Axions, Dark Matter, and Primordial Density Perturbations

Takeshi Kobayashi

IBS-ICTP Workshop on Axion-Like Particles, October 2021

OUTLINE

- brief review of axion cosmology
- new mechanism for axion DM production

  TK, Lorenzo Ubaldi 1907.00984, 2006.09389
- impact of primordial electromagnetic fields on axions

  TK, Rajeev Kumar Jain 2012.00896
- axion-like origin of the primordial density perturbation

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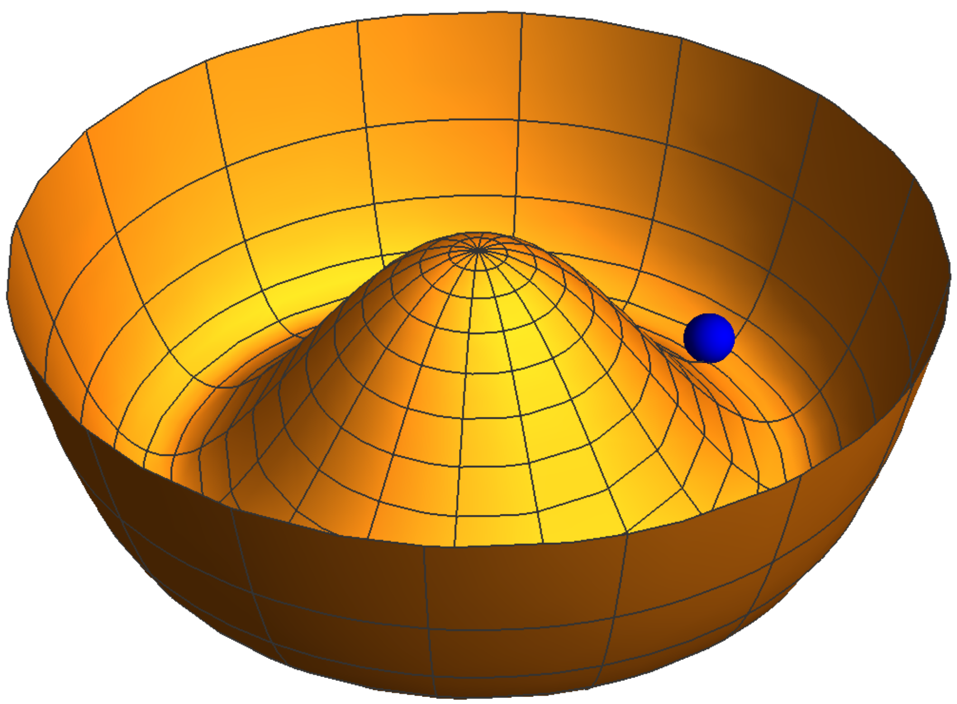
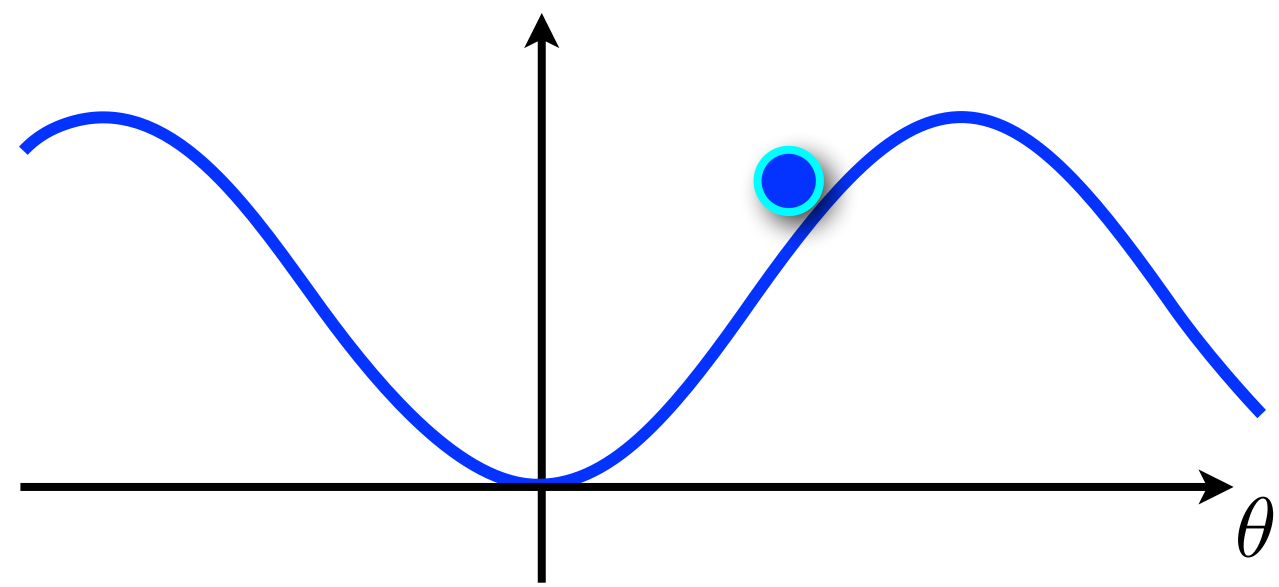
AXION = PNGB of a spontaneously broken global U(1)

e.g. QCD axion, string axions

Peccei, Quinn '77 Weinberg '78 Wilczek '78 Svrcek, Witten '06 Arvanitaki et al. '09



$$U(\Phi) = \lambda\left(|\Phi|^2 - f^2\right)^2$$



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$$V(\theta) = m^2 f^2 (1 - \cos\theta)$$

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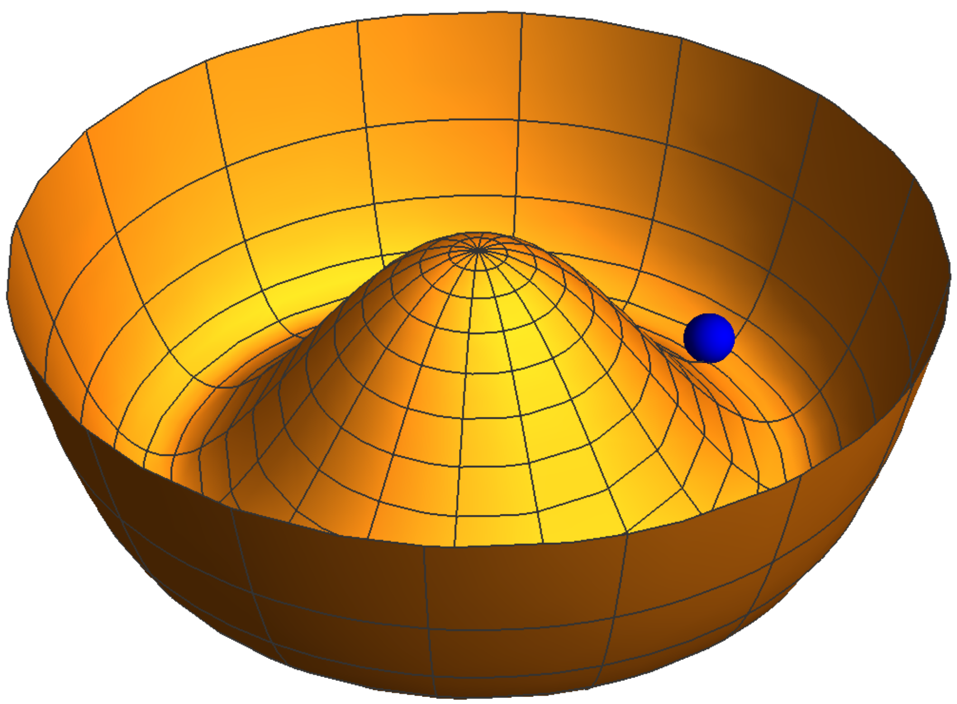

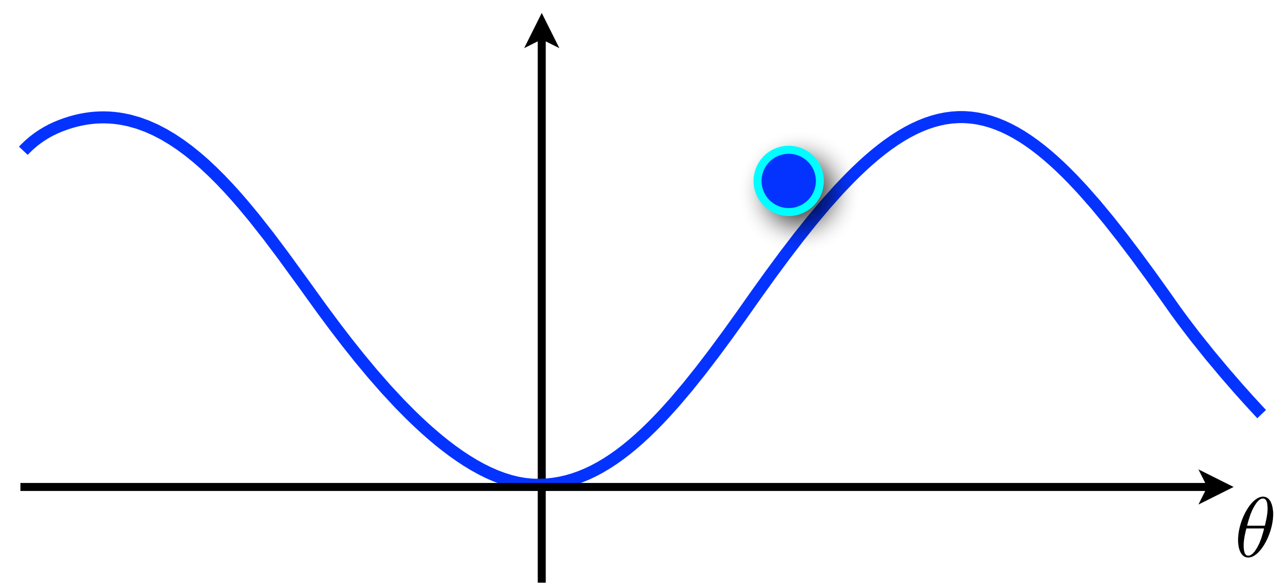

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two characterizing parameters:

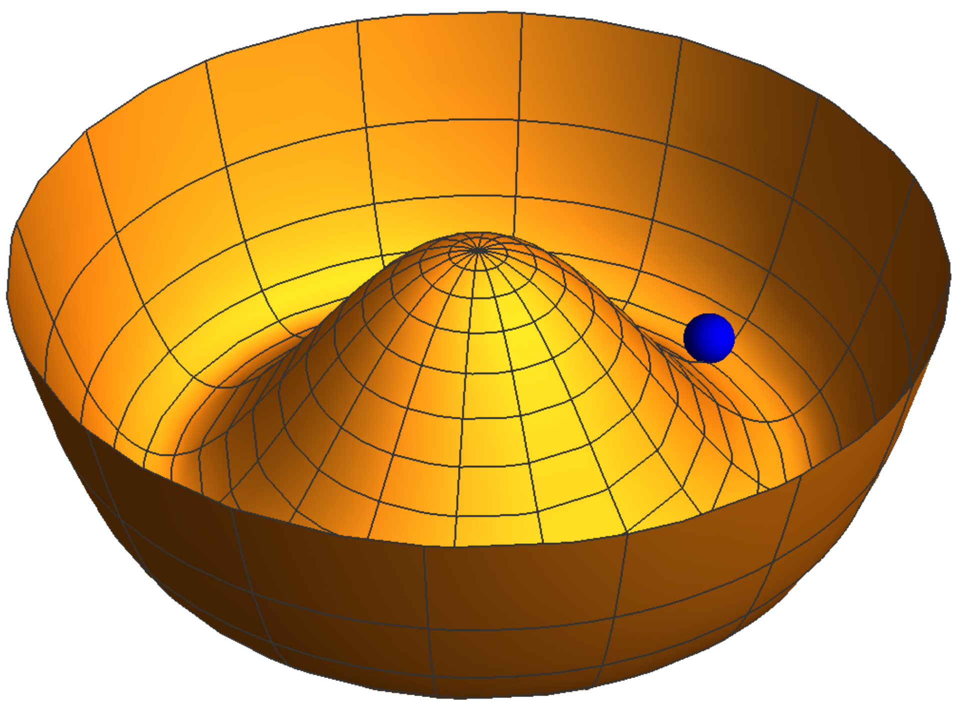
mass m & symmetry breaking scale (decay constant) f

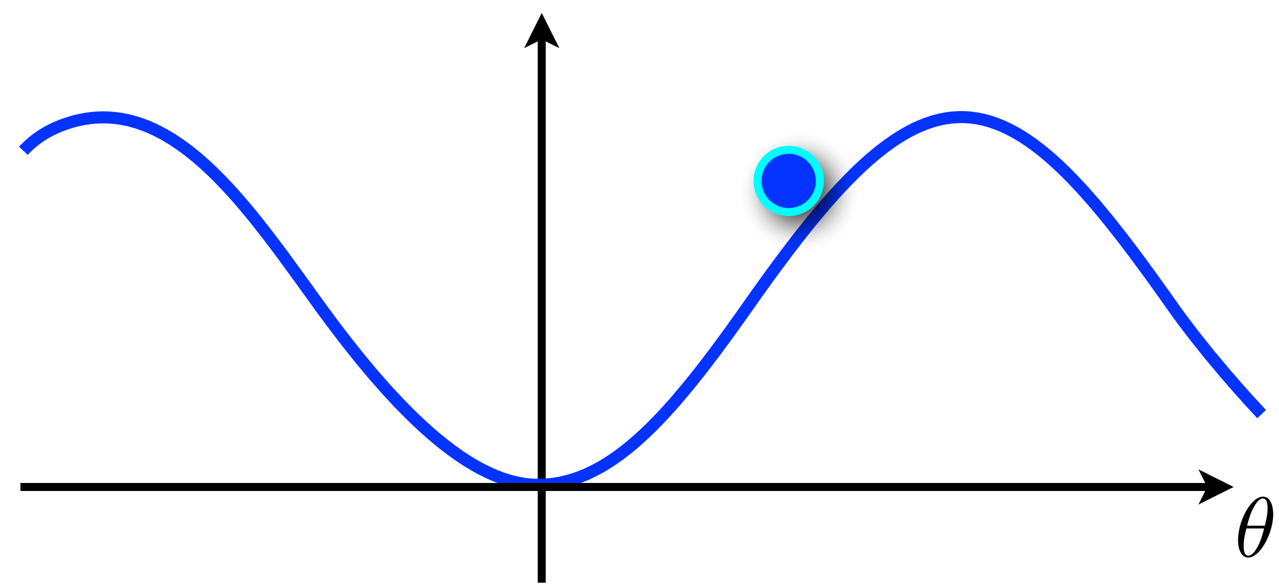
(for the QCD axion: $mf \sim \Lambda_{\rm QCD}^2$)

VACUUM MISALIGNMENT

Preskill, Wise, Wilczek '83   Abbott, Sikivie '83   Dine, Fischler '83

If symmetry breaking happens before inflation ($f > H_{\rm inf}$),





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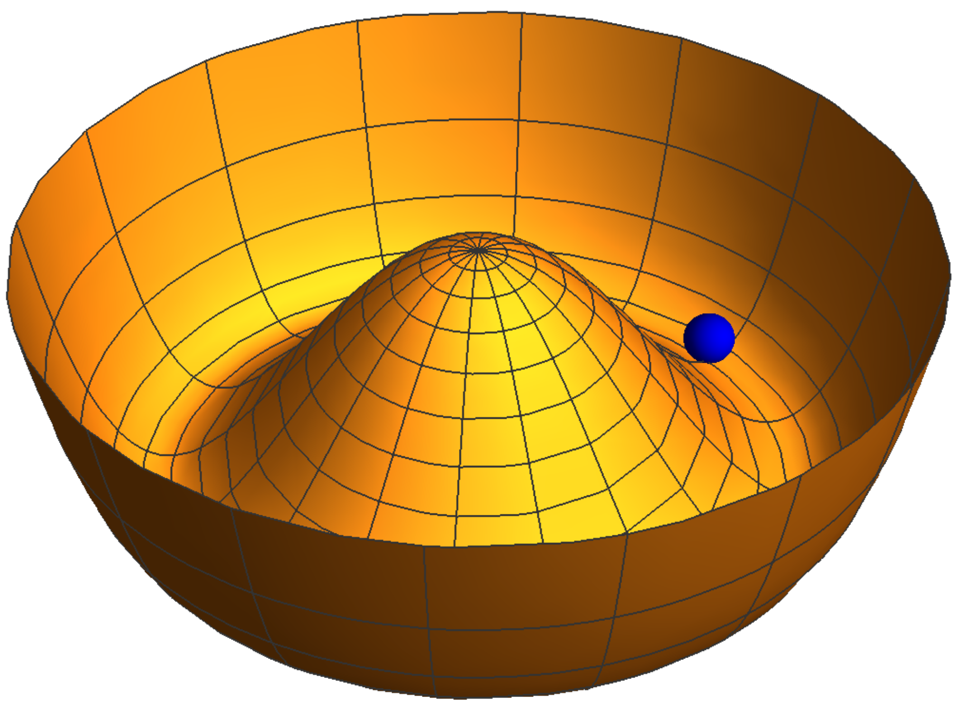

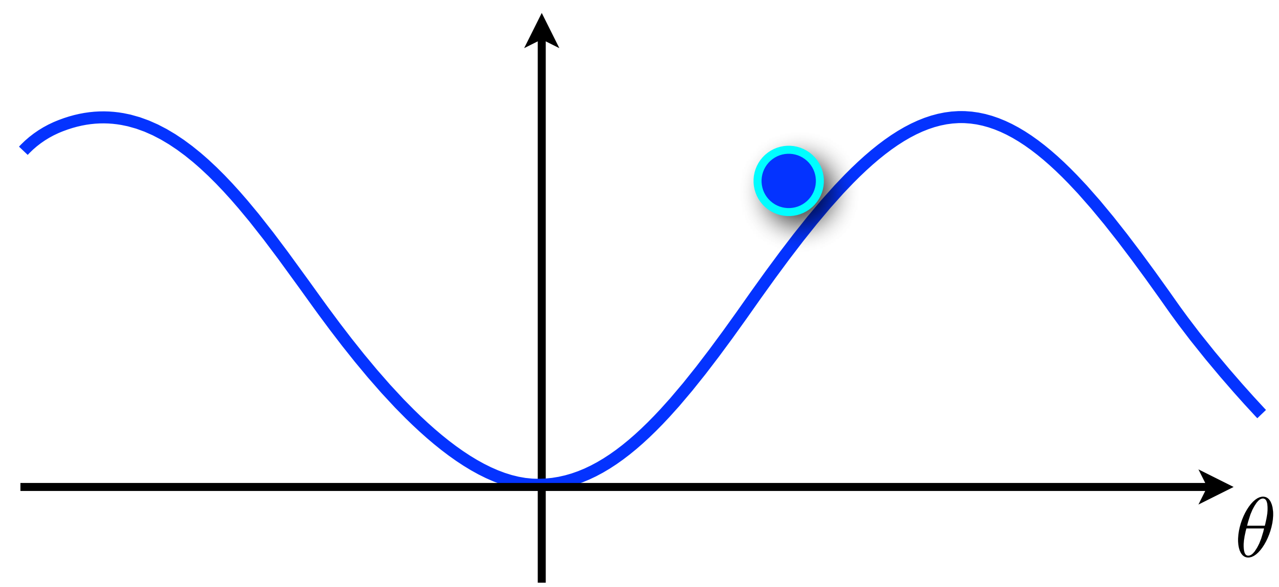

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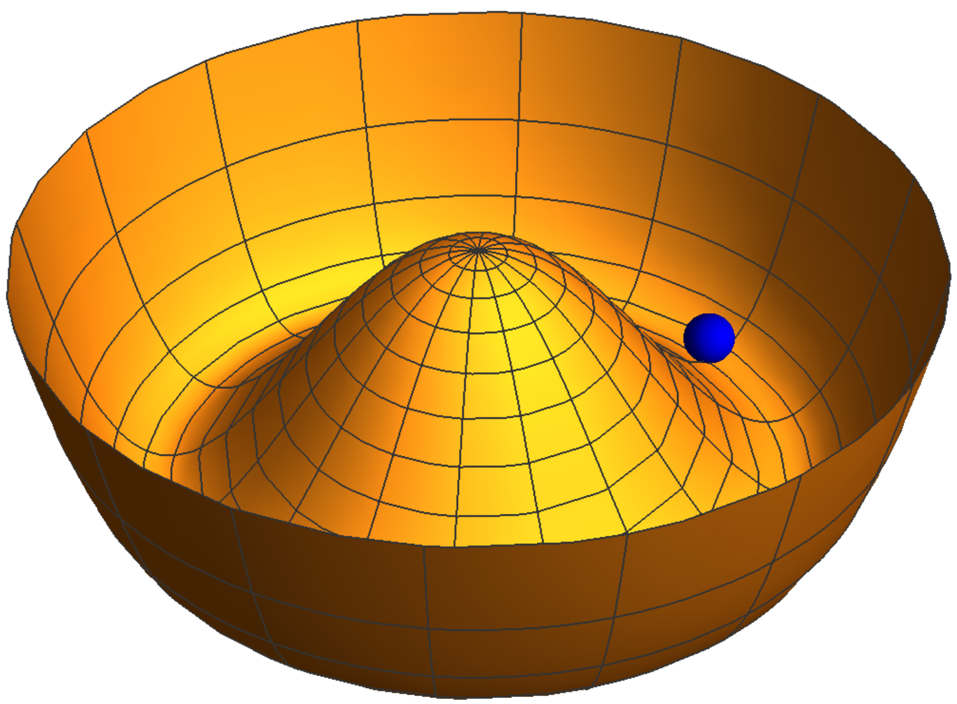

