Reheating after Axion Inflation

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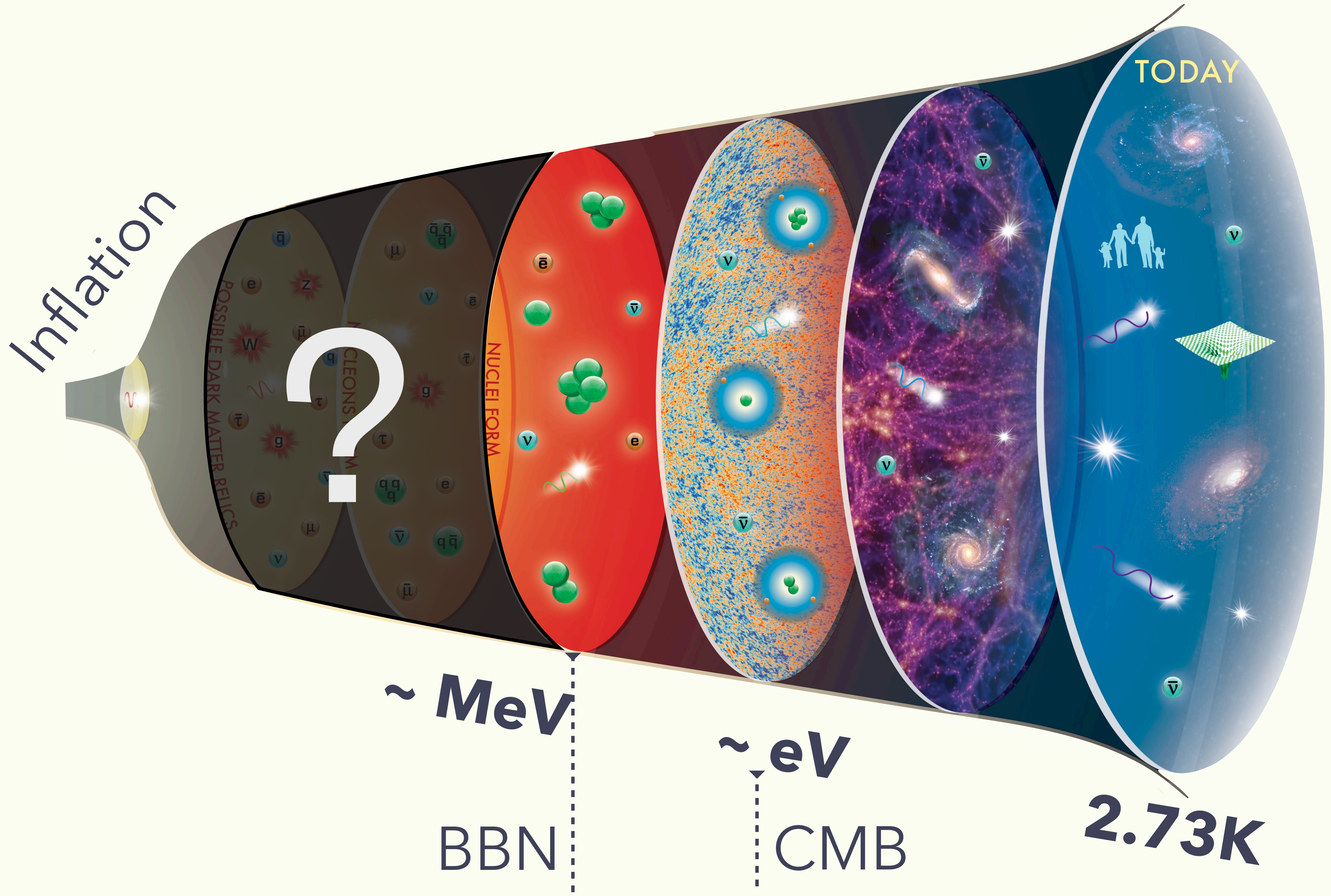
w/ T.Fujita, T.Tsuji

2503.01228

Introduction

Inflationary Cosmology



- Cosmic Inflation
  - Solve Horizon/Flatness problems
  - Provide the seeds of the structure of Universe
  - Predict slightly red-tilted spectrum

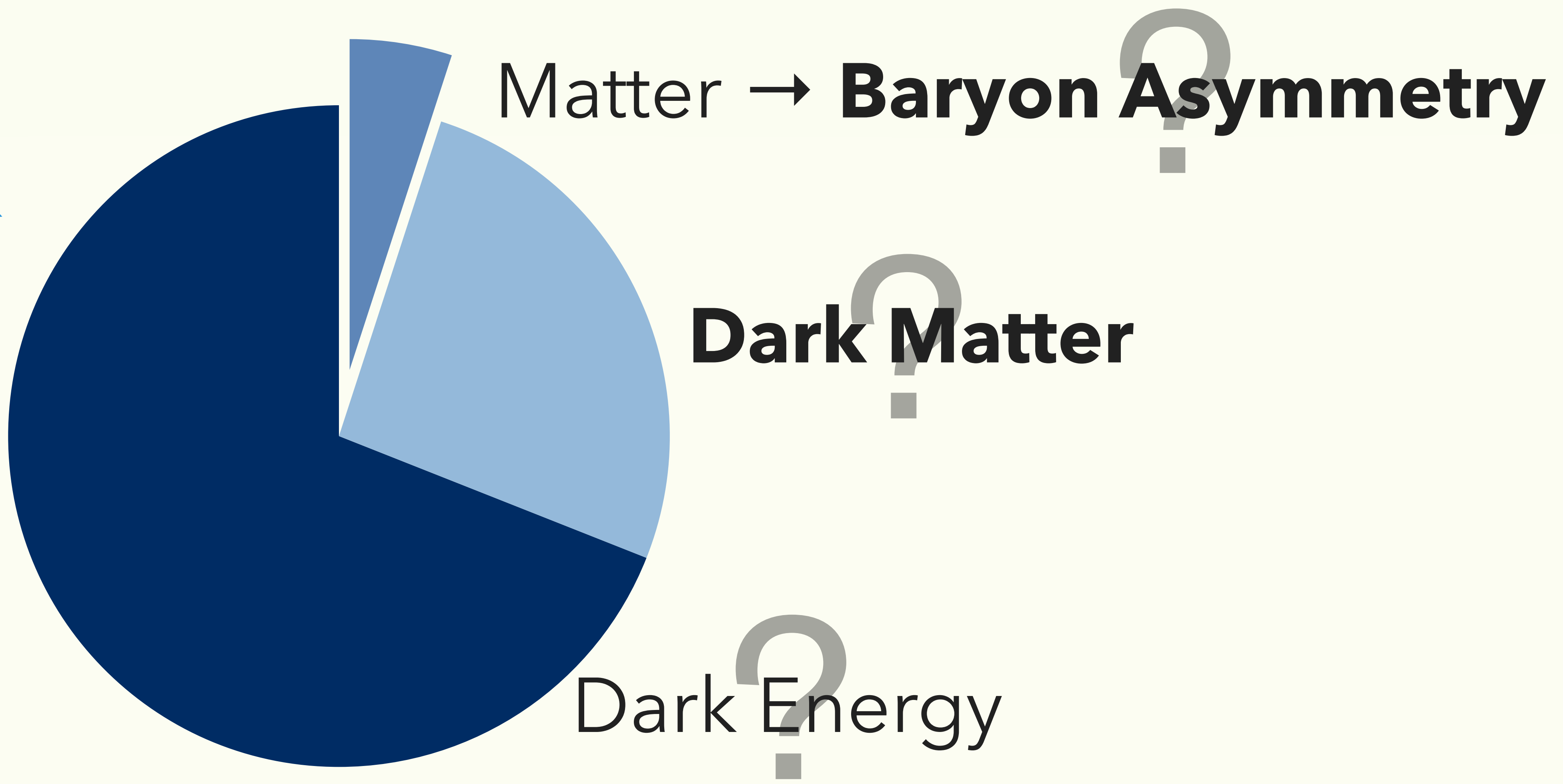
?

Reheating

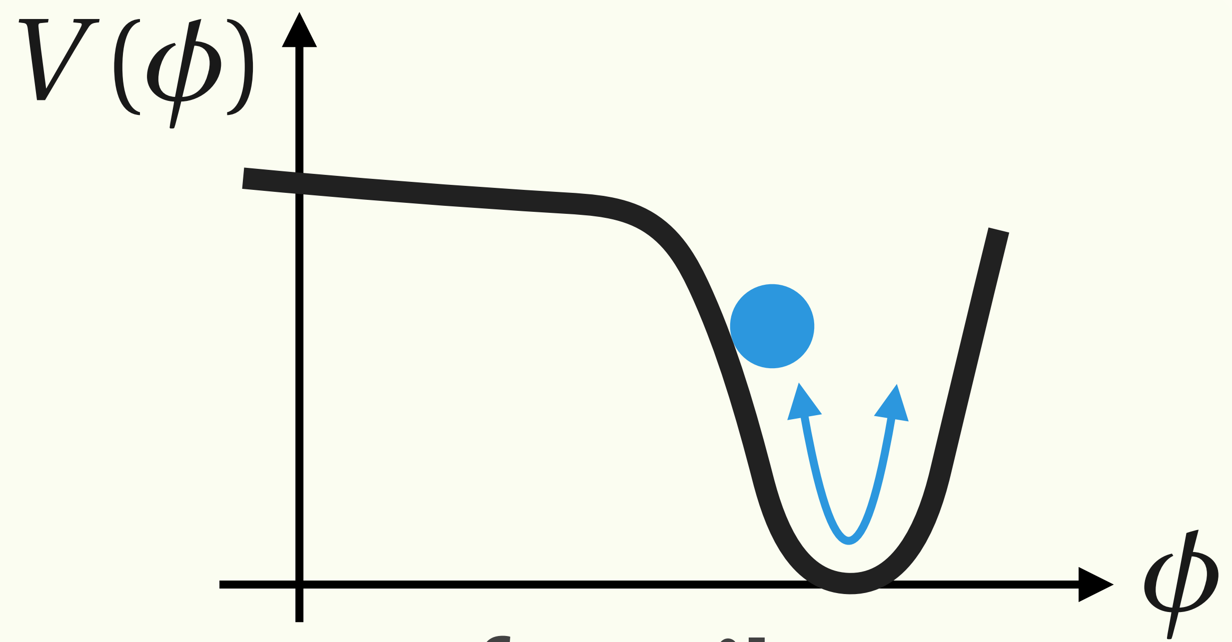
?

