Università di Pisa
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DE L'ÉCOLE NORMALE SUPÉRIEURE
cnrs

Primordial black holes from stochastic tunnelling

Chiara Animali

DarkCosmoGrav Conference

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Primordial Black Holes

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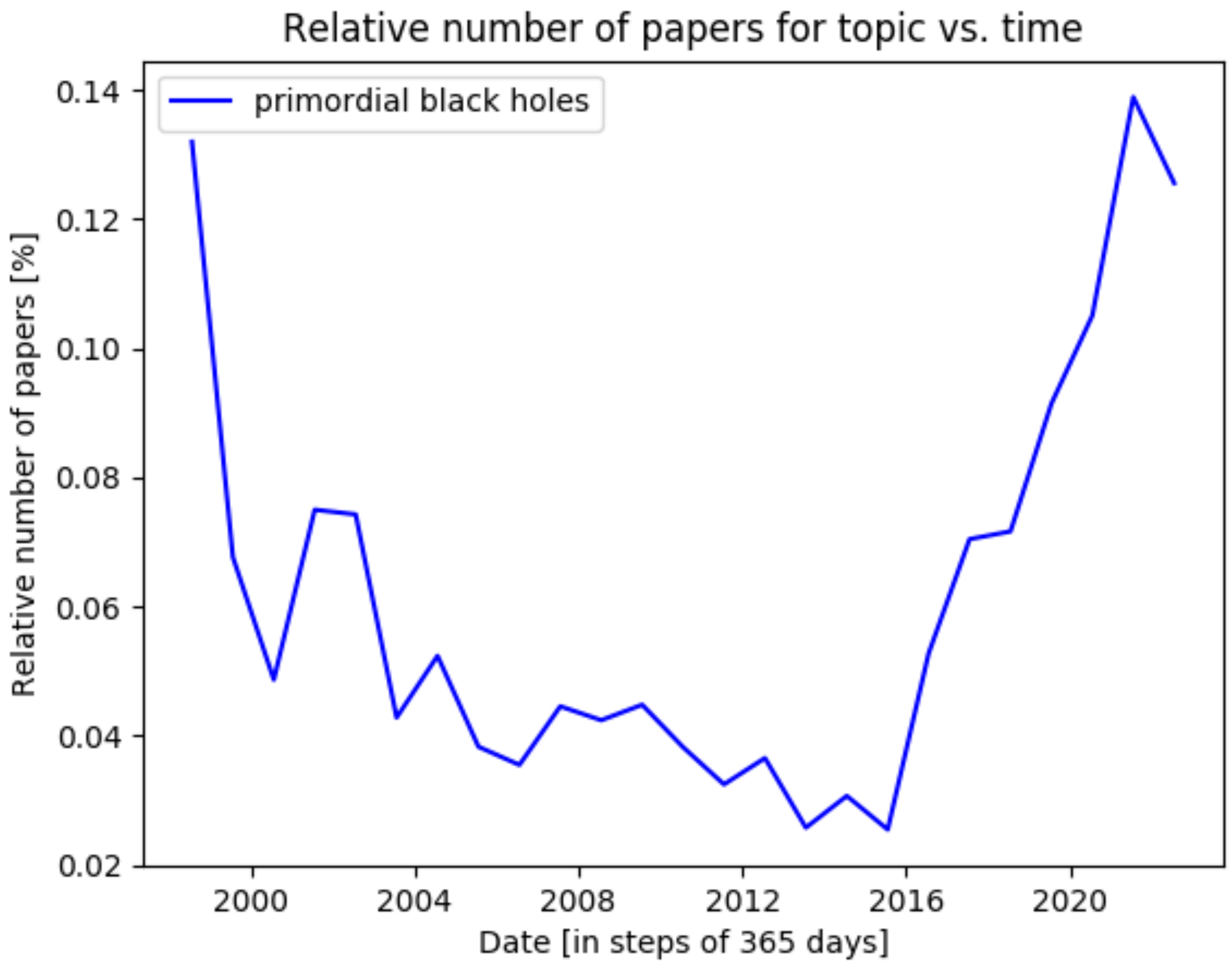

[Plot realised via www.benty-fields.com/trending]

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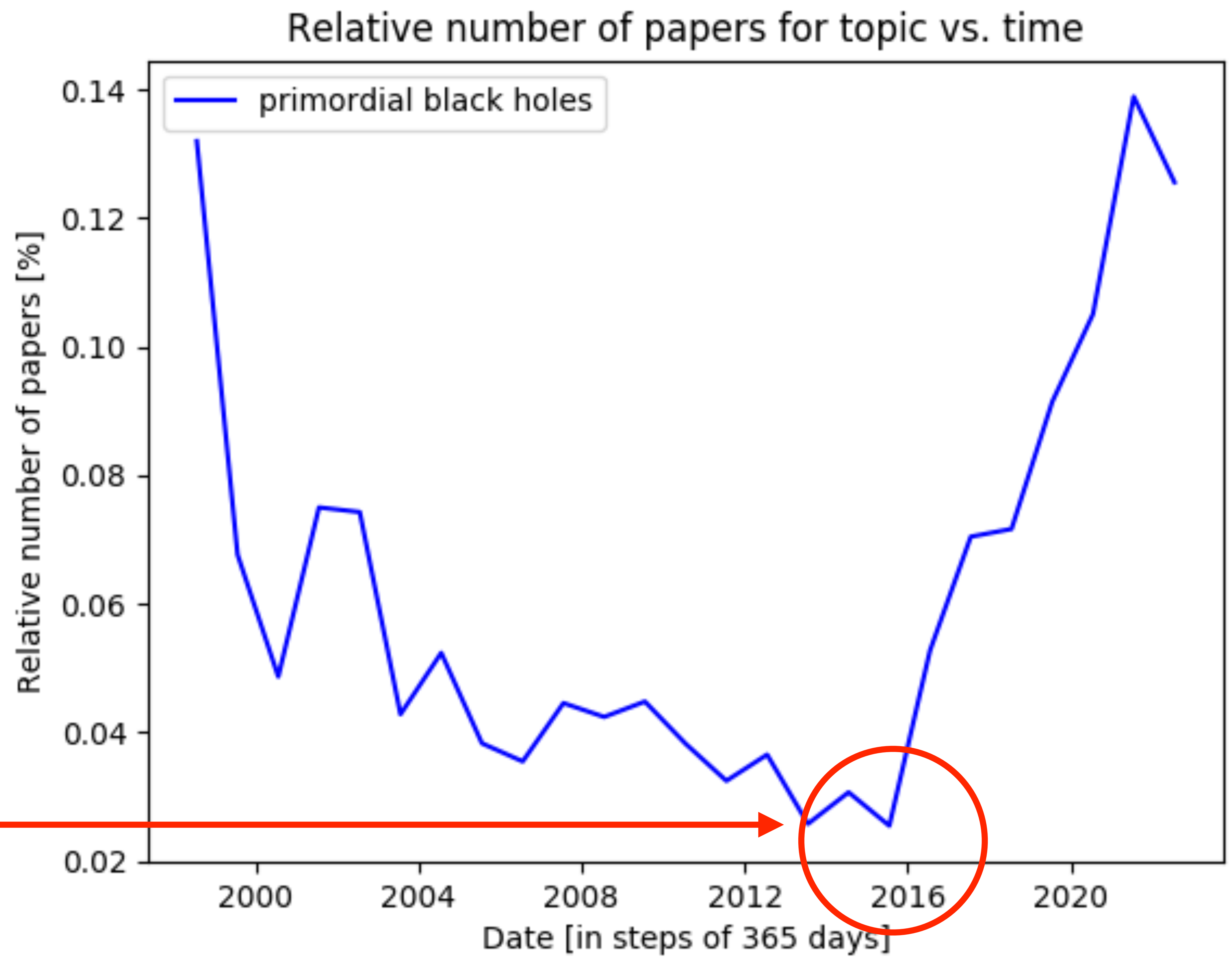

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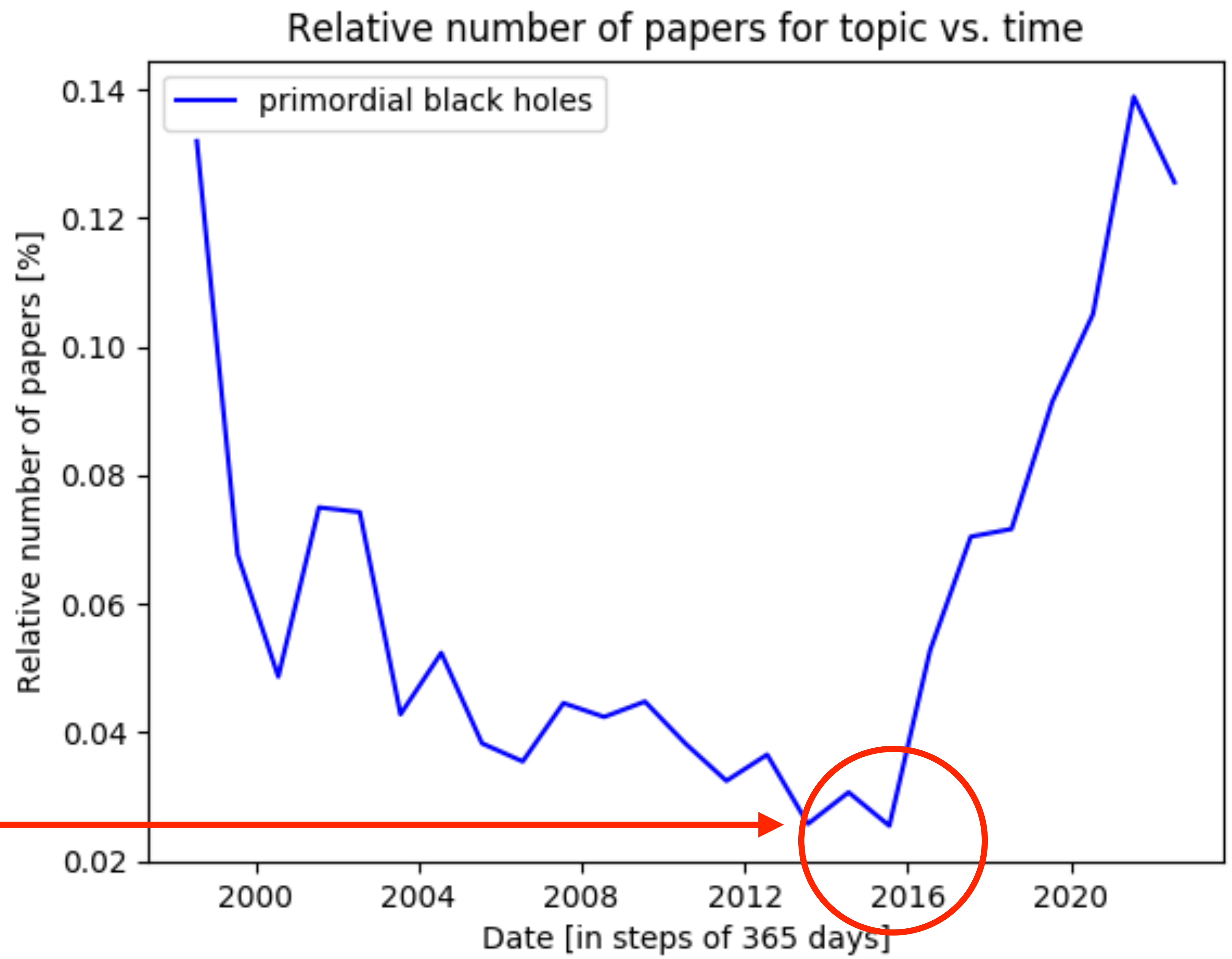

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S. Bird, I. Cholis, J.B. Muñoz, Y. Ali-Haïmoud,
M. Kamionkowski, E. D. Kovetz, A. Raccanelli, A. G. Riess [2016]:
Did LIGO detect dark matter?

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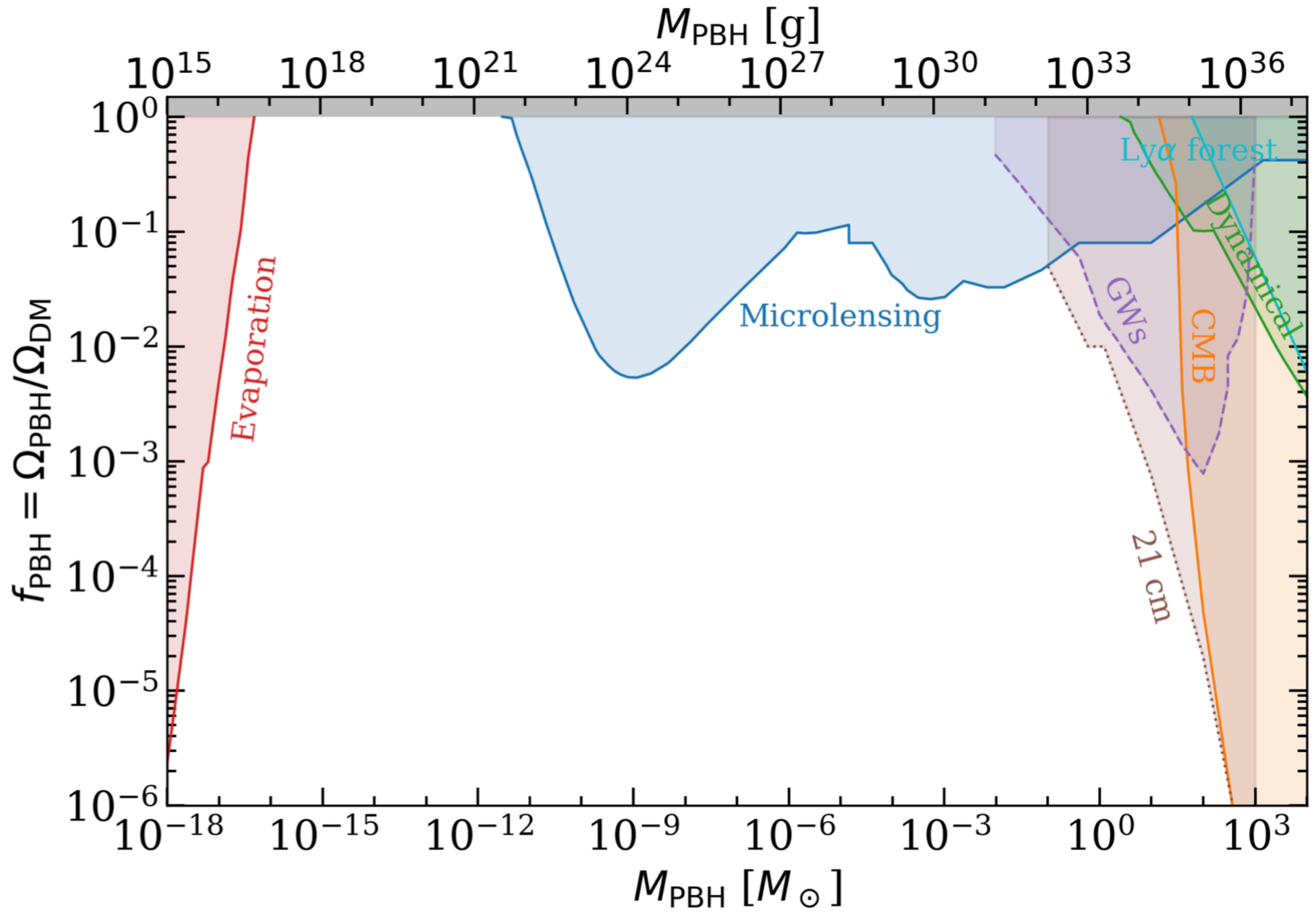

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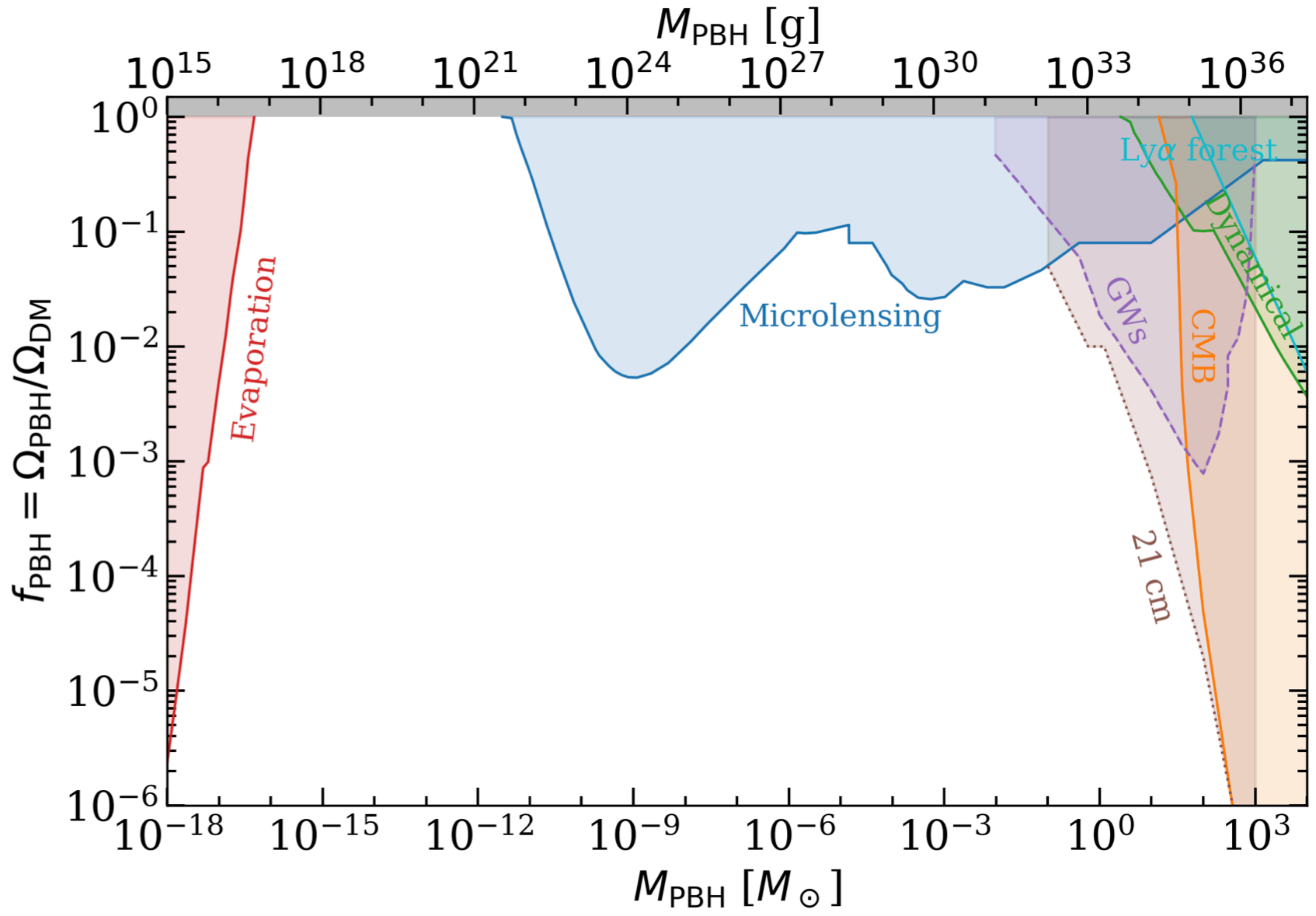

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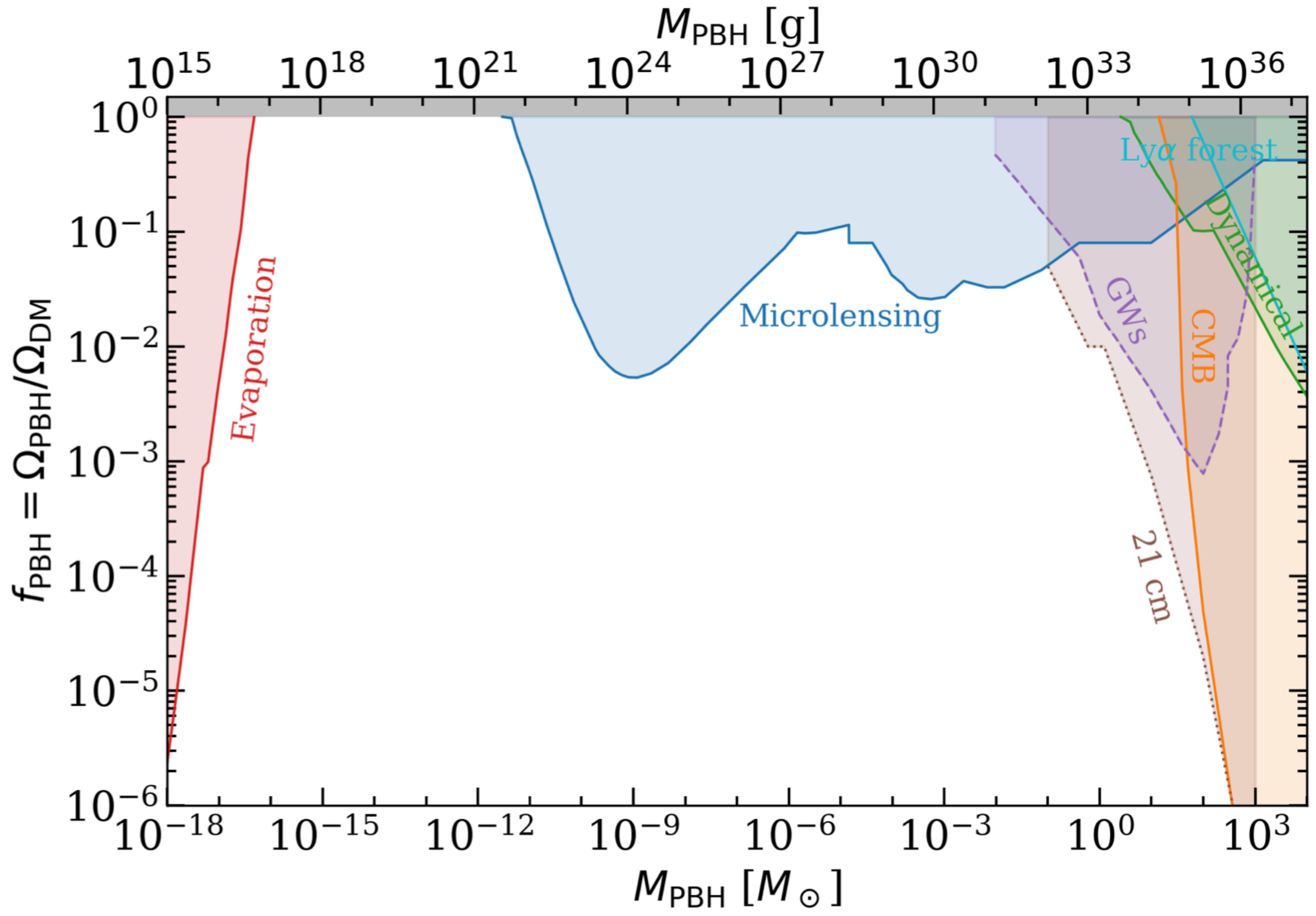

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- They could extend the region of the inflationary potential we can probe

- They provide a place to look for quantum effects (such as quantum diffusion)

Inflation

Inflation

- High energy phase of accelerated expansion of spacetime $ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -dt^2 + a^2(t)d\vec{x}^2$ $\dot{a}, \ddot{a} > 0$

$$(10 \text{ MeV})^4 < \rho < (10^{16} \text{ GeV})^4$$

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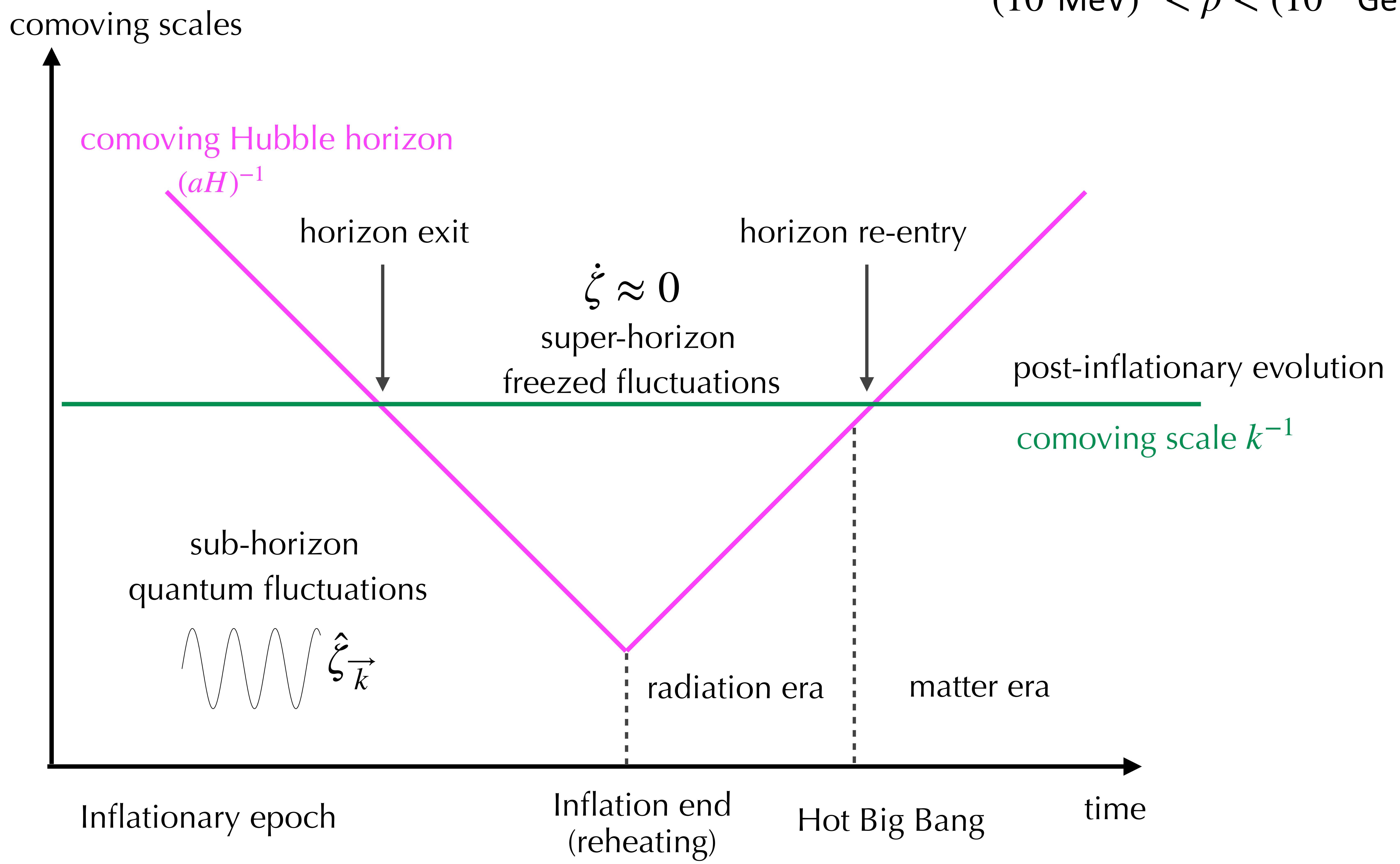

