Title: Inflation, infinity, equilibrium and the observable Universe

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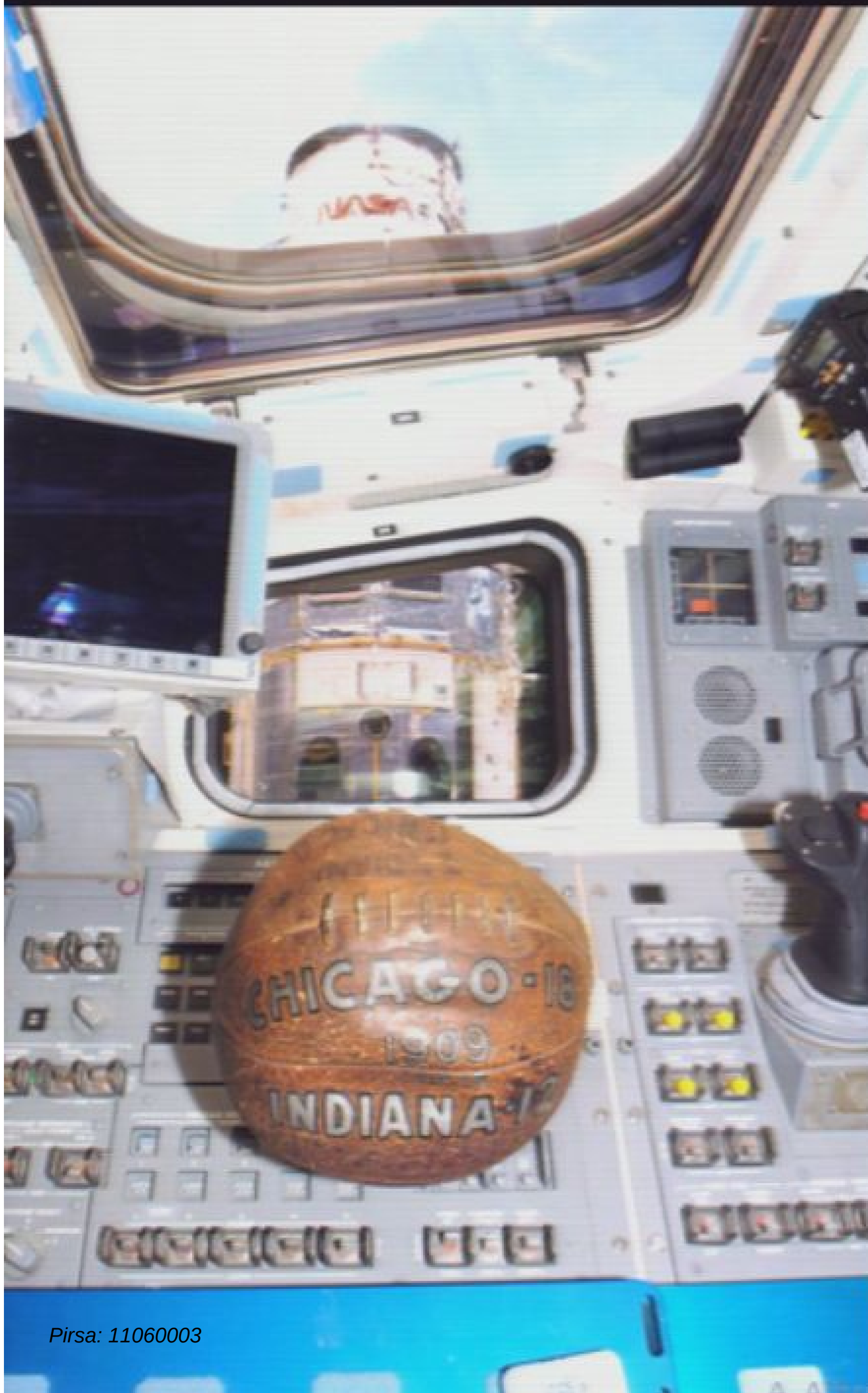
Abstract: Cosmic inflation has given us a remarkably successful cosmological phenomenology. But the original goal of explaining why the cosmos is *likely* to take the form we observe has proven very difficult to realize. I review the status of "eternal inflation" with an eye on the roles various infinities have (both helpful and unhelpful) in our current understanding. I then discuss attempts to construct an alternative cosmological framework that is truly finite, using ideas about equilibrium and dark energy. I report some recent results that point to observable signatures.

Inflation, infinity, equilibrium and the observable Universe

Andreas Albrecht
UC Davis
PI colloquium
June 15, 2011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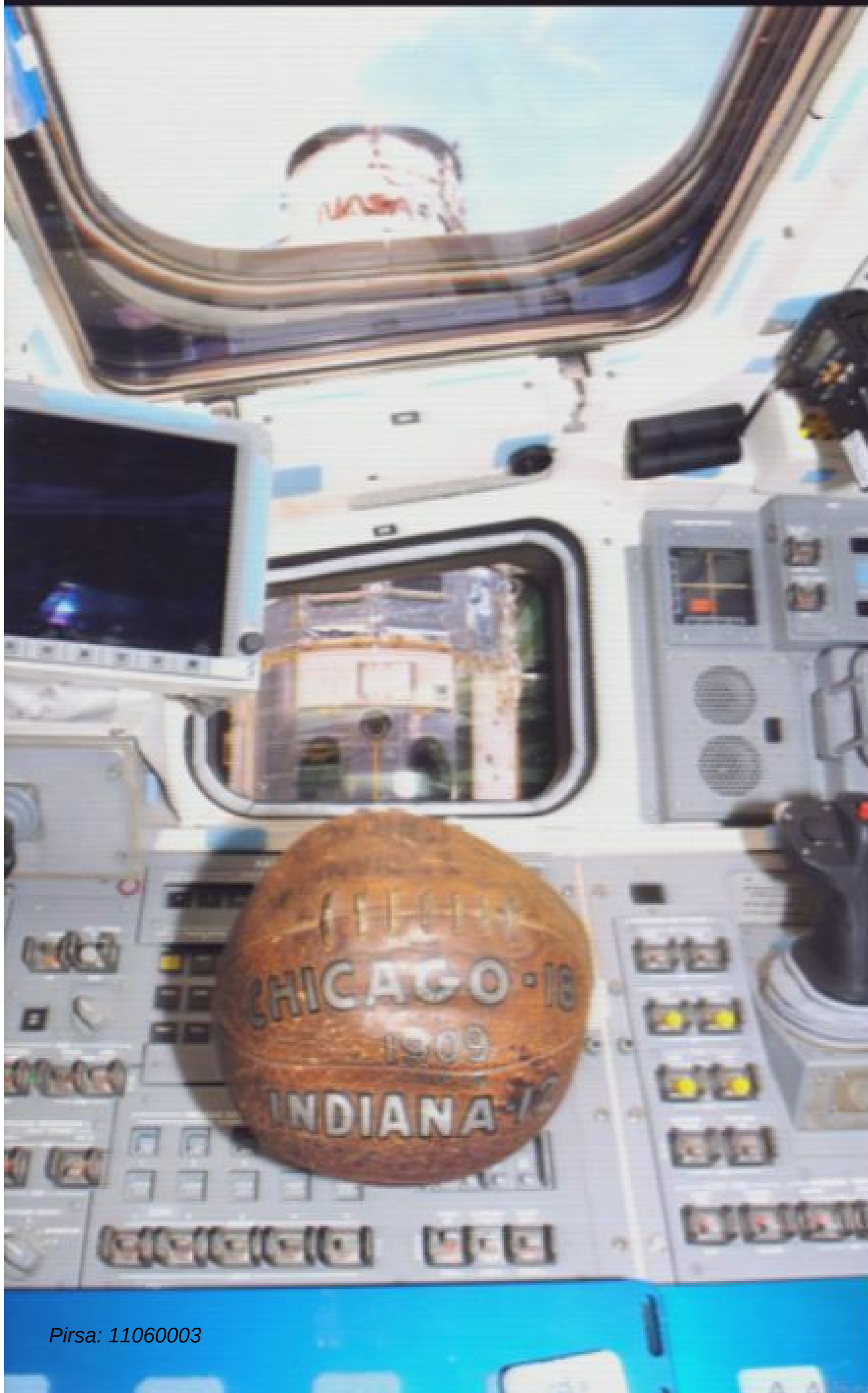
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Cosmic Inflation:

➔ Great phenomenology, but

➔ Original goal of explaining why the cosmos is *likely* to take the form we observe has proven very difficult to realize.

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➔ Original goal of explaining *why the cosmos is *likely* to take the form we observe* has proven very difficult to realize.

This Talk

Cosmic Inflation:

- ➔ Great phenomenology, but
- ➔ Original goal of explaining *why the cosmos is *likely* to take the form we observe* has proven very difficult to realize.
- ➔ OR: Just be happy we have equations to solve?

OUTLINE

1. Big Bang & inflation basics
2. Eternal inflation
3. de Sitter Equilibrium cosmology
4. Cosmic curvature from de Sitter Equilibrium cosmology

Friedmann Eqn.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\left(\rho_k + \rho_r + \rho_m + \rho_{DE}\right)$$

Scale factor

Friedmann Eqn.

$$\propto a^{-2}$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\left(\rho_k + \rho_r + \rho_m + \rho_{DE}\right)$$

Curvature

Friedmann Eqn.

$\propto a^{-2}$

$\propto a^{-4}$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\left(\rho_k + \rho_r + \rho_m + \rho_{DE}\right)$$

Curvature

Relativistic Matter

Friedmann Eqn.

$$\propto a^{-2} \qquad \propto a^{-4} \qquad \propto a^{-3}$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\left(\rho_k + \rho_r + \rho_m + \rho_{DE}\right)$$

Curvature

Relativistic Matter

Non-relativistic Matter

Friedmann Eqn.

$\propto a^{-2}$ $\propto a^{-4}$ $\propto a^{-3}$ $\propto a^{\approx 0}$

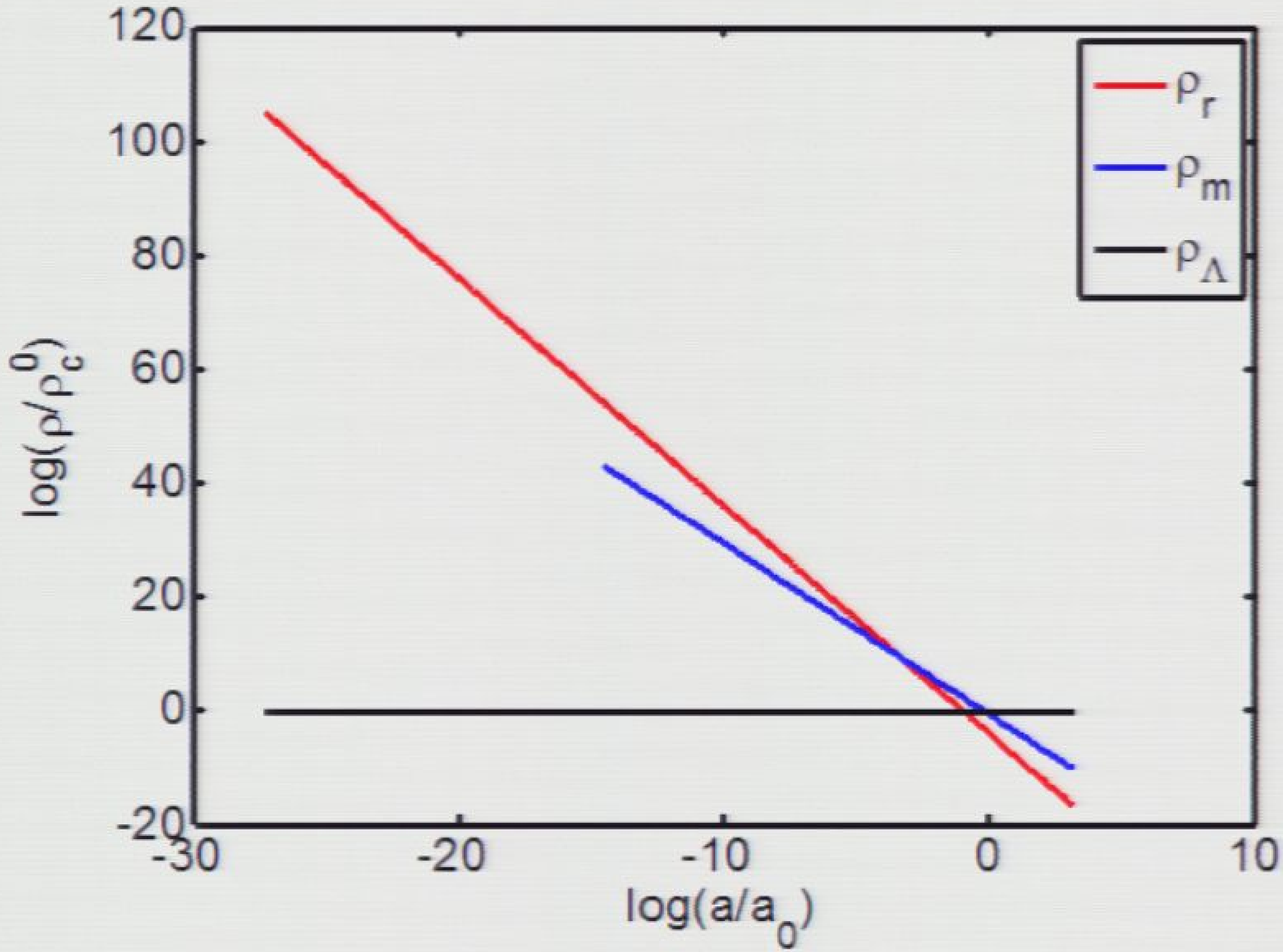
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G(\rho_k + \rho_r + \rho_m + \rho_{DE})$$

Curvature

Relativistic Matter

Non-relativistic Matter

Dark Energy



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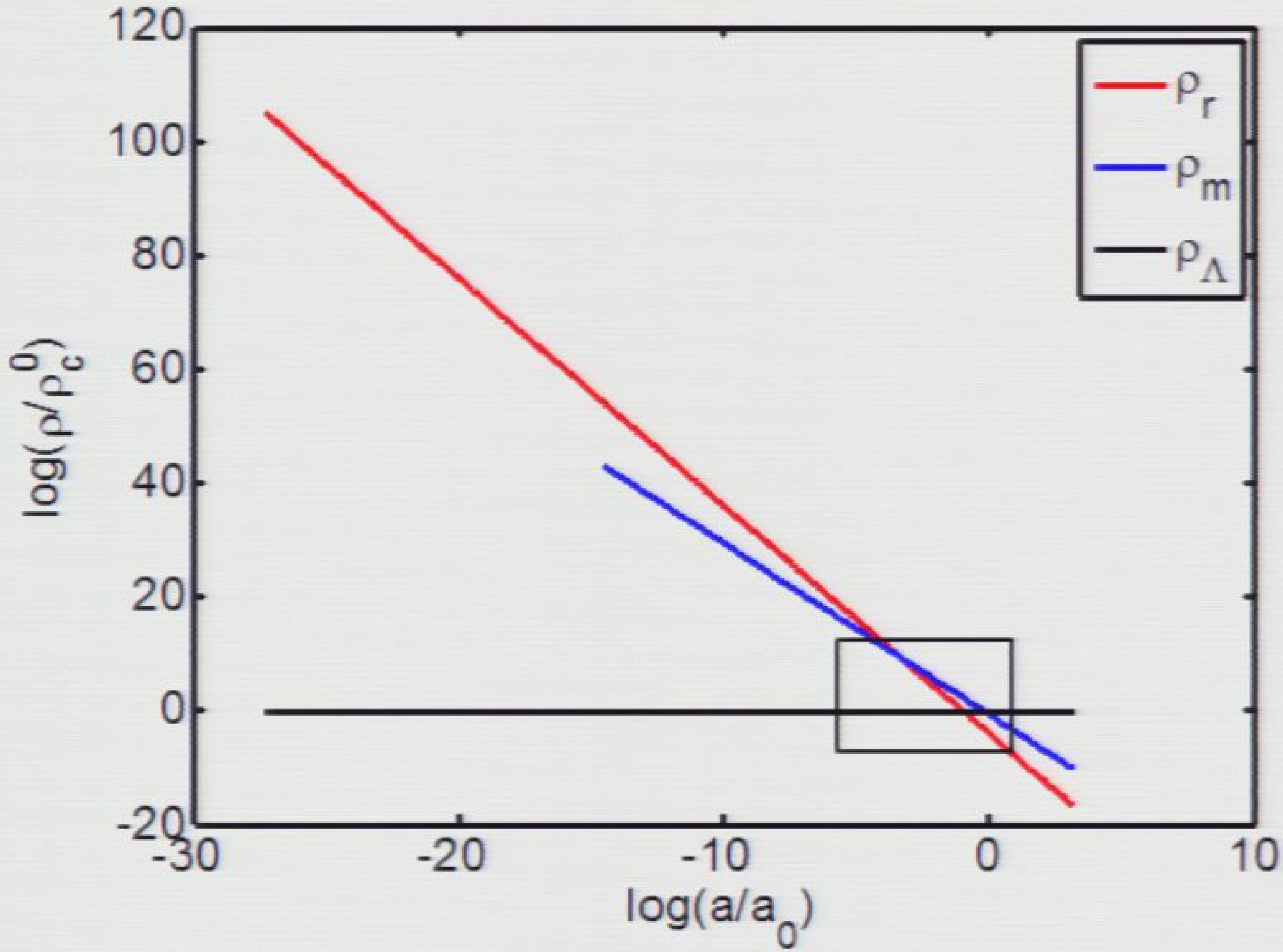
ρ_r
ρ_m
ρ_Λ



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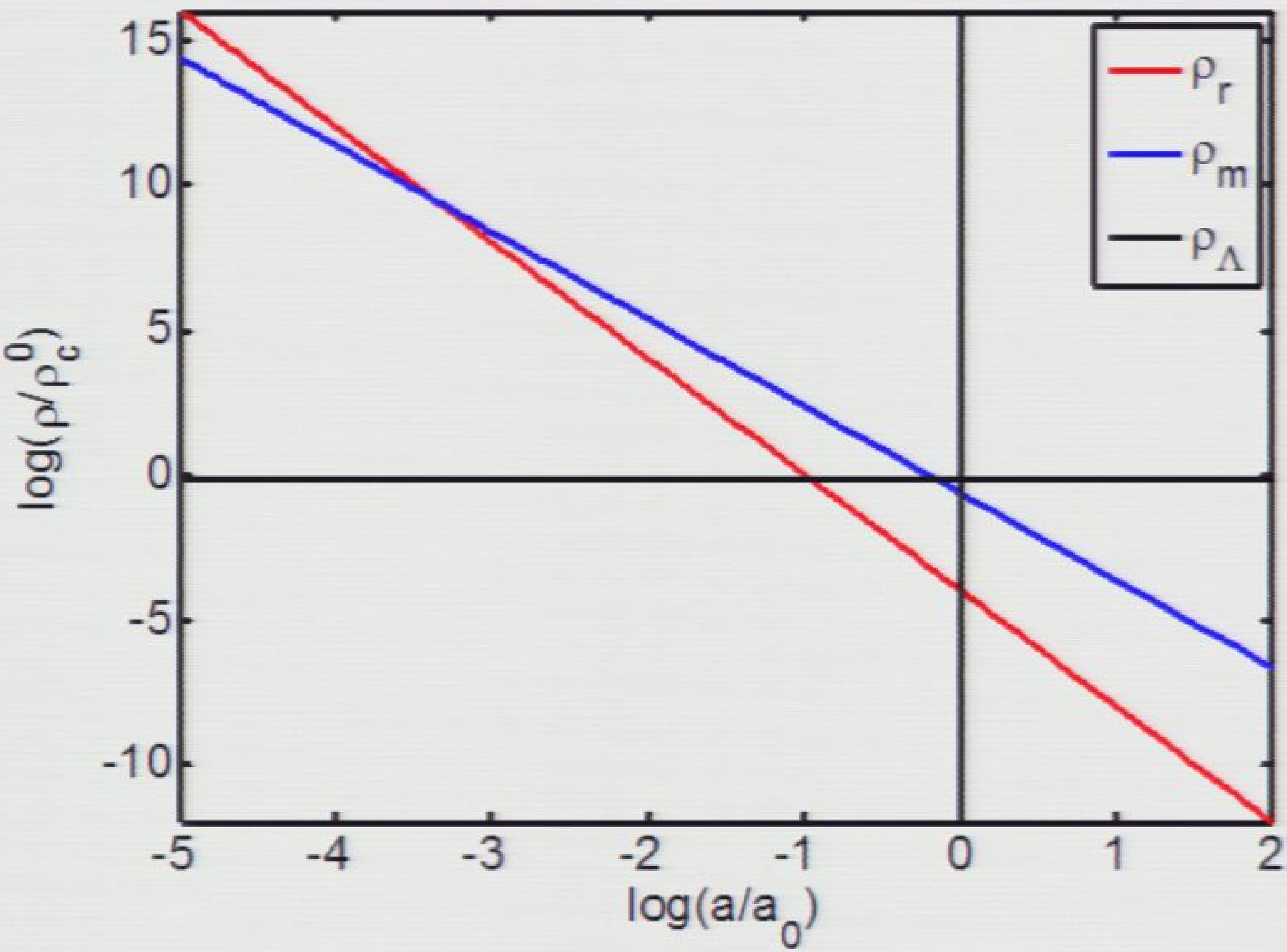

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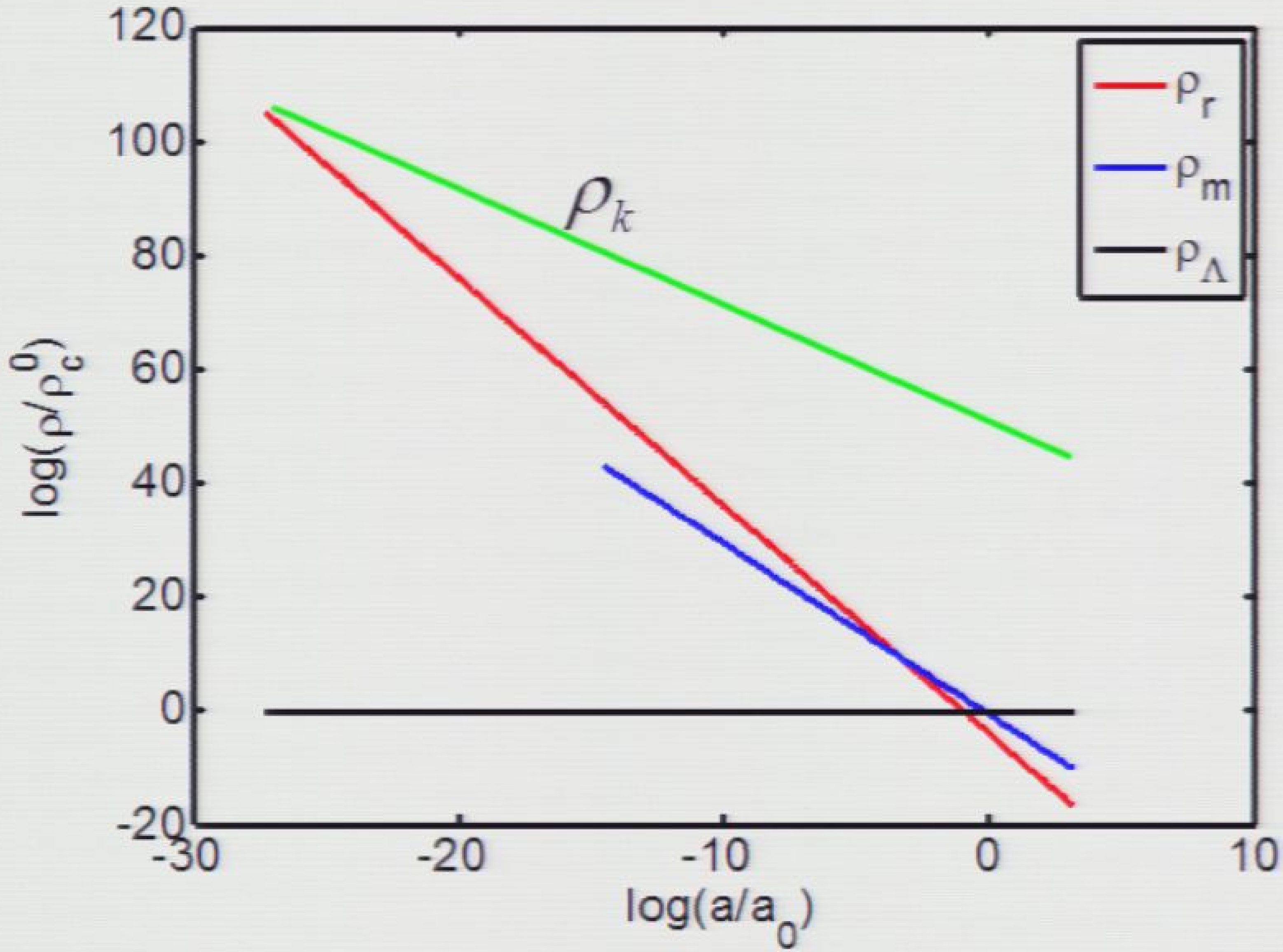
$\log(a/a_0)$
ρ_r
ρ_m
ρ_Λ

The curvature feature/“problem”



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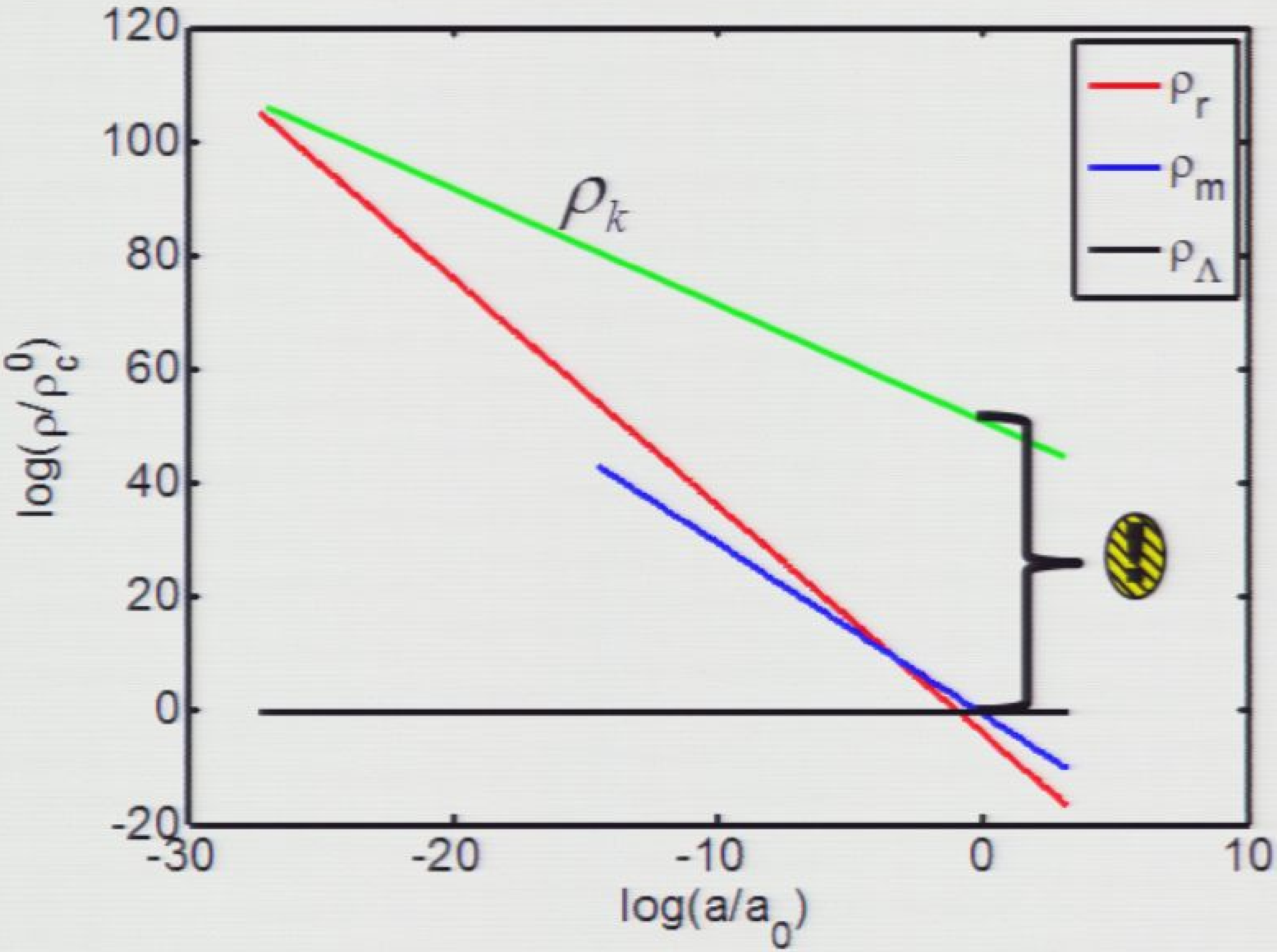

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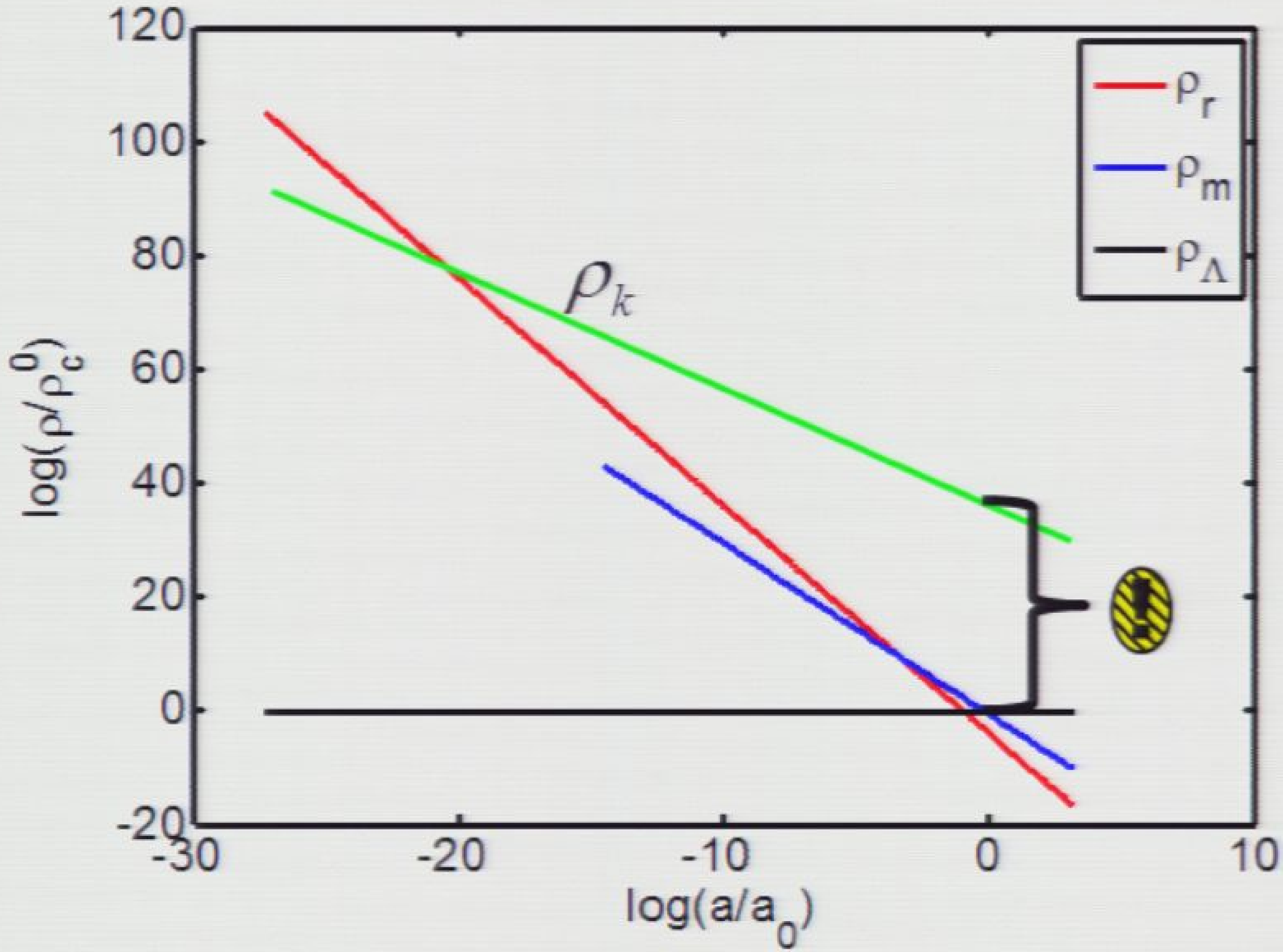

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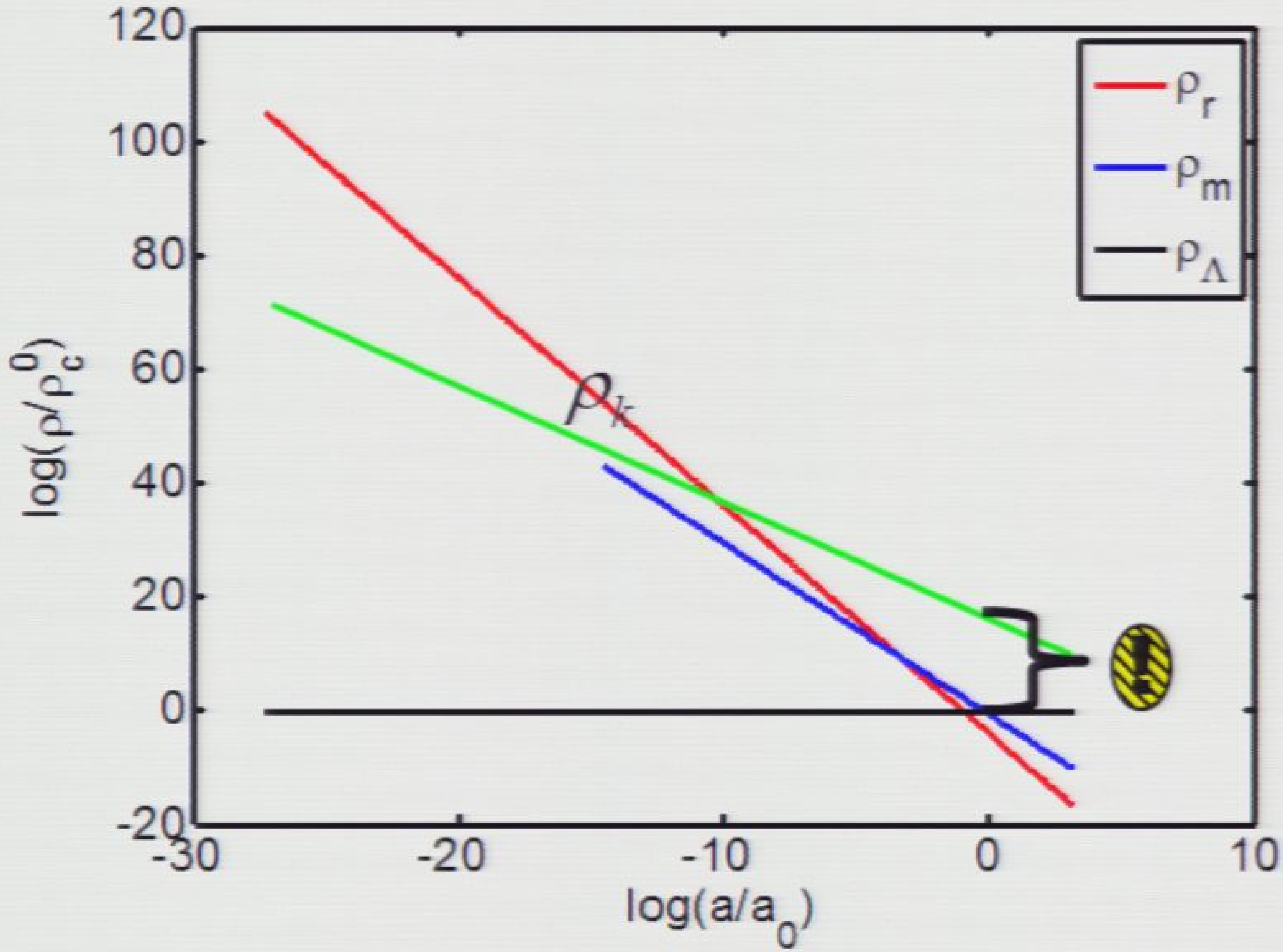

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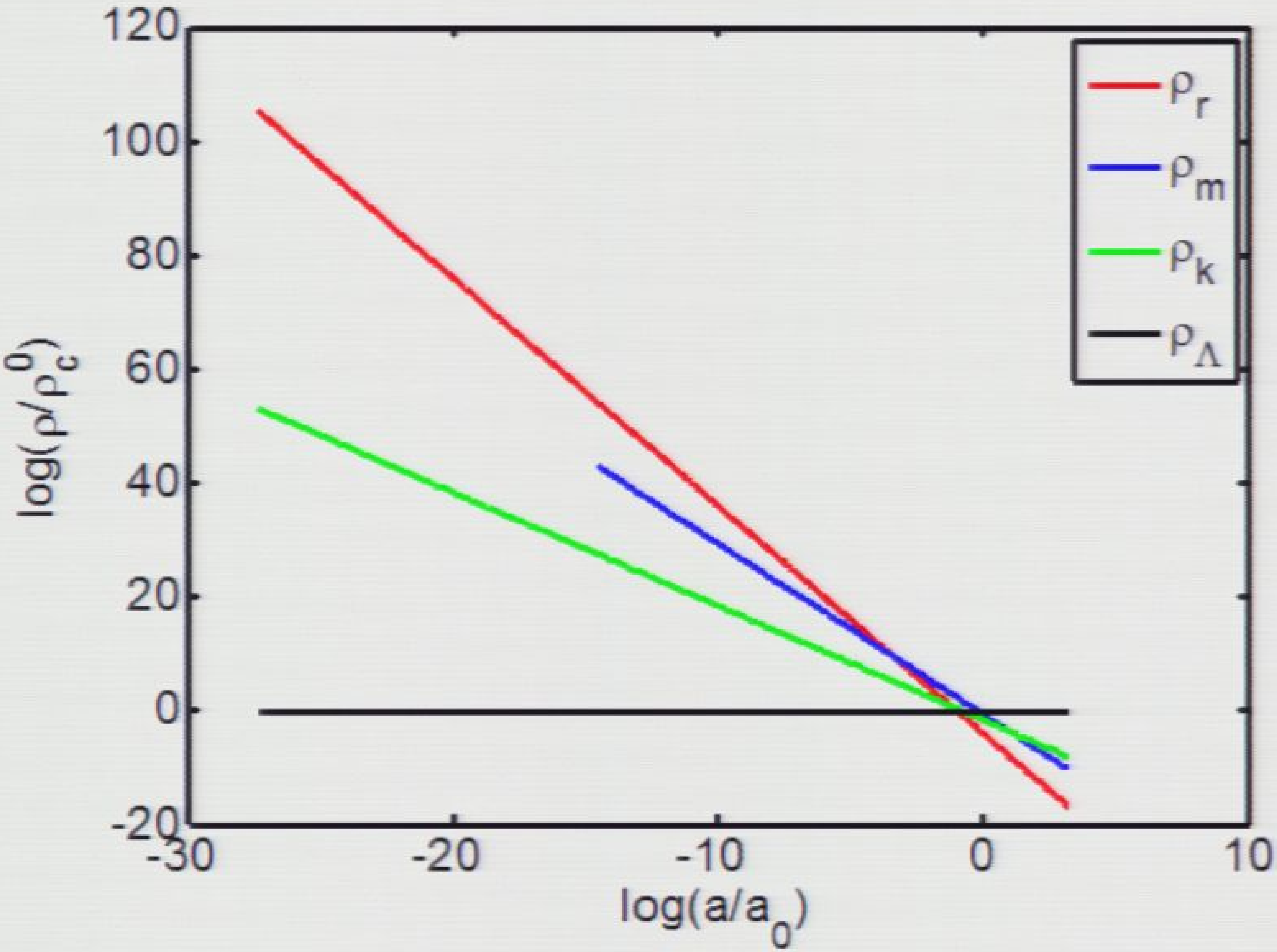

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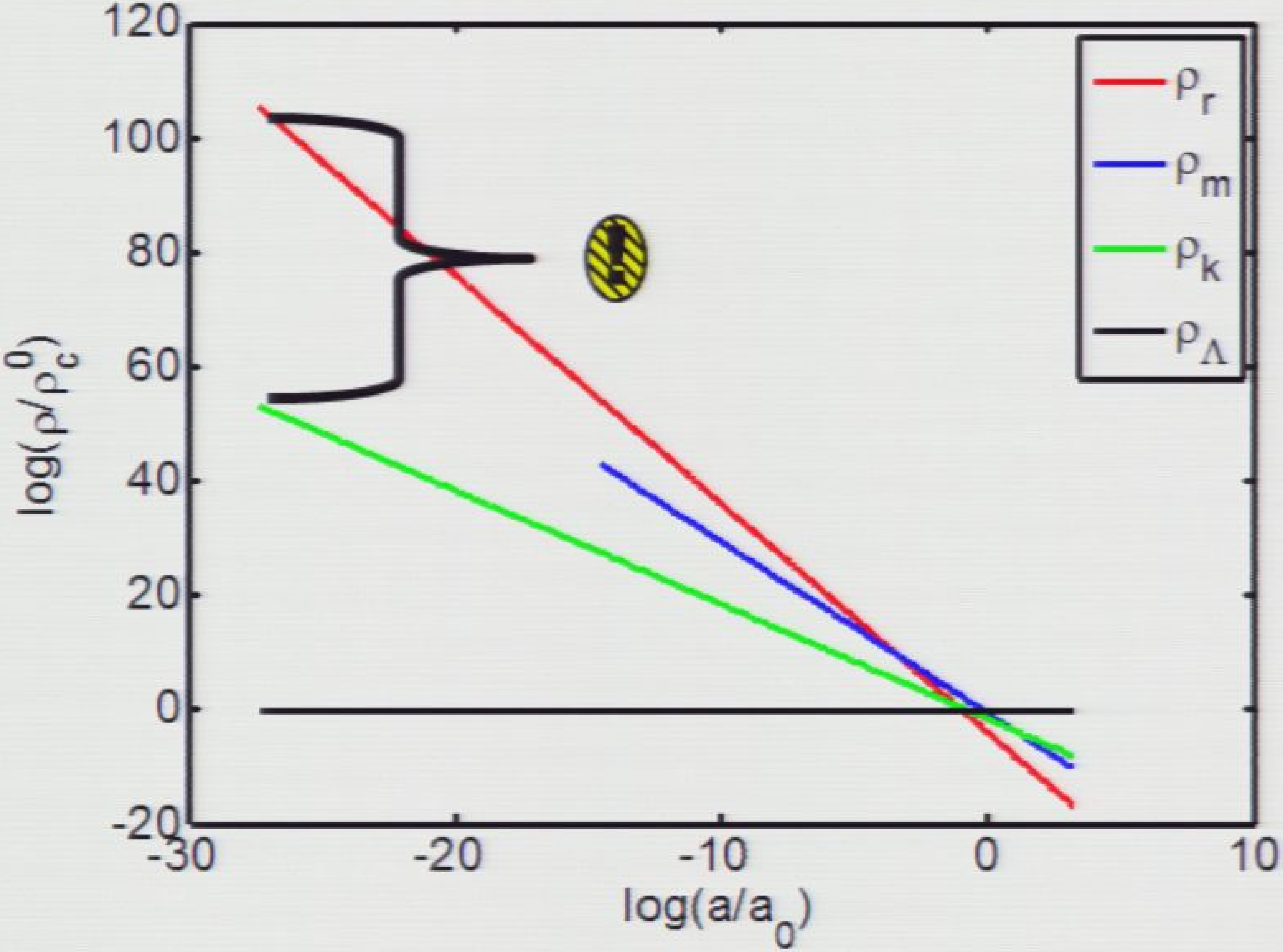
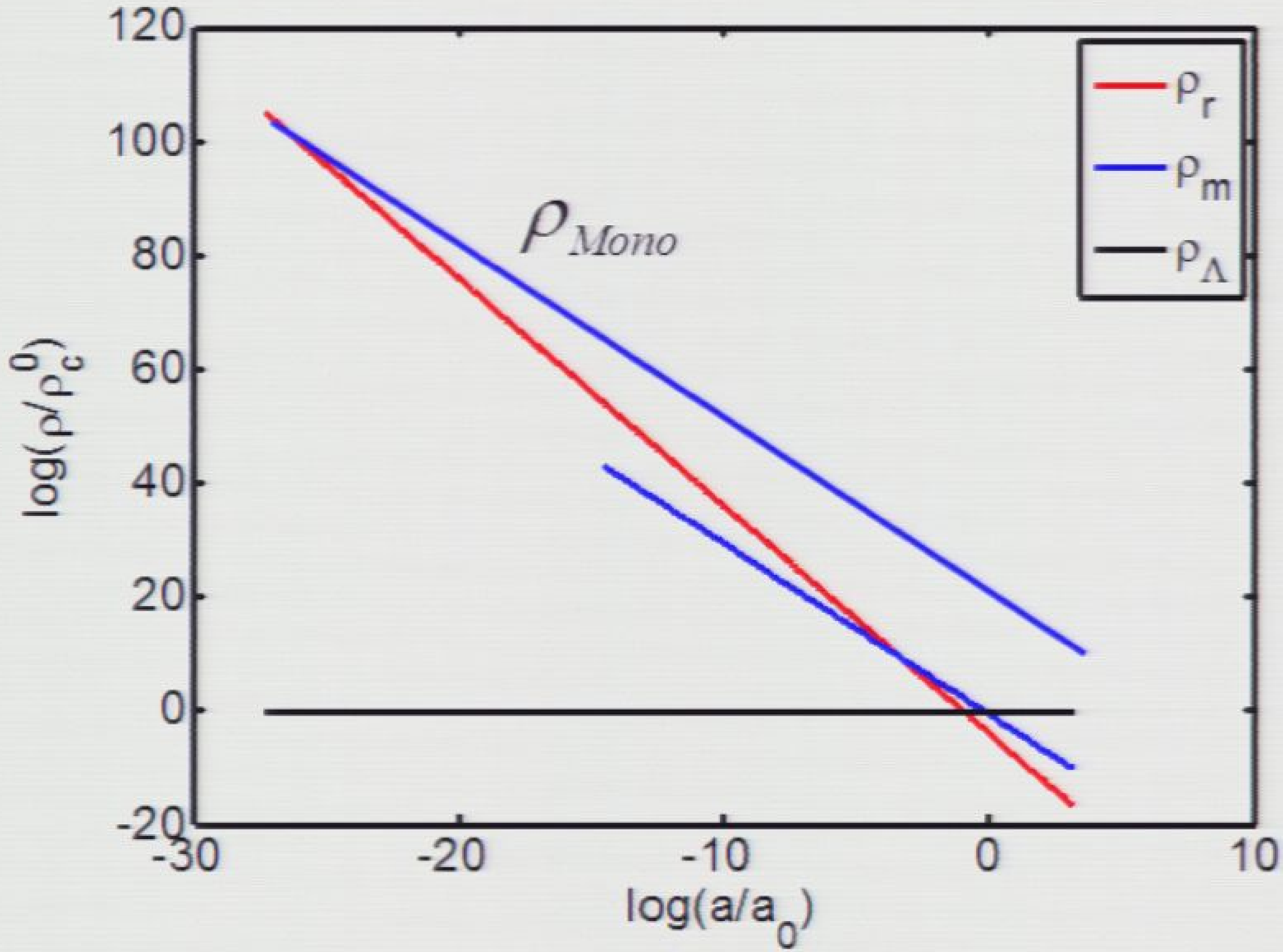


The monopole "problem"



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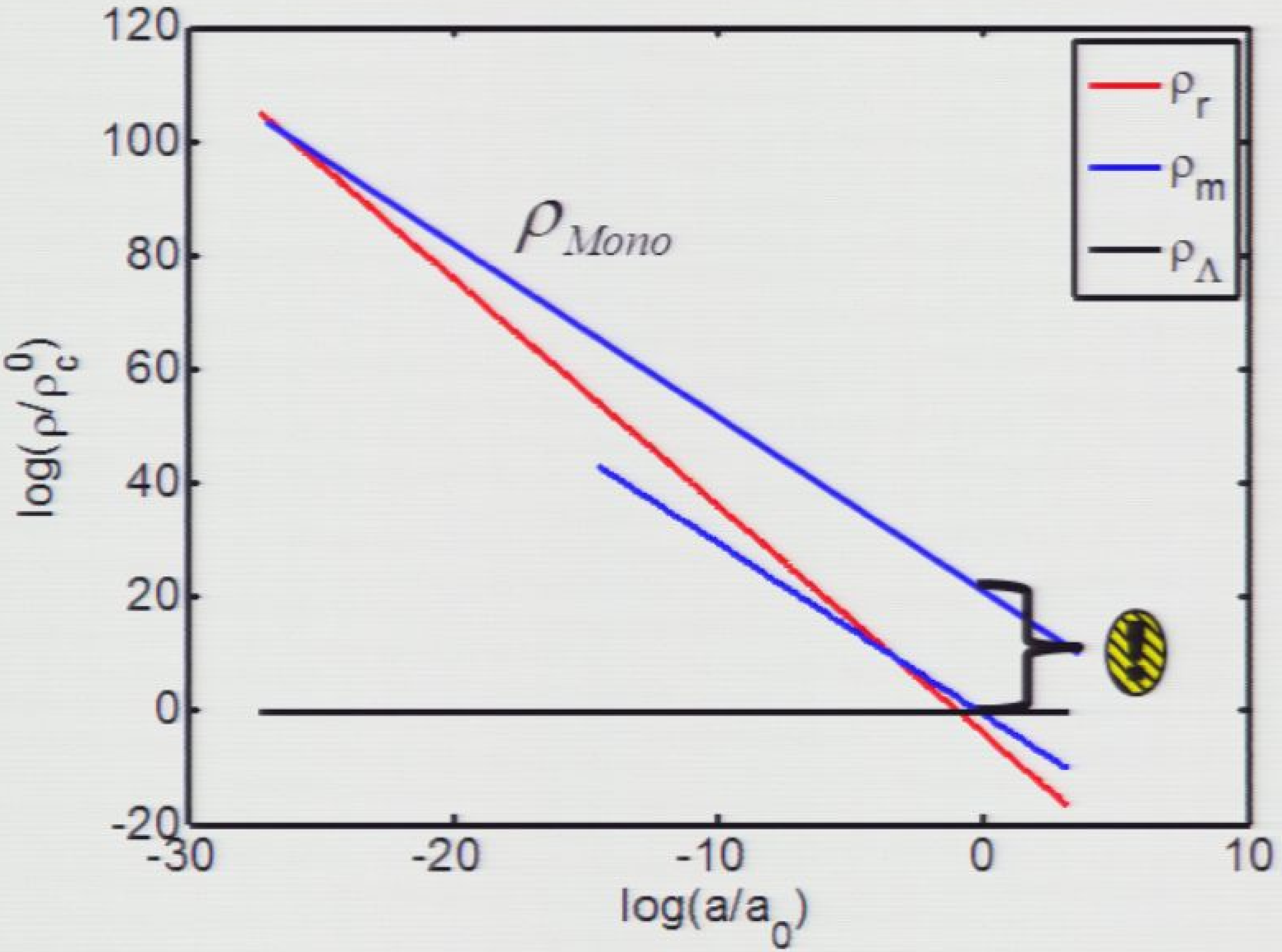


Friedmann Eqn.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\left(\rho_k + \rho_r + \rho_m + \rho_{DE}\right)$$

ρ_k: Curvature, $\propto a^{-2}$

ρ_r: Relativistic Matter, $\propto a^{-4}$

ρ_m: Non-relativistic Matter, $\propto a^{-3}$

ρ_{DE}: Dark Energy, $\propto a^{\approx 0}$

Now add cosmic inflation

Friedmann Eqn.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\left(\rho_I + \rho_k + \rho_r + \rho_m + \rho_{DE}\right)$$

$\rho_I \propto a^{\approx 0}$ — Inflaton

$\rho_k \propto a^{-2}$ — Curvature

$\rho_r \propto a^{-4}$ — Relativistic Matter

$\rho_m \propto a^{-3}$ — Non-relativistic Matter

$\rho_{DE} \propto a^{\approx 0}$ — Dark Energy

Now add cosmic inflation

Friedmann Eqn.

$\propto a^{\approx 0}$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\left(\rho_I + \rho_k + \rho_r + \rho_m + \rho_{DE}\right)$$

Inflaton

Curvature

Relativistic Matter

Non-relativistic Matter

Dark Energy

The inflaton:

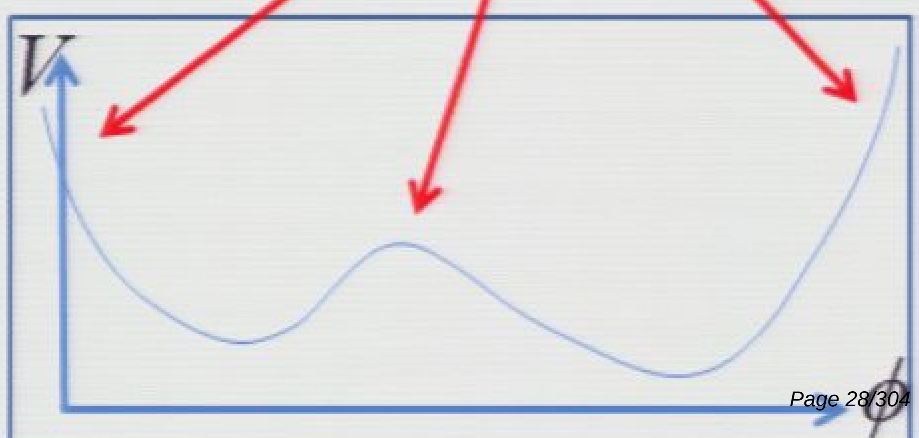
~Homogeneous scalar field ϕ obeying

$$\ddot{\phi} + 3H\dot{\phi} = -\Gamma_{\phi}\dot{\phi} - V'(\phi)$$

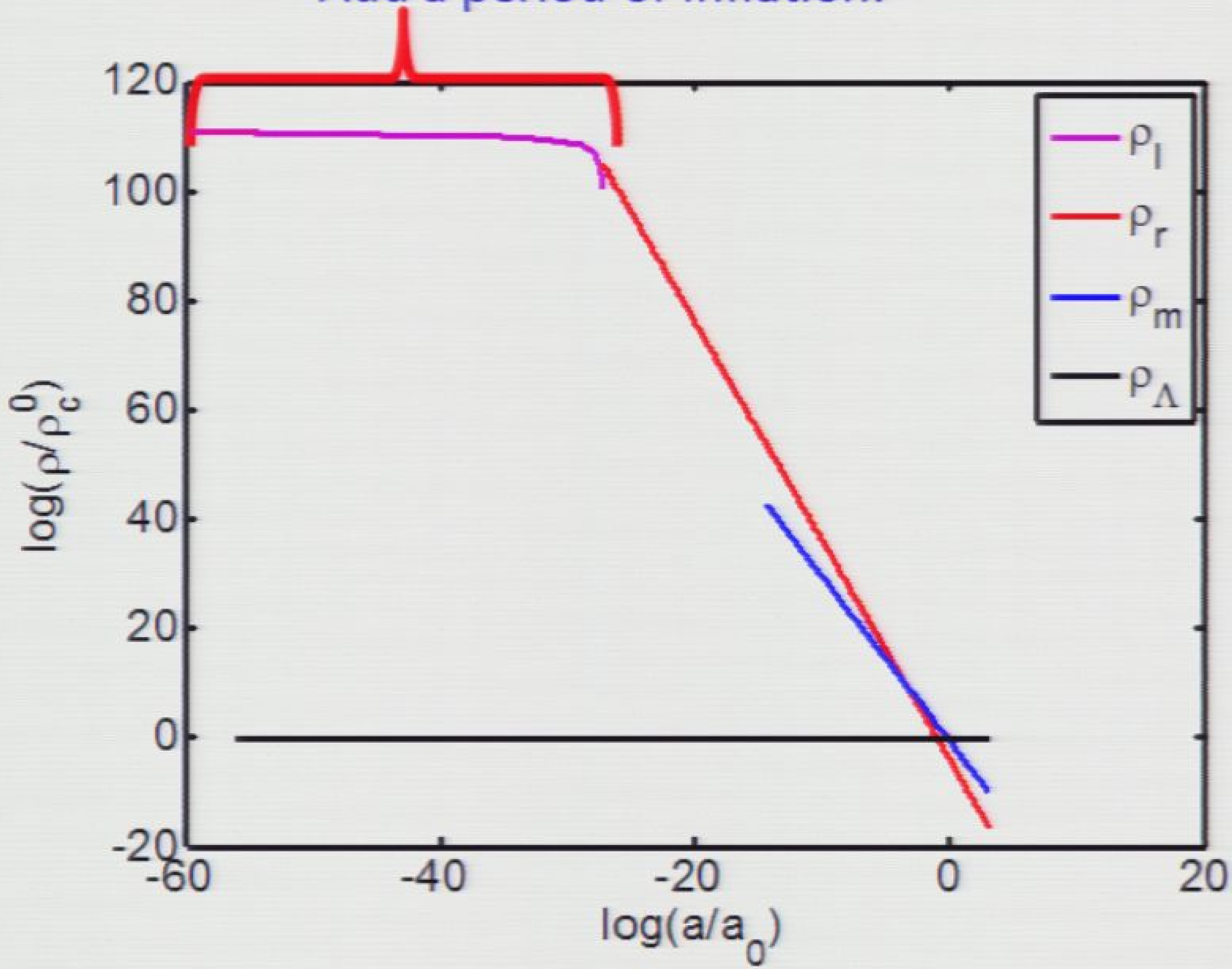
Cosmic damping *Coupling to ordinary matter*

All potentials have a "low roll" (overdamped) regime where

$$\rho_I = \frac{1}{2}\dot{\phi}^2 + V(\phi) \approx V(\phi) \approx const. \propto a^{\approx 0}$$



Add a period of Inflation:



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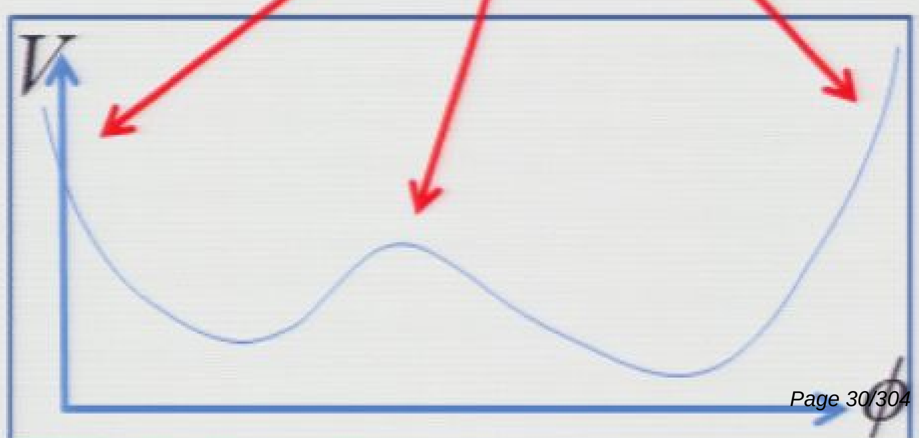

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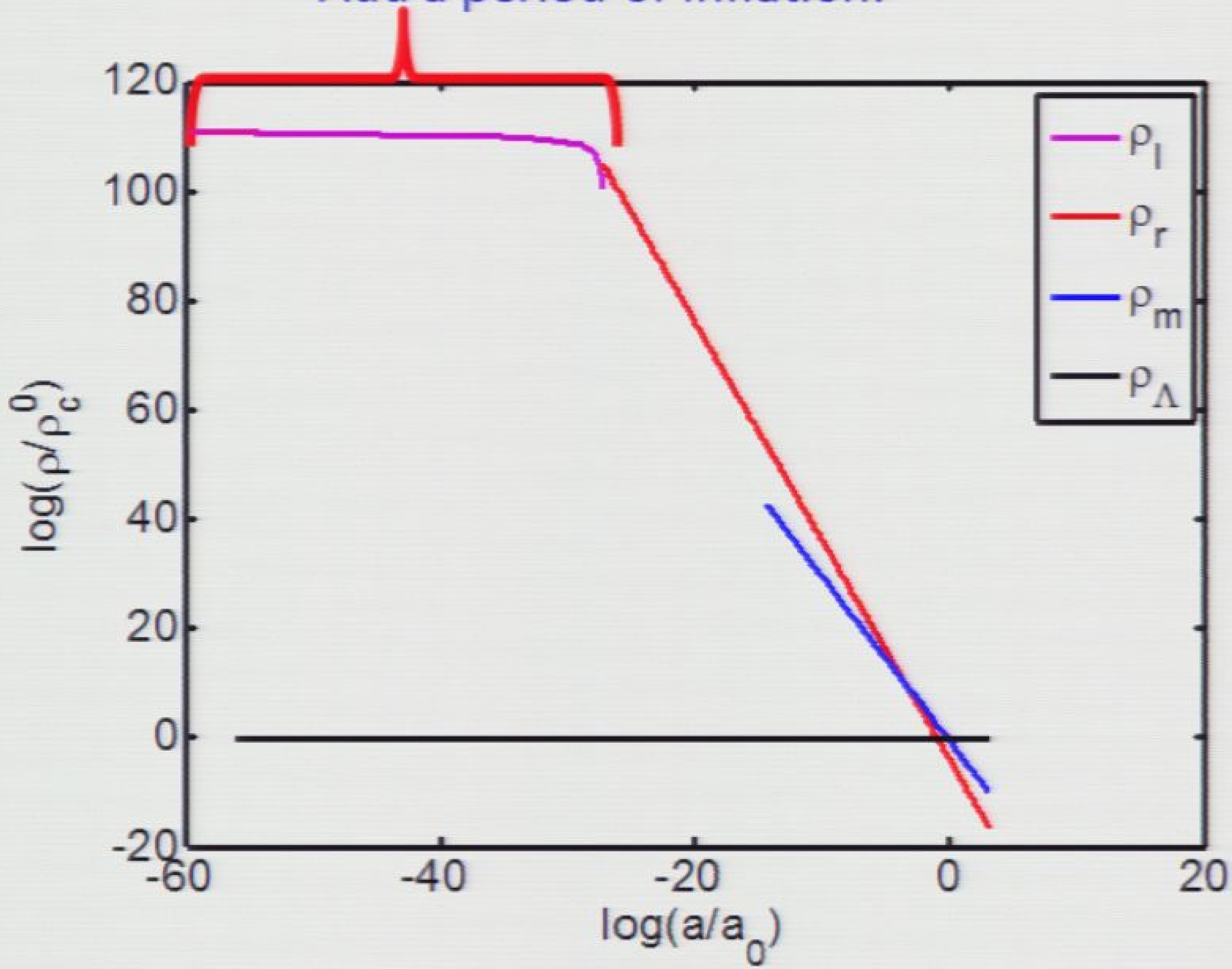
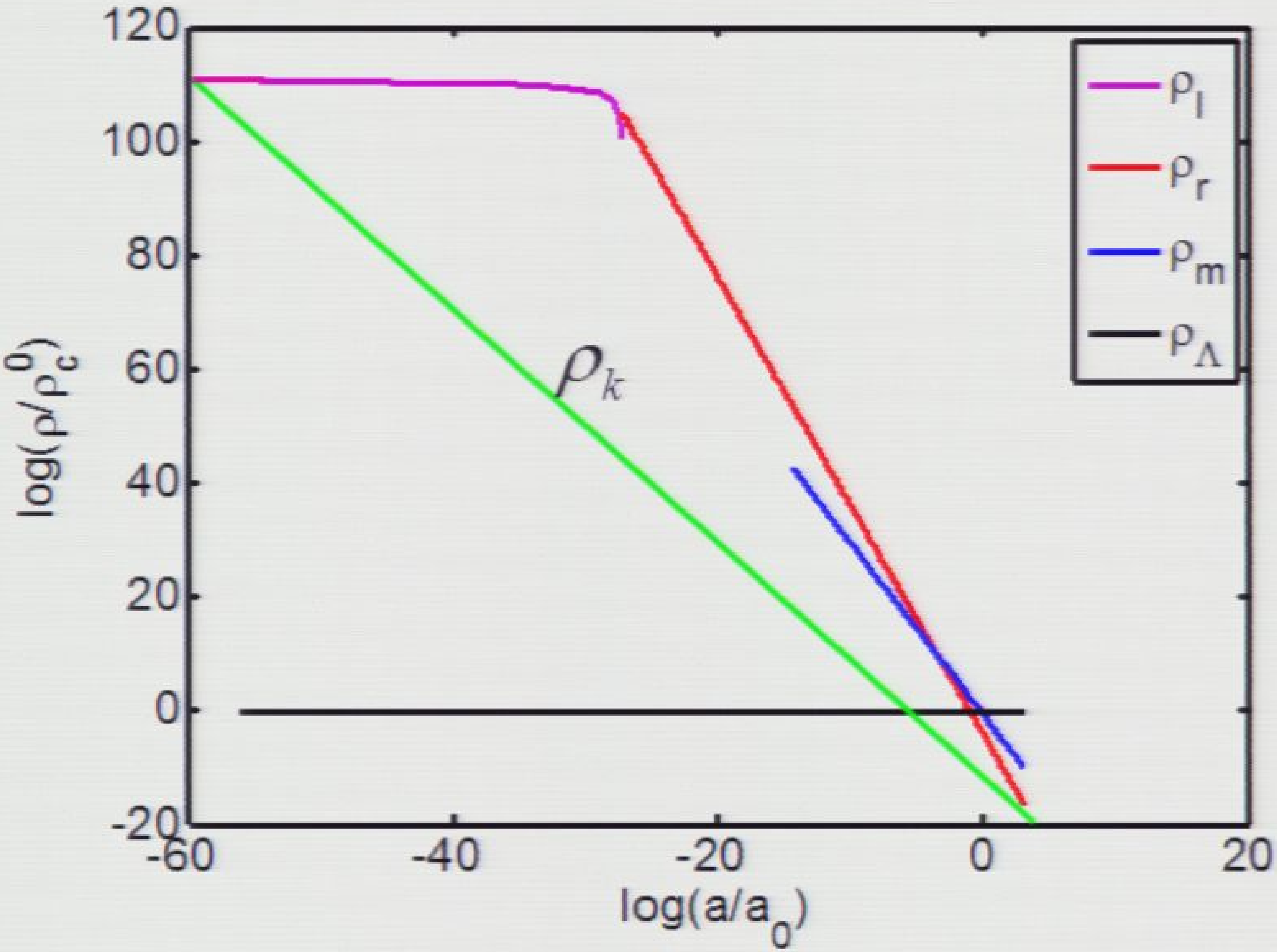
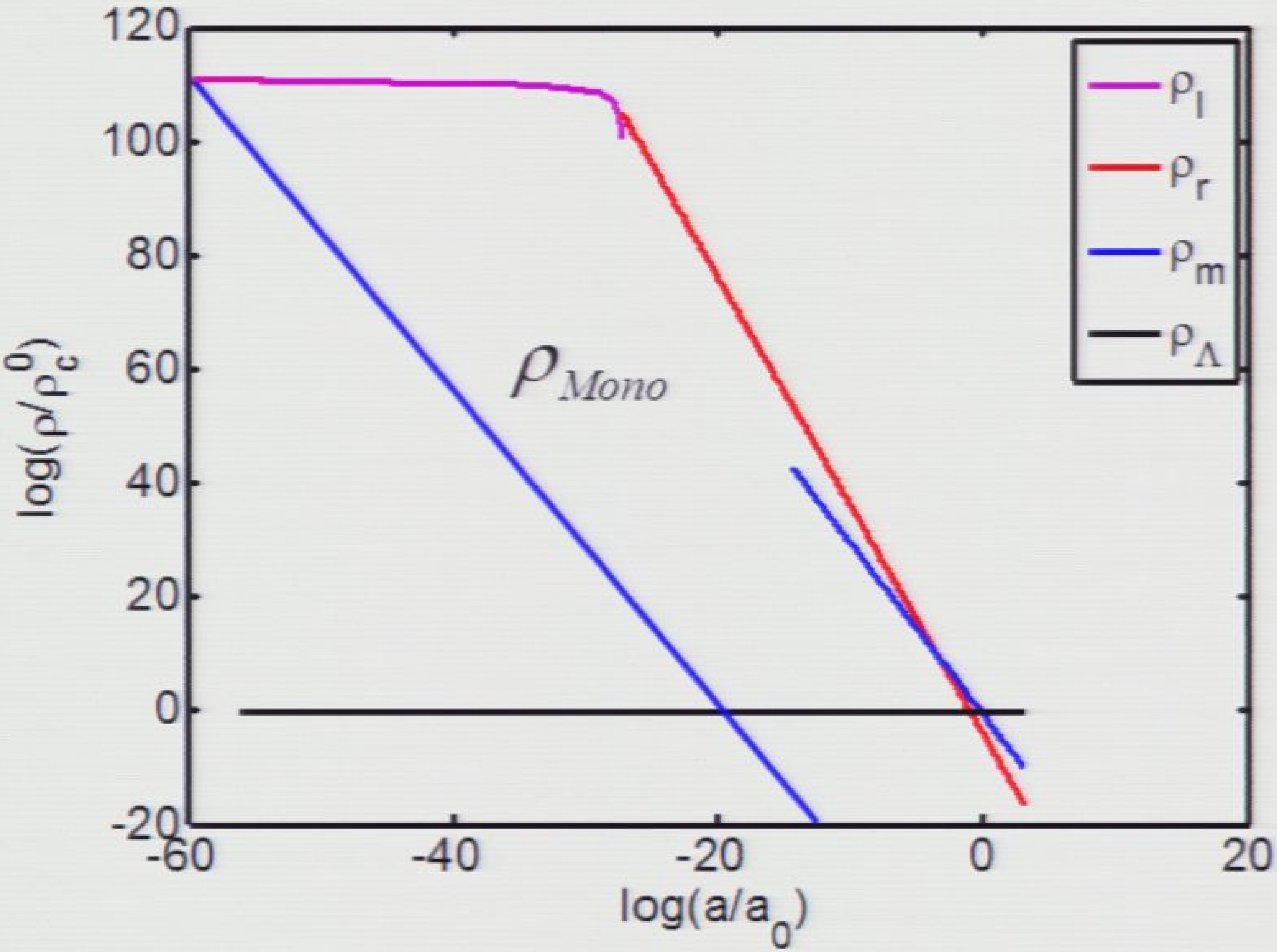


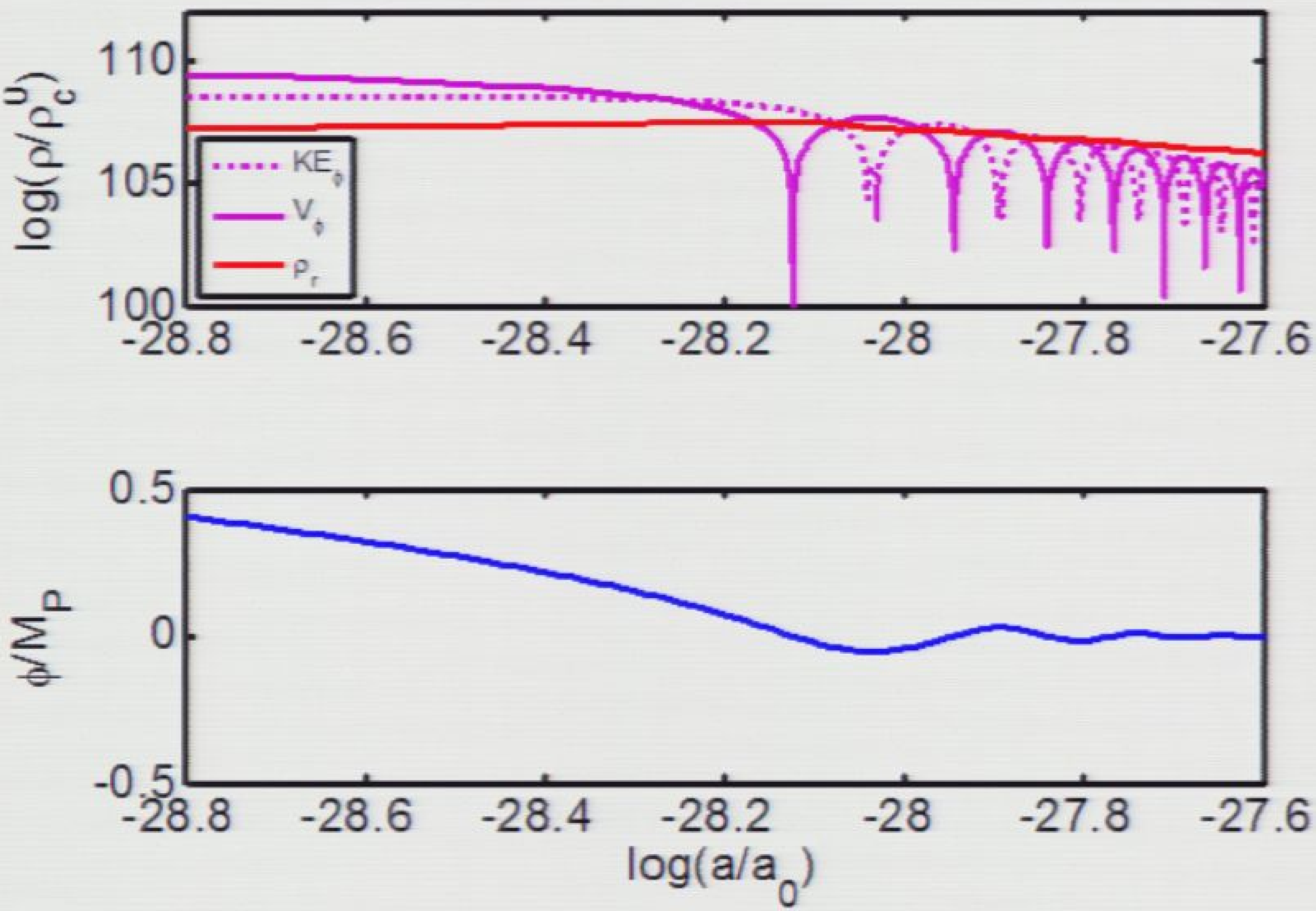
With inflation, initially large curvature is OK:



Vith inflation, early production of large amounts of non-relativistic natter (monopoles) is ok :



nflation detail:



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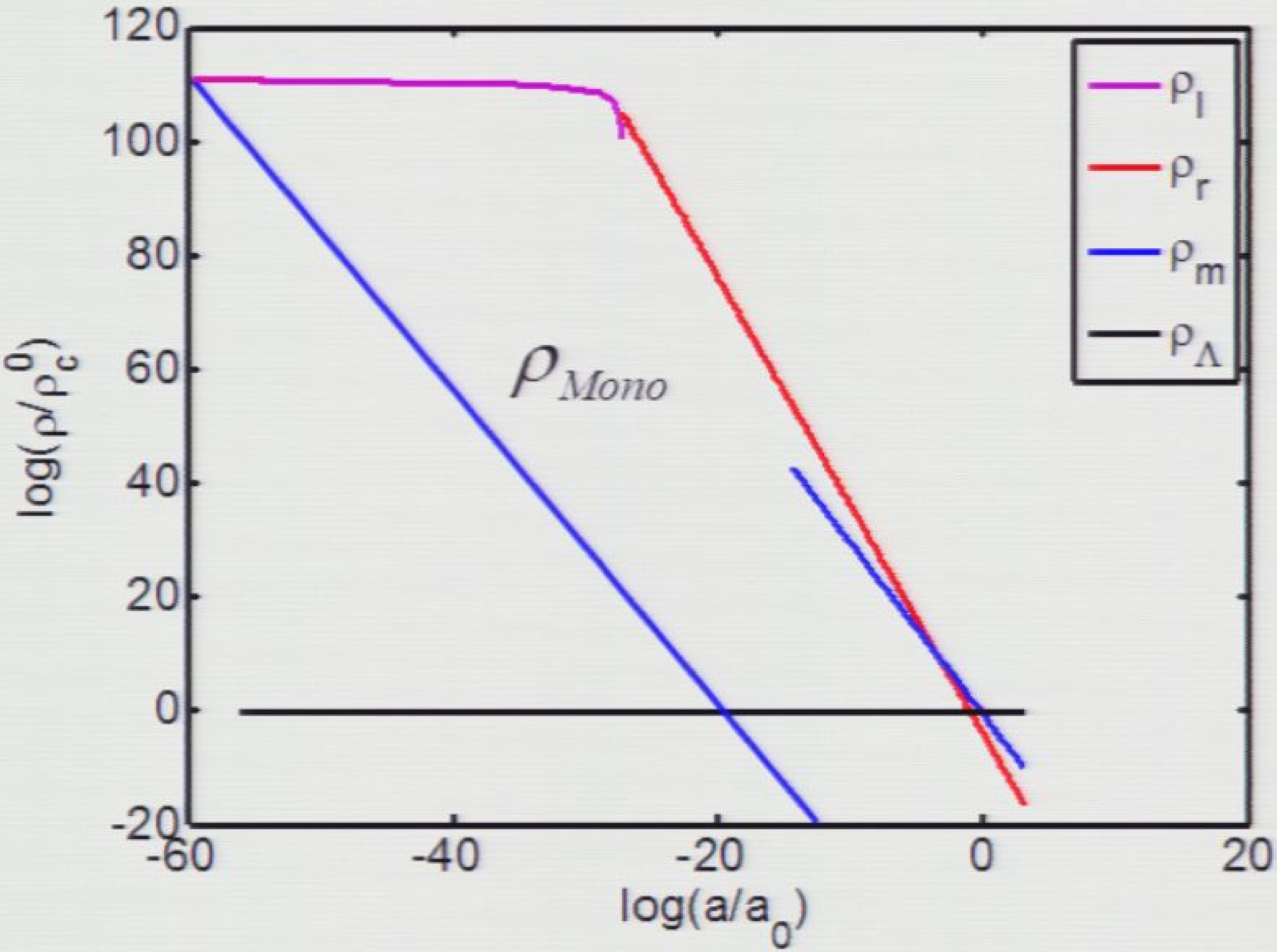

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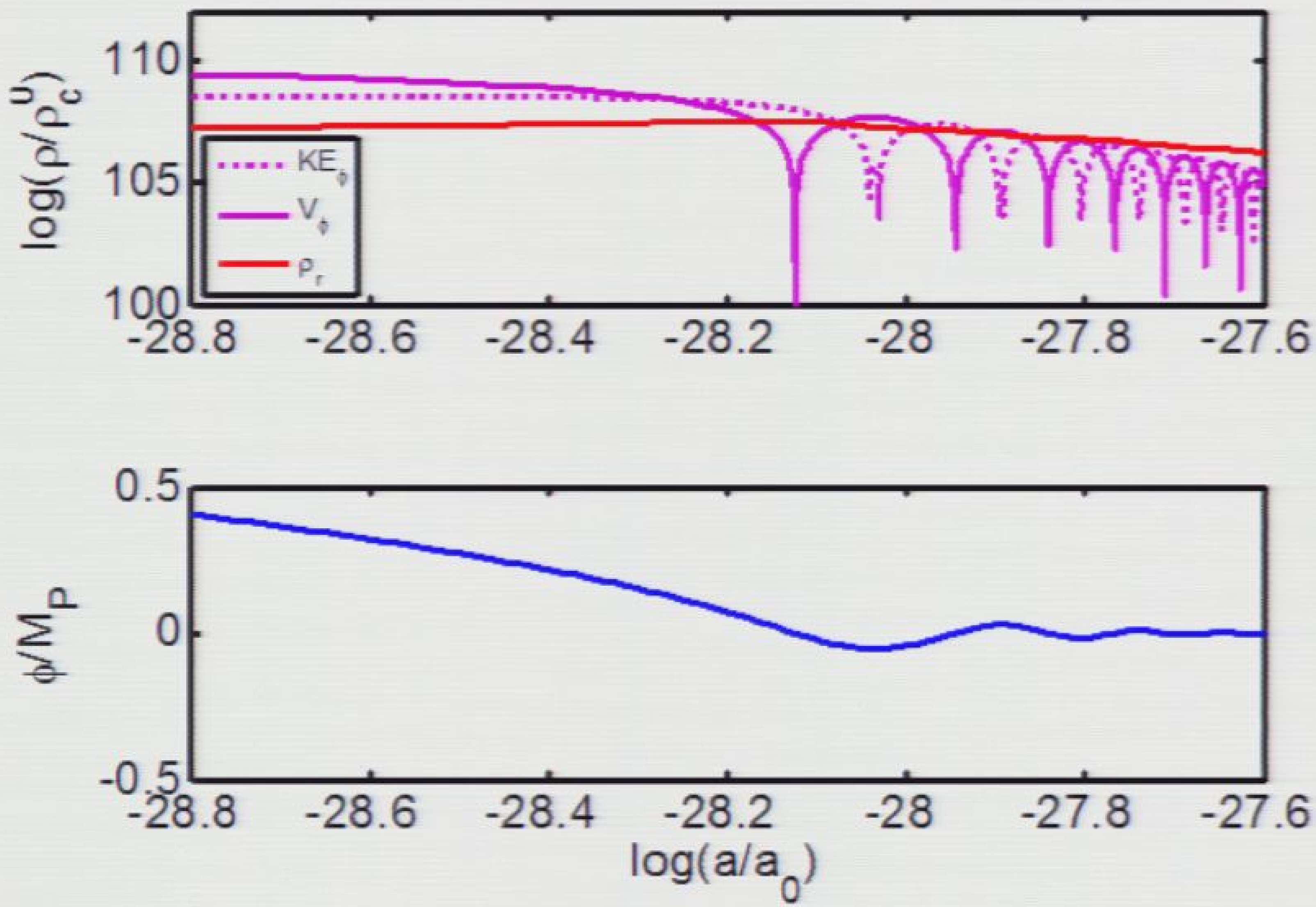

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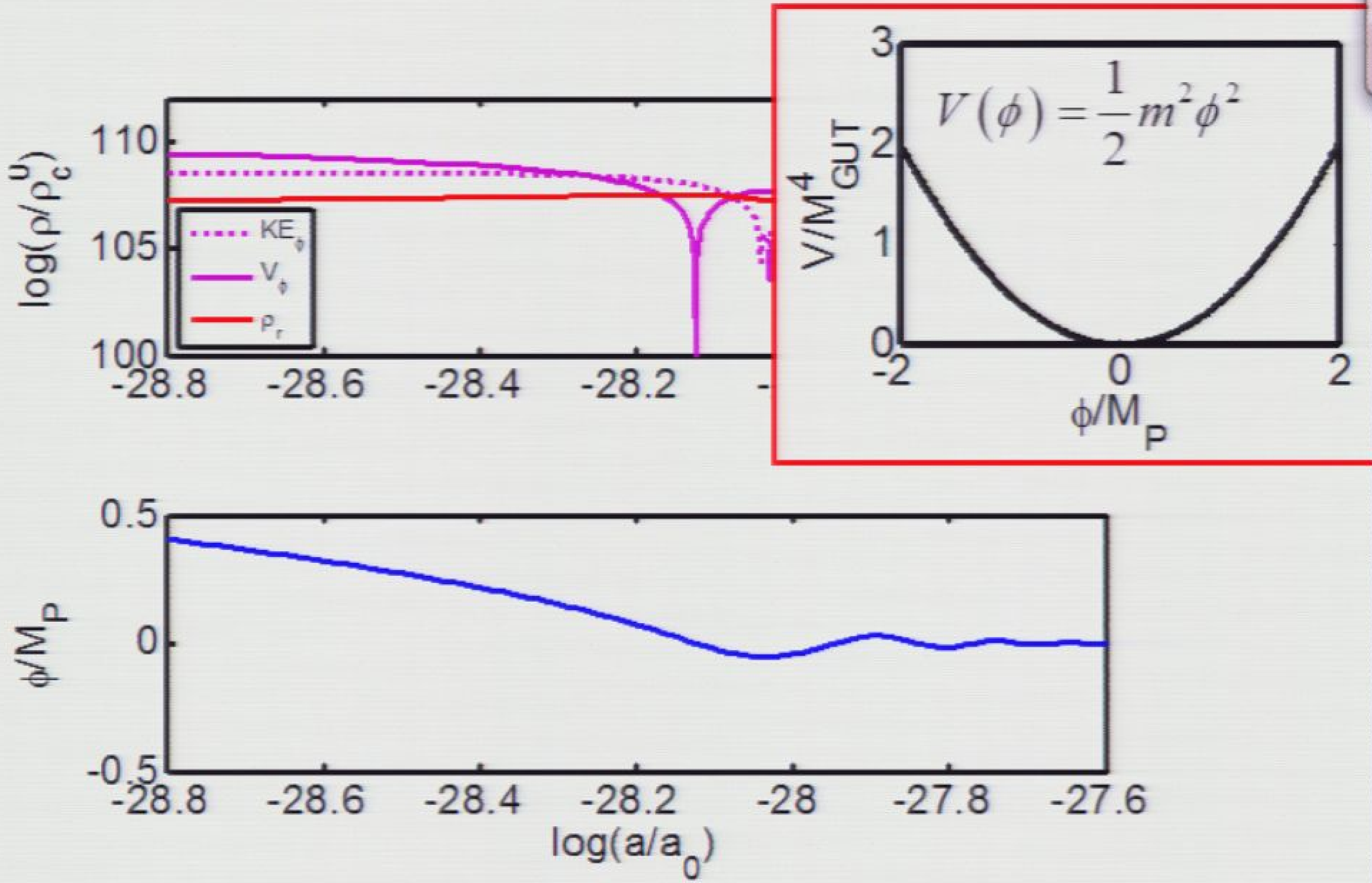

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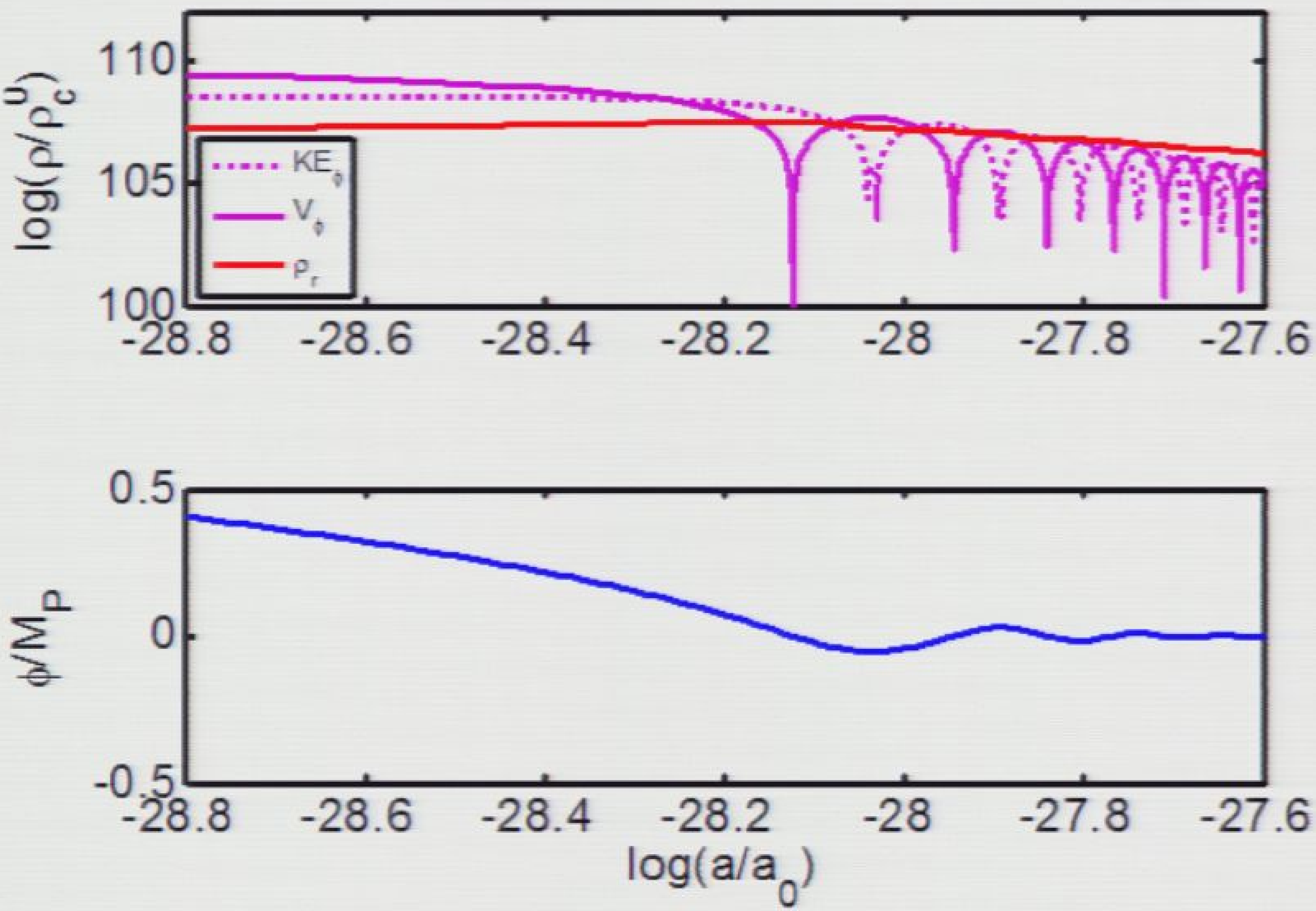

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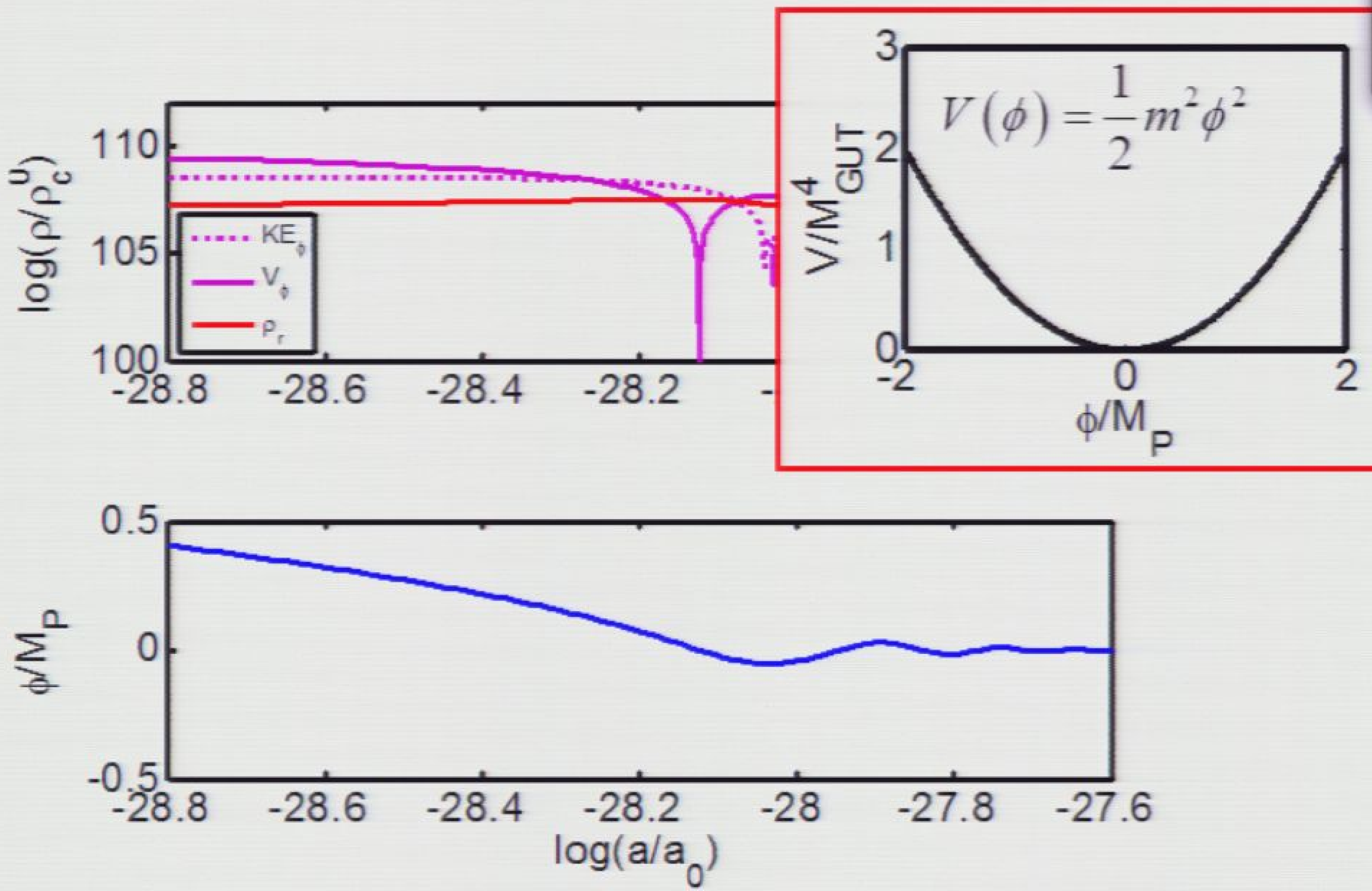

Hubble Length

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\left(\rho_I + \rho_k + \rho_r + \rho_m + \rho_{DE}\right) \equiv \frac{8\pi}{3} G\rho_{Tot}$$

$$R_H \equiv \frac{c}{H} \propto \frac{1}{\rho_{Tot}^{1/2}}$$

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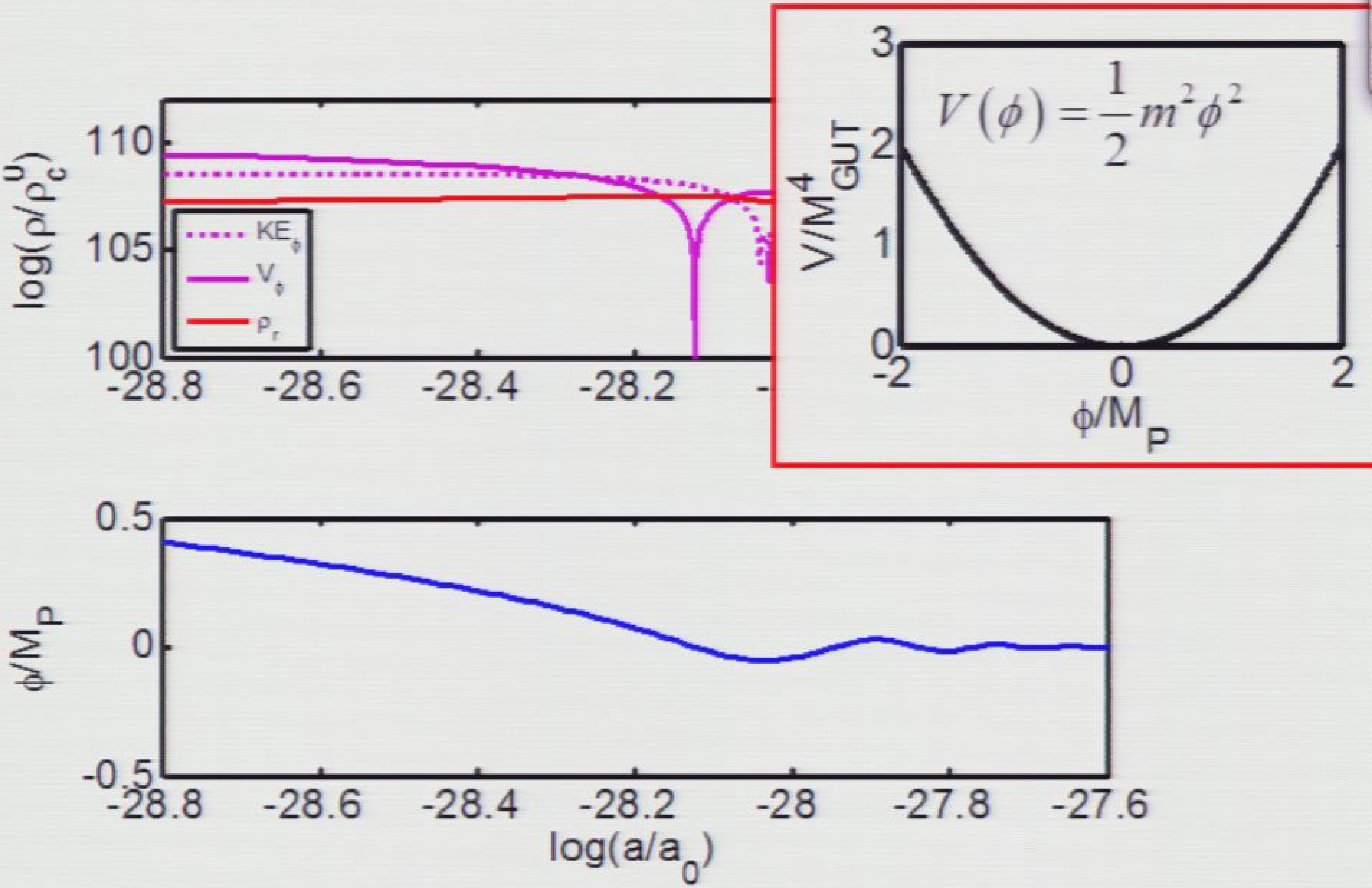
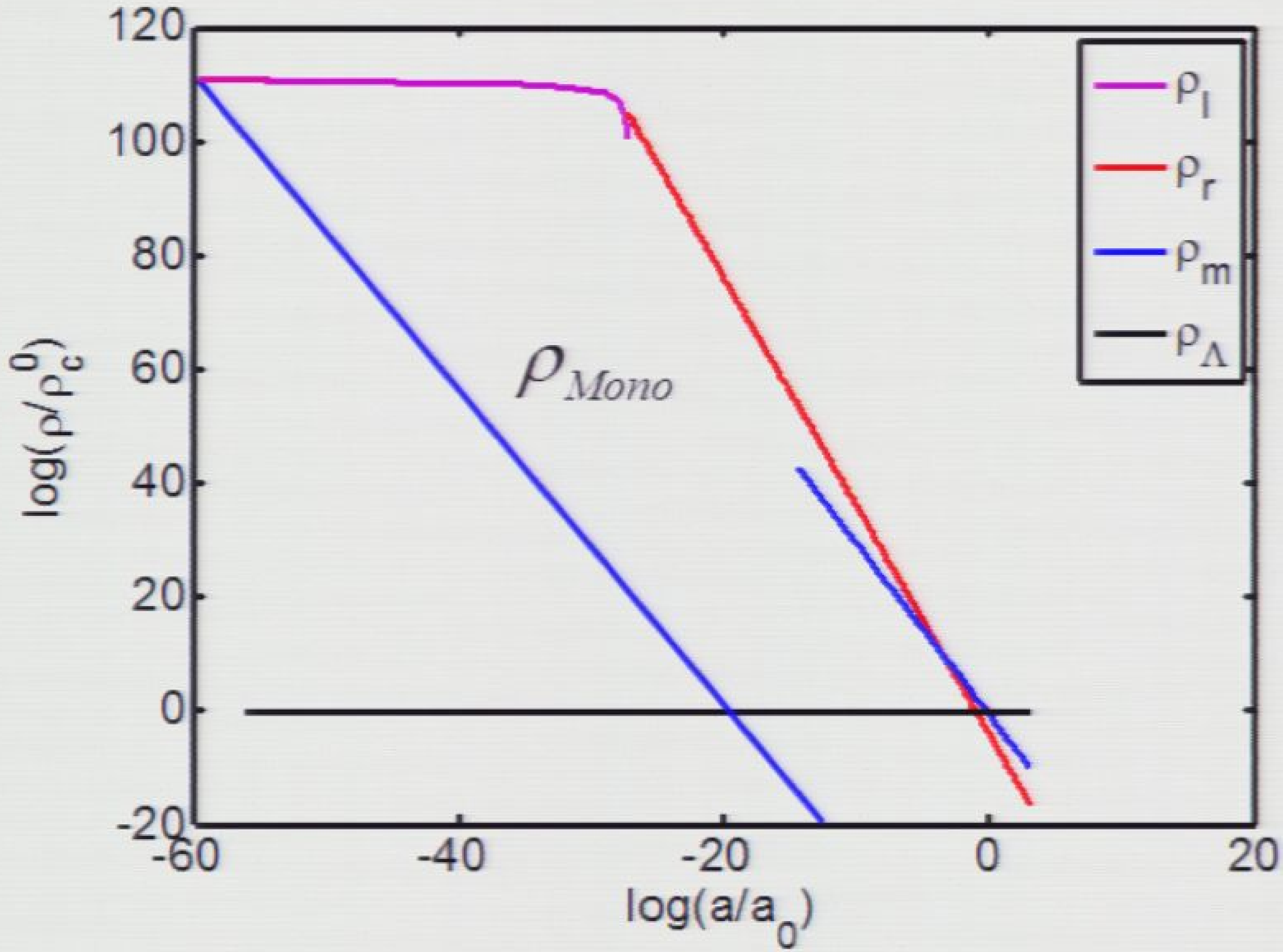


