Thermal Perturbations from Cosmological Constant Relaxation

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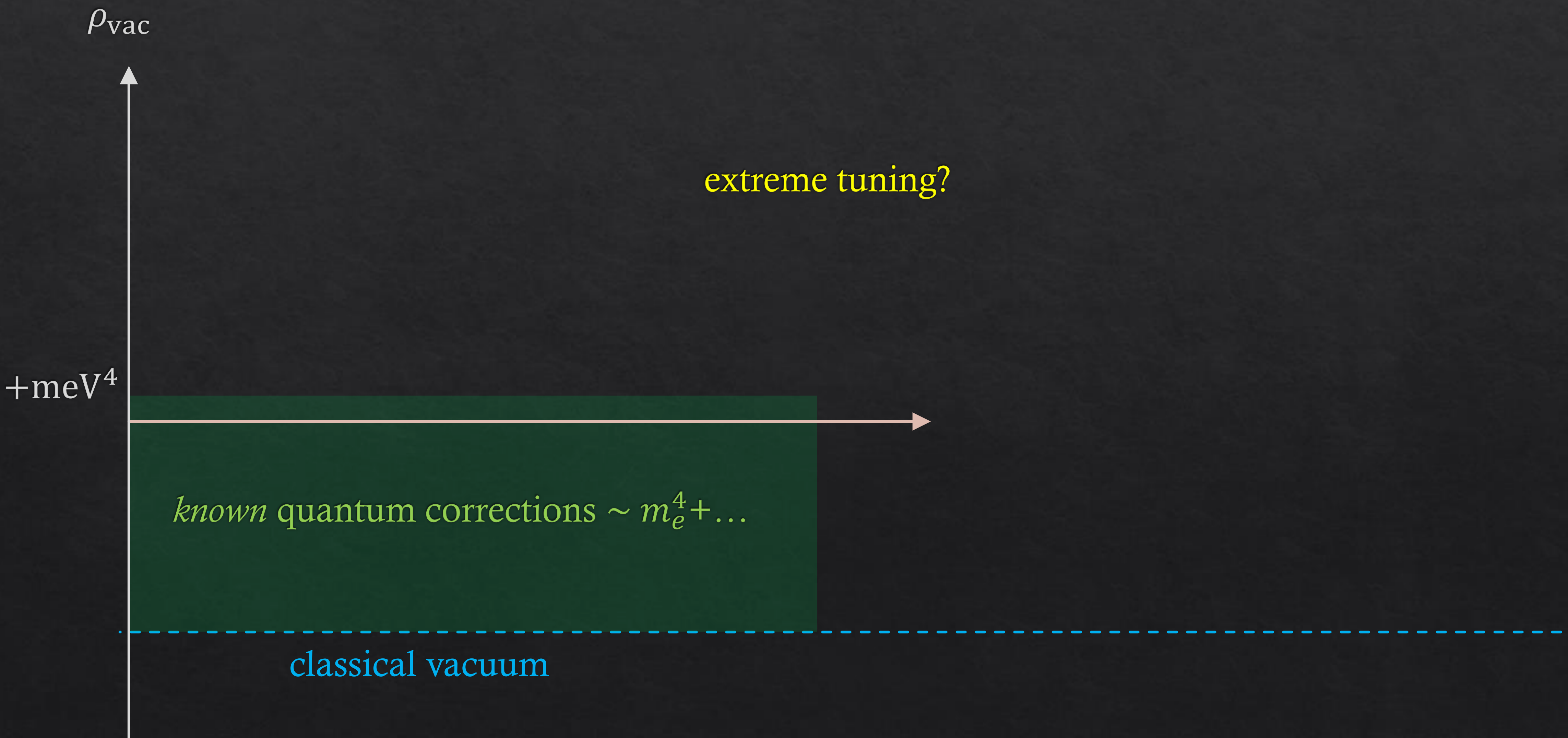
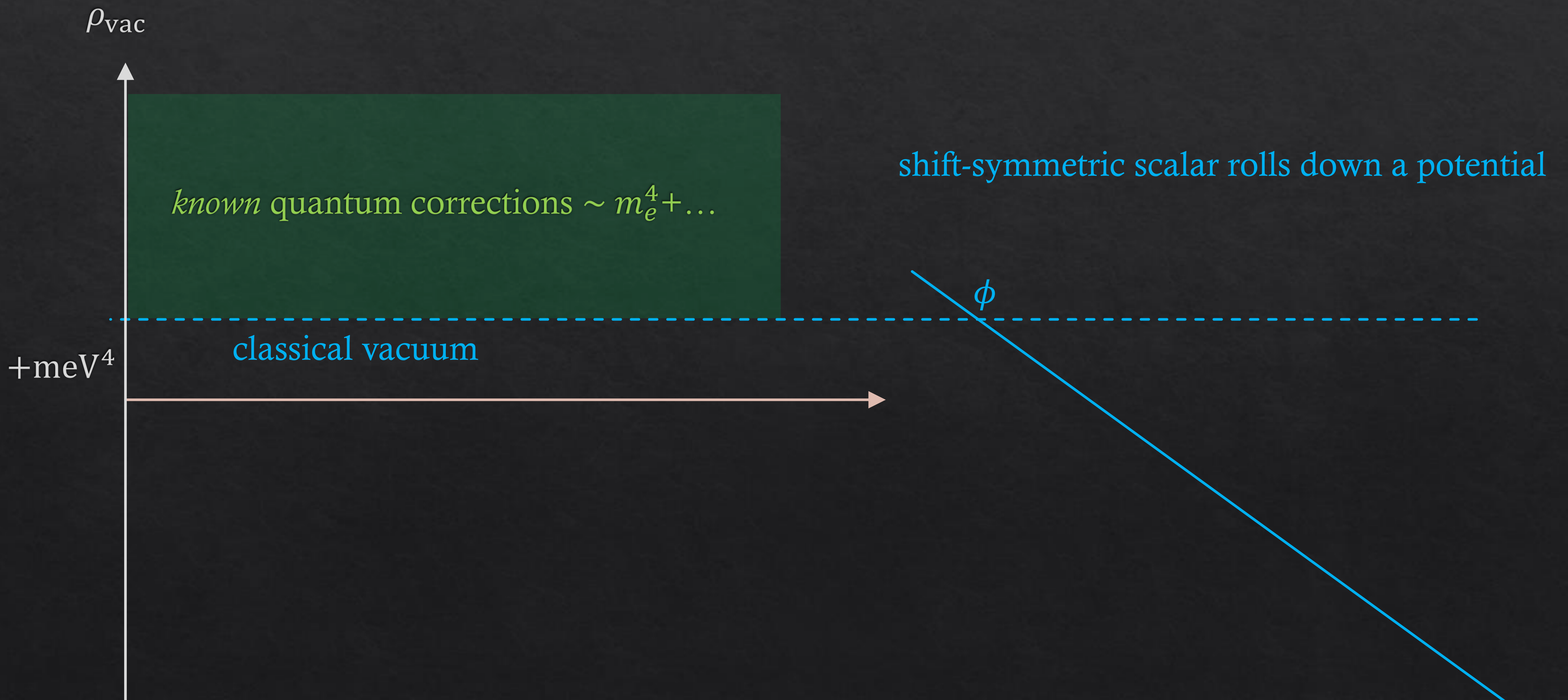
Cosmological Constant Problem



Cosmological Constant Relaxation

Abbott (1985)