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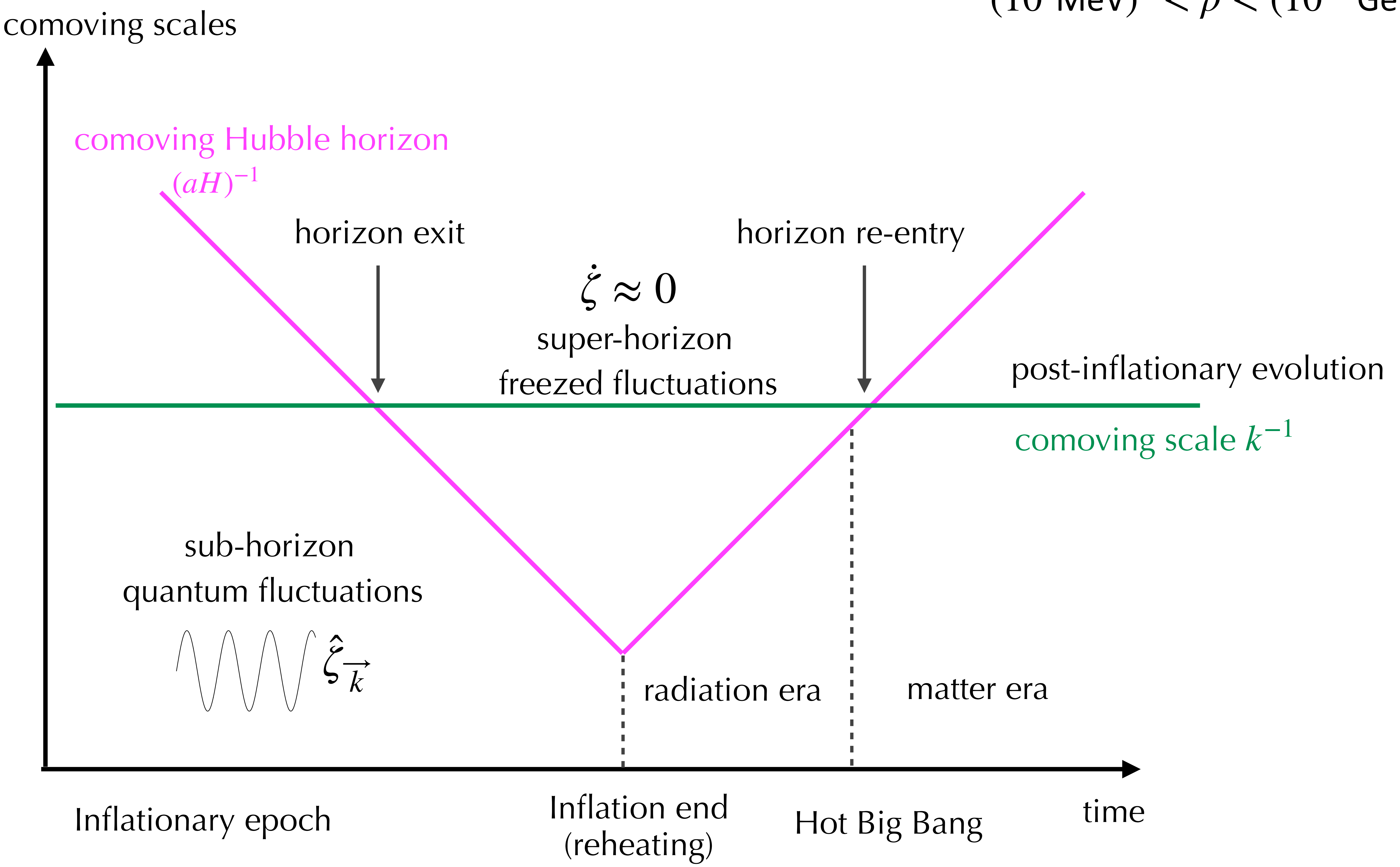

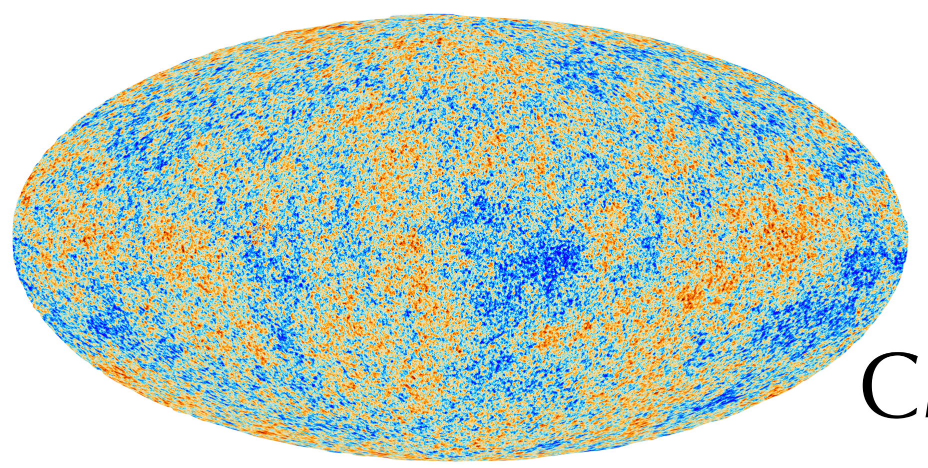

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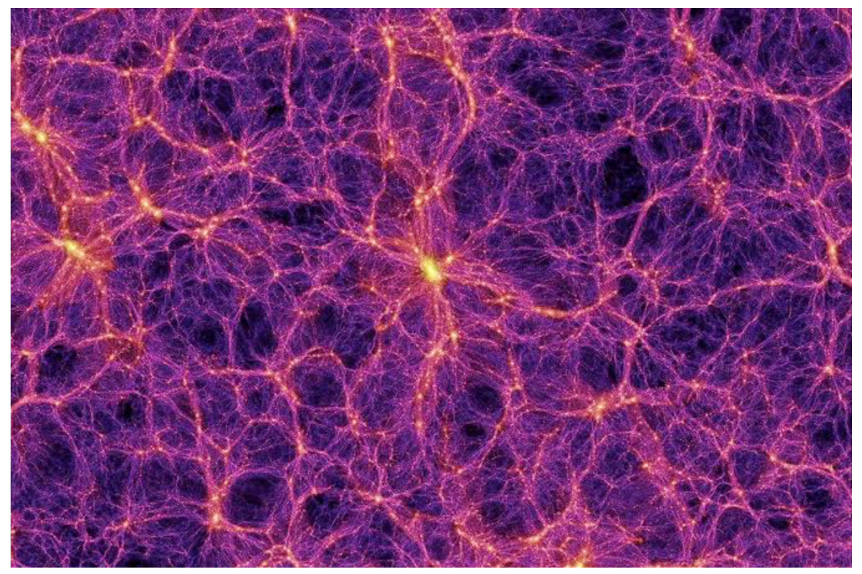
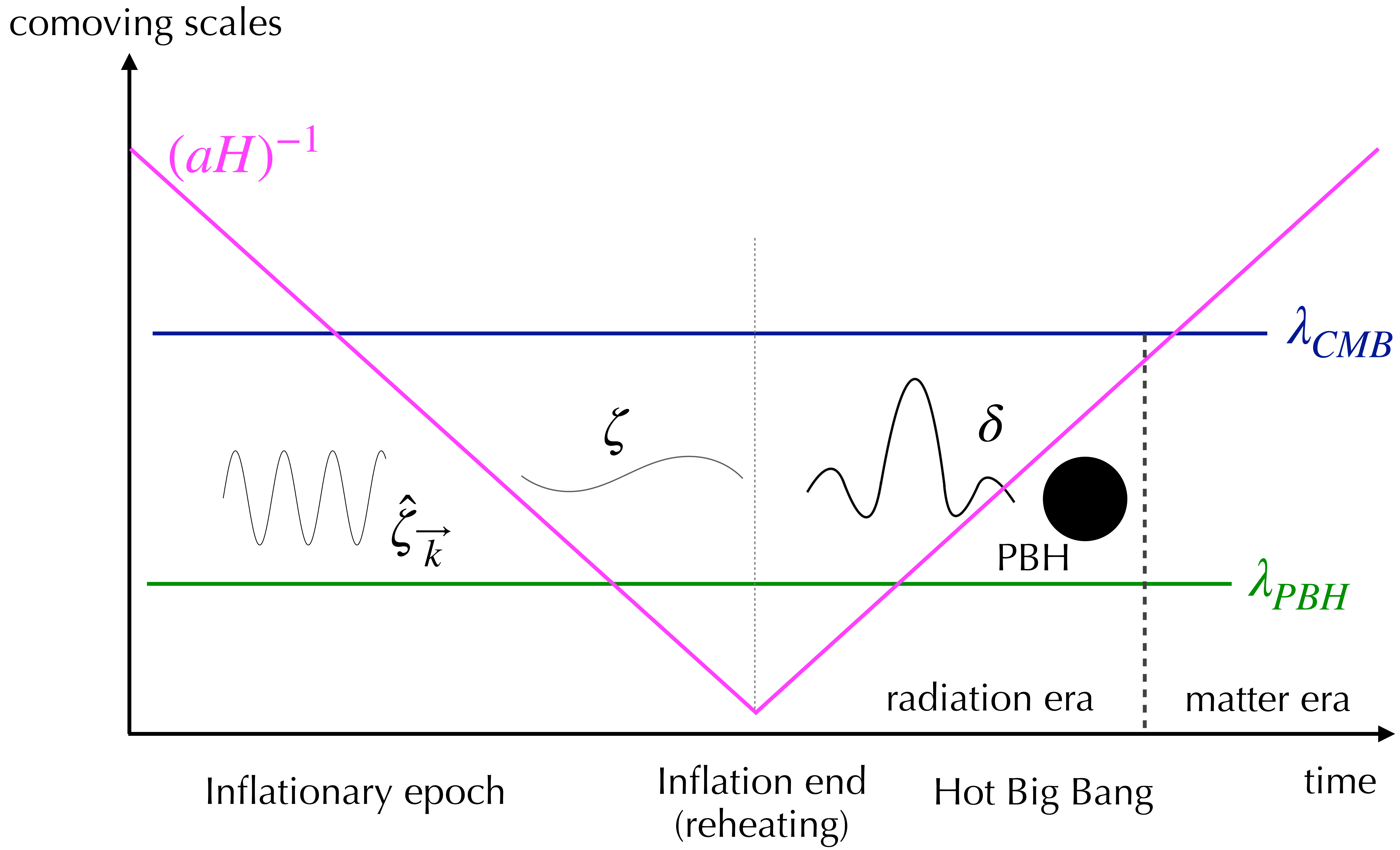


LSS

Primordial Black Holes : How?

- PBHs may be originated from peaks of the density perturbations generated in the early universe



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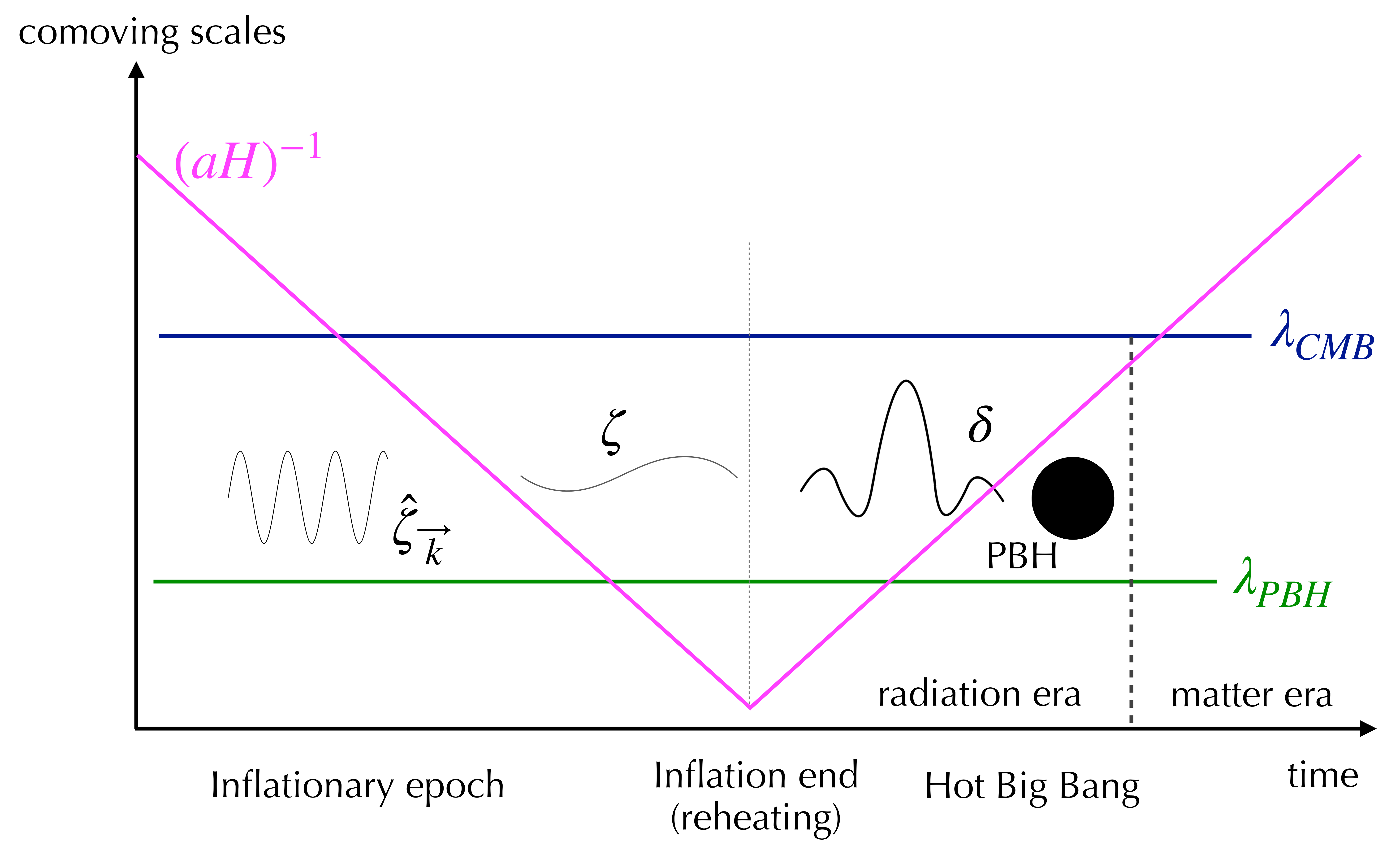

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- Can inflation give rise to such enhanced perturbations?

Inflation

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- Simplest realisation: slow-roll inflation

  scalar field ϕ (inflaton) slowly rolling towards the minimum of its potential

$$S_\phi = \int d^4x \sqrt{-g}\, \left(\frac{1}{2} g^{\mu\nu}\, \partial_\mu\phi\partial_\nu\phi - V(\phi)\right)$$

$$\epsilon = -\frac{\dot{H}}{H^2} = \frac{1}{16\,\pi\, G}\left(\frac{V_{,\phi}}{V}\right)^2$$

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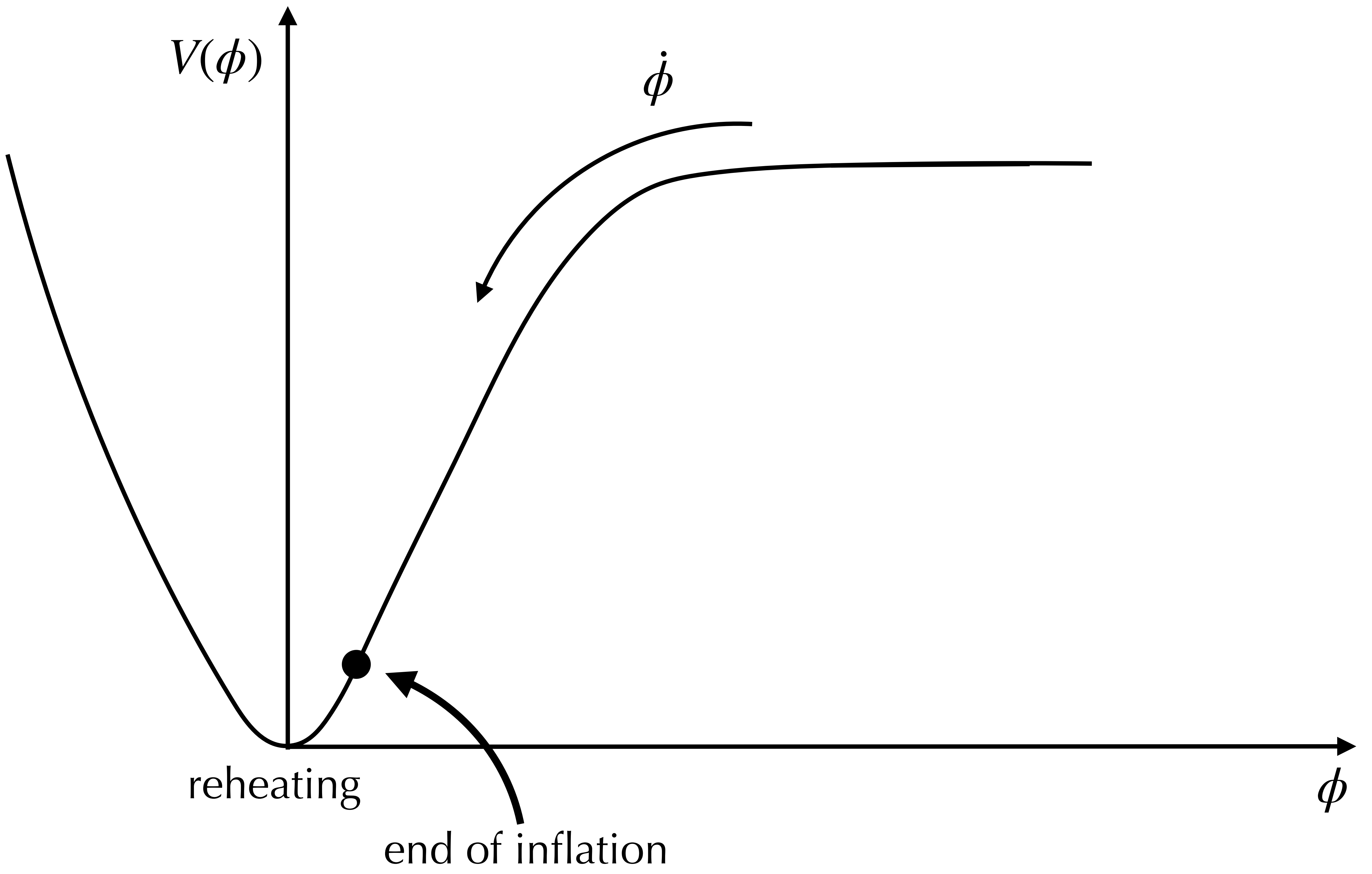

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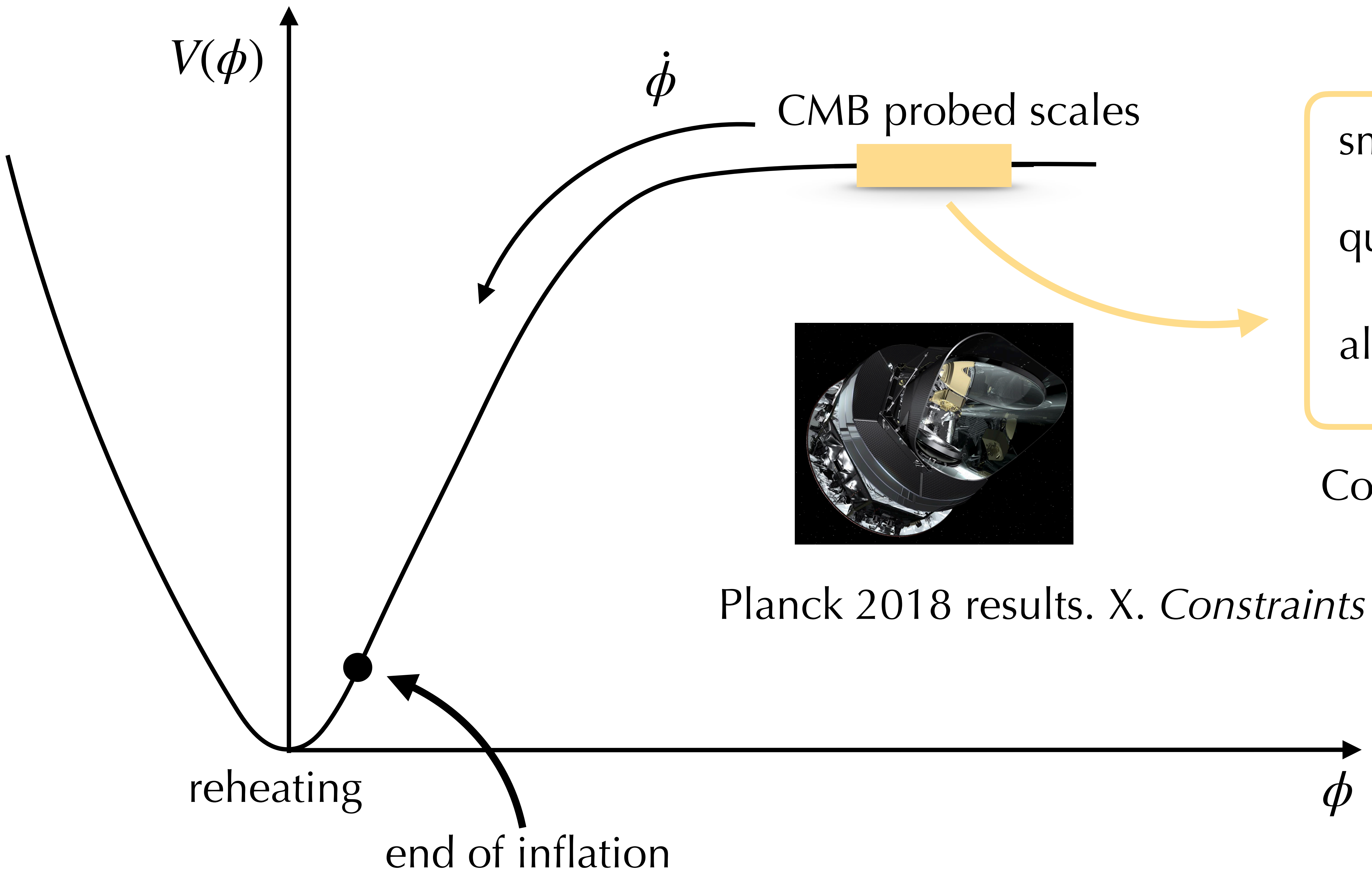

small perturbations $\zeta \simeq 10^{-5}$

quasi-Gaussian

almost scale invariant

Constrained window ~ 7 e-folds

Planck 2018 results. X. *Constraints on inflation*

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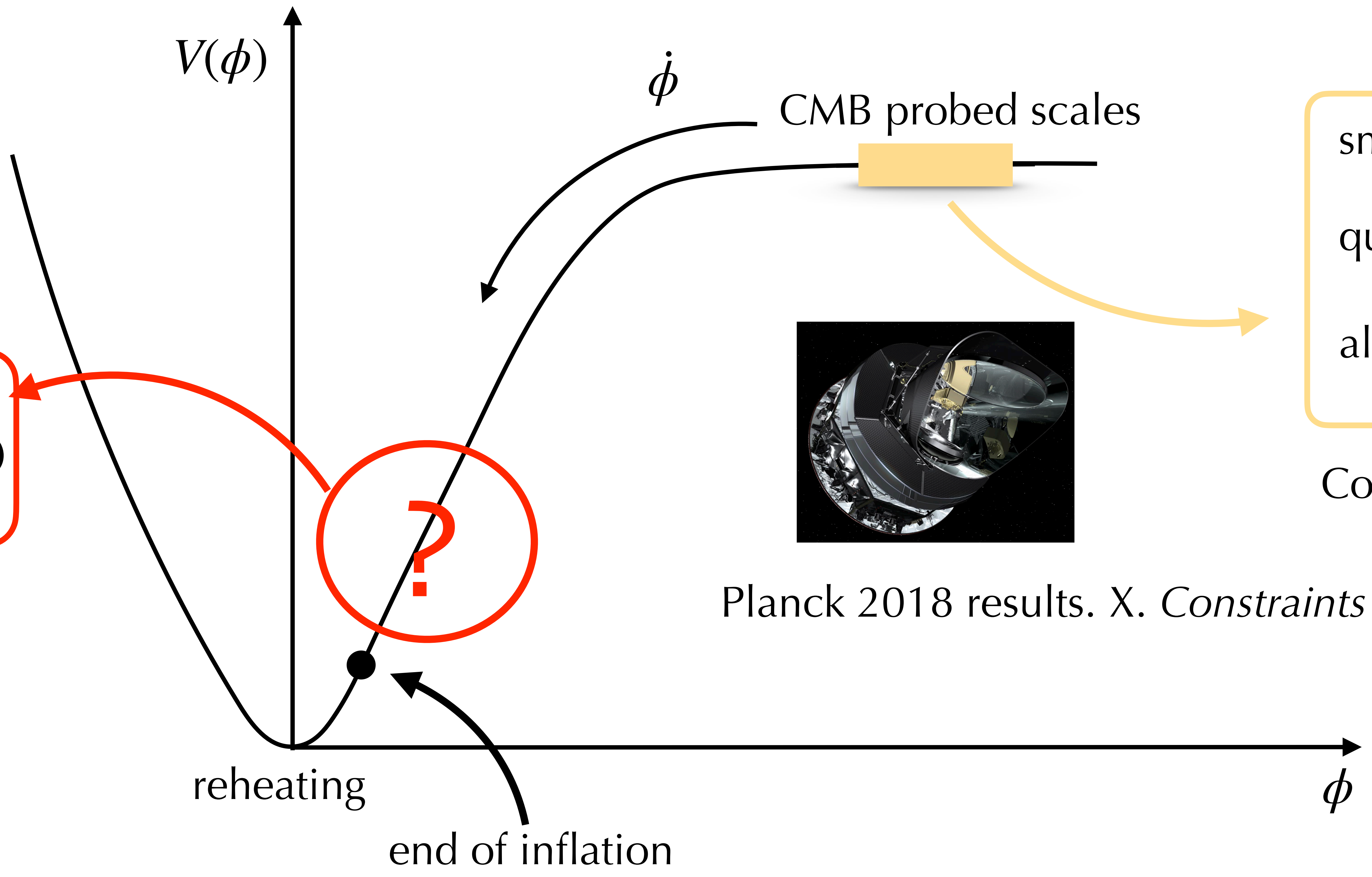
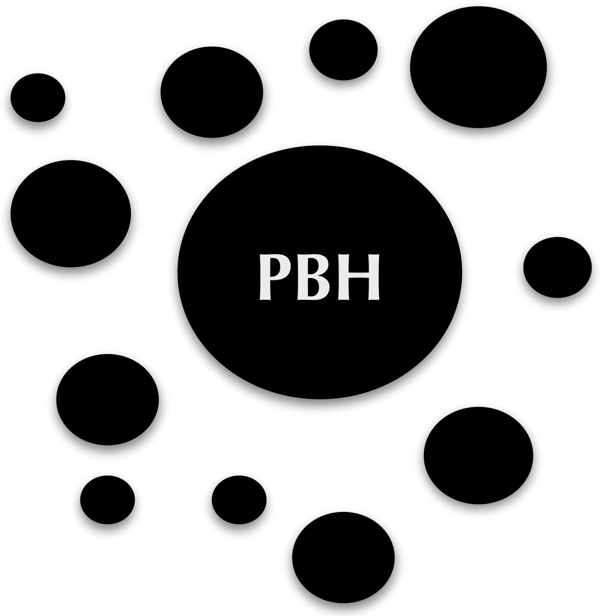
small scales unconstrained

possible enhancement $\zeta \sim \mathcal{O}(1)$





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- Large fluctuations are needed to form PBHs