With inflation, early production of large amounts of non-relativistic matter (monopoles) is ok :



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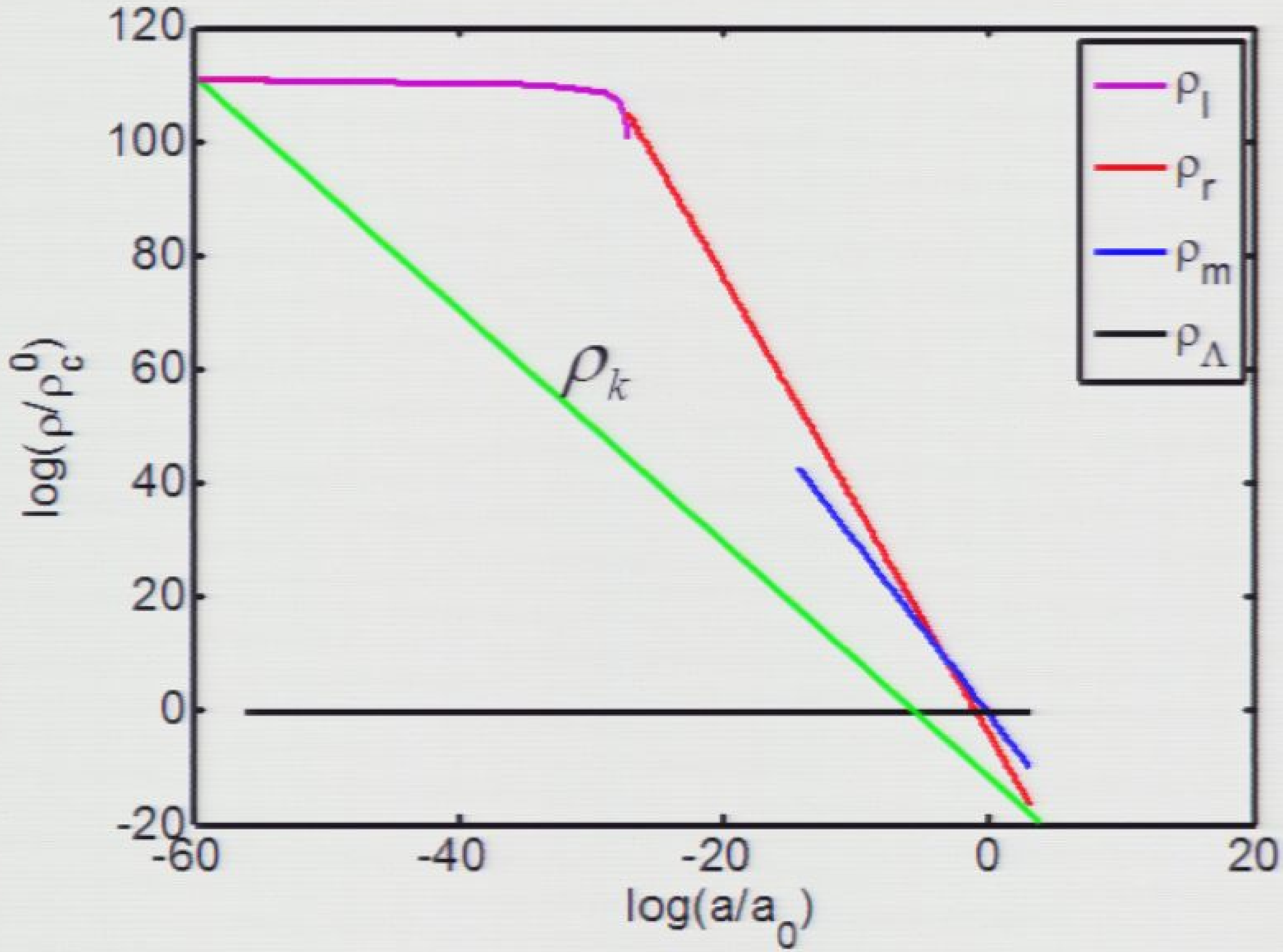

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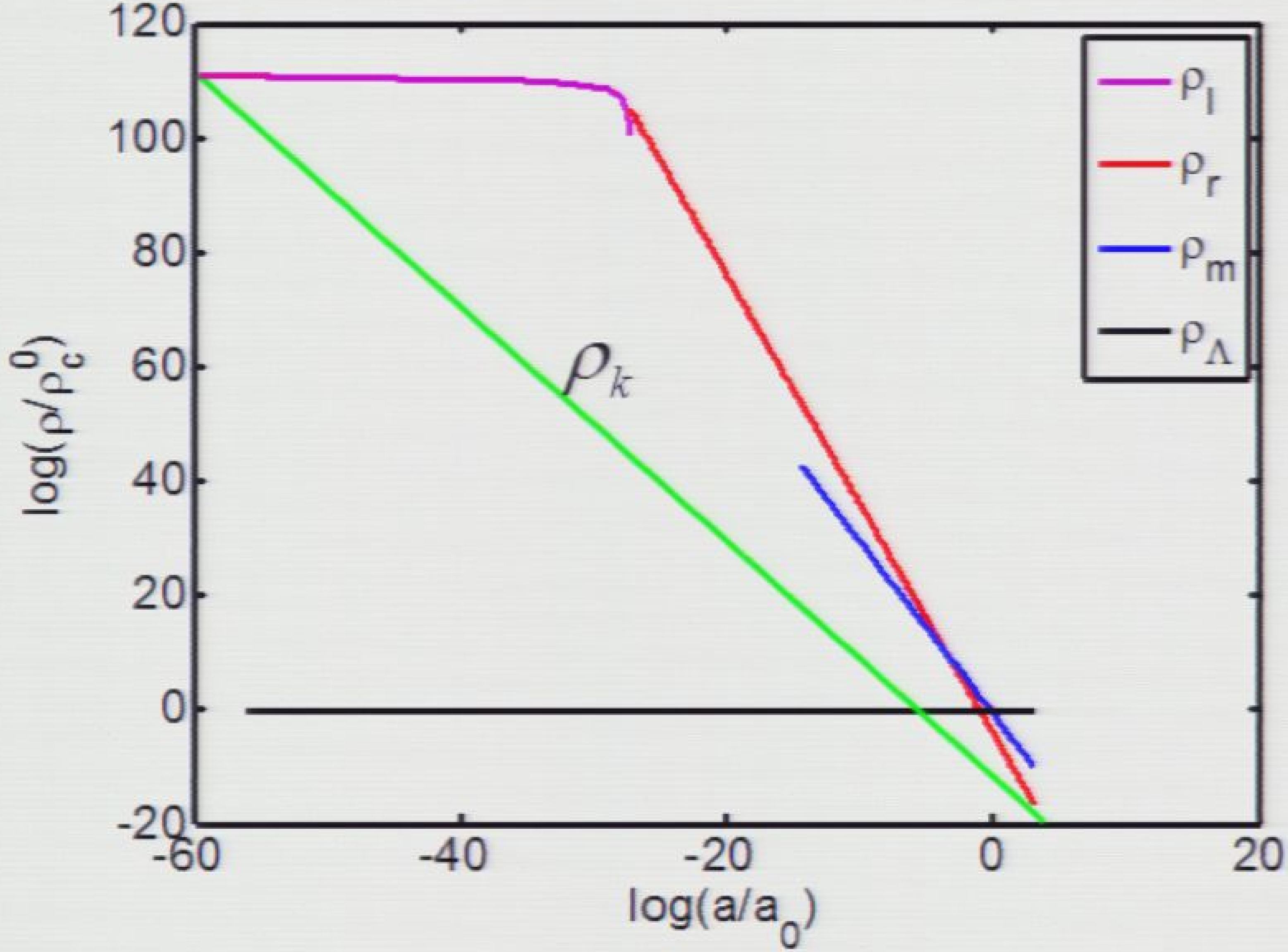

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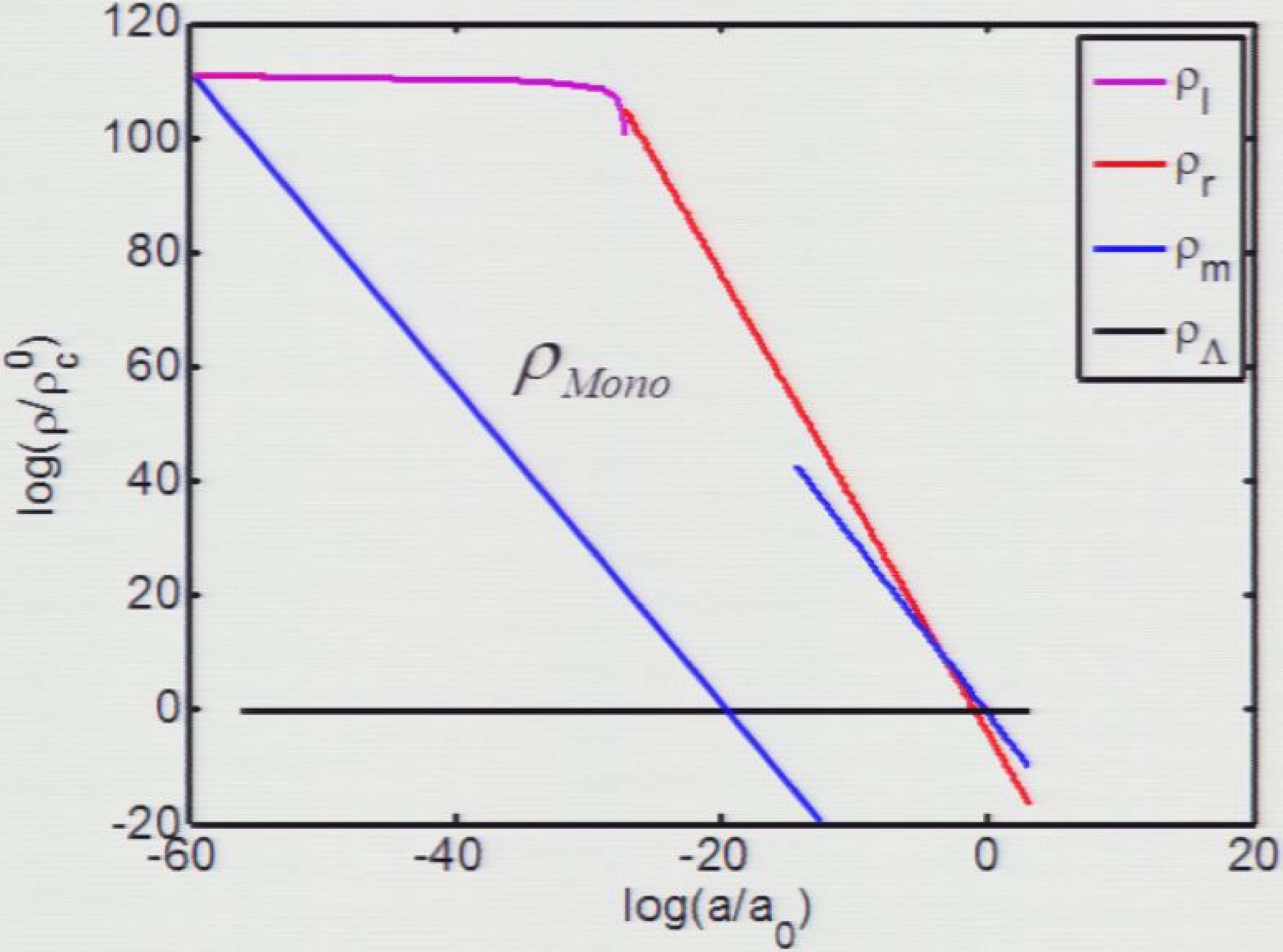

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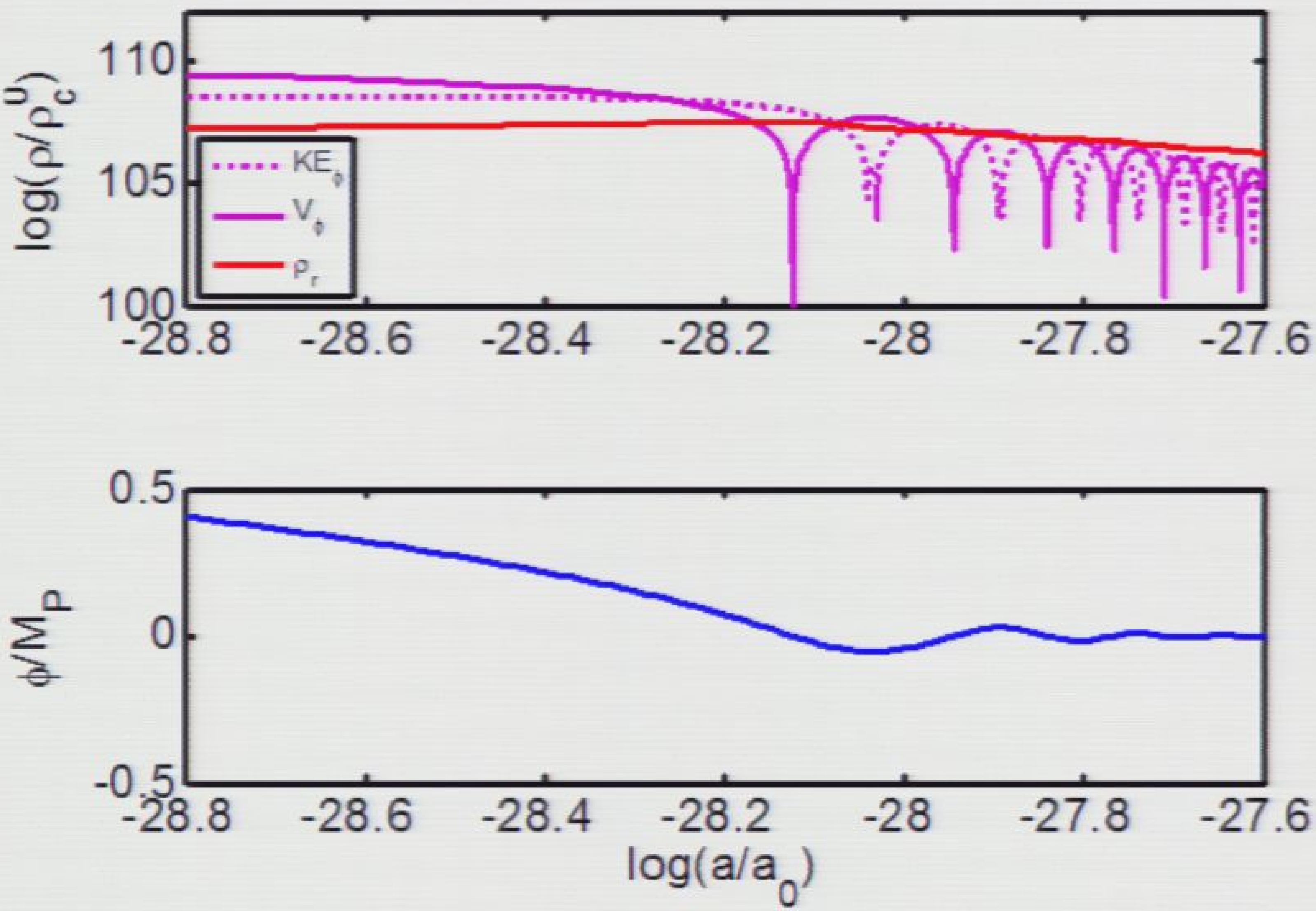

Hubble Length

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Hubble Length

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↑

(aka ρ_c)

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Hubble Length

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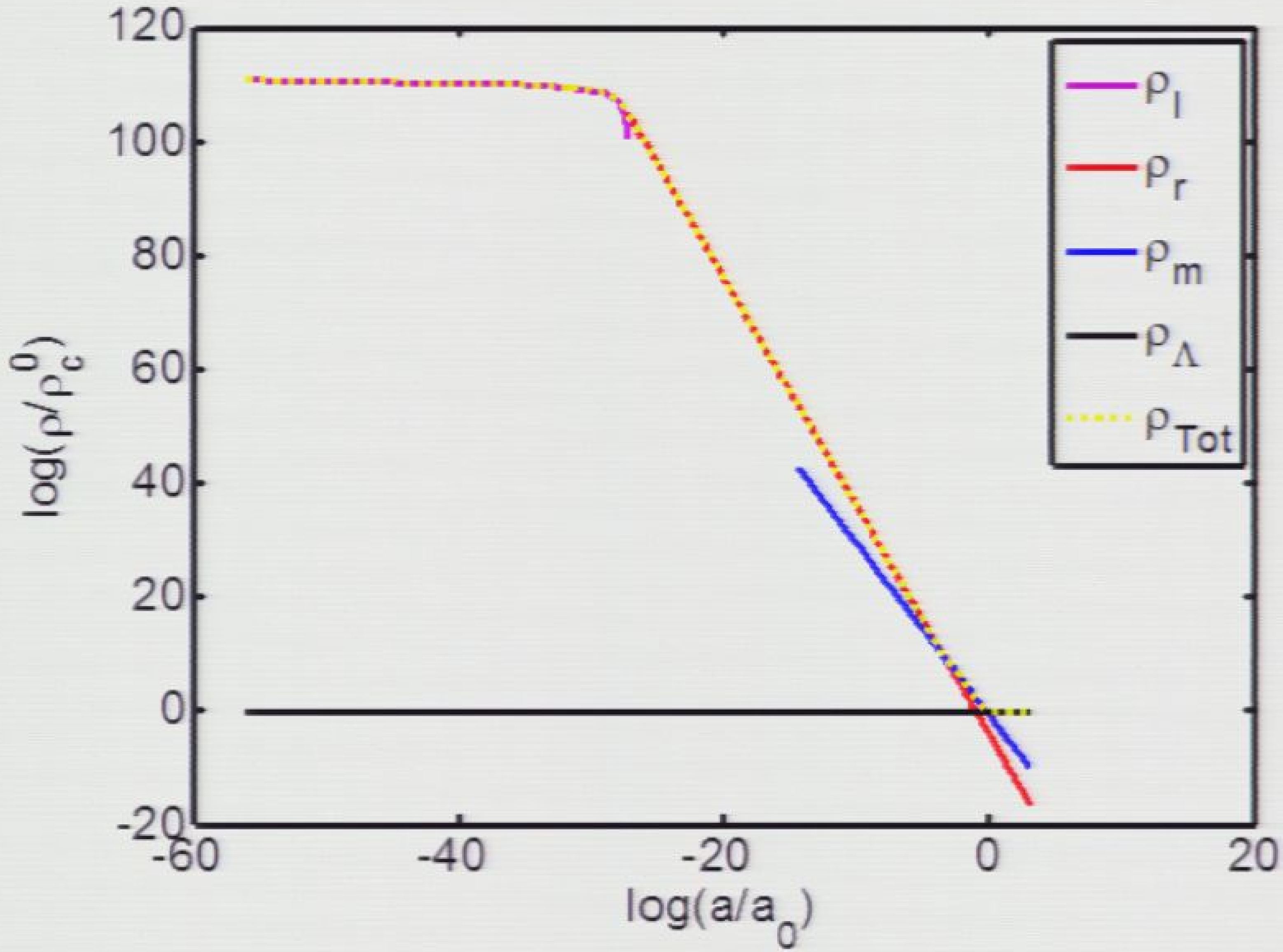
Distance light travels in one e-folding of expansion.



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$\log(\rho/\rho_c^0)$
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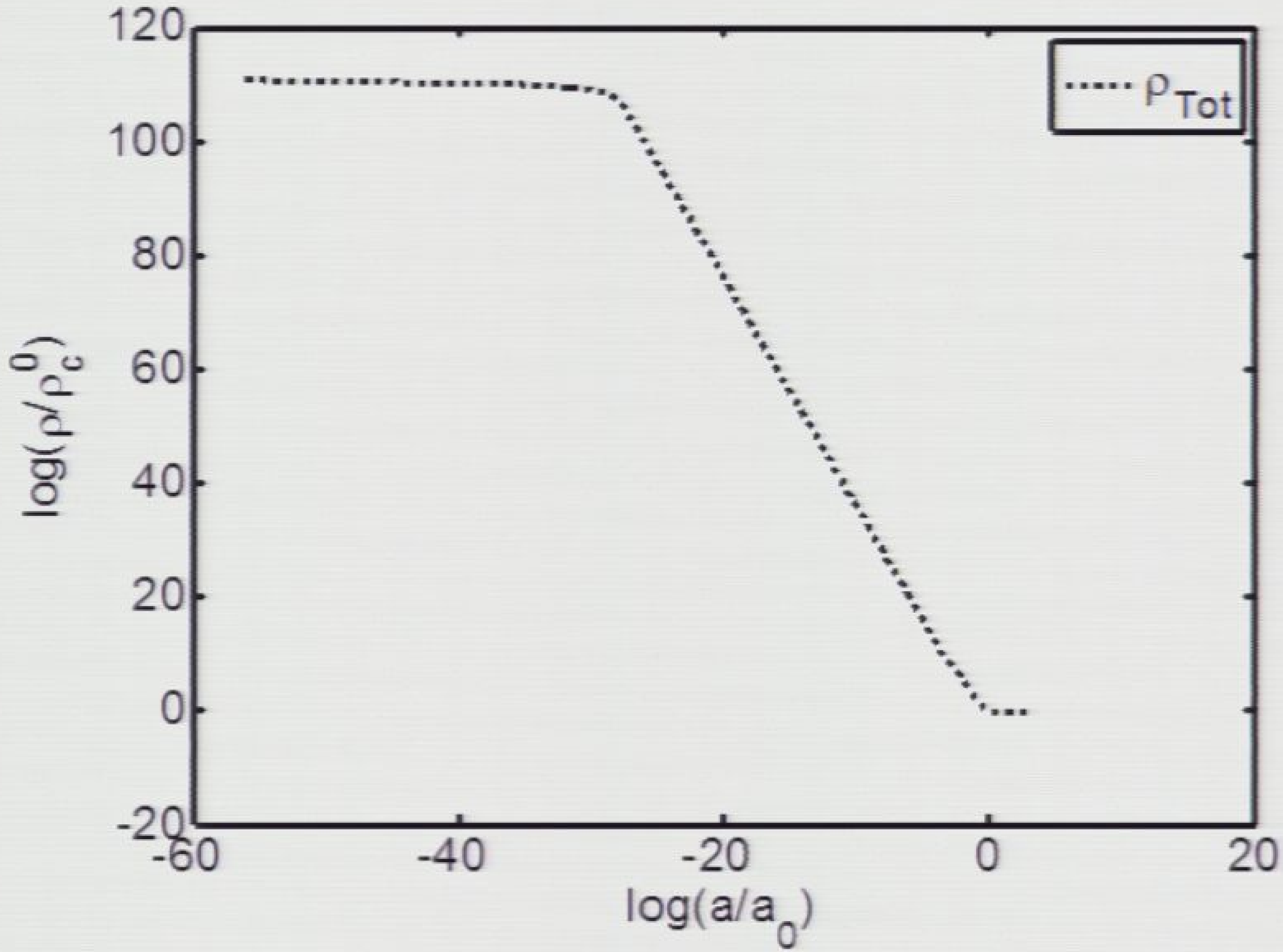
ρ_{Tot}



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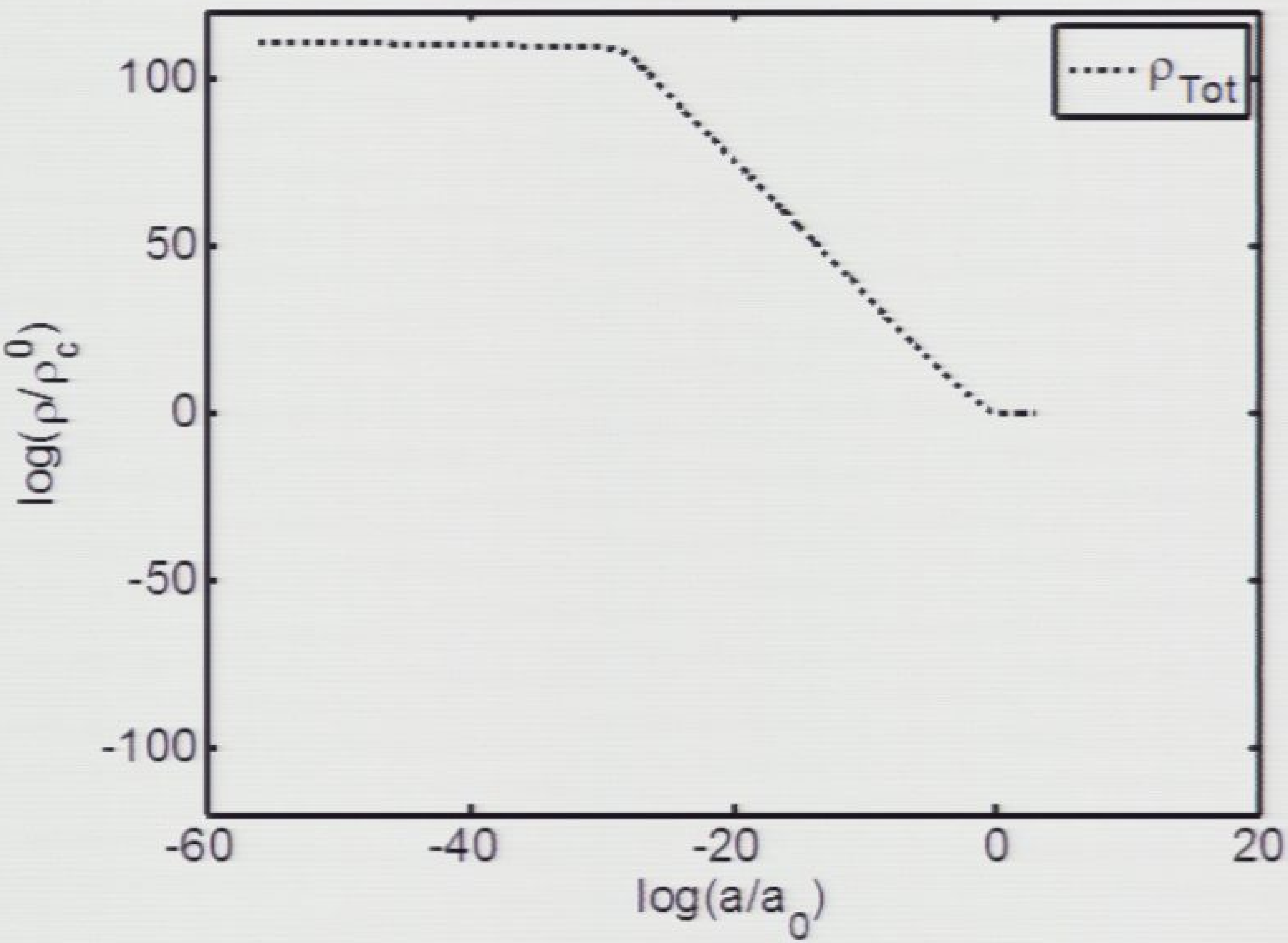
log(a/a0)
log(ρ/ρc0)
ρTot



ρ_Tot
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log(ρ/ρ_c^0)
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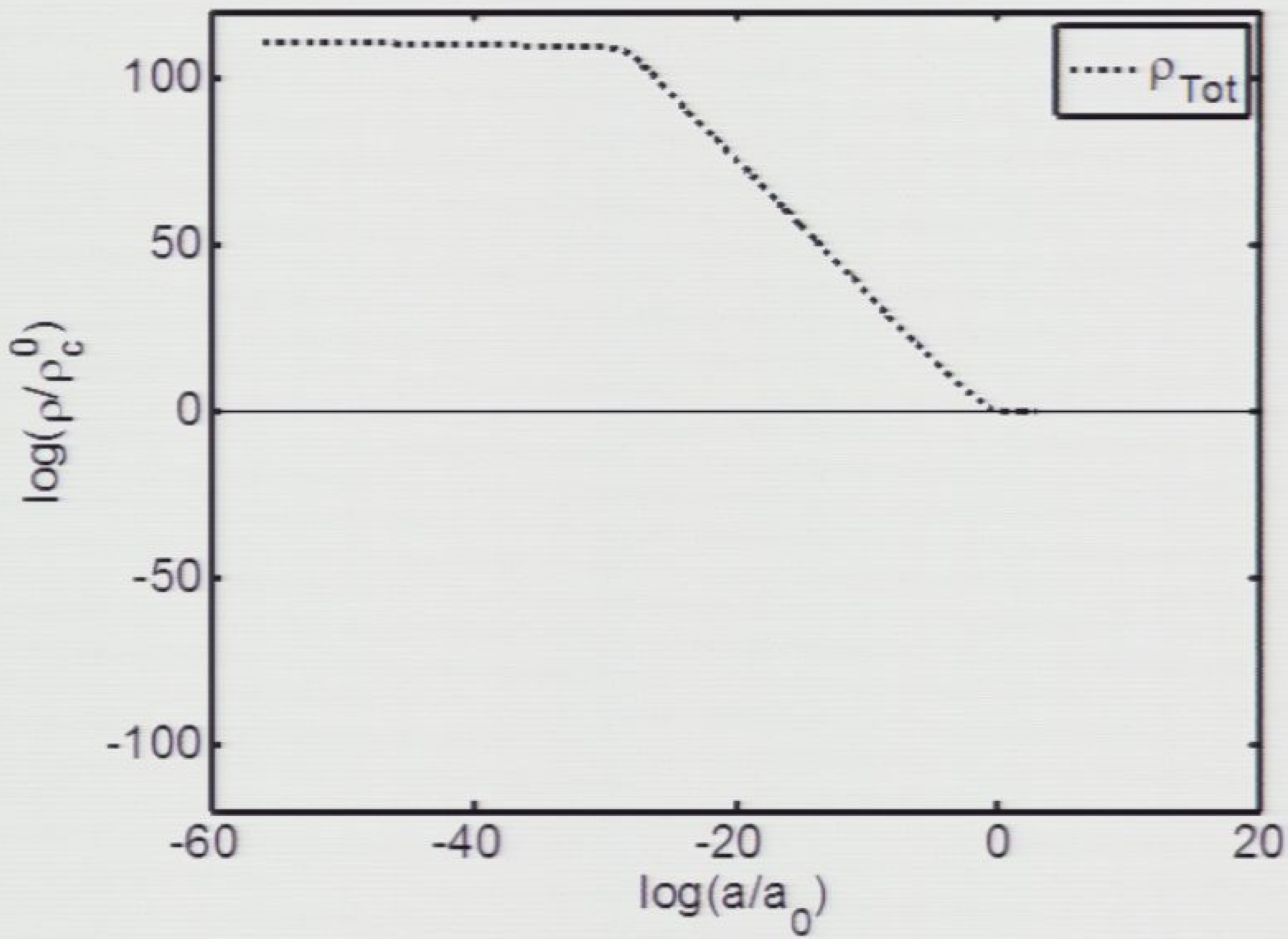
log(a/a_0)



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-100
-60
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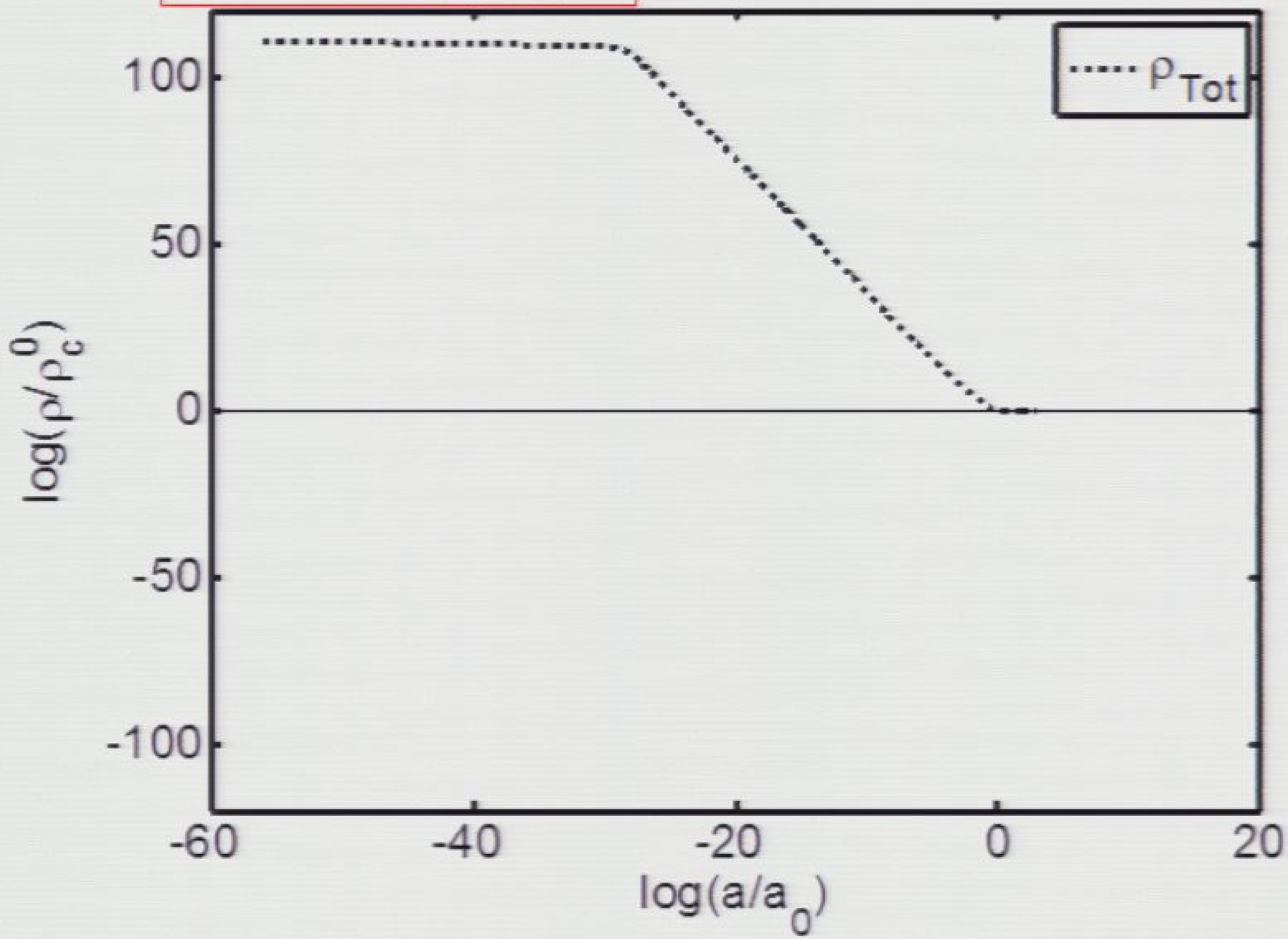
0
20
log(a/a0)
log(ρ/ρc0)
ρTot

$$R_H \equiv \frac{c}{H} \propto \left(\frac{1}{\rho_{Tot}}\right)^{1/2}$$



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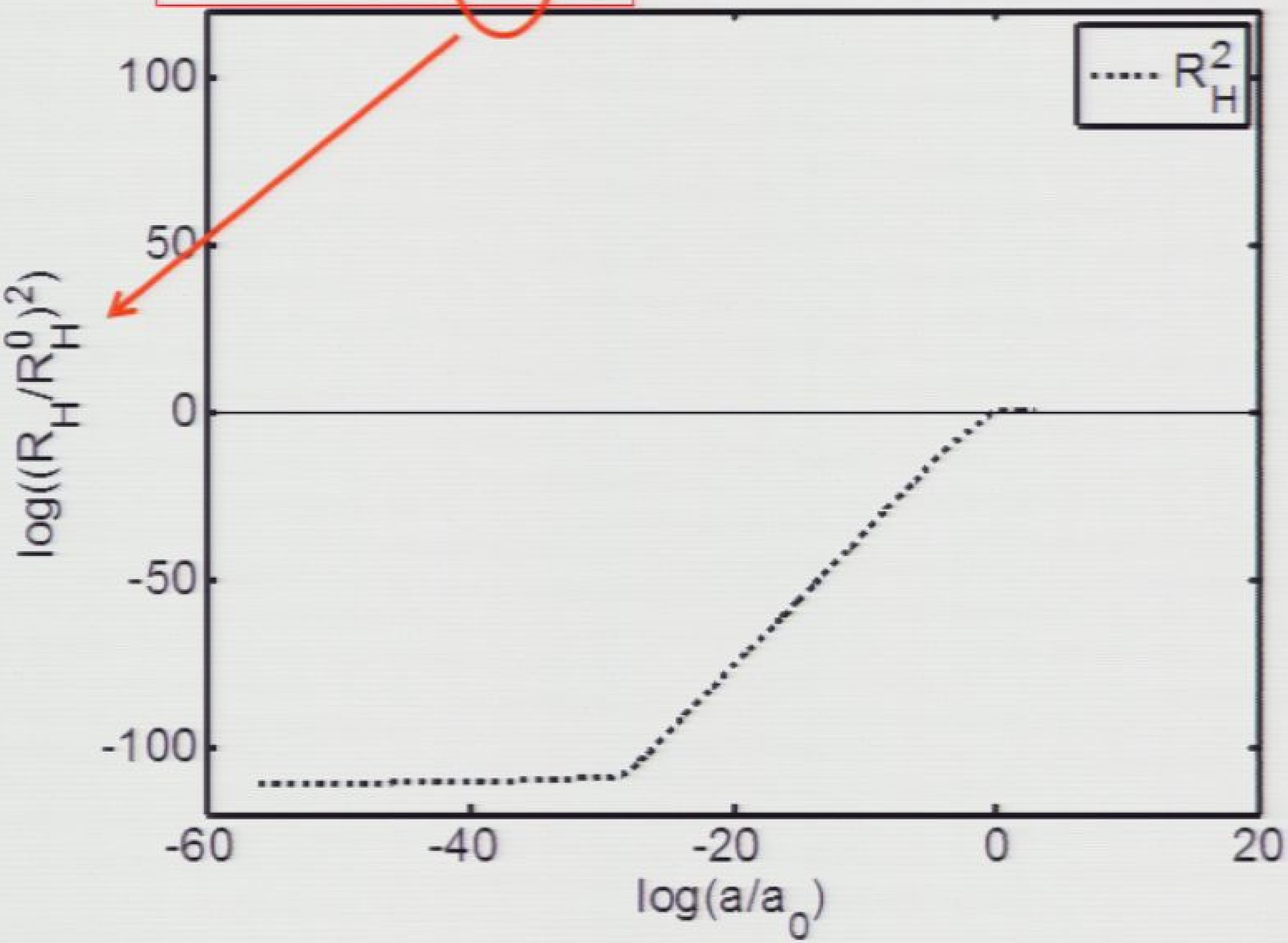

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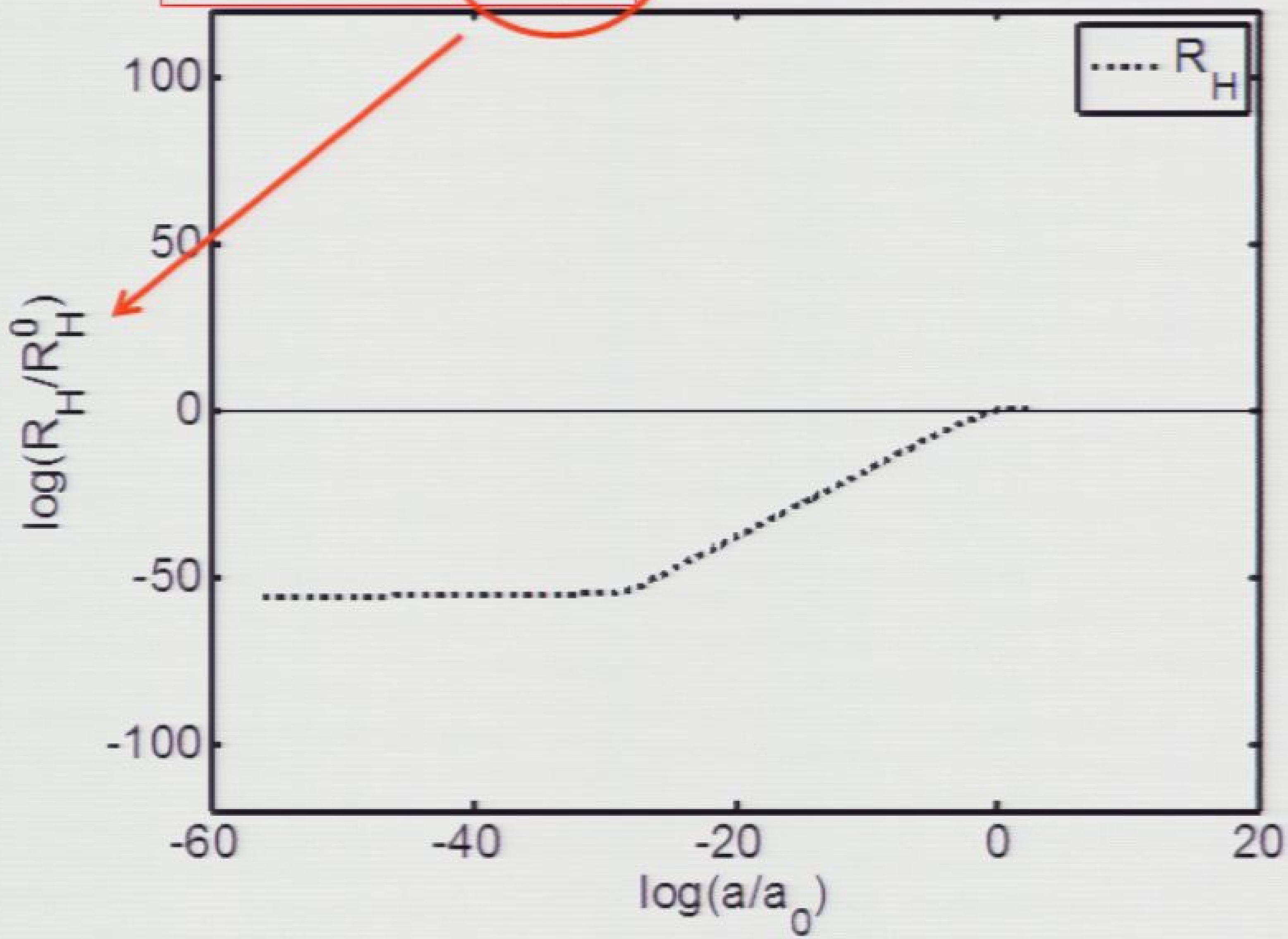

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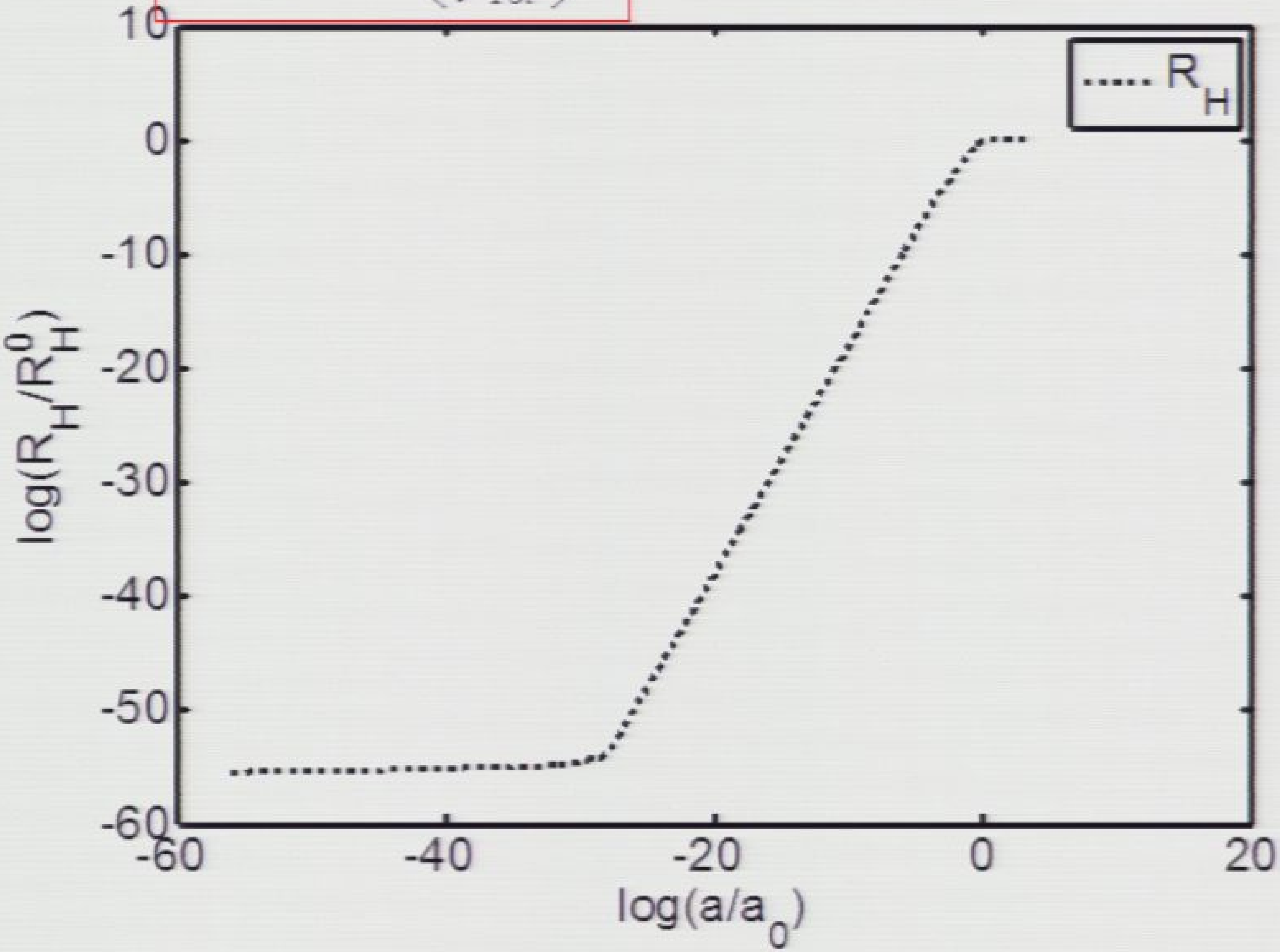
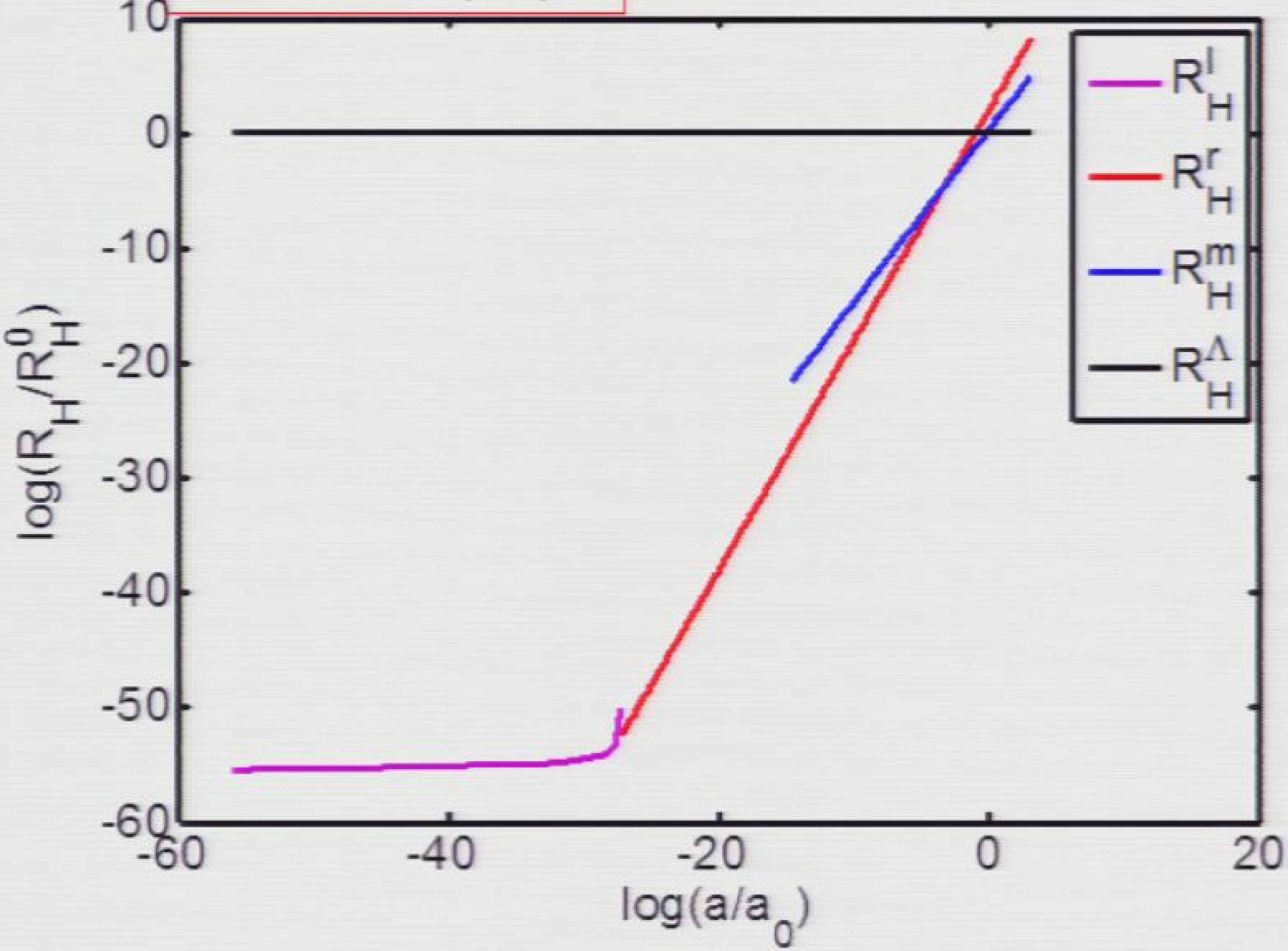


$$R_H^i \equiv \frac{c}{H_i} \propto \left(\frac{1}{\rho_i}\right)^{1/2}$$



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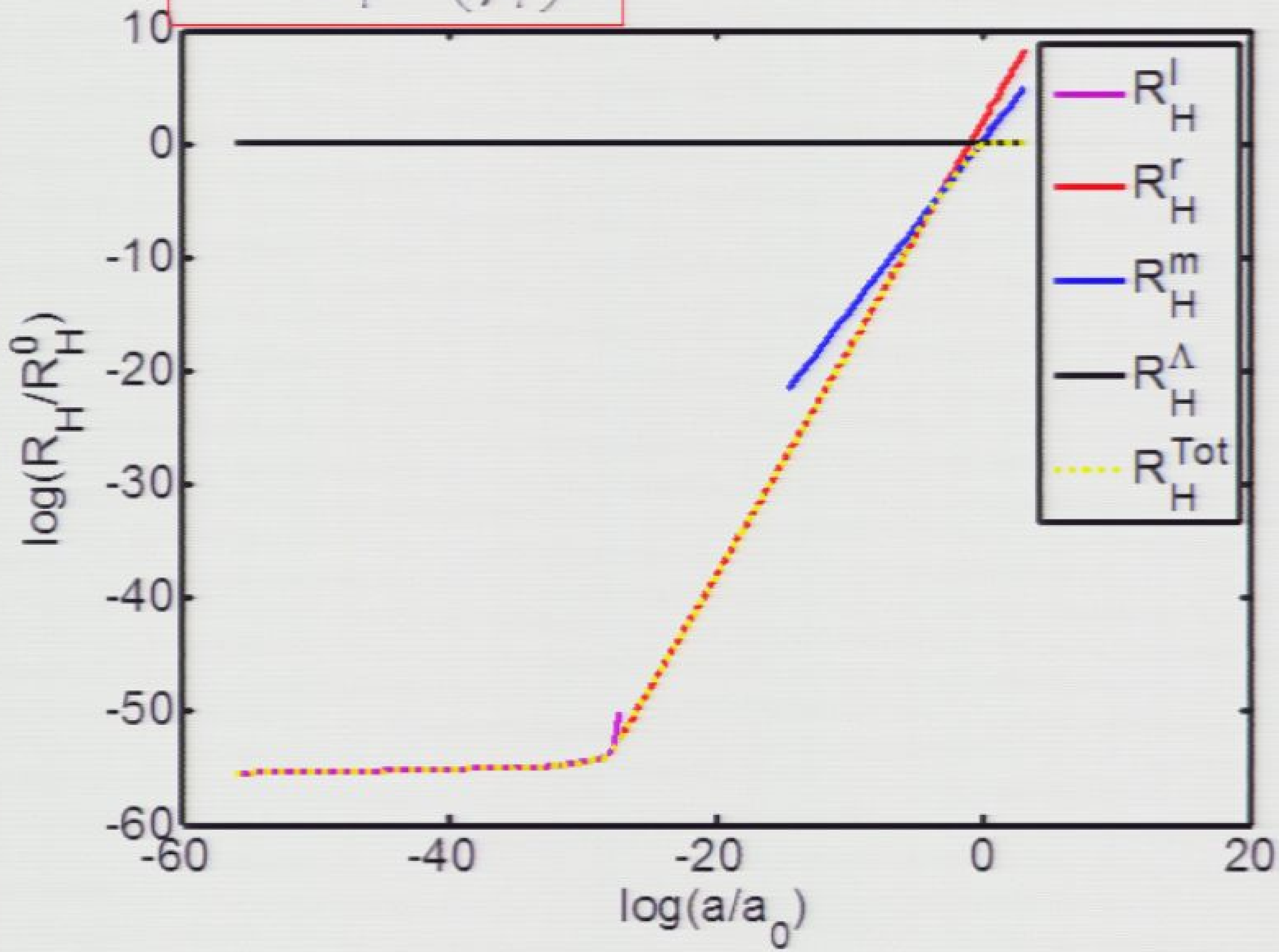

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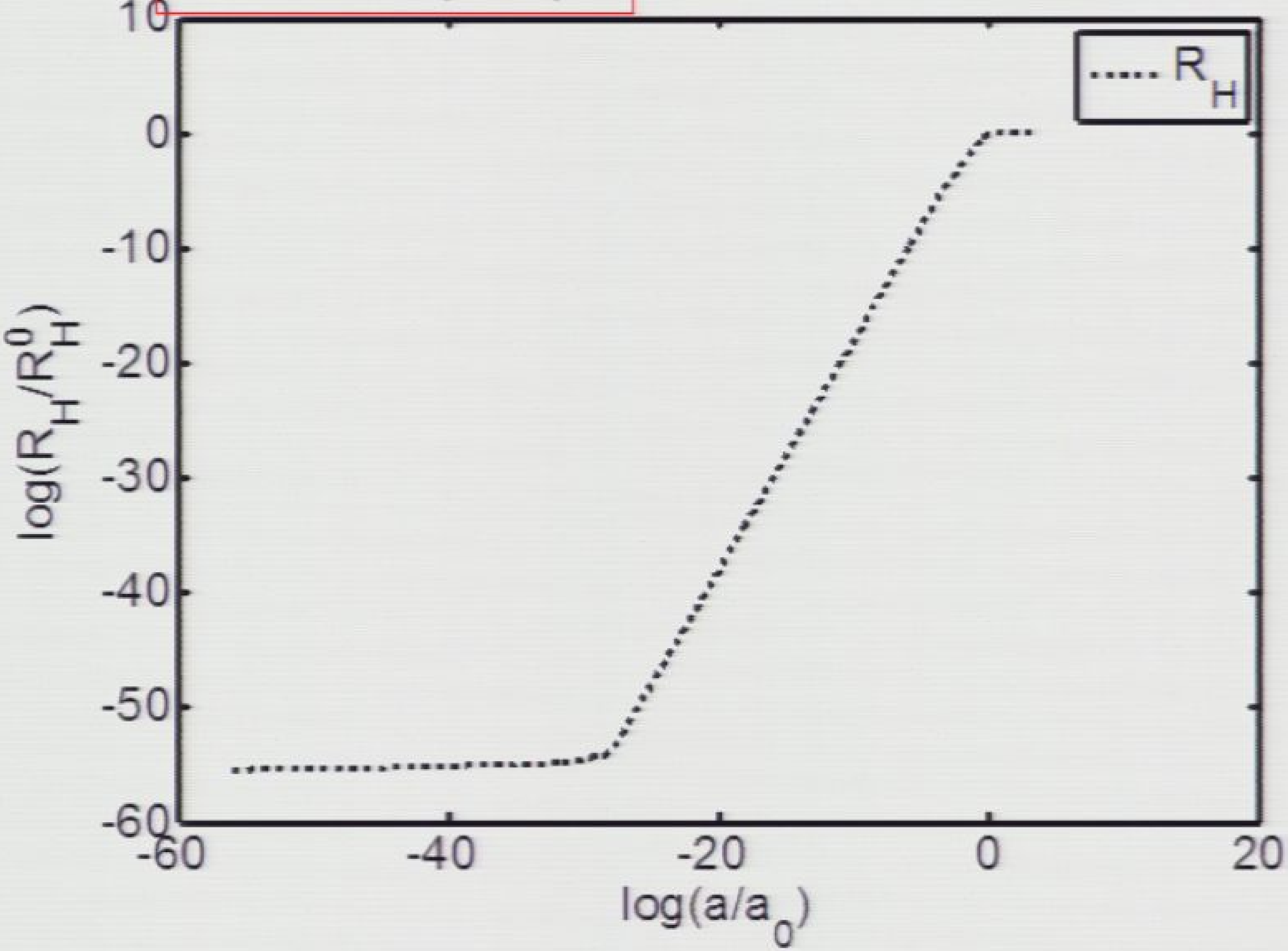

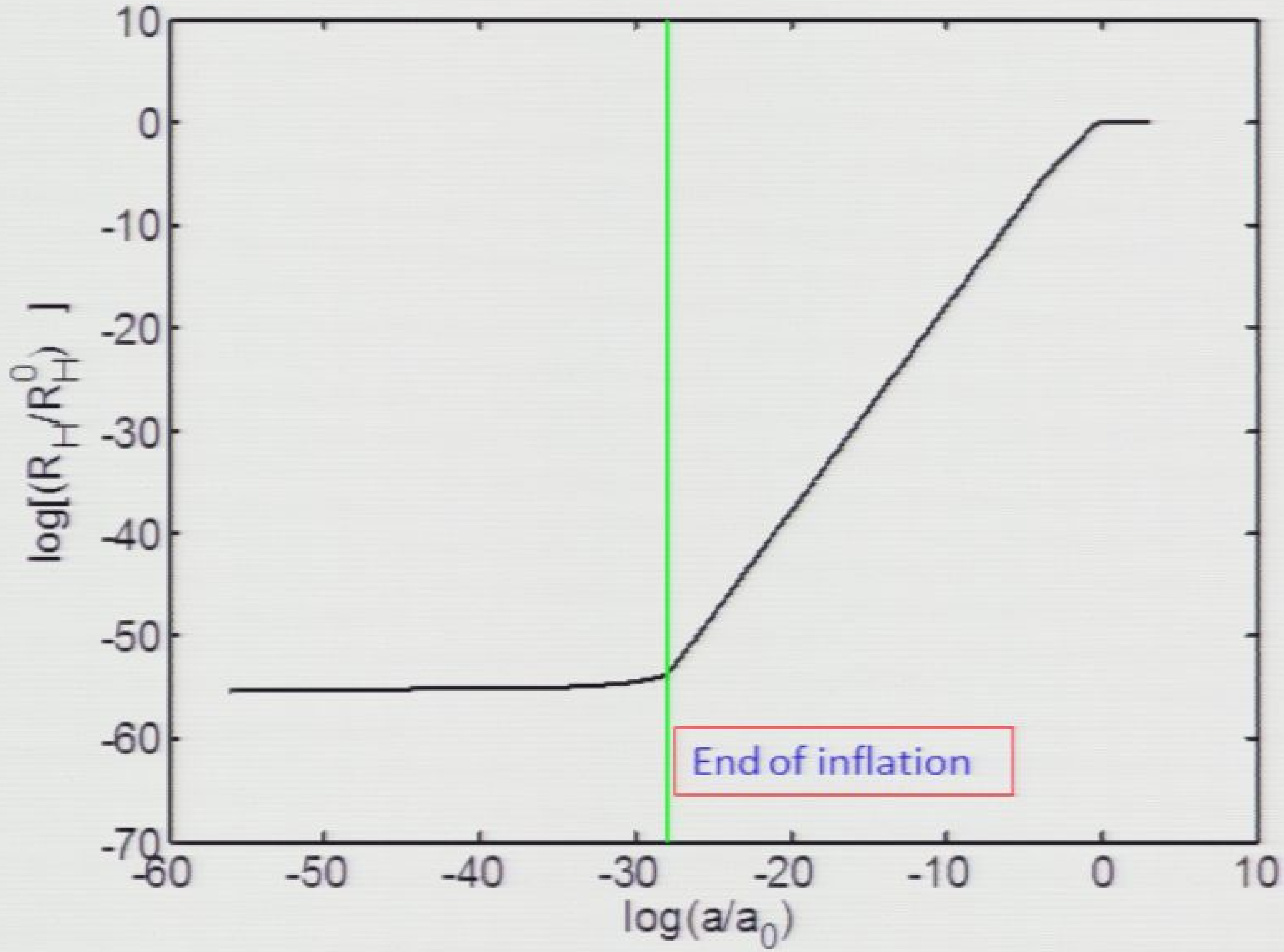

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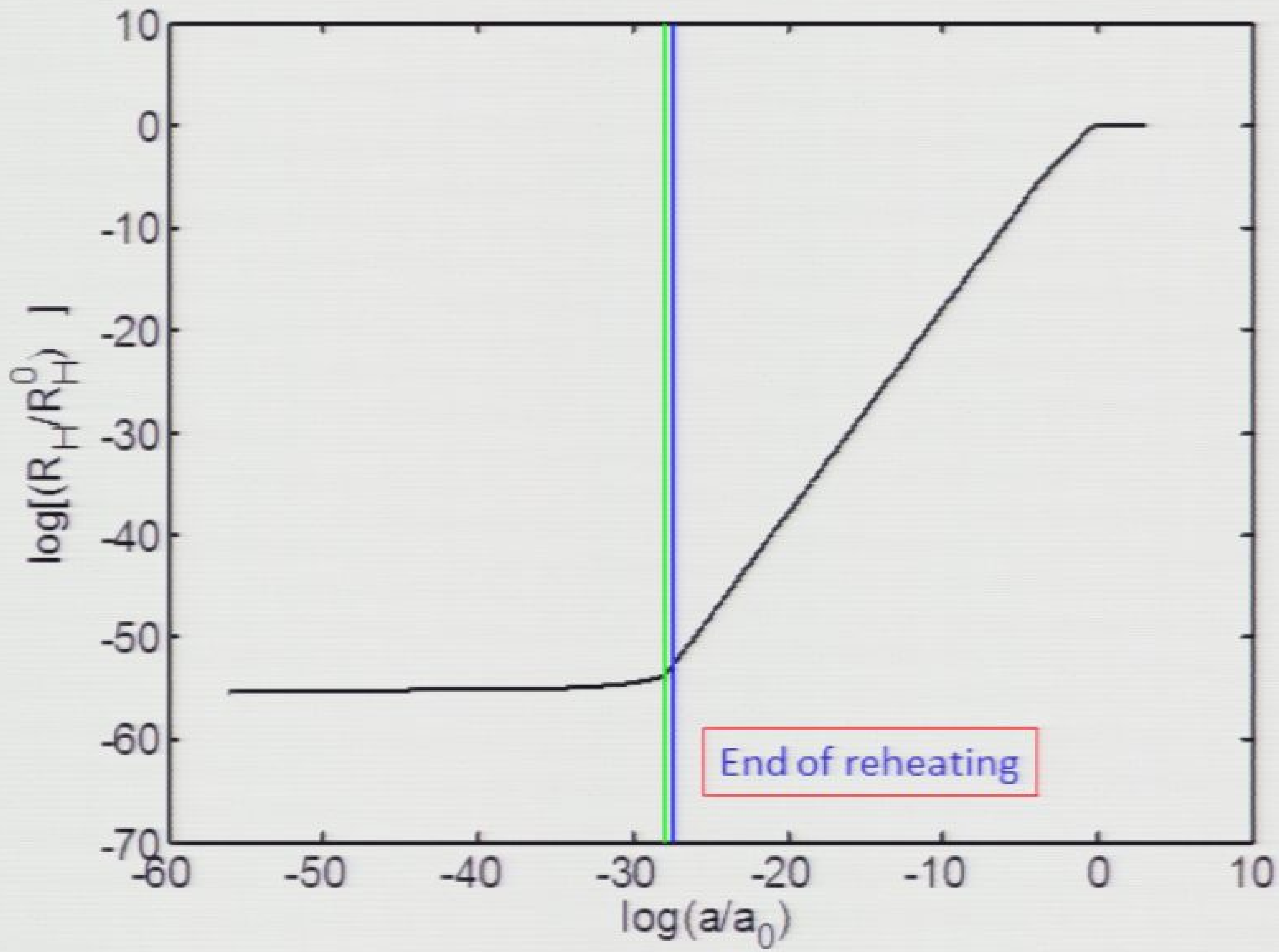
log[(R_H/R_H^0)]
log(a/a_0)
End of inflation



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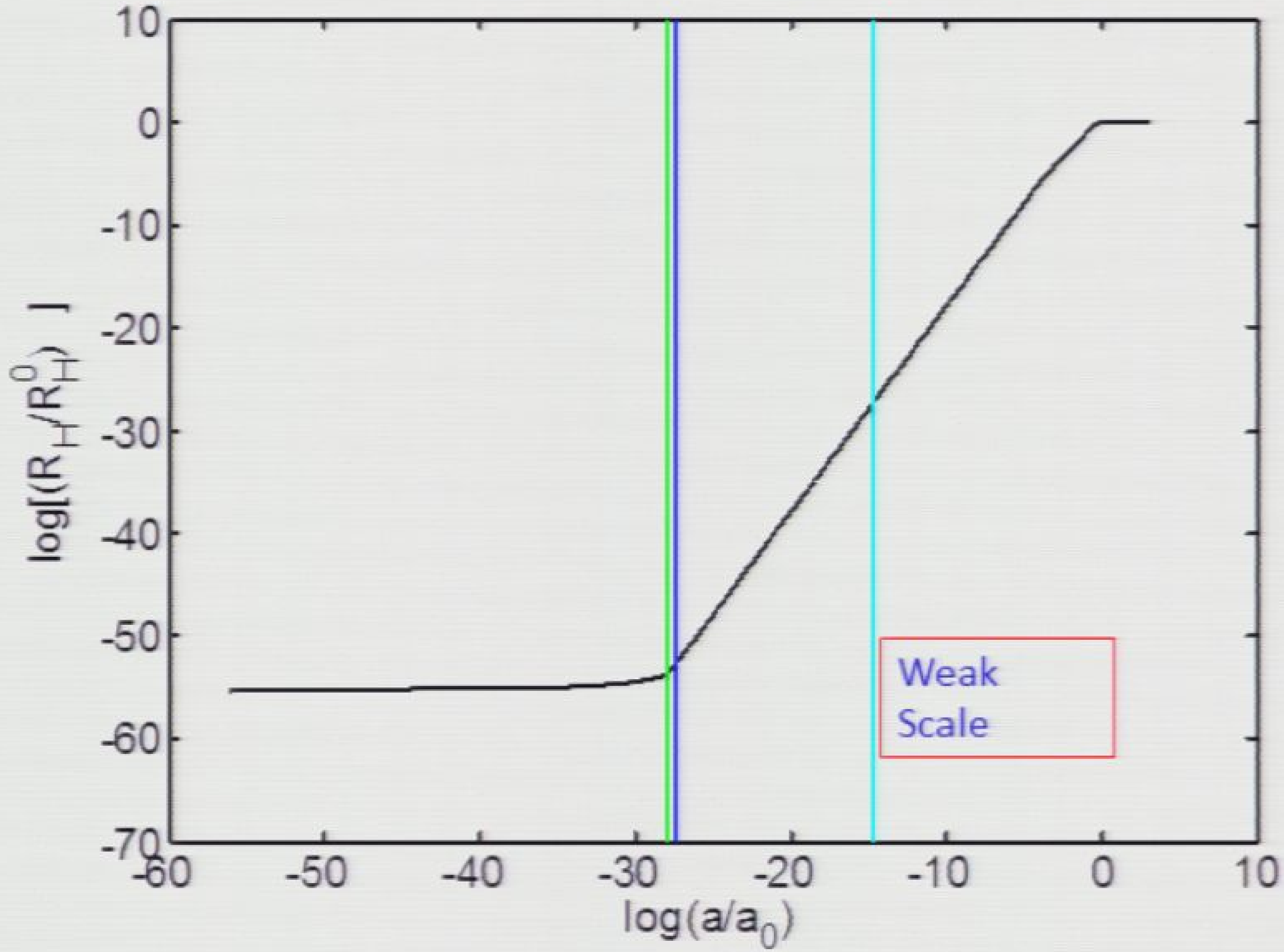
$\log[(R_H/R_H^0)]$
$\log(a/a_0)$
End of reheating



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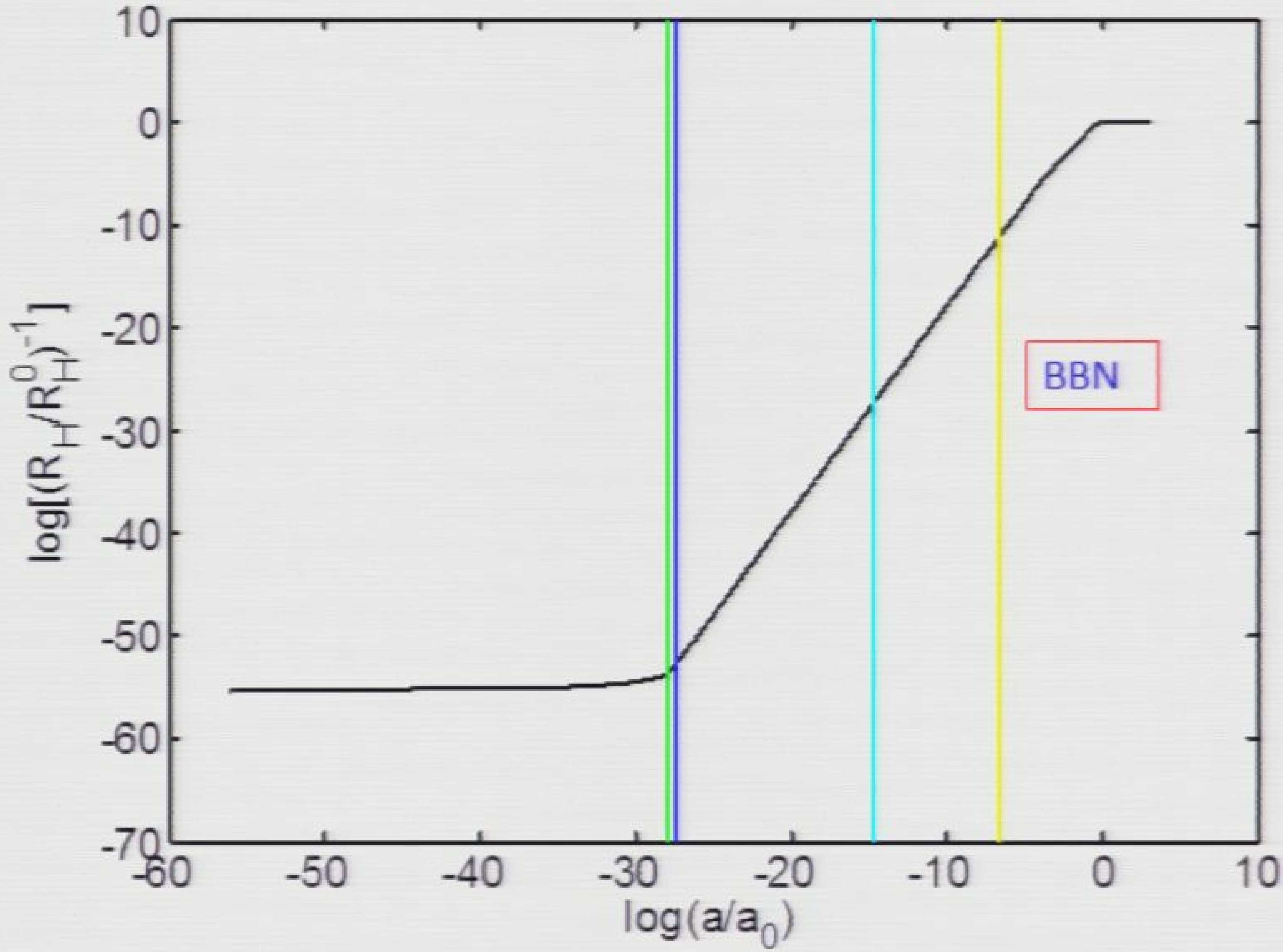
10
$\log[(R_H/R_H^0)]$
$\log(a/a_0)$
Weak
Scale



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-70
log[(R_H/R^0_H)^-1]
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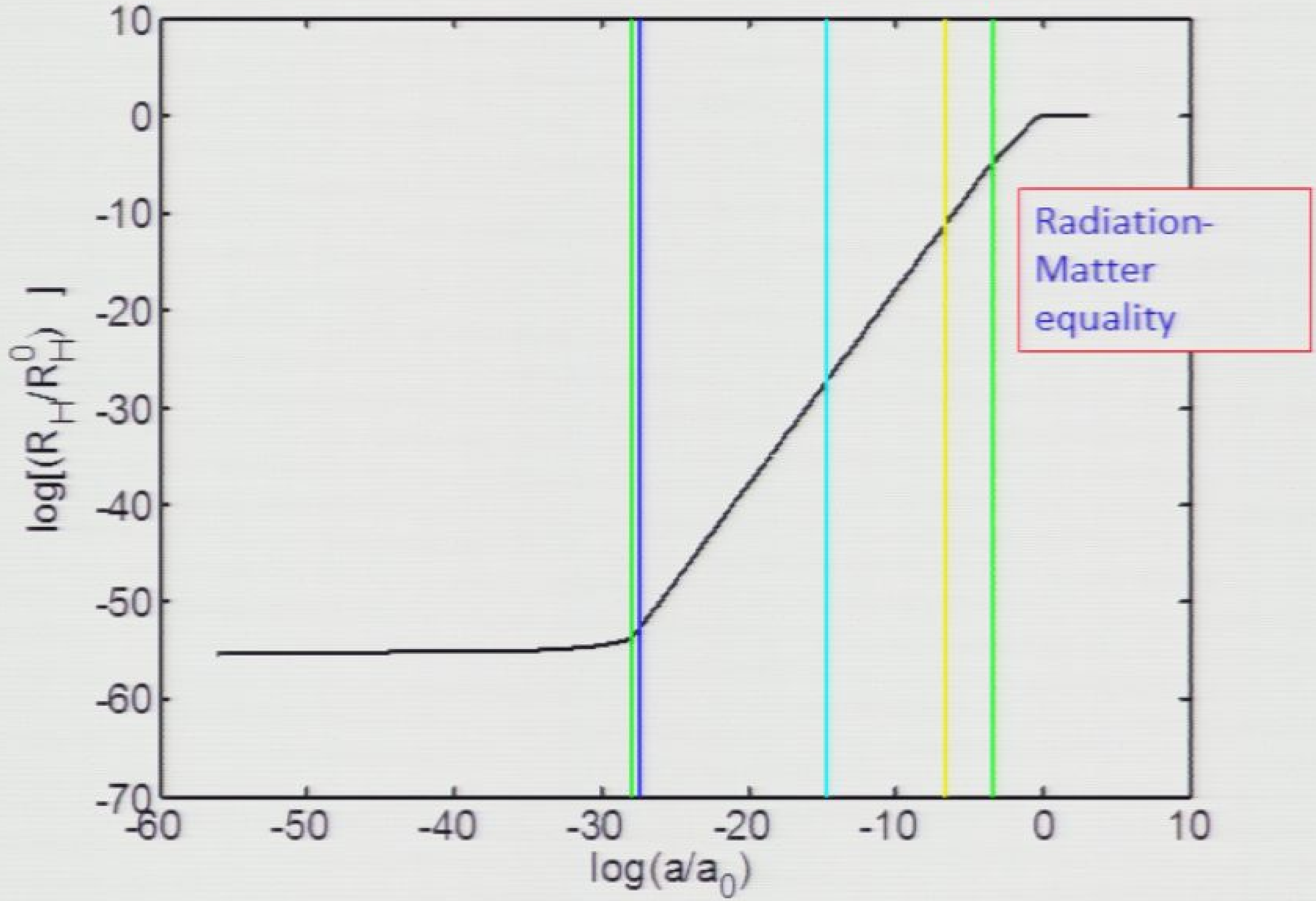
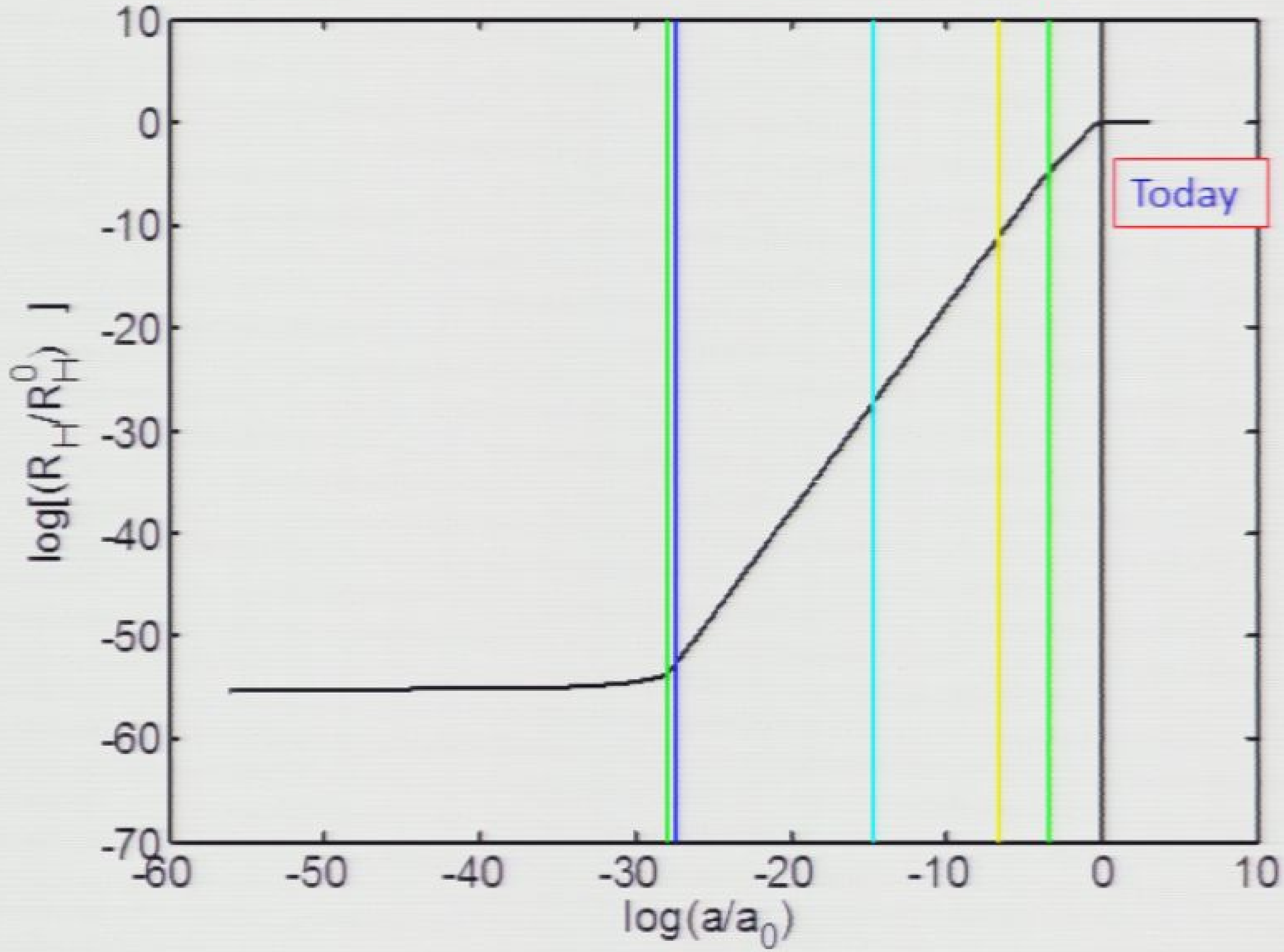
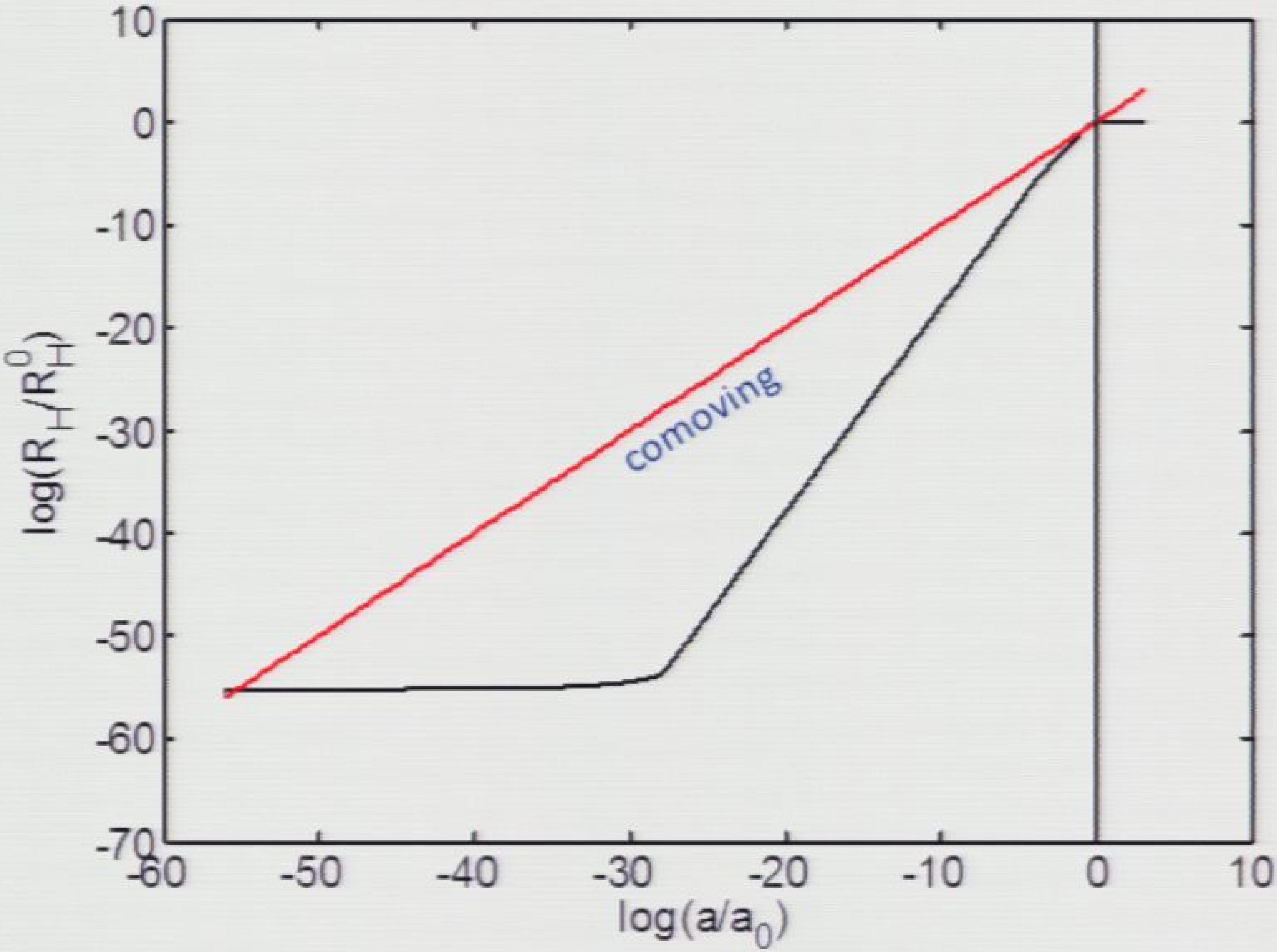
-50
-40
-30
-20
-10
0
10
log(a/a_0)
BBN



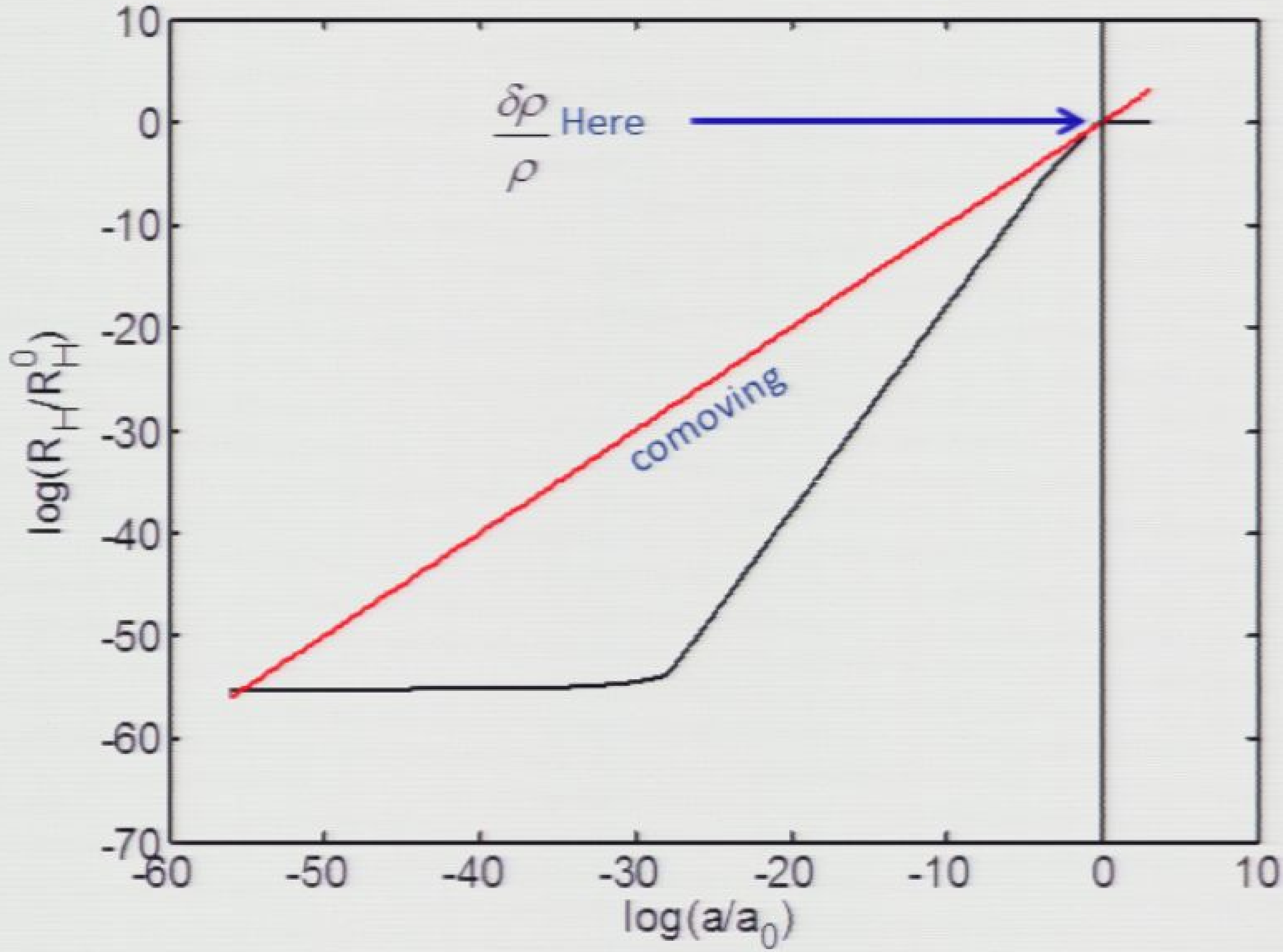
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10
$\log[(R_H/R_H^0)]$
$\log(a/a_0)$
Radiation-
Matter
equality


10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10
$\log[(R_H/R_H^0)]$
$\log(a/a_0)$
Today

