A Dynamical Explanation of the Dark Matter-Baryon Coincidence

Anson Hook

University of Maryland

w/ Dawid Brzeminski 2310.07777

Dark Matter

We know VERY little about dark matter

1) **Non-relativistic**
2) **Gravitational Interactions**
3) **No evidence for any other interactions**
4) **Adiabatic (small isocurvature) perturbations**
5) $\rho_{DM} \approx 10\,\mathbf{meV}^4$

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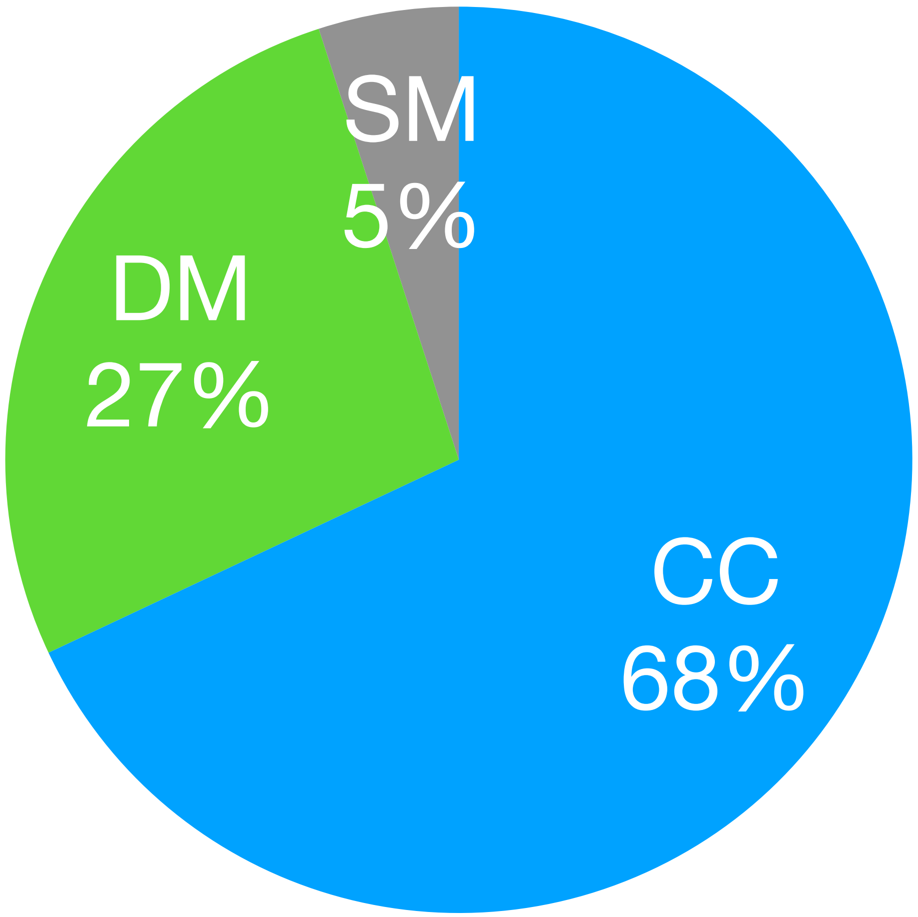
Time dependent and has units

Coincidence

$$\frac{\rho_{DM}}{\rho_{baryons}} = 5.36$$



This is a VERY surprising coincidence

Dimensional Transmutation : Upside

Back in the olden days $m_p \ll M_{Pl}$

Very elegant solution $m_p = M_{Pl}\, e^{\mathcal{O}(1)/\alpha_s}$

Proton mass exponentially sensitive to UV parameters

Dimensional Transmutation : Downside

$$\rho_B = m_p n_B \sim e^{\mathcal{O}(1)/\alpha_s} \; \ldots$$

Baryon abundance also exponentially sensitive

$$\rho_D = 5\rho_B$$

Exponential coincidence - Demands Explanation!

Previous Approach

Only one type of solution currently on the market

$$\rho_D \sim \rho_B$$

$$n_D \sim n_B \qquad\qquad m_D \sim m_B$$

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$$\rho_D \sim \rho_B$$

$$n_D \sim n_B$$

Mirror world baryogenesis

Asymmetric Dark Matter

$$m_D \sim m_B$$

(Broken) Mirror world

Coupled CFTs

Dark/SM unification

Goal

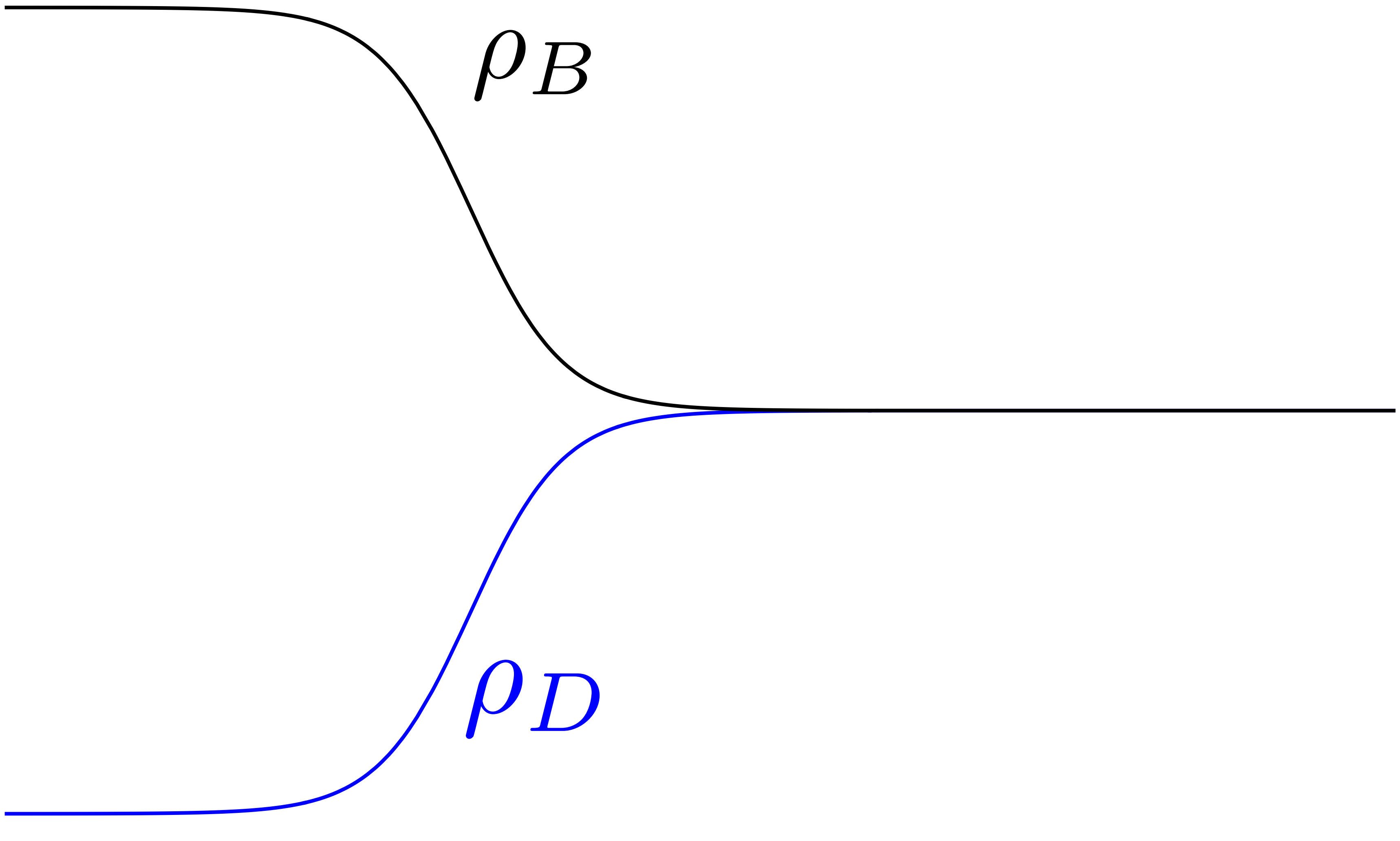
Does this implay that dark matter must have its mass around a few GeV?

I like other DM candidates such as ultra light and ultra heavy DM though…

Goal of this talk : Present a new approach that works for (almost) any DM candidate

Idea Sketch

Couple a scalar to dark matter and baryon mass terms such that at its finite density minimum the energy densities are comparable



Toy Model

Take dark matter to get its mass from the confinement of a dark sector gauge group

$$m_D = \Lambda_D^2 / f_a$$

Couple our scalar as

Beta Functions

O(1) constants

$$\mathcal{L}_{\text{Toy}} = \frac{\phi}{f} \left(\frac{\beta_B c_B}{32\pi^2} G_B^2 - \frac{\beta_D c_D}{64\pi^2} G_D^2 \right)$$

Toy Model

Ala dimensional transmutation

$$m_B(\phi) \; = \; \Lambda_B(\phi) = \Lambda_B(0) e^{c_B \phi/f}$$

$$m_D(\phi) = \Lambda_D^2(\phi)/f_a = m_D(0) e^{-c_D \phi/f}$$

Imagine somehow we create baryons and dark matter
Finite density potential

$$V(\phi) = m_B(\phi) n_B + m_D(\phi) n_D$$

Toy Model

Find Minimum

$$f\ V'(\phi) = c_B\, m_B(\phi)\, n_B - c_D\, m_D(\phi)\, n_D = 0$$

$$\rho_D/\rho_B = c_B/c_D \sim \mathcal{O}(1)$$

Regardless of number densities, identity of DM, this mechanism automatically sets the baryon and dark matter energy densities similar!

