Title: New Ekpyrotic Cosmology

Date: Mar 06, 2008 02:00 PM

URL: http://pirsa.org/08030038

Abstract:

NEW EKPYROTIC COSMOLOGY

Evgeny Buchbinder, Justin Khoury, Burt Ovrut

❋ Creminelli, Senatore
❋ Lehners, McFadden, Turok, Steinhardt

- Pre-Big Bang - Gasperini, Veneziano
- Ekpyrotic Cosmology - Khoury, Ovrut, Steinhardt, Turok
- Big Crunch/Big-Bang - K,O,S,T+Seiberg
- Cyclic Models - Steinhardt, Turok

Ekpyrotic Phase

eal scalar field - ϕ

agrangian density -

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

here the KE is canonical, Text

$$V(\phi) < 0$$

nd

$$\epsilon \equiv M_P^{-2}\left(\frac{V}{V_{,\phi}}\right)^2, \quad \eta \equiv 1 - \frac{V_{,\phi\phi}V}{V_{,\phi}^2}$$

tisfy the "fast-roll" conditions

$$\epsilon << 1, \quad |\eta| << 1$$

V(ϕ) is steep and nearly exponential

ssume spatially flat, FRW spacetime

$$ds^2 = -dt^2 + a(t)^2 \vec{dx}^2$$

Friedmann equation

$$3H^2 M_P^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

calar equation

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}$$

olving gives the exact scaling solution

$$a(t) \sim (-t)^p, \quad H = \frac{p}{t}$$

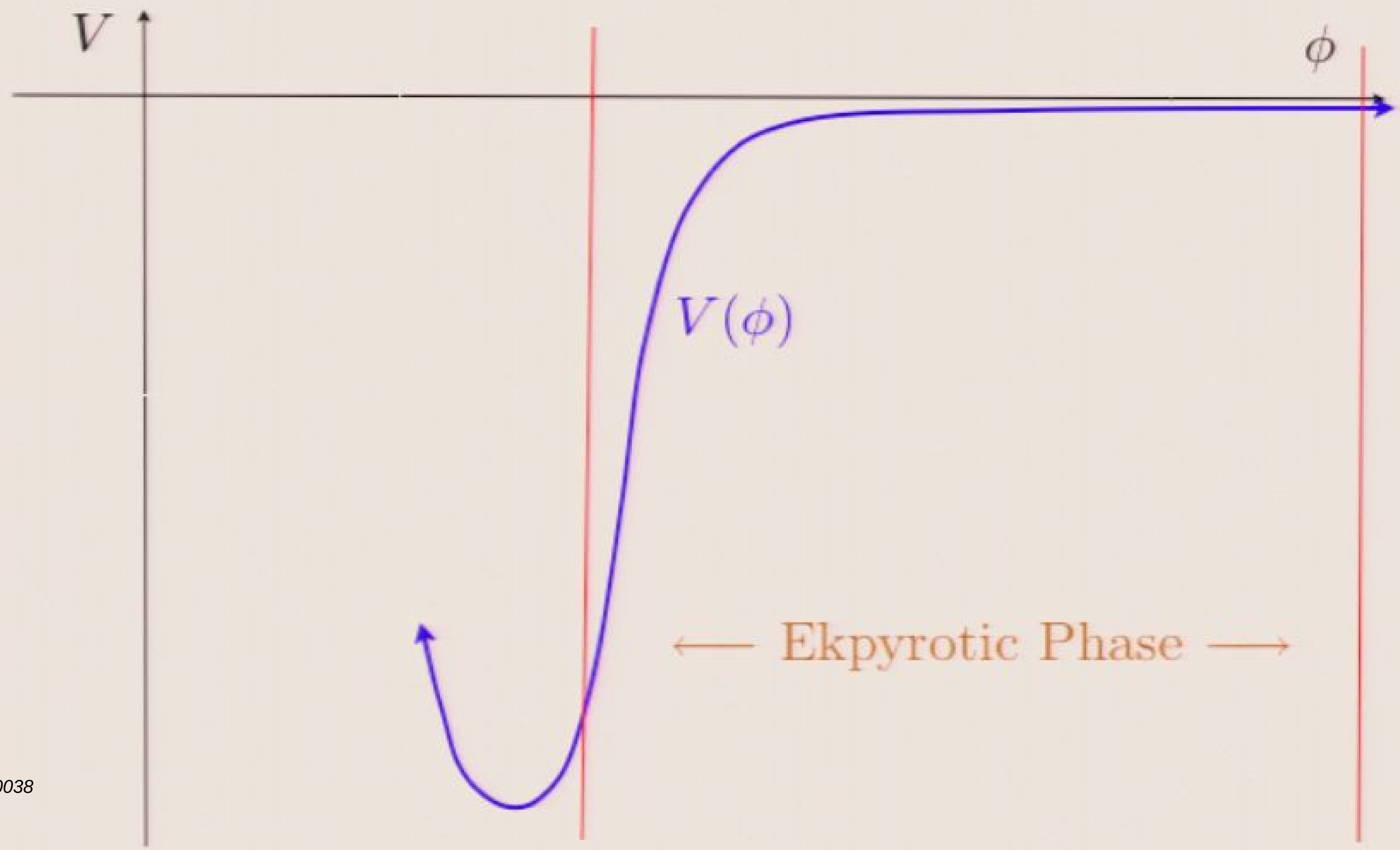
$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_p^2 p(1-3p)}} t \right)$$

or example,

$$V(\phi) = -V_0 e^{-\sqrt{\frac{2}{p}}\frac{\phi}{M_P}}, \quad p << 1$$

⇒

$$\epsilon = \frac{p}{2} << 1, \quad \eta = 0$$



ssume spatially flat, FRW spacetime

$$ds^2 = -dt^2 + a(t)^2 \vec{dx}^2$$

› Friedmann equation

$$3H^2 M_P^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

:alar equation

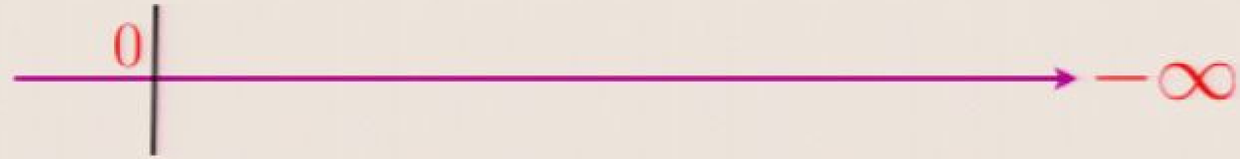
$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}$$

olving gives the exact scaling solution

$$a(t) \sim (-t)^p, \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_p^2 p(1-3p)}} t \right)$$

here



operties:

$$a(t) \sim (-t)^p \xrightarrow{t \to 0} 0$$

slowly contracting spacetime

~ constant

$$p << 1 \Longrightarrow \text{slowly}$$

$$R_H \equiv |H^{-1}| = \frac{-t}{p} \xrightarrow{t \to 0} 0$$

decreasing Hubble radius

⇒ "dual" to inflation!

equation of state

$$\omega \equiv \frac{\mathcal{P}}{\rho} = \frac{2}{3p} - 1 >> 1$$

$\rho_\phi \sim a^{-2/p}$ "blueshifts" faster than curvature $(\sim a^{-2})$,

atter $(\sim a^{-3})$, radiation $(\sim a^{-4})$, anisotropy $(\sim a^{-6})$

⇒ scalar energy rapidly dominates

Density Perturbations

onsider the gauge invariant variable

$$u \equiv \frac{a\Phi}{\phi'}$$

is the Newtonian potential and $' \equiv \frac{d}{d\tau}$ with conformal time. Fourier modes satisfy

$$u_k'' + \left(k^2 - \frac{p}{(1-p)^2\tau^2}\right)u_k = 0$$

ne solution is

$$u_k = \frac{\sqrt{p}}{(2k)^{3/2}M_P}\sqrt{\frac{\pi}{2}}\sqrt{-k\tau}H_\nu^{(1)}(-k\tau)$$

here $H_\nu^{(1)}$ is a Hankel function with

$$\nu = \frac{(1+p)}{2(1-p)}$$

n large scales

$$k^3 u k^2 \sim k^{-2p/(1-p)}$$

nce p<<1, the spectrum is nearly scale invariant with

$$n_s - 1 \approx -2p \quad (= -4\epsilon)$$

slight red tilt. For more general $V(\phi)$

$$n_s - 1 = -4(\epsilon + \eta)$$

characterizes deviations from the pure exponential and
ın be positive or negative. ⇒ spectrum can have a small
lue tilt if η is negative

Problem!!

ıe relevant variable to track through thre bounce is the
ırvature perturbation

$$\zeta \propto \left(\frac{\Phi}{a'/a^3}\right)'$$

or the scaling solution

$$\Phi_k \longrightarrow \frac{a'}{a^3} \frac{1}{k^{3/2}}$$

or large modes ⇒

$$\zeta_k \longrightarrow \quad 0 \quad \frac{1}{k^{3/2}} + \ldots$$

› a strong blue tilt!

Solution!!

art A:

onsider two (or more) real scalar fields- ϕ_1, ϕ_2

agrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}(\partial_\mu \phi_1)^2 - \frac{1}{2}(\partial_\mu \phi_2)^2 - V(\phi_1 \phi_2)$$

or the scaling solution

$$\Phi_k \longrightarrow \frac{a'}{a^3}\frac{1}{k^{3/2}}$$

or large modes ⇒

$$\zeta_k \longrightarrow \quad 0 \quad \frac{1}{k^{3/2}} + \ldots$$

› a strong blue tilt!

Solution!!

art A:

onsider two (or more) real scalar fields- ϕ_1, ϕ_2

agrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}(\partial_\mu \phi_1)^2 - \frac{1}{2}(\partial_\mu \phi_2)^2 - V(\phi_1 \phi_2)$$

or the scaling solution

$$\Phi_k \longrightarrow \frac{a'}{a^3}\frac{1}{k^{3/2}}$$

or large modes ⇒

$$\zeta_k \longrightarrow \quad 0 \quad \frac{1}{k^{3/2}} + \ldots$$

› a strong blue tilt!

Solution!!

art A:

onsider two (or more) real scalar fields- ϕ_1, ϕ_2

agrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}(\partial_\mu\phi_1)^2 - \frac{1}{2}(\partial_\mu\phi_2)^2 - V(\phi_1\phi_2)$$

or example

$$V(\phi_1,\phi_2) = -V_1 e^{-\sqrt{\frac{2}{p_1}}\frac{\phi_1}{M_P}} - V_2 e^{-\sqrt{\frac{2}{p_2}}\frac{\phi_2}{M_P}}$$

ith $p_1 << 1, p_2 << 1.$ Defining new variables

$$\phi = \frac{\sqrt{p_1}\phi_1 + \sqrt{p_2}\phi_2}{\sqrt{p_1+p_2}}, \quad \chi = \frac{\sqrt{p_2}\phi_1 - \sqrt{p_1}\phi_2}{\sqrt{p_1+p_2}}$$

→

$$V(\phi,\chi) = -V_0 e^{-\sqrt{\frac{2}{p}}\frac{\phi}{M_P}} \left(1 + \frac{1}{pM_P^2}(\chi-\chi_t)^2 + ...\right)$$

Koyama, Wands

here $p \equiv p_1 + p_2 \quad (<< 1),$

$$\chi_t \equiv \sqrt{\frac{p_1 p_2}{2p}} ln\left(\frac{p_2 V_1}{p_1 V_2}\right)$$

d

$$V_0 \equiv \left(1 + \frac{p_2}{p_1}\right) V_1 e^{\sqrt{\frac{p_2}{p_1 p}}\frac{\chi_t}{M_P}}$$

or example

$$V(\phi_1,\phi_2) = -V_1 e^{-\sqrt{\frac{2}{p_1}}\frac{\phi_1}{M_P}} - V_2 e^{-\sqrt{\frac{2}{p_2}}\frac{\phi_2}{M_P}}$$

ith $p_1 << 1, p_2 << 1.$ Defining new variables

$$\phi = \frac{\sqrt{p_1}\phi_1 + \sqrt{p_2}\phi_2}{\sqrt{p_1+p_2}}, \quad \chi = \frac{\sqrt{p_2}\phi_1 - \sqrt{p_1}\phi_2}{\sqrt{p_1+p_2}}$$

→

$$V(\phi,\chi) = -V_0 e^{-\sqrt{\frac{2}{p}}\frac{\phi}{M_P}}\left(1 + \frac{1}{pM_P^2}(\chi-\chi_t)^2 + ...\right)$$

Koyama, Wands

here $p \equiv p_1 + p_2 \quad (<< 1),$

$$\chi_t \equiv \sqrt{\frac{p_1 p_2}{2p}} ln\left(\frac{p_2 V_1}{p_1 V_2}\right)$$

nd

$$V_0 \equiv \left(1+\frac{p_2}{p_1}\right) V_1 e^{\sqrt{\frac{p_2}{p_1 p}}\frac{\chi_t}{M_P}}$$

or example

$$V(\phi_1,\phi_2) = -V_1 e^{-\sqrt{\frac{2}{p_1}}\frac{\phi_1}{M_P}} - V_2 e^{-\sqrt{\frac{2}{p_2}}\frac{\phi_2}{M_P}}$$

ith $p_1 << 1, p_2 << 1.$ Defining new variables

$$\phi = \frac{\sqrt{p_1}\phi_1 + \sqrt{p_2}\phi_2}{\sqrt{p_1+p_2}}, \quad \chi = \frac{\sqrt{p_2}\phi_1 - \sqrt{p_1}\phi_2}{\sqrt{p_1+p_2}}$$

>

$$V(\phi,\chi) = -V_0 e^{-\sqrt{\frac{2}{p}}\frac{\phi}{M_P}}\left(1 + \frac{1}{pM_P^2}(\chi-\chi_t)^2 + ...\right)$$

Koyama, Wands

here $p \equiv p_1 + p_2 \quad (<< 1),$

$$\chi_t \equiv \sqrt{\frac{p_1 p_2}{2p}} ln\left(\frac{p_2 V_1}{p_1 V_2}\right)$$

nd

$$V_0 \equiv \left(1 + \frac{p_2}{p_1}\right) V_1 e^{\sqrt{\frac{p_2}{p_1 p}}\frac{\chi_t}{M_P}}$$

or example

$$V(\phi_1,\phi_2) = -V_1 e^{-\sqrt{\frac{2}{p_1}}\frac{\phi_1}{M_P}} - V_2 e^{-\sqrt{\frac{2}{p_2}}\frac{\phi_2}{M_P}}$$

ith $p_1 << 1, p_2 << 1.$ Defining new variables

$$\phi = \frac{\sqrt{p_1}\phi_1 + \sqrt{p_2}\phi_2}{\sqrt{p_1+p_2}}, \quad \chi = \frac{\sqrt{p_2}\phi_1 - \sqrt{p_1}\phi_2}{\sqrt{p_1+p_2}}$$

>

$$V(\phi,\chi) = -V_0 e^{-\sqrt{\frac{2}{p}}\frac{\phi}{M_P}} \left(1 + \frac{1}{pM_P^2}(\chi-\chi_t)^2 + ...\right)$$

Koyama, Wands

here $p \equiv p_1 + p_2 \quad (<< 1),$

$$\chi_t \equiv \sqrt{\frac{p_1 p_2}{2p}} ln\left(\frac{p_2 V_1}{p_1 V_2}\right)$$

nd

$$V_0 \equiv \left(1 + \frac{p_2}{p_1}\right) V_1 e^{\sqrt{\frac{p_2}{p_1 p}}\frac{\chi_t}{M_P}}$$

or example

$$V(\phi_1,\phi_2) = -V_1 e^{-\sqrt{\frac{2}{p_1}}\frac{\phi_1}{M_P}} - V_2 e^{-\sqrt{\frac{2}{p_2}}\frac{\phi_2}{M_P}}$$

ith $p_1 << 1, p_2 << 1.$ Defining new variables

$$\phi = \frac{\sqrt{p_1}\phi_1 + \sqrt{p_2}\phi_2}{\sqrt{p_1+p_2}}, \quad \chi = \frac{\sqrt{p_2}\phi_1 - \sqrt{p_1}\phi_2}{\sqrt{p_1+p_2}}$$

>

$$V(\phi,\chi) = -V_0 e^{-\sqrt{\frac{2}{p}}\frac{\phi}{M_P}}\left(1 + \frac{1}{pM_P^2}(\chi-\chi_t)^2 + ...\right)$$

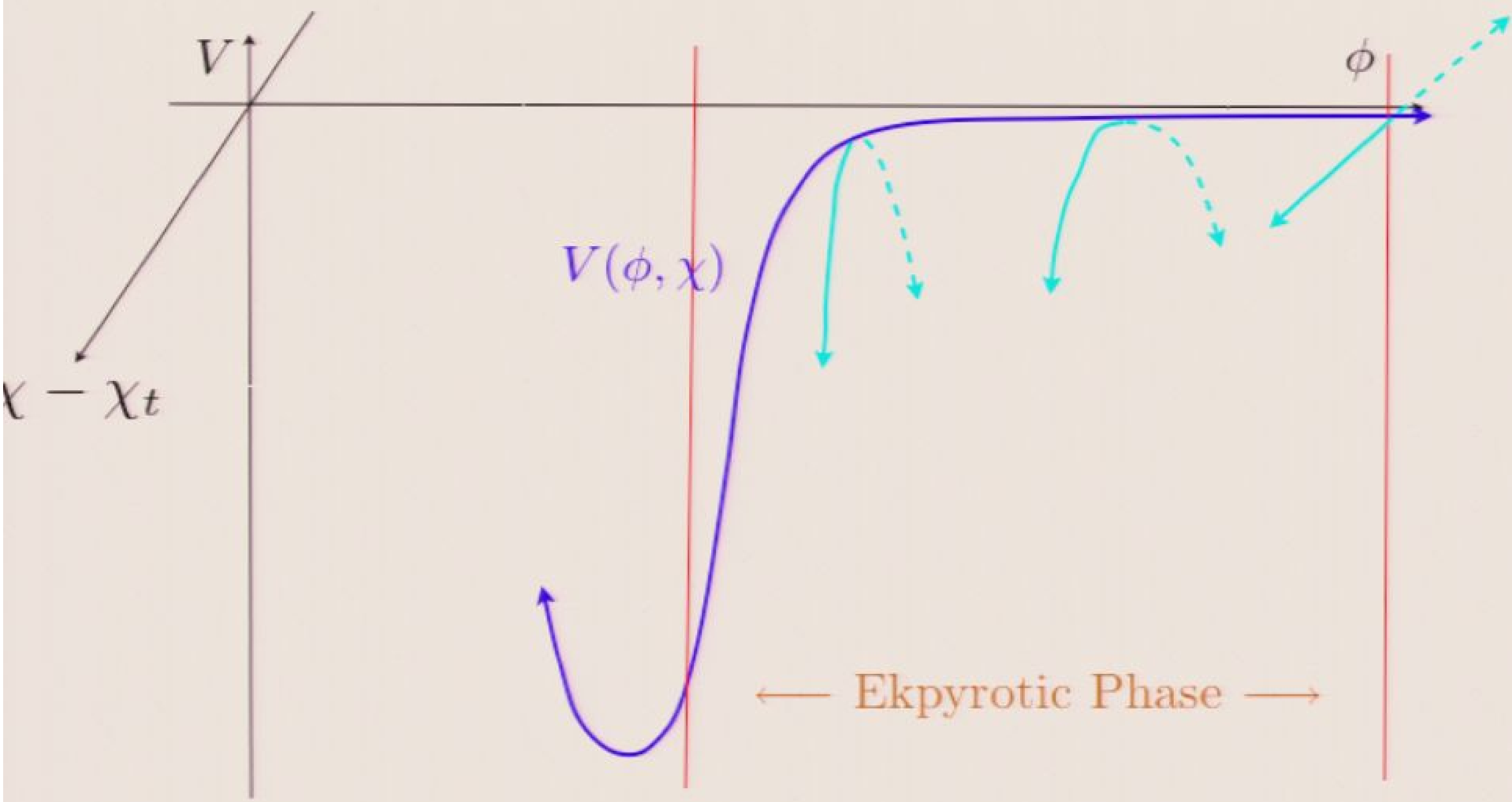
Koyama, Wands

here $p \equiv p_1 + p_2 \quad (<< 1),$

$$\chi_t \equiv \sqrt{\frac{p_1 p_2}{2p}} ln\left(\frac{p_2 V_1}{p_1 V_2}\right)$$

nd

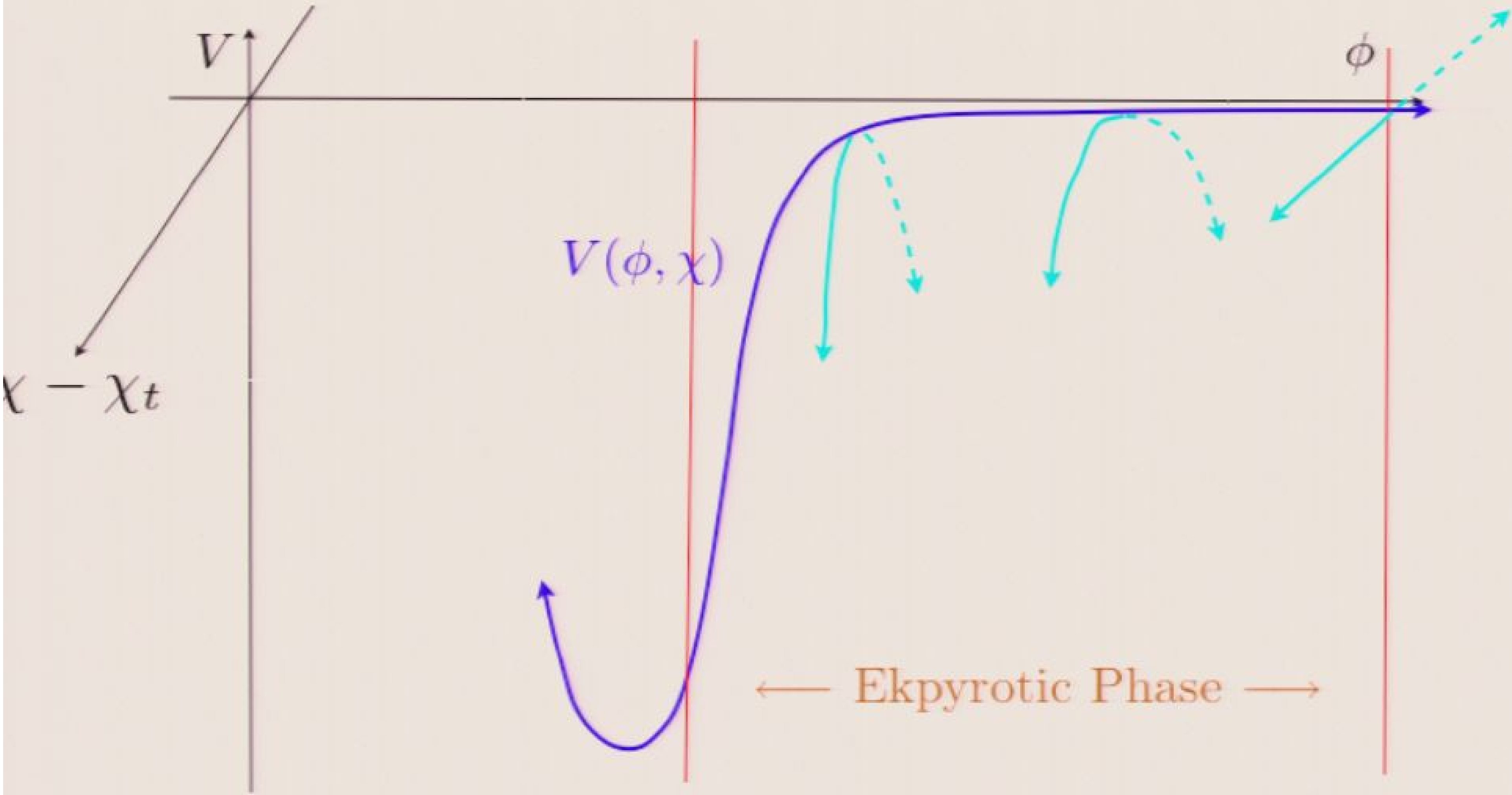
$$V_0 \equiv \left(1 + \frac{p_2}{p_1}\right) V_1 e^{\sqrt{\frac{p_2}{p_1 p}}\frac{\chi_t}{M_P}}$$



calar equations

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}\,, \quad \ddot{\chi} + 3H\dot{\chi} = -V_{,\chi}$$

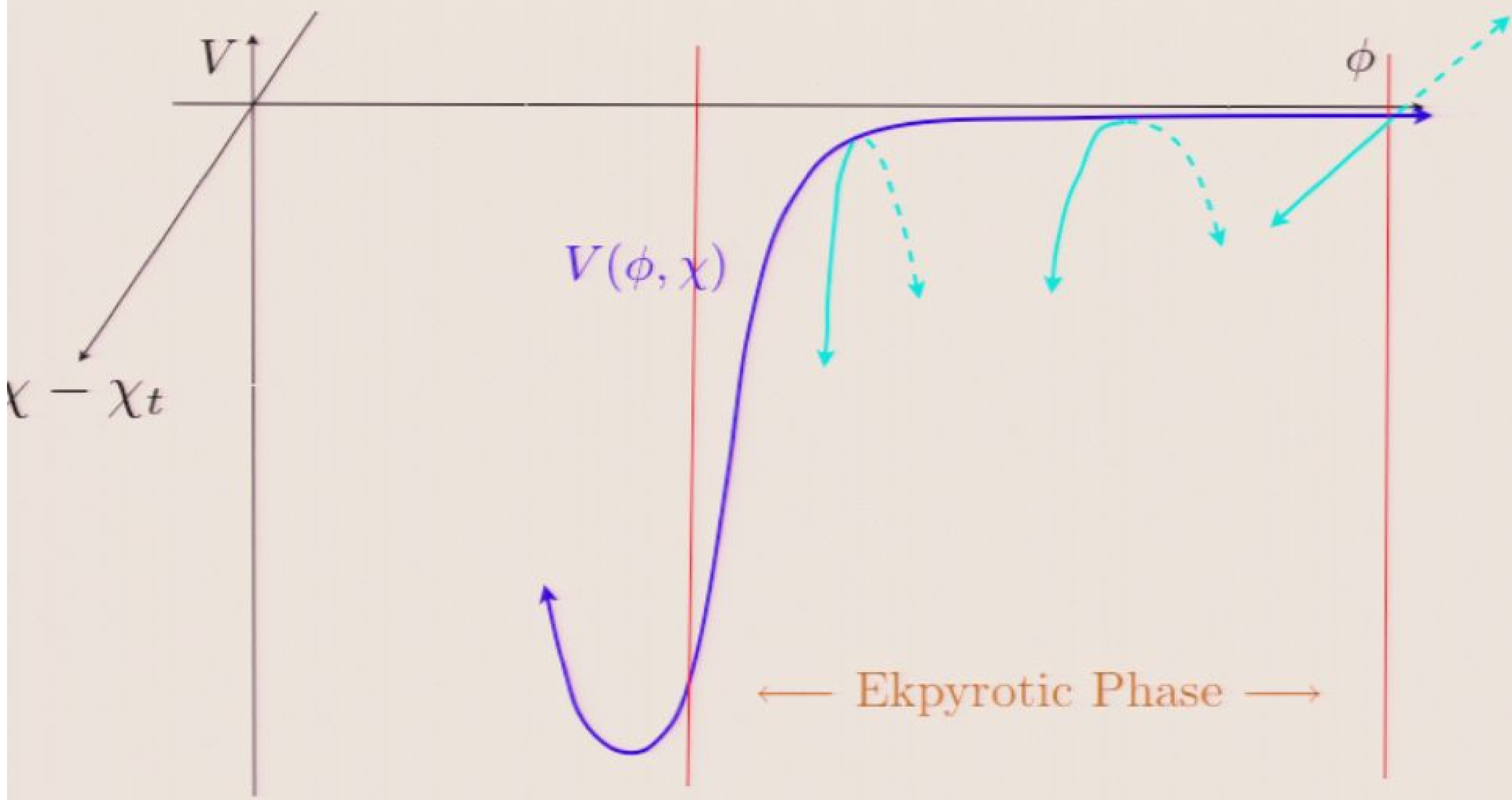
olving gives scaling solution



calar equations

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}\ , \quad \ddot{\chi} + 3H\dot{\chi} = -V_{,\chi}$$

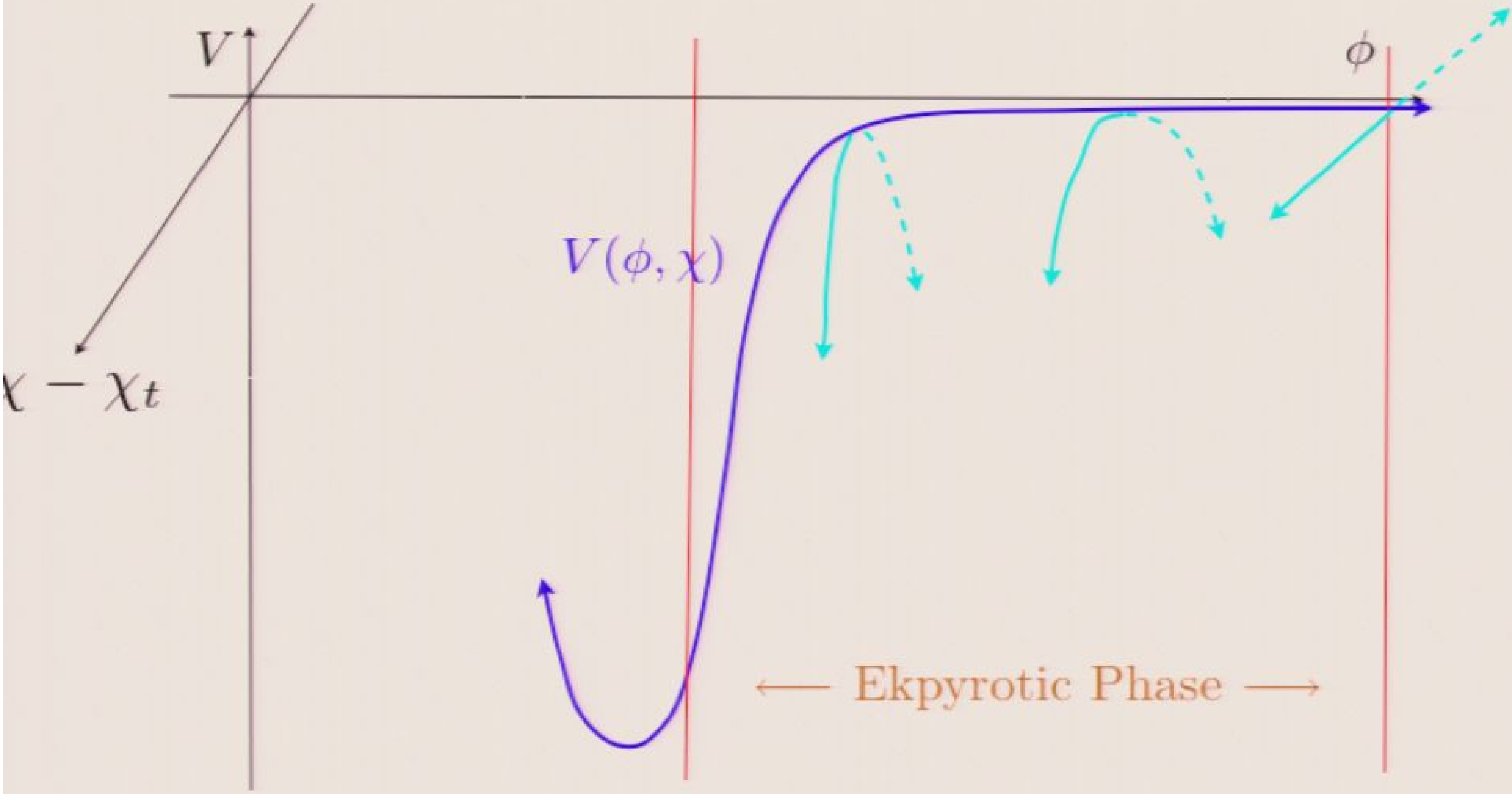
olving gives scaling solution



calar equations

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}\ , \quad \ddot{\chi} + 3H\dot{\chi} = -V_{,\chi}$$

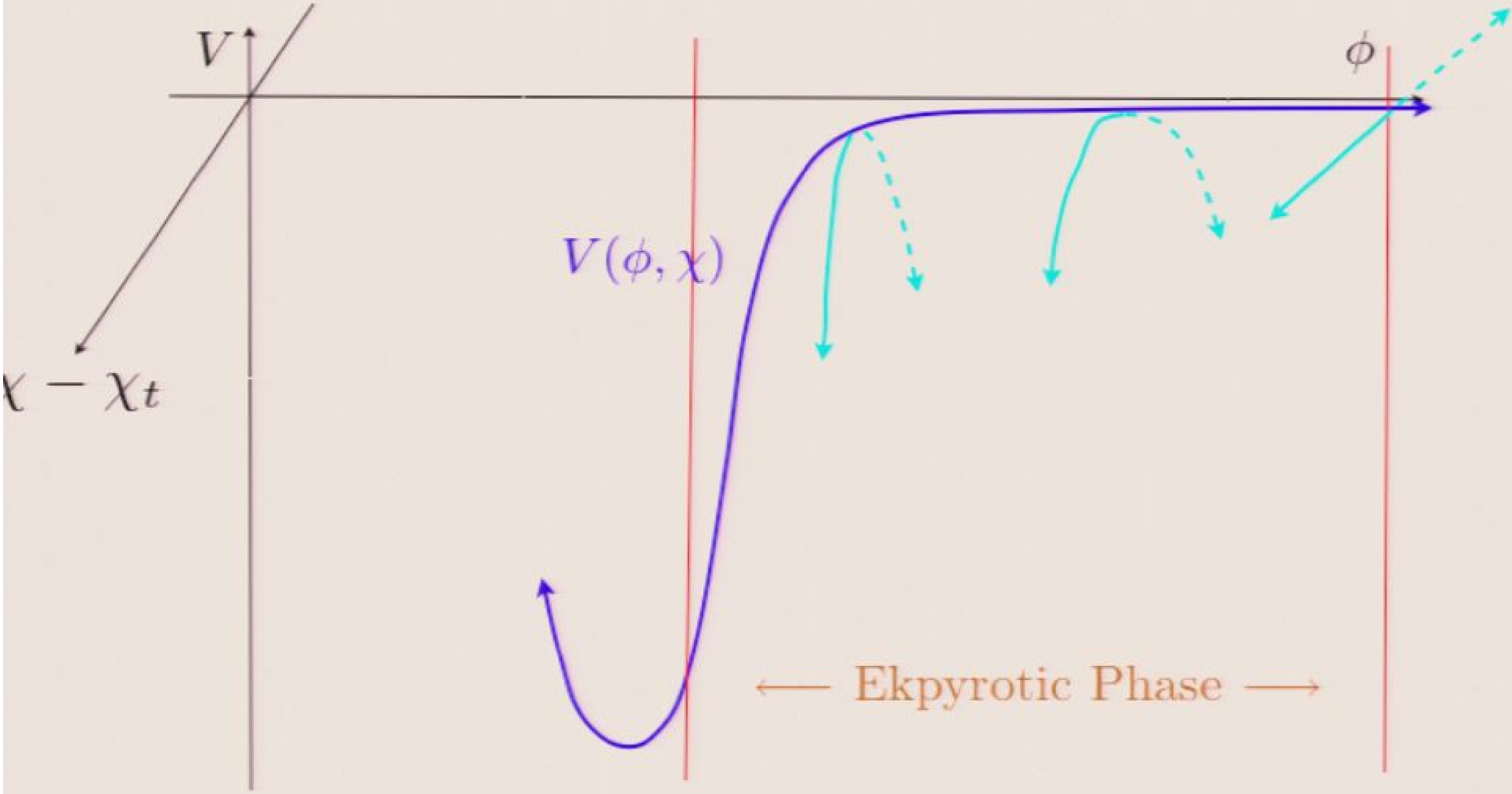
olving gives scaling solution



calar equations

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}\,, \quad \ddot{\chi} + 3H\dot{\chi} = -V_{,\chi}$$

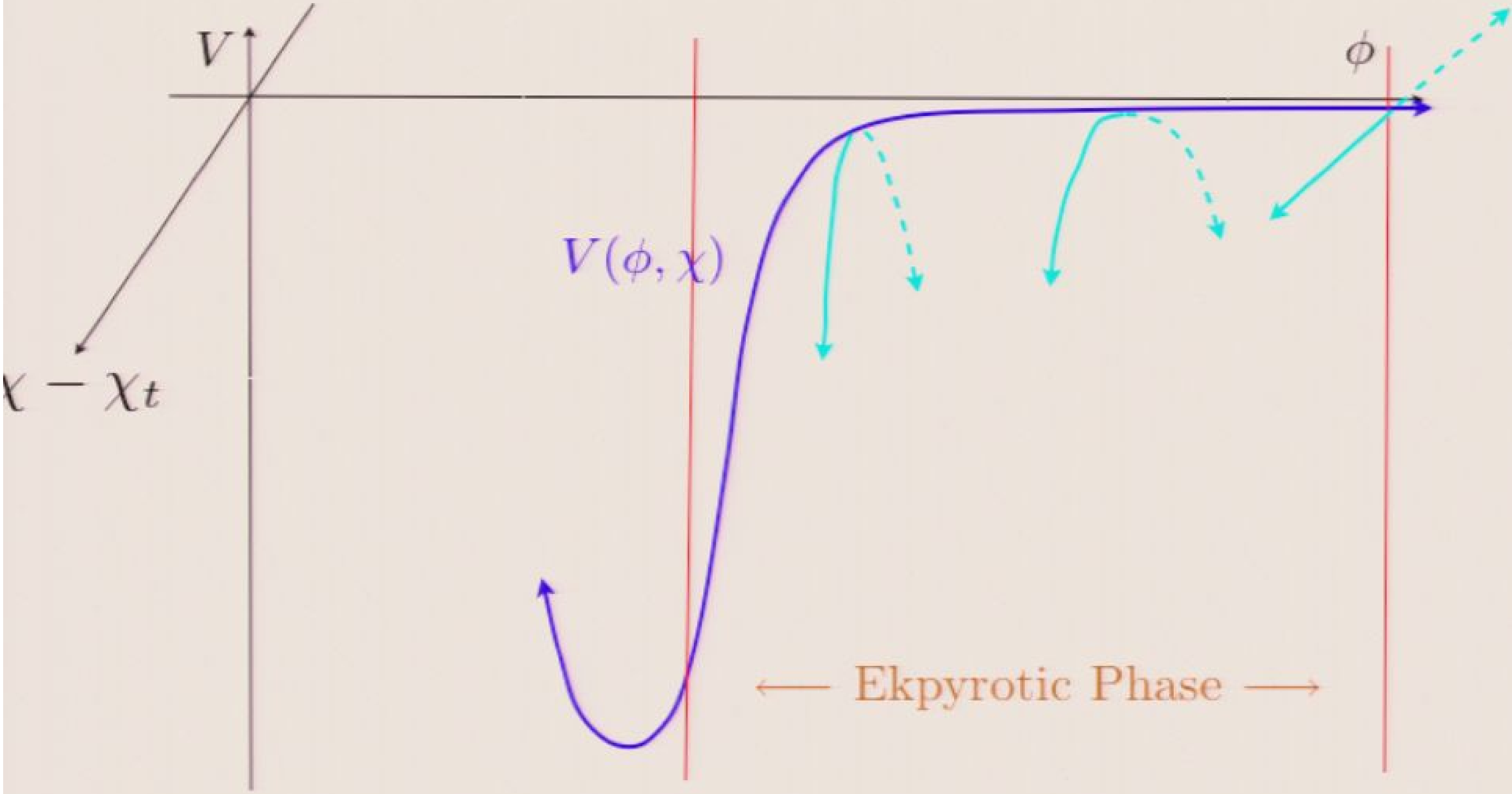
olving gives scaling solution



calar equations

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}\ , \quad \ddot{\chi} + 3H\dot{\chi} = -V_{,\chi}$$

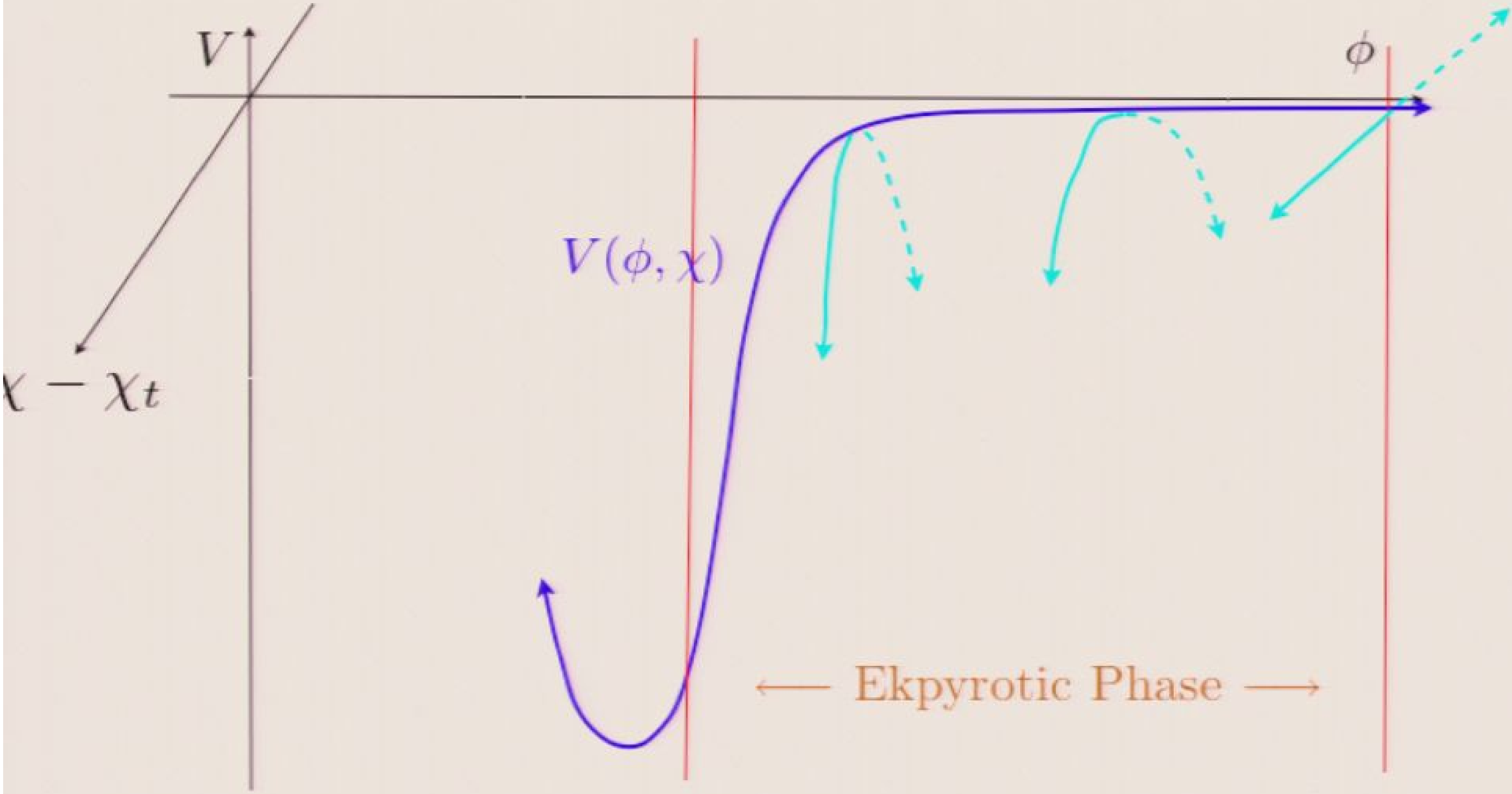
olving gives scaling solution



calar equations

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}\ , \quad \ddot{\chi} + 3H\dot{\chi} = -V_{,\chi}$$

olving gives scaling solution



calar equations

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}\ , \quad \ddot{\chi} + 3H\dot{\chi} = -V_{,\chi}$$

olving gives scaling solution

$$a(t) \sim (-t)^p \ , \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t \right)$$

$$\chi = \chi_t$$

roperties:

- Slowly contracting spacetime
- decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t} , \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

$$a(t) \sim (-t)^p \,, \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t \right)$$

$$\chi = \chi_t$$

roperties:

- Slowly contracting spacetime
- decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t}, \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

$$a(t) \sim (-t)^p \;, \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t \right)$$

$$\chi = \chi_t$$

roperties:

- Slowly contracting spacetime

- decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t} , \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

$$a(t) \sim (-t)^p \ , \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t \right)$$

$$\chi = \chi_t$$

roperties:

Slowly contracting spacetime

decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t} , \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

$$a(t) \sim (-t)^p \,, \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t \right)$$

$$\chi = \chi_t$$

roperties:

- Slowly contracting spacetime
- decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t} , \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

$$a(t) \sim (-t)^p \,, \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t \right)$$

$$\chi = \chi_t$$

roperties:

- Slowly contracting spacetime

- decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t} , \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

$$a(t) \sim (-t)^p\ , \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t \right)$$

$$\chi = \chi_t$$

roperties:

- Slowly contracting spacetime
- decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t}, \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

$$a(t) \sim (-t)^p \,, \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln\left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t\right)$$

$$\chi = \chi_t$$

roperties:

Slowly contracting spacetime

decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t} , \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

Density Perturbations

Consider the entropy fluctuation - $\delta\chi$

ourier modes satisfy

$$\delta\ddot{\chi}_k + 3H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\chi_k = 0$$

Using property 4. $\Rightarrow$

$$k^3\delta\chi_k \sim k^{2p}$$

pectrum is nearly scale invariant with

$$n_s - 1 = 2p \; (= 4\epsilon)$$

$\Rightarrow$ slight blue tilt

Density Perturbations

Consider the entropy fluctuation - $\delta\chi$

Fourier modes satisfy

$$\delta\ddot{\chi}_k + 3H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\chi_k = 0$$

Using property 4. $\Rightarrow$

$$k^3\delta\chi_k \sim k^{2p}$$

Spectrum is nearly scale invariant with

$$n_s - 1 = 2p \ (= 4\epsilon)$$

$\Rightarrow$ slight blue tilt

$$a(t) \sim (-t)^p \ , \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t \right)$$

$$\chi = \chi_t$$

roperties:

- Slowly contracting spacetime

- decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t}, \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

$$a(t) \sim (-t)^p \,, \quad H = \frac{p}{t}$$

$$\phi(t) = \sqrt{2p} M_P ln \left(-\sqrt{\frac{V_0}{M_P^2 p(1-3p)}} t \right)$$

$$\chi = \chi_t$$

roperties:

- Slowly contracting spacetime

- decreasing Hubble radius

$$\omega = \frac{2}{3p} - 1 \quad >> 1$$

$$V_{,\phi\phi}|_{\chi=\chi_t} = V_{,\chi\chi}|_{\chi=\chi_t}, \quad V_{,\phi\phi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

$$m^2_{tachyon} \equiv -V_{,\phi\phi}|_{\chi=\chi_t} \approx \frac{2H^2}{p^2}$$

Density Perturbations

Consider the entropy fluctuation - $\delta\chi$

Fourier modes satisfy

$$\delta\ddot{\chi}_k + 3H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\chi_k = 0$$

Using property 4. $\Rightarrow$

$$k^3\delta\chi_k \sim k^{2p}$$

Spectrum is nearly scale invariant with

$$n_s - 1 = 2p \; (= 4\epsilon)$$

$\Rightarrow$ slight blue tilt

Density Perturbations

Consider the entropy fluctuation - $\delta\chi$

Fourier modes satisfy

$$\delta\ddot{\chi}_k + 3H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\chi_k = 0$$

Using property 4. $\Rightarrow$

$$k^3\delta\chi_k \sim k^{2p}$$

Spectrum is nearly scale invariant with

$$n_s - 1 = 2p \ (= 4\epsilon)$$

$\Rightarrow$ slight blue tilt

Density Perturbations

Consider the entropy fluctuation - $\delta\chi$

Fourier modes satisfy

$$\delta\ddot{\chi}_k + 3H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\chi_k = 0$$

Using property 4. $\Rightarrow$

$$k^3\delta\chi_k \sim k^{2p}$$

Spectrum is nearly scale invariant with

$$n_s - 1 = 2p \; (= 4\epsilon)$$

$\Rightarrow$ slight blue tilt

Density Perturbations

Consider the entropy fluctuation - $\delta\chi$

ourier modes satisfy

$$\delta\ddot{\chi}_k + 3H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\chi_k = 0$$

sing property 4. $\Rightarrow$

$$k^3\delta\chi_k \sim k^{2p}$$

pectrum is nearly scale invariant with

$$n_s - 1 = 2p \; (= 4\epsilon)$$

$\Rightarrow$ slight blue tilt

Density Perturbations

Consider the entropy fluctuation - $\delta\chi$

Fourier modes satisfy

$$\delta\ddot{\chi}_k + 3H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\chi_k = 0$$

Using property 4. $\Rightarrow$

$$k^3\delta\chi_k \sim k^{2p}$$

Spectrum is nearly scale invariant with

$$n_s - 1 = 2p \ (= 4\epsilon)$$

$\Rightarrow$ slight blue tilt

Density Perturbations

Consider the entropy fluctuation - $\delta\chi$

Fourier modes satisfy

$$\delta\ddot{\chi}_k + 3H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\chi_k = 0$$

Using property 4. $\Rightarrow$

$$k^3\delta\chi_k \sim k^{2p}$$

Spectrum is nearly scale invariant with

$$n_s - 1 = 2p \; (= 4\epsilon)$$

$\Rightarrow$ slight blue tilt

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1 + \frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}} f(\phi)(\chi-\chi_t)^2 + F(\phi,\chi-\chi_t)\right)$$

or any

$$\chi_t = constant, f(\phi) \approx 1$$

inction $F(\phi,\chi-\chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv {M_P}^{-2}\left(\frac{\mathcal{V}}{{}_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1 - \frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_\phi^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

hoosing

$$f(\phi) \equiv 1 + 3\delta, |\delta| \ll 1$$

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1 + \frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}} f(\phi)(\chi-\chi_t)^2 + F(\phi,\chi-\chi_t)\right)$$

ɔr any

$$\chi_t = constant, f(\phi) \approx 1$$

ınction $F(\phi,\chi-\chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv {M_P}^{-2}\left(\frac{\mathcal{V}}{_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1 - \frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_\phi^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

:hoosing

$$f(\phi) \equiv 1 + 3\delta, |\delta| \ll 1$$

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1+\frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}}f(\phi)(\chi-\chi_t)^2+F(\phi,\chi-\chi_t)\right)$$

or any

$$\chi_t = constant, f(\phi) \approx 1$$

unction $F(\phi,\chi-\chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv {M_P}^{-2}\left(\frac{\mathcal{V}}{{}_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1-\frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_\phi^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

hoosing

$$f(\phi) \equiv 1+3\delta, |\delta| \ll 1$$

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1 + \frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}} f(\phi)(\chi-\chi_t)^2 + F(\phi,\chi-\chi_t)\right)$$

or any

$$\chi_t = constant, f(\phi) \approx 1$$

unction $F(\phi,\chi-\chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv M_P{}^{-2}\left(\frac{\mathcal{V}}{{}_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1 - \frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_{\phi}^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

Choosing

$$f(\phi) \equiv 1 + 3\delta, |\delta| \ll 1$$

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1 + \frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}} f(\phi)(\chi-\chi_t)^2 + F(\phi,\chi-\chi_t)\right)$$

or any

$$\chi_t = constant, f(\phi) \approx 1$$

inction $F(\phi,\chi-\chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv {M_P}^{-2}\left(\frac{\mathcal{V}}{_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1 - \frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_\phi^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

hoosing

$$f(\phi) \equiv 1 + 3\delta, |\delta| \ll 1$$

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1+\frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}}f(\phi)(\chi-\chi_t)^2 + F(\phi,\chi-\chi_t)\right)$$

or any

$$\chi_t = constant, f(\phi) \approx 1$$

unction $F(\phi,\chi-\chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv M_P{}^{-2}\left(\frac{\mathcal{V}}{{}_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1-\frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_\phi^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

hoosing

$$f(\phi) \equiv 1+3\delta, |\delta| \ll 1$$

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1 + \frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}} f(\phi)(\chi - \chi_t)^2 + F(\phi, \chi - \chi_t)\right)$$

or any

$$\chi_t = constant, f(\phi) \approx 1$$

ınction $F(\phi, \chi - \chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv {M_P}^{-2}\left(\frac{\mathcal{V}}{_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1 - \frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_\phi^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

:hoosing

$$f(\phi) \equiv 1 + 3\delta, |\delta| \ll 1$$

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1 + \frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}} f(\phi)(\chi-\chi_t)^2 + F(\phi,\chi-\chi_t)\right)$$

or any

$$\chi_t = constant, f(\phi) \approx 1$$

ınction $F(\phi,\chi-\chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv M_P{}^{-2}\left(\frac{\mathcal{V}}{_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1 - \frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_{\phi}^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

Choosing

$$f(\phi) \equiv 1 + 3\delta, |\delta| \ll 1$$

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1 + \frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}} f(\phi)(\chi-\chi_t)^2 + F(\phi,\chi-\chi_t)\right)$$

or any

$$\chi_t = constant, f(\phi) \approx 1$$

inction $F(\phi,\chi-\chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv {M_P}^{-2}\left(\frac{\mathcal{V}}{_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1 - \frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_{\phi}^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

hoosing

$$f(\phi) \equiv 1 + 3\delta, |\delta| \ll 1$$

ieneral form for the two field potential is

$$V(\phi,\chi) = \mathcal{V}\left(1 + \frac{1}{2}\frac{\mathcal{V}_{,\phi\phi}}{\mathcal{V}} f(\phi)(\chi-\chi_t)^2 + F(\phi,\chi-\chi_t)\right)$$

or any

$$\chi_t = constant, f(\phi) \approx 1$$

unction $F(\phi,\chi-\chi_t)$ such that

$$F_{,\chi\chi}|_{\chi=\chi_t} = 0$$

nd $\mathcal{V}(\phi)$ where

$$\epsilon \equiv M_P{}^{-2}\left(\frac{\mathcal{V}}{{}_{,\phi}}\right)^2 \ll 1 \qquad |\eta| \equiv |1 - \frac{\mathcal{V}_{,\phi\phi}\mathcal{V}}{\mathcal{V}_\phi^2}| \ll 1$$

lote that

$$V_{,\phi\phi}|_{\chi=\chi_t} \approx V_{,\chi\chi}|_{\chi=\chi_t} \approx -\frac{2}{t^2}$$

;hoosing

$$f(\phi) \equiv 1 + 3\delta, |\delta| \ll 1$$

he spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \longrightarrow \chi$
he entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

here

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

here

$$\Delta\theta \sim \mathcal{O}(1)$$

he spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
he entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

where

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

where

$$\Delta\theta \sim \mathcal{O}(1)$$

ne spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ne entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

where

$$\Delta\theta \sim \mathcal{O}(1)$$

ne spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ne entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ie spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ie entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ne spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ne entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ne spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ne entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

where

$$\Delta\theta \sim \mathcal{O}(1)$$

ne spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

<u>art B:</u>

or a <u>rapid turn</u> in field space from $\phi \rightarrow \chi$
ne entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

ıhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

ʼhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

ʼhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

he spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
he entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

here

$$\Delta\theta \sim \mathcal{O}(1)$$

ie spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ie entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

where

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

> can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

here

$$\Delta\theta \sim \mathcal{O}(1)$$

ie spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ie entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

here

$$\Delta\theta \sim \mathcal{O}(1)$$

he spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
he entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

where

$$\Delta\theta \sim \mathcal{O}(1)$$

ie spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ie entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

ırt B:

ɔr a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
ɛrturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

ʼhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ne spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ne entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

where

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

/here

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

ɔr a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

ʼhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

›r a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

ıhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ne spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ne entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

he spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
he entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

ʼhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ne spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ne entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

here

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

ırt B:

ɔr a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
ɛrturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

ıhere

$$\Delta\theta \sim \mathcal{O}(1)$$

he spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
he entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

here

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

ɔr a rapid turn in field space from $\phi \to \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
ɛrturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

ʼhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

ırt B:

ɔr a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
ərturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

ʼhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

ıhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ɪe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

ɔr a rapid turn in field space from $\phi \to \chi$
ɪe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

ʼhere

$$\Delta\theta \sim \mathcal{O}(1)$$

ıe spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \to \chi$
ıe entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P} \Delta\theta \, \delta\chi_k$$

here

$$\Delta\theta \sim \mathcal{O}(1)$$

ne spectral index generalizes to

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

⇒ can have red tilt if η and/or δ are positive

art B:

or a rapid turn in field space from $\phi \rightarrow \chi$
ne entropy perturbation $\delta\chi_k$ "sources" the curvature
erturbation ζ_k as

$$|\zeta_k| \approx \frac{2\epsilon}{M_P}\,\Delta\theta\,\delta\chi_k$$

vhere

$$\Delta\theta \sim \mathcal{O}(1)$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0.$ In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0.$ In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0$. In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0.$ In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0$. In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0.$ In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0.$ In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with
pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0.$ In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0.$ In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}{m^2}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0$. In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0.$ In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

⇒ inherits a nearly scale-invariant spectrum with pectral index

$$n_s - 1 = 4(\epsilon - \eta - \delta)$$

Problem Solved!!

Another Problem??

uring the Ekpyrotic phase

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \mathcal{V}(\phi)\,,\ \rho_\chi = \frac{1}{2}\dot{\chi}^2 - \frac{1}{2}m^2{}_{tachyon}\chi^2 + \mathcal{O}(\chi^3)$$

here we set $\chi_t = 0$. In the interval

$$t_{ek-end} \geq t \geq t_{ek-beg}$$

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ıust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

ıis ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

ıd, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

nis ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

⇒ exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

his $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ıust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

ıis ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

ıhere Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

ımilarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

ıd, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

his ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ıust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

ıis ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

ıd, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

his ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

his ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

his $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

his ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ıust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

ıis $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

ıhere Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

ıd, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

his ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ıust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

ıis ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

ıd, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ıust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

ıis ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

ıd, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

$\Rightarrow$ exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

his ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

his ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is ⇒

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

exponentially fine-tuned initial conditions!

Solution!

ust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

is $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

here Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

d, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

ıust have the constraint

$$|\rho_\chi| \lesssim |\rho_\phi|$$

ıis $\Rightarrow$

$$\frac{\rho_\chi^{(ek-beg)}}{\rho_\phi^{(ek-beg)}} \lesssim e^{-2N_{ek}} \quad (*)$$

ıhere Nek is the number of e-folds. For example,

$$T_{reheat} = 10^{15} GeV \Rightarrow N_{ek} \simeq 60$$

milarly,

$$\Delta\chi_{ek-end} \lesssim pM_P$$

ıd, hence

$$\Delta\chi_{ek-beg} \lesssim e^{-N_{ek}} pM_P \quad (**)$$

› exponentially fine-tuned initial conditions!

Solution!

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi)\chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

ıd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ıe transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi,\chi) = \cdots + \frac{1}{2} m_\chi^2(\phi)\chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

ıd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ıe transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi,\chi) = \cdots + \frac{1}{2} m_\chi^2(\phi)\chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi,\chi) = \cdots + \frac{1}{2} m_\chi^2(\phi)\chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$m_{eff}^2(\phi) > 0 \Rightarrow$ pre-Ekpyrotic phase

nd for small ϕ

$m_{eff}^2(\phi) < 0 \Rightarrow$ Ekpyrotic phase

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow \text{ pre-Ekpyrotic phase}$$

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow \text{ Ekpyrotic phase}$$

he transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi,\chi) = \cdots + \frac{1}{2} m_\chi^2(\phi)\chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

ıd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ıe transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi)\chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

Add to the potential energy

$$V(\phi,\chi) = \cdots + \frac{1}{2}m_\chi^2(\phi)\chi^2$$

the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow \text{ pre-Ekpyrotic phase}$$

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow \text{ Ekpyrotic phase}$$

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi)\chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ie transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi)\chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

ıd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ıe transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow \text{ pre-Ekpyrotic phase}$$

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow \text{ Ekpyrotic phase}$$

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

Add to the potential energy

$$V(\phi,\chi) = \cdots + \frac{1}{2}m_\chi^2(\phi)\chi^2$$

the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

ıd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ıe transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow \text{ pre-Ekpyrotic phase}$$

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow \text{ Ekpyrotic phase}$$

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

Add to the potential energy

$$V(\phi,\chi) = \cdots + \frac{1}{2}m_\chi^2(\phi)\chi^2$$

the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

ıd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ıe transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

ıd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ıe transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi)\chi^2$$

the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow$$ pre-Ekpyrotic phase

ıd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow$$ Ekpyrotic phase

ıe transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

- Add to the potential energy

$$V(\phi, \chi) = \cdots + \frac{1}{2} m_\chi^2(\phi) \chi^2$$

- the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$$m_{eff}^2(\phi) > 0 \Rightarrow \text{ pre-Ekpyrotic phase}$$

nd for small ϕ

$$m_{eff}^2(\phi) < 0 \Rightarrow \text{ Ekpyrotic phase}$$

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

Pre-Ekpyrotic Phase

Add to the potential energy

$$V(\phi,\chi) = \cdots + \frac{1}{2}m_\chi^2(\phi)\chi^2$$

the χ mass is

$$m_{eff}^2(\phi) = -m_{tachyon}^2(\phi) + m_\chi^2(\phi)$$

hoose $m_\chi(\phi)$ so that for large ϕ

$m_{eff}^2(\phi) > 0 \Rightarrow$ pre-Ekpyrotic phase

nd for small ϕ

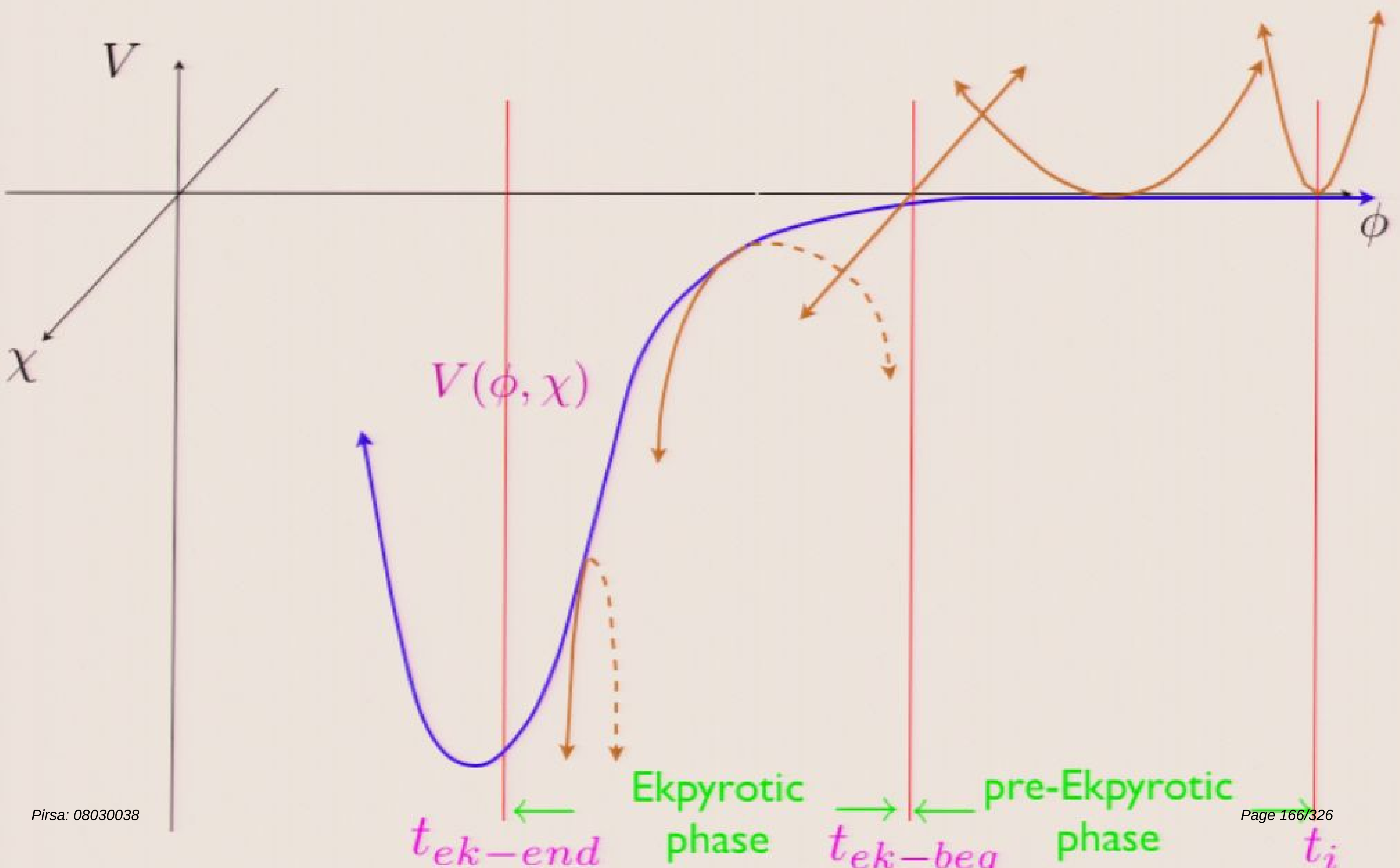
$m_{eff}^2(\phi) < 0 \Rightarrow$ Ekpyrotic phase

ne transition occurs at t_{ek-beg} where

$$m_\chi(t_{ek-beg}) = m_{tachyon}(t_{ek-beg}) \approx \frac{|H_{ek-beg}|}{p}$$

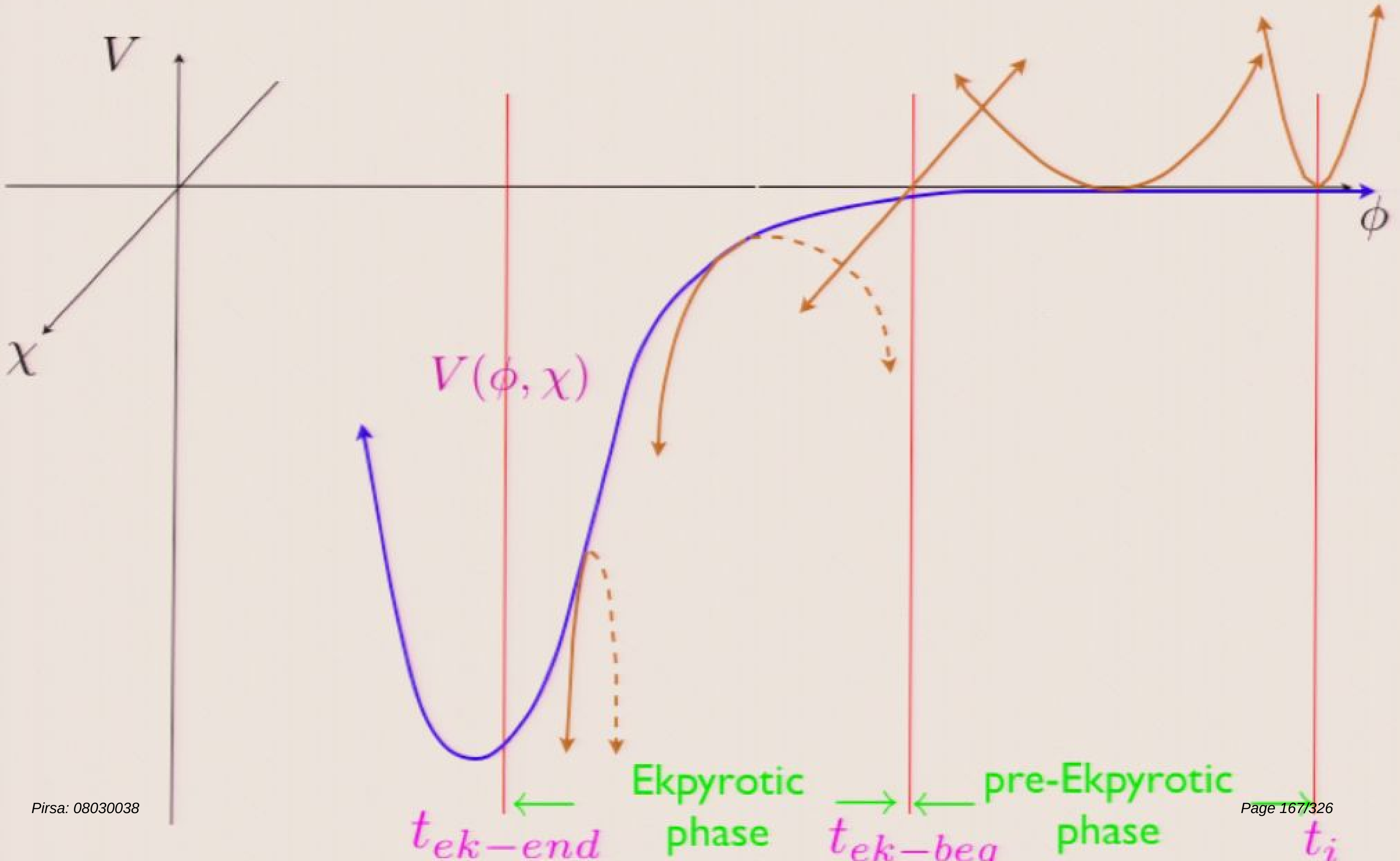
he pre-Ekpyrotic phase occurs in the interval

$$t_{ek-beg} \geq t \geq t_i$$



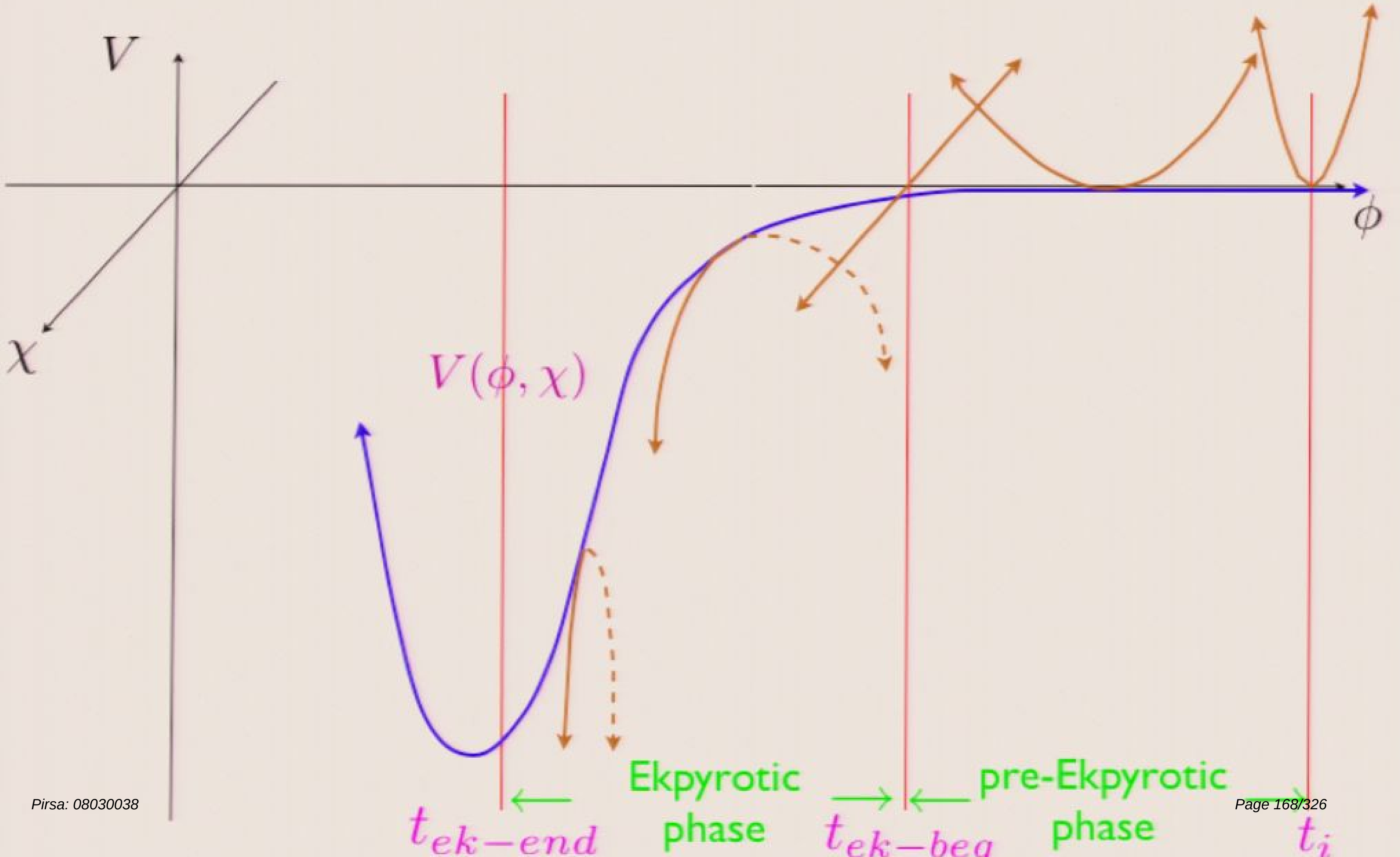
he pre-Ekpyrotic phase occurs in the interval

$$t_{ek-beg} \geq t \geq t_i$$



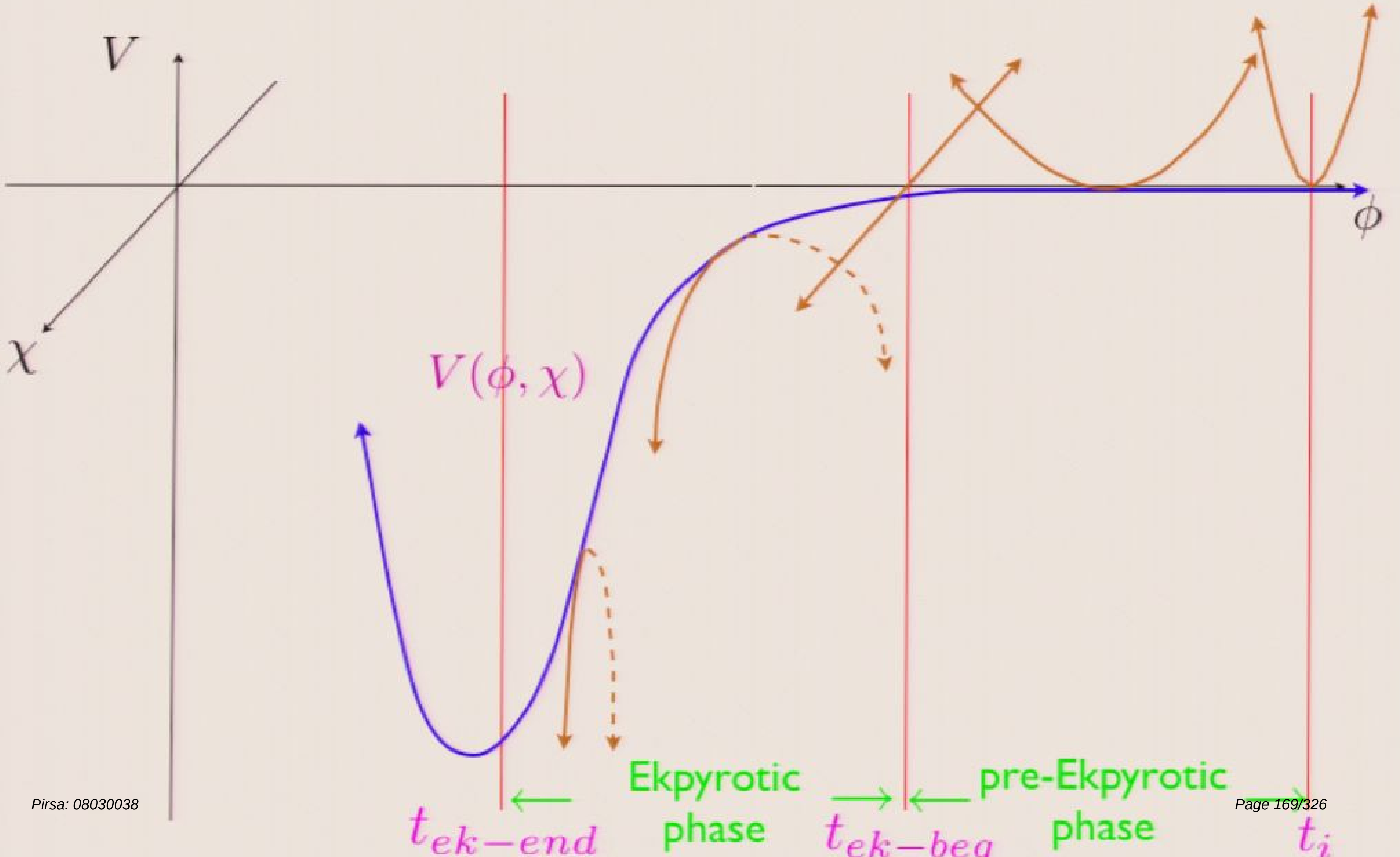
he pre-Ekpyrotic phase occurs in the interval

$$t_{ek-beg} \geq t \geq t_i$$



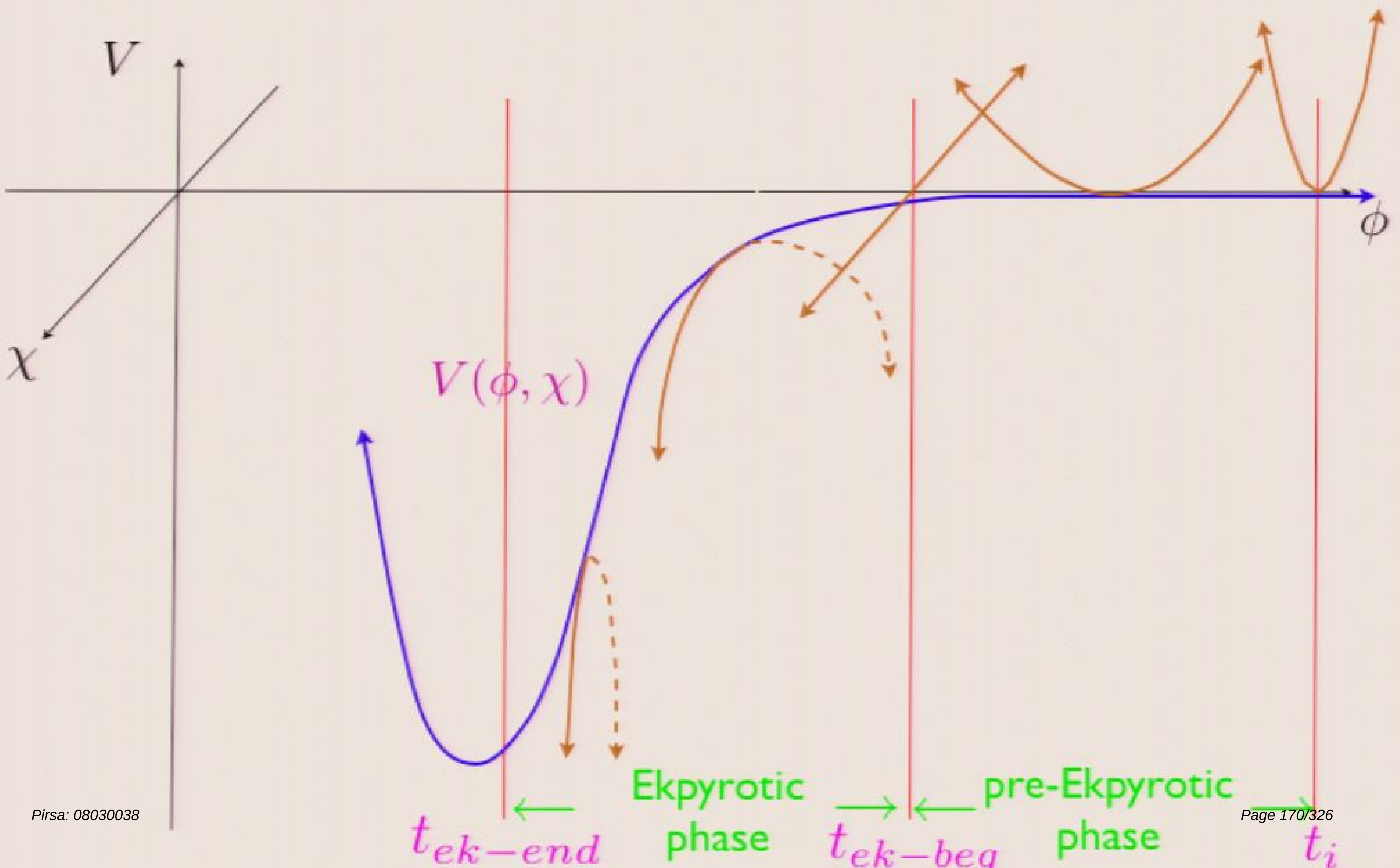
he pre-Ekpyrotic phase occurs in the interval

$$t_{ek-beg} \geq t \geq t_i$$



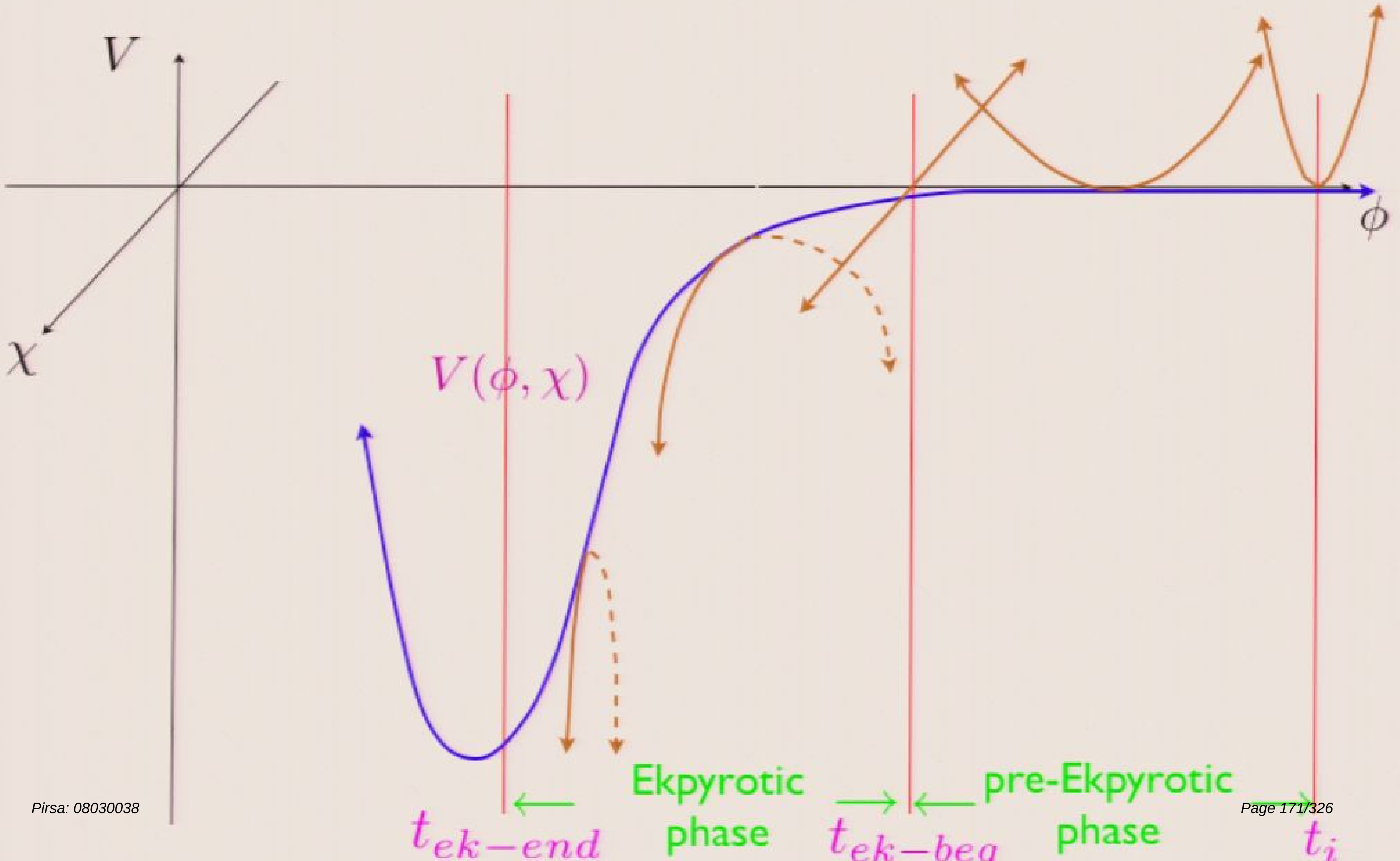
he pre-Ekpyrotic phase occurs in the interval

