Non-linear dynamics of Axion Inflation

Ander Urio (UPV/EHU)

in collaboration with

D. G. Figueroa, J. Lizarraga and J. Urrestilla

From 2303.17436 (Phys.Rev.Lett.) and 24XX.XXXXX

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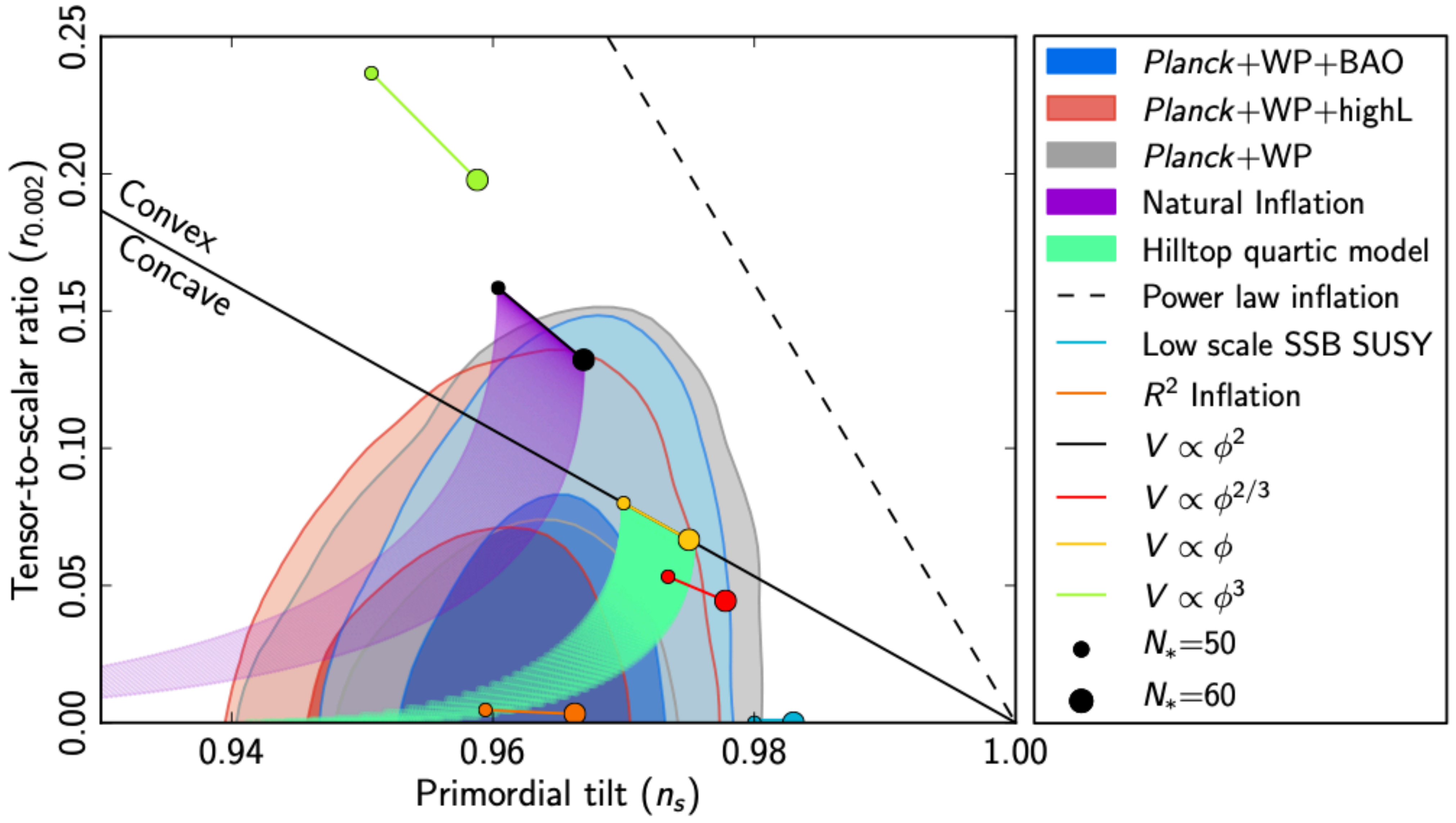

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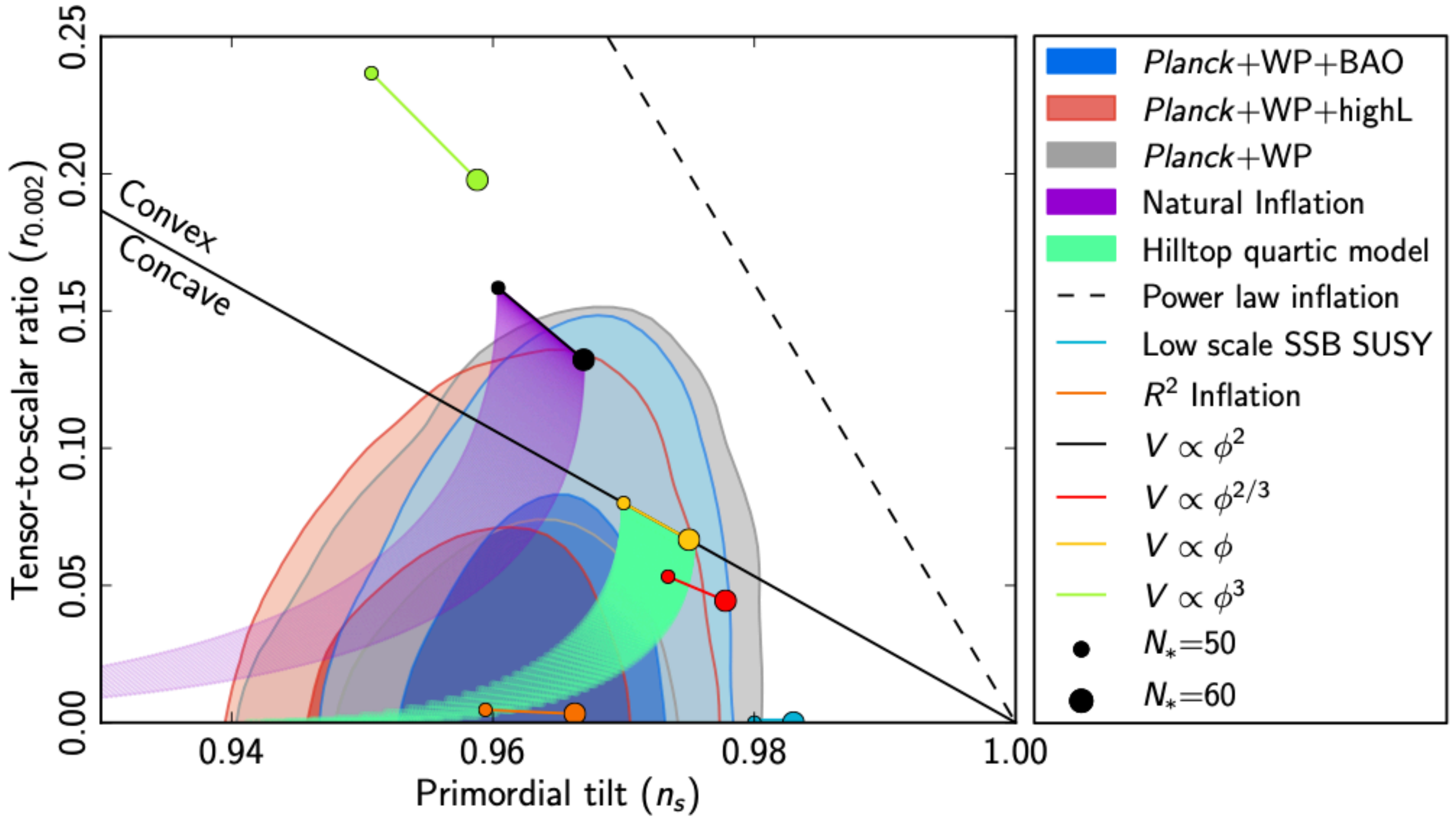

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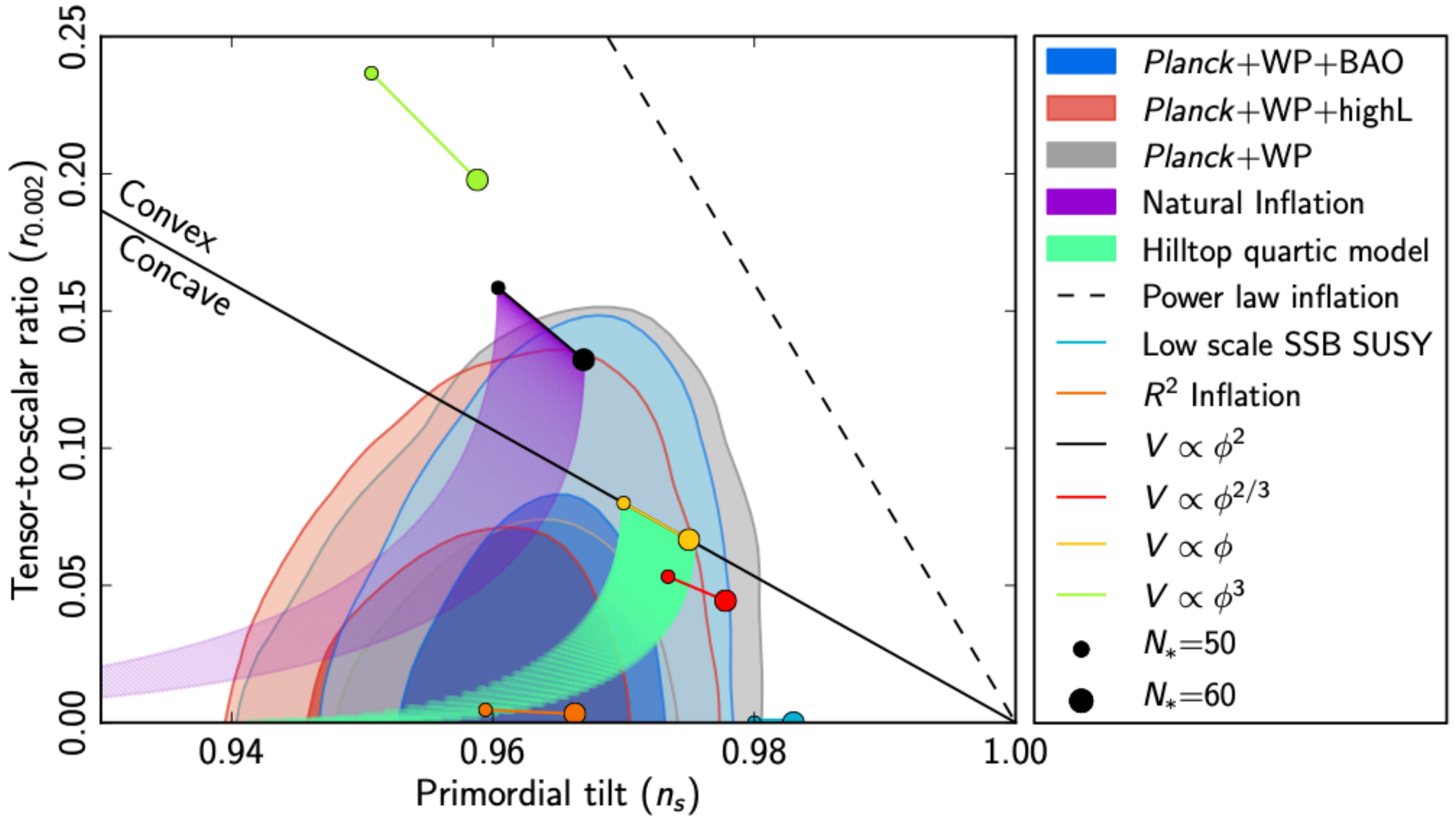

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- **Solution**: shift symmetric particles. Axion like particles (**ALPs**) as the **inflaton**.
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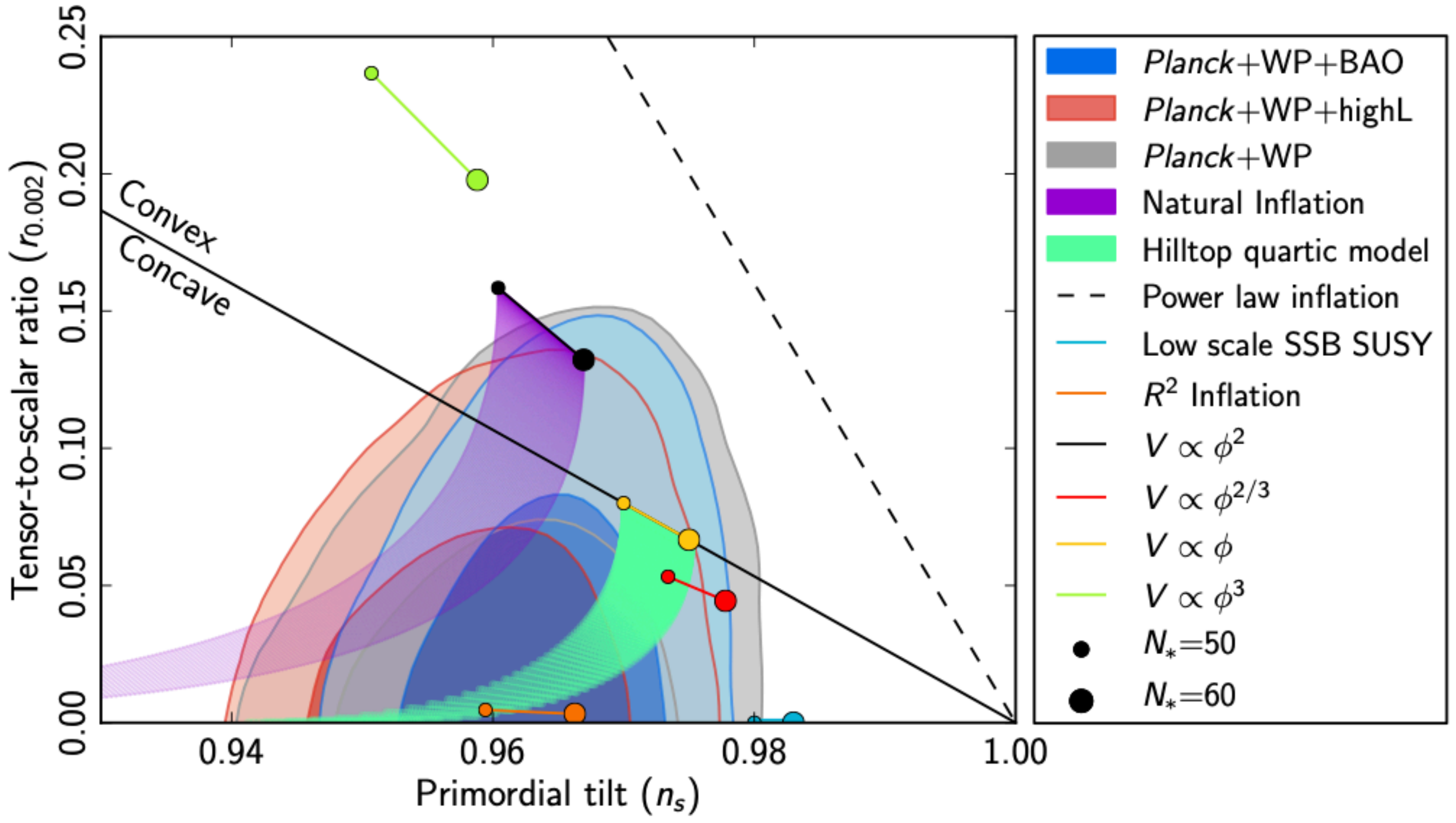
- **Why?** Very **efficient energy transport** between both.
- Leads to interesting **phenomenology**: metric perturbations that produce **PBHs** and **GWs**, for example.



Model

$$S = \int \mathrm{d}x^4 \sqrt{-g} \Big(\frac{1}{2} m_p^2 R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m \phi^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\alpha_\Lambda}{4} \frac{\phi}{m_p} F_{\mu\nu} \tilde{F}^{\mu\nu} \Big)$$

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Gravity

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Gravity: $\frac{1}{2}m_p^2 R$

Matter: $- \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m\phi^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_\Lambda}{4}\frac{\phi}{m_p}F_{\mu\nu}\tilde{F}^{\mu\nu}$

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Axion Like Particle
acting as the
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$$\phi \to \phi + C$$

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Quadratic potential

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U(1) gauge field

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Coupling between both controlled by α_Λ

$$\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}/2$$

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FLRW spacetime

Model

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot{\phi}^2 - \frac{1}{2} a (\vec{\nabla}\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec{E}^2 - a^{-2} \vec{B}^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec{E} \cdot \vec{B} \right)$$

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$$\ddot{\phi} = -3H\dot{\phi} + \frac{1}{a^2} \vec{\nabla}^2 \phi - m^2 \phi$$

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$$\ddot{a} = -\frac{a}{3m_p^2} (2\rho_{\mathrm{K}} - \rho_{\mathrm{V}} + \rho_{\mathrm{EM}})$$

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1st approach: Linear Regime

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Constraints

U(1) Gauge field

$$\vec{\nabla}\cdot\vec{E} = 0 \quad \frac{\alpha_\Lambda}{a m_p}\vec{\nabla}\phi\cdot\vec{B}$$

Friedmann 2

$$H^2 = \frac{1}{3m_p^2}\left(\rho_{\mathrm{K}} + \rho_{\mathrm{G}} + \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

Linear regime

1st approach: Linear Regime

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2}a^3\dot{\phi}^2 - \frac{1}{2}a(\vec{\nabla}\phi)^2 - \frac{1}{2}a^3 m^2\phi^2 + \frac{1}{2}a(\vec{E}^2 - a^{-2}\vec{B}^2) + \frac{\alpha_\Lambda}{m_p}\phi\vec{E}\cdot\vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} + \frac{1}{a^2}\vec{\nabla}^2\phi - m^2\phi + \frac{\alpha_\Lambda}{a^3 m_p}\vec{E}\cdot\vec{B}$$

U(1) Gauge field

$$\dot{\vec{E}} = -H\vec{E} - \frac{1}{a^2}\vec{\nabla}\times\vec{B} - \frac{\alpha_\Lambda}{a m_p}\left(\dot{\phi}\vec{B} - \vec{\nabla}\phi\times\vec{E}\right)$$

Friedmann 1

$$\ddot{a} = -\frac{a}{3m_p^2}\left(2\rho_{\mathrm{K}} - \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

Constraints

U(1) Gauge field

$$\vec{\nabla}\cdot\vec{E} = 0 \quad \frac{\alpha_\Lambda}{a m_p}\vec{\nabla}\phi\cdot\vec{B}$$

Friedmann 2

$$H^2 = \frac{1}{3m_p^2}\left(\rho_{\mathrm{K}} + \rho_{\mathrm{G}} + \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

Linear regime

- Backreactionless inflaton dynamics

1st approach: Linear Regime

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot{\phi}^2 - \frac{1}{2} a (\vec{\nabla}\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec{E}^2 - a^{-2} \vec{B}^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec{E} \cdot \vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} + \frac{1}{a^2}\vec{\nabla}^2\phi - m^2\phi + \frac{\alpha_\Lambda}{a^3 m_p}\vec{E}\cdot\vec{B}$$

U(1) Gauge field

$$\dot{\vec{E}} = -H\vec{E} - \frac{1}{a^2}\vec{\nabla}\times\vec{B} - \frac{\alpha_\Lambda}{a m_p}\left(\dot{\phi}\vec{B} - \vec{\nabla}\phi\times\vec{E}\right)$$

Friedmann 1

$$\ddot{a} = -\frac{a}{3m_p^2}\left(2\rho_{\mathrm{K}} - \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

Constraints

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$$\vec{\nabla}\cdot\vec{E} = 0 \quad \frac{\alpha_\Lambda}{a m_p}\vec{\nabla}\phi\cdot\vec{B}$$

Friedmann 2

$$H^2 = \frac{1}{3m_p^2}\left(\rho_{\mathrm{K}} + \rho_{\mathrm{G}} + \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

Linear regime

- Backreactionless inflaton dynamics
- Inflaton velocity backreacts on the gauge modes

1st approach: Linear Regime

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot{\phi}^2 - \frac{1}{2} a (\vec{\nabla}\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec{E}^2 - a^{-2} \vec{B}^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec{E} \cdot \vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} - m^2 \phi$$

U(1) Gauge field

$$\left(\partial_\tau^2 + k^2 \mp 2k\xi/\tau\right) A^\pm(\tau, k) = 0 \quad \text{with} \quad \xi = \frac{\alpha_\Lambda \dot{\phi}}{2Hm_p}$$

Friedmann 1

$$\ddot{a} = -\frac{a}{3m_p^2}\left(2\rho_\mathrm{K} - \rho_\mathrm{V} + \rho_\mathrm{EM}\right)$$

Constraints

U(1) Gauge field

$$\vec{\nabla} \cdot \vec{E} = 0$$

Friedmann 2

$$H^2 = \frac{1}{3m_p^2}\left(\rho_\mathrm{K} + \rho_\mathrm{G} + \rho_\mathrm{V} + \rho_\mathrm{EM}\right)$$

Linear regime

- Backreactionless inflaton dynamics
- Inflaton velocity backreacts on the gauge modes

1st approach: Linear Regime

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot{\phi}^2 - \frac{1}{2} a (\vec{\nabla}\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec{E}^2 - a^{-2} \vec{B}^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec{E} \cdot \vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} - m^2\phi$$

U(1) Gauge field

$$\left(\partial_\tau^2 + k^2 \mp 2k\xi/\tau\right) A^\pm(\tau, k) = 0 \quad \text{with} \quad \xi = \frac{\alpha_\Lambda \dot{\phi}}{2 H m_p}$$

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U(1) Gauge field

$$\vec{\nabla} \cdot \vec{E} = 0$$

Friedmann 2

$$H^2 = \frac{1}{3m_p^2}\left(\rho_\mathrm{K} + \rho_\mathrm{G} + \rho_\mathrm{V} + \rho_\mathrm{EM}\right)$$

Linear regime

- Backreactionless inflaton dynamics
- Inflaton velocity backreacts on the gauge modes
- Tachyonic growth of the positive helicity

2nd approach: Homo backreaction

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot{\phi}^2 - \frac{1}{2} a (\vec{\nabla}\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec{E}^2 - a^{-2} \vec{B}^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec{E} \cdot \vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} + \frac{1}{a^2}\vec{\nabla}^2\phi - m^2\phi + \frac{\alpha_\Lambda}{a^3 m_p}\vec{E}\cdot\vec{B}$$

U(1) Gauge field

$$\dot{\vec{E}} = -H\vec{E} - \frac{1}{a^2}\vec{\nabla}\times\vec{B} - \frac{\alpha_\Lambda}{a m_p}\left(\dot{\phi}\vec{B} - \vec{\nabla}\phi\times\vec{E}\right)$$

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$$H^2 = \frac{1}{3m_p^2}\left(\rho_\mathrm{K} + \rho_\mathrm{G} + \rho_\mathrm{V} + \rho_\mathrm{EM}\right)$$

2nd approach: Homo backreaction

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot\phi^2 - \frac{1}{2} a (\vec\nabla\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec E^2 - a^{-2} \vec B^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec E \cdot \vec B \right)$$

Dynamics

ALP inflaton

$$\ddot\phi = -3H\dot\phi - m^2\phi + \frac{\alpha_\Lambda}{a^3 m_p} \vec E \cdot \vec B$$

U(1) Gauge field

$$\dot{\vec E} = -H\vec E - \frac{1}{a^2} \vec\nabla \times \vec B - \frac{\alpha_\Lambda}{a m_p} \left(\dot\phi \vec B \right)$$

Friedmann 1

$$\ddot a = -\frac{a}{3m_p^2} \left(2\rho_\mathrm{K} - \rho_\mathrm{V} + \rho_\mathrm{EM} \right)$$

Constraints

U(1) Gauge field

$$\vec\nabla \cdot \vec E = 0$$

Friedmann 2

$$H^2 = \frac{1}{3m_p^2} \left(\rho_\mathrm{K} + \rho_\mathrm{G} + \rho_\mathrm{V} + \rho_\mathrm{EM} \right)$$

2nd approach: Homo backreaction

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2}a^3\dot{\phi}^2 - \frac{1}{2}a(\vec{\nabla}\phi)^2 - \frac{1}{2}a^3 m^2\phi^2 + \frac{1}{2}a(\vec{E}^2 - a^{-2}\vec{B}^2) + \frac{\alpha_\Lambda}{m_p}\phi\vec{E}\cdot\vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} + \frac{1}{a^2}\vec{\nabla}^2\phi - m^2\phi + \frac{\alpha_\Lambda}{a^3 m_p}\langle\vec{E}\cdot\vec{B}\rangle$$

U(1) Gauge field

$$\dot{\vec{E}} = -H\vec{E} - \frac{1}{a^2}\vec{\nabla}\times\vec{B} - \frac{\alpha_\Lambda}{a m_p}\left(\dot{\phi}\vec{B} - \vec{\nabla}\phi\times\vec{E}\right)$$

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$$\ddot{a} = -\frac{a}{3m_p^2}\left(2\rho_{\mathrm{K}} - \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

Constraints

U(1) Gauge field

$$\vec{\nabla}\cdot\vec{E} = 0 \quad \frac{\alpha_\Lambda}{a m_p}\vec{\nabla}\phi\cdot\vec{B}$$

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$$H^2 = \frac{1}{3m_p^2}\left(\rho_{\mathrm{K}} + \rho_{\mathrm{G}} + \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

2nd approach: Homo backreaction

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2}a^3\dot{\phi}^2 - \frac{1}{2}a(\vec{\nabla}\phi)^2 - \frac{1}{2}a^3 m^2\phi^2 + \frac{1}{2}a(\vec{E}^2 - a^{-2}\vec{B}^2) + \frac{\alpha_\Lambda}{m_p}\phi\vec{E}\cdot\vec{B} \right)$$

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$$\ddot{\phi} = -3H\dot{\phi} - m^2\phi + \frac{\alpha_\Lambda}{a^3 m_p}\langle\vec{E}\cdot\vec{B}\rangle$$

U(1) Gauge field
$$\dot{\vec{E}} = -H\vec{E} - \frac{1}{a^2}\vec{\nabla}\times\vec{B} - \frac{\alpha_\Lambda}{a m_p}\left(\dot{\phi}\vec{B}\right)$$

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$$\ddot{a} = -\frac{a}{3m_p^2}\left(2\rho_{\mathrm{K}} - \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

