Center for Particle Cosmology at the University of Pennsylvania

Scale Invariance from Conformal Invariance

Justin Khoury (UPenn)

with K. Hinterbichler, A. Joyce and G. Miller,
to appear

Framework

- Non-inflationary mechanism

- Spontaneous breaking of conformal invariance:

$$SO(4,2) \rightarrow SO(4,1)$$

- Gravity is unimportant, can describe mechanism in flat space

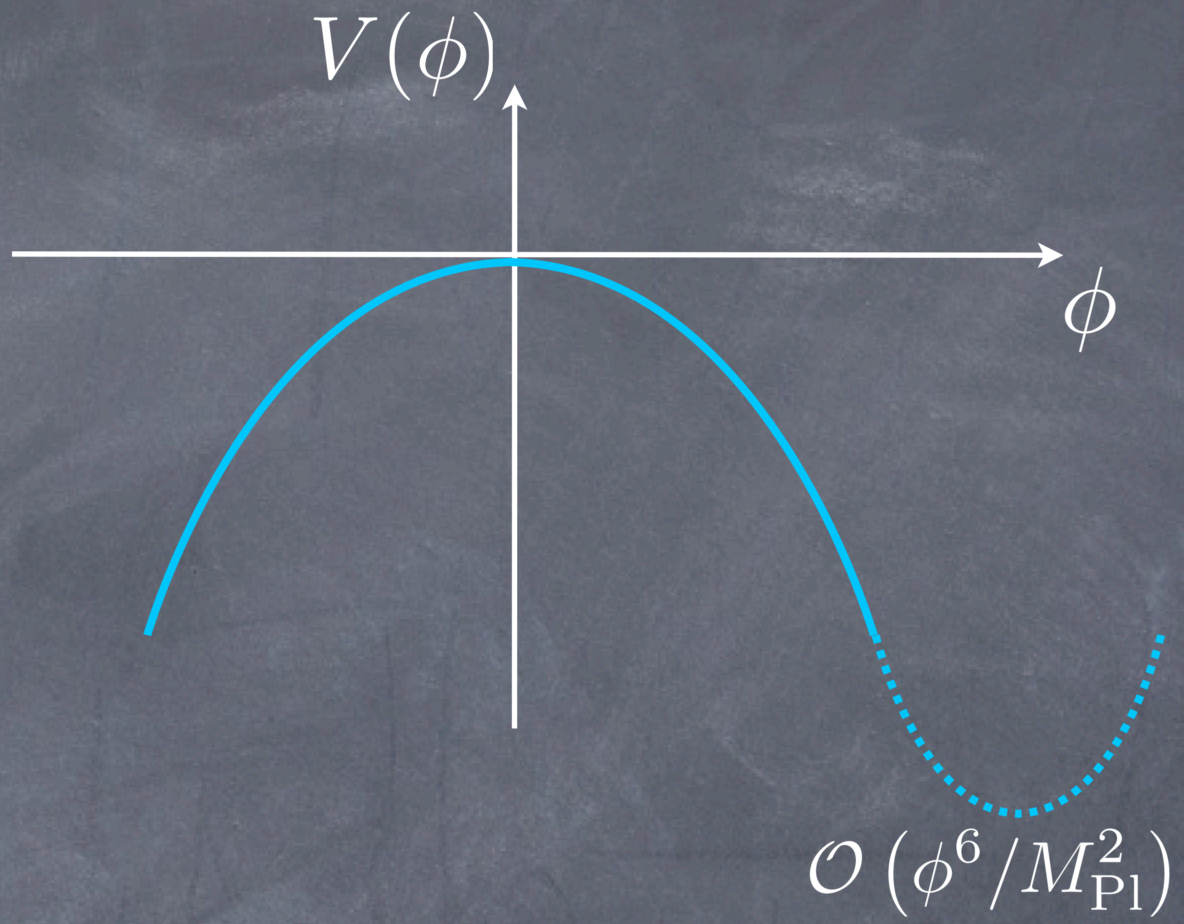
- Related ideas
  - → Rubakov's U(1) model
    Rubakov, 0906:3693
  - → Galilean Genesis
    Creminelli, Nicolis & Trincherini, 1007:0027

- DBI realization

Flat space: simplest realization

$$S_\phi = \int \mathrm{d}^4x \left(-\frac{1}{2}(\partial\phi)^2 + \frac{\lambda}{4}\phi^4 \right)$$

$\lambda > 0 \implies$ asymptotically free



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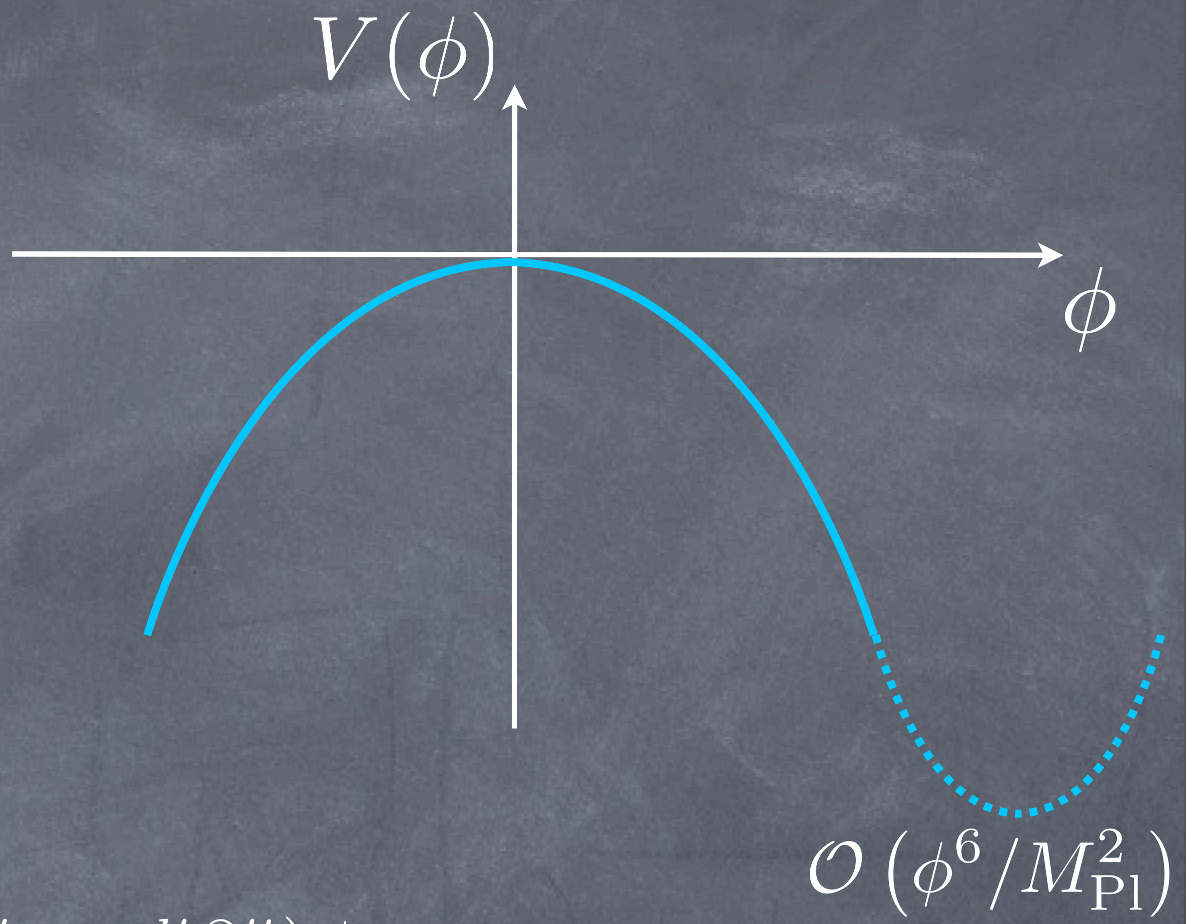