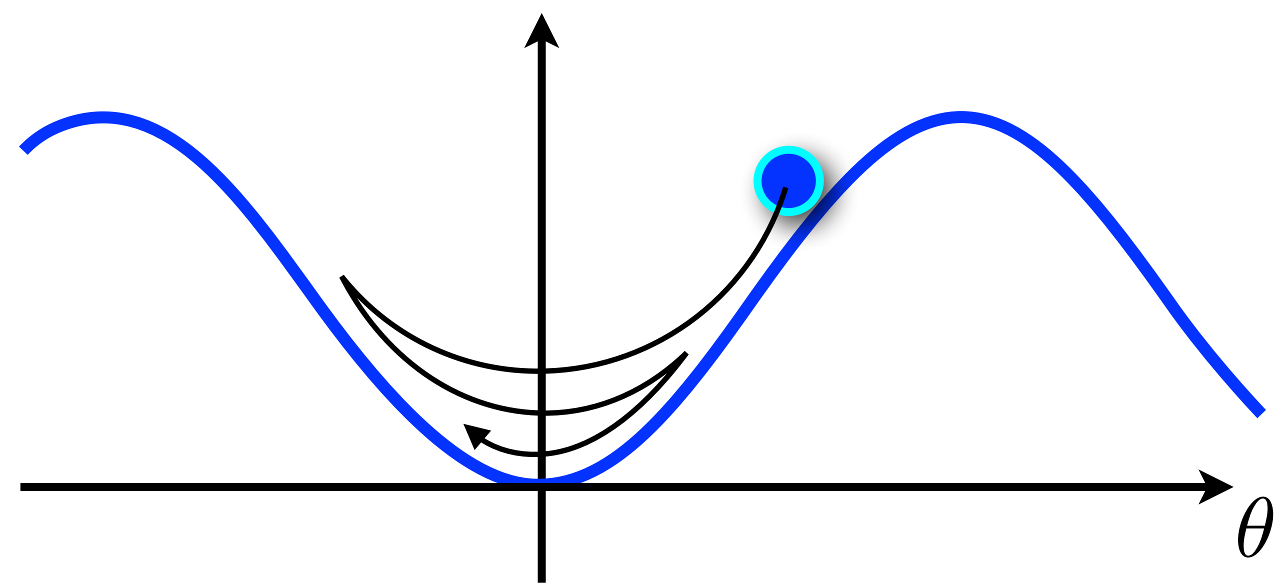

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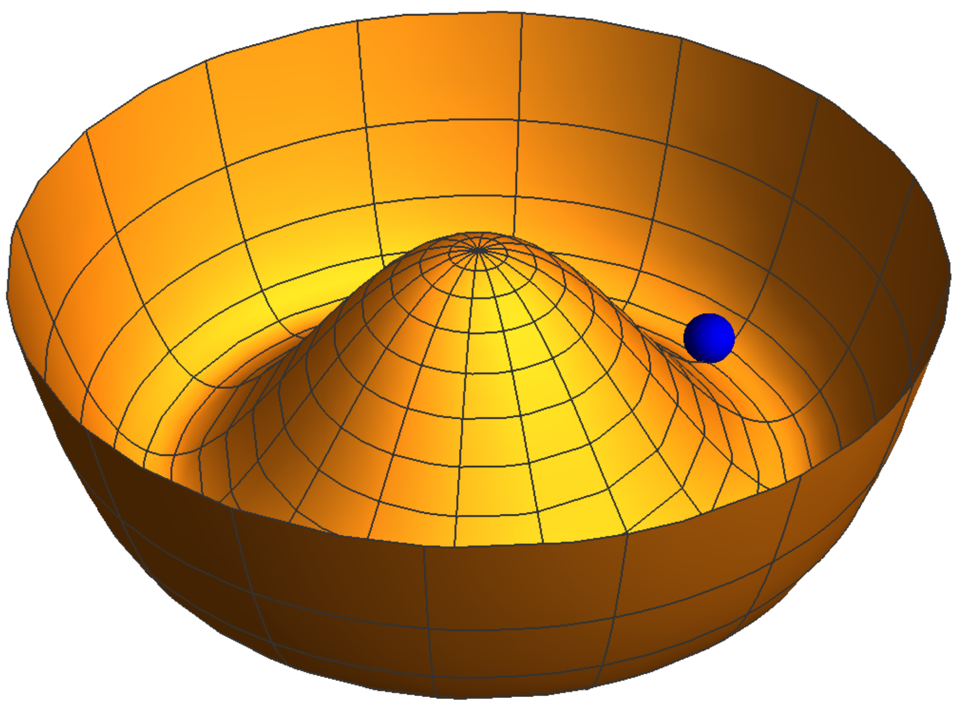

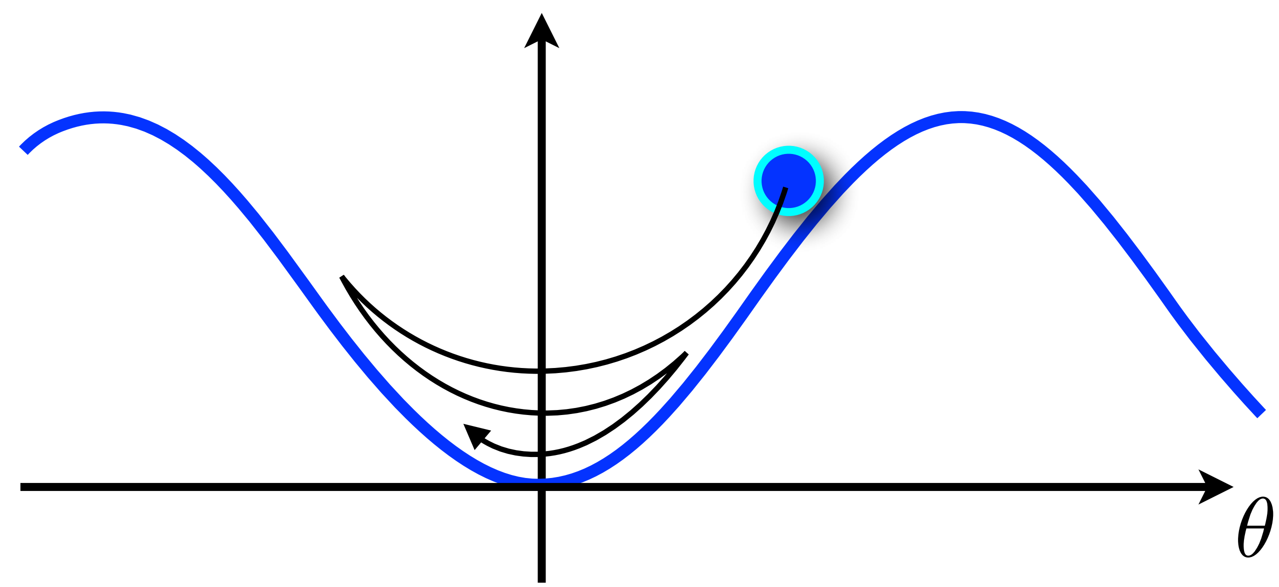

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→ (inevitable) production of axion DM

COSMOLOGICAL CONSTRAINTS

relic abundance of constant-mass axions:

$$\Omega_\theta \sim 10^{-1}\,\theta_\star^2 \left(\frac{f}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

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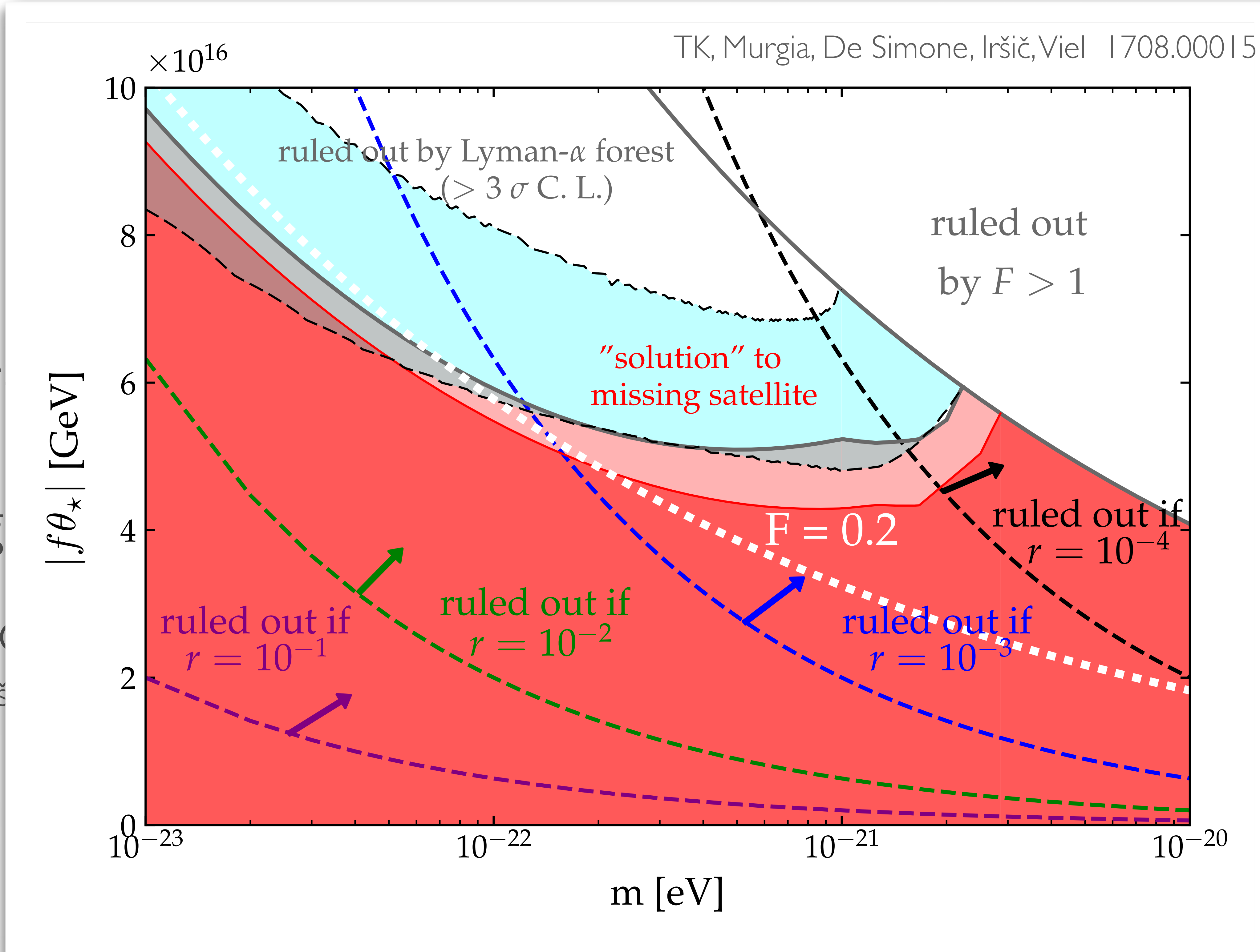
- CMB constrains axion isocurvature perturbations:

$$\frac{\delta\Omega_\theta}{\Omega_\theta} \sim \frac{\delta\theta_\star}{\theta_\star} \sim \frac{H_{\mathrm{inf}}}{f\theta_\star} \lesssim 10^{-5}$$

COSMOLOGICAL CONSTRAINTS



- Make … $10^{-22}\,\mathrm{eV}$
- Being … CDM,

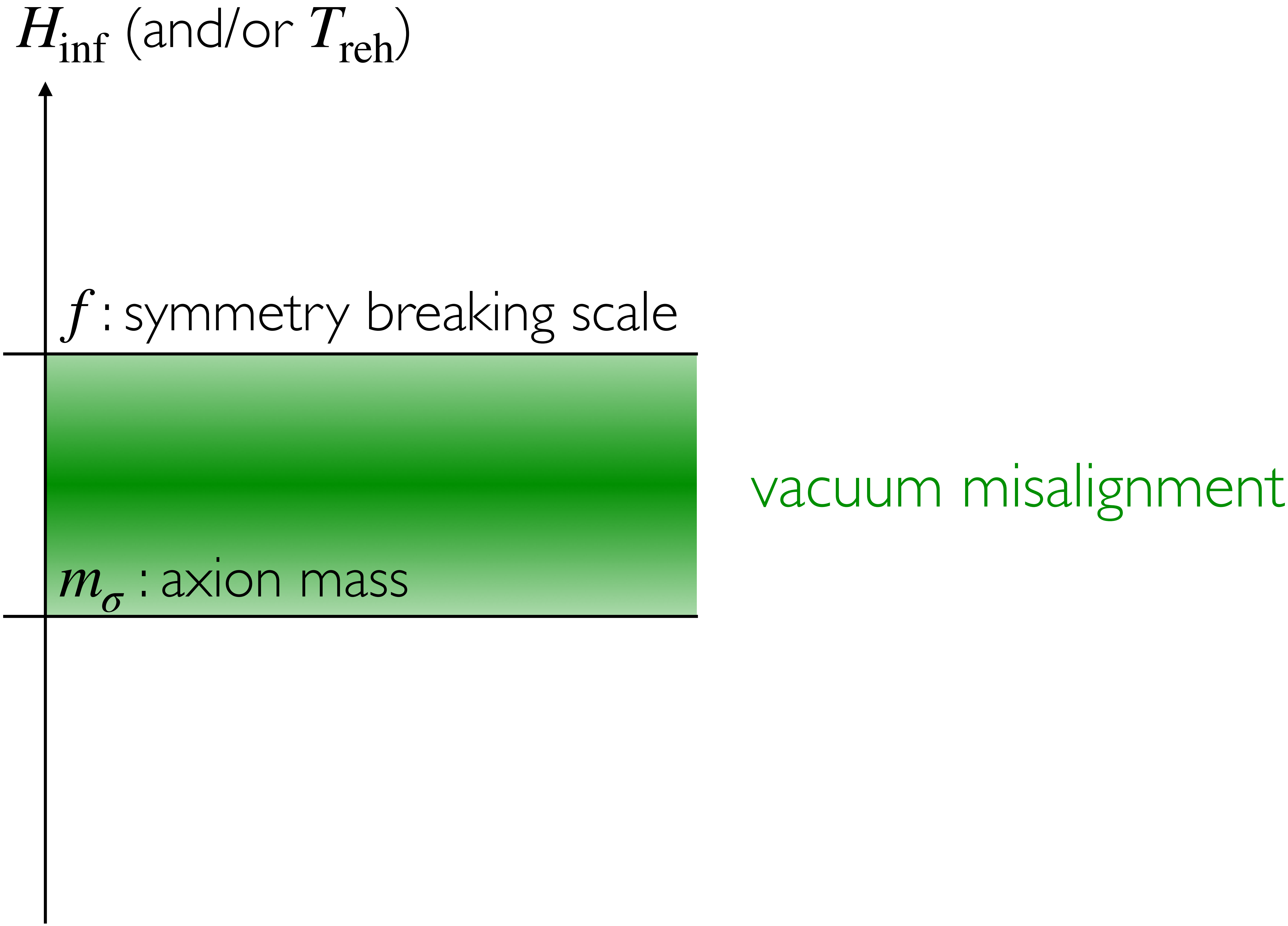
  but c…

  Gruzinov '00

  Irš…
- CMB

Ω_θ … $\theta_\star$ … $f\theta_\star$

POSSIBLE SCENARIOS FOR AXION DM



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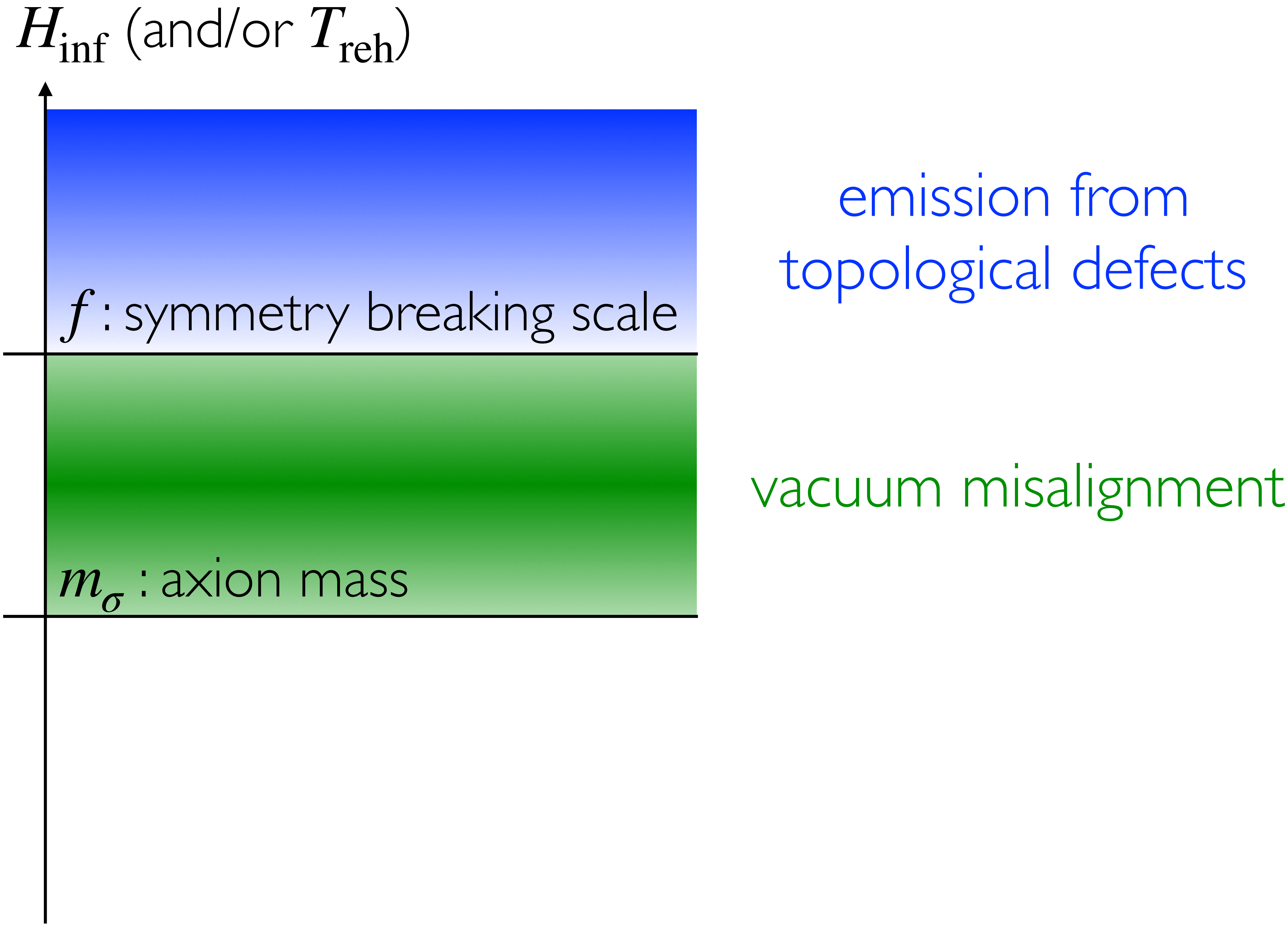

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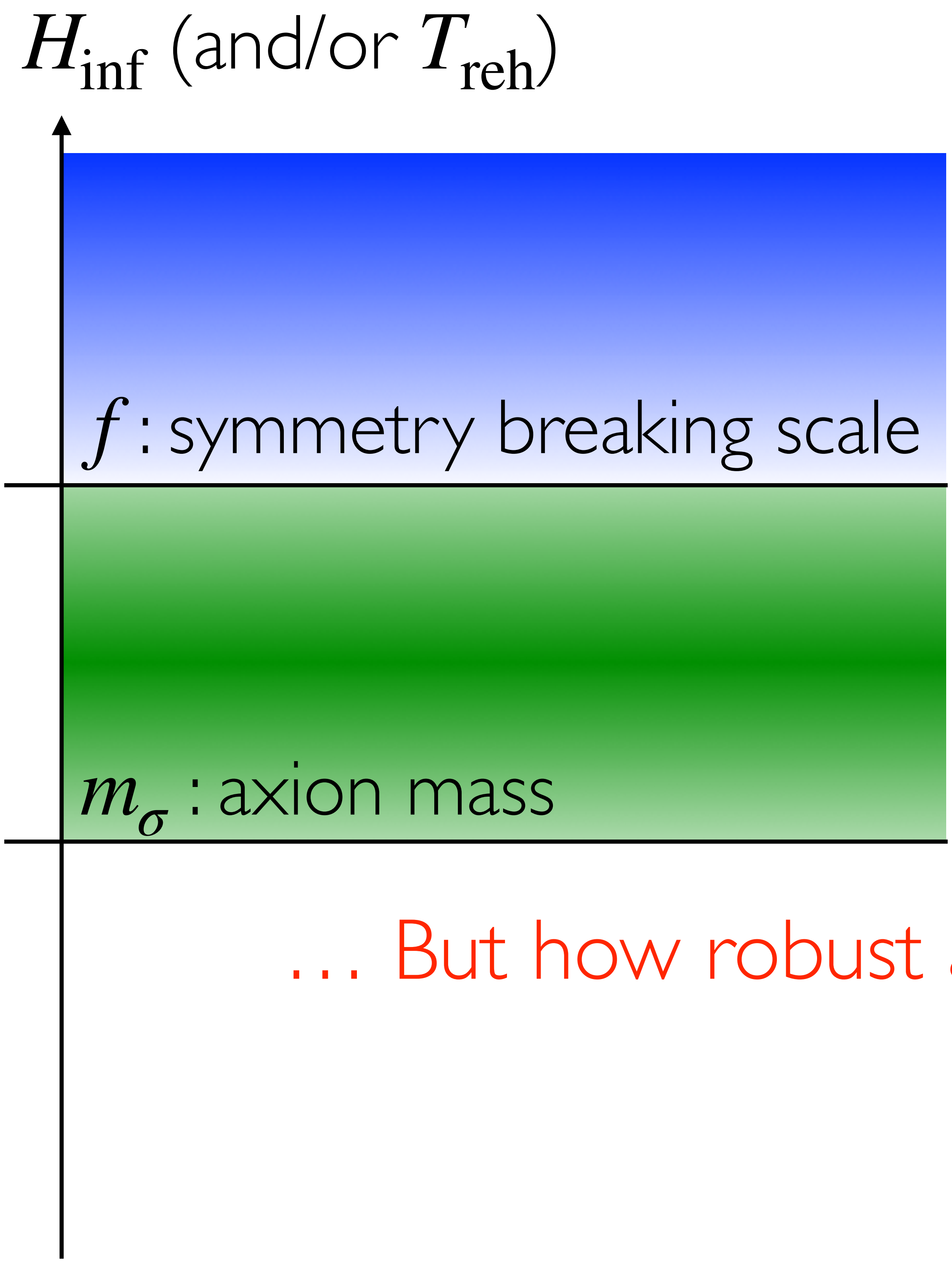

emission from
topological defects

vacuum misalignment

… But how robust are these arguments?