Constraints

U(1) Gauge field
$$\vec{\nabla}\cdot\vec{E} = 0$$

Friedmann 2
$$H^2 = \frac{1}{3m_p^2}\left(\rho_{\mathrm{K}} + \rho_{\mathrm{G}} + \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

Homogeneous backreaction

- Homogenous backreaction in the inflaton dynamics: lengthening of inflation

2nd approach: Homo backreaction

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot{\phi}^2 - \frac{1}{2} a (\vec{\nabla}\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec{E}^2 - a^{-2} \vec{B}^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec{E} \cdot \vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} - m^2 \phi + \frac{\alpha_\Lambda}{a^3 m_p} \langle \vec{E} \cdot \vec{B} \rangle$$

U(1) Gauge field

$$\dot{\vec{E}} = -H\vec{E} - \frac{1}{a^2} \vec{\nabla} \times \vec{B} - \frac{\alpha_\Lambda}{a m_p} \left(\dot{\phi} \vec{B} \right)$$

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$$\ddot{a} = -\frac{a}{3 m_p^2} \left(2\rho_{\mathrm{K}} - \rho_{\mathrm{V}} + \rho_{\mathrm{EM}} \right)$$

Constraints

U(1) Gauge field

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Homogeneous backreaction

- Homogenous backreaction in the inflaton dynamics: lengthening of inflation
- Oscillatory inflaton velocity

2nd approach: Homo backreaction

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2}a^3\dot{\phi}^2 - \frac{1}{2}a(\vec{\nabla}\phi)^2 - \frac{1}{2}a^3 m^2\phi^2 + \frac{1}{2}a(\vec{E}^2 - a^{-2}\vec{B}^2) + \frac{\alpha_\Lambda}{m_p}\phi\vec{E}\cdot\vec{B} \right)$$

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ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} - m^2\phi + \frac{\alpha_\Lambda}{a^3 m_p}\langle \vec{E}\cdot\vec{B}\rangle$$

U(1) Gauge field

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$$\vec{\nabla}\cdot\vec{E} = 0$$

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Homogeneous backreaction

- Homogenous backreaction in the inflaton dynamics: lengthening of inflation
- Oscillatory inflaton velocity
- Still tachyonic growth of the positive helicity

Our approach: Full backreaction

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot{\phi}^2 - \frac{1}{2} a (\vec{\nabla}\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec{E}^2 - a^{-2} \vec{B}^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec{E} \cdot \vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} + \frac{1}{a^2} \vec{\nabla}^2 \phi - m^2 \phi + \frac{\alpha_\Lambda}{a^3 m_p} \vec{E} \cdot \vec{B}$$

U(1) Gauge field

$$\dot{\vec{E}} = -H\vec{E} - \frac{1}{a^2} \vec{\nabla} \times \vec{B} - \frac{\alpha_\Lambda}{a m_p} \left(\dot{\phi} \vec{B} - \vec{\nabla}\phi \times \vec{E} \right)$$

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$$\ddot{a} = -\frac{a}{3m_p^2} \left(2\rho_{\mathrm{K}} - \rho_{\mathrm{V}} + \rho_{\mathrm{EM}} \right)$$

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Our approach: Full backreaction

Backreaction

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$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot{\phi}^2 - \frac{1}{2} a (\vec{\nabla}\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec{E}^2 - a^{-2} \vec{B}^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec{E} \cdot \vec{B} \right)$$

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ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} + \tfrac{1}{a^2}\vec{\nabla}^2\phi - m^2\phi + \tfrac{\alpha_\Lambda}{a^3 m_p}\vec{E}\cdot\vec{B}$$

U(1) Gauge field

$$\dot{\vec{E}} = -H\vec{E} - \tfrac{1}{a^2}\vec{\nabla}\times\vec{B} - \tfrac{\alpha_\Lambda}{a m_p}\left(\dot{\phi}\vec{B} - \vec{\nabla}\phi\times\vec{E}\right)$$

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$$\vec{\nabla}\cdot\vec{E} = -\tfrac{\alpha_\Lambda}{a m_p}\vec{\nabla}\phi\cdot\vec{B}$$

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Our approach: Full backreaction

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2}a^3\dot{\phi}^2 - \frac{1}{2}a(\vec{\nabla}\phi)^2 - \frac{1}{2}a^3 m^2\phi^2 + \frac{1}{2}a(\vec{E}^2 - a^{-2}\vec{B}^2) + \frac{\alpha_\Lambda}{m_p}\phi\vec{E}\cdot\vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} + \frac{1}{a^2}\vec{\nabla}^2\phi - m^2\phi + \frac{\alpha_\Lambda}{a^3 m_p}\vec{E}\cdot\vec{B}$$

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$$\dot{\vec{E}} = -H\vec{E} - \frac{1}{a^2}\vec{\nabla}\times\vec{B} - \frac{\alpha_\Lambda}{a m_p}\left(\dot{\phi}\vec{B} - \vec{\nabla}\phi\times\vec{E}\right)$$

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$$\vec{\nabla}\cdot\vec{E} = -\frac{\alpha_\Lambda}{a m_p}\vec{\nabla}\phi\cdot\vec{B}$$

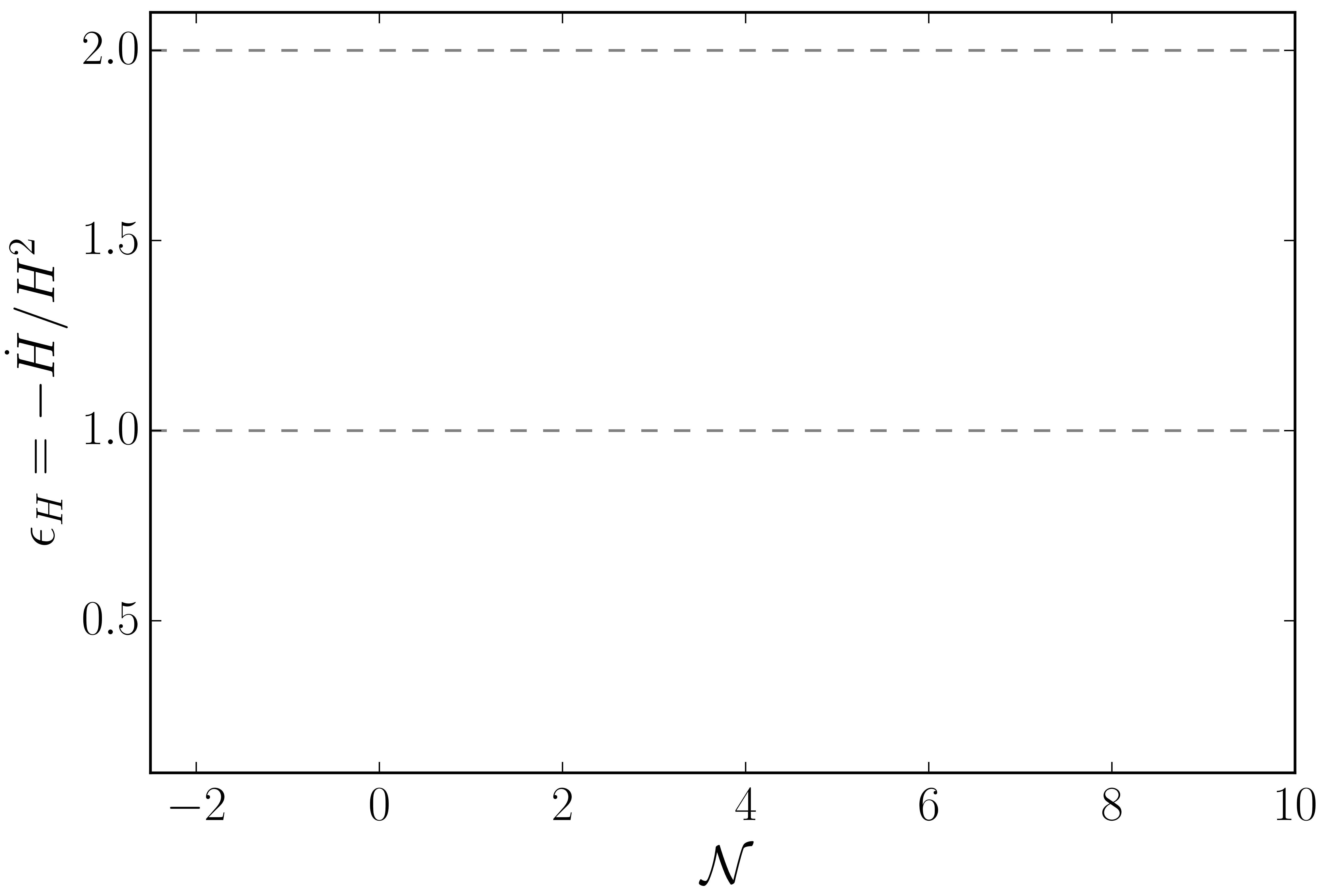
Friedmann 2

$$H^2 = \frac{1}{3m_p^2}\left(\rho_{\mathrm{K}} + \rho_{\mathrm{G}} + \rho_{\mathrm{V}} + \rho_{\mathrm{EM}}\right)$$

CosmoLattice

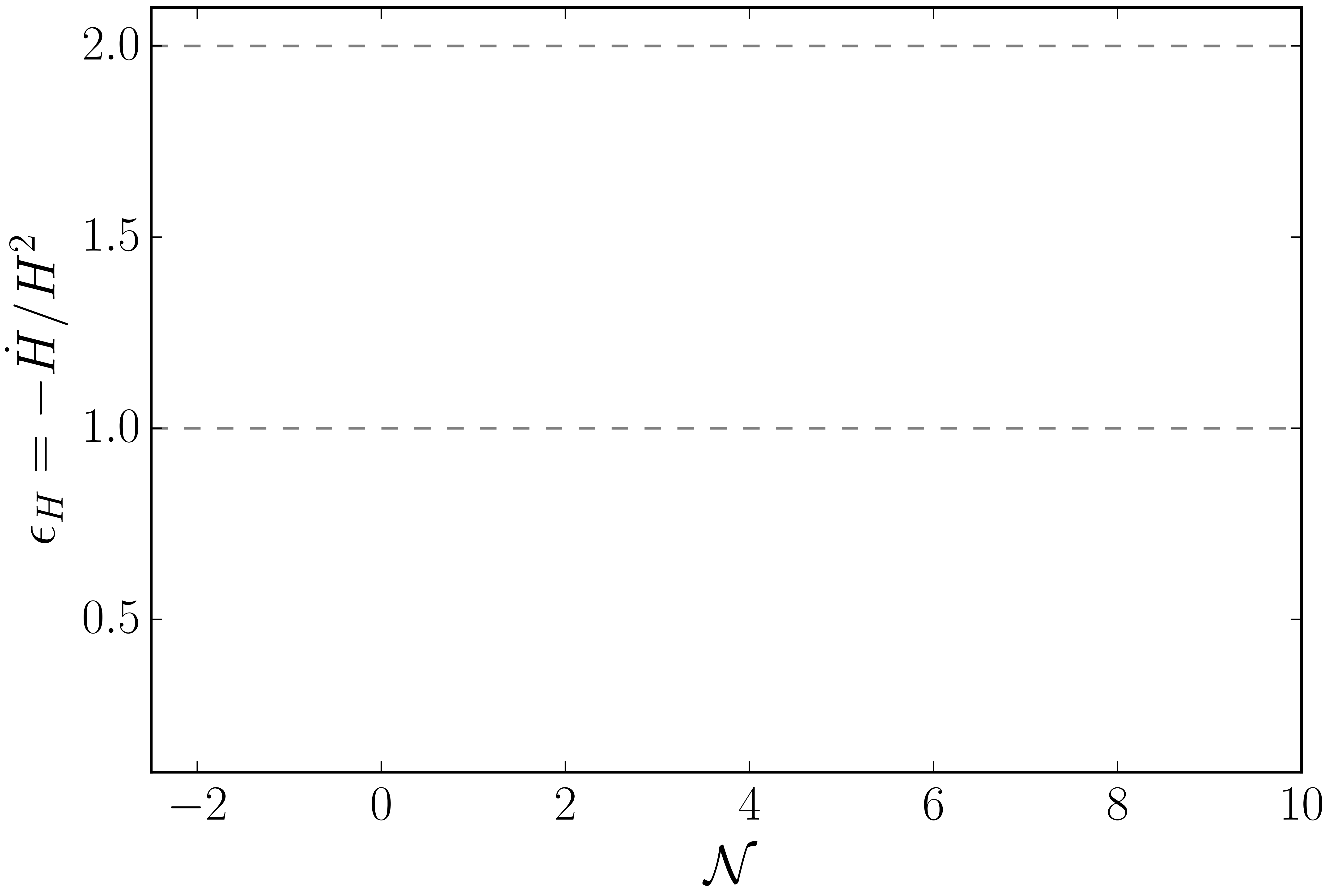
[D. G. Figueroa, A. Florio, F. Torrenti & W. Valkenburg (2006.15122)]
[D. G. Figueroa, A. Florio, F. Torrenti & W. Valkenburg (2102.01031)]

Inflation duration



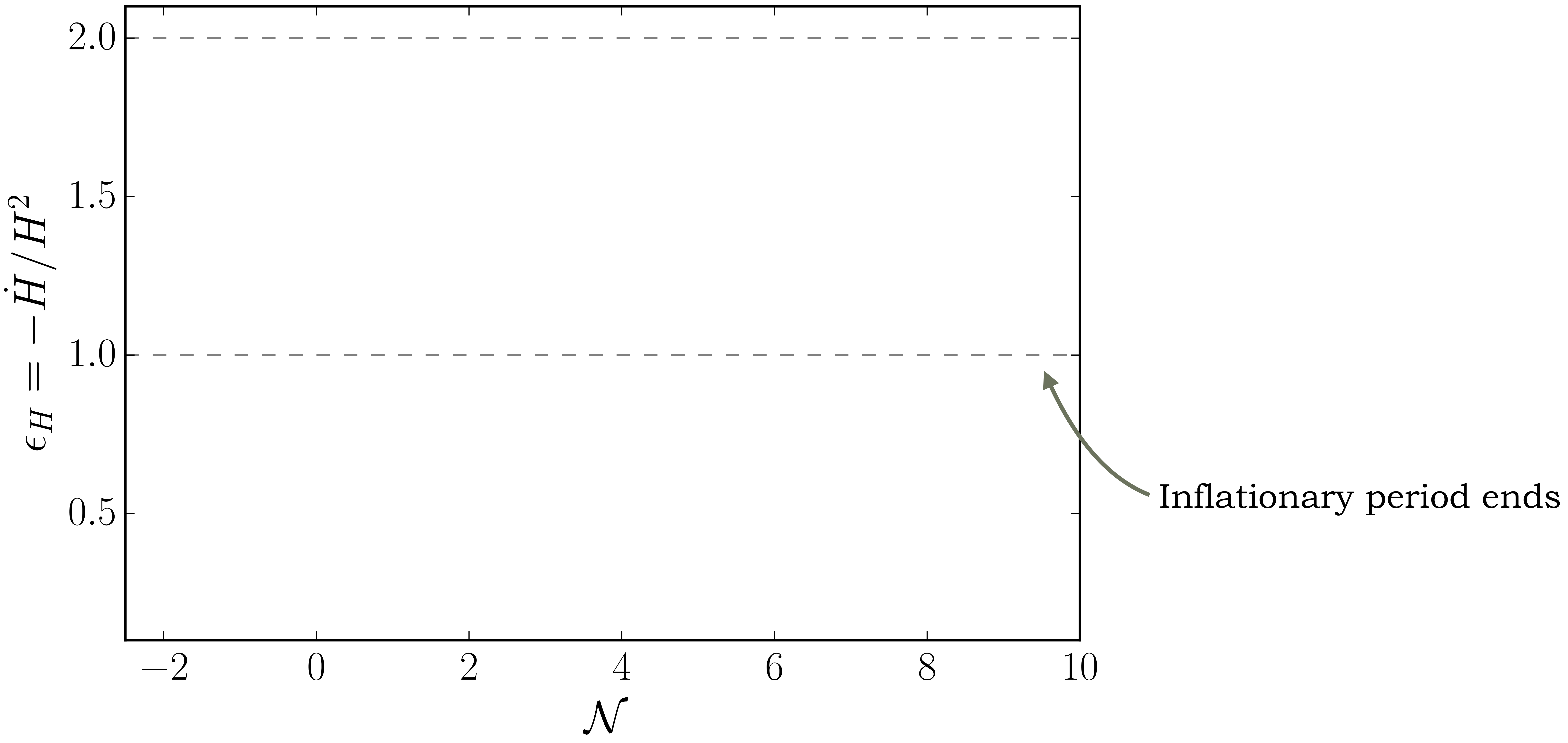
Inflation duration

Also: $\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$



Inflation duration

Also: $\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$



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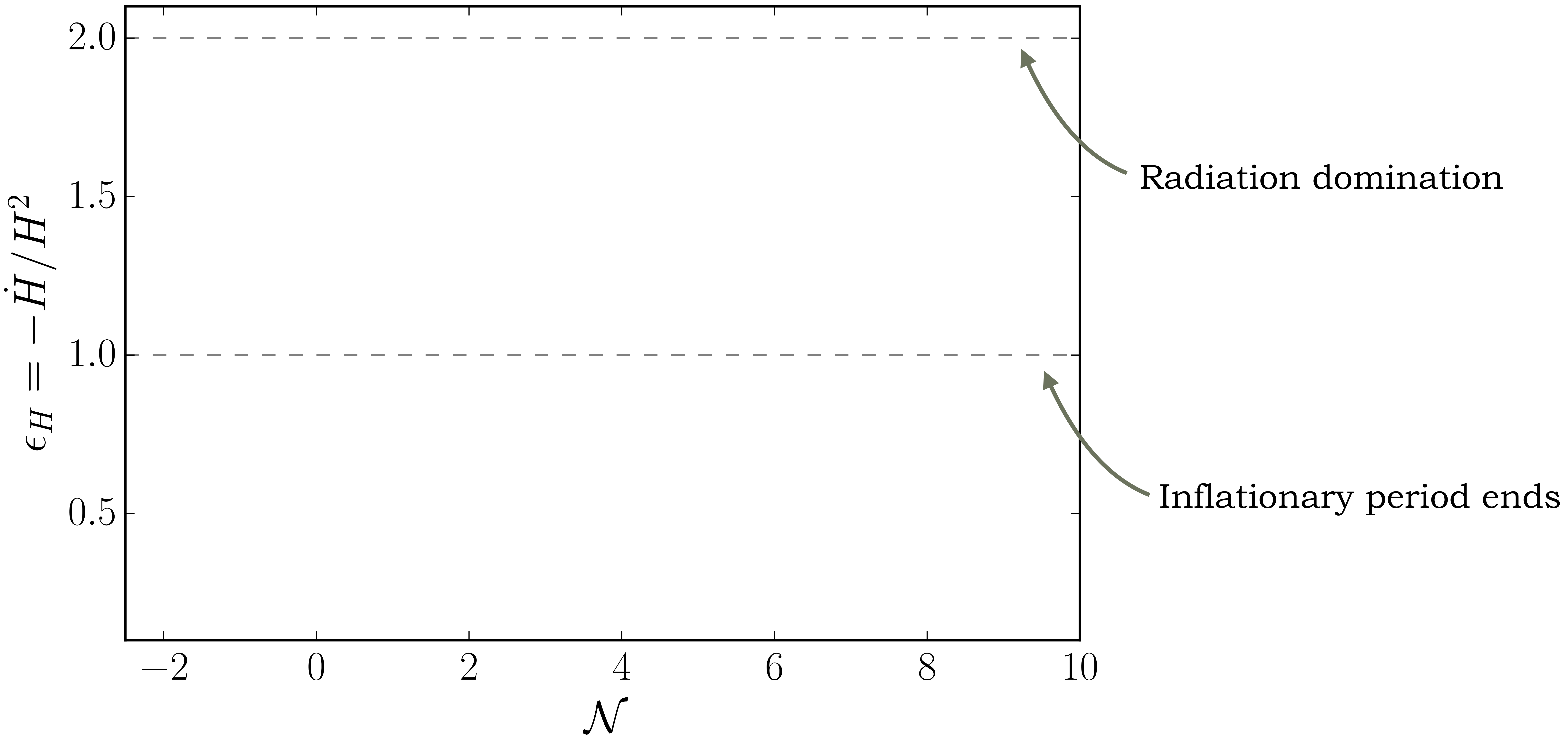
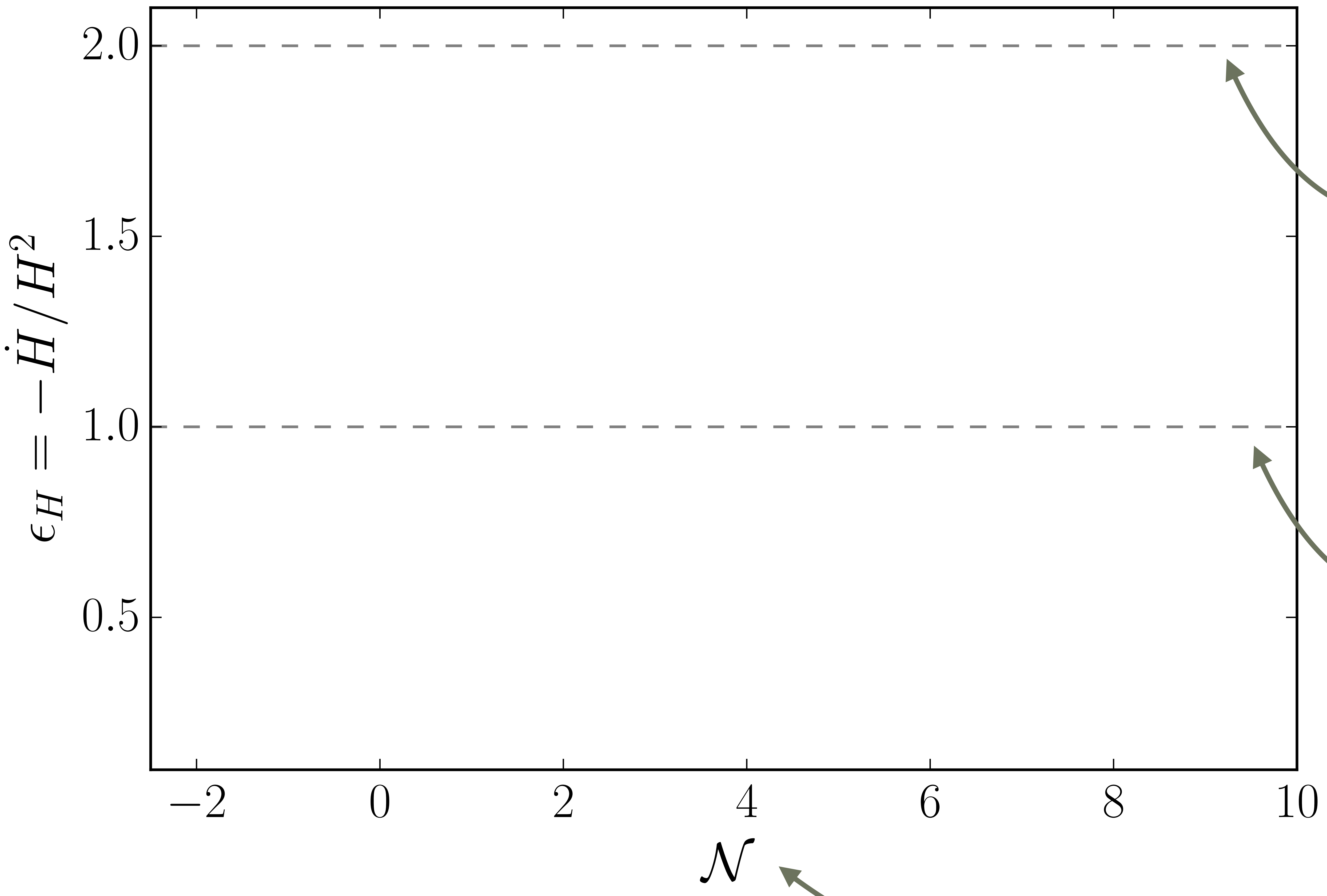