  They could backreact on the expansion dynamics

  Backreaction can be incorporated in an effective (stochastic) theory

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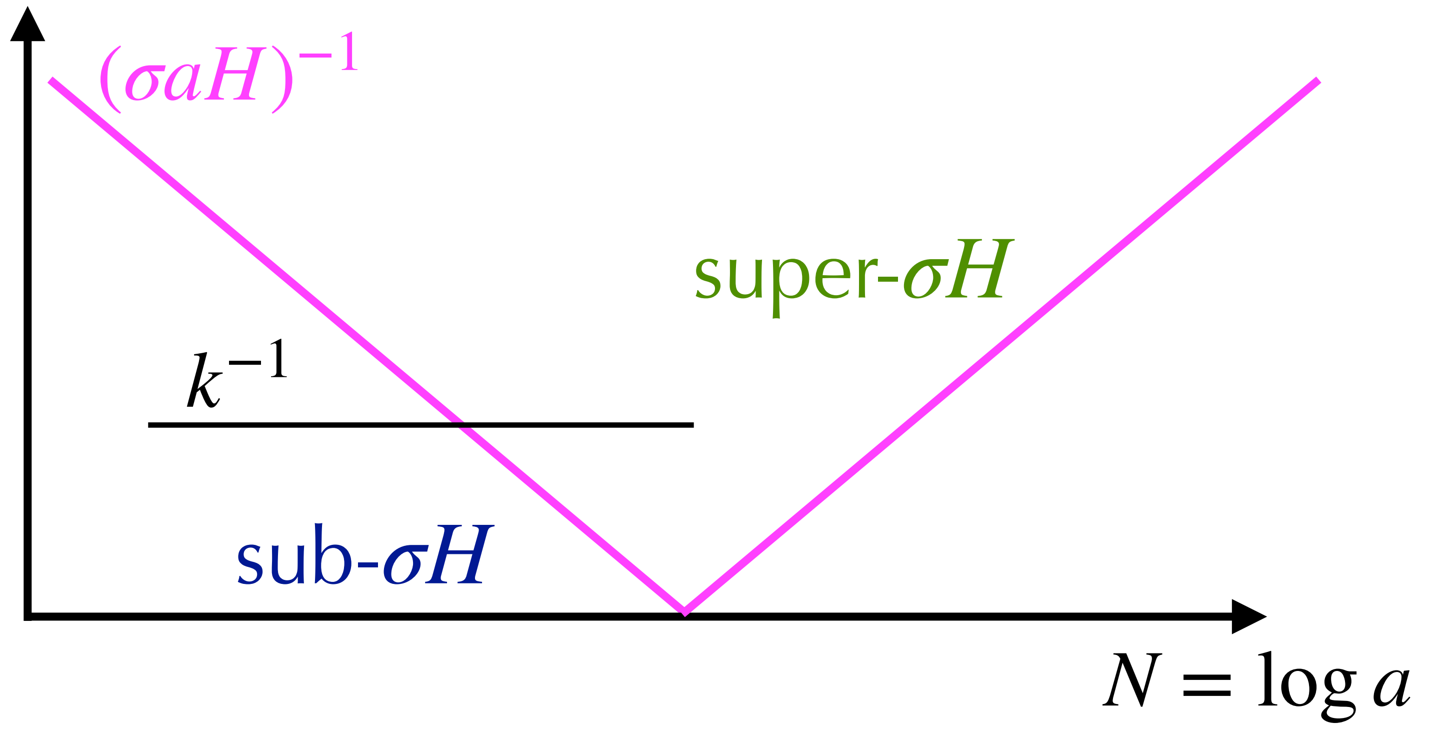
- Stochastic inflation A. Starobinsky [1986] *Stochastic de Sitter (inflationary) stage in the early universe*

Splitting fields into UV and IR part: coarse-graining scale $k_{cg} = \sigma\, a\, H$

$$\phi(x) = \phi_{cg} + \int \frac{dk}{(2\pi)^{3/2}} \theta\left(\frac{k}{\sigma a H}\right) \left[\phi_k(N)\, e^{-i\vec{k}\cdot\vec{x}}\, \hat{a}_{\vec{k}} + h.c.\right]$$



Quantum subhorizon fluctuations source the background

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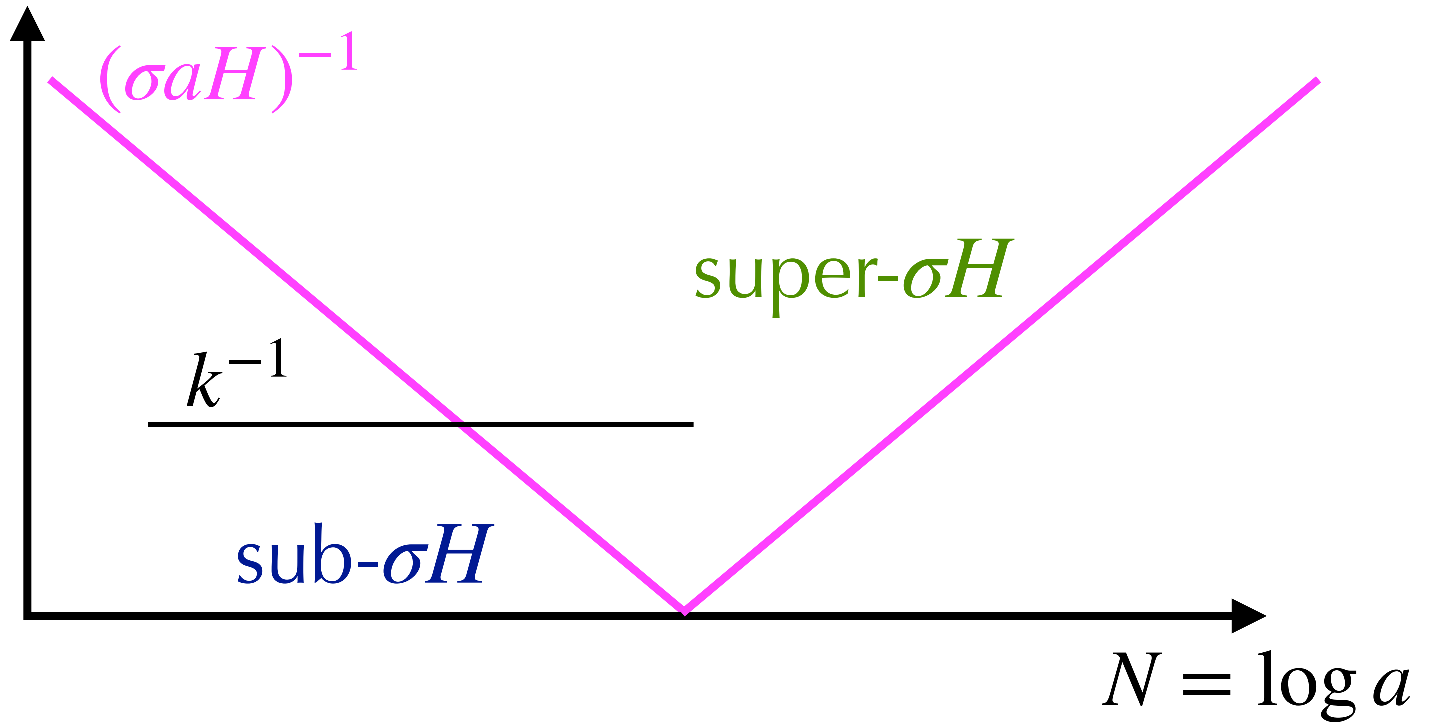
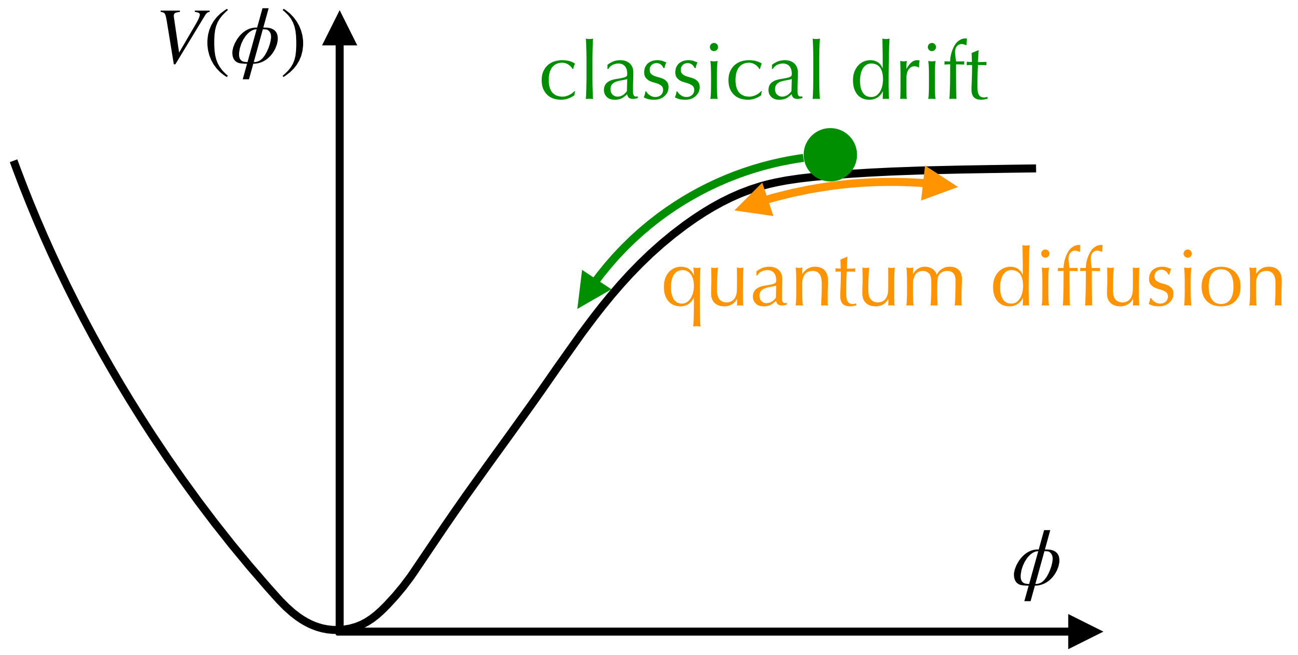


Quantum subhorizon fluctuations source the background

Dynamics at leading order in slow roll: $$\frac{d}{dN}\phi_{cg} = -\frac{V_{,\phi}(\phi_{cg})}{3H^2(\phi_{cg})} + \frac{H(\phi_{cg})}{2\pi}\xi(N)$$



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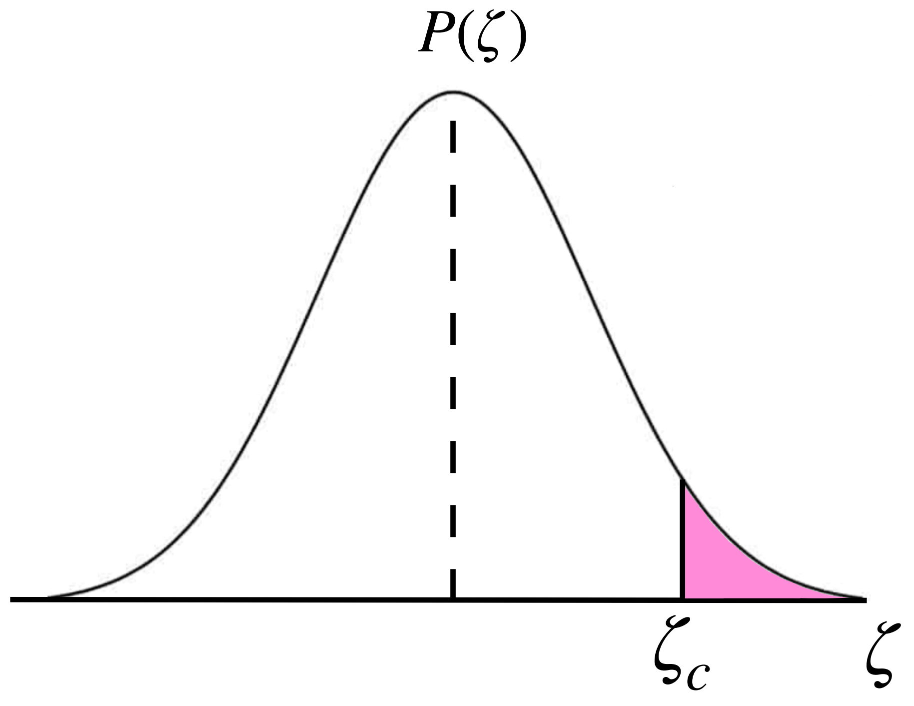
- Abundance of PBHs $\beta(M) = \int_{\zeta_c}^{\infty} P(\zeta)\, d\zeta$



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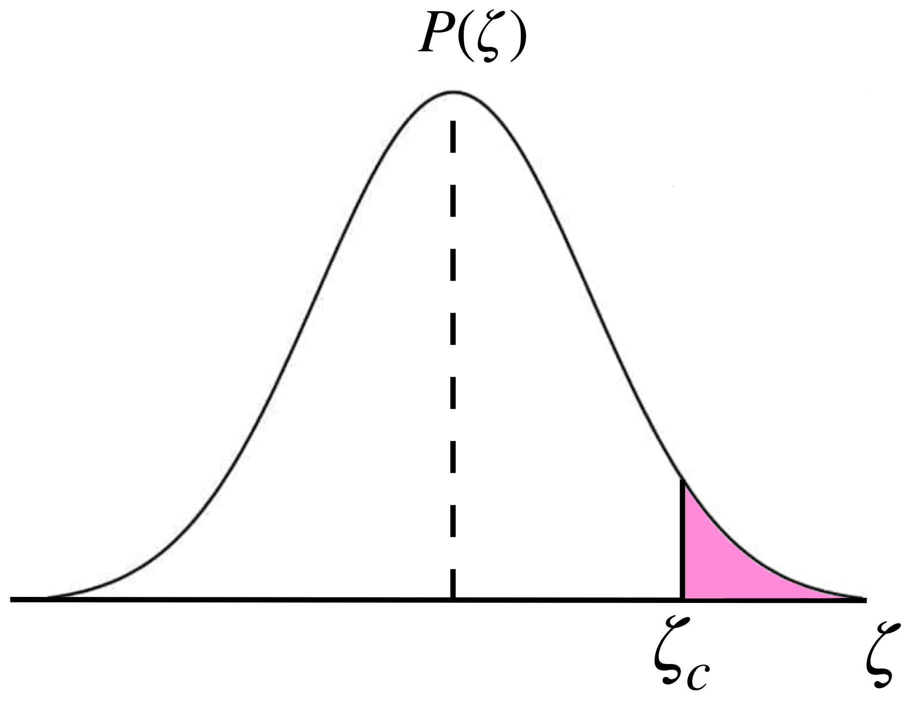

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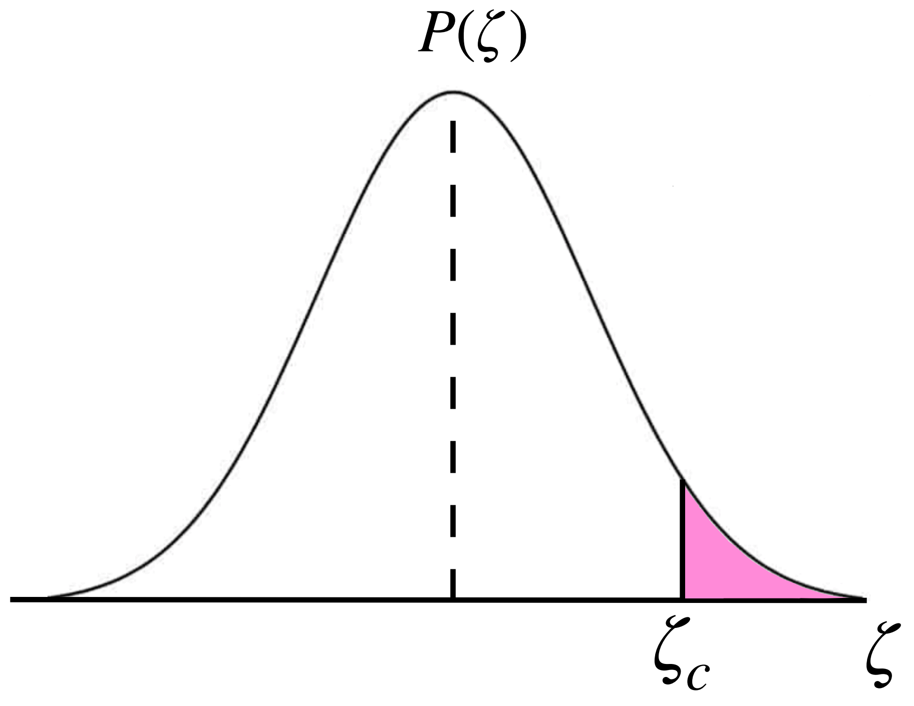

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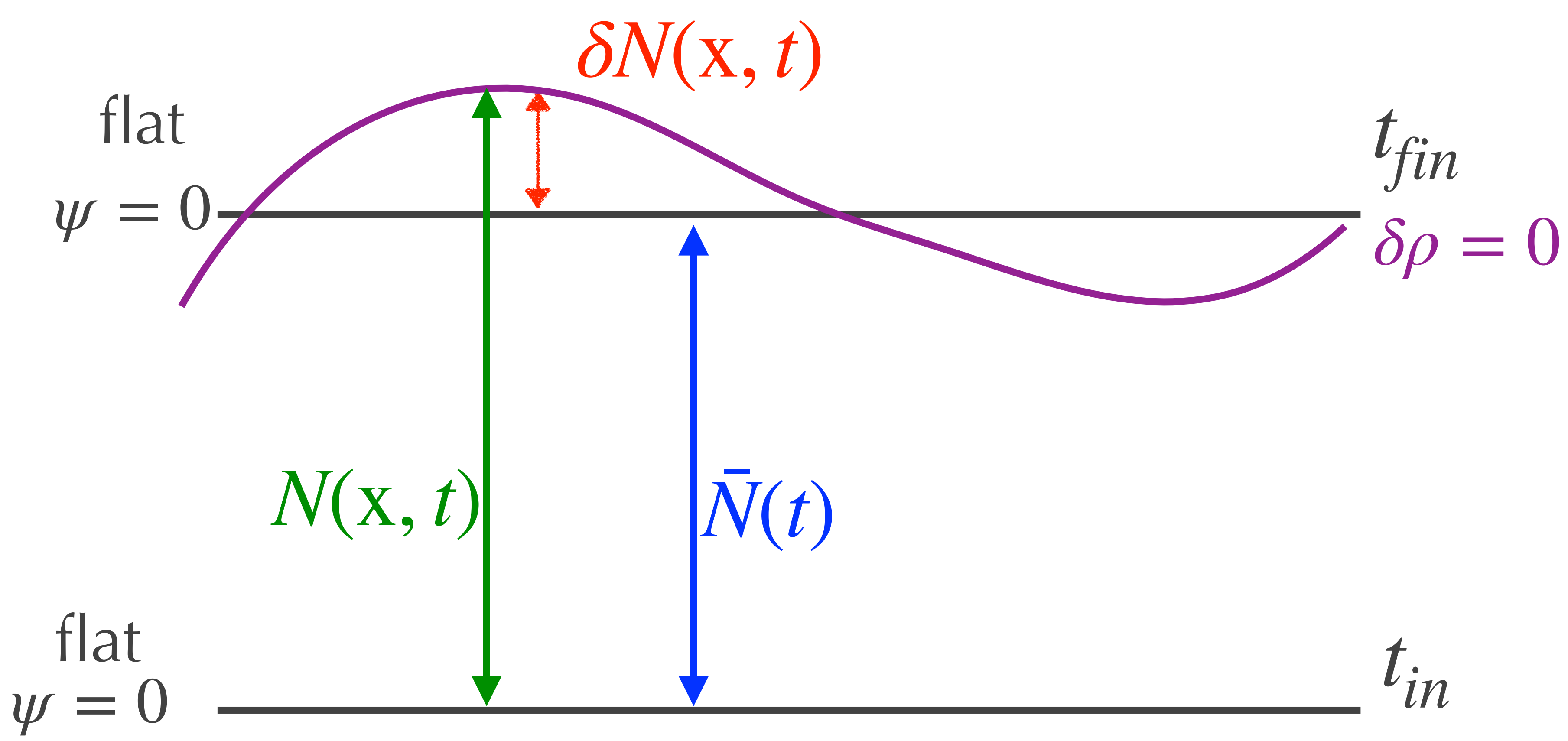
- δN formalism



$$\zeta(t, \mathrm{x}) = N(t, \mathrm{x}) - \bar{N}(t) \equiv \delta N$$

Lifshitz, Khalatnikov [1960]

Starobinsky [1983]

Wands, Malik, Lyth, Liddle [2000]

Primordial Black Holes and Quantum Diffusion

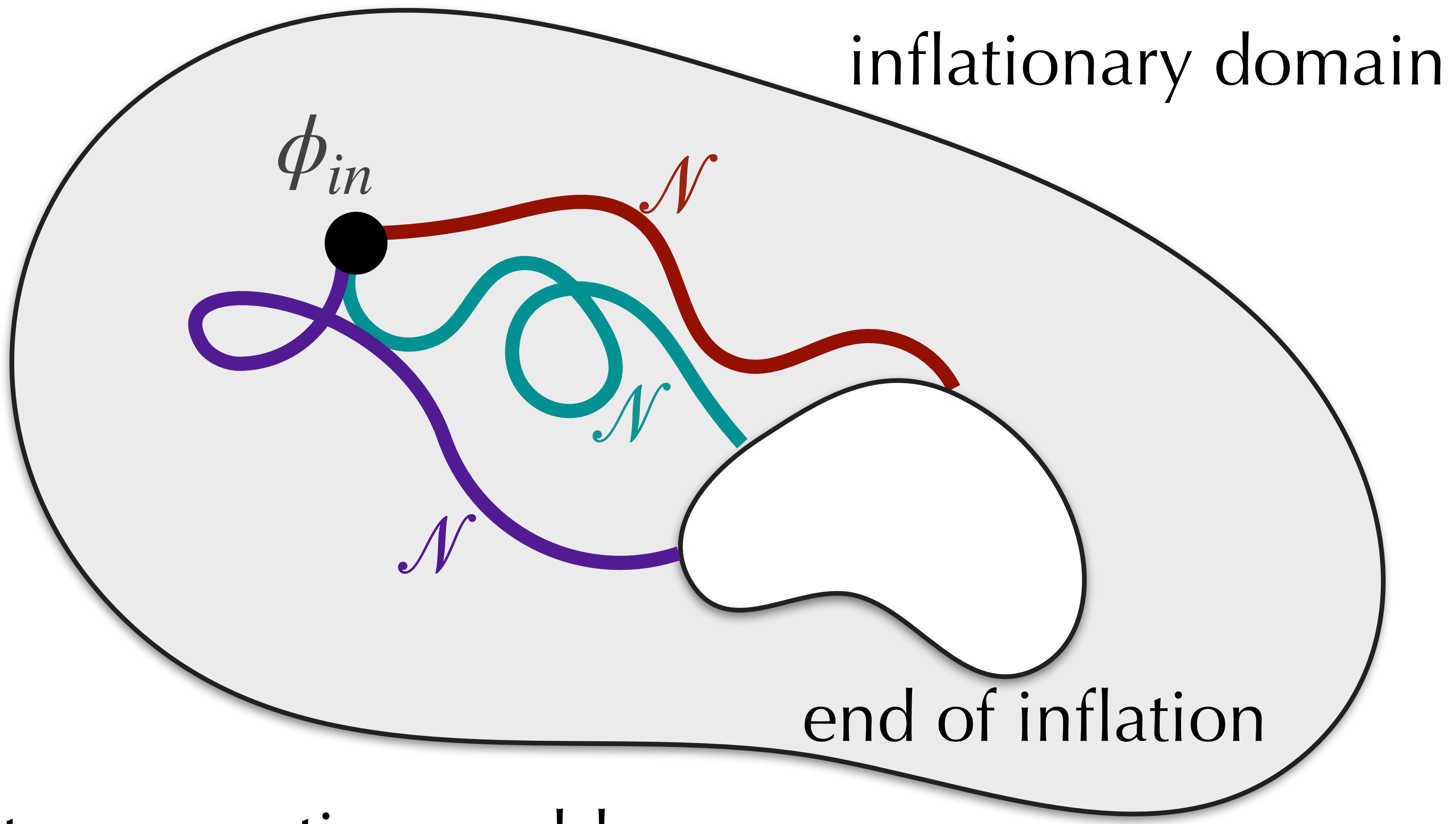
Primordial Black Holes and Quantum Diffusion

- Stochastic-δN formalism

[Enqvist, Nurmi, Podolsky, Rigopoulos [2008]

Vennin, Starobinsky [2015]

