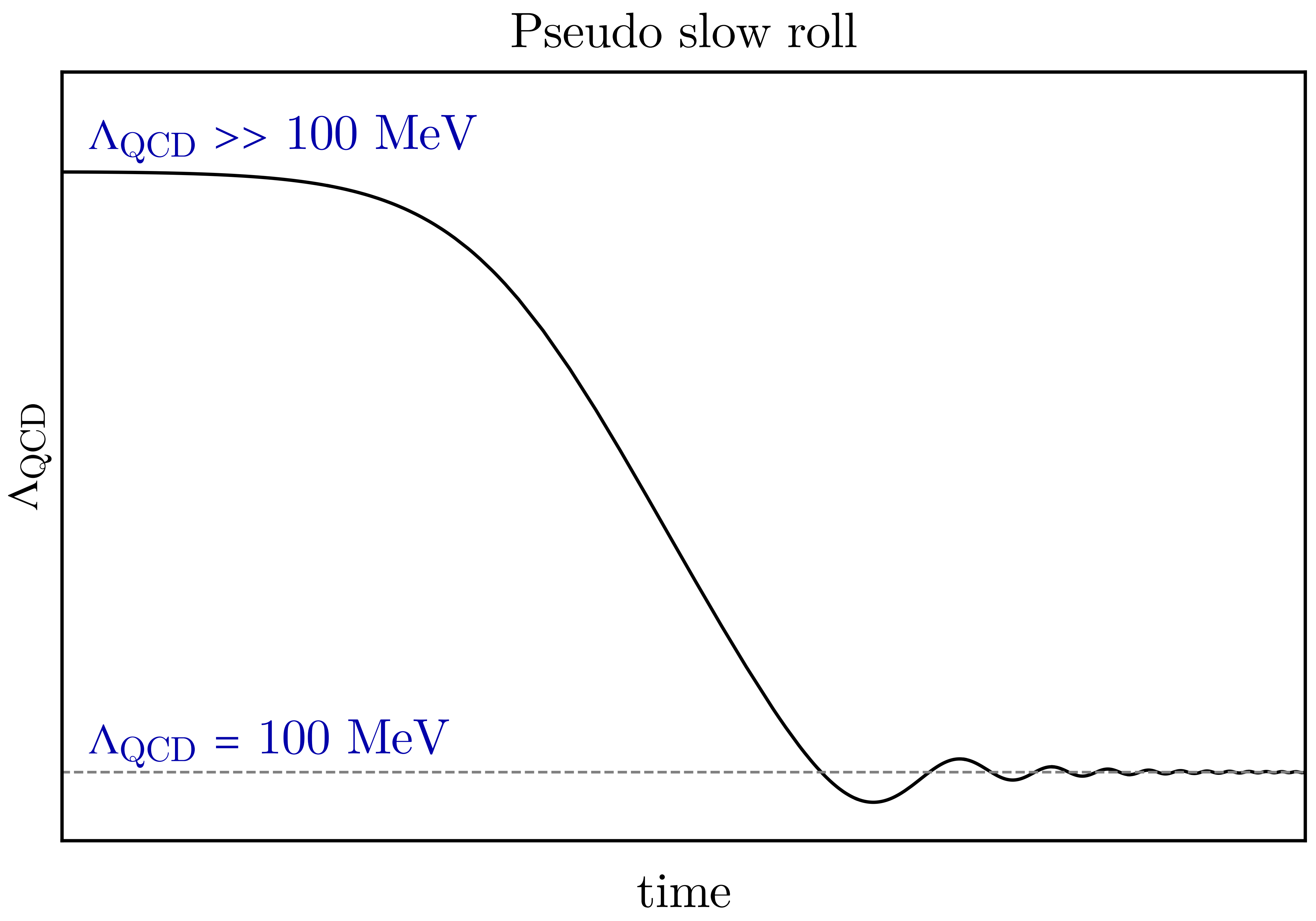
$m_\phi(\phi) \ll H(T)$

Here, the scalar is initially frozen at some initial value

Once $m_\phi(\phi) \approx H(T)$ the field starts rolling down

When it reaches the minimum its kinetic energy is has mostly redshifted away and subsequent oscillations change baryon and DM masses marginally



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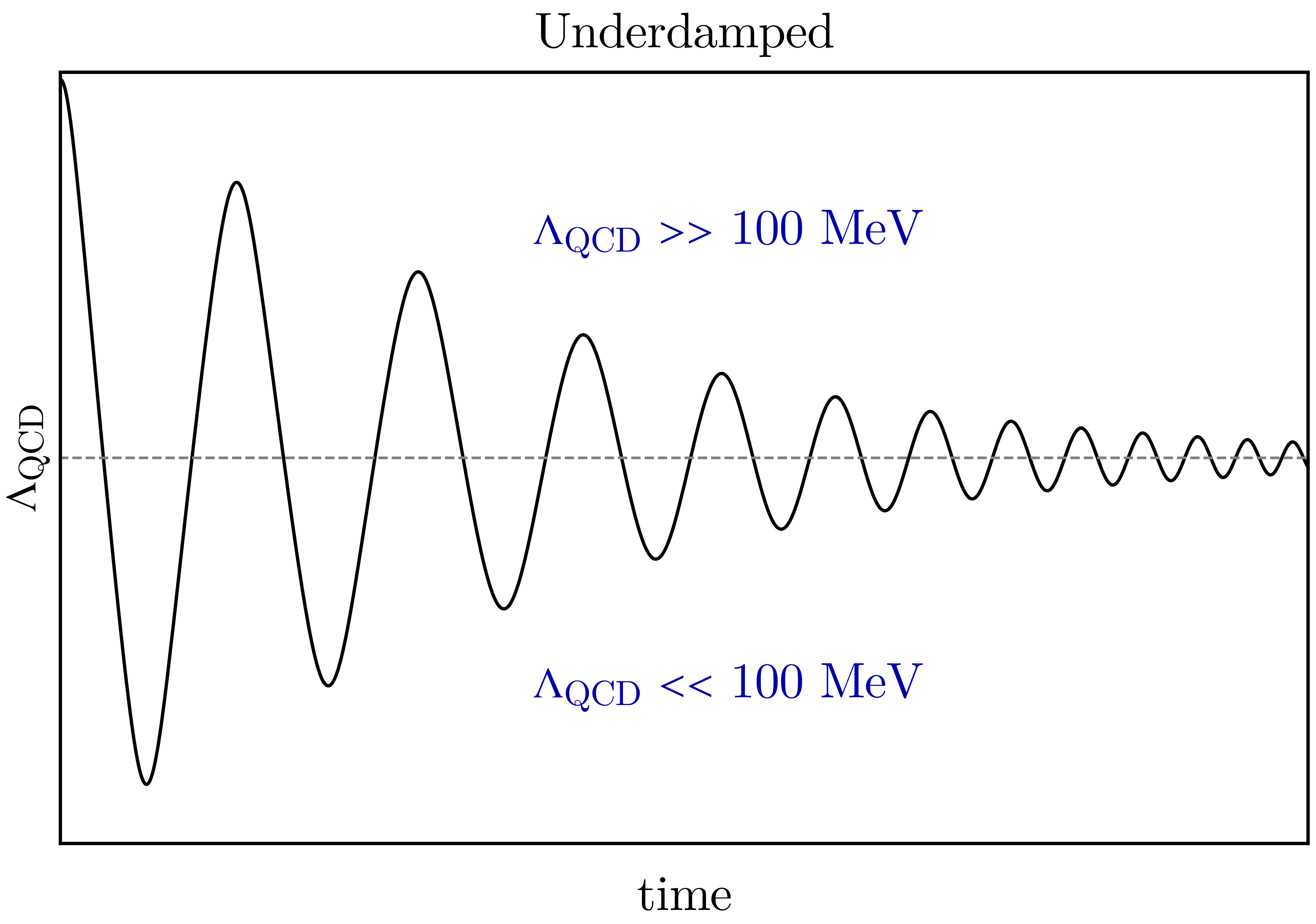
$m_\phi(\phi) \gg H(T)$

The scalar oscillates from the beginning with large amplitude

This can make protons much lighter than 1GeV which can invalidate non-relativistic assumption

For that reason we will not discuss it further



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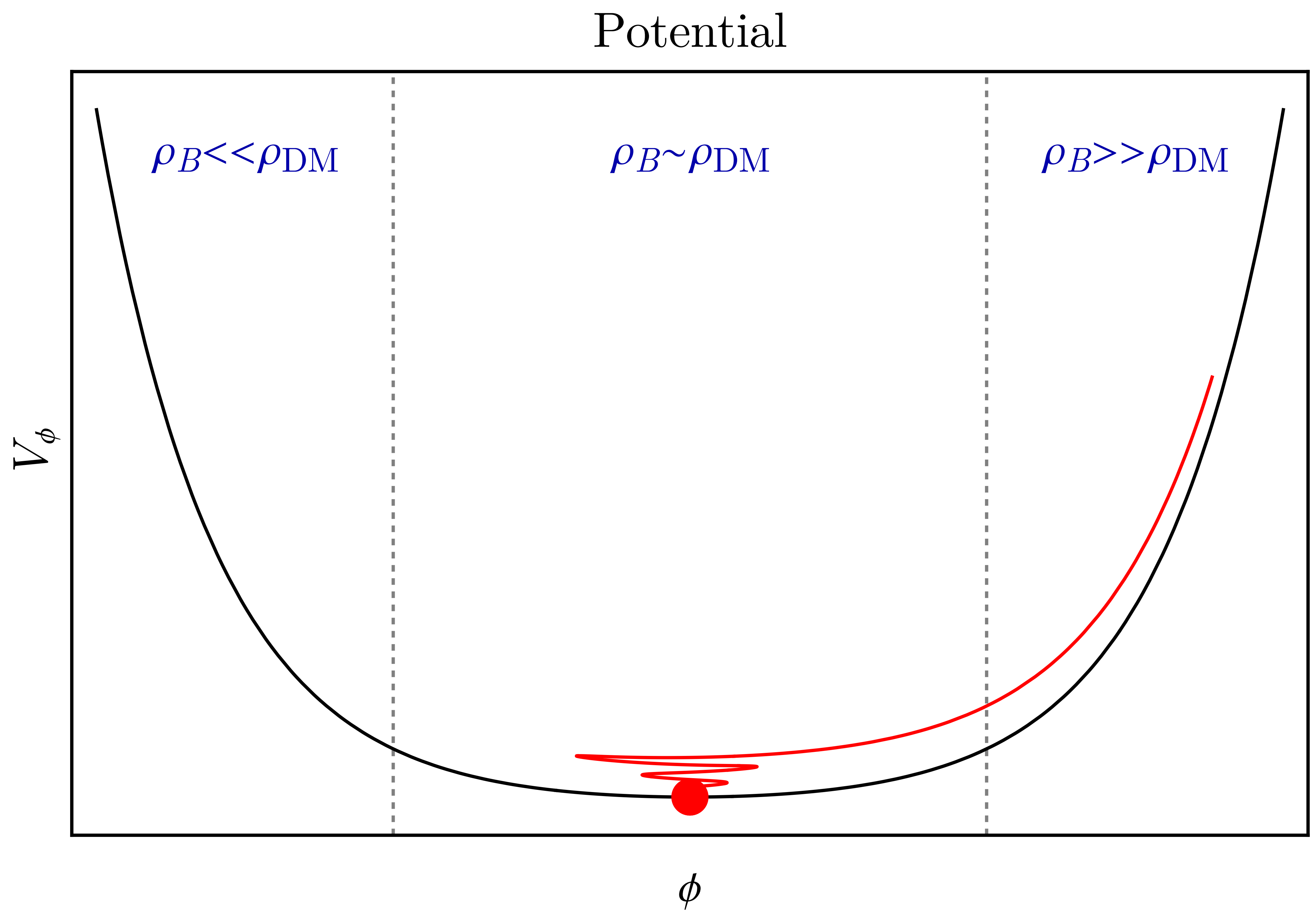
Summary so far

Underdamped initial condition can lead to protons becoming relativistic which would alter the potential

Overdamped initial condition allows for $\Lambda_{QCD} \gg 100$ MeV while preventing protons to become relativistic as the field relaxes towards the minimum



