Les Houches Lectures on Cosmic Inflation

Four Parts

1) Introductory material
2) Entropy, Tuning and Equilibrium in Cosmology
3) Classical and quantum probabilities in the multiverse
4) de Sitter equilibrium cosmology

Andreas Albrecht; UC Davis

Les Houches Lectures; July-Aug 2013

Some preliminary thoughts

- Please interrupt freely with questions!
- I am yours for informal discussion until we leave on Friday. Please exploit that offer

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Les Houches Lectures Part 1

Introductory Material

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Introductory Material

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NASA
CHICAGO·18
1909
INDIANA·12


NASA
CHICAGO·18
1909
INDIANA·12


1909
CHAMPIONS


NASA
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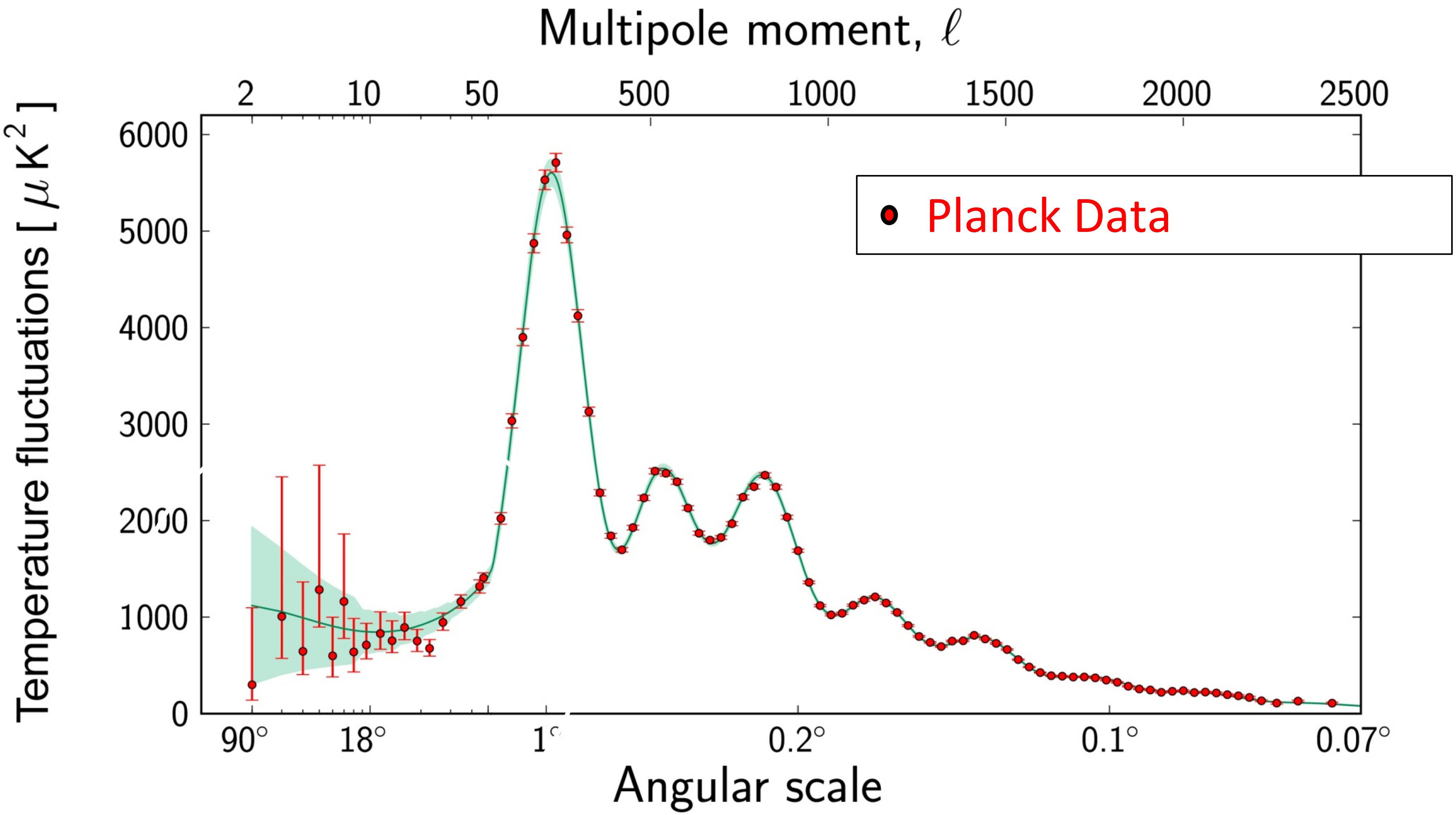
CHAMPIONS



Multipole moment, ℓ
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2000
2500
Temperature fluctuations [μK^2]
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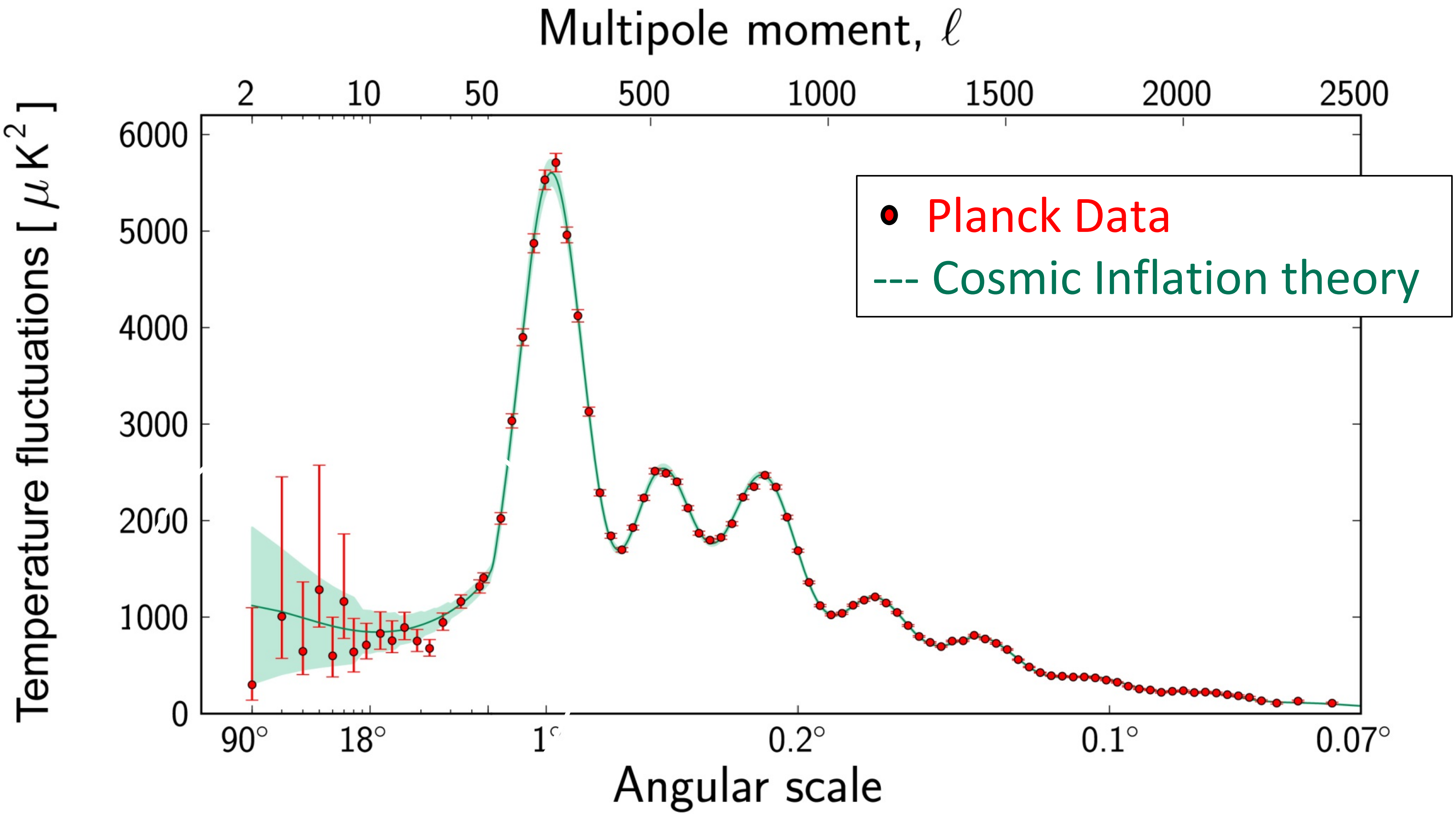
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
Planck Data



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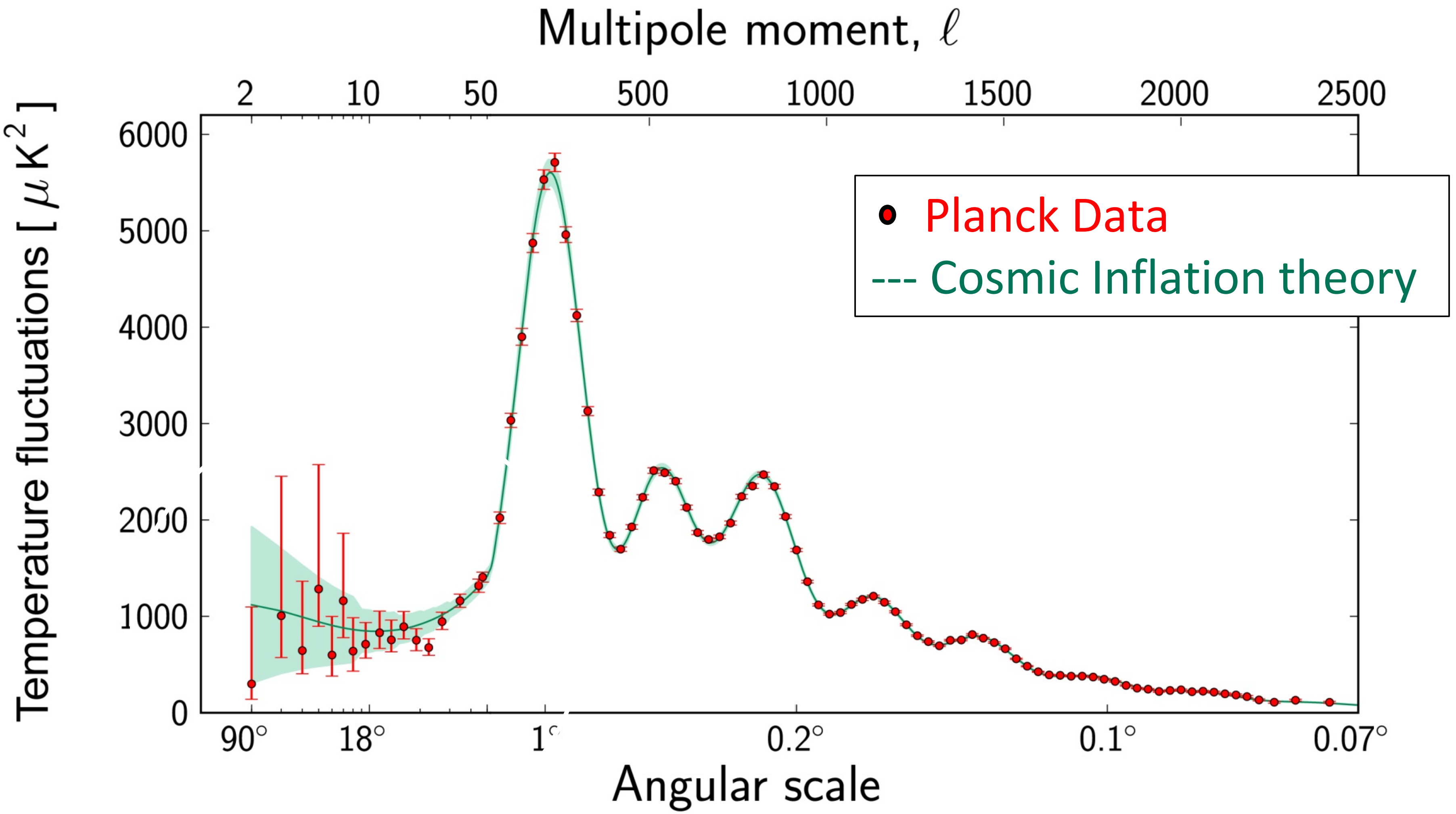
--- Cosmic Inflation theory



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--- Cosmic Inflation theory

Cosmic Inflation:

- ➔ Great phenomenology of cosmic structure, but

- ➔ Original goal of explaining why the cosmos is *likely* to take the form we observe has proven very difficult to realize. (We have not succeeded so far.)

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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. (We have not succeeded so far.)

These Lectures

Original goal inspired by Guth's paper:

PHYSICAL REVIEW D VOLUME 23, NUMBER 2 15 JANUARY 198[illegible]

Inflationary universe: A possible solution to the horizon and flatness problems

Alan H. Guth*

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 11 August 1980)

The standard model of hot big-bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separated regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

Cosmic Inflation:

- Great phenomenology of cosmic structure, but

- Original goal of explaining why the cosmos is *likely* to take the form we observe has proven very difficult to realize. (We have not succeeded so far.)

- OR: Just be happy we have equations to solve?

Part 1 outline

1. Big Bang & inflation

2. Eternal inflation

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Friedmann Eqn.

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

Friedmann Eqn.

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Hubble parameter
("constant")

Friedmann Eqn.

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Hubble parameter
("constant")

"Scale factor"

Friedmann Eqn.

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

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

Curvature

"Scale factor"

Friedmann Eqn.

$\propto a^{-2}$

$\propto a^{-4}$

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

Curvature

Relativistic Matter

“Scale factor”

Friedmann Eqn.

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

Curvature

Relativistic Matter

Non-relativistic Matter

"Scale factor"

Friedmann Eqn.

$$\boxed{H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\left(\overset{\propto a^{-2}}{\rho_k} + \overset{\propto a^{-4}}{\rho_r} + \overset{\propto a^{-3}}{\rho_m} + \overset{\propto a^{\approx 0}}{\rho_{DE}}\right)}$$

Dark Energy

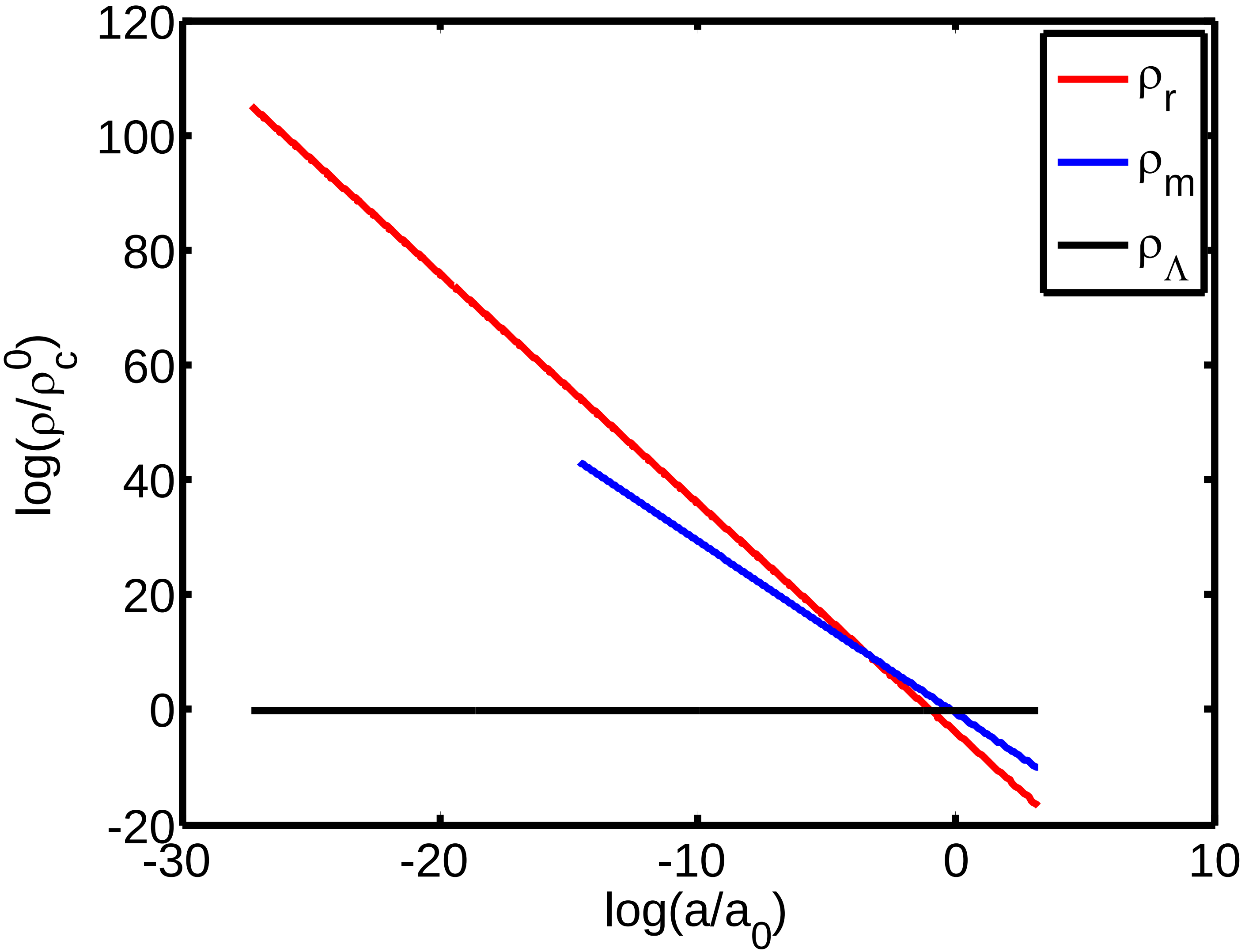
Curvature

Relativistic Matter

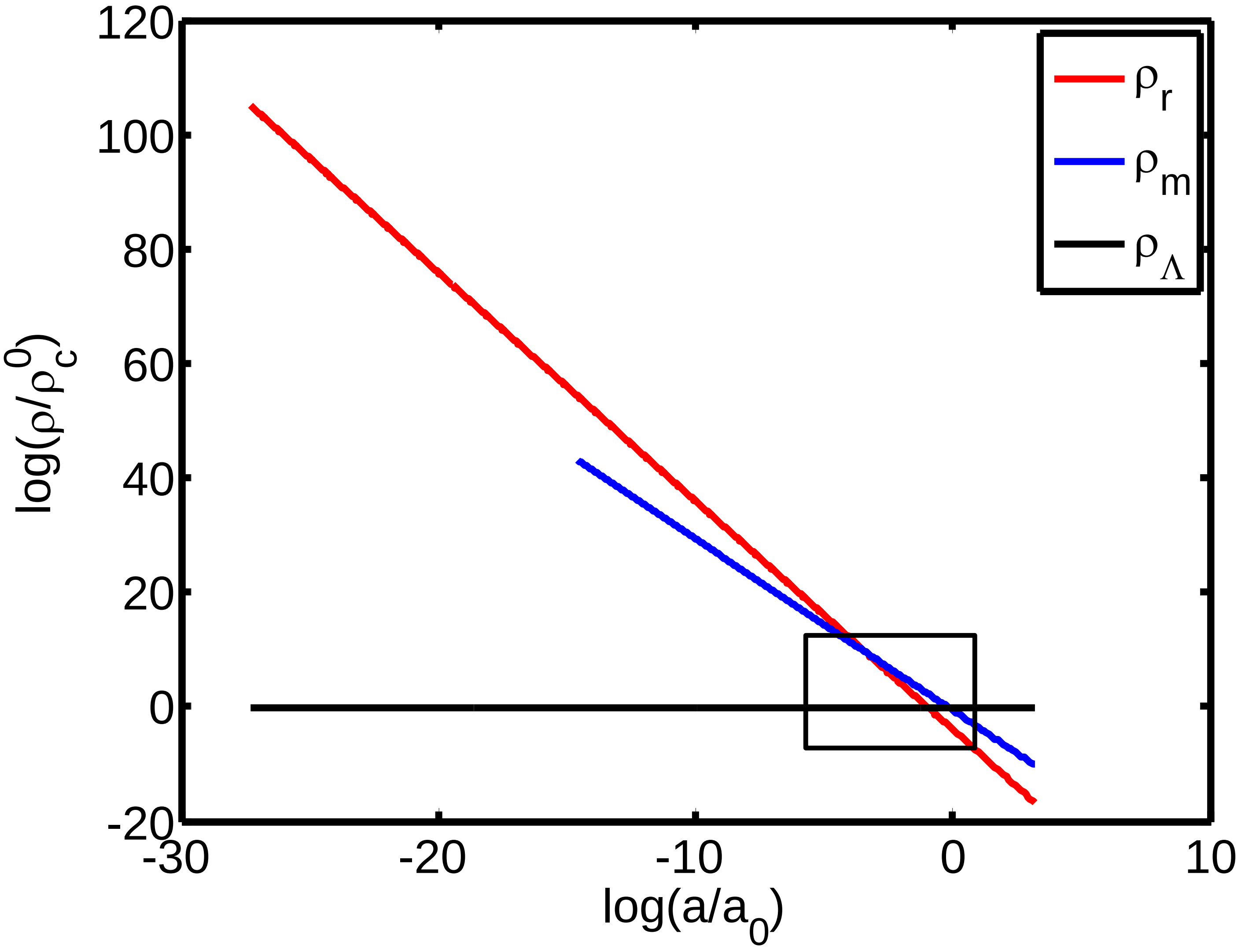
Non-relativistic Matter

"Scale factor"

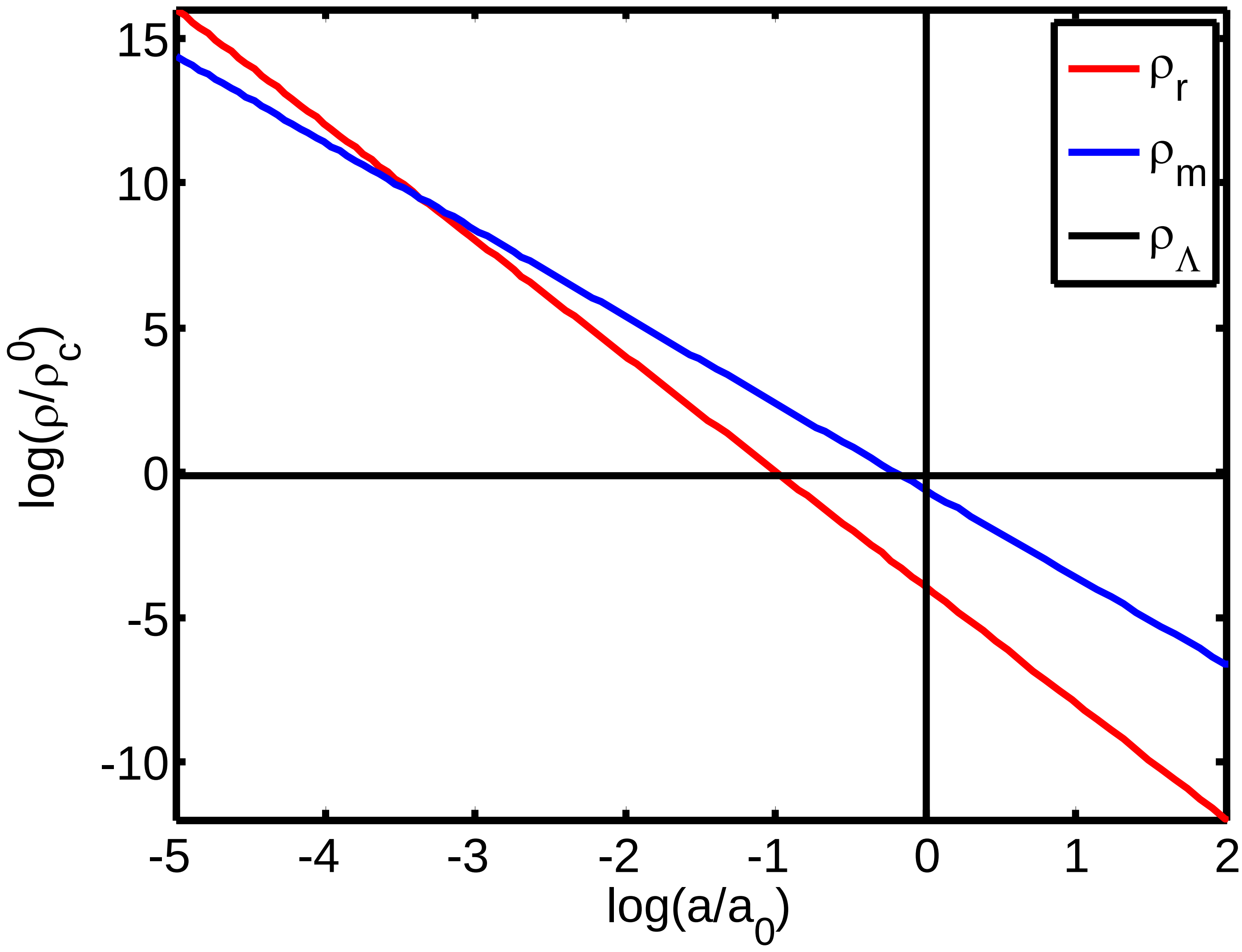
Evolution of Cosmic Matter



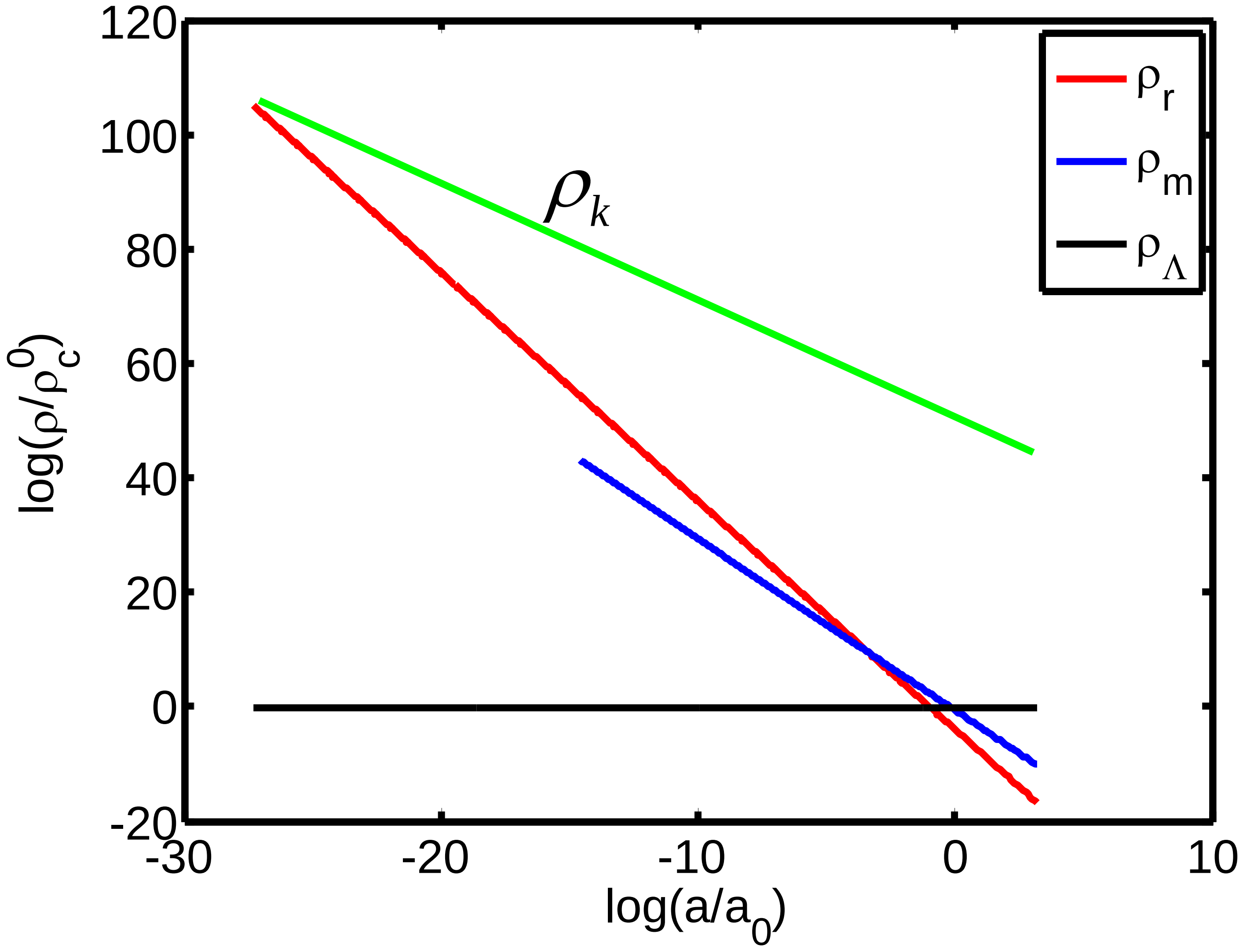
Evolution of Cosmic Matter



Evolution of Cosmic Matter



The curvature feature/"problem"