$$t_{ek-beg} \geq t \geq t_i$$



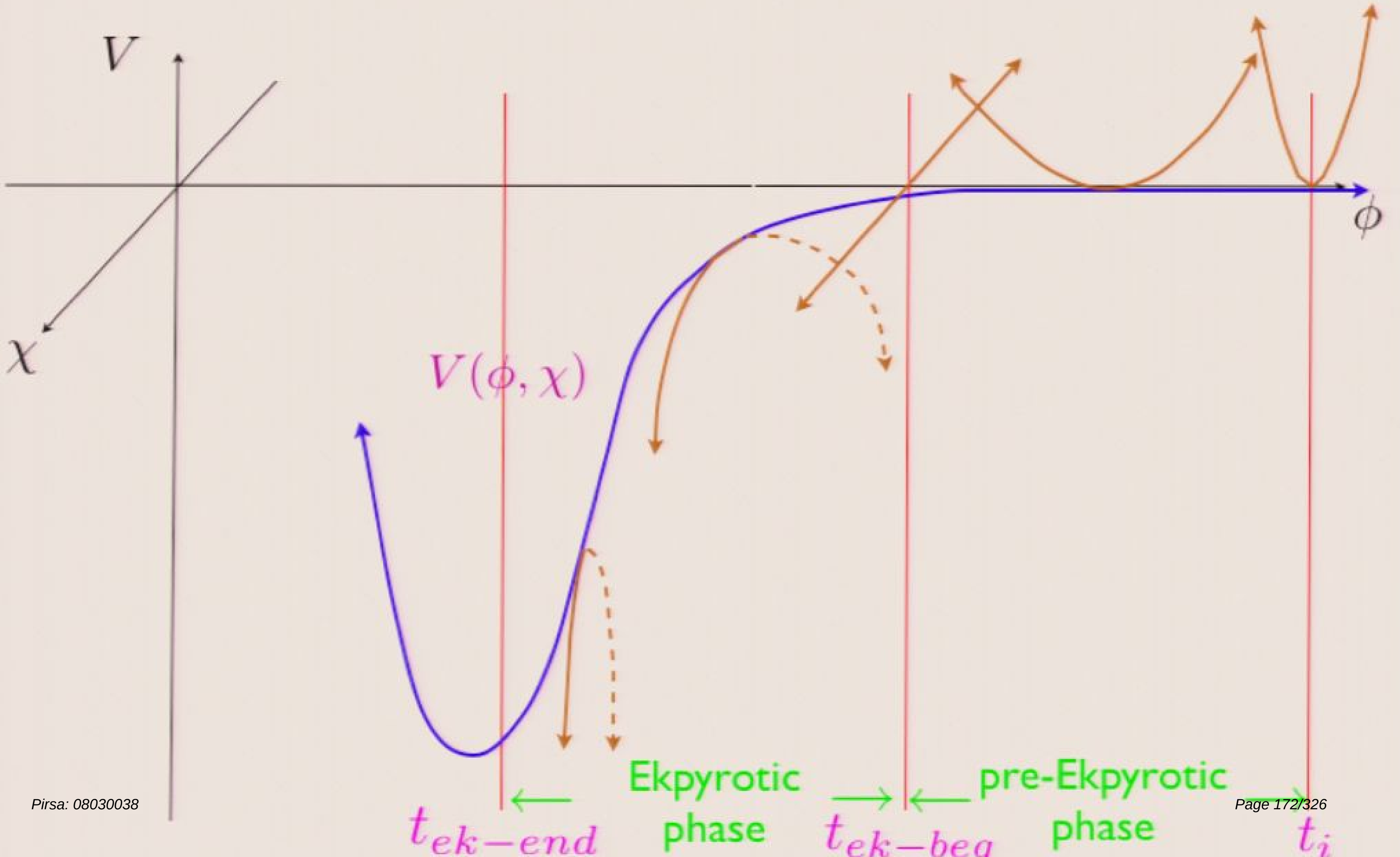
he pre-Ekpyrotic phase occurs in the interval

$$t_{ek-beg} \geq t \geq t_i$$



he pre-Ekpyrotic phase occurs in the interval

$$t_{ek-beg} \geq t \geq t_i$$



› to achieve a bounce must violate the NEC. Requires phase where

$$\omega < -1$$

Ghost Condensate

eal scalar field- ϕ

grangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

here P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

nd m,M are arbitrary mass scales

calar equation

$$\frac{d}{dt}(a^3 P_{,X}\dot{\phi}) = 0$$

› to achieve a bounce must violate the NEC. Requires
phase where

$$\omega < -1$$

Ghost Condensate

eal scalar field- ϕ

grangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

here P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

d m,M are arbitrary mass scales

alar equation

$$\frac{d}{dt}(a^3 P_{,X}\dot{\phi}) = 0$$

› to achieve a bounce must violate the NEC. Requires phase where

$$\omega < -1$$

Ghost Condensate

eal scalar field- ϕ

ıgrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

here P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

ıd m,M are arbitrary mass scales

:alar equation

$$\frac{d}{dt}(a^3 P_{,X} \dot{\phi}) = 0$$

› to achieve a bounce must violate the NEC. Requires phase where

$$\omega < -1$$

Ghost Condensate

eal scalar field- ϕ

ıgrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

here P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

ıd m,M are arbitrary mass scales

calar equation

$$\frac{d}{dt}(a^3 P_{,X}\dot{\phi}) = 0$$

› to achieve a bounce must violate the NEC. Requires phase where

$$\omega < -1$$

Ghost Condensate

eal scalar field- ϕ

ıgrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

here P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

ıd m,M are arbitrary mass scales

:alar equation

$$\frac{d}{dt}(a^3 P_{,X}\dot{\phi}) = 0$$

⇒ to achieve a bounce must violate the NEC. Requires phase where

$$\omega < -1$$

Ghost Condensate

eal scalar field- ϕ

grangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

here P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

d m,M are arbitrary mass scales

alar equation

$$\frac{d}{dt}(a^3 P_{,X}\dot{\phi}) = 0$$

⇒ to achieve a bounce must violate the NEC. Requires a phase where

$$\omega < -1$$

) Ghost Condensate

Real scalar field- ϕ

Lagrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

where P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

and m,M are arbitrary mass scales

Scalar equation

$$\frac{d}{dt}(a^3 P_{,X} \dot{\phi}) = 0$$

⇒ to achieve a bounce must violate the NEC. Requires a phase where

$$\omega < -1$$

) Ghost Condensate

Real scalar field- ϕ

Lagrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

where P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

and m,M are arbitrary mass scales

Scalar equation

$$\frac{d}{dt}(a^3 P_{,X} \dot{\phi}) = 0$$

⇒ to achieve a bounce must violate the NEC. Requires a phase where

$$\omega < -1$$

) Ghost Condensate

Real scalar field- ϕ

Lagrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

where P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

and m,M are arbitrary mass scales

Scalar equation

$$\frac{d}{dt}(a^3 P_{,X} \dot{\phi}) = 0$$

⇒ to achieve a bounce must violate the NEC. Requires a phase where

$$\omega < -1$$

) Ghost Condensate

Real scalar field- ϕ

Lagrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

where P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

and m,M are arbitrary mass scales

Scalar equation

$$\frac{d}{dt}(a^3 P_{,X} \dot{\phi}) = 0$$

⇒ to achieve a bounce must violate the NEC. Requires a phase where

$$\omega < -1$$

) Ghost Condensate

Real scalar field- ϕ

Lagrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

where P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

and m,M are arbitrary mass scales

Scalar equation

$$\frac{d}{dt}(a^3 P_{,X} \dot{\phi}) = 0$$

⇒ to achieve a bounce must violate the NEC. Requires a phase where

$$\omega < -1$$

) Ghost Condensate

Real scalar field- ϕ

Lagrangian density-

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X)$$

where P(X) is a function of

$$X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

and m,M are arbitrary mass scales

Scalar equation

$$\frac{d}{dt}(a^3 P_{,X} \dot{\phi}) = 0$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P}\right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential $V(\phi)$ where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P}\right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P}\right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P}\right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P}\right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P}\right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P}\right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t \qquad \text{ghost condensate}$$

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P} \right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

Assume

$$P_{,X}|_{X_0} = 0$$

is a minimum (⇒ ghost-free). Scaling m ⇒ can take

$$X_0 = \frac{1}{2}$$

⇒ solution is

$$\phi(t) = -m^2 t$$ ghost condensate

Corresponds to

$$\omega = -1$$

To obtain $\omega < -1$ add potential V(ϕ) where

$$|V_{,\phi}| \ll M^3 \left(\frac{M^3}{m^2 M_P}\right)$$

Writing

$$\phi(t) = -m^2 t + \pi_0(t)$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V\ ,\ \mathcal{P} \simeq -V$$

$\Rightarrow$

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0\ ,\ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right)\ ,\ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

:he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

vhere $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

$\Rightarrow$

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

:he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

vhere $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

:he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

vhere $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

$\Rightarrow$

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

$\Rightarrow$

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

$\Rightarrow$

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

vhere $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2K$$

:he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

vhere $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

$\Rightarrow$

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

:he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

vhere $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V\ ,\ \mathcal{P} \simeq -V$$

$\Rightarrow$

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0\ ,\ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right)\ ,\ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$

he scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \; , \; \mathcal{P} \simeq -V$$

⇒

$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

$$\rho + \mathcal{P} < 0 \; , \; \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \; , \; \Lambda^2 \ll M^2 K$$

the scalar equation becomes

$$\ddot{\pi}_0 + 3H\dot{\pi}_0 \simeq -\frac{V_{,\phi}}{K}\left(\frac{m}{M}\right)^4$$

where $K = P_{,XX}|_{X_0=\frac{1}{2}}$. For any solution

$$\rho \simeq \frac{-KM^2\dot{\pi}_0}{m^2} + V \ , \ \mathcal{P} \simeq -V$$

⇒

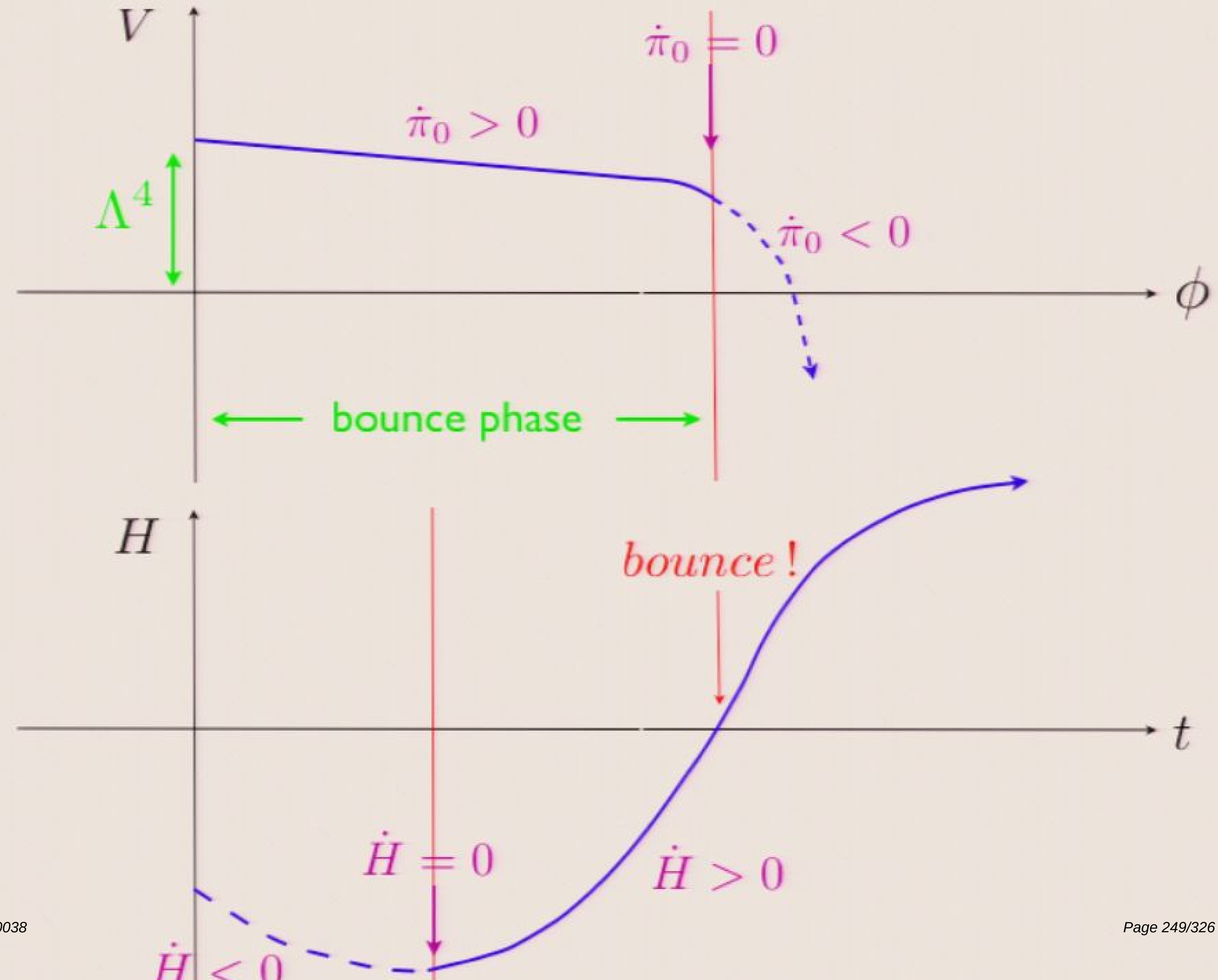
$$\rho + \mathcal{P} = -\frac{KM^2\dot{\pi}_0}{m^2}$$

Can choose V(ϕ) so that $\dot{\pi}_0 > 0 \Rightarrow$

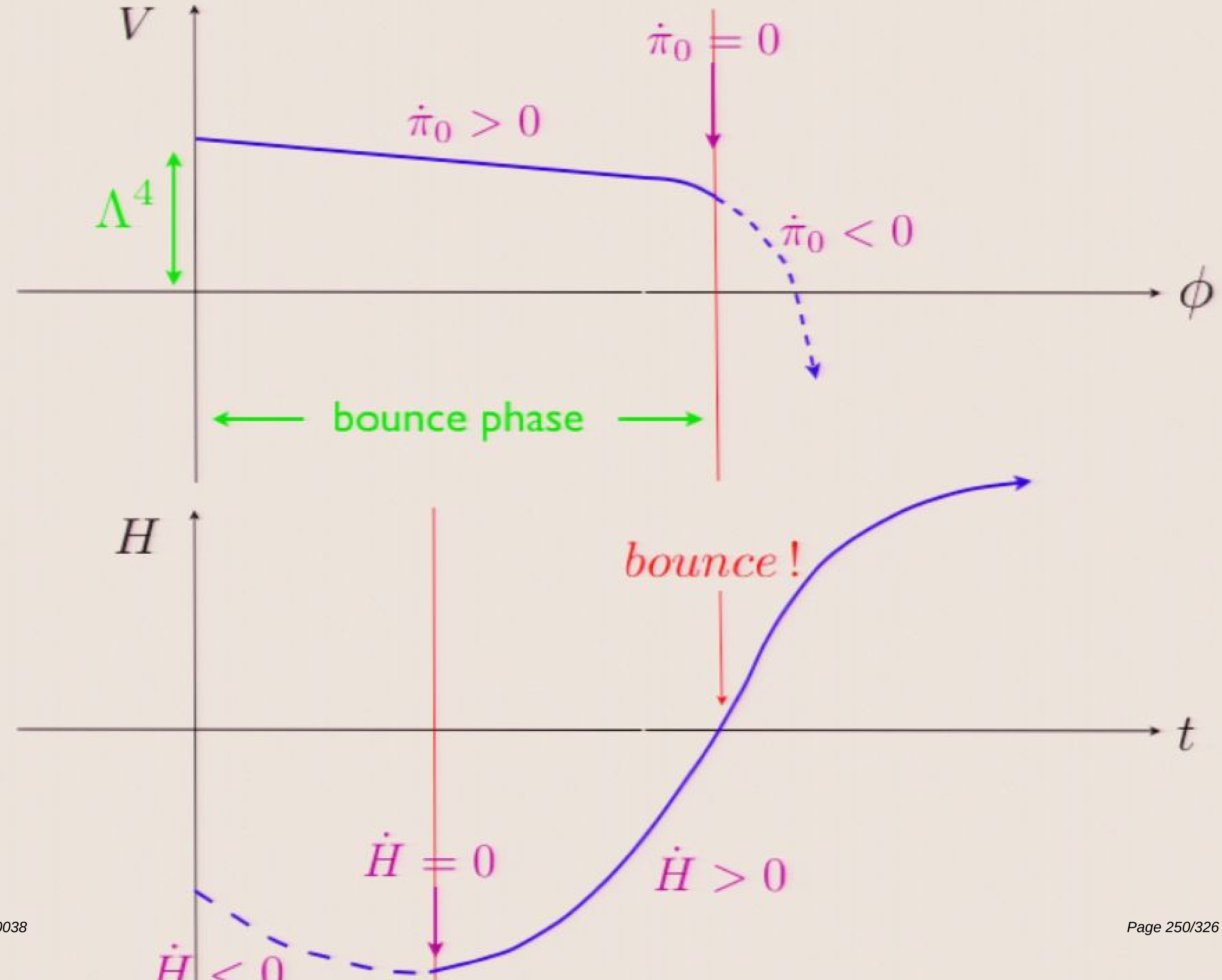
$$\rho + \mathcal{P} < 0 \ , \ \omega < -1$$

⇒ ghost condensate violates the NEC! For example, take

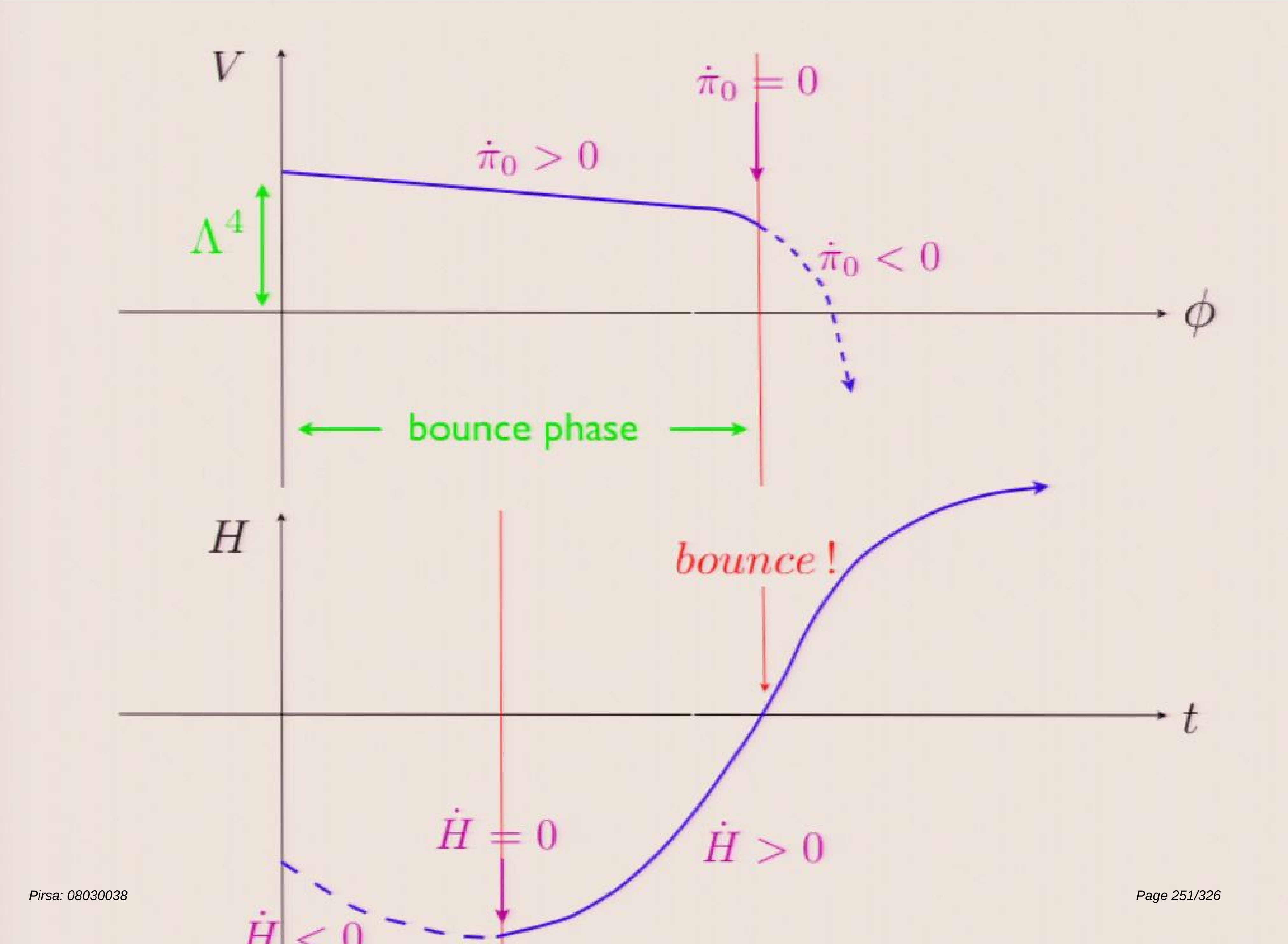
$$V(\phi) = \Lambda^4\left(1 - \frac{\Lambda^2}{m^2}\frac{\phi}{M_P}\right) \ , \ \Lambda^2 \ll M^2 K$$



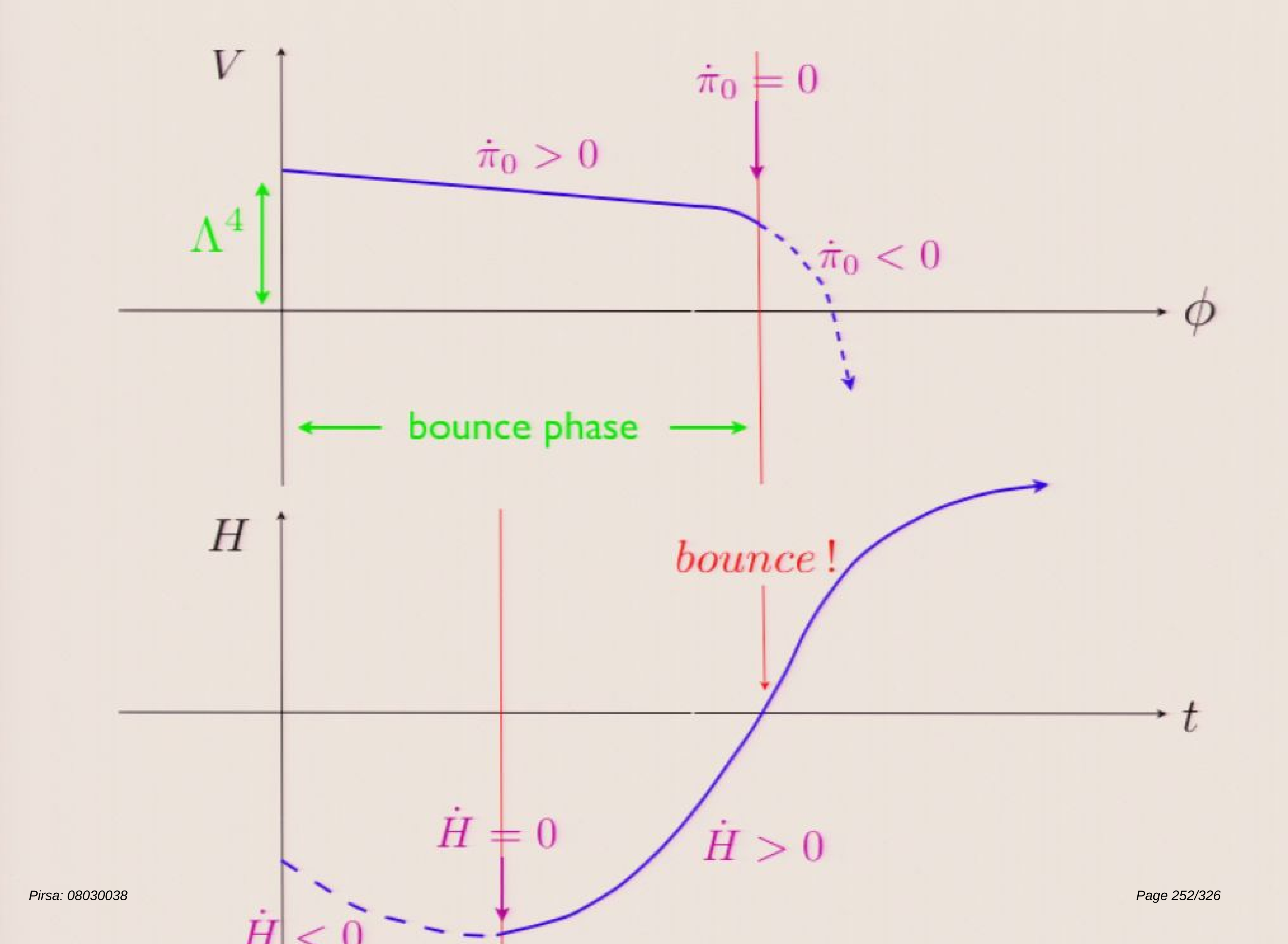
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce !
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



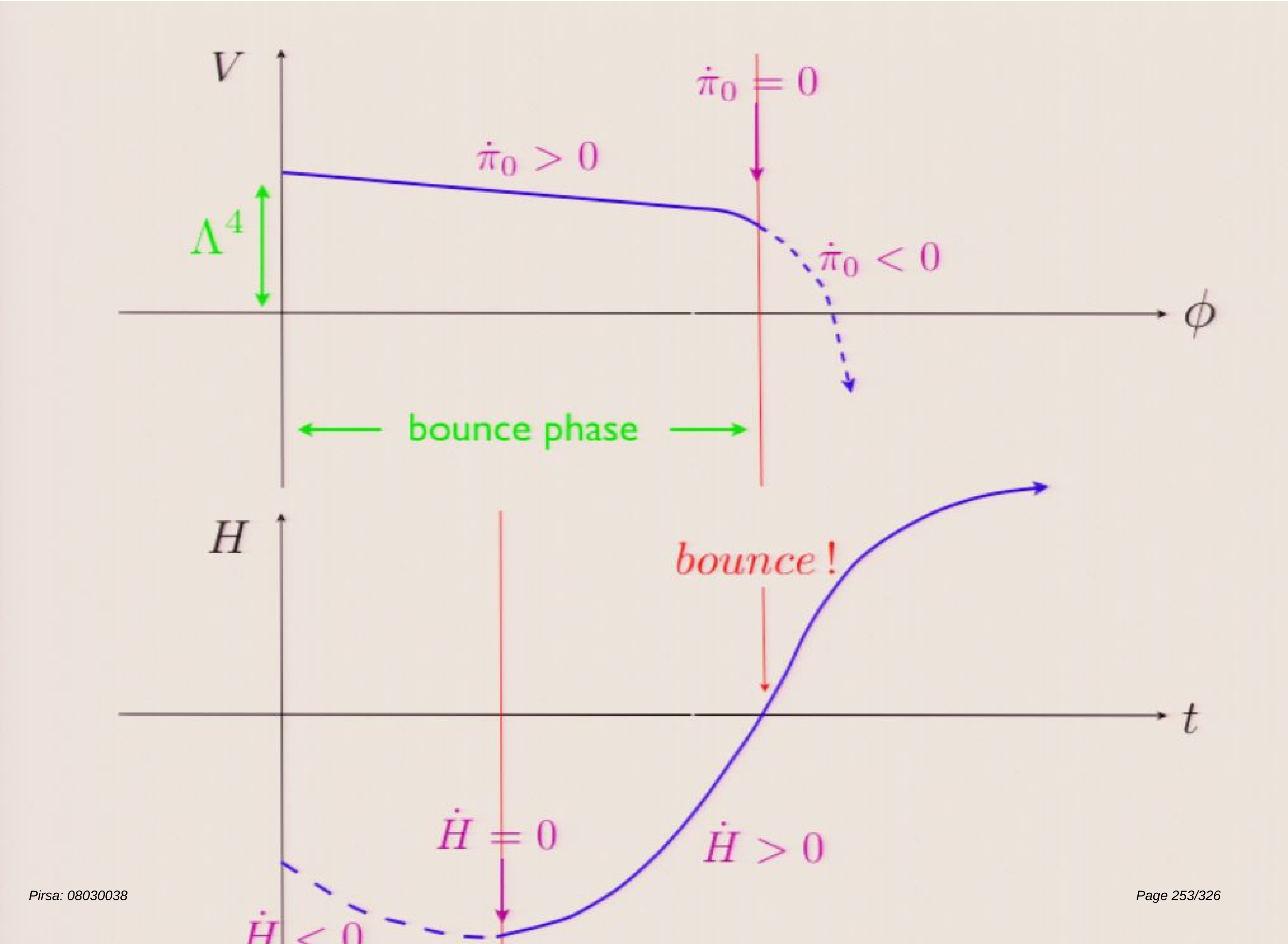
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce\,!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



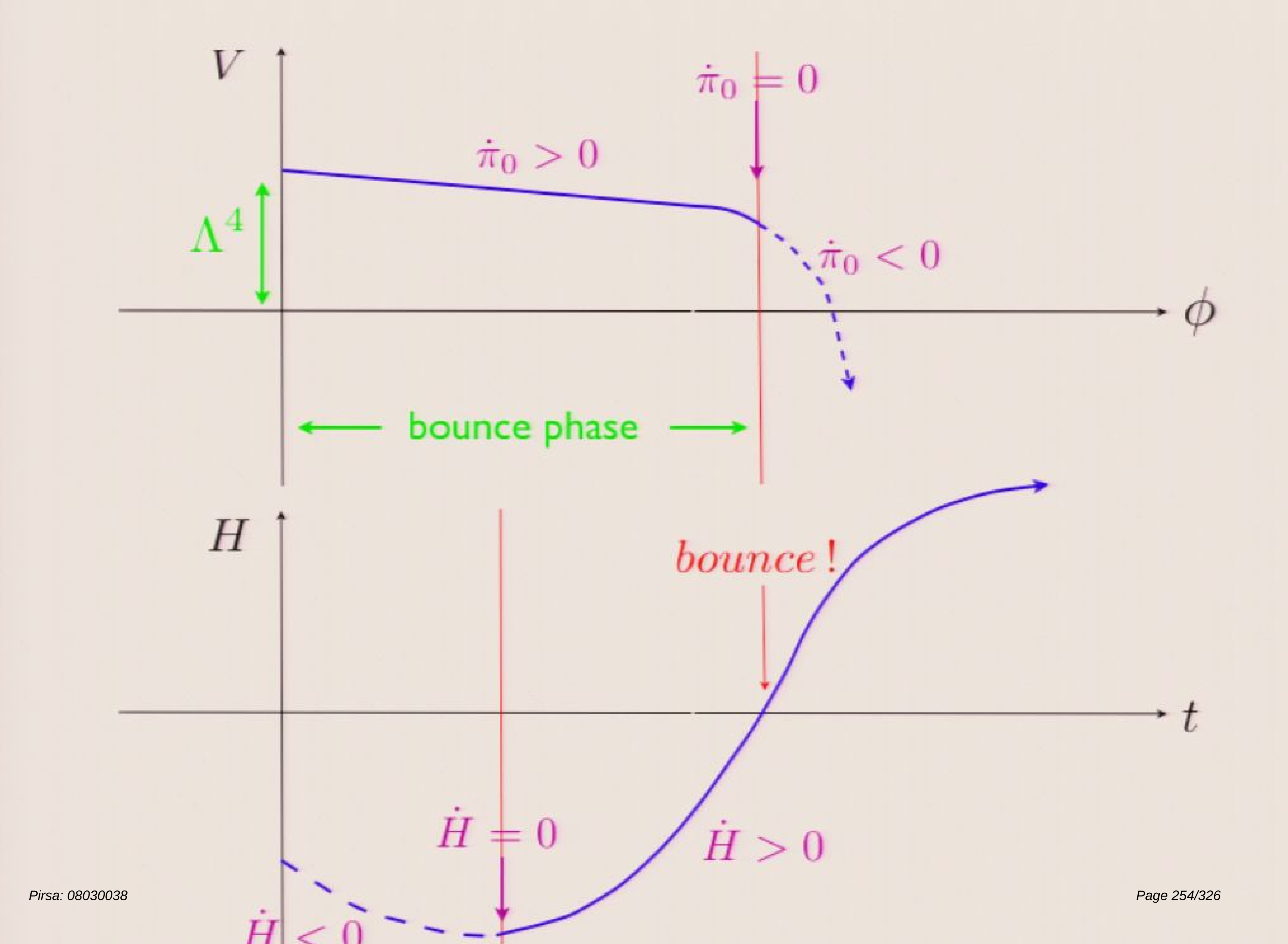
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



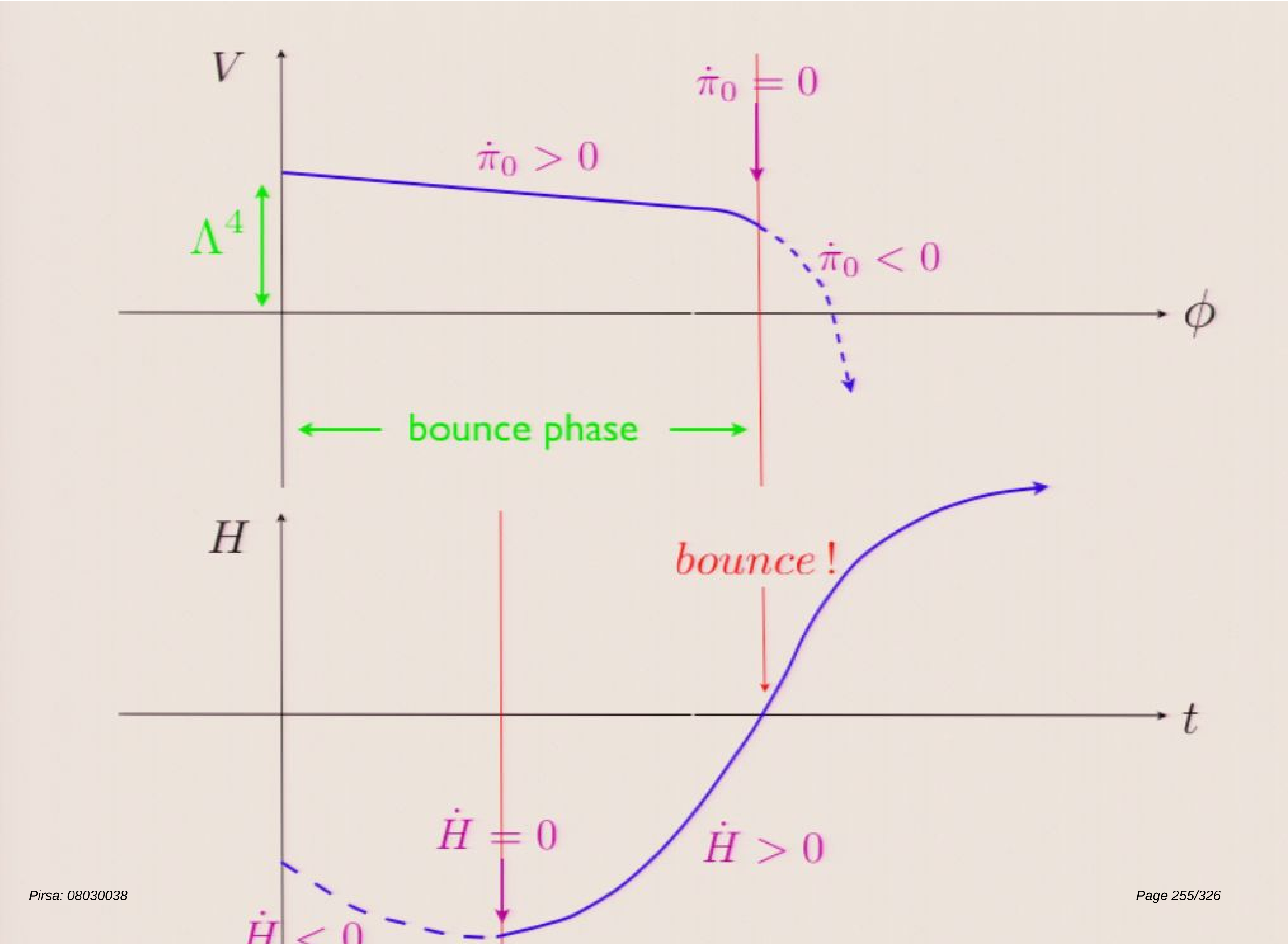
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce\,!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



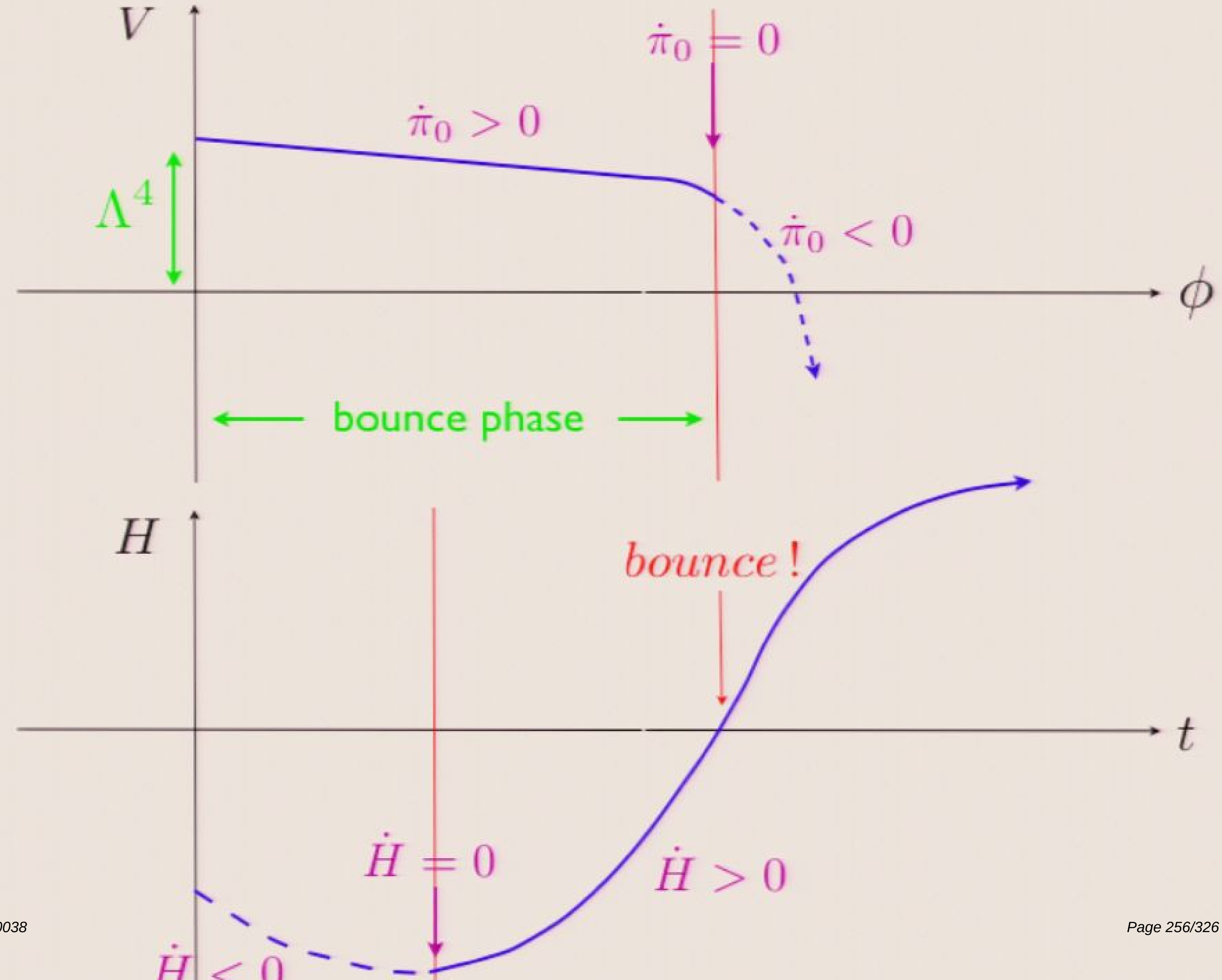
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

