Some novel and attractive features of Warm Inflation

Suratna Das
Ashoka University

In collaboration with Rudnei O. Ramos, Archana Santosh, Swagat Mishra, Varun Sahni

Cosmic Inflation

- Inflation is a very brief epoch when the universe expanded exponentially
- The dynamics is determined by Einstein's General Theory of Relativity :

$$G_{\mu\nu} = 8\pi G \; T_{\mu\nu}$$

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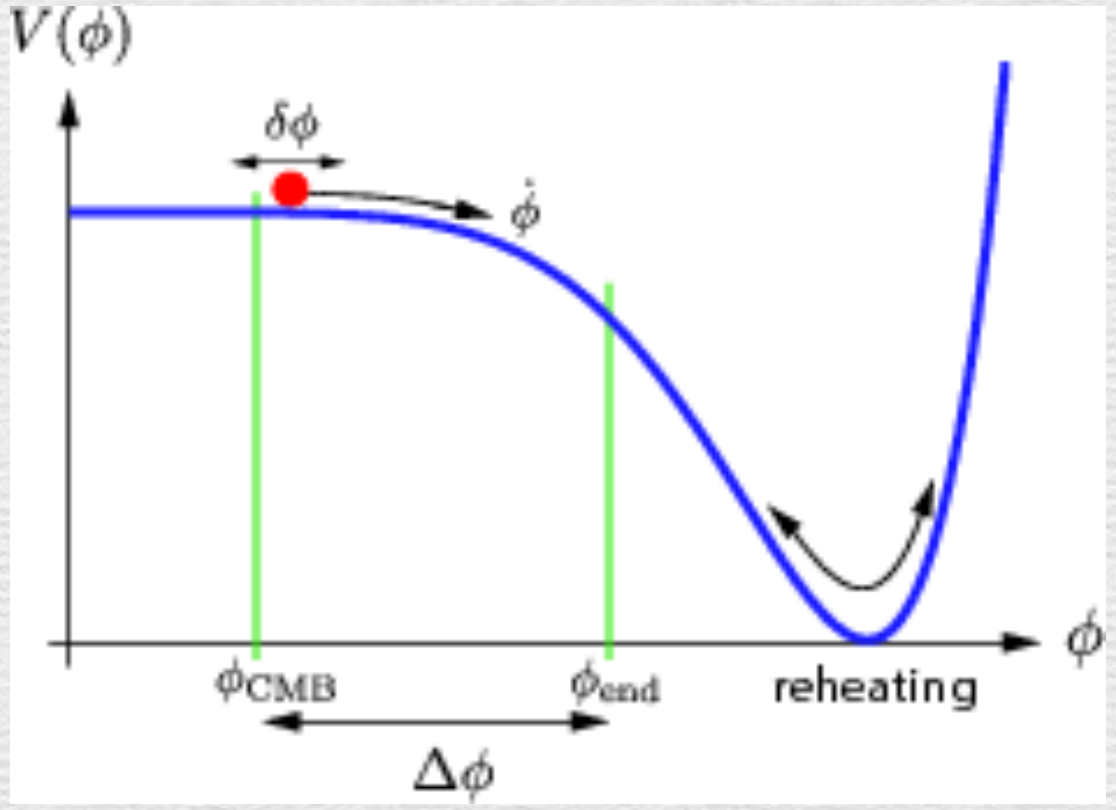
Slowly rolling scalar field :
Inflaton field $\phi(t)$

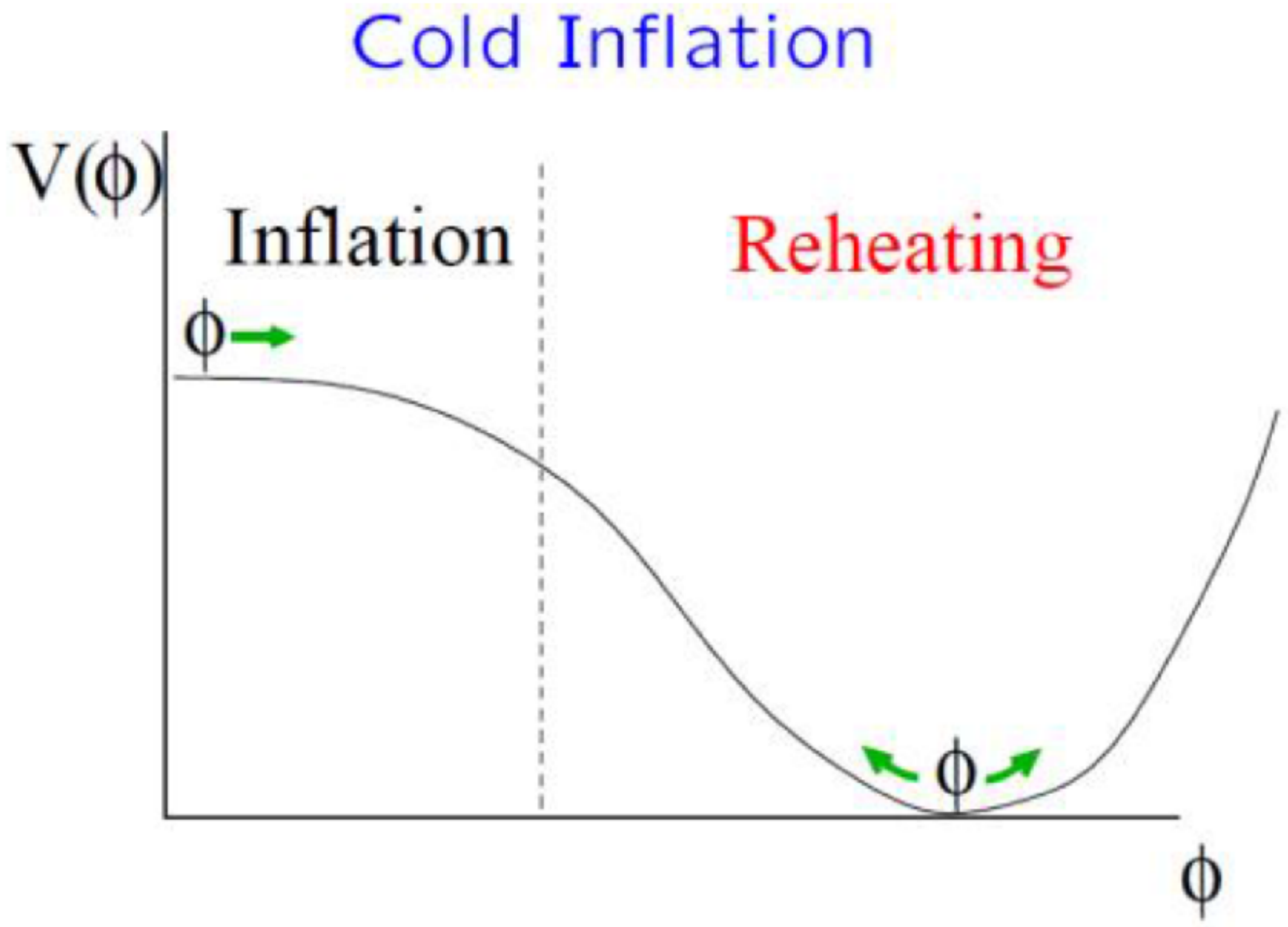


$$\epsilon_V = \frac{M_{\rm Pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2$$

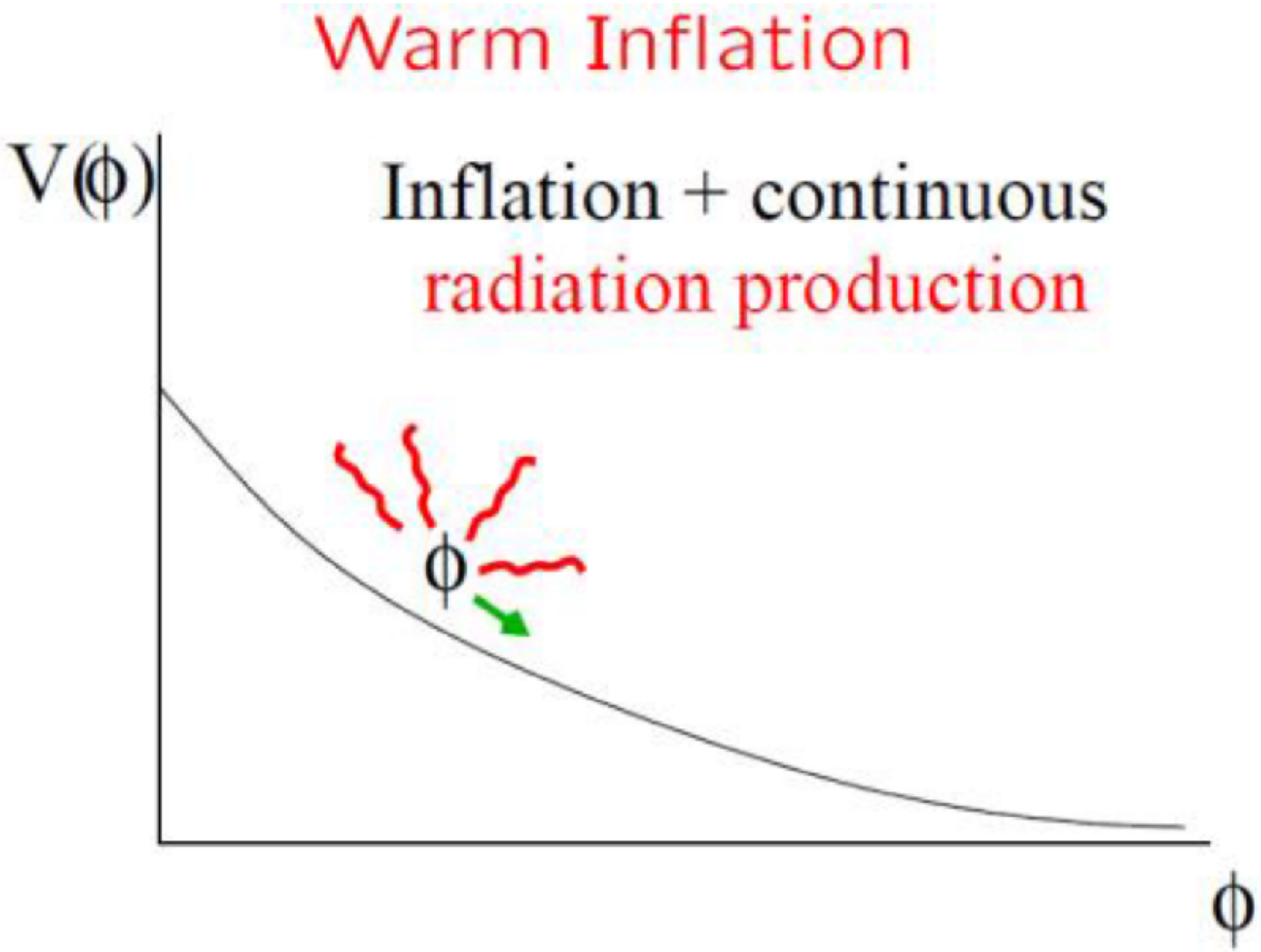
$$\eta_V = M_{\rm Pl}\left(\frac{V_{,\phi\phi}}{V}\right)$$

A variant Inflationary scenario:
Warm Inflation

Cold Inflation vs Warm Inflation



$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$



$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = -\Upsilon(T,\phi)\dot{\phi}$$

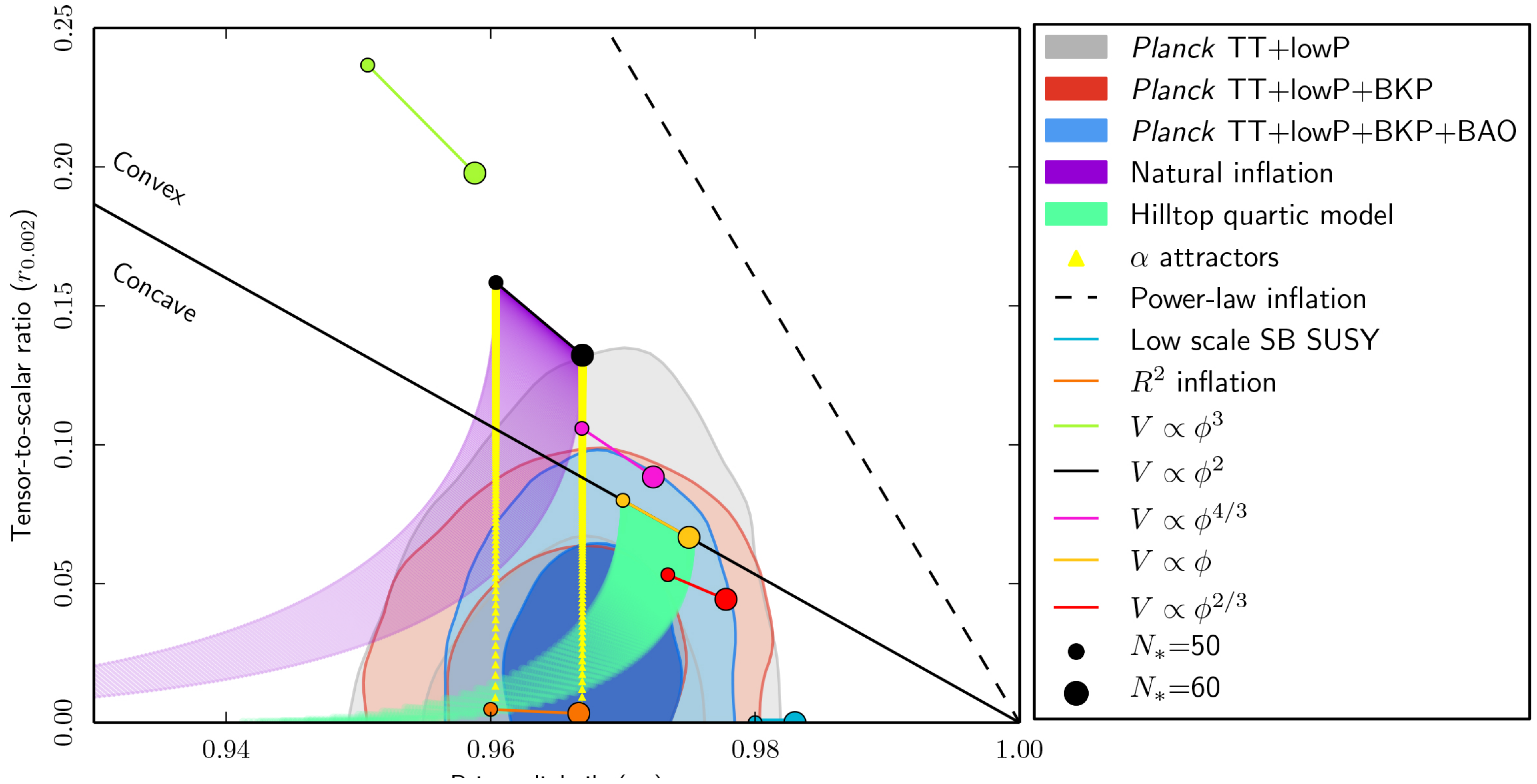
$$\dot{\rho}_R + 4H\rho_R = \Upsilon(T,\phi)\dot{\phi}^2$$

