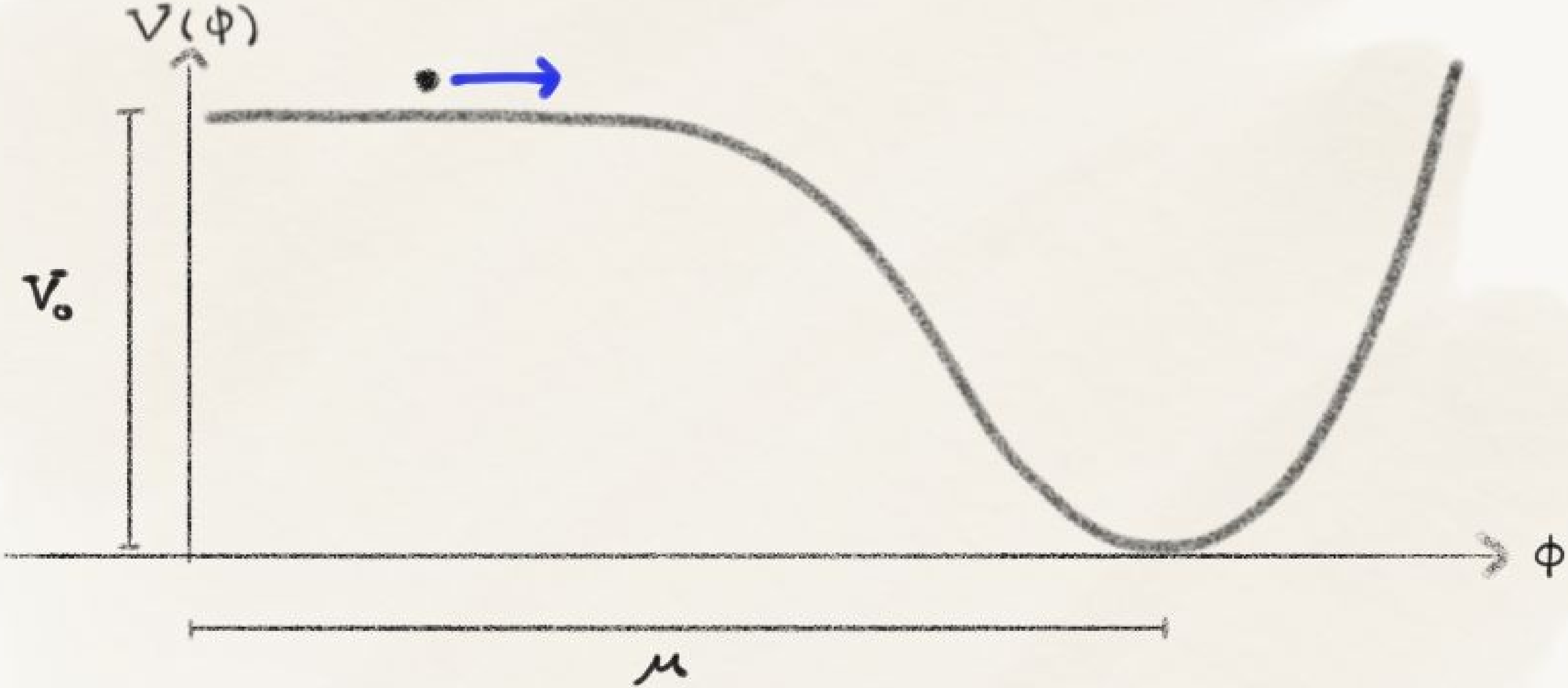
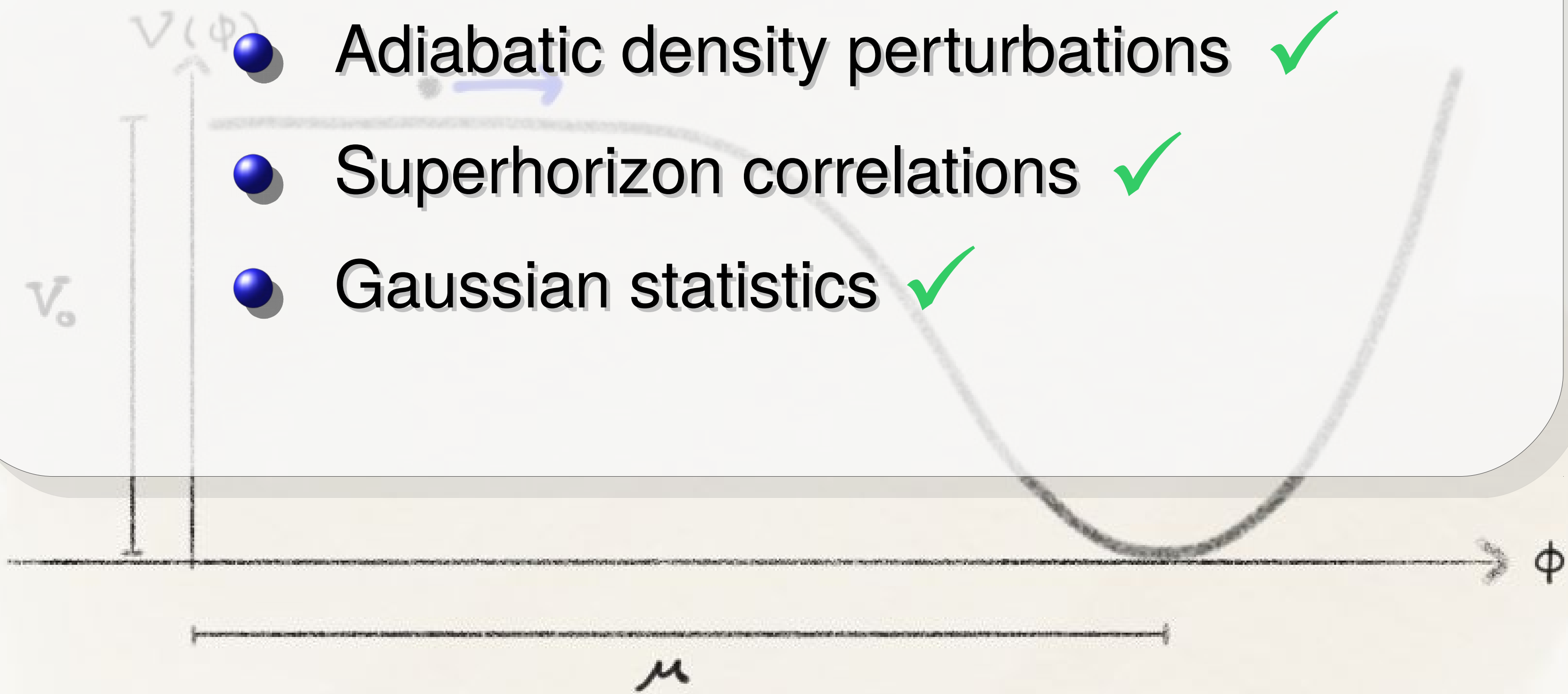
Swamp Creatures of the Inflation Landscape

Will Kinney
Helsinki Institute of Physics
3 April 2019

Inflation: Basic Predictions



Inflation: Basic Predictions

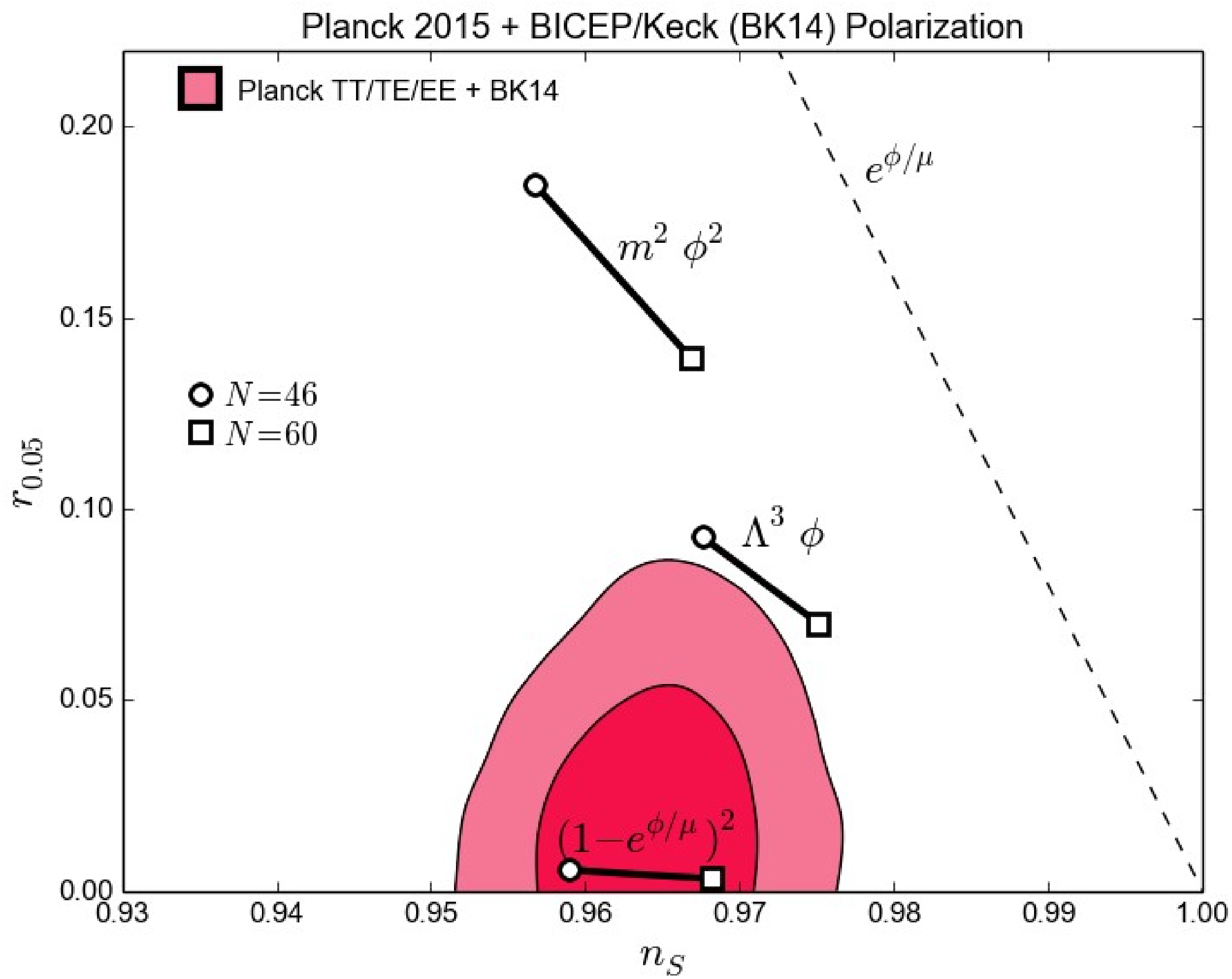


- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics ✓

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi)$$

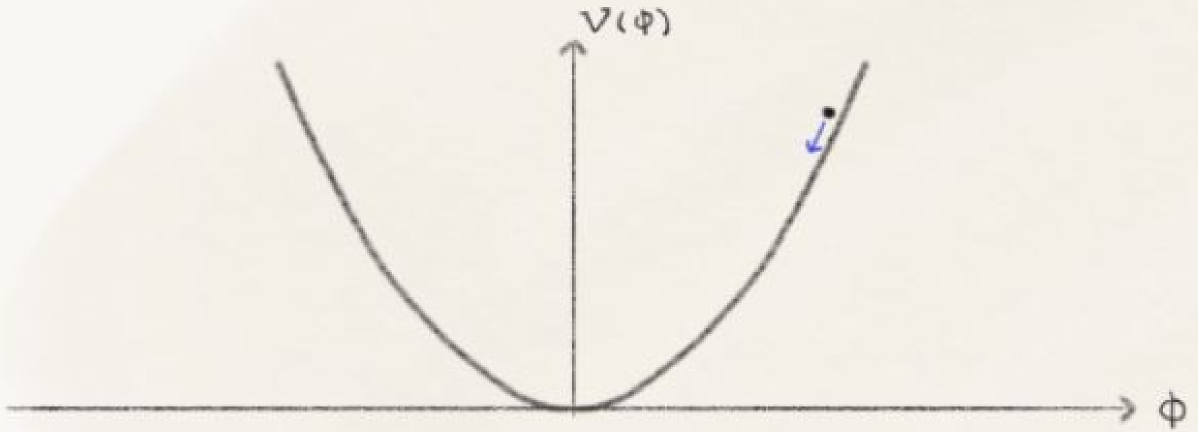
Fully consistent with data.

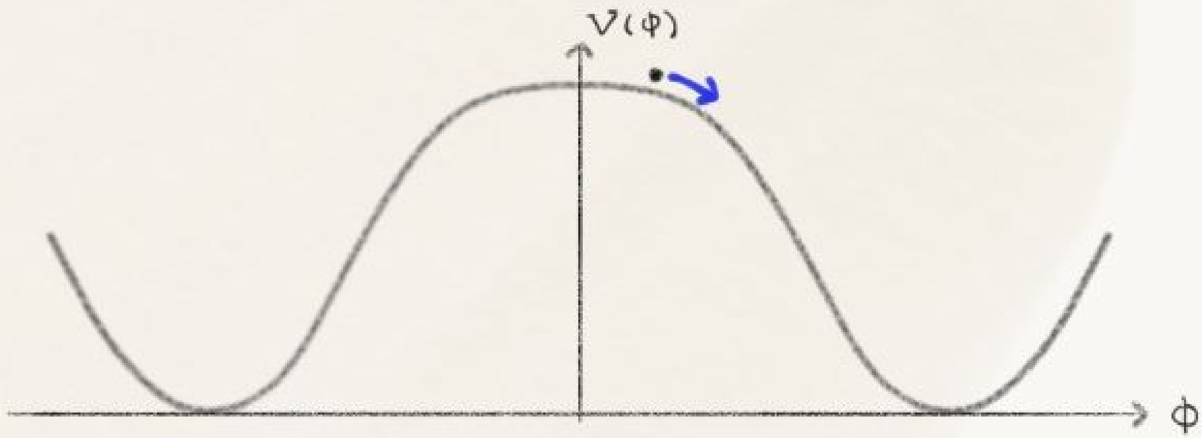
$$r = 8M_P^2\left(\frac{V'}{V}\right)^2$$

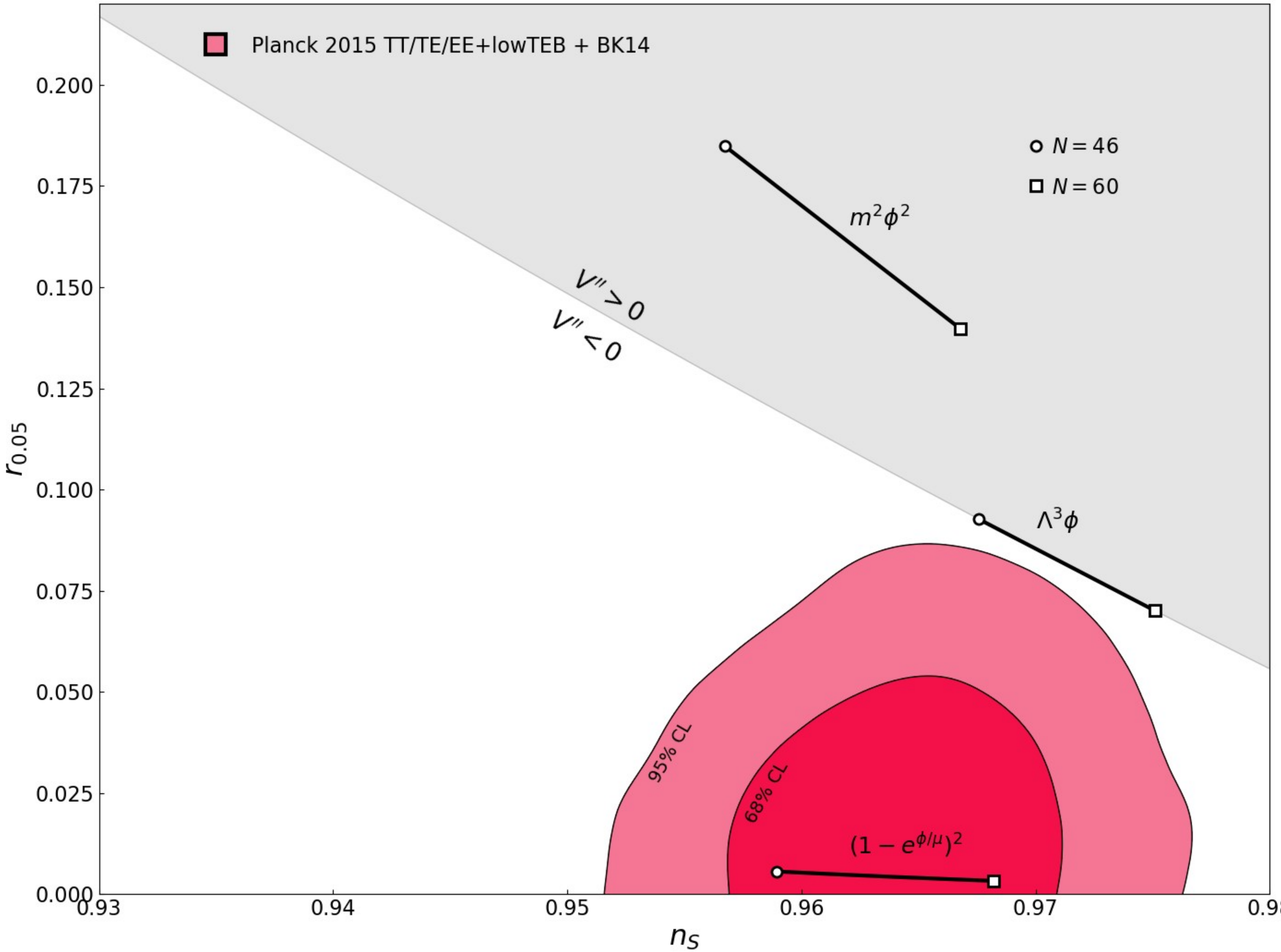


$$n_S = 1 - 3M_P^2\left(\frac{V'}{V}\right)^2 + 2M_P^2\frac{V''}{V}$$

Convex or Concave?

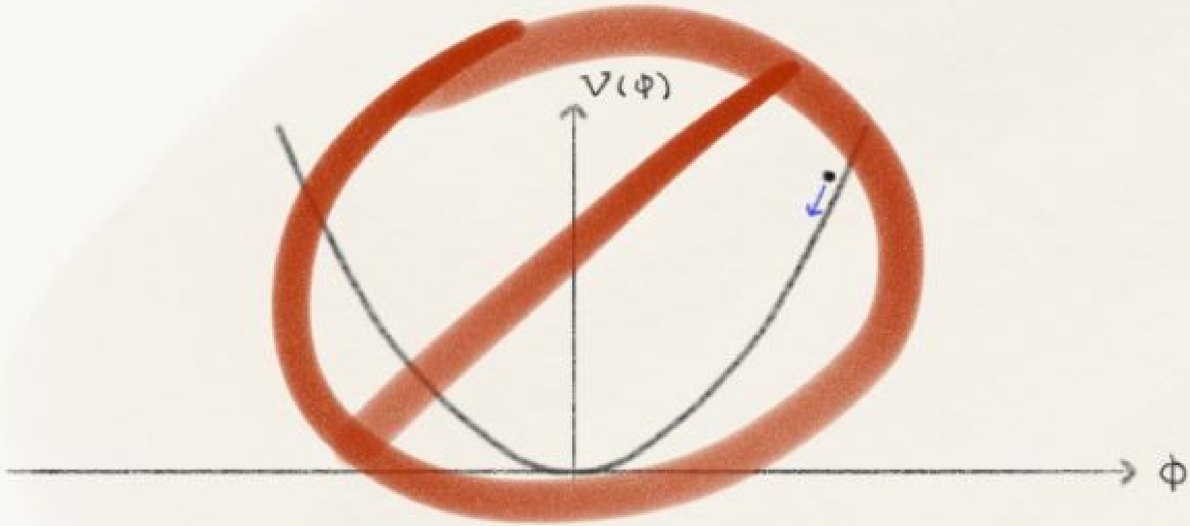


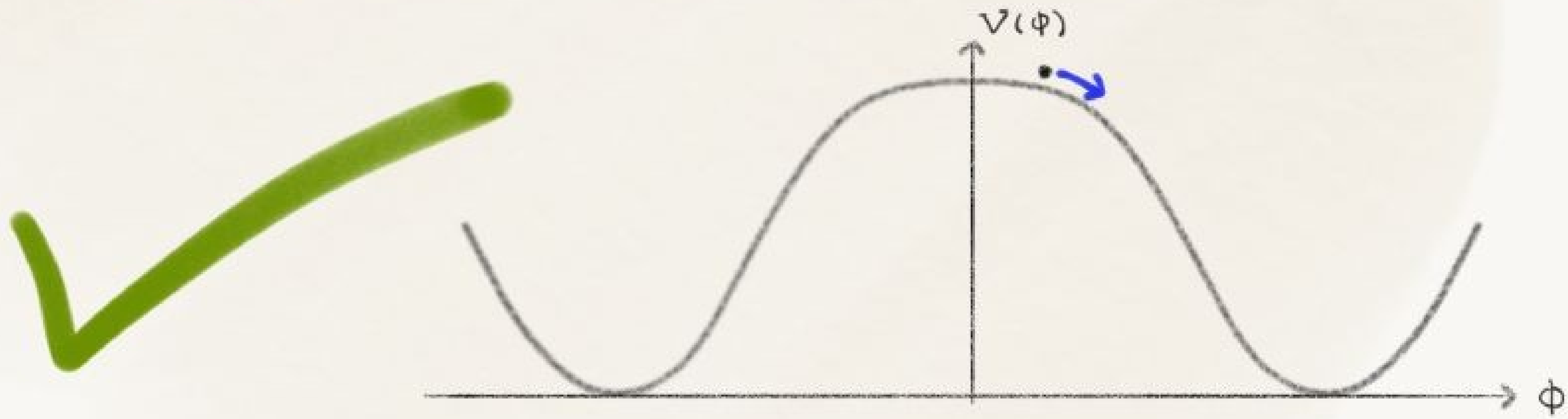




Planck 2015 TT/TE/EE+lowTEB + BK14
$N=46$
$N=60$
$m^2\phi^2$
$V''>0$
$V''<0$
$\Lambda^3\phi$
95% CL
68% CL
$(1-e^{\phi/\mu})^2$
$r_{0.05}$
n_S
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
0.93
0.94
0.95
0.96
0.97
0.98

Convex or Concave?

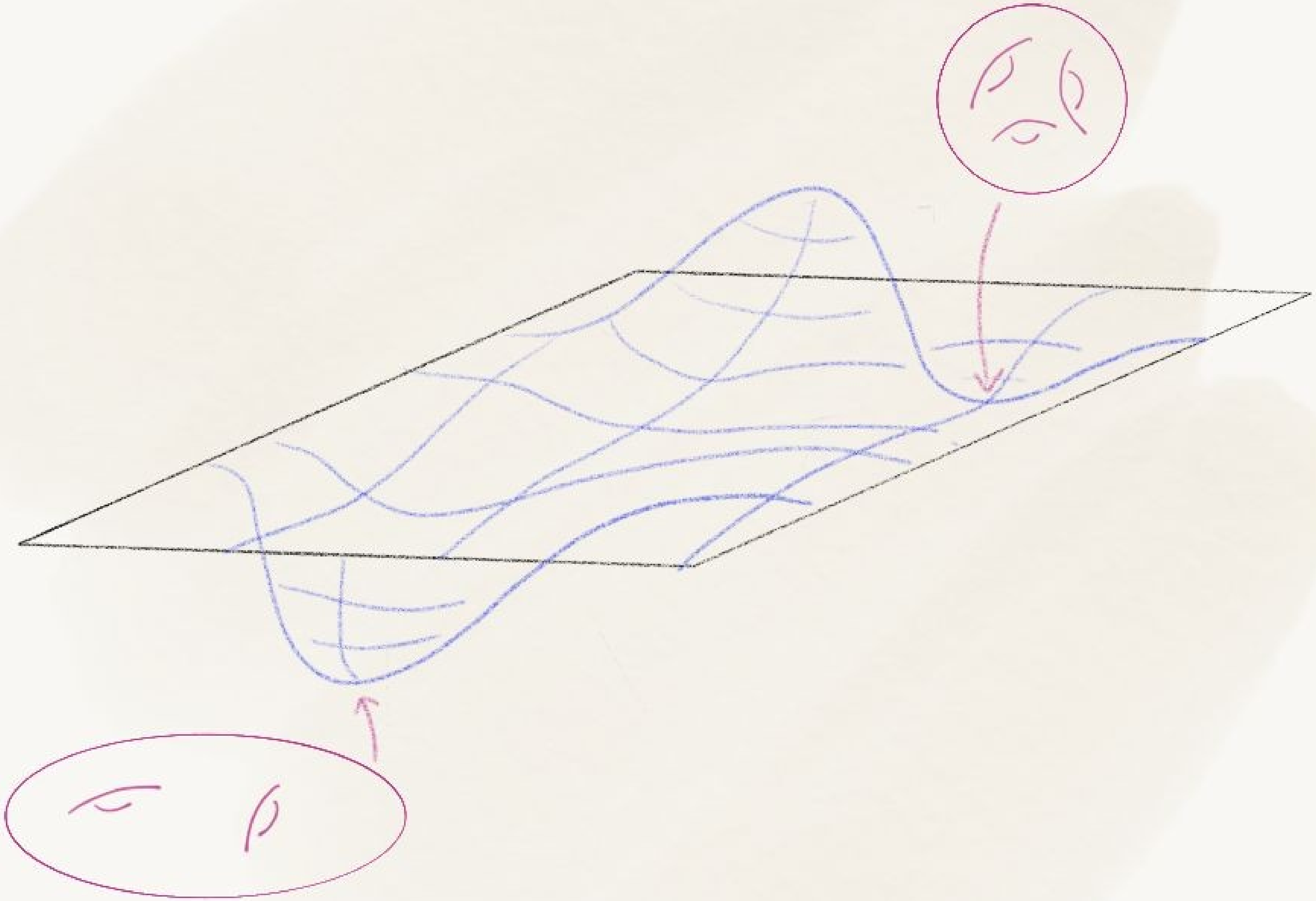




Inflation: Swampland or Landscape?