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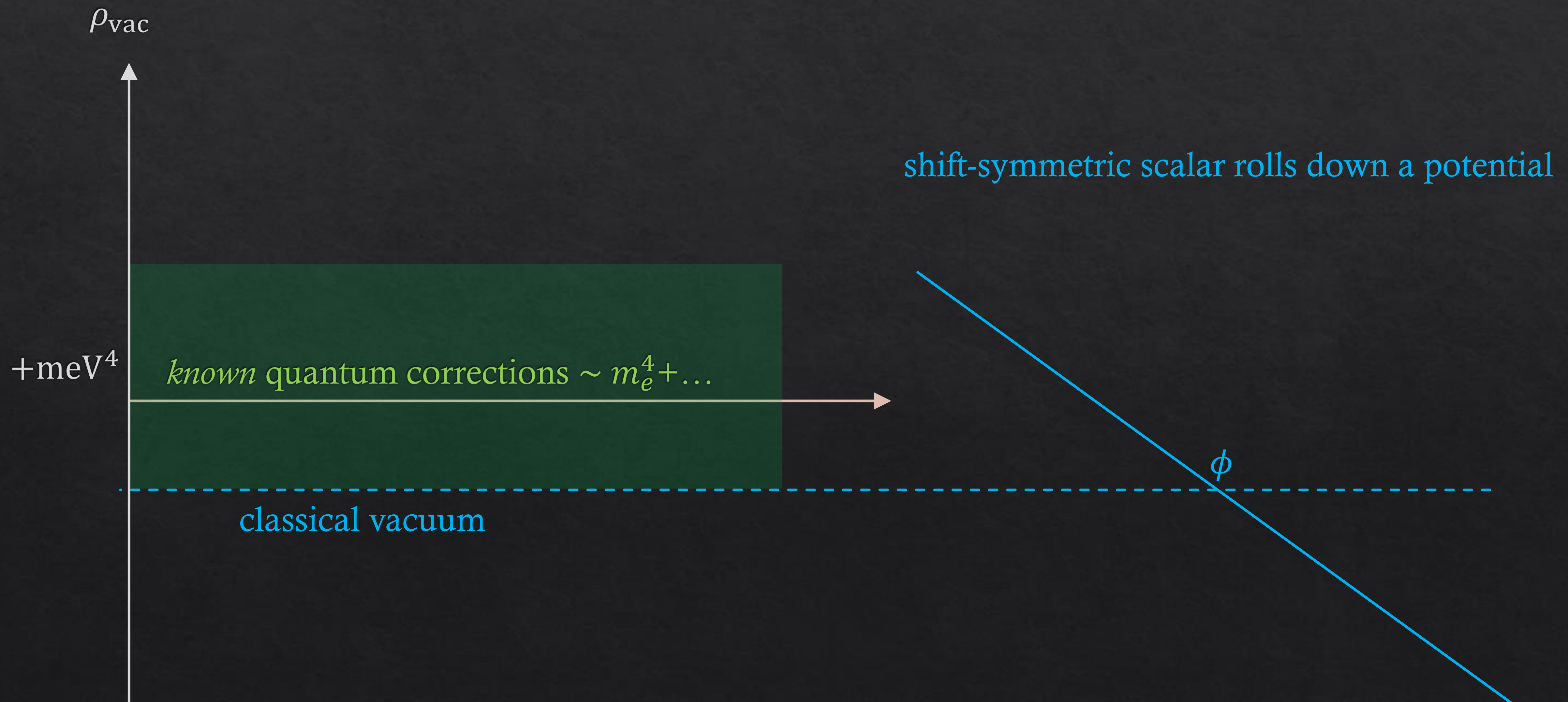
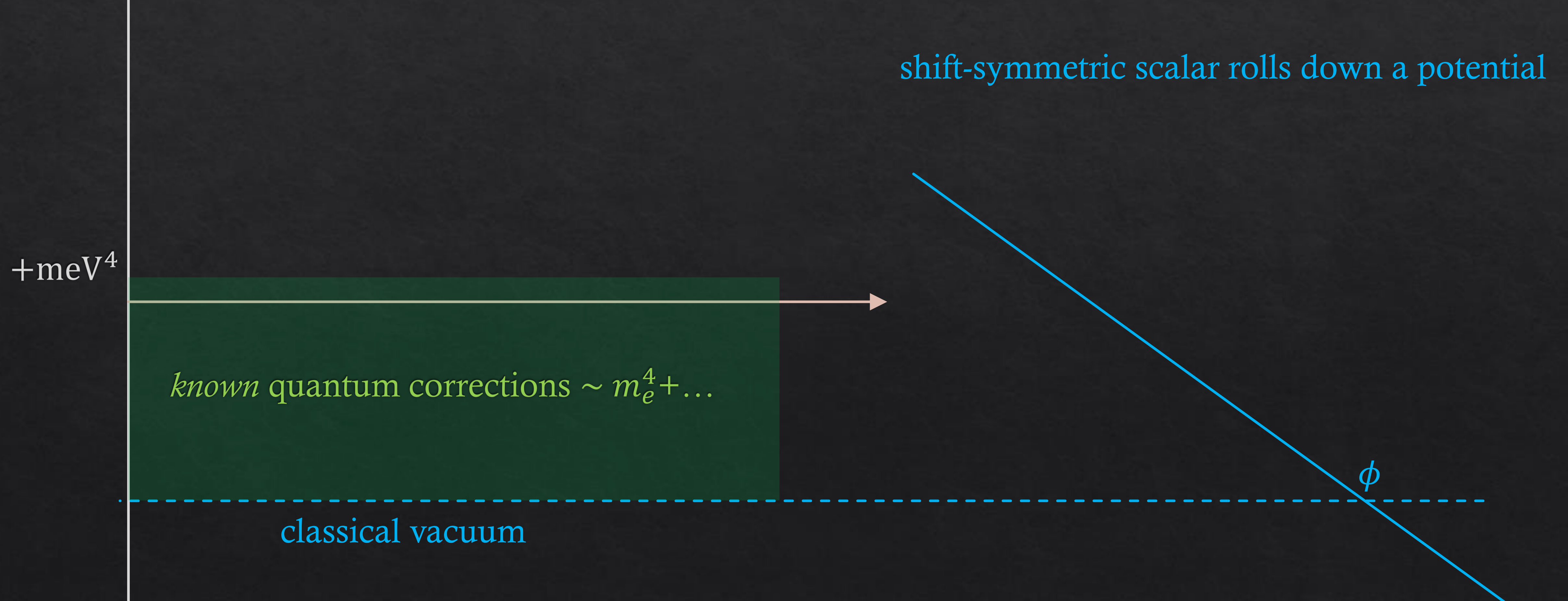


Cosmological Constant Relaxation

Abbott (1985)

- $\rho_{\text{vac}} \sim \text{meV}^4$ dynamically
- but now the universe is empty
- how to initiate hot big bang?