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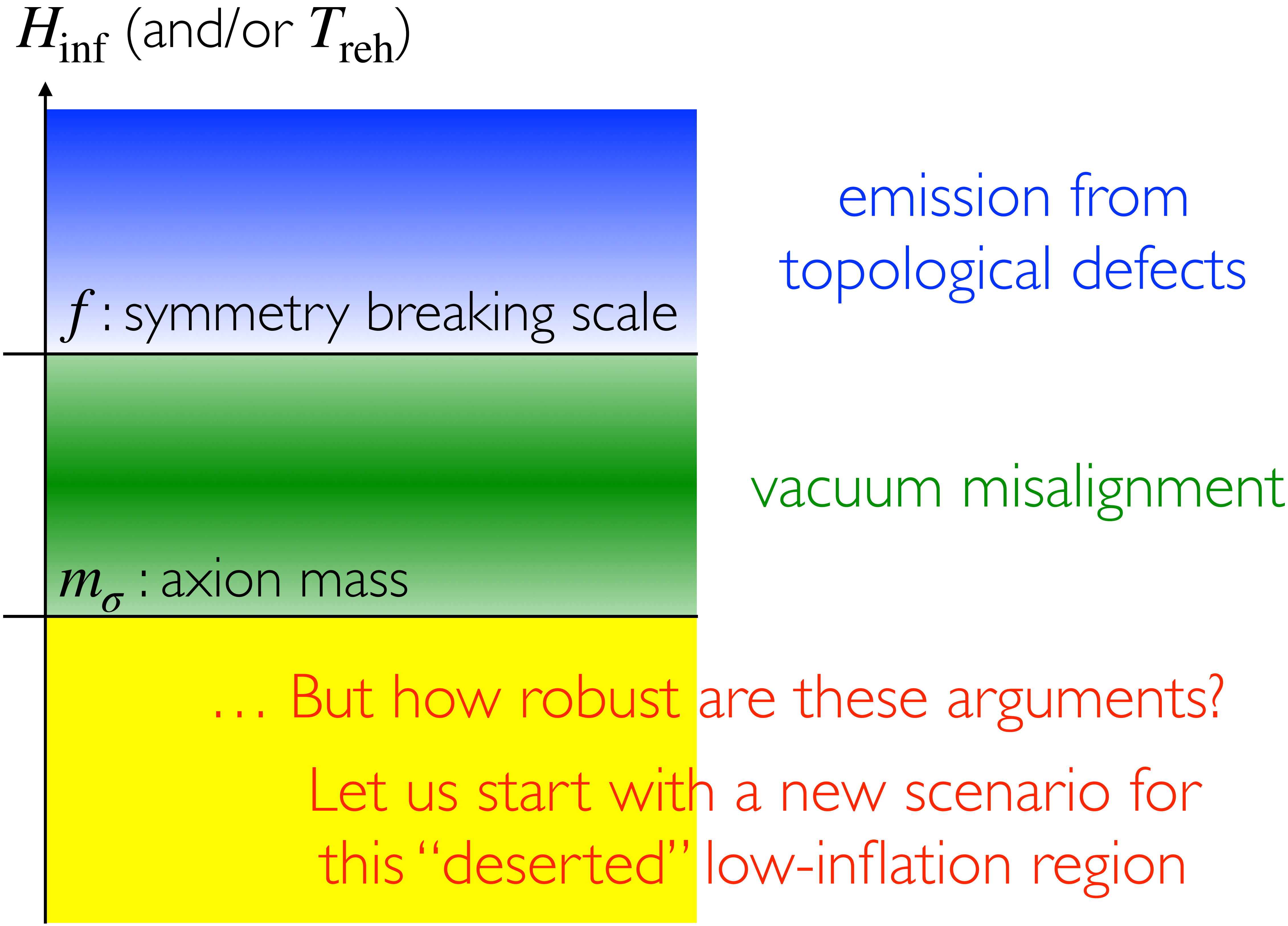

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Let us start with a new scenario for this "deserted" low-inflation region

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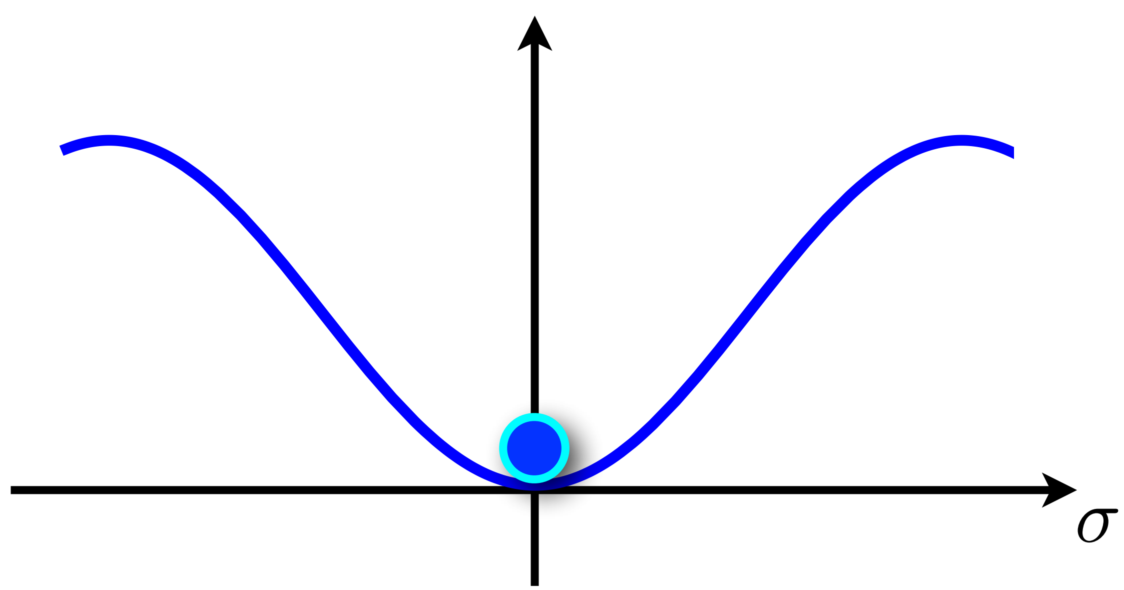
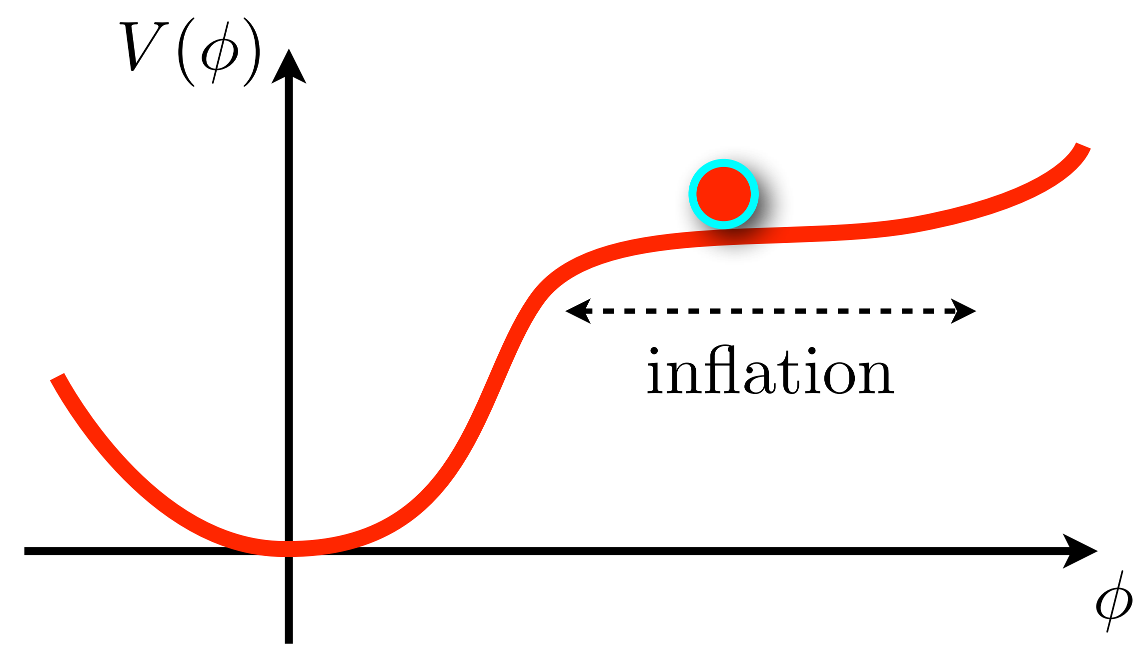
low-scale inflation with $H_{\rm inf} < m_\sigma$





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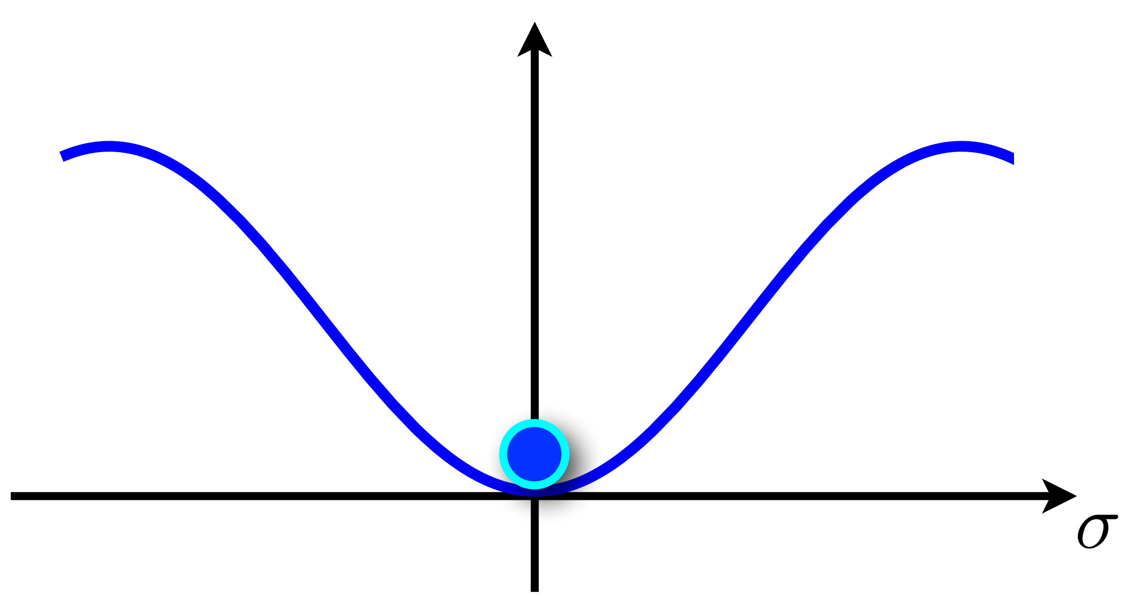

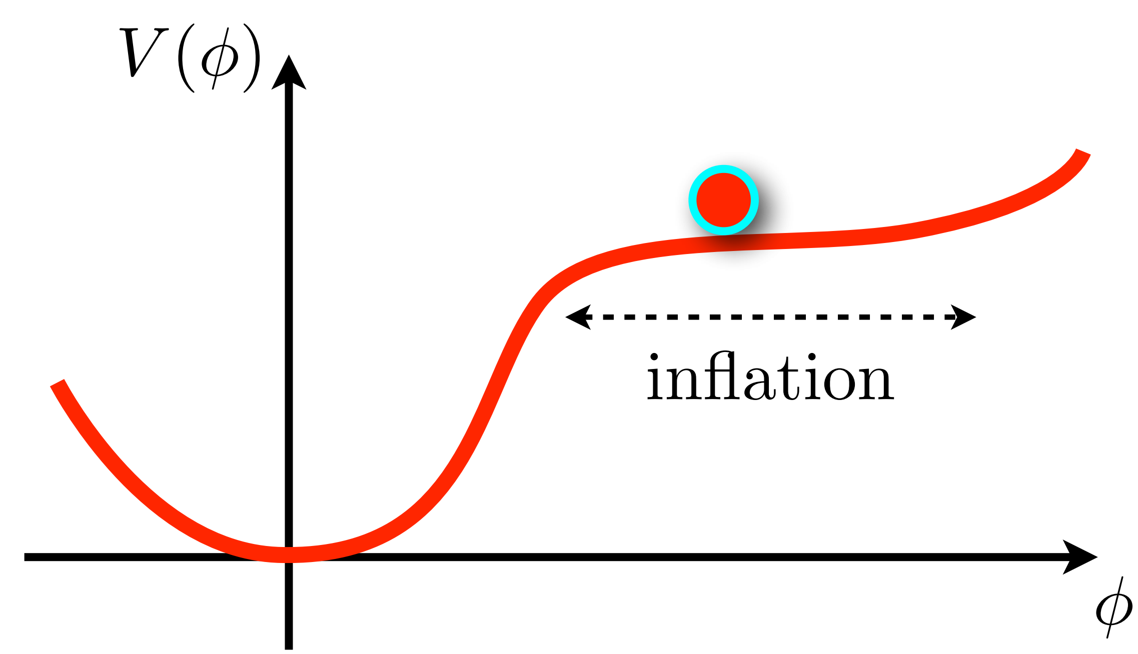

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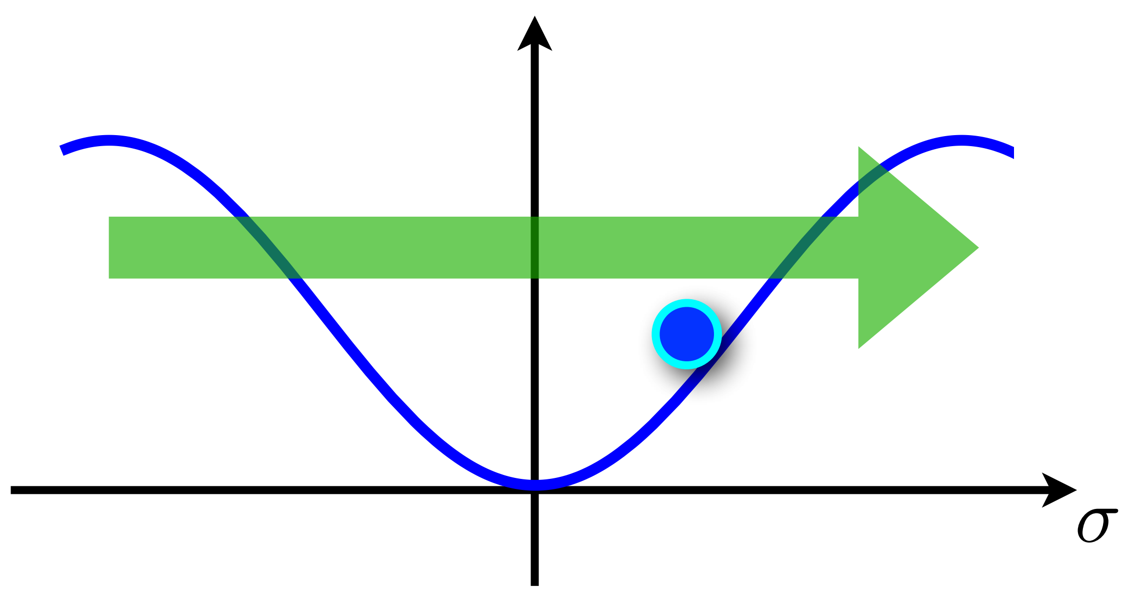

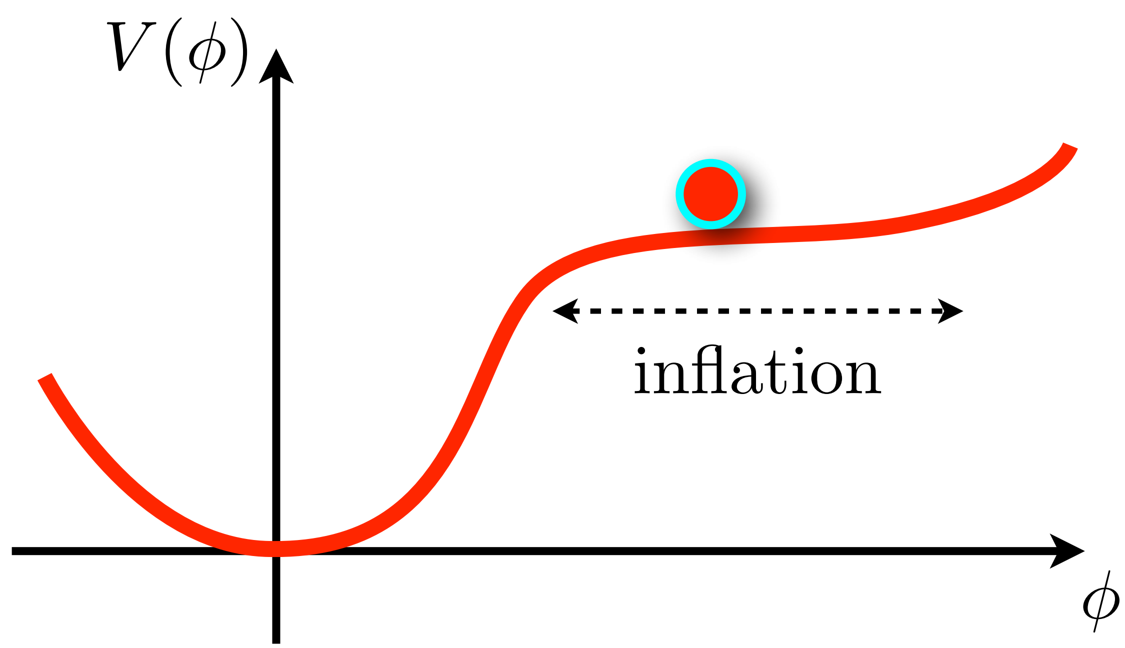

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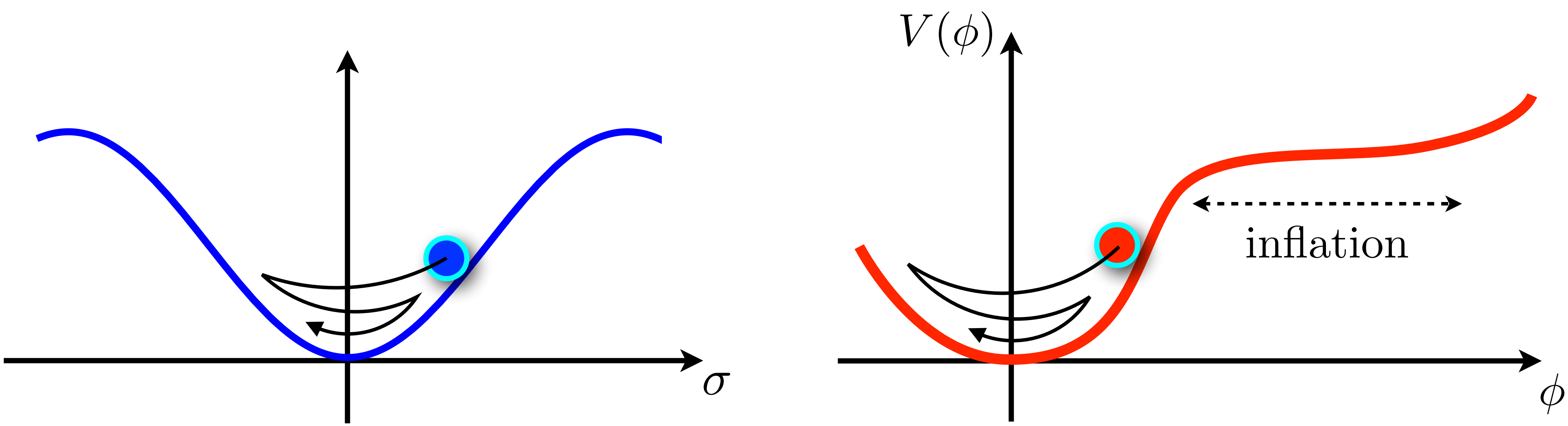