WHK, Vagnozzi, Visinelli [arXiv:1808.0624]

The String Landscape




NO UV COMPLETION
NO UV COMPLETION

High Energy Physics - Theory

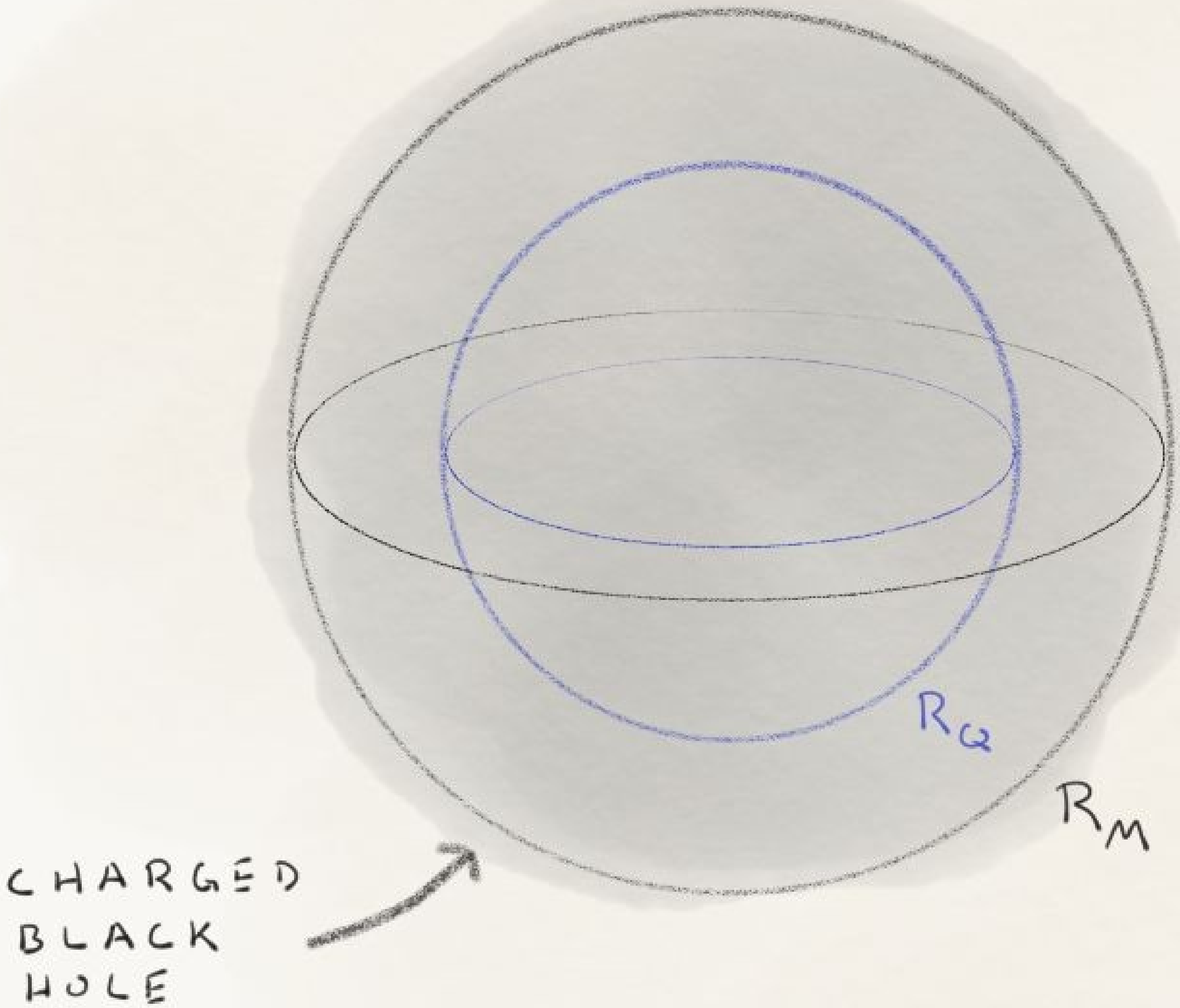
The Marshland Conjecture

David M.C. Marsh, J.E. David Marsh

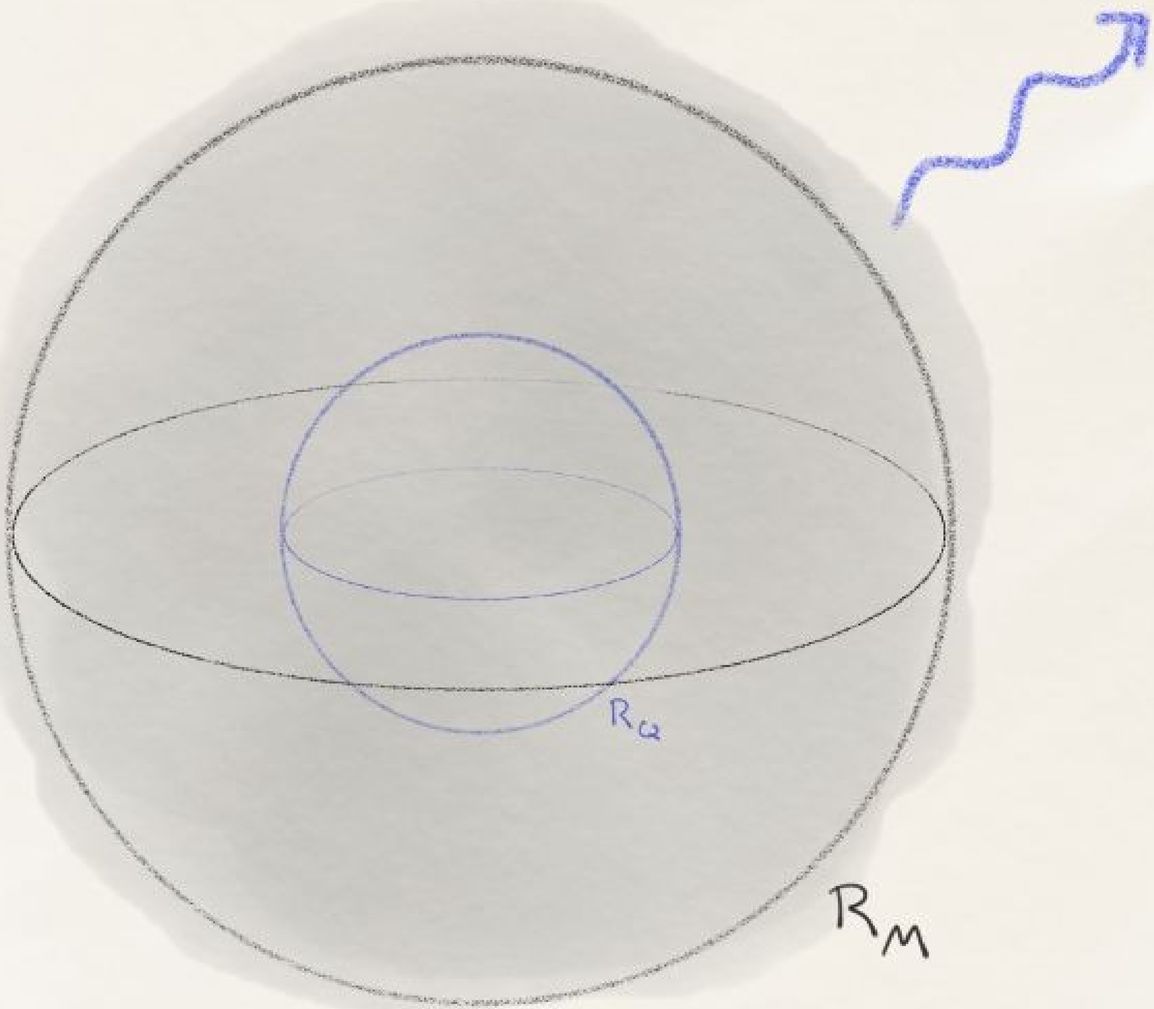
(Submitted on 29 Mar 2019)

We posit the existence of the Marshland within string theory. This region is the boundary between the landscape of consistent low-energy limits of quantum gravity, and the swampland of theories that cannot be embedded within string theory because they violate certain trendy and obviously uncontroversial conjectures. The Marshland is probably fractal, and we show some pretty pictures of fractals that will be useful in talks. We further show that the Marshland contains theories with a large number of light axions, allowing us to cite lots of our own papers. We show that the Marshland makes up most of the volume of the landscape, and admits a novel, weakly broken $\mathbb{Z}_2$ Marshymmetry that we find strong evidence for by considering a carefully crafted example.

The Weak Gravity Conjecture



The Weak Gravity Conjecture



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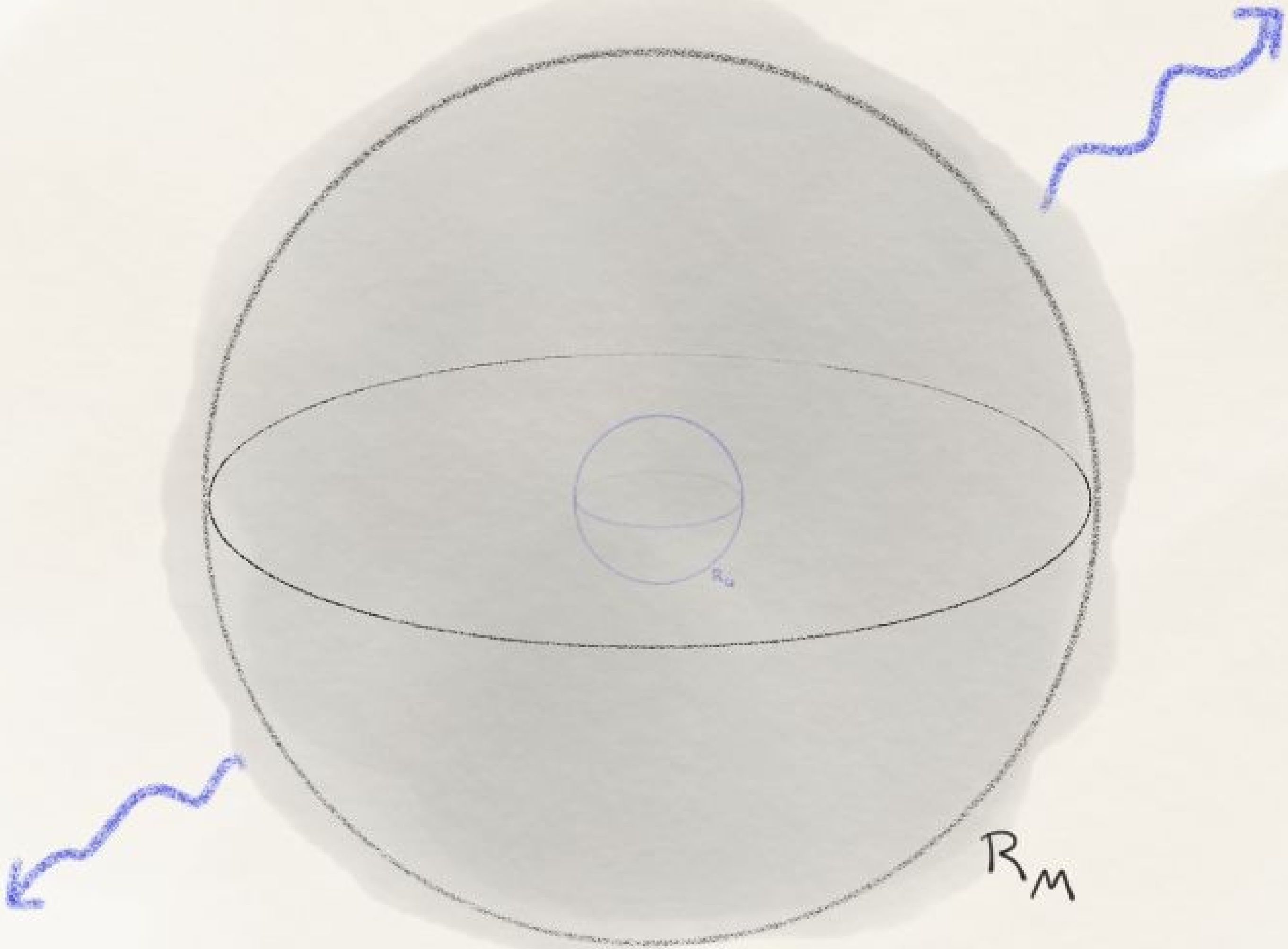

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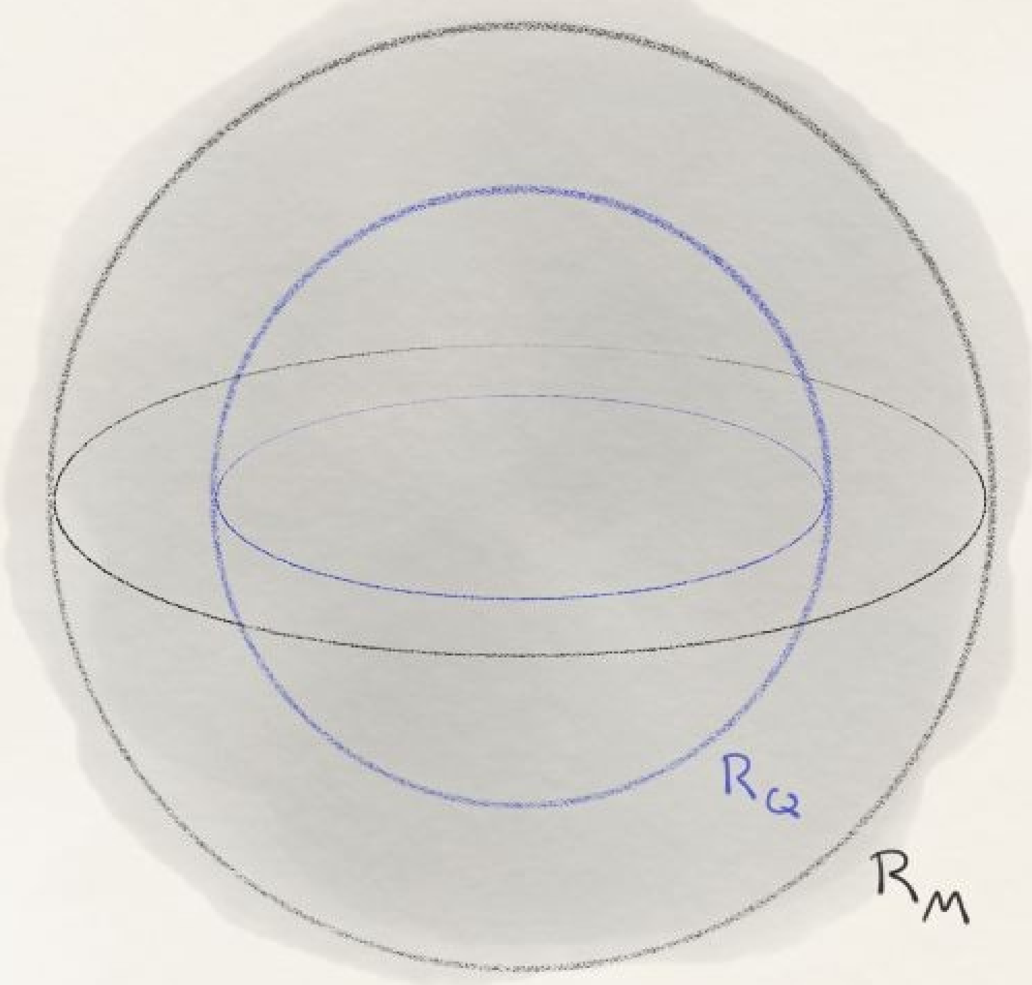

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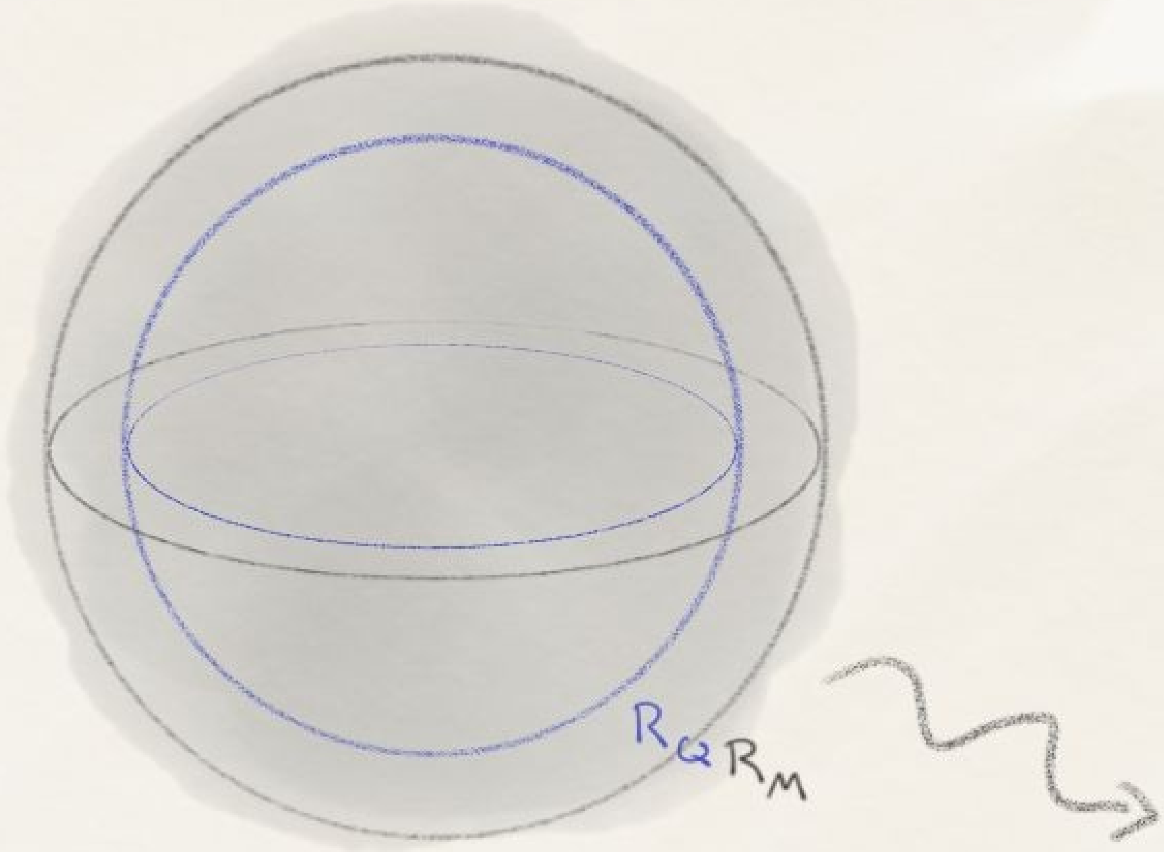

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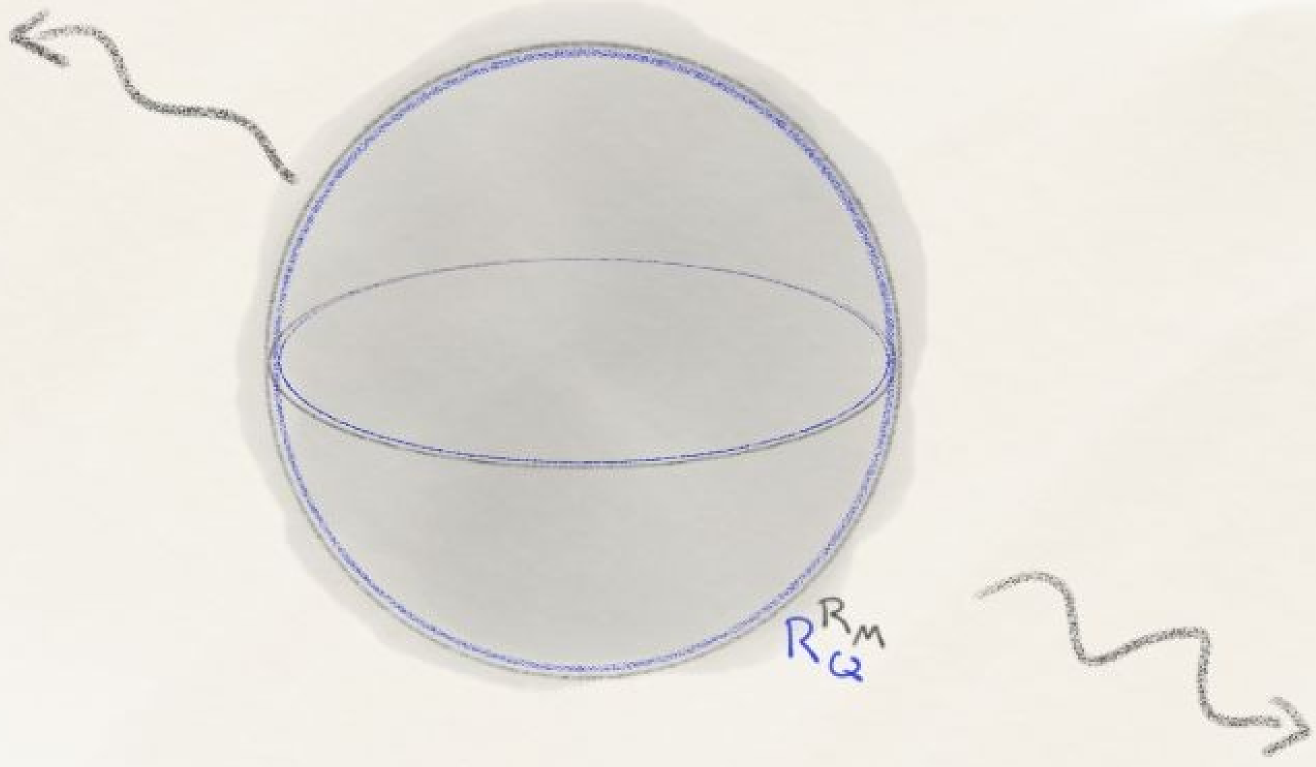

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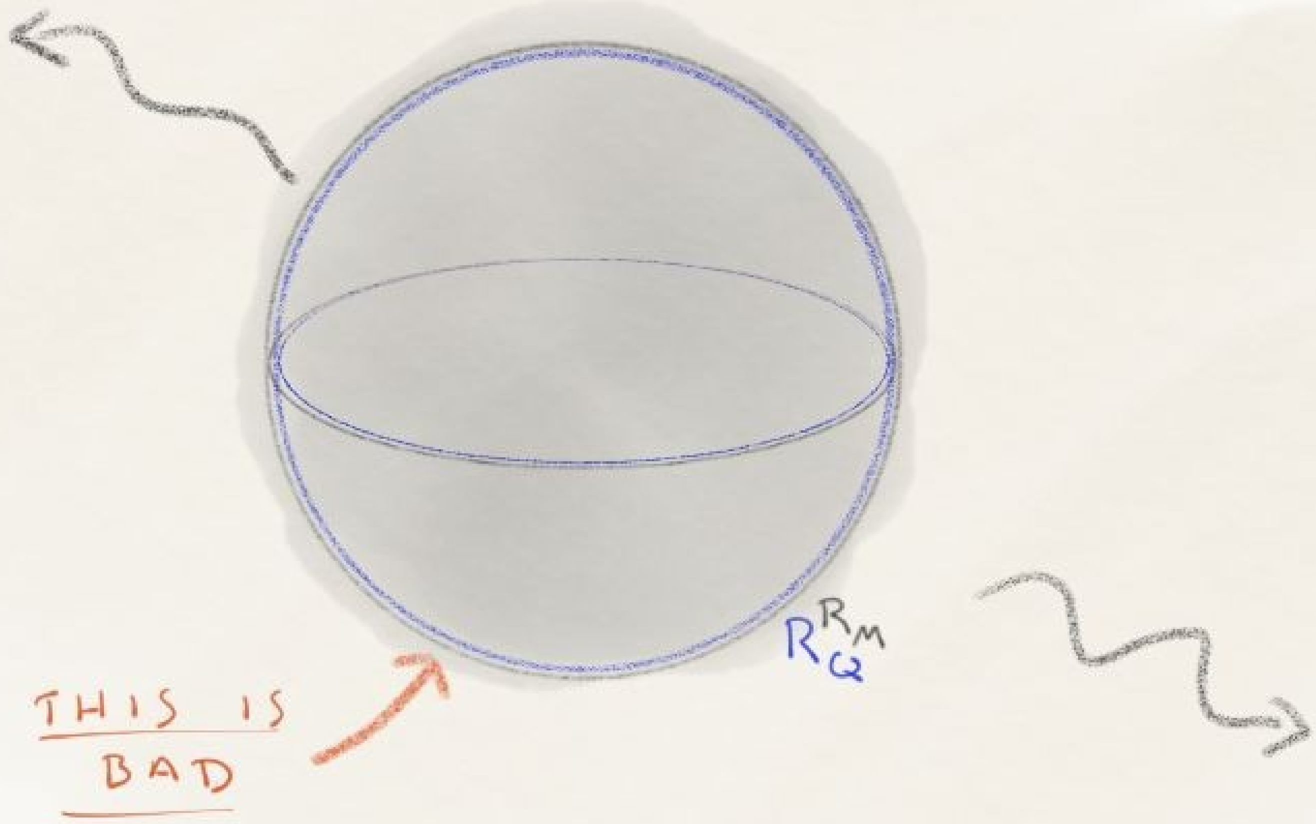
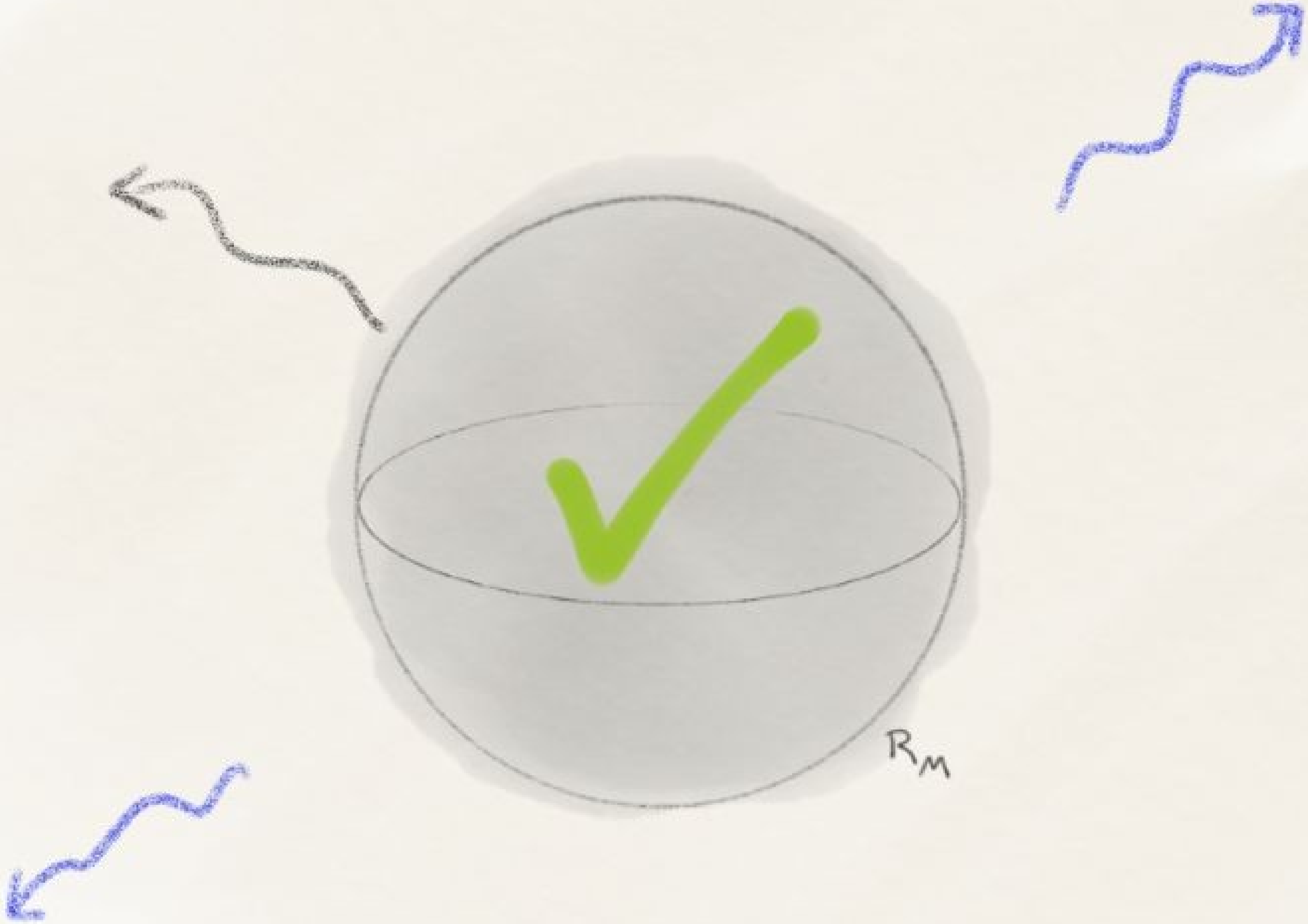