Inflation duration

Also: $\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$



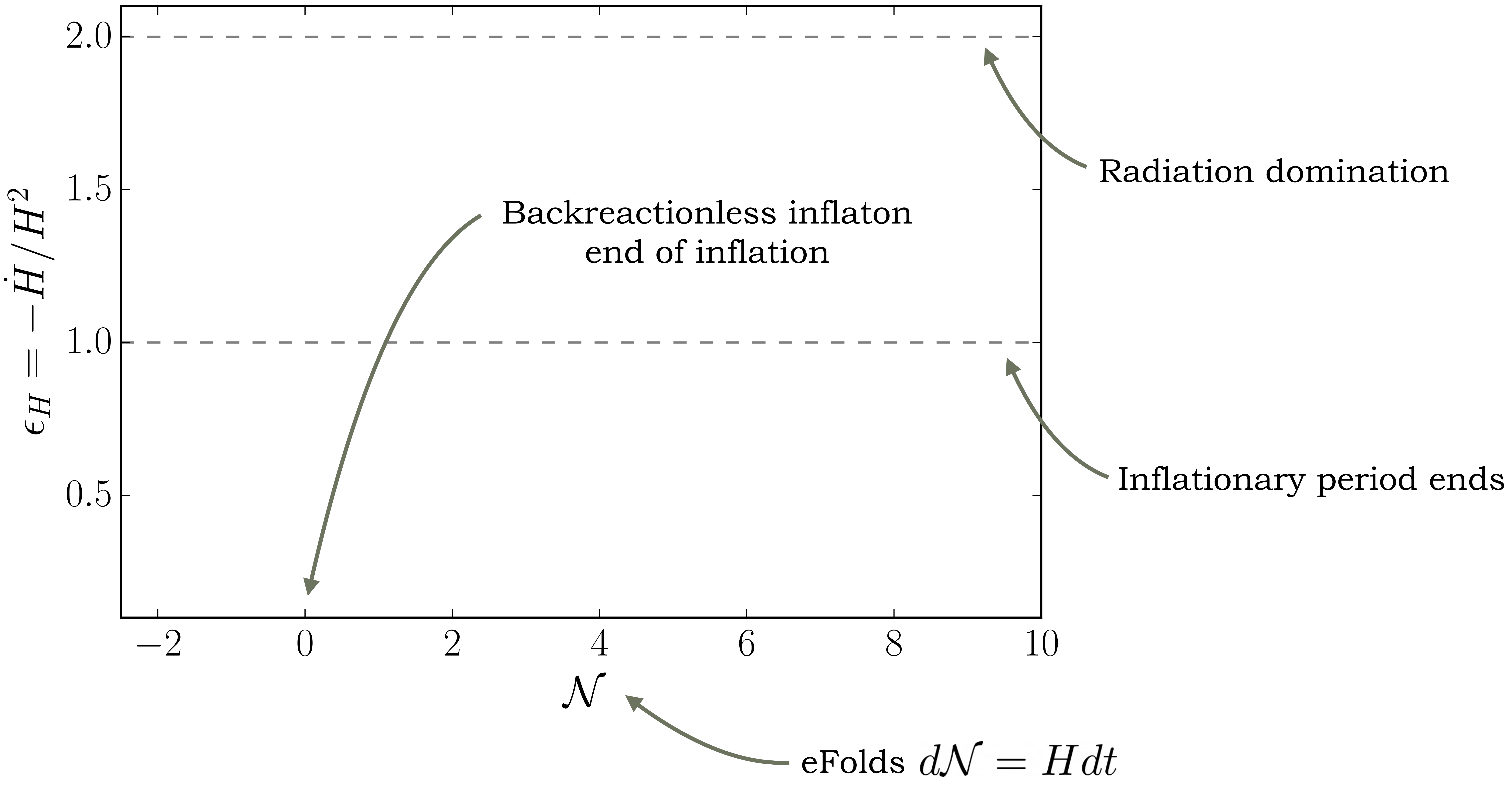
Radiation domination

Inflationary period ends

eFolds $d\mathcal{N} = H dt$

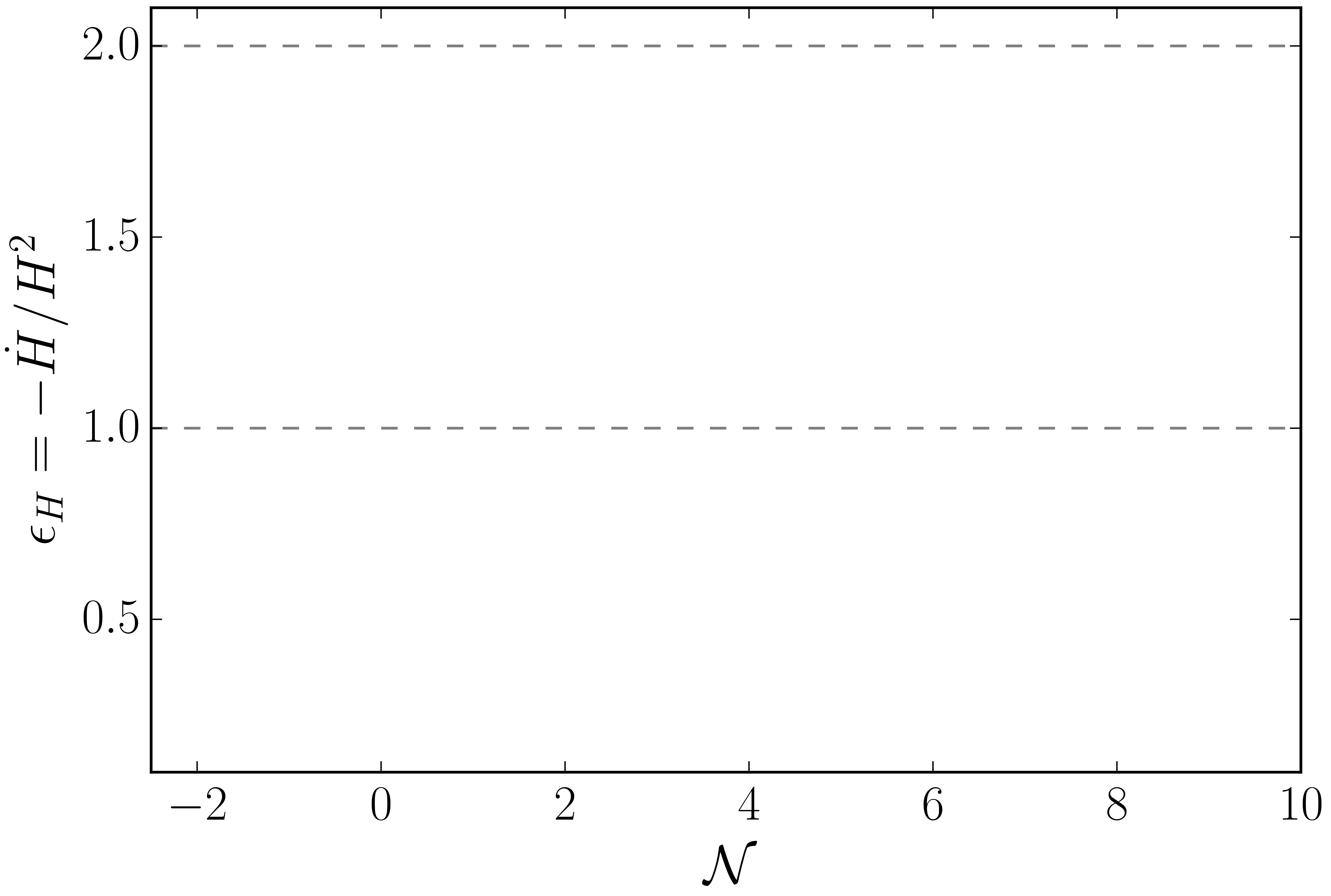
Inflation duration

Also: $\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$



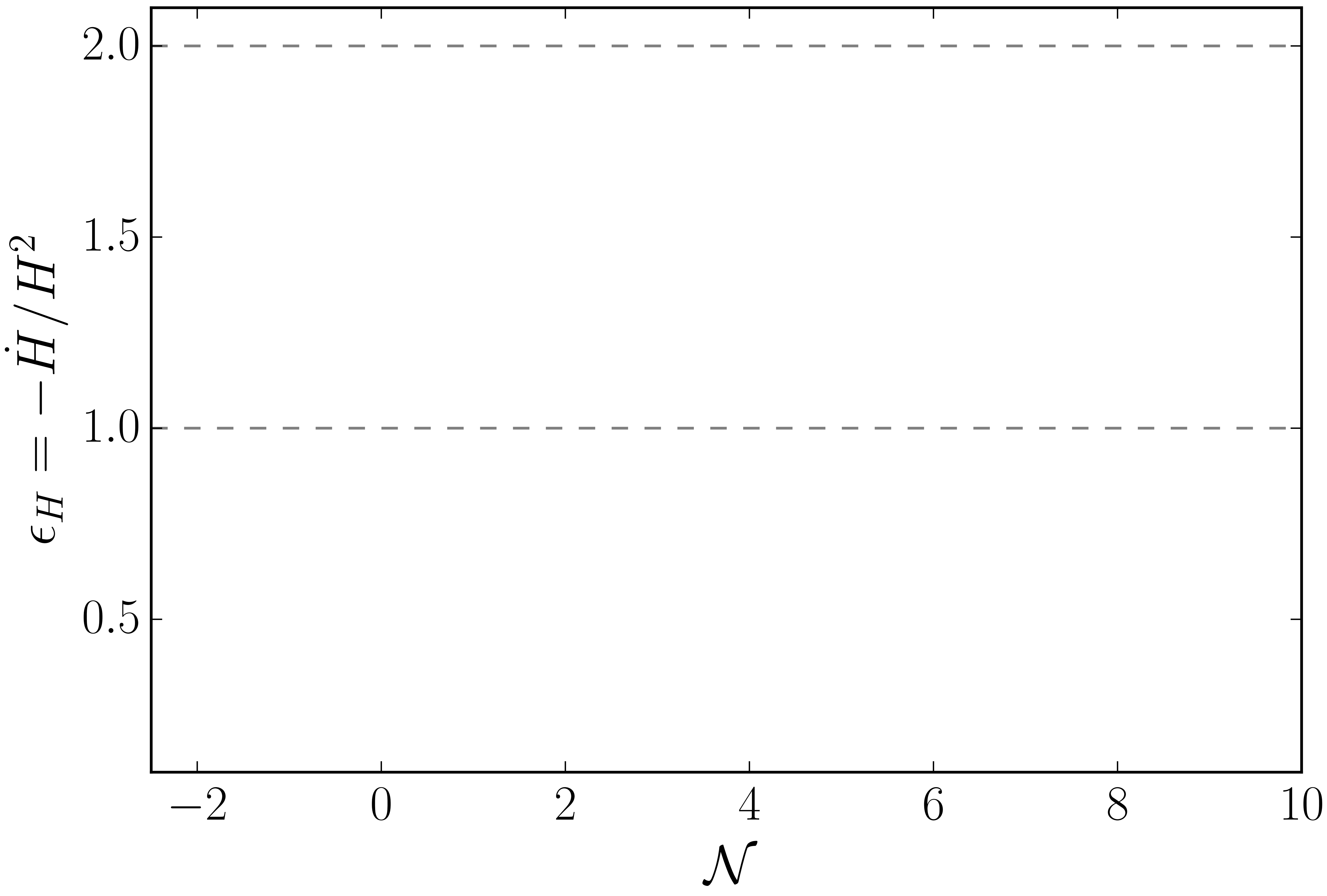
Inflation duration

Also: $\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$



Inflation duration

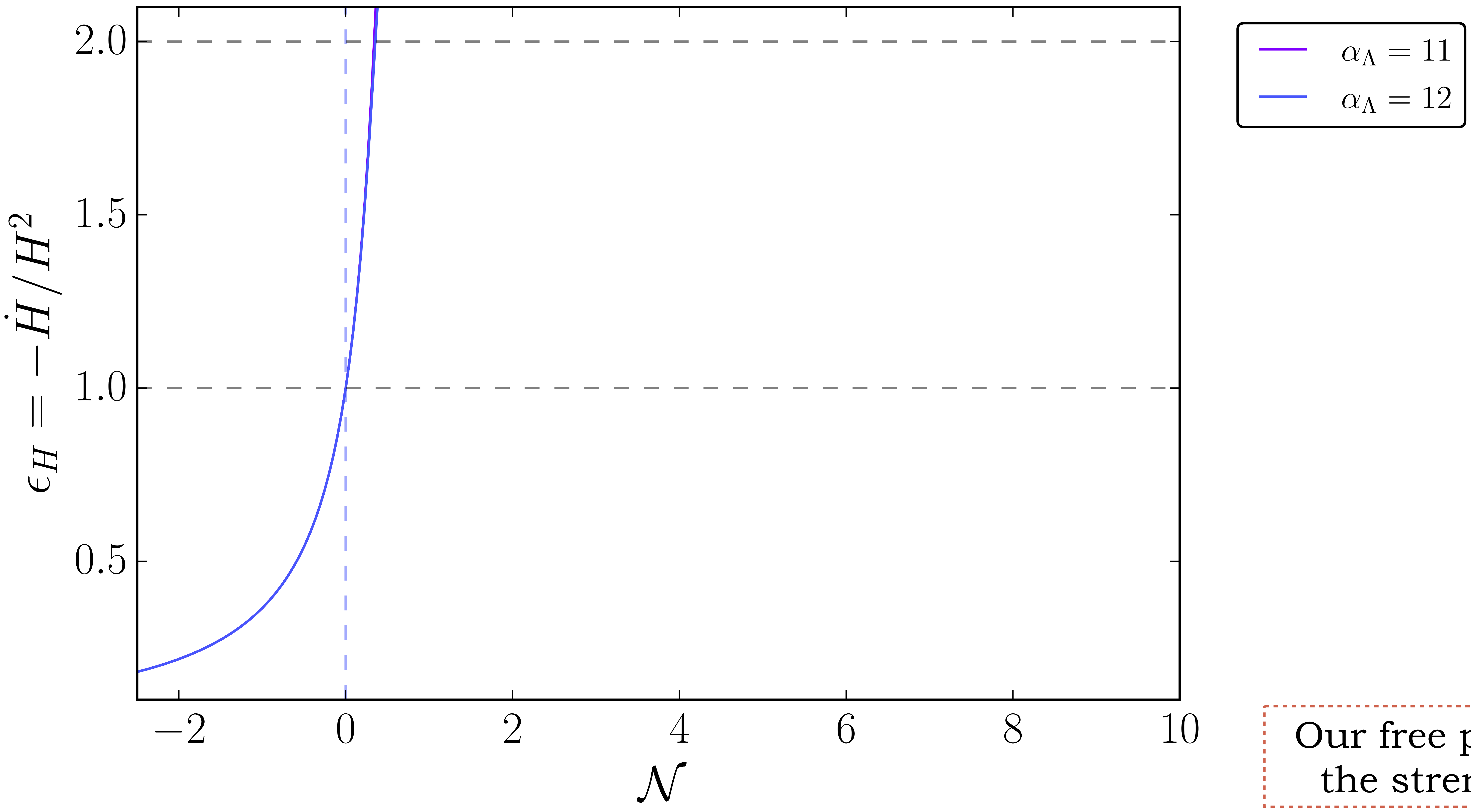
Also: $\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$



Our free parameter is α_Λ : controls the strength of the backreaction!

Inflation duration

Also: $\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$



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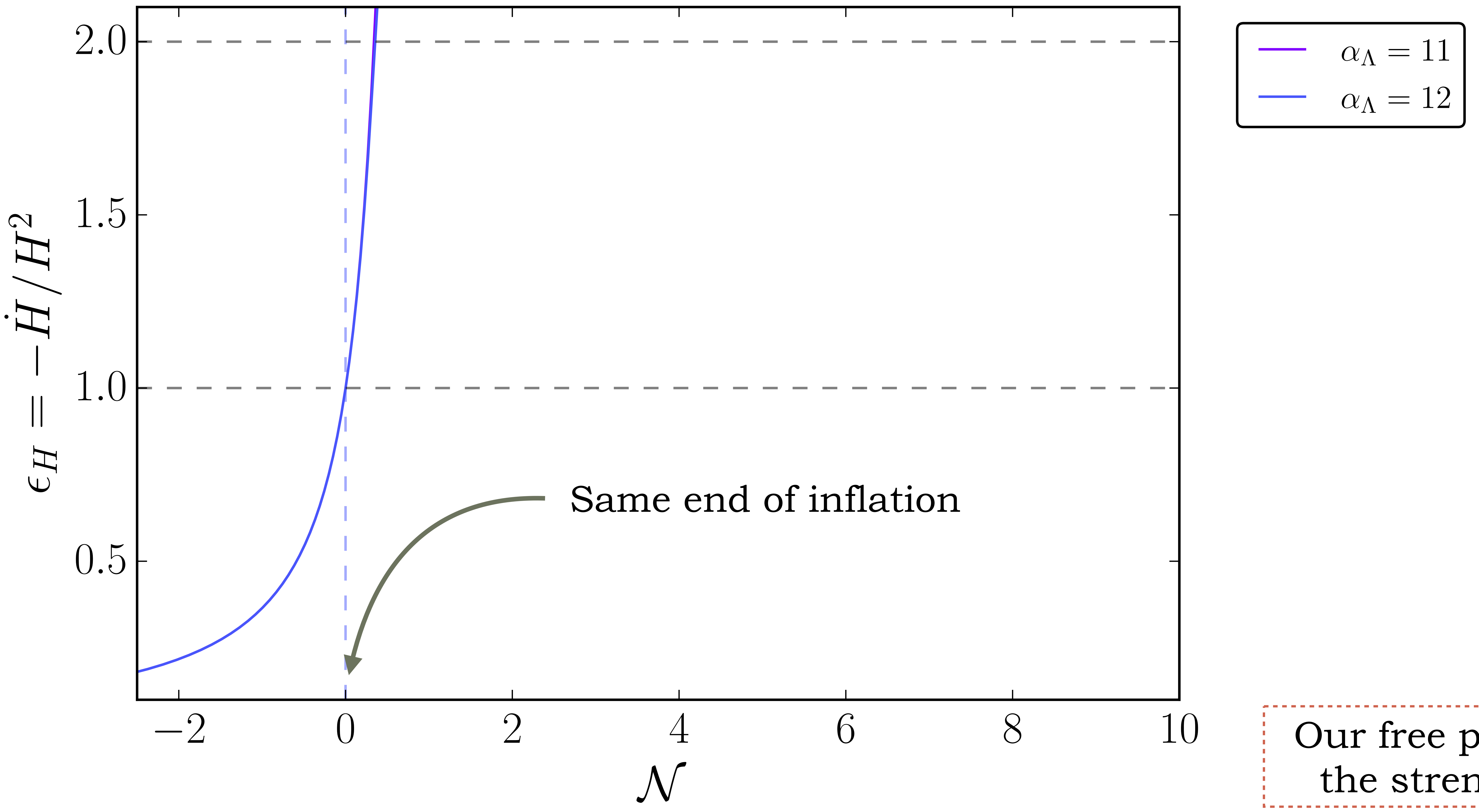

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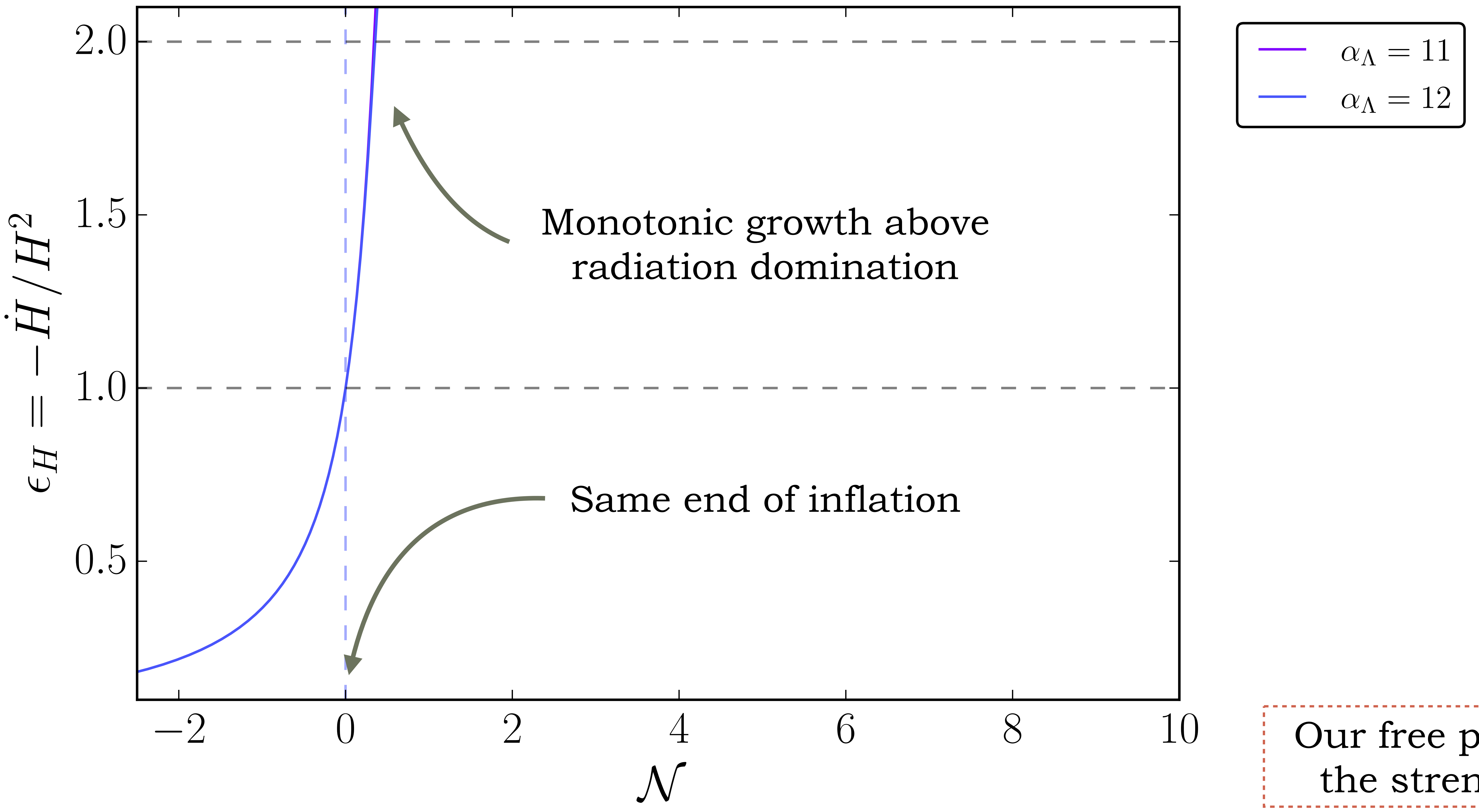
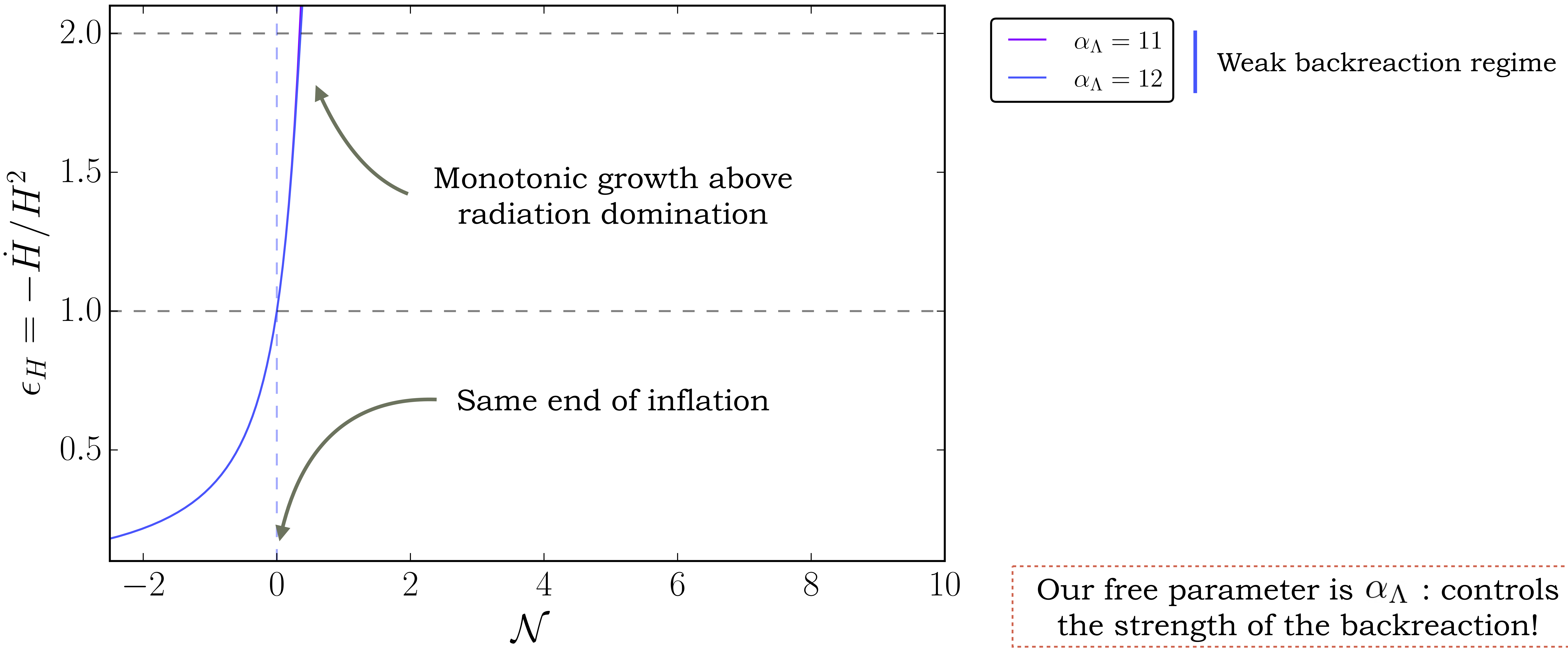


Our free parameter is α_Λ : controls the strength of the backreaction!

Inflation duration

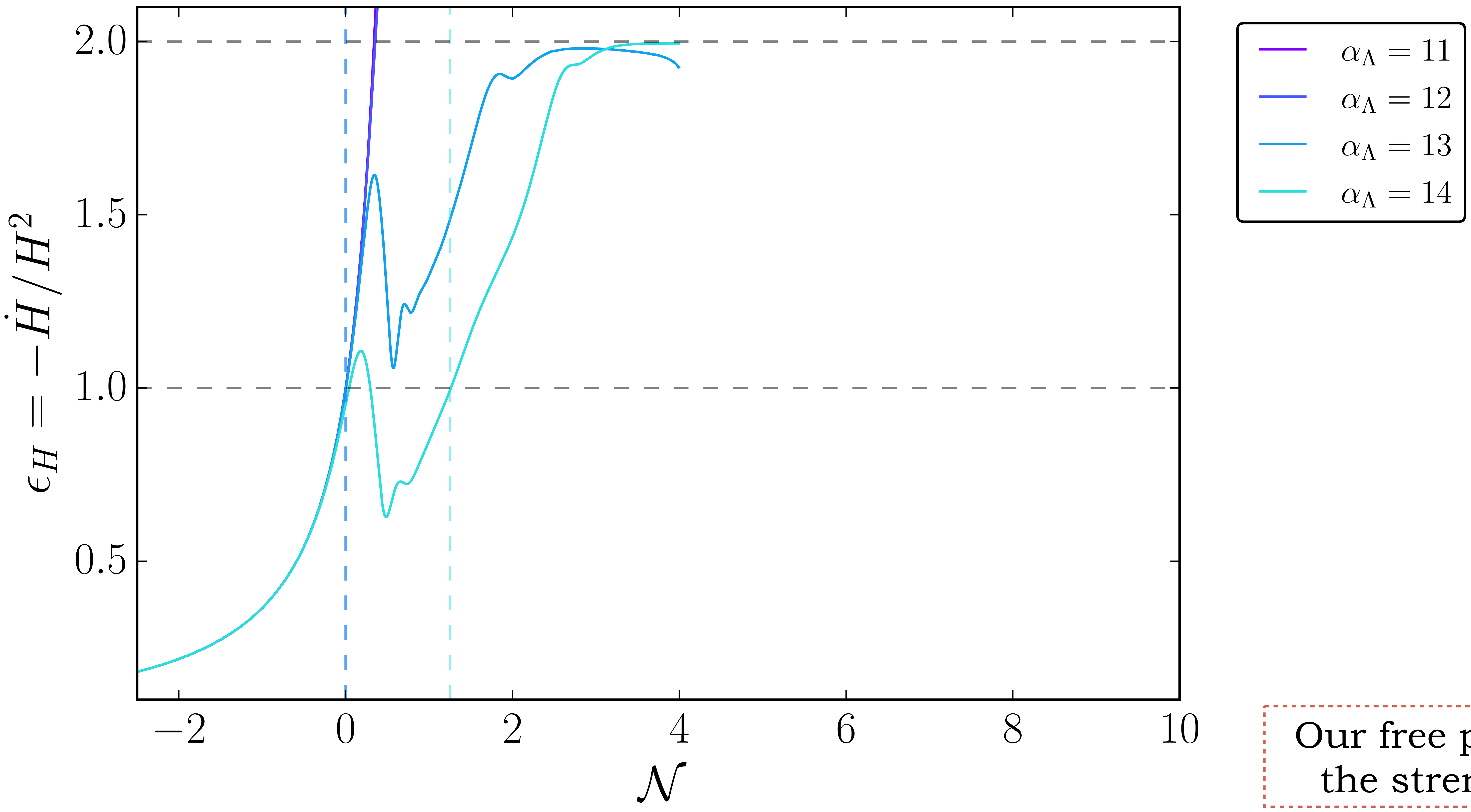
Also: $\epsilon_H = 1 + (2\rho_{\mathrm{K}} - \rho_{\mathrm{V}} + \rho_{\mathrm{EM}})/\rho_{\mathrm{tot}}$



Our free parameter is α_Λ : controls the strength of the backreaction!

