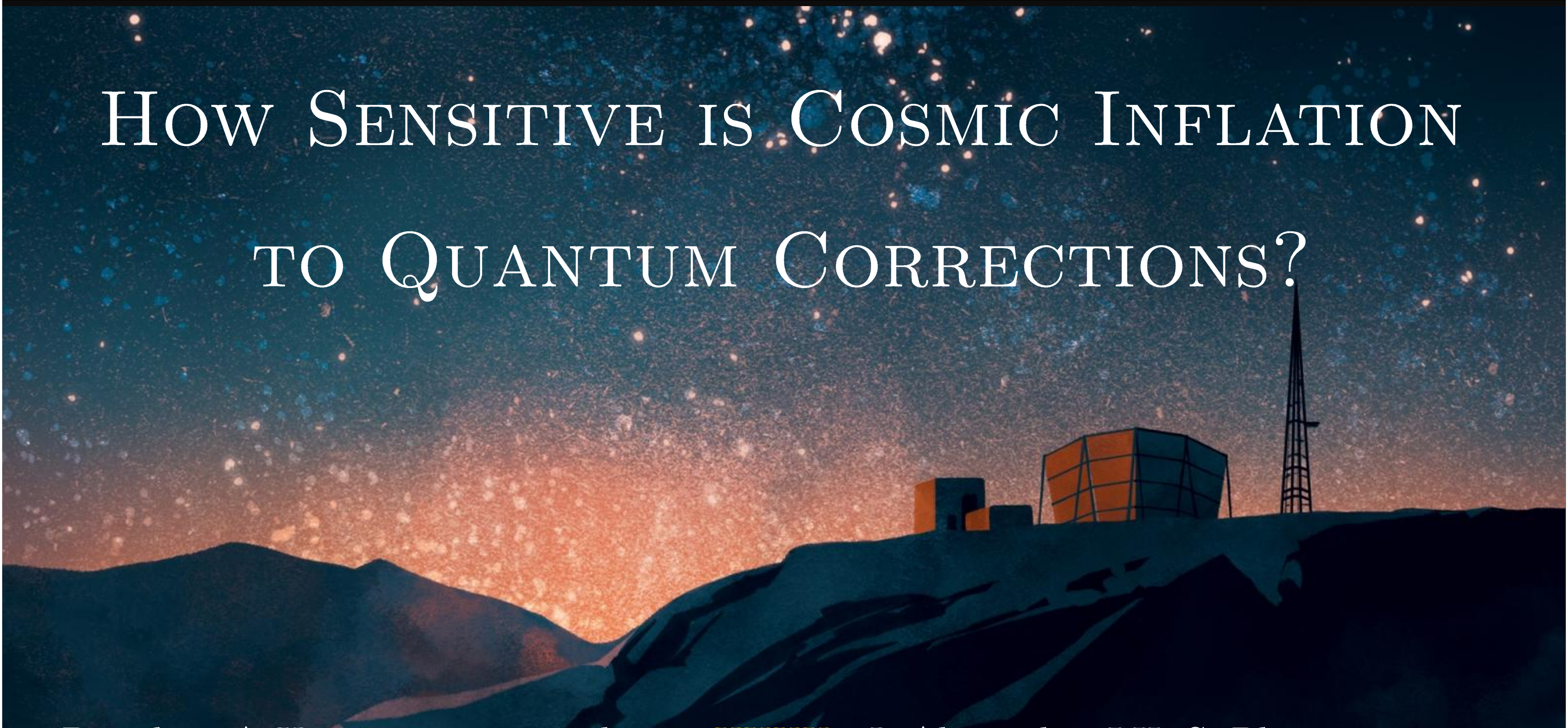
PASCOS 2026

Lucien Heurtier



How Sensitive is Cosmic Inflation to Quantum Corrections?

Based on ArXiv:2511.05296 and 2606.XXXX– J. Alexandre, LH, S. Pla

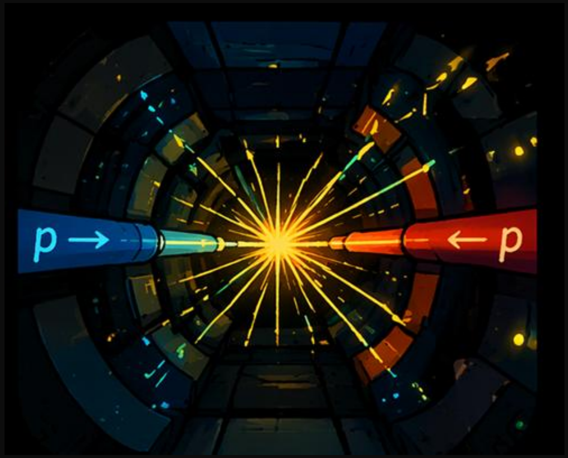
King's College London

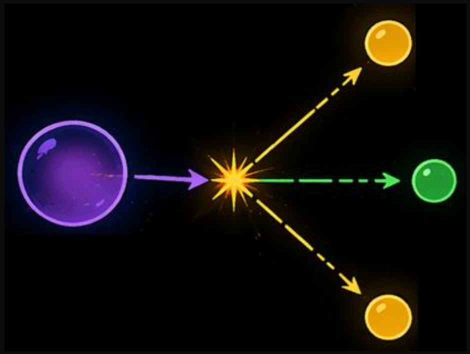
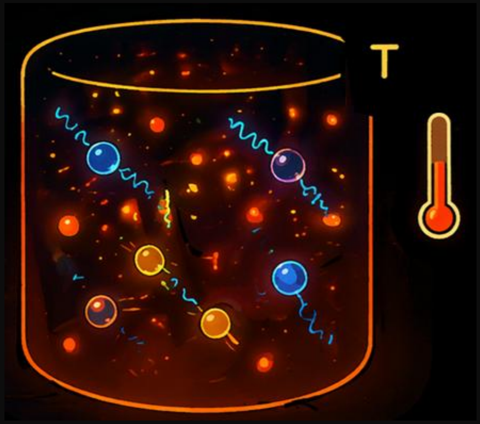
UKRI Science and Technology Facilities Council

In QFT, renormalisation is crucial

Observables independent on renormalisation scale μ, but dependent on the energy scale of the system

- Collision ⟶ $\sqrt{s}$ (CoM energy)
- Particle decay ⟶ m (vacuum/thermal mass)
- Thermal bath ⟶ T (temperature)



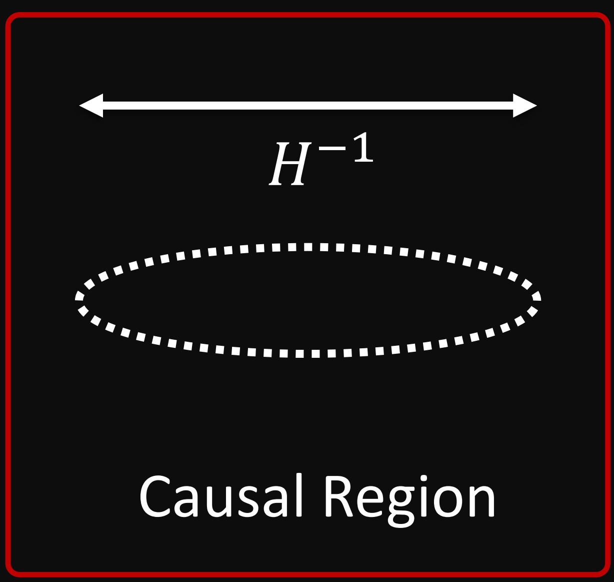
In particle physics experiments, this scale is set by an external operator

What happens inside the experiment does not affect this choice.

… unlike in cosmology

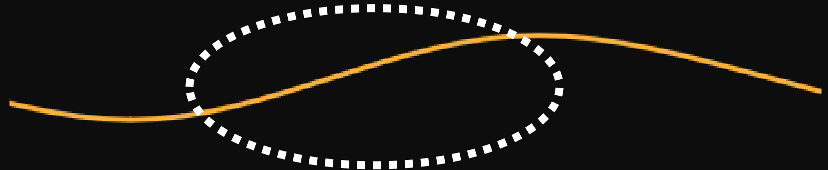
In cosmology

$$\frac{a'(t)}{a(t)} \equiv H(t)$$ Hubble scale

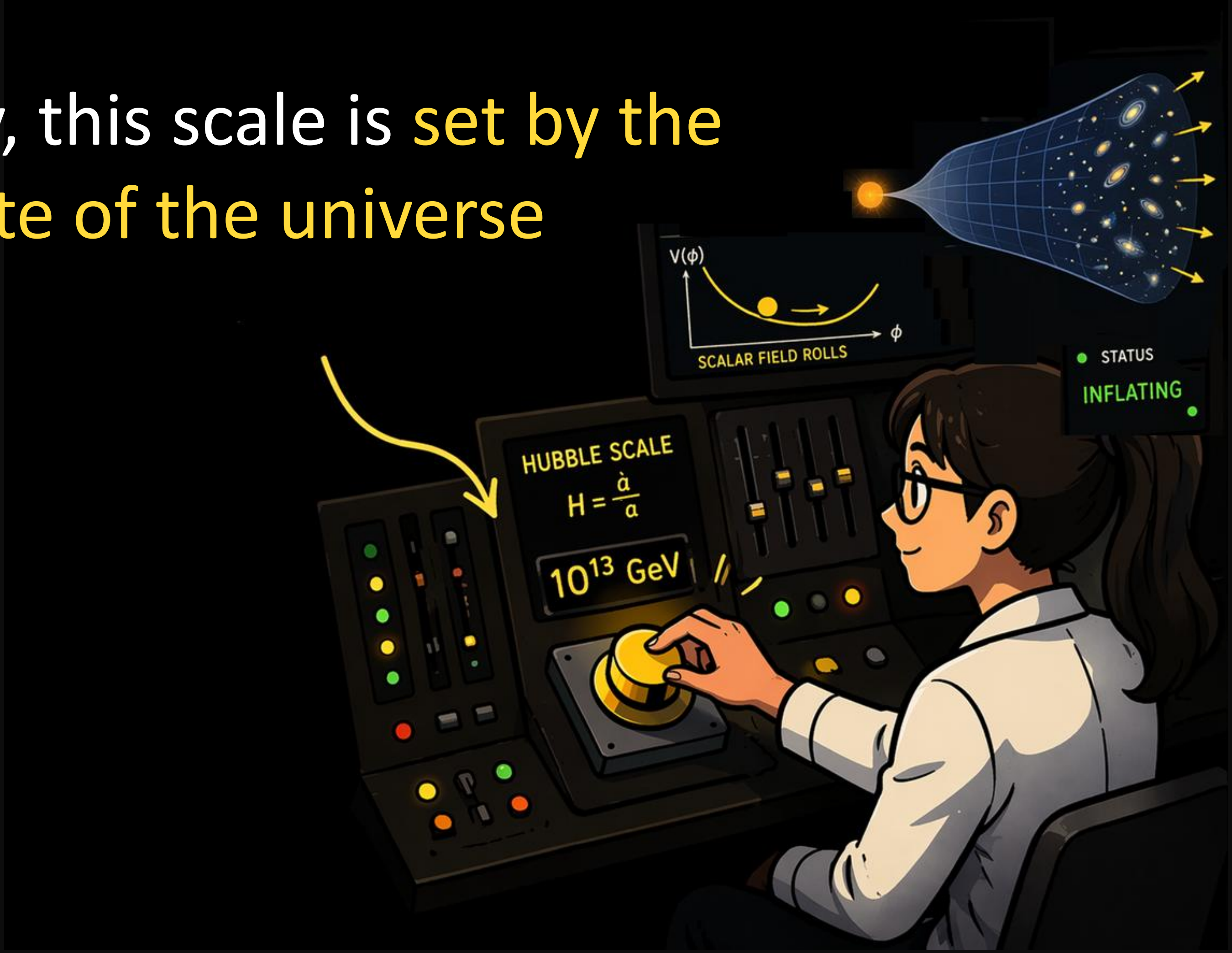


Small-scale fluctuations $\omega \gg H$ Ultraviolet theory (quantum)

Large-scale fluctuations $\omega \ll H$ Infrared Theory (classical)



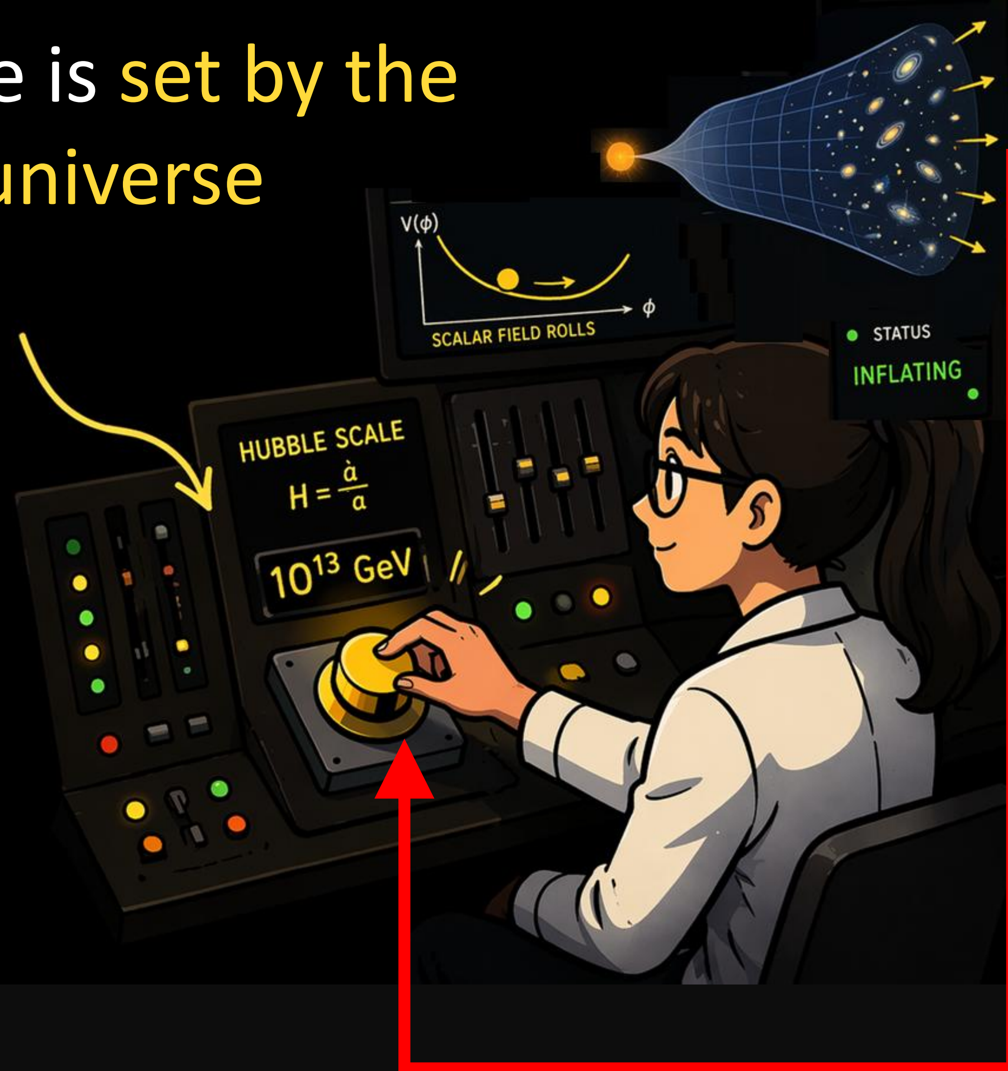
In cosmology, this scale is set by the expansion rate of the universe



In cosmology, this scale is set by the expansion rate of the universe

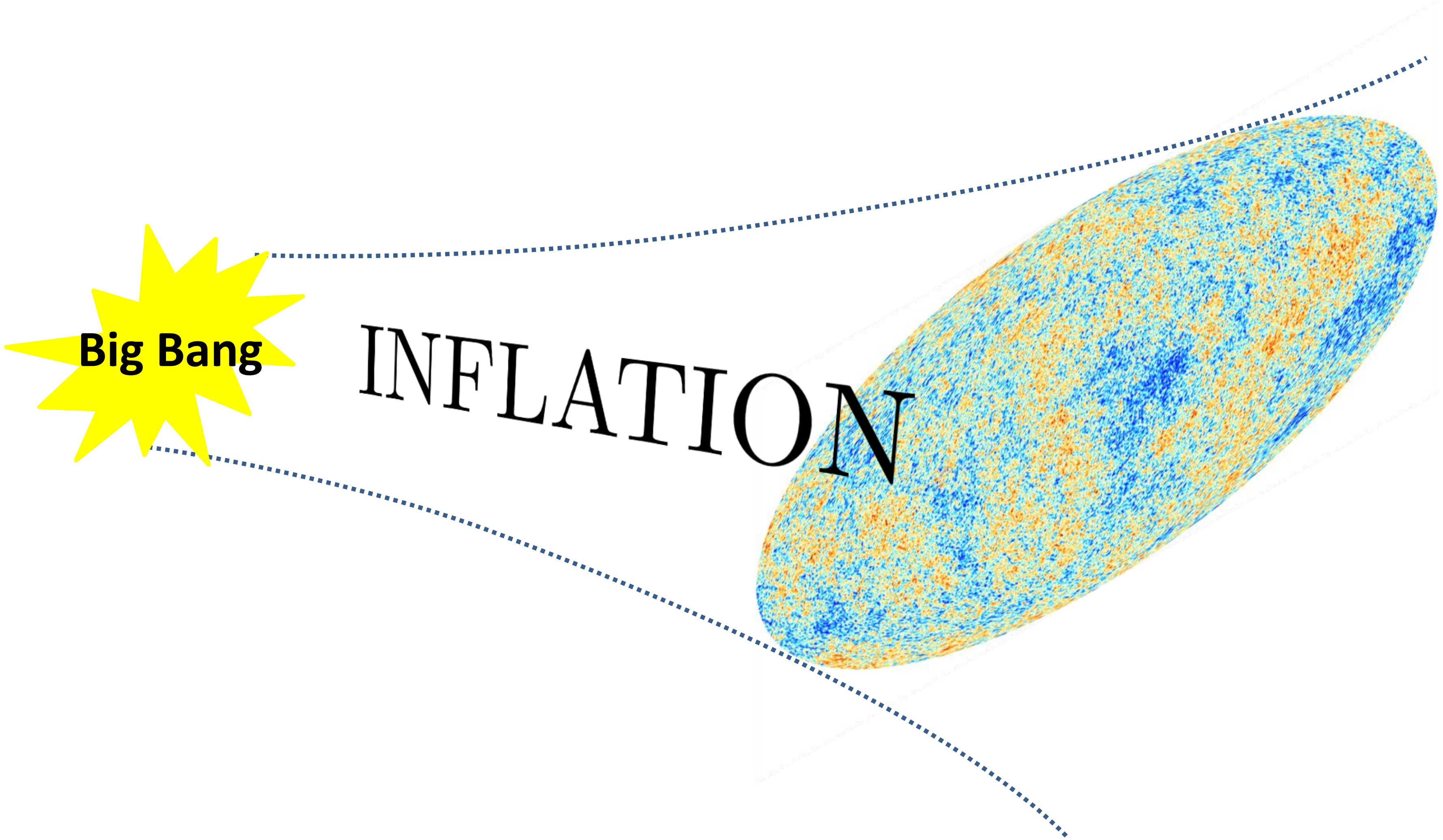
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

Friedmann equations



What happens inside the experiment perturbs the operator!