Thermal plasma

- Big Bang Nucleosynthesis
- Cosmic Microwave Background



Reheating and Inflation



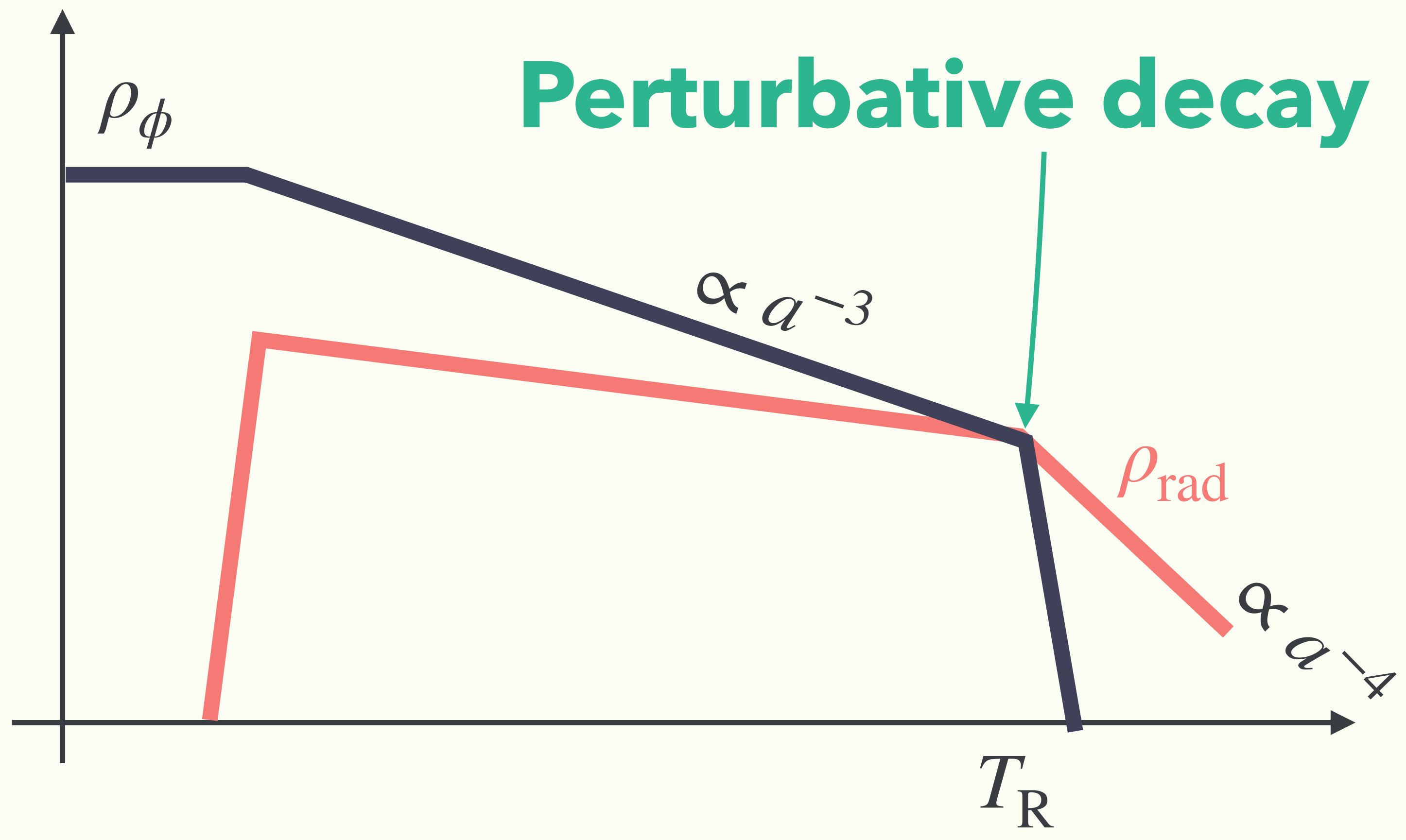
out of equil.
Inflaton condensate

Decay

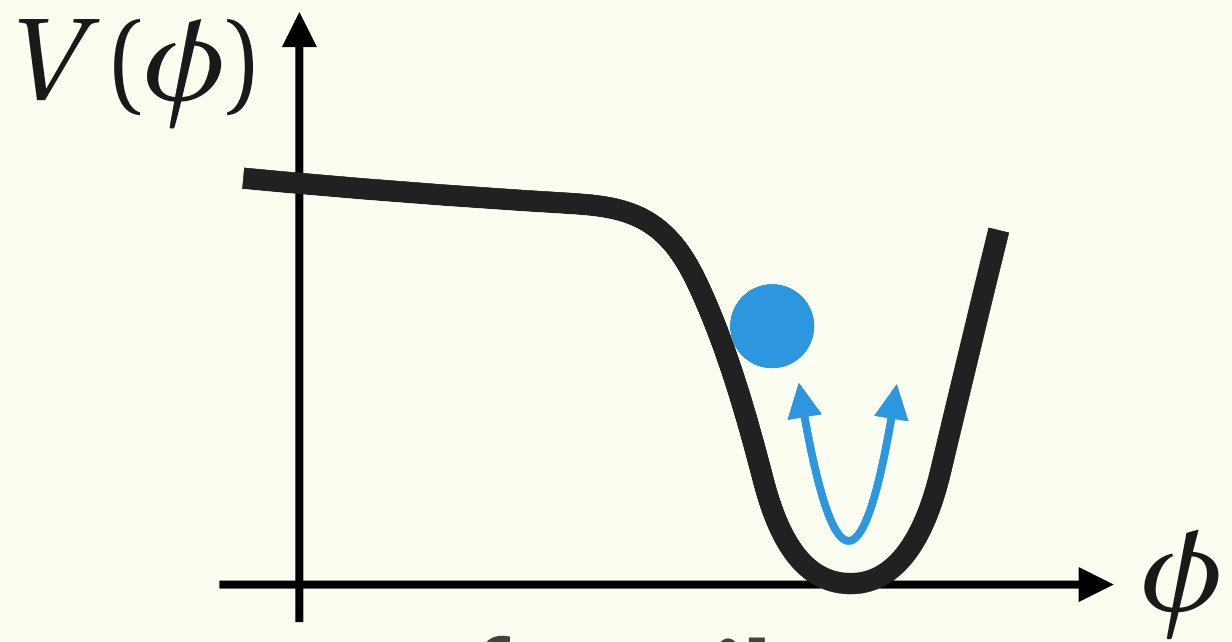
Radiation

Thermal equil.

- Completion of reheating?



Reheating and Inflation



out of equil.
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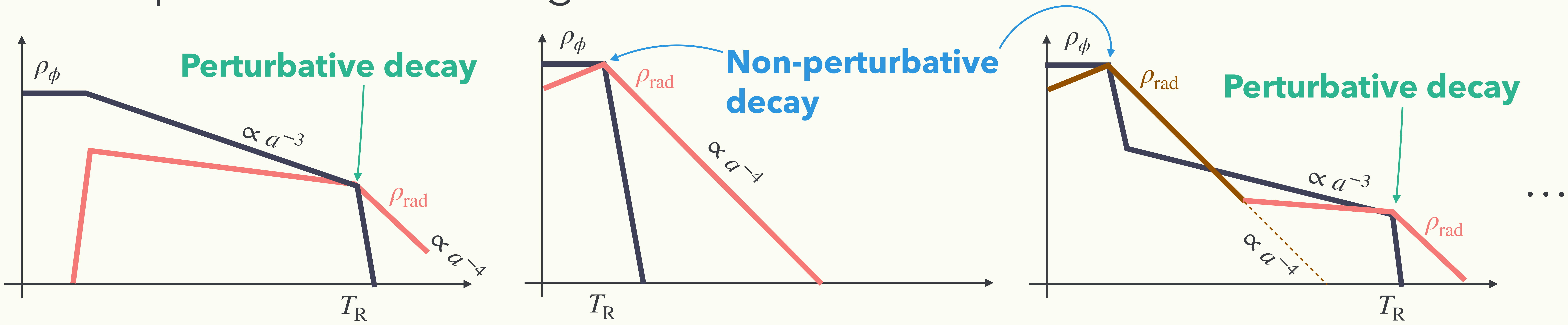
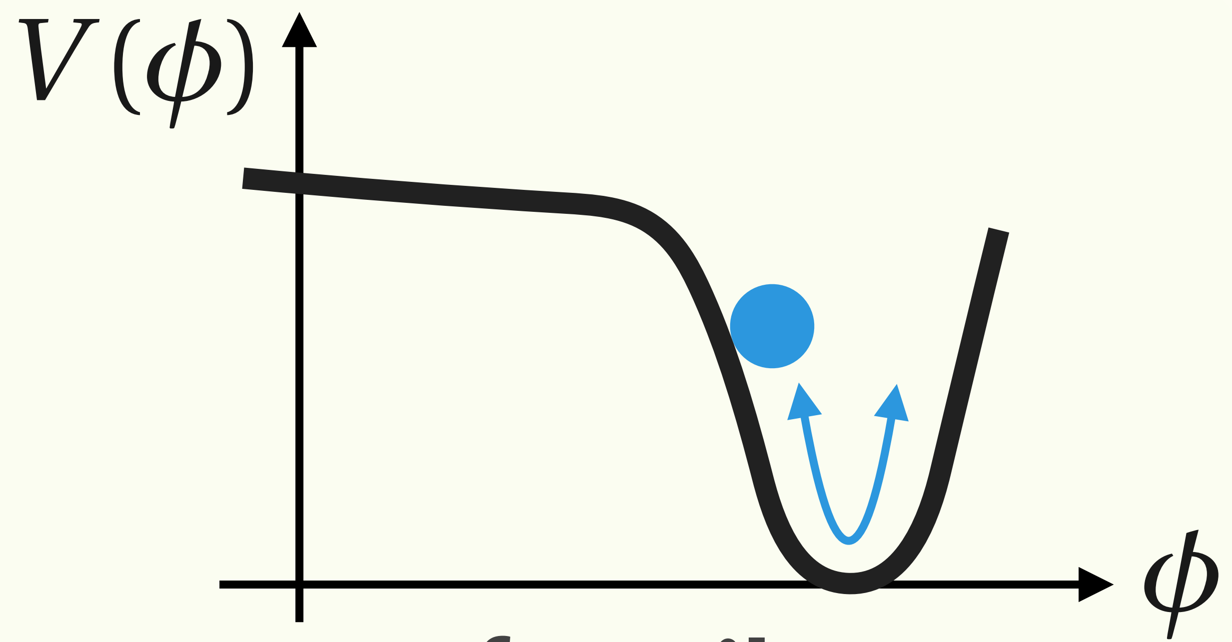


Reheating and Axion Inflation



out of equil.
Inflaton condensate

Decay

Chern–Simons coupling $\phi F\tilde{F}$

Radiation

Thermal equil.

- Approximate shift symmetry protects the flatness
- **Tachyonic instability** provides rich phenomenology
  - Non-Gaussianity/CP violation in the scalar/tensor perturbations
  - Enhancement of perturbations at small scales
  - Baryogenesis ...

but huge complications

Axion Inflation + Pure U(1) as a warm up

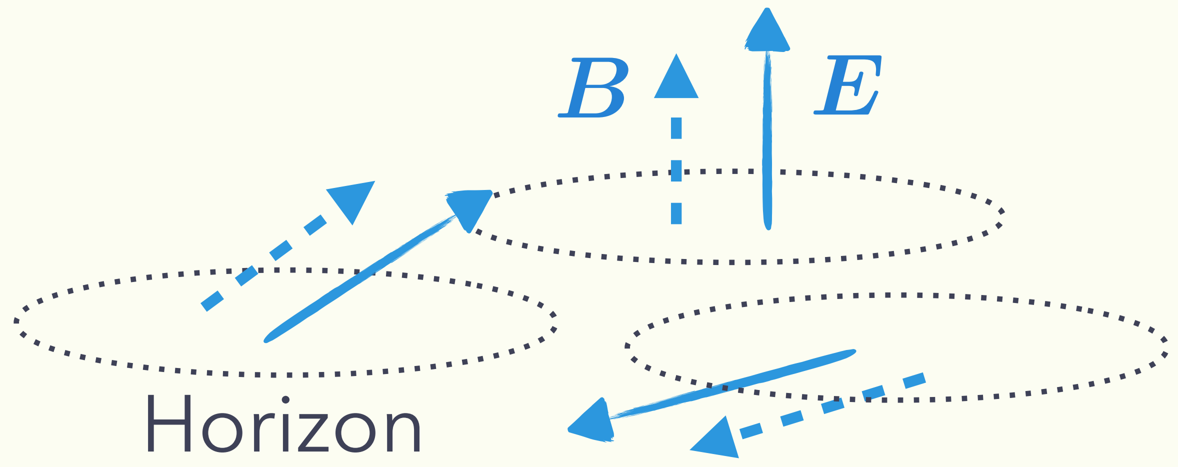
$$\mathcal{L}_{\text{inf}} = \frac{1}{2}\left(\partial\phi\right)^2 - V(\phi)$$

Decay

Chern–Simons coupling $\dfrac{\phi}{8\pi\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu}$

$$\mathcal{L}_{\text{rad}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

- **Tachyonic instability** in one polarization
  - Equation of motion for gauge fields under $\dot{\phi} \neq 0$



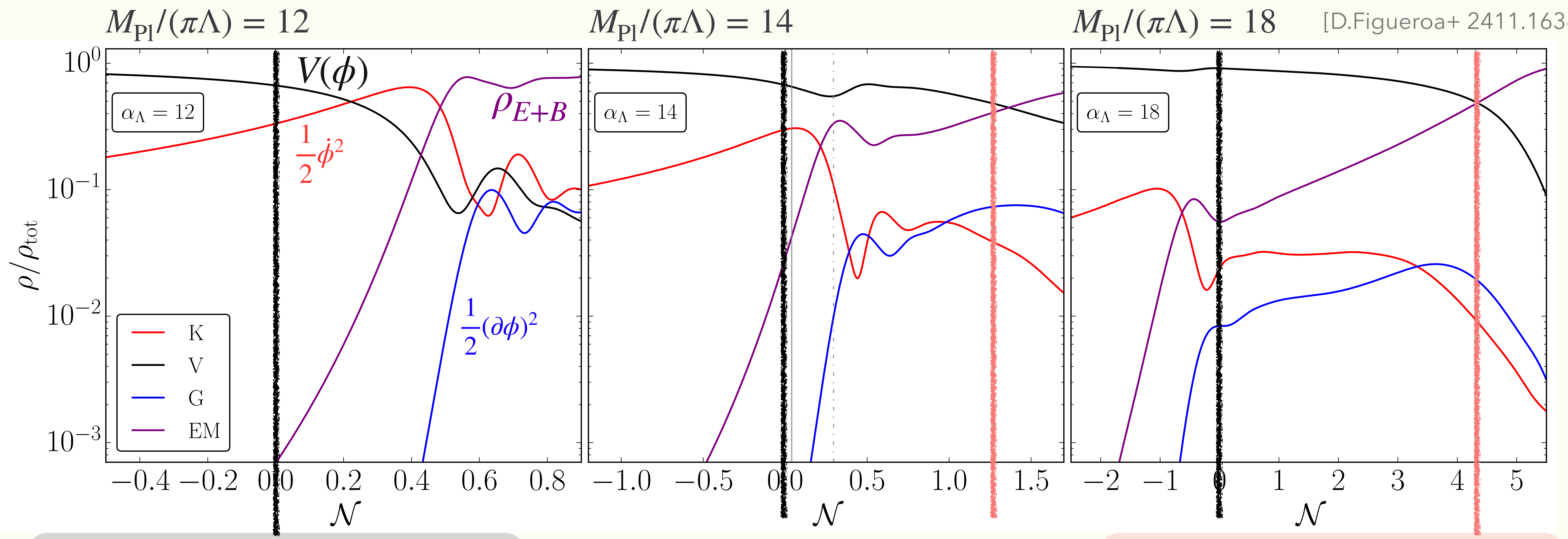
$$0 = \left[\partial_\eta^2 + k\left(k \pm \frac{\phi'}{2\pi\Lambda}\right)\right]A_\pm(\eta, \boldsymbol{k}) \quad \text{for } i\boldsymbol{k} \times \boldsymbol{e}_\pm(\boldsymbol{k}) = \pm\, k\boldsymbol{e}_\pm(\boldsymbol{k})$$

$$\begin{cases} A_+ \nearrow & \text{for } \ \dot{\phi} < 0 \\ A_- \nearrow & \text{for } \ \dot{\phi} > 0 \end{cases}$$

