Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

名古屋大学 NAGOYA UNIVERSITY

Axions, Dark Matter, and the Primordial Density Perturbation

Takeshi Kobayashi

TK, Ubaldi 1907.00984, 2006.09389
TK 2005.01741

Less Travelled Path of Dark Matter: Axions and Primordial Black Holes, ICTS-TIFR

AXIONS FOR:

* In this talk, an "axion" refers to a generic PNGB of a spontaneously broken global U(1) (e.g. QCD axion, string axions)

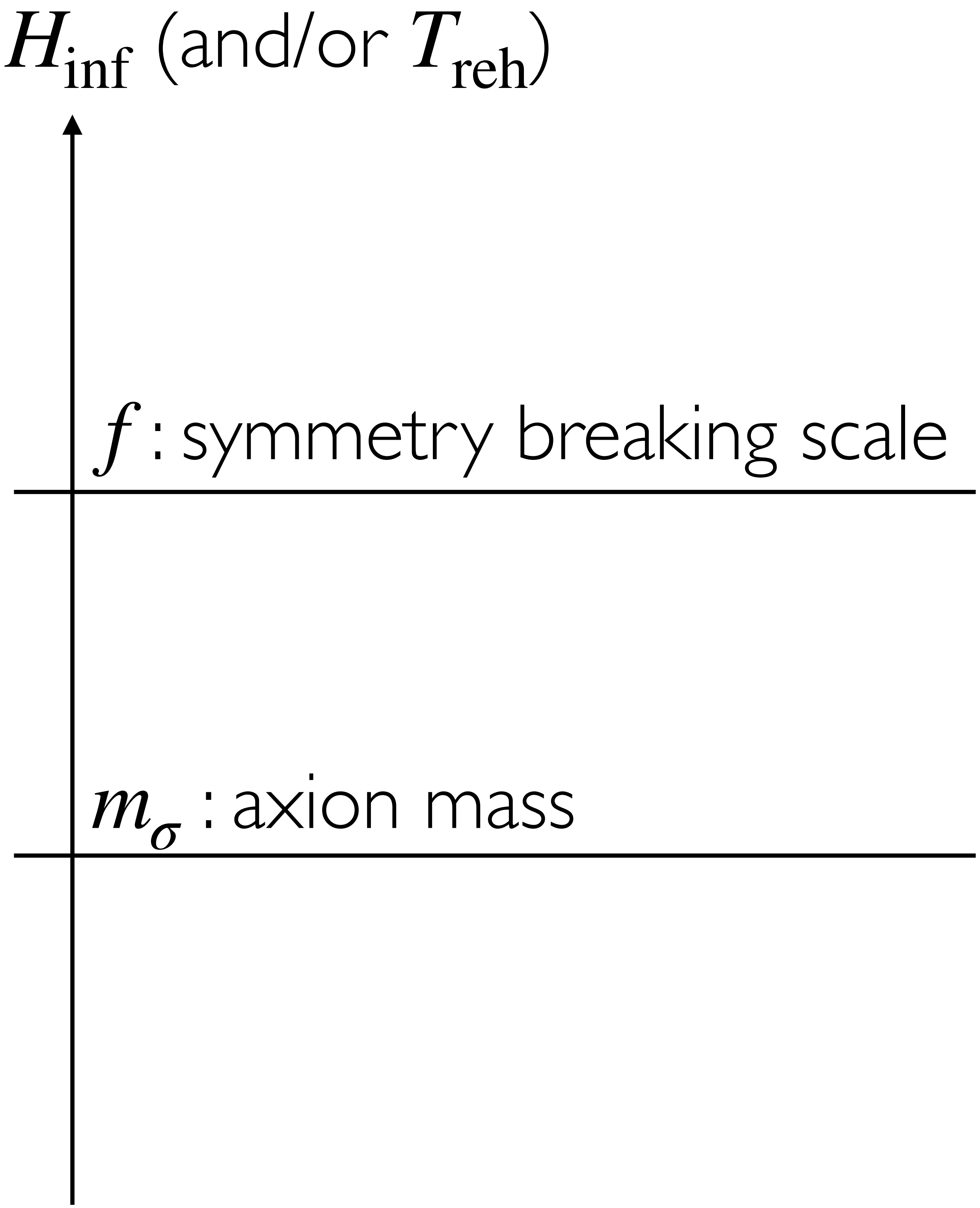
I. Dark Matter

"Inflaxion" mechanism for producing axion DM

TK, Ubaldi 1907.00984, 2006.09389

Image: Chandra X-ray Observatory

PRODUCTION OF AXION DARK MATTER



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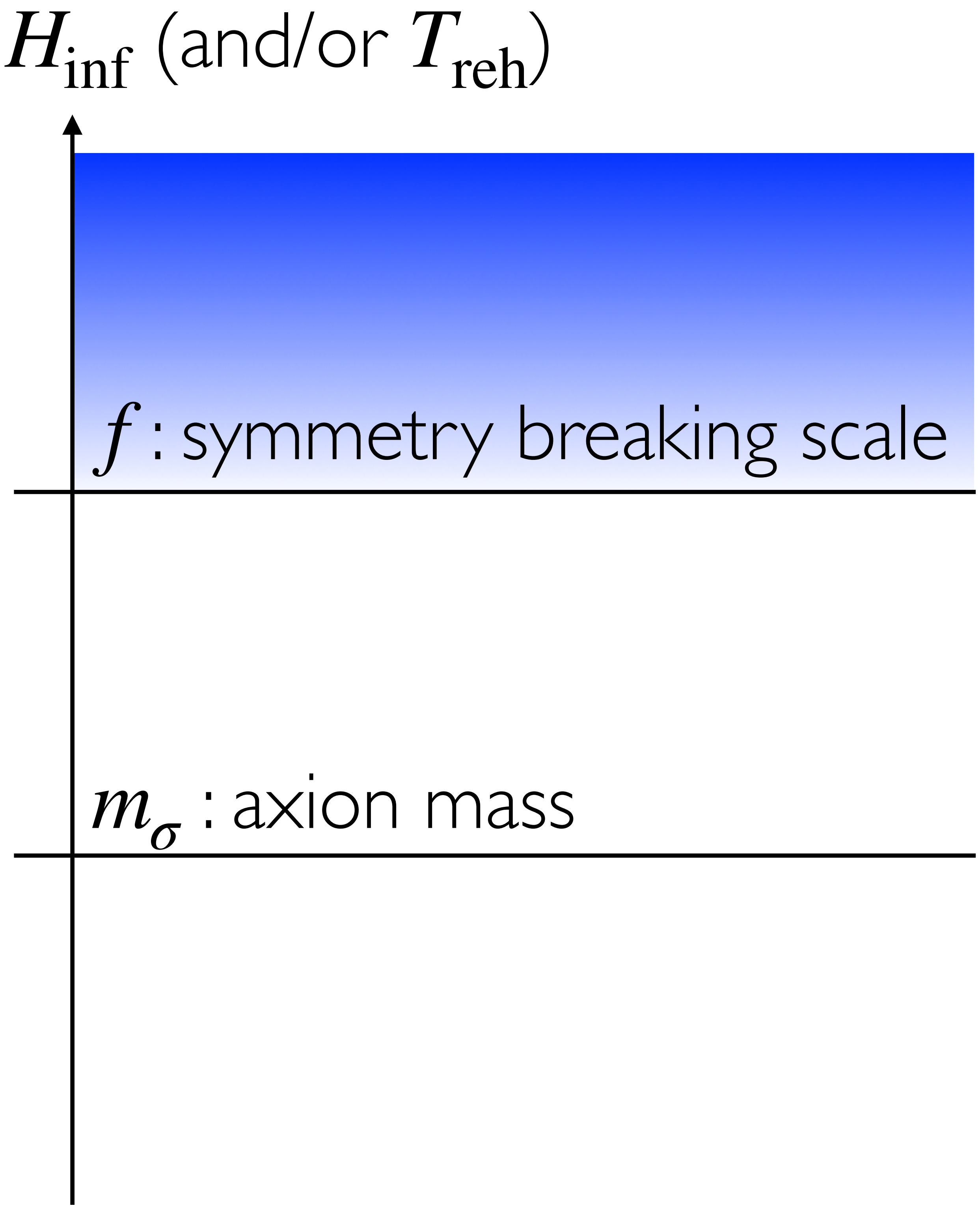

emission from
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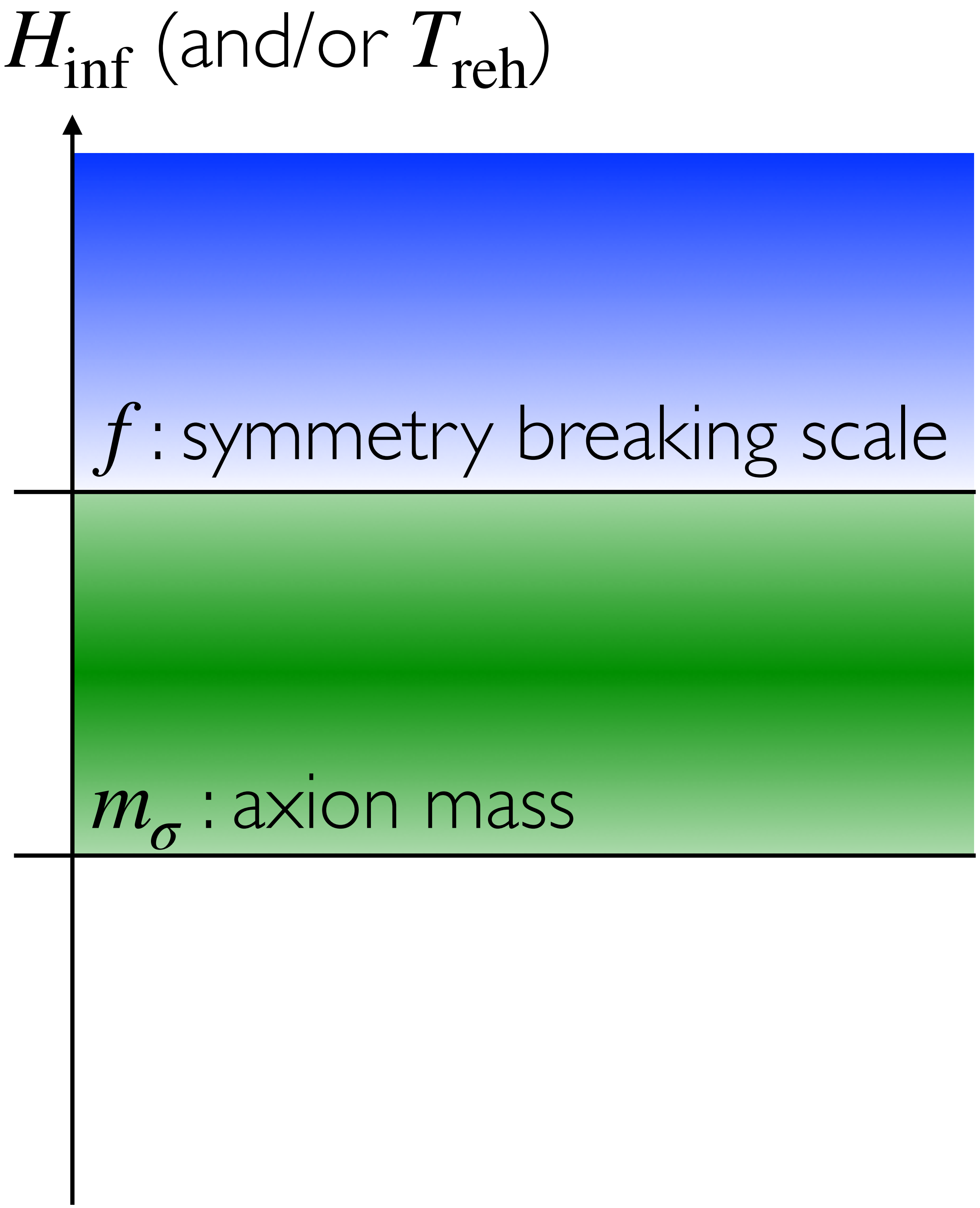
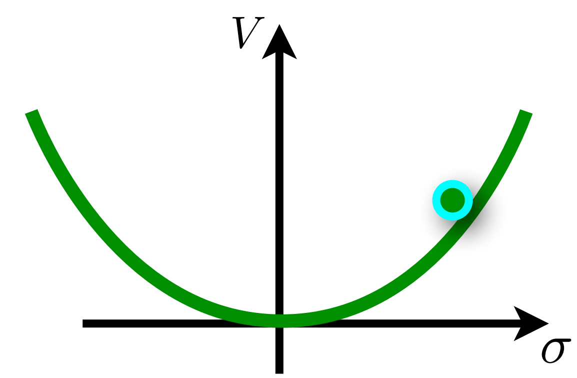


emission from topological defects

vacuum misalignment



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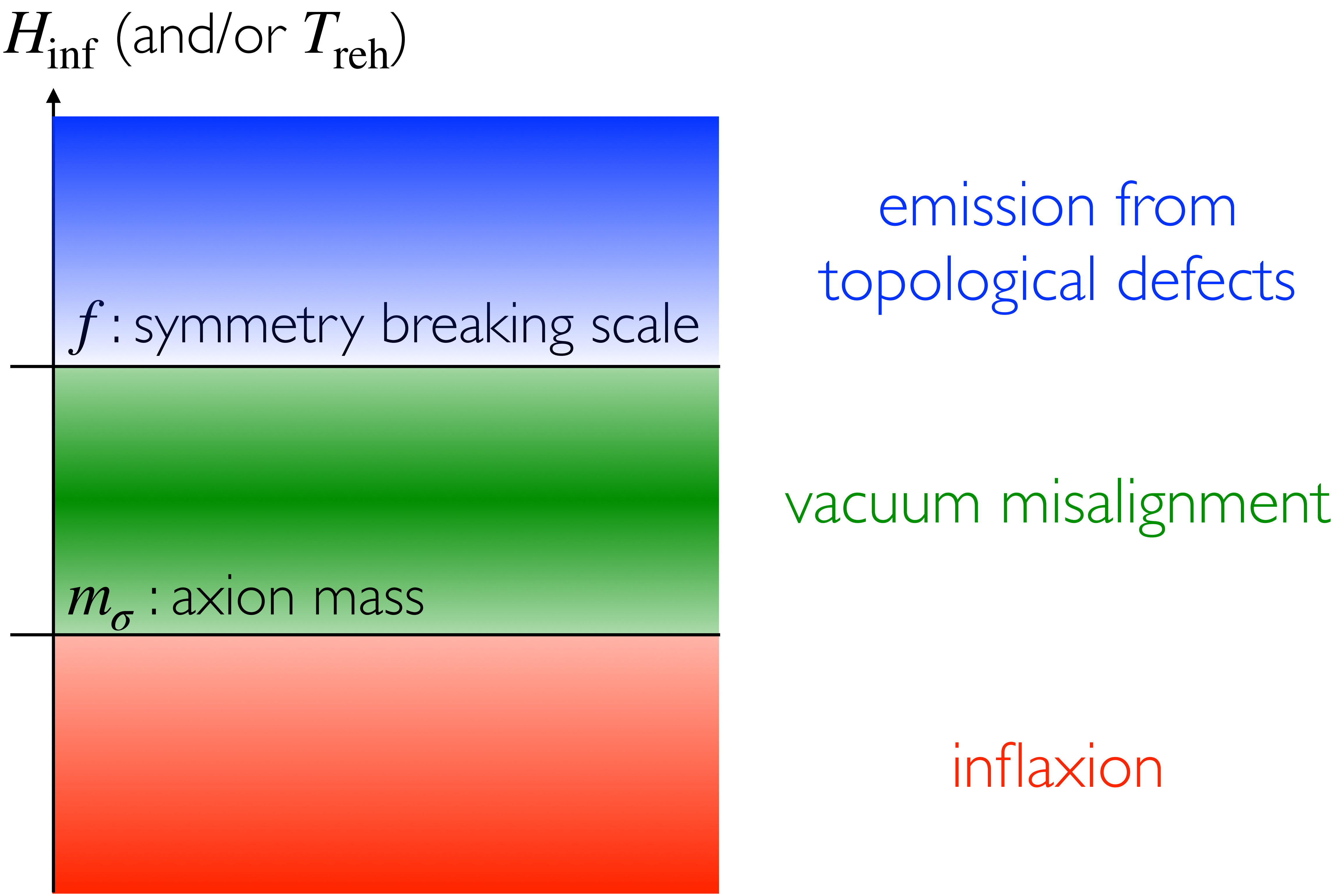