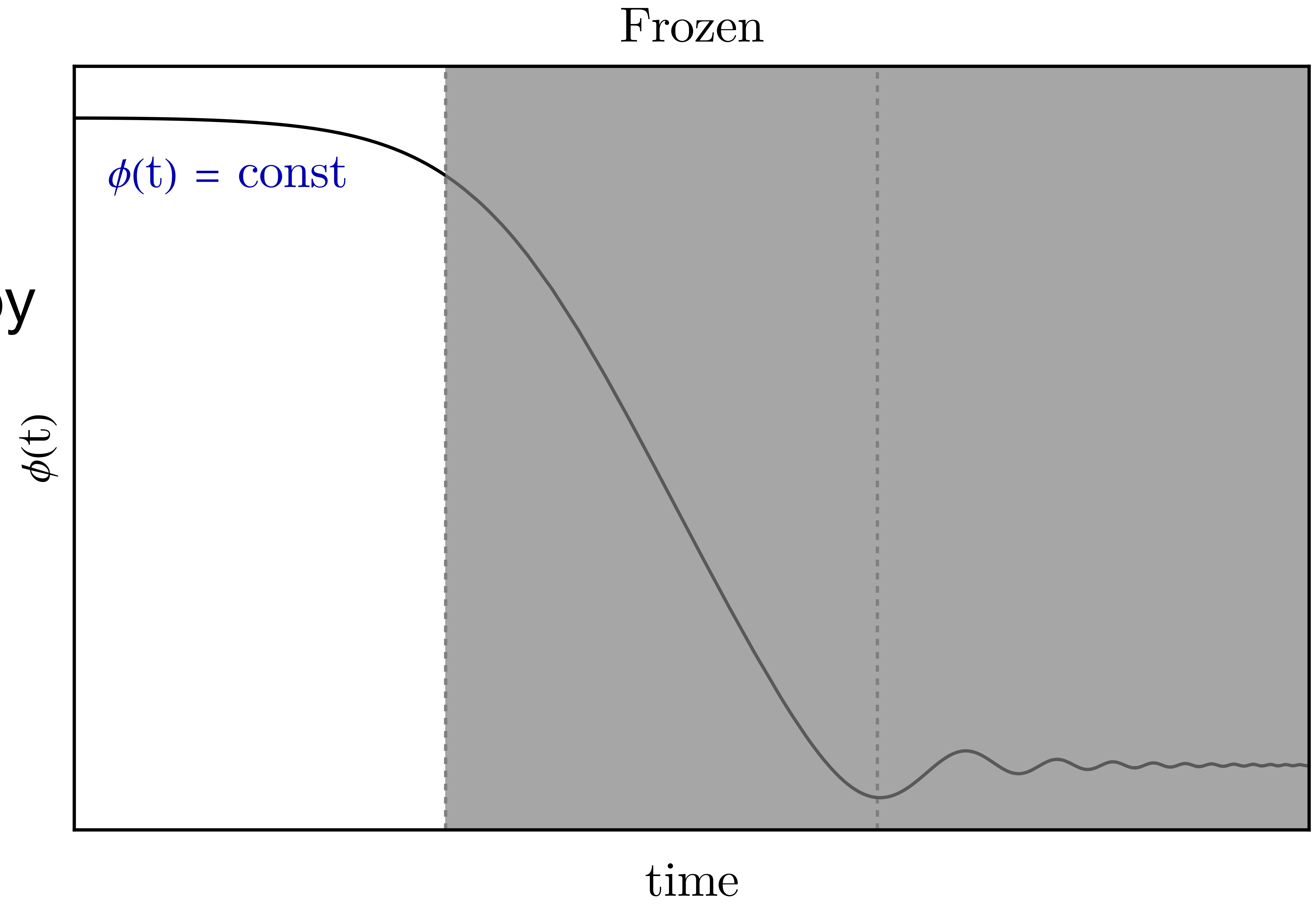
$m_\phi(\phi) \ll H(T)$: Frozen phase

Throughout this talk we will be assuming RD.

Initially the evolution is dominated by Hubble friction

$$\ddot{\phi} + 3H\dot{\phi} \approx 0$$

$$\phi(t) = \text{const}$$



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$m_\phi(\phi) \ll H(T)$: Pseudo slow roll phase

$$\ddot{\phi} + 3H\dot{\phi} + \frac{c_B \rho_B(0)}{f} e^{c_B \phi / f} = 0$$

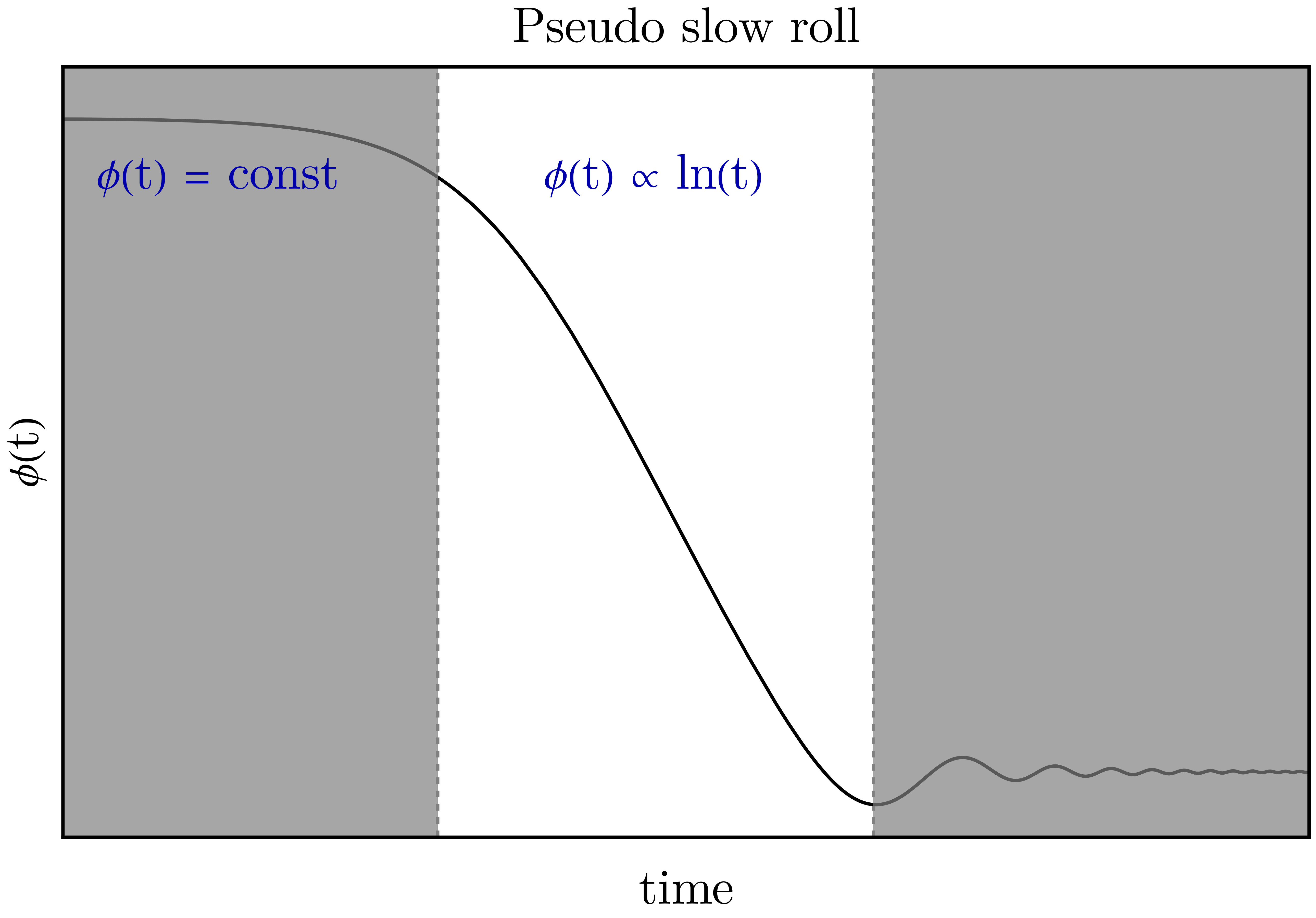
The field value changes logarithmically in time

$\phi \propto \ln t$

We can use this observation to find how Baryon mass changes

$$\ddot{\phi} + 3H\dot{\phi} \propto t^{-2} \rightarrow \frac{c_B \rho_B(0)}{f} e^{c_B \phi / f} \propto t^{-2}$$

$$m_B \propto e^{c_B \phi / f} \propto t^{-1/2} \propto a^{-1} \propto T$$



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$m_\phi(\phi) \ll H(T)$: Pseudo slow roll phase

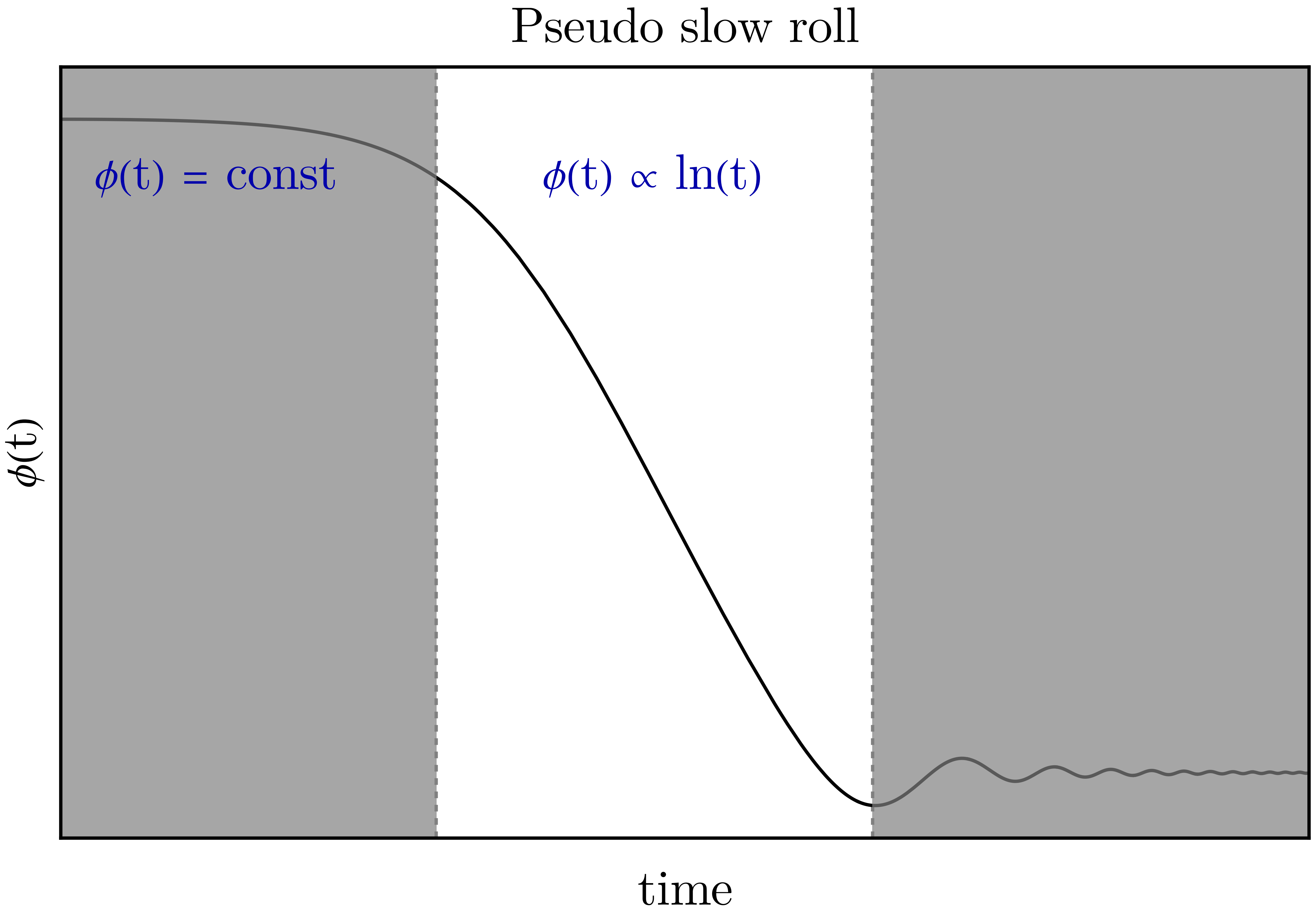
Amusingly, we can find exact trajectory the field follows by changing variables in the EOM to

$$x(t) = \frac{a(t)}{a(t_i)} e^{\frac{c_B \phi}{f}}$$

Since this quantity is constant during this phase, all we have to do is to find a static solution which reads

$$x(t) = \frac{f^2 H(t_i)^2}{c_B^2 m_B(0) n_B(t_i)} \rightarrow m_\phi(\phi) = H(T)$$

This means that once field starts rolling its mass will equal Hubble until it reaches minimum. As a result this phase is independent of initial conditions!



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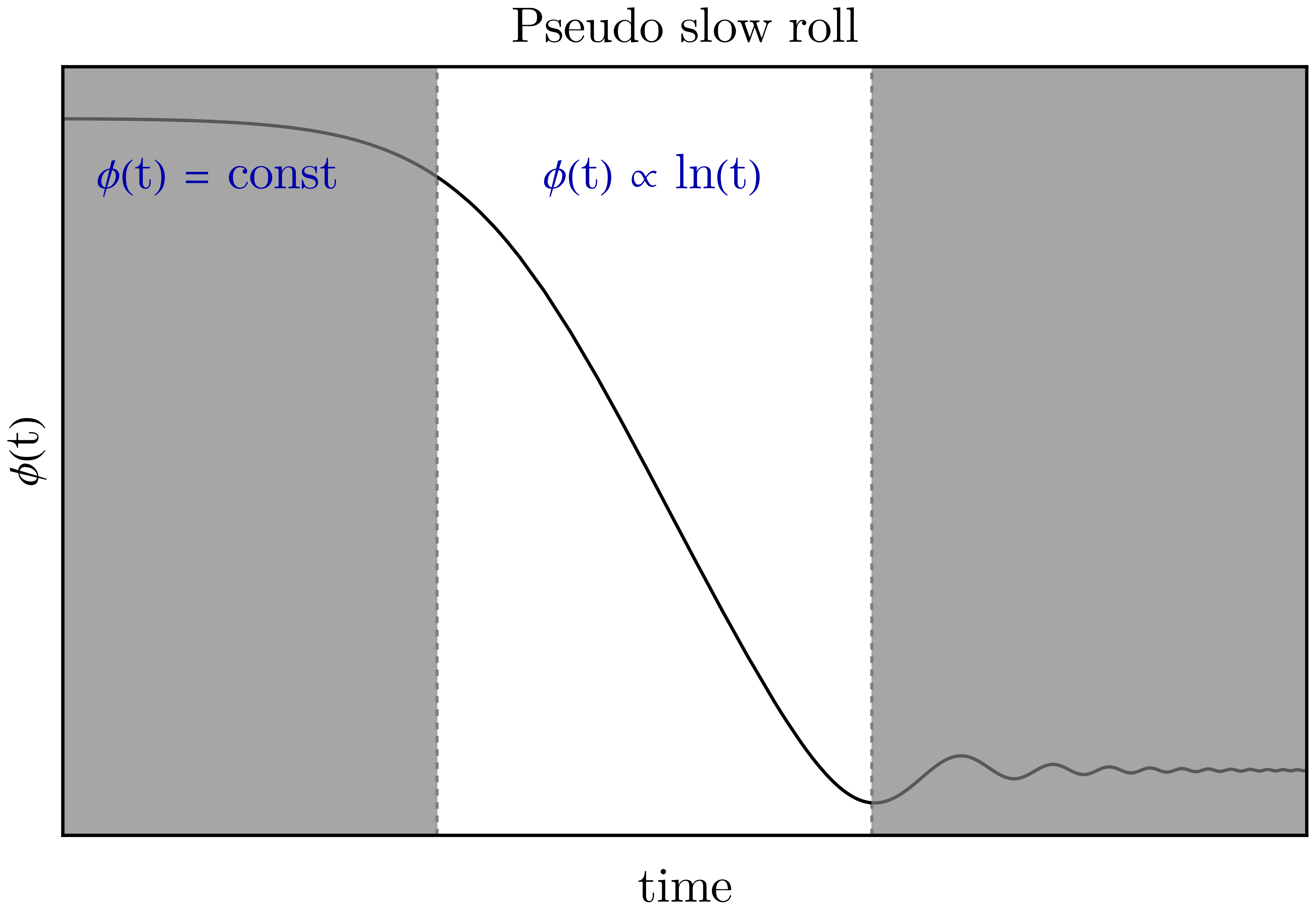
$m_\phi(\phi) \ll H(T)$: Pseudo slow roll phase