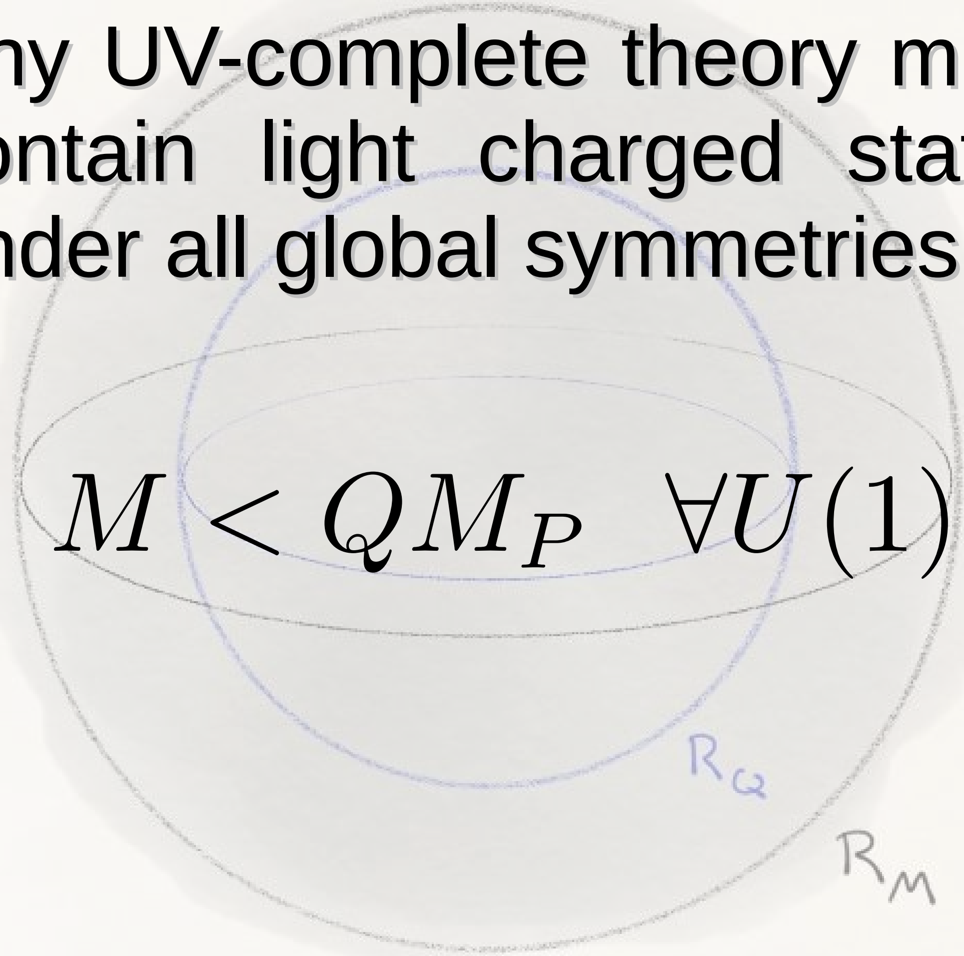
The Weak Gravity Conjecture



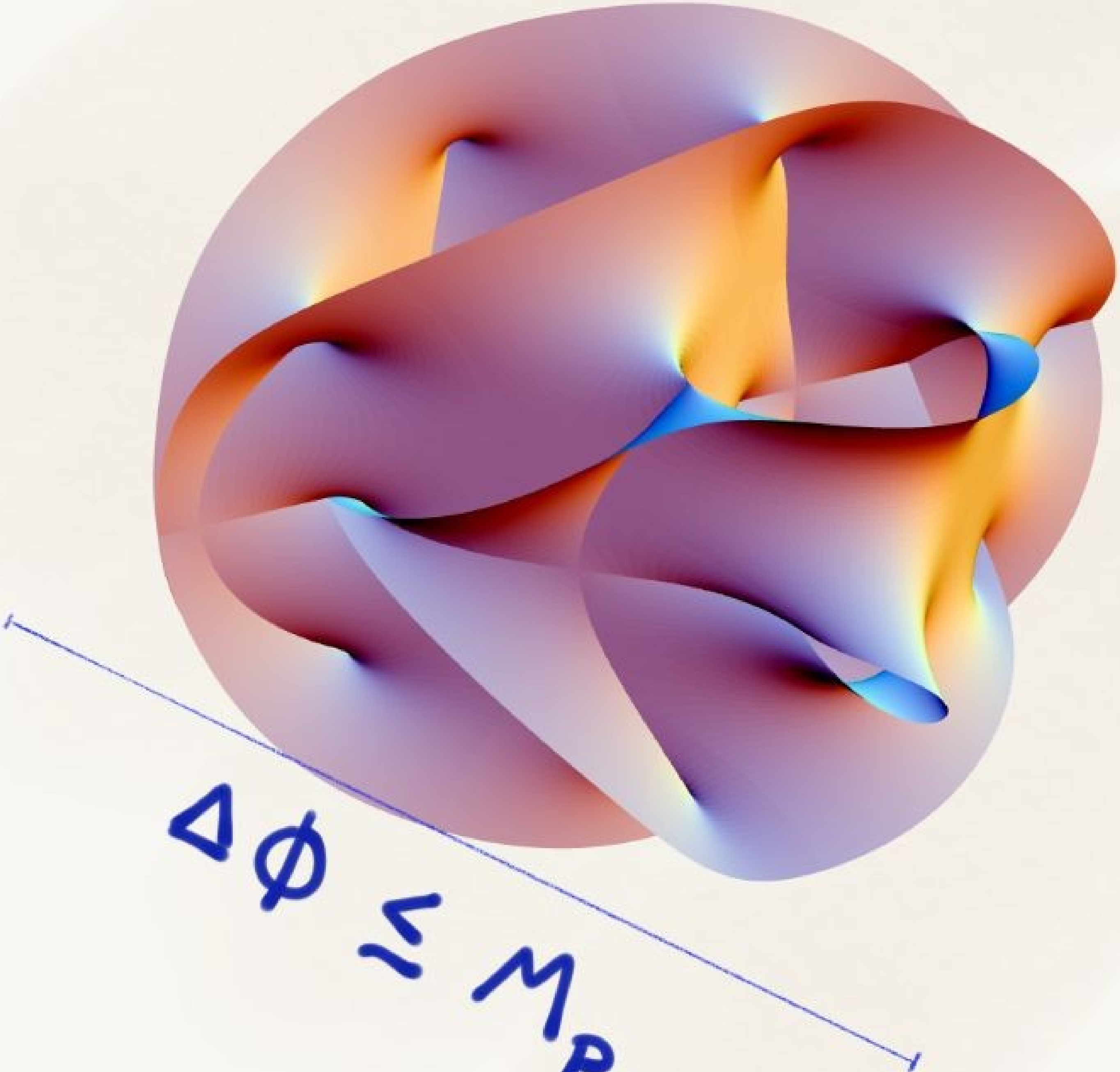
The Weak Gravity Conjecture

Any UV-complete theory must contain light charged states under all global symmetries.

$$M < QM_P \quad \forall U(1)$$



The deSitter Swampland Conjecture



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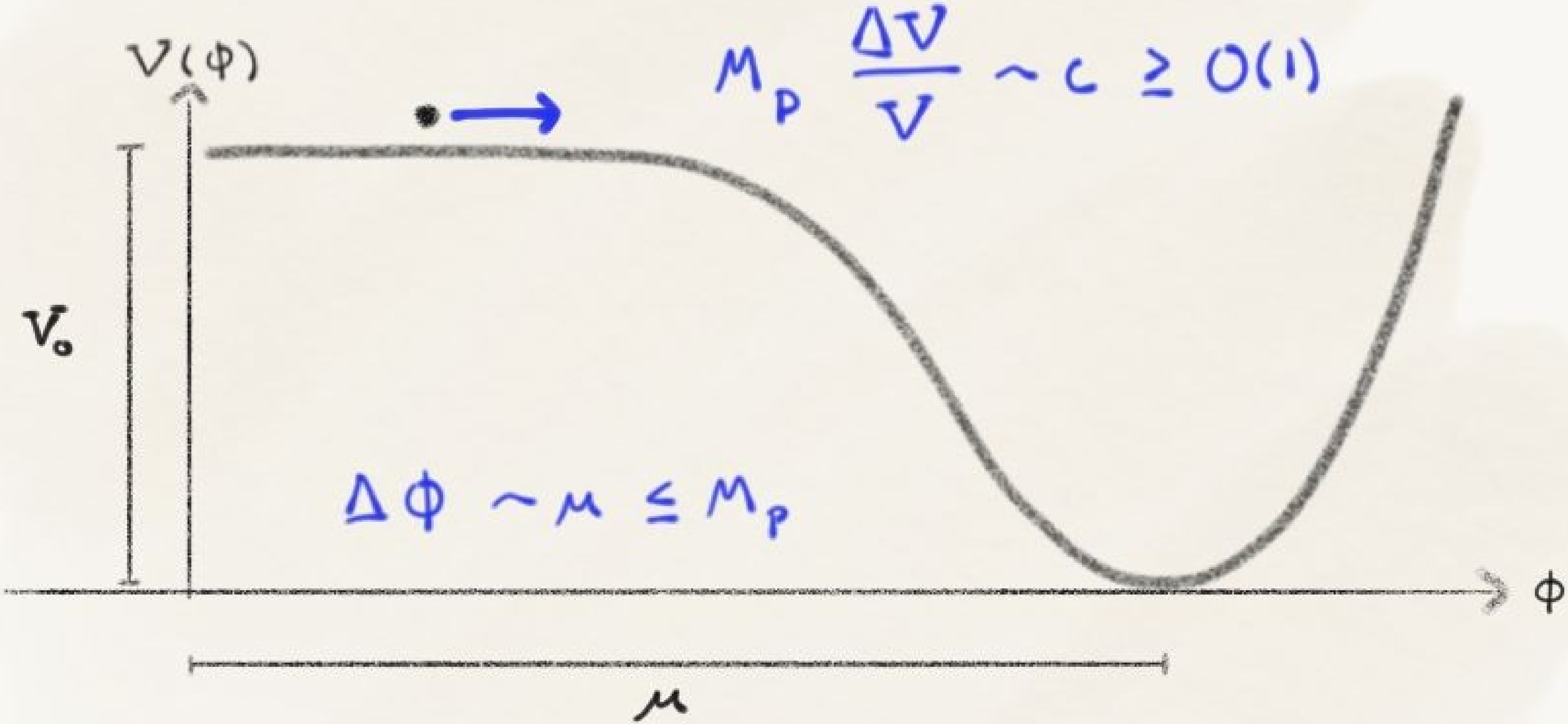
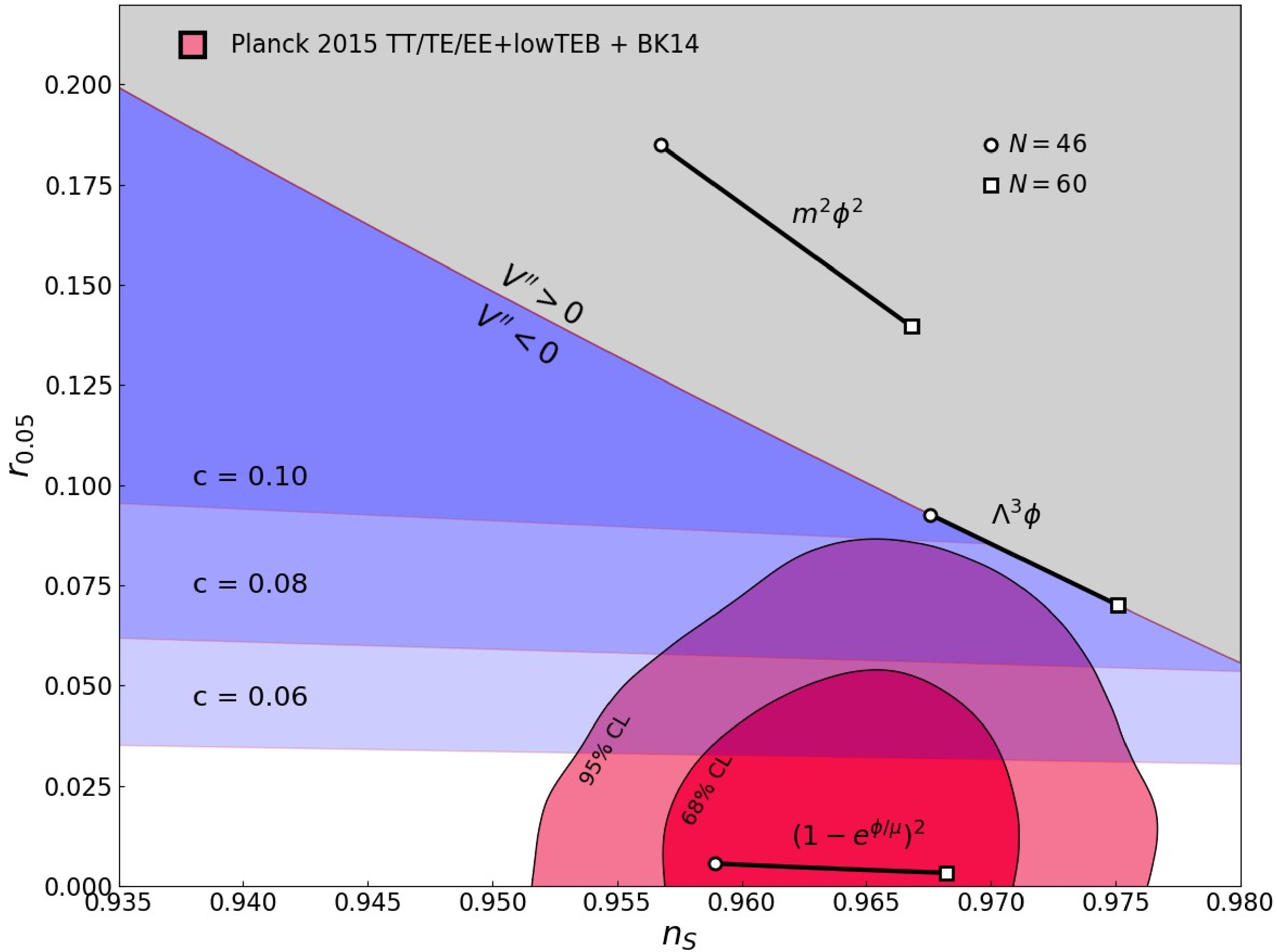
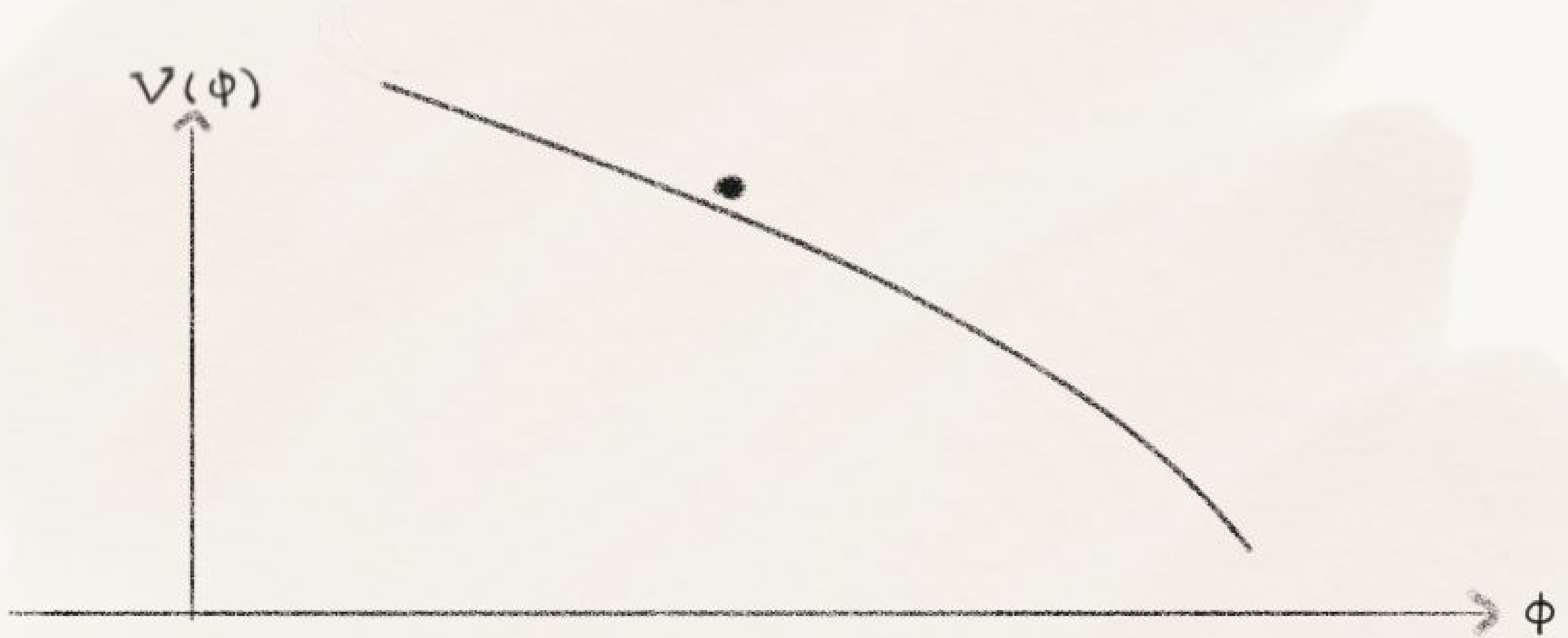


Single-Field Inflation and the Swampland



WHK, Vagnozzi, Visinelli [arXiv:1808.0624]

Eternal Inflation



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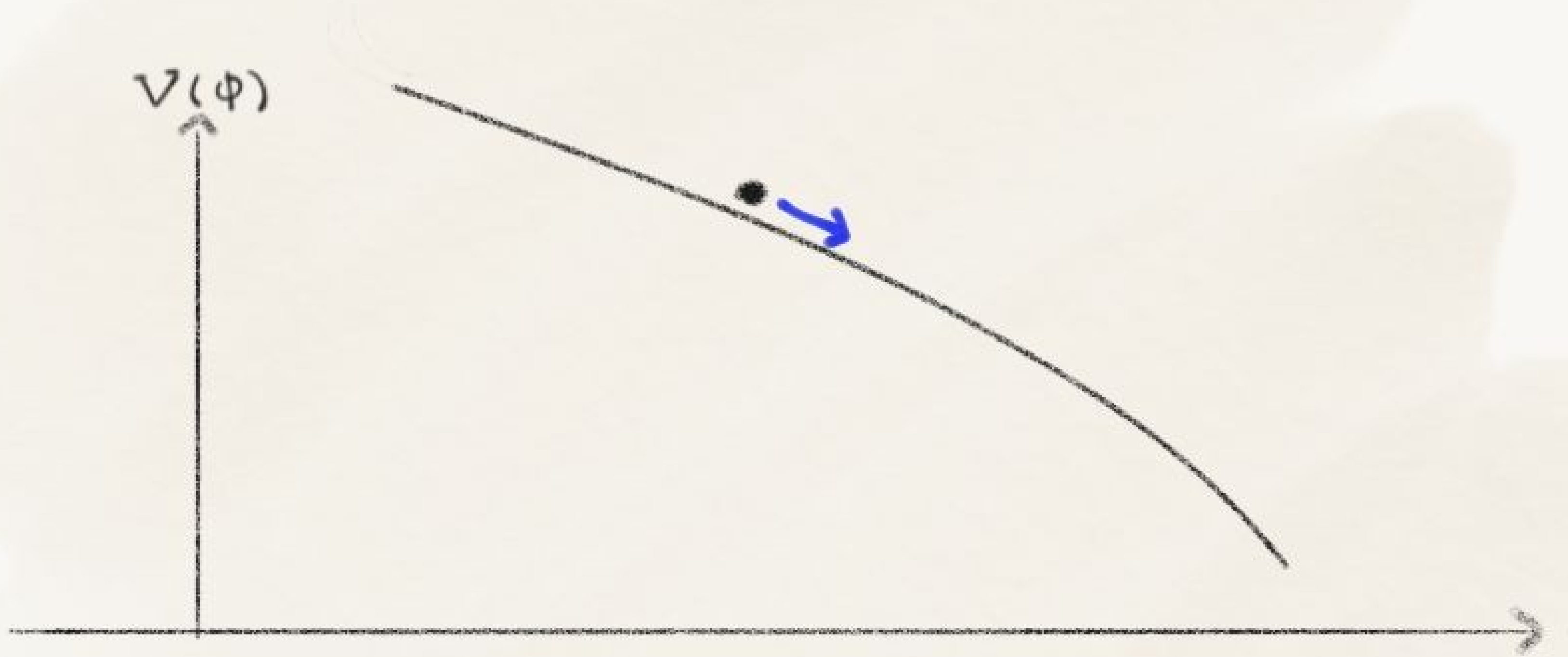
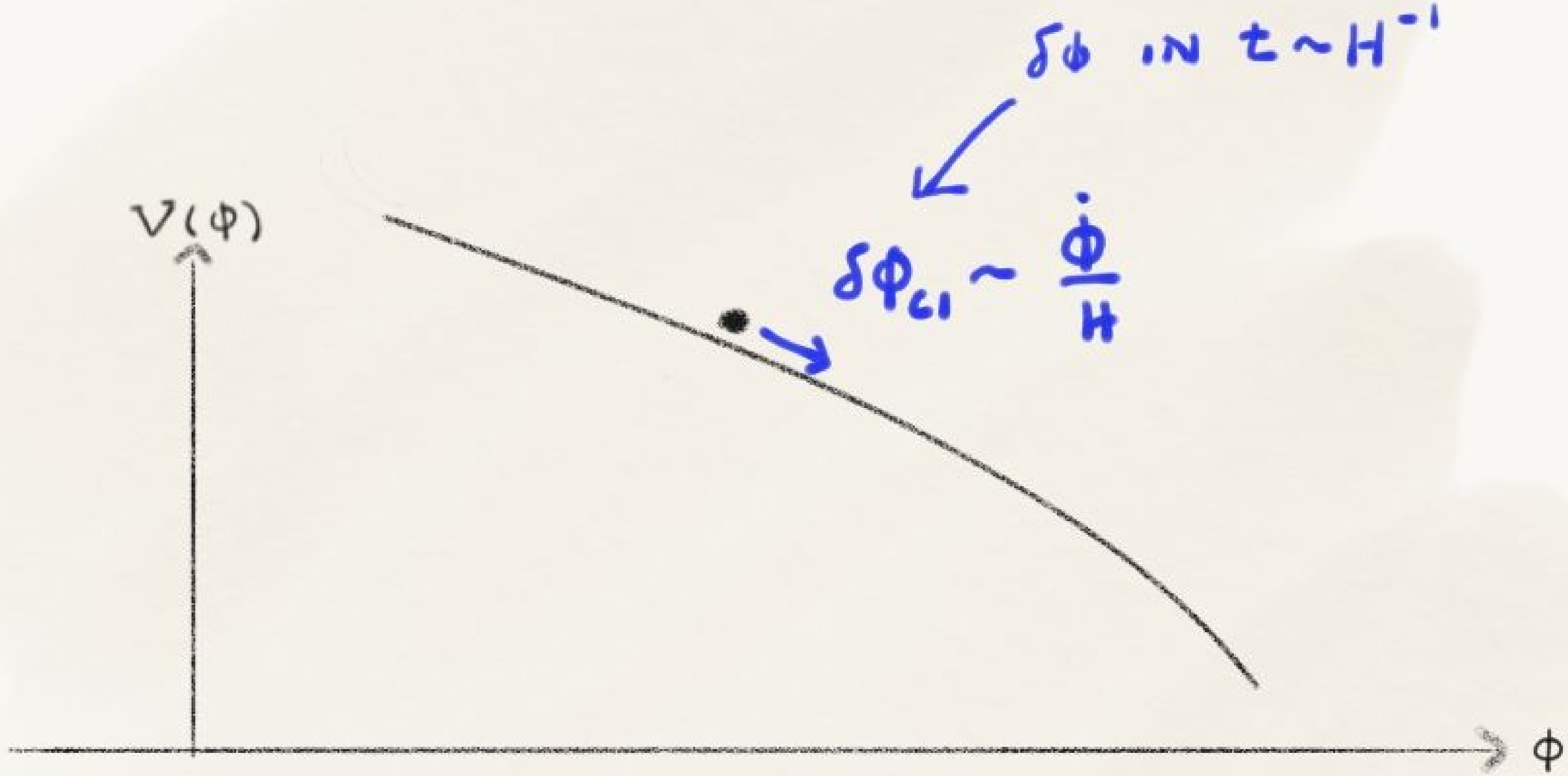


$$\ddot{\phi} + 3H\dot{\phi} + \frac{\delta V}{\delta \phi} = 0$$

CLASSICAL EVOLUTION

Eternal Inflation



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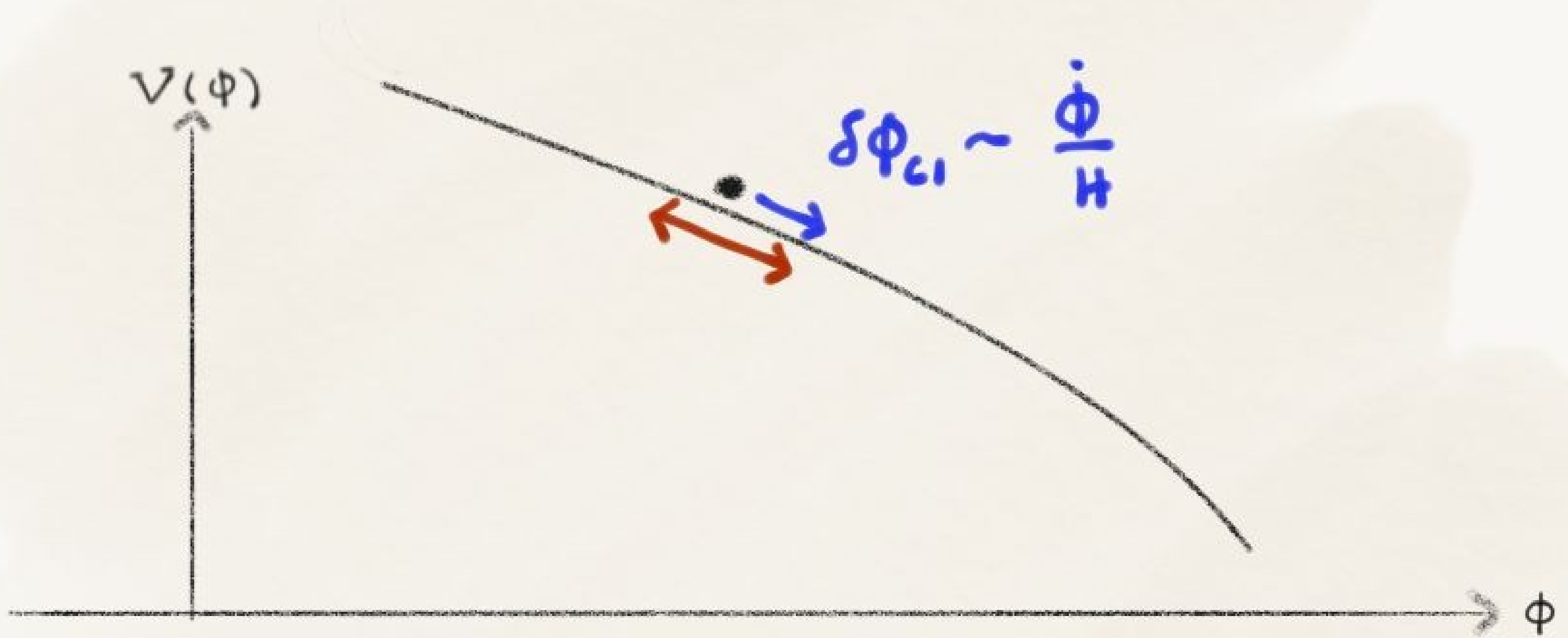