Invariant (classically) under:

$$\delta_{P_\mu}\phi = -\partial_\mu\phi\,; \qquad \delta_{J^{\mu\nu}}\phi = (x^\mu\partial^\nu - x^\nu\partial^\mu)\phi\,;$$

$$\delta_D\phi = -(1 + x^\mu\partial_\mu)\phi\,; \qquad \delta_{K_\mu}\phi = \left(-2x_\mu - 2x_\mu x^\nu\partial_\nu + x^2\partial_\mu\right)\phi\,.$$

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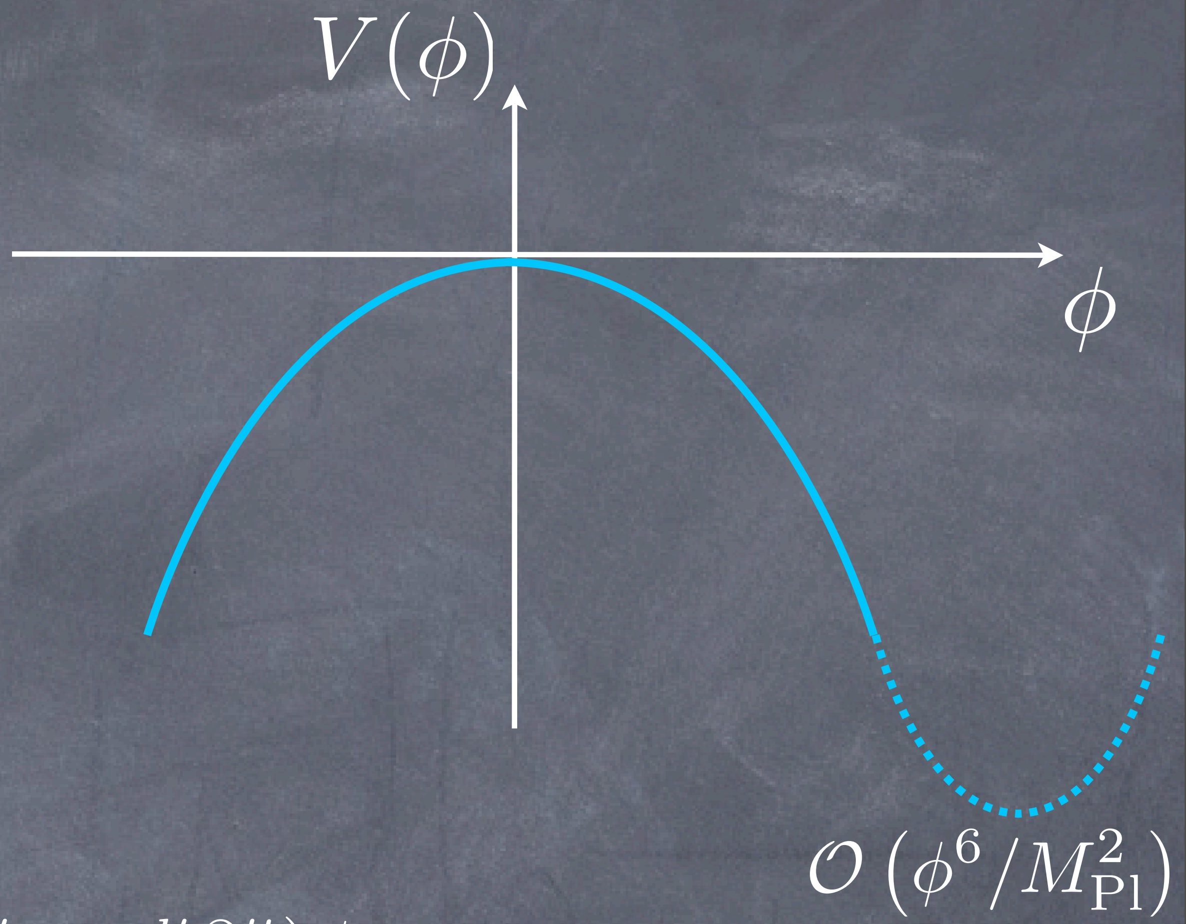

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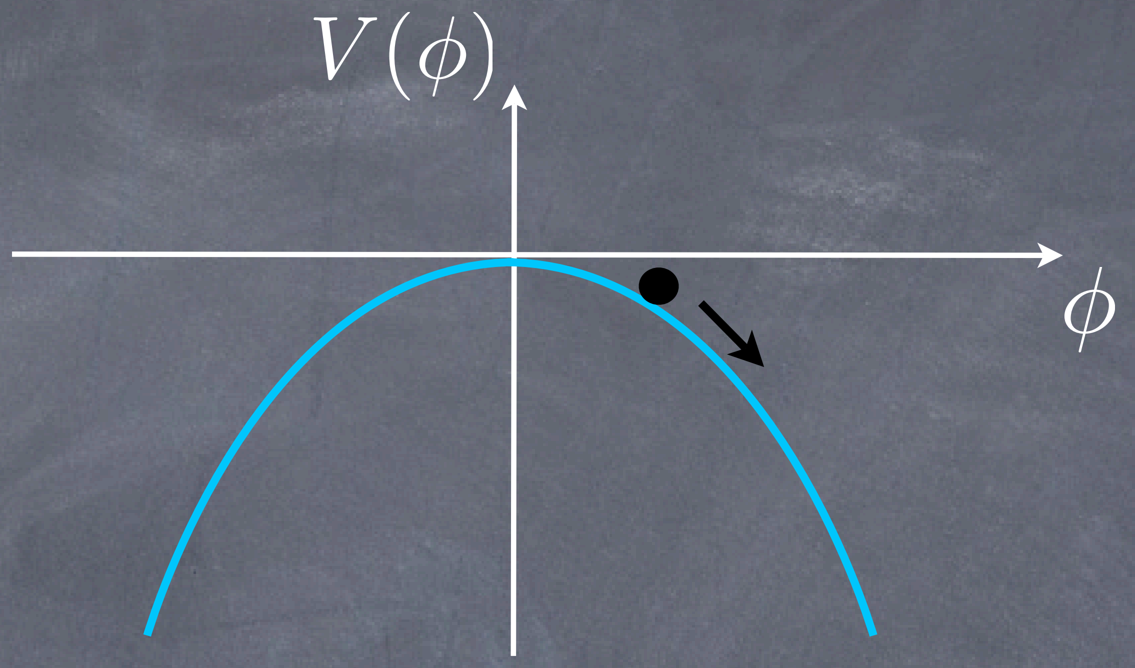
Assume existence of conformal weight 0 fields χ