Number of e-folds is a stochastic variable $\mathcal{N}$



first passage time problem

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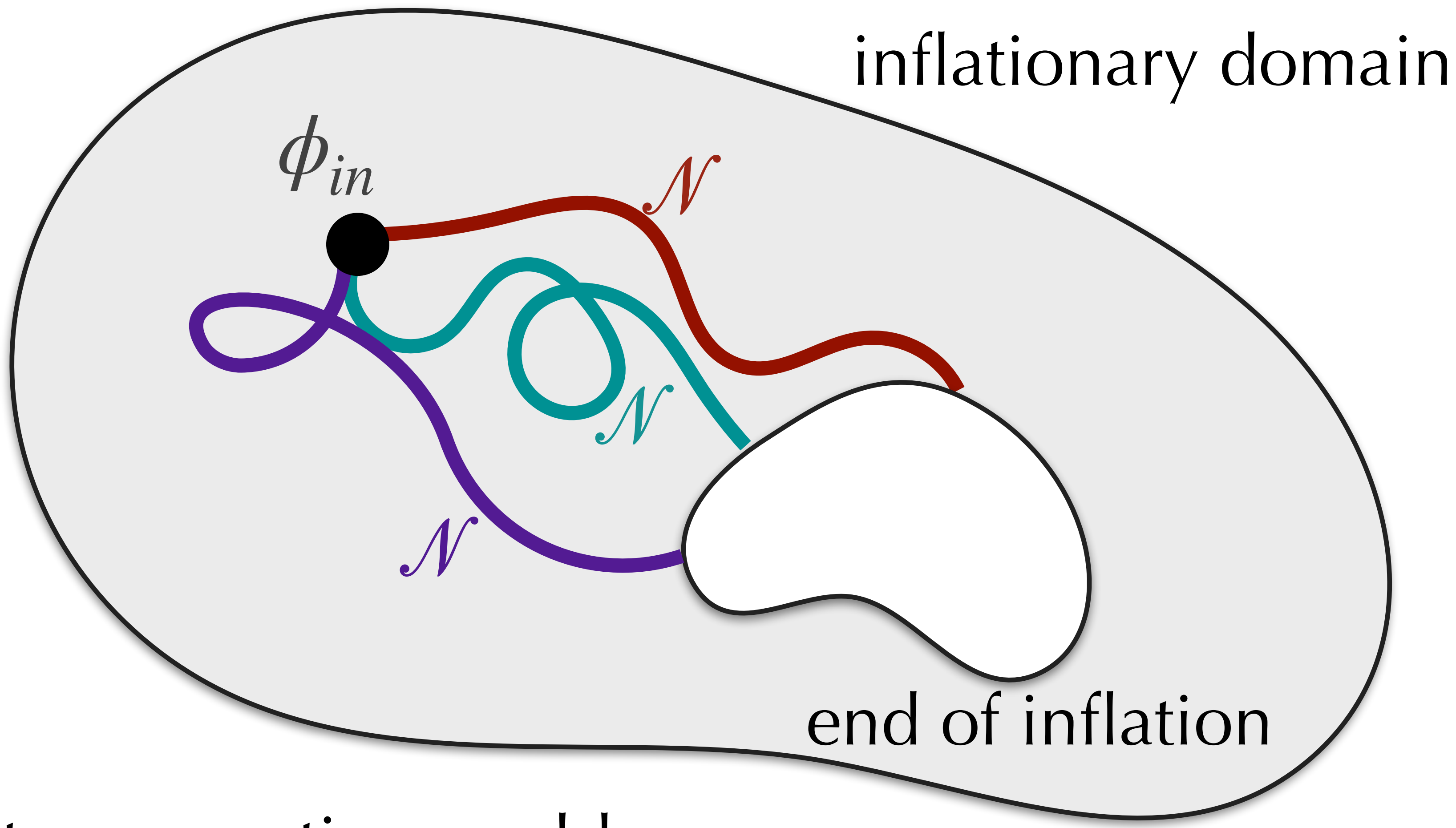

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Statistics of ζ from the statistics of $\mathcal{N}$

$$\zeta_{cg}(\mathrm{x}) = \mathcal{N}(\mathrm{x}) - \langle \mathcal{N} \rangle$$

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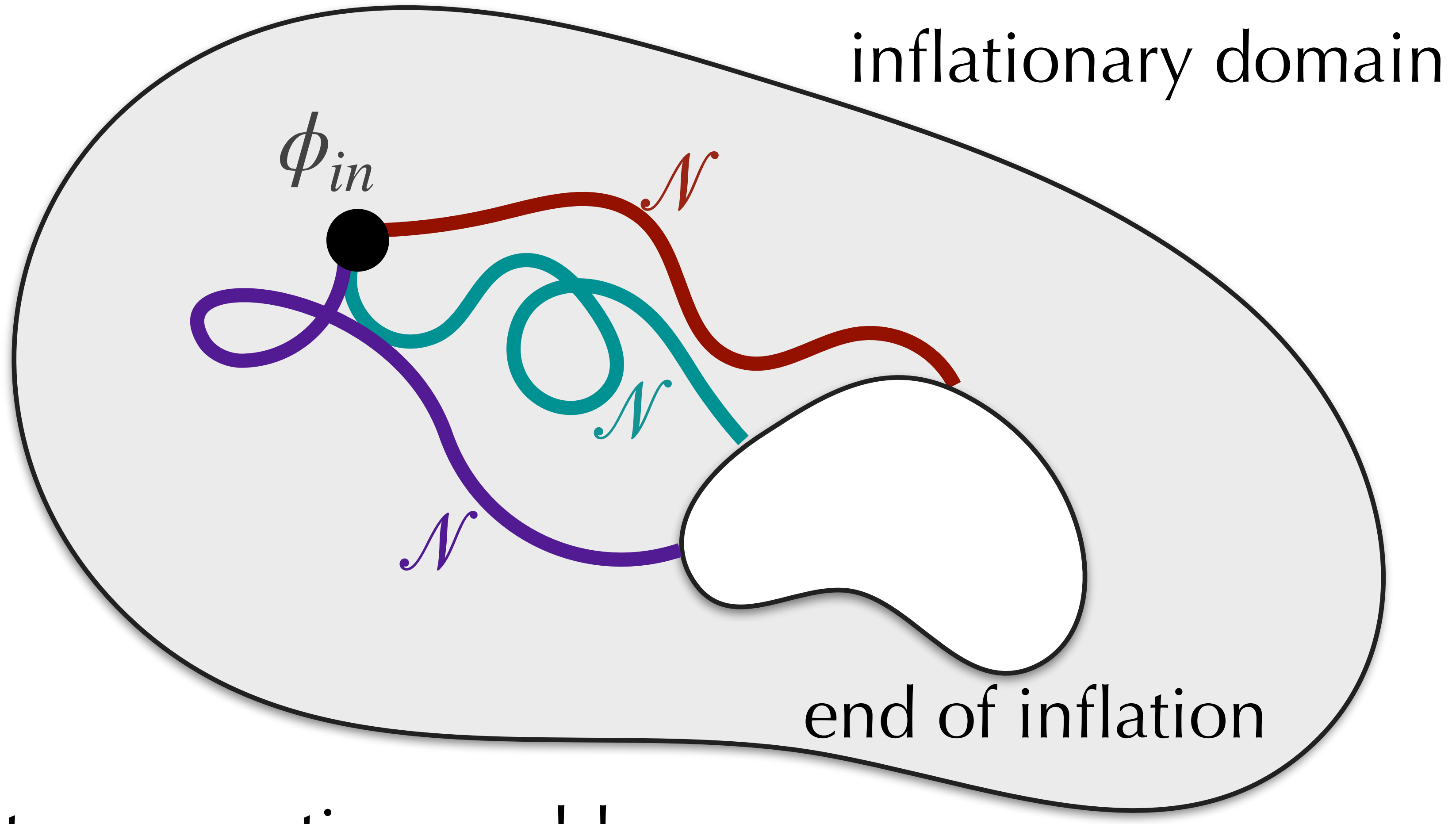

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Distribution function for the duration of inflation (first passage time)

$$\frac{\partial}{\partial \mathcal{N}} P(\mathcal{N}, \phi) = \mathcal{L}^{\dagger}_{FP}(\phi) \cdot P(\mathcal{N}, \phi) \qquad \frac{1}{M_{Pl}^2} \mathcal{L}^{\dagger}_{FP}(\phi) = -\frac{v'(\phi)}{v(\phi)} \frac{\partial}{\partial \phi} + v(\phi) \frac{\partial^2}{\partial \phi^2} \qquad v = \frac{V}{24\pi^2 M_{Pl}^4}$$

Stochastic-δN formalism: exponential tails

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- Full PDF of the first passage time

Pattison, Vennin, Assadullahi, Wands [2017]

Characteristic function (includes all moments)

$$\chi(t,\phi) \equiv \langle e^{it\mathcal{N}} \rangle = \int_{-\infty}^{\infty} e^{it\mathcal{N}} P(\mathcal{N},\phi)\, d\mathcal{N}$$

→

Obeys differential equation

$$\mathcal{L}^{\dagger}_{FP} \cdot \chi(t,\phi) = -\, i\, t\, \chi(t,\phi)$$

→

Full PDF given by inverse Fourier transform

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- Useful trick: pole expansion — [Ezquiaga, Garcia-Bellido, Vennin (2020)]

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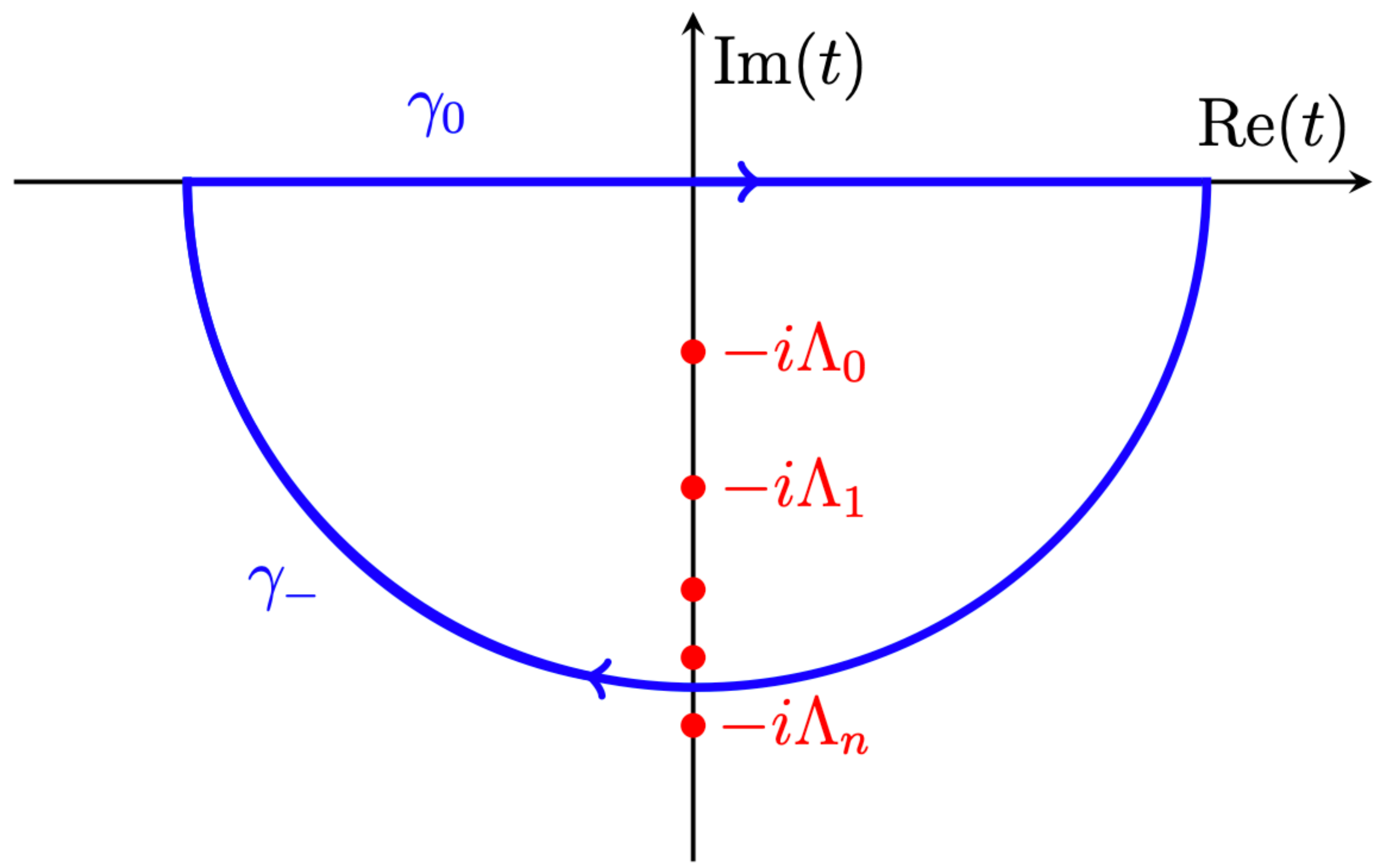

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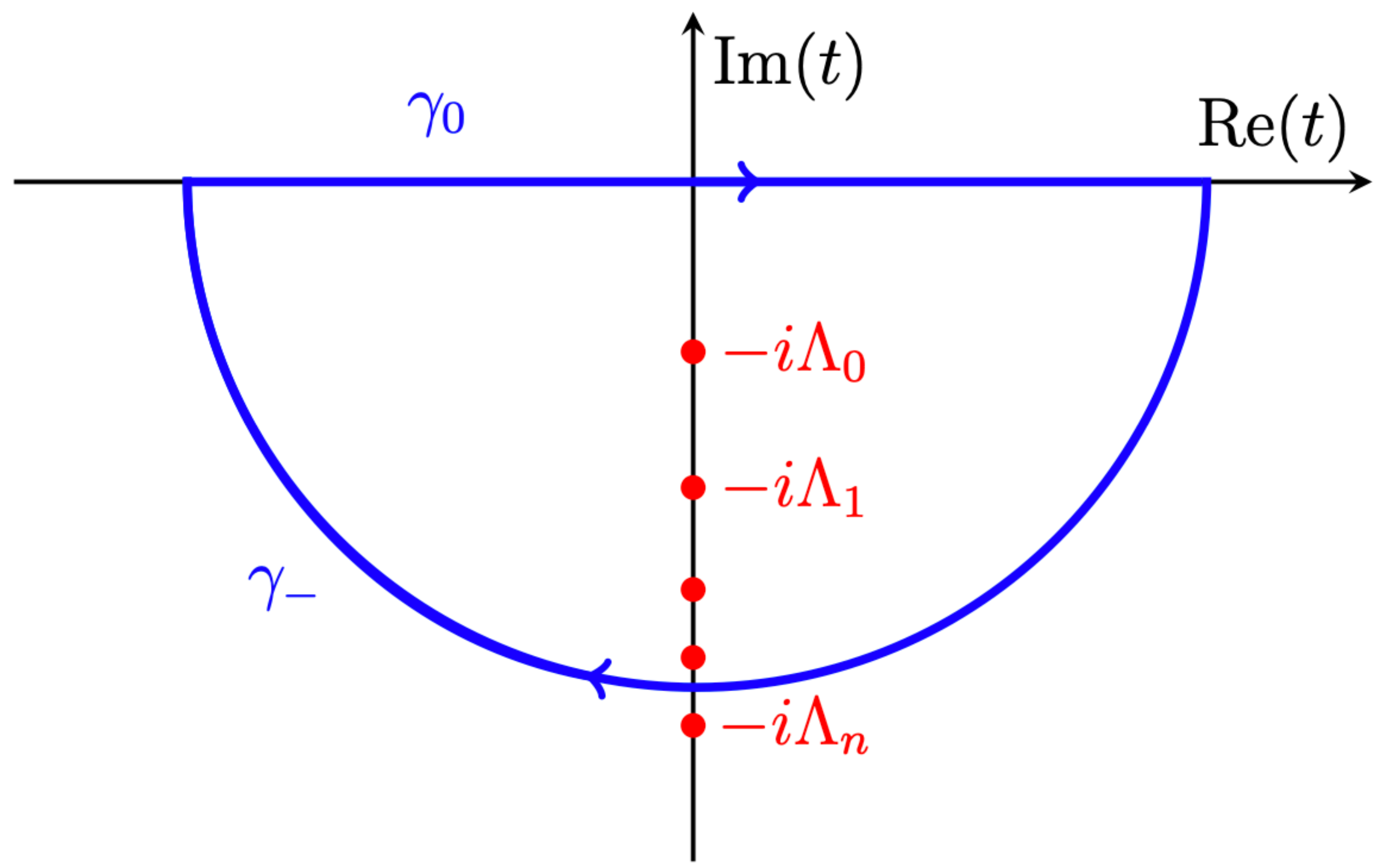

Tail of the PDF for ζ has an exponential fall-off behaviour

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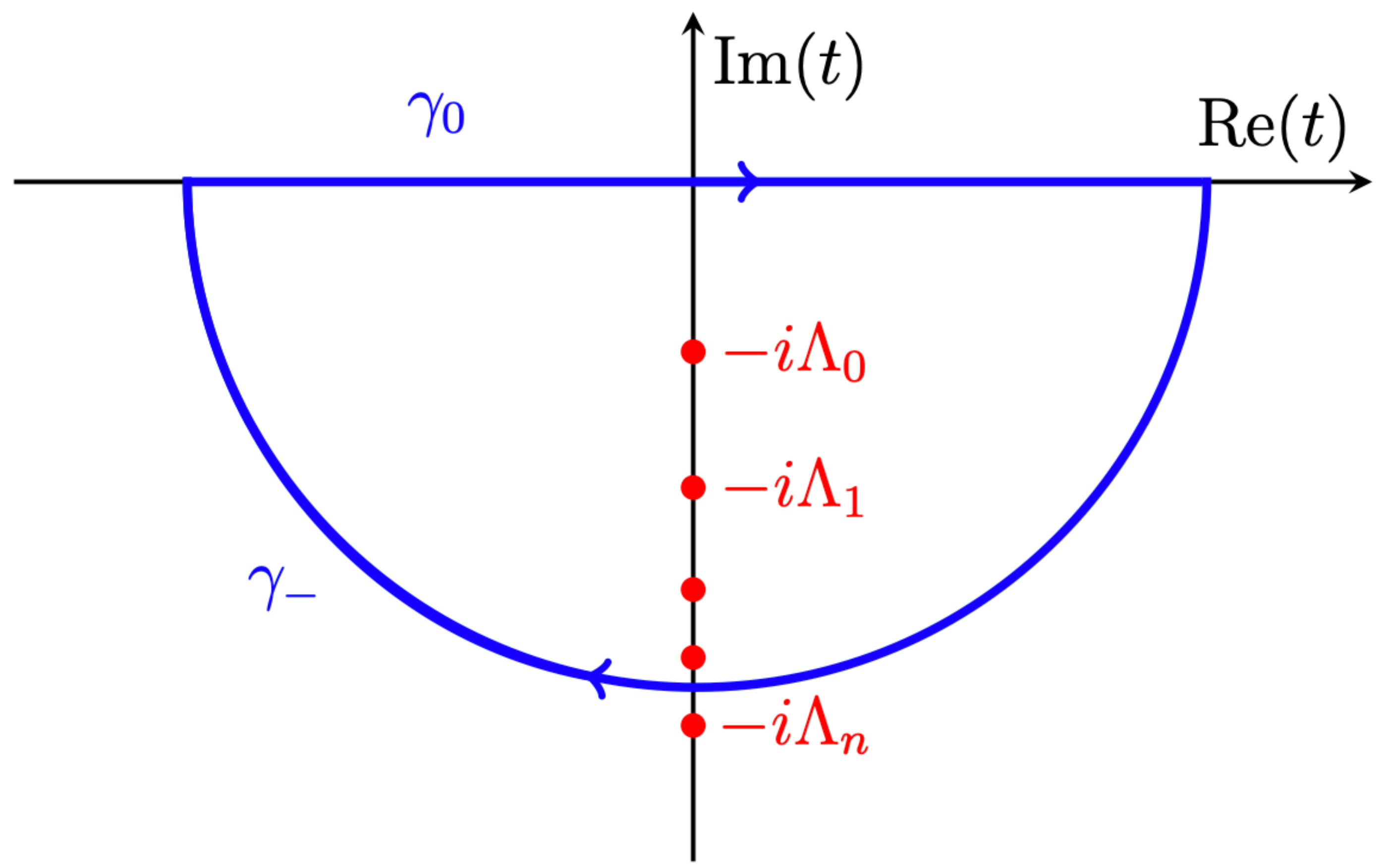
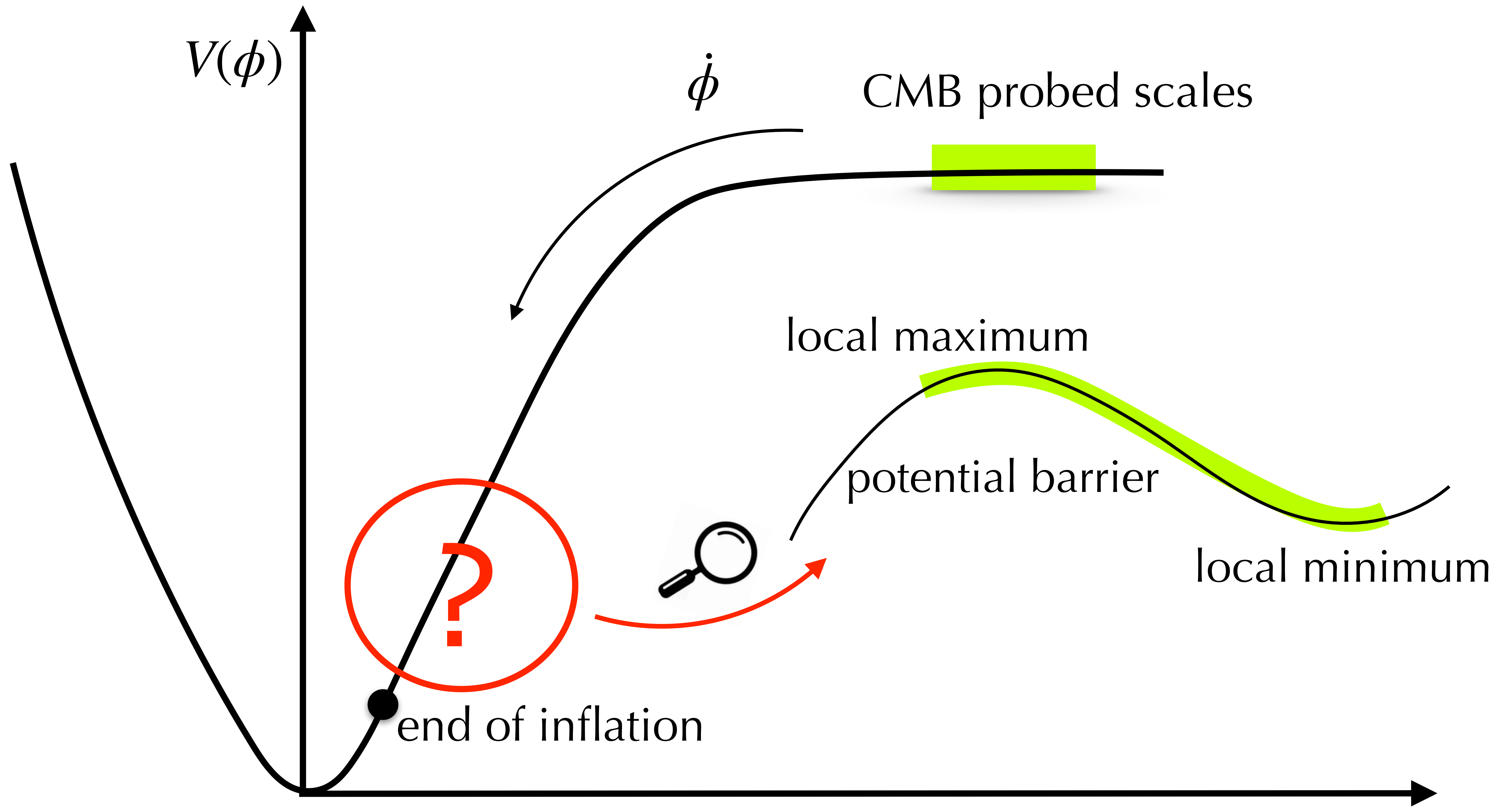


Tail of the PDF for ζ has an exponential fall-off behaviour

This type of non-Gaussianities cannot be captured by perturbative parametrisations (such as the f_{NL} expansion) !