Toy Cosmology

Assume DM and Baryons have been produced in a radiation dominated universe and are non-relativistic

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{c_B}{f} m_B^0 e^{c_B \phi / f} n_B + \frac{c_D}{f} m_D^0 e^{-c_D \phi / f} n_D$$

Assume Baryons heavier than a GeV

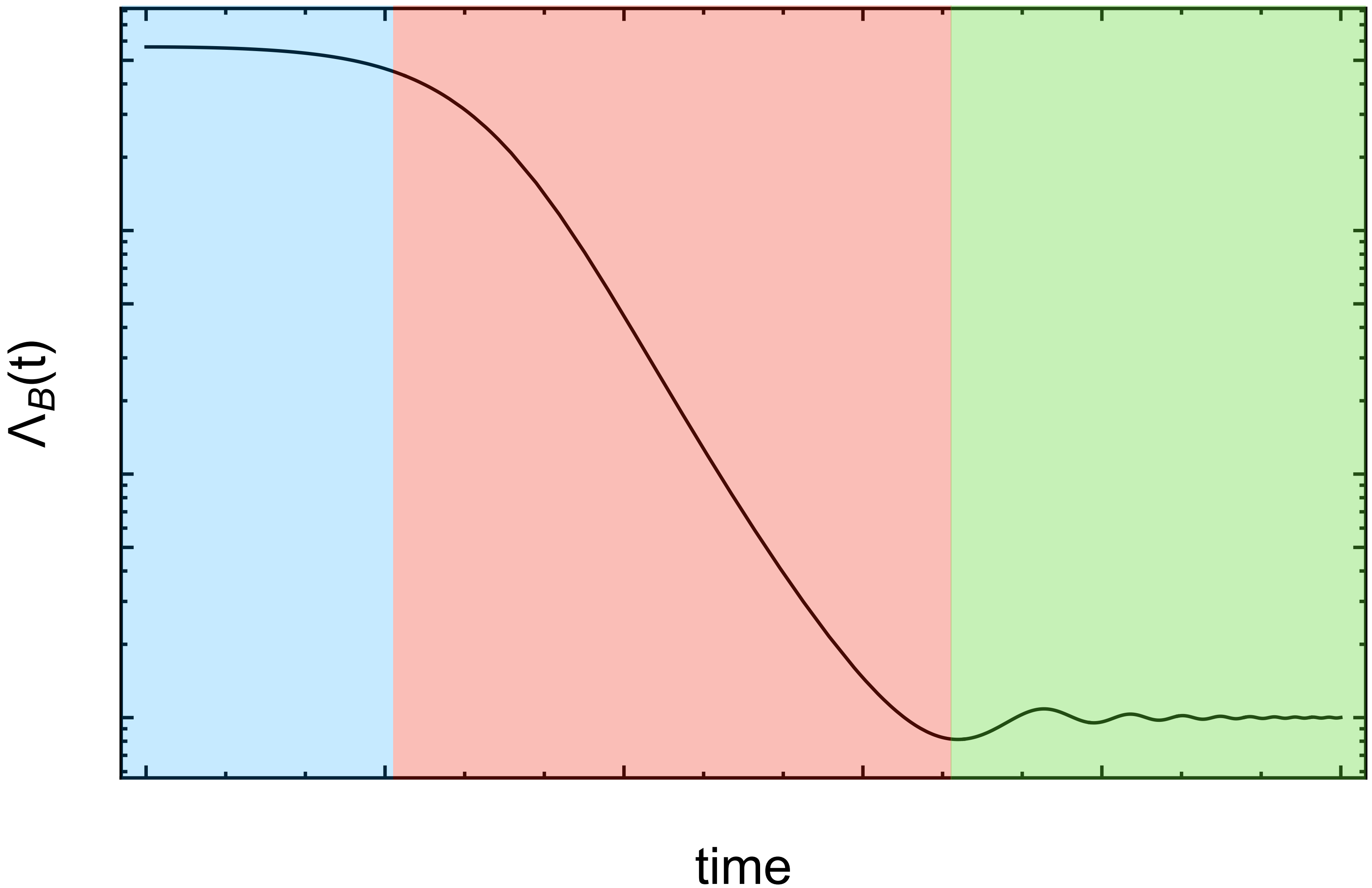
Initially, we have

$$\ddot{\phi} + 3H\dot{\phi} \approx -\frac{c_B}{f} \rho_B(\phi) \qquad\qquad m_\phi^2 = V'' \approx \frac{c_B^2}{f^2} \rho_B$$