$$S_\chi = -\frac{1}{2}\int \mathrm{d}^4x \left(\phi^2\eta^{\mu\nu}\partial_\mu\chi\partial_\nu\chi + \phi^4\lambda_\chi\chi^2\right)$$

$\implies \chi$ couples to an effective metric $g^{\rm eff}_{\mu\nu} = \phi^2\eta_{\mu\nu}$

Spontaneous breaking



Assuming homogeneous evolution,

$$\ddot{\phi} = \lambda\phi^3$$

$$\implies \boxed{\phi(t) = \frac{\sqrt{2}}{\sqrt{\lambda}(-t)}}$$

(assuming E = 0)

$-\infty < t < 0$

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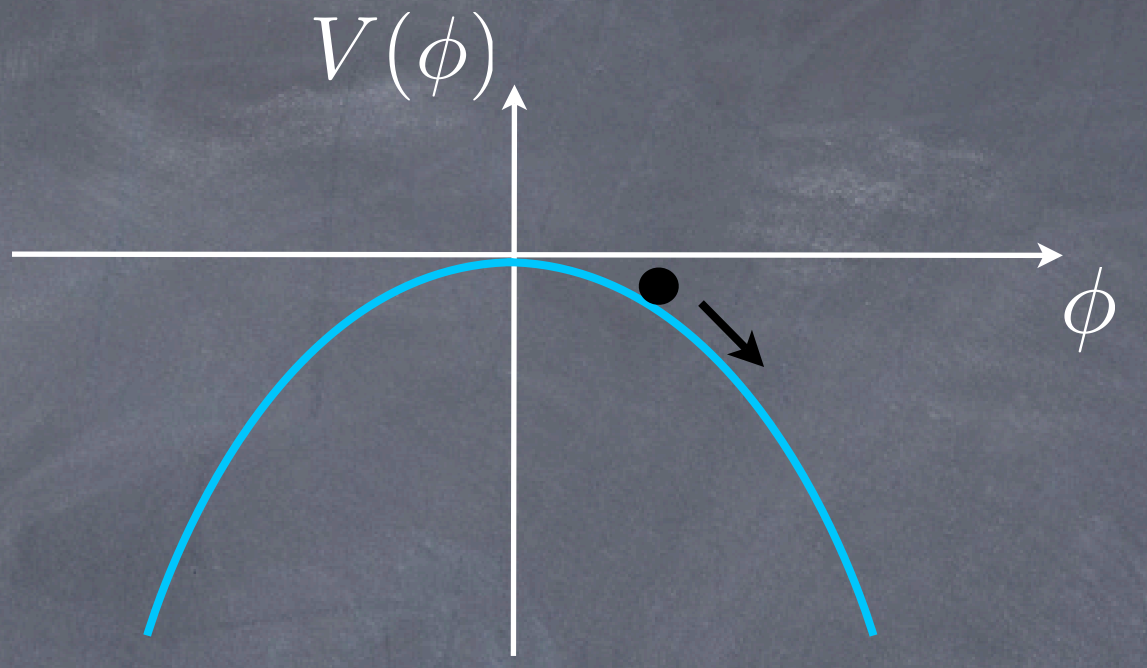

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Coming back to $S_\chi = -\frac{1}{2}\int \mathrm{d}^4x \left(\phi^2 \eta^{\mu\nu}\partial_\mu\chi\partial_\nu\chi + \phi^4\lambda_\chi\chi^2\right)$

$$\Longrightarrow \quad g^{\mathrm{eff}}_{\mu\nu} = \phi^2\eta_{\mu\nu} \sim \frac{1}{t^2}\eta_{\mu\nu}$$

de Sitter

$\therefore$ χ will acquire scale inv. perturbations

(if λ_χ is sufficiently small)

Symmetry Breaking Pattern

Background $\bar{\phi}(t) \sim \frac{1}{t}$ is annihilated by the 10 generators:

$$\delta_{P_i}\,, \quad \delta_D\,, \quad \delta_{J_{ij}}\,, \quad \delta_{K_i}\,; \qquad i = 1, 2, 3.$$

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Define: $\delta_{J_{-2,-1}} = \delta_D\,, \quad \delta_{J_{-2,i}} = \frac{1}{2}\left(\delta_{P^i} - \delta_{K^i}\right)\,, \quad \delta_{J_{-1,i}} = \frac{1}{2}\left(\delta_{P^i} + \delta_{K^i}\right)\,.$

$$\Longrightarrow \quad \boxed{[\delta_{J_{ab}}, \delta_{J_{cd}}] = \eta_{ac}\delta_{J_{bd}} - \eta_{bc}\delta_{J_{ad}} + \eta_{bd}\delta_{J_{ac}} - \eta_{ad}\delta_{J_{bc}}}$$

$$\eta_{ab} = \mathrm{diag}(-1, 1, 1, 1, 1)$$

Commutation relations of SO(4,1)