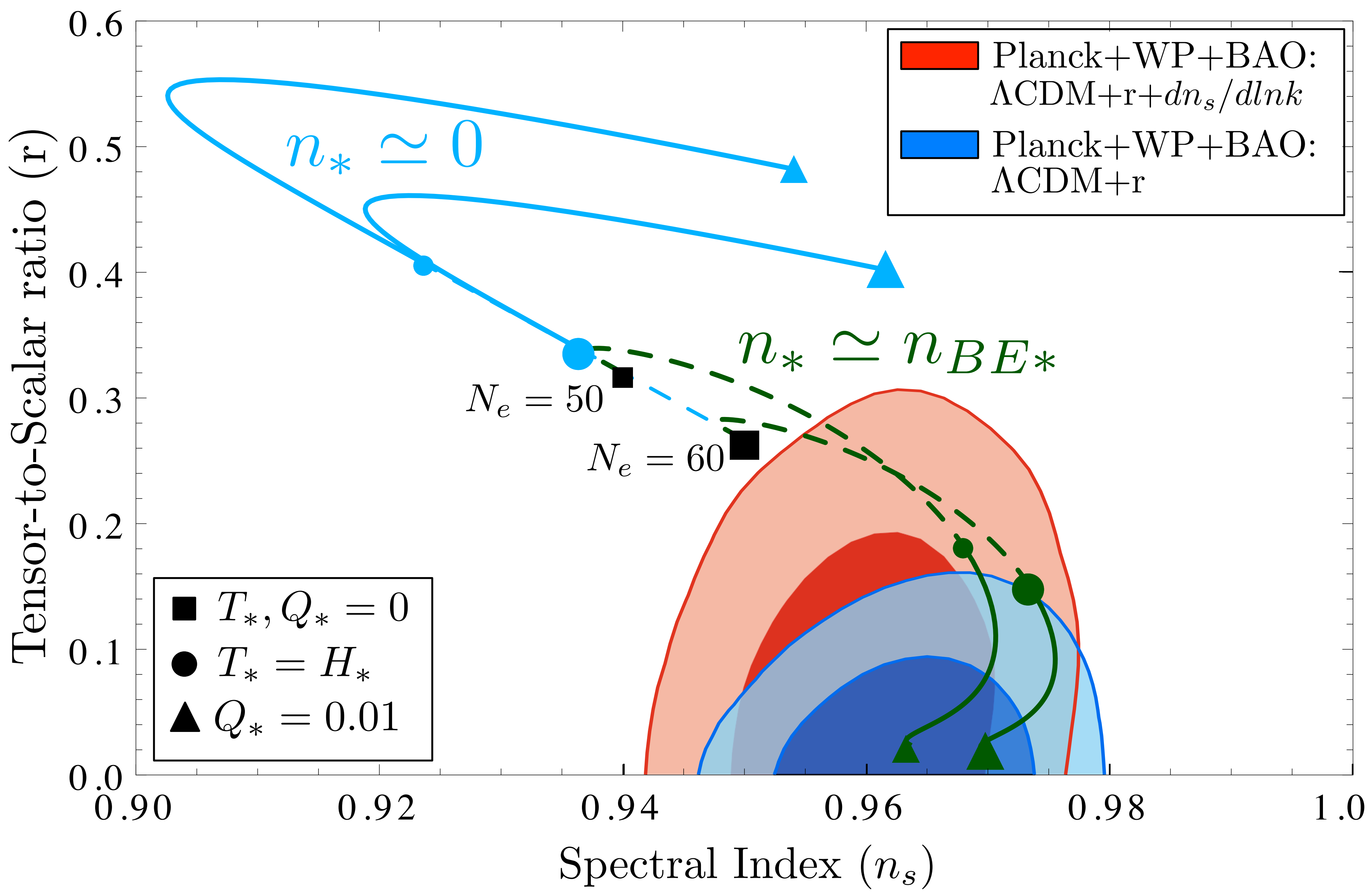
Diagram: Berera, Moss, Ramos 2009

Why Warm Inflation?

- Warm Inflation does not require a subsequent "reheating" phase, physics of which is still unknown. WI smoothly ends in a radiation dominated phase

- WI has a more enhanced scalar power spectrum than CI. Thus yields a smaller tensor-to-scalar ratio. The potentials that are ruled out in CI for generating large tensor-to-scalar ratios can be accommodated in WI.





Bartrum et al 2014

Why Warm Inflation?

- Strong dissipative $(Q \gg 1)$ WI models prefer small-field inflation models whereas CI is often realised in large-field models. Present data prefers small-field models.

- WI significantly alleviates the eta-problem and the gravitino problem in the context of Supergravity.

- WI is favoured over CI if one considers the *Swampland Conjectures* arising in String Theory. PRD '19 (2 papers), Physics of the Dark Universe '20, PRD '20 (two papers)

The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems

Alan H. Guth (SLAC)

Jul, 1980

32 pages

Part of QUANTUM COSMOLOGY, 139-148

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astrophysics | inflation | thermodynamics | critical phenomena | Einstein equation: solution | fundamental constant | grand unified theory: SU(5) | baryon number: violation | CP: violation | tensor: energy-momentum | Show all (17)

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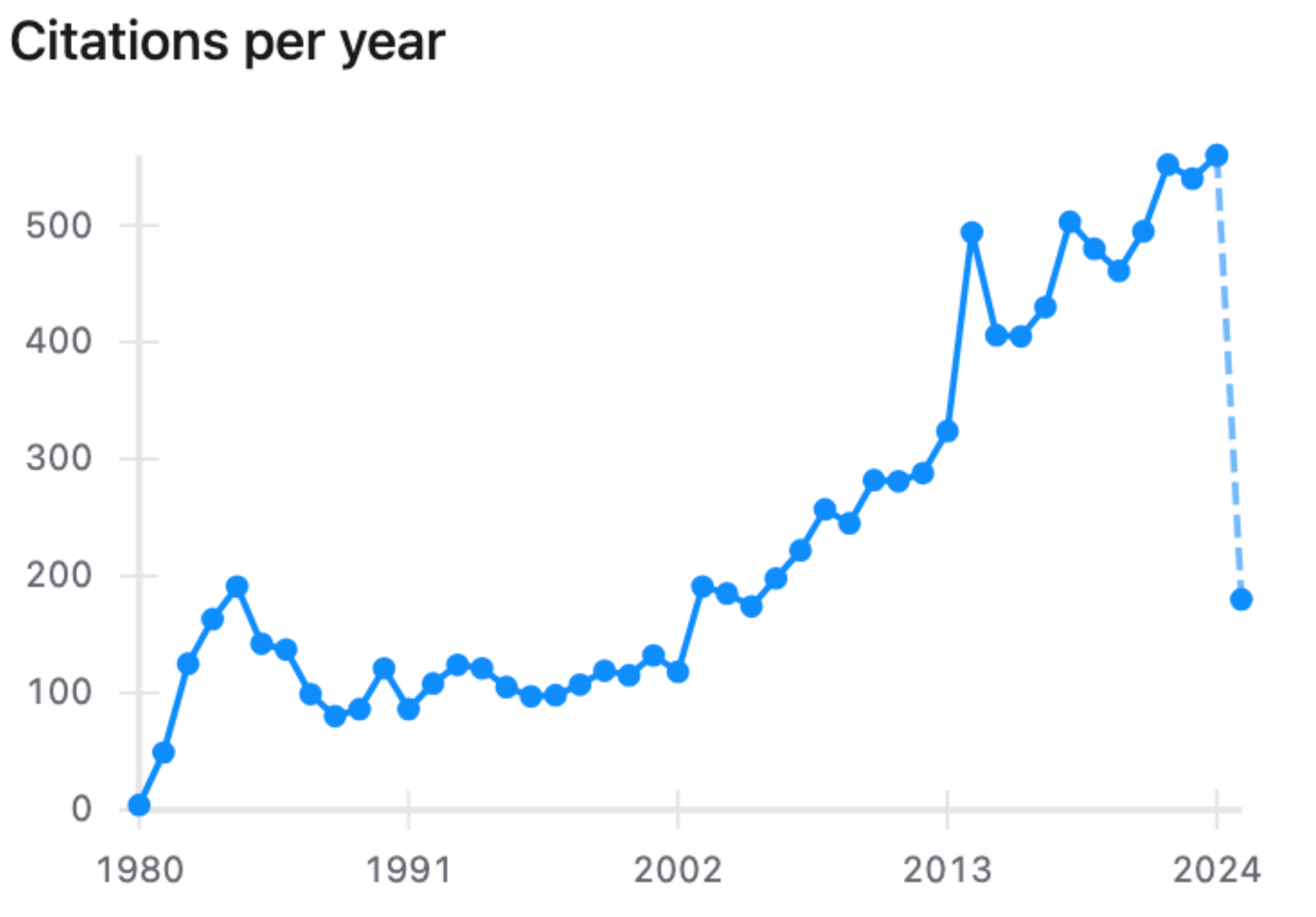

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Warm inflation

Arjun Berera (Penn State U.)

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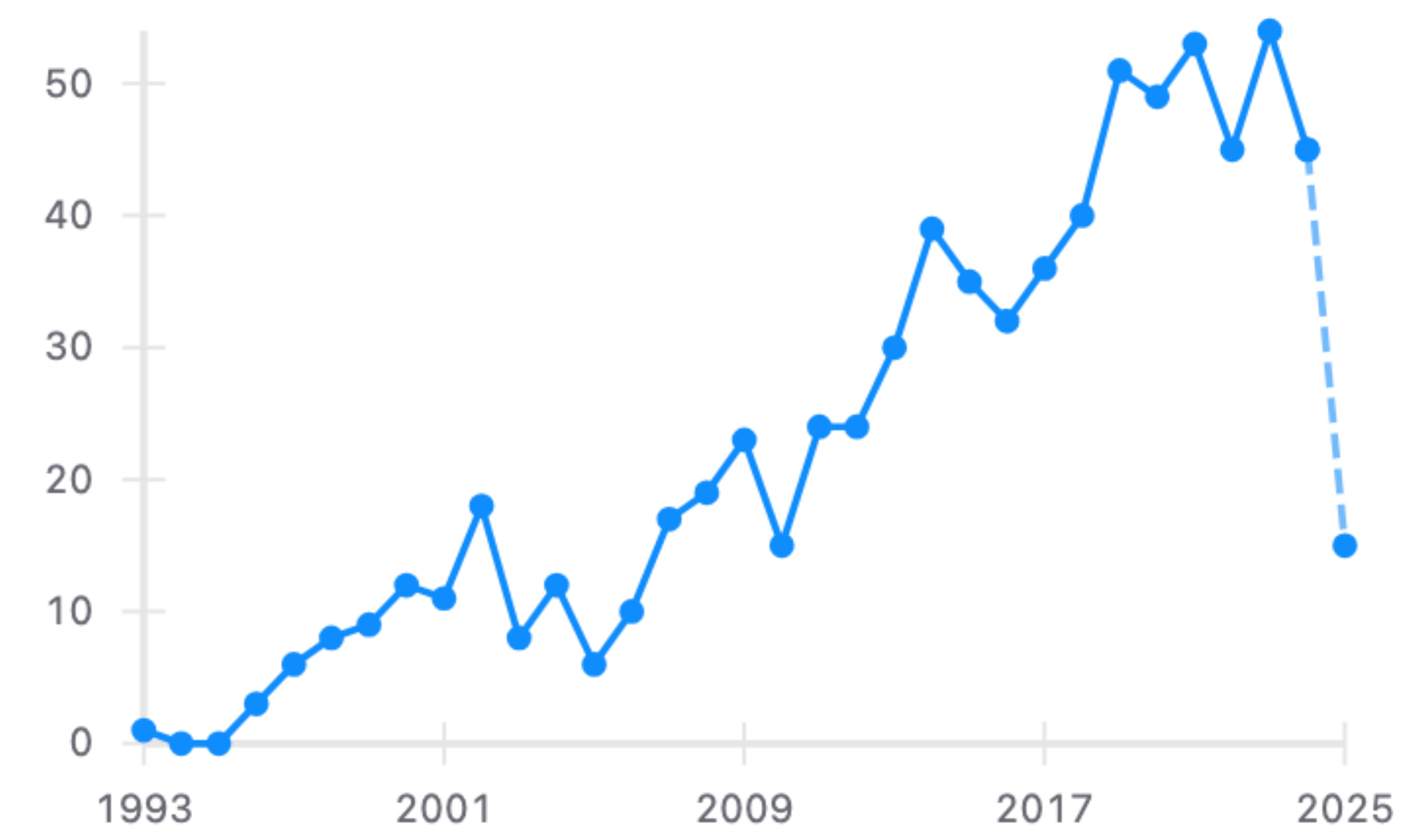

