Title: A Matter Bounce By Means of Ghost Condensation

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Abstract: TBA

Ghost Bounce

鬼跌

A matter bounce by means of ghost condensation

R. Brandenberger, L. Levasseur and C. Lin

arXiv:1007.2654

Chunshan Lin
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Outline

I. Alternative inflation models
  - Necessity
  - Matter bounce

II. Ghost condensation
  - Basic philosophy
  - Applications
  - Interesting features
  - Instability

III. Matter bounce by means of ghost condensation
  - Several advantages:
    ghost free, stable against radiation and anisotropic stress...
  - Perturbation
  - Cut off issue

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Part I

Alternative inflation models

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- Inflation suffers from some conceptual problems

Flatness problem

Amplitude problem $\frac{V(\varphi)}{\Delta\varphi^4} \leq 10^{-12}$

Trans-Planckian problem

Singularity problem

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- Some other attempts

Matter bounce, Ekpyrotic, String gas, pre big bang theory......

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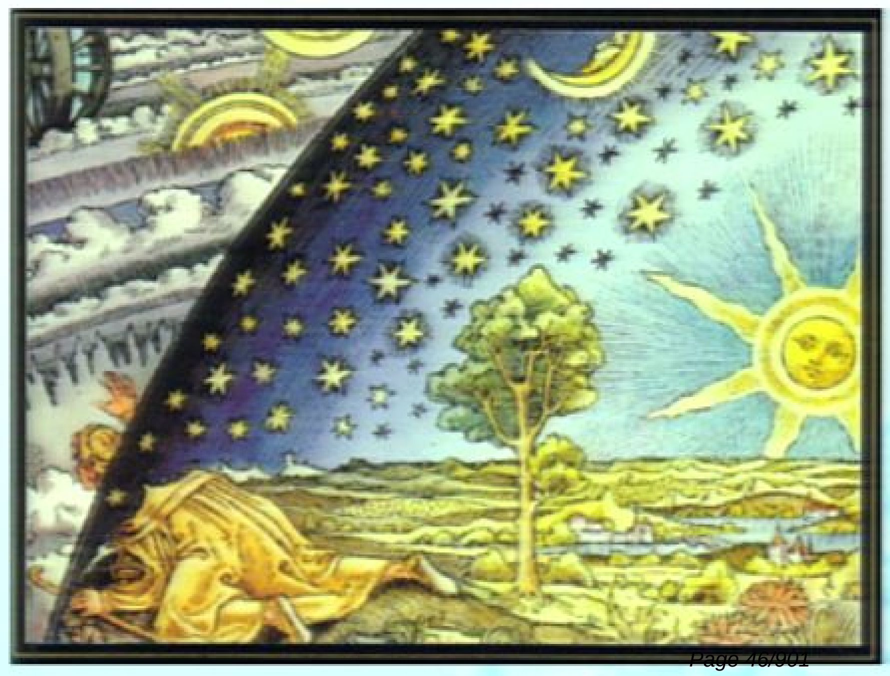

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- Cold pressureless matter
- Scale invariant spectrum

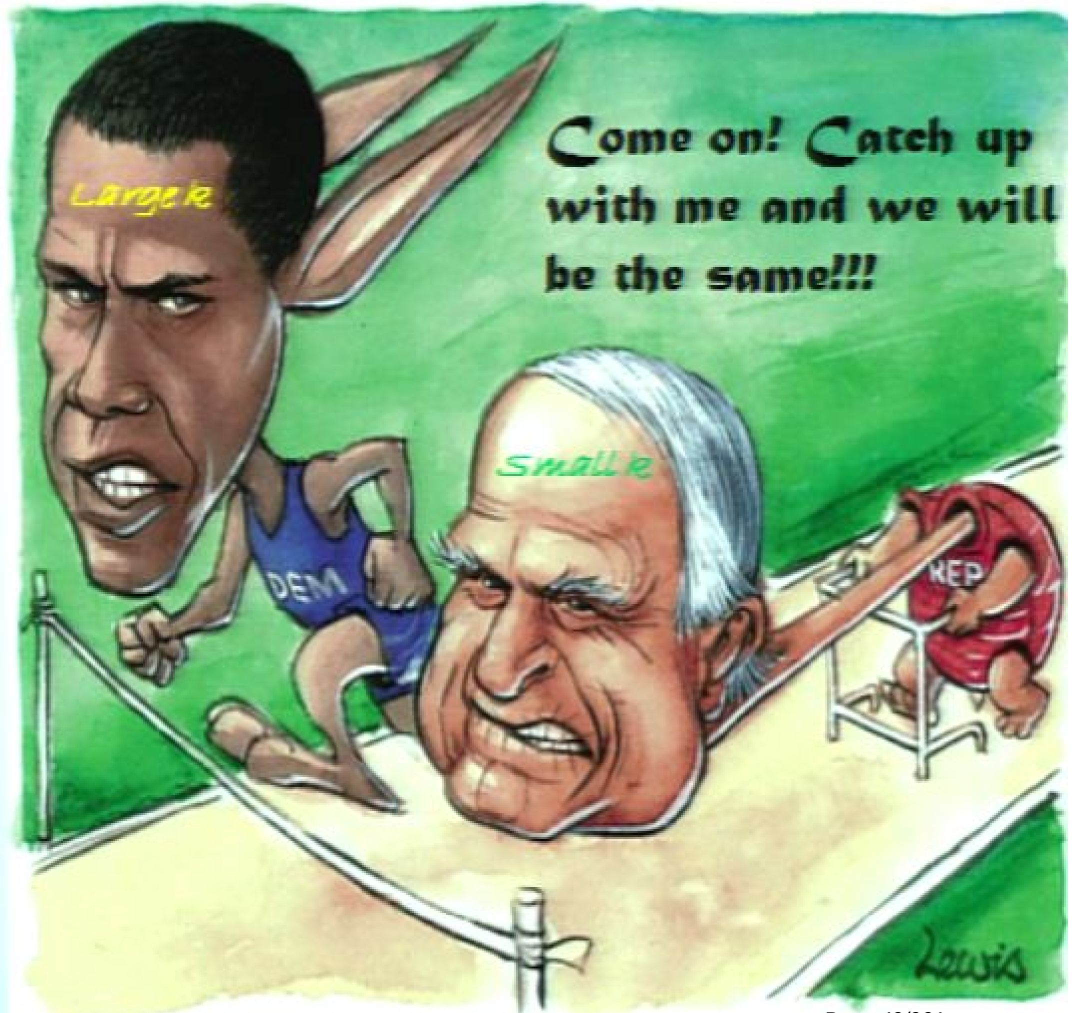
Horizon crossing

$$\delta\varphi_* \propto H_* \propto t_*^{-1}$$

super horizon growing

$$\varsigma(t) \propto t^{-1}$$

Amplitude of the larger scale perturbation mode will catch up with the smaller scale perturbation mode.



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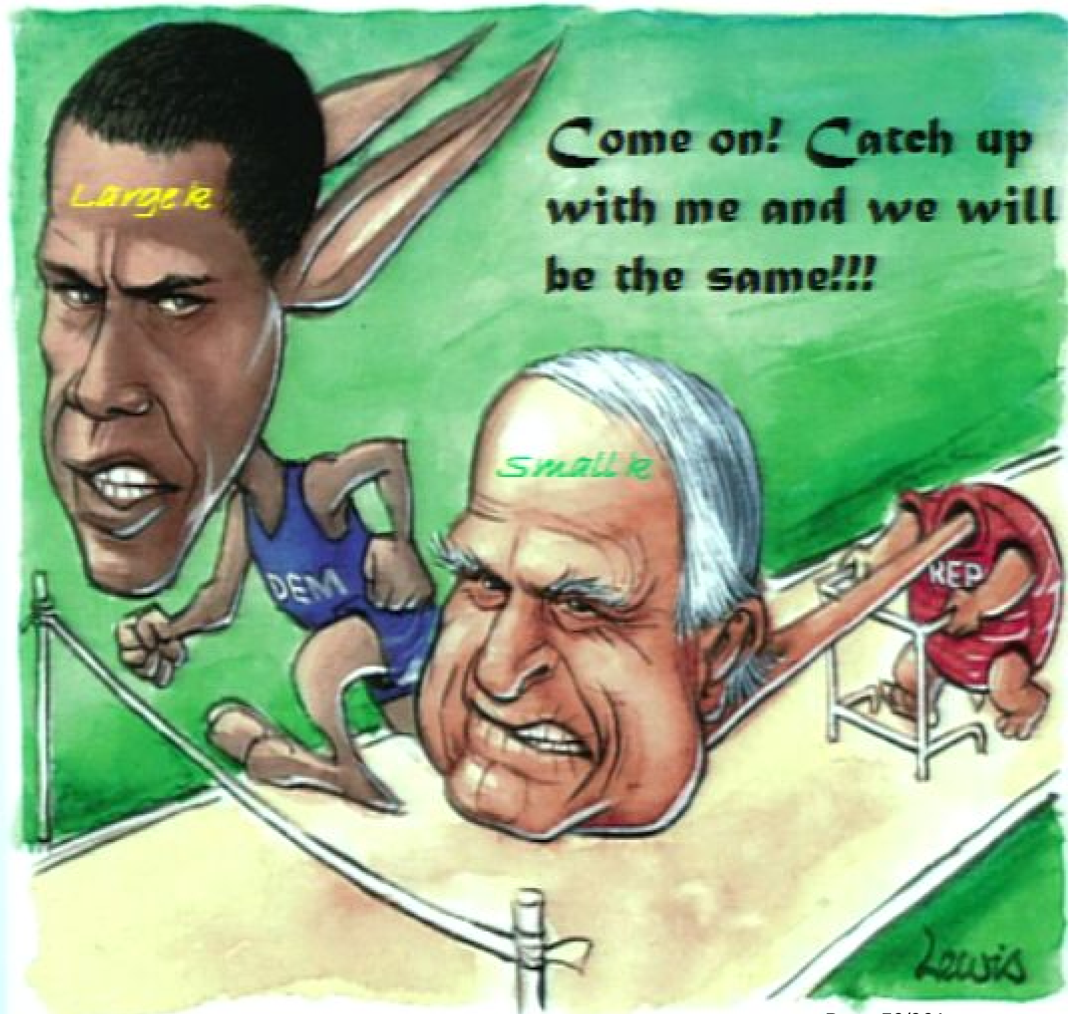

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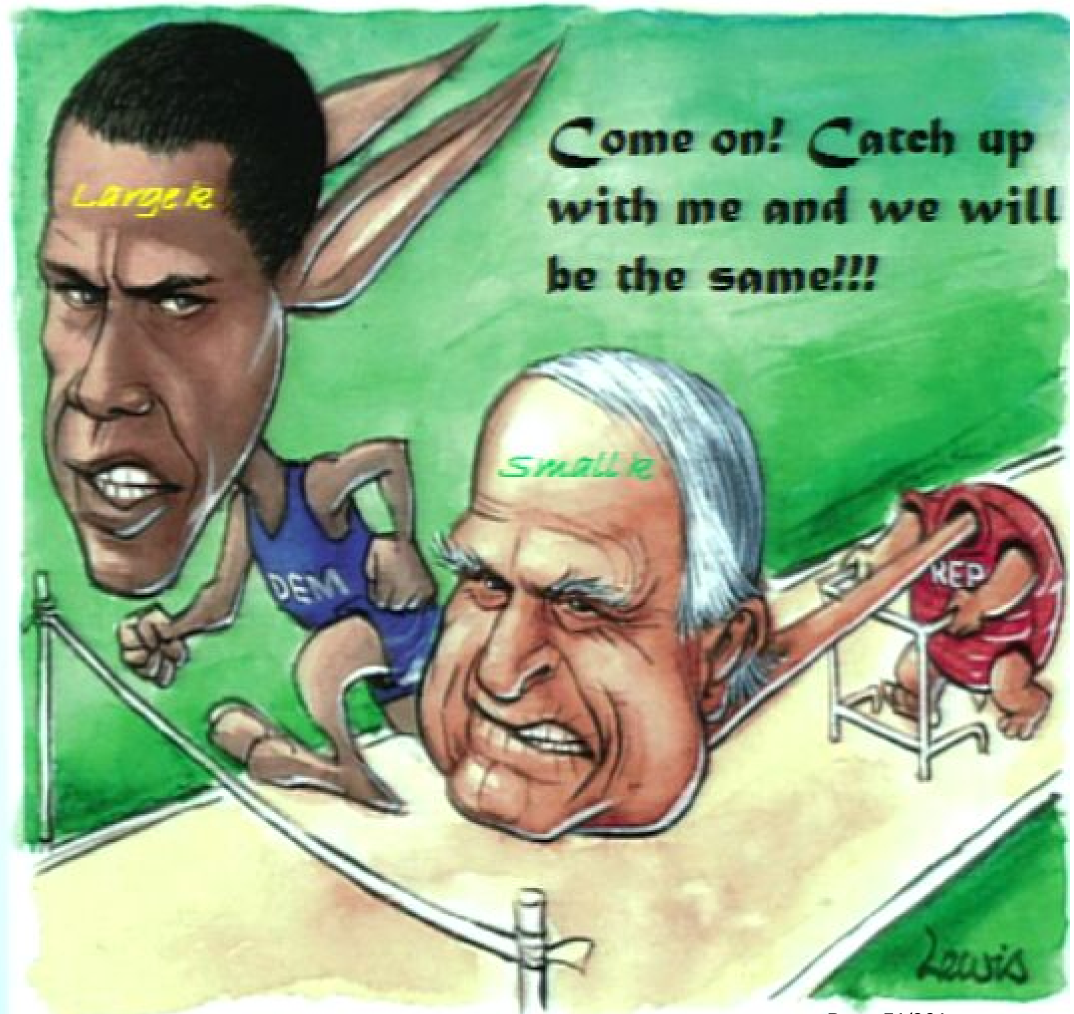

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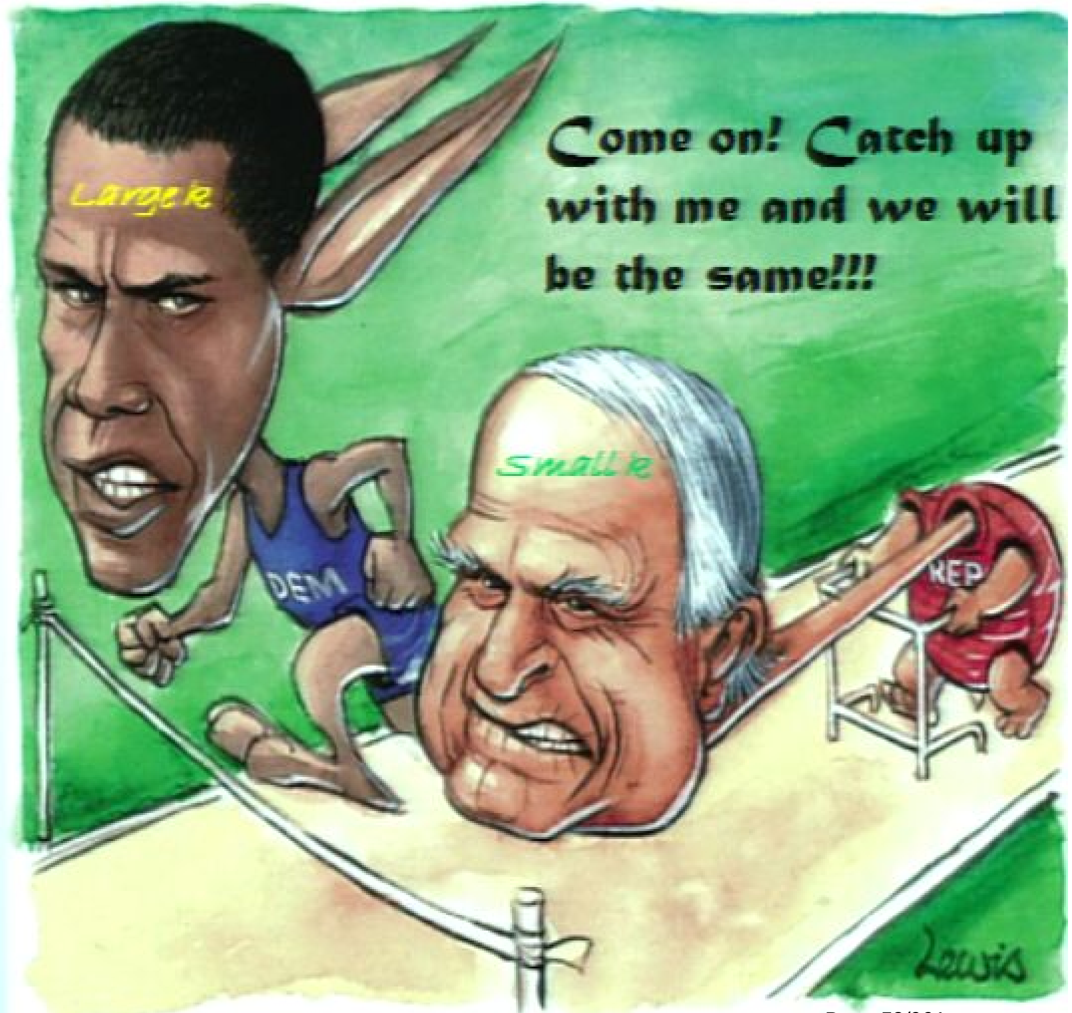

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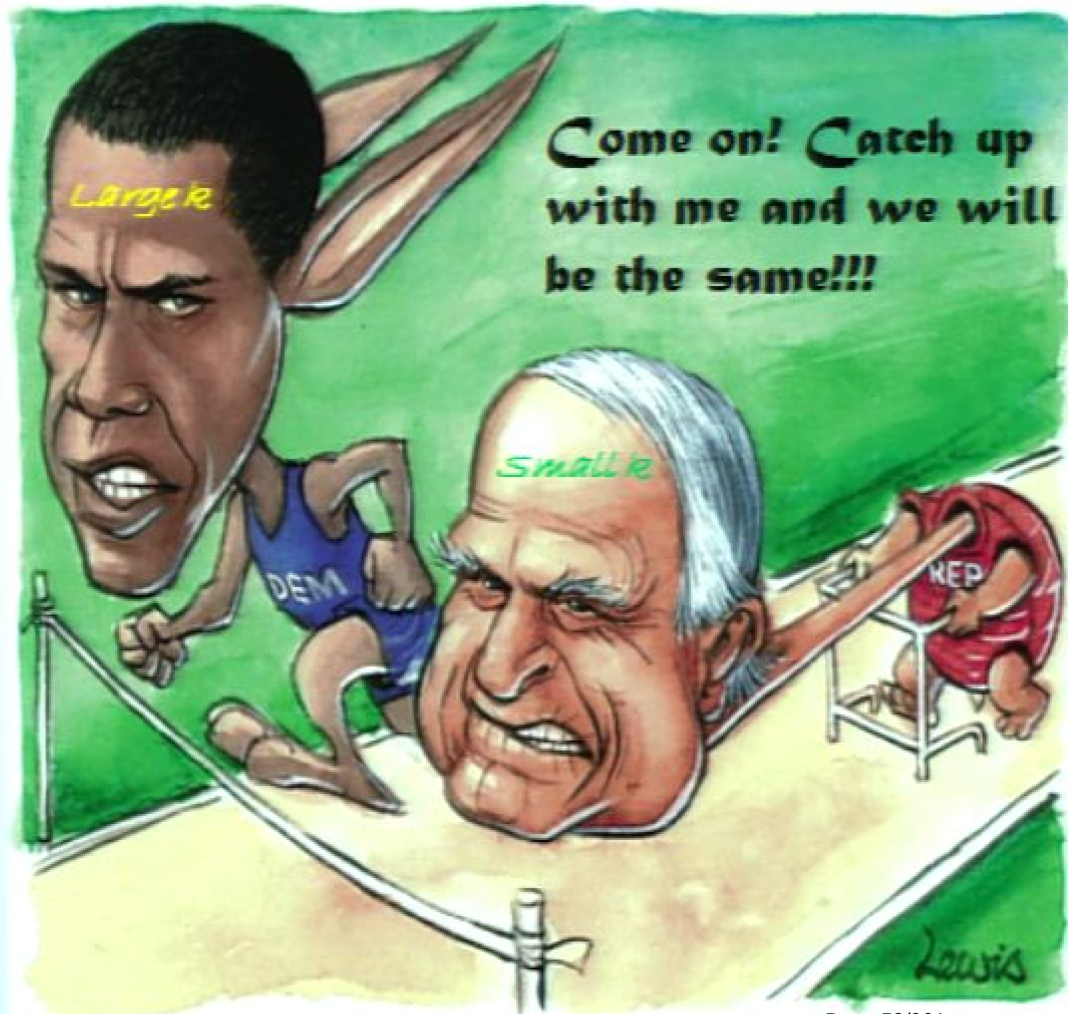

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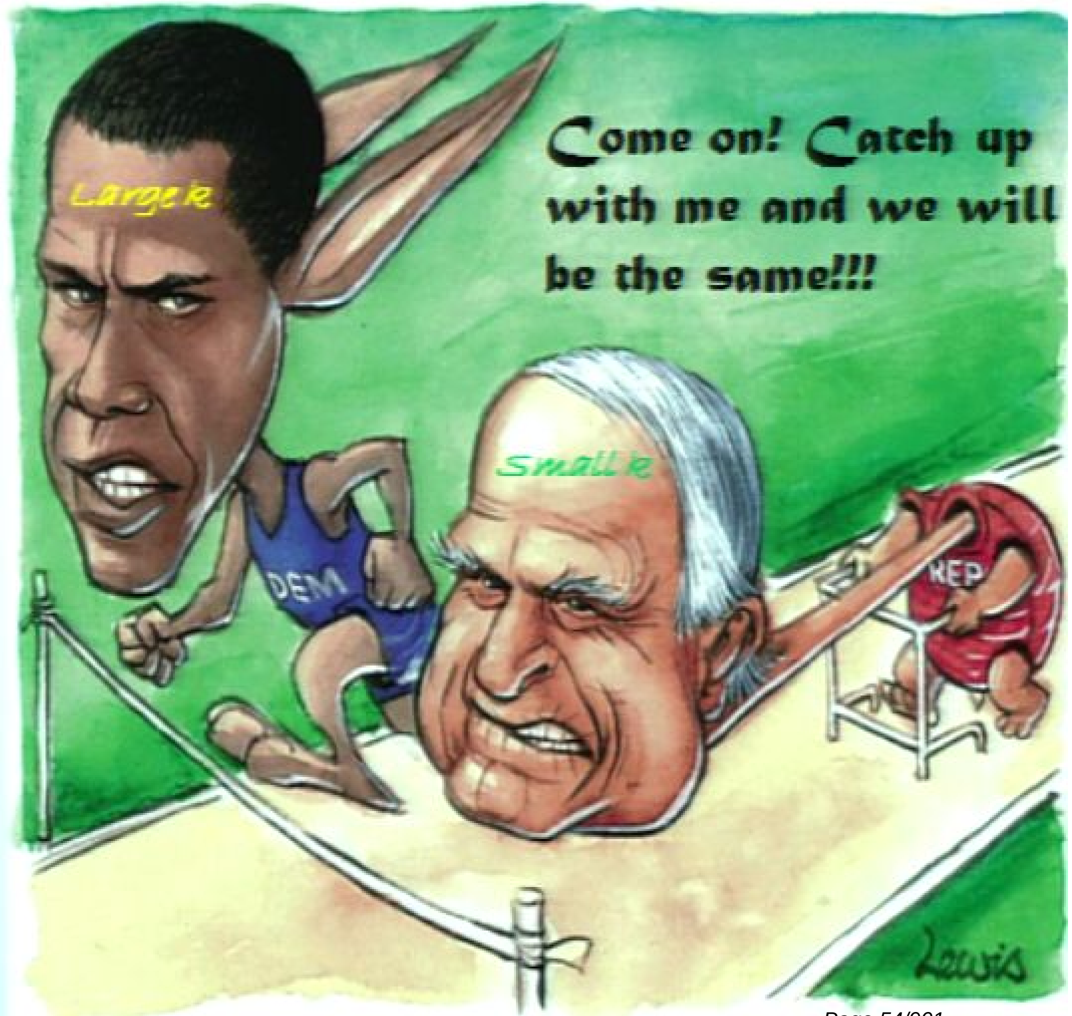

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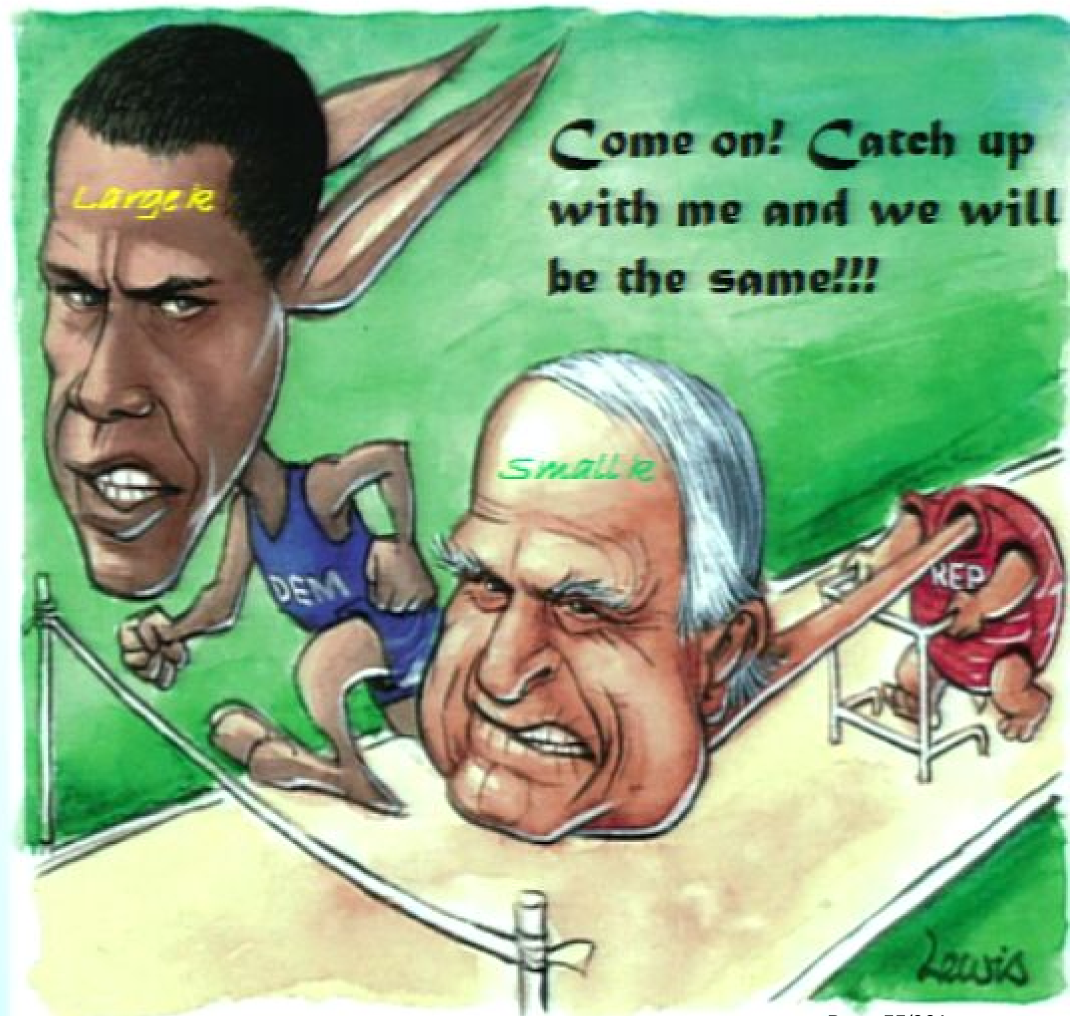

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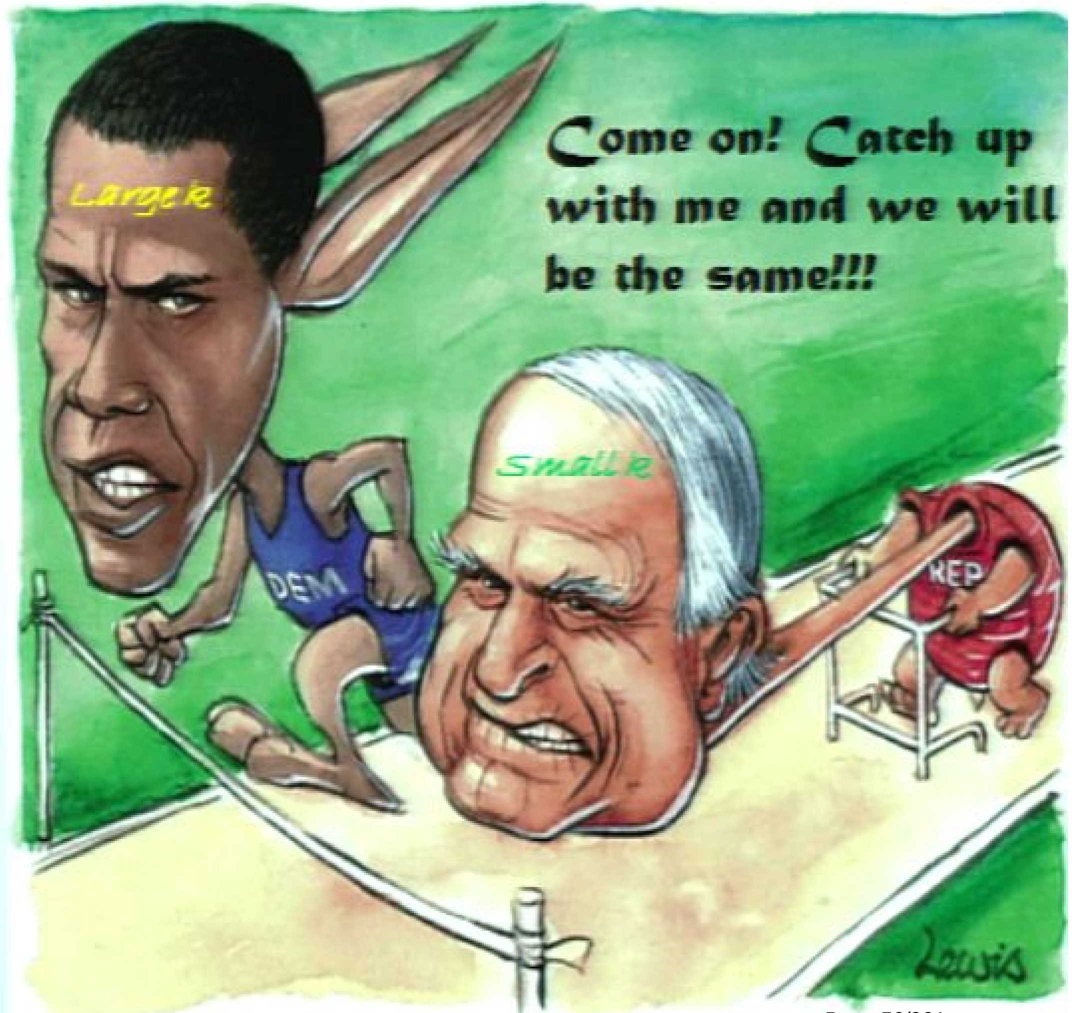

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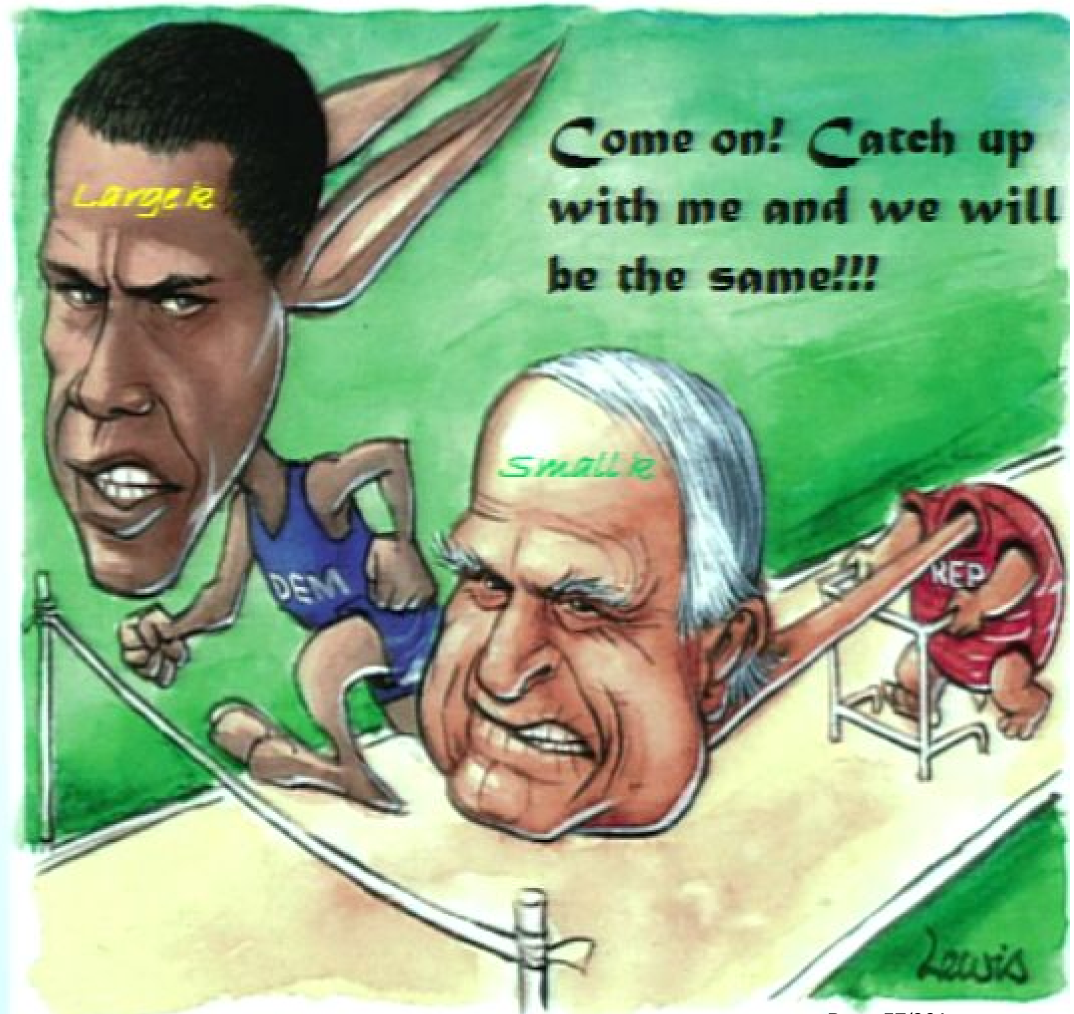

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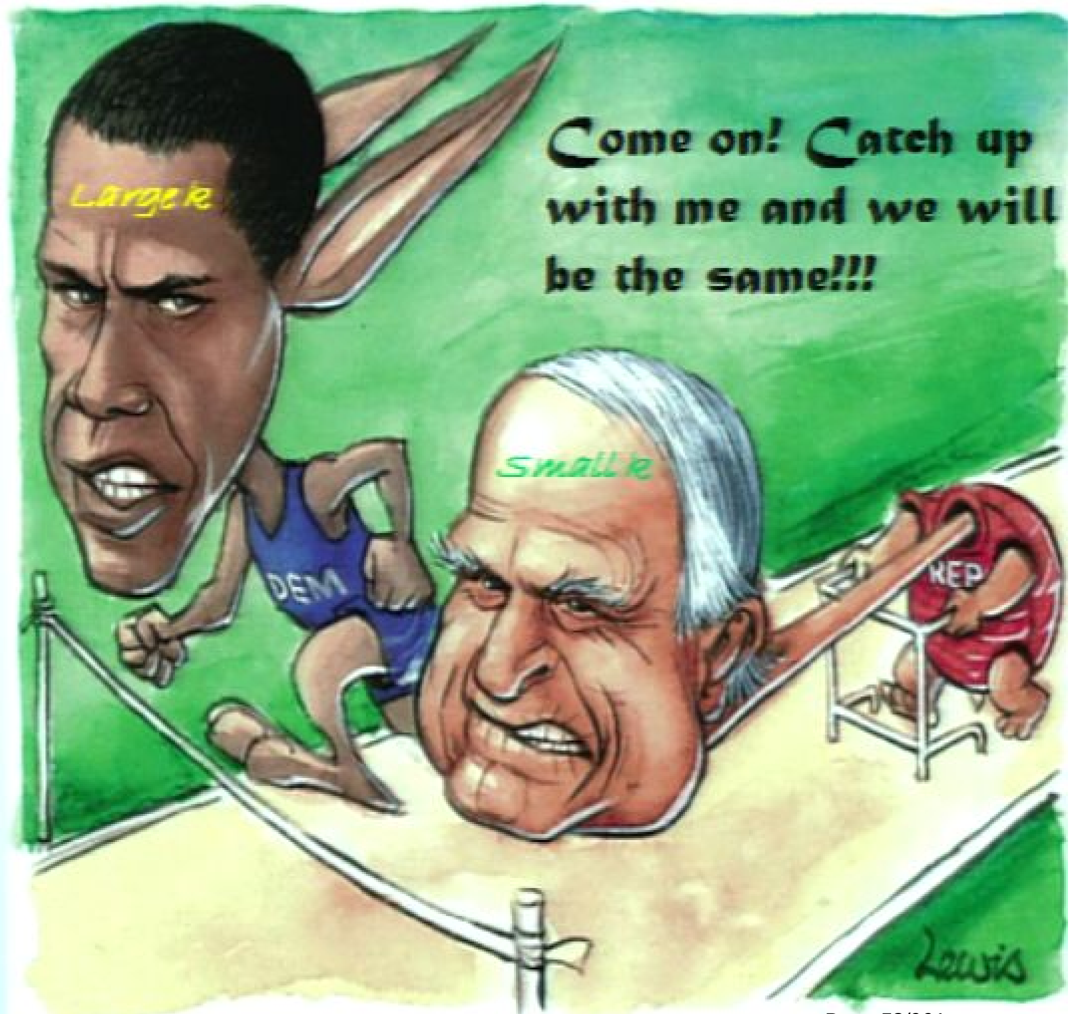

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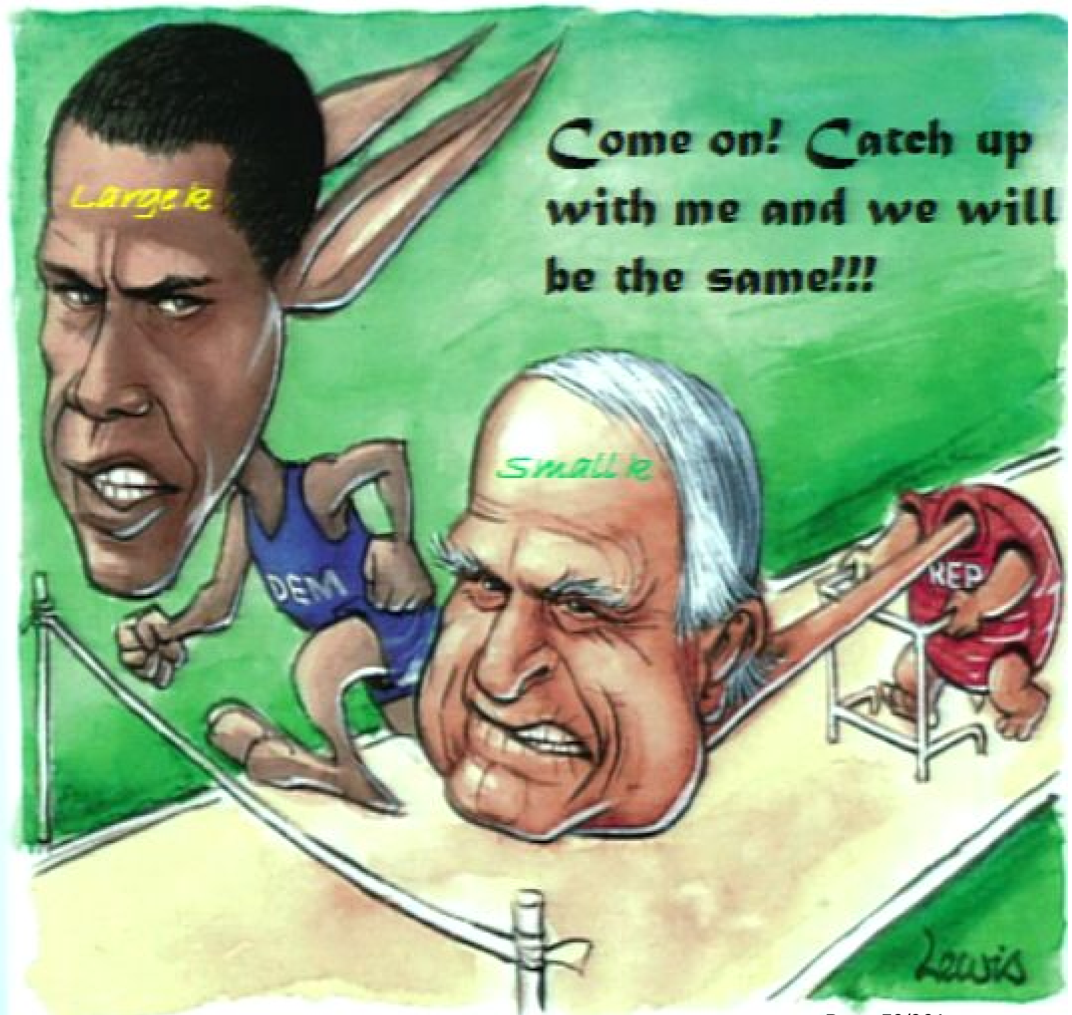

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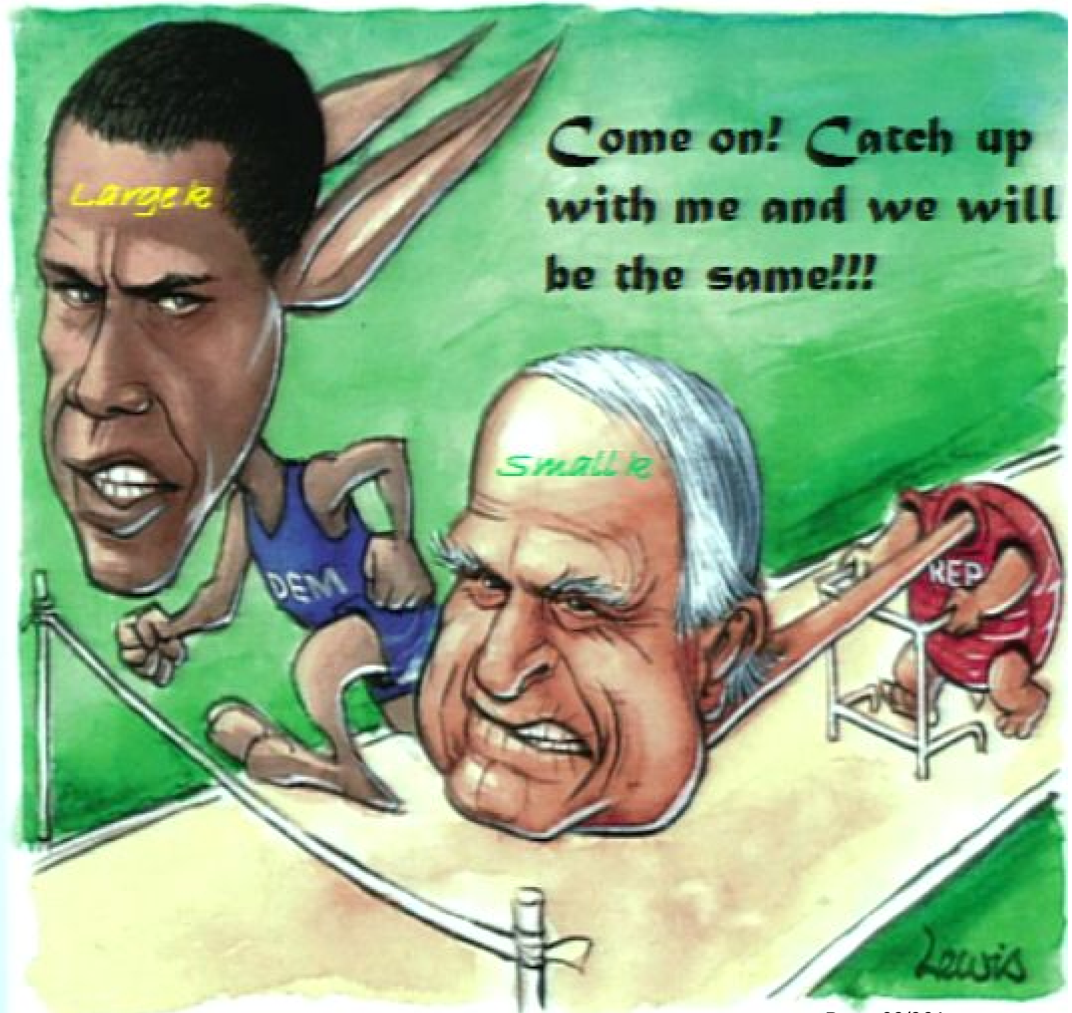

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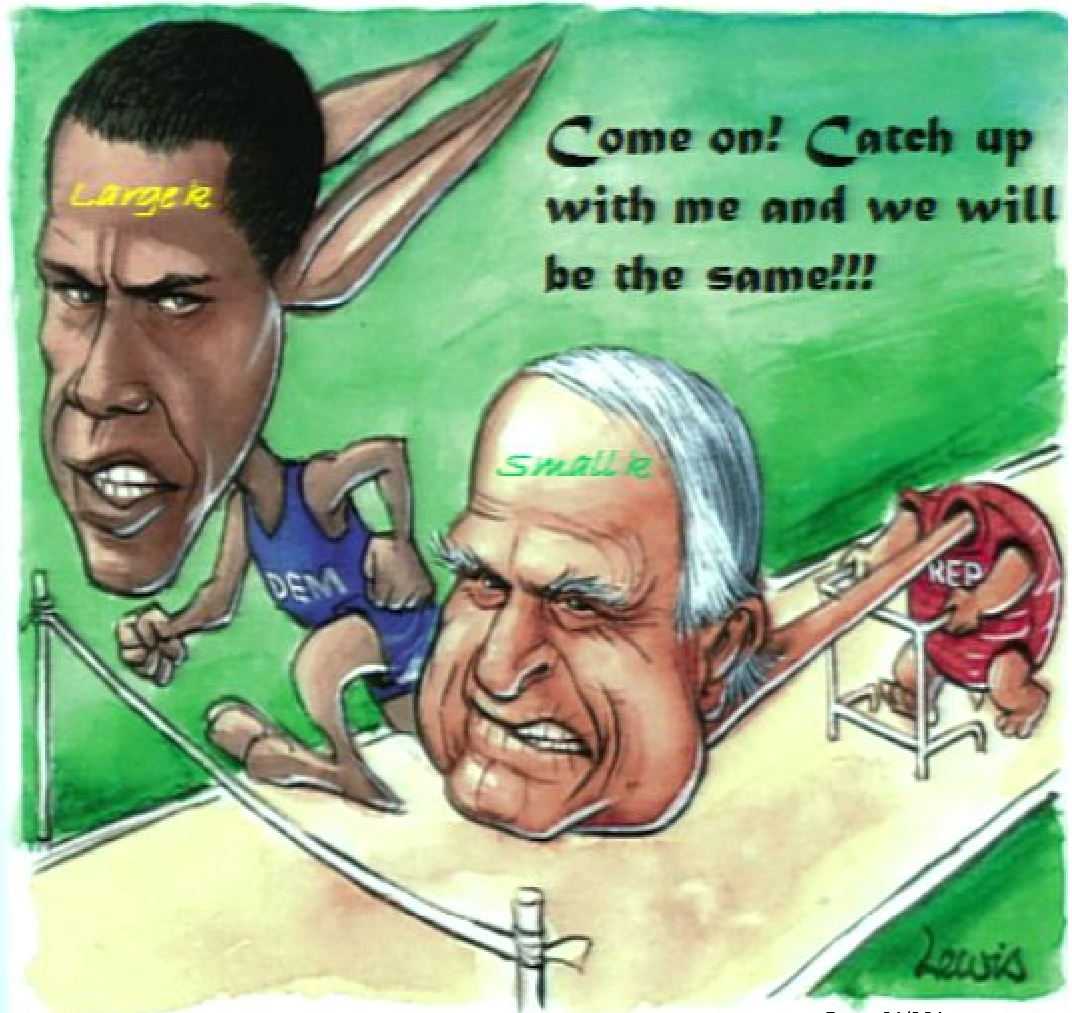

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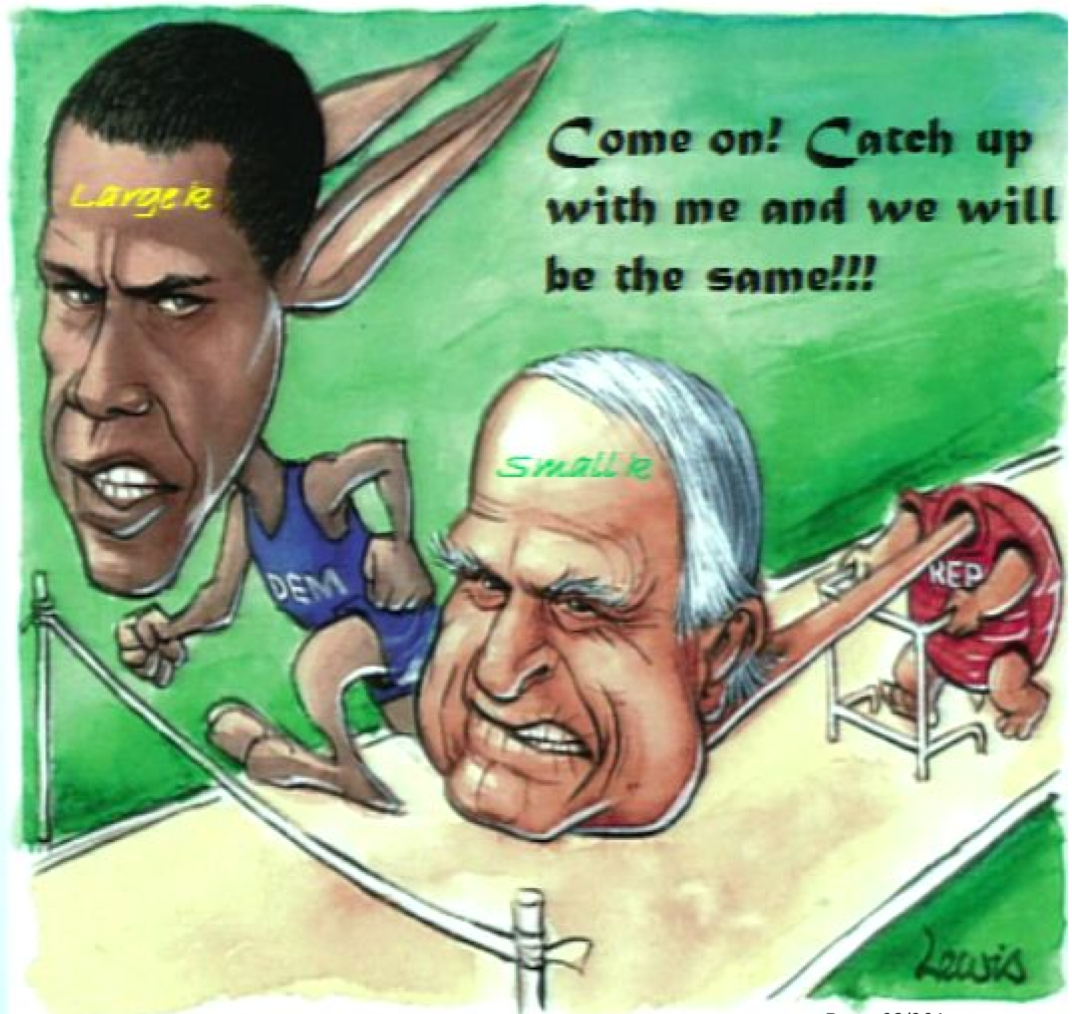

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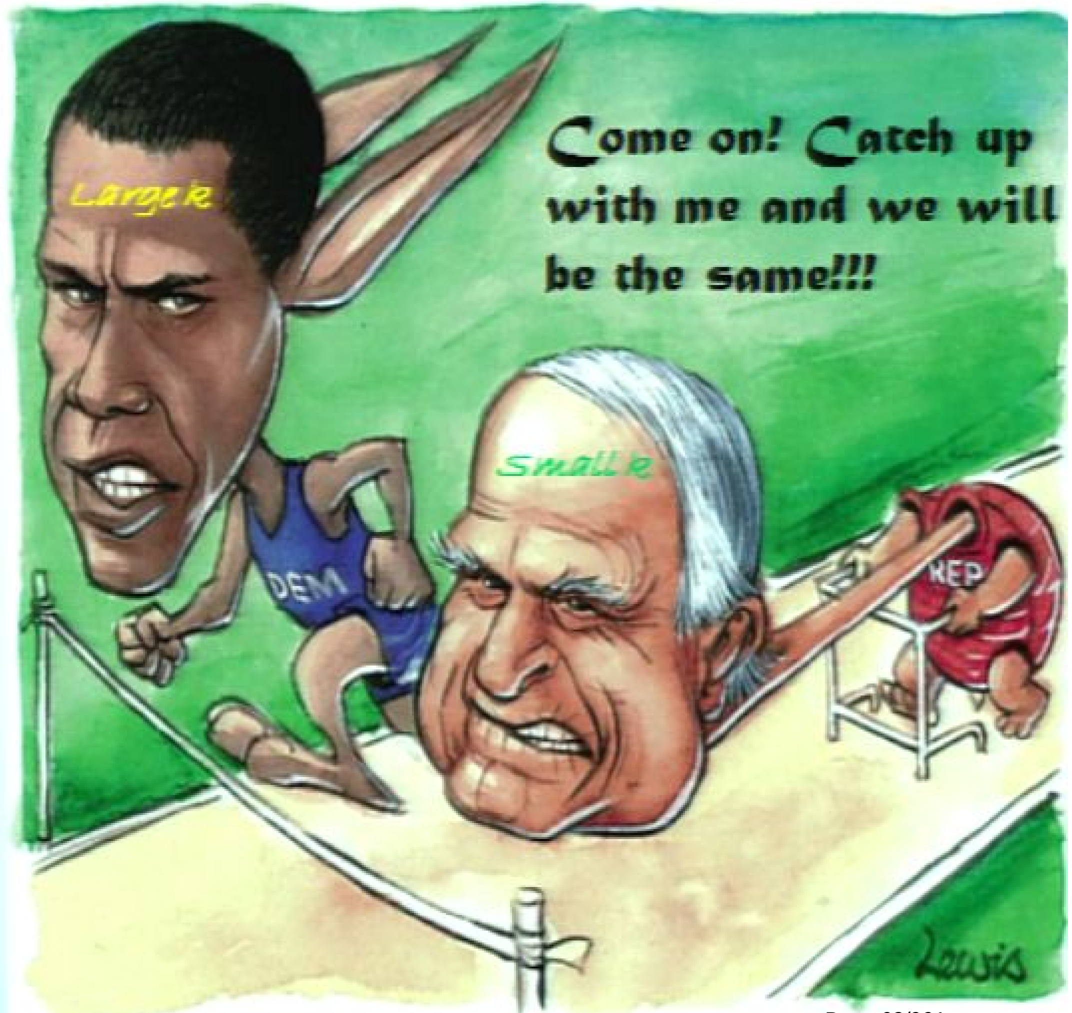

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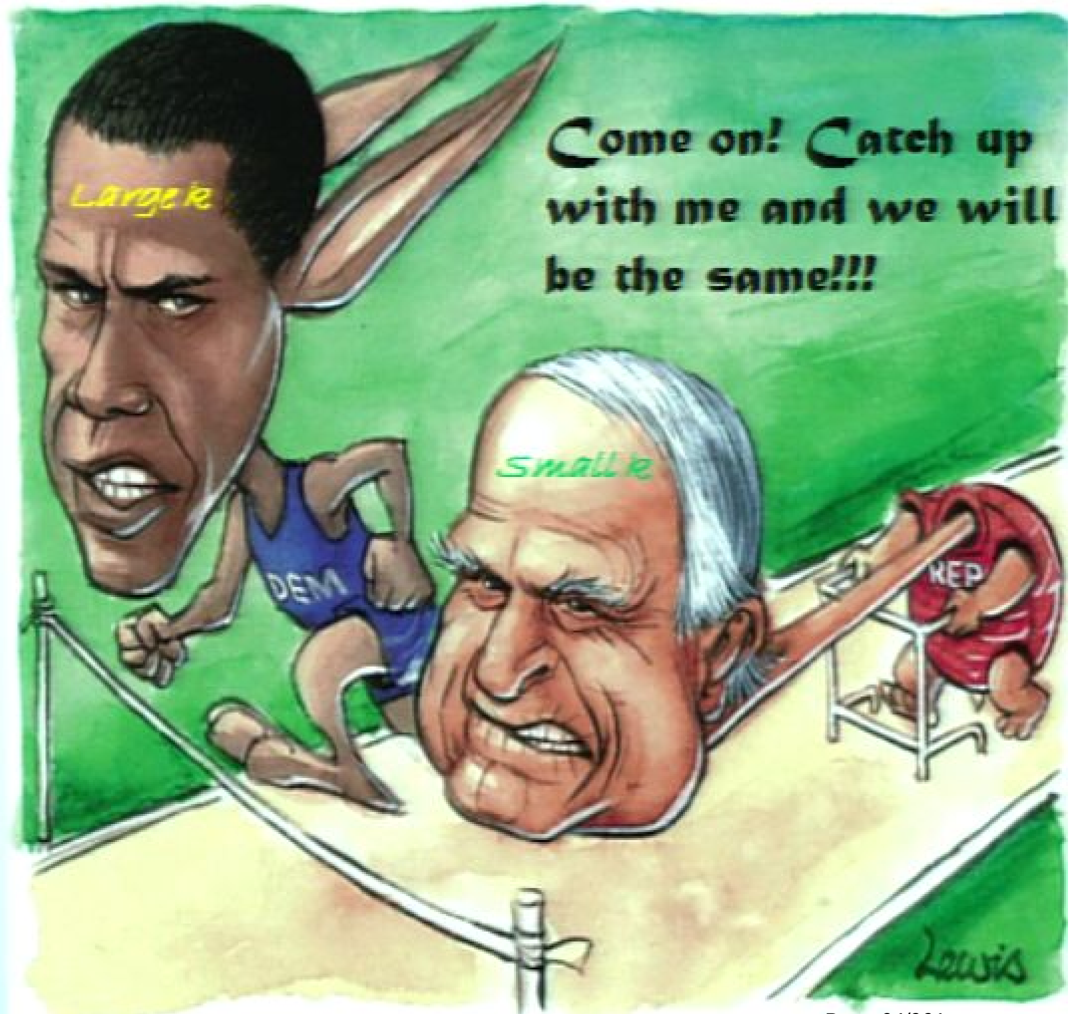

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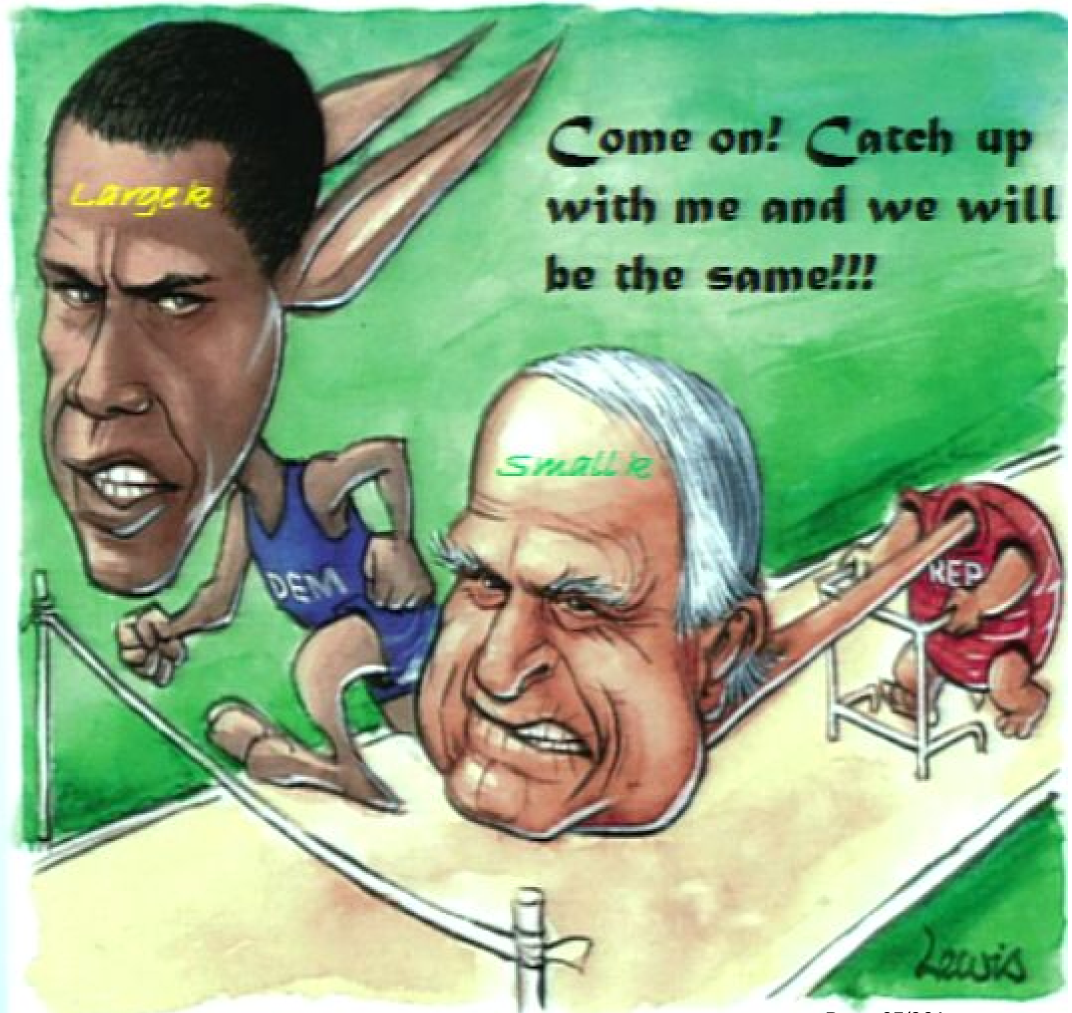

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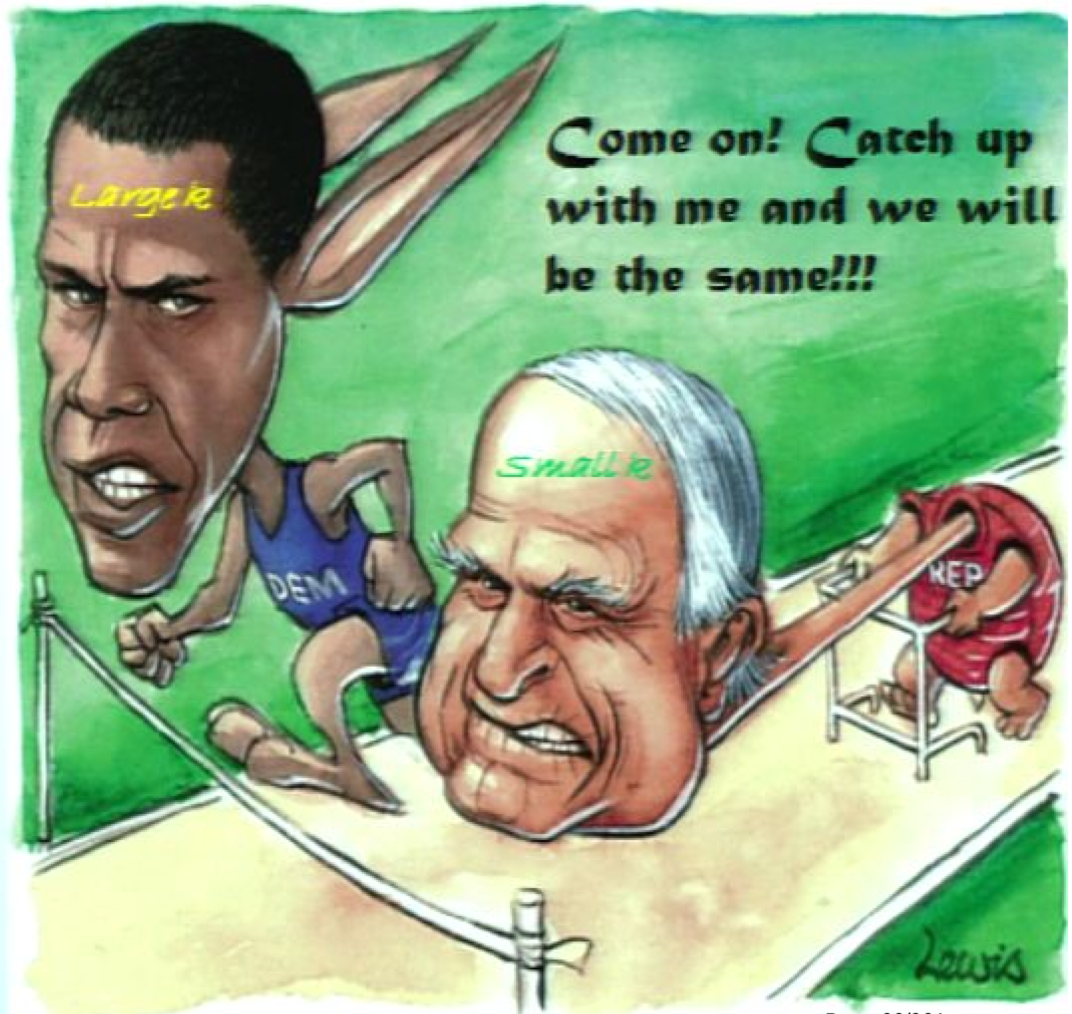

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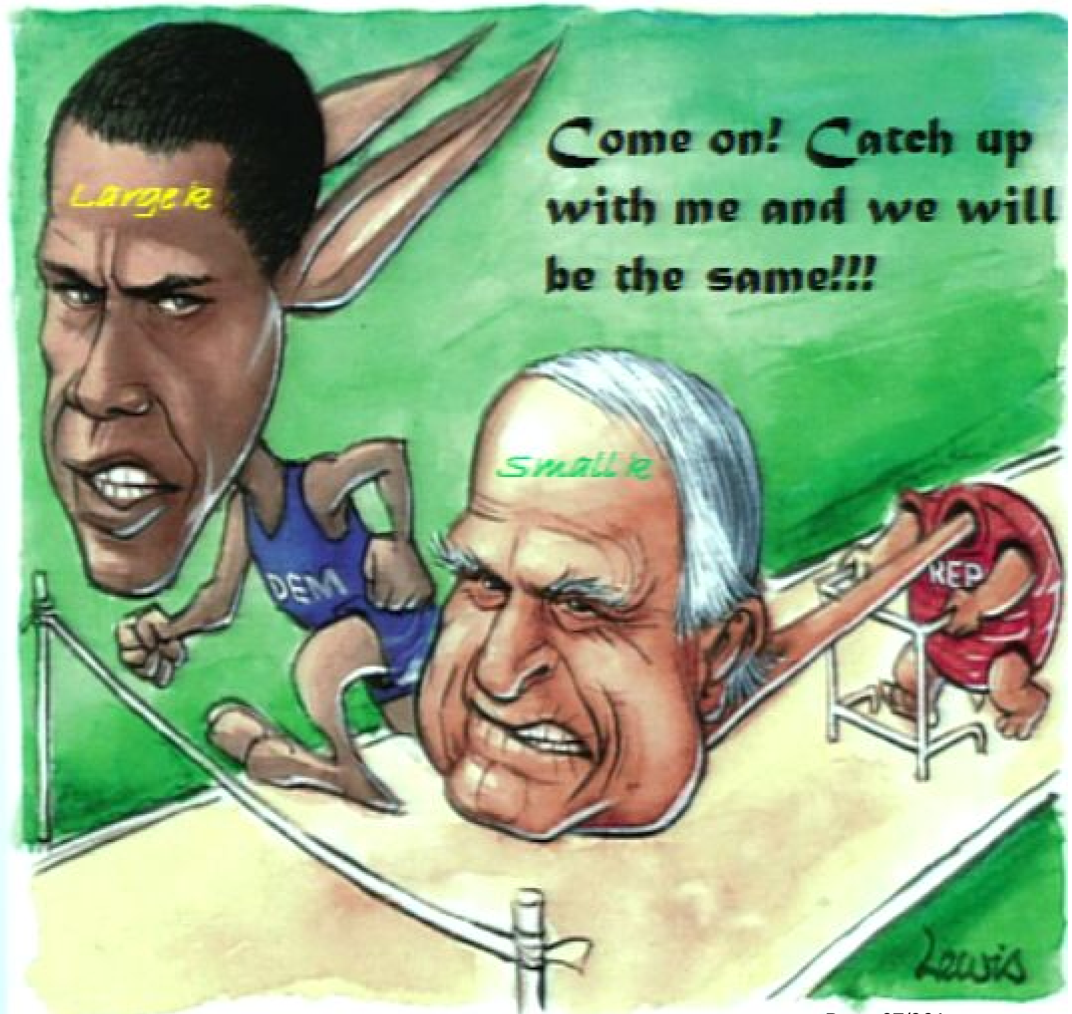

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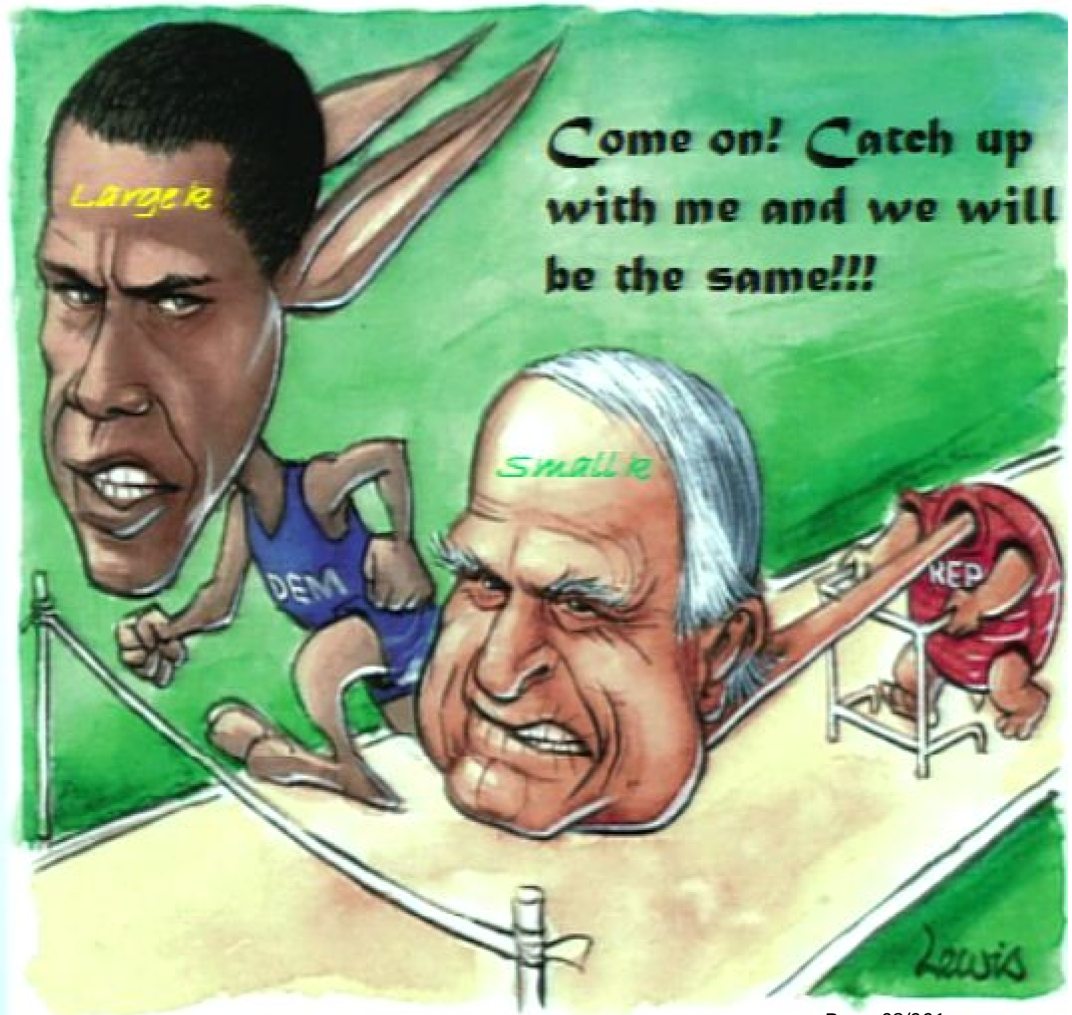

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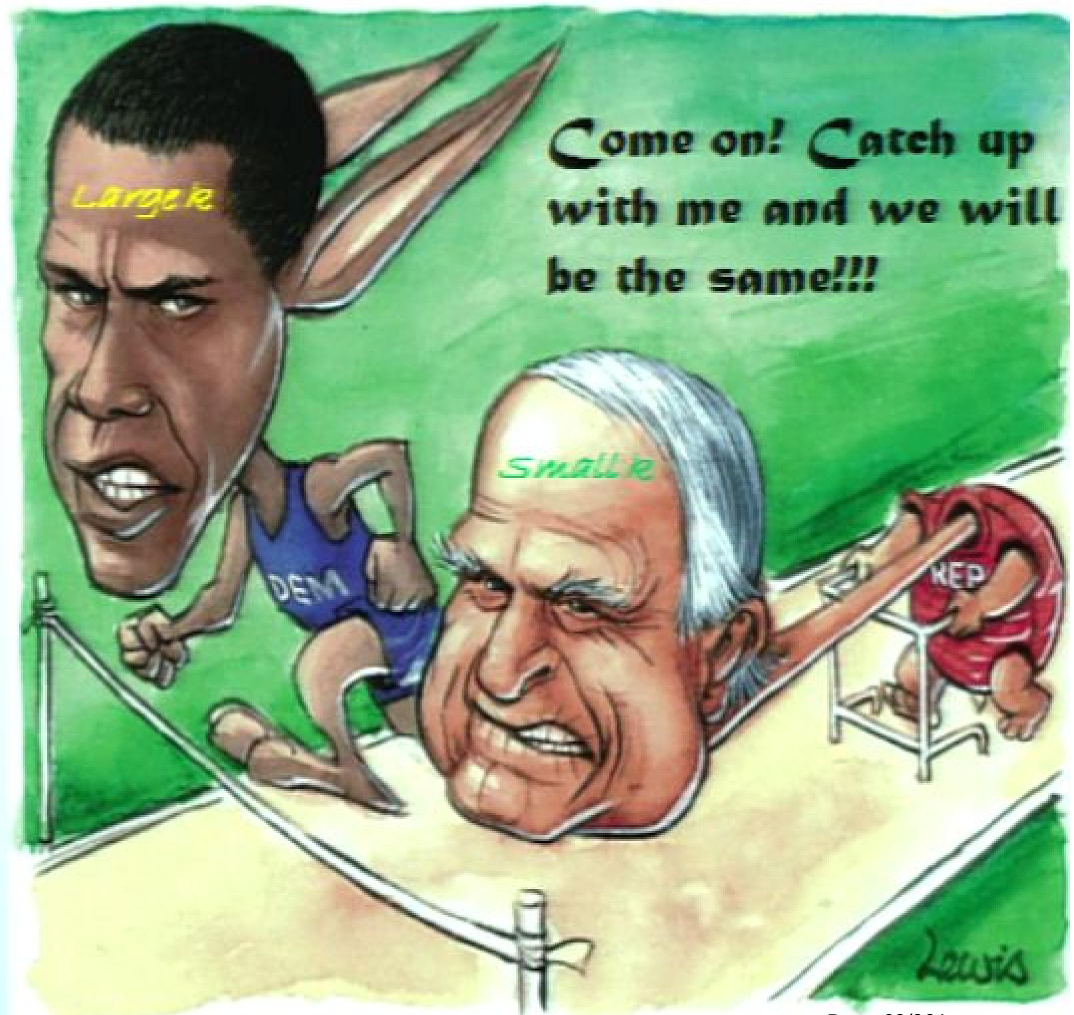