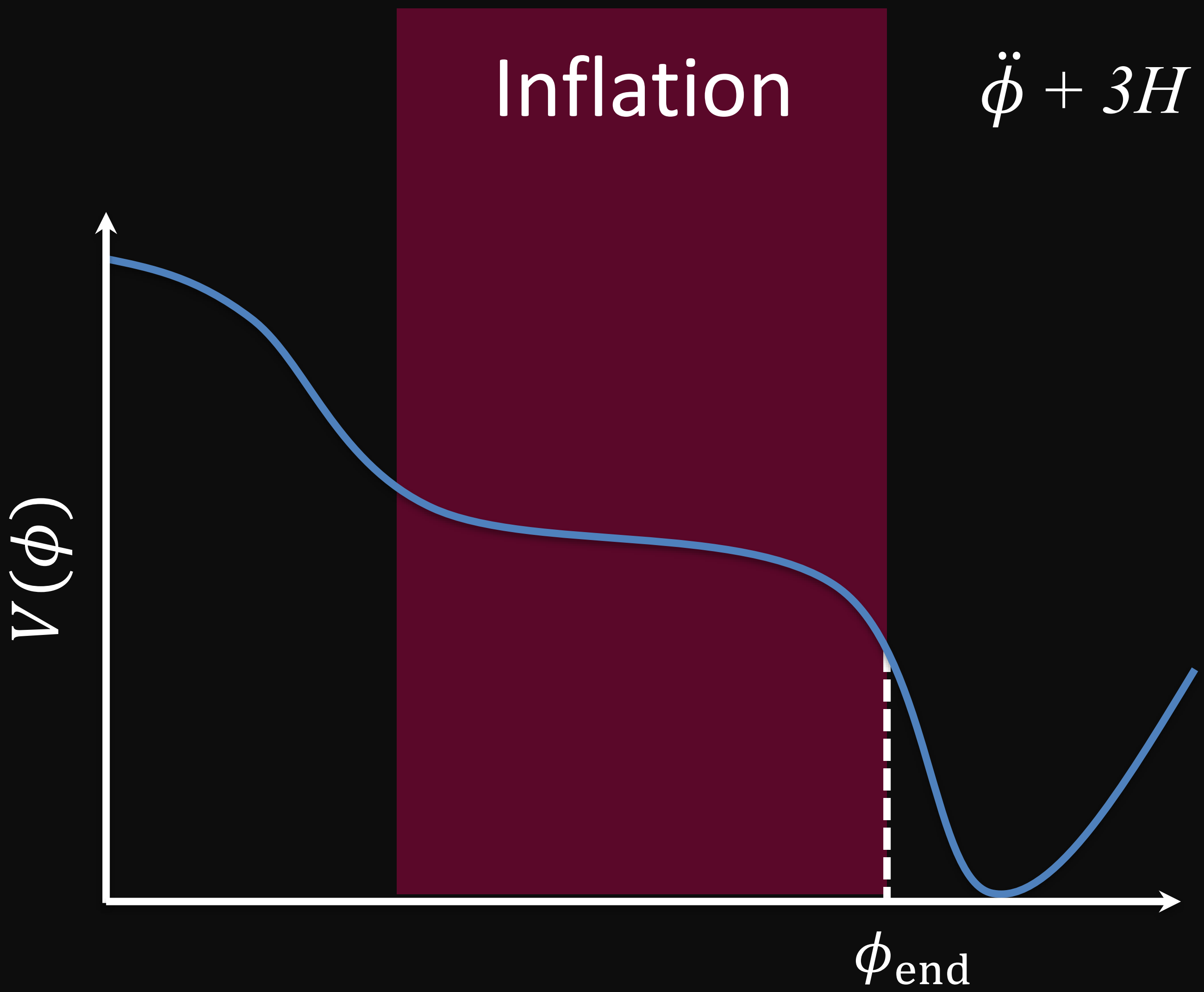
Cosmic Inflation



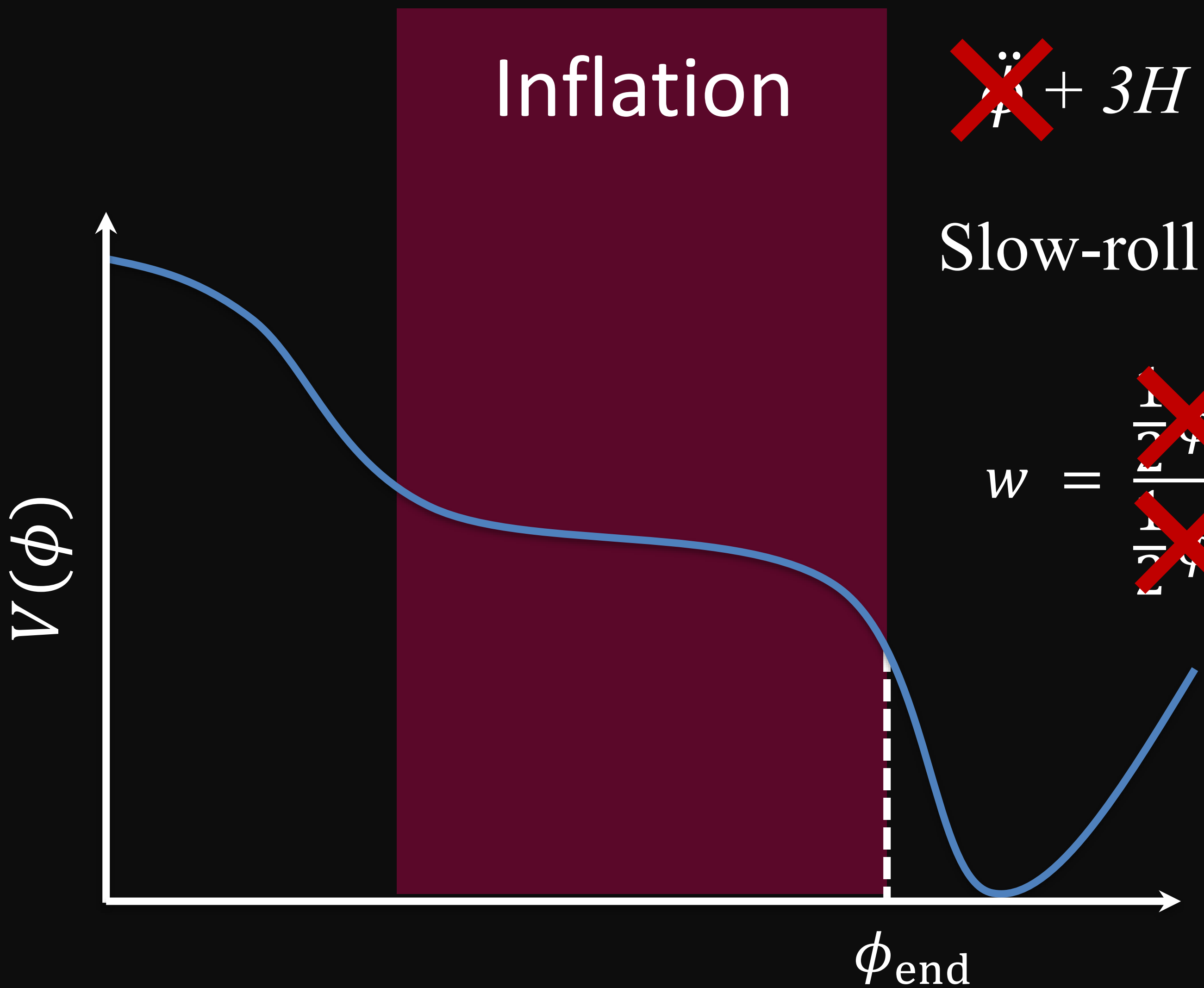
→ **Homogeneous, flat universe**

Inflation Potential

$$\ddot{\phi} + 3H\,\dot{\phi} + V'(\phi) = 0$$



Inflation Potential



$$\cancel{\ddot{\phi}} + 3H\,\dot{\phi} + V'(\phi) = 0$$

Slow-roll: $3H\,\dot{\phi} \sim V'(\phi)$

$$w = \frac{\cancel{\frac{1}{2}\dot{\phi}^2} - V(\phi)}{\cancel{\frac{1}{2}\dot{\phi}^2} + V(\phi)} \approx -1$$

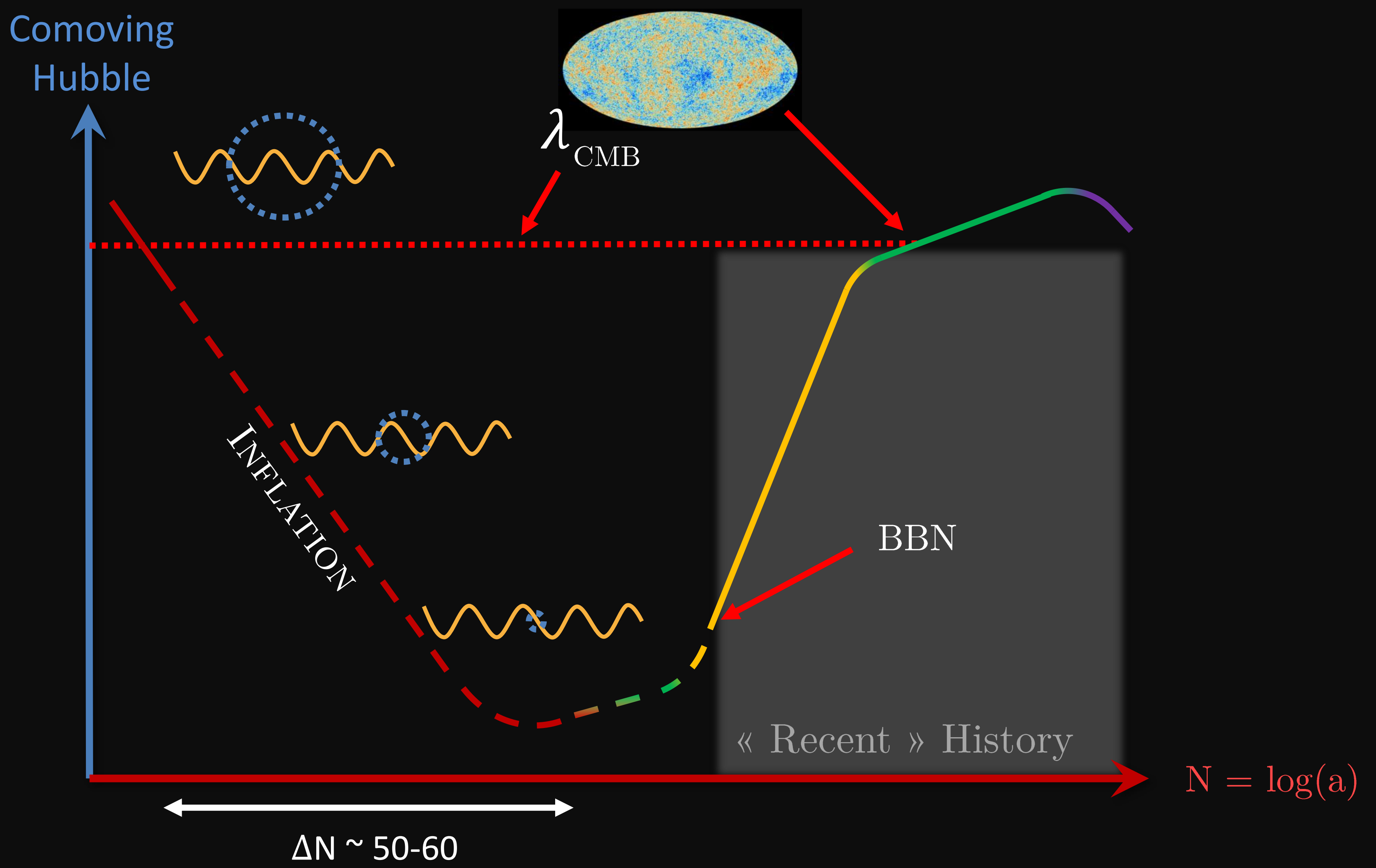
Inflation Potential

$$V(\phi) = V_0 + g_1\,\phi + g_2\phi^2 + g_3\phi^3 + \cdots$$

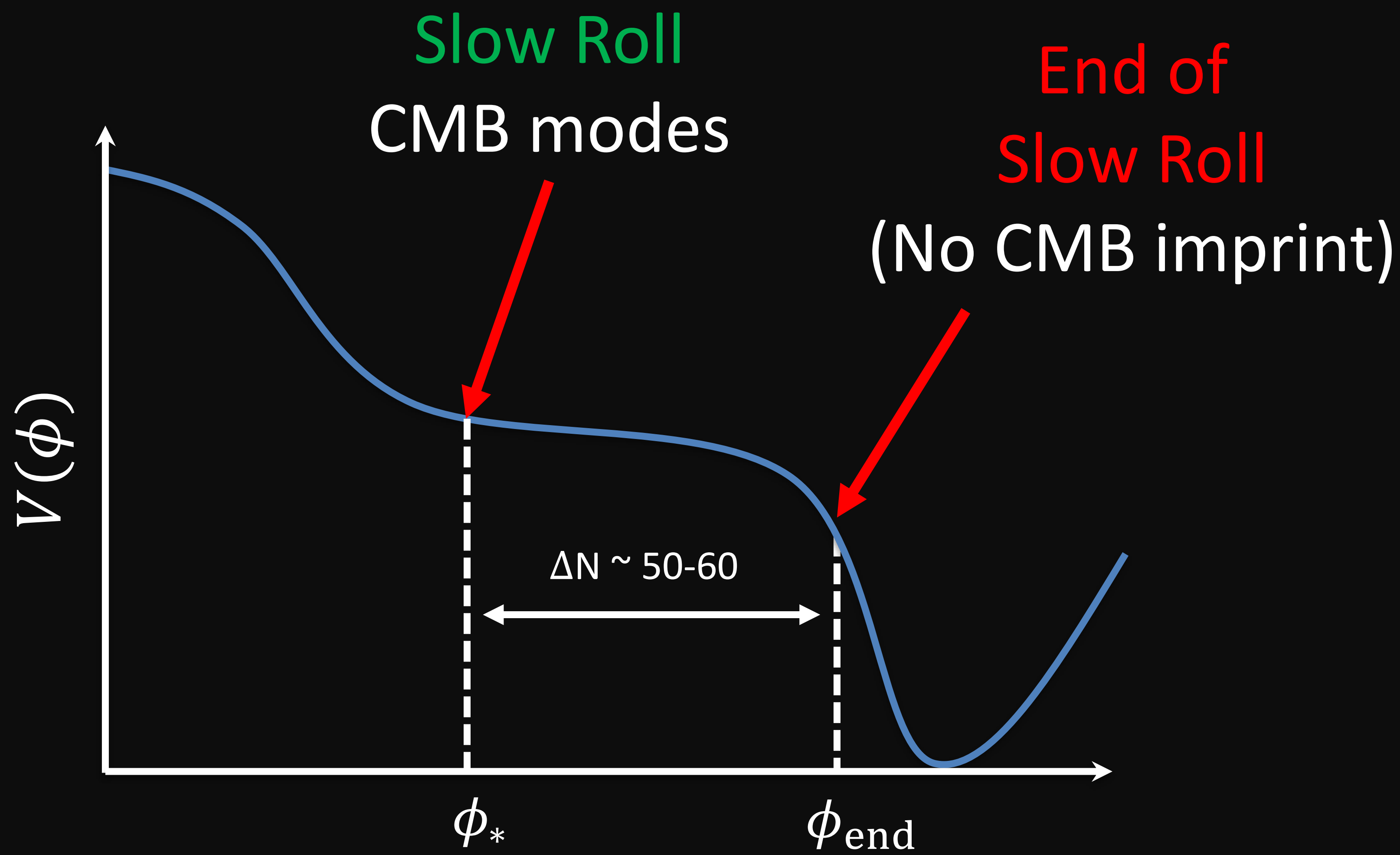
All couplings measured in the CMB

$(id\ est\ @\ H = H_{\mathrm{CMB}})$

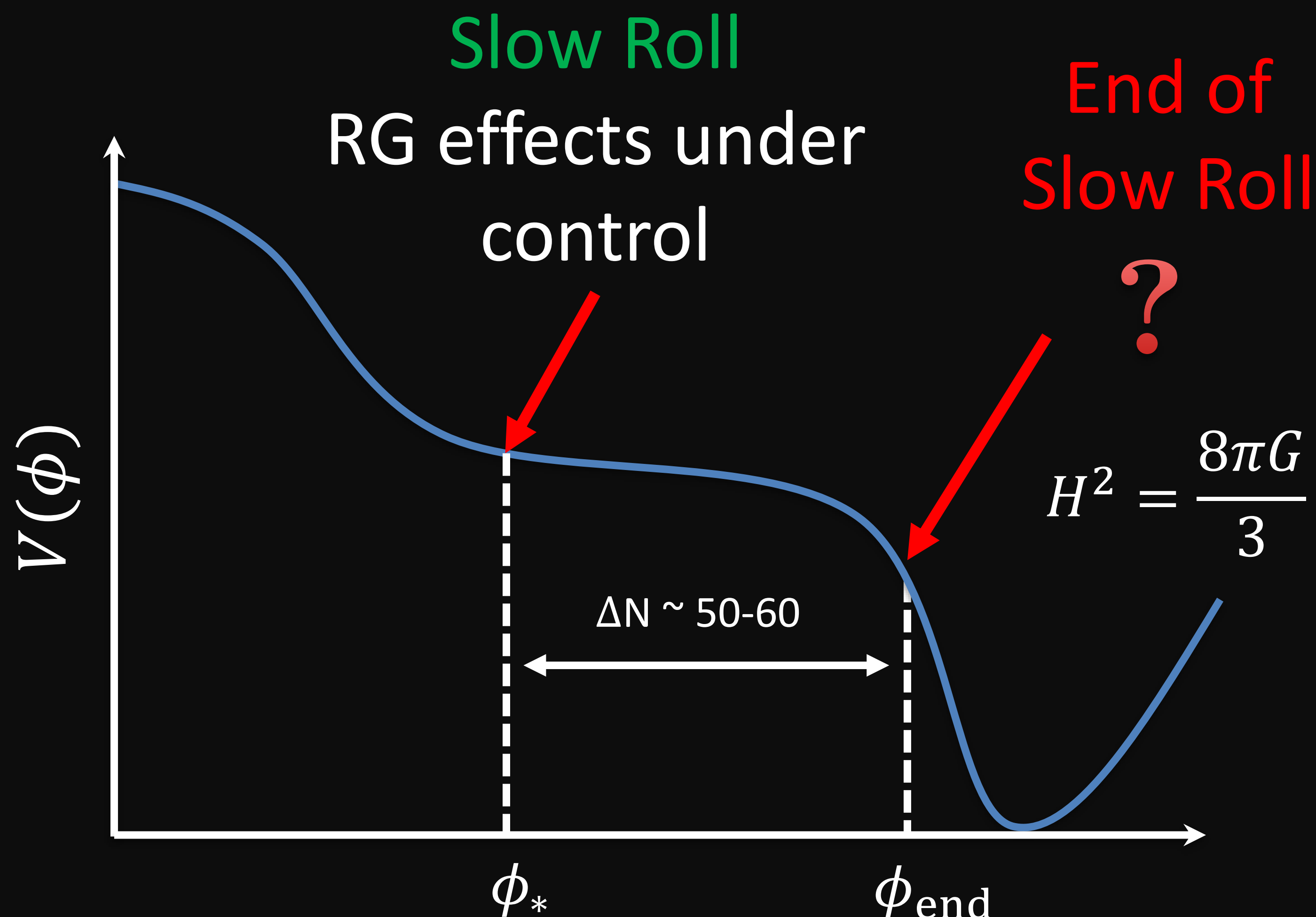
EFT of inflation



Inflation Observables



Inflation Observables



$$H^2 = \frac{8\pi G}{3}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right)$$