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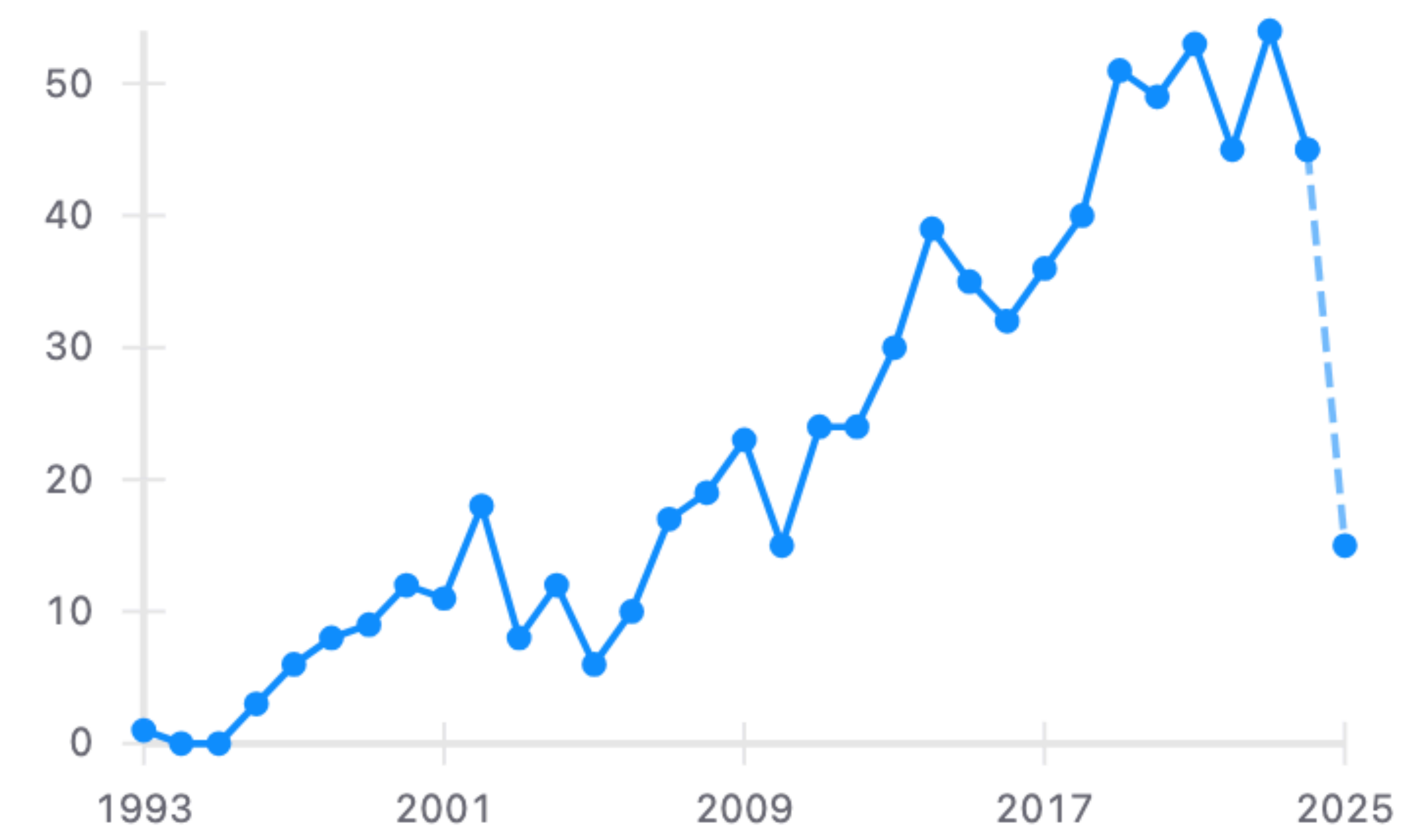

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Today’s Topic: “How inflation ends?”
a.k.a. Graceful Exit

Graceful Exit?

- Inflation is a phase when the Universe has expanded exponentially (accelerated) for a very brief amount of time.

- Feeding in the FRW metric into the Einstein Field equations with the matter as perfect fluid p=ωρ, we get two Friedmann equations which tell us about the expansion history of the universe:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho, \qquad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(1+3\omega)\rho$$

- Thus ω=-1 fluid can easily drive inflation, like a Cosmological Constant Λ

- The problem is with CC inflation will never end and hence no Graceful Exit

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The inflaton & its slow-roll

- A simple scalar field's energy density and pressure:

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) + \frac{(\nabla\phi)^2}{2a^2}, \qquad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) - \frac{(\nabla\phi)^2}{6a^2}$$

- Potential energy dominated scalar filed, a.k.a. the inflaton field, can drive inflation

- The potential needs to be very flat, so that the kinetic term is negligible ⟶ slow-roll of the inflaton on its flat potential

- Slow-roll parameter $\epsilon_V \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \ll 1$

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Slow-roll & Graceful Exit

- Slow-roll EoM of inflaton:

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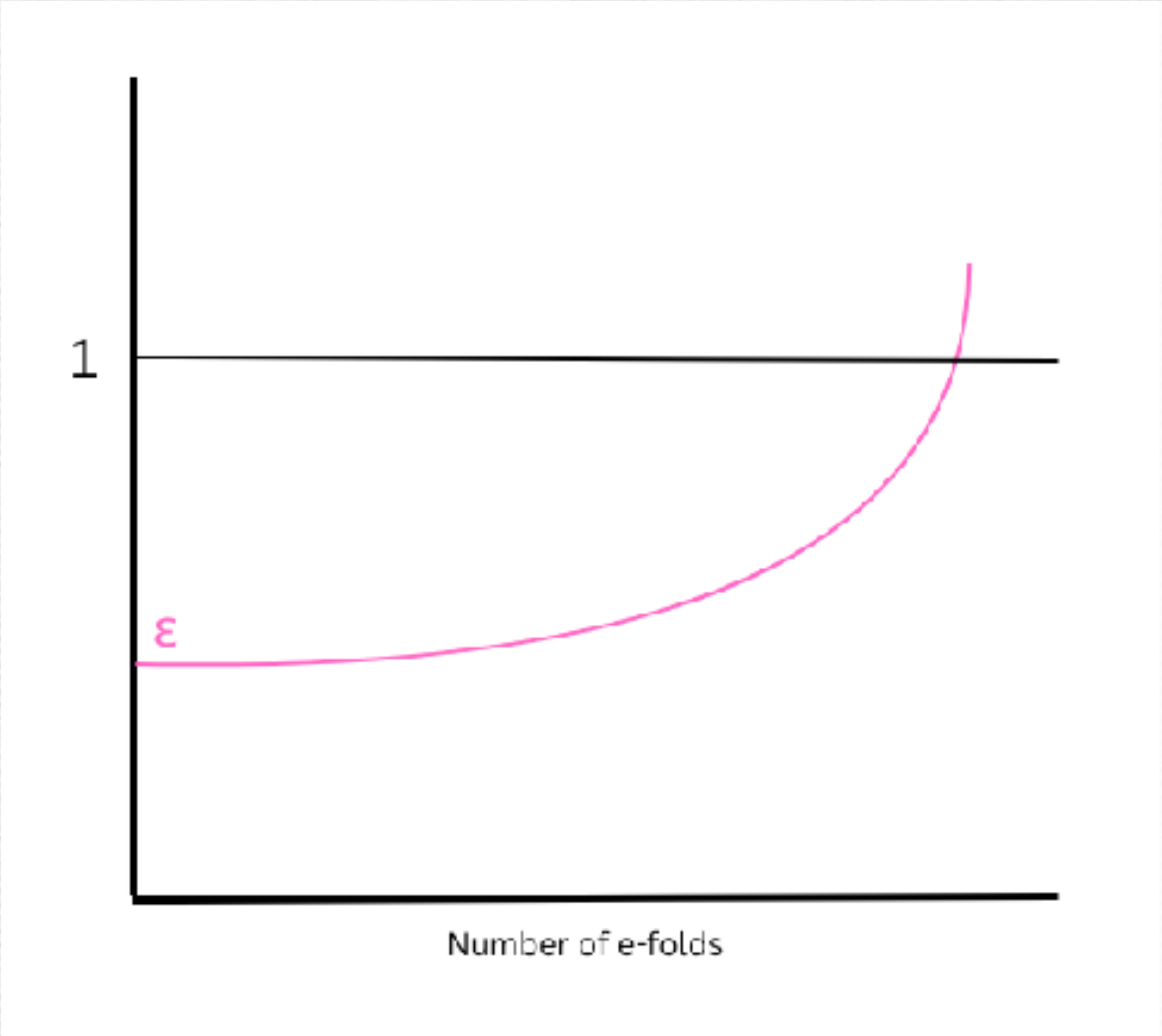

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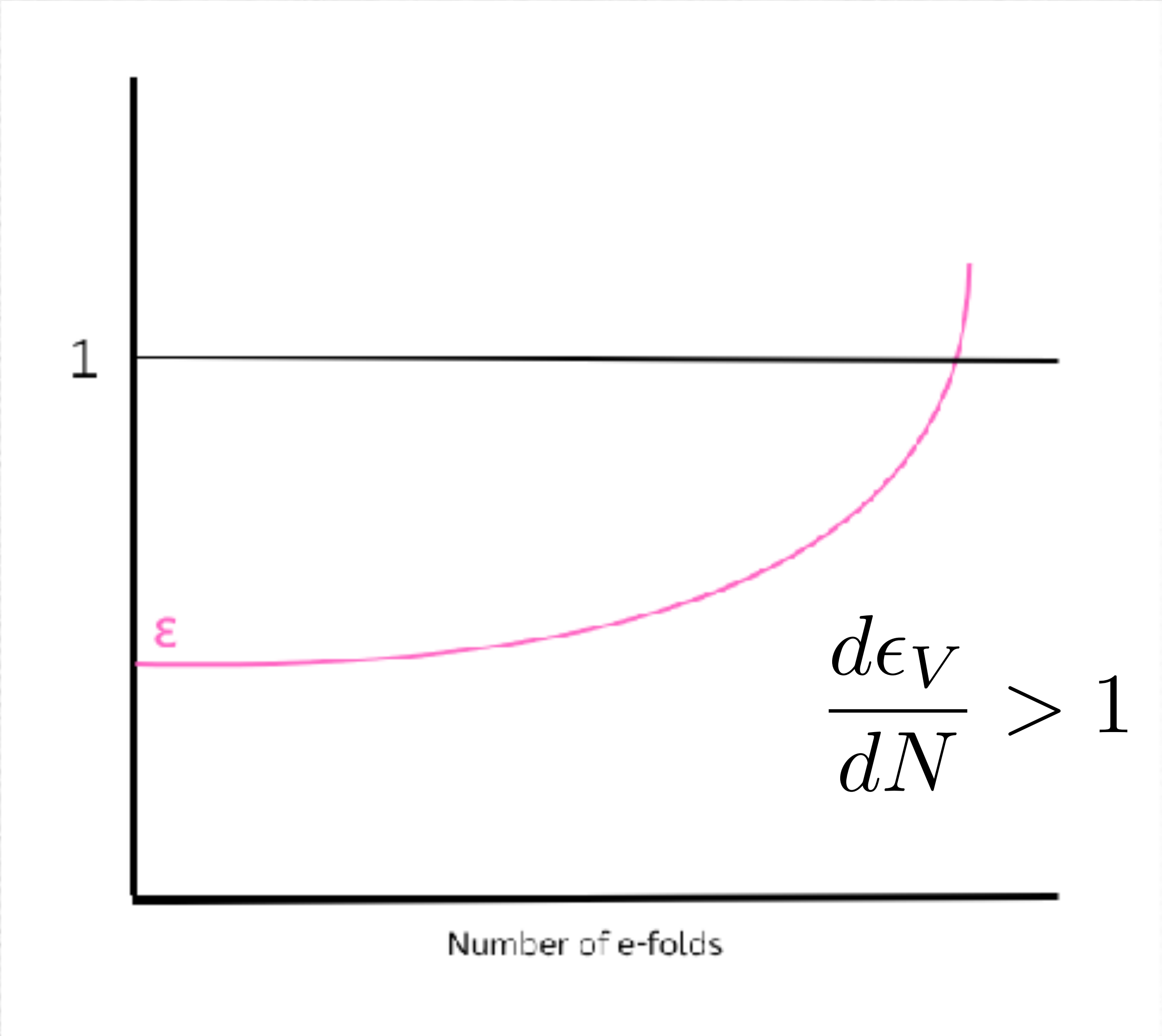