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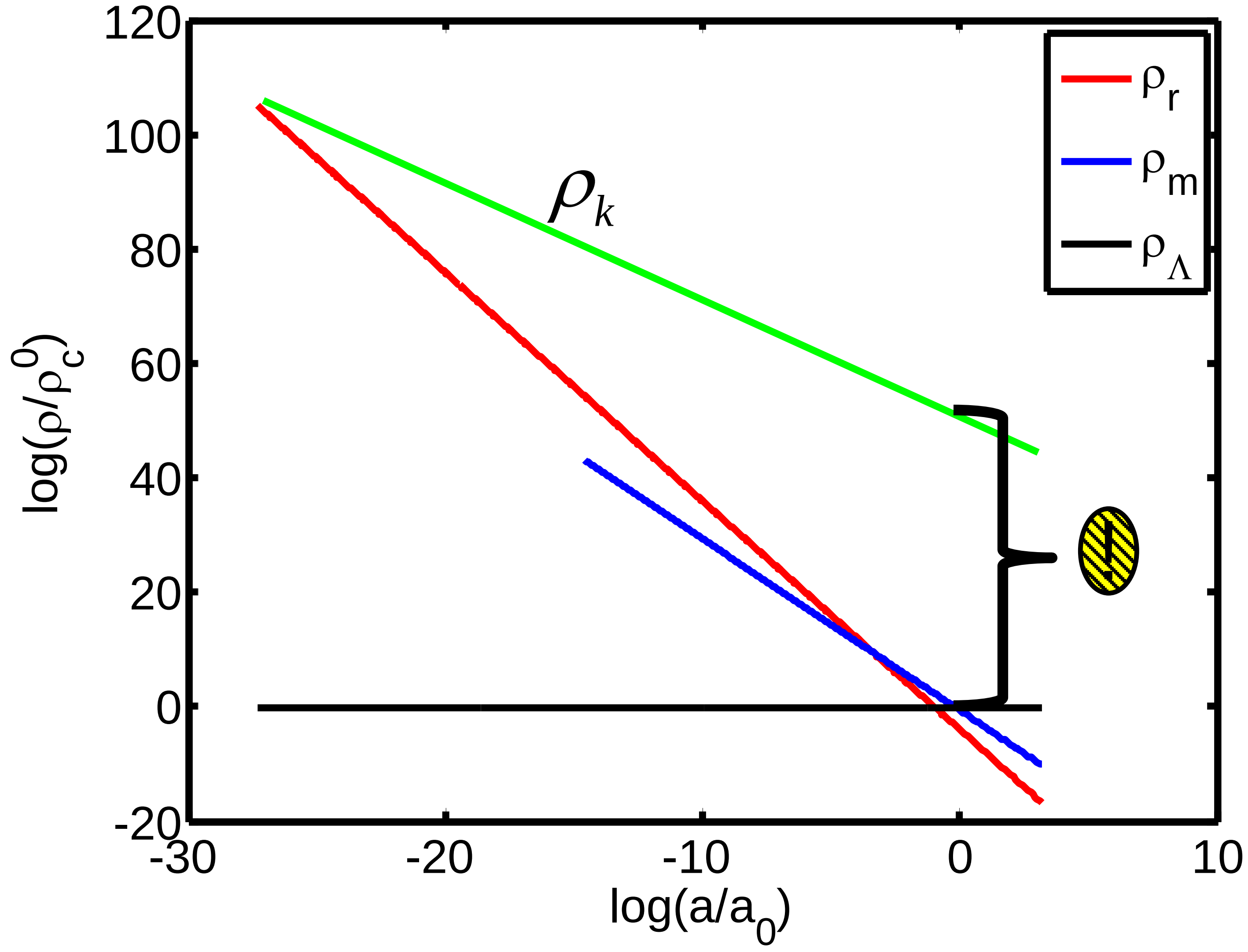

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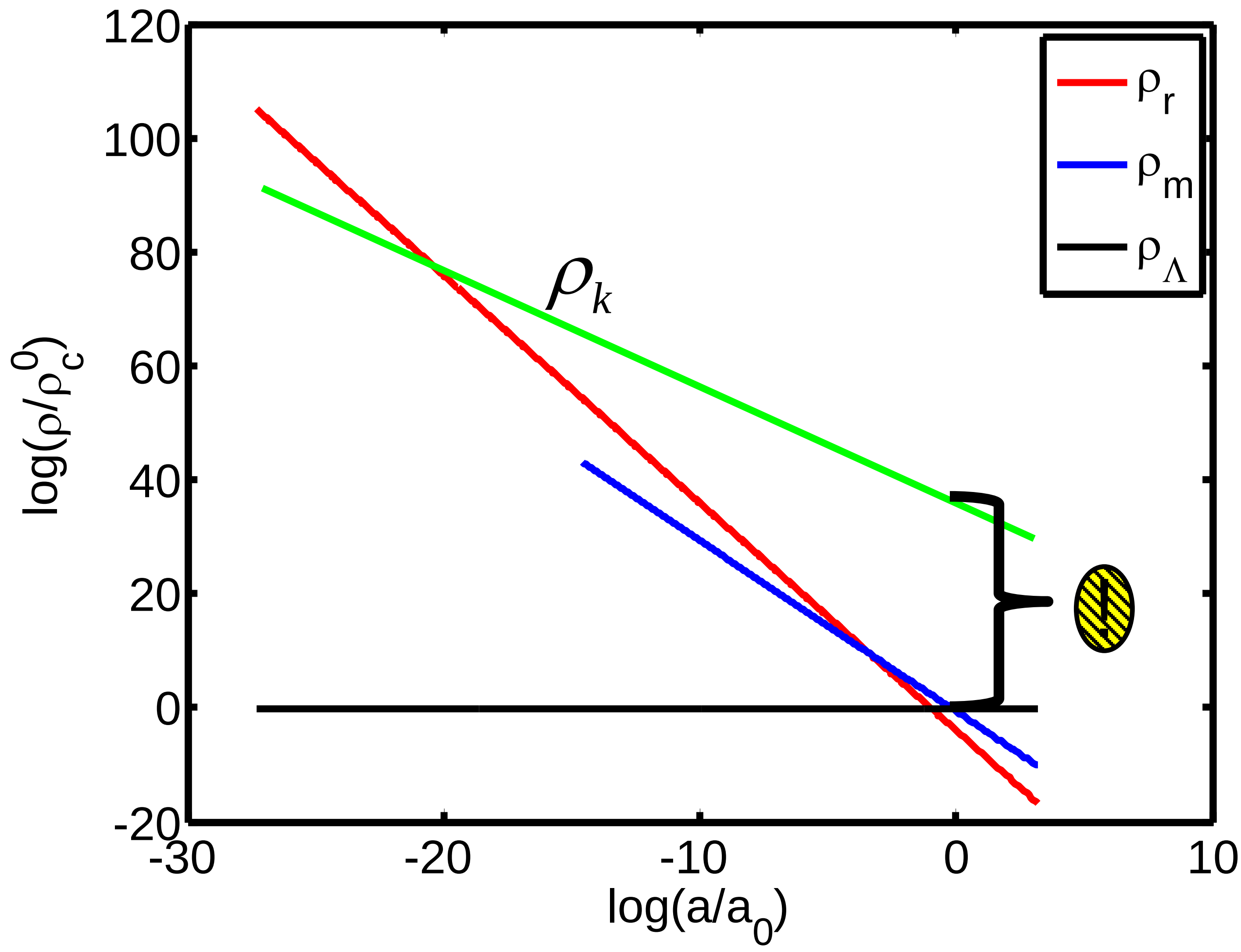

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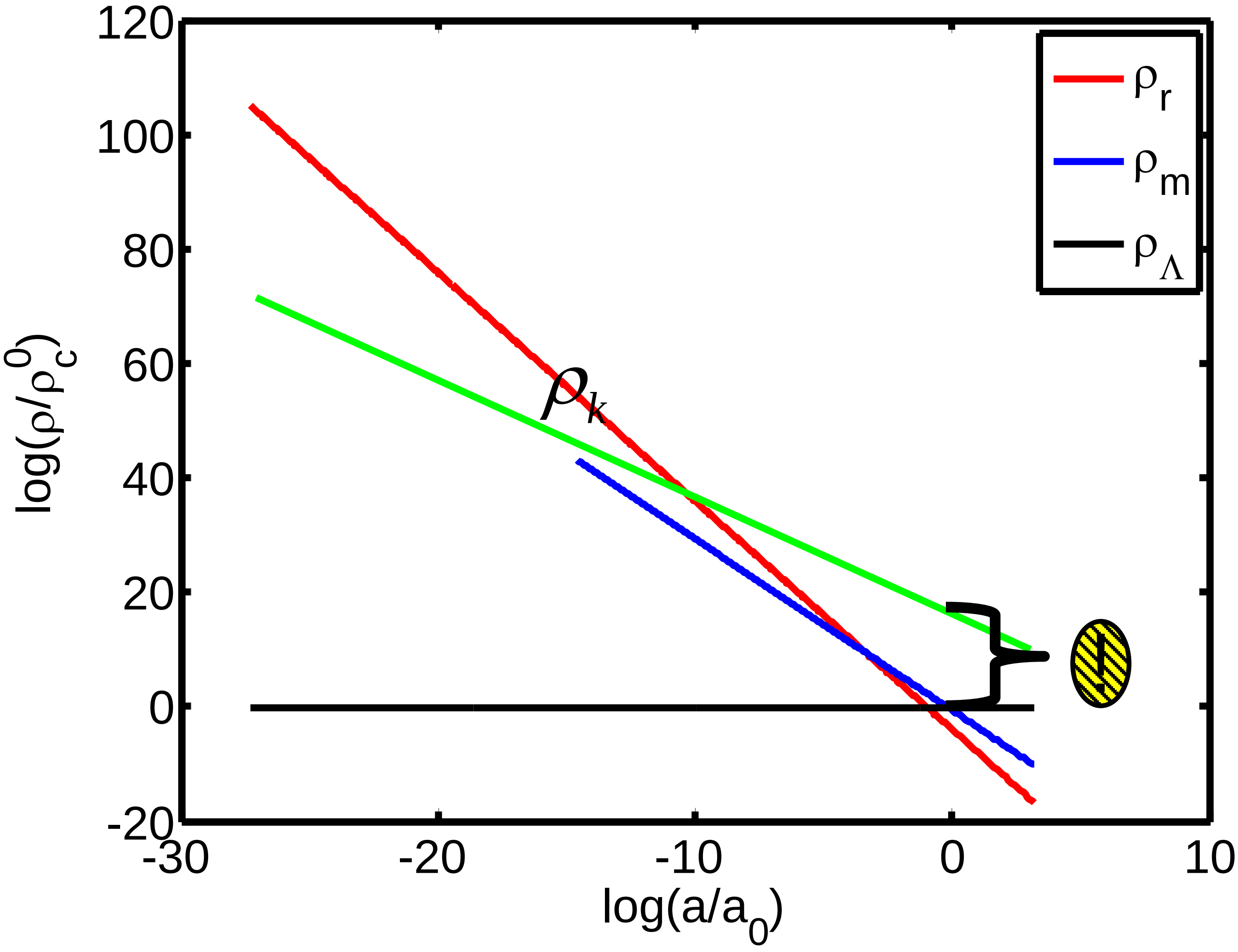

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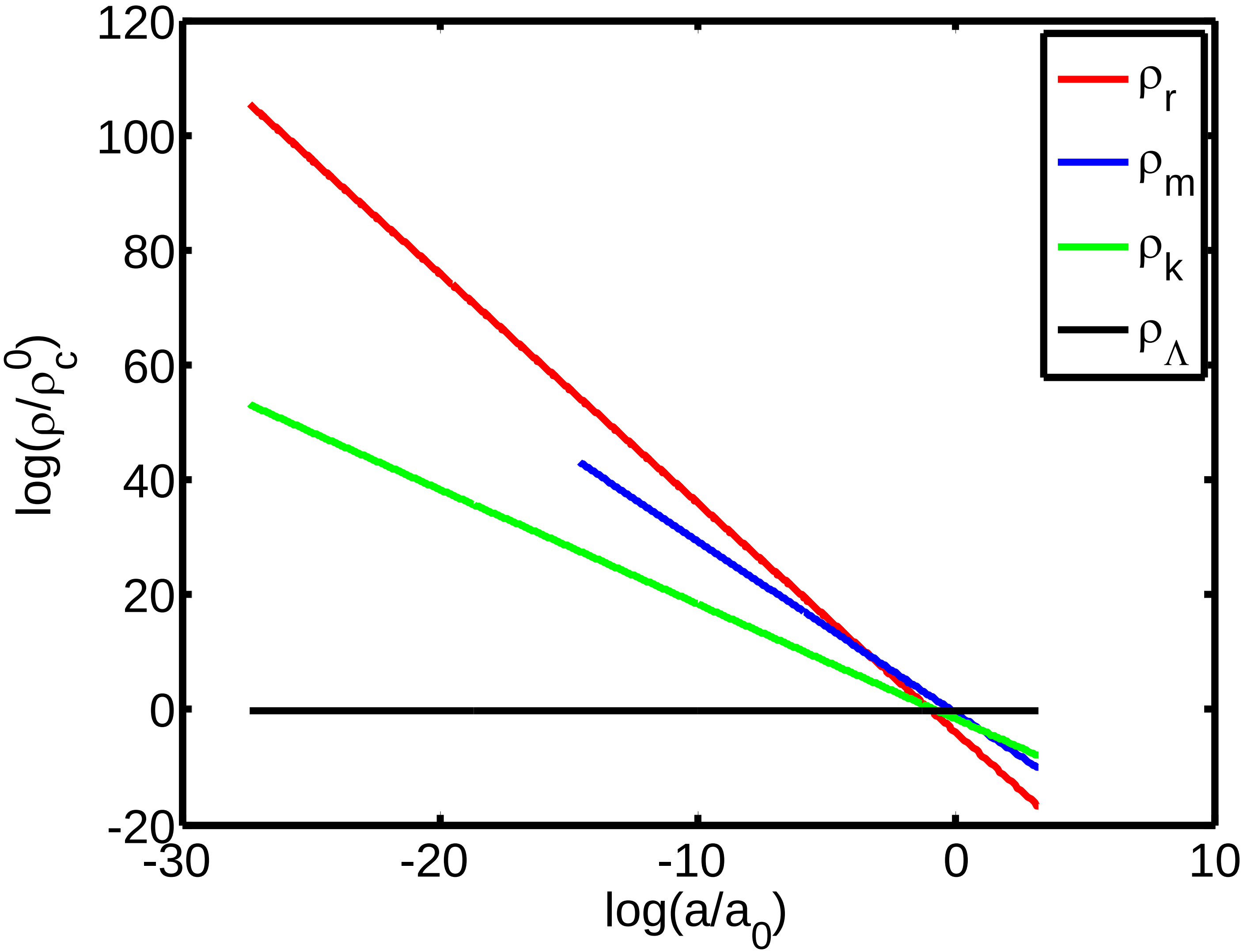

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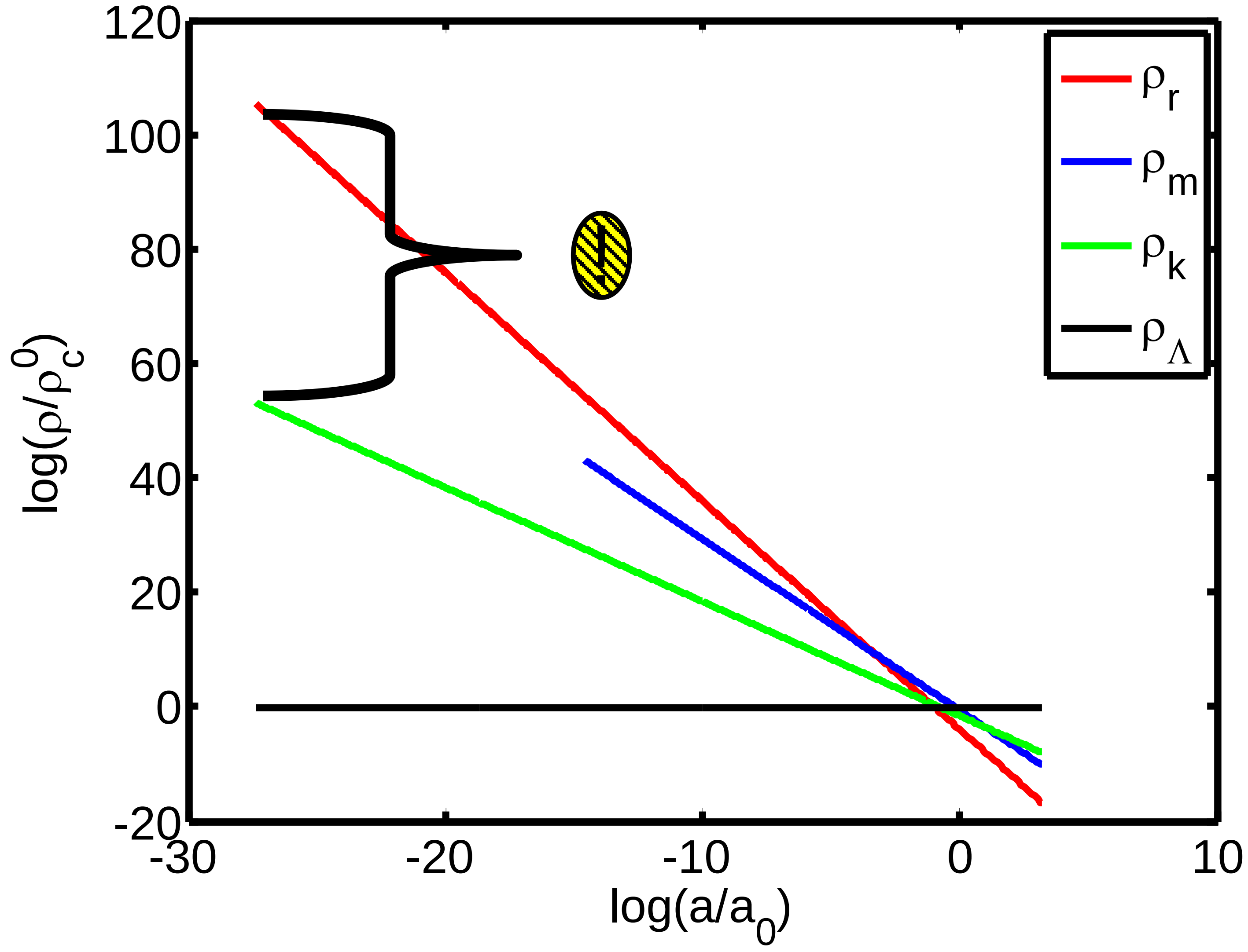
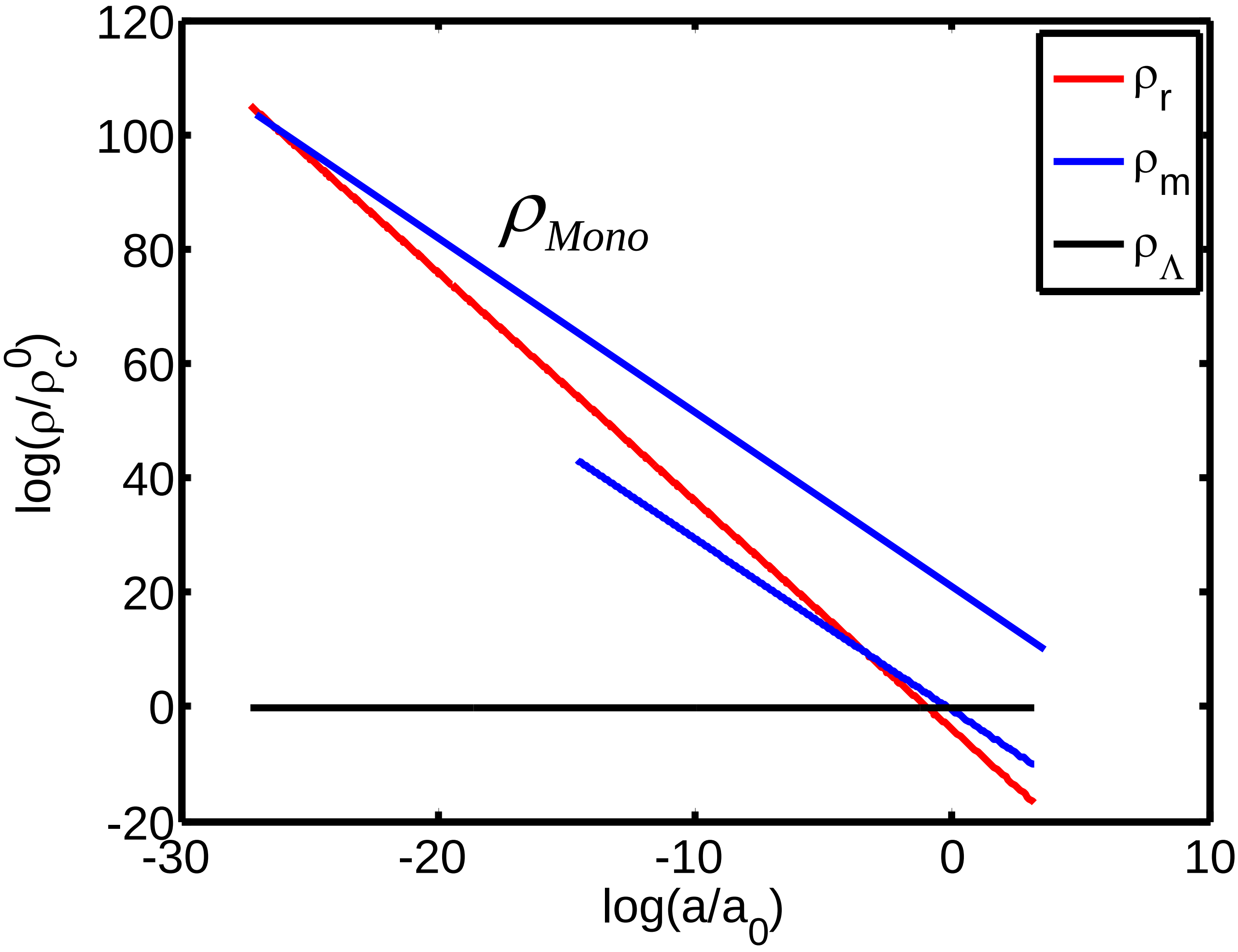


The monopole "problem"



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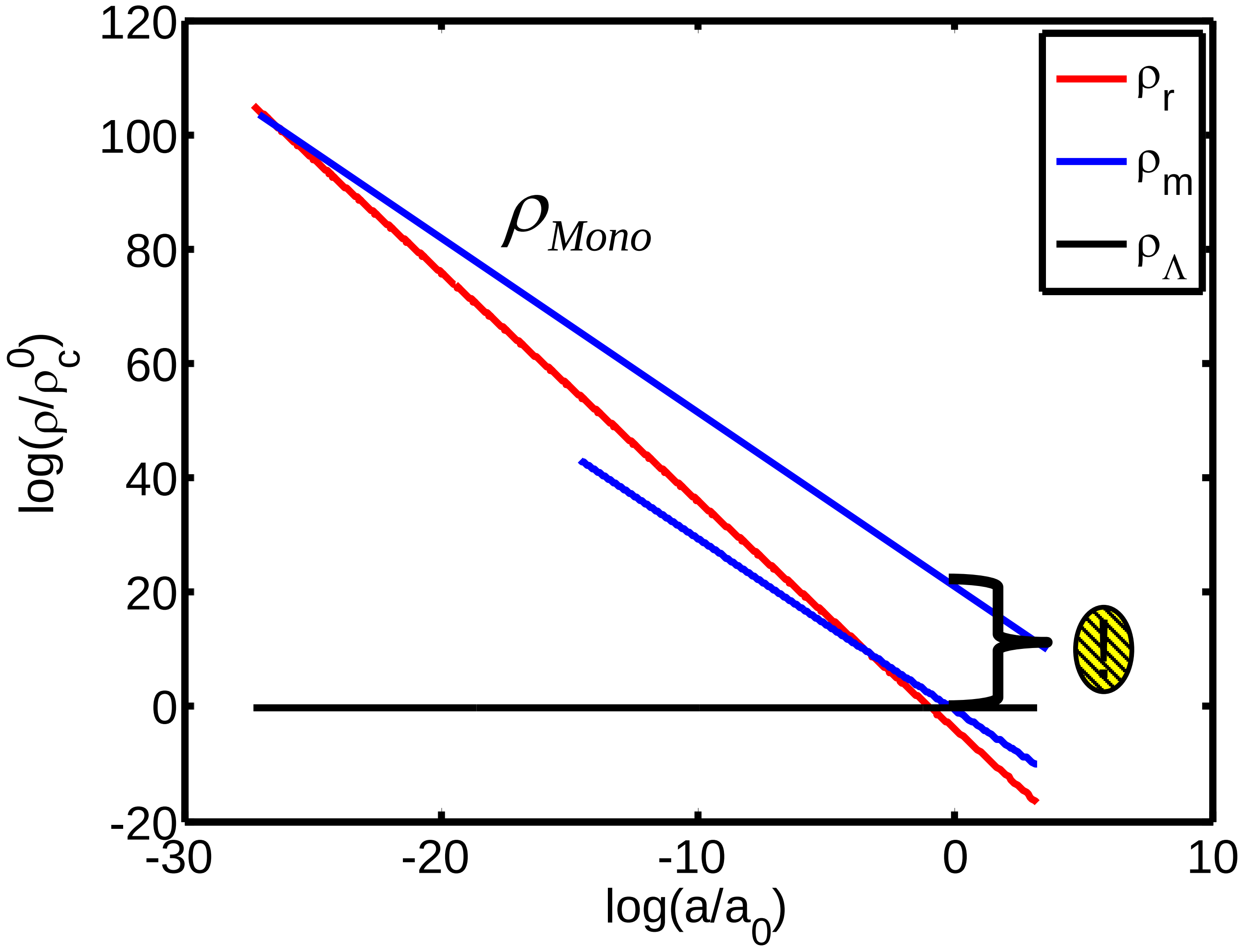

Friedmann Eqn.