Inflation duration

Also: $\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$

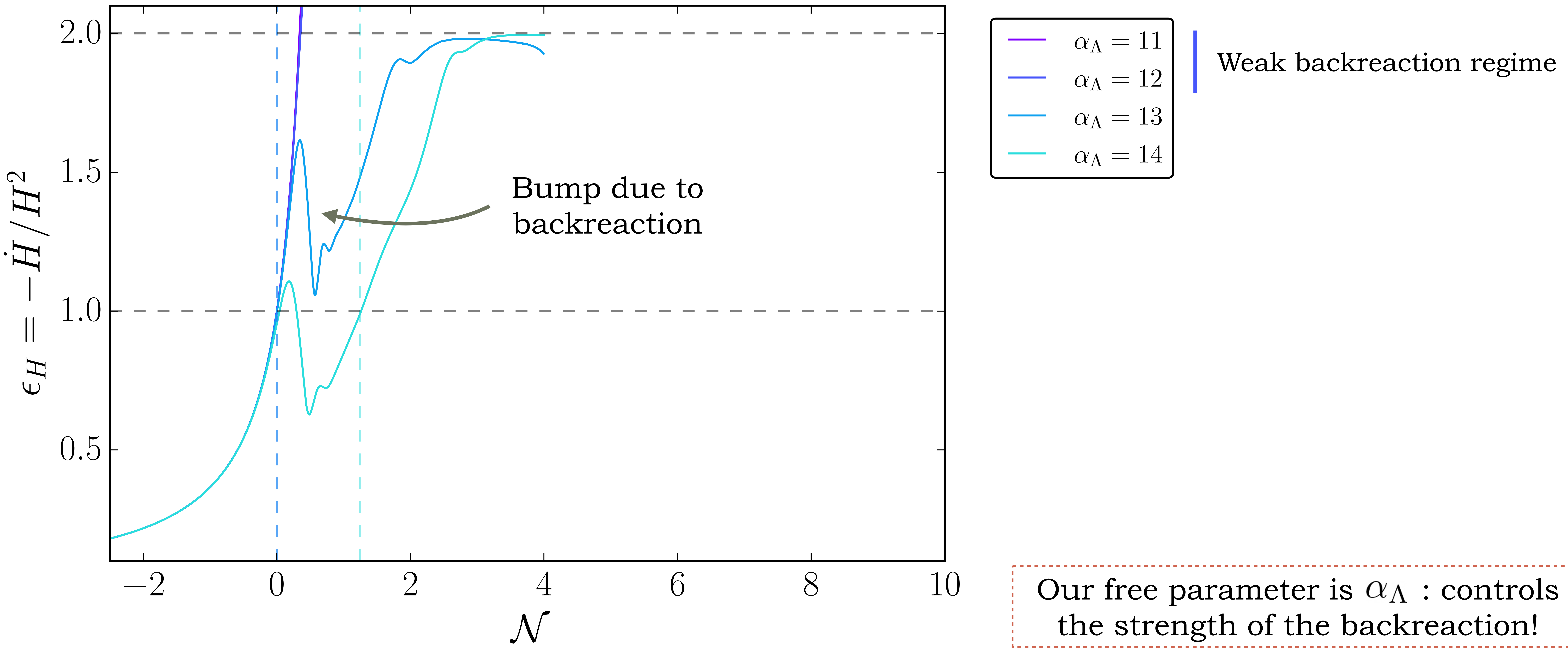


Weak backreaction regime

Our free parameter is α_Λ : controls the strength of the backreaction!

Inflation duration

Also: $\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$



Our free parameter is α_Λ : controls the strength of the backreaction!

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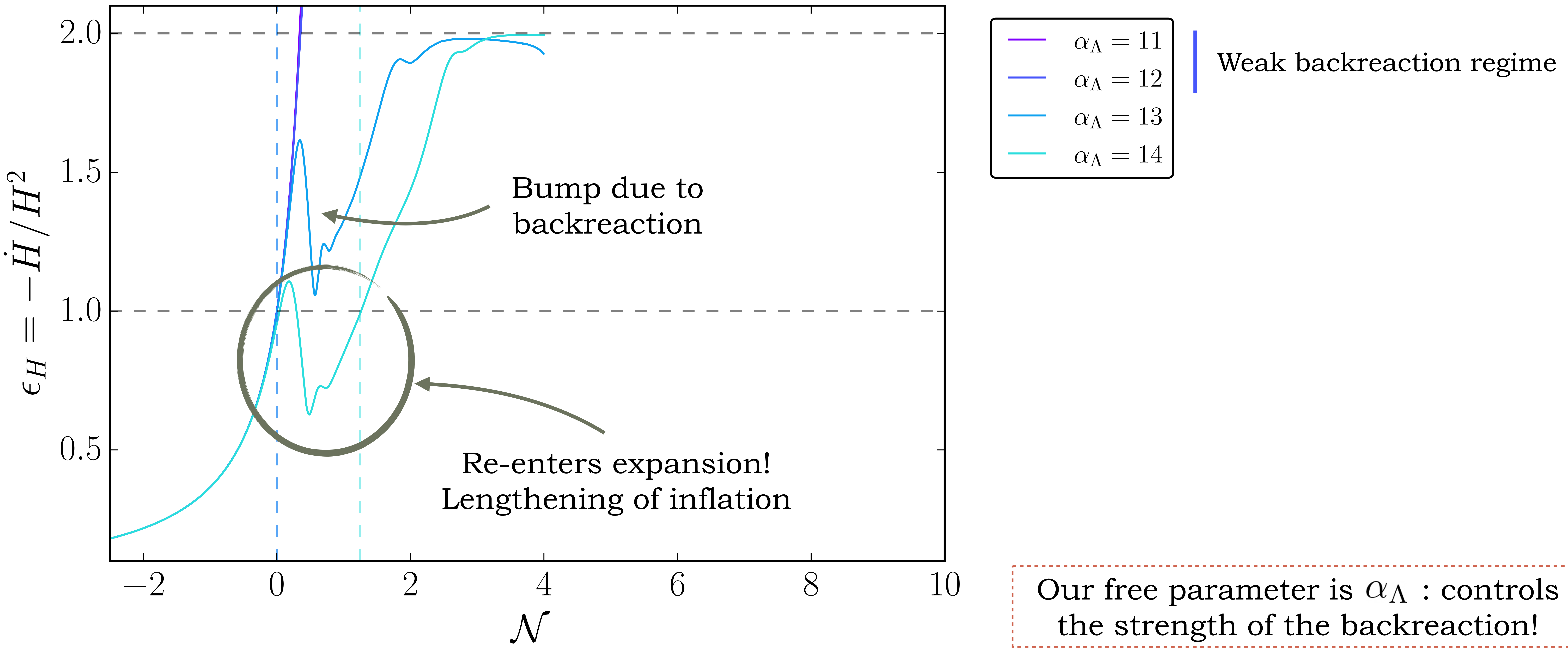

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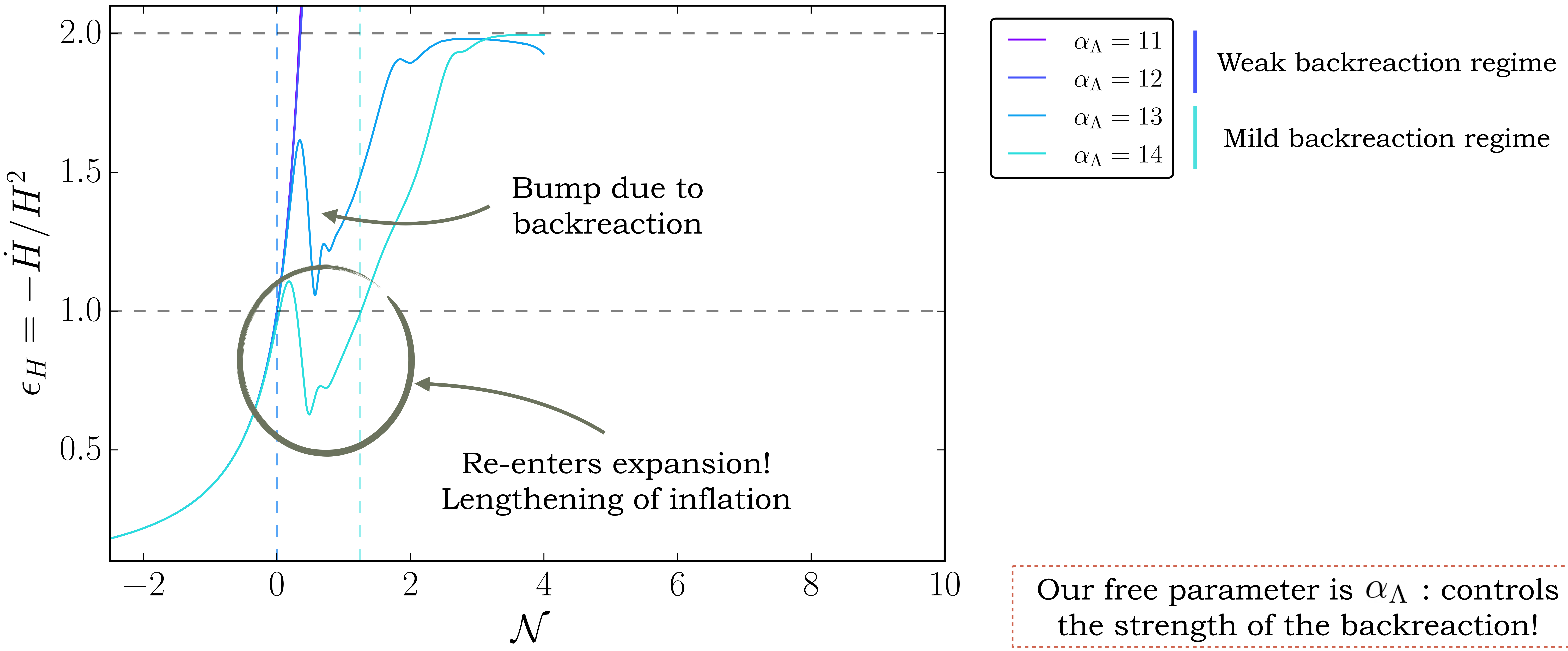

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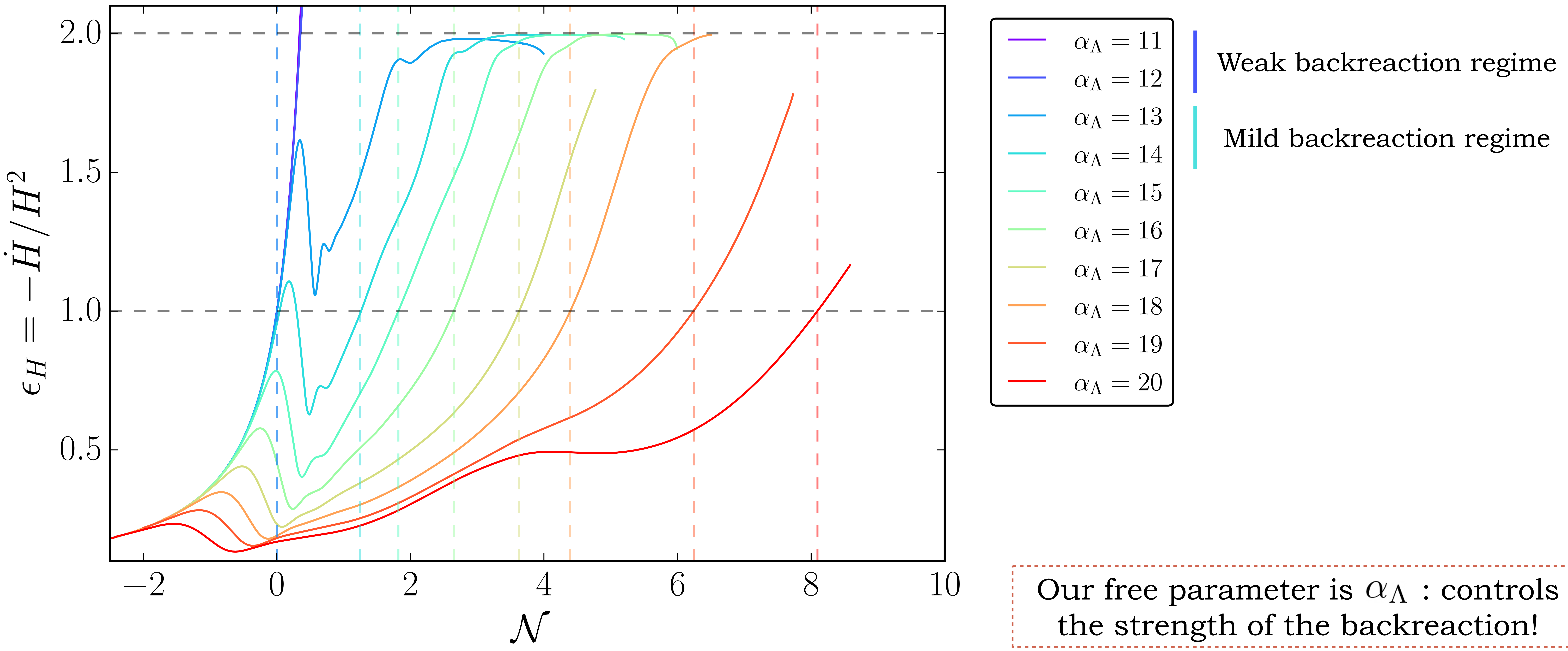

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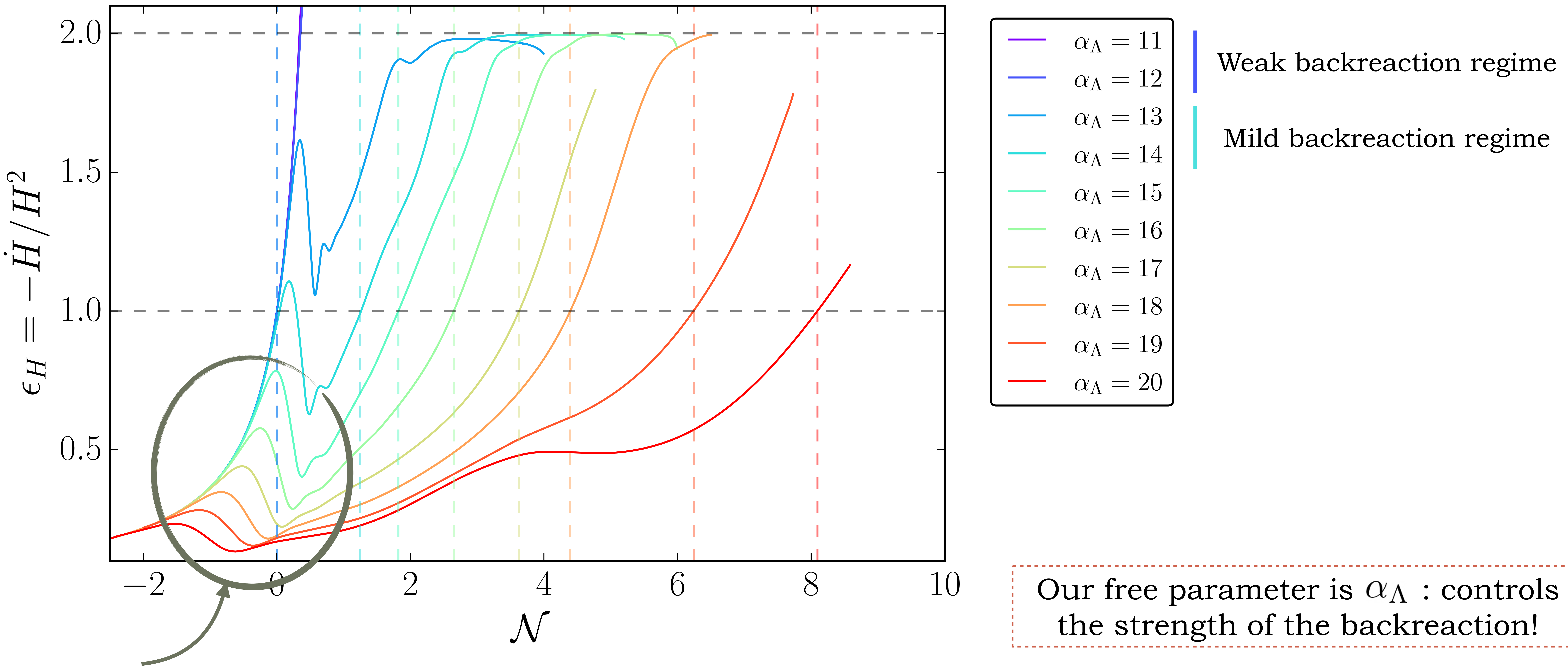

Bump before inflation end
Earlier for higher couplings

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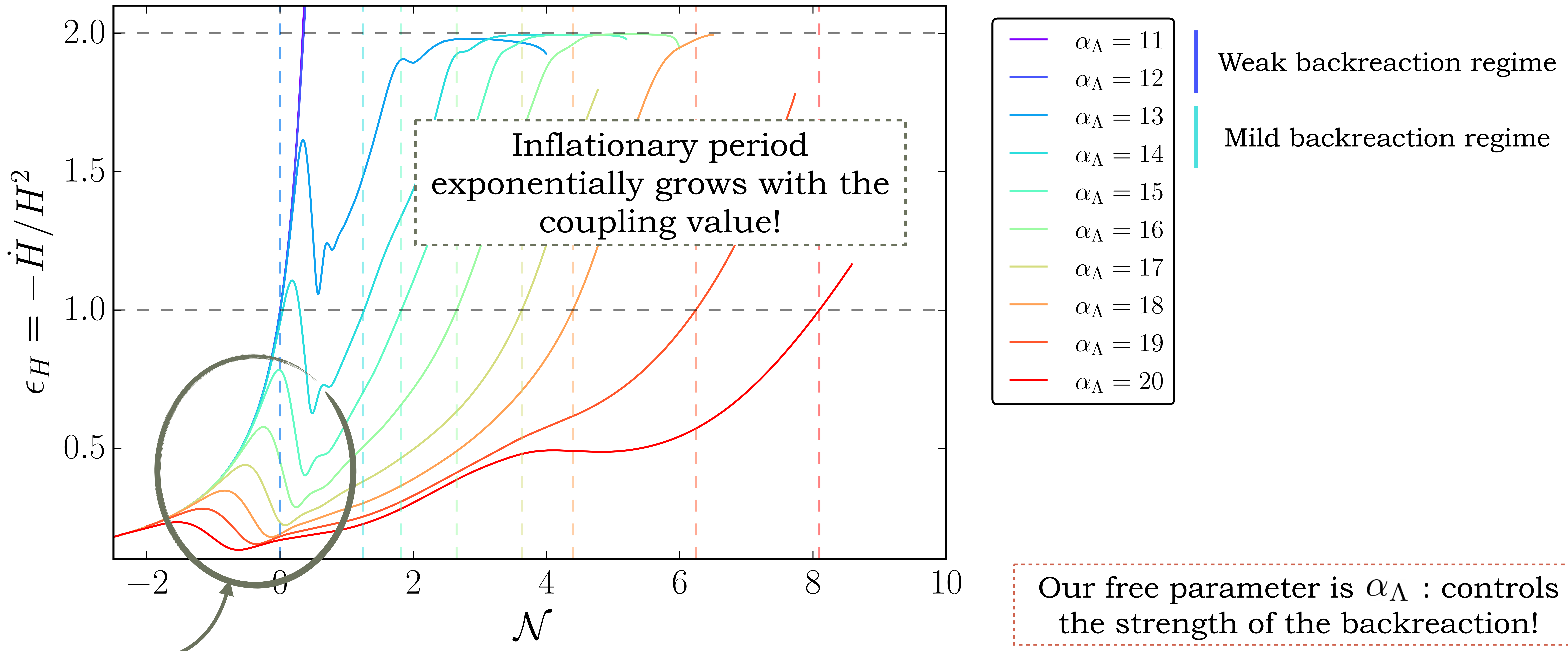

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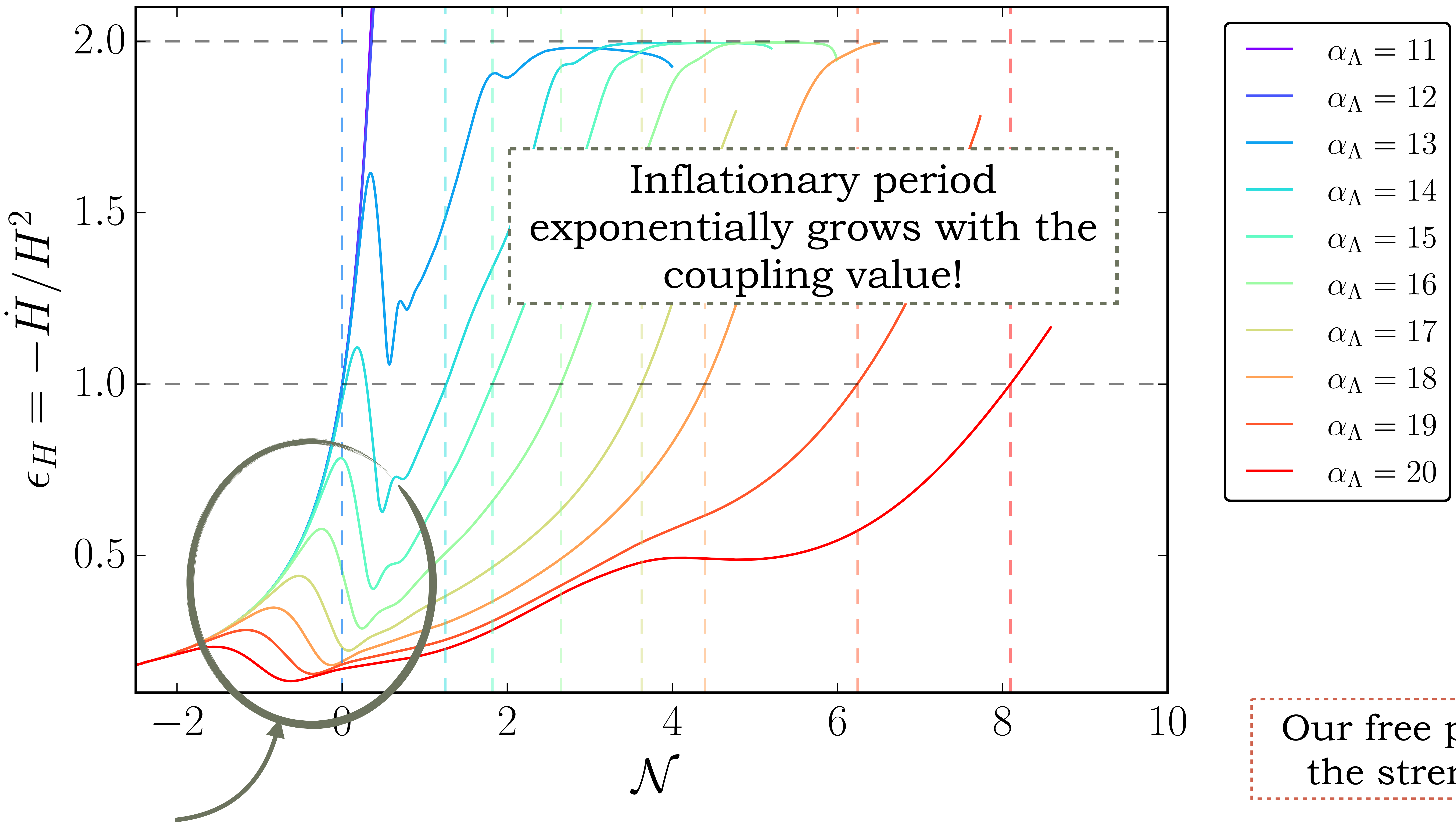