INFLAXION MECHANISM

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}(\partial\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

σ : axion ϕ : inflaton

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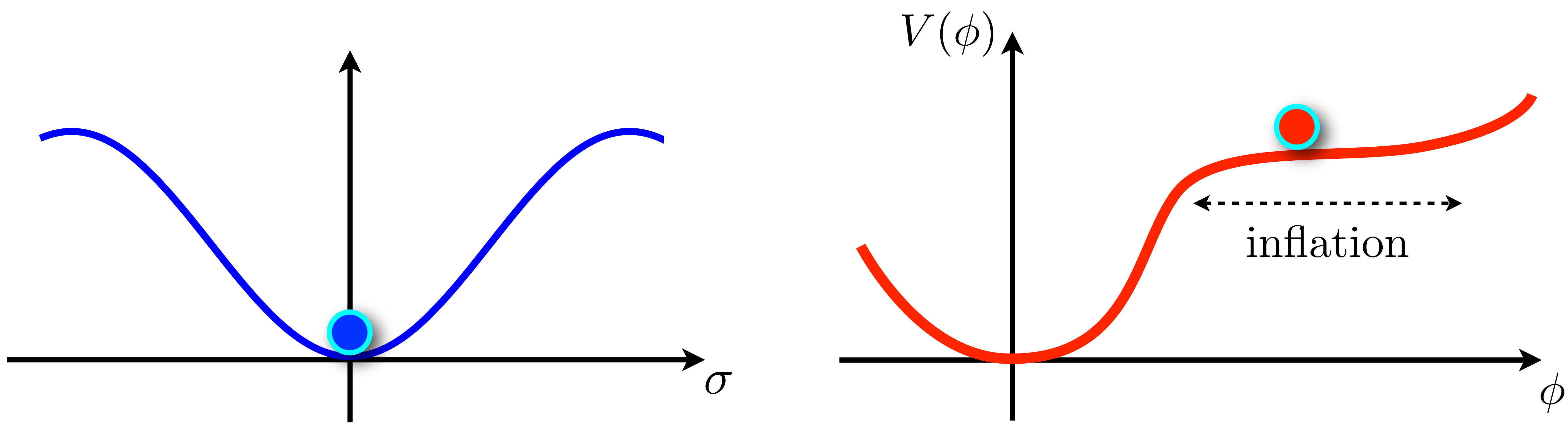
low-scale inflation with $H_{\rm inf} < m_\sigma$



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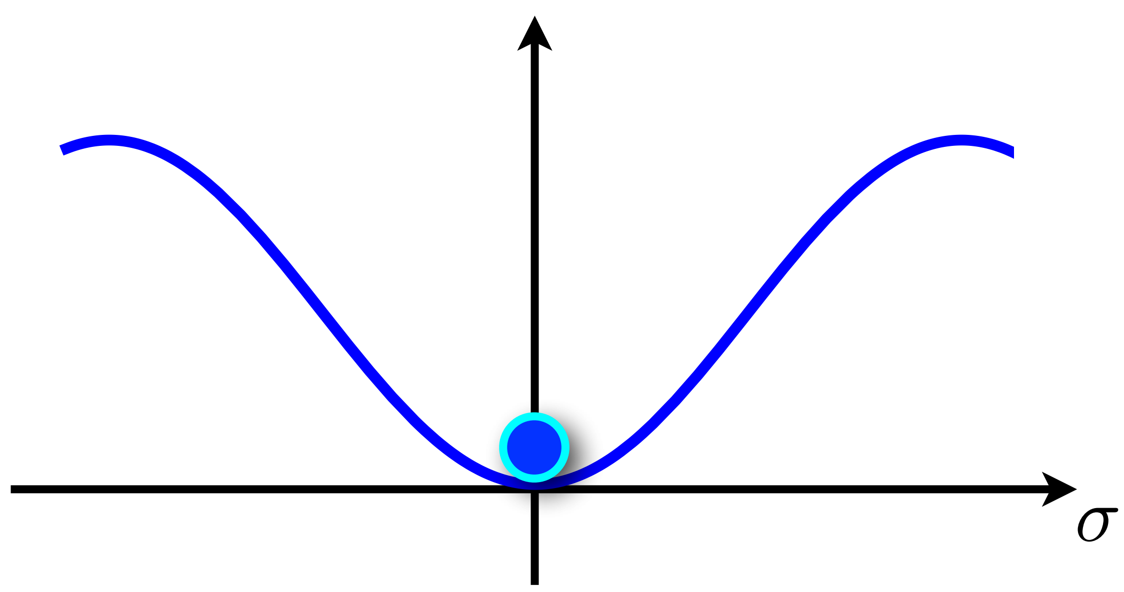

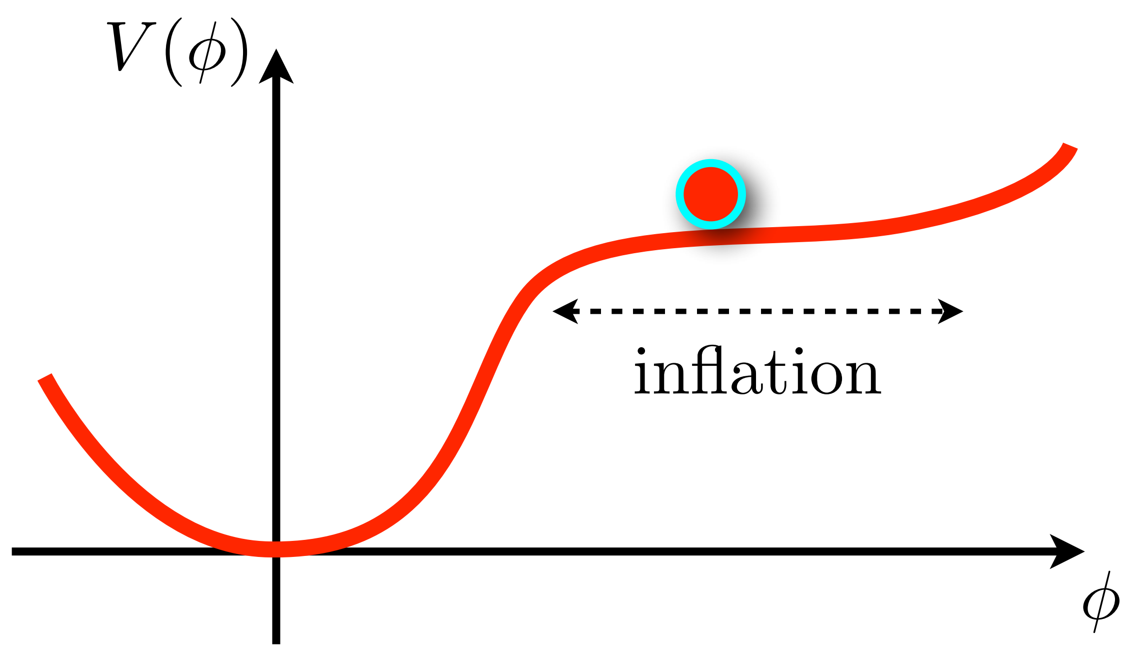

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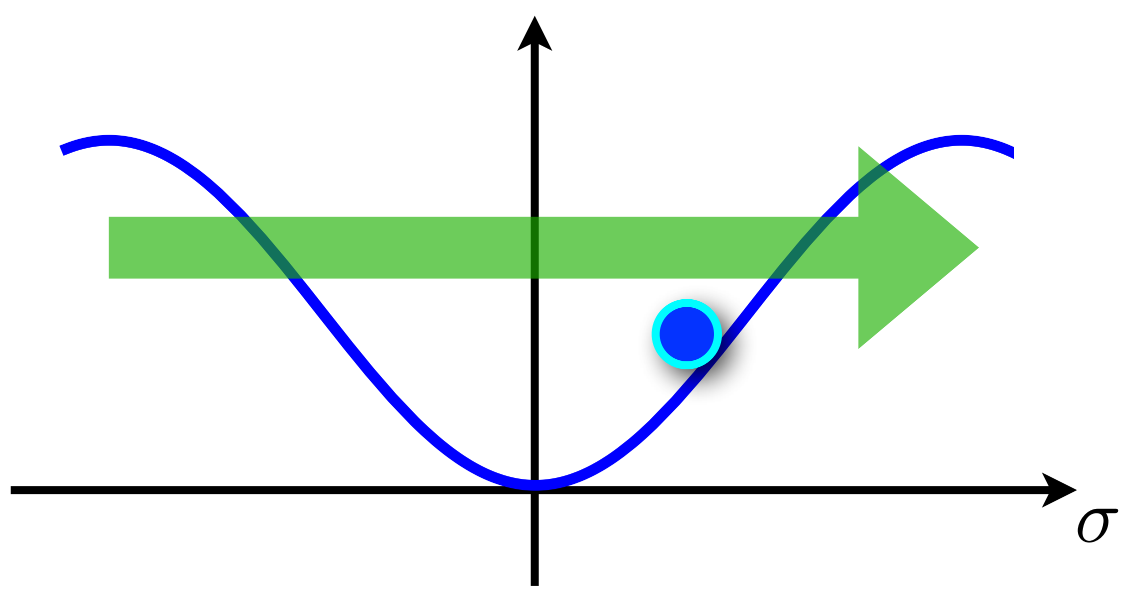

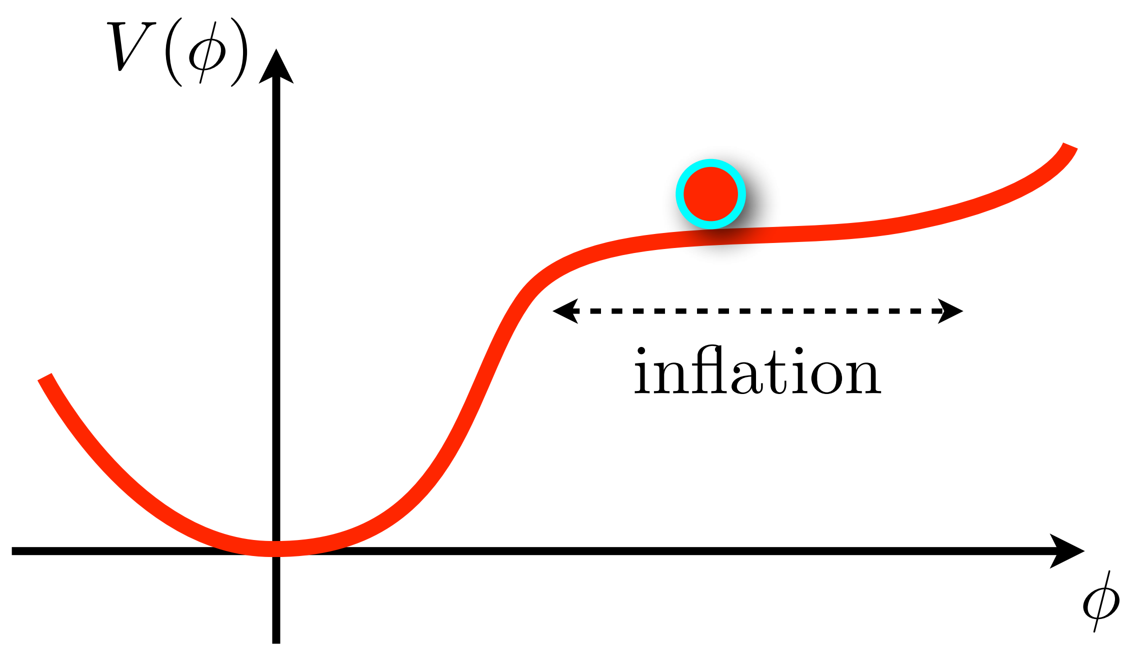

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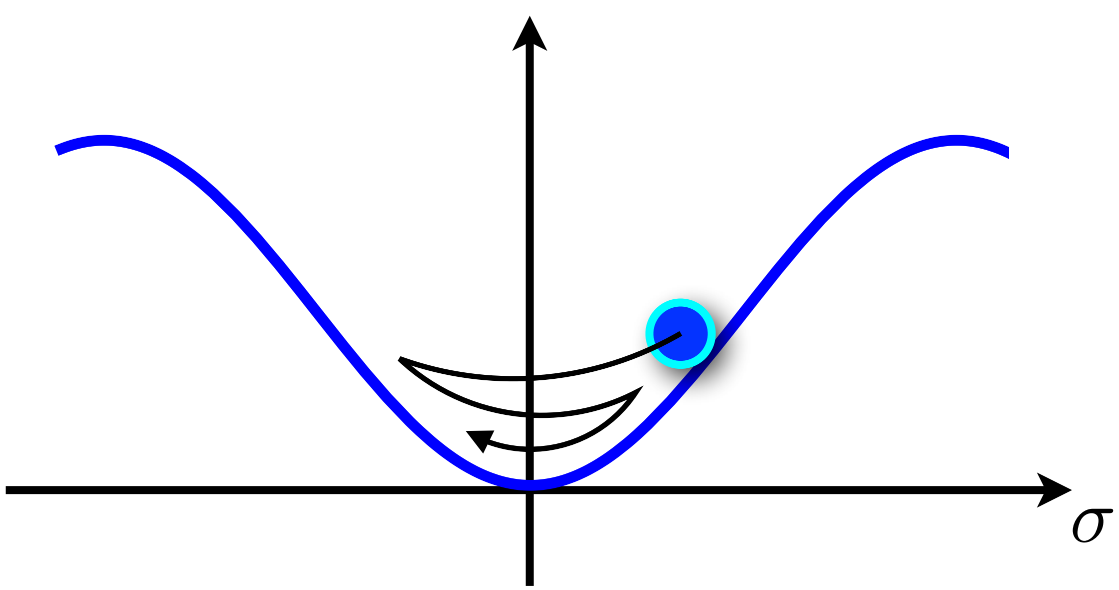
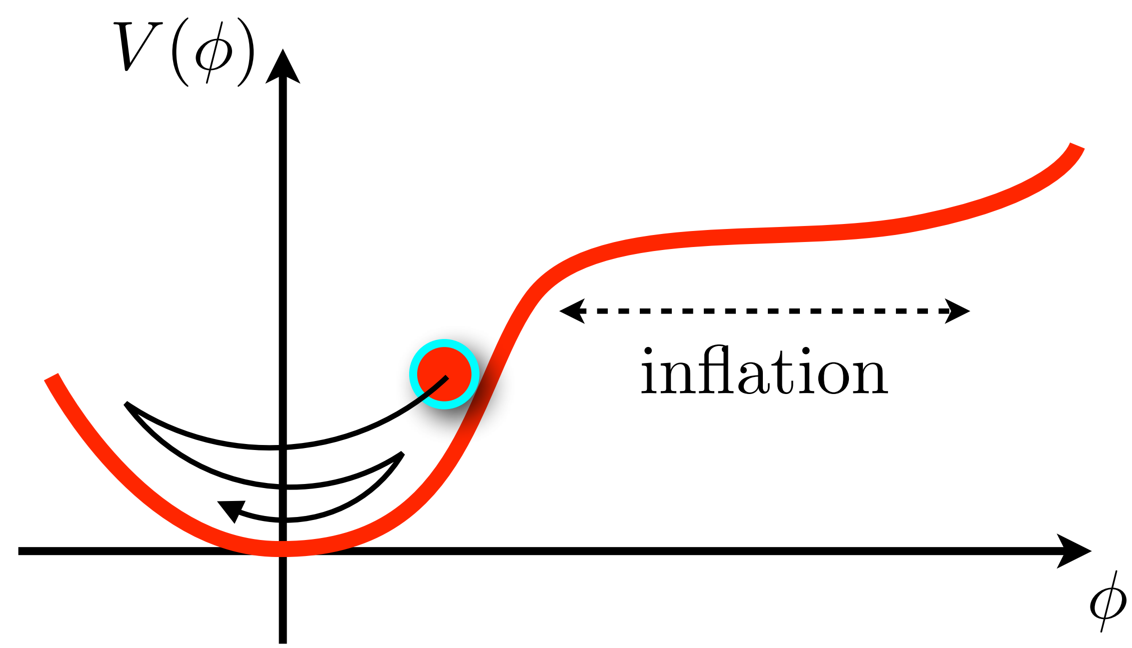
after inflation