Toy Cosmology

3 Stage Cosmology

Frozen Out Pseudo-Slow Roll Damped Oscillations



Toy Cosmology : Frozen Out

$$m_\phi \ll H$$

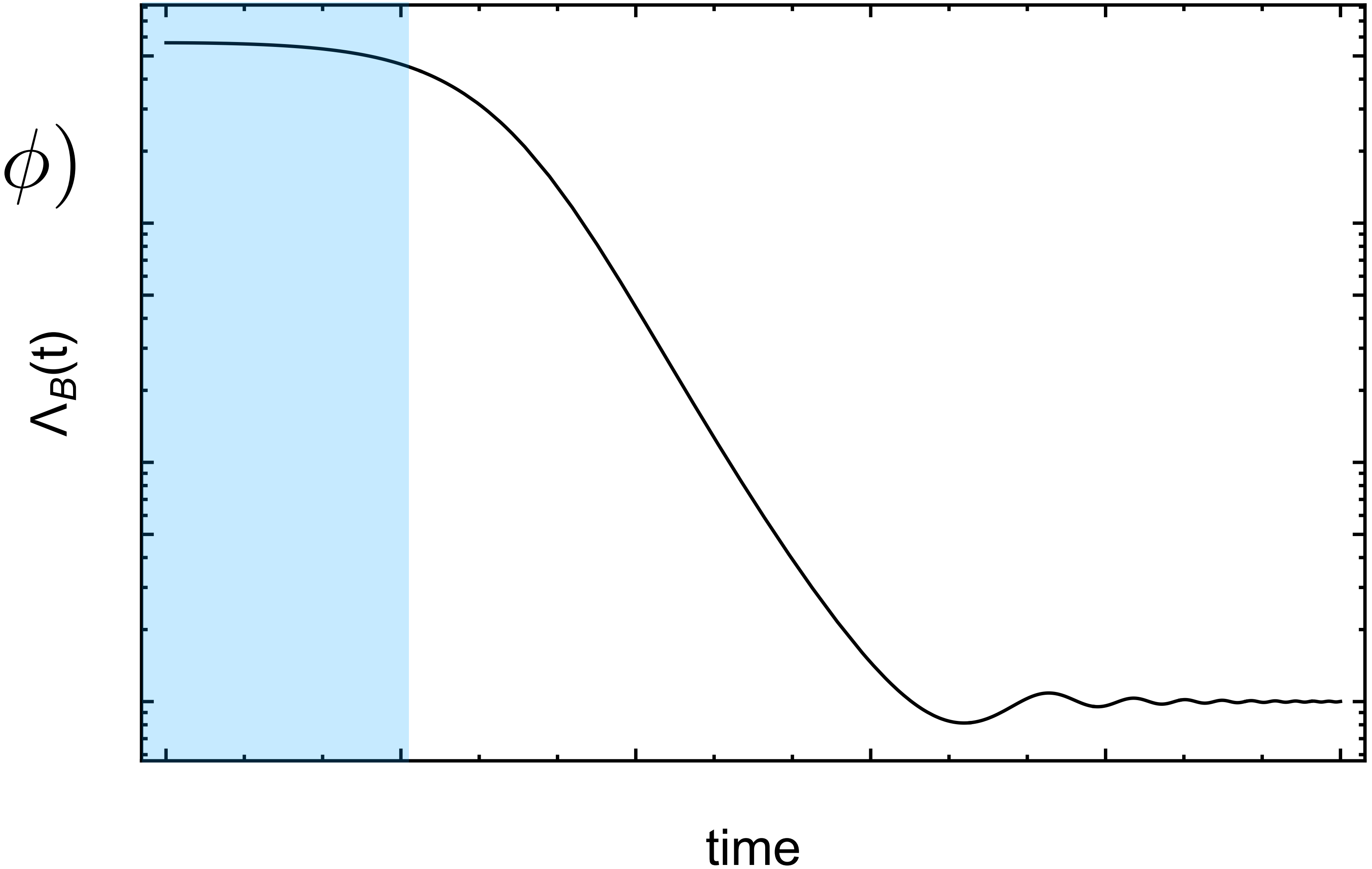
Not much happens

Everything just redshifts as usual

Frozen Out

$$\ddot{\phi} + 3H\dot{\phi} \approx -\frac{c_B}{f}\rho_B(\phi)$$

$$\dot{\phi} \approx 0$$



Toy Cosmology : Pseudo-Slow roll

$$m_\phi \approx H$$

Schematically

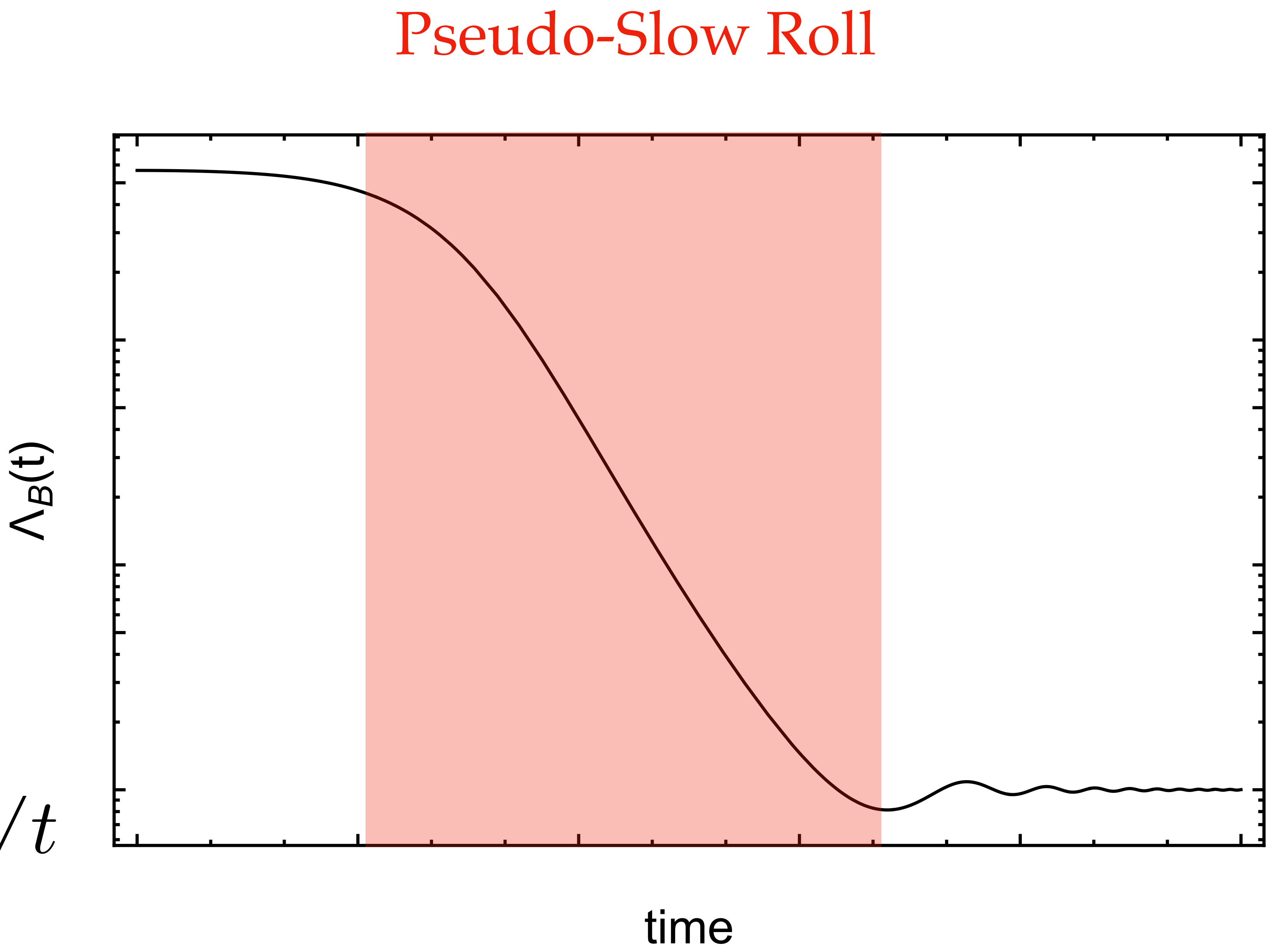
$$\phi \sim \log t$$

So that

$$\ddot{\phi} + 3H\dot{\phi} \approx -\frac{c_B}{f}\rho_B(\phi)$$

$$\sim 1/t^2 \qquad\qquad \sim 1/t^2$$

$$\Lambda_{QCD} \sim 1/a(t) \sim 1/\sqrt{t}$$



Toy Cosmology : Pseudo-Slow roll

$$m_\phi \approx H$$

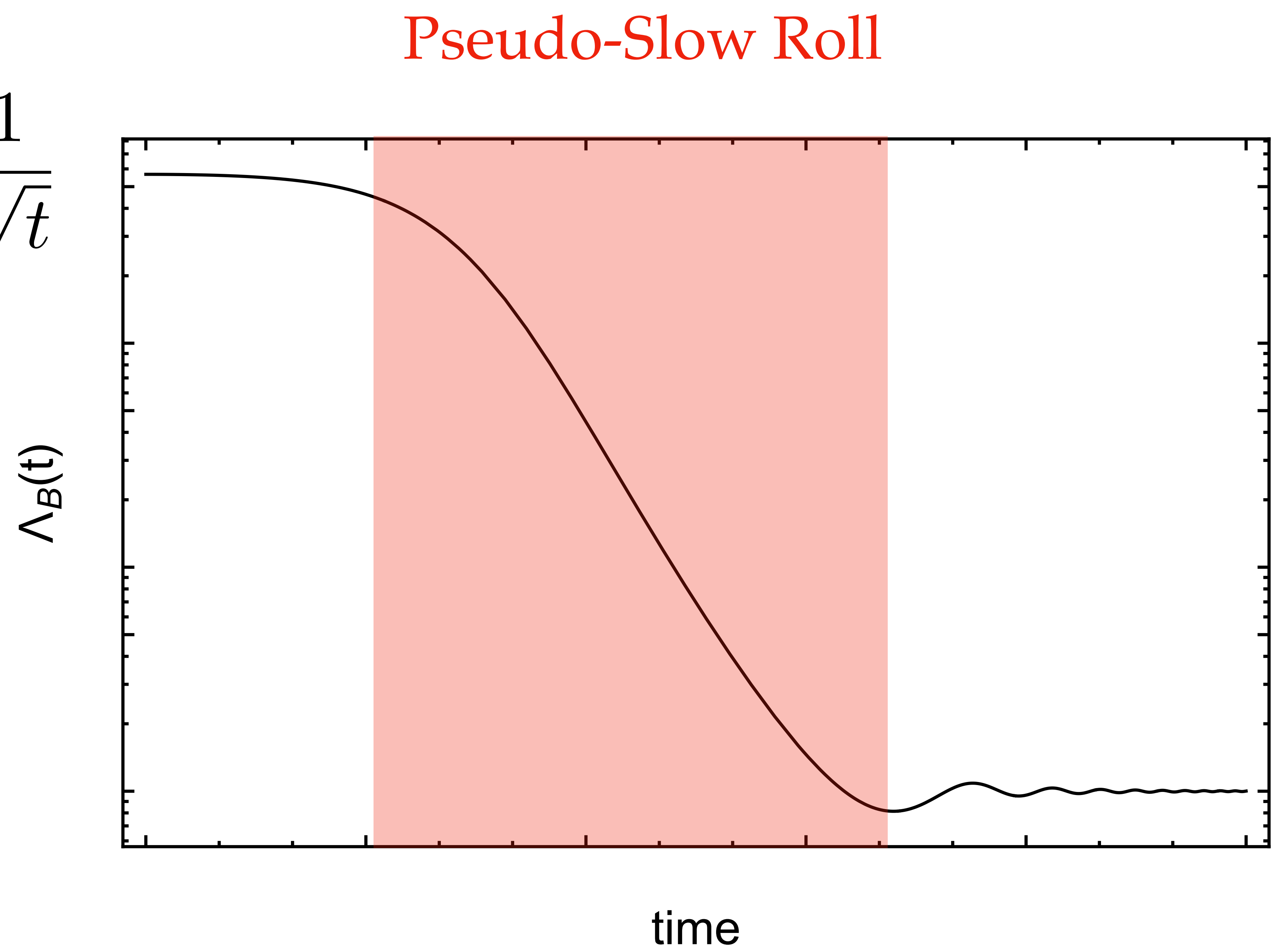
Check List

1) $m_B \sim \Lambda_{QCD} \sim \frac{1}{\sqrt{t}}$

2) $\rho_B \sim \frac{1}{t^2}$

3) $m_\phi = H$

4) $\frac{1}{2}\dot{\phi}^2 = \frac{1}{2}\rho_B$



Toy Cosmology : Damped Oscillations

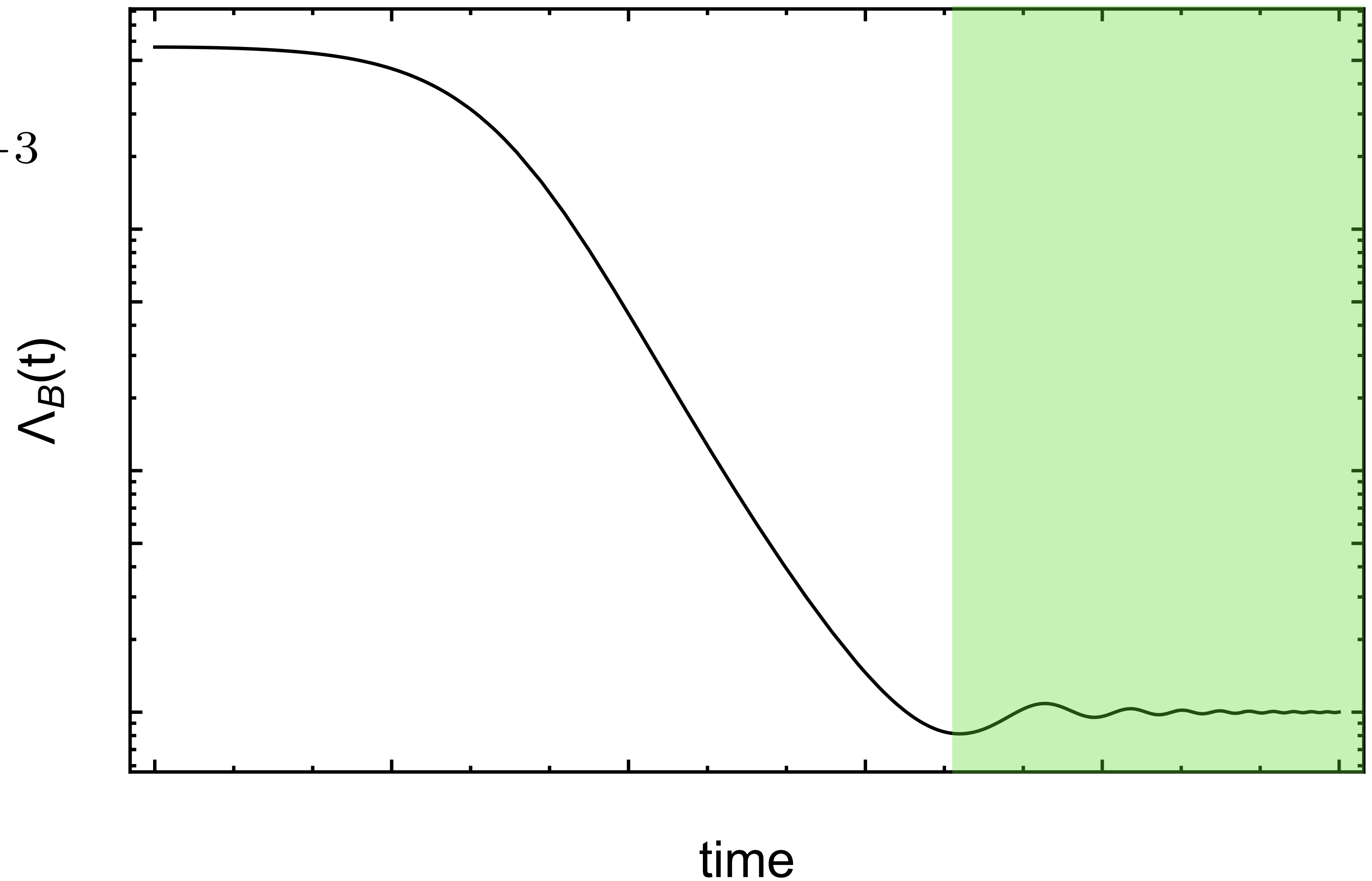
$$m_\phi \gg H$$

Dark Matter becomes important

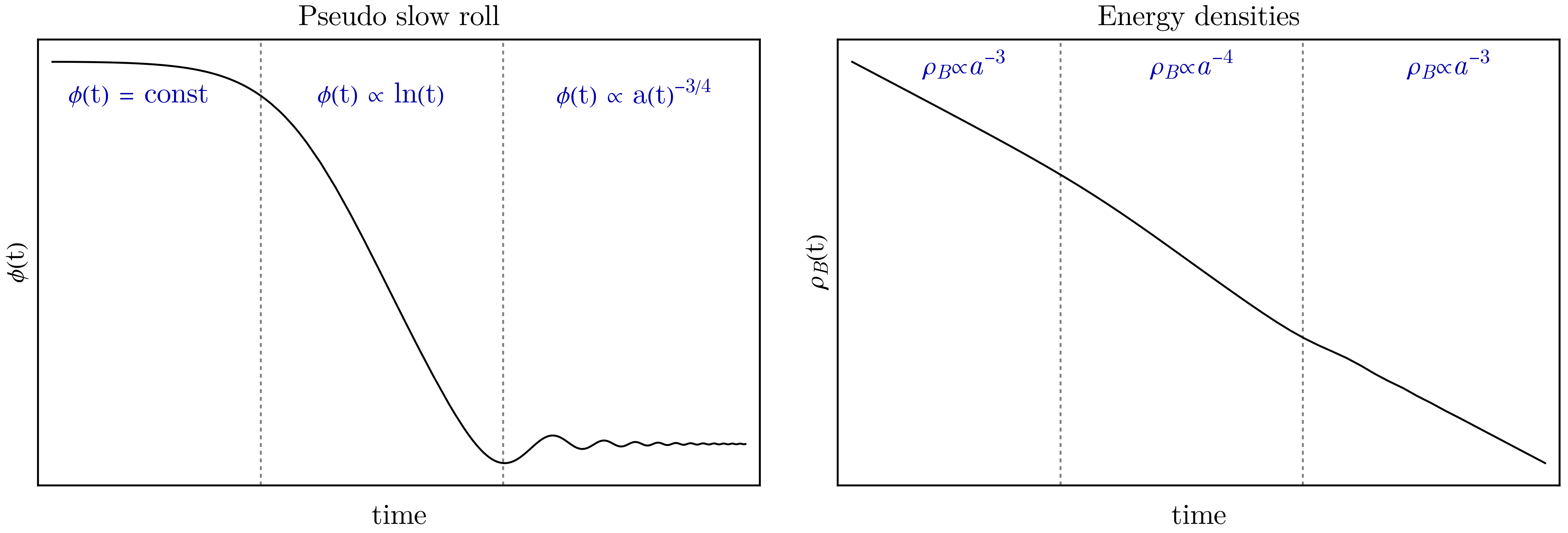
$$m_\phi^2 = \frac{c_B^2}{f^2}\rho_B + \frac{c_D^2}{f^2}\rho_D \sim a^{-3}$$