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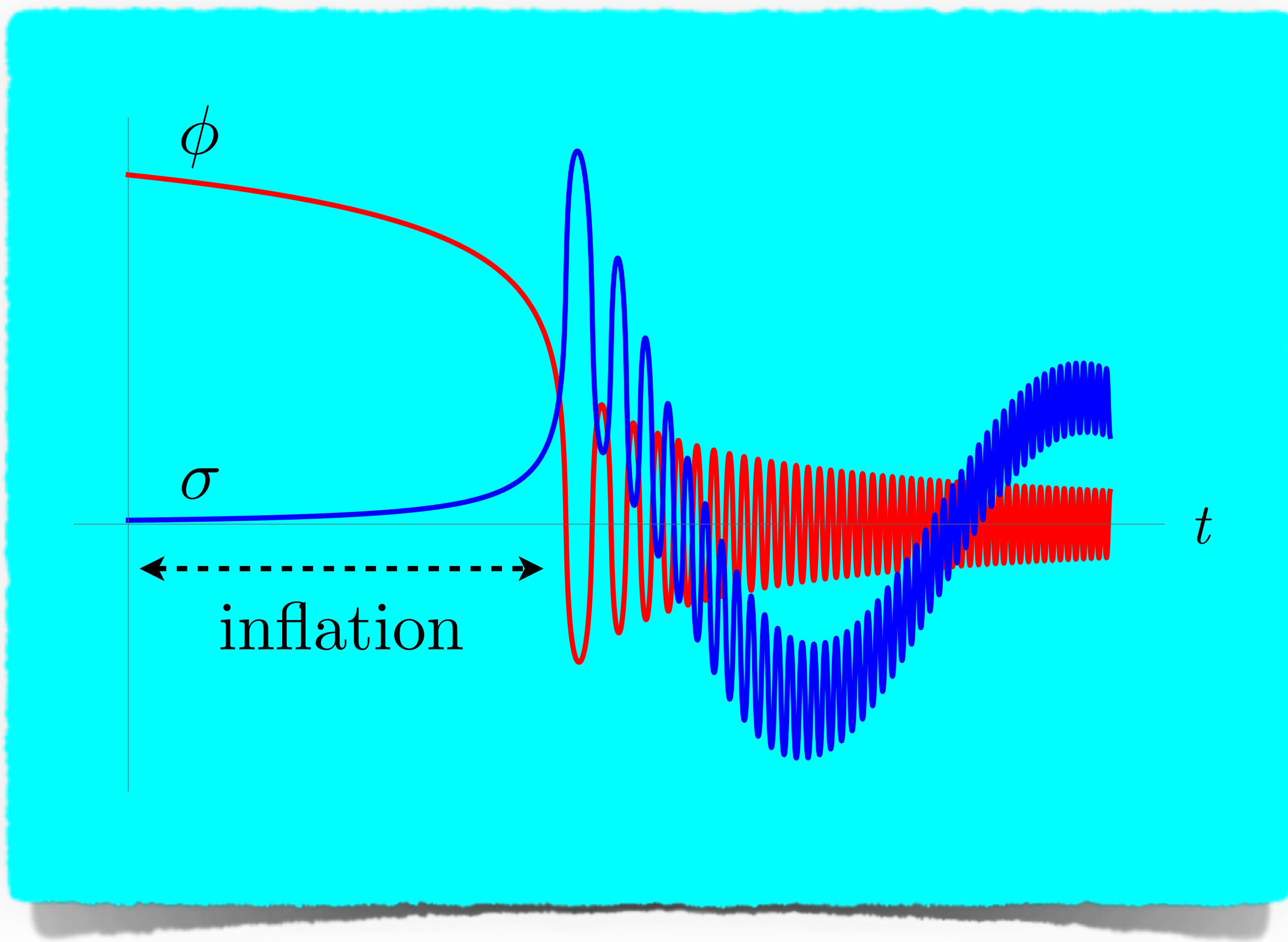

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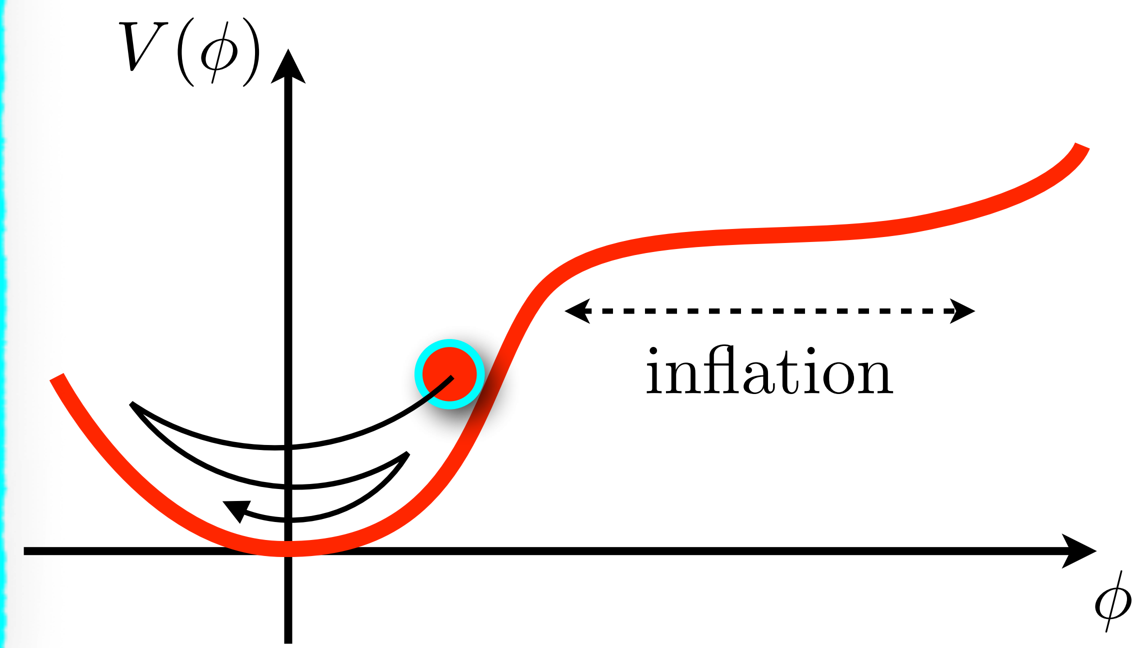

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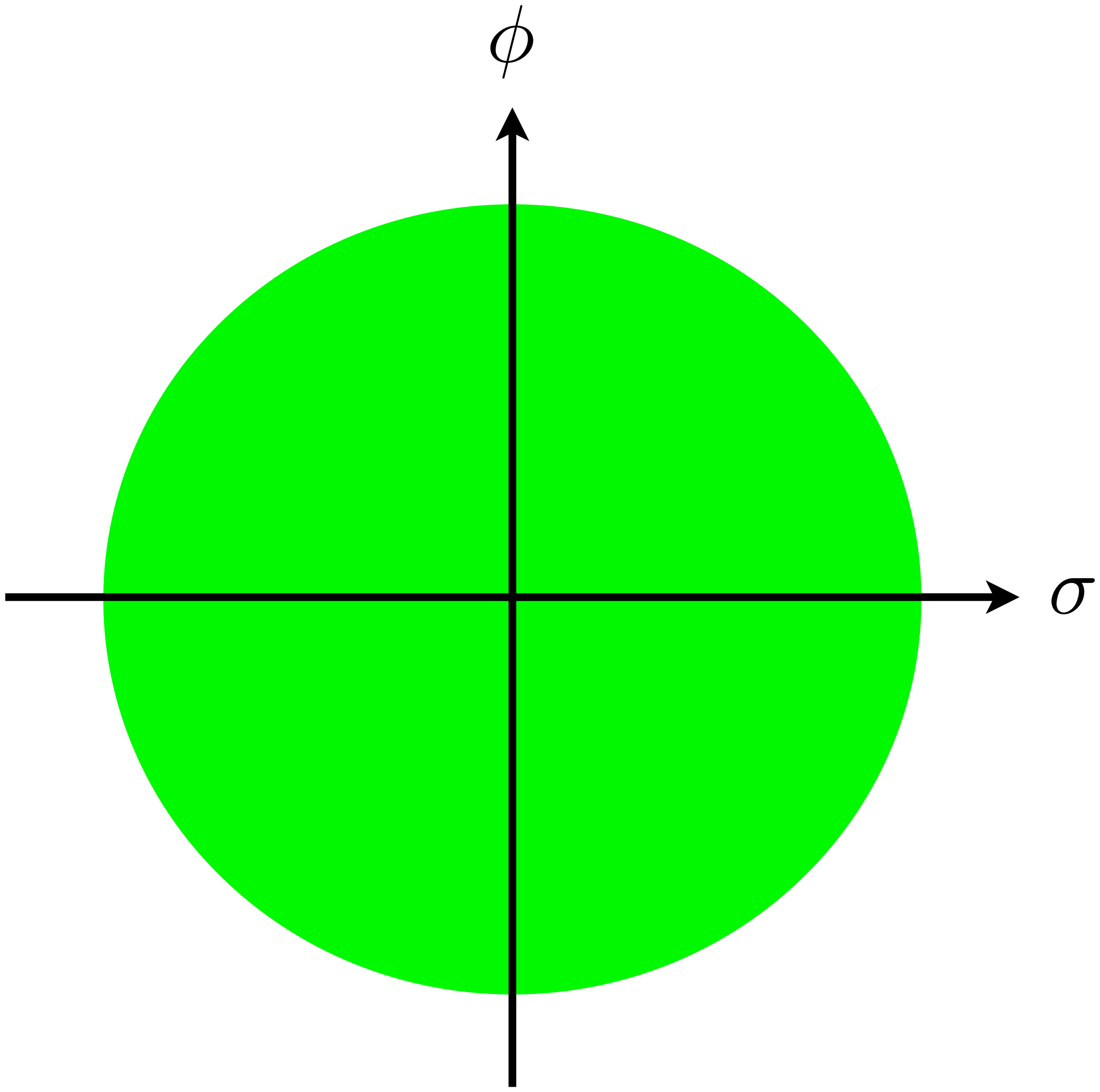

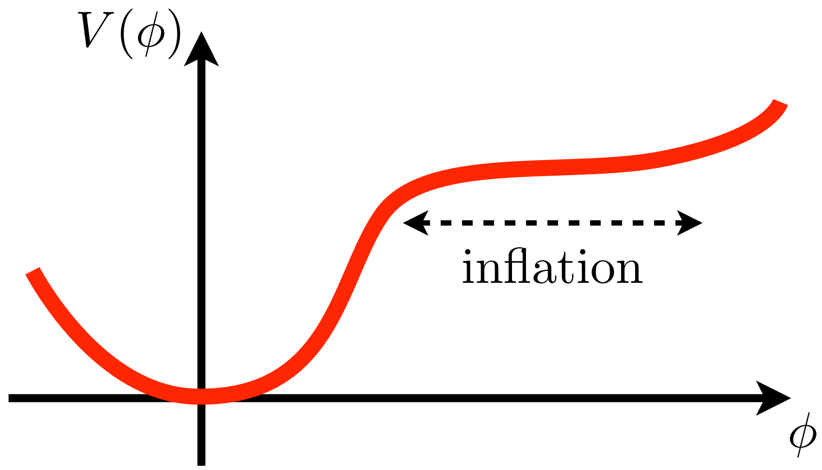

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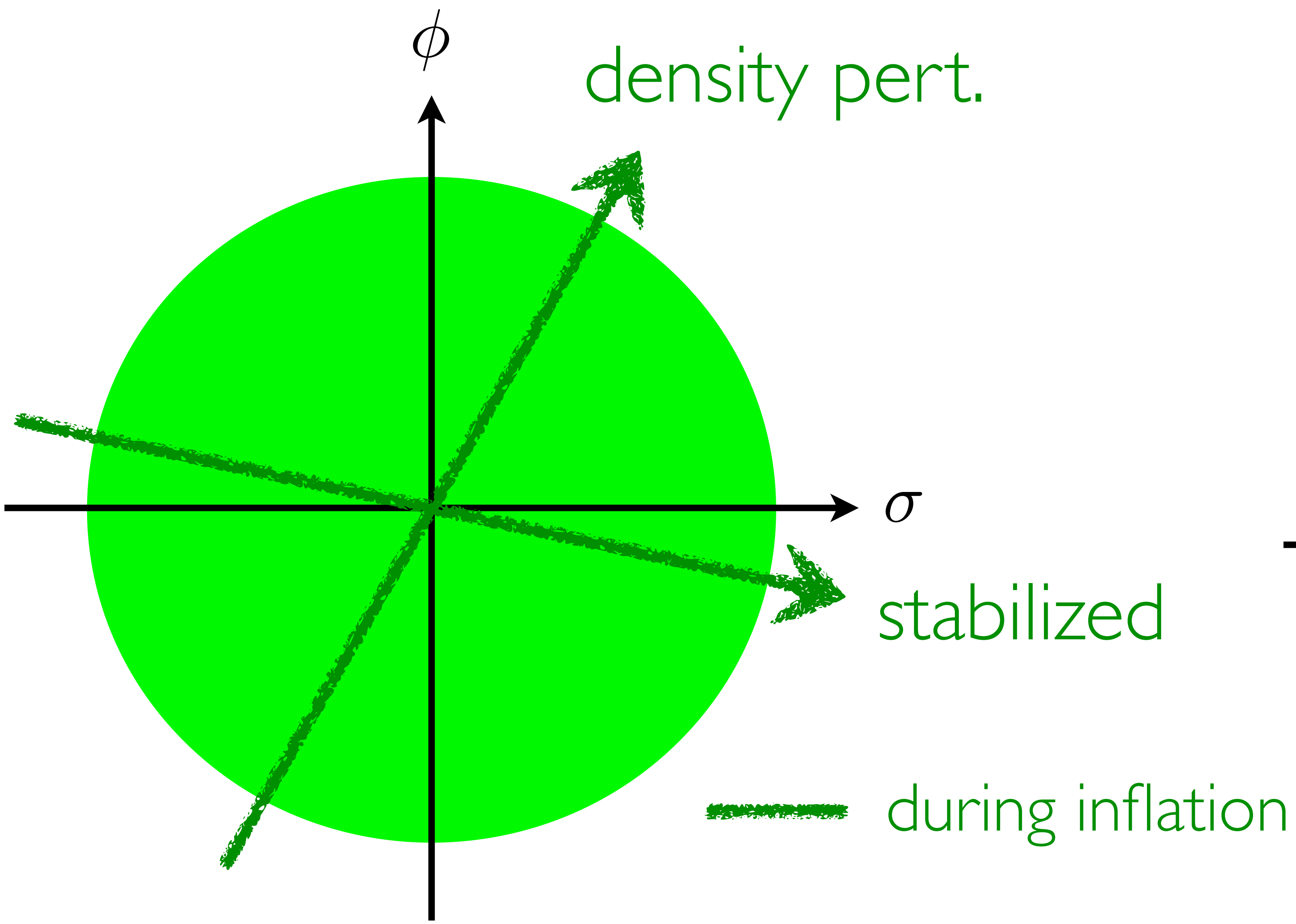