$$\therefore \quad SO(4,2) \to SO(4,1)$$

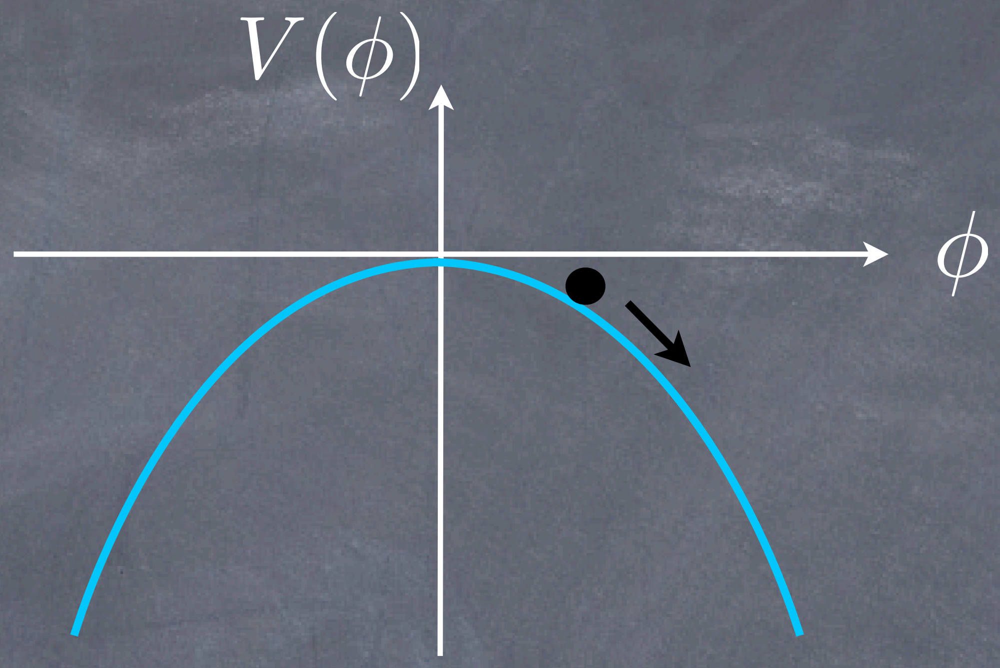
Perturbations: Attractor Property

$$\ddot{\varphi}_k + k^2\varphi_k = 3\lambda\bar{\phi}^2\varphi_k = \frac{6}{t^2}\varphi_k$$

$$\Longrightarrow \varphi_k \sim \frac{1}{t^2} \quad \text{and} \quad \varphi_k \sim t^3$$

growing decaying

(recall $-\infty < t < 0$)



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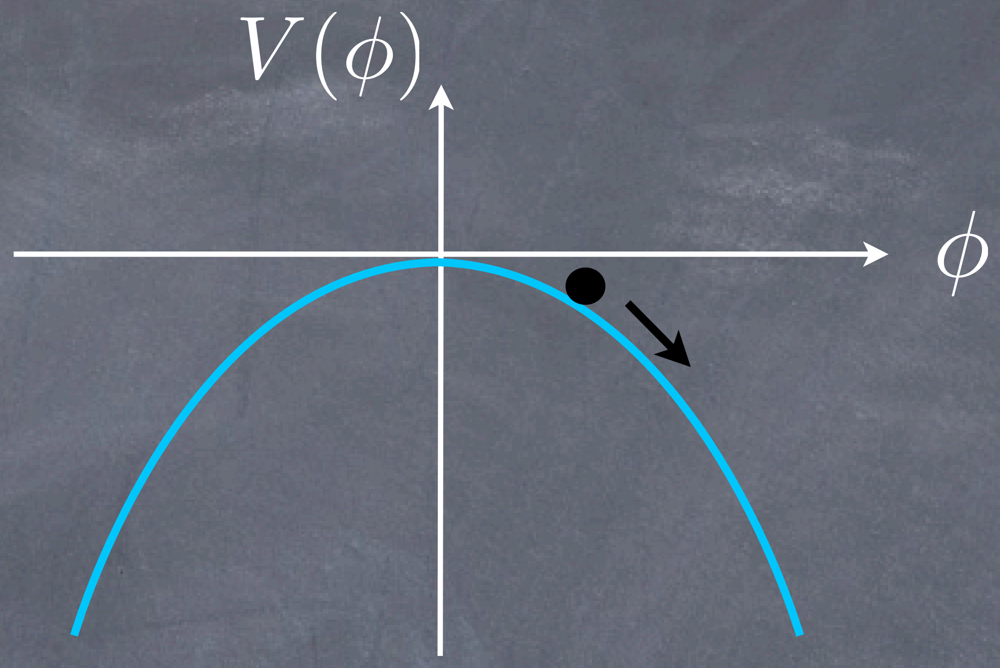

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$$\bar{\phi}(t+\varepsilon) = \bar{\phi}(t) + \varepsilon\dot{\bar{\phi}}(t) = \bar{\phi}(t) + \frac{\sqrt{2}}{\sqrt{\lambda}t^2}\varepsilon$$

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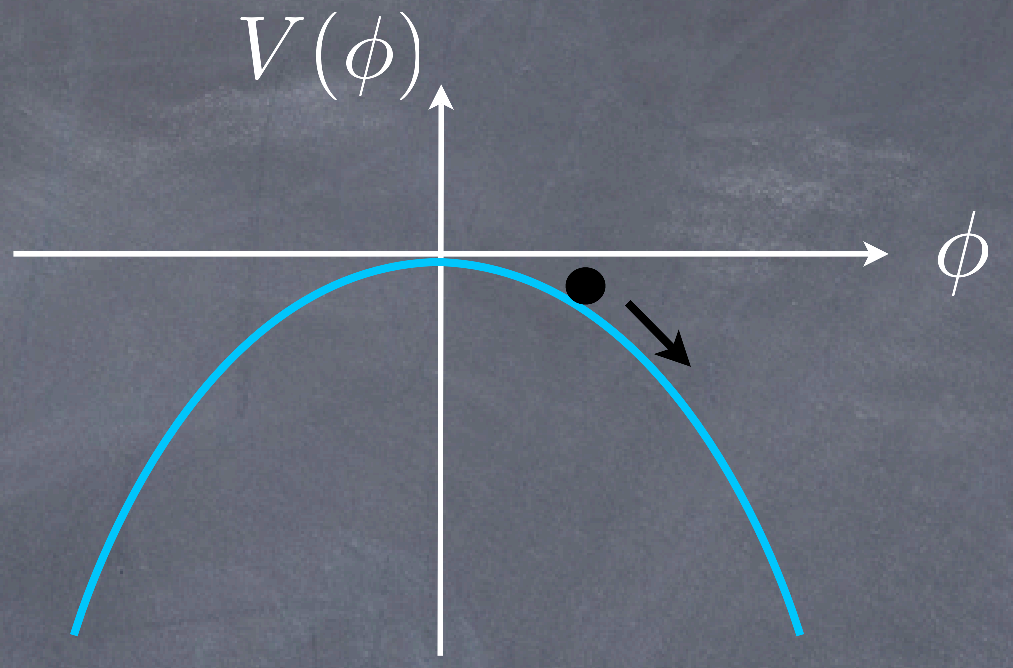

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Quantum fluctuations: assuming adiabatic vacuum,

$$\varphi_k = \frac{\sqrt{-t}}{4\sqrt{2}\pi} H^{(1)}_{5/2}(-kt) \to \frac{3}{4\pi^{3/2}} \frac{1}{k^{5/2}t^2}$$

$\Longrightarrow$ red spectrum

But weight-0 field gets S.I. spectrum:

Assuming $\lambda_\chi = 0$ for simplicity,

$$\ddot{\chi}_k + 2\frac{\dot{\phi}}{\phi}\dot{\chi}_k + k^2\chi_k = 0$$

Choosing adiabatic vacuum,

$$\chi_k = \frac{\sqrt{\lambda}(-t)}{\sqrt{2}}\frac{e^{-ikt}}{\sqrt{2k}}\left(1 - \frac{i}{kt}\right).$$

$$\Longrightarrow \quad \boxed{k^{3/2}|\chi_k| \simeq \frac{\sqrt{\lambda}}{2}}$$