Weak backreaction regime

Mild backreaction regime

Strong backreaction regime

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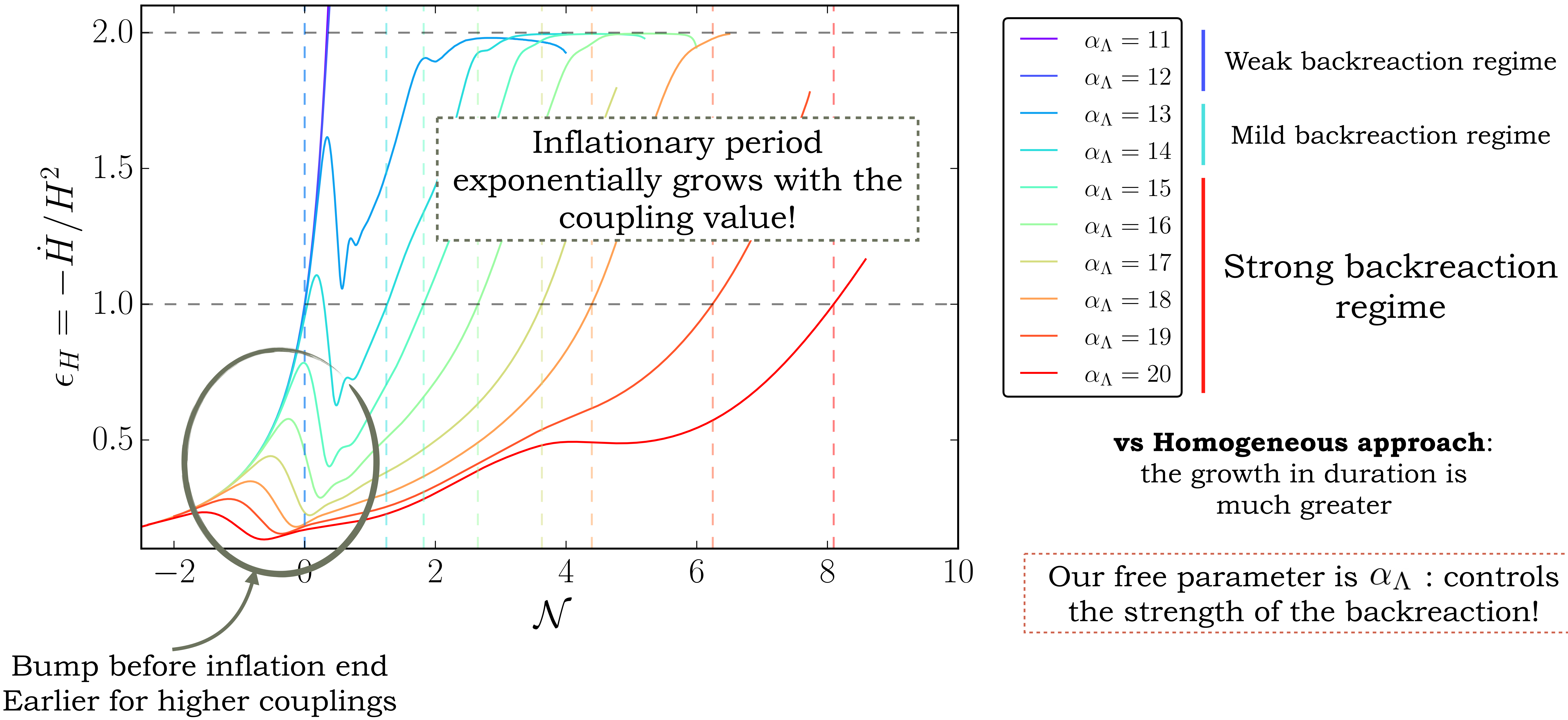

vs Homogeneous approach: the growth in duration is much greater

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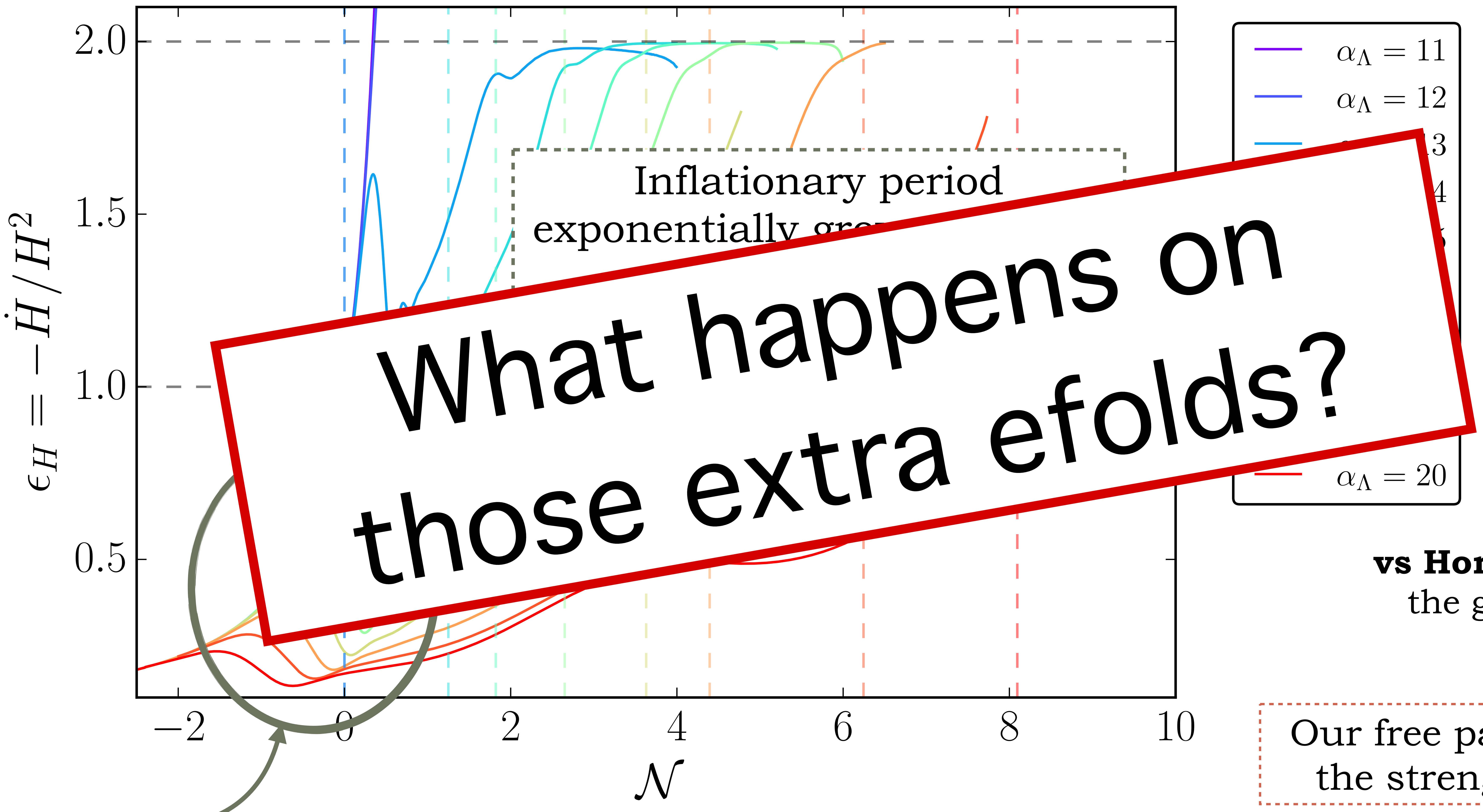

What happens on those extra efolds?

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Mild backreaction regime

Strong backreaction regime

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Earlier for higher couplings

vs Homogeneous approach:
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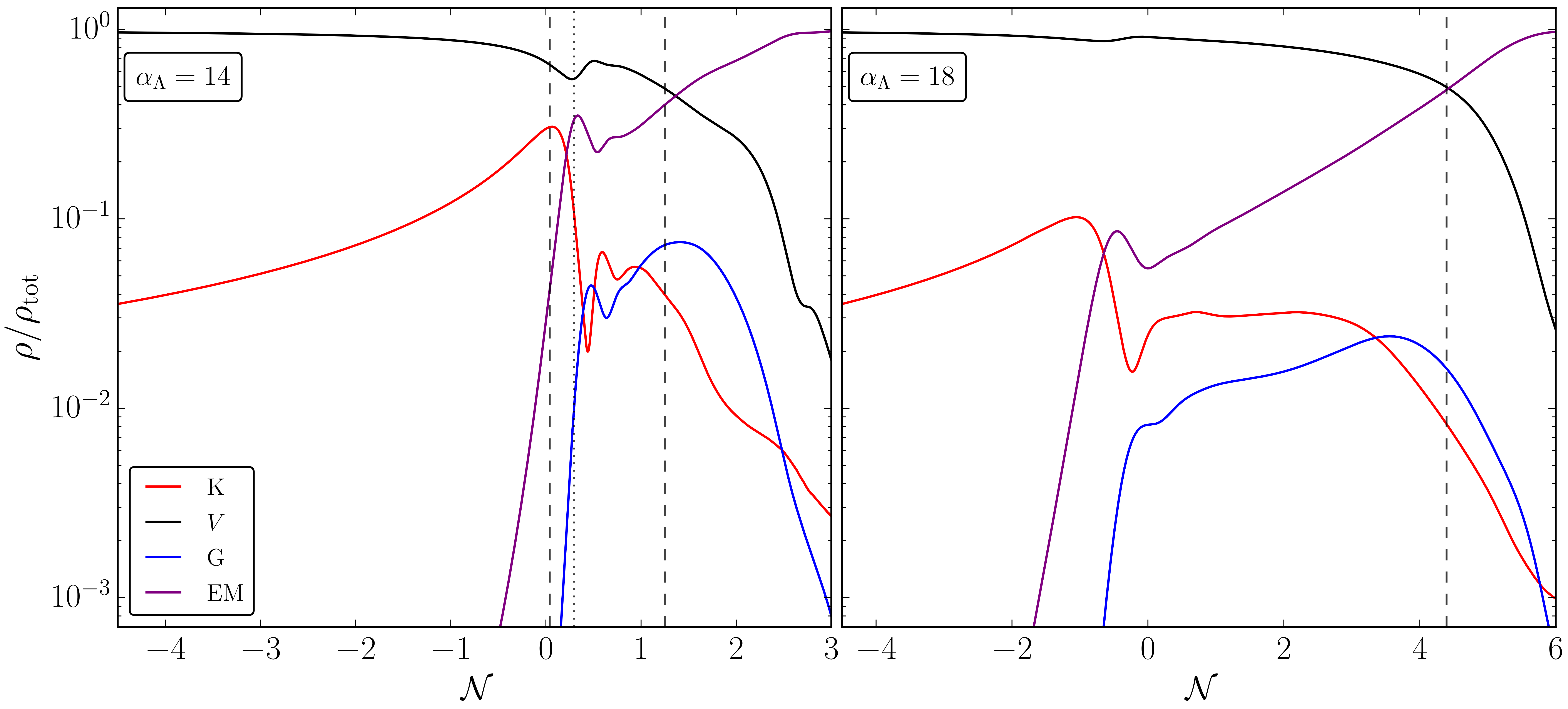
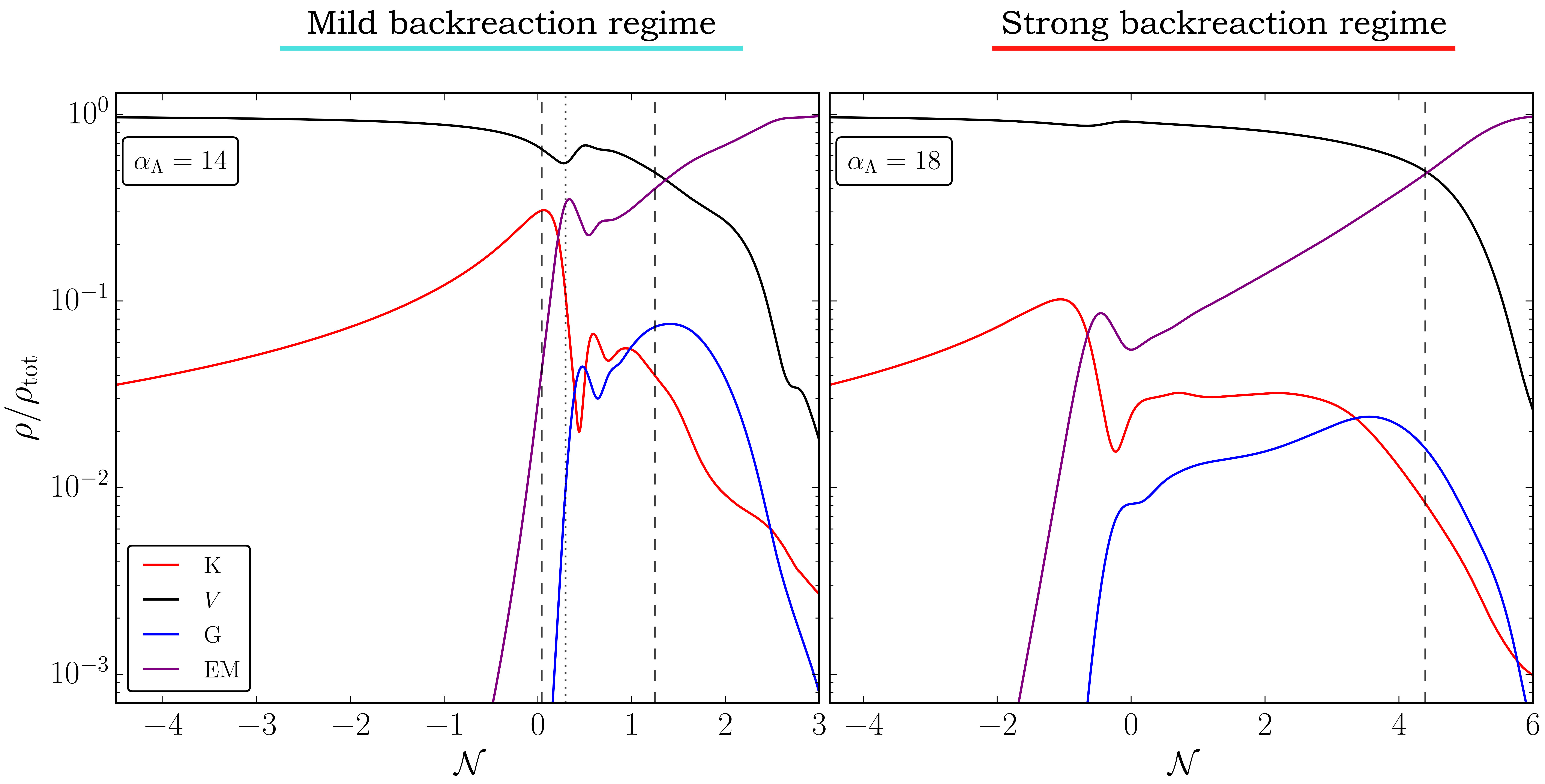
Energy density evolution

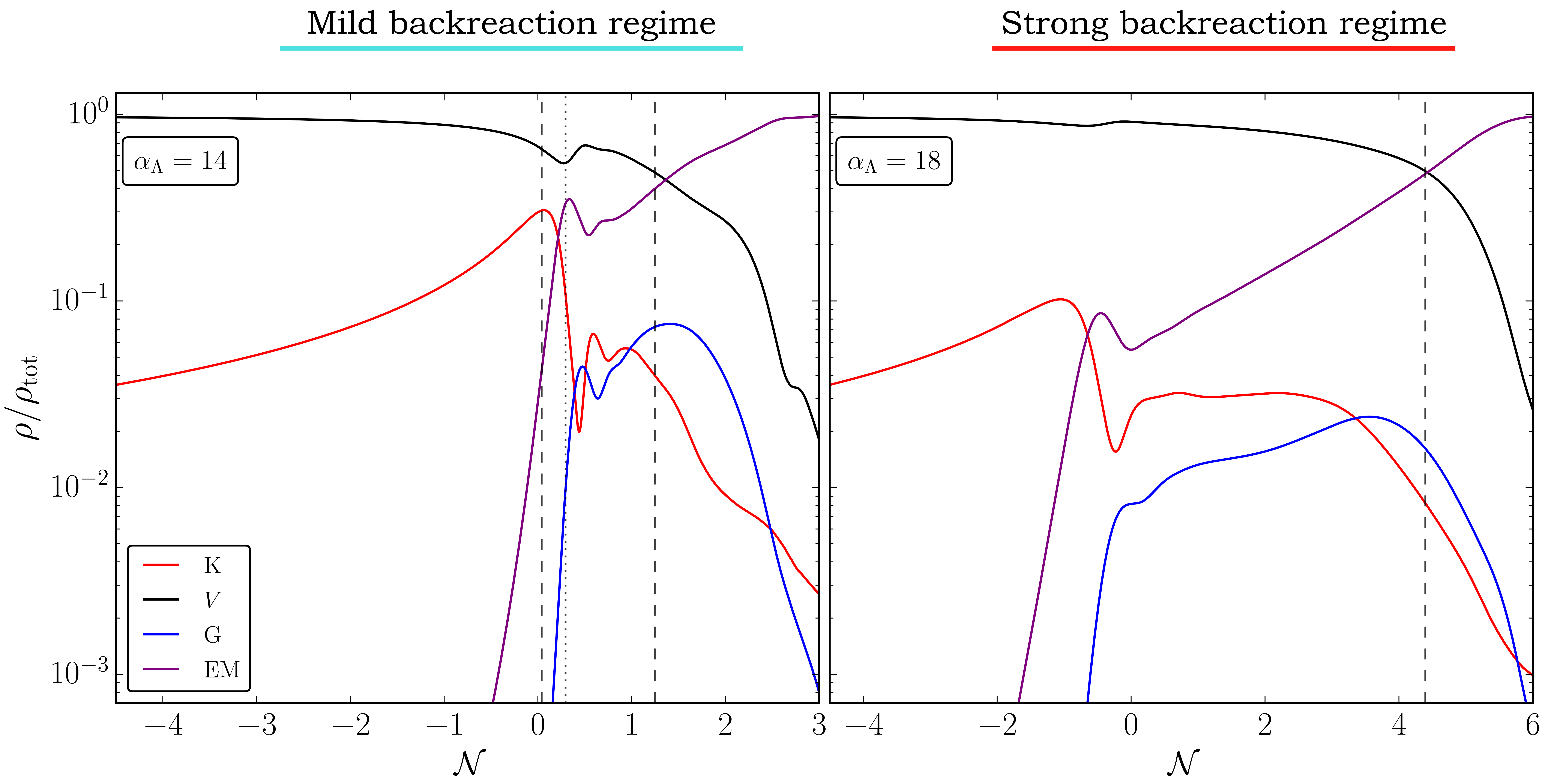


Energy density evolution



Energy density evolution

$$\epsilon_H = 1 + (2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM})/\rho_{\rm tot}$$



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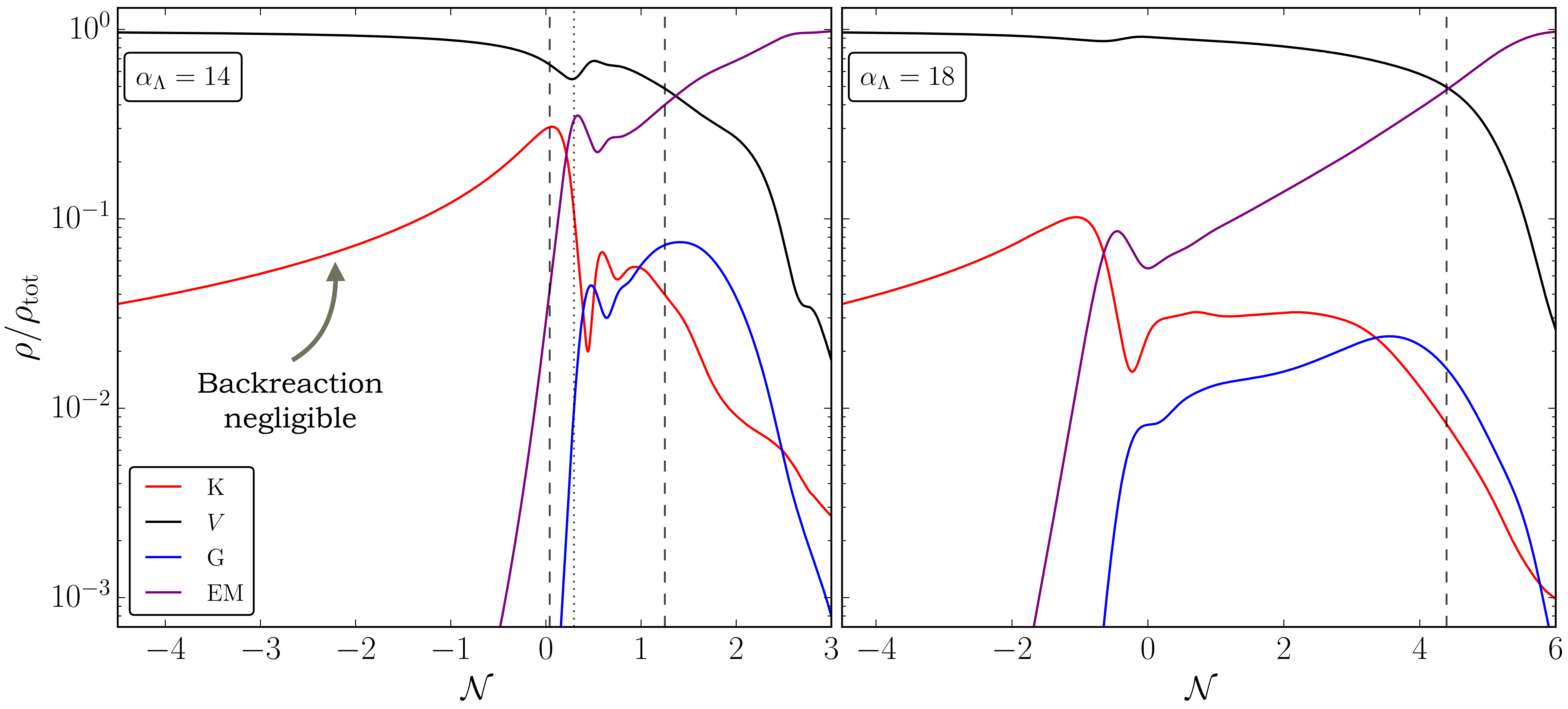
Mild backreaction regime

Strong backreaction regime



Energy density evolution

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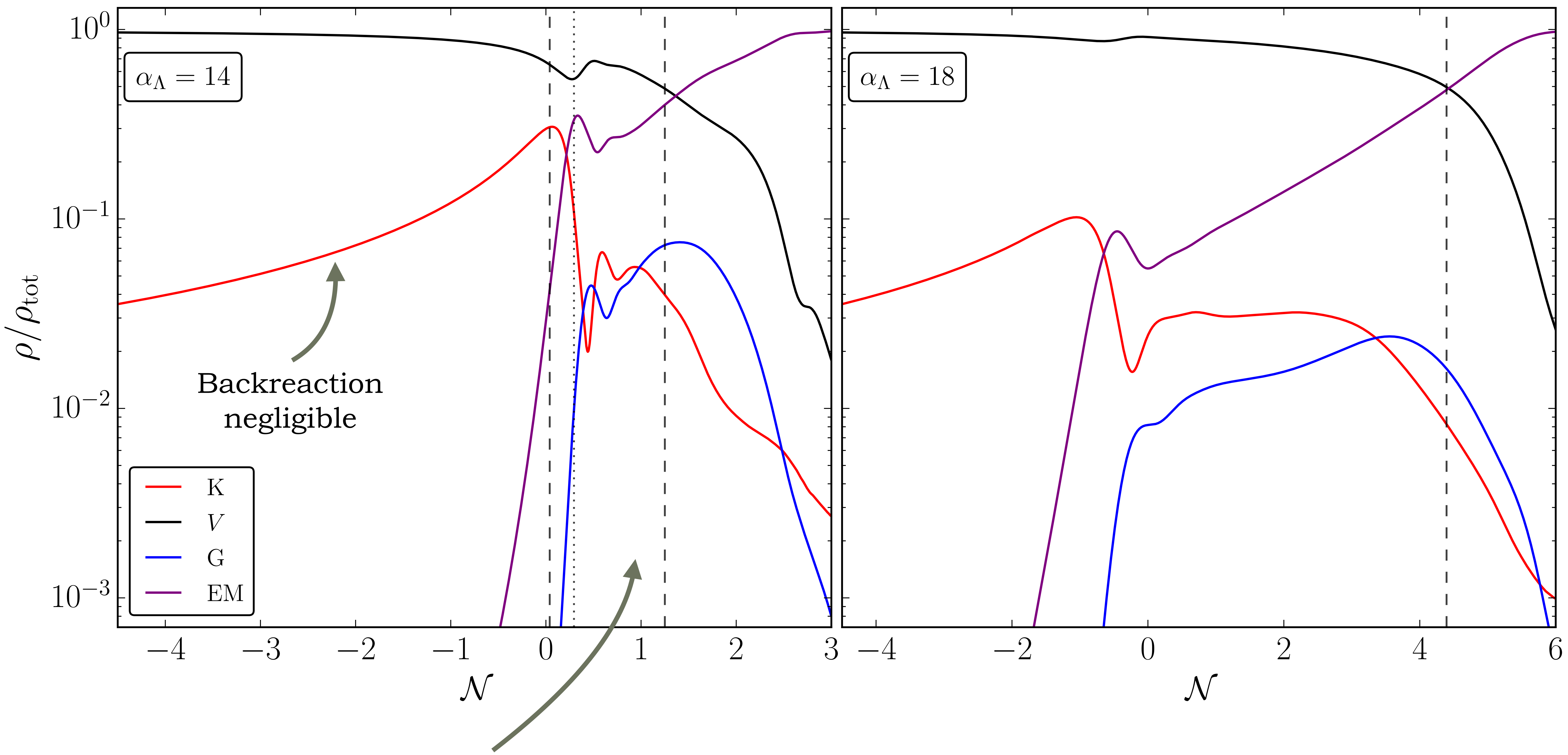
Strong backreaction regime



Re-enters inflation with EM dominating and gradients slowing down kinetic energy density

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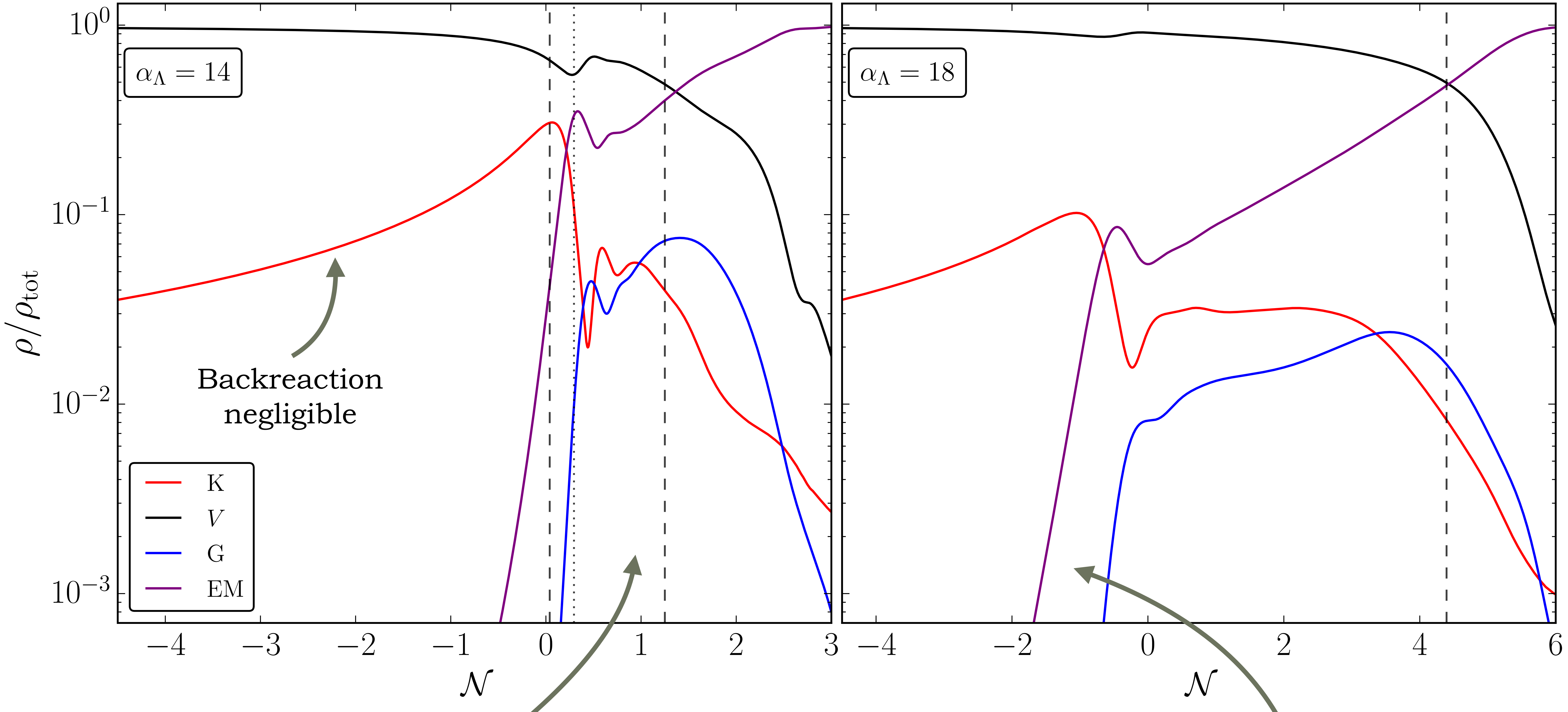