Inflation Potential

$$V(\phi) = V_0 + g_1\,\phi + g_2\phi^2 + g_3\phi^3 + \cdots$$

All couplings measured in the CMB

$(id\ est\ @\ H = H_{\mathrm{CMB}})$

When Hubble (and the field) evolves, the theory must be described by

$$U(\phi, H) =$$

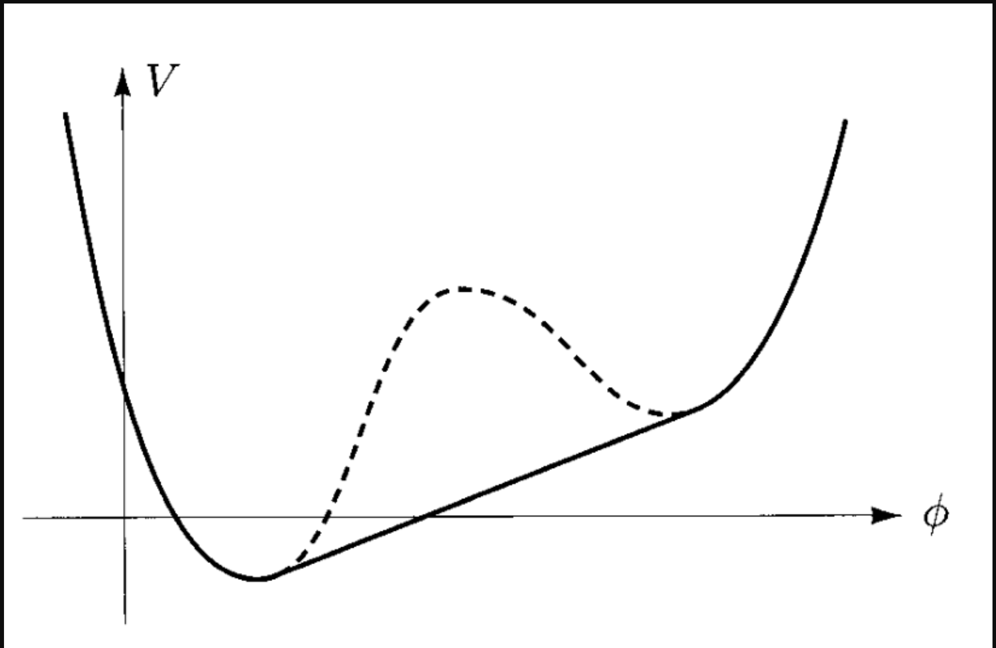
$$U_0 + g_1(H)\,\phi + g_2(H)\phi^2 + g_3(H)\phi^3 + \cdots$$

Our Approach: Effective Action

$$Z[J] = e^{-iE[J]} = \int \mathcal{D}\phi \exp\Big[i \int d^4x \, (\mathcal{L}[\phi] + J\phi) \Big].$$

$$\Gamma[\phi_{\rm cl}] \equiv -E[J] - \int d^4y \, J(y)\phi_{\rm cl}(y).$$

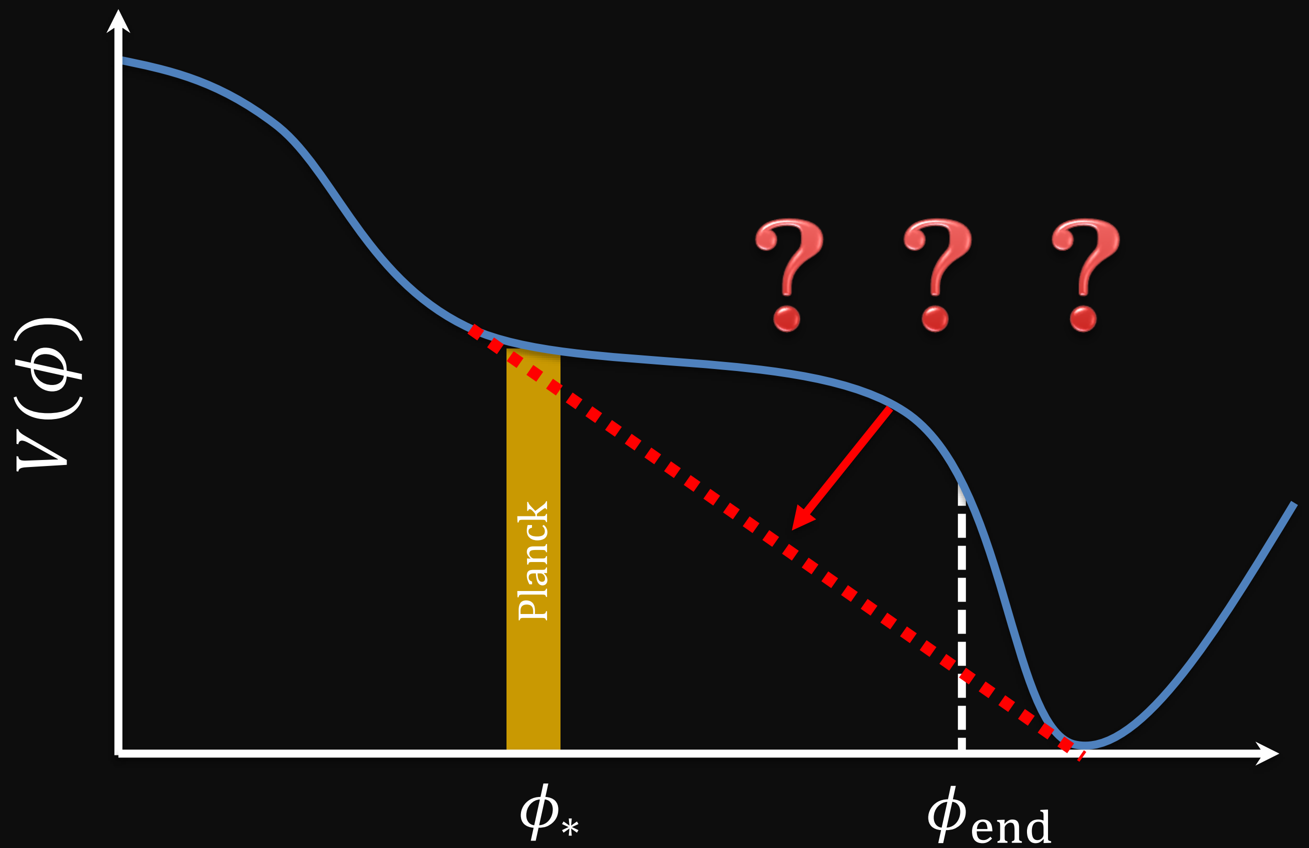
$$\Gamma[\phi_{\rm cl}] = -(VT) \cdot V_{\rm eff}(\phi_{\rm cl}).$$



Effective Potential

(Always Convex)

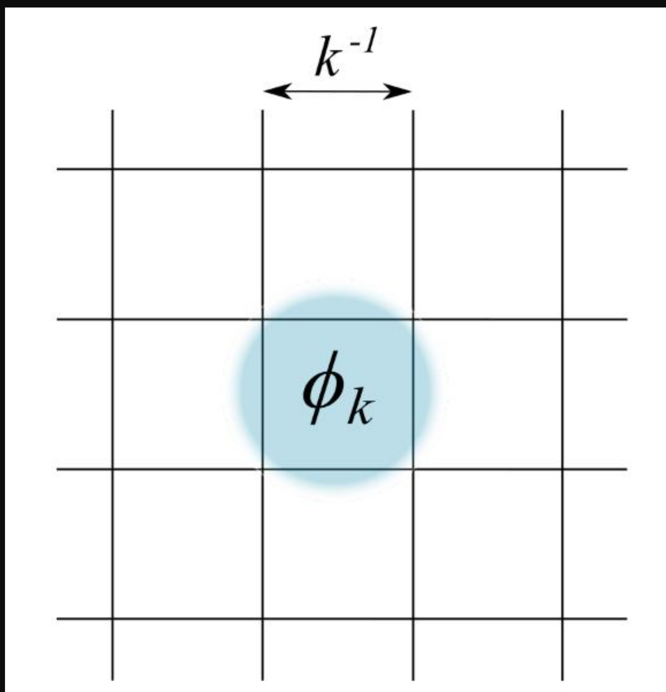
Effective Action



Exact Renormalisation Group

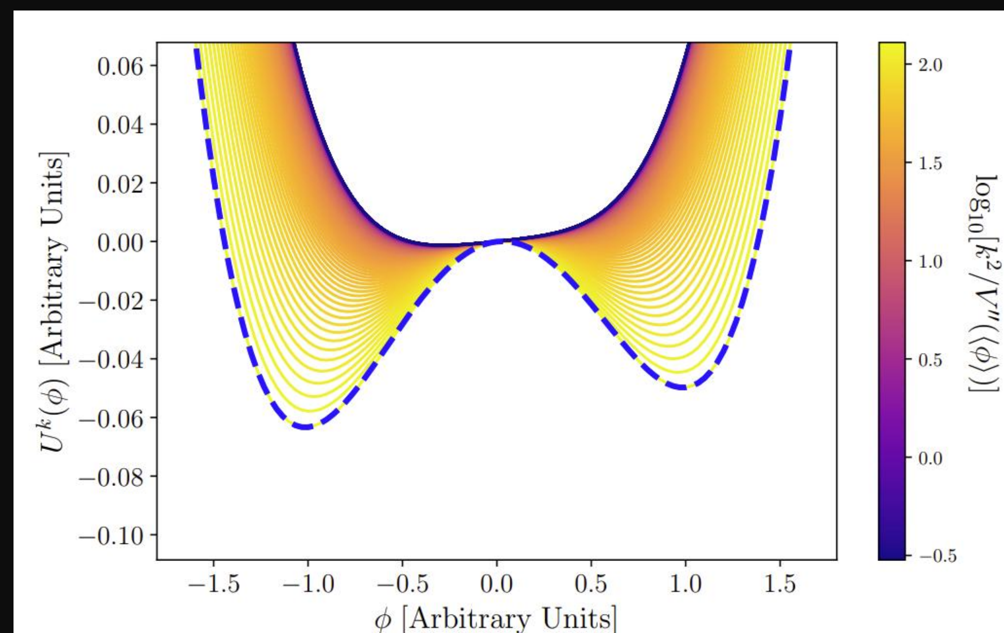
At every scale: coarse grain the theory.

Litim, Wetterich, and many



Flow equation for the effective potential

$$\partial_k V_k(\varphi) \;\propto\; \frac{k^{d+1}}{k^2 + V_k''(\varphi)}.$$



S. Abel, LH, JHEP 08 (2025) 198

Exact Renormalisation Group

4D-Euclidean space $\longrightarrow$ 3+1 FLRW problem

$$\partial_\kappa U_\kappa(\phi) = \frac{aT^{-1}}{6\pi^2}\mathcal{D}_E^{-1}\left(a^{-1}\kappa^4\right)$$

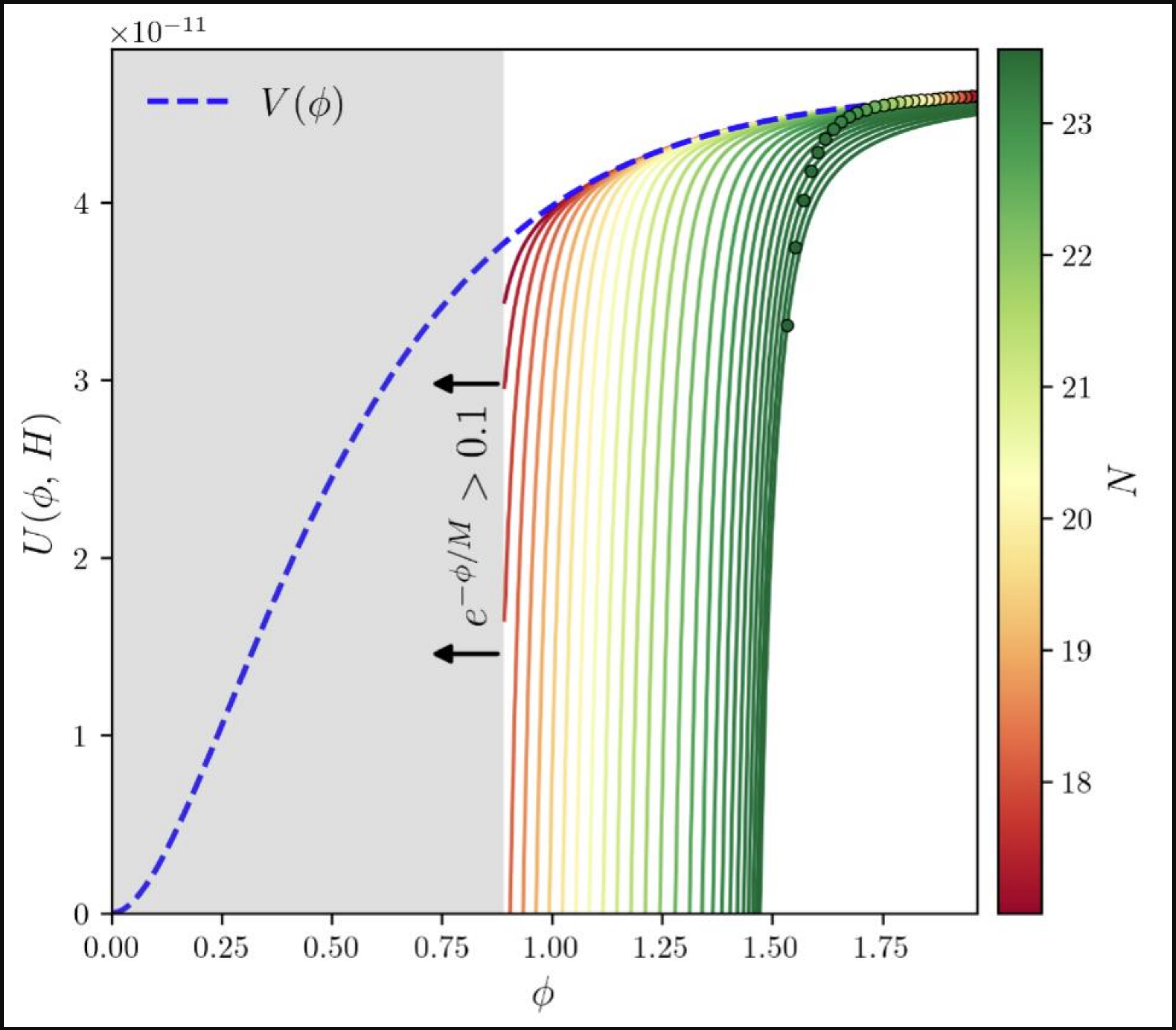
$$\ddot{F} + H\dot{F} + (\partial_\phi^2 U - H^2 - \dot{H})F = \frac{T^{-1}H^4}{6\pi^2}$$