Stochastic tunnelling

C.A., V. Vennin [2022]
“Primordial black holes from stochastic tunneling”



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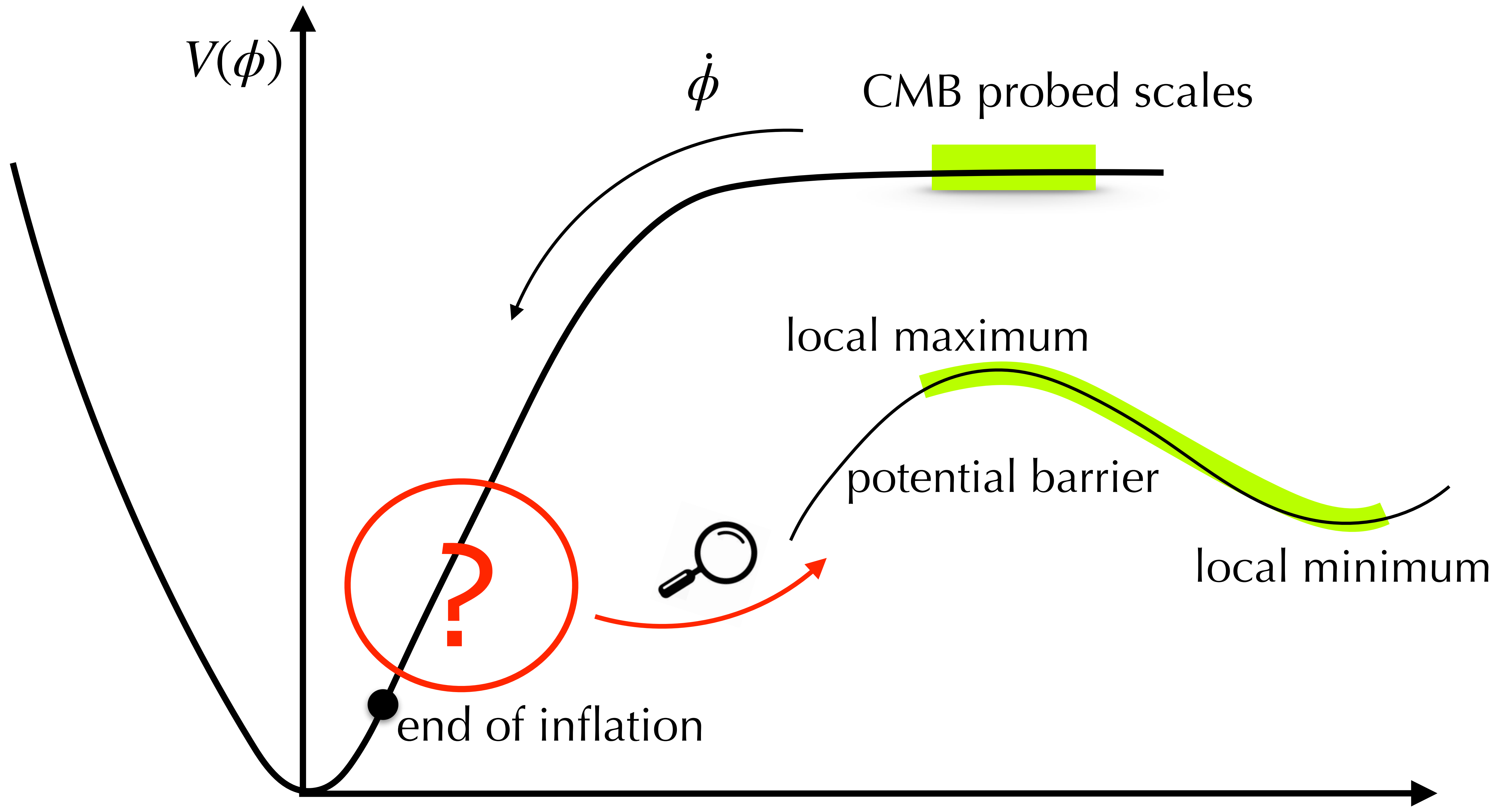
- False vacuum state



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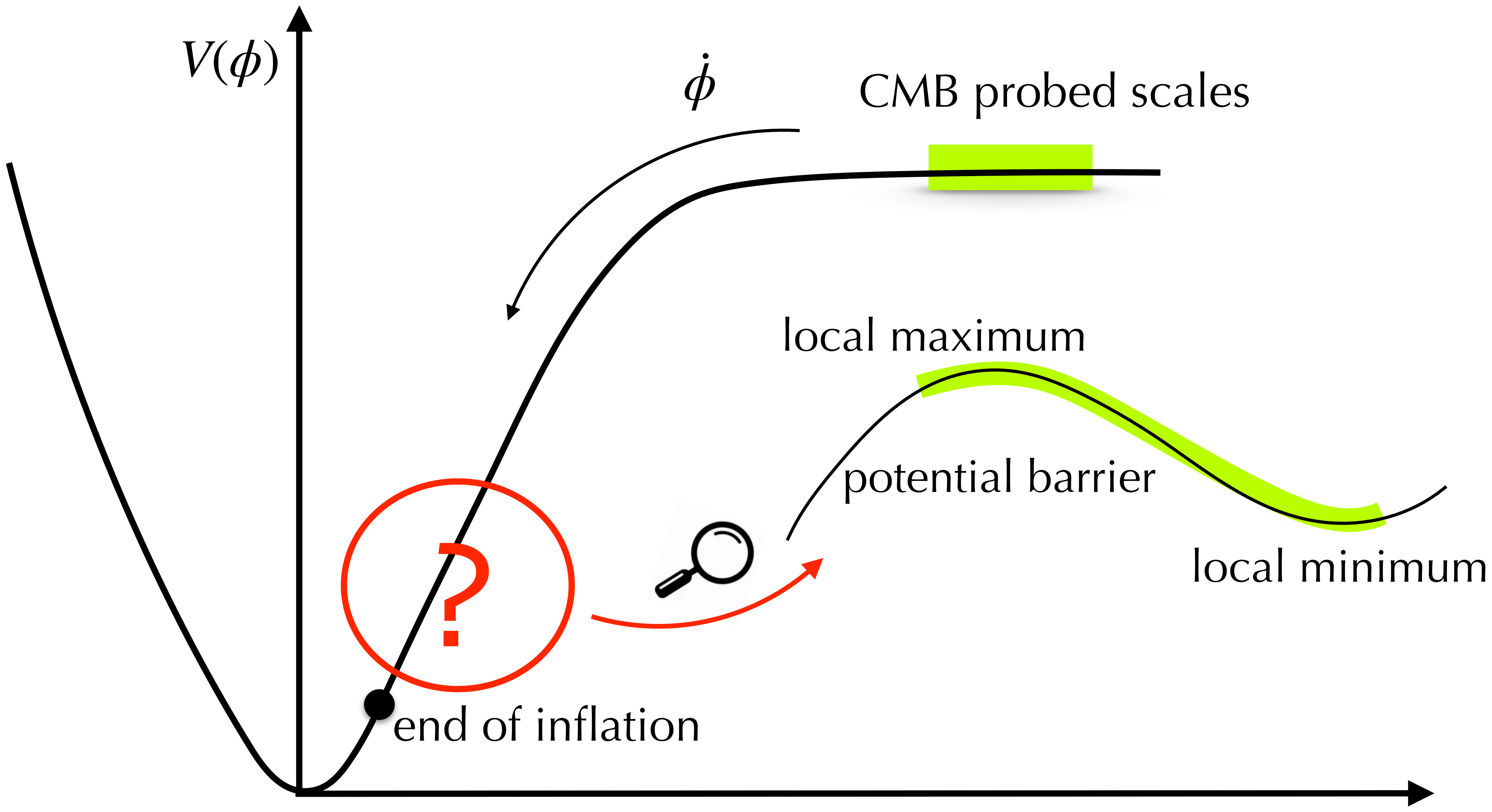
- False vacuum state

- Local minima naturally appear in various contexts: - high energy constructions (supersymmetry, supergravity)
  - breaking of flat-inflection point condition through radiative corrections
  - etc.



Stochastic tunnelling

C.A., V. Vennin [2022]
"Primordial black holes from stochastic tunneling"

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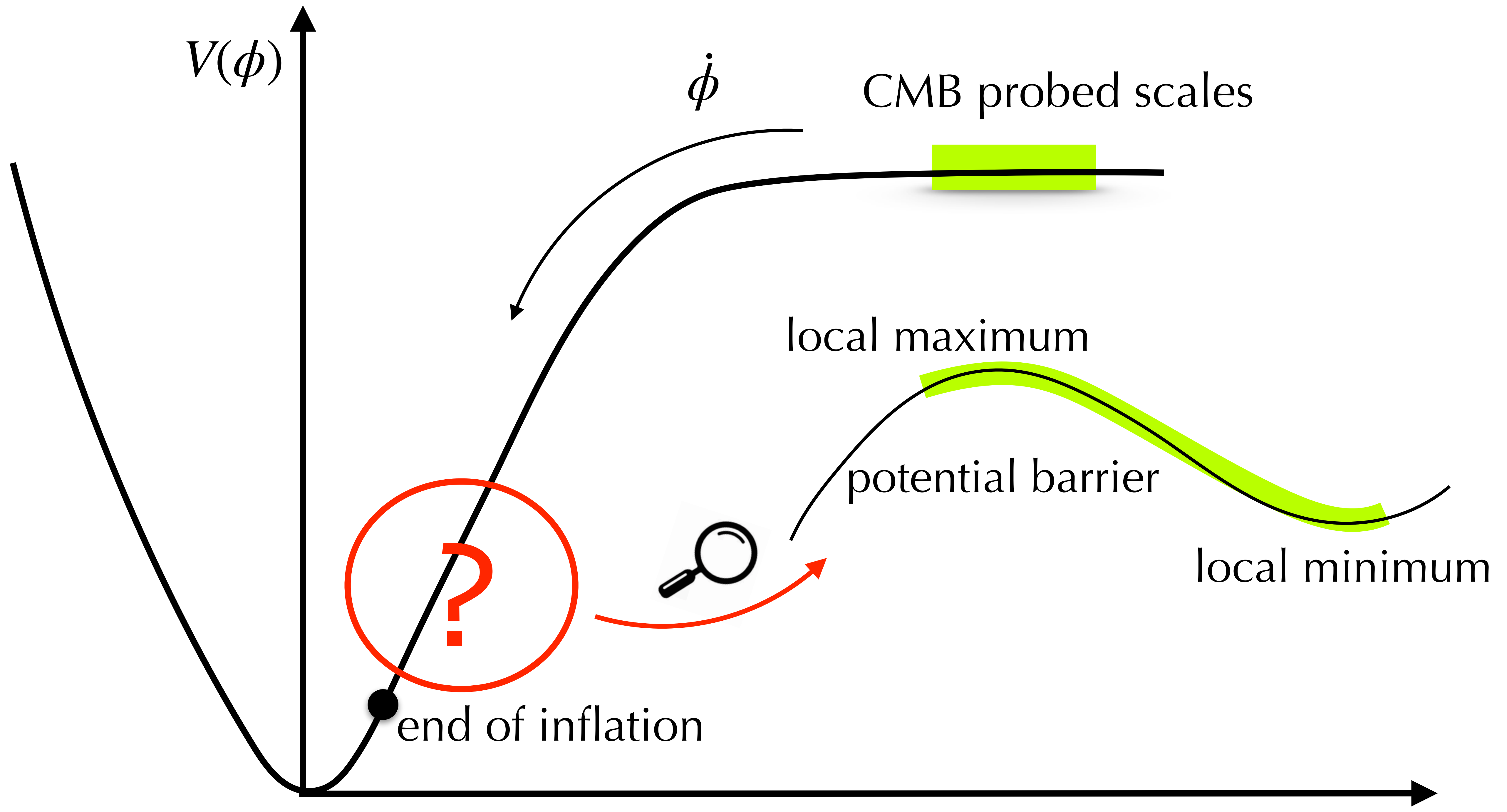

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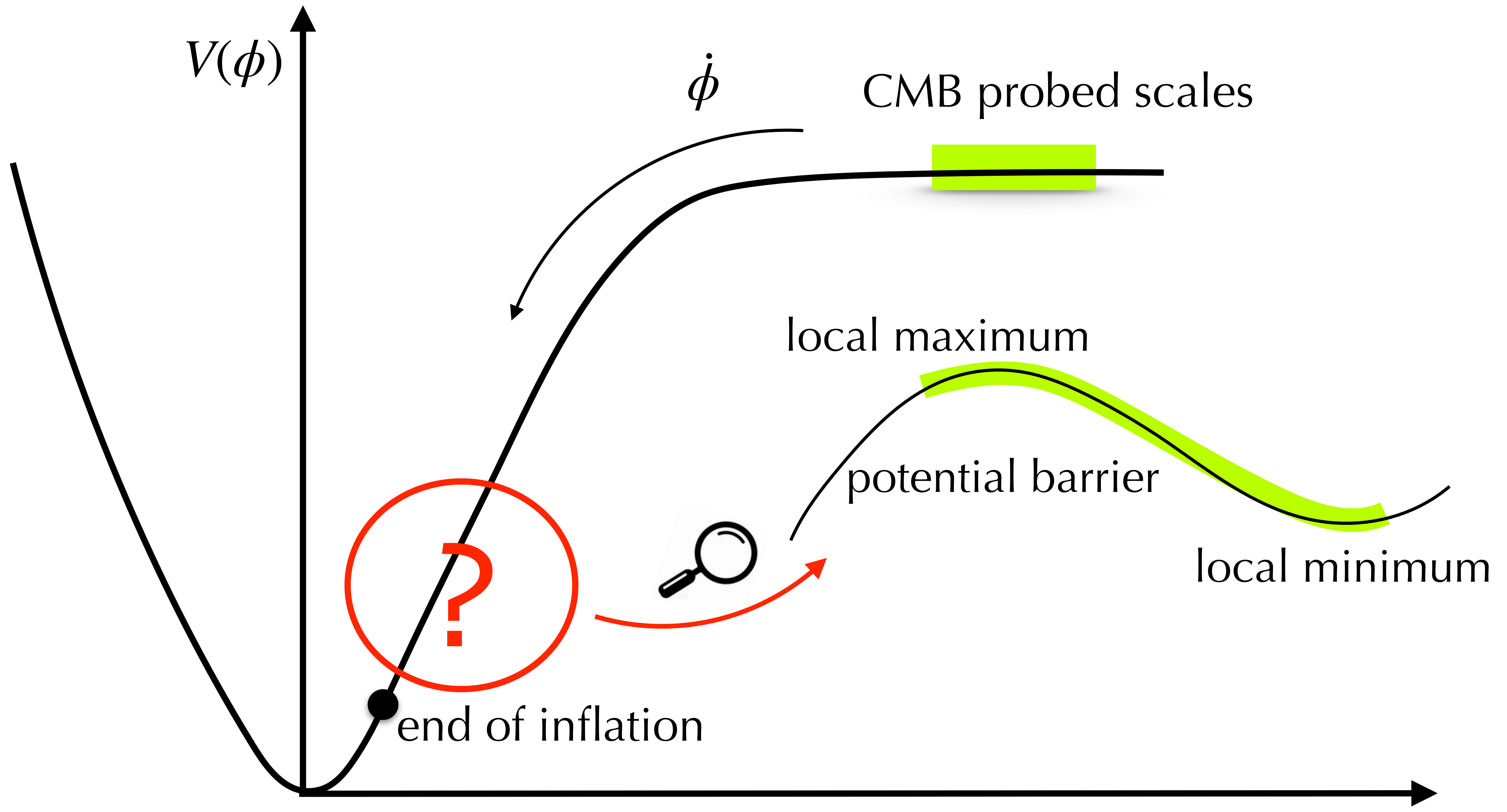

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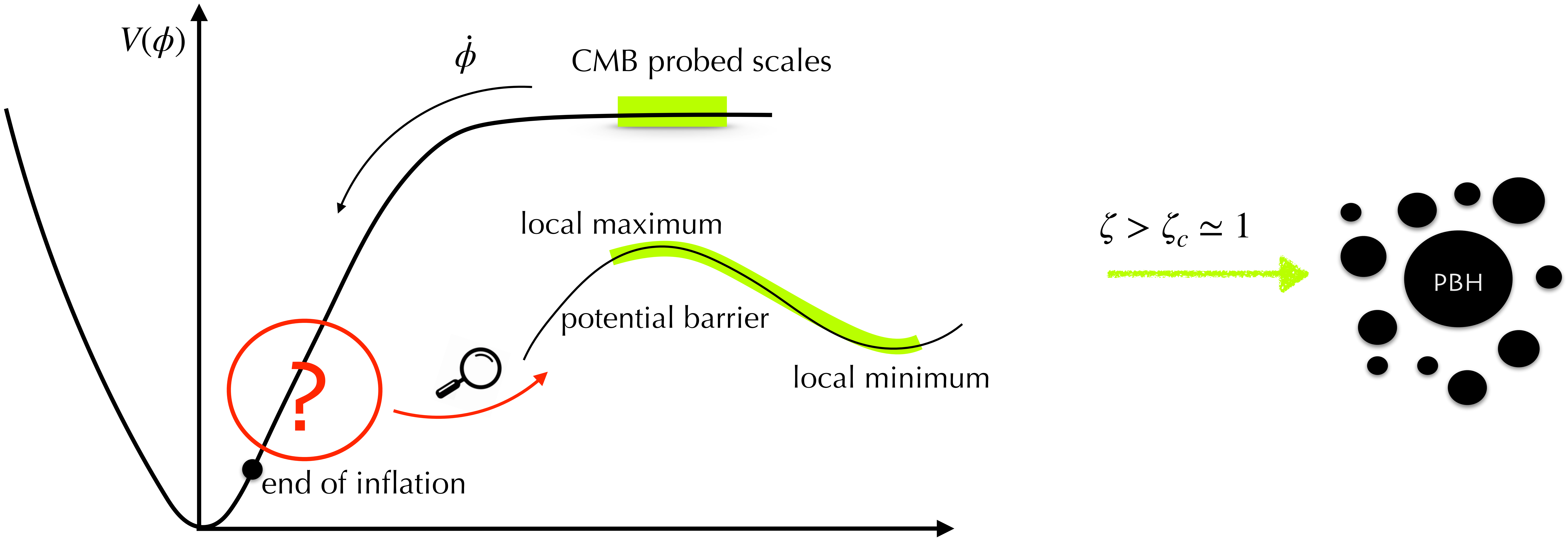

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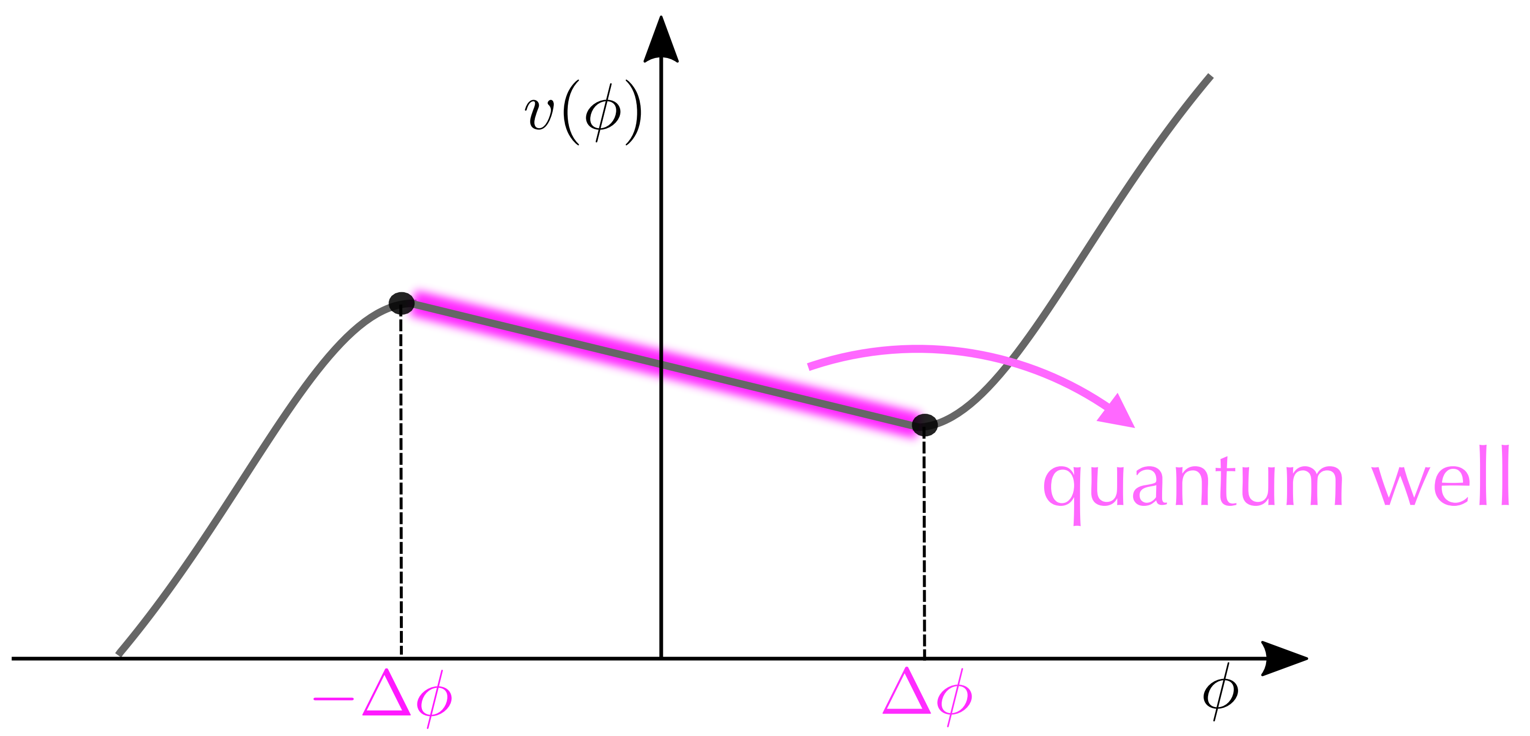

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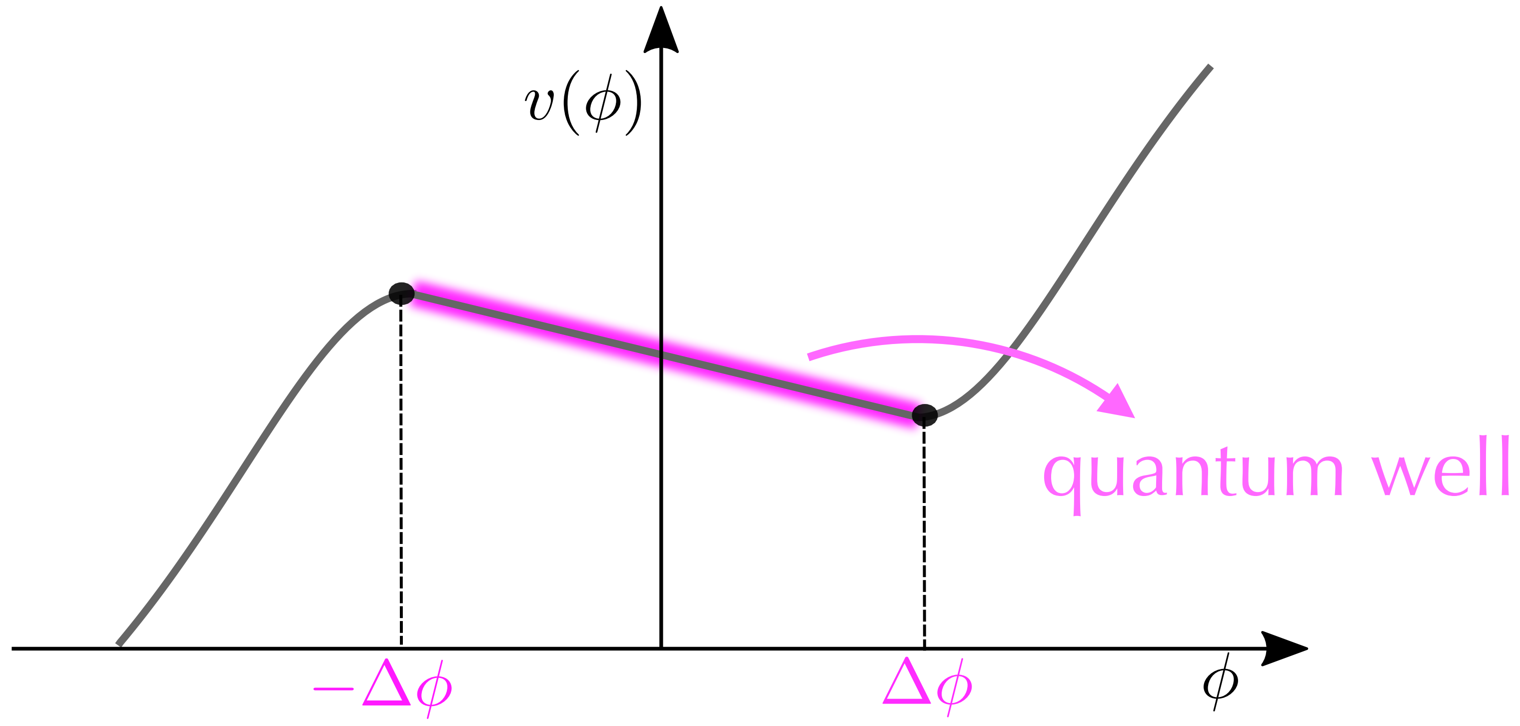

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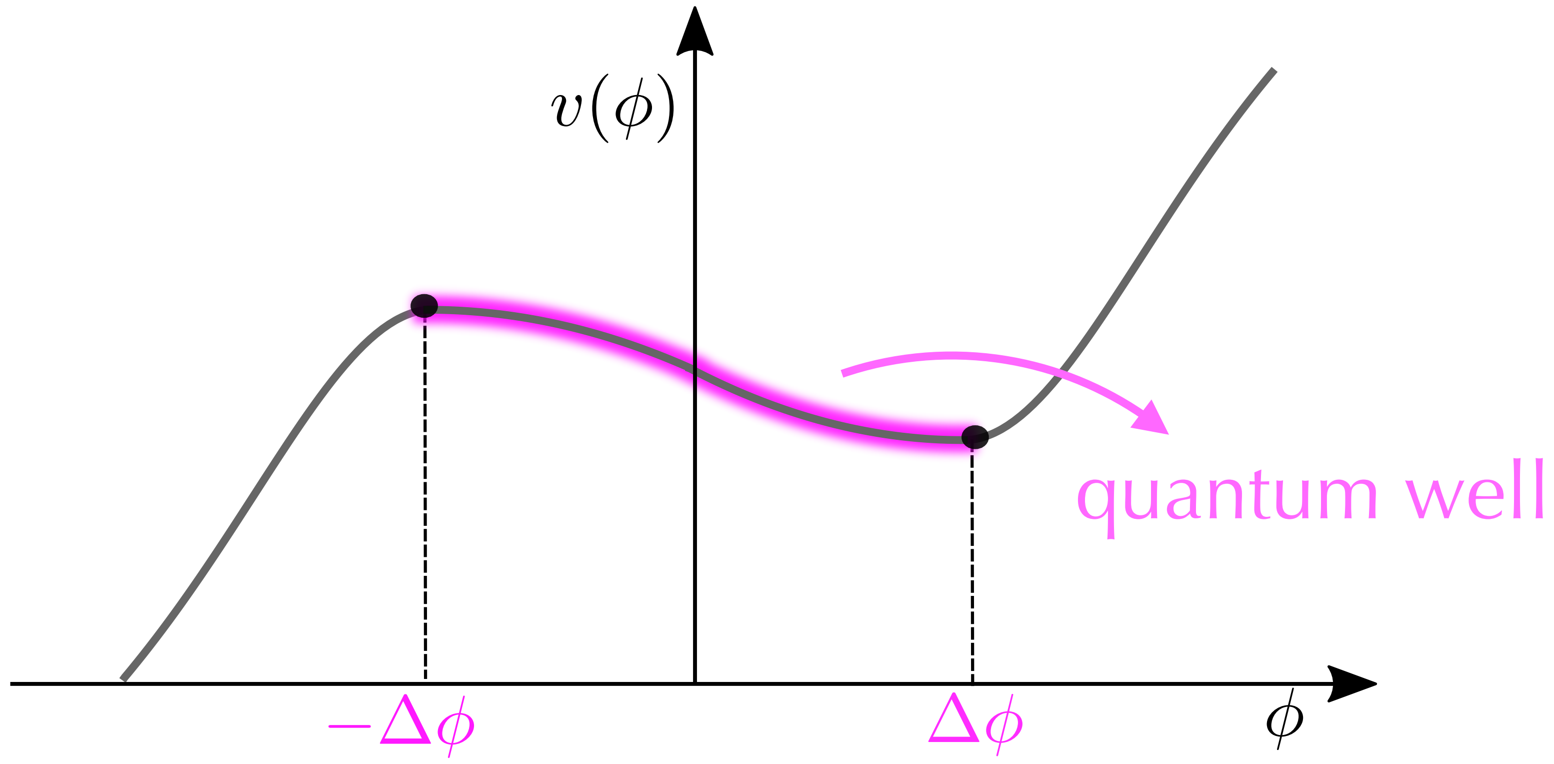