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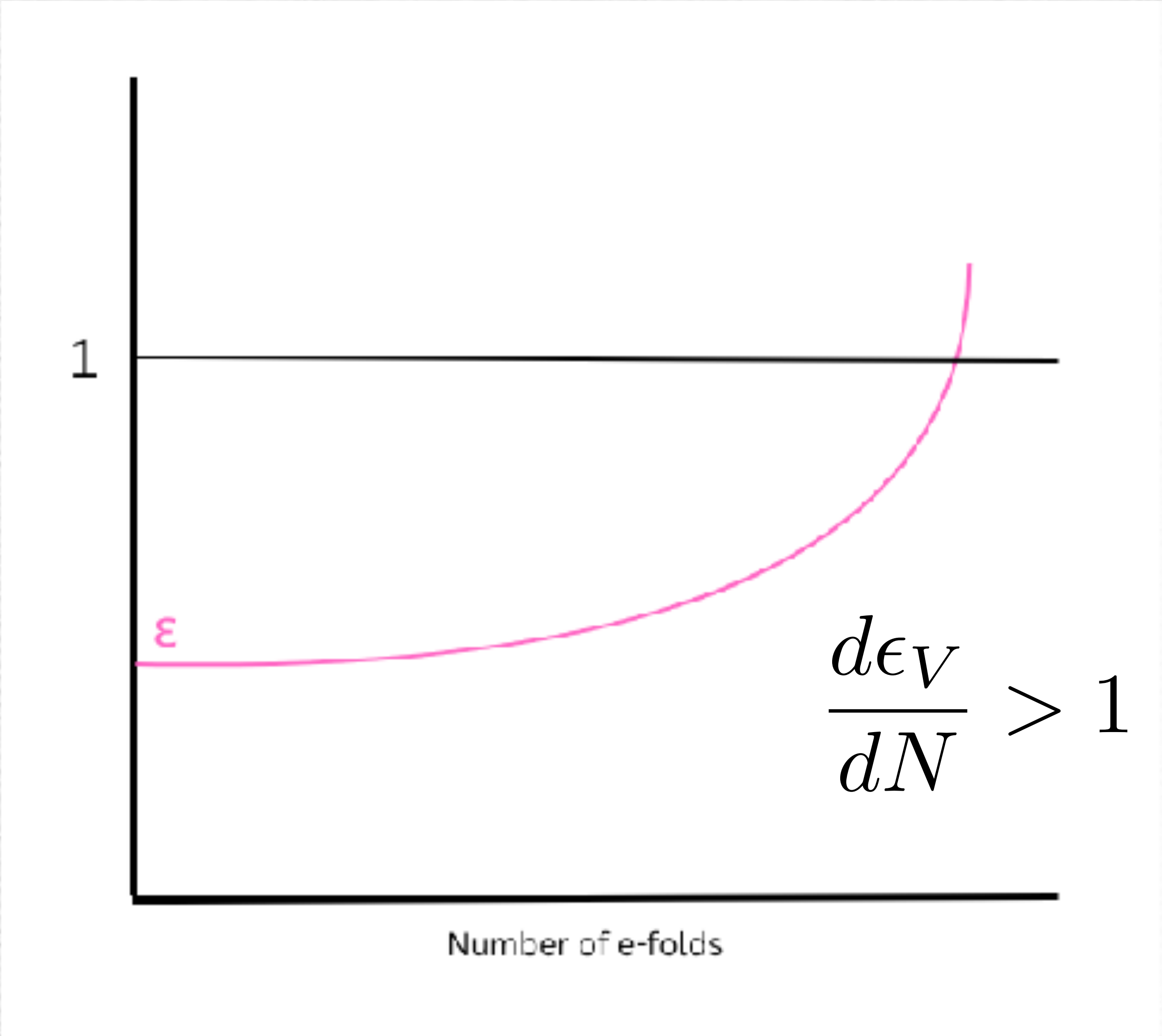
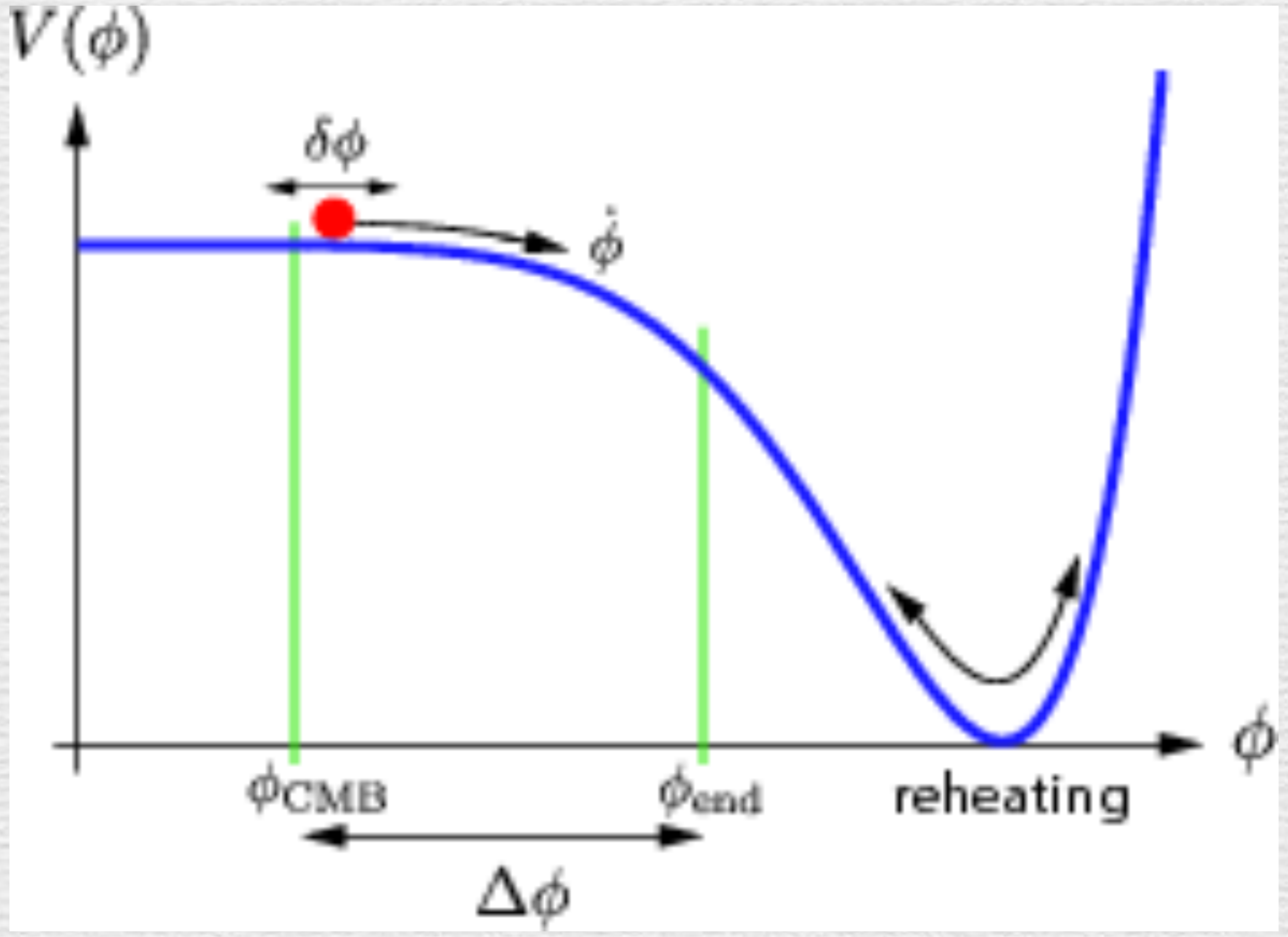




Graceful Exit in Warm Inflation

- The slow-roll EoM of the inflaton field in Warm Inflation

$$3H(1+Q) \approx -V_{,\phi} \qquad || \qquad Q \equiv \frac{\Upsilon}{3H}$$

- Thus inflation happens when $\epsilon_V \ll 1+Q$ and ends when $\epsilon_V \sim 1+Q$
- Graceful exit depends on the evolution of both ε and Q
- Assuming a simple form of the dissipative coefficient $\Upsilon \propto T^p \phi^c$

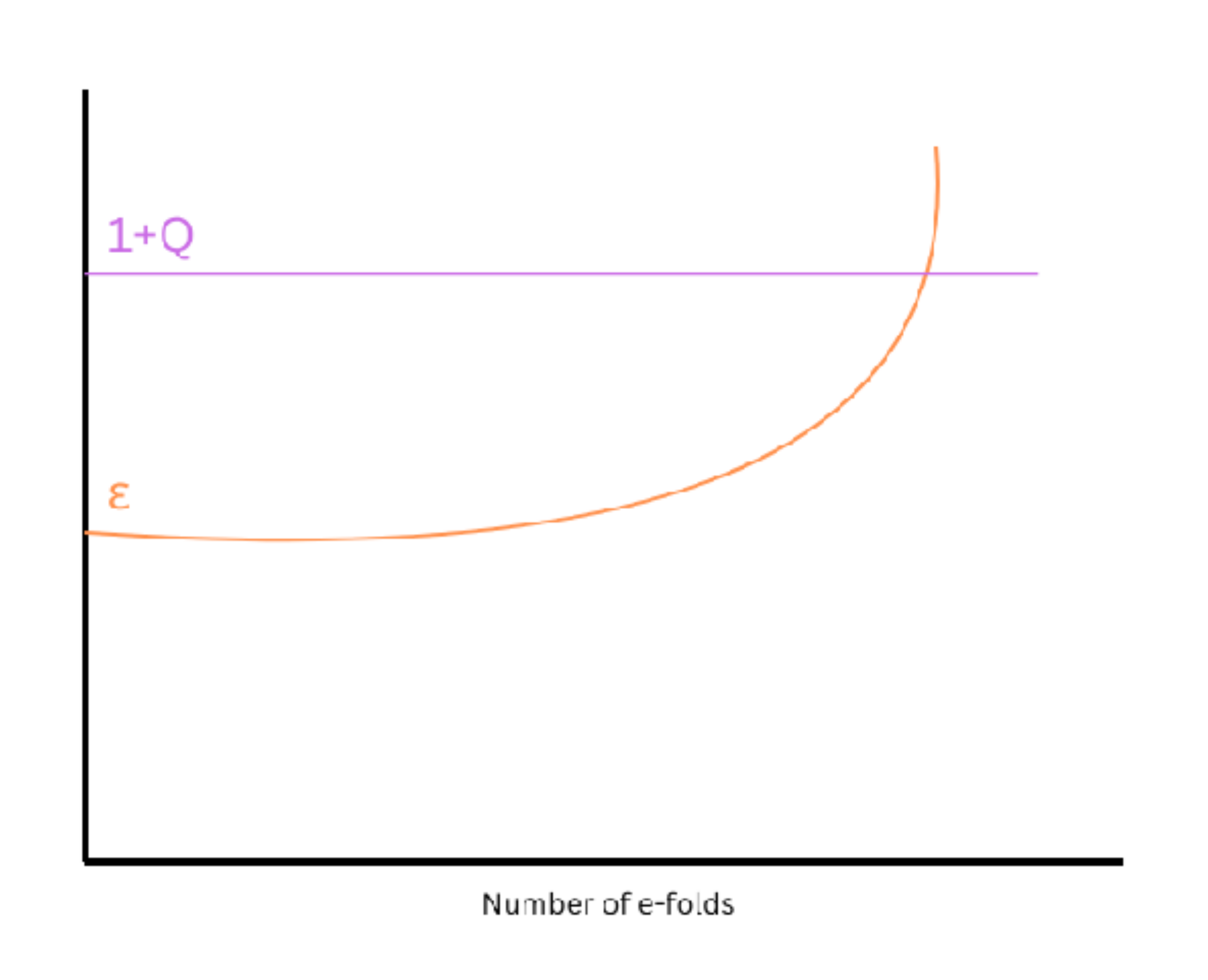
$$\frac{d\ln\epsilon_V}{dN} = \frac{4\epsilon_V - 2\eta_V}{1+Q}, \qquad \frac{d\ln Q}{dN} = \frac{(2p+4)\epsilon_V - 2p\eta_V - 4c\kappa_V}{4-p+(4+p)Q}$$

How many ways Warm Inflation can Gracefully exit?

i.e. meeting the condition $\varepsilon=1+Q$

When ε grows

When ε grows



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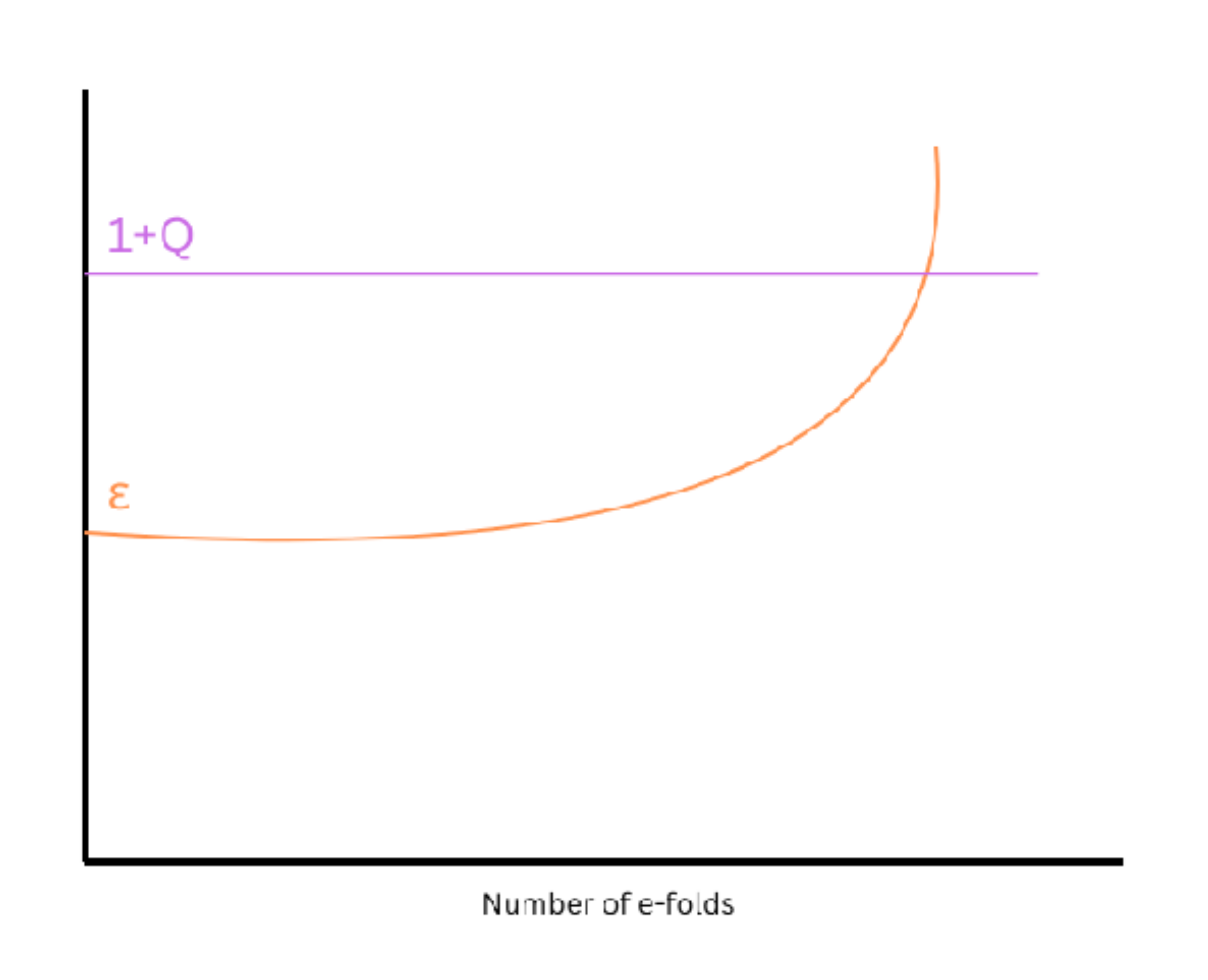