where $F \equiv \partial_H U$

UV theory: $\boxed{U(\phi, H_0) = V(\phi)}$

UV cutoff: $T^{-1} = H_0$

ArXiv:2511.05296 – J. Alexandre, LH, S. Pla



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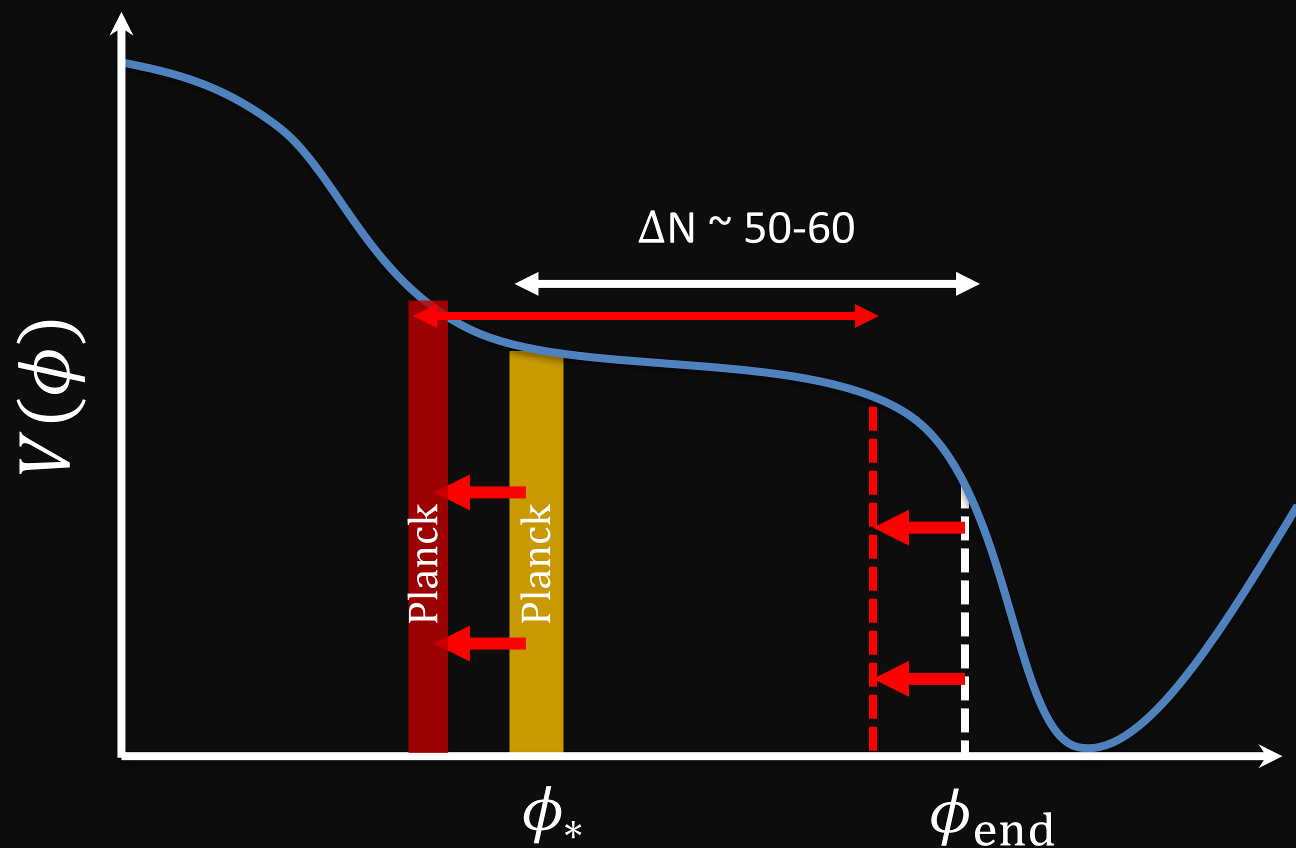
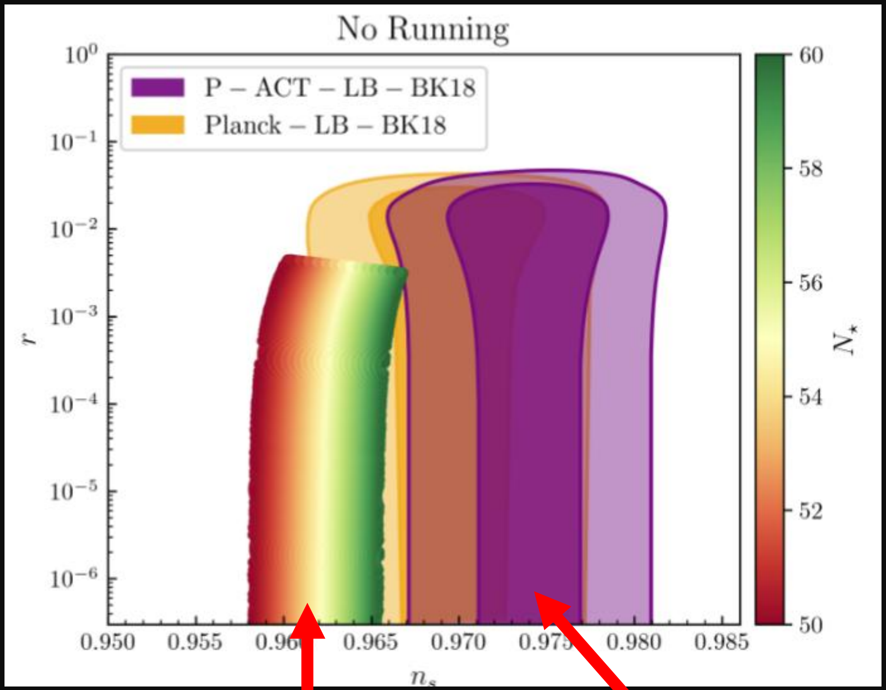
CMB measurements

Planck: $\mathbf{k \sim 0.05\ Mpc^{-1}}$



Effect on CMB observables

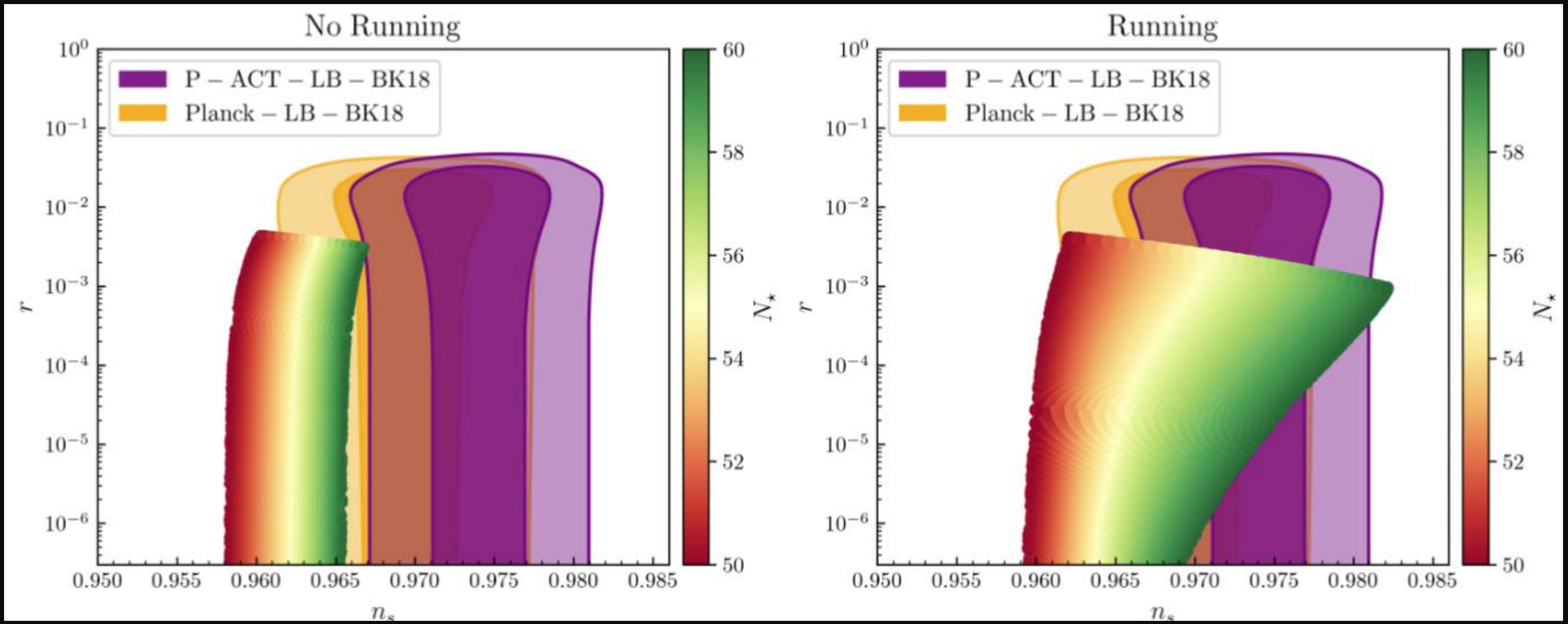


A popular model prediction

The Data

ArXiv:2511.05296 – J. Alexandre, LH, S. Pla

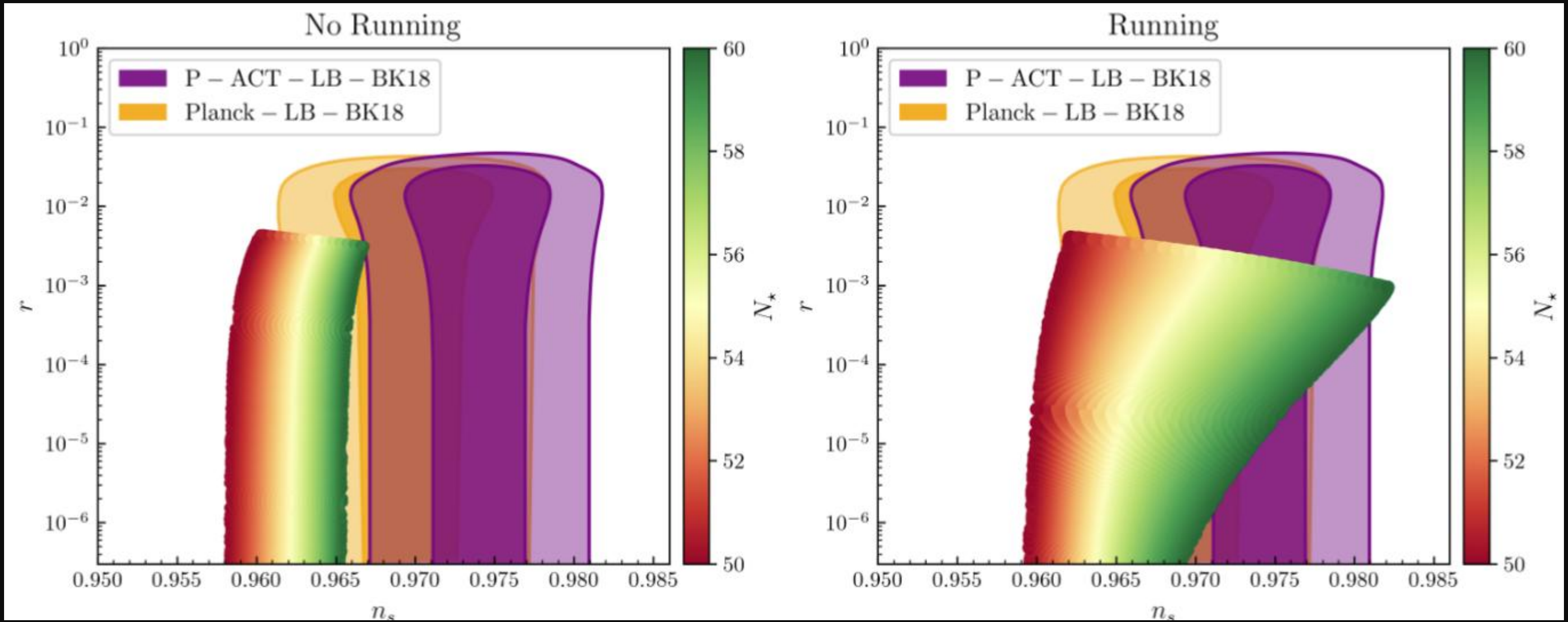
Effect on CMB observables



Reduced number of e-folds → Shift to larger n_s

ArXiv:2511.05296 – J. Alexandre, LH, S. Pla

Effect on CMB observables



Reduced number of e-folds → Shift to larger n_s

Many more avenues to be explored: Axion DM, dark energy dynamics, cosmological constant problem, bouncing cosmologies, etc.

ArXiv:2511.05296 – J. Alexandre, LH, S. Pla

Thank You!

1PI Effective Action

Classical Theory

$$V(\phi)$$

RG Improved

$$V(\phi) + \Delta V(\phi)$$

Markannen *et al*, '18
Ellis *et al*, '25

$$\Delta V = \frac{1}{64\pi^2}\left[\mathcal{M}_\phi^4\left(\log\frac{|\mathcal{M}_\phi^2|}{\mu^2} - \frac{3}{2}\right) + 2b_s \log\frac{|\mathcal{M}_\phi^2|}{\mu^2}\right]$$

$$R = 6(2H^2 + \dot{H})$$

$$b_s = -\frac{1}{180}R_{\mu\nu}R^{\mu\nu} + \frac{1}{180}R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} \simeq -\frac{H^4}{15}$$

$$\mathcal{M}_\phi^2 = V''(\phi) + \frac{1}{6}R$$ [redacted]

1PI Effective Action

Classical Theory

$V(\phi)$ $\longrightarrow$ $V(\phi) + \Delta V(\phi)$

RG Improved

Markannen *et al*, '18
Ellis *et al*, '25

Slow-roll

$$R = 6(2H^2 + \cancel{\dot{H}})$$

$$H \approx H(\phi)$$

$$\Delta V = \frac{1}{64\pi^2}\left[\mathcal{M}_\phi^4\left(\log\frac{|\mathcal{M}_\phi^2|}{\mu^2} - \frac{3}{2}\right) + 2b_s \log\frac{|\mathcal{M}_\phi^2|}{\mu^2}\right]$$

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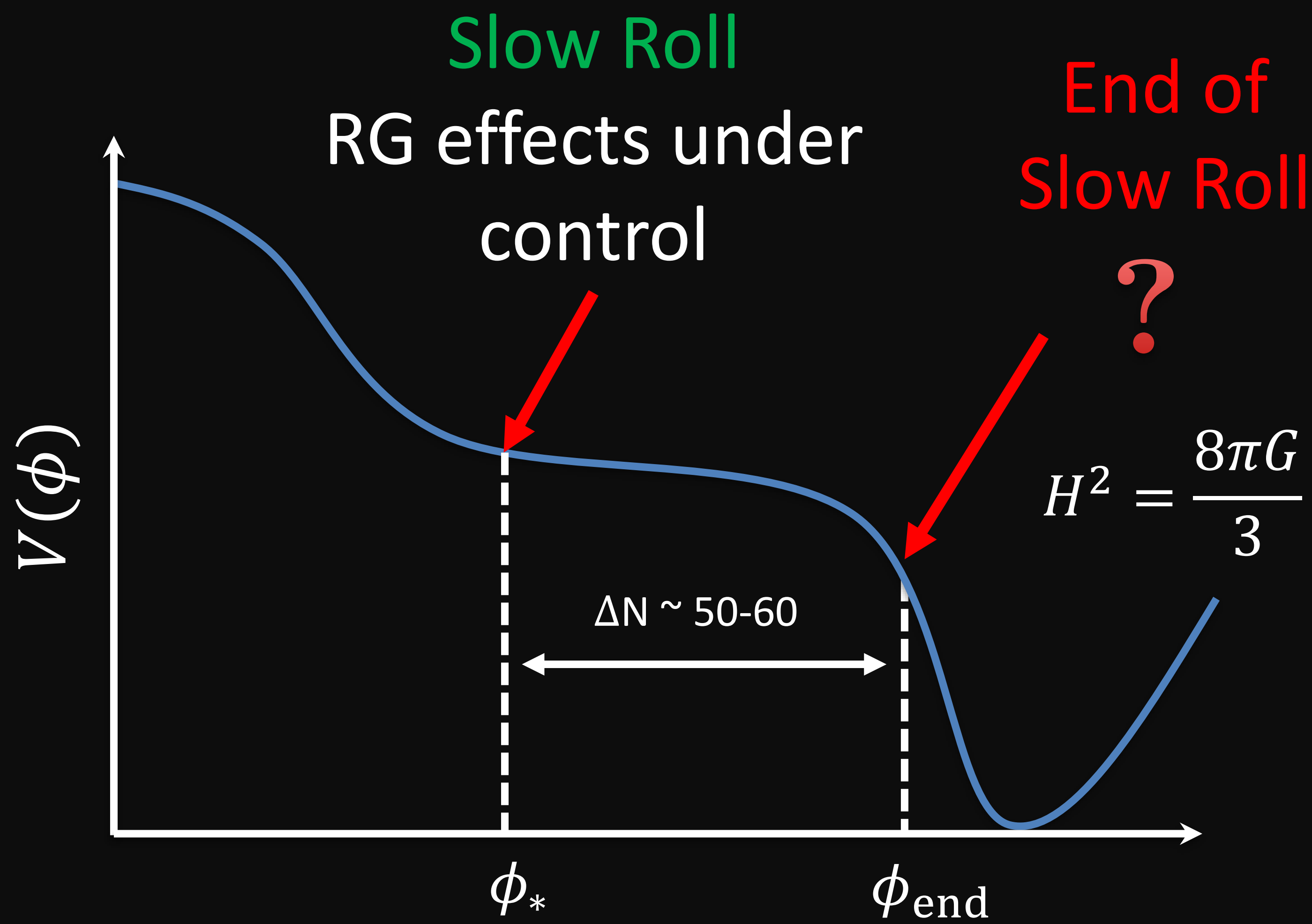
$$\mathcal{M}_\phi^2 = V''(\phi) + \frac{1}{6}R \simeq \cancel{V''(\phi)} - 2H^2$$

$\boxed{\text{Negligible Self-Int.} \quad \Delta V \sim H^4 \sim 10^{-10} V}$

Inflation Observables



$$H^2 = \frac{8\pi G}{3}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right)$$