$\propto a^{-2}$

$\propto a^{-4}$

$\propto a^{\approx 0}$

$\propto a^{-3}$

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

Dark Energy

Curvature

Relativistic Matter

Non-relativistic Matter

Now add cosmic inflation

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Inflaton

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

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Inflaton

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$$H_I = \frac{\dot{a}}{a} \approx const \rightarrow \boxed{a \approx e^{Ht}}$$

Now add cosmic inflation

Friedmann Eqn.

$$\boxed{\propto a^{\approx 0}}$$

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

Inflaton

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The inflaton:

~Homogeneous scalar field ϕ obeying

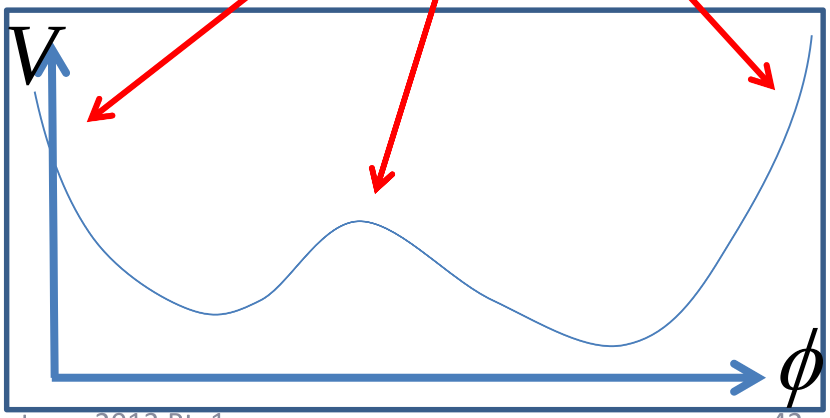
$$\ddot{\phi} + 3H\dot{\phi} = -\Gamma_{\phi}\dot{\phi} - V'(\phi)$$

Cosmic damping

Coupling to ordinary matter

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

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



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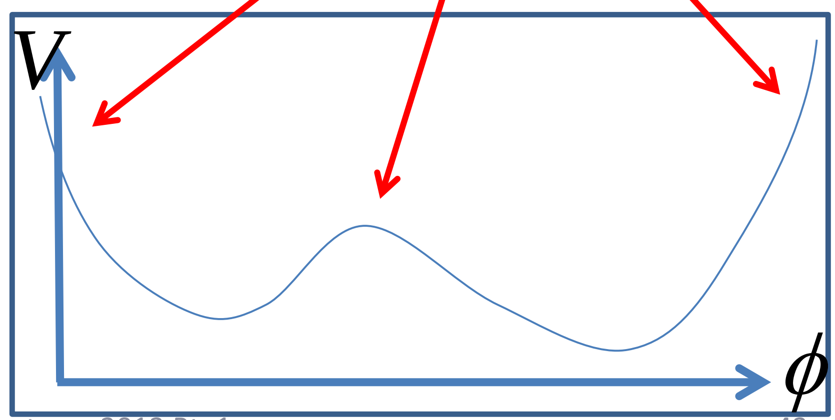
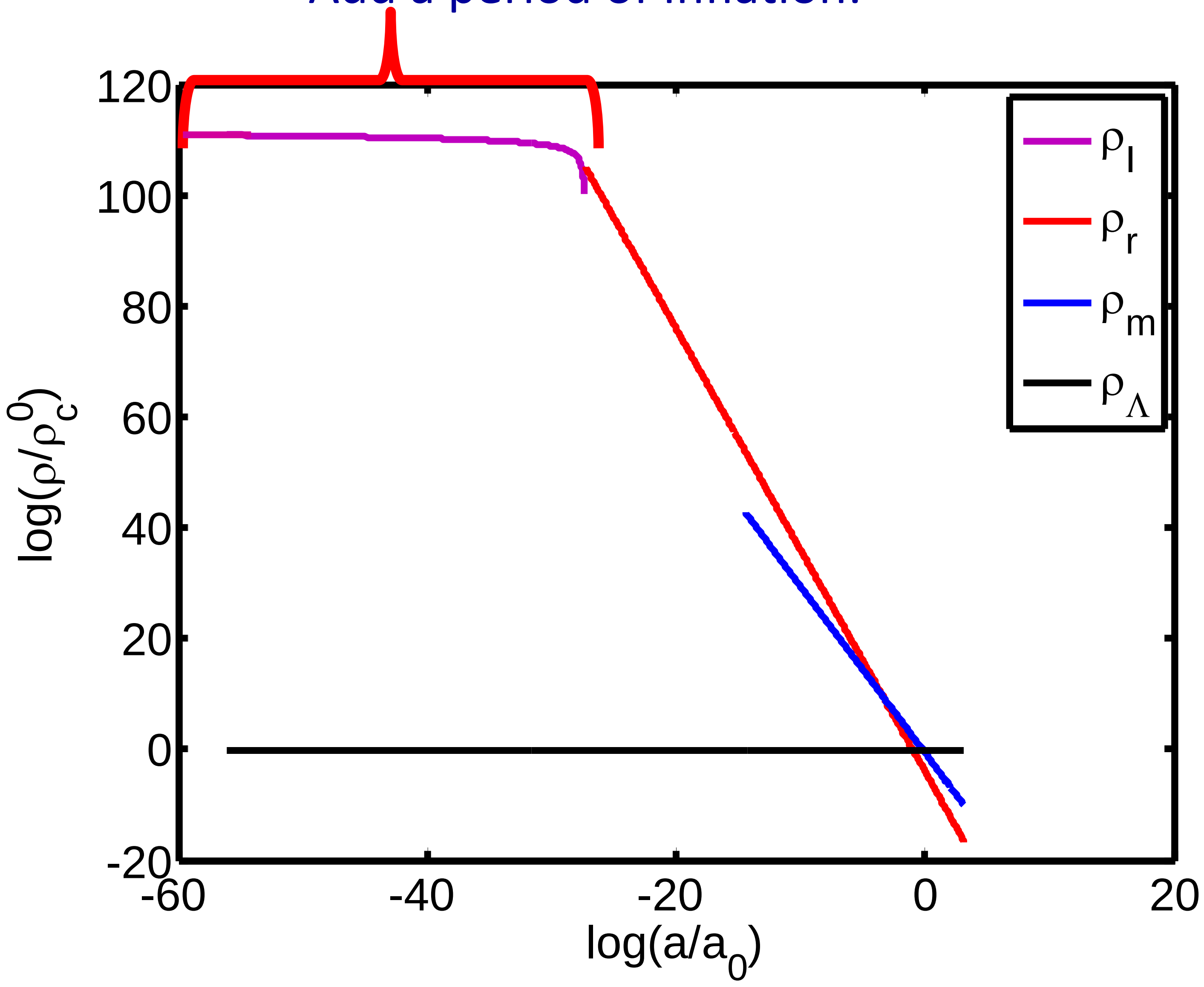
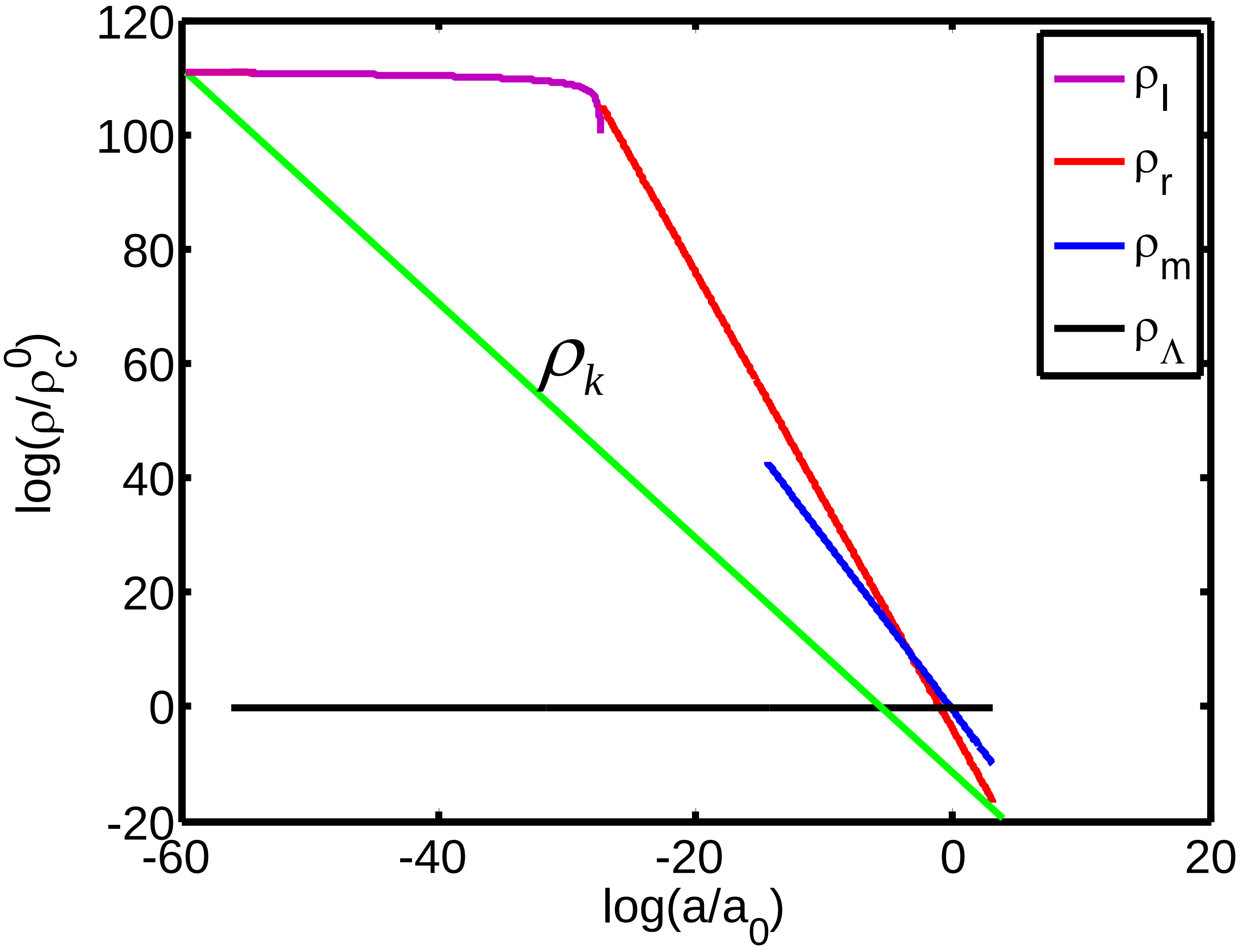


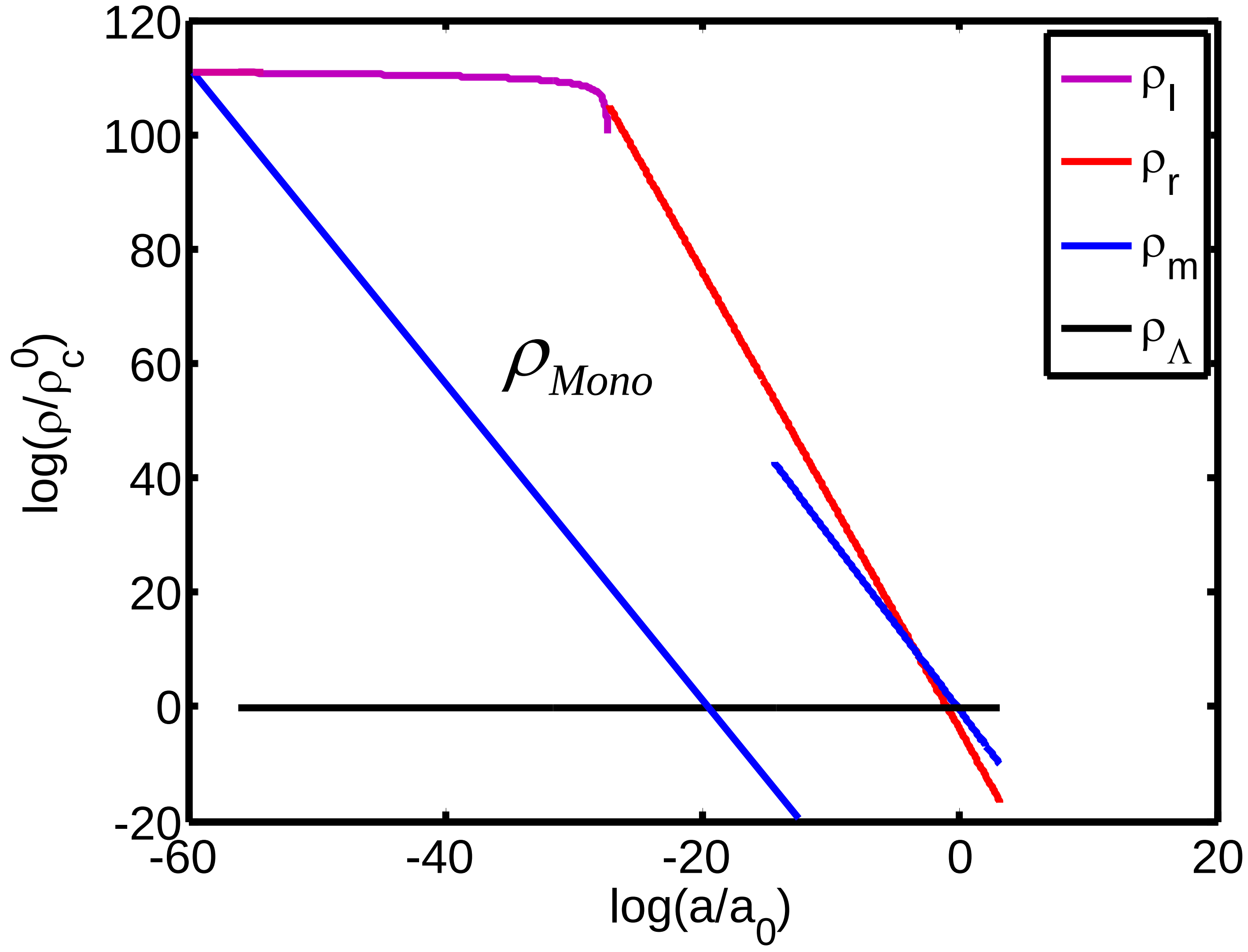
Add a period of Inflation:



With inflation, initially large curvature is OK:



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



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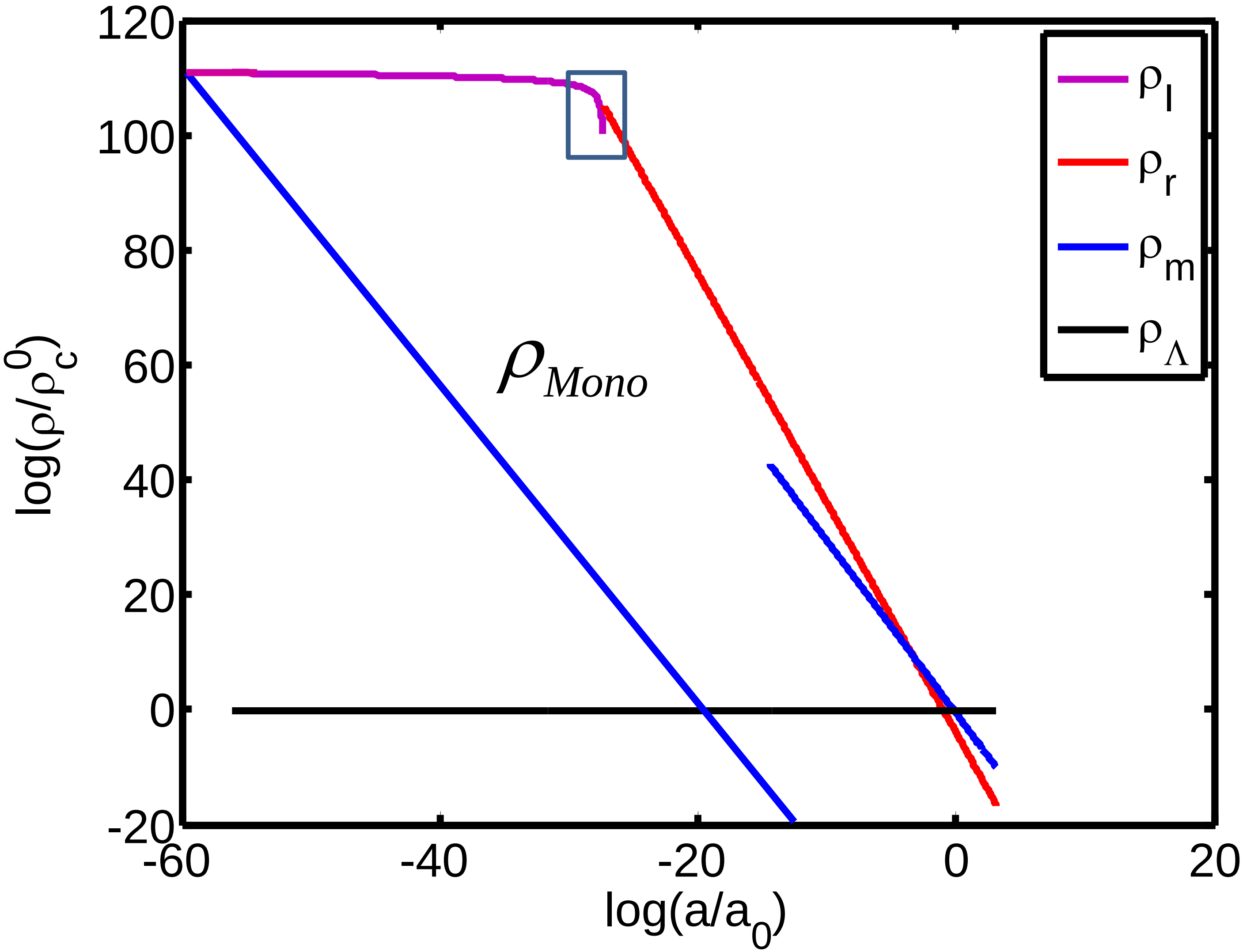
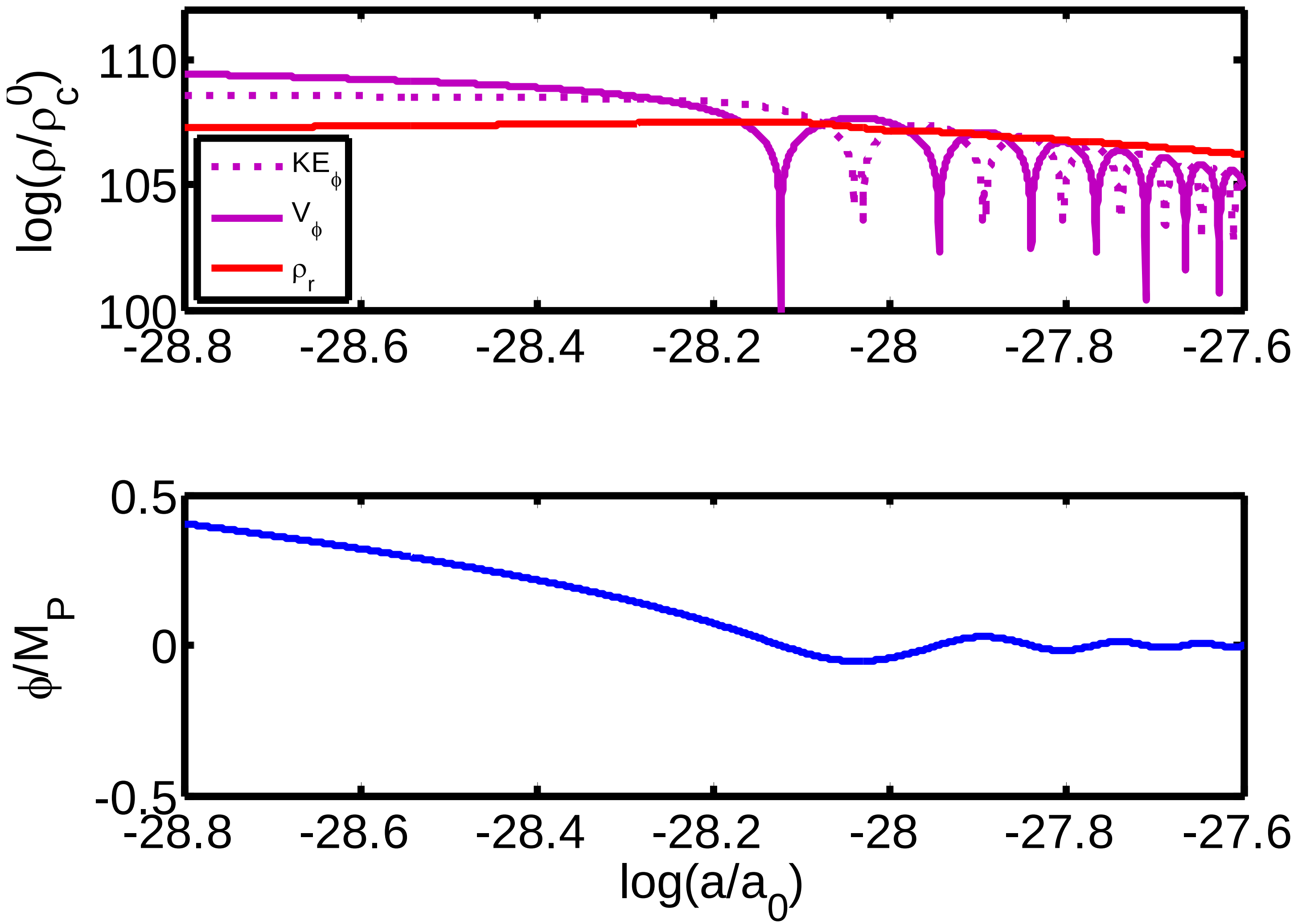


Inflation detail:



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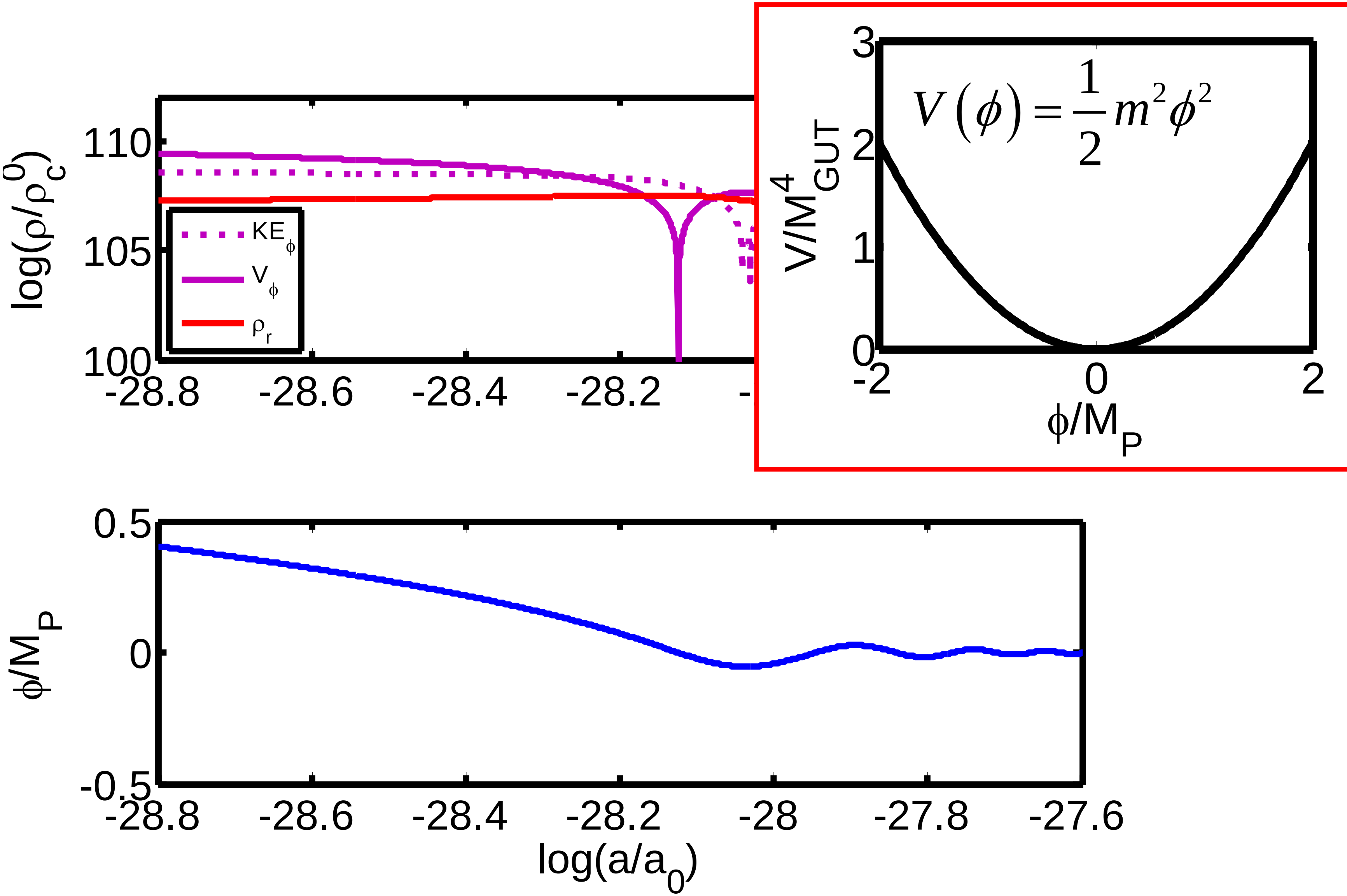

Hubble Length

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

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

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(aka ρ_c)

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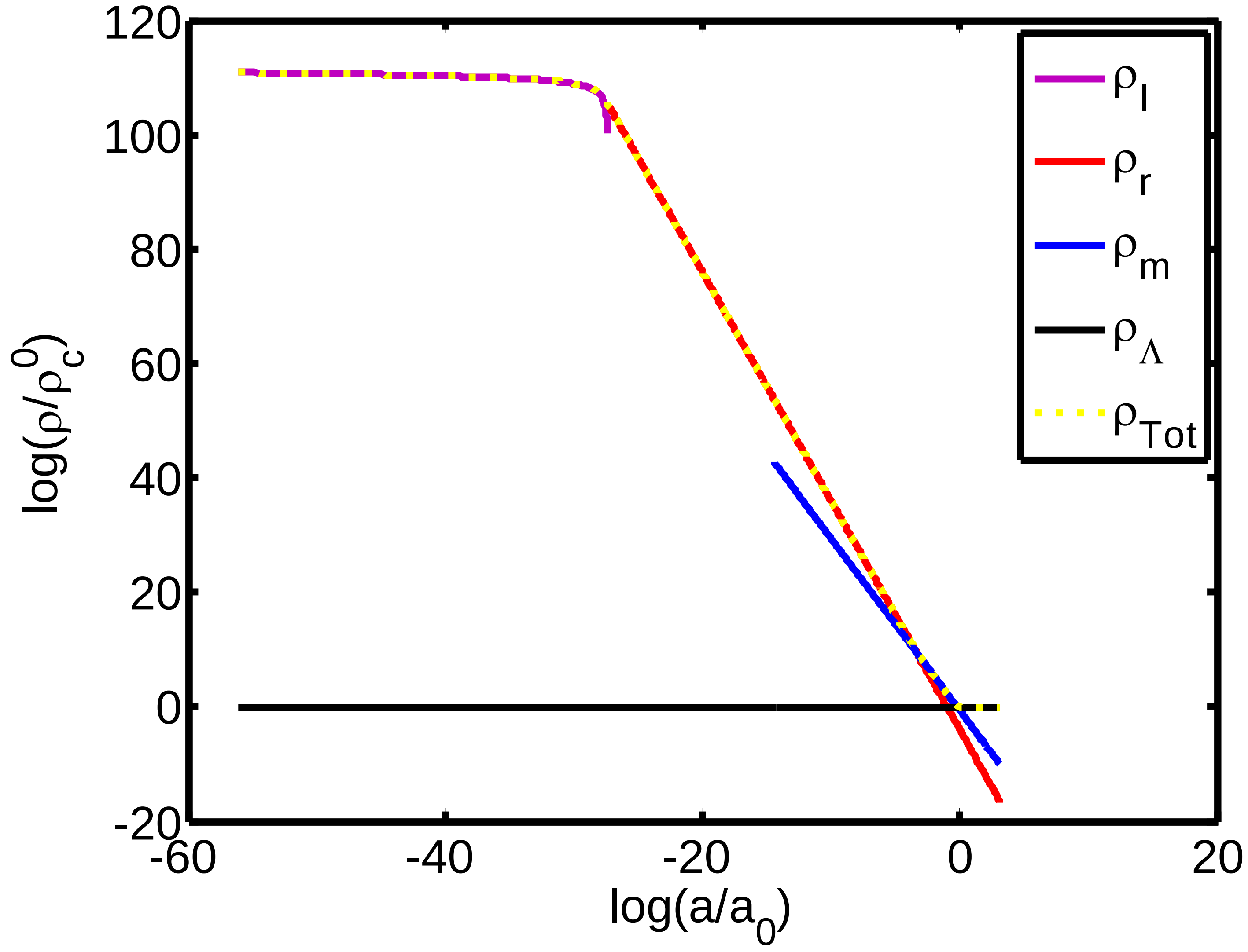