$$\rho_\phi = m_\phi n_\phi \sim \frac{1}{a^{4.5}}$$

Damped Oscillations



Toy Cosmology : Summary



SM example : Challenges

Two basic issues with implementing this in the SM

1. Its very excluded

2. Temperature effects

SM example : Challenges

Constraints

Mechanism works anywhere and everywhere

In a neutron star, clearly energy densities of baryons and dark matter are not the same

SM example : Challenges

Solution

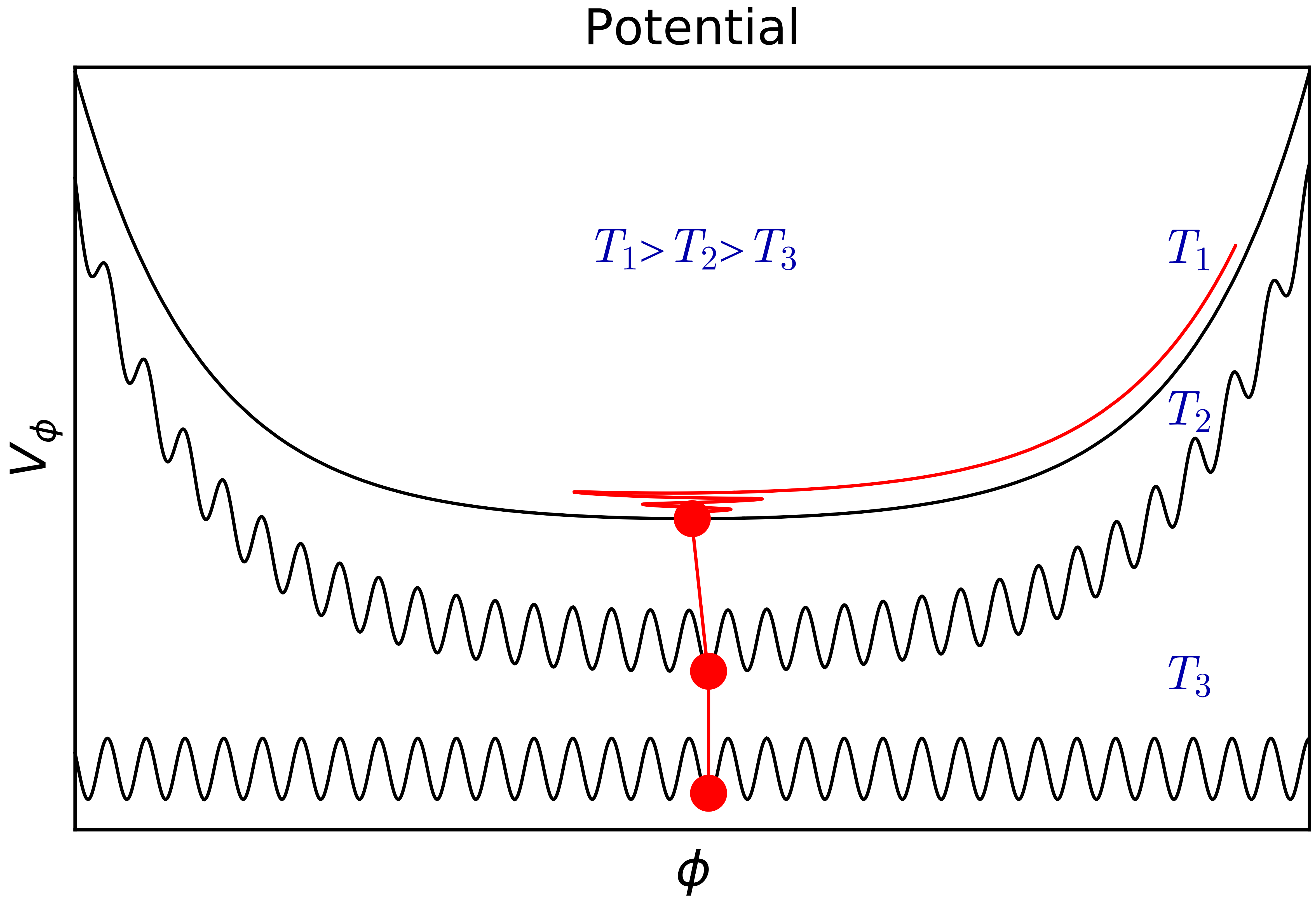
Add a bare potential

$$V = e^{c_B \phi/f} \rho_{NS} + \Lambda_0^4 \cos\left(\frac{\phi}{F} + \theta\right)$$

Neutron star doesn't change proton mass by much as long as

$$\frac{\Lambda_0^4}{F} \gtrsim \frac{c_B}{f} \rho_{NS}$$

SM example : Challenges



SM example : Challenges

Two basic issues with implementing this in the SM

1. Its very excluded
2. Temperature effects

SM example : Challenges

Finite Temperature

1. Scanning the QCD scale inevitably leads to scanning the fine structure constant

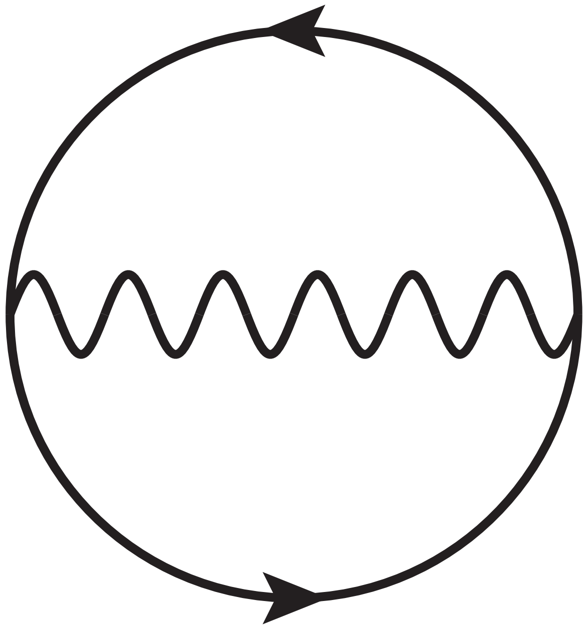
$$\frac{\phi}{f}\frac{c_B \beta_{QCD}}{32\pi^2}G^2 \longrightarrow \mathcal{O}(1)\frac{\phi}{f}\frac{c_B}{32\pi^2}F^2$$