Axion Inflation + Pure U(1) as a warm up

- Significant gauge-field production already during inflation

[D.Figueroa+ 2411.16368]



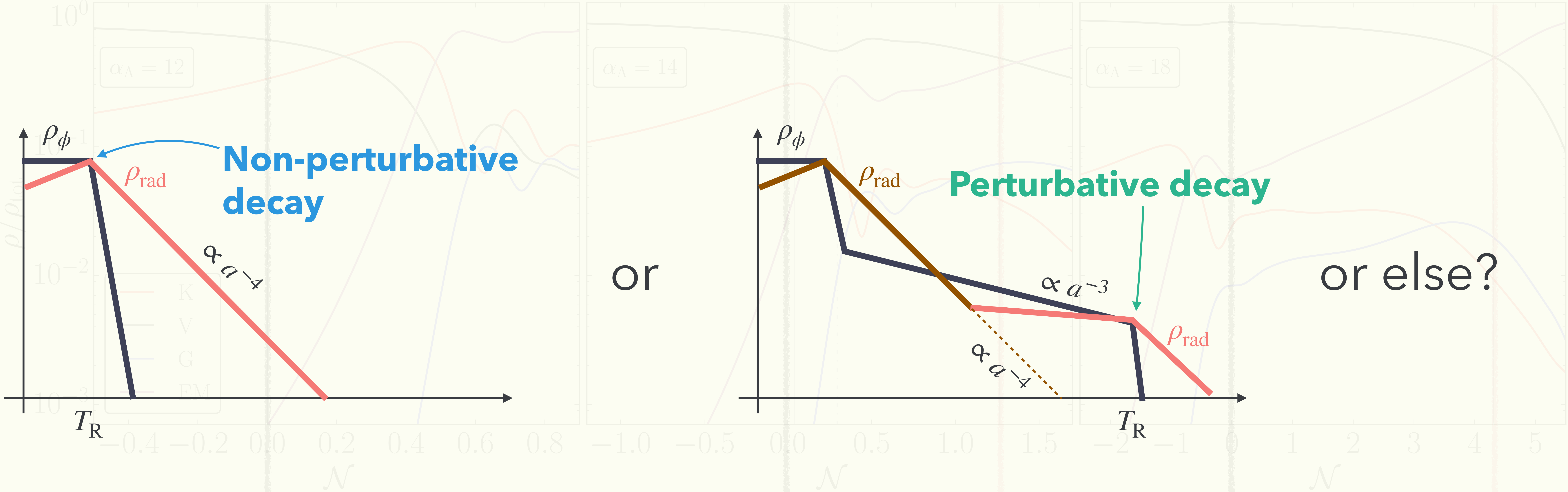
inflation end
w/o gauge field backreaction

delayed inflation end
w/ gauge field backreaction

Axion Inflation + Pure U(1) as a warm up

- Significant gauge-field production already during inflation

[D.Figueroa+ 2411.16368]



Axion Inflation + U(1)$_Y$ in SM?

[V.Domcke, **KM** 1806.08769; **KM+** 1905.13318]

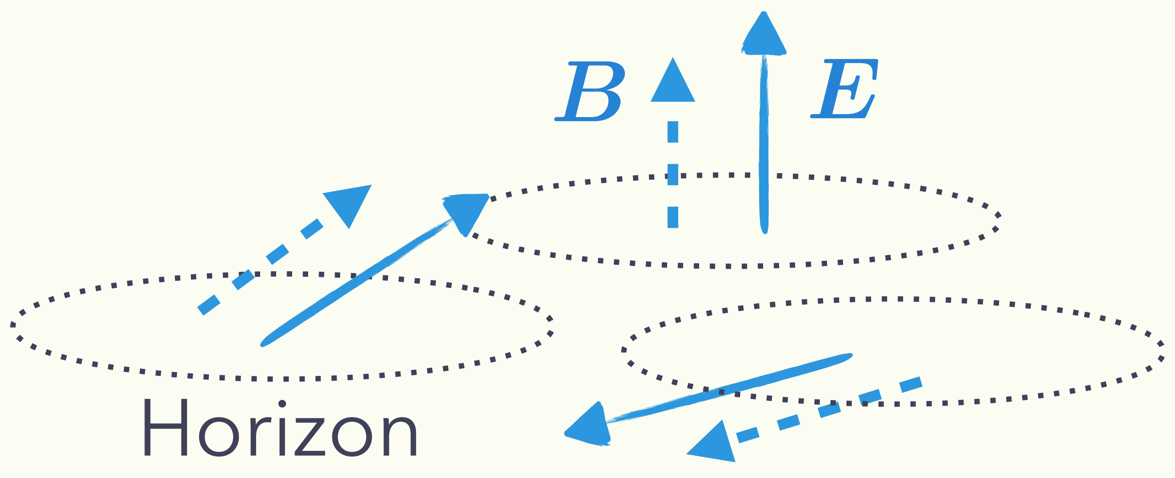
$$\mathscr{L}_{\rm inf} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

Decay

Chern–Simons coupling $\quad \dfrac{\phi}{8\pi\Lambda} Y_{\mu\nu}\tilde{Y}^{\mu\nu}$

$$\mathscr{L}_{\rm rad} = -\frac{1}{4}Y_{\mu\nu}Y^{\mu\nu} + \sum_\alpha \bar{\psi}_\alpha i(\partial\!\!\!/ + ig' Q_{Y,\alpha} Y\!\!\!/)\psi_\alpha$$

- Rapid SM particle production via Schwinger effect



Induced current $\quad g'\left|J_Y\right| = \sum_\alpha N_\alpha \dfrac{(g'|Q_{Y,a}|)^3}{12\pi^2}\coth\left(\dfrac{\pi B_Y}{E_Y}\right)E_Y B_Y \dfrac{1}{H}$

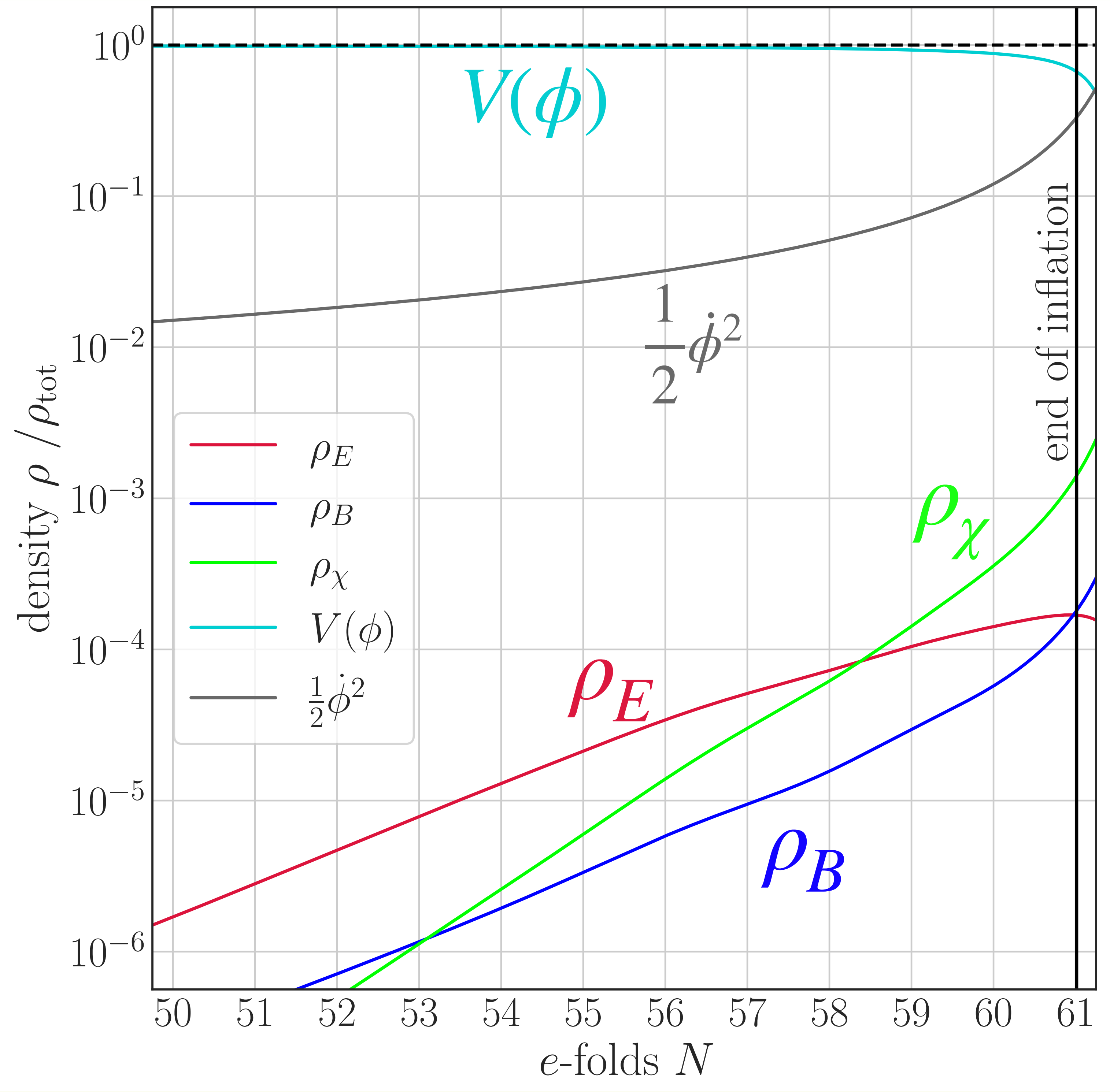
- Instability is **not** completely killed
  - gapless mode owing to the magnetic 1-form symmetry of U(1) $\quad$ cf) Chiral Plasma Instability in MHD

Axion Inflation + U(1)$_Y$ in SM?

[**KM+** 2204.01180; R. von Eckardstein+ 2408.16538]

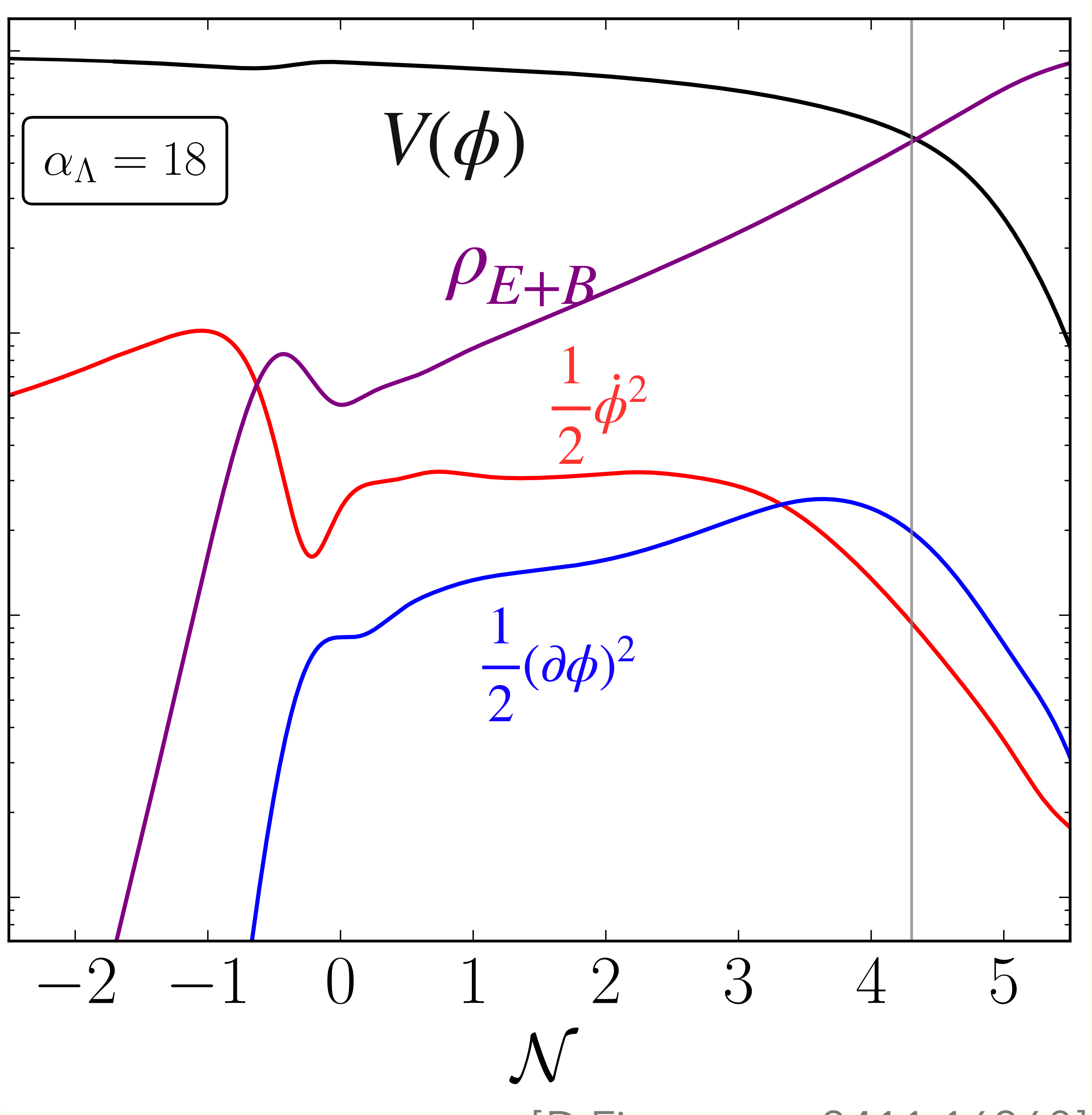
- Charged matter significantly suppresses gauge fields