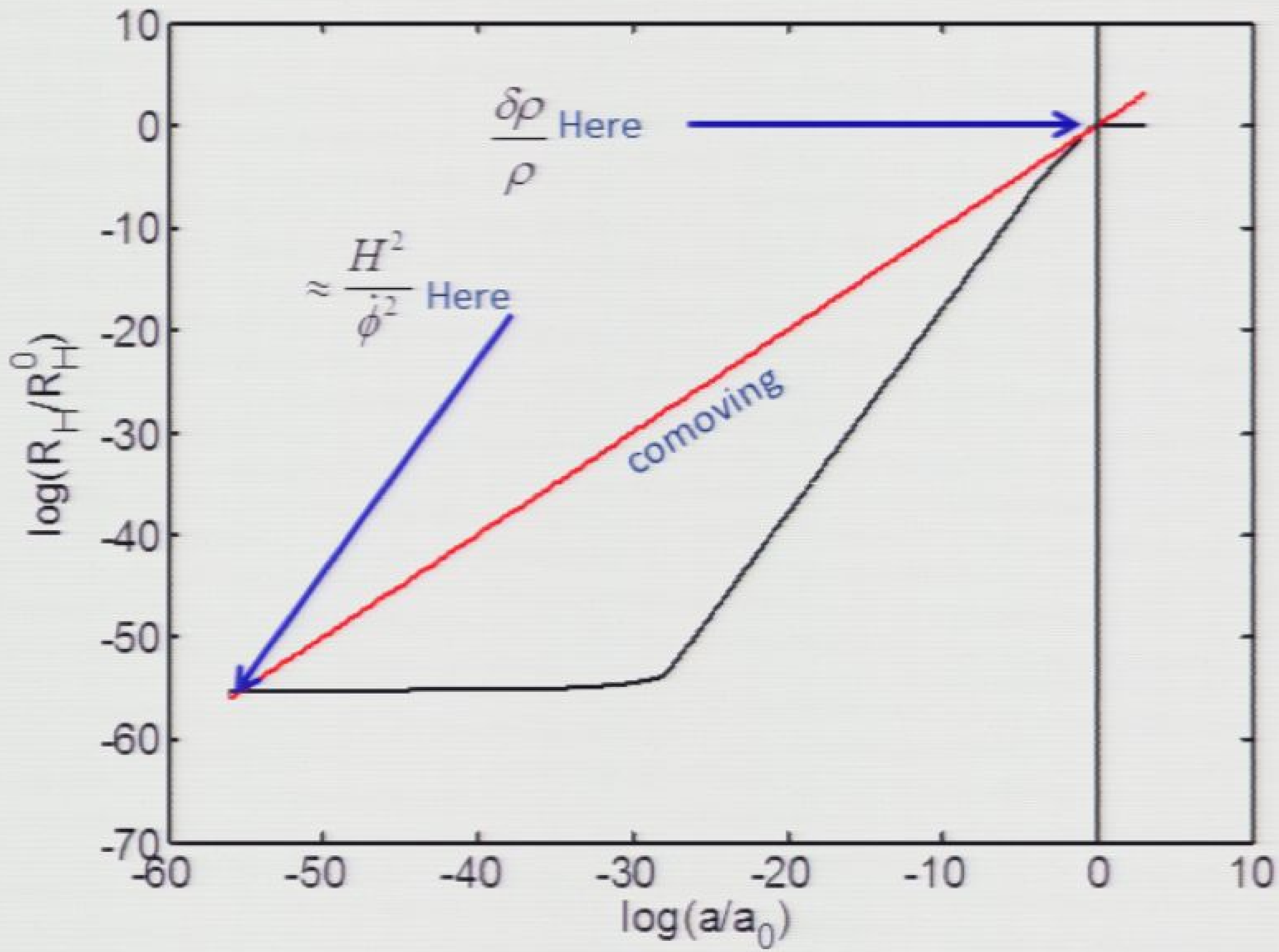
Perturbations from inflation

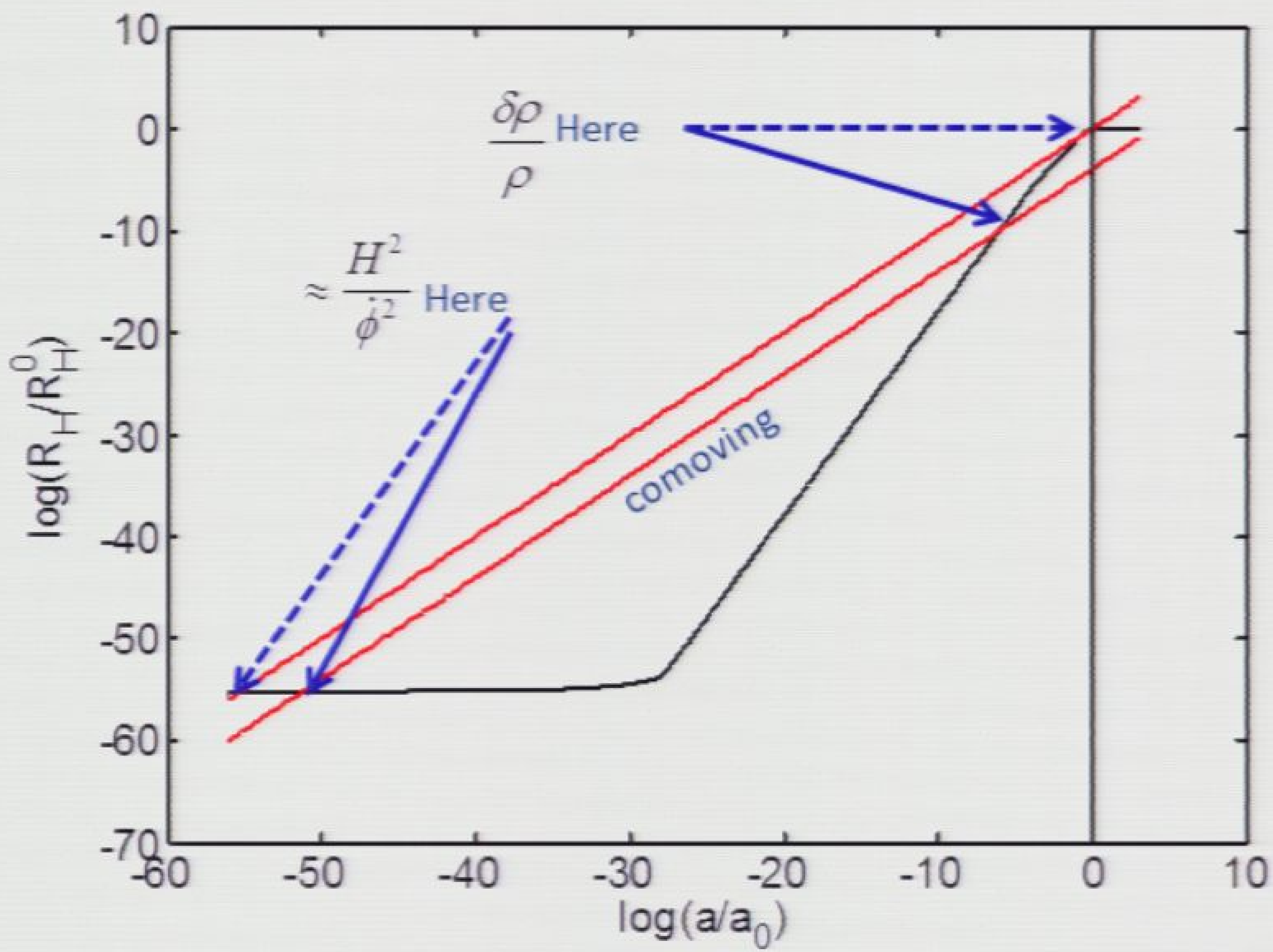


Perturbations from inflation

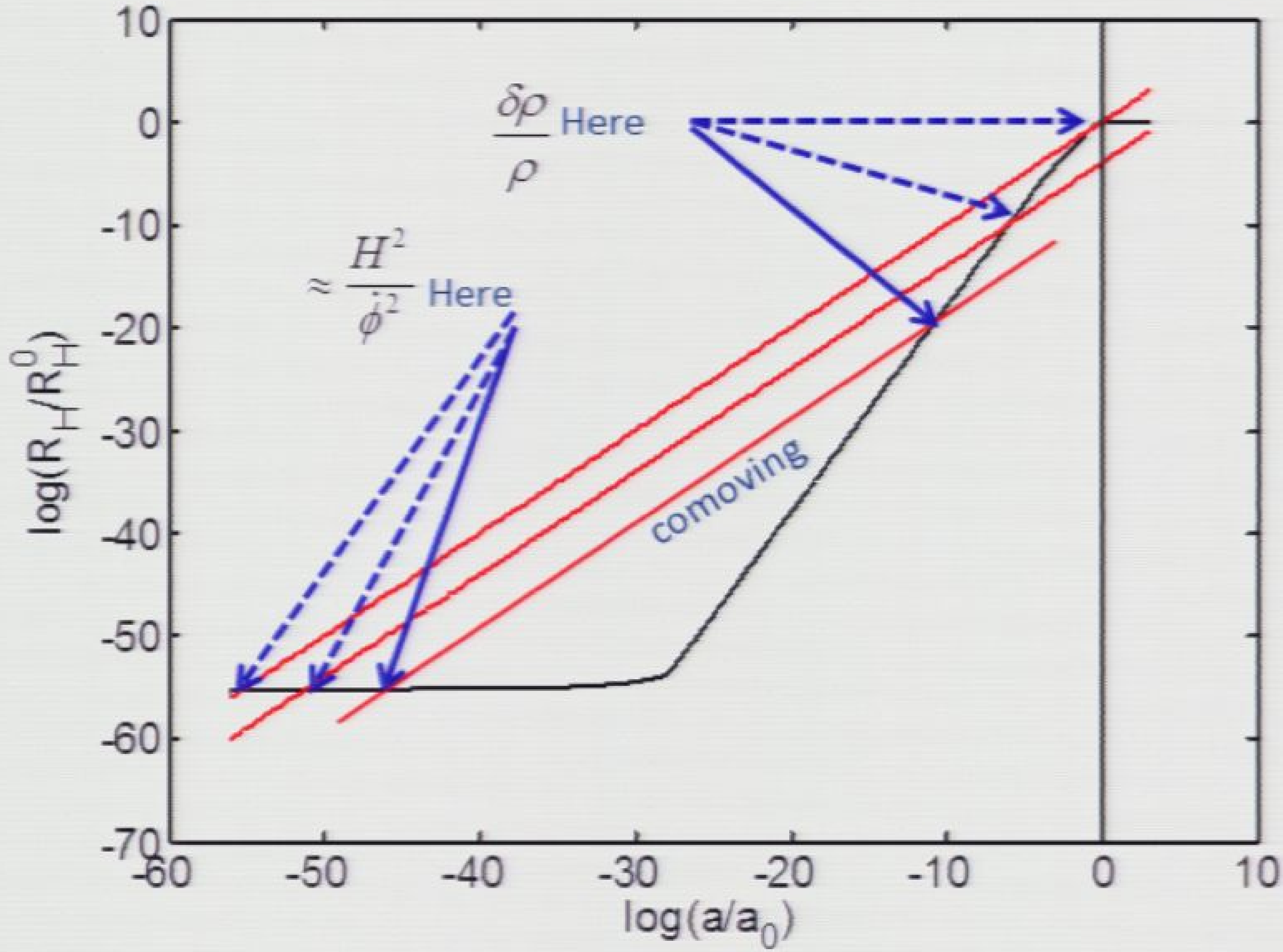


Perturbations from inflation



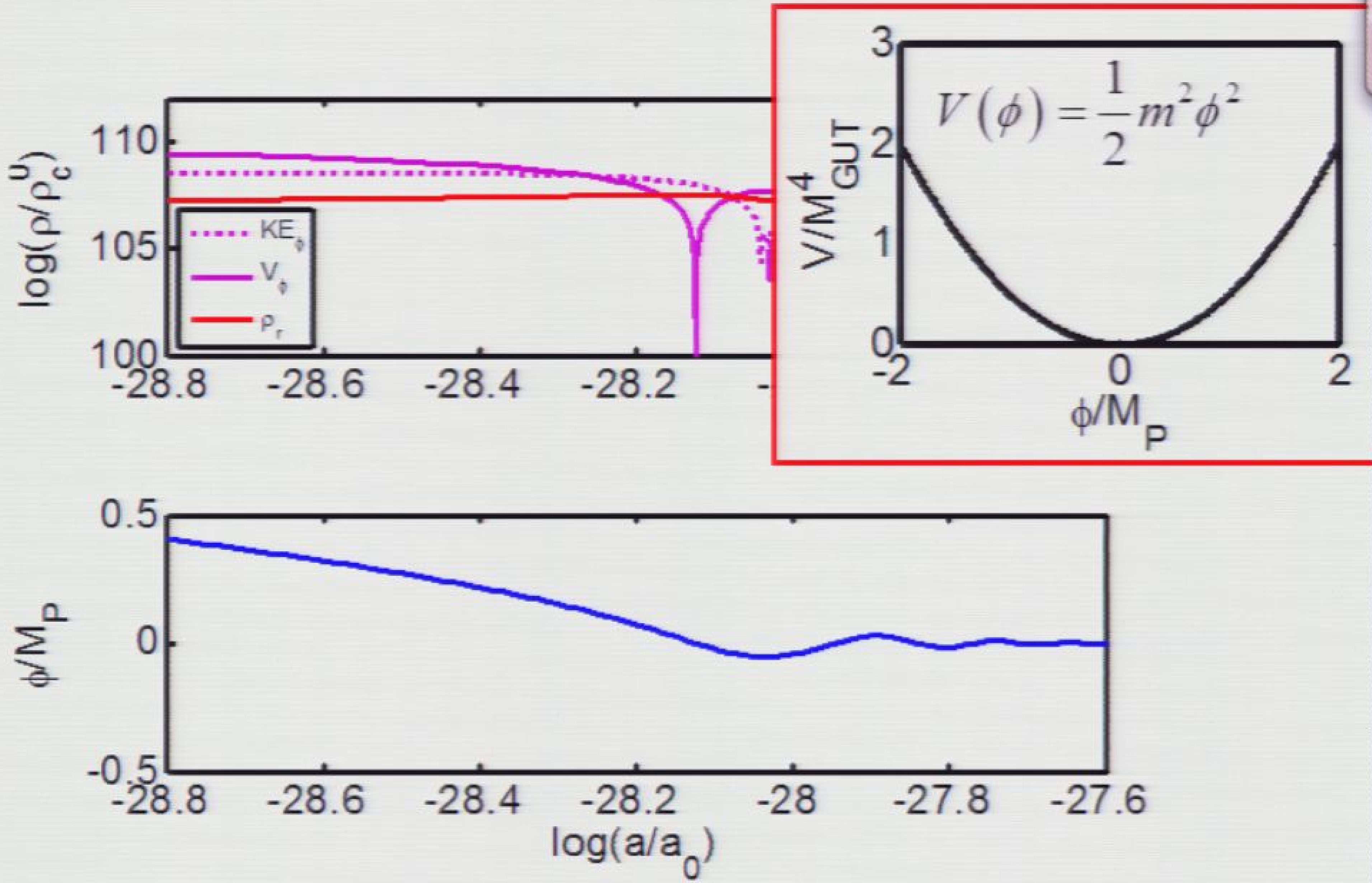


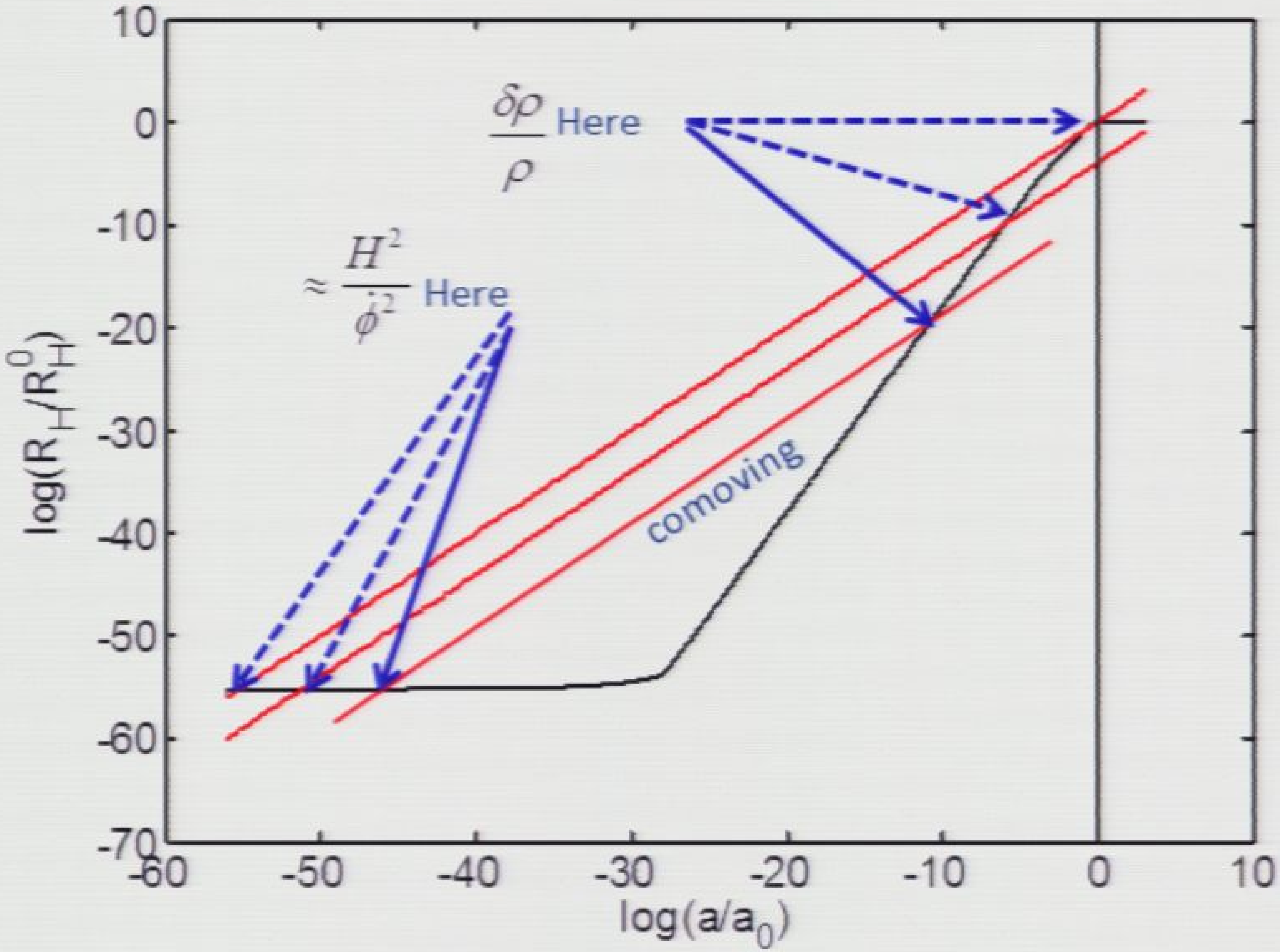
$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}^2}$ Here
comoving
log(R_H/R_H^0)
log(a/a_0)



$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}^2}$ Here
comoving
log(R_H/R_H^0)
log(a/a_0)
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10

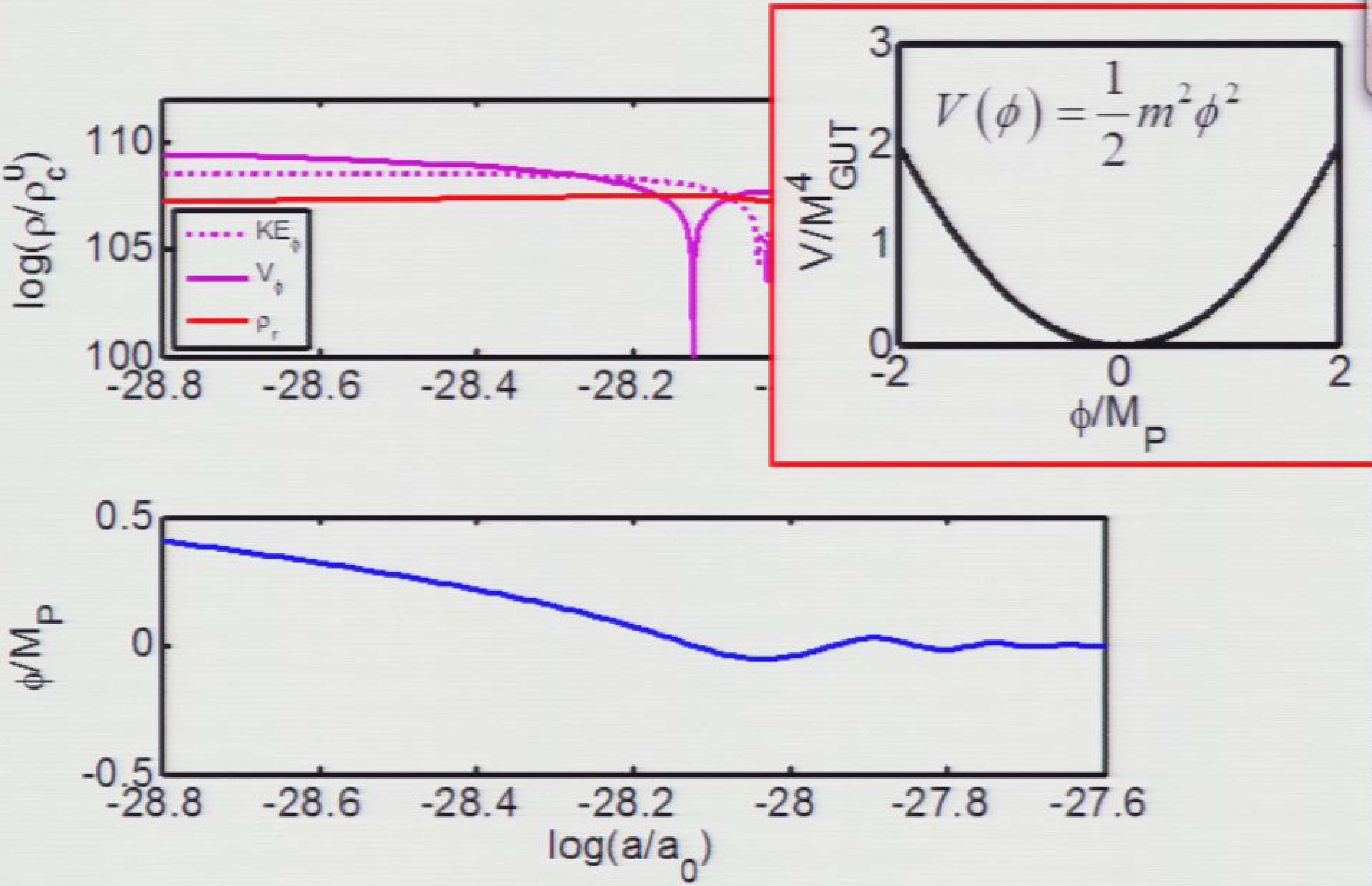
nflation detail:



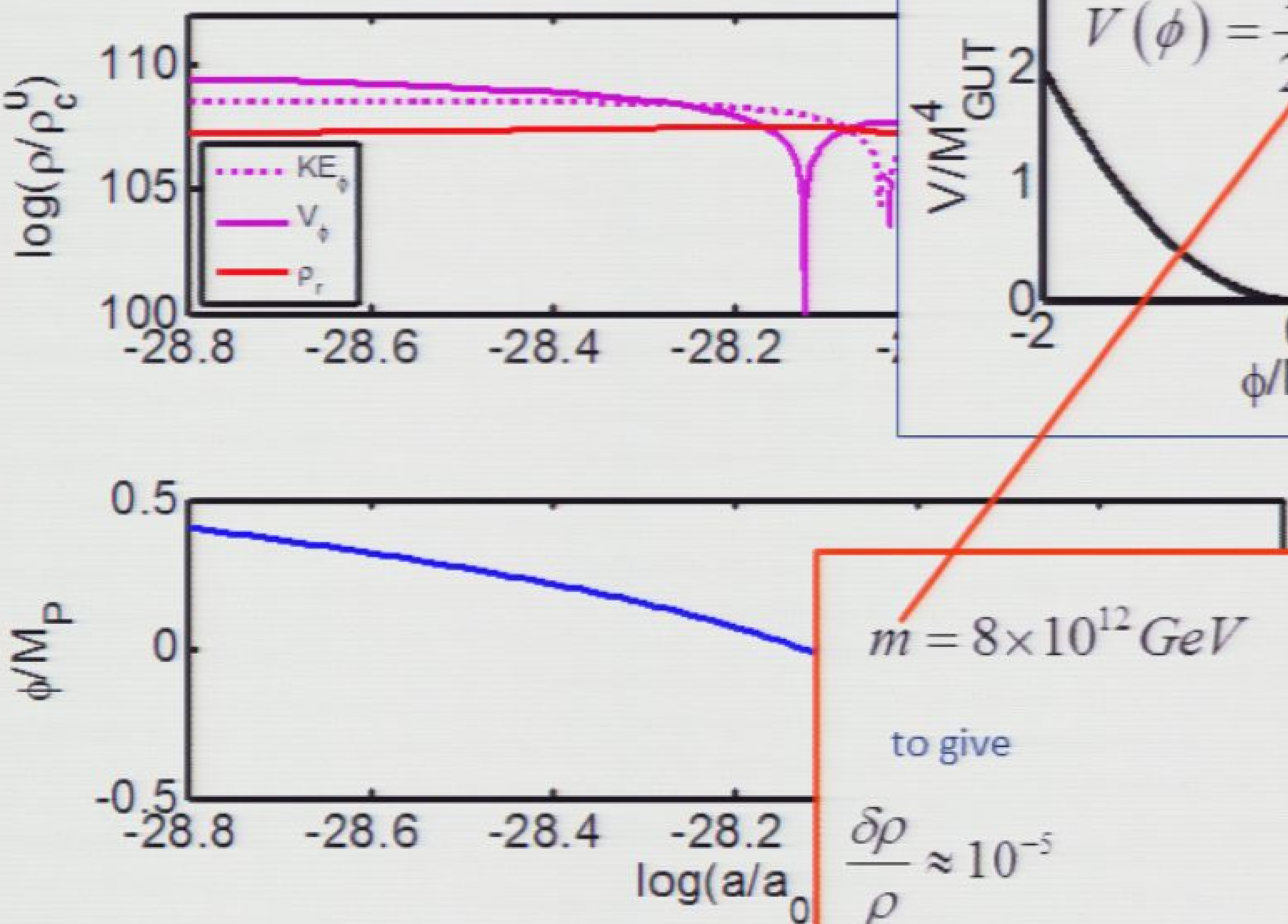


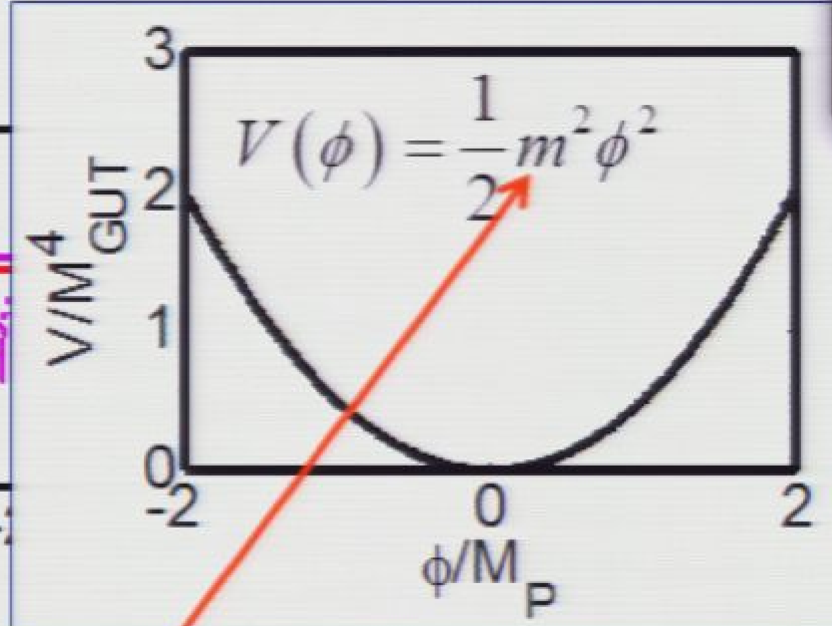
$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}^2}$ Here
comoving
log(R_H/R_H^0)
log(a/a_0)
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10

nflation detail:



nflation detail:



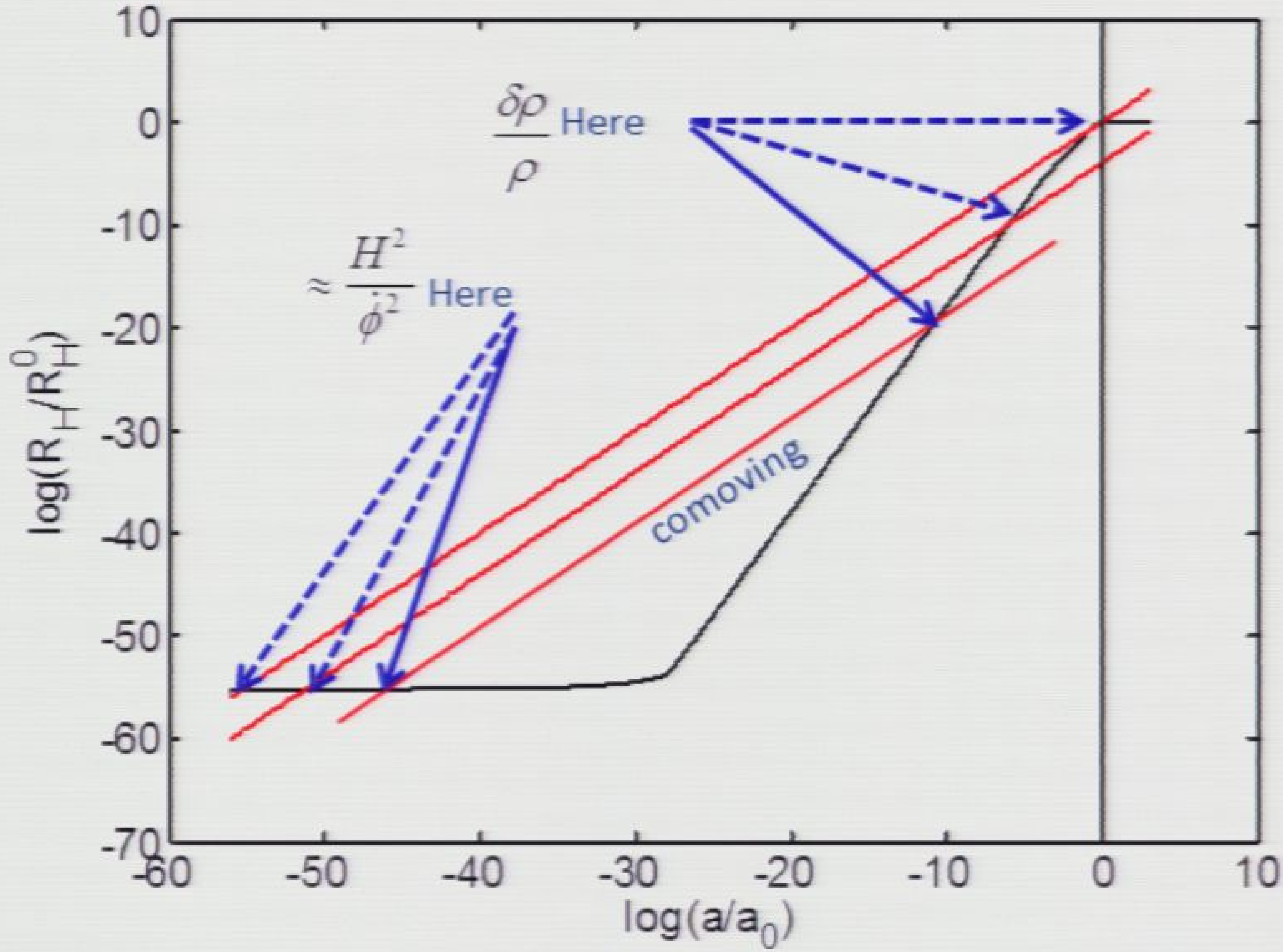


$$V(\phi) = \frac{1}{2}m^2\phi^2$$

$$m = 8\times 10^{12}\,GeV$$

to give

$$\frac{\delta\rho}{\rho} \approx 10^{-5}$$



$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}^2}$ Here
comoving
log(R_H/R_H^0)
log(a/a_0)
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10

HIANG et al. 2010

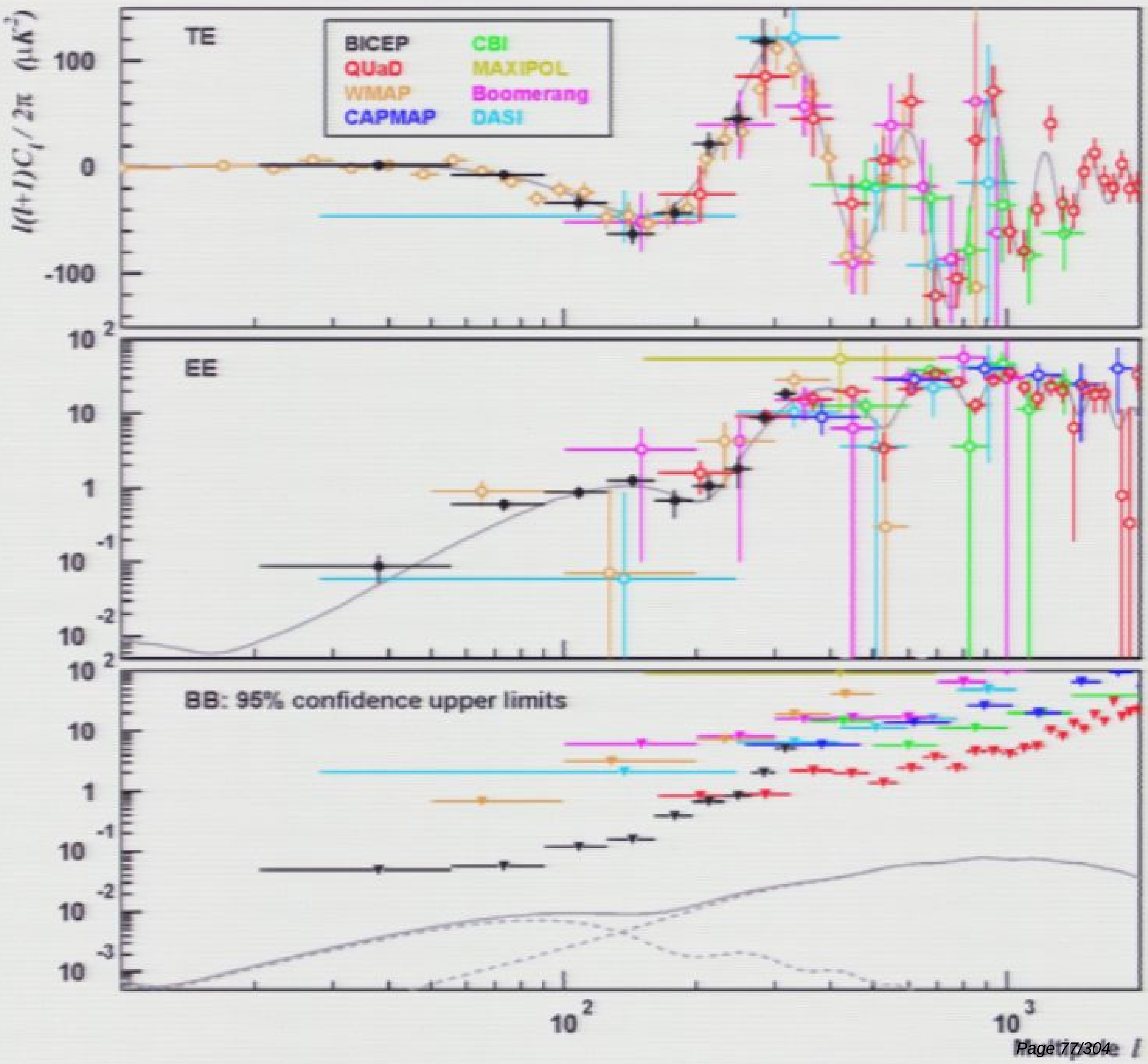
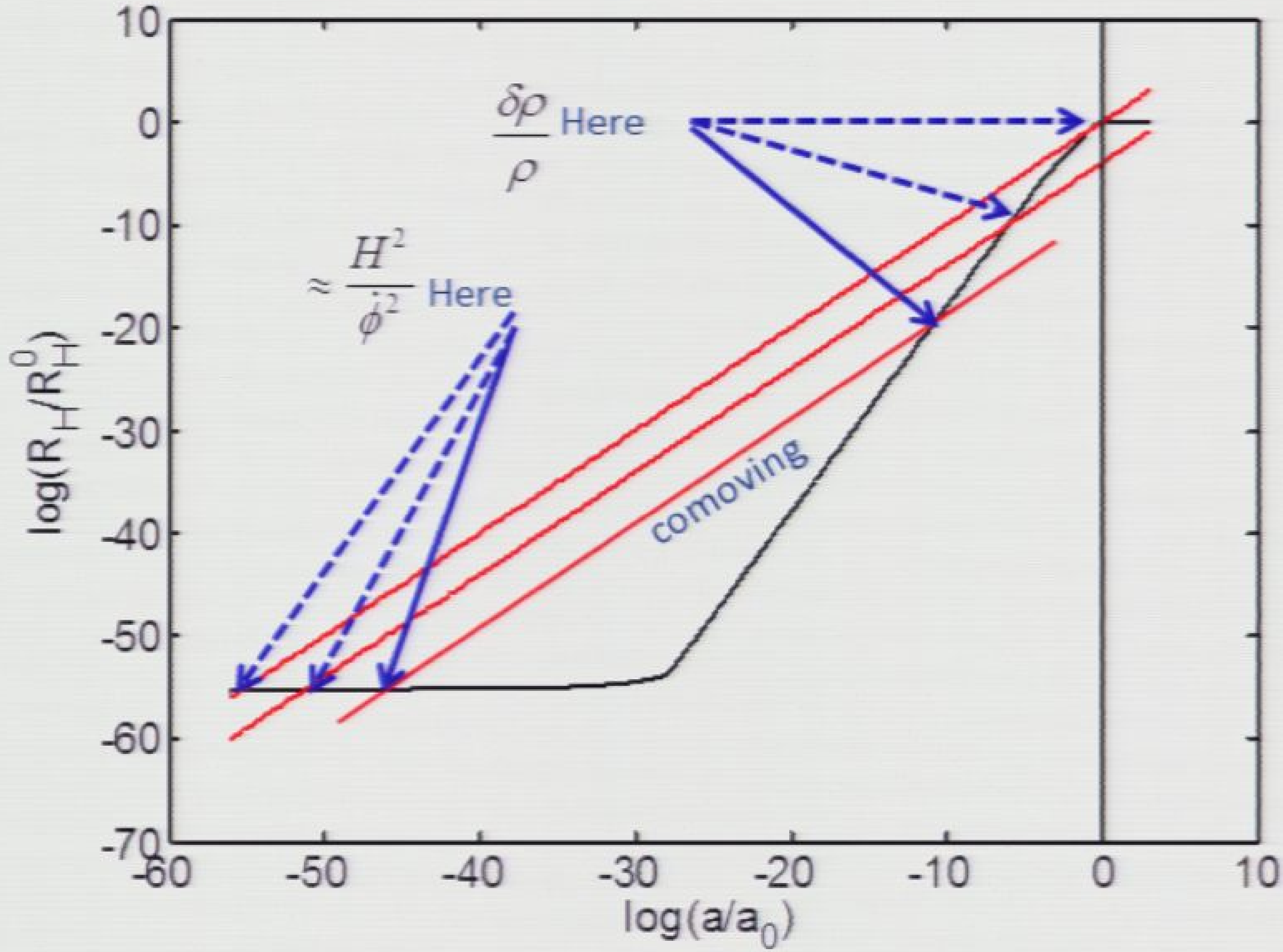
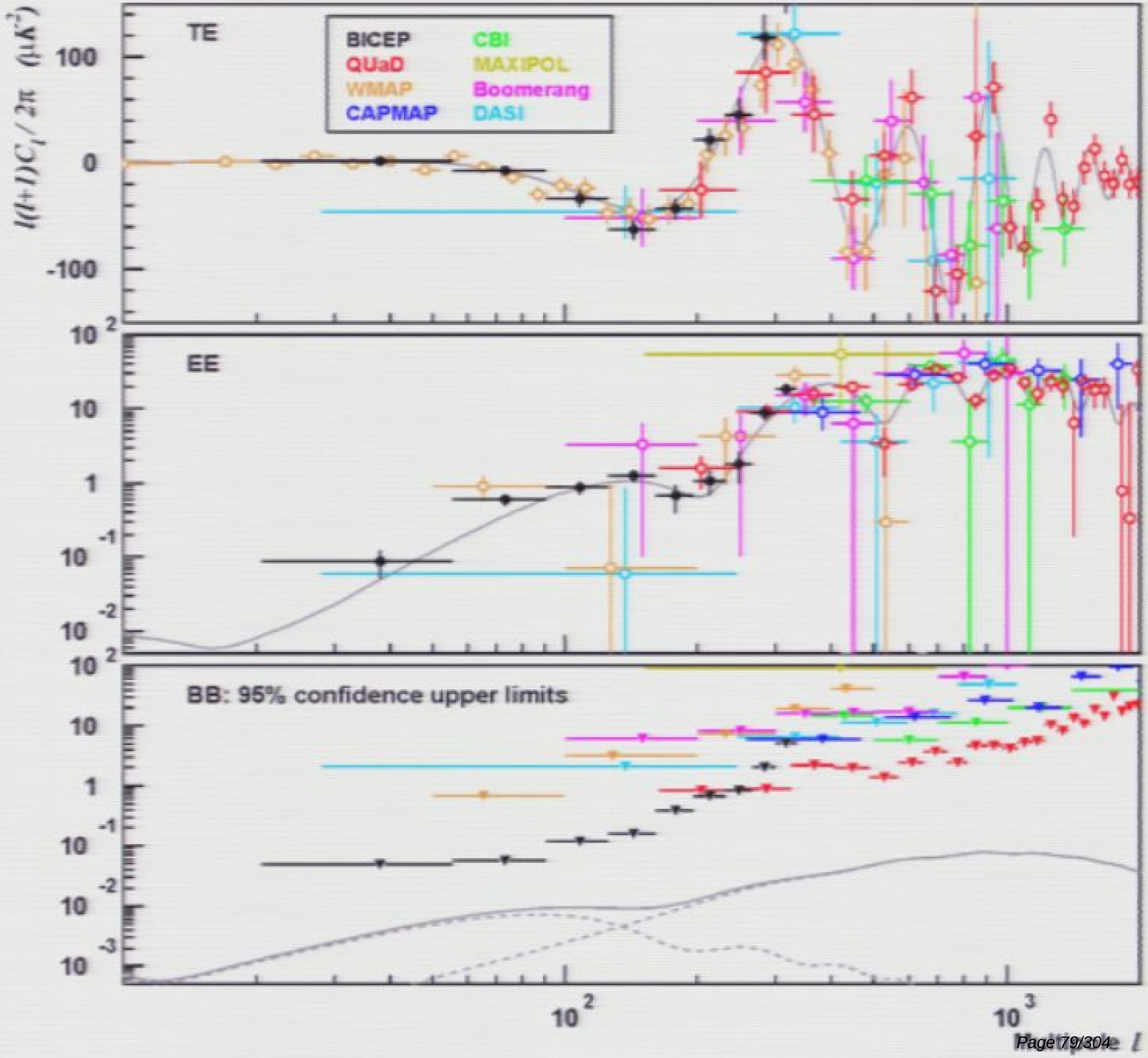


FIG. 13.— BICEP's *TE*, *EE*, and *BB* power spectra complement existing data from other CMB polarization experiments (Leitch et al. 2005; Montroy et al. 2006; Piacentini et al. 2006; Sievers et al. 2007; Wu et al. 2007; Bischoff et al. 2008; Nolta et al. 2009; Brown et al. 2009). Theoretical spectra from a ΛCDM



$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}^2}$ Here
comoving
log(a/a$_0$)
log(R$_H$/R$_H^0$)

HIANG et al. 2010



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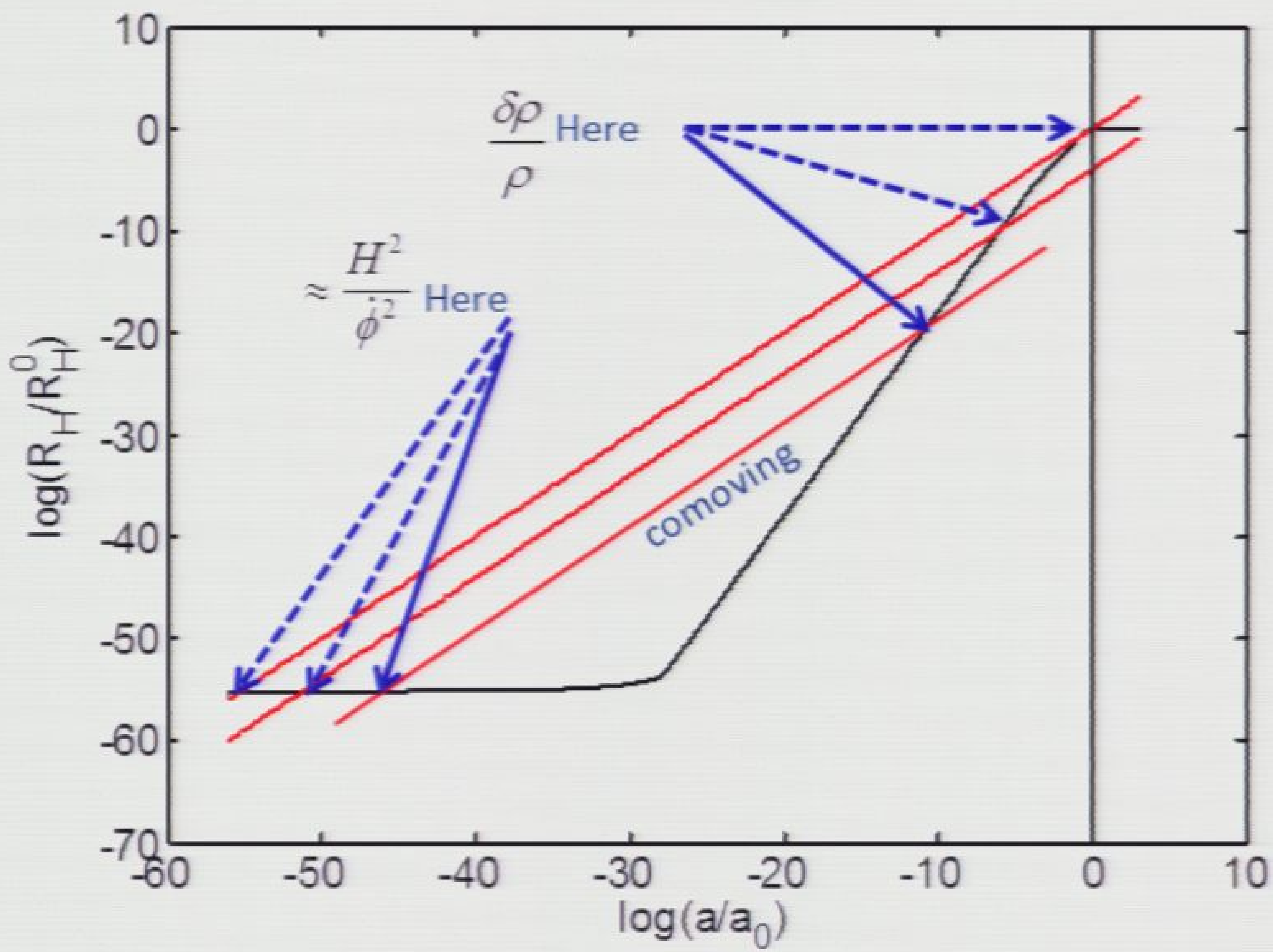
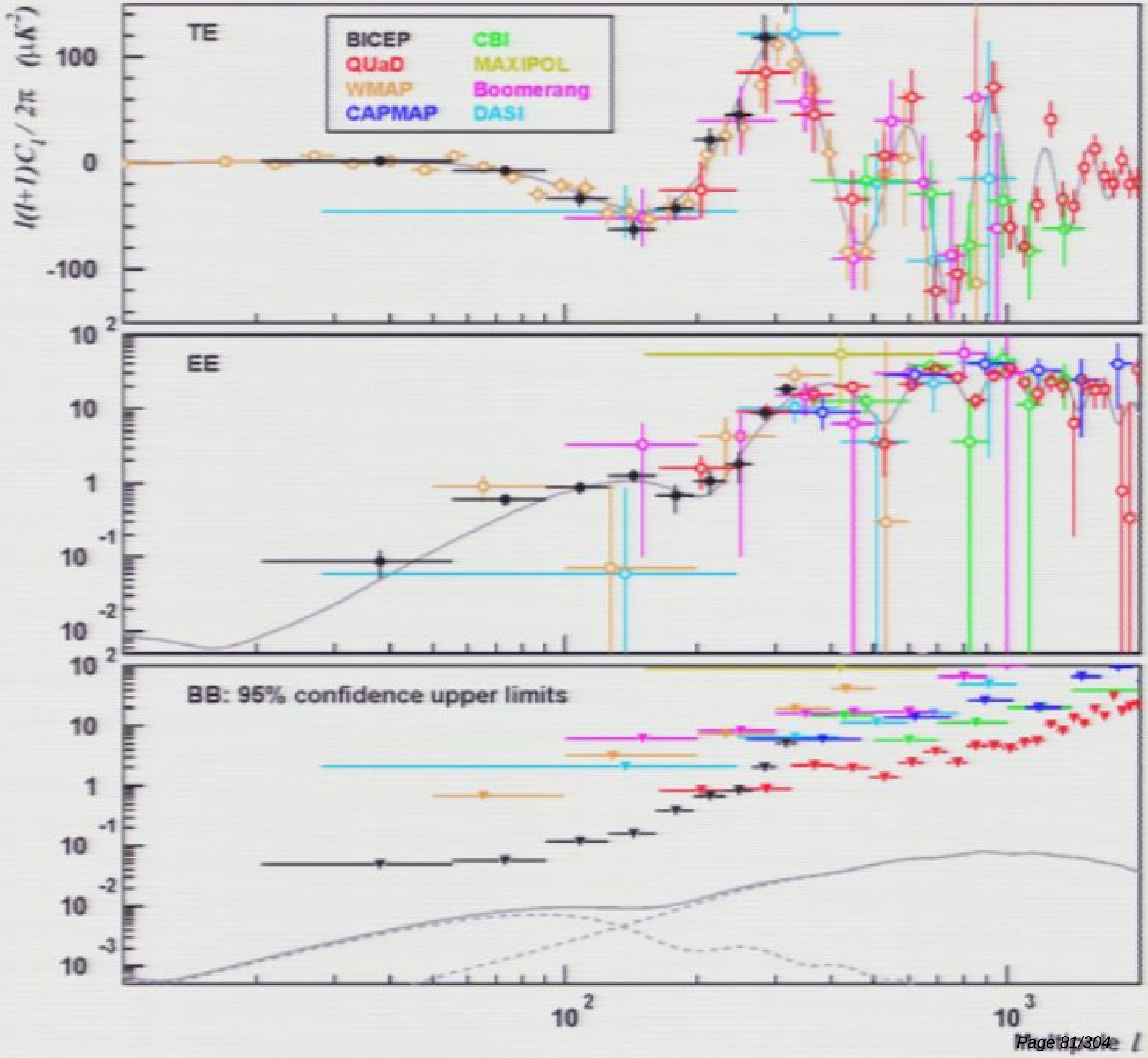


$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}^2}$ Here
comoving
log(R_H/R_H^0)
log(a/a_0)
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10

HIANG et al. 2010



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Hlozek et al. May 2011

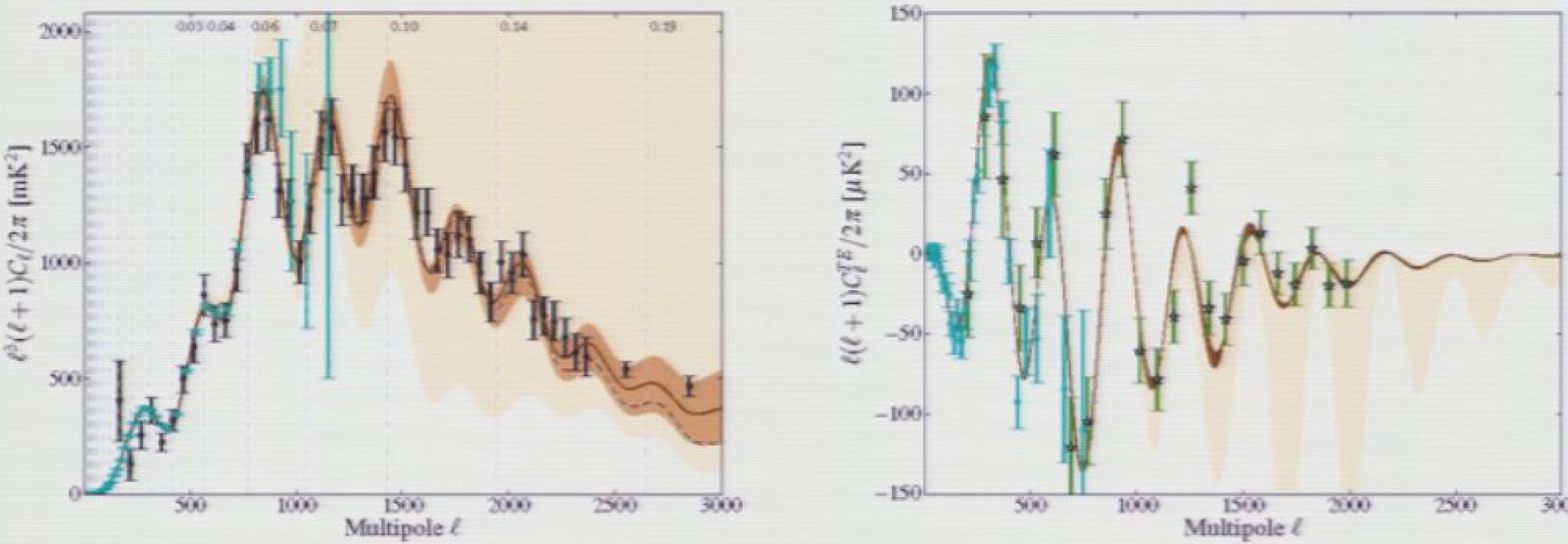

FIG. 3.— Mapping primordial power to the angular power spectrum: the constraints on the primordial power spectrum from Figure
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e higher order peaks. The dashed vertical lines show the multipoles corresponding to the wavenumbers under consideration, using $\ell =$
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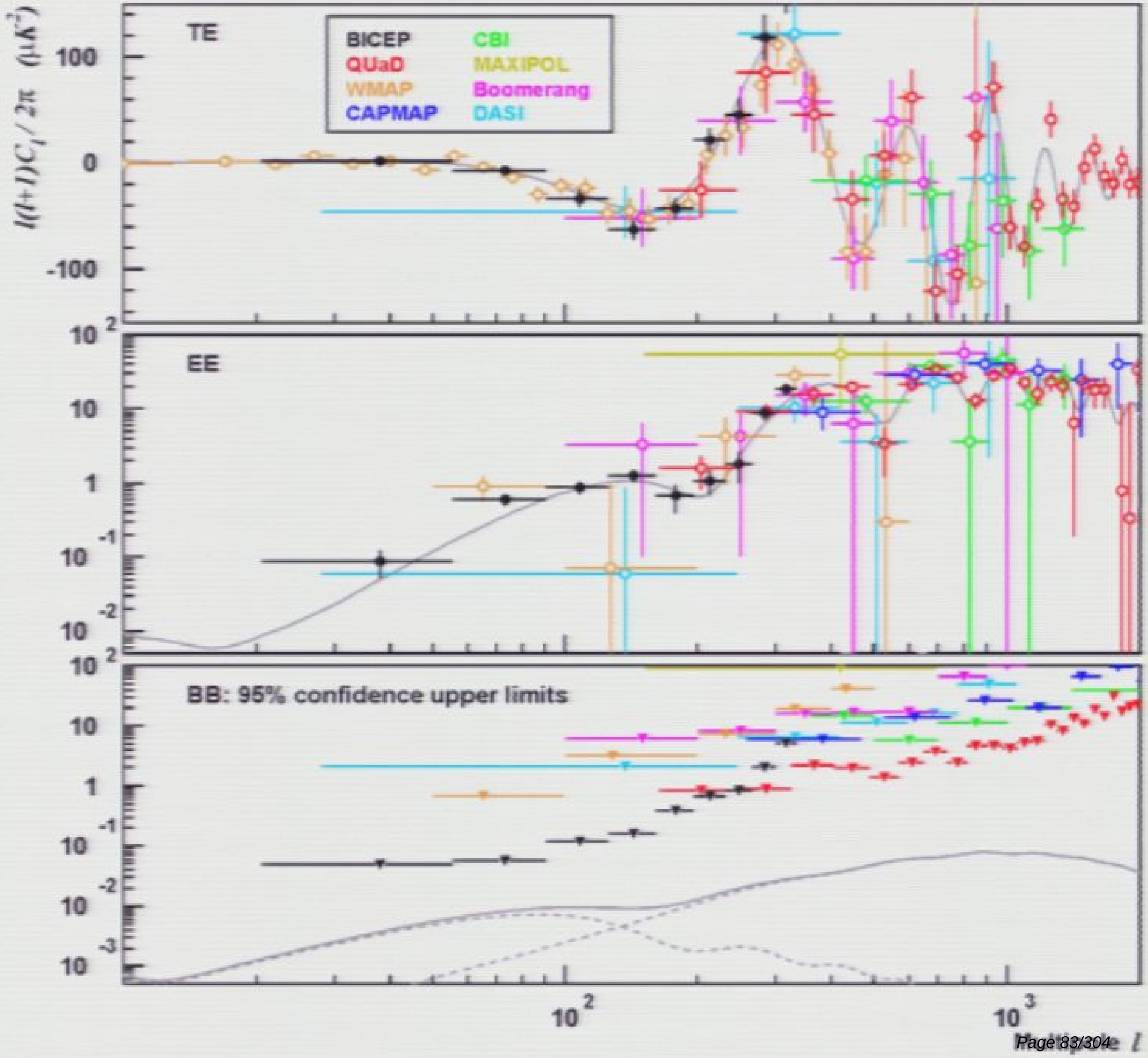
HIANG et al. 2010



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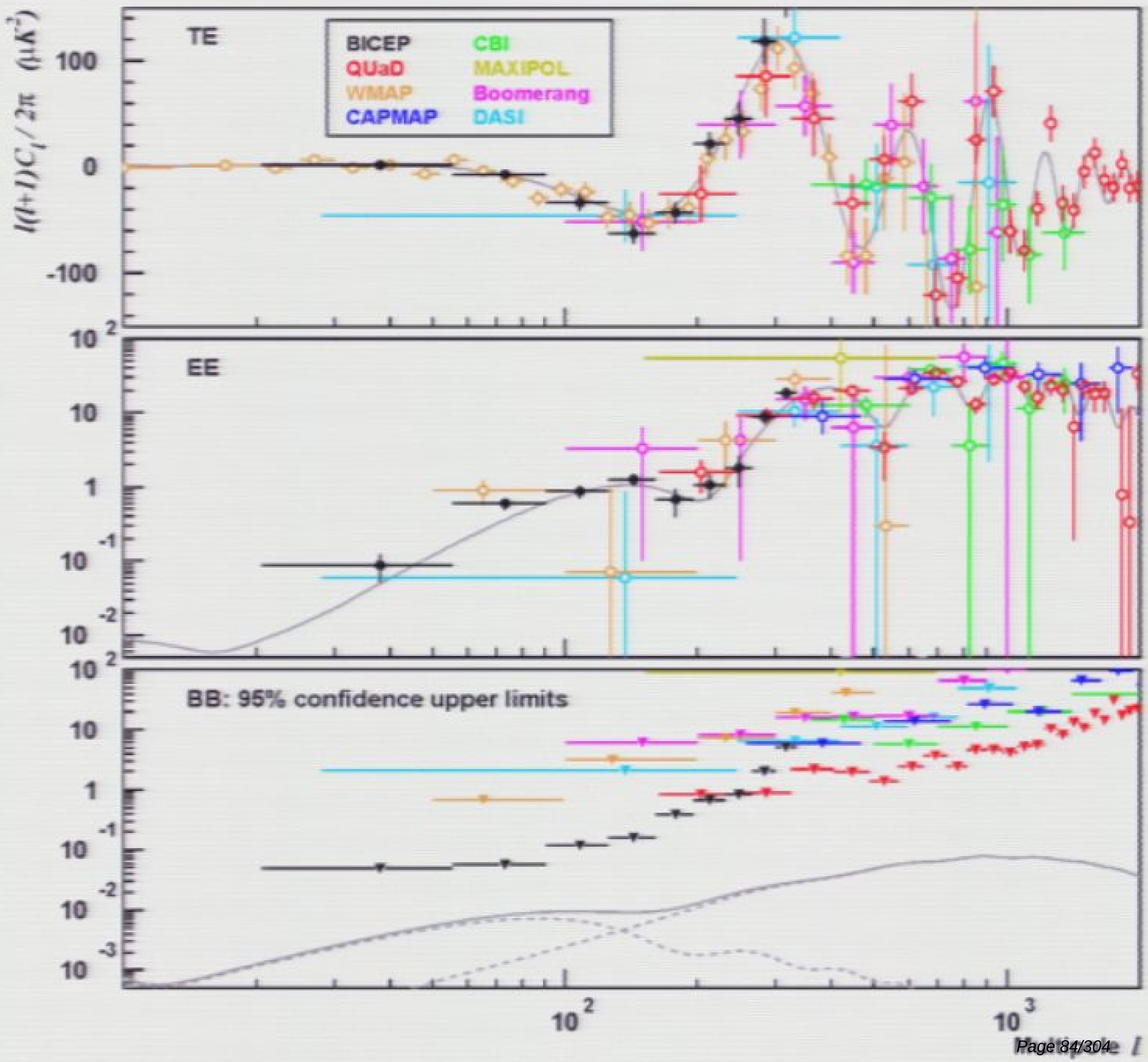
HIANG et al. 2010



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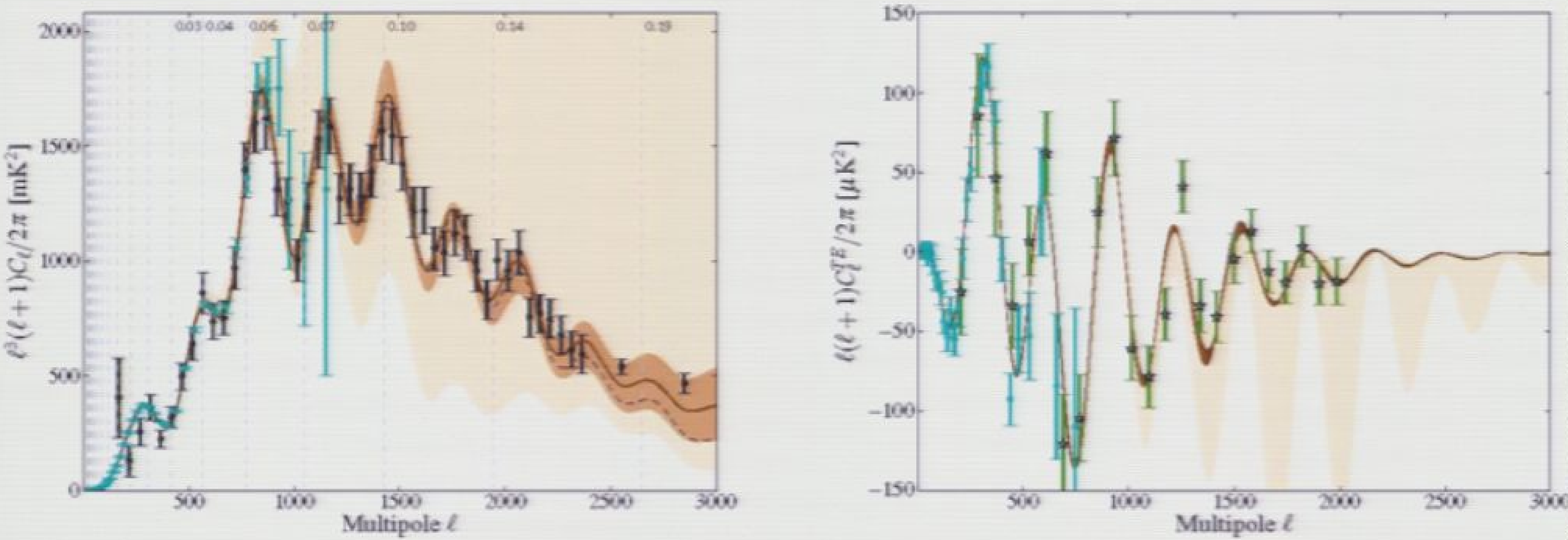
Hlozek et al. May 2011



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OUTLINE

1. Big Bang & inflation basics ⟸
2. Eternal inflation
3. de Sitter Equilibrium cosmology
4. Cosmic curvature from de Sitter Equilibrium cosmology

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1. Big Bang & inflation basics
2. Eternal inflation
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Does inflation make the SBB natural?

How easy is it to get inflation to start?

What happened before inflation?

OUTLINE

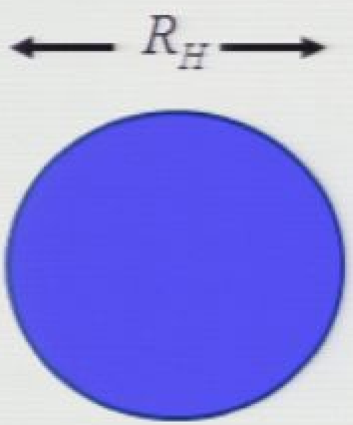
1. Big Bang & inflation basics
2. Eternal inflation ⬅
3. de Sitter Equilibrium cosmology
4. Cosmic curvature from de Sitter Equilibrium cosmology

Does inflation make the SBB natural?

How easy is it to get inflation to start?

What happened before inflation?

Quantum fluctuations during slow roll:



A region of one field coherence length ($= R_H$) gets a new quantum contribution to the field value from an uncorrelated commoving mode of size $\Delta\phi = H$ in a time $\Delta t = H^{-1}$ leading to a (random) quantum rate of change:

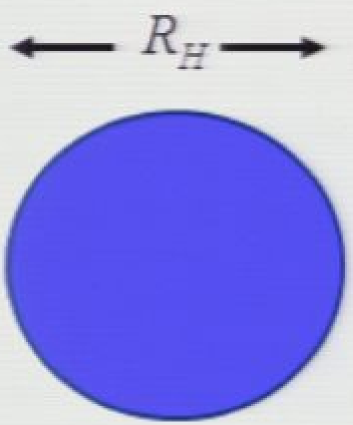
$$\frac{\Delta\phi}{\Delta t} \equiv \dot{\phi}_Q = H^2$$

Thus

$$\frac{\dot{\phi}_Q}{\dot{\phi}} = \frac{H^2}{\dot{\phi}}$$

measures the importance of quantum fluctuations in the field evolution

Quantum fluctuations during slow roll:



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$$\frac{\dot{\phi}_Q}{\dot{\phi}} = \frac{H^2}{\dot{\phi}} \quad \left(\approx \frac{\delta\rho}{\rho} \approx 10^{-5} \right)$$

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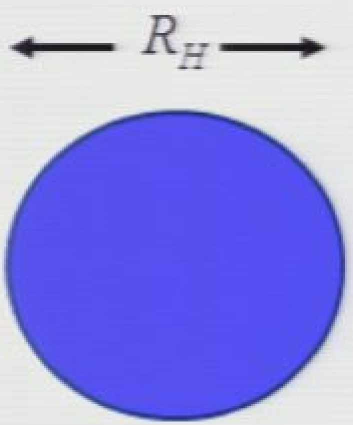

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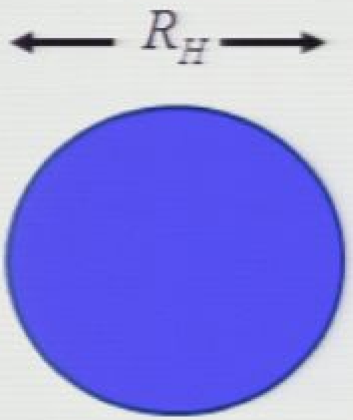

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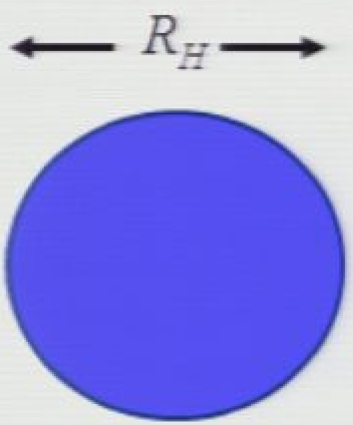
Quantum fluctuations during slow roll:



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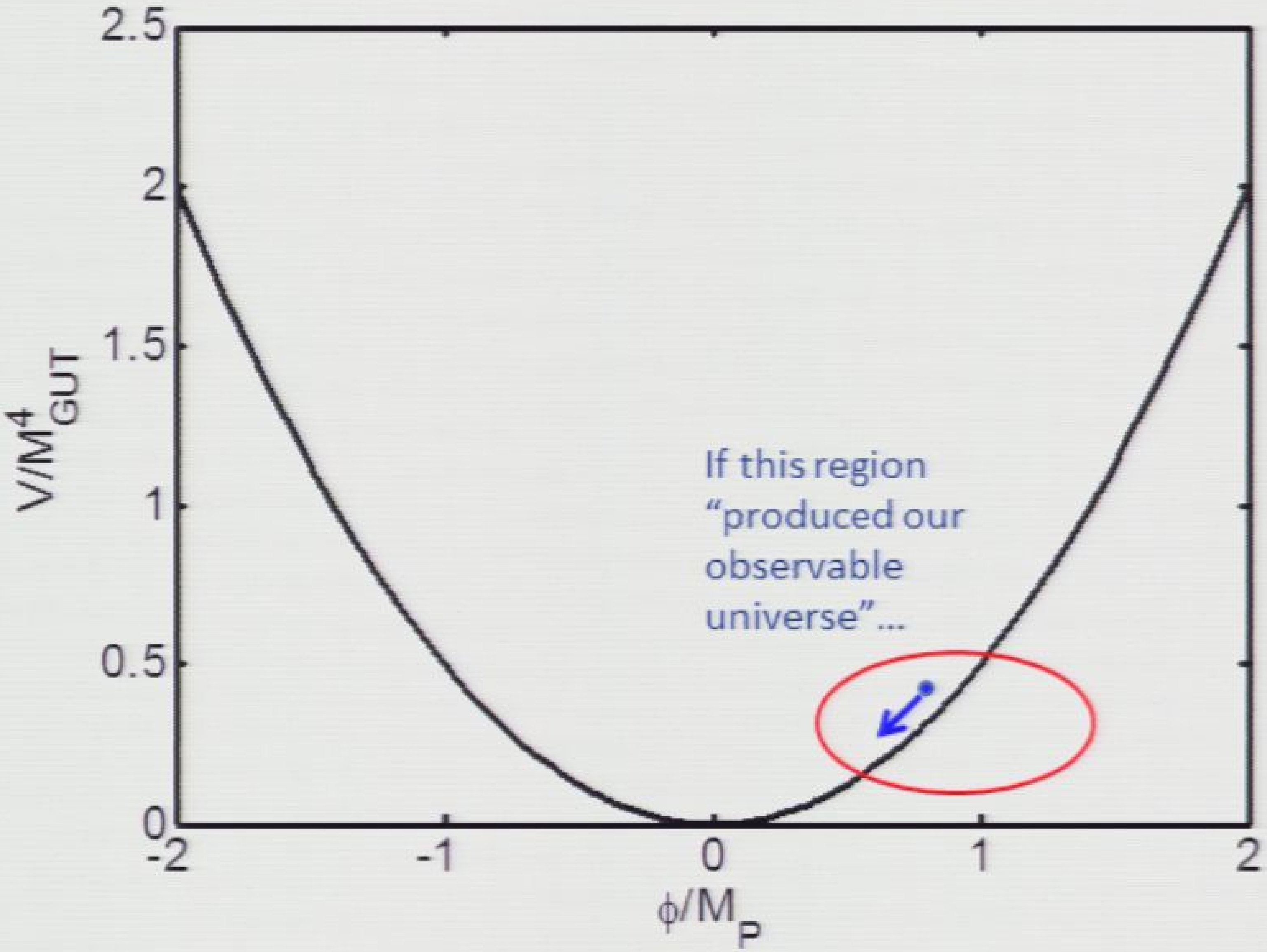
Thus

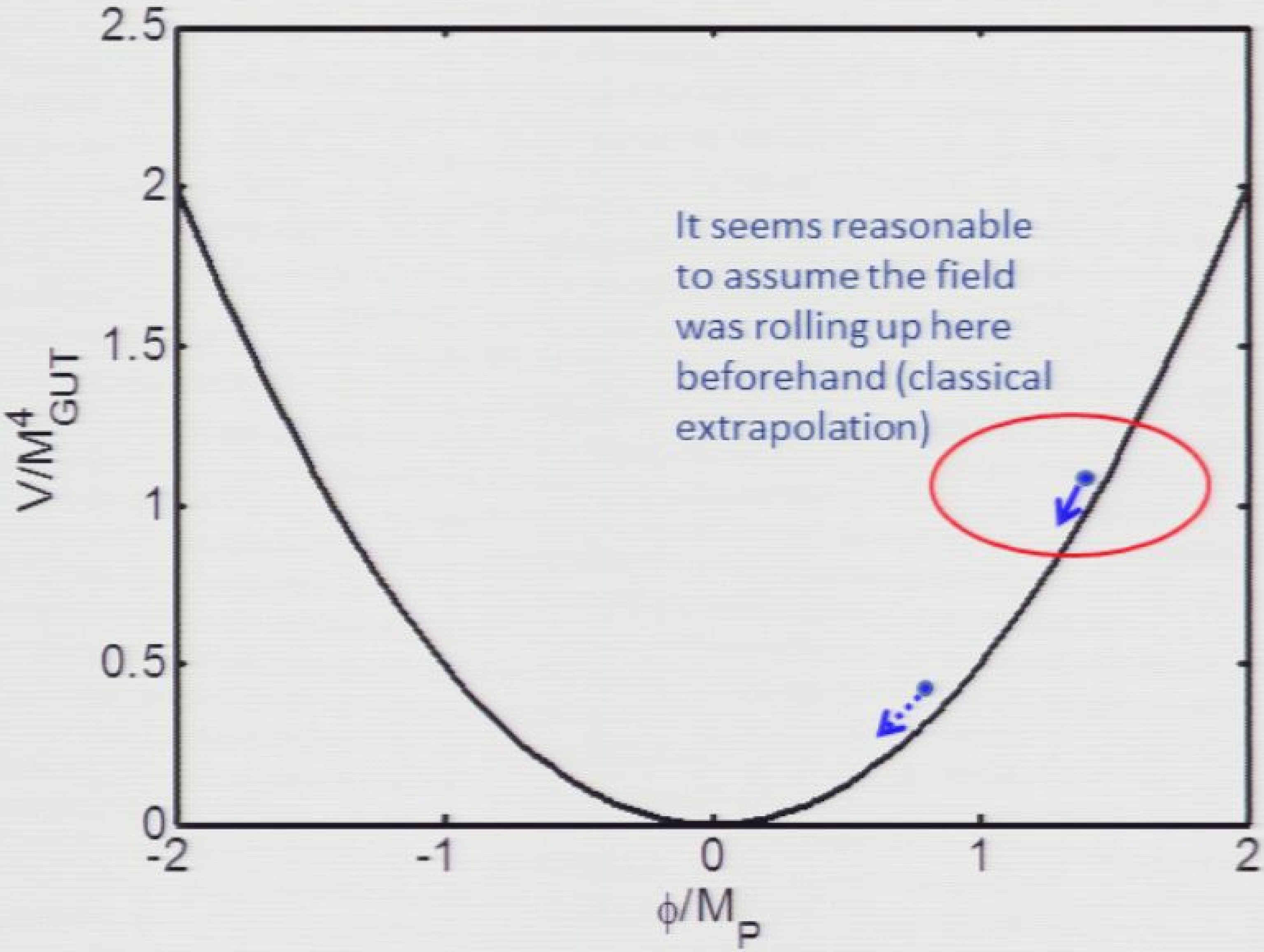
$$\frac{\dot{\phi}_Q}{\dot{\phi}} = \frac{H^2}{\dot{\phi}} \quad \left(= \frac{\delta\rho}{\rho} \approx 10^{-5} \right)$$

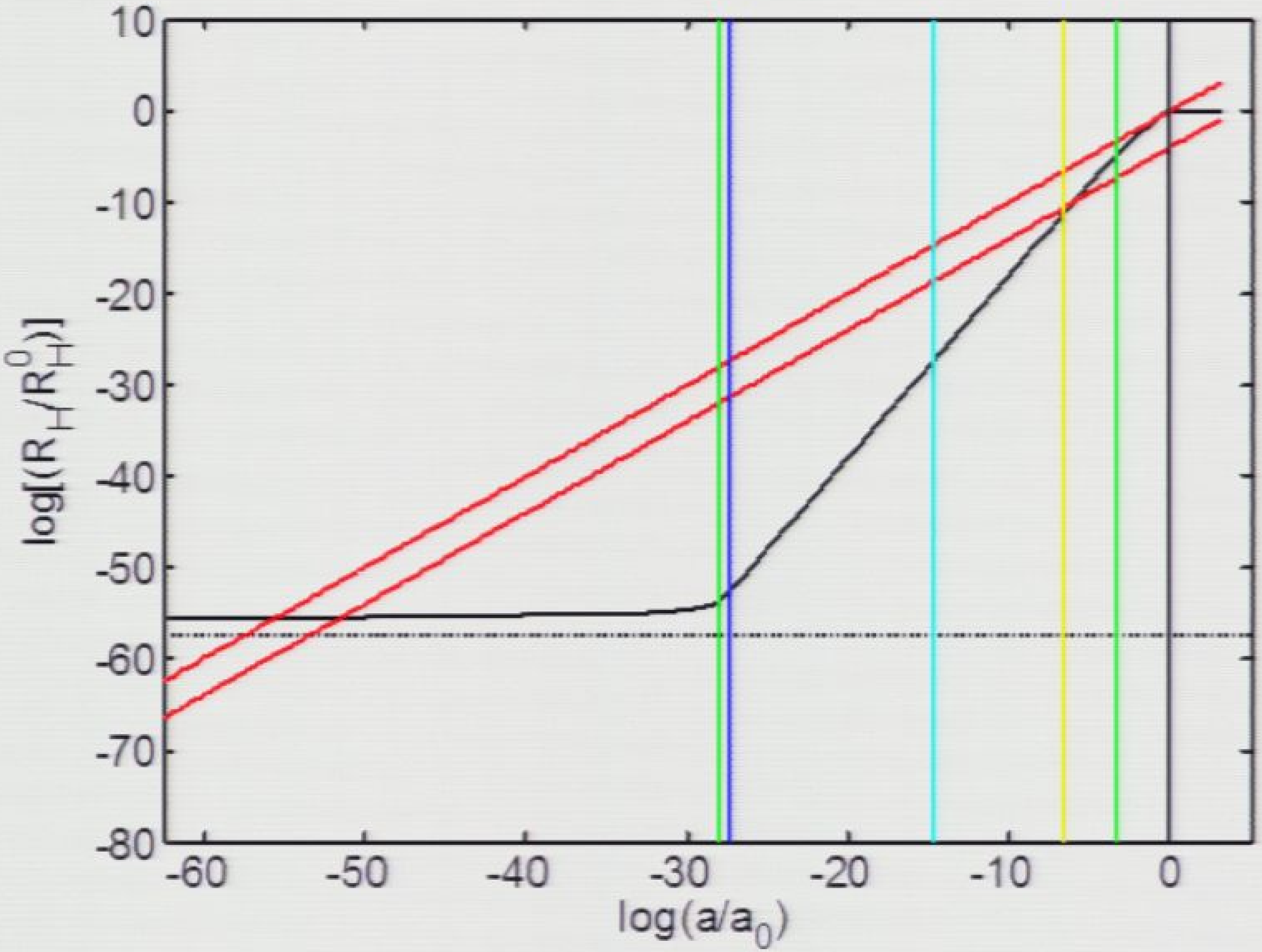
measures the importance of quantum fluctuations in the field evolution

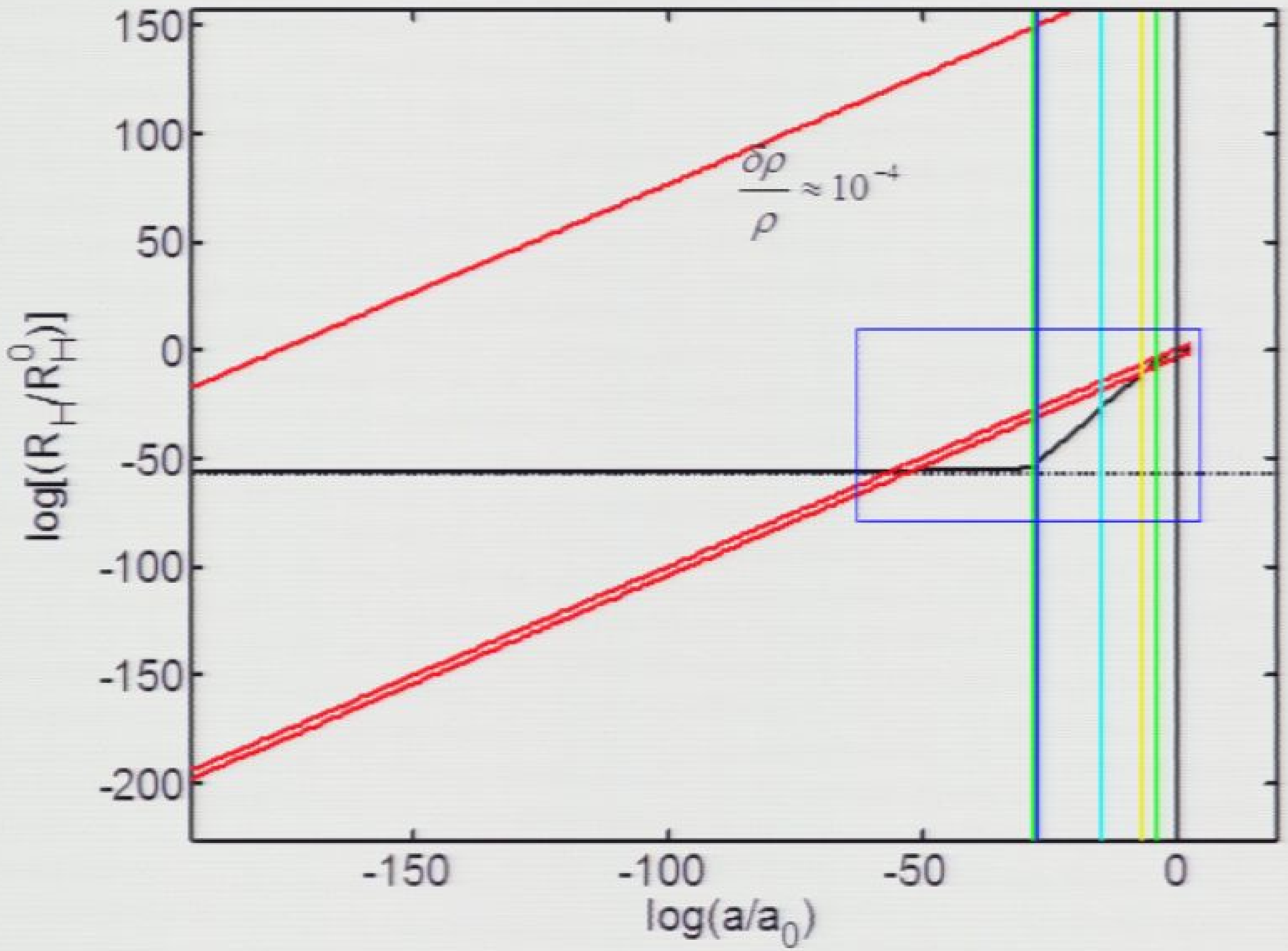
For realistic perturbations the evolution is very classical



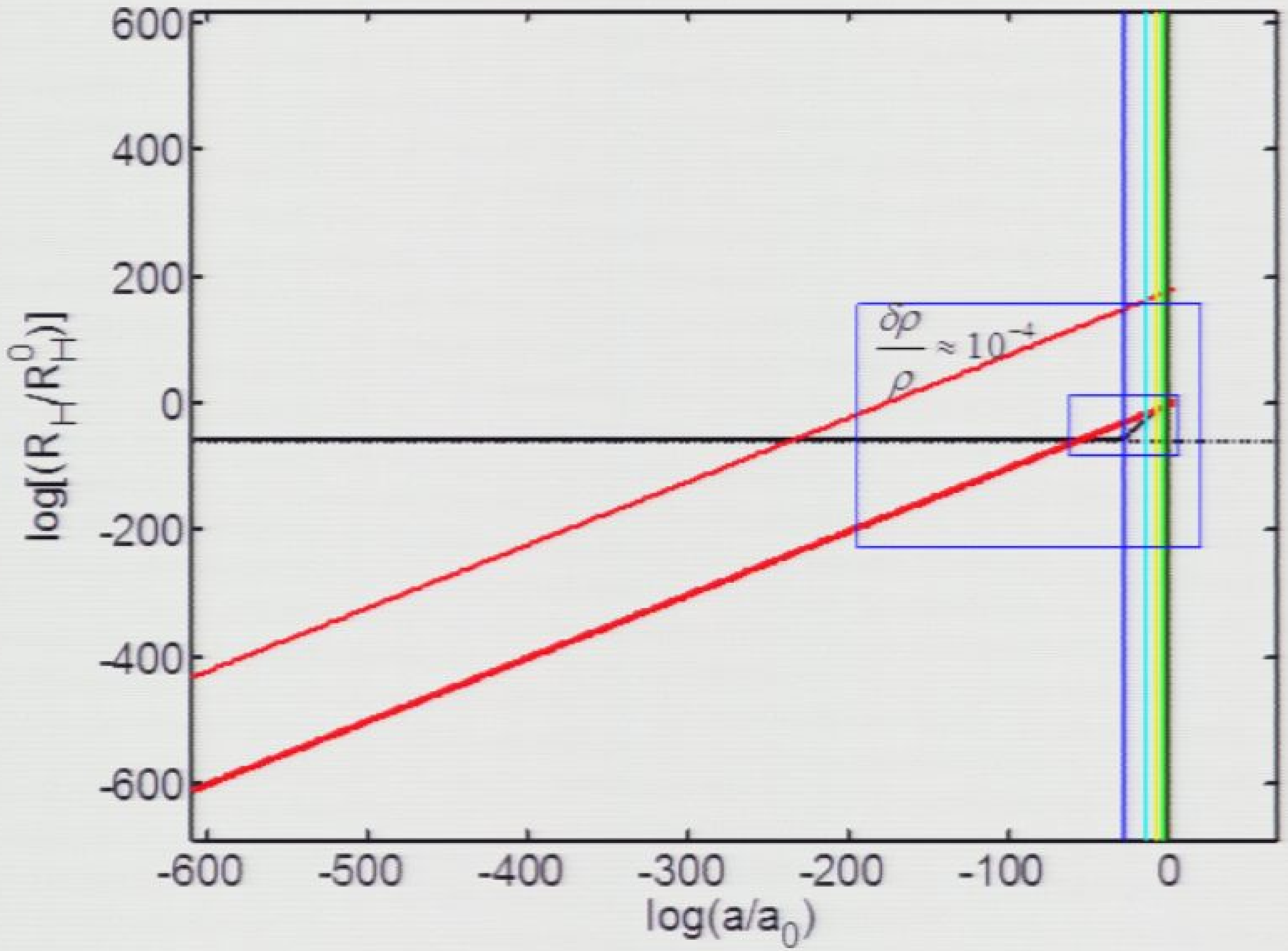
2.5
2
1.5
1
0.5
0
-2
-1
0
1
2
V/M^4_{GUT}
ϕ/M_P
If this region
"produced our
observable
universe"...