To summarize here are the most important results

1. $m_B \propto \Lambda_{QCD} \propto a^{-1}$

2. $\rho_B \propto a^{-4}$

3. $m_\phi(\phi) = H(T)$



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$m_\phi(\phi) \ll H(T)$: Oscillation phase

Here, the field undergoes small oscillations around the minimum. We can use adiabatic invariant to understand the field evolution

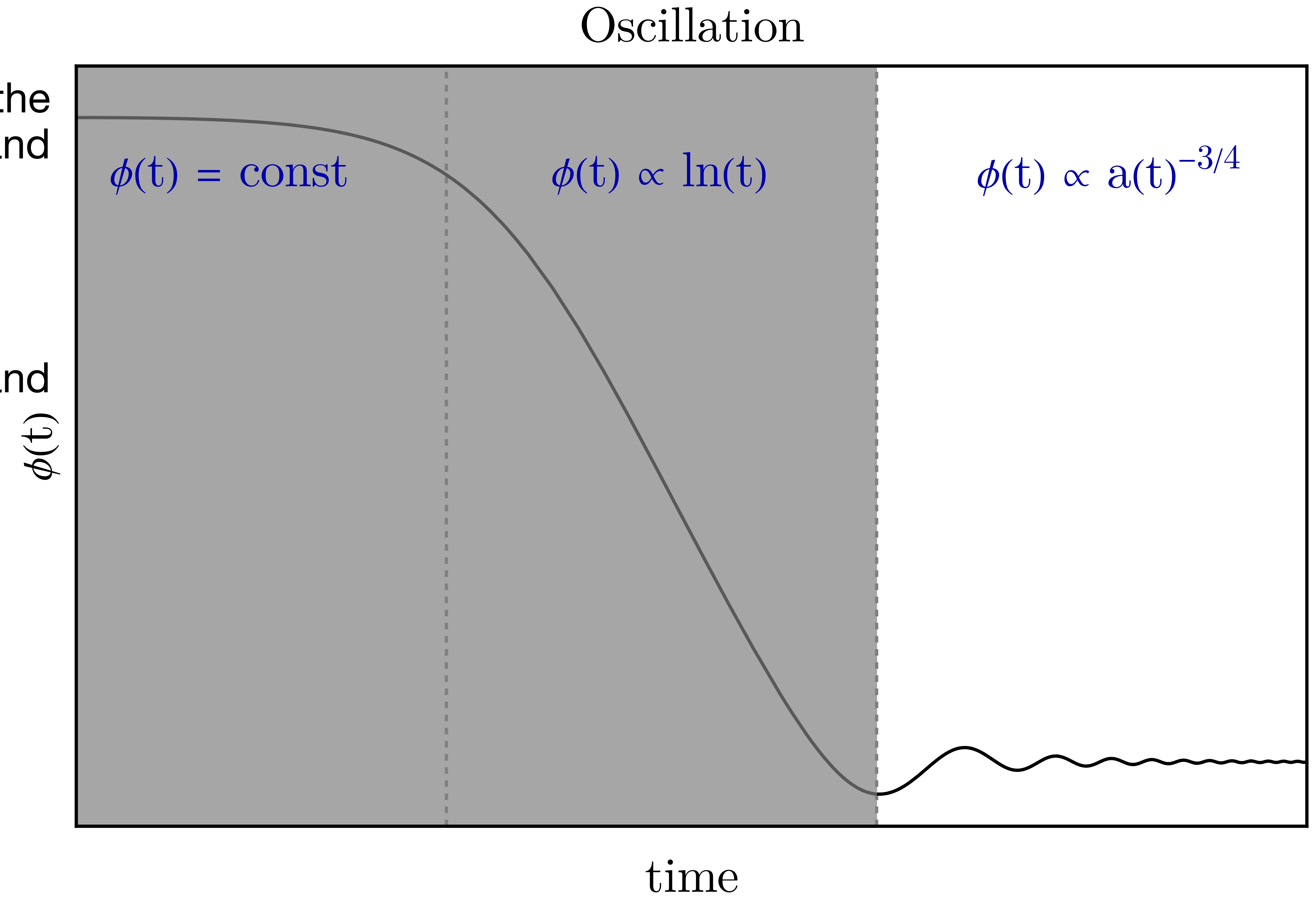
$$n_\phi a^3 = m_\phi \phi^2 a^3 = \text{const}$$

Mass depends on the linear combination of baryon and DM densities. Since both are non-relativistic we get

$$m_\phi^2 = \frac{c_B^2}{f^2}\rho_B(0) + \frac{c_D^2}{f^2}\rho_{DM}(0) \propto a^{-3}$$

$$\phi \propto m_\phi^{-1/2} a^{-3/2} \propto a^{-3/4}$$

$$\rho_\phi = m_\phi n_\phi \propto a^{-4.5}$$



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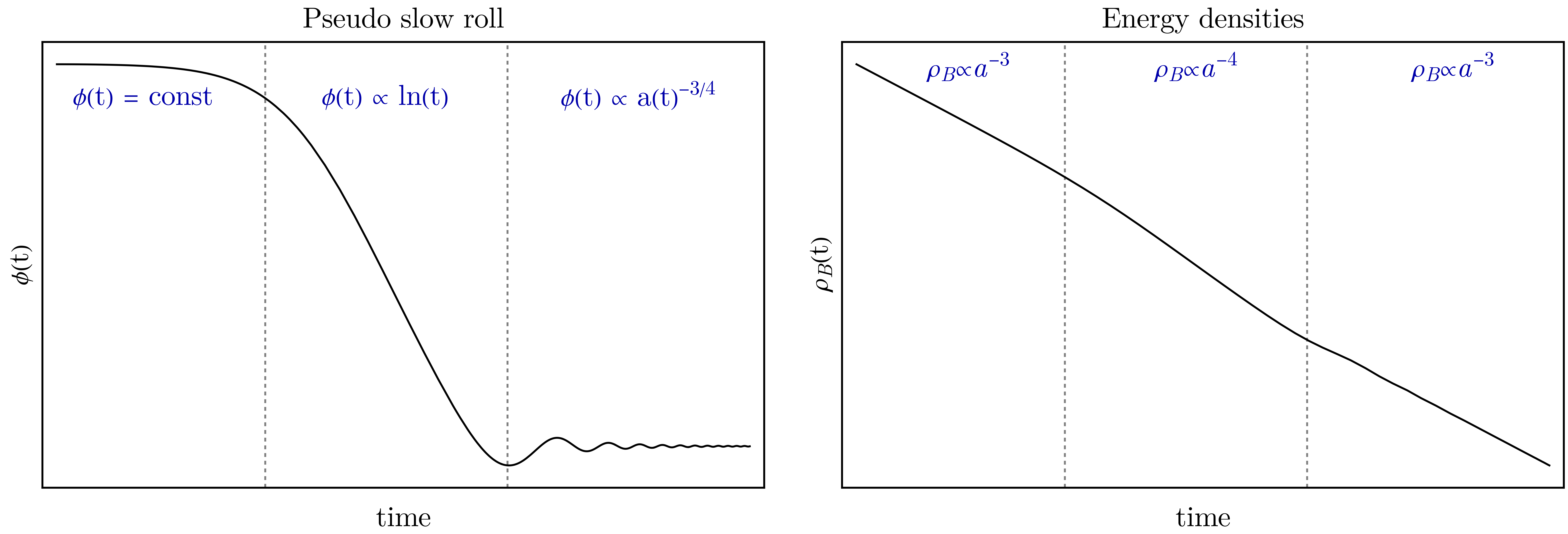
$m_\phi(\phi) \ll H(T)$: Summary



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Does the scalar overclose the universe?

Slow roll regime allows us to make precise prediction about the energy of the scalar

$$\rho_\phi = \frac{\dot{\phi}^2}{2} \propto t^{-2} \propto a^{-4} \propto \rho_B$$

We can find the ratio of these energies semianalytically $\rho_\phi/\rho_B \leq 1/2$

As the field reaches the minimum it undergoes small oscillations and its energy redshifts as $\rho_\phi = m_\phi n_\phi \propto n_B^{1/2} n_\phi \propto a^{-4.5}$

Checklist

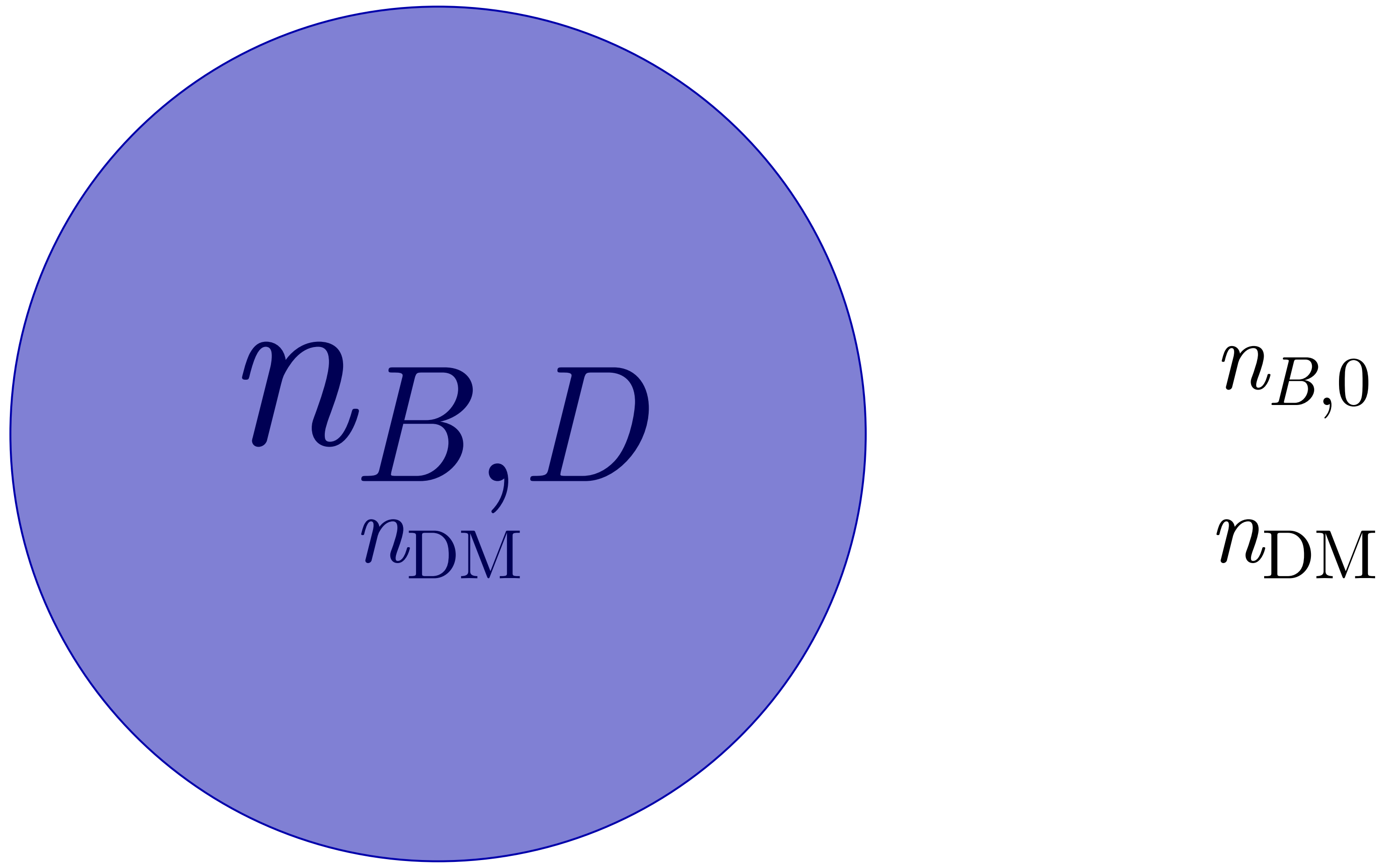
- Toy model ☑️
- More realistic model
- Example
- Bounds and signals

How to make it happen

Main challenges to overcome:

1. Finite density effects today
2. SM bath contribution to the potential

Macroscopic objects



The potential we are considering is very sensitive to finite density effects. In particular it has vastly different minima in the vacuum and inside dense objects.