w/ charged matter χ @ $M_{\rm Pl}/(\pi\Lambda) = 25$



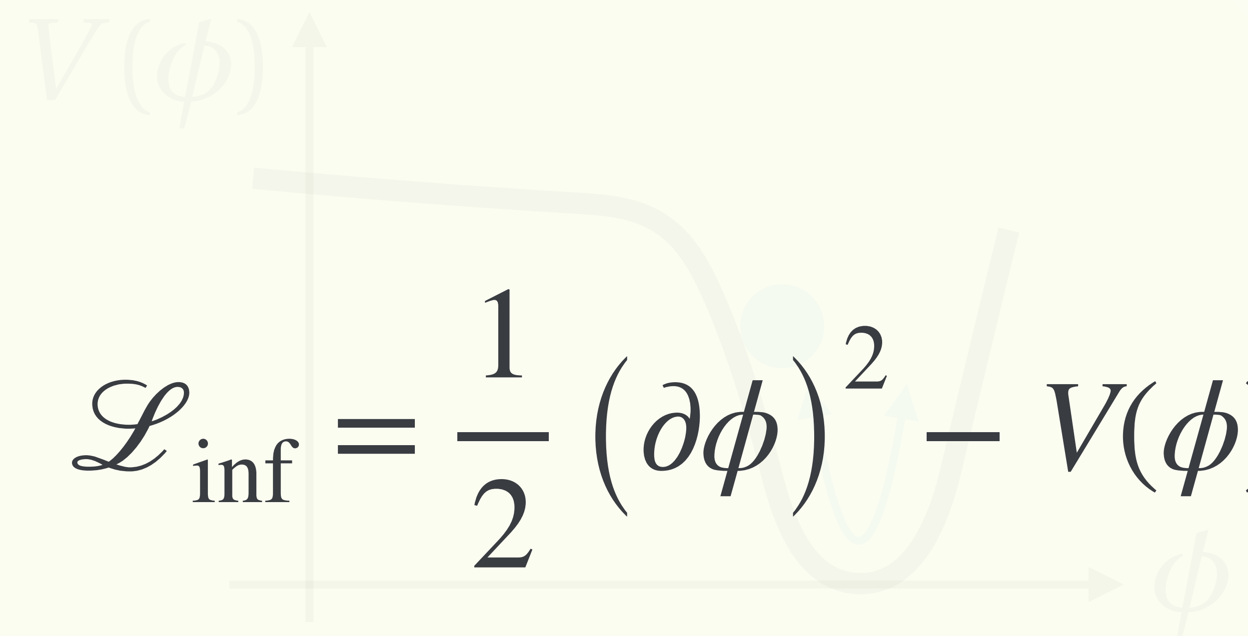
[R. von Eckardstein+ 2408.16538]

w/o charged matter @ $M_{\rm Pl}/(\pi\Lambda) = 18$



[D.Figueroa+ 2411.16368]

Axion Inflation + Pure SU(N)



$$\mathscr{L}_{\rm inf} = \frac{1}{2}\left(\partial\phi\right)^2 - V(\phi)$$

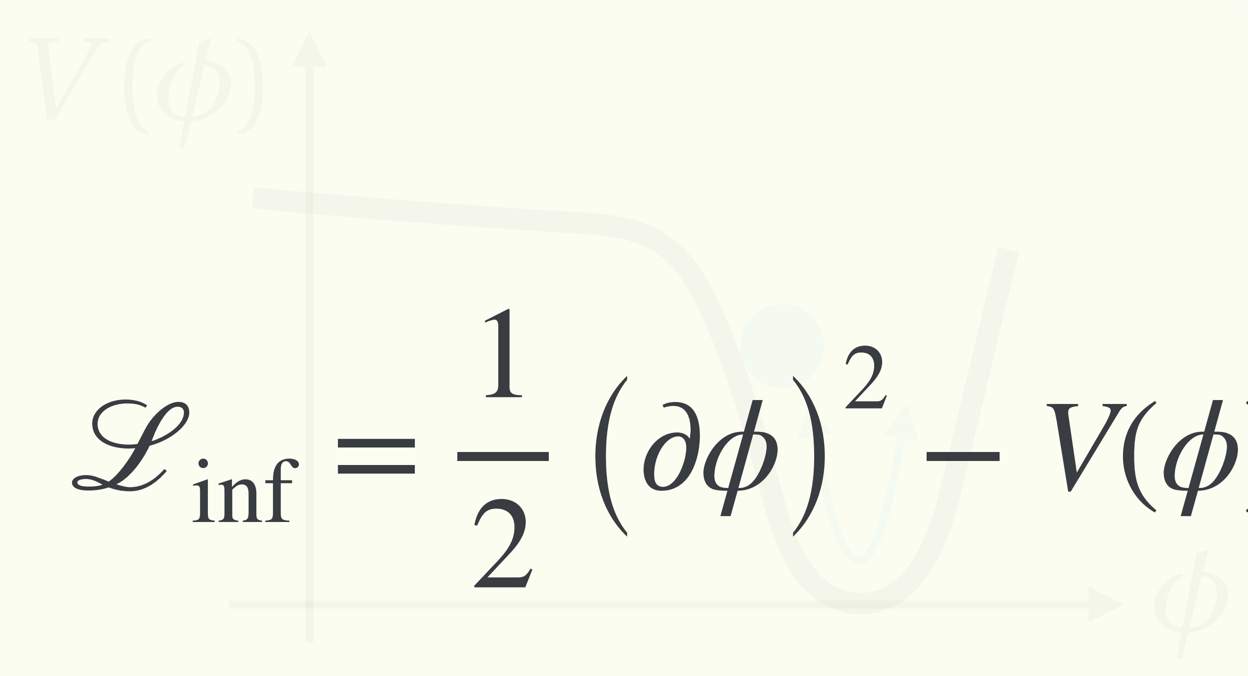
Decay

Chern–Simons coupling $\frac{\phi}{8\pi\Lambda}F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$

$$\mathscr{L}_{\rm rad} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$$

- Prototype to investigate reheating after axion inflation
  - Self interactions leads to **thermalization**
  - No gapless mode in YM plasma (magnetic mass), i.e., **instability can be completely killed**

Axion Inflation + Pure SU(N) (+ Radiation)



$$\mathcal{L}_{\rm inf} = \frac{1}{2}\left(\partial\phi\right)^2 - V(\phi) \quad \xleftrightarrow{\frac{\phi}{8\pi\Lambda}F^a_{\mu\nu}\tilde{F}^{a\mu\nu}} \quad \mathcal{L}_{\rm YM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} \quad \xleftrightarrow{\frac{1}{m_X^n}} \quad \text{Radiation}$$

glueball @ low T

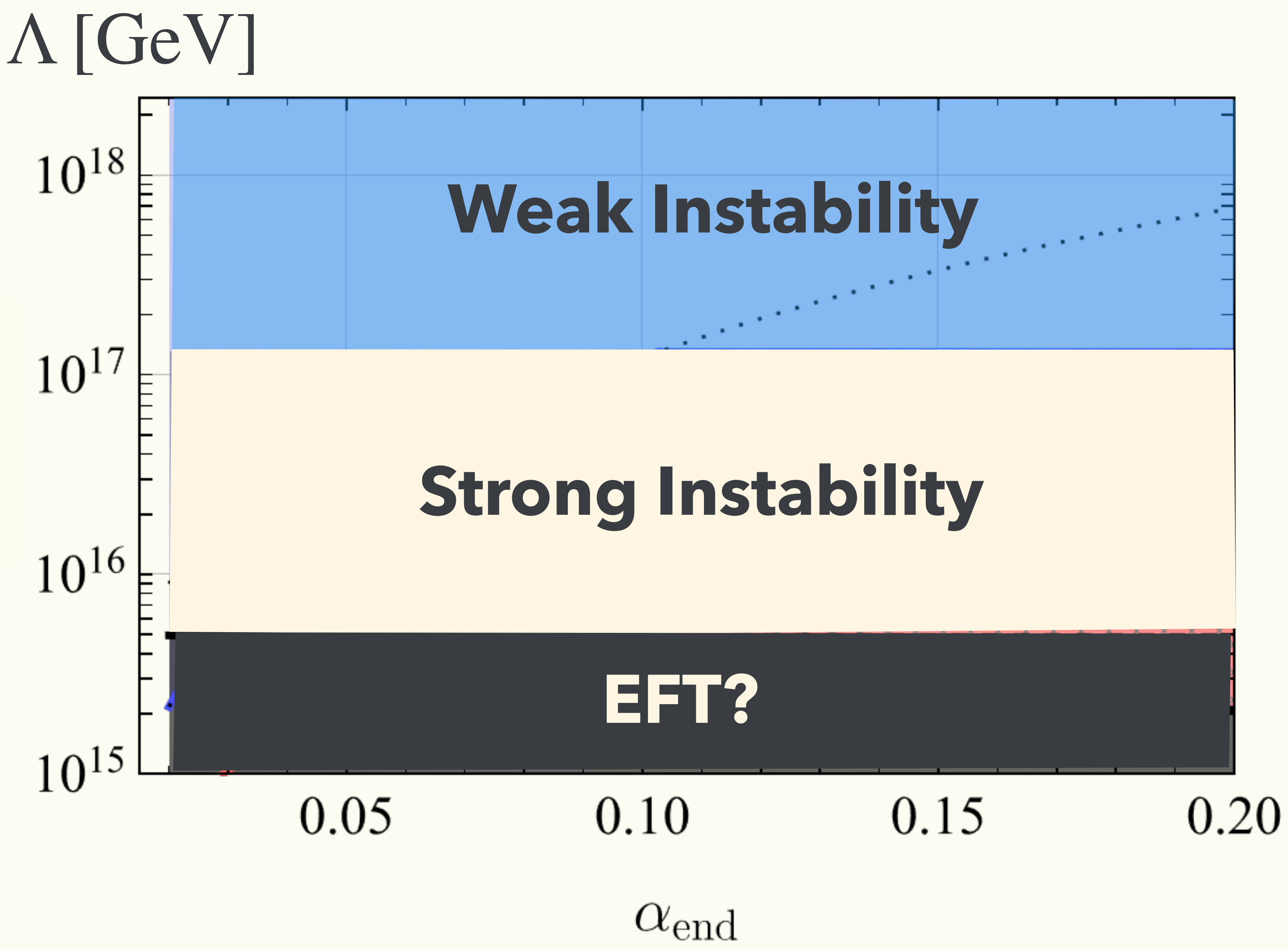
- Prototype to investigate reheating after axion inflation
  - Self interactions leads to **thermalization**
  - No gapless mode in YM plasma (magnetic mass), i.e., **instability can be completely killed**

→ **Completion of reheating?**

During Inflation

Gauge Fields during Inflation

- Axion inflation + pure U(1)
  - Efficient gauge field production during inflation if $\Lambda \ll \mathcal{O}(0.1)M_{\rm Pl}$



Gauge Fields during Inflation

[T.Fujita, **KM**, T.Tsuji 2503.01228]

- Axion inflation + pure SU(N) (+ Radiation)
  - Efficient gauge field production during inflation if $\Lambda \ll \mathcal{O}(0.1)M_{\rm Pl}$
  - Self interaction of SU(N) leads to **thermalization**

[DeRocco+ 2107.07517]