Matter Bounce

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- Scale invariant spectrum

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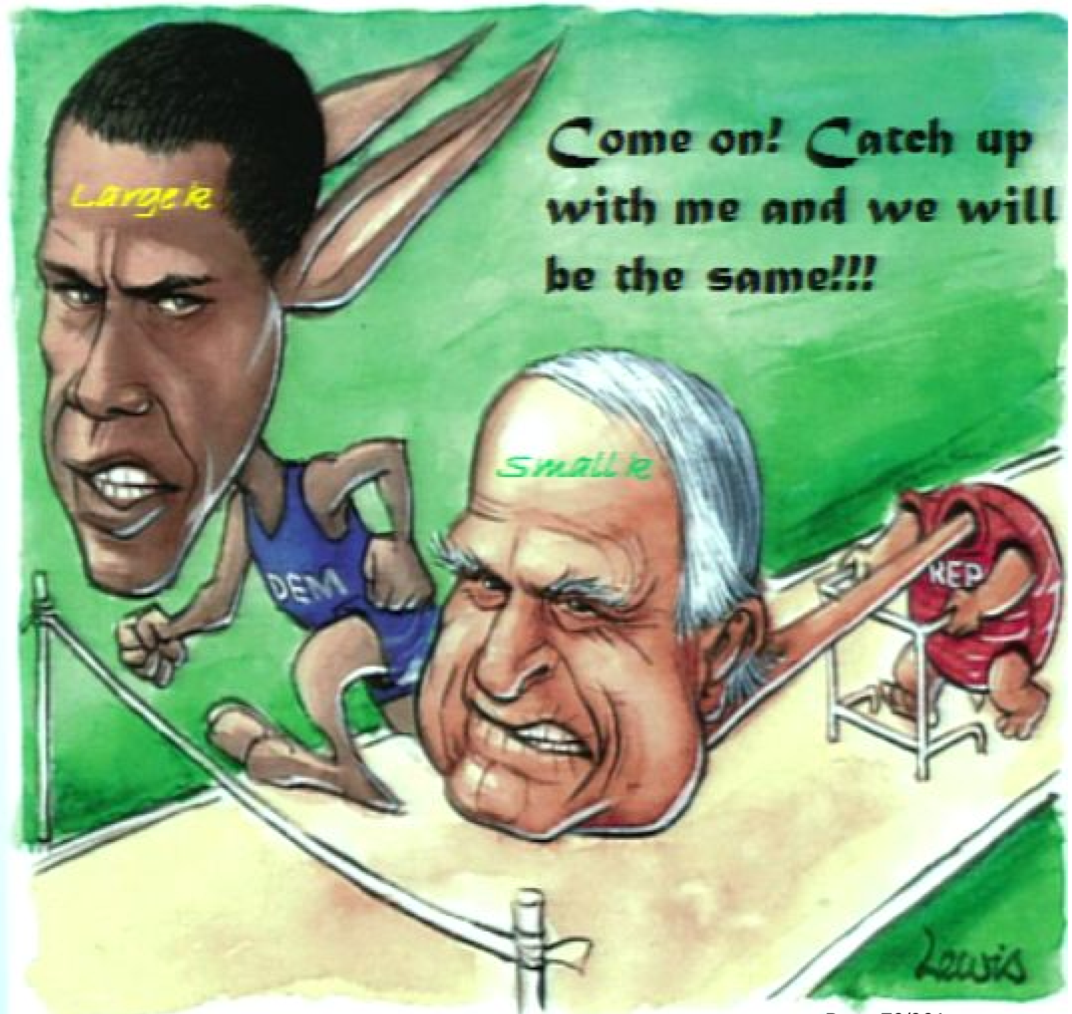

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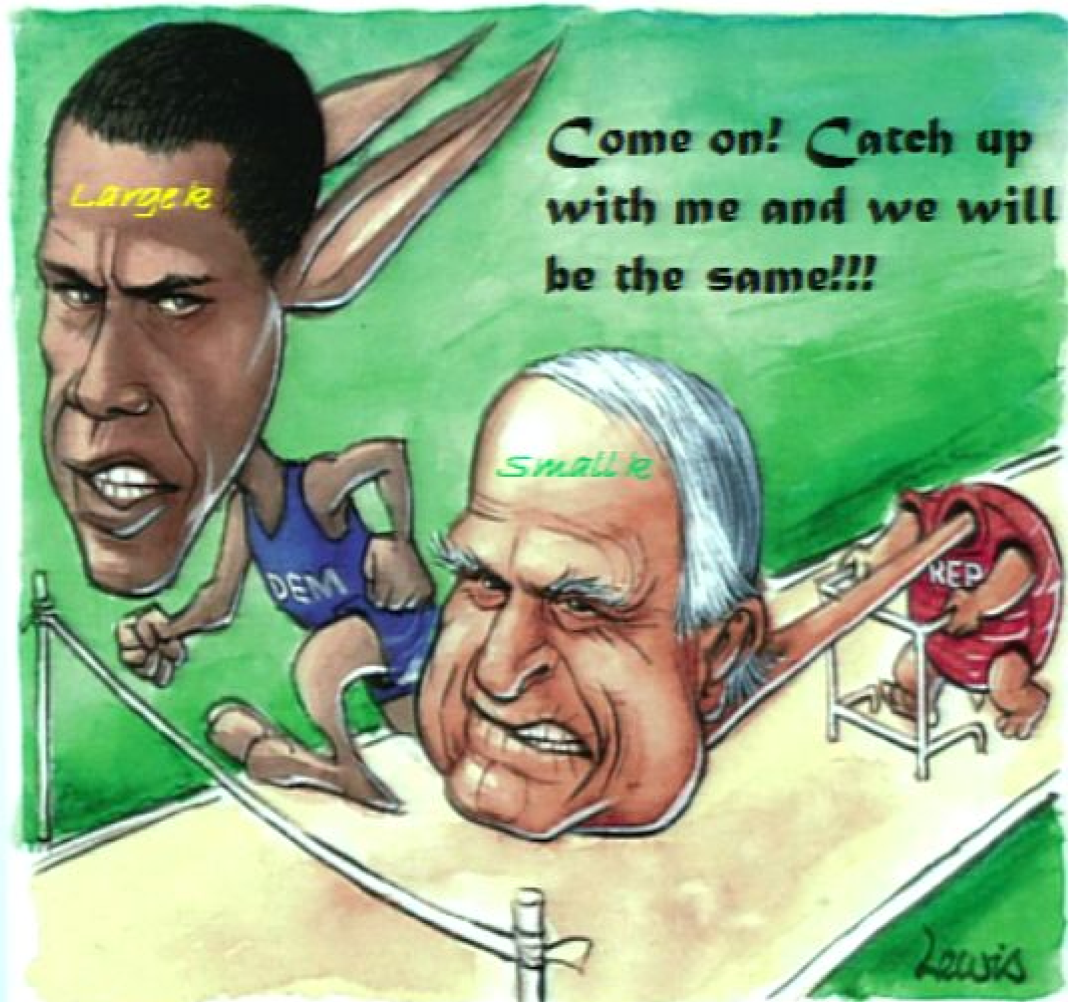

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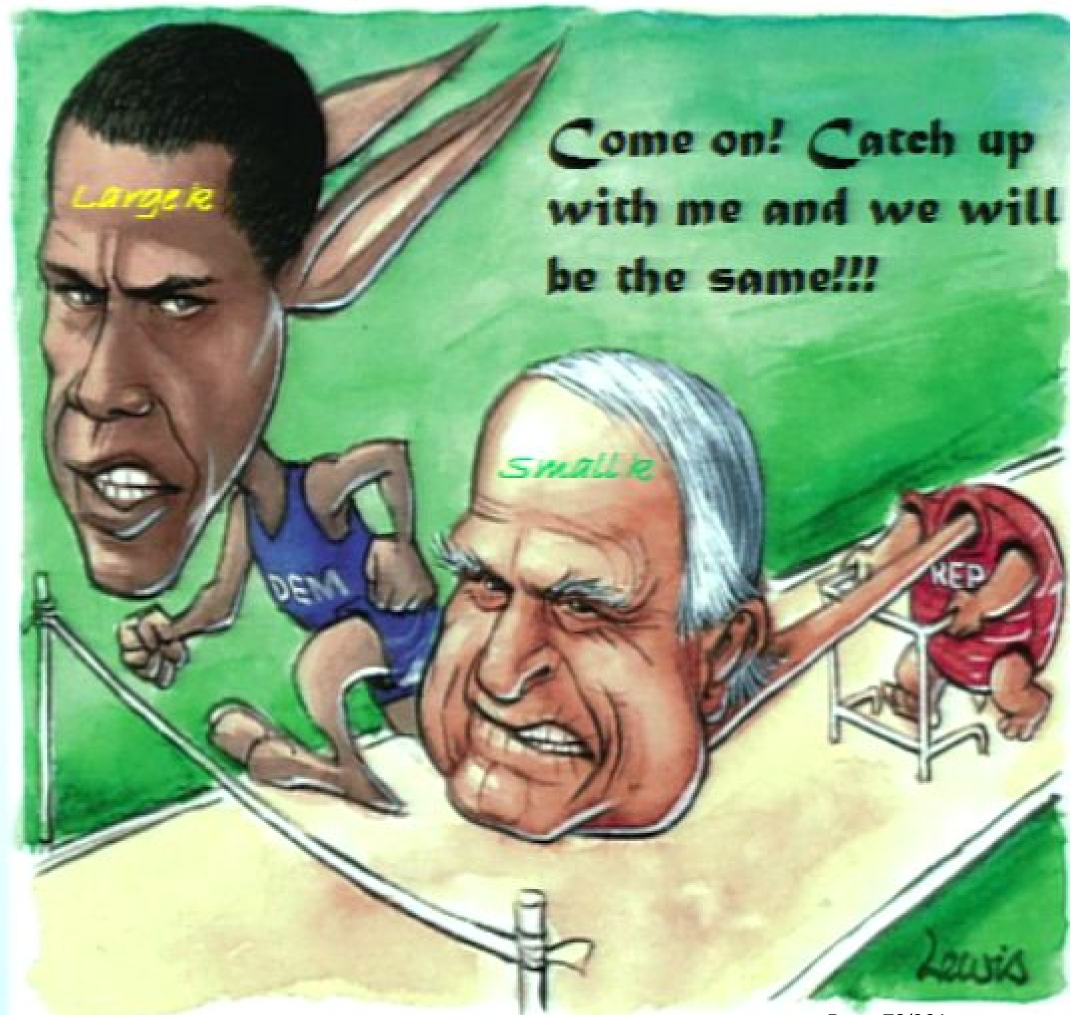

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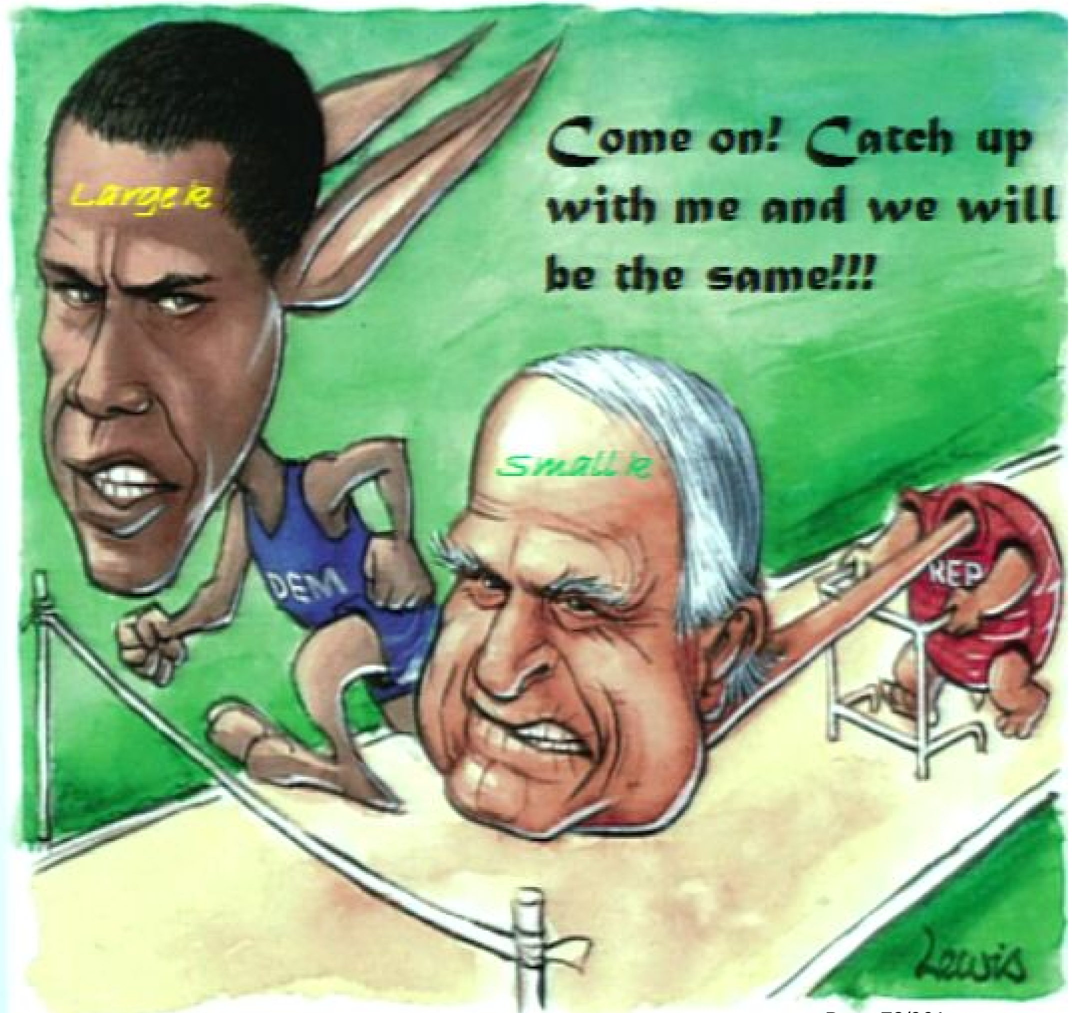

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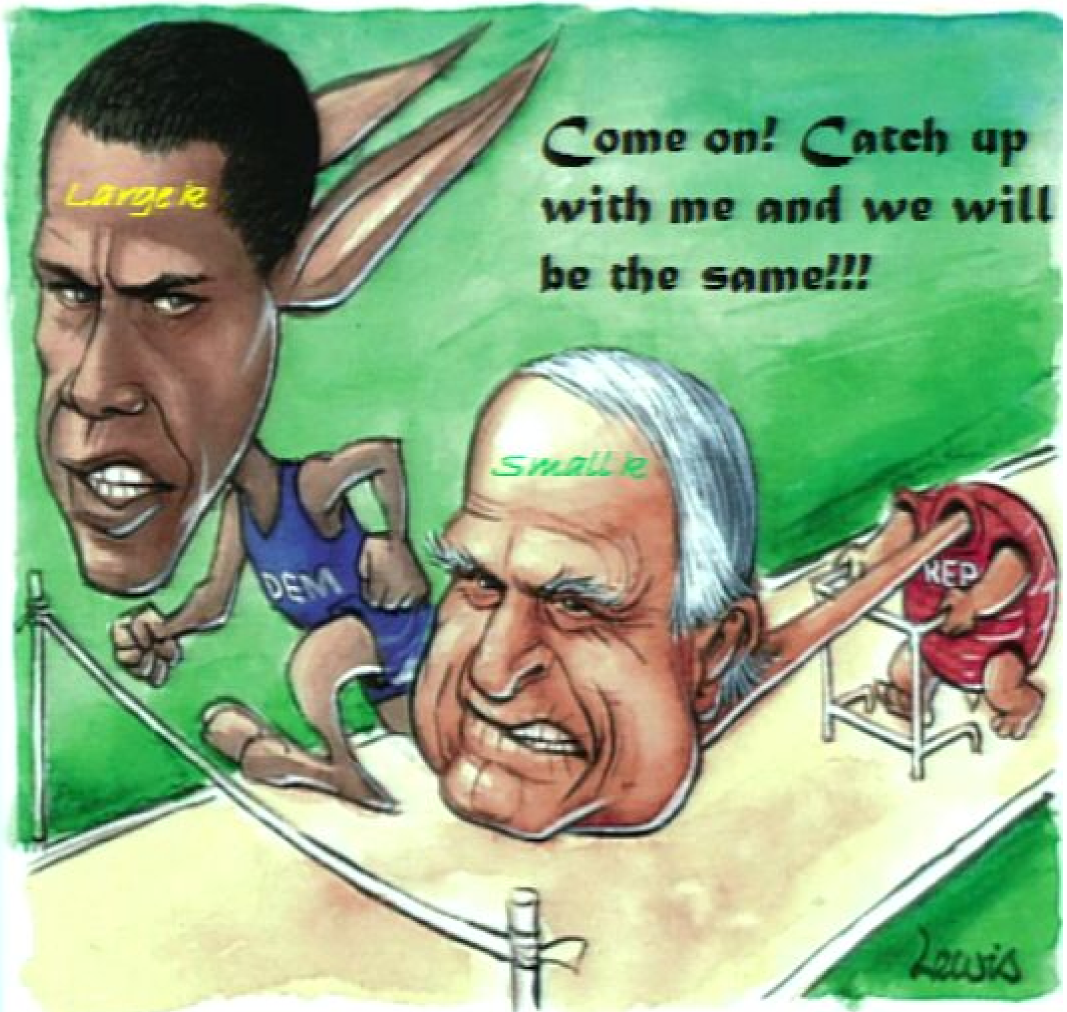

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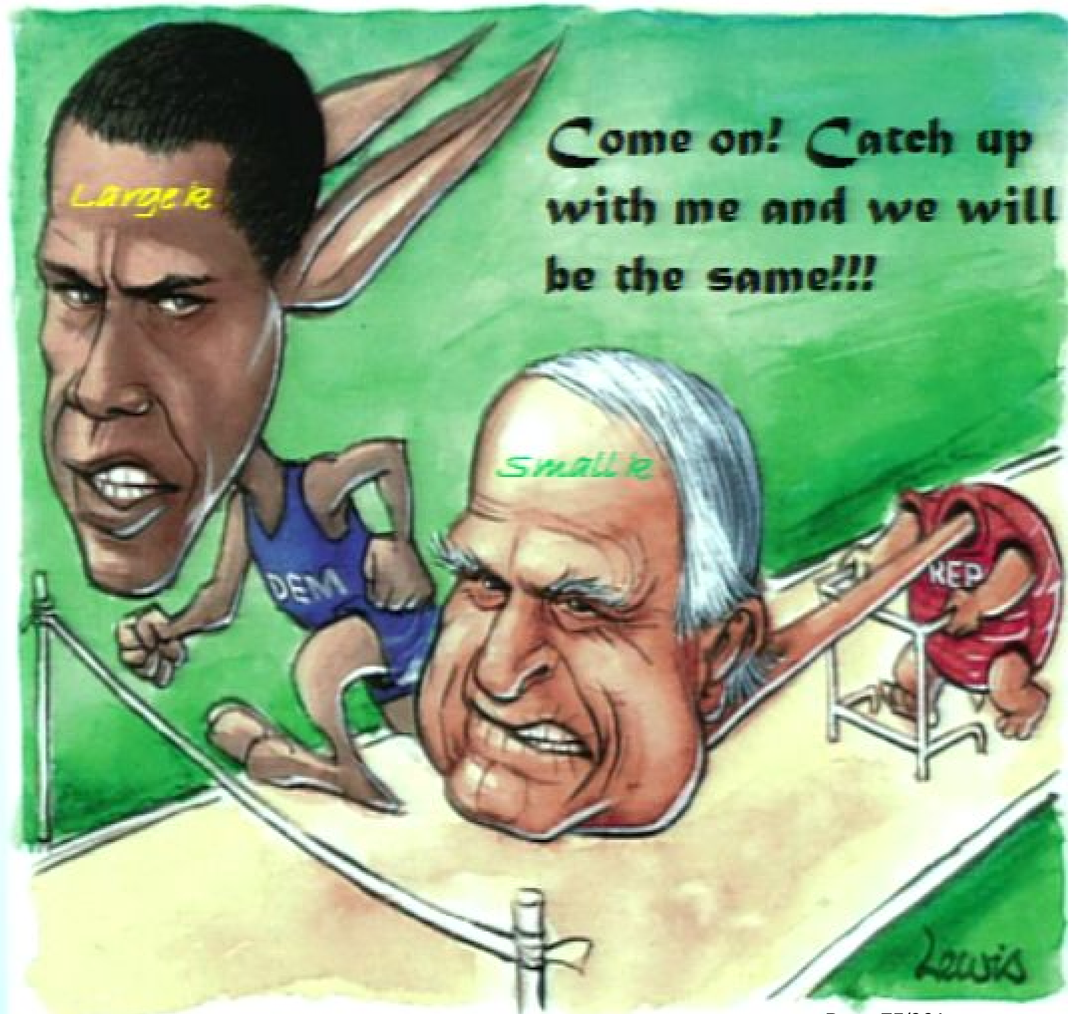

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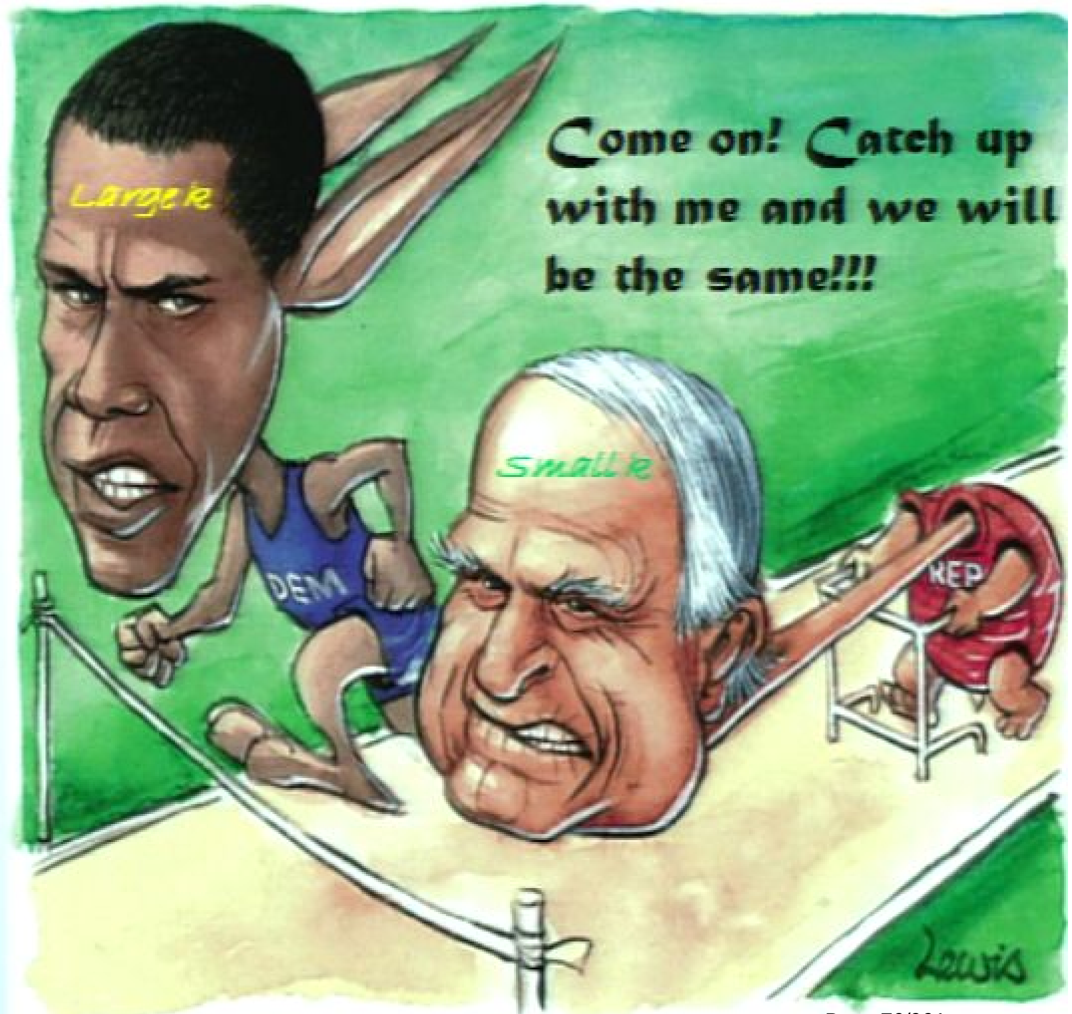

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Ghost condensation

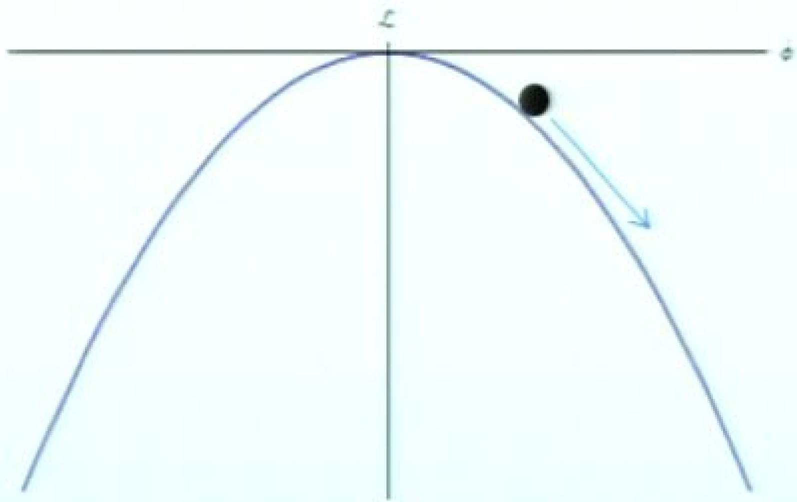
Part II

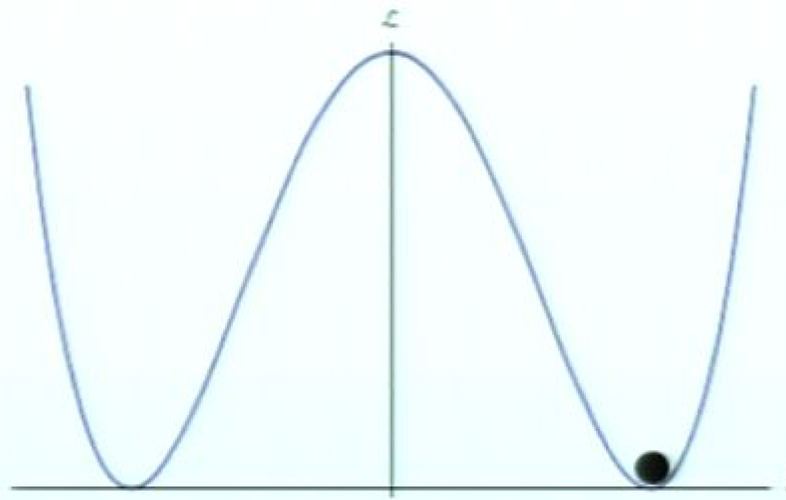
Ghost Condensation Theory

Ghost Condensation

$$L = -\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi + \ldots$$

$$P = \frac{1}{8}(X - c^{2})^{2}, \quad X = \partial^{\mu}\phi\partial_{\mu}\phi$$





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$$V_{tachyon} = -\frac{1}{2}m^{2}\phi^{2} + \lambda\phi^{4} + \ldots$$

Higher order potential (kinetic) terms stablize vacuum.

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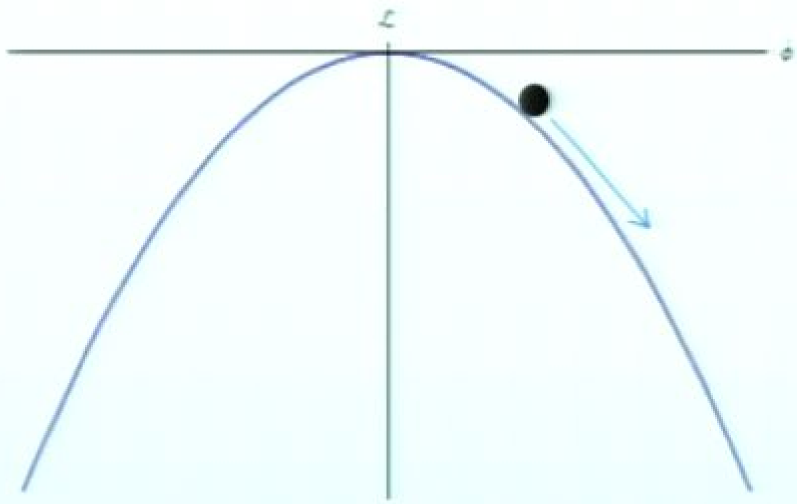

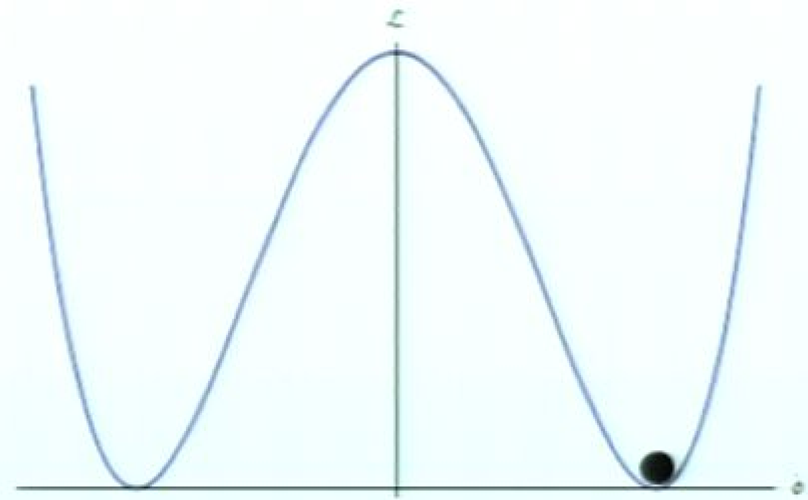

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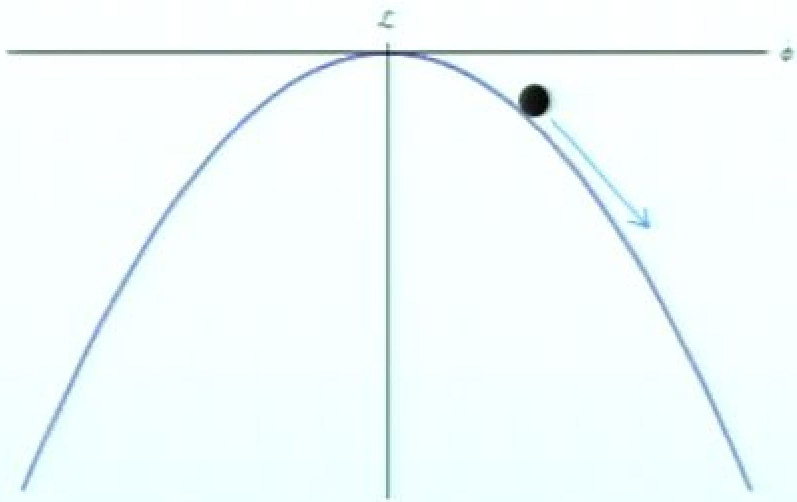

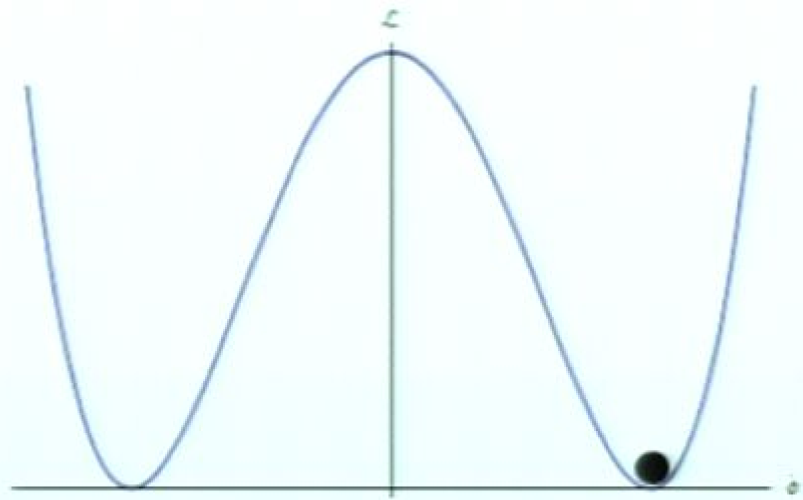

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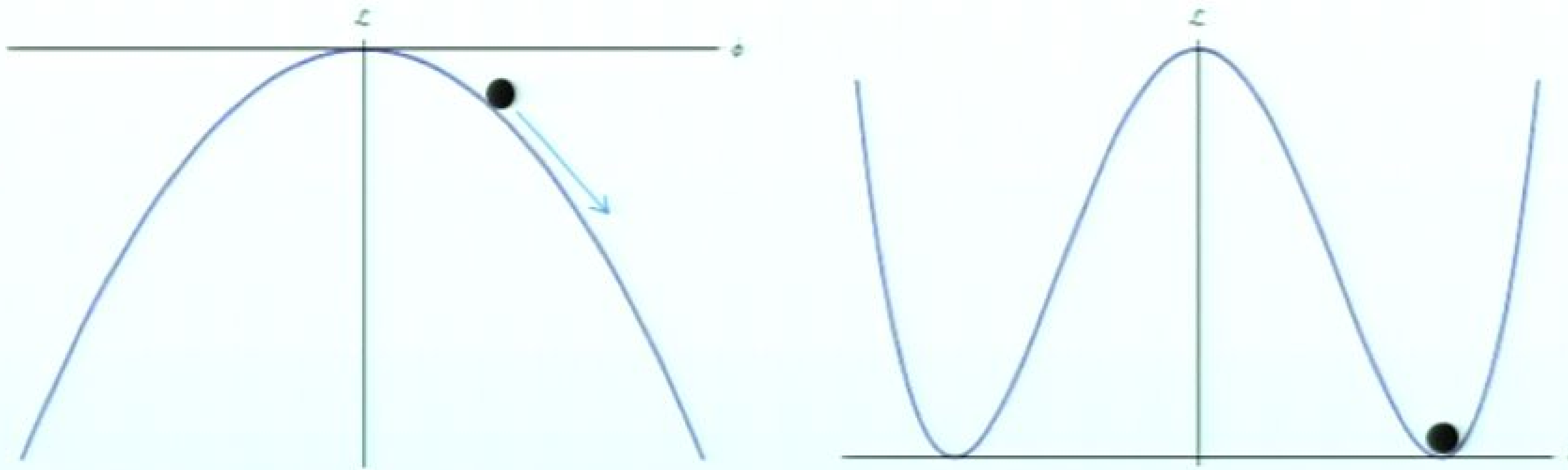

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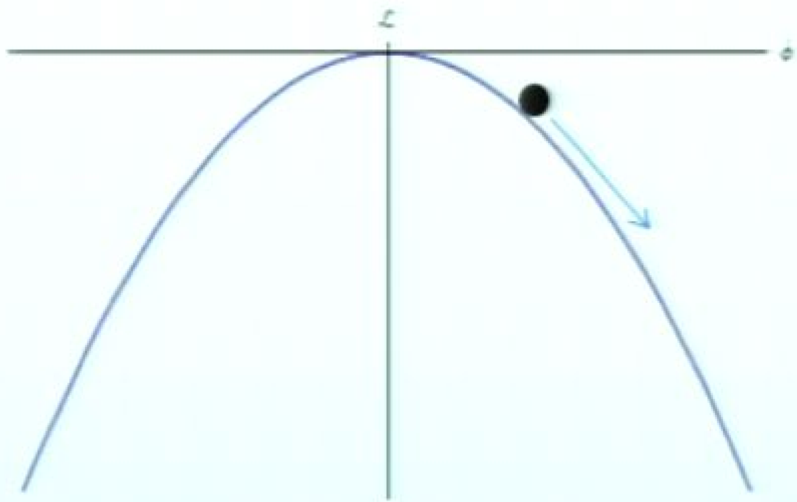

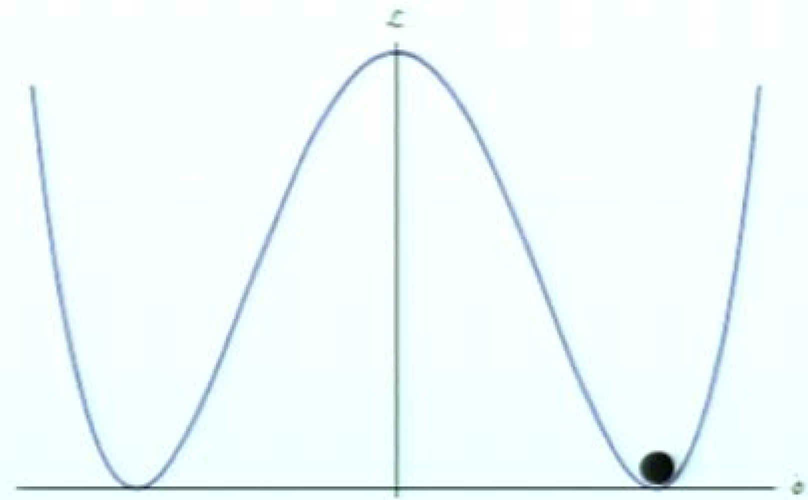

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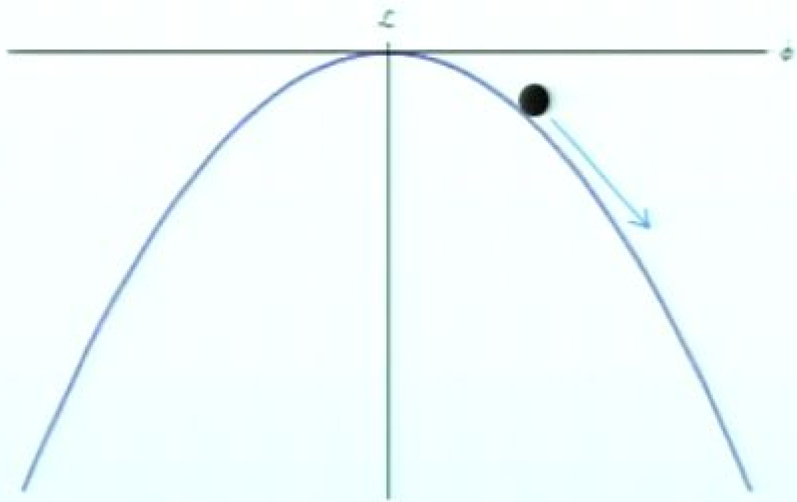

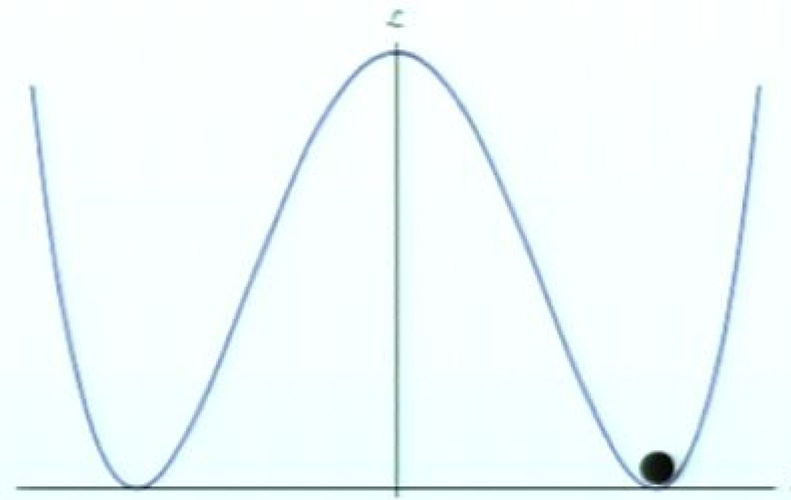

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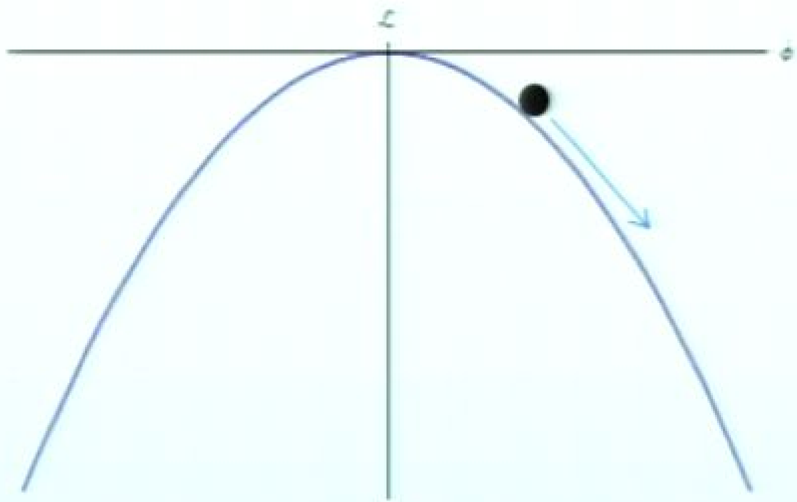

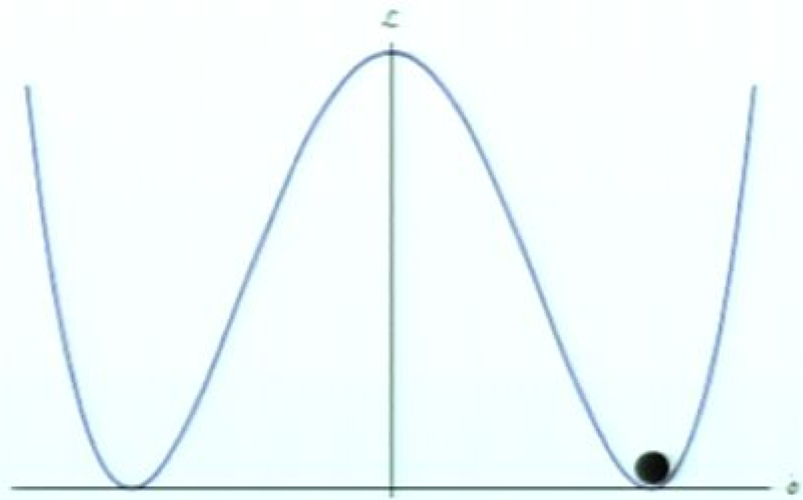

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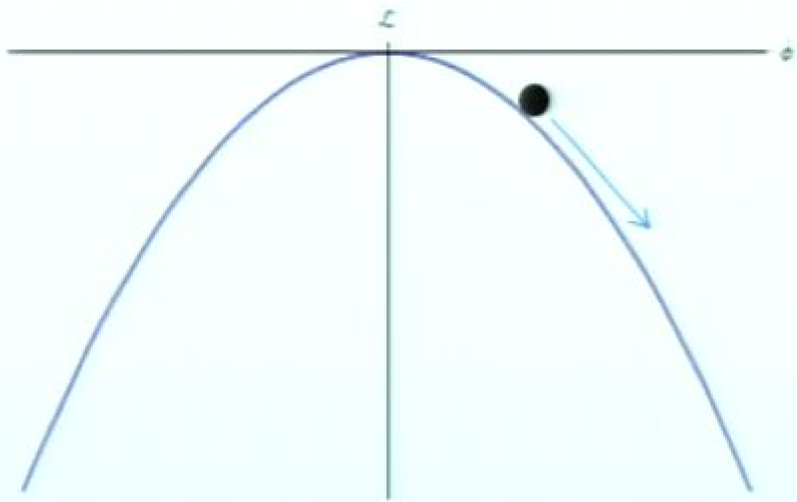

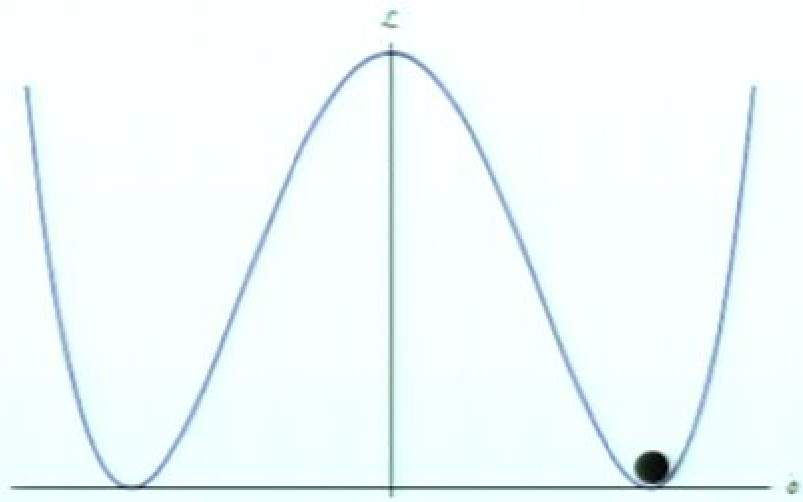

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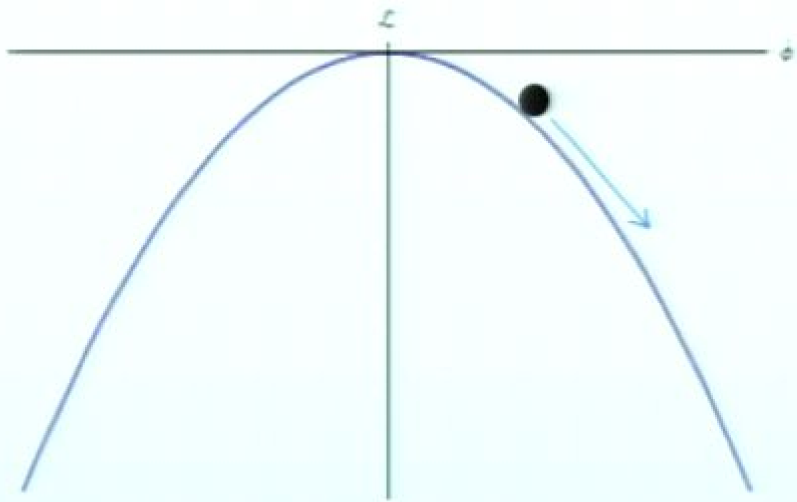

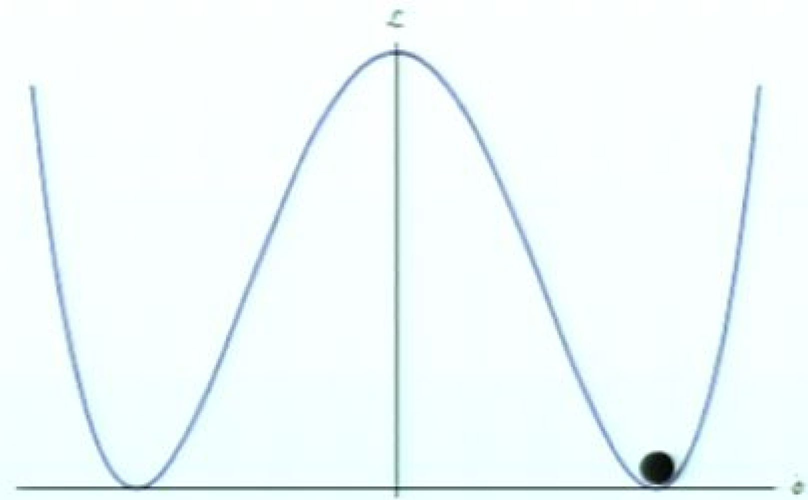

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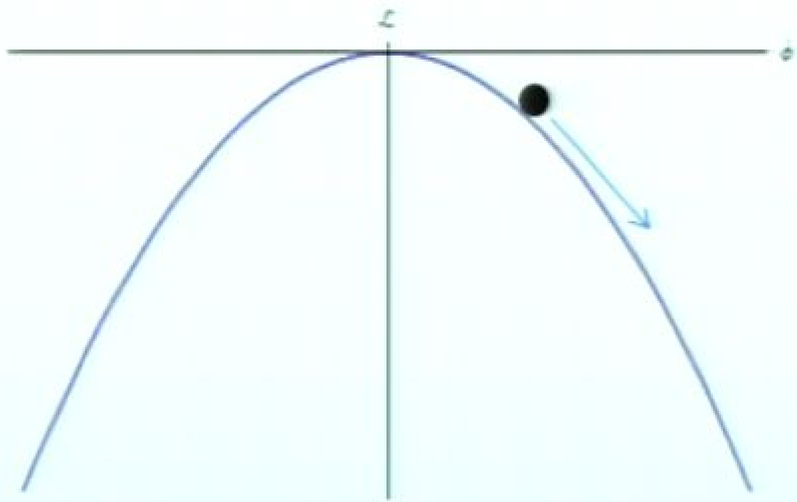

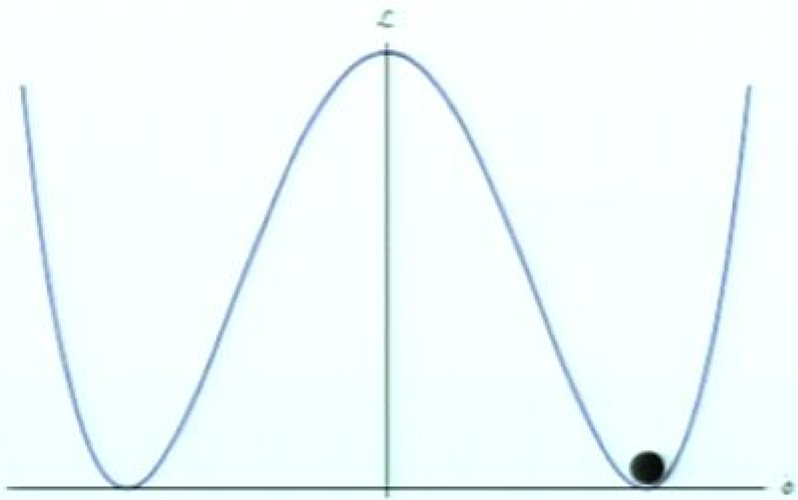

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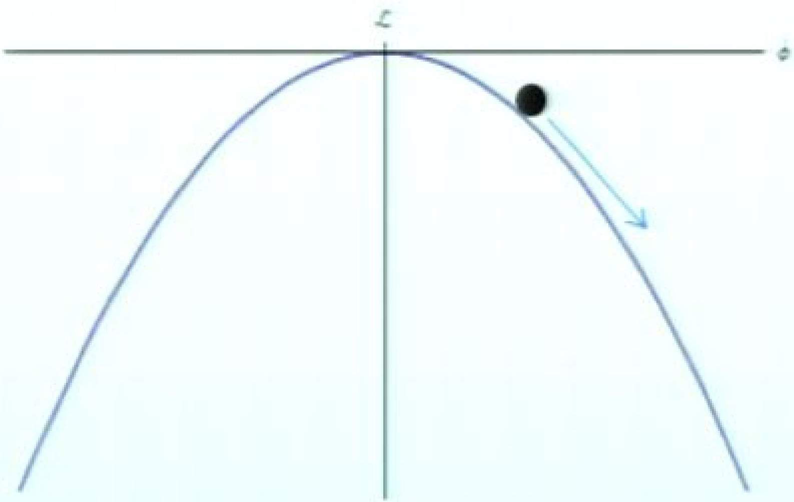

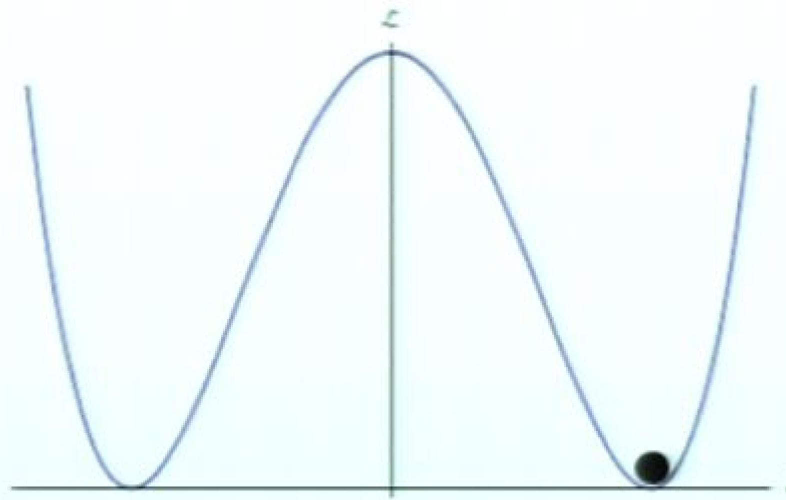

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Inflation, Dark Energy	Dark matter
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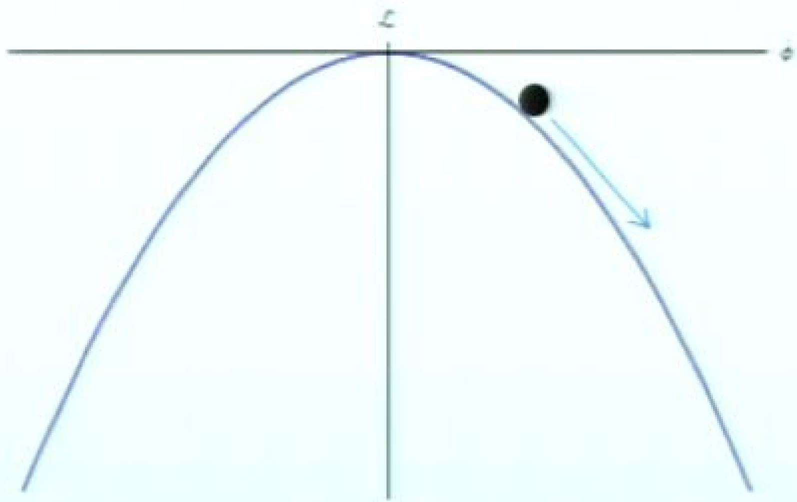

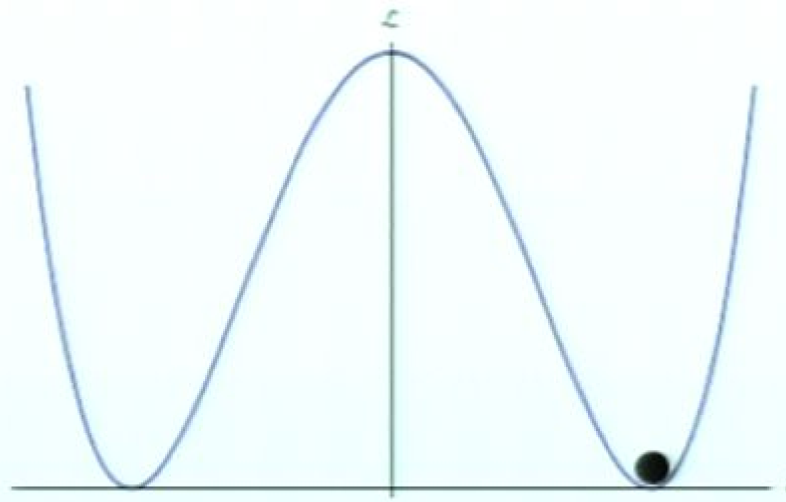

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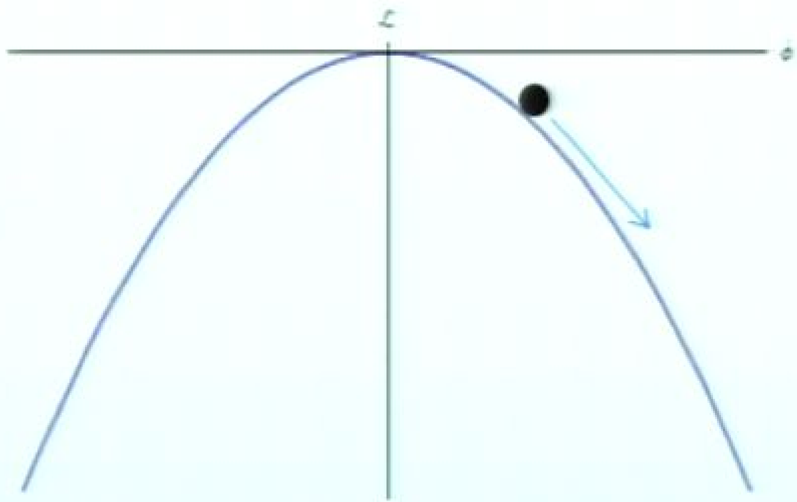

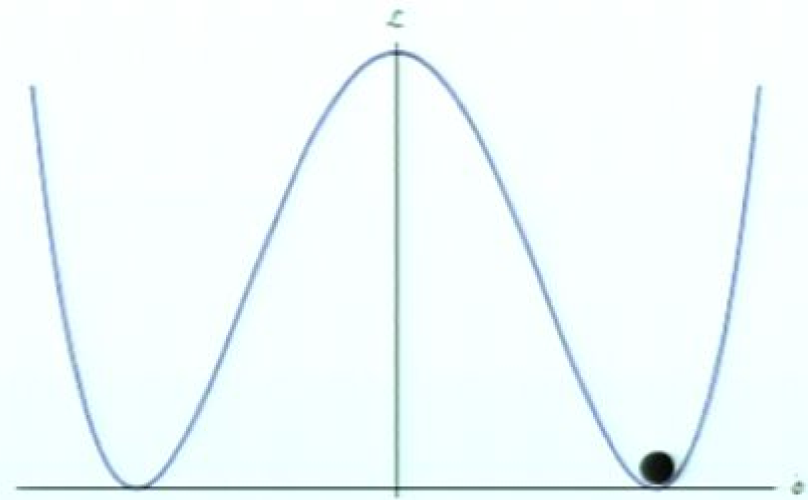

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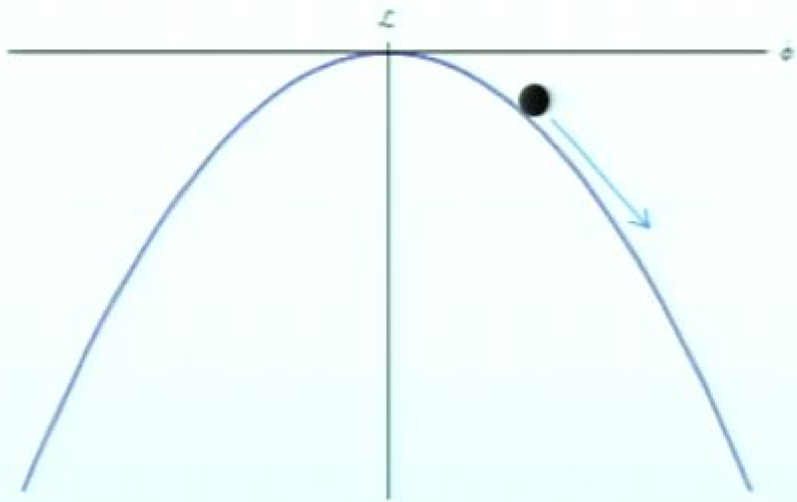

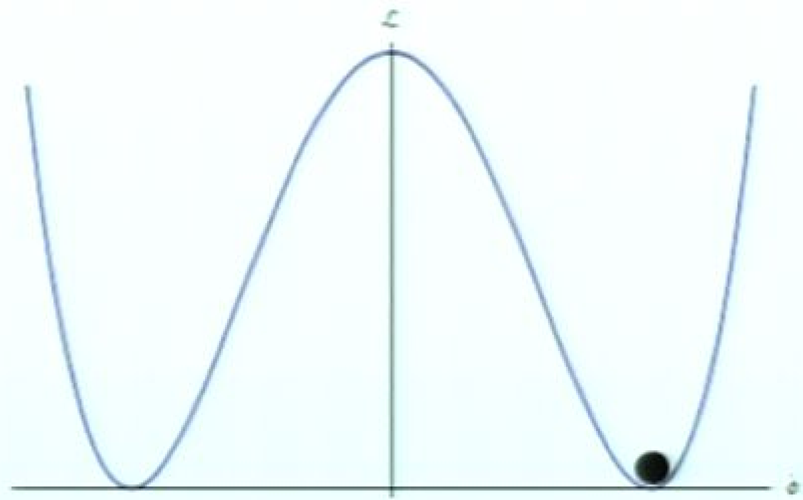

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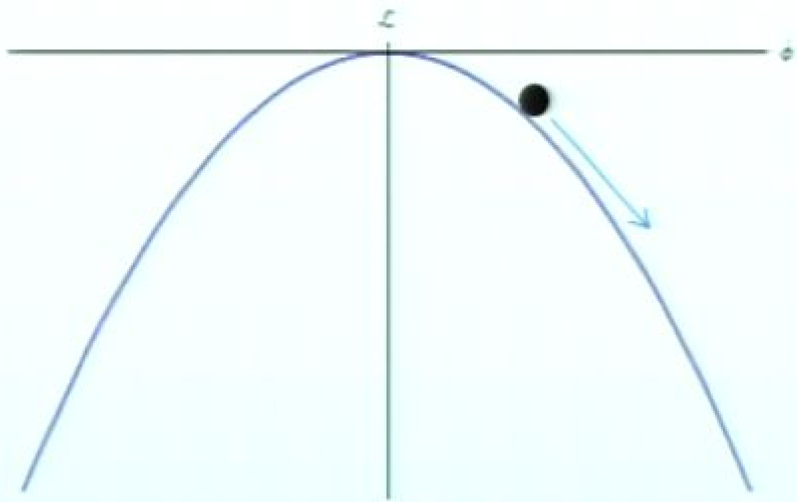

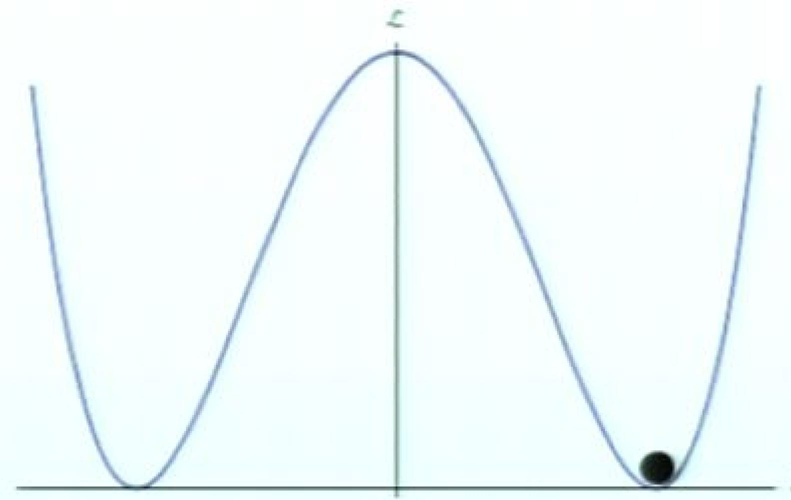

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$$w = -1$$

Inflation, Dark Energy

$$P'(X) \neq 0, \quad \mathrm{P}(X) = 0$$

$$T_{00} \sim M^4 P' \sim a^{-3}, \quad T_{ij} = 0$$

$$w = 0$$

Dark matter

res

Application

$$T_{\mu\nu} = -M^4 P(X) g_{\mu\nu} + 2M^4 P'(X)\partial_\mu$$

$\partial^\nu \phi \partial_\mu \partial_\nu \phi + \cdots .$

excitation

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Da

Matter Bounce

Interesting features

More generally,

$$\mathcal{L} = M^4 P(X) + M^2 S_1(X)(\Box\phi)^2 + M^2 S_2(X)\partial^\mu\partial^\nu\phi\partial_\mu\partial_\nu\phi + \cdots .$$

Ghost field locate at the minima, with scalar excitation

$$\phi = ct + \pi$$

Low energy effective action for π is

$$S \sim \int d^4x \left[\frac{1}{2}\dot{\pi}^2 - \frac{1}{2M^2}(\nabla^2\pi)^2 + \cdots\right].$$

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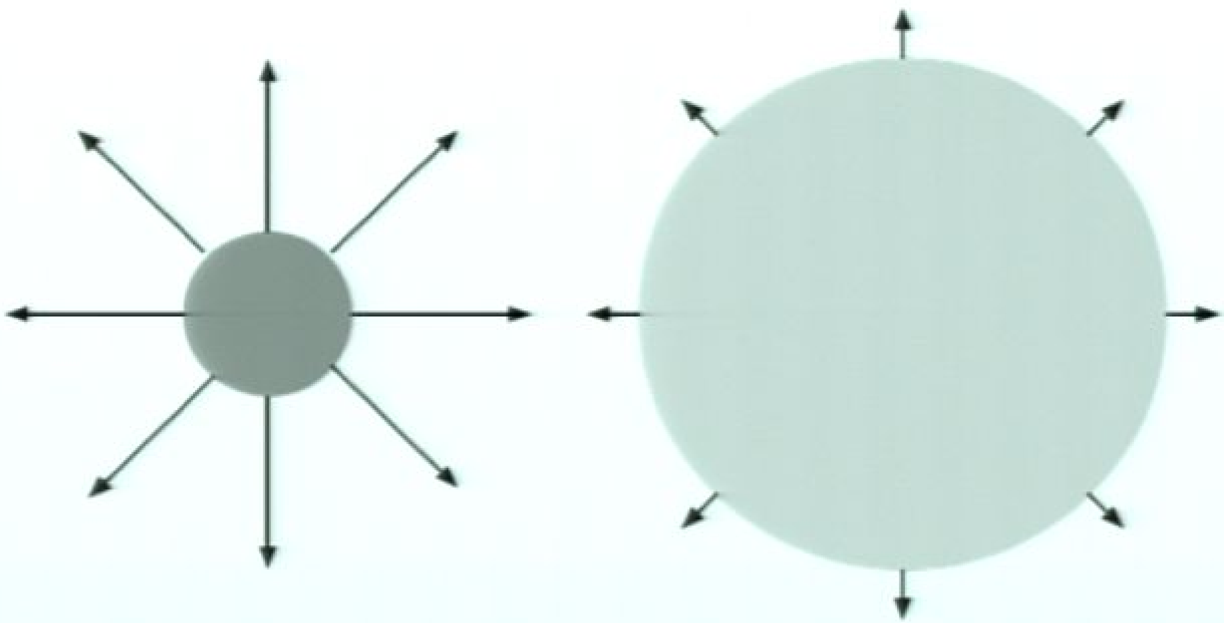

➢ Small lumps expand faster than larger lumps since $\omega^2 \sim \frac{k^4}{M^2}$.