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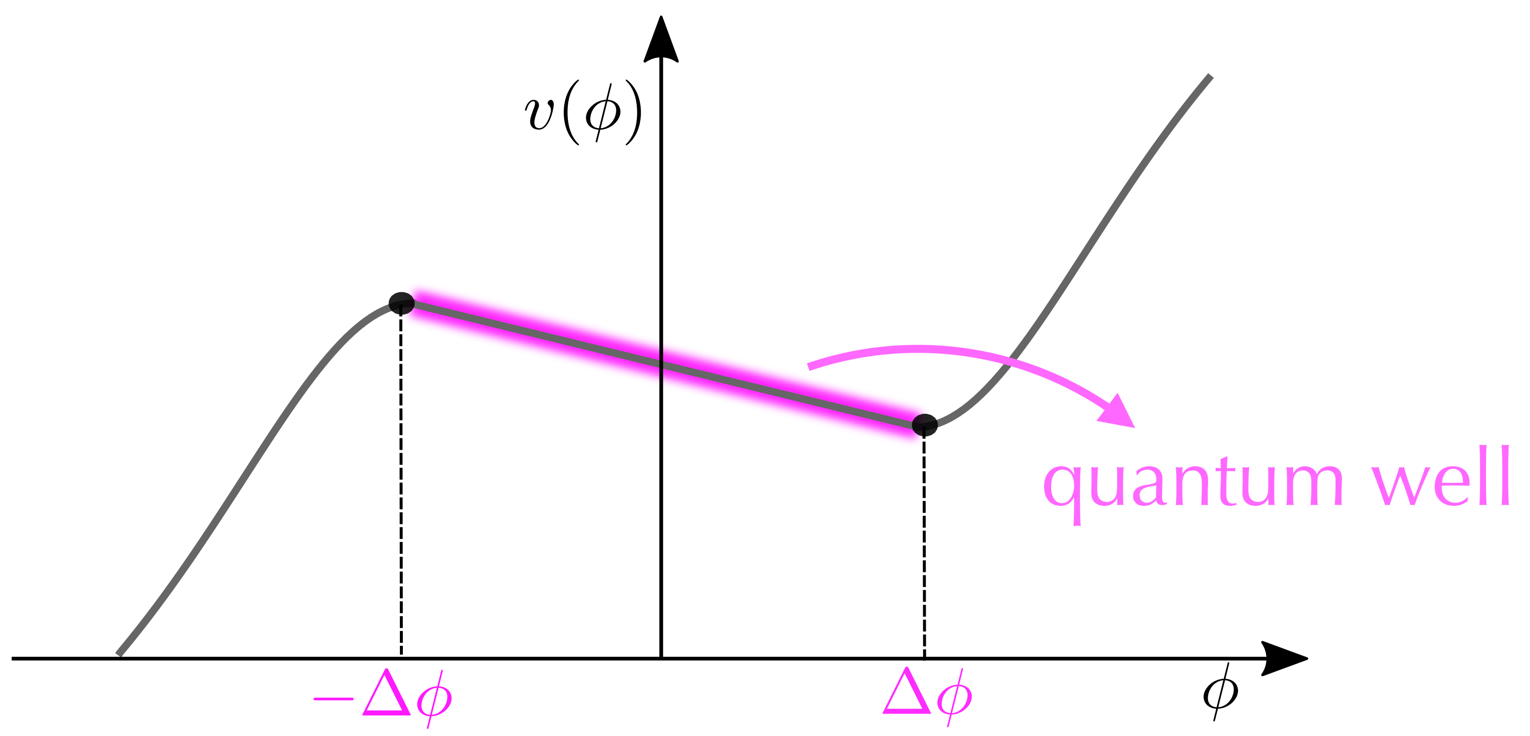

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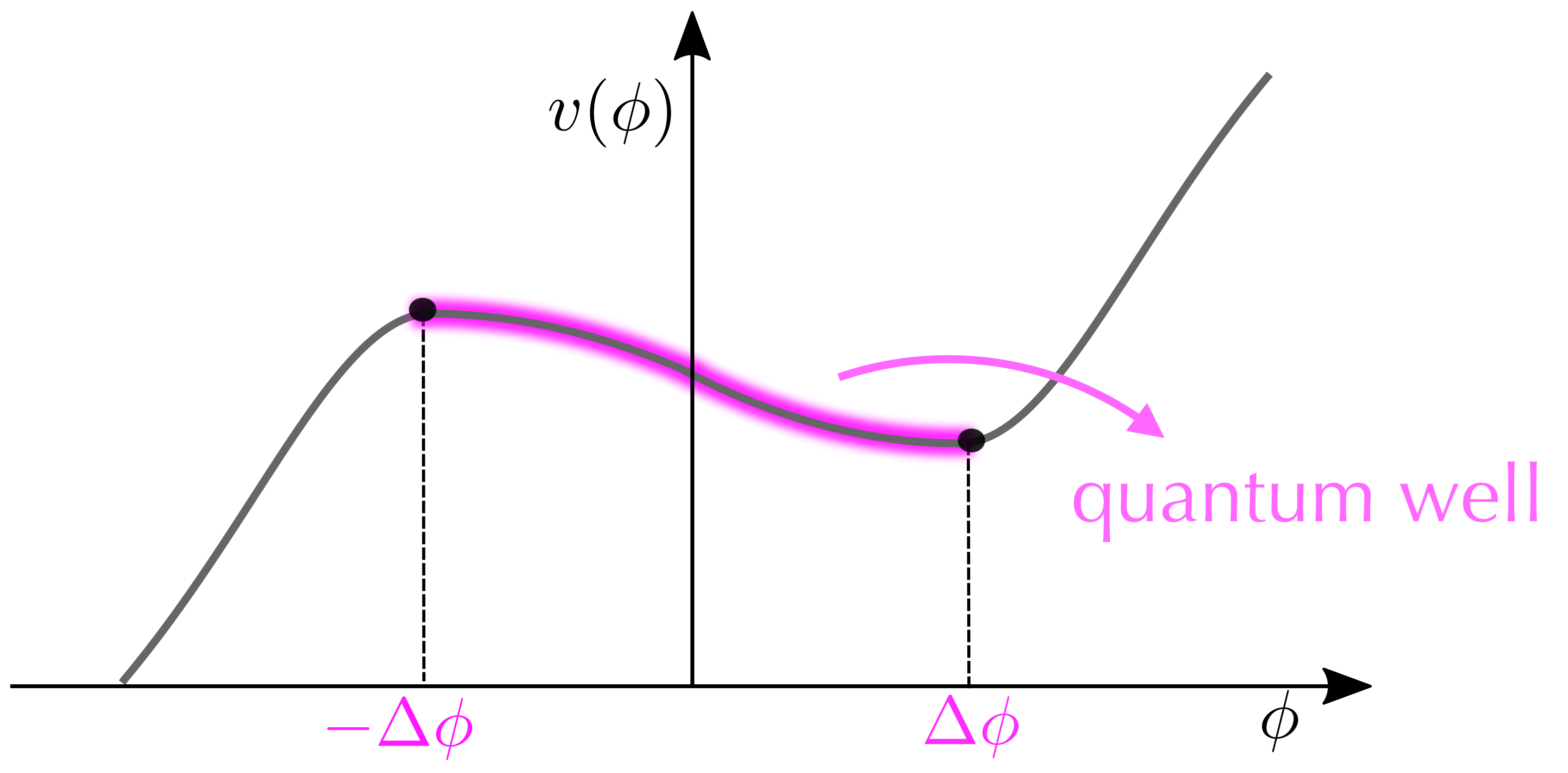

Quantum diffusion in highlighted regions, potential gradient elsewhere

Slow roll preserved: $\epsilon = \frac{M_{Pl}^2}{2}\left(\frac{v'}{v}\right)^2 \ll 1, \ |\eta| = \left| M_{Pl}^2 \frac{v''}{v} \right| \ll 1$

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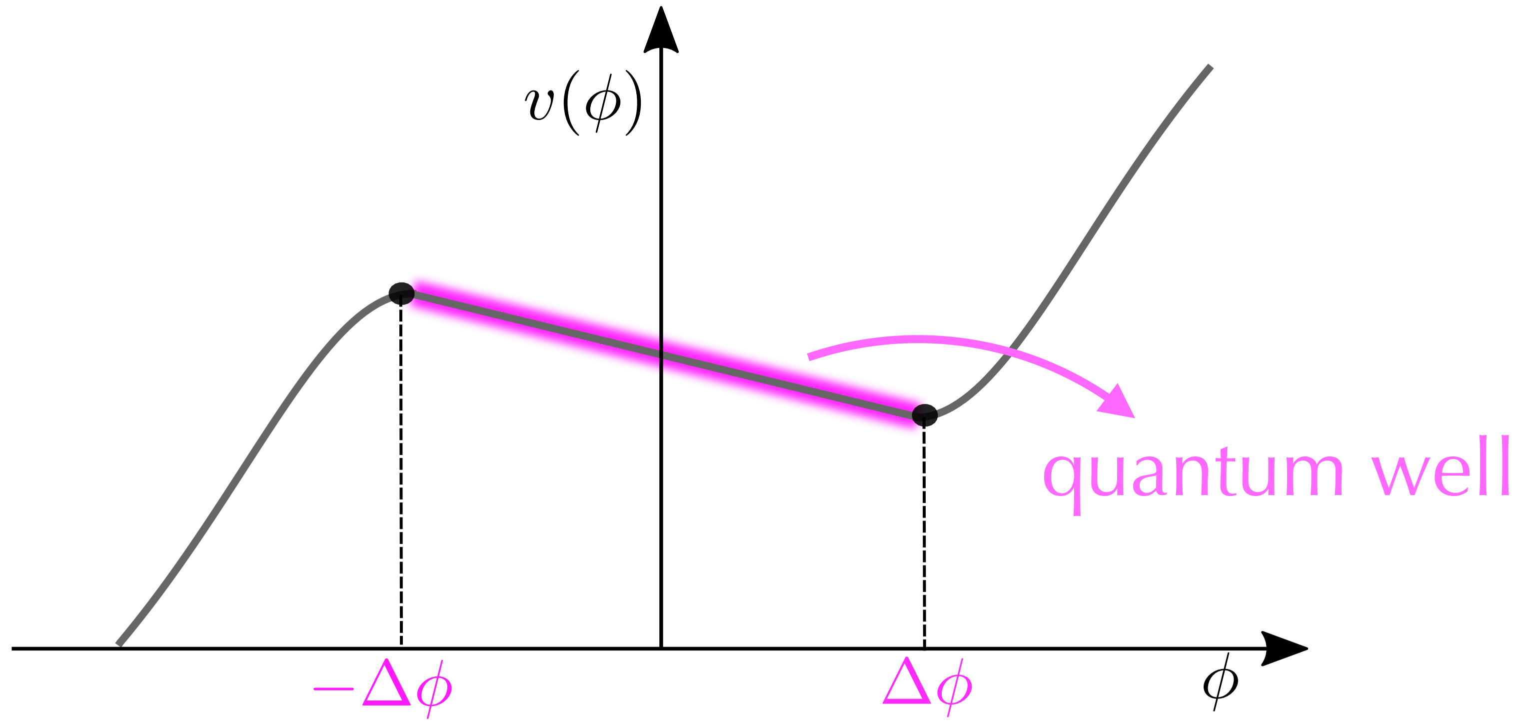

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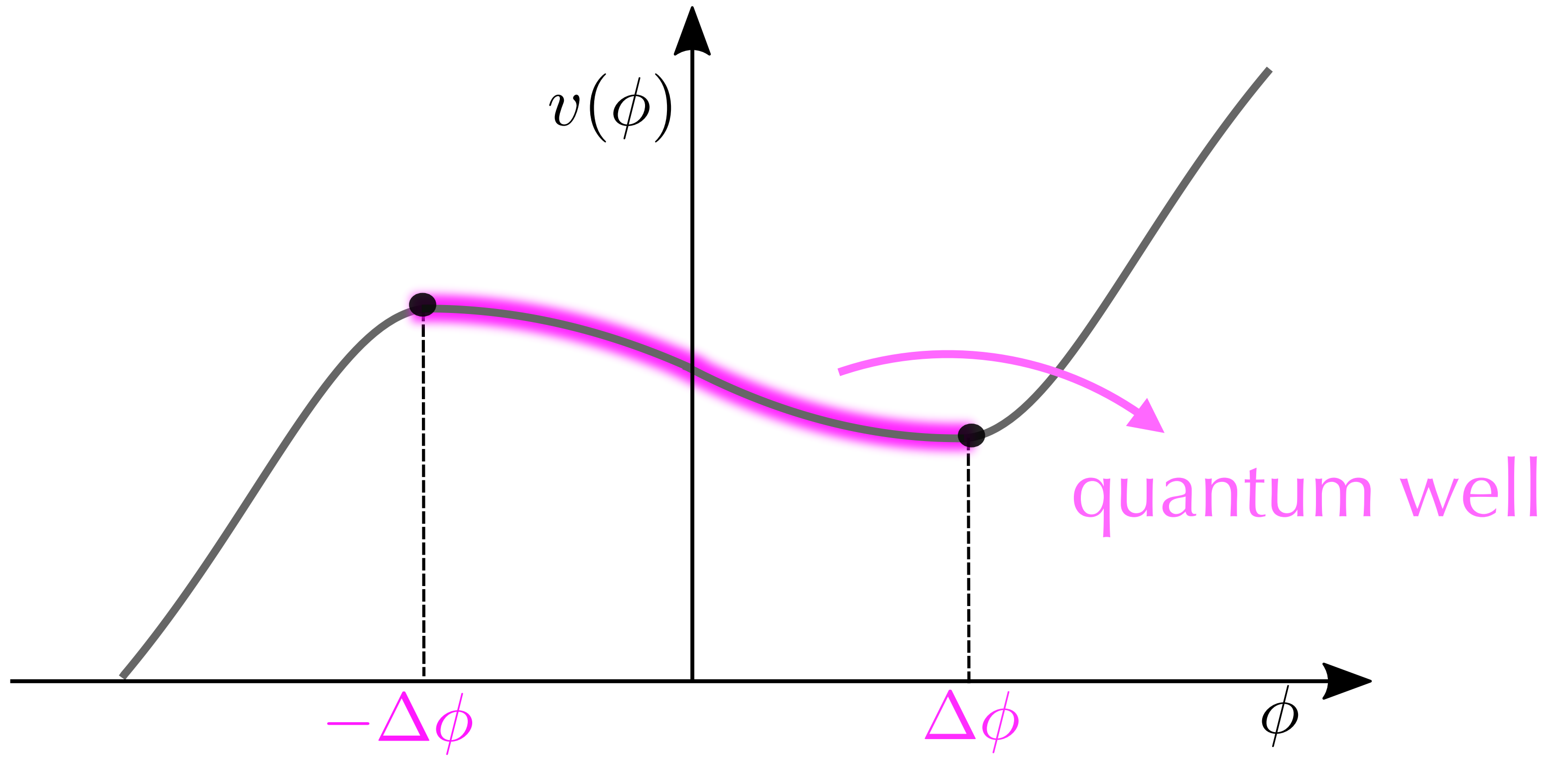

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$$\mu^2 = \frac{(2\,\Delta\phi)^2}{v_0\, M_{Pl}^2} \propto \frac{M_{Pl}^2\,\Delta\phi^2}{V}$$

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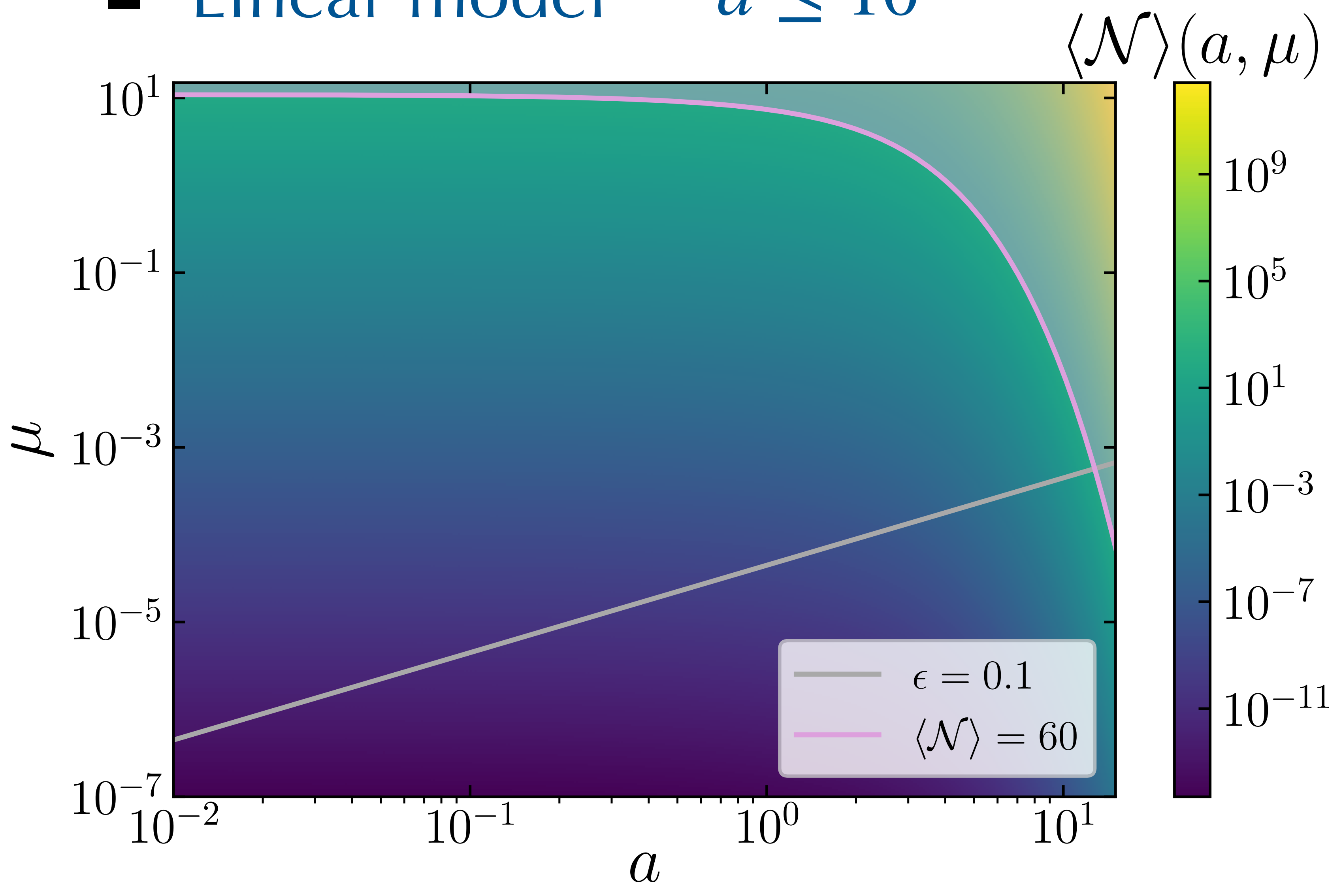

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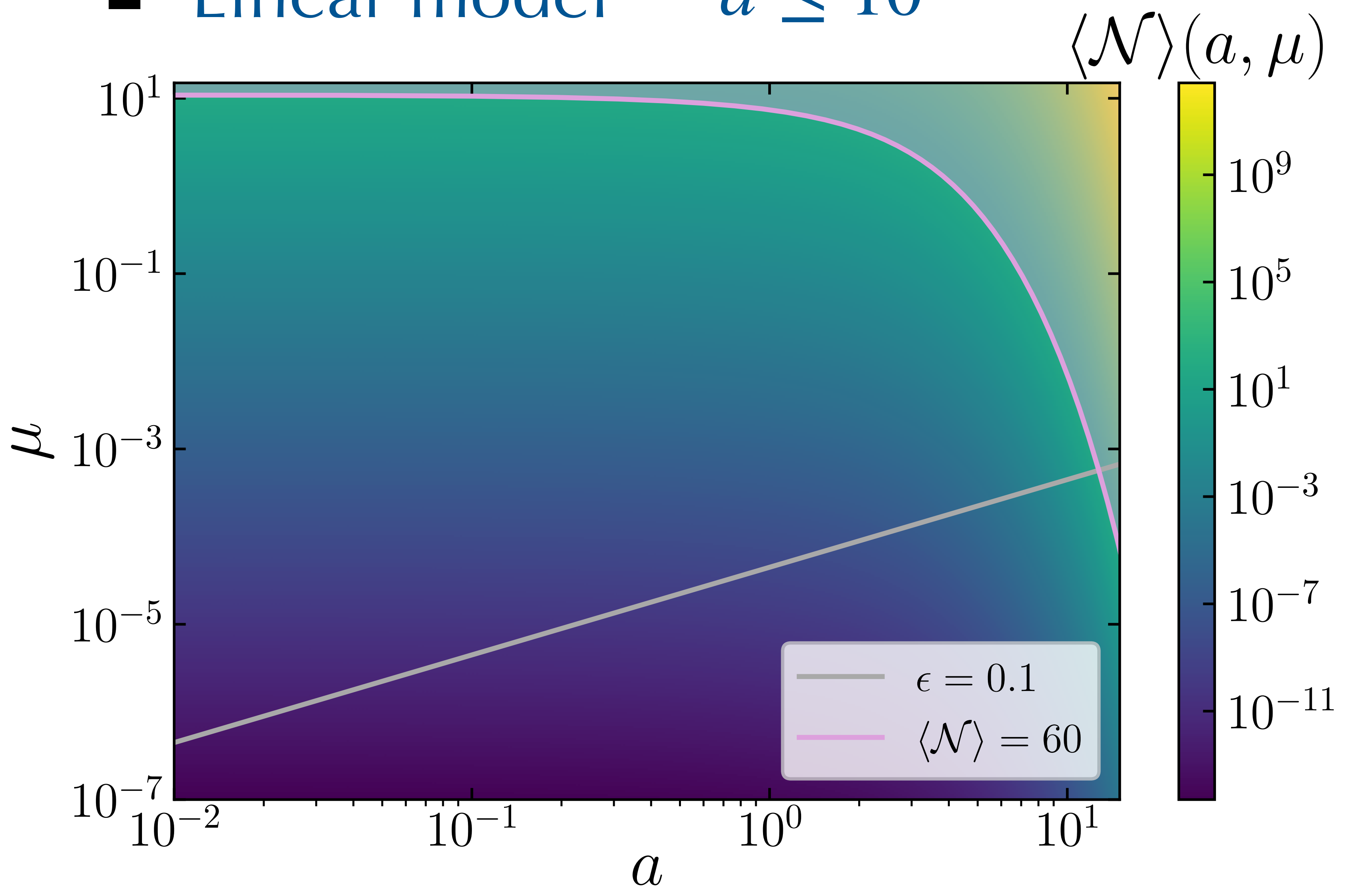

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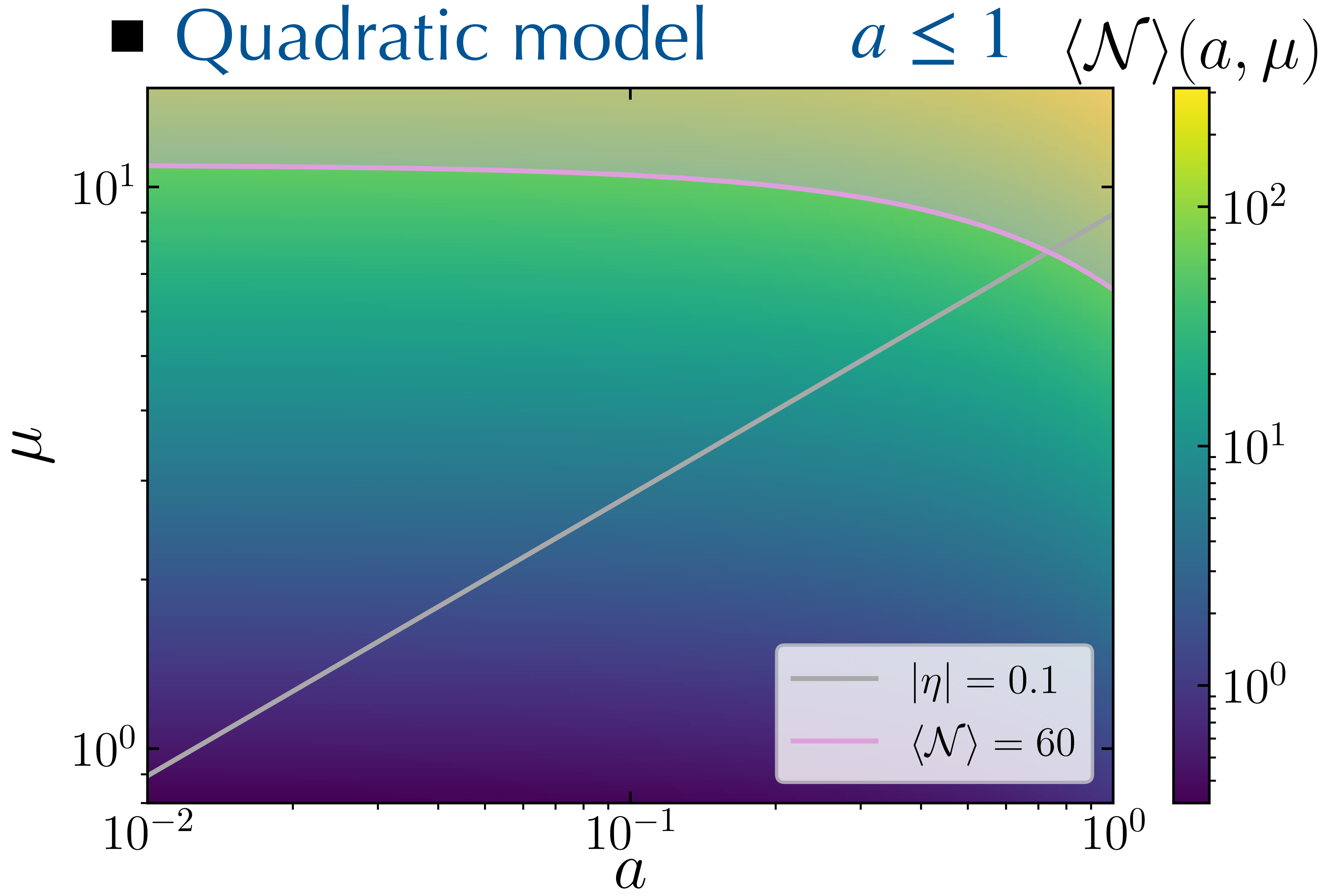