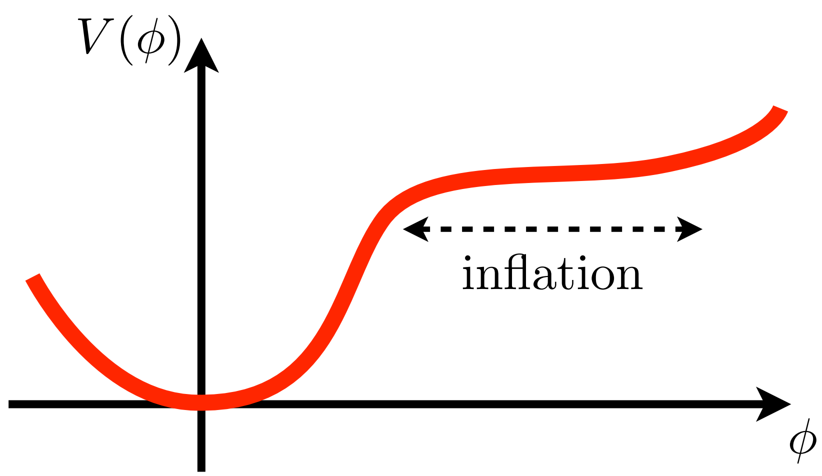

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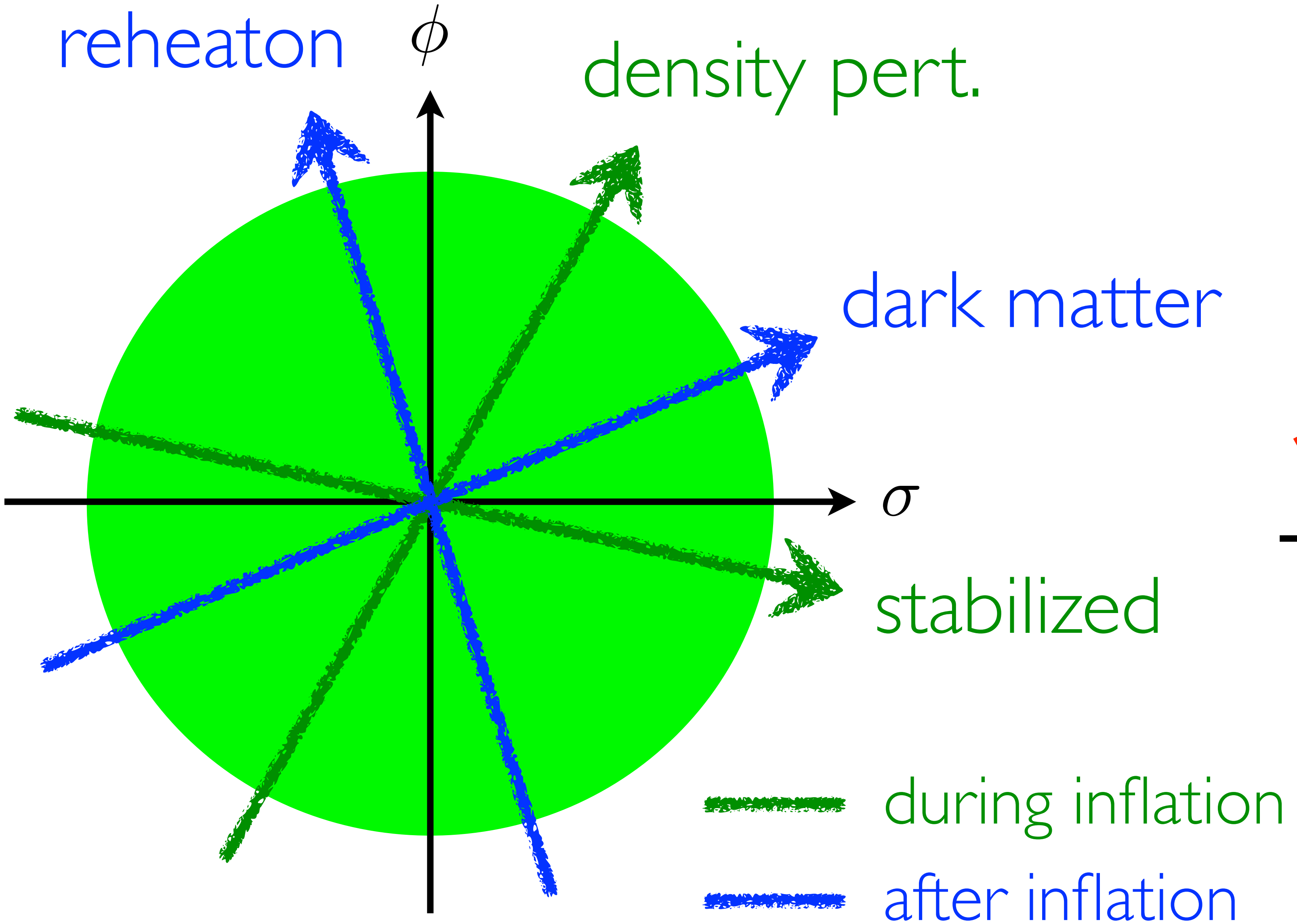
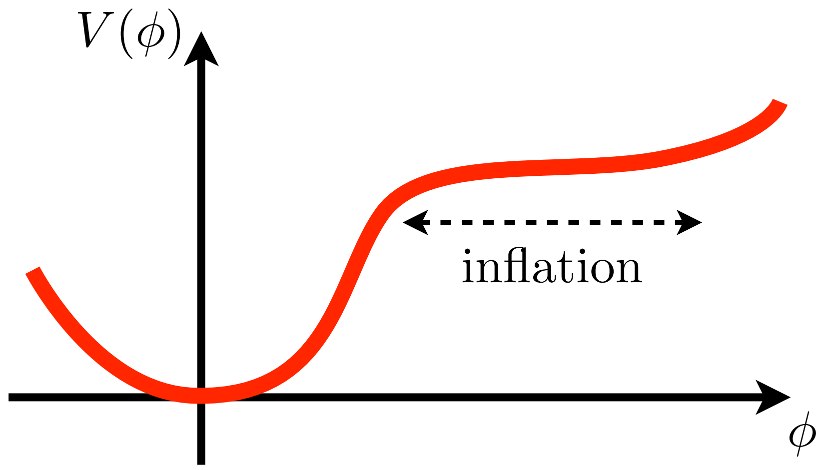
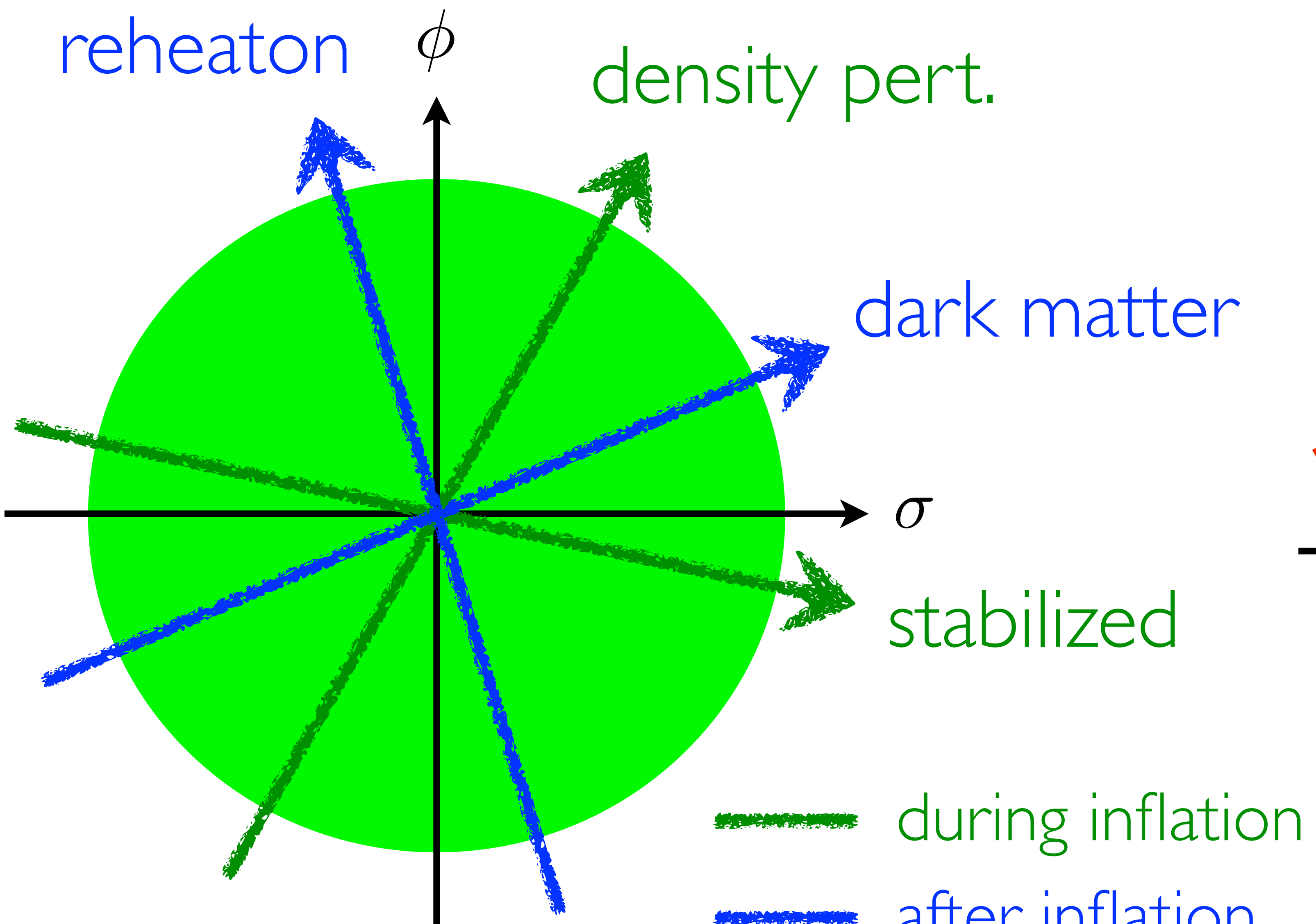
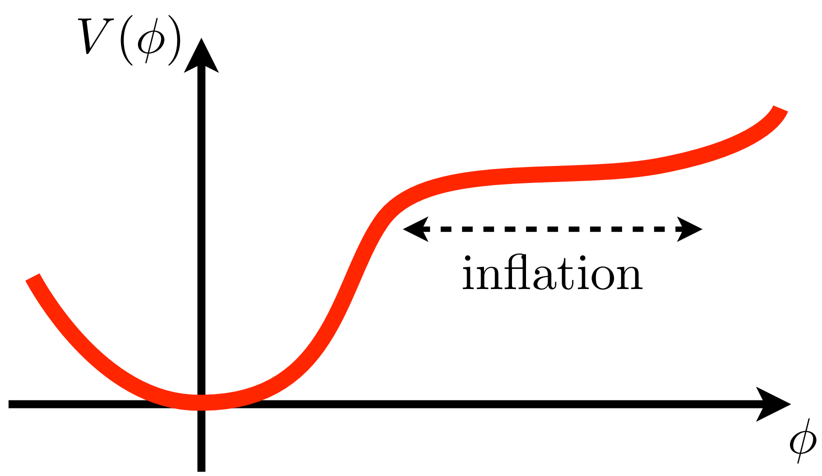




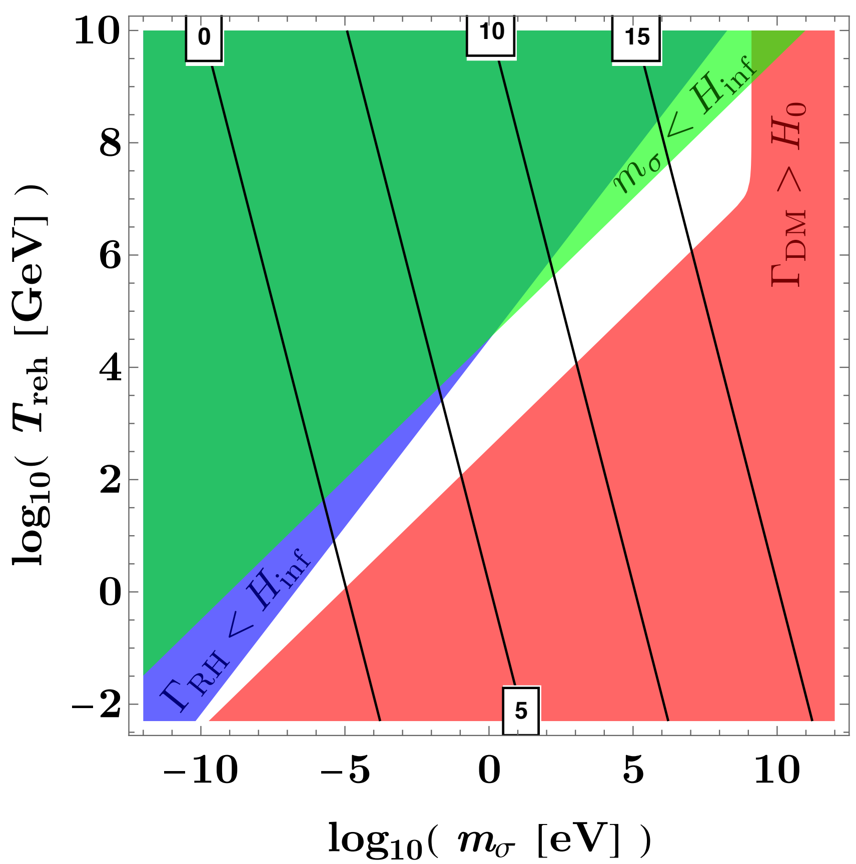
Different combinations of the inflaton and axion (= **inflaxions**) play various cosmological roles



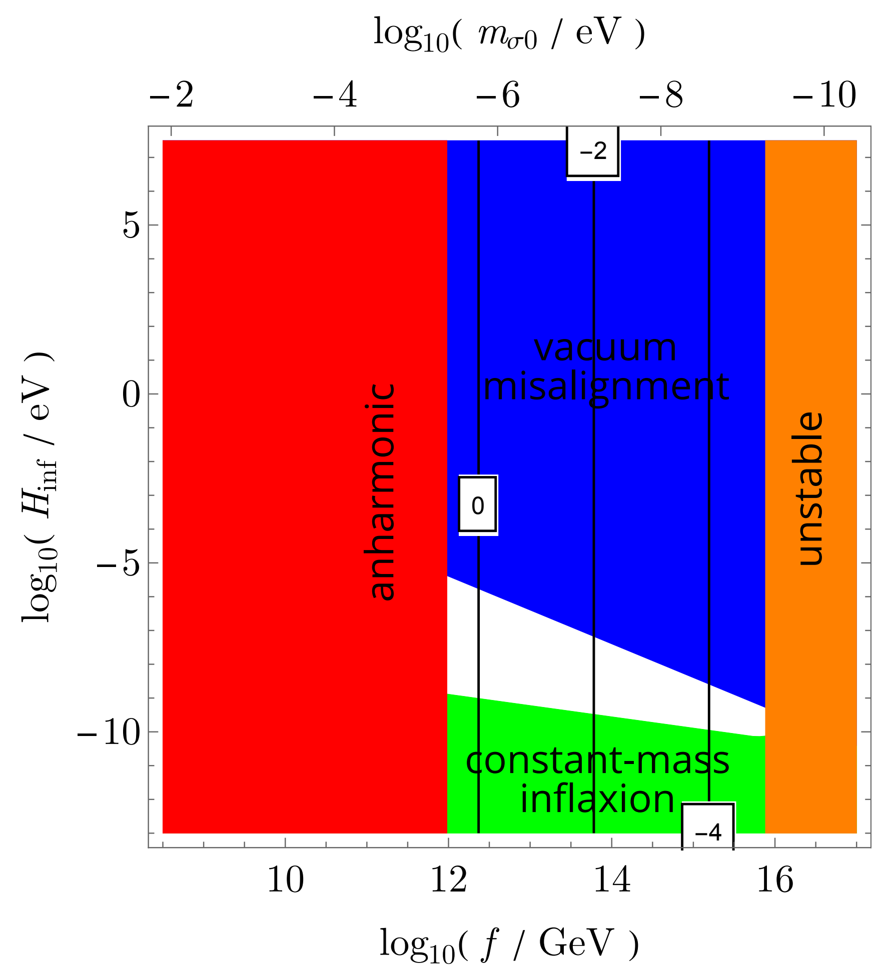


INFLAXION WINDOWS

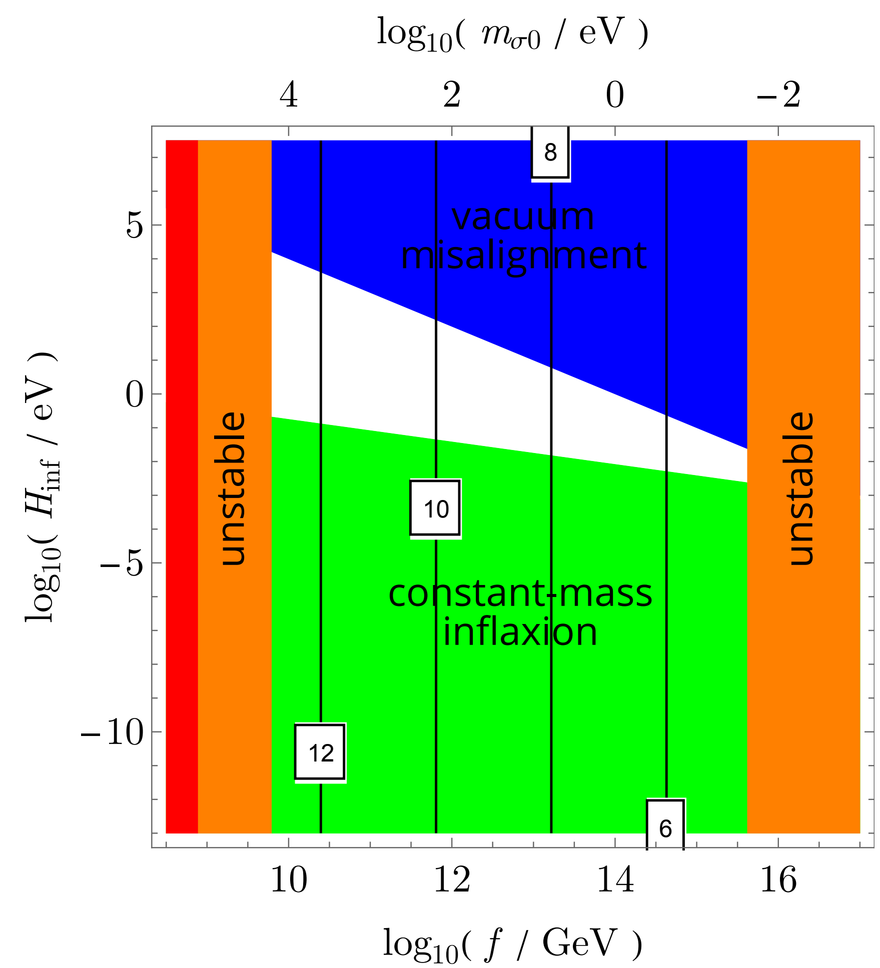
$$L_{\rm int} = -\alpha\,\partial\sigma\cdot\partial\phi + \frac{\alpha_\gamma}{8\pi f}\sigma F\tilde{F} + g\phi\bar{\psi}i\gamma^5\psi \qquad \alpha\sim 1/3 \qquad g\sim 10^{-2}$$



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



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



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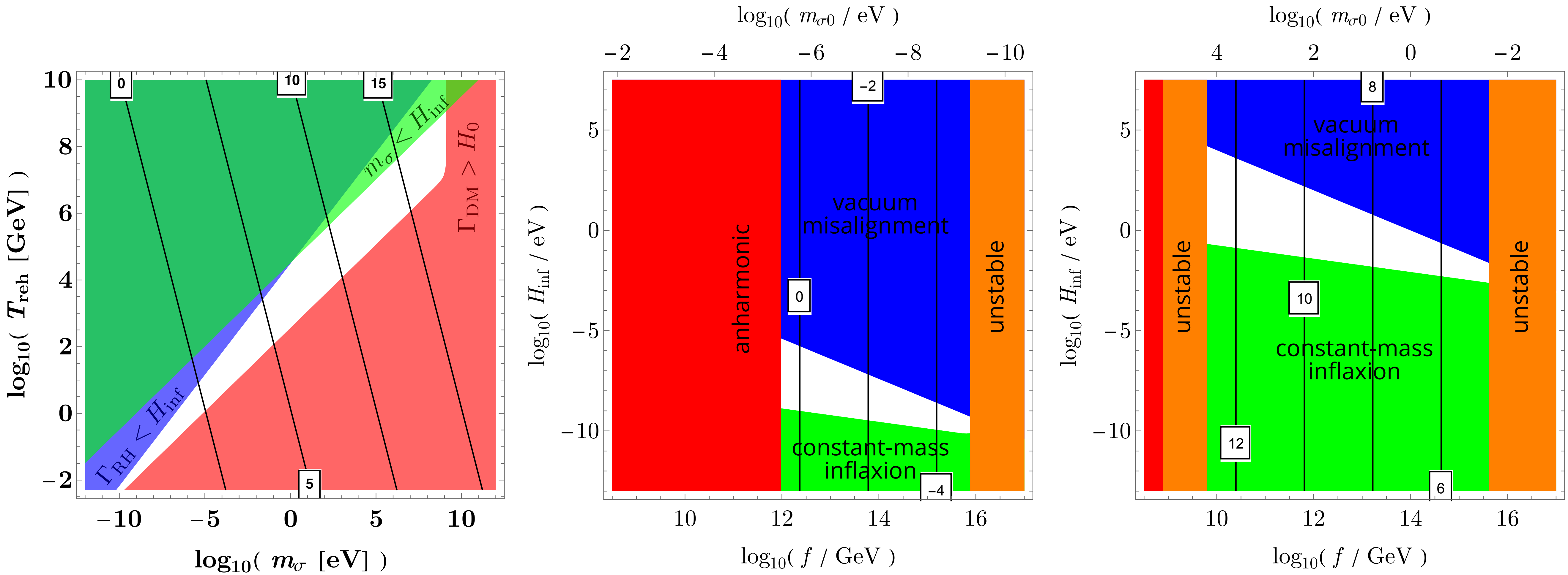

constant-mass axion
($f = 10^{17}$ GeV)

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

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

Opens up new axion windows, especially at low $H_{\rm inf}$ and high f

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

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AXIONS AND ELECTROMAGNETIC FIELDS

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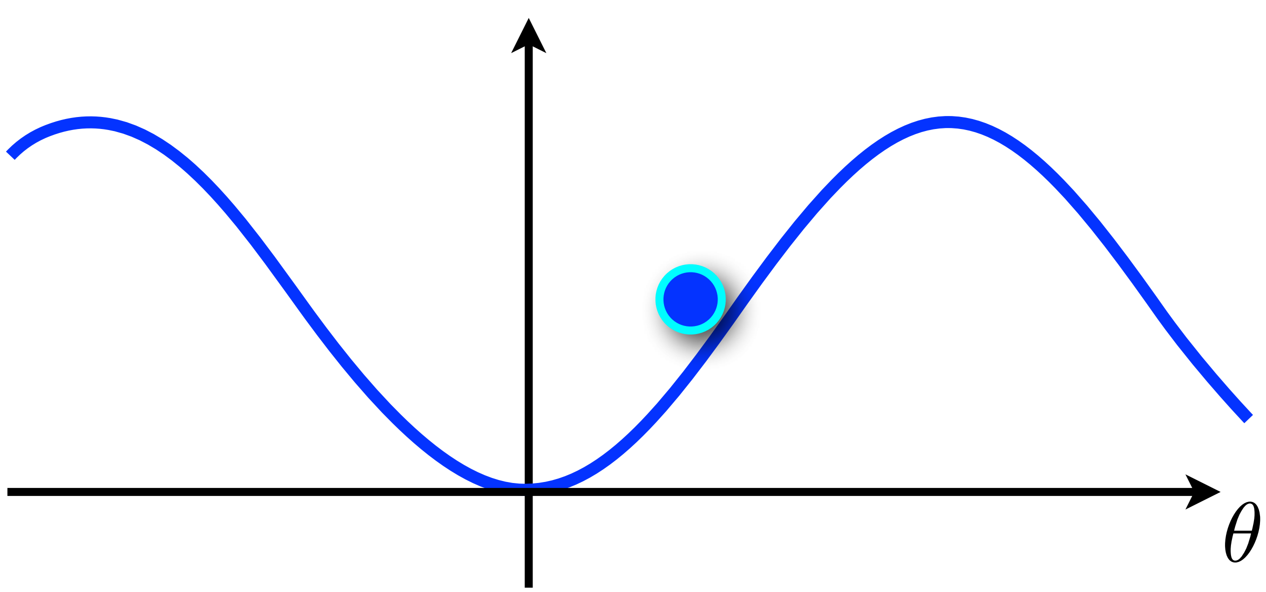
- Many studies on gauge field excitations in the early universe (e.g. cosmological magnetic fields, source of GW, vector DM), in particular on parity-violating mechanisms