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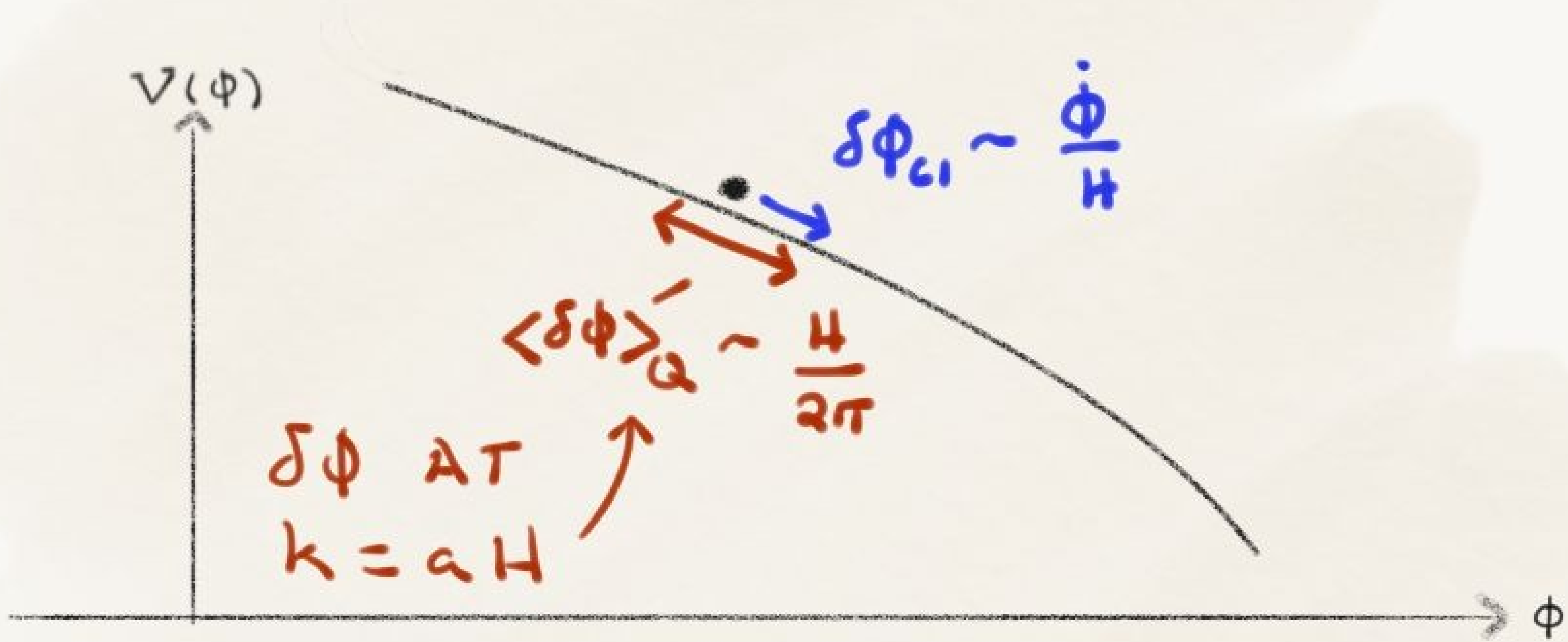
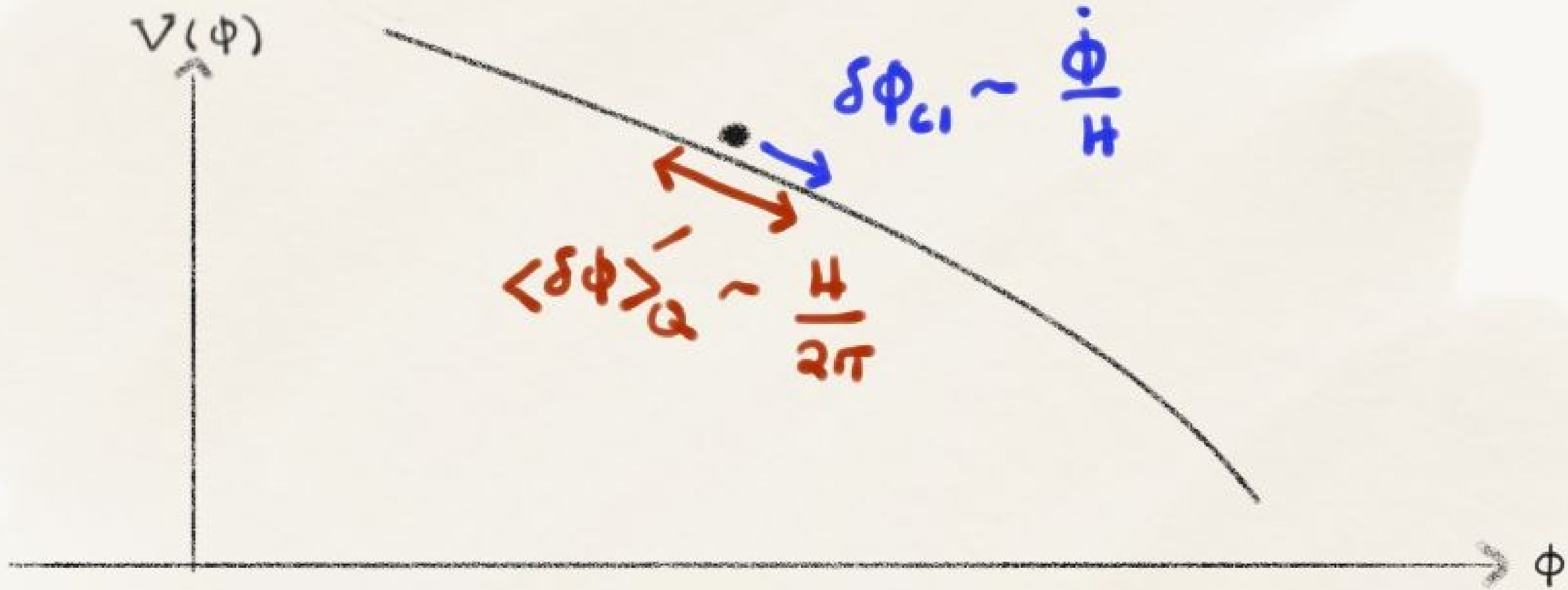
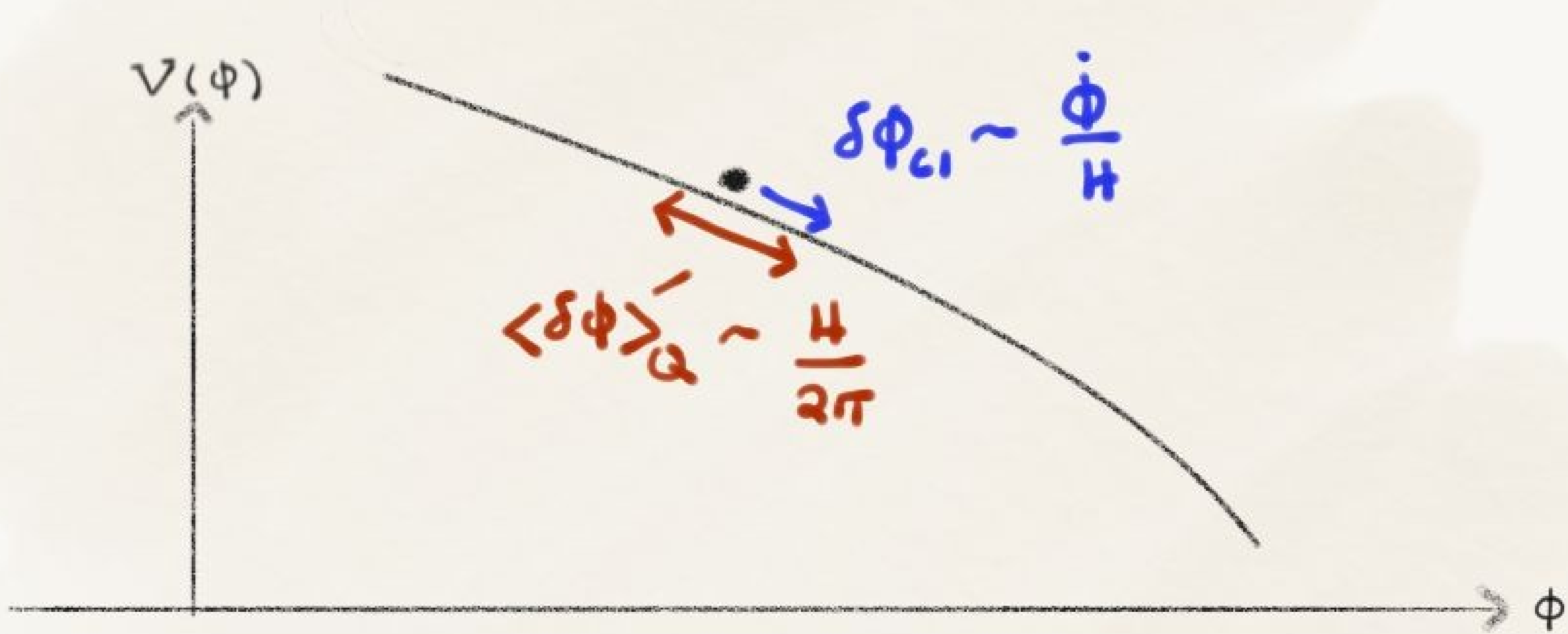


Eternal Inflation



$$\frac{\langle\delta\phi\rangle_Q}{\delta\phi_{cl}} = \frac{H^2}{2\pi\dot{\phi}} = P(k) > 1$$

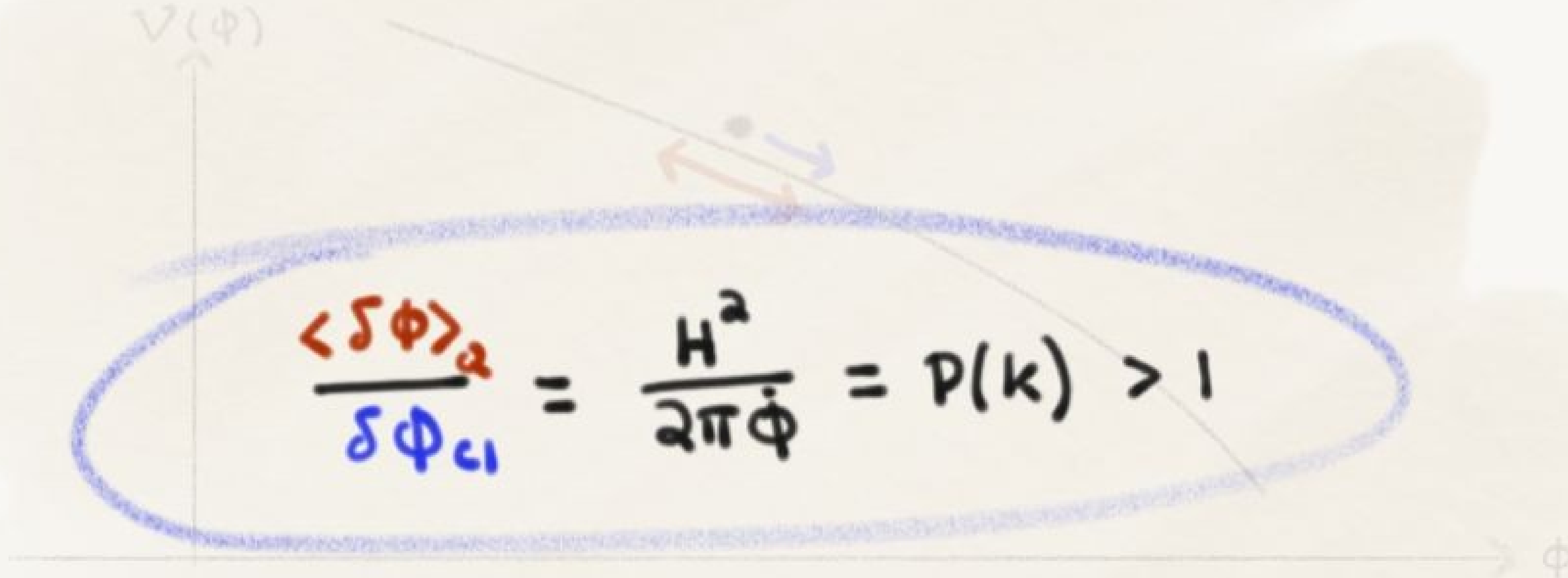
Eternal Inflation



$$\frac{\langle \delta\phi \rangle_Q}{\delta\phi_{cl}} = \underbrace{\frac{H^2}{2\pi\dot{\phi}} = P(k)} > 1$$

↖ CURVATURE PERTURBATION!

Condition for Eternal Inflation

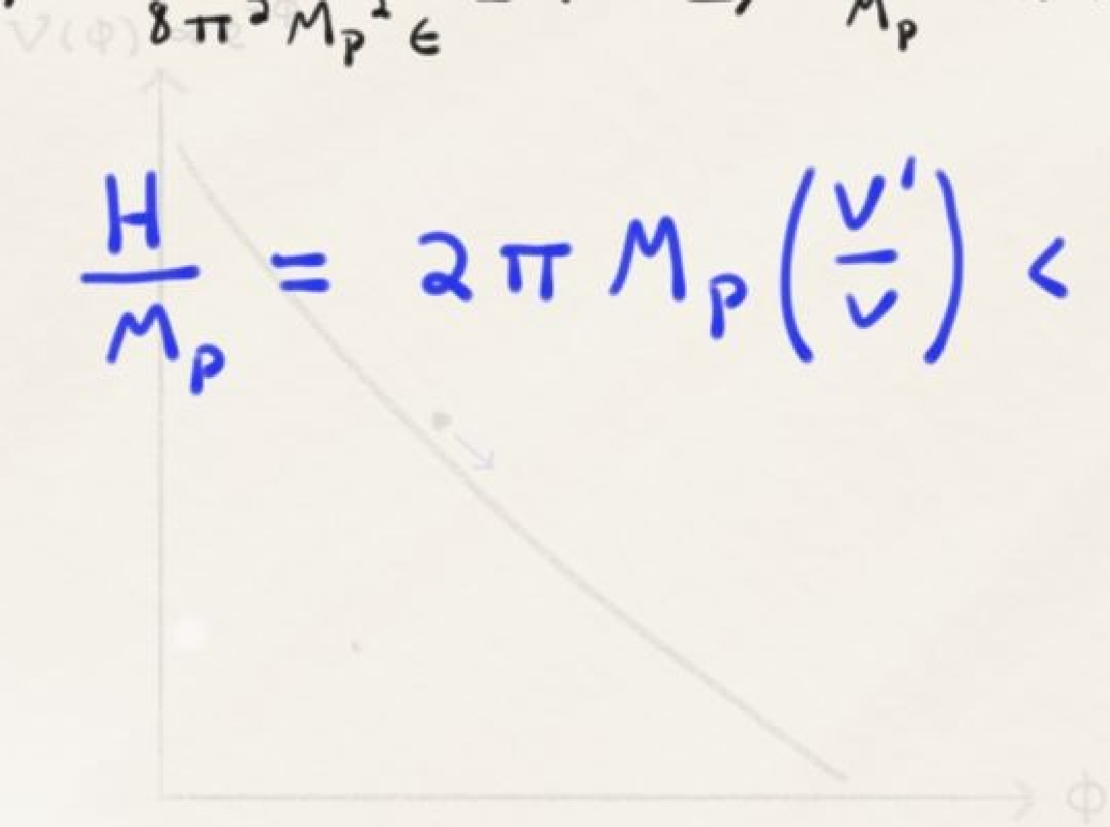


$$\frac{\langle \delta\phi \rangle_q}{\delta\phi_{cl}} = \frac{H^2}{2\pi\dot{\phi}} = P(k) > 1$$

$$P(k) = \frac{H^2}{8\pi^2 M_p^2 \epsilon} = 1 \quad \Rightarrow \quad \frac{H}{M_p} = 2\pi\sqrt{2\epsilon}$$

Eternal Inflation and the Swampland

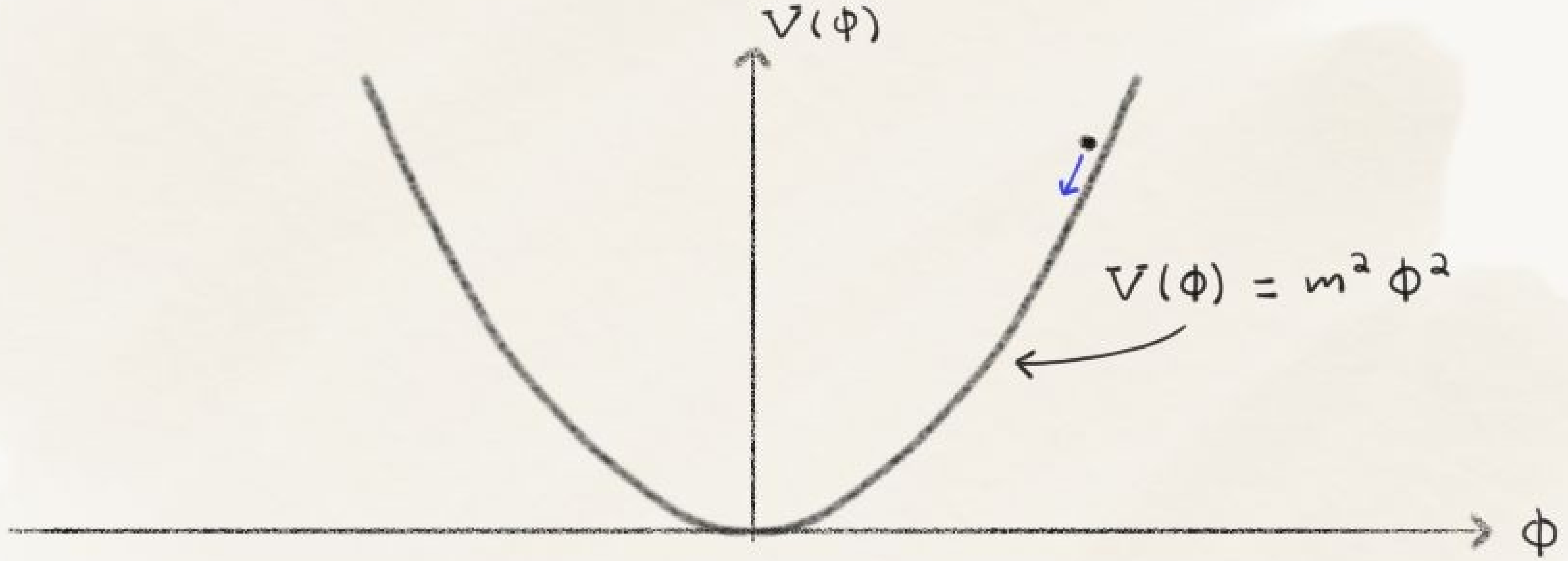
$$P(k) = \frac{H^2}{8\pi^2 M_p^2 \epsilon} = 1 \quad \Rightarrow \quad \frac{H}{M_p} = 2\pi\sqrt{2\epsilon}$$



$$\frac{H}{M_p} = 2\pi M_p \left(\frac{V'}{V}\right) < 1$$

Matsui & Takahashi [arXiv:1807.11938]

Chaotic Inflation



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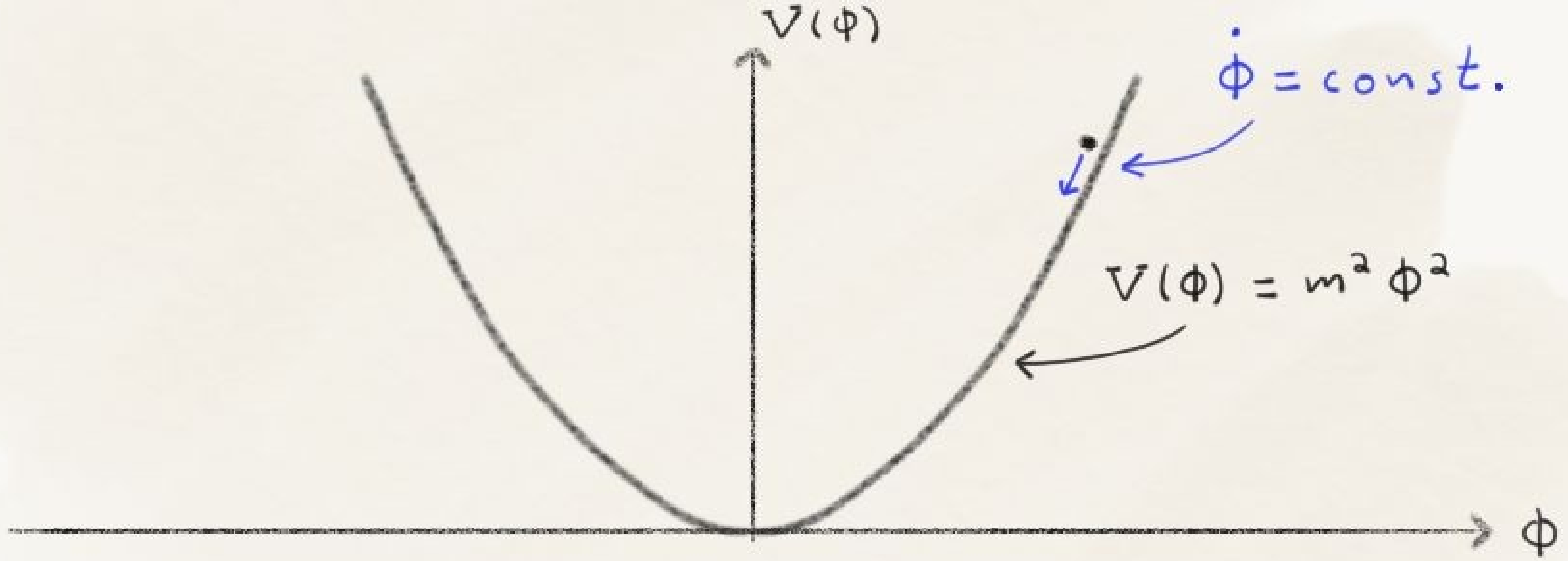