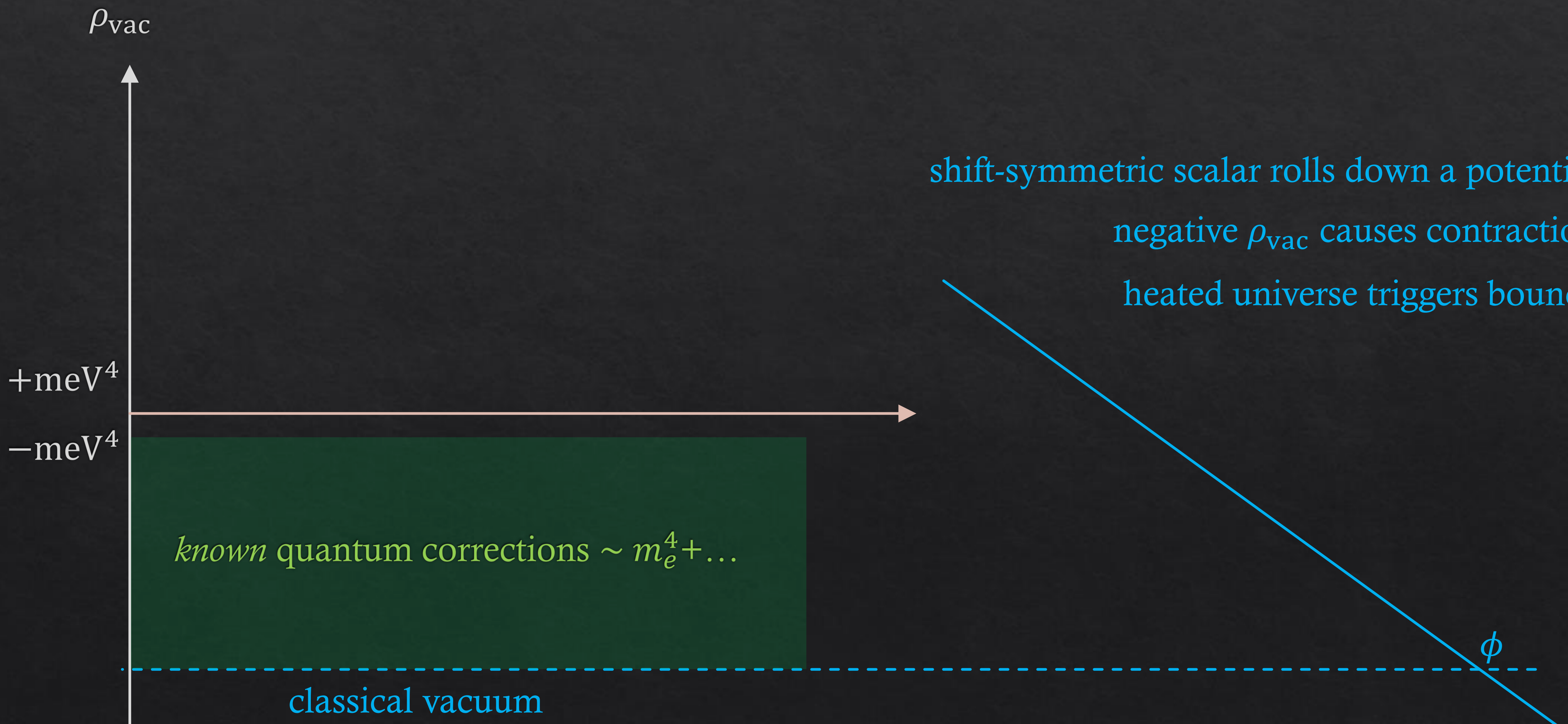
Cosmological Constant Relaxation

Graham, Kaplan, Rajendran (2019)

shift-symmetric scalar rolls down a potential

negative ρ_{vac} causes contraction

heated universe triggers bounce



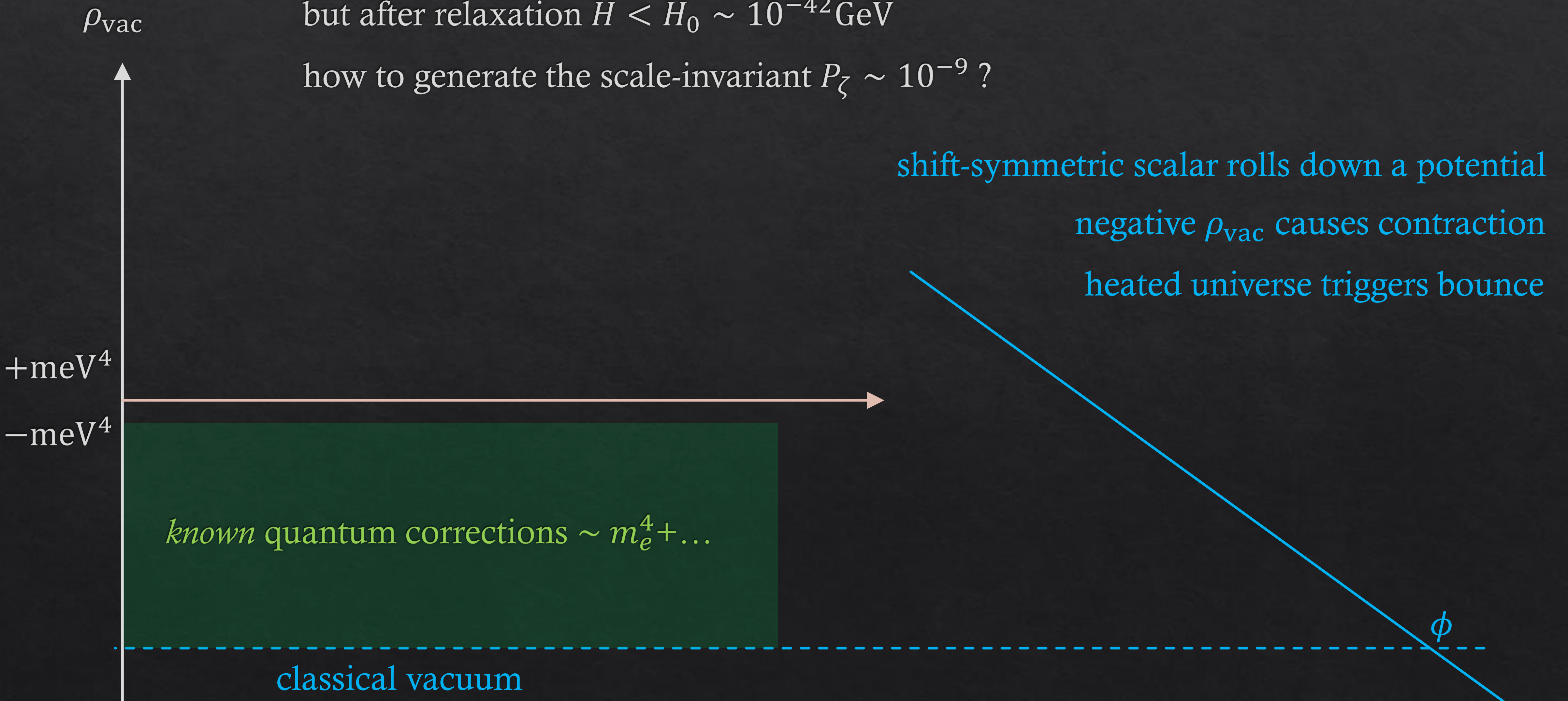
Cosmological Constant Relaxation

Graham, Kaplan, Rajendran (2019)