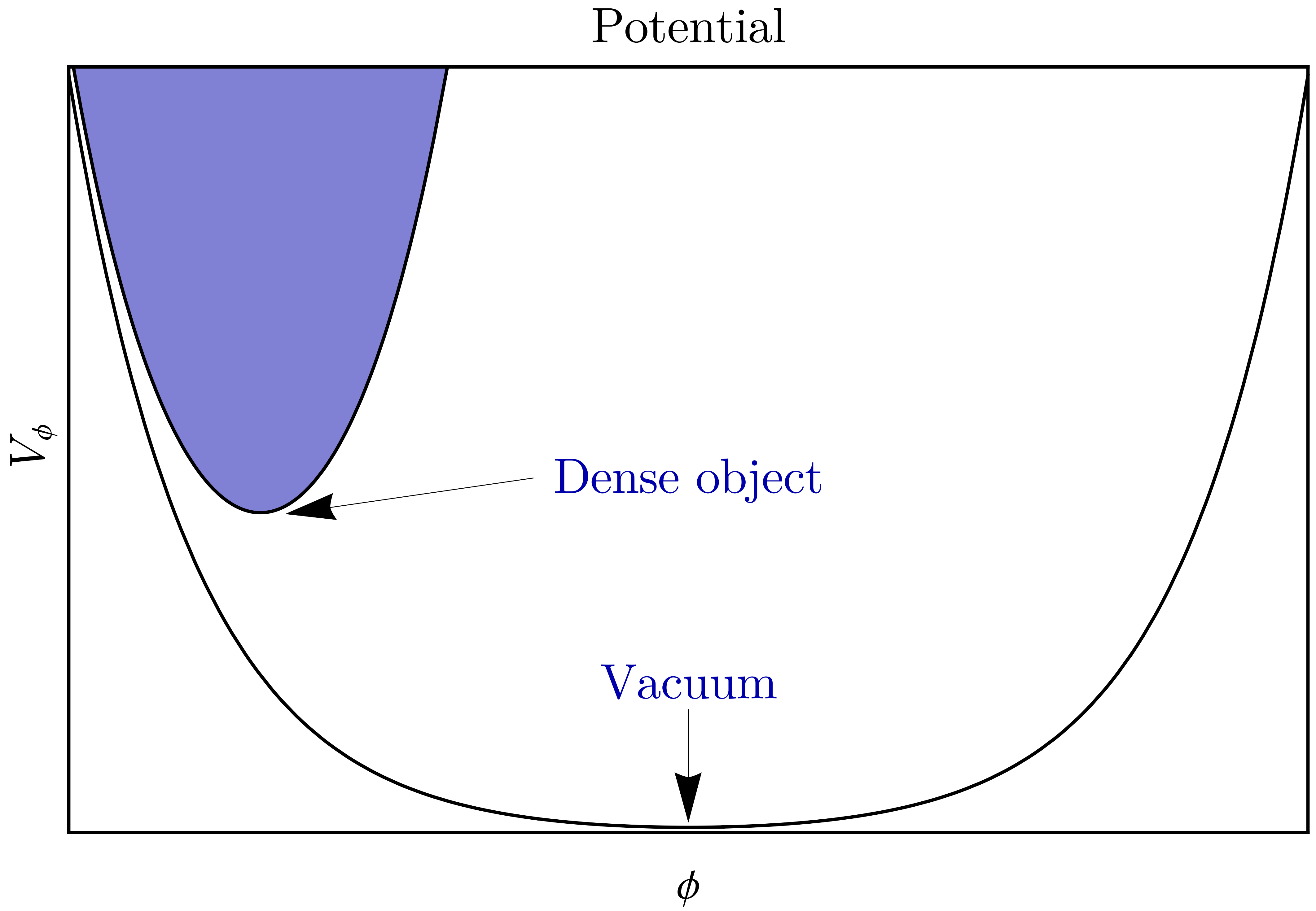
Vacuum

$$V = m_B(0) n_{B,0} e^{\frac{c_B \phi}{f}} + m_{DM}(0) n_{DM} e^{-\frac{c_D \phi}{f}}$$

Inside dense object

$$V = m_B(0) n_{B,D} e^{\frac{c_B \phi}{f}} + m_{DM}(0) n_{DM} e^{-\frac{c_D \phi}{f}}$$

As a result baryons would be much lighter on earth than in the vacuum!



Solution

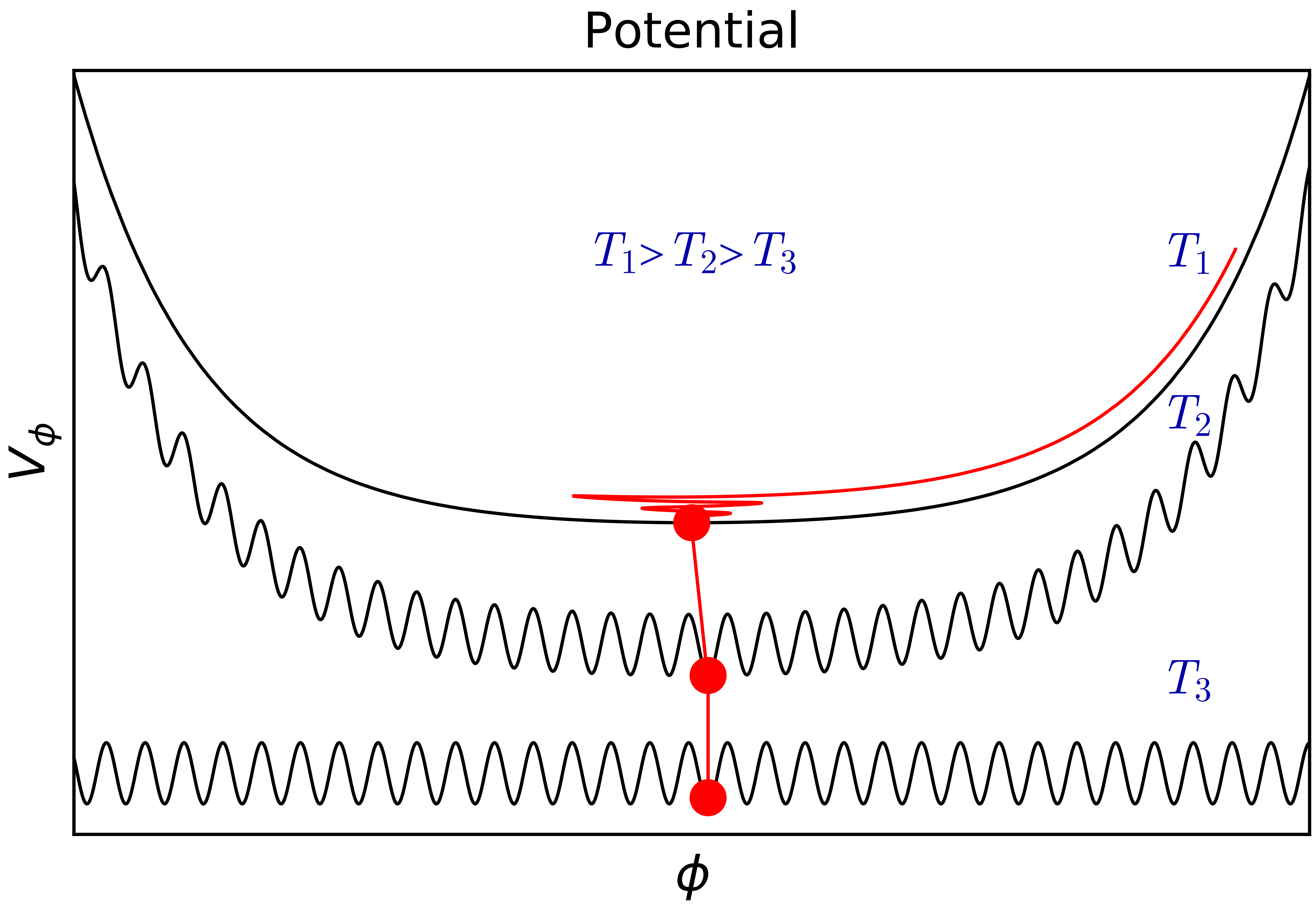
We solve this problem by introducing vacuum potential that becomes important once the scalar reaches the minimum

$$V_0 = \Lambda_0^4 \cos \frac{\phi}{F} + \theta$$

Once this happens, the scalar becomes a subdominant component of DM
$\rho_\phi \propto a^{-3}$

Vacuum potential

In order to preserve $\rho_B \sim \rho_{DM}$
we require $F \lesssim f/c$



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Vacuum potential

The most dense object that we need to consider are neutron stars
$\rho_{NS} \sim (100 \text{ MeV})^4$

In order for the vacuum potential to solve the problem we need

$$V_0' > V_{NS}' \to \Lambda_0 > \frac{c_B F}{f} \rho_{NS}^{\;1/4}$$

How to make it happen

Main challenges to overcome:

1. Finite density effects today ☑️
2. SM bath contribution to the potential

Coupling to photons

We expect quantum corrections to generate coupling to photons

$$\mathscr{L} \supset \frac{\phi}{f}\frac{c_B\beta_B}{32\pi^2}G_B^2 + c_\gamma F^2$$

We can estimate the coupling by RG evolving through confinement

$$\frac{d}{d\ln\mu}\alpha^{-1}|_{\mu>4\pi\Lambda_{QCD}} = \frac{\beta_\gamma^{3\text{ flavor}}}{2\pi} + \cdots \quad \text{and} \quad \frac{d}{d\ln\mu}\alpha^{-1}|_{\mu<4\pi\Lambda_{QCD}} = \frac{\beta_\gamma^{\pi,K}}{2\pi} + \cdots$$

Coupling to photons

Since the QCD is exponentially sensitive to a change in scalar value, we get

$$\Delta\alpha^{-1} \sim \frac{\beta^{3\text{ flavor}} - \beta^{\pi,K}}{2\pi} \ln \Lambda_{QCD} \sim \frac{c_B \phi}{2\pi f}$$

Thus, we see that $c_\gamma \sim O(1)\dfrac{c_B}{32\pi^2}$

SM bath

Correction to the free energy density due to EM interactions is given by

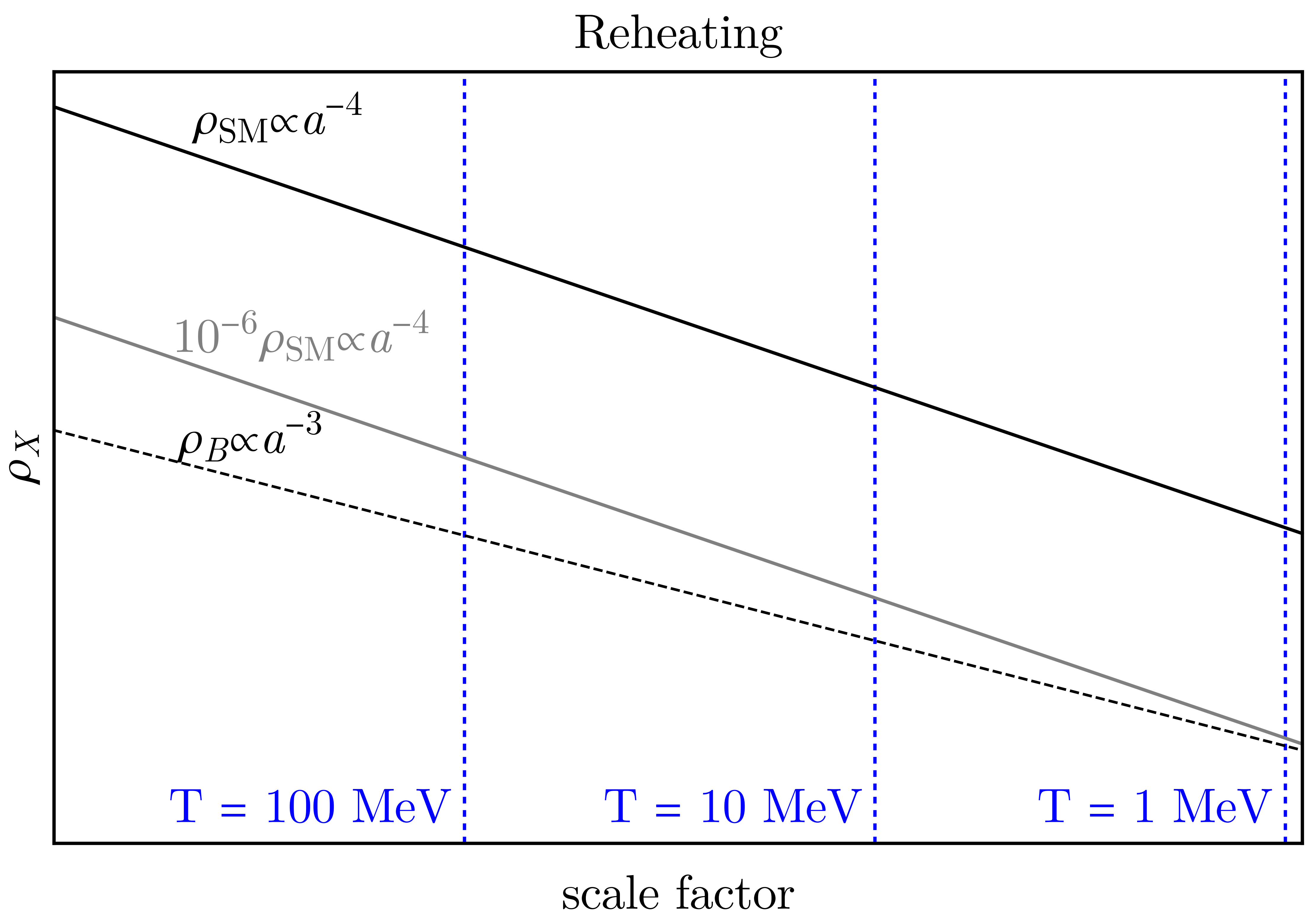
$$f_{EM} = \frac{5}{288} e^2(\phi) T^4 \sim 10^{-6} T^4 \frac{c_B \phi}{f}$$

While the Baryon contribution is

$$f_B = 6 \times 10^{-10} m_p(\phi) T^3 \frac{c_B \phi}{f}$$

The mechanism has to finish before BBN, but at $T \gtrsim 1$ MeV EM contribution dominates over baryons.

We are forced to consider other cosmology in order to make mechanism possible.