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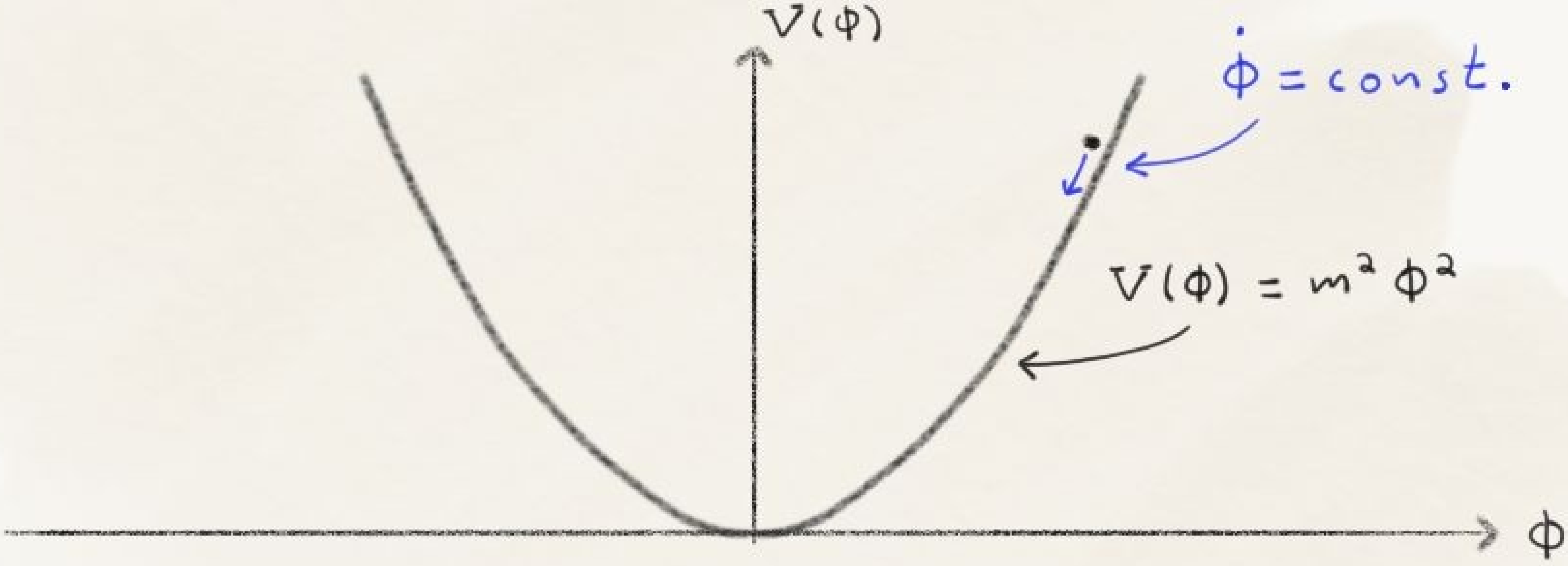
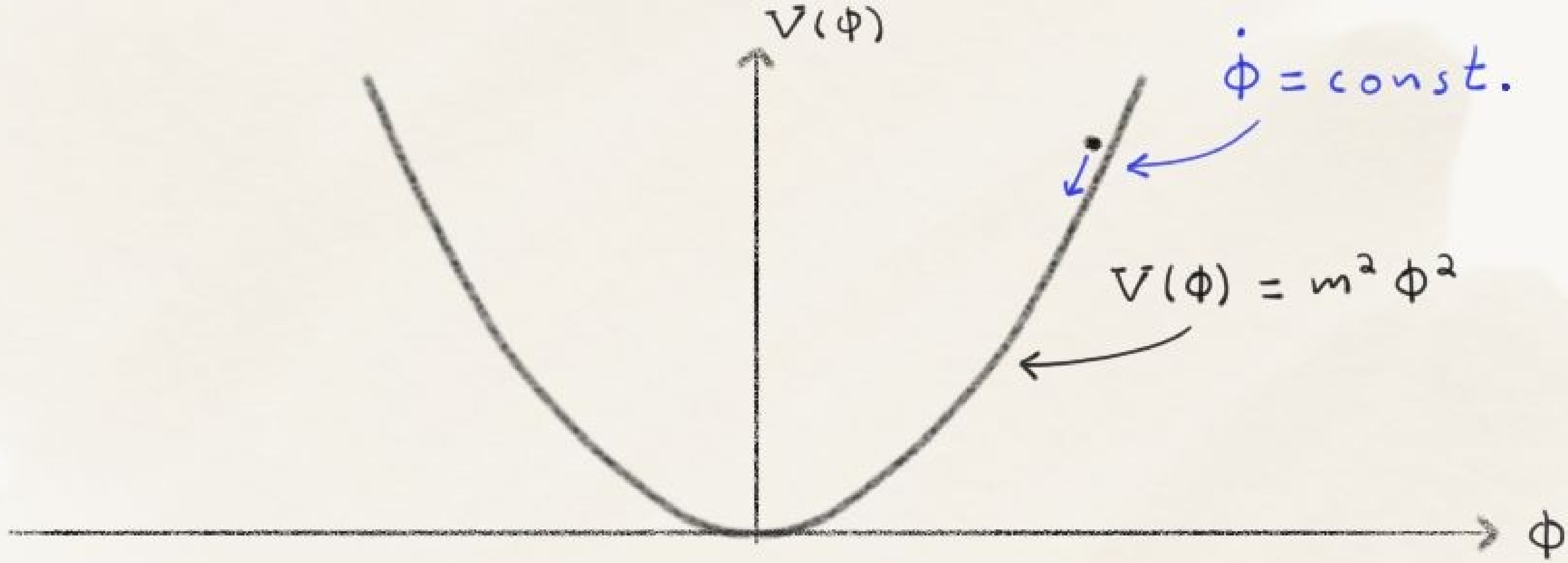


$$P(k) = \frac{H^4}{4\pi^2 \dot{\phi}^2}$$

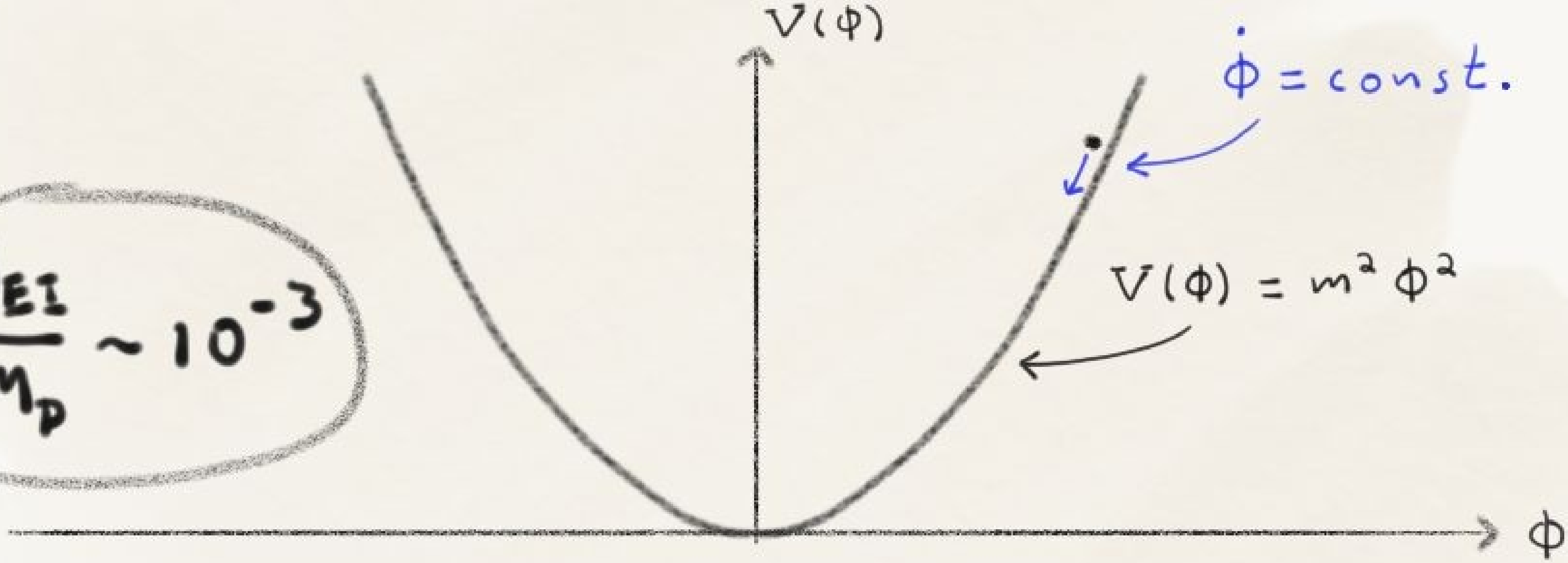
Chaotic Inflation



$$P(k) = \frac{H^4}{4\pi^2 \dot{\phi}^2} \Rightarrow \frac{H_{eI}}{H_*} = \frac{1}{[P(k_*)]^{1/4}} \sim 10^2$$

Chaotic Inflation

$$\frac{H_{EI}}{M_p} \sim 10^{-3}$$



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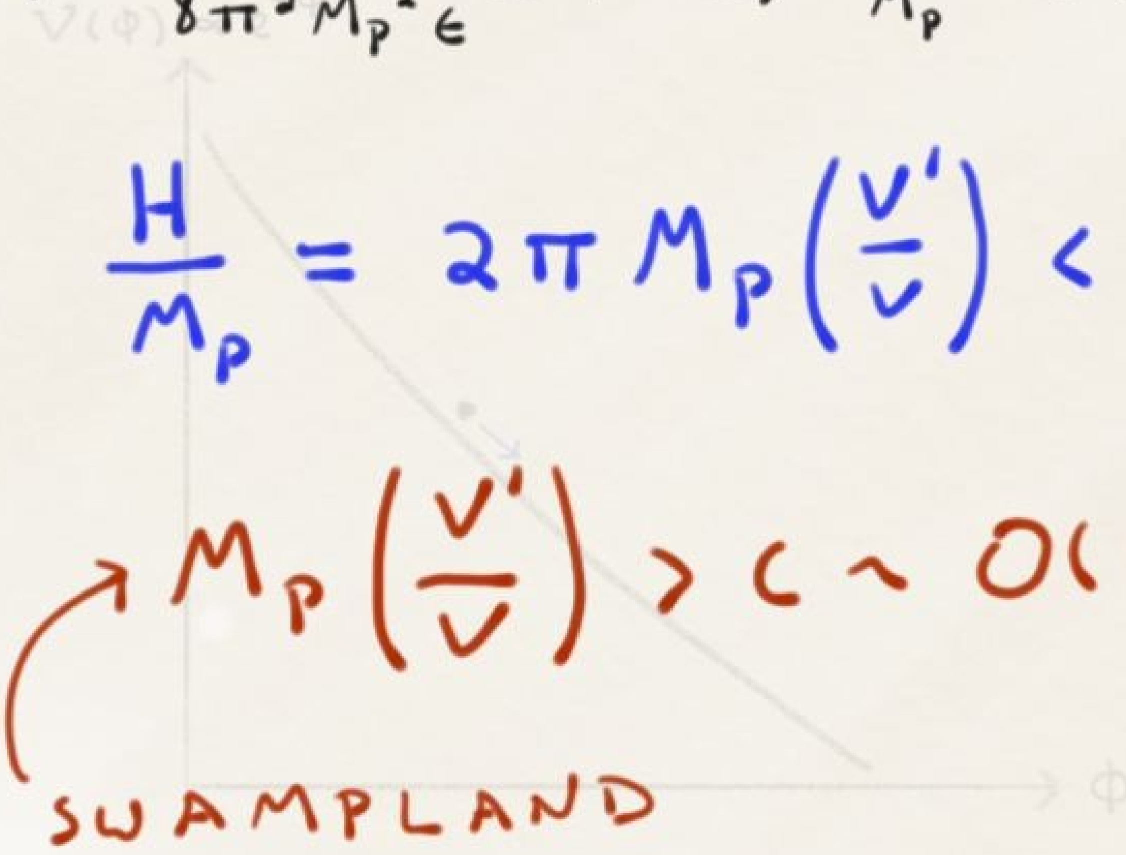
Eternal Inflation and the Swampland

$$P(k) = \frac{H^2}{8\pi^2 M_p^2 \epsilon} = 1 \quad \Rightarrow \quad \frac{H}{M_p} = 2\pi\sqrt{2\epsilon}$$

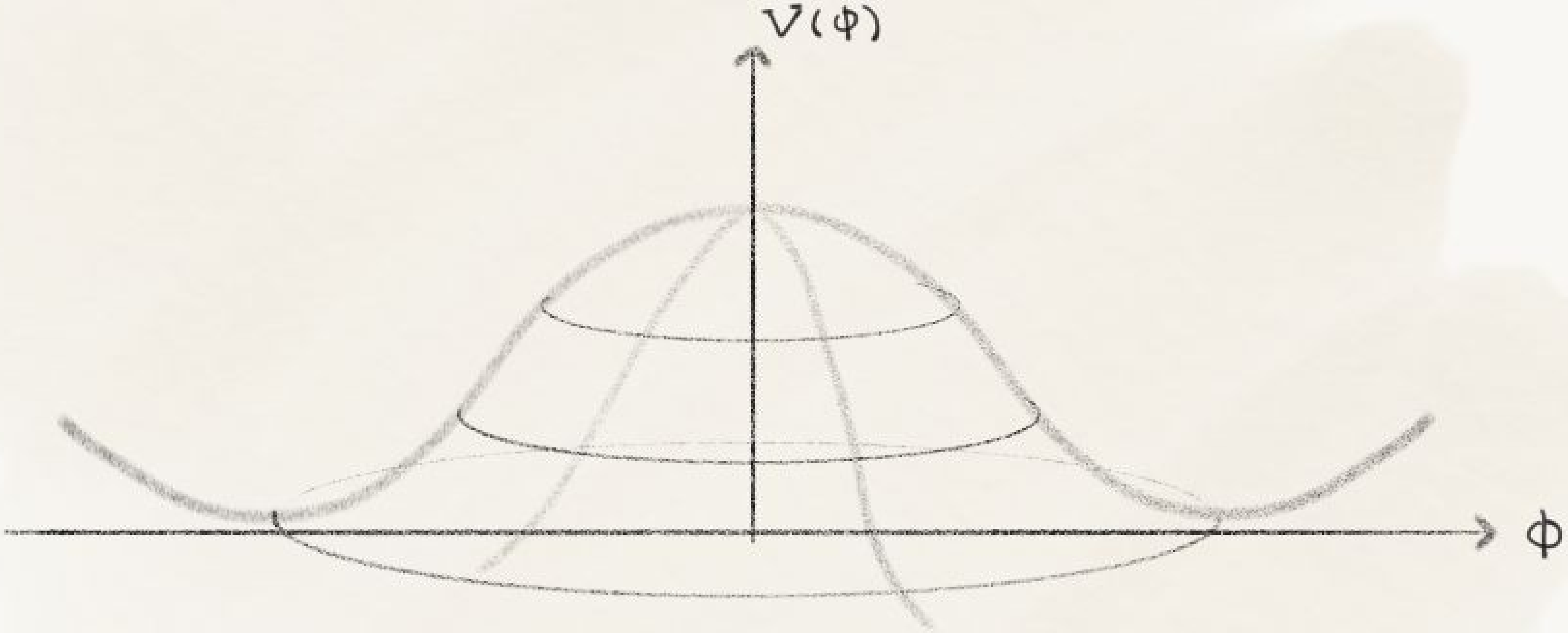
$$\frac{H}{M_p} = 2\pi M_p \left(\frac{V'}{V}\right) < 1$$

$$M_p \left(\frac{V'}{V}\right) > c \sim O(1)$$



Matsui & Takahashi [arXiv:1807.11938]

What about symmetry breaking?



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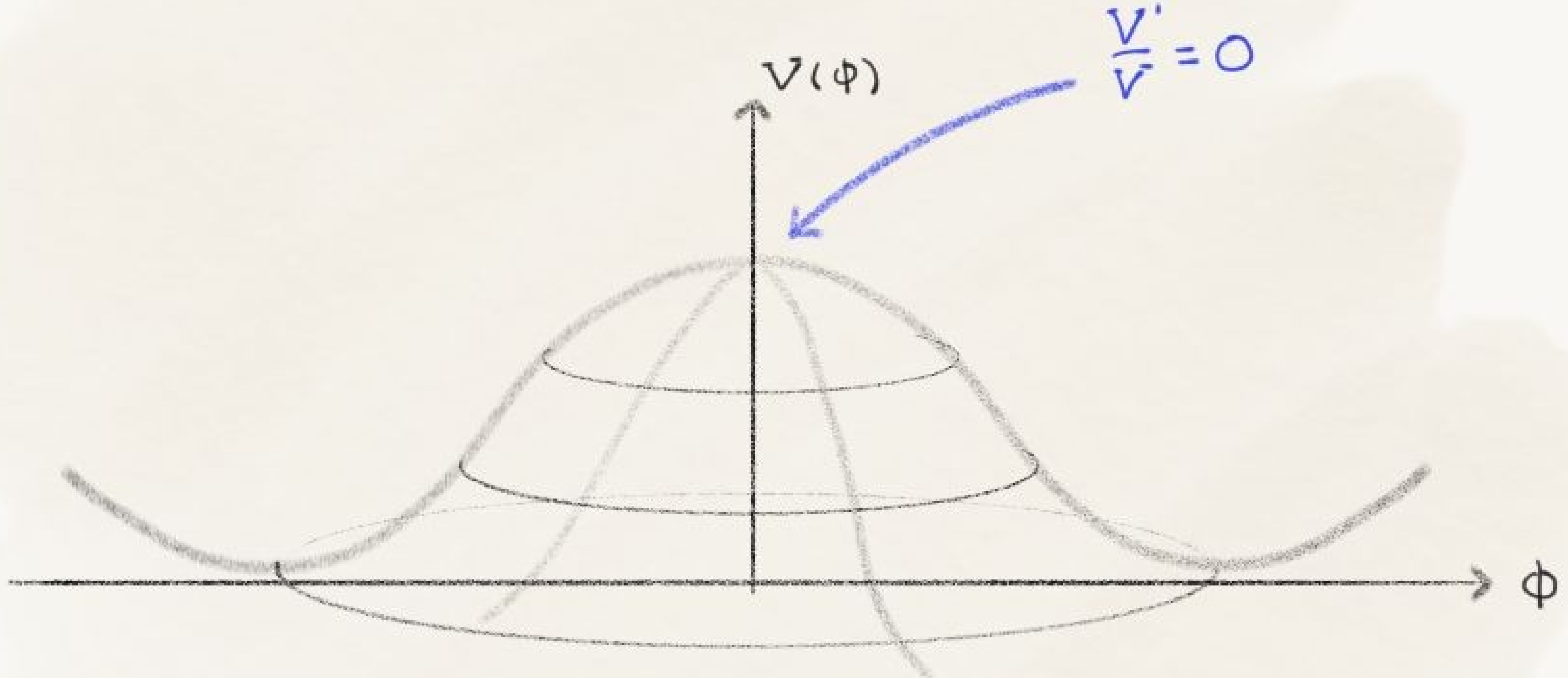
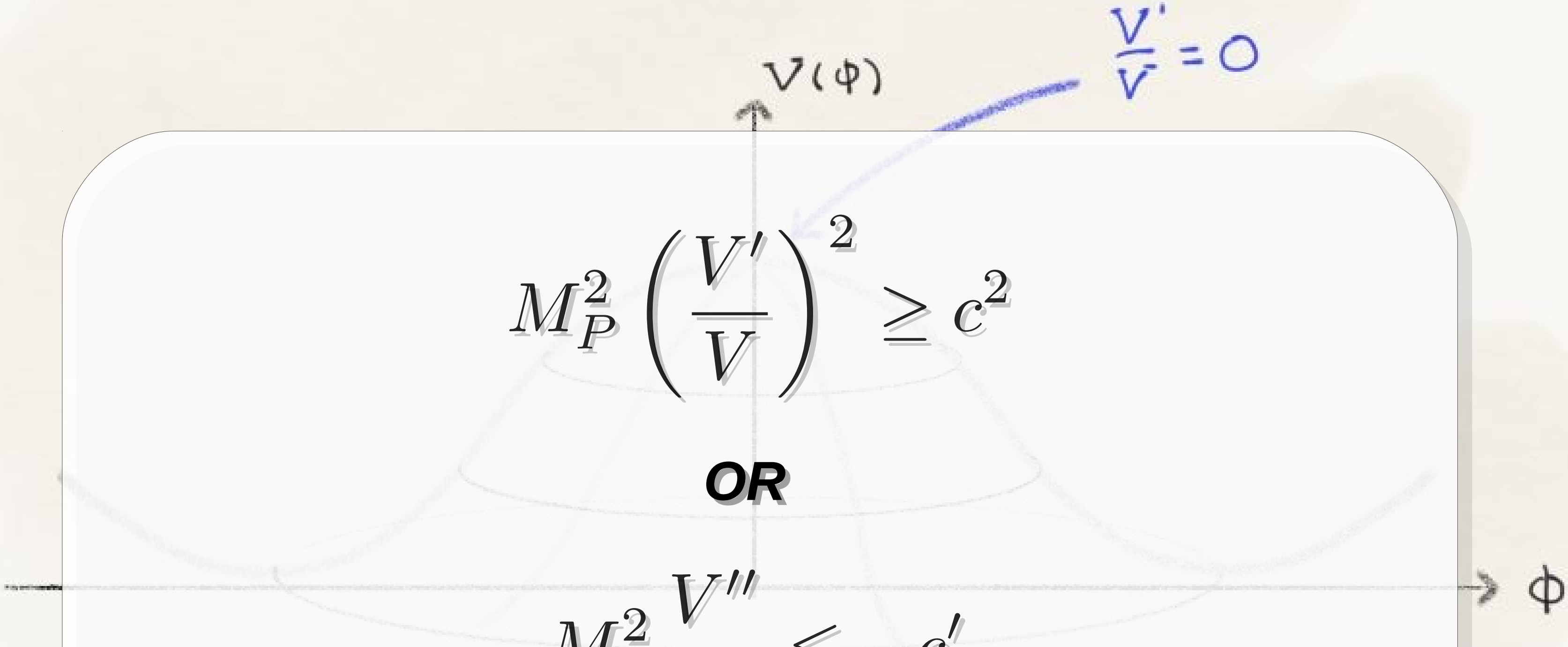


The Refined Swampland Conjecture



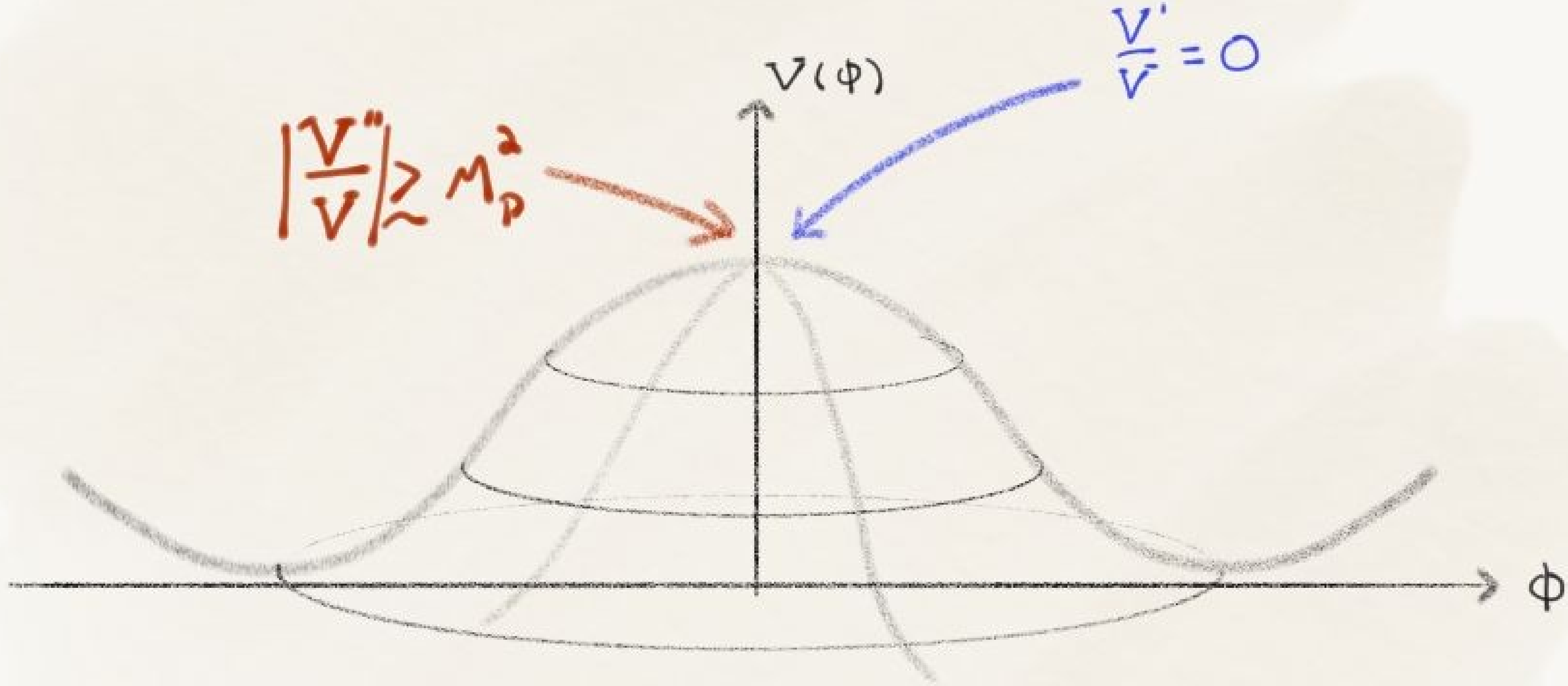
$$M_P^2 \left(\frac{V'}{V}\right)^2 \geq c^2$$

OR

$$M_P^2 \frac{V''}{V} \leq -c'$$

Ooguri, Palti, Shiu, Vafa [arXiv:1810.05506]

The *Refined* Swampland Conjecture



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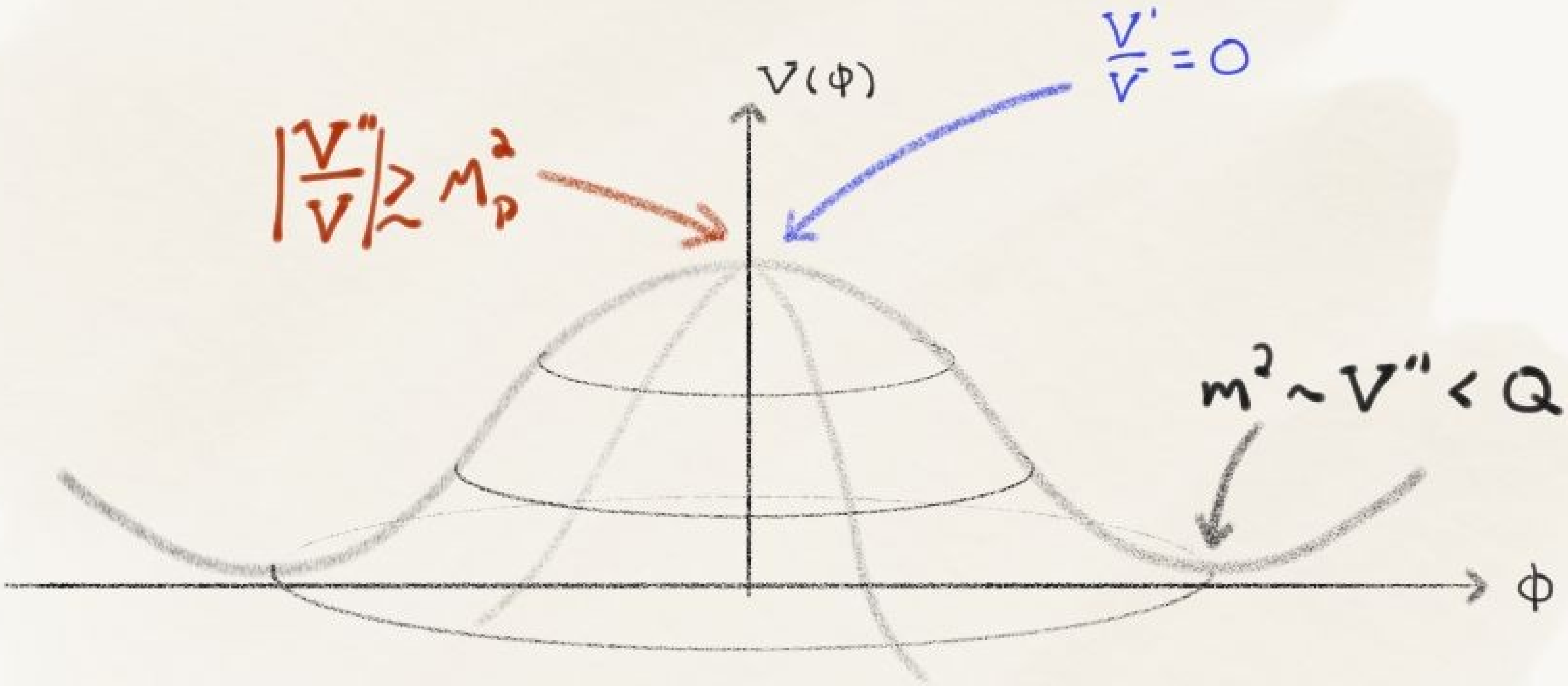