2.5
2
1.5
1
0.5
0
V/M_{GUT}^4
-2
-1
0
1
2
ϕ/M_P
It seems reasonable to assume the field was rolling up here beforehand (classical extrapolation)

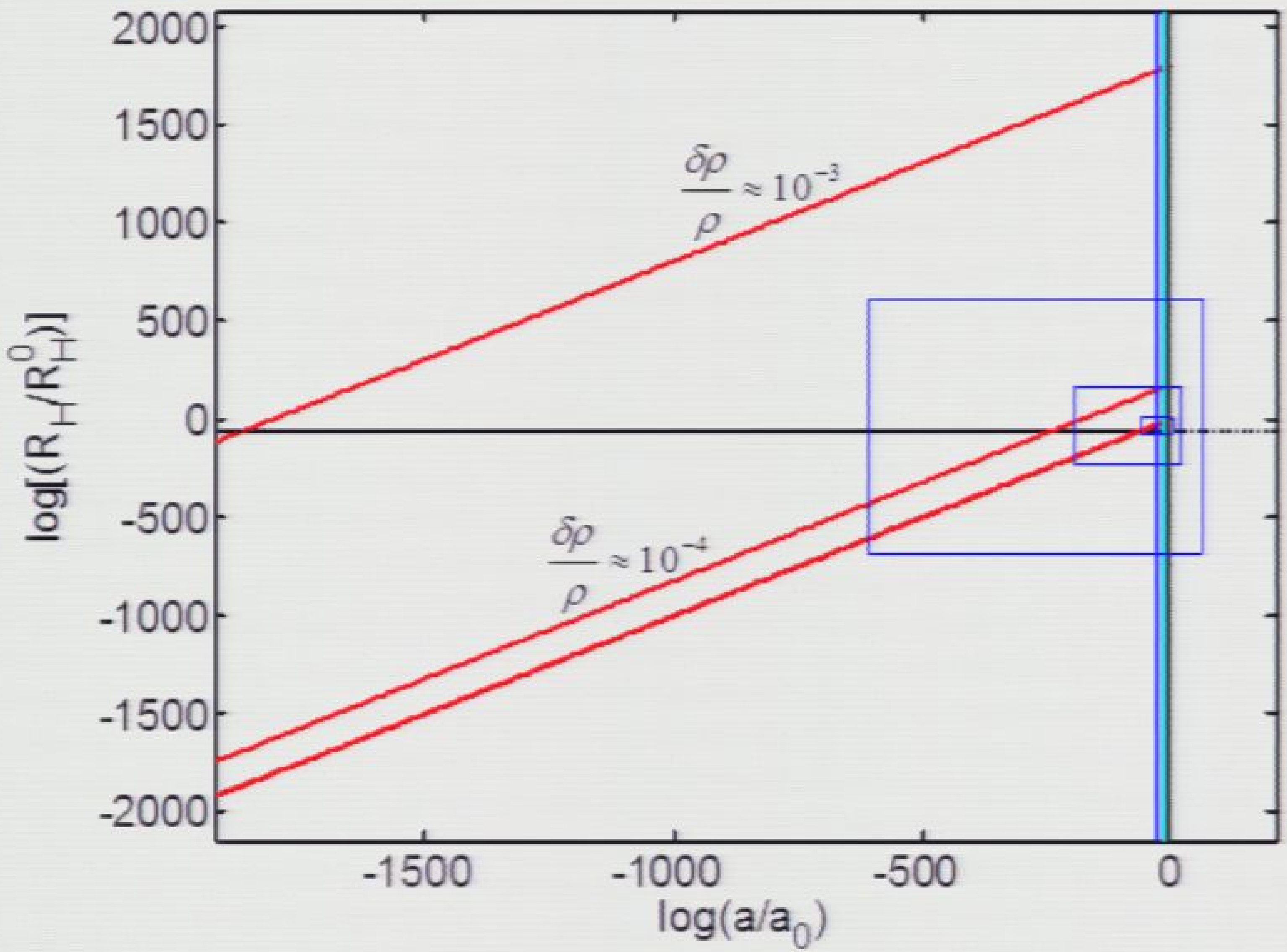

10
0
-10
-20
-30
-40
-50
-60
-70
-80
log[(R_H/R_H^0)]
-60
-50
-40
-30
-20
-10
0
log(a/a_0)

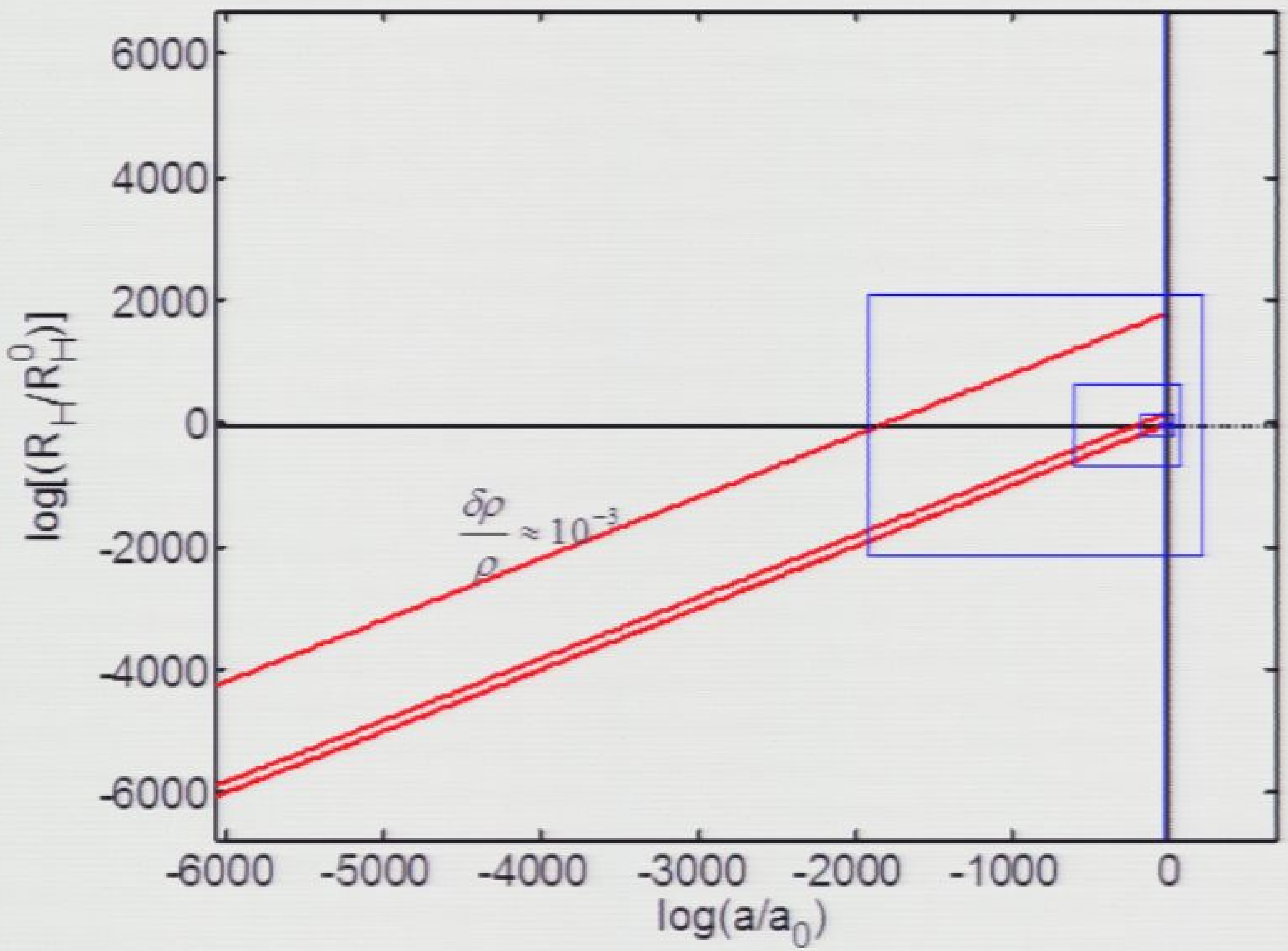


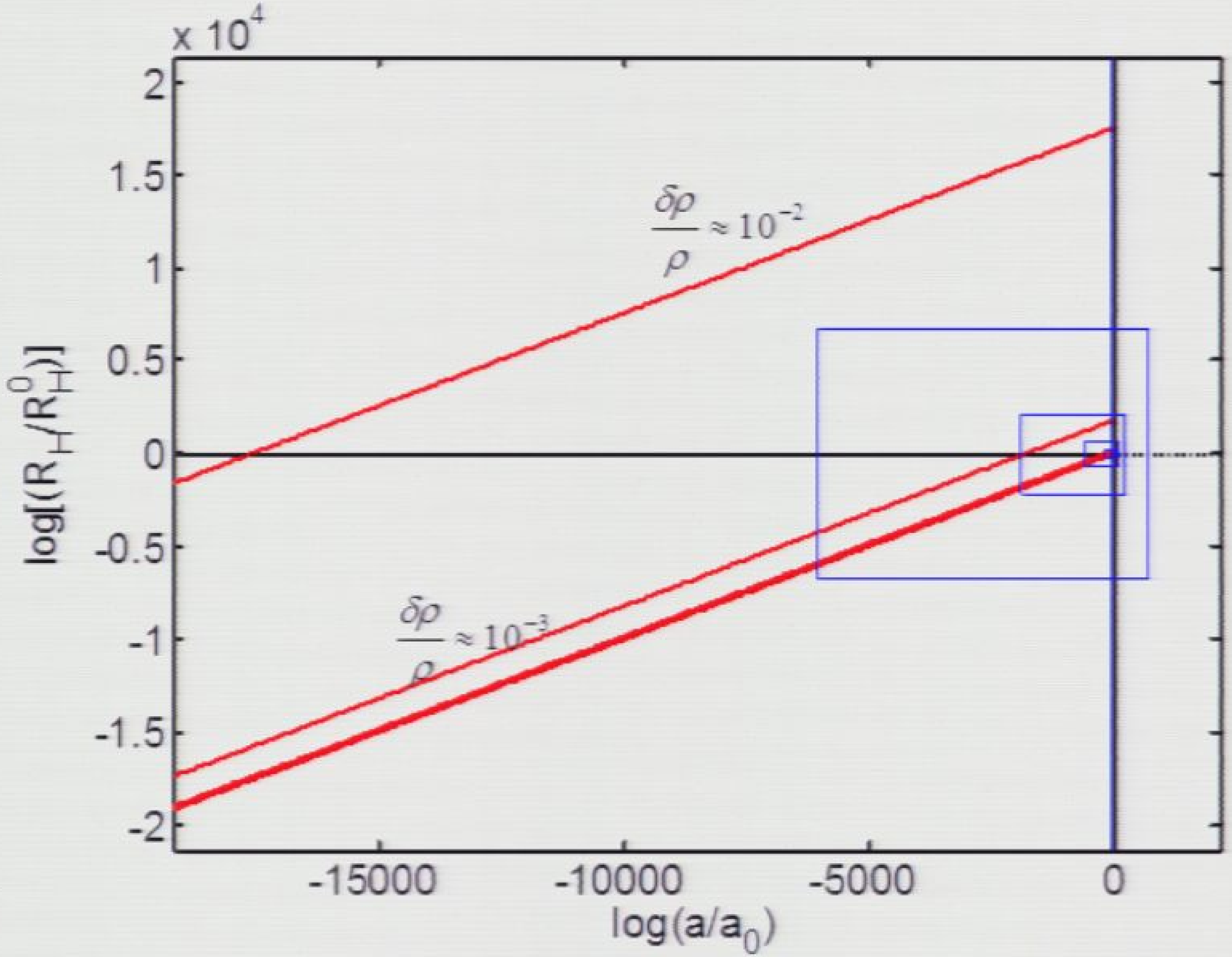
150
100
50
0
-50
-100
-150
-200
$\frac{\delta\rho}{\rho} \approx 10^{-4}$
-150
-100
-50
0
$\log(a/a_0)$
$\log[(R_H/R_H^0)]$

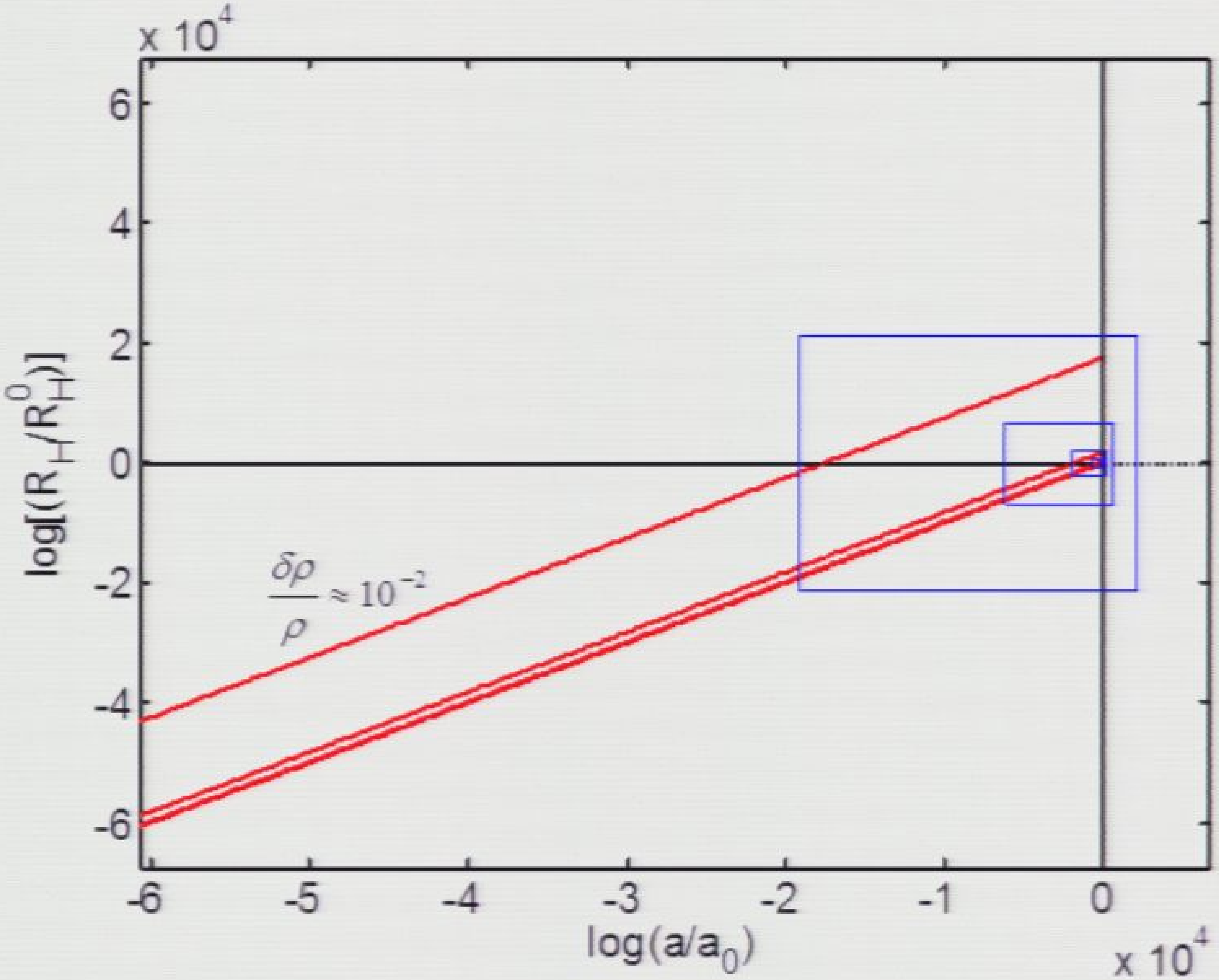


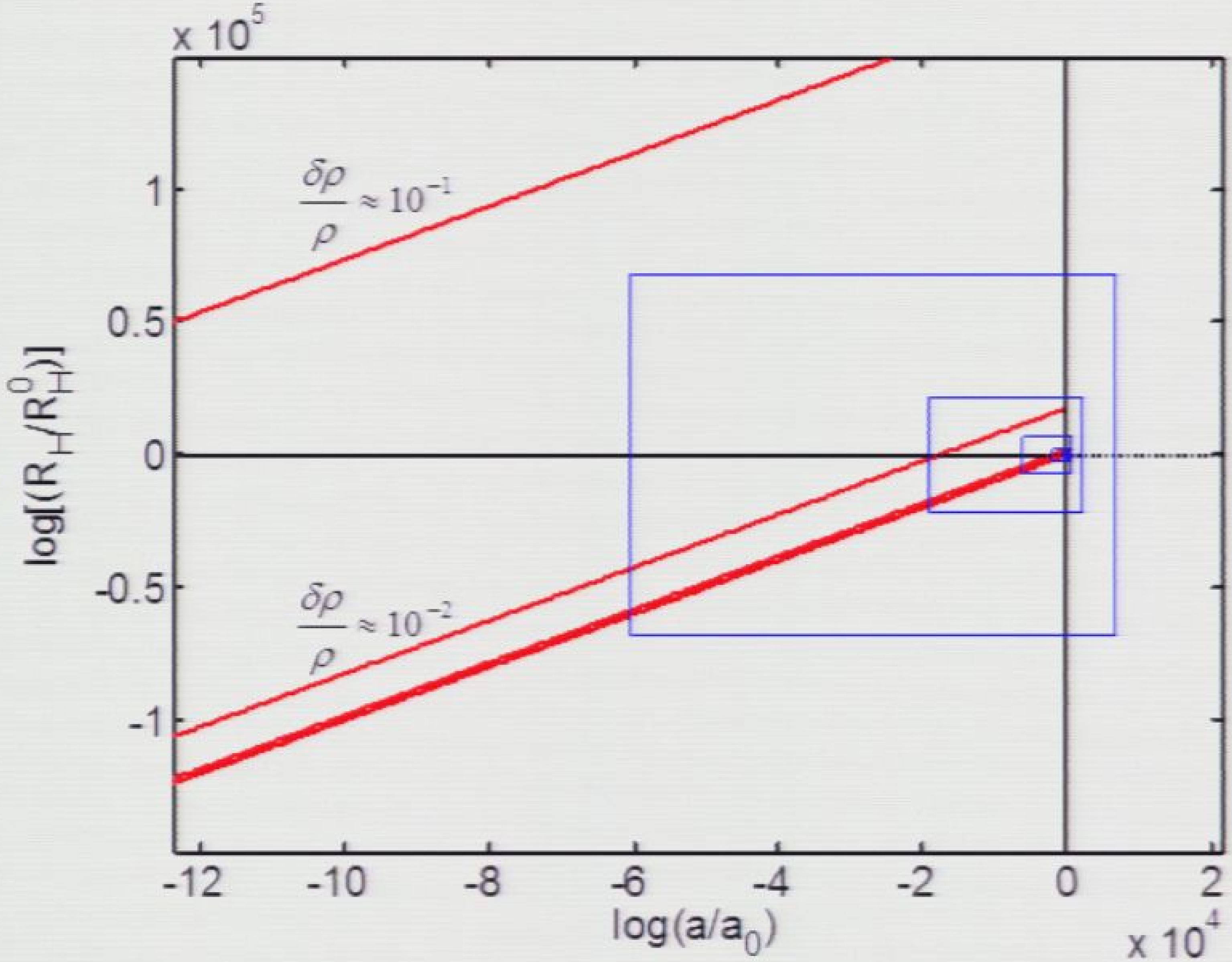
600
400
200
0
-200
-400
-600
log[(R_H/R_H^0)]
-600
-500
-400
-300
-200
-100
0
log(a/a_0)
δρ/ρ ≈ 10^-4

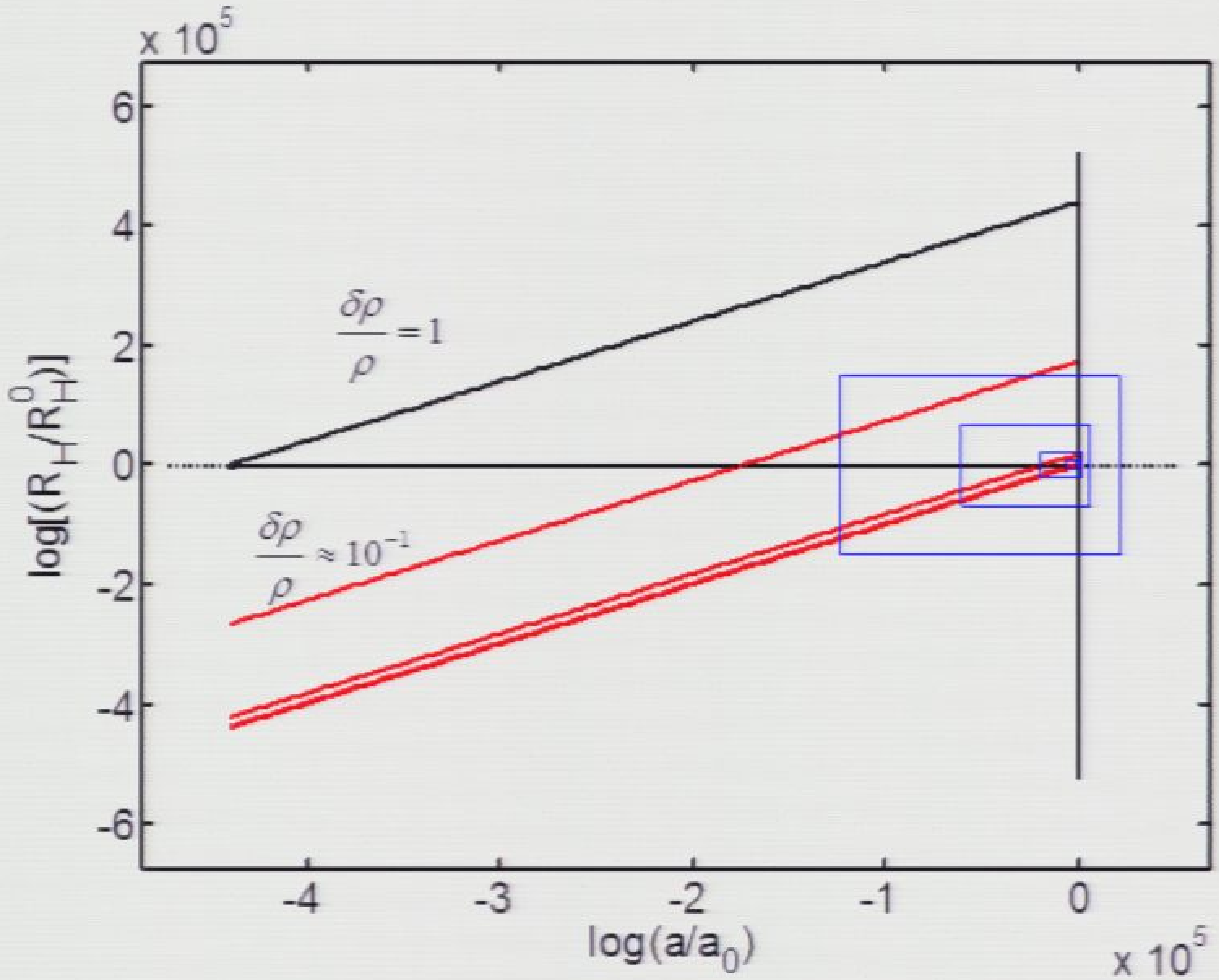

2000
1500
1000
500
0
-500
-1000
-1500
-2000
log[(R_H/R_H^0)]
-1500
-1000
-500
0
log(a/a_0)
δρ/ρ ≈ 10^-3
δρ/ρ ≈ 10^-4


6000
4000
2000
0
-2000
-4000
-6000
log[(R_H/R_H^0)]
$\frac{\delta\rho}{\rho} \approx 10^{-3}$
-6000 -5000 -4000 -3000 -2000 -1000 0
log(a/a_0)

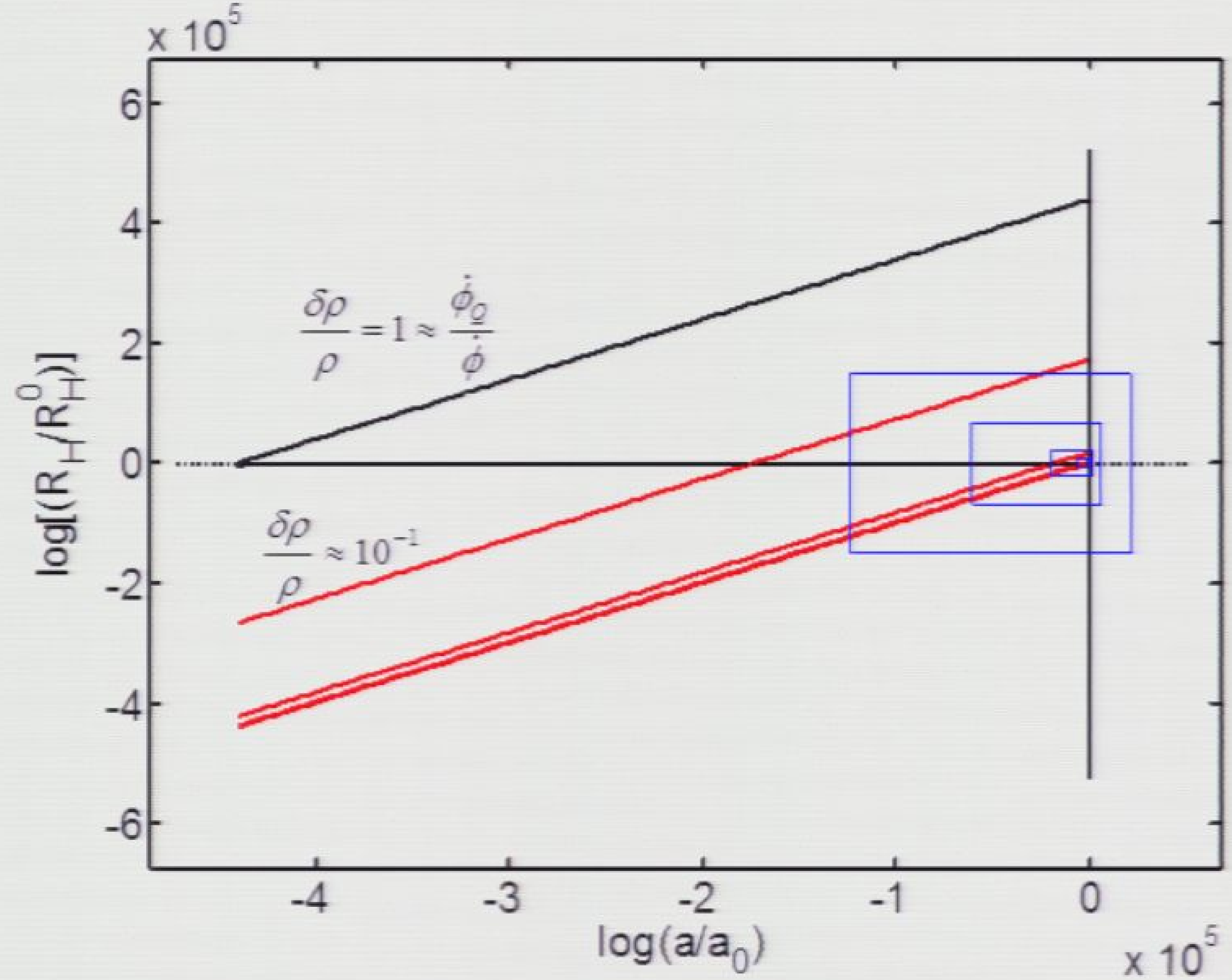

x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
log[(R_H/R_H^0)]
δρ/ρ ≈ 10^-2
δρ/ρ ≈ 10^-3
-15000
-10000
-5000
0
log(a/a_0)

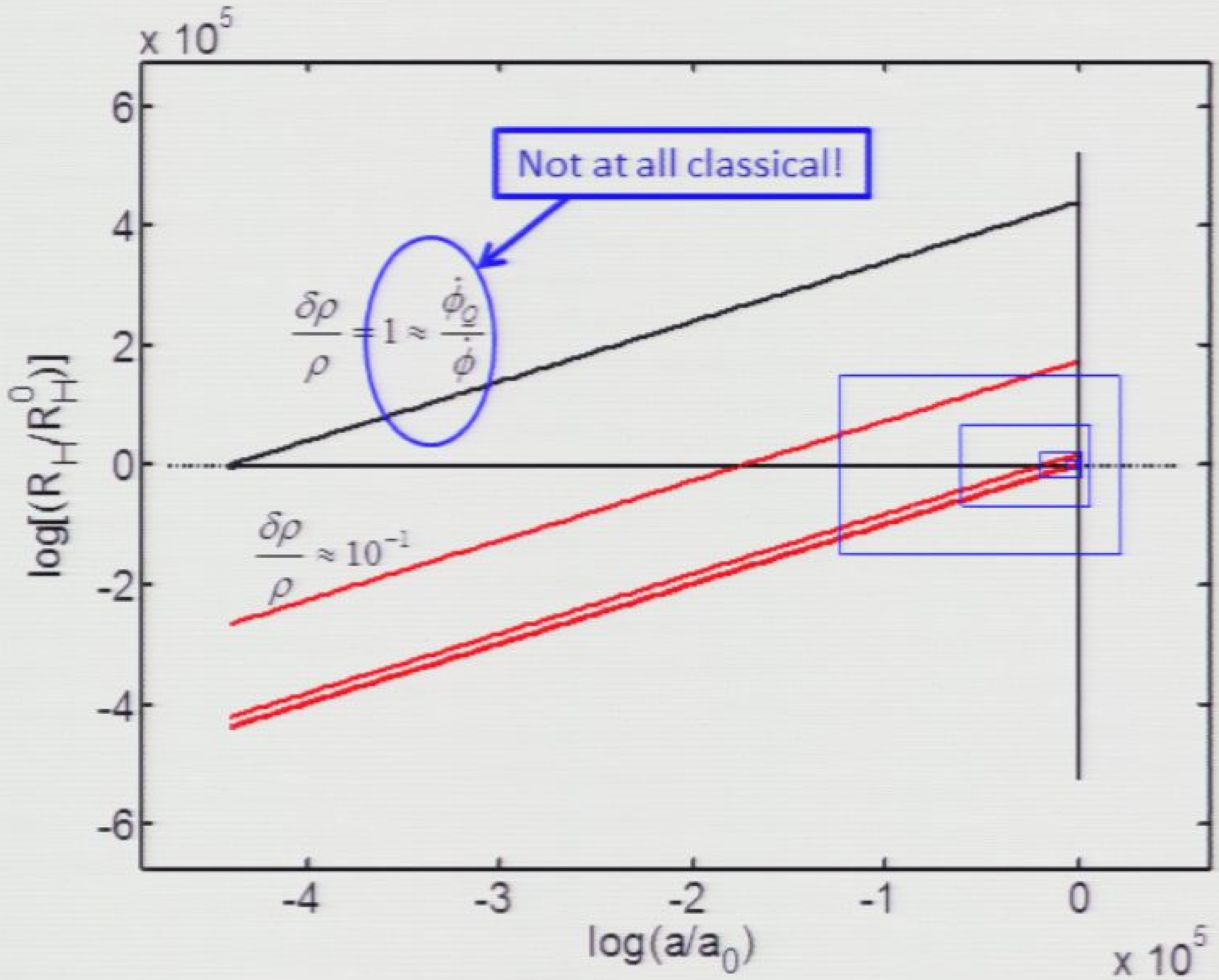

x 10^4
6
4
2
0
-2
-4
-6
log[(R_H/R^0_H)]
$\frac{\delta\rho}{\rho} \approx 10^{-2}$
-6
-5
-4
-3
-2
-1
0
log(a/a_0)
x 10^4

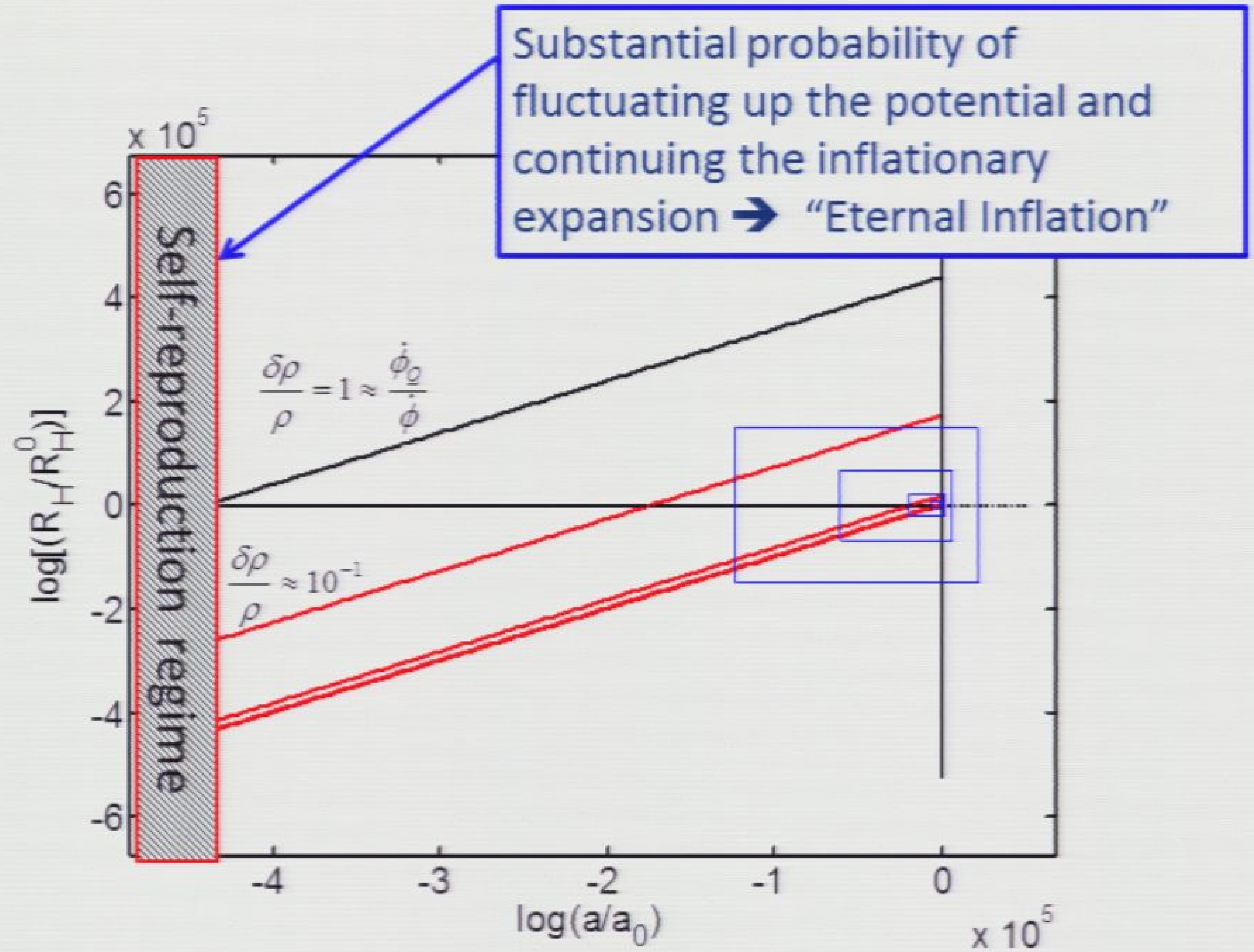

x 10^5
$\frac{\delta\rho}{\rho} \approx 10^{-1}$
$\frac{\delta\rho}{\rho} \approx 10^{-2}$
1
0.5
0
-0.5
-1
$\log[(R_H/R_H^0)]$
-12
-10
-8
-6
-4
-2
0
2
$\log(a/a_0)$
x 10^4



x 10^5
6
4
2
0
-2
-4
-6
log[(R_H/R_H^0)]
δρ/ρ = 1
δρ/ρ ≈ 10^-1
-4
-3
-2
-1
0
log(a/a_0)
x 10^5


x 10^5
6
4
2
0
-2
-4
-6
log[(R_H/R_H^0)]
δρ/ρ = 1 ≈ φ̇_Q/φ̇
δρ/ρ ≈ 10^-1
-4
-3
-2
-1
0
log(a/a_0)
x 10^5


x 10^5
Not at all classical!
$\frac{\delta\rho}{\rho} = 1 \approx \frac{\dot{\phi}_Q}{\dot{\phi}}$
$\frac{\delta\rho}{\rho} \approx 10^{-1}$
log[(R_H/R_H^0)]
log(a/a_0)
x 10^5
6
4
2
0
-2
-4
-6
-4
-3
-2
-1
0


Substantial probability of fluctuating up the potential and continuing the inflationary expansion ➔ "Eternal Inflation"
x 10^5
Self-reproduction regime
$\frac{\delta\rho}{\rho} = 1 \approx \frac{\dot{\phi}_Q}{\dot{\phi}}$
$\frac{\delta\rho}{\rho} \approx 10^{-1}$
log[(R_H/R_H^0)]
log(a/a_0)
x 10^5

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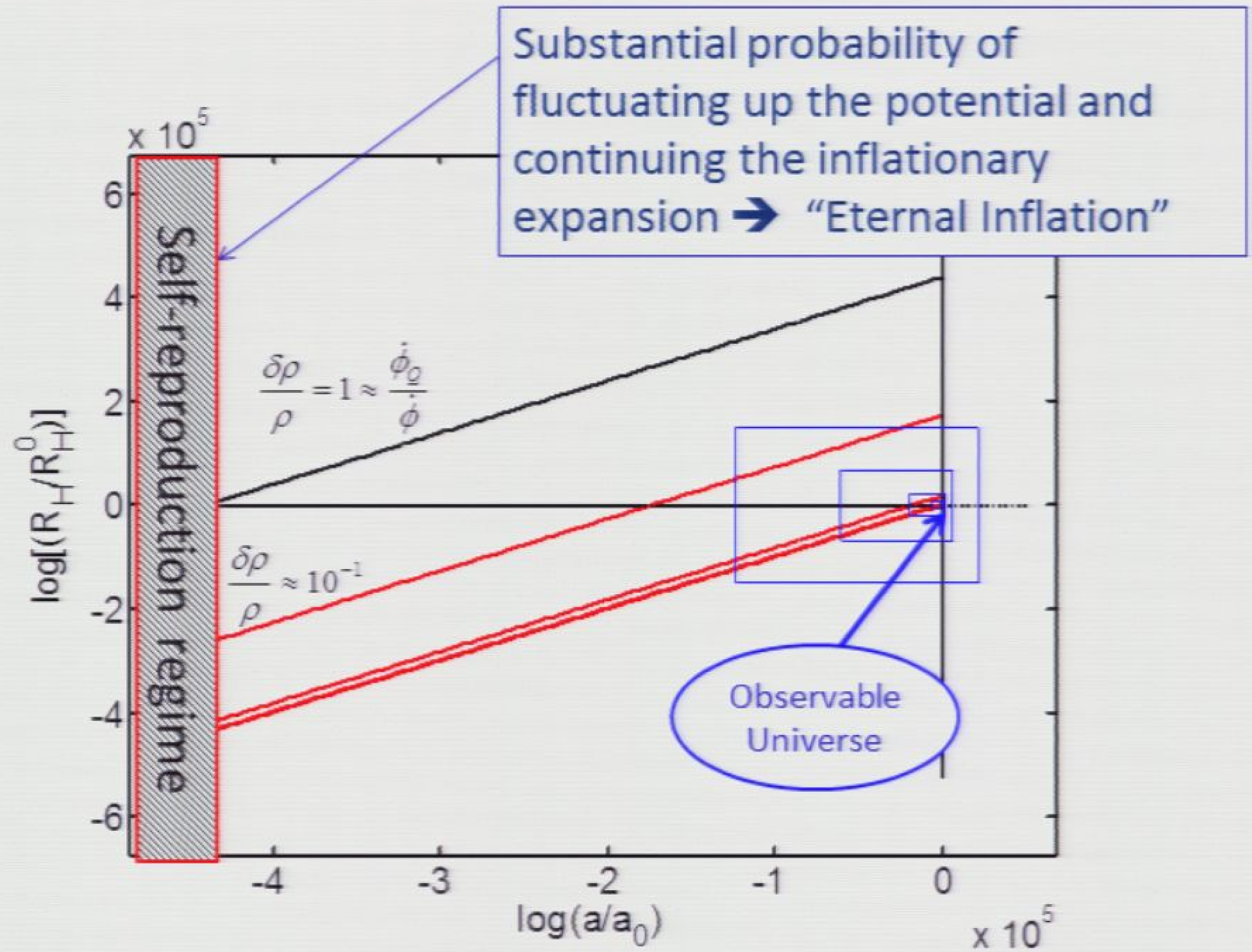
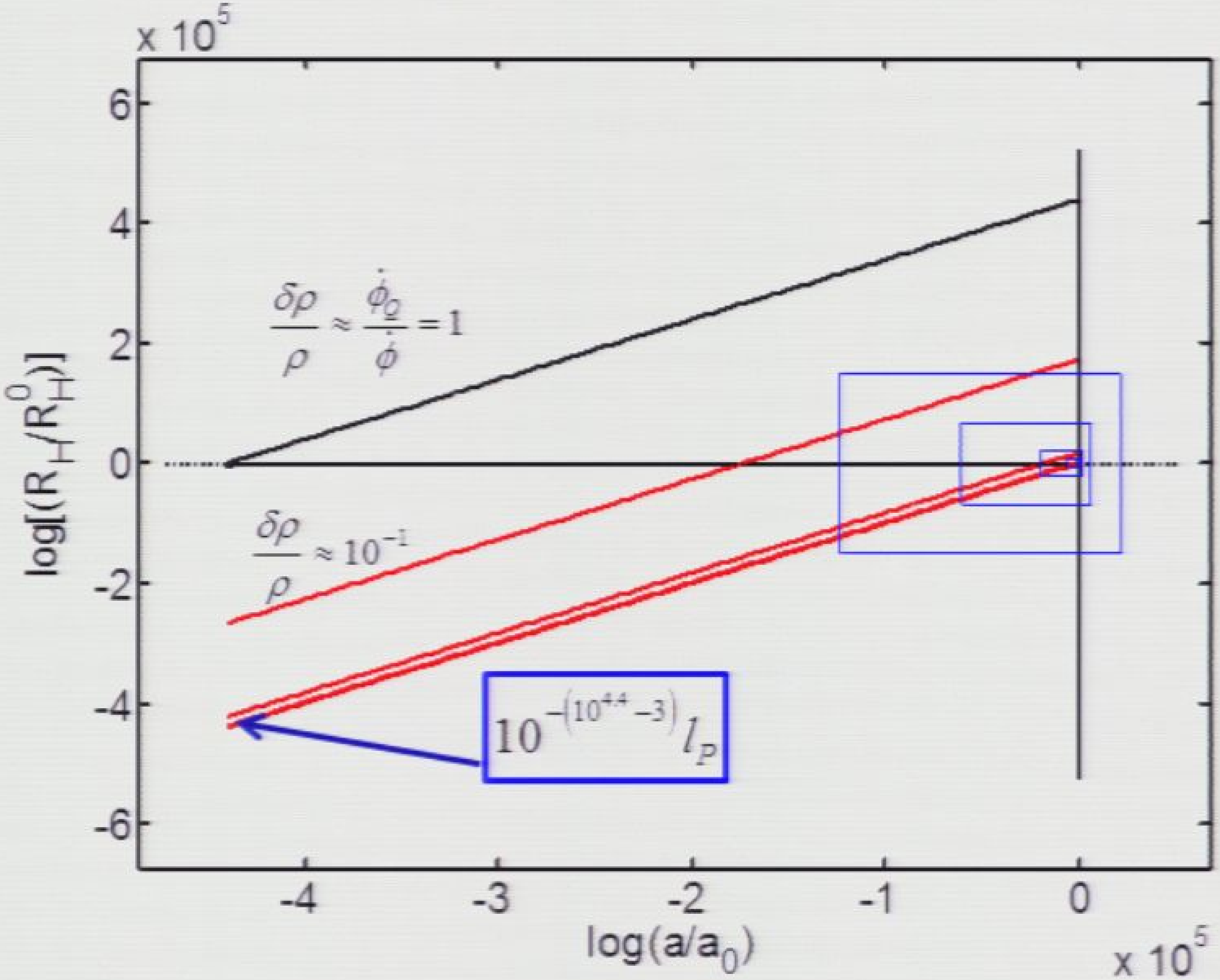
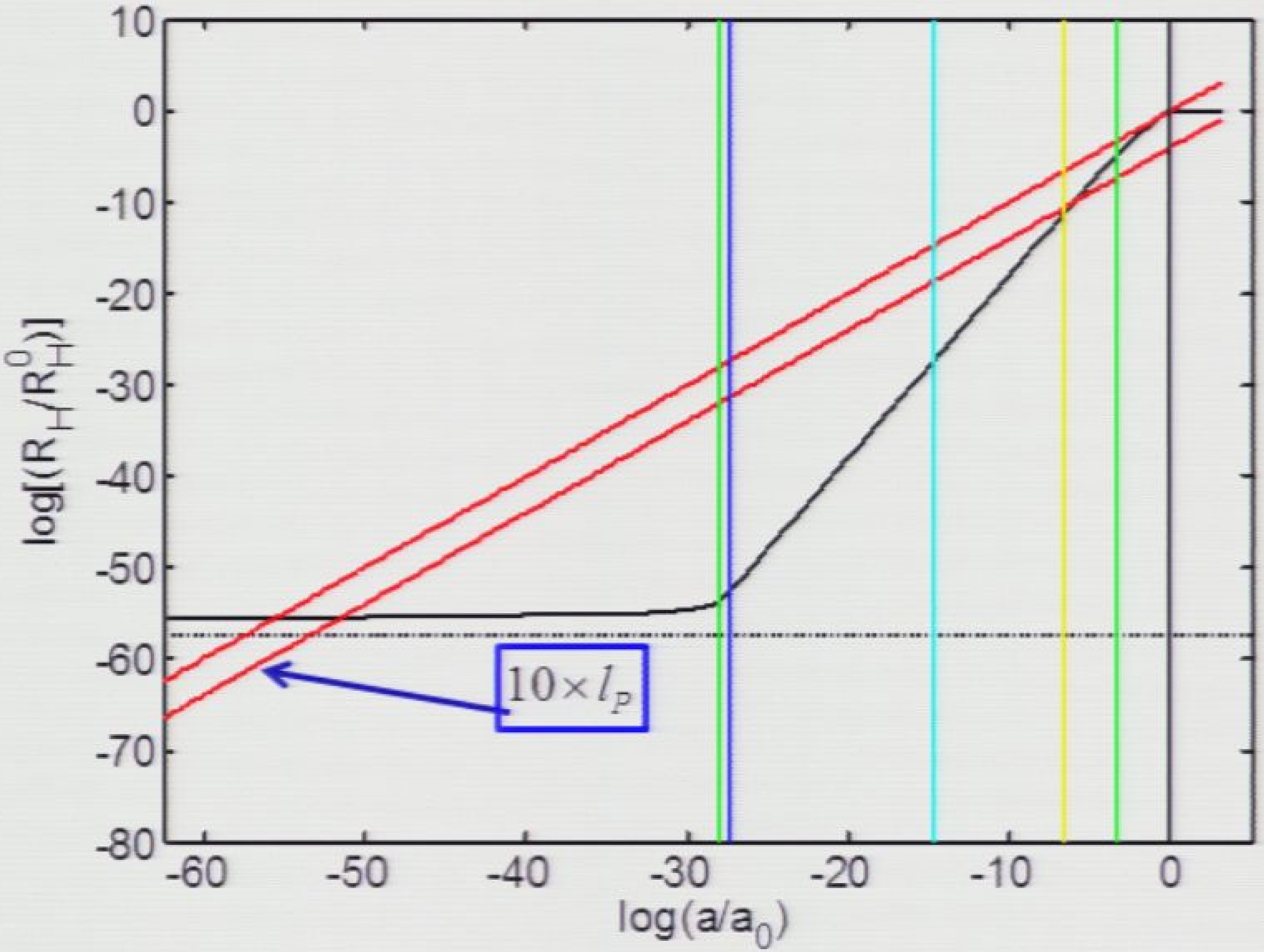


Substantial probability of fluctuating up the potential and continuing the inflationary expansion → "Eternal Inflation"
x 10^5
6
4
2
0
-2
-4
-6
log[(R_H/R_H^0)]
Self-reproduction regime
δρ/ρ = 1 ≈ φ̇_Q/φ̇
δρ/ρ ≈ 10^-1
Observable Universe
-4
-3
-2
-1
0
log(a/a_0)
x 10^5

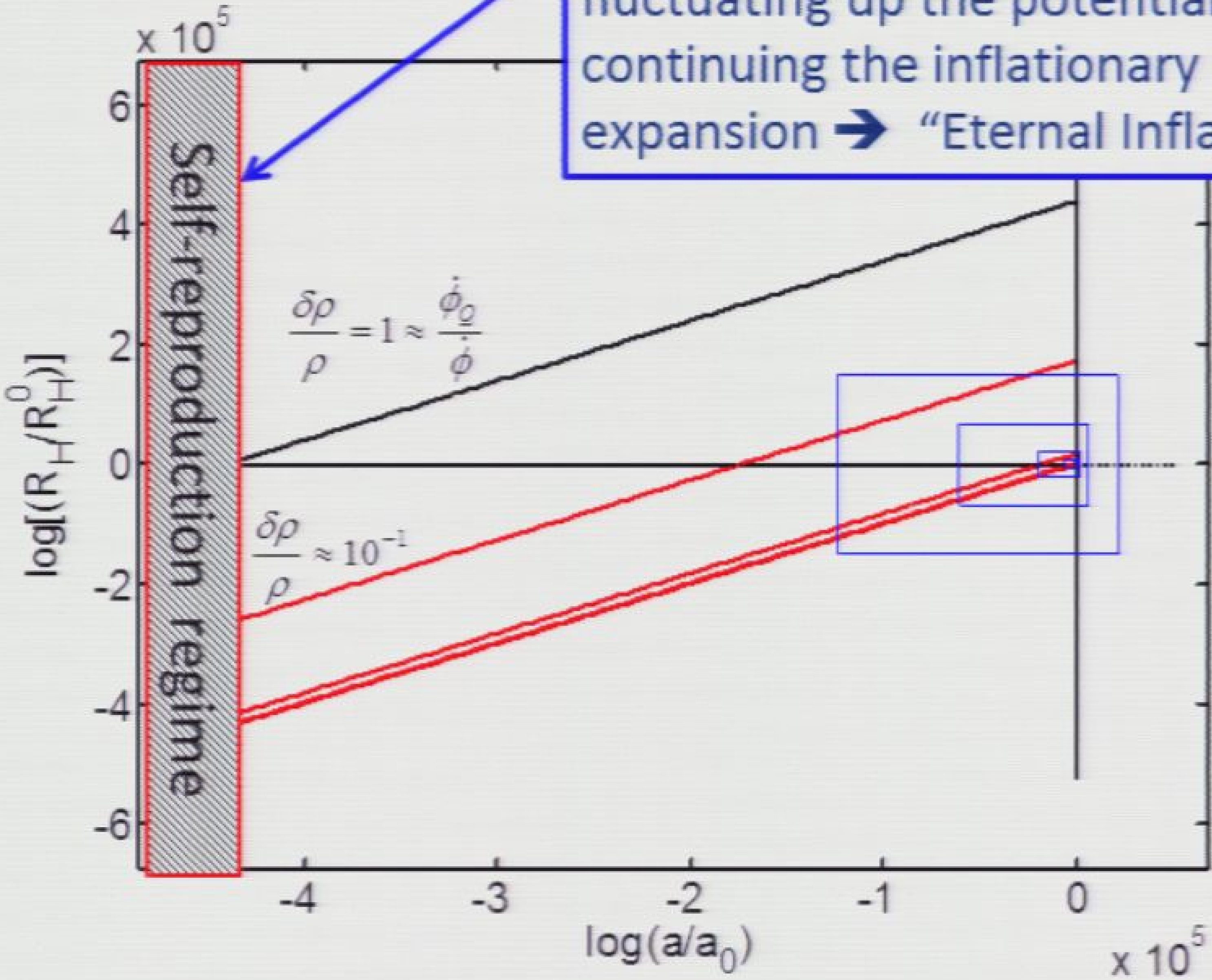


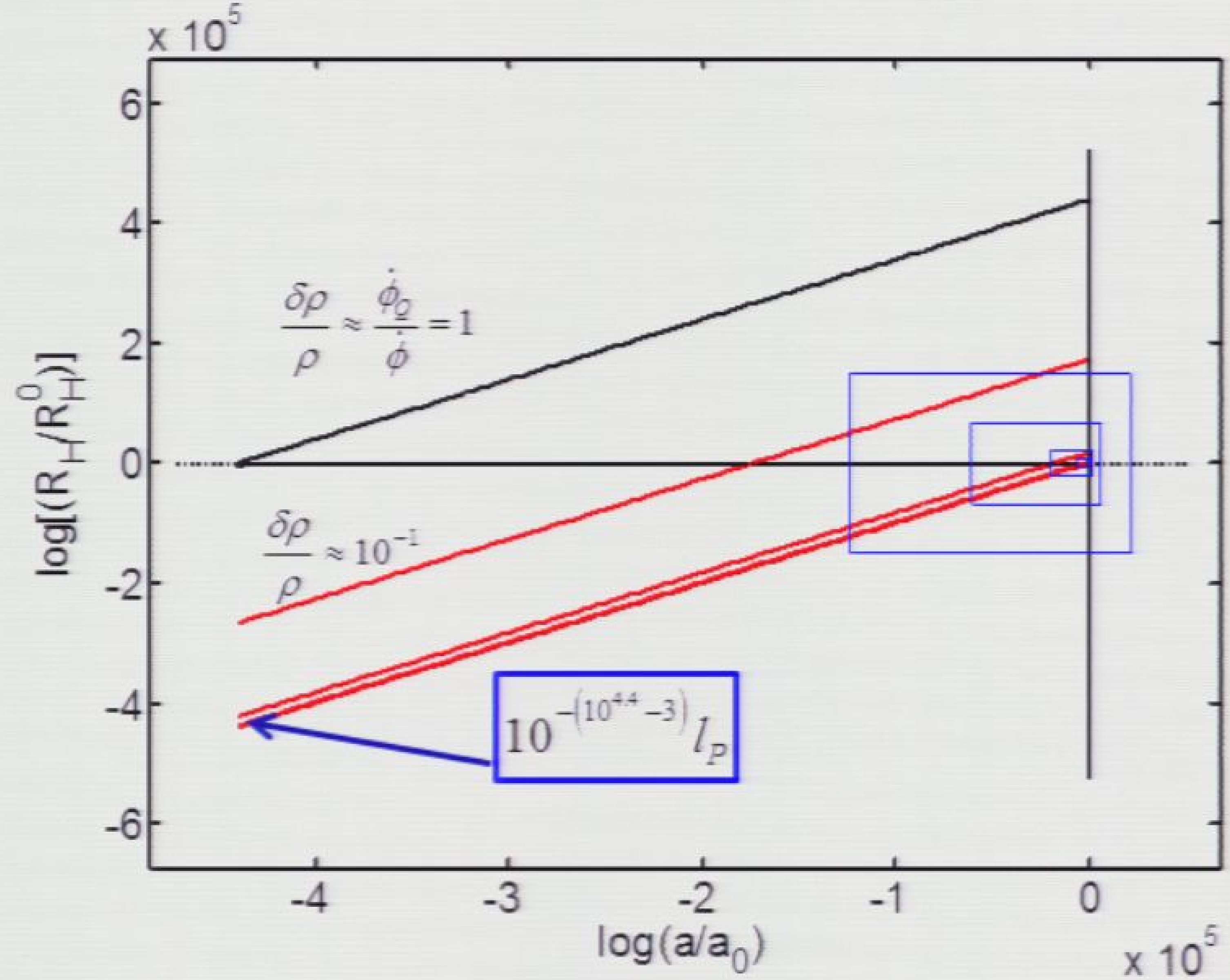
x 10^5
6
4
2
0
-2
-4
-6
log[(R_H/R_H^0)]
$\frac{\delta\rho}{\rho} \approx \frac{\dot{\phi}_Q}{\dot{\phi}} = 1$
$\frac{\delta\rho}{\rho} \approx 10^{-1}$
$10^{-(10^{44}-3)} l_P$
-4
-3
-2
-1
0
log(a/a_0)
x 10^5



10
0
-10
-20
-30
-40
-50
-60
-70
-80
-60
-50
-40
-30
-20
-10
0
log[(R_H/R_H^0)]
log(a/a_0)
10×l_P

Substantial probability of fluctuating up the potential and continuing the inflationary expansion ➔ “Eternal Inflation”





x 10^5
6
4
2
0
-2
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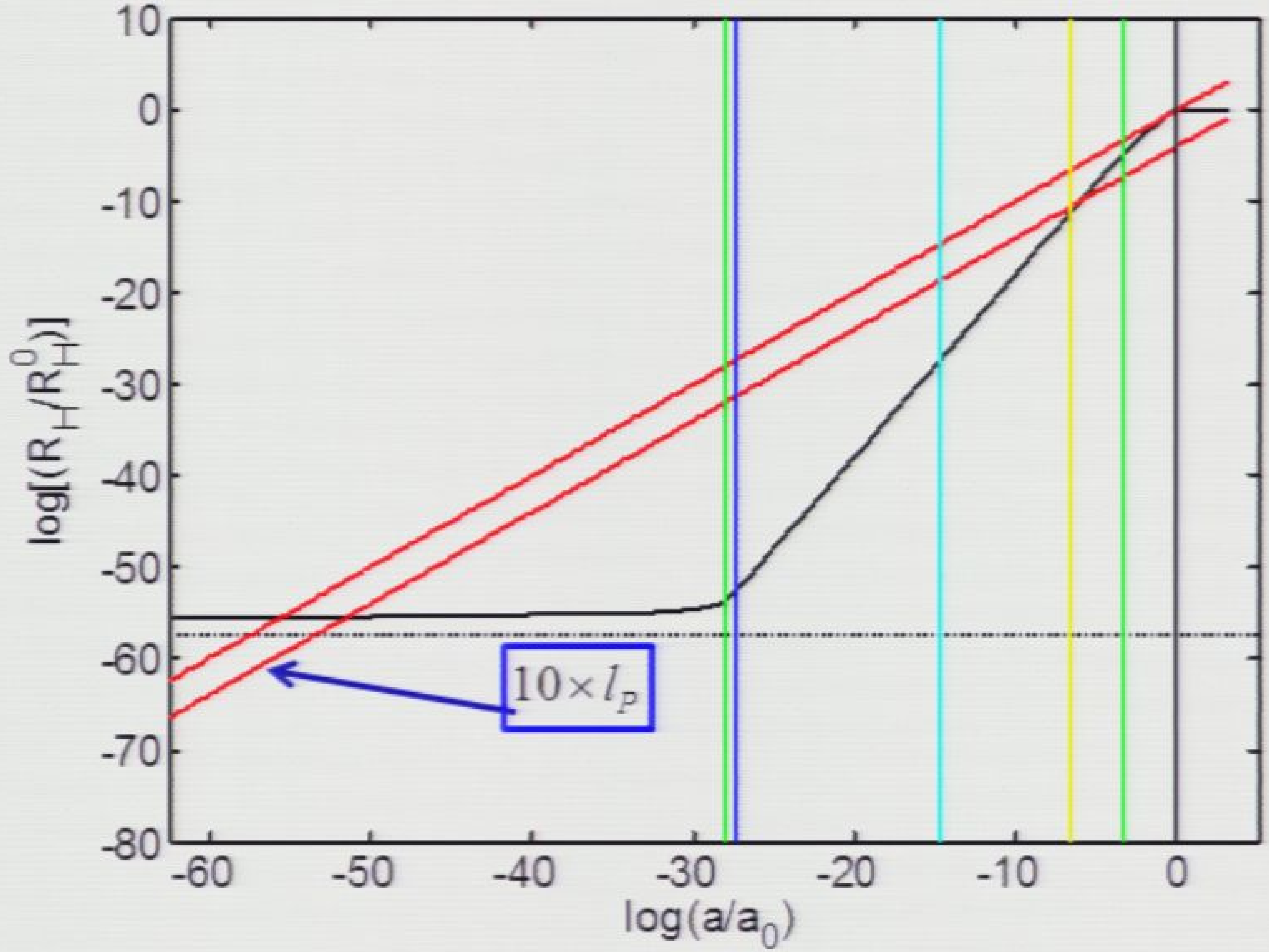
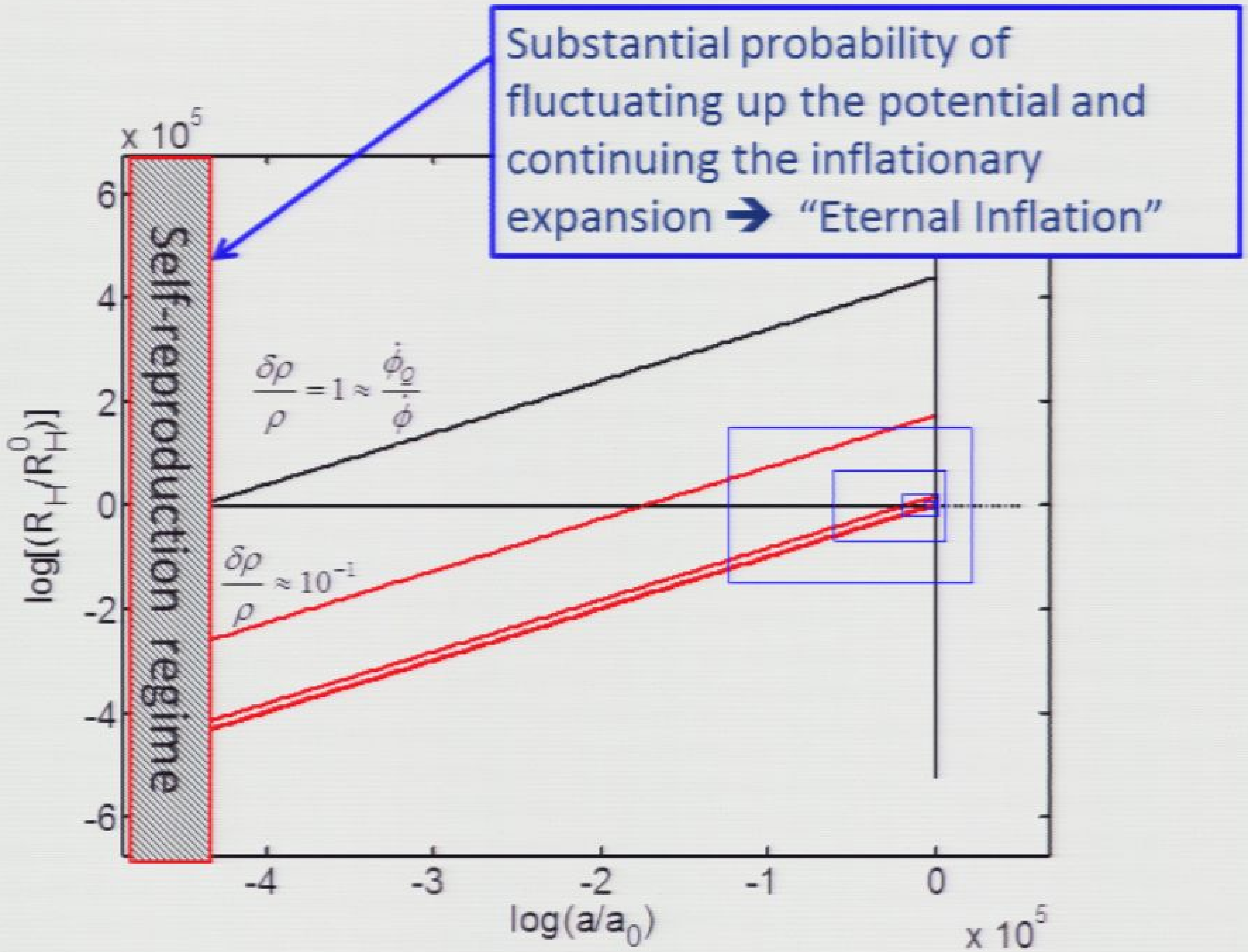
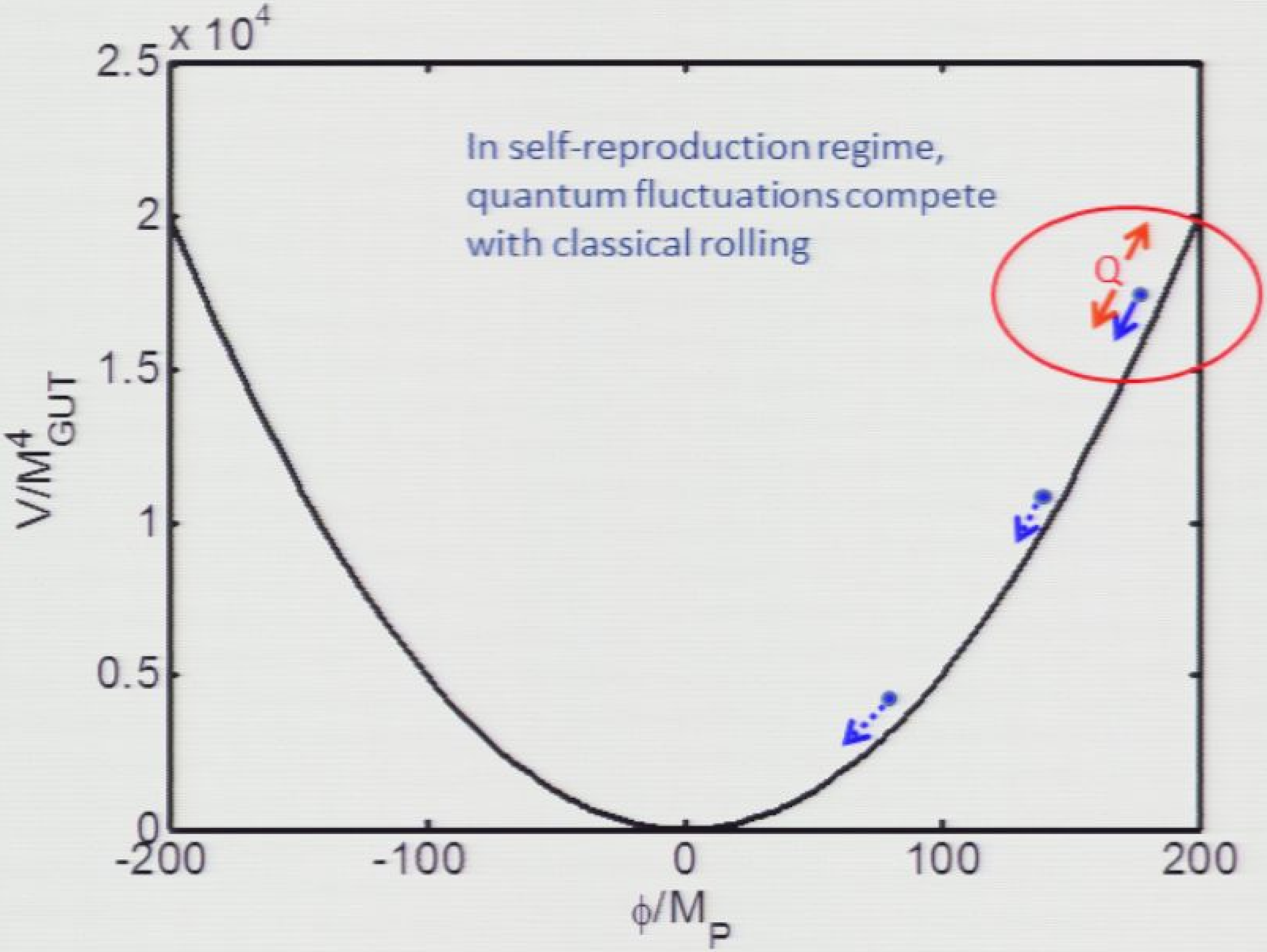
-6
log[(R_H/R_H^0)]
$\frac{\delta\rho}{\rho} \approx \frac{\dot{\phi}_Q}{\dot{\phi}} = 1$
$\frac{\delta\rho}{\rho} \approx 10^{-1}$
$10^{-(10^{44}-3)} l_P$
-4
-3
-2
-1
0
log(a/a_0)
x 10^5



10
0
-10
-20
-30
-40
-50
-60
-70
-80
log[(R_H/R_H^0)]
-60
-50
-40
-30
-20
-10
0
log(a/a_0)
$10 \times l_P$



Substantial probability of fluctuating up the potential and continuing the inflationary expansion → "Eternal Inflation"
x 10^5
6
4
2
0
-2
-4
-6
Self-reproduction regime
log[(R_H/R_H^0)]
$\frac{\delta\rho}{\rho} = 1 \approx \frac{\dot\phi_Q}{\dot\phi}$
$\frac{\delta\rho}{\rho} \approx 10^{-1}$
-4
-3
-2
-1
0
log(a/a_0)
x 10^5


x 10^4
2.5
2
1.5
1
0.5
0
V/M^4_GUT
In self-reproduction regime,
quantum fluctuations compete
with classical rolling
Q
-200
-100
0
100
200
ϕ/M_P

Self-reproduction is a generic feature of any inflaton potential:

During inflation

$$\ddot{\phi} + 3H\dot{\phi} = -\Gamma_{\phi}\dot{\phi} - V'(\phi)$$

↓

$$3H\dot{\phi} \approx -V'(\phi)$$

↓

$$\dot{\phi} \approx \frac{-V'(\phi)}{3H}$$

$$\frac{\dot{\phi}_Q}{\dot{\phi}} = \frac{H^2}{\dot{\phi}} \approx \frac{H^3}{-V'(\phi)} \propto \frac{V^{3/2}}{V'} \approx \frac{V^{3/2}}{(V/\phi)} = V^{1/2}\phi$$

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≥ 1 for self-reproduction

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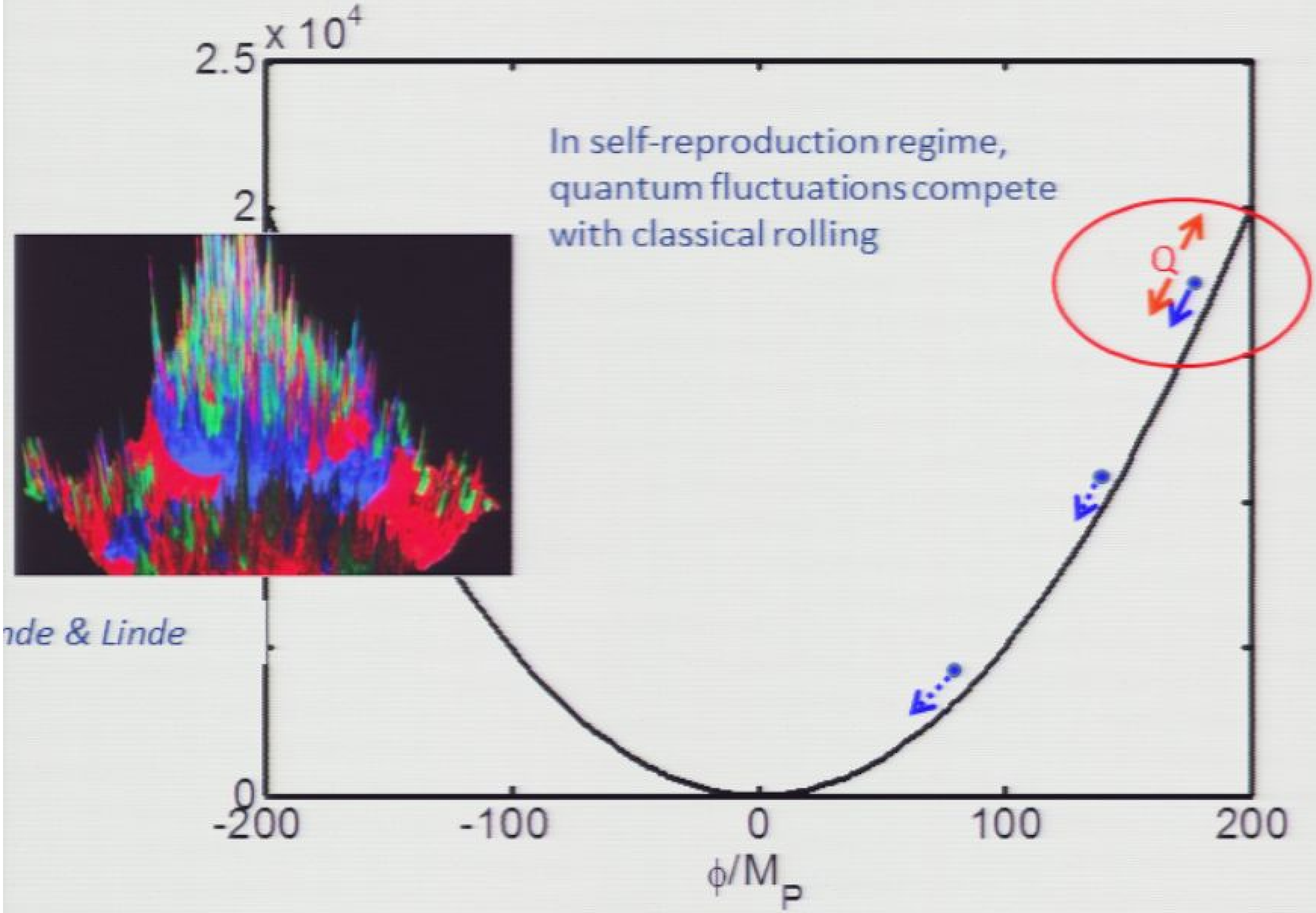
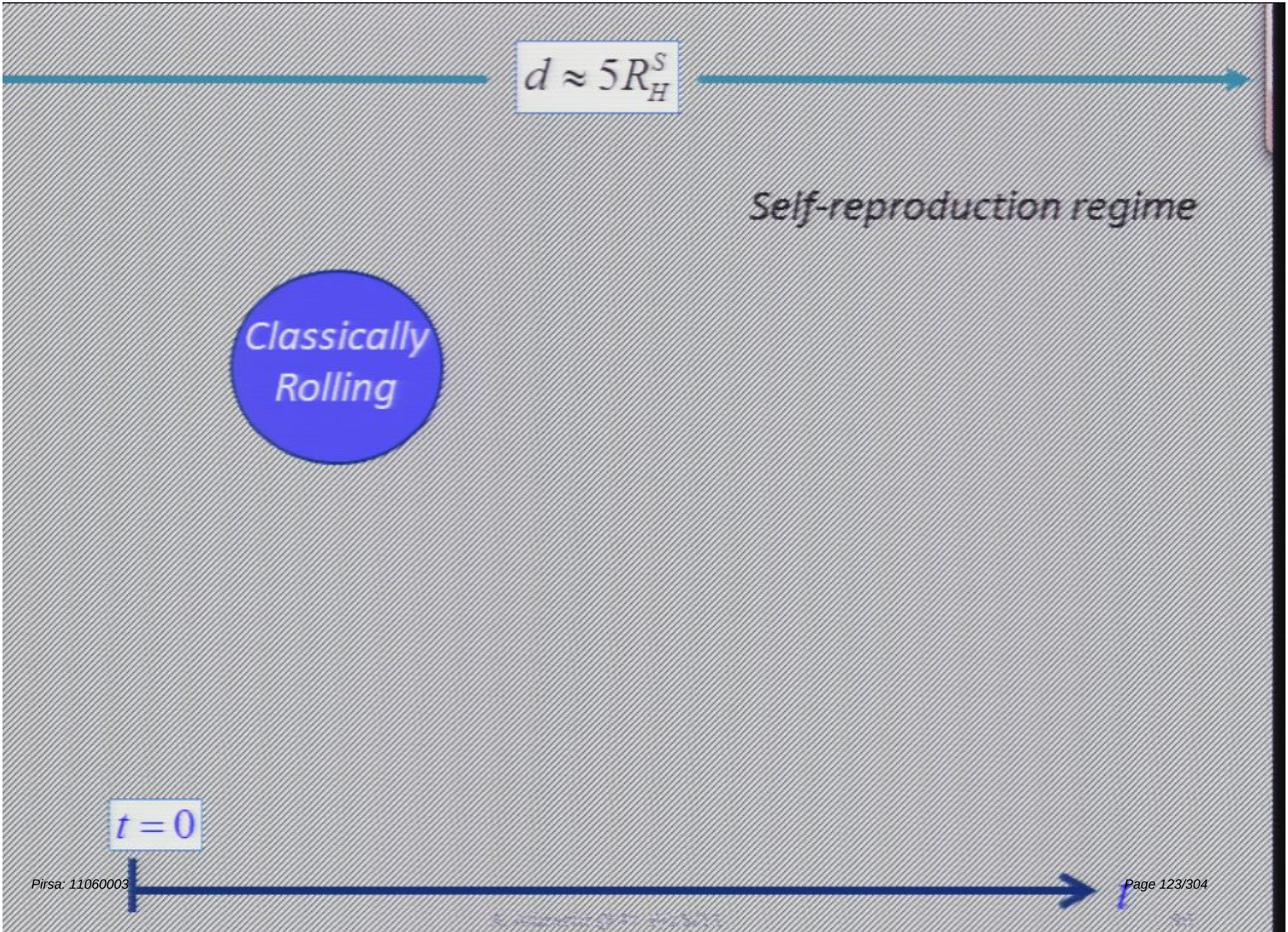
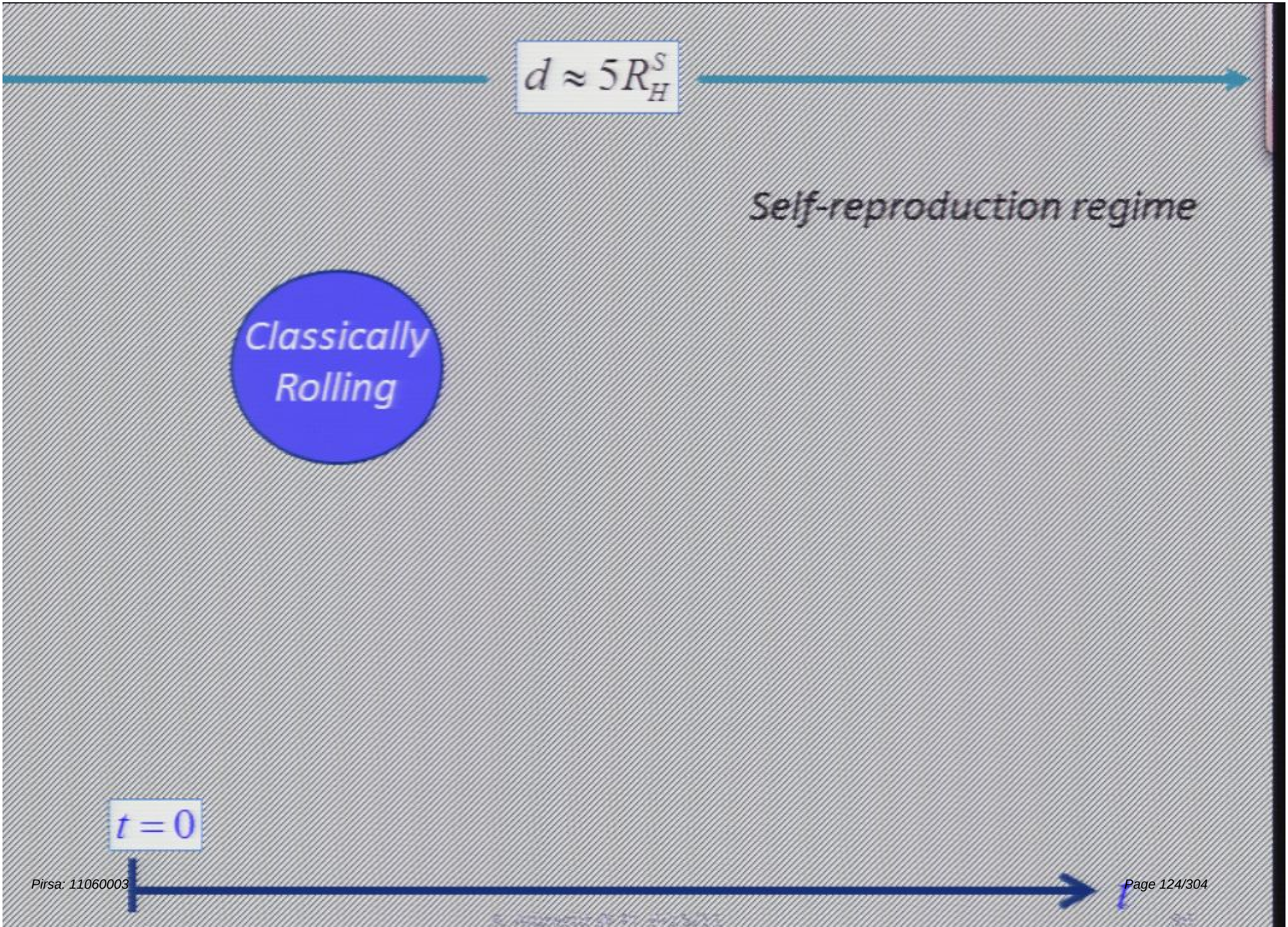
≥ 1 for self-reproduction


In self-reproduction regime,
quantum fluctuations compete
with classical rolling
Q
2.5
x 10^4
2
0
-200
-100
0
100
200
ϕ/M_P
nde & Linde


$d \approx 5R_H^S$
Self-reproduction regime
Classically Rolling
$t = 0$
t



$d \approx 5R_H^S$
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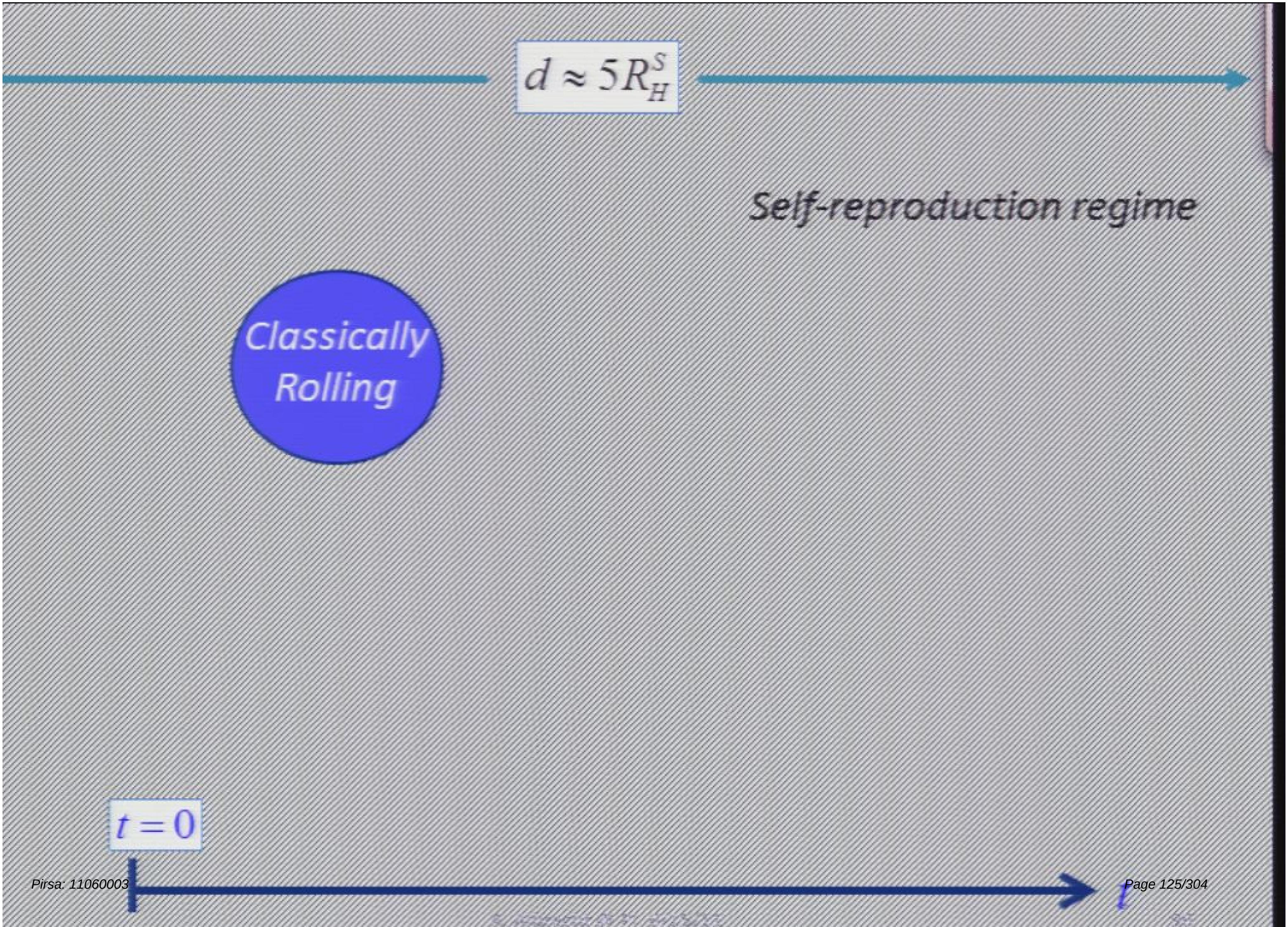
t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Self-reproduction regime
Classically Rolling
$t = 0$
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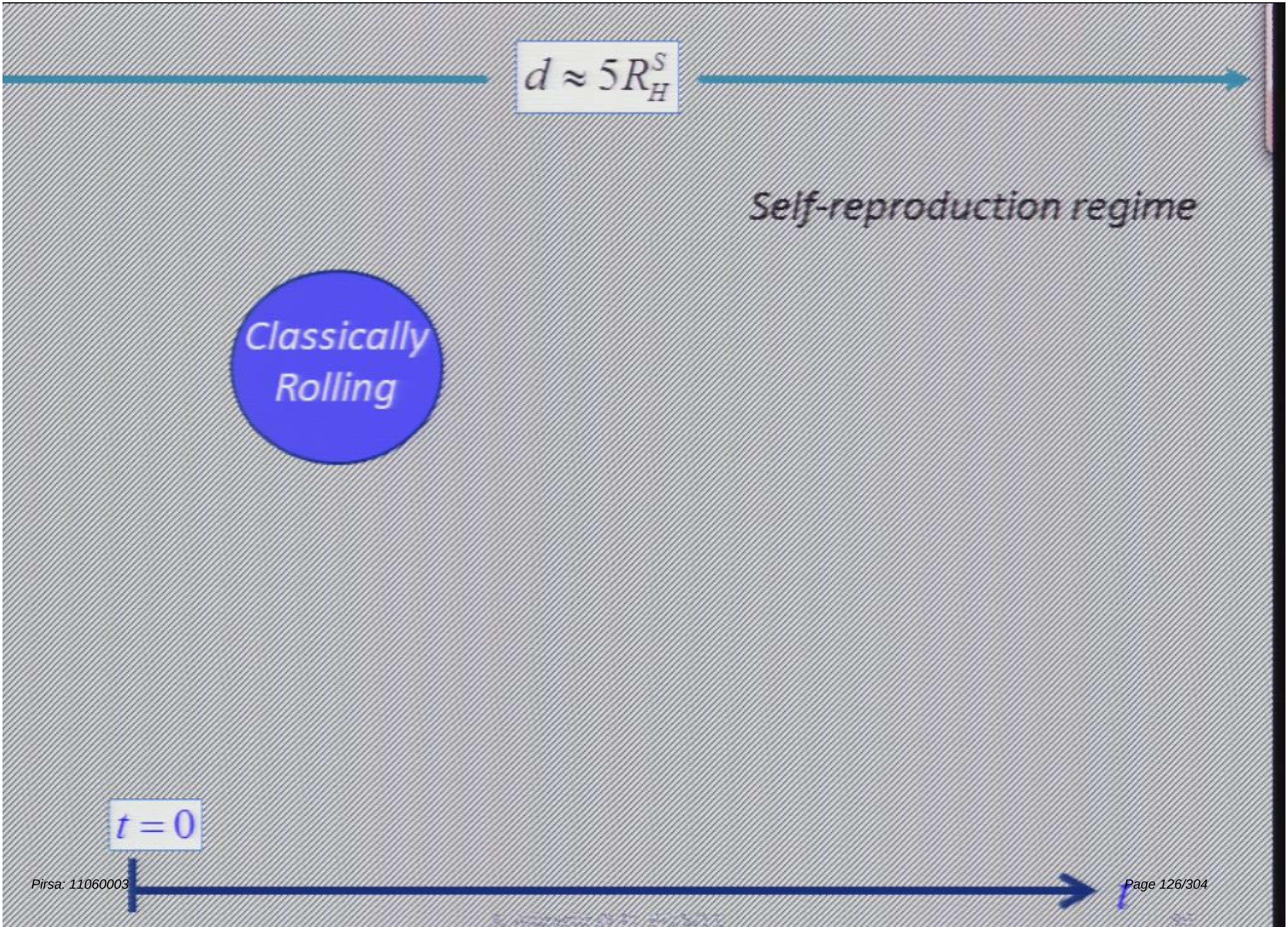
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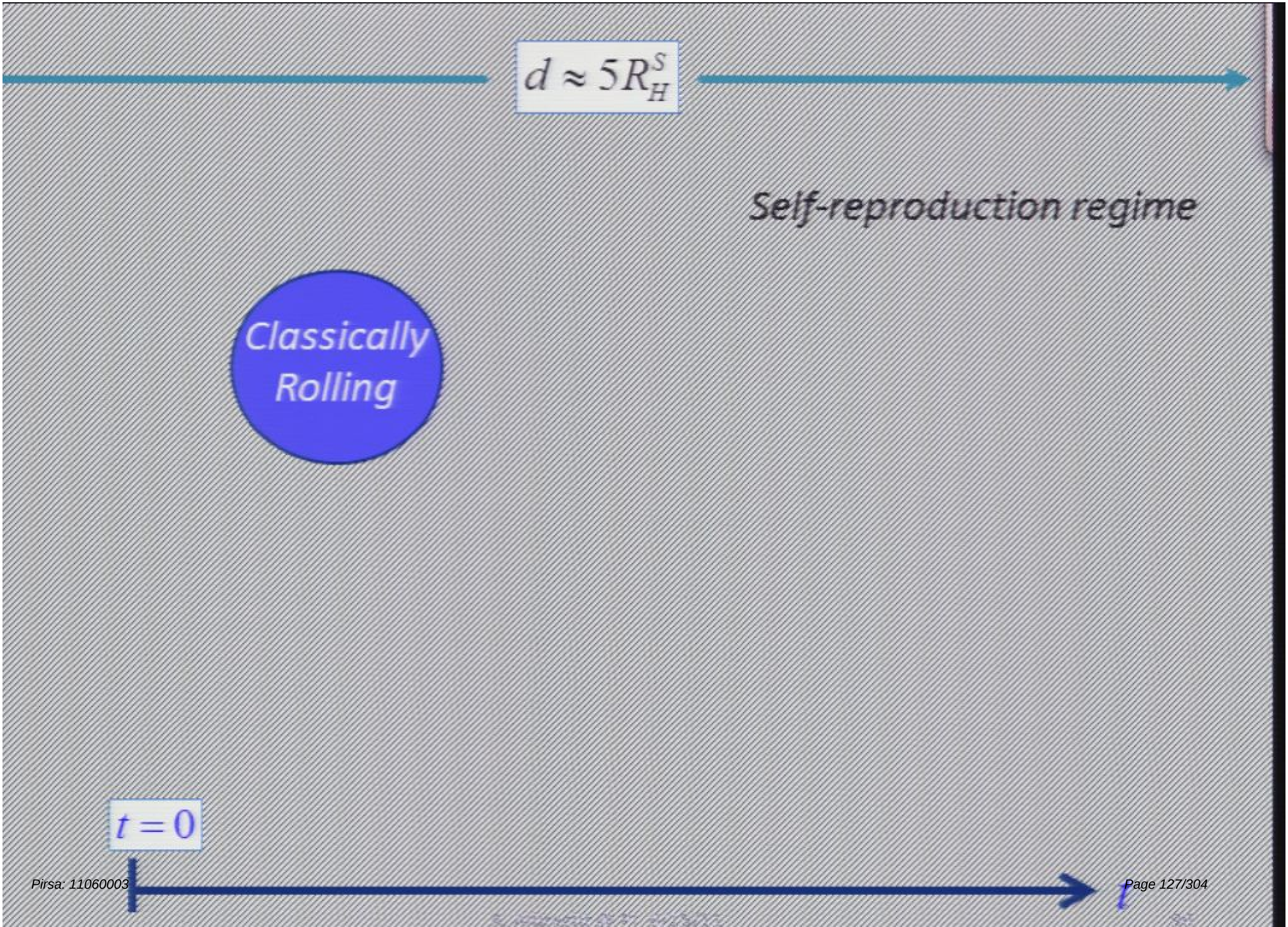
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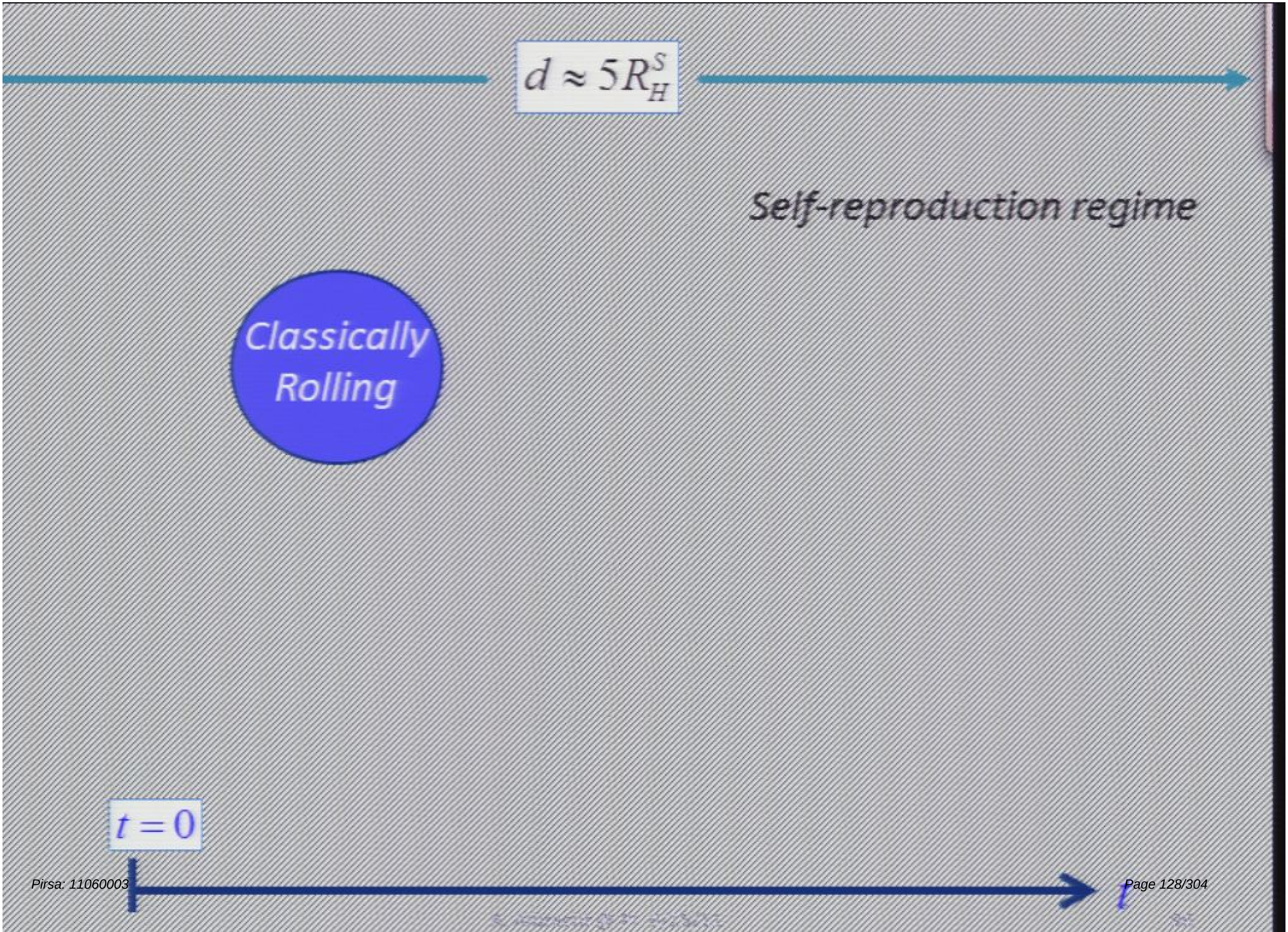
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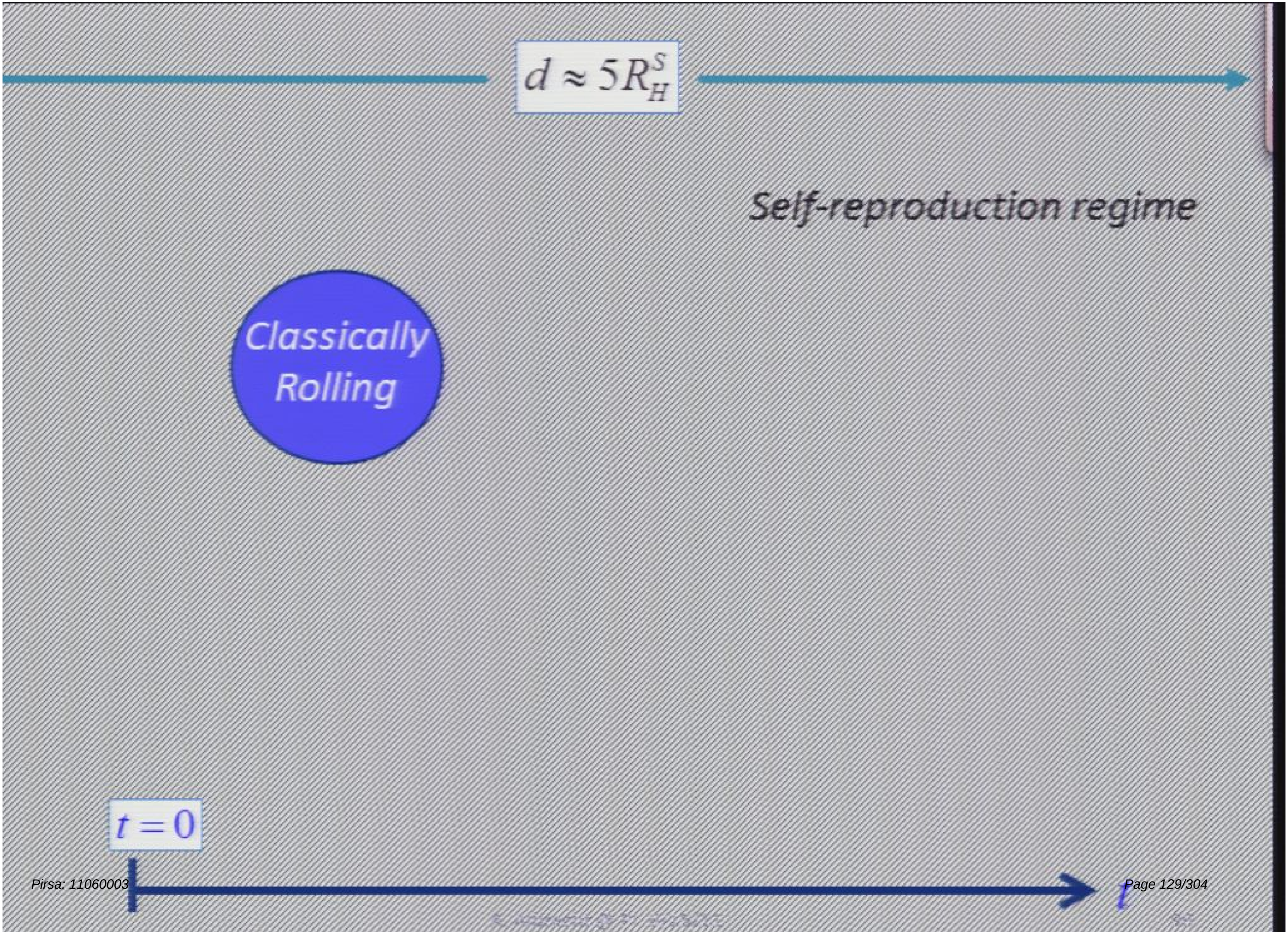
Self-reproduction regime
Classically Rolling
$t = 0$
t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Rolling
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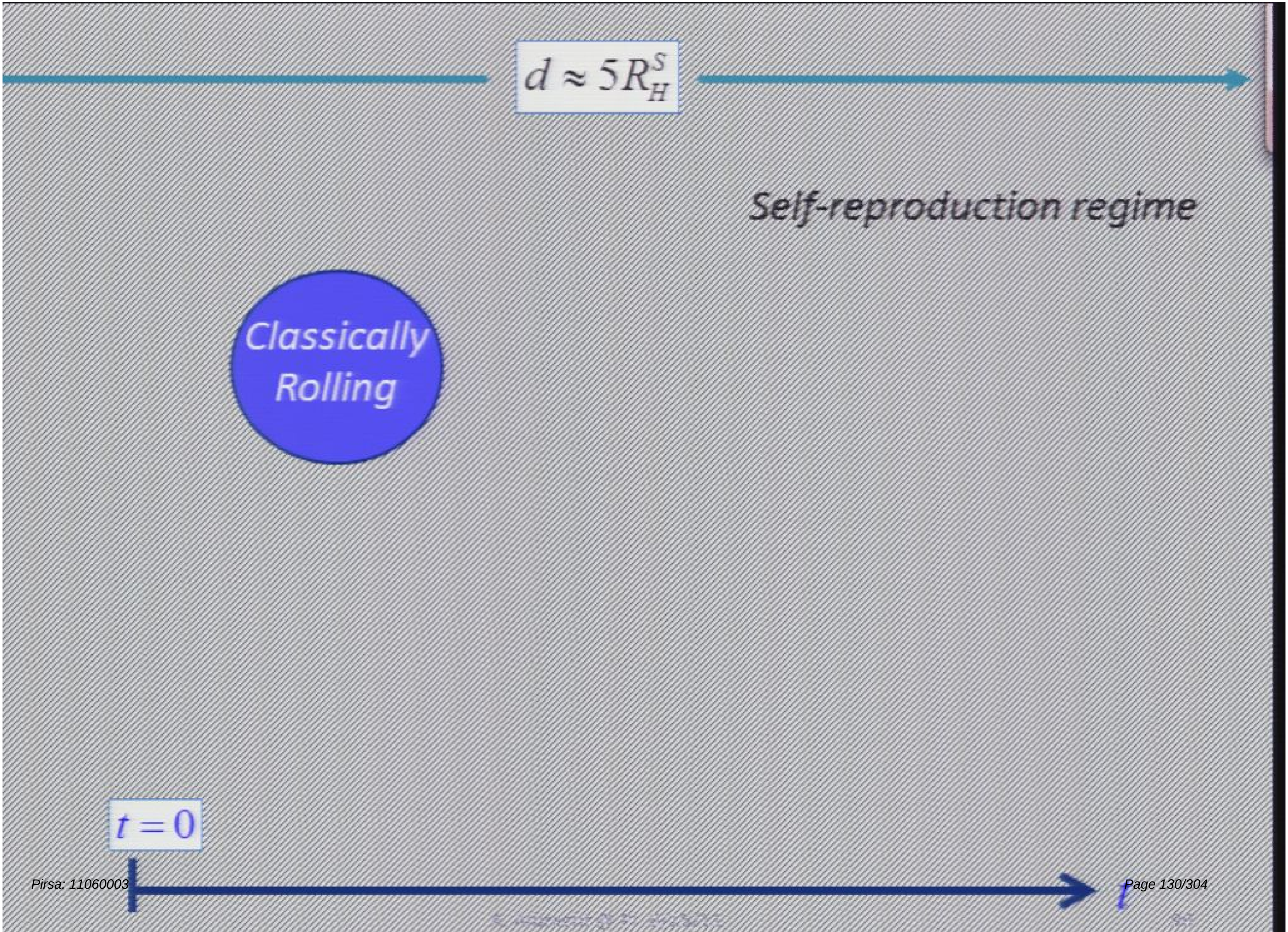
t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$t = 0$
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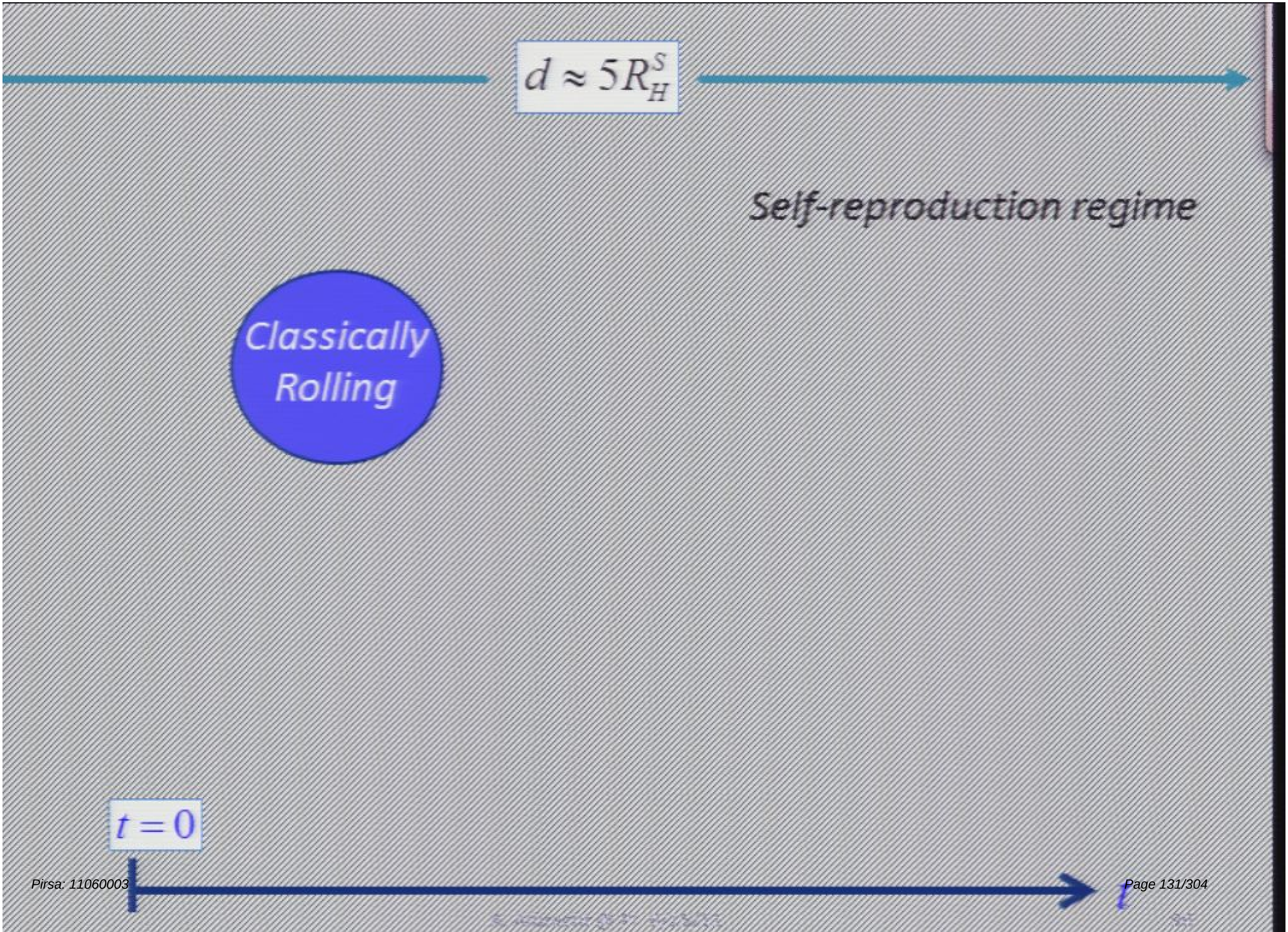
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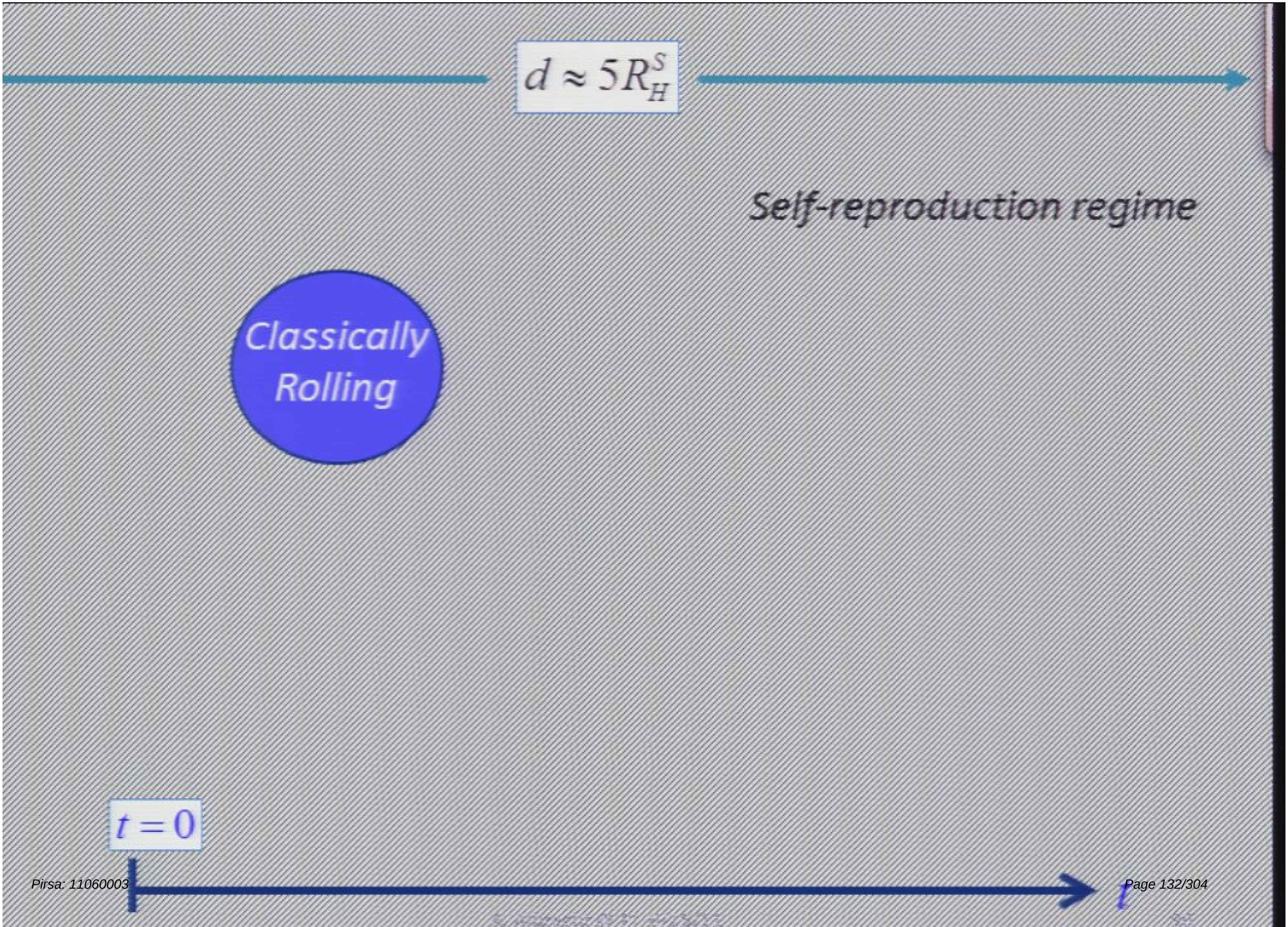