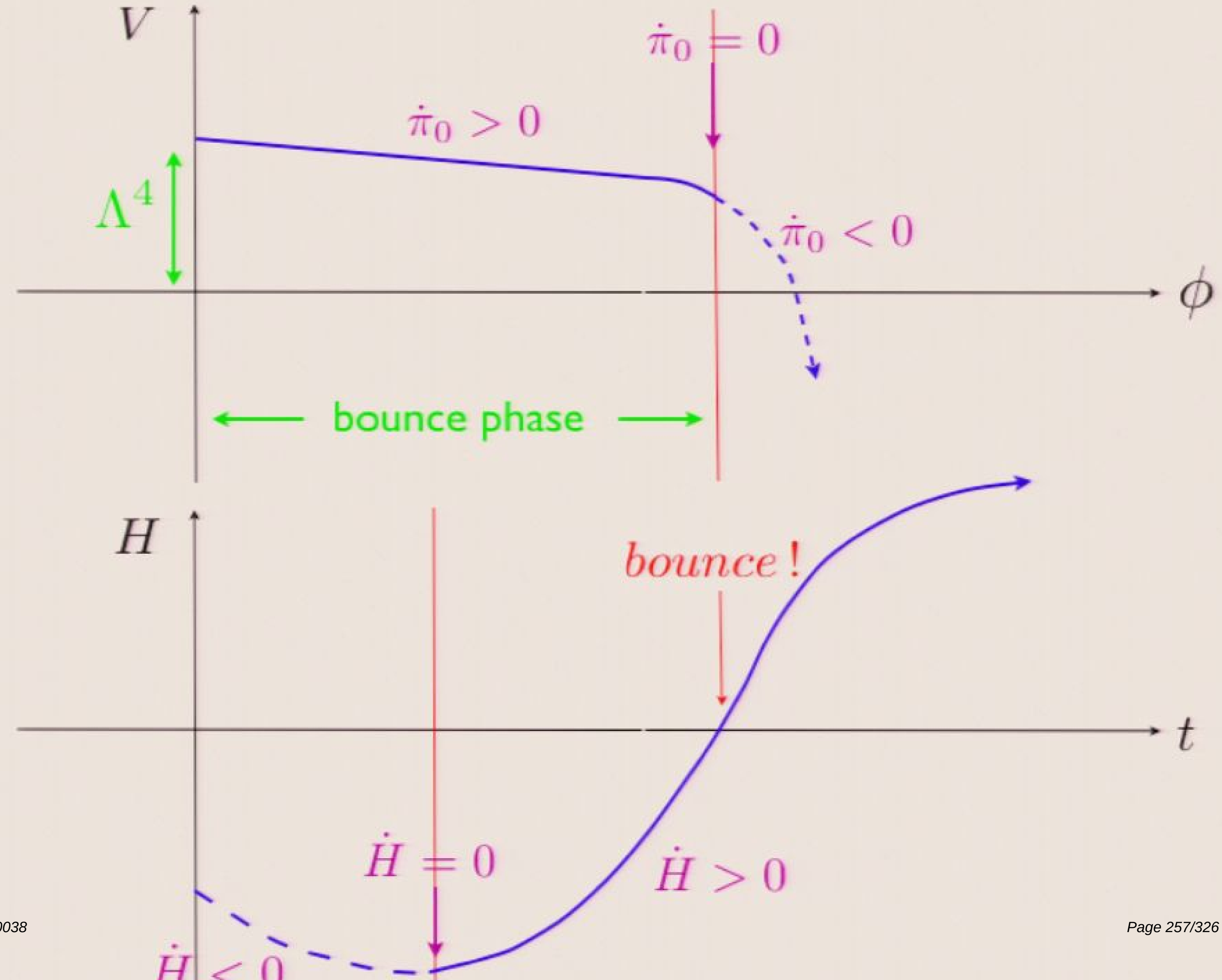


V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

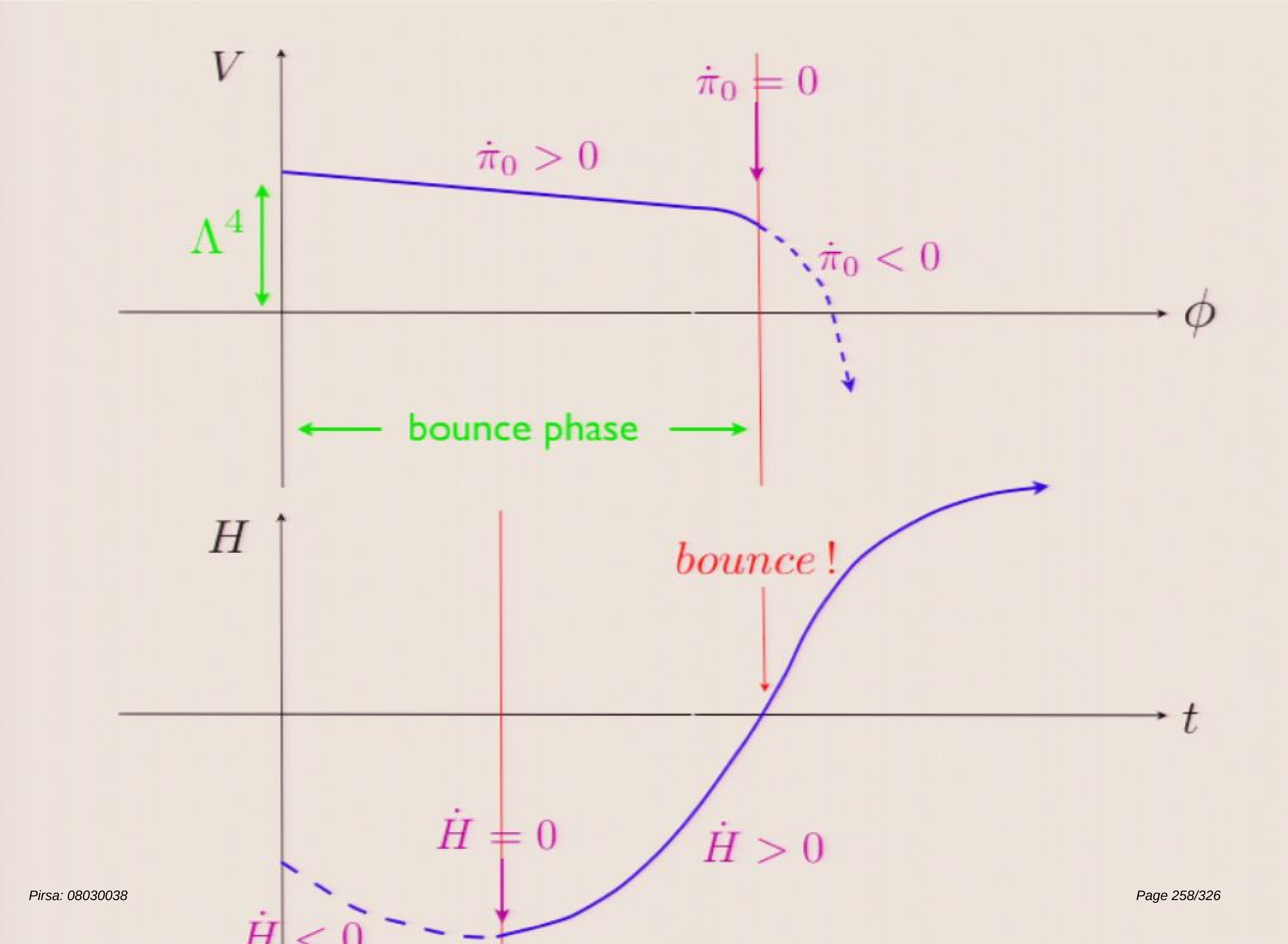


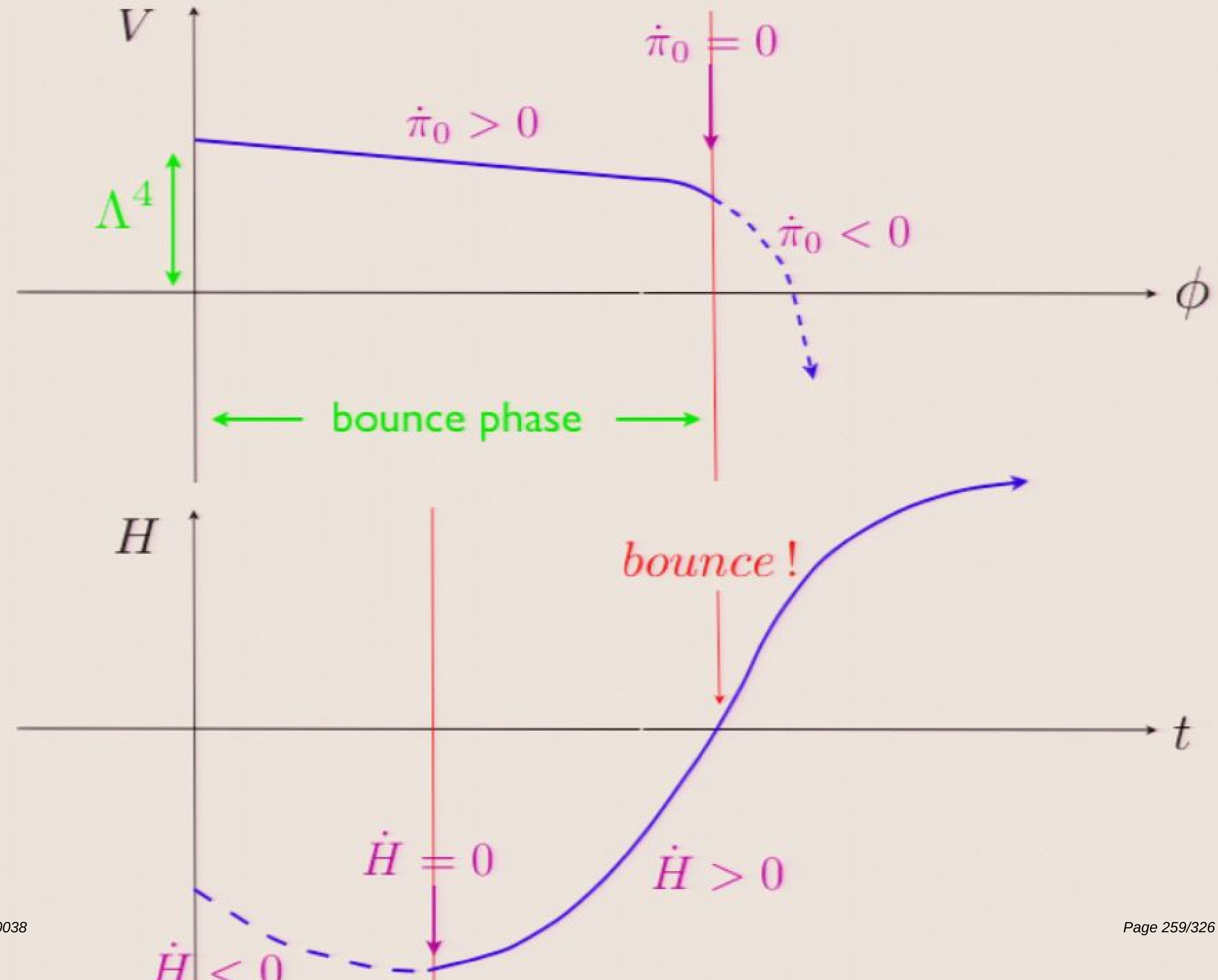
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

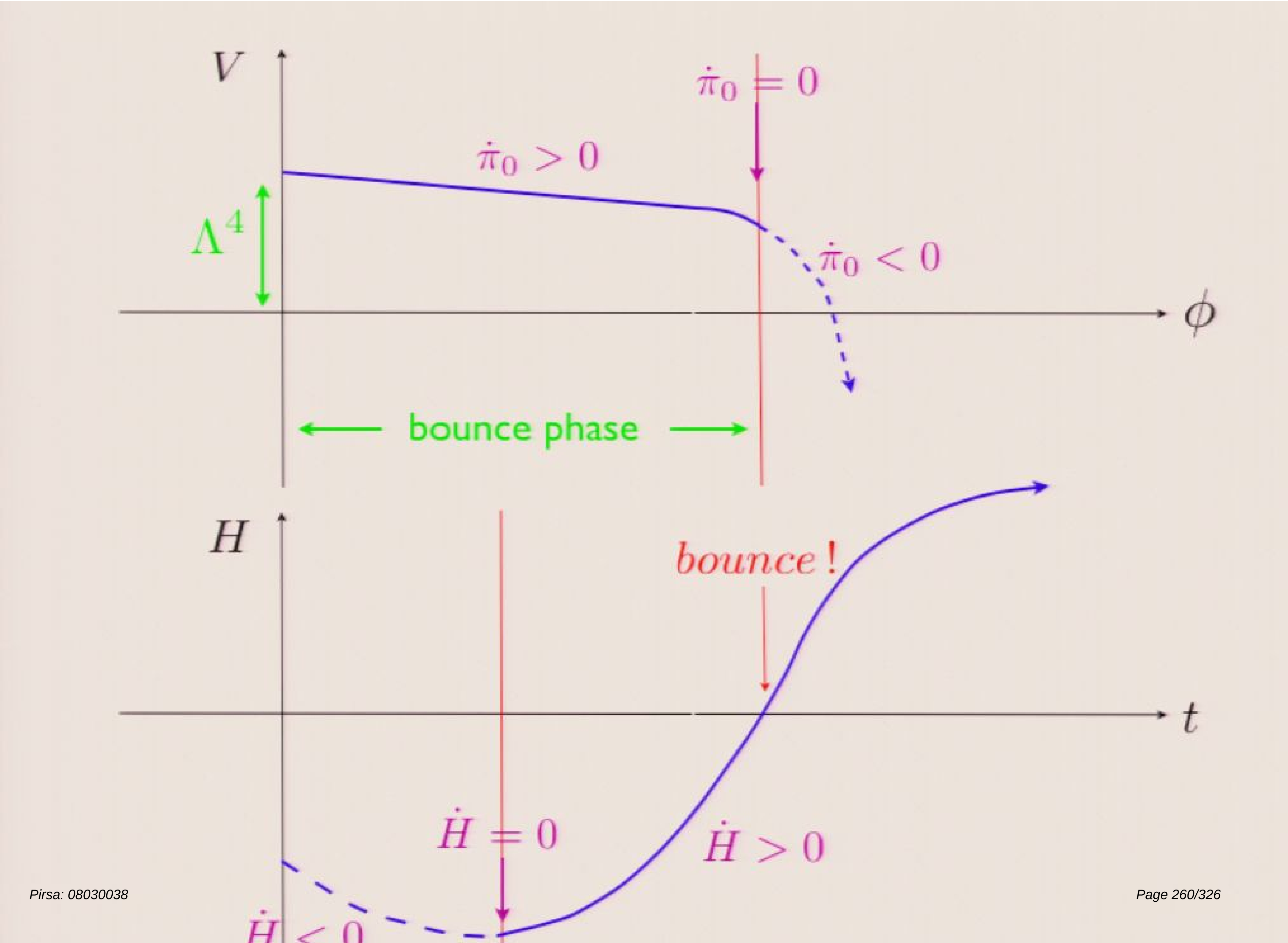

V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce\,!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



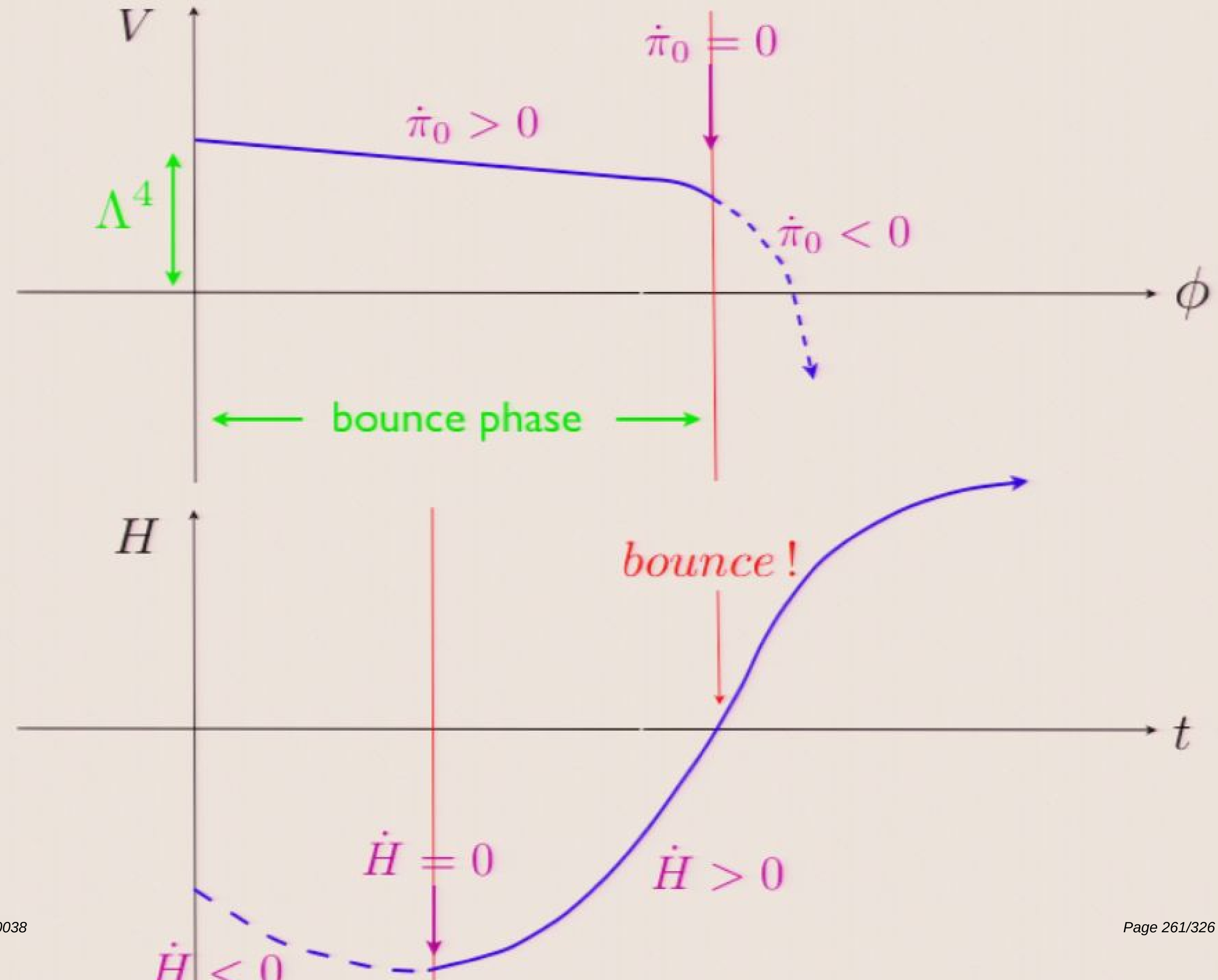
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

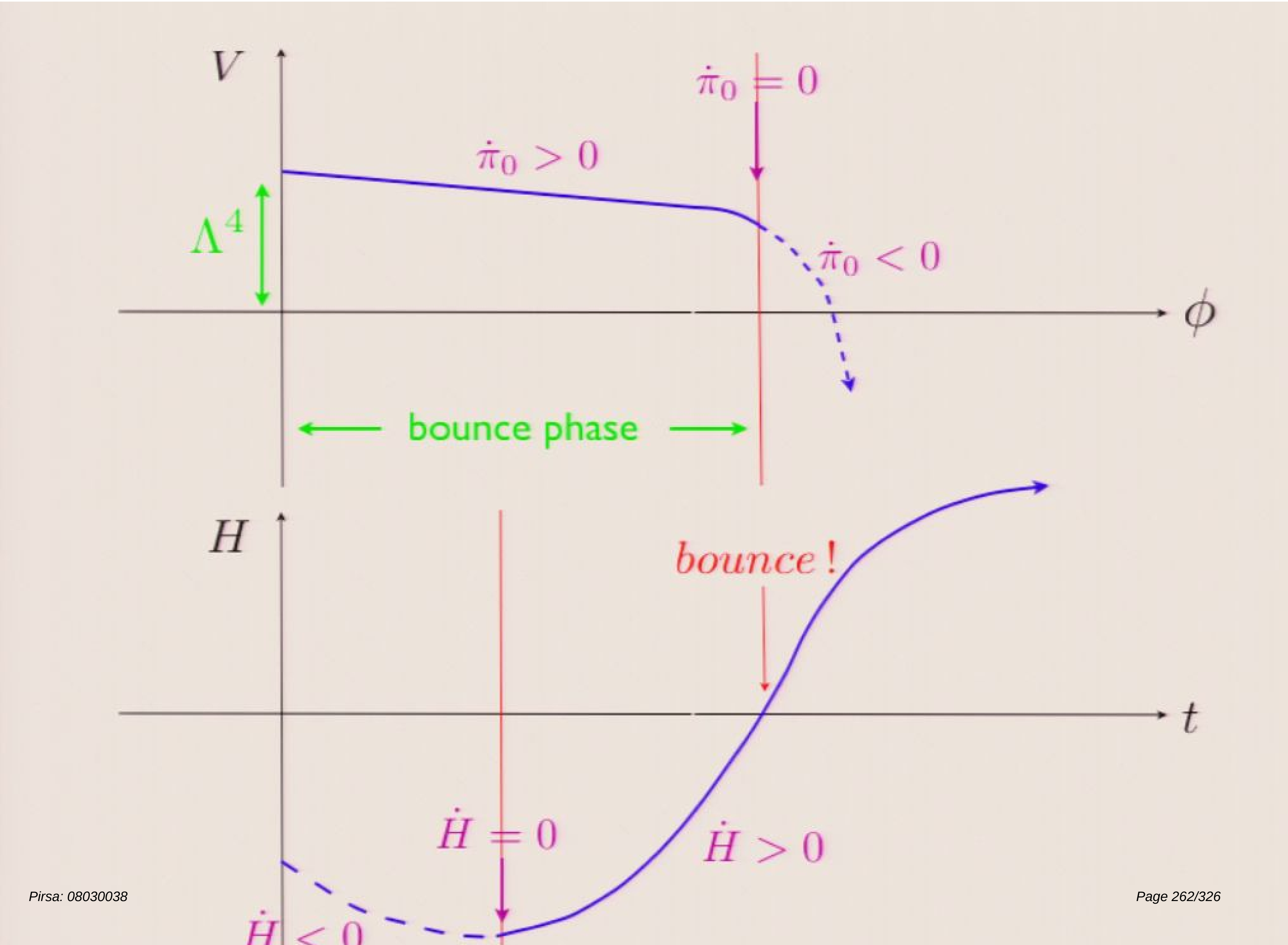

V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$


V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

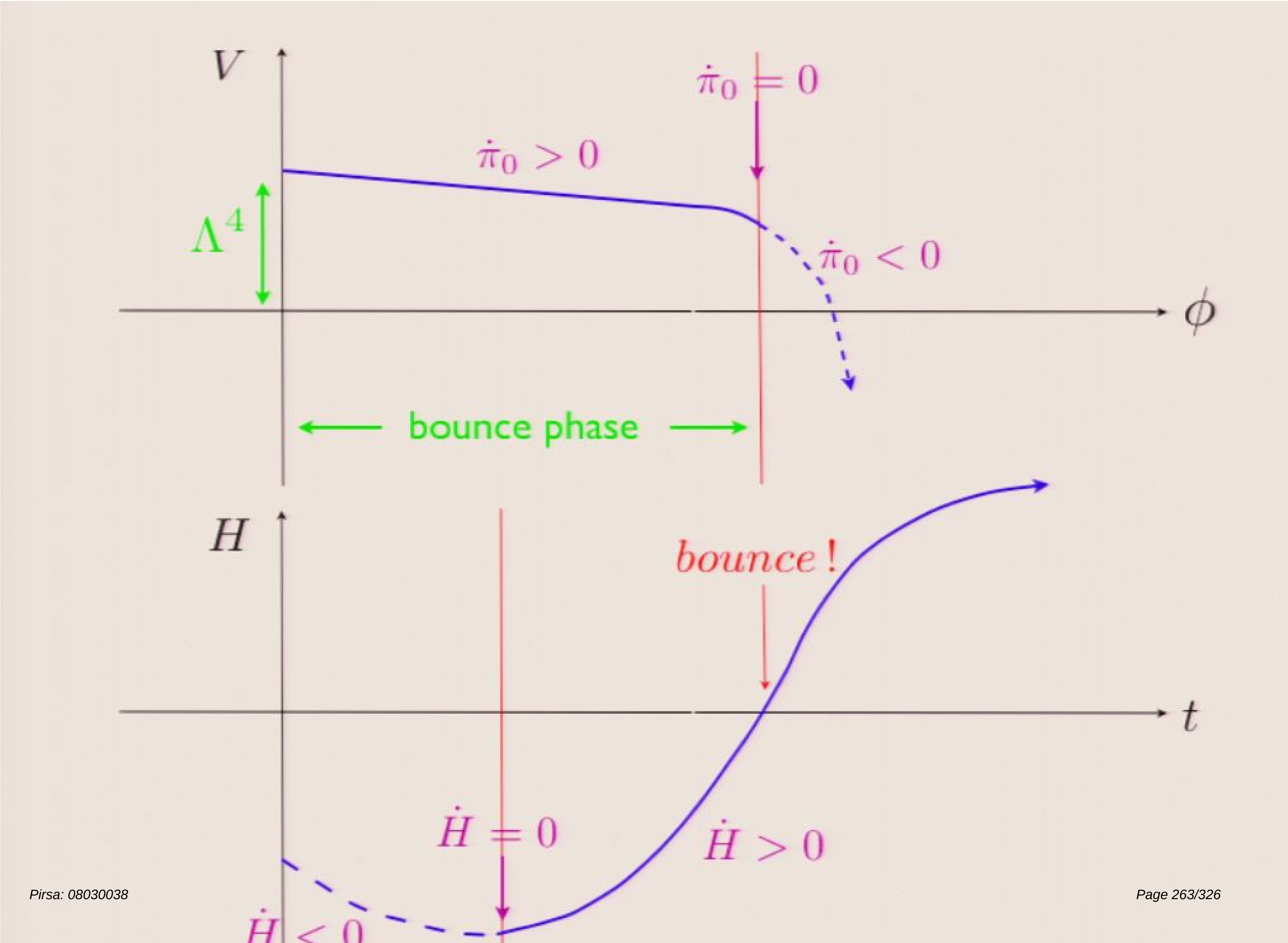


V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

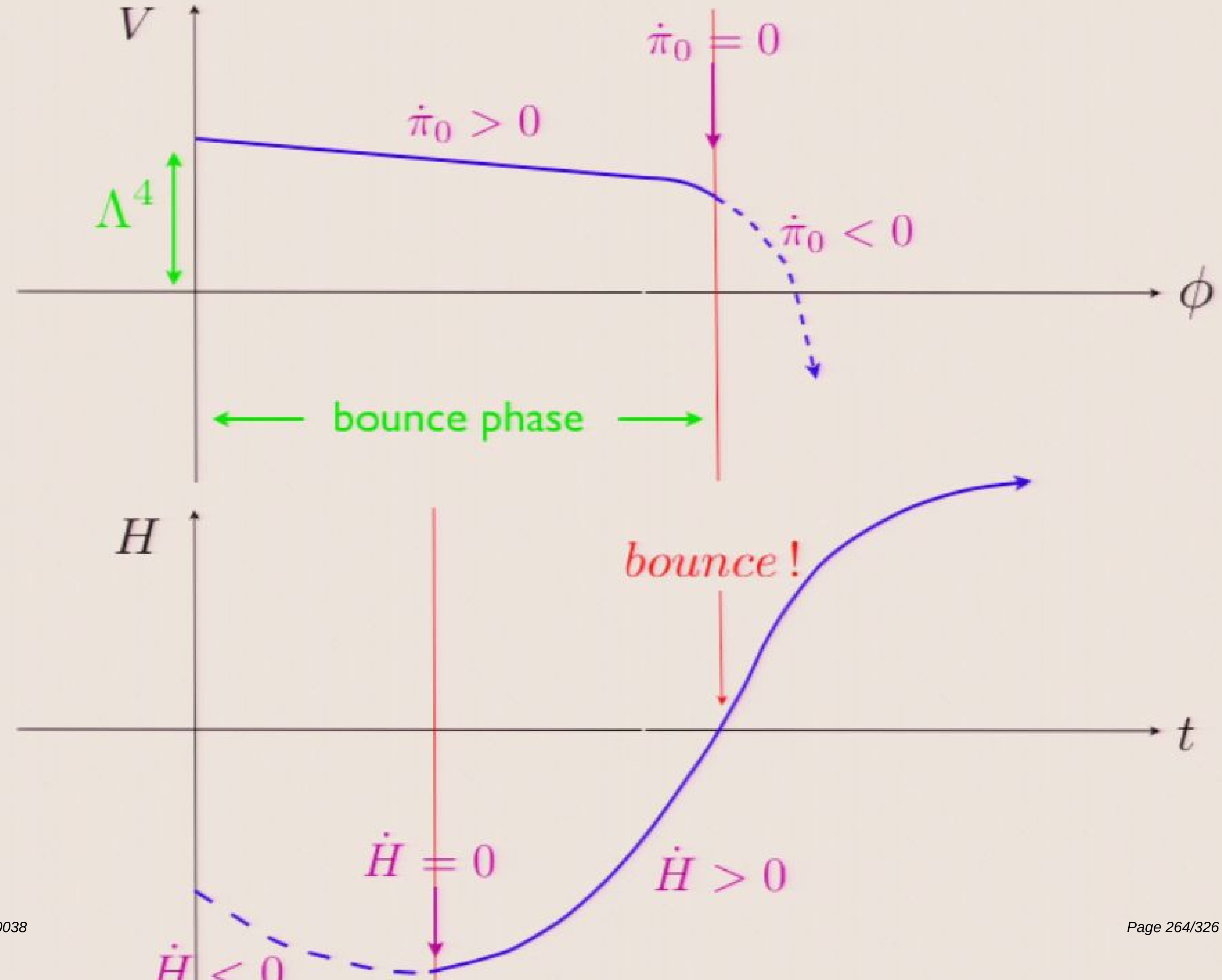

V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



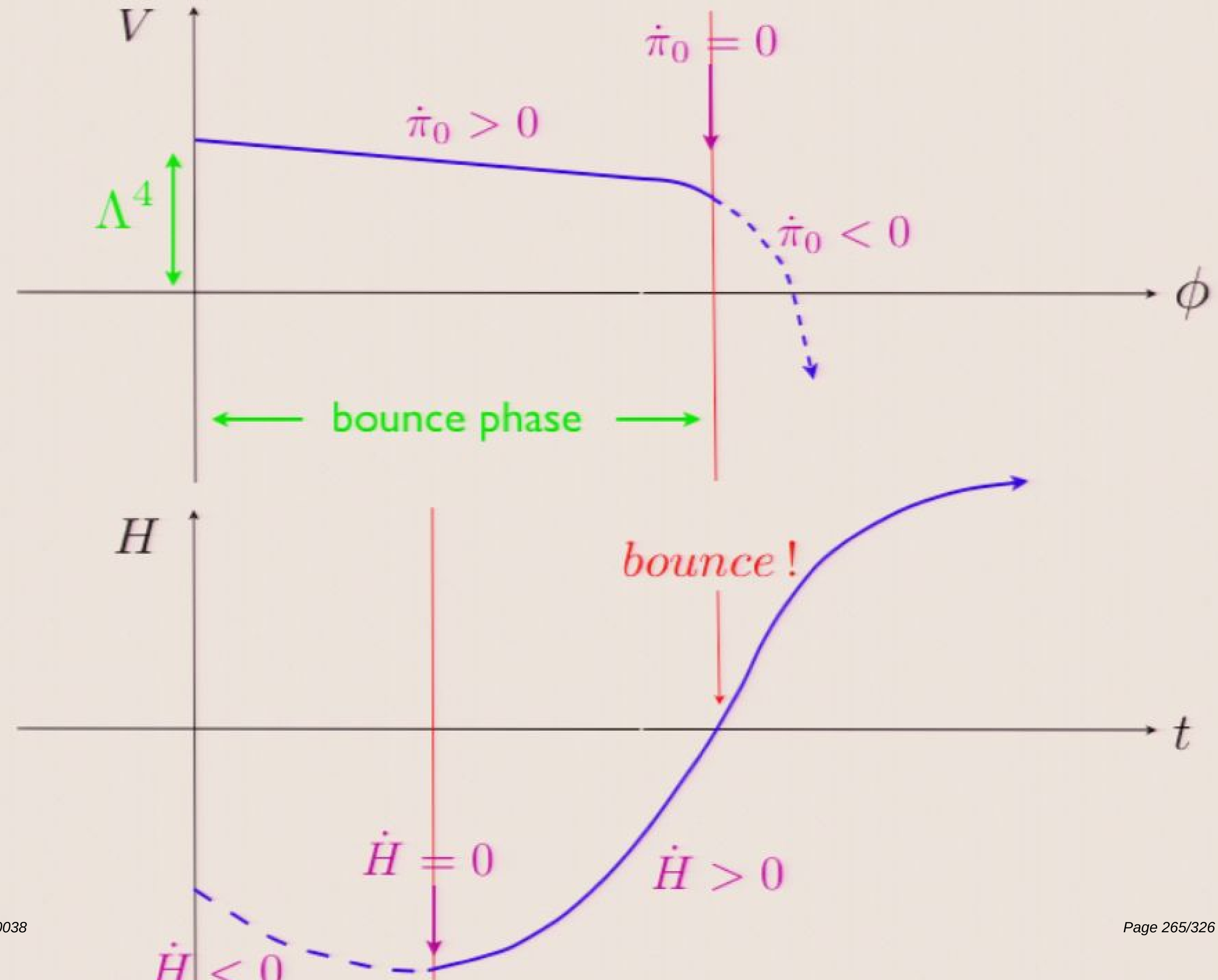
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce\,!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



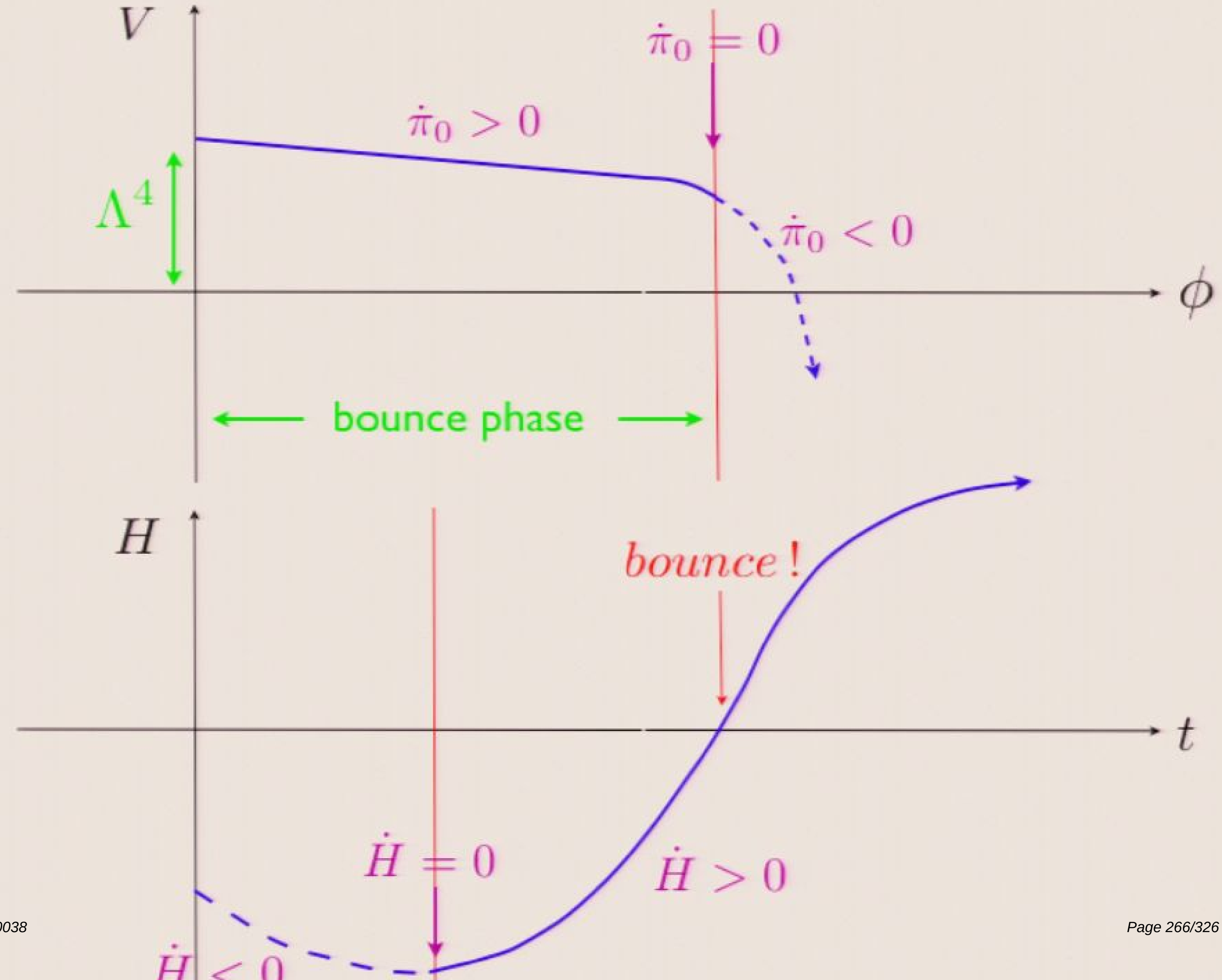
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



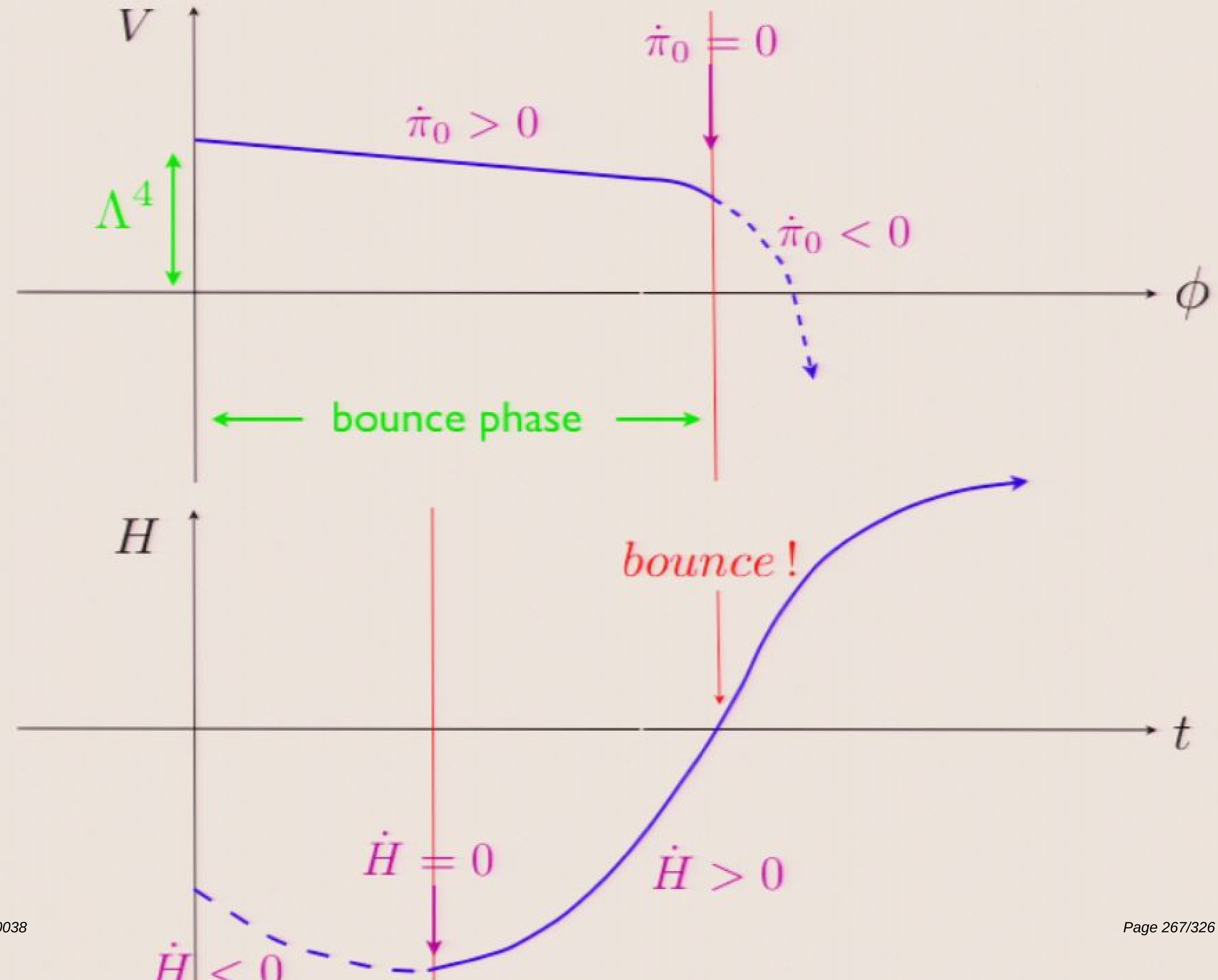
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



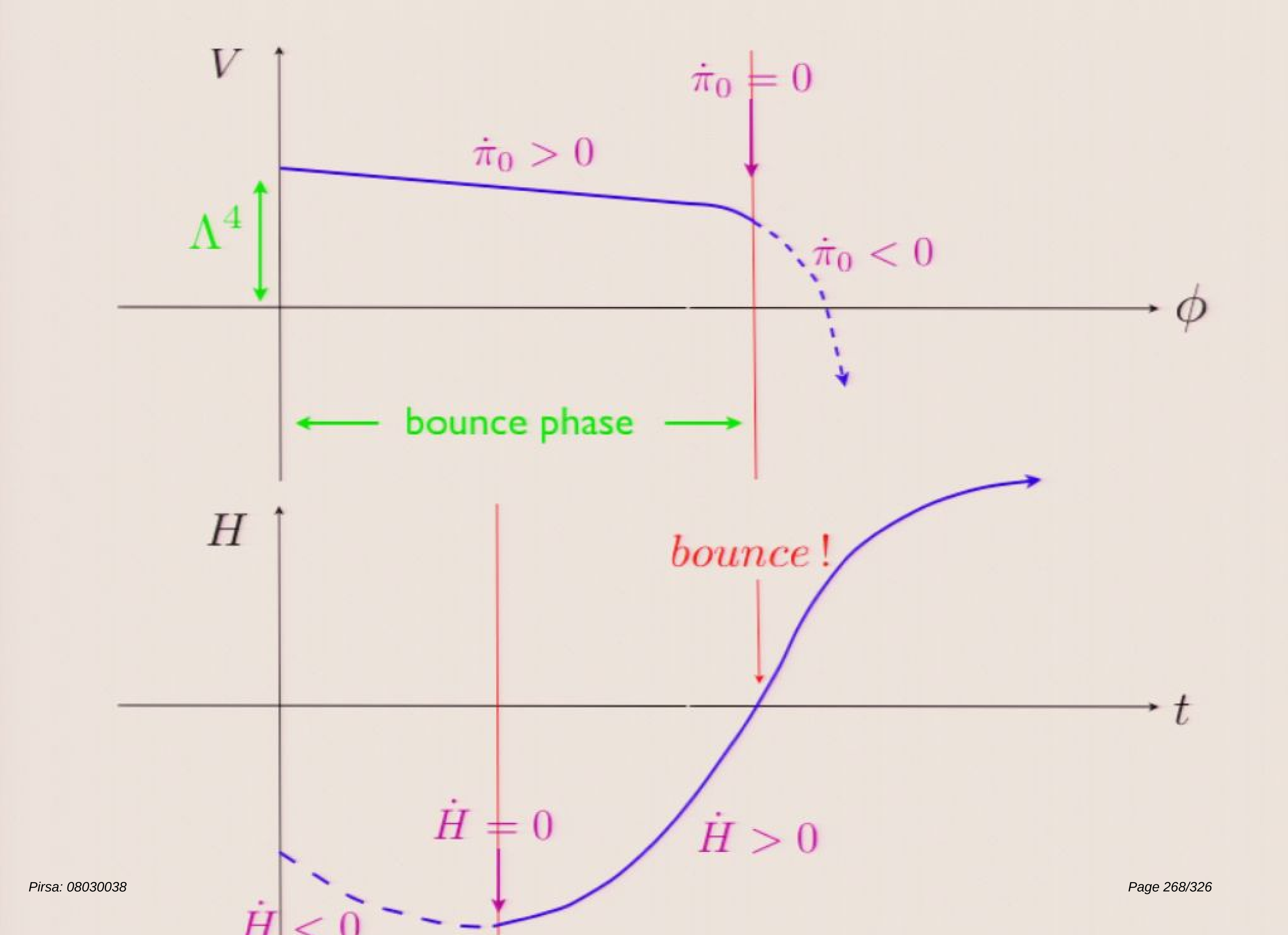
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