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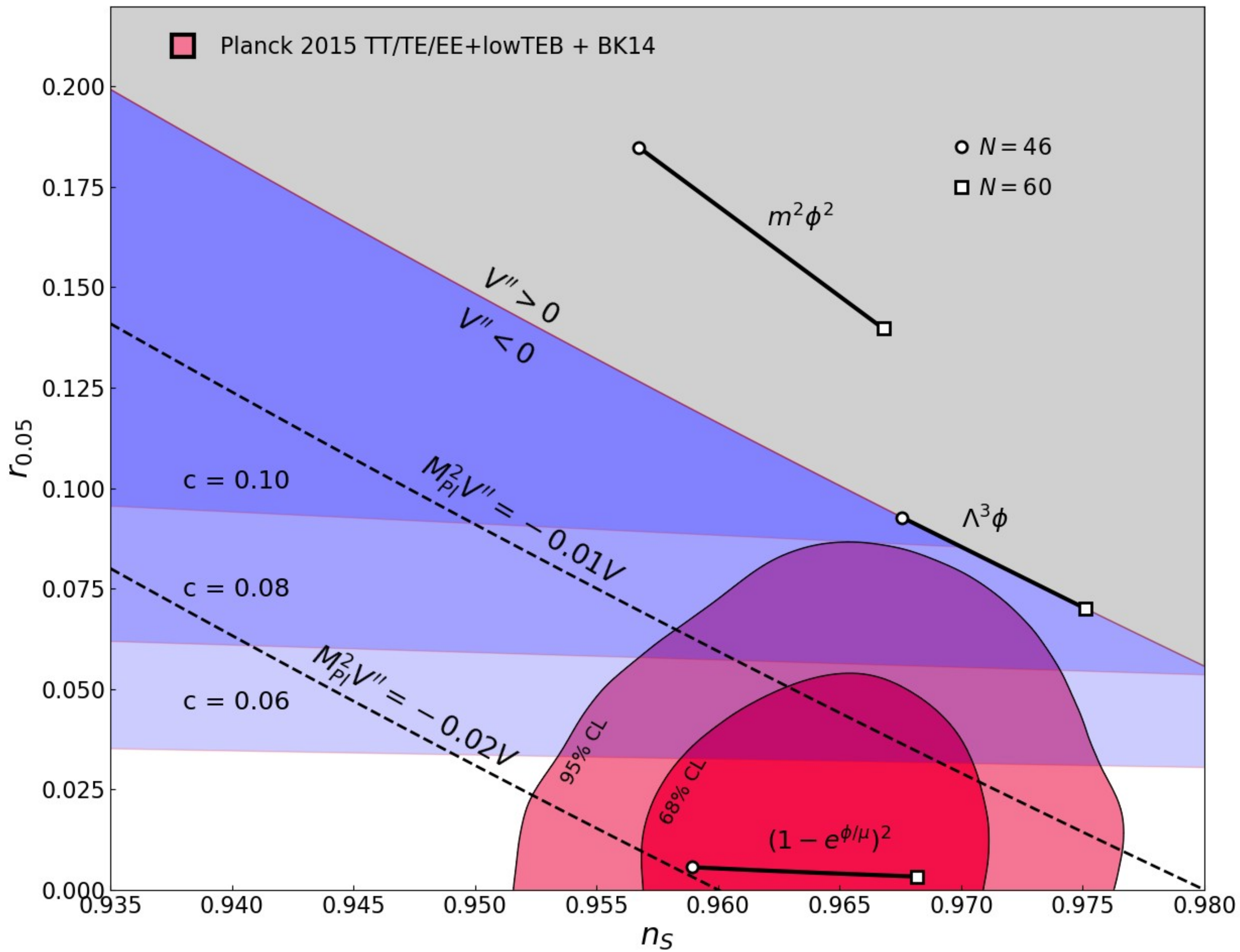

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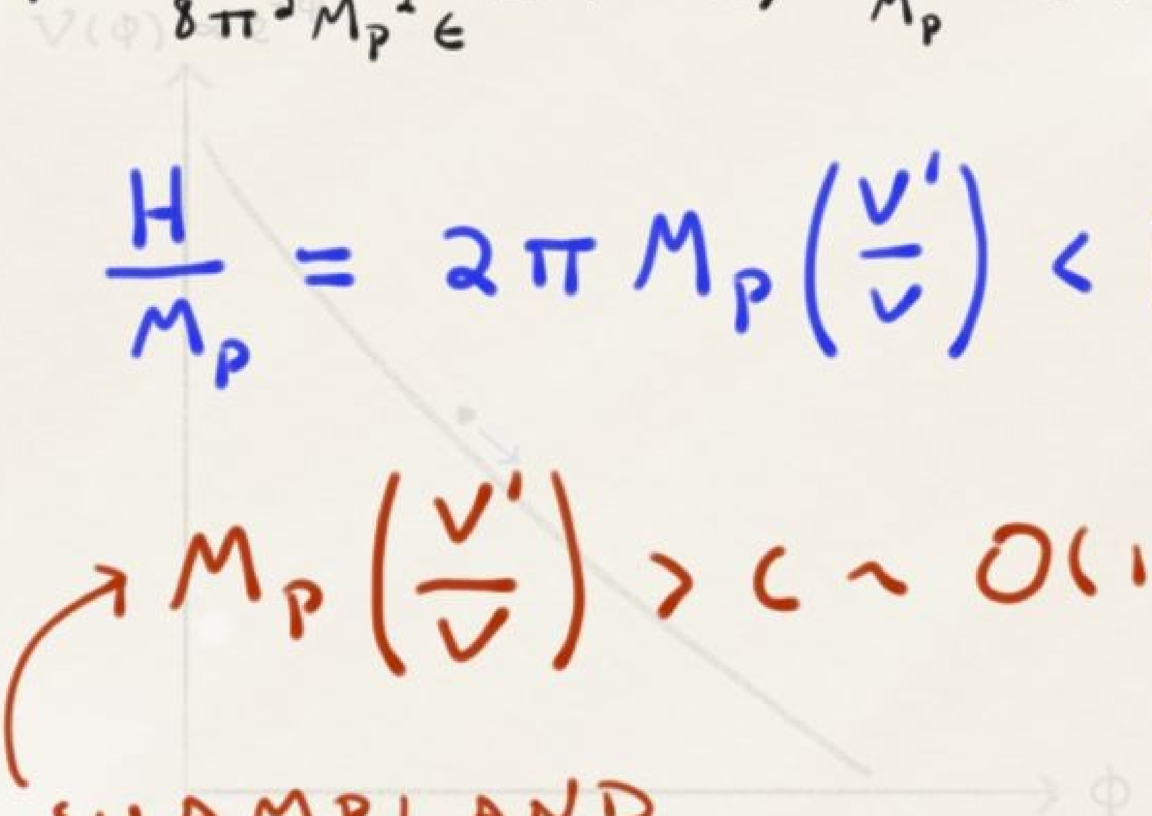

$$\frac{H}{M_p} = 2\pi M_p \left(\frac{V'}{V}\right) < 1$$

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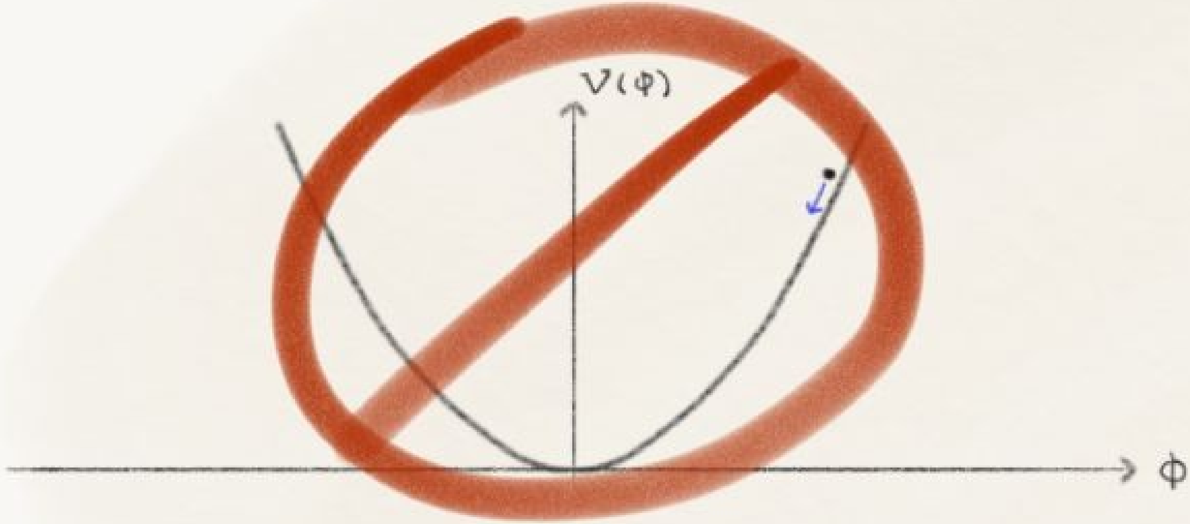
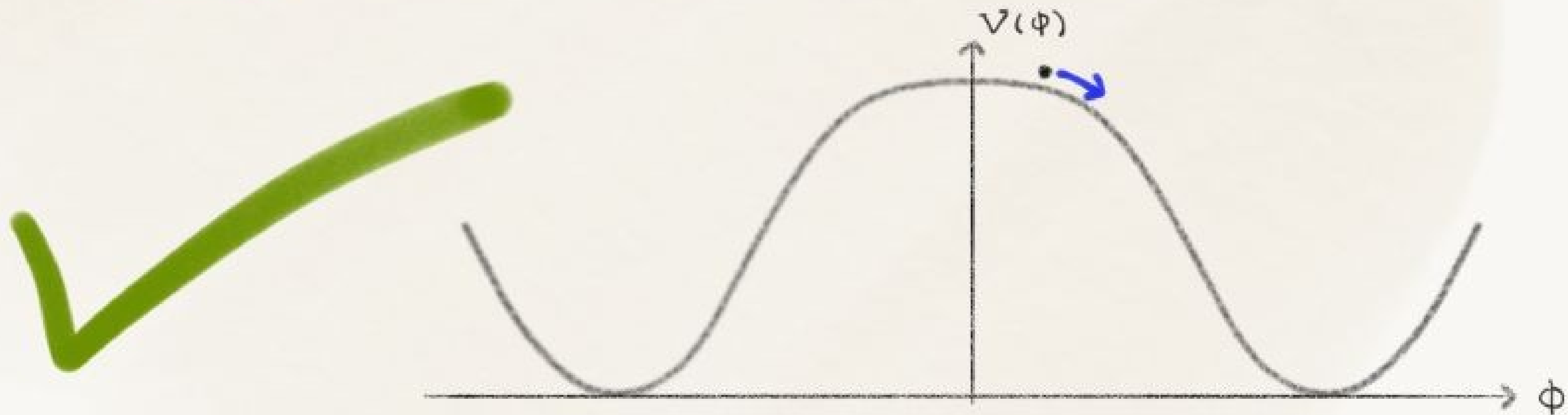
SWAMPLAND

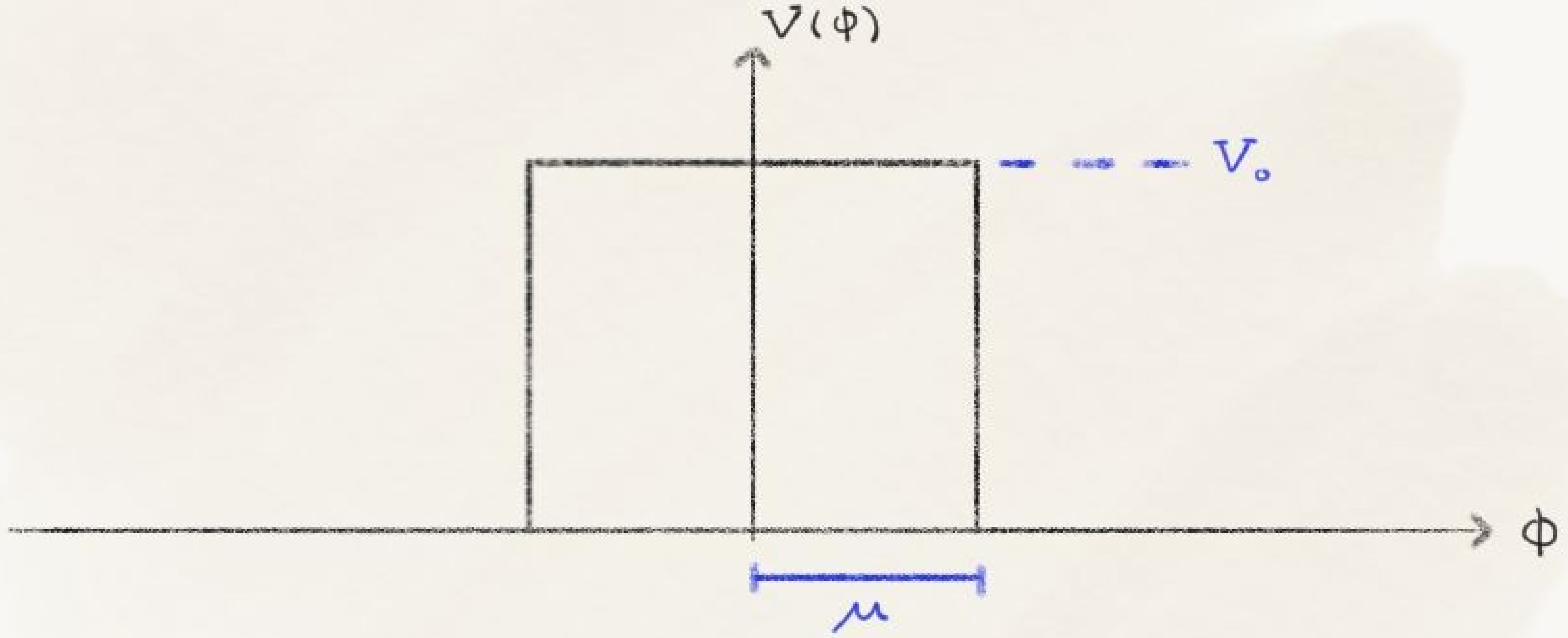
Matsui & Takahashi [arXiv:1807.11938]

Convex or Concave?





Top-Hat Potentials



Barenboim, WHK, Park, [arXiv:1601.08140]

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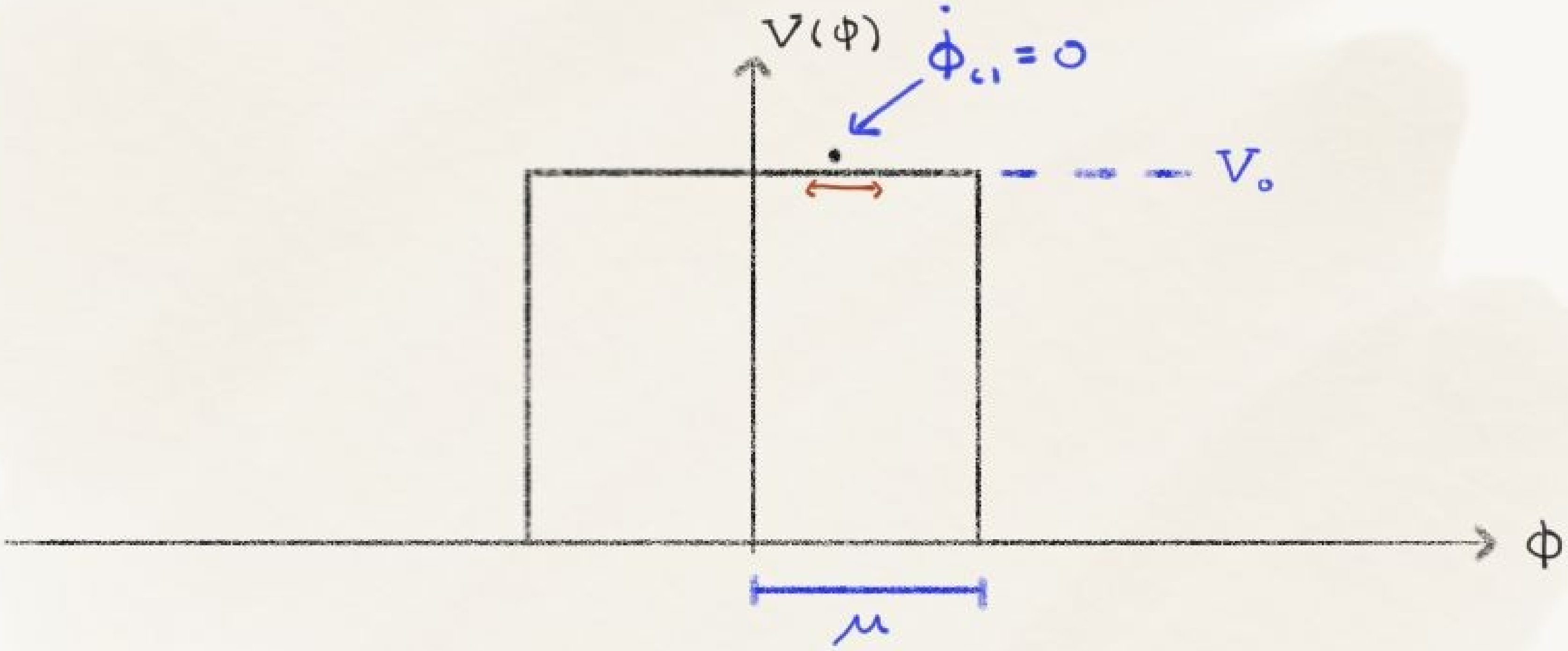

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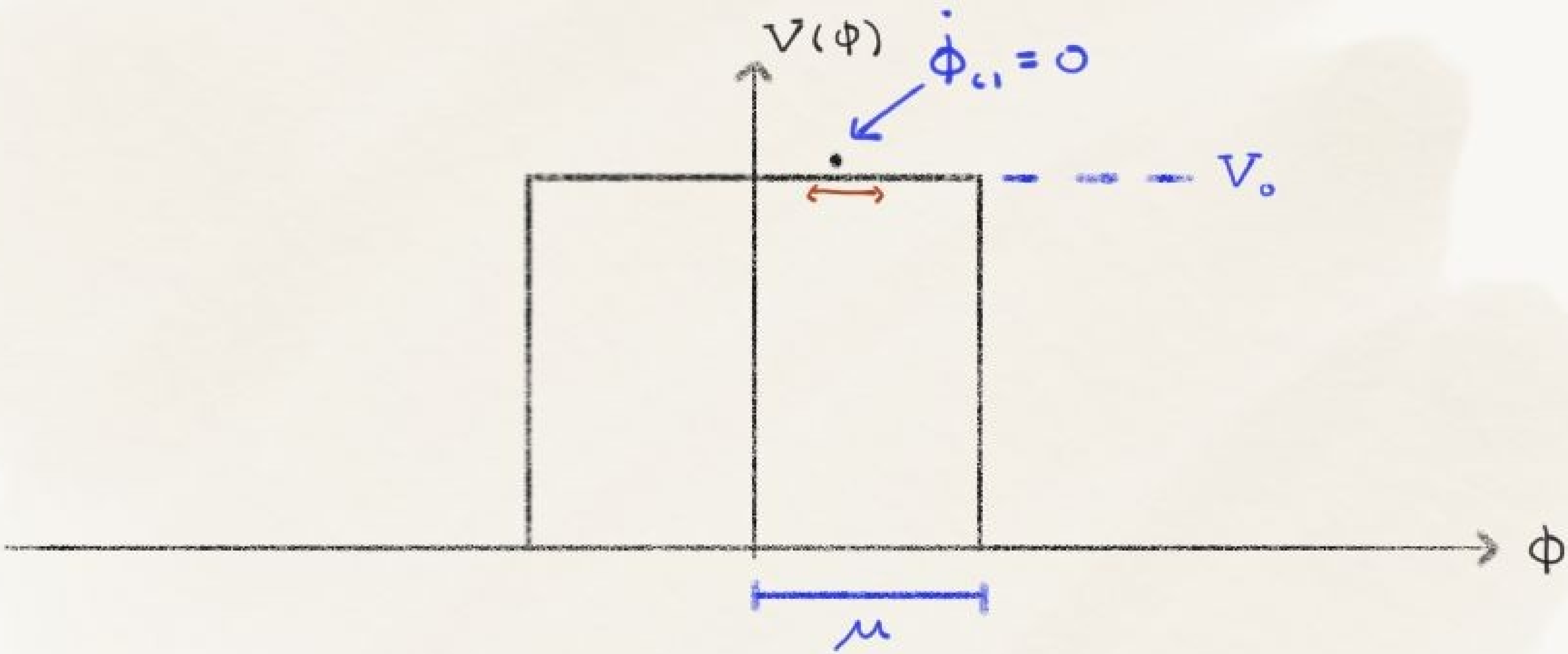
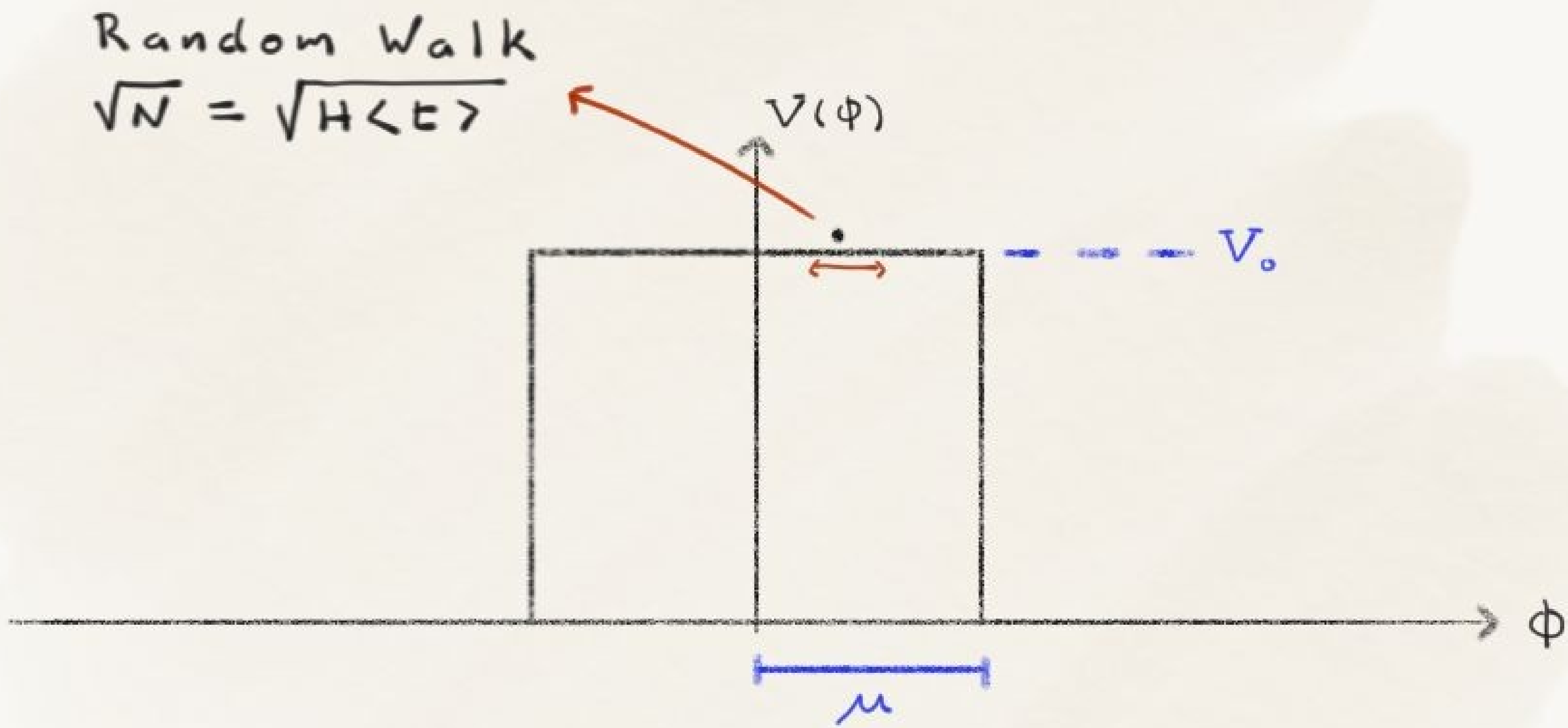


$$P(k) = \frac{H^2}{2\pi \dot{\phi}} \longrightarrow \infty$$

Barenboim, WHK, Park, [arXiv:1601.08140]

Top-Hat Potentials



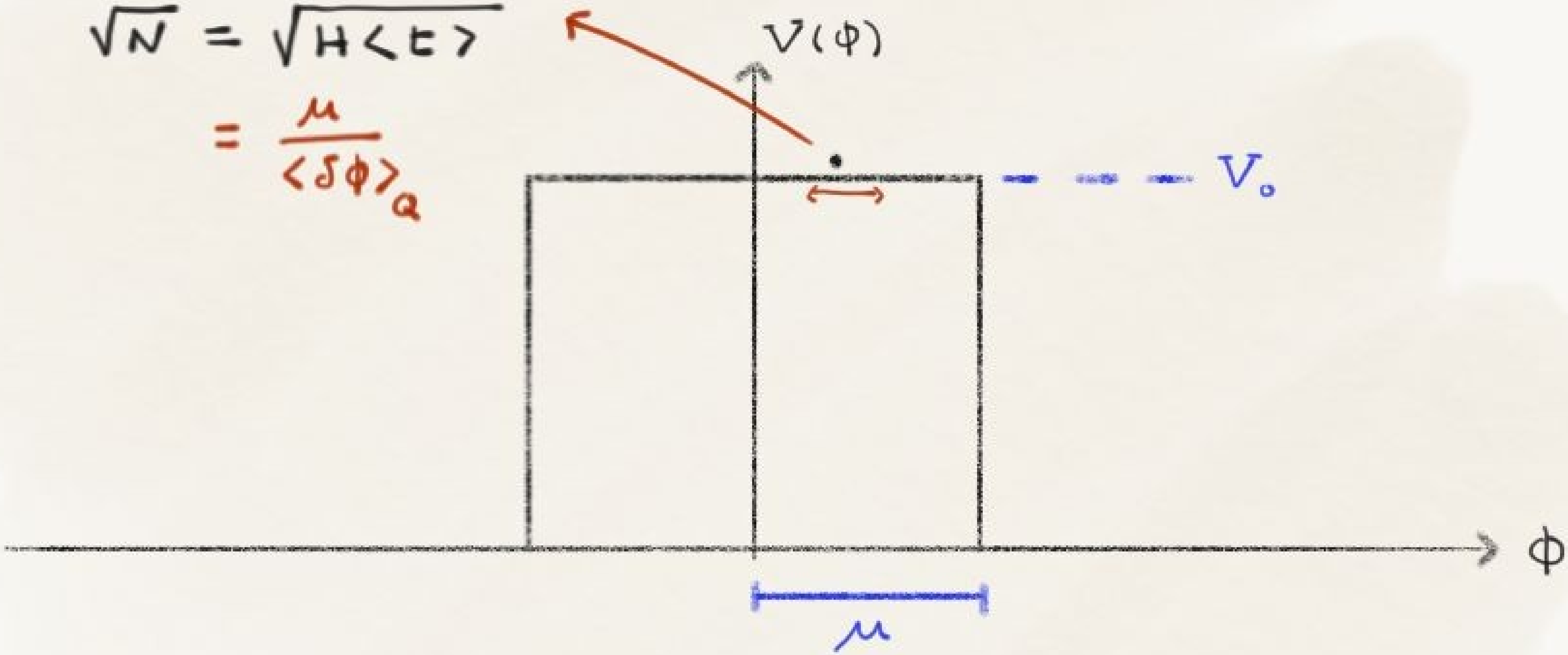
Barenboim, WHK, Park, [arXiv:1601.08140]