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- 2nd field only amplifies to a constant (attractor)
- Contrast from other 2-field mechanisms...
- No special tuning necessary

e.g. Buchbinder, Khoury & Ovrut, hep-th/0702154
Creminelli & Senatore, hep-th/0702165
Tolley & Wesley, hep-th/0703101

Existing examples

- Rubakov's U(1) model: $\mathcal{L}_{\rm Rubakov} = -\frac{1}{2}\partial_\mu\psi\partial^\mu\psi^* + \frac{\lambda}{4}|\psi|^4$

  0906:3693

  In terms of polar coordinates, $\psi = \phi e^{i\chi}$,

$$\mathcal{L}_{\rm Rubakov} = -\frac{1}{2}(\partial\phi)^2 + \frac{\lambda}{4}\phi^4 - \frac{1}{2}\phi^2(\partial\chi)^2$$

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  - ψ is a spectator field (here: drives cosmology)

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- Galilean Genesis   Creminelli, Nicolis & Trincherini, 1007:0027

$$\mathcal{L}_{\rm Genesis} = \frac{1}{2}(\partial\phi)^2 + c\left(\frac{1}{2}\frac{(\partial\phi)^2\Box\phi}{\phi^3} - \frac{1}{4}\frac{(\partial\phi)^4}{\phi^4}\right).$$

wrong sign

$$\Longrightarrow \qquad \phi = \frac{\sqrt{3c}}{\sqrt{2}(-t)}$$

  - Violates Null Energy Condition
  - Superluminal propagation

General framework

Let ϕ_I be a set of conformal scalars with weights d_I

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On the perturbations, $\varphi_I = \phi_I - \bar{\phi}_I$, we have

$$\begin{aligned} \delta_{P_i}\varphi_I &= -\partial_i\varphi_I, \\ \delta_{J^{ij}}\varphi_I &= (x^i\partial^j - x^j\partial^i)\varphi_I, \\ \delta_D\varphi_I &= -(d_I + x^\mu\partial_\mu)\varphi_I, \\ \delta_{K_i}\varphi_I &= \left(-2x_i d_I - 2x_i x^\nu\partial_\nu + x^2\partial_i\right)\varphi_I. \end{aligned}$$

$$\begin{aligned} \delta_{P_0}\varphi_I &= -\frac{d_I}{t}\bar{\phi}_I - \dot{\varphi}_I, \\ \delta_{J^{0i}}\varphi_I &= \frac{d_I}{t}x^i\bar{\phi}_I + (t\partial_i + x^i\frac{\mathrm{d}}{\mathrm{d}t})\varphi_I, \\ \delta_{K_0}\varphi_I &= x^2\frac{d_I}{t}\bar{\phi}_I + \left(2td_I + 2tx^\nu\partial_\nu + x^2\frac{\mathrm{d}}{\mathrm{d}t}\right)\varphi_I. \end{aligned}$$

Phenomenological Lagrangian

$$\mathcal{L}_{\rm quad} = \frac{1}{2} M_1^{IJ}(t) \dot{\varphi}_I \dot{\varphi}_J - \frac{1}{2} M_2^{IJ}(t) \vec{\nabla} \varphi_I \cdot \vec{\nabla} \varphi_J - \frac{1}{2} M_3^{IJ}(t) \varphi_I \varphi_J$$

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Imposing linearly and non-linearly realized symmetries:

$$\mathcal{L}_{\rm quad}^{(d_I \neq 0)} \sim (-t)^{2(d_I-1)}\eta^{\mu\nu}\partial_\mu\varphi_I\partial_\nu\varphi^I - (-t)^{2(d_I-2)}(d_I+1)(d_I-4)\varphi_I\varphi^I$$

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Exception is the $d_I = 0$ sector:

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In progress... Hinterbichler, Joyce & Khoury, to appear

- Coset construction: non-linear realization of SO(4,2), with linearly realized SO(4,1) subgroup.

cf. Coleman, Wess & Zumino (1969); Salam & Strathdee (1969); Low & Manohar (2002).

Turning on Gravity

$$S = \int \mathrm{d}^4x\sqrt{-g_{\mathrm{E}}}\left(\frac{M_{\mathrm{Pl}}^2}{2}R_{\mathrm{E}} - \frac{1}{2}(\partial\phi)^2 + \frac{\lambda}{4}\phi^4 - \frac{1}{2}\frac{\phi^2}{M^2}g^{\mu\nu}\partial_\mu\tilde{\chi}\partial_\nu\tilde{\chi}\right).$$

where matter fields $\tilde{\chi} = M\chi$ couple to

$$g_{\mu\nu}^{\mathrm{J}} = \frac{\phi^2}{M^2}g_{\mu\nu}^{\mathrm{E}}$$

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At sufficiently early times, gravity can be neglected:

$$\boxed{\phi(t) \simeq \frac{\sqrt{2}}{\sqrt{\lambda}(-t)}} \qquad -\infty < t < 0$$

$$\dot{H}_{\mathrm{E}} = -\frac{1}{2M_{\mathrm{Pl}}^2}\dot{\phi}^2 = -\frac{1}{\lambda t^4 M_{\mathrm{Pl}}^2} \qquad \Longrightarrow \qquad \boxed{H_{\mathrm{E}}(t) \approx \frac{1}{3\lambda t^3 M_{\mathrm{Pl}}^2}}$$

Contracting universe

Flatness and Homogeneity

$$H_{\mathrm{E}}(t) \approx \frac{1}{3\lambda t^3 M_{\mathrm{Pl}}^2} \quad \Longrightarrow \quad \boxed{a_{\mathrm{E}}(t) \simeq 1 - \frac{1}{6\lambda t^2 M_{\mathrm{Pl}}^2}}$$

Nearly static

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Nearly static

Universe becomes increasingly flat and homogeneous:

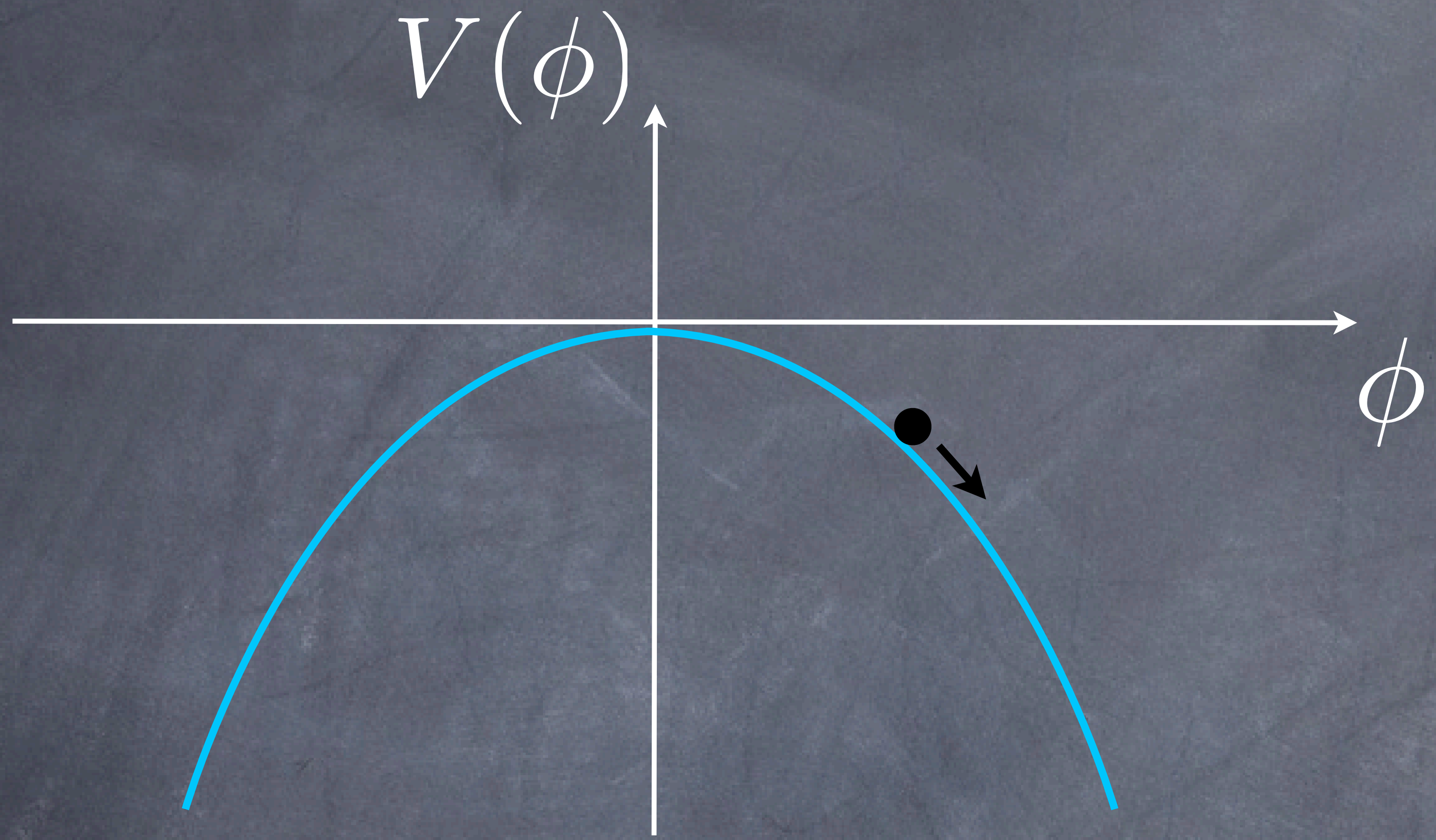
$$3H_{\rm E}^2 M_{\rm Pl}^2 = \underbrace{\frac{K}{a_{\rm E}^2} + \frac{C_{\rm mat}}{a_{\rm E}^3} + \frac{C_{\rm rad}}{a_{\rm E}^4} + \frac{C_{\rm aniso}}{a_{\rm E}^6}}_{\simeq\ \rm const.} + \ldots + \rho_\phi$$

$$\rho_\phi \sim \frac{1}{\lambda^2 t^6 M_{\rm Pl}^2}$$

Akin to ekpyrotic cosmologies (contracting universe with w >> 1)

Gratton, Khoury, Steinhardt & Turok (2003);
Erickson, Wesley, Steinhardt & Turok (2004).

Duration:



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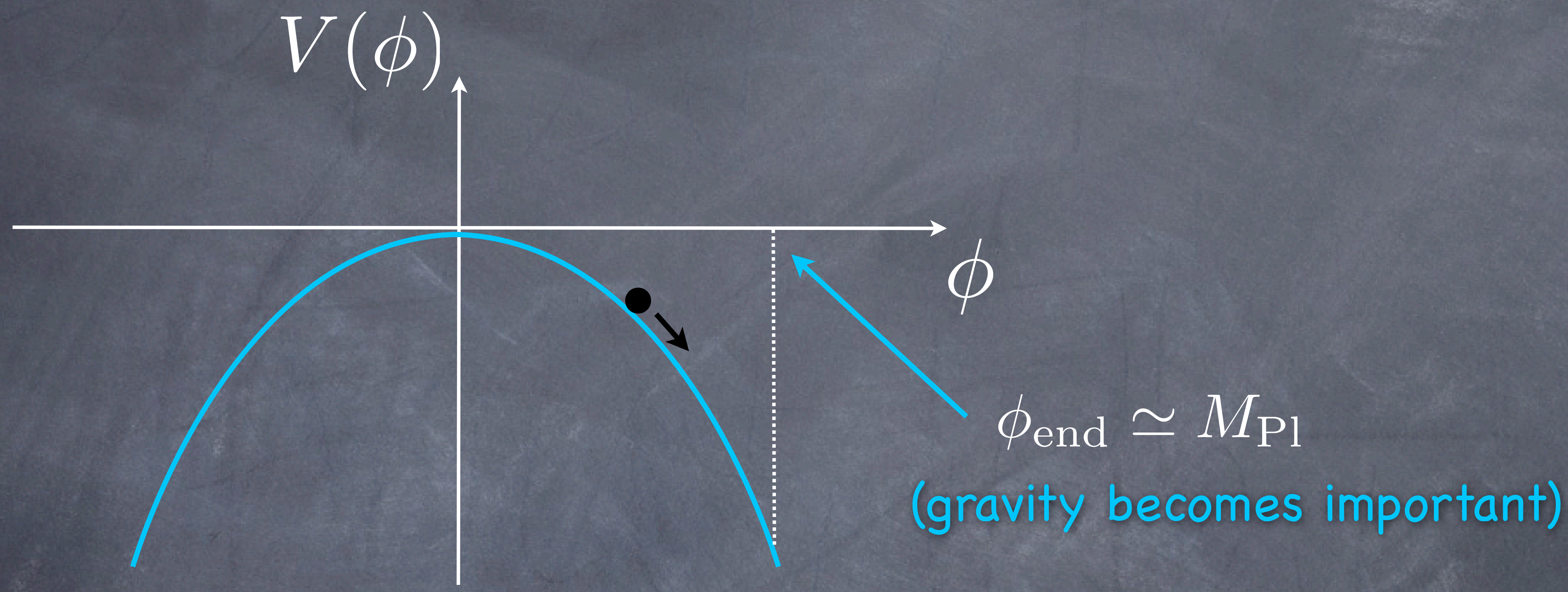