$\rho_{\text{vac}} \sim -\,\text{meV}^4$ (easy to fix), hot big bang

but after relaxation $H < H_0 \sim 10^{-42}\,\text{GeV}$

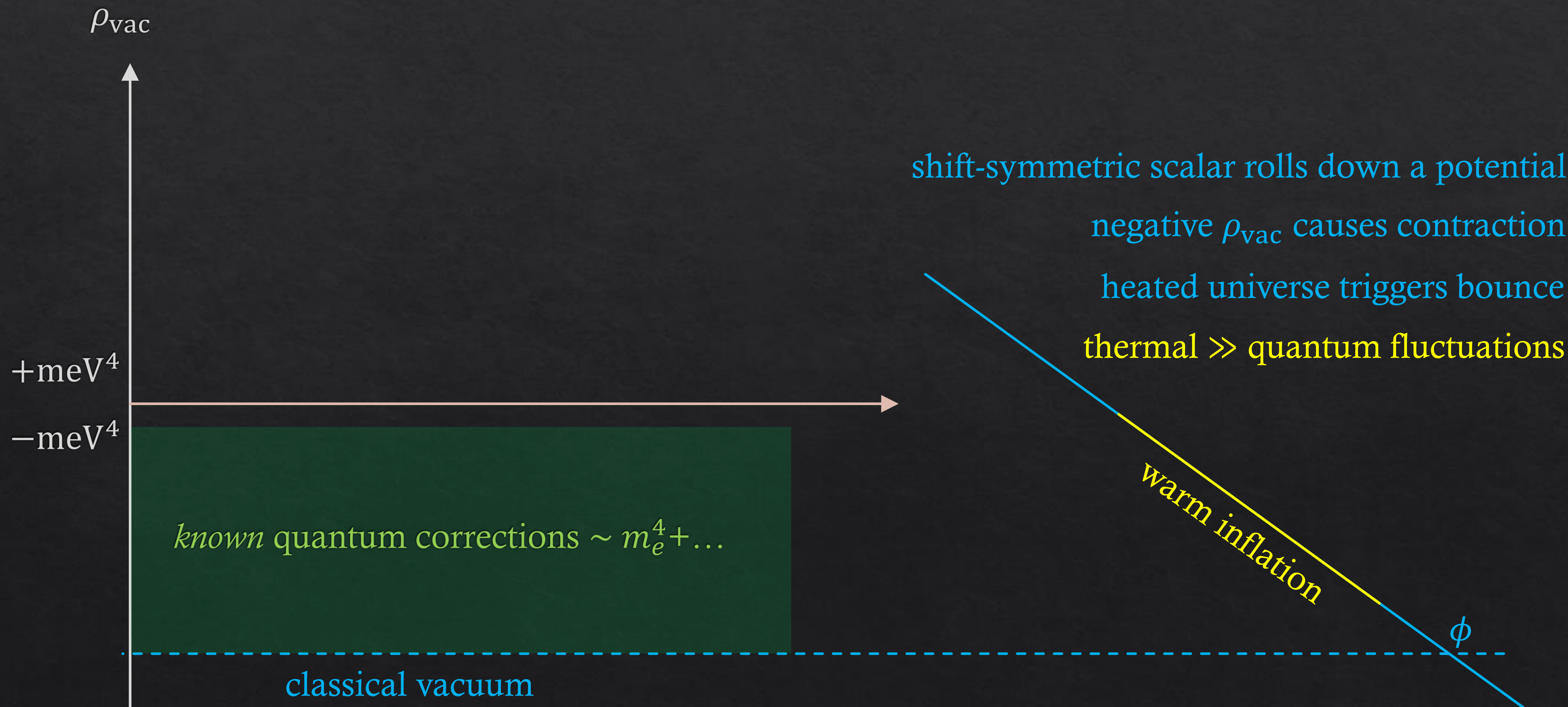
how to generate the scale-invariant $P_\zeta \sim 10^{-9}$?



Cosmological Constant Relaxation

This work:

$\rho_{\rm vac} \sim -\,\text{meV}^4$ (easy to fix), hot big bang, scale-invariant $P_\zeta \sim 10^{-9}$



The Model

$$\mathcal{L} = \cdots + \frac{1}{2}(\partial\phi)^2 - \left(-g^3\phi + \frac{1}{4}GG + \frac{\alpha}{8\pi f_G}\phi G\tilde{G}\right)$$

$\rho_{\text{vac}} = -g^3\phi$ dark $SU(N)$, deconfined

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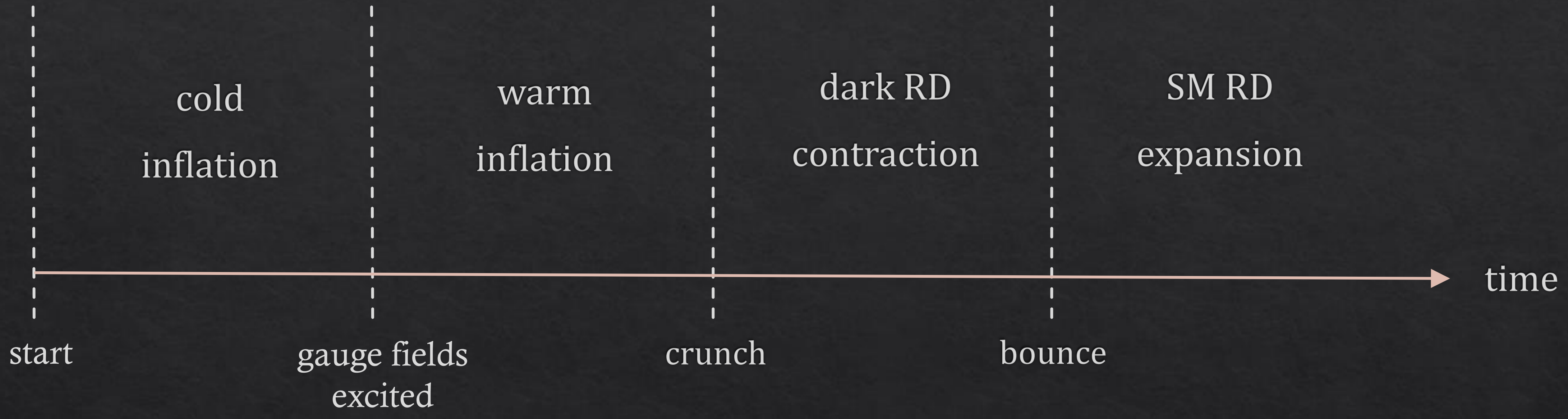

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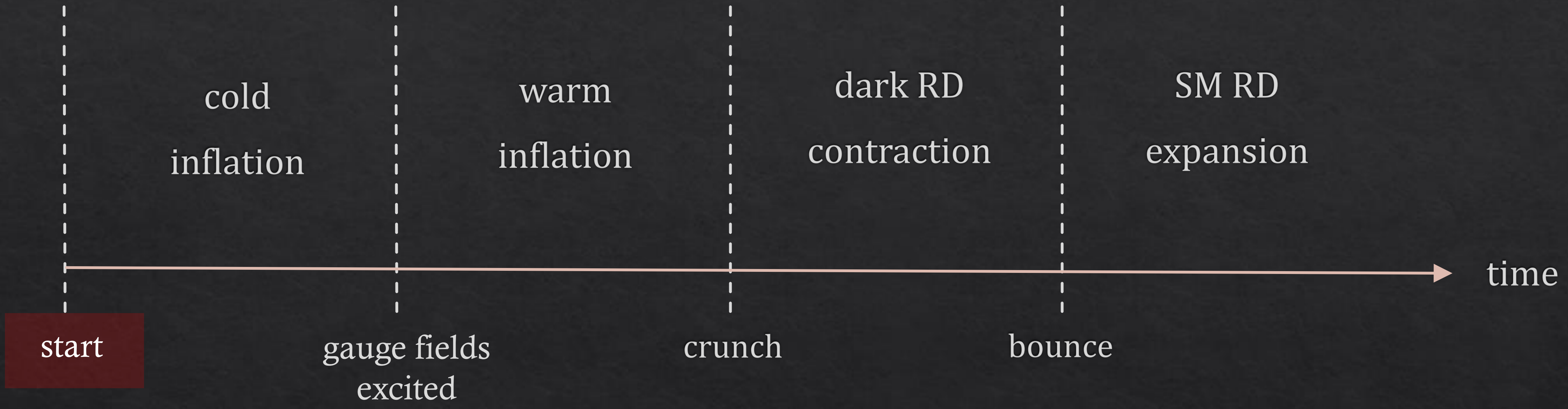

$\rho_{\rm vac}$ = large positive

Largest $\rho_{\rm vac}$ limited by $\dot{\phi}_i H_i^{-1} \gtrsim H_i$ (no eternal inflation)