1PI Effective Action

Classical Theory

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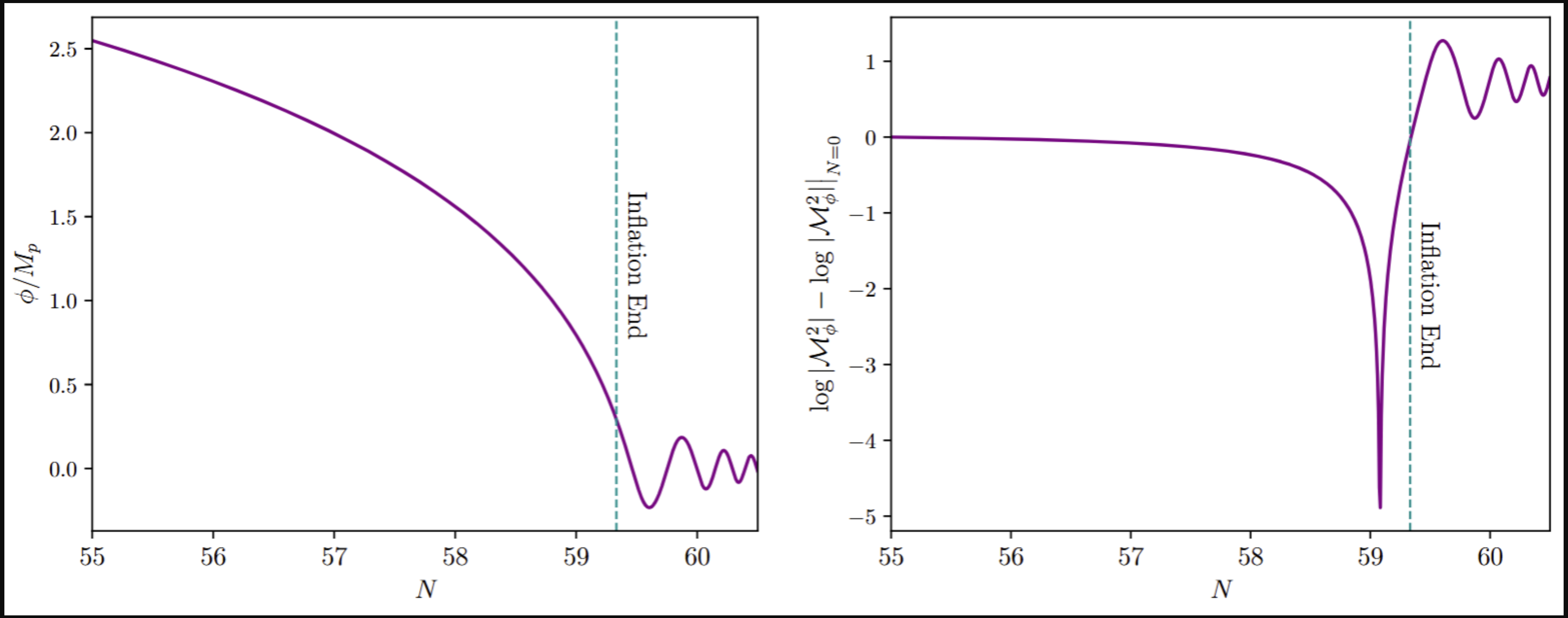
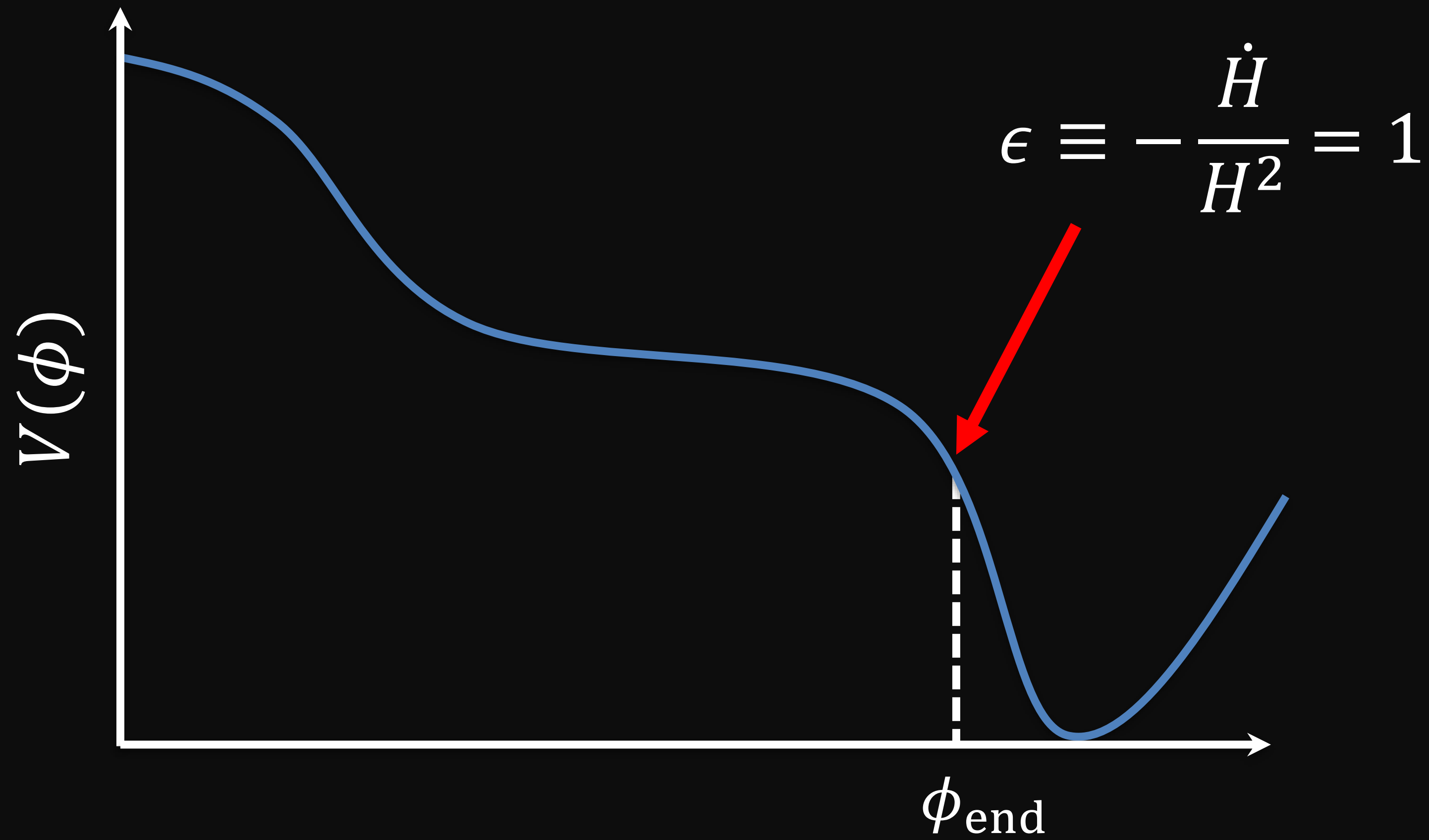
$$V(\phi) \rightarrow V(\phi) + \Delta V(\phi)$$



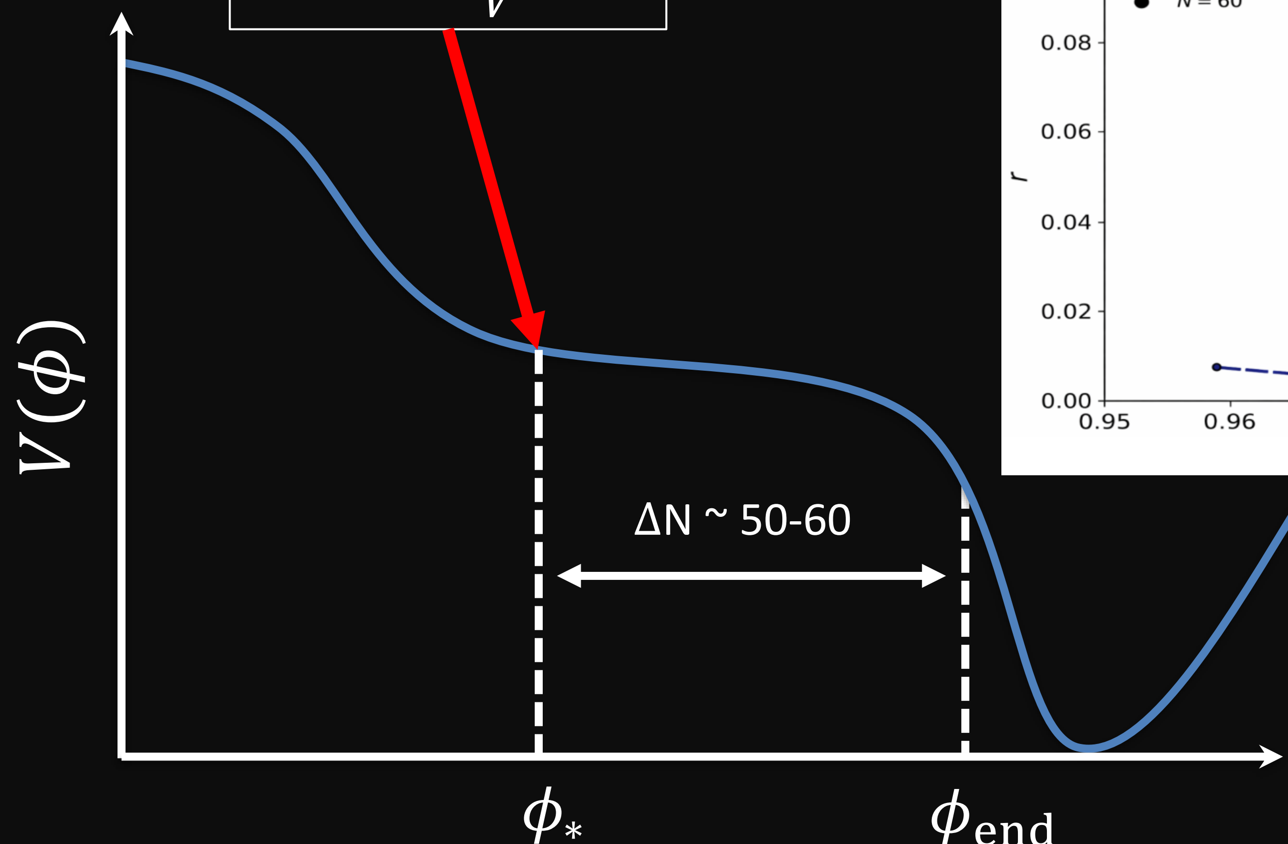
Inflation Observables

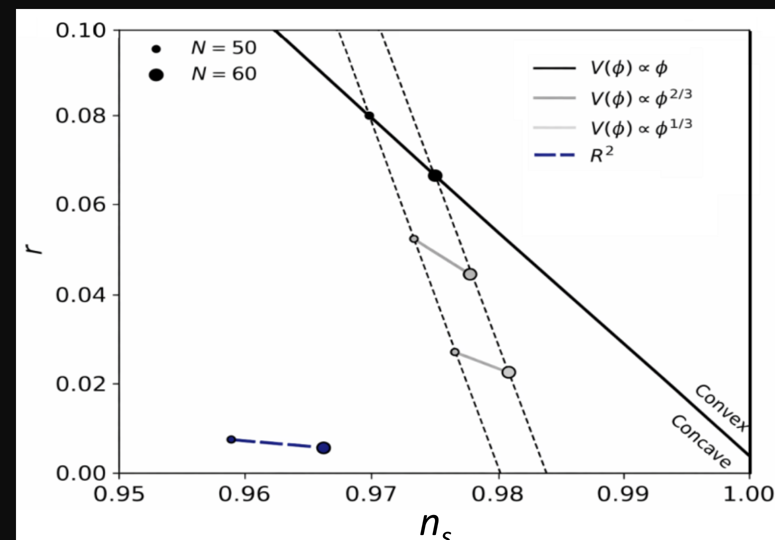


Inflation Observables

$$\epsilon_V \equiv \frac{M_p^2}{2}\frac{V'}{V},$$
$$\eta_V \equiv \frac{M_p^2 V''}{V}$$

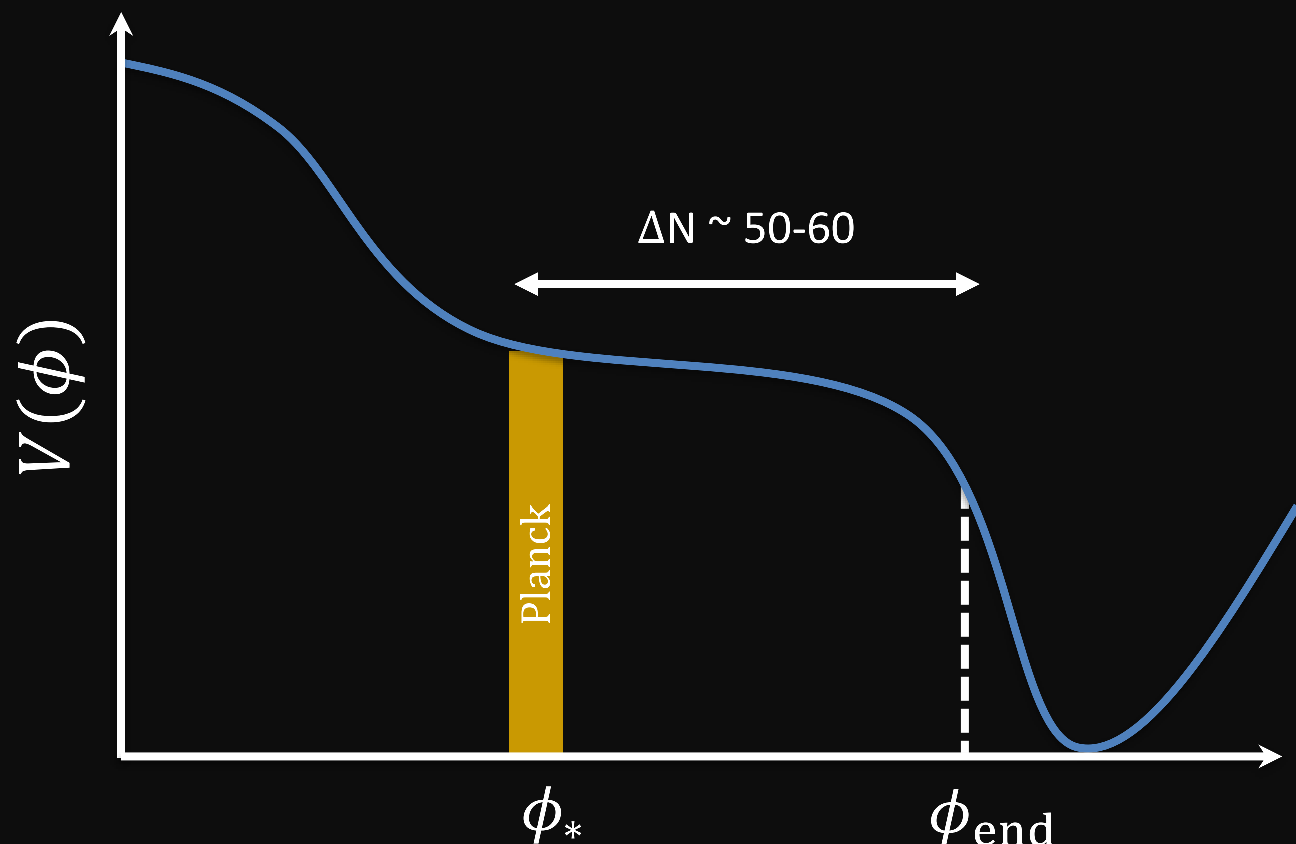
$$r = 16\,\epsilon_V,$$
$$n_s = 1 - 6\epsilon_V + 2\eta_V$$





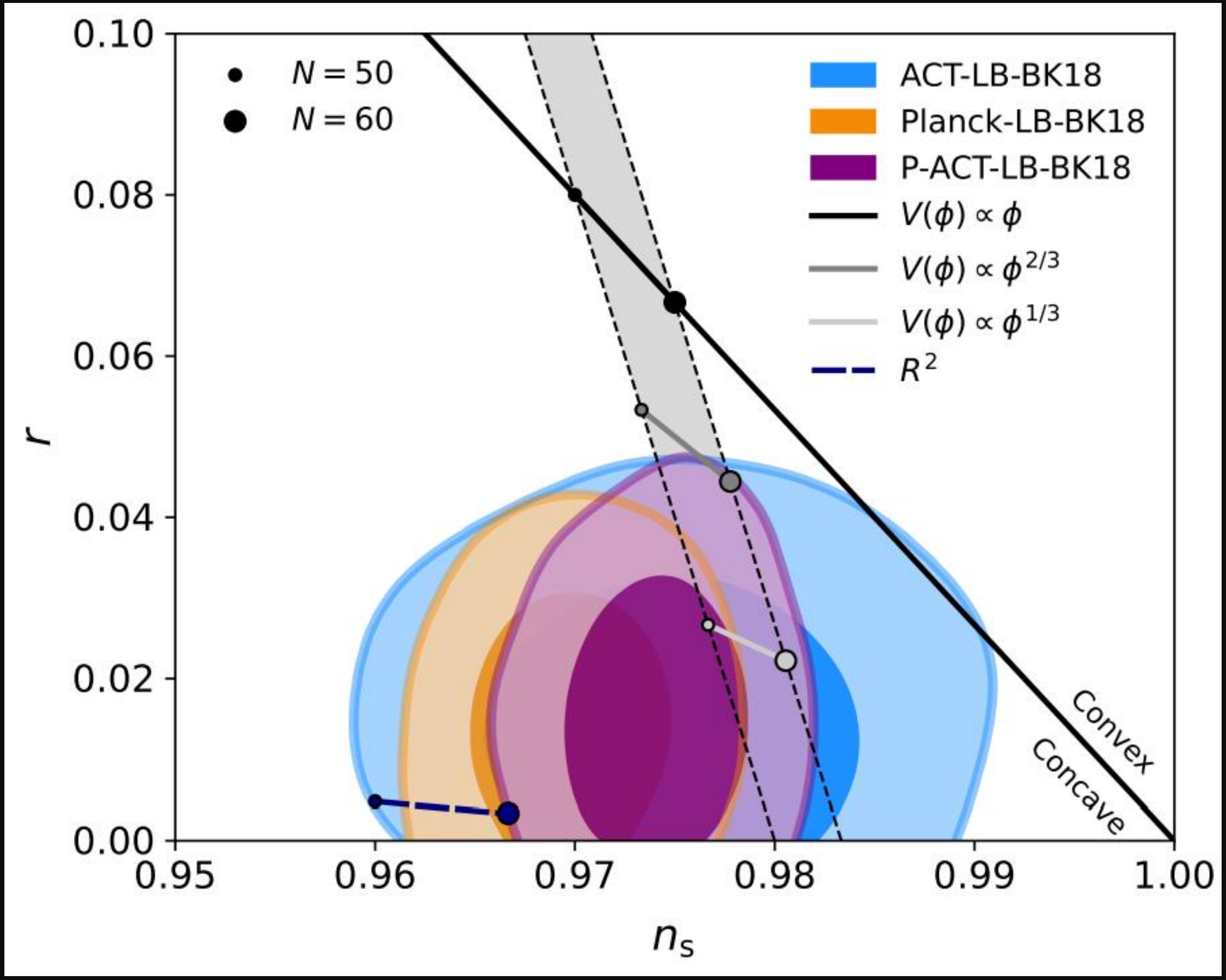
Inflation Model Building

Planck: $k \sim 0.05\ \mathrm{Mpc}^{-1}$



Spectral Index Running

ACT DR6, March 2025



What about

quantum corrections?