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Lorentz invariance

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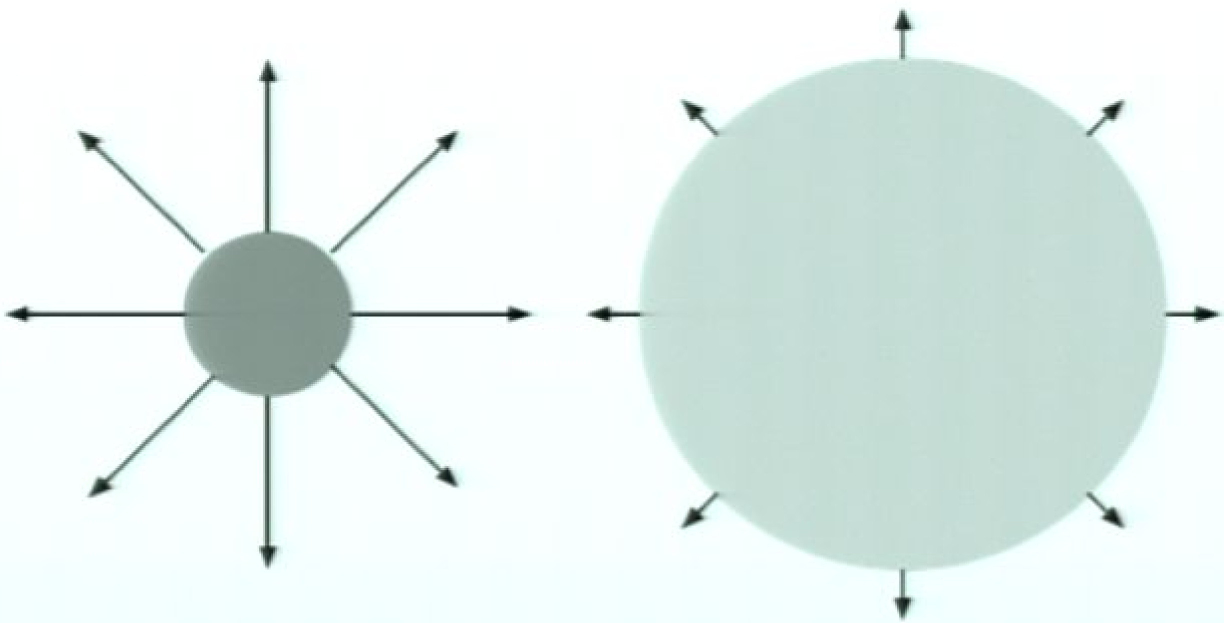

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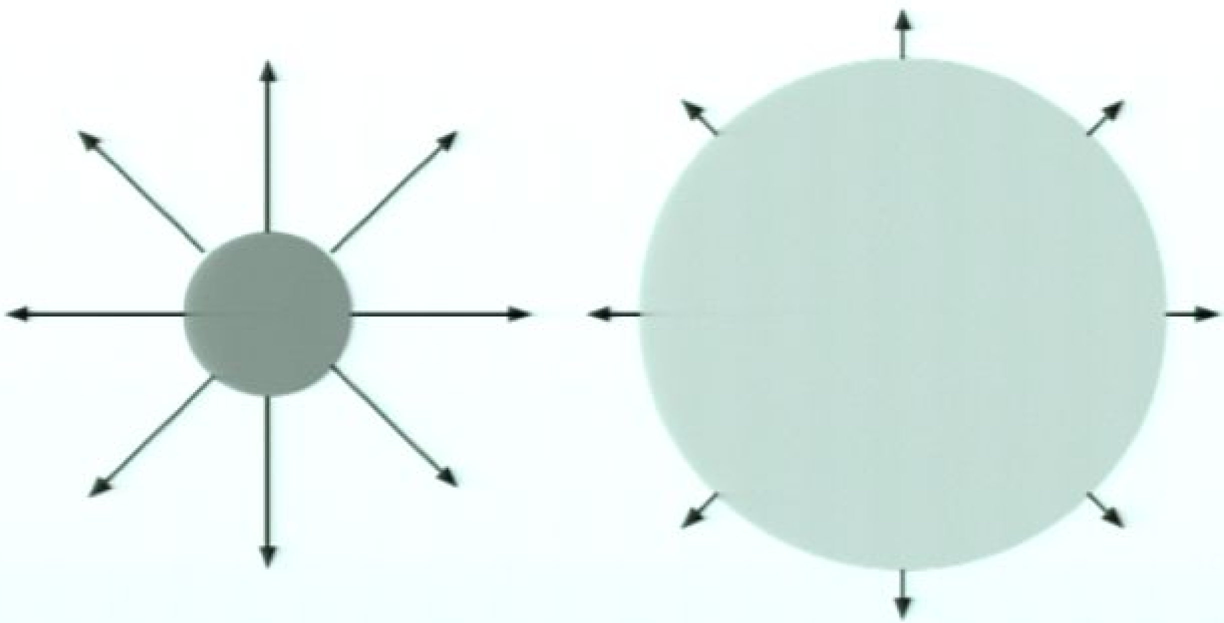

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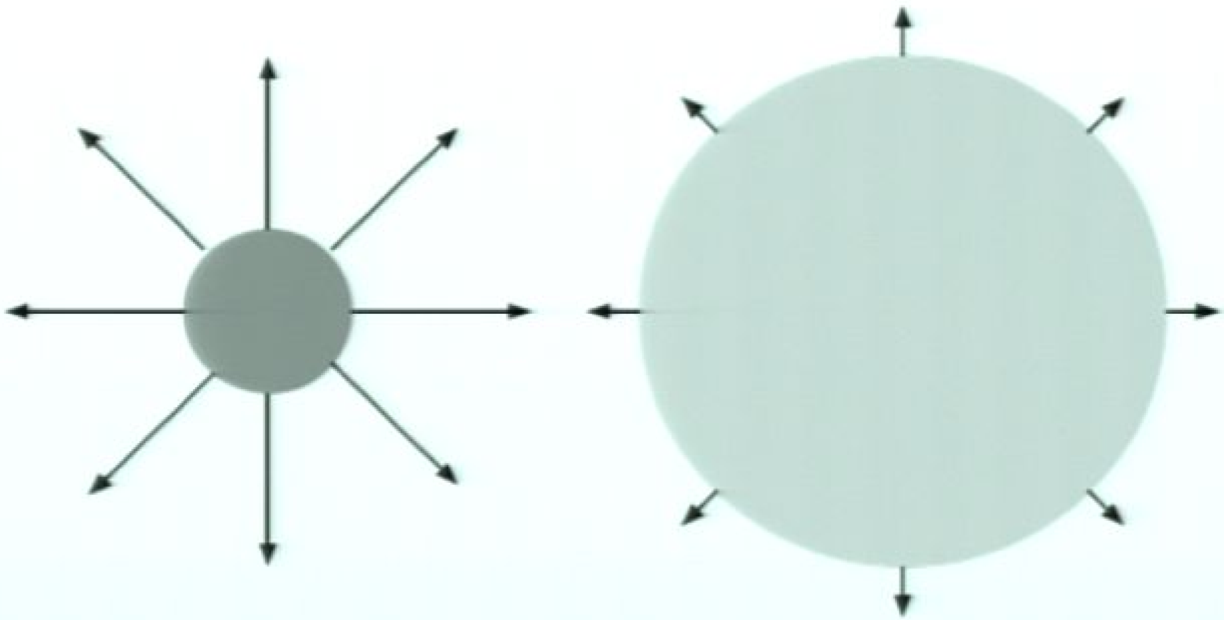

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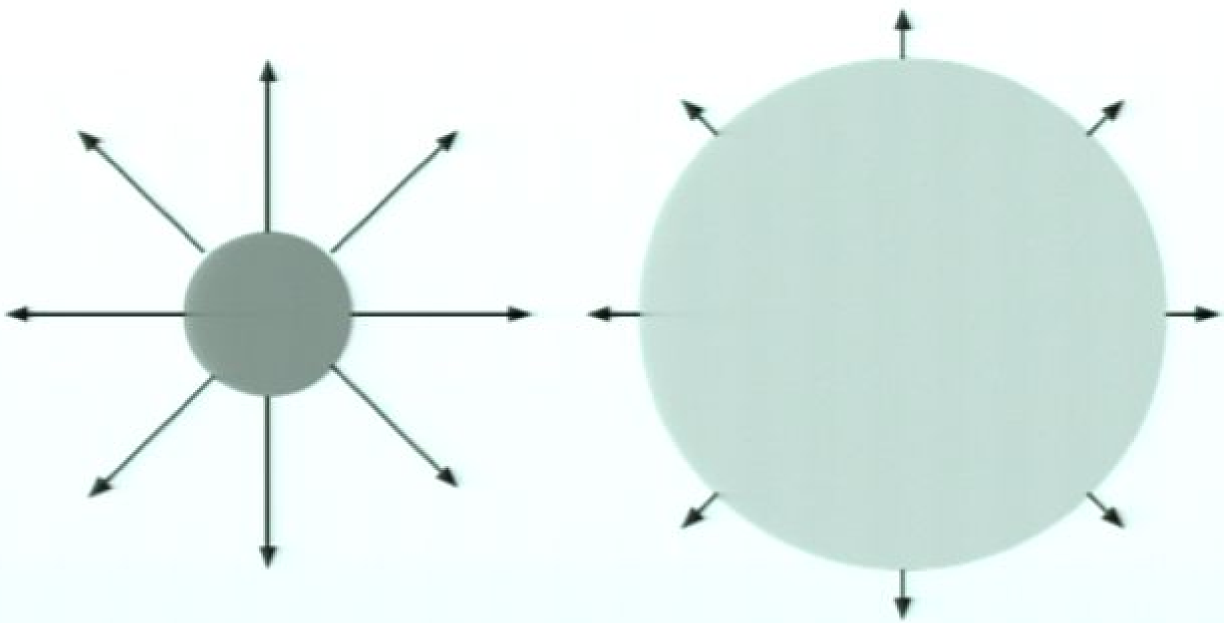

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$$\mathcal{E}_{\rm pp} = \int d^3x\, T_{00} - c_* Q \sim \frac{1}{2}\dot{\pi}^2 + \frac{(\nabla^2\pi)^2}{2M^2} + \cdots$$

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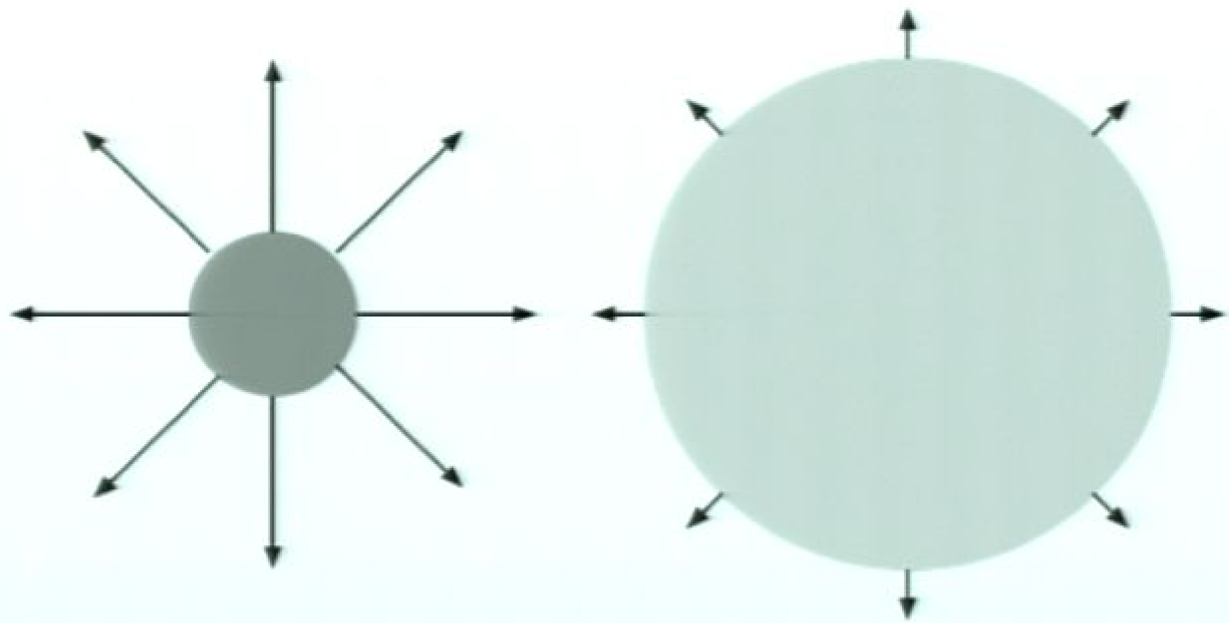

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$$\mathcal{L} = M^4 P(X) + M^2 S_1(X)(\Box\phi)^2 + M^2 S_2(X)\partial^\mu\partial^\nu\phi\partial_\mu\partial_\nu\phi + \cdots .$$

Ghost field locate at the minima, with scalar excitation

$$\phi = ct + \pi$$

Low energy effective action for π is

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Matter Bounce

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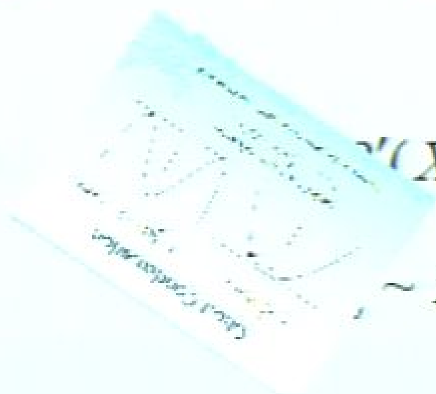

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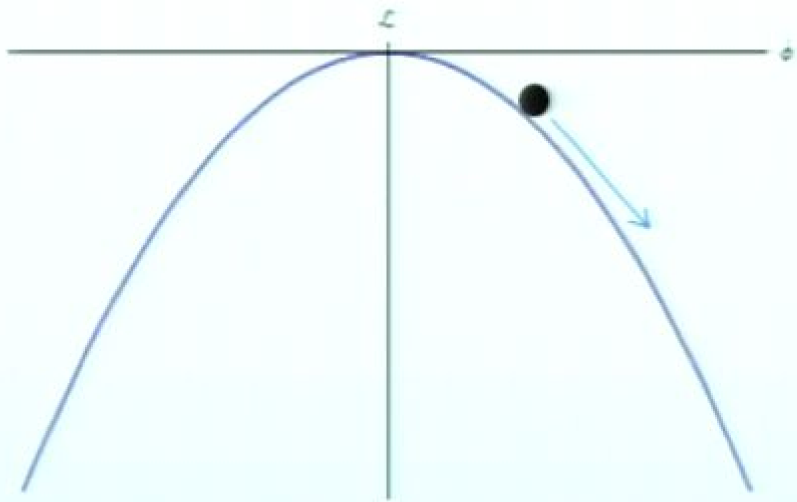

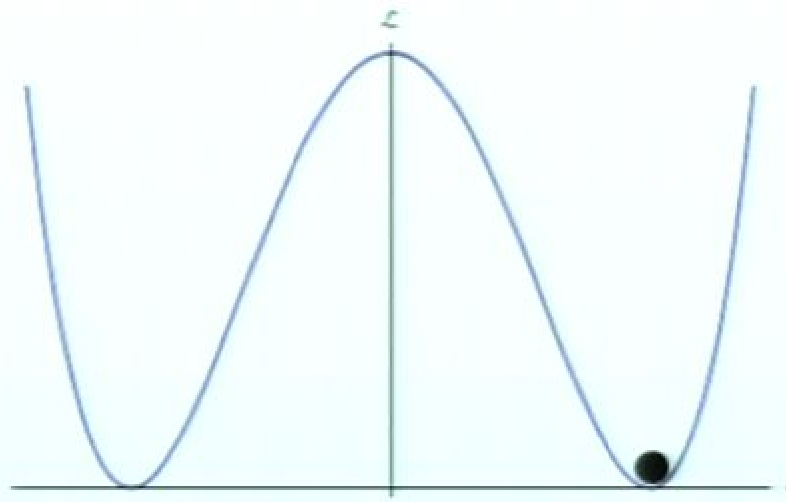

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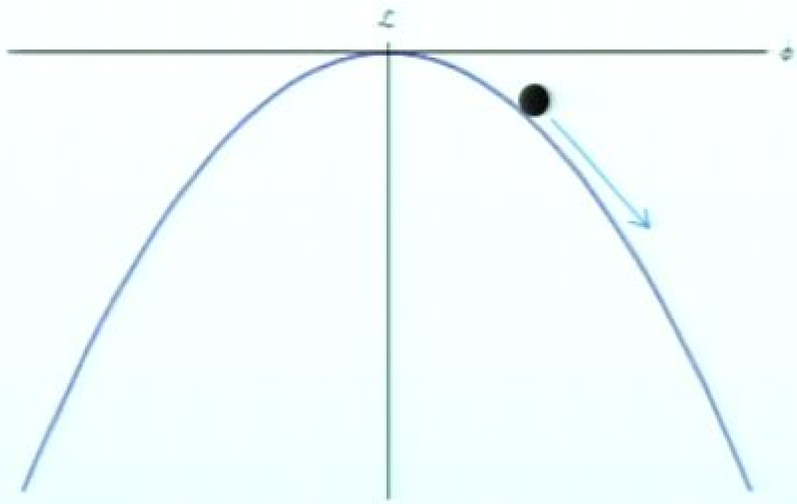

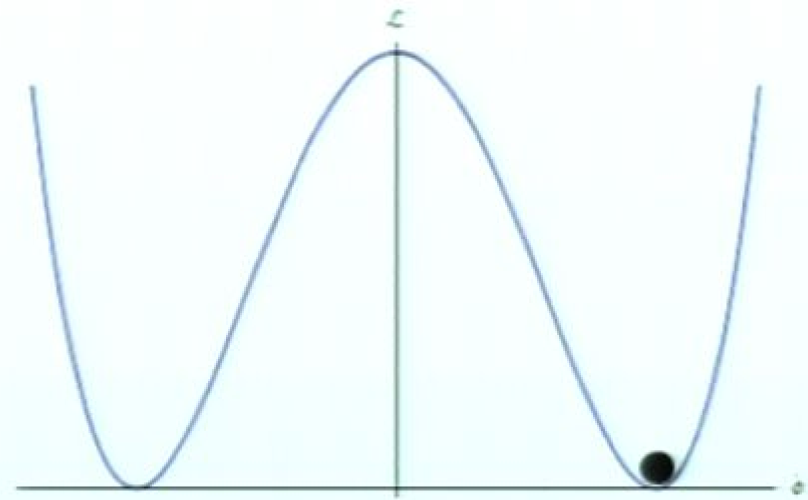

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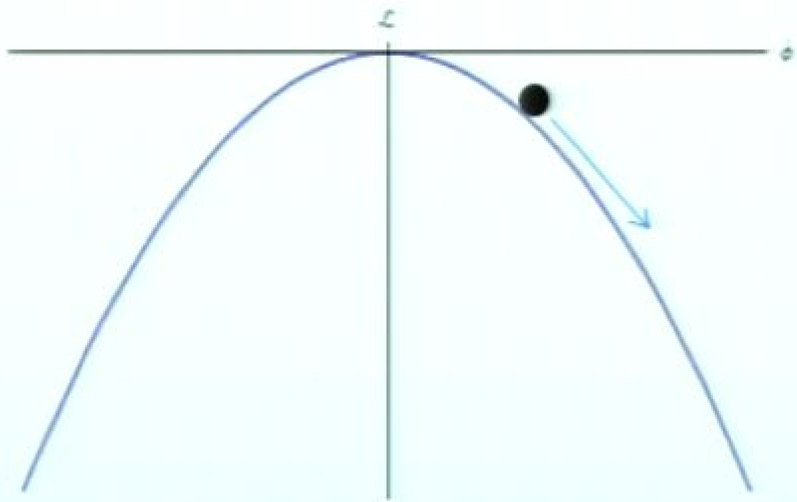

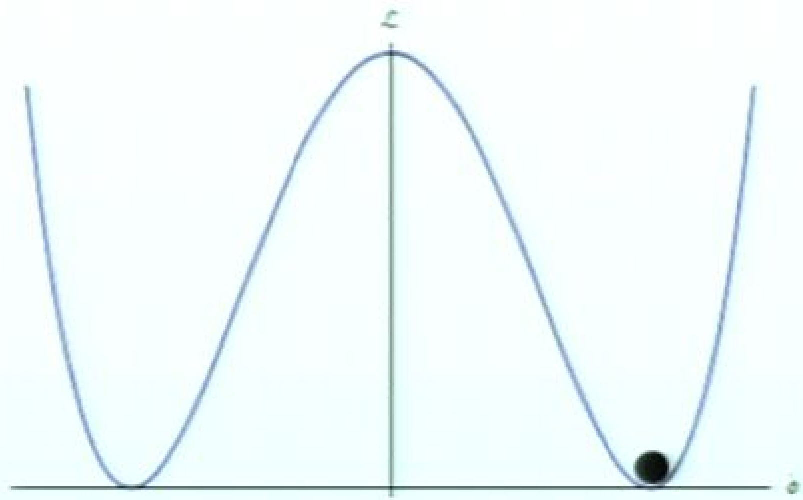

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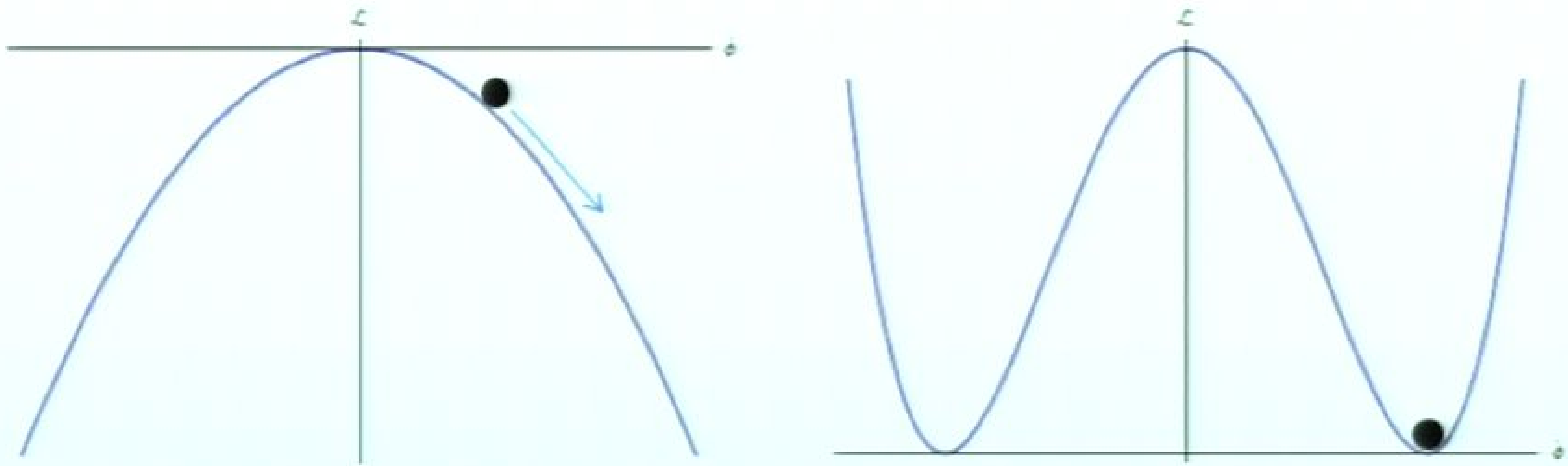

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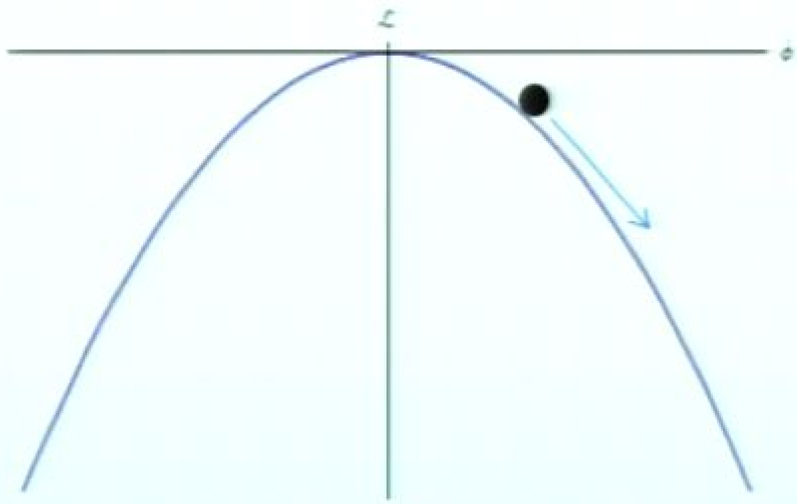

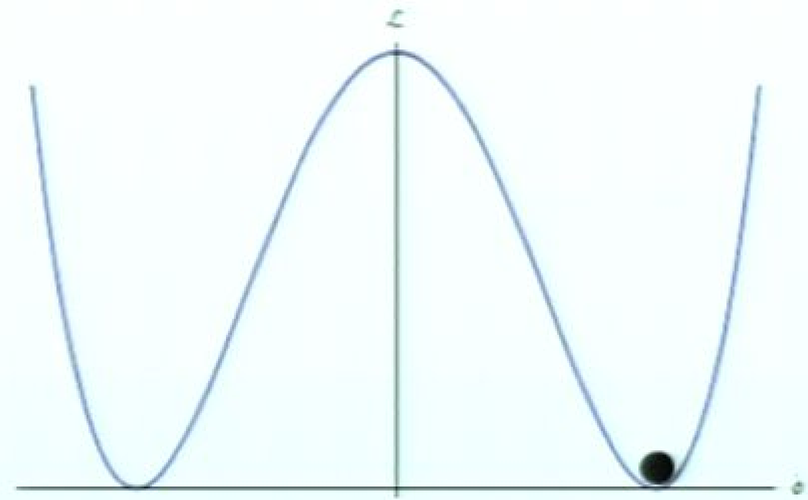

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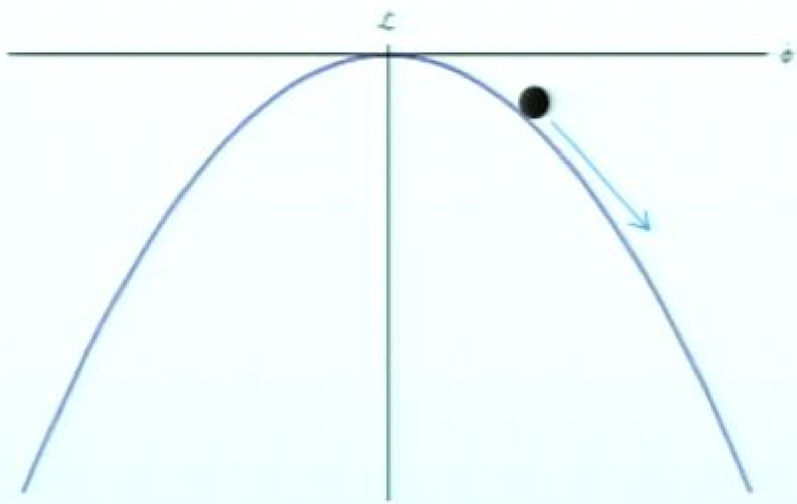

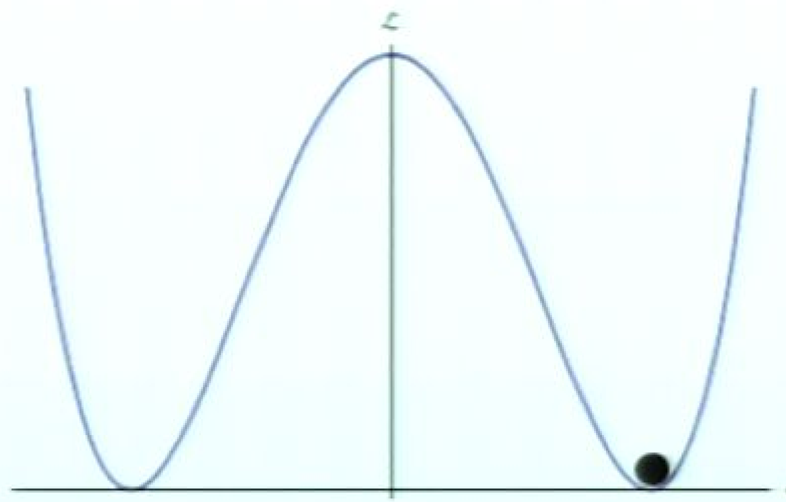

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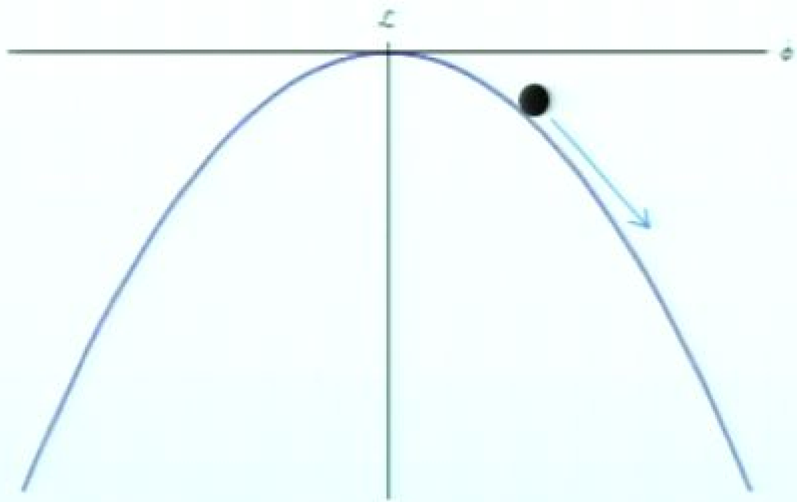

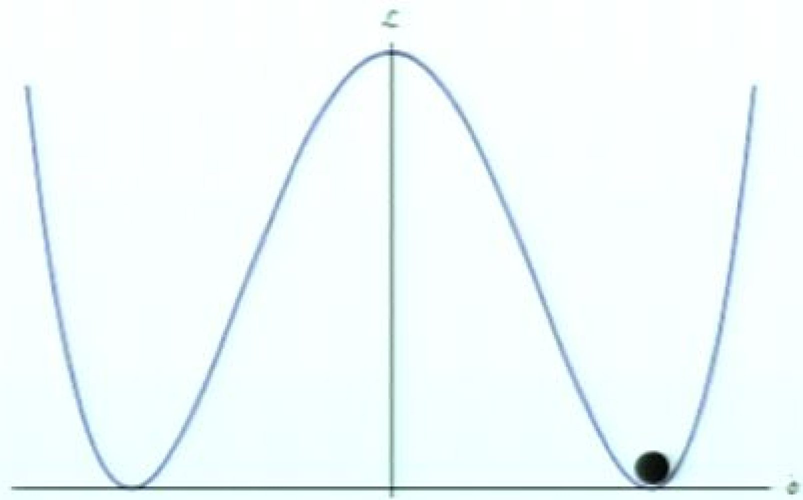

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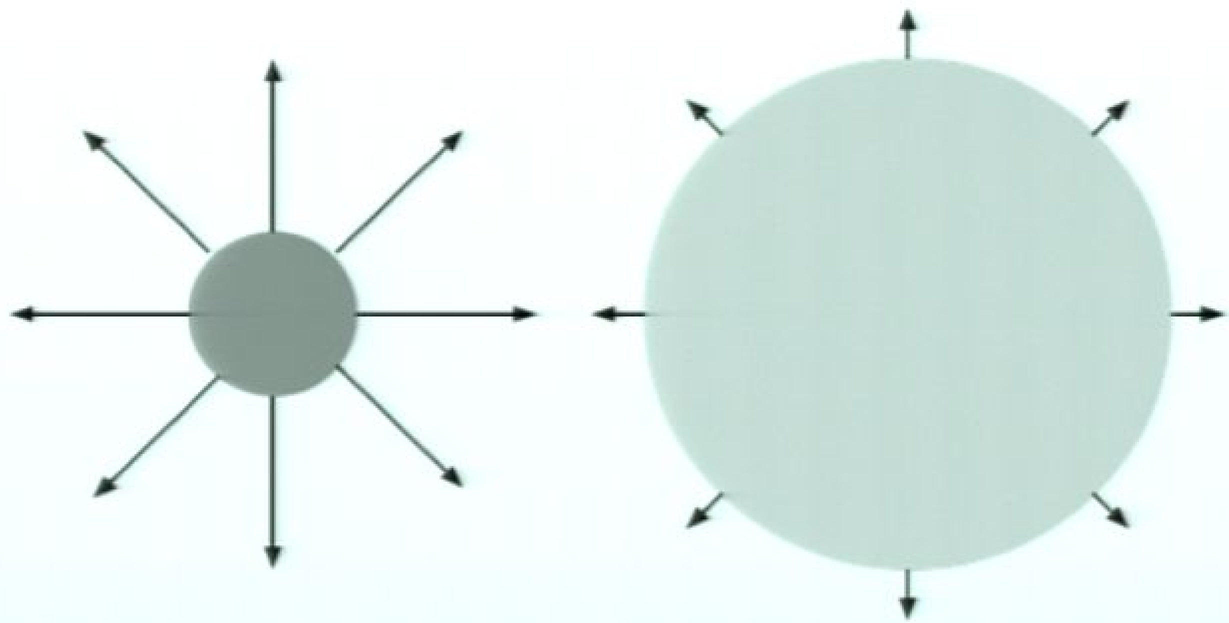

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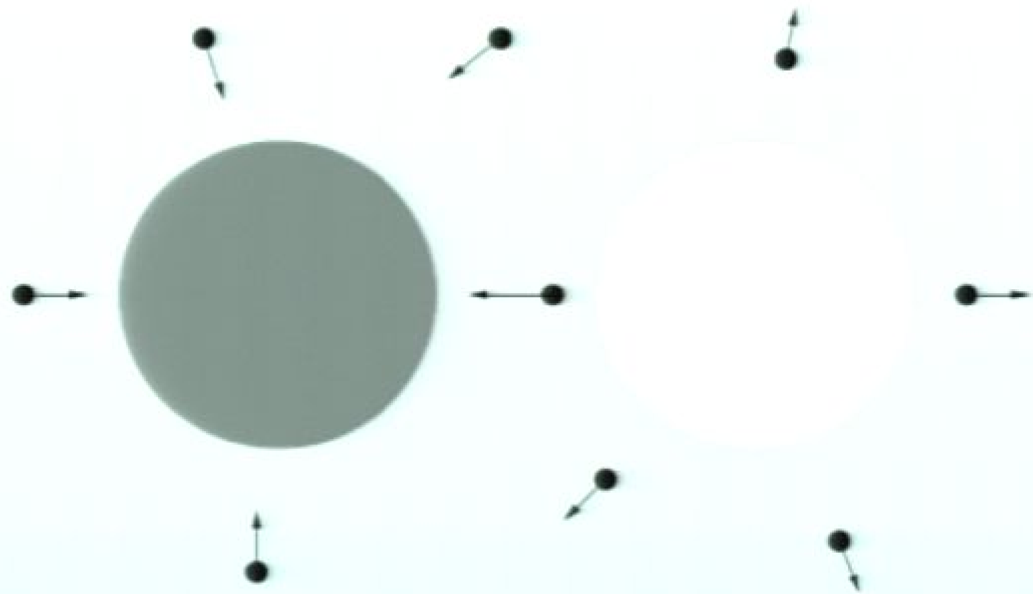

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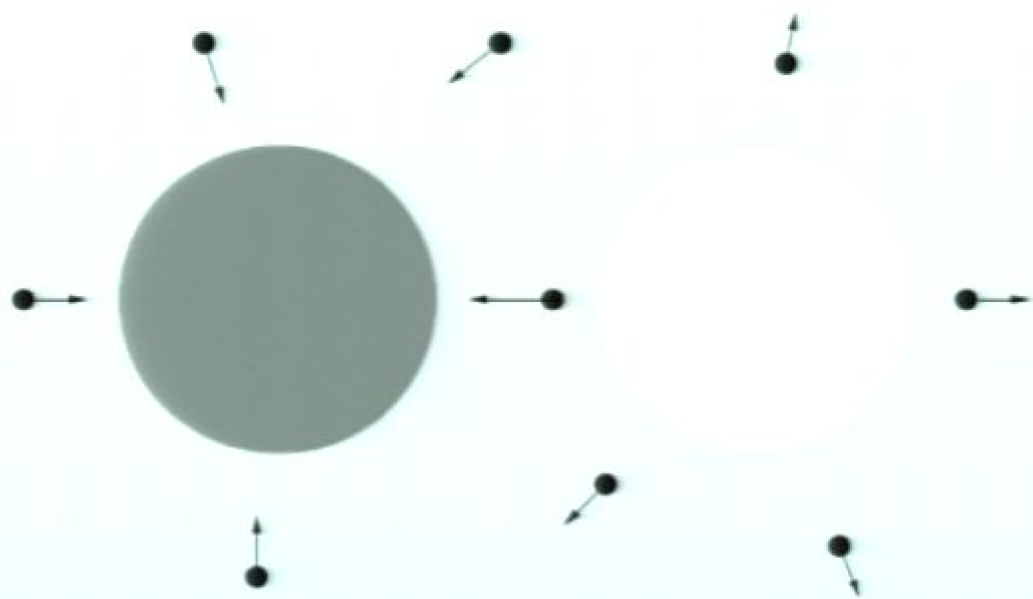

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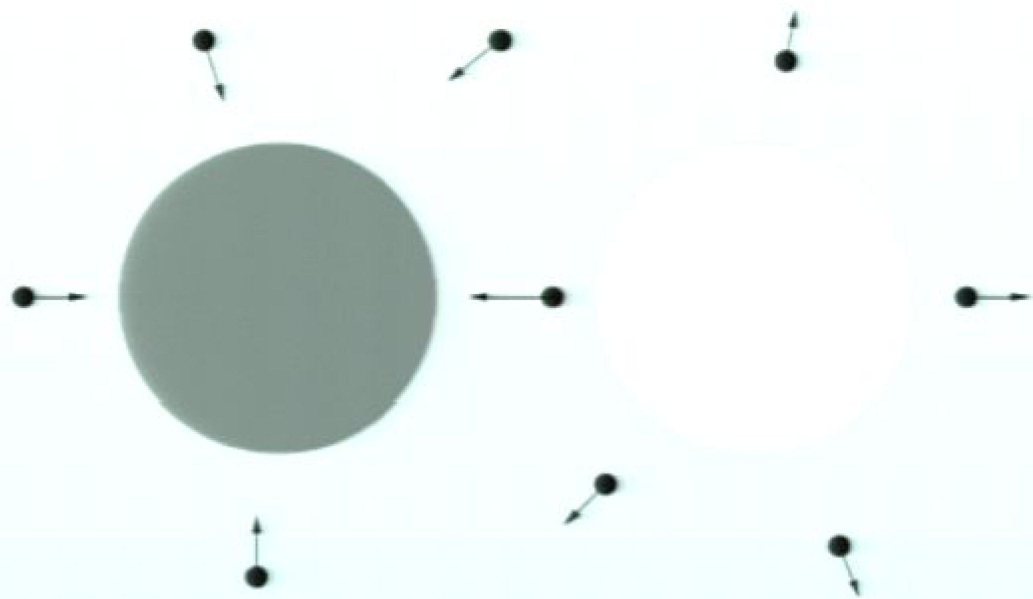

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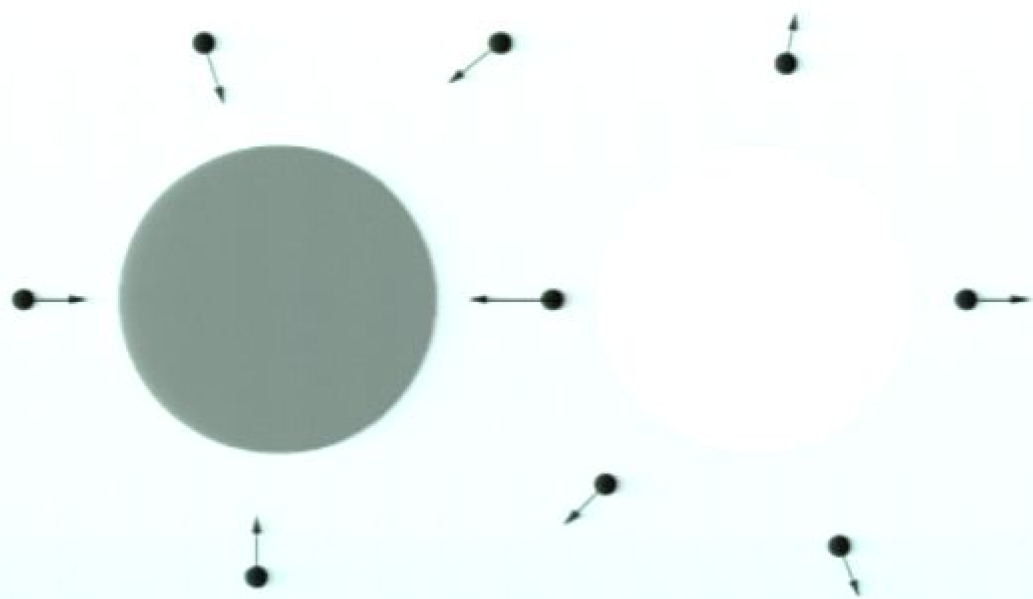

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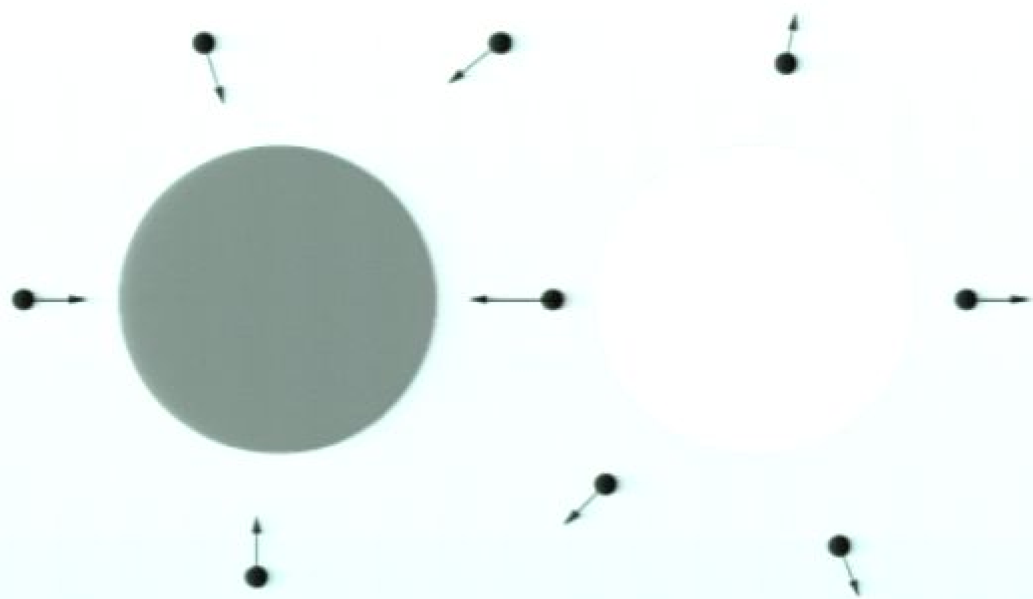

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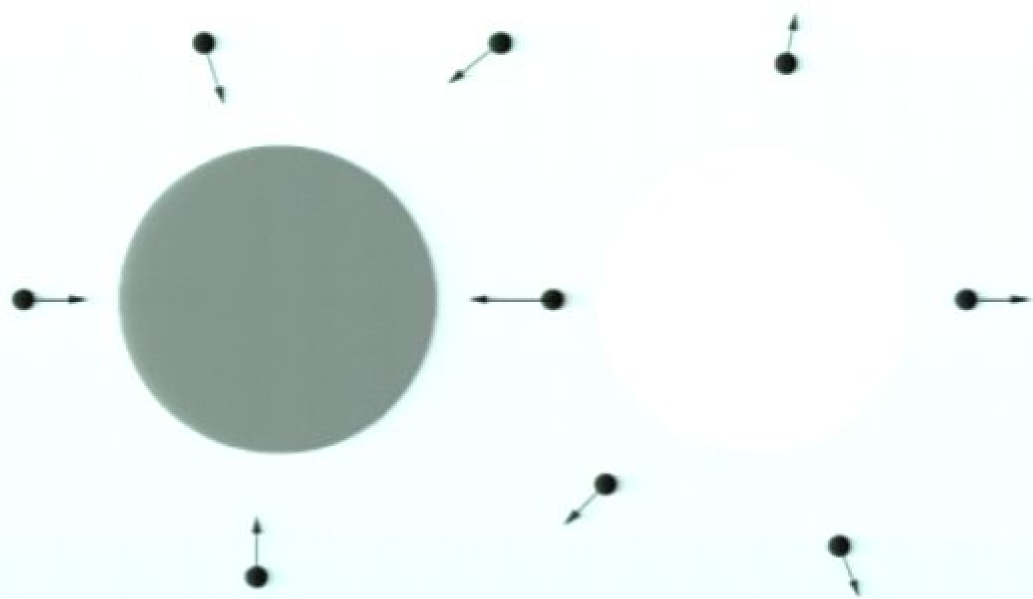

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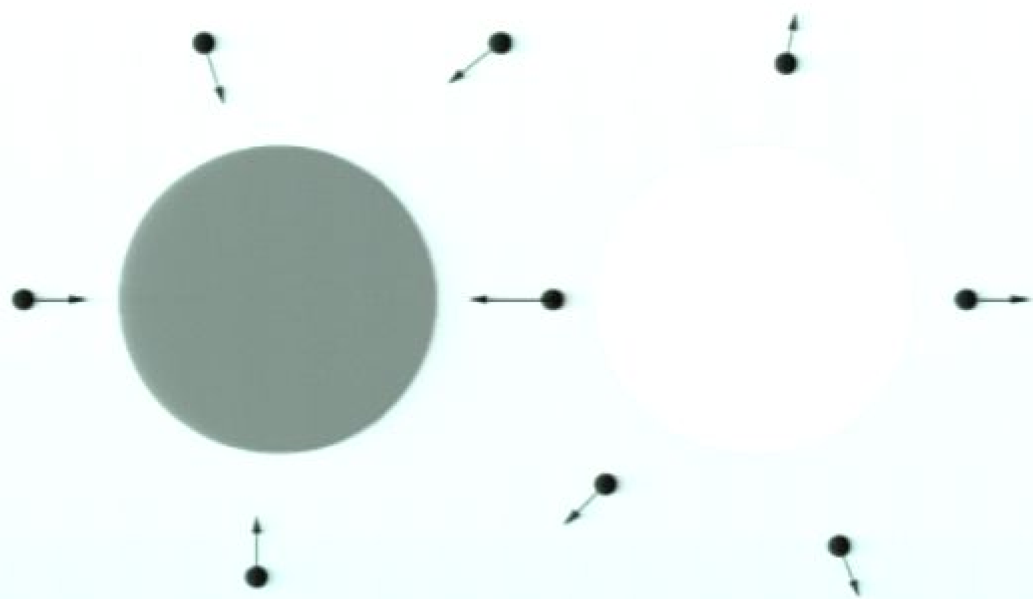
Inertial Mass!

- Gravitational energy density

$$\mathcal{E}_{\rm grav} = T_{00} \sim M^2 \dot{\pi} + \cdots$$

Gravitational Mass!

Interesting features



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$\dot{\pi} > 0$ **attractive**

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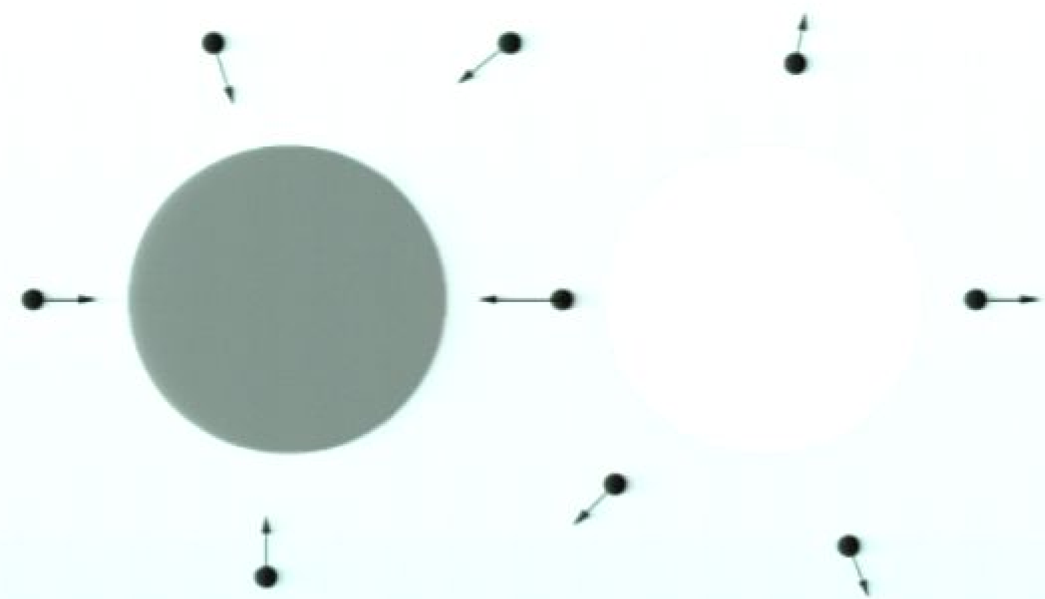

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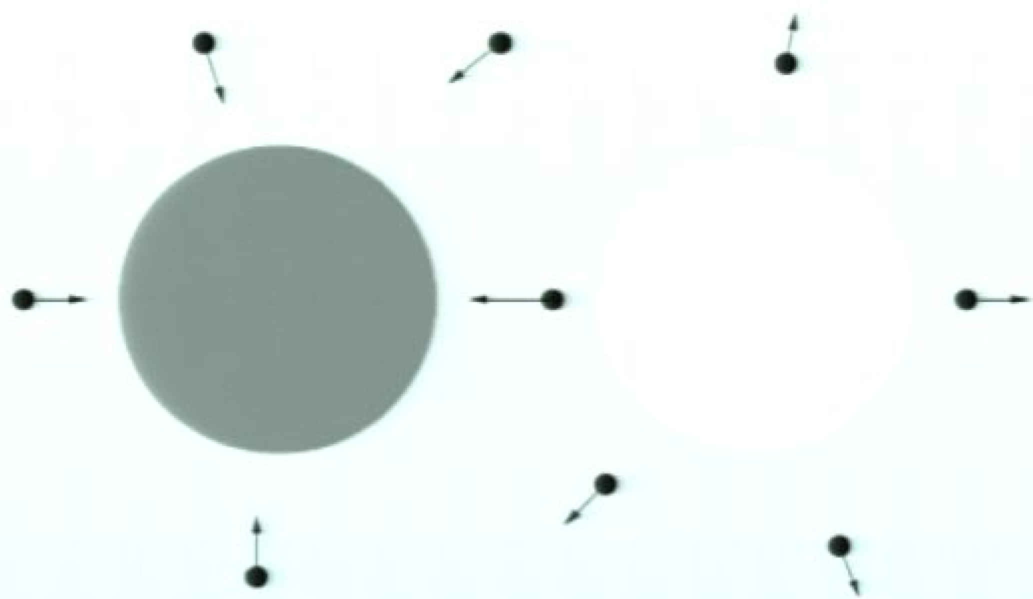

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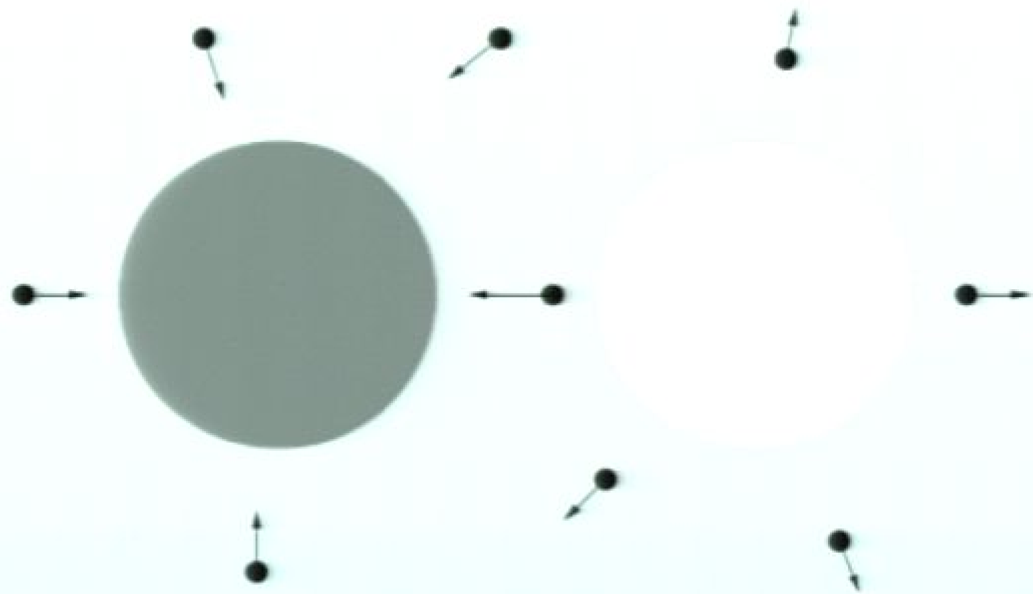

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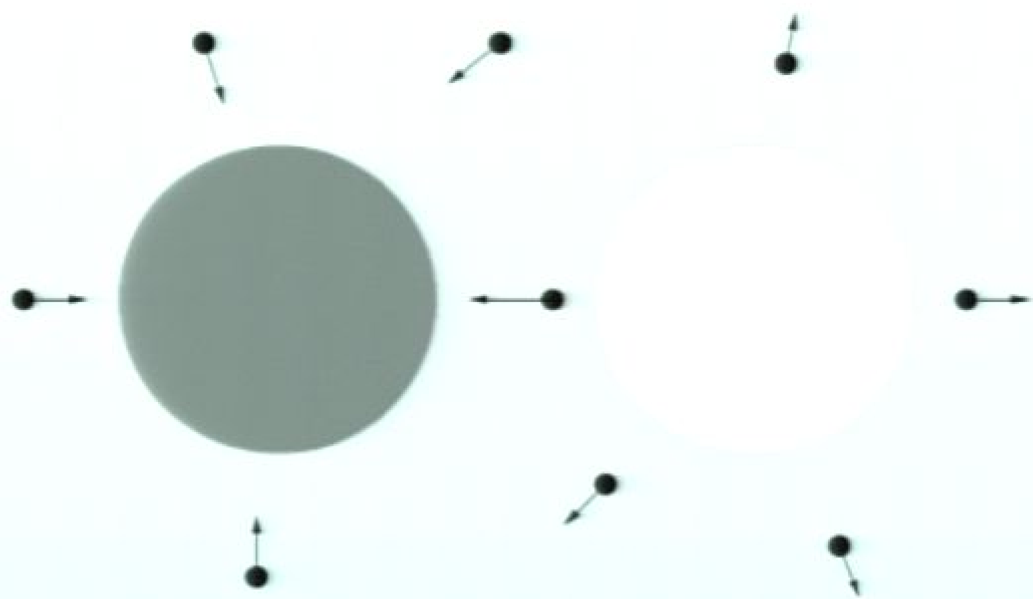

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- For a fluid with pressure p and energy density ρ,

$$\omega^2 = \frac{\delta p}{\delta \rho} k^2 - \omega_J^{\ 2}, \quad \text{where} \quad \omega_J^{\ 2} = \frac{\rho}{2 M_{Pl}^{\ 2}}.$$

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$P' + 2P''\dot{\phi}^2 > 0$ is ghost free condition, so we get

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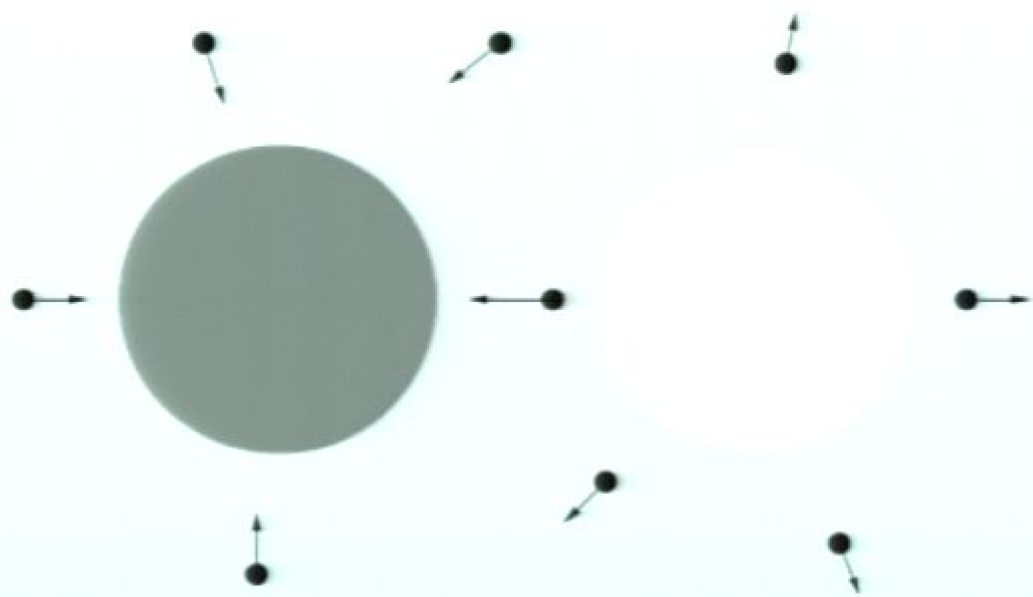
Interesting features



Lumps come from scalar excitation, its energy density always positive in terms of "particle physics", but the induced gravity can be either attractive or repulsive!

$\dot{\pi} > 0$ attractive

$\dot{\pi} < 0$ repulsive

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$P' + 2P''\dot{\phi}^2 > 0$ is ghost free condition, so we get

$$\omega_{grad}^2 > 0$$

Ghost condensation stablize vacuum on background and perturbation level !

Gradient stability

- Up to 2nd order,

$$\mathcal{L} = M^4\left[(P' + 2P''c^2)\dot{\pi}^2 - P'(\nabla\pi)^2\right] + M^2(S_1 + S_2)(\nabla^2\pi)^2$$

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Part III

Realization of Matter Bounce

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Ghost bounce

- Matter sector + ghost condensation

$$\rho_m(t) \sim a(t)^{-3(1+w_m)} \qquad \rho_X \sim a(t)^{-p}$$

minimal requirement $p > 3$

against radiation $p > 4$

against anisotropic stress $p > 6$

- Lagrangian of GC takes the following general form

$$\mathcal{L} = M^4 P(X) - V(\phi)$$

$P(X)$ takes the prototypical form

$$P(X) = \frac{1}{8}(X - c^2)^2$$

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against anisotropic stress $p > 6$

- Lagrangian of GC takes the following general form

$$\mathcal{L} = M^4 P(X) - V(\phi)$$

$P(X)$ takes the prototypical form

$$P(X) = \frac{1}{8}(X - c^2)^2$$

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- Matter sector + ghost condensation

$$\rho_m(t) \sim a(t)^{-3(1+w_m)} \qquad \rho_X \sim a(t)^{-p}$$

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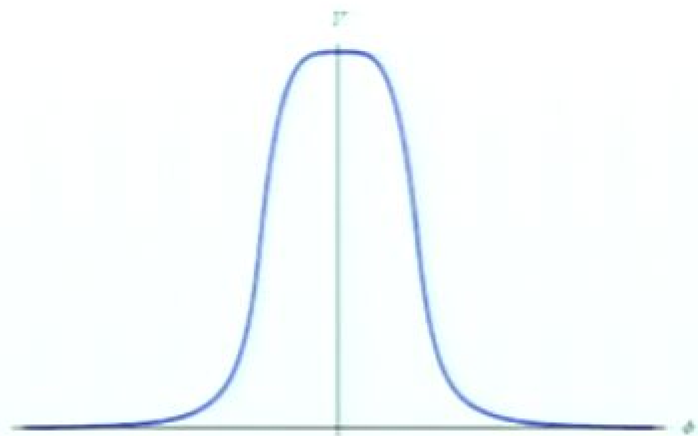

- Ghost field changes as

$$\phi(t) = ct + \pi(t)$$

$\pi(t)$ is the small deviation from minima, its EoM

$$\ddot{\pi} + 3H\dot{\pi} = 2c^{-2} V_0 M^{-4-\alpha} \alpha (ct)^{-(\alpha+1)}$$

It yields $\rho_X \sim \dot{\pi} \sim t^{-\alpha}$.

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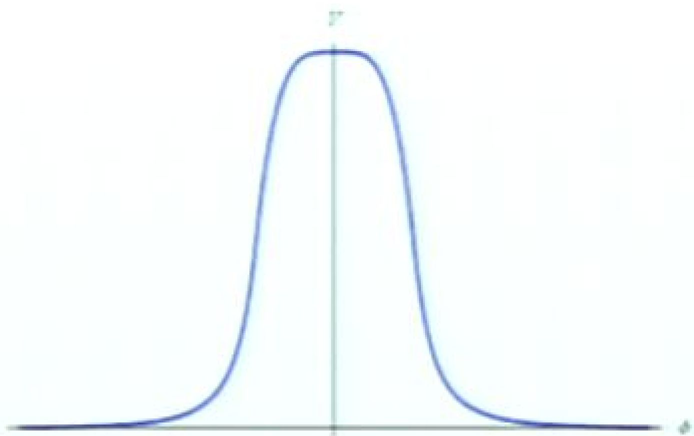

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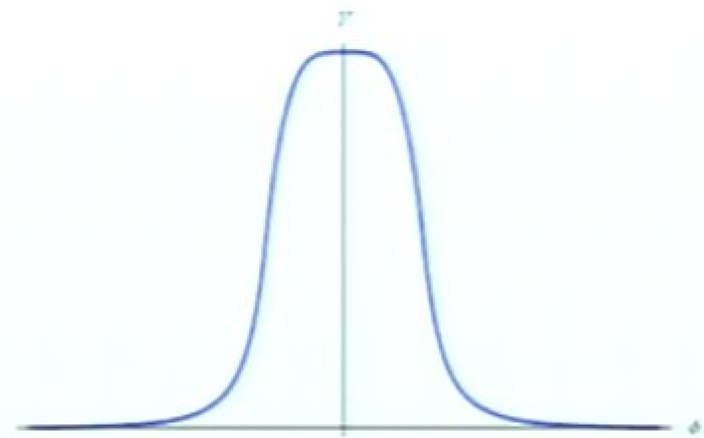

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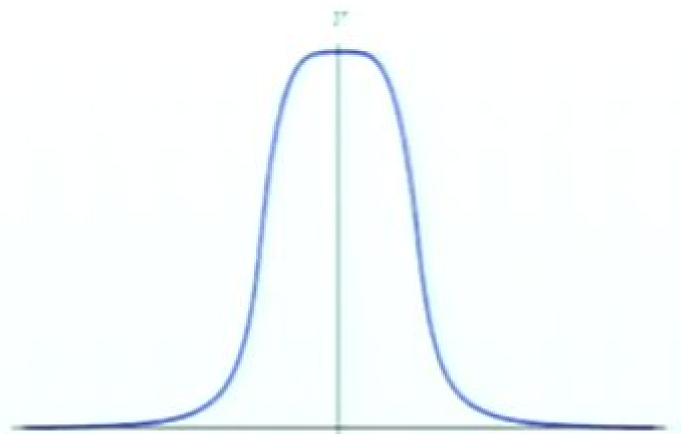

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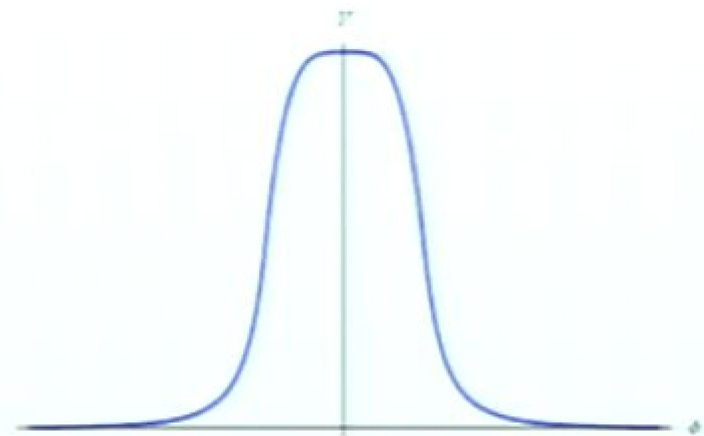

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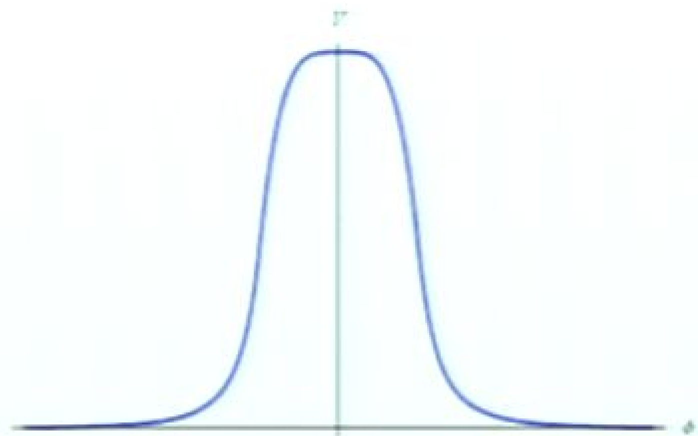

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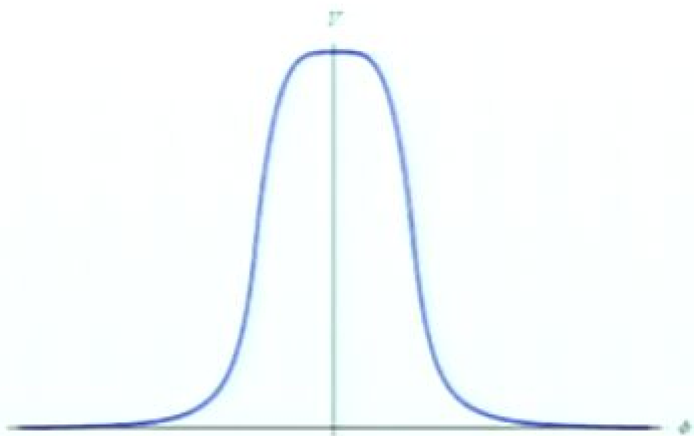

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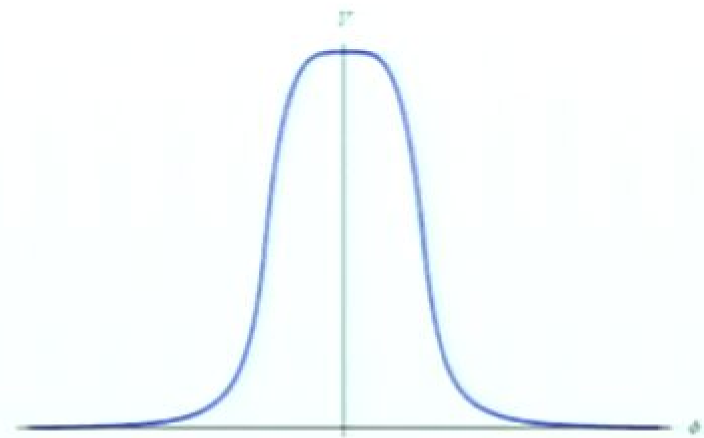

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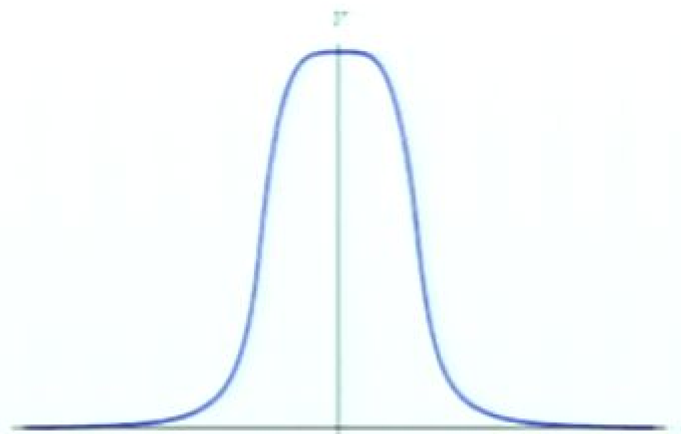

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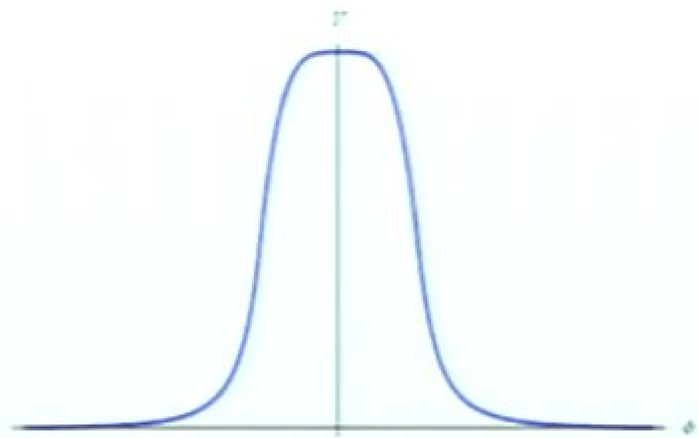

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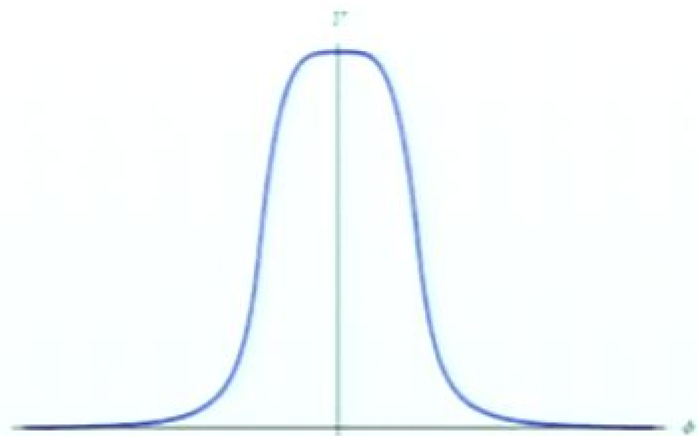

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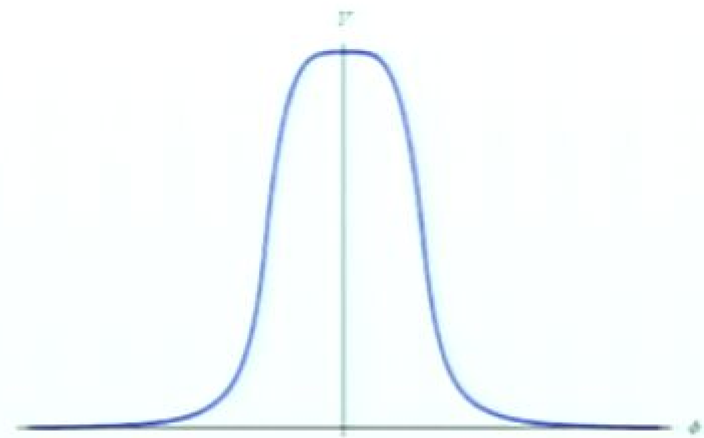

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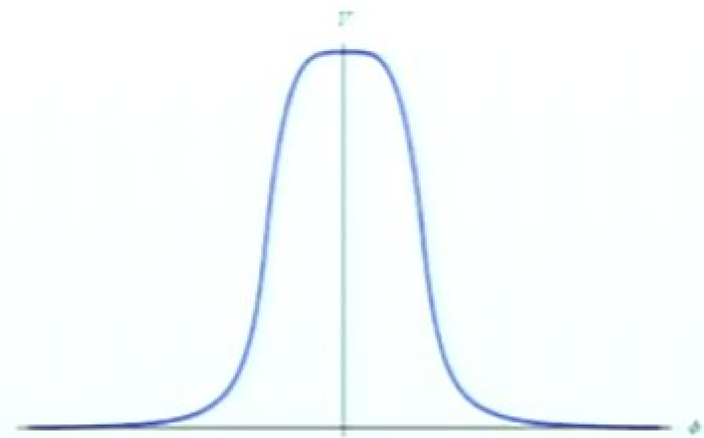

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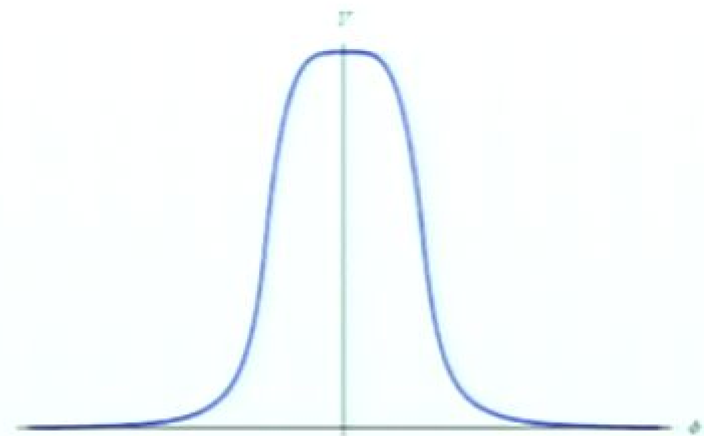

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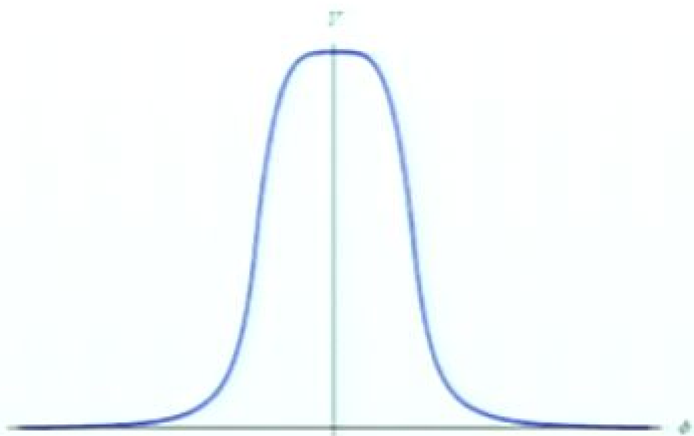

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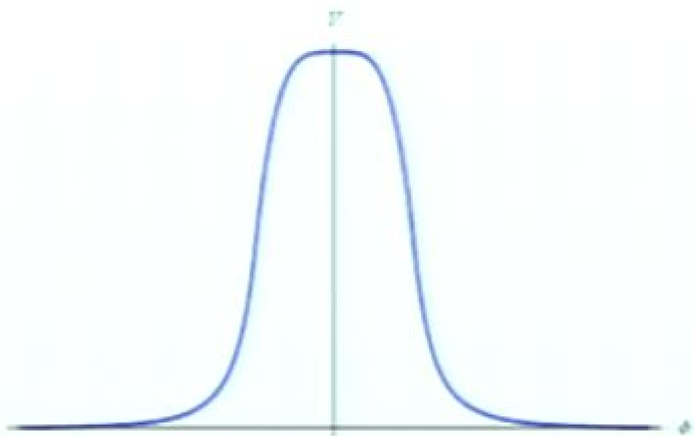

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$$\phi(t) = ct + \pi(t)$$

$\pi(t)$ is the small deviation from minima, its EoM

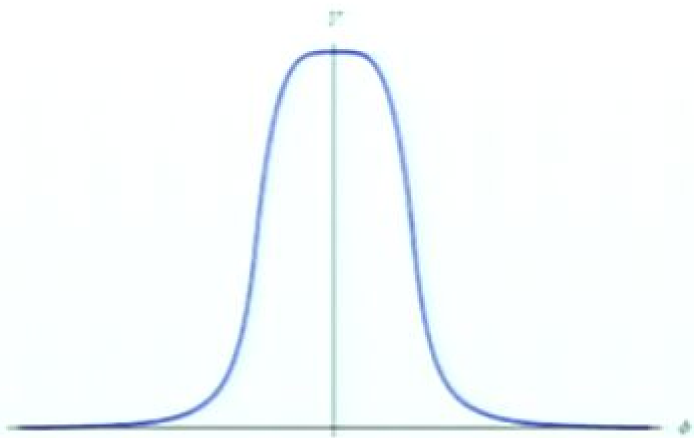
$$\ddot{\pi} + 3H\dot{\pi} = 2c^{-2}V_0 M^{-4-\alpha}\alpha(ct)^{-(\alpha+1)}$$

It yields $\rho_X \sim \dot{\pi} \sim t^{-\alpha}$.

$\alpha = 4$ Marginally stable against anisotropic stress

$\alpha = 6$ stable

Ghost bounce



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Divergence is cut off at M^4

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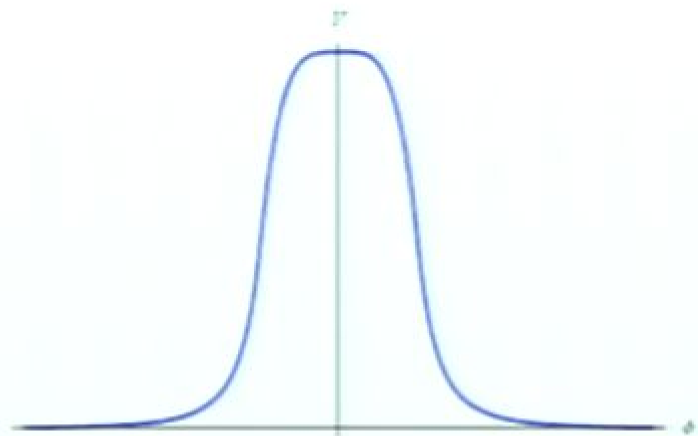

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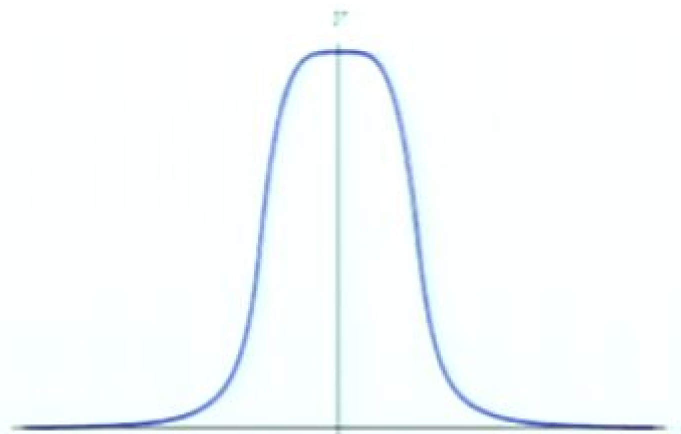

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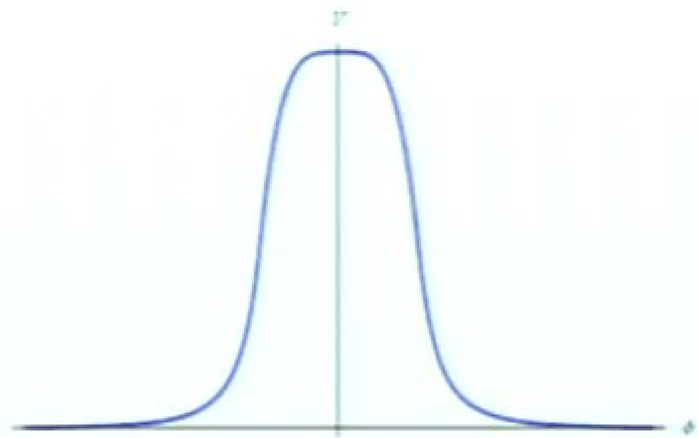

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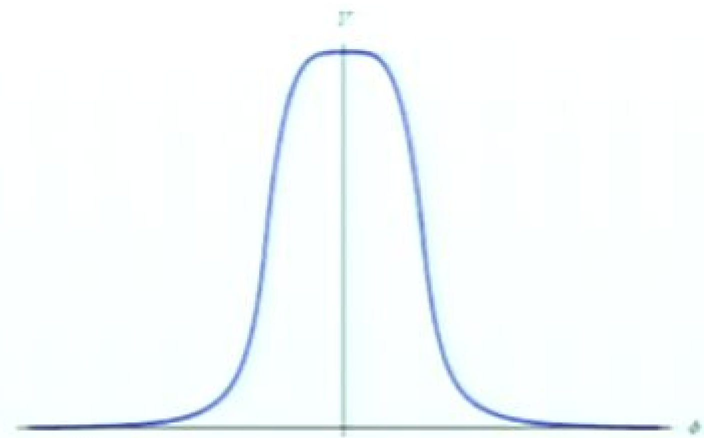

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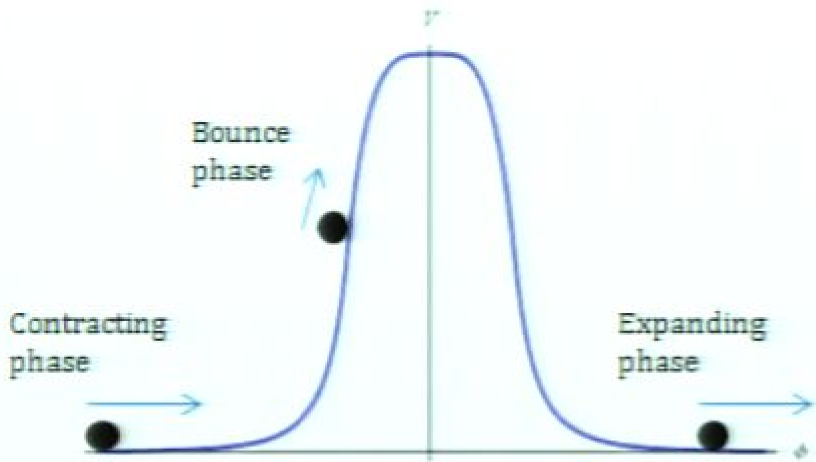

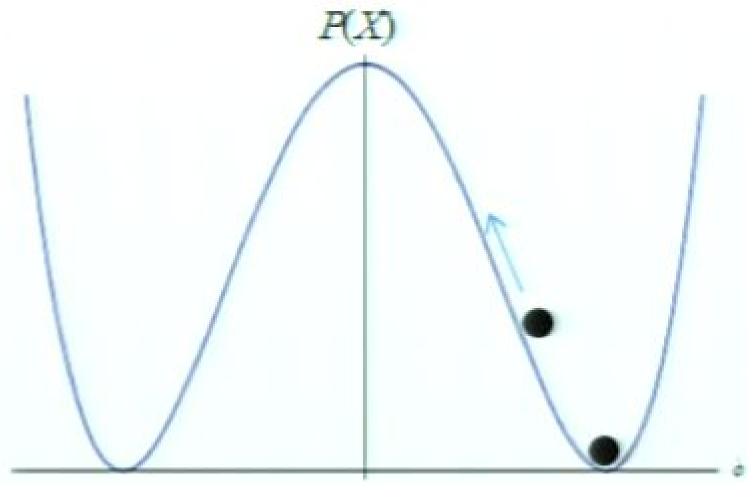

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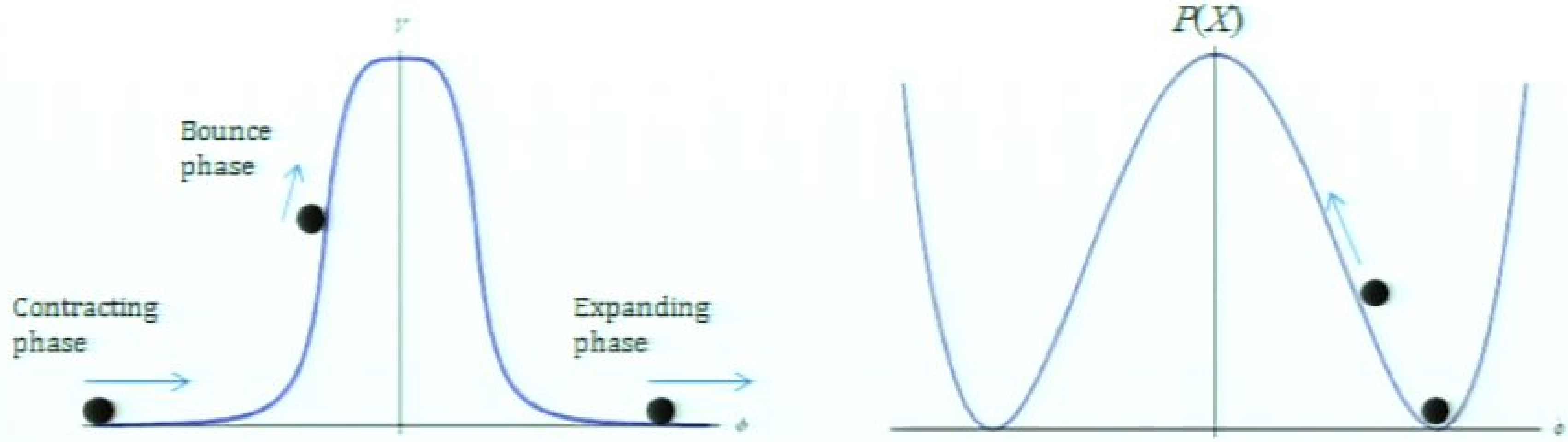
Realization of NEC violation!