Top-Hat Potentials

Random Walk

$$\sqrt{N} = \sqrt{H\langle t\rangle}$$

$$= \frac{\mu}{\langle\delta\phi\rangle_Q}$$



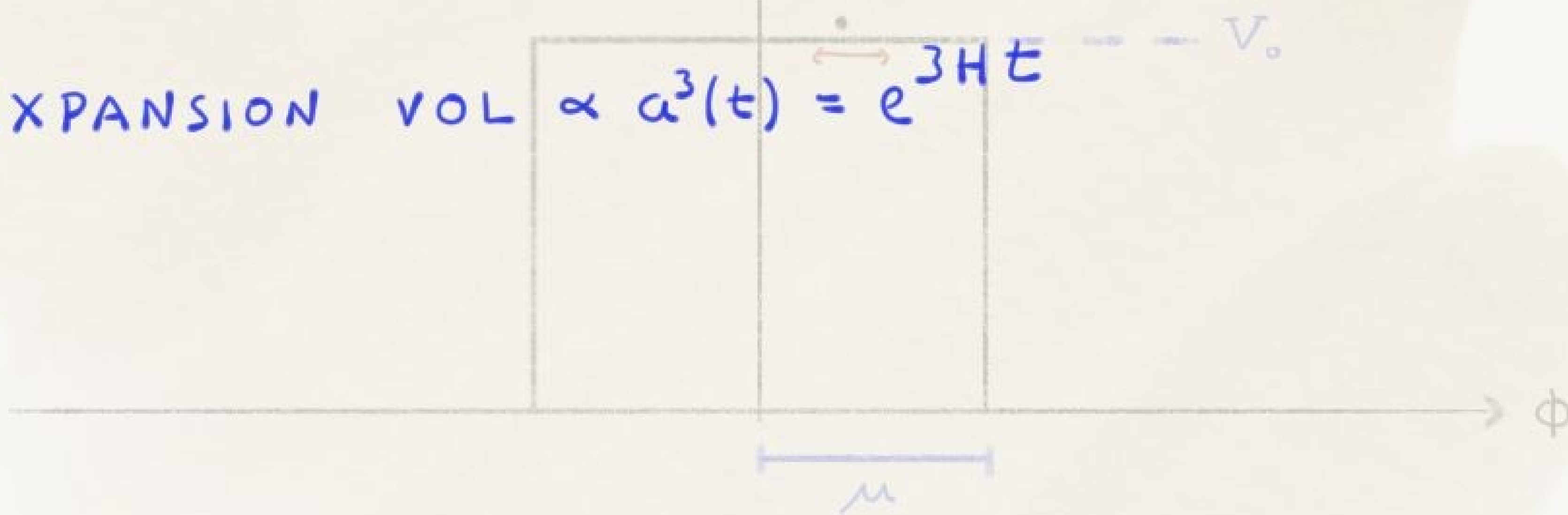
$$\Gamma_I \propto e^{-t/\langle t\rangle} = \exp\left[-\left(\frac{\langle\delta\phi\rangle_Q}{\mu}\right)^2 H t\right]$$

↑ PROBABILITY THAT INFLATION ENDS IN TIME t

Top-Hat Potentials

$$\Gamma_I \propto e^{-t/\langle t \rangle} = \exp\left[-\left(\frac{\langle \delta\phi \rangle_Q}{\mu}\right)^2 H t\right]$$

EXPANSION VOL $\propto a^3(t) = e^{3Ht}$



Barenboim, WHK, Park, [arXiv:1601.08140]

Top-Hat Potentials

$$\Gamma_I \propto e^{-t/\langle t\rangle} = \exp\left[-\left(\frac{\langle\delta\phi\rangle_Q}{\mu}\right)^2 H t\right]$$

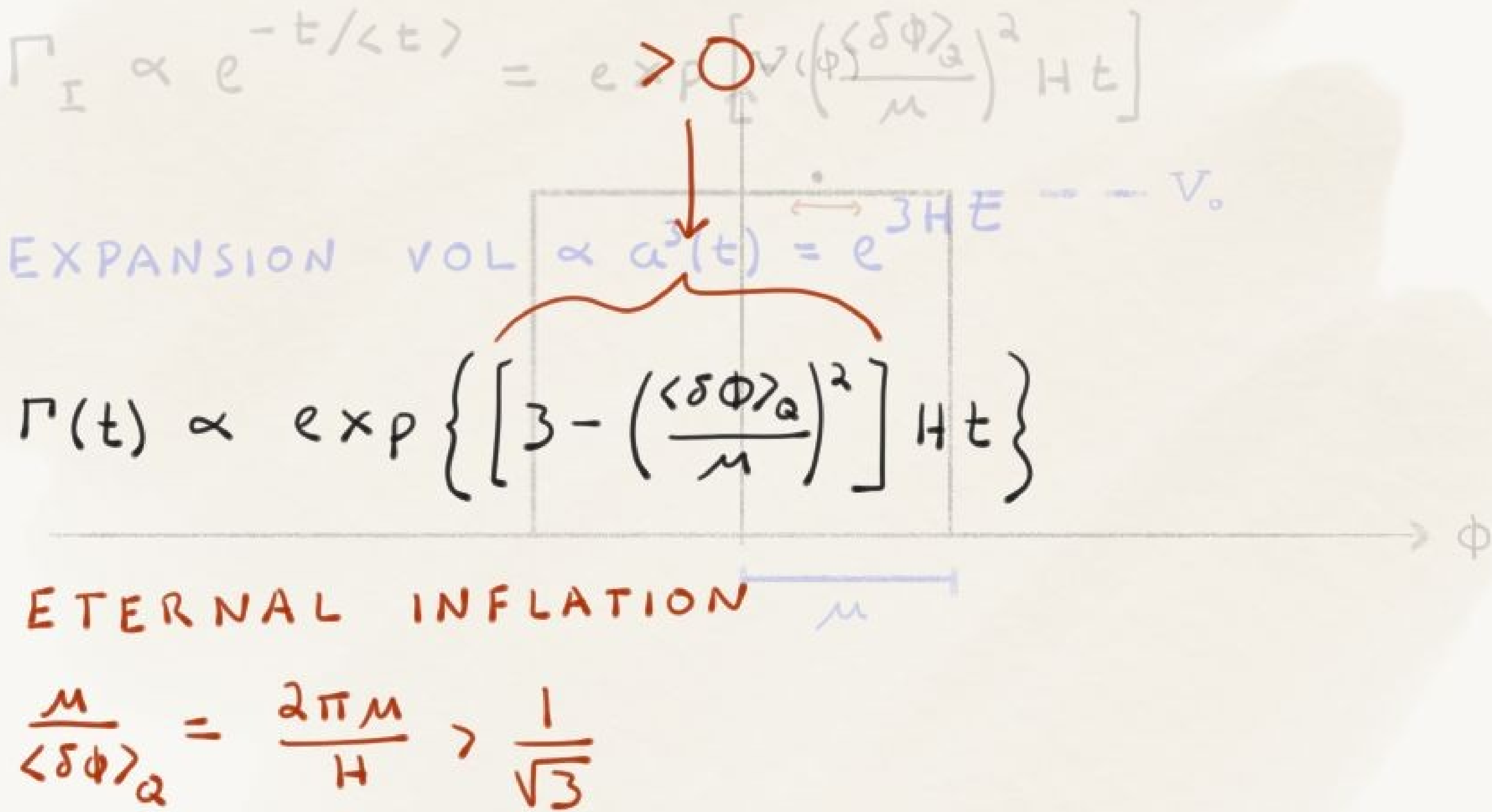
EXPANSION VOL $\propto a^3(t) = e^{3Ht}$

$$\Gamma(t) \propto \exp\left\{\left[3-\left(\frac{\langle\delta\phi\rangle_Q}{\mu}\right)^2\right] H t\right\}$$

↑ FRACTION OF HUBBLE PATCHES IN DE SITTER PHASE

Barenboim, WHK, Park, [arXiv:1601.08140]

Top-Hat Potentials



Barenboim, WHK, Park, [arXiv:1601.08140]

Top-Hat Potentials

$$\Gamma_I \propto e^{-t/\langle t \rangle} = \exp\left[V(\phi) \left(\frac{\langle \delta\phi \rangle_Q}{\mu} \right)^2 H t \right] \quad \to > 0$$

$\dot{\phi} \longleftrightarrow$ V_0

EXPANSION VOL $\propto a^3(t) = e^{3Ht}$

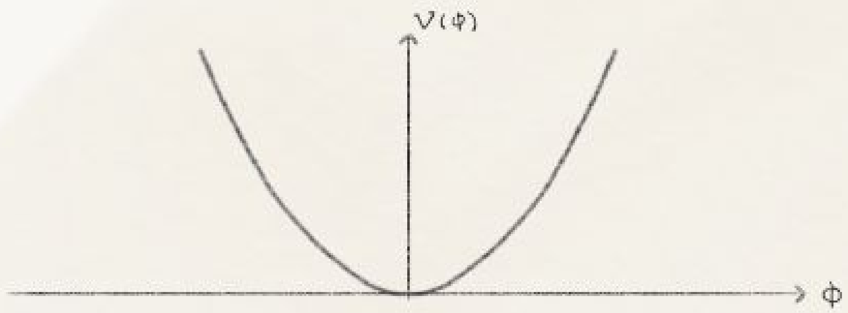
$$\Gamma(t) \propto \exp\left\{ \left[3 - \left(\frac{\langle \delta\Phi \rangle_Q}{\mu} \right)^2 \right] H t \right\}$$

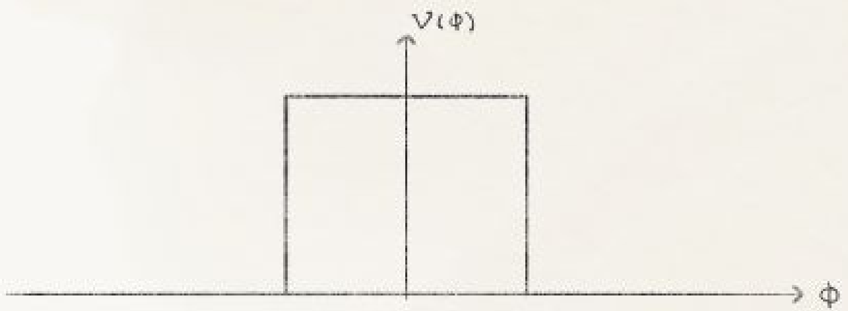
ϕ $\quad \mu$

ETERNAL INFLATION

$$\frac{\mu}{\langle \delta\phi \rangle_Q} = \frac{2\pi\mu}{H} > \frac{1}{\sqrt{3}} \Rightarrow \mu > \frac{\sqrt{V_0}}{6\pi M_p}$$

Two Qualitatively Different Types





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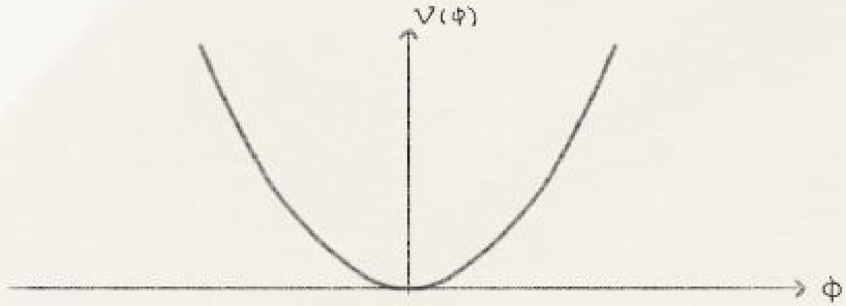

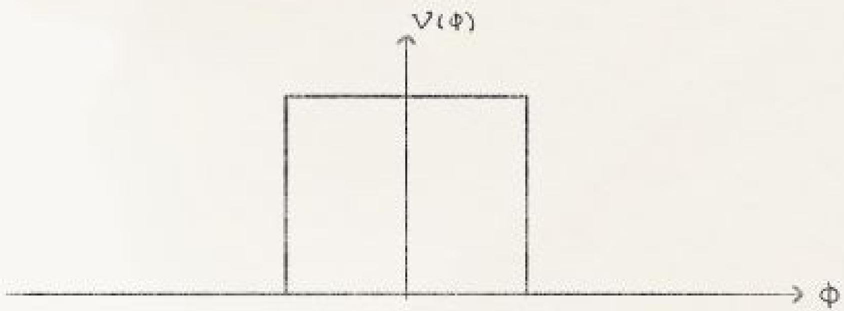

$\dot{\phi} \sim \text{const.}$

$H_{EI} \gg H_*$

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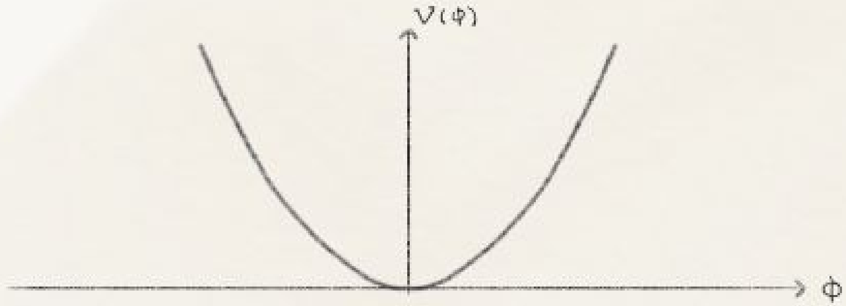

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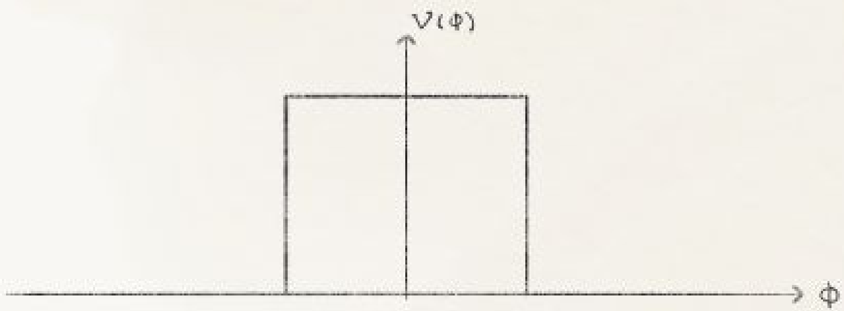

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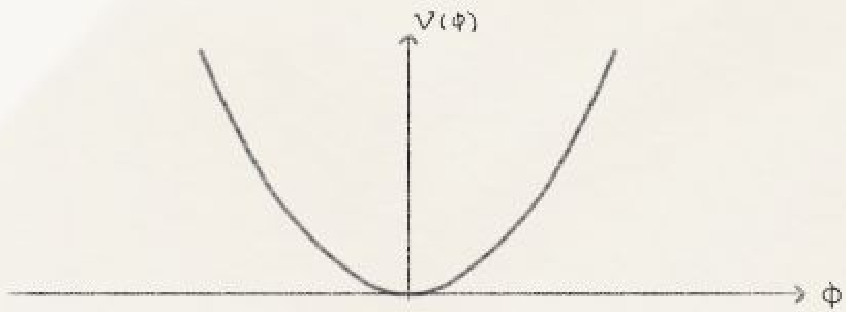

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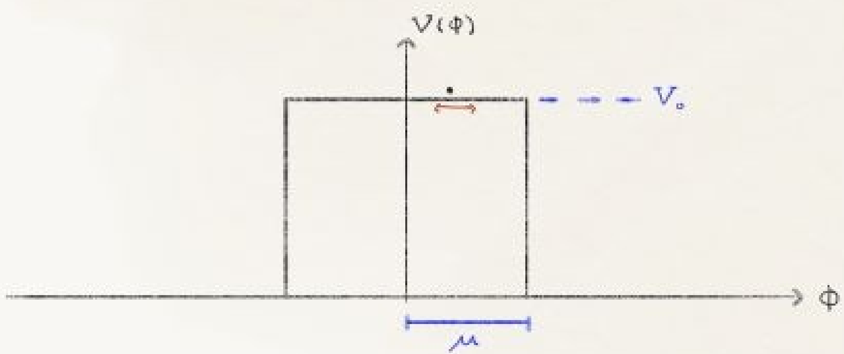

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$$V_0 \sim \Lambda^4 \quad \Rightarrow \quad \frac{\mu}{\Lambda} > \frac{\Lambda}{6\pi M_p}$$

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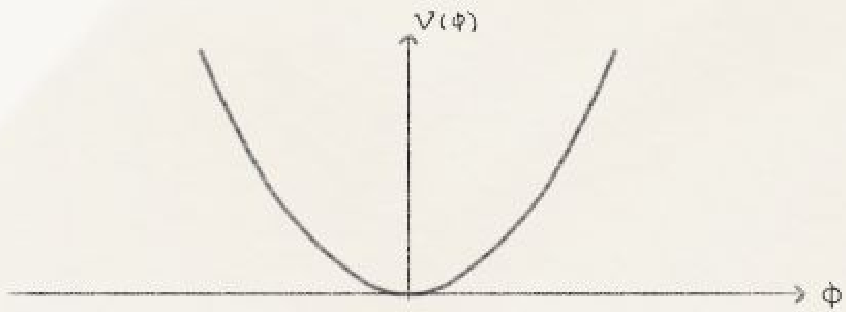

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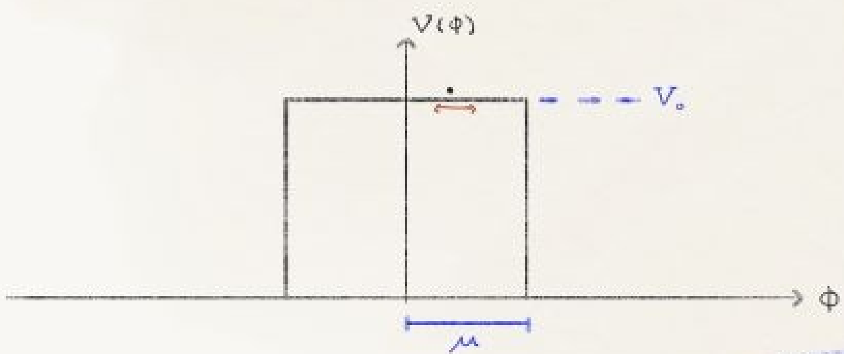

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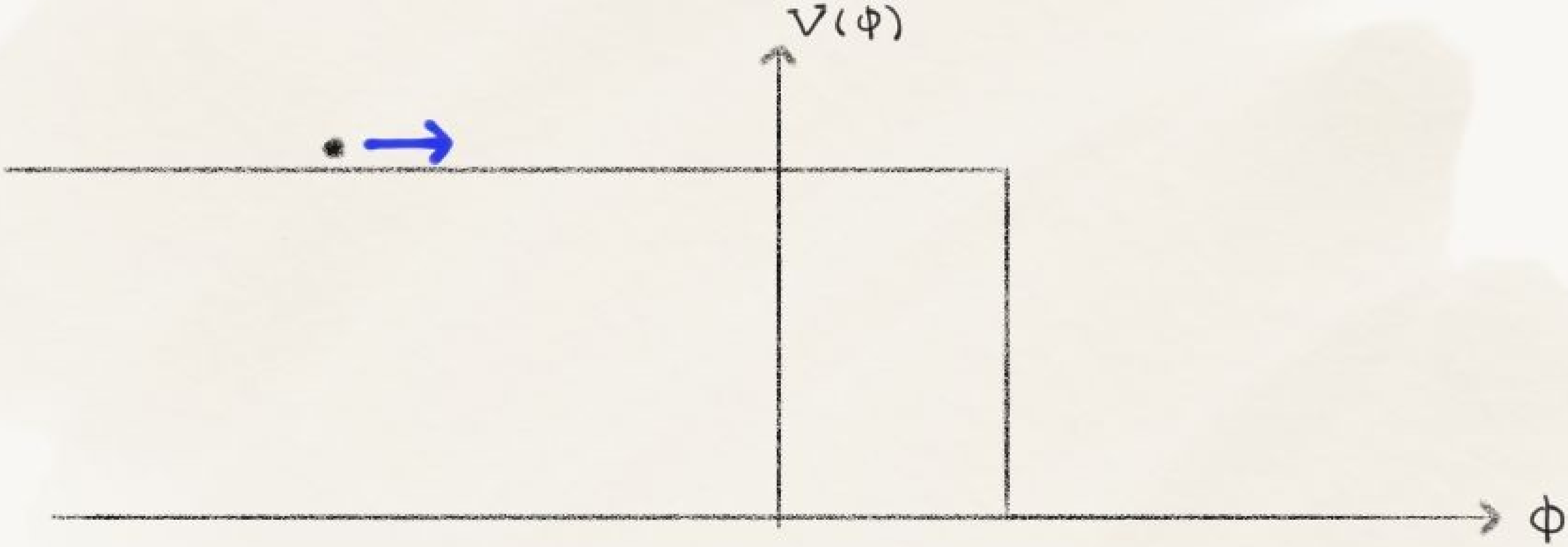
← NO INHERENT SCALE

Plateau Potentials (*e.g.* Starobinsky)



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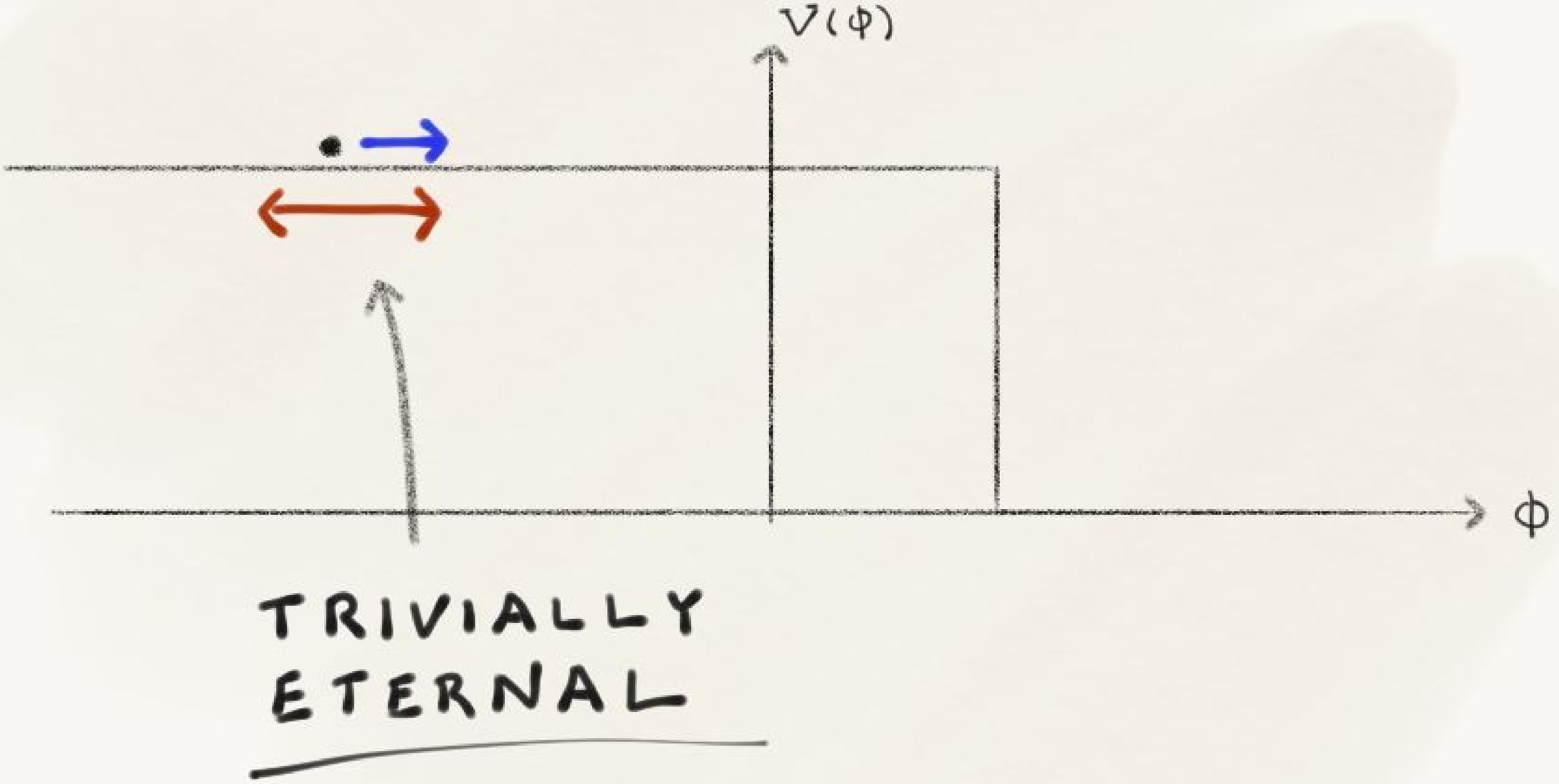
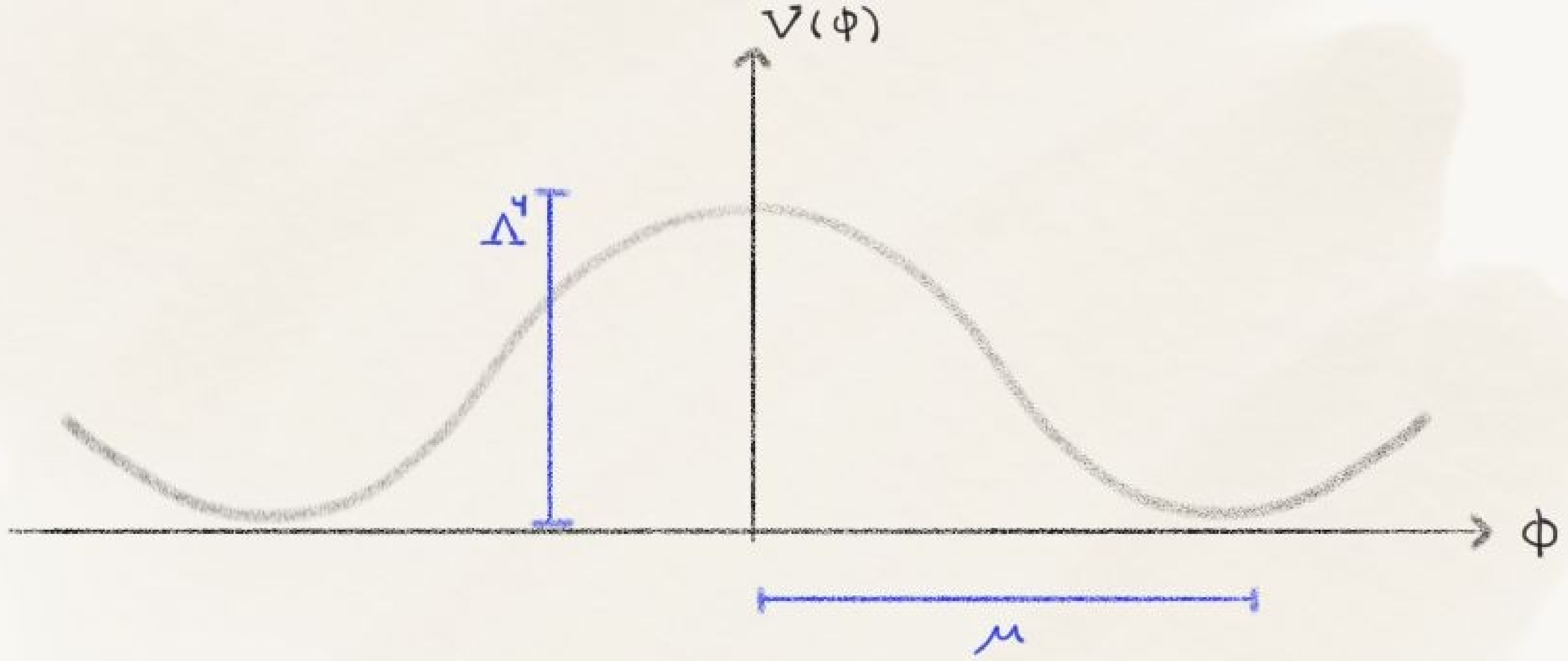
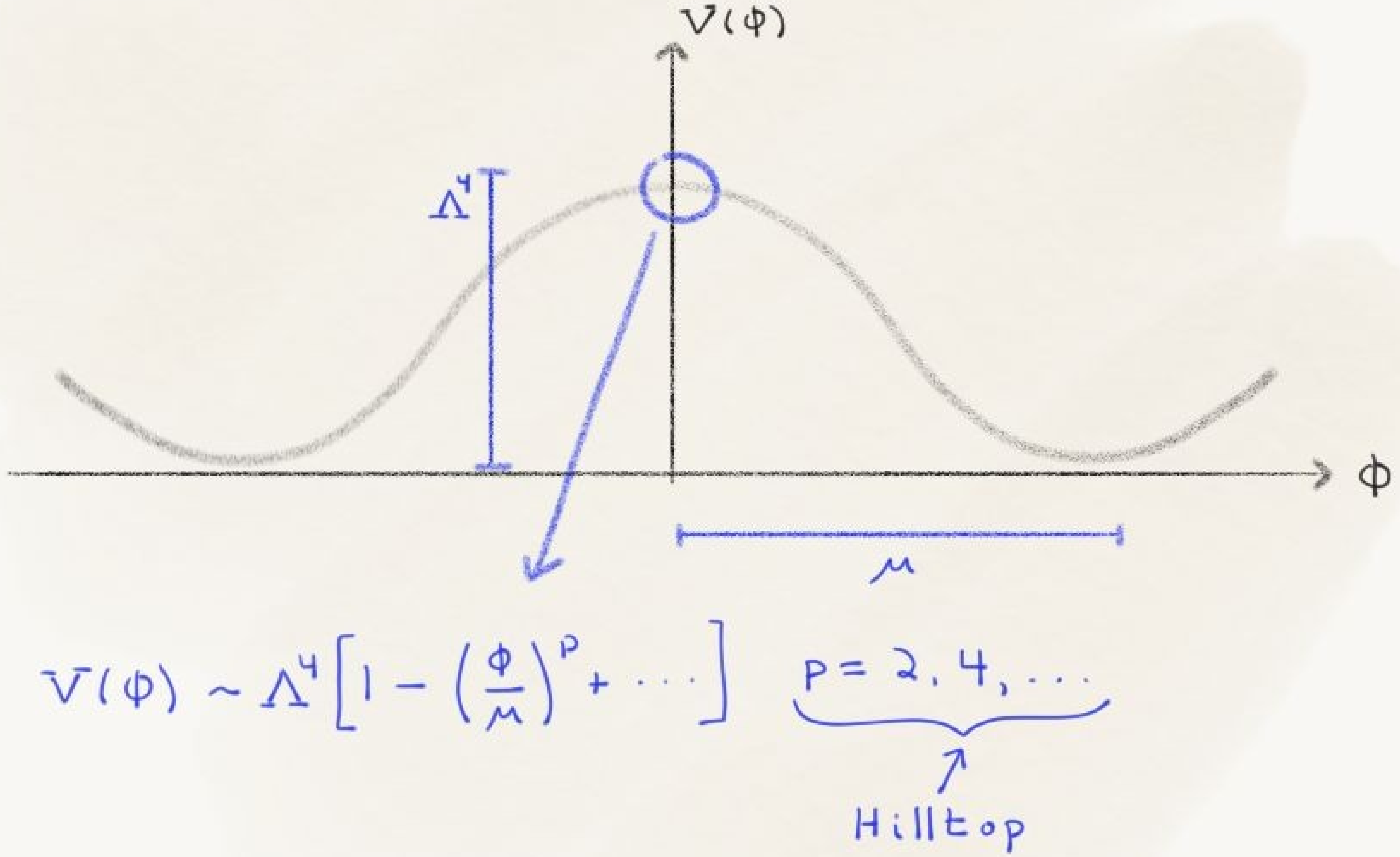