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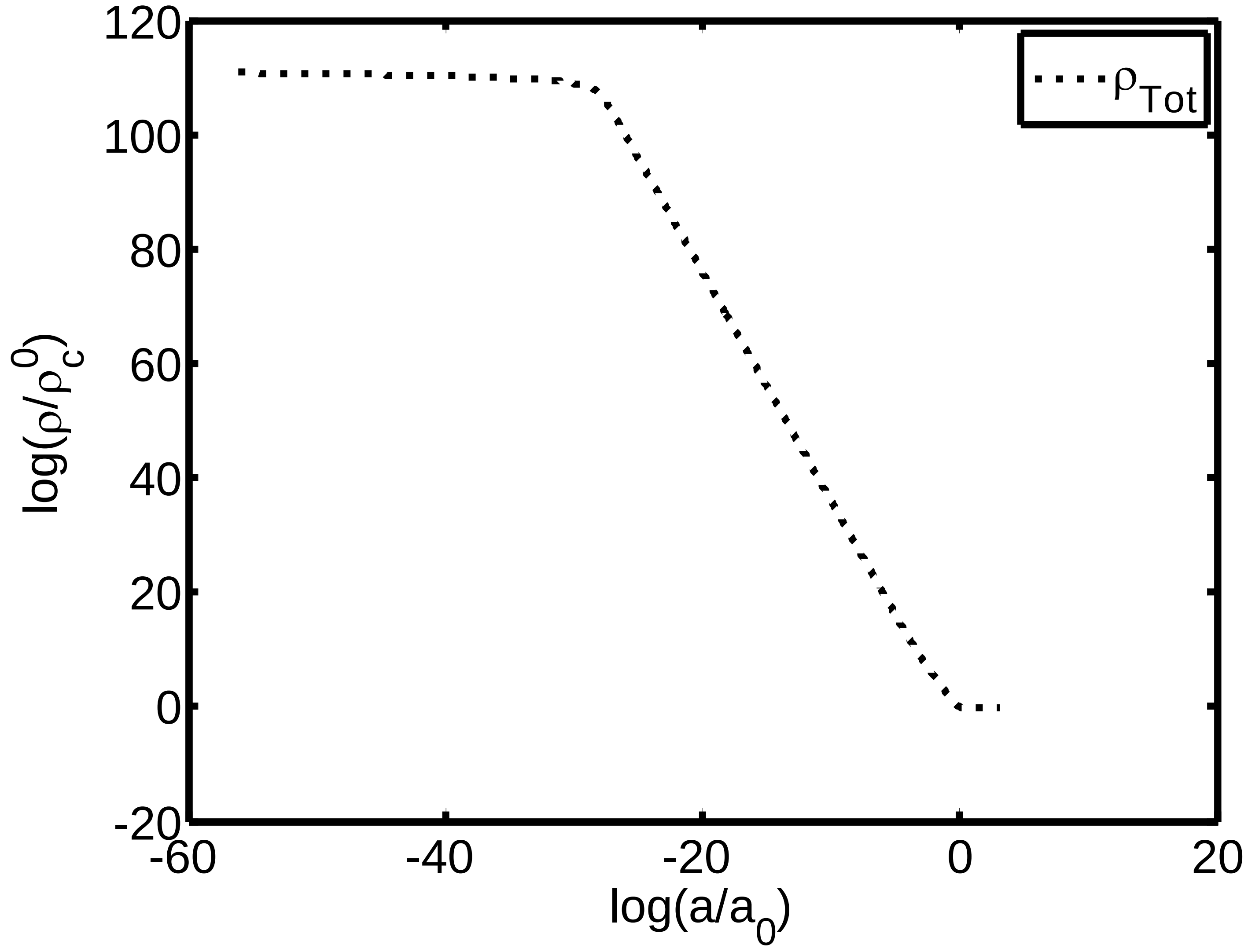

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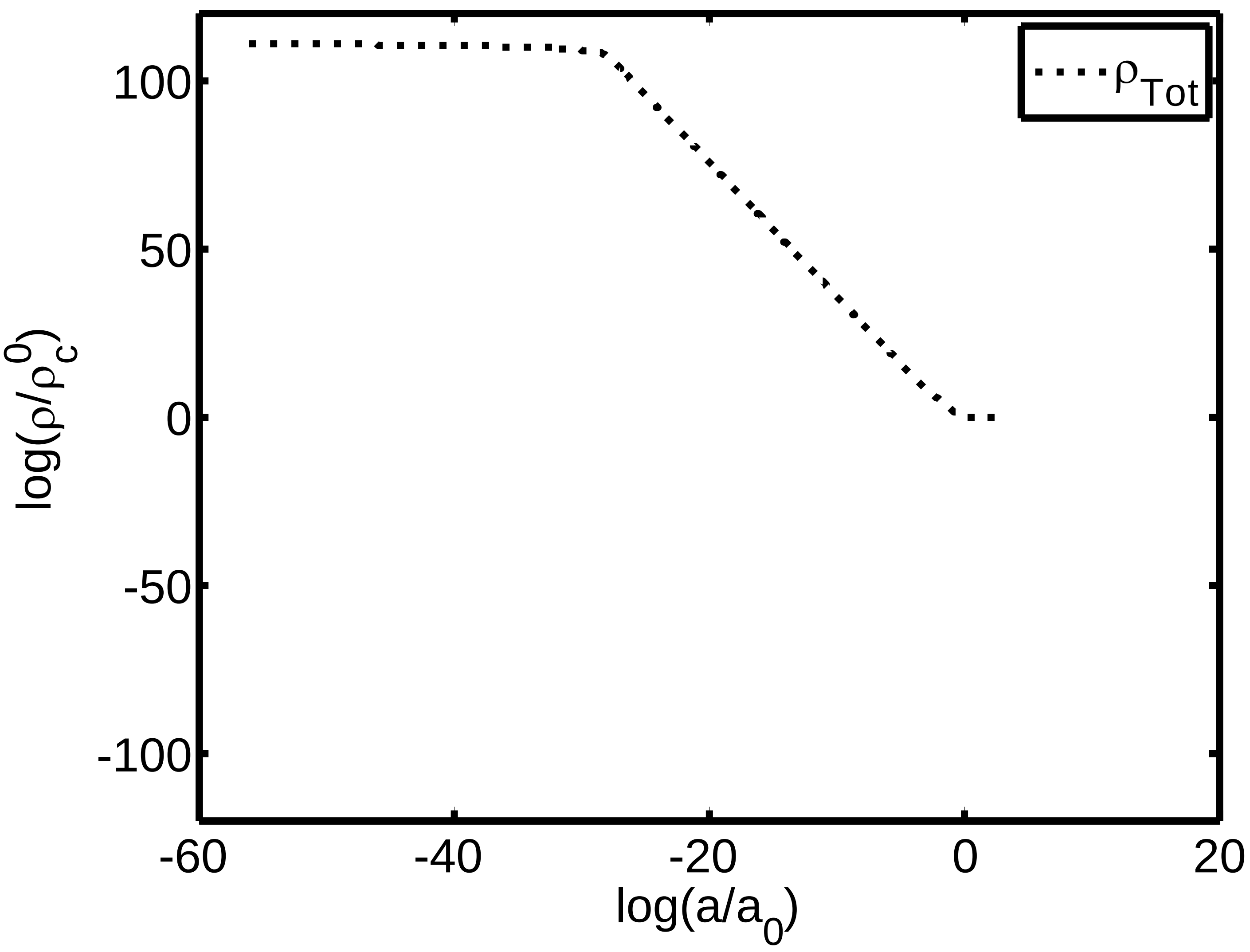

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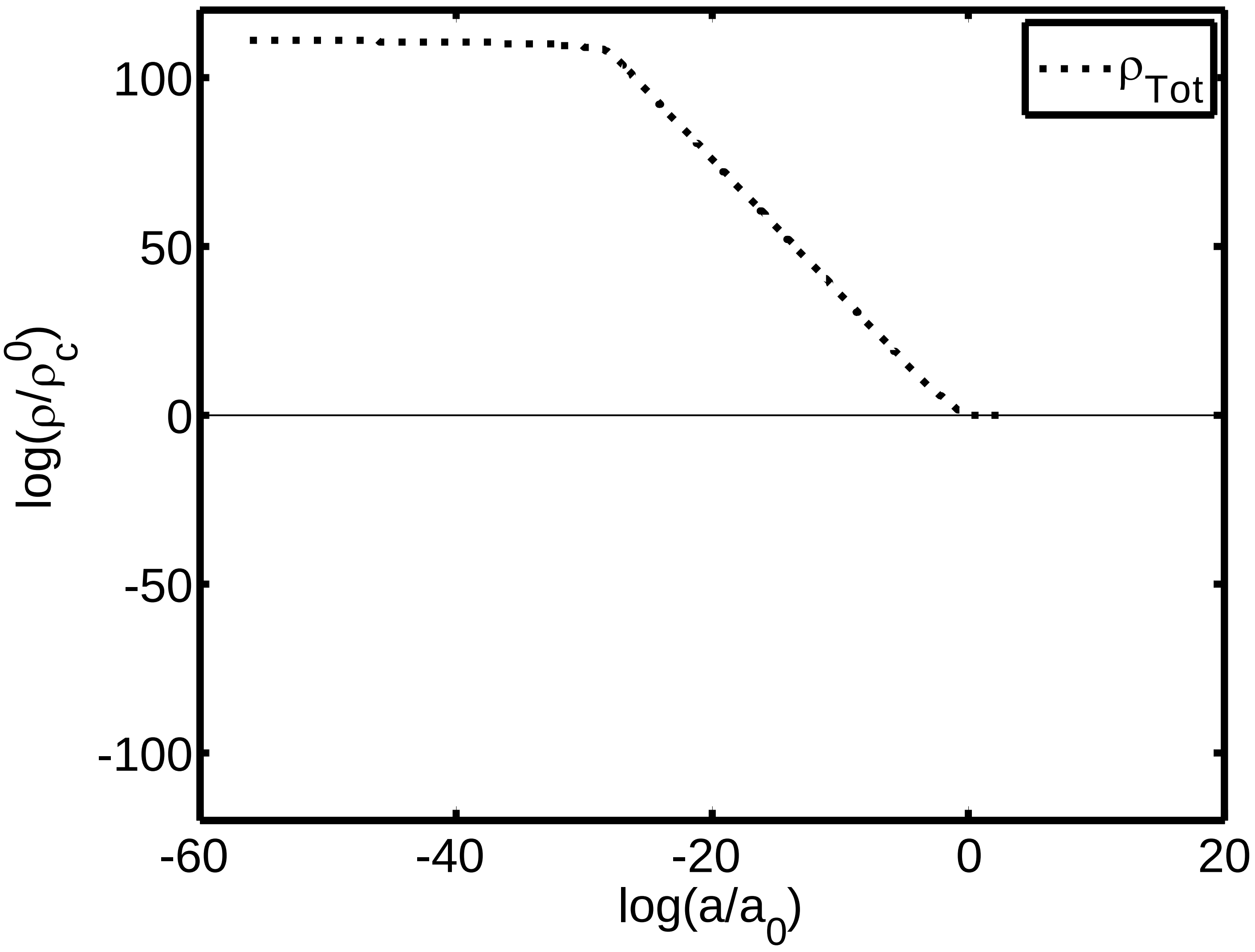

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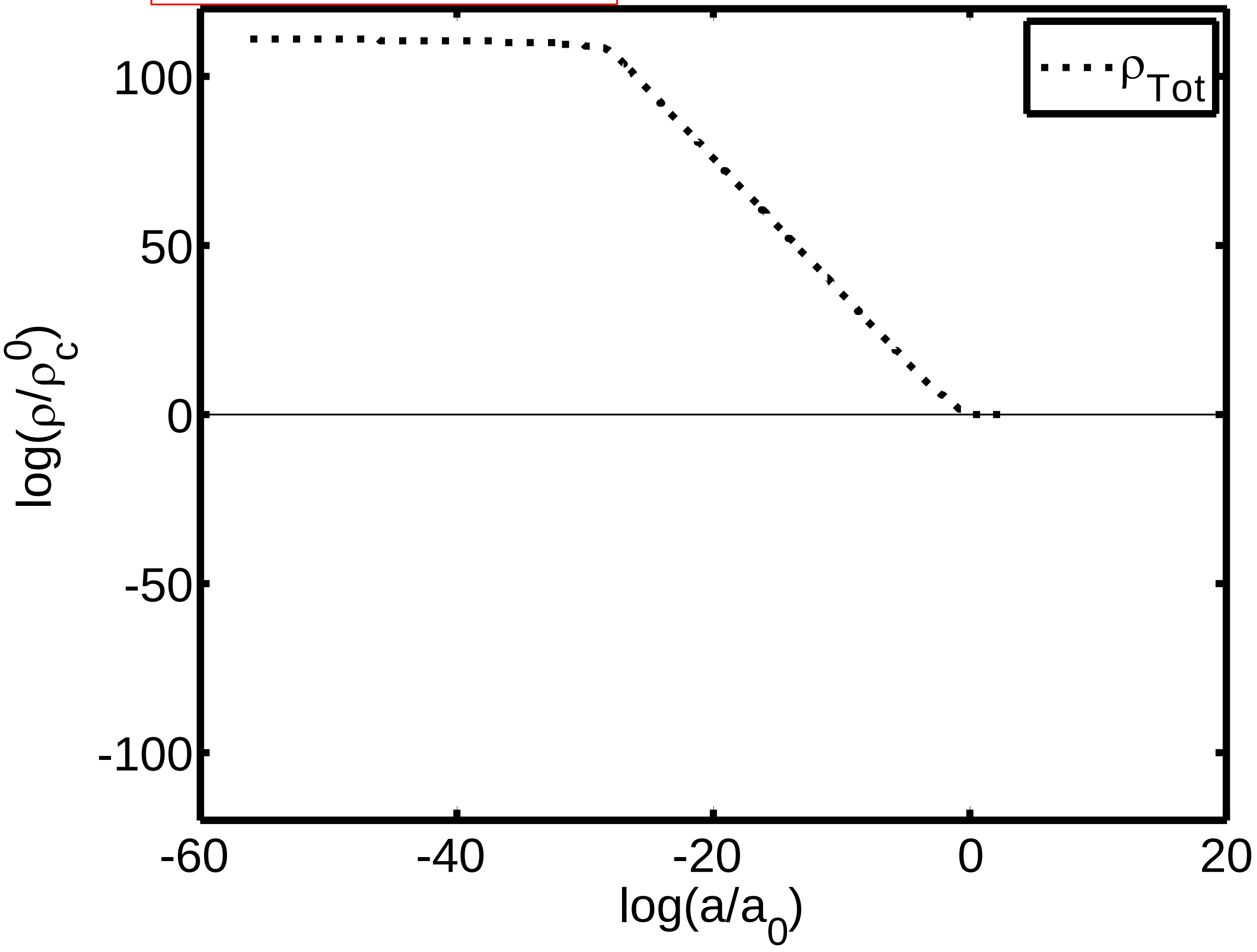

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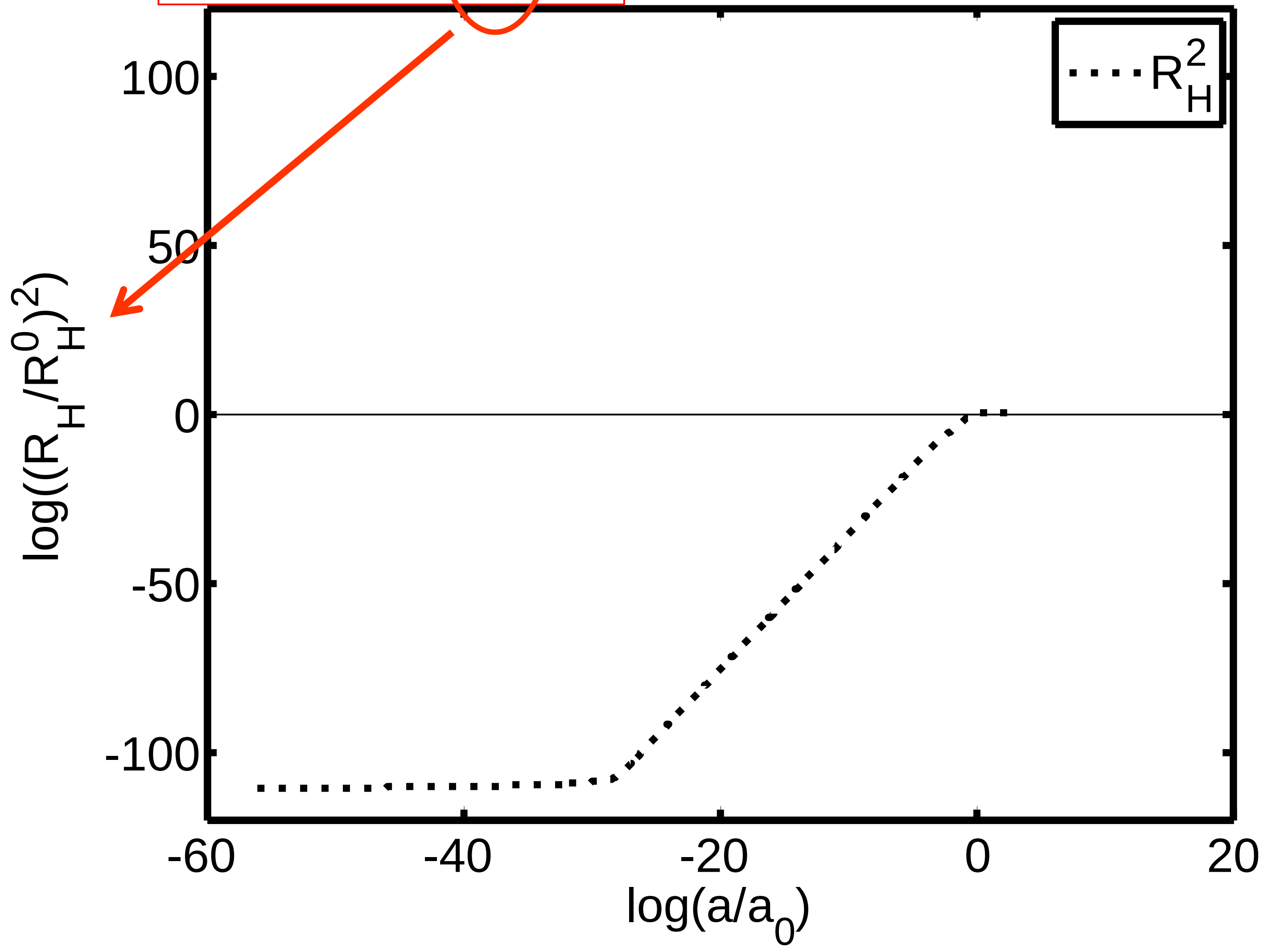

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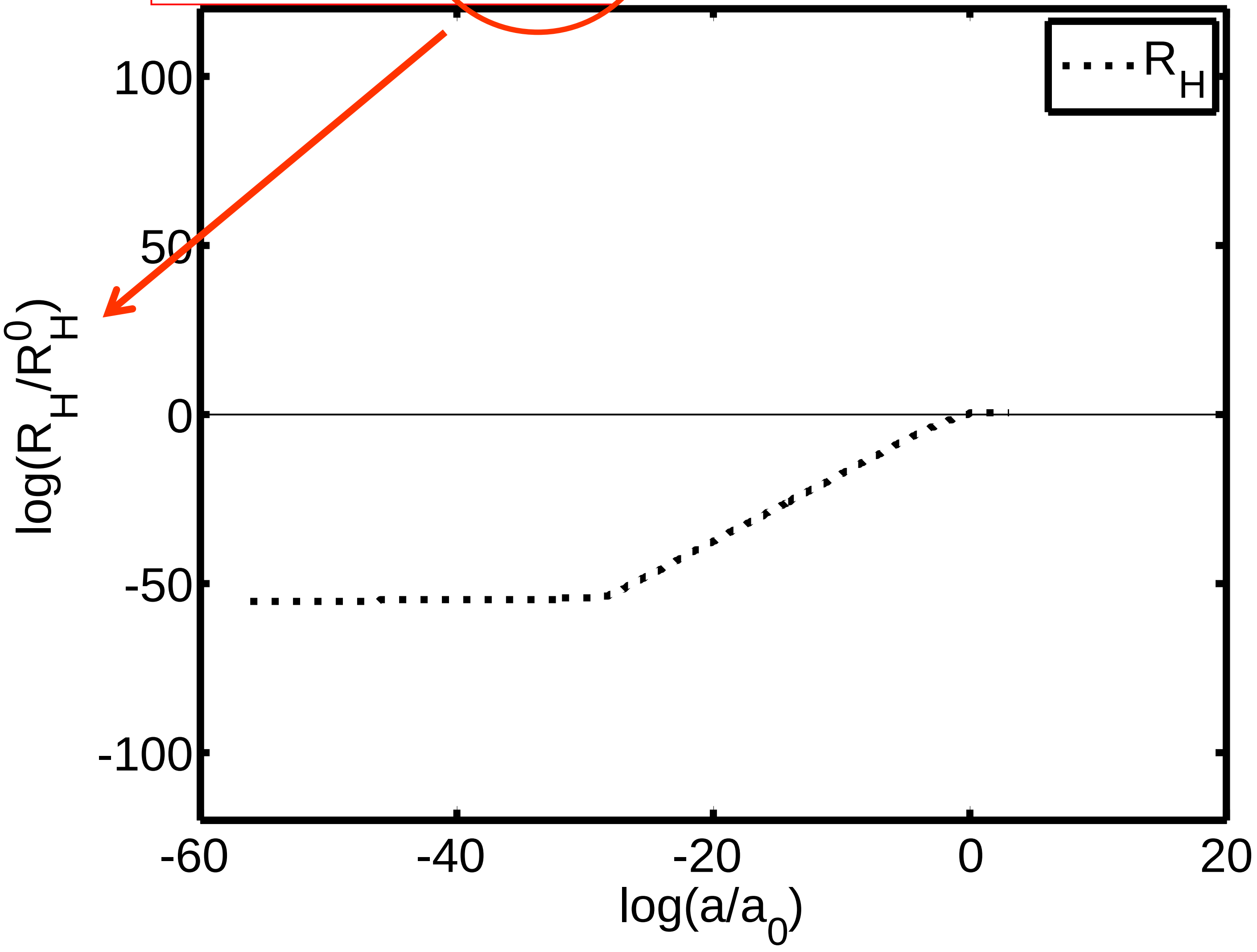

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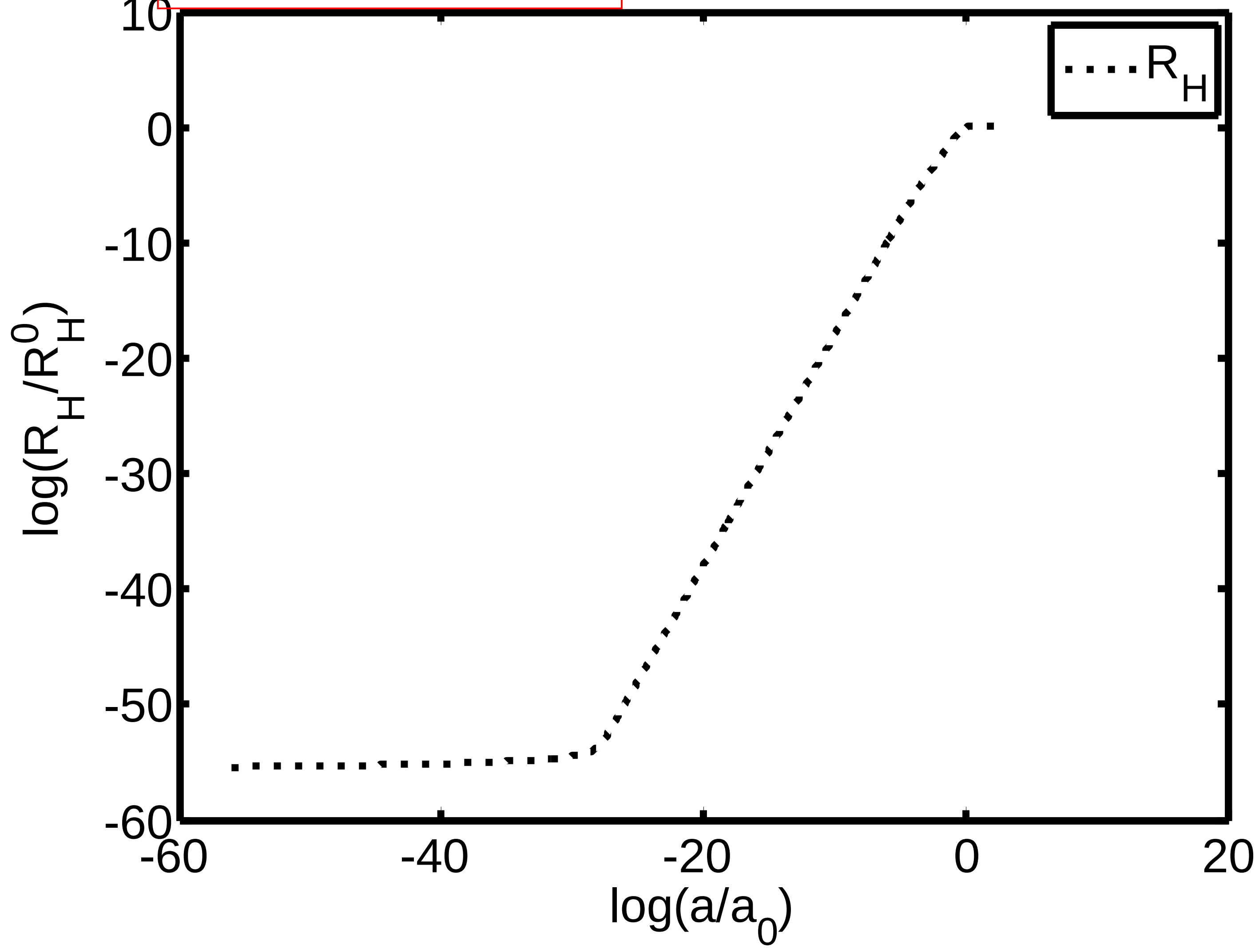