SM example : Challenges

Finite Temperature

2. Free energy at low energies depends on fine structure constant

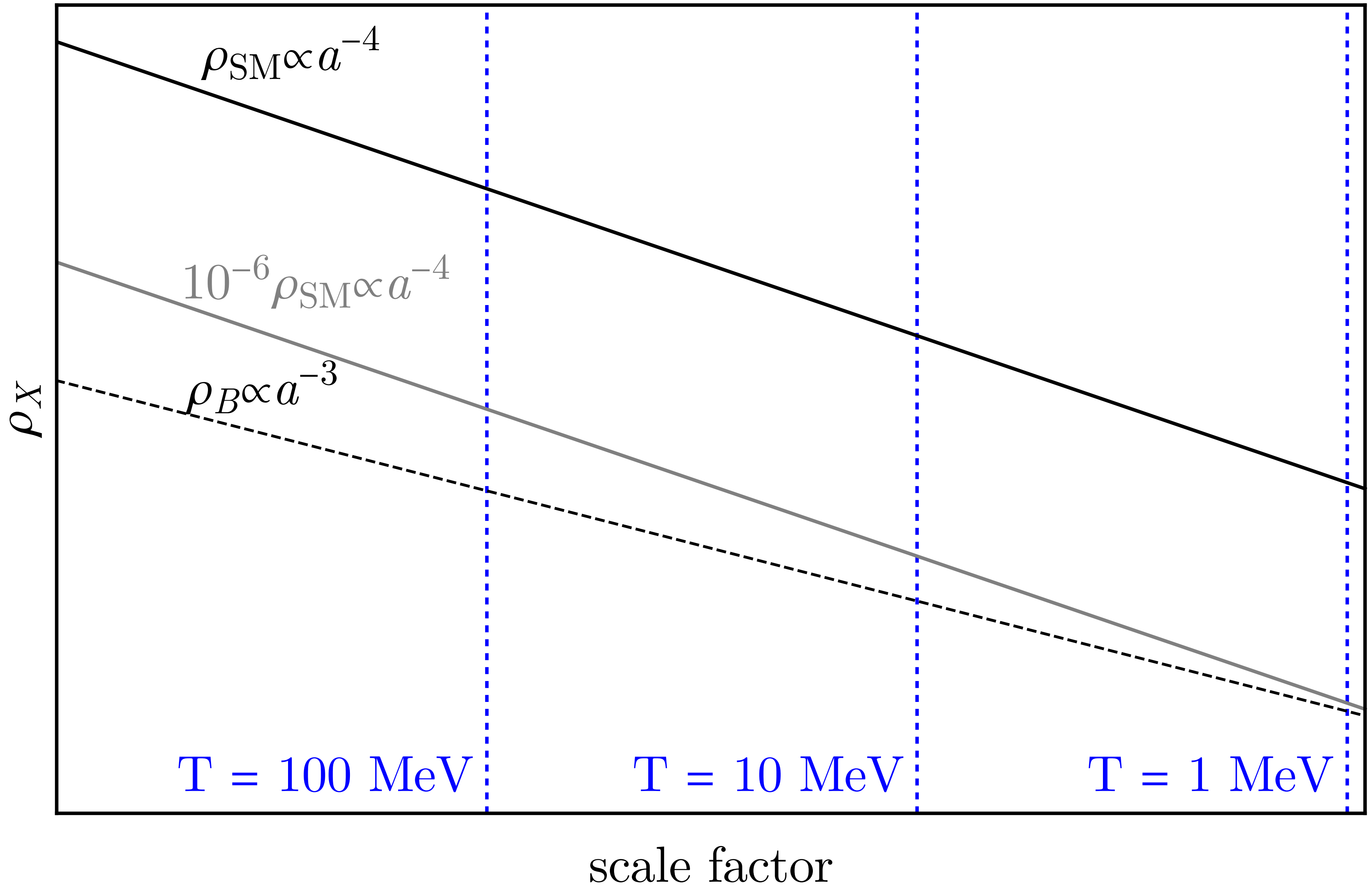
$$f = \frac{5}{288} e^2(\phi) T^4 \sim 10^{-6}\, T^4\, \frac{c_B \phi}{f}$$



SM example : Challenges

$$V(\phi) \sim \frac{c_B}{f}\rho_B + \frac{c_B}{f}10^{-6}\rho_{SM}$$

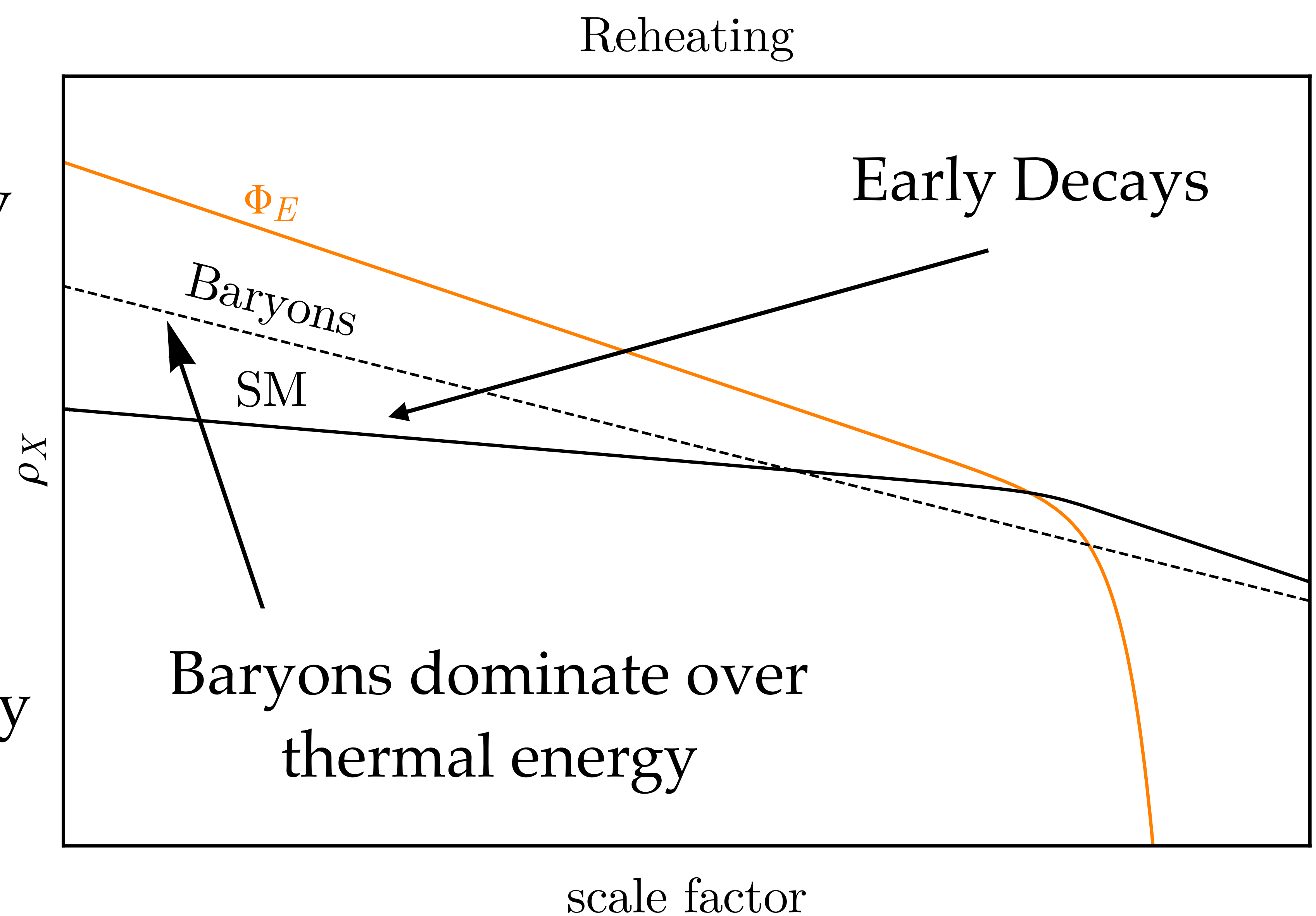
Standard Cosmology



SM example : Challenges

Non Standard Cosmology
Entropy Dump

Need something like
Affleck-Dine to get large
Baryon number asymmetry



SM example : Lagrangian

$$\mathscr{L} = \frac{\phi}{f}\left(\frac{\beta_B c_b}{32\pi^2}G^2 - \frac{\beta_D c_D}{64\pi^2}G_D^2\right) + \Lambda_0^4 \cos\left(\frac{\phi}{F} + \theta\right)$$