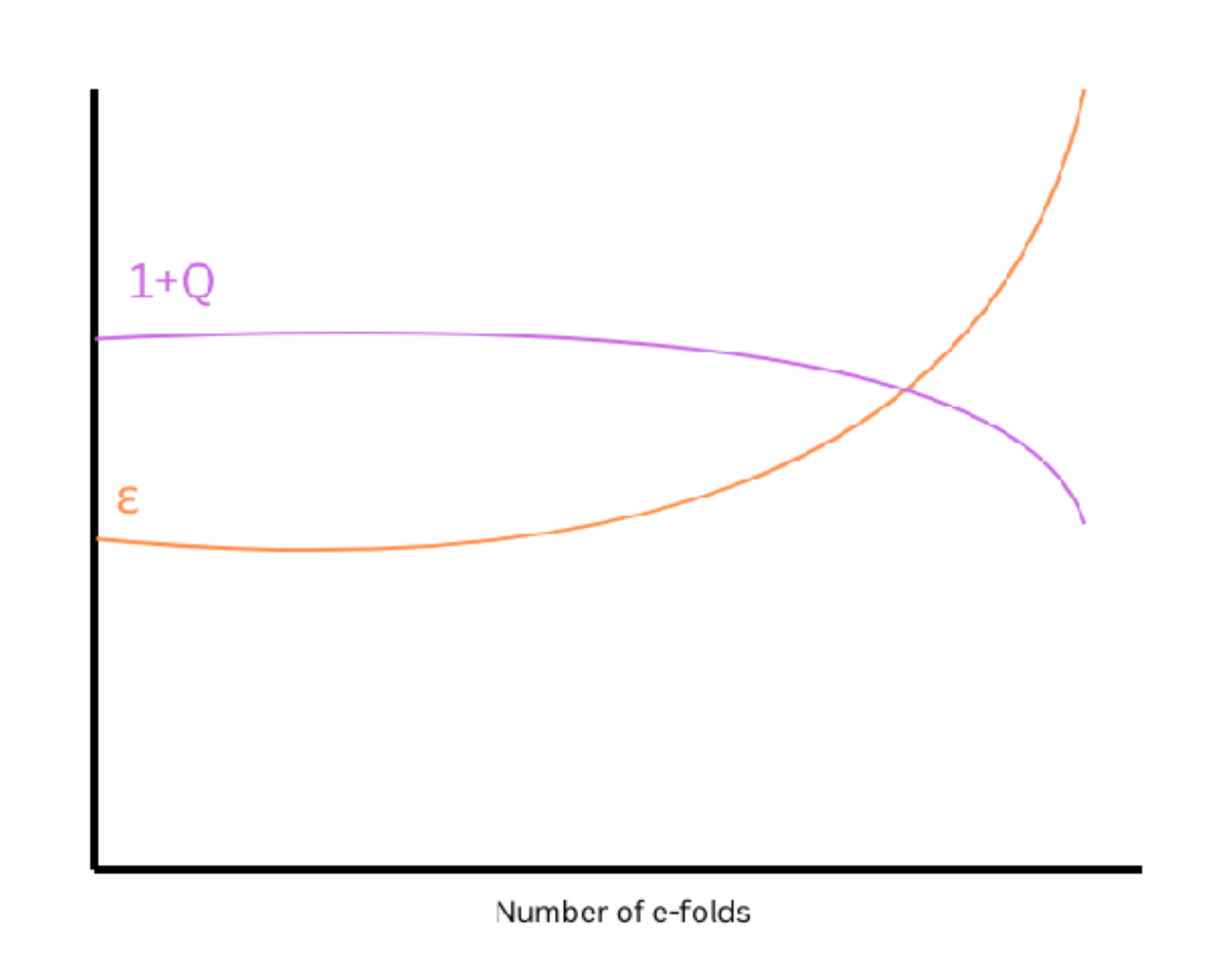

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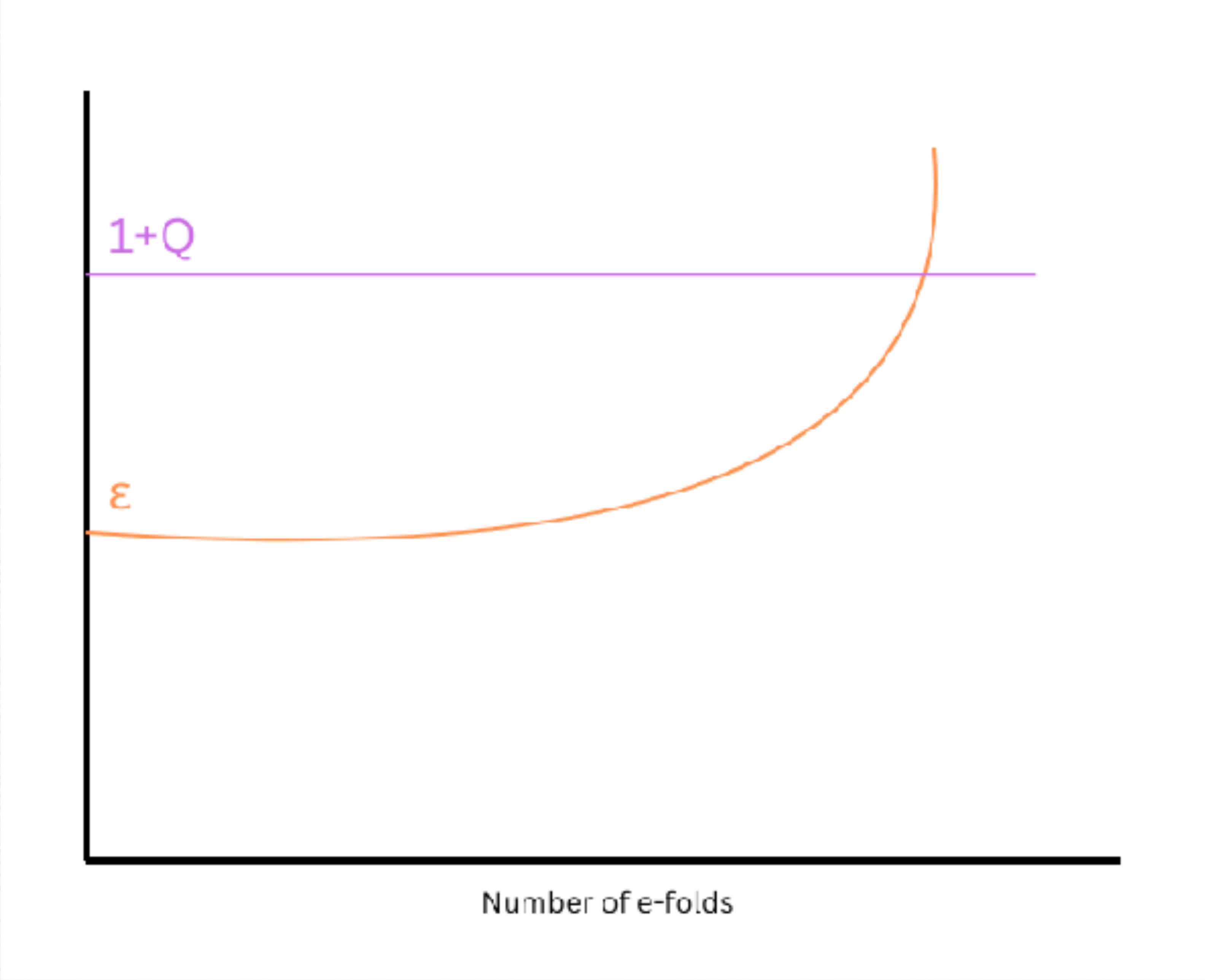
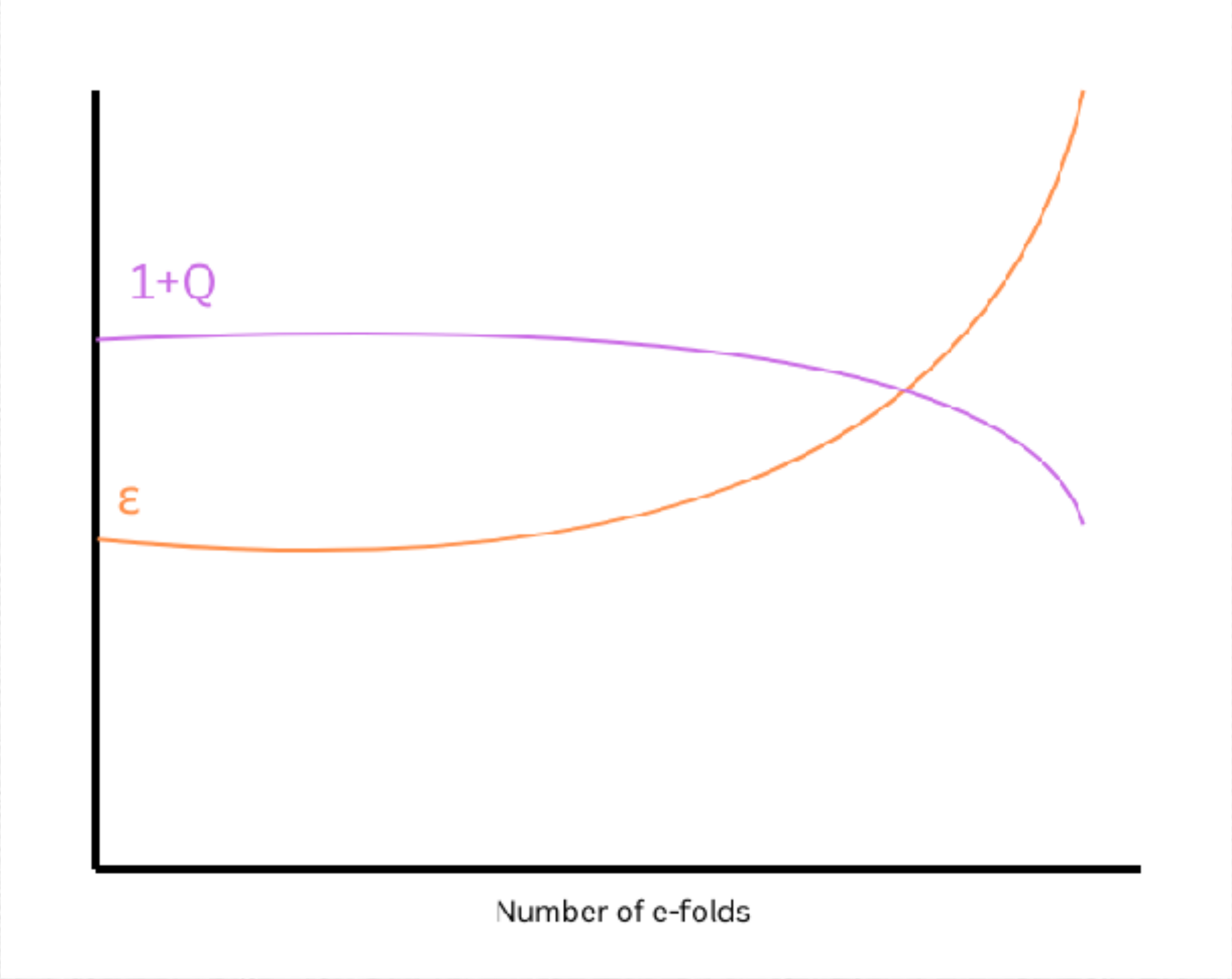