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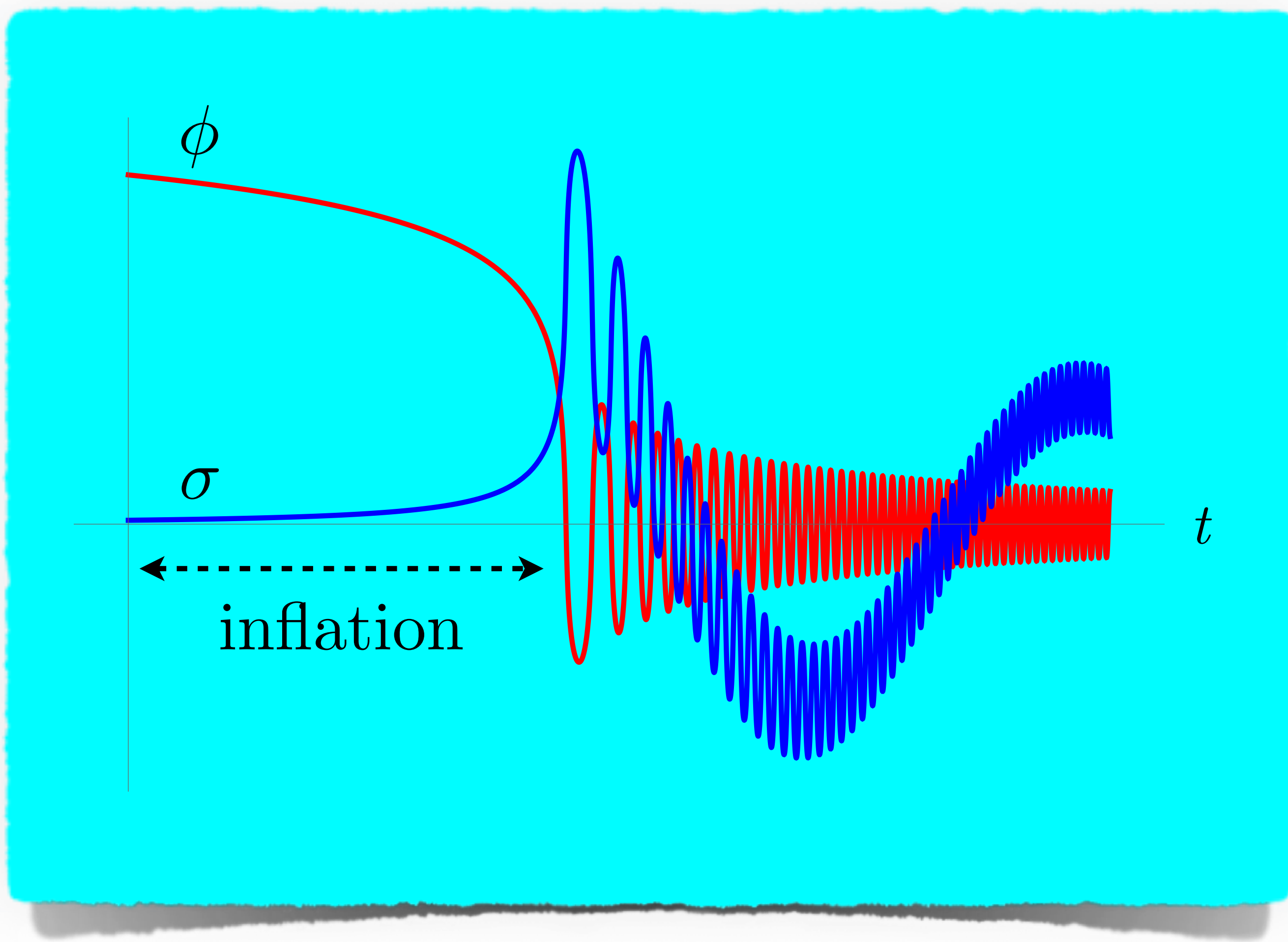

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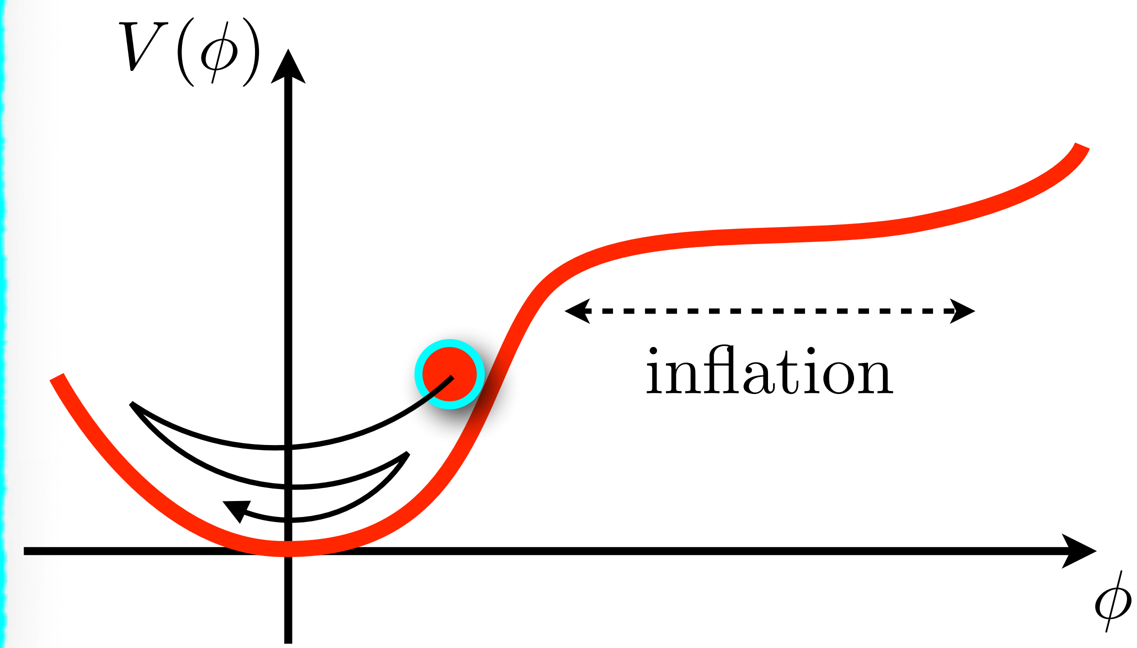

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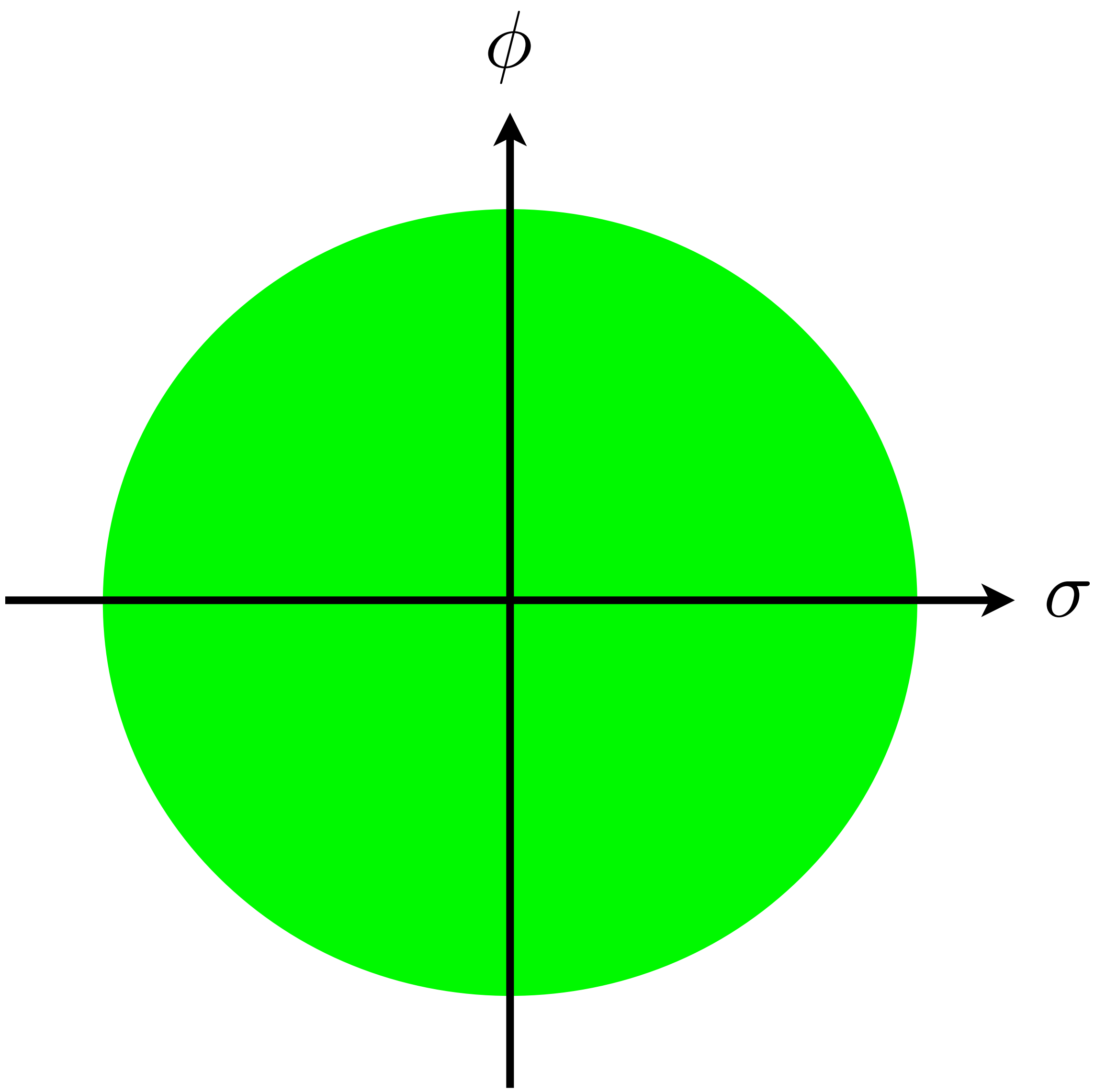

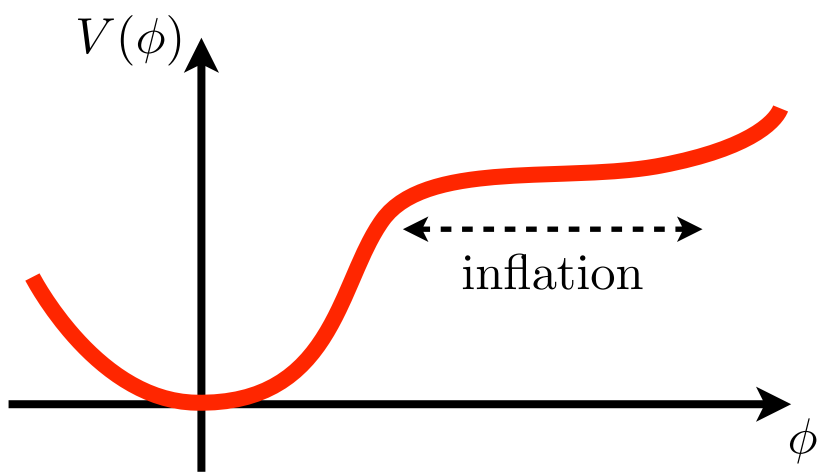

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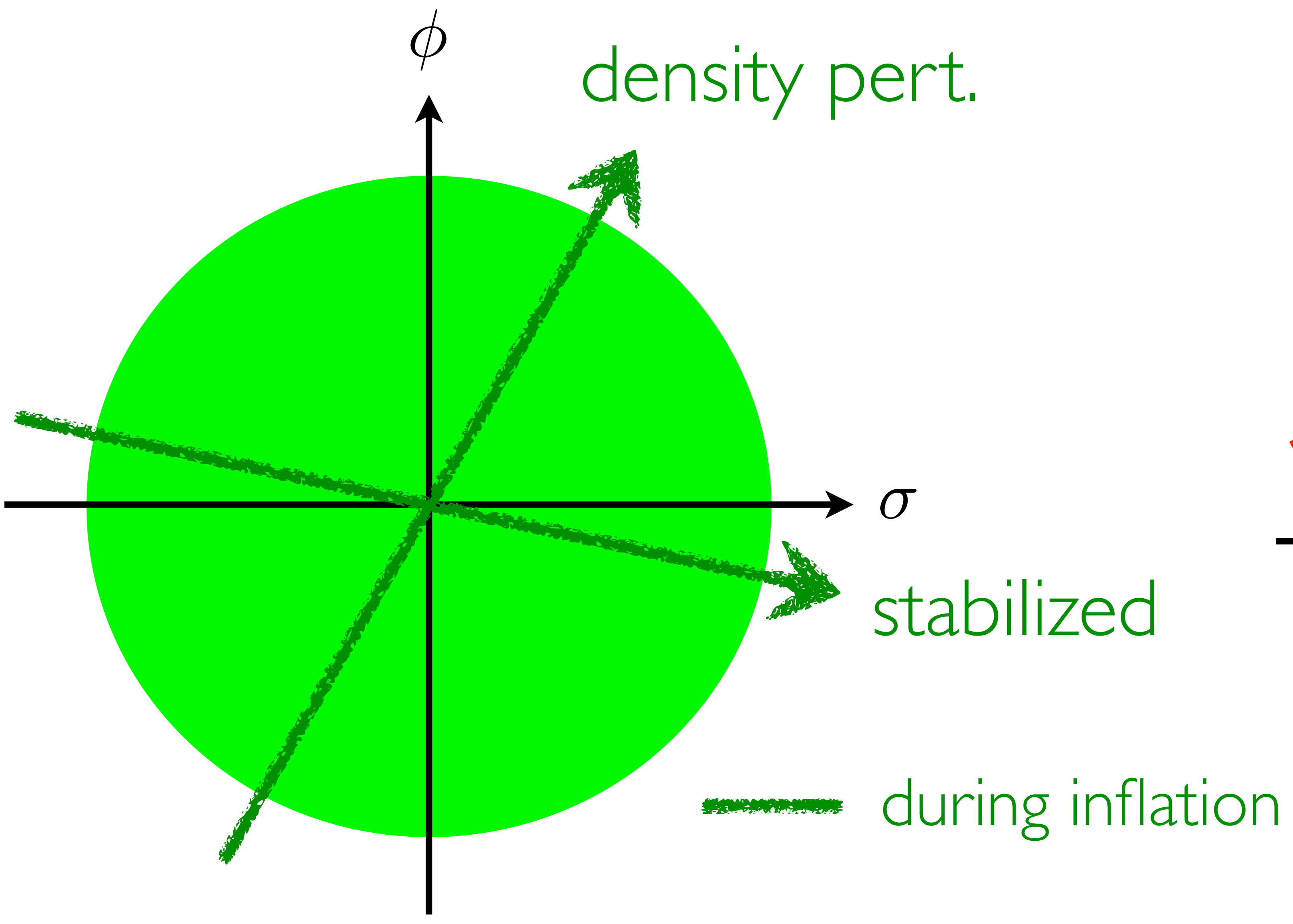