The Model

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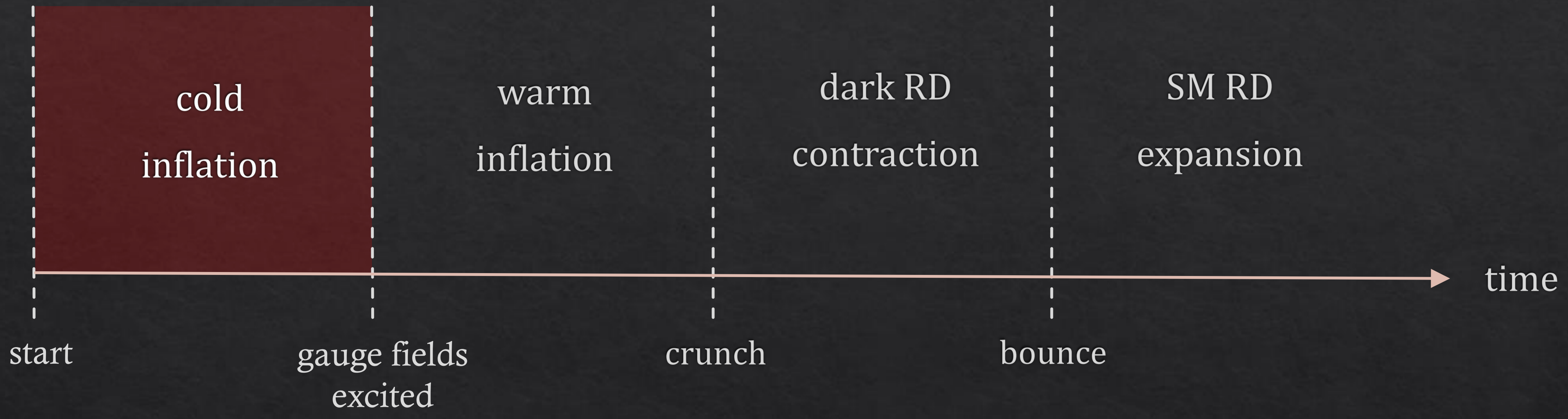

ρ_{vac} drives inflation

$\ddot{\phi} + 3H\dot{\phi} - g^3\phi = 0$

slow-roll $\dot{\phi} \sim g^3/H$

$\ddot{A}_k^{a+} + H\dot{A}_k^{a+} + [k(k - k_{\text{tach}})]A_k^{a+} + (\text{nonabelian terms}) = 0$

tachyonic modes: $k < k_{\text{tach}} = \dfrac{\alpha\dot{\phi}}{8\pi f_G}$

at this stage $k_{\text{tach}} \ll H$

The Model

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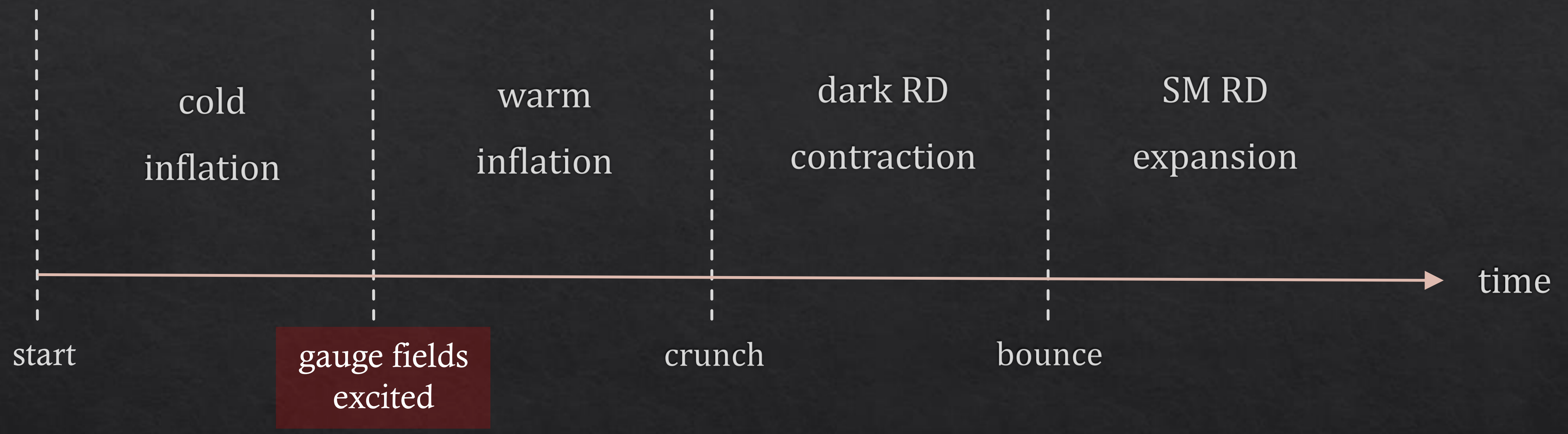

$k_{\rm tach} \gtrsim H$

tachyonic modes grow

non-abelian self-interactions lead to thermalization

The Model

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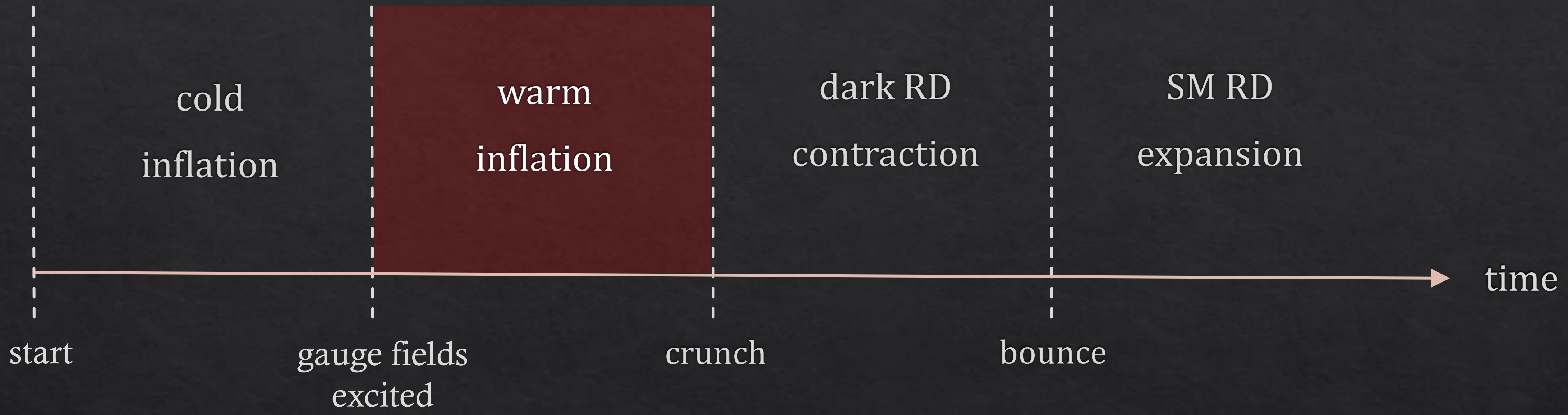
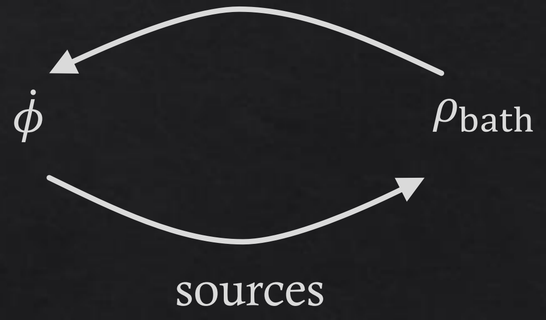


thermal friction $\Upsilon = \frac{T^3}{f^2} \gg H$



$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} - g^3 = 0$$

$$\dot{\rho}_{\rm bath} + 4H\rho_{\rm bath} = \Upsilon\dot{\phi}^2$$

steady state: $\dot{\phi} \approx \frac{g^3}{\Upsilon}$, $\rho_{\rm bath} \approx \frac{\Upsilon}{4H}\dot{\phi}^2$, until $\dot{H} \sim H^2$ $(H \sim H_{\rm end})$