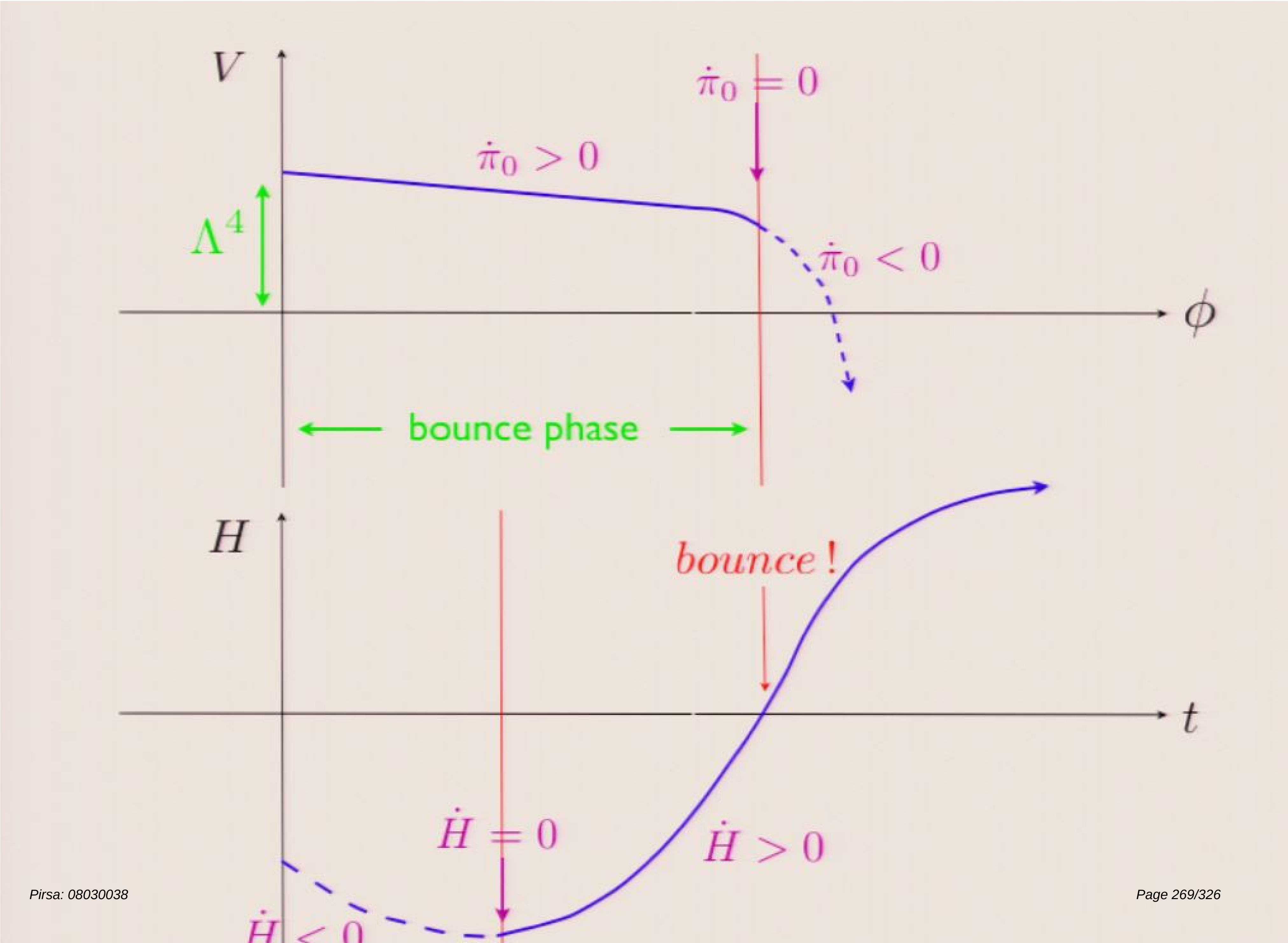
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce\,!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

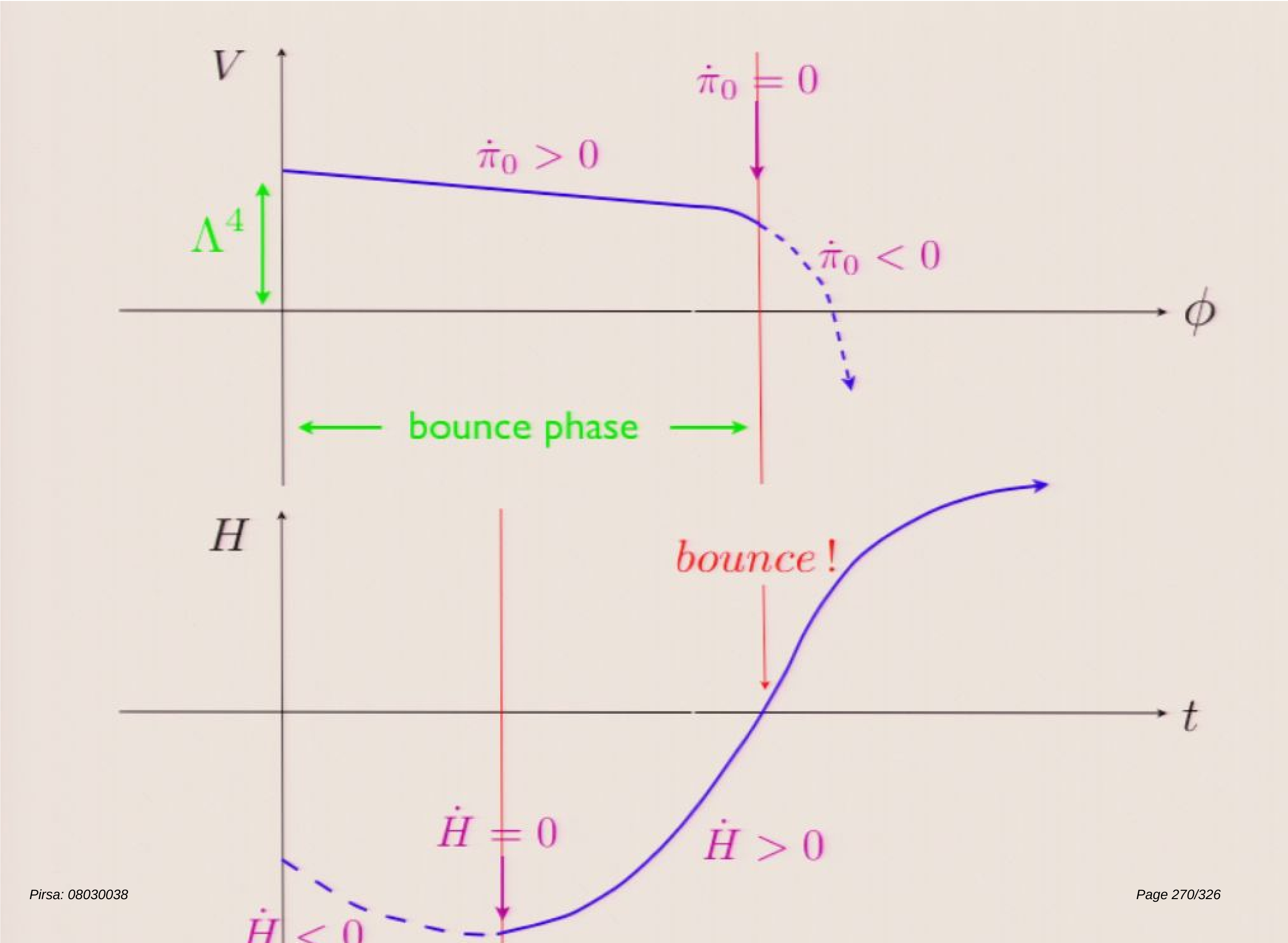


V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce !
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

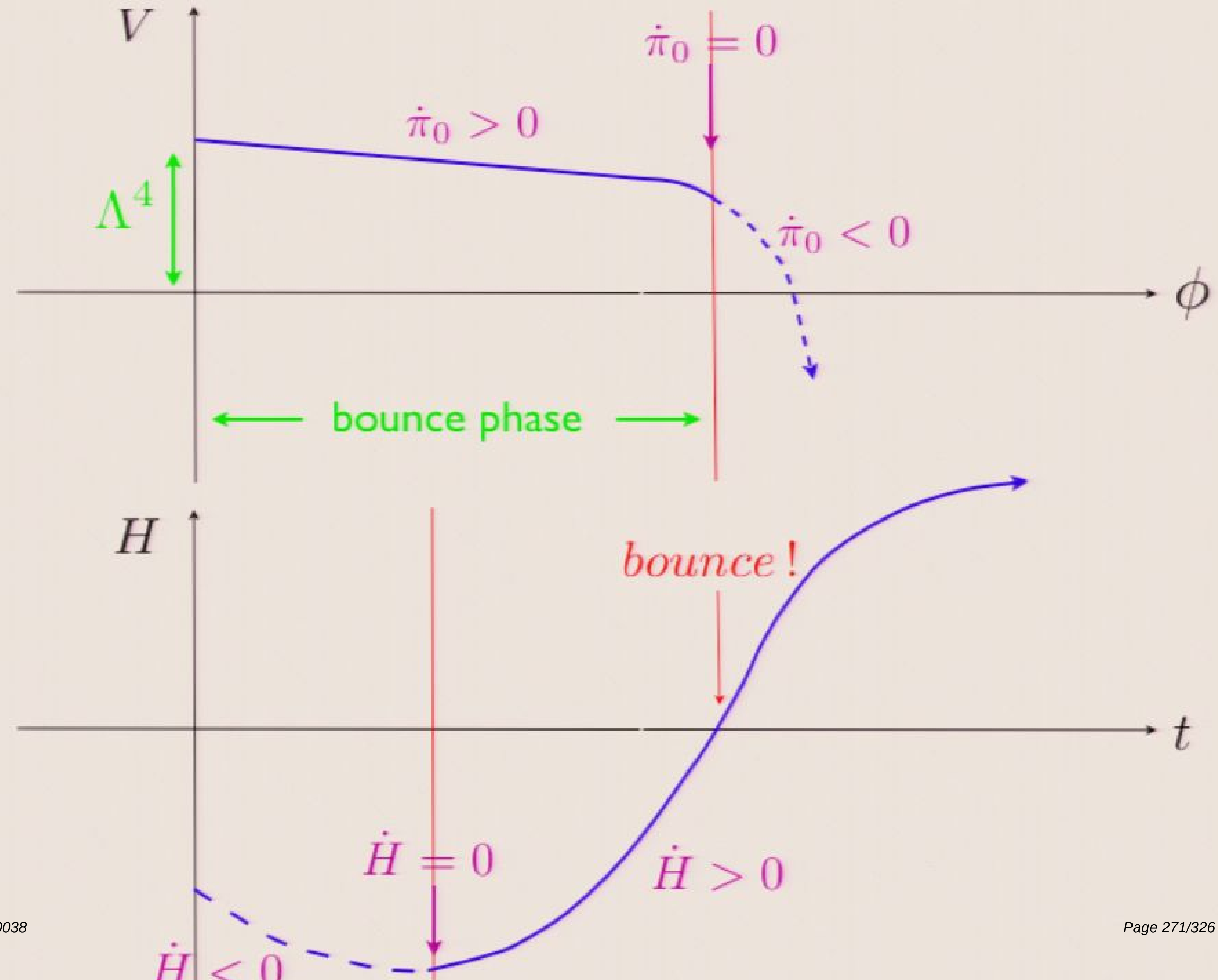


V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

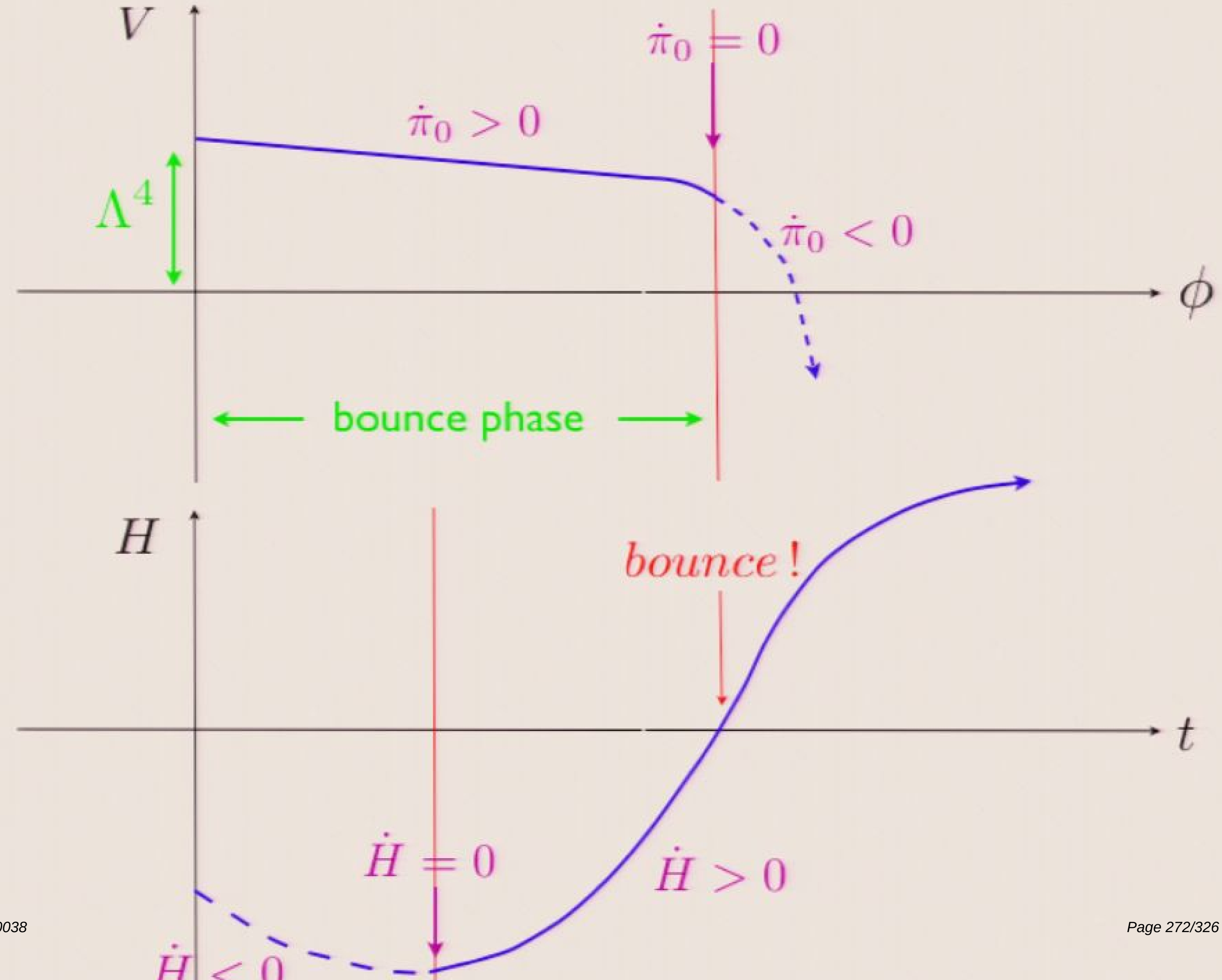

V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



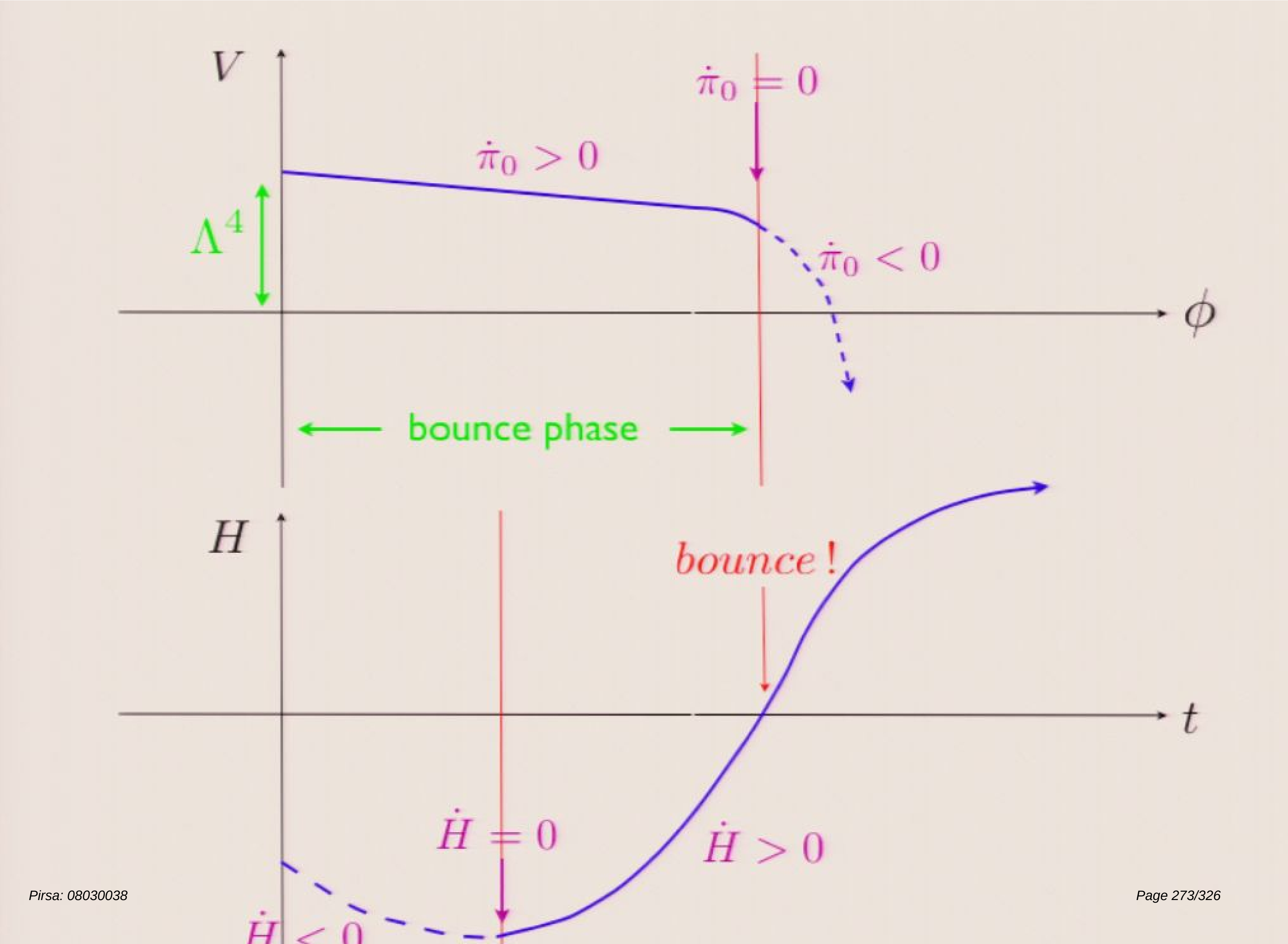
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

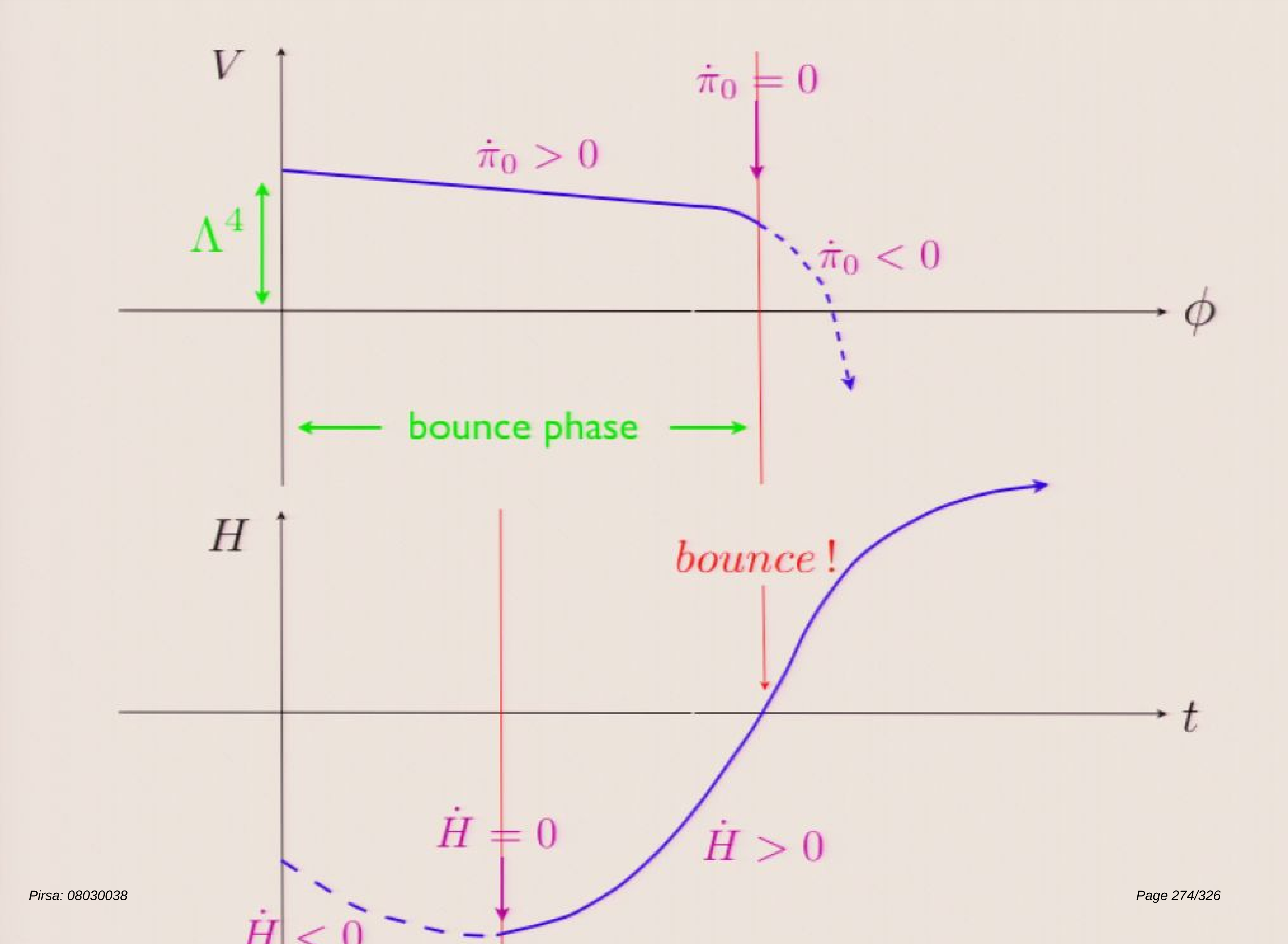


V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce\,!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

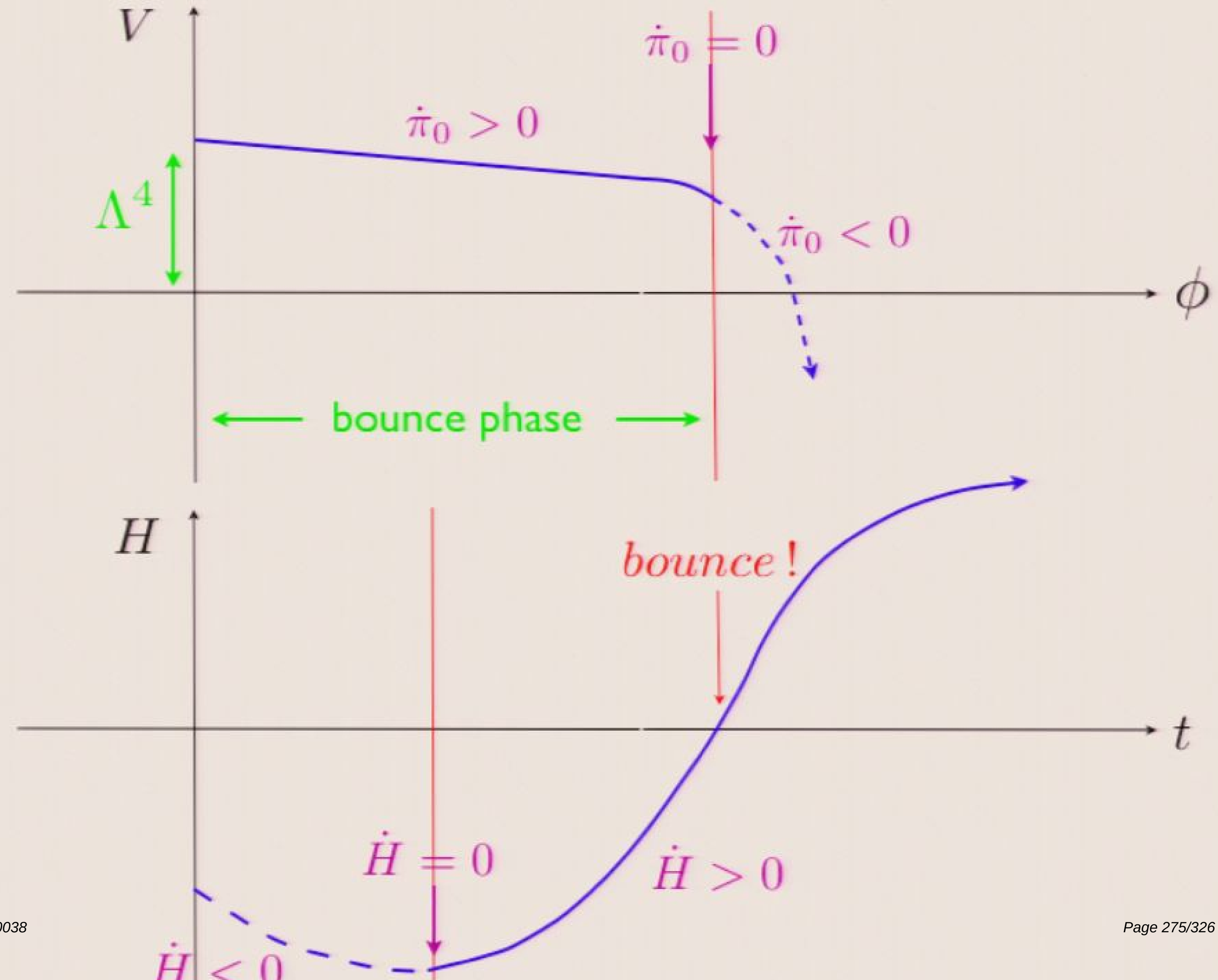


V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

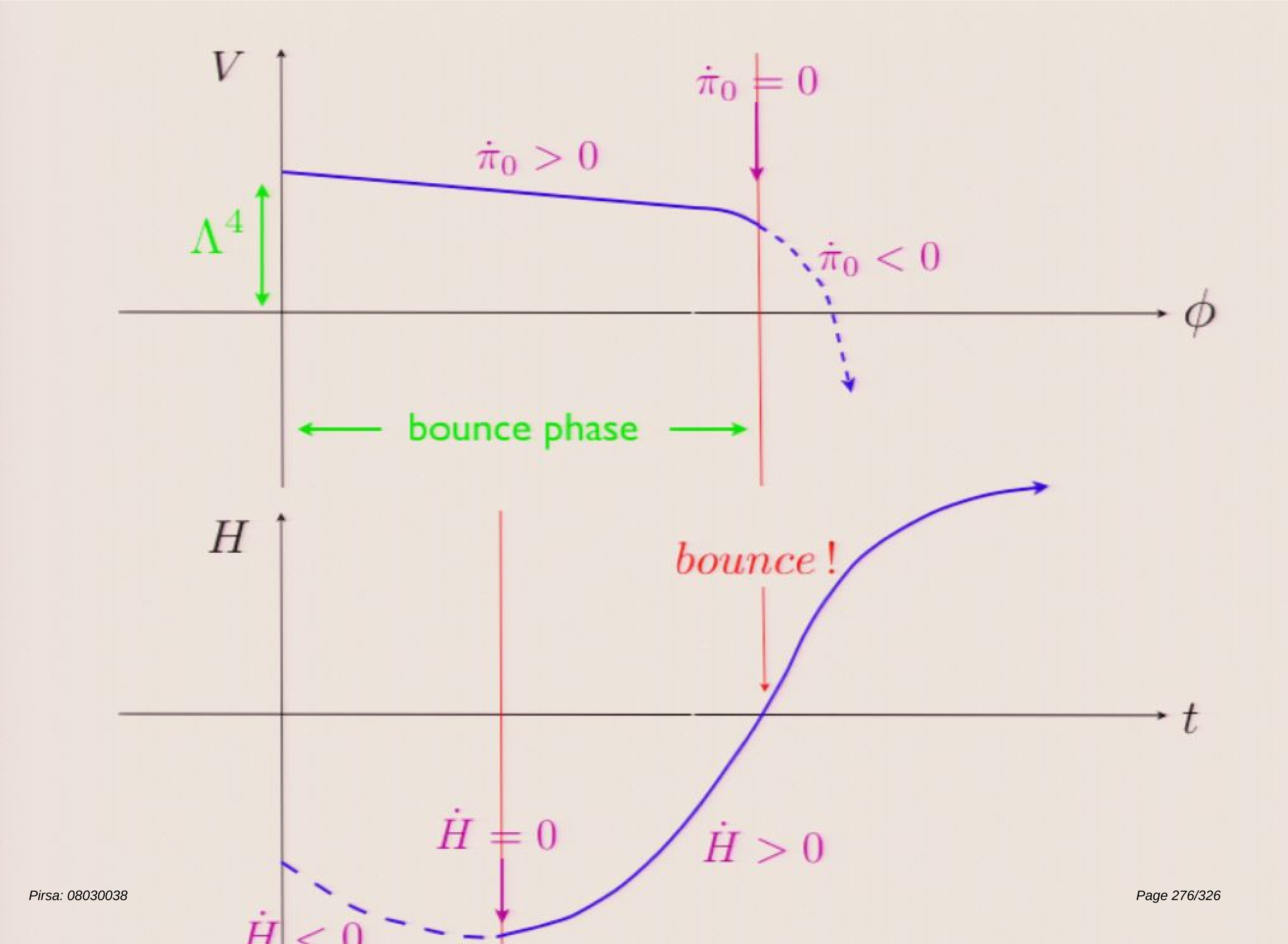

V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



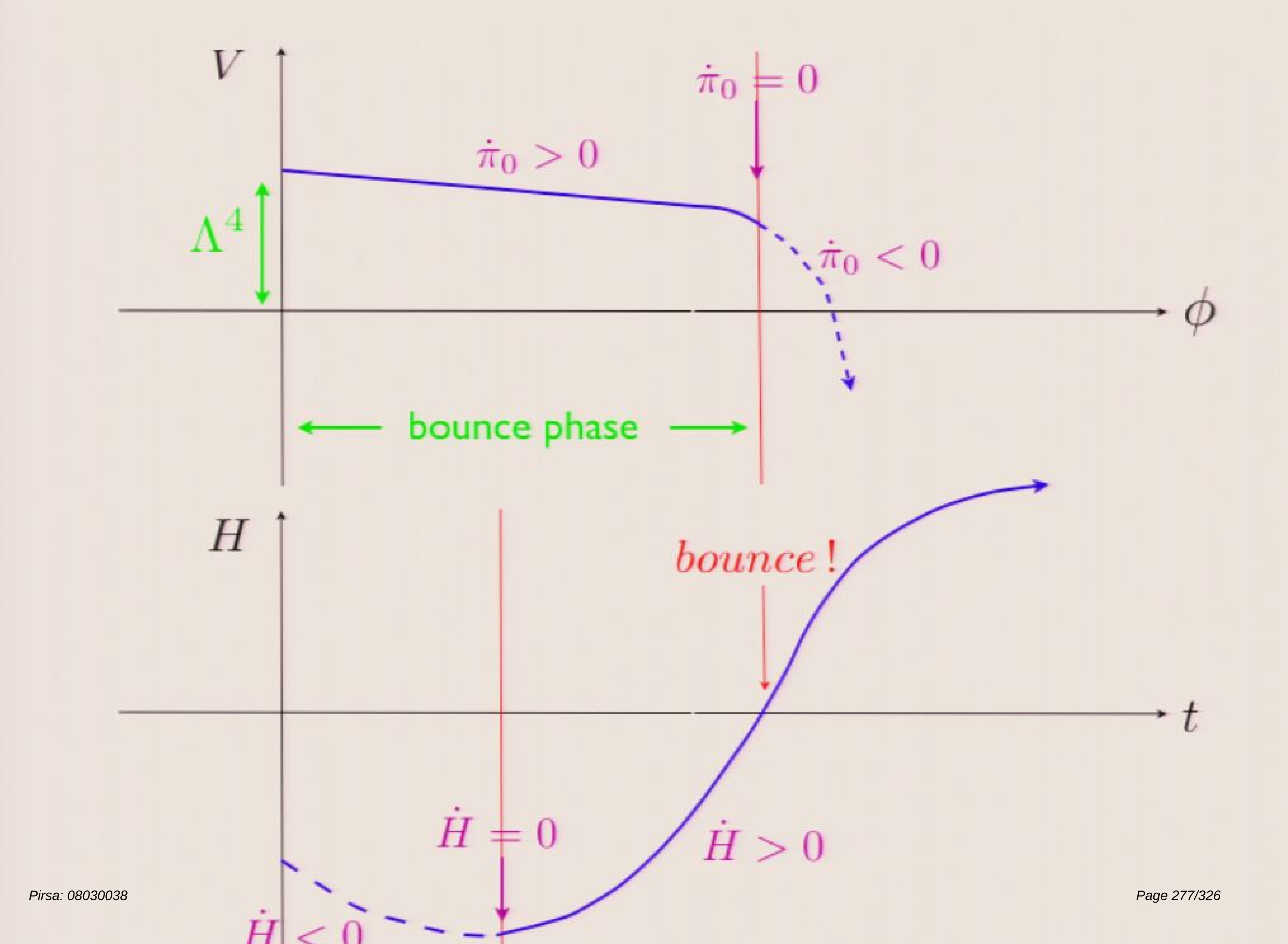
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce\,!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



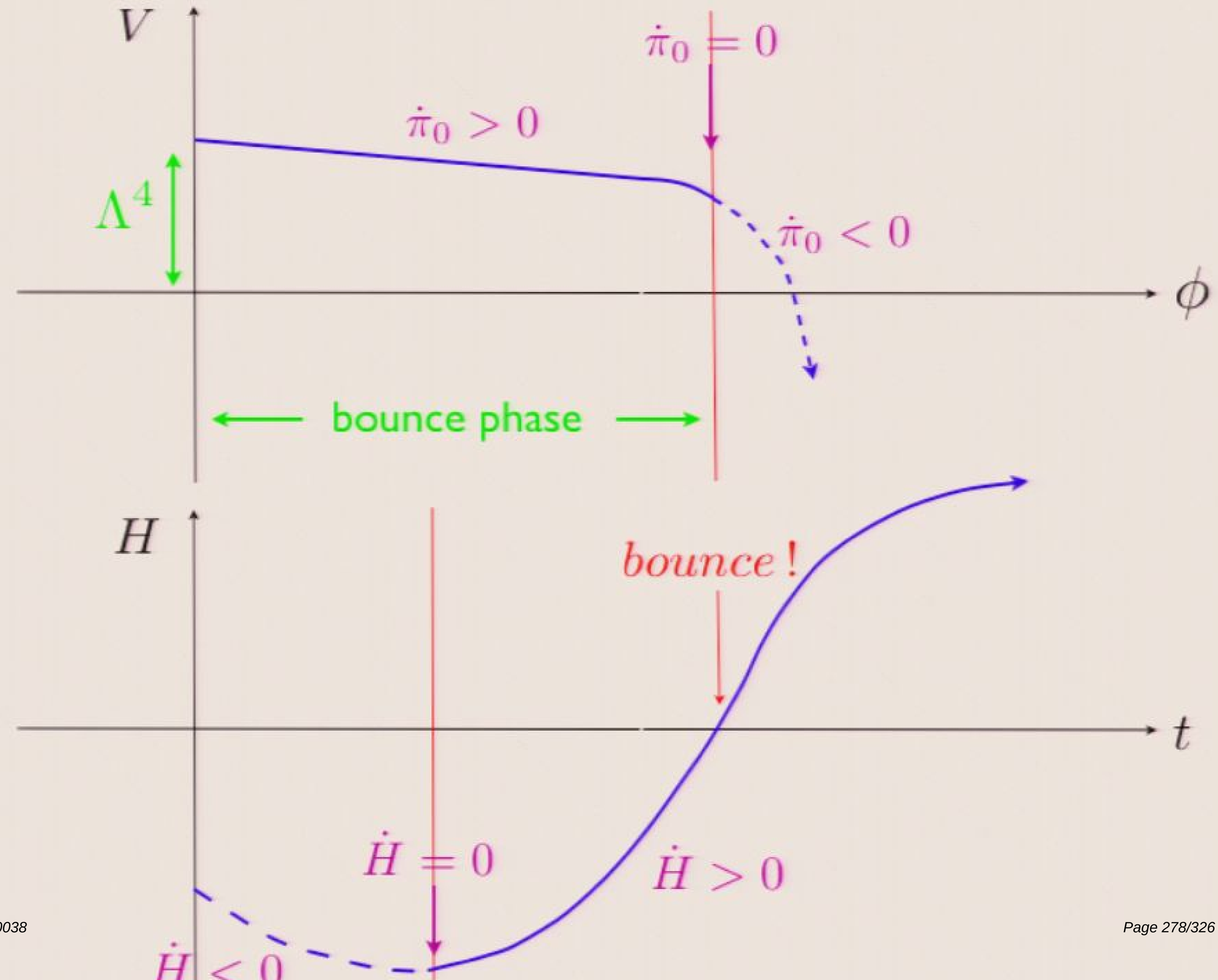
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce\,!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



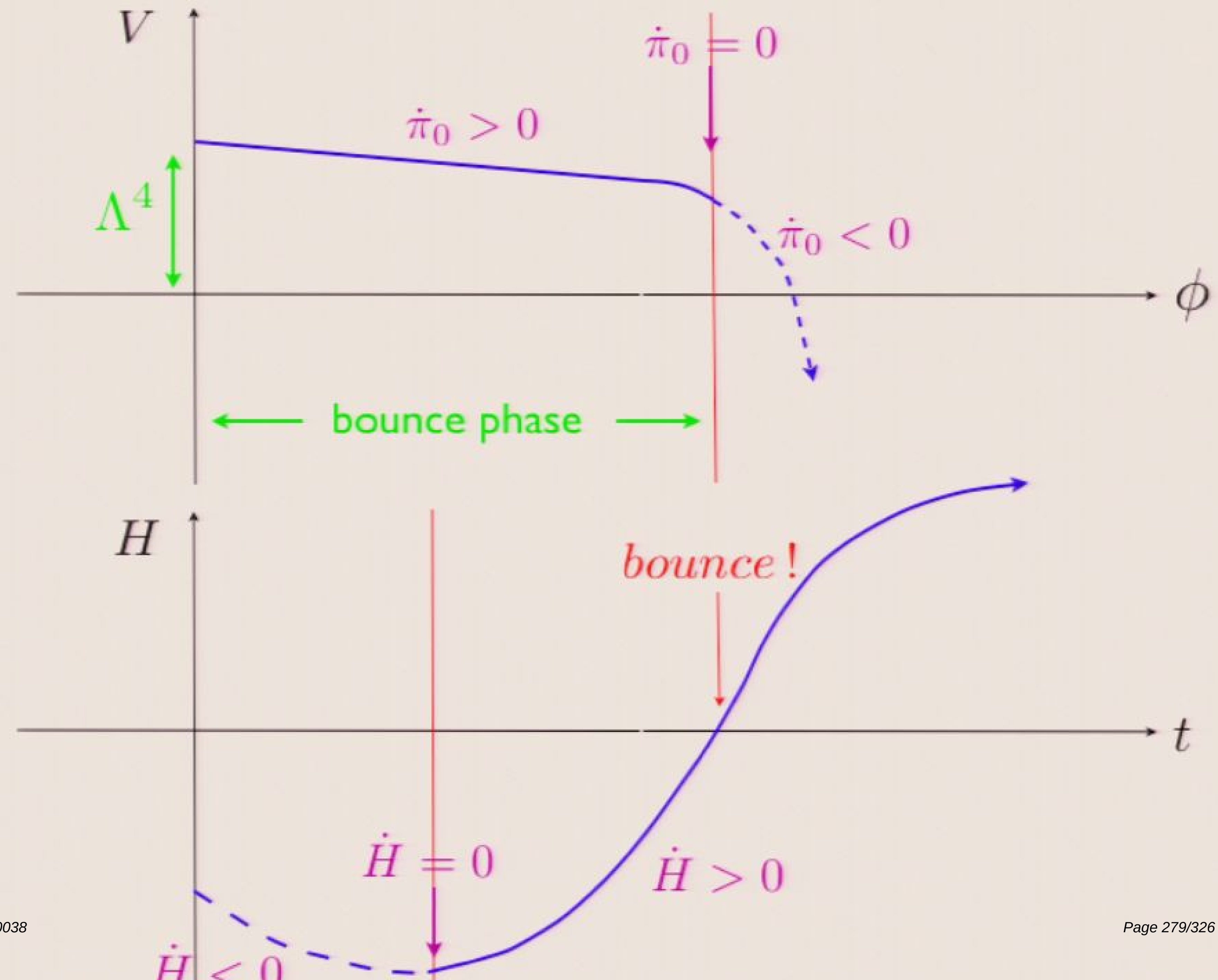
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



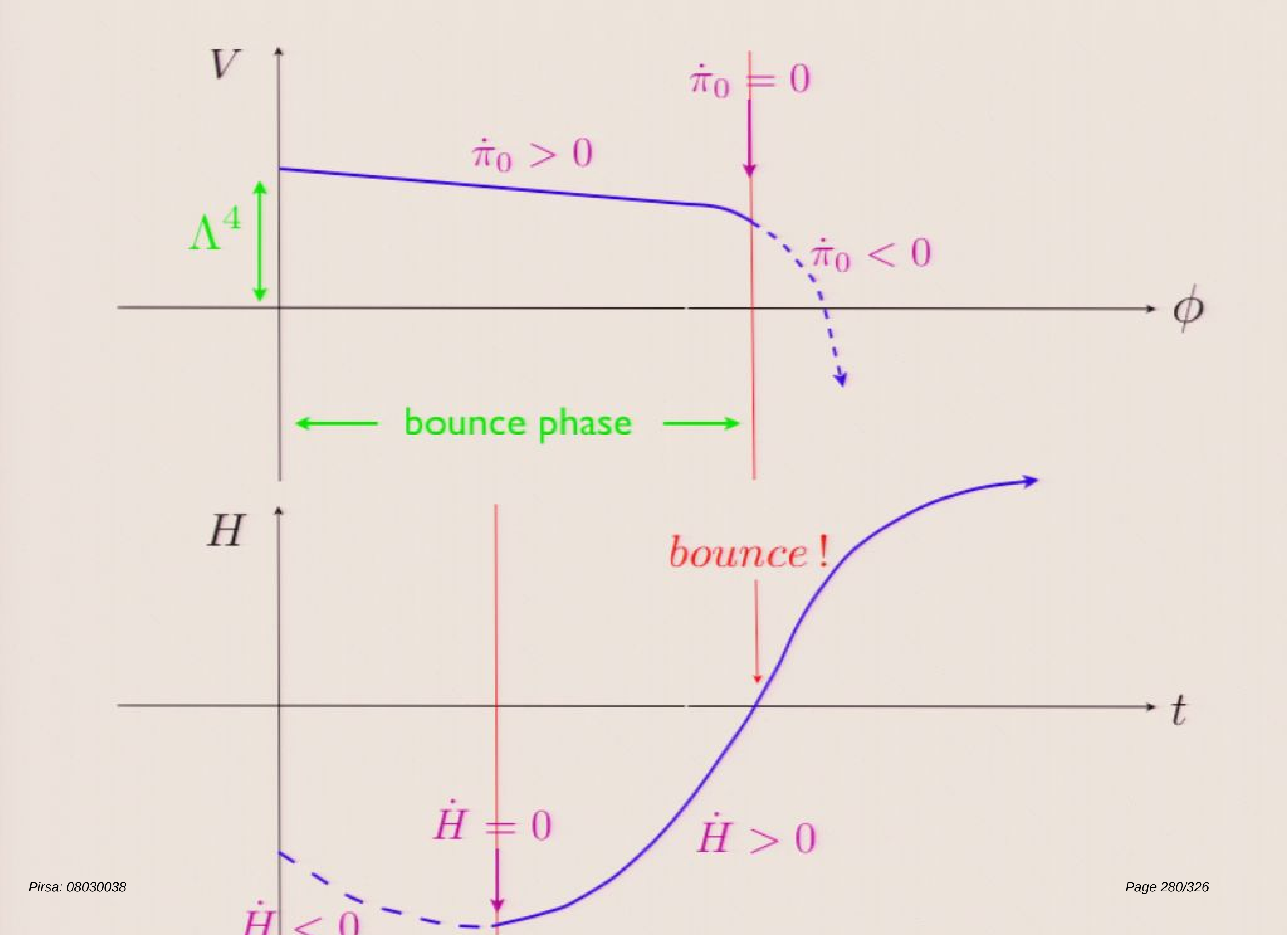
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
$bounce\,!$
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