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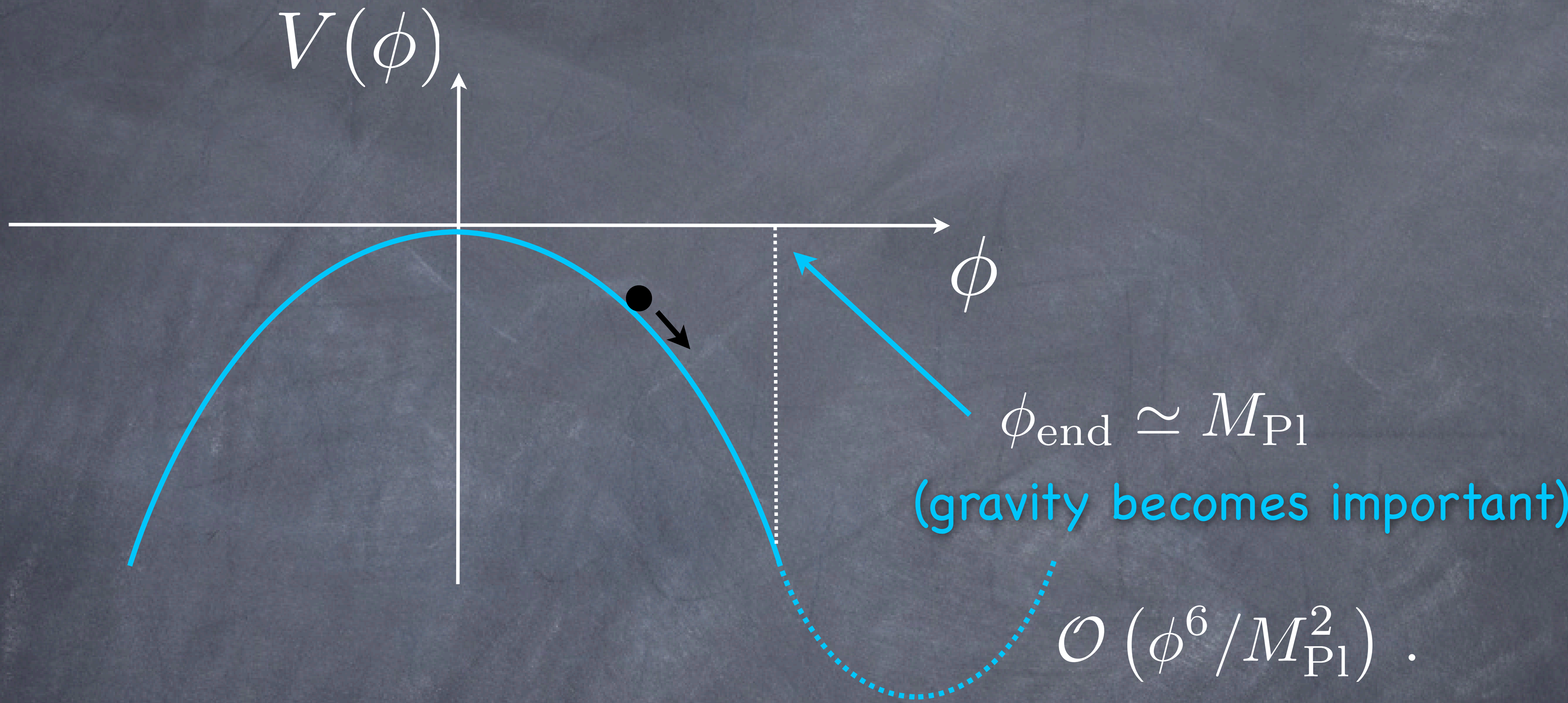
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(gravity becomes important)
$\mathcal{O}\left(\phi^6/M_{\rm Pl}^2\right)$.

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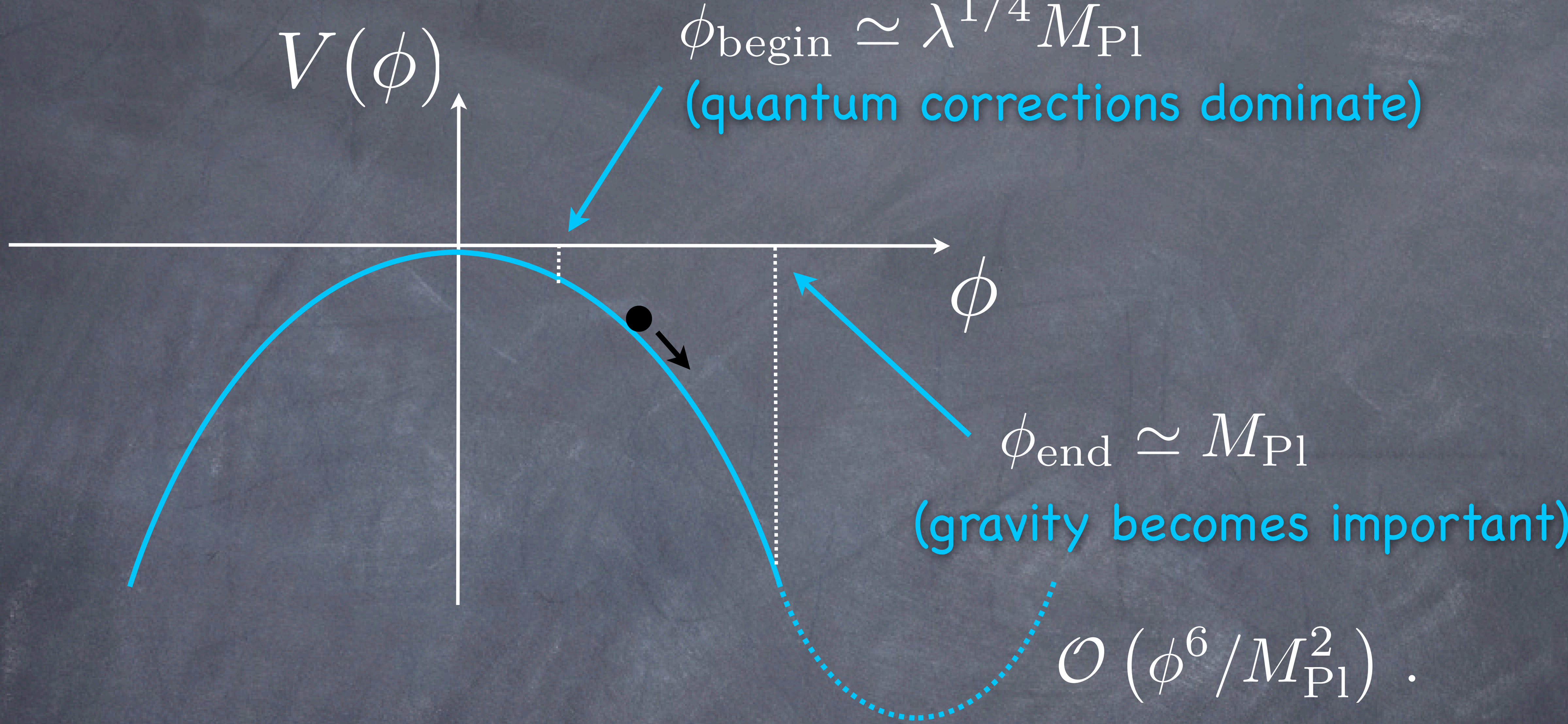