to solve CC problem, need $H_{\rm end} \lesssim 10^{-42}\,\mathrm{GeV}$

The Model

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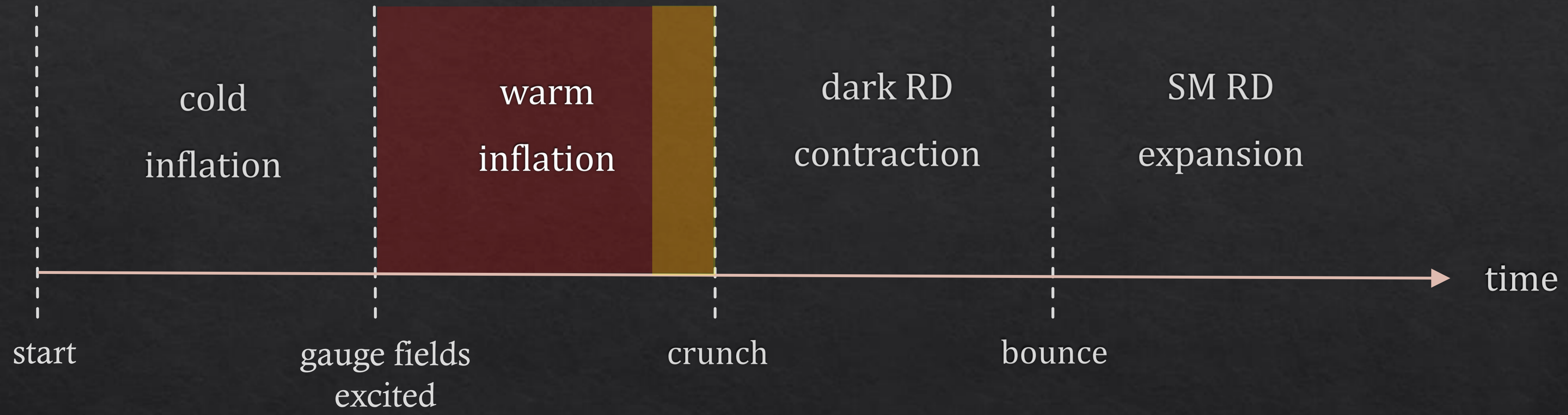

CMB scales turn superhorizon tens of e-folds before $H \sim H_{\text{end}}$

$\delta\phi$ dominated by thermal fluctuations

$P_\zeta = \#\left(H^2/\dot{\phi}\right)^2(\Upsilon/H)^8(T/H)$

slightly blue-tilted, but fixable

Bastero-Gil, Berera, Ramos 2011

The Model

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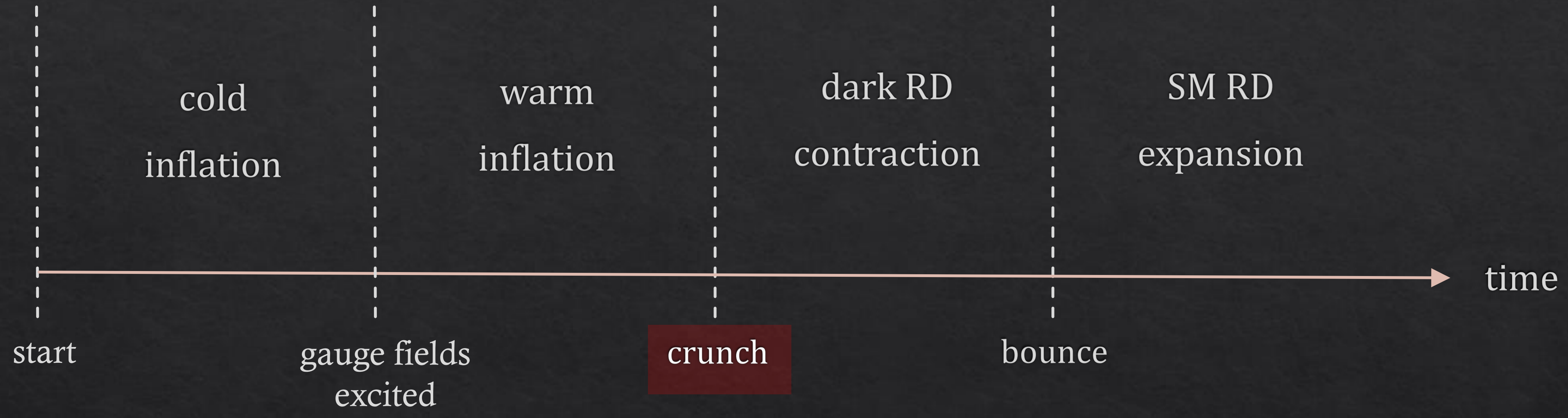

$$3M_{\text{P}}^2H^2 = \cancel{\frac{1}{2}\dot{\phi}^2} + \rho_{\text{bath}} + \rho_{\text{vac}}$$

$$M_{\text{P}}^2\dot{H} = -\cancel{\frac{1}{2}\dot{\phi}^2} - \frac{2}{3}\rho_{\text{bath}} < 0$$

warm inflation ends when $\rho_{\text{vac}} \sim \rho_{\text{bath}}$

then ρ_{vac} becomes negative and cancels the other terms

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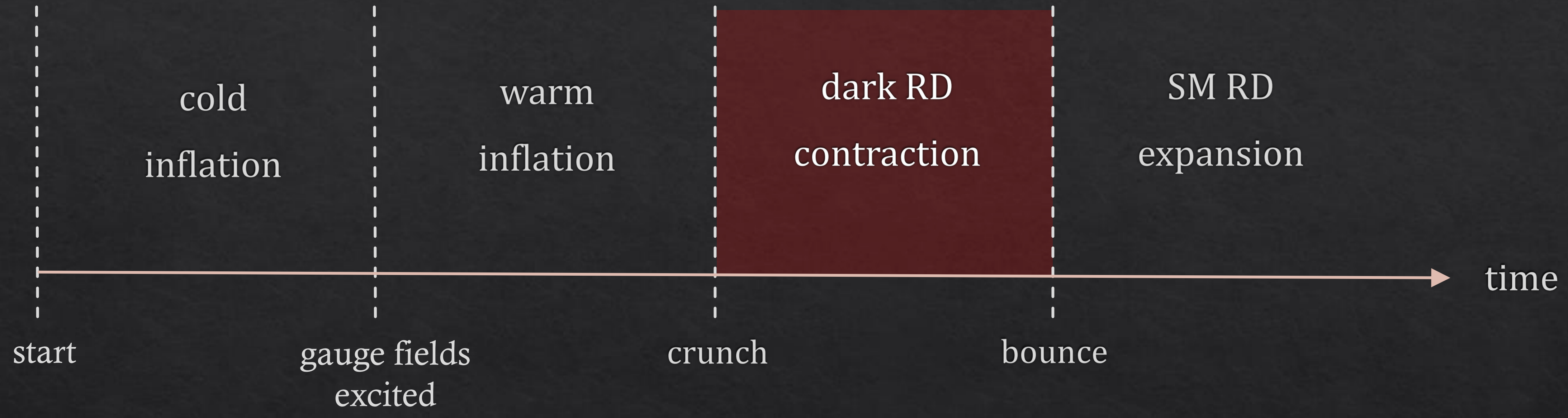

universe heats up, dark radiation dominates

$\dot{\phi}\downarrow$, $H\uparrow$: ρ_{vac} changes less and less, stalls at a negative value

to solve CC problem, need $|\rho_{\text{vac}}| \lesssim \text{meV}^4$ ($\leftrightarrow H_{\text{end}} \lesssim 10^{-42}\,\text{GeV}$)

EFT breaks down

UV completion reheats SM

The Model

$$\mathcal{L} = \cdots + \frac{1}{2}(\partial\phi)^2 - \left(-g^3\phi + \frac{1}{4}GG + \frac{\alpha}{8\pi f_G}\phi G\tilde{G}\right)$$