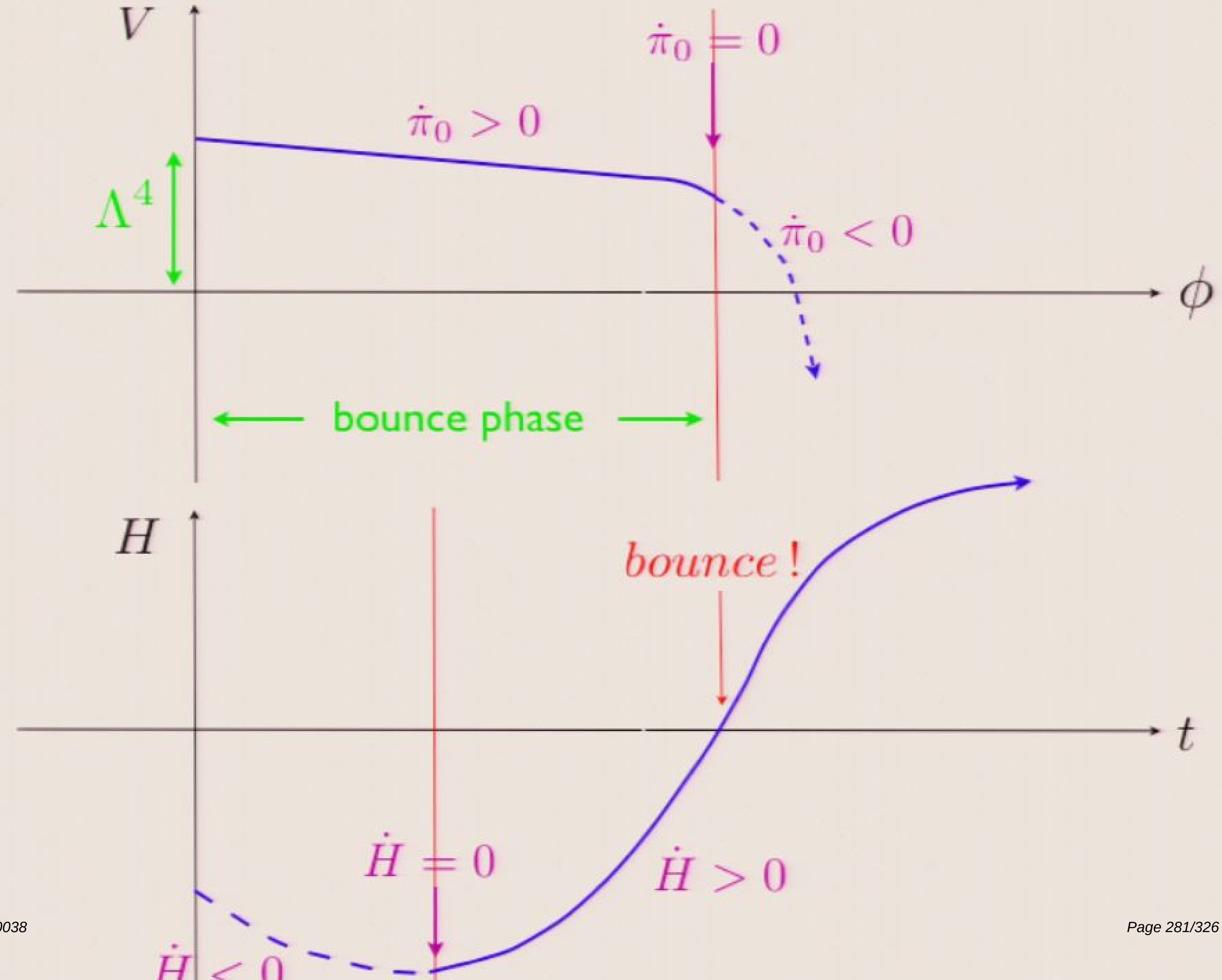
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



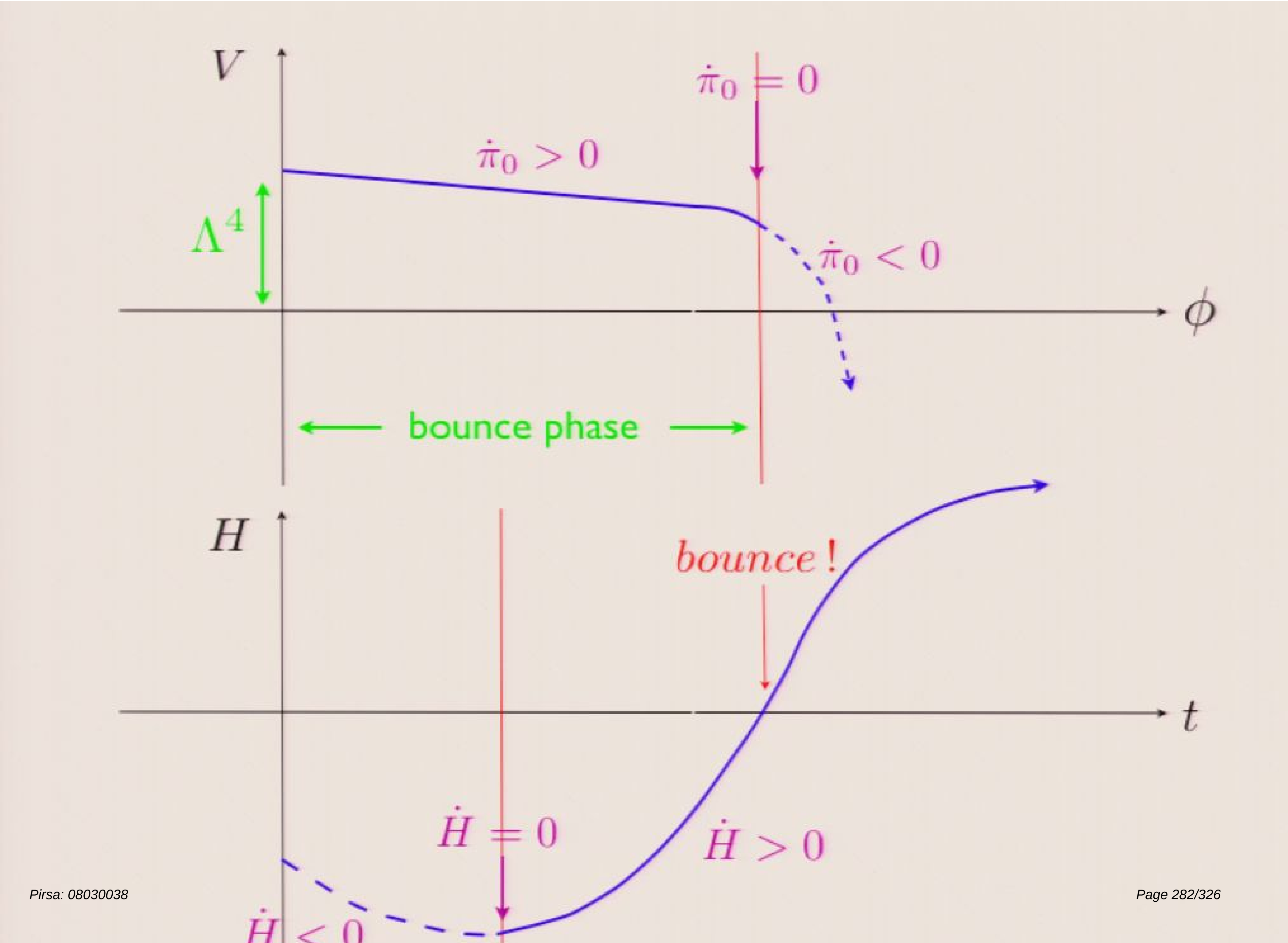
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



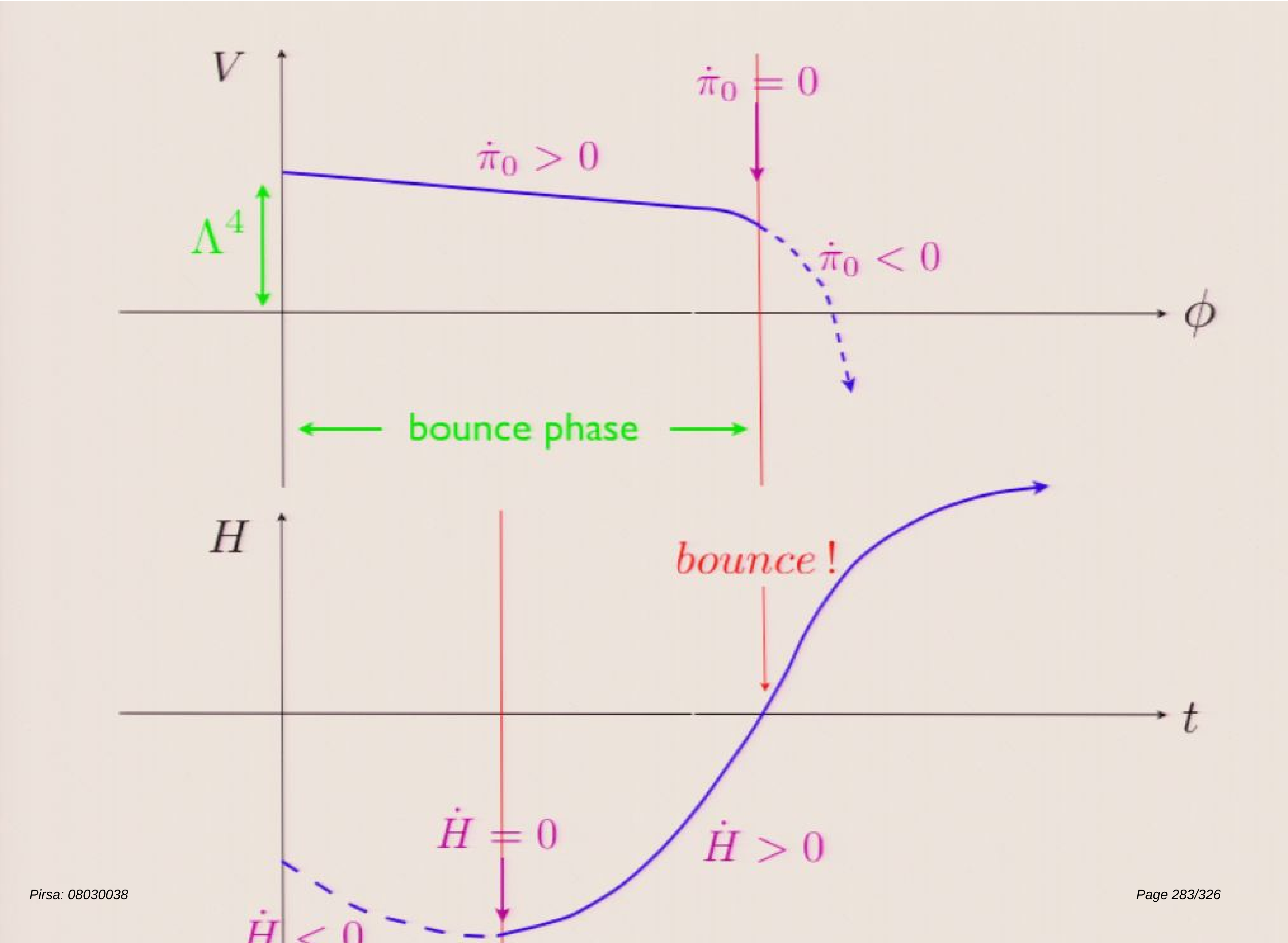
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



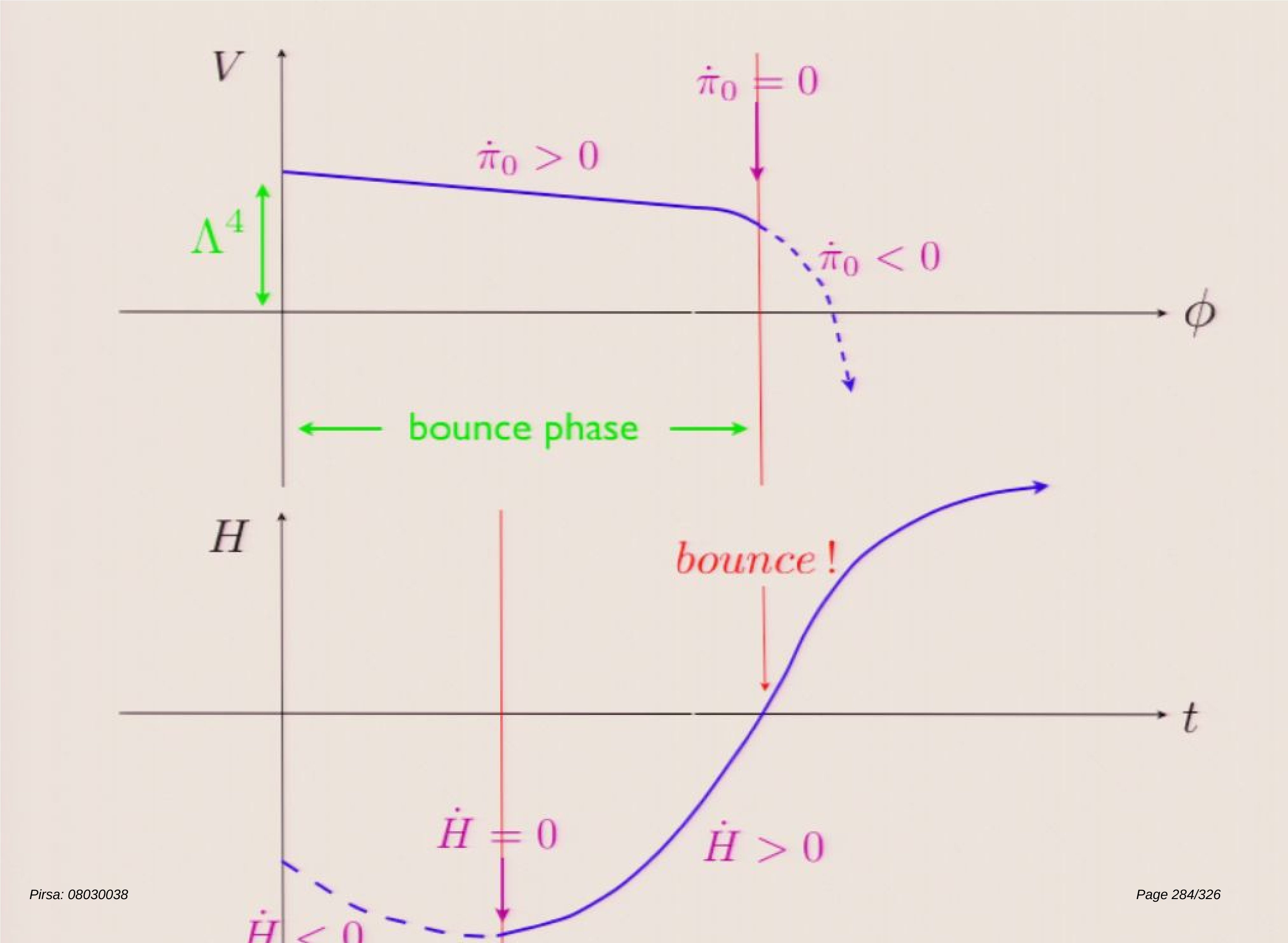
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$



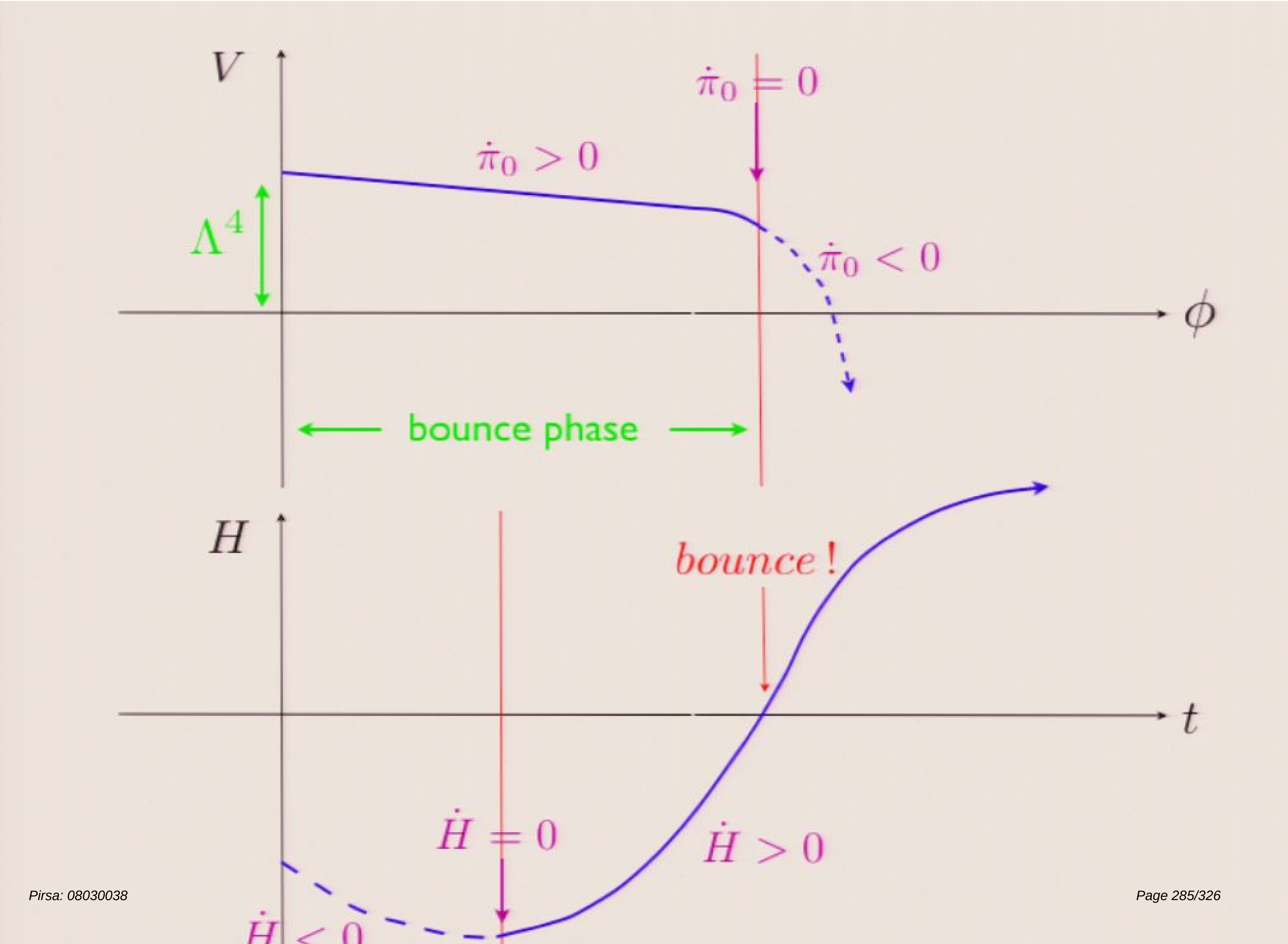
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



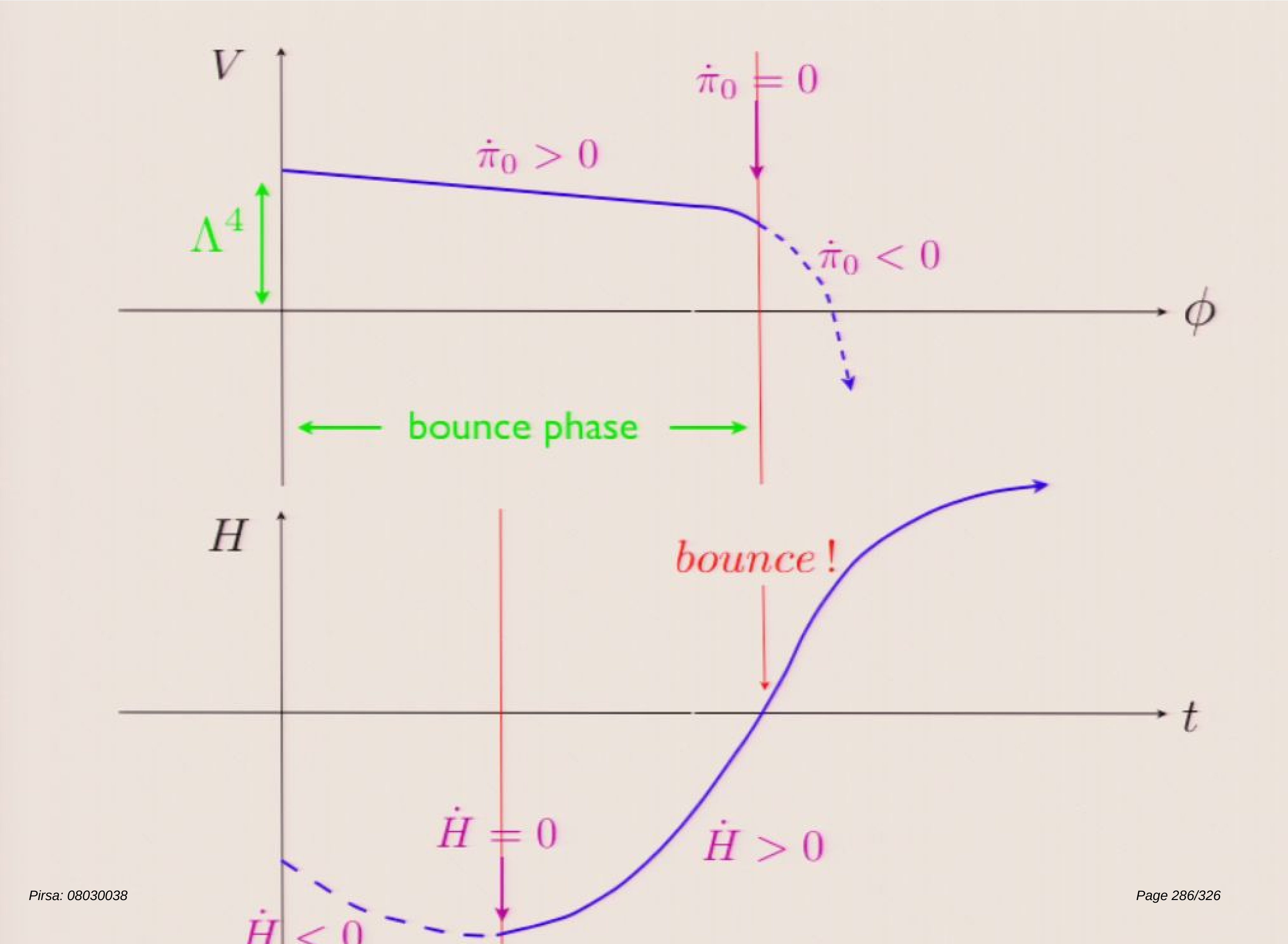
V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$



V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

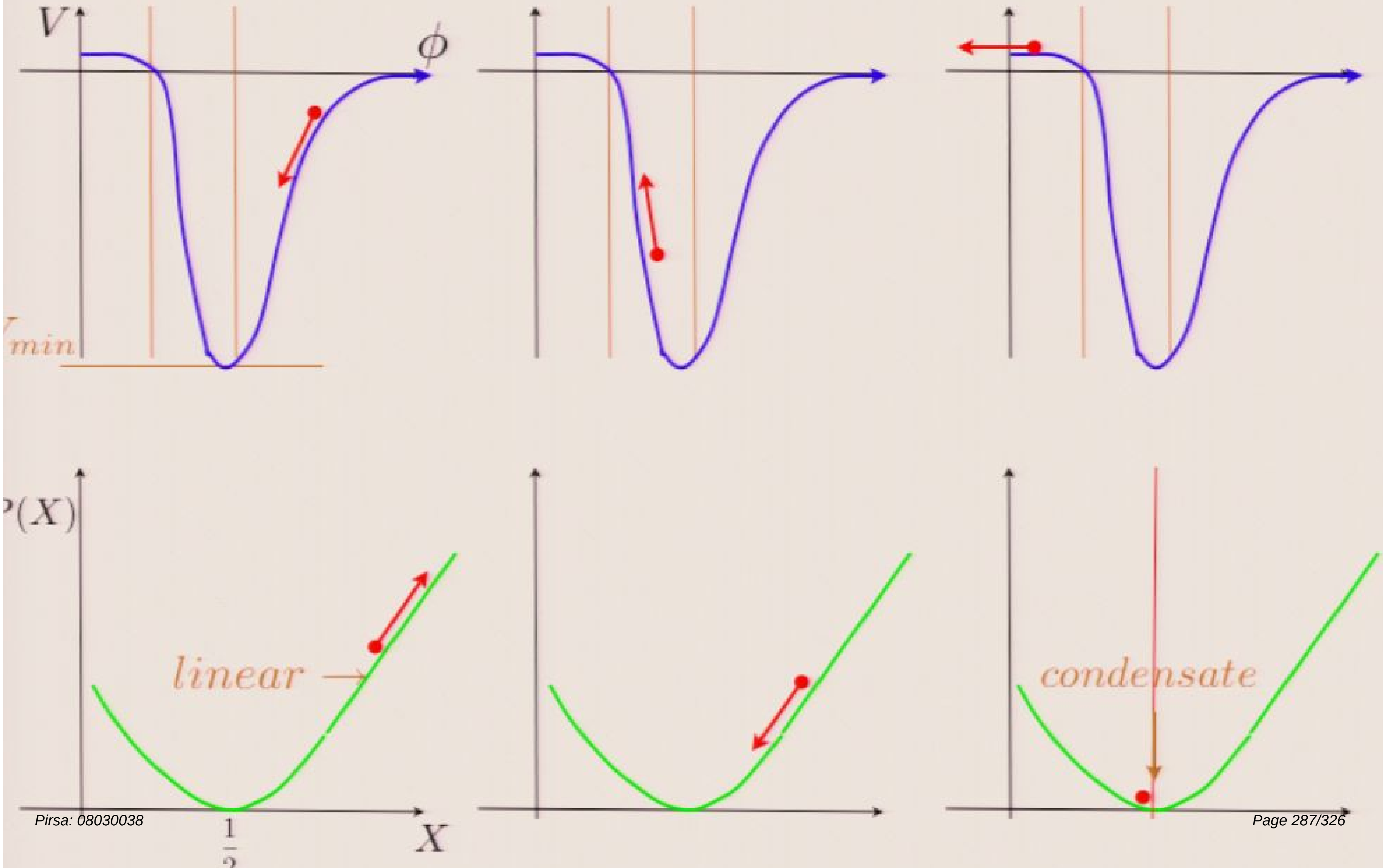


V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

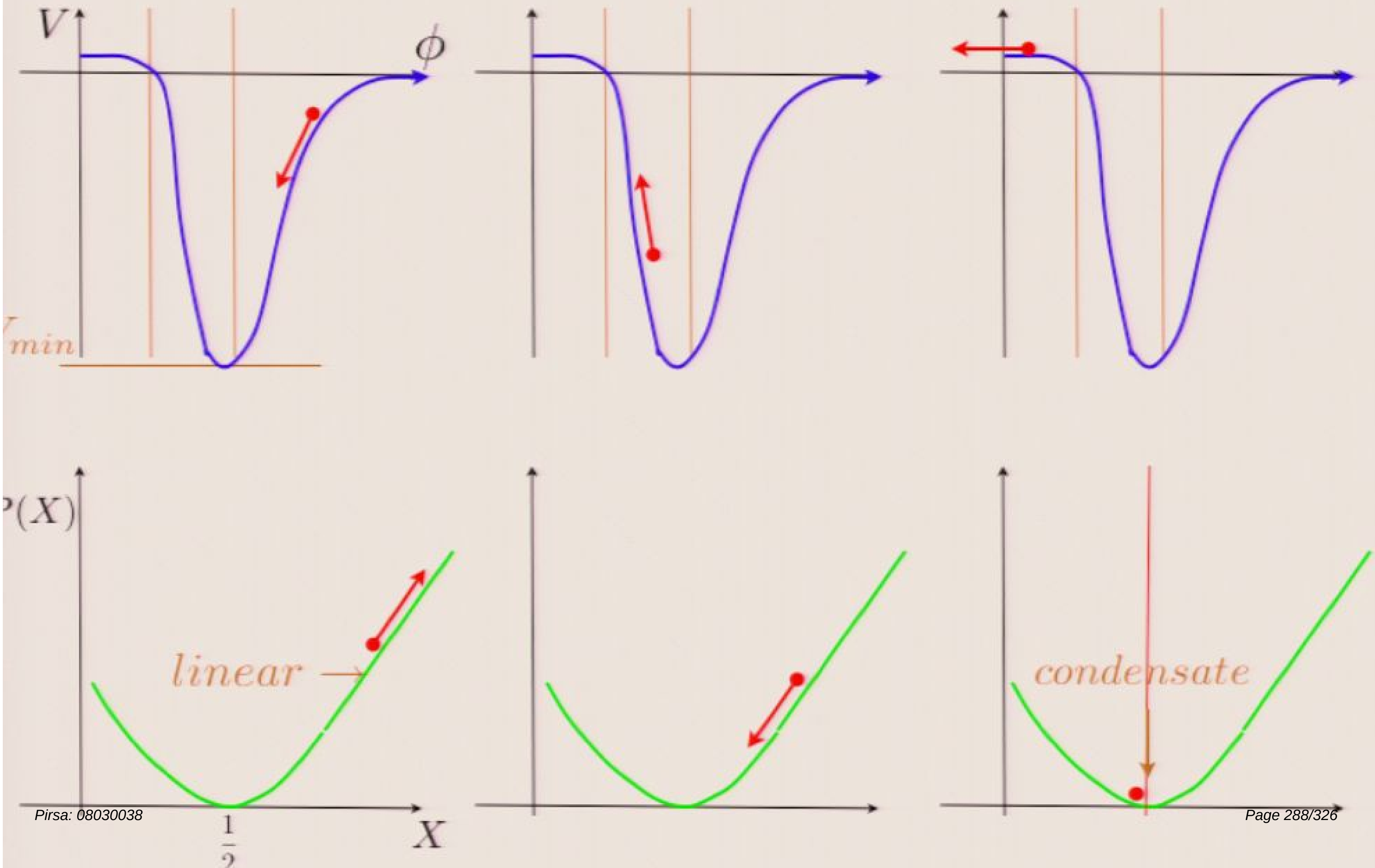


V
$\dot{\pi}_0 = 0$
$\dot{\pi}_0 > 0$
Λ^4
$\dot{\pi}_0 < 0$
ϕ
bounce phase
H
bounce!
t
$\dot{H} = 0$
$\dot{H} > 0$
$\dot{H} < 0$