Ghost bounce



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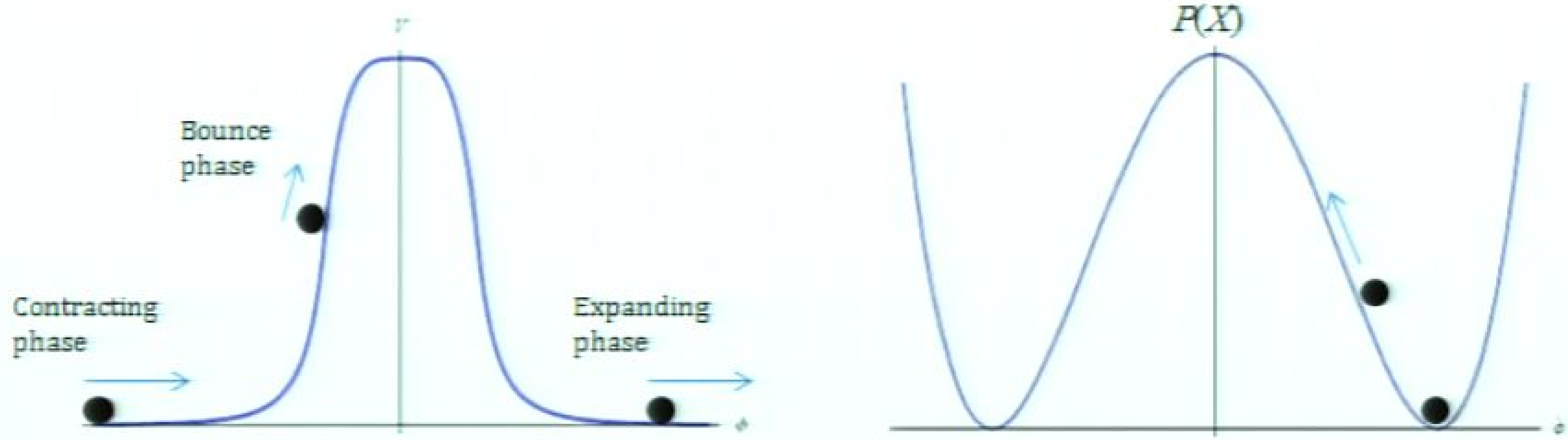

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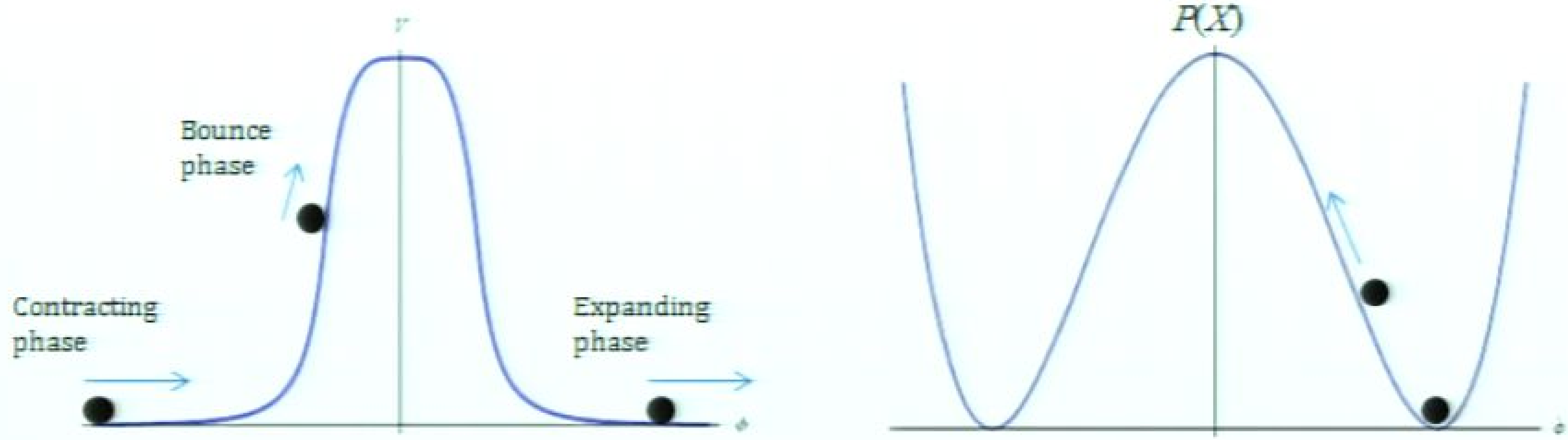

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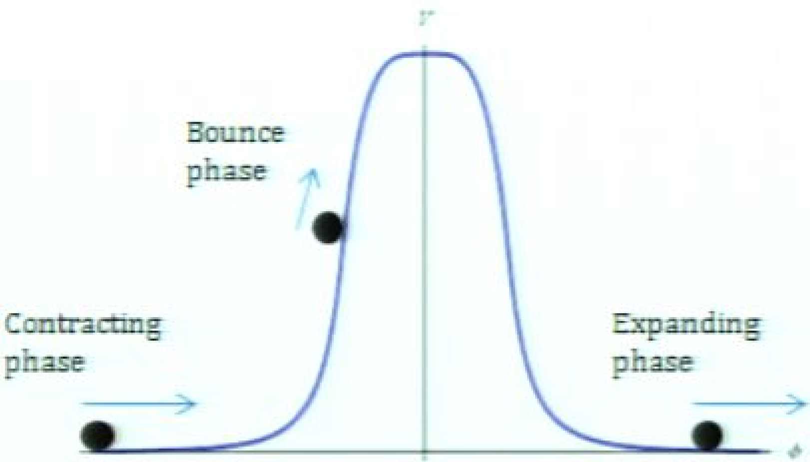

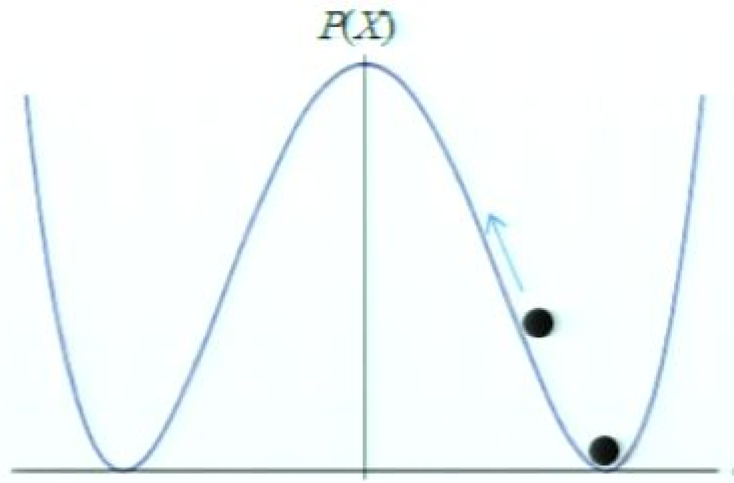

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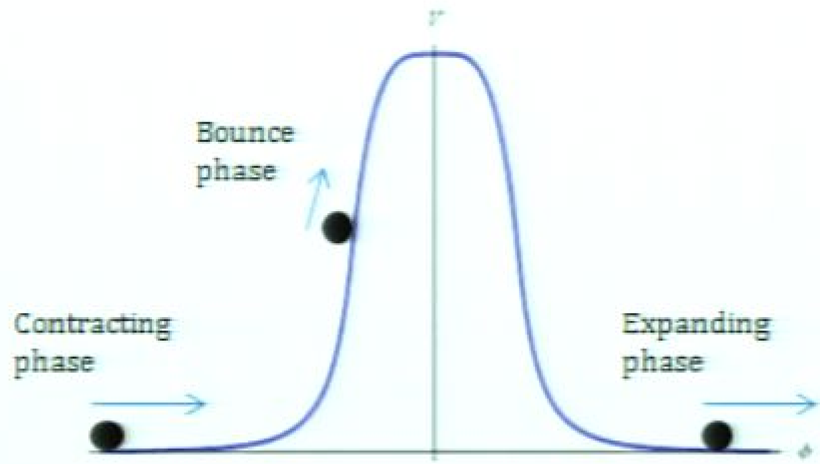

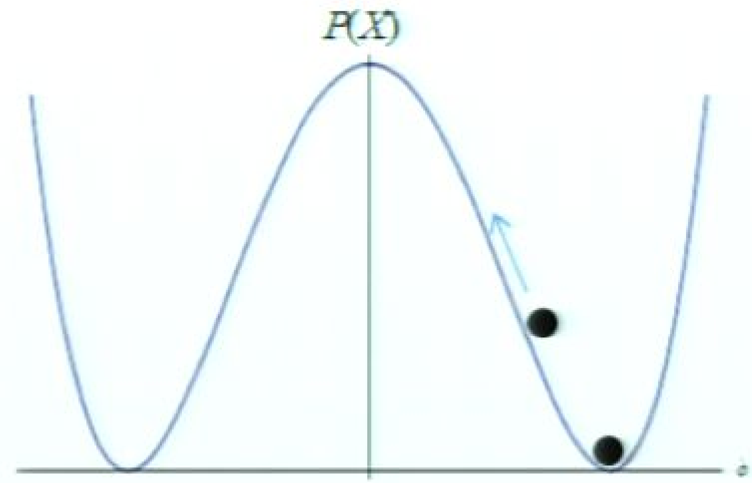

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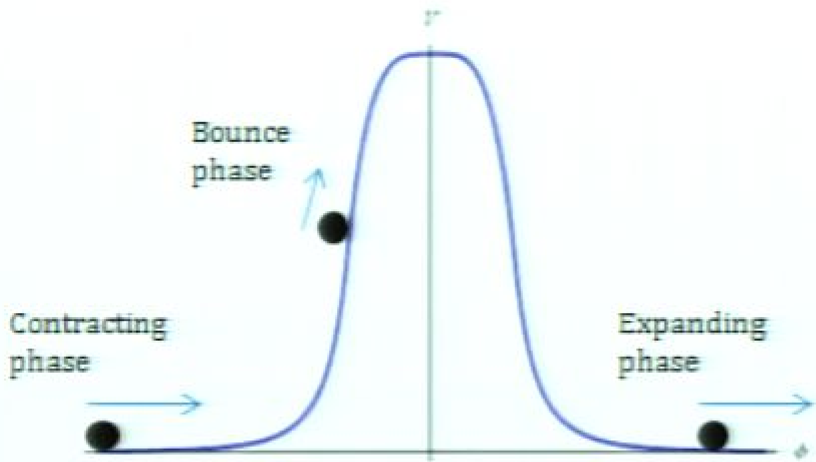

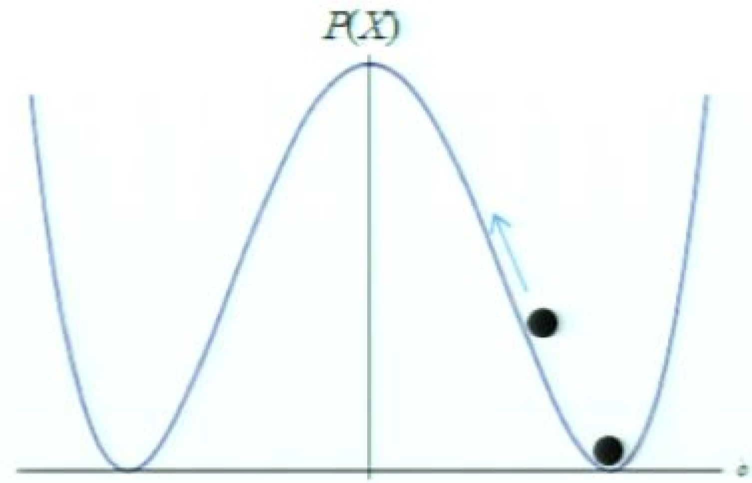

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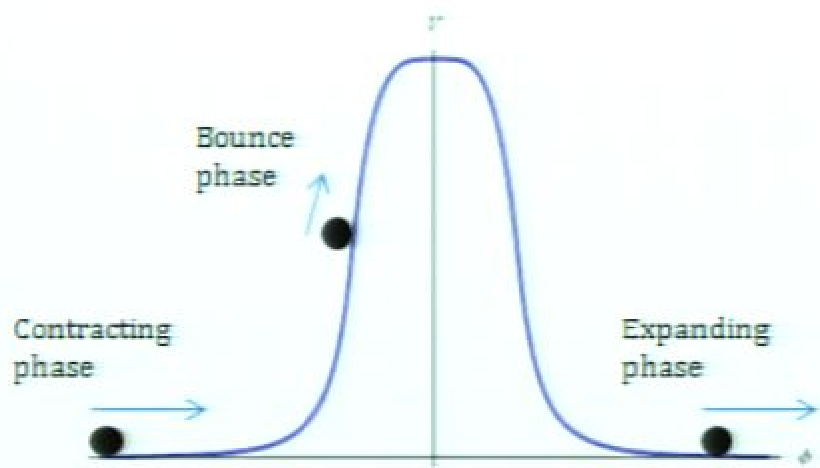

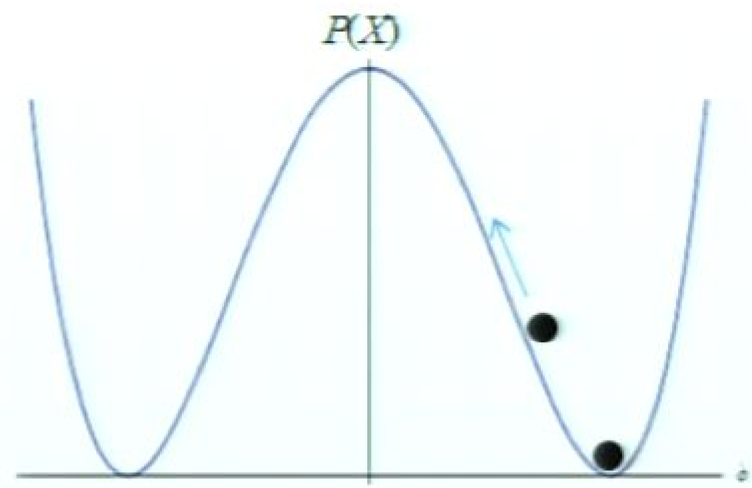

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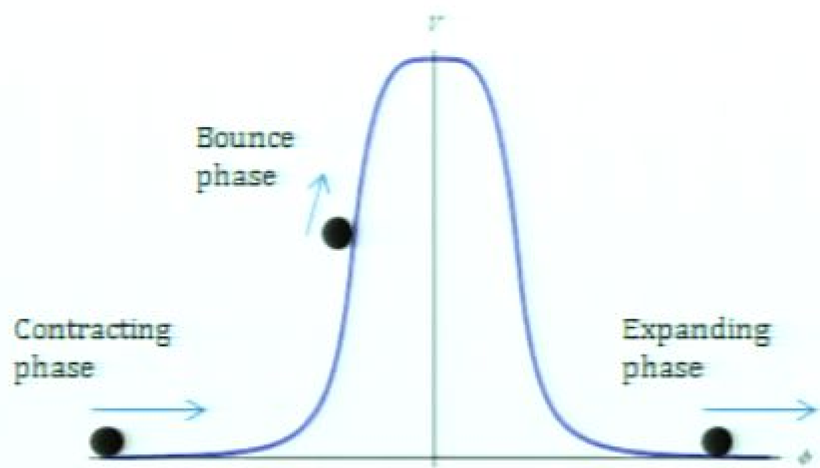

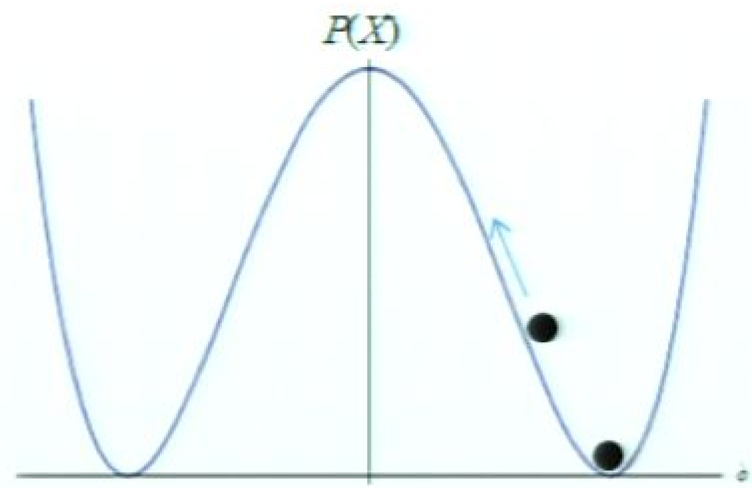

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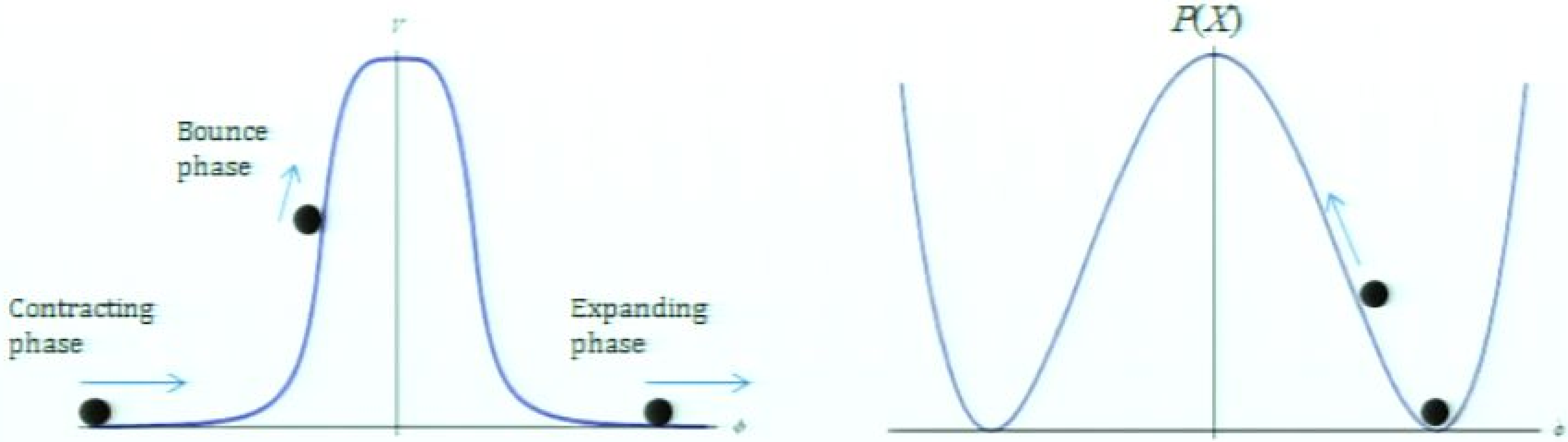

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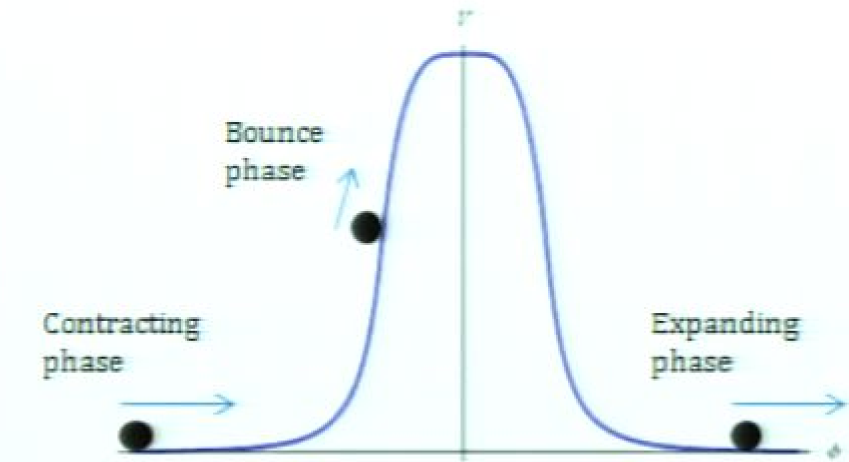

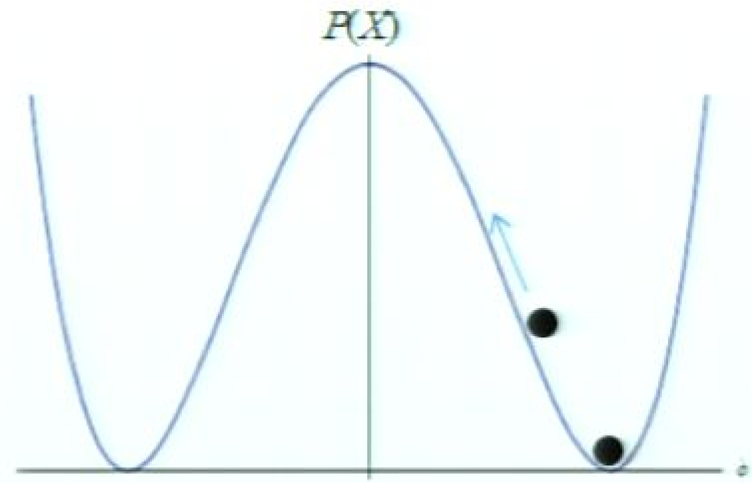

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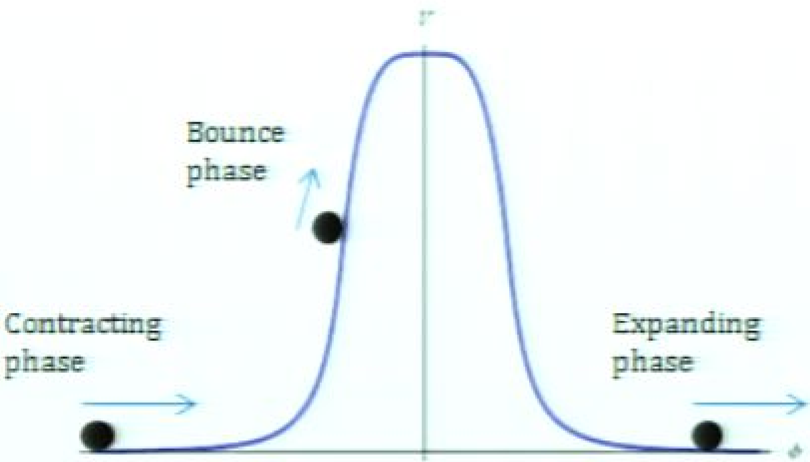

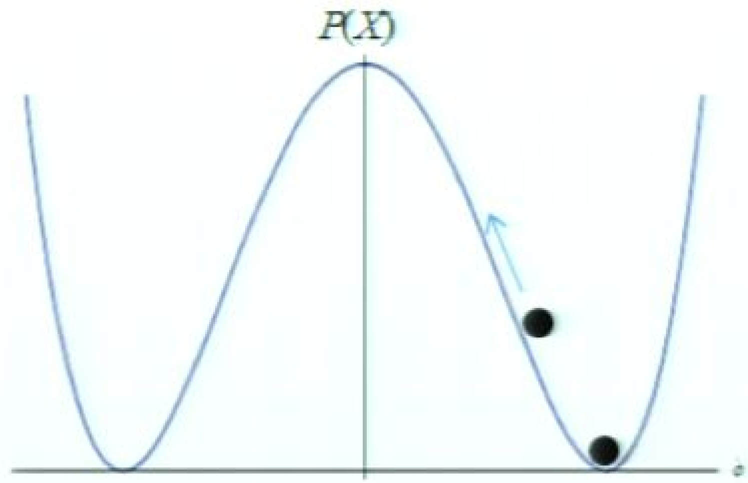

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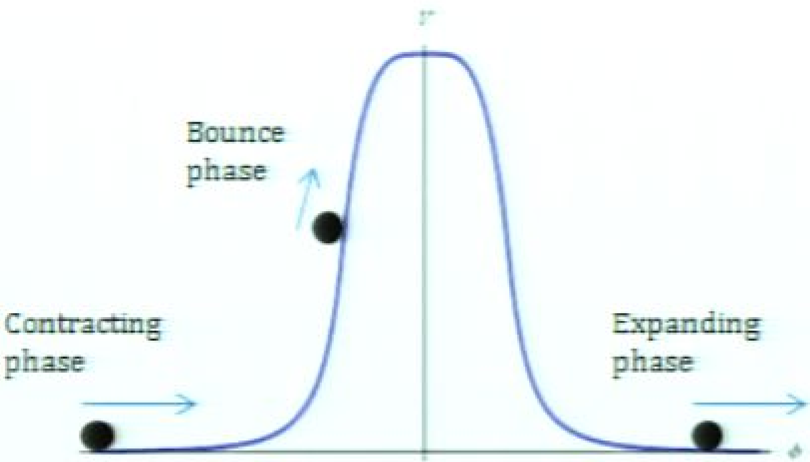
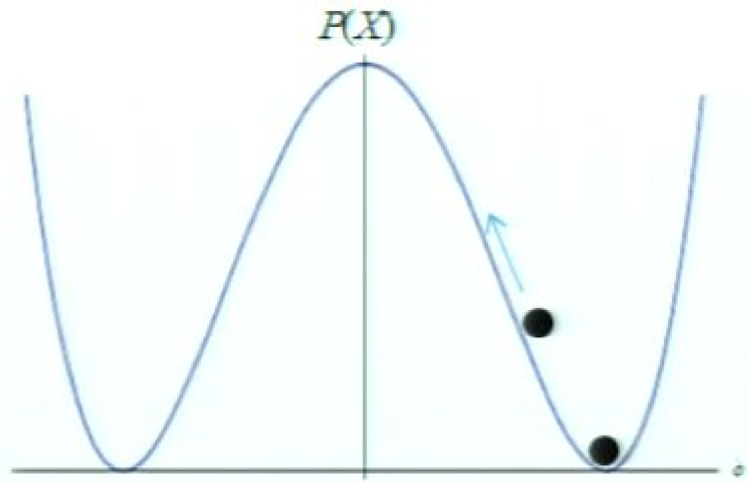
Realization of NEC violation!

NR Matter → Radiation dominant → AS grows up → Ghost

Ghost bounce





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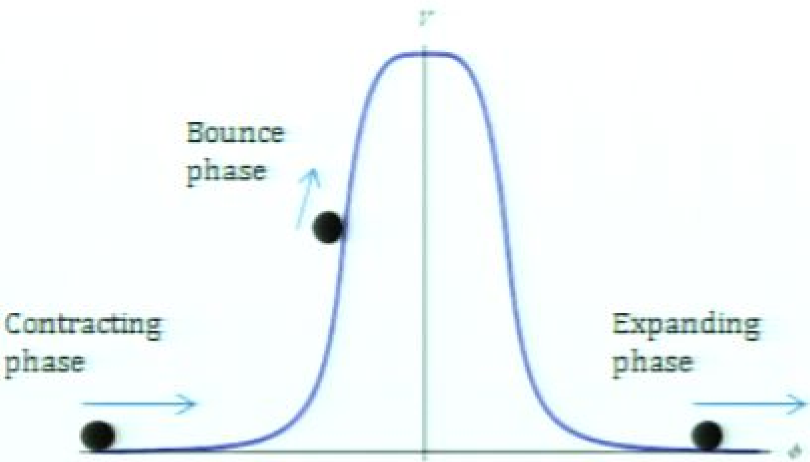

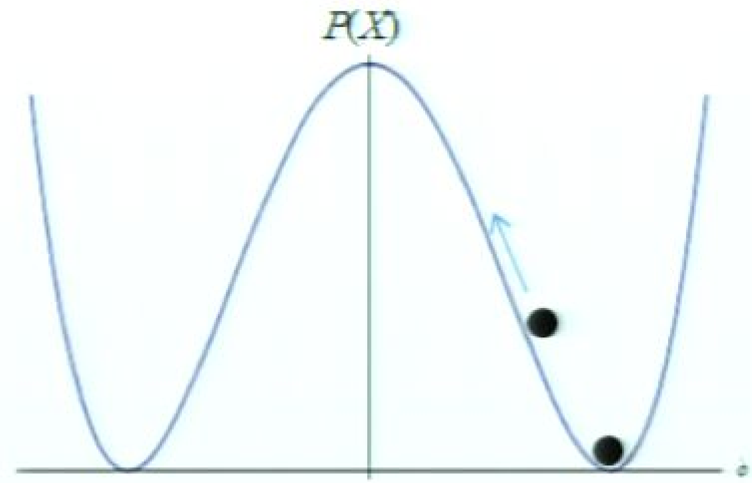

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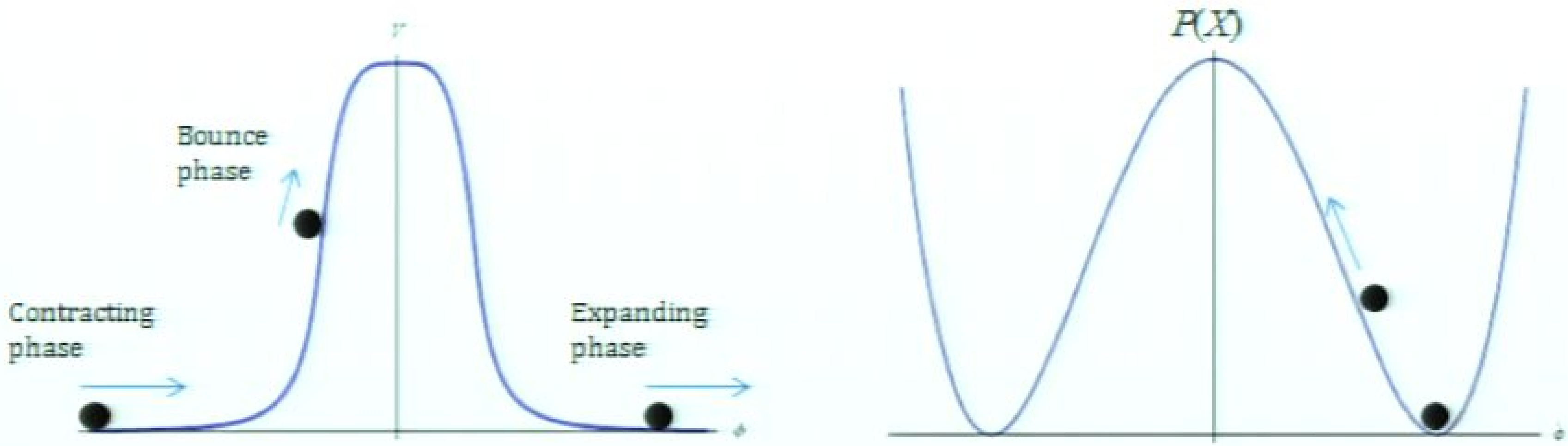

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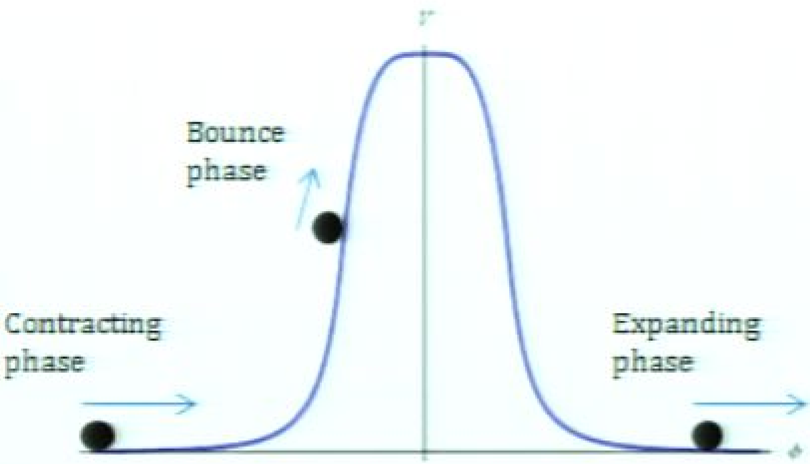

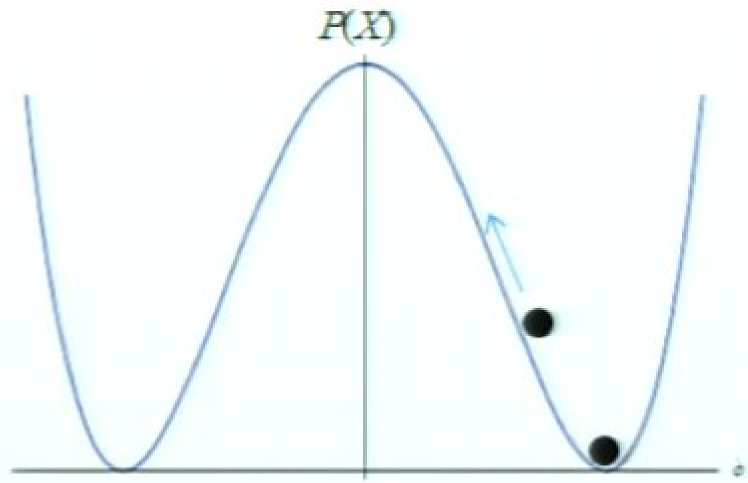

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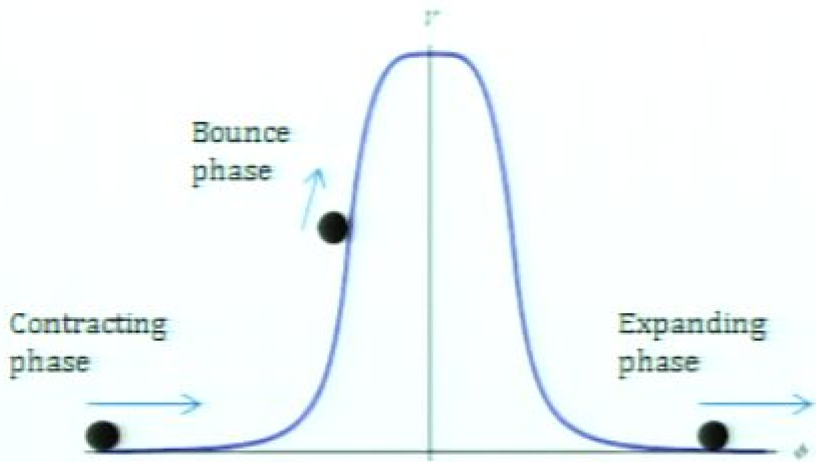

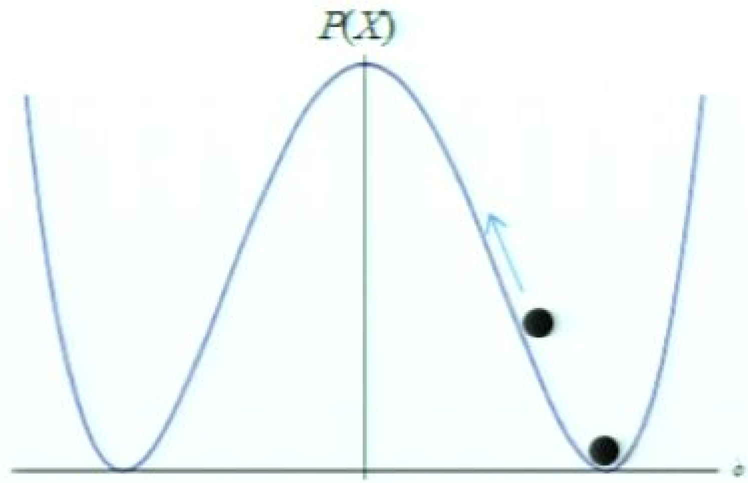

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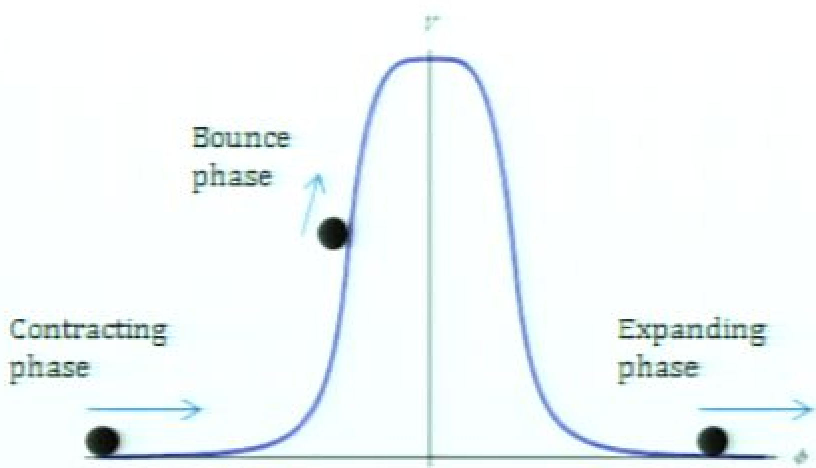

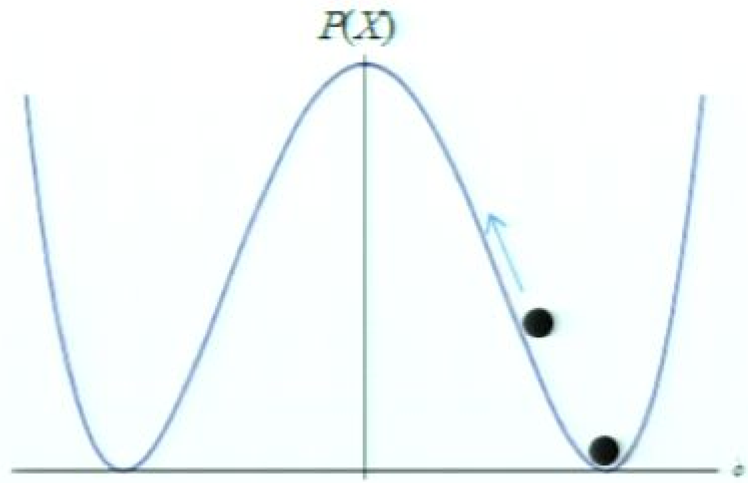

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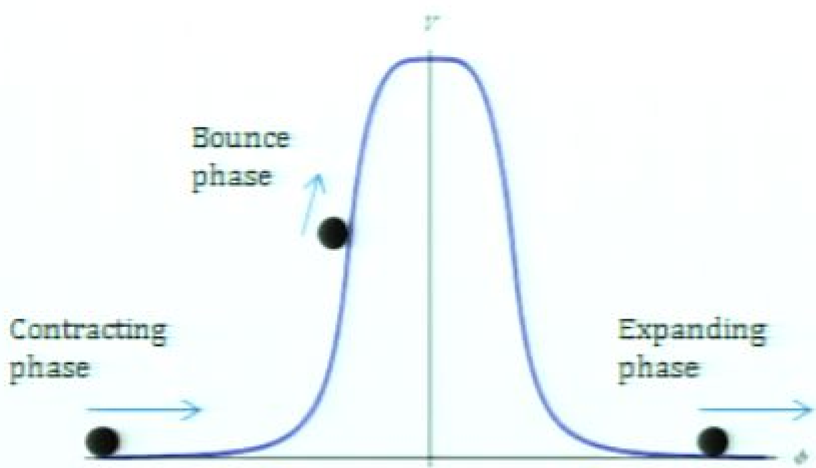

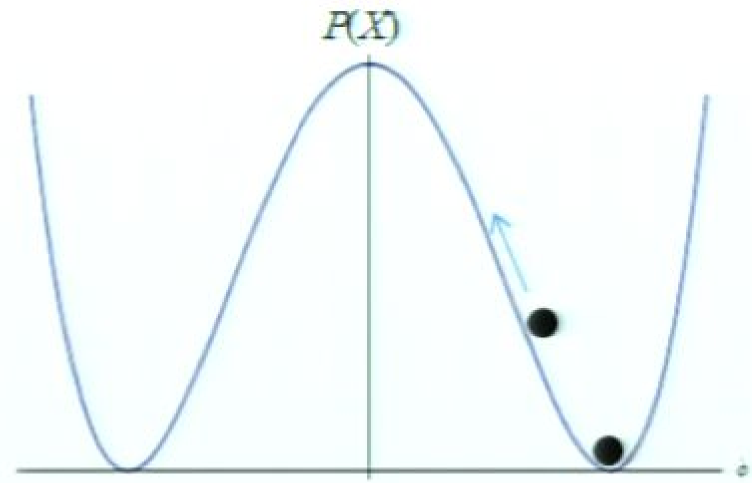

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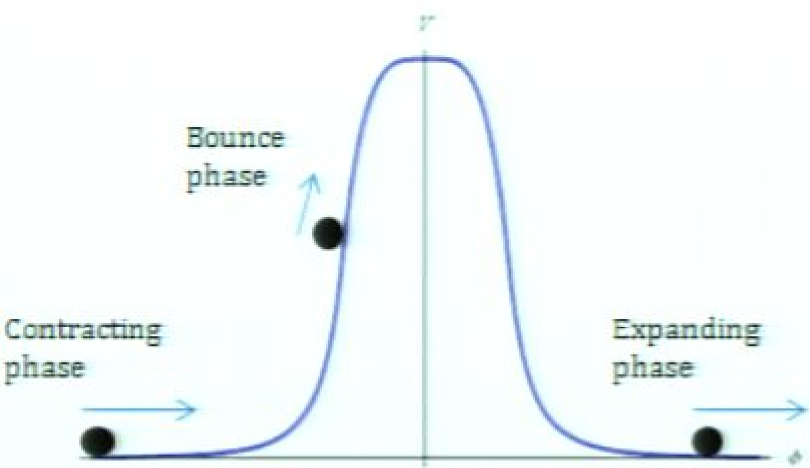

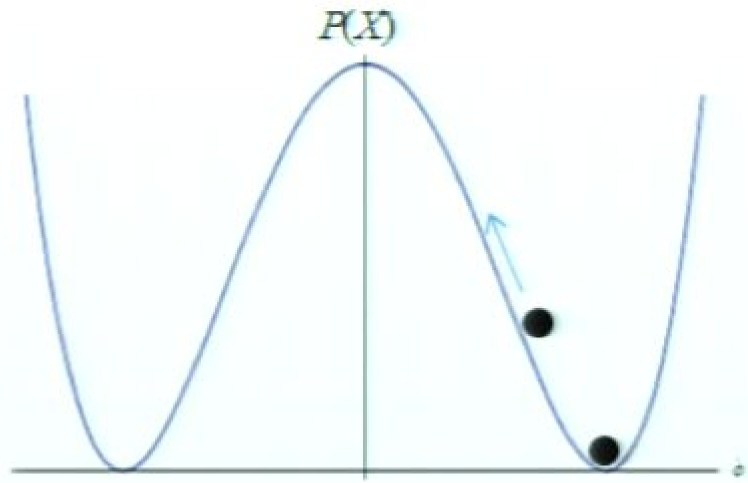

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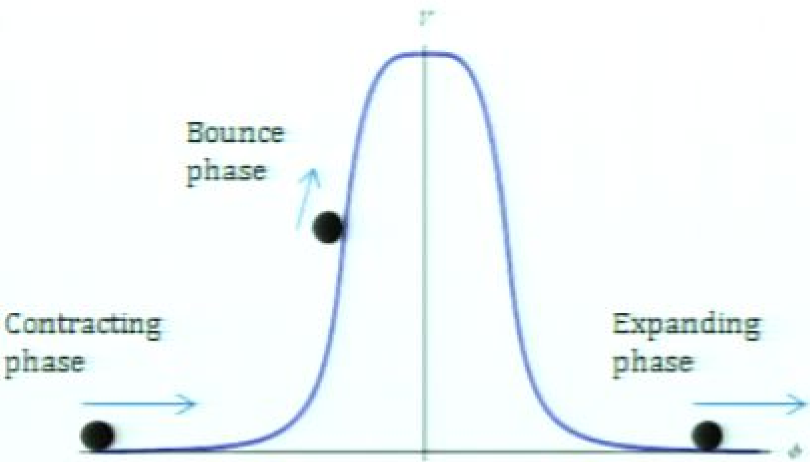

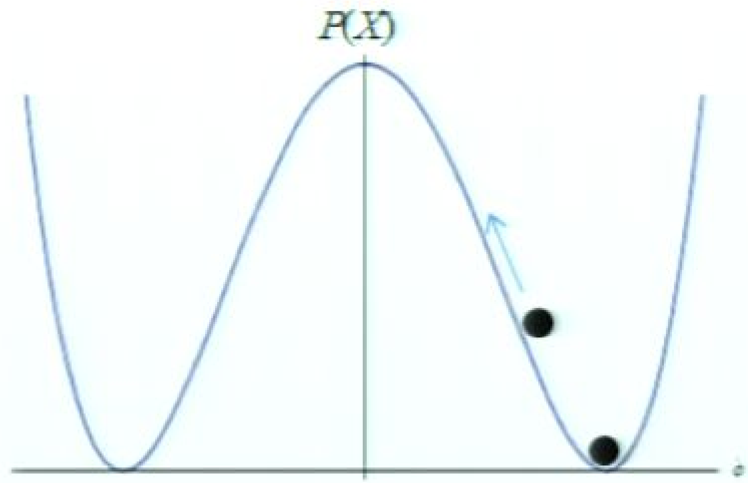

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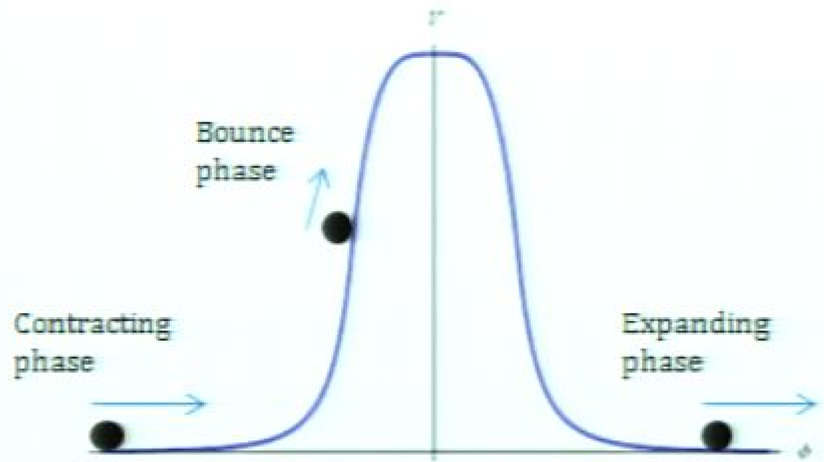

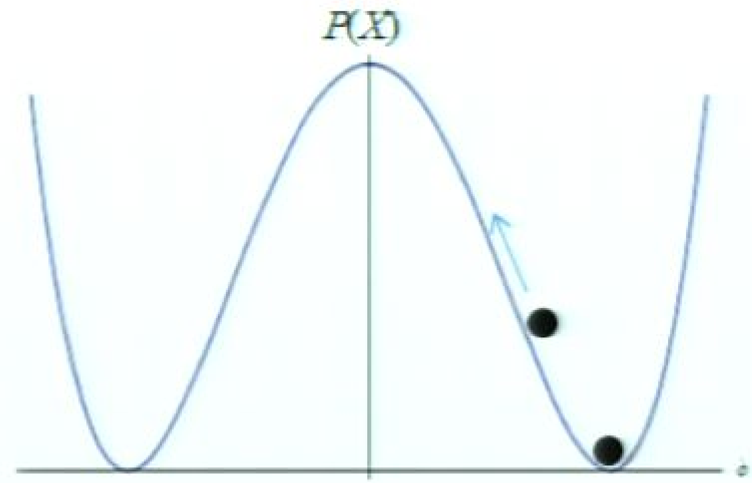

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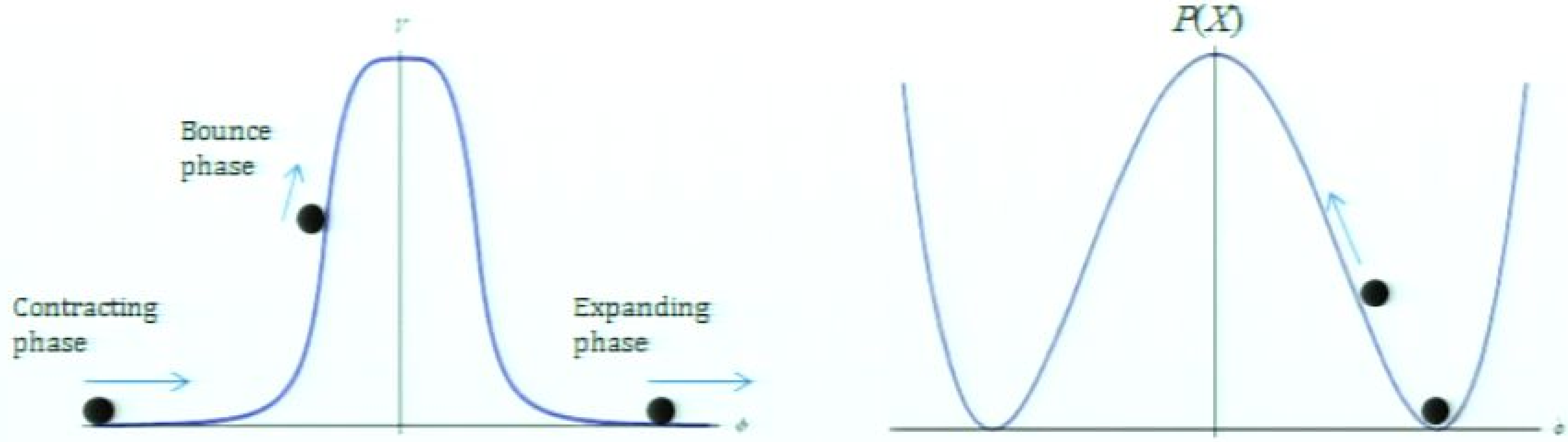

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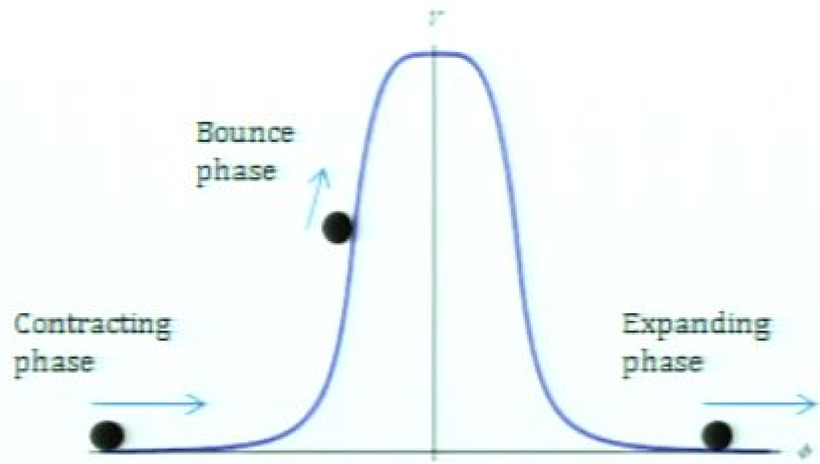

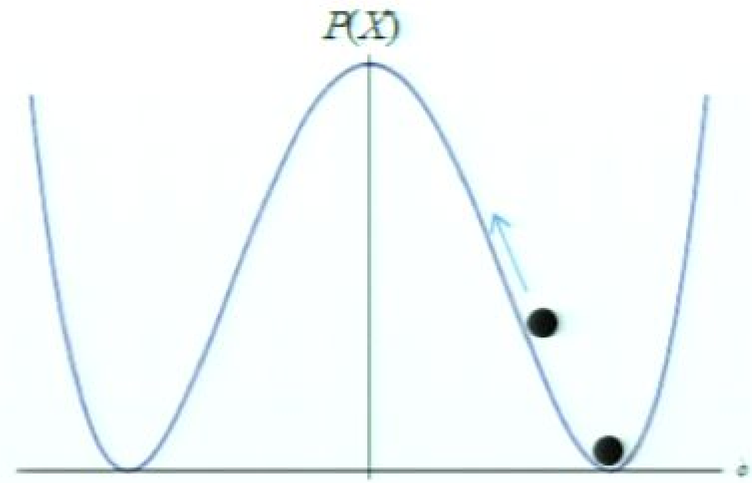

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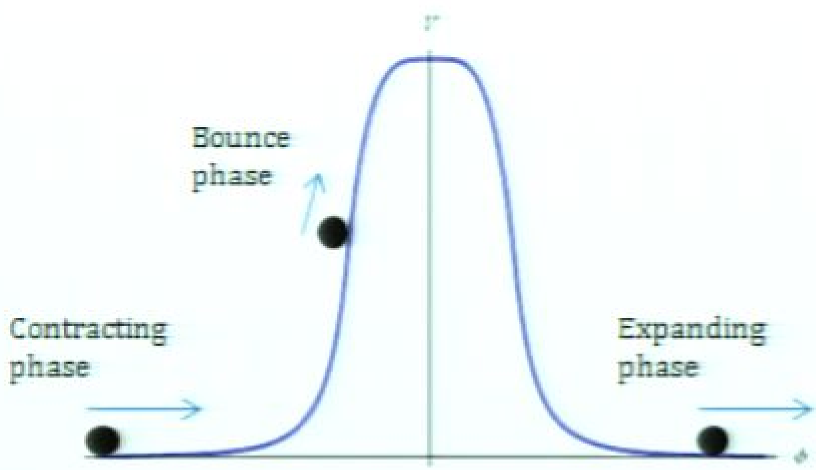

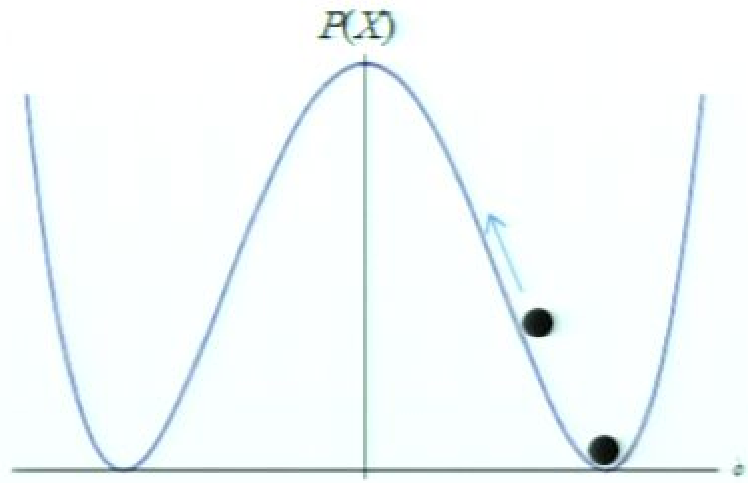

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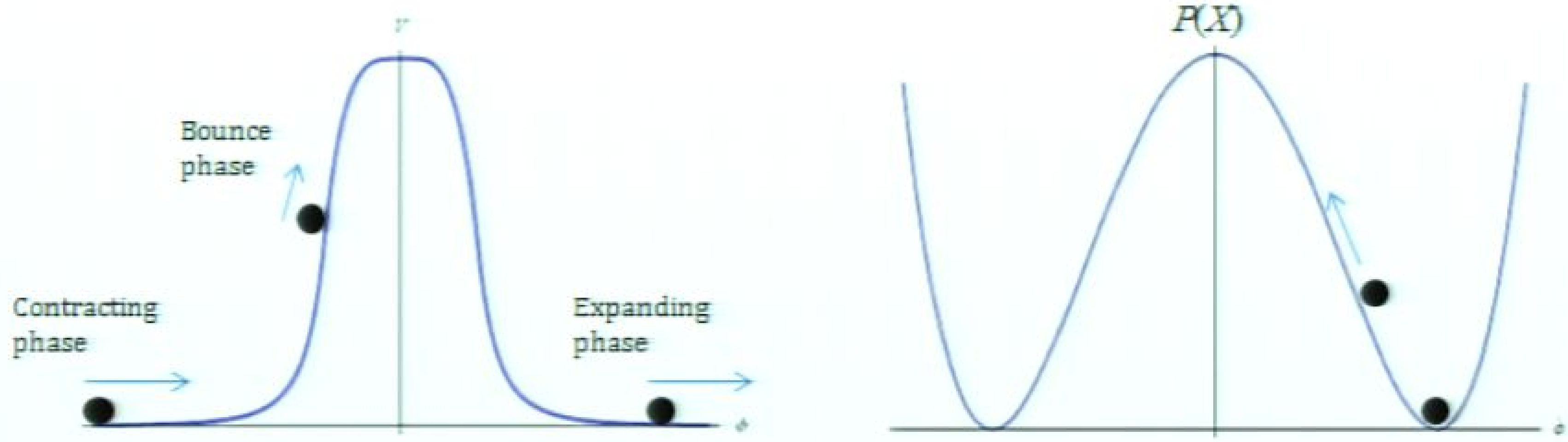

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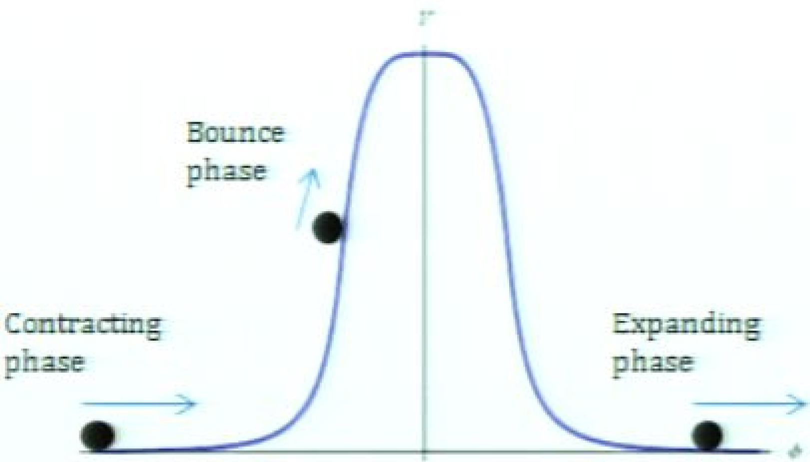

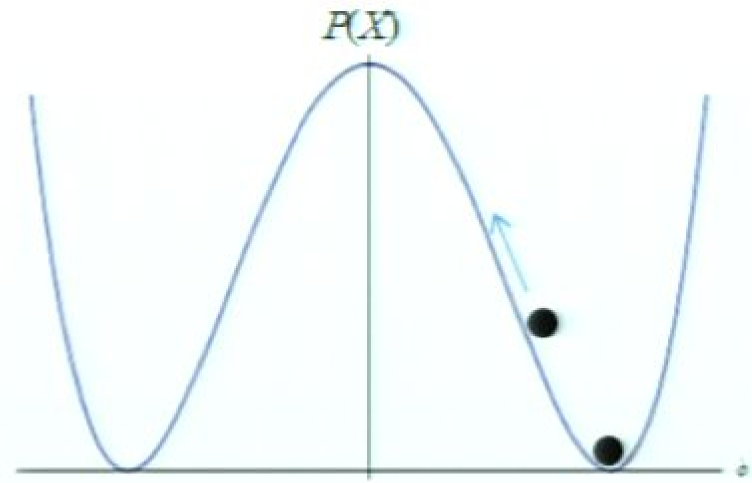

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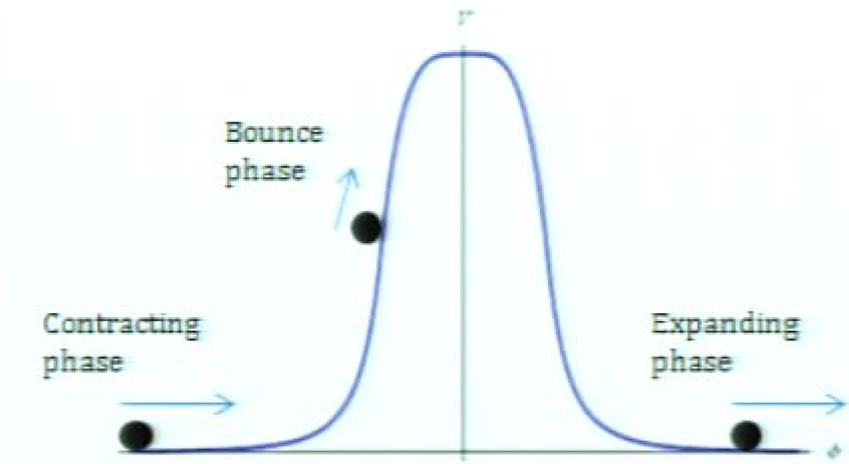

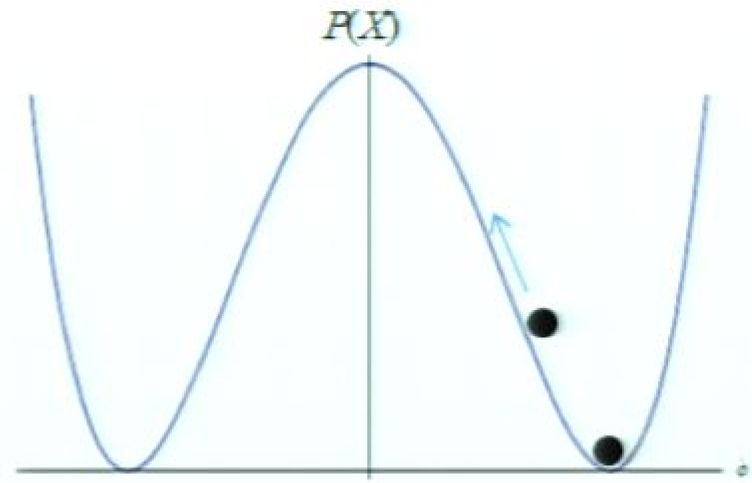

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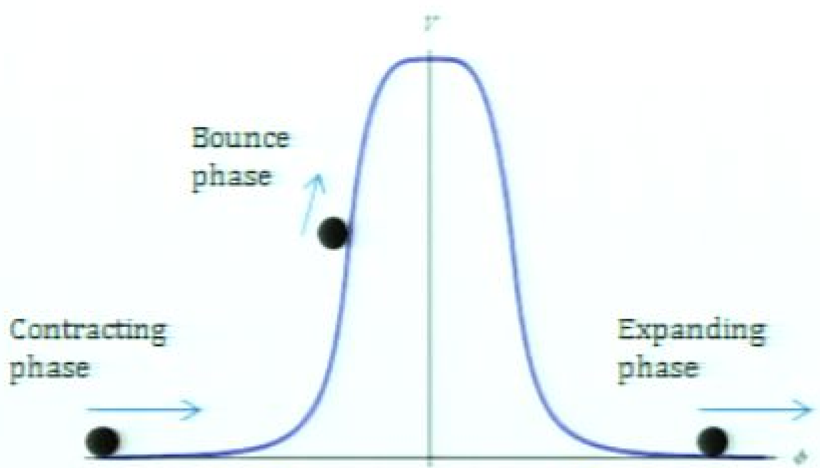
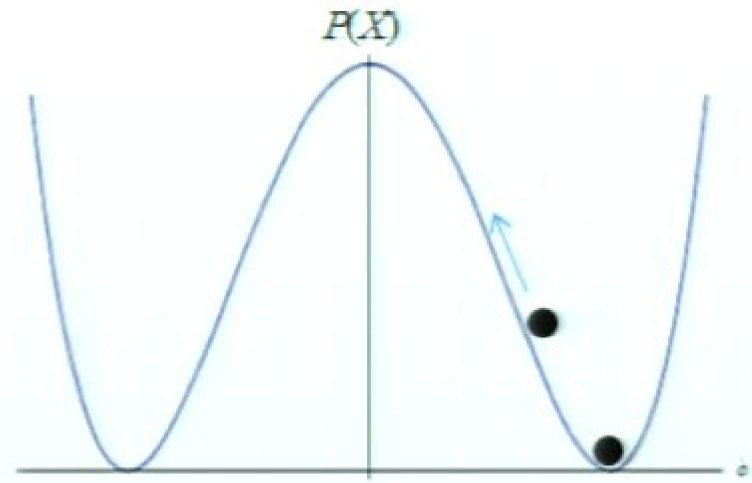
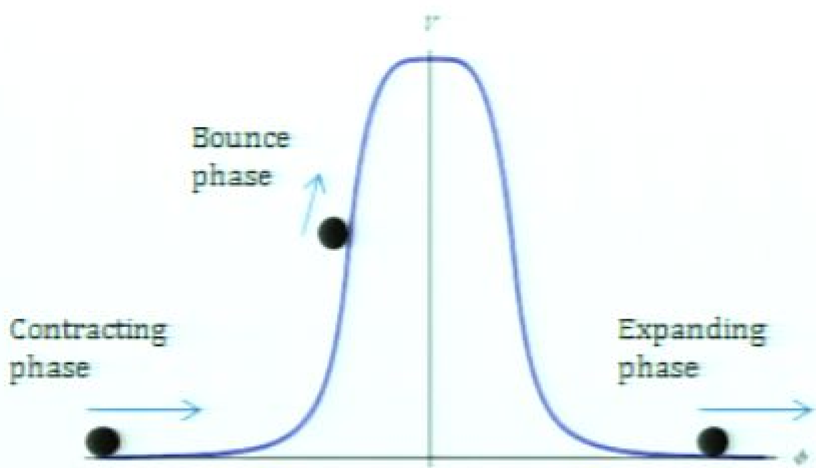


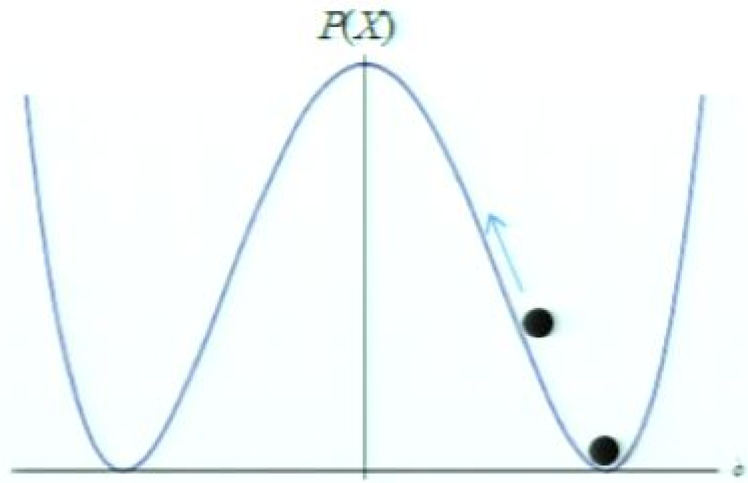


$$2M_p^2\dot{H} = -2M^4XP' - (1+w_m)\rho_m$$

Realization of NEC violation!