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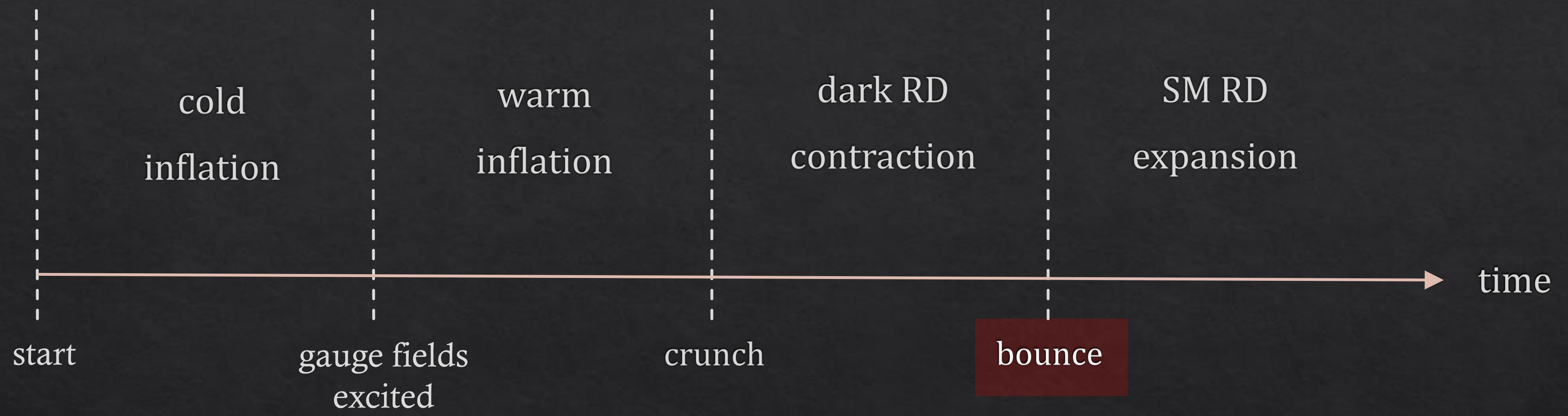

UV completion excites NEC-violating sector

The Model

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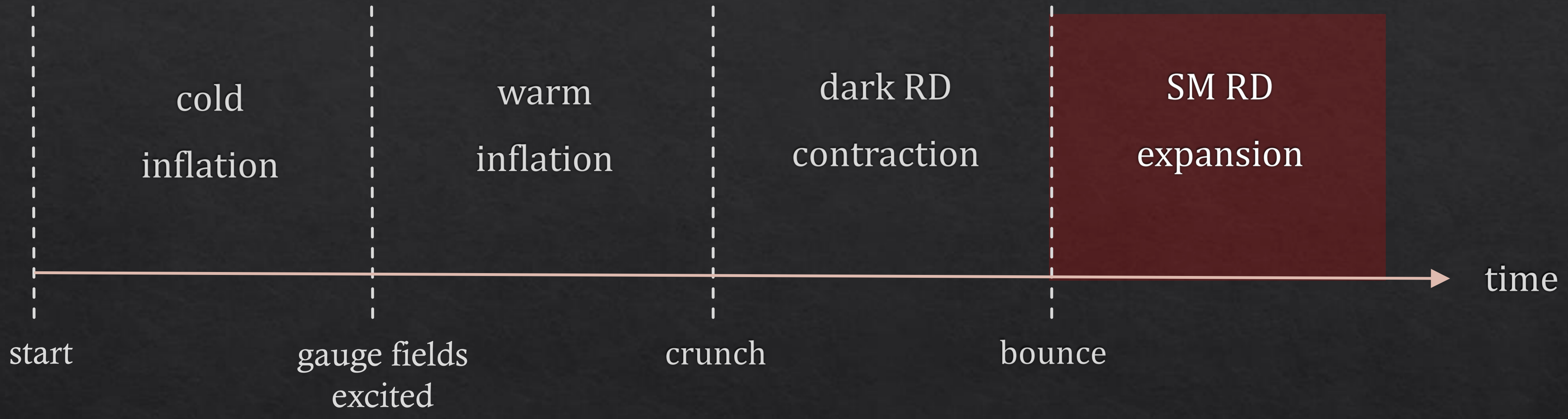


hot big bang

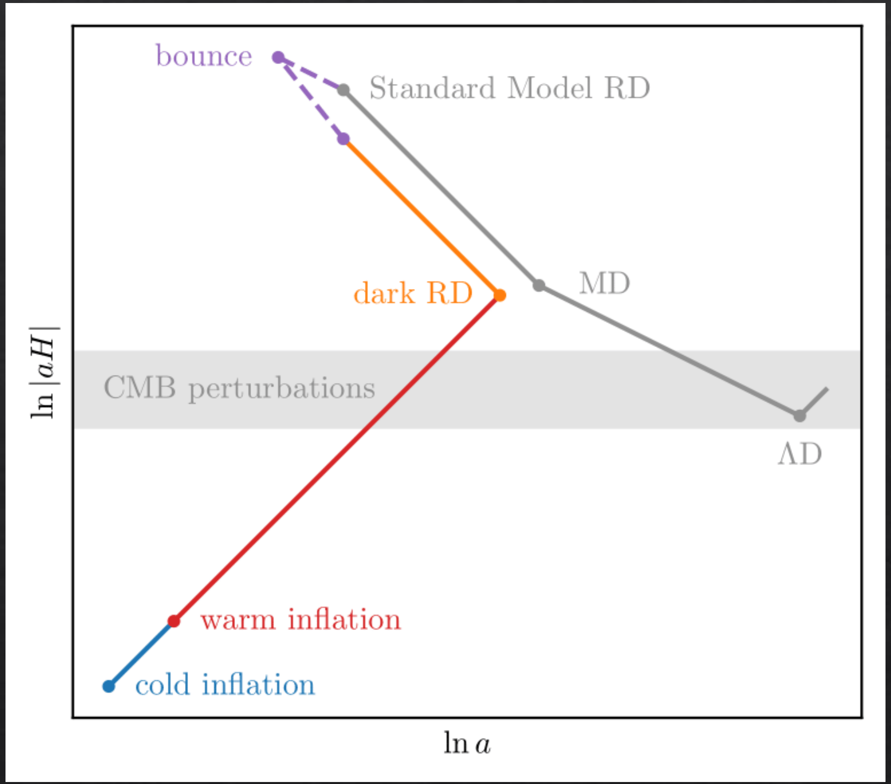
$|\rho_{\text{vac}}| \lesssim \text{meV}^4$

$P_\zeta \sim 10^{-9}$ at CMB scales

Summary

- Dynamical relaxation can solve the cosmological constant problem
- Showed a simple model that:

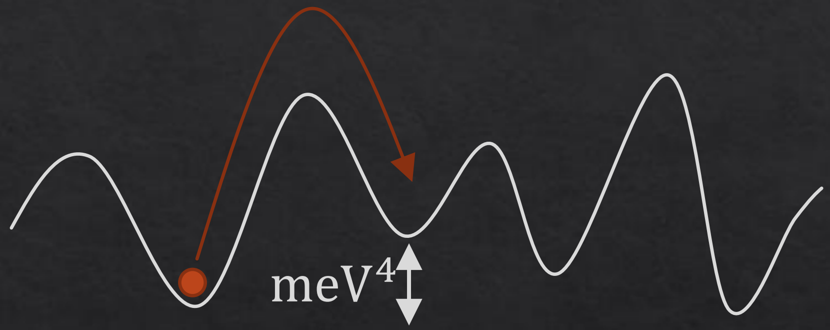
  relaxes $\rho_{\rm vac}$, reheats the universe, and explains $P_\zeta \sim 10^{-9}$
- Testable:
  - a rolling scalar ϕ $\rightarrow$ $w_{\rm DE}(t) \neq -1$, derivative couplings to SM
  - dissipation $\rightarrow$ dark radiation, non-gaussianities
  - contraction and bounce $\rightarrow$ scalar and tensor power spectrum
- Future: different variants, more complete, more realistic