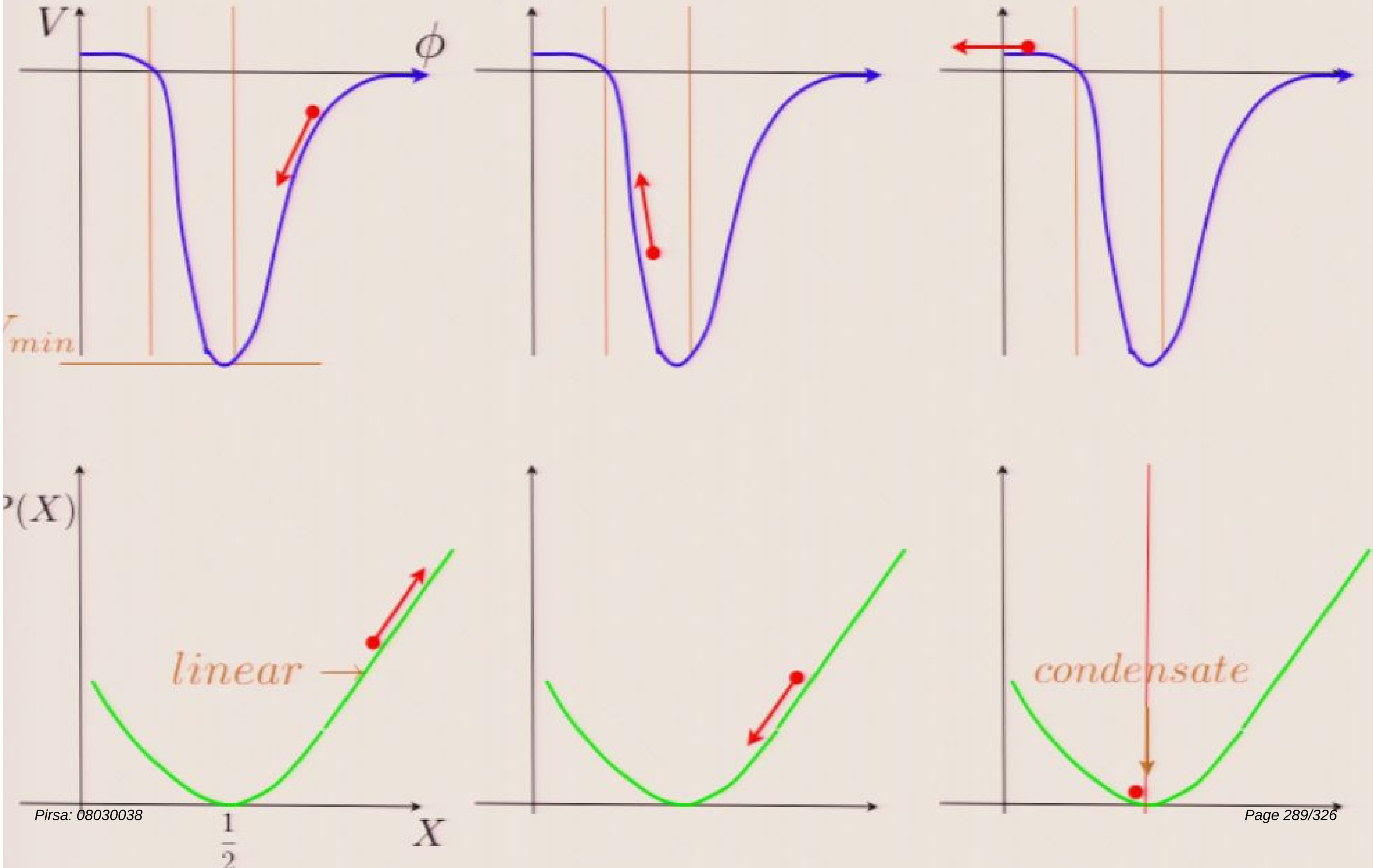
b) Merger with Ekpyrosis



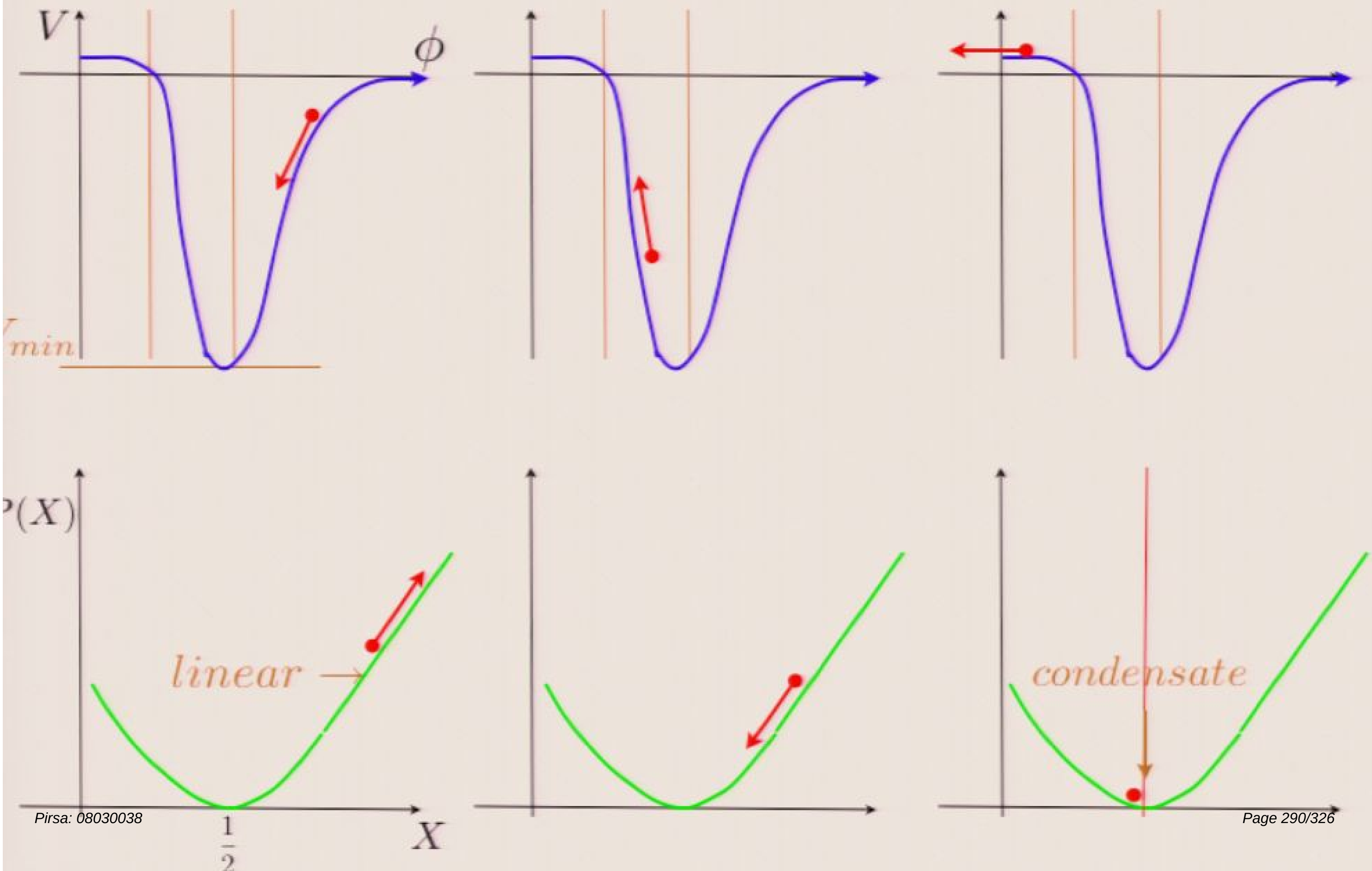
b) Merger with Ekpyrosis



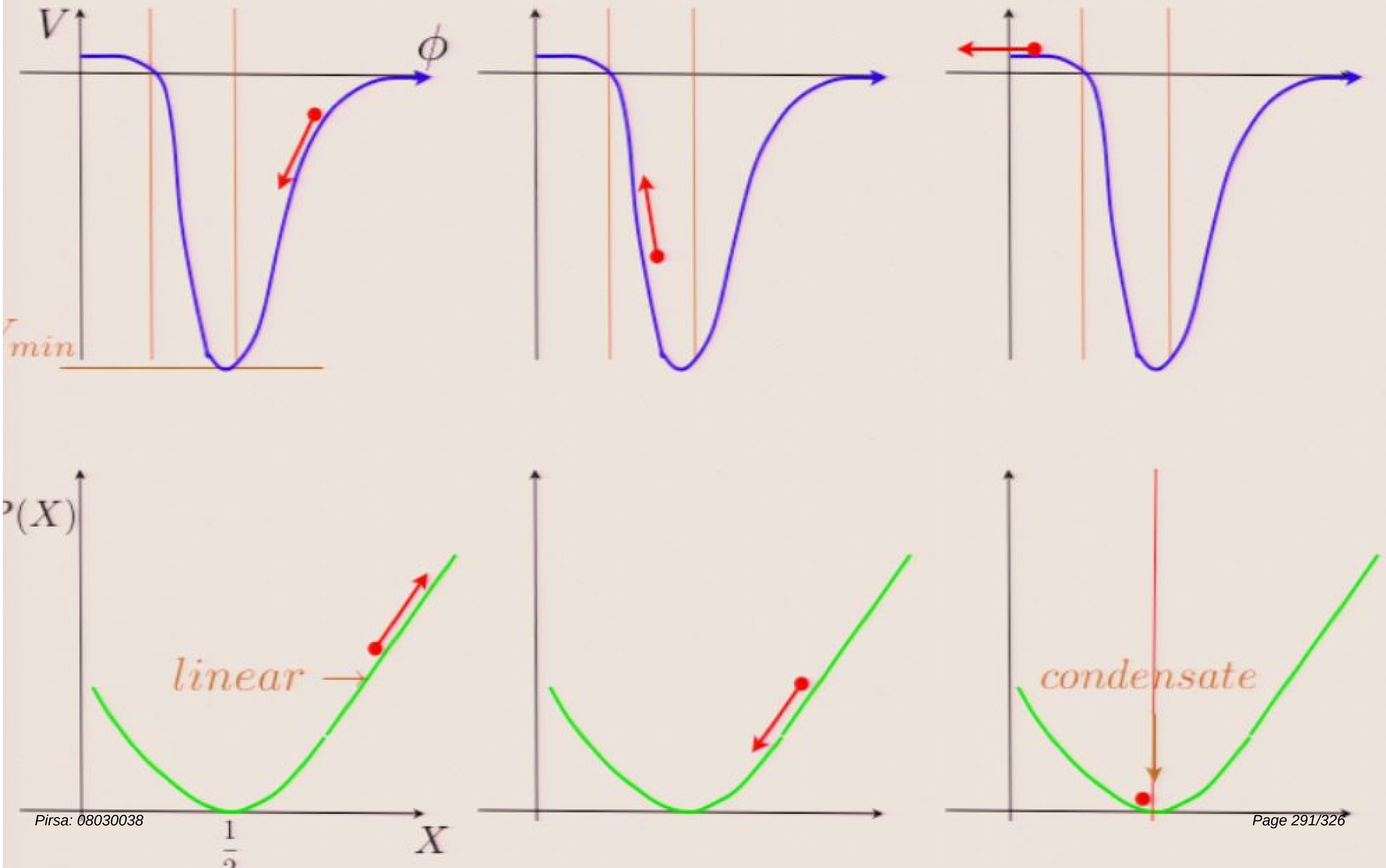
b) Merger with Ekpyrosis



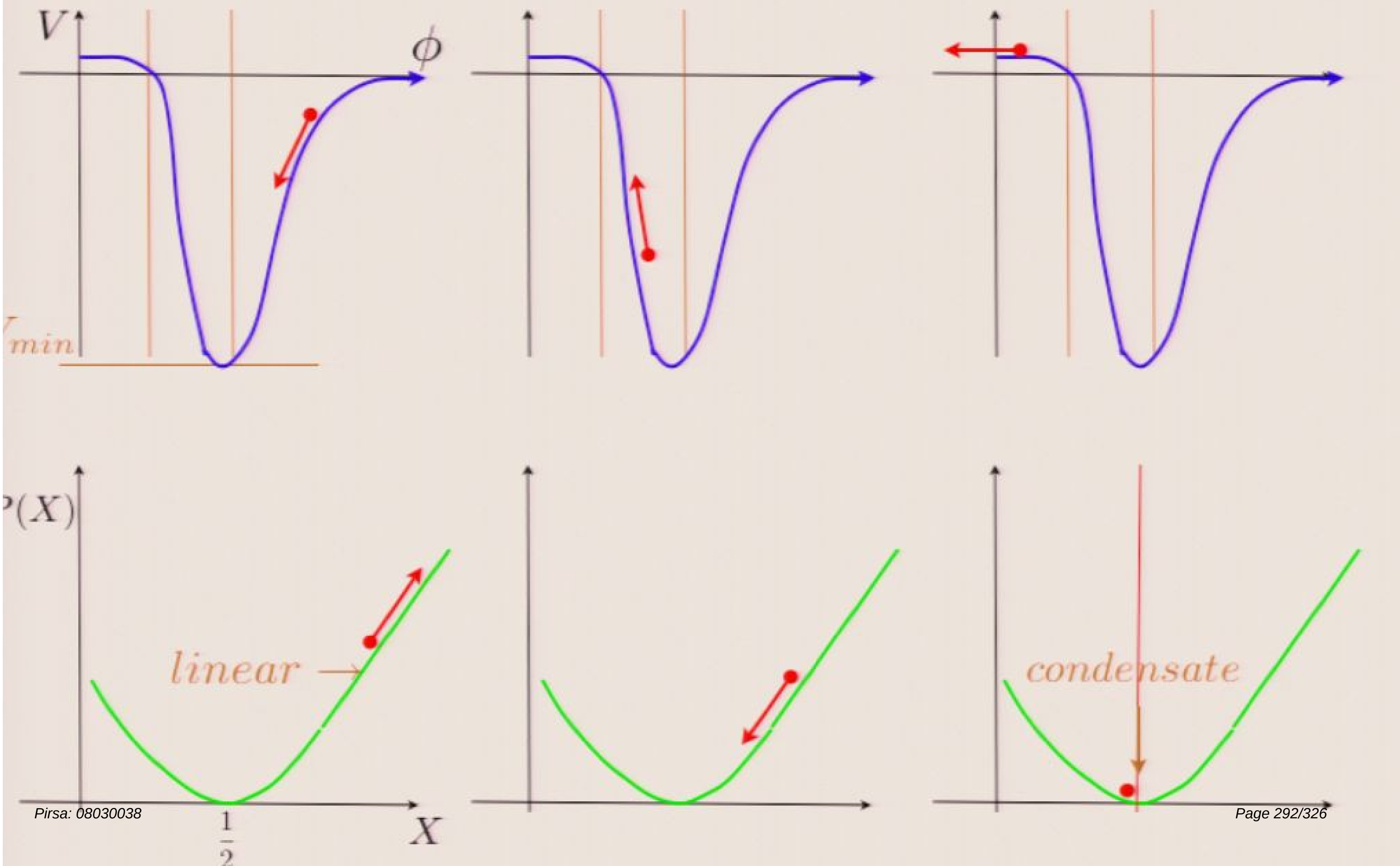
b) Merger with Ekpyrosis



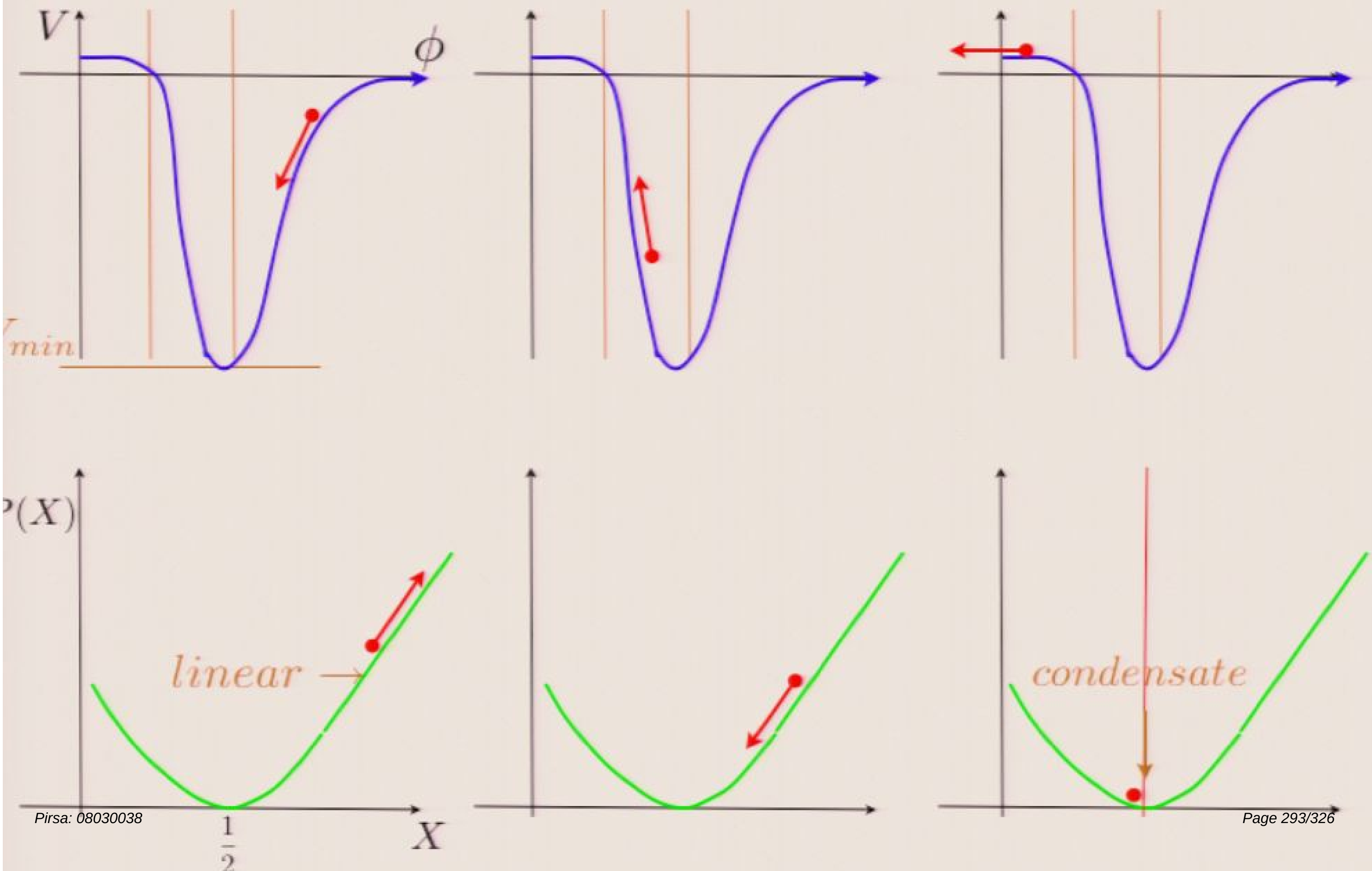
b) Merger with Ekpyrosis



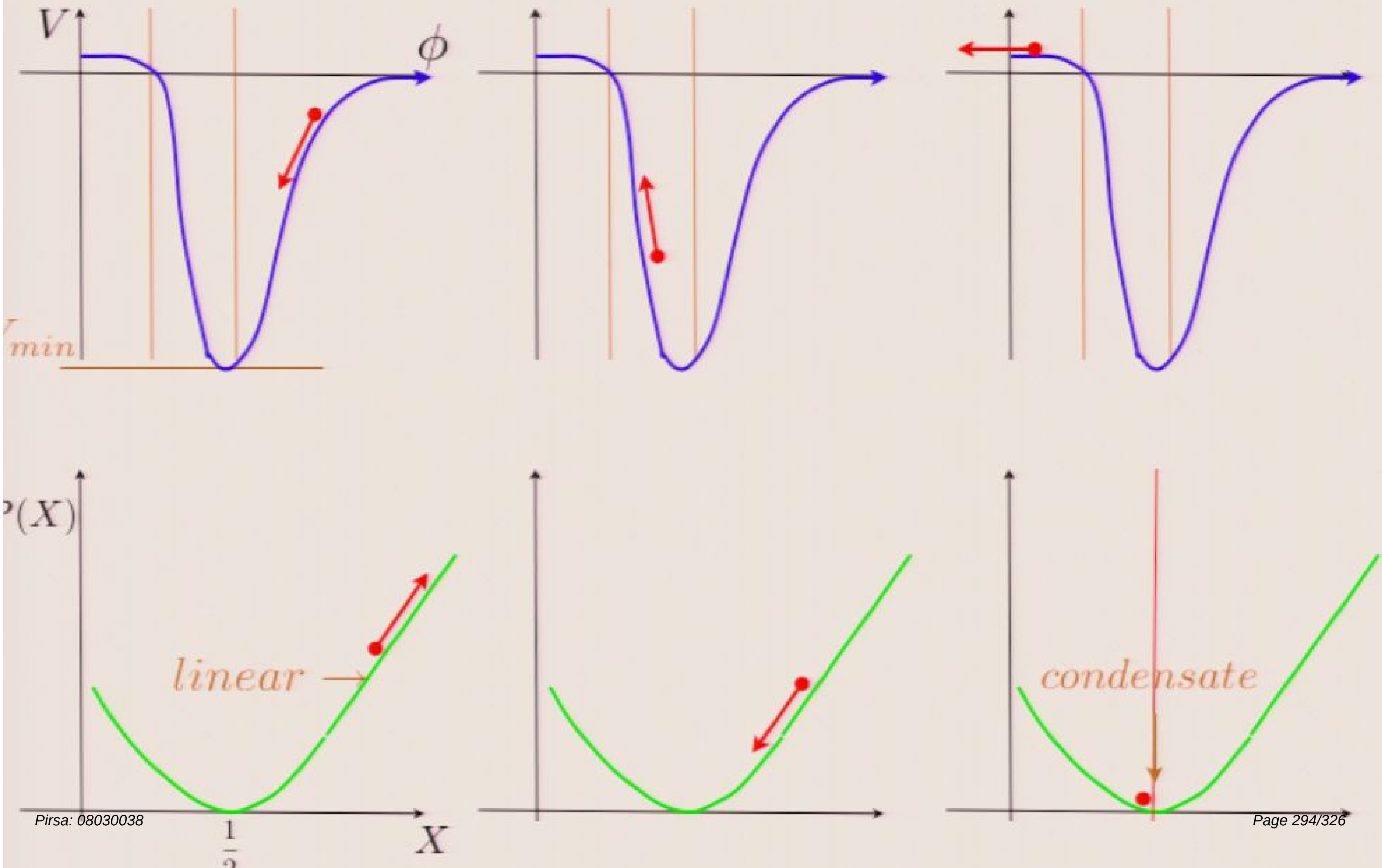
b) Merger with Ekpyrosis



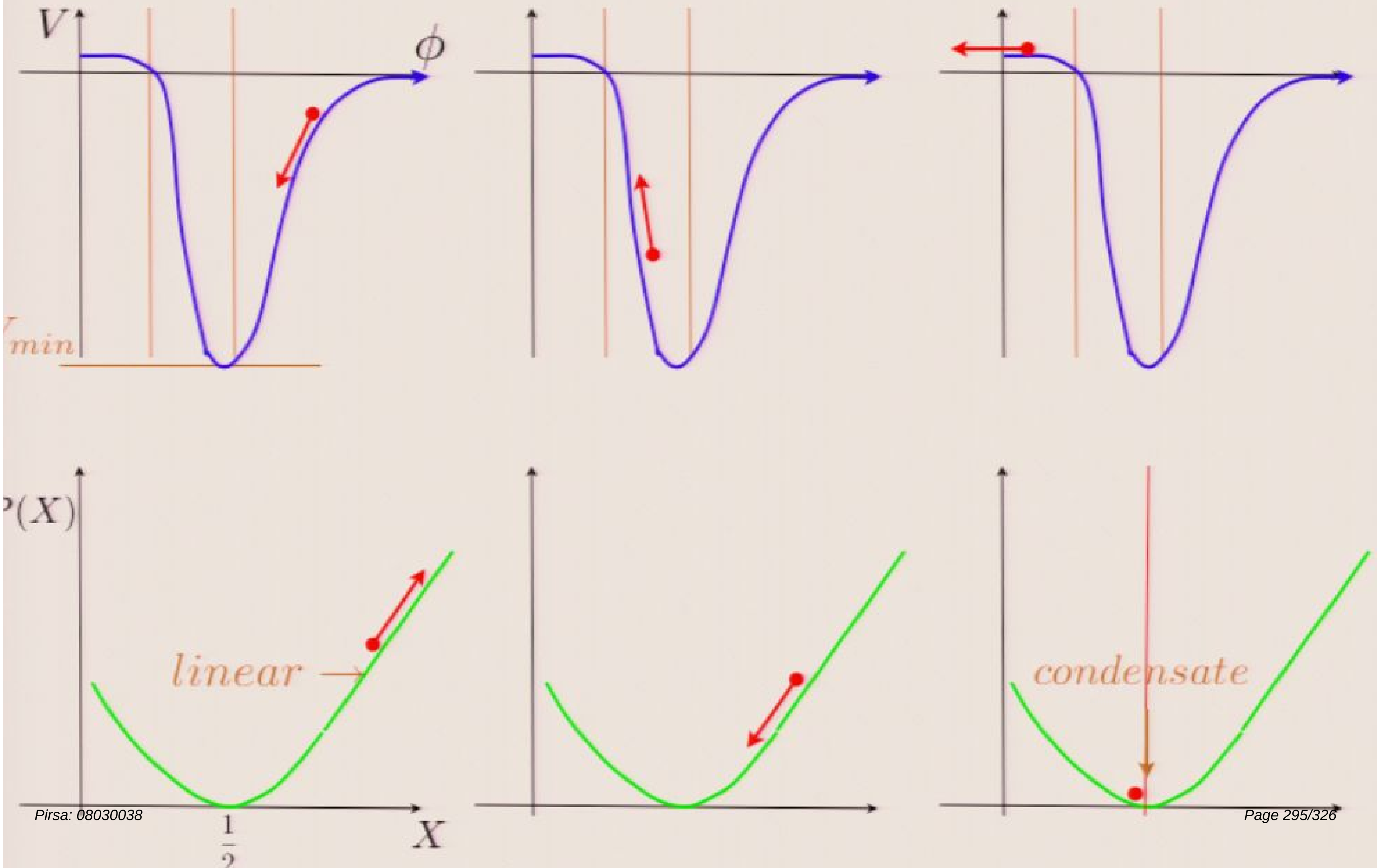
b) Merger with Ekpyrosis



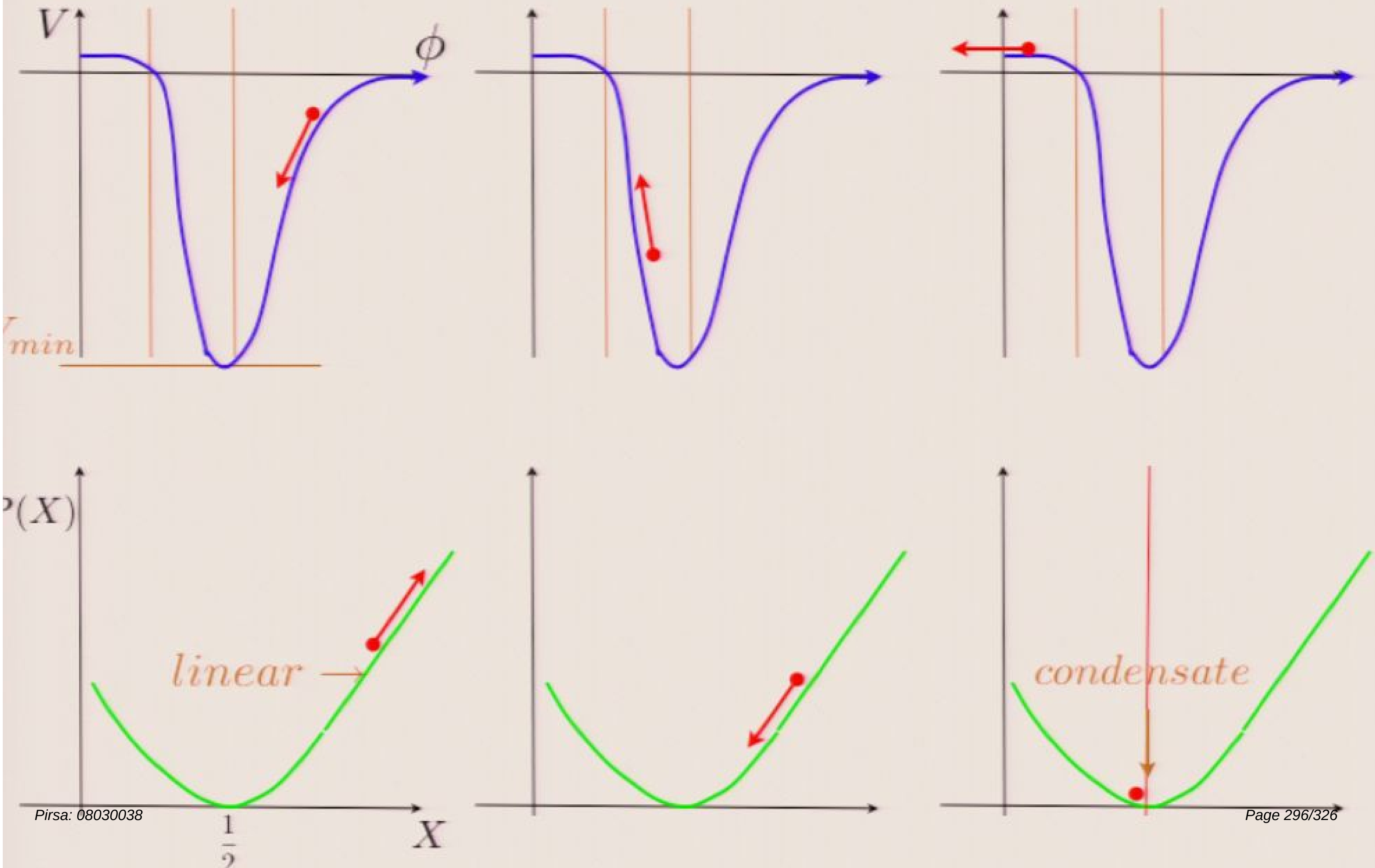
ɔ) Merger with Ekpyrosis



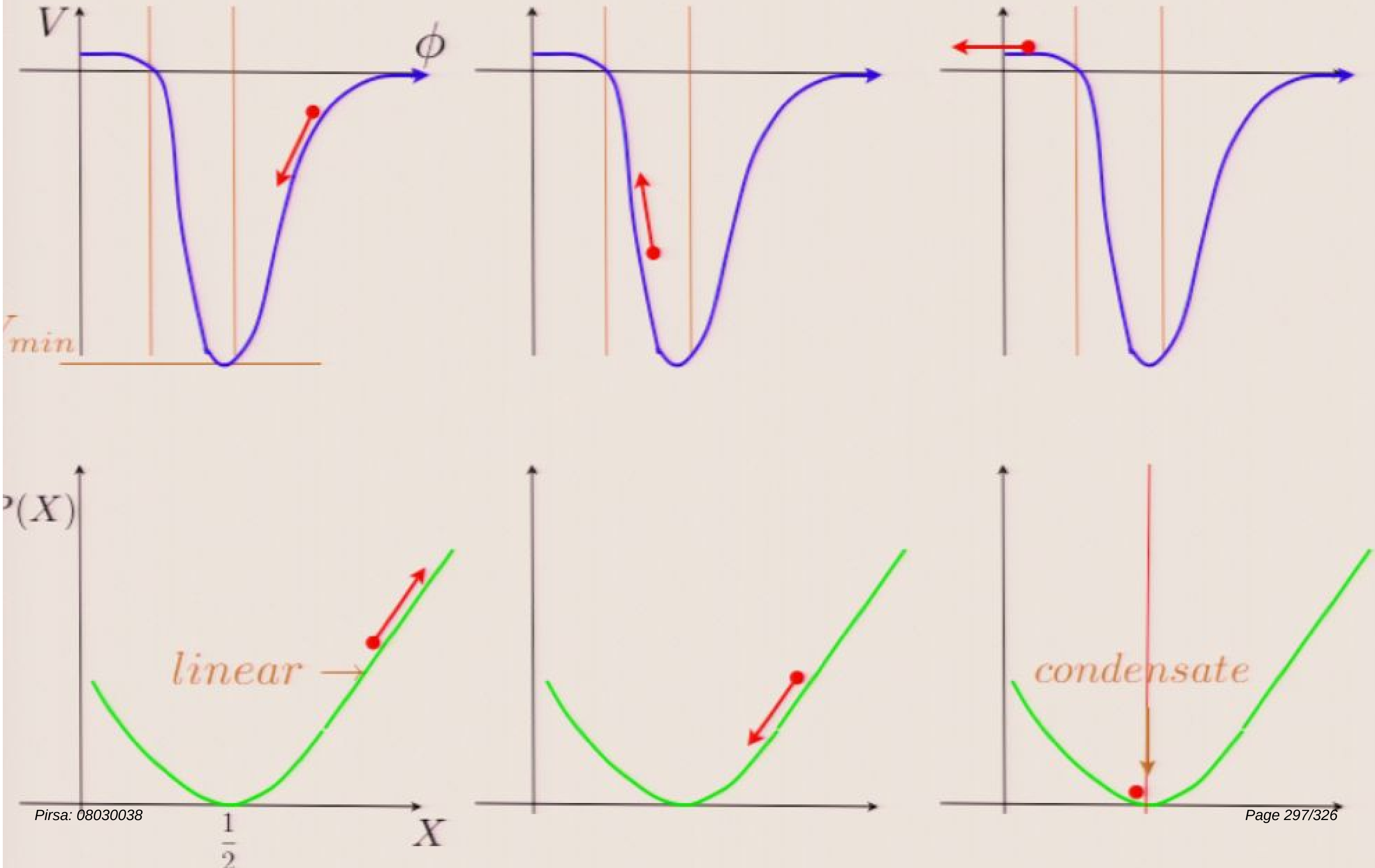
b) Merger with Ekpyrosis



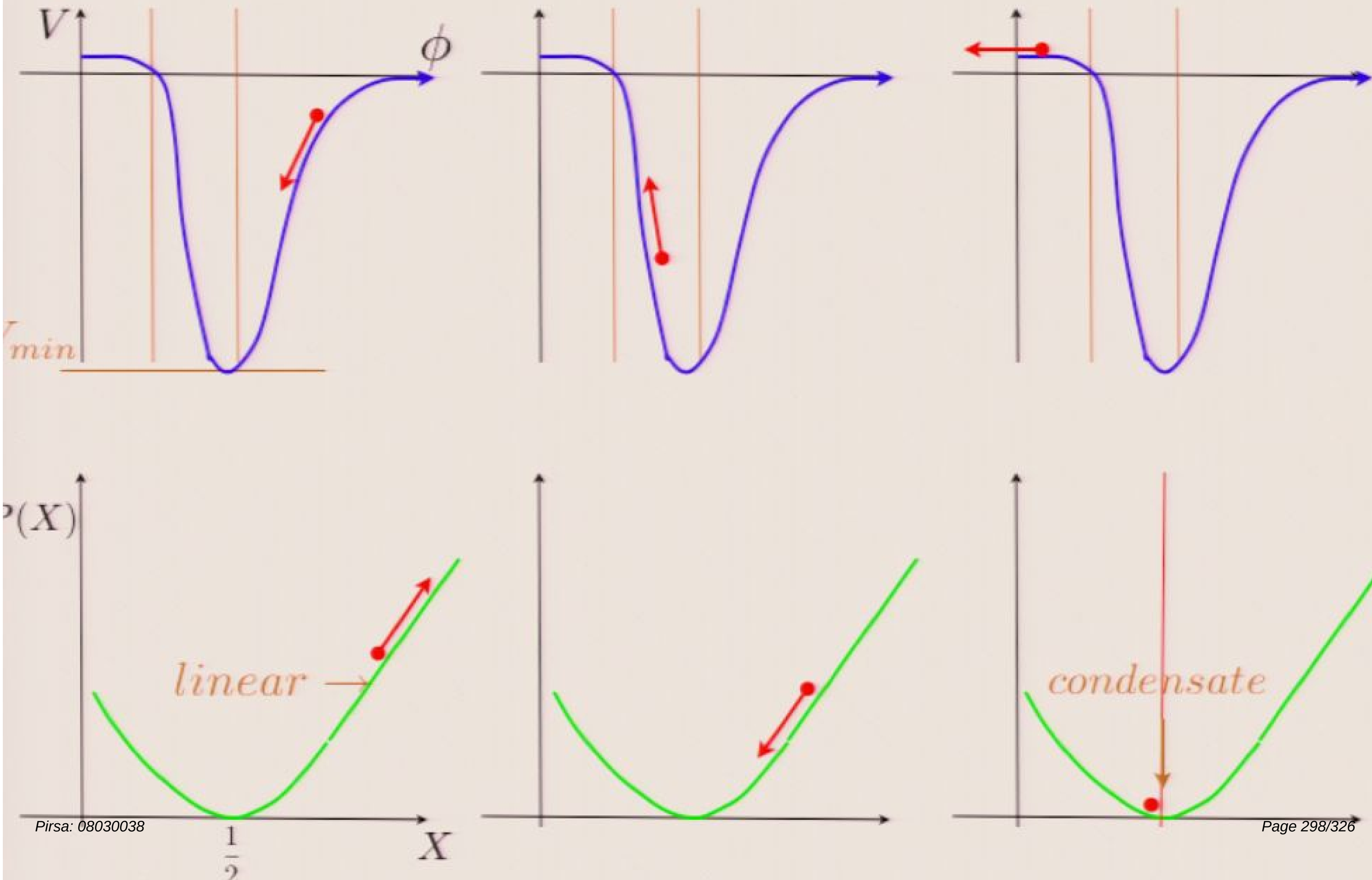
b) Merger with Ekpyrosis



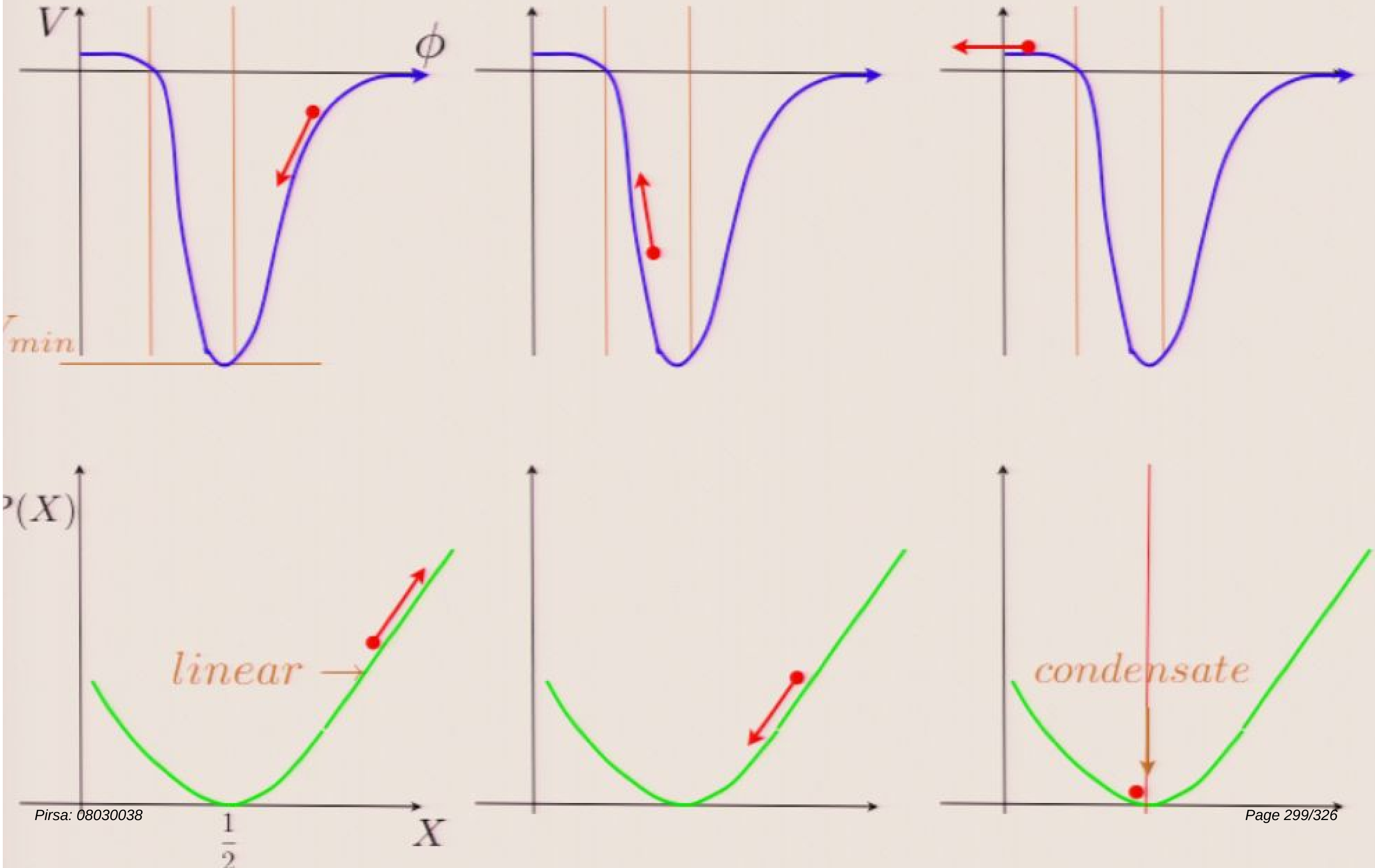
b) Merger with Ekpyrosis



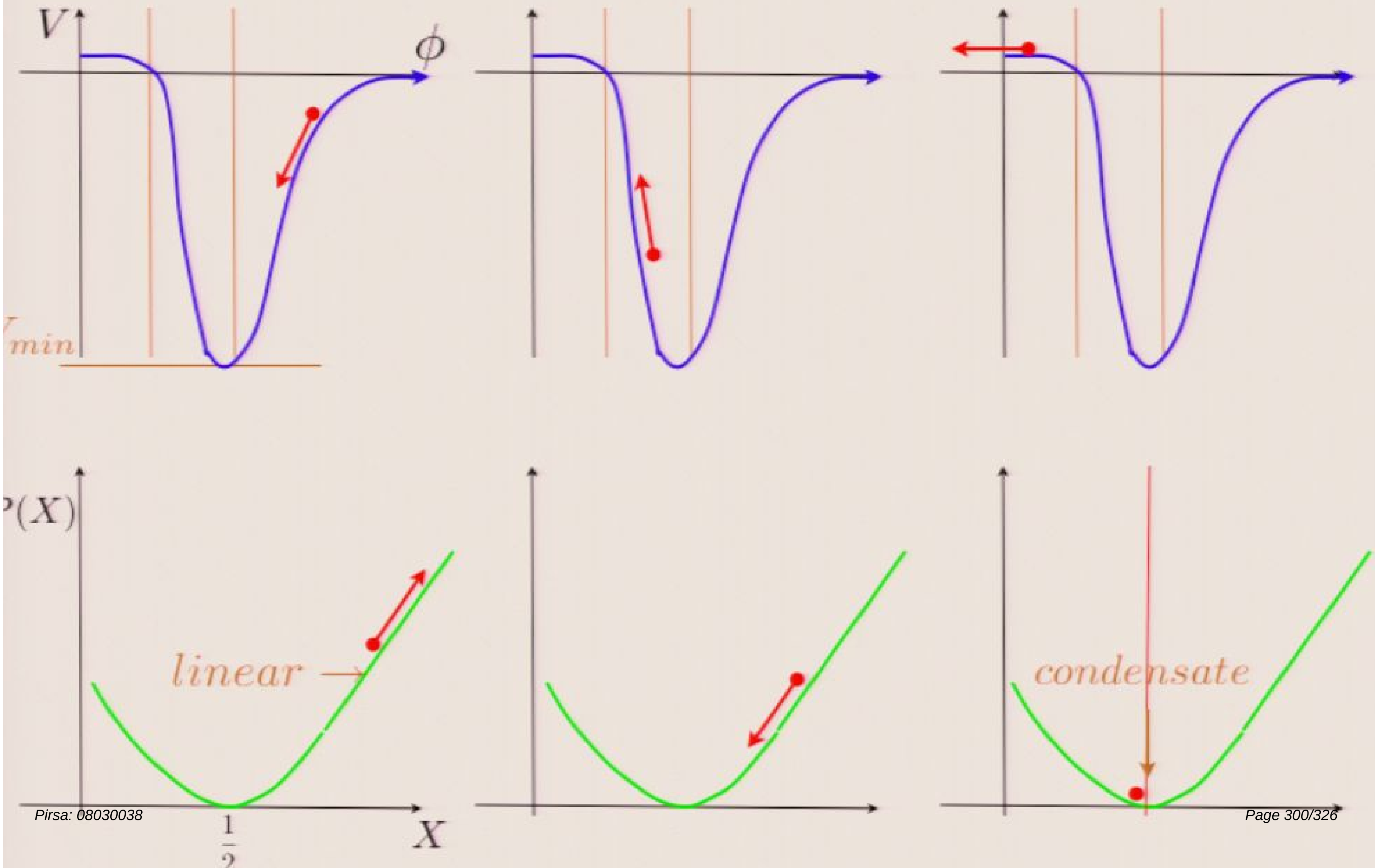
b) Merger with Ekpyrosis



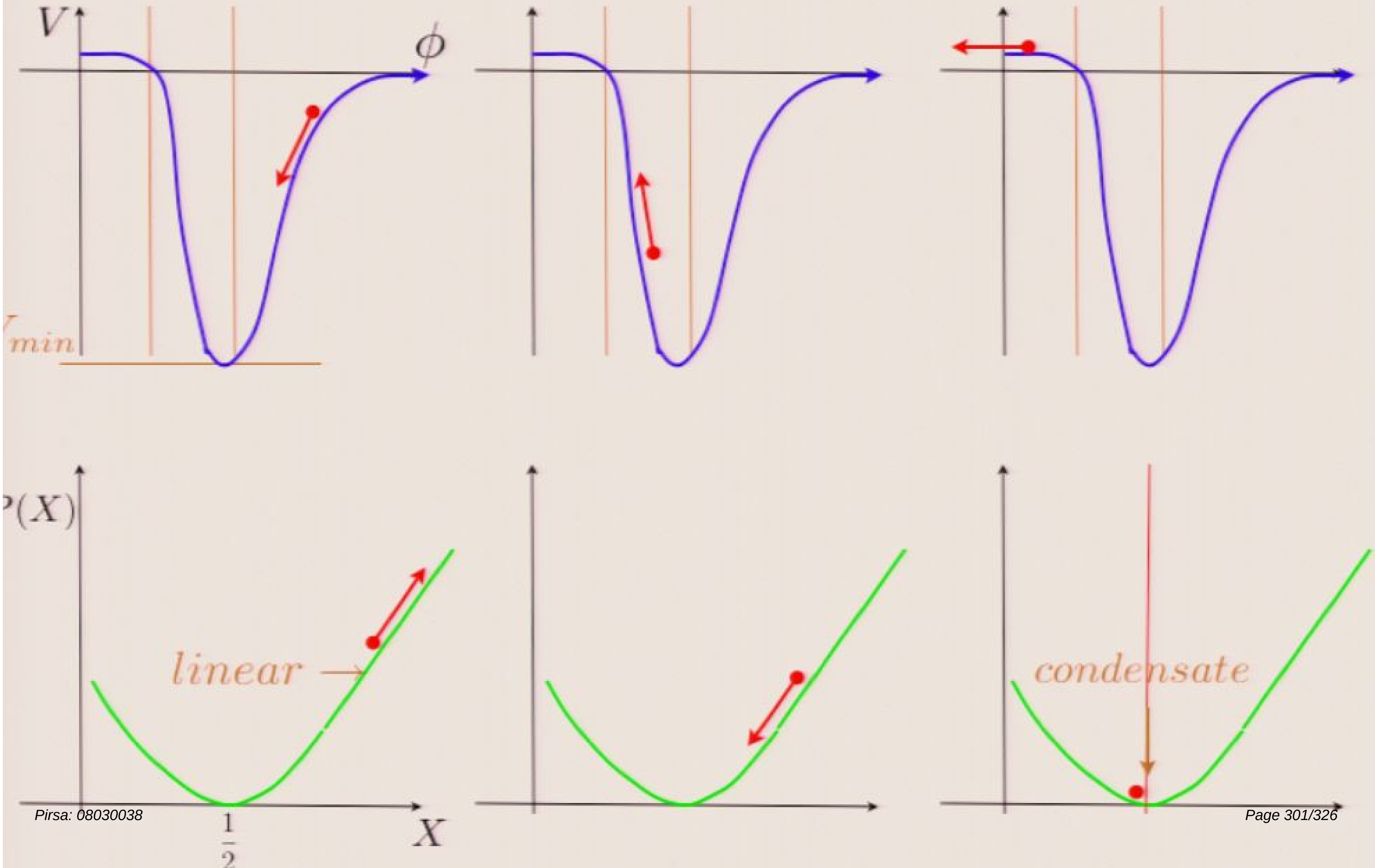
b) Merger with Ekpyrosis



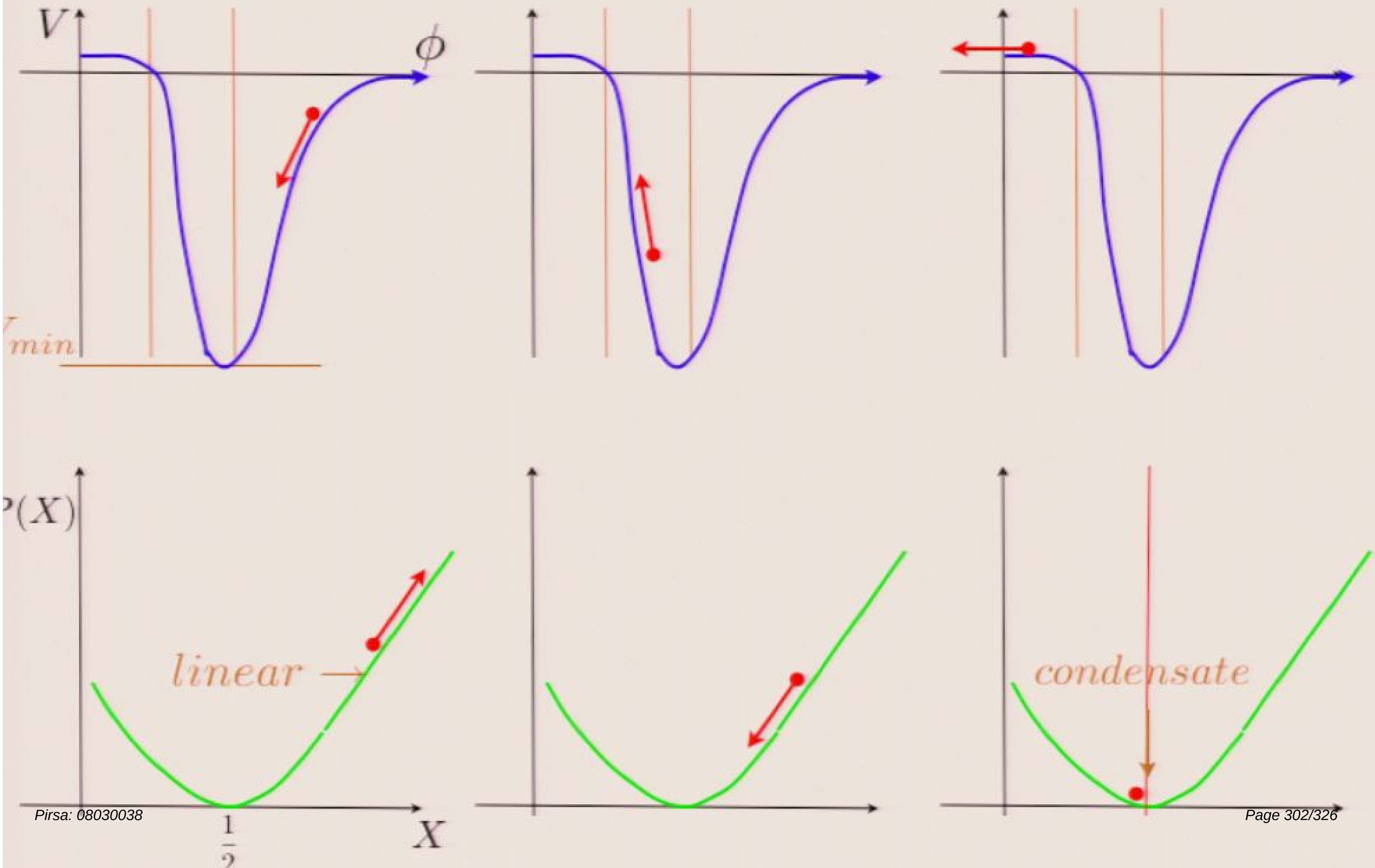
b) Merger with Ekpyrosis



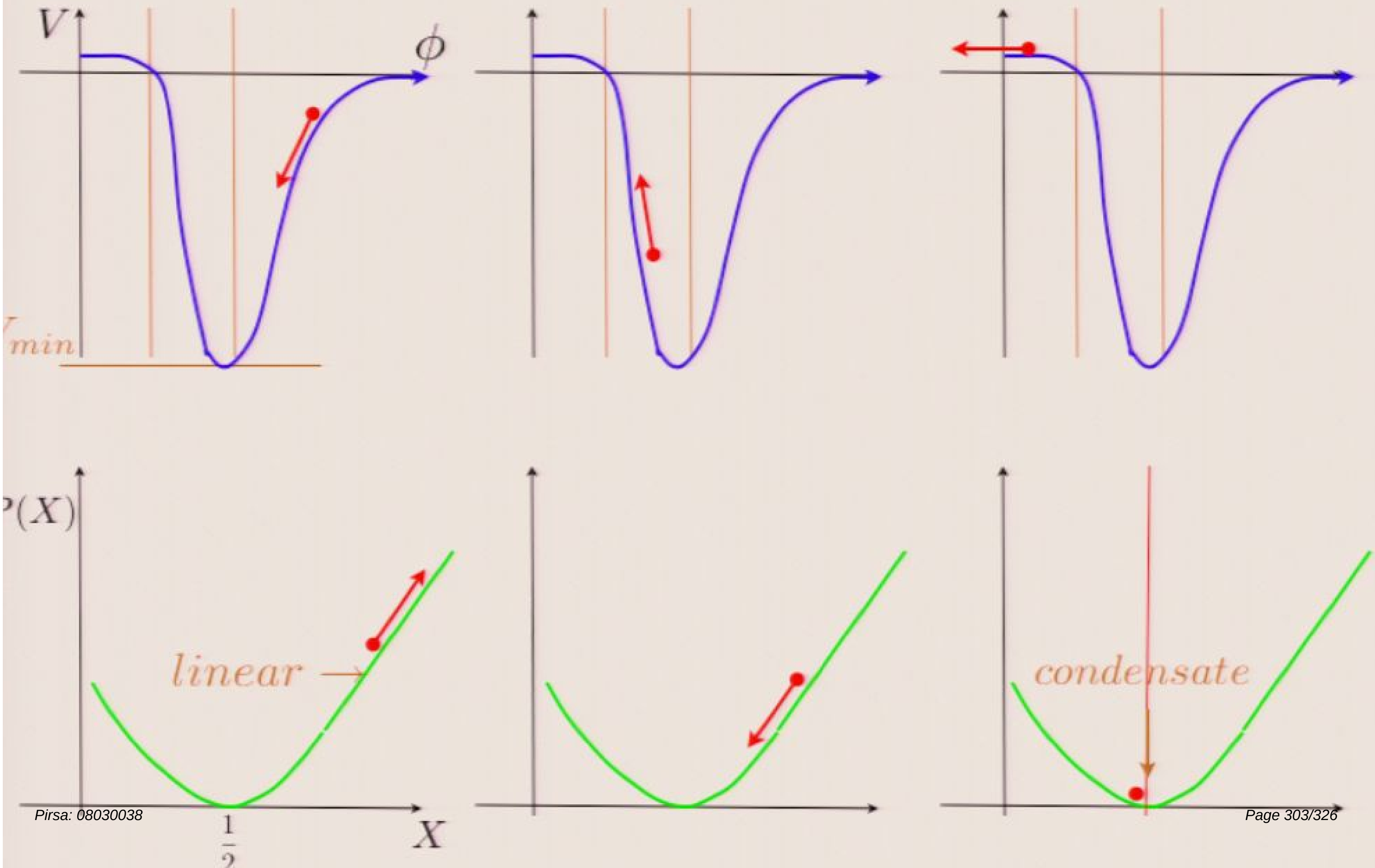
b) Merger with Ekpyrosis



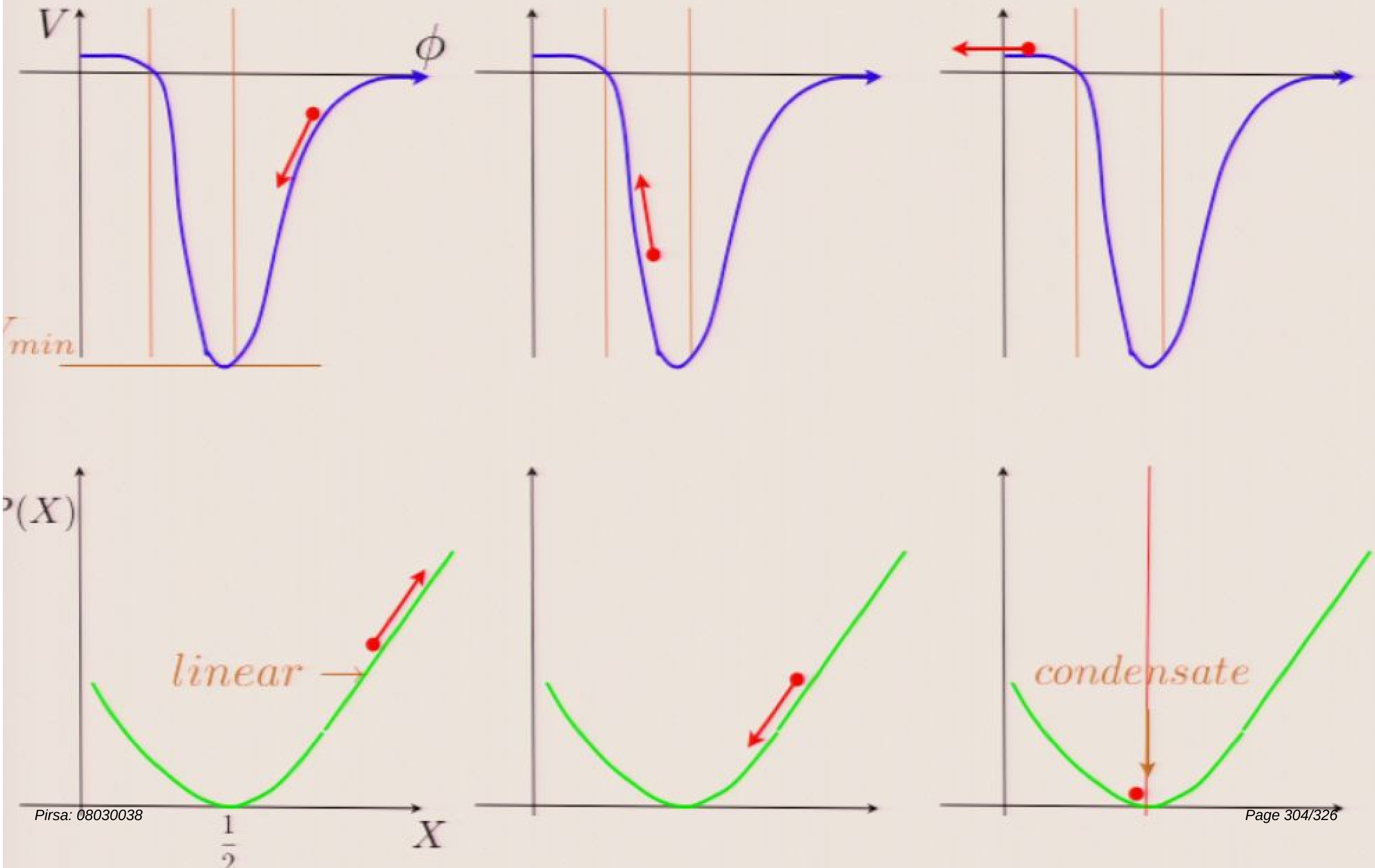
b) Merger with Ekpyrosis



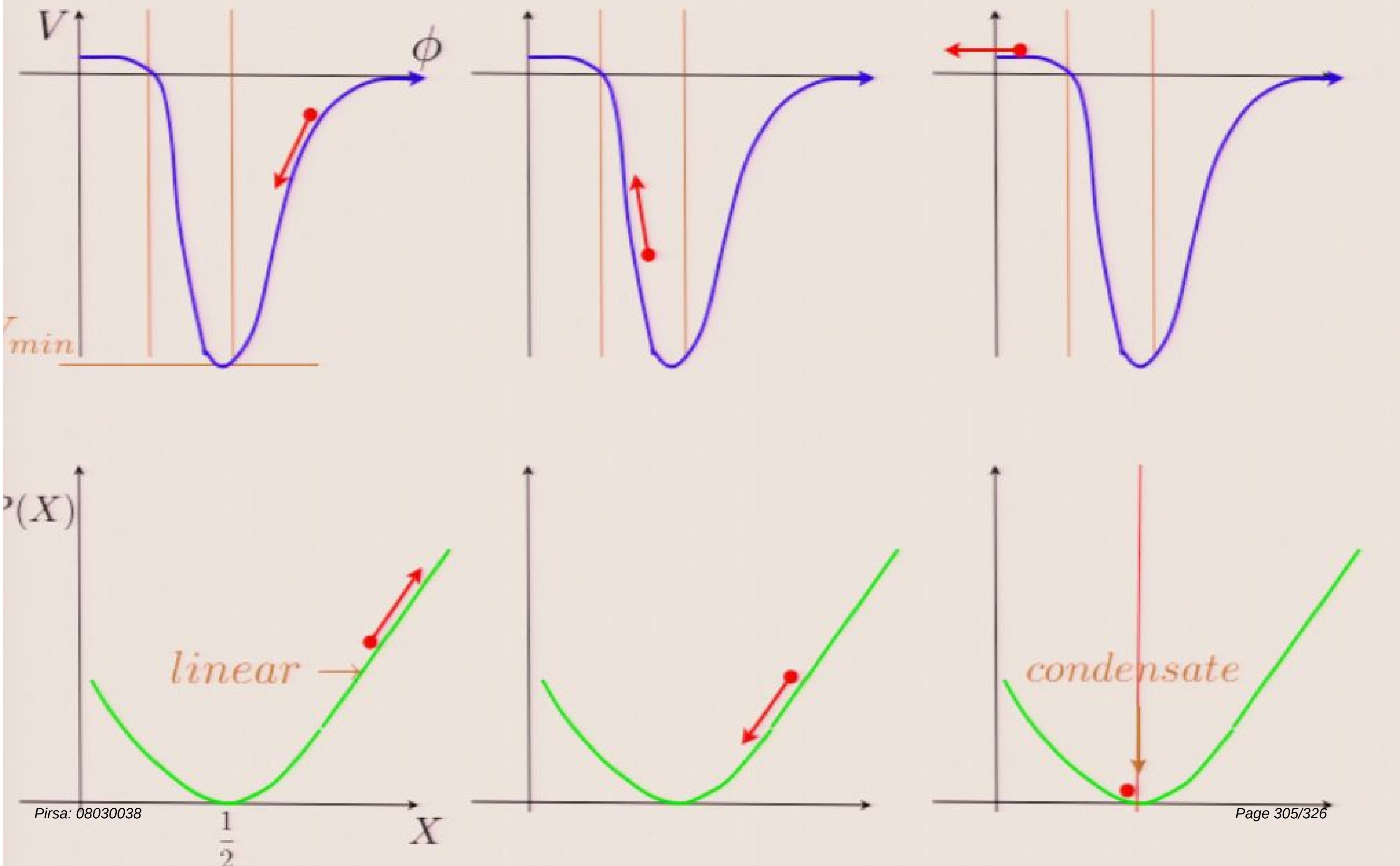
b) Merger with Ekpyrosis



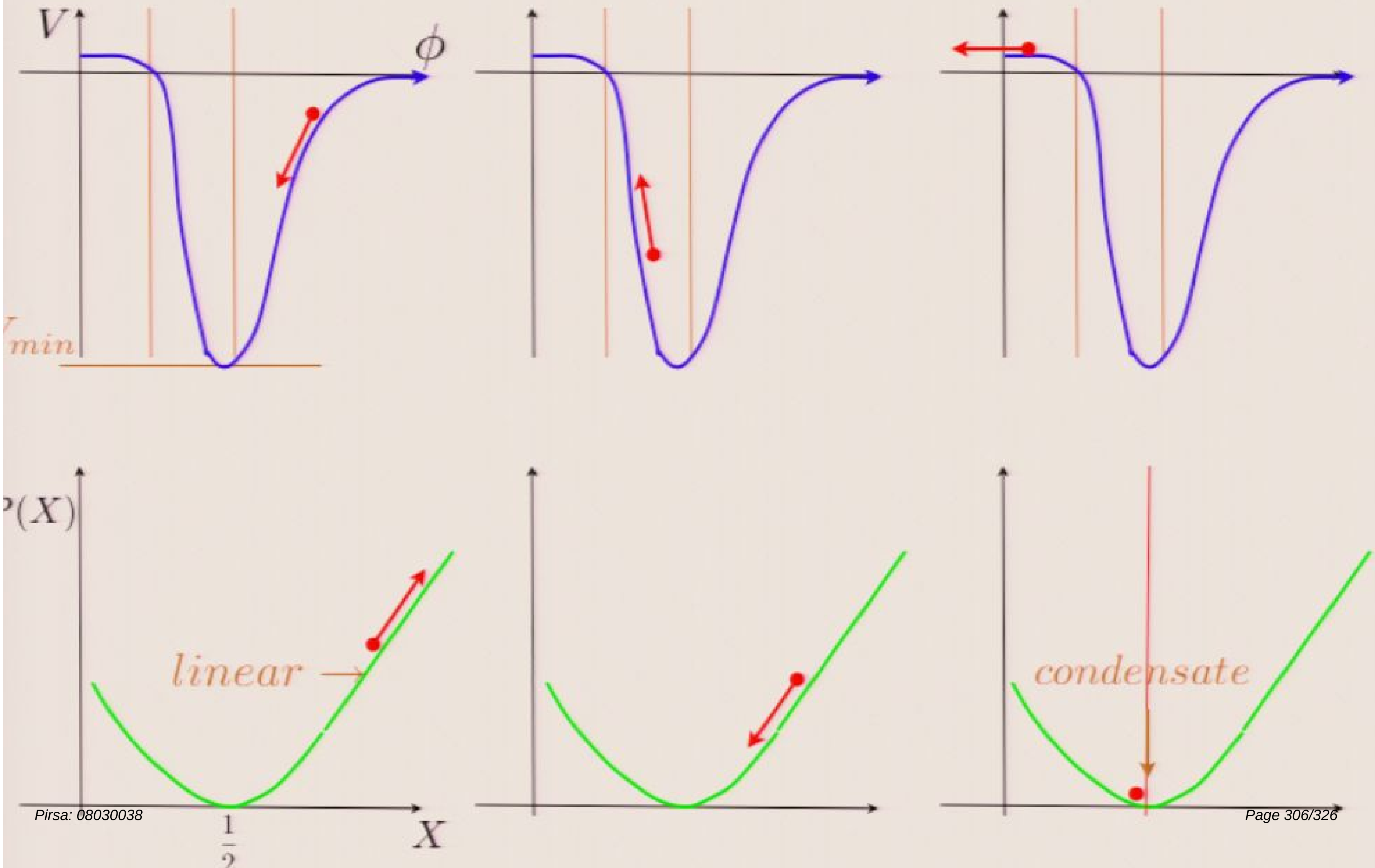
b) Merger with Ekpyrosis



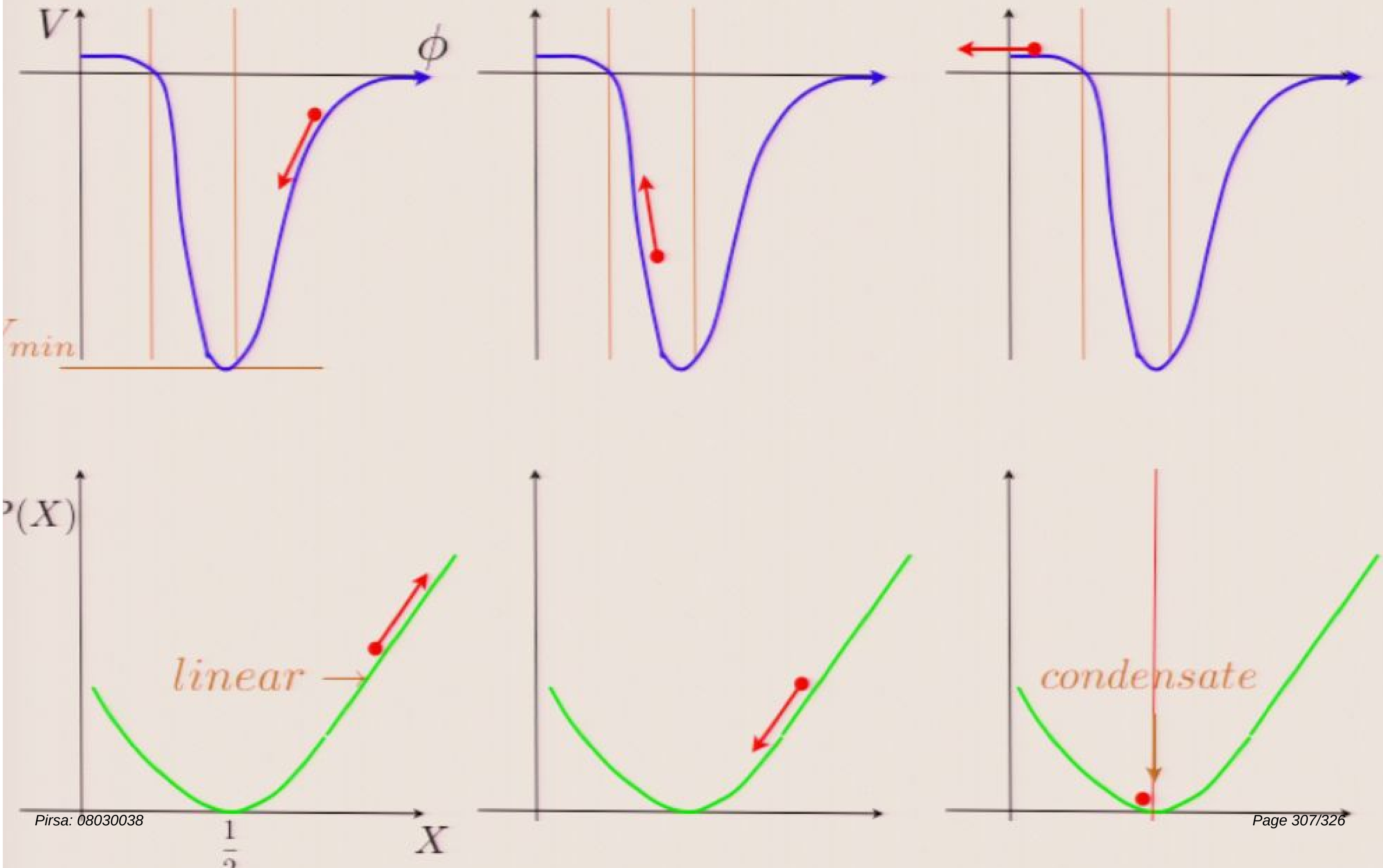
b) Merger with Ekpyrosis



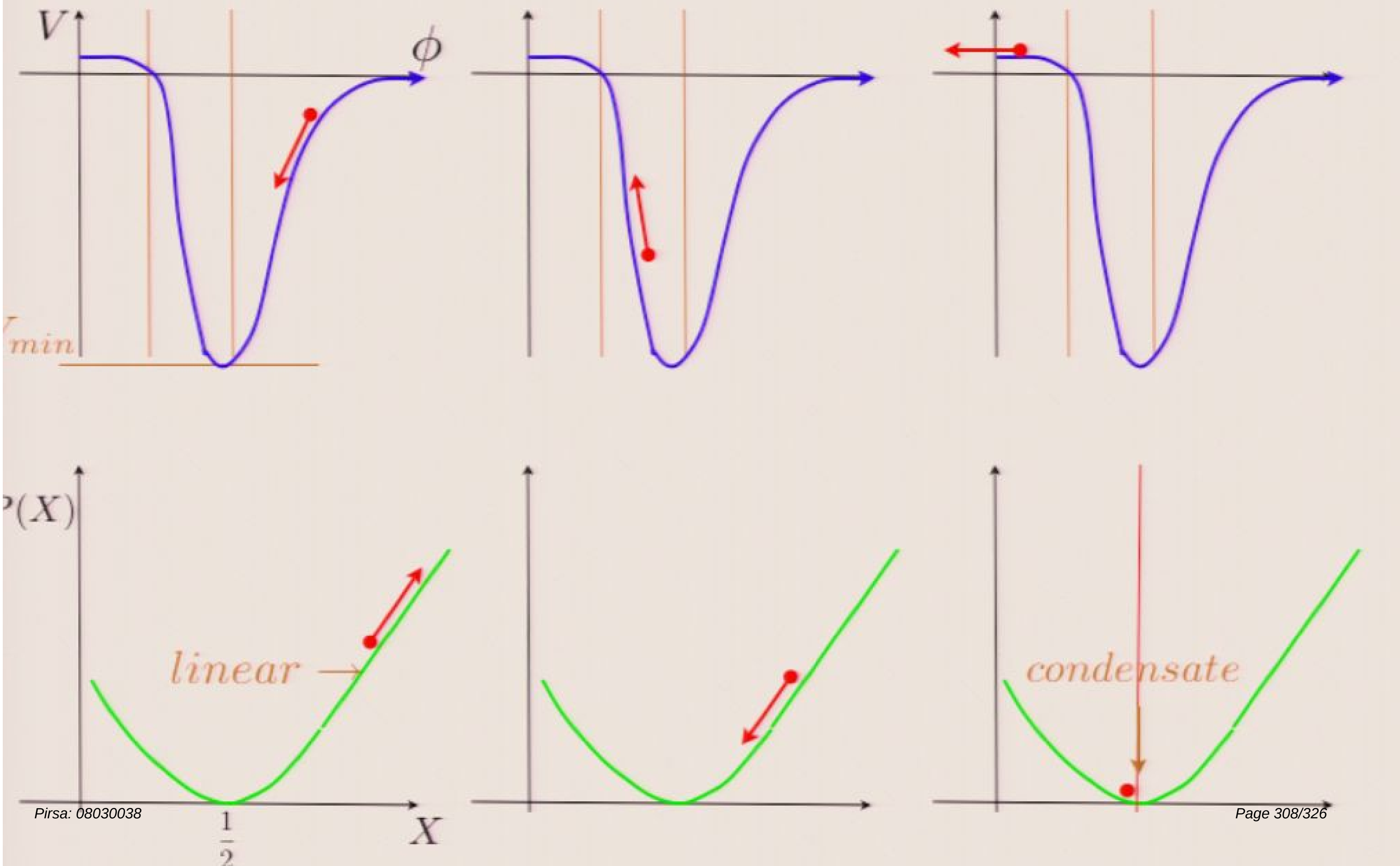
b) Merger with Ekpyrosis



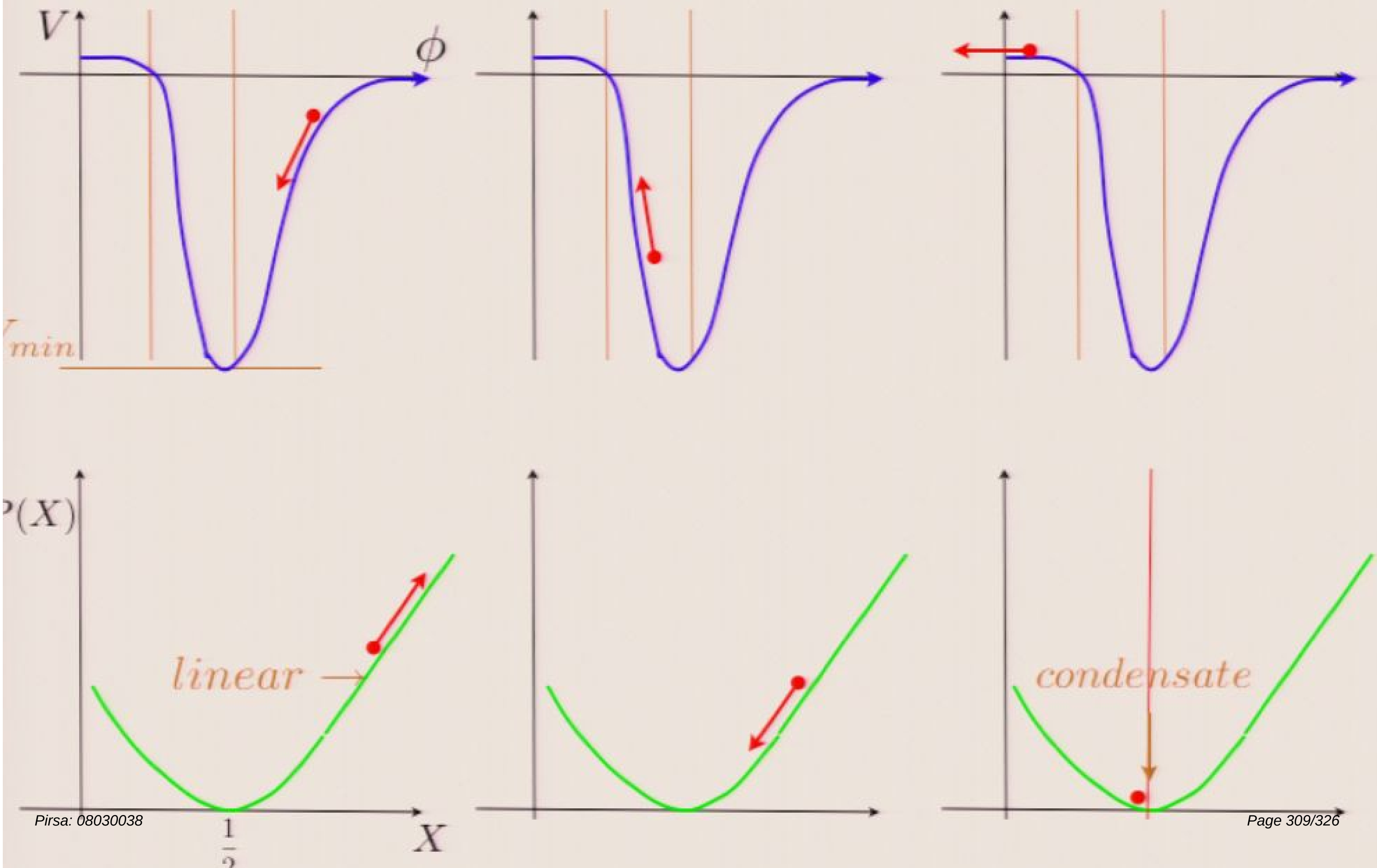
b) Merger with Ekpyrosis



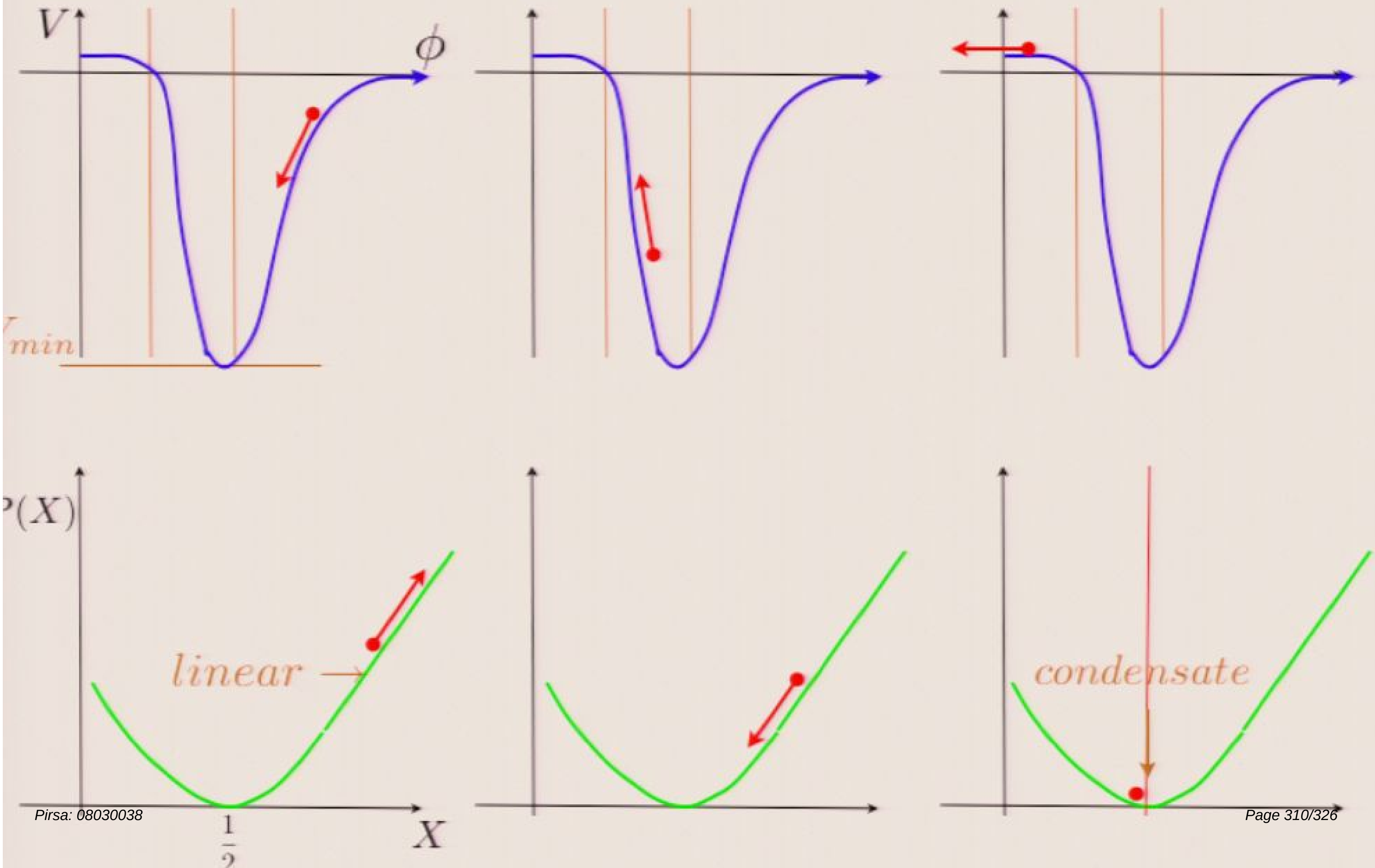
b) Merger with Ekpyrosis



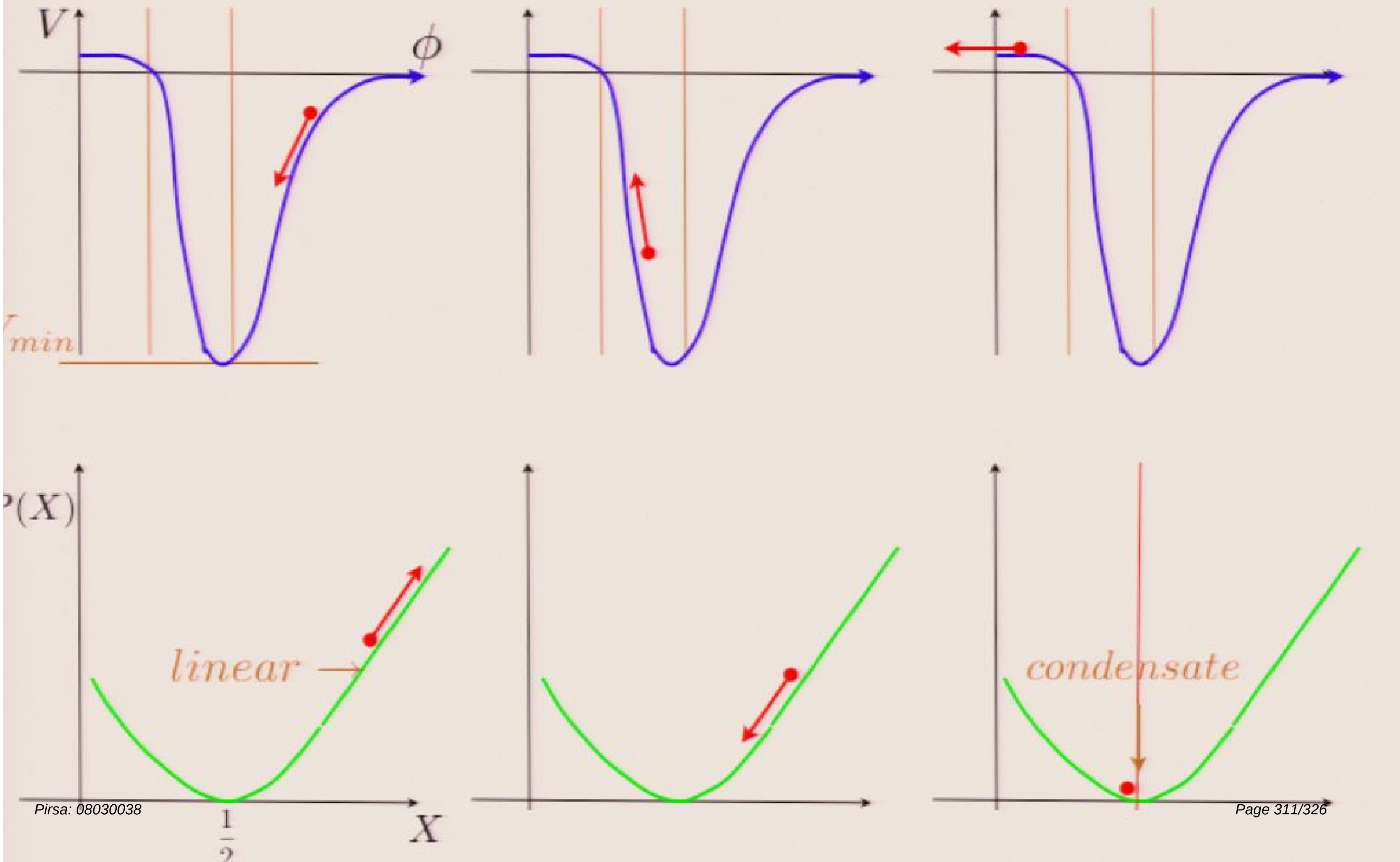
b) Merger with Ekpyrosis



b) Merger with Ekpyrosis



b) Merger with Ekpyrosis



Merger Condition

$X \gg \frac{1}{2}$ during the Ekpyrotic phase plus $X \approx \frac{1}{2}$

during bounce phase $\Rightarrow$

$$m^4 e^{2N_{ek}} \ll |V_{min}| \ll \frac{M^4 K}{p}$$

For example, $T_{reheat} = 10^{15} GeV,\ N_{ek} \simeq 60,\ p \simeq 10^{-2} \Rightarrow$

$$m \lesssim 10^3 GeV,\ M > 10^{16} GeV$$

Ghosts?

Recall

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X) - V(\phi),\ \ X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

Merger Condition

$X \gg \frac{1}{2}$ during the Ekpyrotic phase plus $X \approx \frac{1}{2}$ during bounce phase $\Rightarrow$

$$m^4 e^{2N_{ek}} \ll |V_{min}| \ll \frac{M^4 K}{p}$$

For example, $T_{reheat} = 10^{15} GeV,\ N_{ek} \simeq 60,\ p \simeq 10^{-2} \Rightarrow$

$$m \lesssim 10^3 GeV,\ M > 10^{16} GeV$$

Ghosts?

Recall

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X) - V(\phi),\ X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

Merger Condition

$X \gg \frac{1}{2}$ during the Ekpyrotic phase plus $X \approx \frac{1}{2}$ during bounce phase $\Rightarrow$

$$m^4 e^{2N_{ek}} \ll |V_{min}| \ll \frac{M^4 K}{p}$$

For example, $T_{reheat} = 10^{15} GeV,\ N_{ek} \simeq 60,\ p \simeq 10^{-2} \Rightarrow$

$$m \lesssim 10^3 GeV,\ M > 10^{16} GeV$$

Ghosts?

Recall

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X) - V(\phi),\ X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

'lerger Condition

$\chi \gg \frac{1}{2}$ during the Ekpyrotic phase plus $X \approx \frac{1}{2}$

luring bounce phase ⇒

$$m^4 e^{2N_{ek}} \ll |V_{min}| \ll \frac{M^4 K}{p}$$

'or example, $T_{reheat} = 10^{15} GeV,\ N_{ek} \simeq 60,\ p \simeq 10^{-2} \Rightarrow$

$$m \lesssim 10^3 GeV,\ M > 10^{16} GeV$$

Ghosts?

Recall

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X) - V(\phi),\ X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

Merger Condition

$X \gg \frac{1}{2}$ during the Ekpyrotic phase plus $X \approx \frac{1}{2}$ during bounce phase $\Rightarrow$

$$m^4 e^{2N_{ek}} \ll |V_{min}| \ll \frac{M^4 K}{p}$$

For example, $T_{reheat} = 10^{15} GeV,\, N_{ek} \simeq 60,\, p \simeq 10^{-2} \Rightarrow$

$$m \lesssim 10^3 GeV,\, M > 10^{16} GeV$$

Ghosts?

Recall

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X) - V(\phi),\ X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

Merger Condition

$X \gg \frac{1}{2}$ during the Ekpyrotic phase plus $X \approx \frac{1}{2}$

during bounce phase $\Rightarrow$

$$m^4 e^{2N_{ek}} \ll |V_{min}| \ll \frac{M^4 K}{p}$$

For example, $T_{reheat} = 10^{15} GeV,\ N_{ek} \simeq 60,\ p \simeq 10^{-2} \Rightarrow$

$$m \lesssim 10^3 GeV,\ M > 10^{16} GeV$$

Ghosts?

Recall

$$\frac{\mathcal{L}}{\sqrt{-g}} = M^4 P(X) - V(\phi),\ \ X = -\frac{1}{2m^4}(\partial_\mu \phi)^2$$

Expand

$$\phi(t,\vec{x}) = -m^2 t + \pi_0(t) + \pi(t,\vec{x})$$

Using $P_{,X}|_{\frac{1}{2}} = 0,\ P_{,XX}|_{\frac{1}{2}} = K \Rightarrow$

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M^4 K}{m^4}\left(\frac{\dot{\pi}^2}{2} + \frac{\dot{\pi}_0}{2m^2}(\vec{\nabla}\phi)^2 + \dots\right)$$

Recall