Ghost bounce





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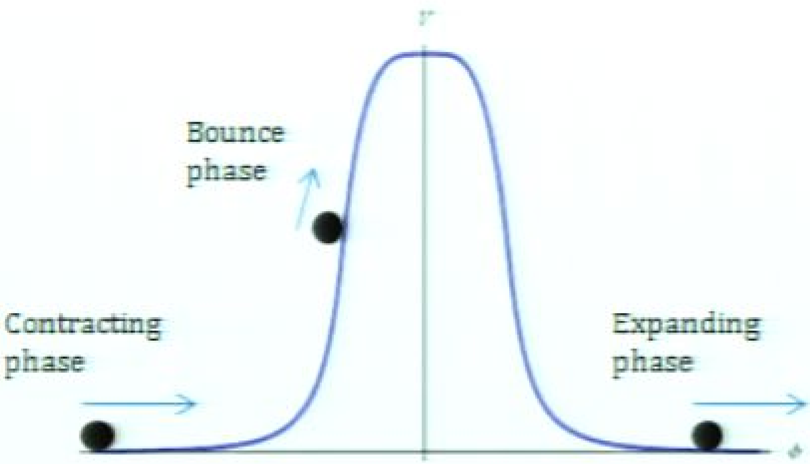

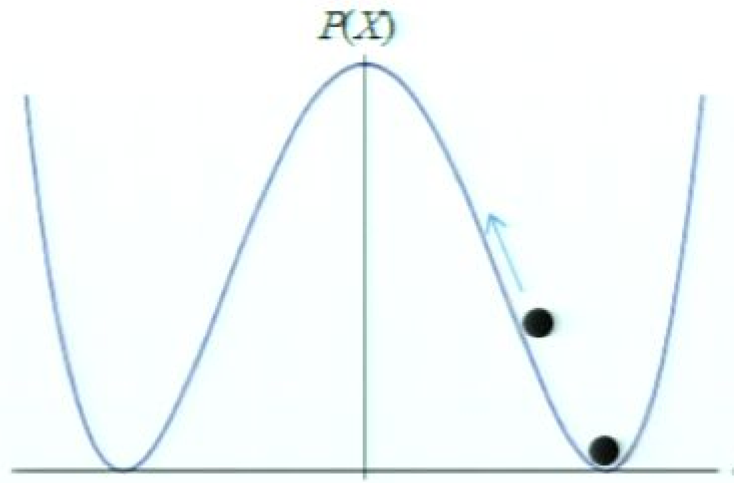

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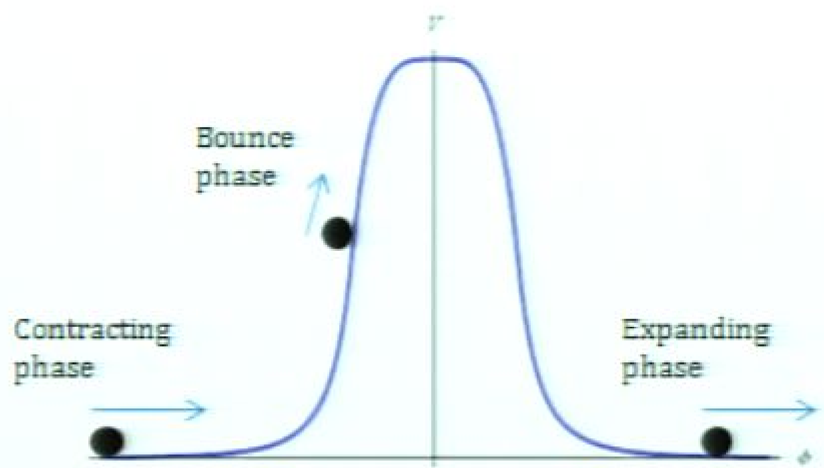

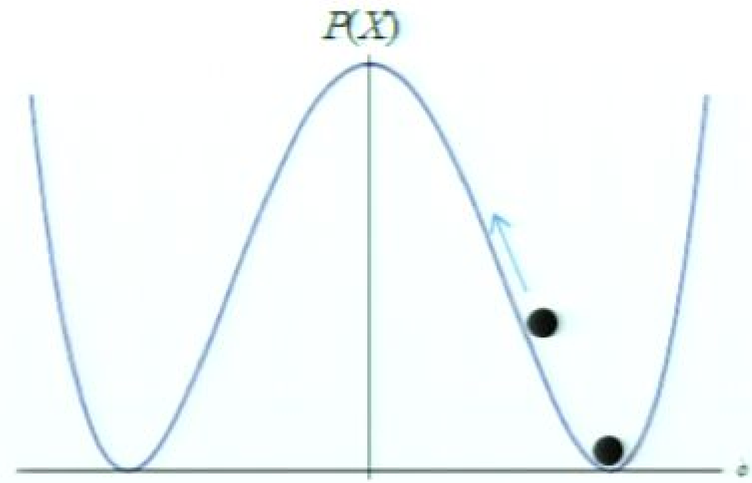

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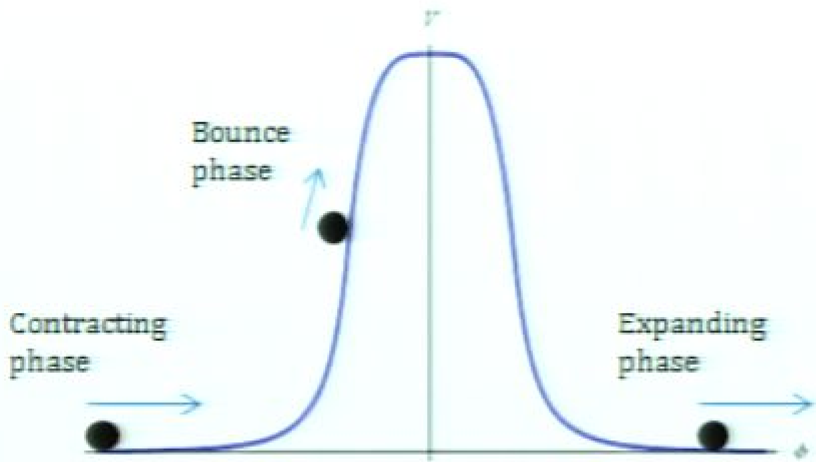

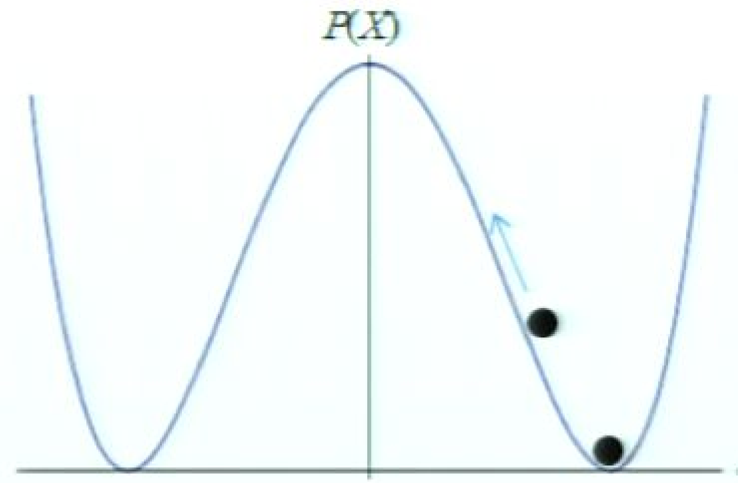

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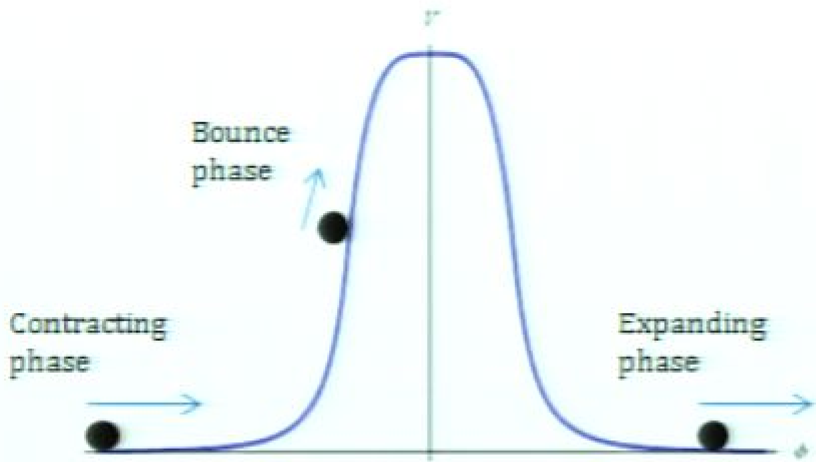

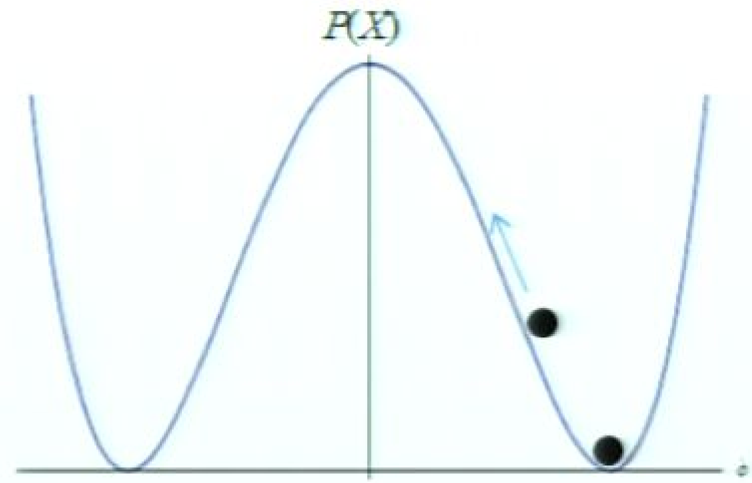

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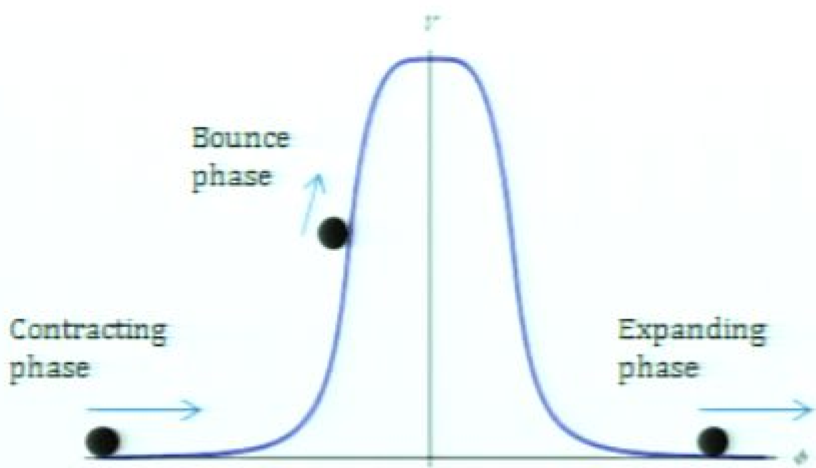

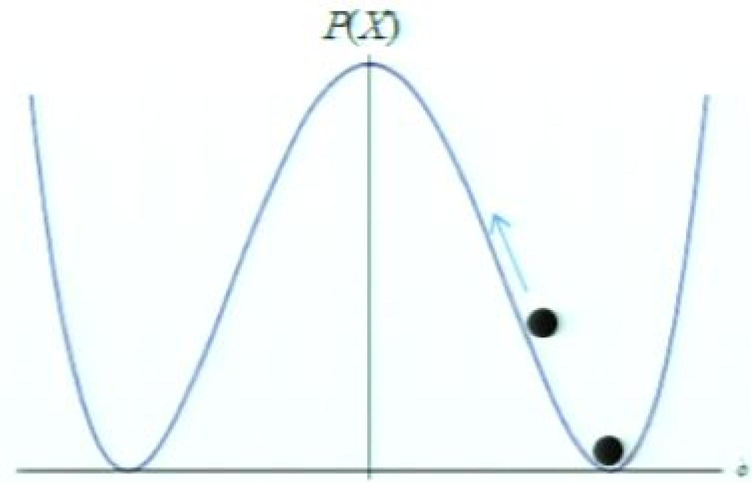

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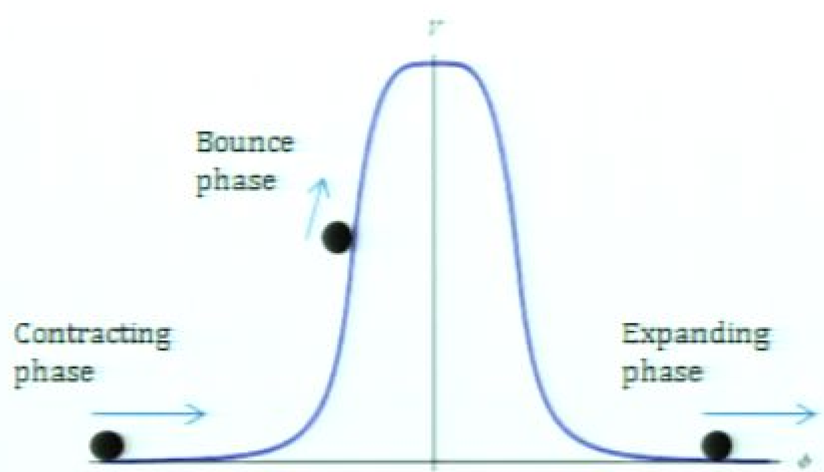

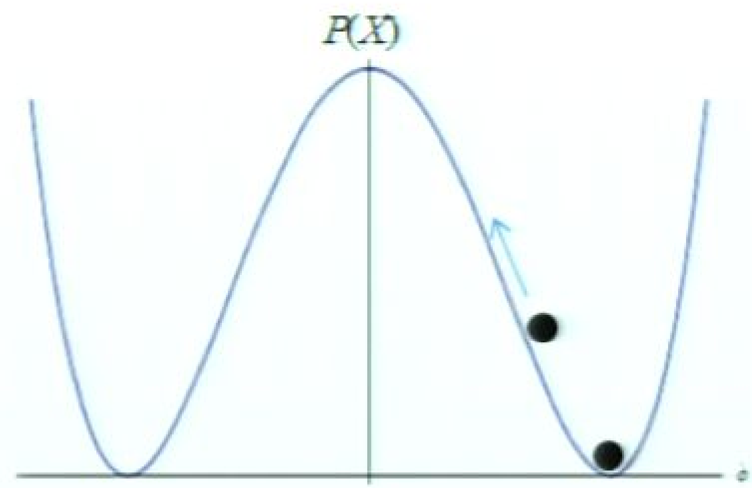

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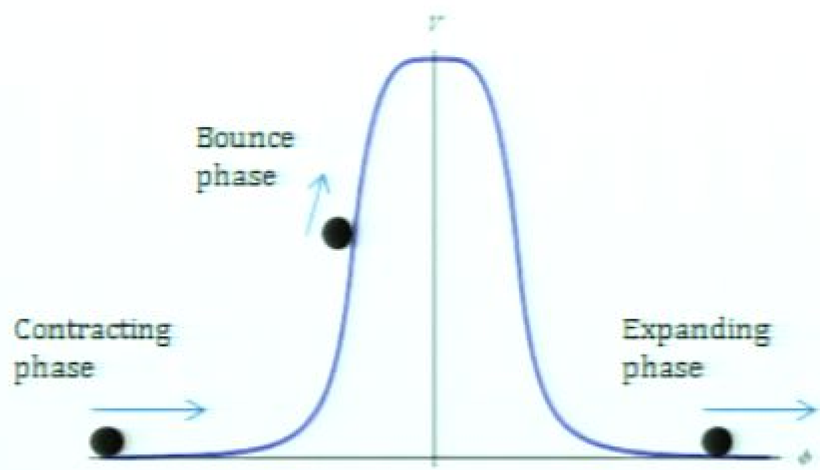

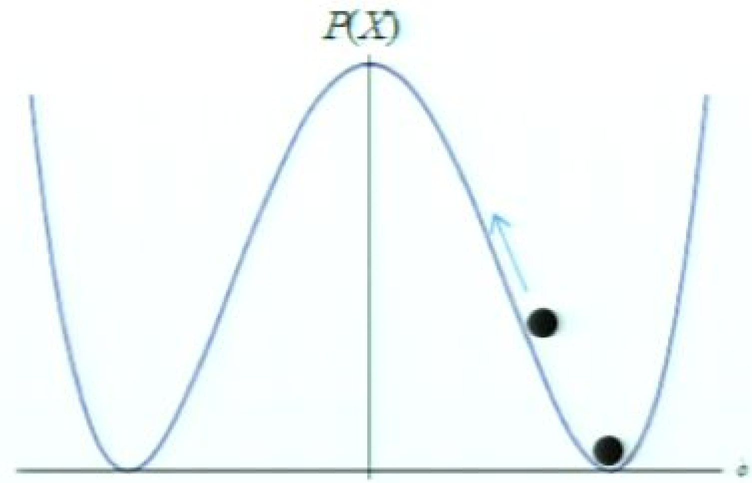

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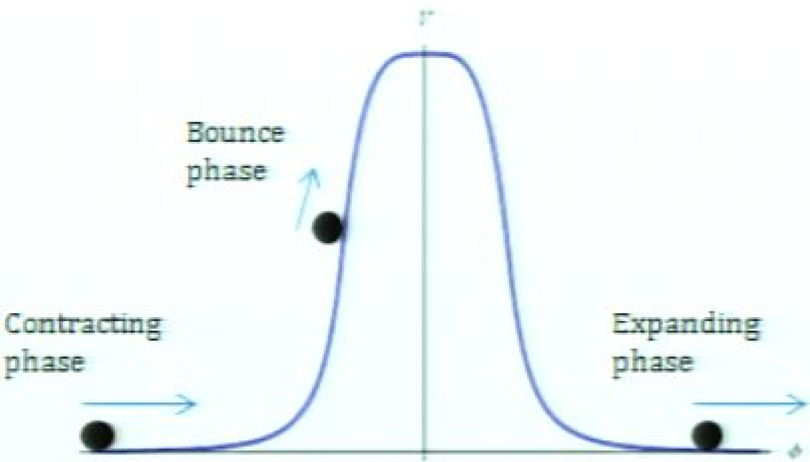

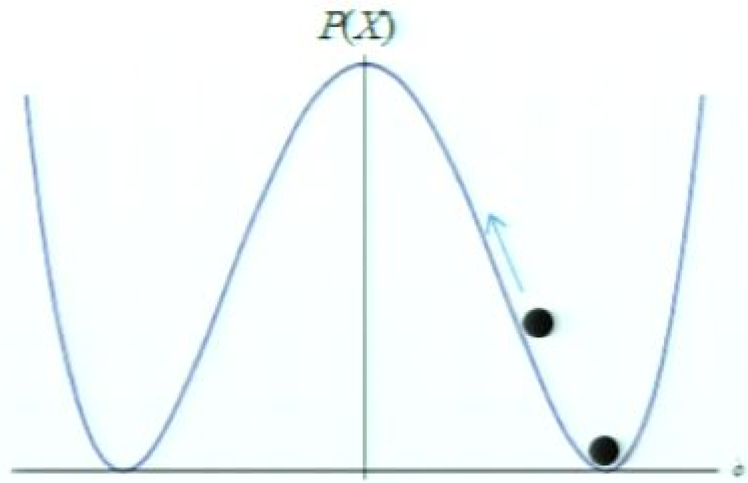

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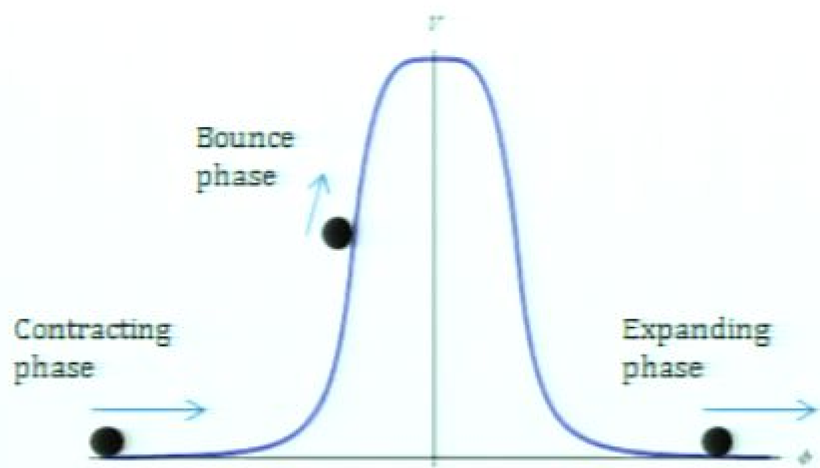

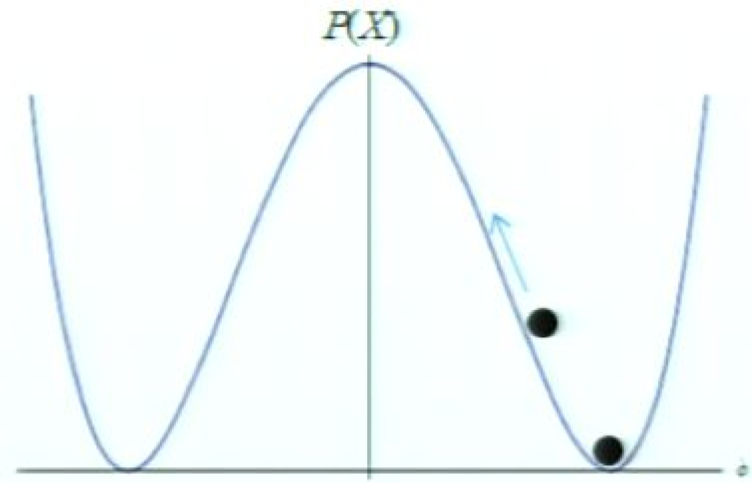

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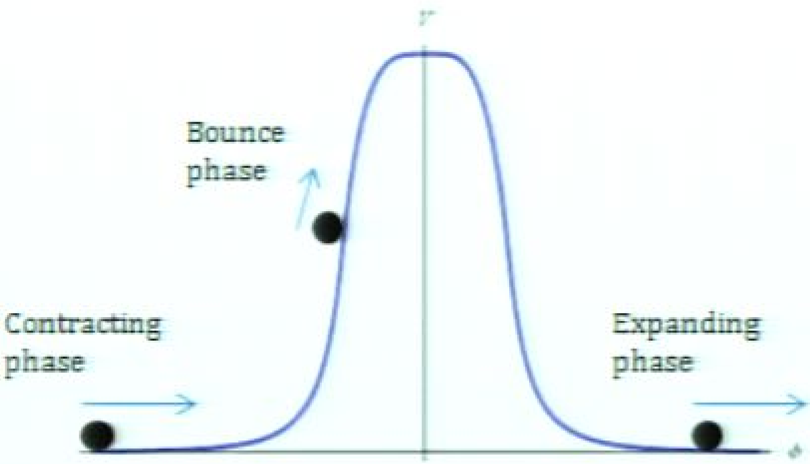

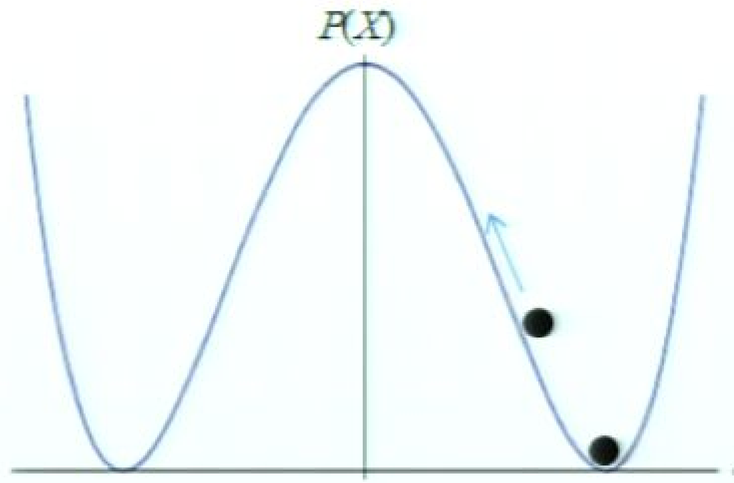

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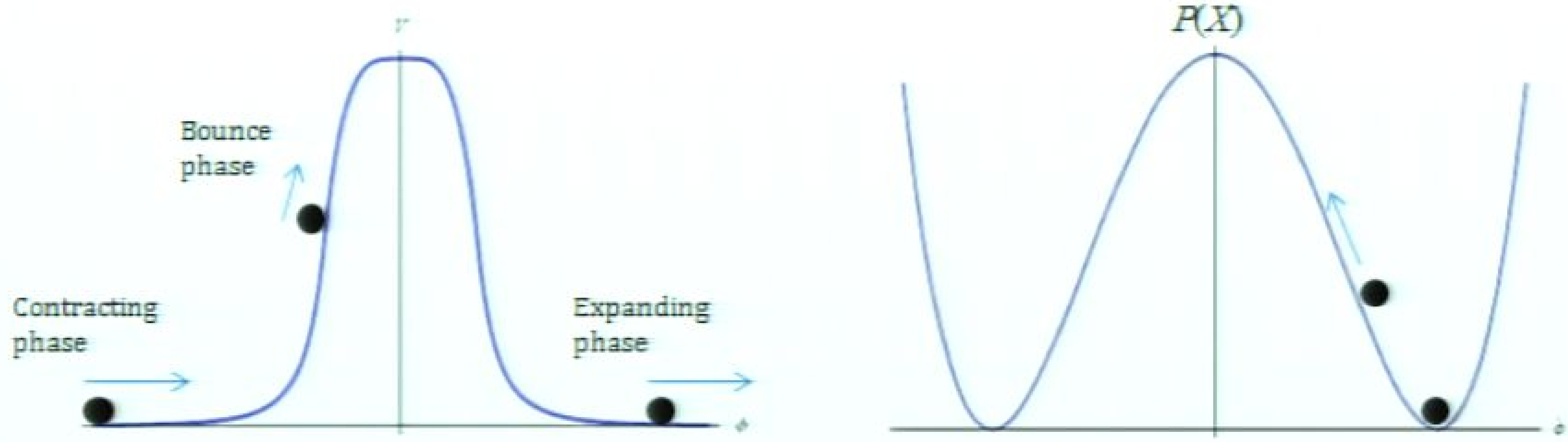

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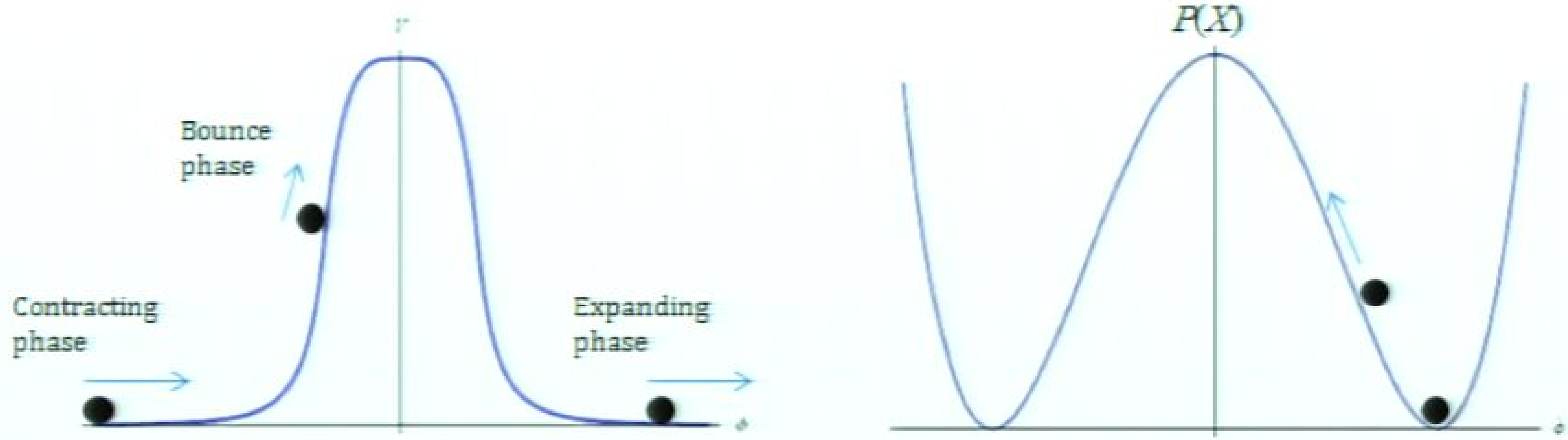

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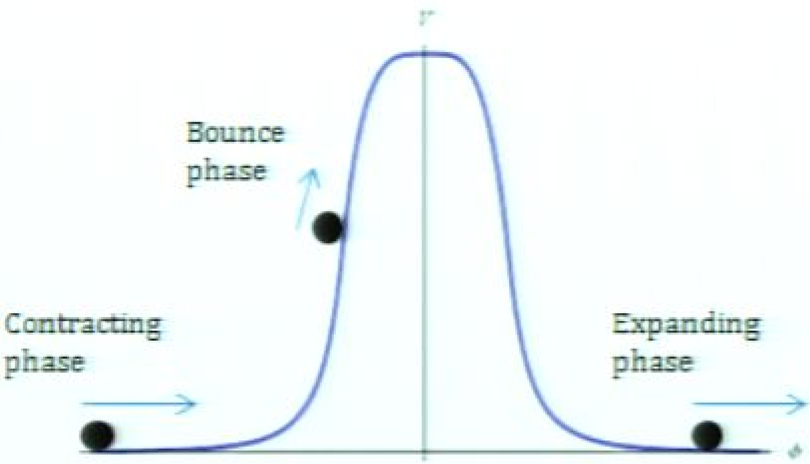

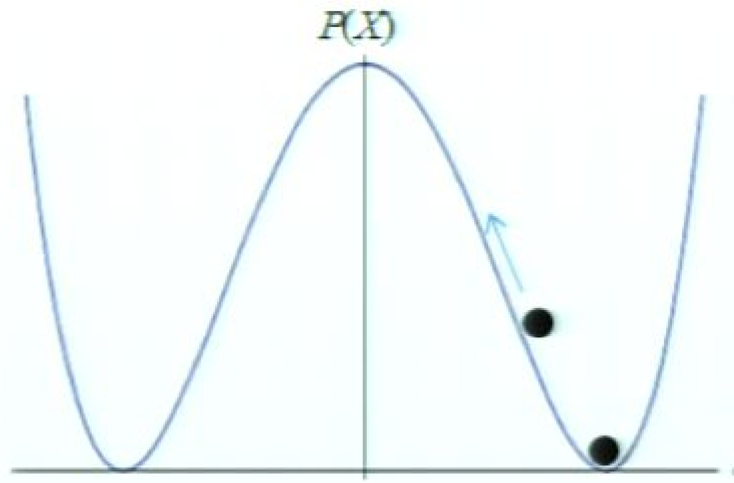

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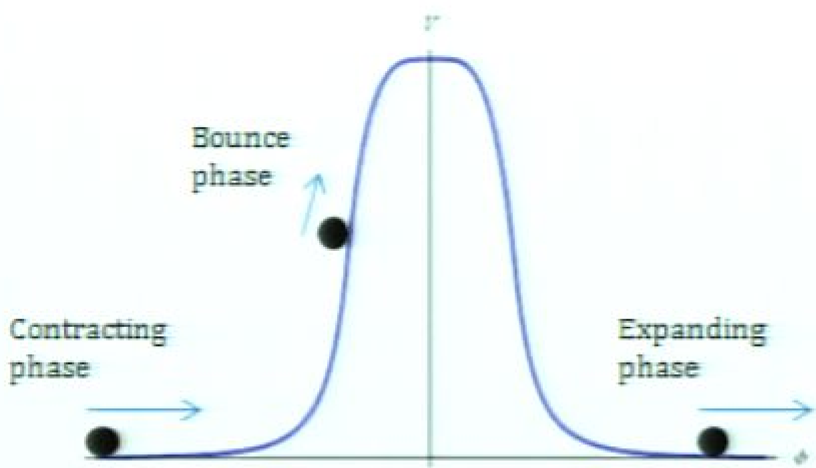

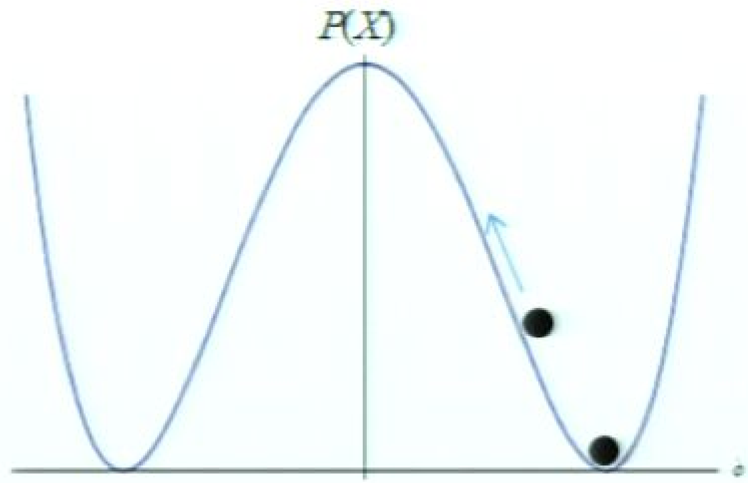

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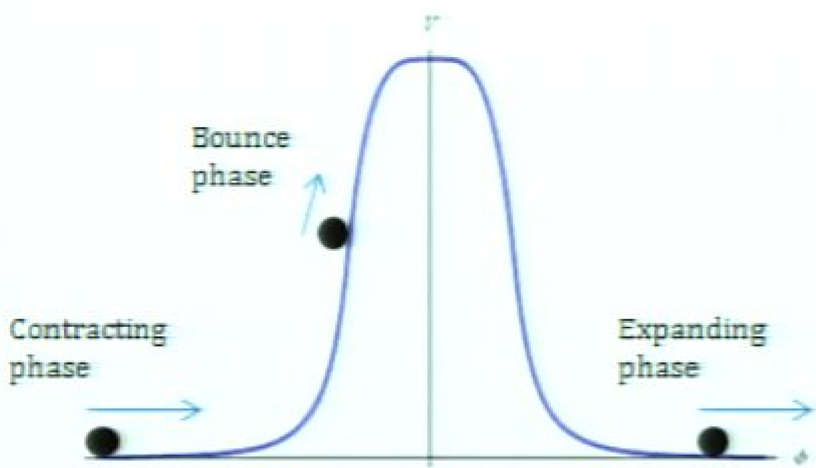

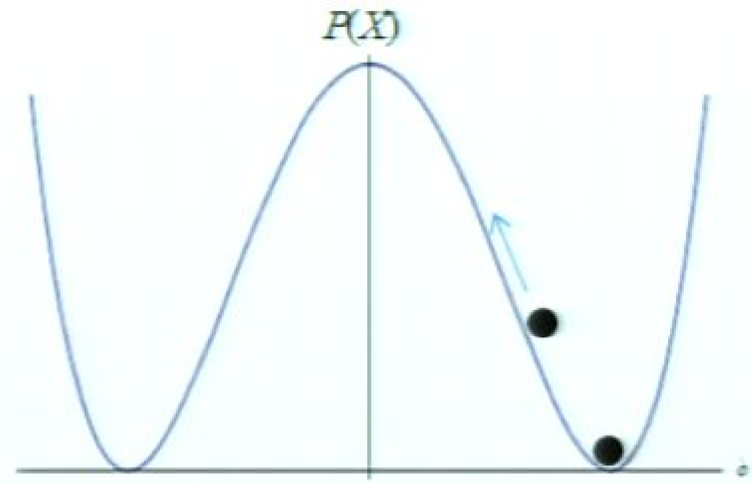

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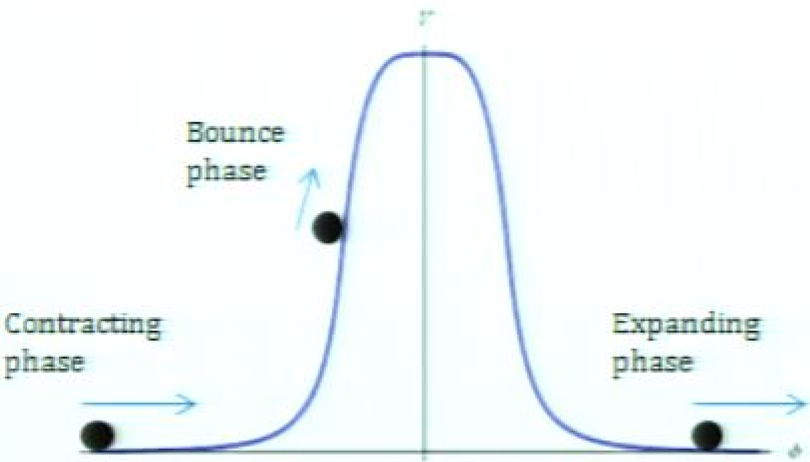

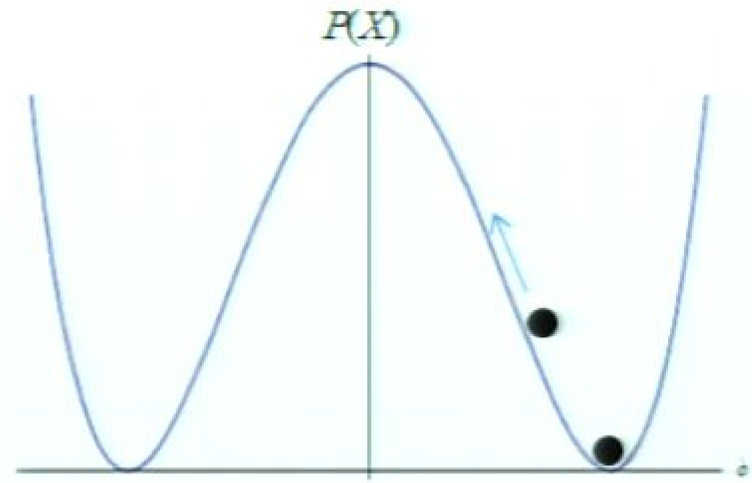

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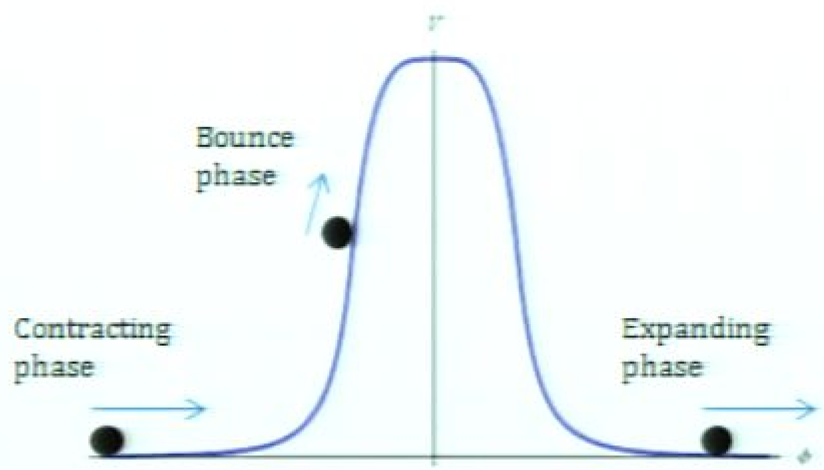

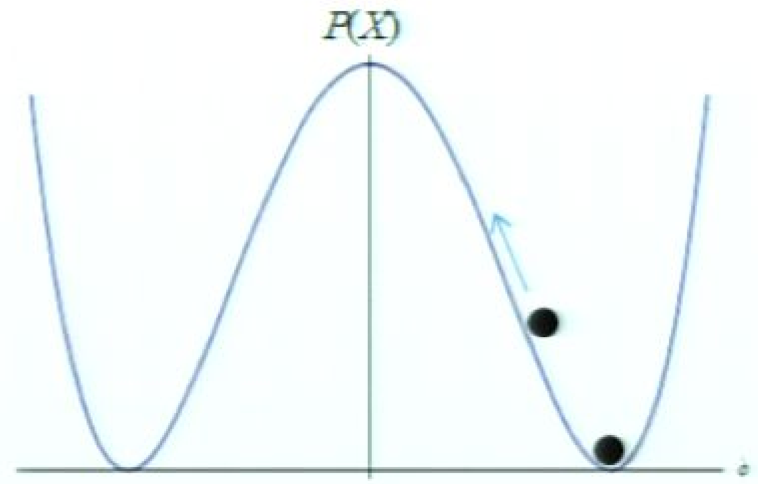

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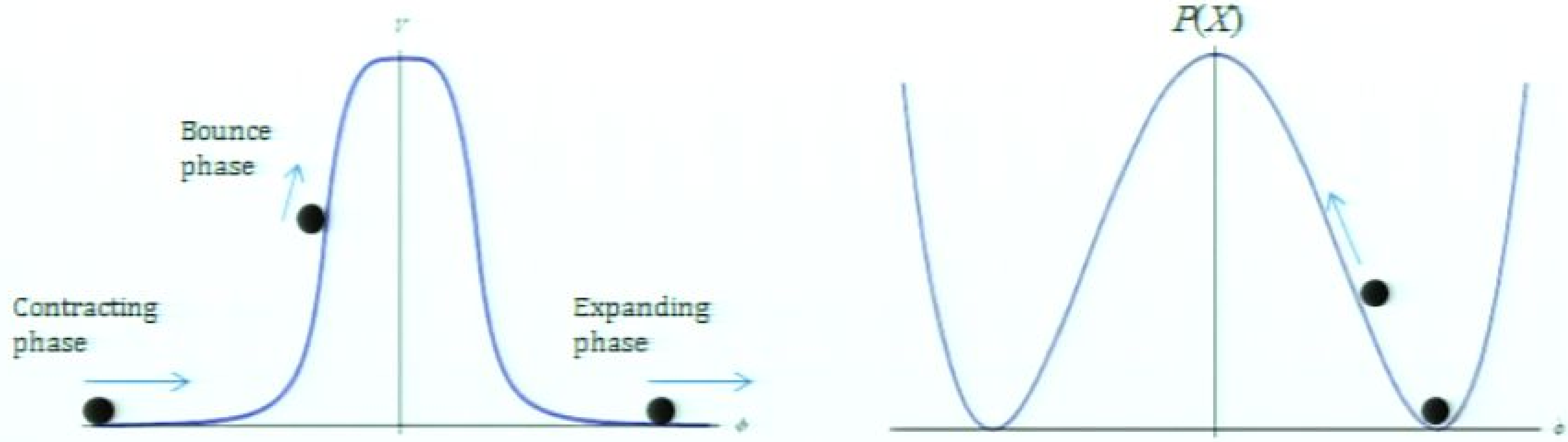

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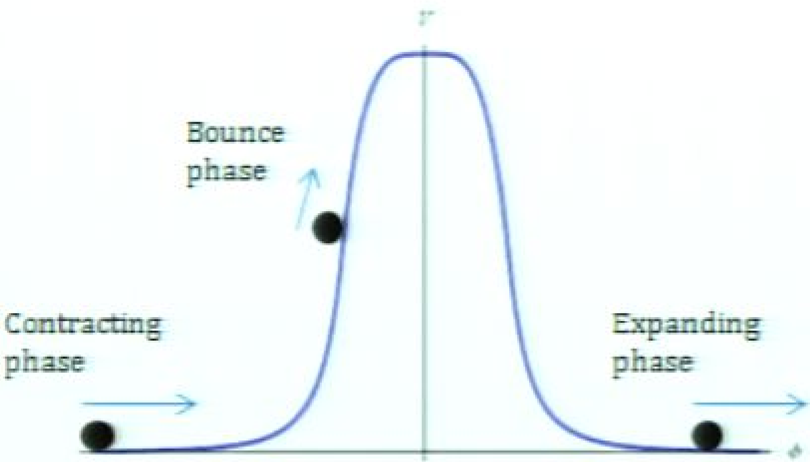

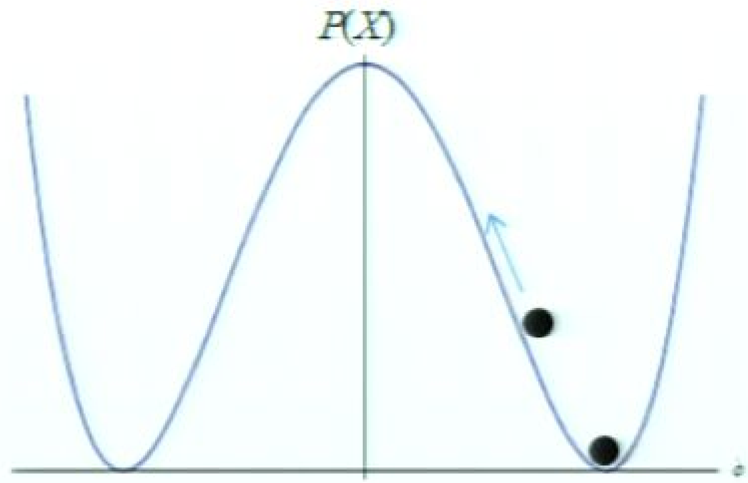

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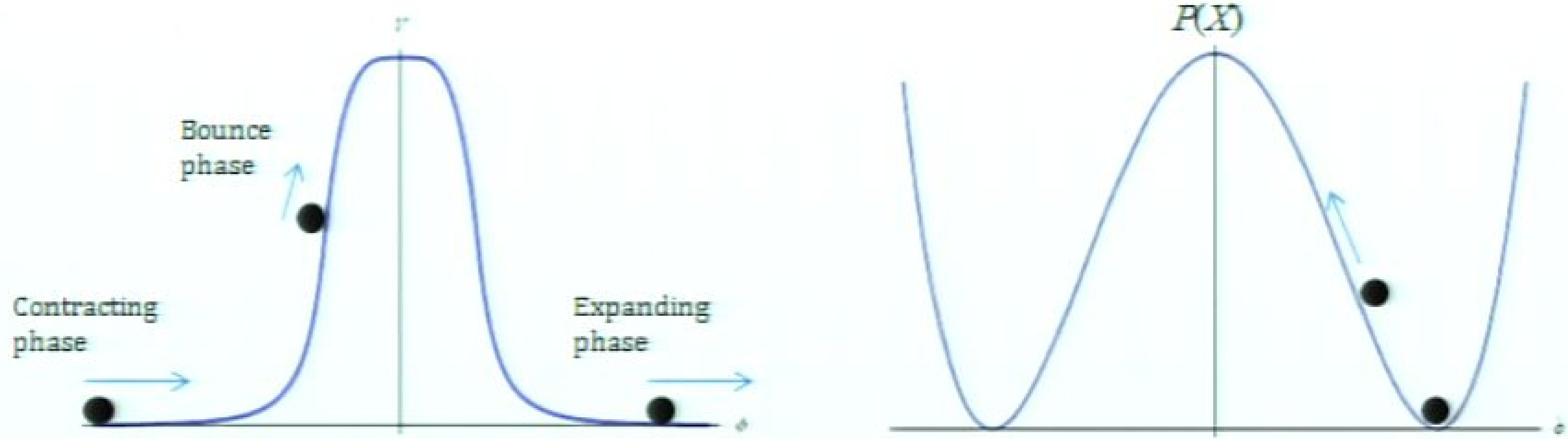

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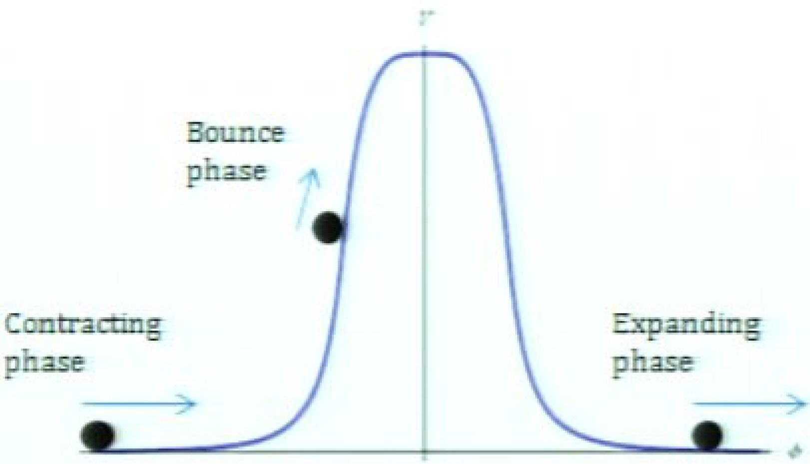

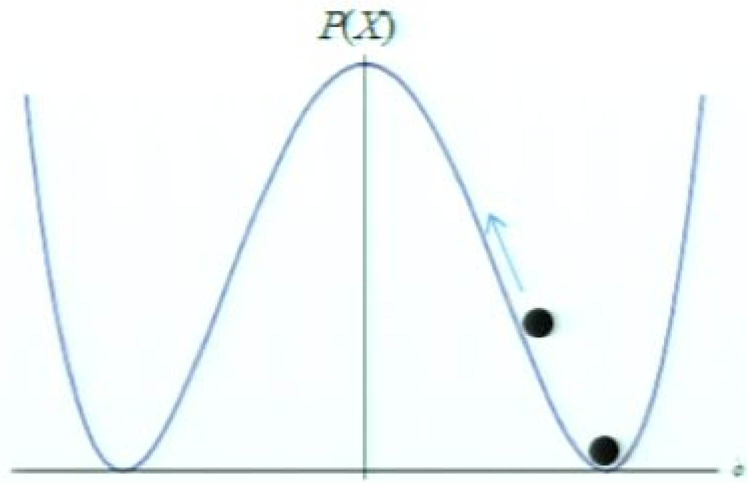

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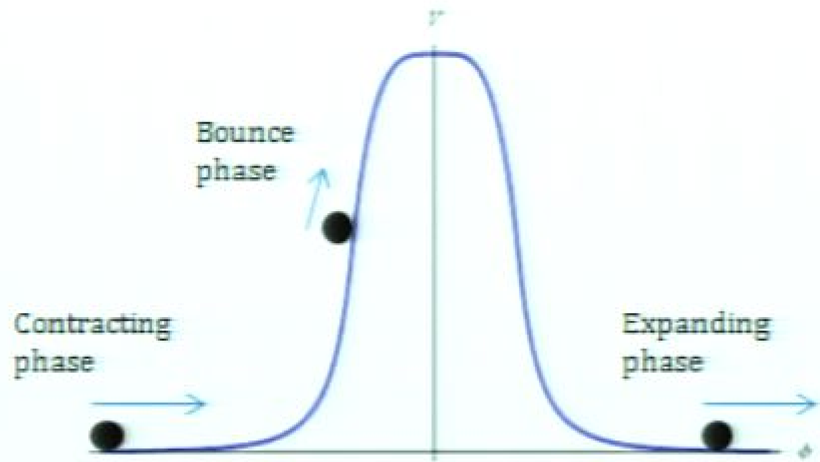

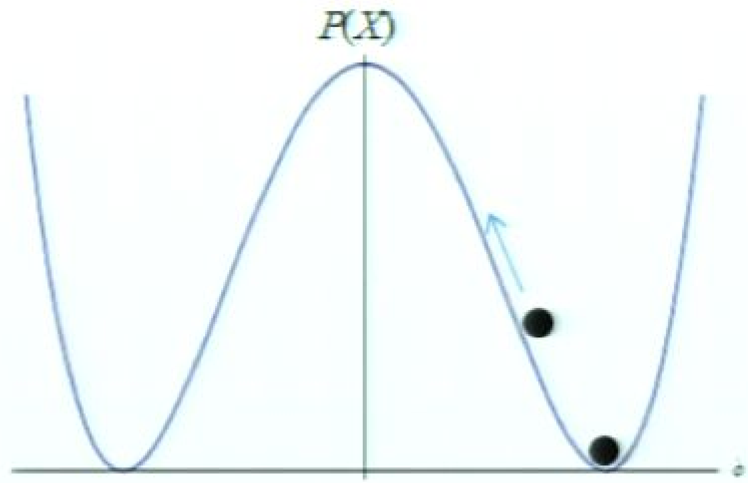

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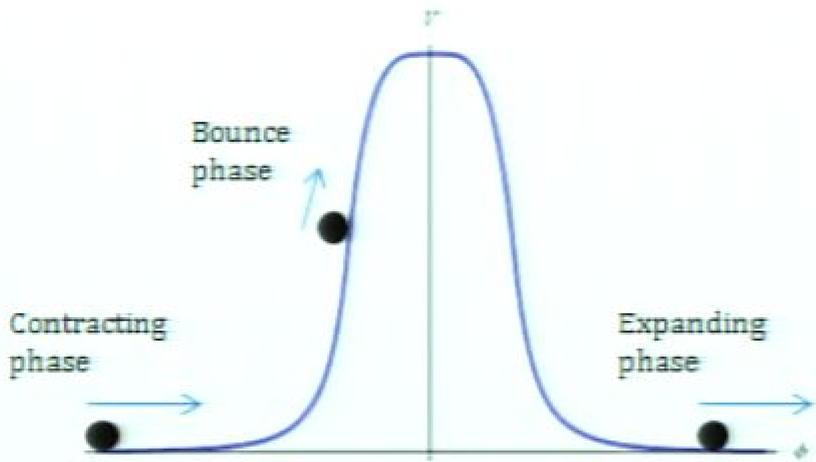

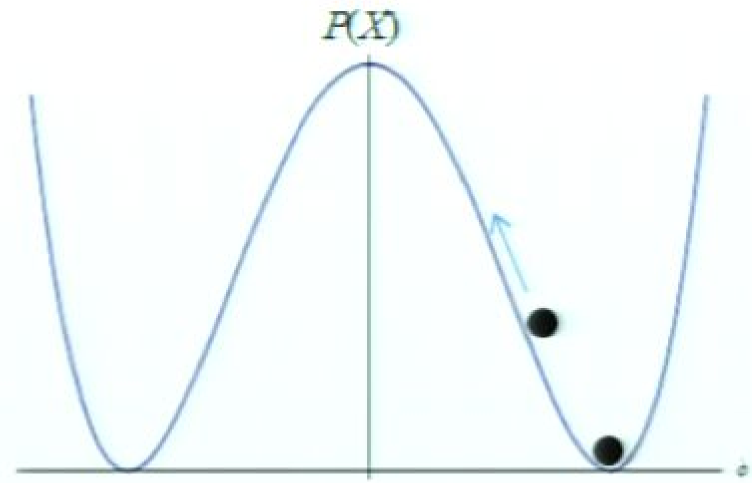

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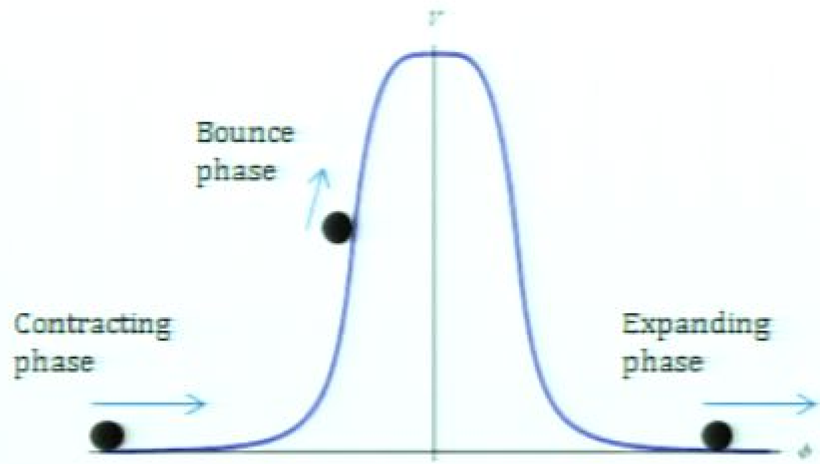

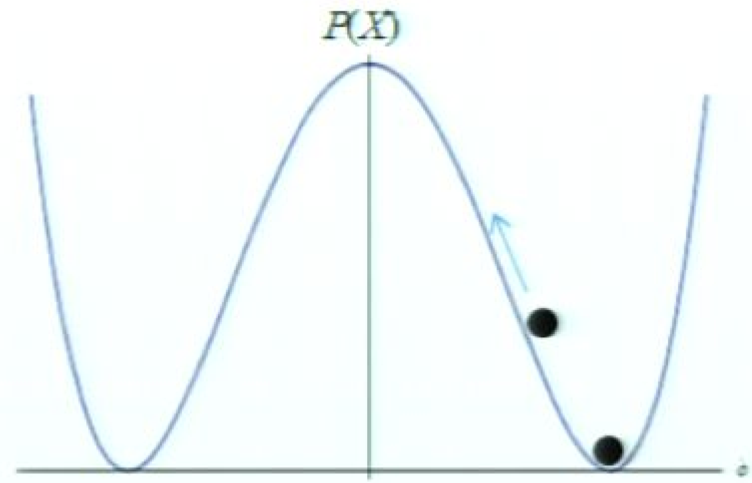

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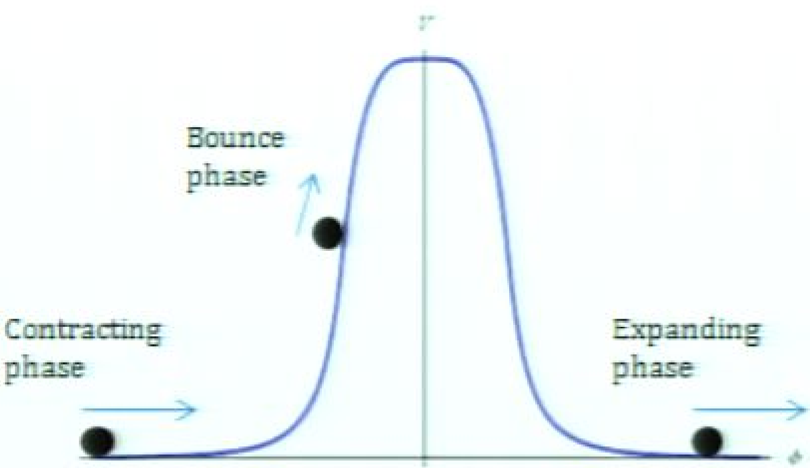

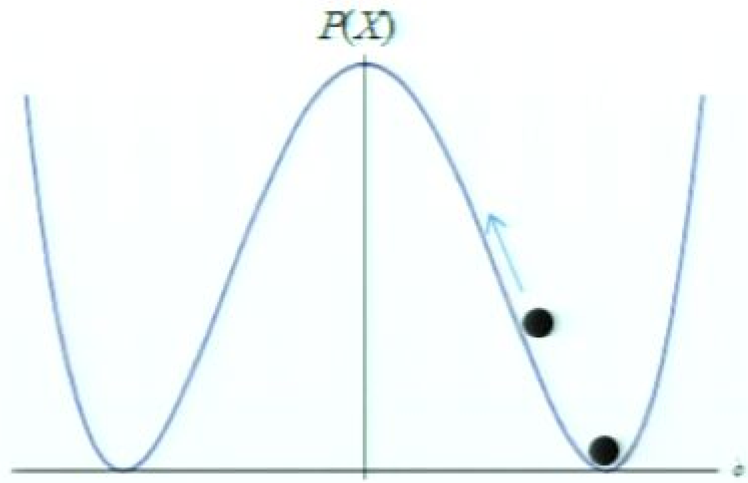

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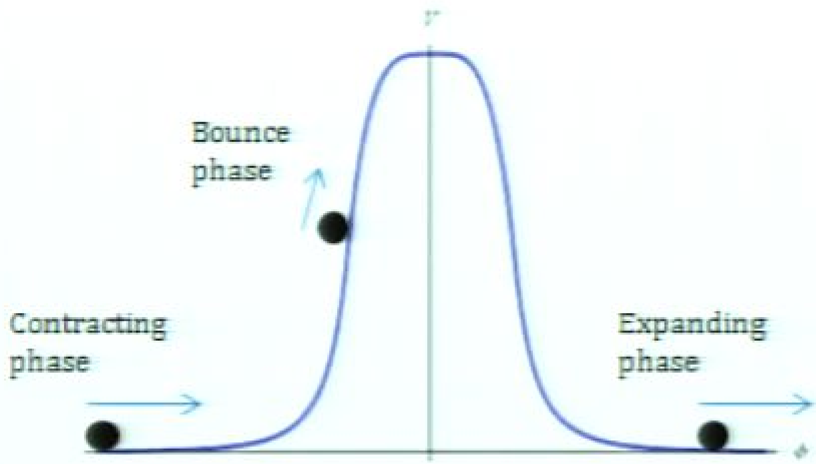

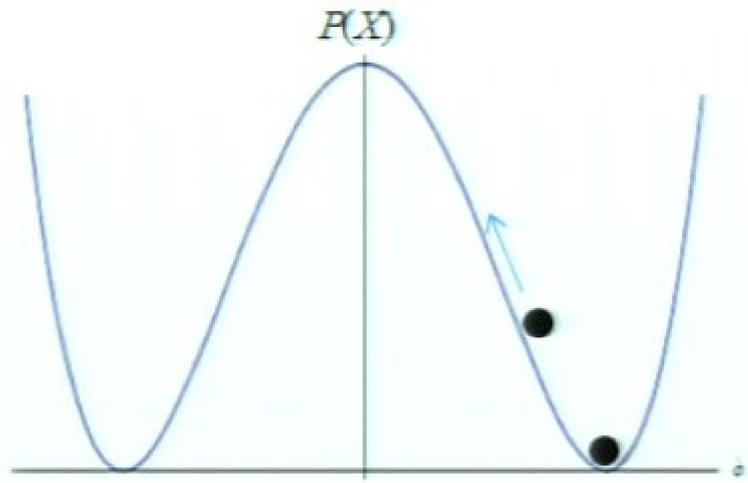

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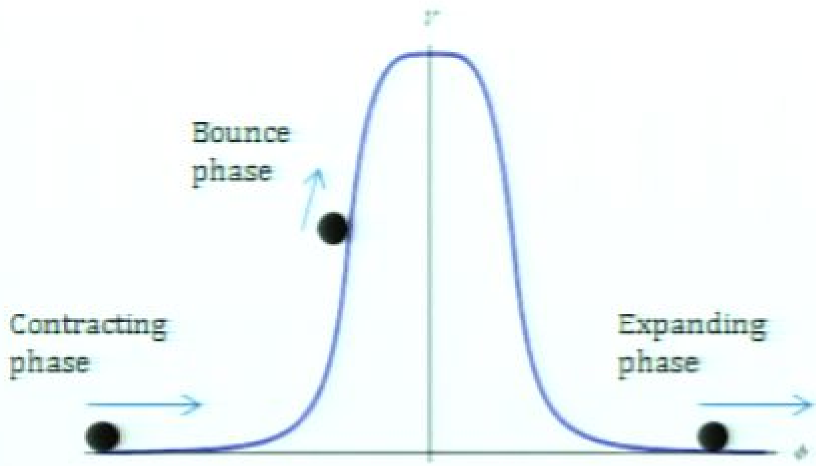

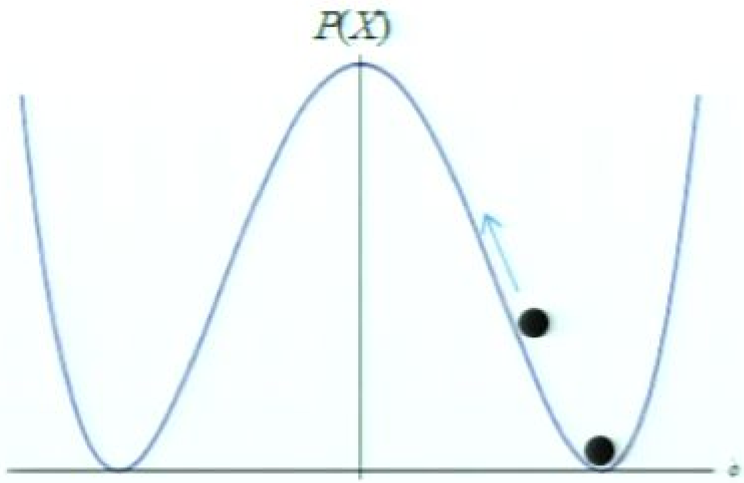

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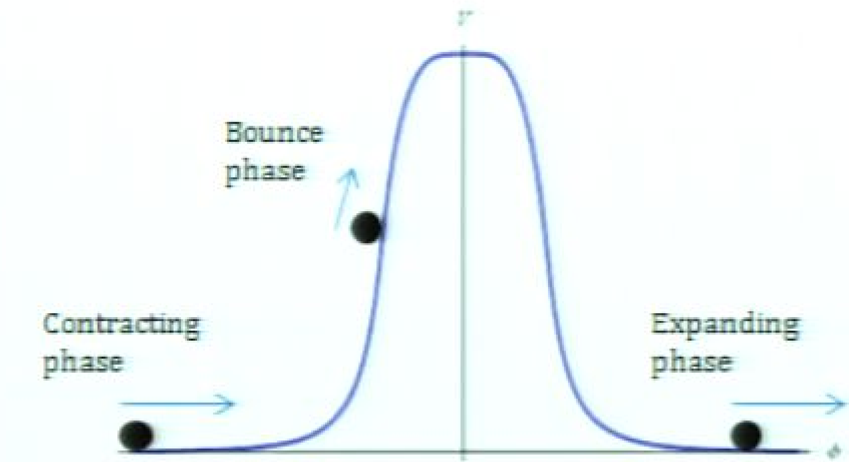

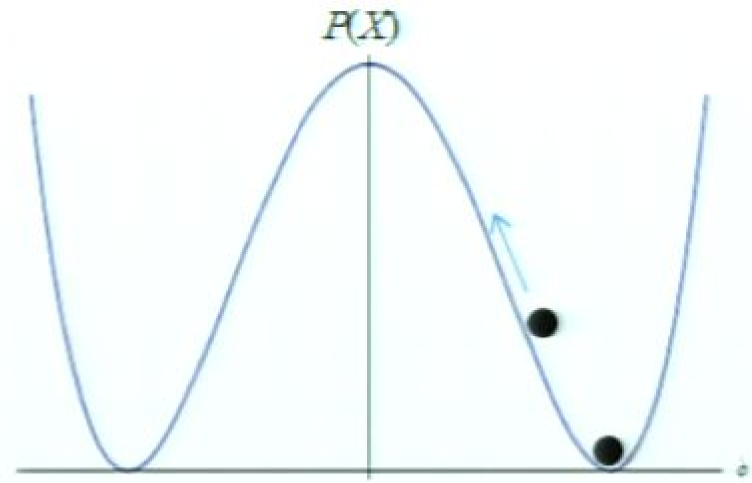

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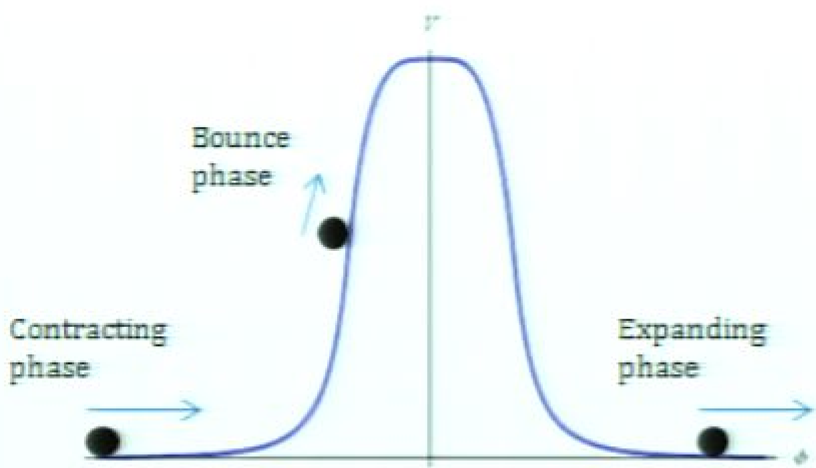

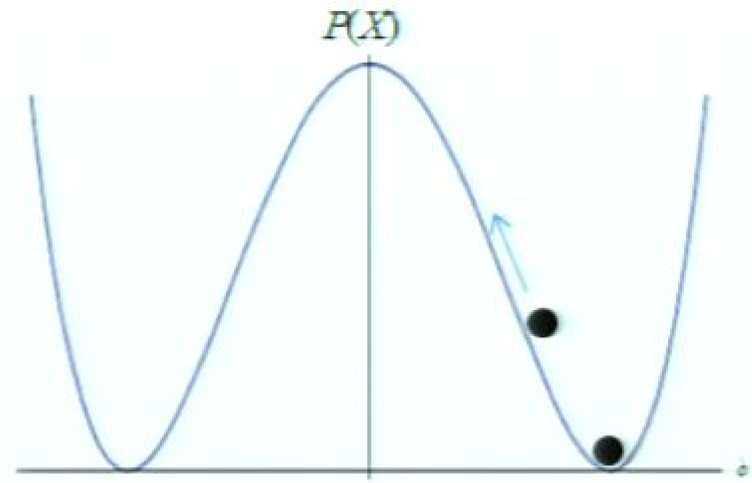

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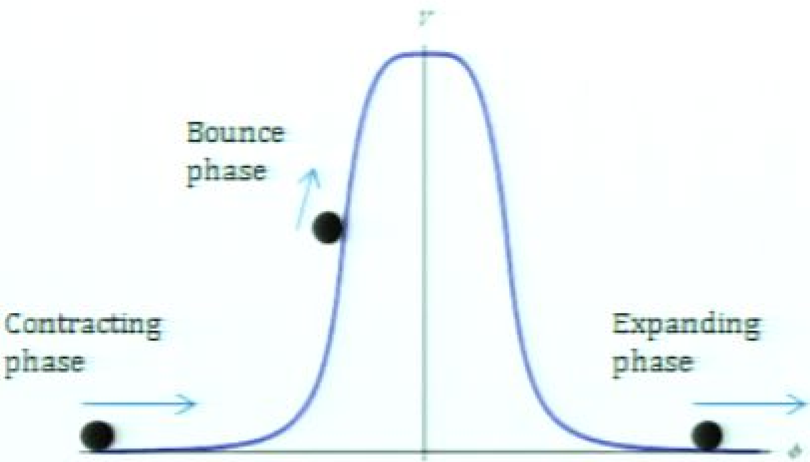

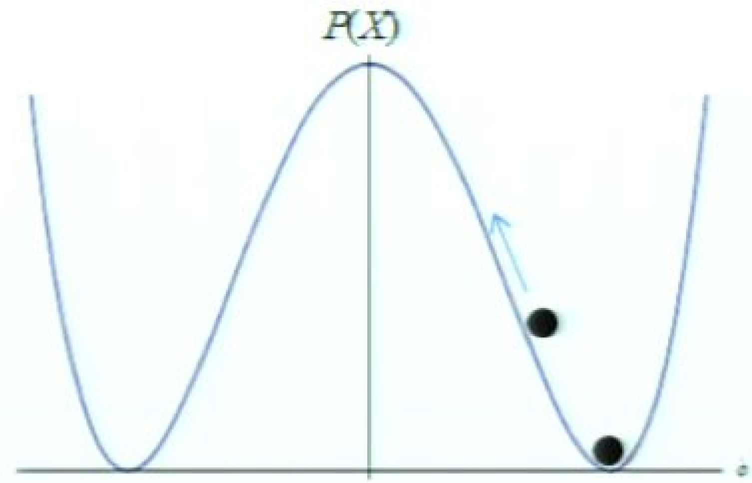

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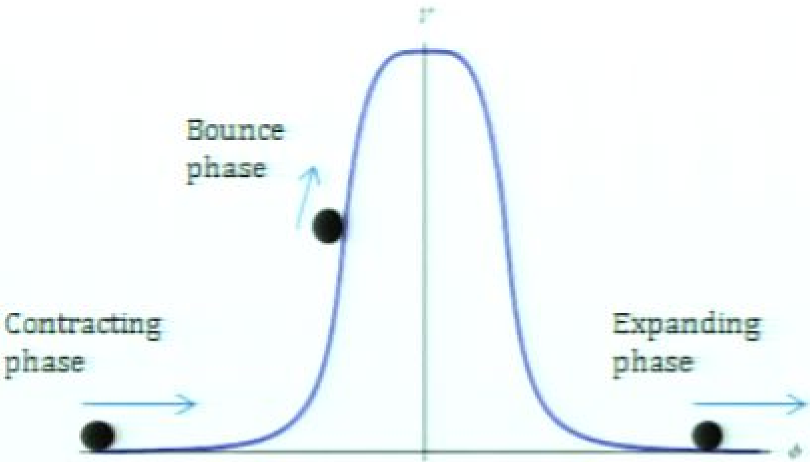

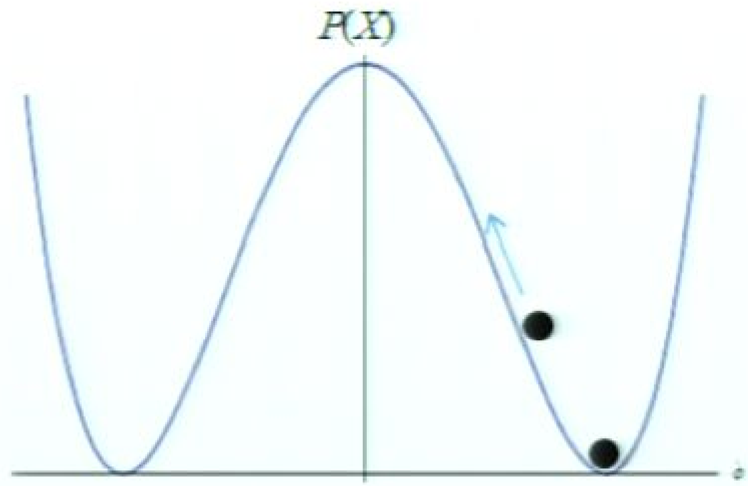

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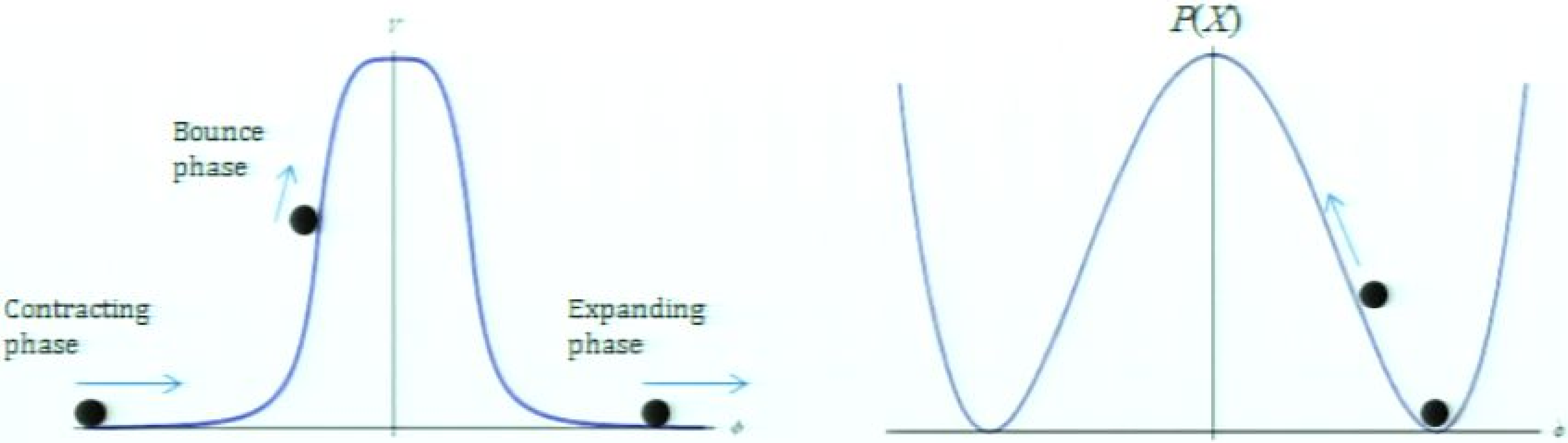
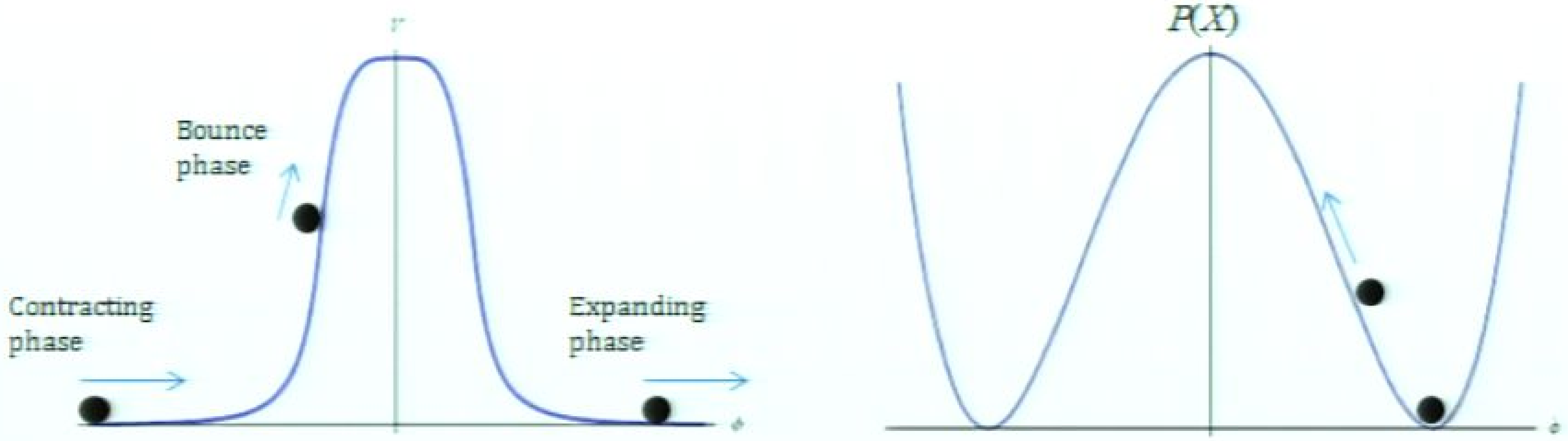


$$2M_p^2\dot{H} = -2M^4XP' - (1+w_m)\rho_m$$

Realization of NEC violation!