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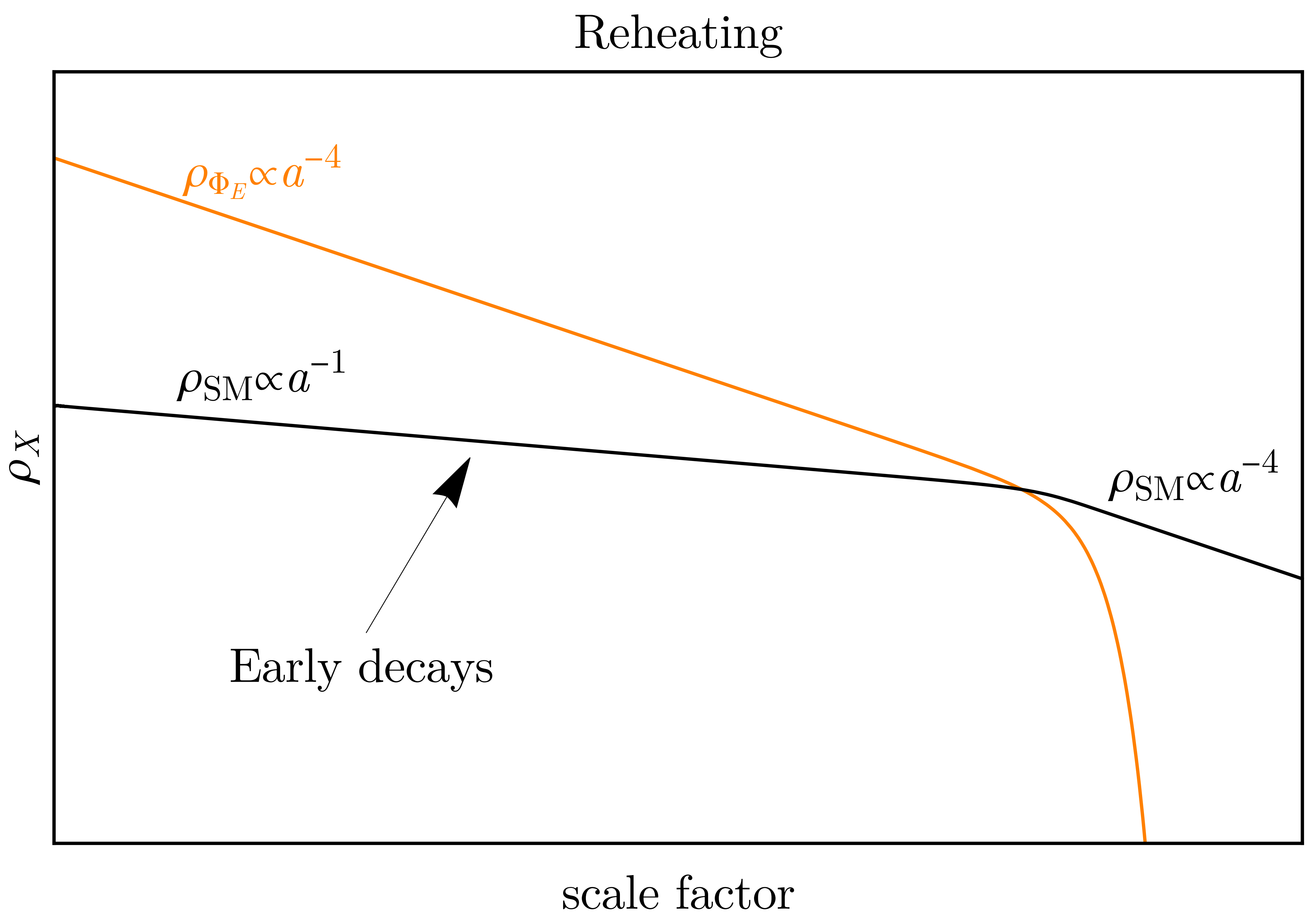
Entropy dump

We can evade this hiccup while keeping RD by introducing a relativistic scalar that dumps entropy into the SM through decays to Higgs

$$\mathscr{L}_E = \kappa \Phi_E H H^\dagger$$

In order to avoid detection at colliders we take its mass to be large, e.g.

$m_\Phi = 10$ TeV



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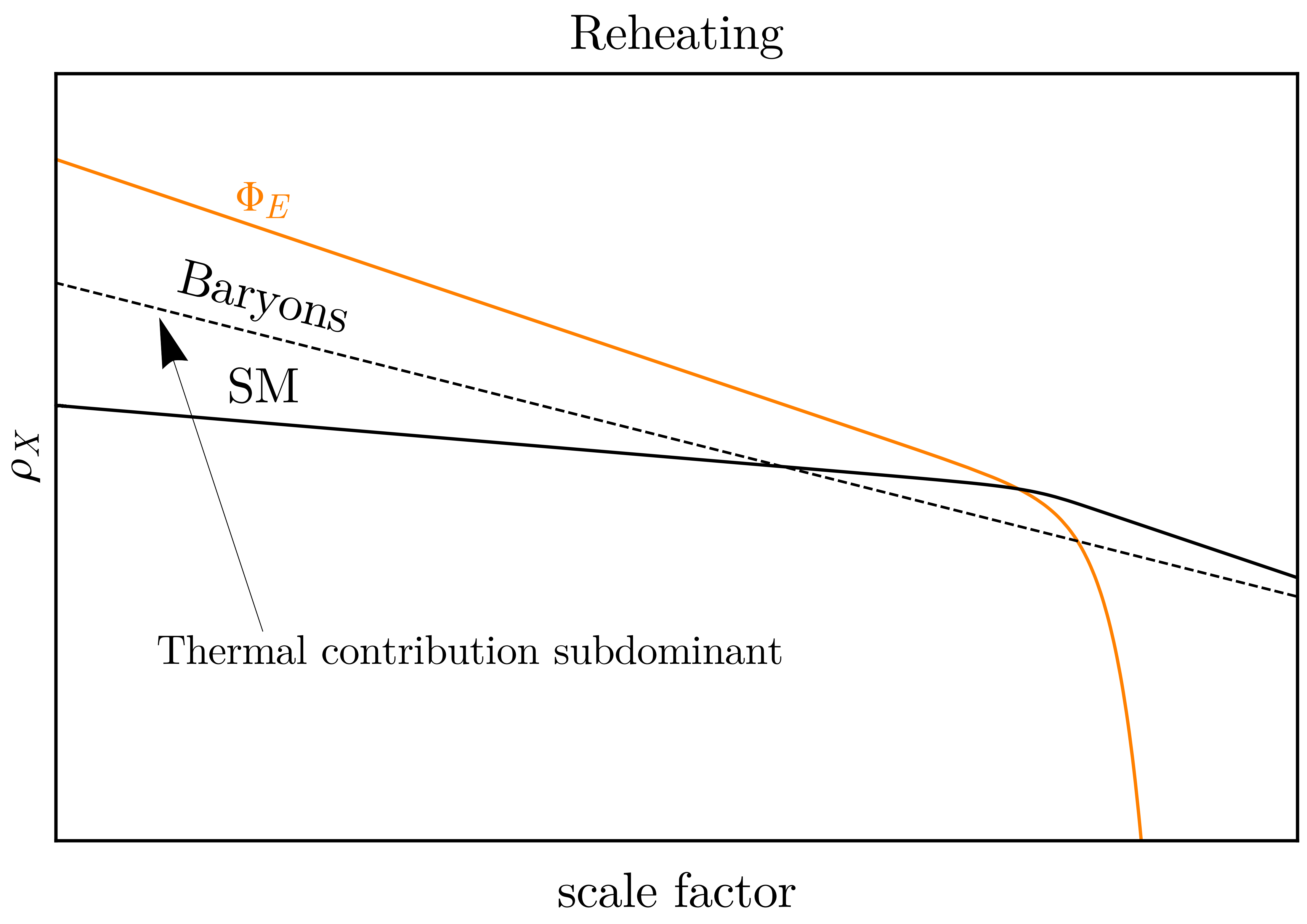
Initial conditions

We use initial conditions inspired by today, where non-relativistic baryons have more energy than the relativistic content of the SM

There are examples of Baryogenesis mechanisms that can generate such hierarchy, e.g. Affleck-Dine

As a result we avoid SM contribution from affecting the mechanism.



How to make it happen

Main challenges to overcome:

1. Finite density effects today ☑️
2. SM bath contribution to the potential ☑️

Checklist

- Toy model ☑️
- More realistic model ☑️
- Example
- Bounds and signals

Putting everything together

Initial conditions

$f/c_B = 10^{12}$ GeV

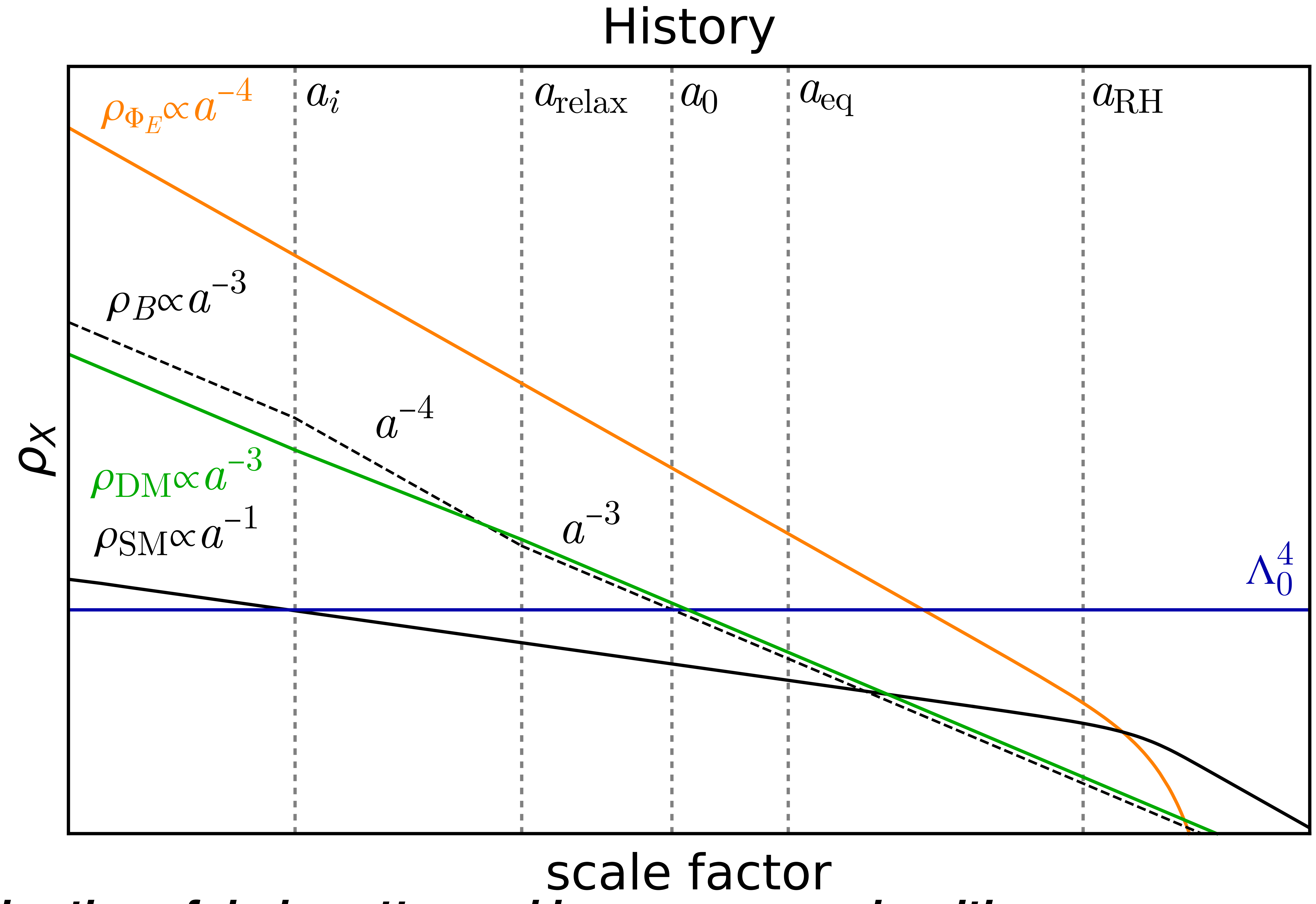
$c_B/c_D = 5$

$F = 3 \times 10^6$ GeV

$\Lambda_0 = 100$ MeV

$\rho_{DM}/\rho_B = 1/50$

$T_{rh} = 10$ MeV



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Putting everything together

Scalar starts rolling

$a_i = 10^{-7}$

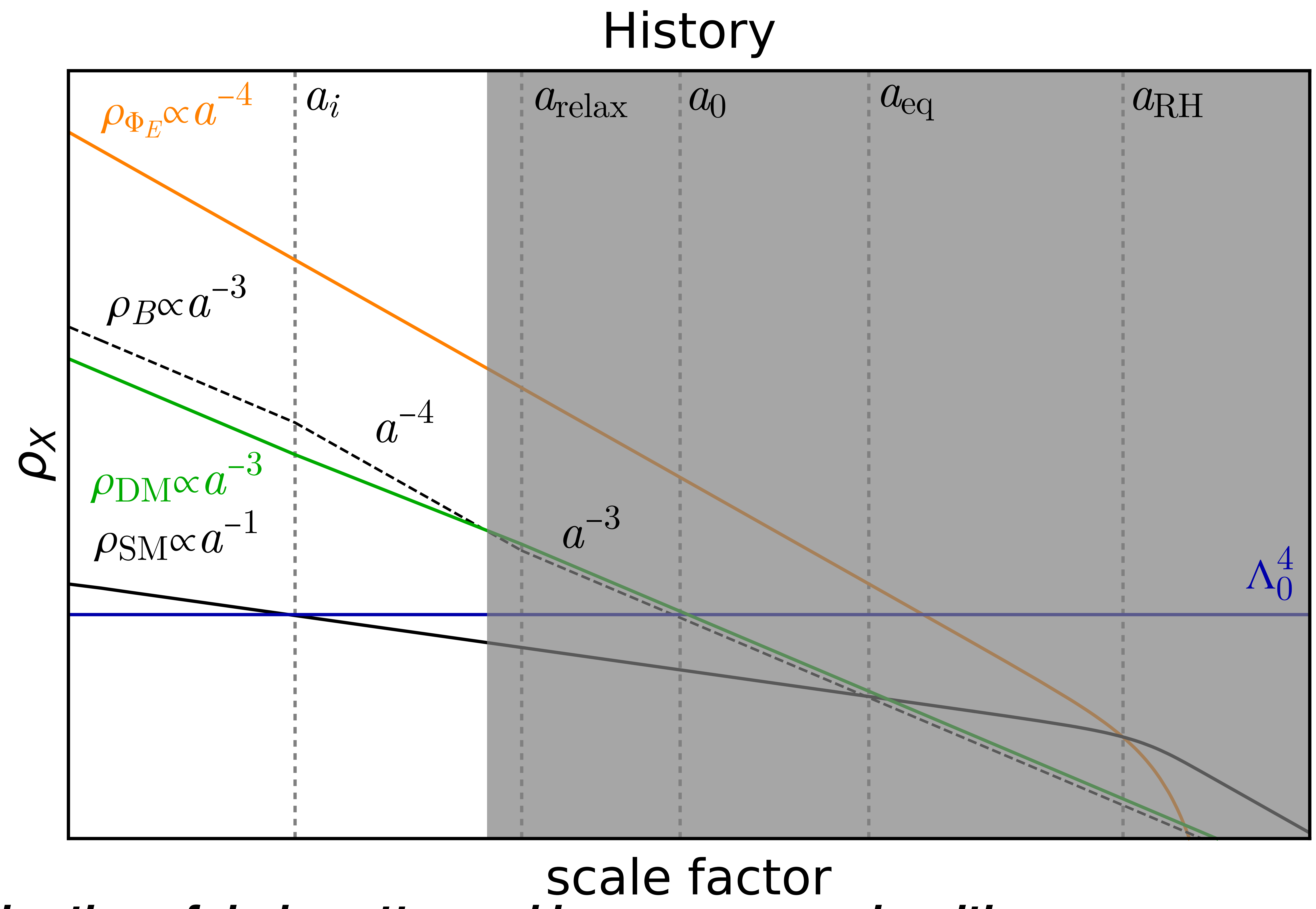
$\rho_{\Phi_E} = 10^8$ TeV^4

$\rho_{SM} = 10^{-1}$ GeV^4

$\rho_B = 2 \times 10^7$ GeV^4

$\rho_{DM} = \rho_B/50$

$m_p = 100$ GeV



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Putting everything together

Scalar falls into the minimum

$a_{\text{relax}} = 10^{-5}$

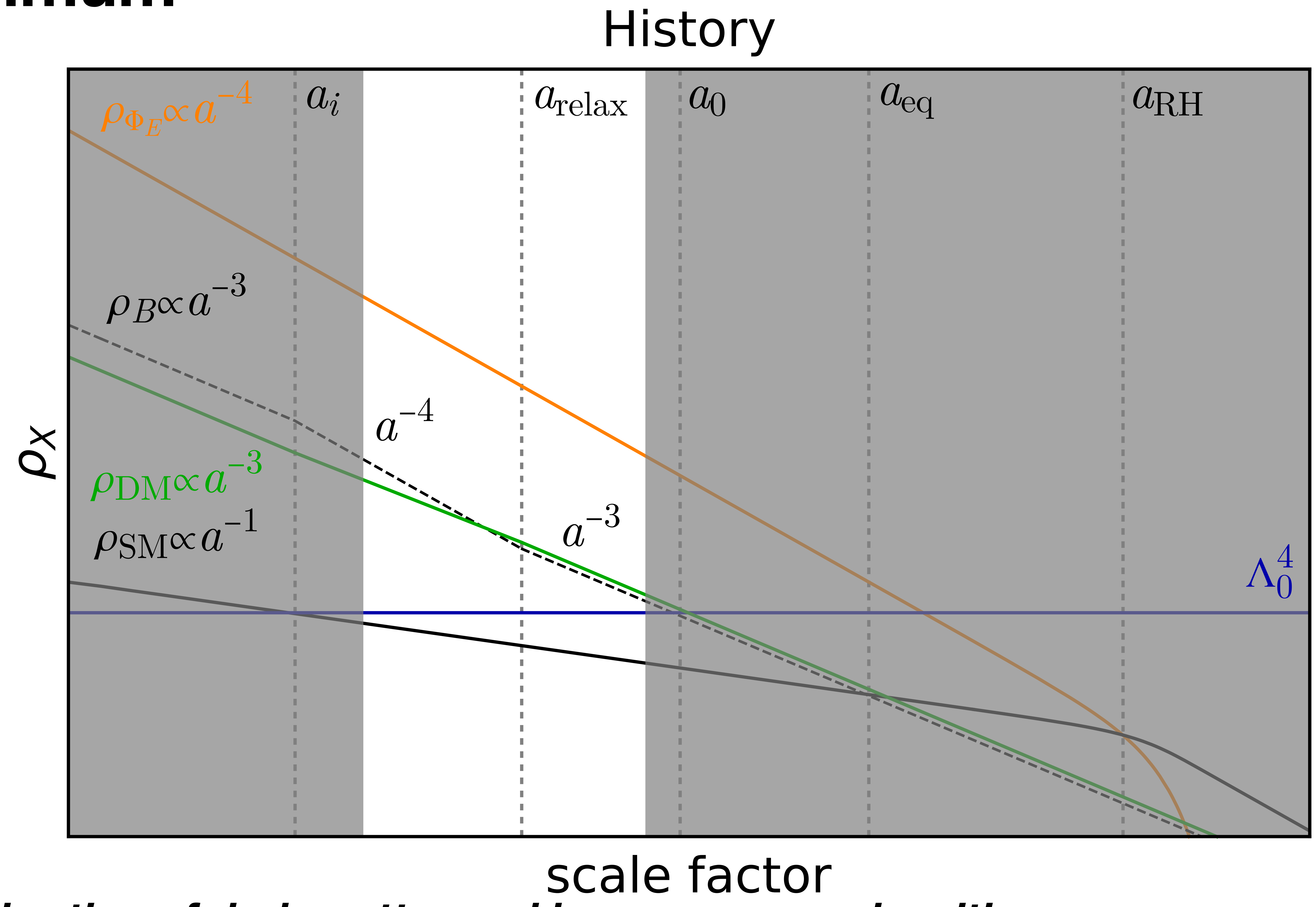
$\rho_{\Phi_E} = 1 \text{ TeV}^4$

$\rho_{SM} = 10^{-3} \text{ GeV}^4$

$\rho_B = 2 \times 10^{-1} \text{ GeV}^4$

$\rho_{DM} = 5\rho_B$

$m_p = 1 \text{ GeV}$



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Putting everything together

Vacuum potential (a_0) and SM bath (a_{eq}) become important

$$a_0 \approx a_{eq} = 10^{-4}$$

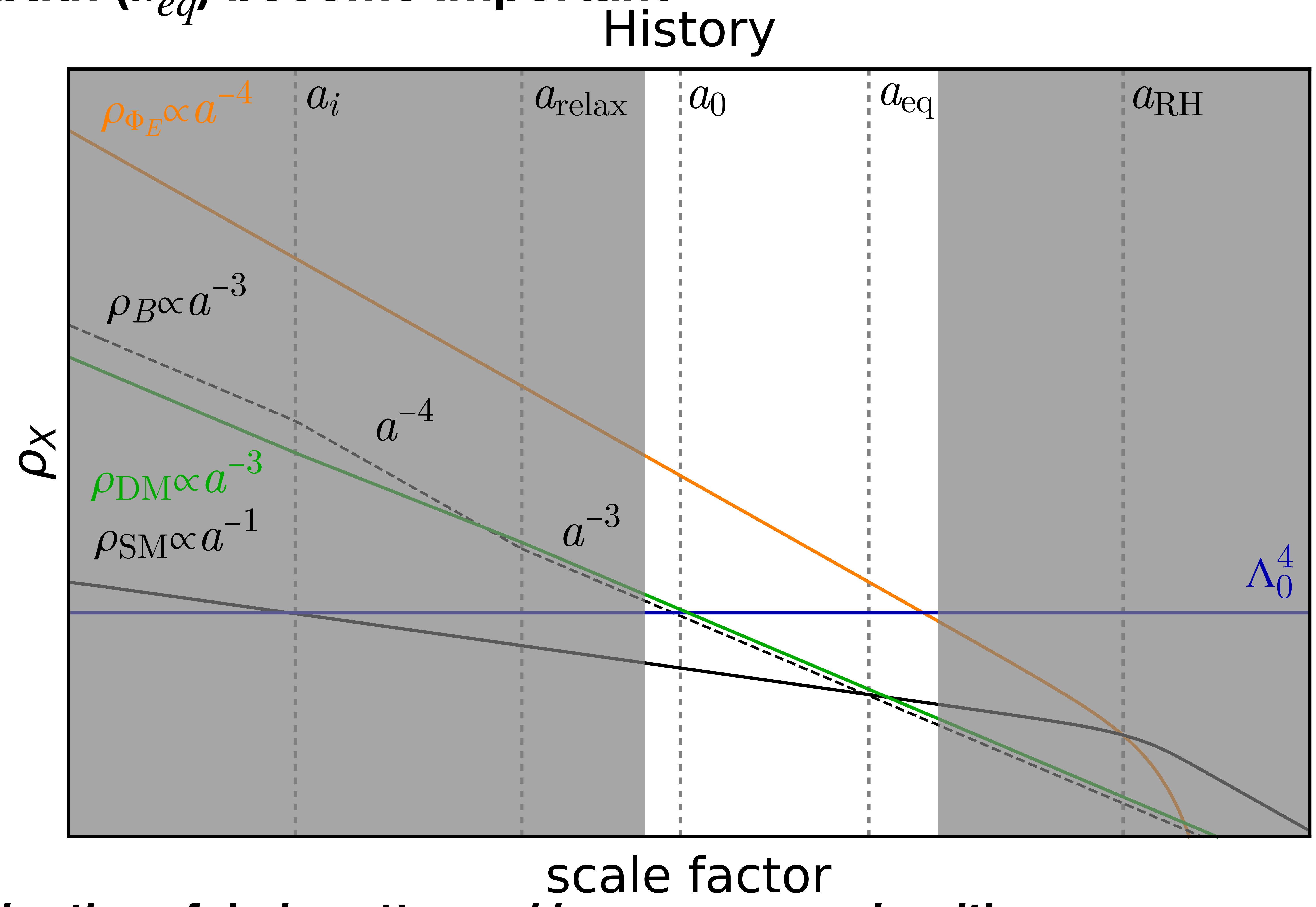
$$\rho_{\Phi_E} = 10^8 \text{ GeV}^4$$

$$\rho_{SM} = (100 \text{ MeV})^4$$

$$\rho_B = (100 \text{ MeV})^4$$

$$\rho_{DM} = 5\rho_B$$

$$m_p = 1 \text{ GeV}$$



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Putting everything together

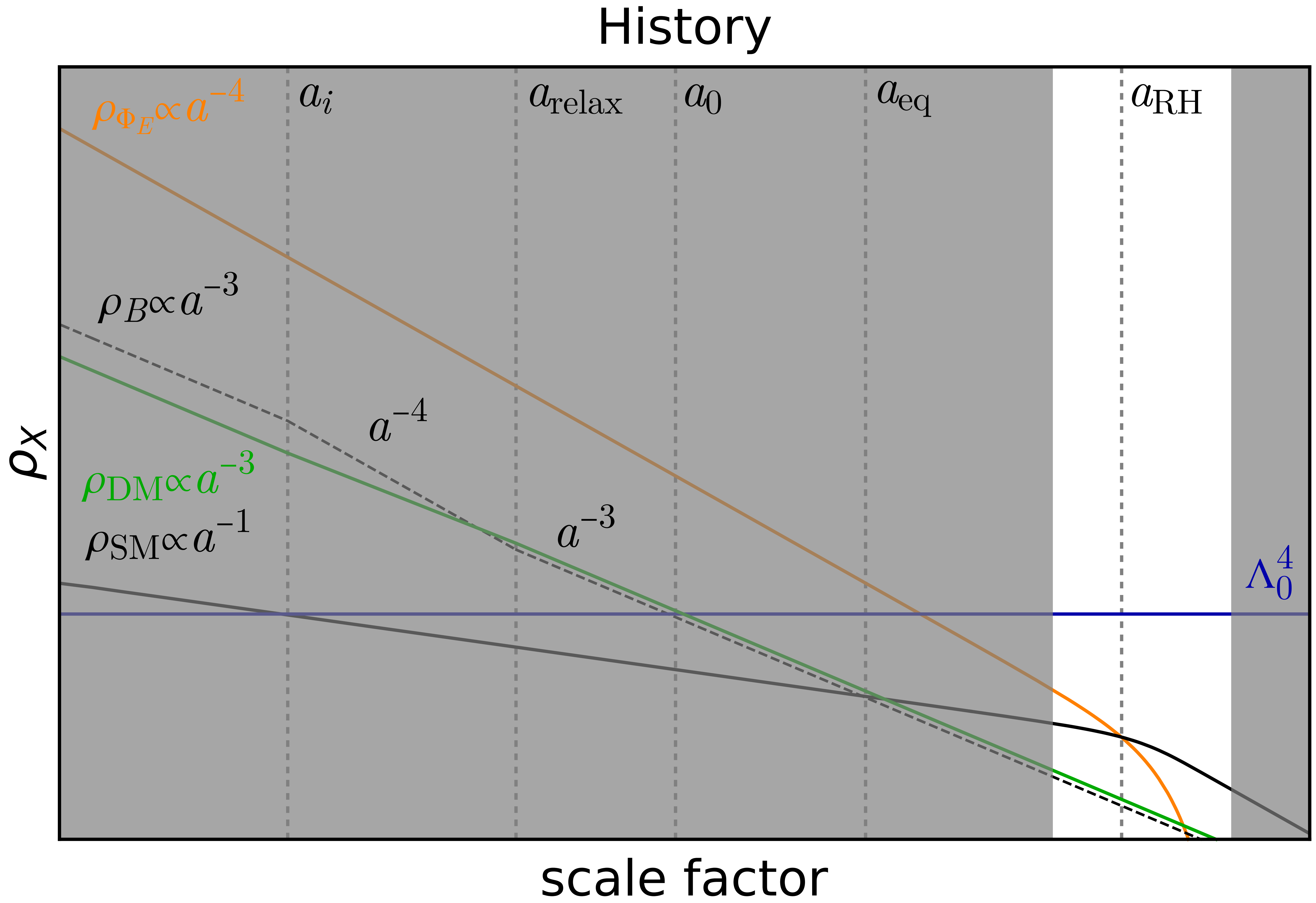