Rapid self interaction

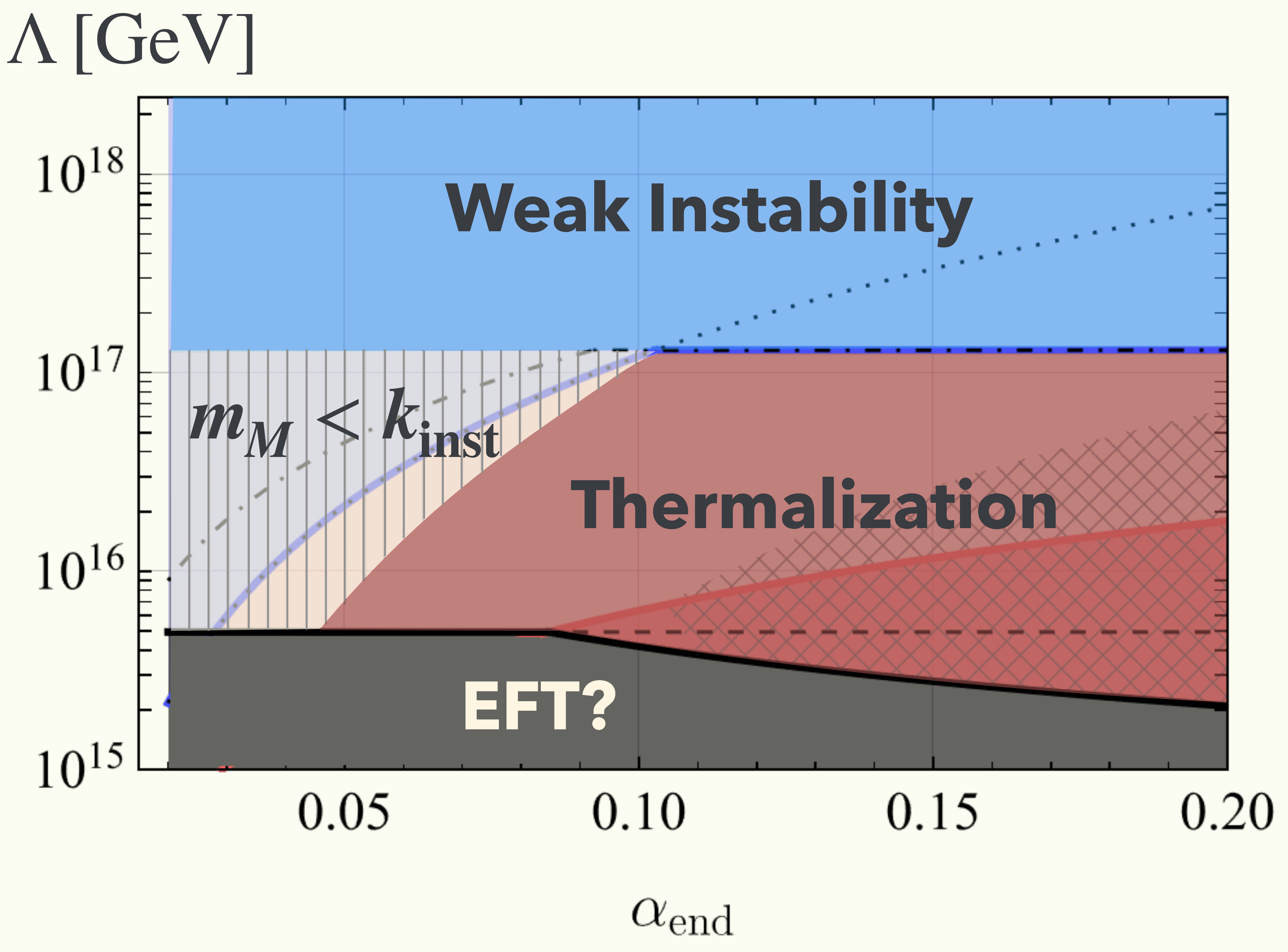
$$\Gamma_{\rm th} > H \quad \longrightarrow \quad \rho_{\rm YM} \gtrsim \left(\frac{H}{N^2\alpha^2}\right)^4$$

thermalization rate: $\Gamma_{\rm th} \sim N^2\alpha^2 T$

Magnetic mass kills the instability [T.Fujita, **KM**, T.Tsuji 2503.01228]

$$m_M > k_{\rm inst} = \frac{|\dot{\phi}|}{2\pi\Lambda} \quad \longrightarrow \quad \Lambda \lesssim (N^2-1)\,N^4\alpha^4 M_{\rm Pl}$$

magnetic mass: $m_M \sim Ng^2T$



Warm Inflation Attractor

[T.Fujita, **KM**, T.Tsuji 2503.01228]

- **Attractor** once thermal plasma of $\alpha^2 T \gg m_\phi$ is established
  - Equation of motion

$$\begin{cases} 0 = \ddot{\phi} + \left(\Gamma_\phi + 3H\right)\dot{\phi} + V' \longrightarrow \dot{\phi} \simeq -\dfrac{1}{1+Q}\dfrac{V'}{3H} & \text{w/ } Q \equiv \dfrac{\Gamma_\phi}{3H} \\ \left(\partial_t + 4H\right)\rho_{\mathrm{rad}'} = \Gamma_\phi \dot{\phi}^2 \longrightarrow \rho_{\mathrm{rad}'} \simeq \dfrac{\Gamma_\phi \dot{\phi}^2}{4H} & \text{w/ } \rho_{\mathrm{rad}'} \equiv \rho_{\mathrm{YM}} + \rho_{\mathrm{rad}} \end{cases}$$

Chern–Simons diffusion

$$\Gamma_\phi \sim \left(N^2 - 1\right)N^3 \frac{\alpha^3 T^3}{\Lambda^2}$$

for $\alpha^2 T \gg m_\phi$

- **Attractor solution**

modified slow-roll prm.

$$\epsilon_T \equiv \frac{1}{1+Q}\frac{M_{\mathrm{Pl}}^2}{2}\left(\frac{V'}{V}\right)^2$$

$$\rho_{\mathrm{rad}'}(T) \simeq \frac{Q(\phi, T)}{1 + Q(\phi, T)}\epsilon_T(\phi, T)V(\phi) \quad \blacktriangleright \quad T(\phi)$$

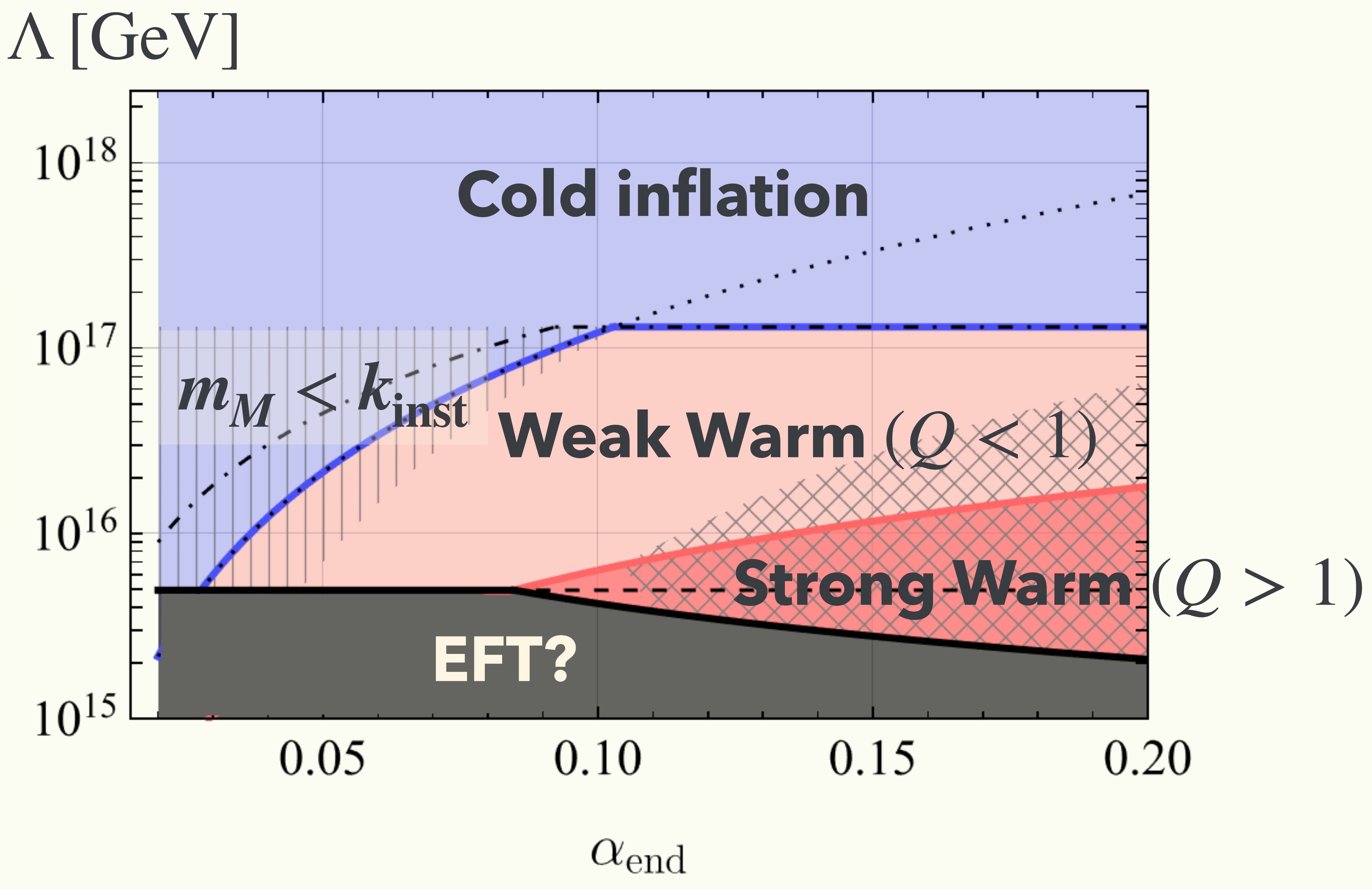
[DeRocco+ 2107.07517]

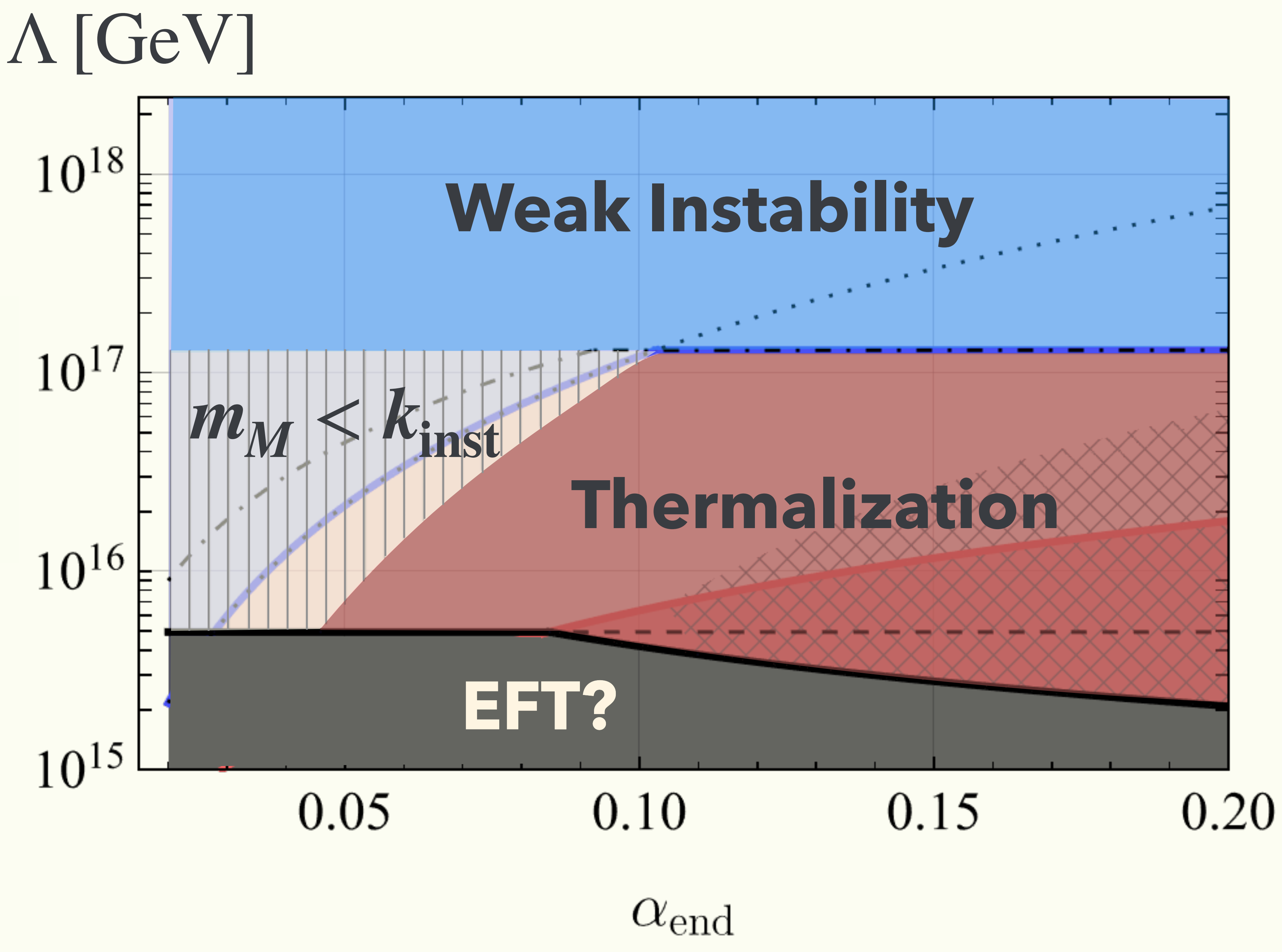
$$\because \begin{cases} \text{If } T_{\mathrm{ini}} > T(\phi), & \text{quickly redshifted to } T_{\mathrm{ini}}/a(t) \to T(\phi) \\ \text{If } T_{\mathrm{ini}} < T(\phi), & T \sim \dfrac{\alpha^3 \dot{\phi}_{\mathrm{ini}}^2}{\Lambda^2} t \to T(\phi) \text{ within } t < H^{-1} \end{cases}$$