Ghost bounce



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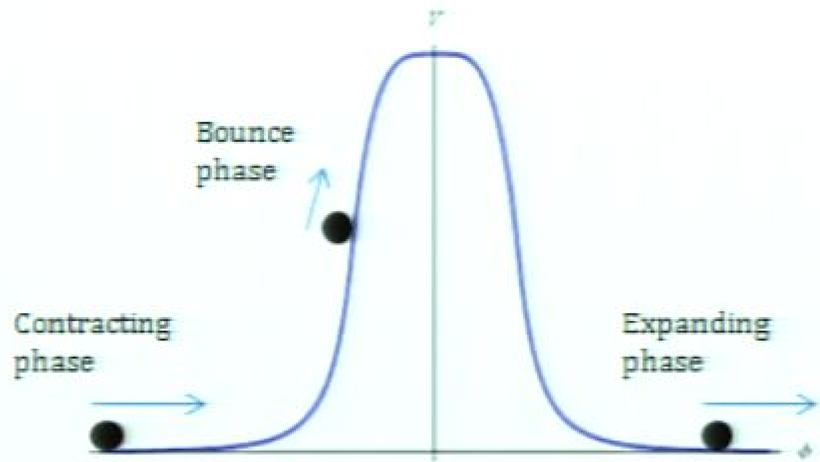

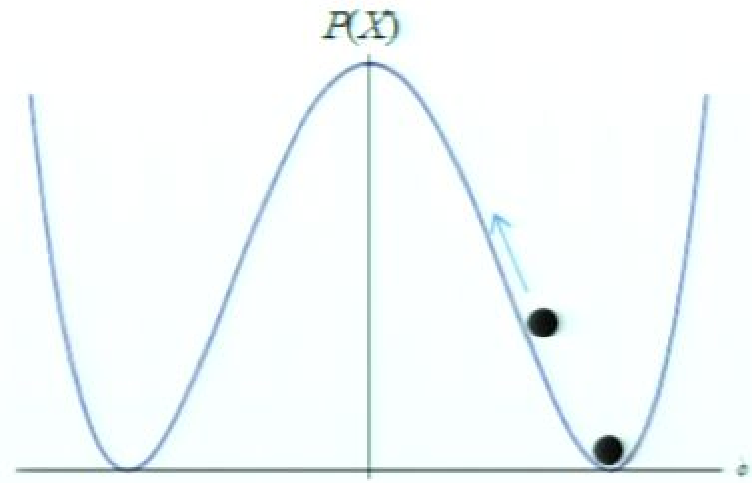

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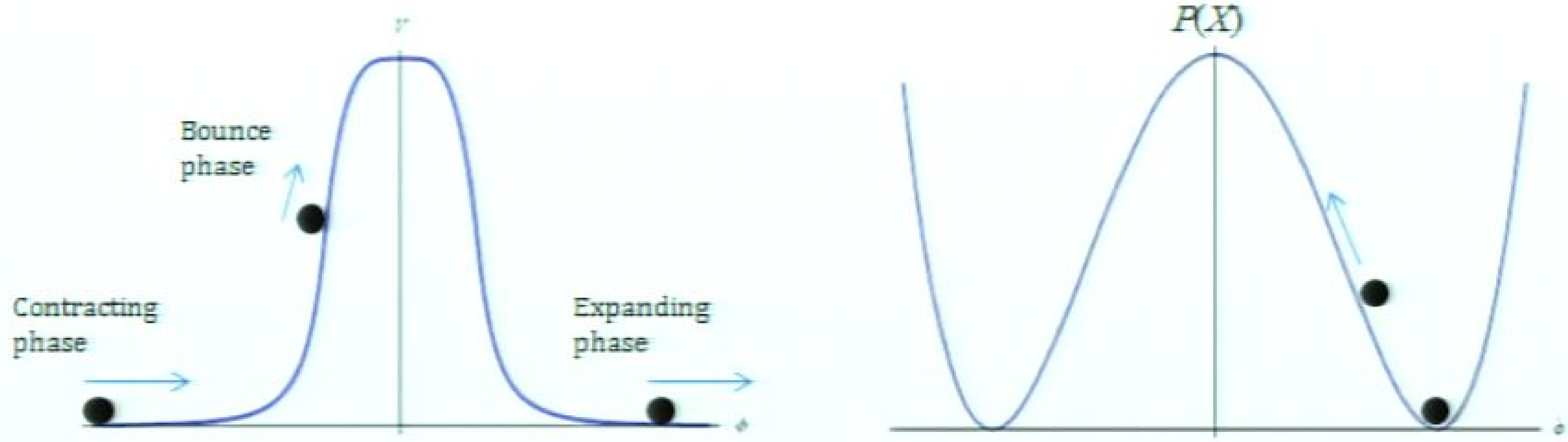

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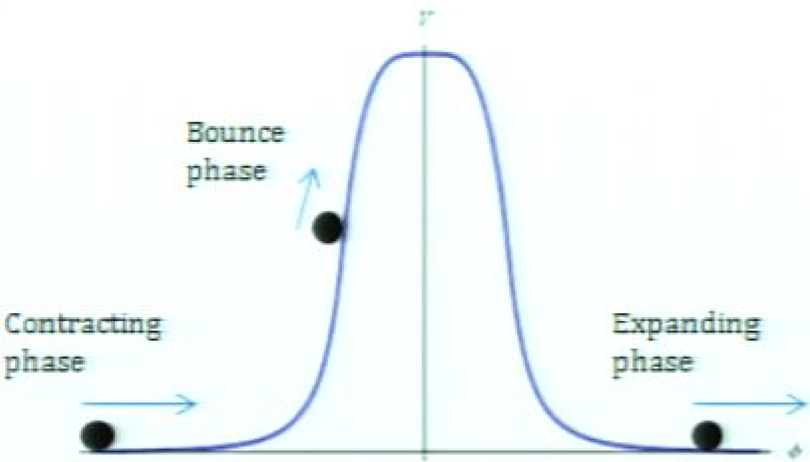

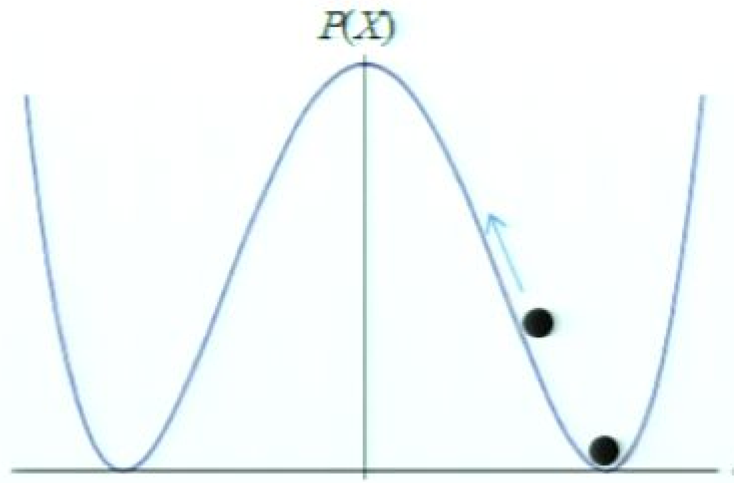

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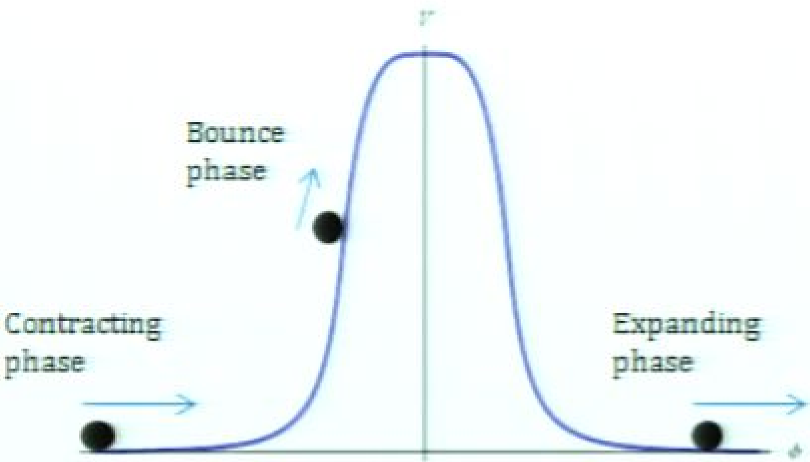

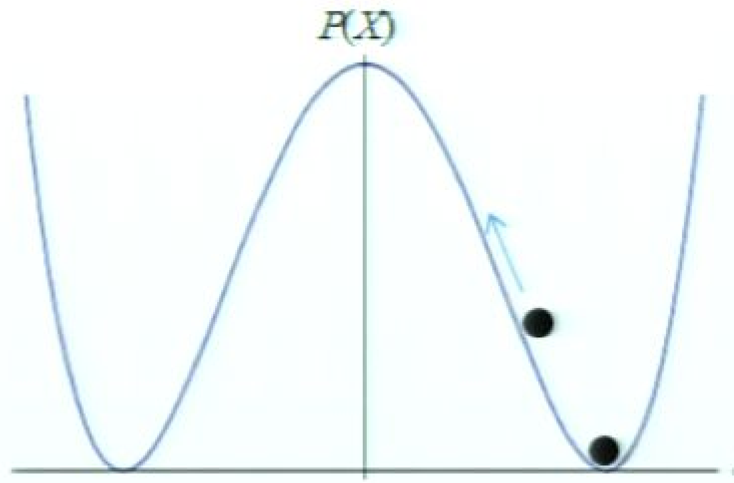

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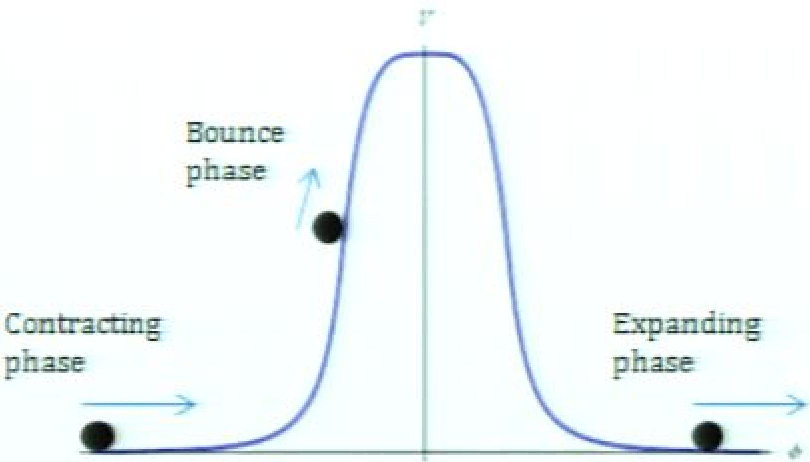

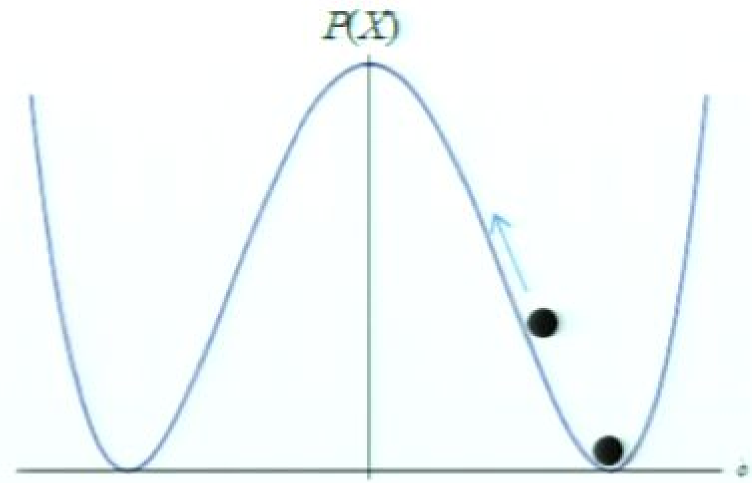

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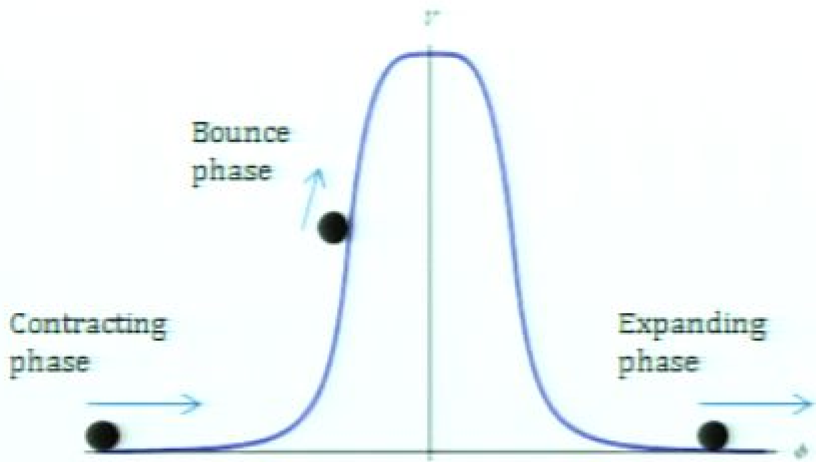

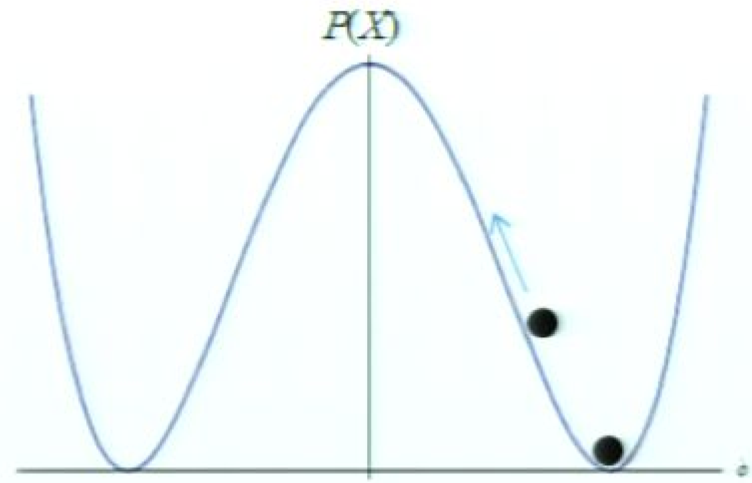

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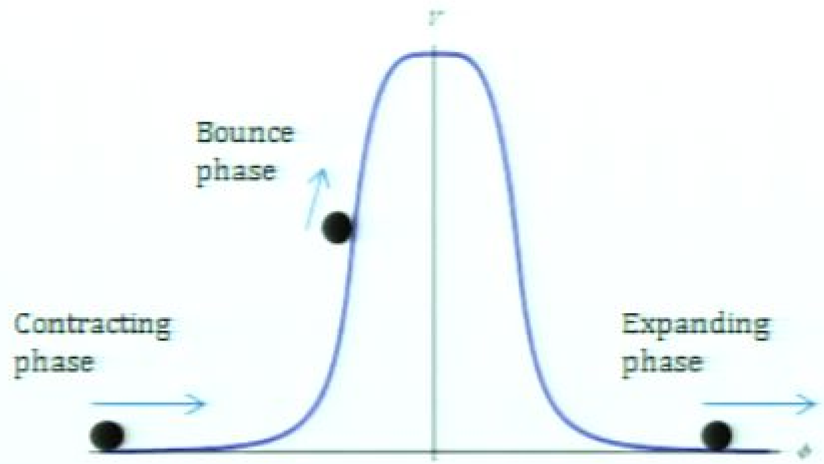

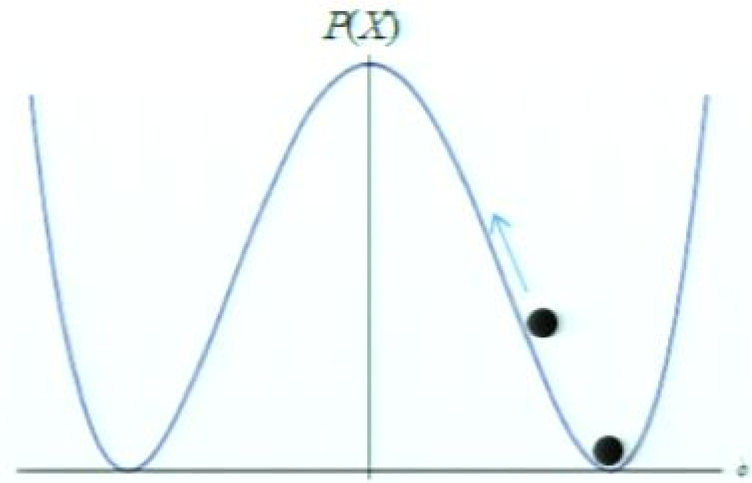

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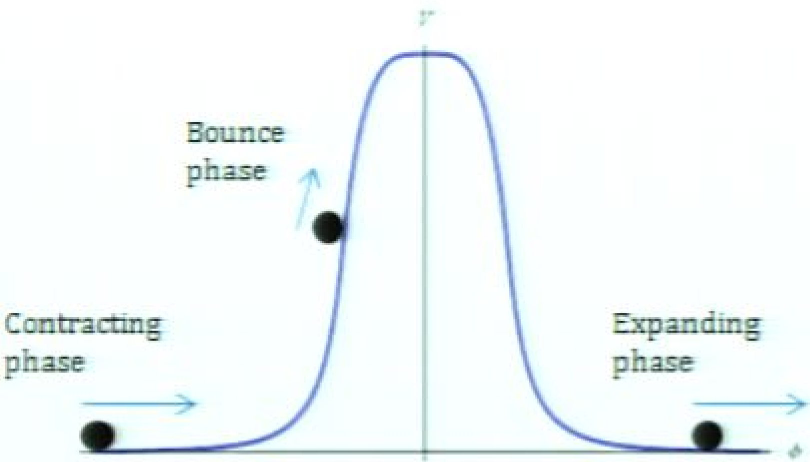

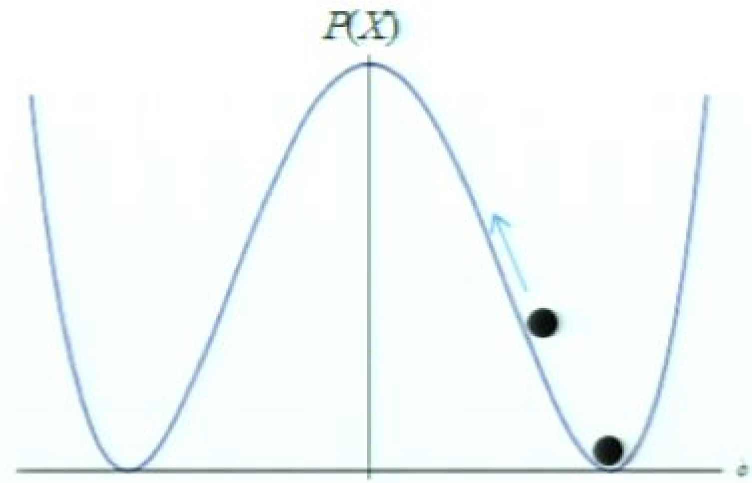

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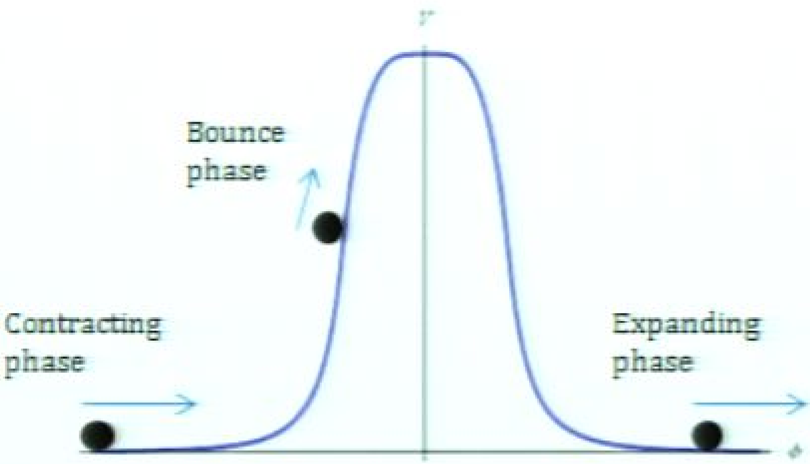

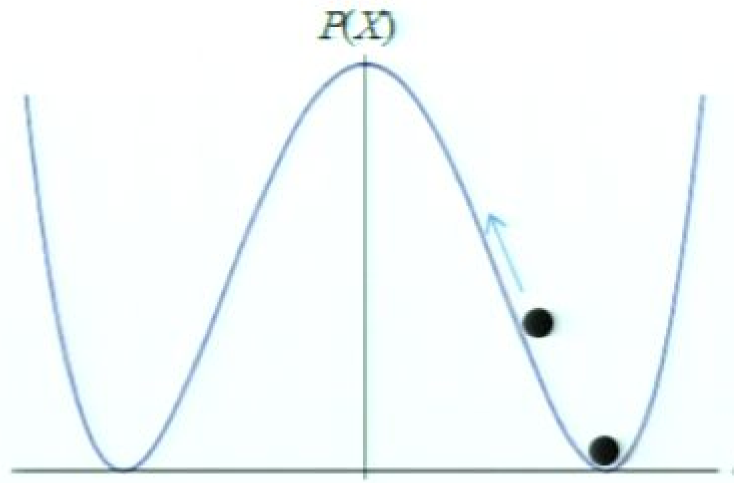

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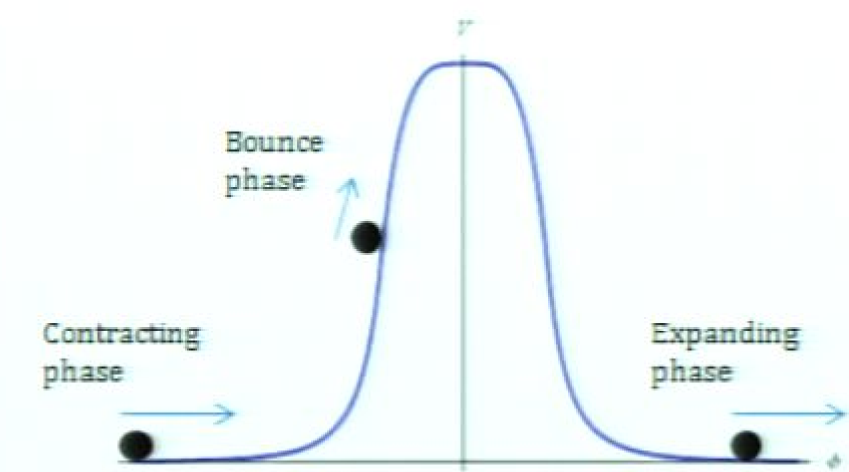

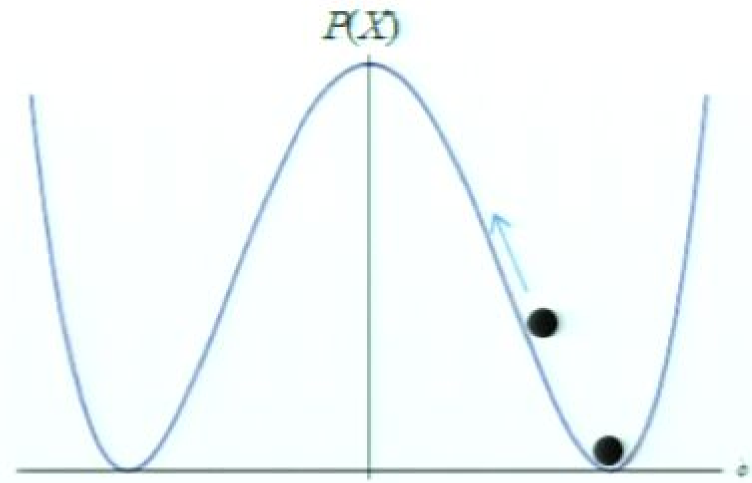

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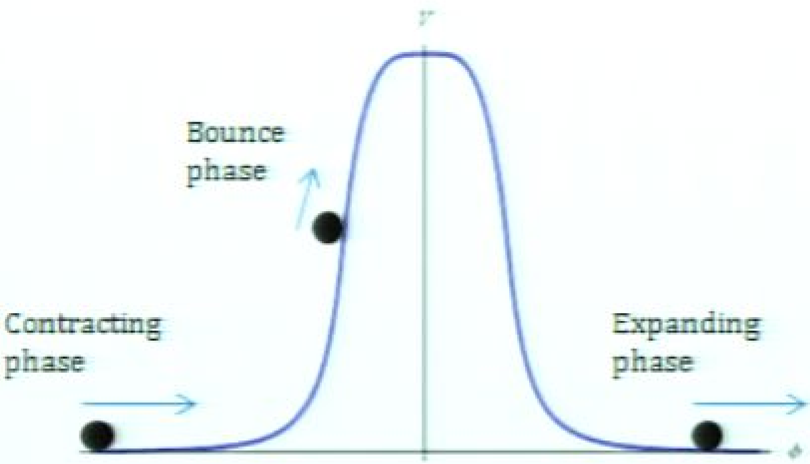

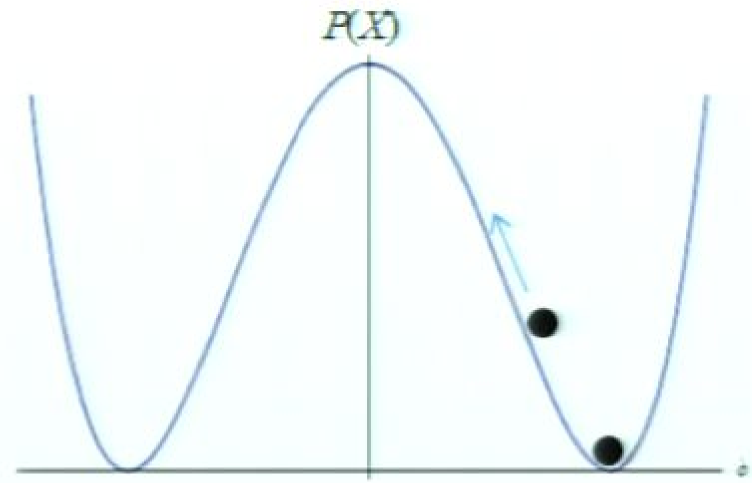

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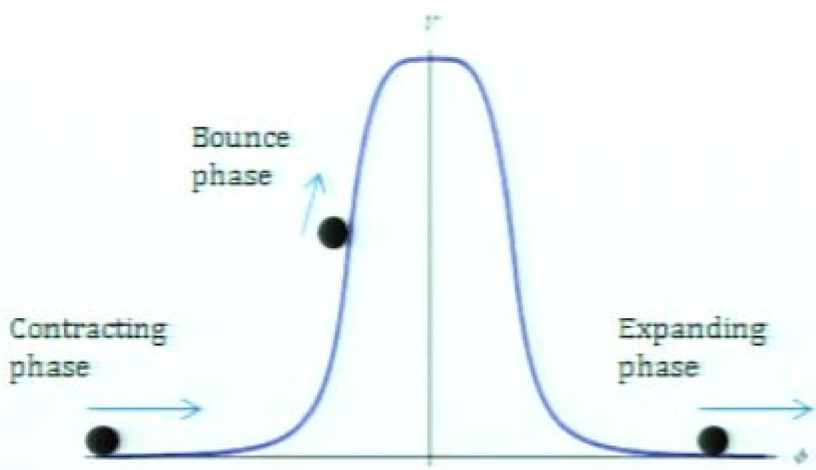

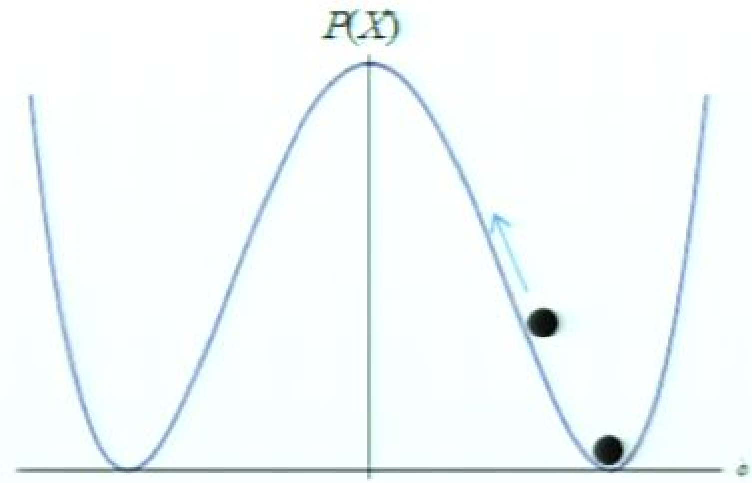

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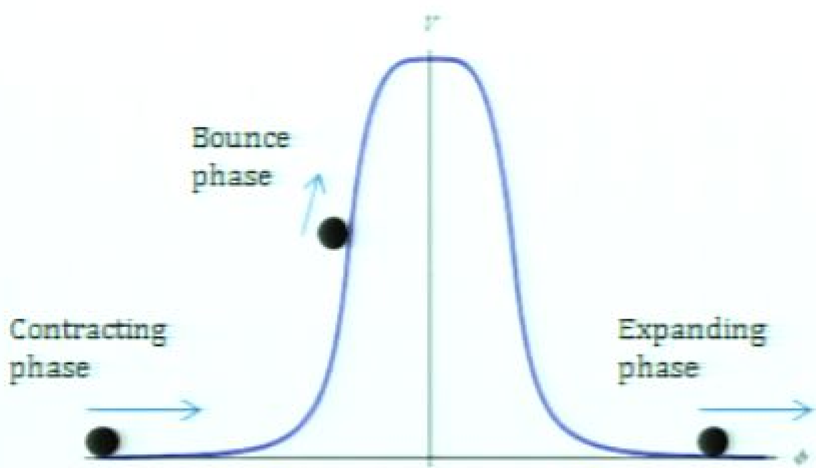

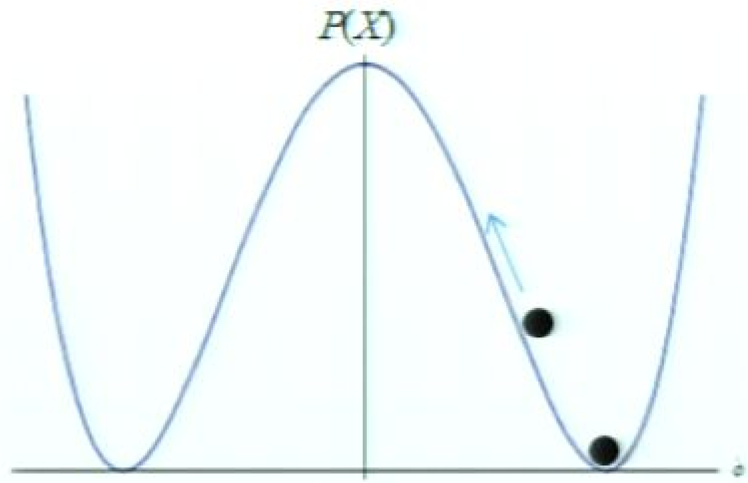

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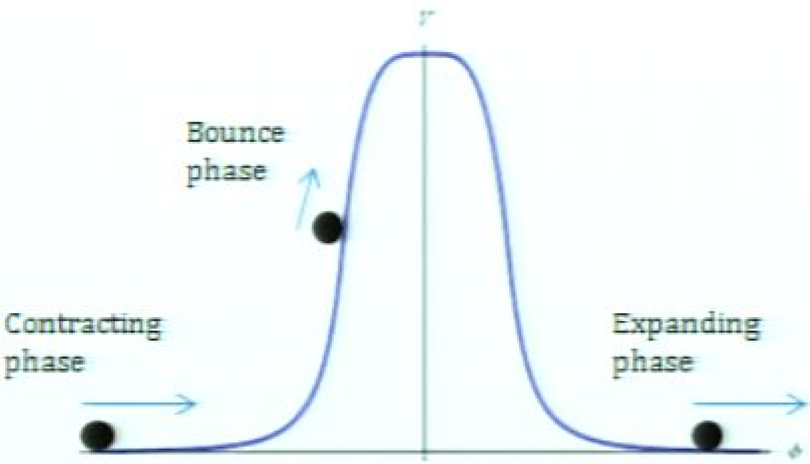

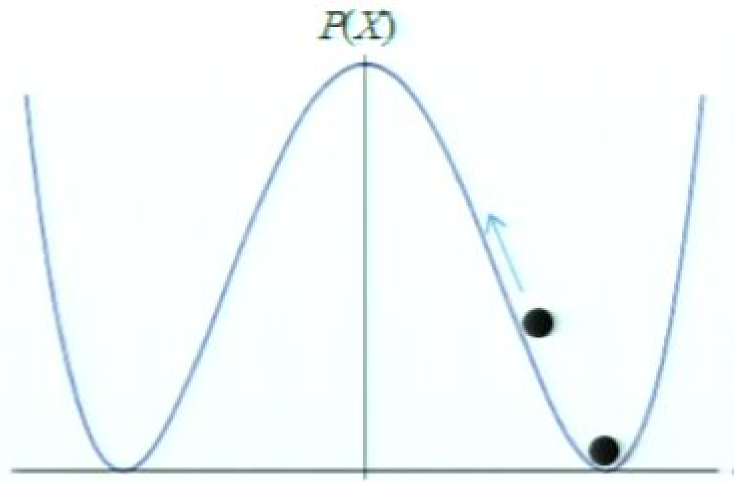

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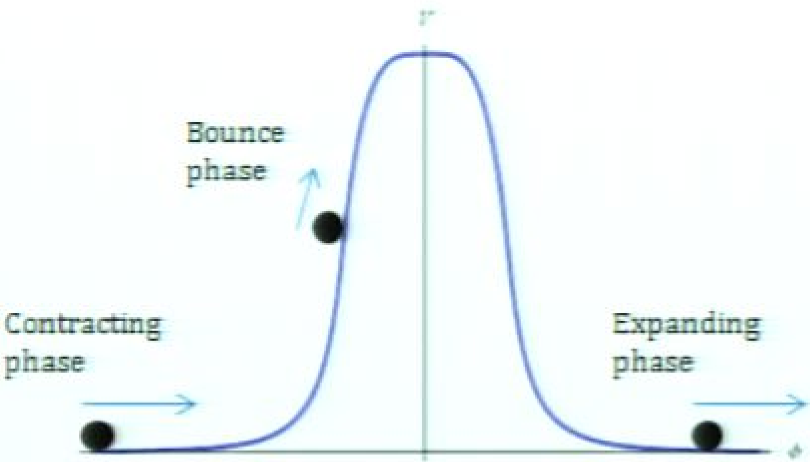

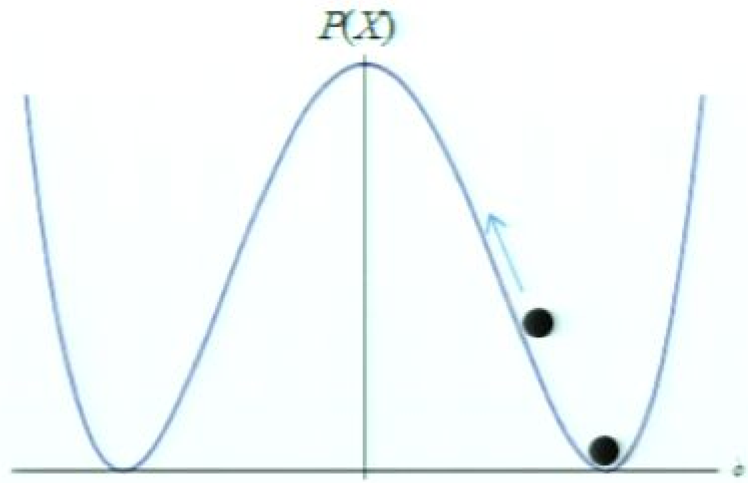

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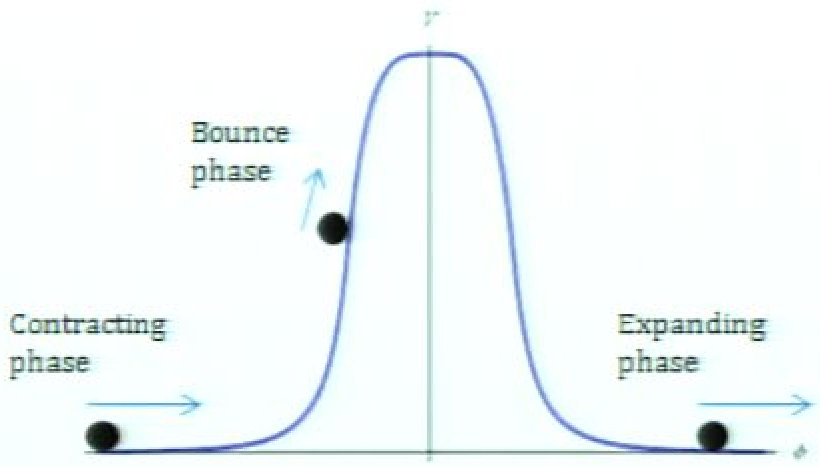

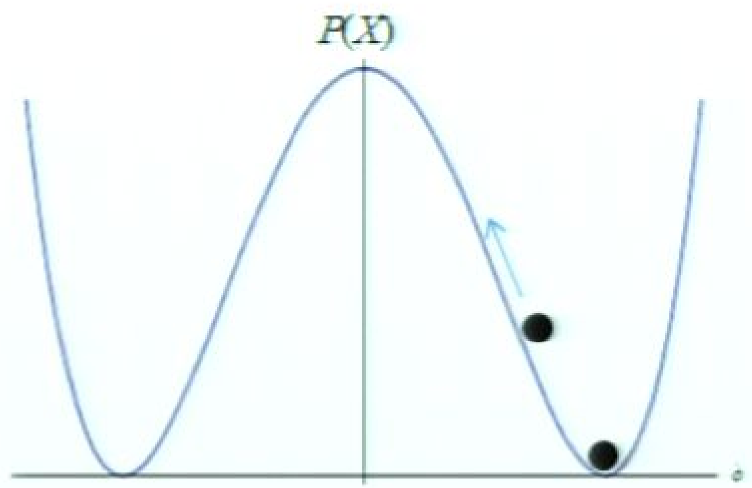

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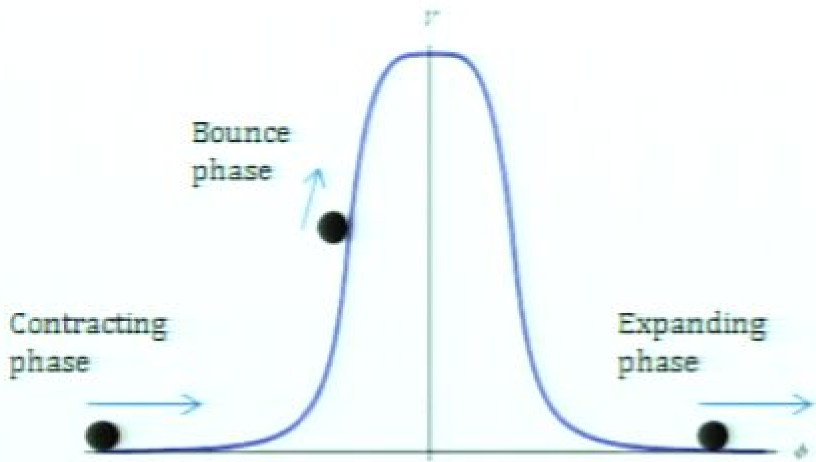

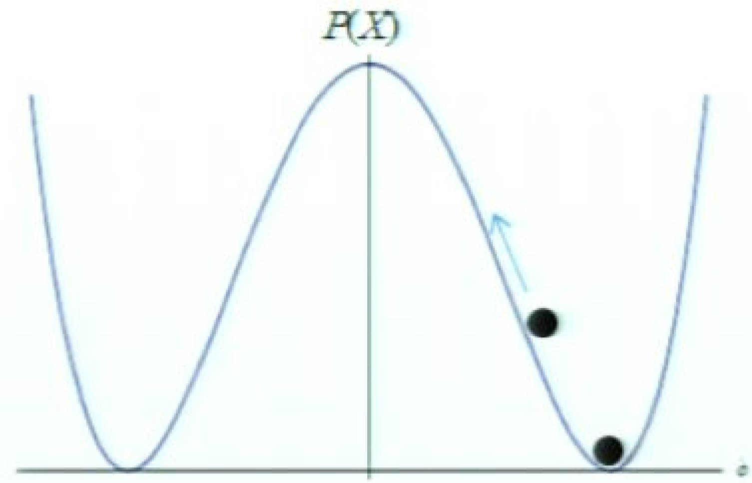

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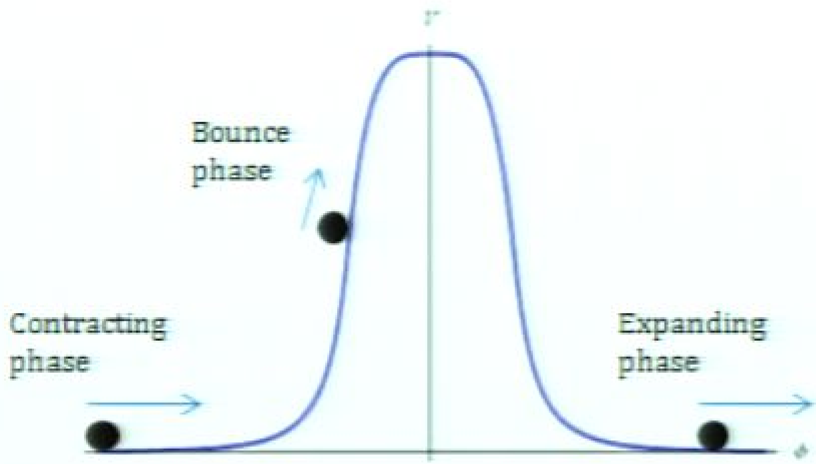

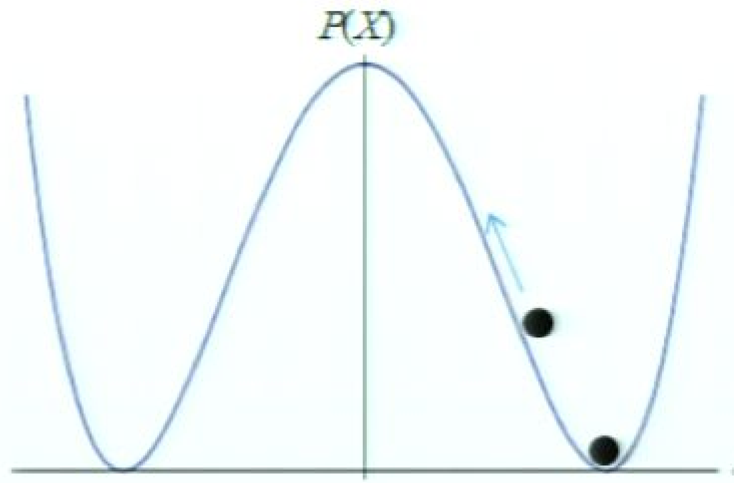

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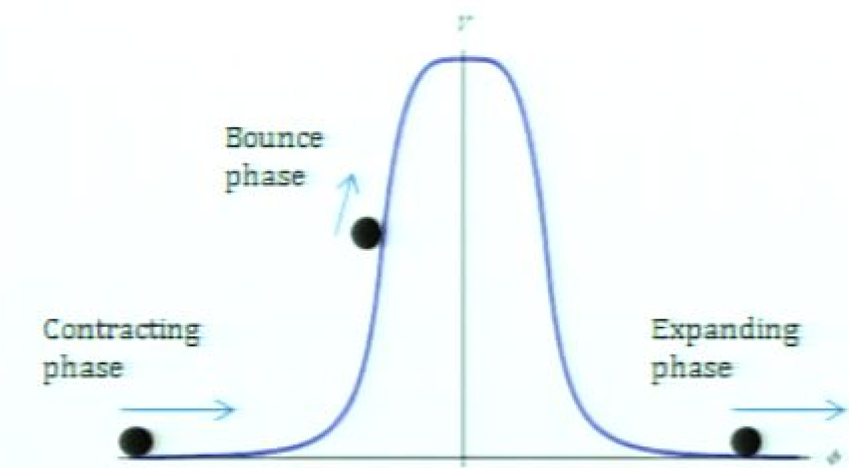

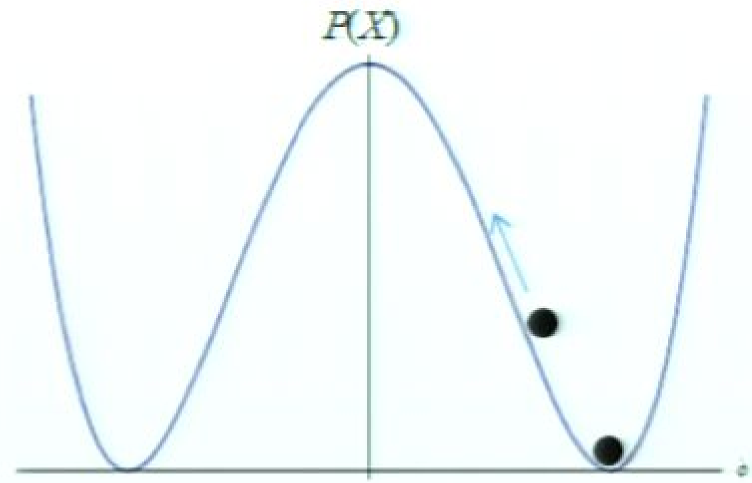

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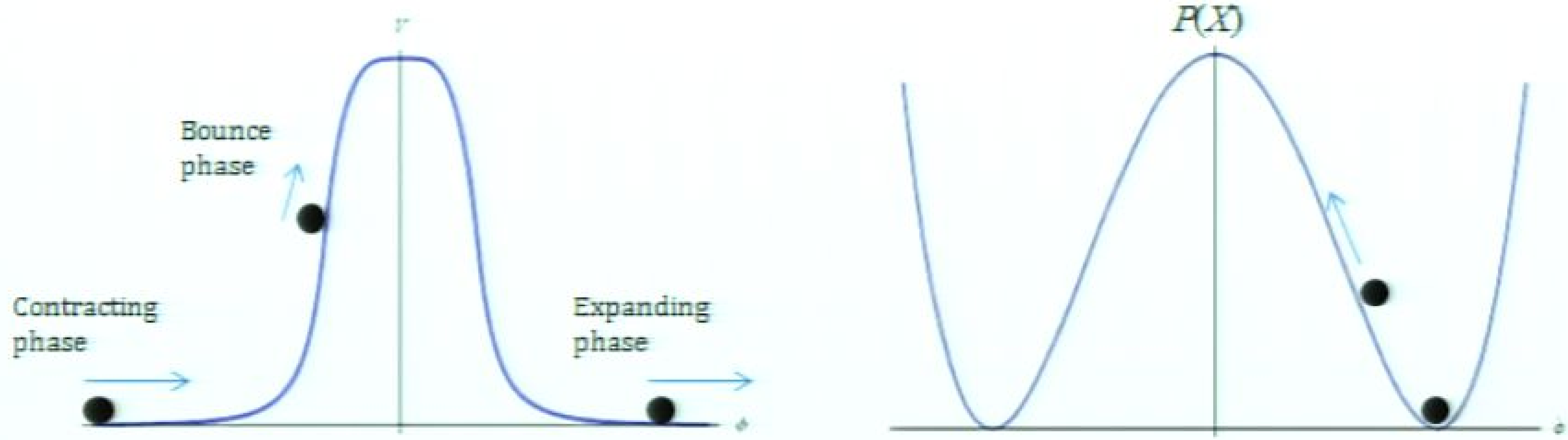

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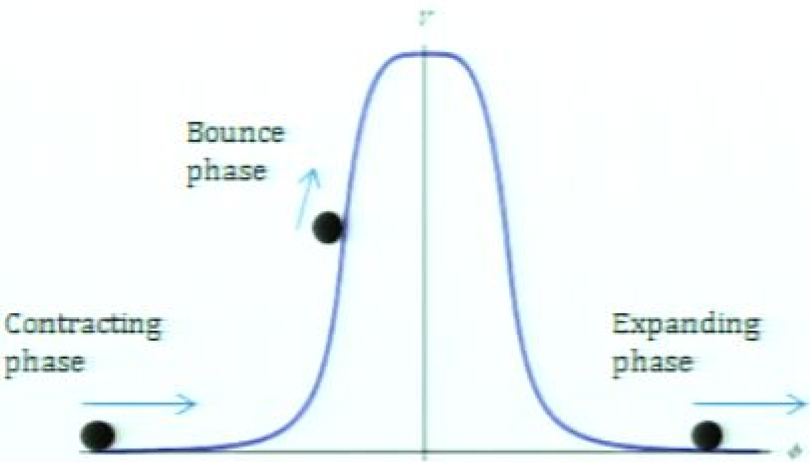

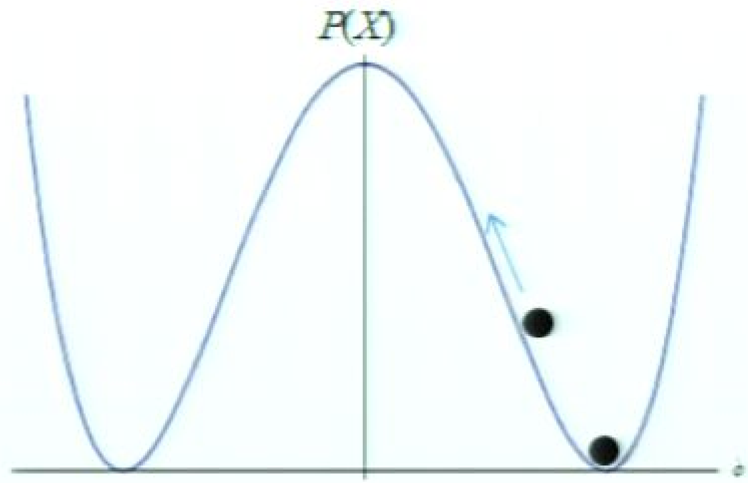

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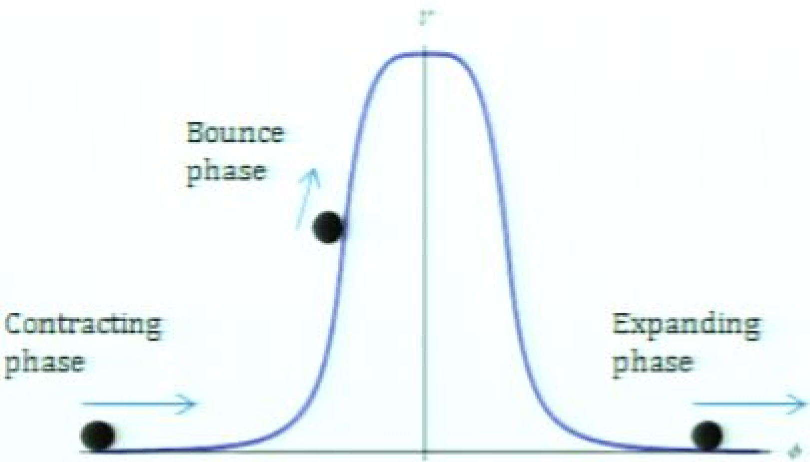

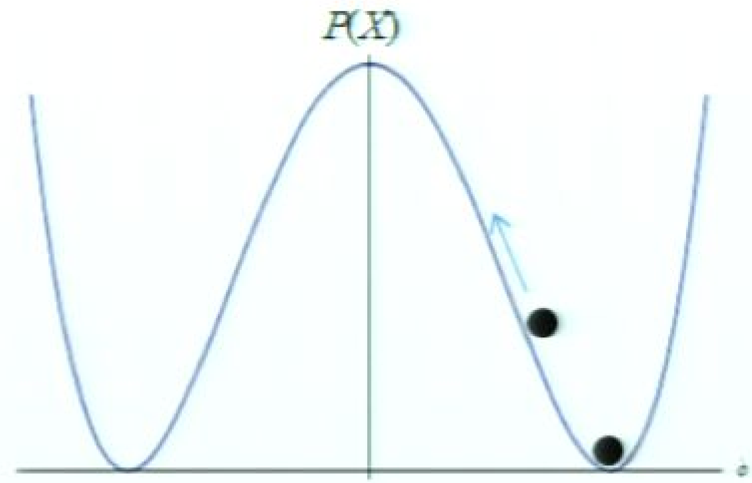

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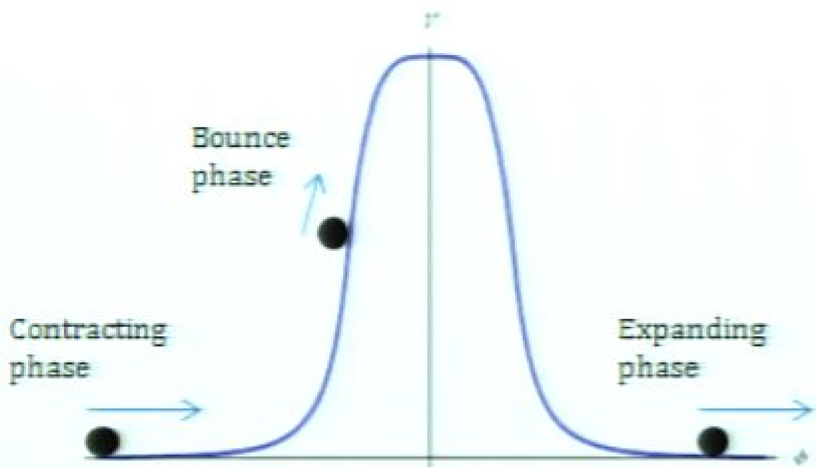

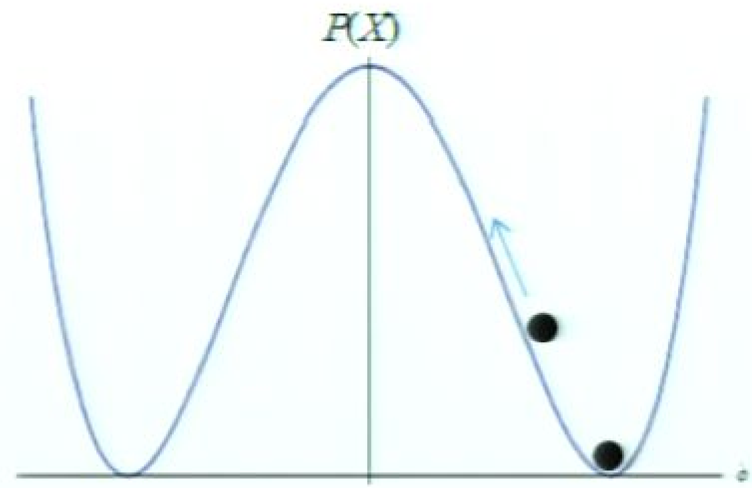

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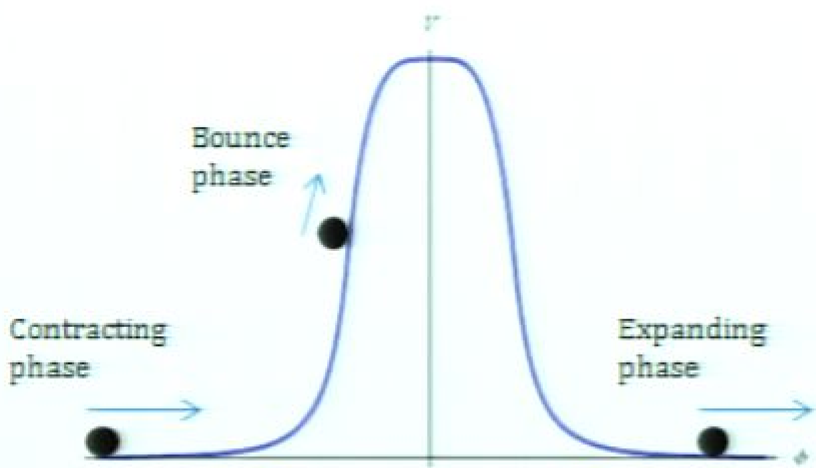

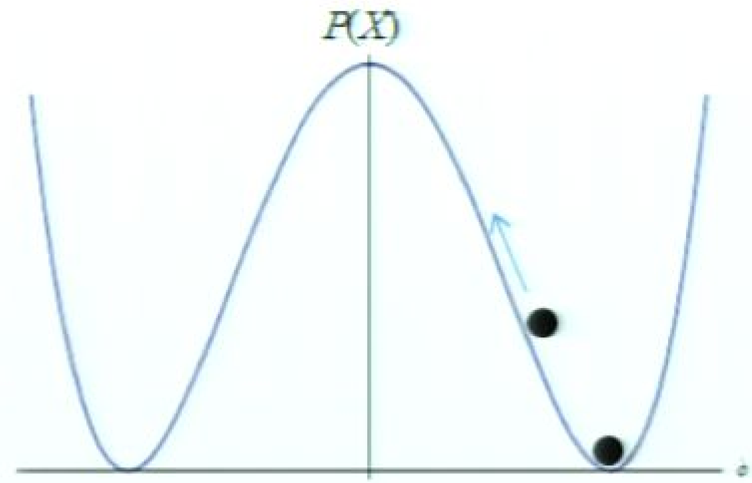

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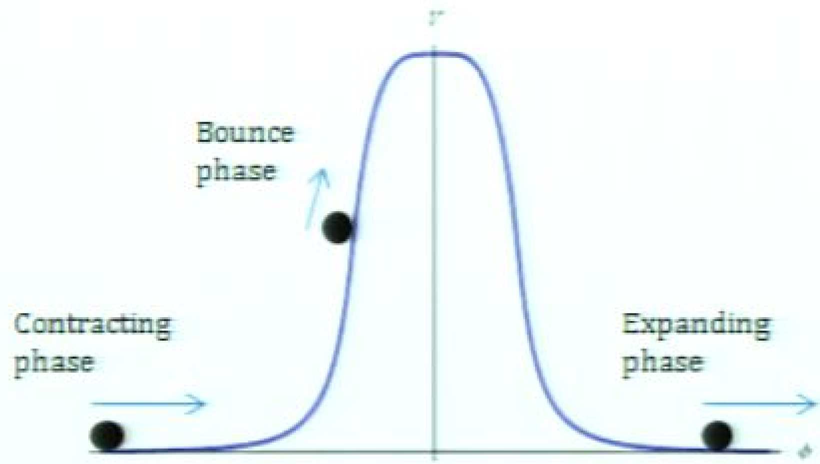

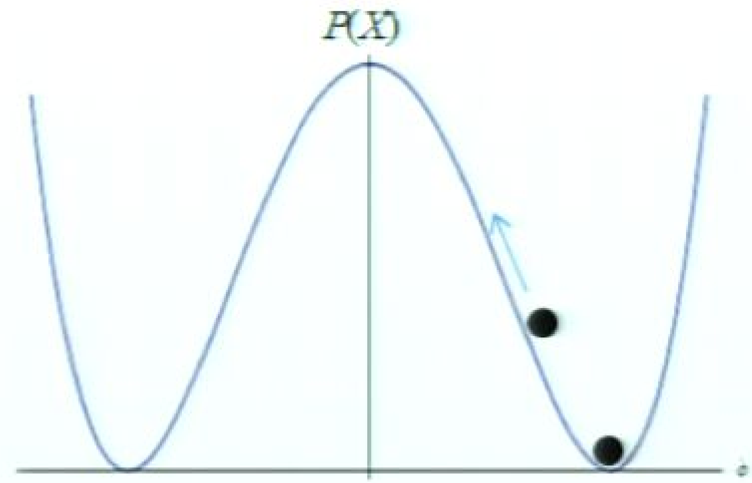

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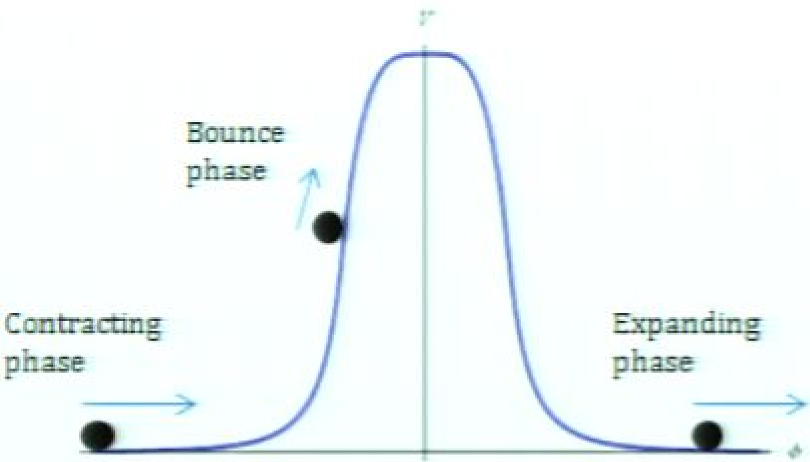

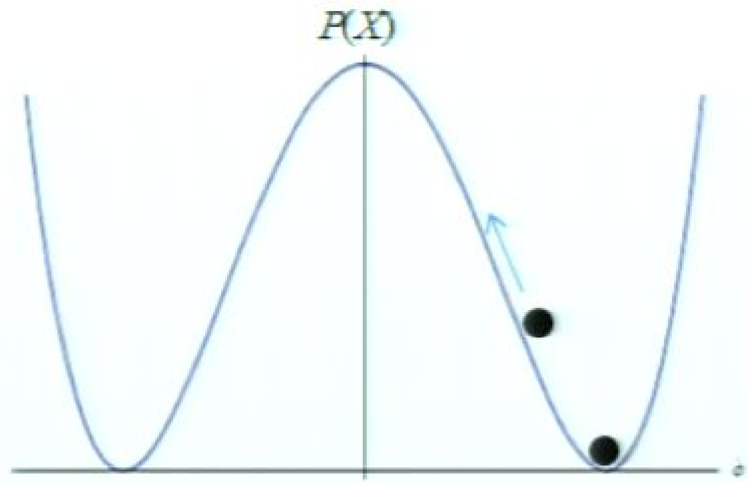

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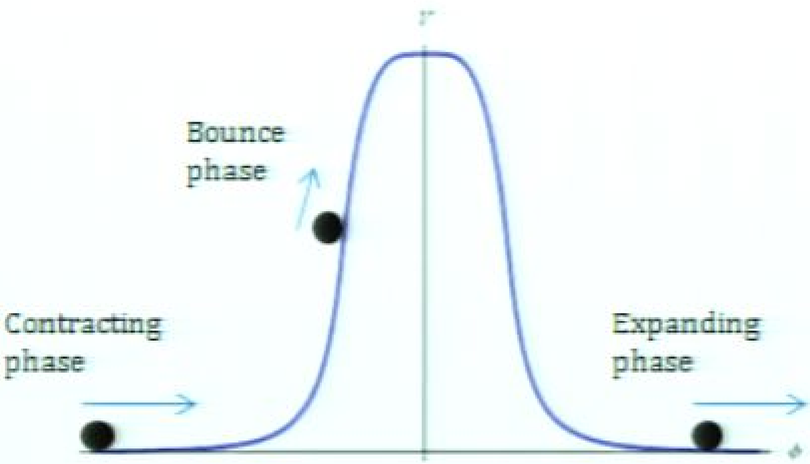

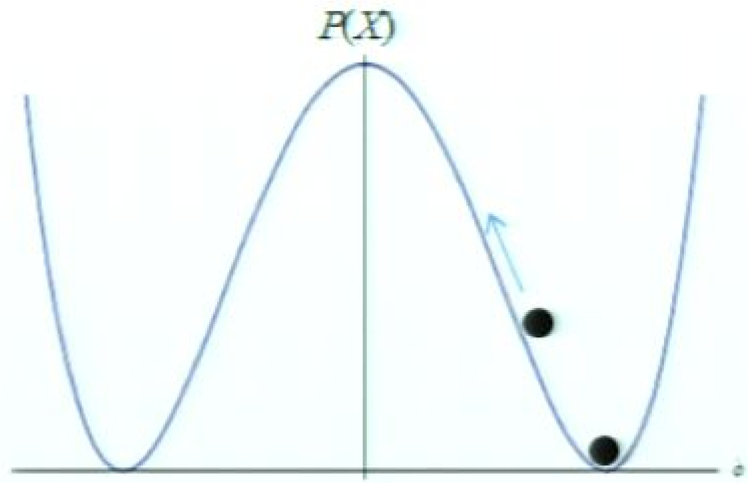

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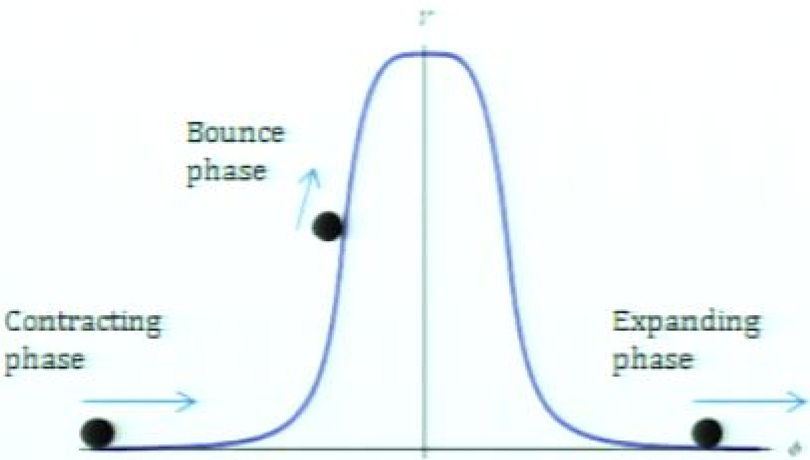

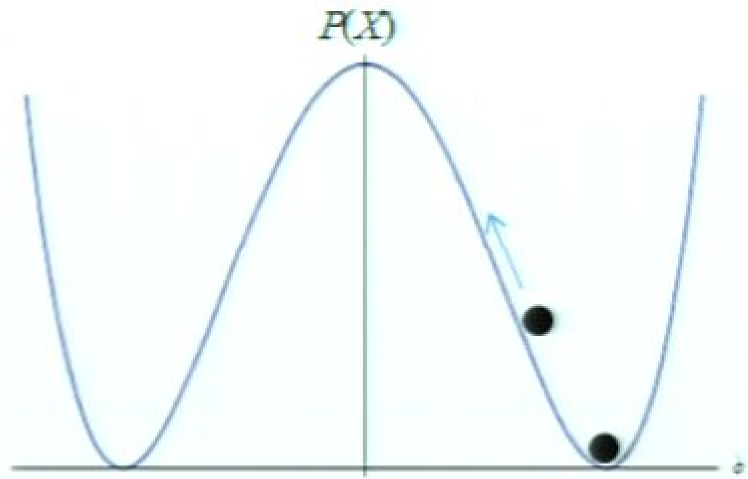

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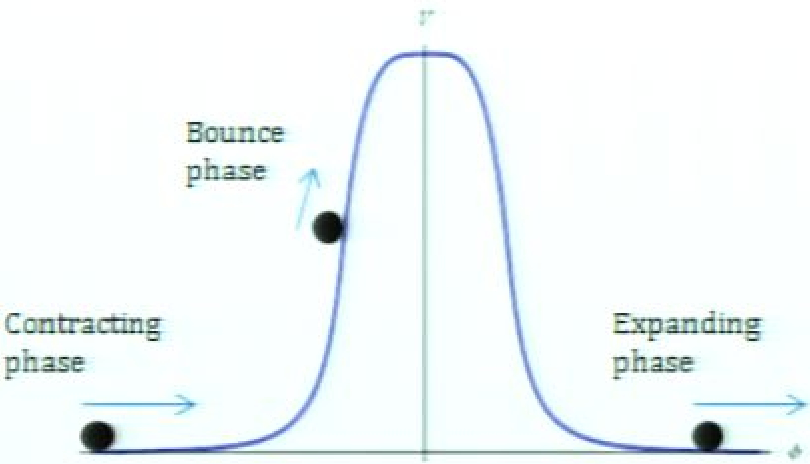

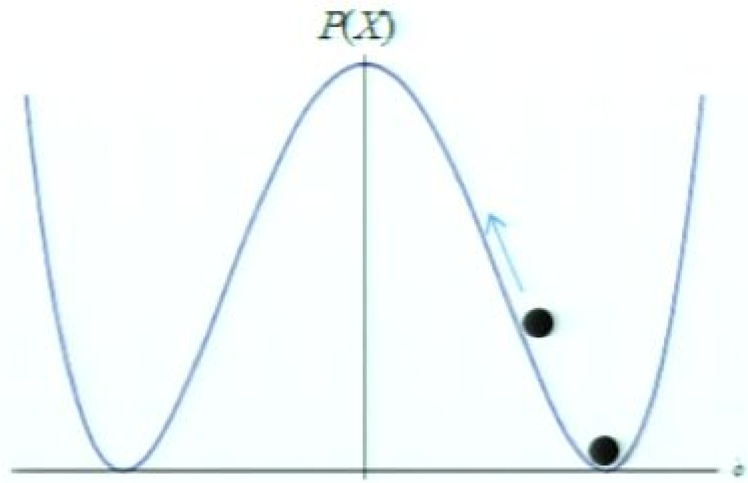

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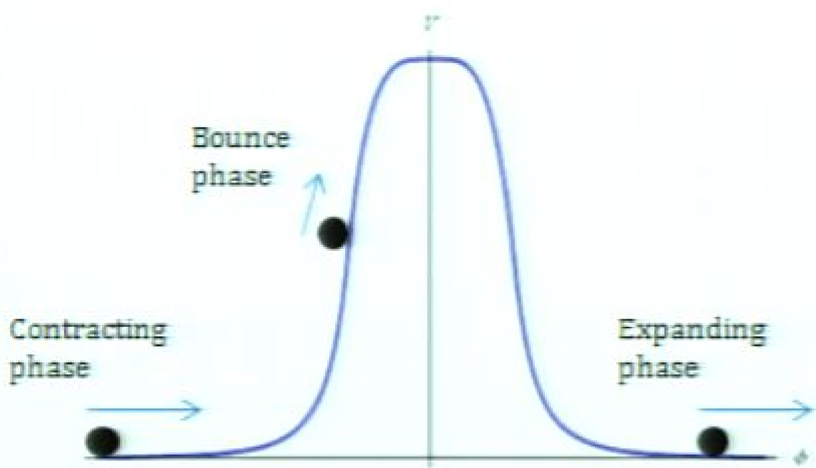

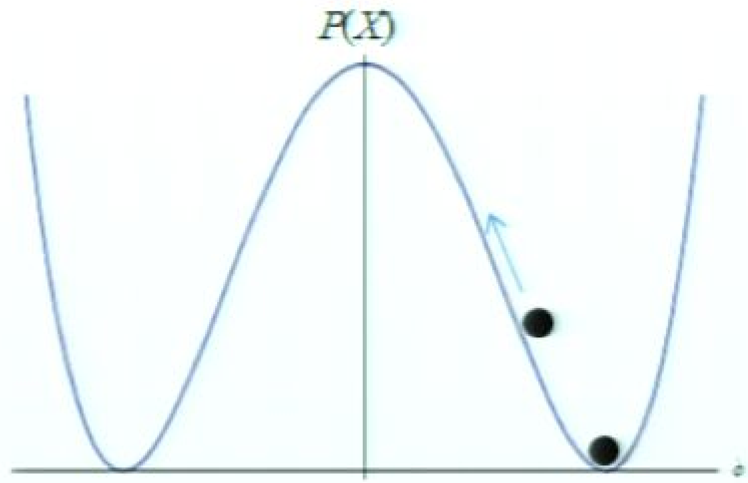

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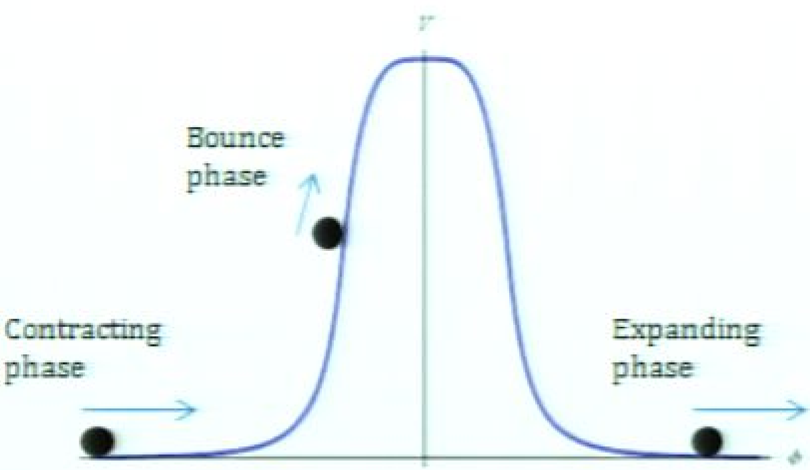

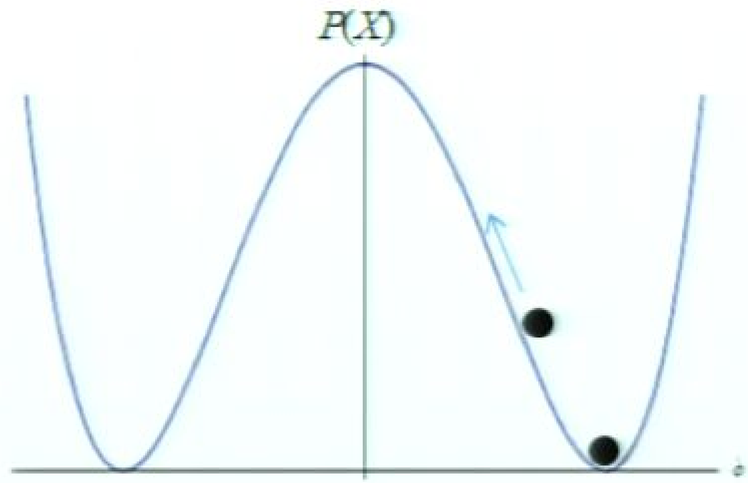

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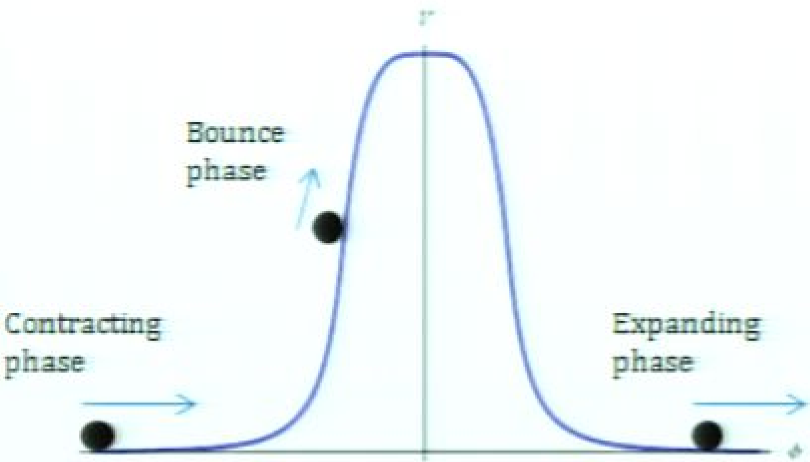

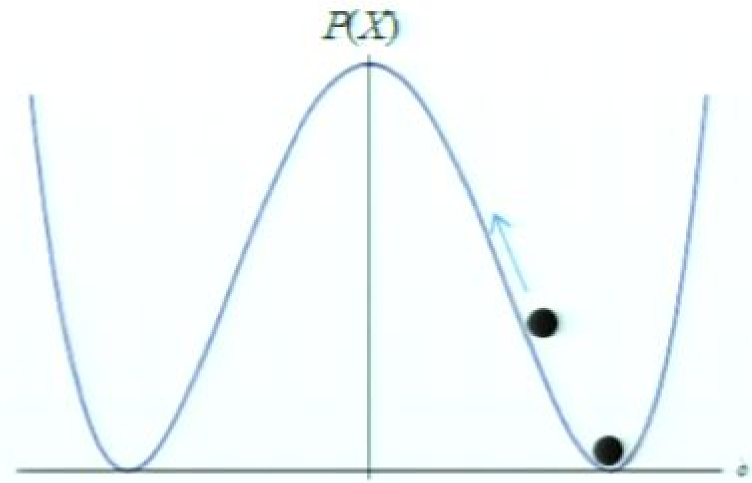

$$2M_p^2\dot{H} = -2M^4XP' - (1+w_m)\rho_m$$

Realization of NEC violation!