Reheating

$$a_{RH} = 1$$

$$\rho_{SM} = 3 \times (10 \text{ MeV})^4$$

$$\rho_B = 4 \times 10^{-4} \text{ MeV}^4$$

$$\rho_{DM} = 5\rho_B$$



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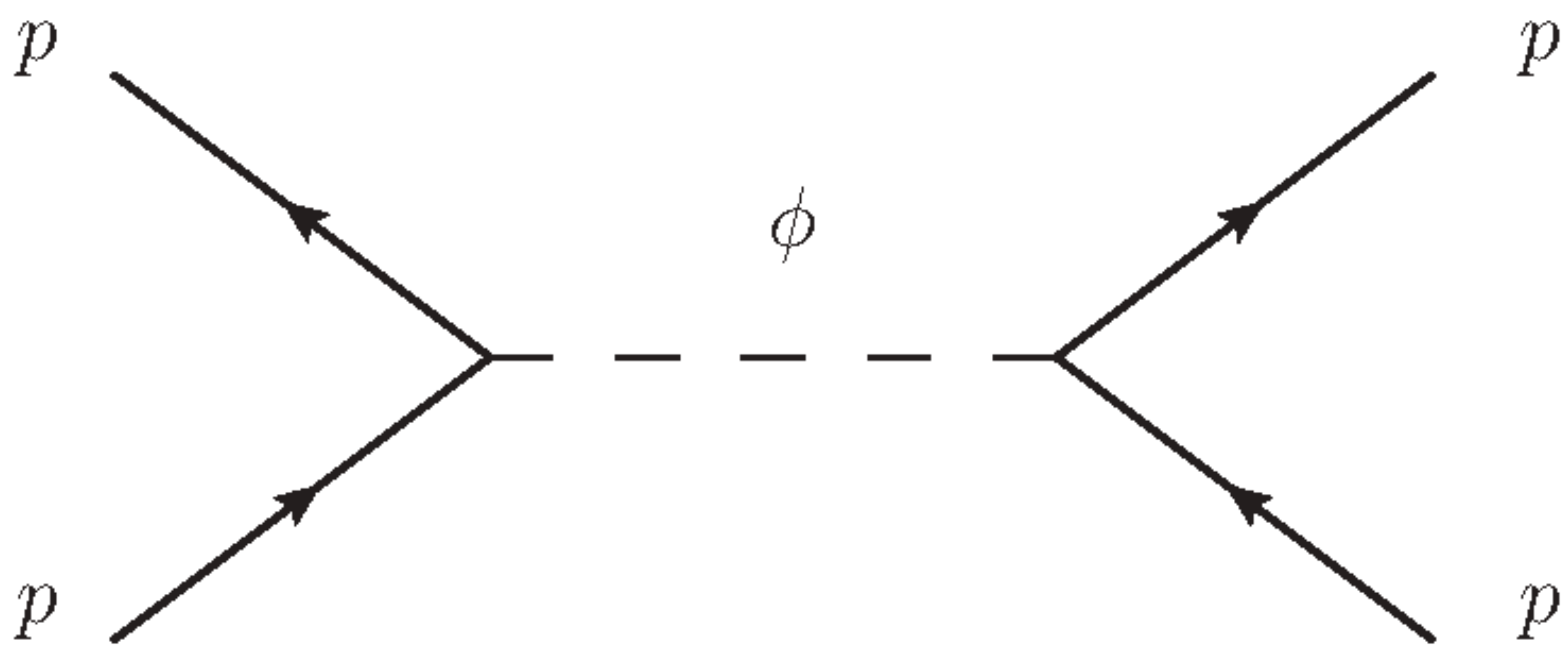
Coupling to nuclei

The baryon part of the Lagrangian gives rise to a fifth force between nuclei

$$\mathscr{L} \supset e^{c_B \phi / f} m_p \bar{\psi} \psi \approx \frac{c_B \phi}{f} m_p \bar{\psi} \psi$$



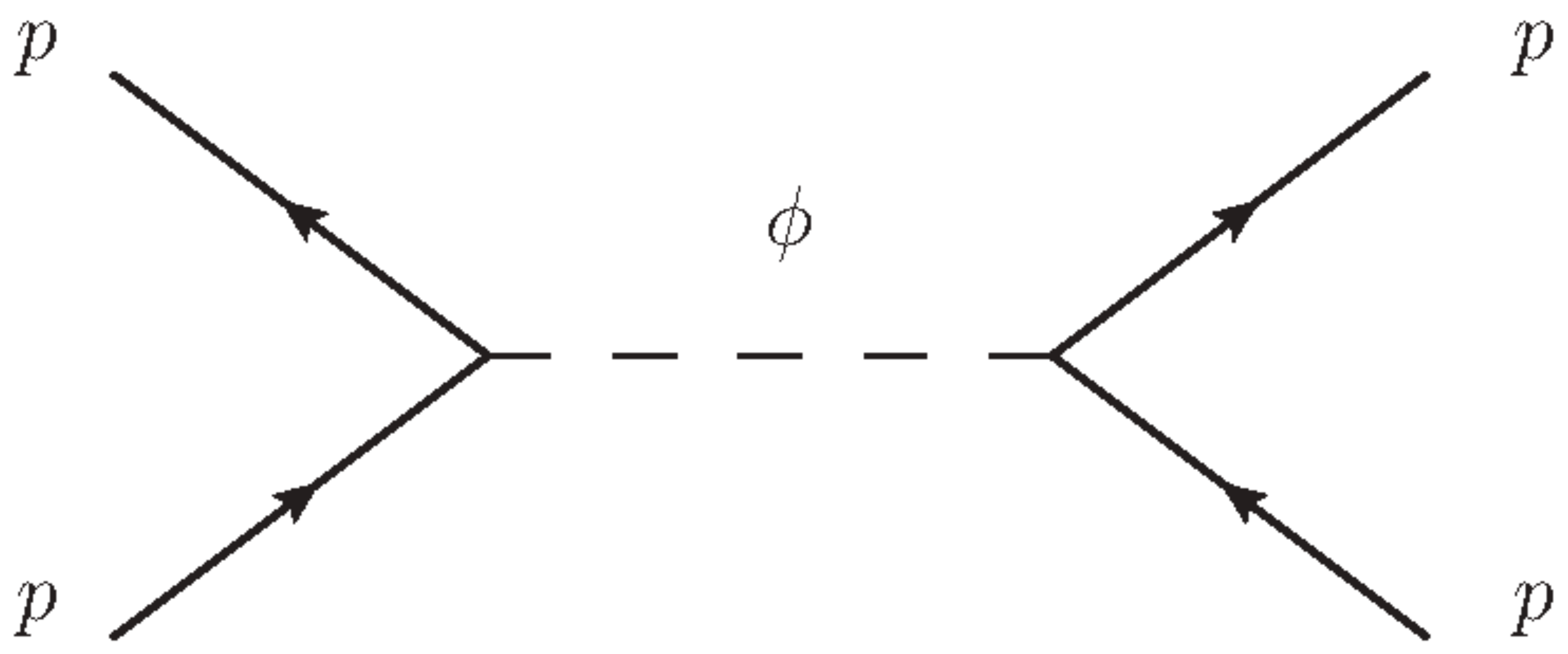
The range of the force is controlled by the vacuum potential

$$m_\phi = \Lambda_0^2 / F$$

Coupling to nuclei

At macroscopic ranges the coupling is subject to constraints from experiments looking for Equivalence Principle violating forces.

At masses above $m_\phi \gtrsim 1$ eV the stellar cooling bounds are the dominant source of constraints



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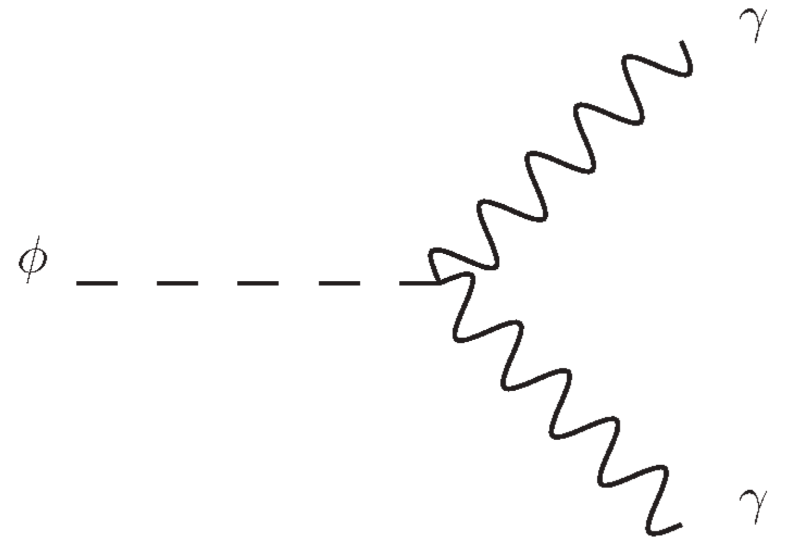
Decay into photons

Linear coupling to photons inevitably results in the decay into photons

$$\mathscr{L} \supset \frac{c_\gamma \phi}{f} F^2$$



Parametrically, the decay rate is

$$\Gamma_{\phi\gamma\gamma} = \frac{c_\gamma}{f}^2 m_\phi^3$$

For masses $m_\phi \sim 1$ eV we need to satisfy $f/c_B \gtrsim 10^{10}$ GeV

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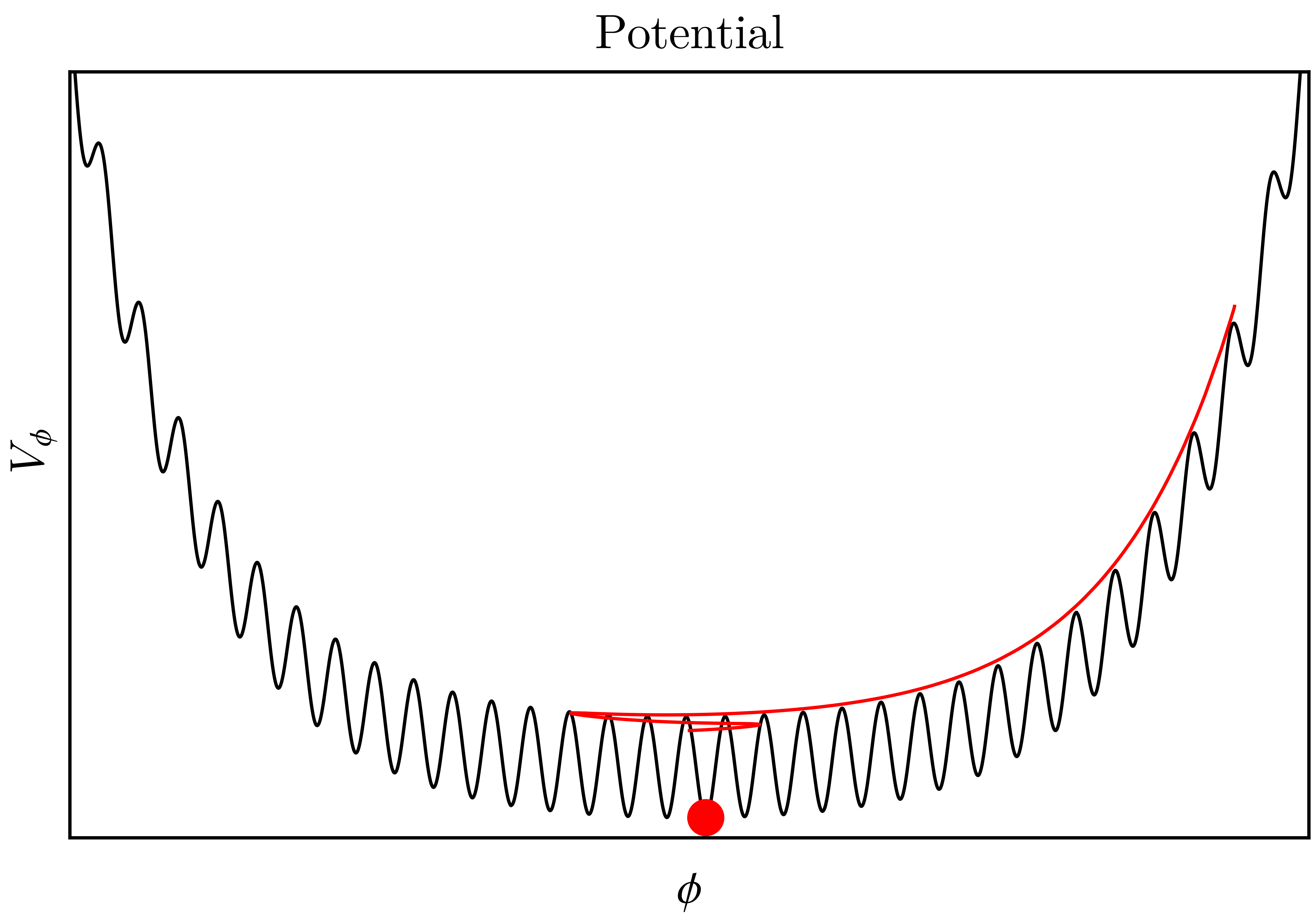
Parametric resonance

The scalar gets trapped in the vacuum potential once its kinetic energy falls below the height of the potential $\rho_\phi \lesssim \Lambda_0^4$.