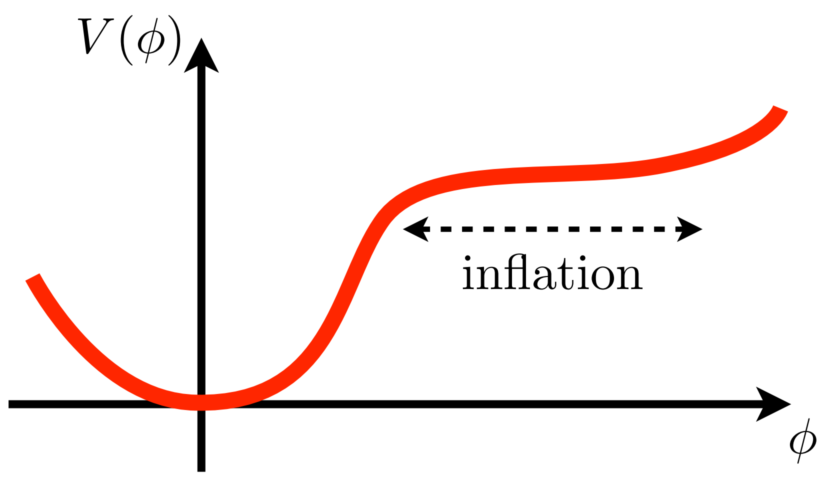

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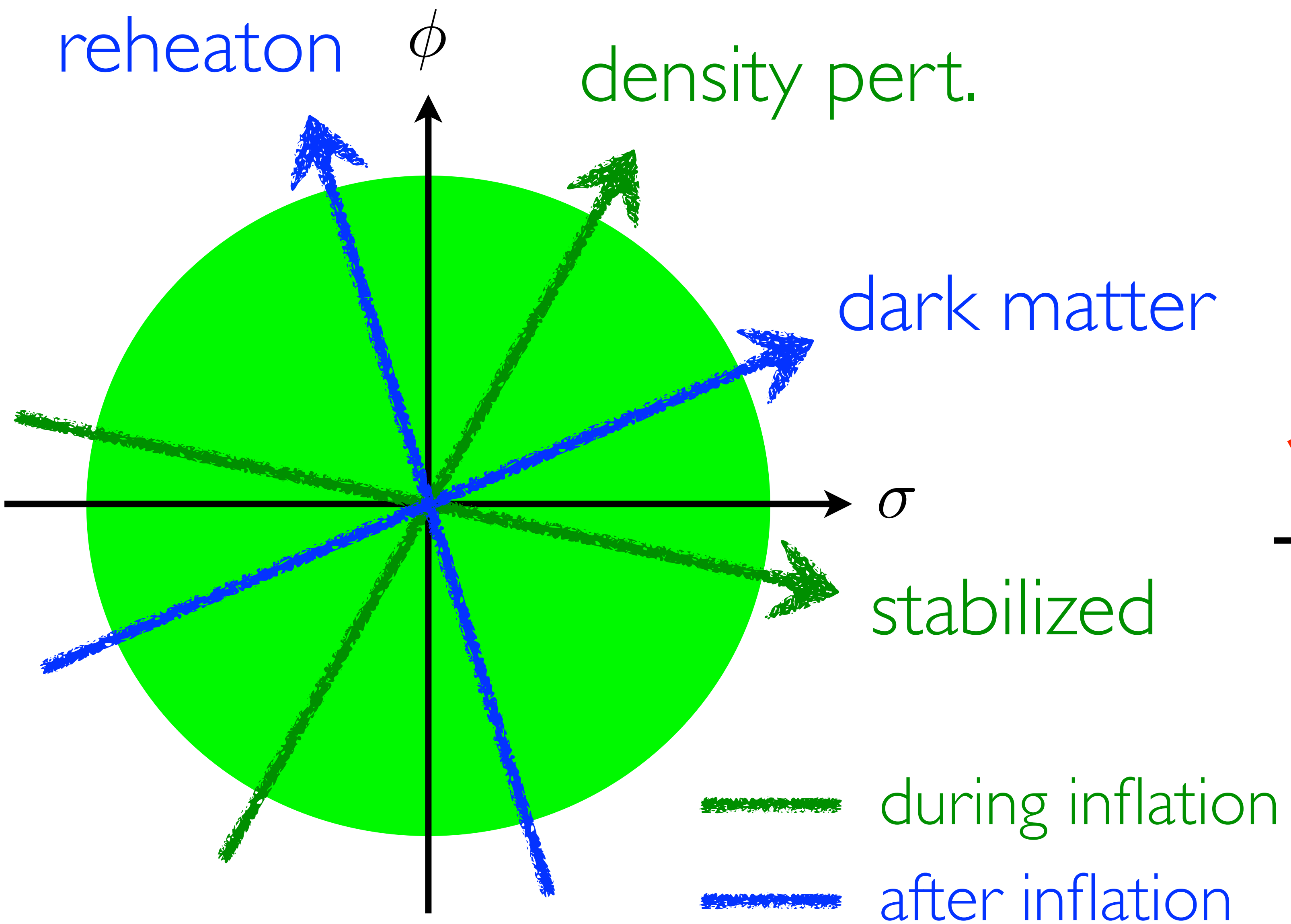
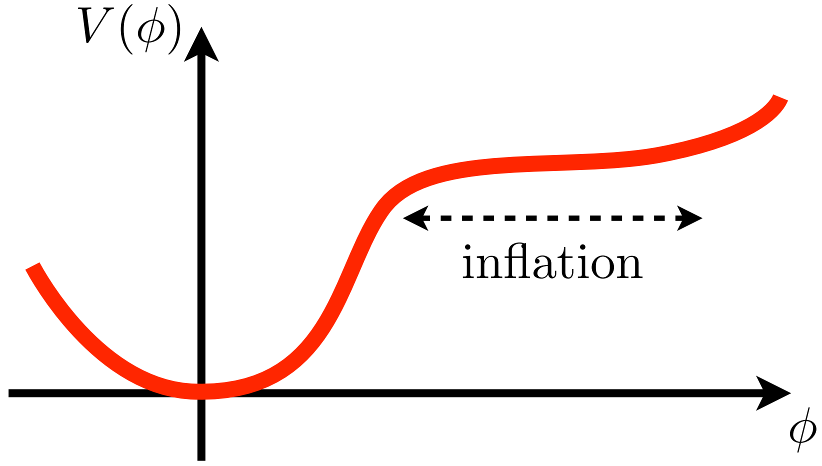
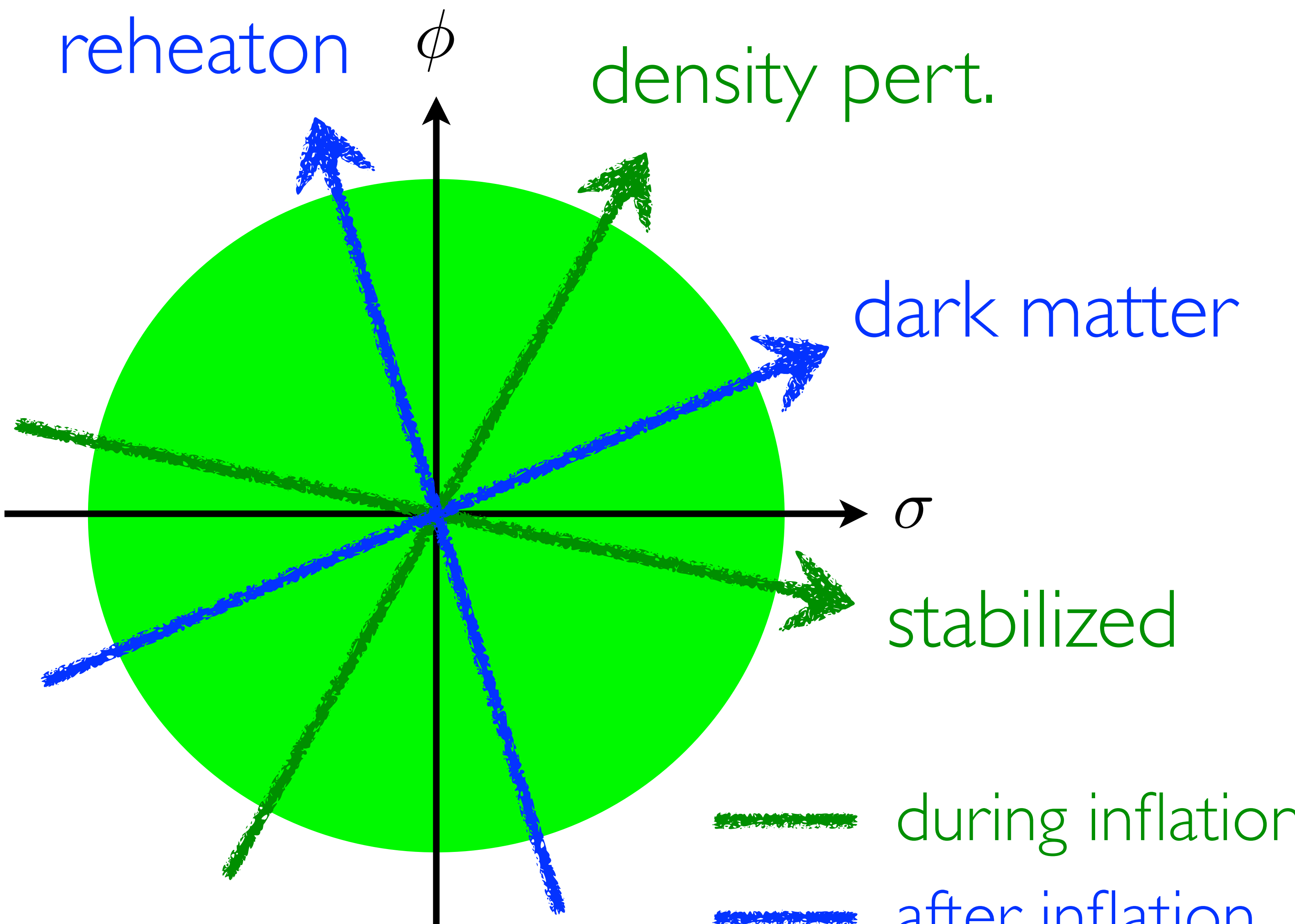
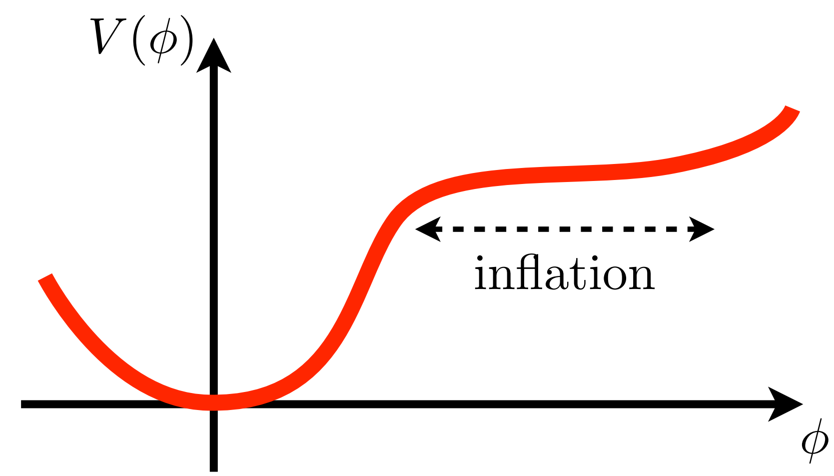




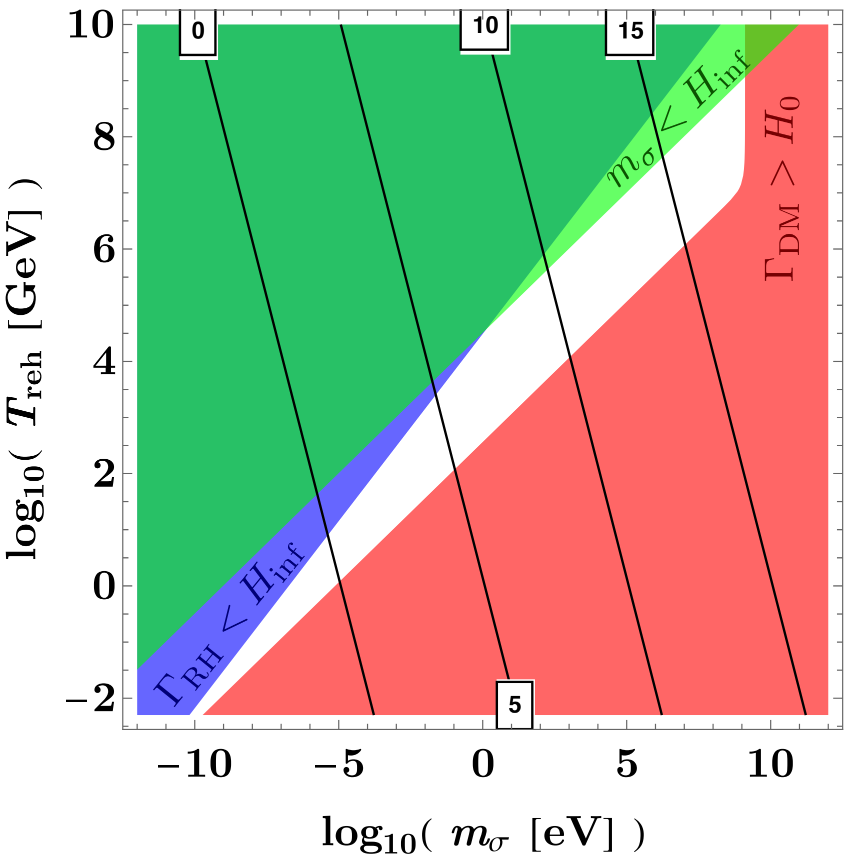
Different combinations of the inflaton and axion (= **inflaxions**) play various cosmological roles.



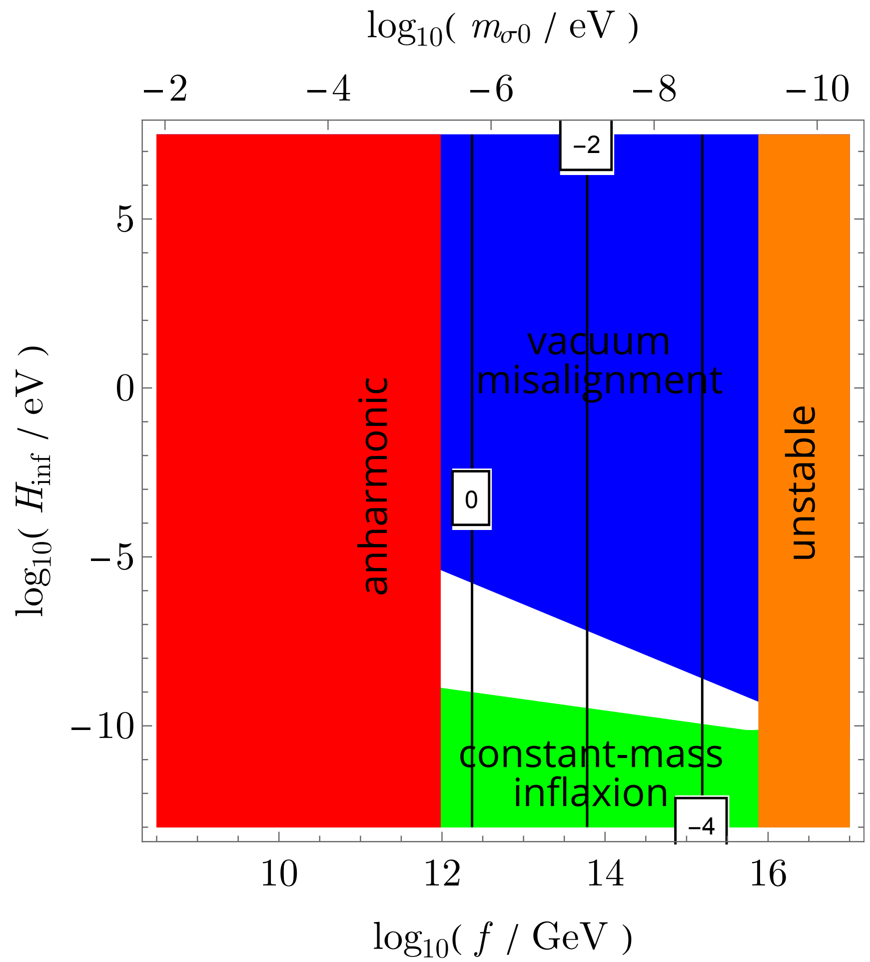


INFLAXION WINDOWS

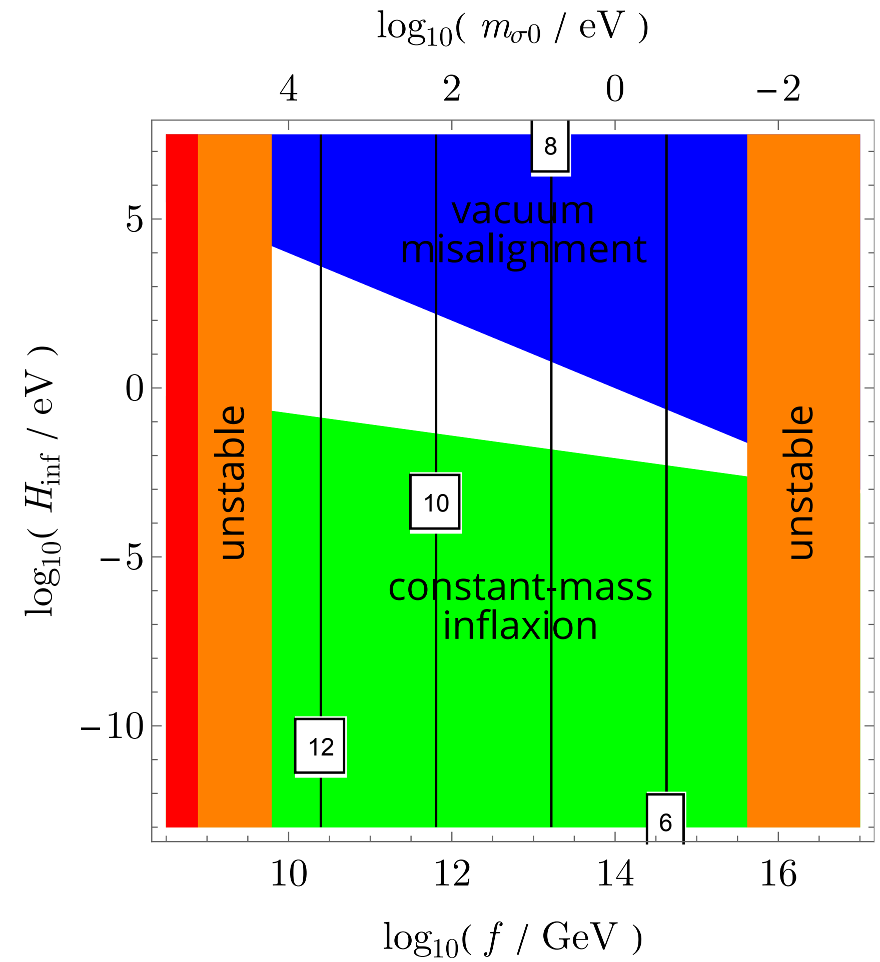
$$L_{\rm int} = -\alpha\, \partial\sigma \cdot \partial\phi + \frac{\alpha_\gamma}{8\pi f}\sigma F\tilde{F} + g\phi\bar{\psi}i\gamma^5\psi \qquad \alpha \sim 1/3 \qquad g \sim 10^{-2}$$



constant-mass axion
($f = 10^{17}\,\mathrm{GeV}$)