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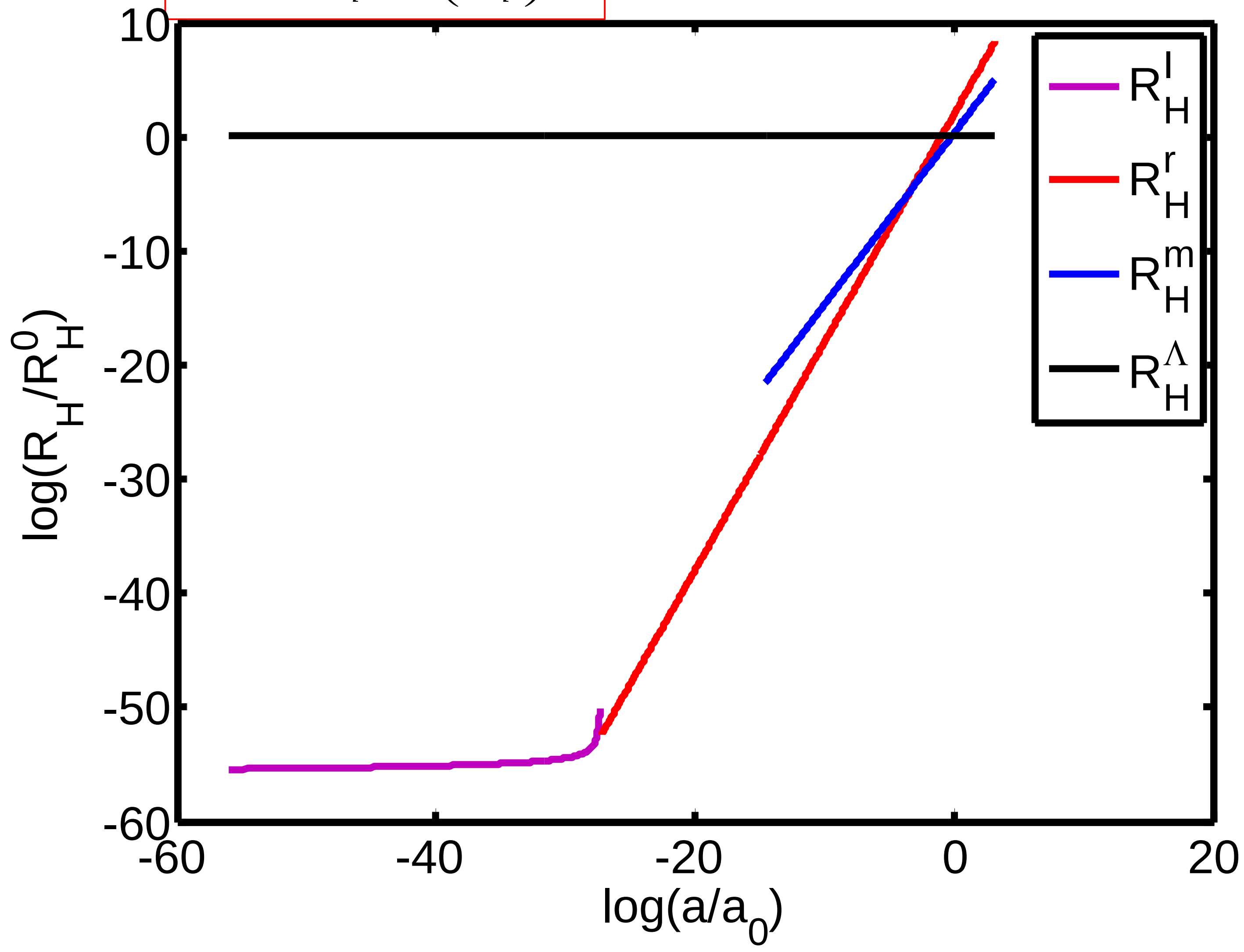

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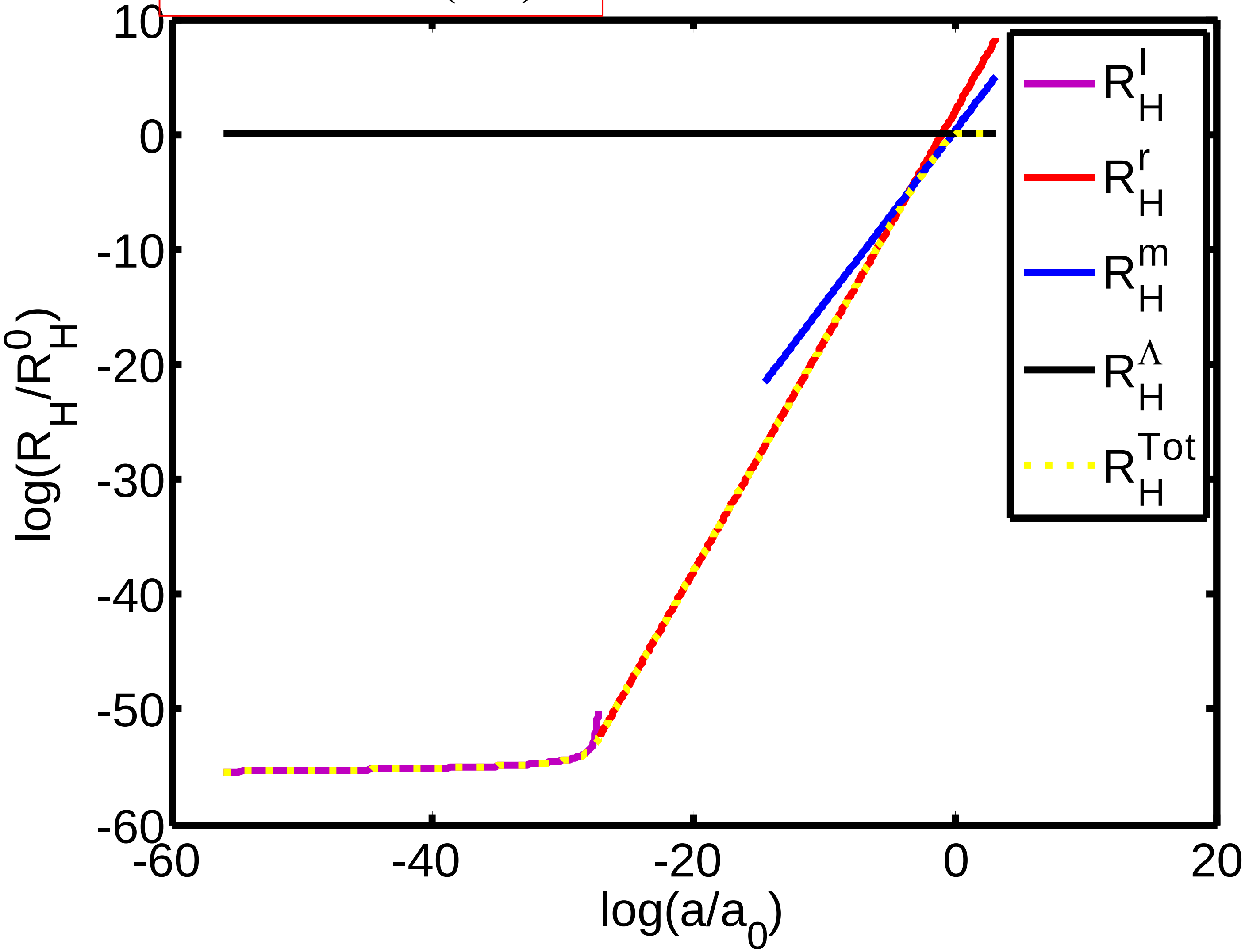

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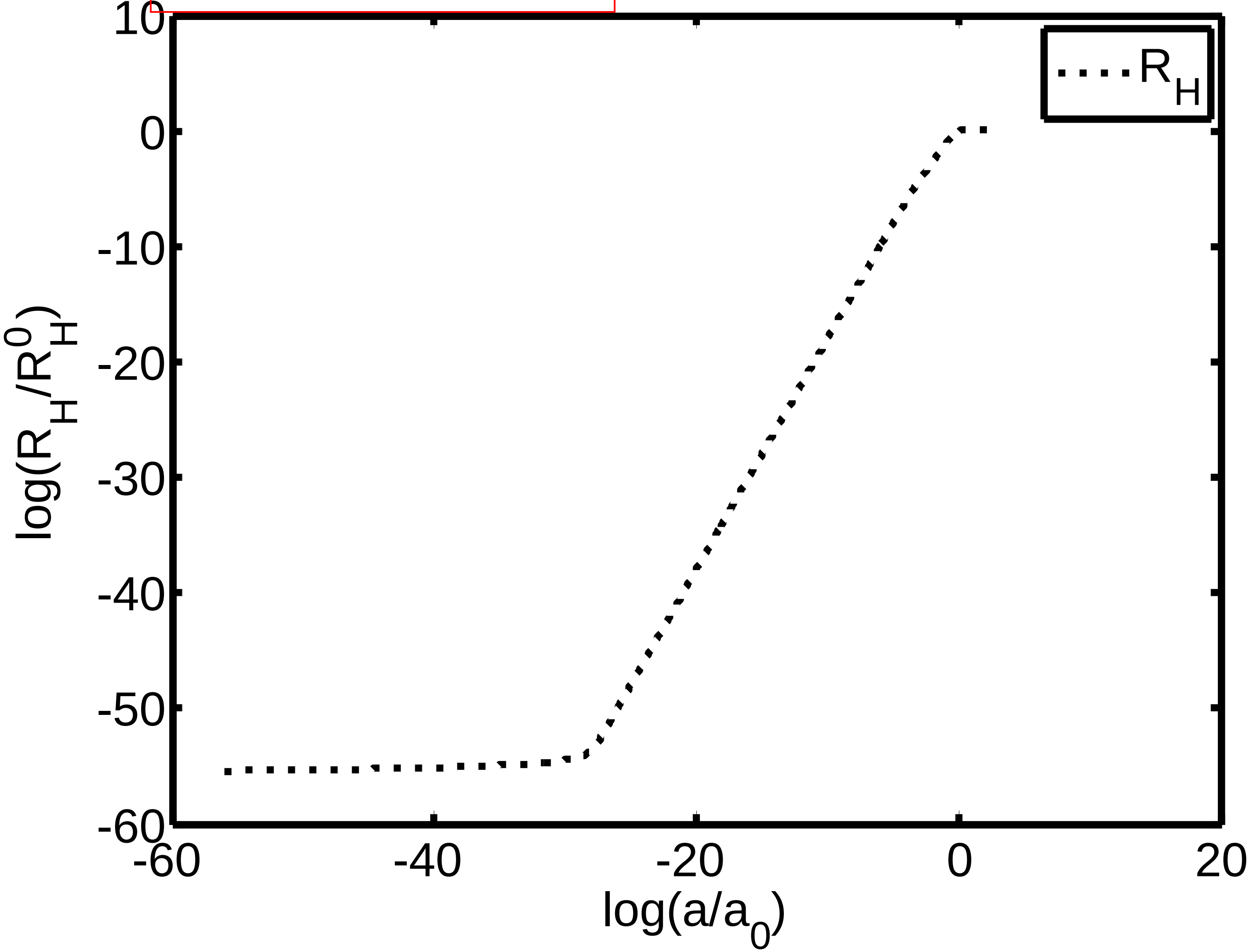
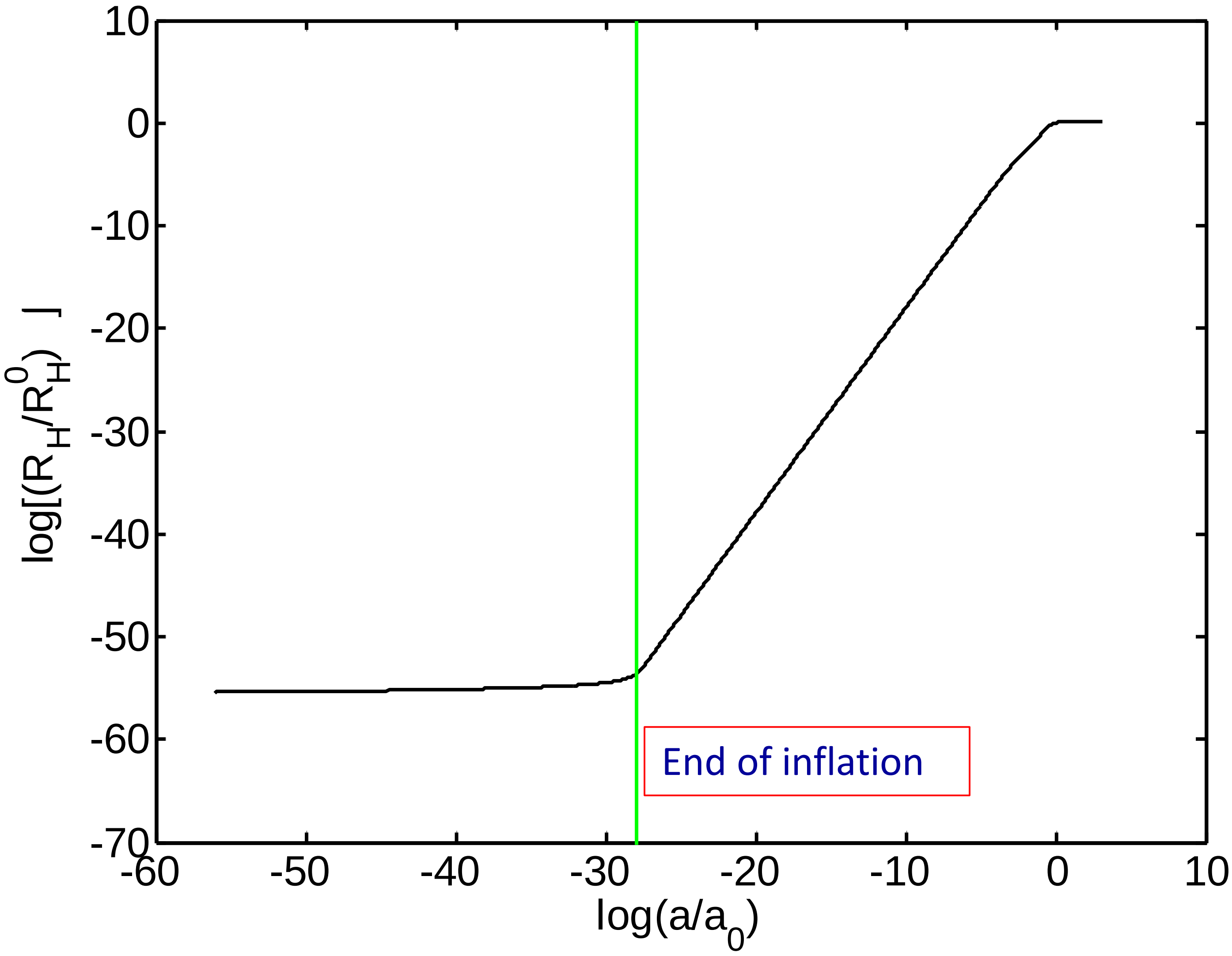


Evolution of Cosmic Length



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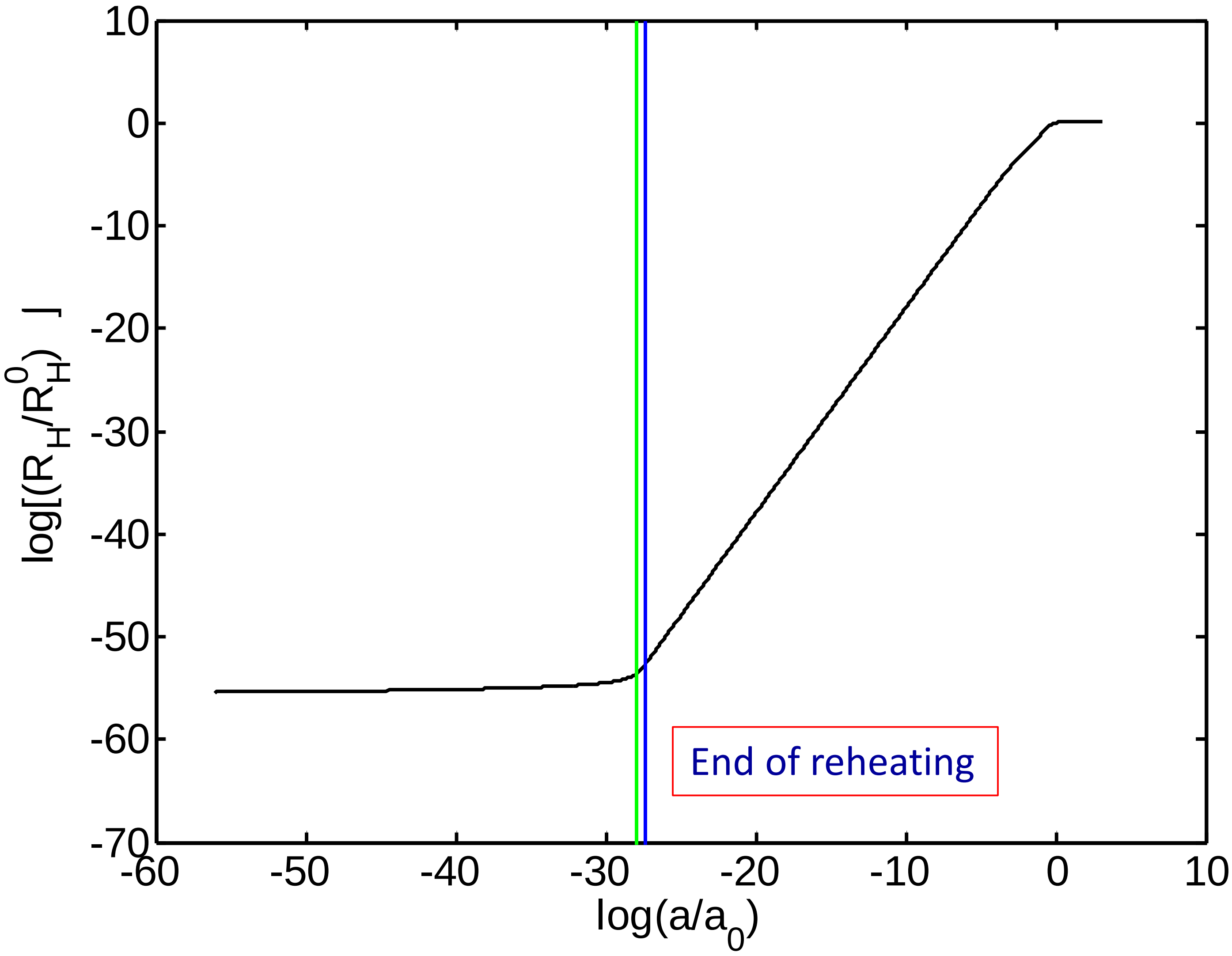

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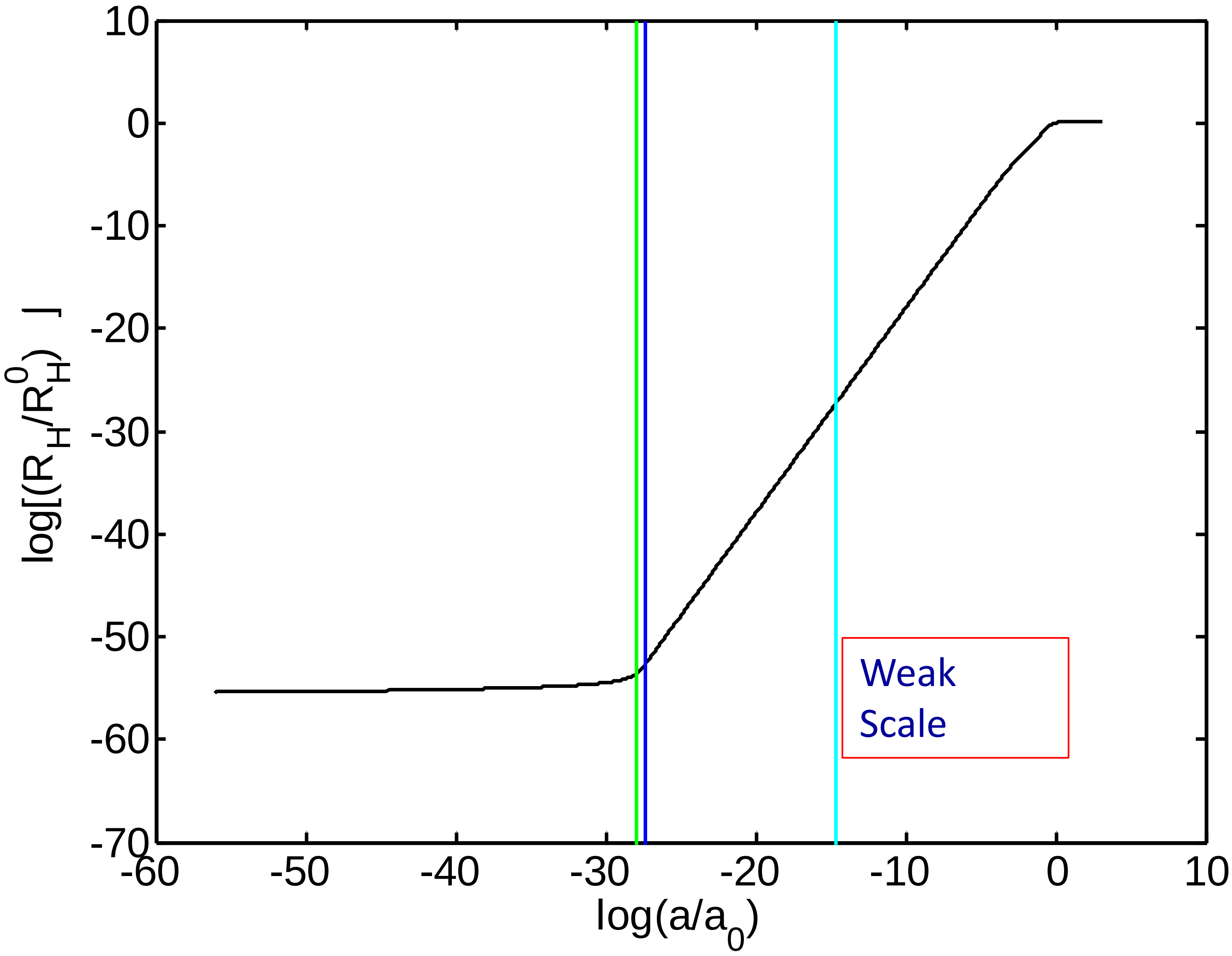

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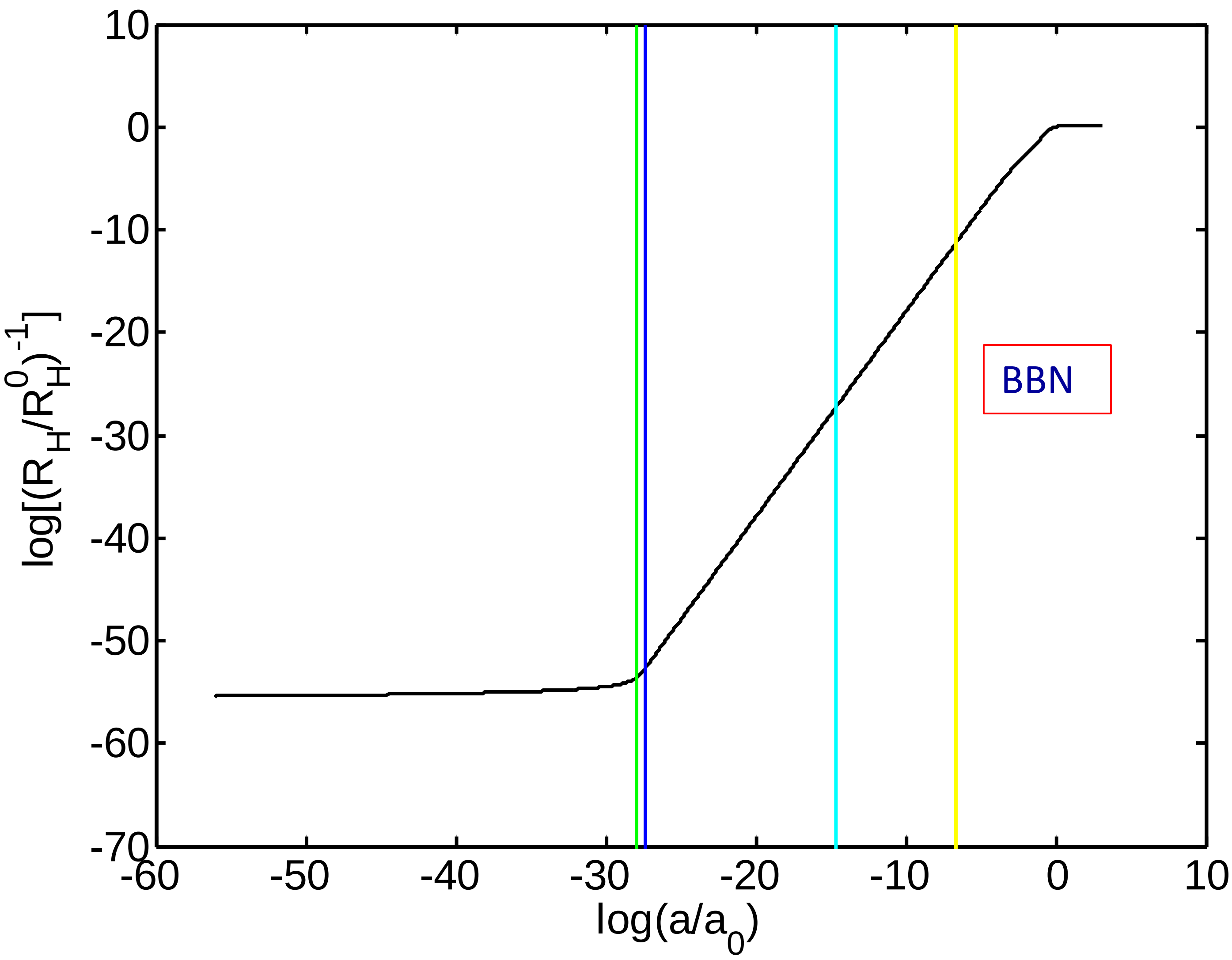