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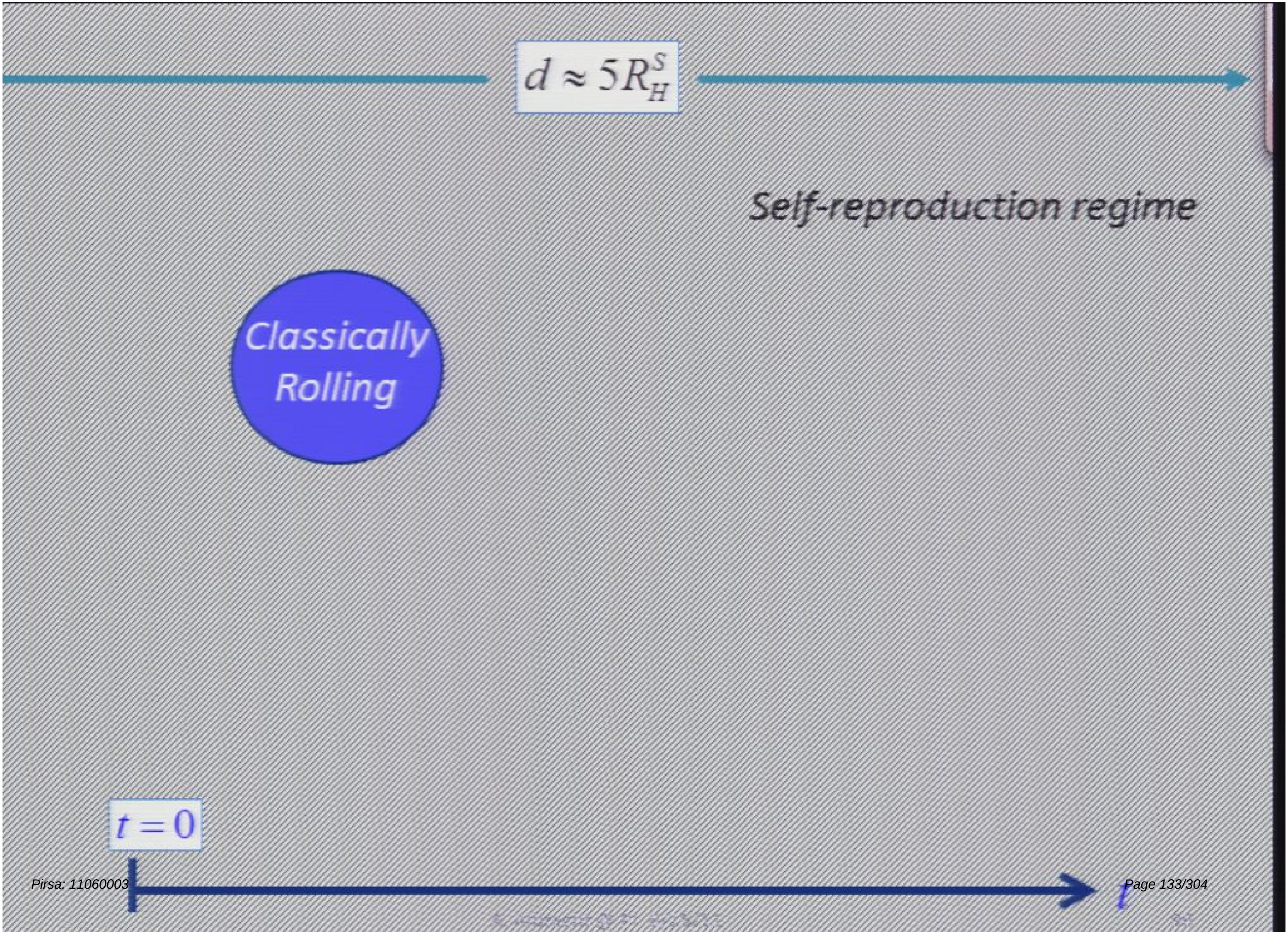
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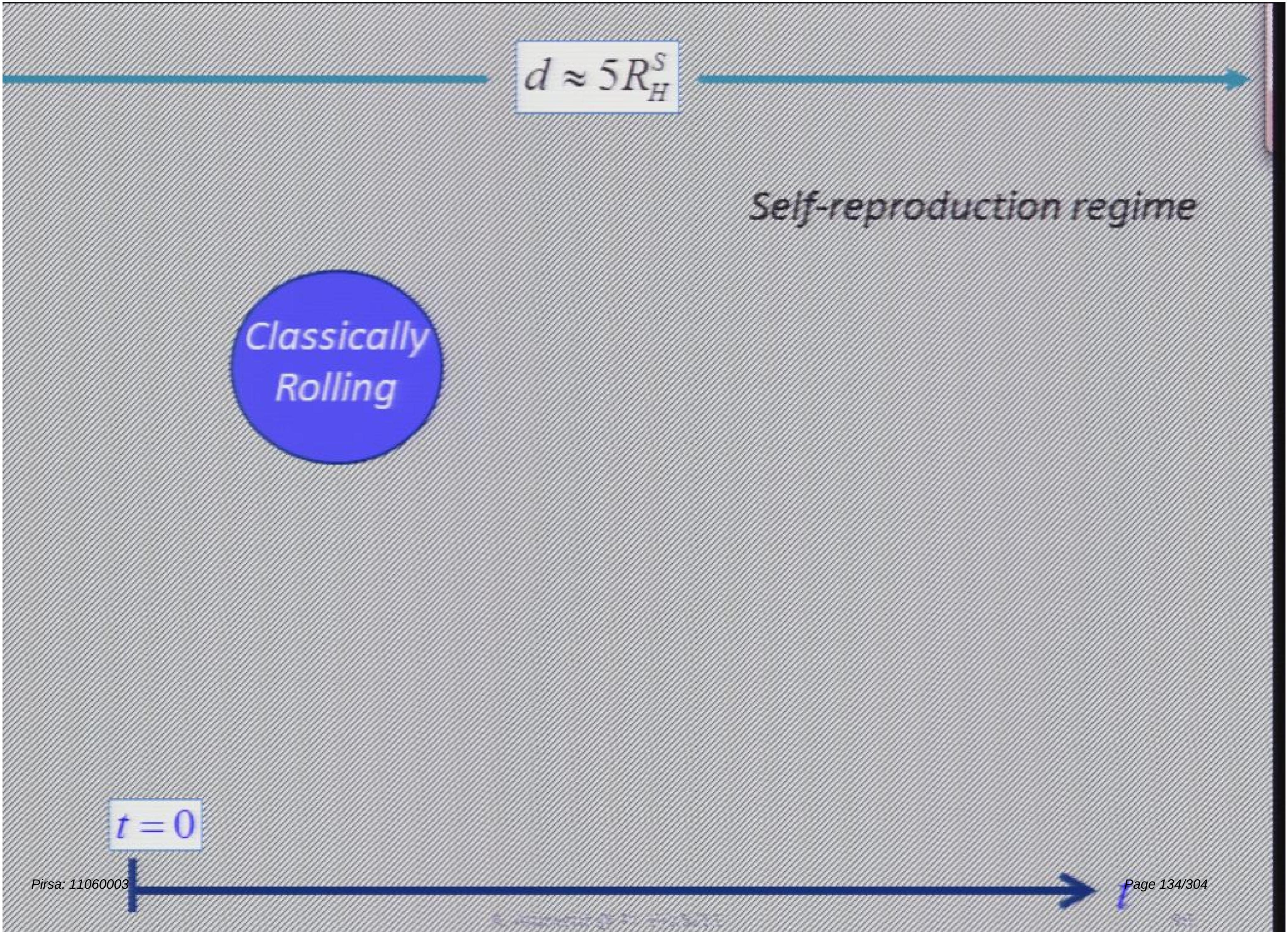
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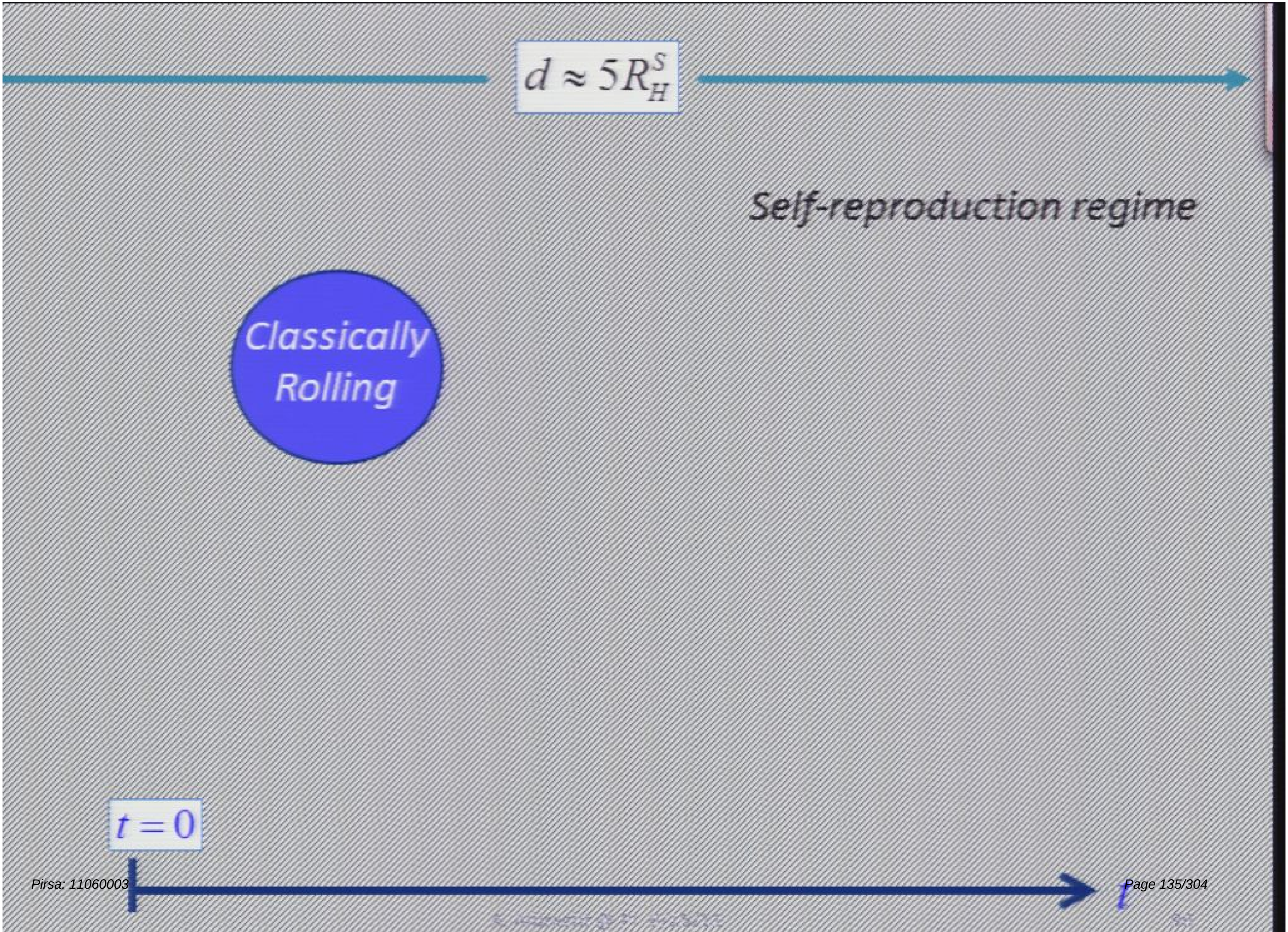
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Self-reproduction regime
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Rolling
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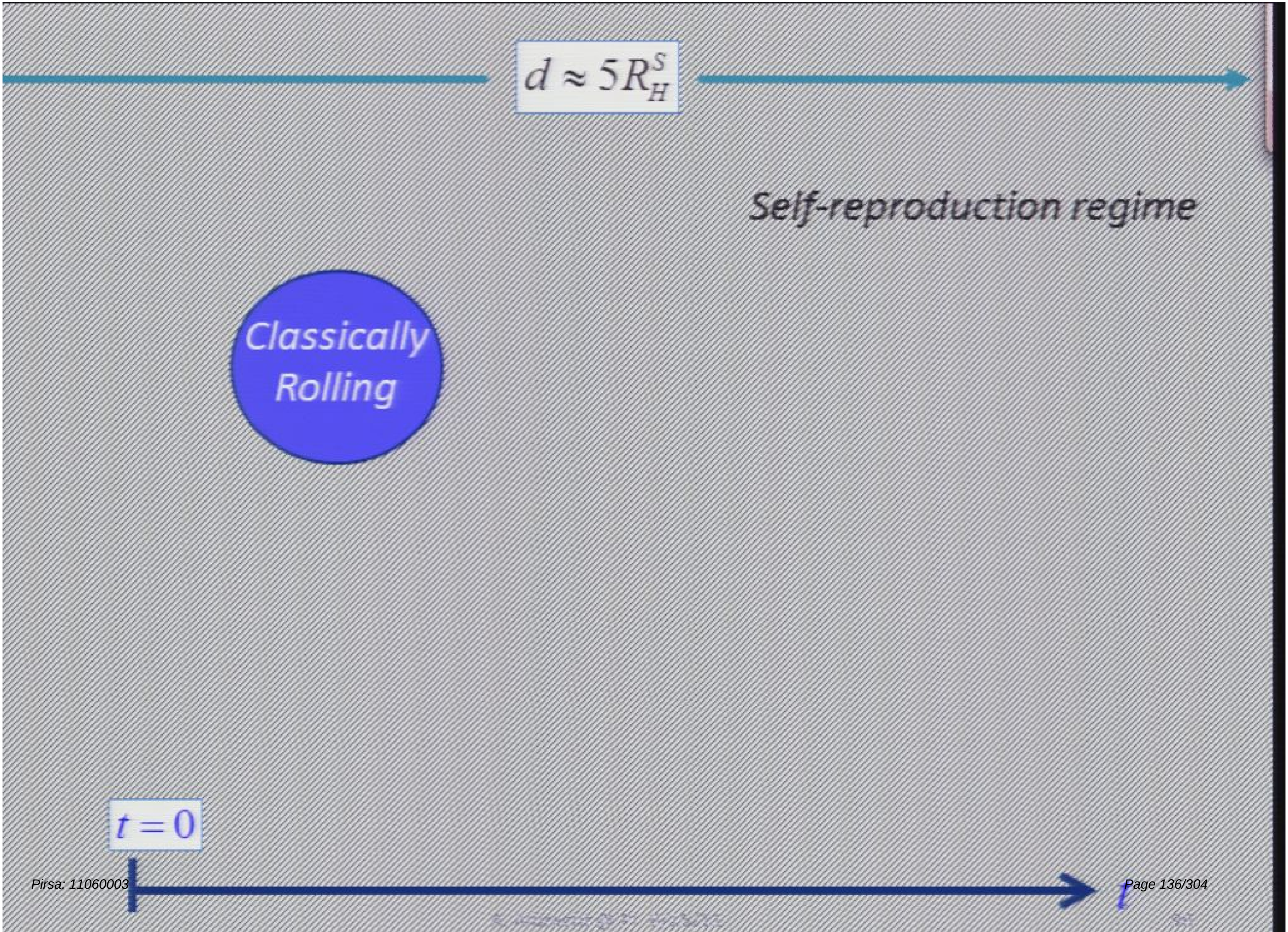
t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Self-reproduction regime
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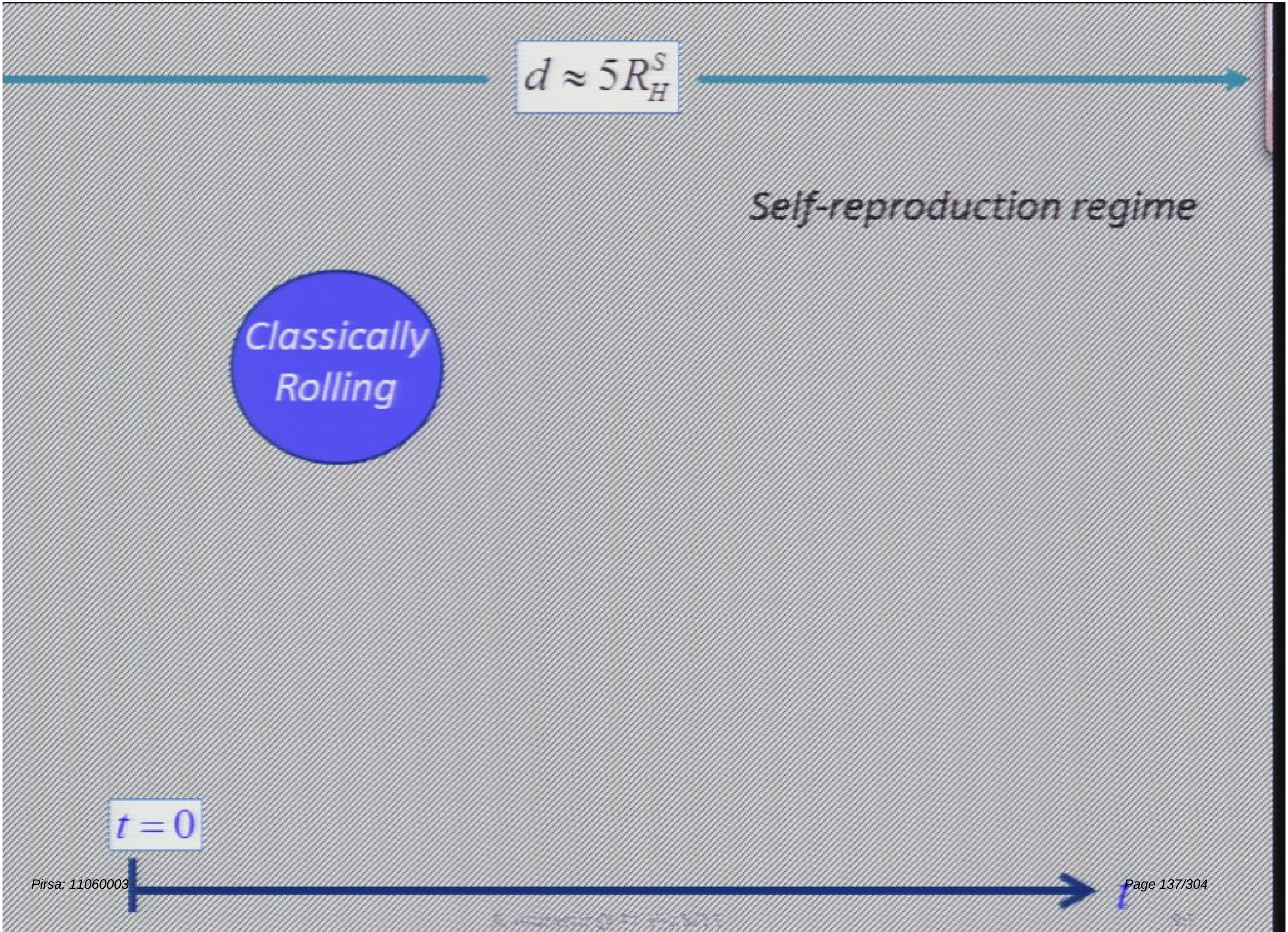
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Self-reproduction regime
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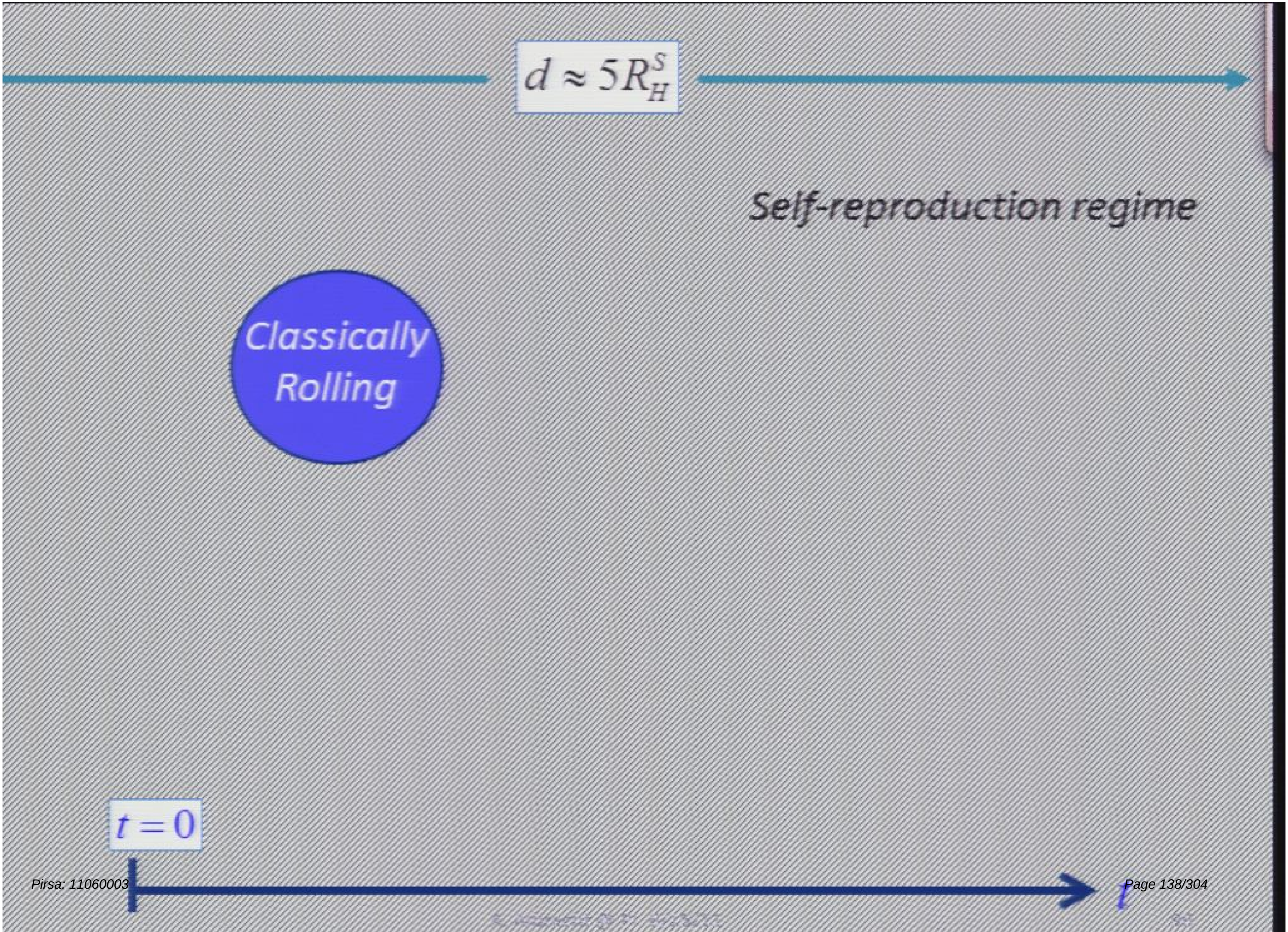
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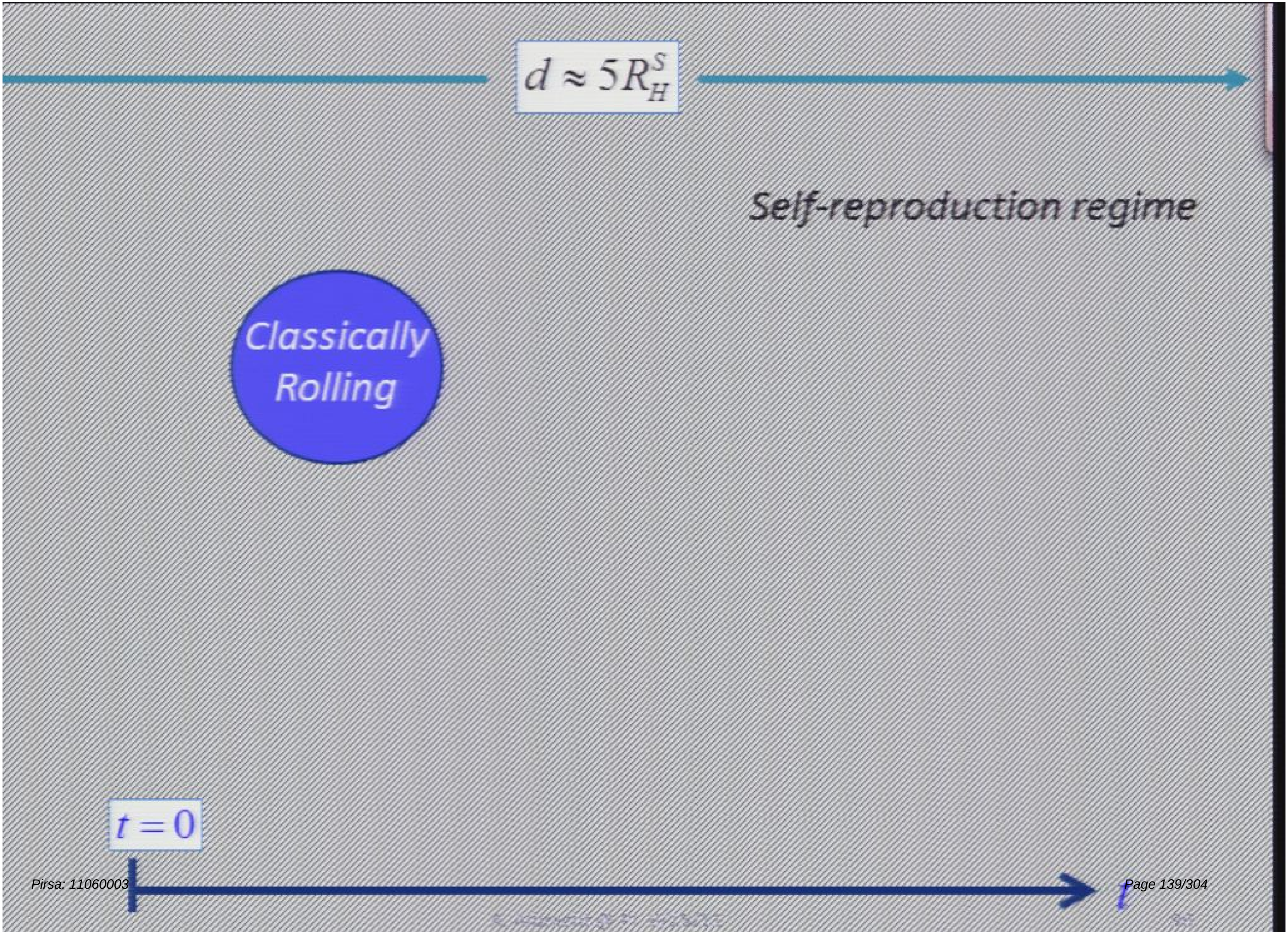

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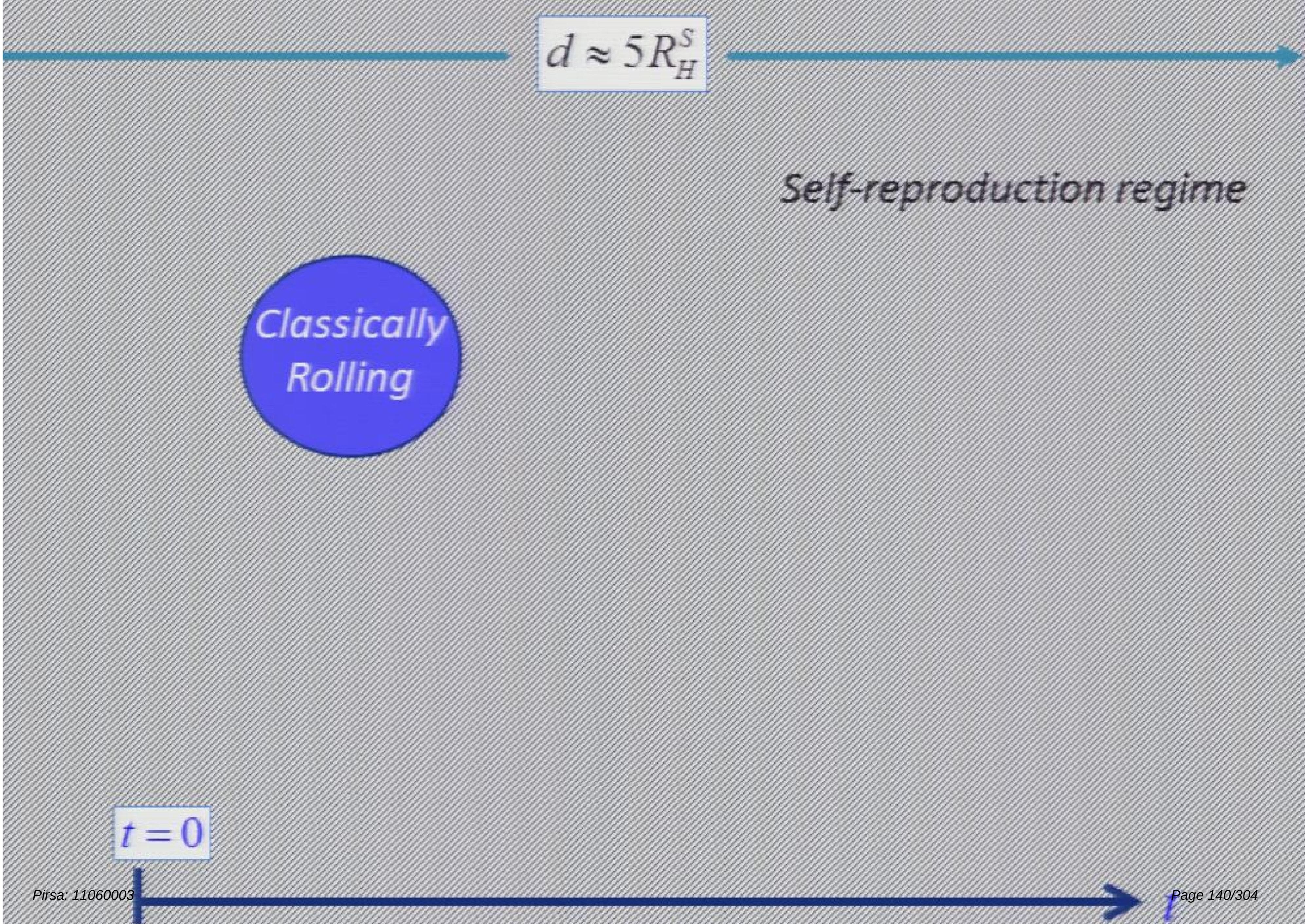
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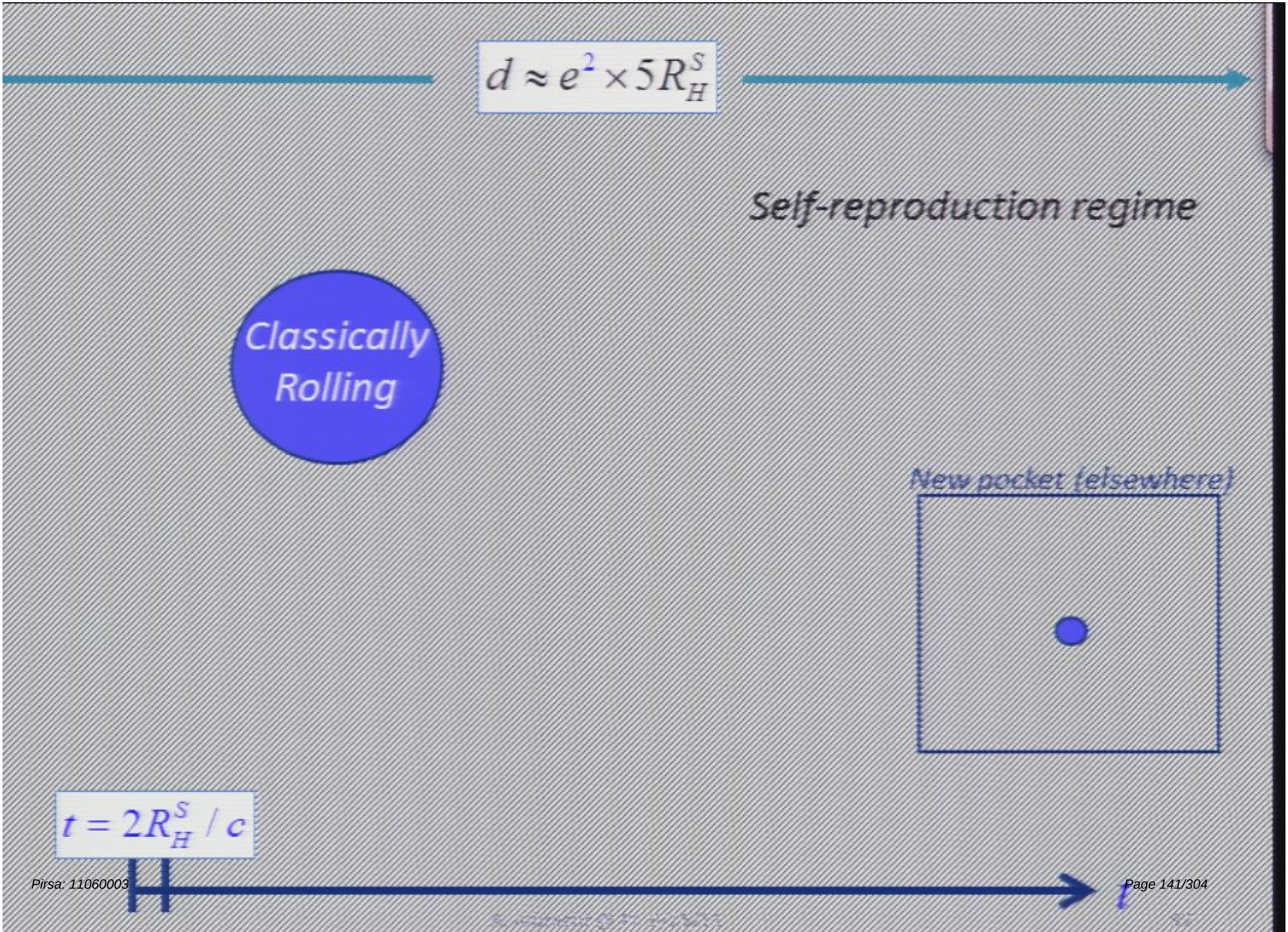
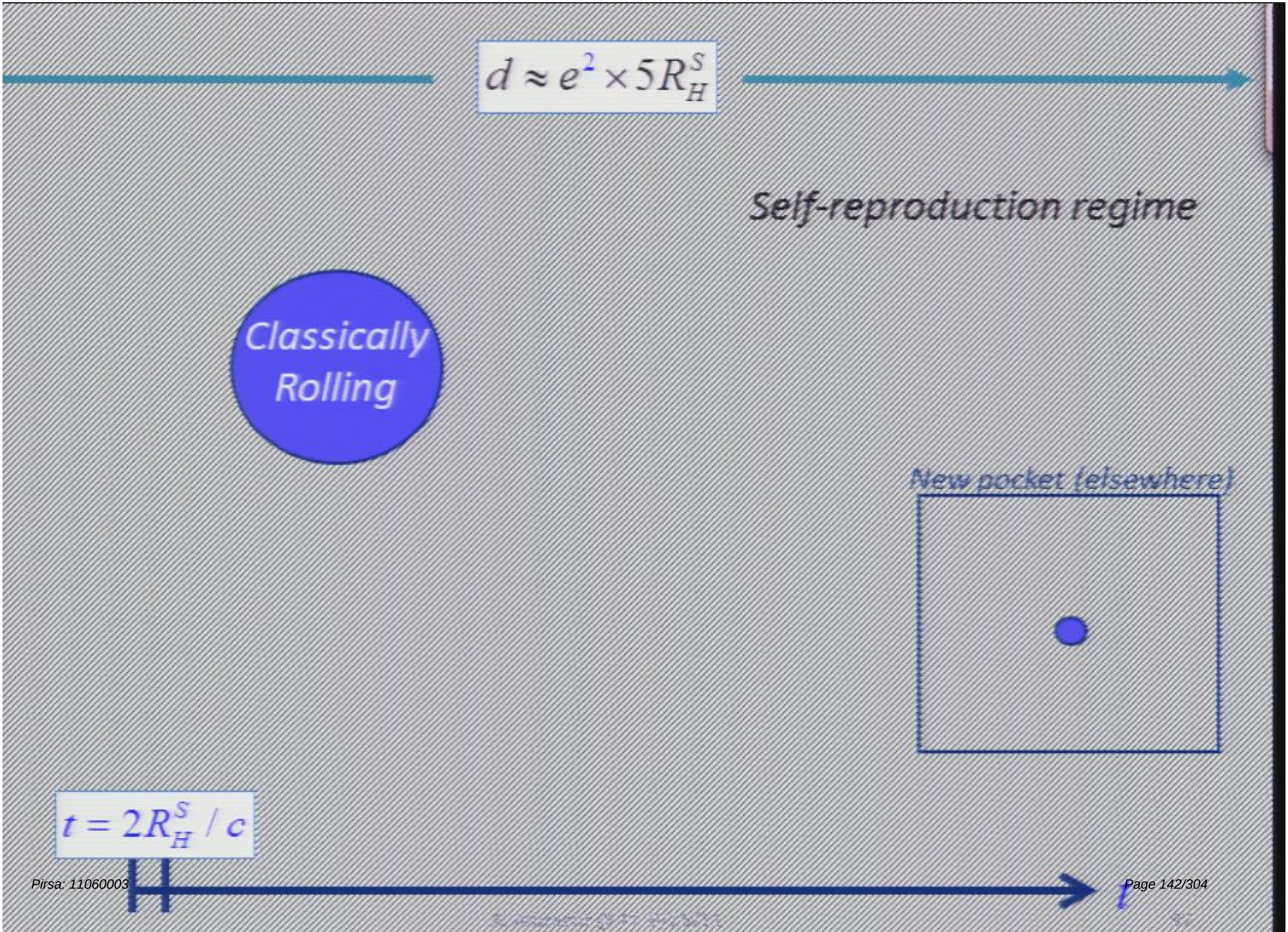
$t=0$
t


$d \approx e^{2} \times 5R_H^S$
Self-reproduction regime
Classically Rolling
New pocket (elsewhere)
$t = 2R_H^S / c$
t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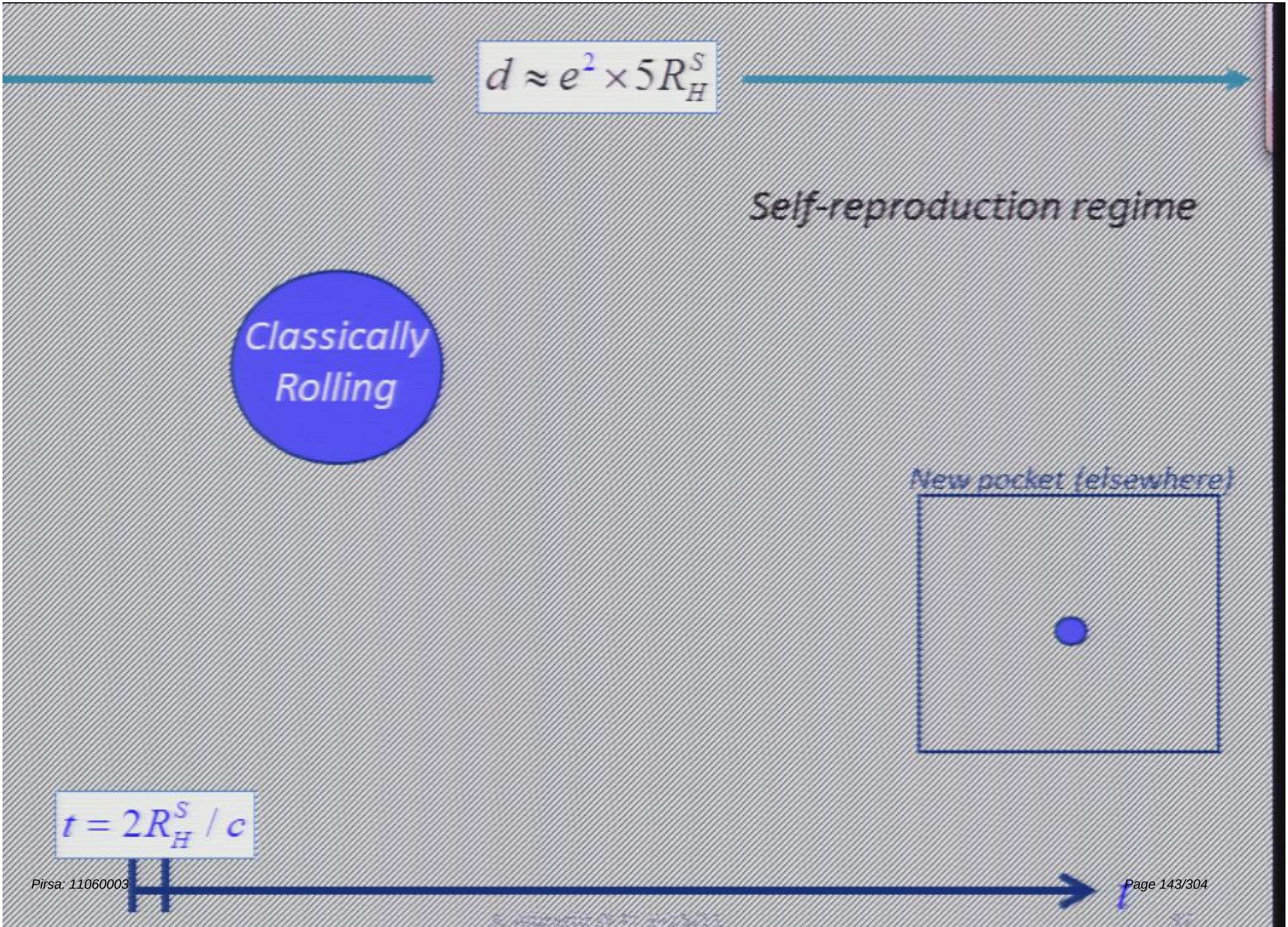
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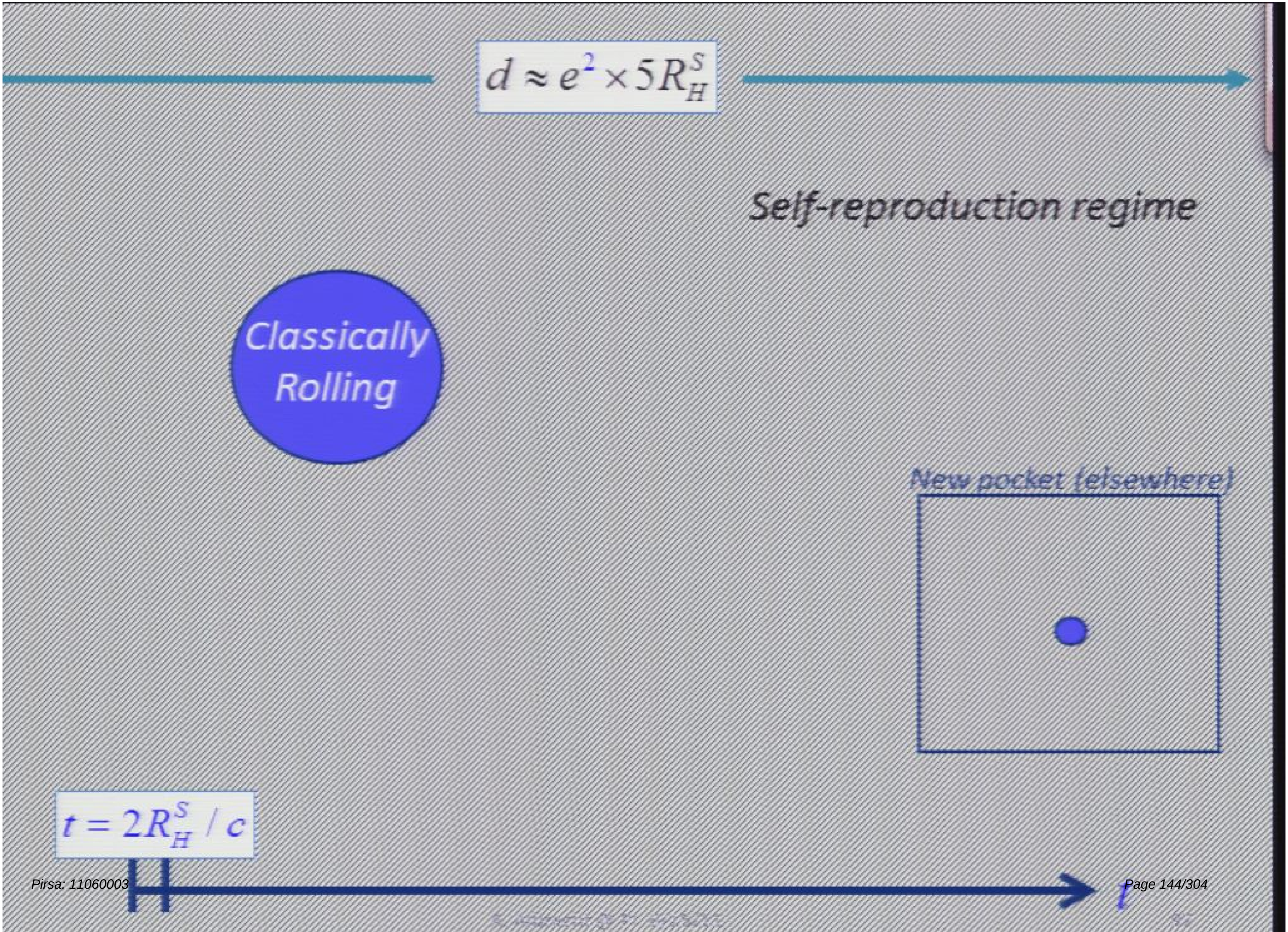
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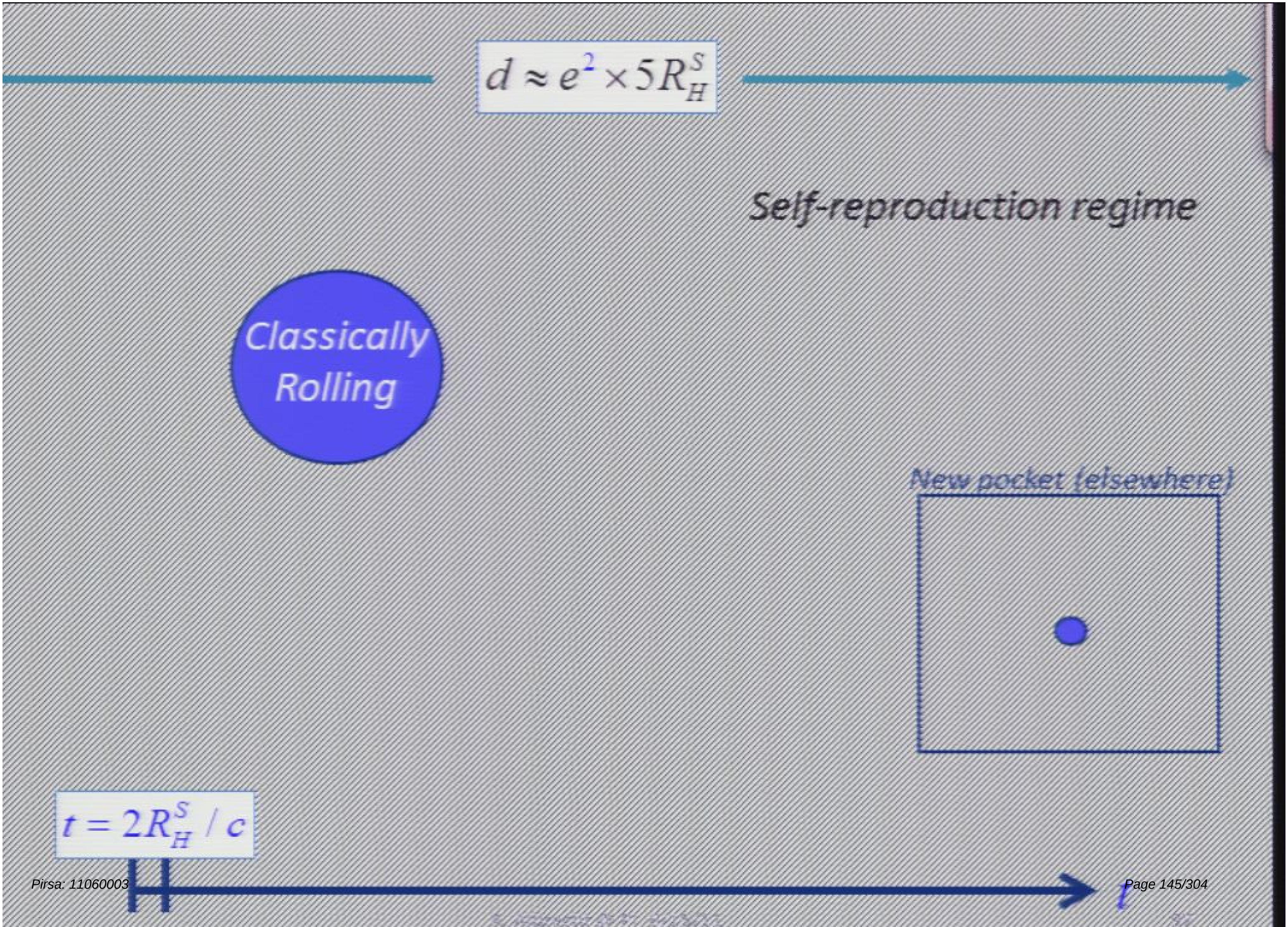
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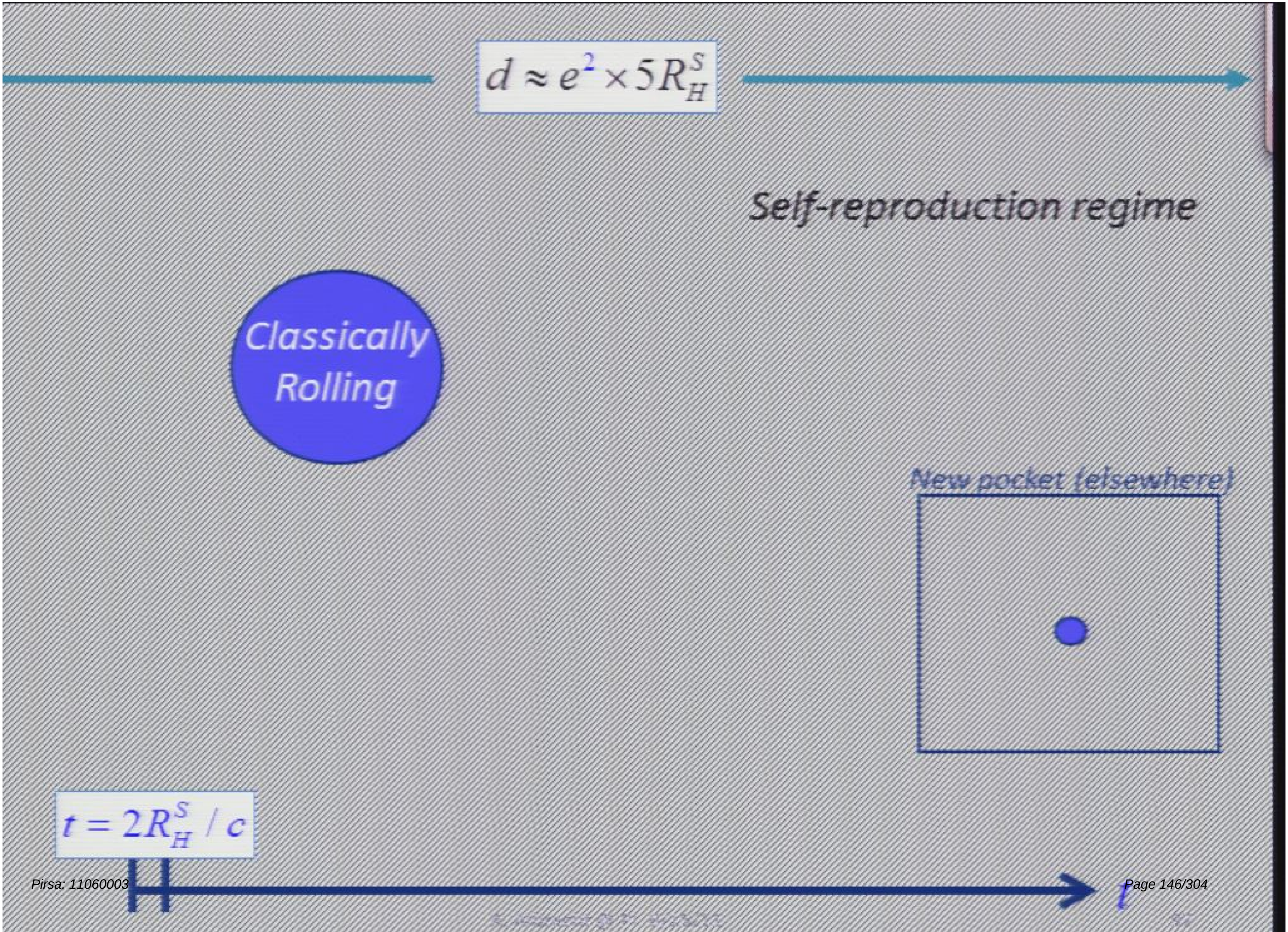
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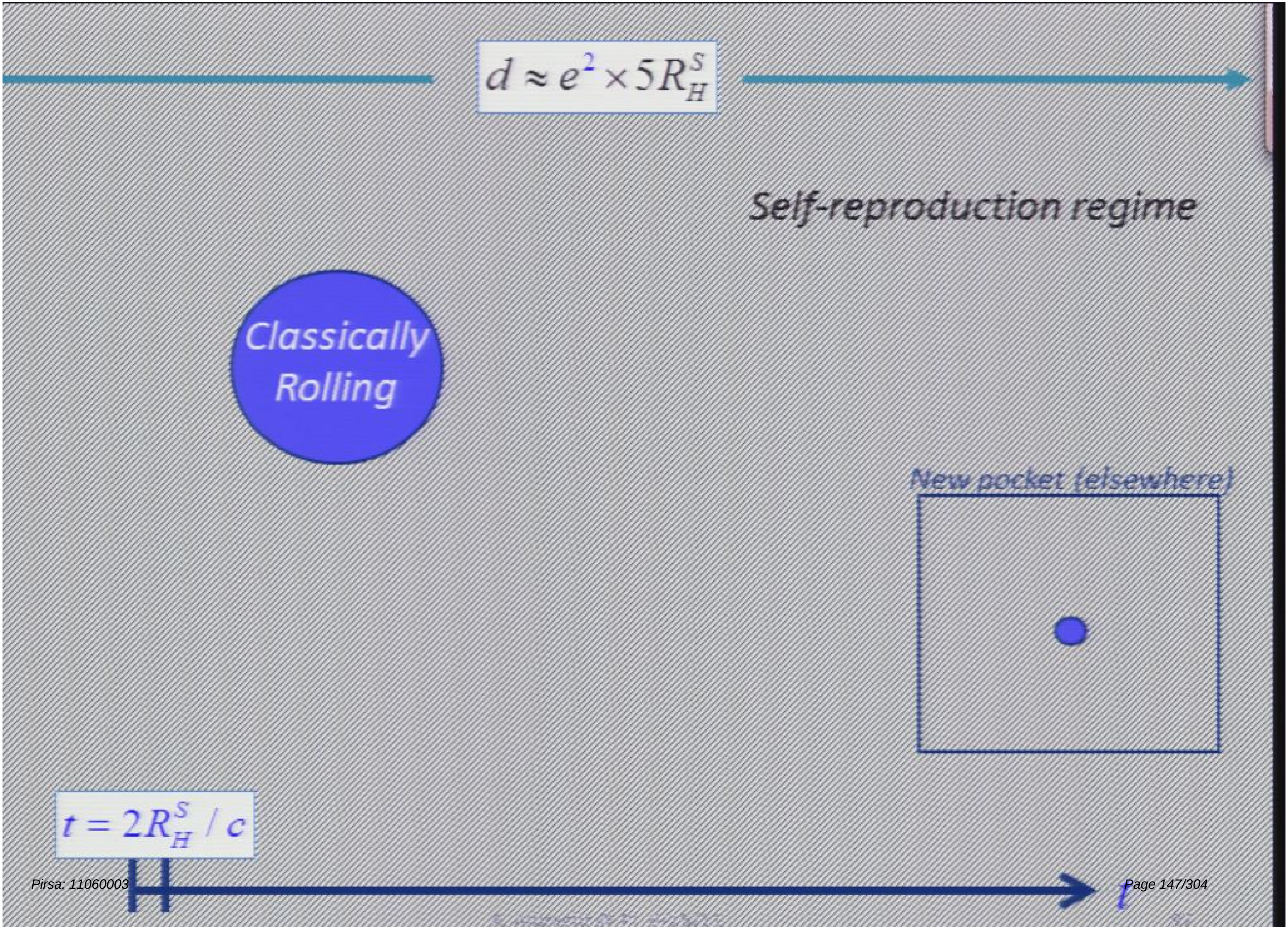
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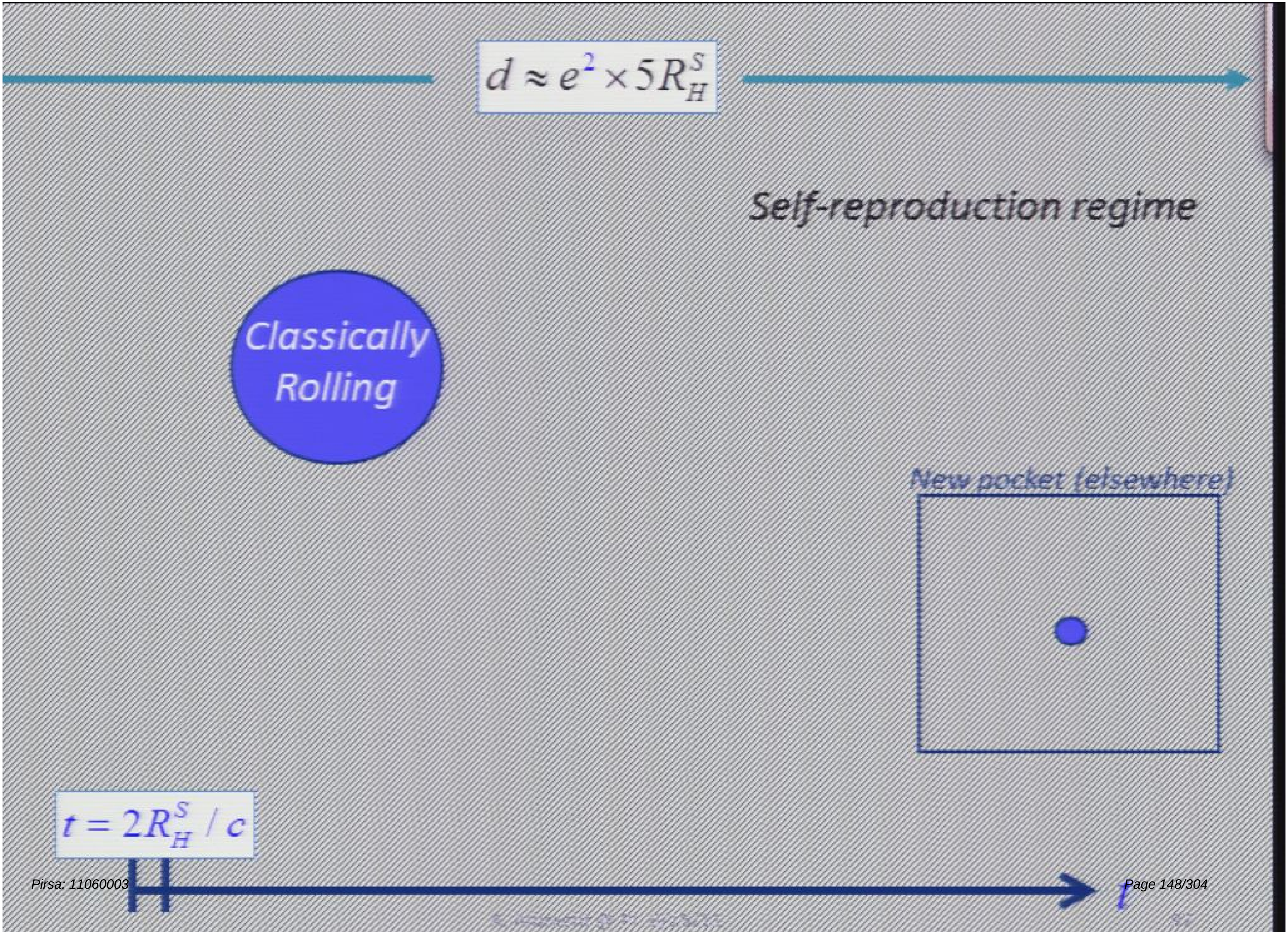
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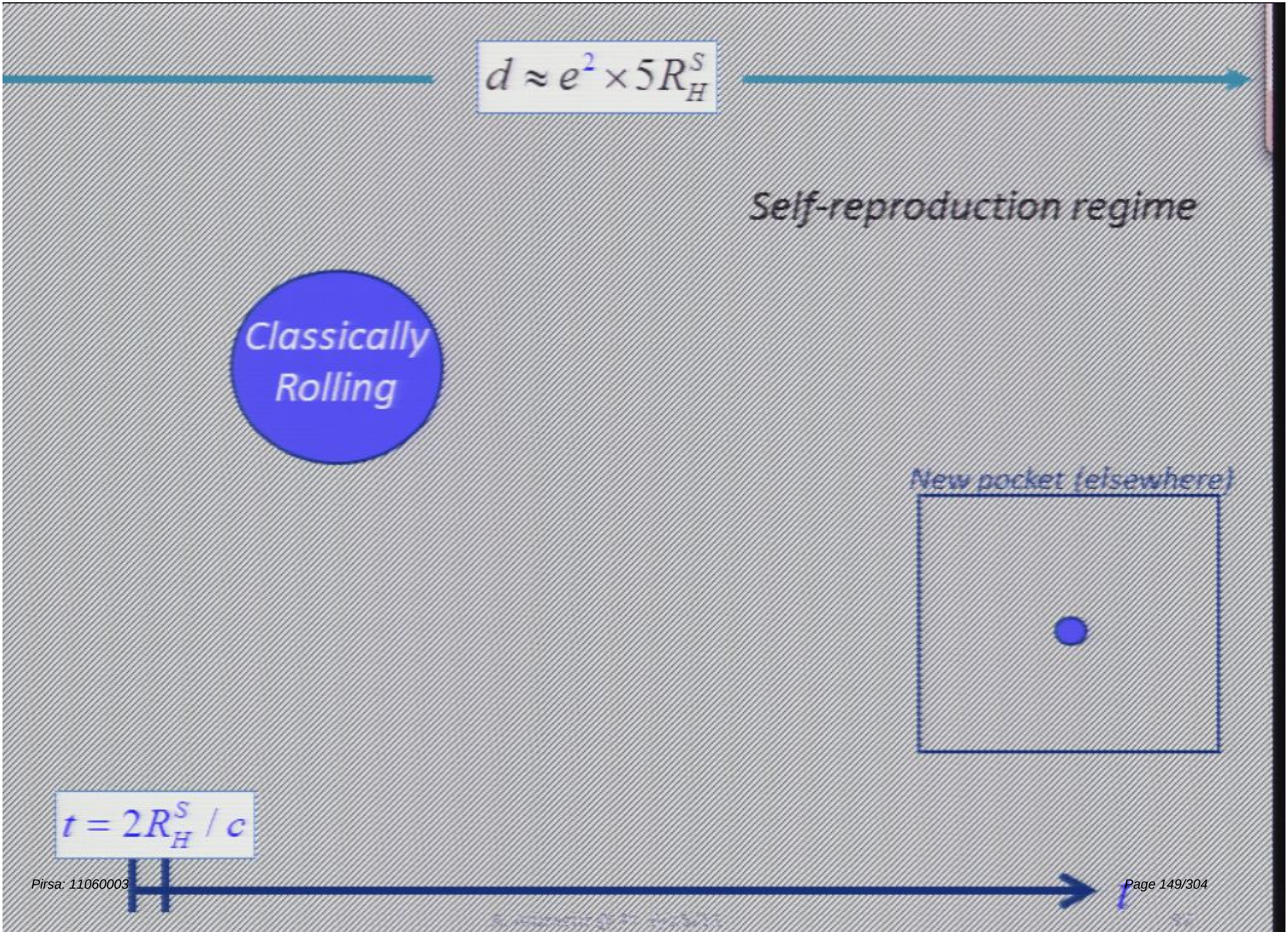
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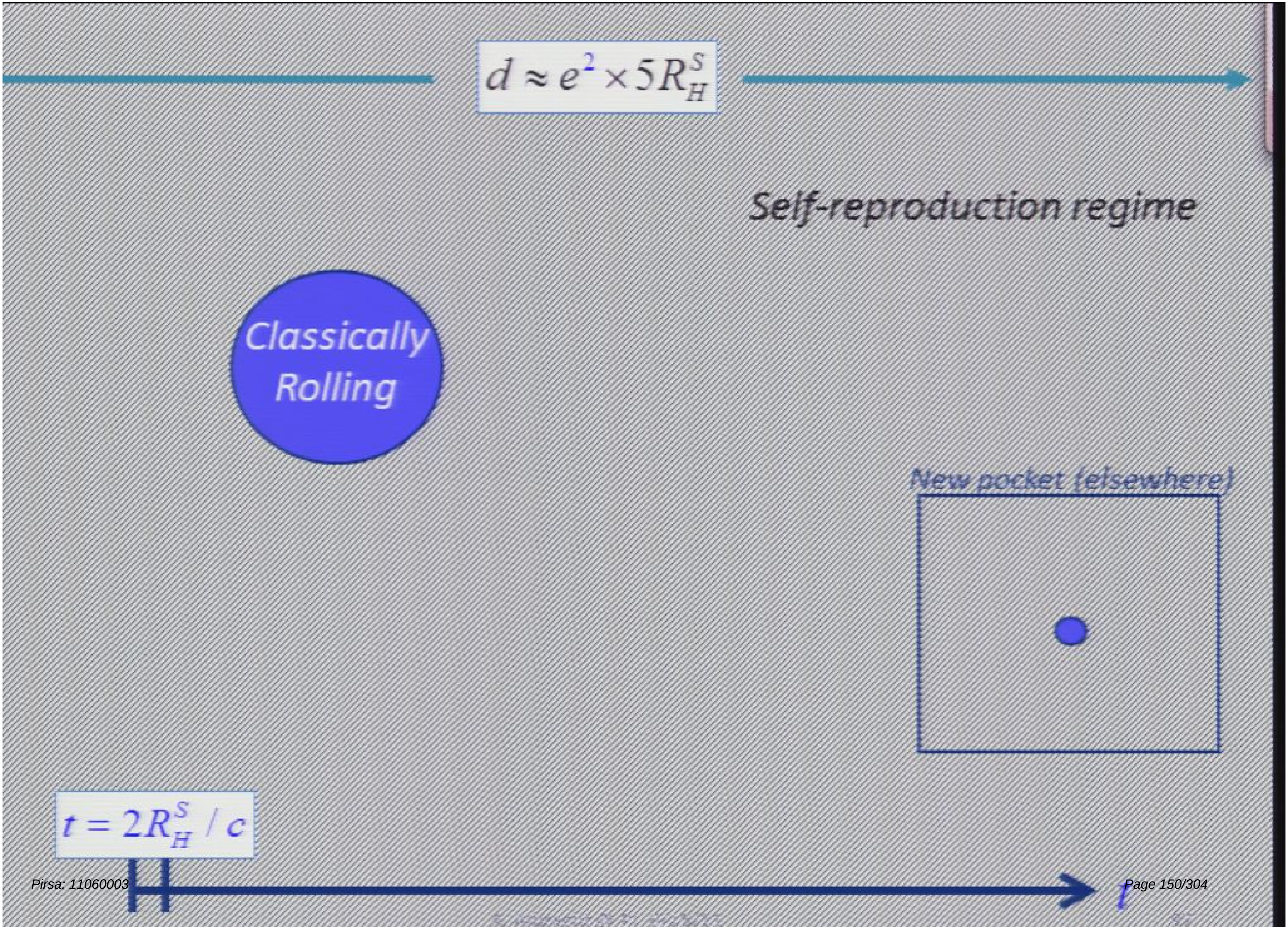
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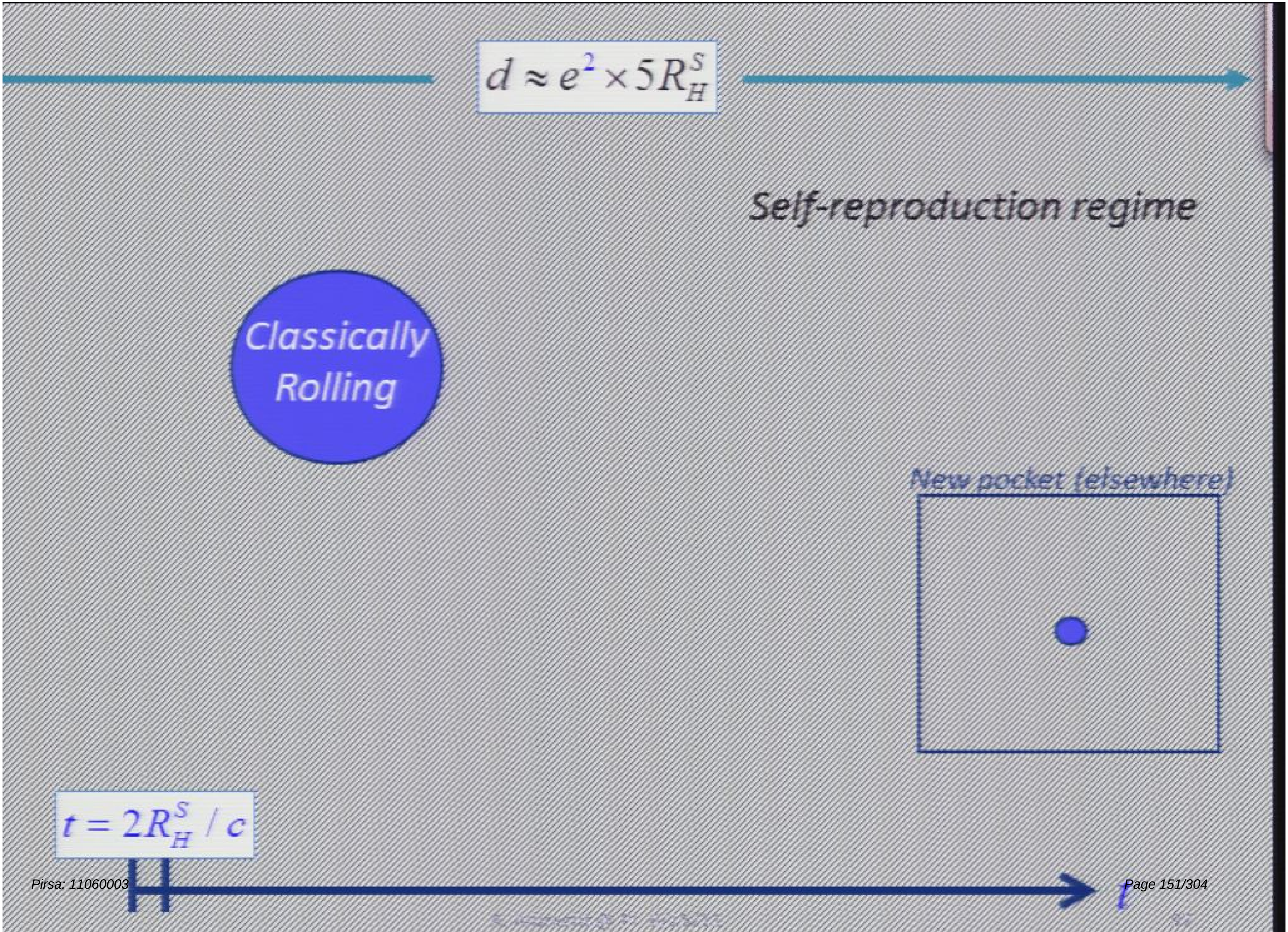
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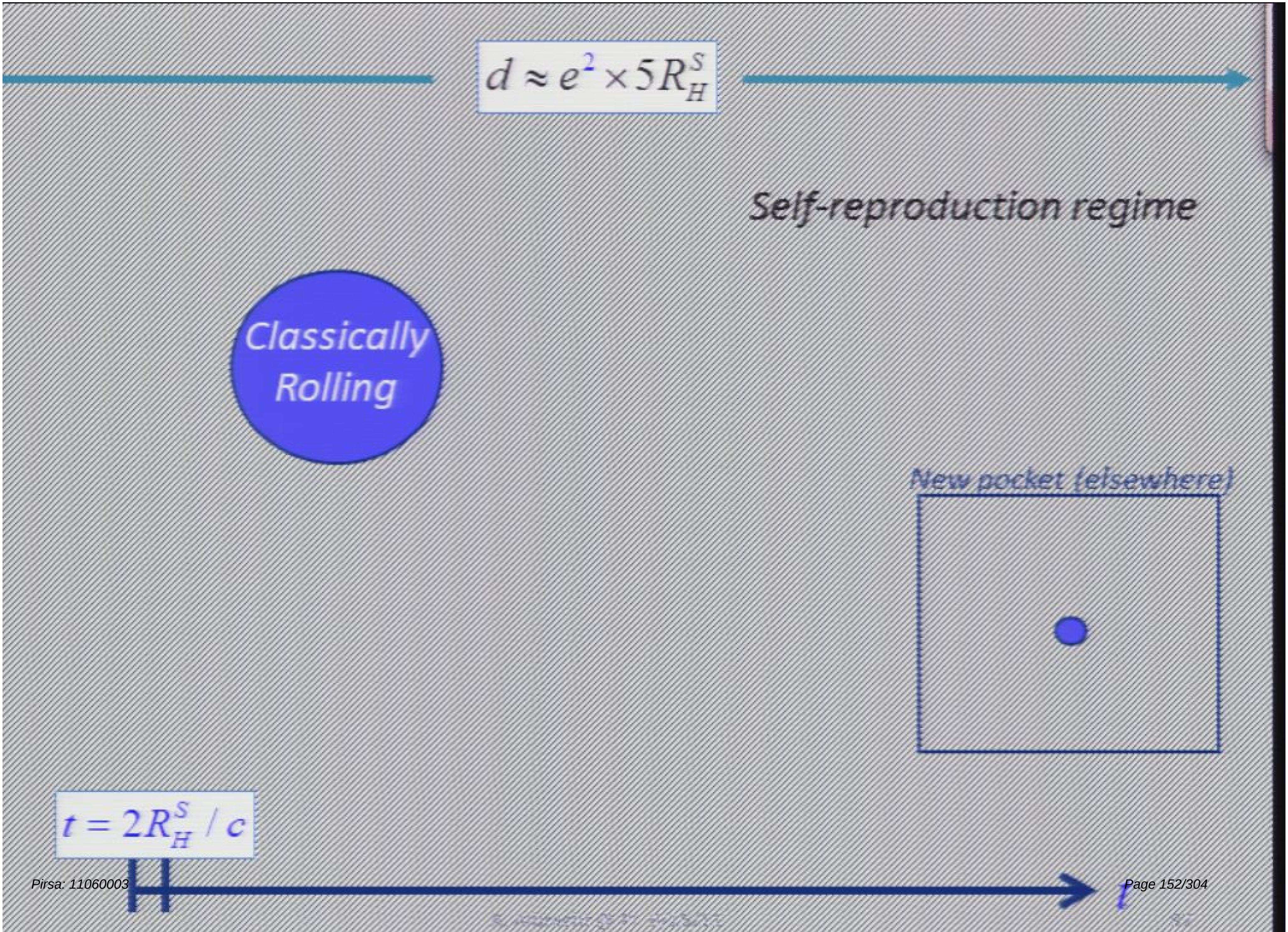
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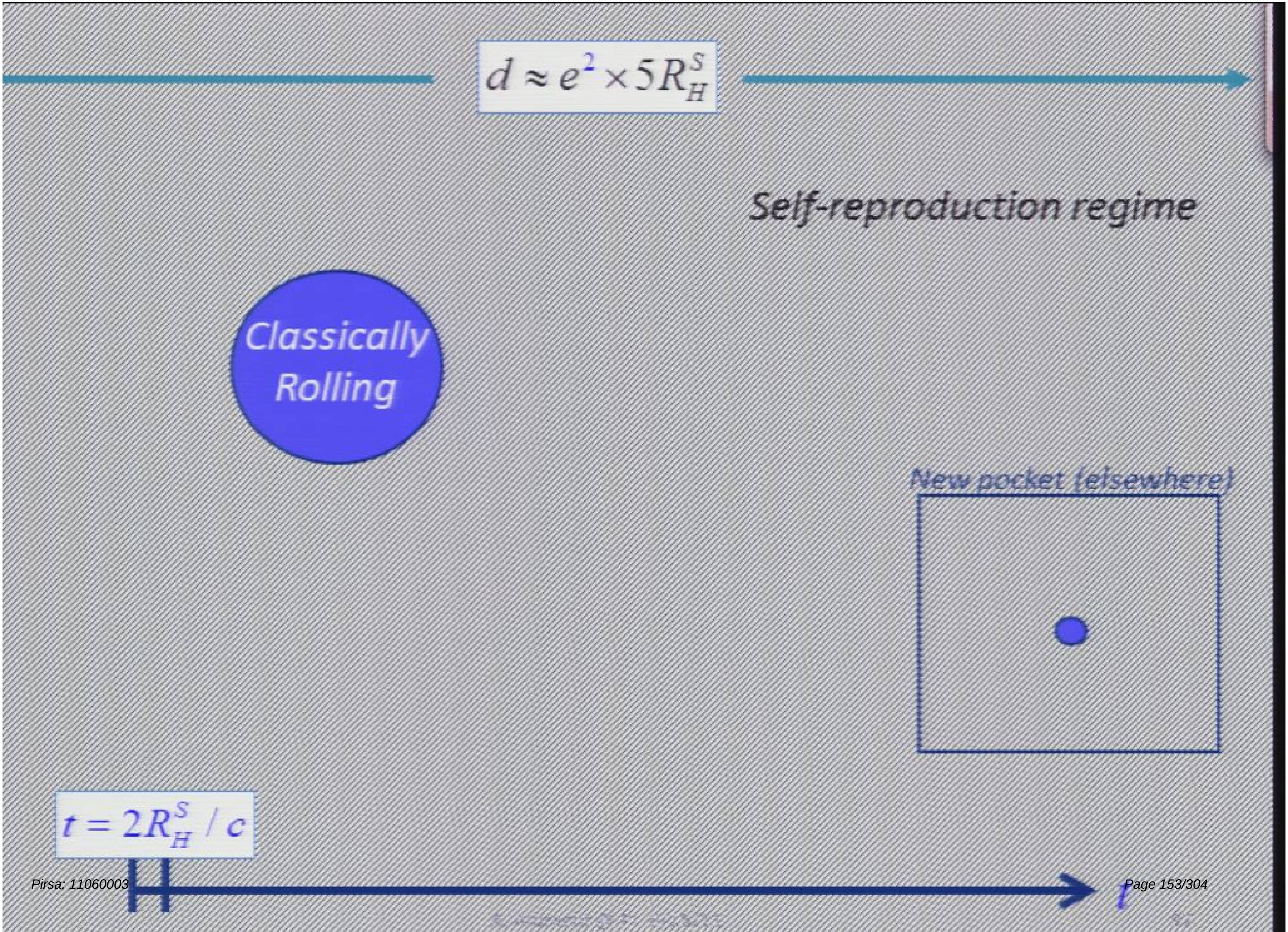
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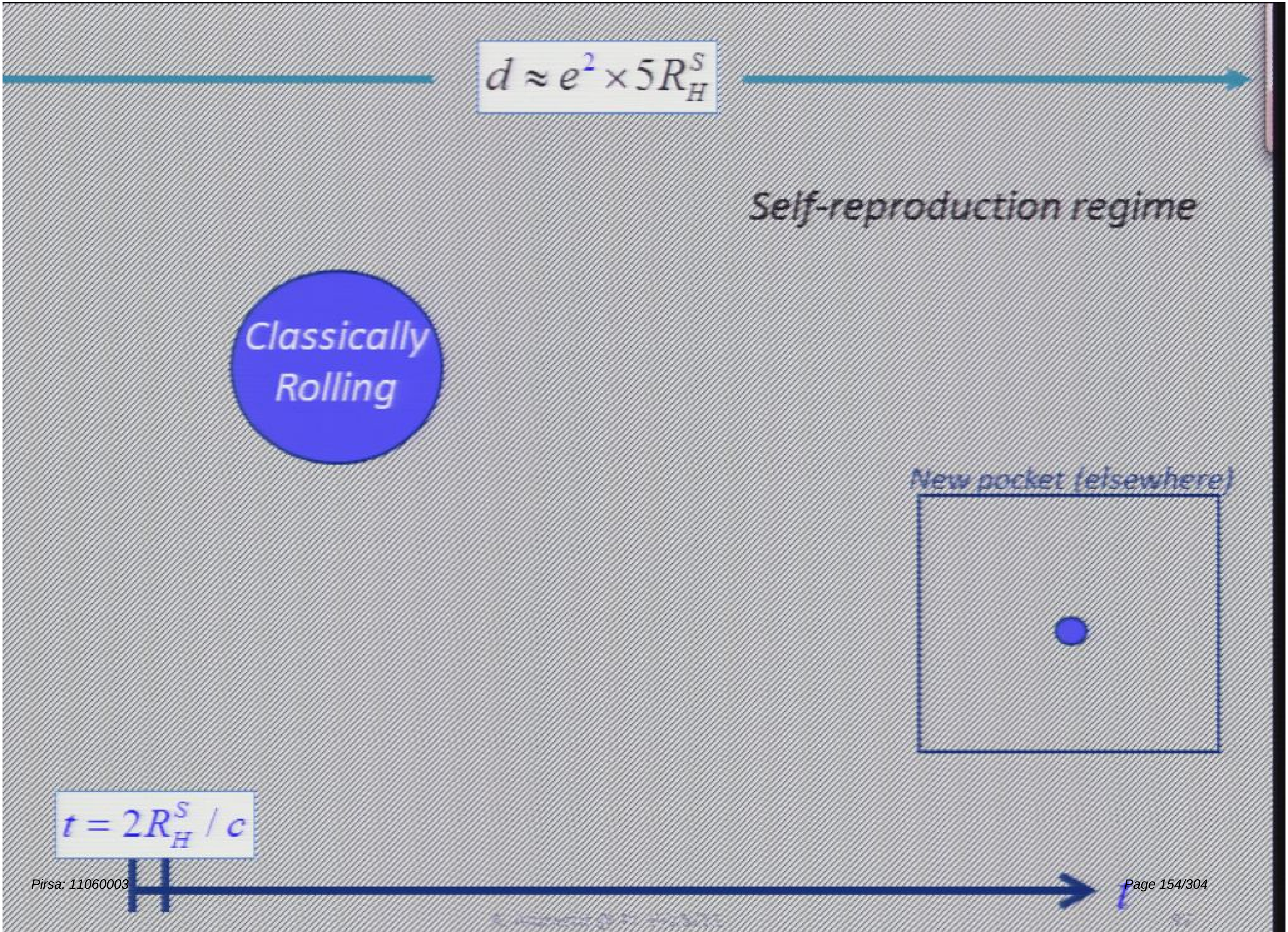
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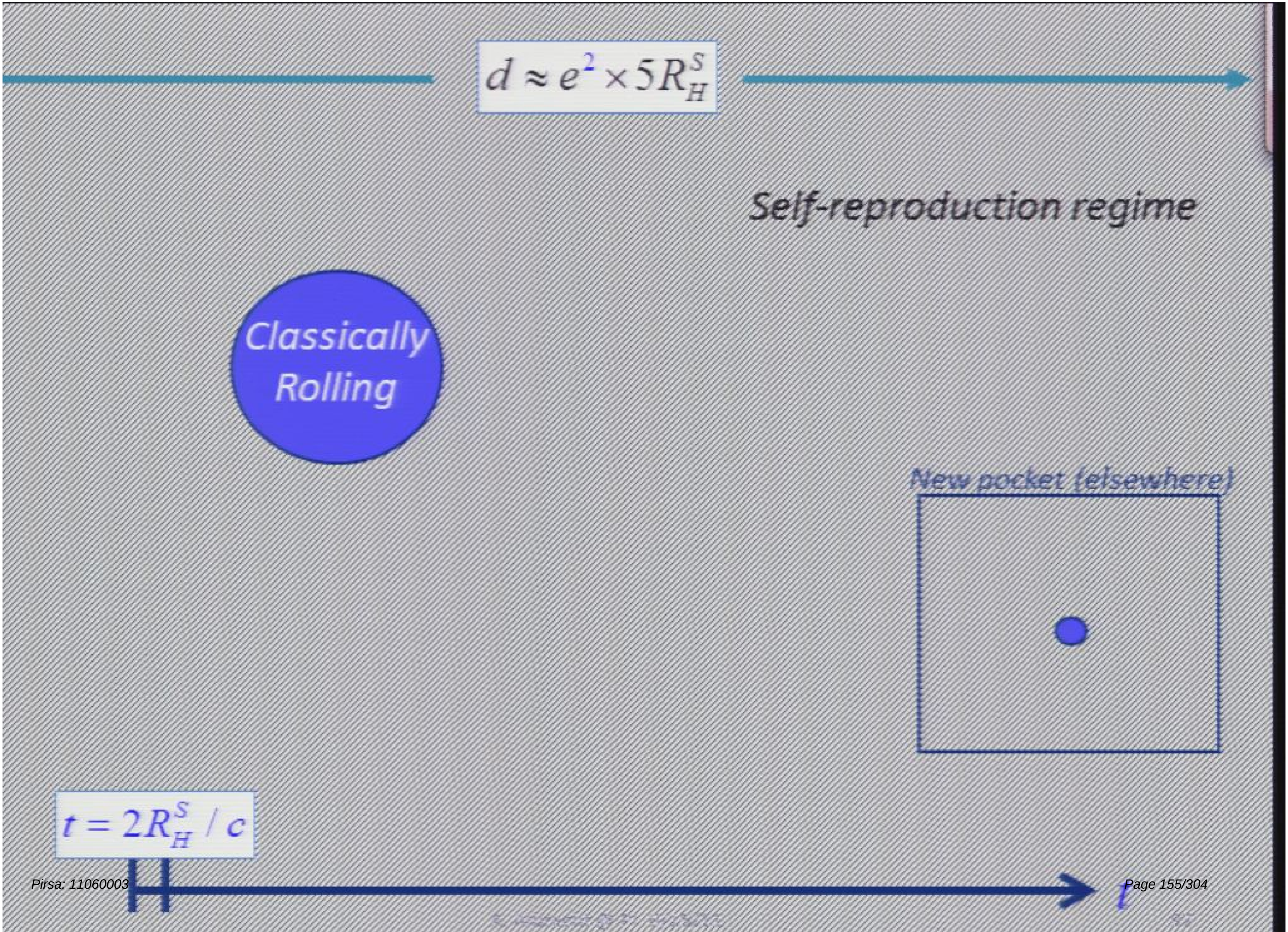
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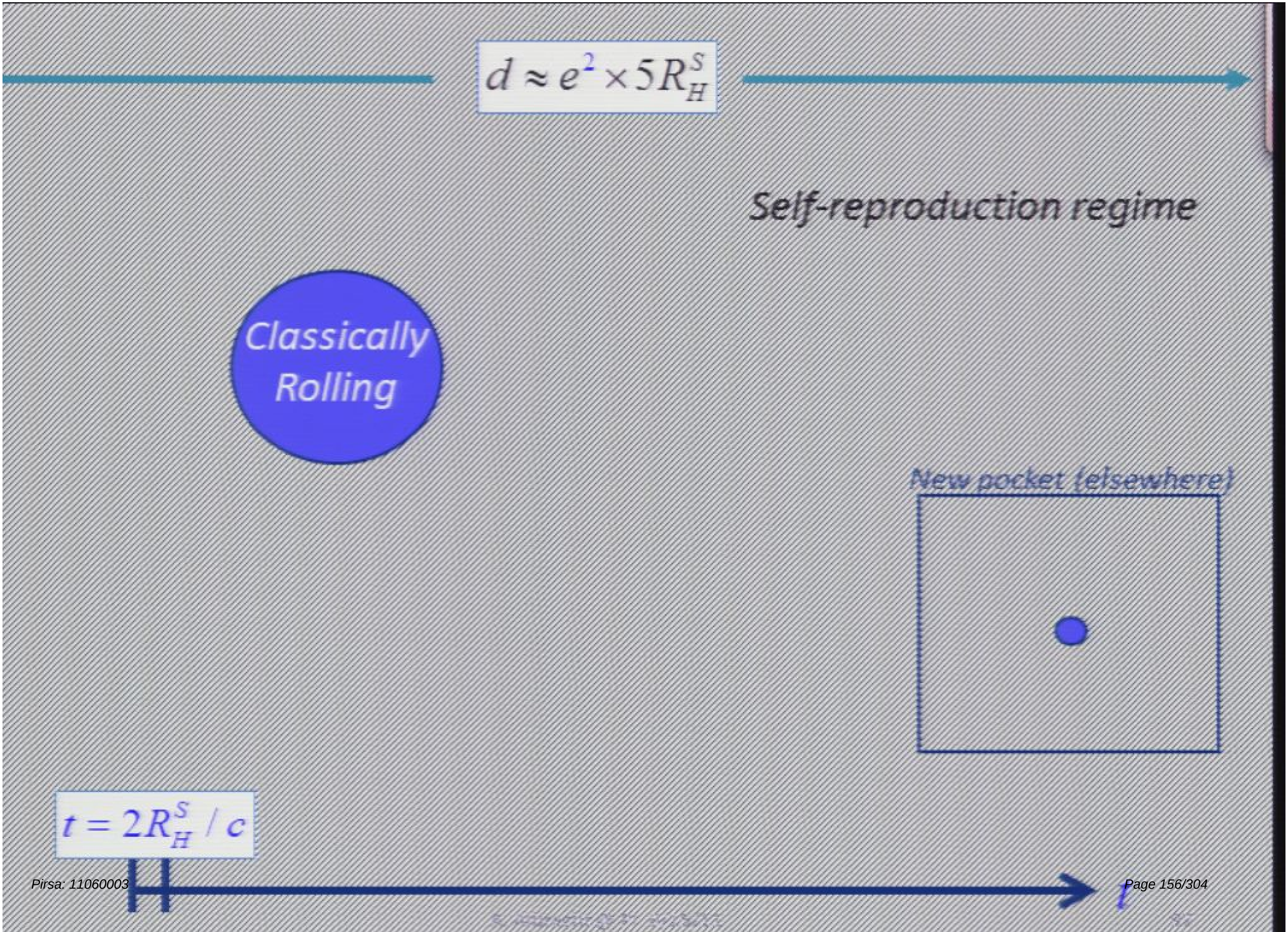
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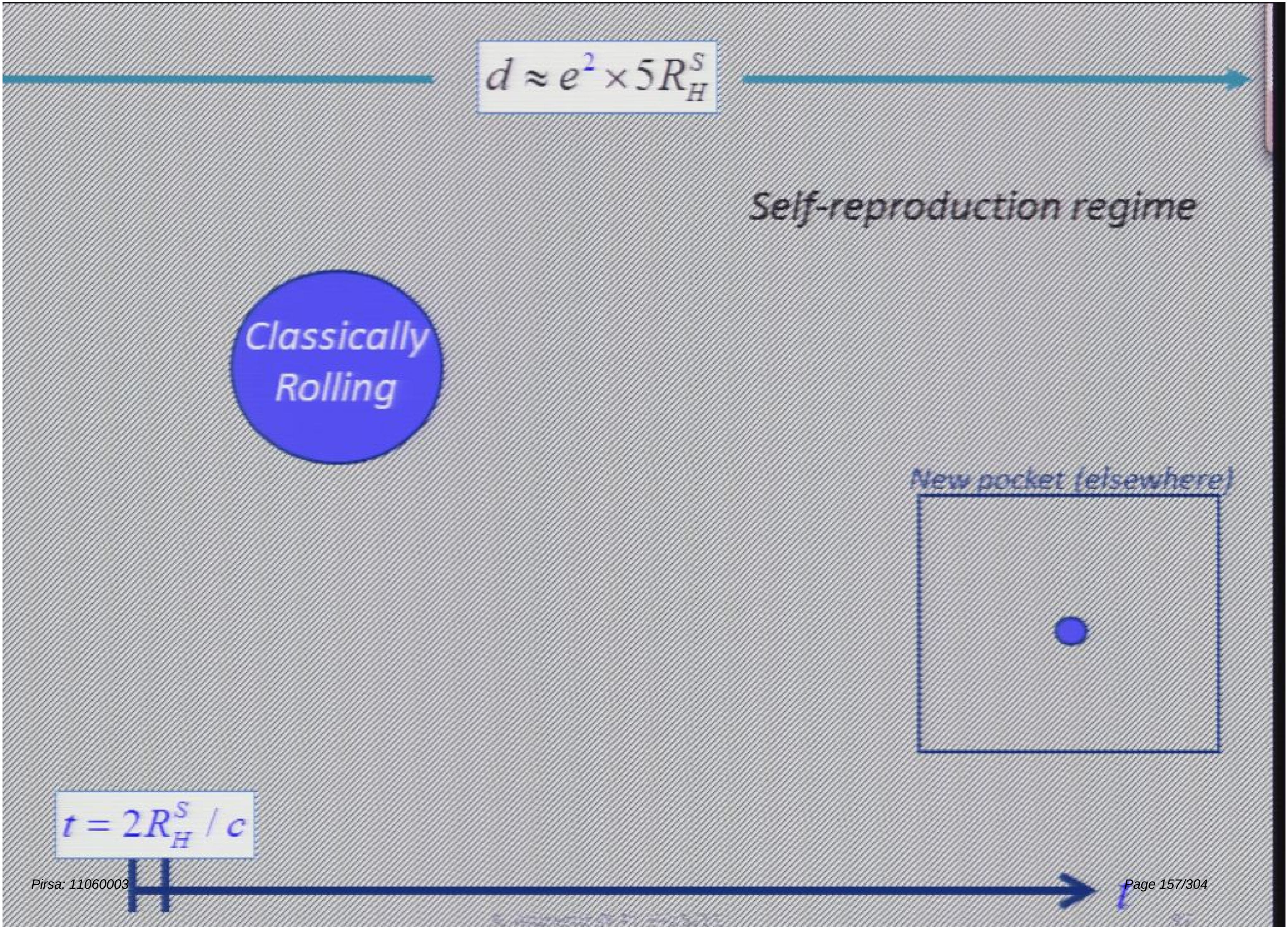
$d \approx e^2 \times 5R_H^S$
Self-reproduction regime
Classically Rolling
New pocket (elsewhere)
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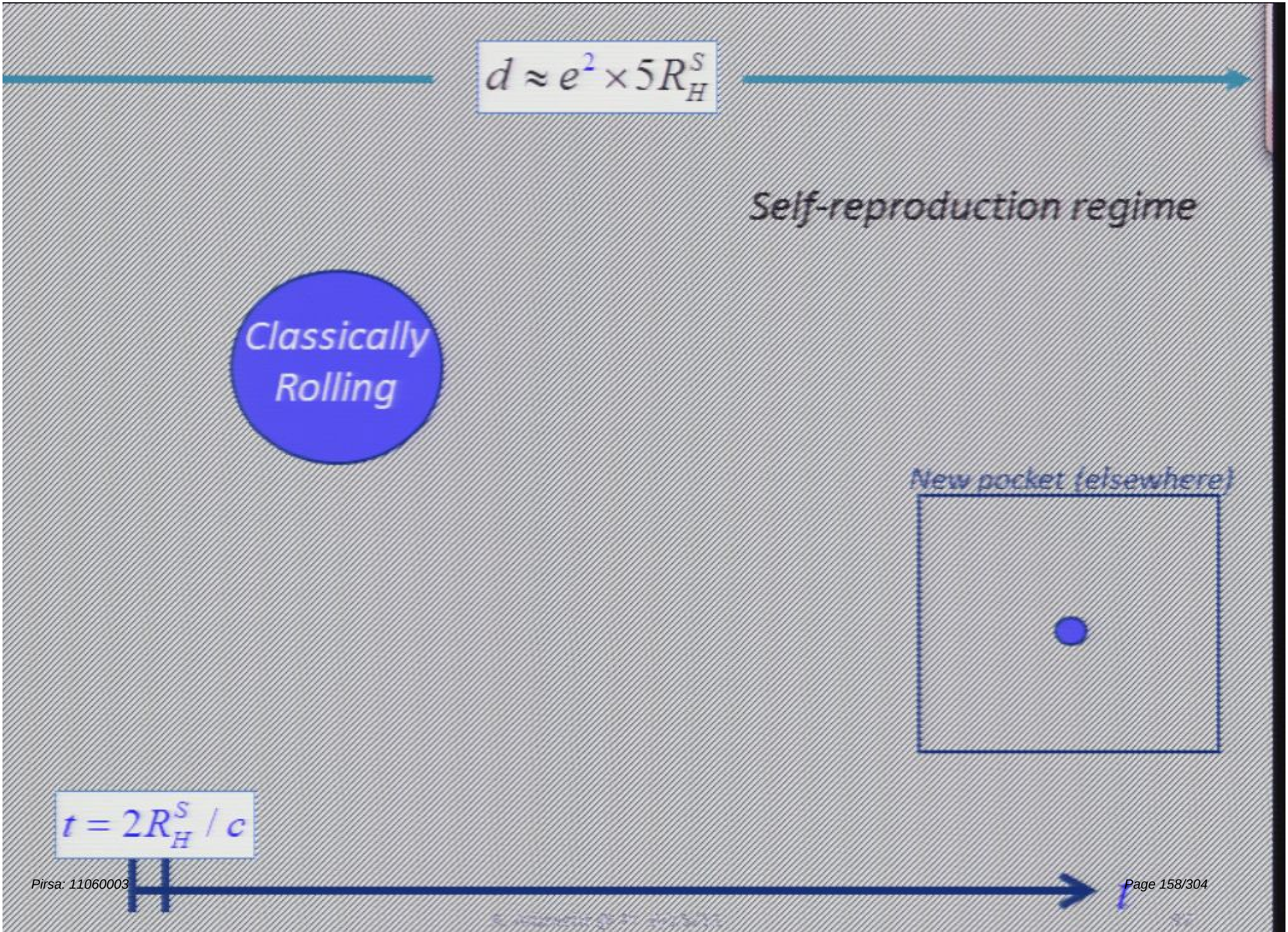
t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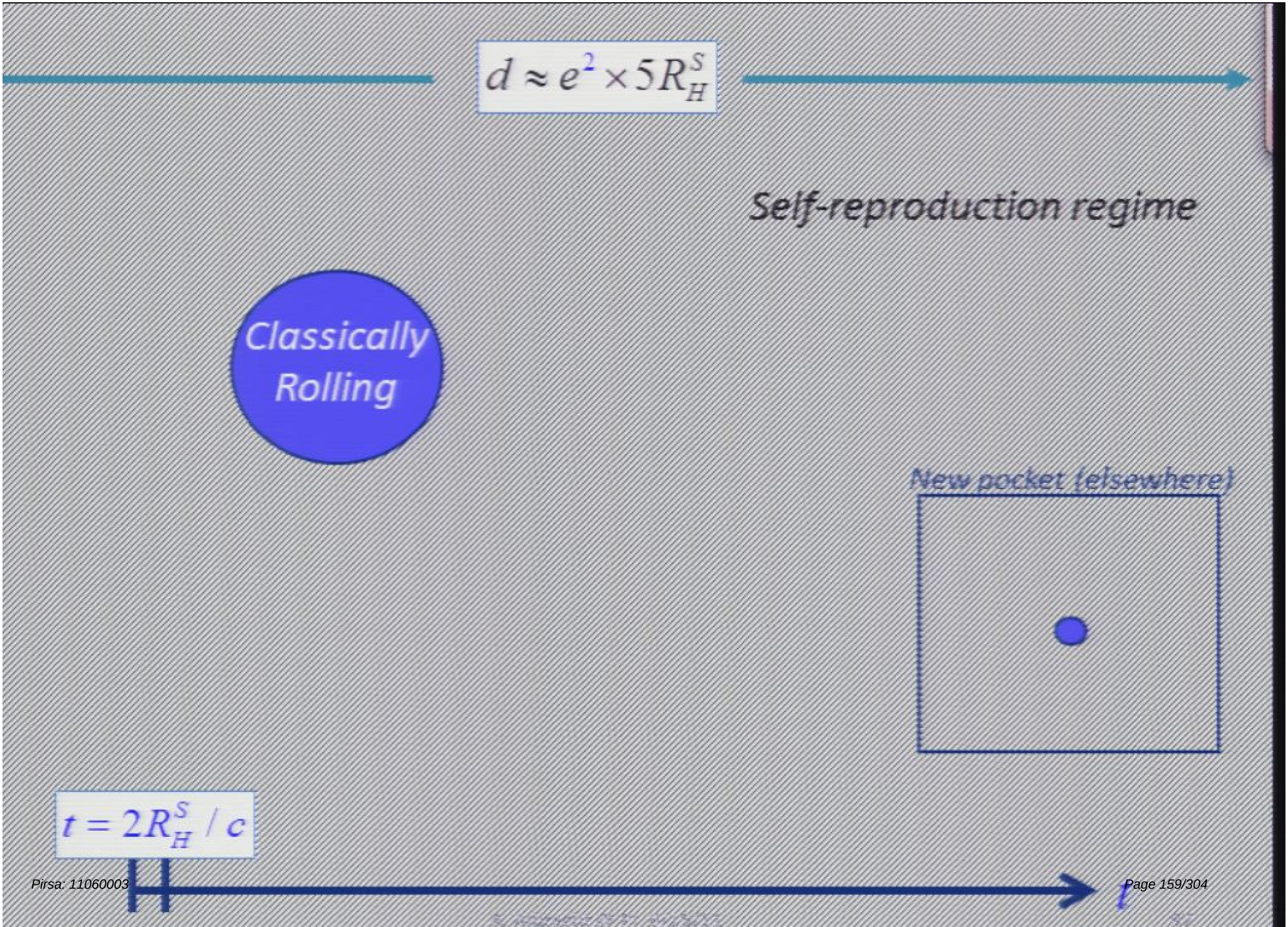
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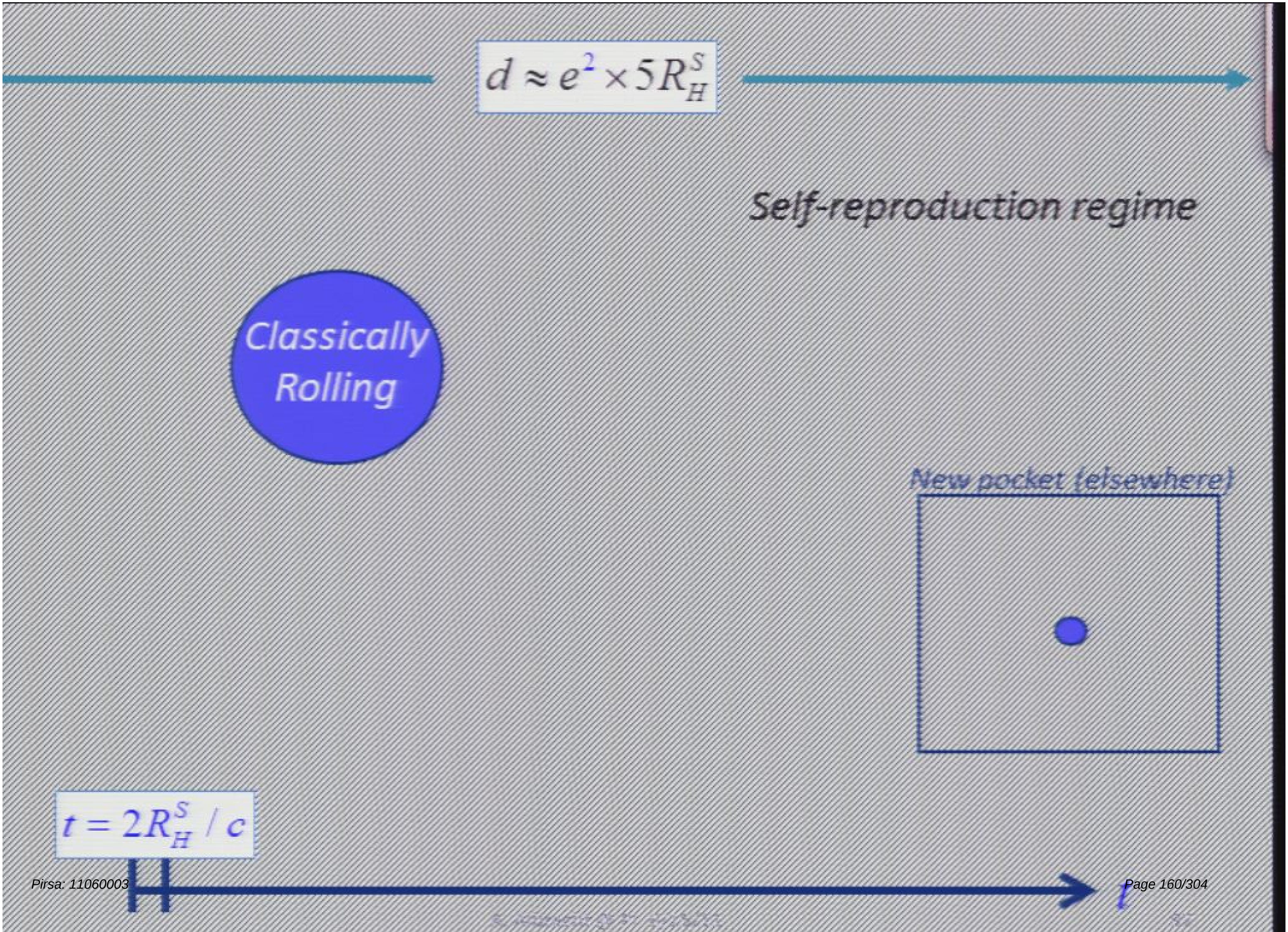
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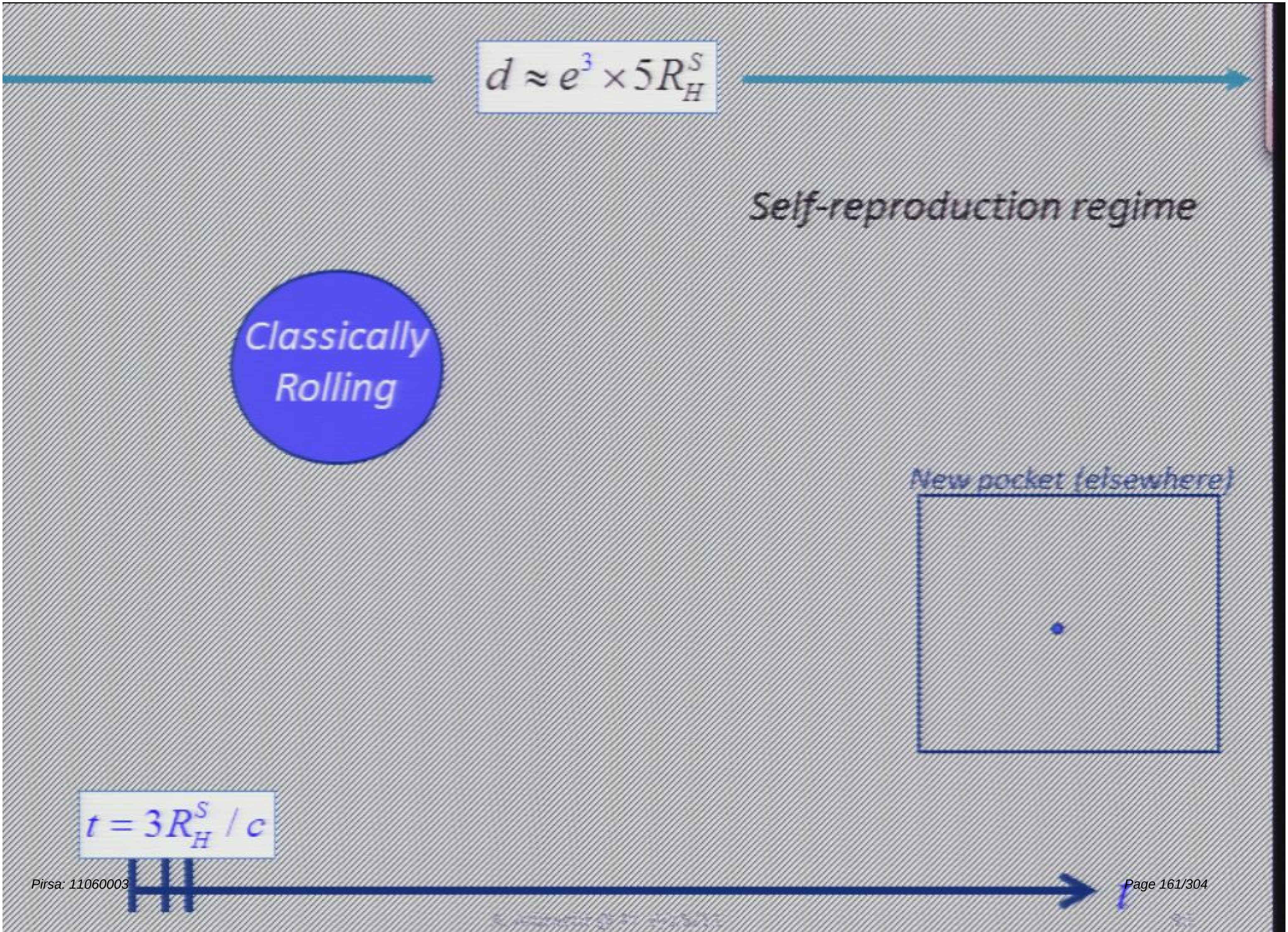
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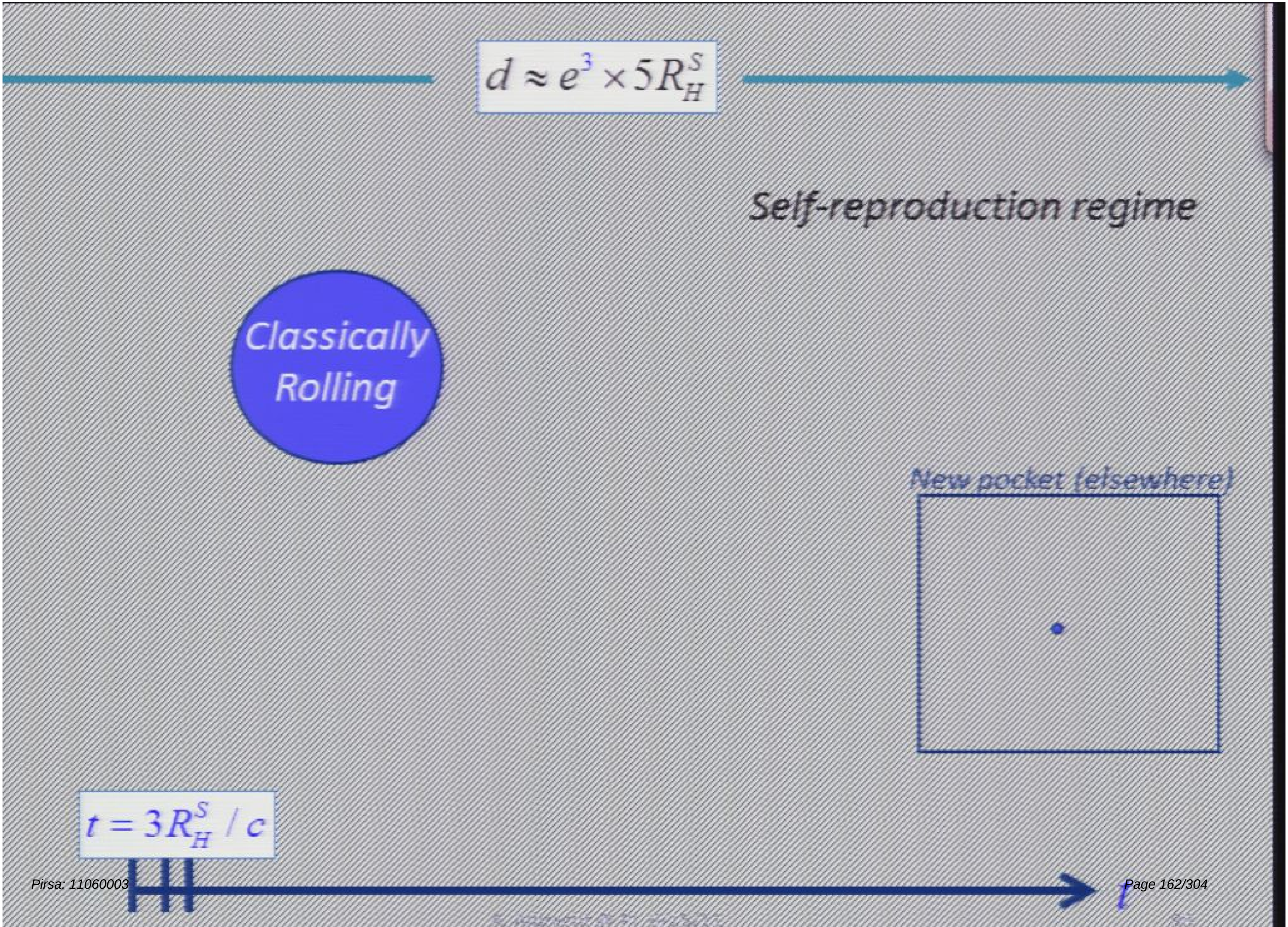
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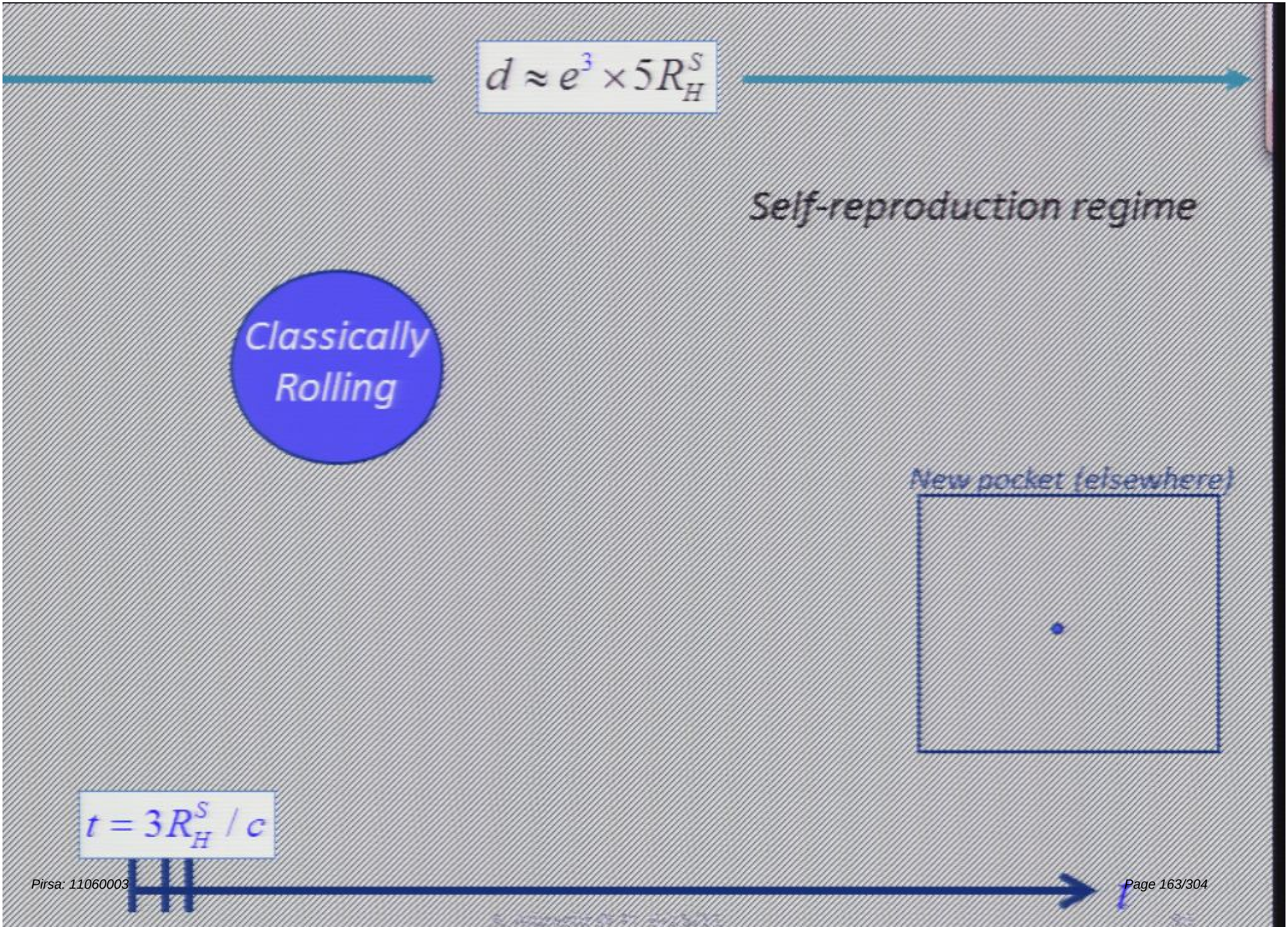