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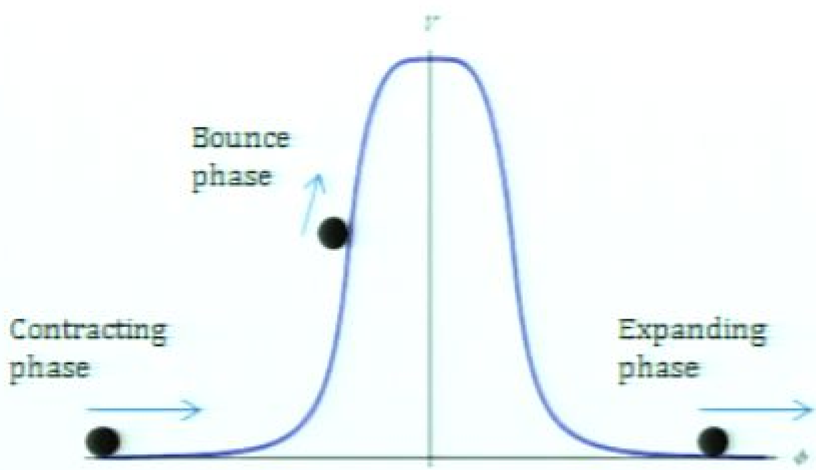

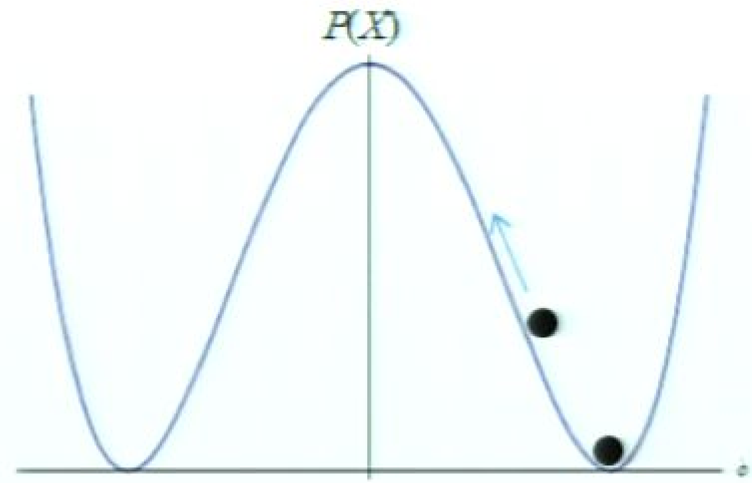

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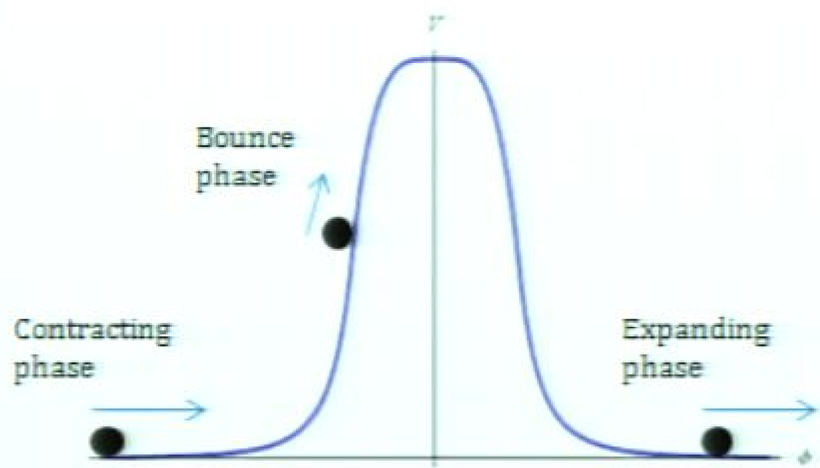

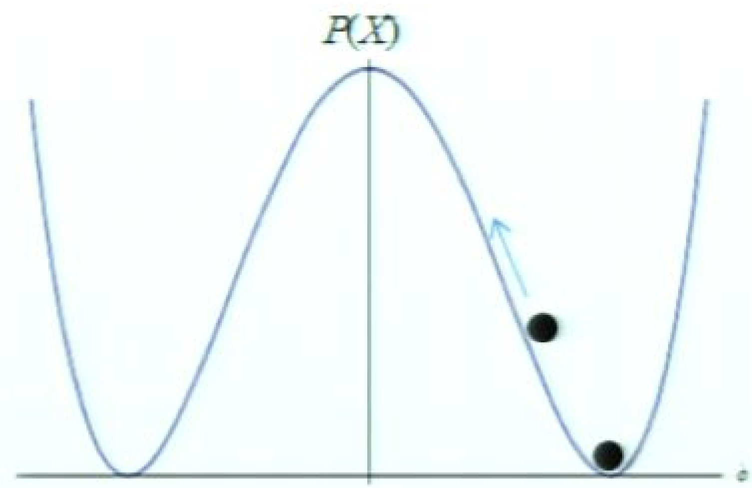

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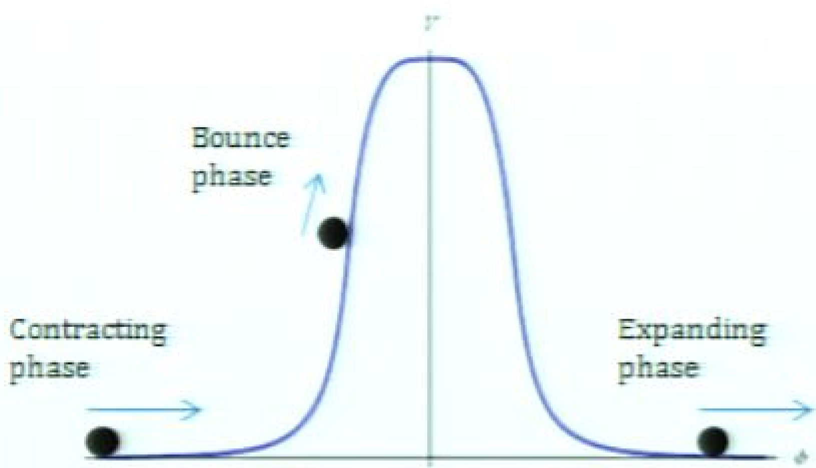

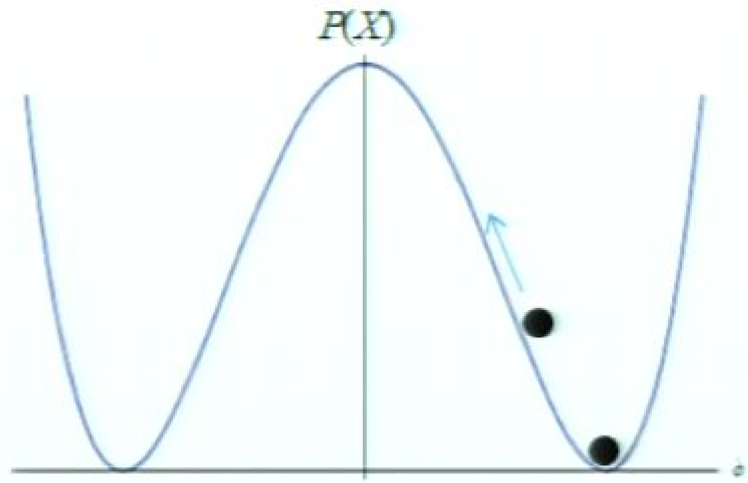

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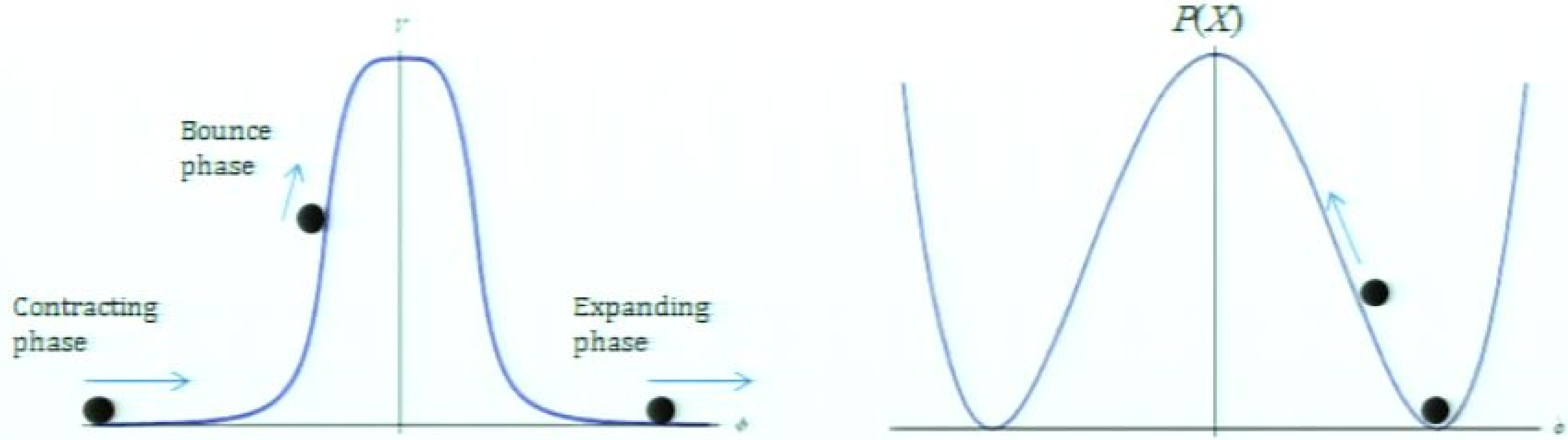

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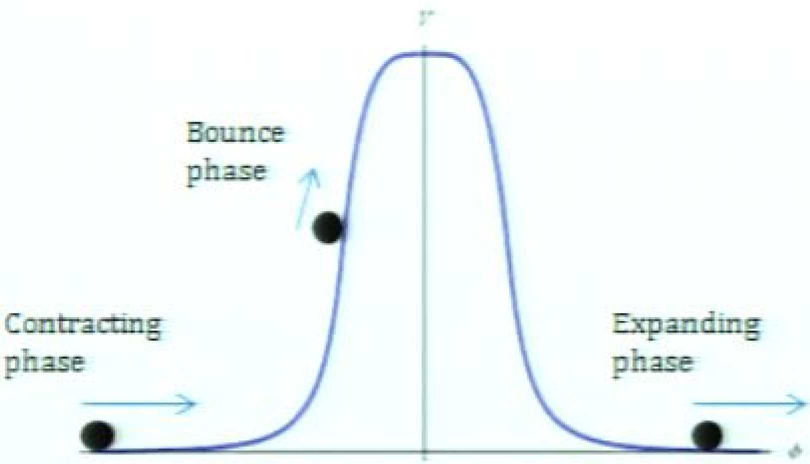

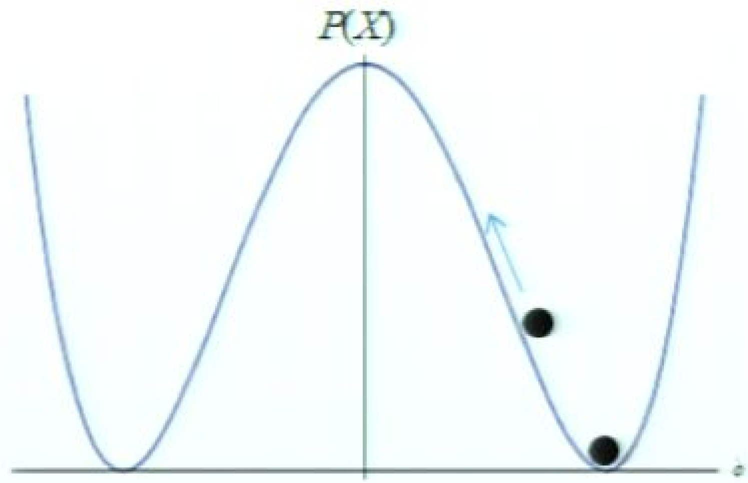

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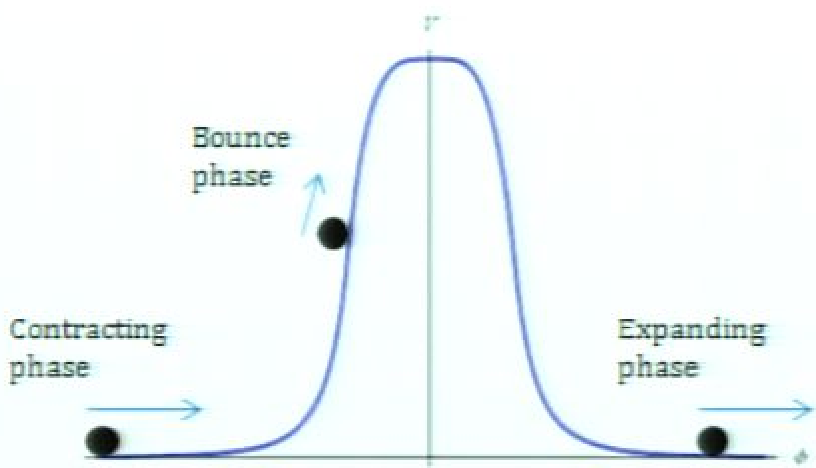

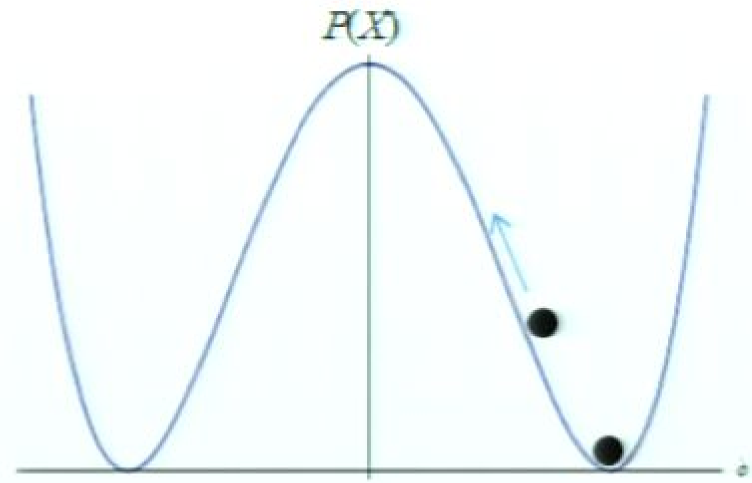

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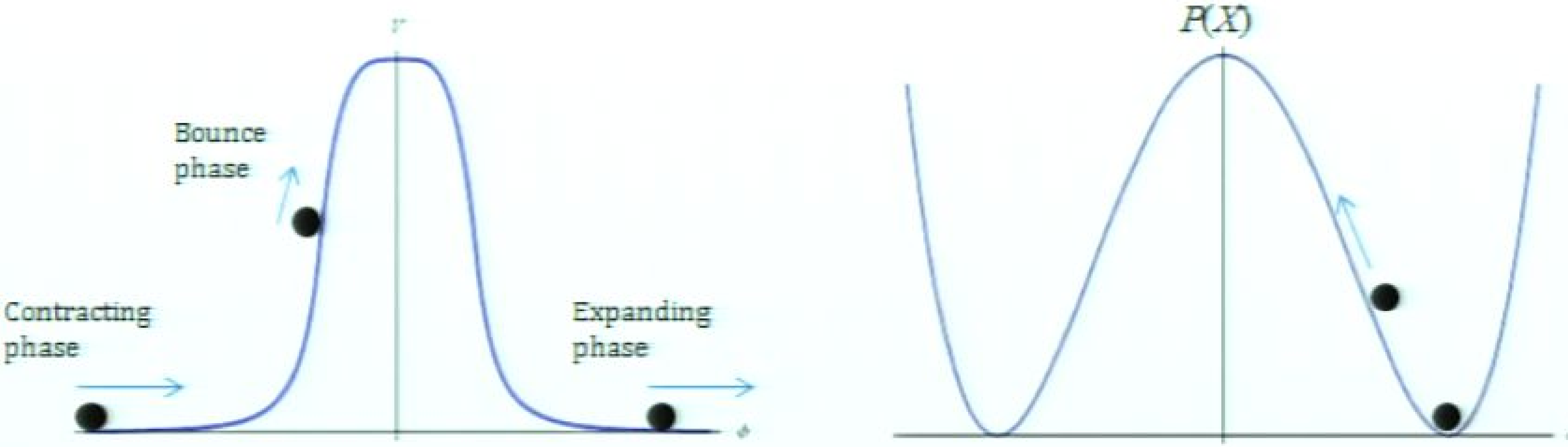

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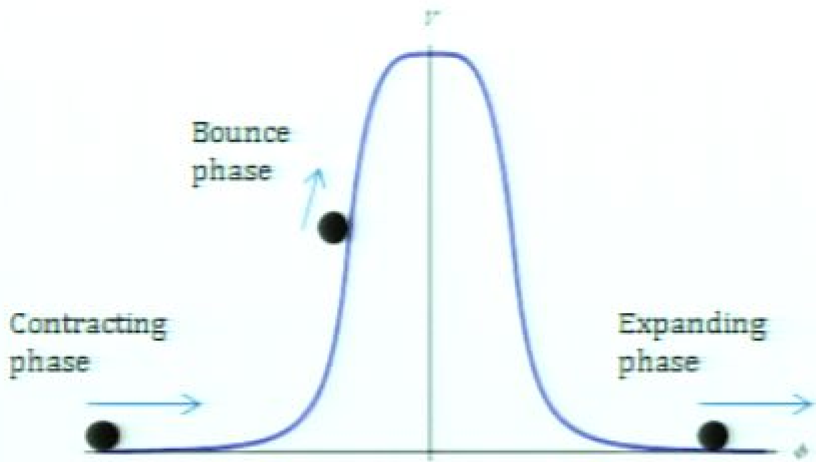

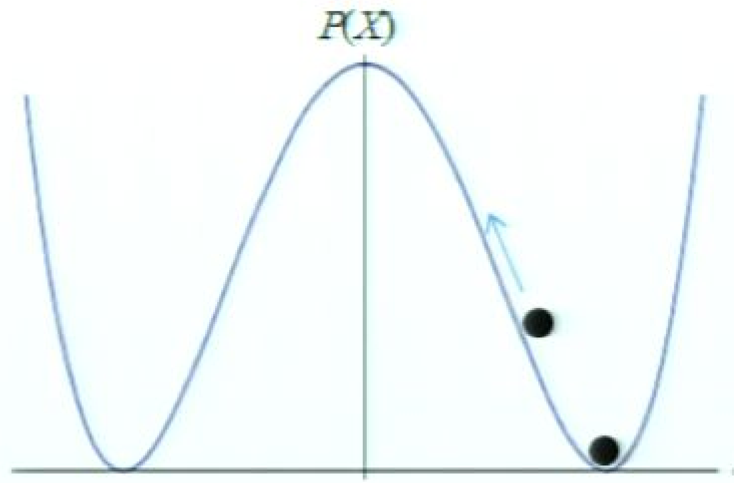

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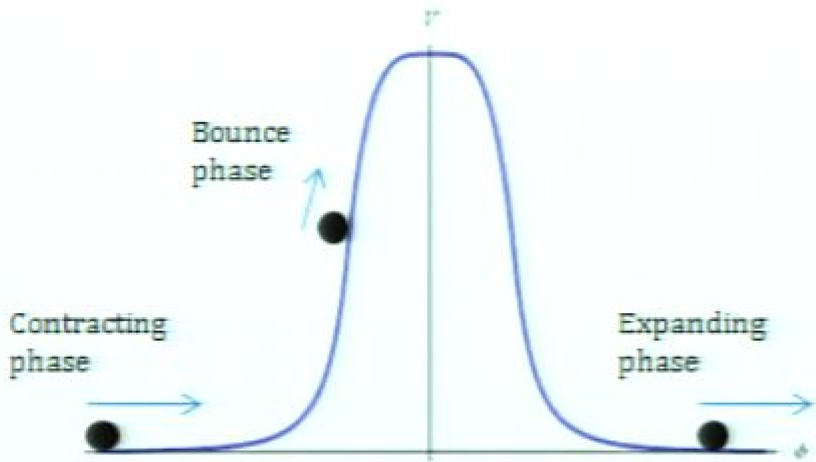

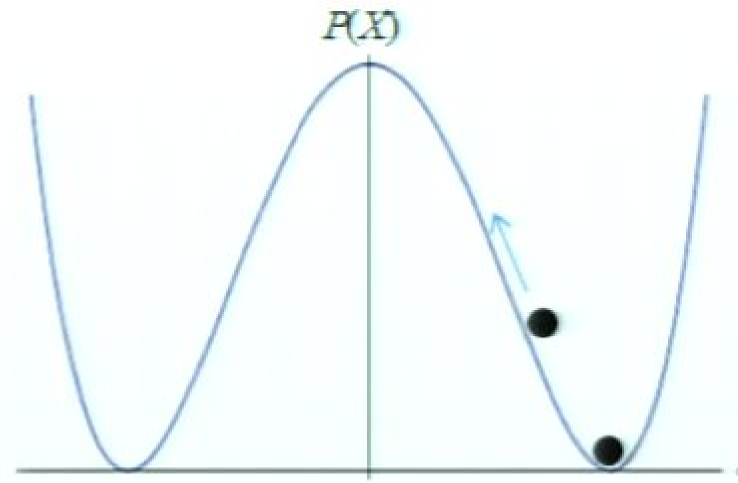

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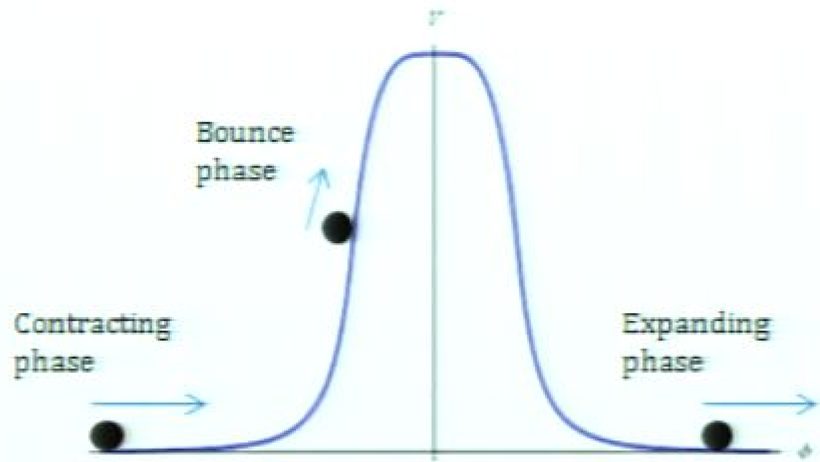

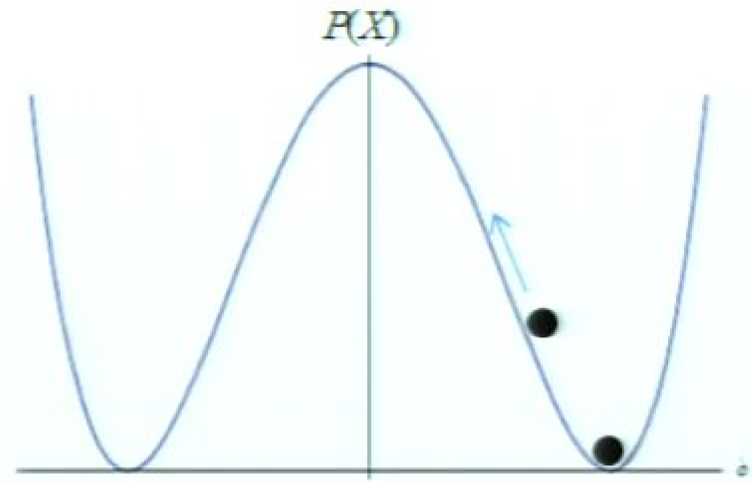

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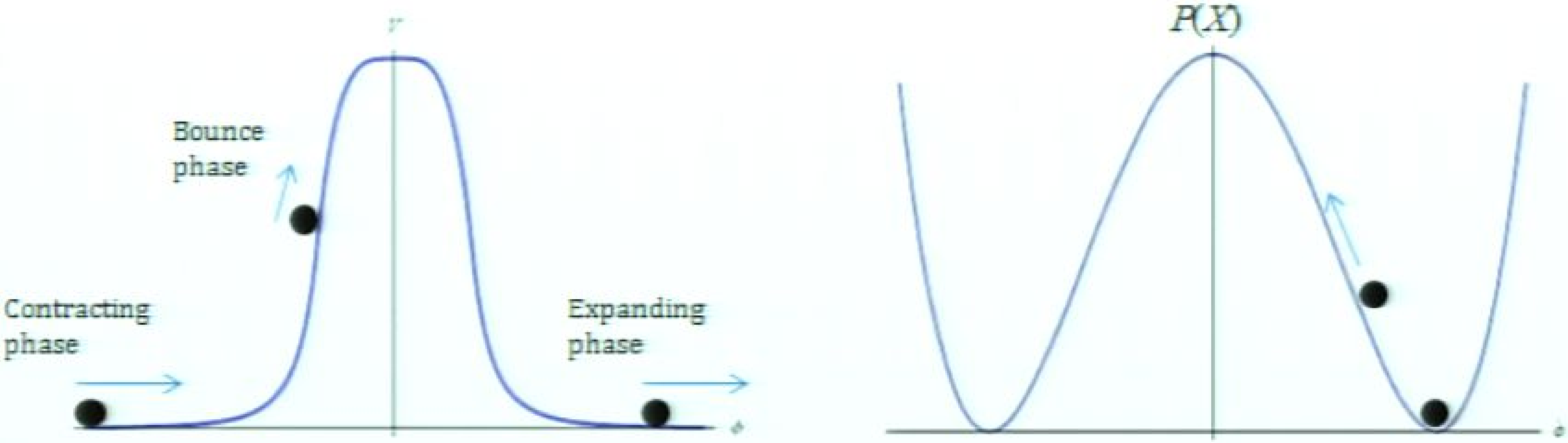

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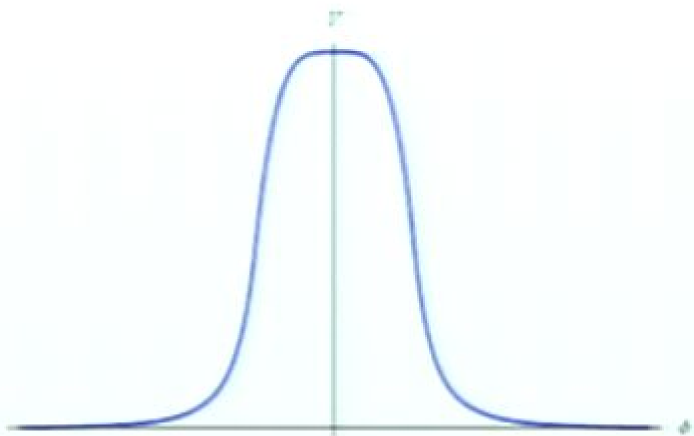

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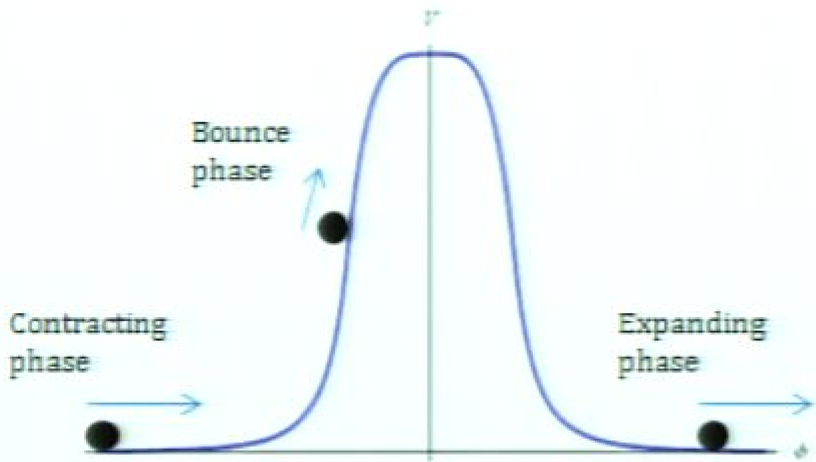

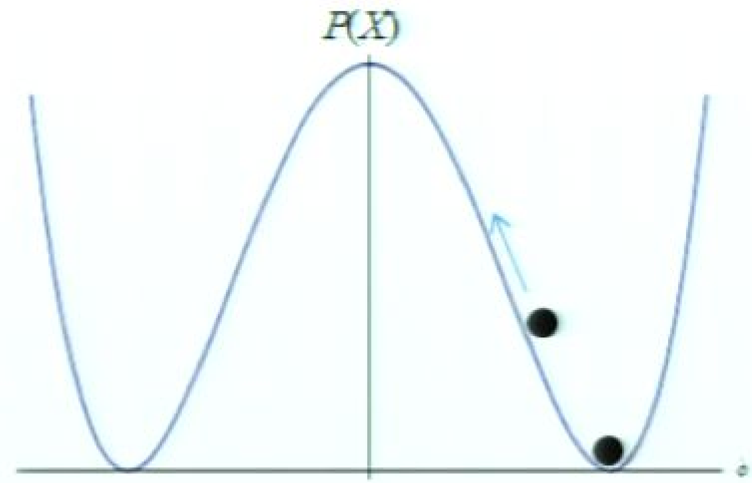

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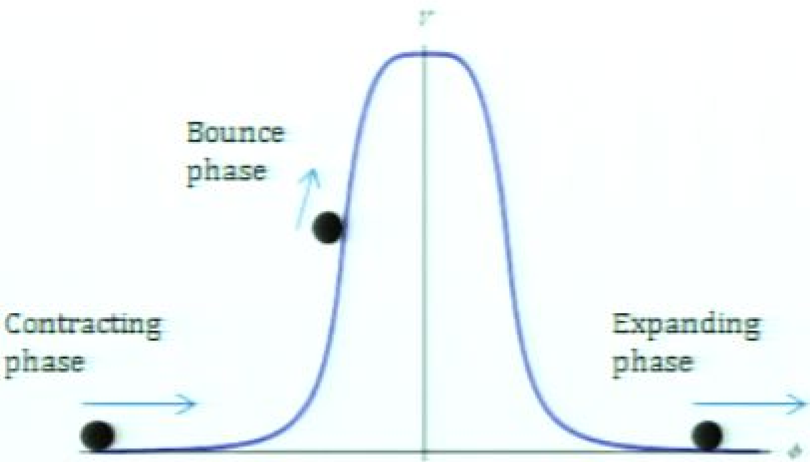

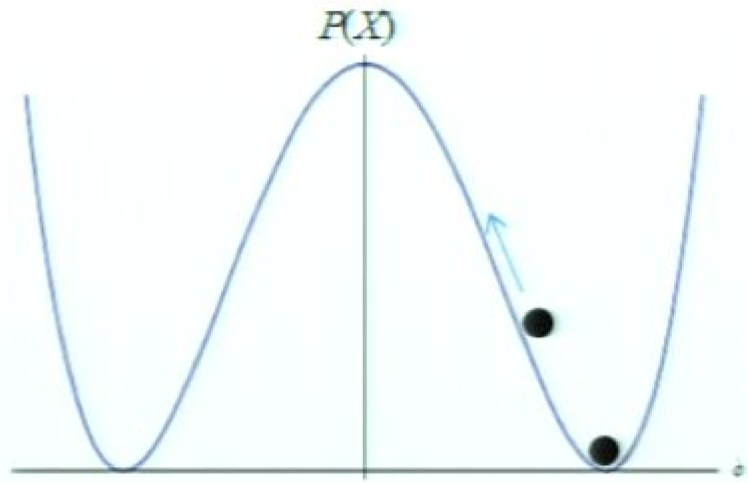

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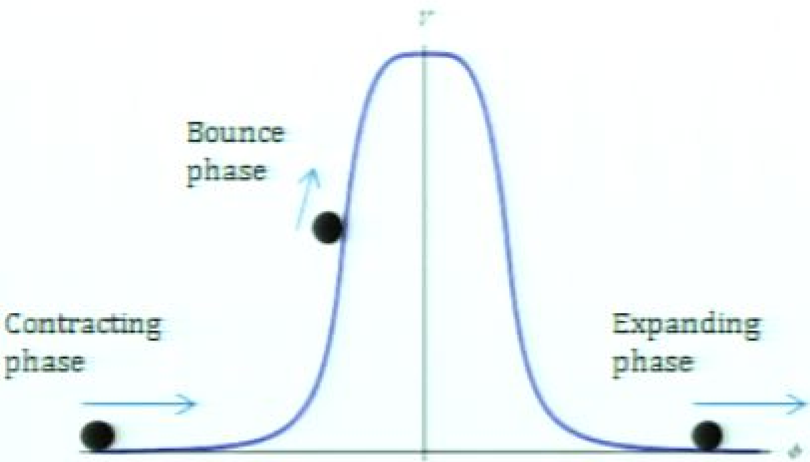

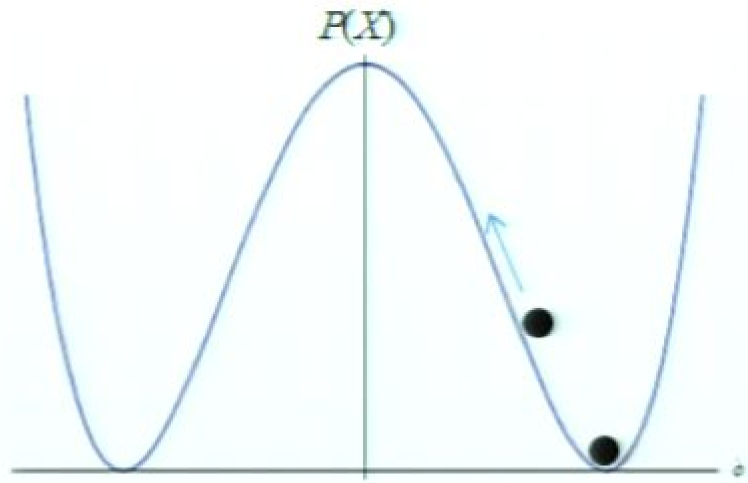

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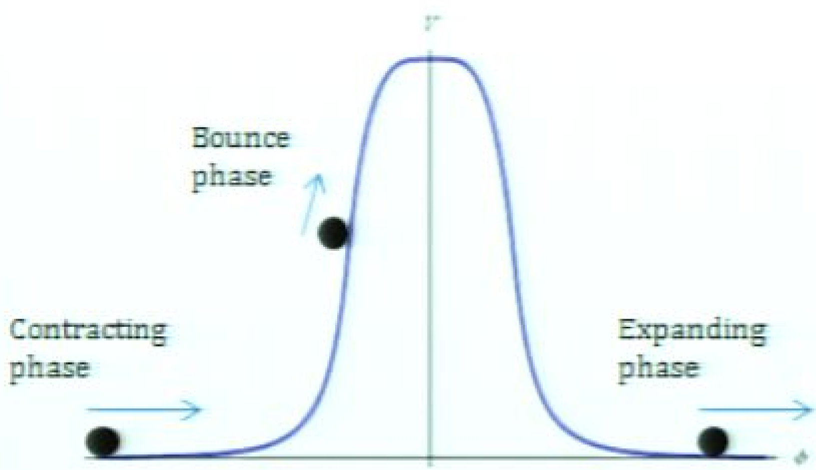

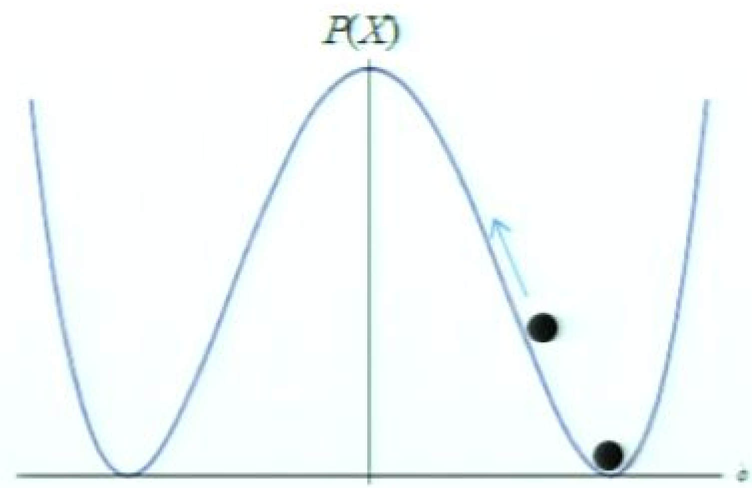

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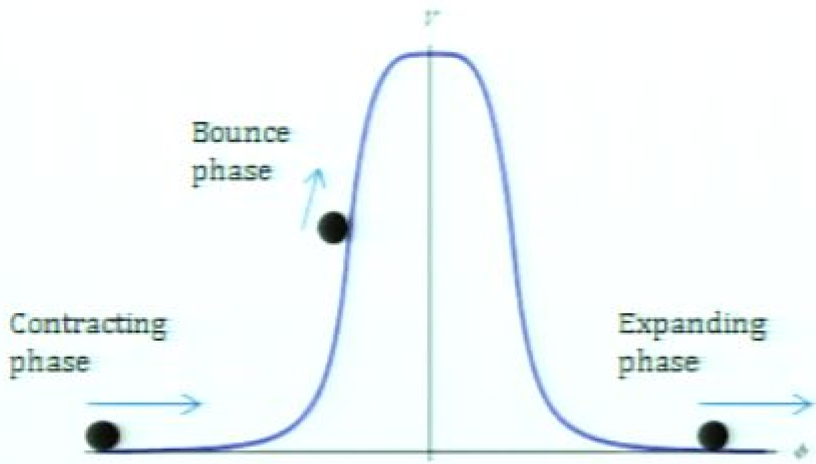

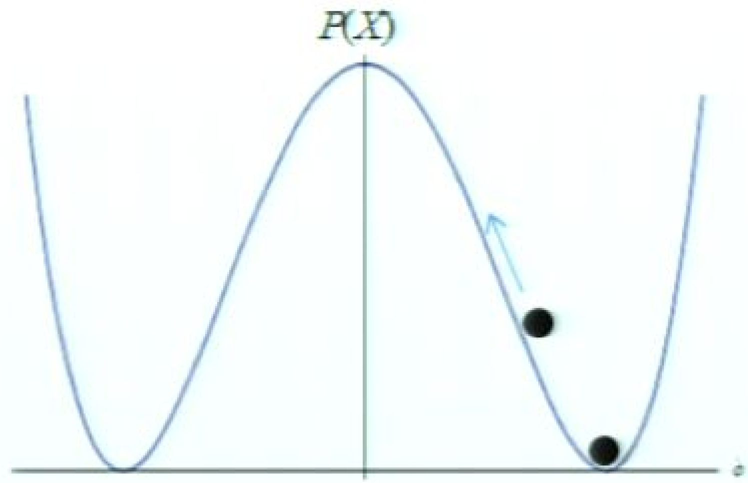

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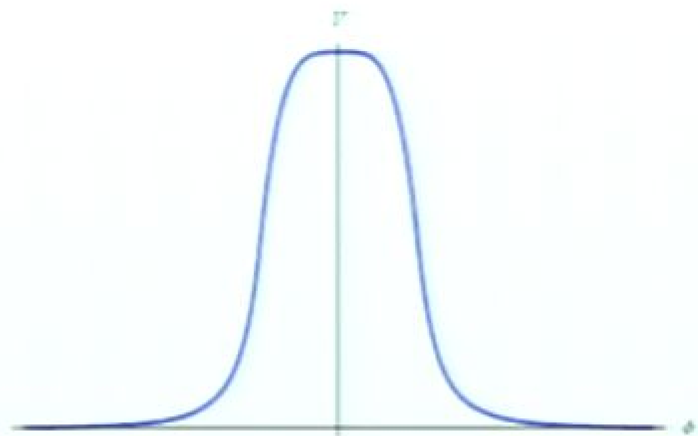

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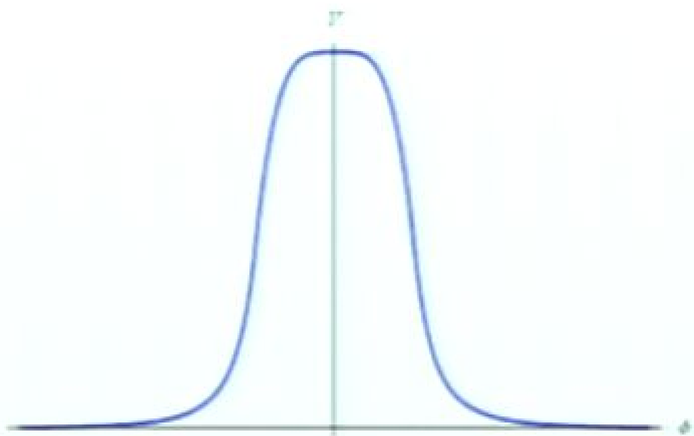

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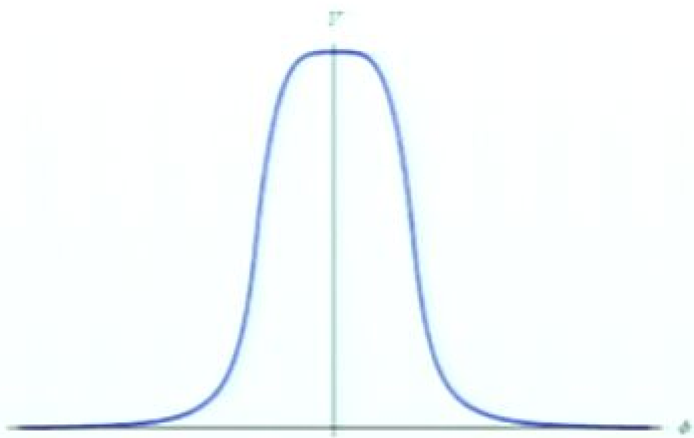

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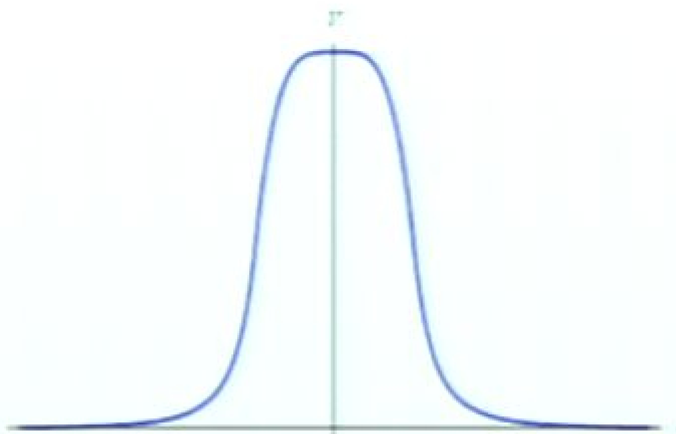

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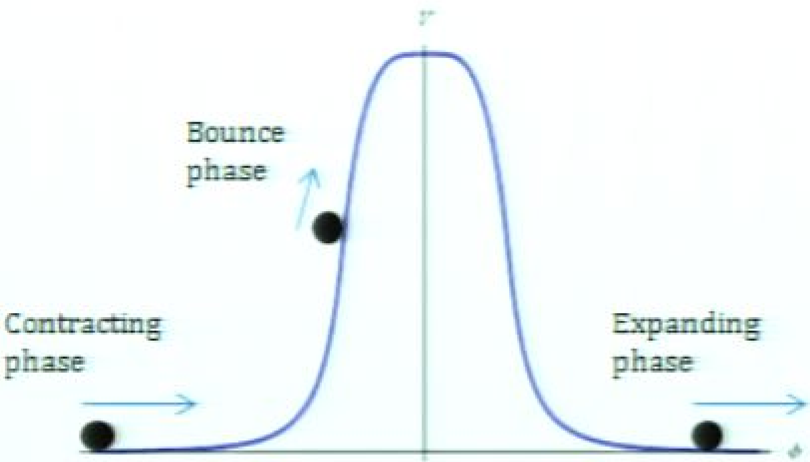

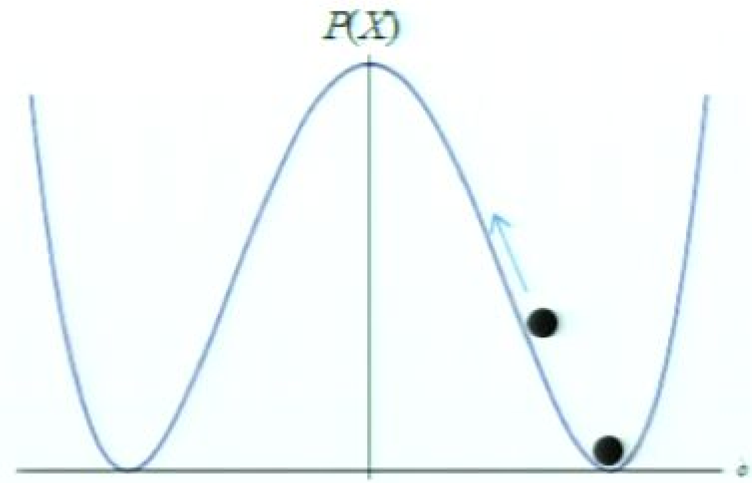

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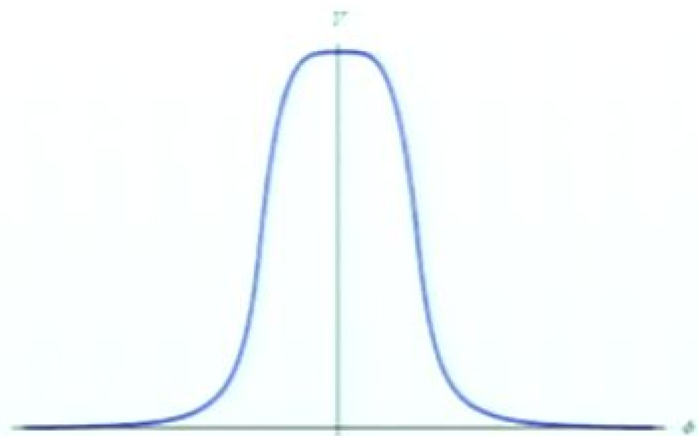

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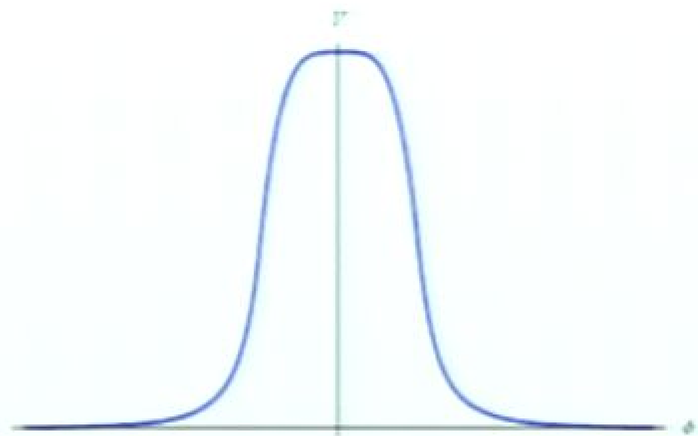

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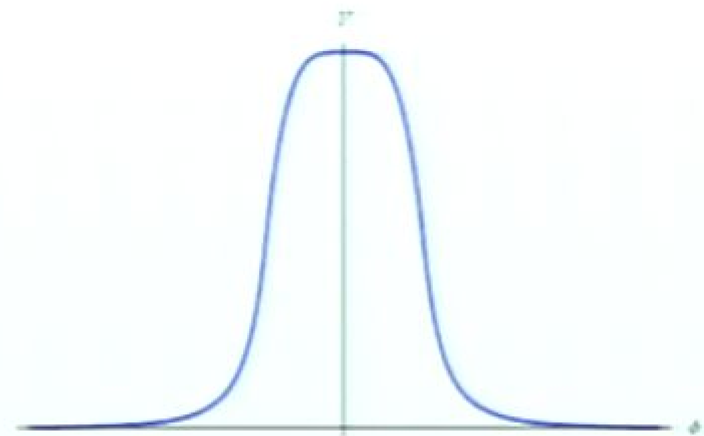

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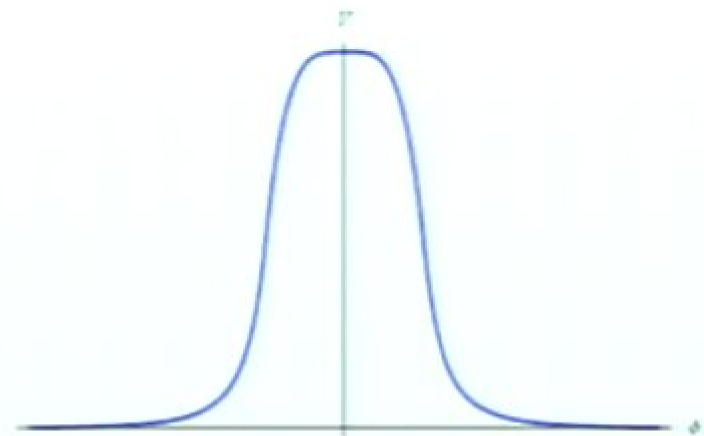

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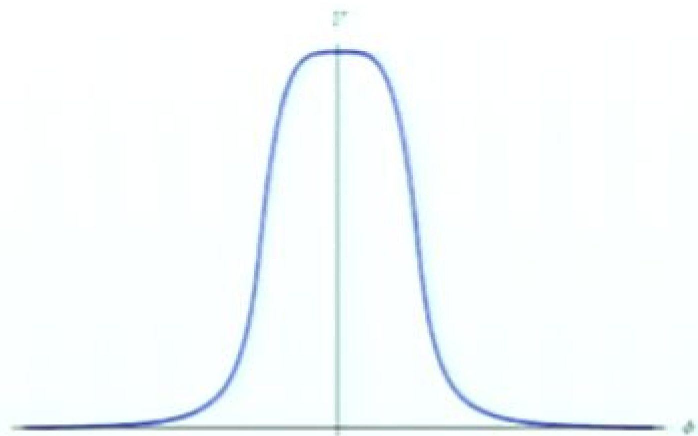

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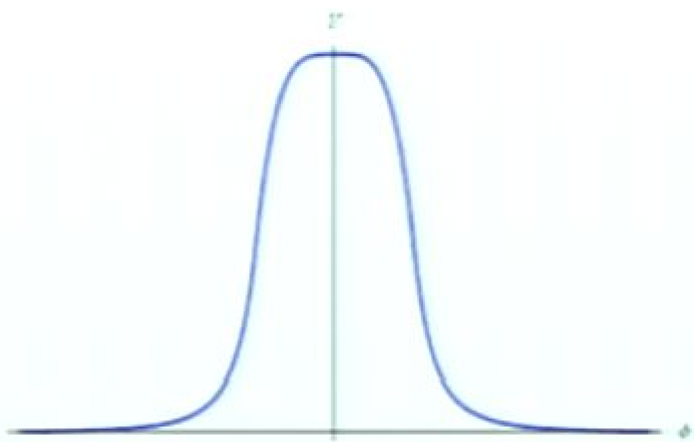

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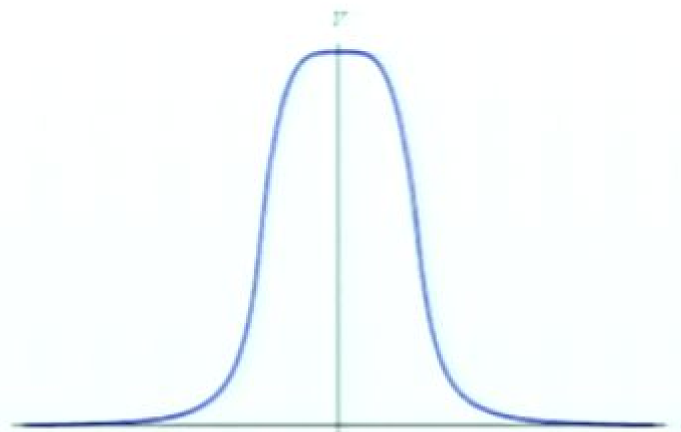

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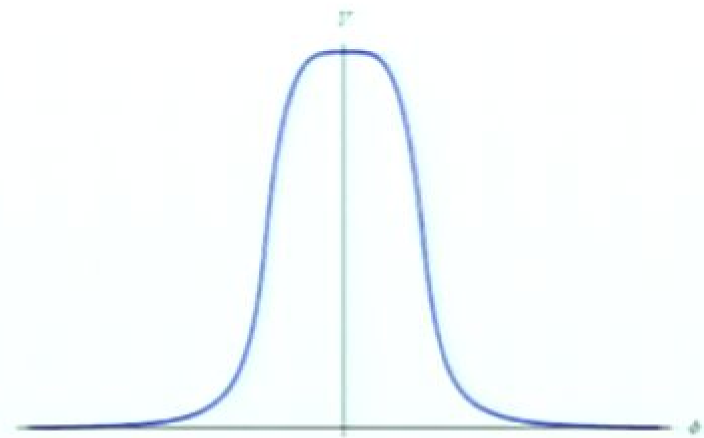

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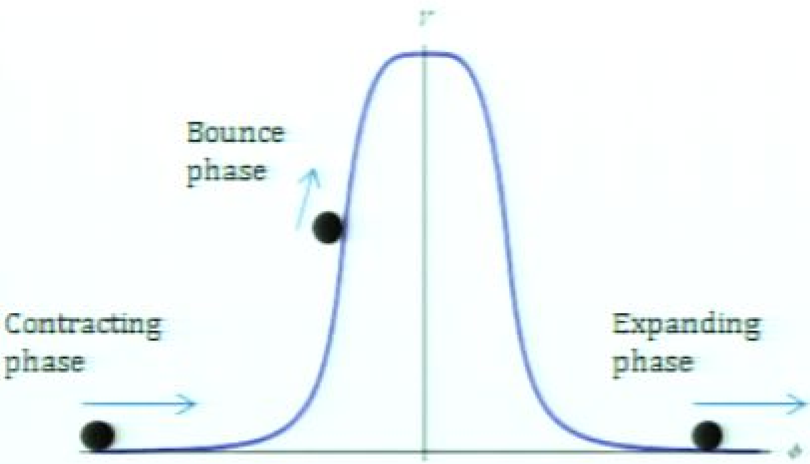

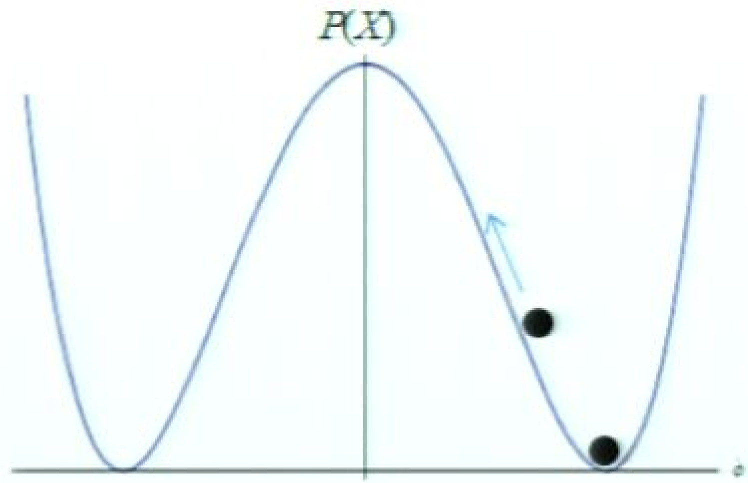

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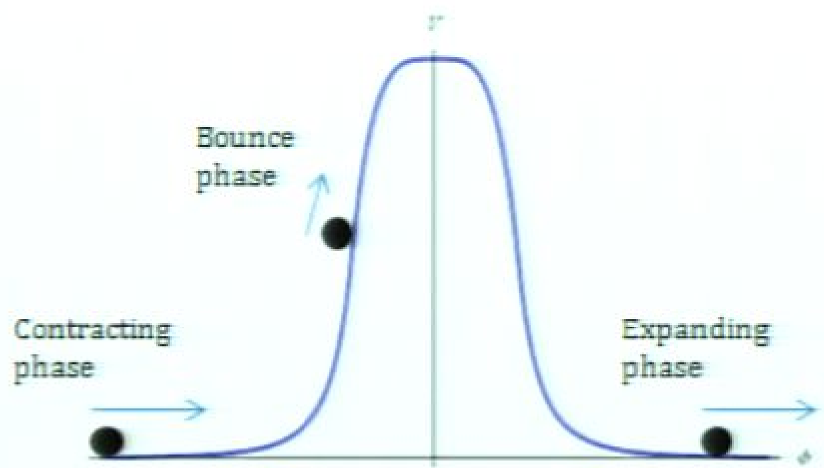

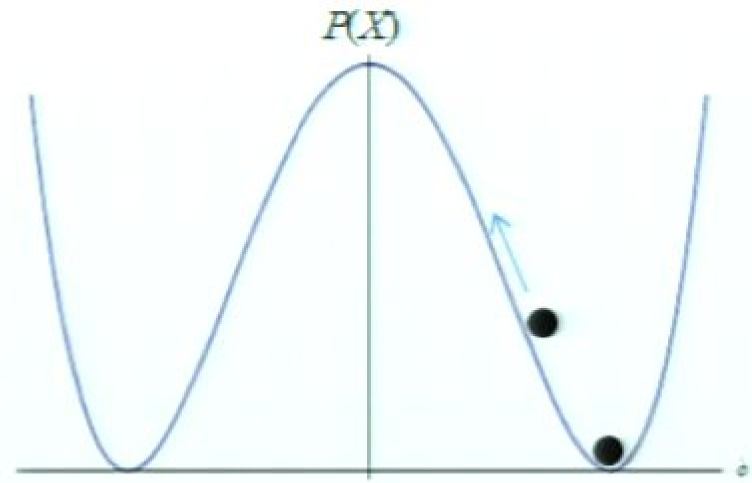

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Realization of NEC violation!

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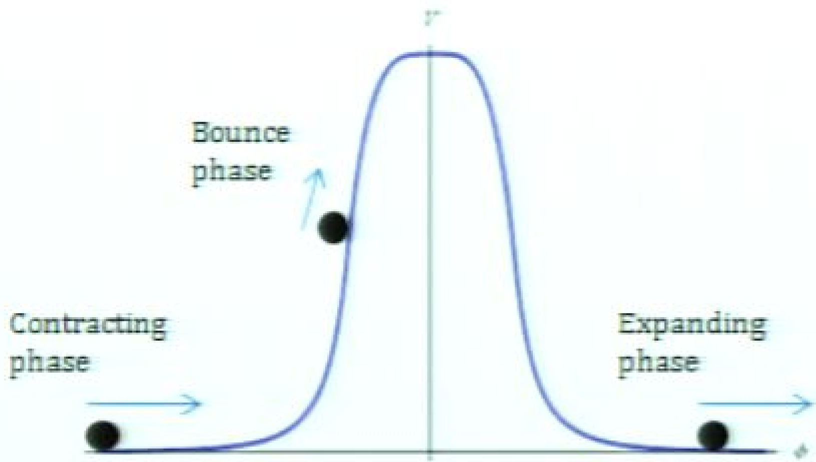

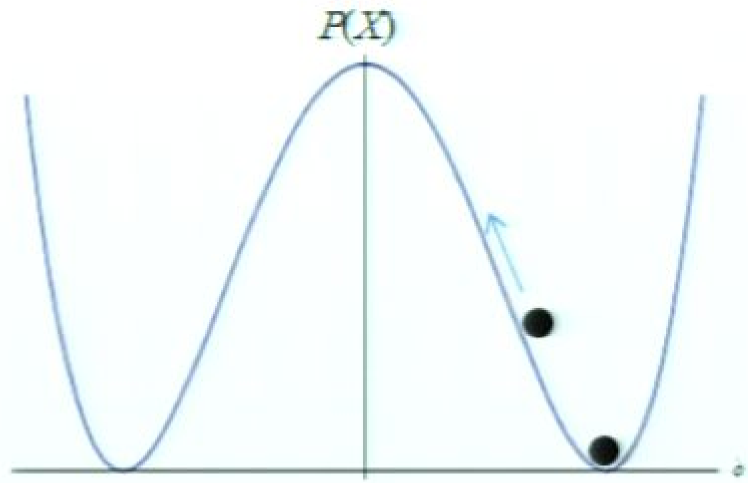

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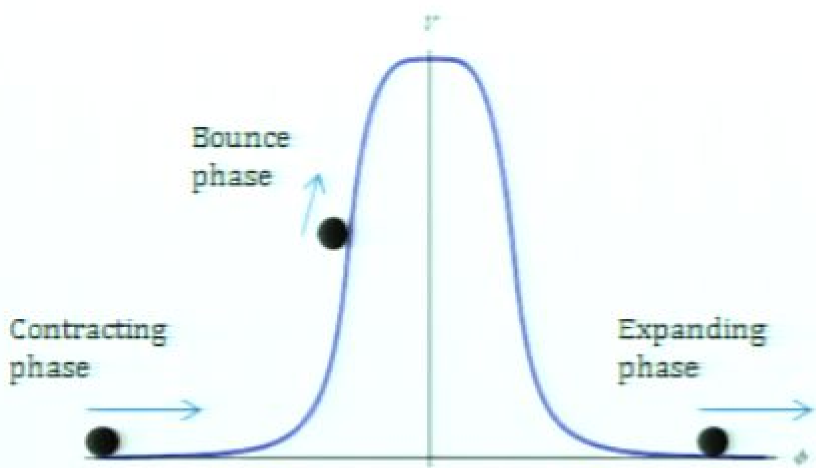

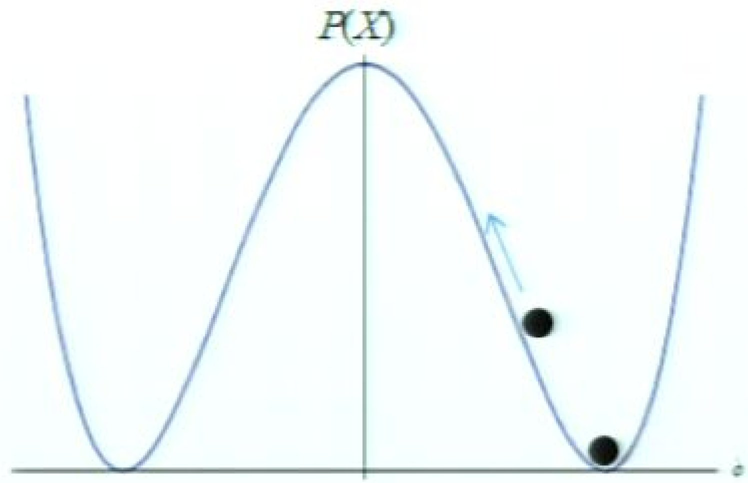

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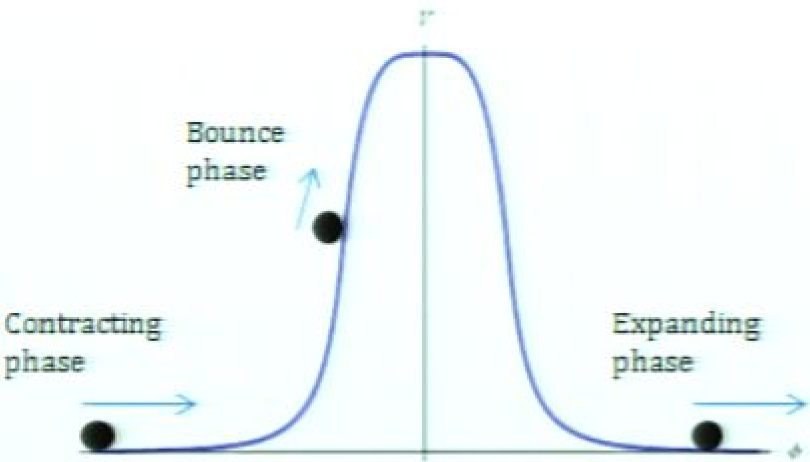

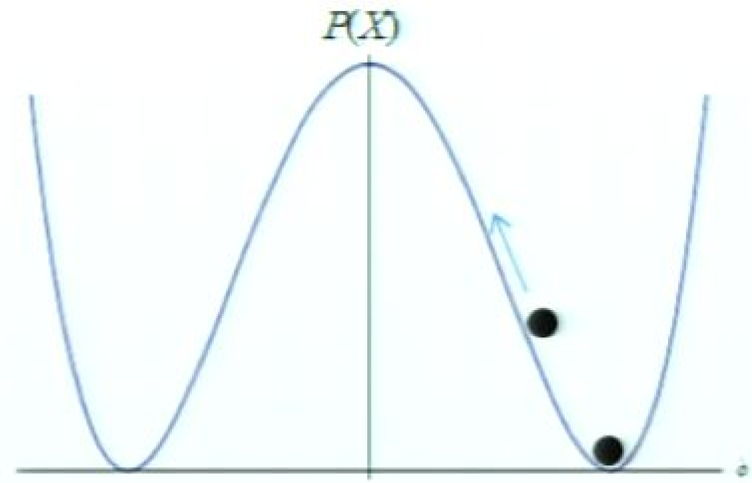

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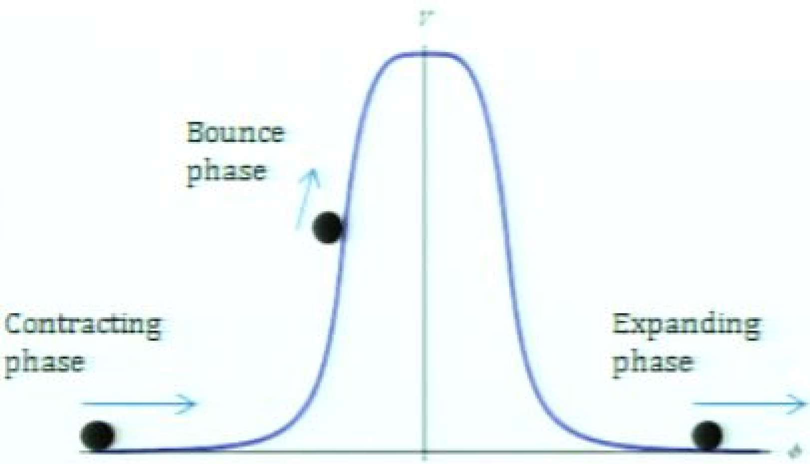

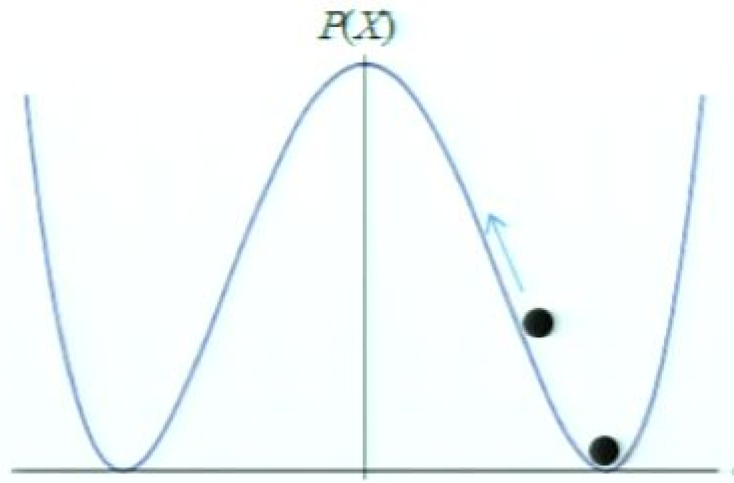

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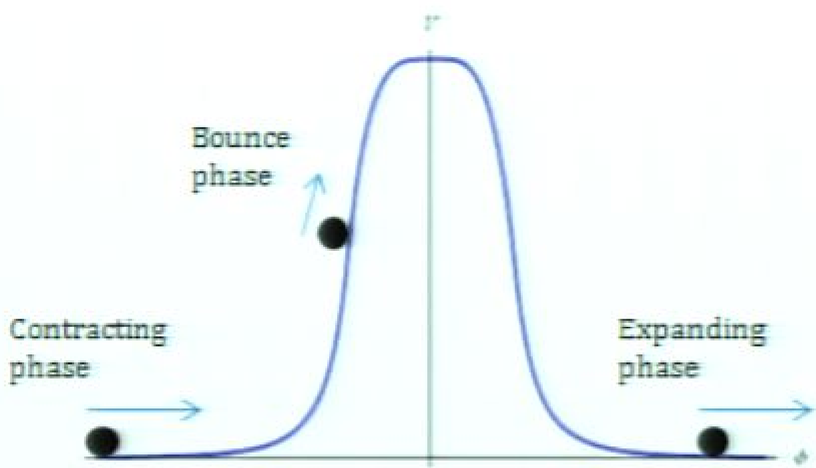

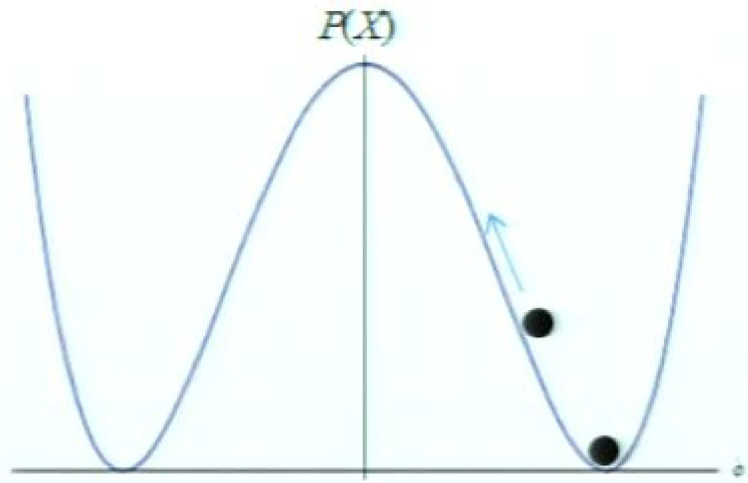

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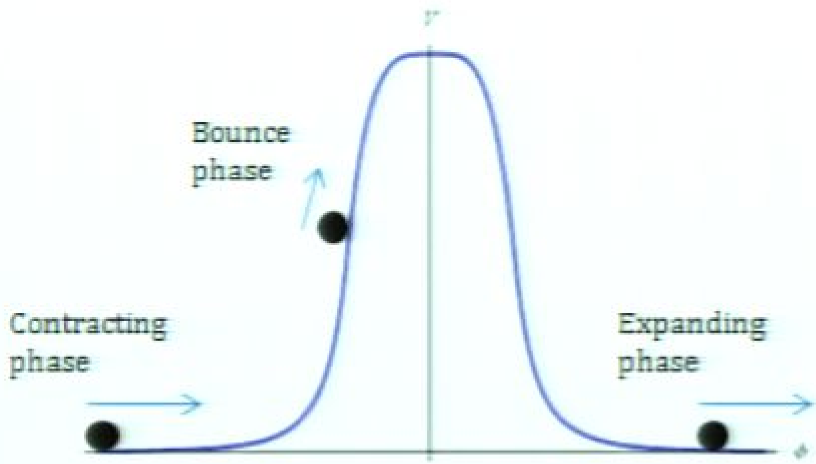

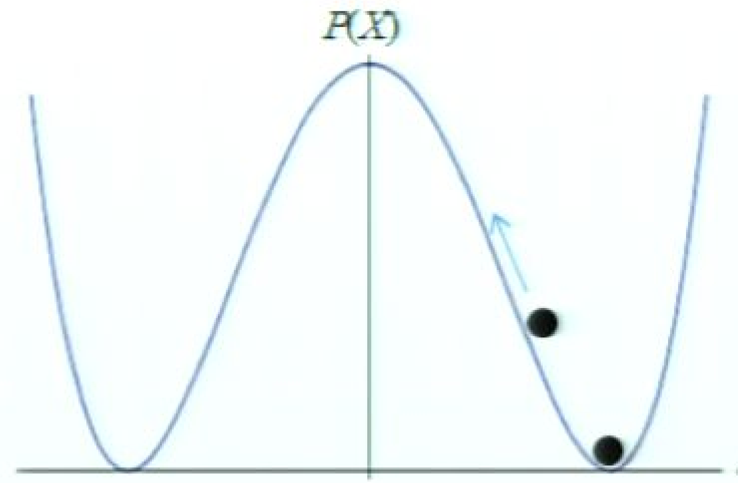

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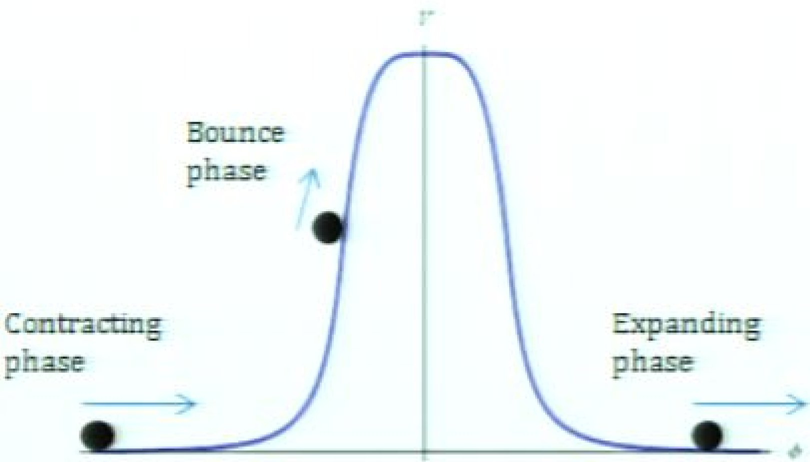

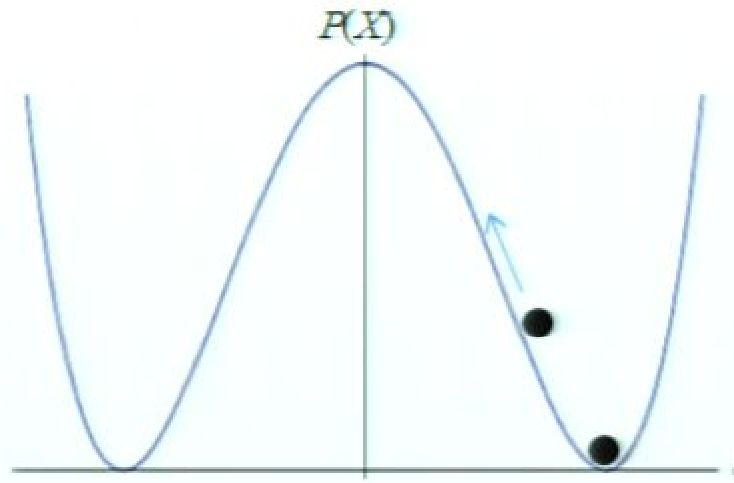

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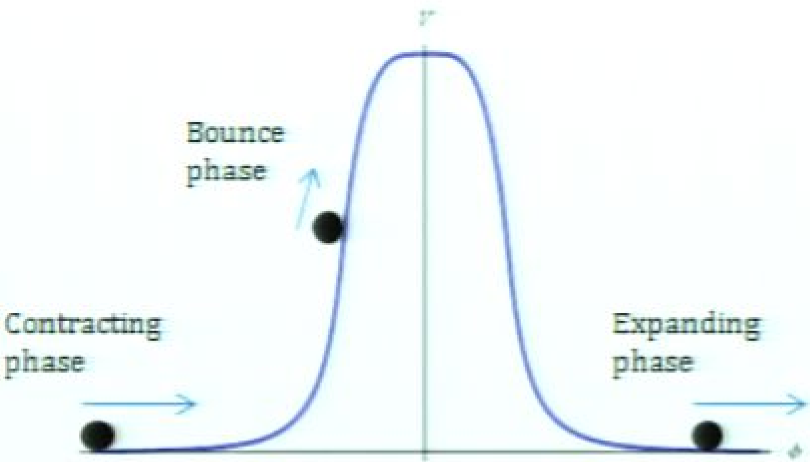

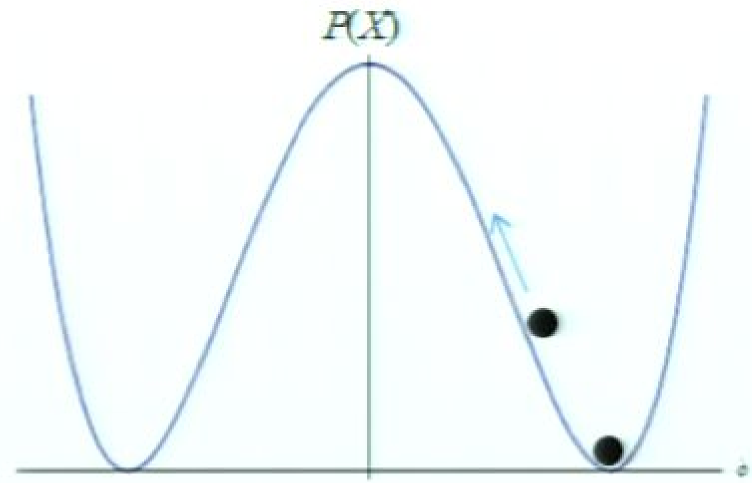

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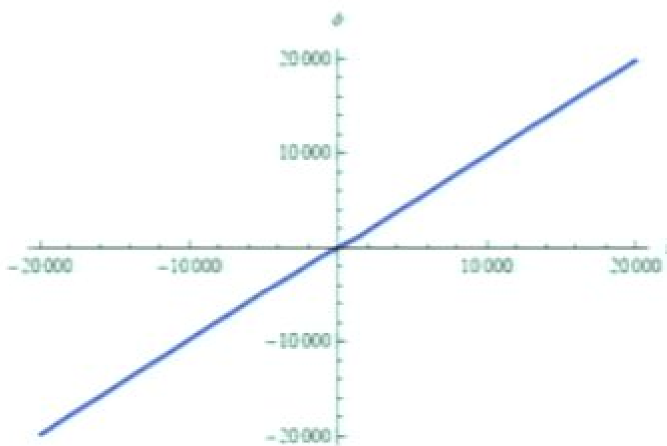