Scan dark matter mass

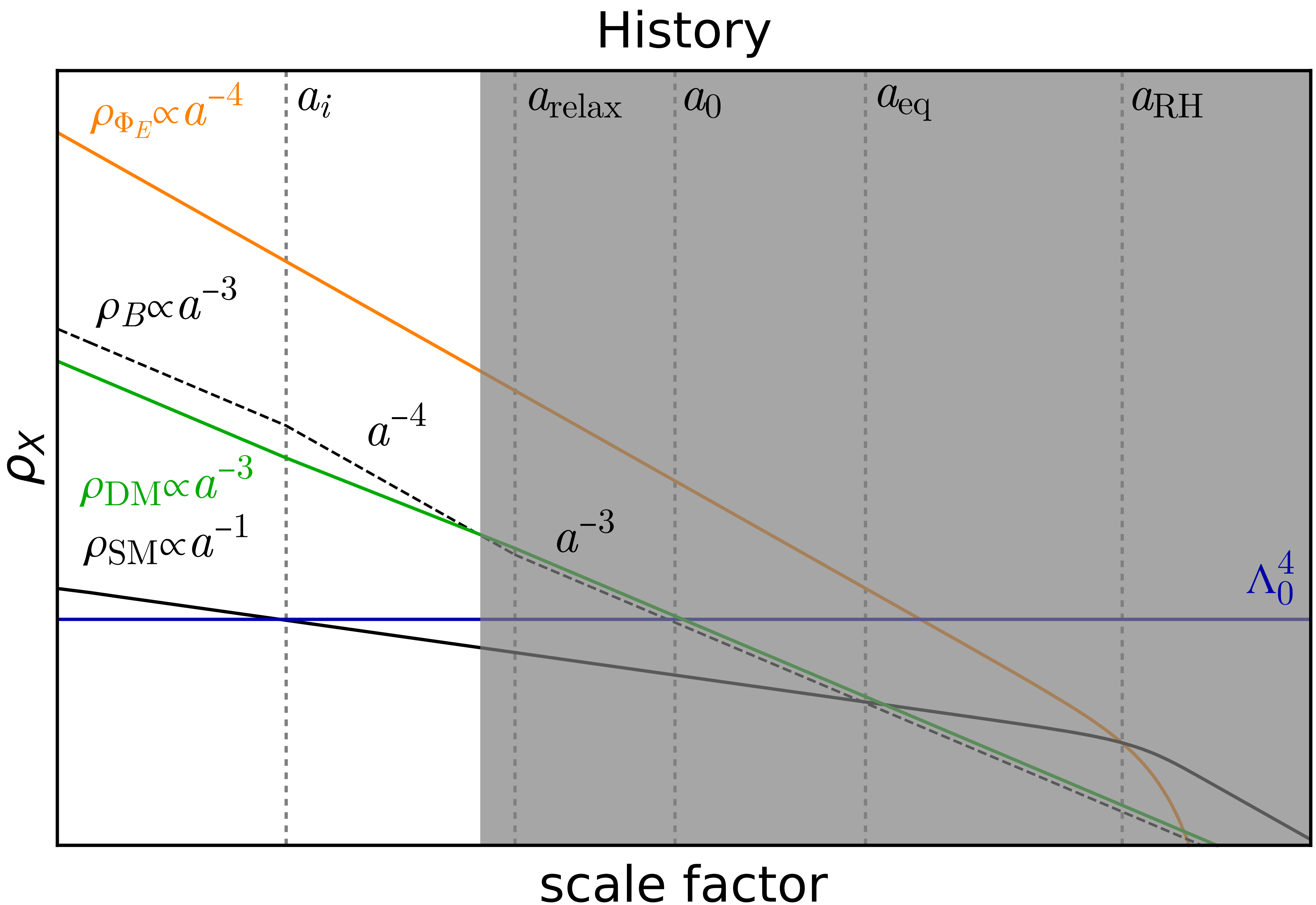
Scan baryon mass

Do nothing at early times, but prevent late time constraints

A Full SM Example

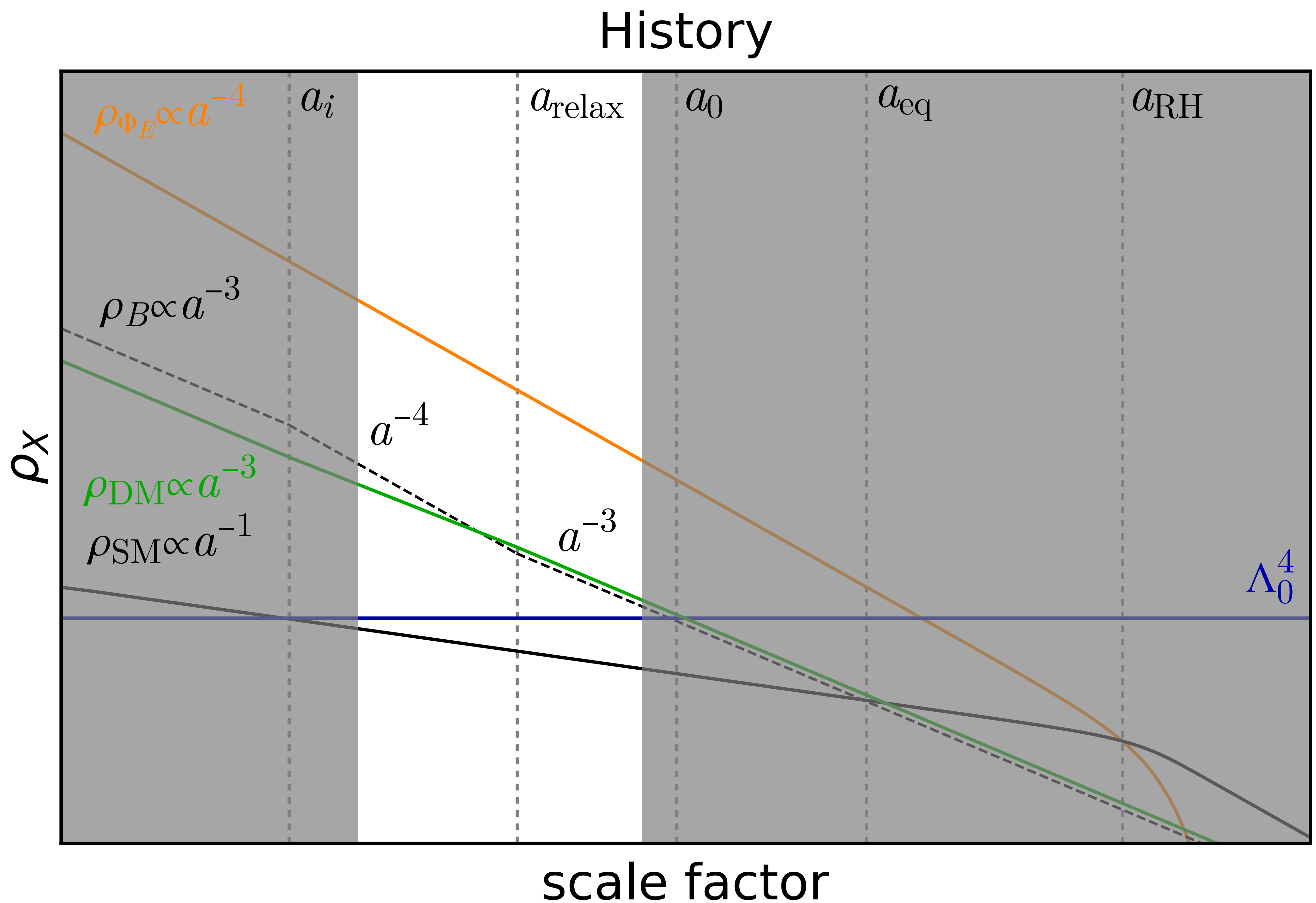
Coupling to Baryons	$f/c_B = 10^{12}\,\mathrm{GeV}$
Baryon/DM ratio	$c_B/c_D = 5$
Non-zero mass	$F = 10^7\,\mathrm{GeV}$ $\quad m_\phi = \ \mathrm{eV}$
Barrier to stop late time rolling	$\Lambda_0 = 100\,\mathrm{MeV}$
Reheat Temperature	$T_{RH} = 10\,\mathrm{MeV}$