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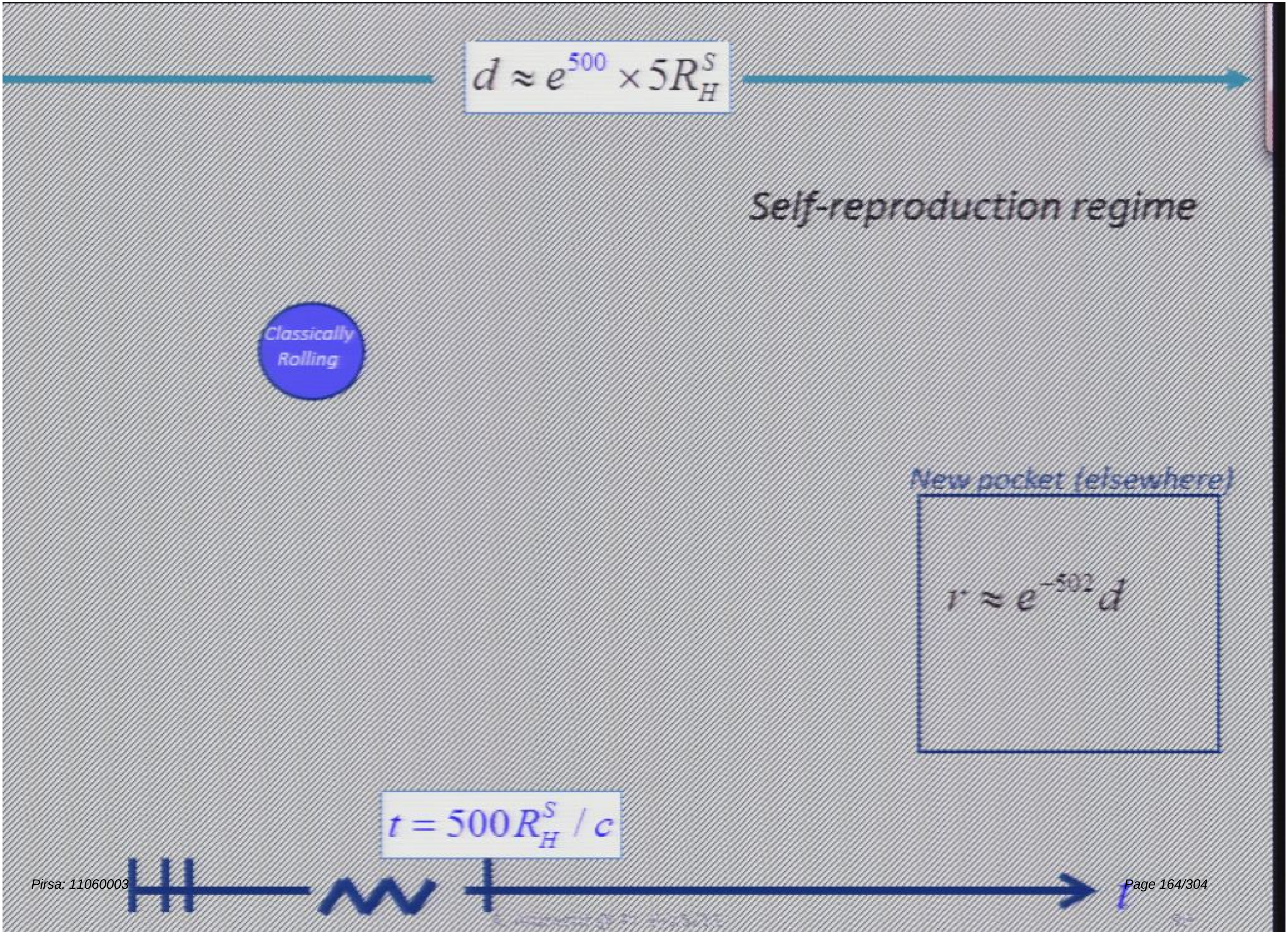

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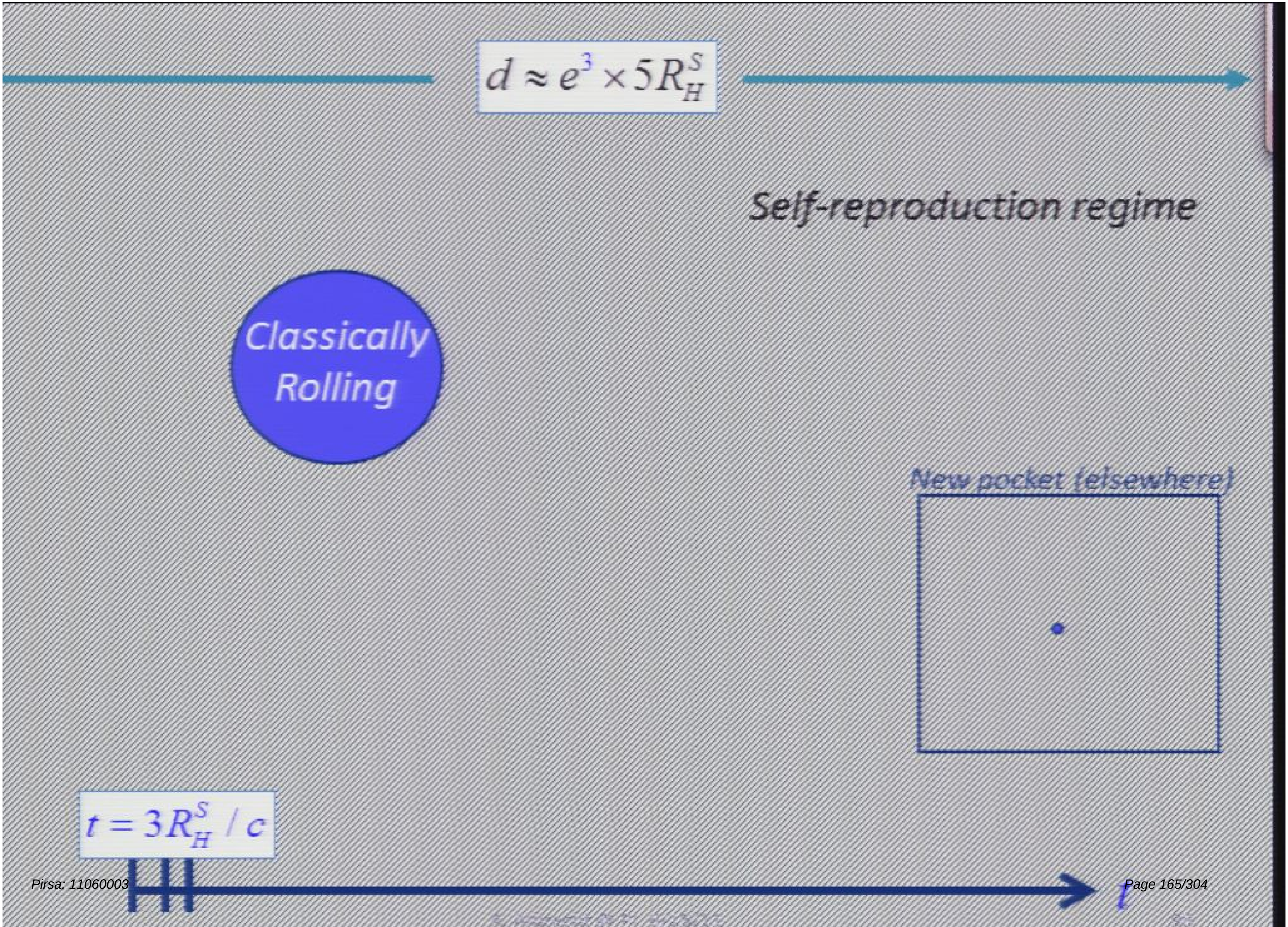

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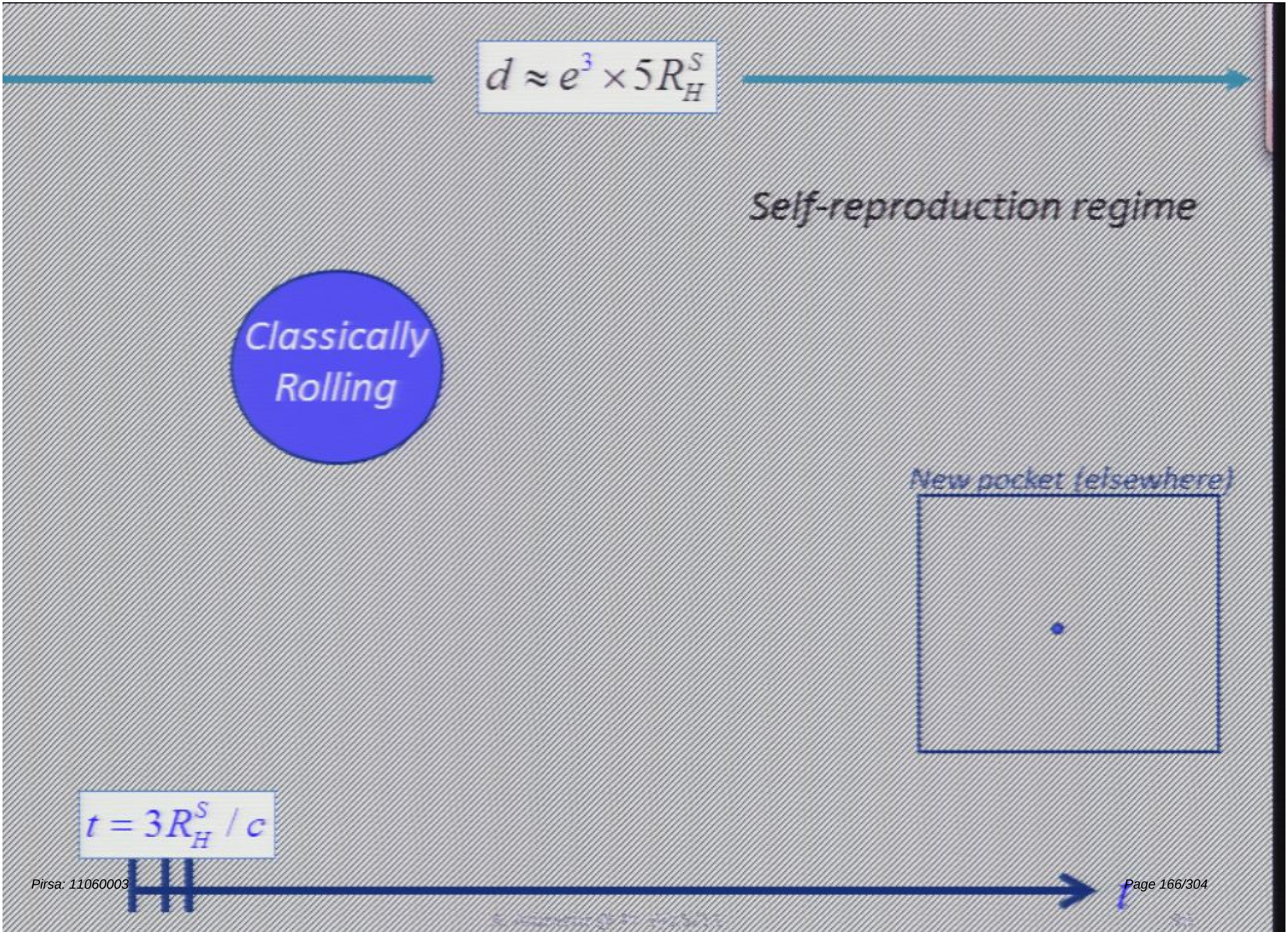
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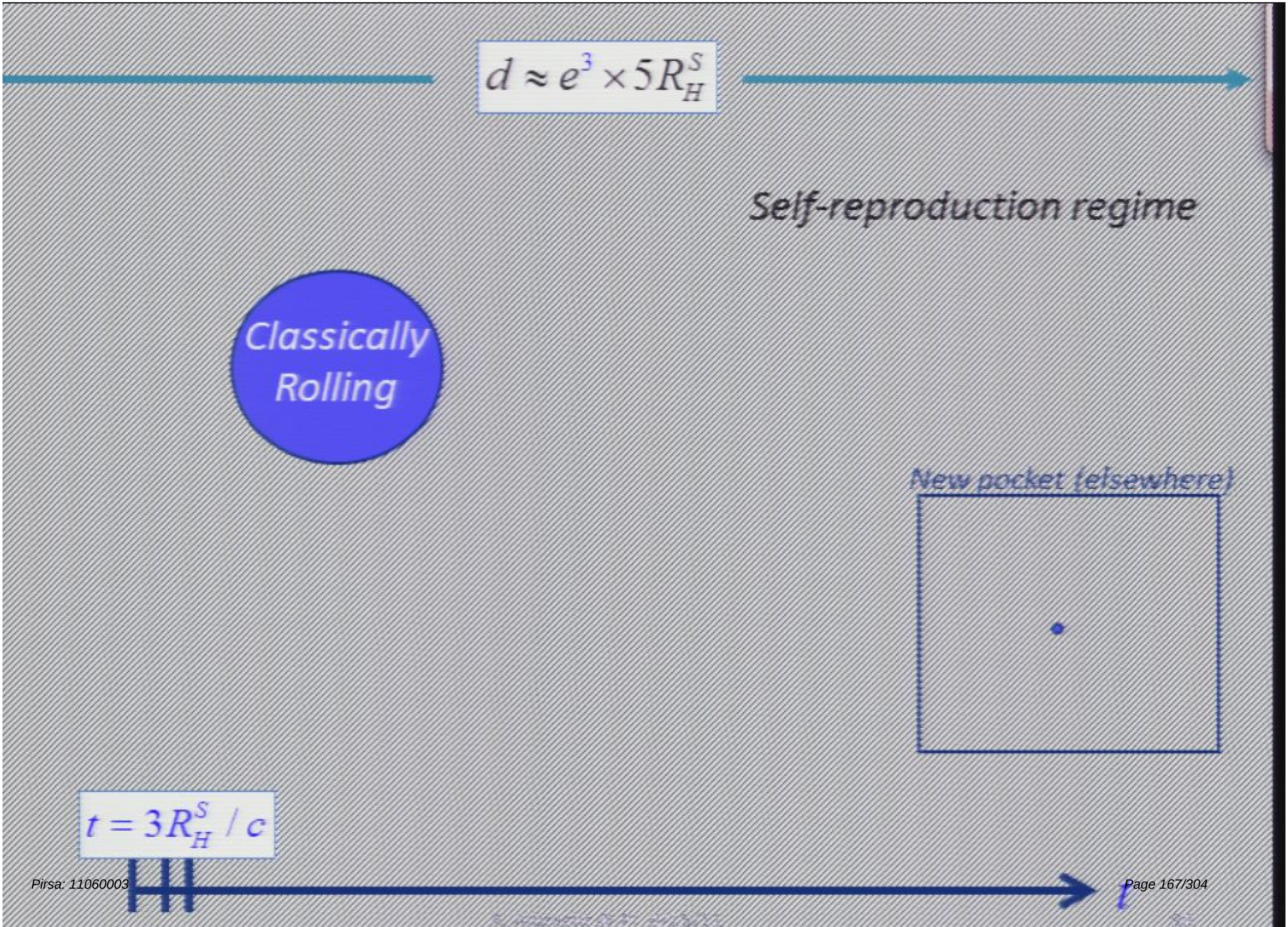
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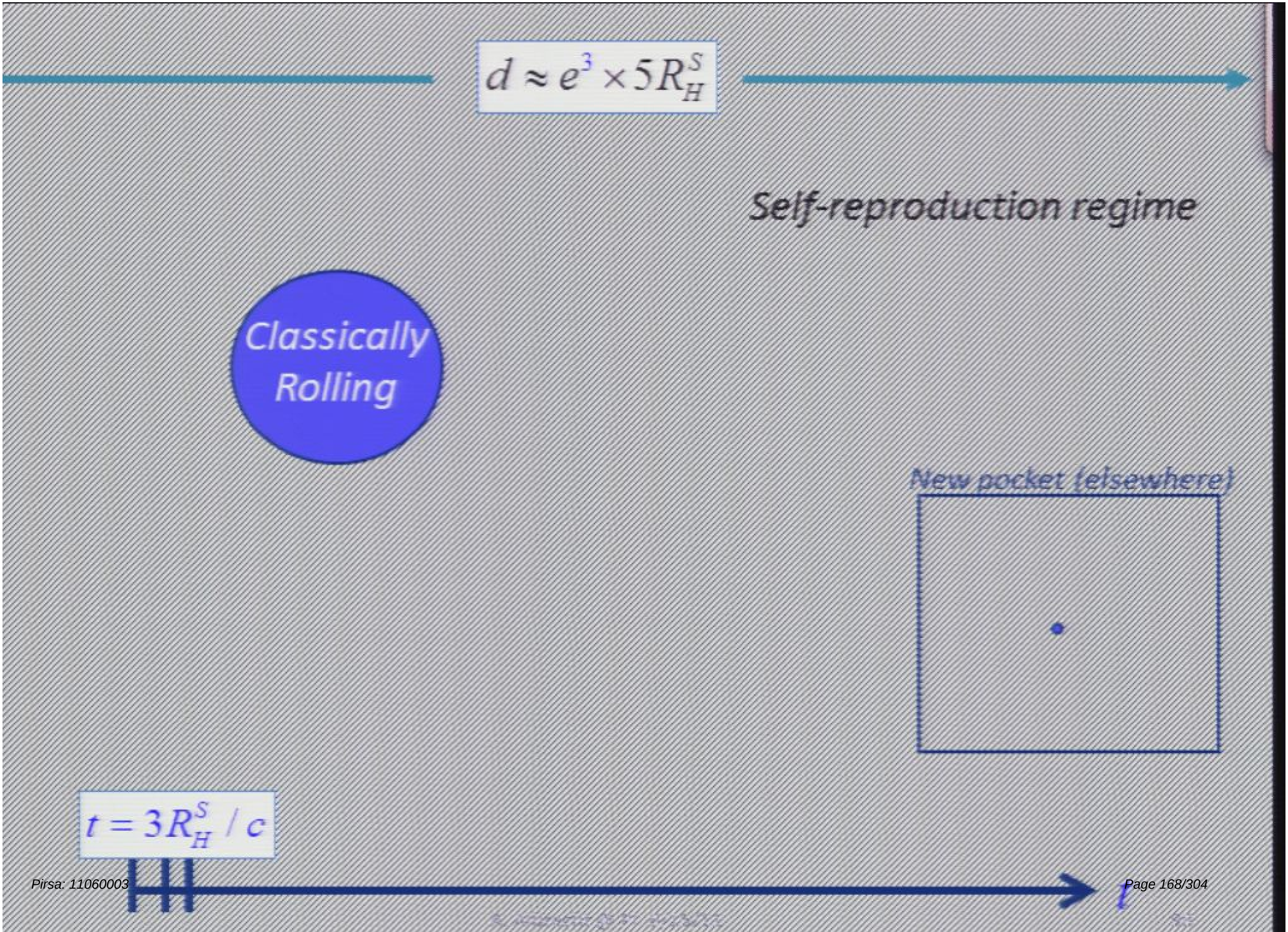
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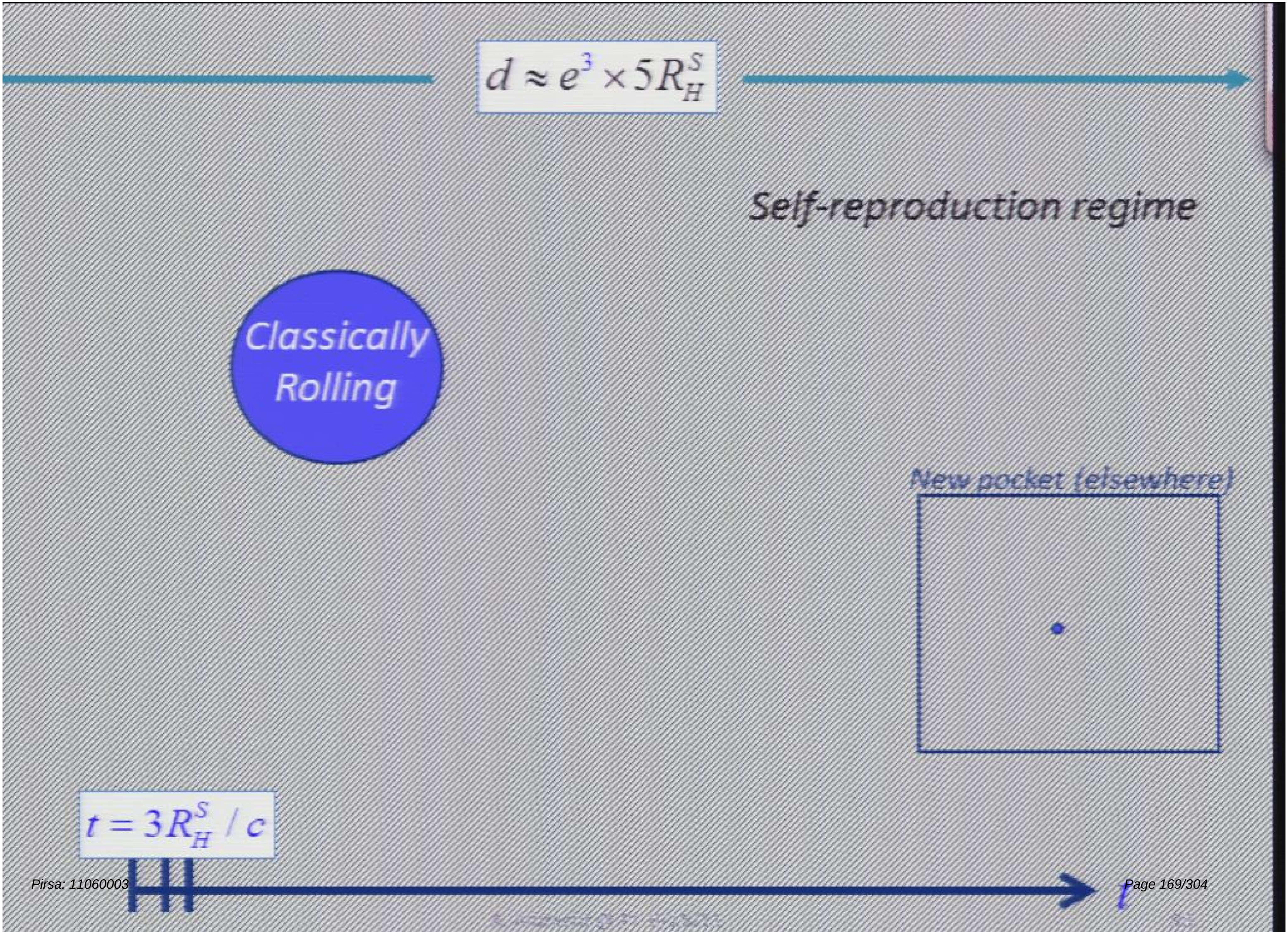
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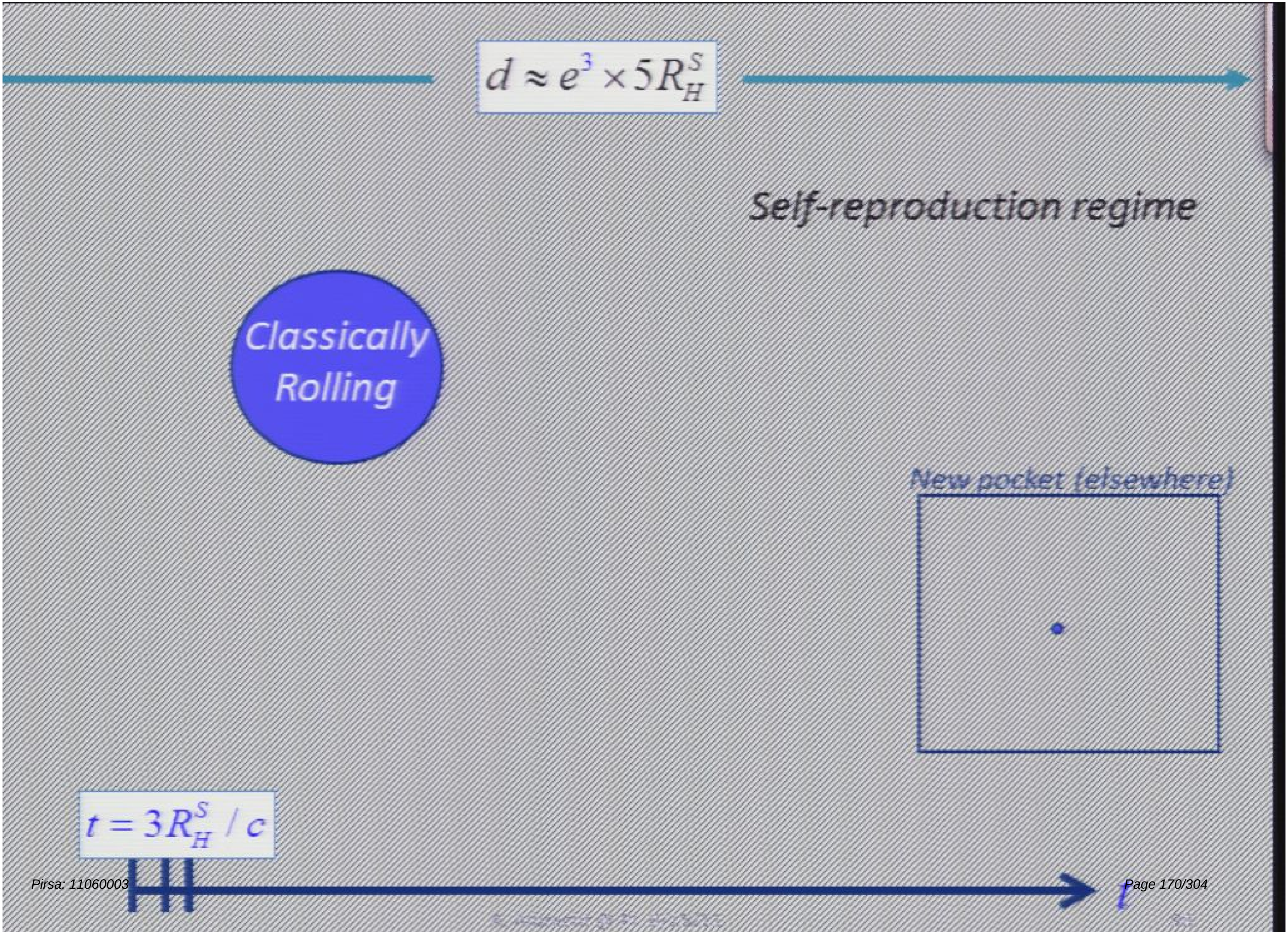
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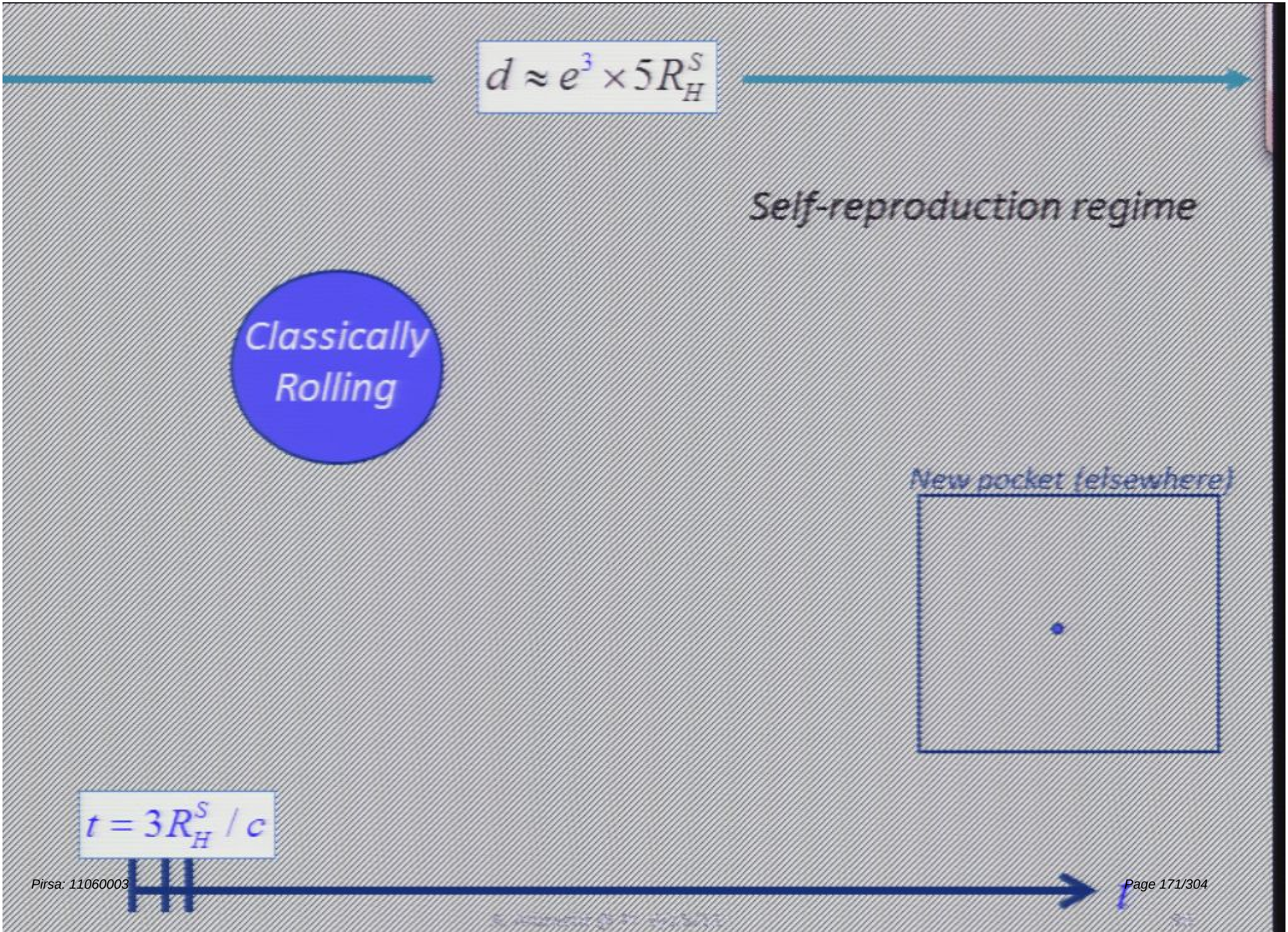
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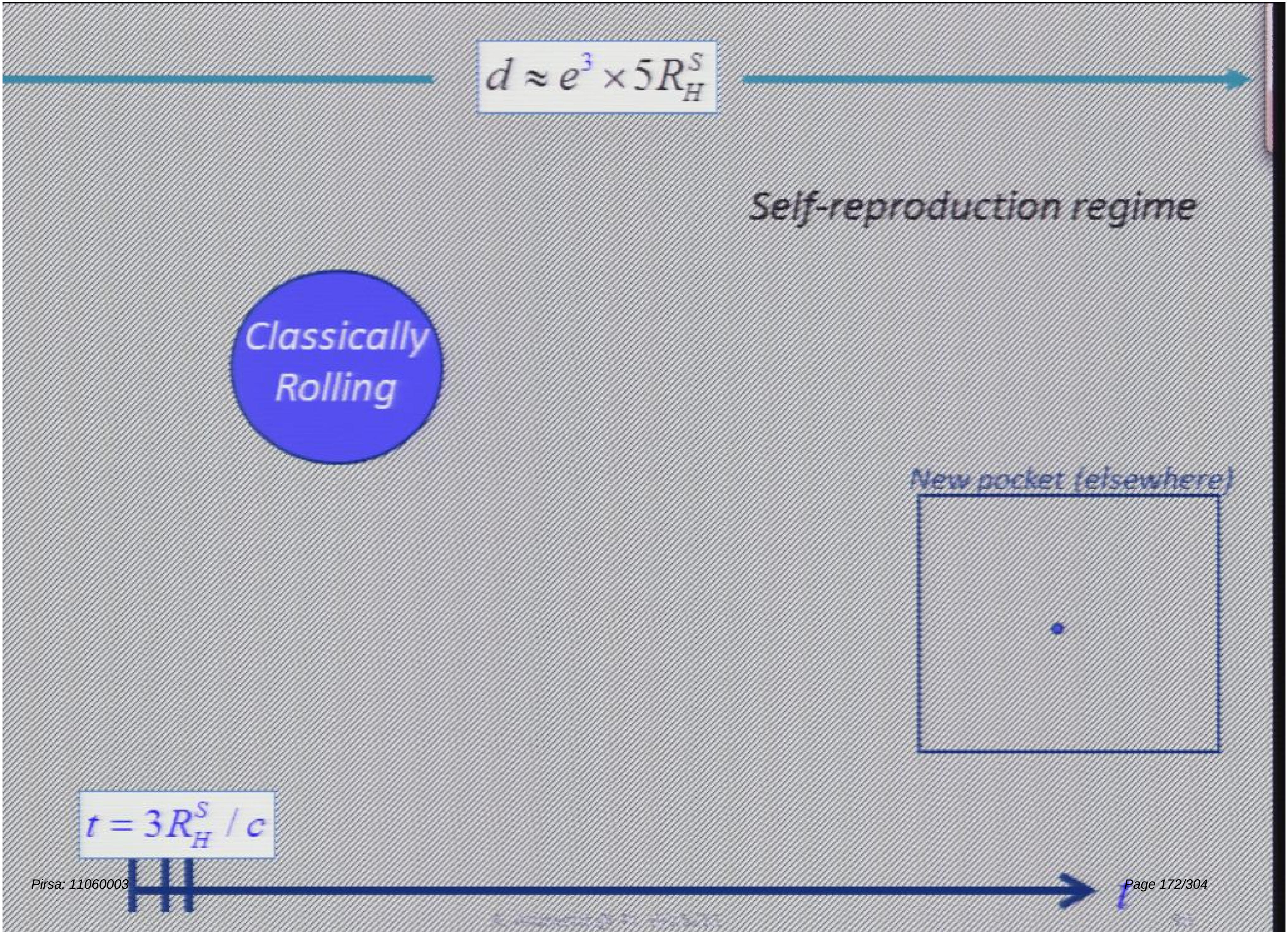
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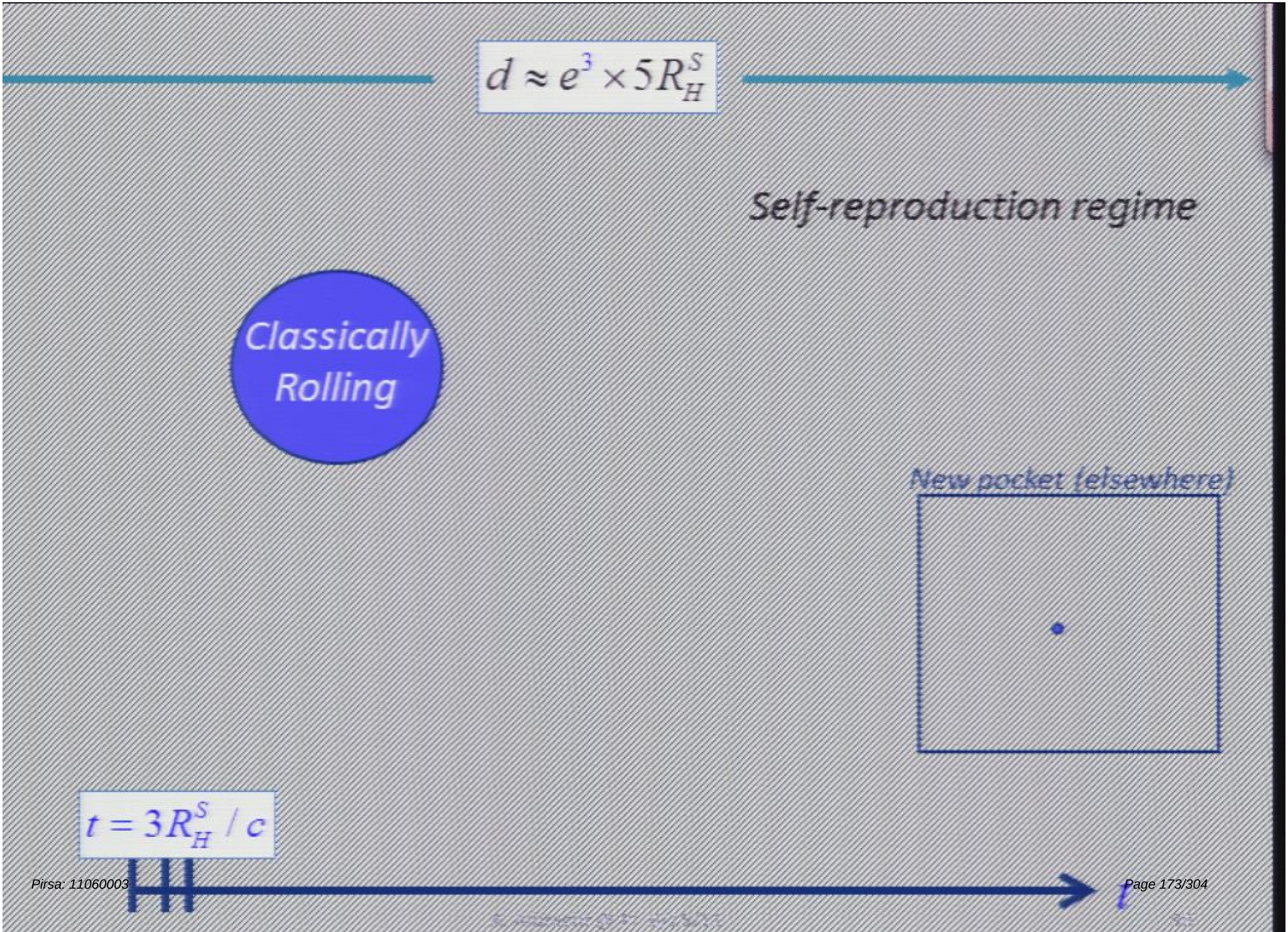

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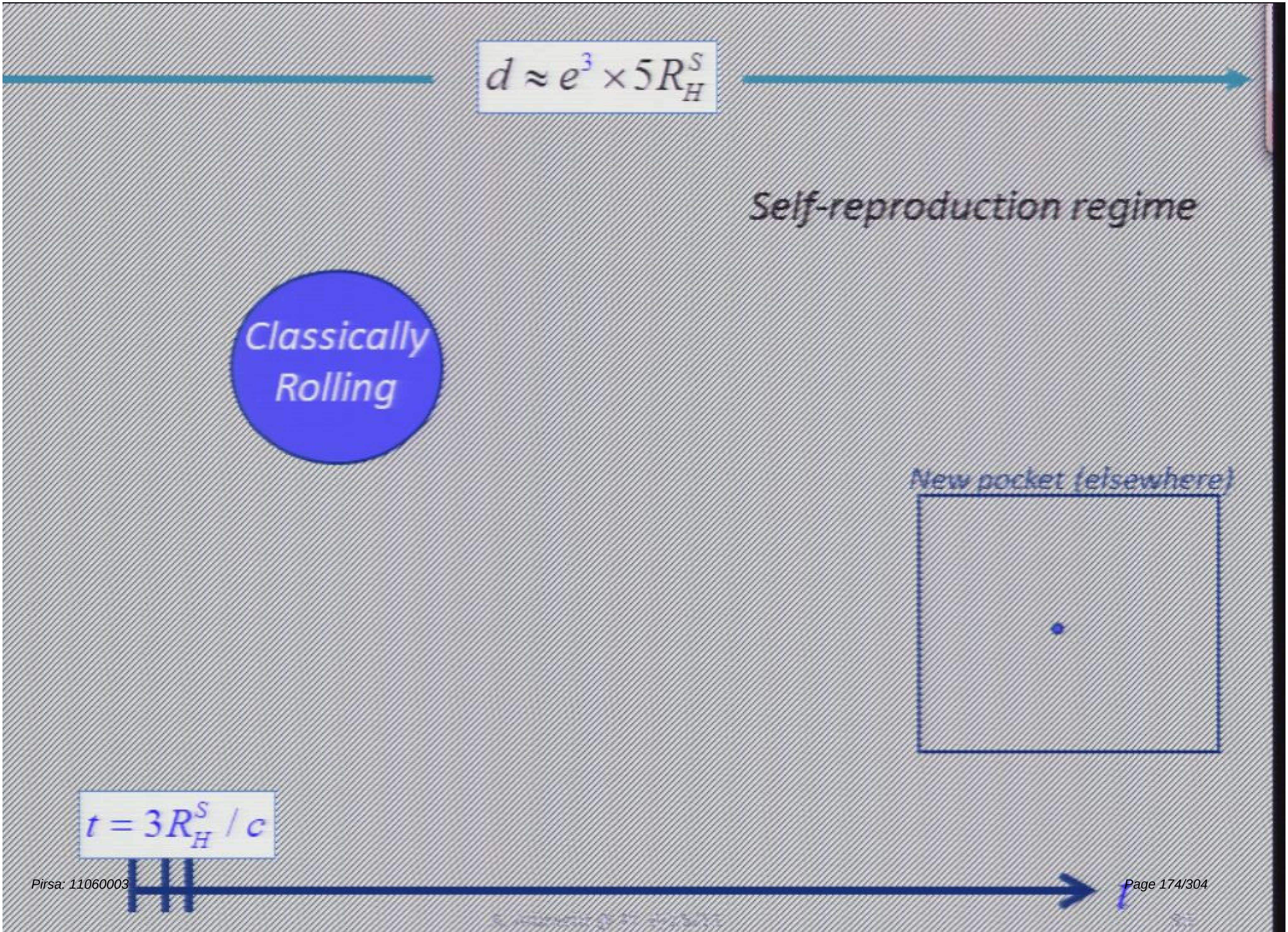
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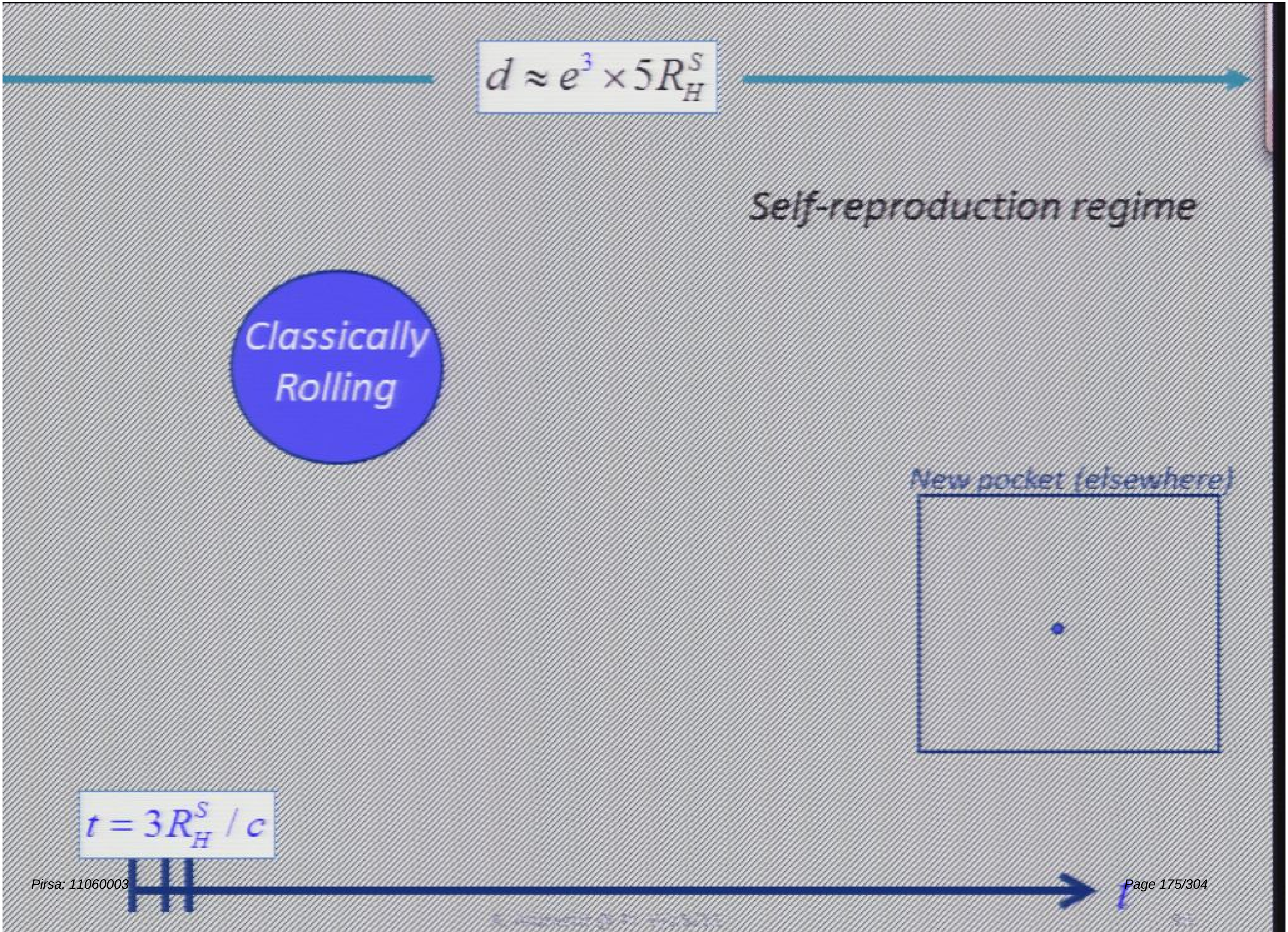
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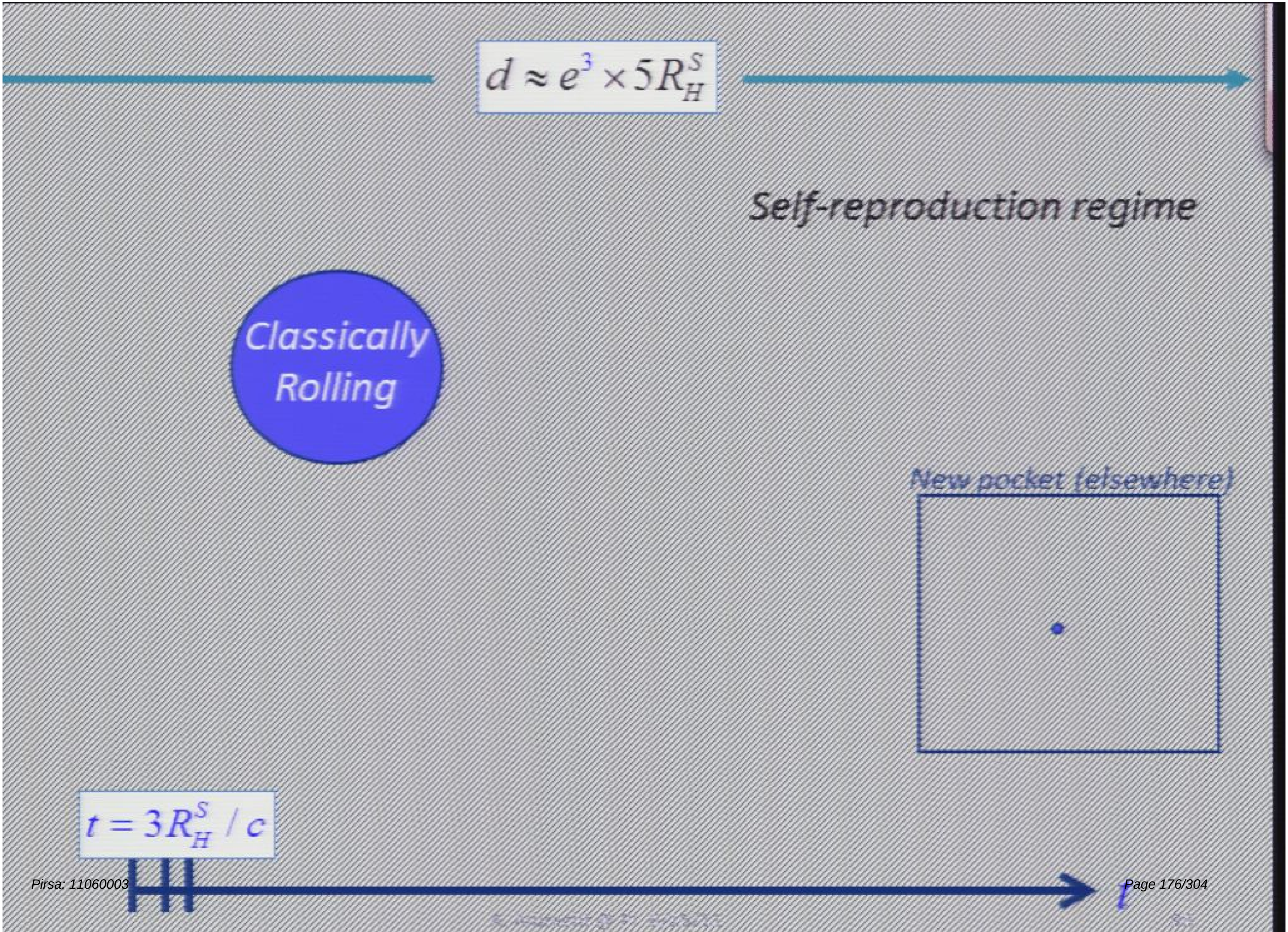
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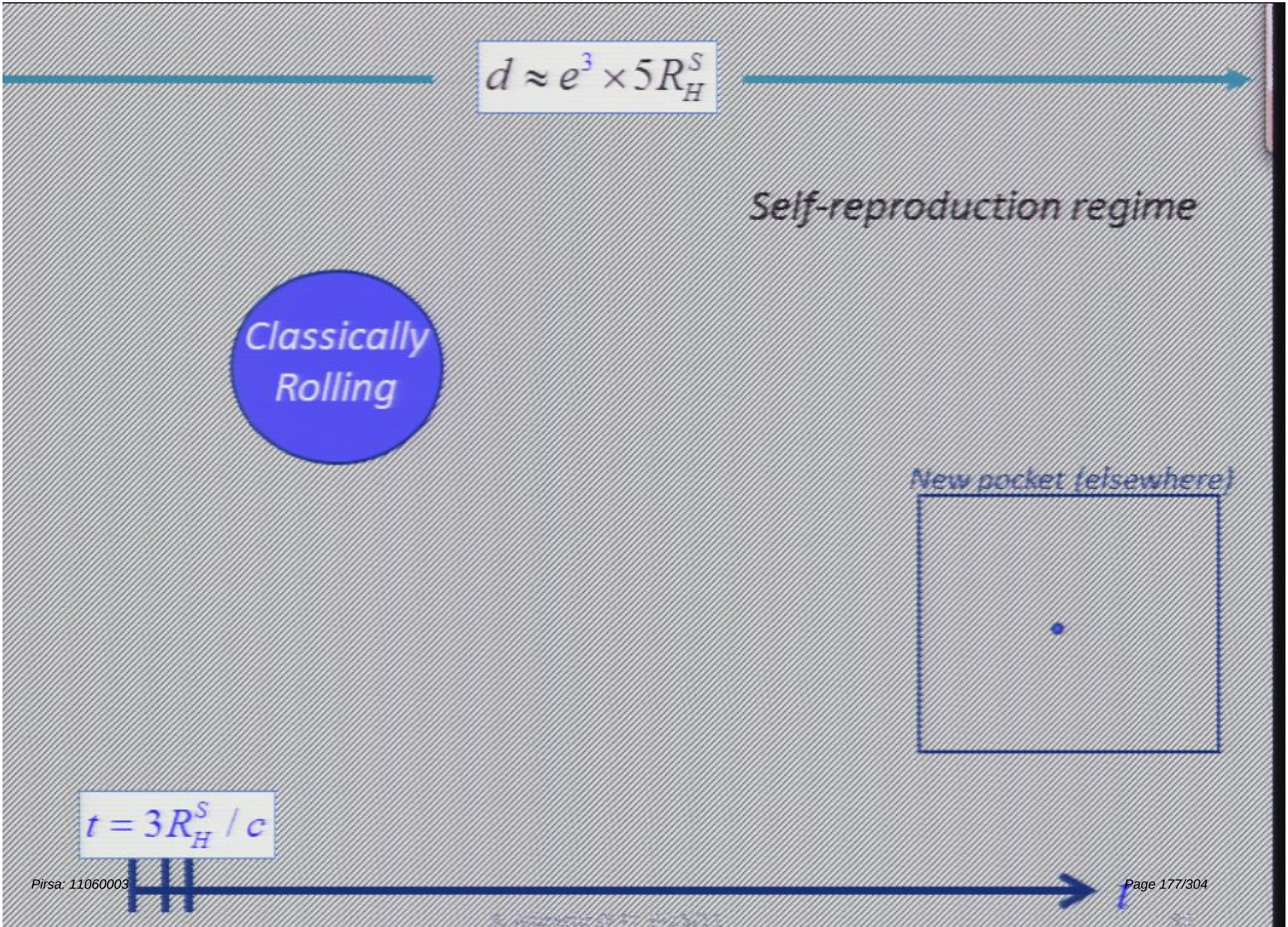
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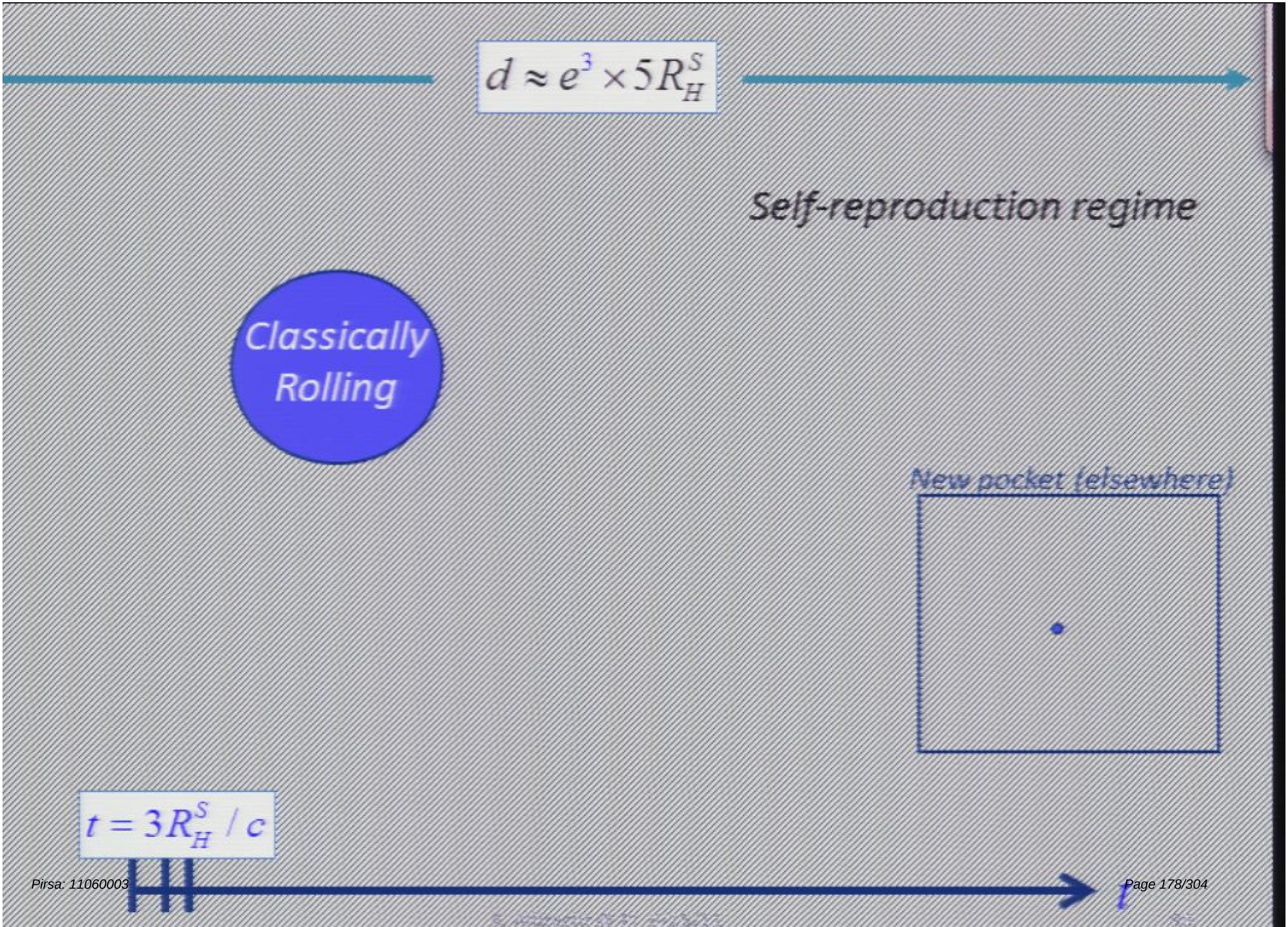