Outlook at the end of inflation

[T.Fujita, **KM**, T.Tsuji 2503.01228]

- Axion inflation + pure SU(N) (+ Radiation)
  - Classification of inflation phases: cold inflation ($\alpha^2 T \lesssim H$), warm inflation ($\alpha^2 T \gtrsim H$)





Reheating after Inflation

Outlook at the end of inflation

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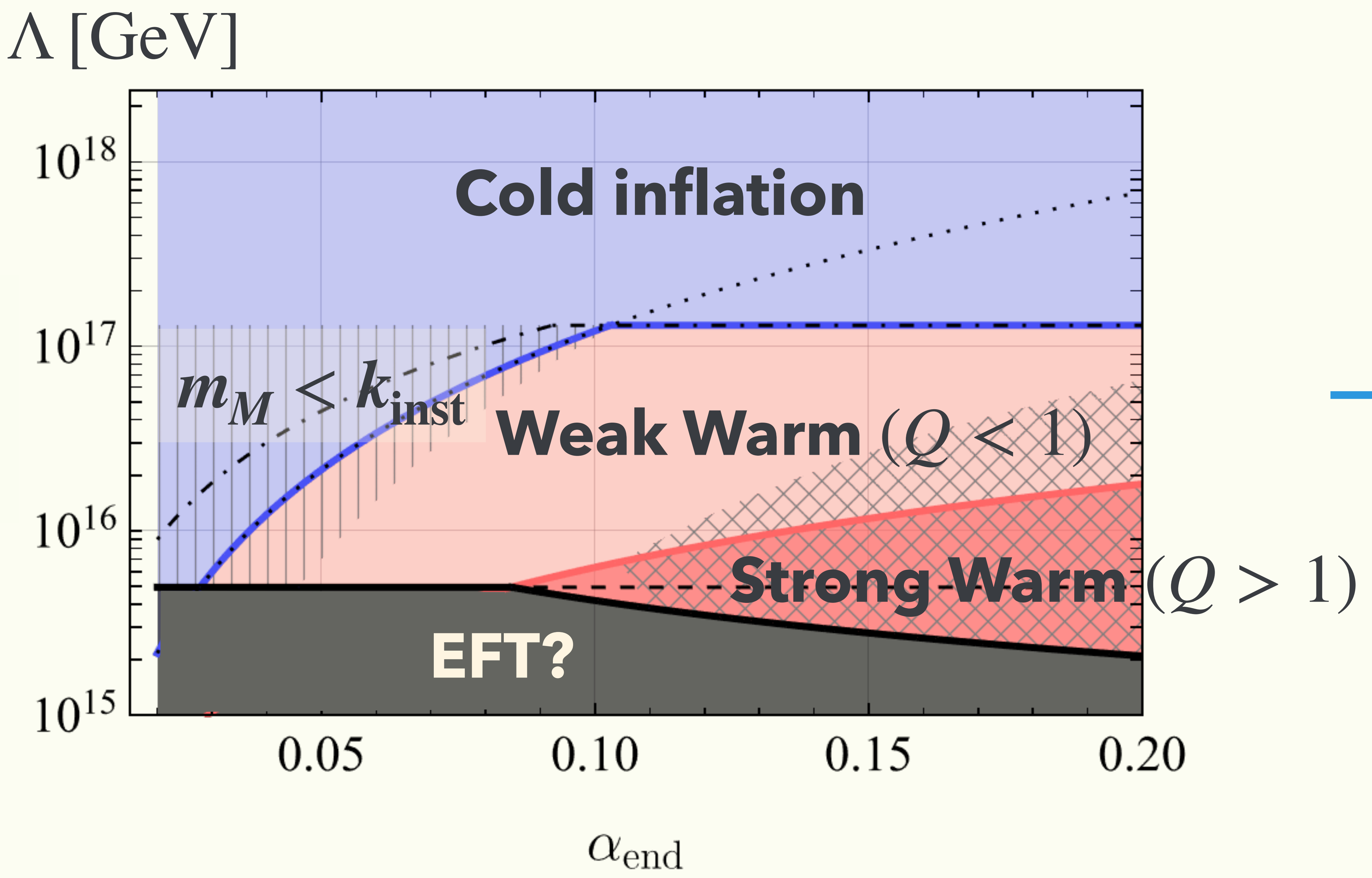


→ **Completion of reheating?**

Reheating after Strong Warm Inflation ($Q_{\rm end} > 1$)

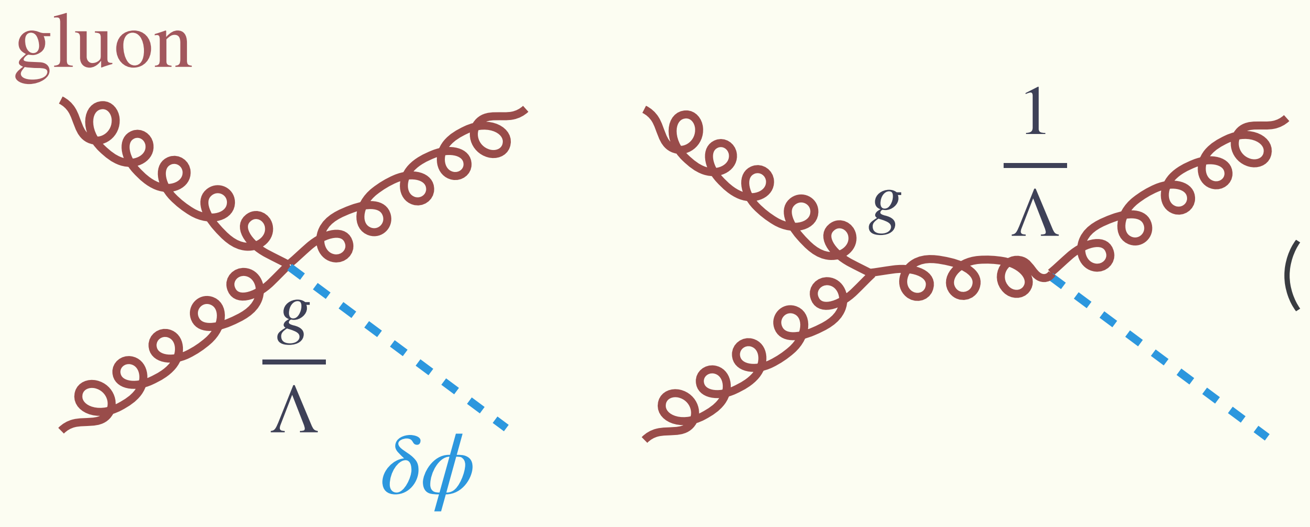
- Late-time **inflaton particle** domination [T.Fujita, **KM**, T.Tsuji 2503.01228]

  - Strong thermal dissipation of inflaton condensate

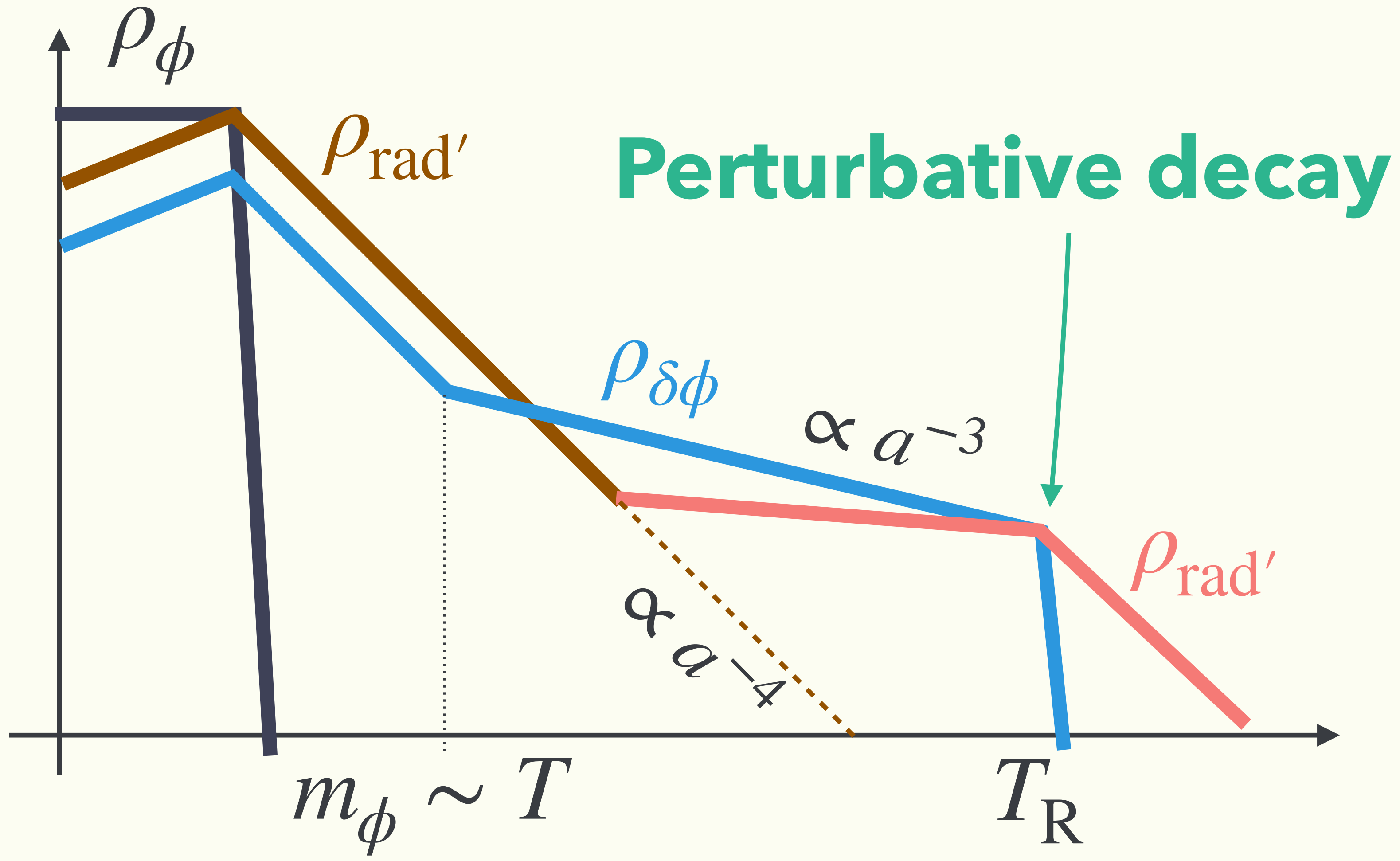
$$0 = \ddot{\phi} + \left(\Gamma_\phi + 3H\right)\dot{\phi} + m_\phi^2 \phi \;\longrightarrow\; \phi \propto \exp\left(-\int_{t_{\rm end}}^{t_{\rm osc}} {\rm d}t\, \frac{m_\phi^2}{\Gamma_\phi(T)} - \int_{t_{\rm osc}}^{t_{\rm dec}} {\rm d}t\, \frac{\Gamma_\phi(T)}{2} \right) \sim e^{-\frac{\Gamma_\phi(T_{\rm osc})}{H_{\rm osc}}} \ll 1$$

$$@\ \Gamma_\phi > m_\phi > H \qquad @\ m_\phi > \Gamma_\phi > H$$

  - Thermal **inflaton particle** production & Late-time decay



(+ crossings) $\sim (N^2-1)N\dfrac{\alpha T^3}{\Lambda^2} f(T)$



* $f(T)$ requires HTL/beyond HTL resummation. [Graf+ 1008.4528, Salvio+ 1310.6982, Bouzoud+ 2404.06113]

Reheating after Weak Warm Inflation ($Q_{\rm end} < 1$)