A Full SM Example



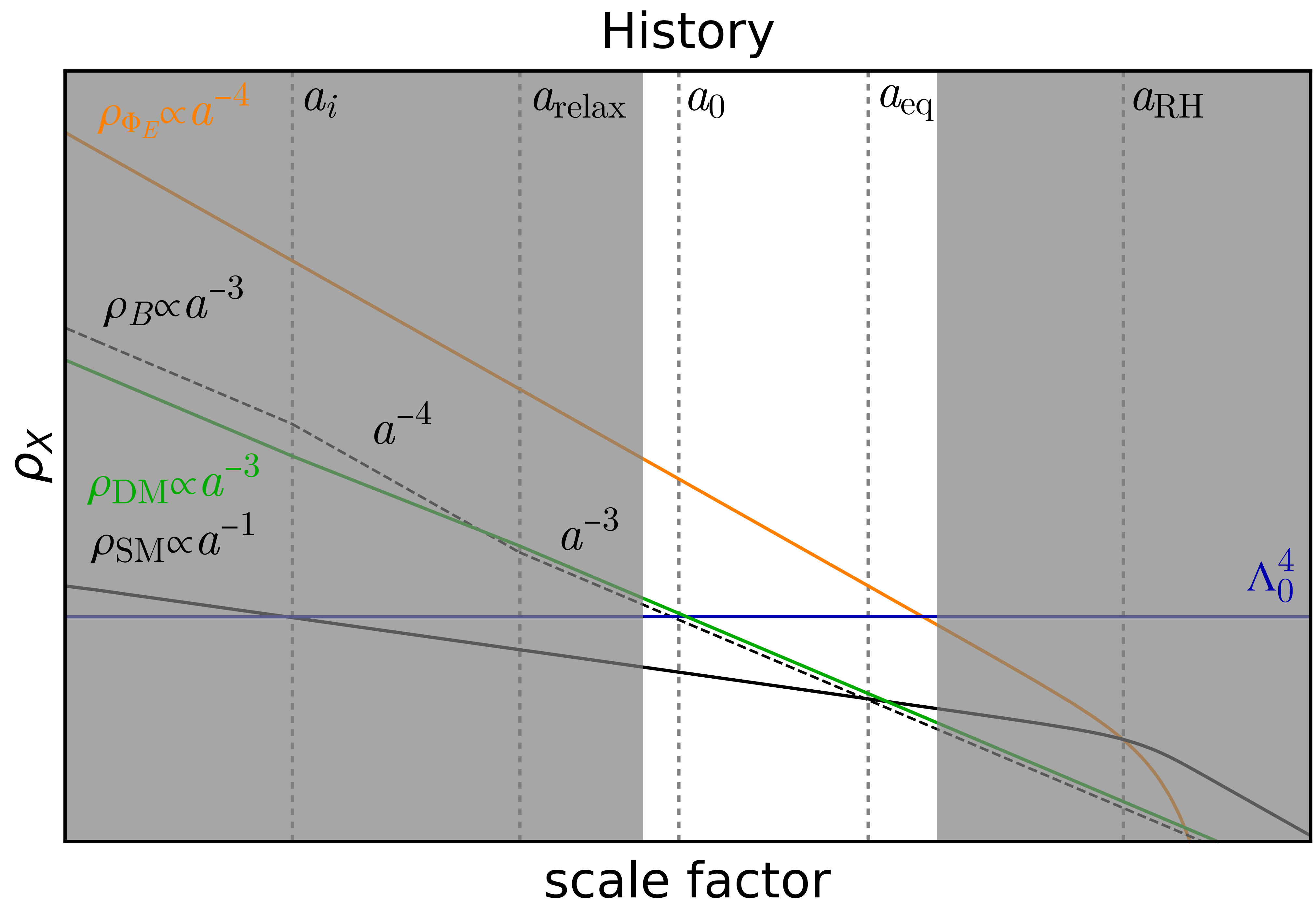
Start Relaxation

A Full SM Example



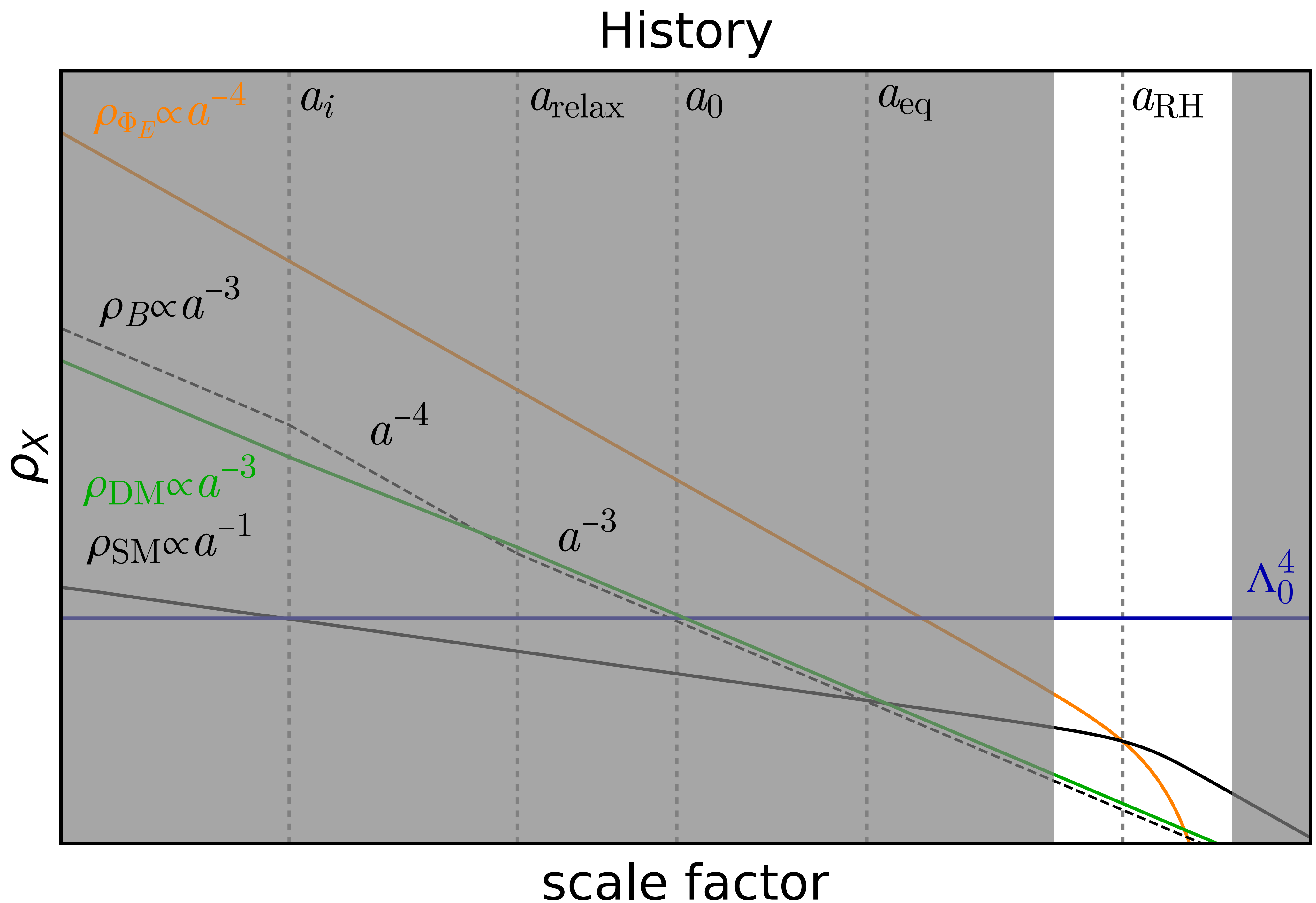
End Relaxation

A Full SM Example



Density independent potential becomes important

A Full SM Example



Reheat Standard Model

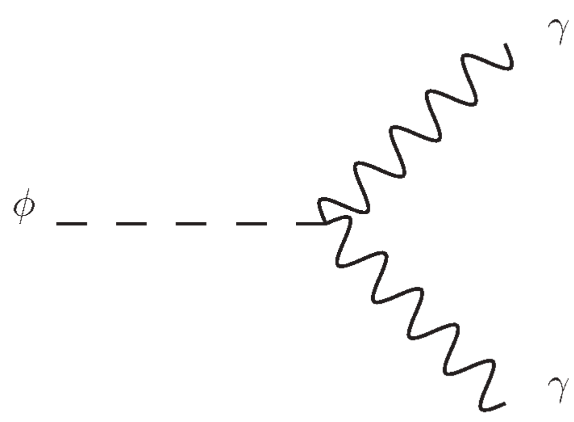
Constraints

From coupling to nucleons

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

5th Force and Stellar Cooling

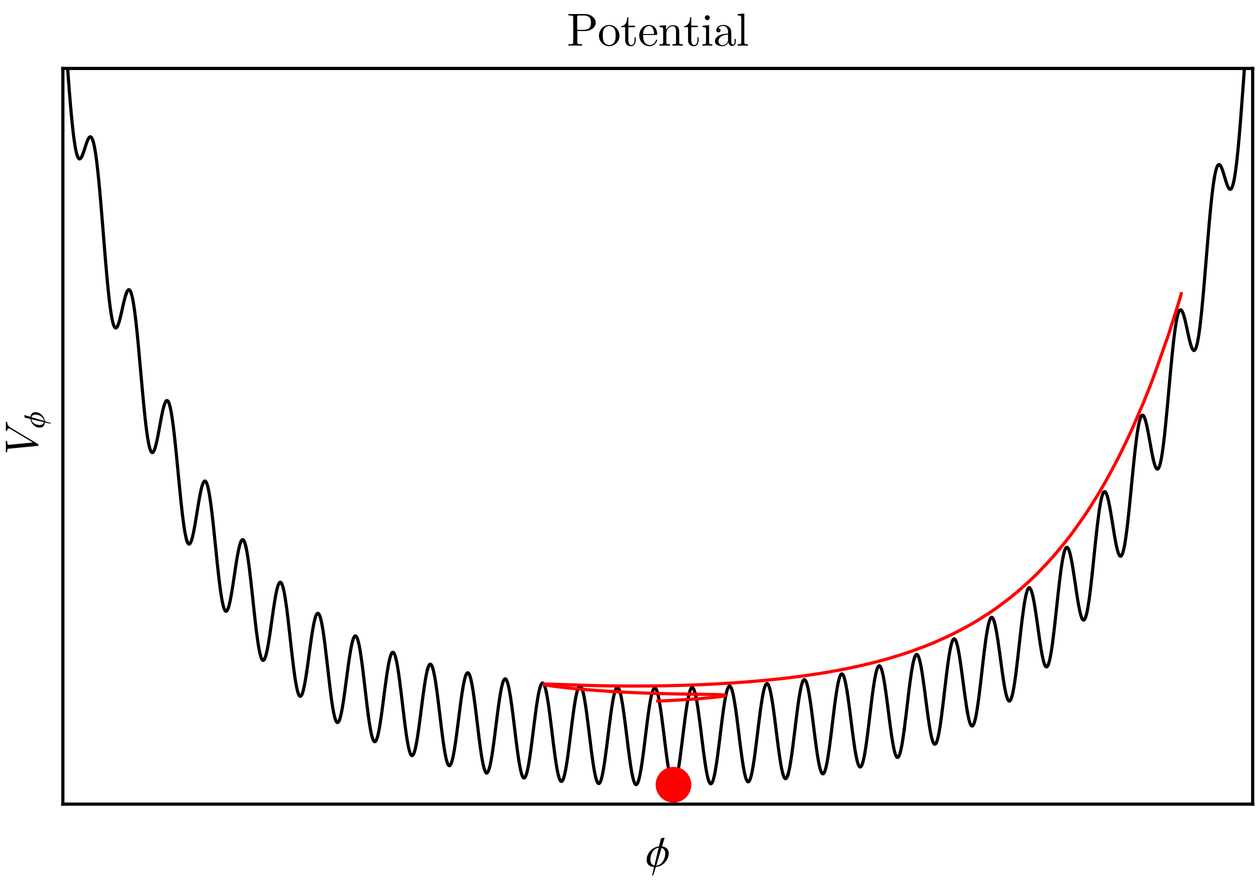
Scalar is around today and can decay into photons