1PI Effective Action

Classical Theory

$V(\phi)$ → $V(\phi) + \Delta V(\phi)$

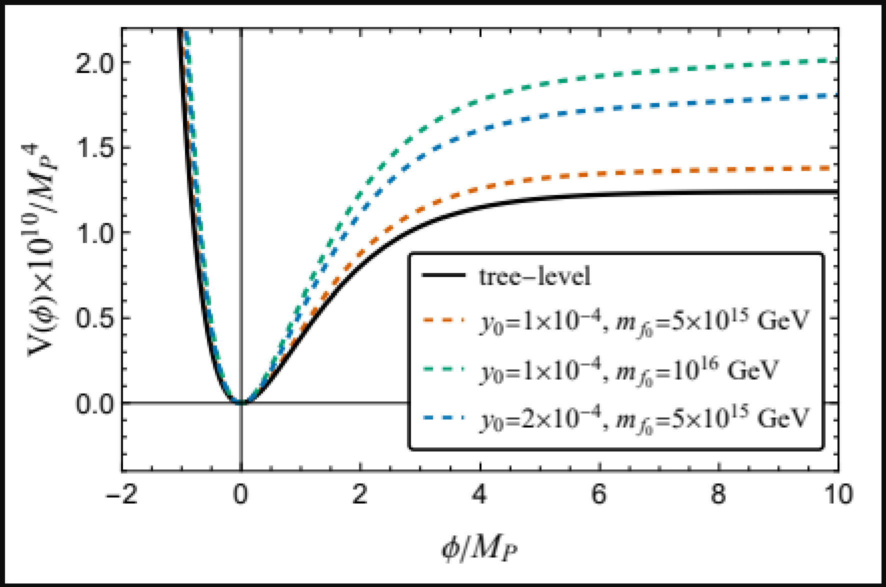
RG Improved

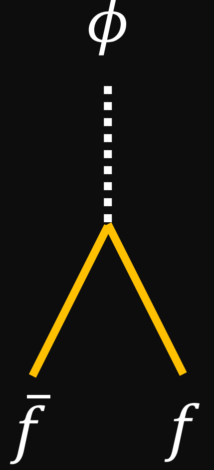
Markannen *et al*, '18
Ellis *et al*, '25

Slow-roll

$$\boxed{R = 6(2H^2 + \cancel{\dot{H}})}$$

$$H \approx H(\phi)$$





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$$R = 6(2H^2 + \dot{H})$$

$$b_s = -\frac{1}{180}R_{\mu\nu}R^{\mu\nu} + \frac{1}{180}R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

$$\mathcal{M}_\phi^2 = V''(\phi) + \frac{1}{6}R$$

1PI Effective Action

Classical Theory

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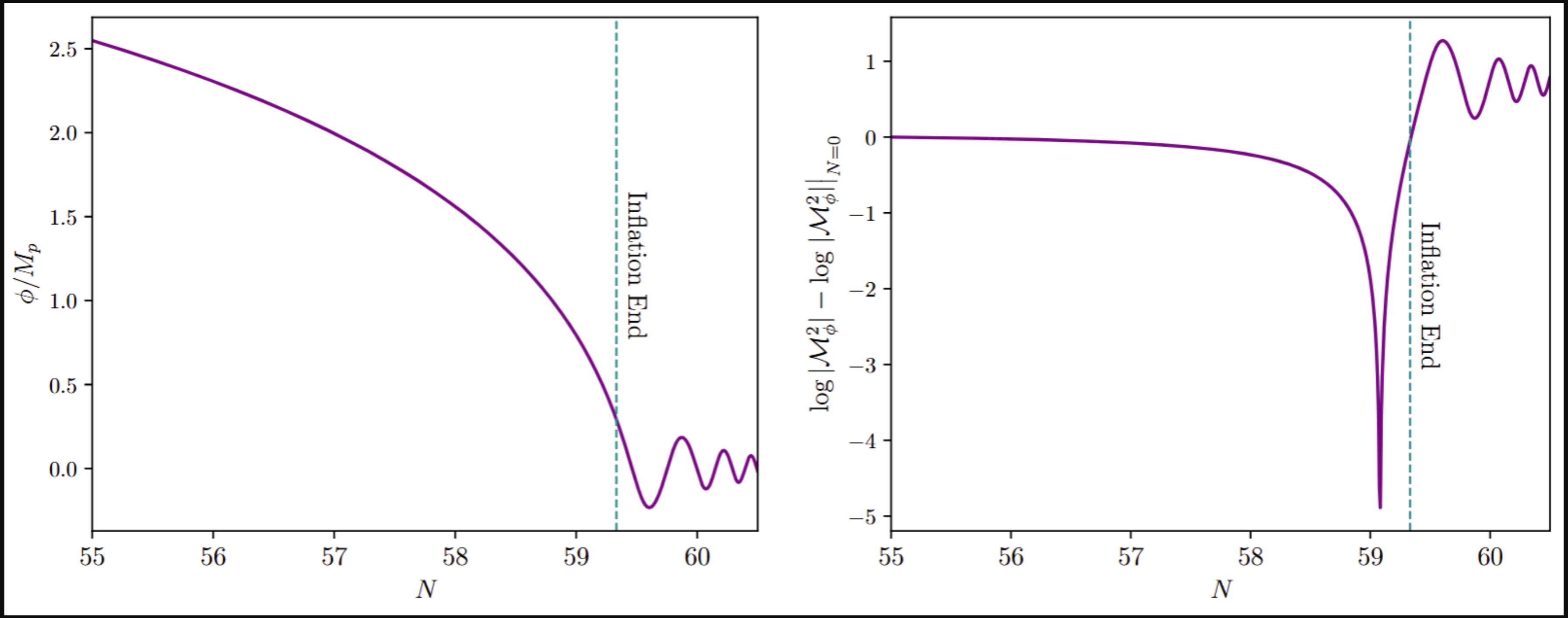
$$V(\phi) \longrightarrow V(\phi) + \Delta V(\phi)$$



How can we do better?

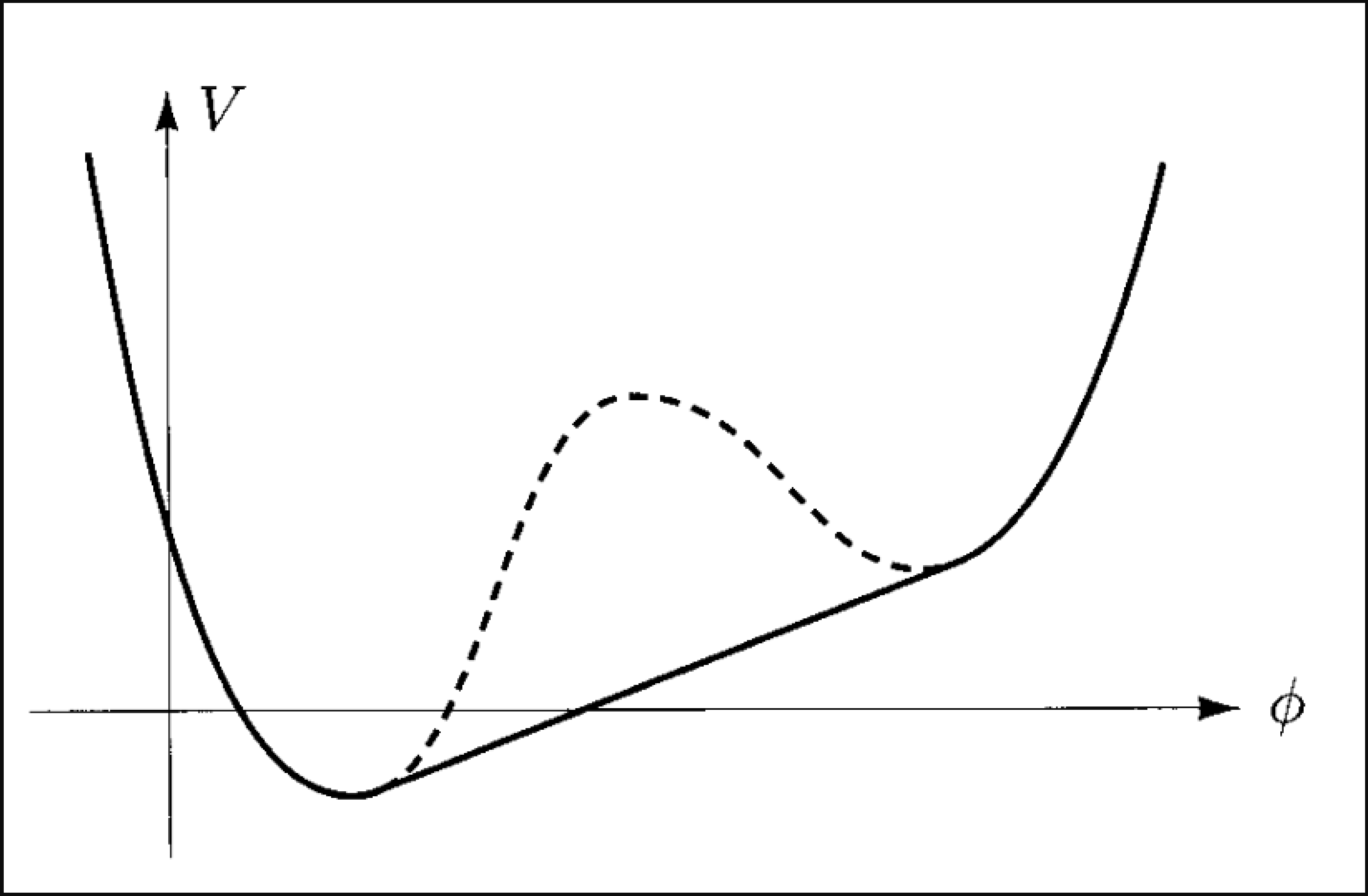
Back to Basics: Effective Action

$$Z[J] = e^{-iE[J]} = \int \mathcal{D}\phi \exp\left[i \int d^4x \left(\mathcal{L}[\phi] + J\phi \right) \right].$$

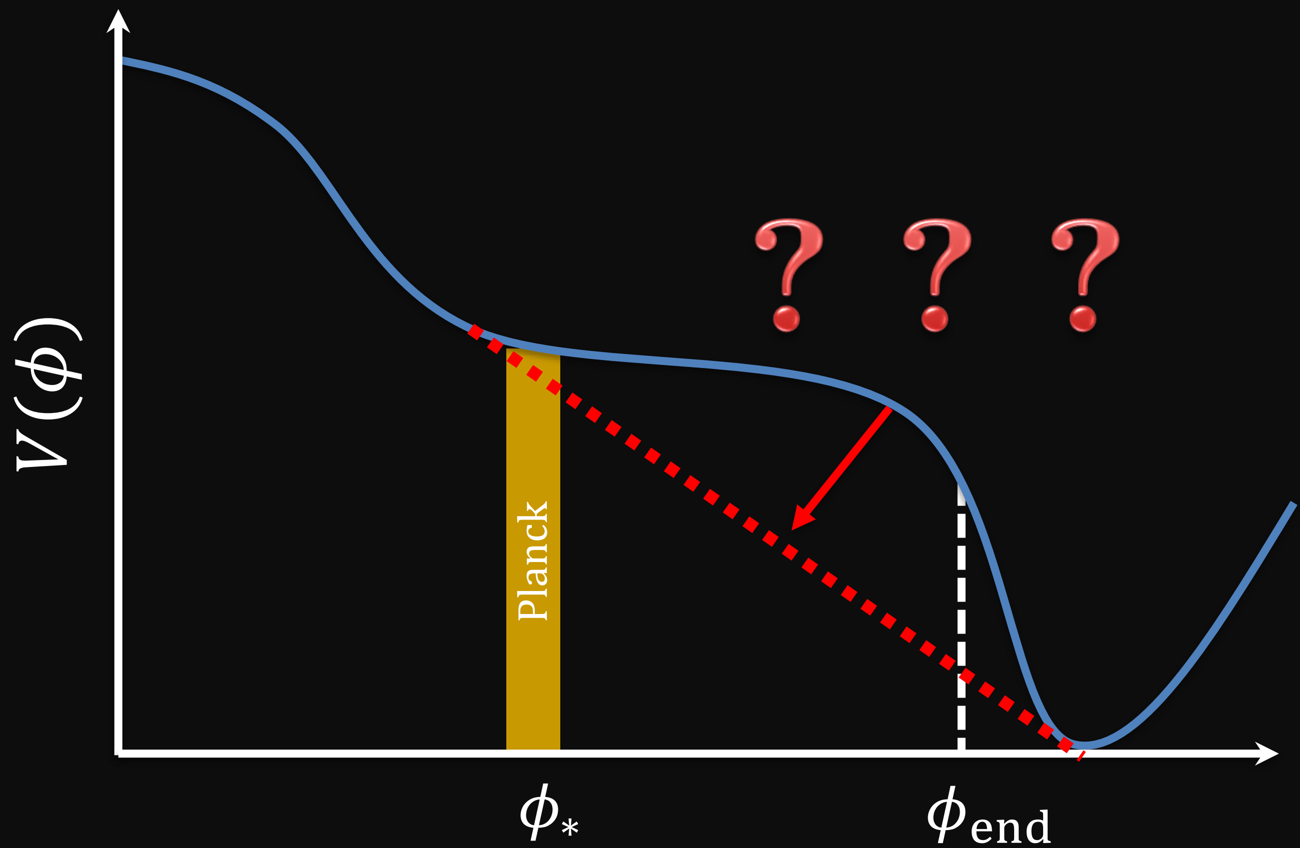
$$\Gamma[\phi_{\rm cl}] \equiv -E[J] - \int d^4y \, J(y)\phi_{\rm cl}(y).$$

$$\Gamma[\phi_{\rm cl}] = -(VT) \cdot V_{\rm eff}(\phi_{\rm cl}).$$

Effective Action

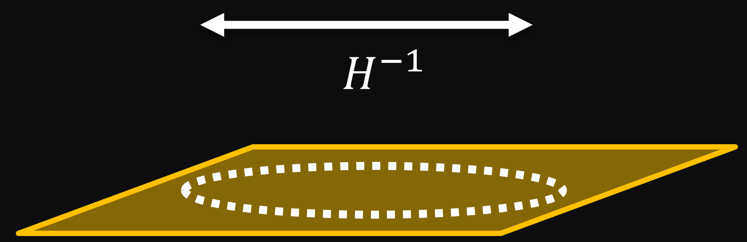


Effective Action



EFT of inflation

Homogeneous Background:



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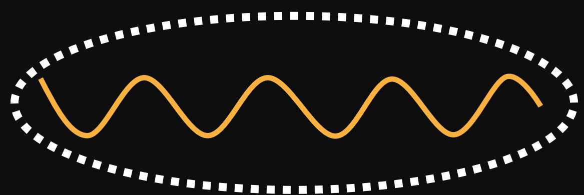
Quantum Perturbations

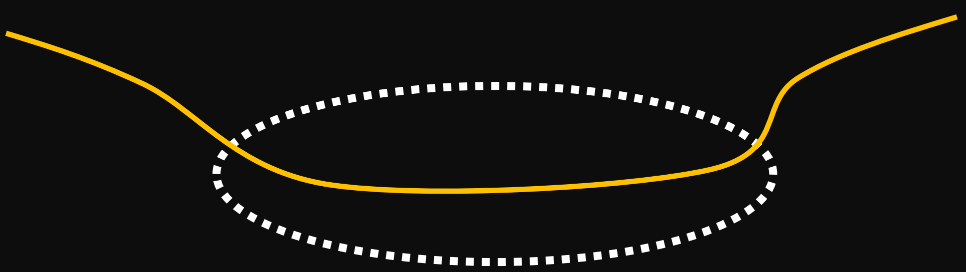
(integrated out)



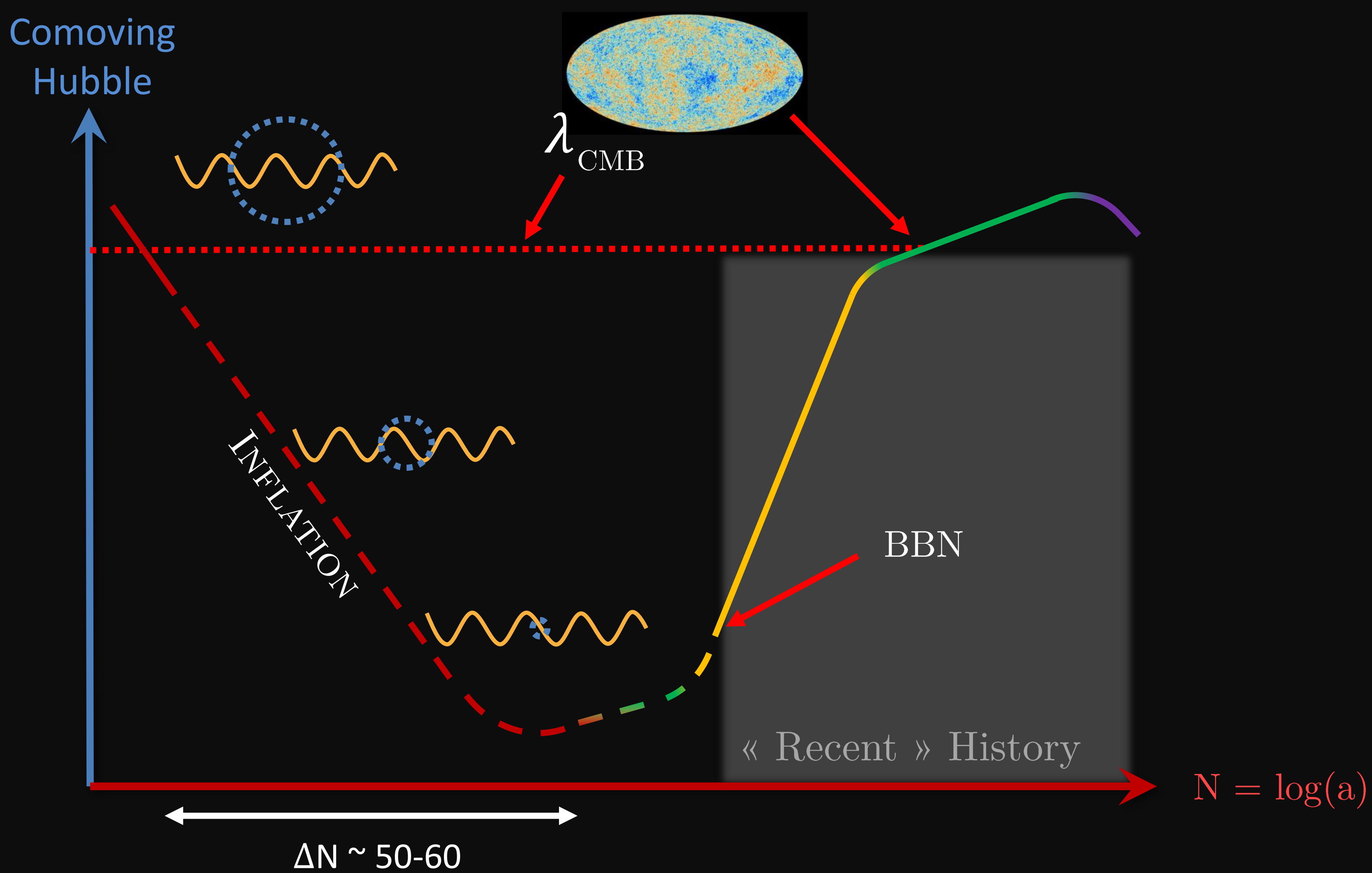
$+$

Classical Perturbations

(super-horizon)