Garretson, Field, Carroll '92 Anber, Sorbo '06 Durrer, Hollenstein, Jain '10 …

CONSEQUENCE OF $E \cdot B$

- Let us consider a simple case: an axion coupled to hidden photons, that are excited in the early universe to form a homogeneous $E \cdot B$ background



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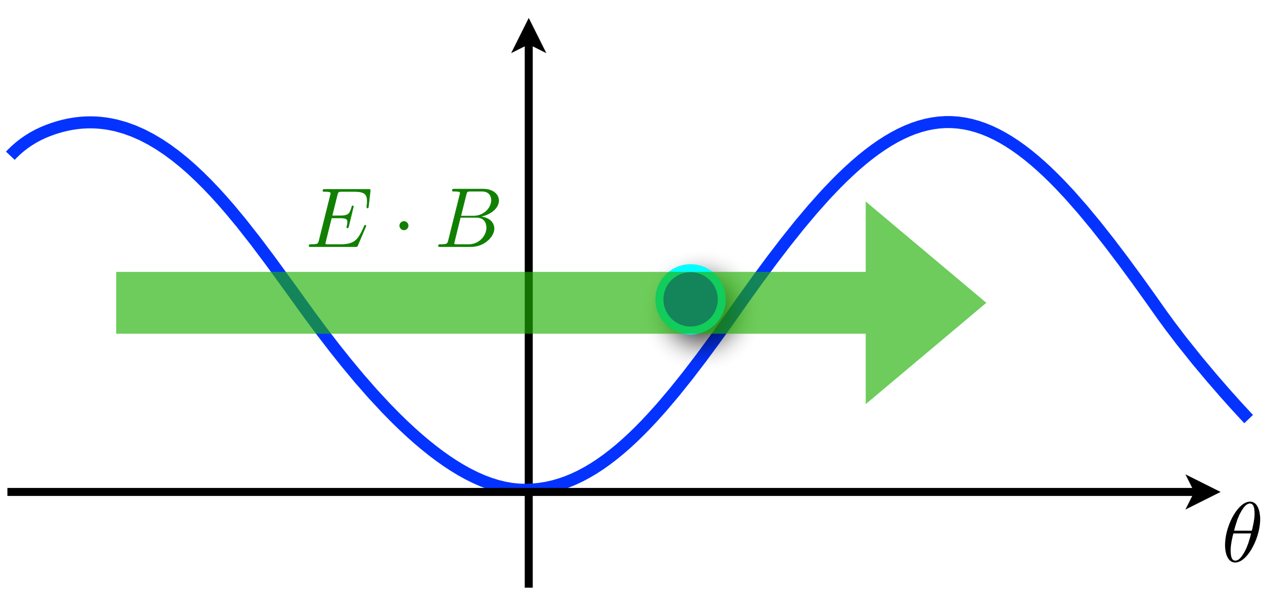
- The $E \cdot B$ gives an effective linear potential to the axion via $\alpha\theta F\tilde{F}$, and sources a field velocity of $\dot{\theta} \sim \alpha F\tilde{F}/f^2 H$



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- Let us consider a simple case: an axion coupled to hidden photons, that are excited in the early universe to form a homogeneous $E \cdot B$ background

- The $E \cdot B$ gives an effective linear potential to the axion via $\alpha\theta F\tilde{F}$, and sources a field velocity of $\dot{\theta} \sim \alpha F\tilde{F}/f^2 H$

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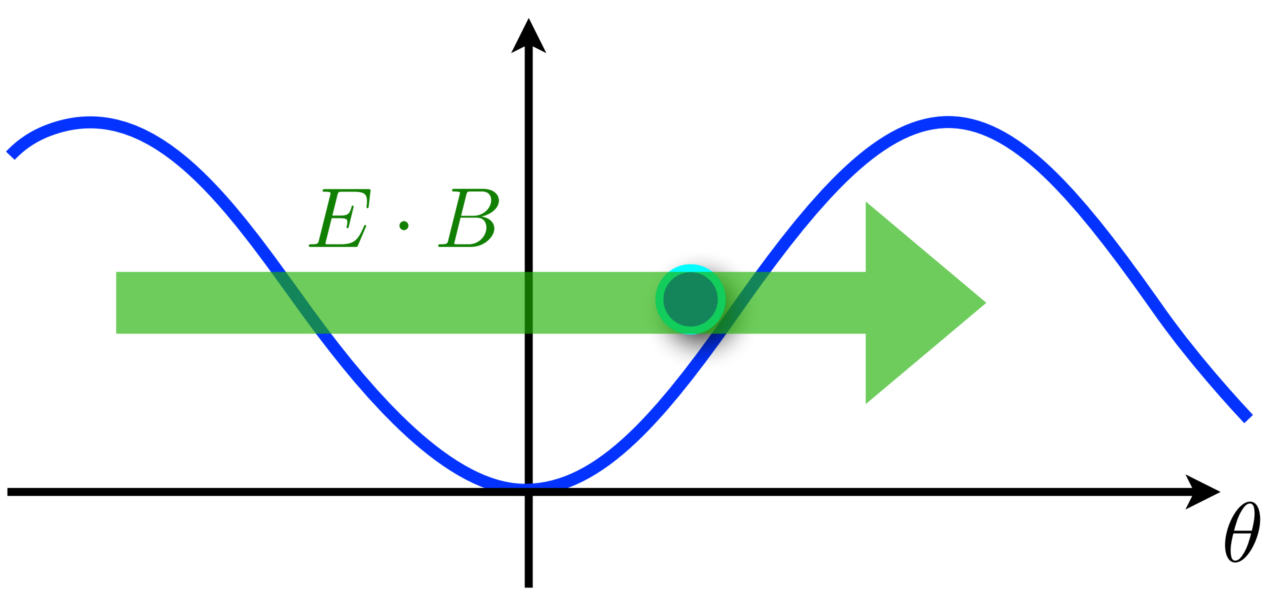

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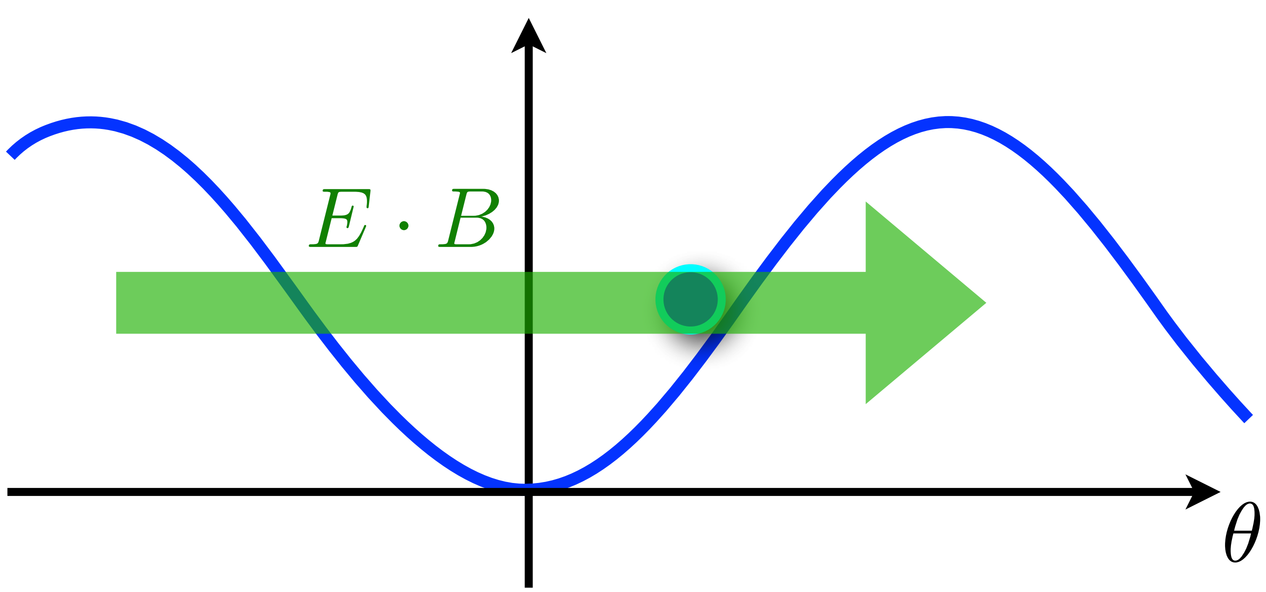
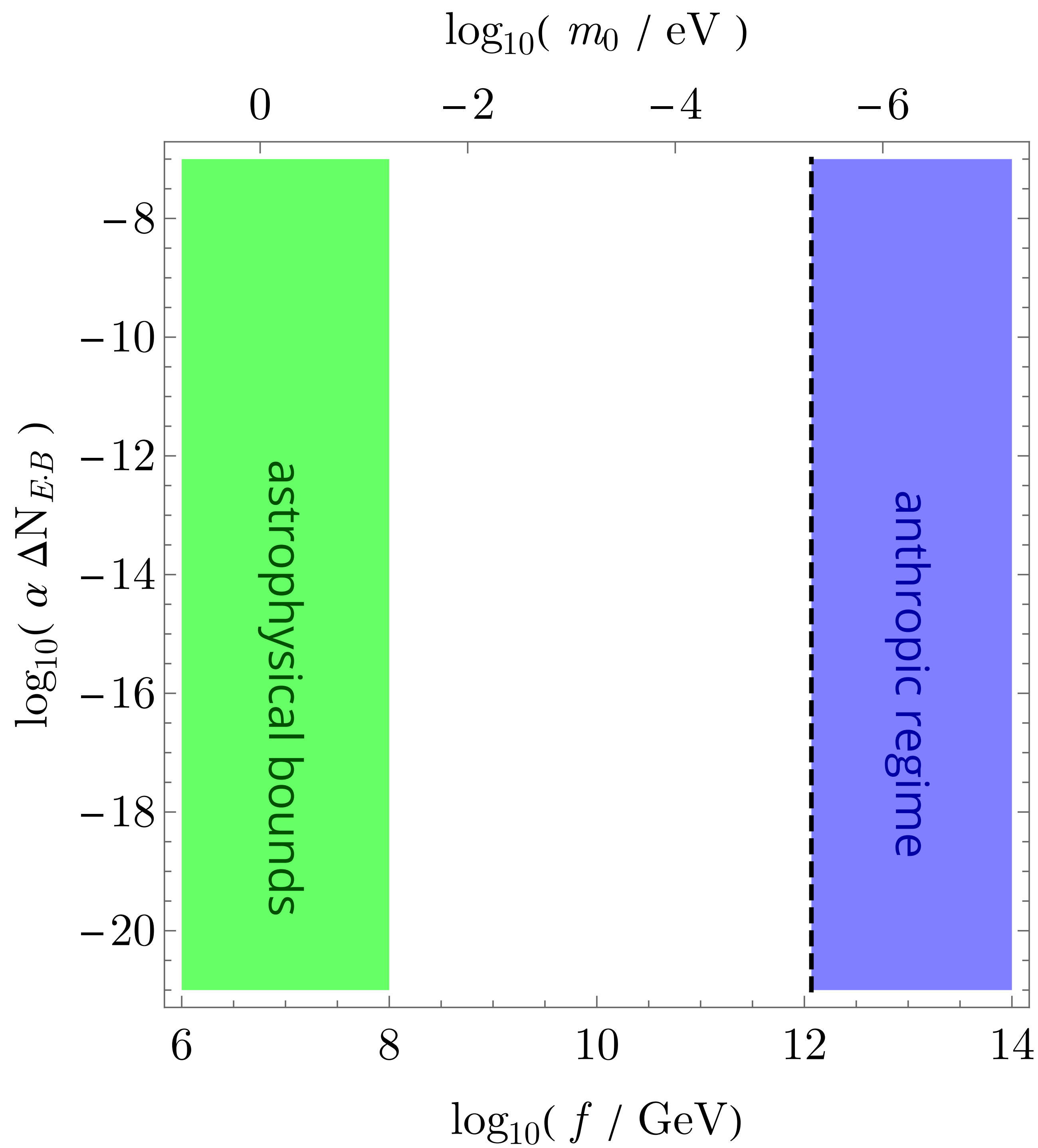


net effect: enhancement of axion relic abundance

QCD AXION WINDOW

$$\Delta N_{E\cdot B} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{|E\cdot B|}{\rho_\gamma}$$

$$\leq \Delta N_{\rm eff} \lesssim 10^{-1} \text{ (CMB)}$$



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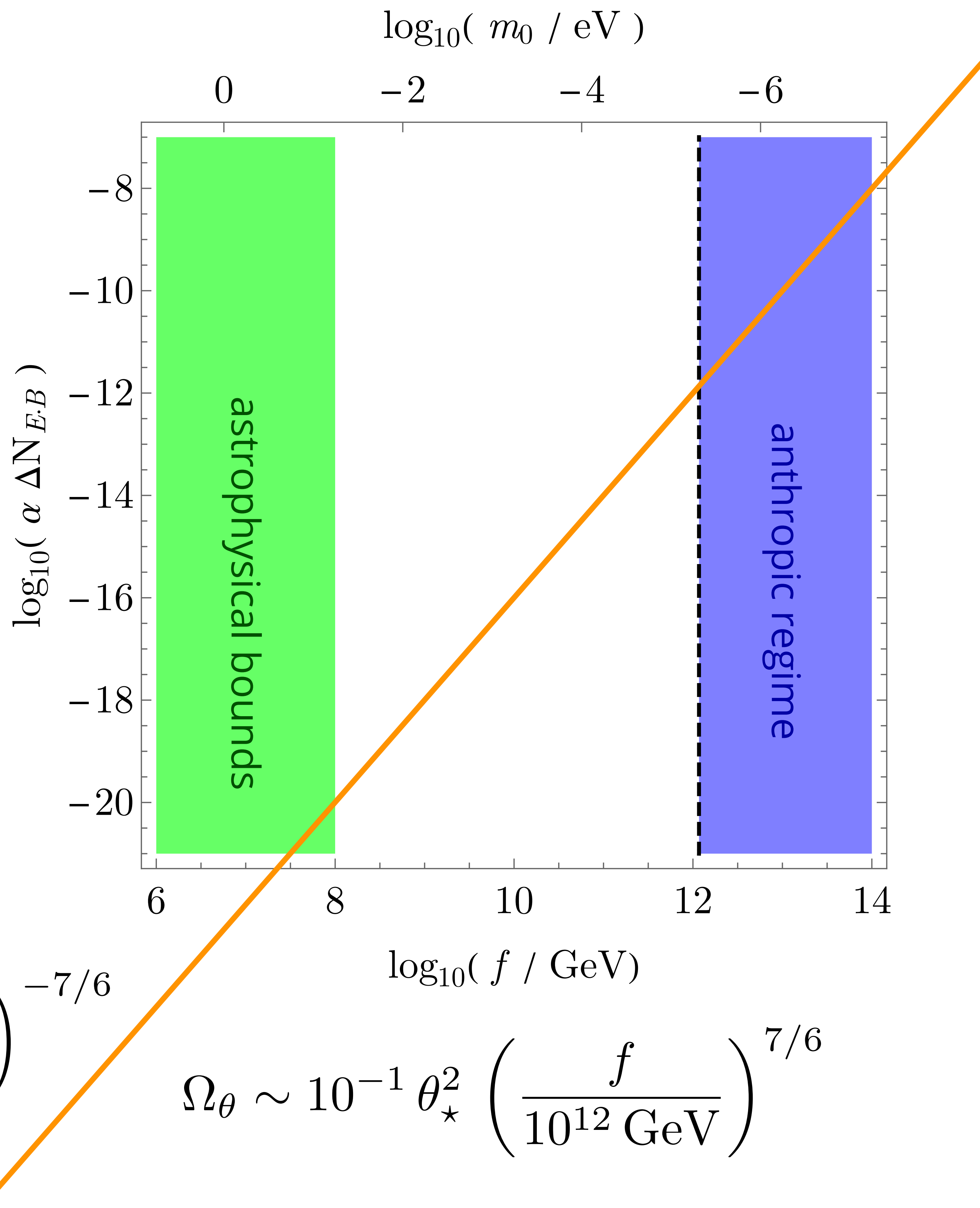

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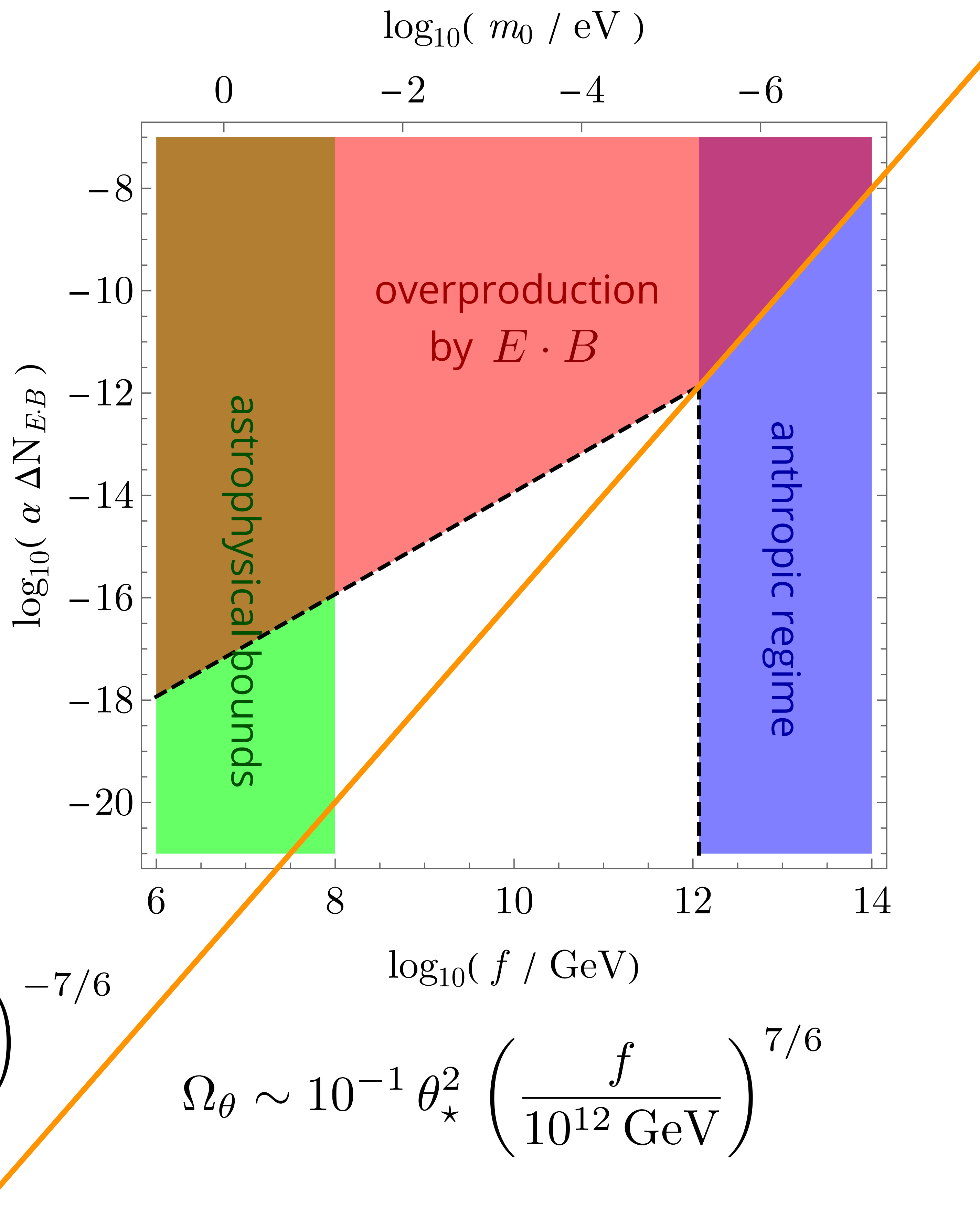