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EM grows sufficiently early to surpass kinetic energy before $\mathcal{N} = 0$ and avoids inflation ending

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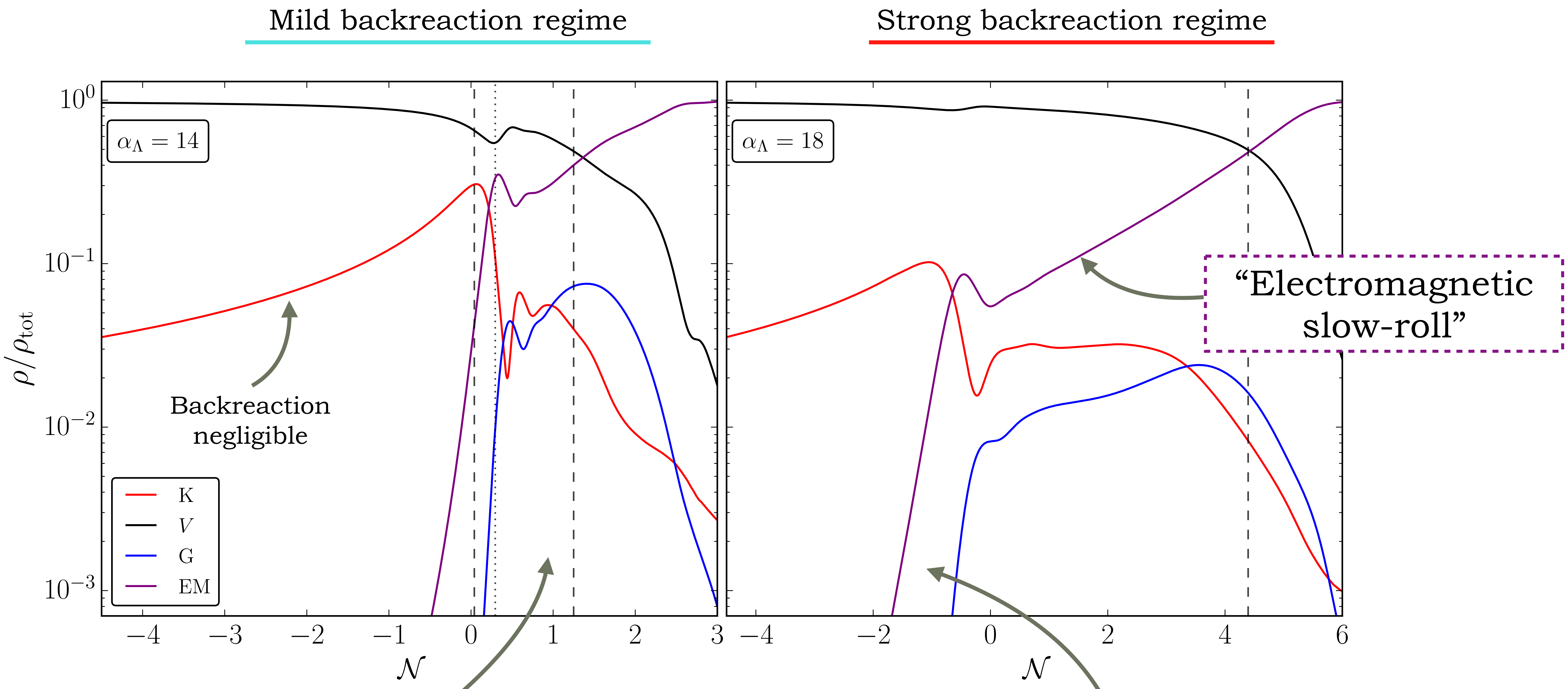

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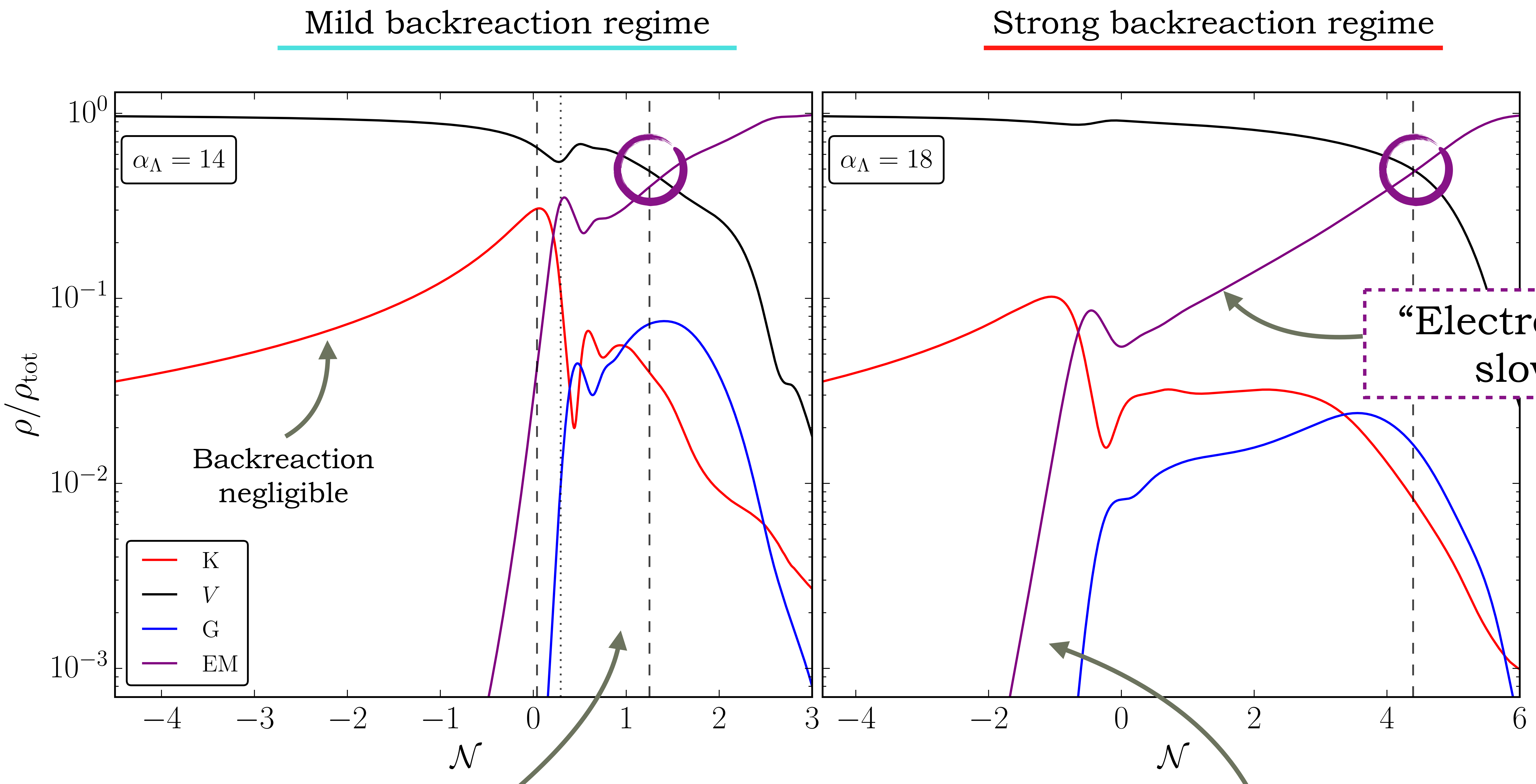

Inflation ends when the U(1) gauge field meets the potential

"Electromagnetic slow-roll"

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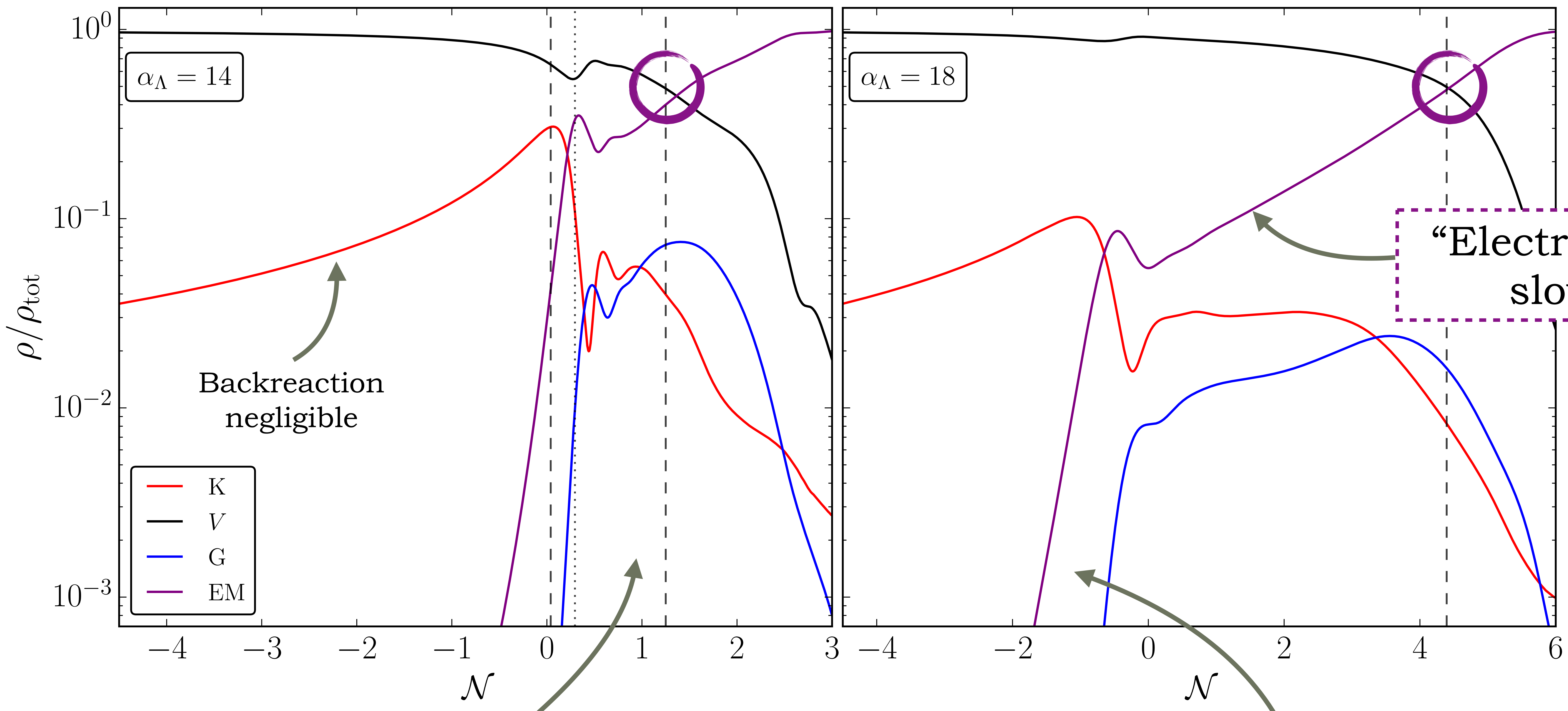

Inflation ends when the U(1) gauge field meets the potential

"Electromagnetic slow-roll"

vs Homogeneous approach:

- Magnetic energy dominates in the inflation: "Magnetic slow-roll"
- No oscillatory behavior on the inflaton velocity

Re-enters inflation with EM dominating and gradients slowing down kinetic energy density

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Conclusions

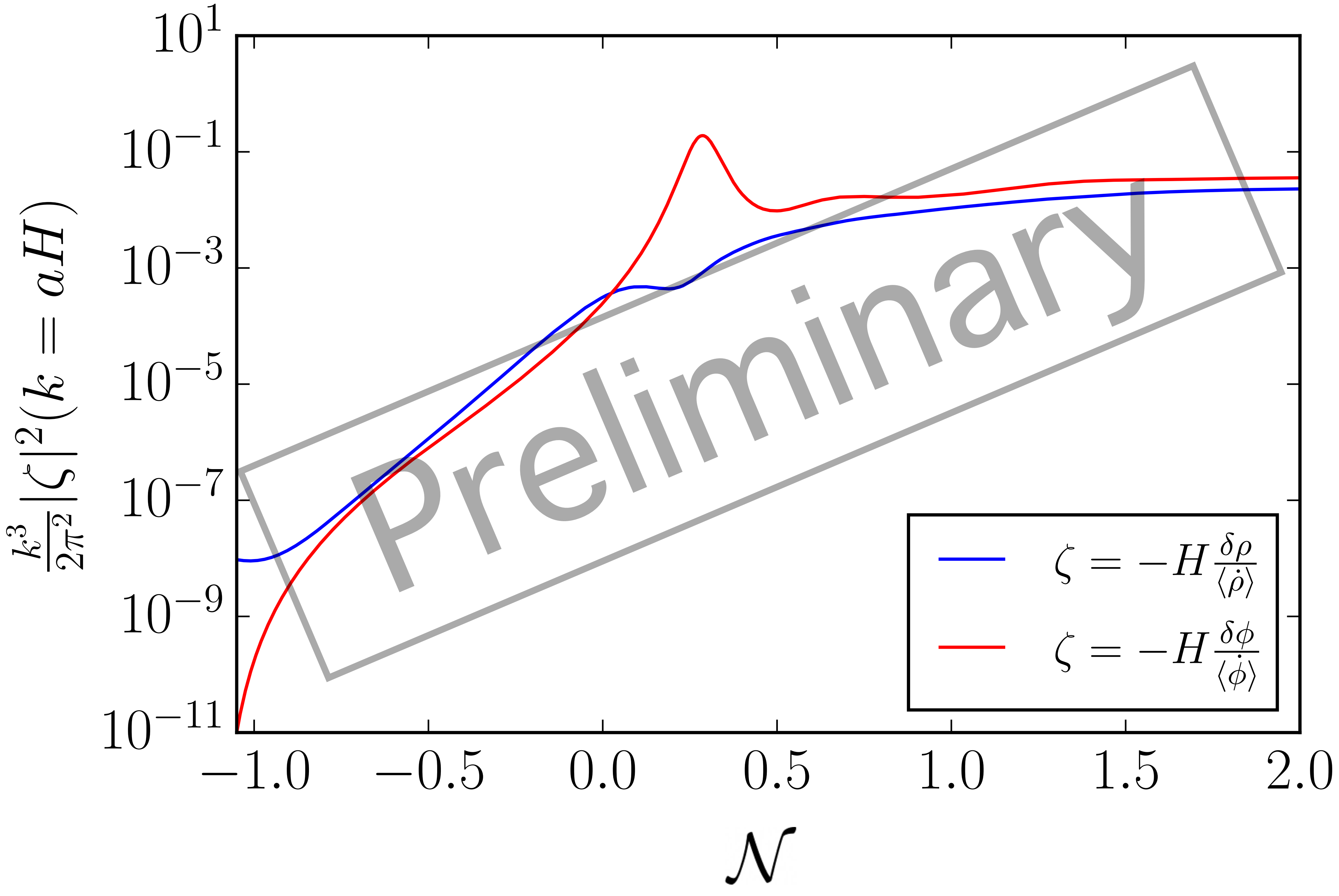
- In the **full backreaction** approach, which includes the contribution of the inhomogeneities, when in the the strong **backreaction** regime we can see:
    1. **Exponential lengthening** of the **inflationary period** with increasing coupling.
    2. **“Magnetic slow-roll”** behavior during the extra efoldings.
    3. **Power** in the gauge field spectrum is **transferred** to the **UV scales**, implying that a **wide dynamical range** is necessary to fully **capture** the **physics** for the highest couplings considered.
- **Homogenous** approach is **not sufficient** to fully capture the non-linear dynamics
- **Phenomenological result**s should be **re-studied** in the full backreaction regime: ongoing work!
- As for now, the only way is to make use of **“Lattice cosmology”**.

CosmoLattice

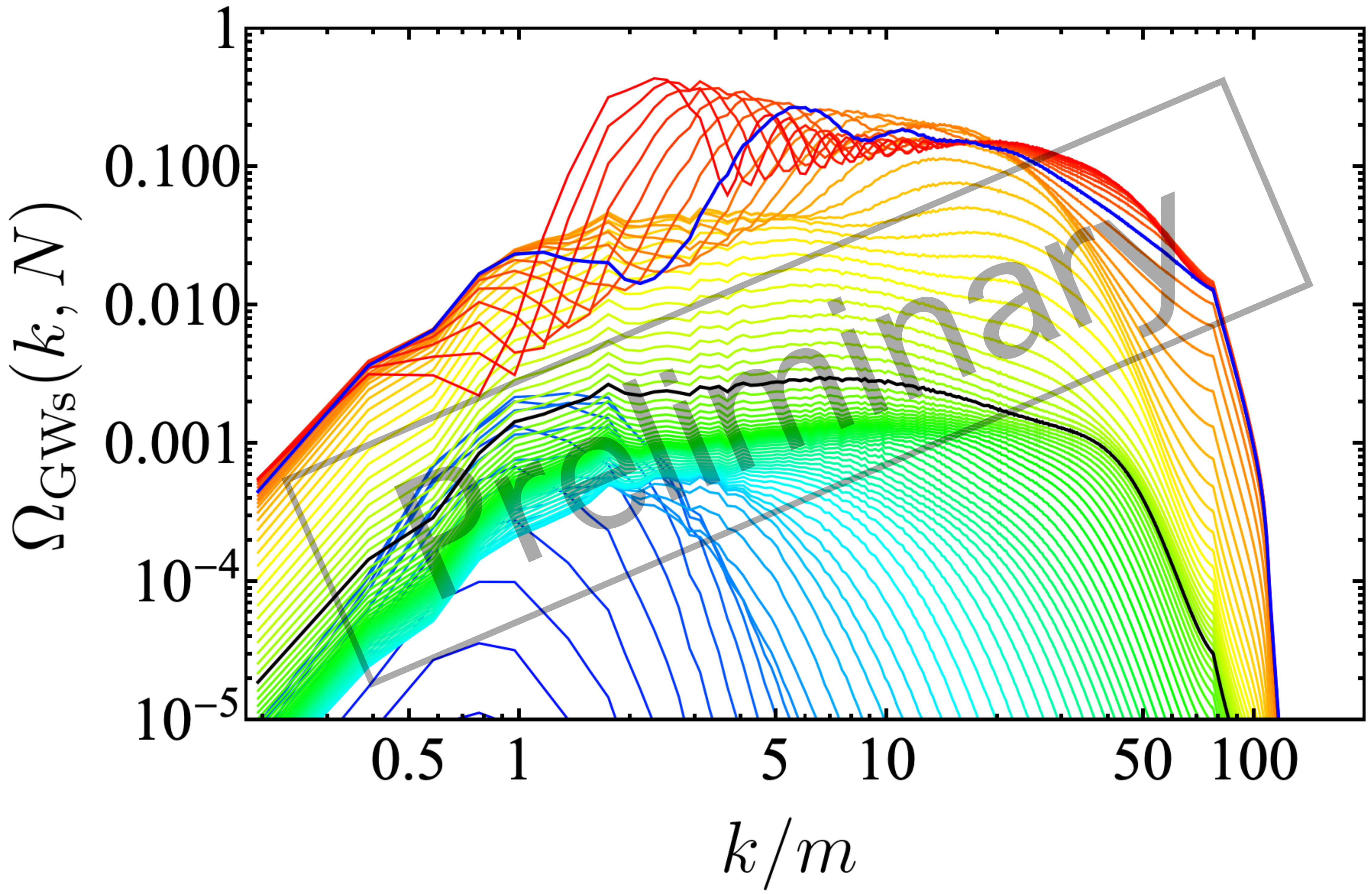
Ongoing work

What about the the phenomenology in the full strong backreaction?

Scalar perturbations of the metric and PBH formation (in collab with V. Domcke)



Tensorial perturbations of the metric and production GWs (in collab with N. Loayza)



Backup slides

Our approach: Full backreaction

Backreaction

FLRW spacetime

$$S_m = \int \mathrm{d}x^4 \left(\frac{1}{2} a^3 \dot{\phi}^2 - \frac{1}{2} a (\vec{\nabla}\phi)^2 - \frac{1}{2} a^3 m^2 \phi^2 + \frac{1}{2} a (\vec{E}^2 - a^{-2} \vec{B}^2) + \frac{\alpha_\Lambda}{m_p} \phi \vec{E} \cdot \vec{B} \right)$$

Dynamics

ALP inflaton

$$\ddot{\phi} = -3H\dot{\phi} + \frac{1}{a^2} \vec{\nabla}^2 \phi - m^2 \phi + \frac{\alpha_\Lambda}{a^3 m_p} \vec{E} \cdot \vec{B}$$

U(1) Gauge field

$$\dot{\vec{E}} = -H\vec{E} - \frac{1}{a^2} \vec{\nabla} \times \vec{B} - \frac{\alpha_\Lambda}{a m_p} \left(\dot{\phi} \vec{B} - \vec{\nabla}\phi \times \vec{E} \right)$$

Friedmann 1

$$\ddot{a} = -\frac{a}{3 m_p^2} \left(2\rho_{\mathrm{K}} - \rho_{\mathrm{V}} + \rho_{\mathrm{EM}} \right)$$

Constraints

U(1) Gauge field

$$\vec{\nabla} \cdot \vec{E} = -\frac{\alpha_\Lambda}{a m_p} \vec{\nabla}\phi \cdot \vec{B}$$

Friedmann 2

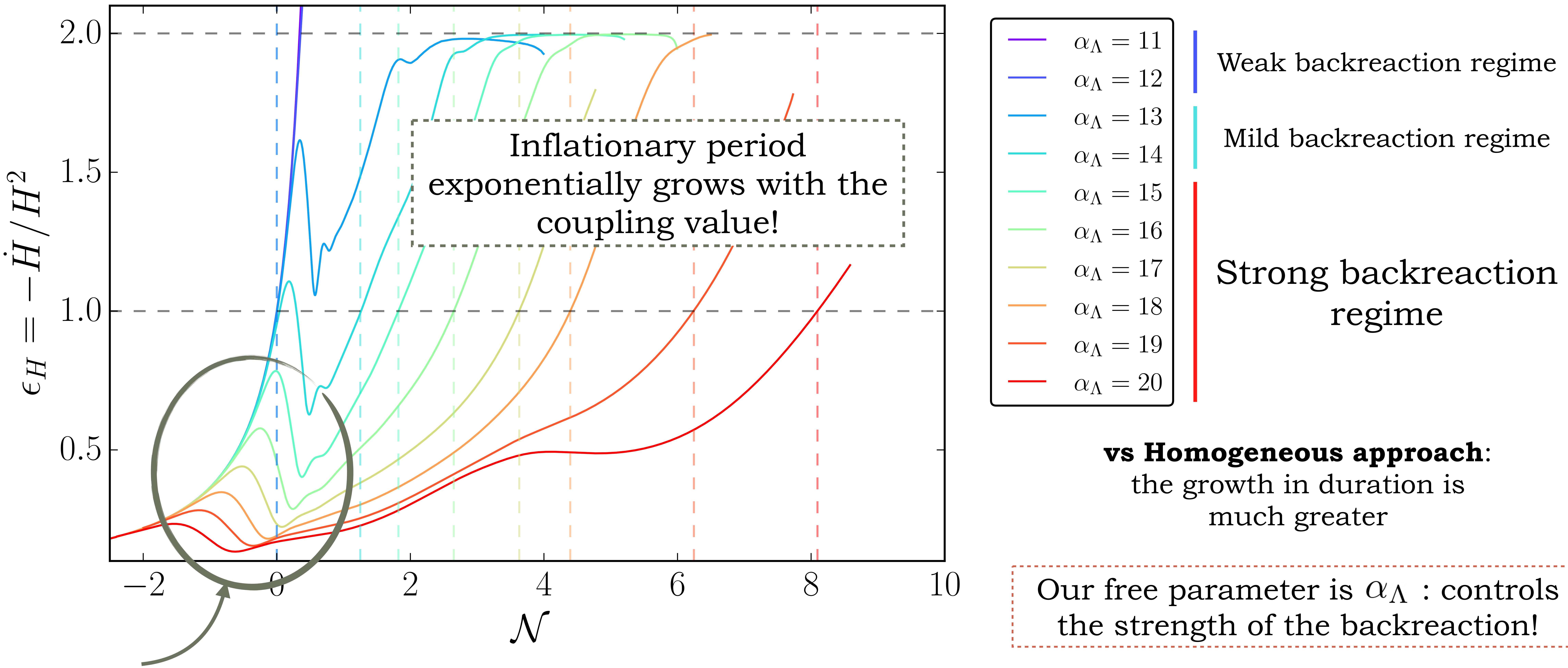
$$H^2 = \frac{1}{3 m_p^2} \left(\rho_{\mathrm{K}} + \rho_{\mathrm{G}} + \rho_{\mathrm{V}} + \rho_{\mathrm{EM}} \right)$$

CosmoLattice

[D. G. Figueroa, A. Florio, F. Torrenti & W. Valkenburg (2006.15122)]
[D. G. Figueroa, A. Florio, F. Torrenti & W. Valkenburg (2102.01031)]