EFT of inflation

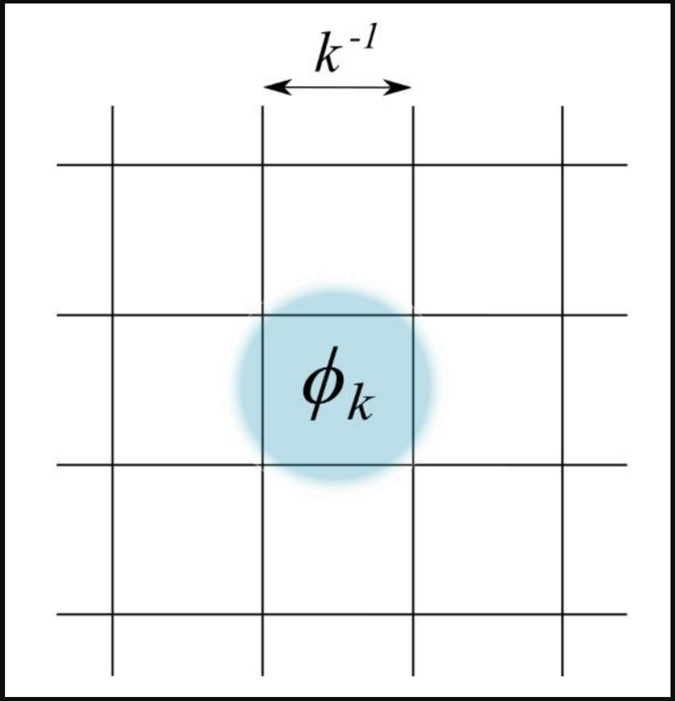


Exact Renormalisation Group

At every scale: coarse grain the theory.

- Short wavelengths are integrated out.
- Large wavelengths live in the effective field theory.

Litim, Wetterich, and many



$$Z_k[J] = \int \mathcal{D}\phi \, \exp\left(-S[\phi] - \boxed{\Delta S_k[\phi]} + \int J\phi \right)$$

$$\Delta S_k[\phi] = \frac{1}{2} \int \frac{d^d q}{(2\pi)^d} \, \phi(-q) \, R_k(q) \, \phi(q).$$

$$R_k(q) \xrightarrow[q^2 \ll k^2]{} k^2, \qquad R_k(q) \xrightarrow[q^2 \gg k^2]{} 0.$$

$$W_k[J] = \ln Z_k[J].$$

$$\Gamma_k[\varphi] = \sup_J \left(\int J\varphi - W_k[J] \right) - \boxed{\Delta S_k[\varphi].}$$

$$\boxed{\Gamma_{k\to\Lambda} \to S, \qquad \Gamma_{k\to 0} \to \Gamma.}$$

Exact Renormalisation Group

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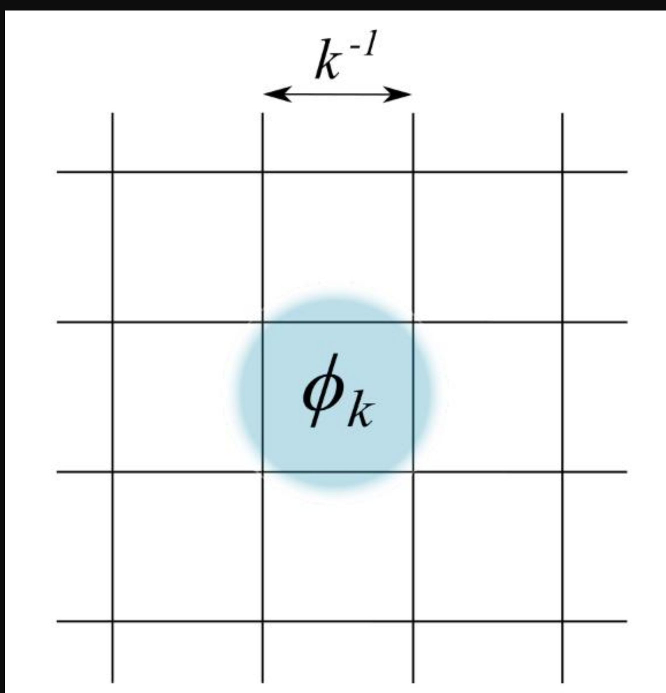
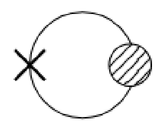
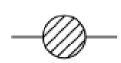


$$\frac{\partial}{\partial t}\Gamma_k[\varphi] = \frac{1}{2}\,\mathrm{Tr}\Big[\big(\Gamma_k^{(2)}[\varphi] + R_k\big)^{-1}\partial_t R_k\Big].$$

$\frac{\partial}{\partial t}\Gamma_k \;=\; \frac{1}{2}$ 

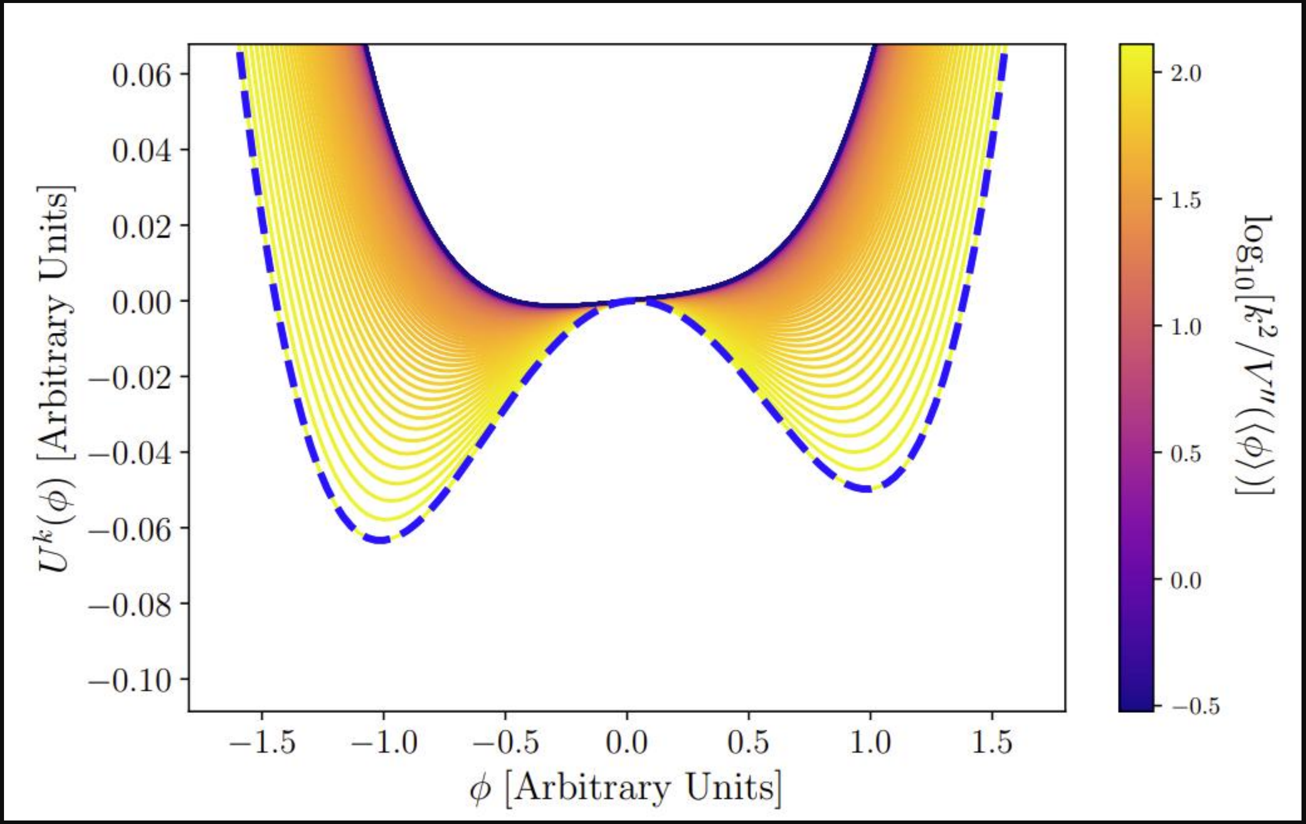
$\times \;=\; \frac{\partial}{\partial t}R_k$

 = full k-dependent propagator

$$R_k(q) = (k^2 - q^2)\theta(k^2 - q^2)$$

$$\partial_k V_k(\varphi) \;\propto\; \frac{k^{d+1}}{k^2 + V_k''(\varphi)}.$$

Exact Renormalisation Group



S. Abel, LH, JHEP 08 (2025) 198

Exact Renormalisation Group

4D-Euclidean space ⟶ 3+1 FLRW problem

$$Z_k[j] \equiv e^{(i/\hbar)W_k[j]} \tag{25}$$
$$= \int \mathcal{D}[\varphi] \exp\Big((i/\hbar)S[\Phi] + (i/\hbar)\int dt\sqrt{-g}\int d^3x\, j\varphi$$
$$\boxed{-(i/2\hbar)\int dt\sqrt{-g}\int_p \varphi(t,\vec{p})\varphi(t,-\vec{p})(C_k - i\varepsilon)}\Big) \;,$$

$$\frac{\delta\Gamma_k}{\delta k(t)} = \frac{\sqrt{-g(t)}}{2}\int\frac{d^3p}{(2\pi)^3}\int\frac{d^3q}{(2\pi)^3}\delta(\vec{p}+\vec{q})$$
$$\int dt'\delta(t-t')\;\mathcal{O}(t,t',\vec{p},\vec{q})\;\partial_k C_k(p)\;, \tag{5}$$

where

$$\mathcal{O}(t,t',\vec{p},\vec{q}) =$$
$$\left[\sqrt{|g|}(C_k(p) - i\varepsilon)\delta(\vec{p}+\vec{q})\delta(t-t') - \frac{\delta^2\Gamma_k}{\delta\varphi_b(t,\vec{p})\delta\varphi_b(t',\vec{q})}\right]^{-1}, \tag{6}$$

ArXiv:2511.05296 – J. Alexandre, LH, S. Pla

Exact Renormalisation Group

4D-Euclidean space $\longrightarrow$ 3+1 FLRW problem

+ Local Potential Approximation

$$\Gamma_k[\phi] = \int dt\sqrt{-g}\int d^3x\left(-\frac{g^{\mu\nu}}{2}\partial_\mu\phi\partial_\nu\phi - U_k(\phi)\right)$$

+ Litim Top-Hat Regulator

$$\partial_\kappa U_\kappa(\phi) = \frac{aT^{-1}}{6\pi^2}\mathcal{D}_E^{-1}\left(a^{-1}\kappa^4\right)\ , \tag{9}$$

where

$$\mathcal{D}_E = -\frac{d^2}{dt^2} - 3H\frac{d}{dt} + \kappa^2 + \partial_\phi^2 U_\kappa(\phi)\ , \tag{10}$$

$T^{-1} \equiv \lim_{t'\to t}\delta(t-t')$ is a cut-off frequency

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Exact Renormalisation Group

4D-Euclidean space $\longrightarrow$ 3+1 FLRW problem

+ Specify the coarse-graining scale: $\boxed{\kappa = \sigma H}$

(natural choice: $\sigma = 1$)

+ Multiply by inverse propagator

$$\partial_\kappa U_\kappa(\phi) = \frac{aT^{-1}}{6\pi^2}\mathcal{D}_E^{-1}\left(a^{-1}\kappa^4\right)$$

$$\ddot{F} + H\dot{F} + (\partial_\phi^2 U - H^2 - \dot{H})F = \frac{T^{-1}H^4}{6\pi^2}$$

where $F \equiv \partial_H U$

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RG running of inflation

Bare potential $\boxed{V(\phi)}$ $\longrightarrow$ RG-Improved potential $\boxed{U(\phi)}$

Static field: $\boxed{\phi \sim \text{cst.}} \longrightarrow \boxed{H = H(\phi)} \longrightarrow \boxed{U = V_{RGI}(\phi)}$

Valid in the deep slow-roll era only

Rolling field: $\boxed{\phi(t), \dot{\phi}(t)} \longrightarrow \boxed{\phi(t), H(t)} \longrightarrow \boxed{U = U(\phi, H)}$

Allows for deviations from slow-roll

RG running of inflation

UV theory: $\boxed{U(\phi, H_0) = V(\phi)}$ UV cutoff: $T^{-1} = H_0$

$$
\begin{aligned}
F'' &= \frac{H_0 H^2}{6\pi^2} - \left(1 + \frac{H'}{H}\right) F' - \left(\frac{\partial_\phi^2 U}{H^2} - \frac{H'}{H} - 1\right) F\,, \\
\phi'' &= -\left(3 + \frac{H'}{H}\right)\phi' - \frac{\partial_\phi U}{H^2}\,, \\
H' &= -\frac{H}{2M_p^2}\left((\phi')^2 + \frac{F'}{3H}\right).
\end{aligned}
\tag{17}
$$

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Exact Renormalisation Group

- de Sitter Case

$$H_0 F_{\rm dS} = -\frac{H_0^4}{6\pi^2(1-\partial_\phi^2 U_{\rm dS}/H_0^2)}$$

$$U_{\rm dS} = 3M_p^2 H_0^2 - \frac{H_0^4}{6\pi^2(1-\partial_\phi^2 U_{\rm dS}/H_0^2)}$$

Compatible with $\phi' = H' = F' = 0$

- Inflation Case

E-Model: $$U(\phi, H_0) = V(\phi) = V_0\left(1 - e^{\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_p}}\right)^2 .$$

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Exact Renormalisation Group

E-models

$$U(\phi, H_0) = V(\phi) = V_0 \left(1 - e^{\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_P}}\right)^2 .$$

$$U_H(\phi) = \sum_{n=0}^{\infty} U_n(H)\, e^{-n\phi/M}$$

$$F = \sum_{n=0}^{\infty} F_n\, e^{-n\phi/M} \;, \quad \text{with} \quad F_n = \frac{dU_n}{dH}$$

$$\begin{aligned} F_n'' = {} & \delta_{n,0}\frac{H_0 H^2}{6\pi^2} - F_n'\left[-2n\frac{\phi'}{M} + \left(1 + \frac{H'}{H}\right)\right] \\ & + F_n\left[n\frac{\phi''}{M} - \left(n\frac{\phi'}{M}\right)^2 + \left(1 + \frac{H'}{H}\right)\left(1 + n\frac{\phi'}{M}\right)\right] \\ & - \frac{1}{H^2 M^2}\left(\sum_{l=0}^{n} l^2 U_l F_{n-l}\right) , \qquad n \geqslant 0. \end{aligned} \tag{26}$$

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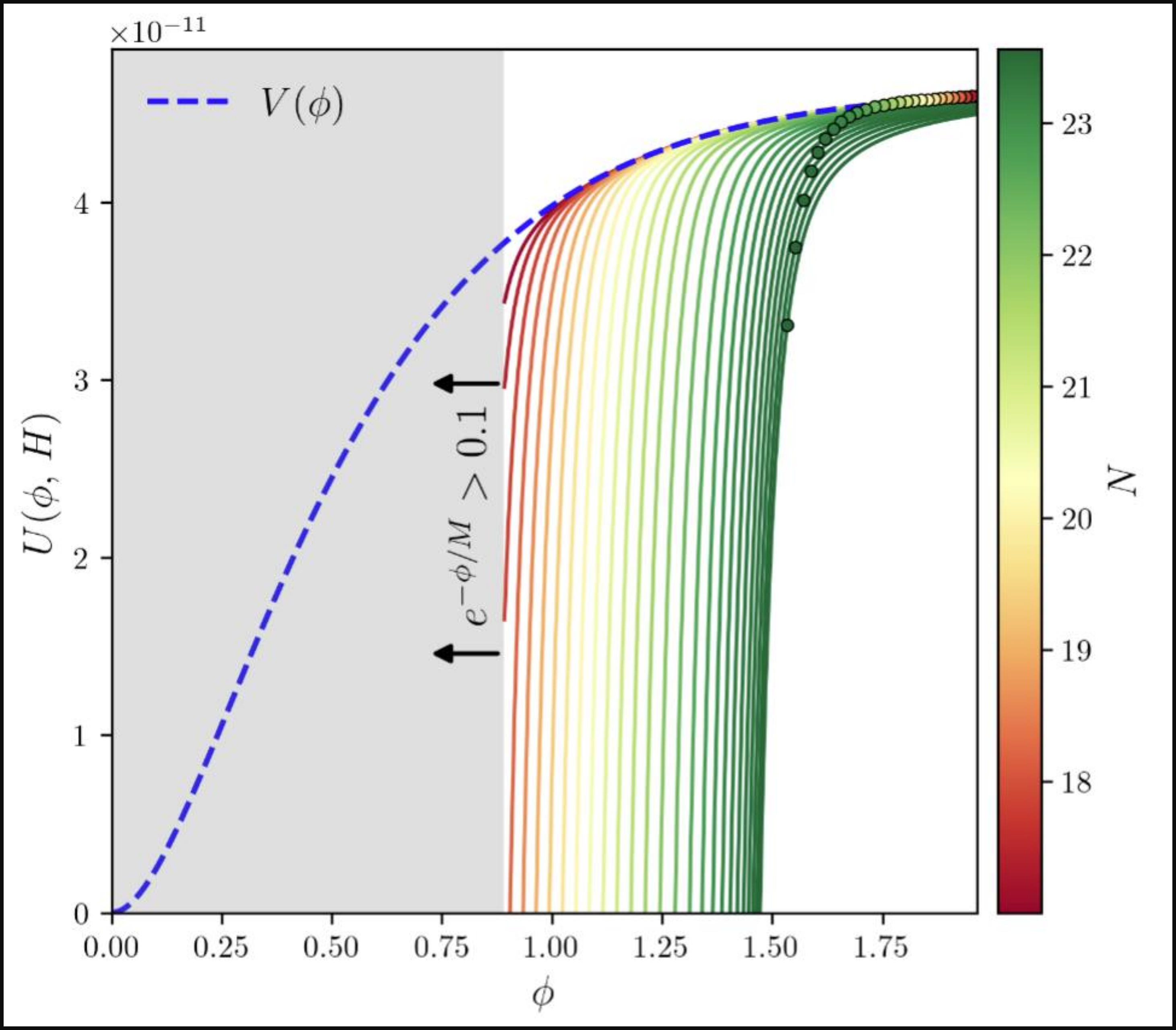