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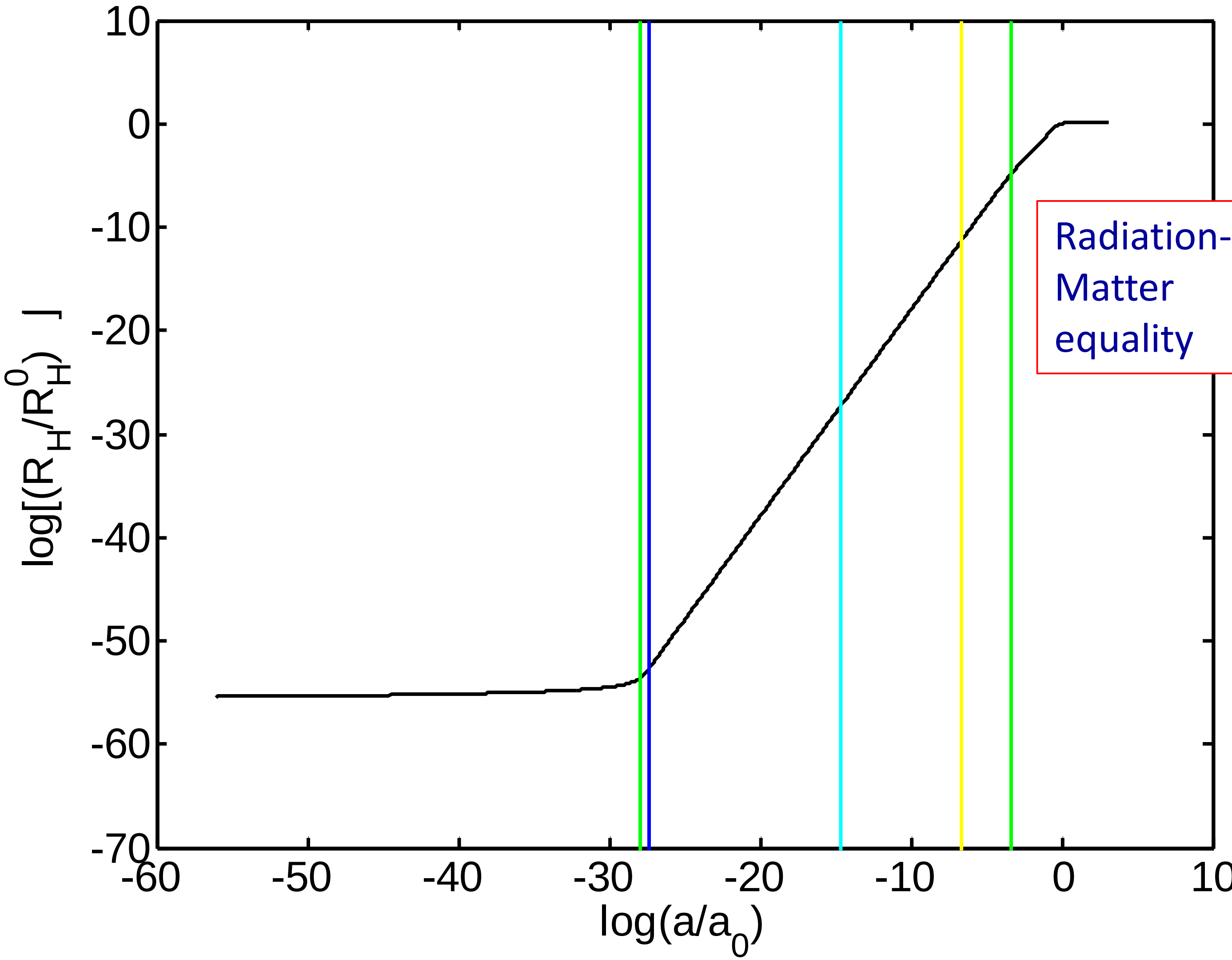
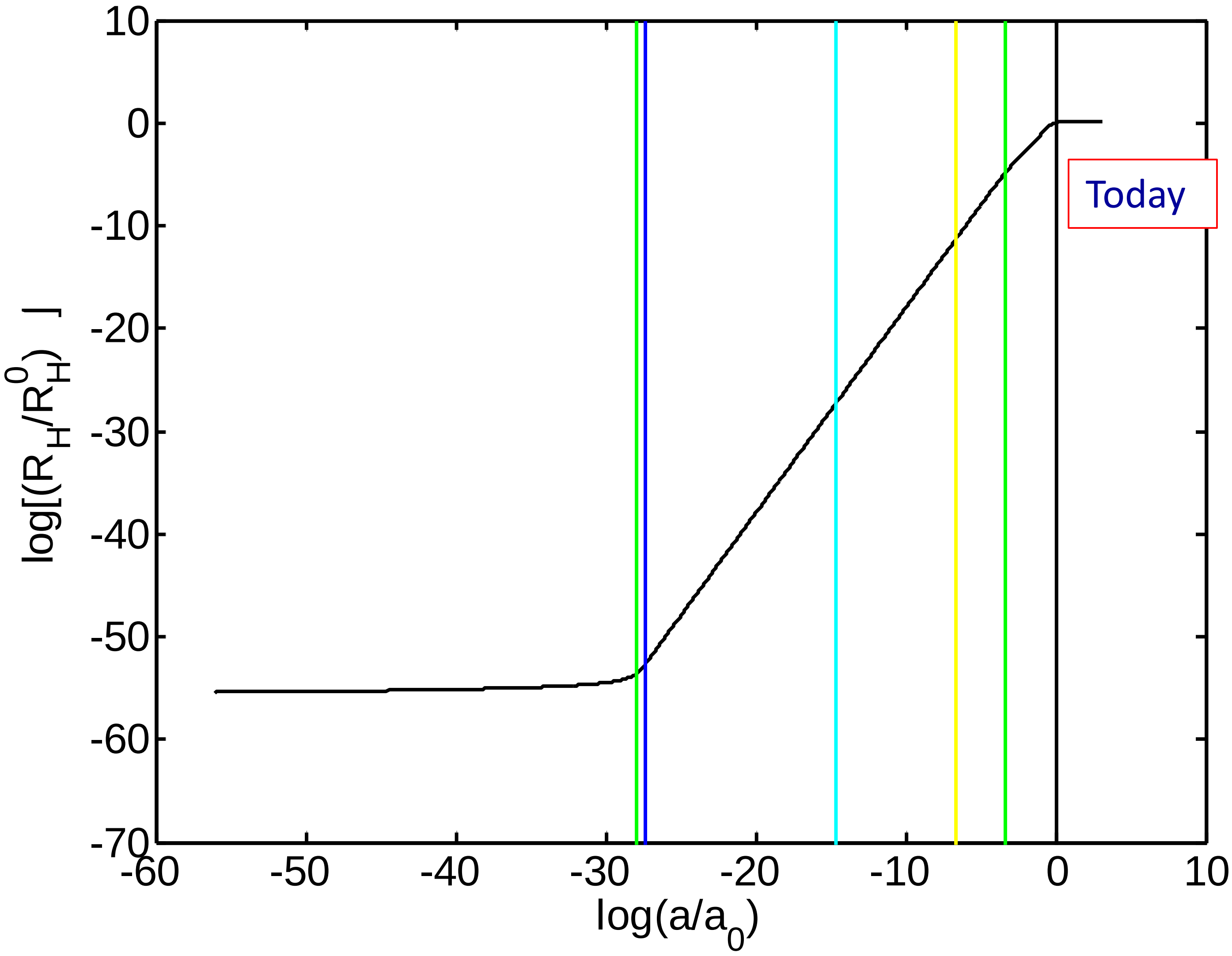
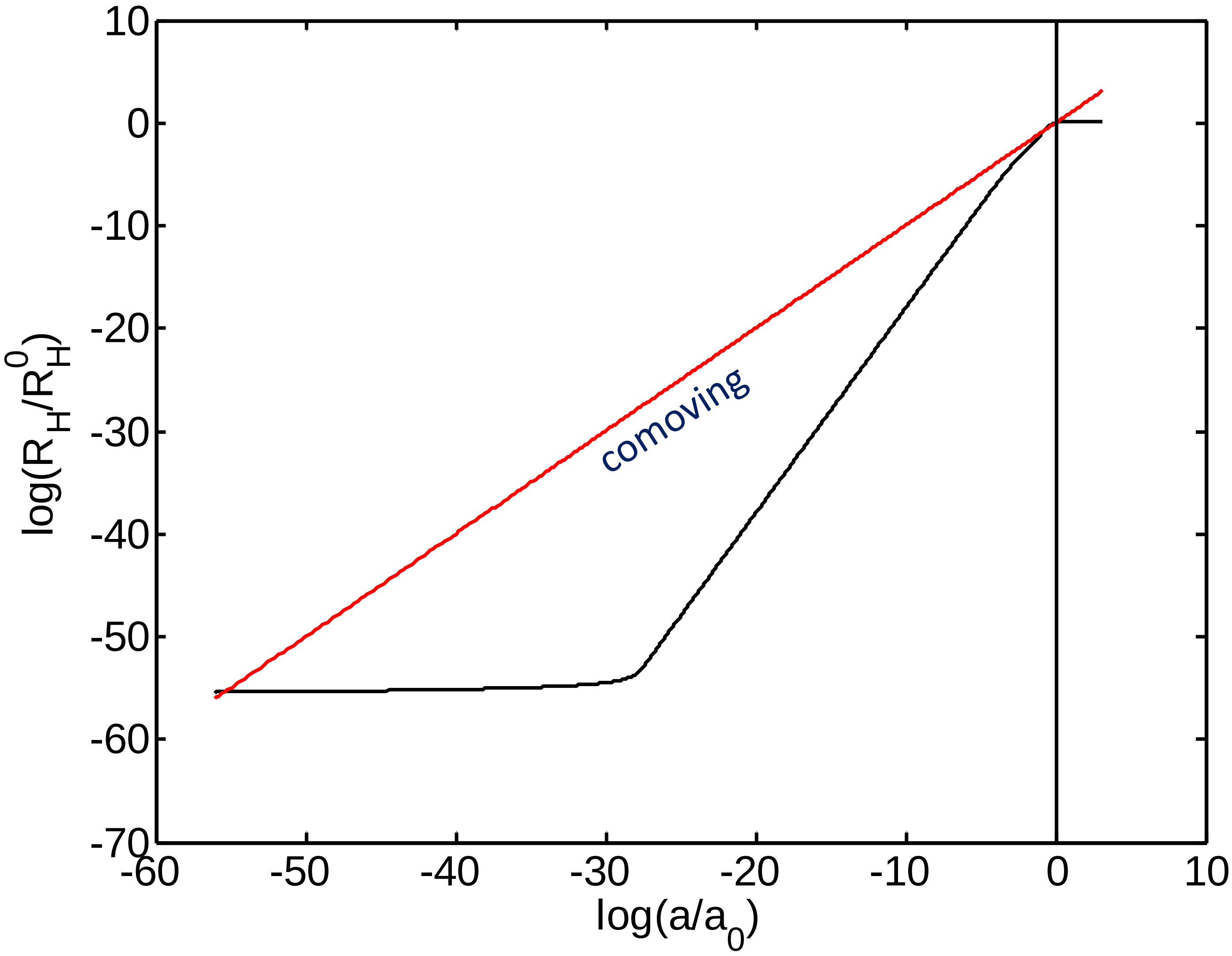


Radiation-Matter equality

Evolution of Cosmic Length



Perturbations from inflation



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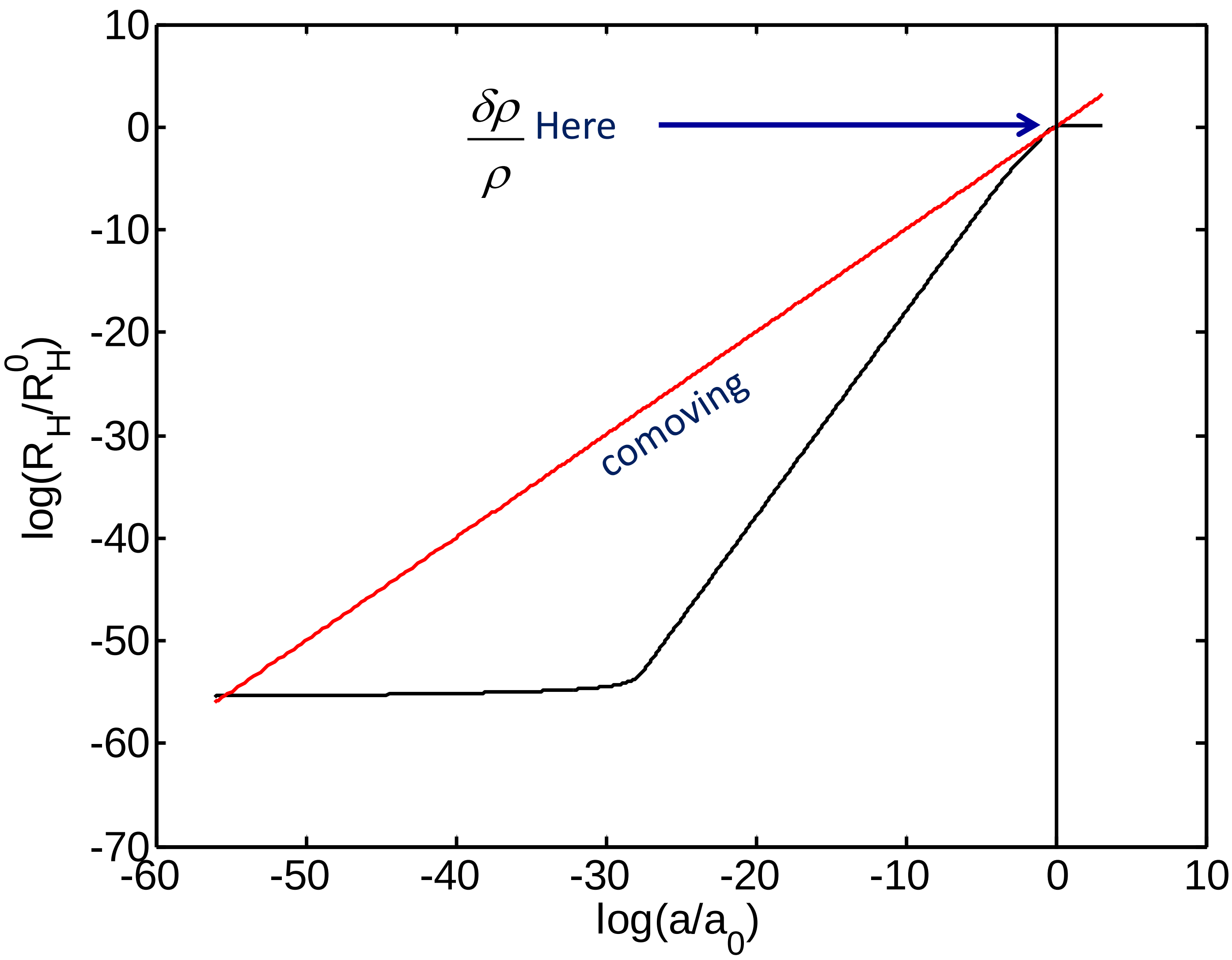
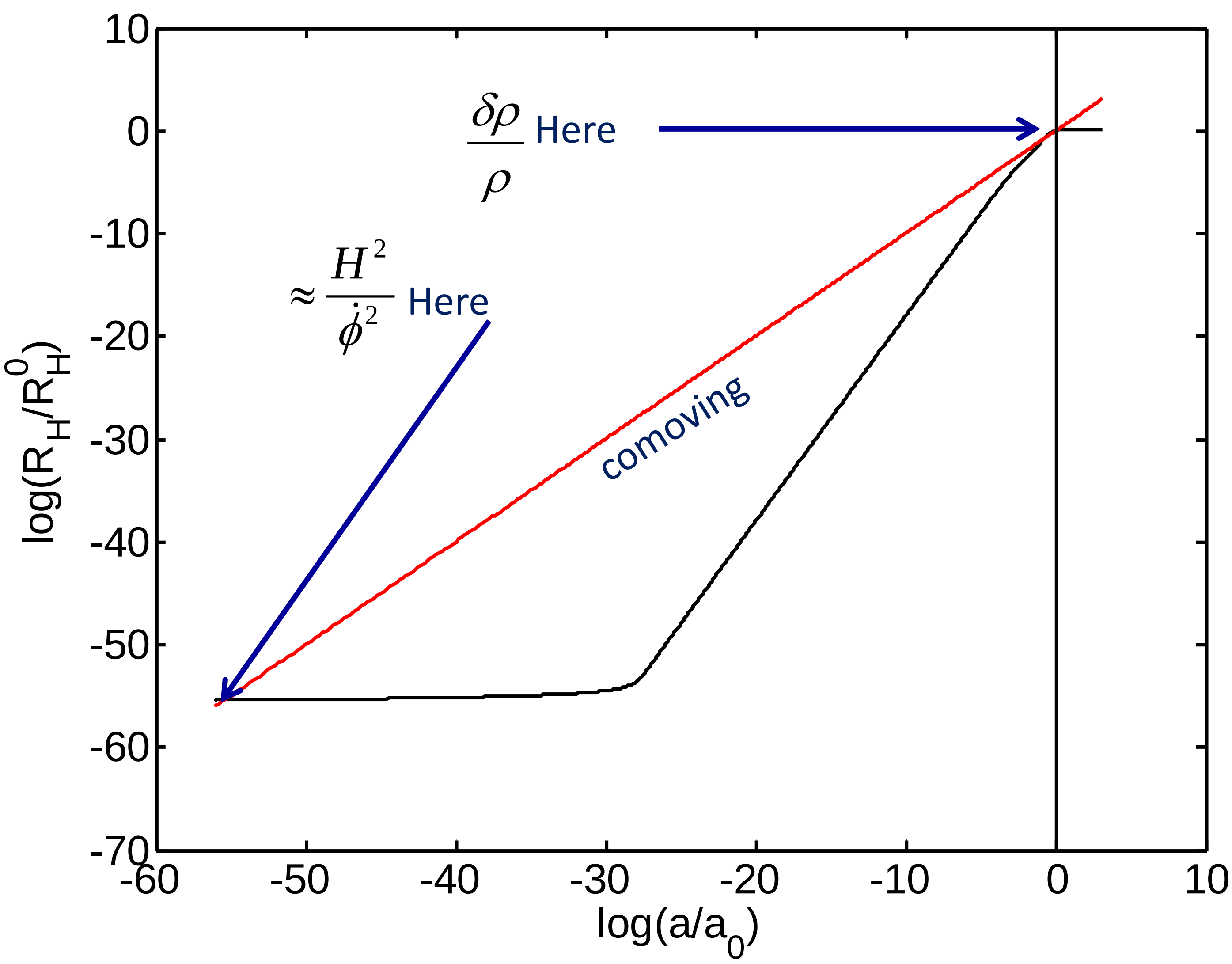
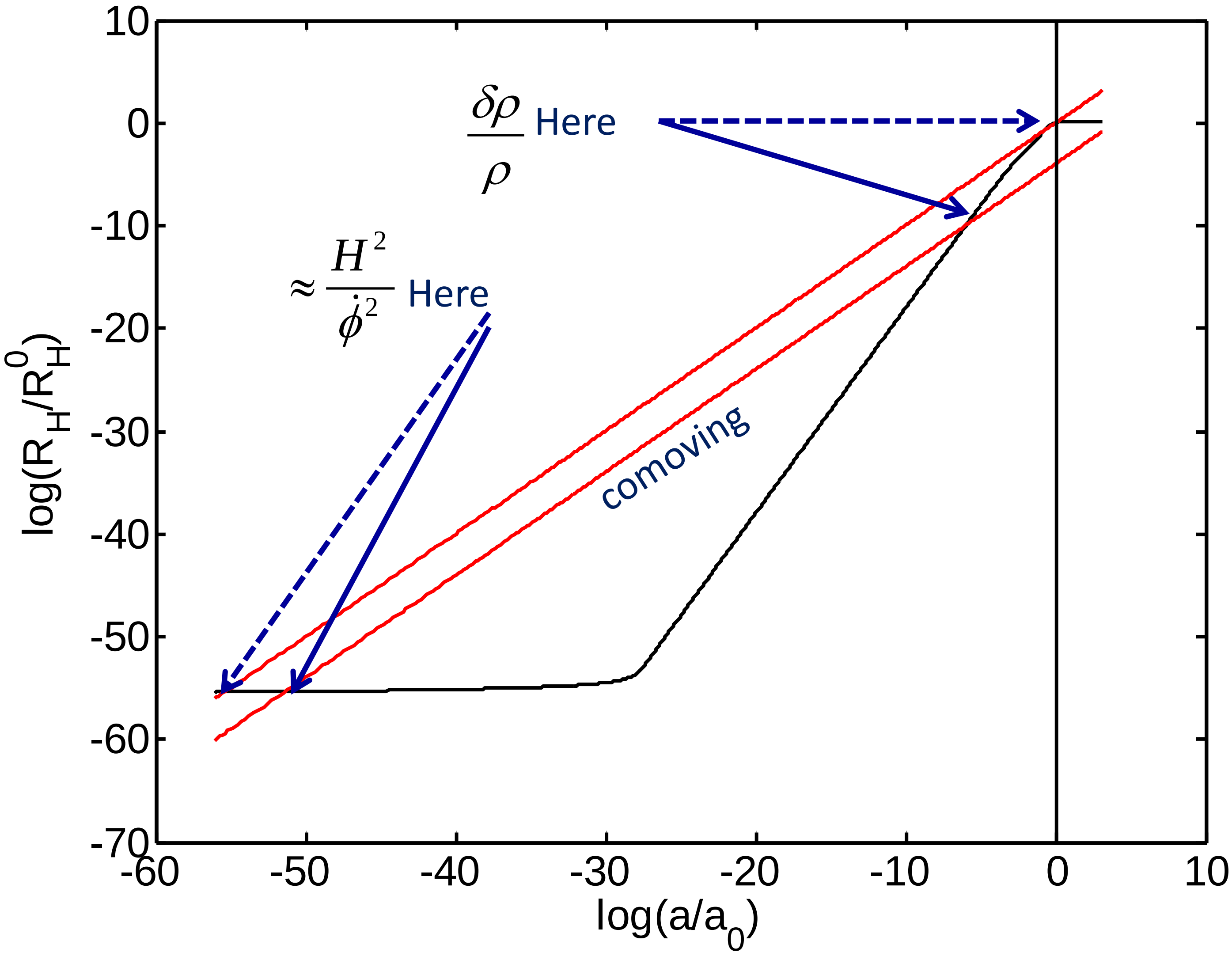
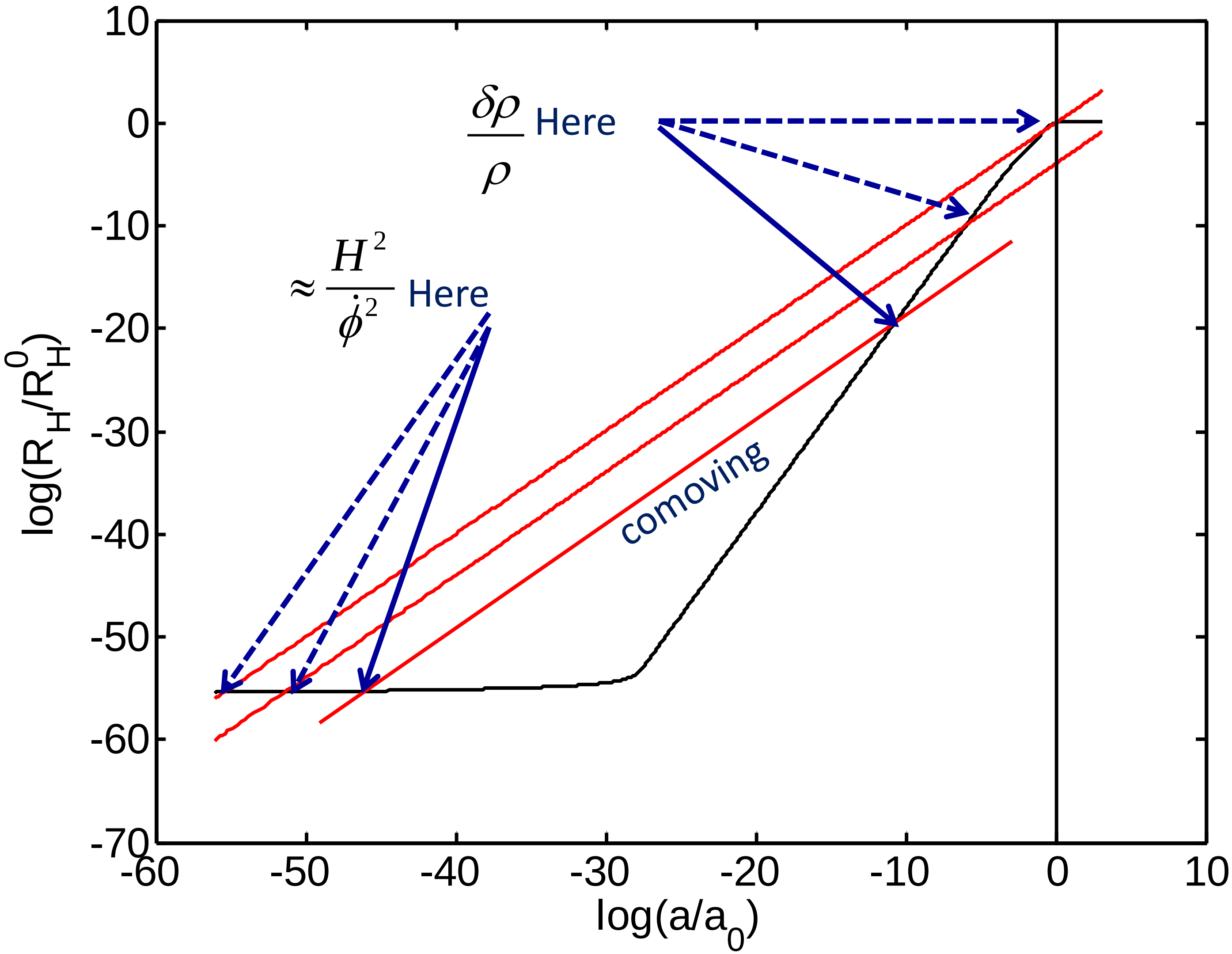


Perturbations from inflation




$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}^2}$ Here
comoving
log(a/a$_0$)
log(R$_H$/R$_H^0$)
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10



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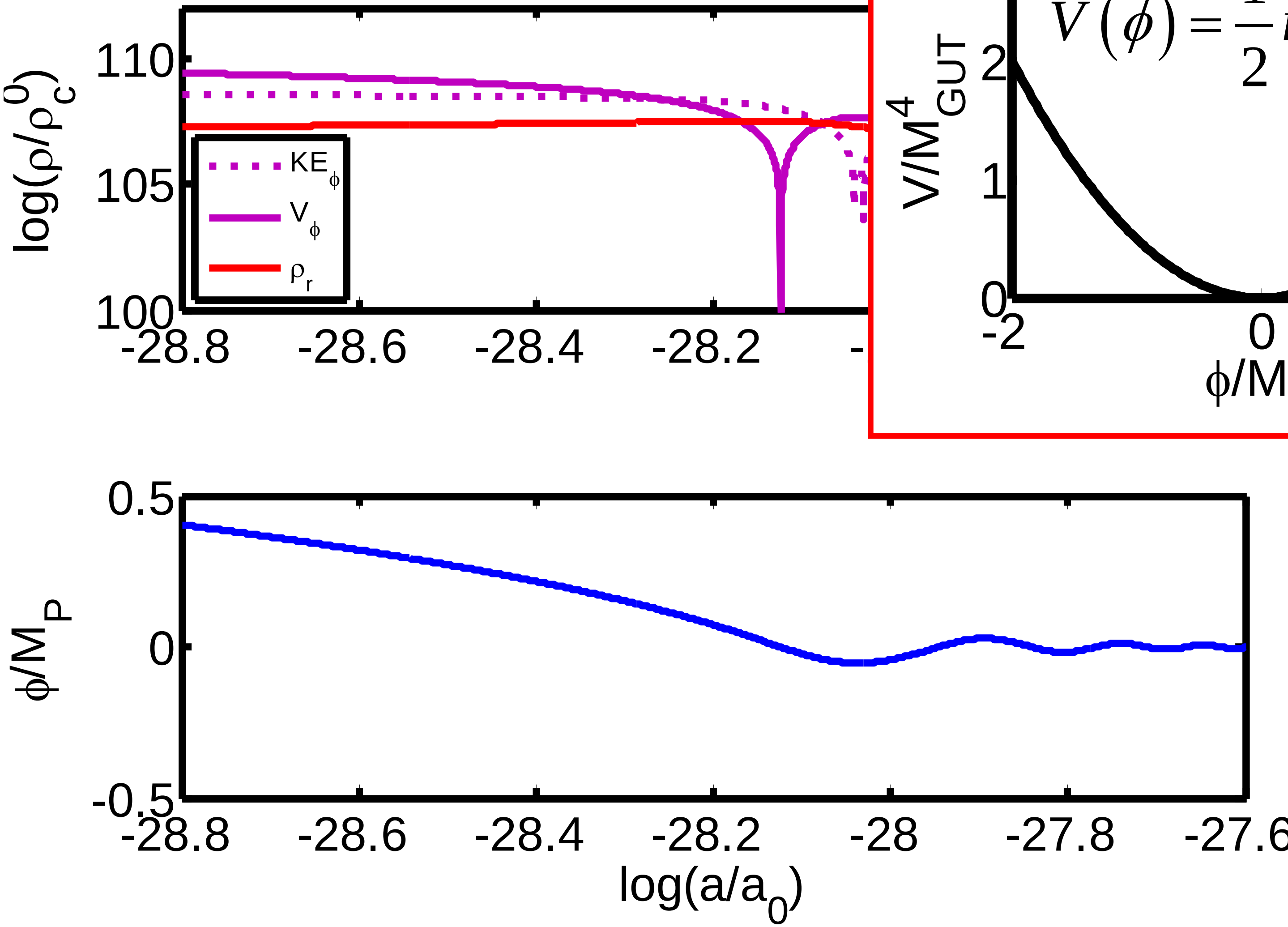
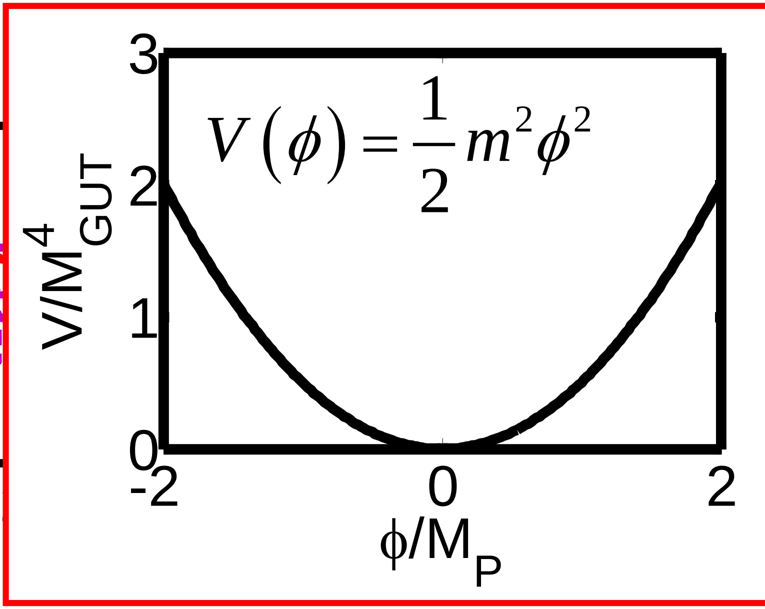
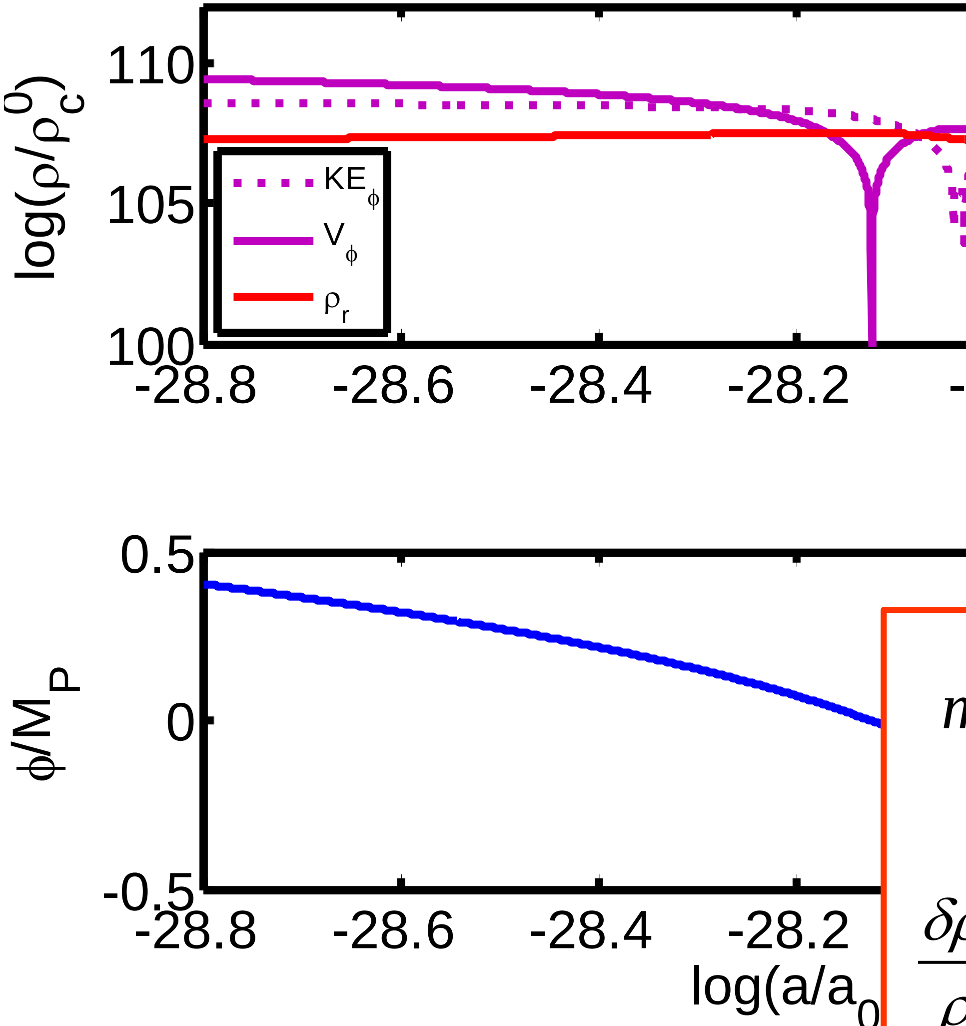
comoving
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10
$\log(R_H/R_H^0)$
$\log(a/a_0)$