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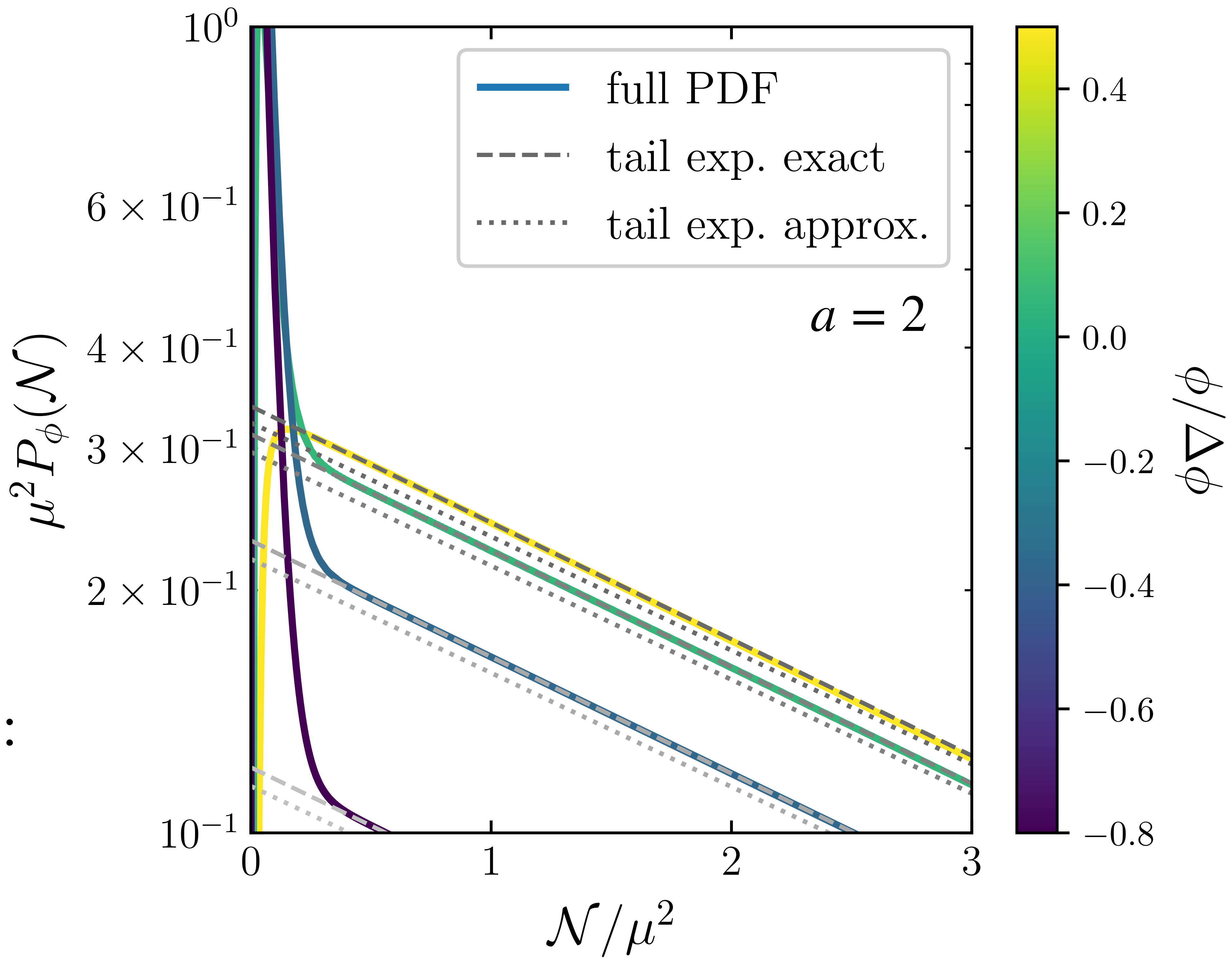

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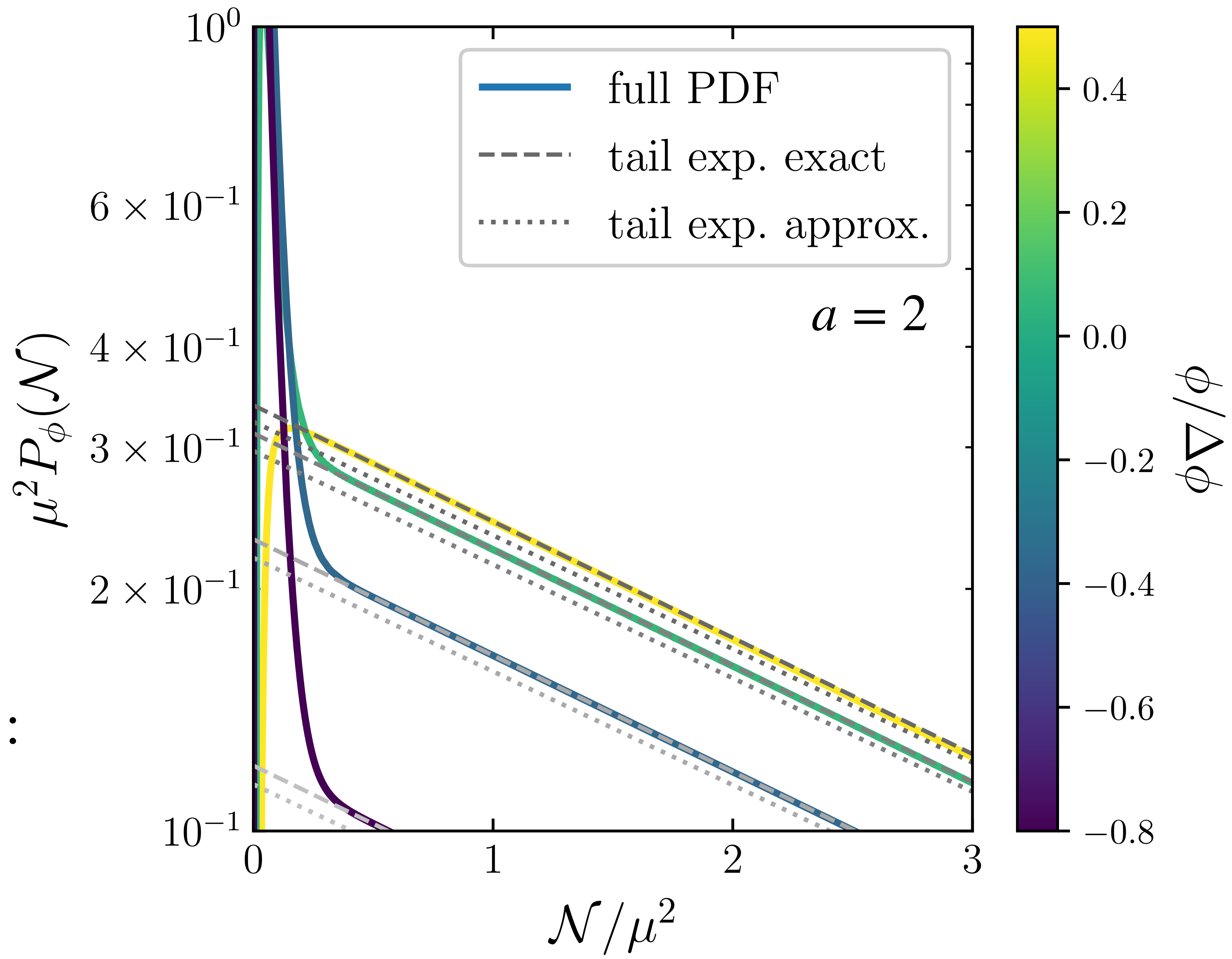

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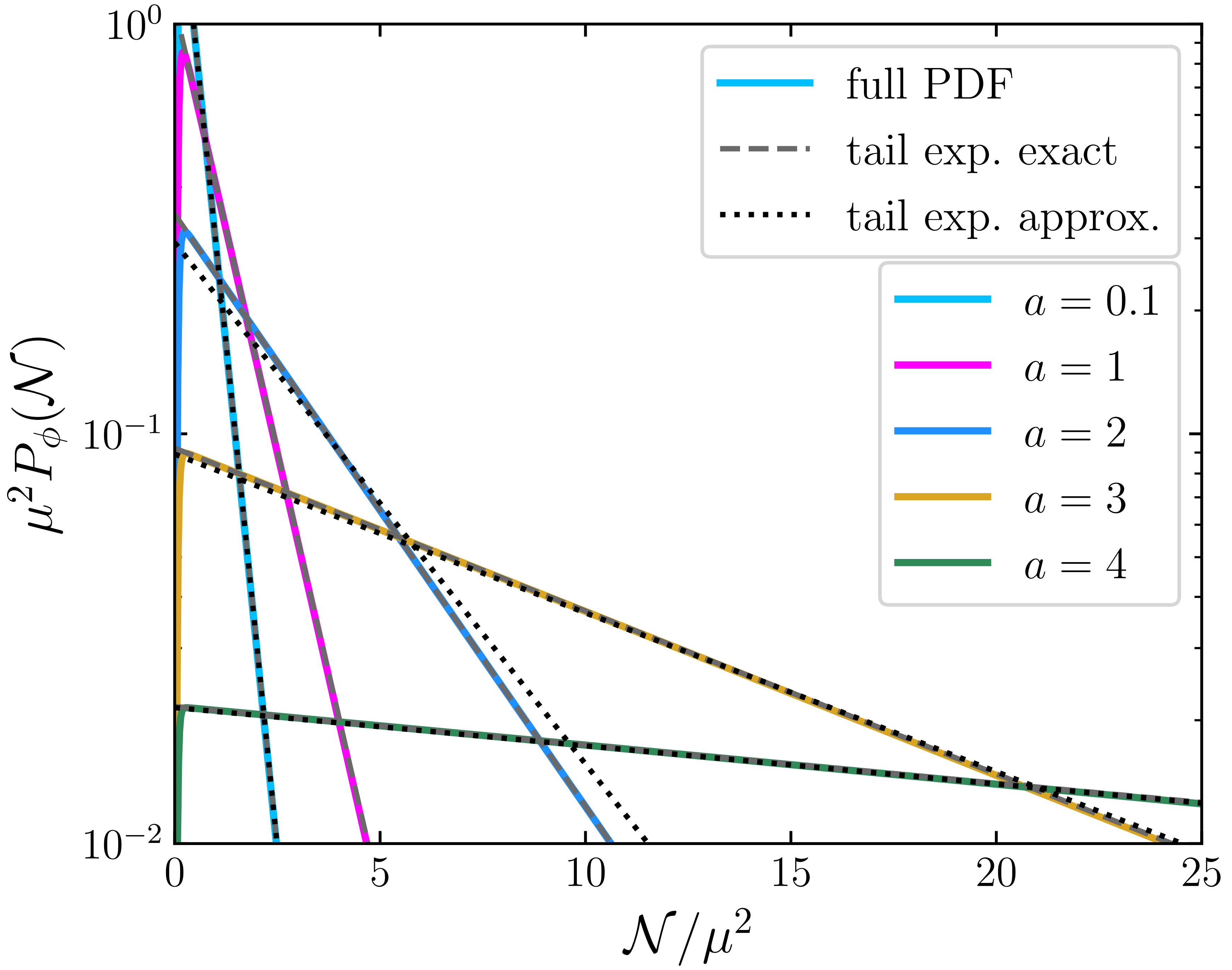

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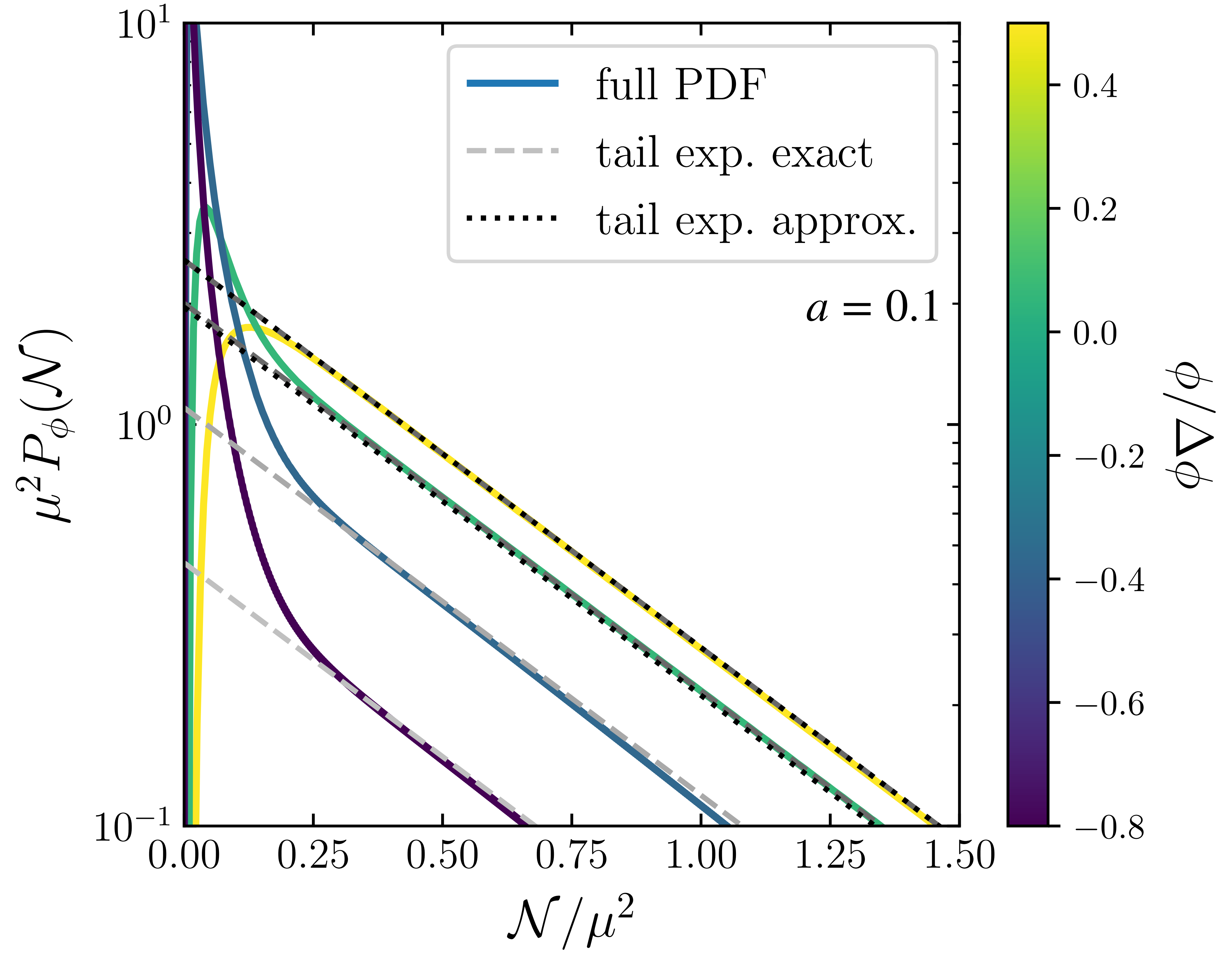

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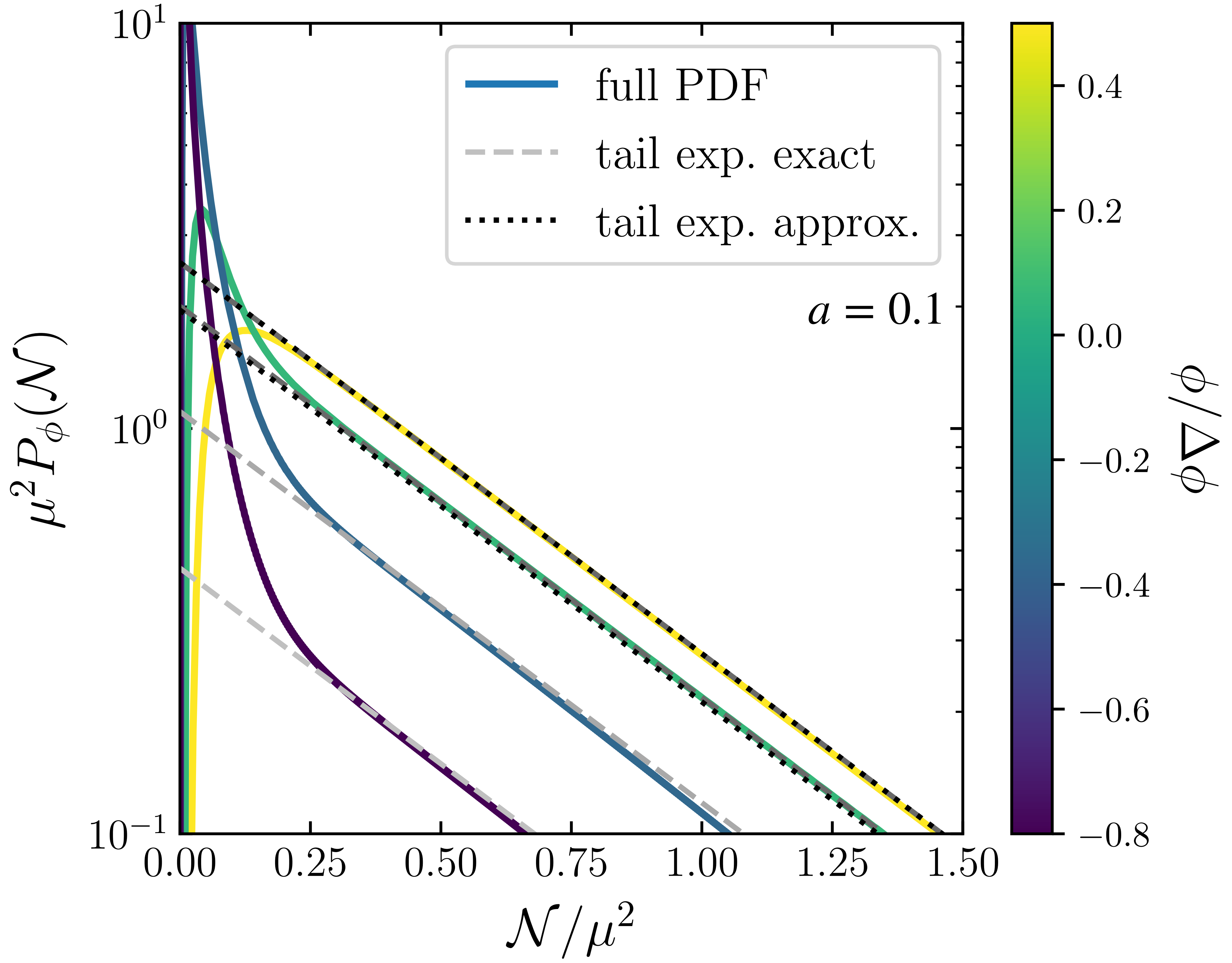

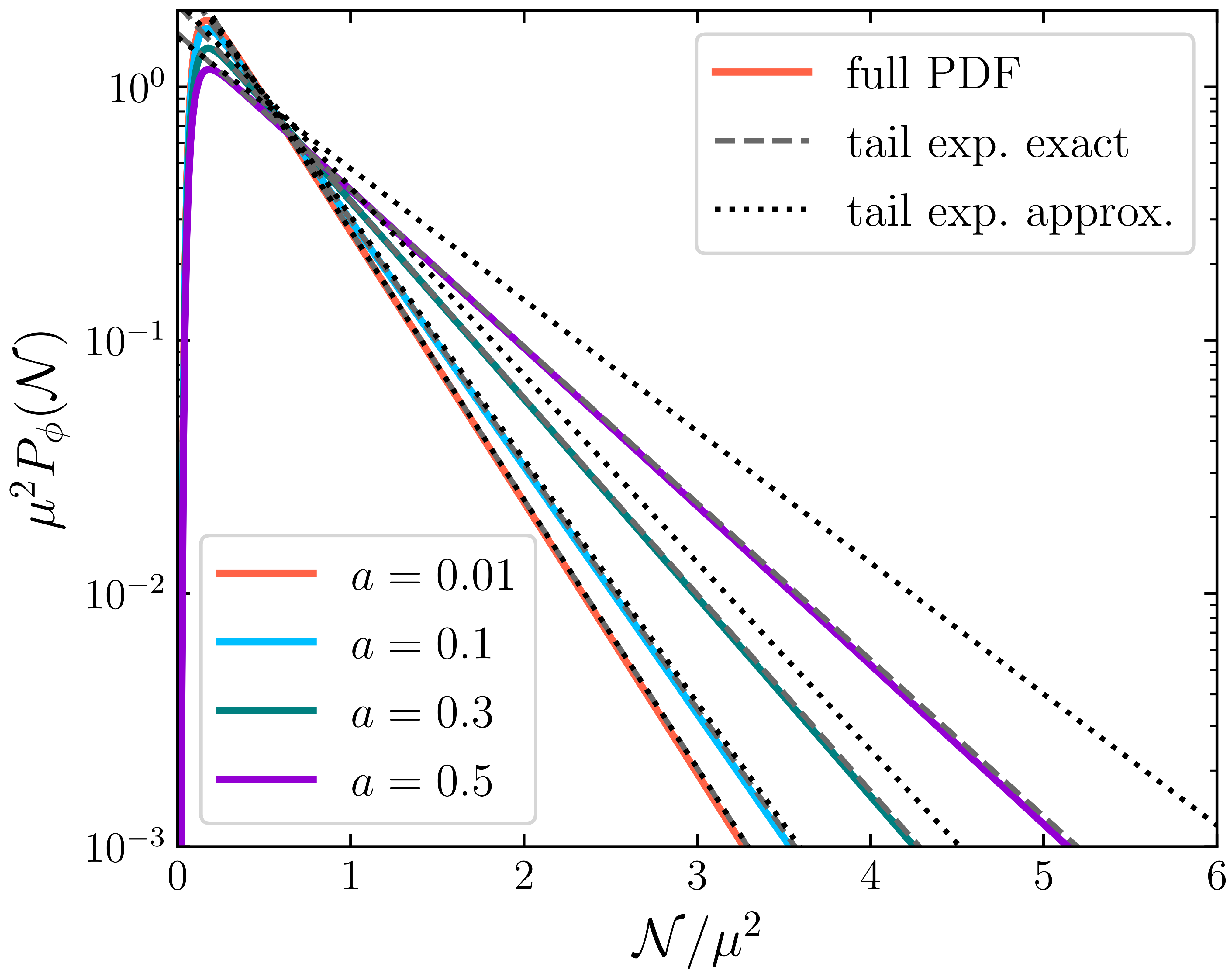

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⟶ super-exponential dependence on a

PBHs are overproduced when $a \gtrsim 8$

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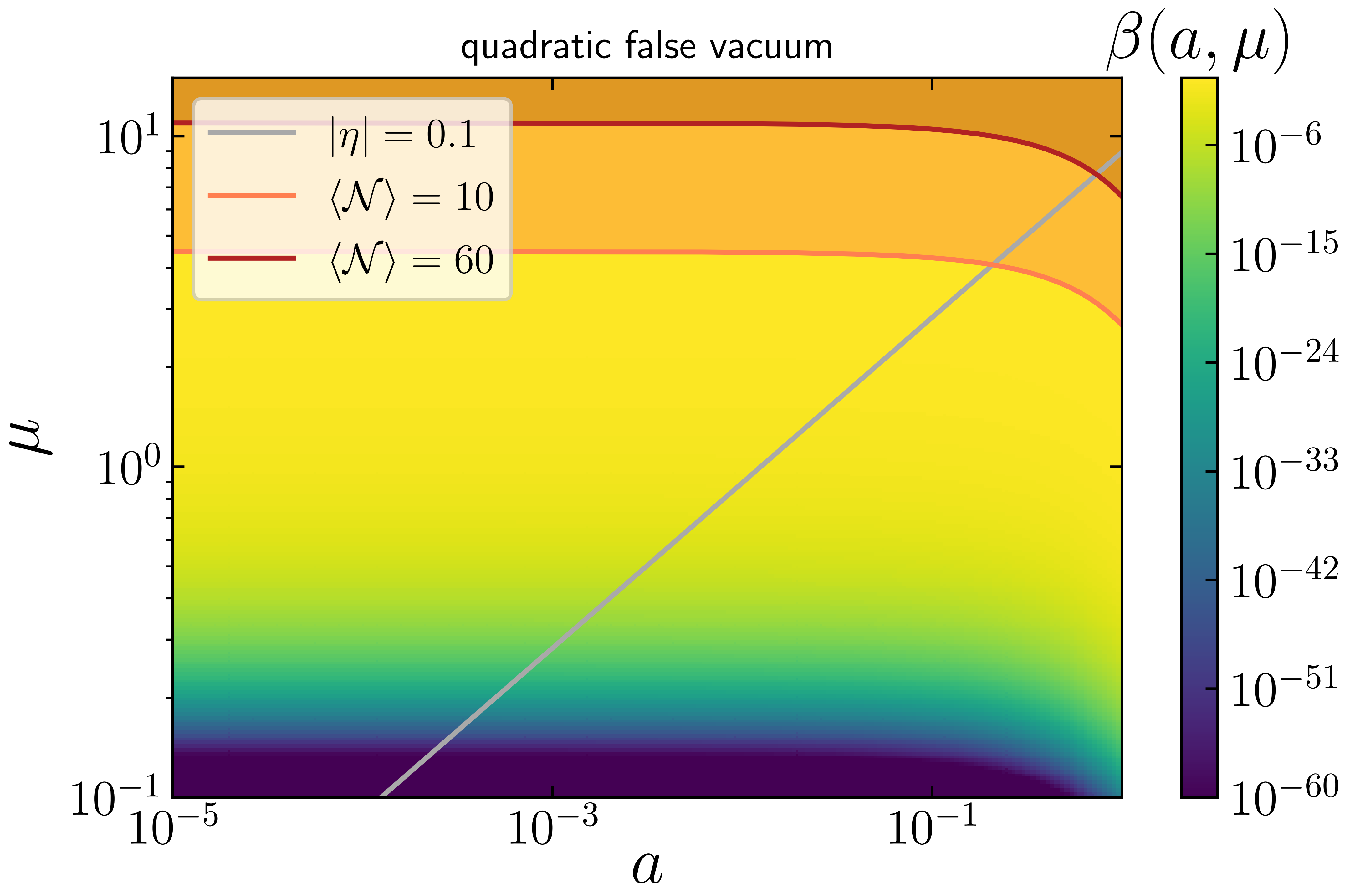
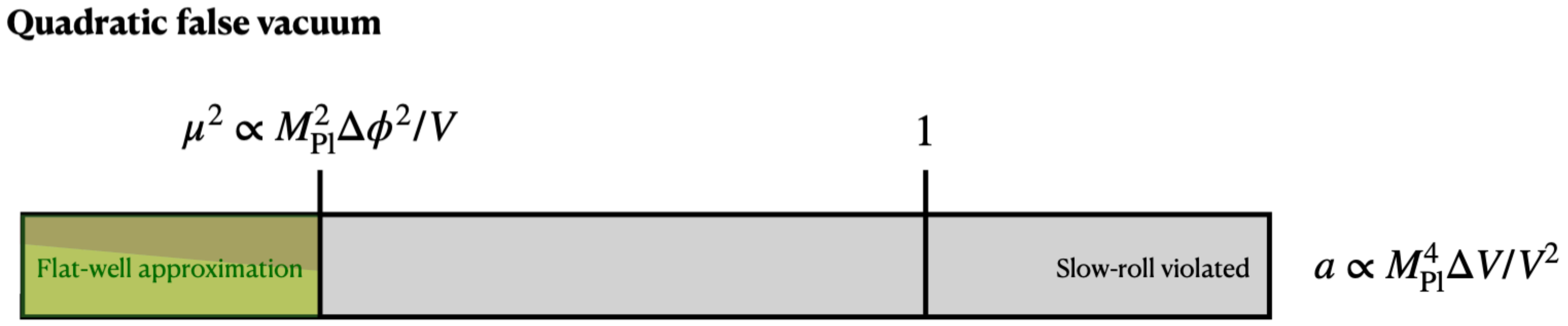
Quadratic model