QCD axion
($T_{\rm max} > \Lambda_{\rm QCD}$)



axion coupled to a hidden strong group
($T_{\rm max} > \Lambda = 10^3\,\mathrm{GeV}$)

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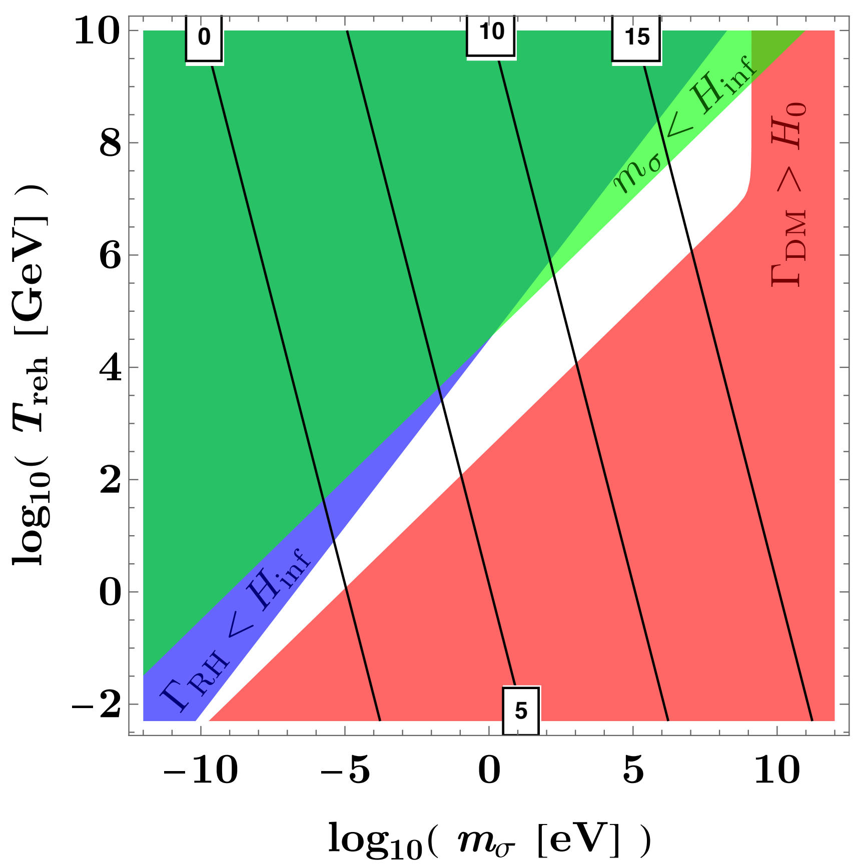

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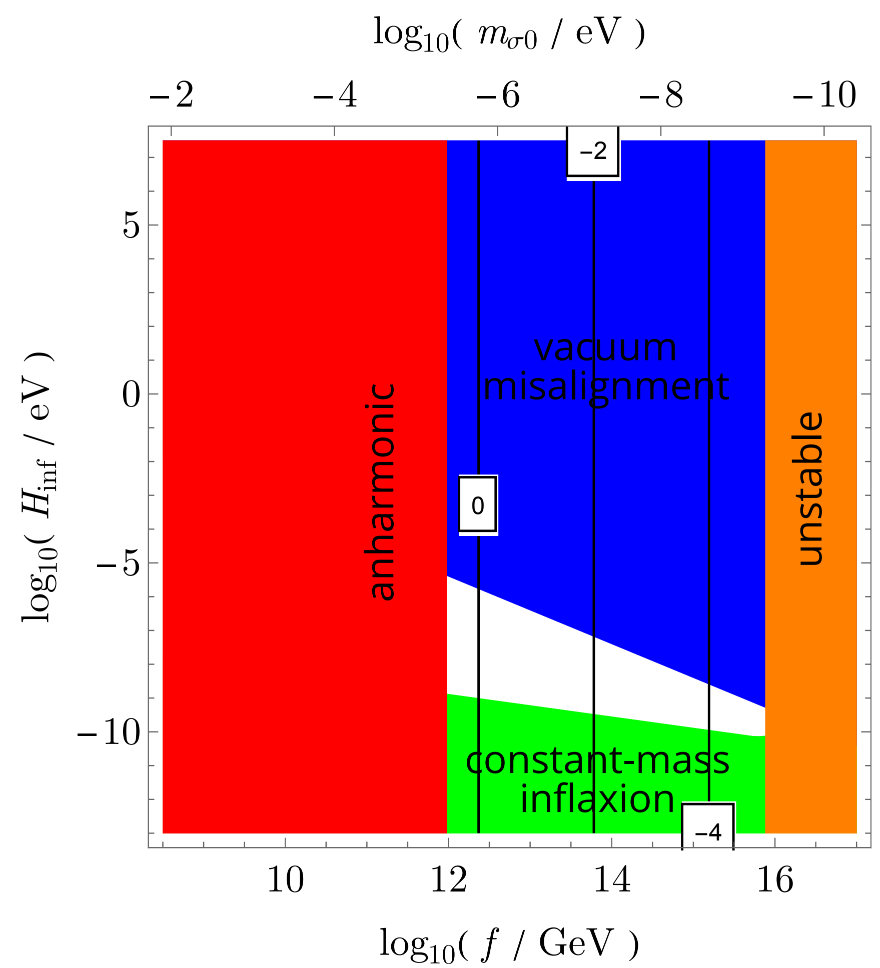
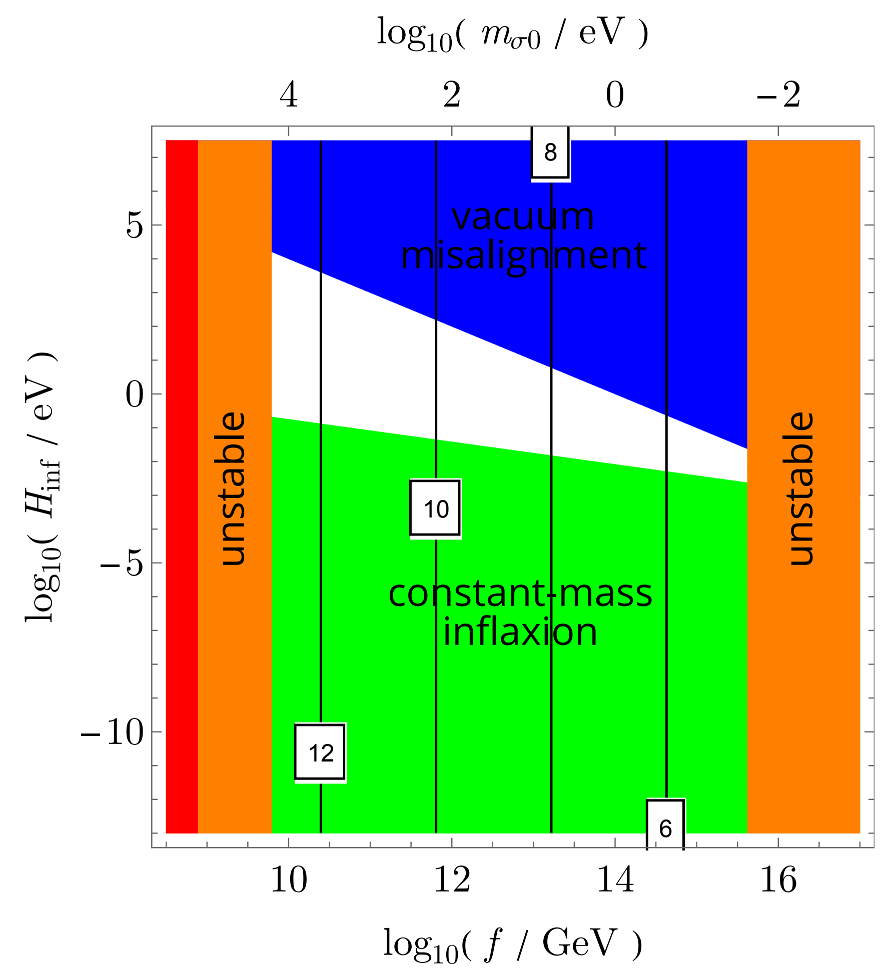


QCD axion
($T_{\mathrm{max}} > \Lambda_{\mathrm{QCD}}$)



axion coupled to a hidden strong group
($T_{\mathrm{max}} > \Lambda = 10^3$ GeV)

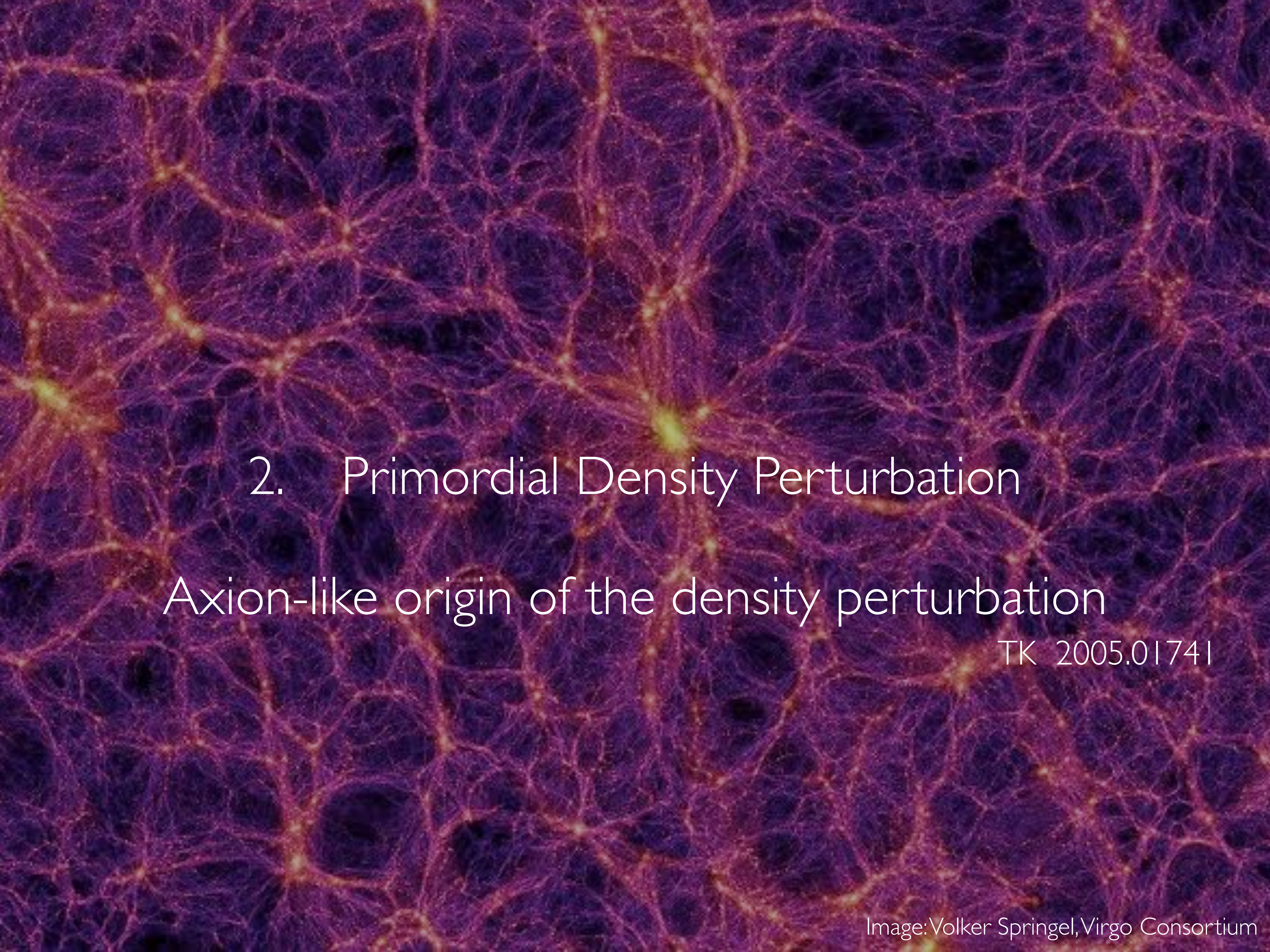
Opens up new axion windows, especially large *f* regions.

OBSERVATIONAL CONSEQUENCES

- Link between reheating temperature and axion-matter couplings
  - DM lifetime can be short even with large f
  - Parts of the new axion window can be probed by upcoming experiments, e.g. ABRACADABRA

- QCD inflaxion with reheating into neutrinos

- No DM isocurvature



2. Primordial Density Perturbation

Axion-like origin of the density perturbation

TK 2005.01741

Image: Volker Springel, Virgo Consortium

SEEDS OF COSMIC STRUCTURES

Observations have revealed that the primordial density perturbation was adiabatic, red tilted, and nearly Gaussian.

Was this generated by the inflaton, or something else?