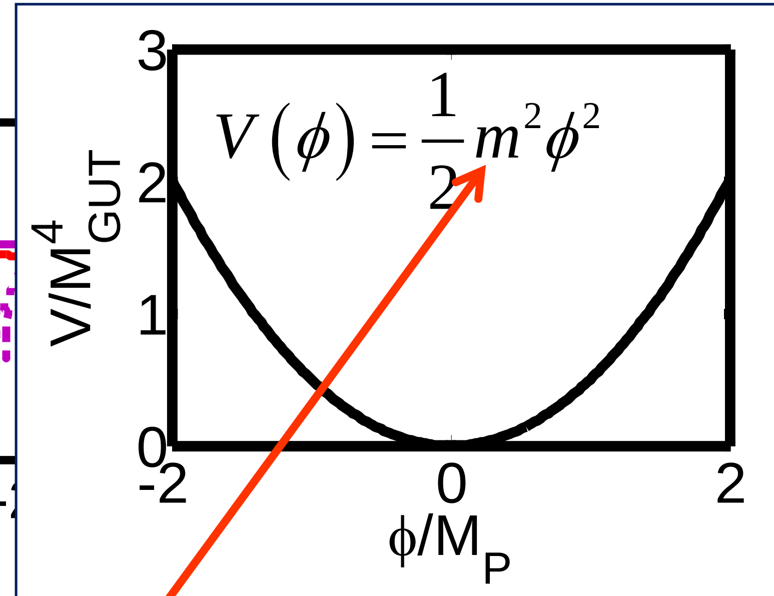
Inflation detail:





Inflation detail:

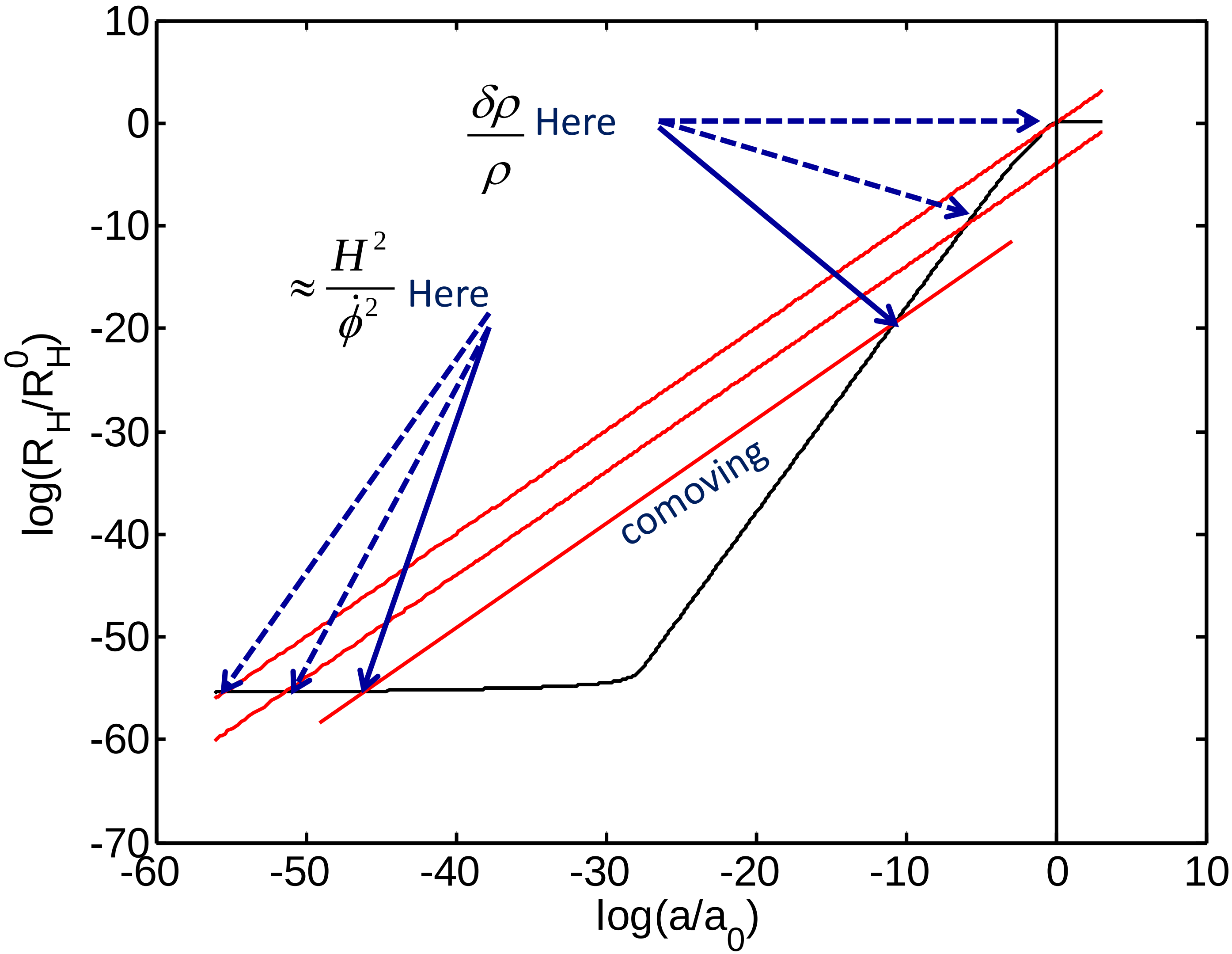




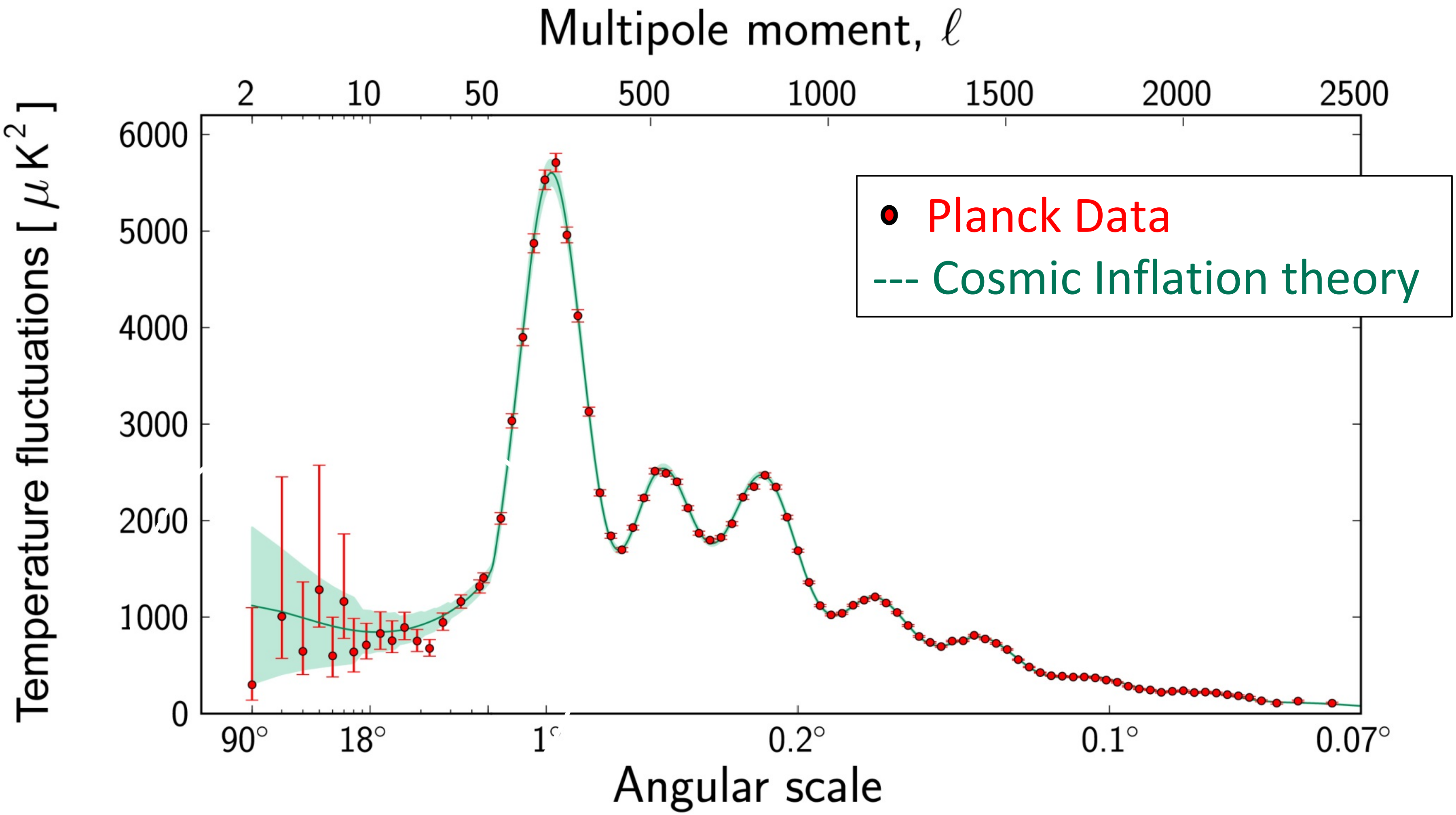
$m = 8 \times 10^{12}\, GeV$

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



Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
Planck Data
--- Cosmic Inflation theory

Part 1 outline

1. Big Bang & inflation
2. Eternal inflation

Part 1 outline

1. Big Bang & inflation

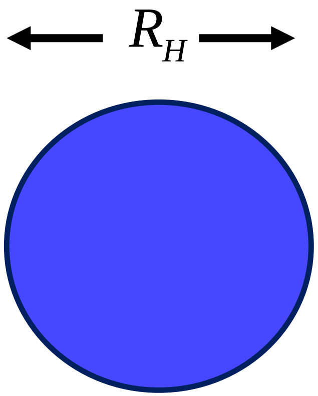
2. Eternal inflation

Does inflation make the SBB (observed universe) 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

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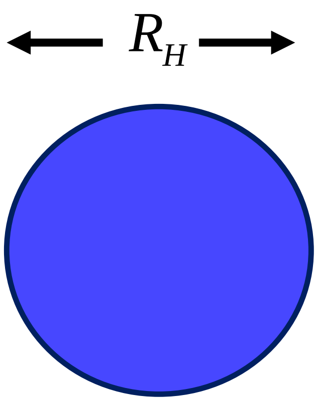

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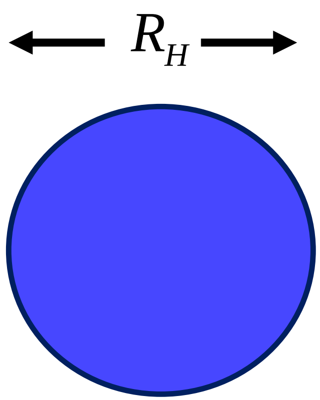

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For realistic perturbations the evolution is very classical

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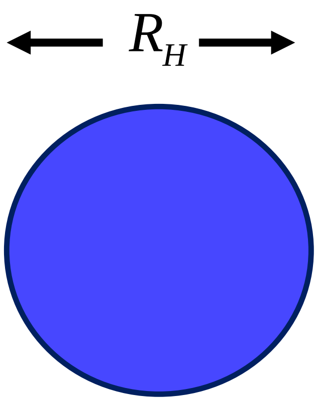

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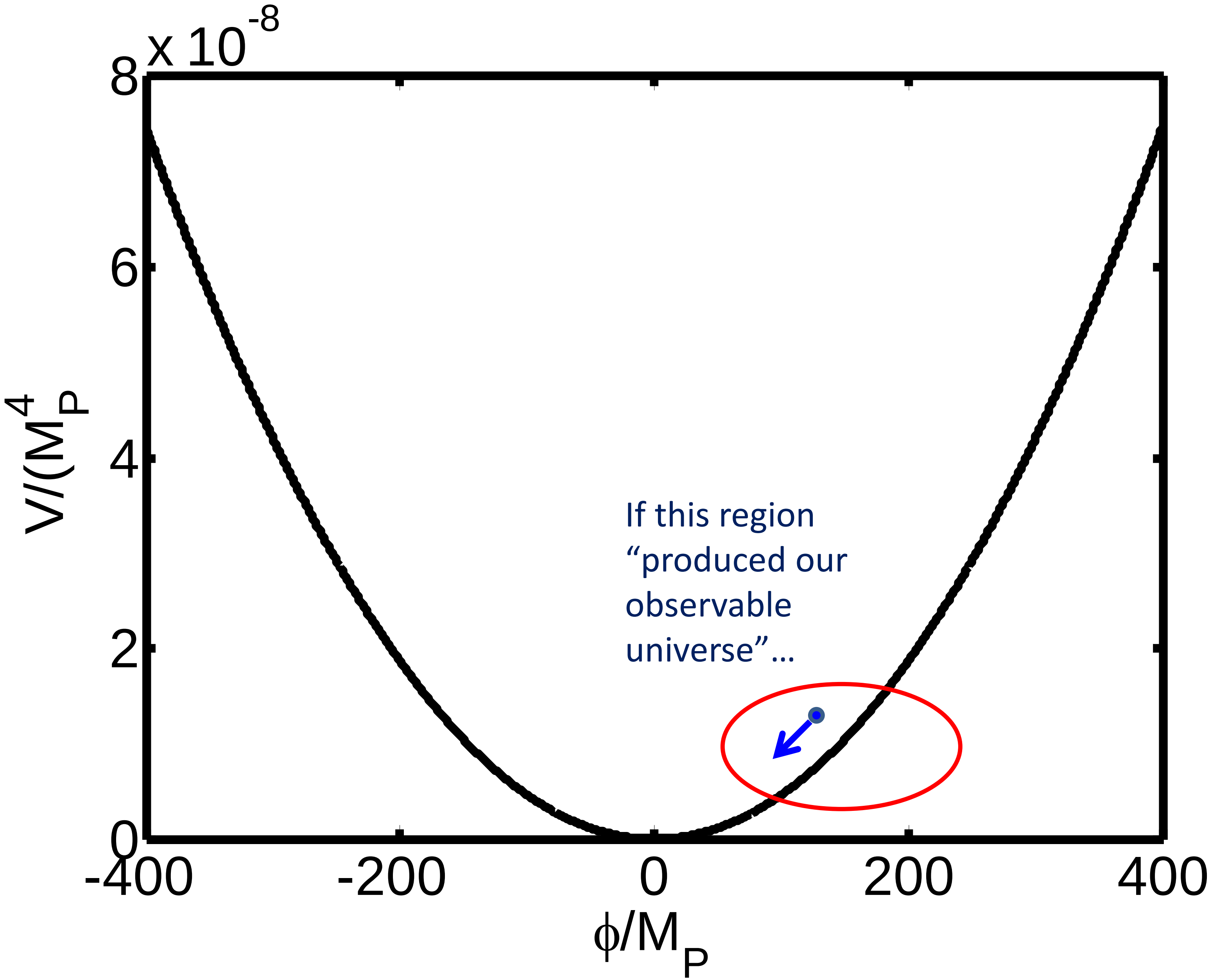
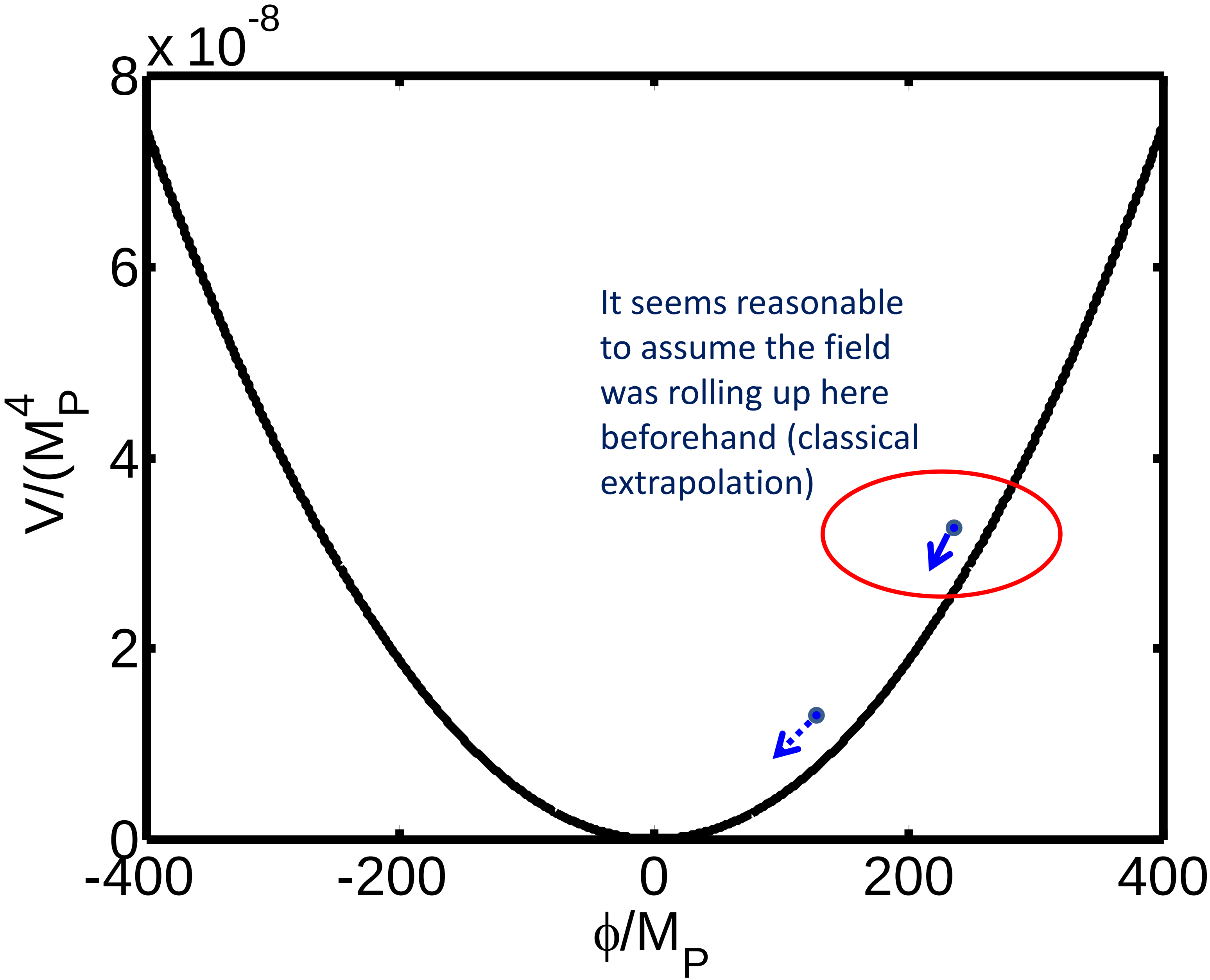
measures the importance of quantum fluctuations in the field evolution

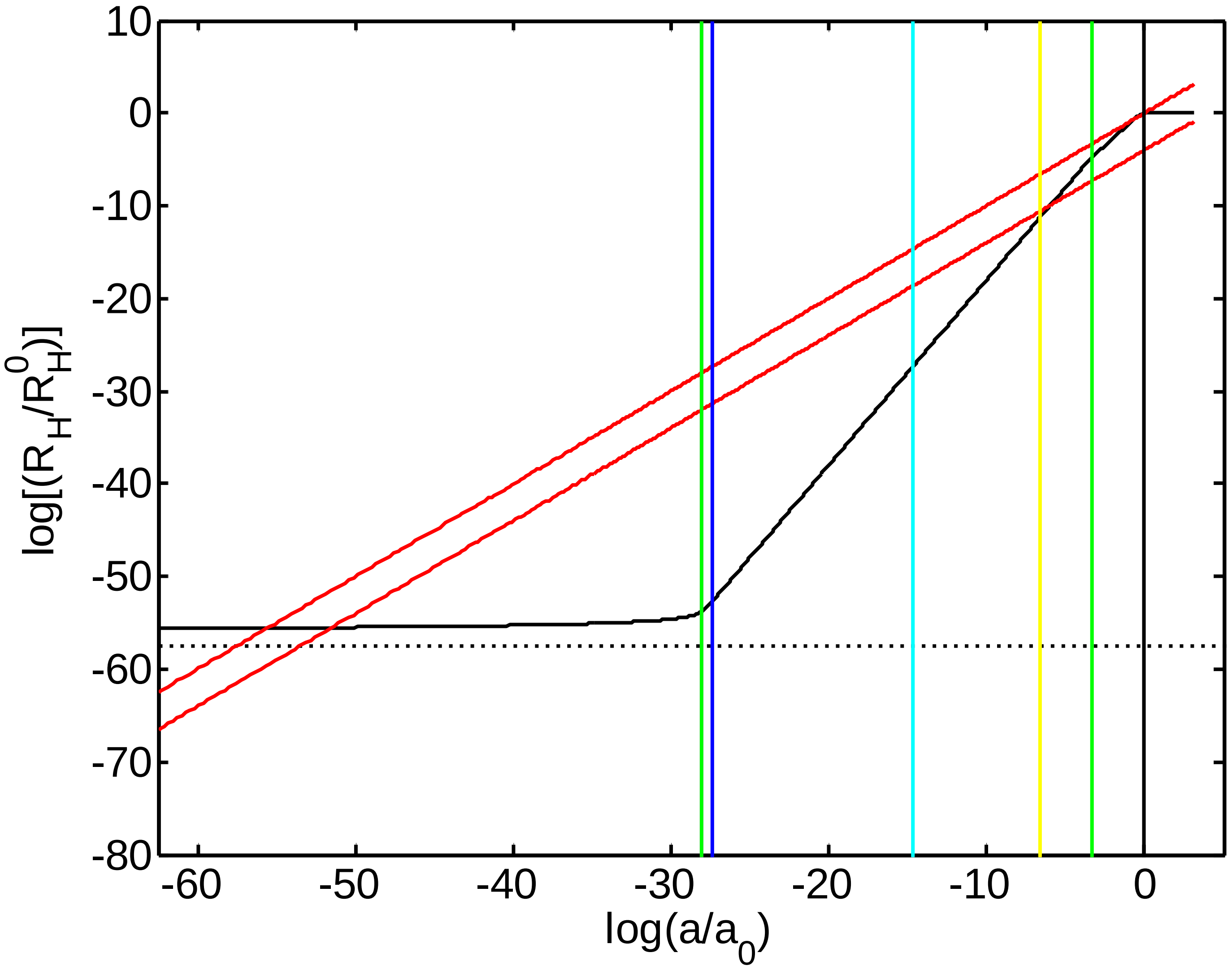
For realistic perturbations the evolution is very classical

(But not as classical as most classical things we know!)