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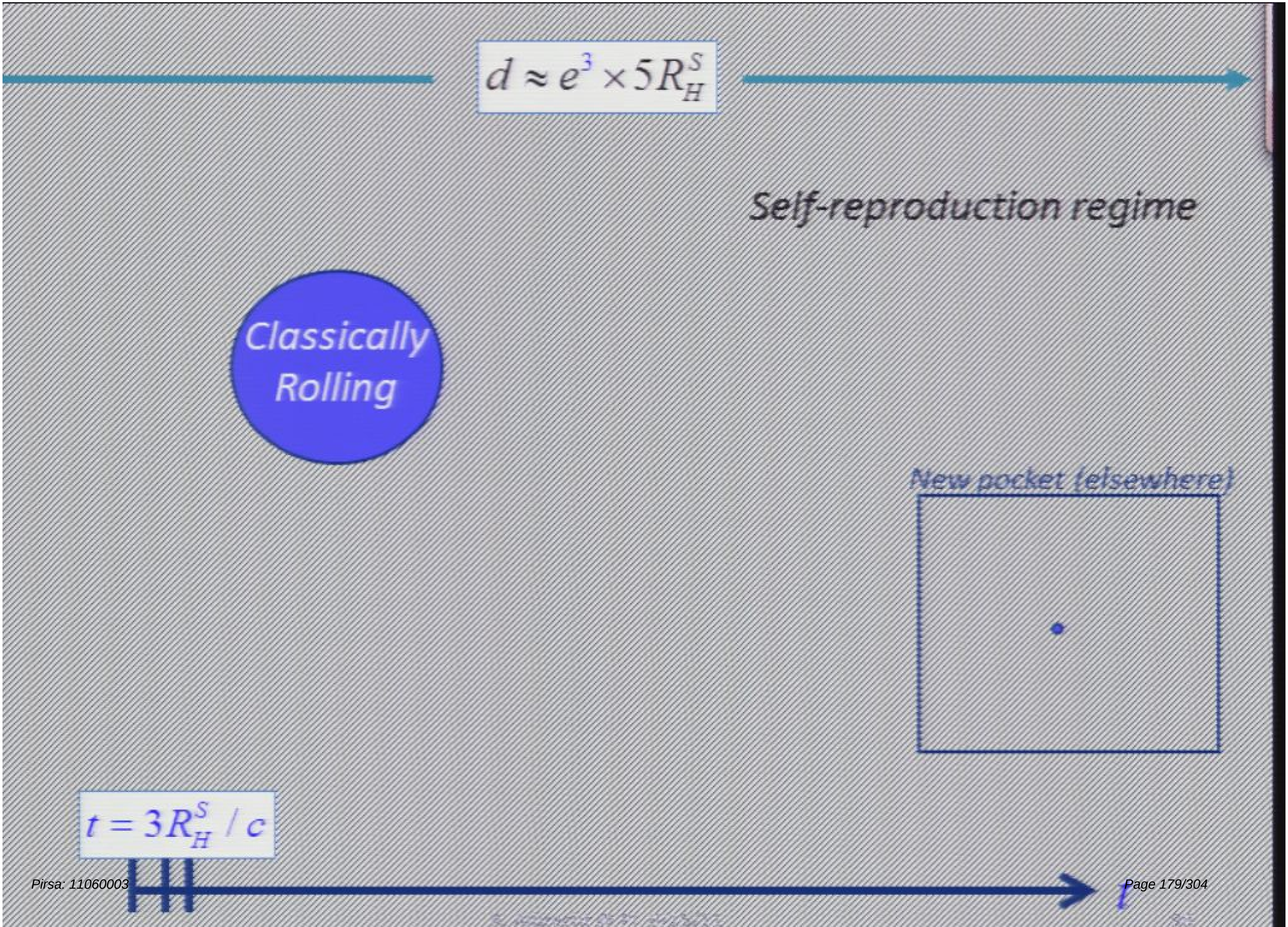
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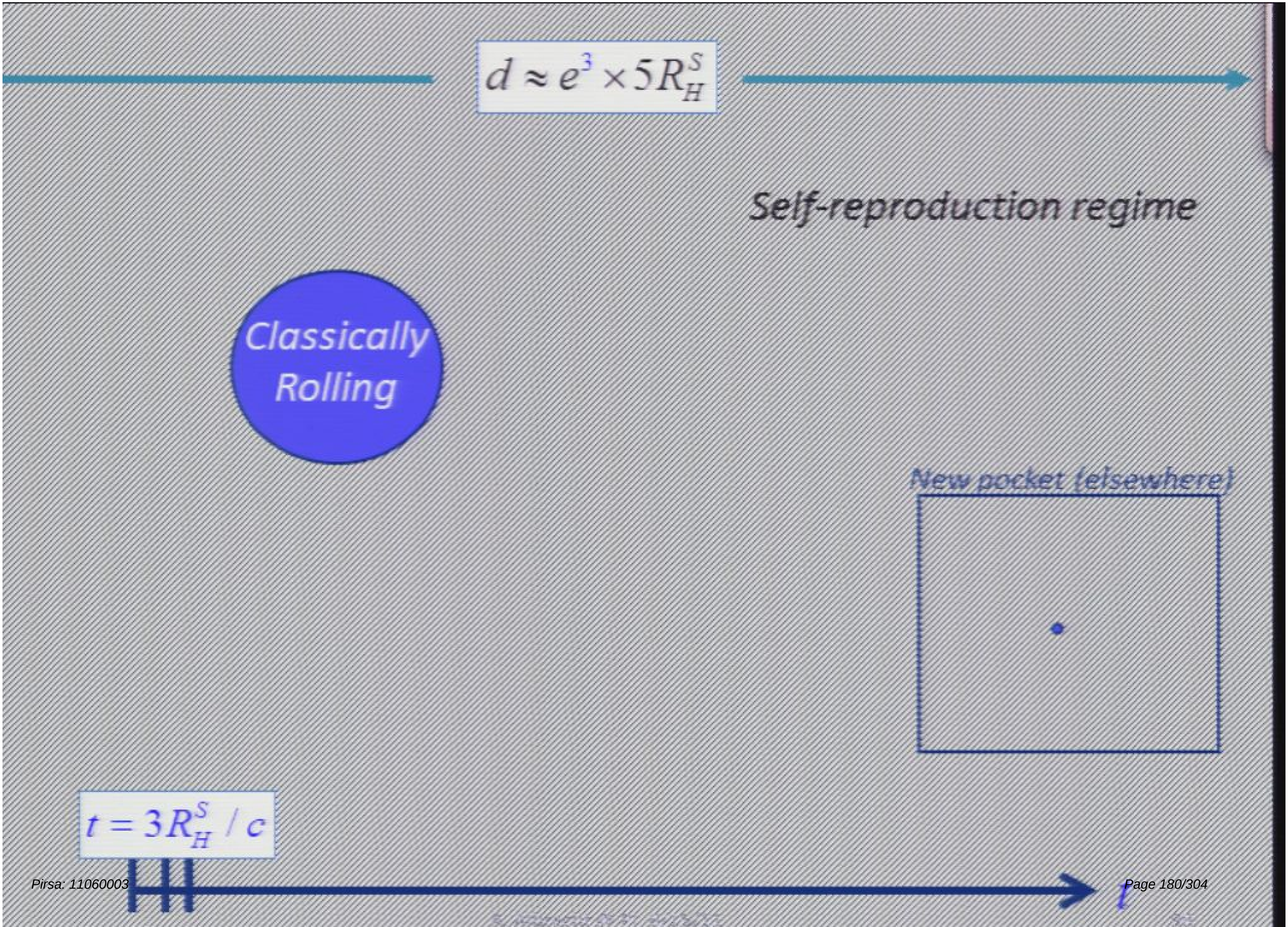
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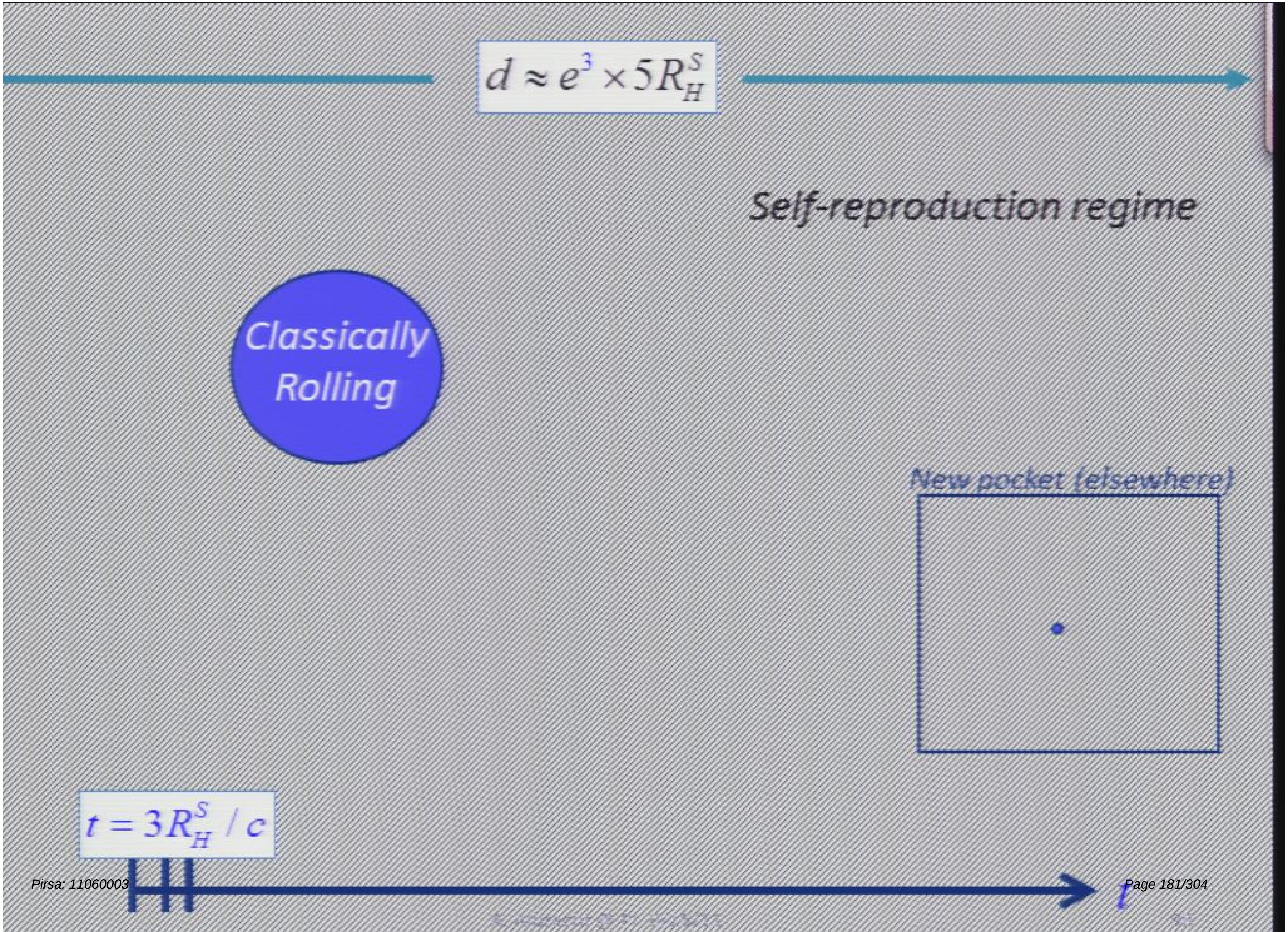
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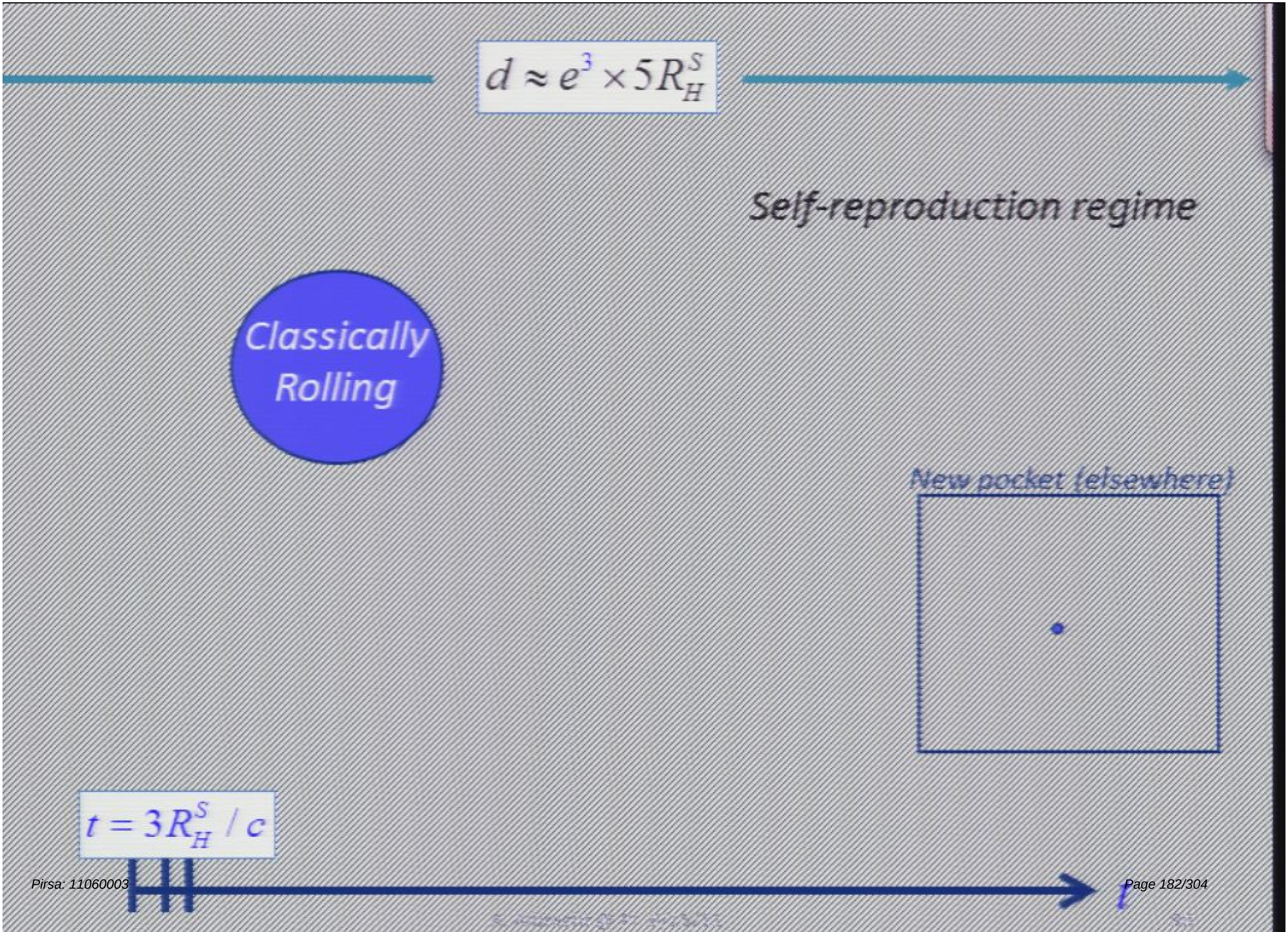
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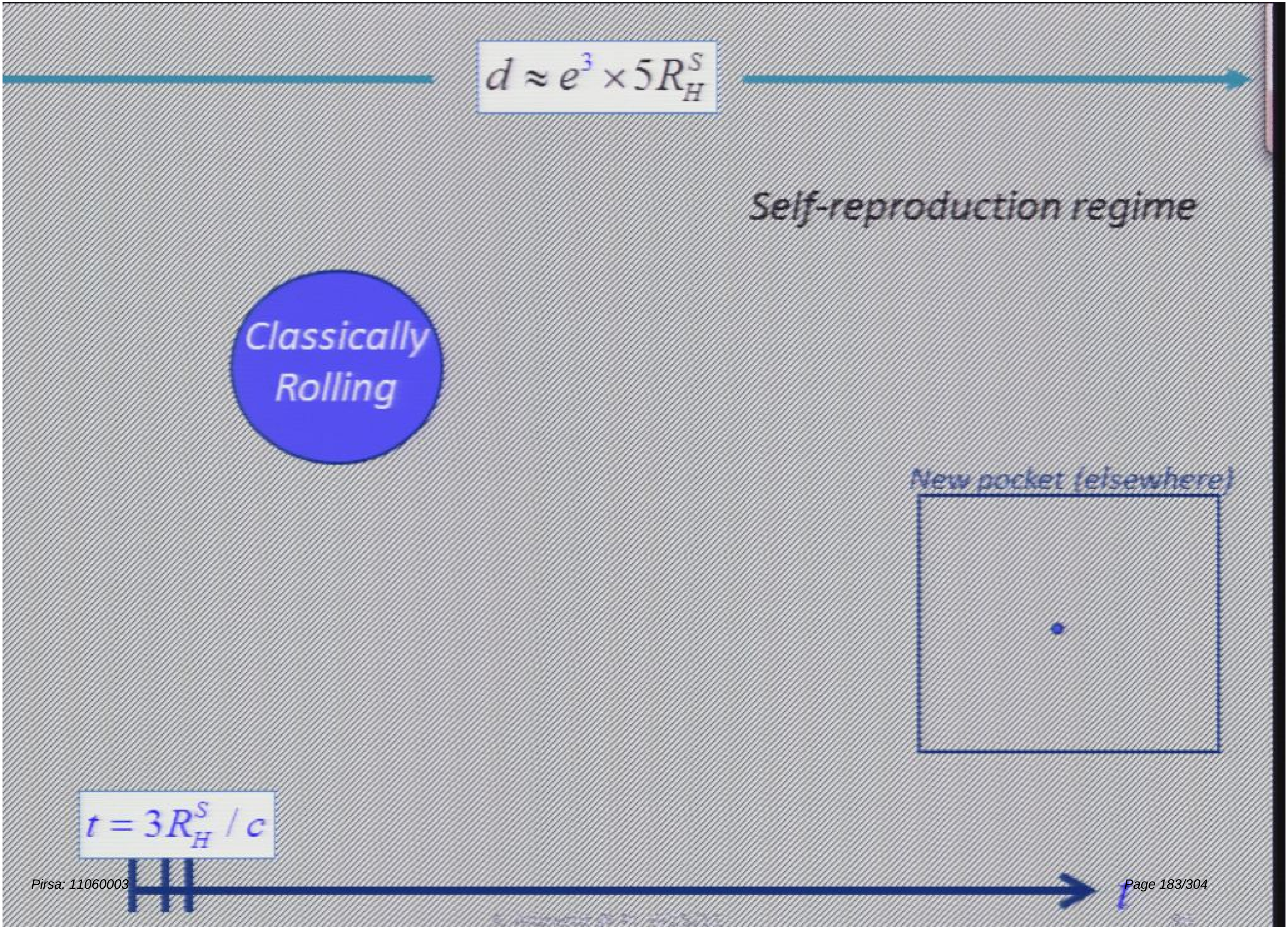
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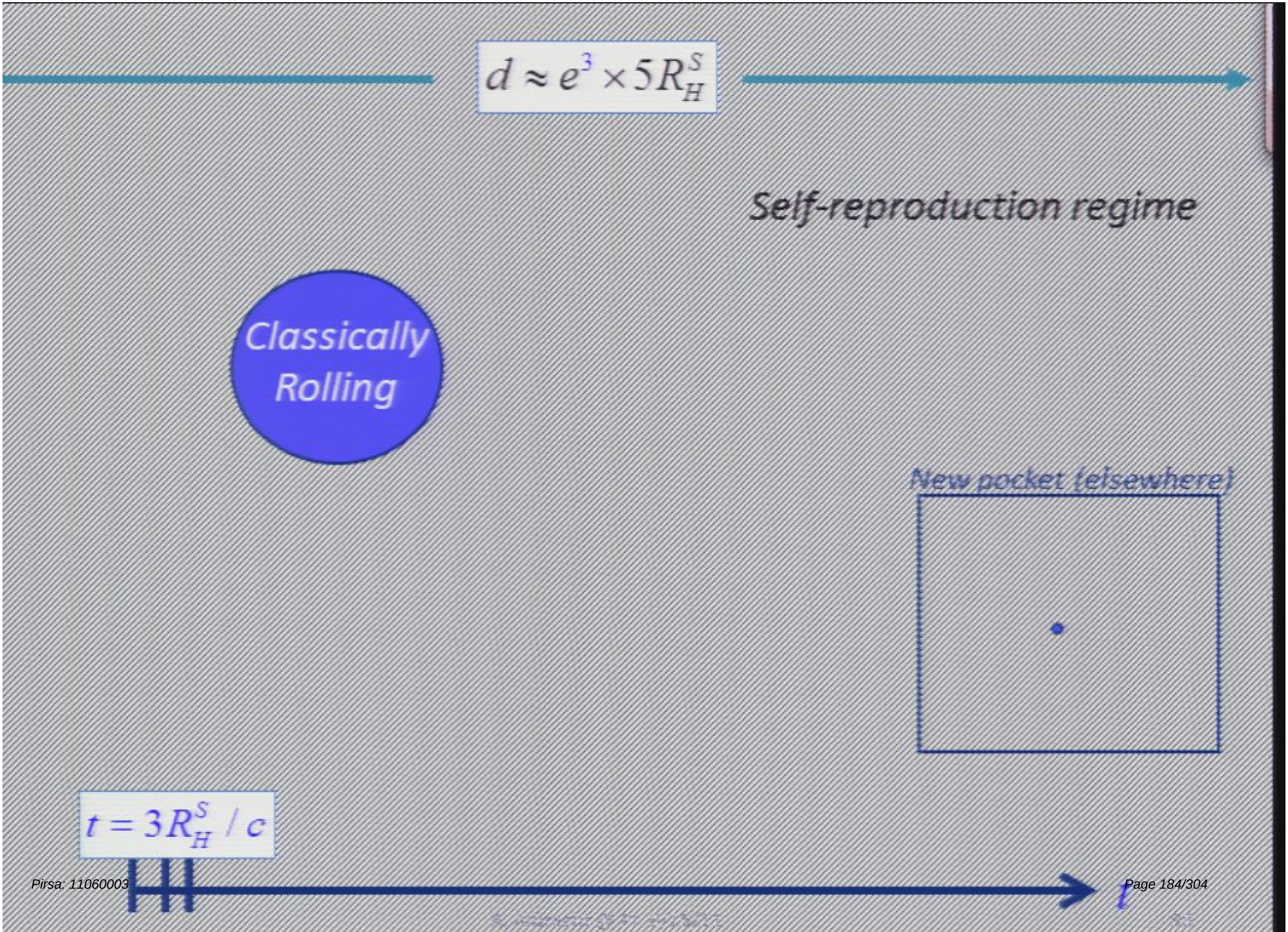
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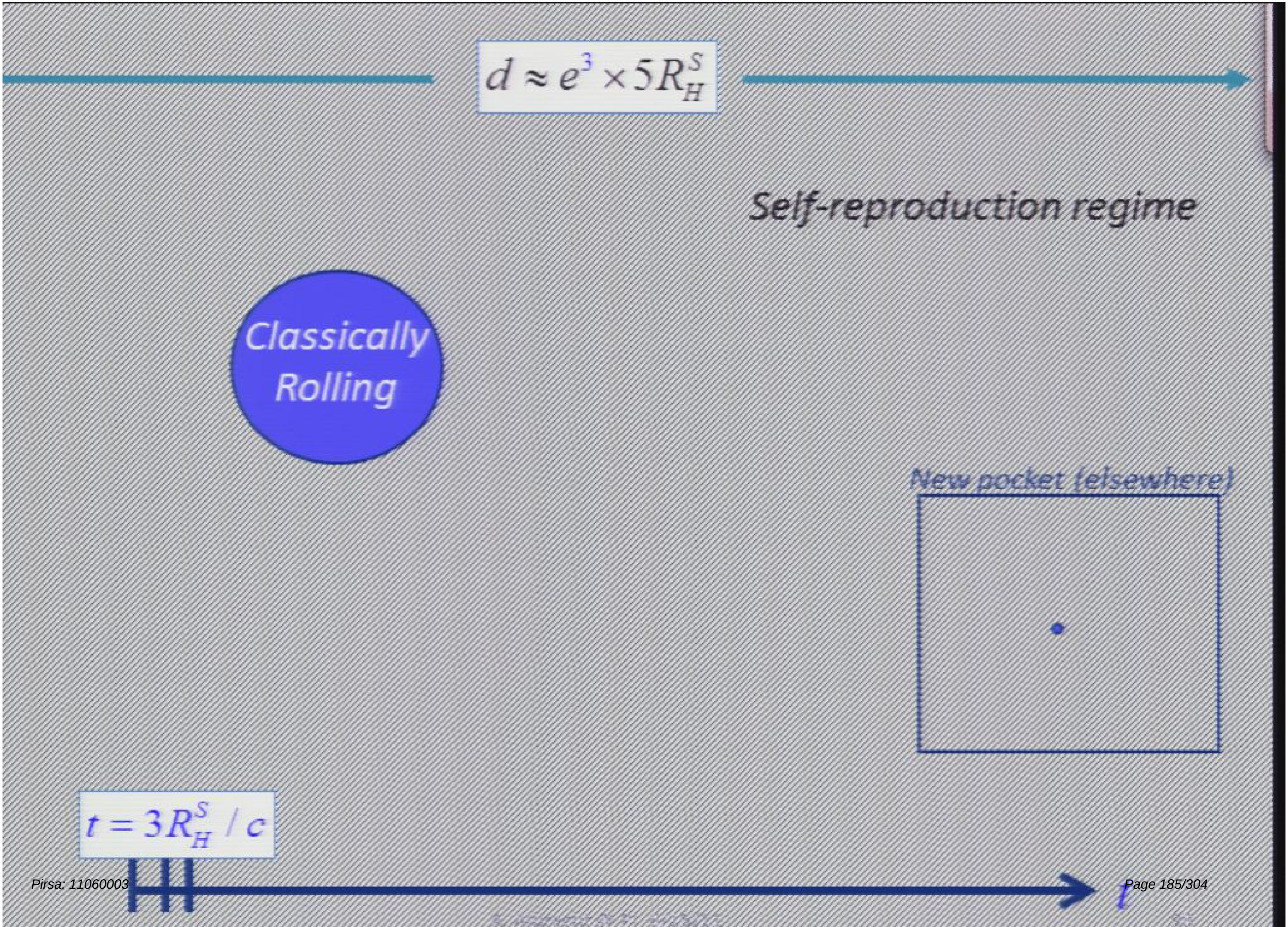
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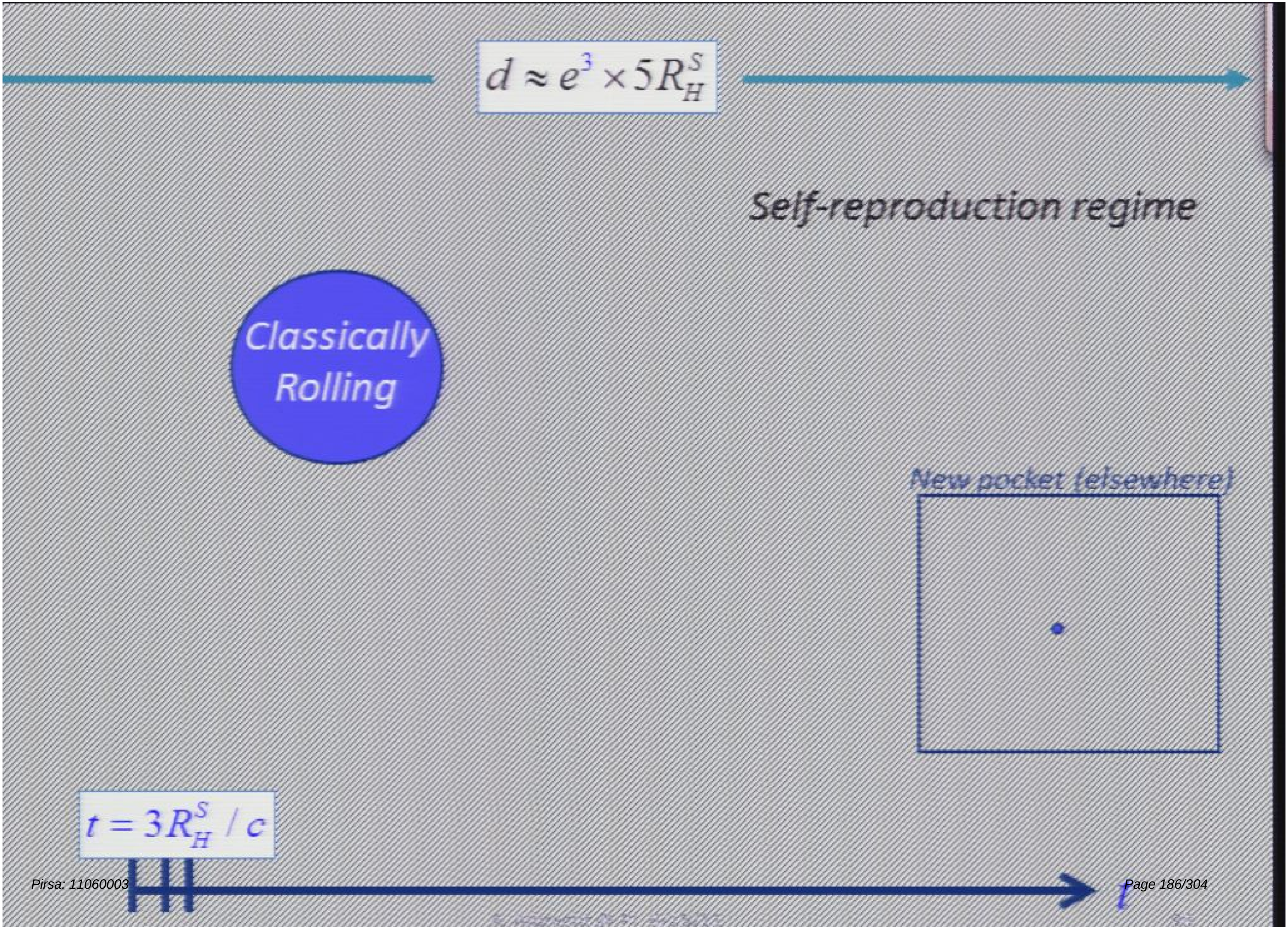
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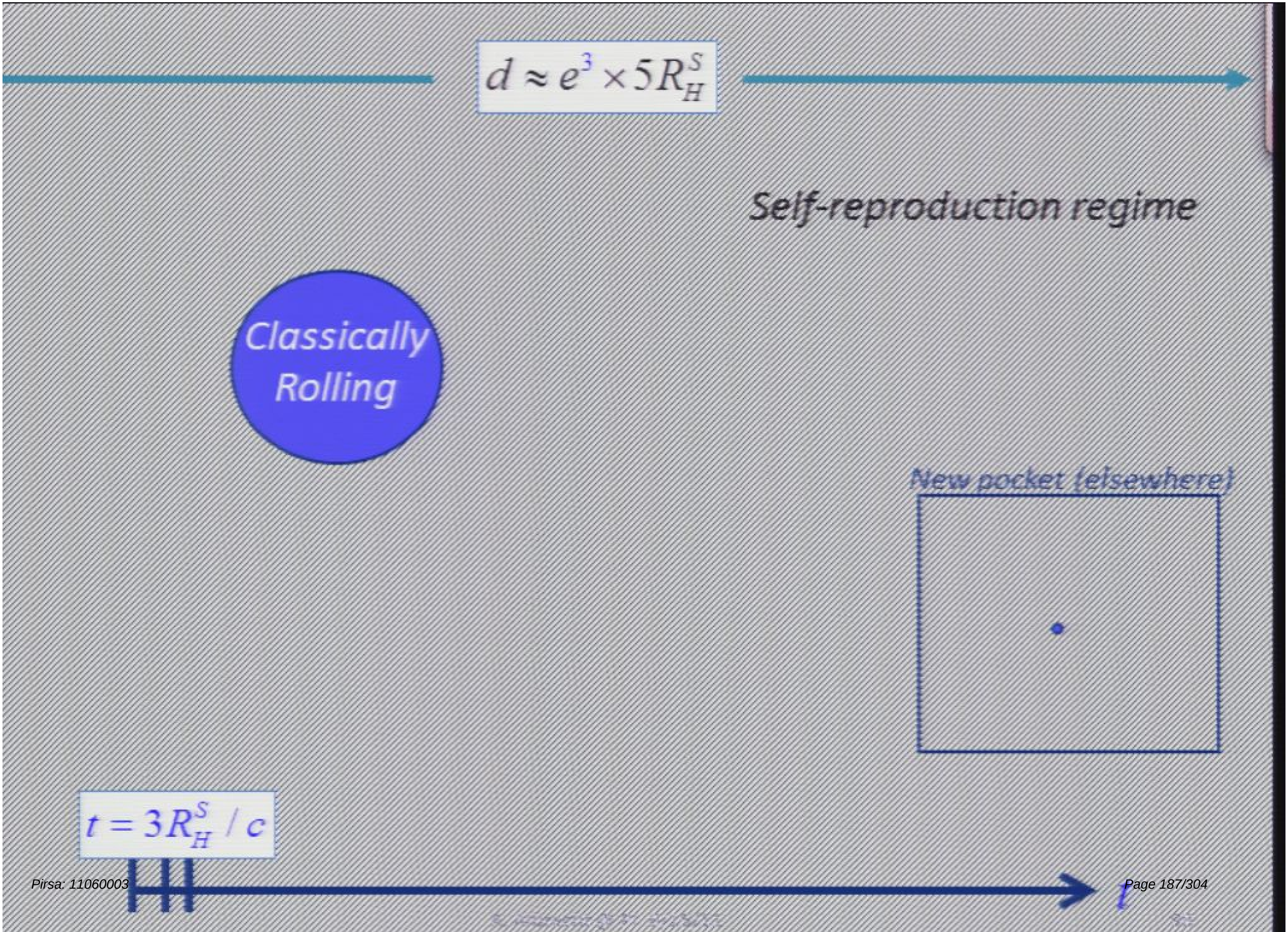
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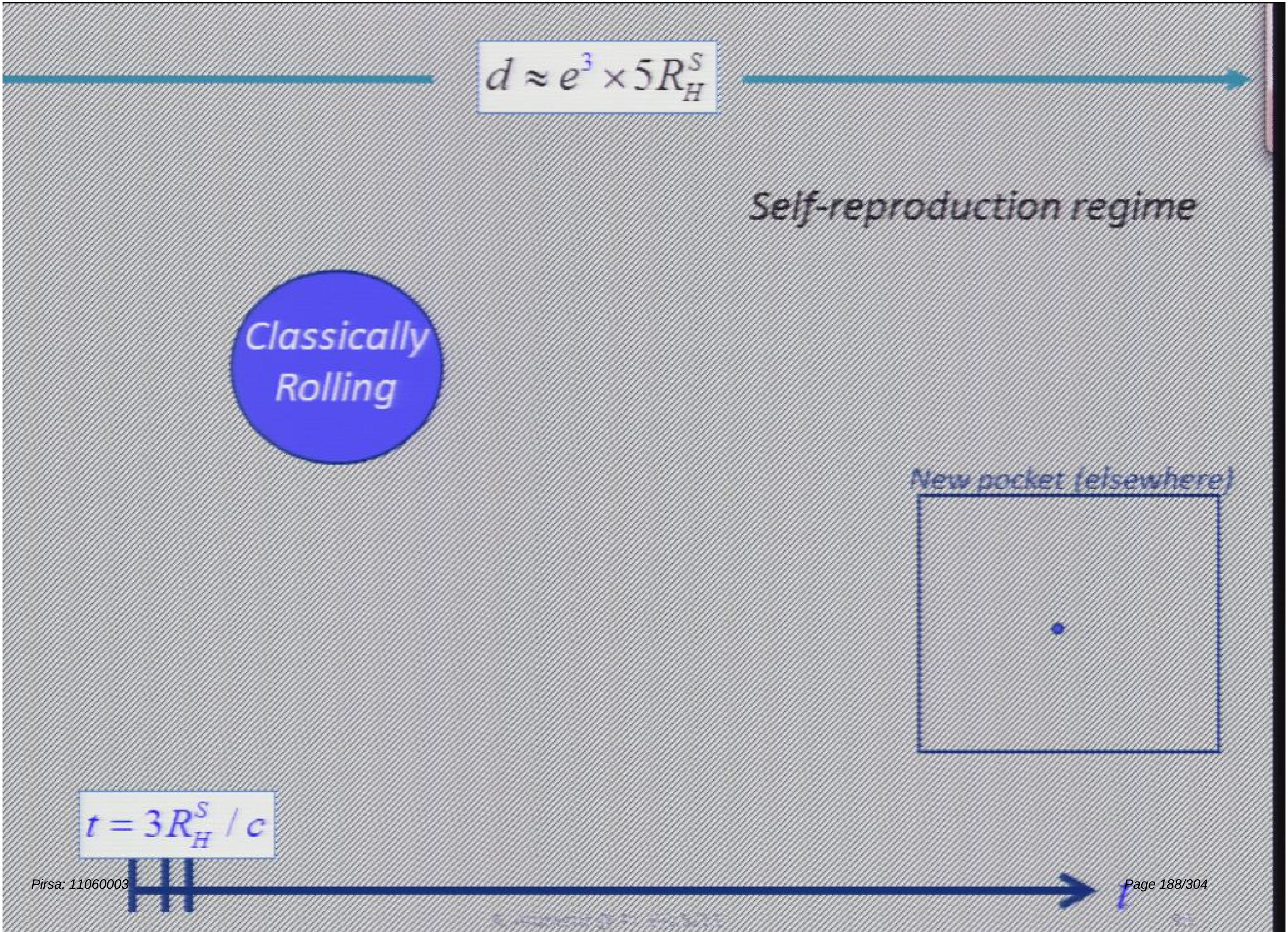
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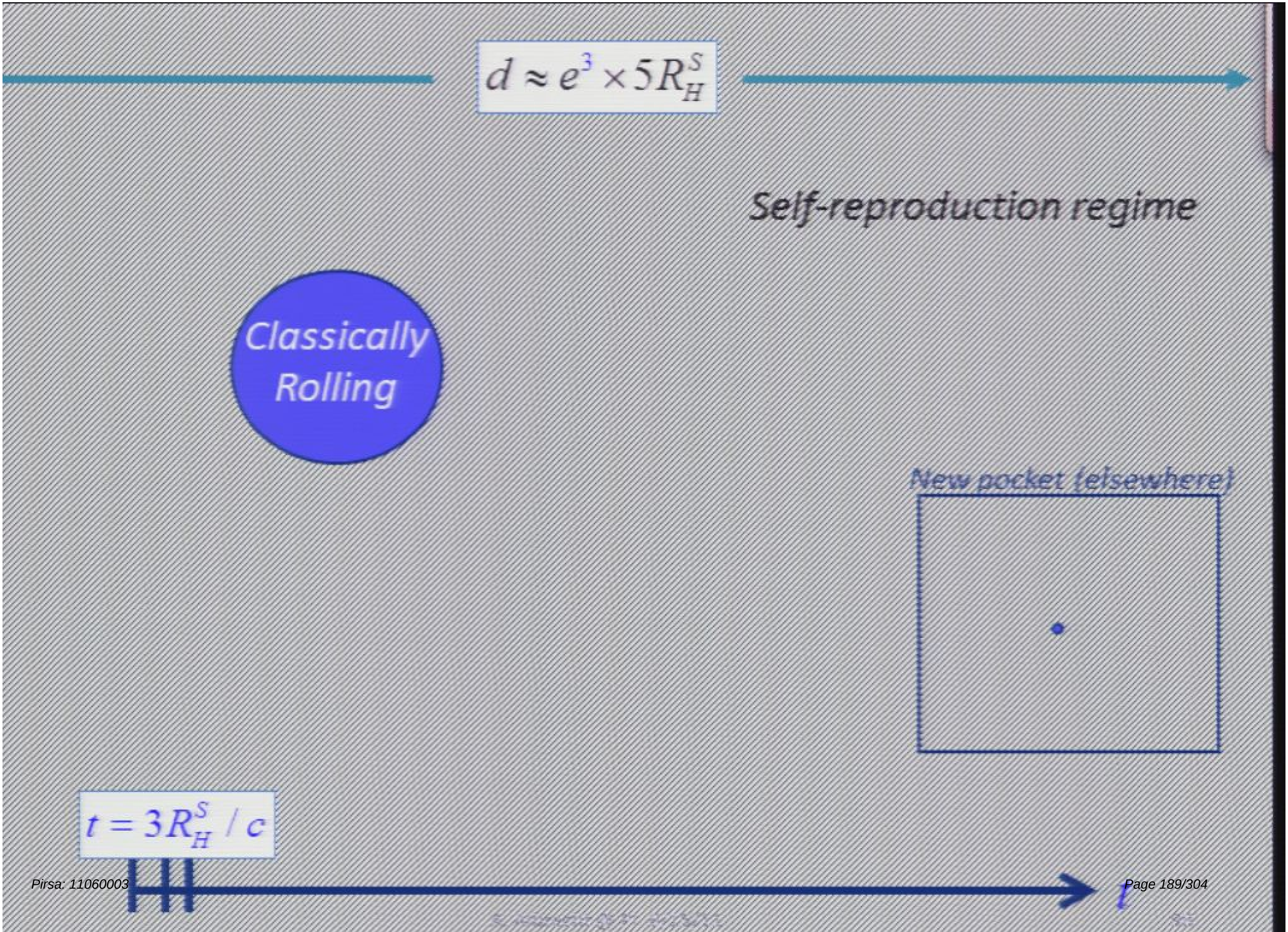
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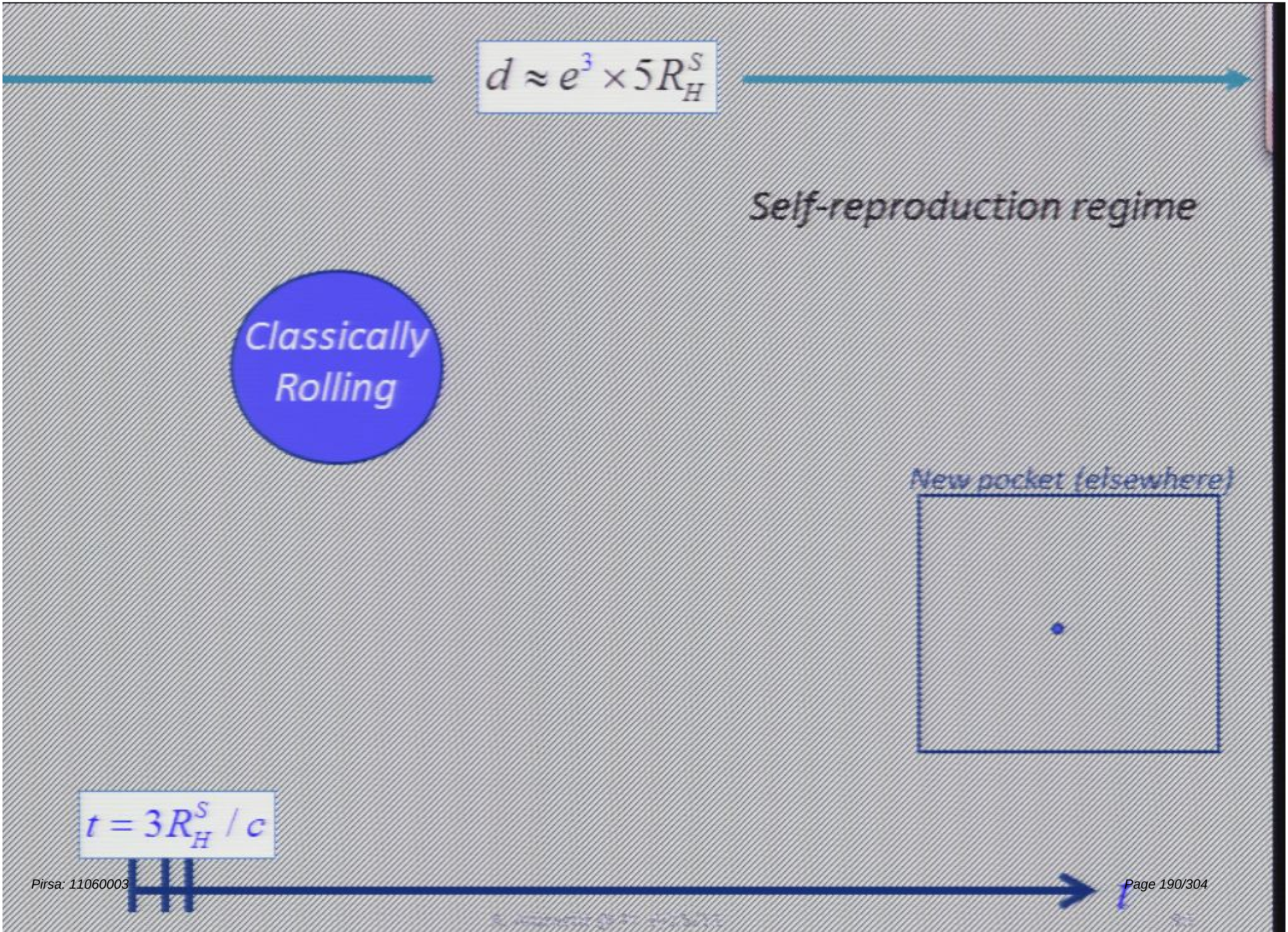
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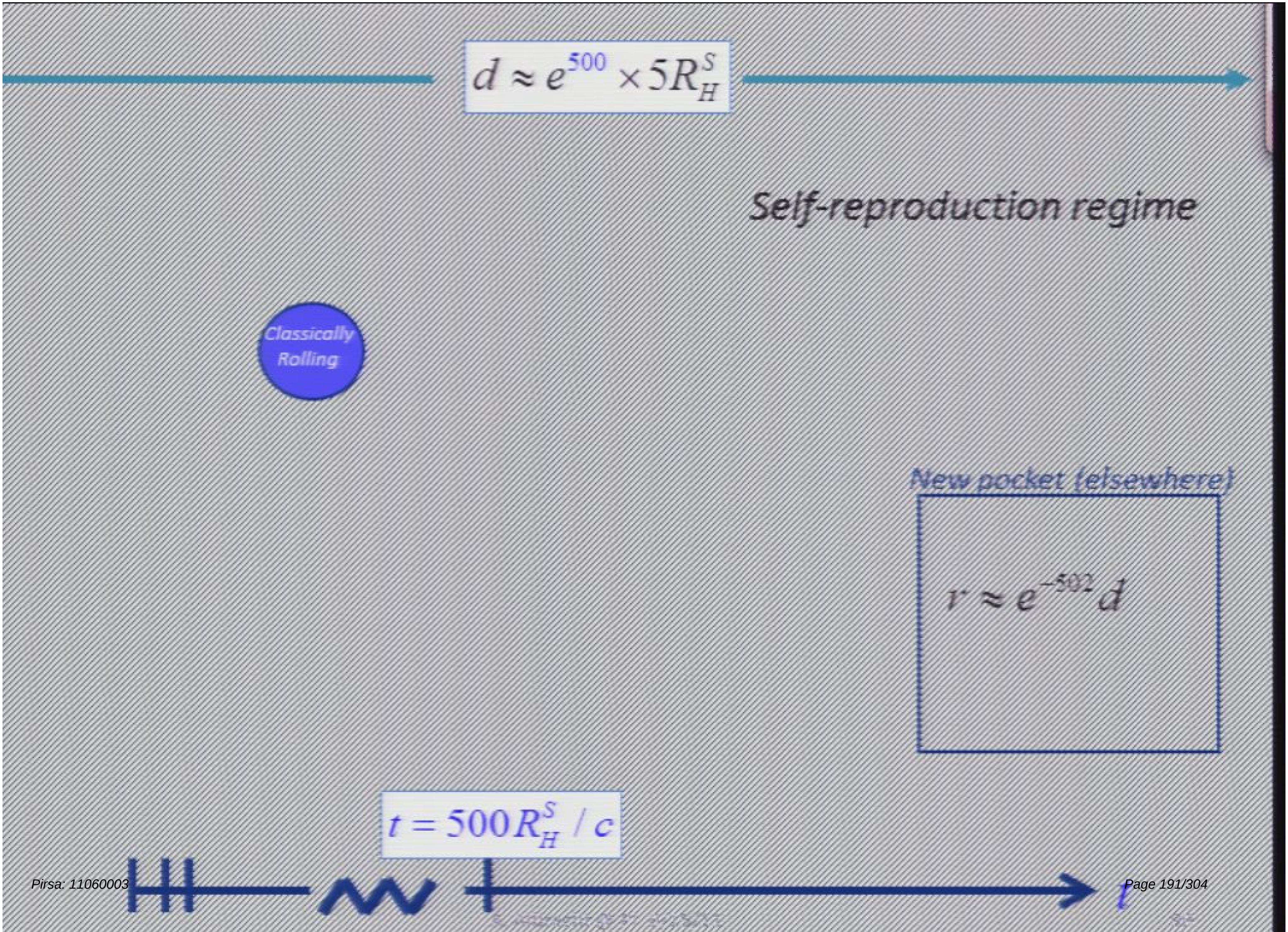

$d \approx e^{500} \times 5R_H^S$
Self-reproduction regime
Classically Rolling
New pocket (elsewhere)
$r \approx e^{-502} d$
$t = 500 R_H^S / c$
t

$$d \approx e^{500} \times 5R_H^S$$

Self-reproduction regime

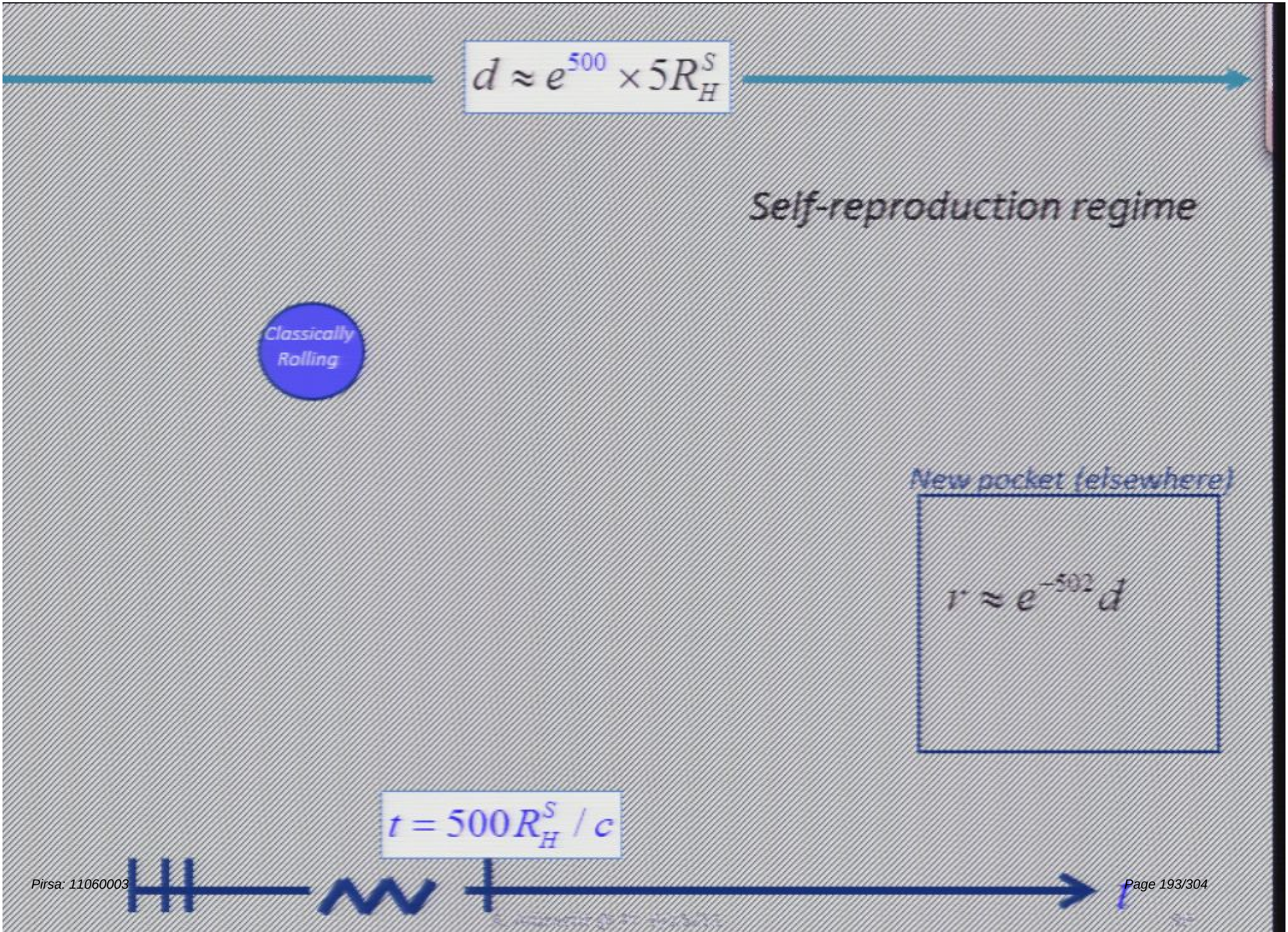
Classically Rolling

New pocket (elsewhere)

$$r \approx e^{-502} d$$

$$t = 500 R_H^S / c$$

t



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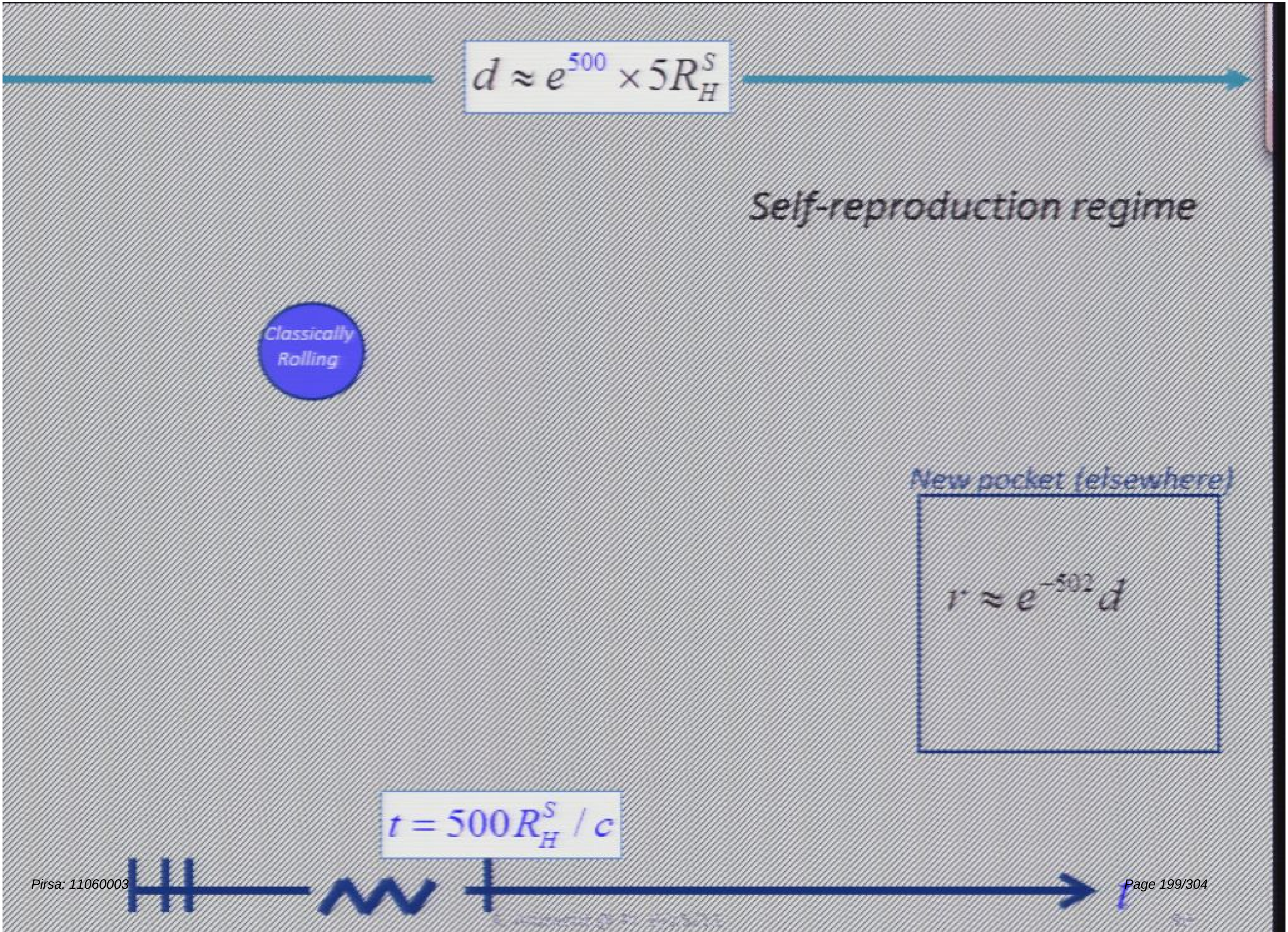
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Self-reproduction regime
Classically Rolling
New pocket (elsewhere)
$r \approx e^{-502} d$
$t = 500 R_H^S / c$
t

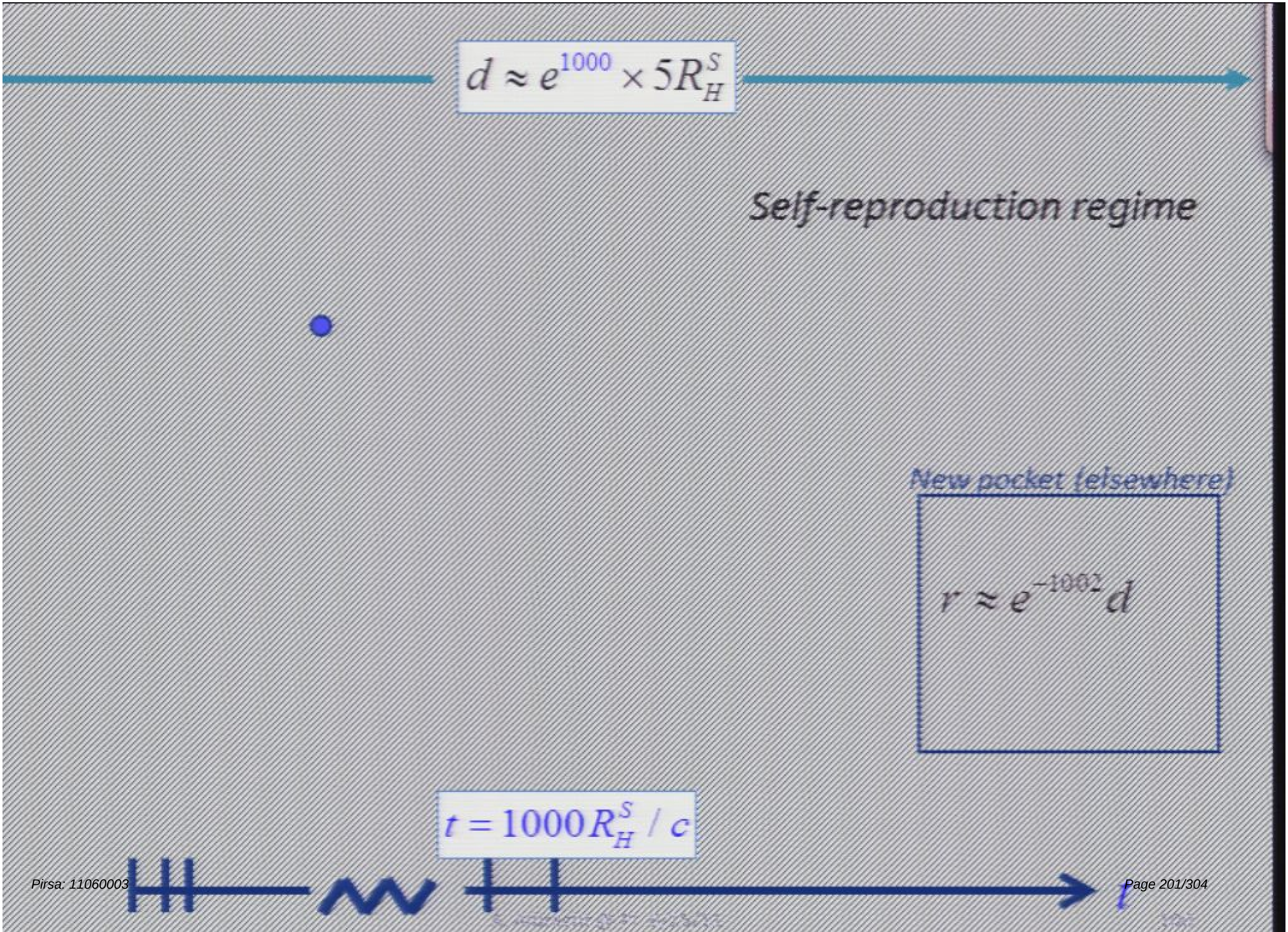
$$d \approx e^{1000} \times 5R_H^S$$

Self-reproduction regime

New pocket (elsewhere)

$$r \approx e^{-1002} d$$

$$t = 1000 R_H^S / c$$


$d \approx e^{1000} \times 5R_H^S$
Self-reproduction regime
New pocket (elsewhere)
$r \approx e^{-1002} d$
$t = 1000 R_H^S / c$
t

$$d \approx e^{1400} \times 5R_H^S$$

Self-reproduction regime

New pocket (elsewhere)

$$r \approx e^{-1402} d$$

$$t = 1400 R_H^S / c$$

t

$$d \approx e^{1400} \times 5R_H^S$$

Self-reproduction regime

New pocket (elsewhere)

$$r \approx e^{-1402} d$$

$$t = 1400 R_H^S / c$$

t

$$d \approx e^{1400} \times 5R_H^S$$

Self-reproduction regime

New pocket (elsewhere)

$$r \approx e^{-1402} d$$

$$t = 1400 R_H^S / c$$

t

$$d \approx e^{1395} \times 5R_H^S$$

Self-reproduction regime

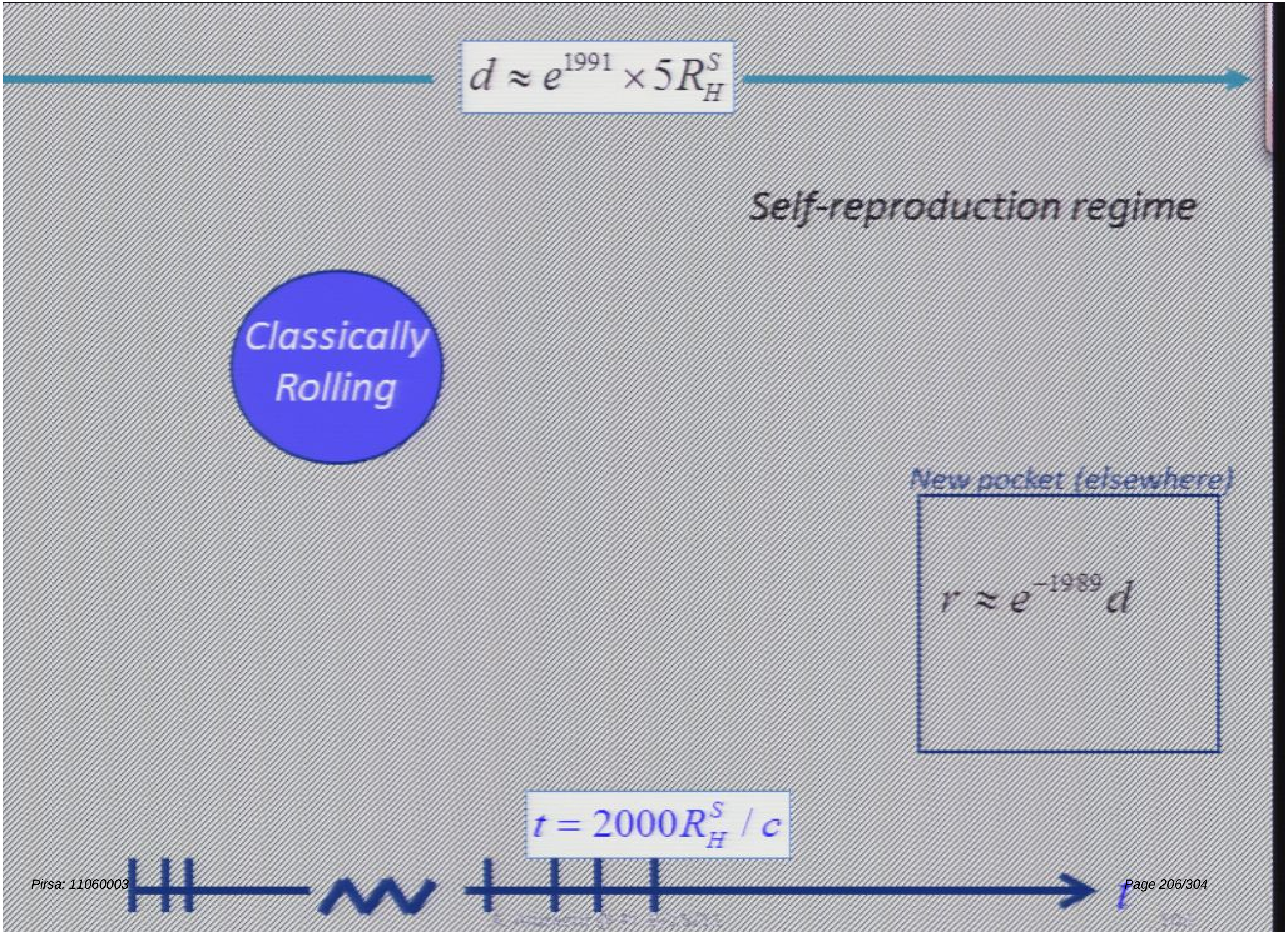
Classically Rolling

New pocket (elsewhere)

$$r \approx e^{-1393} d$$

$$t = 1400 R_H^S / c$$

t


$d \approx e^{1991} \times 5R_H^S$
Self-reproduction regime
Classically Rolling
New pocket (elsewhere)
$r \approx e^{-1989} d$
$t = 2000 R_H^S / c$
t

$$d \approx e^{534395} \times 5R_H^S \equiv R_H^{Iend}$$

Self-reproduction regime

Classically Rolling

New pocket (elsewhere)

$$r \approx e^{-534393} d$$

$$t = (602,785)\, R_H^S / c$$

t

$$d \approx e^{534395} \times 5 R_H^S \equiv R_H^{Iend}$$

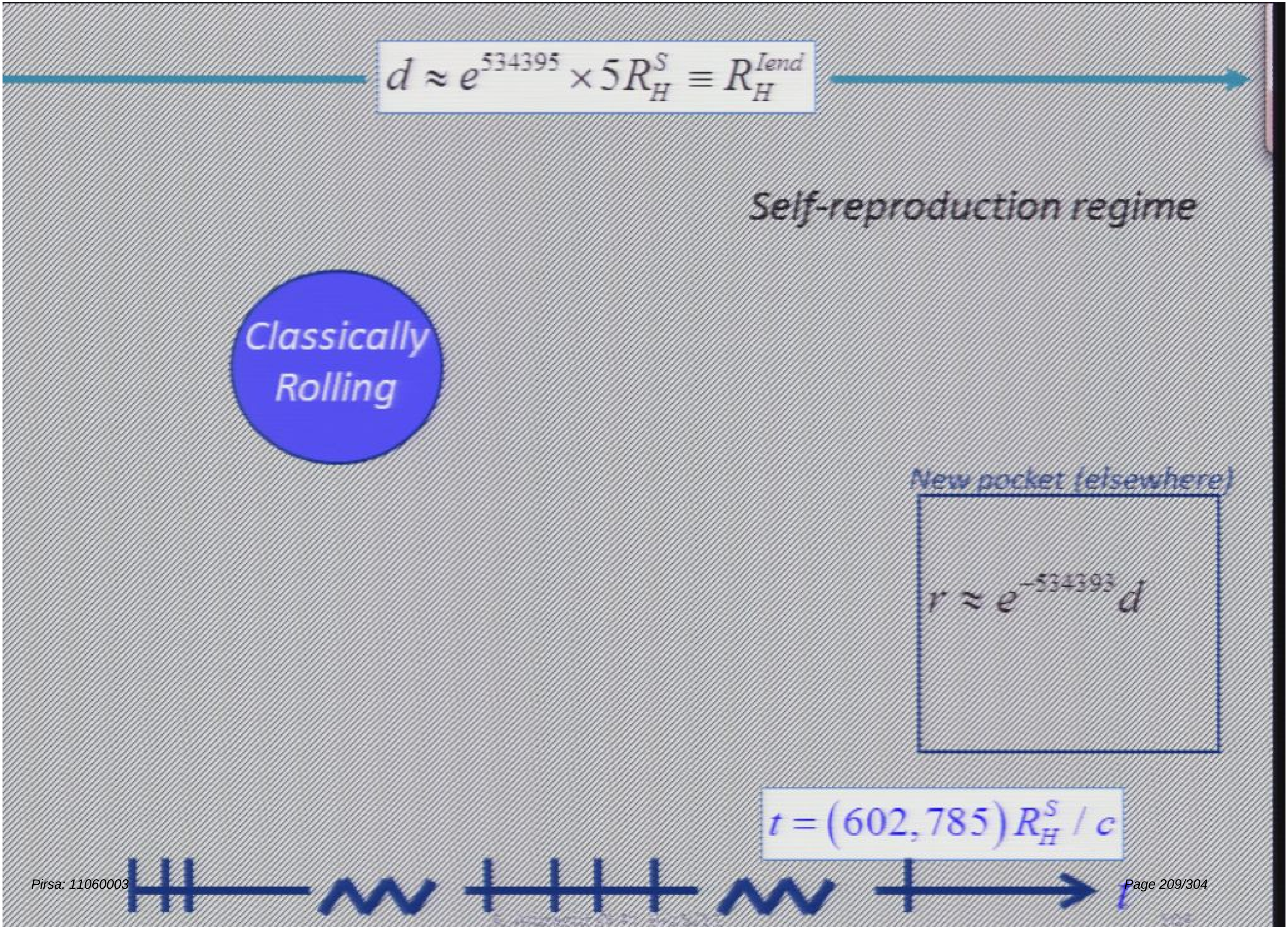
Self-reproduction regime

Classically Rolling

New pocket (elsewhere)

$$r \approx e^{-534393} d$$

$$t = (602,785)\, R_H^S / c$$



$d \approx e^{534395} \times 5R_H^S \equiv R_H^{Iend}$
Self-reproduction regime
Classically Rolling
New pocket (elsewhere)
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$t = (602,785) R_H^S / c$
t

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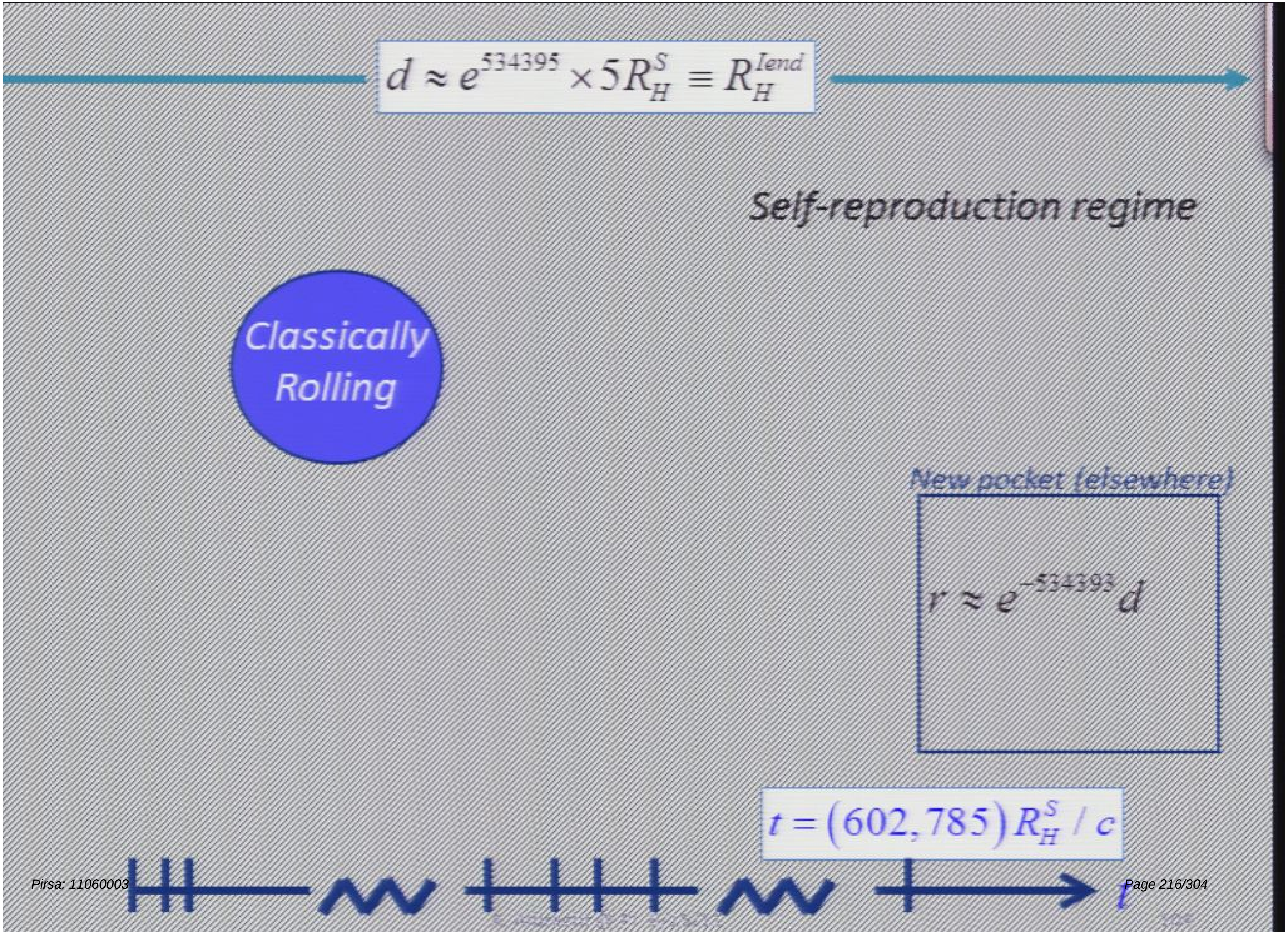
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t

$$d \approx e^{534395} \times 5R_H^S \equiv R_H^{Iend}$$

Self-reproduction regime

← Reheating

New pocket (elsewhere)

$$r \approx e^{-534393} d$$

$$t = 2R_H^{Iend} / c$$

$$d \approx e^{534395} \times 5R_H^S \equiv R_H^{Iend}$$

Self-reproduction regime

Reheating

New pocket (elsewhere)

$$r \approx e^{-534393} d$$

$$t = 2R_H^{Iend} / c$$

t

$$d \approx e^{534395} \times 5R_H^S \equiv R_H^{Iend}$$

Self-reproduction regime

Radiation Era

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A. 115

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Eternal inflation

Multiply by 10^{500} to get landscape story!

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> ➢ Multiple (∞) copies of "you" in the wavefunction ➔ Page's "Born Rule Crisis"

em

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A. 118

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A. 119

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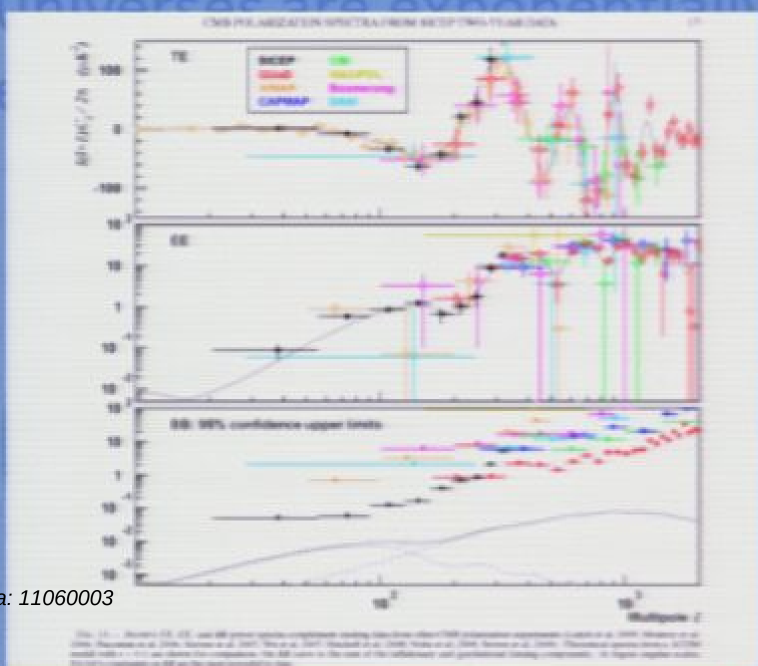
➢ Young universe problem

Or, just be happy we have equations to solve?

➢ State ... making predictions, the experts are using the data to infer the "correct measure"



roblem has been detected and your calculation has been shut down
prevent damage

ATIVE_PROBABILITY_OVERFLOW

this is the first time you have seen this stop error screen,
tart your calculation. If this screen appears again, follow
se steps:

ck to make sure all extrapolations are justified and equations
valid. If you are new to this calculation consult your theory
ufacturer for any measure updates you might need.

the problems continue, disable or remove features of the theory
t cause the overflow error. Disable BS options such as self-
roduction or infinite time. If you need to use safe mode to
ove or disable components, restart your computation and utilize S_Λ
select holographic options.

OUTLINE

1. Big Bang & inflation basics
2. Eternal inflation ⬅
3. de Sitter Equilibrium cosmology
4. Cosmic curvature from de Sitter Equilibrium cosmology

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de Sitter Equilibrium (dSE) cosmology

- Take ideas from Holography, Λ to construct a finite cosmology

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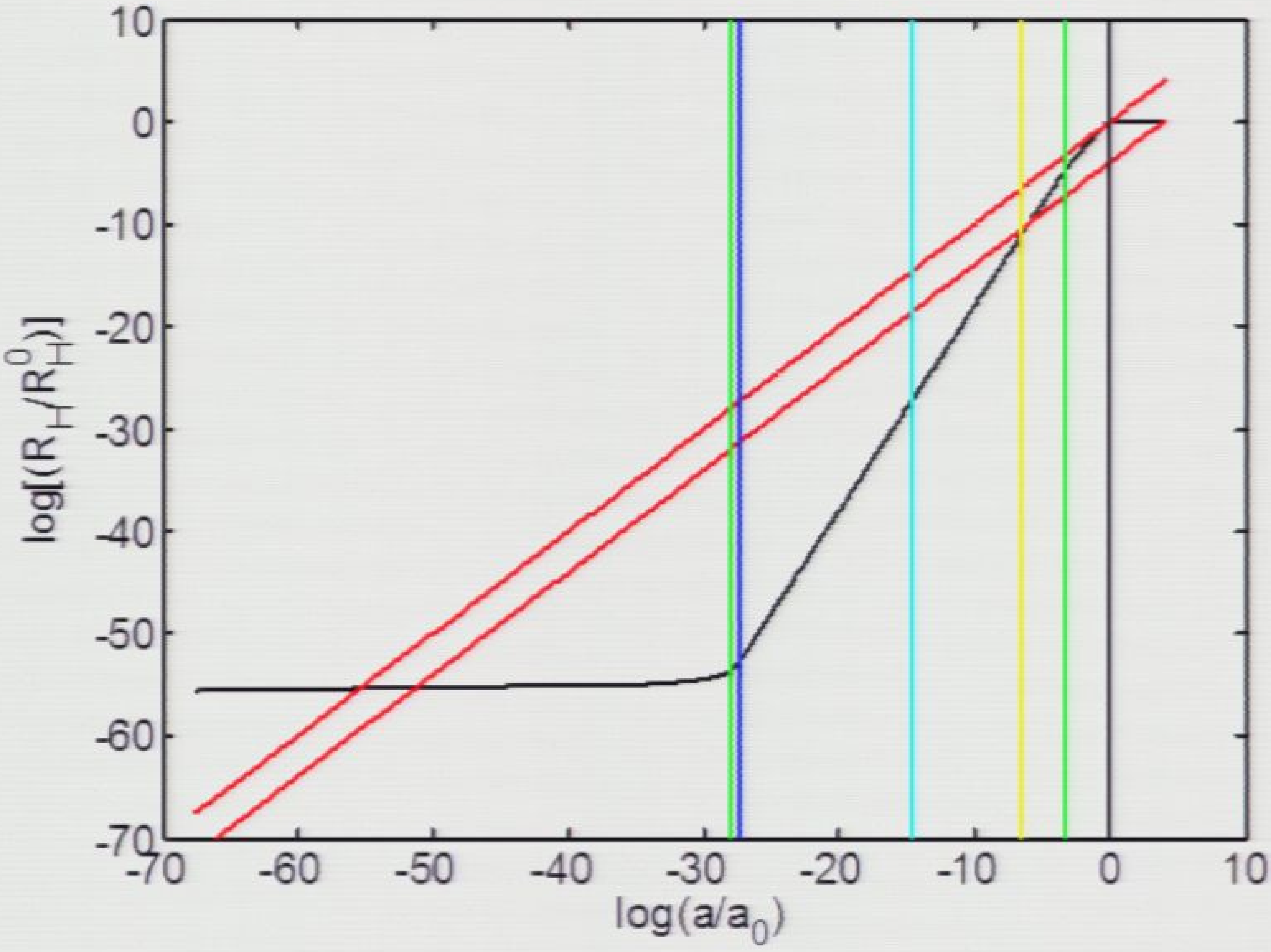
AA: arXiv:1104.3315
AA: arXiv:0906.1047
AA & Sorbo: hep-th/0405270



10
0
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-40
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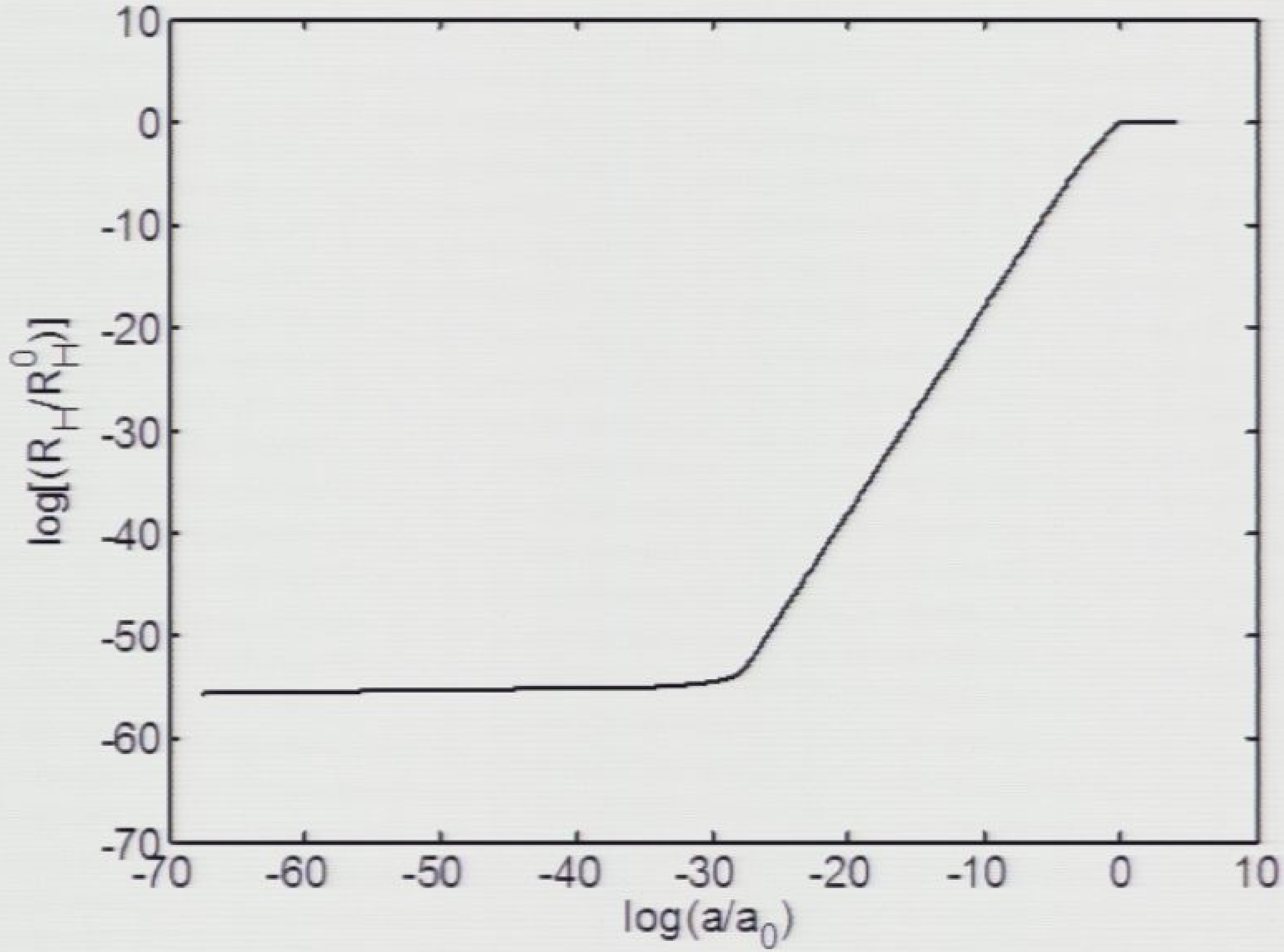
-60
-70
log[(R_H/R_H^0)]
-70
-60
-50
-40
-30
-20
-10
0
10
log(a/a_0)



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-40
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-10
0
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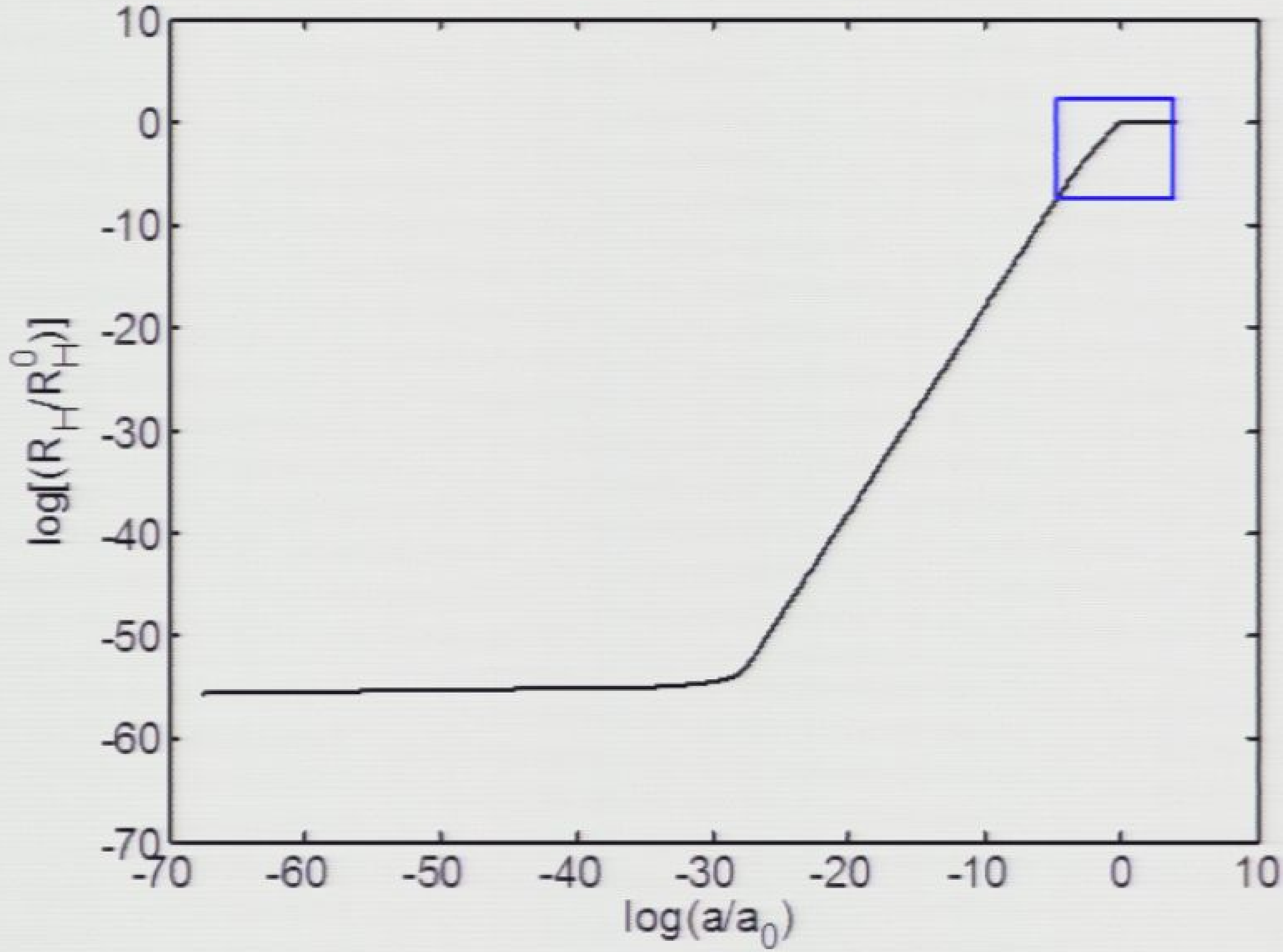
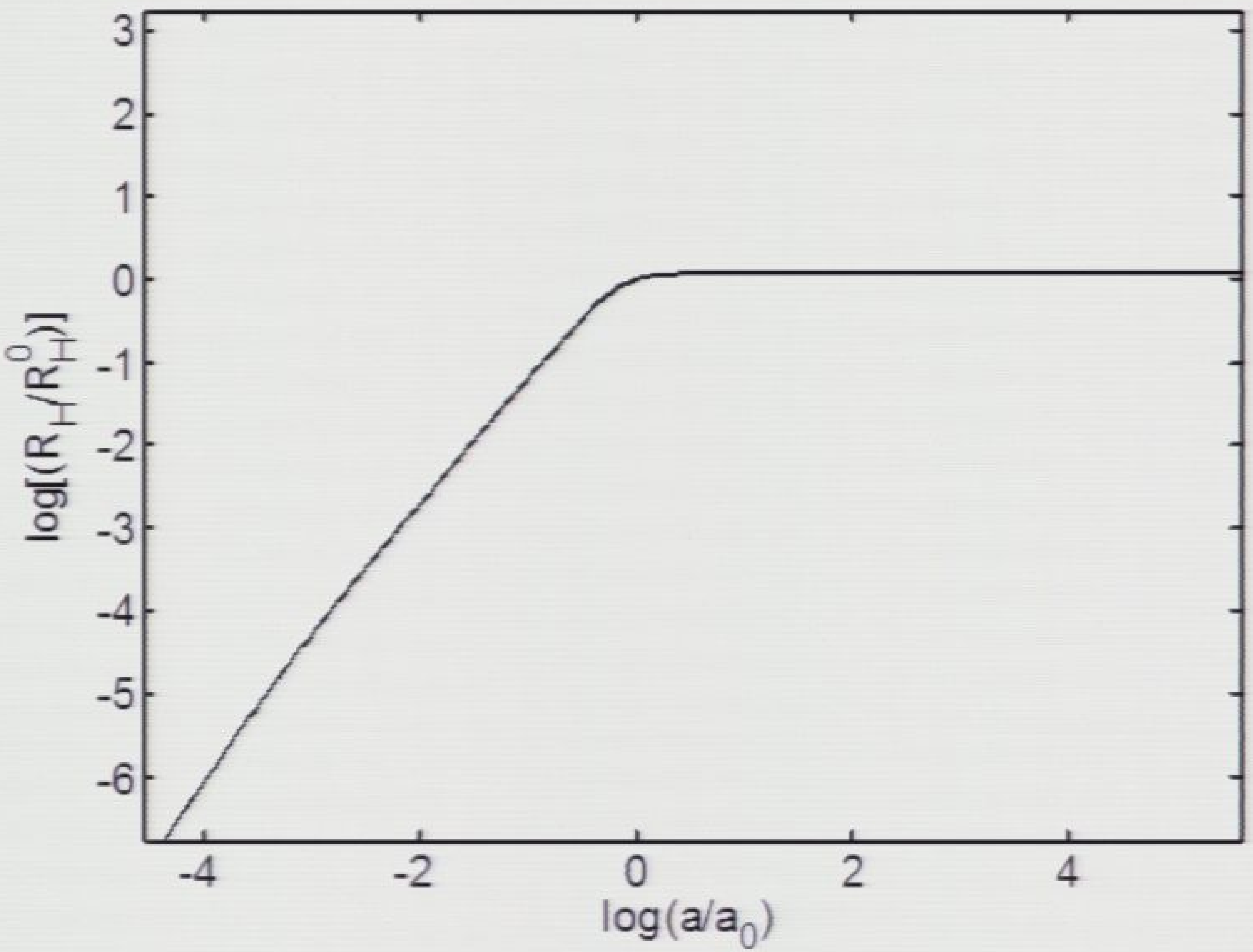
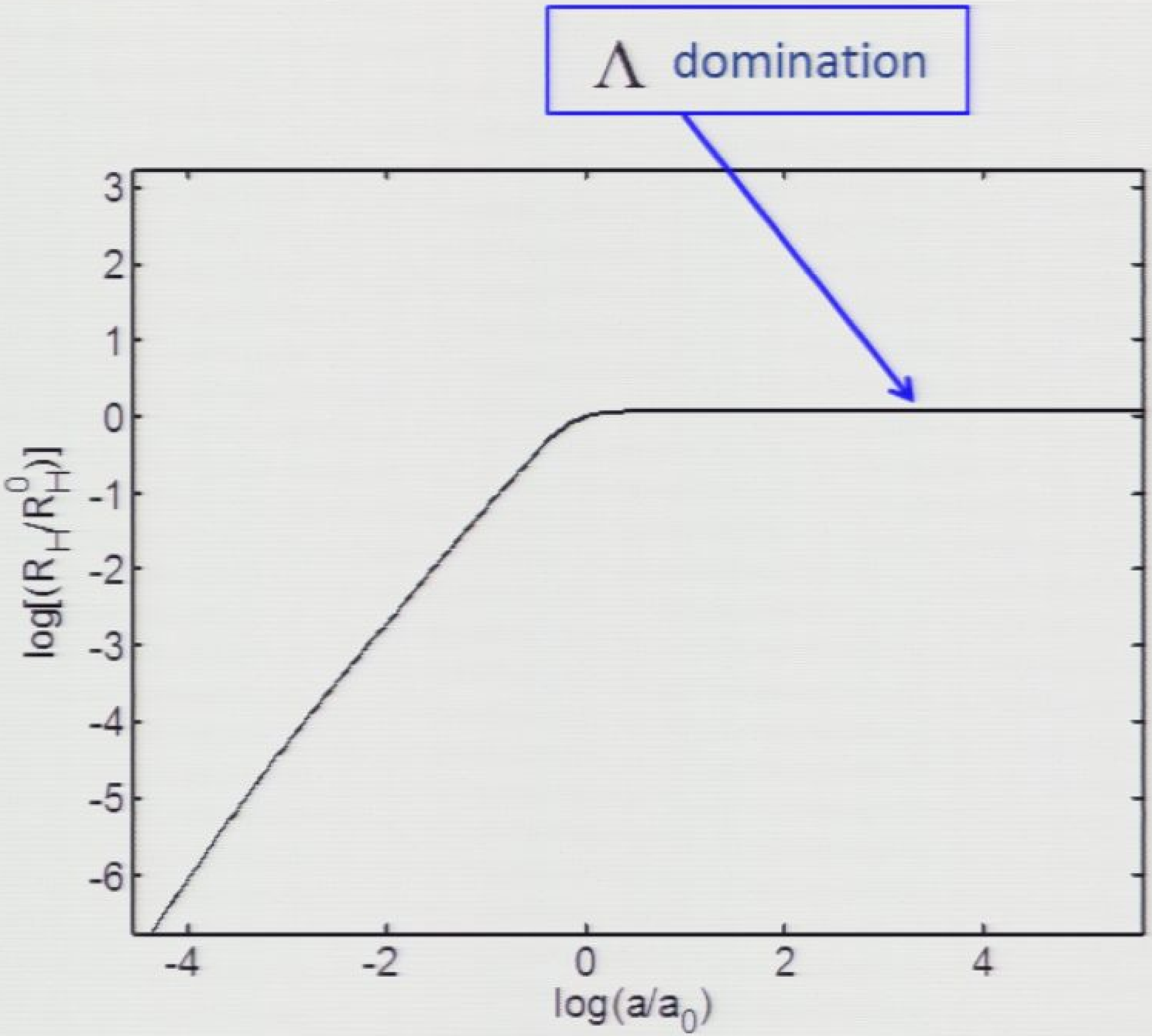
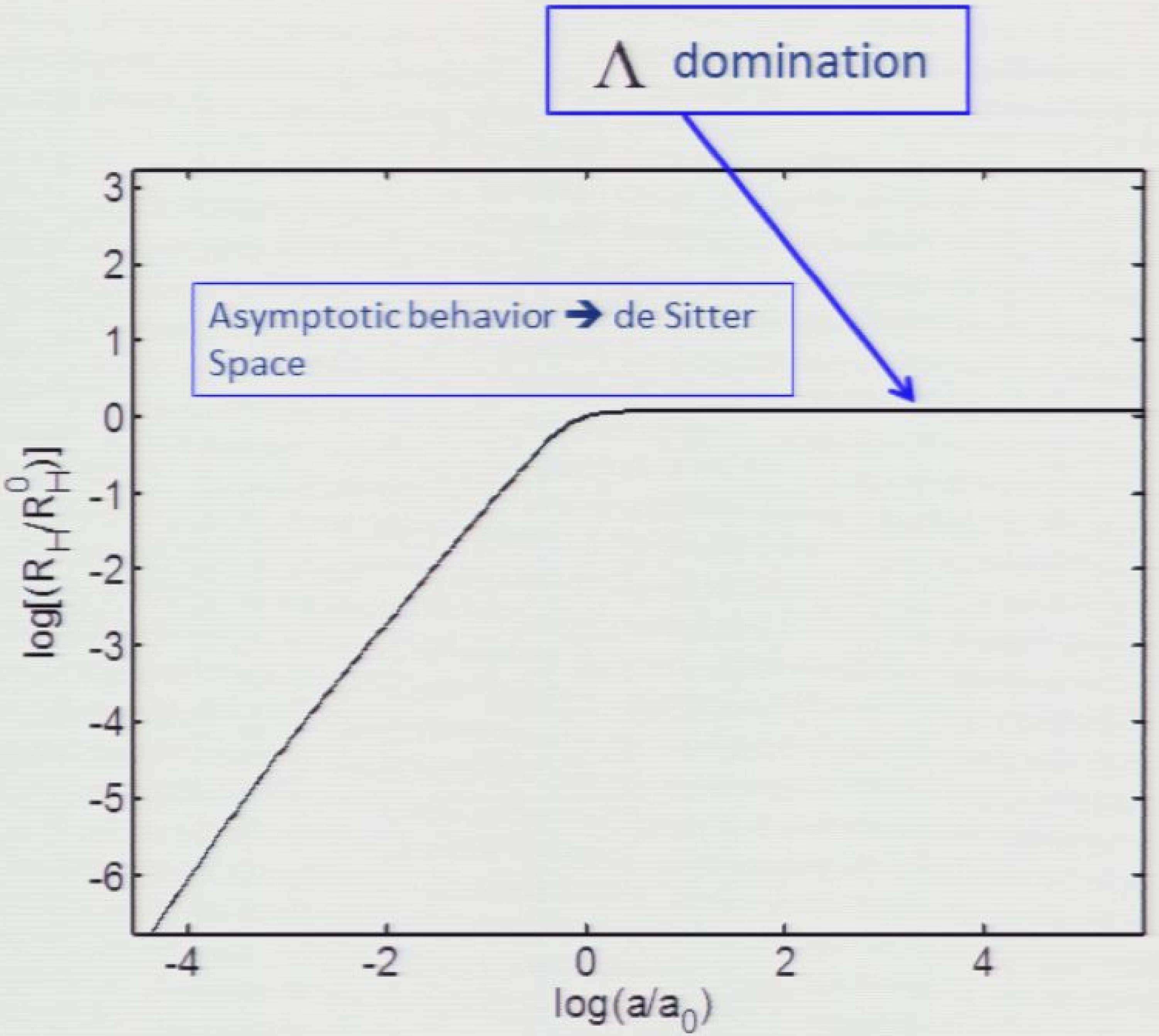


log[(R_H/R_H^0)]
log(a/a_0)
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10

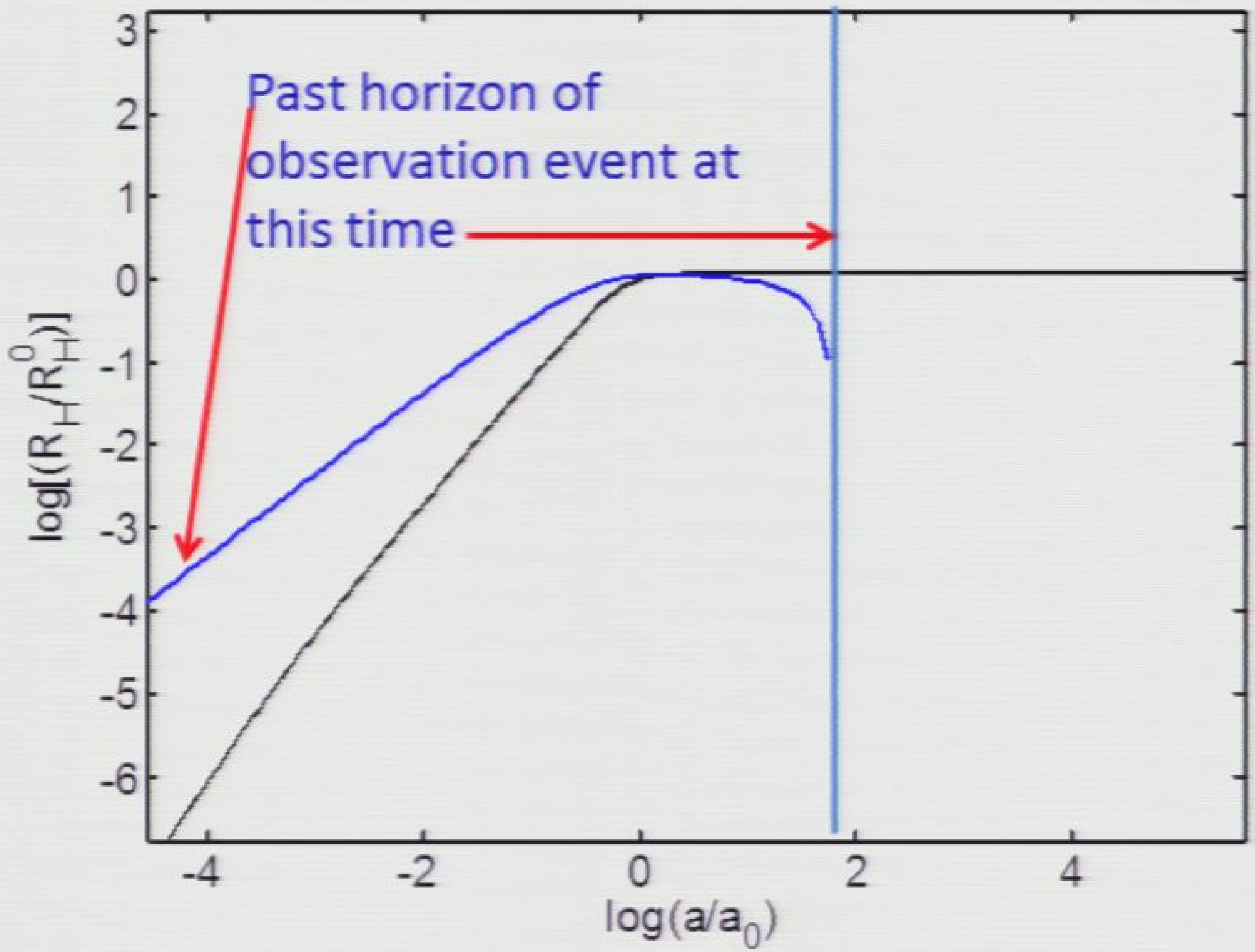


3
2
1
0
-1
-2
-3
-4
-5
-6
log[(R_H/R_H^0)]
-4
-2
0
2
4
log(a/a_0)


Λ domination
log[(R_H/R_H^0)]
3
2
1
0
-1
-2
-3
-4
-5
-6
-4
-2
0
2
4
log(a/a_0)

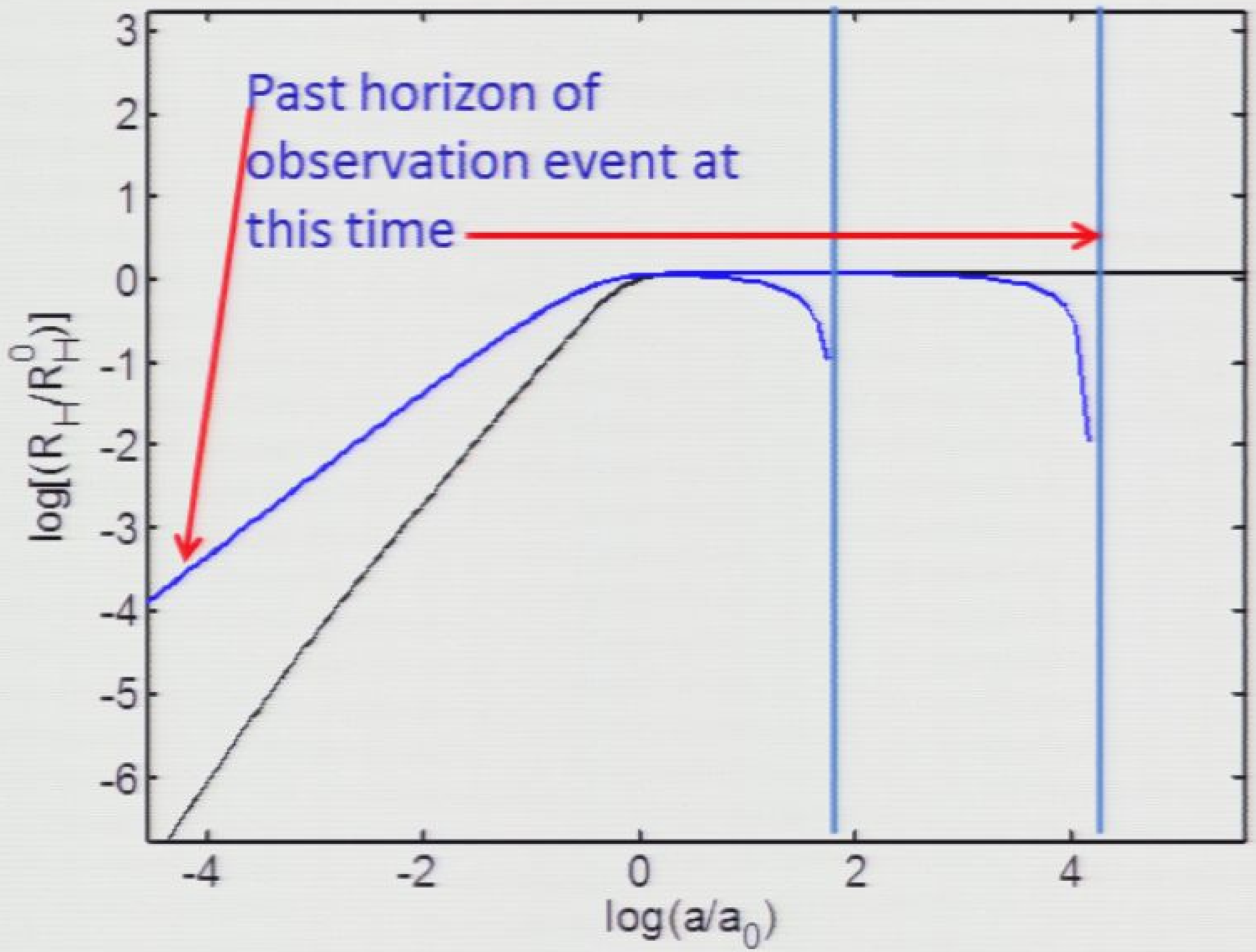

Λ domination
Asymptotic behavior → de Sitter Space
log[(R_H/R_H^0)]
log(a/a_0)
3
2
1
0
-1
-2
-3
-4
-5
-6
-4
-2
0
2
4

ne de Sitter horizon



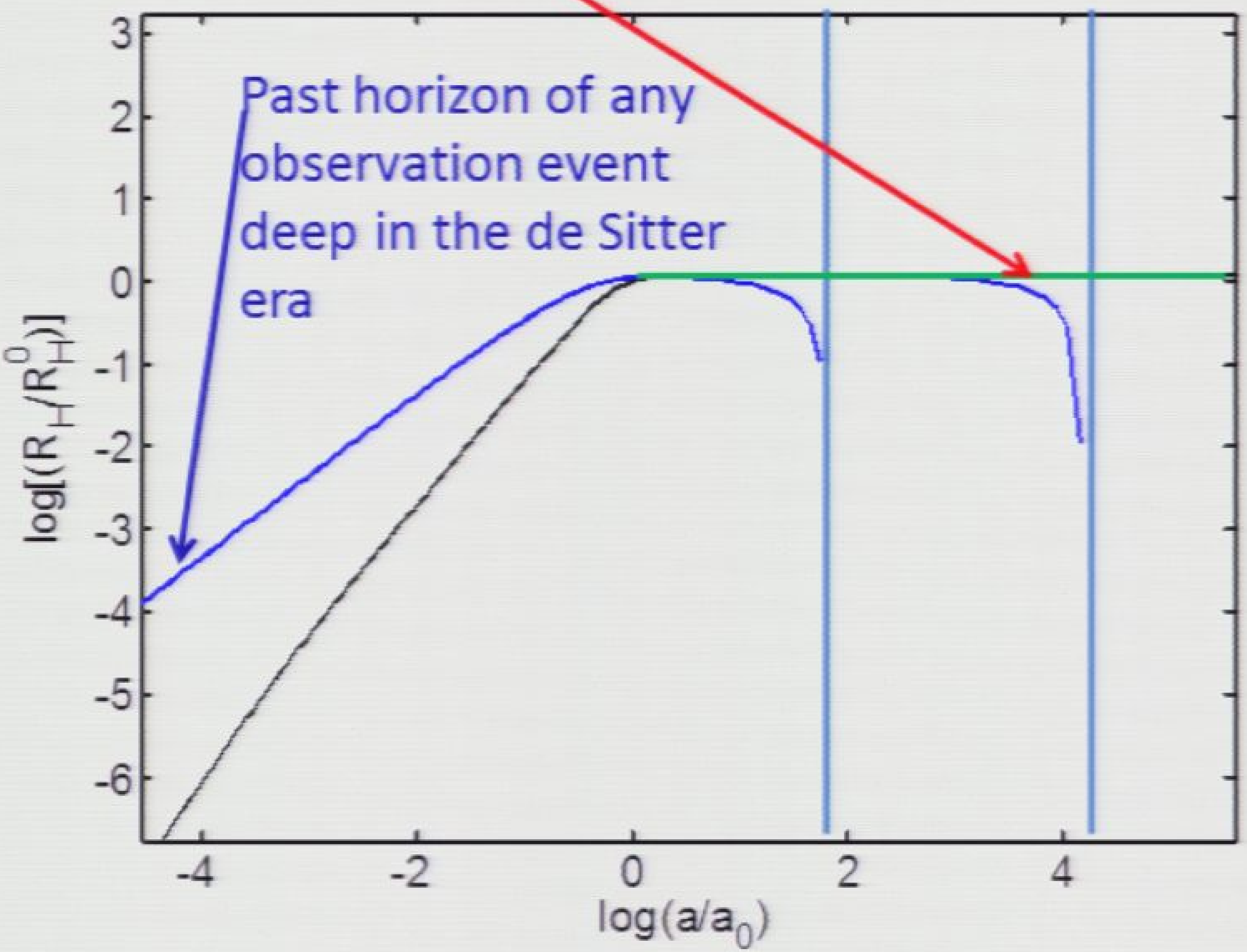
Past Horizon: Physical distance from (comoving) observer of a photon that will

ne de Sitter horizon



Past Horizon: Physical distance from (comoving) observer of a photon that will reach the observer at the time of the observation

he de Sitter horizon



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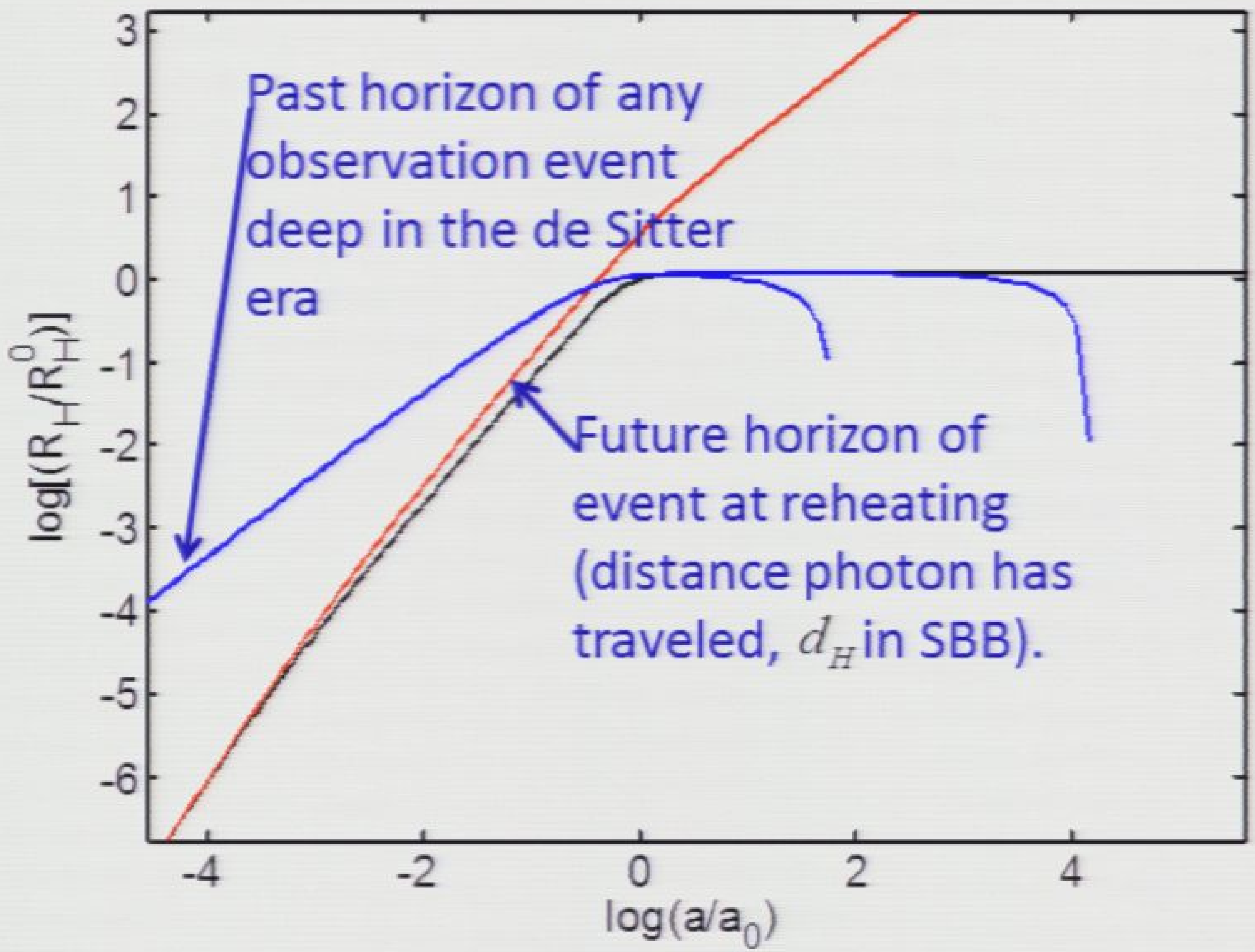

Past Horizon: Physical distance from (comoving) observer of a photon that will

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- Maximum entropy

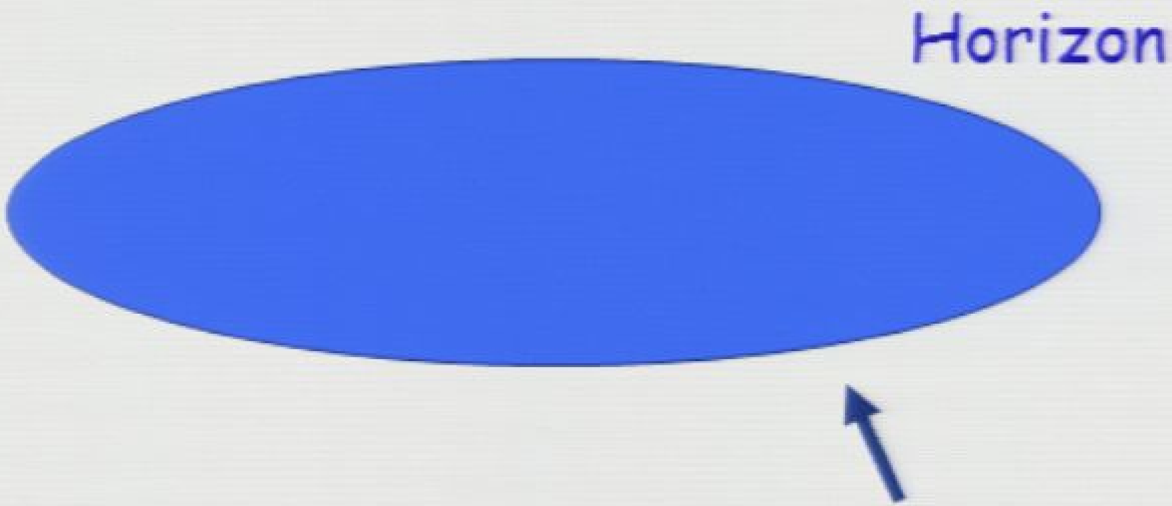
$$S_\Lambda \propto A = H_\Lambda^{-2} = \left(\frac{\Lambda}{3}\right)^{-1}$$

- Gibbons-Hawking Temperature

$$T_{GH} = H_\Lambda = \sqrt{\frac{8\pi G}{3}\rho_\Lambda}$$

Gibbons & Hawking 1977

"De Sitter Space: The ultimate equilibrium for the universe?



$$S \propto A = H^{-2} = \Lambda^{-1}$$

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- Only a finite volume ever observed
- If Λ is truly constant: Cosmology as fluctuating Eqm.
- Maximum entropy $\longrightarrow$ finite Hilbert space of dimension $N = e^{S_\Lambda}$

Banks & Fischler & Dyson et al.