Hilltop Inflation



Barenboim, WHK, Park, [arXiv:1601.08140]

Hilltop Inflation



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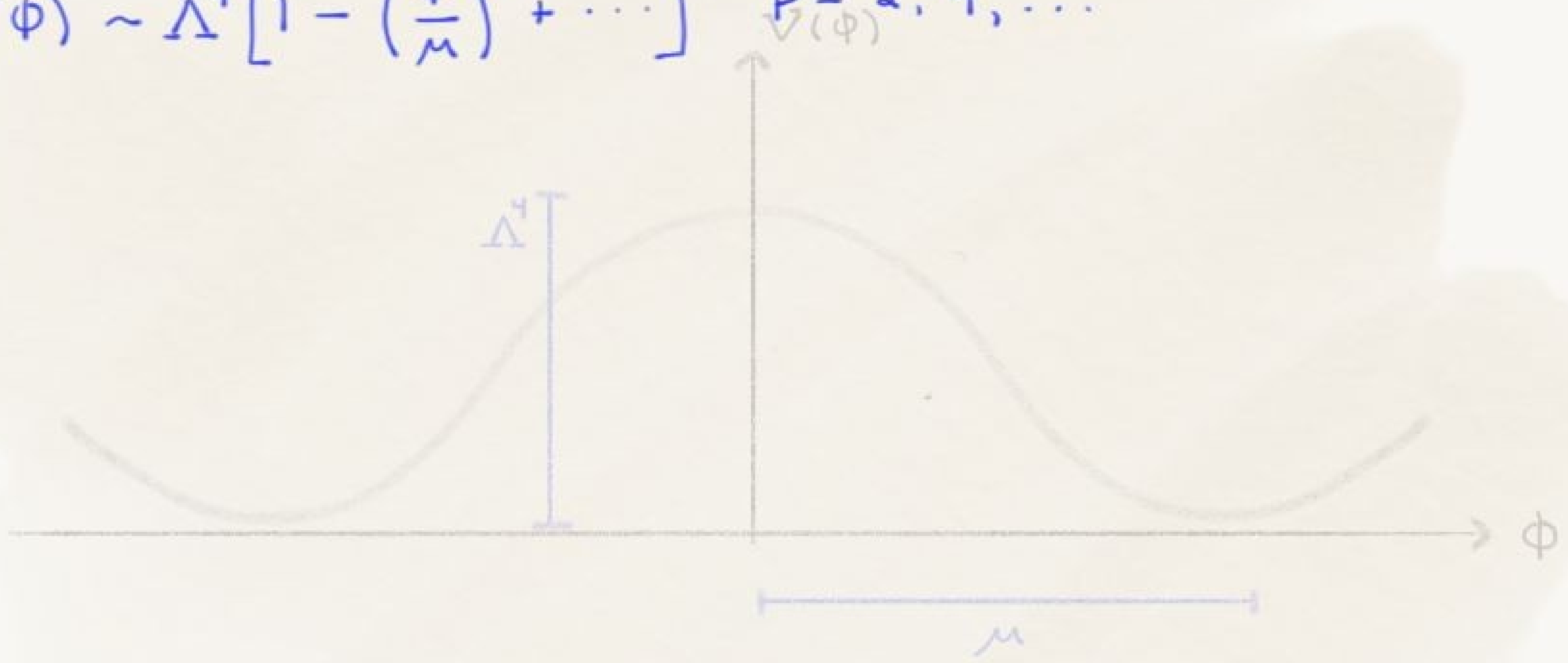
Hilltop Inflation

$$V(\phi) \sim \Lambda^4\left[1 - \left(\frac{\phi}{\mu}\right)^p + \cdots\right] \quad p = 2, 4, \ldots$$



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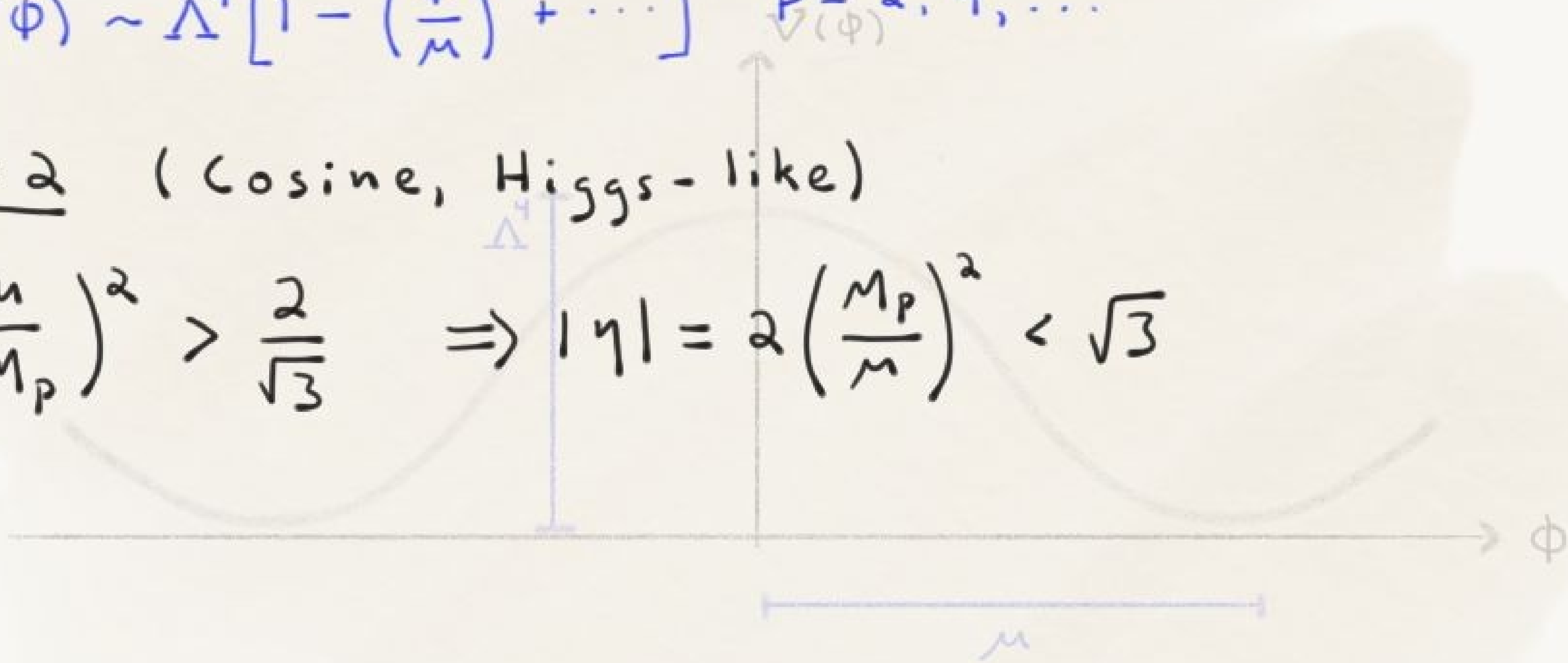

$p = 2$ (Cosine, Higgs-like)

$$\left(\frac{\mu}{M_p}\right)^2 > \frac{2}{\sqrt{3}} \quad \Rightarrow \quad |\eta| = 2\left(\frac{M_p}{\mu}\right)^2 < \sqrt{3}$$

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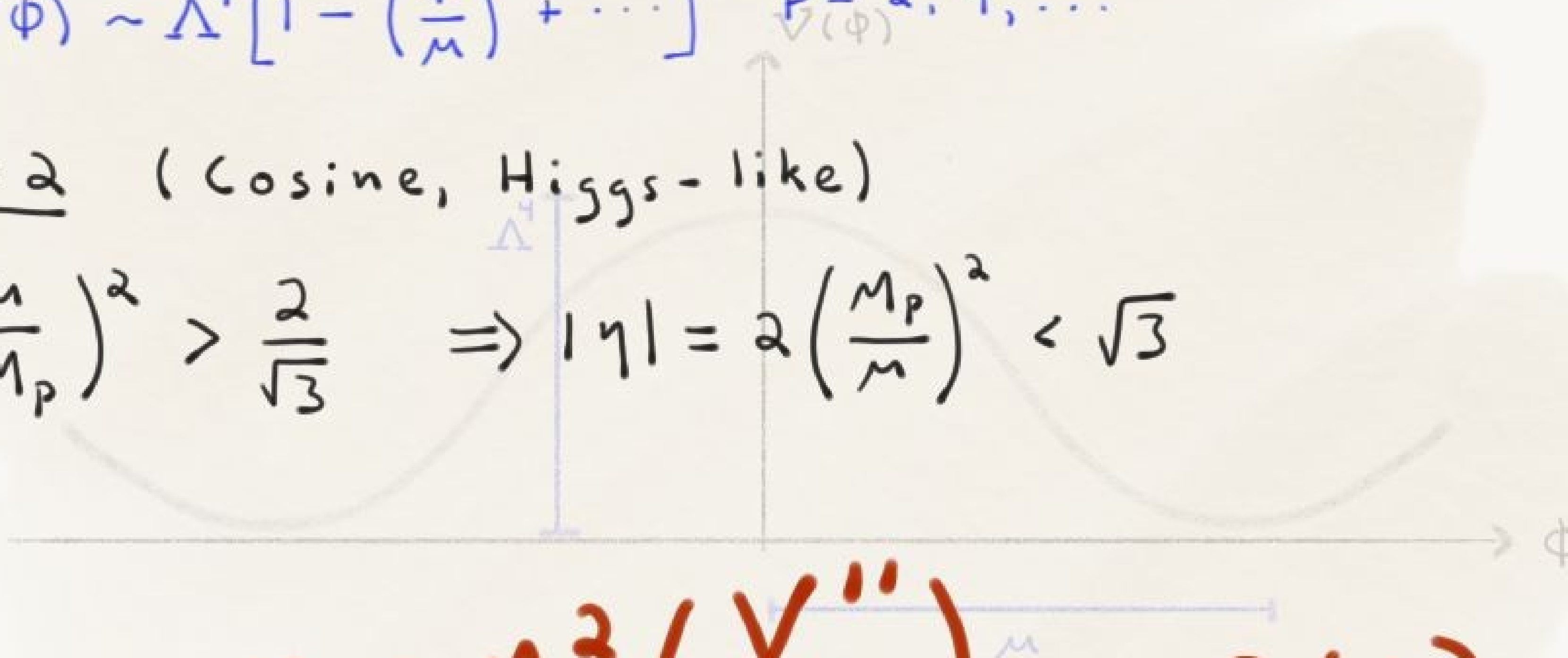
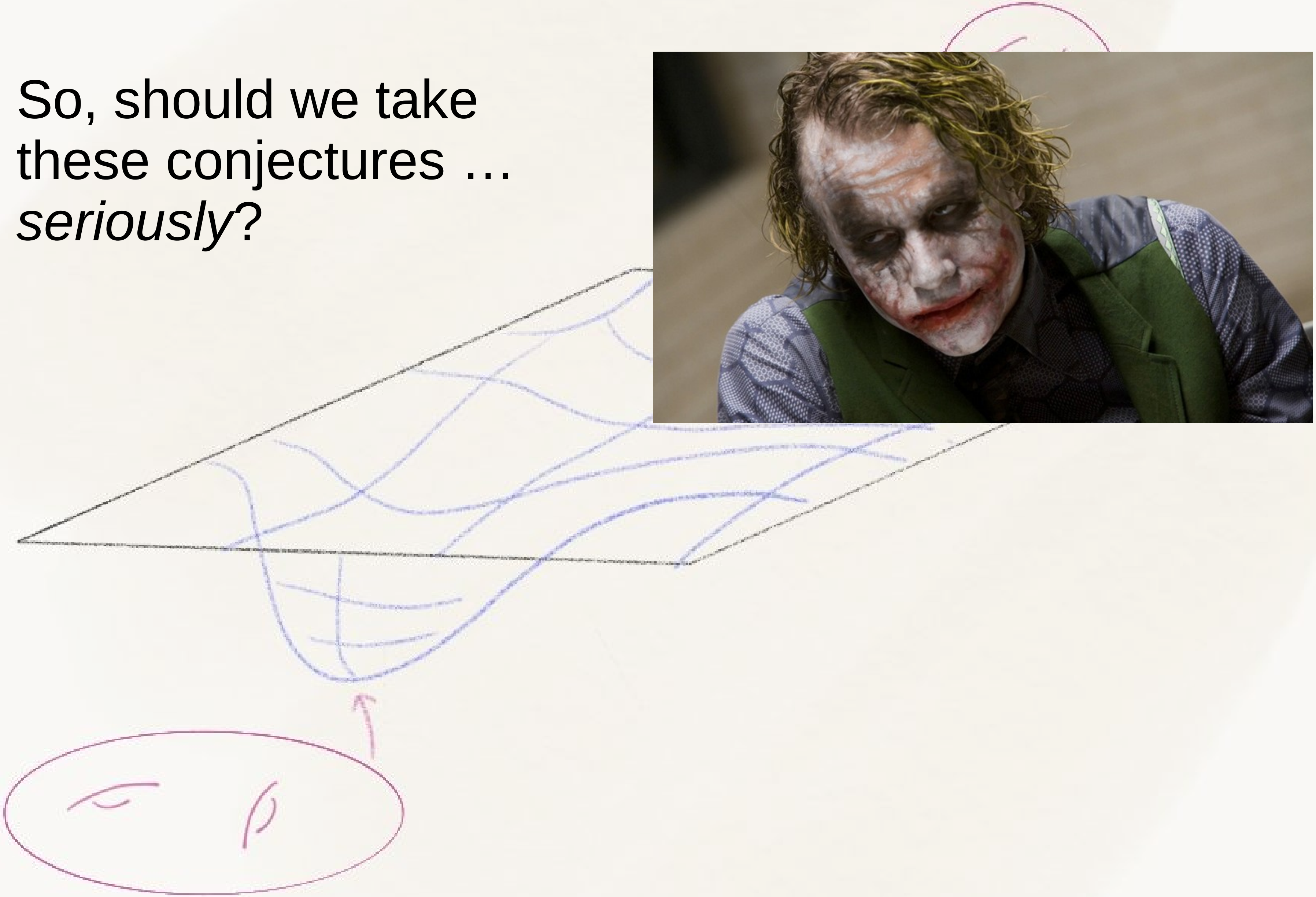


$$\eta = M_p^2 \left(\frac{V''}{V}\right) \sim O(1)$$

WHK [arXiv:1811.11698]

Conjecture, Smonjecture…

So, should we take these conjectures … *seriously*?



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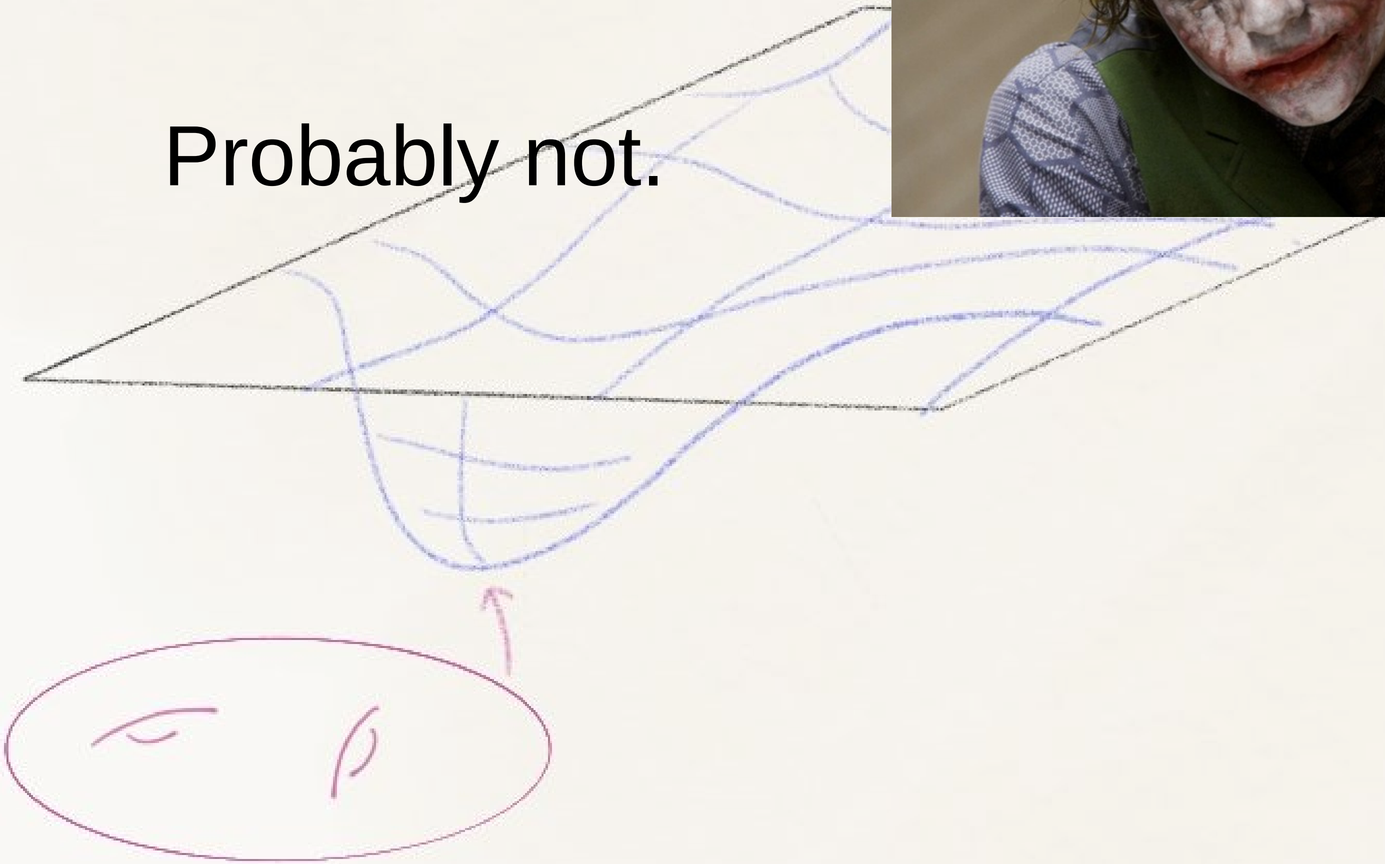
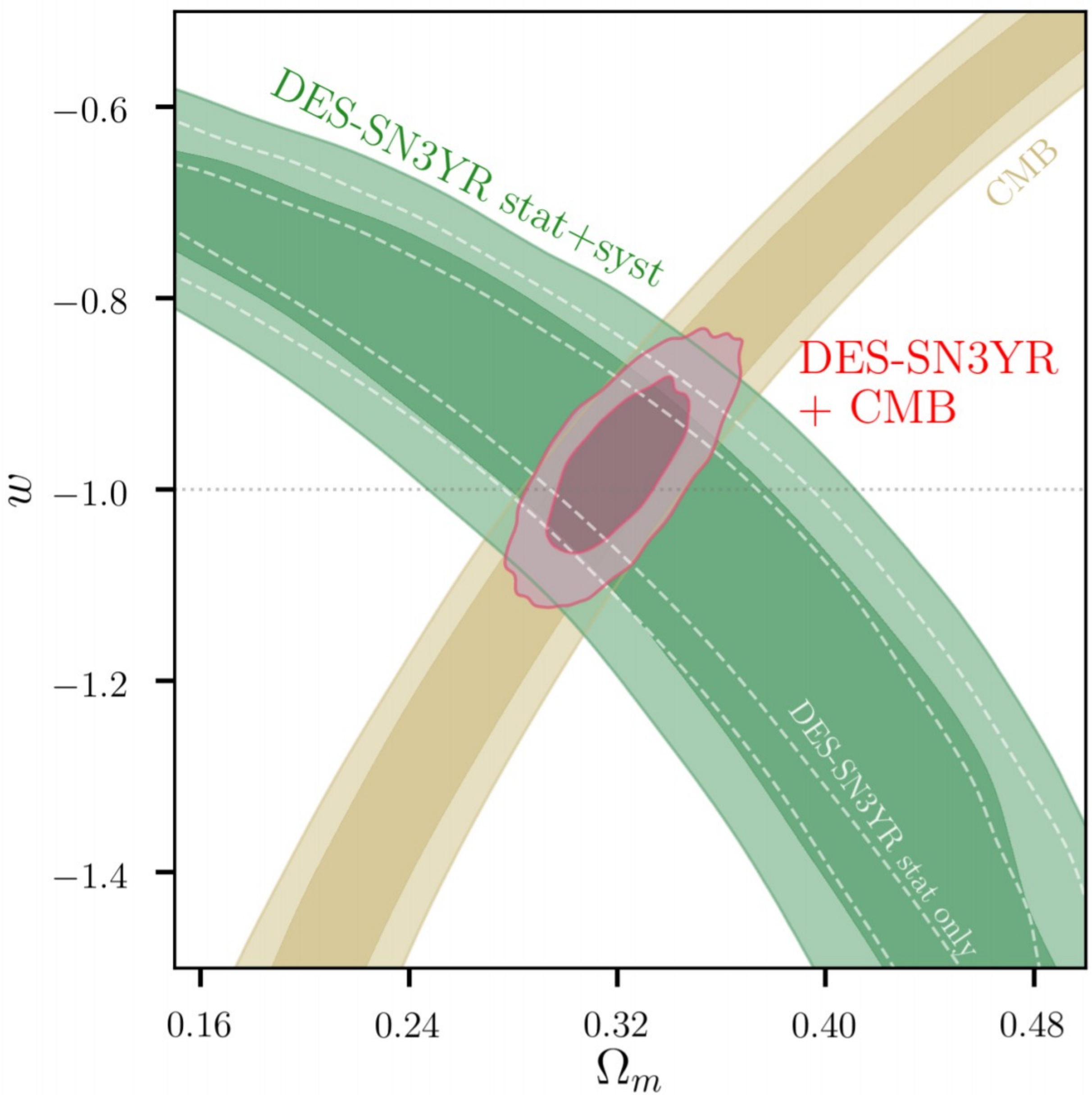


DES-SN + CMB Constraints



Flat wCDM:

$$w = -0.978 \pm 0.059$$

Flat w_0/w_a CDM:

$$w_0 = -0.885 \pm 0.114$$

$$w_a = -0.387 \pm 0.430$$

[Abbott, *et al.* ArXiv:1811.02374]

Conjecture, Smonjecture…

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If string theory doesn't support de Sitter solutions, so what?

Danielsson & Van Riet, [arXiv:1804.01120]