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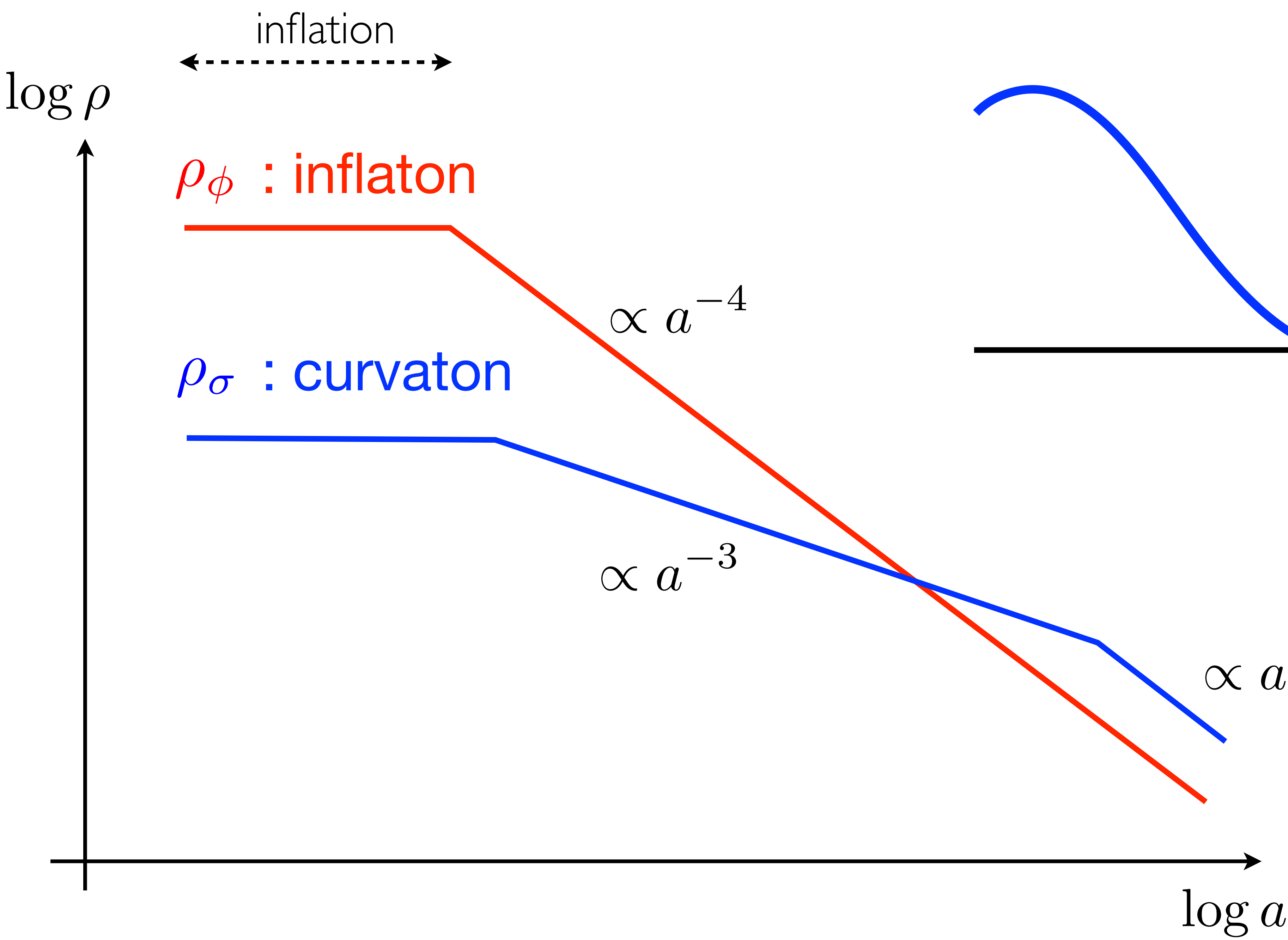
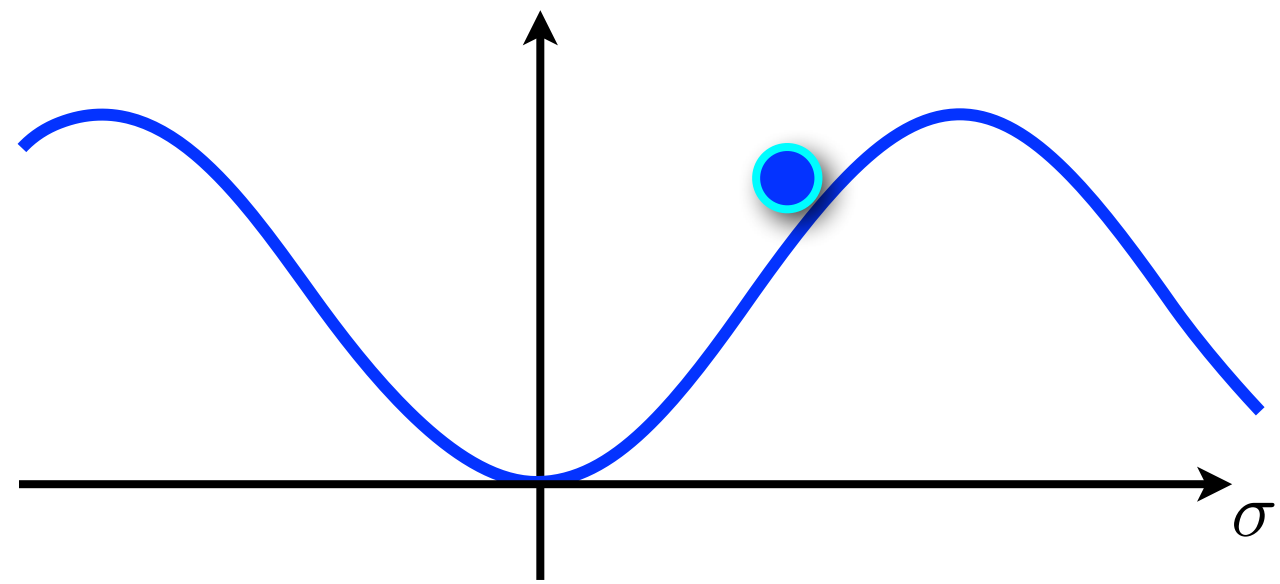
An axion-like field coupled to a new confining sector can generate the perturbation à la curvaton.

CURVATON PARADIGM

Mollerach '90 Linde, Mukhanov '96 Enqvist, Sloth '01 Lyth, Wands '01 Moroi, Takahashi '01





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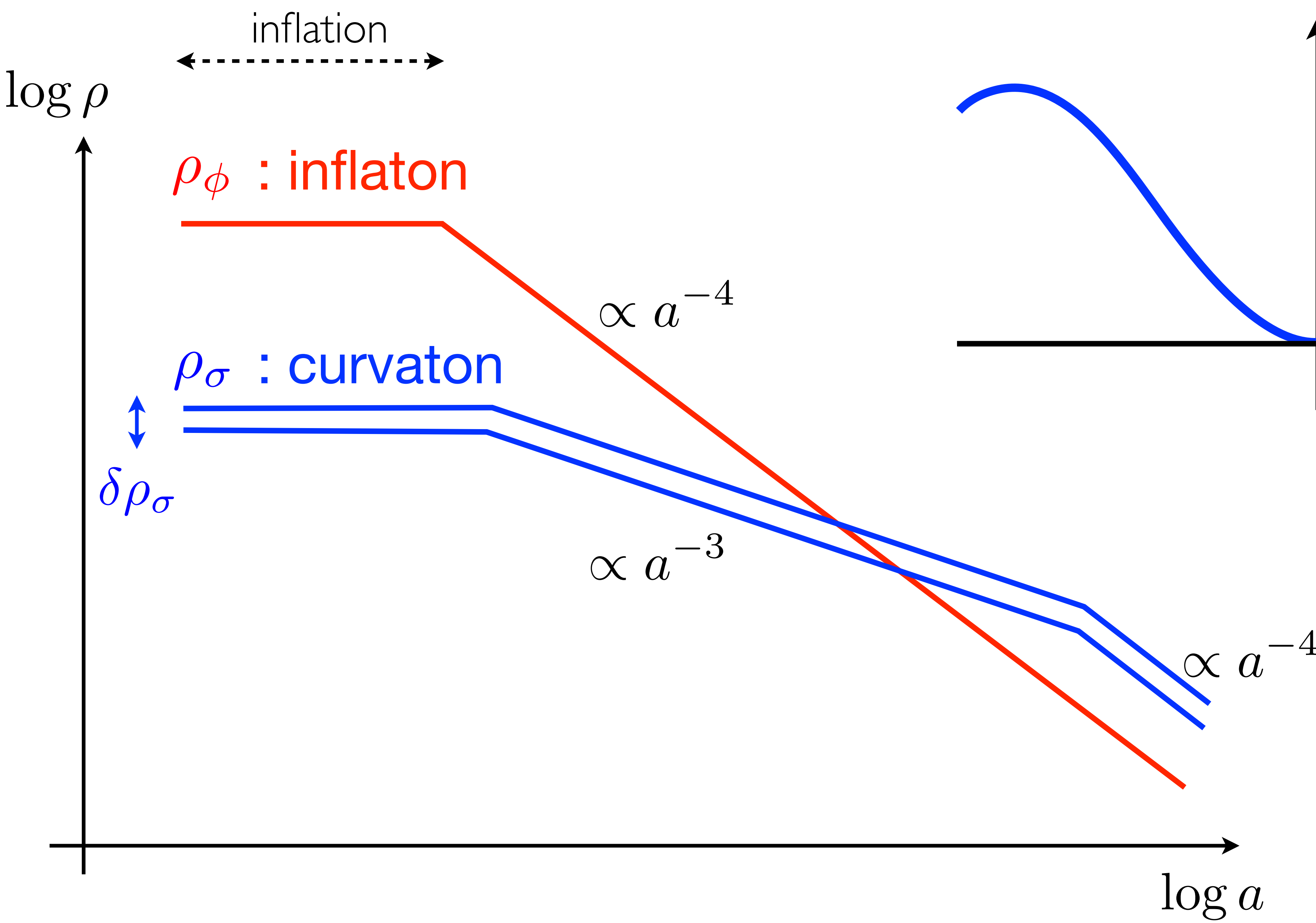

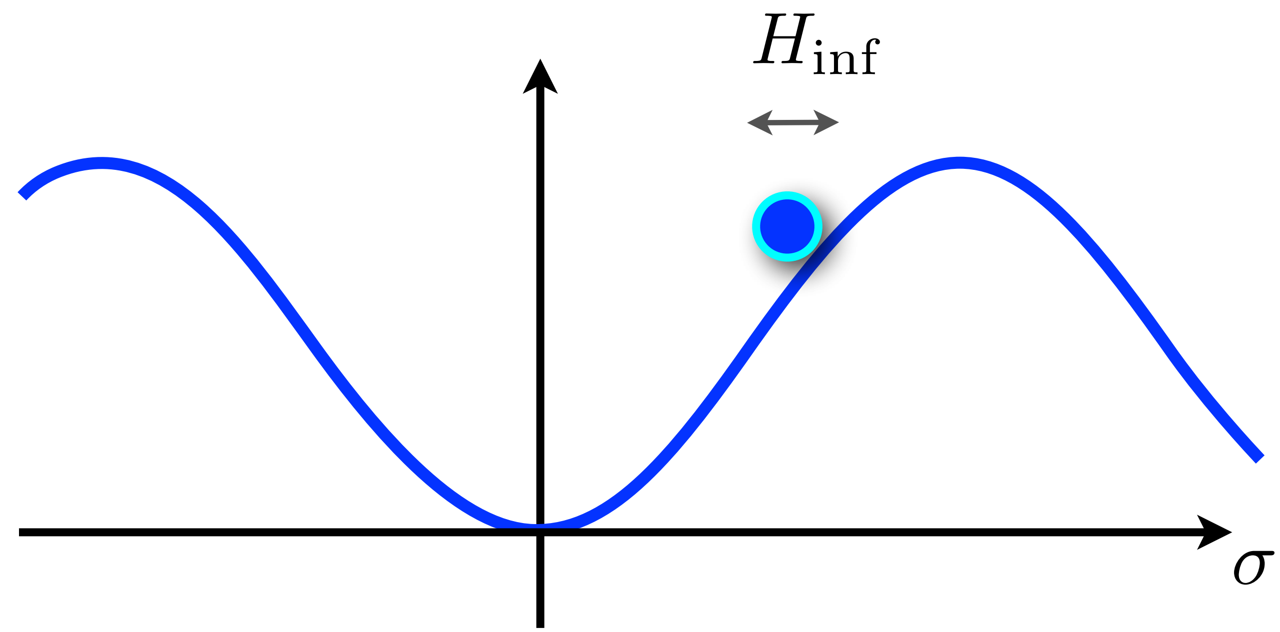

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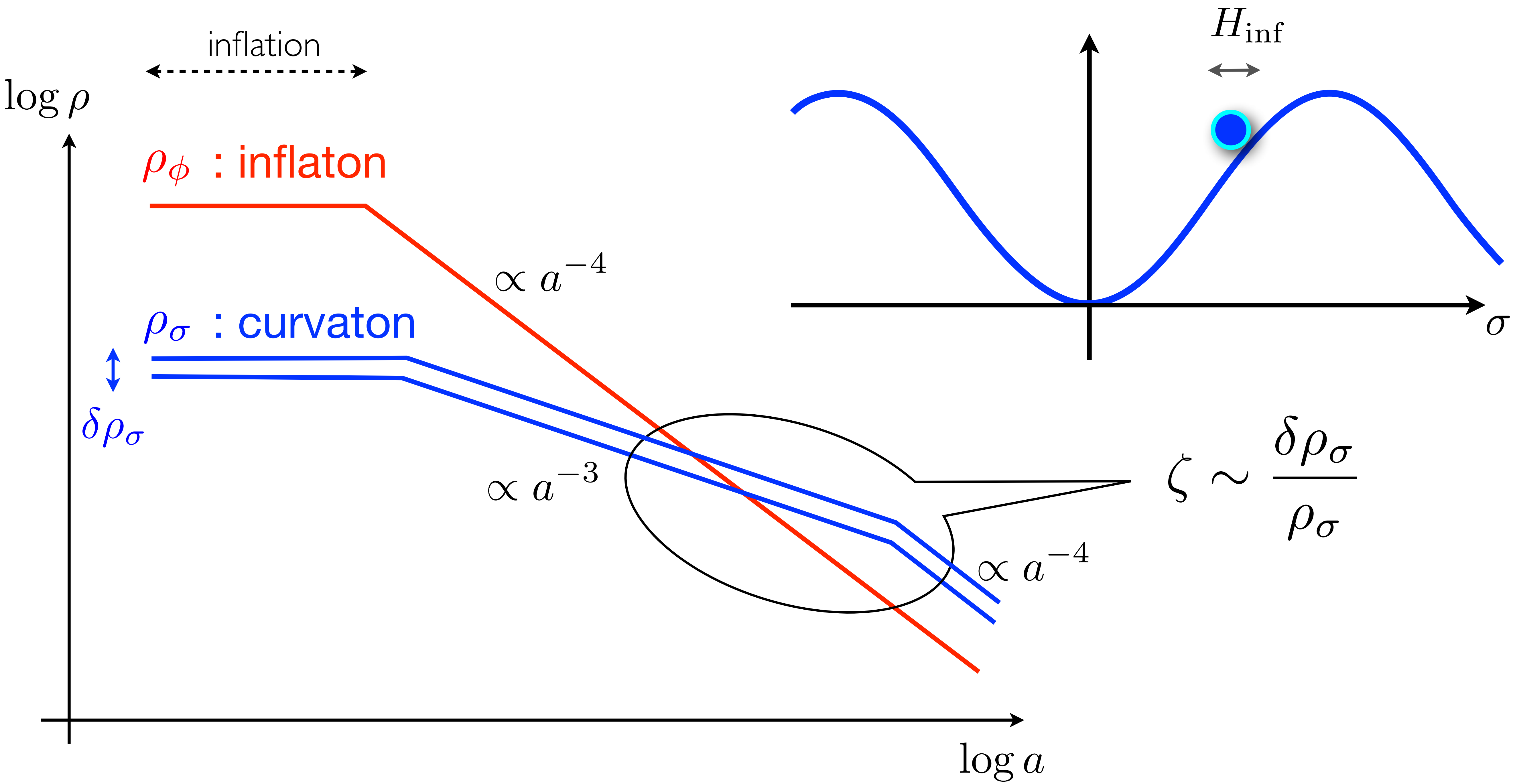
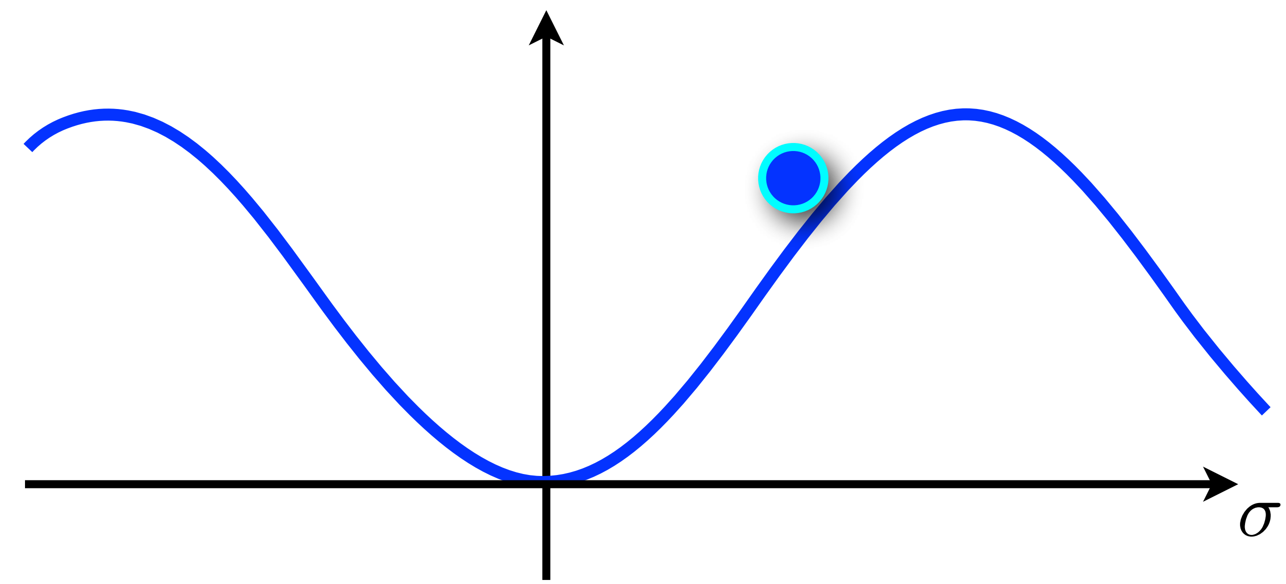