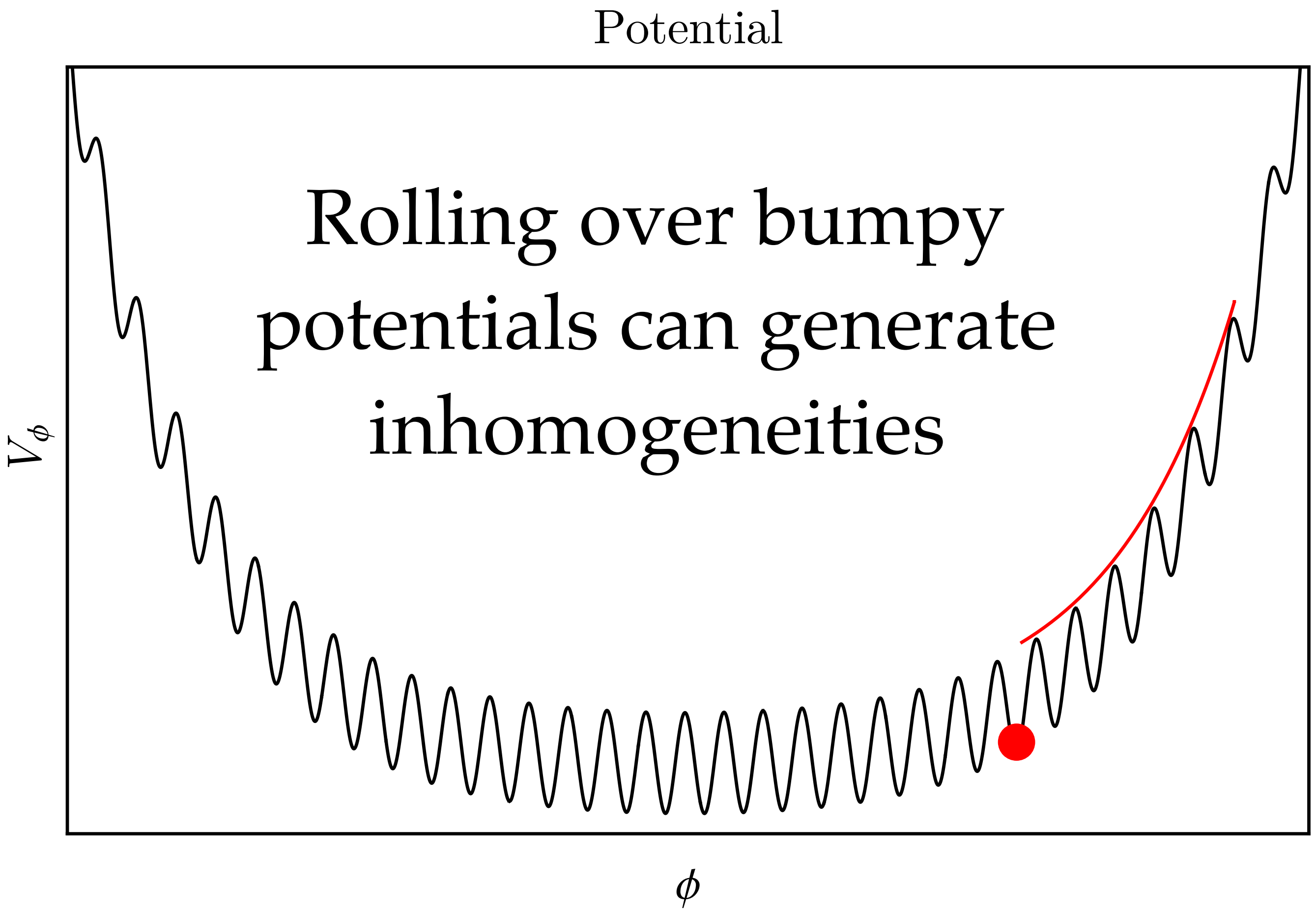


Not a strong constraint for our parameters but can be strong

Constraints

Parametric Resonance

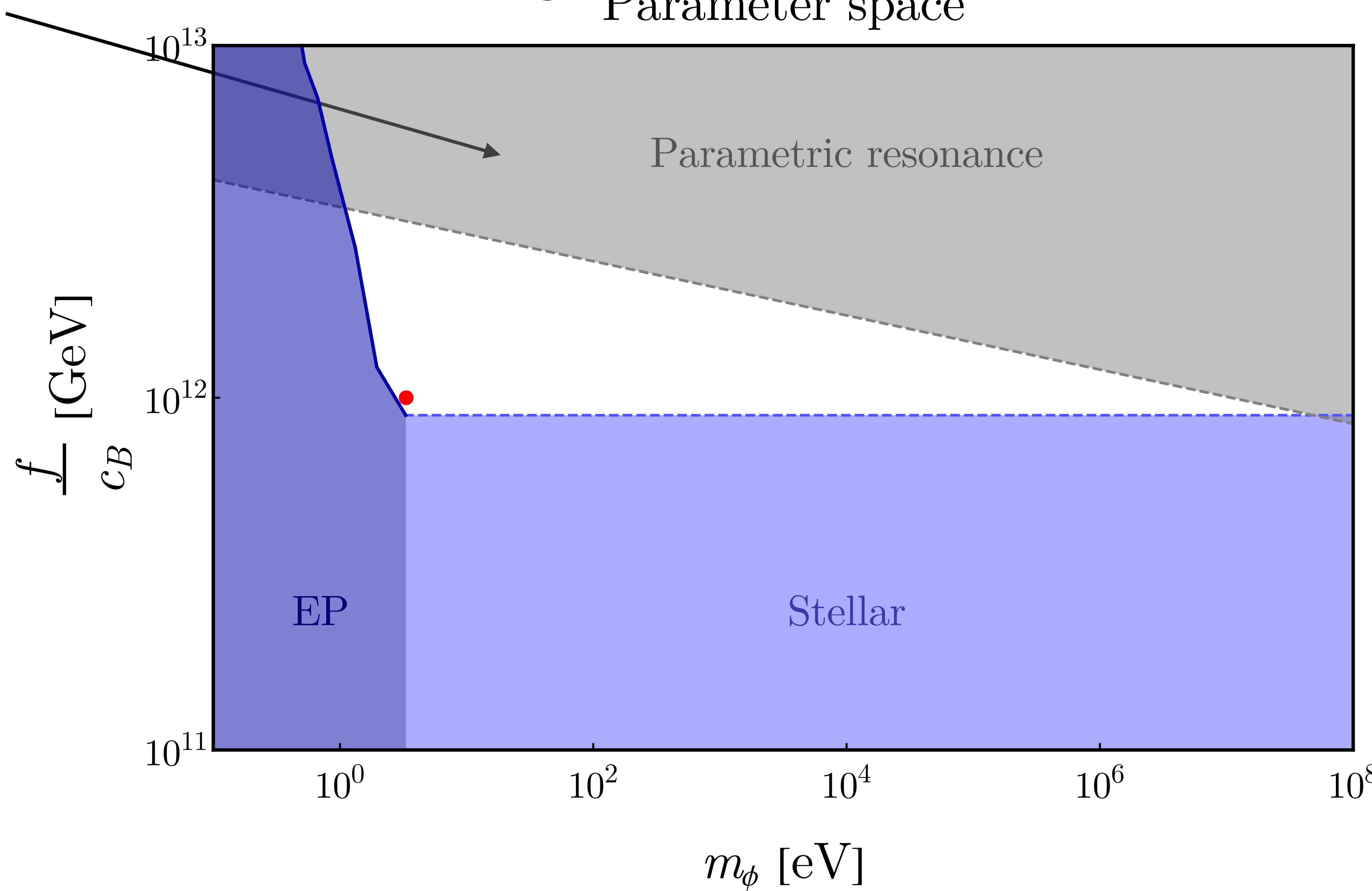




Constraints

Can evade this constraint with only a little bit of extra model building

Parameter space



Conclusion

The baryon/DM coincidence problem is a very troubling problem

So little known about DM, need to have some opinion on this

Scalar adjusts DM and baryon masses until energy densities are about equal

Model is very observable

Severe quality (hierarchy) problem

Interesting experimental signatures!

New solution that applies to almost all models of DM!

Backup Slides

Amusing Sociology

WIMP miracle

$$\frac{\rho_{DM}}{\rho_{\rm baryon}} \sim \frac{m_{DM}^2}{\alpha^2 M_{pl} 10^{-10}\,{\rm GeV}}$$

Historically WIMP masses between 10 GeV - 10 TeV

WIMP miracle was that it got within 6 orders of magnitude of the correct answer!

PNGBs of Z_N

Start with a NGB of a U(1)

$$\frac{\phi}{f} = 2\pi + \frac{\phi}{f}$$

Make it non-linearly realize a Z_N symmetry

$$\frac{\phi}{f} \rightarrow \frac{\phi}{f} + \frac{2\pi}{N} \qquad V(\frac{\phi}{f}) = V(\frac{\phi}{f} + \frac{2\pi}{N})$$

PNGBs of Z_N

Any potential for this PNGB can be written as

$$V(\phi) \propto \sum_{k=0}^{N-1} F(\frac{\phi}{f} + \frac{2\pi k}{N})$$

Written in this form, if F is independent of N, then this is a Riemann Sum!

PNGBs of Z_N

$$V(\phi) \propto \sum_{k=0}^{N-1} F(\frac{\phi}{f} + \frac{2\pi k}{N}) = \frac{N}{2\pi} \int_0^{2\pi} F(\theta) d\theta + \mathcal{O}(N^0)$$

Large N limit is independent of the PNGB

Expected since as N goes to infinity, you have a continuous shift symmetry

Convergence Theorems

Riemann sums have a lot of theorems associated with them

$$E_N(F) = \int_0^{2\pi} F(\theta) d\theta - \frac{2\pi}{N} \sum_{k=0}^{N-1} F(\frac{\phi}{f} + \frac{2\pi k}{N})$$

The potential for the PNGB comes entirely from the error in the Riemann sum in approximating an integral

Euler-Maclaurin Theorem

If the function F is analytic

Then there is a strip around the real axis from -i a to i a
where F is a holomorphic function with a bound M

$$|E_N(F)| \leq \frac{4\pi M}{e^{Na} - 1}$$

Well behaved potentials where no particle becomes massless result in exponentially suppressed PNGB masses

Light G^2 scalar

Consider N decoupled QCDs all with one new vector-like fermion

QCDs / Fermions exchange under Z_N

$$G_k \to G_{k+1} \quad \psi_k \to \psi_{k+1}$$

Scalar (non)-linearly realizes the Z_N

$$\Phi \to e^{2\pi i/N}\Phi \qquad \phi/f \to \phi/f + 2\pi/N$$

$$\Phi = f e^{i\phi/f}$$

Light G² scalar

$$\mathcal{L} \supset \sum_j \left(M + y e^{\frac{2\pi j}{N}} \Phi \right) \bar{\psi}_j \psi_j$$

Yukawa coupled scalar

$$V_{CW} = \sum_j \Lambda^2 M_j^2 + M_j^4 \log M_j^2 / \Lambda^2$$

$$\propto M^4 \left(\frac{yf}{M}\right)^N \cos\left(\frac{N\phi}{f}\right)$$

Exponentially suppressed potential