$$M_P^2 \dot{H} = -\frac{1}{2}(\rho + \mathcal{P}) = \frac{K M^4 \dot{\pi}_0}{2m^2} \qquad \Rightarrow \qquad \frac{\dot{\pi}_0}{2m^2} = \frac{\dot{H} M_P^2}{K M^4}$$

Hence

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M^4 K}{m^4}\left(\frac{\dot{\pi}^2}{2} + \frac{\dot{H} M_P^2}{K M^4}(\vec{\nabla}\pi)^2\right)$$

⇒ the dispersion relation

$$\omega^2 = -2\frac{\dot{H} M_P^2}{K M^4}|\vec{k}|^2$$

n the NEC violating phase

$$\dot{H} > 0 \Rightarrow$$ "gradient" instability

Add

$$\frac{\mathcal{L}}{\sqrt{-g}} = \cdots - \frac{M^4 K}{m^4}\frac{(\Box\phi)^2}{2M'^2} +$$ higher dimension operators

Can ignore the higher dimension operators for

$$k^2 \ll M'$$

⇒ the dispersion relation is modified to

$$\omega^2 = -\frac{2\dot{H} M_P^2}{K M^4}|\vec{k}|^2 + \frac{|\vec{k}|^4}{M'^2}$$

Has instability only at long wavelengths. The rate of instability peaks at

$$\omega^2_{grad} = -\left(\frac{\dot{H} M_P^2 M'}{K M^4}\right)^2$$

Harmless if

$$|\omega_{grad}| \lesssim |H|$$

$\Rightarrow$ the bound

$$\frac{\dot{H}}{H} \lesssim \frac{K M^4}{M_P^2 M'}$$

which we implement.

Now, even though its the wrong thing to do, let us analyze the above dispersion relation for arbitrary k^2 but dropping the higher dimension operators. For simplicity, ignore the term proportional to $\dot{H}|\vec{k}|^2$ and take $a = 1$

$\Rightarrow$

$$\omega^2 = \frac{(-\omega^2 + |\vec{k}|^2)^2}{M'^2}$$

Four solutions $\omega = \pm\omega_i\,,\ i = 1, 2$

$$\omega_1 = \frac{1}{2}\left(\sqrt{M'^2 + 4|\vec{k}|^2} - M'\right)\,,\ \omega_2 = \frac{1}{2}\left(\sqrt{M'^2 + 4|\vec{k}|^2} + M'\right)$$

For $|\vec{k}|^2 \ll M'^2 \Rightarrow$

$$\omega \approx \pm\frac{|\vec{k}|^2}{M'}\,,\ low\ frequency$$

but also

$$\omega \approx \pm M'\,,\ high\ frequency$$

Claim (Linde et. al.):

High frequency solution corresponds to "ghosts" with negative energy

$$\omega_{ghost} \approx -M'$$

Answer: Note that $k = (\omega, \vec{k}) \Rightarrow$

$$k^2_{ghost} \approx M'^2$$

But effective theory is only valid for $k^2 \ll M'^2$. As

$k^2 \longrightarrow M'^2$ must include all higher dimension operators!

Explicit example:

Consider

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \phi')^2 - \frac{1}{2}(\partial_\mu \chi')^2 - \frac{\Lambda^2}{2}\chi'^2$$

Both fields have canonical KE with zero and positive $(mass)^2$ respectively. Let

$$\phi' = \phi + \chi' \,,\, \chi' = \frac{1}{\sqrt{2}}\chi$$

$\Rightarrow$

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu\phi)^2 - (\partial_\mu\phi)(\partial^\mu\chi) - \frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{2}(\frac{\Lambda^2}{2})\chi^2$$

"Integrating out" the heavy field $\chi \Rightarrow$

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2\Lambda^2}(\Box\phi)\frac{1}{(1-2\frac{\Box}{\Lambda^2})}(\Box\phi)$$

$$= -\frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2\Lambda^2}(\Box\phi)^2 + \frac{1}{\Lambda^4}(\Box\phi)(\Box^2\phi) + \ldots$$

Truncate the Lagrangian to

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2\Lambda^2}(\Box\phi)^2 \ \ (+0)$$

This is equivalent to

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu\phi)^2 - (\partial_\mu\psi)(\partial^\mu\phi) - \frac{1}{2}\Lambda^2\psi^2$$

where ψ is an auxiliary field.

Now let

$$\phi = \rho - \psi$$

$\Rightarrow$

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \rho)^2 + \frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{2}\Lambda^2 \psi^2$$

Ghost with negative energy

$$\omega_{ghost} = -\Lambda$$

But, its not really there. An artifact of truncating the higher dimension operators!

Non-Gaussianity

The 3-point function in New Ekpyrotic cosmology is

$$\langle \zeta_{k_1}, \zeta_{k_2}, \zeta_{k_3} \rangle = (2\pi)^3 \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B(k_1, k_2, k_3)$$

where

$$B(k_1, k_2, k_3) = \frac{6}{5} f_{NL} \{ P_\zeta(k_1) P_\zeta(k_2) + perm \}$$

is of the "local" form and

$$k^3 P_\zeta(k) = \beta^2 \frac{H_{end}^2}{2\epsilon M_P^2}$$

$\Rightarrow$ the 3-point function fully specified by f_{NL} .

Two contributions:

)

$$\mathcal{L} = \cdots - \mathcal{V} \frac{\alpha_3}{3! \epsilon^{\frac{3}{2}} M_P^3} \chi^3 \quad \Rightarrow f_{NL}^{int} = \mp \frac{5}{18} \frac{\alpha_3}{\beta \epsilon}$$

b) Non-linear relation between $\zeta, \delta\chi \Rightarrow$

$$f_{NL}^{conv} = \frac{5}{24}\frac{1}{\beta^2\epsilon}$$

Adding these gives

$$f_{NL} = \frac{5}{24\beta^2\epsilon}\left(1 \mp \frac{4}{3}\alpha_3\beta\right)$$

Conclusions:

1) $f_{NL} \sim \frac{1}{\epsilon}, \epsilon \ll 1 \Rightarrow$ large non-Gaussianity !

Contrast to slow-roll inflation where $f_{NL} \sim \epsilon \Rightarrow$ very small non-Gaussianity.

2) Choosing $\beta = 1, \epsilon = 10^{-2}, (-)sign, 2.046 > \alpha_3 > -2.85 \Rightarrow$

$-36 < f_{NL} < 100$ "old" WMAP bound