SPECTRAL INDEX FROM CURVATON

$$P_\zeta(k) = P_\zeta(k_*) \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$n_s - 1 = \frac{2}{3}\frac{V''}{H_{\rm inf}^2} + 2\frac{\dot{H}_{\rm inf}}{H_{\rm inf}^2}$$



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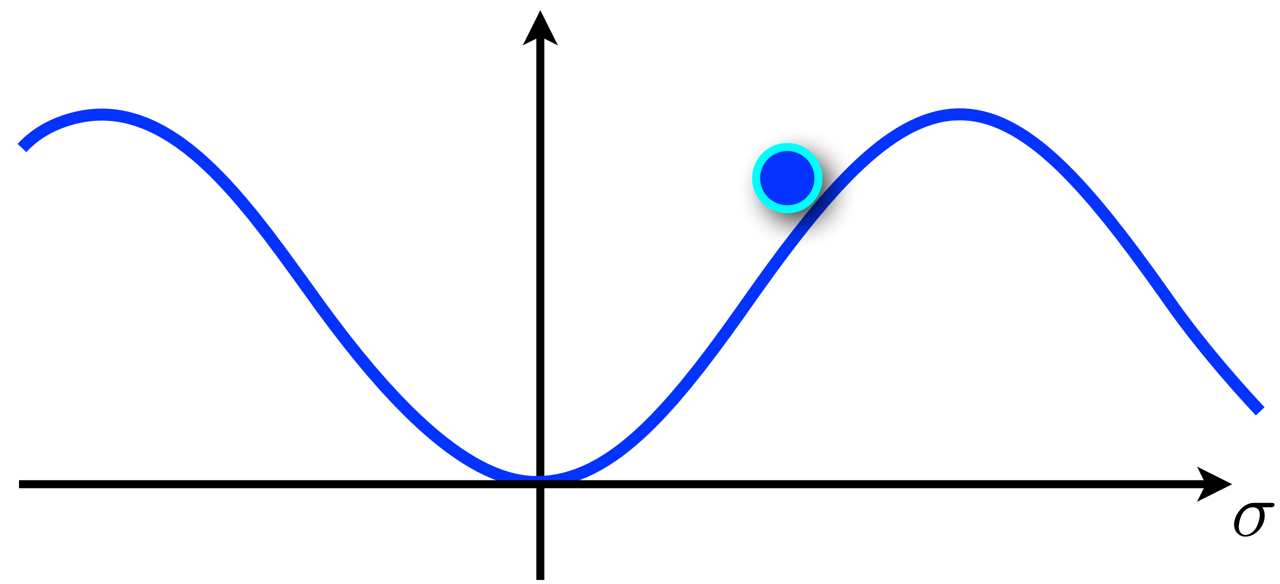

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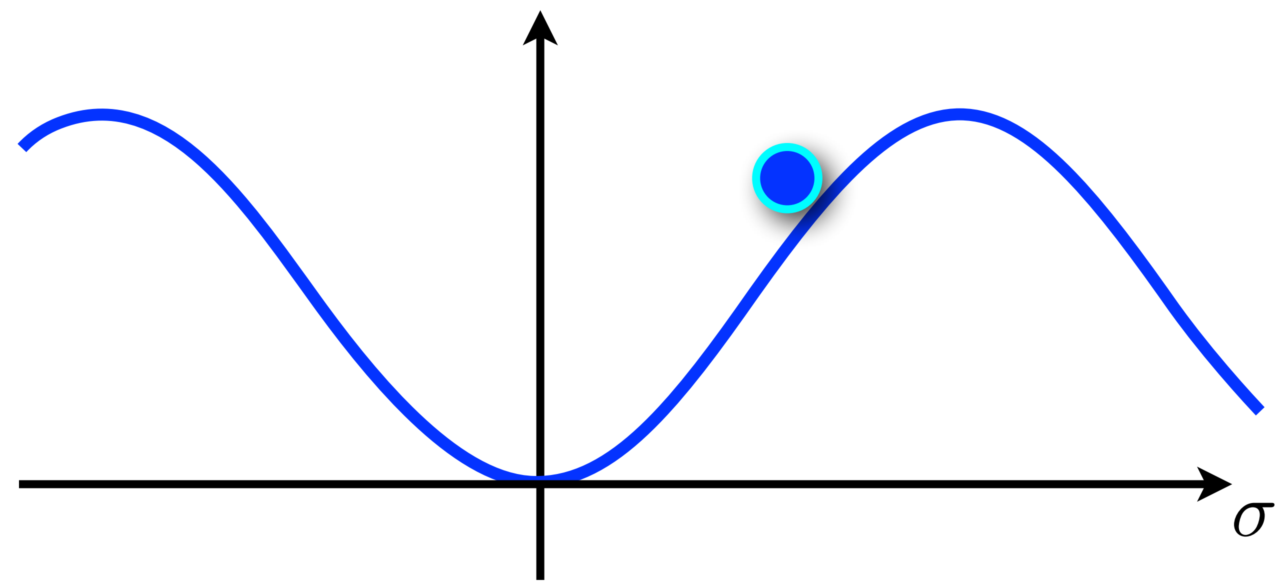

Two options for getting the red tilt:

(i) $-\dot{H}/H^2 \sim 10^{-2}$, i.e. super-Planckian inflation

(ii) concave curvaton potential

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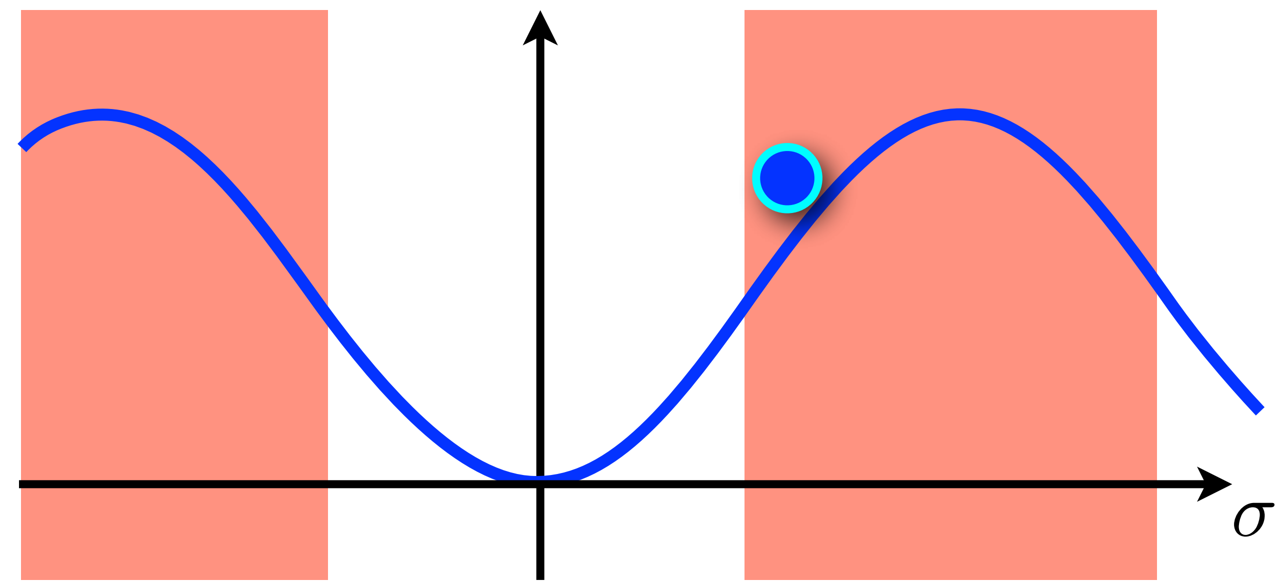

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Axion potentials (by definition) contain concave regions.

AXION-LIKE CURVATON COUPLED TO A NEW CONFINING GAUGE GROUP

$$m_0 \sim \frac{\Lambda^2}{f}$$

$$P_\zeta \sim \left(\frac{H_{\rm inf}}{3\pi f}\right)^2 \approx 2 \times 10^{-9} \qquad n_s - 1 \sim -\frac{2}{3}\left(\frac{m_0}{H_{\rm inf}}\right)^2 \approx -0.04$$

$$f \sim 2000 H_{\rm inf} \qquad \Lambda \sim 20 H_{\rm inf}$$

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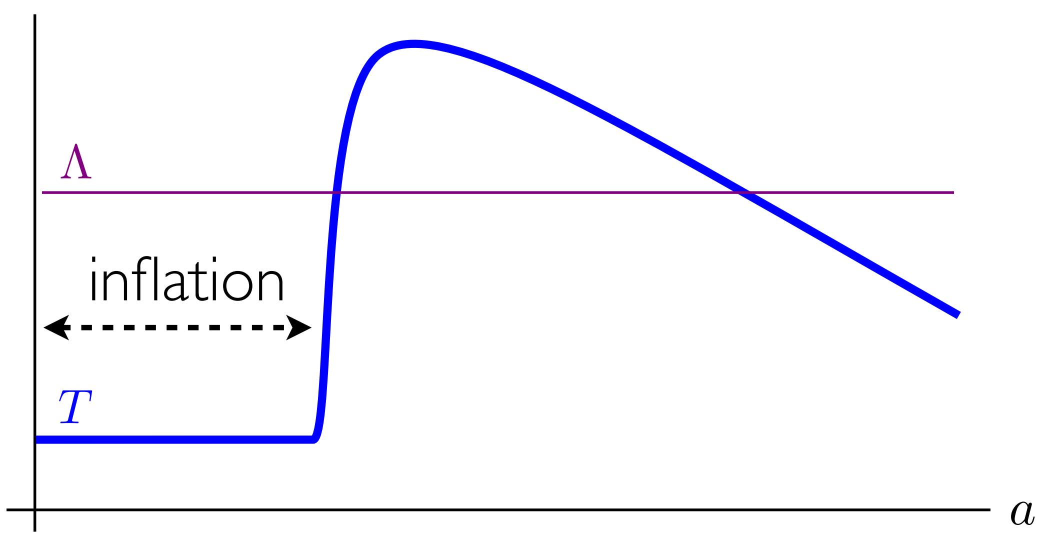
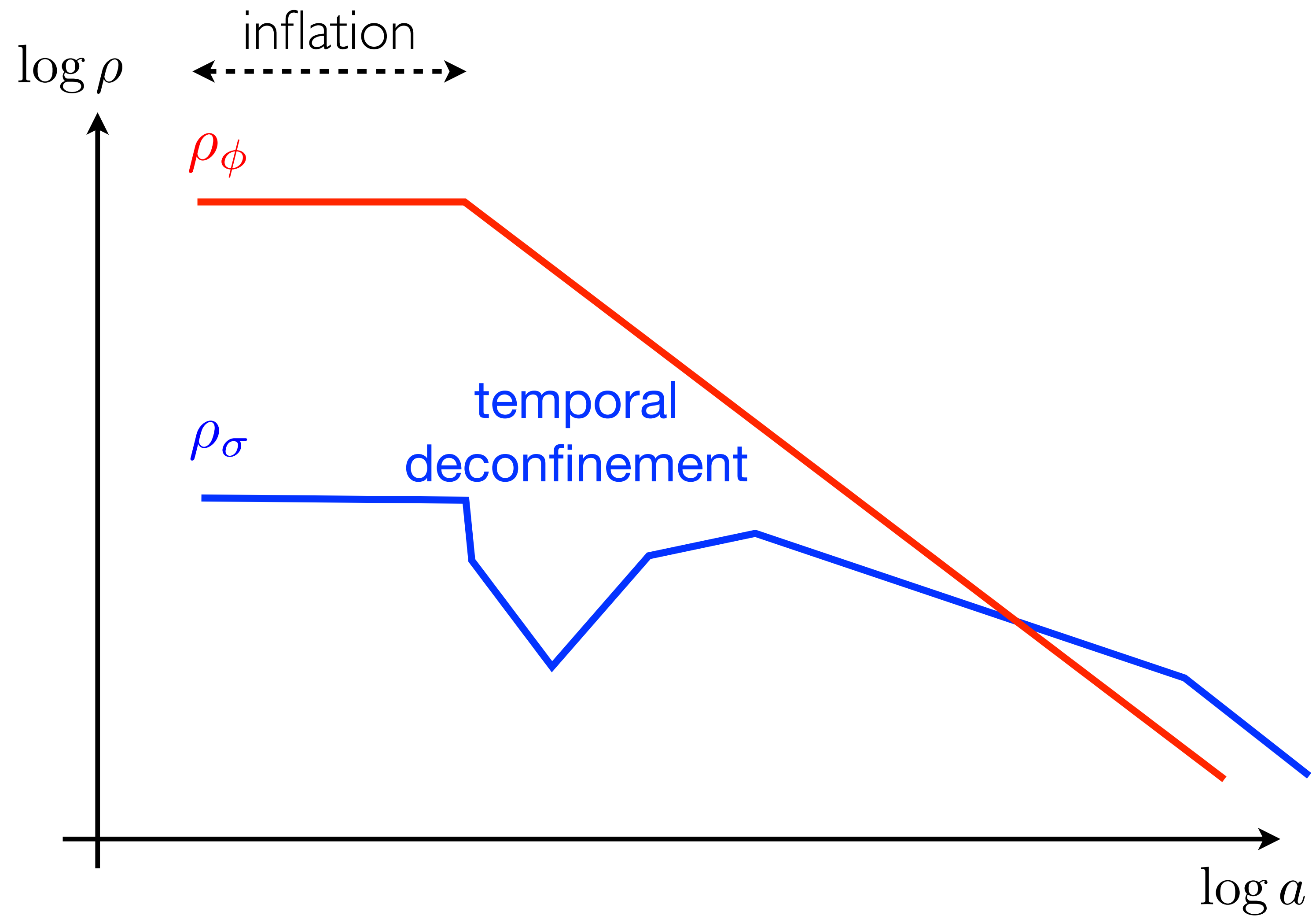
→ temporal deconfinement after inflation

THE IMPORTANCE OF DECONFINING

$$T_{\rm inf} < \Lambda < T_{\rm max}$$





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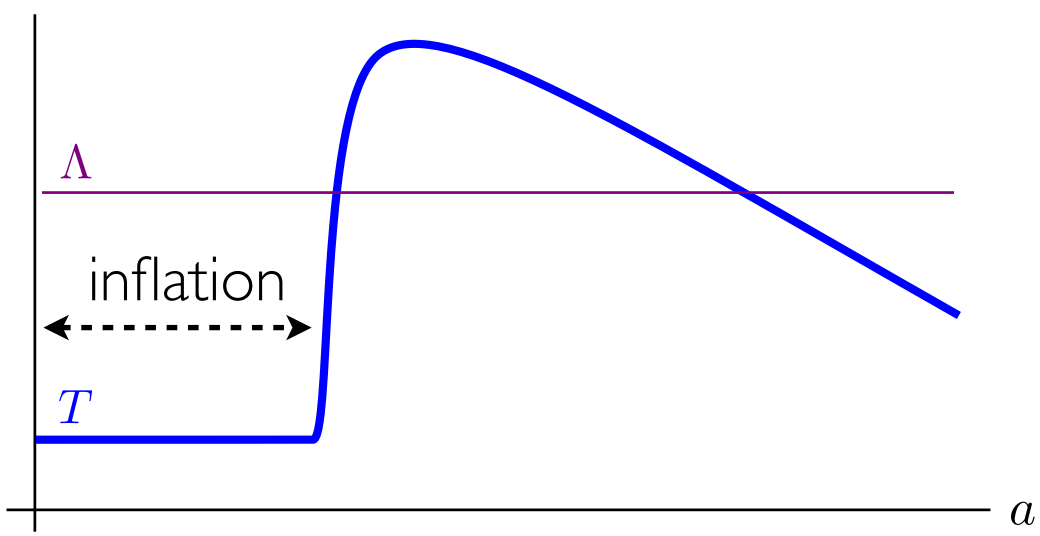