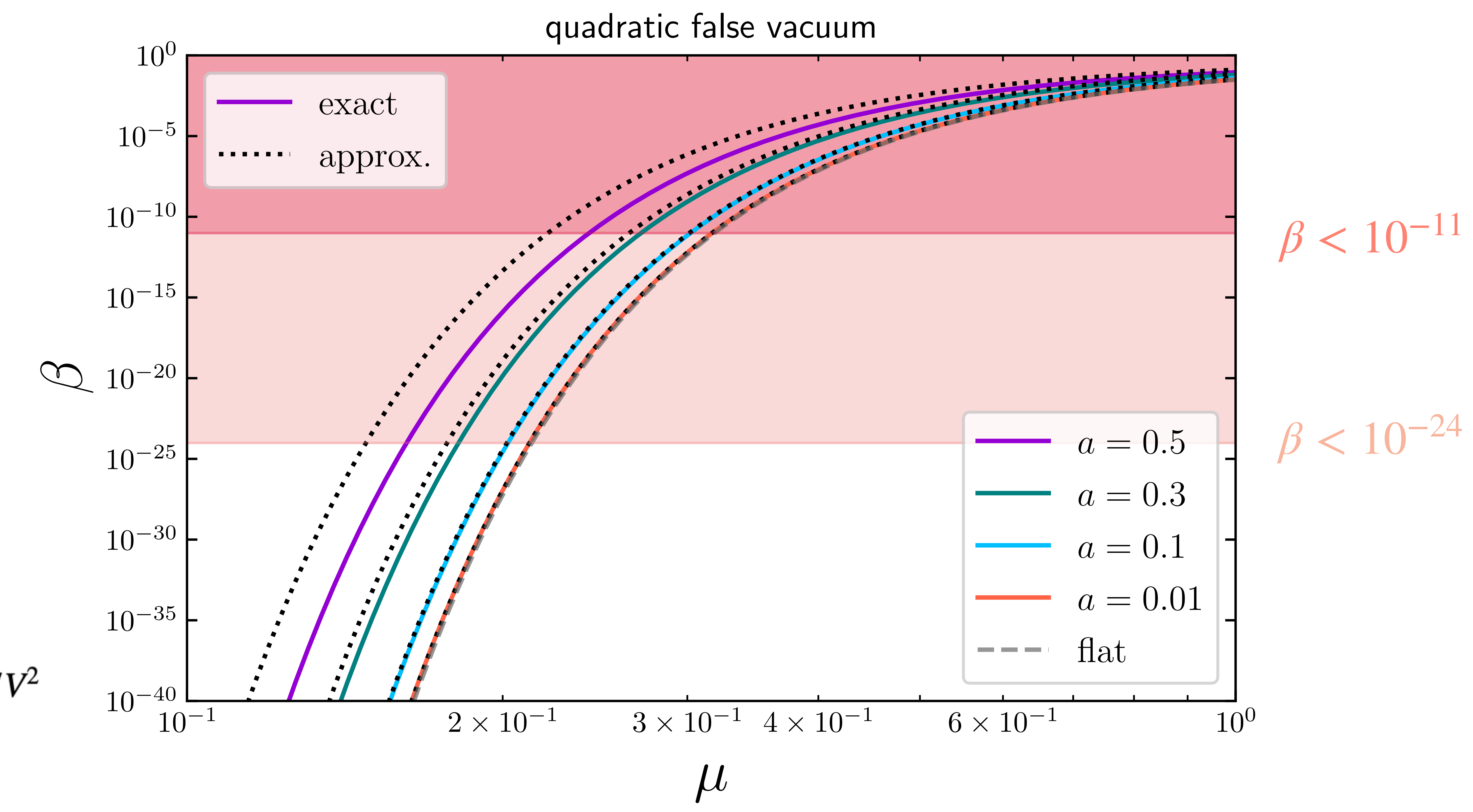


PBH abundance well captured by a flat-well limit ($a = 0$)

If $\mu \ll 1$, tiny amount of PBHs produced

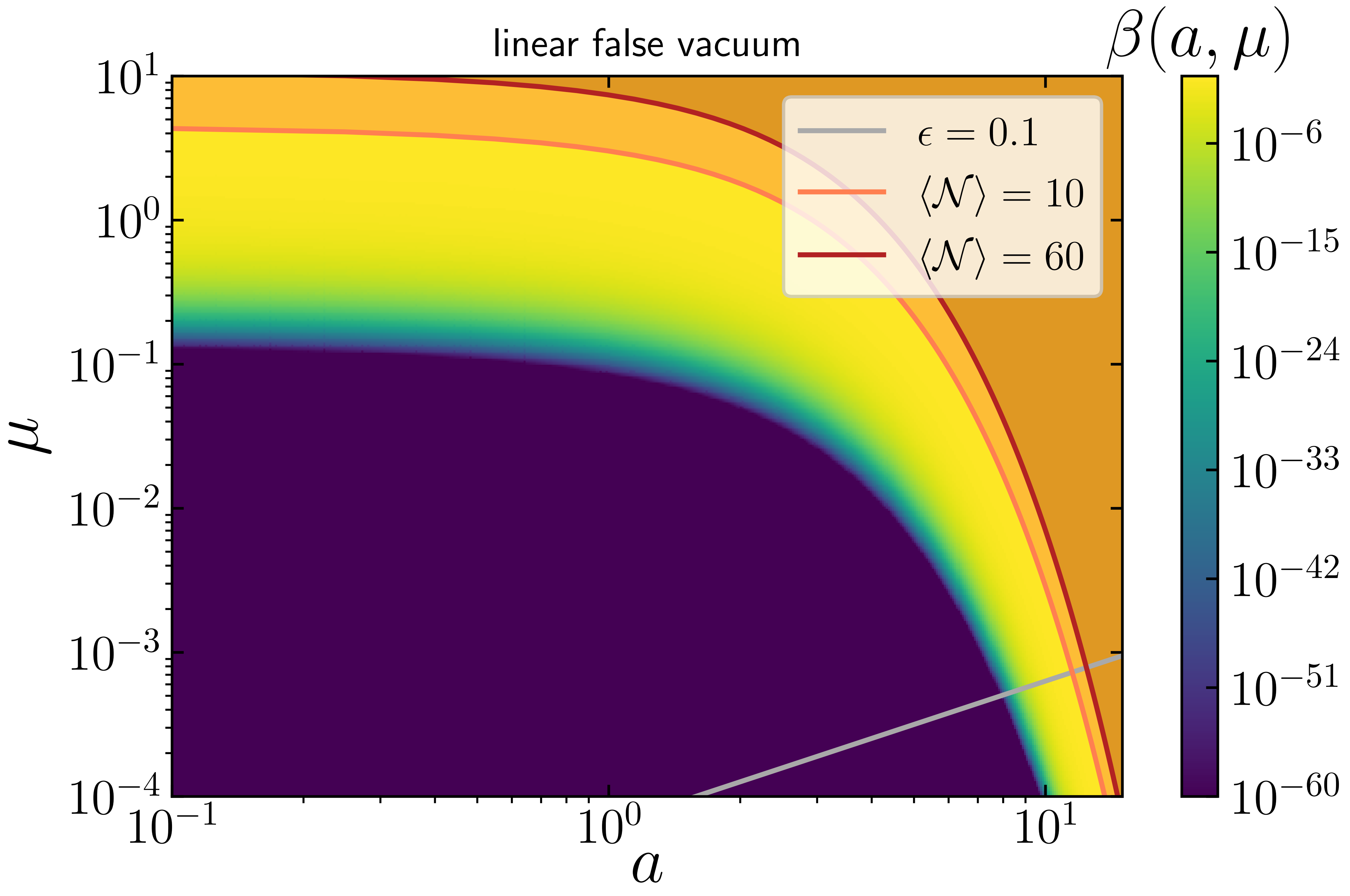
If $\mu \lesssim 1$, PBHs produced with sizable abundance

If $\mu \gtrsim 1$, PBHs overproduced



False vacuum: implications for Primordial Black Holes

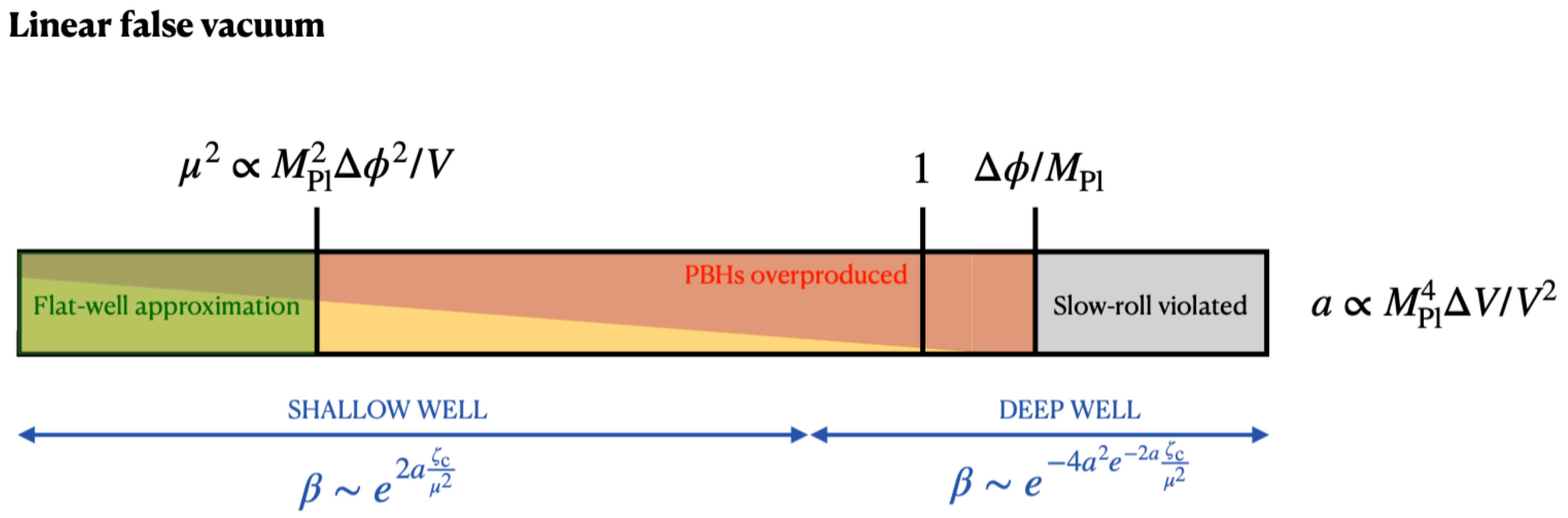
Linear model

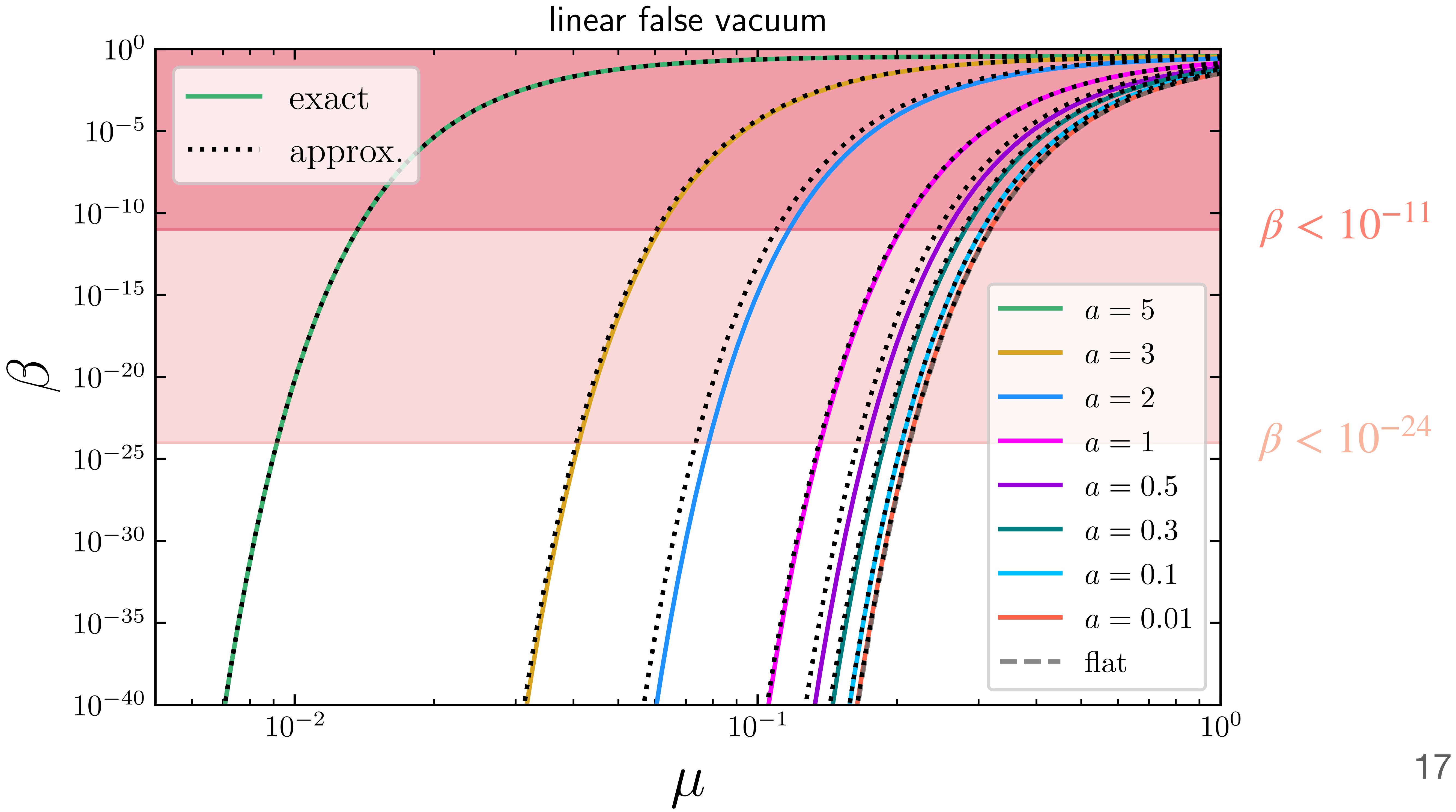


Additional regimes:

If $\mu^2 \ll a \ll 1$ (μ small):
large deviations from flat-well, still shallow-well domain;
non-trivial imprint of the false-vacuum profile

If $a \sim \mathcal{O}(1)$: large PBH production





Take home message

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- Impact of non-gaussian tails on different properties of PBHs, and in different scenarios,
  even at CMB and LSS scales

Università di Pisa

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DE L'ÉCOLE NORMALE SUPÉRIEURE

cnrs

Many thanks for the attention!

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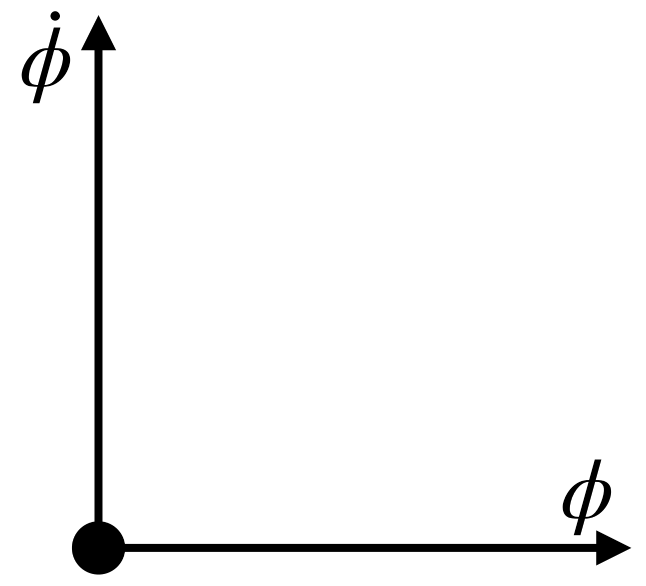
False vacuum: preserving slow roll

Slow roll requires: $|\ddot\phi| \ll 3H|\dot\phi|, |V_{,\phi}|$

What happens if $|V_{,\phi}| = 0$?

$$\ddot\phi + 3\,H(\phi,\dot\phi)\,\dot\phi + V_{,\phi} = 0 \qquad H^2(\phi,\dot\phi) = \frac{1}{3M_{Pl}^2}\left(V(\phi) + \frac{\dot\phi^2}{2}\right)$$



minimum $(\phi = 0, \dot\phi = 0)$

$V(\phi) \simeq V_0 + m^2\phi^2/2$

Linearised Klein-Gordon equation

$$\ddot\phi + 3H_0\,\dot\phi + m^2\phi = 0 \qquad H_0^2 = \frac{V_0}{3\,M_{Pl}^2}$$

$$\phi = A\exp\left[-\frac{3}{2}\left(1 + \sqrt{1 - \frac{4\,m^2}{9\,H_0^2}}\right)H_0\,t\right] + B\exp\left[-\frac{3}{2}\left(-1 - \sqrt{1 - \frac{4\,m^2}{9\,H_0^2}}\right)H_0\,t\right]$$

$m \gg 3H_0/2$: damped oscillations, friction term $3H\dot\phi$ subdominant: far from slow-roll regime

$$m \ll 3H_0/2 \qquad \phi \simeq A\exp\left(-3H_0 t\right) + B\exp\left(-\frac{1}{3}\frac{m^2}{H_0^2}H_0 t\right) \simeq B\exp\left(-\frac{m^2 t}{3H_0}\right)$$

$$3H\dot\phi \simeq -m^2\phi = -V_{,\phi}(\phi) \qquad \ddot\phi \simeq \frac{m^4}{9\,H_0^2}\phi = \frac{m^2}{9\,H_0^2}V_{,\phi} \ll V_{,\phi}(\phi)$$

slow-roll regime: acceleration term subdominant
(m^2/H_0^2 - suppressed)

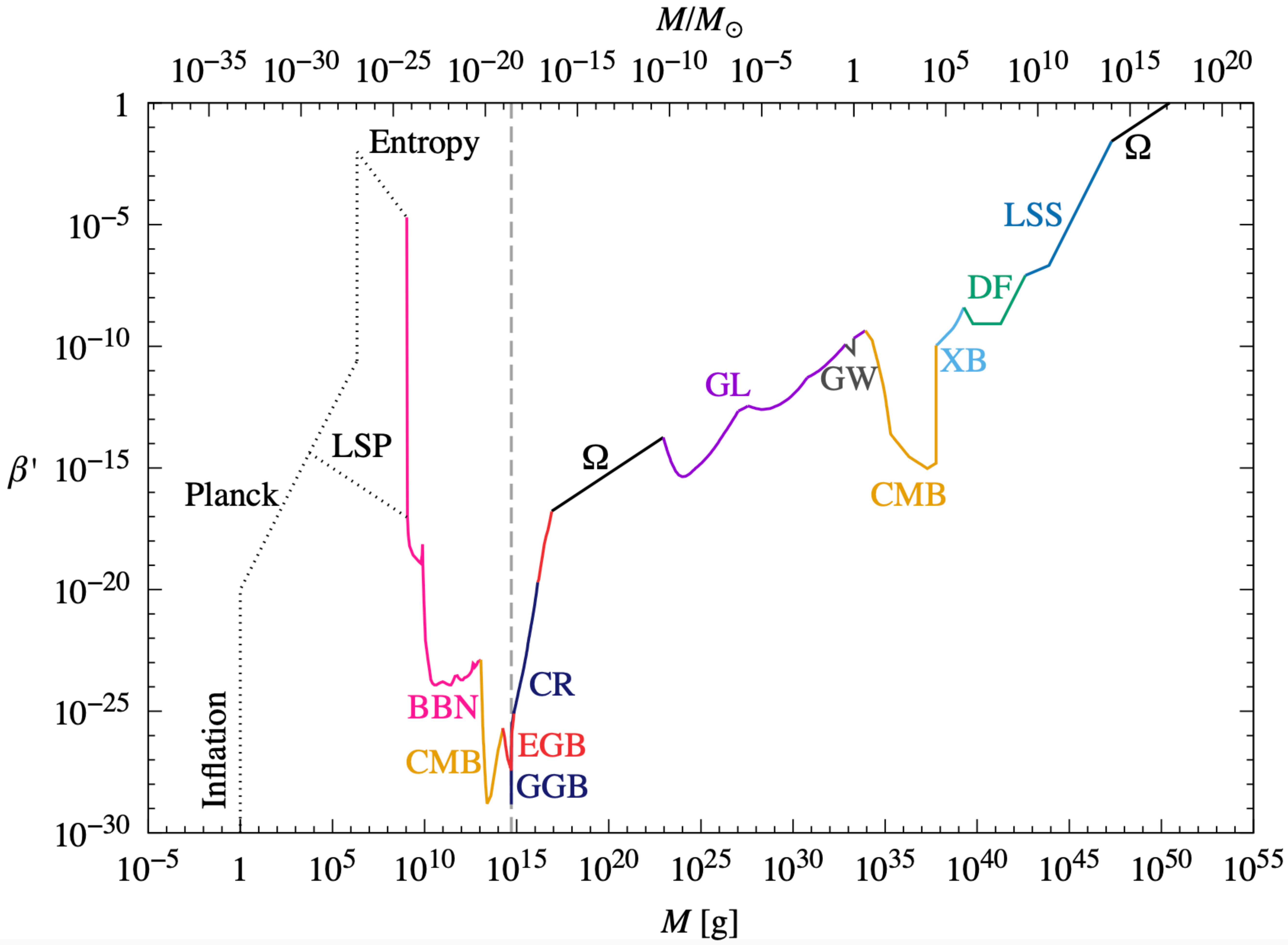
Primordial black holes: observational constraints

Depends on the mass at which PBHs form

$10^9 g < M_{PBH} < 10^{16} g \longrightarrow$ from $\beta < 10^{-24}$ to $\beta < 10^{-17}$ PBH Hawking evaporation on Big Bang Nucleosynthesis and on the extragalactic photon background

$10^{16} g < M_{PBH} < 10^{50} g \longrightarrow$ from $\beta < 10^{-11}$ to $\beta < 10^{-5}$ Gravitational and astrophysical effects

$M_{PBH} < 10^9 g$ Not yet evaporated: no direct observational constraints



B. Carr, K. Kohri, Y. Sendouda, J. Yokoyama [2021]
Constraints on Primordial Black Holes

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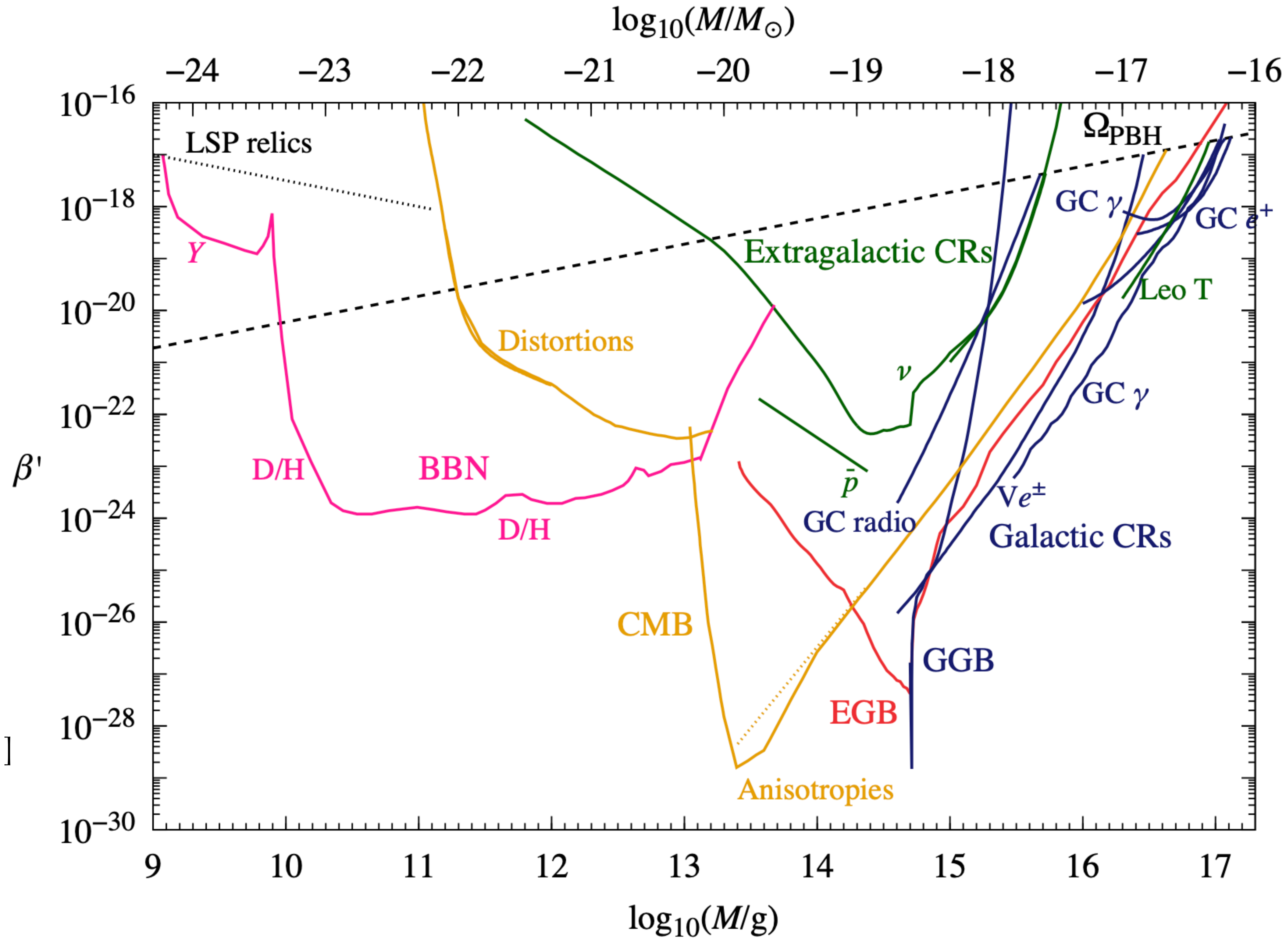

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