1+Q
ε
Number of e-folds



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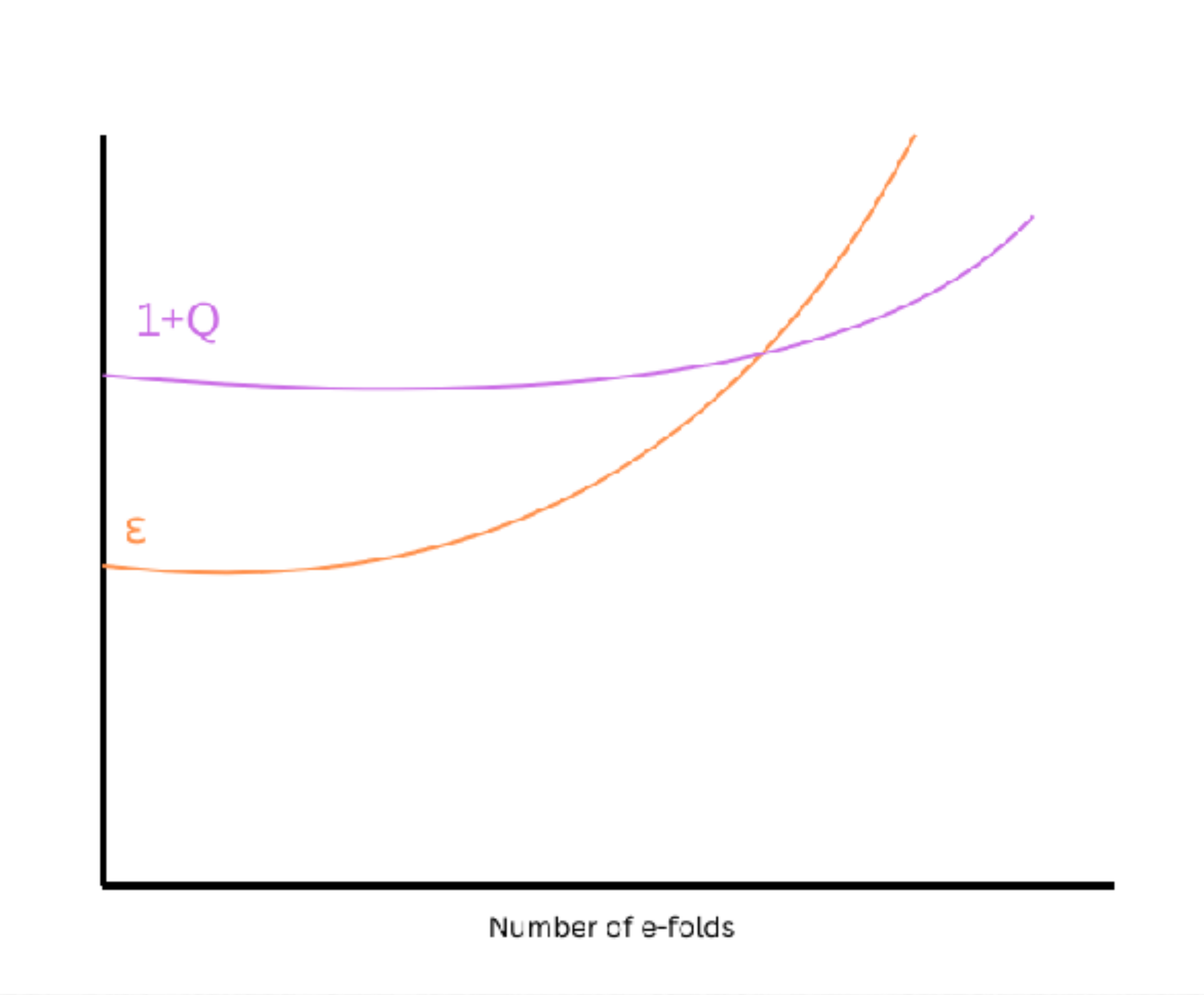

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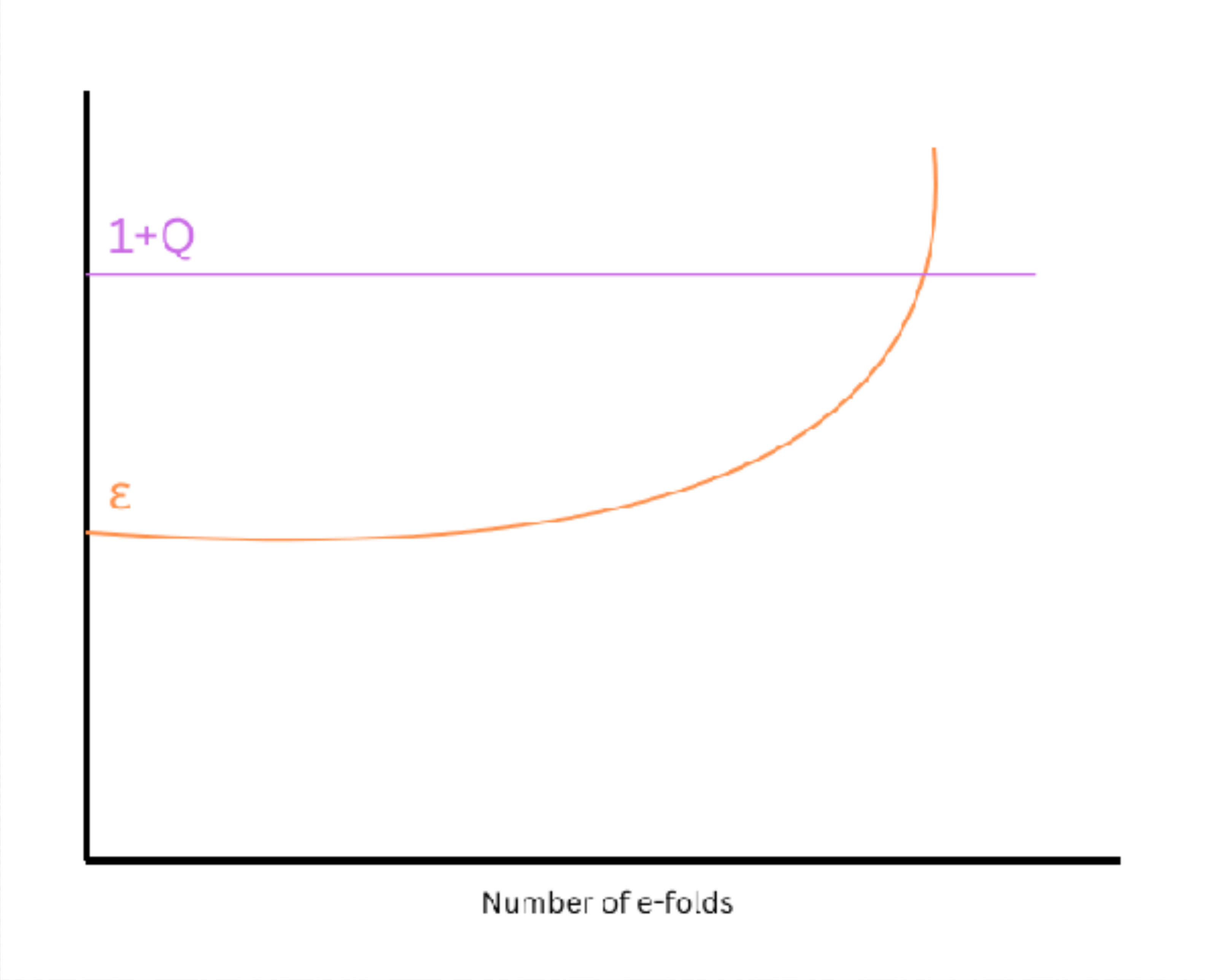

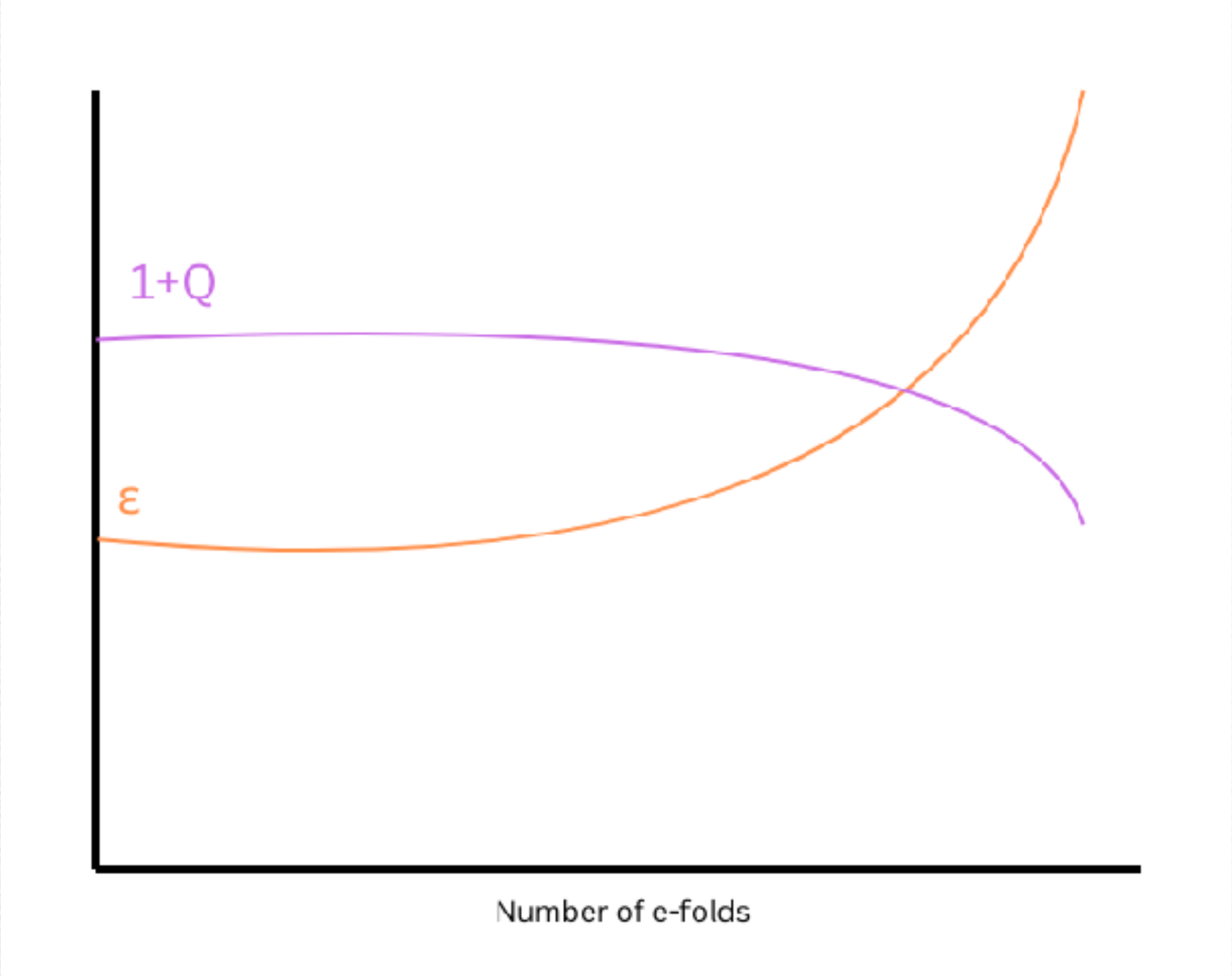

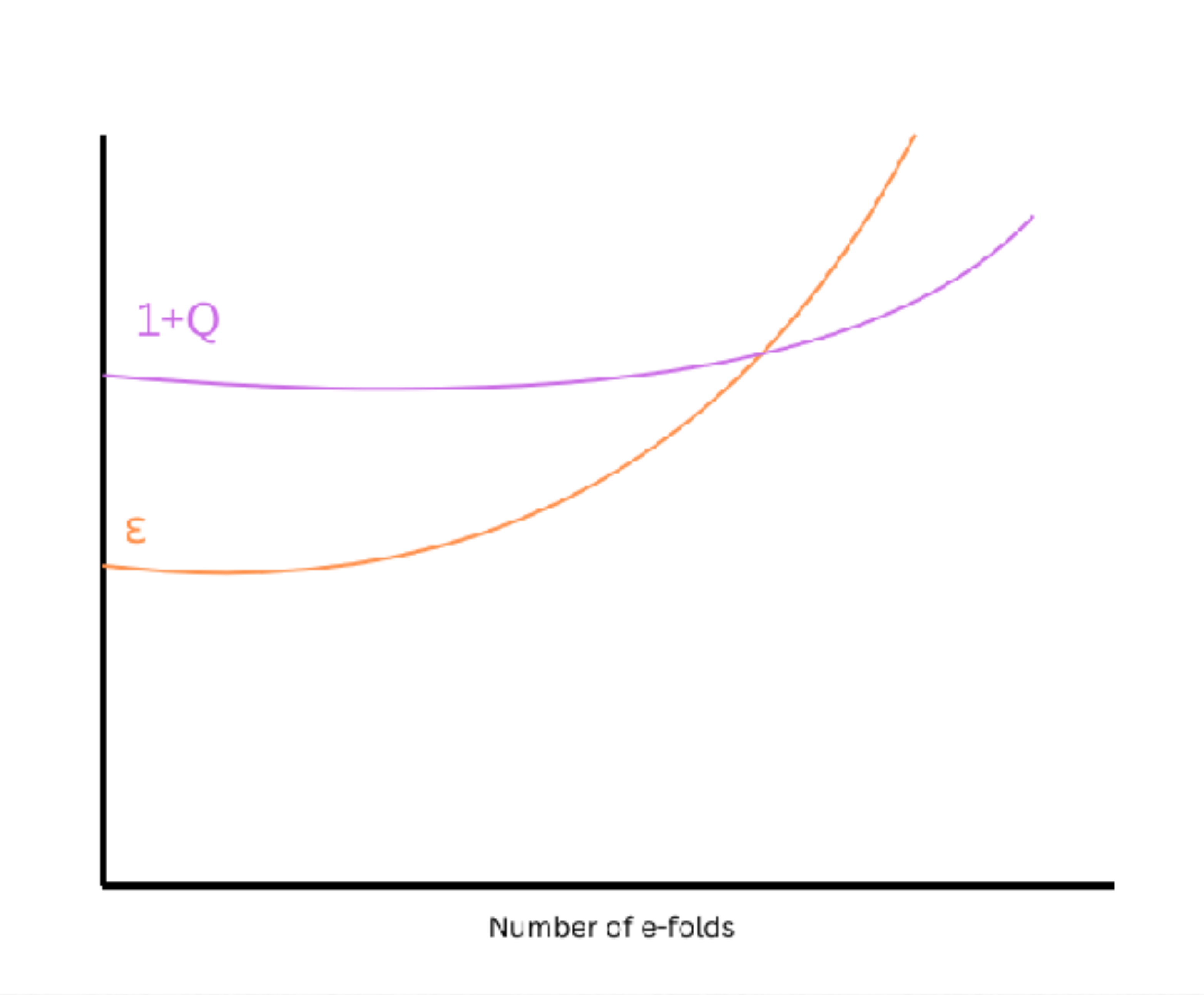

If Q increases faster than ε then there would be no graceful exit!!