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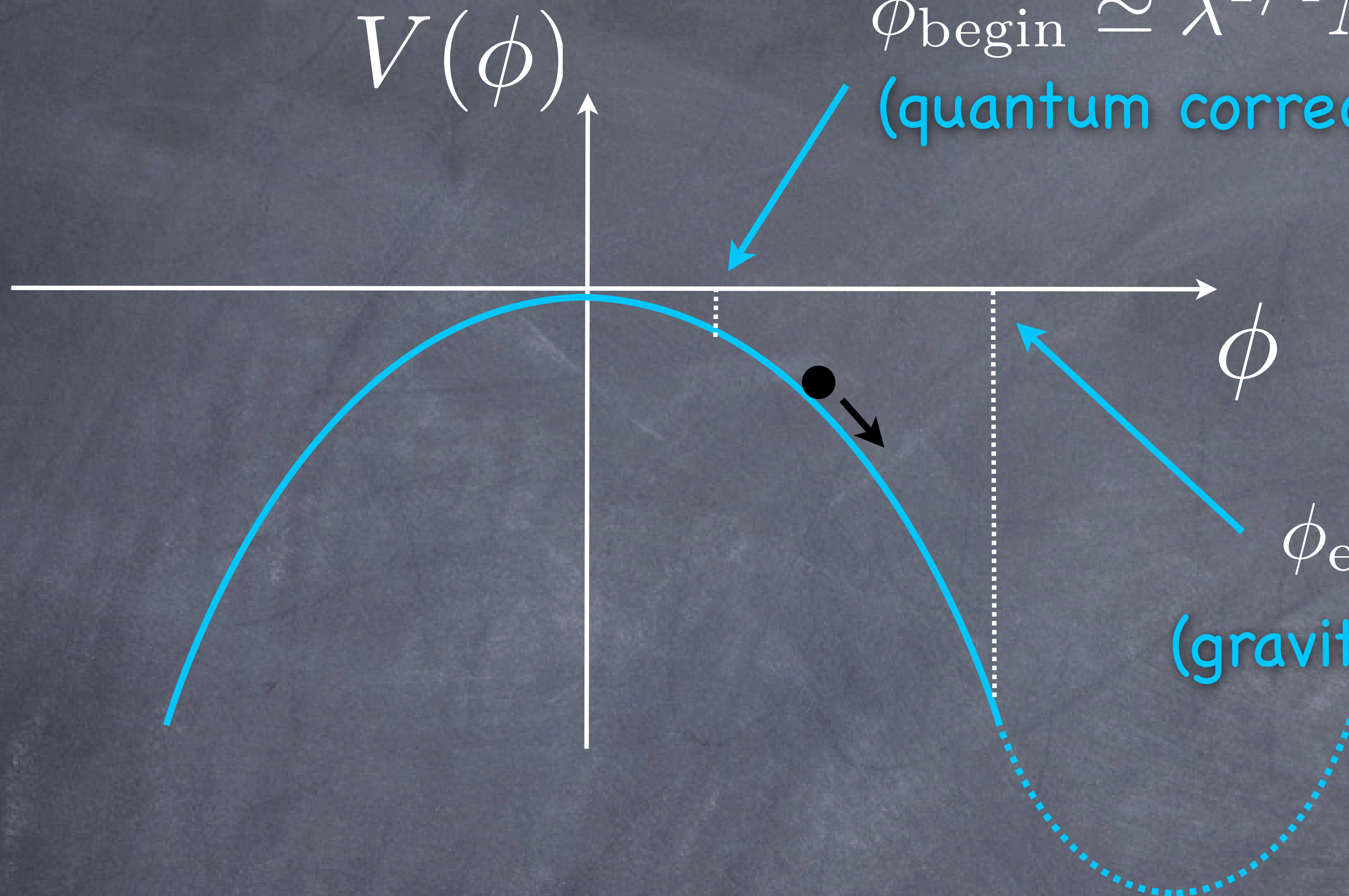

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$$\Longrightarrow \quad \boxed{\frac{k_{\text{end}}}{k_{\text{begin}}} = \frac{\phi_{\text{end}}}{\phi_{\text{begin}}} = \lambda^{-1/4}}$$

Note: Modes are all super-Hubble by ϕ_{end}

DBI extension

Hinterbichler, Khoury & Miller, to appear

$$\mathcal{L}_{\rm DBI} = -\phi^4\sqrt{1+\frac{(\partial\phi)^2}{\phi^4}} + \left(1+\frac{\lambda}{4}\right)\phi^4$$

Special conformal transformations realized non-linearly:

$$\begin{aligned}
\delta_\epsilon\phi &= \epsilon(\phi + x^\mu\partial_\mu\phi)\,; \\
\delta_v\phi &= v_\mu x^\mu\phi - \partial_\mu\phi\left(\frac{1}{2}v^\mu x^2 - (v\cdot x)x^\mu - \frac{1}{2\phi^2}v^\mu\right)\,.
\end{aligned}$$

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Equation of motion is more intricate...

$$-\frac{{\rm d}}{{\rm d}t}\left(\frac{\dot\phi}{\sqrt{1-\dot\phi^2/\phi^4}}\right) - \frac{2\dot\phi^2}{\phi\sqrt{1-\dot\phi^2/\phi^4}} + 4\phi^3\left(1+\frac{\lambda}{4}-\sqrt{1-\dot\phi^2/\phi^4}\right) = 0$$

...but still admits a 1/t solution:

$$\boxed{\phi(t) = \frac{1+\lambda/4}{\sqrt{1+\lambda/8}}\frac{\sqrt{2}}{\sqrt{\lambda}(-t)}}$$

Conclusions

- Spontaneous conformal symmetry breaking: $SO(4,2) \rightarrow SO(4,1)$
- For scalar ϕ_I of conformal weight d_I, this is realized by

$$\phi_I \sim t^{-d_I}$$

- Action for Goldstones φ_I fixed by symmetry breaking pattern

$\Longrightarrow$ Background is attractor

$\Longrightarrow$ Conformal weight-0 fields χ acquire S.I. spectrum

- Gravity unimportant at early times, universe driven to flatness and homogeneity
- Generic Predictions: - significant non-gaussianity

  - negligible gravity waves