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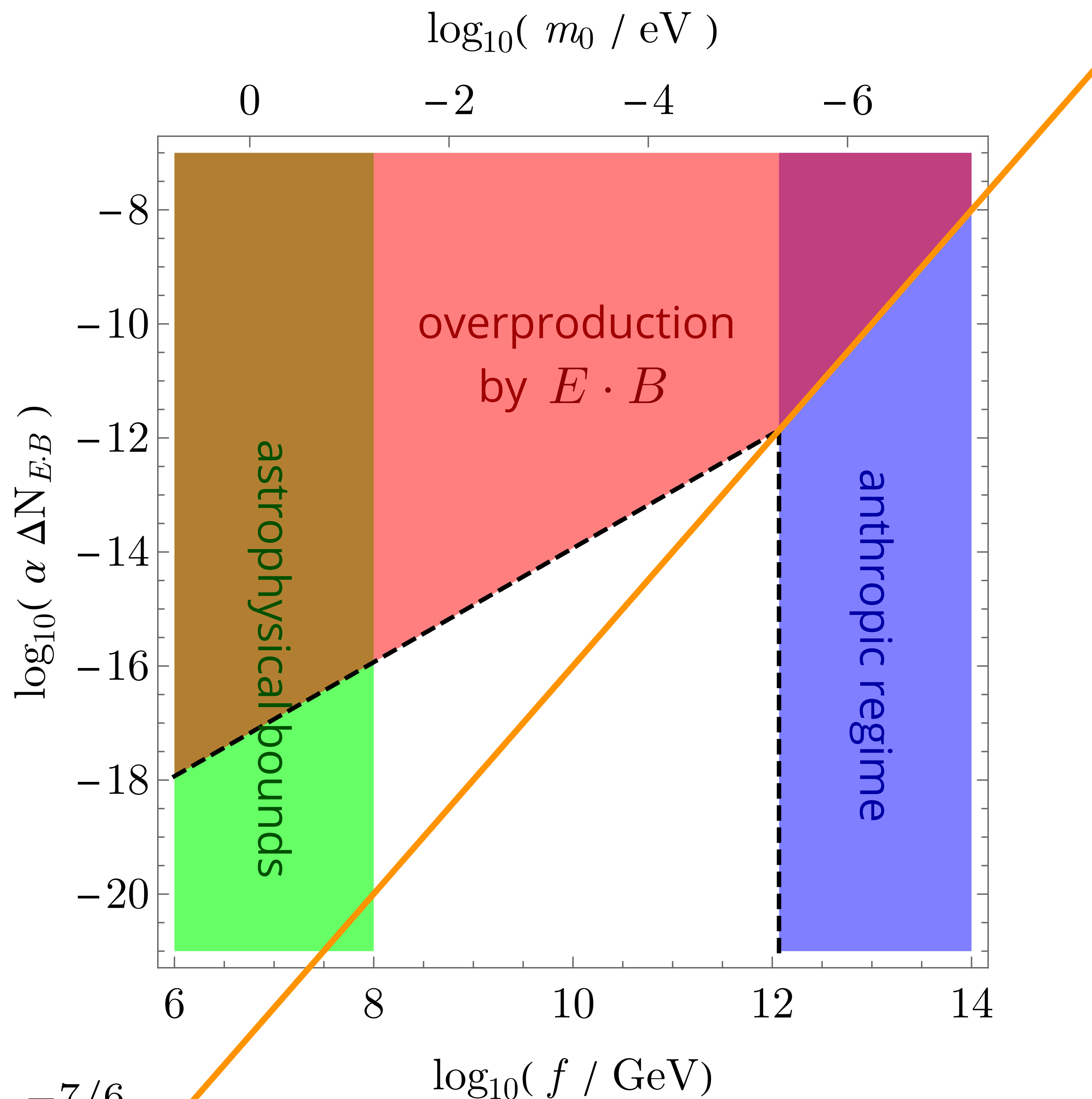

Conventional axion window completely closed for $\alpha\,\Delta N_{E\cdot B} \gtrsim 10^{-12}$

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COMMENTS (FUTURE WORKS)

- Effect of SM $\boldsymbol{E} \cdot \boldsymbol{B}$ is normally negligible, Long, Vachaspati '15 Dvornikov, Semikoz '20 but can be strong if the reheating temperature is low

- Inhomogeneous $\boldsymbol{E} \cdot \boldsymbol{B}$ instead sources axion isocurvature

- Effects also on the post-inflation SSB scenario, especially on domain wall formation

OUTLINE

- brief review of axion cosmology
- new mechanism for axion DM production
  TK, Lorenzo Ubaldi 1907.00984, 2006.09389
- impact of primordial electromagnetic fields on axions
  TK, Rajeev Kumar Jain 2012.00896
- axion-like origin of the primordial density perturbation
  TK 2005.01741

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

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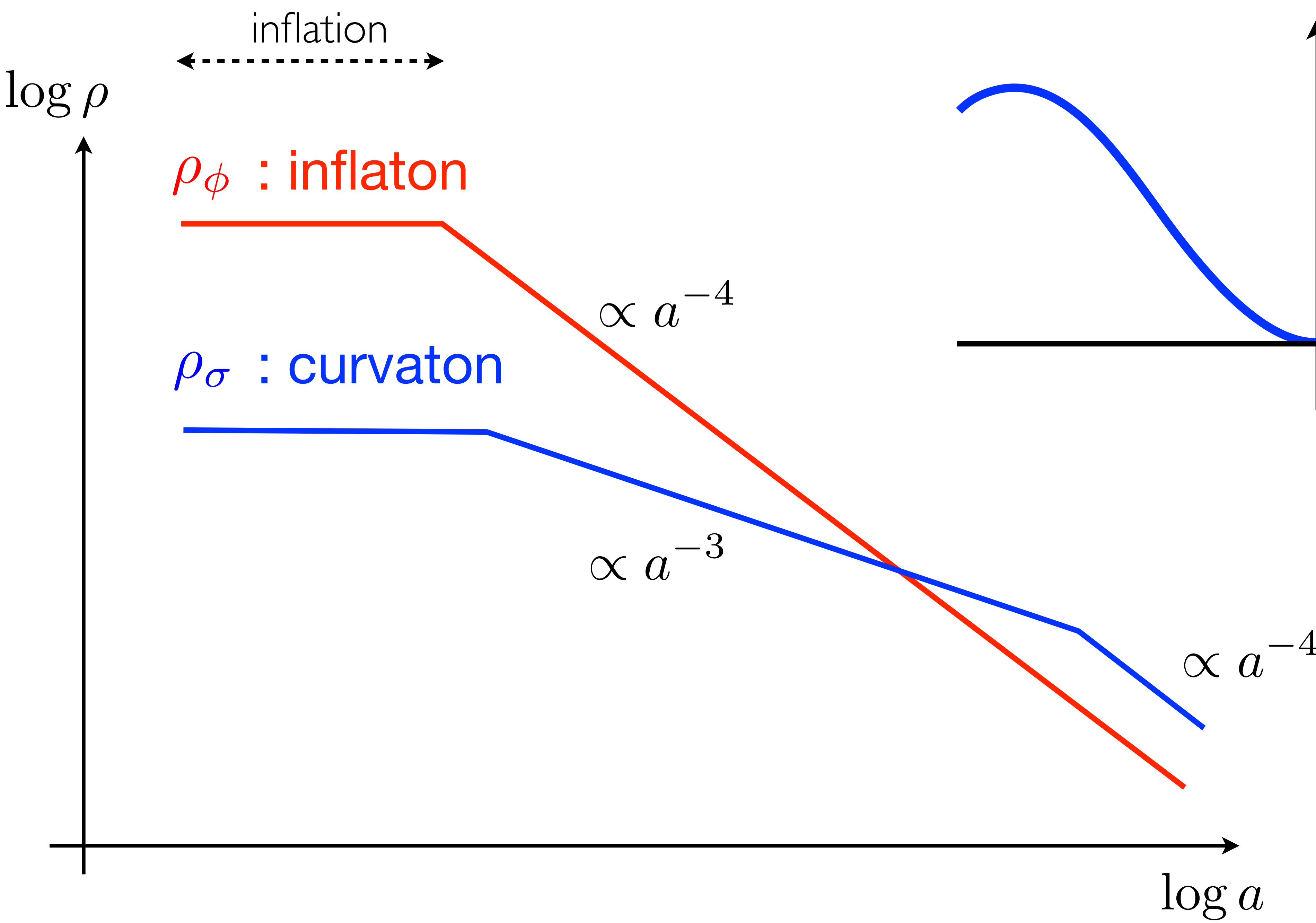

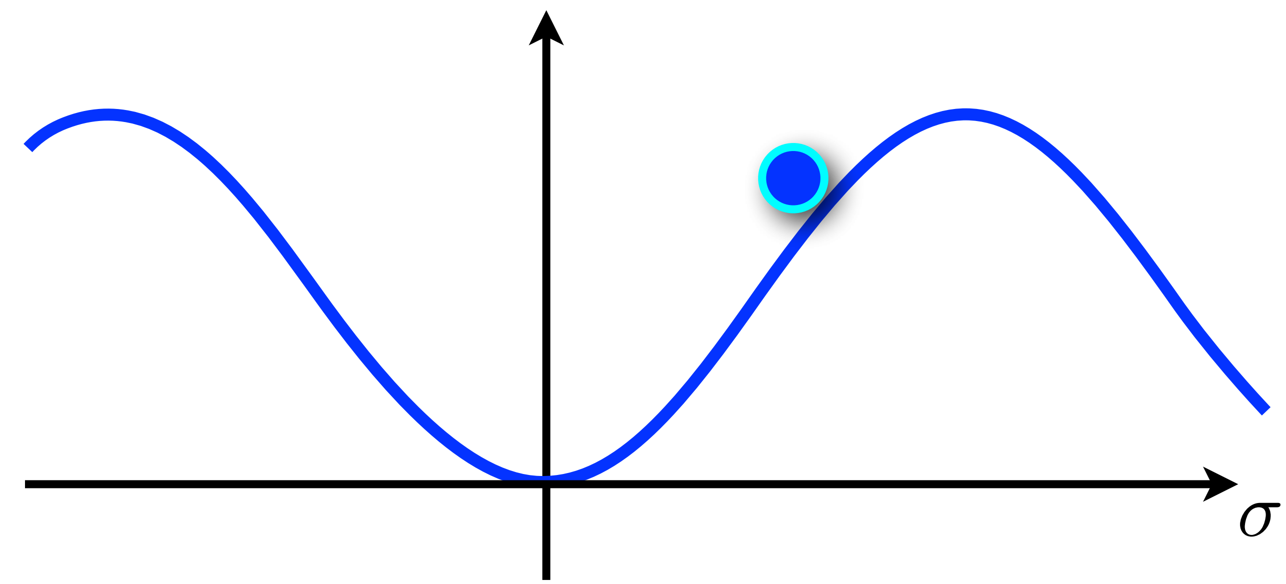

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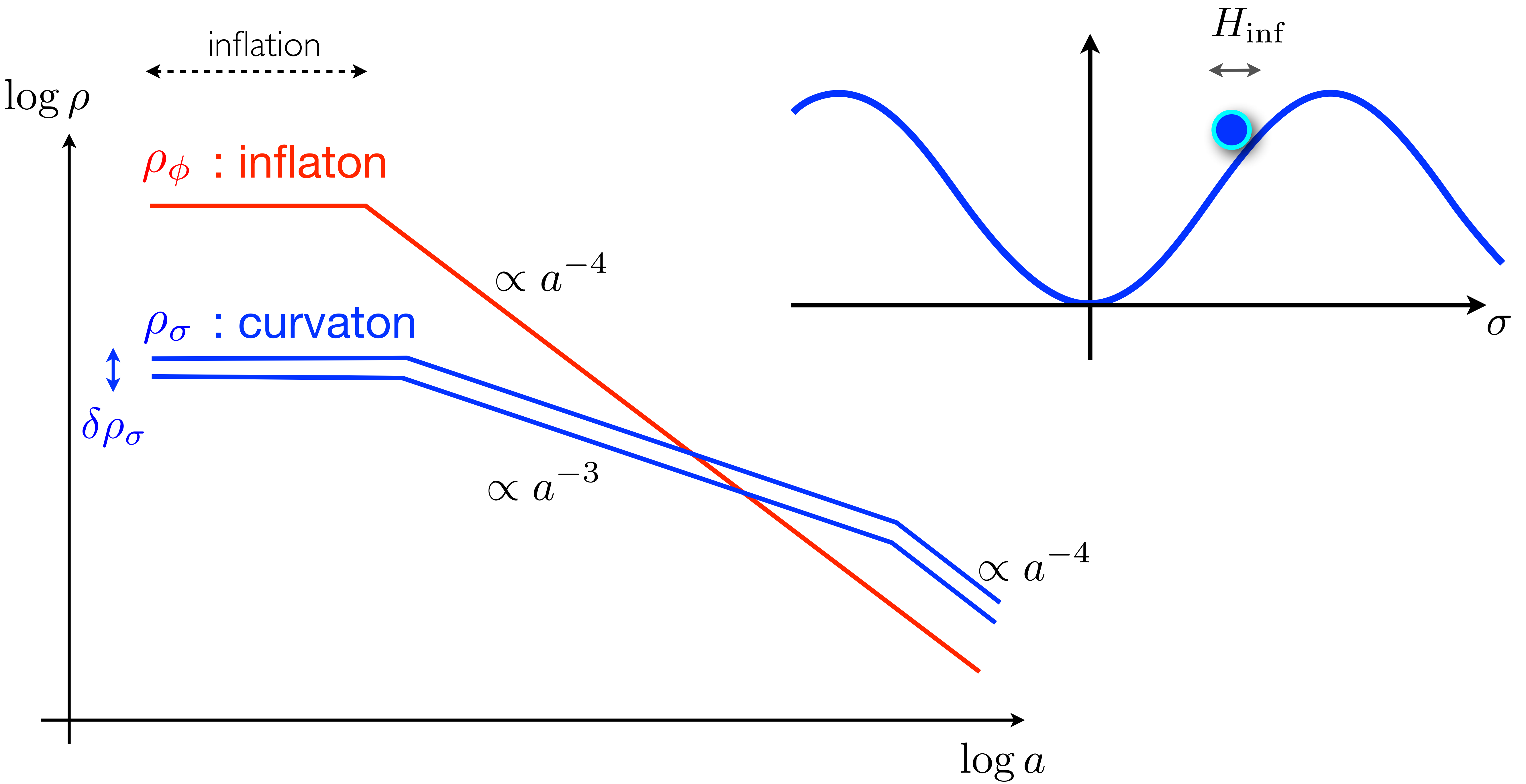

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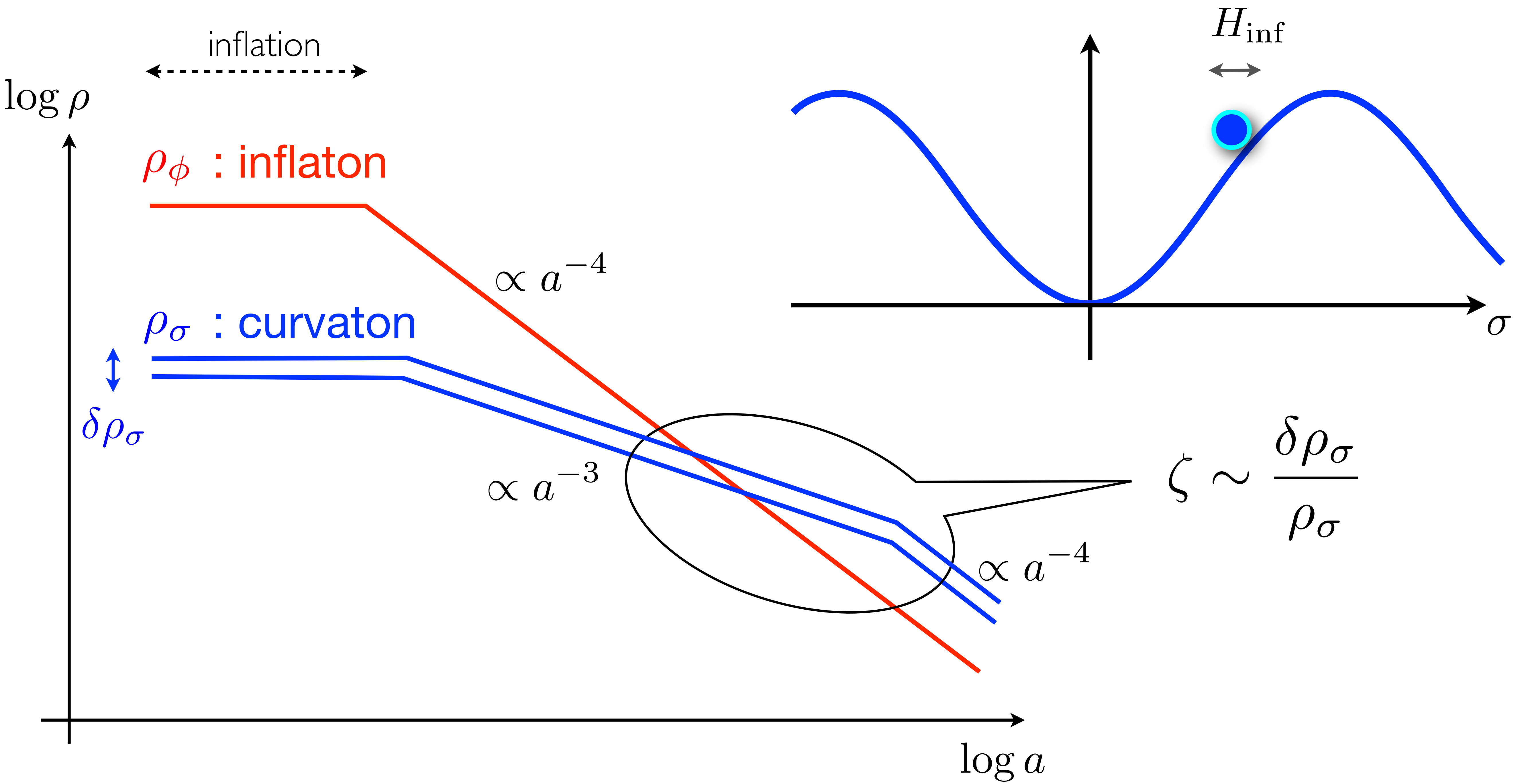

SPECTRAL INDEX FROM CURVATON

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

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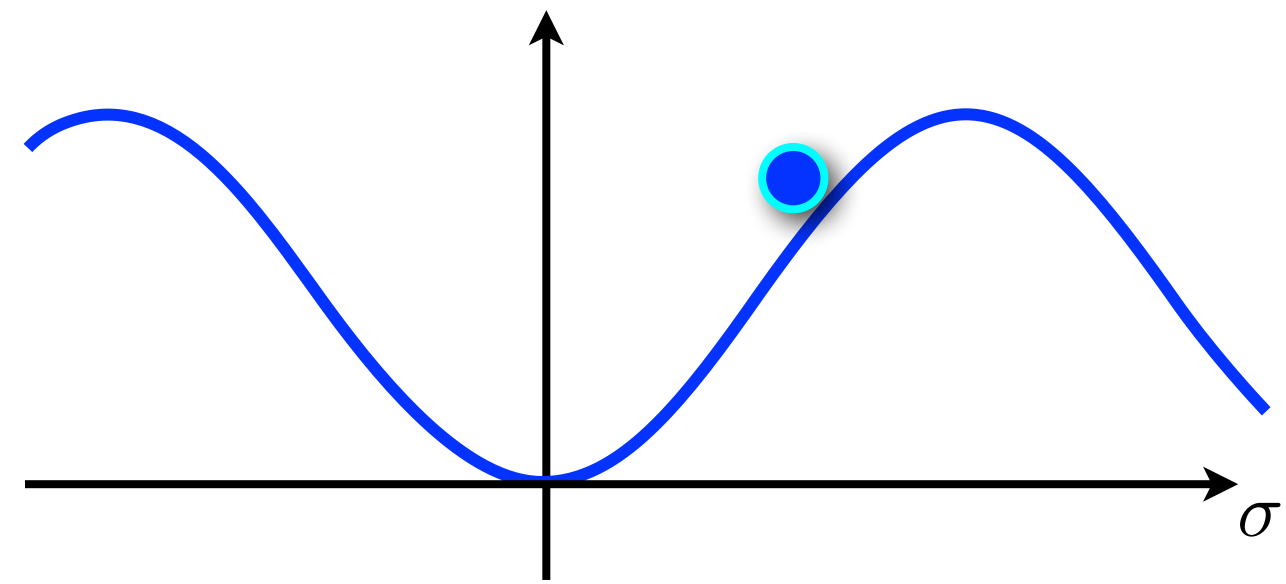

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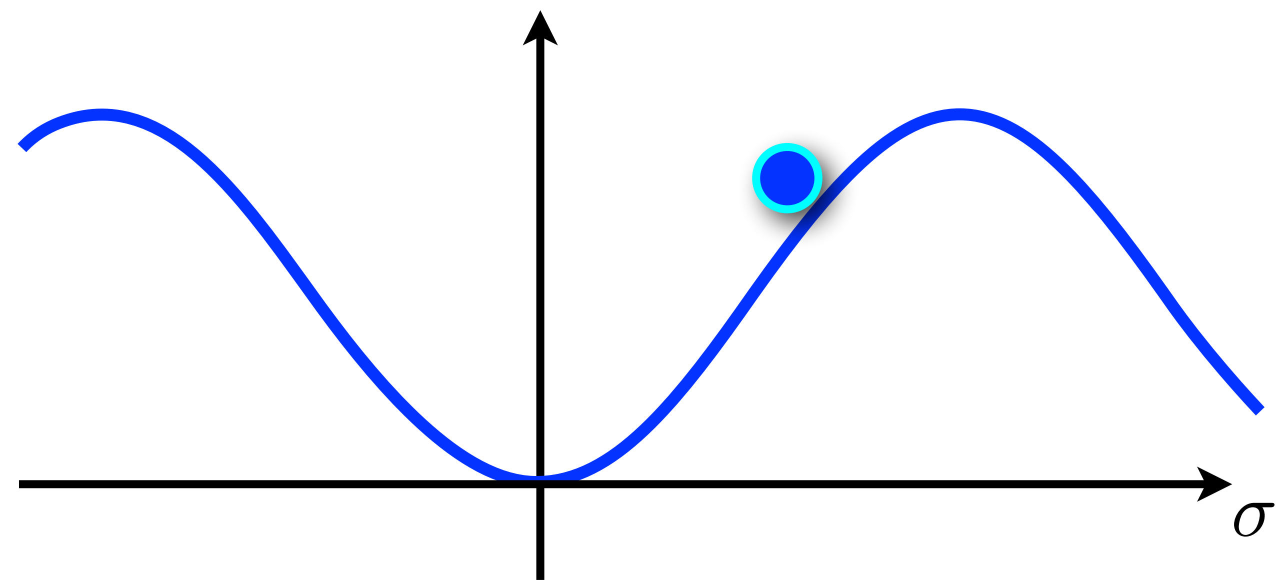