Before then it will roll over bumps of vacuum potential.



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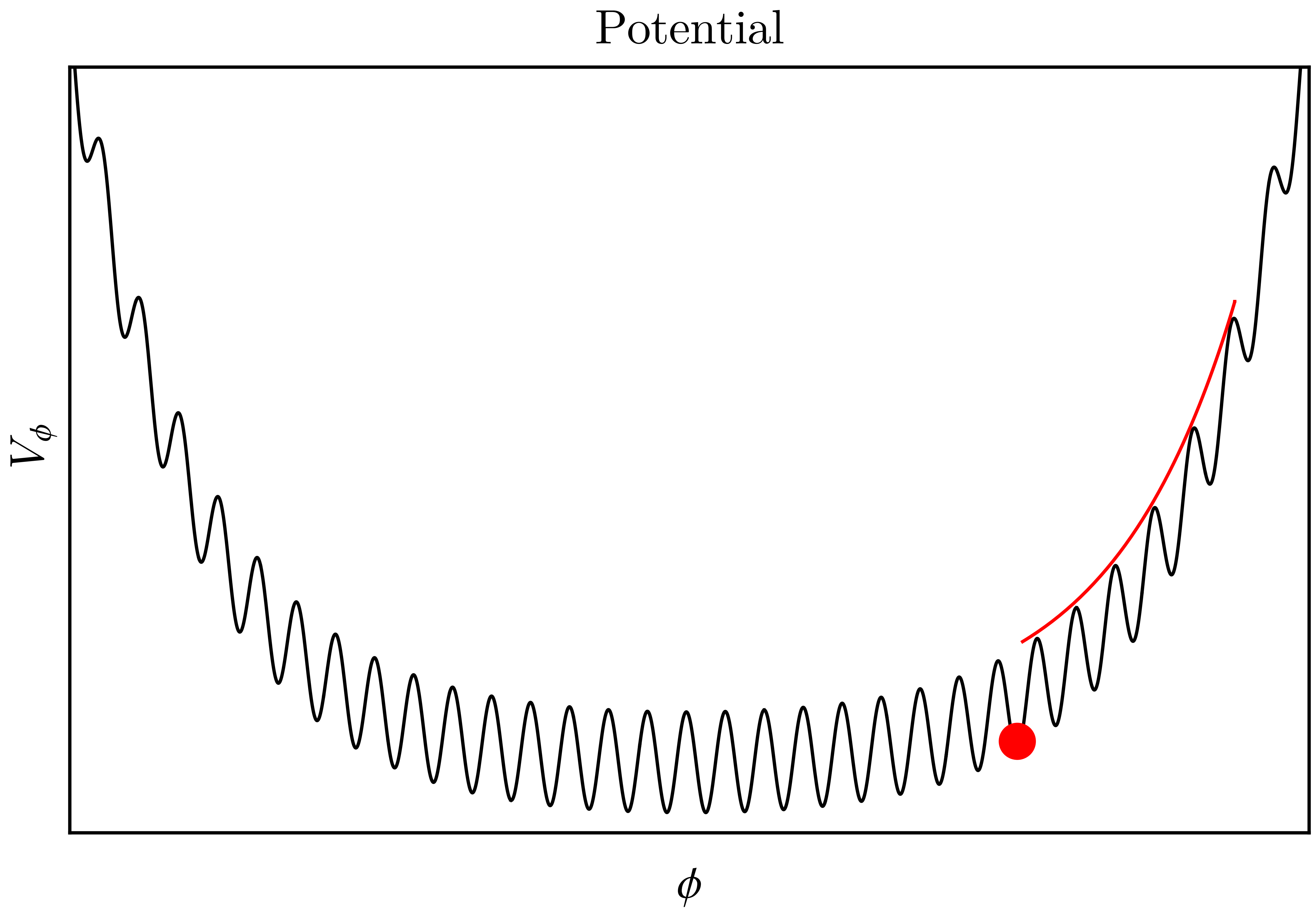
Parametric resonance

This can lead to parametric resonance that could remove energy from zero mode before the scalar reaches the minimum. (*Fonseca, Morgante, Sato, Servant, 2020*)

The timescale of this process is $t_{\text{frag}} \sim \frac{F\dot{\phi}^3}{\Lambda_0^8}$.

In order to prevent this effect from being important we require $Ht_{\text{frag}} \gtrsim 1$ at $a = a_{\text{relax}}$.



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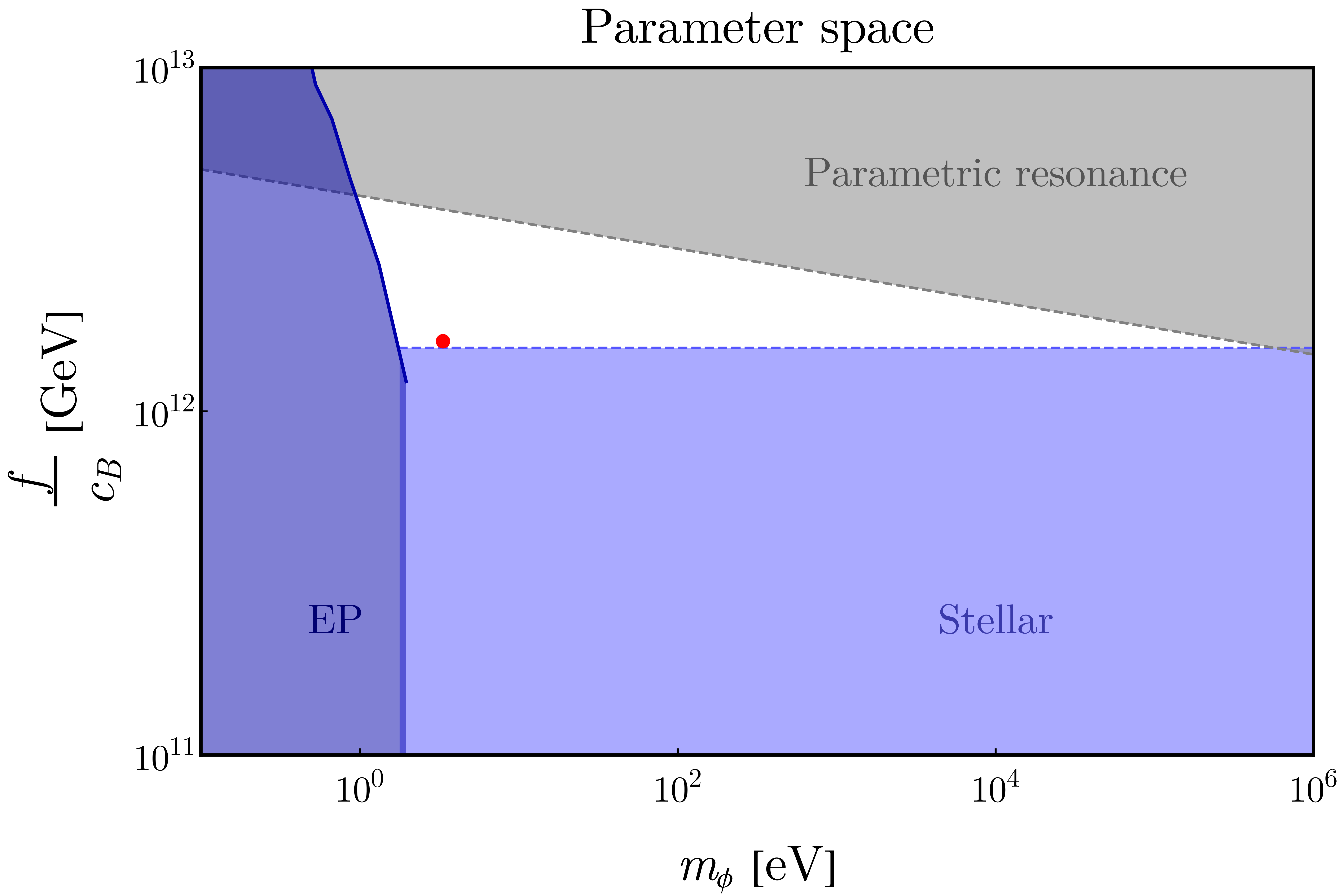
Parameter space

$T_{RH} = 10$ MeV

$\Lambda_0 = 20$ MeV



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Summary

- $\rho_{DM} \approx 5\rho_B$ seems accidental
- All models that address this problem predict DM of order GeV
- We presented a dynamical solution that explains $\rho_{DM} \approx 5\rho_B$ without assuming any DM mass
- UV complete model with QCD axion/ALP in progress
- It would be interesting to see applications of the mechanism to other models

Thank you!

Backup slides

Naturalness problem

We can protect the mass of the scalar by using Z_N symmetry (*Hook 2018, Brzeminski, Chacko, Dev, Hook, 2021*)

The coupling to gluons is generated by integrating out heavy fermions which are charged under (dark) $SU(N)$ and whose mass is controlled by the scalar

$$m_f(\phi) = m_0 \pm yf\cos(\phi/f + 2\pi k/N))$$

where k is the number of the copy of the SM/dark sector.

This affects IR value of the strong coupling as $\Delta(\alpha^{-1}) = -\frac{N_\chi}{3\pi}\log\frac{m_f(\phi)}{\Lambda_{UV}}$

Which translates to a ϕ-dependence of the confinement scale

$$\Lambda(\phi) = \Lambda(0)1 + \frac{yf\cos\phi/f}{m_0}^{\frac{2N_\chi}{3\beta}} \approx \Lambda(0)\exp(c_B\cos\phi/f) \approx \Lambda(0)\exp(c_B\phi/f)$$

Naturalness problem

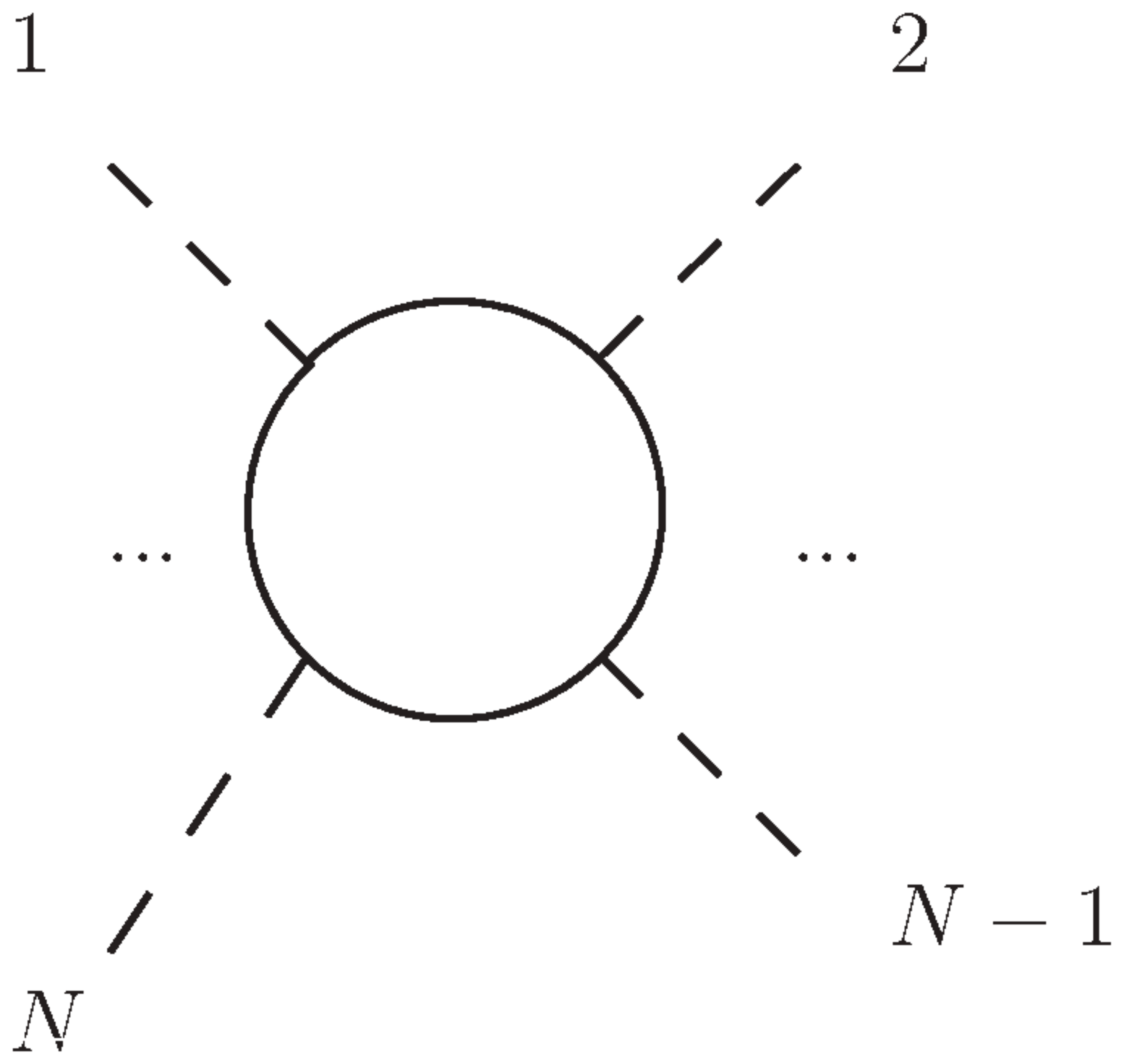
To get a quick estimate of the leading term in the Coleman-Weinberg potential we notice that

$$\sum_{k=1}^{N} \cos^m(\phi/f + 2\pi k/N) = \text{const if } m < N,$$

Therefore, we need N insertions of the cosine

$$V(\phi) \sim m_0^4 \frac{yf}{m_0}^N \cos N\phi/f$$

where $yf/m_0 < 1$



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