When ε remains constant

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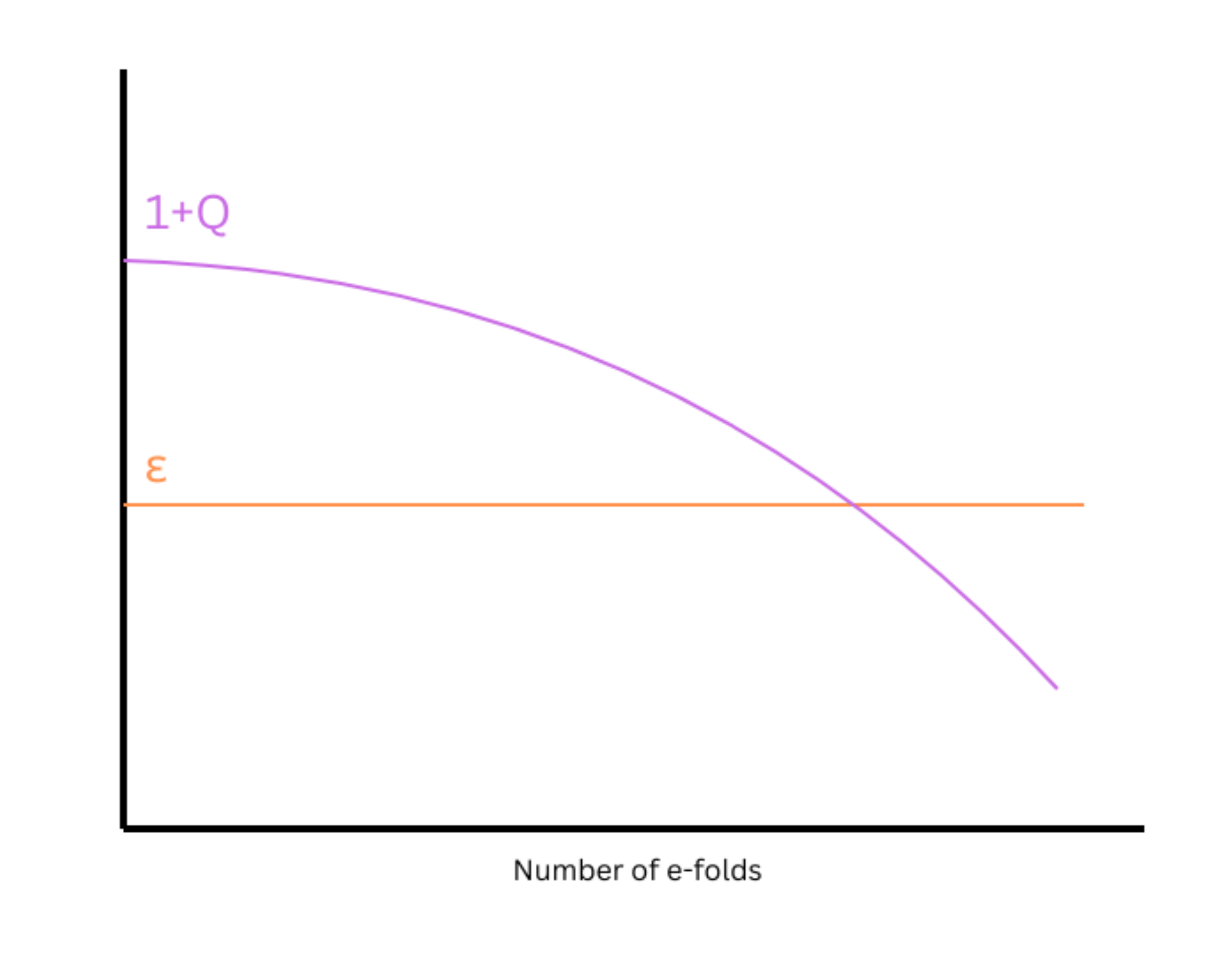

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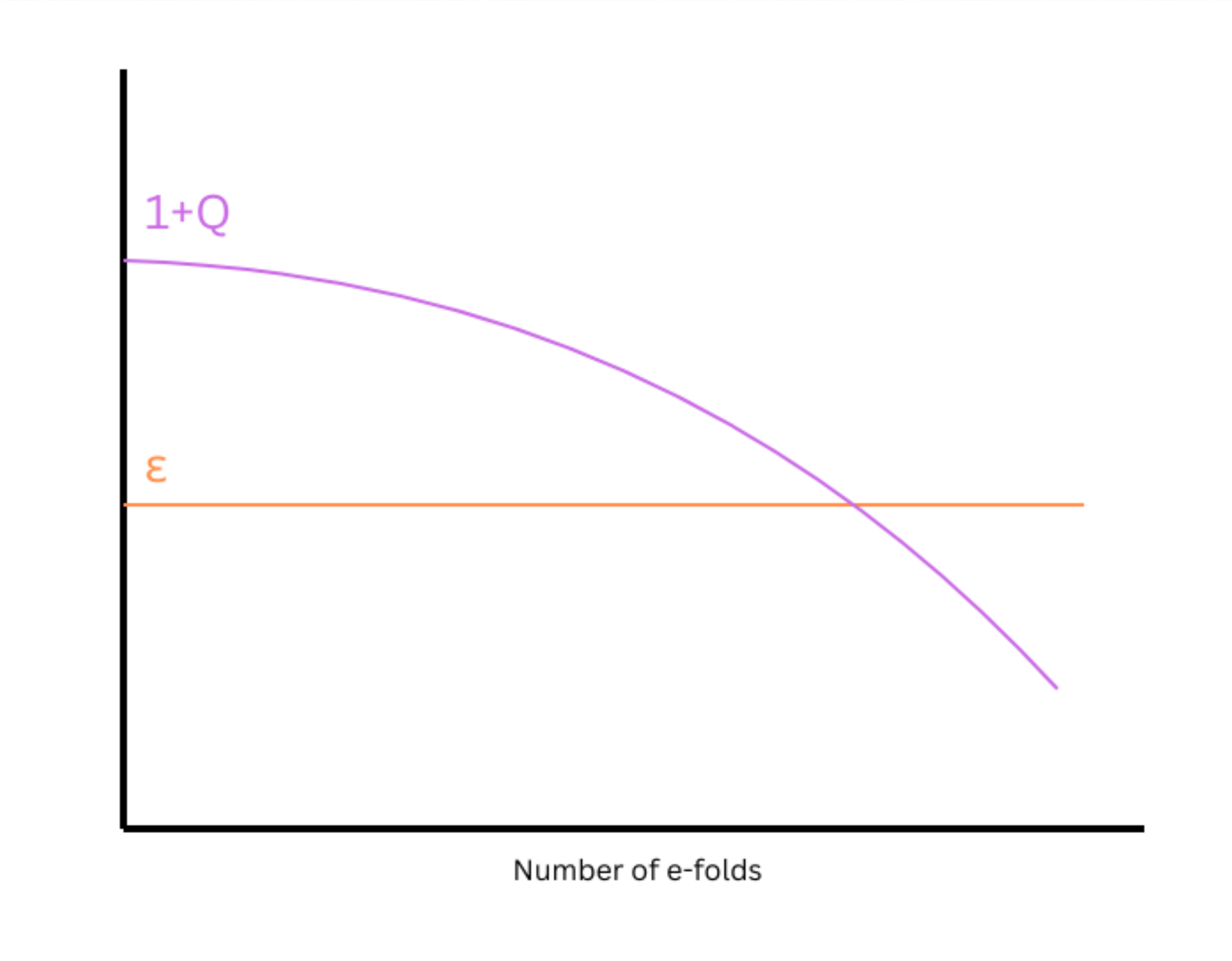
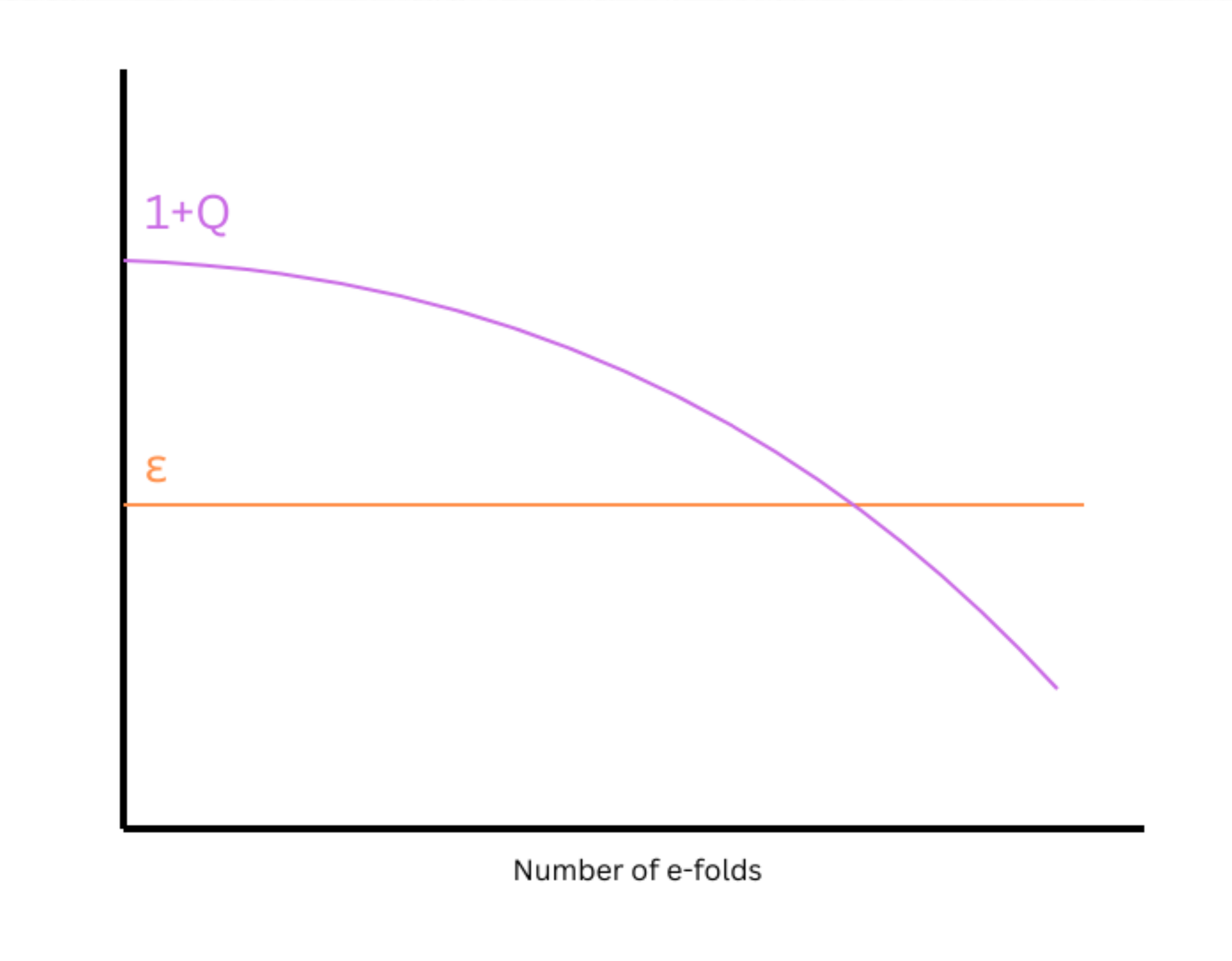


Graceful Exit in Power-law inflation possible in WI !!