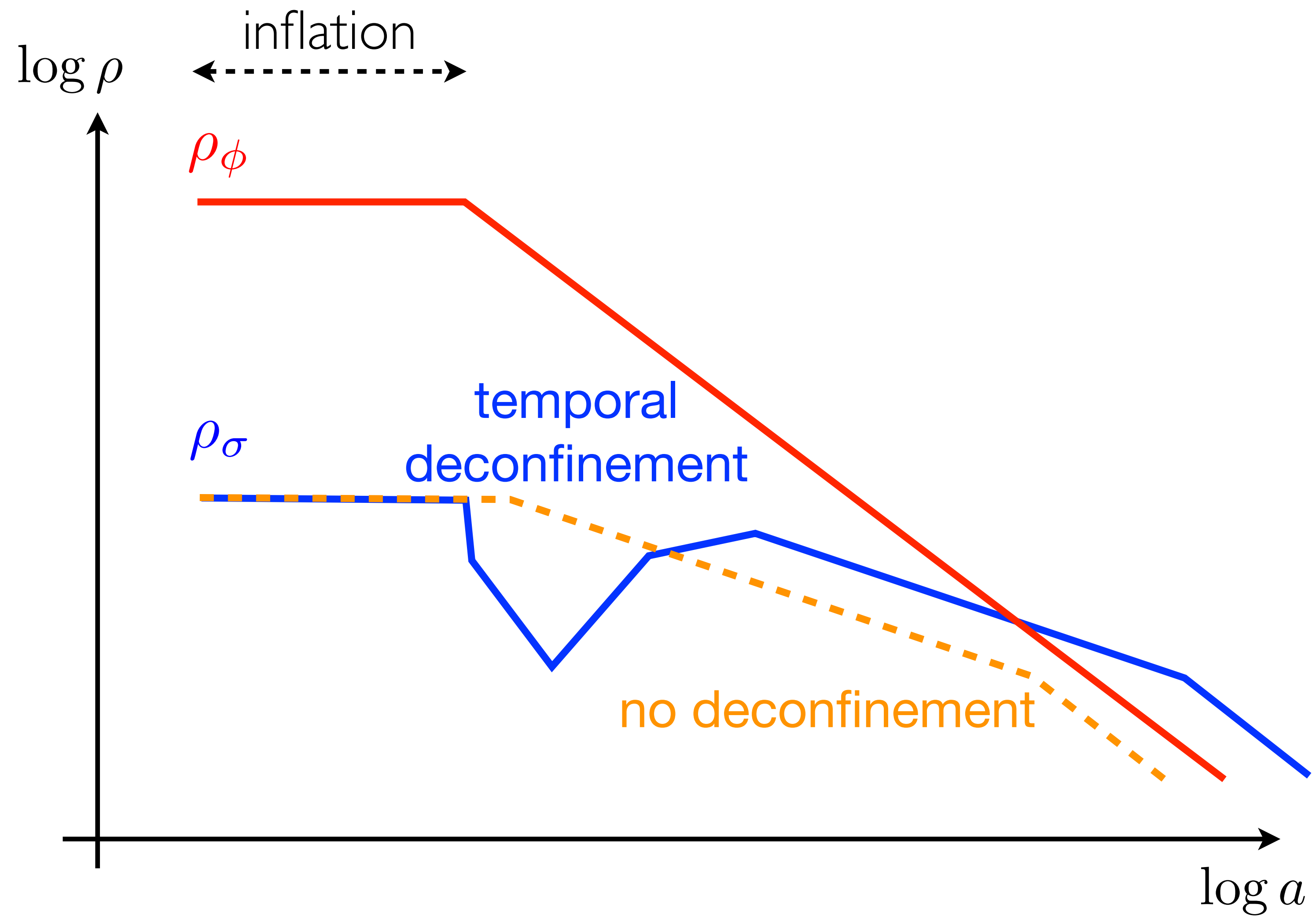

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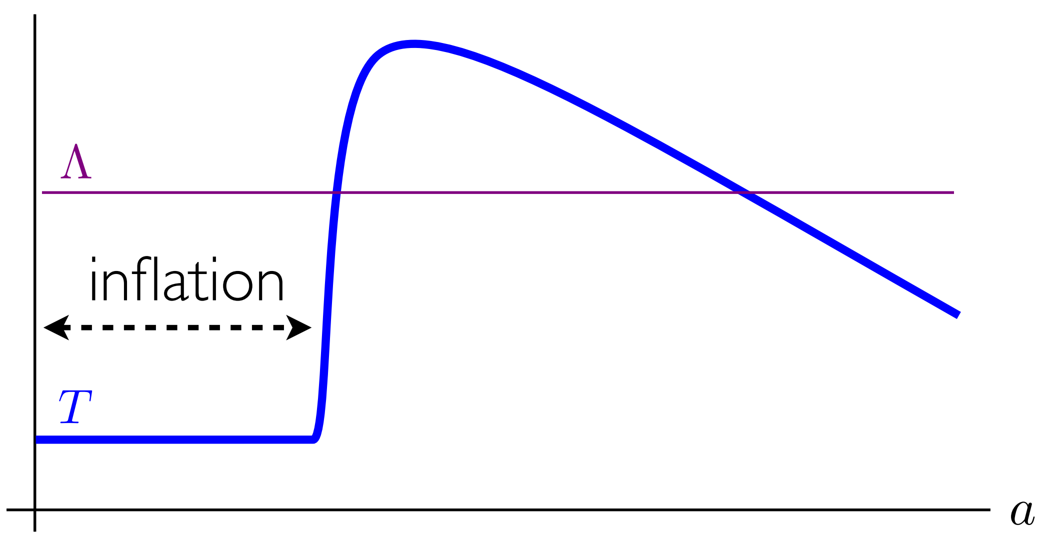

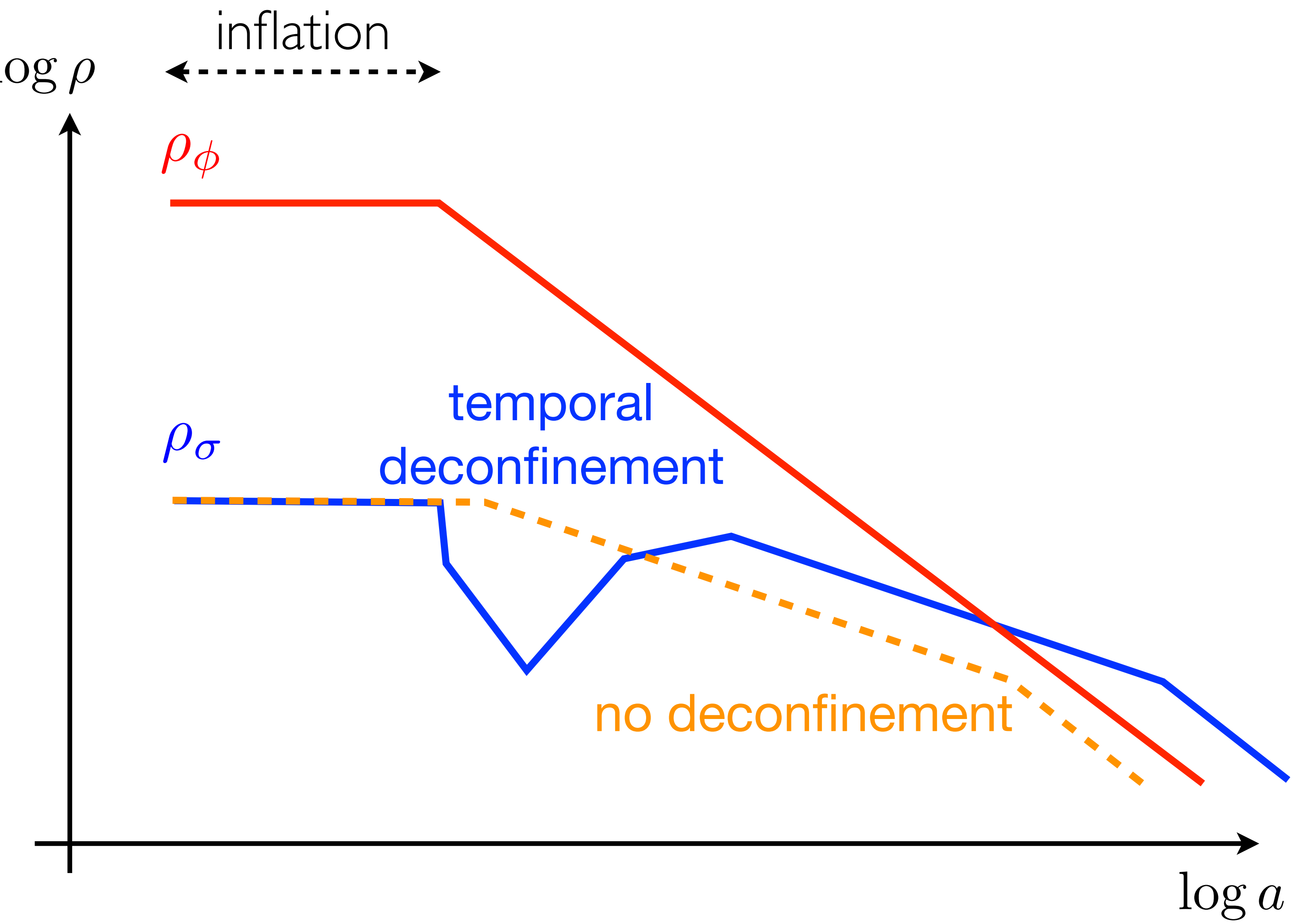

A temporal deconfinement delays the axion oscillation, which helps the axion dominate the universe before decaying.

(Alternatively the axion can be initially placed close to the hilltop, but this produces $f_{\rm NL} \sim 10$ and thus is ruled out. Kawasaki, TK, Takahashi '11)

OBSERVATIONAL CONSEQUENCES

- Positive local-type non-Gaussianity of $f_{\rm NL} \sim 1$
  (cf. single-field inflation $|f_{\rm NL}| \ll 1$, vanilla curvaton $f_{\rm NL} \sim -1$):
  testable with upcoming LSS surveys, e.g. SPHEREx

- Blue tilt on small scales: enhanced perturbations can form ultracompact minihalos (but probably no PBHs in the minimal model)

- Running non-Gaussianity: $f_{\rm NL} \to -1$ towards small scales

SUMMARY

- Inflaxion dark matter
  - An axion-inflaton kinetic mixing allows for a production of axion DM even with low-scale inflation ($H_{\rm inf} < m_\sigma$)
  - Inflaxions integrate a single-field inflaton, reheaton, DM, and opens up new windows (e.g. low $H_{\rm inf}$, $f \gtrsim 10^{16}\,{\rm GeV}$)

- Axion-like curvaton coupled to a new confining sector
  - Parameters are fixed by observations, which suggest a temporal deconfinement of the gauge group after inflation
  - Temperature-dependent and periodic axion potential gives rise to the red tilt as well as $f_{\rm NL} \sim 1$

BACKUP SLIDES

AXION-LIKE CURVATON: PARAMETERS

$$\frac{\mathcal{L}}{\sqrt{-g}} - \frac{1}{2} f^2 (\partial\theta)^2 - m(T)^2 f^2 \left(1 - \cos\theta\right) + \frac{\alpha}{8\pi} \theta F \tilde{F} \qquad m_0 \sim \frac{\Lambda^2}{f}$$

$$P_\zeta \sim \left(\frac{H_{\rm inf}}{3\pi f}\right)^2 \approx 2\times 10^{-9} \quad n_s - 1 \sim -\frac{2}{3}\left(\frac{m_0}{H_{\rm inf}}\right)^2 \approx -0.04 \quad f_{\rm NL} \sim 1$$

$$f \sim 2000 H_{\rm inf} \qquad \Lambda \sim 20 H_{\rm inf}$$

$$T_{\rm inf} < \Lambda < \boxed{T_{\rm max} < f} \qquad T_{\rm max} \sim (M_p H_{\rm inf})^{1/2}$$

$$\boxed{10^{11}\,{\rm GeV} \lesssim H_{\rm inf}} \lesssim 10^{14}\,{\rm GeV}$$

$$\boxed{10^{-11}\,(10^{-13})} \lesssim \alpha \lesssim \boxed{10^{-2}\,(10^{3})} \qquad \text{for} \quad H_{\rm inf} = 10^{11}\,(10^{14})\,{\rm GeV}$$

decay before BBN curvaton domination

AXION-LIKE CURVATON: PERTURBATION

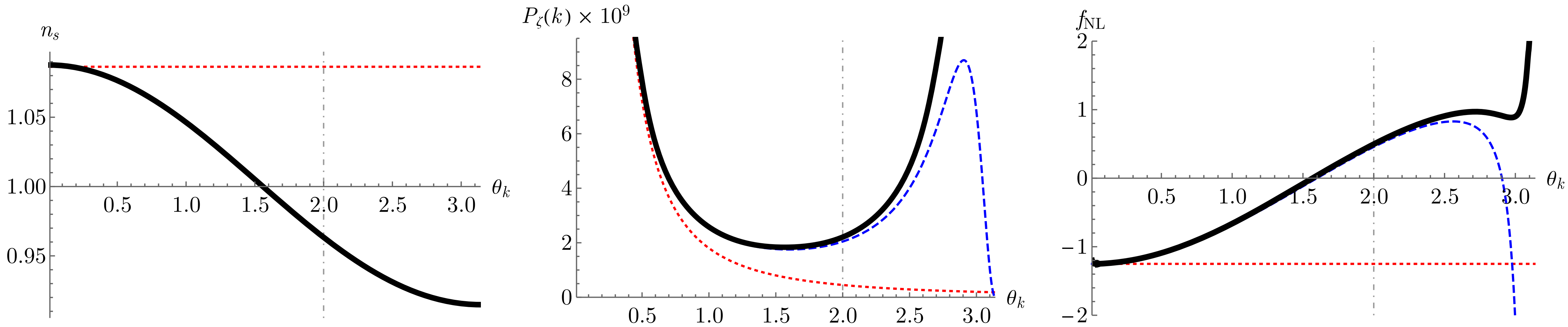

FIG. 1. Curvature perturbation as a function of the axion angle when the pivot scale exits the horizon during inflation. The axion decay constant and strong coupling scale are taken as $f = 2500H_{\rm inf}$ and $\Lambda = 30H_{\rm inf}$, so that the power spectrum amplitude and the spectral index match with observations at $\theta_k \approx 2.0$. The black solid lines show the numerical results, while the blue dashed lines are analytic approximations. Results for vanilla curvatons are shown as the red dotted lines.

$$P_\zeta(k) \simeq \left(\frac{R}{3R+4} \frac{1+\cos\theta_{\rm end}}{\sin\theta_k} \frac{H_k}{2\pi f} \right)^2 \qquad R \equiv \left(\frac{\rho_\theta}{\rho_{\rm r}} \right)_{\rm dec}$$

$$f_{\rm NL} \simeq \frac{5}{6} \left\{ \frac{4}{R} + \frac{4}{3R+4} - \left(3 + \frac{4}{R} \right) \frac{1 - \cos\theta_{\rm end} + \cos\theta_k}{1 + \cos\theta_{\rm end}} \right\}$$

$$n_s - 1 \simeq \frac{2}{3} \frac{m_0^2}{H_k^2} \cos\theta_k + 2 \frac{\dot{H}_k}{H_k^2}$$