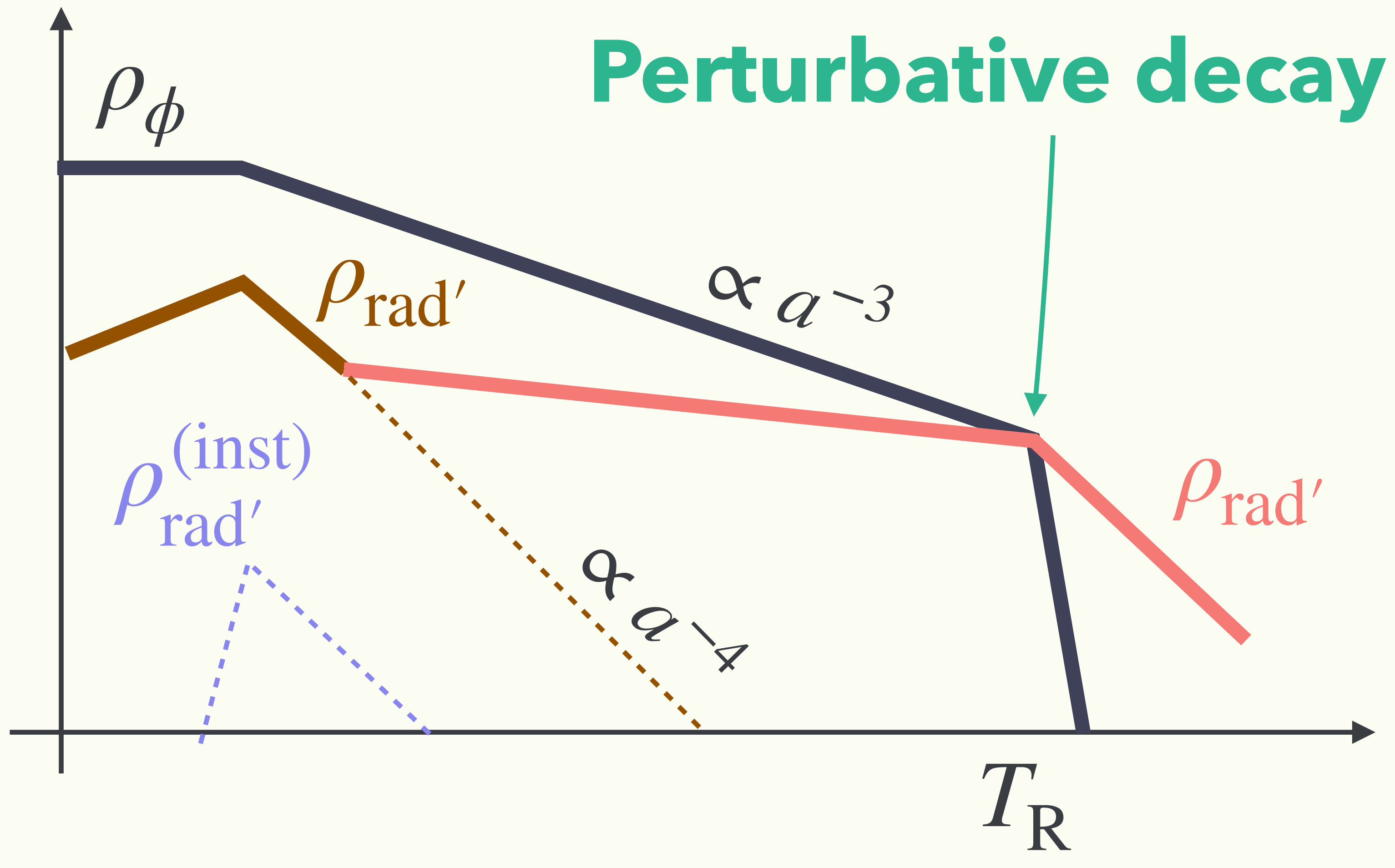
- Inflaton condensate domination

[T.Fujita, **KM**, T.Tsuji 2503.01228]

  - Inefficient **thermal** dissipation of inflaton condensate

Inflaton condensate domination

$$\rho_{\rm rad'}\Big|_{\rm end} \simeq \frac{Q_{\rm end}}{1+Q_{\rm end}} V_{\rm end} < \rho_\phi\Big|_{\rm end} \quad \blacktriangleright \quad Q \propto \frac{\Gamma_\phi}{H} \propto \frac{a^{-3}}{a^{-3/2}} \propto a^{-3/2}$$



  - Inefficient **preheating** in most cases

Instability becomes weaker & weaker

$$\frac{m_M}{k_{\rm inst}} \propto \frac{T}{\phi} \propto \frac{a^{-1}}{a^{-3/2}} \propto a^{1/2}$$

Dominant production right after inflation

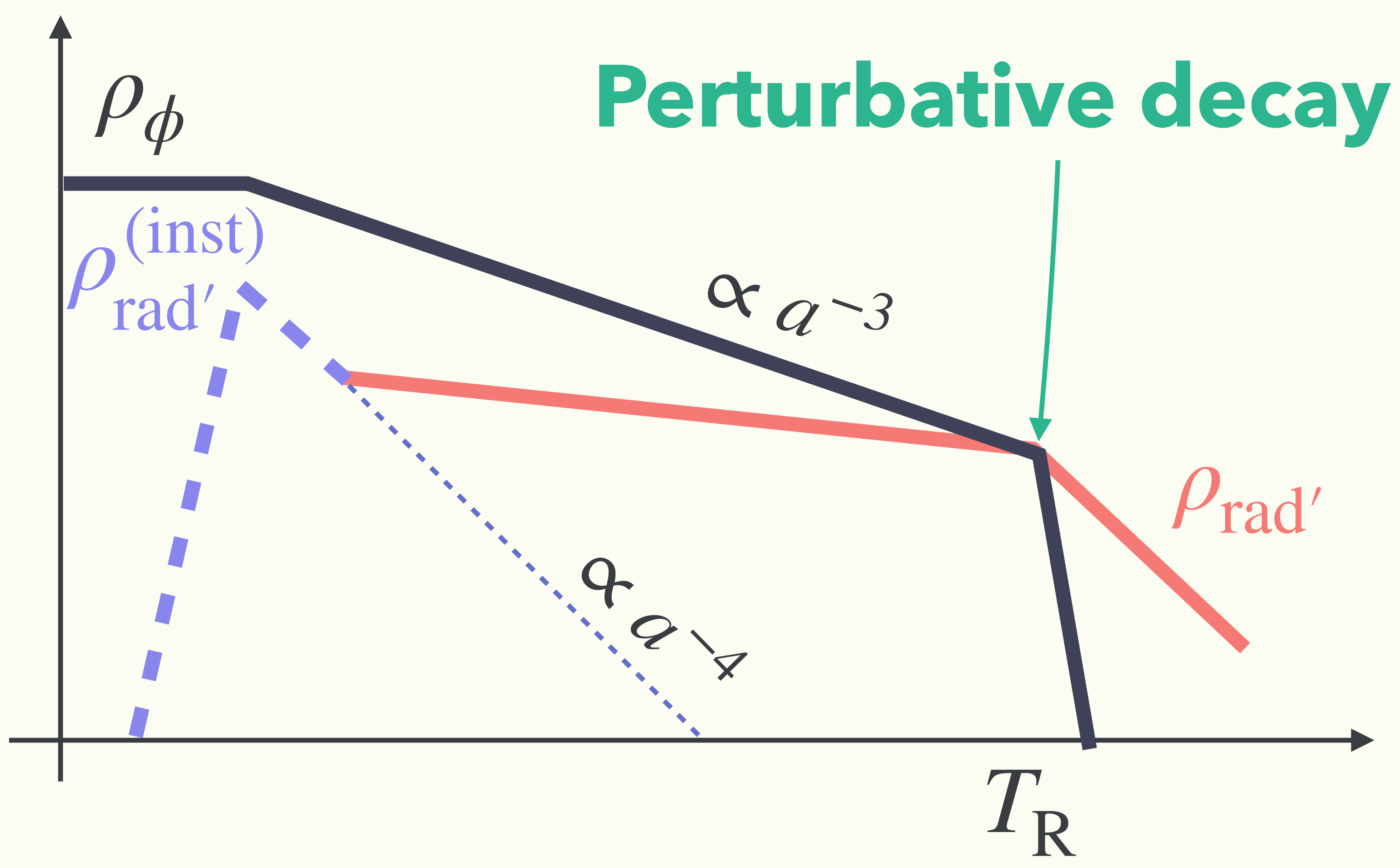
but… $\rho_{\rm rad'}^{\rm (inst)} \sim \delta\rho_{\rm rad'}^{\rm (inst)} \dfrac{m_\phi}{H} < \rho_{\rm rad'}$ for $\Lambda \lesssim 2\times 10^{18}\,{\rm GeV} \left(\dfrac{\alpha}{0.1}\right)^{13/4}$

(* self interaction kills exponential enhancement)

Reheating after Cold Inflation

- Inflaton condensate domination

[T.Fujita, **KM**, T.Tsuji 2503.01228]



- No **preheating**

No instability if

$$\mathcal{O}(1) < \frac{k_{\mathrm{inst}}}{m_\phi} \propto a^{-3/2} \longrightarrow \Lambda \gtrsim 10^{17}\,\mathrm{GeV} \times \left(\frac{\phi_{\mathrm{end}}}{M_{\mathrm{Pl}}}\right)$$

- Inefficient **preheating** for sizable α

Thermalization within one oscillation if

$$\Gamma_{\mathrm{th}} > m_\phi \longrightarrow \rho_{\mathrm{YM}} \gtrsim \left(\frac{m_\phi}{N^2\alpha^2}\right)^4 \equiv \rho^{(\mathrm{osc})}_{\mathrm{th}}$$

For $\rho^{(\mathrm{osc})}_{\mathrm{th}} < \delta\rho^{(\mathrm{inst})}_{\mathrm{rad}'}$, thermalize for each oscillation

For $\rho^{(\mathrm{osc})}_{\mathrm{th}} > \delta\rho^{(\mathrm{inst})}_{\mathrm{rad}'}$, non-thermal

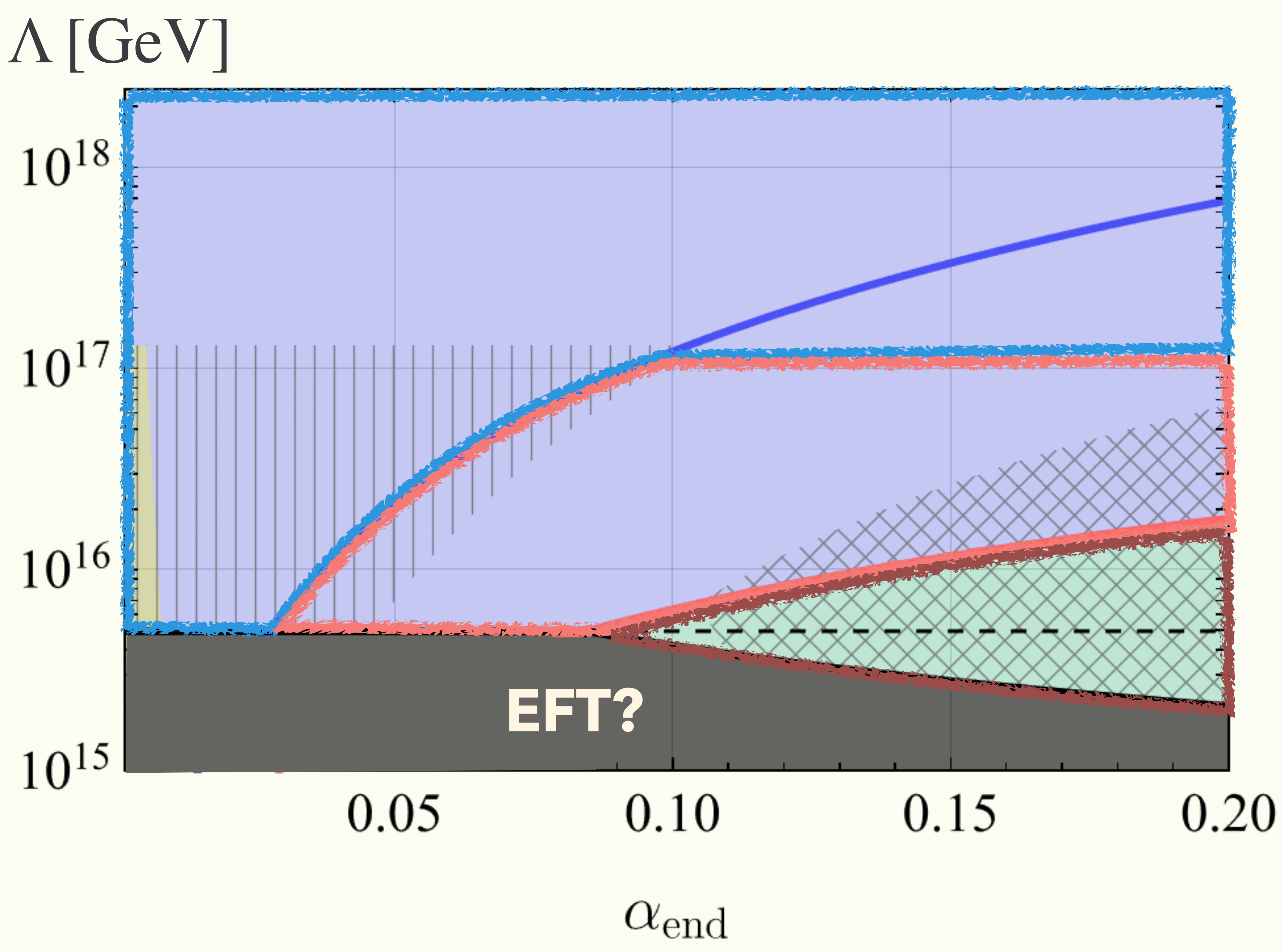
$$\rho^{(\mathrm{inst})}_{\mathrm{rad}'} \sim \delta\rho^{(\mathrm{inst})}_{\mathrm{rad}'} \frac{m_\phi}{H} < \rho_\phi \quad \text{for } \Lambda \gtrsim 10^{15}\,\mathrm{GeV}\left(\frac{\alpha}{0.01}\right)^{-8}$$

Completion of Reheating after Axion Inflation

[T.Fujita, **KM**, T.Tsuji 2503.01228]

- **Perturbative decay** after Inflaton particle/condensate domination

  - After **cold** inflation
    - ϕD → **Perturbative decay**
    - Strong Instability?
  - After **weak warm** inflation
    - ϕD → **Perturbative decay**
  - After **strong warm** inflation
    - RD → $\delta\phi$D → **Perturbative decay**