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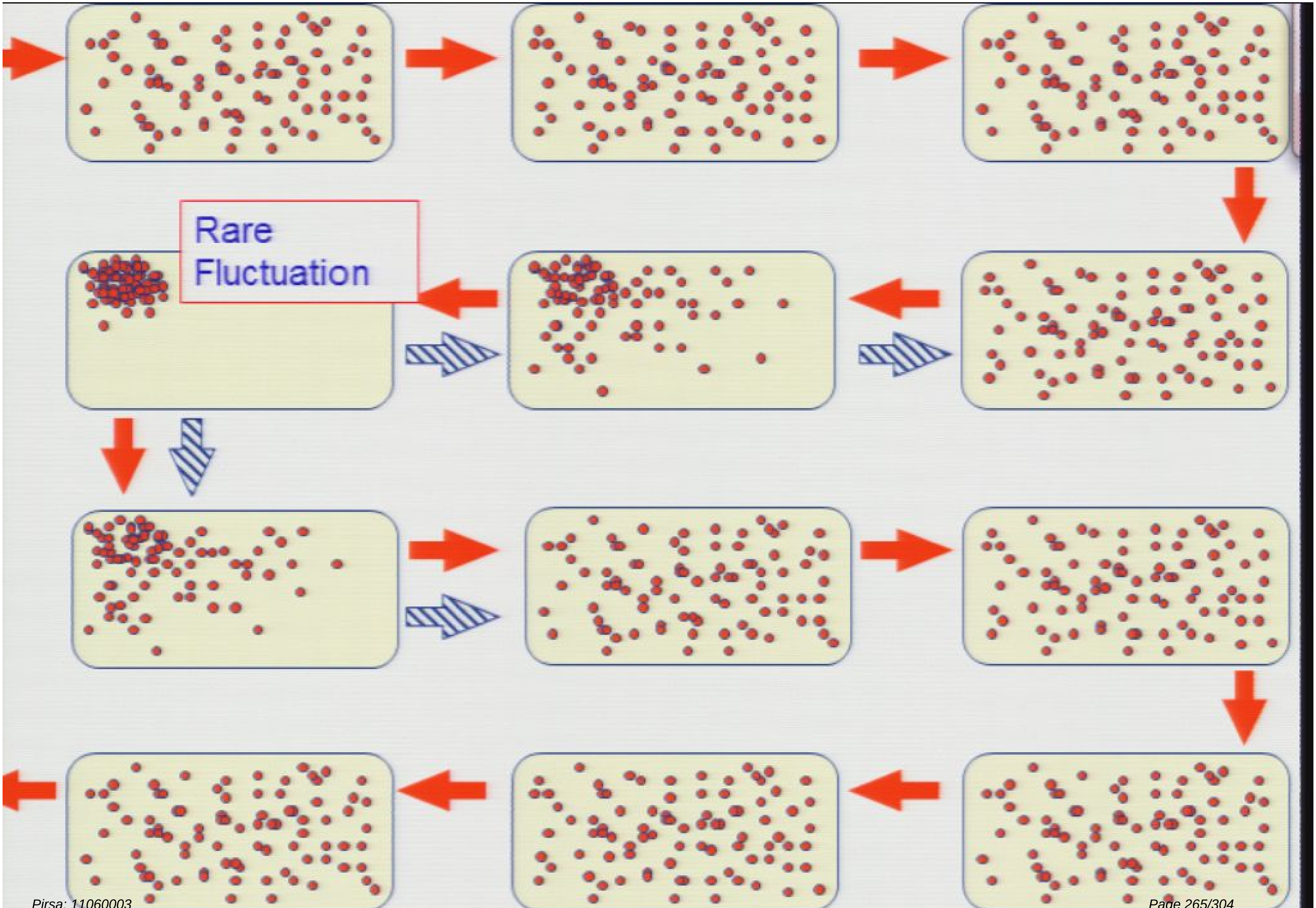
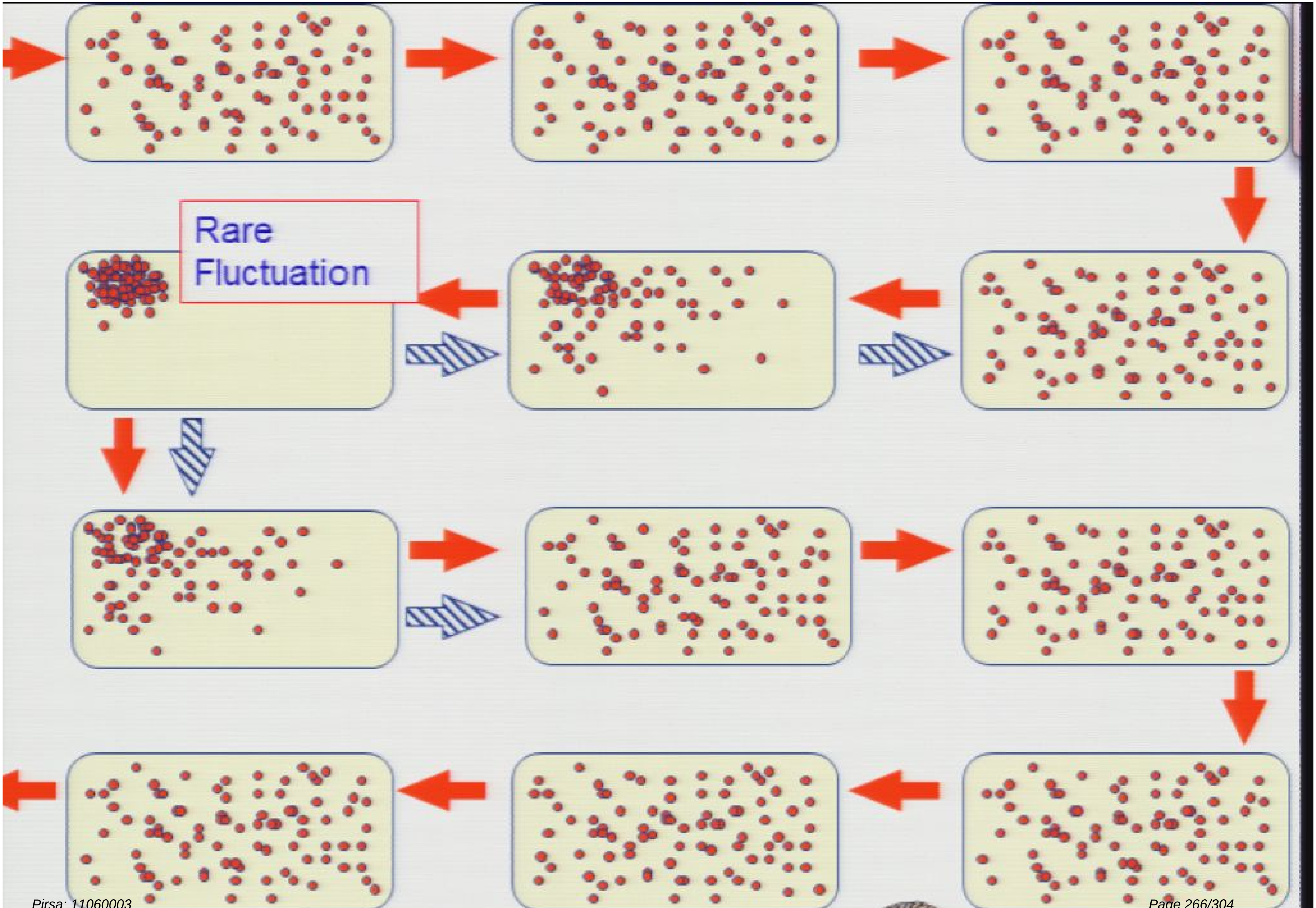
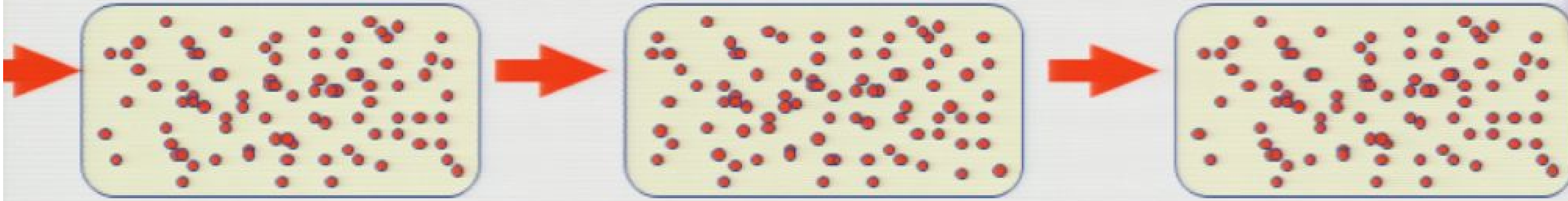
dSE cosmology

Equilibrium Cosmology

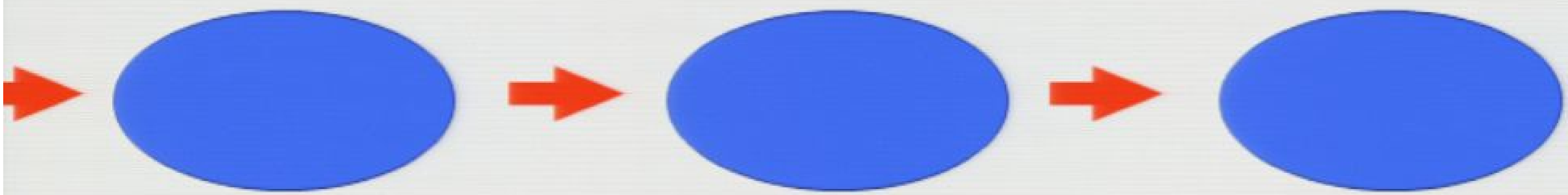

Rare
Fluctuation


Rare
Fluctuation

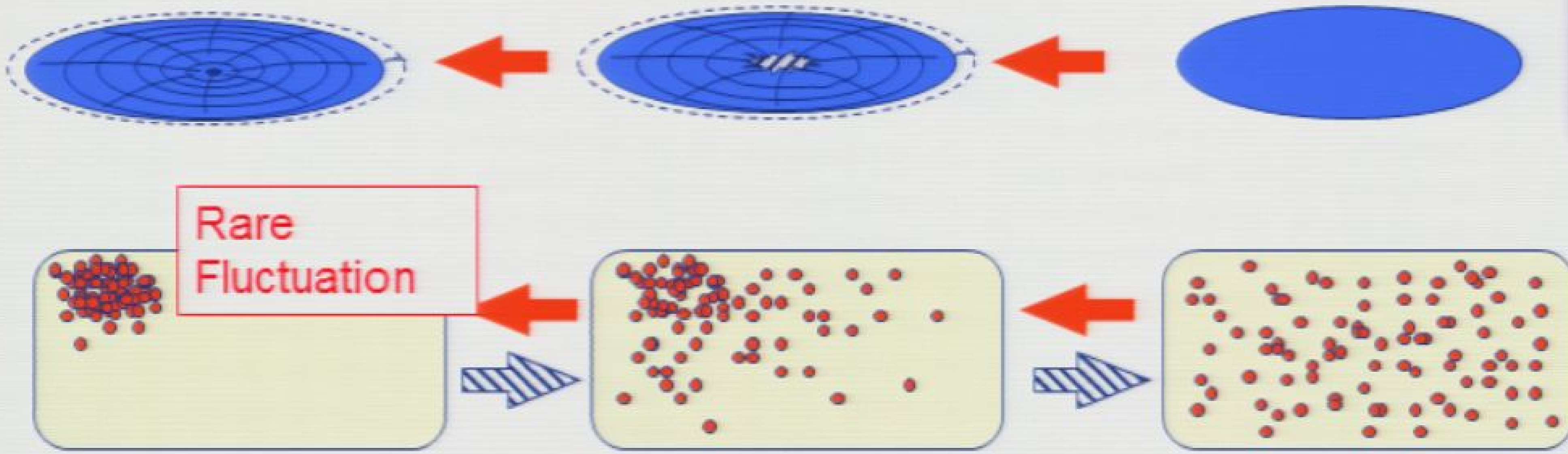
oncept:



ealization:



"de Sitter Space"


Rare
Fluctuation

Fluctuating from dSE to inflation:

- The process of an inflaton fluctuating from late time de Sittter to an inflating state is dominated by the "Guth-Farhi process"
- A "seed" is formed from the Gibbons-Hawking radiation that can then tunnel via the Guth-Farhi instanton.
- Rate is well approximated by the rate of seed formation:

$$\propto e^{-\frac{m_s}{T_{GH}}} = e^{-\frac{m_s}{H_\Lambda}}$$

- Seed mass:

$$m_s = \rho_I \left(cH_I^{-1}\right)^3 = 0.0013kg\left(\frac{\left(10^{16}GeV\right)^4}{\rho_I}\right)^{1/2}$$

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Small seed can produce an entire universe ➔ Evade "Boltzmann Brain" problem

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See important new work on G-F process by Andrew Ulvestad & AA

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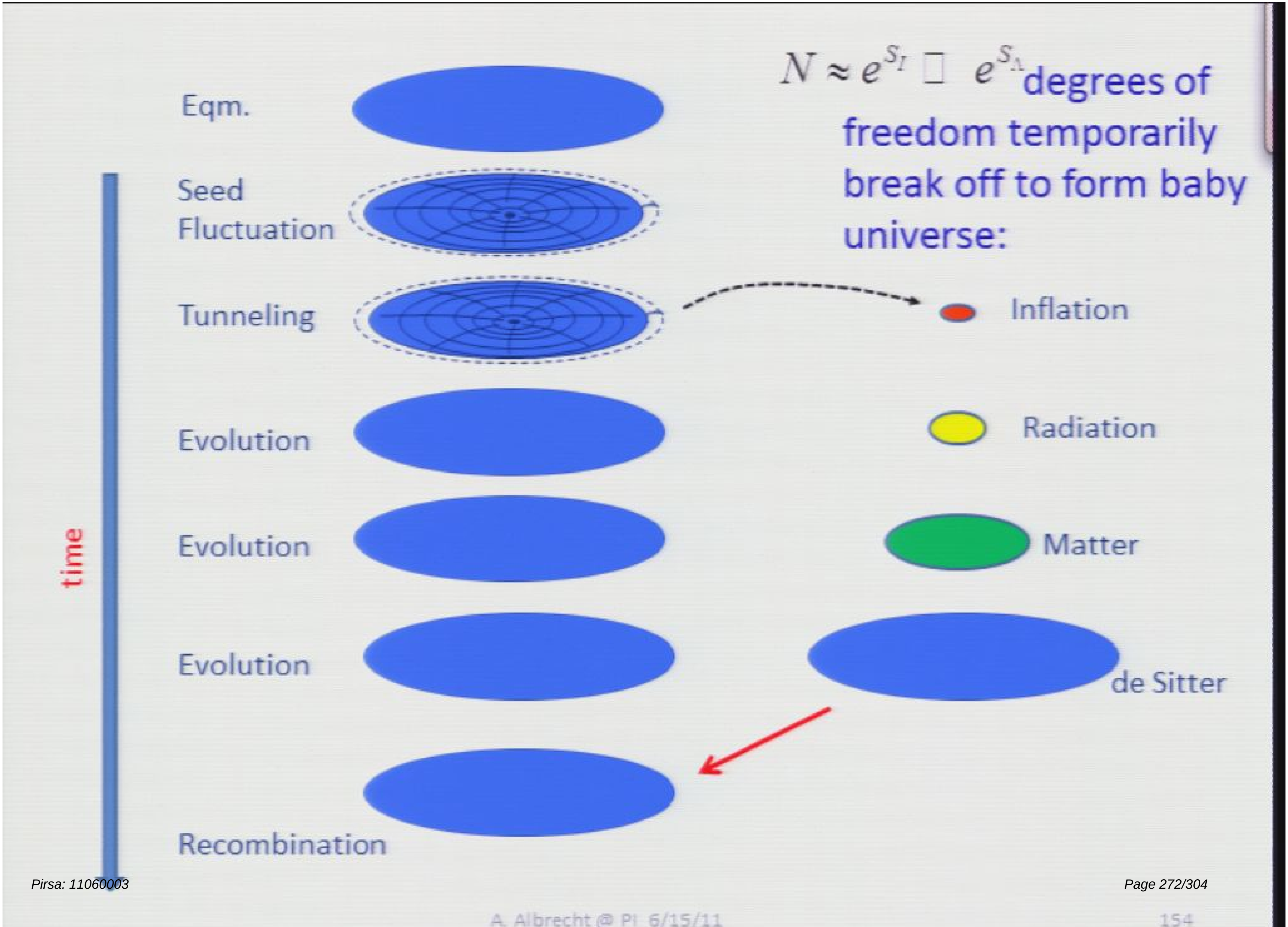
$N \approx e^{S_I} \ll e^{S_\Lambda}$ degrees of freedom temporarily break off to form baby universe:
Eqm.
Seed Fluctuation
Tunneling
Evolution
Evolution
Evolution
Recombination
time
Inflation
Radiation
Matter
de Sitter
A. Albrecht @ PI 6/15/11
154

Implications of finite Hilbert space $N = e^{S_\Lambda}$

- Recurrences

- Eqm.

- Breakdown of continuum field theory

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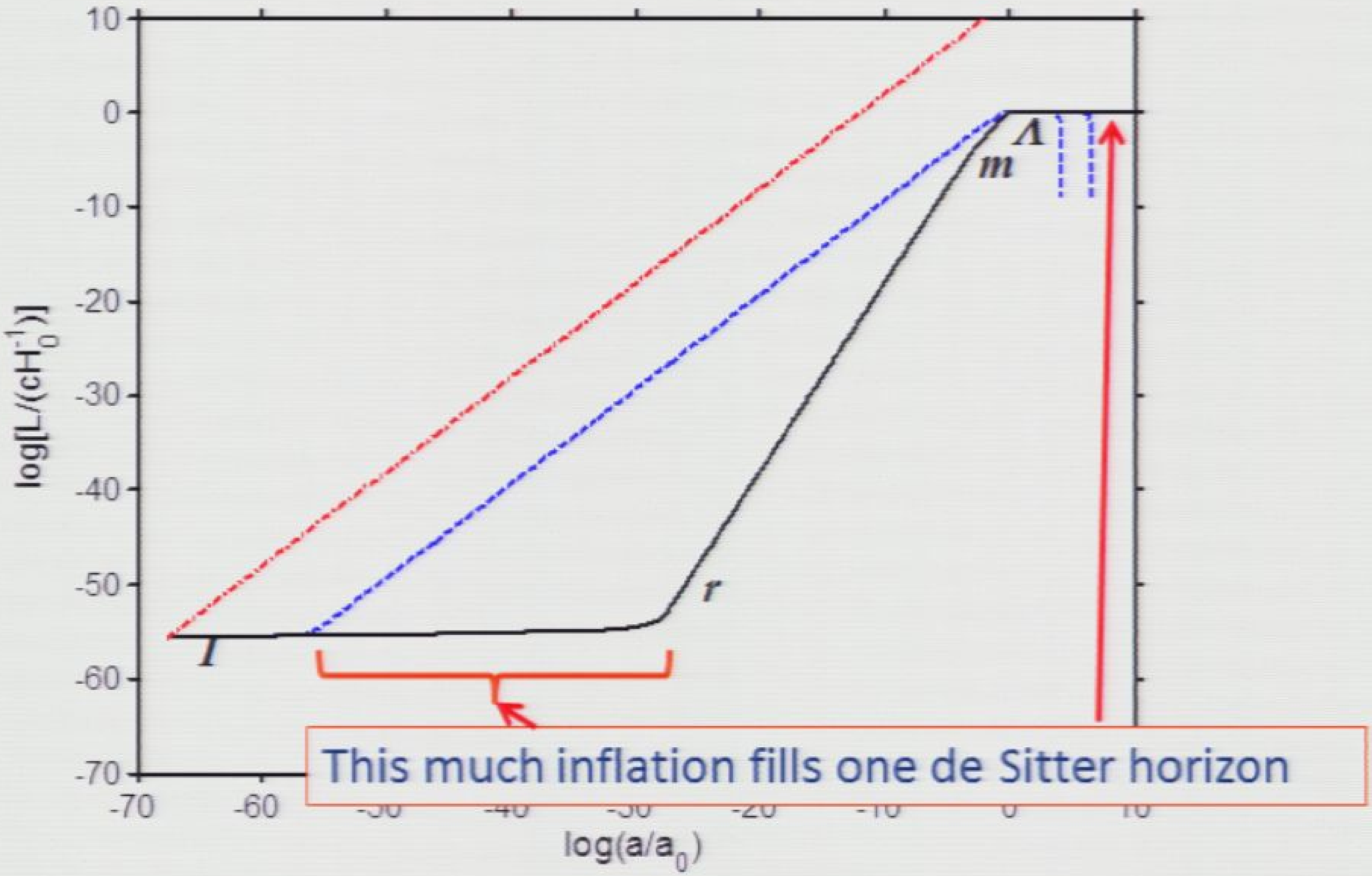

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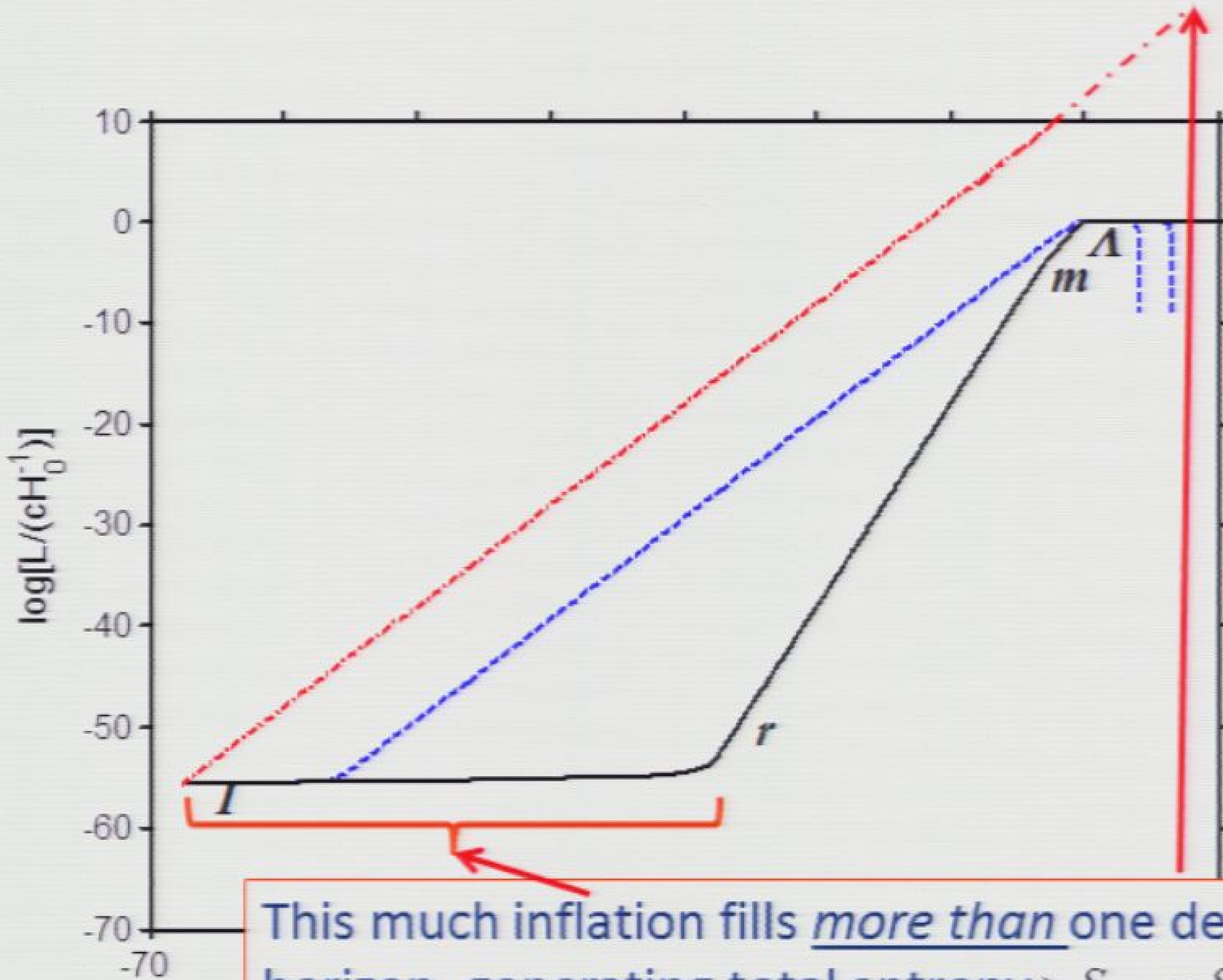
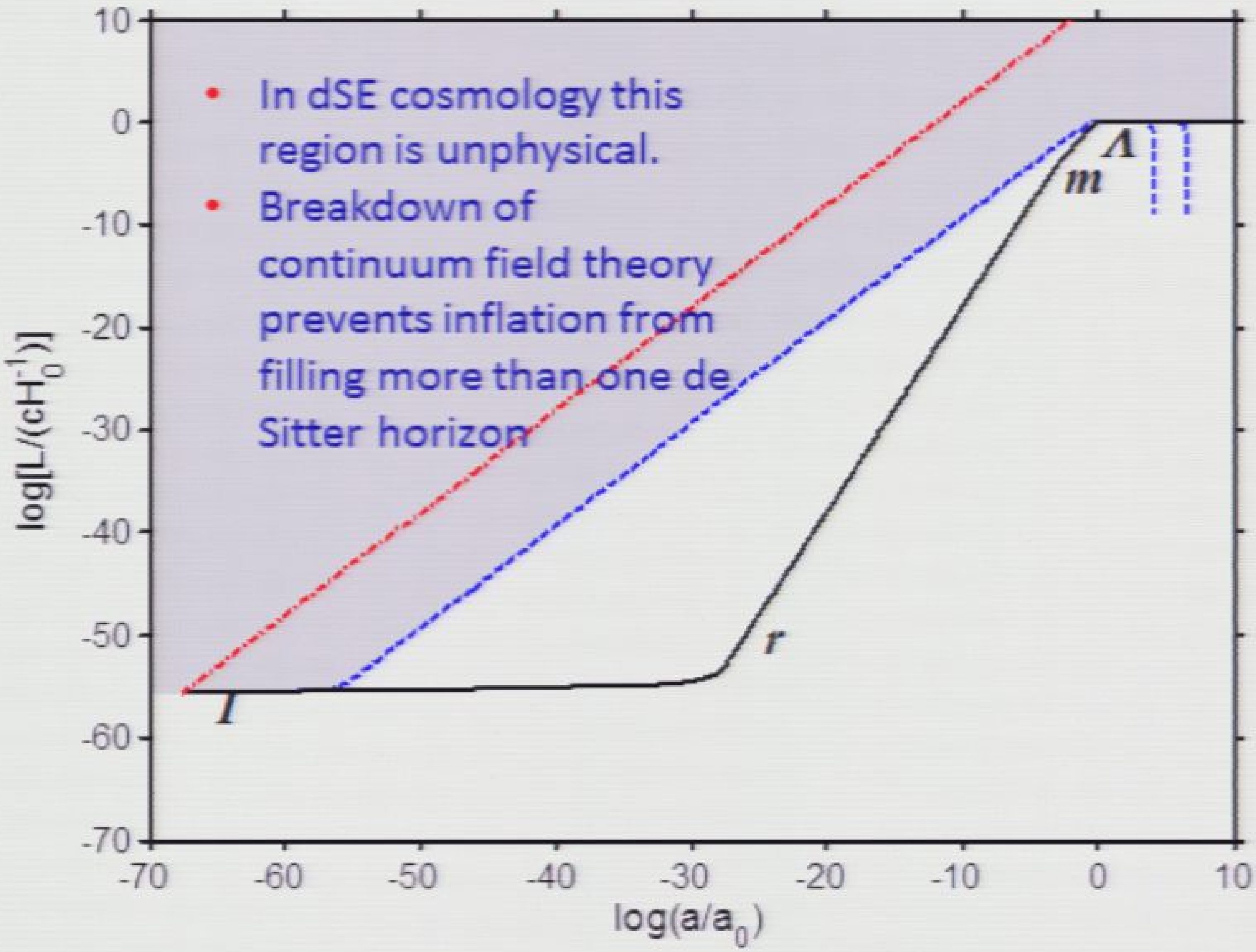
-70
log[L/(cH$_0^{-1}$)]
-70
-60
0
10
log(a/a$_0$)
Λ
m
r
I
This much inflation fills one de Sitter horizon



This much inflation fills *more than* one de Sitter horizon, generating total entropy $> S_{Max} = S_\Lambda$ and affecting regions beyond the horizon of the observer



In dSE cosmology this region is unphysical.
Breakdown of continuum field theory prevents inflation from filling more than one de Sitter horizon
log[L/(cH$_0^{-1}$)]
log(a/a$_0$)
I
r
m
Λ
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10

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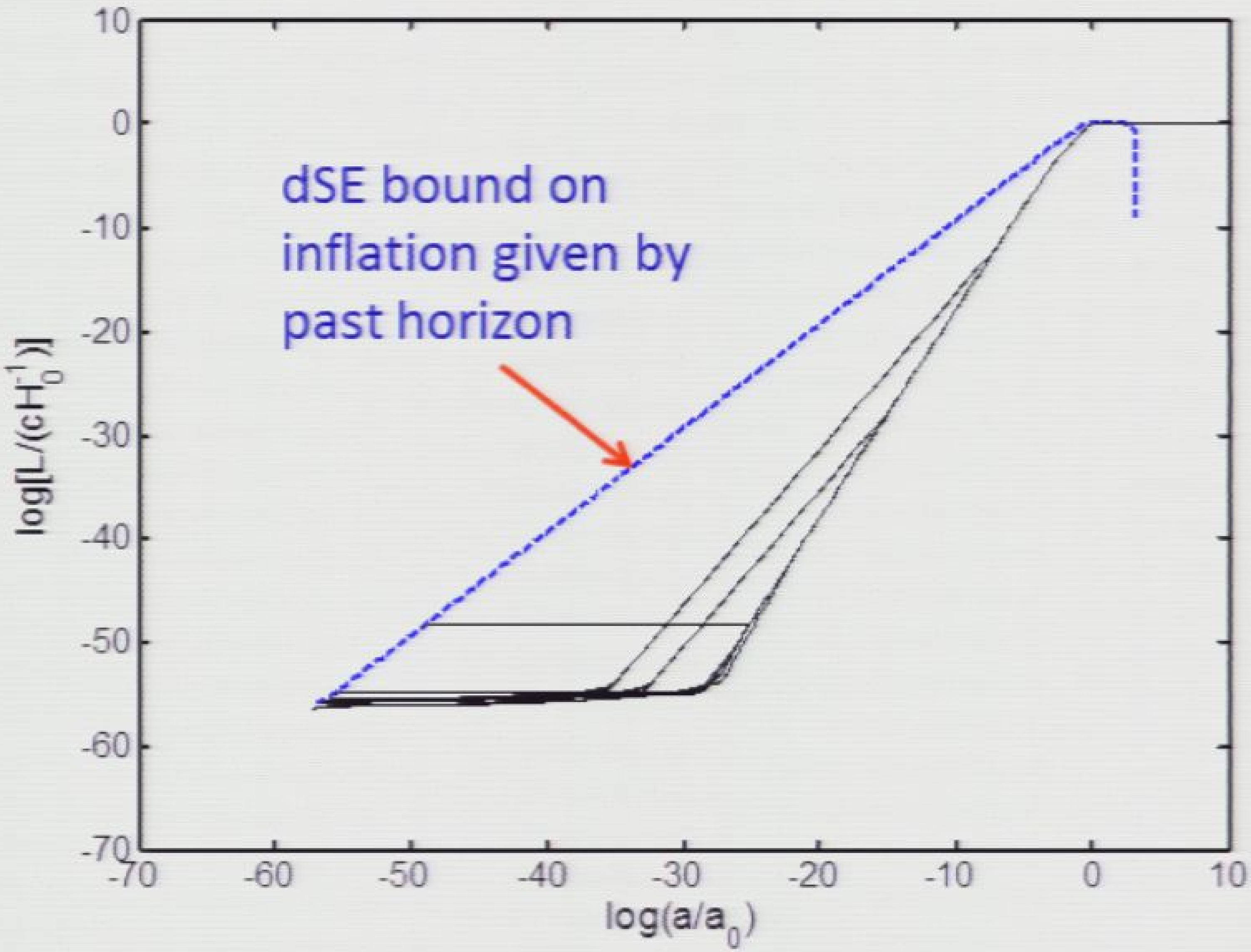
Large ρ_I exponentially favored → saturation of dSE bound



dSE bound on
inflation given by
past horizon
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0
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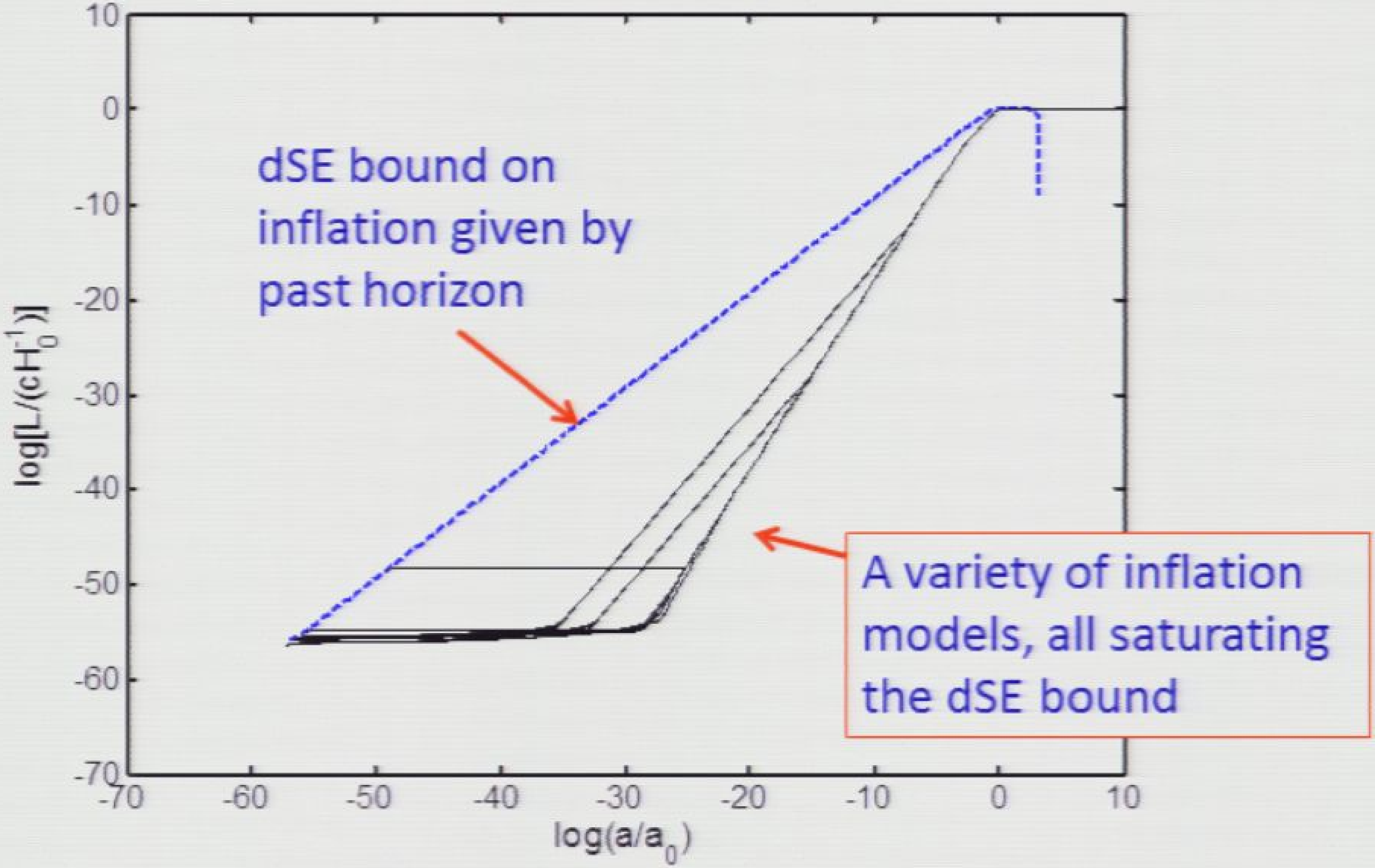
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10
log(a/a0)
log[L/(cH0-1)]



dSE bound on inflation given by past horizon
A variety of inflation models, all saturating the dSE bound
log[L/(cH$_0^{-1}$)]
log(a/a$_0$)
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10

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4. Cosmic curvature from de Sitter Equilibrium cosmology

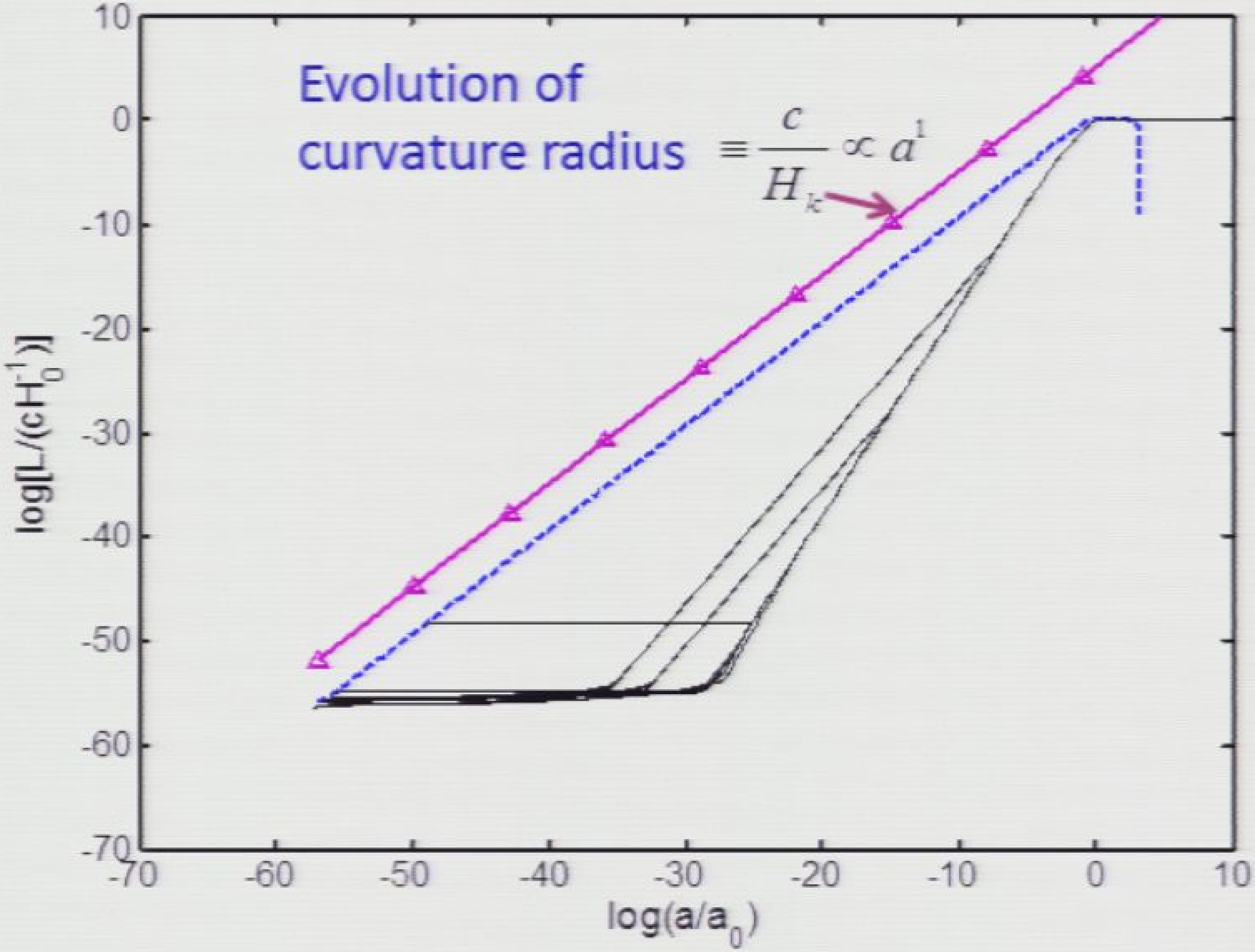
dSE Cosmology and cosmic curvature

- The Guth-Farhi process starts inflation with an initial curvature set by the curvature of the Guth-Farhi Bubble Ω_k^B
- Inflation dilutes the curvature, but dSE cosmology has a minimal amount of inflation

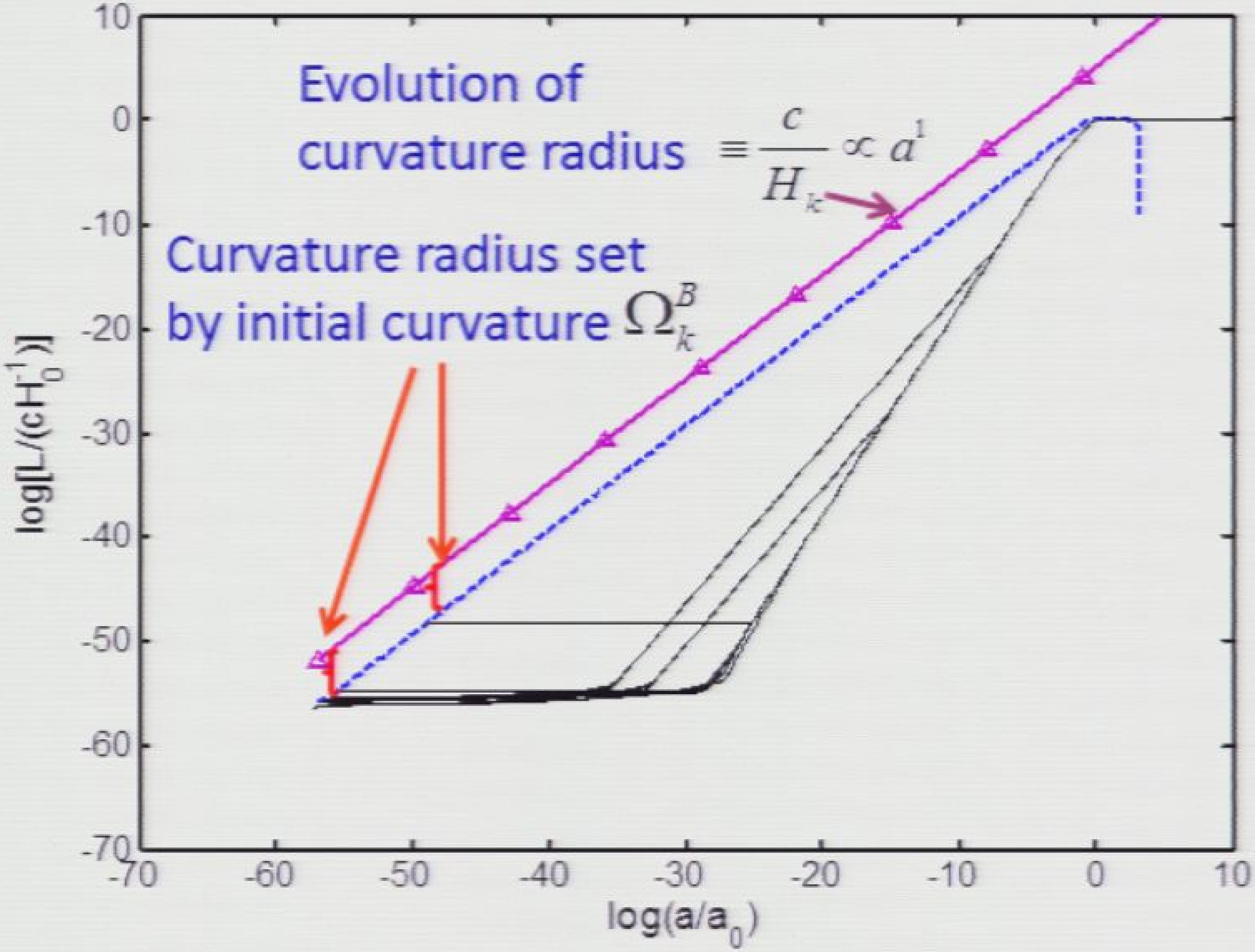
Friedmann Eqn.

$$\propto a^{-2}$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\left(\rho_I + \rho_k + \rho_r + \rho_m + \rho_{DE}\right)$$



AA: arXiv:1104.3315



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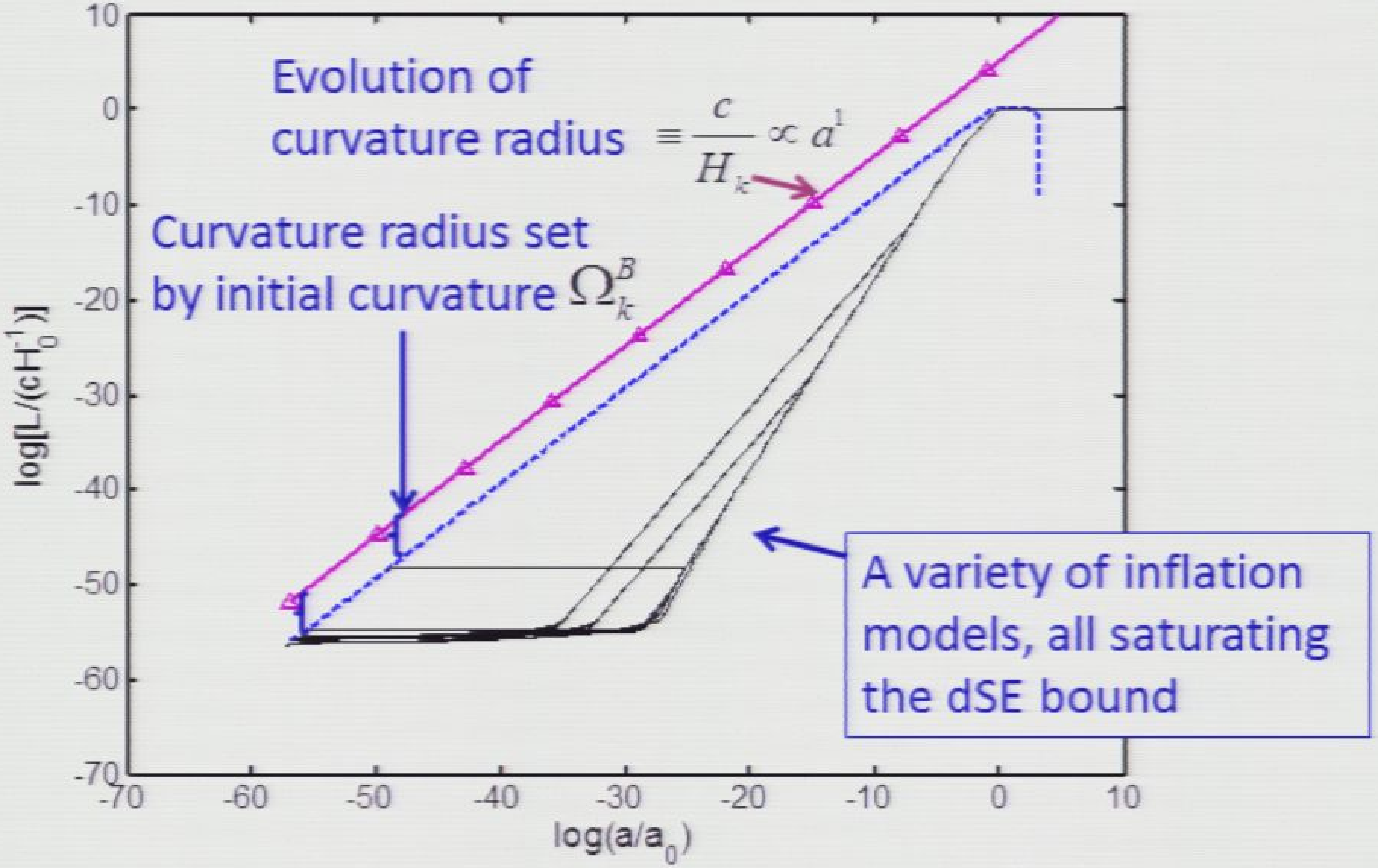

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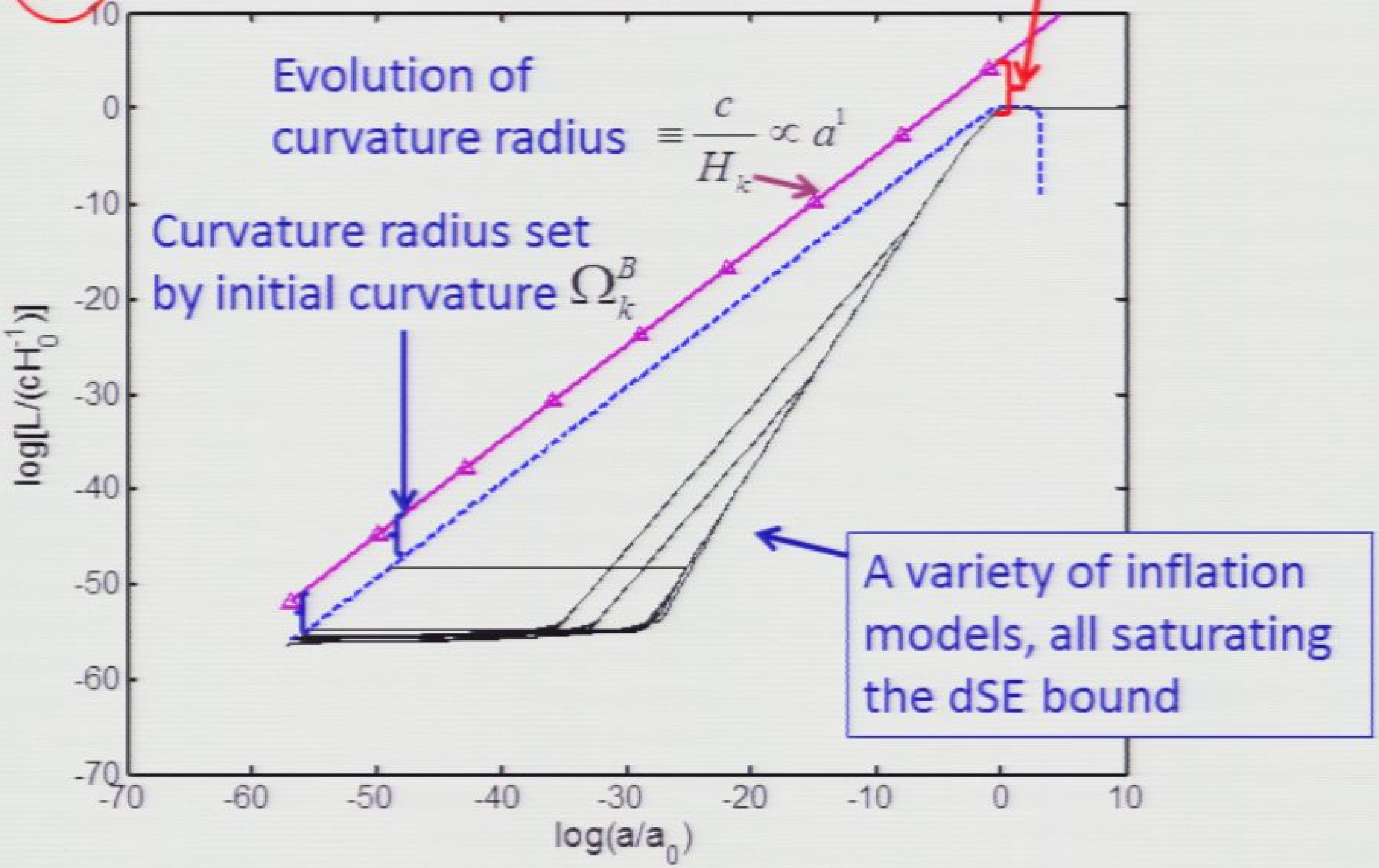
$$\Omega_k \equiv \frac{\rho_k}{\rho_c} = \left(\frac{H_k}{H_0}\right)^2 \equiv \left(\frac{R_{H_0}}{R_k}\right)^2$$ is given by this gap



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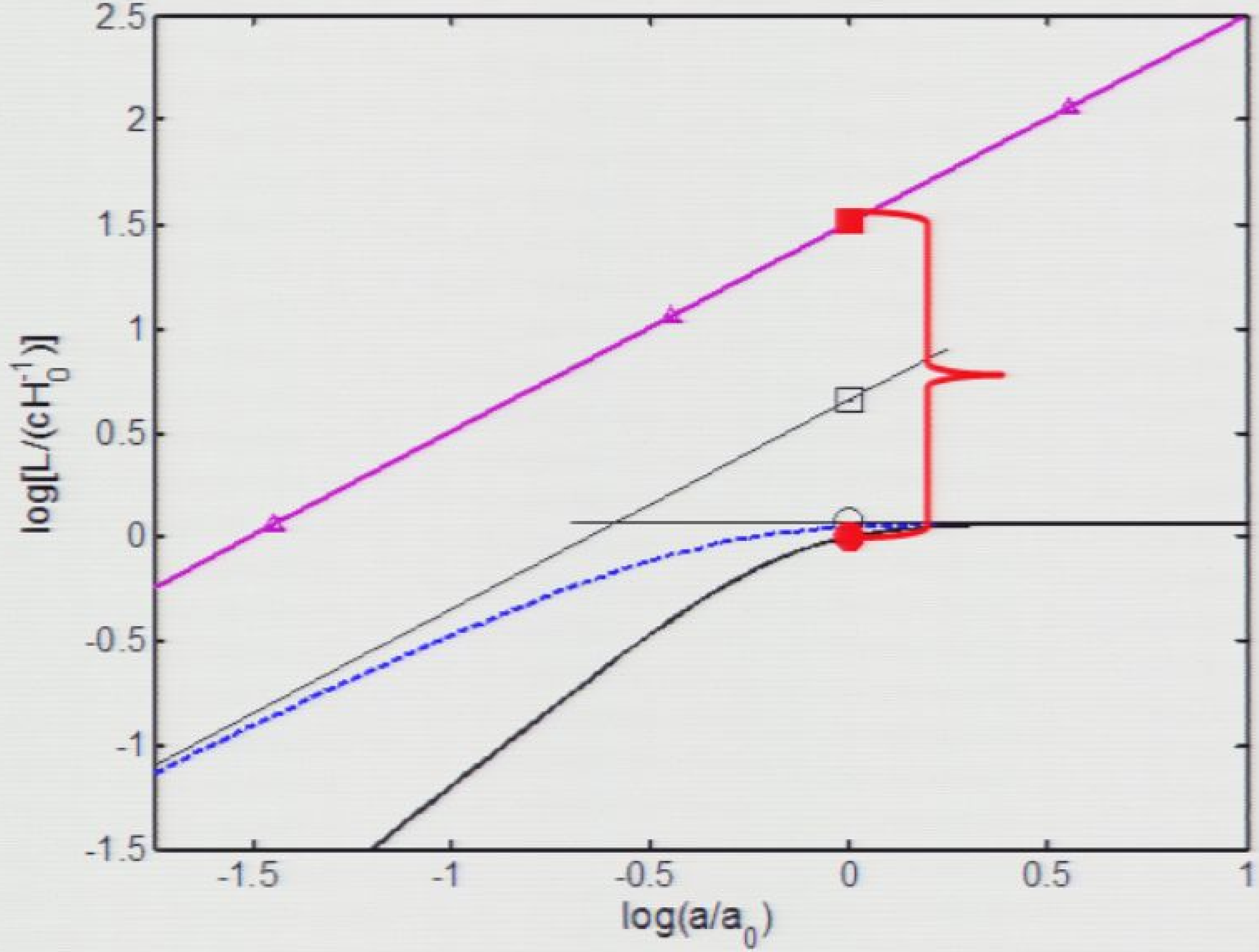

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$$\Omega_k = \frac{1}{g^2} \frac{\Omega_k^B}{\left(\frac{\rho_m^0}{\rho_\Lambda} + \frac{\rho_k^0}{\rho_\Lambda} + 1\right)}$$

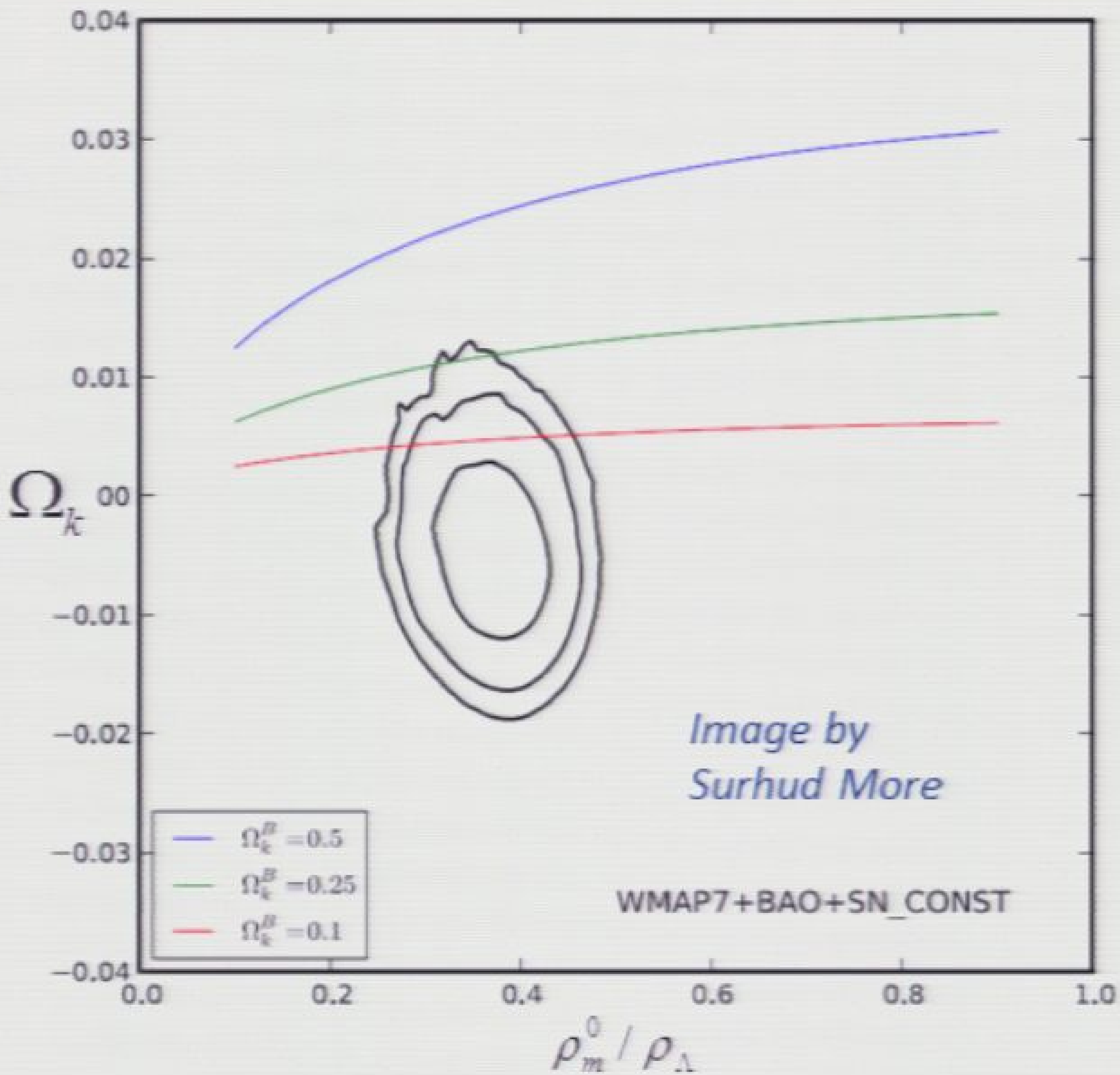
where

$$g\left(\frac{\rho_m^0}{\rho_\Lambda}, \frac{\rho_k^0}{\rho_\Lambda}\right) \equiv \int_0^\infty \frac{dx}{x^2\sqrt{x^{-3}\frac{\rho_m^0}{\rho_\Lambda} + x^{-2}\frac{\rho_k^0}{\rho_\Lambda} + 1}}$$

AA: arXiv:1104.3315

Predicted Ω_k from dSE cosmology is:

- Independent of almost all details of the cosmology
- Just consistent with current observations
- Will easily be detected by future observations



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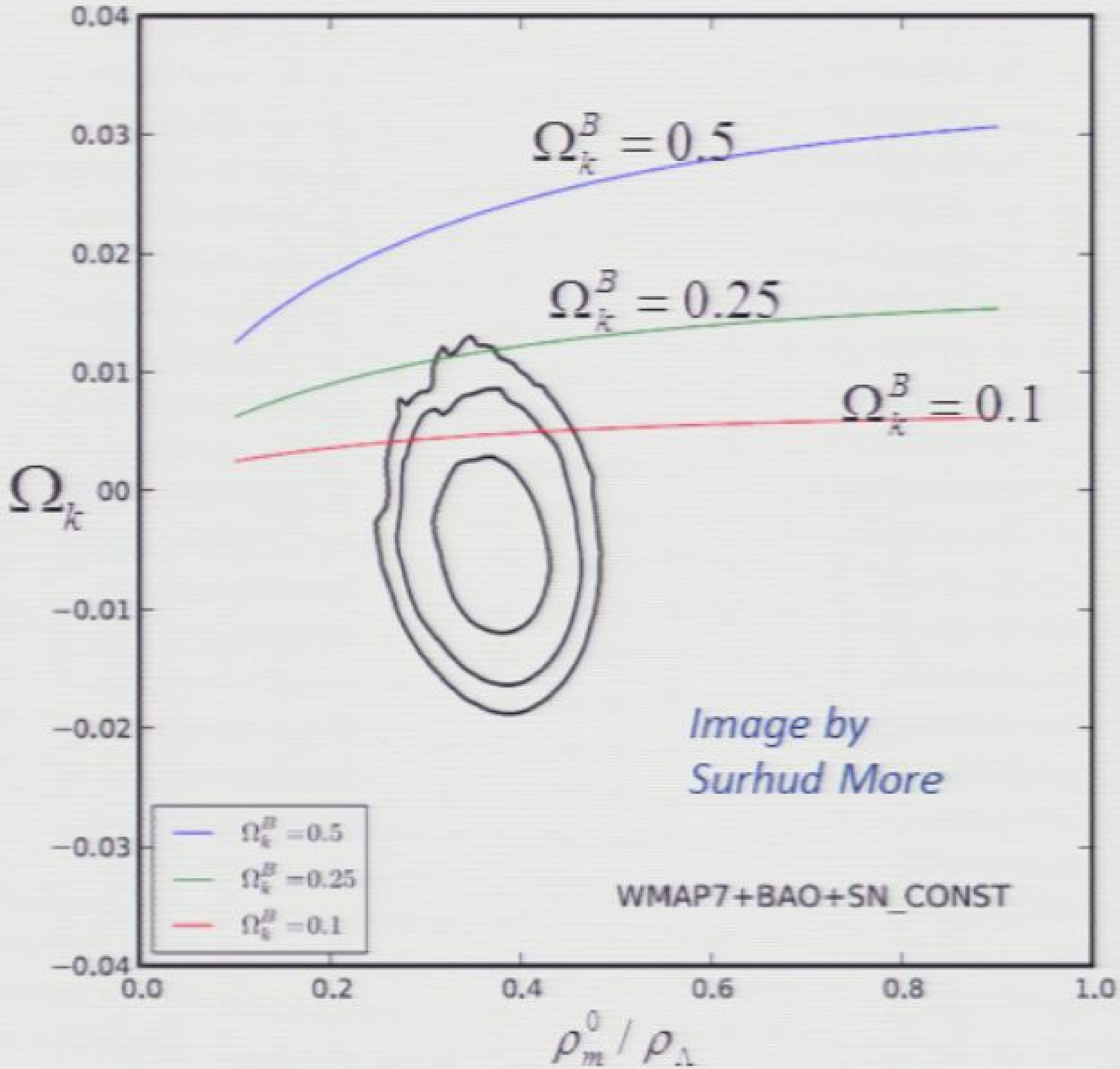

Work in progress on expected values of Ω_k^B (Andrew Ulvestad & AA)

Conclusions

- The search for a "big picture" of the Universe that explains why the region we observe should take this form has proven challenging, but has generated exciting ideas.
- We know we can do science with the Universe
- It appears that there is something right about cosmic inflation
- dSE cosmology offers a finite alternative to the extravagant (and problematic) infinities of eternal inflation
- Predictions of observable levels of cosmic curvature from dSE cosmology will give an important future test

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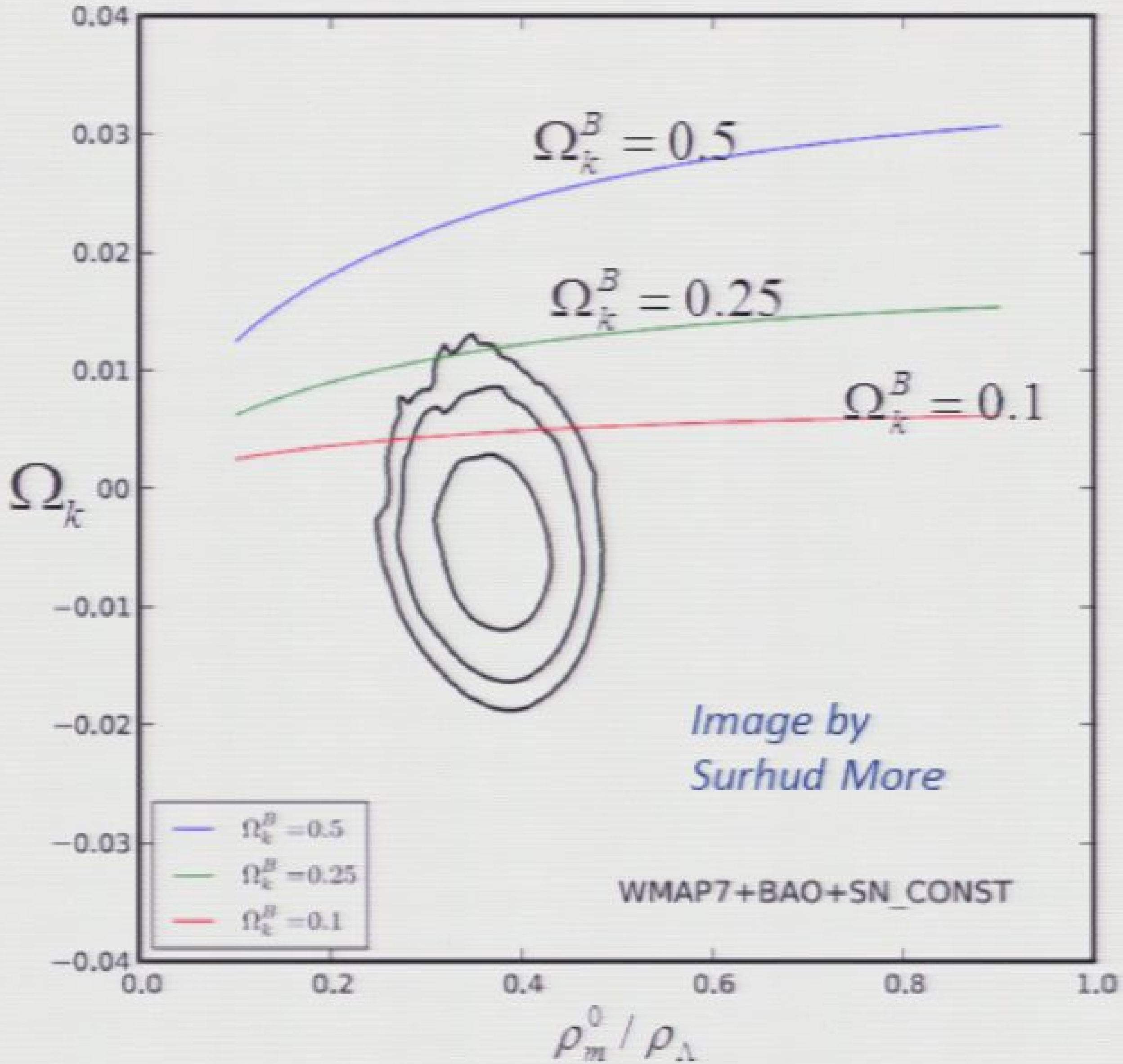

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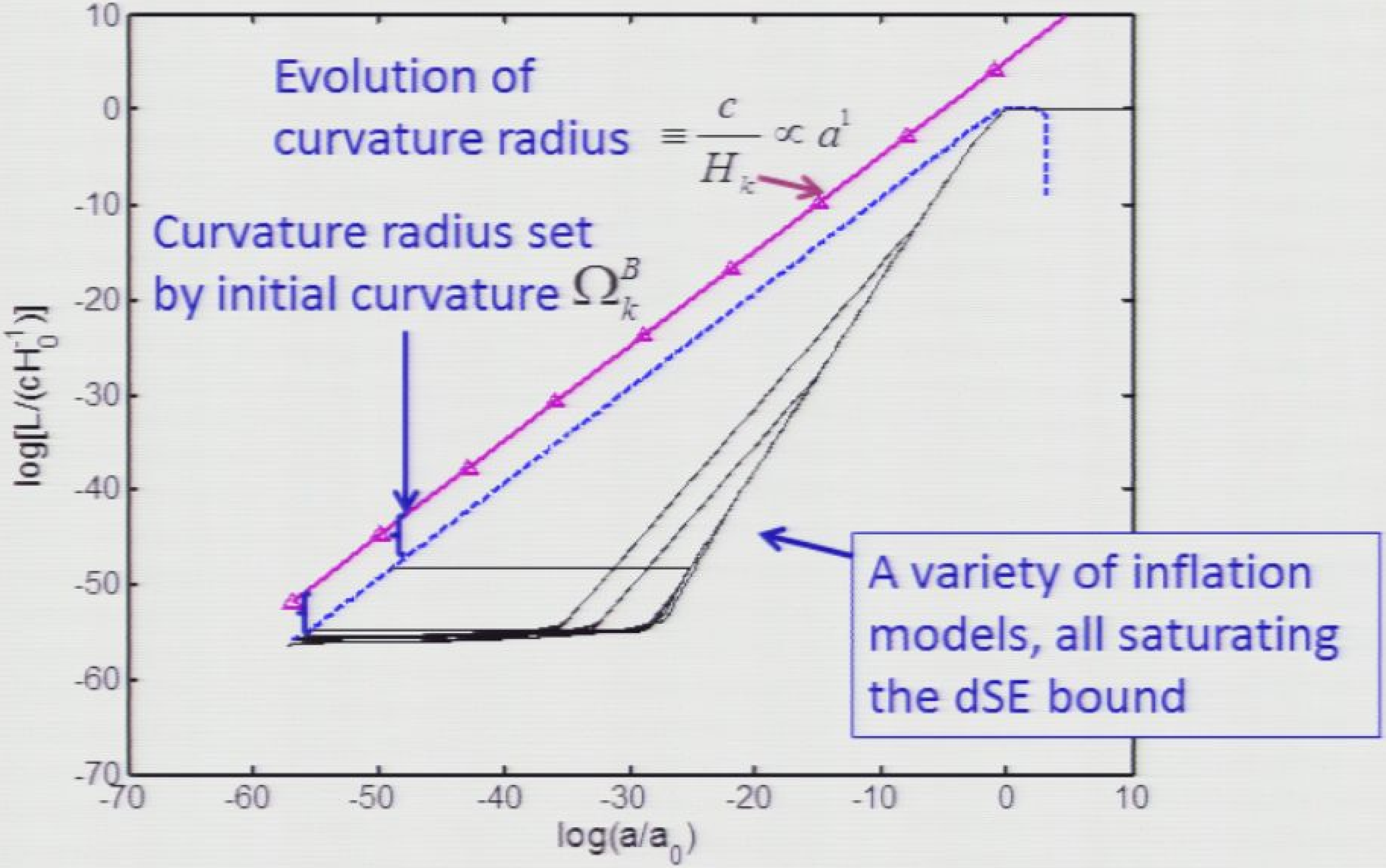

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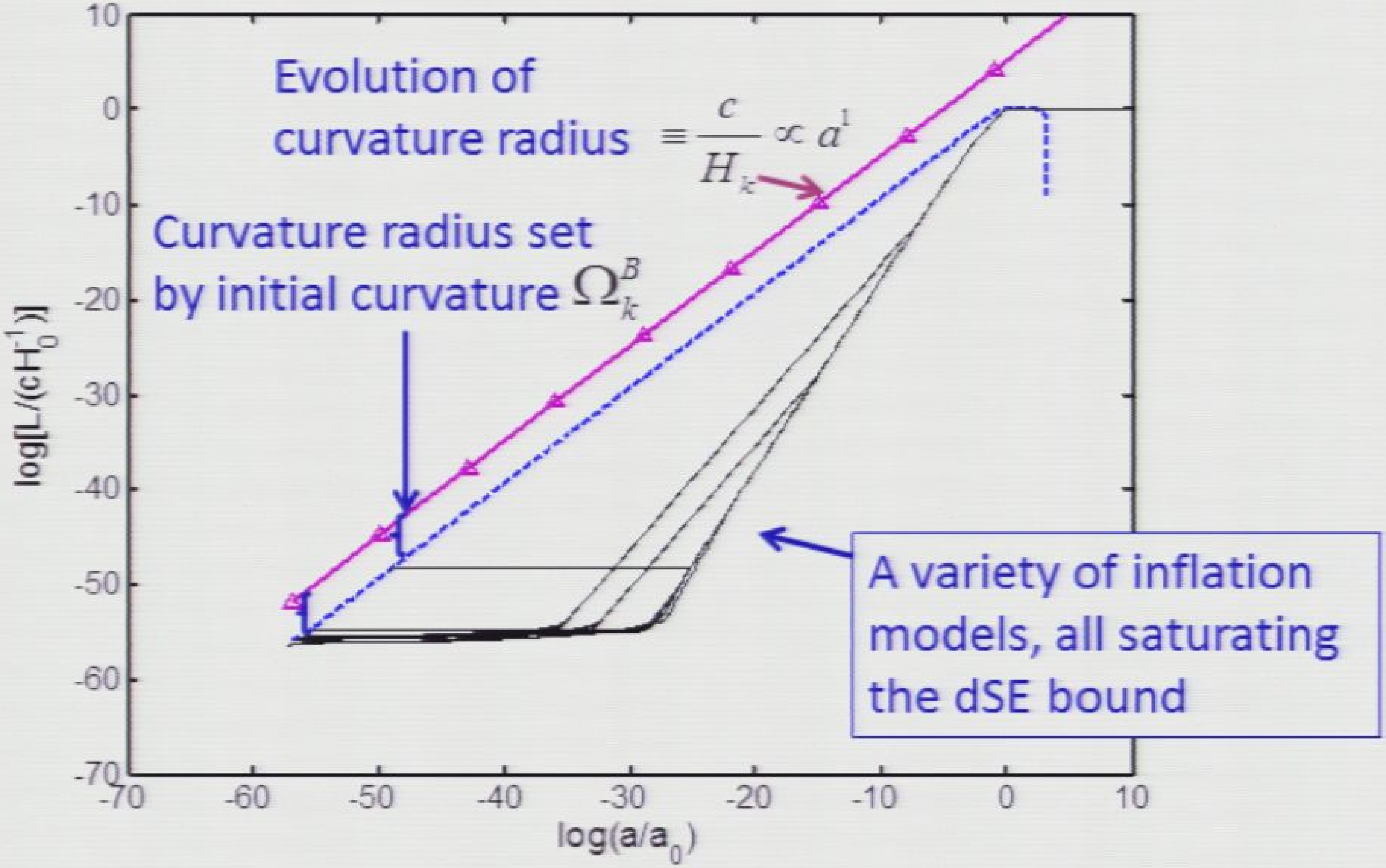

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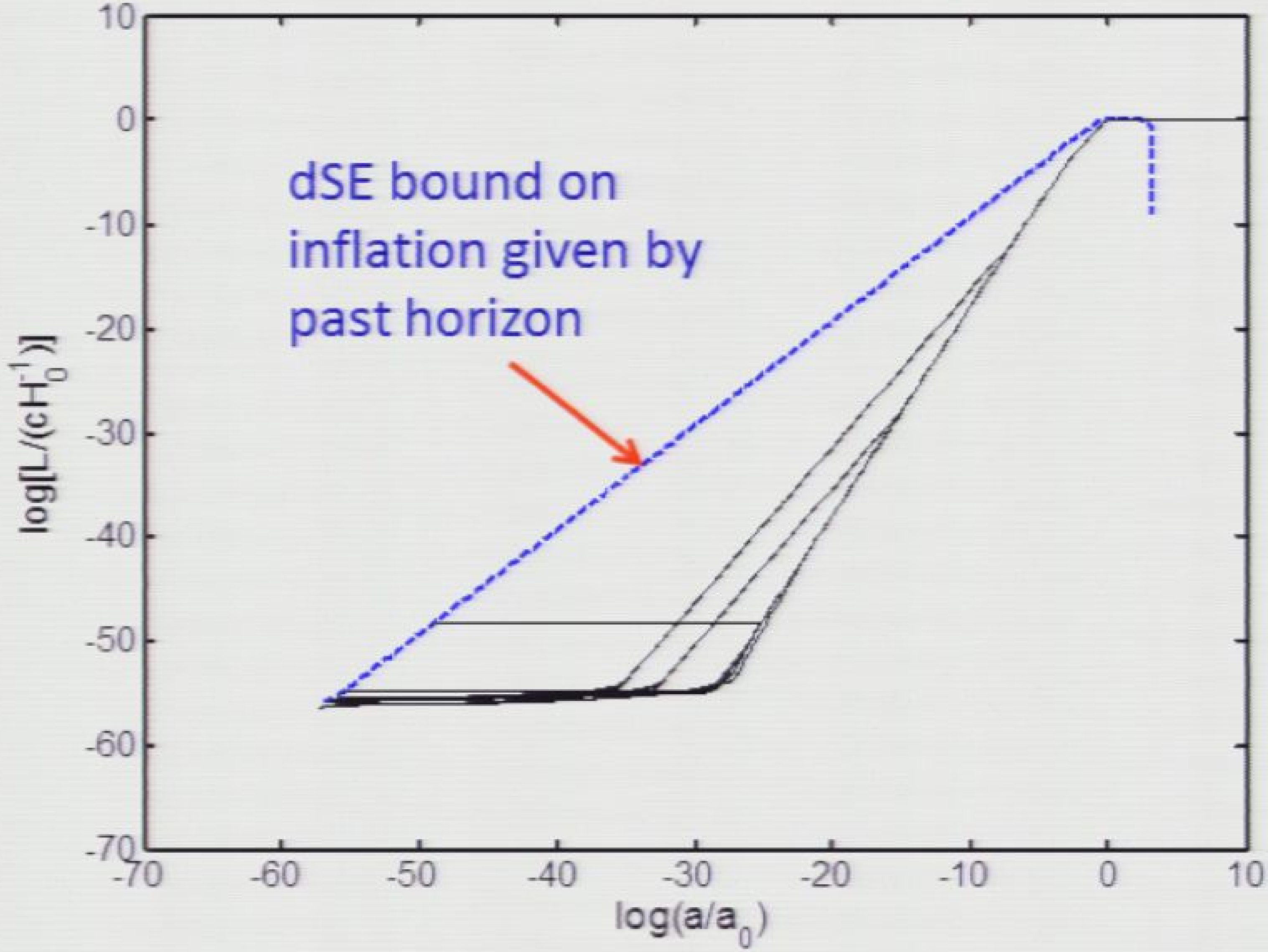
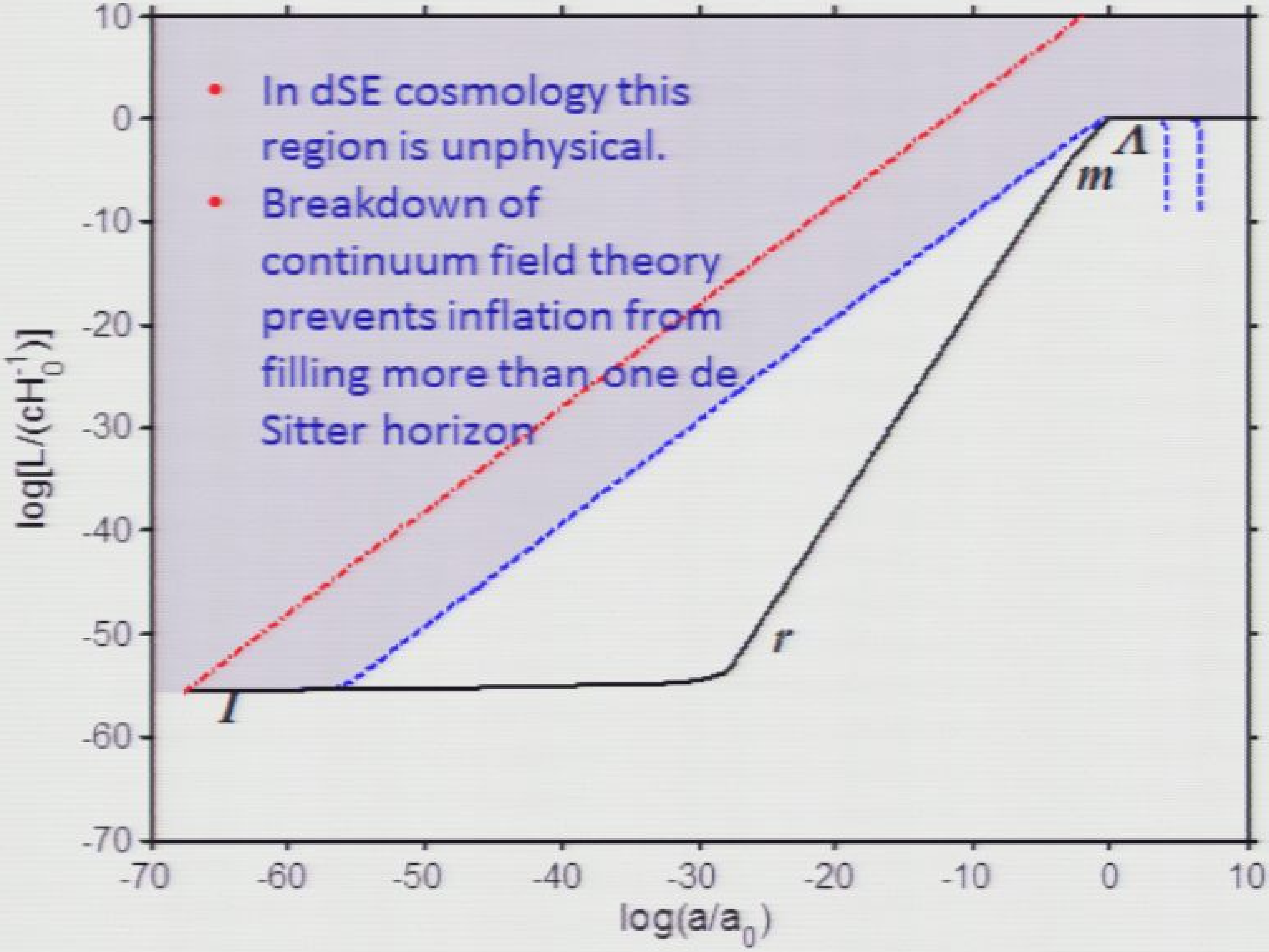
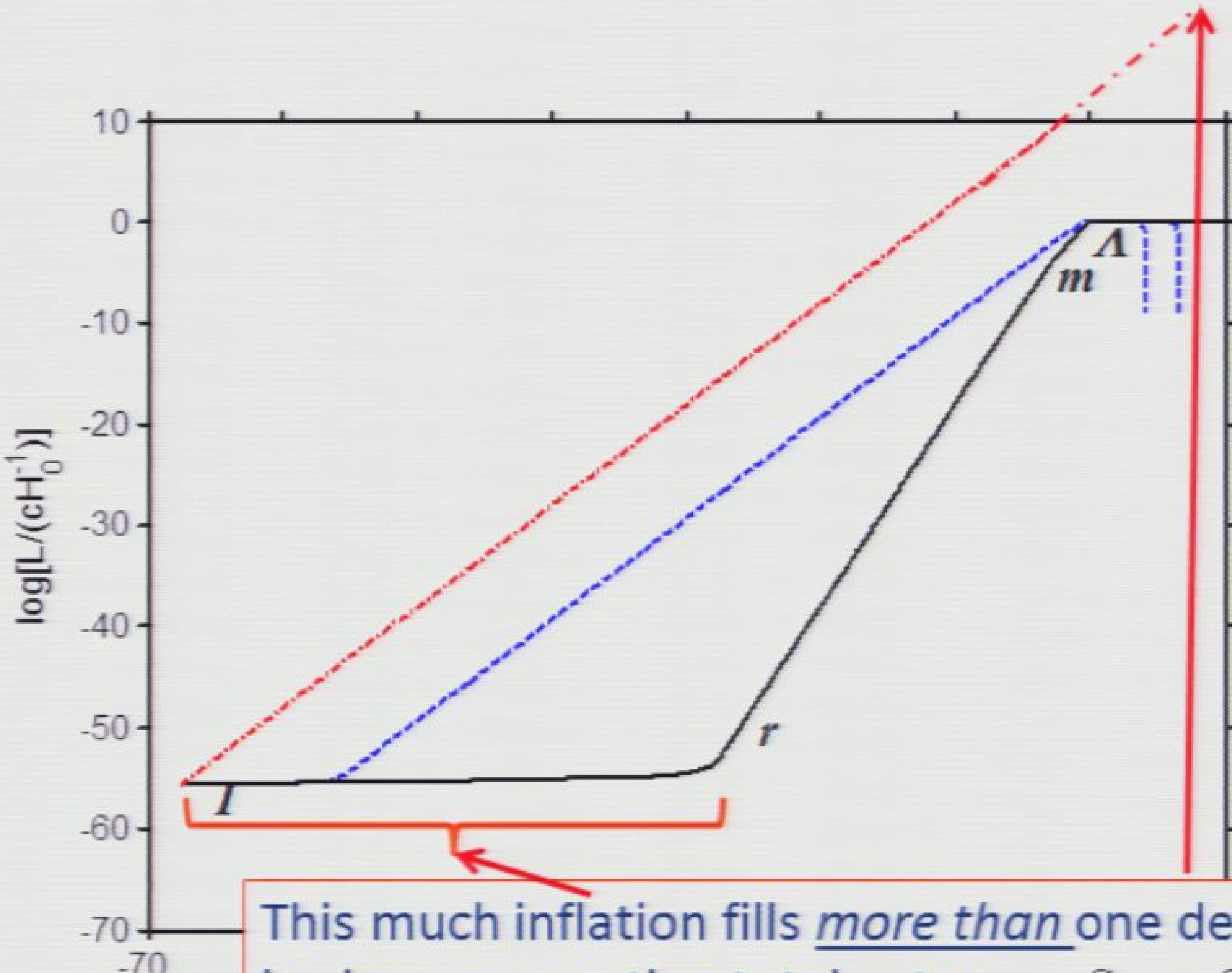


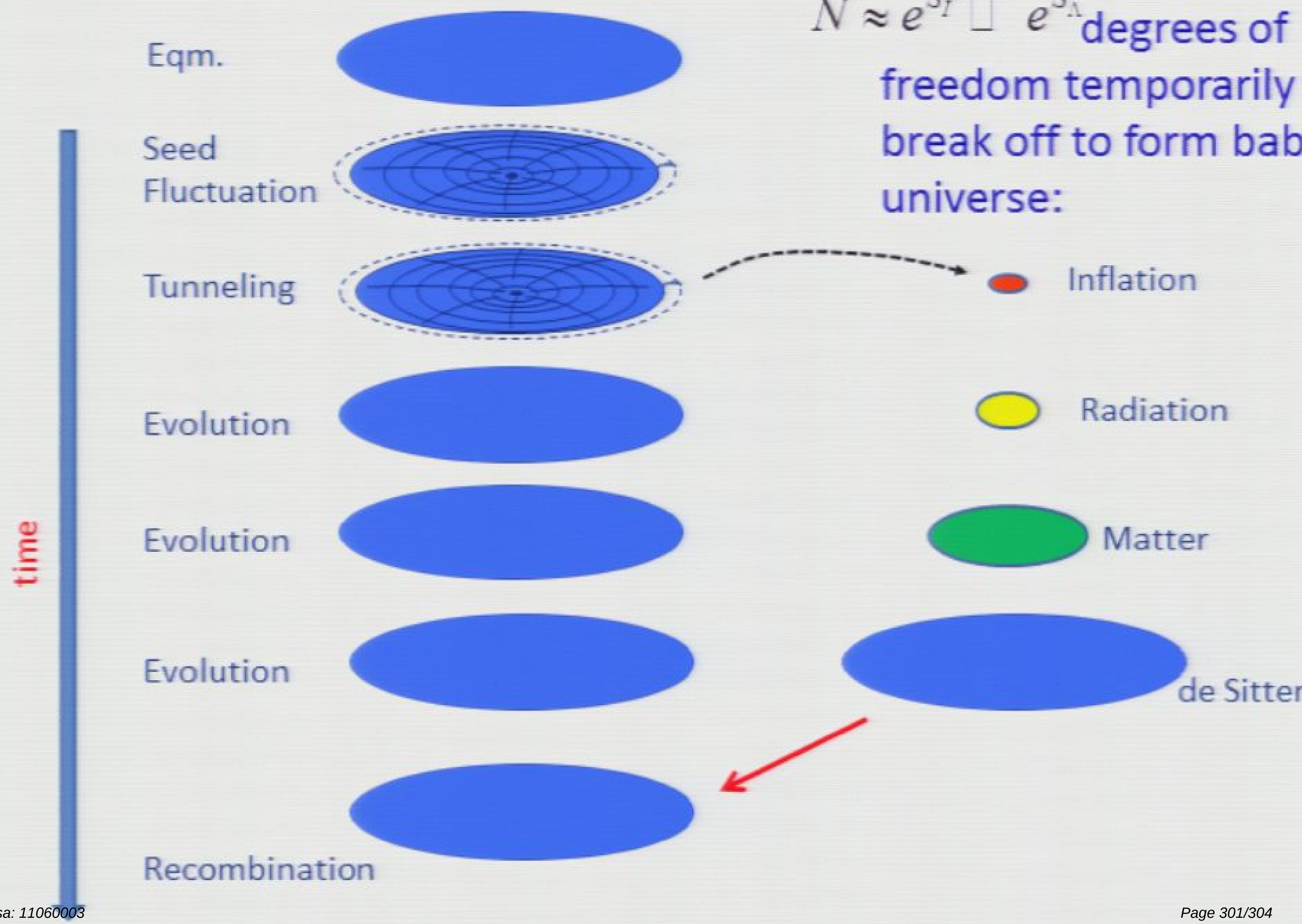
dSE bound on inflation given by past horizon
$\log[L/(cH_0^{-1})]$
$\log(a/a_0)$
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10


In dSE cosmology this region is unphysical.
Breakdown of continuum field theory prevents inflation from filling more than one de Sitter horizon
log[L/(cH$_0^{-1}$)]
log(a/a$_0$)
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10
I
r
m
Λ



This much inflation fills *more than* one de Sitter horizon, generating total entropy $> S_{Max} = S_\Lambda$ and affecting regions beyond the horizon of the observer

$N \approx e^{S_I} \ll e^{S_\Lambda}$ degrees of freedom temporarily break off to form baby universe:



Fluctuating from dSE to inflation:

- The process of an inflaton fluctuating from late time de Sittter to an inflating state is dominated by the "Guth-Farhi process"
- A "seed" is formed fro[m] ... radiation that can then tunnel via the Guth-Farhi instanton.
- Rate is well approximated by the rate of seed formation:

$$\propto e^{-\frac{m_s}{T_{GH}}} = e^{-\frac{m_s}{H_\Lambda}}$$

- Seed mass:

$$m_s = \rho_I \left(cH_I^{-1}\right)^3 = 0.0013kg \left(\frac{\left(10^{16} GeV\right)^4}{\rho_I}\right)^{1/2}$$

See important new work on G-F process by Andrew Ulvestad & AA

Fluctuating from dSE to inflation:

- The process of an inflaton fluctuating from late time de Sittter to an inflating state is dominated by the "Guth-Farhi process"
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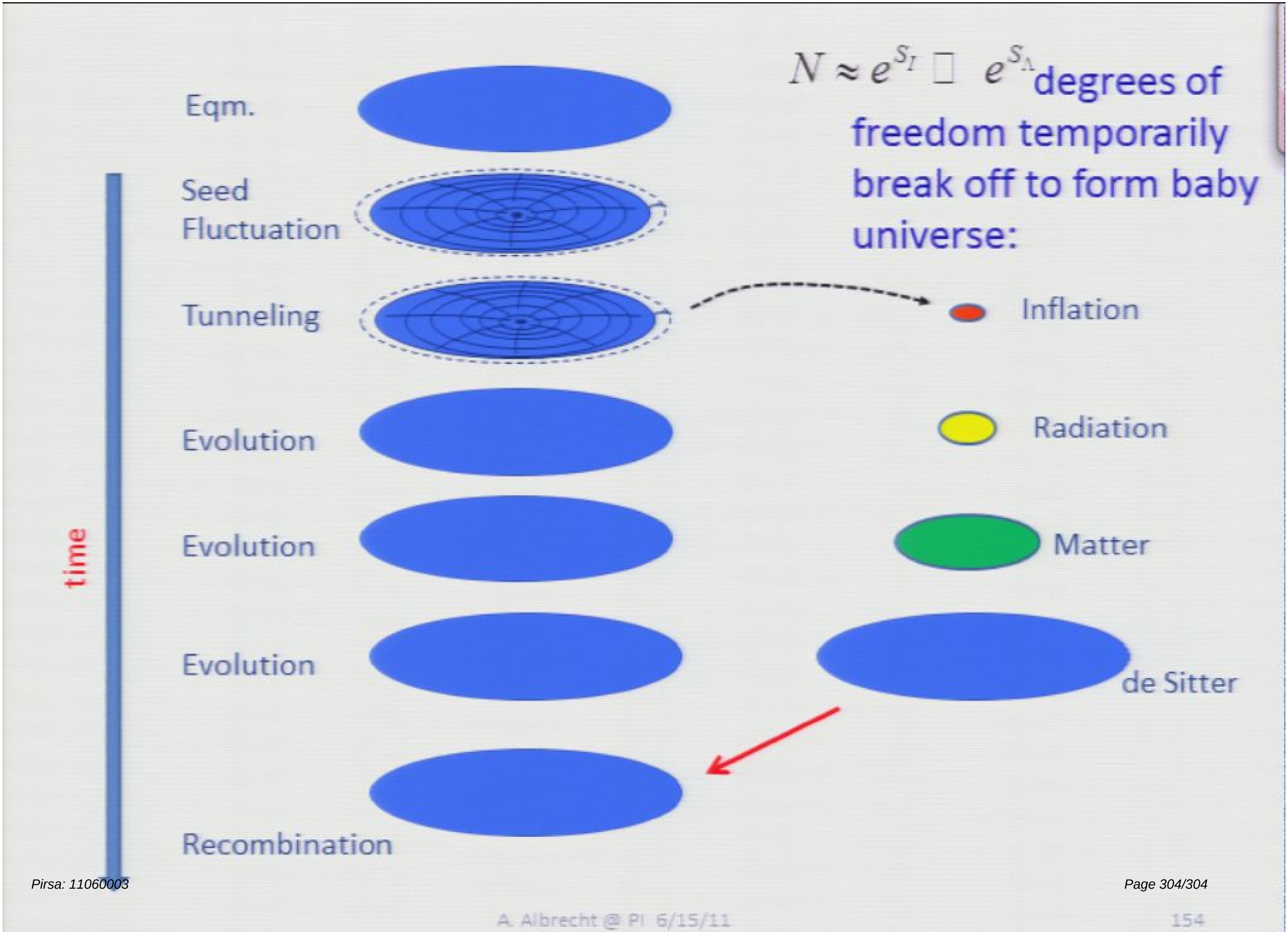
Small seed can produce an entire universe → Evade "Boltzmann Brain" problem


$N \approx e^{S_I}$ □ e^{S_Λ} degrees of
freedom temporarily
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Evolution
Recombination
time
Inflation
Radiation
Matter
de Sitter
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