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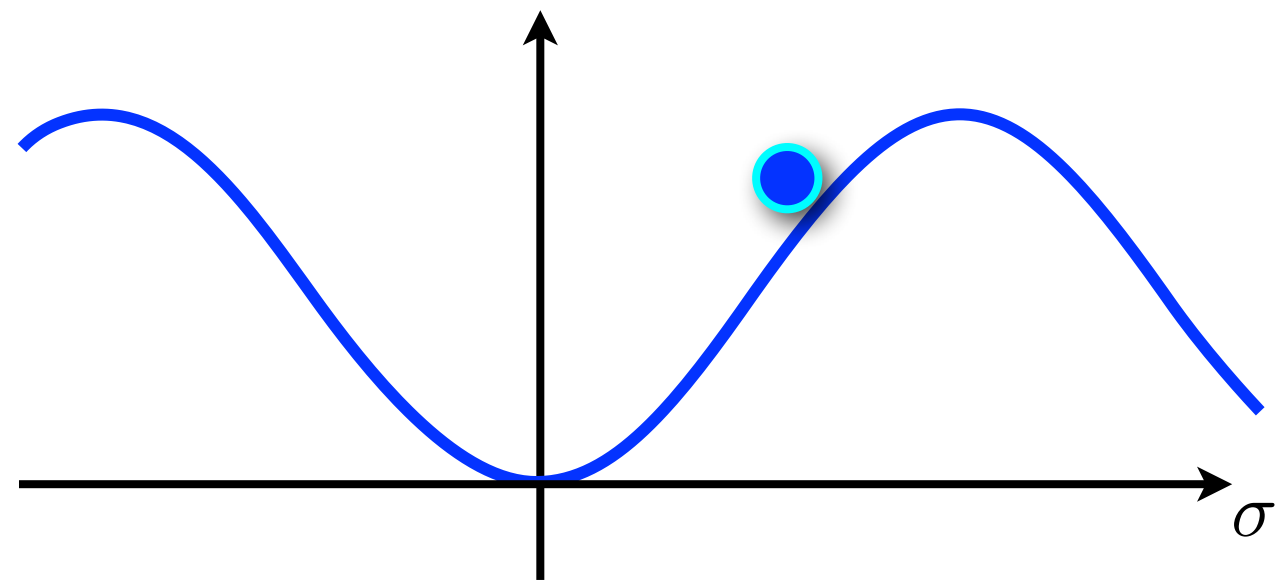

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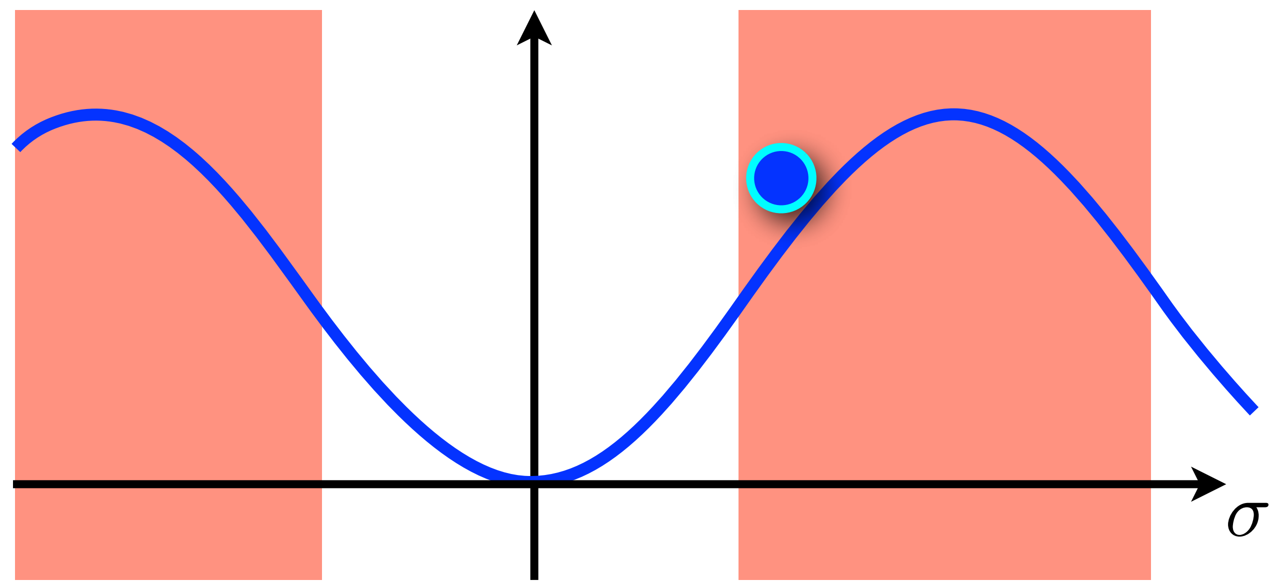

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Axion potentials (by definition) contain concave regions

AXION-LIKE CURVATON COUPLED TO A NEW CONFINING GAUGE GROUP

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temporal deconfinement after inflation

THE IMPORTANCE OF DECONFINING

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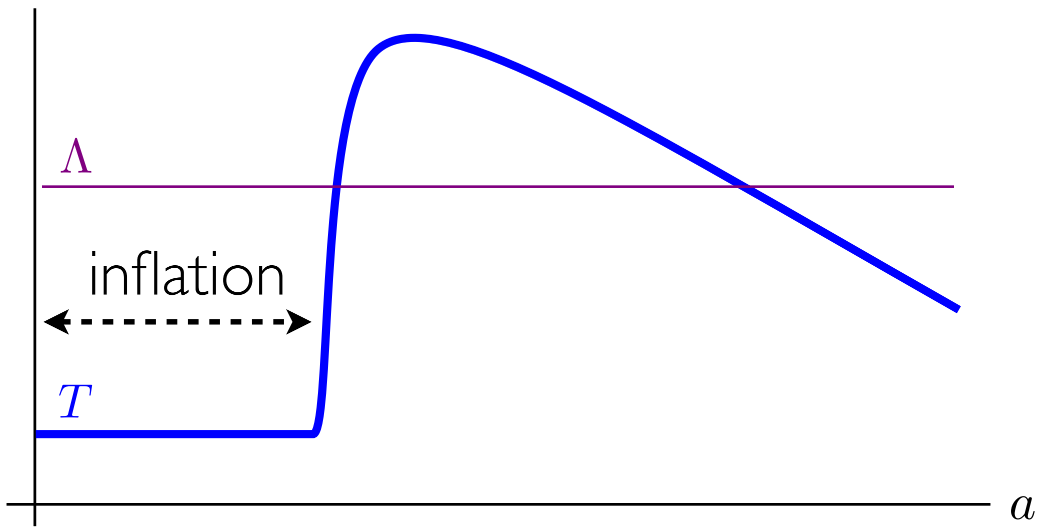

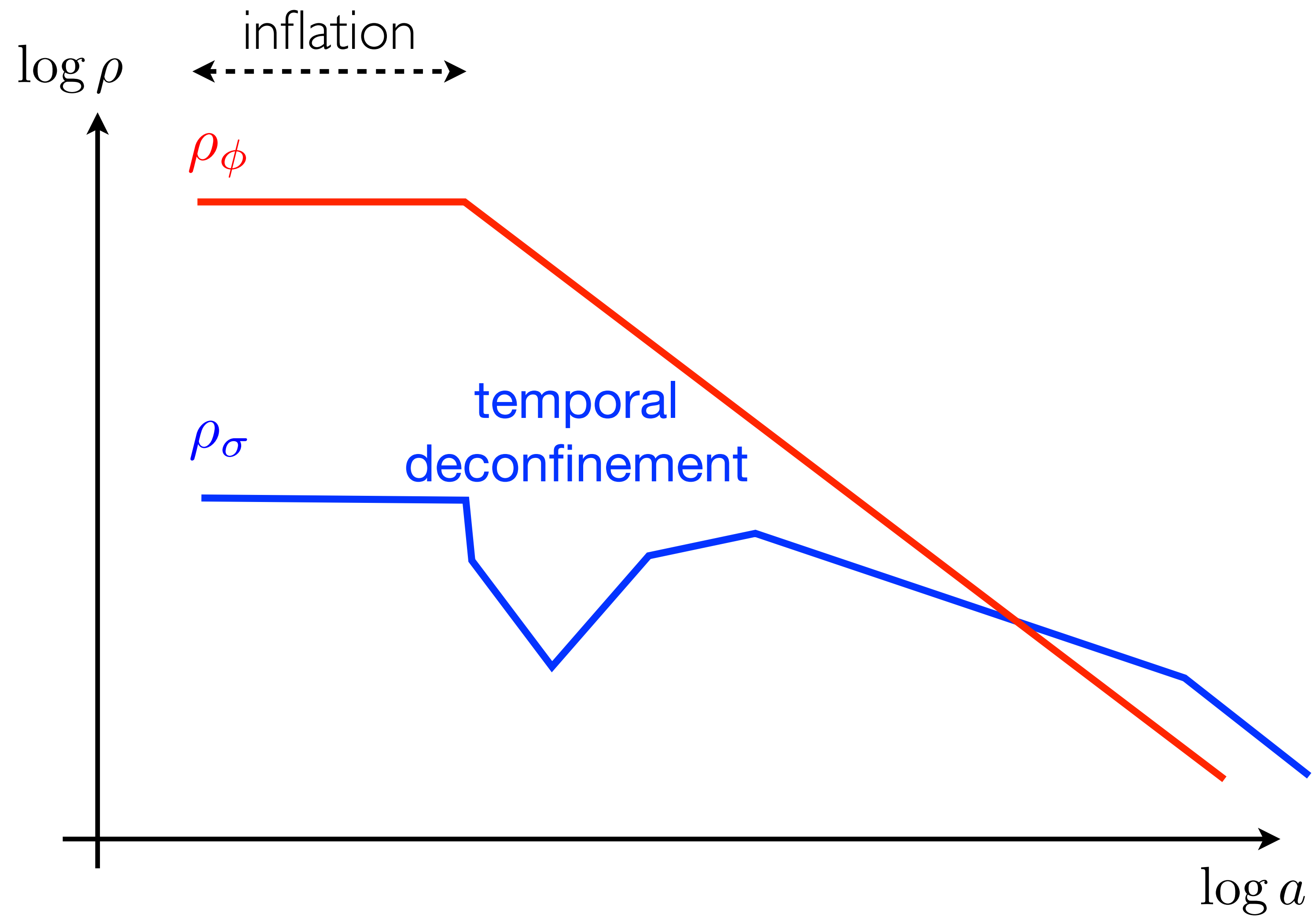

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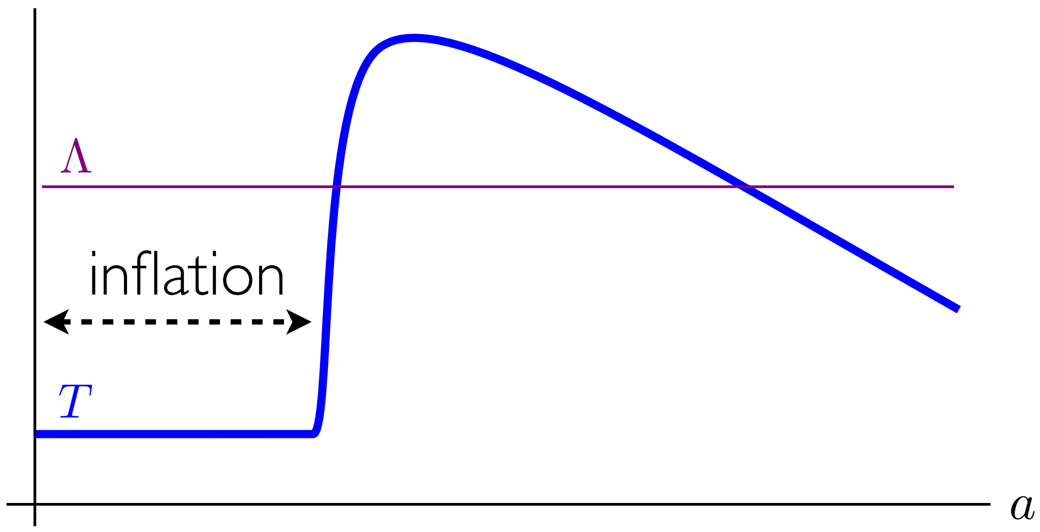

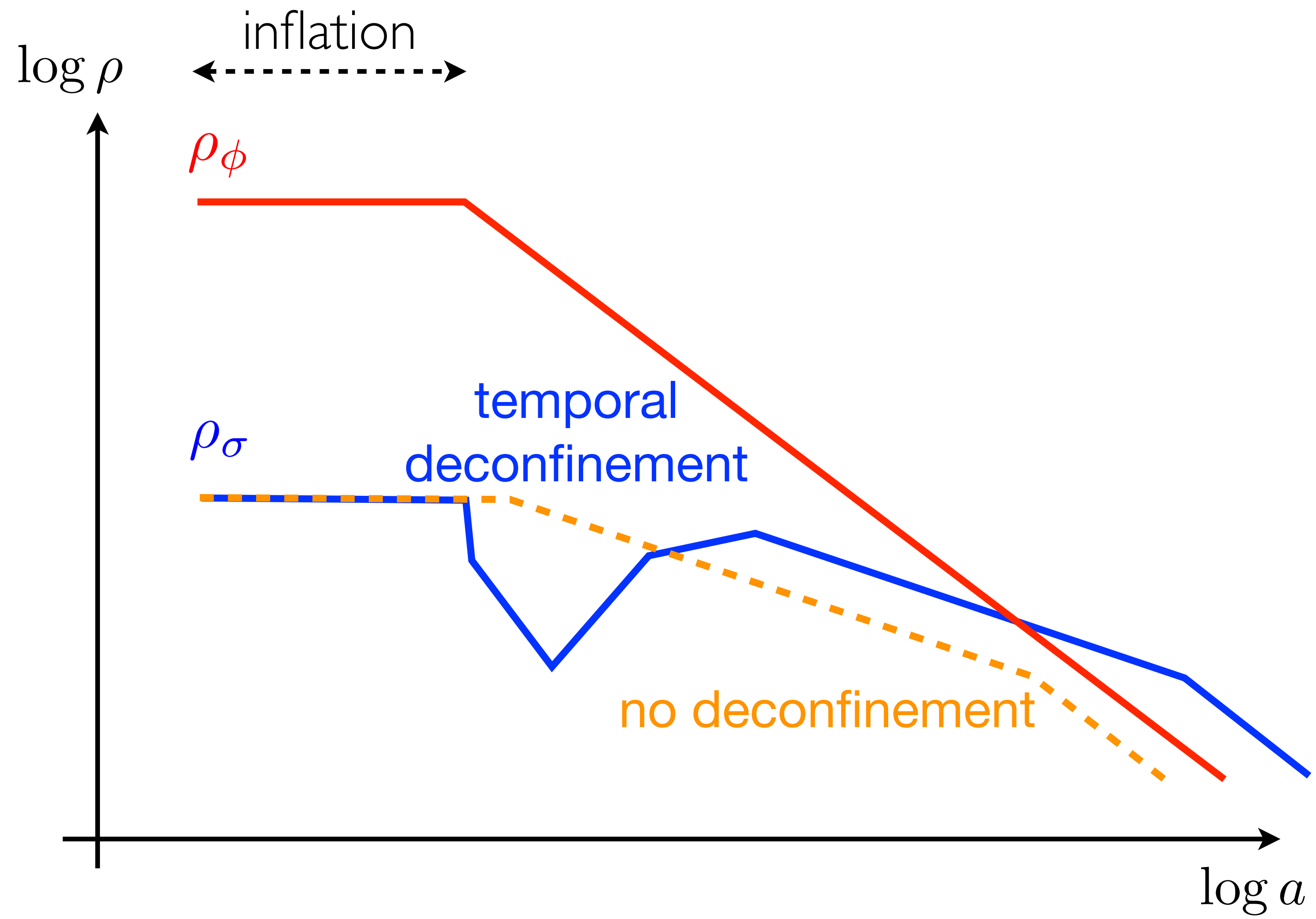

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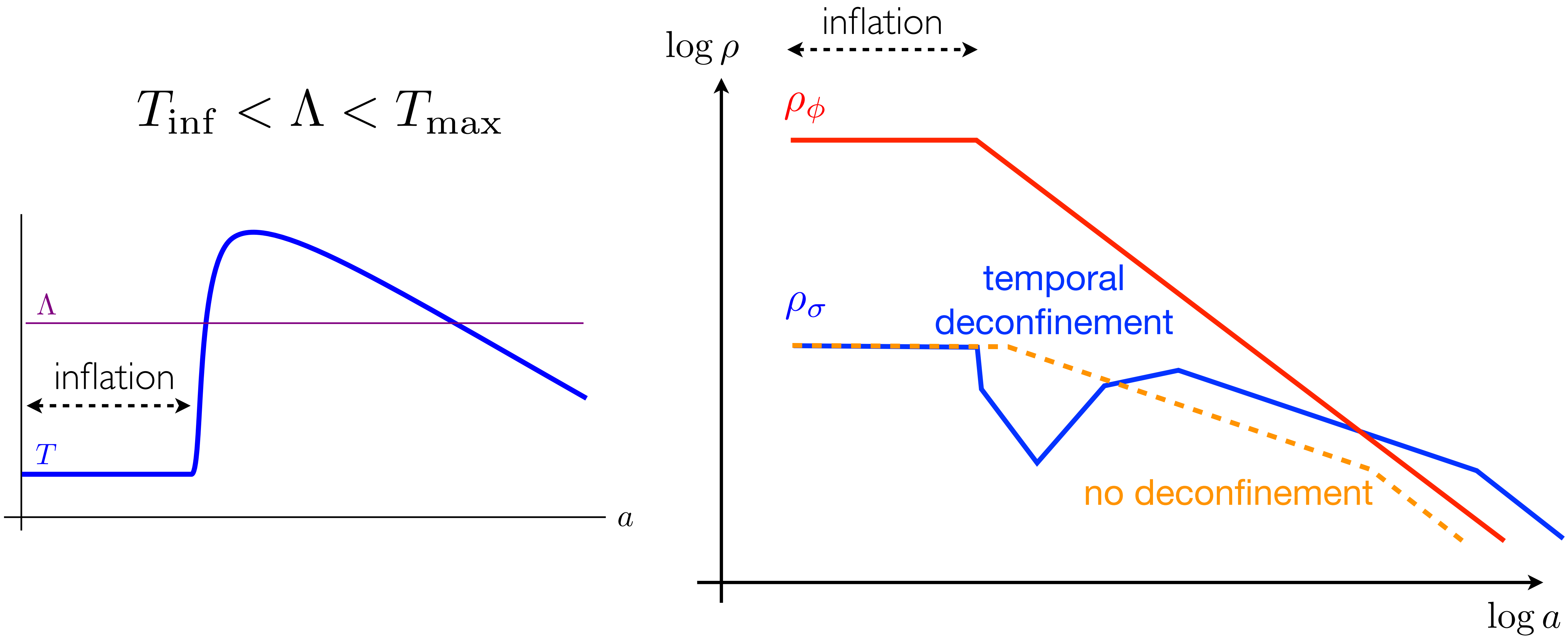

A temporal deconfinement delays the axion oscillation, which helps the axion dominate the universe before decaying

(Alternatively the axion can be initially placed close to the hilltop, but this produces $f_{\rm NL} \sim 10$ and 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 small-scale perturbations can form ultracompact minihalos

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

SUMMARY

- Plenty of wiggle room in the "standard picture" of axion cosmology
  - Inflaxion: integrates single-field inflaton, reheaton, DM, and opens up new windows (e.g. low $H_{\rm inf}$, $f \gtrsim 10^{16}\,{\rm GeV}$)
  - Strong impact of primordial electromagnetic fields on the axion abundance; QCD axion excluded if $\alpha\,\Delta N_{E\cdot B} \gtrsim 10^{-12}$

- Axions also provide a viable curvaton candidate when coupled to a new confining sector
  - Temporal deconfinement of the gauge group after inflation, and predicts $f_{\rm NL}$ running $1 \to -1$