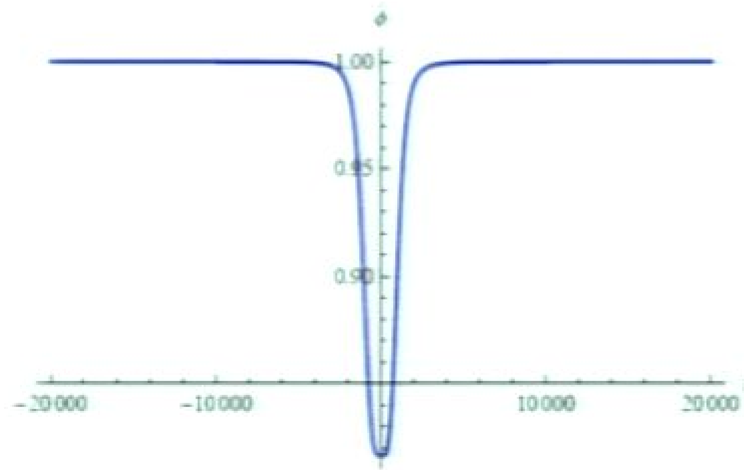

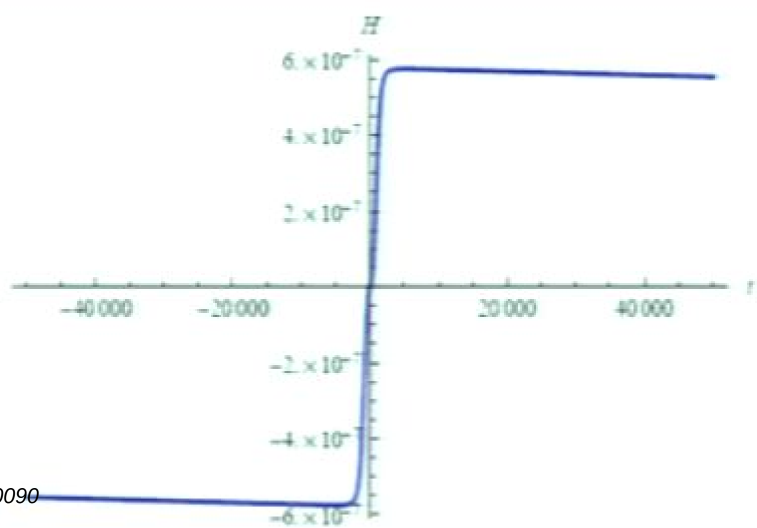

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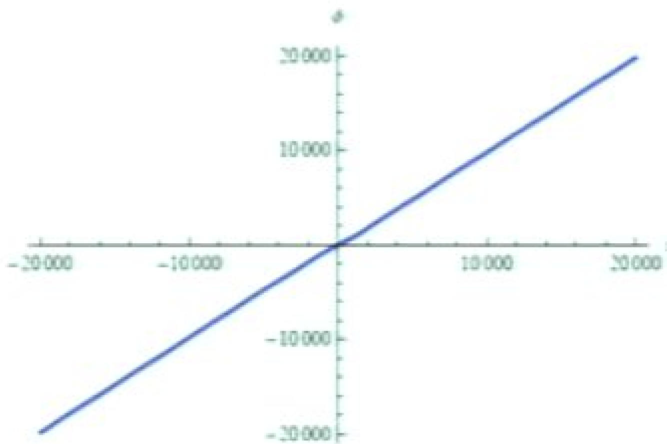

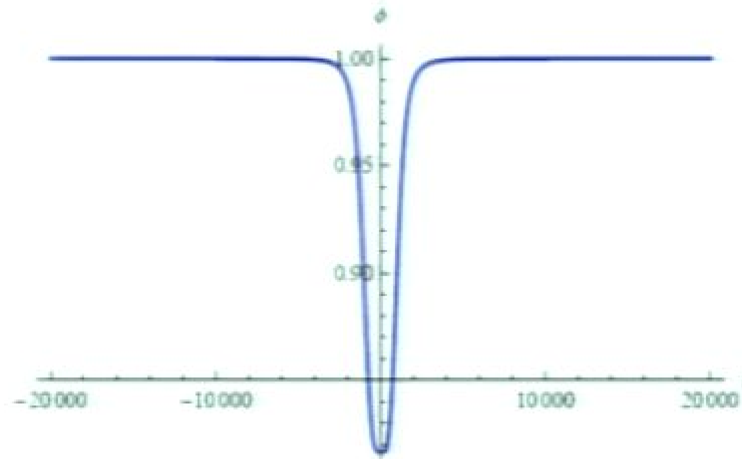

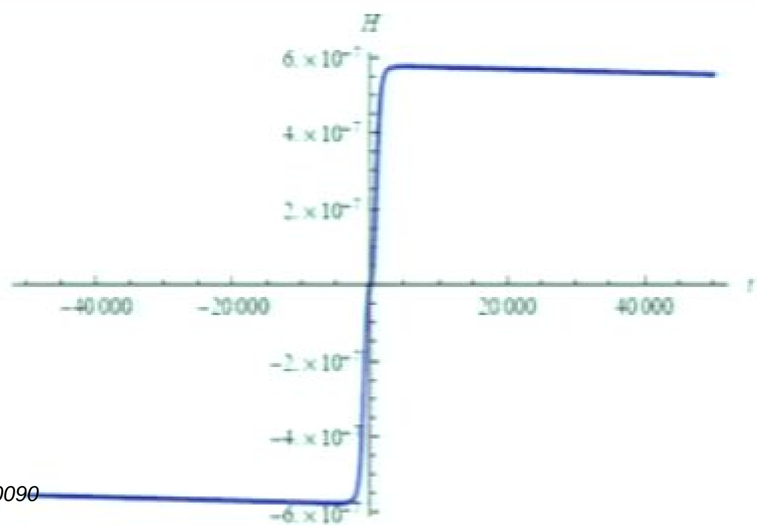

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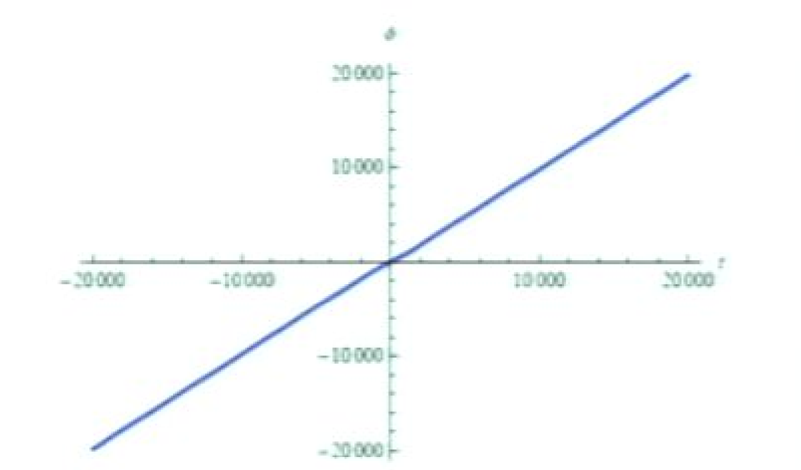

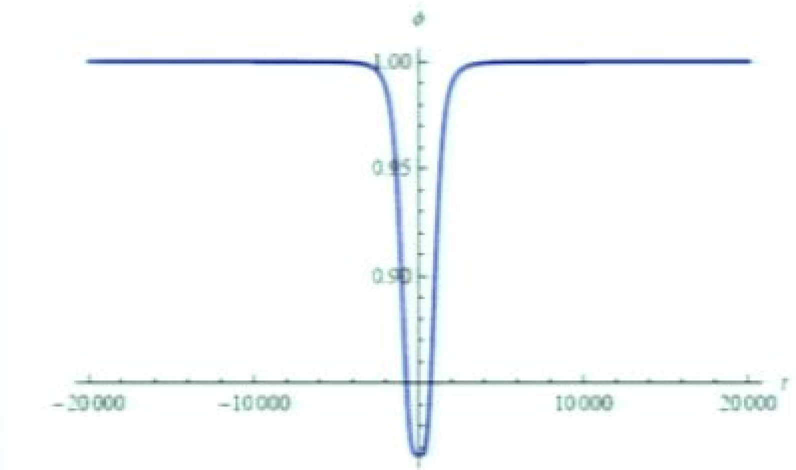

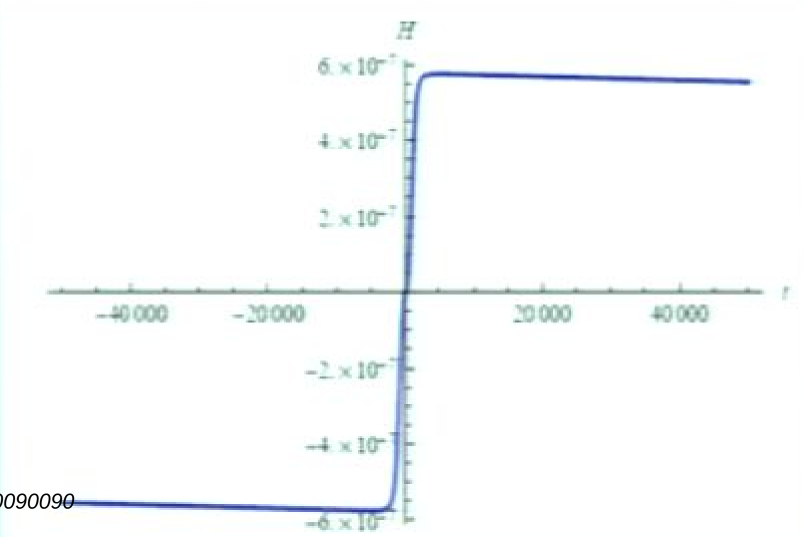

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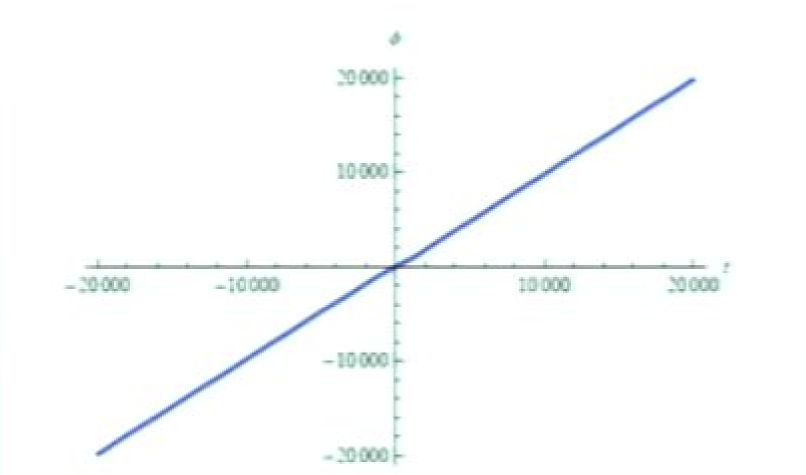

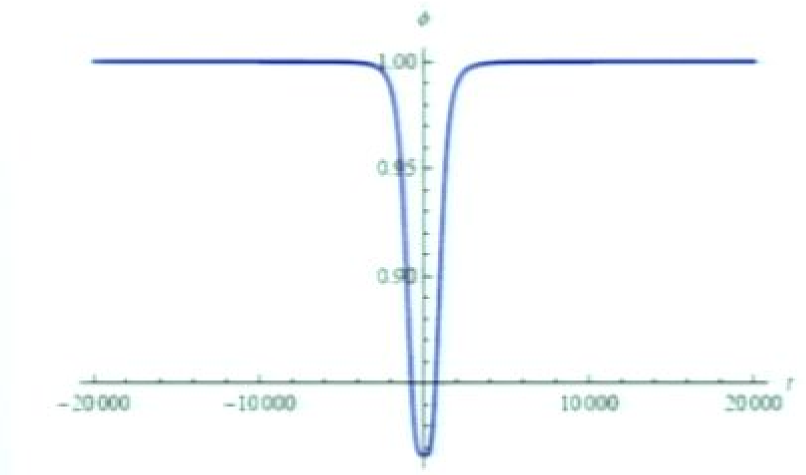

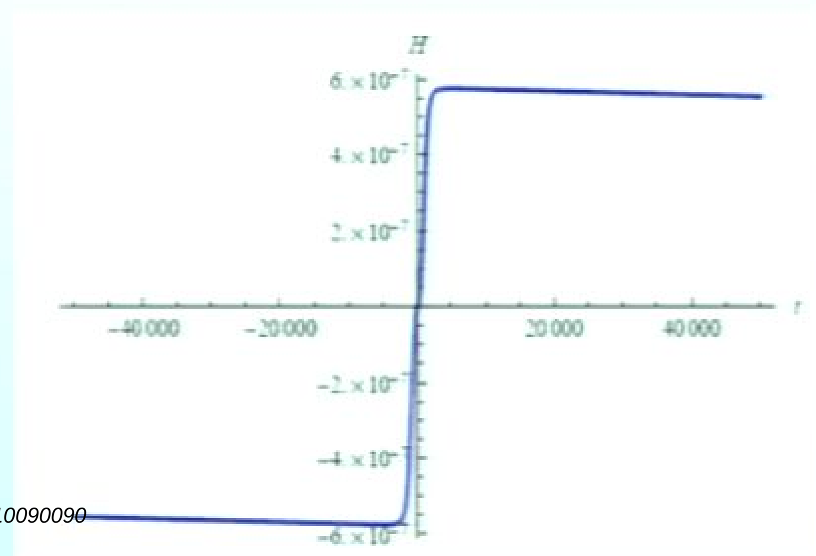

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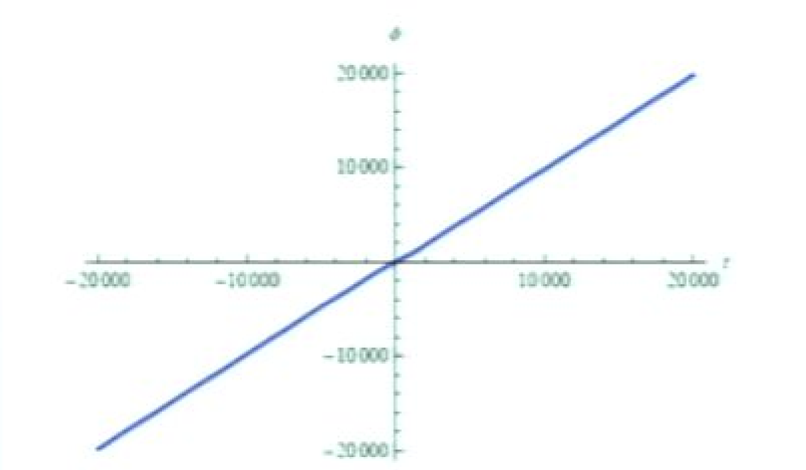

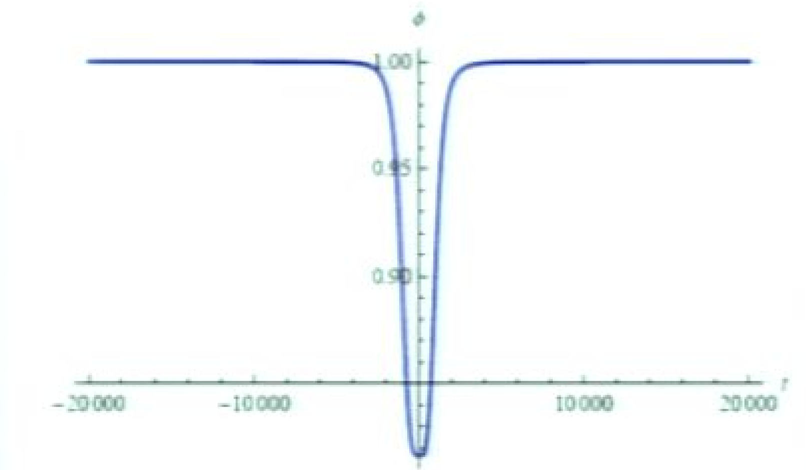

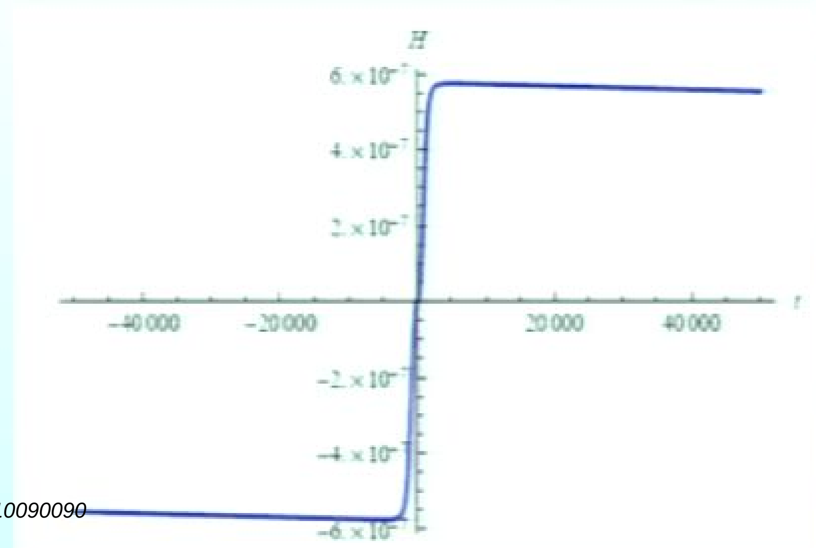

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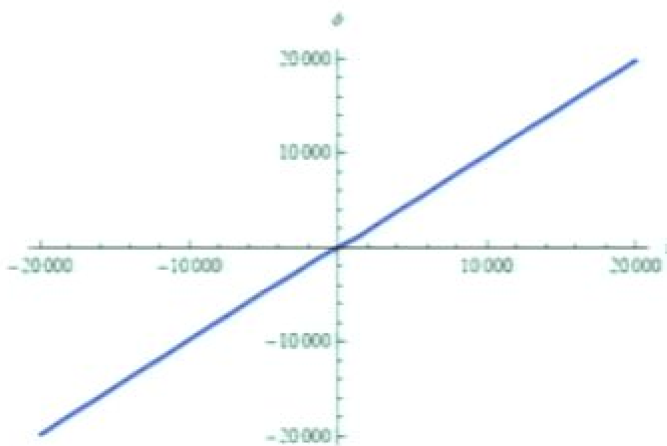

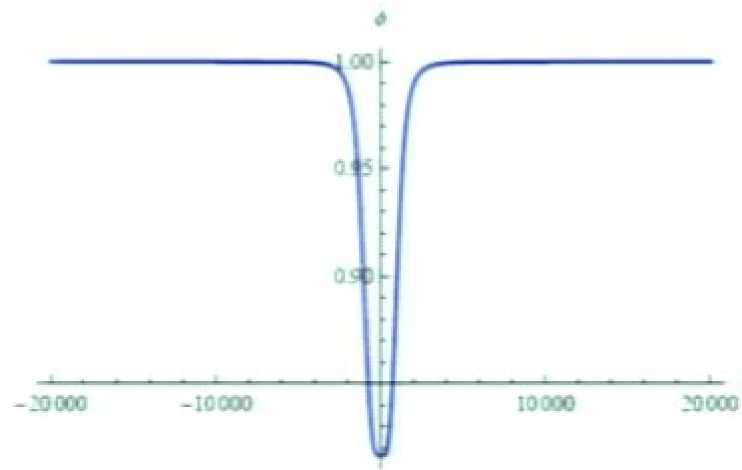

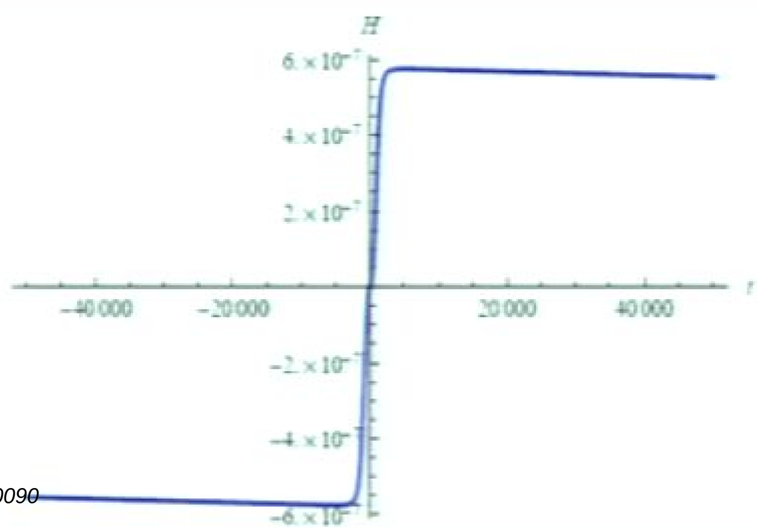

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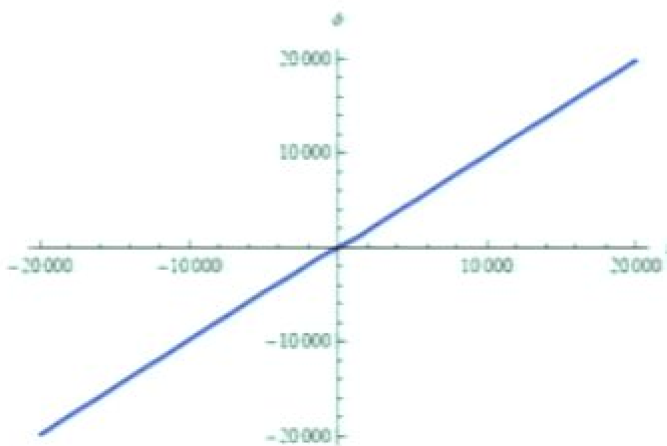

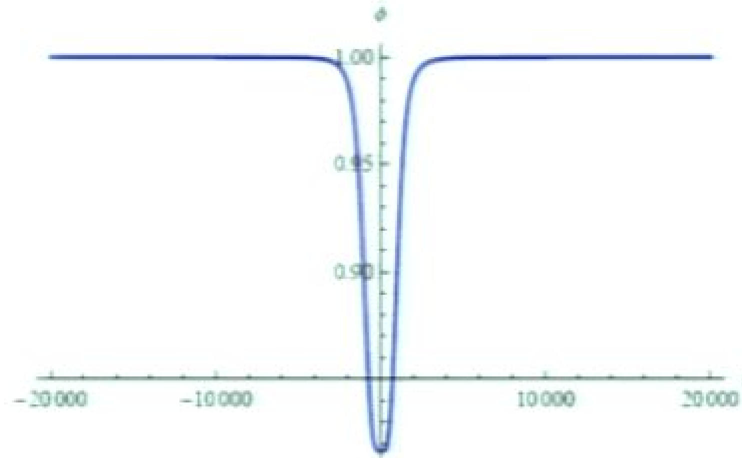

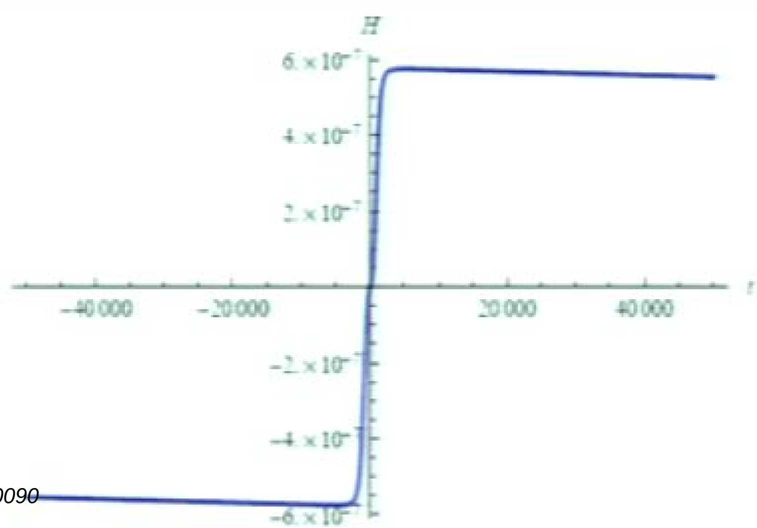

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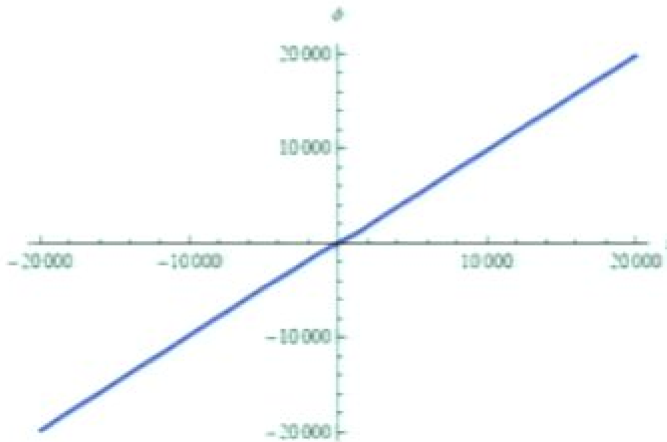

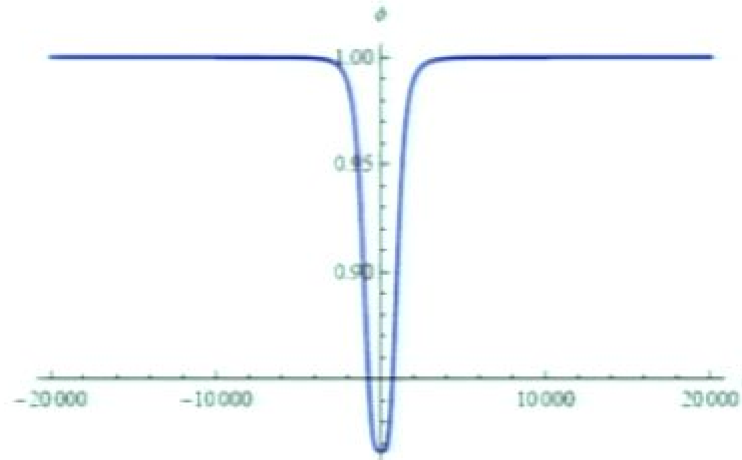

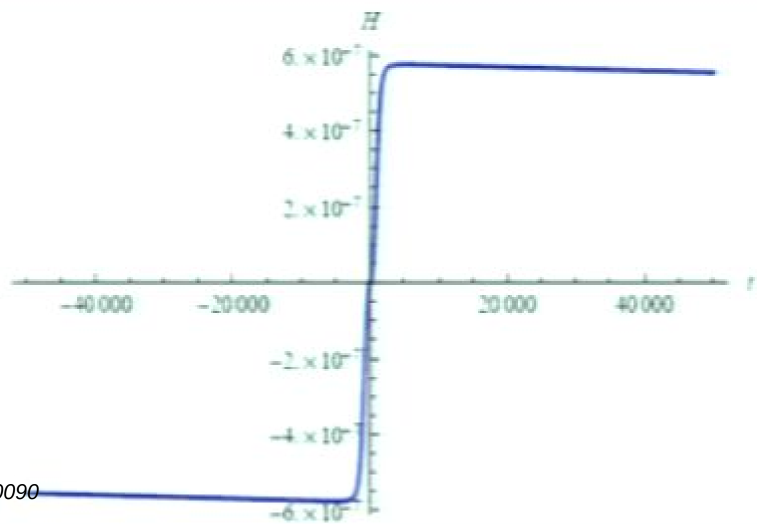

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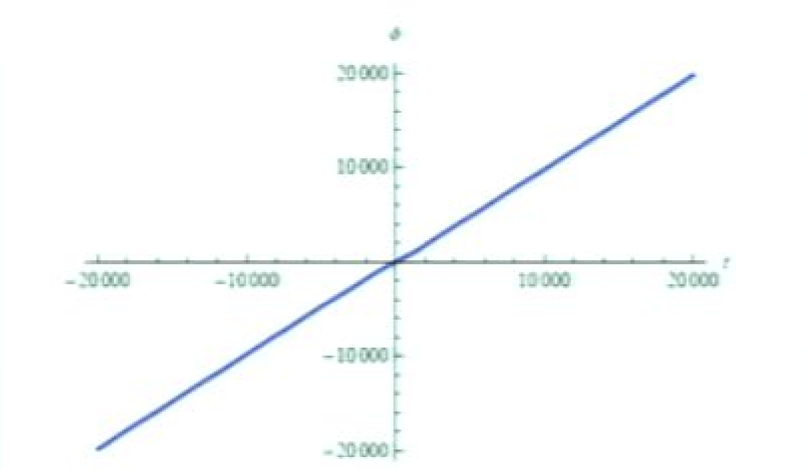

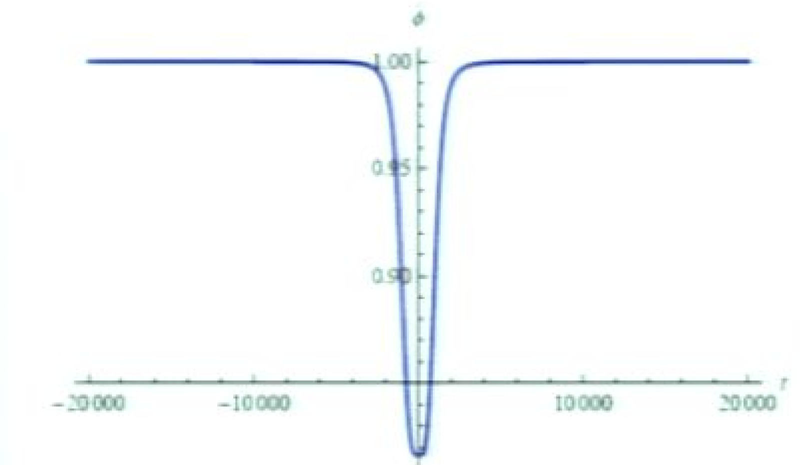

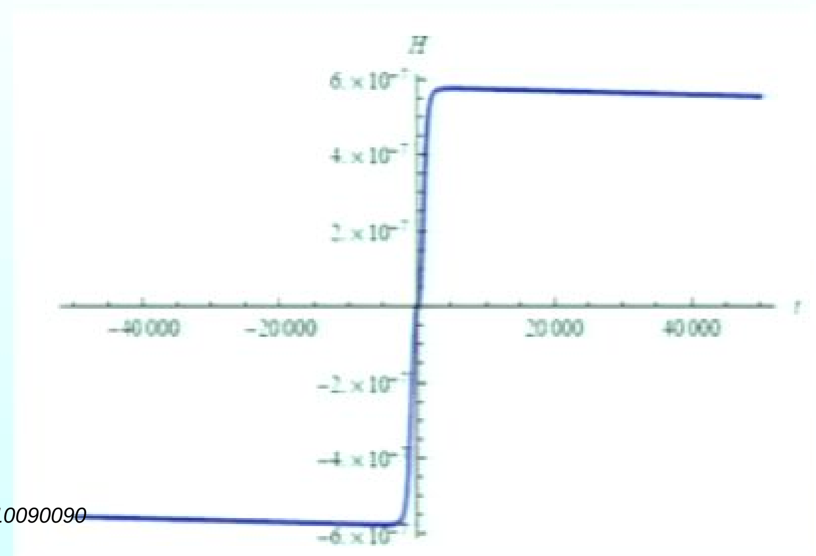

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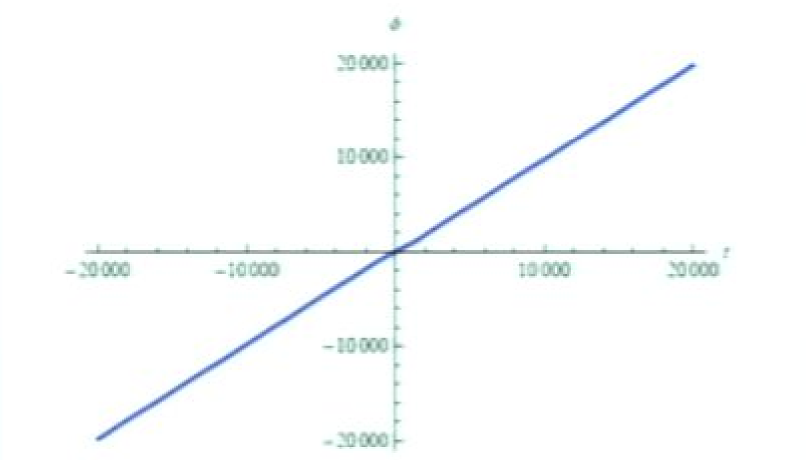

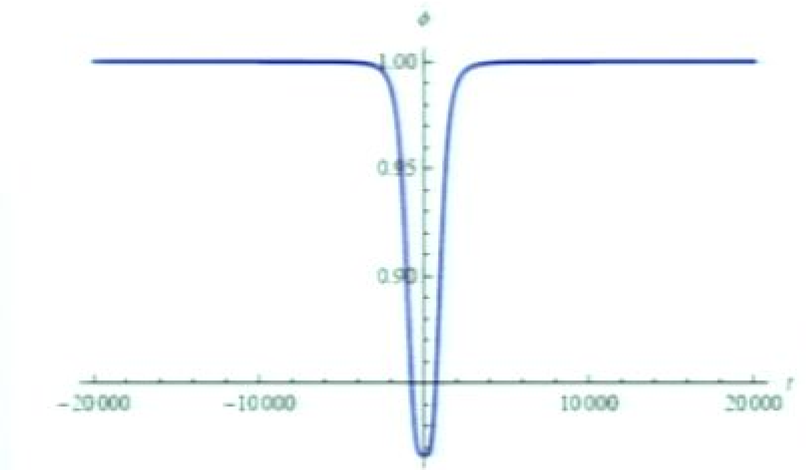

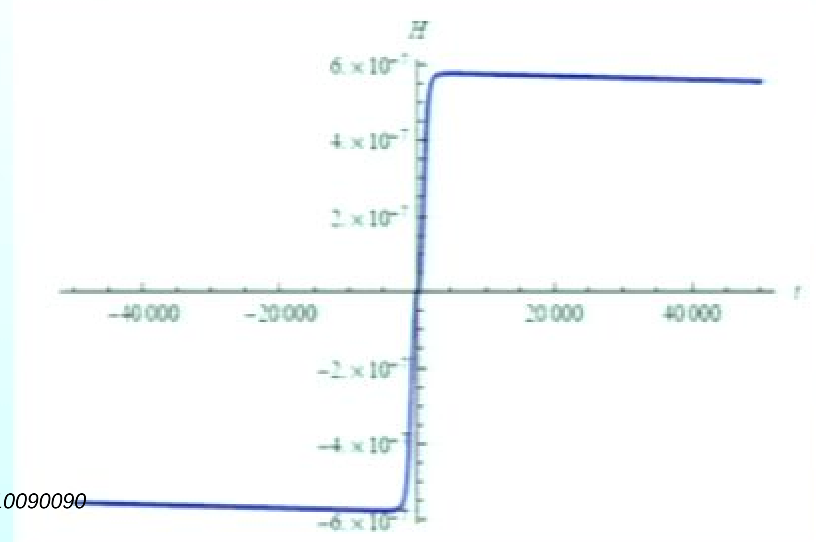

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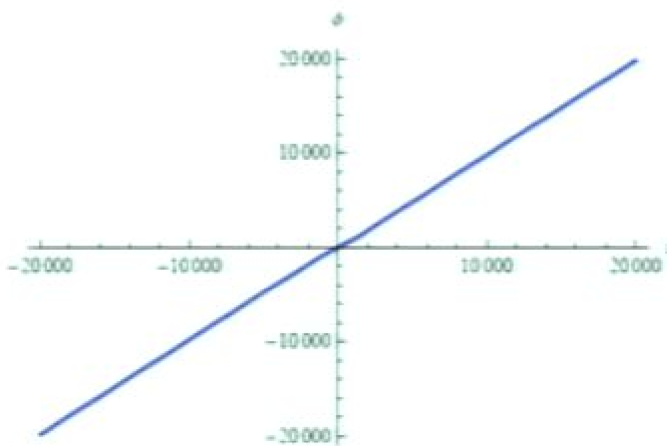

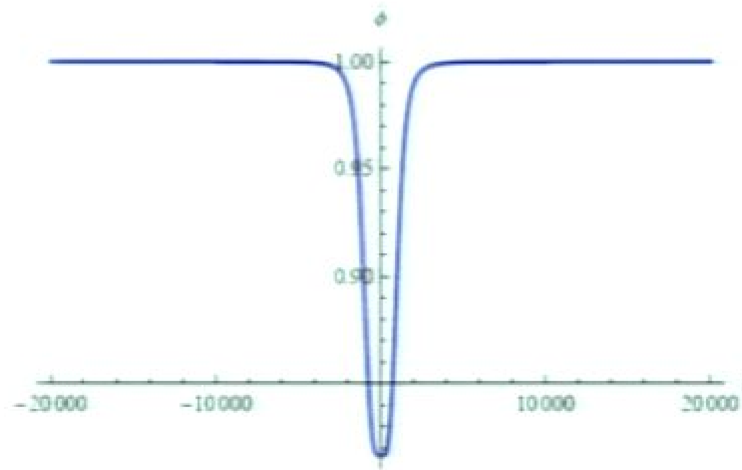

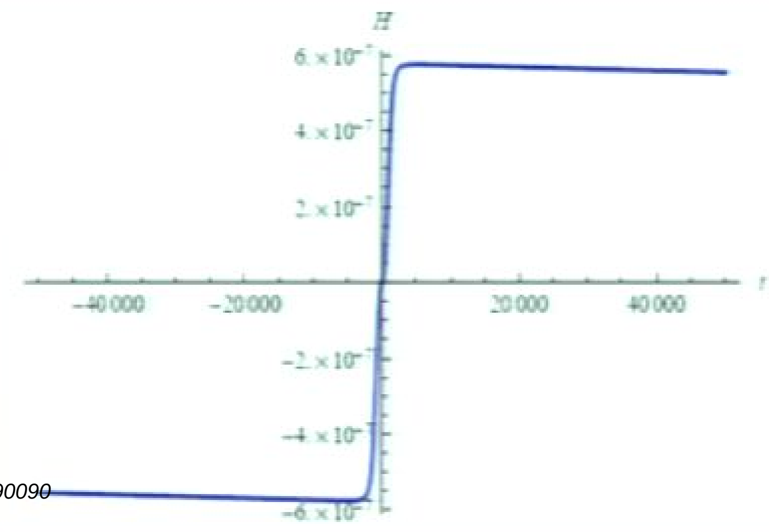

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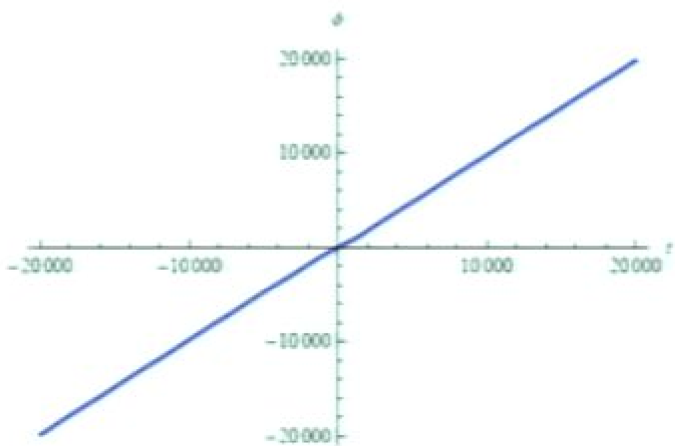

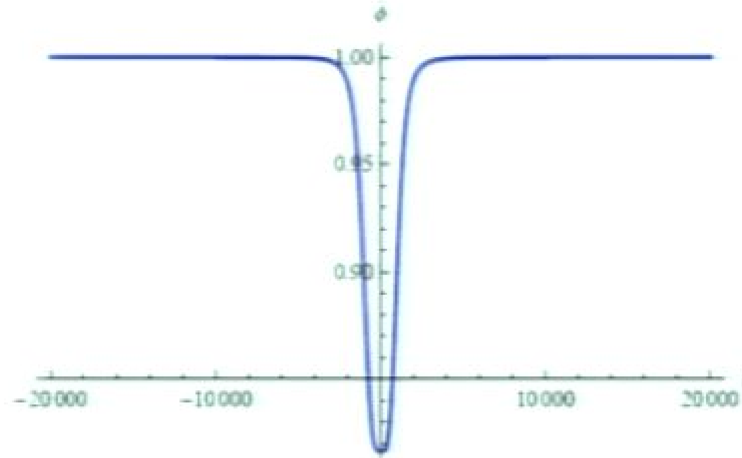

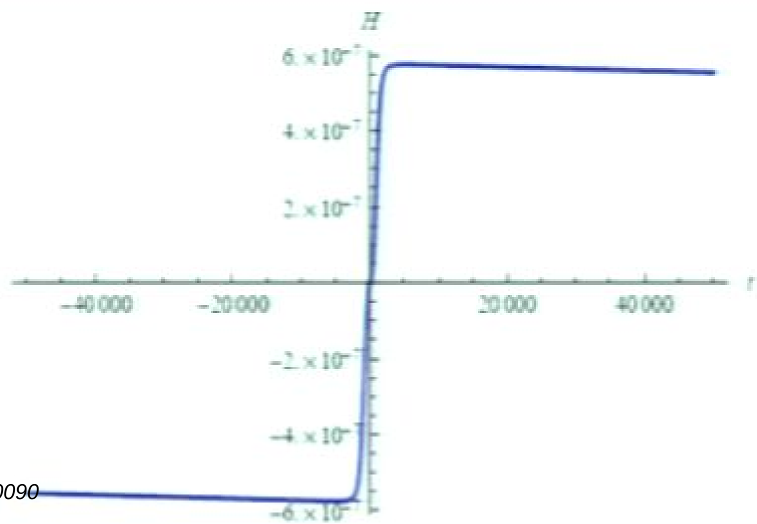

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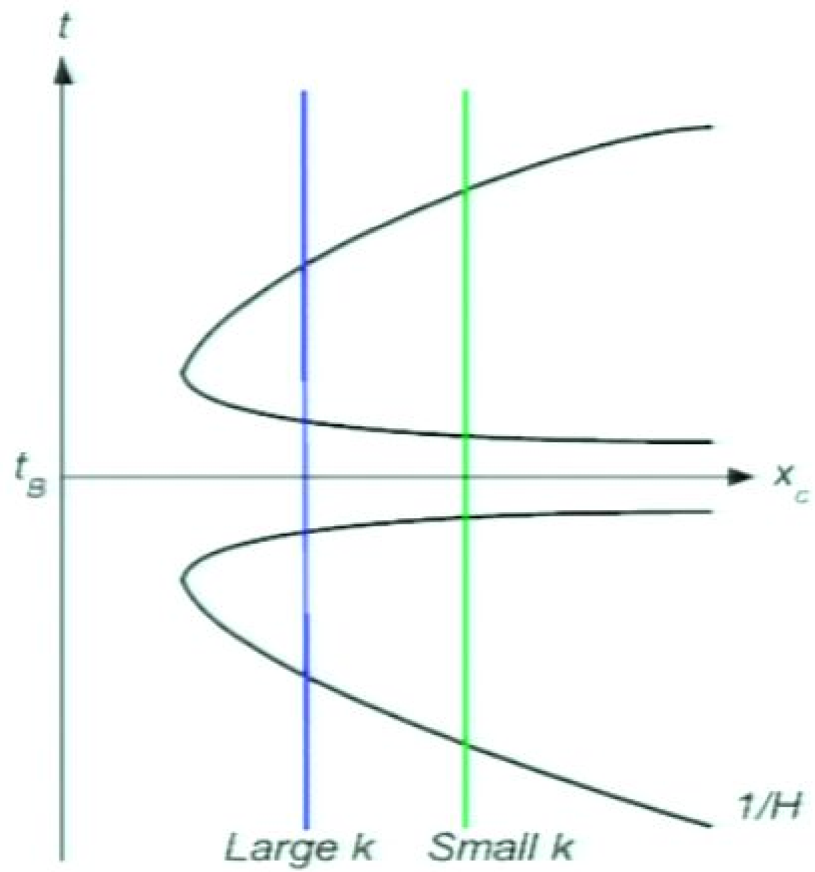
Matter perturbation



The metric in Newtonian gauge

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Psi)d\mathbf{x}^2$$

$$\varphi(\eta,\mathbf{x}) = \varphi_0(\eta) + \delta\varphi(\eta,\mathbf{x})$$

Introduce M-S Variable

$$v = a[\delta\varphi + \frac{z}{a}\Phi]$$

$$S^{(2)} = \frac{1}{2}\int d^4x[v'^2 - v_{,i}v_{,i} + \frac{z''}{z}v^2]$$

EoM:

$$v_k'' + k^2 v_k - \frac{z''}{z}v_k = 0$$

In matter contracting phase $z \sim a$

$$v(t) \sim t^{-1/3}$$

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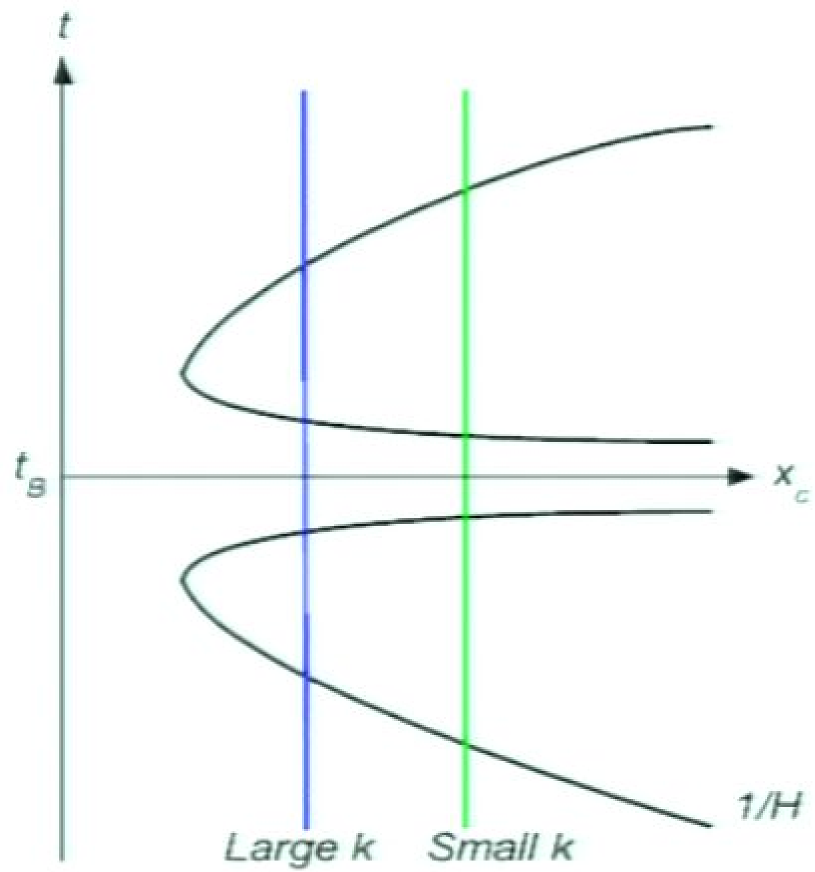

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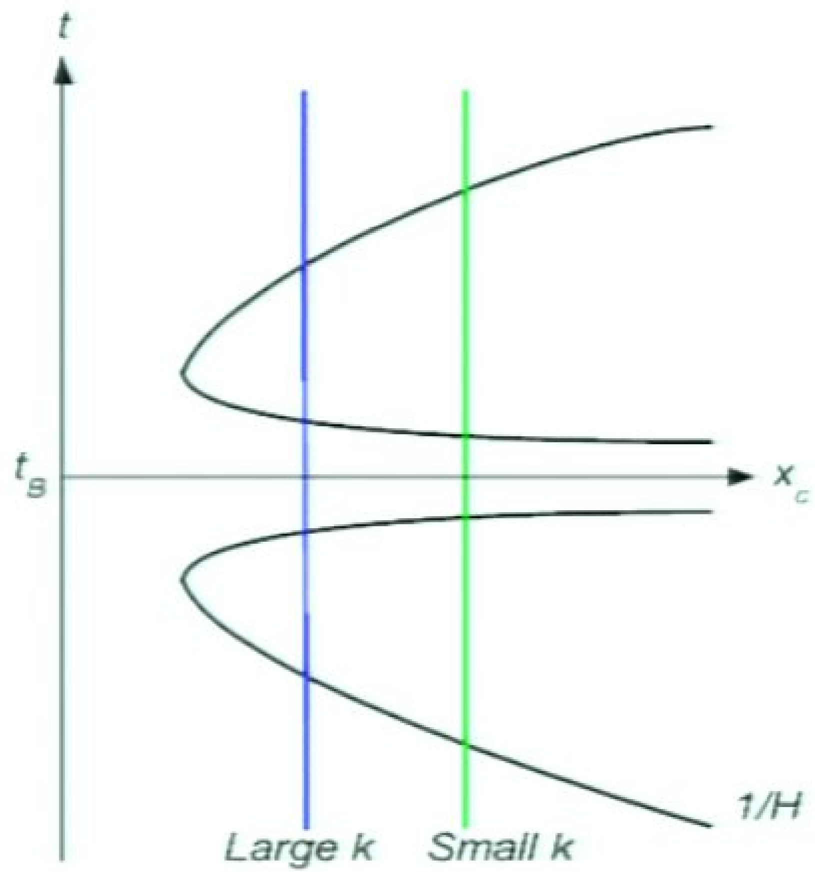

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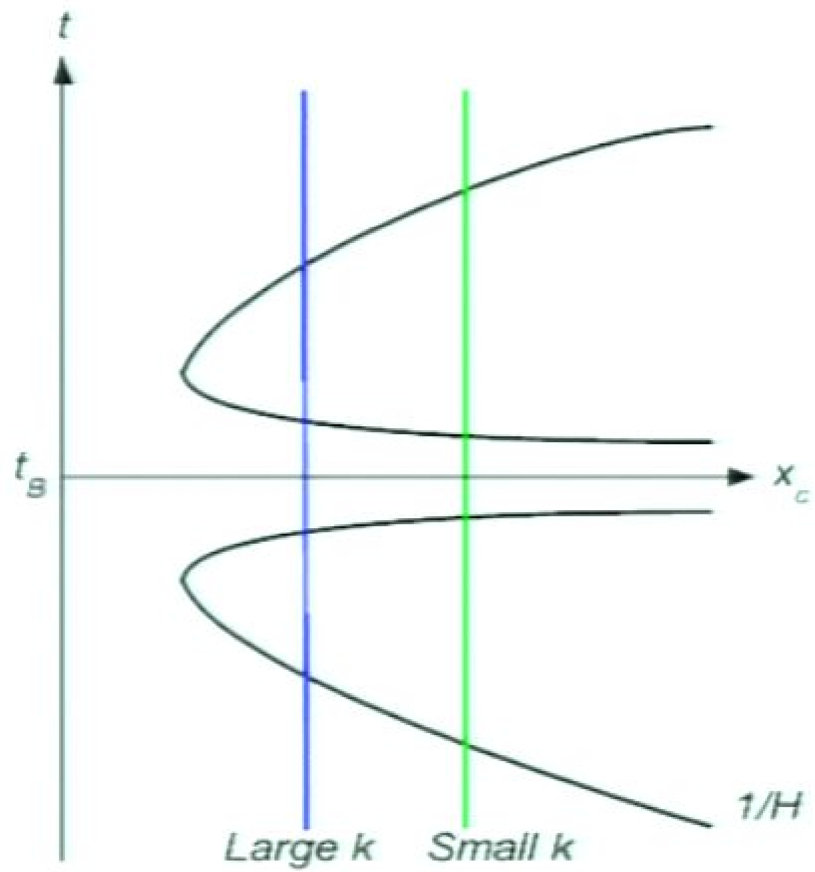

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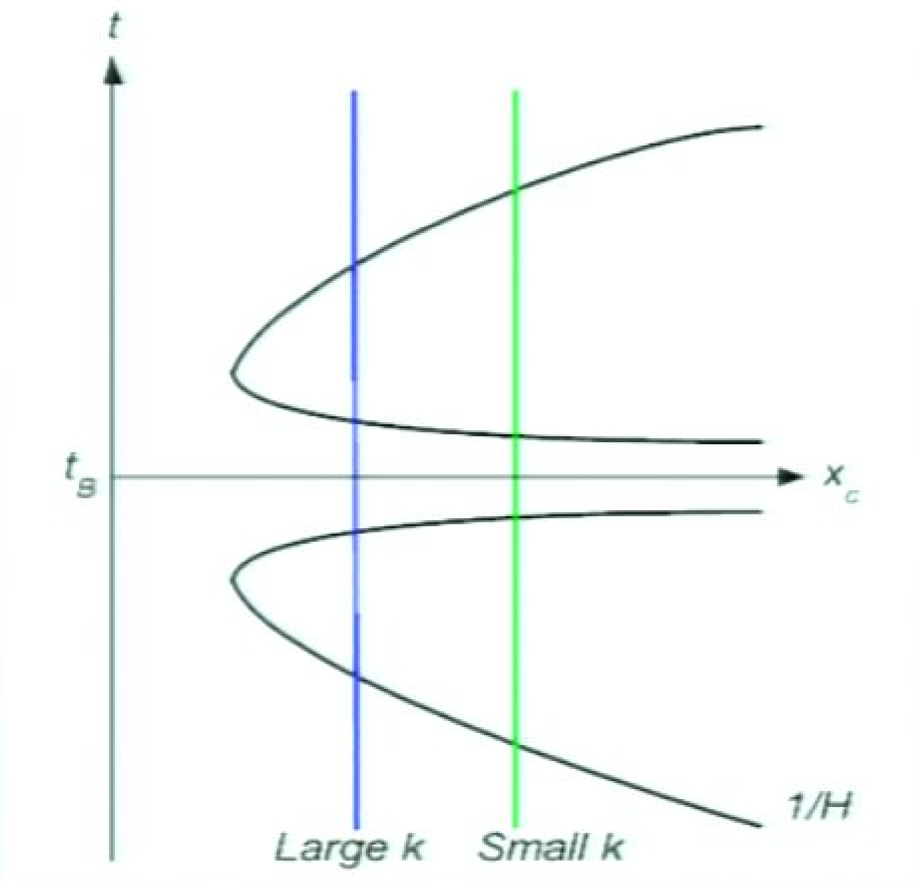
In matter contracting phase $z \sim a$

$$v(t) \sim t^{-1/3}$$

Matter perturbation



The metric in Newtonian gauge

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Psi)d\mathbf{x}^2$$

$$\varphi(\eta,\mathbf{x}) = \varphi_0(\eta) + \delta\varphi(\eta,\mathbf{x})$$

Introduce M-S Variable

$$v = a[\delta\varphi + \frac{z}{a}\Phi]$$

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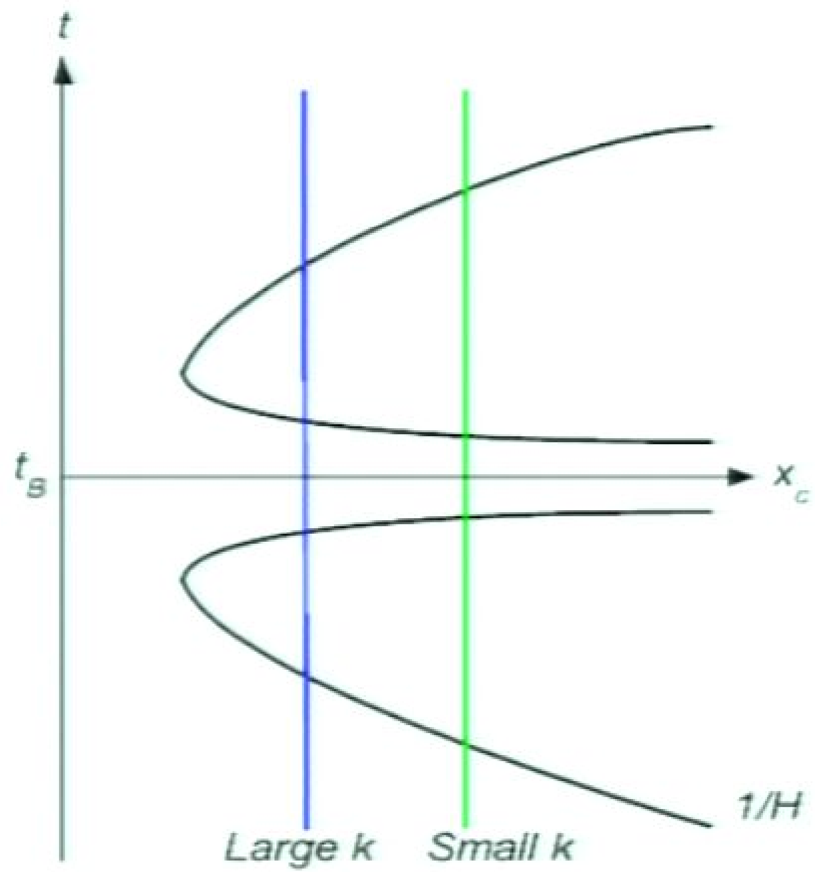

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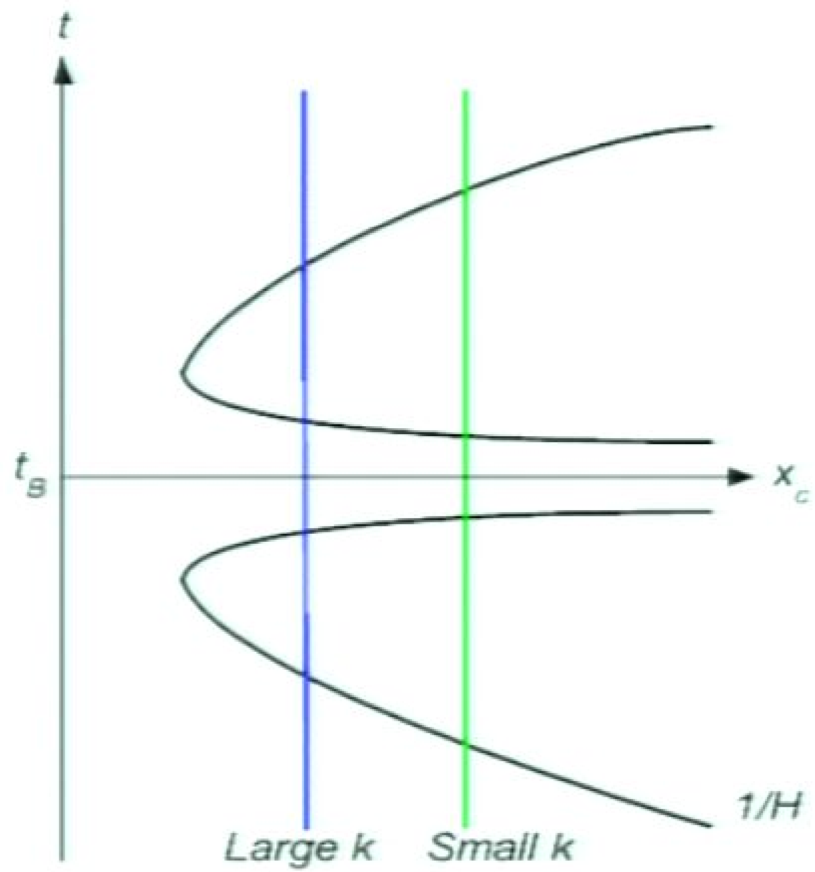

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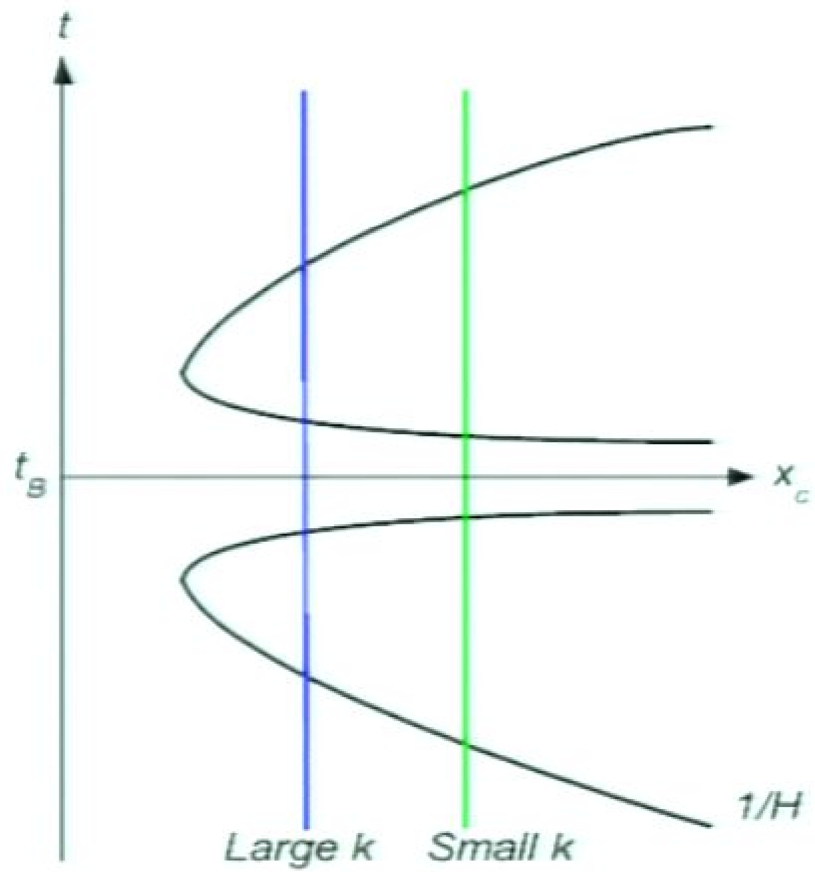

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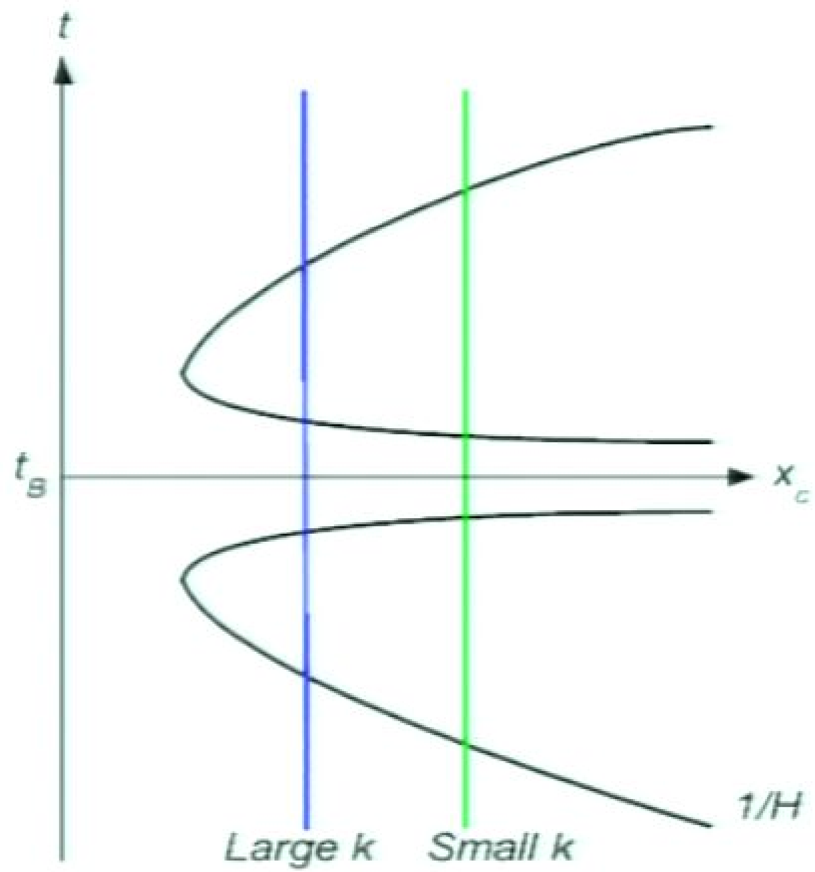

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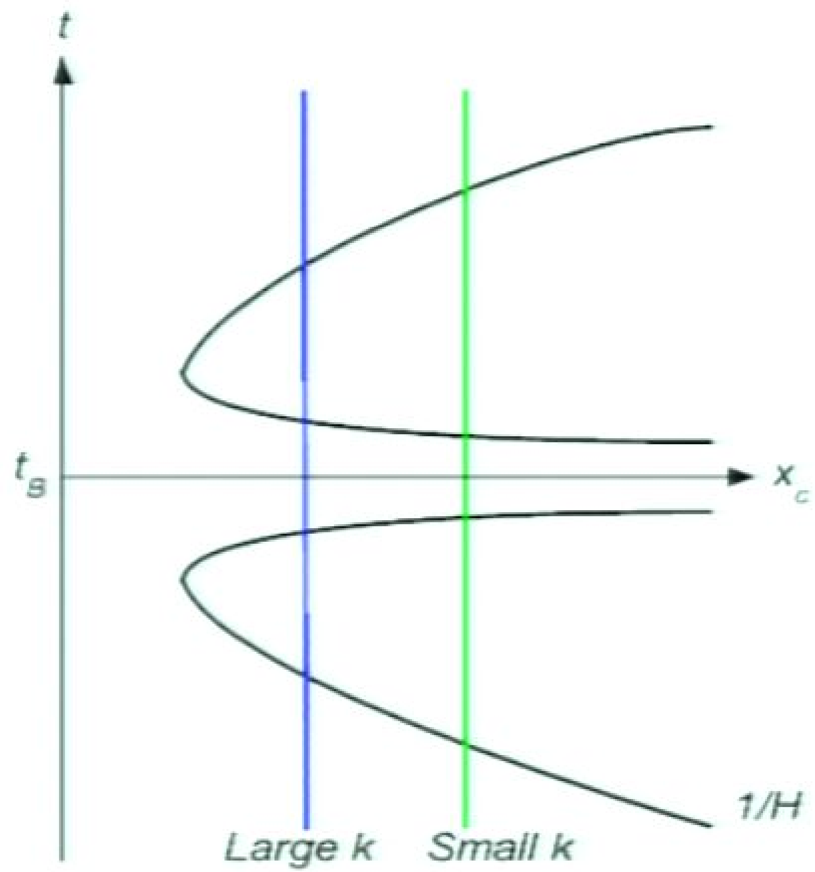

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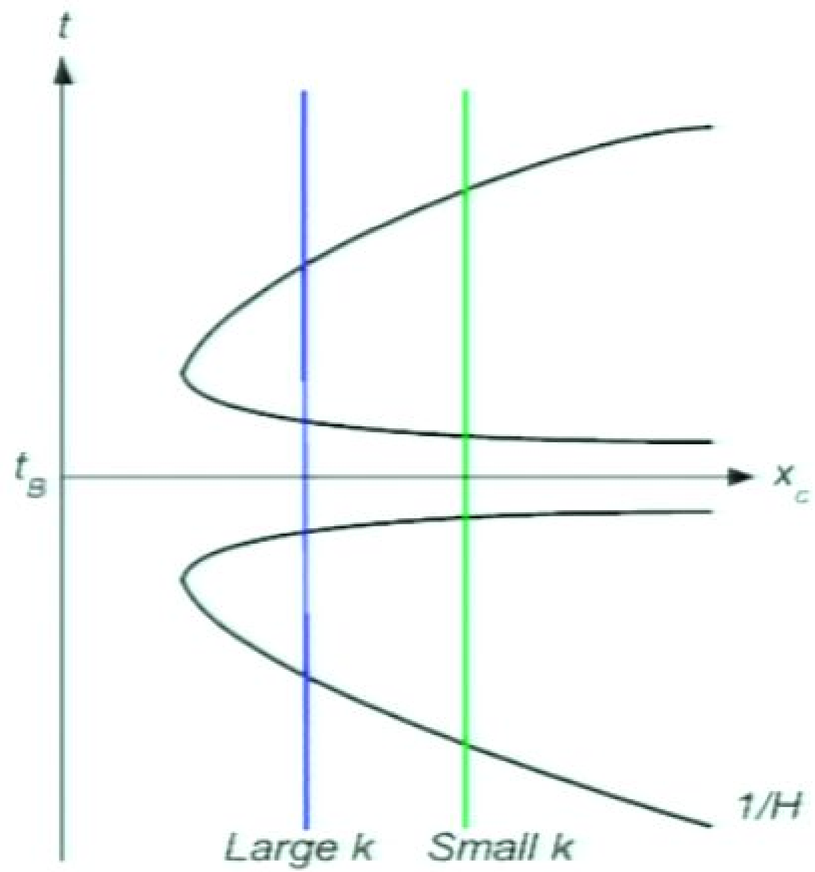

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  - a) In matter contracting phase, Ghost perturbation does NOT grow faster than matter perturbation;
  - b) The spectrum of ghost perturbation can NOT be red;
  - c) There is NO large amplification of ghost perturbation around bounce phase;
- Focus on matter dominant contracting background

$$M_{pl}^2 G_{\mu\nu} = T_{\mu\nu}^{(\phi)} + T_{\mu\nu}$$

Linear decompose Newtonian potential

$$\Phi = \Phi_m + \Phi_g$$

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$$\tilde{\Phi}_g^p(\tau) \simeq k^2\gamma\tau\left(\frac{D}{3}\tau^3 - \frac{S}{2}\tau^{-2}\right)$$

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- Since the duration of bounce phase is short

$$H = \theta \cdot (t - t_B)$$

Where $\theta \gg H_c^2$ we interested in large scale perturbation

$$\partial_t^2 \Phi_g + \theta \Phi_g = 0$$

the solution is

$$\Phi_g = d_1 e^{i\sqrt{\theta}t} + d_2 e^{-i\sqrt{\theta}t}$$

Since the bounce phase is very short

$$\Phi_g(t) \simeq \Phi_g^c$$

This result is still true near bounce point since $k^2 \ll \theta$ is still true.

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This result is still true near bounce point since $k^2 \ll \theta$ is still true.

Ghost perturbation

- Since the duration of bounce phase is short

$$H = \theta \cdot (t - t_B)$$

Where $\theta \gg H_c^2$ we interested in large scale perturbation

$$\partial_t^2 \Phi_g + \theta \Phi_g = 0$$

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$$\Phi_g = d_1 e^{i\sqrt{\theta}t} + d_2 e^{-i\sqrt{\theta}t}$$

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$$L_J \sim \frac{M_{Pl}}{M^2}. \qquad T_J \sim \frac{M_{Pl}^2}{M^3}$$

So we need a very small M to protect the IR gravity.

A constraint condition has been given in hep-ph/0507120, where

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Our ghost bounce model is free from cut-off upper bound

$$\alpha = 4, \qquad \rho_g \sim a^{-6}$$

Meszaros effect

↓

Radiation epoch δ_g ⟶ Logarithmic growing

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  - Stablize vacuum
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Preserve scale invariant spectrum:

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$$\Downarrow$$

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  3. We have a high energy scale bounce>>100Gev

  Preserve scale invariant spectrum:

  1. Grows slower than matter perturbation;
  2. Blue spectrum;
  3. No large amplification during bounce phase;
  4. The gradient instability during bounce phase has no enough time to develop.

Conclusion & Discussion

- Ghost condensation theory
  - Stablize vacuum
  - Interesting feature
  - Jeans instability → low energy scale 100Gev
- We realize matter bounce by means of ghost condensation

Advantages:

1. No ghost;
2. Background is stable against radiation and anisotropic stress;
3. We have a high energy scale bounce>>100Gev

Preserve scale invariant spectrum:

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Stability during bounce

the dispersion relation

$$\omega^2 = \frac{-(\tilde{M}^2 M^4 + 4M_{pl}^4 \dot{H})k^2 + 2M_{pl}^2 \tilde{M}^2 k^4}{2M_{pl}^2 M^4}$$

the typical instability rate

$$\omega_c = \frac{1}{4}\frac{\tilde{M} M^2}{M_{pl}^2} + \dot{H}\frac{M_{pl}^2}{M^2 \tilde{M}}$$

Its growing rate during bounce phase

$$\Delta t \omega_c \sim \left(\frac{V_0}{M^4}\right)^{1/\alpha}\left[\frac{1}{4}\frac{\tilde{M} M}{M_{pl}^2} + \dot{H}\frac{M_{pl}^2}{M^3 \tilde{M}}\right]$$

Since $\dot{H} \sim \frac{M^4 \dot{\pi}}{M_{pl}^2}$ if $V_0 \ll M^4$ We get

$$\Delta t \omega_c \ll 1$$

Ghost perturbation

- Since the duration of bounce phase is short

$$H = \theta \cdot (t - t_B)$$

Where $\theta \gg H_c^2$ we interested in large scale perturbation

$$\partial_t^2 \Phi_g + \theta \Phi_g = 0$$

the solution is

$$\Phi_g = d_1 e^{i\sqrt{\theta} t} + d_2 e^{-i\sqrt{\theta} t}$$

Since the bounce phase is very short

$$\Phi_g(t) \simeq \Phi_g^c$$

This result is still true near bounce point since $k^2 \ll \theta$ is still true.

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Since the bounce phase is very short

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This result is still true near bounce point since $k^2 \ll \theta$ is still true.

Ghost perturbation

- Since the duration of bounce phase is short

$$H = \theta \cdot (t - t_B)$$

Where $\theta \gg H_c^2$ we interested in large scale perturbation

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Since the bounce phase is very short

$$\Phi_g(t) \simeq \Phi_g^c$$

This result is still true near bounce point since $k^2 \ll \theta$ is still true.

Ghost perturbation

- Since the duration of bounce phase is short

$$H = \theta \cdot (t - t_B)$$

Where $\theta \gg H_c^2$ we interested in large scale perturbation

$$\partial_t^2 \Phi_g + \theta \Phi_g = 0$$

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Interesting Features

~~Equivalence principle~~

- "Particle physics" energy density

$$\mathcal{E}_{\rm pp} = \int d^3x\, T_{00} - c_* Q \sim \frac{1}{2}\dot{\pi}^2 + \frac{(\nabla^2\pi)^2}{2M^2} + \cdots$$

Inertial Mass!

- Gravitational energy density

$$\mathcal{E}_{\rm grav} = T_{00} \sim M^2\dot{\pi} + \cdots$$

Gravitational Mass!

Interesting features

More generally,

$$\mathcal{L} = M^4 P(X) + M^2 S_1(X)(\Box\phi)^2 + M^2 S_2(X)\partial^\mu\partial^\nu\phi\partial_\mu\partial_\nu\phi + \cdots .$$

Ghost field locate at the minima, with scalar excitation

$$\phi = ct + \pi$$

Low energy effective action for π is

$$S \sim \int d^4x \left[\frac{1}{2}\dot{\pi}^2 - \frac{1}{2M^2}(\nabla^2\pi)^2 + \cdots\right].$$

The dispersion relation $\omega^2 \sim \dfrac{k^4}{M^2}$.

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