Inflation duration

Also: $\epsilon_H = 1 + (2\rho_K - \rho_V + \rho_{EM})/\rho_{tot}$



Bump before inflation end
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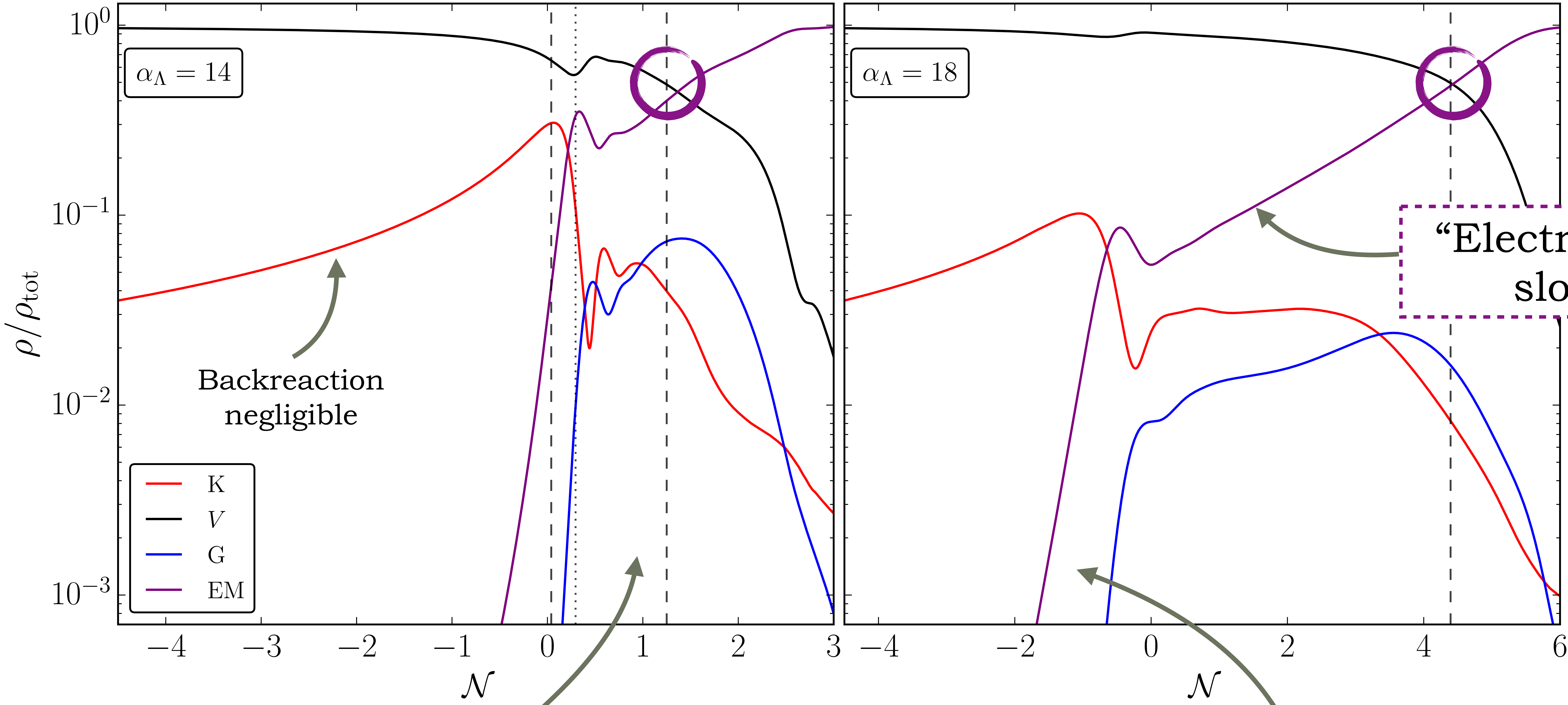
Mild backreaction regime

Strong backreaction regime



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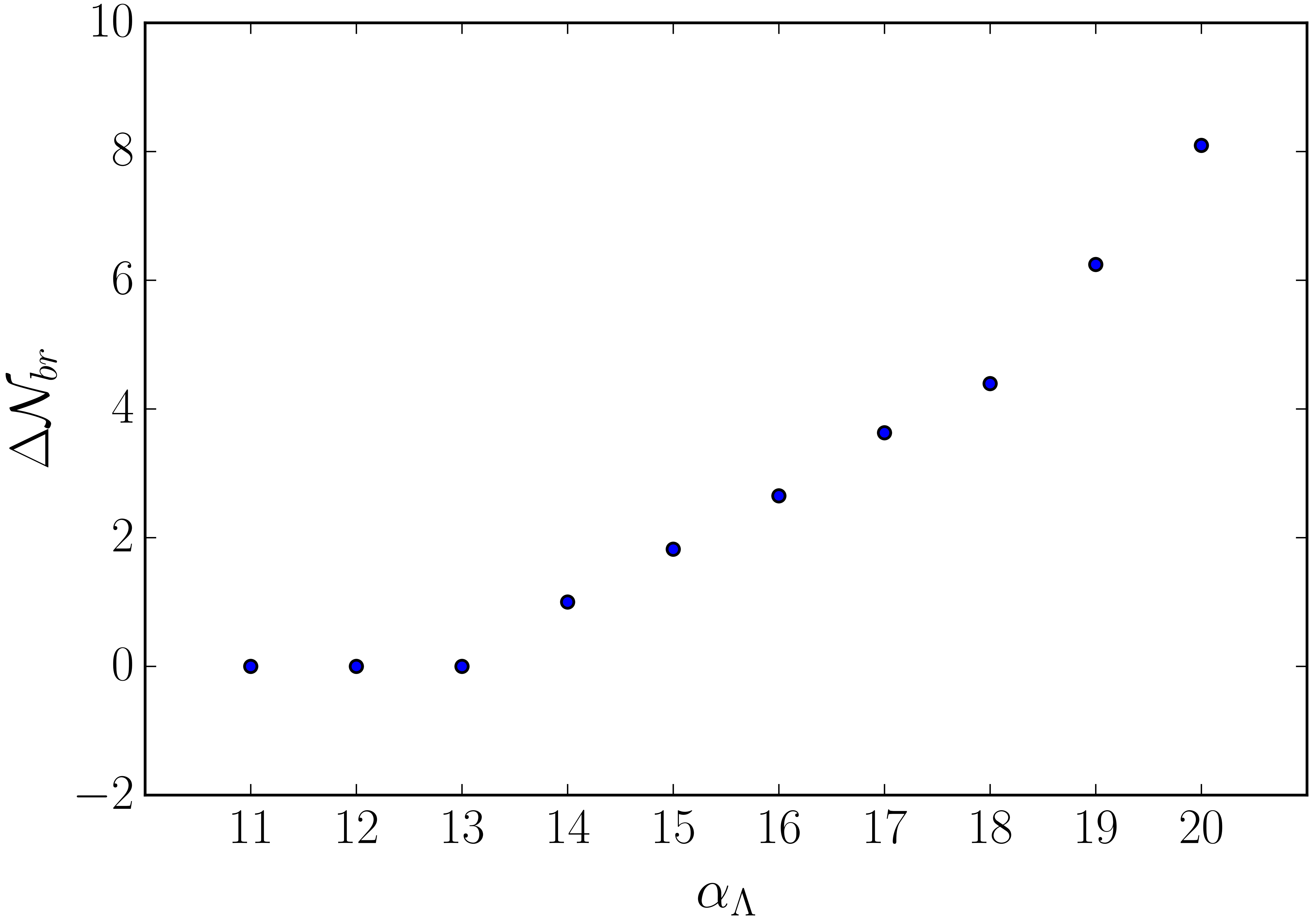
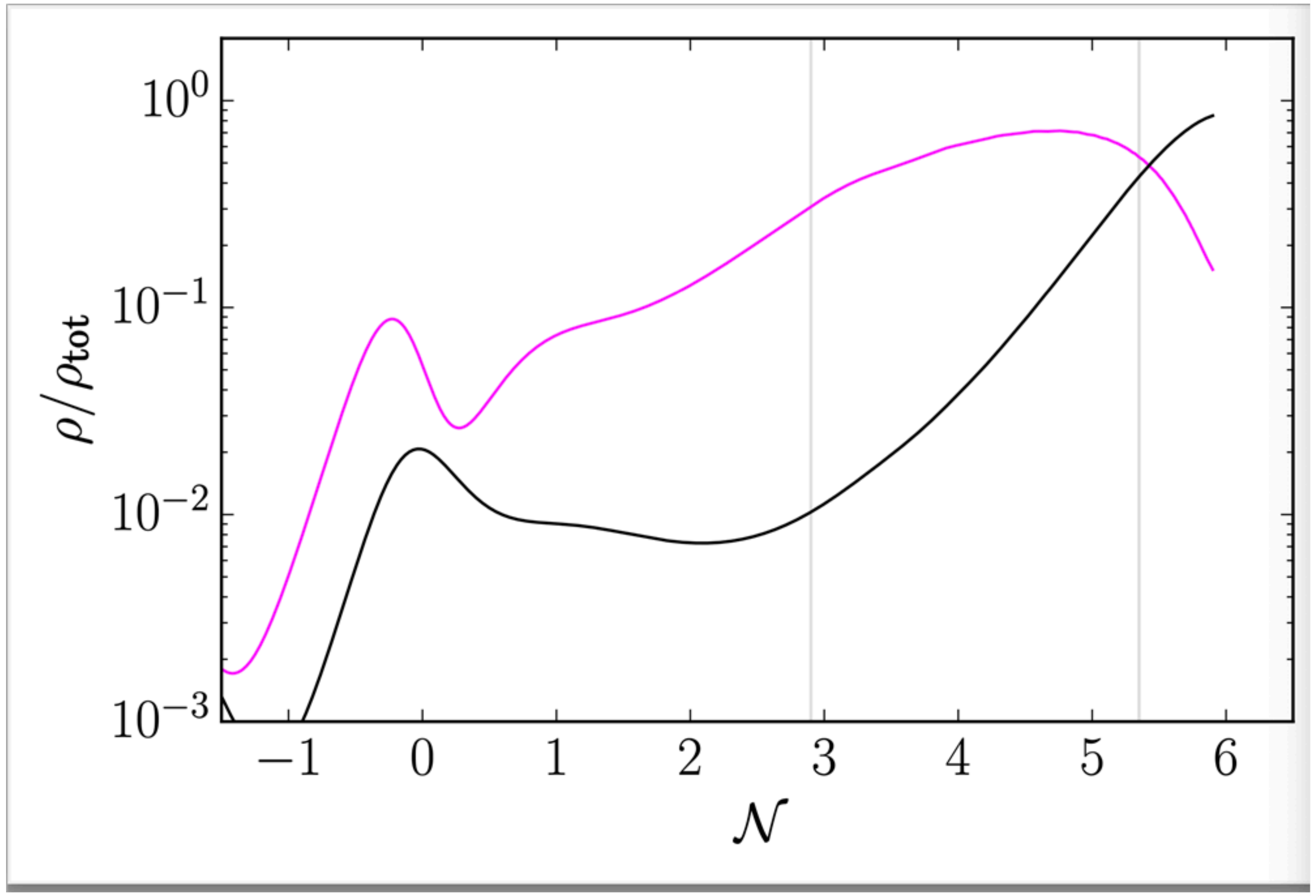
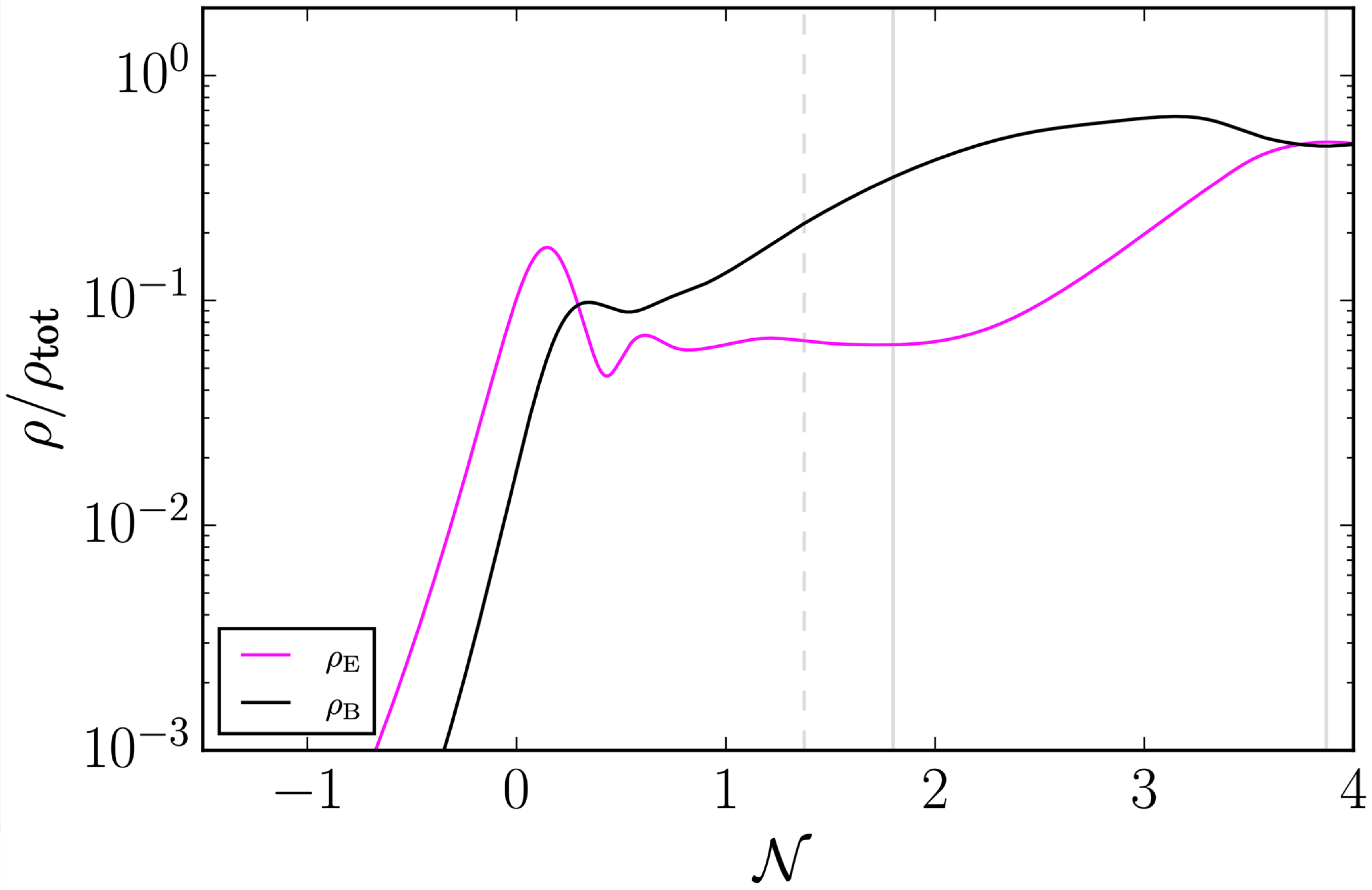
Extra efoldings vs couplings