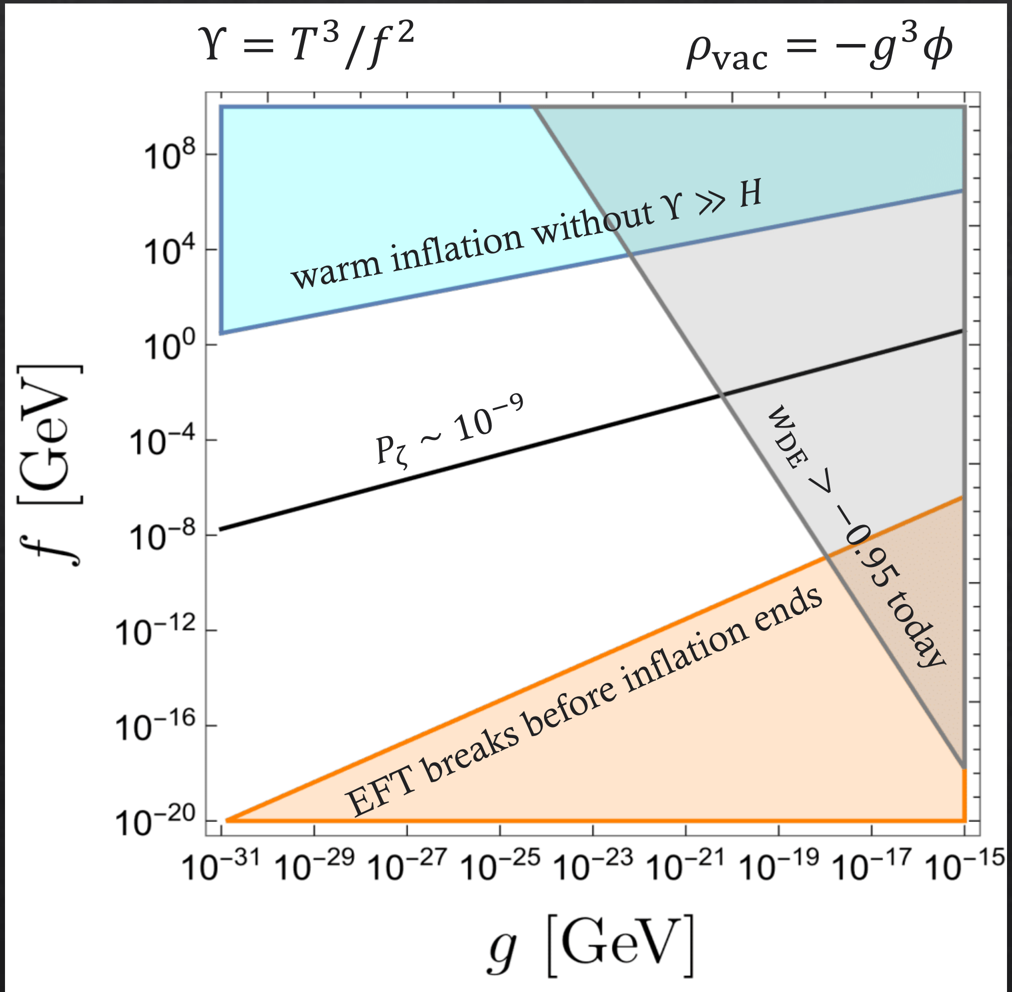
Thank You

Unspecified Ingredients

- Non-singular bounce to reheat the universe
  - NEC-violation, vorticity, relevant dofs excited at high temperatures
- Reheating the Standard Model
  - higher dimensional operators turn on at high temperatures
- From $\rho_{\rm vac} \sim -\,\mathrm{meV}^4 \to +\mathrm{meV}^4$
  - phase transition in a separate sector (not in the EFT)
- Red scalar spectral tilt
  - $n_s - 1 = \frac{6}{7}(11\epsilon_V - 8\eta_V)$, $\quad \epsilon_V \propto \left(\frac{V'}{V}\right)^2$, $\quad \eta_V \propto \frac{V''}{V}$
  - couple ϕ to another (confined) gauge sector



Main Constraints



- $w_{DE} \approx \frac{-(2\text{ meV})^4 + \rho_{DR,0}/3}{(2\text{ meV})^4 + \rho_{DR,0}} < -0.95$ and $\rho_{DR,0} \sim \left(\frac{f^2 g^6}{H_0}\right)^{4/7}$
- $T_{\text{end}} = (M_P f^2 g^6)^{1/9} < \frac{f_G}{\alpha}$
- $P_\zeta \sim 10^{-13}\left(\frac{g^{12} M_P^{11}}{f^{23}}\right)^{\frac{2}{3}} \sim 10^{-9}$
- $H_{\text{strong}} \gg H_{\text{end}}$ ($\Upsilon \gg H \rightarrow$ the above expression holds)

CC Relaxation Facts

- Highest ρ_{vac} that can be relaxed: $(100\ \mathrm{MeV})^4$ (or GeV^4 without $P_\zeta \sim 10^{-9}$)
- Number of e-folds $\sim \frac{M_\mathrm{P}^2 H_\mathrm{i}^4}{g^6} \lesssim \left(\frac{M_\mathrm{P}}{g}\right)^2 \sim 10^{76}$
- Total amount of time $\sim \frac{M_\mathrm{P}^2 H_\mathrm{i}^3}{g^6} \lesssim \frac{M_\mathrm{P}^2}{g^3} \sim 10^{58}$ yr
- Field excursion $\sim \frac{M_\mathrm{P}^2 H_i^2}{g^3} \lesssim 10^{38}\ M_\mathrm{P}$

Gauge Field Thermalization

- $-\frac{1}{4}\langle G^2\rangle_H \sim 10^{-4}\frac{e^{2\pi\xi}}{\xi^3}H^4$ (tachyonic growth and Hubble dilution balance, Anber & Sorbo 2009)
- $-\frac{1}{4}\langle G^2\rangle_{\mathrm{NL}} \sim \frac{(\xi H)^4}{\alpha}$ (non-abelian terms become important)
- $-\frac{1}{4}\langle G^2\rangle_{\mathrm{th}} \sim \frac{10^{-5}}{\alpha^8}H^4$ (thermalization rate beats Hubble, $\alpha^2 T_{\mathrm{th}} \gtrsim H$)
- $\alpha^2 T_{\mathrm{th}} > H$ as soon as the gauge fields become non-linear if $N_c\alpha \gtrsim 0.1$

Warm Inflation Details

- $\Upsilon = T^3/f^2, \quad f \sim 0.1\alpha^{-5/2} f_G$
- $\ddot{\phi} + (3H + \Upsilon)\dot{\phi} - g^3\phi = 0$
- $\dot{\rho}_{\text{bath}} + 4H\rho_{\text{bath}} = \Upsilon\dot{\phi}^2$
- steady state $\dot{\phi} \approx \frac{g^3}{\Upsilon + 3H}, \qquad \rho_{\text{bath}} \approx \frac{\Upsilon}{4H}\dot{\phi}^2$
- weak regime $(\Upsilon \lesssim H) : \dot{\phi} \propto H^{-1}, \quad T \propto H^{-3}$
- strong regime $(\Upsilon \gtrsim H) : \dot{\phi} \propto H^{-3/7}, \qquad T \propto H^{-1/7}$
- $H_{\text{end}} = \left(\frac{f^4 g^{12}}{M_P^7}\right)^{1/9}, \qquad T_{\text{end}} = \left(M_P f^2 g^6\right)^{1/9}$