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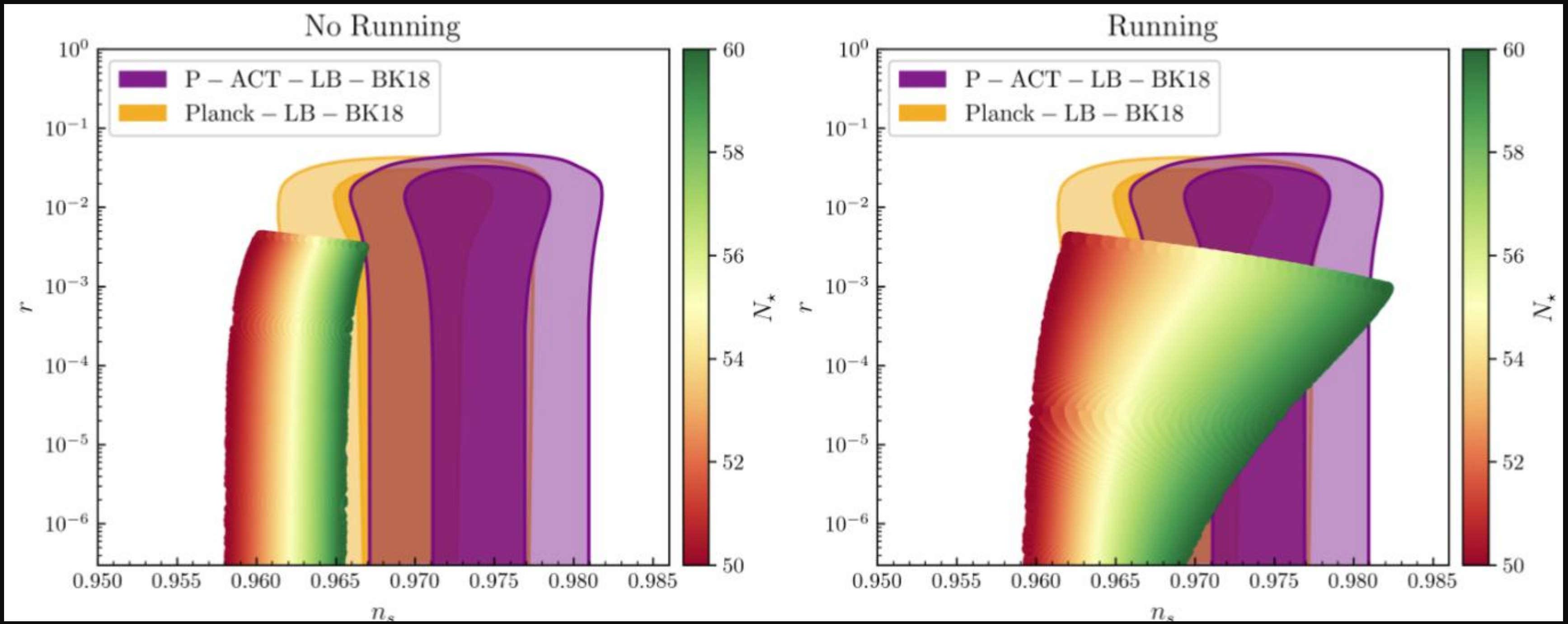
Exact Renormalisation Group



Effect on Observables:

Reduced number of e-folds $\longrightarrow$ Shift to larger n_s

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Further Refinements

1PI Matching

Adiabatic Limit + Minkowsky $\longrightarrow$ Vanilla 1PI result? YES!

$H = 0$ and $\dot\kappa = \dot\phi = \dot T = 0$

$$\partial_\kappa U_\kappa(\phi) = \frac{T^{-1}}{6\pi^2}\frac{\hbar\kappa^4}{\kappa^2 + \partial_\phi^2 U_\kappa(\phi)} \, .$$

if one identifies T^{-1} with $3\kappa/16$

Adiabatic Limit + FLRW

$$\partial_\kappa U_\kappa(\phi) = \frac{\hbar}{32\pi^2}\frac{\kappa^5}{\kappa^2 + \mathcal{M}_i^2} + \mathcal{O}(\hbar^2)$$

$$U_\kappa(\phi) = U_i(\phi) + \mathcal{O}(\hbar)$$

$$\mathcal{M}_i^2 = \partial_\phi^2 U_i(\phi) + (\xi - 1/6)R$$

$$U_{ren}^{(1)} = U_i + \frac{\hbar}{64\pi^2}\left(\mathcal{M}_i^2\right)^2\left(\ln\left(\frac{\mathcal{M}_i^2}{\mu^2}\right) + C\right)$$

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1PI Matching

if one identifies T^{-1} with $3\kappa/16$ $\longrightarrow$ $\boxed{T = T(H)}$

New Formulation: $F \equiv \partial_H U$ $\longrightarrow$ $X \equiv H^{-1}\partial_H U$

$$
\begin{aligned}
X'' &= \frac{\sigma^6 H^2}{32\pi^2} - \left(1 + \frac{H'}{H}\right) X' \\
&\quad - \left(\frac{\partial_\phi^2 U}{H^2} - \frac{H'}{H} - 2 + \sigma^2\right) X\,, \\
\phi'' &= -\left(3 + \frac{H'}{H}\right)\phi' - \frac{\partial_\phi U}{H^2}\,, \\
H' &= -\frac{H}{2M_p^2}\left[(\phi')^2 + \frac{1}{3}\left(\frac{H'}{H}X + X'\right)\right].
\end{aligned}
\tag{80}
$$

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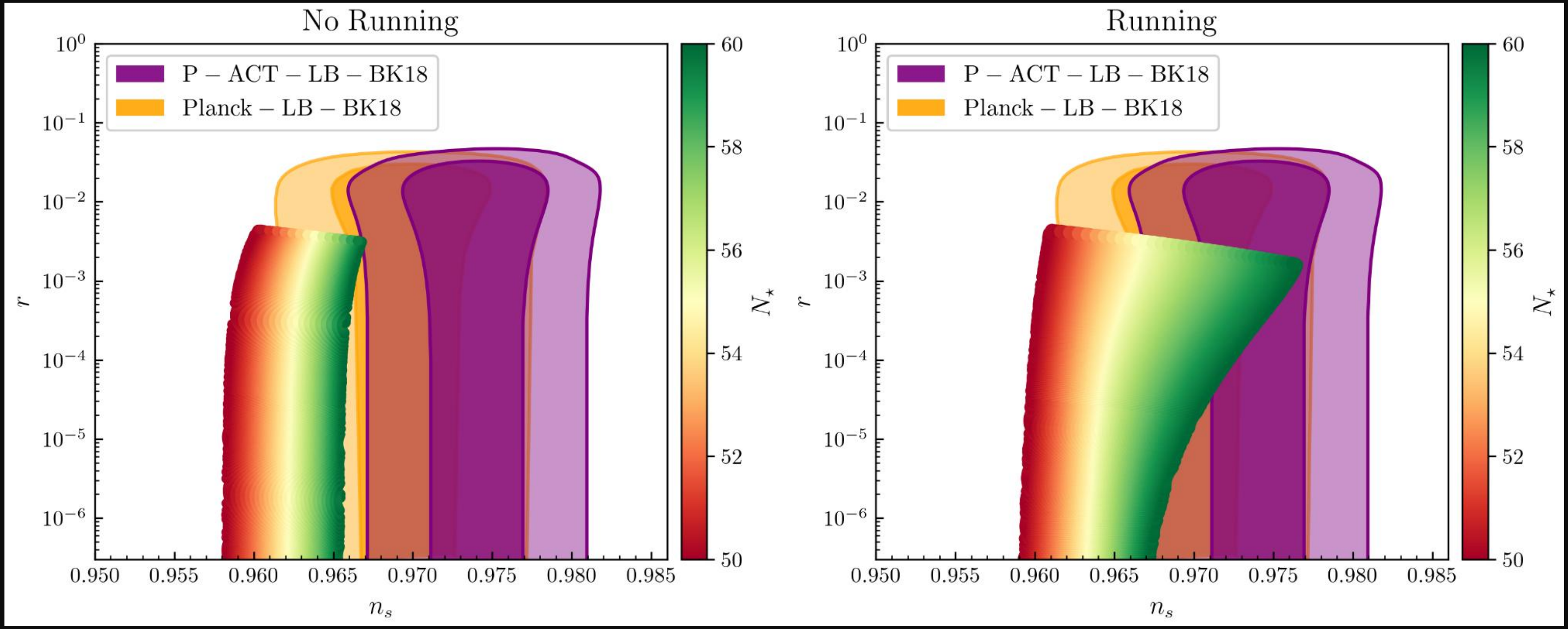
1PI Matching



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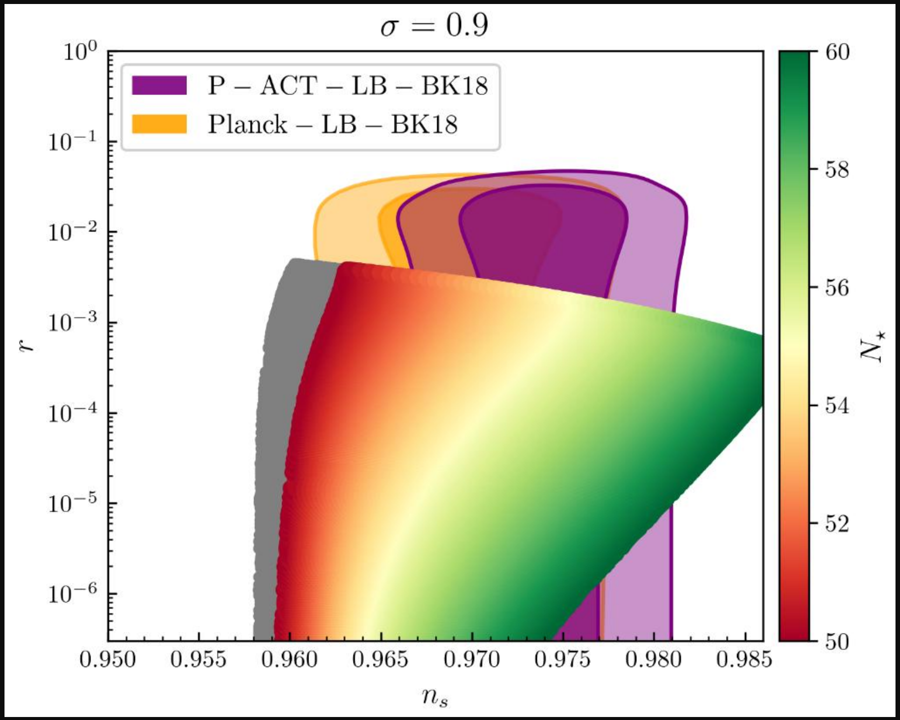
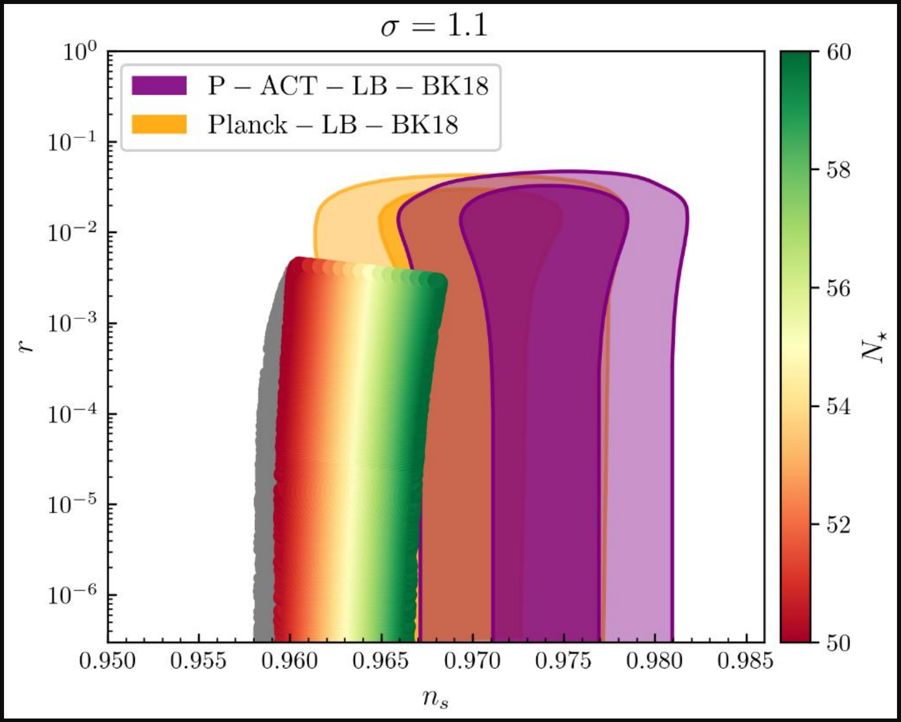
Coarse-Graining Size Effect





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Discussion

Open questions:

- What happens after inflation?
- What is the role of metric fluctuations?
- What about other potentials?
- What about RG corrections to the Kinetic term?
- Where has the spinodal instability gone?

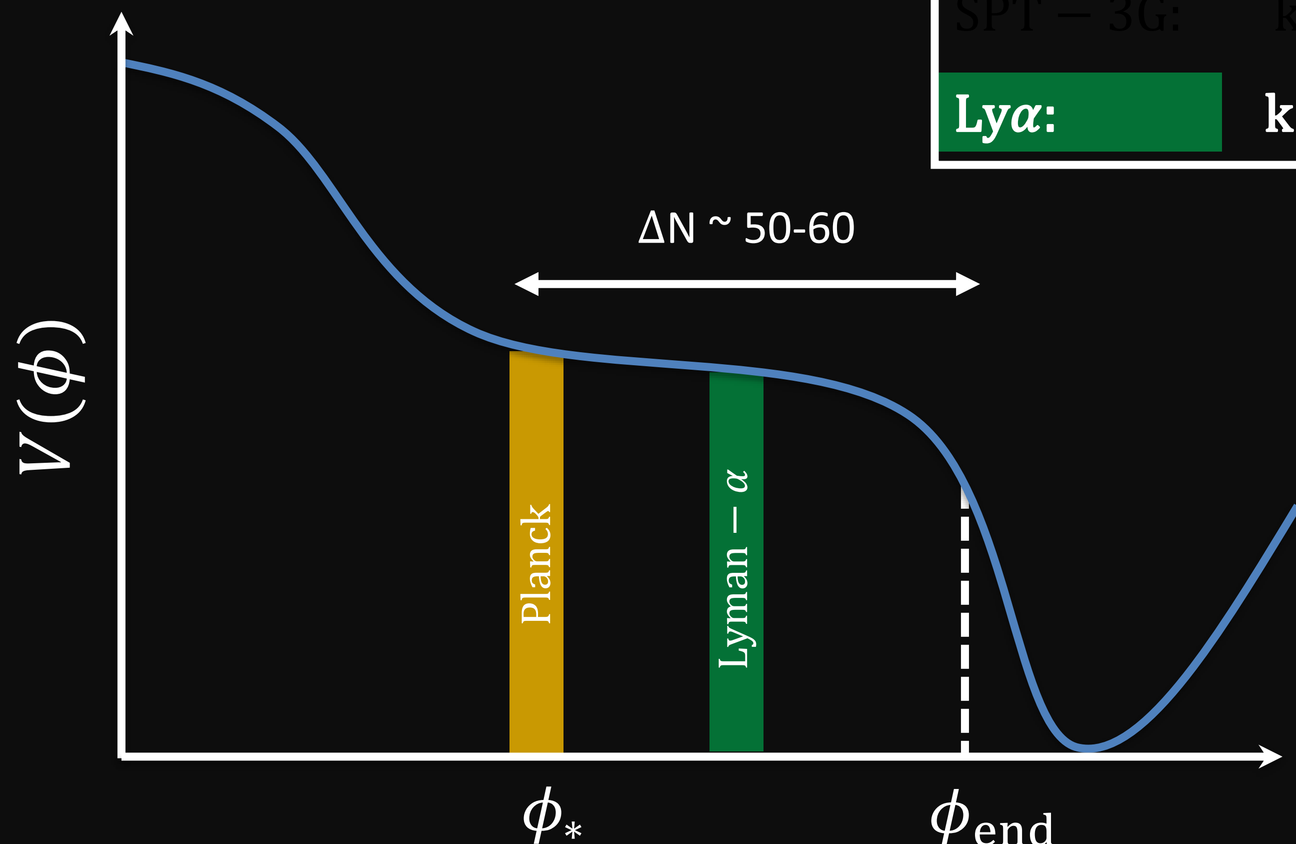
Future Directions:

- Application to oscillating scalars and oscillon formation
- Application to quintessence scenarios
- UV-IR interactions: CTP formalism and stochastic inflation

谢谢！

Constraints Across Scales

Planck:	$\mathbf{k \sim 0.05\ Mpc^{-1}}$
ACT:	$k \lesssim 0.6\ \mathrm{Mpc}^{-1}$
SPT − 3G:	$k \lesssim 0.7\ \mathrm{Mpc}^{-1}$
Lyα:	$\mathbf{k \sim 0.2 - 2.5\ Mpc^{-1}}$



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