When ε remains constant



$$\Upsilon \propto T^3 \quad \text{or} \quad T^3/\phi^2$$

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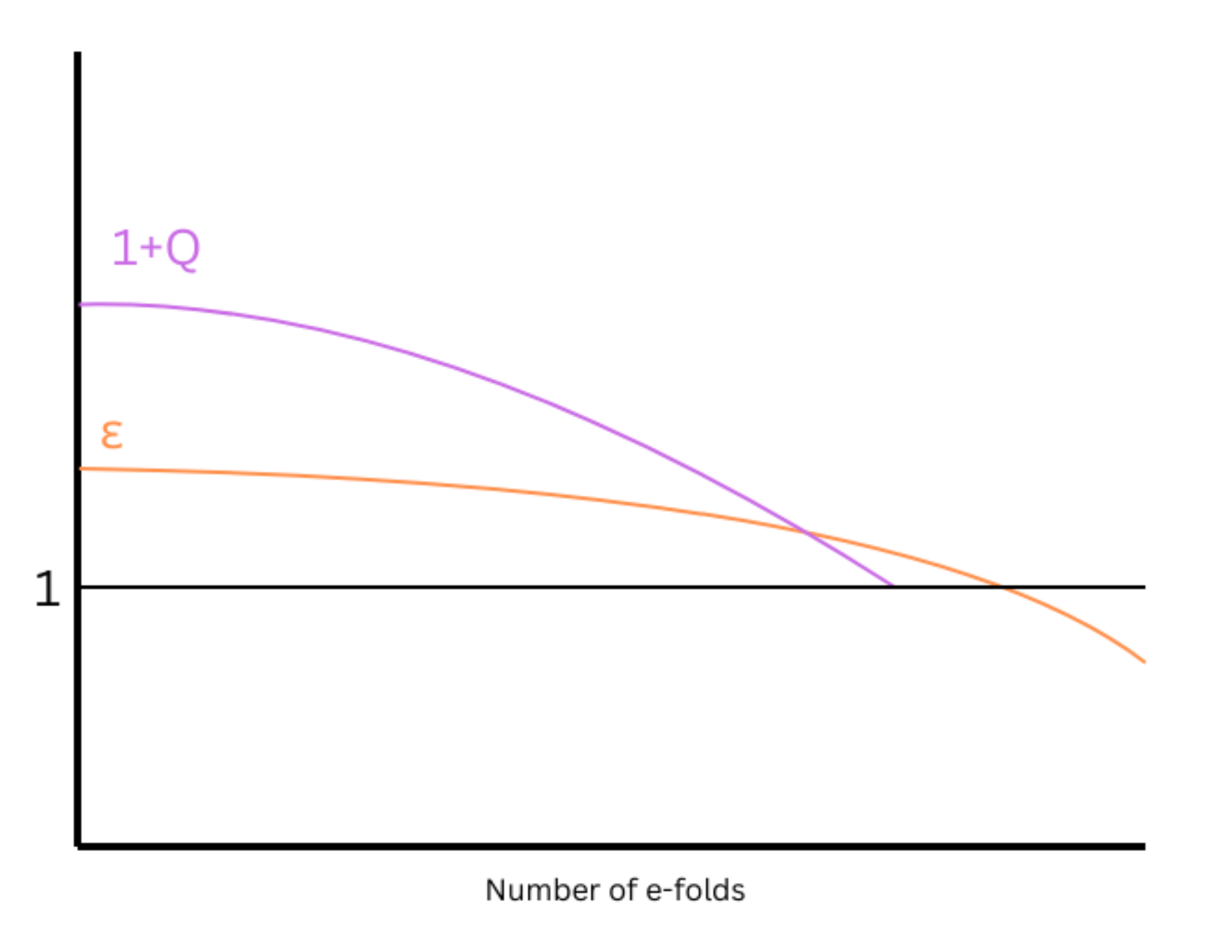
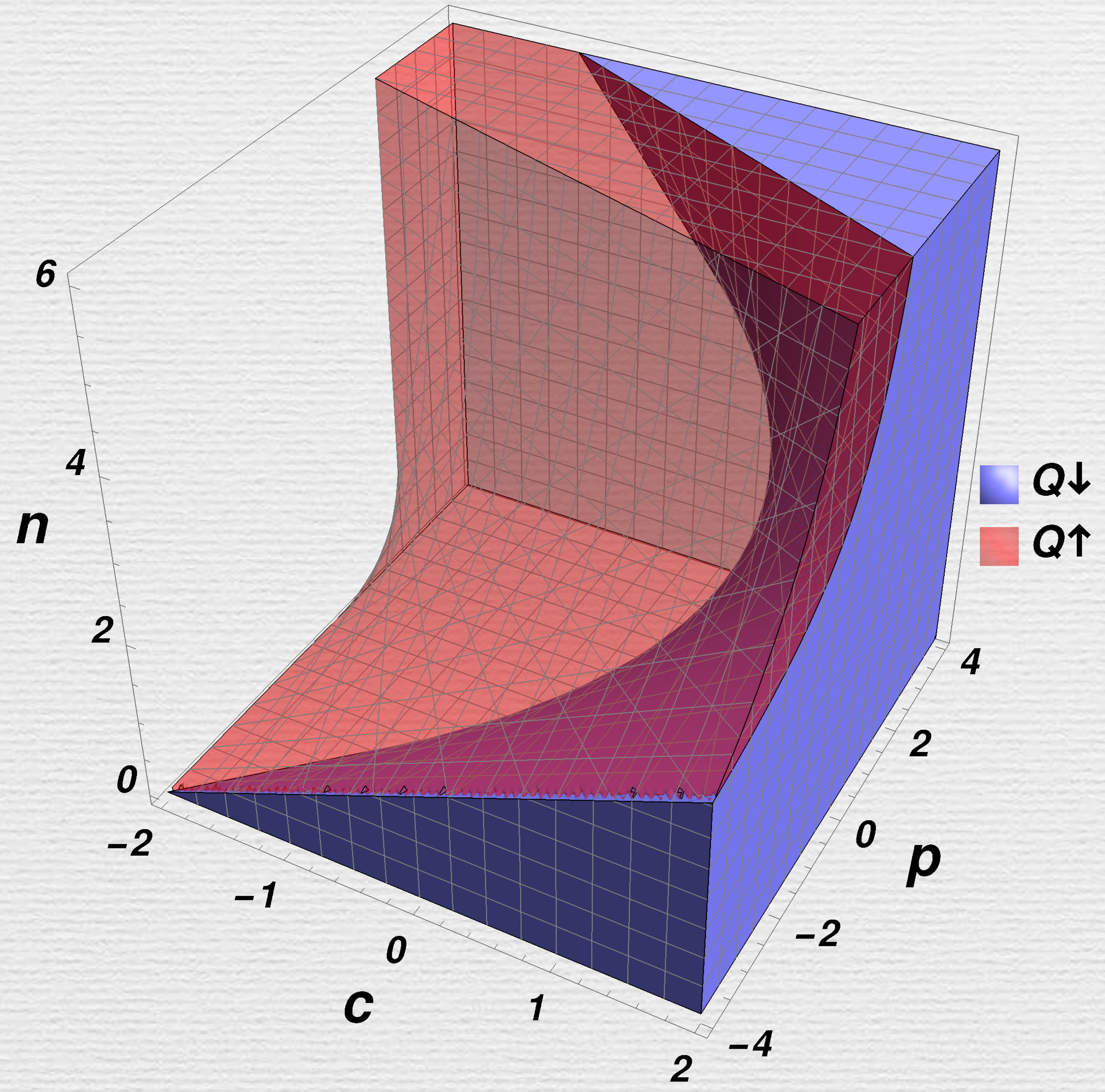
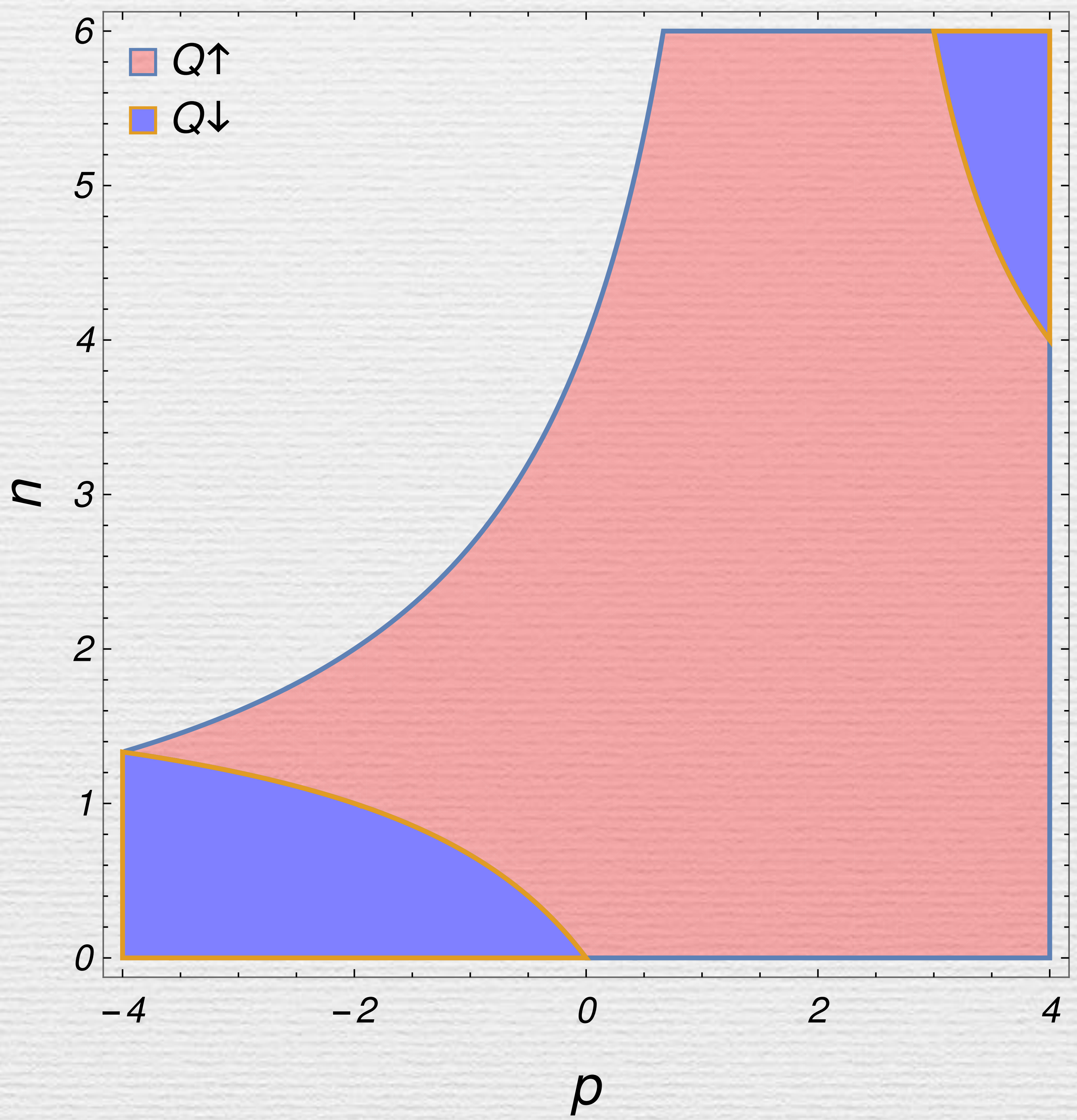


These Graceful Exit conditions put constraint on the combination of the inflaton potential and the form of the dissipative coefficient

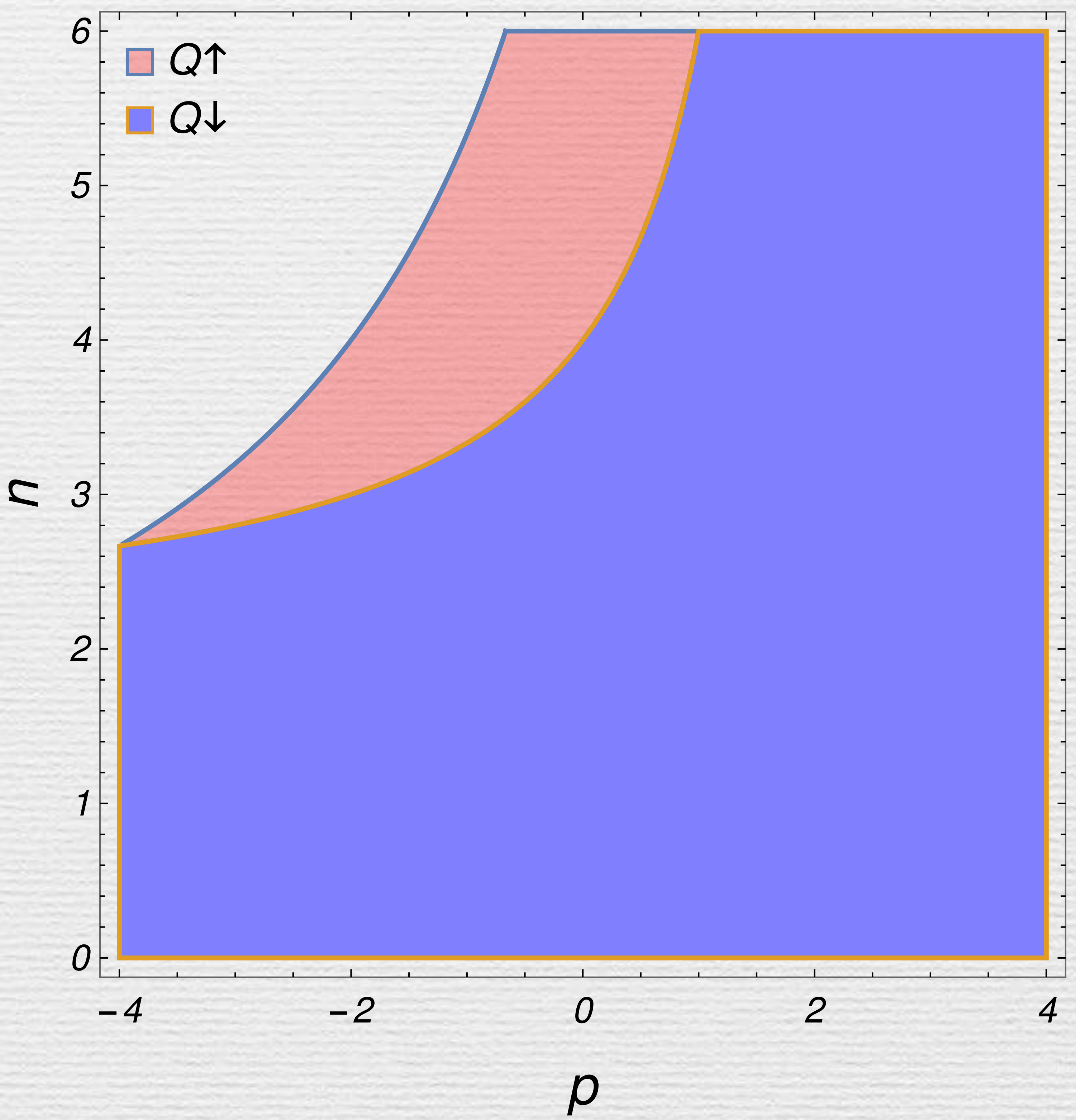
$$V(\phi) = \lambda \phi^n, \qquad \Upsilon \propto T^p \phi^c$$



(a)3d parameter space (c, p, n)



(b)Plane $c = 0$



(c)Plane $c = 2$

Does Warm Inflation always gracefully exits to a radiation dominated Universe?

- The EoMs of Warm Inflation

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = -\Upsilon(T,\phi)\dot{\phi} \qquad \dot{\rho}_R + 4H\rho_R = \Upsilon(T,\phi)\dot{\phi}^2$$

- When a constant radiation bath is maintained

$$\rho_R \approx \frac{3}{2} Q \rho_{\text{K.E.}}$$

- In models where Q decreases, radiation energy density falls below kinetic energy density
- Warm Inflation can gracefully exit in a kination period in those models!
- Such kination period can have potential Gravitational Wave signatures!

- The EoMs of Warm Inflation

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = -\Upsilon(T,\phi)\dot{\phi} \qquad \dot{\rho}_R + 4H\rho_R = \Upsilon(T,\phi)\dot{\phi}^2$$

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Background Analysis of Warm inflation is not a mundane task!

It reveals the nature of the Warm Inflation model

Thank you