Magnetic slow-roll

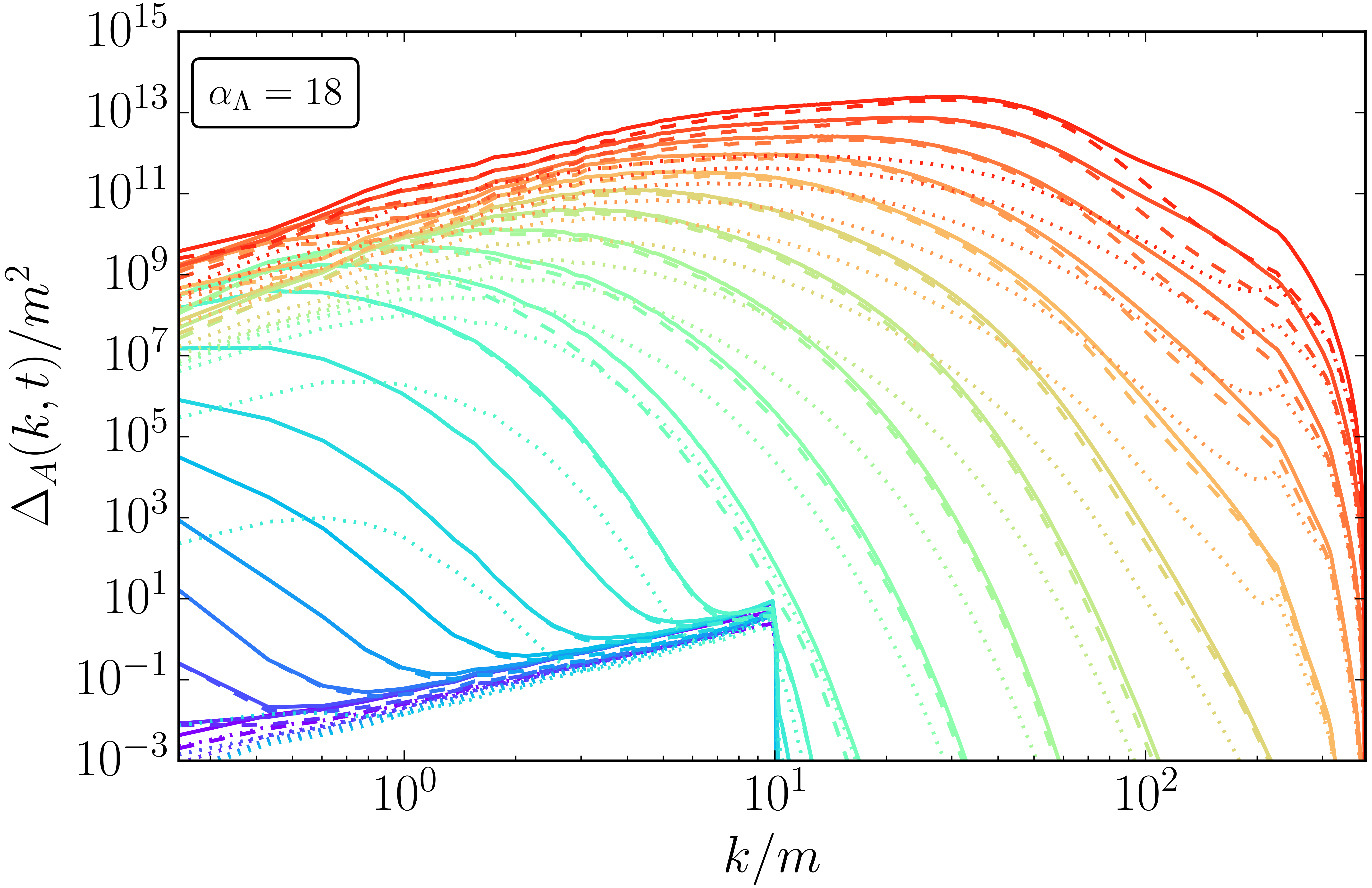


Homogeneous backreaction approach

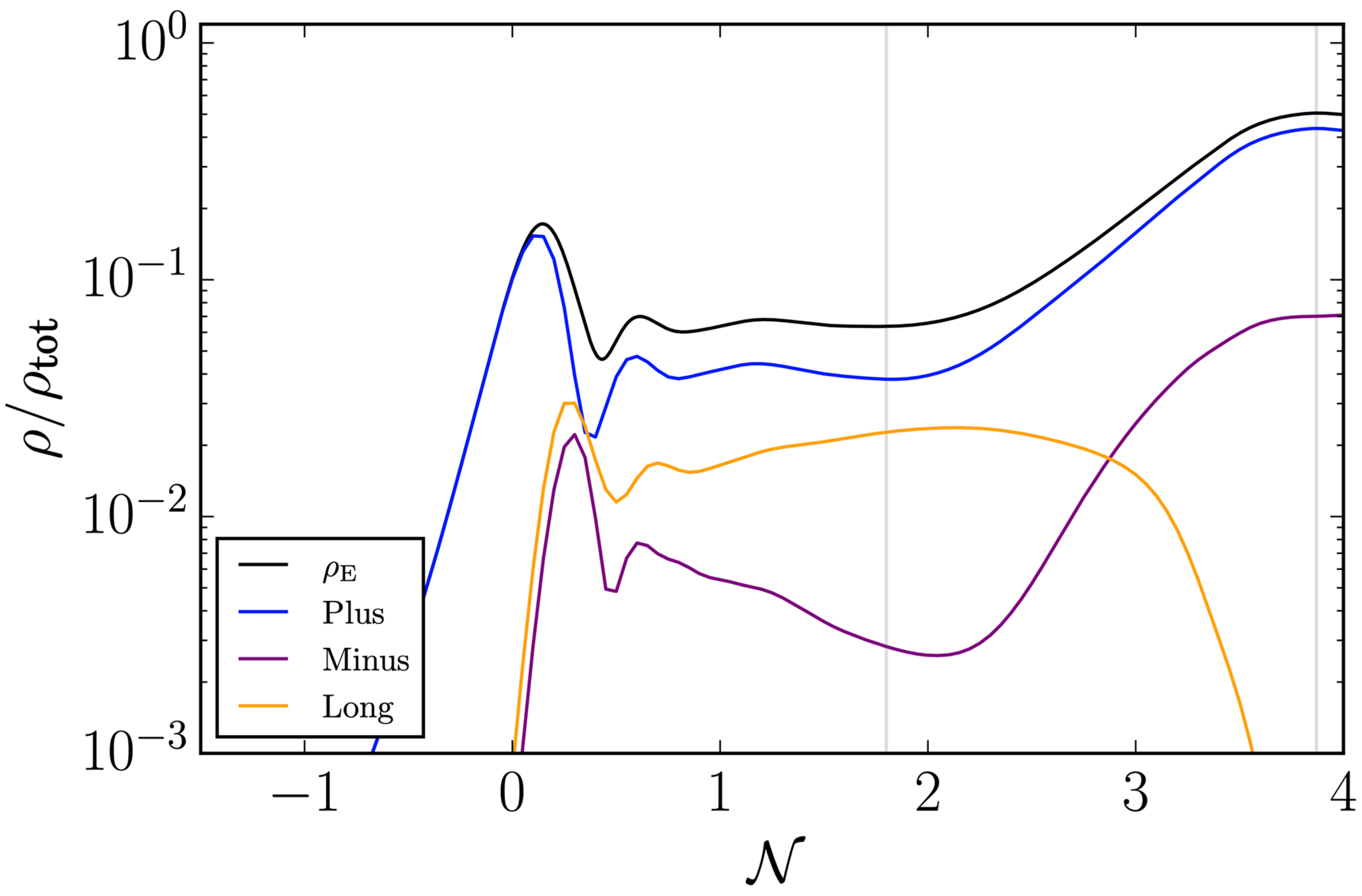


Full backreaction approach

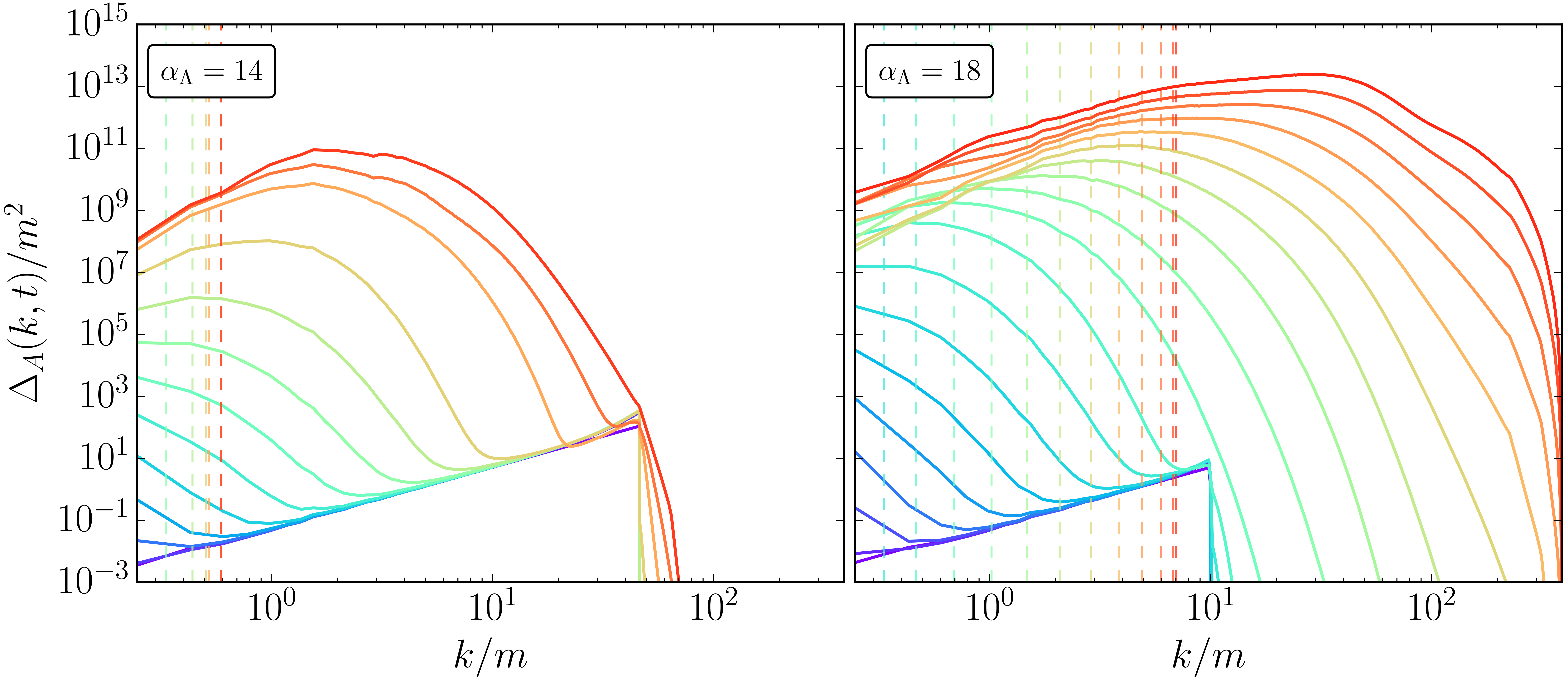
Spectra of the gauge modes: helicities



Helicities and longitudinal mode

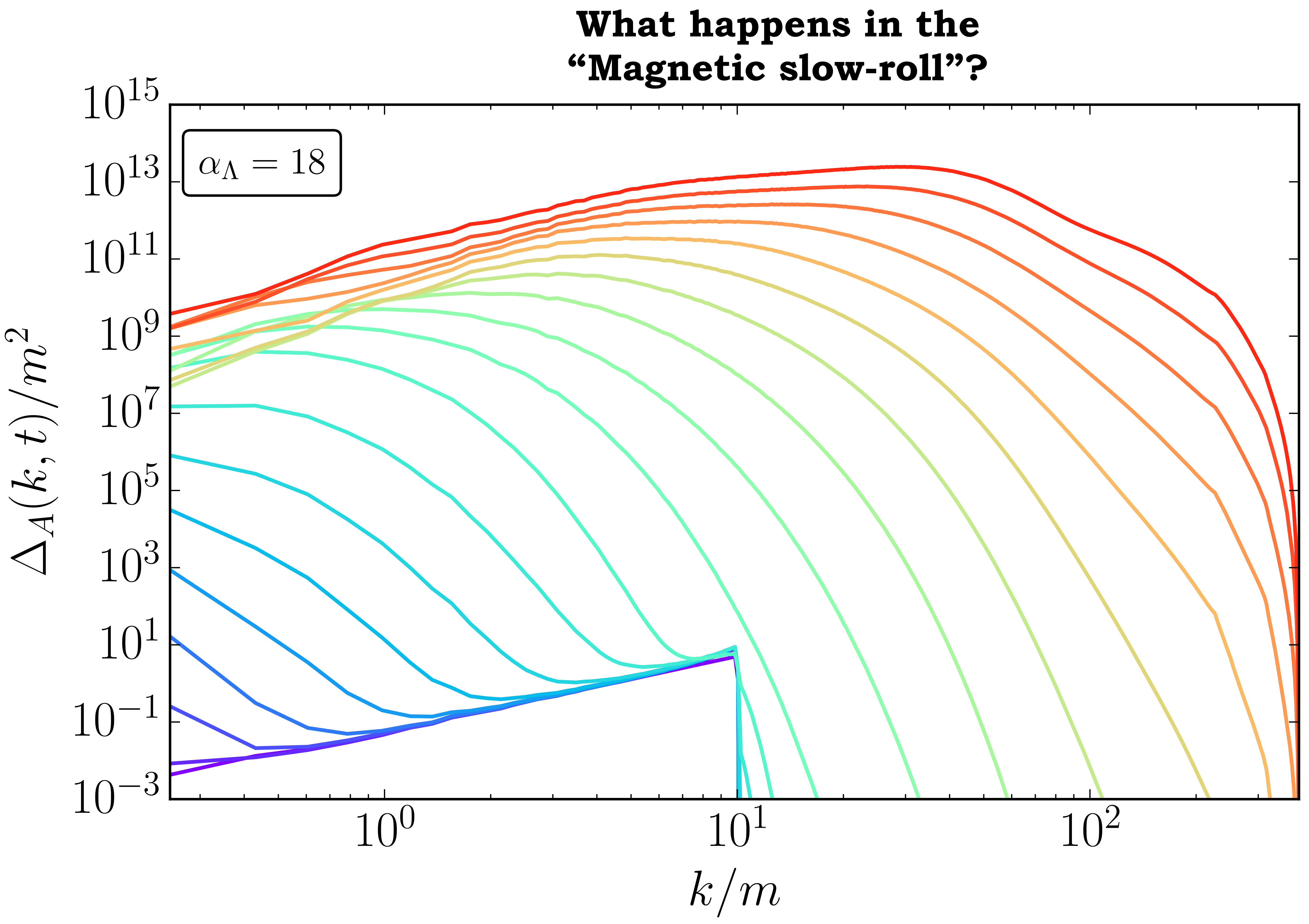


Spectra of the gauge modes: mild vs strong



Spectra of the gauge modes

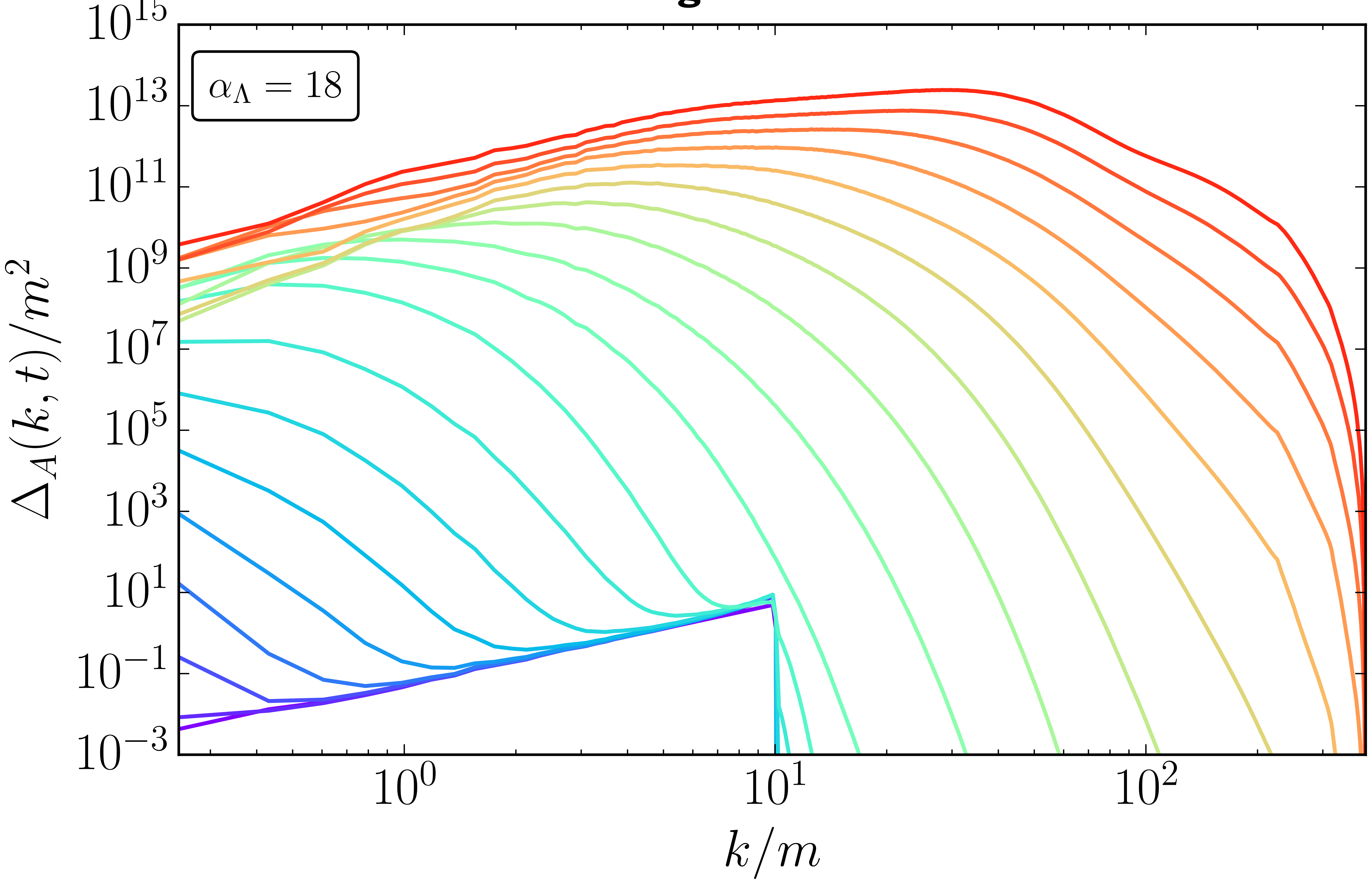
Spectra of the gauge modes



Spectra of the gauge modes

Evolution in
0.5 efolding gaps

What happens in the
“Magnetic slow-roll”?



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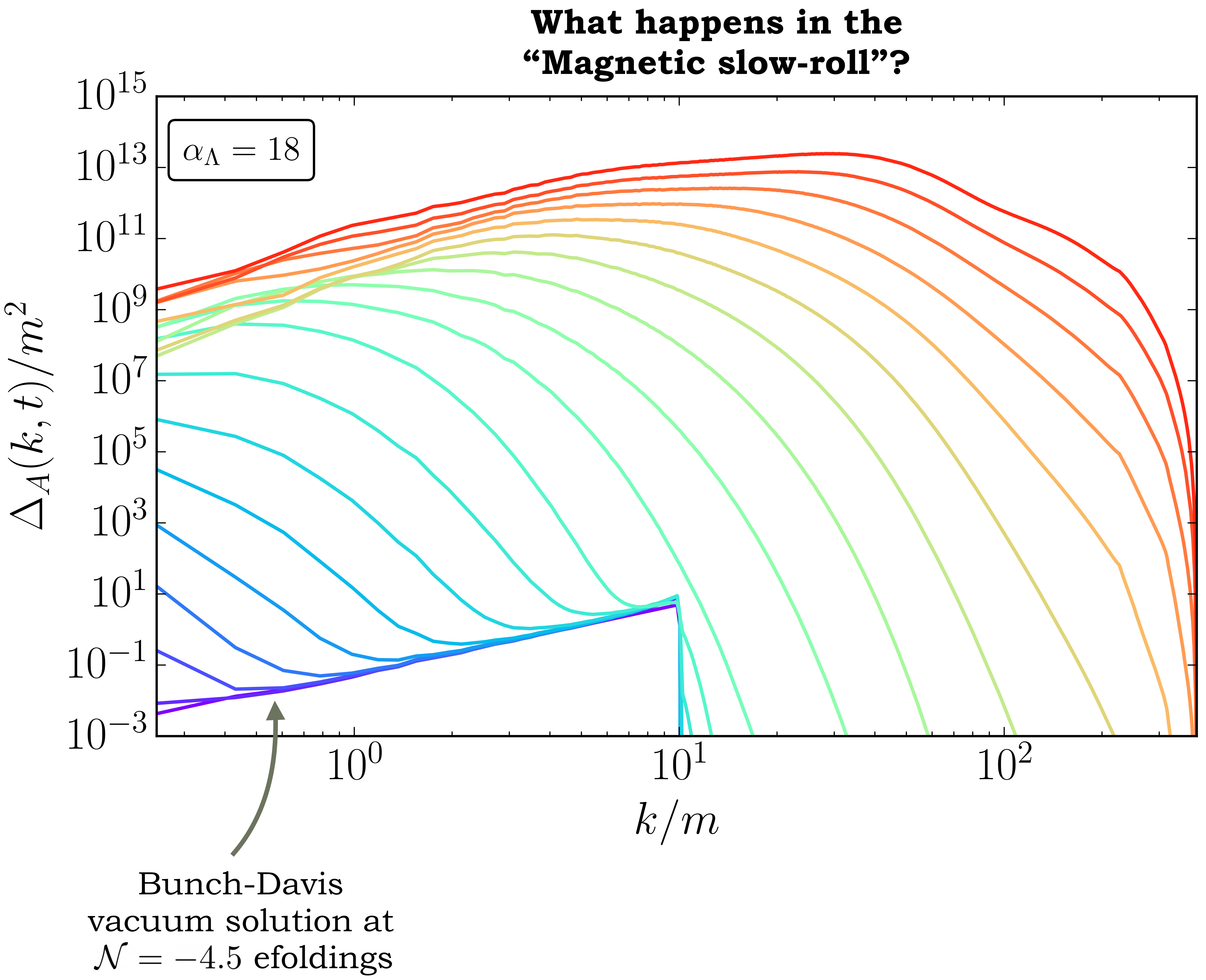

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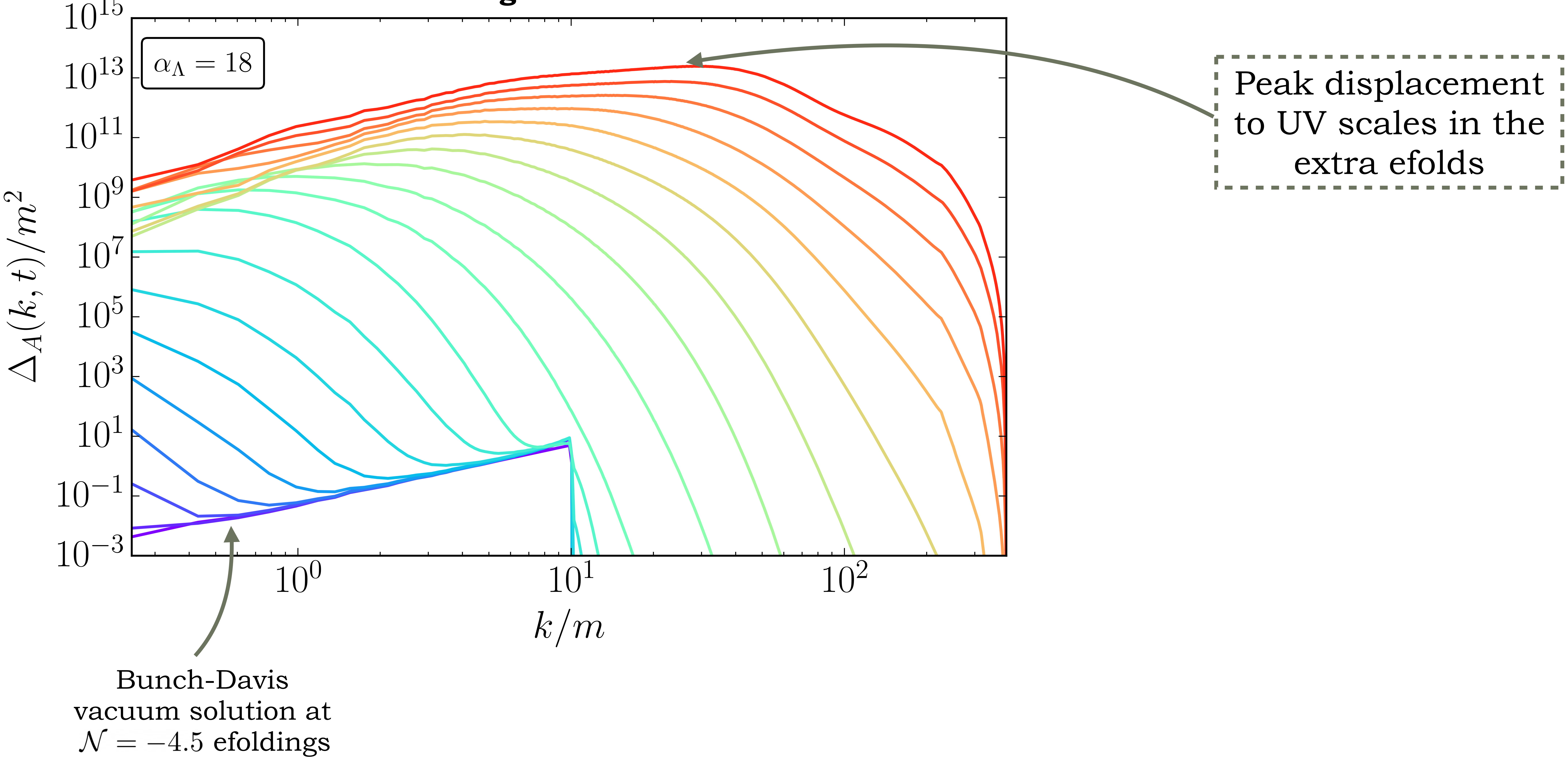

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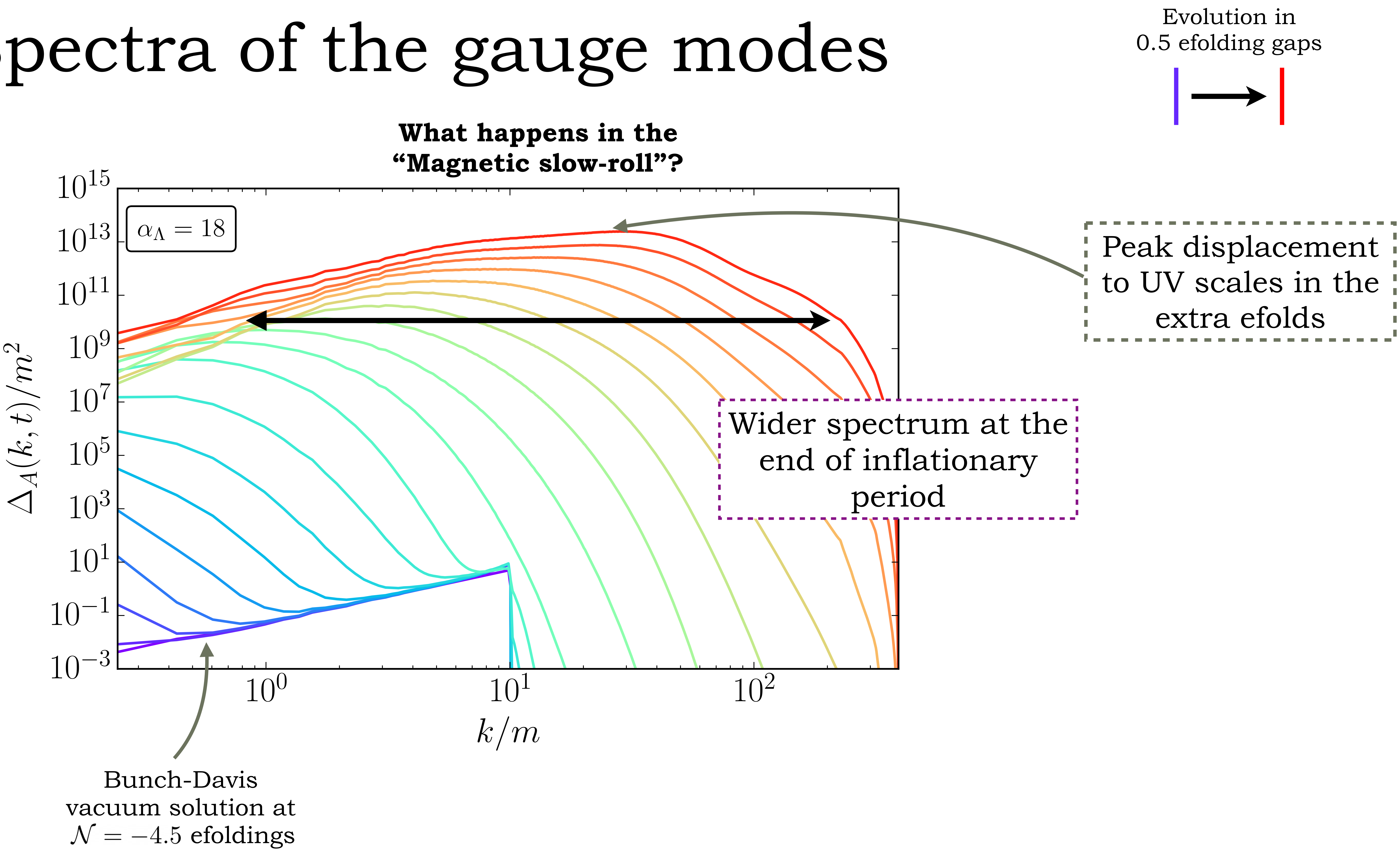

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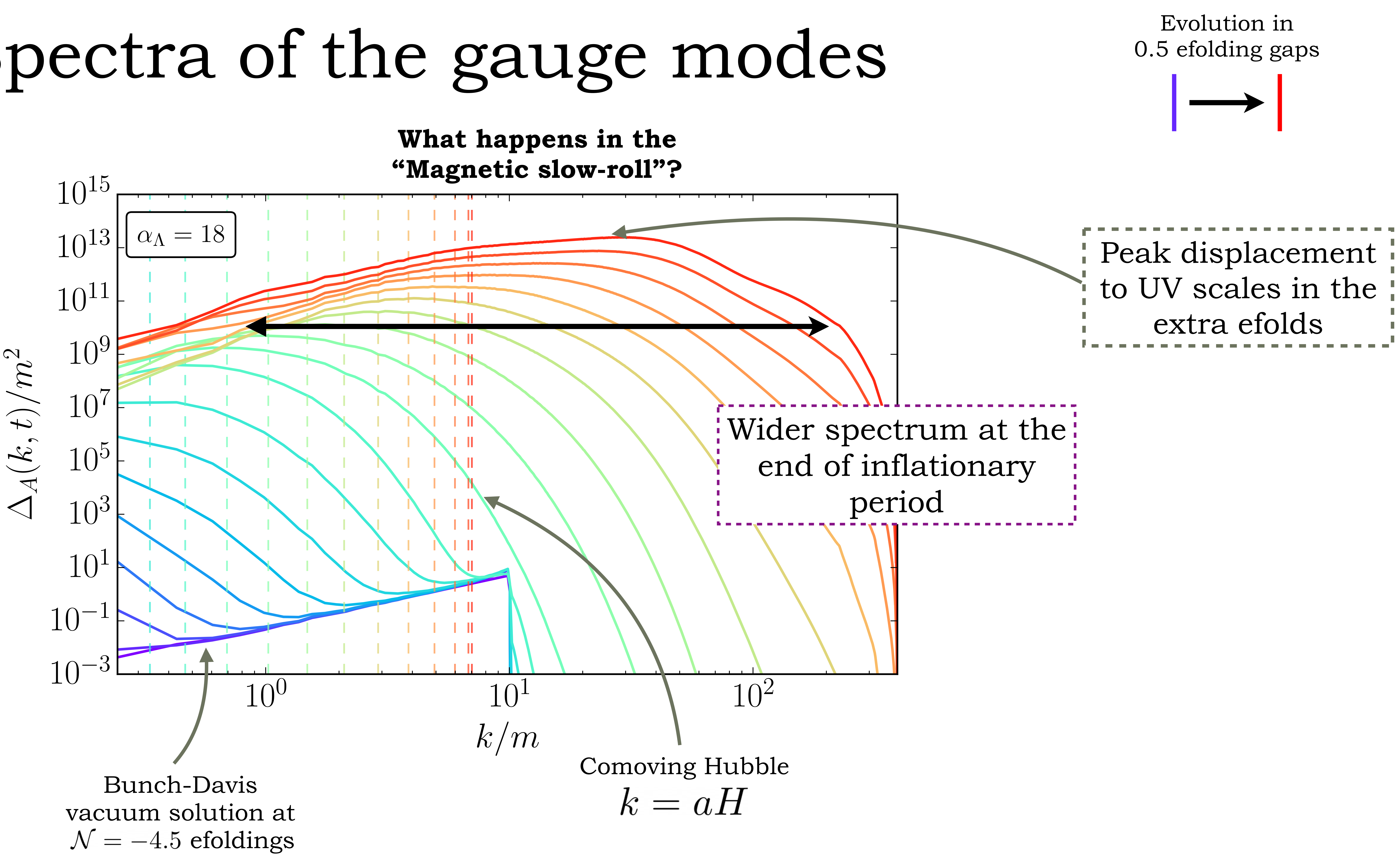

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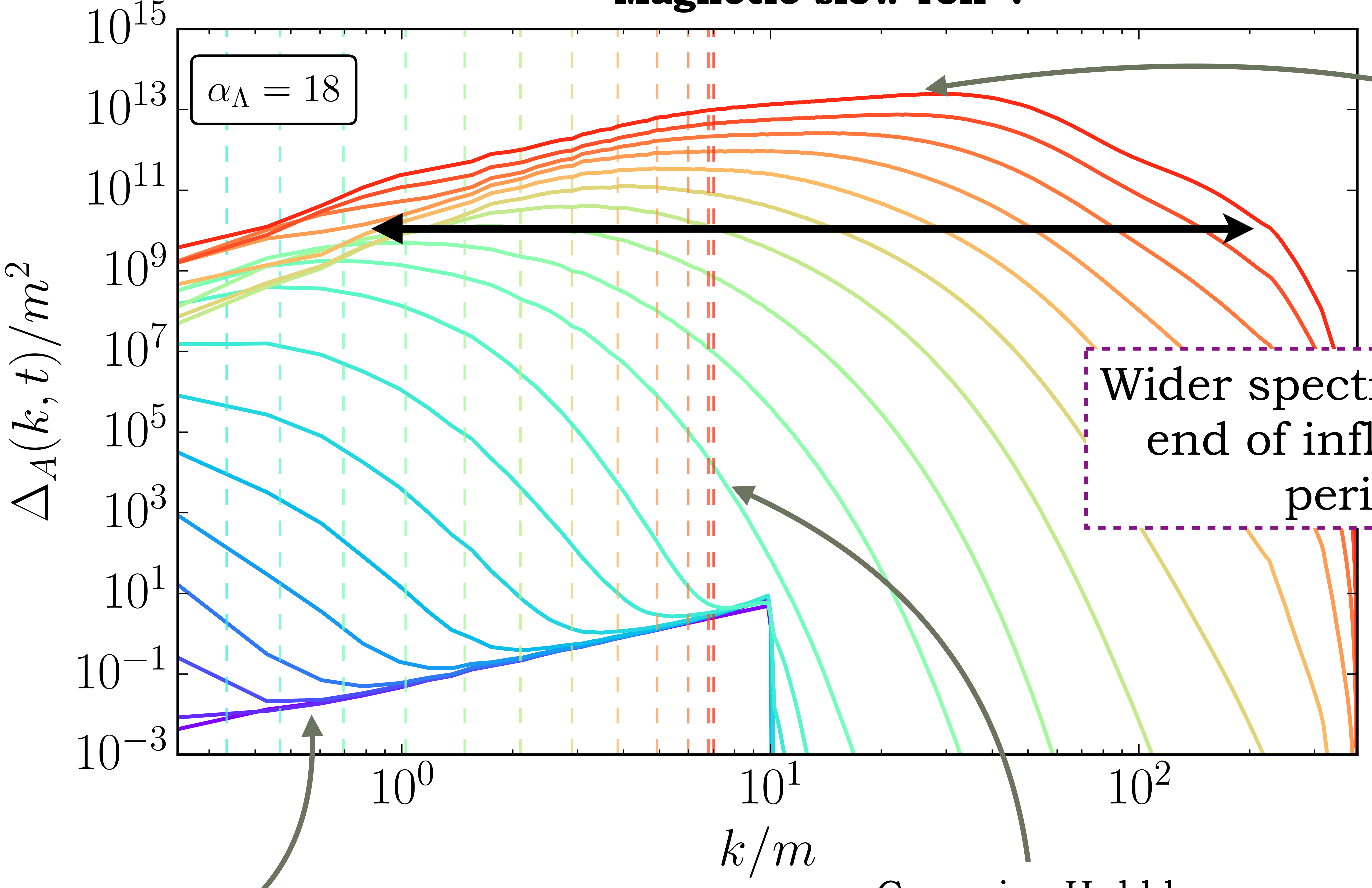

Peak displacement to UV scales in the extra efolds

Wider spectrum at the end of inflationary period

Bunch-Davis vacuum solution at $\mathcal{N} = -4.5$ efoldings

Comoving Hubble
$k = aH$

vs Homogeneous approach:

- Sub-hubble peak at the end of inflation
- No oscillatory features in the spectra