Summary

[T.Fujita, **KM**, T.Tsuji 2503.01228]

- Completion of reheating after axion inflation is non-trivial

  - Generic takehome message

    Reheating may be completed by **perturbative decay**

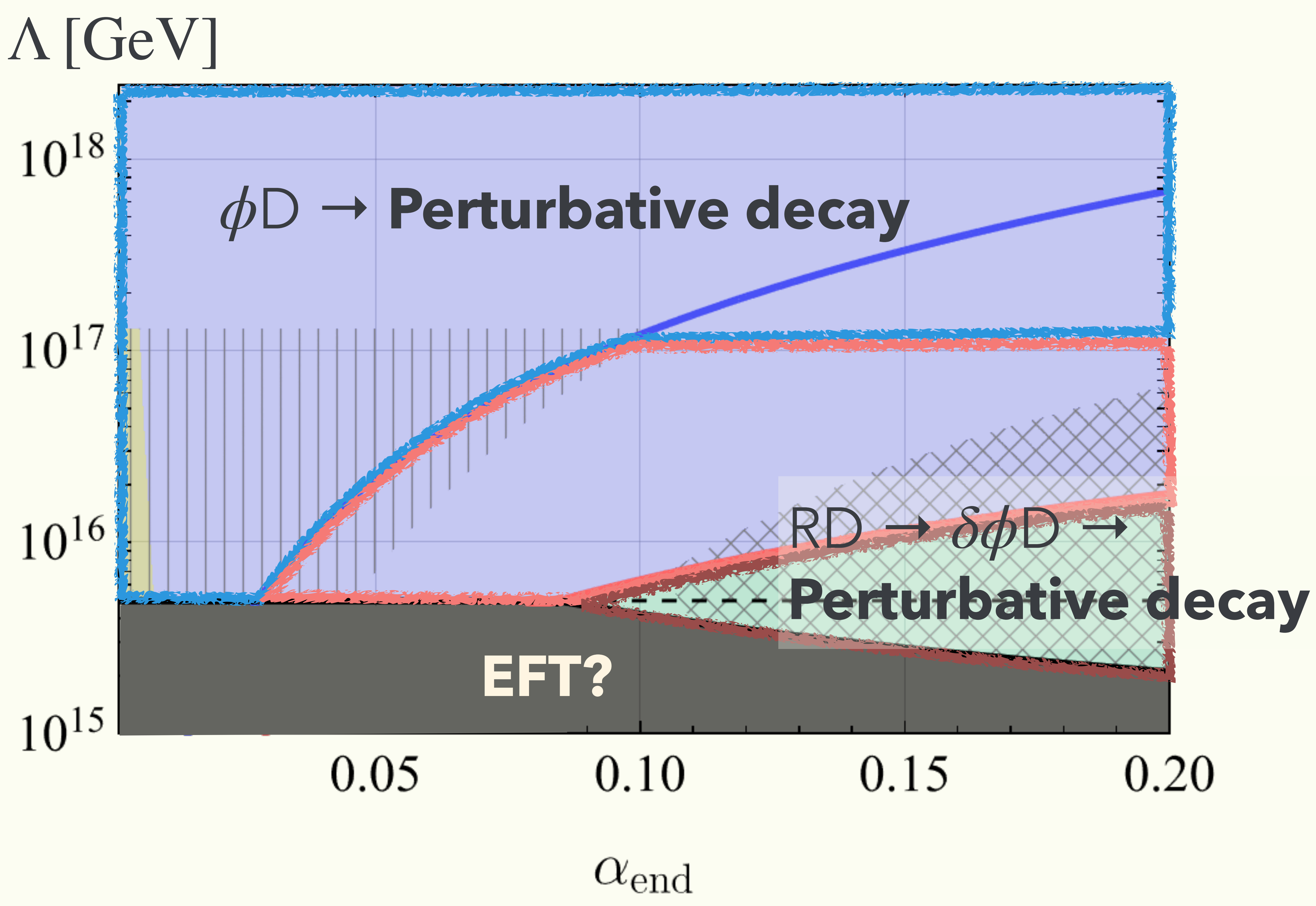
    Pay attention to **inflaton particle production**

  - But conclusion is not general

    Different inflaton potential, matter contents, $m_X, \ldots$

  - Open questions

    U(1) + charged matter?, chromonatural phase?, pure U(1)?, …



Backup

Glueball Domination

$$\mathscr{L}_{\rm inf} = \frac{1}{2}\left(\partial\phi\right)^2 - V(\phi) \quad \xleftrightarrow{\;\frac{\phi}{8\pi\Lambda}F^a_{\mu\nu}\tilde{F}^{a\mu\nu}\;} \quad \mathscr{L}_{\rm YM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} \quad \xleftrightarrow[\frac{1}{m_X^n} \sim \frac{1}{M_{\rm Pl}^n}]{\text{Small coupling}} \quad \boxed{\text{Radiation}}$$

glueball @ low T

- **Glueball domination** is a generic consequence for large m_X
  - Glueball decay

$$\Gamma_{\rm glueball} = \begin{cases} \Gamma_{\rm glueball \to rad} \sim \dfrac{\Lambda^5_{\rm conf}}{m_X^4} \\ \Gamma_{\rm glueball \to \delta\phi\delta\phi} \sim \dfrac{\Lambda^5_{\rm conf}}{\Lambda^4} \quad \text{for} \quad \Lambda_{\rm conf} > m_\phi \end{cases}$$

$$\text{glueball} \longrightarrow \delta\phi \longrightarrow \text{rad}$$

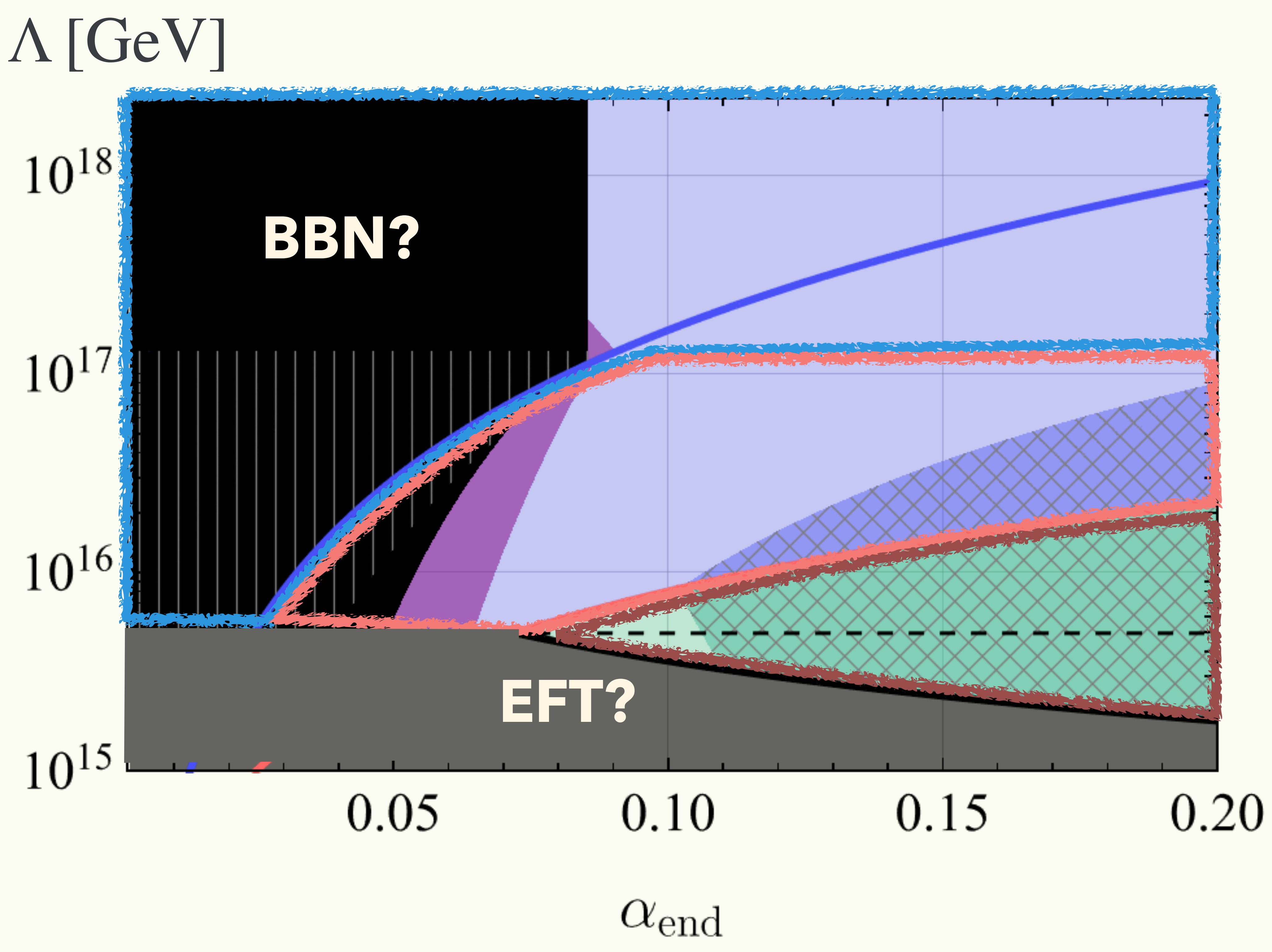
e.g. $\Gamma_{\delta\phi \to \rm rad} \sim \dfrac{\Lambda^8_{\rm conf}}{\Lambda^2 m_X^4 m_\phi}$ for $\Lambda_{\rm conf} > m_\phi$

w/ $H^\dagger H F^a_{\mu\nu}F^{a\mu\nu}/m_X^2$

Glueball Domination

[T.Fujita, **KM**, T.Tsuji 2503.01228]

- **Perturbative decay** after $\phi/\delta\phi/$glueball domination
  - After **cold** inflation
    - ϕD → gD → **Perturbative decay**
  - After **weak warm** inflation
    - ϕD → gD → **Perturbative decay**
    - ϕD → **Perturbative decay**
    - ϕD → RD → gD → **Perturbative decay**
  - After **strong warm** inflation
    - RD → $\delta\phi$D → gD → **Perturbative decay**
    - RD → gD → $\delta\phi$D → **Perturbative decay**



More on Self Interactions

- Self interactions **kill** the exponential enhancement
  - When do self interactions become relevant? [DeRocco+ 2107.07517]

free eom: $\Box A^a \quad \longleftrightarrow \quad$ self-interactions: $g f_{abc} A^b \partial A^c$

$$A_{\rm NL} \sim \frac{k_{\rm inst}}{gN} \quad \longrightarrow \quad \rho_{\rm YM}^{\rm NL} \sim (N^2-1)\frac{k_{\rm inst}^4}{\alpha N^2}$$

  - Immediate thermalization if

$$\Gamma_{\rm th} > H \quad \longrightarrow \quad \rho_{\rm YM}^{\rm NL} \gtrsim \left(\frac{H}{N^2\alpha^2}\right)^4$$

Cascade by **elastic scattering** for weakly overoccupied system

e.g., [Kurkela, Morre 1107.5050]

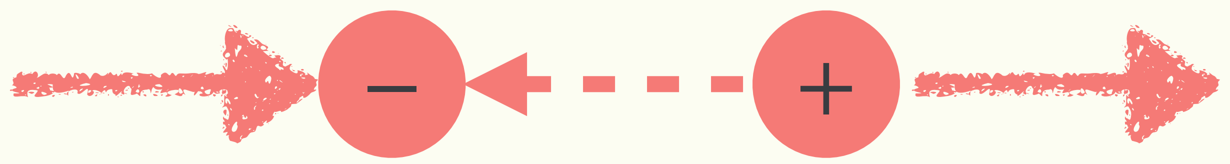
$$\Gamma_{\rm th} \sim \alpha^2 T_{\rm final}$$

  - Magnetic mass, m_M, completely terminates the instability if

$$m_M > k_{\rm inst} = \frac{|\dot\phi|}{2\pi\Lambda} \quad \text{with} \quad m_M \sim N g^2 T \quad \xrightarrow[T(\phi)]{\text{warm attractor}} \quad \Lambda \lesssim (N^2-1)\,N^4\alpha^4 M_{\rm Pl}$$

More on magnetic mass

- Magnetic **one-form symmetry** in U(1) gauge theories
  - Electric flux gets screened, but magnetic flux does NOT.

$\vec{E}$  $\sim \dfrac{e^{-m_{\mathrm{D}} r}}{r}$ $\qquad$ $\vec{B}$  $\sim \dfrac{1}{r}$

  - Bianchi identity = magnetic one-form symmetry: $U(1)_M^{[1]}$

  Bianchi identity → conservation law: $0 = \mathrm{d}F \quad \longrightarrow \quad$ Charge: $Q(\Sigma_2) = \int_{\Sigma_2} F$ $\qquad$ i.e., $\vec{B}$ cannot be cut

- **No** magnetic one-form symmetry in **SU(N) gauge theories**
  - non-Abelian Bianchi identity

$0 = \mathrm{D}F \quad \longrightarrow \quad \mathrm{d}F = igA \wedge F \longleftarrow \cancel{U(1)_M^{[1]}}$

magnetic mass (i.e., 3D confinement scale)

$\rightarrow m_M \sim g_3^2 \sim g^2 T$