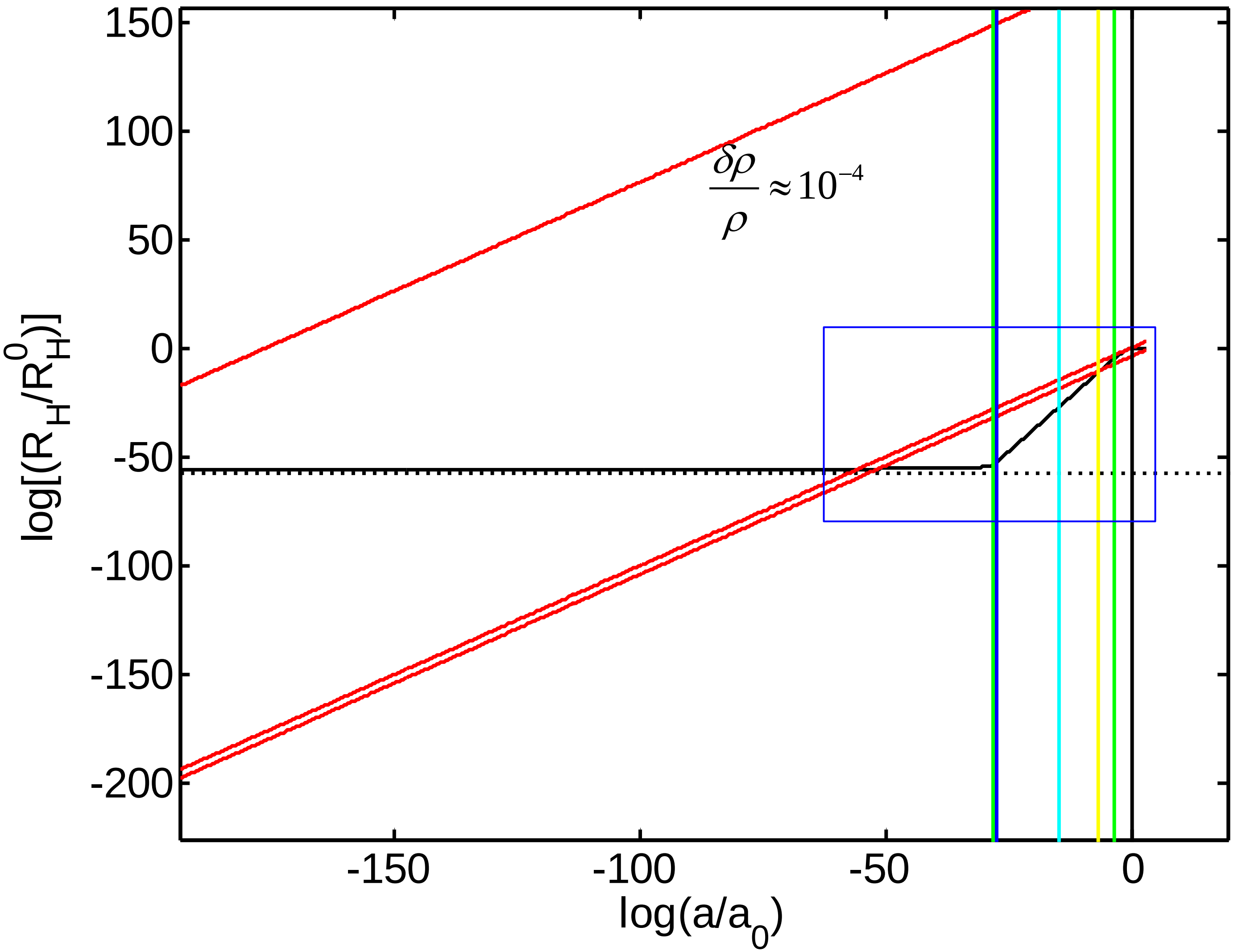

x 10^-8
8
6
4
2
0
V/(M_P^4
-400
-200
0
200
400
ϕ/M_P
If this region
"produced our
observable
universe"…


x 10^-8
8
6
4
2
0
V/(M_P^4)
-400
-200
0
200
400
φ/M_P
It seems reasonable
to assume the field
was rolling up here
beforehand (classical
extrapolation)

Evolution of Cosmic Length



Evolution of Cosmic Length (zooming out)



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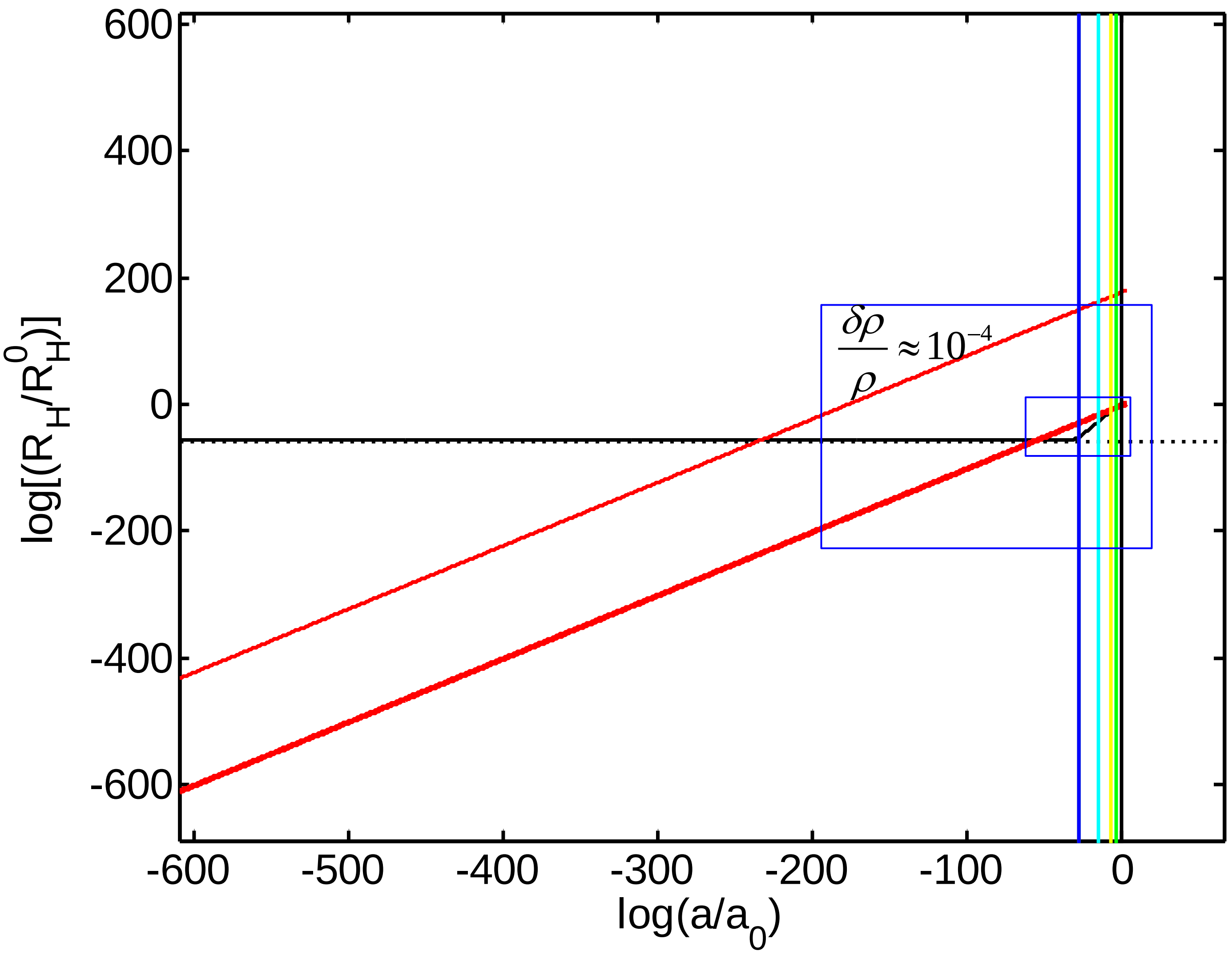

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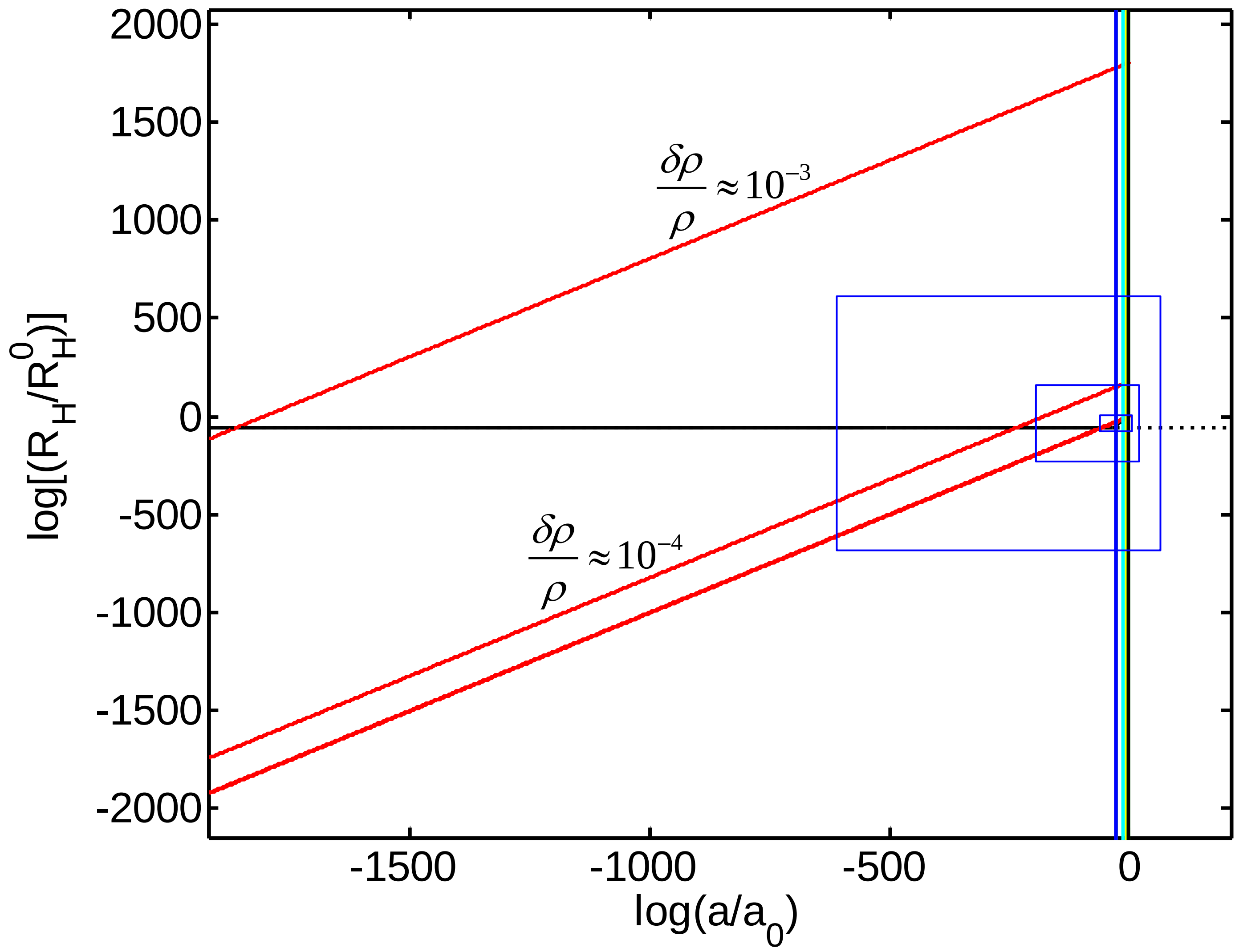

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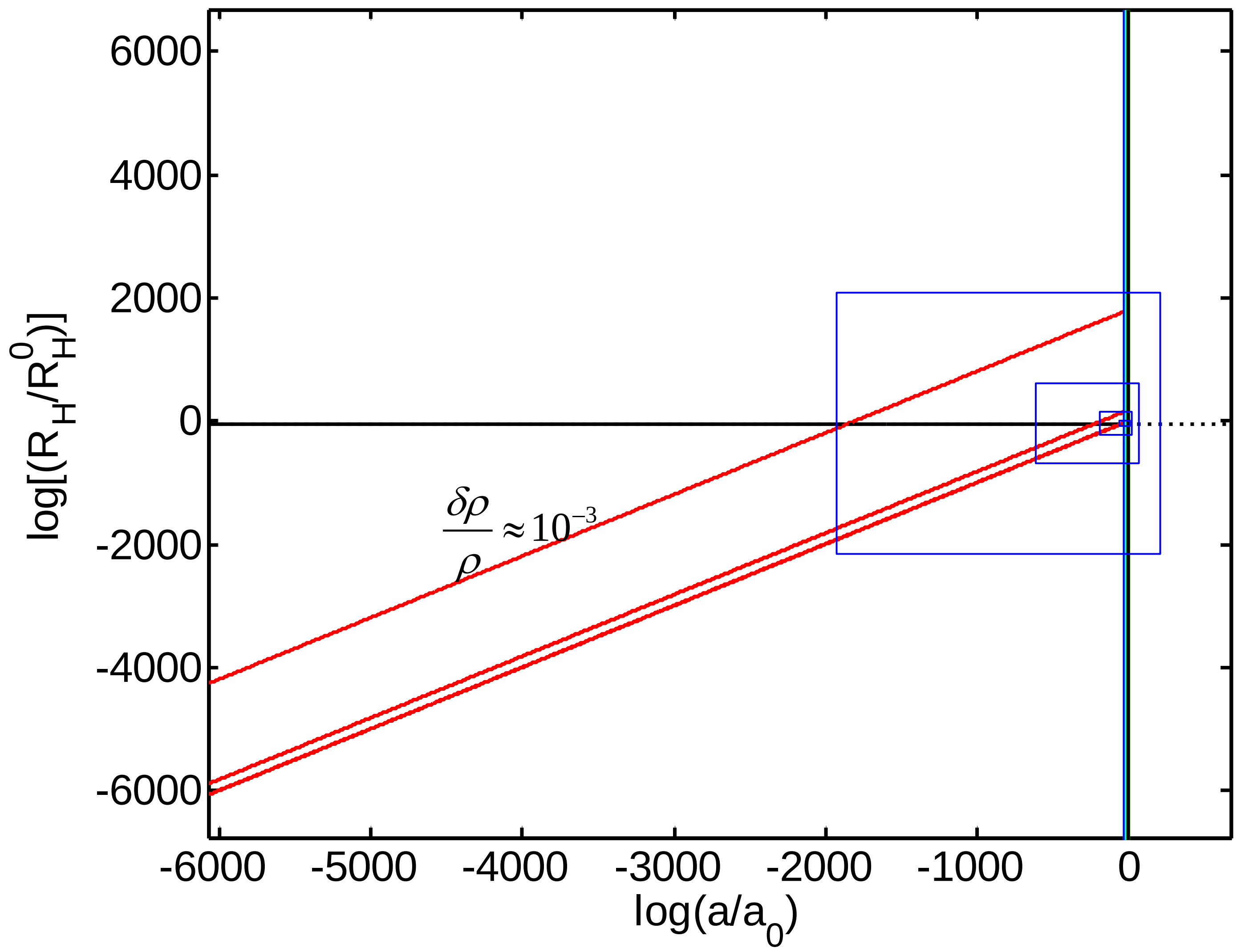

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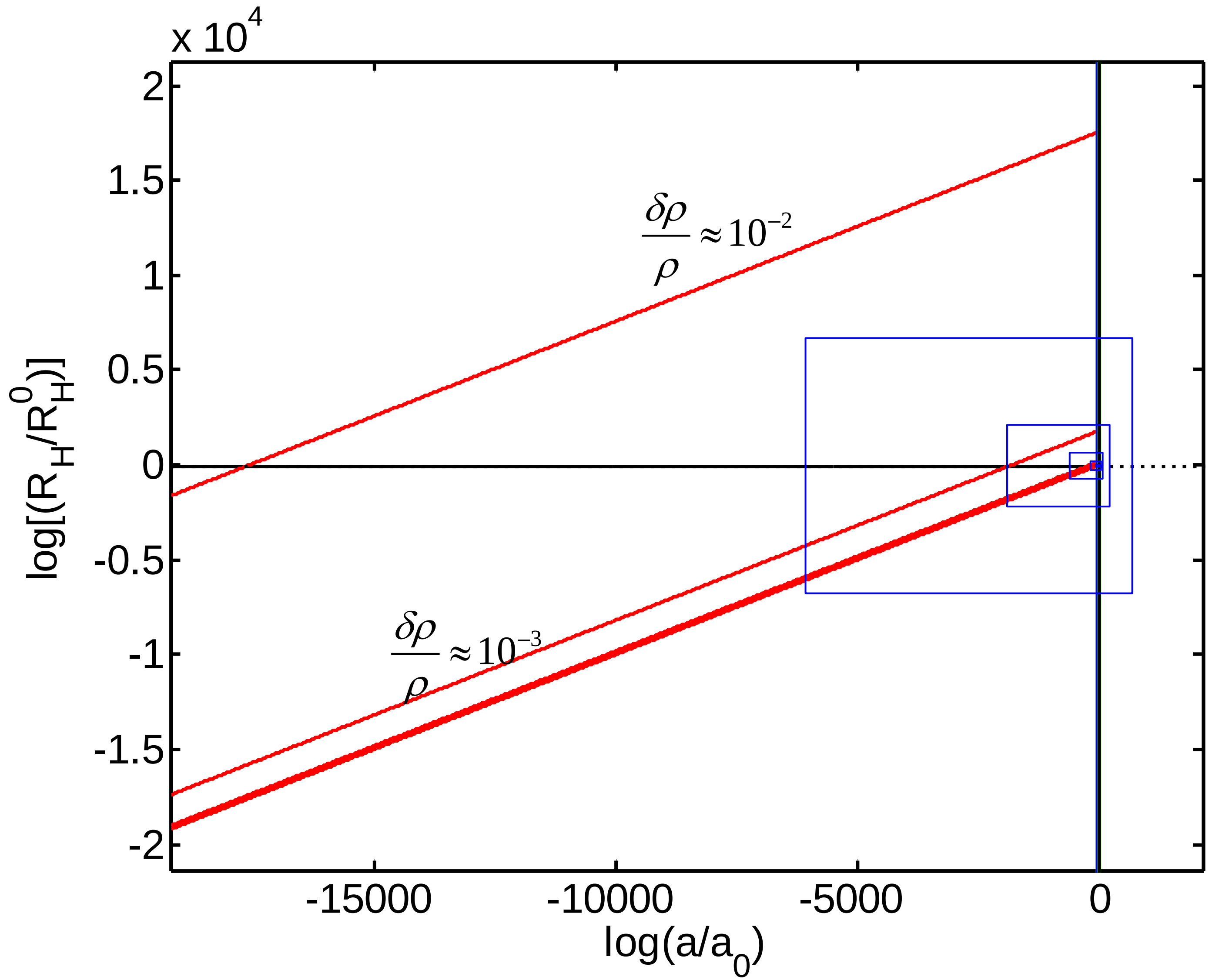
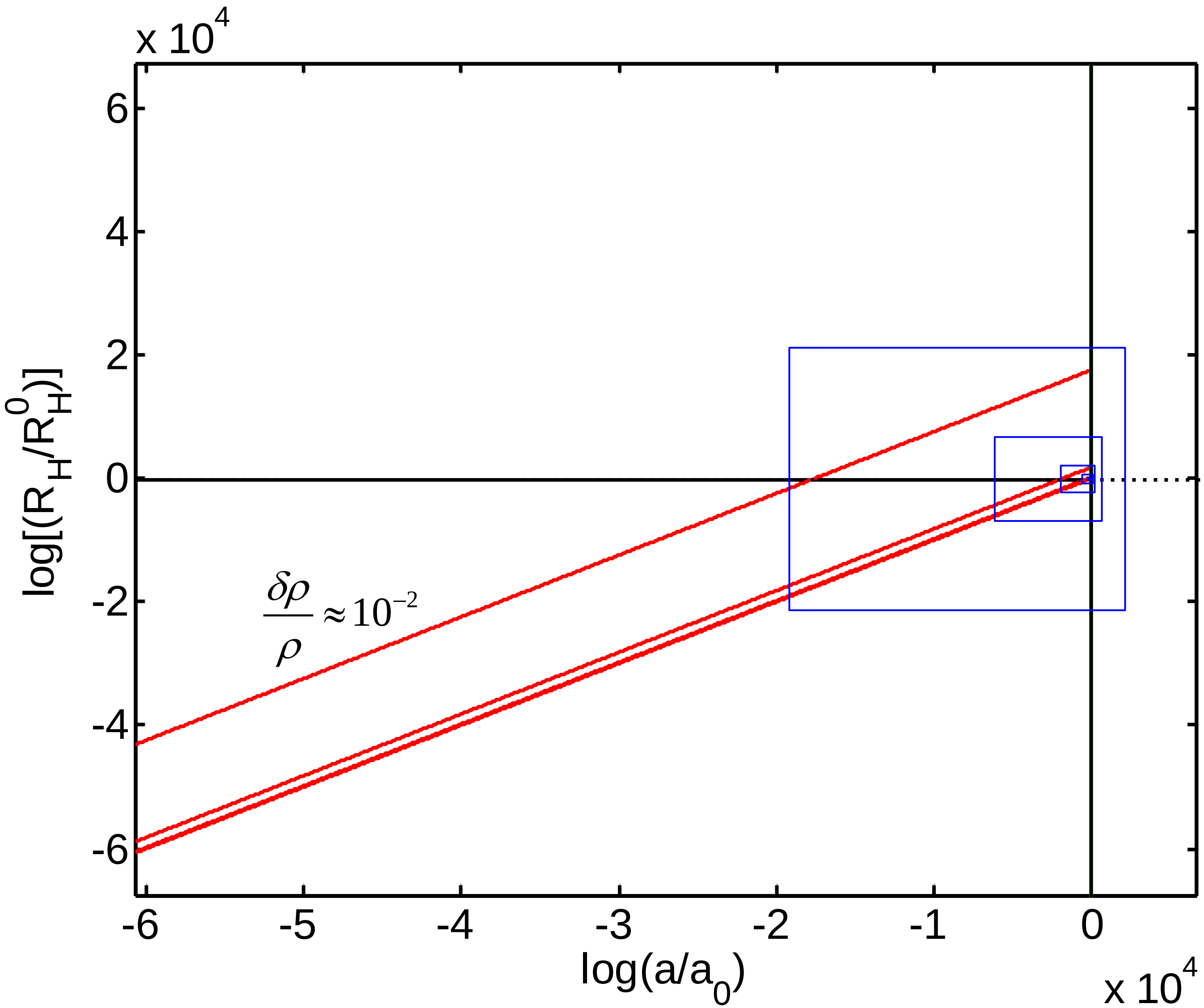
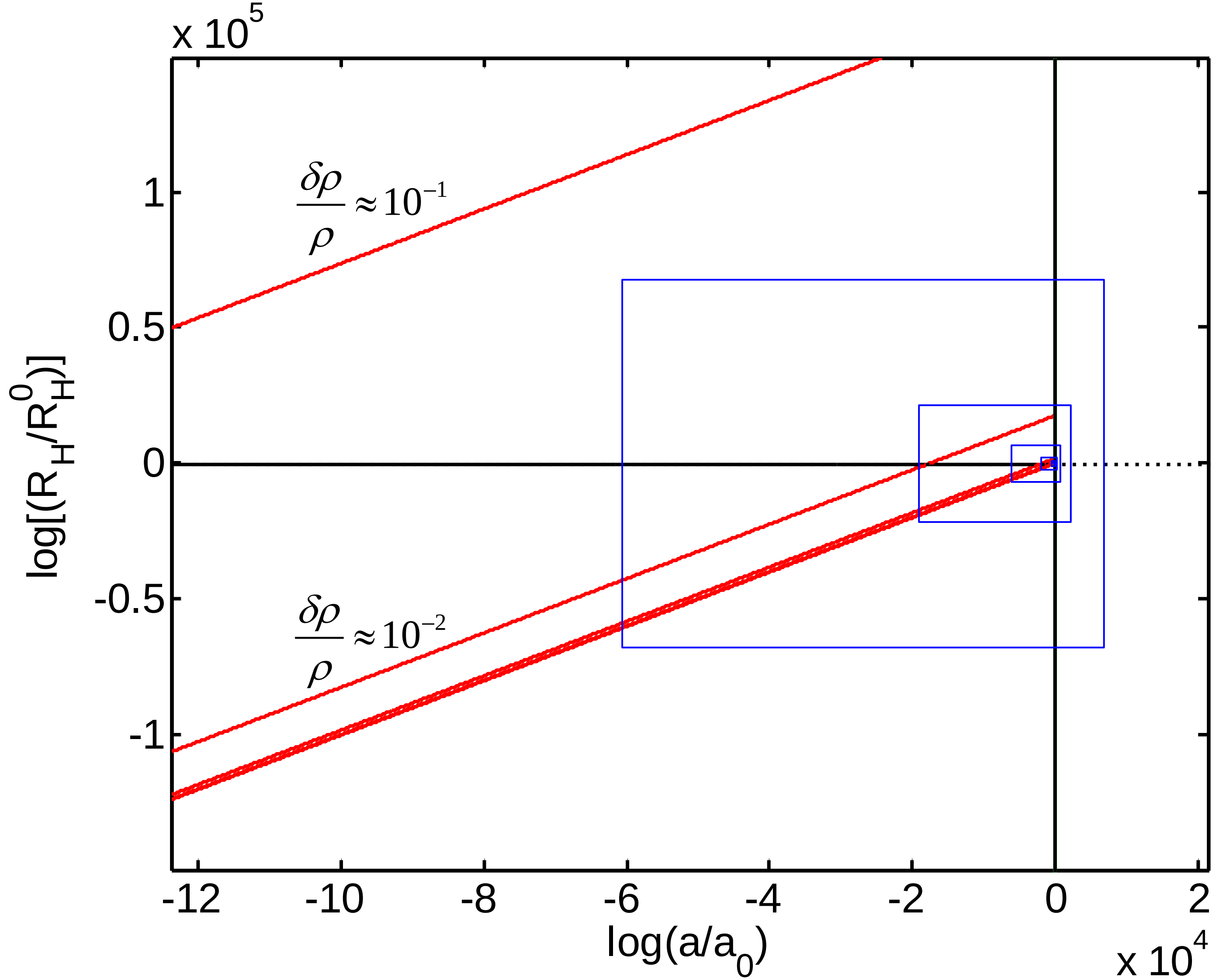


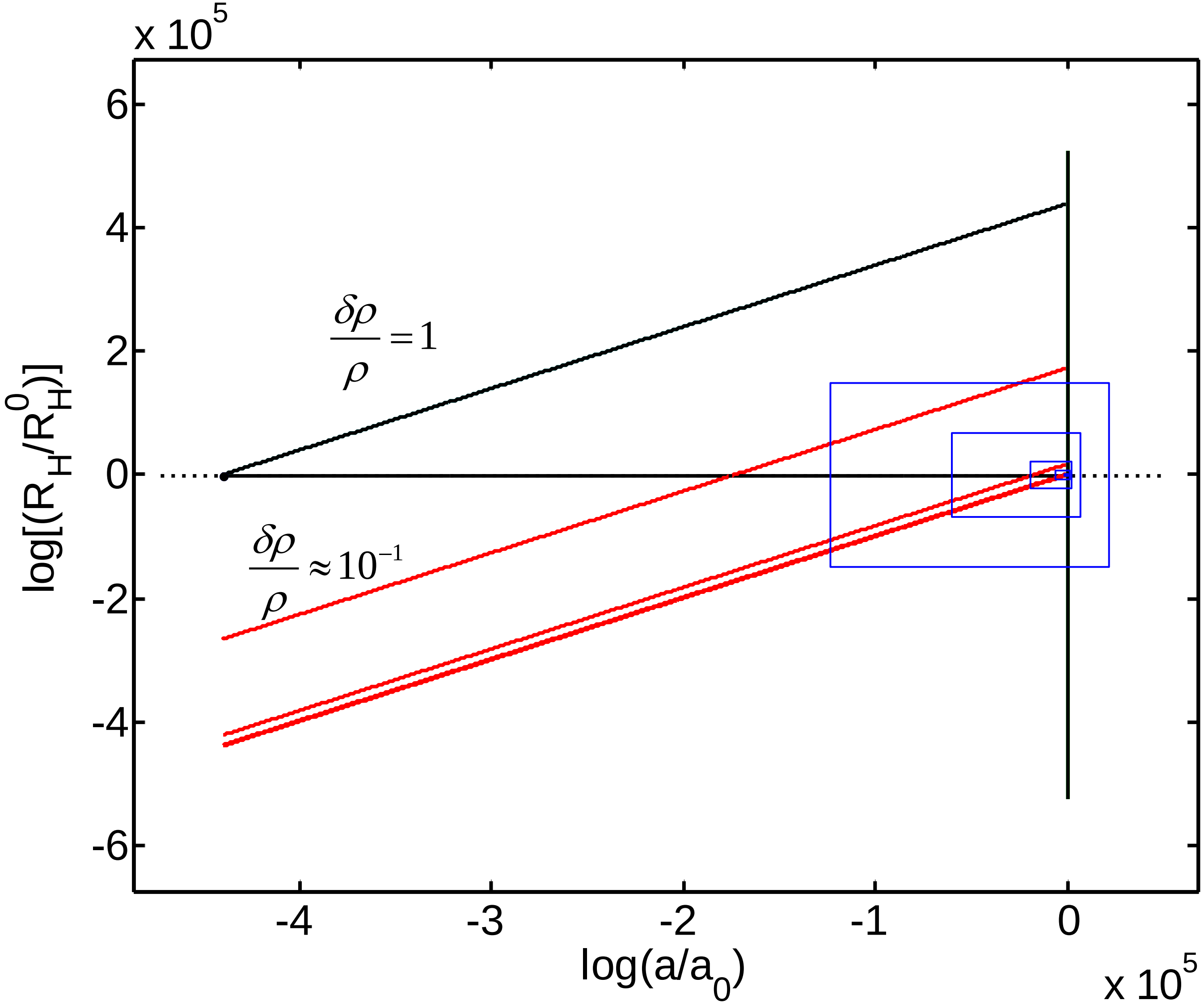
Evolution of Cosmic Length (zooming out)



Evolution of Cosmic Length (zooming out)



Evolution of Cosmic Length (zooming out)



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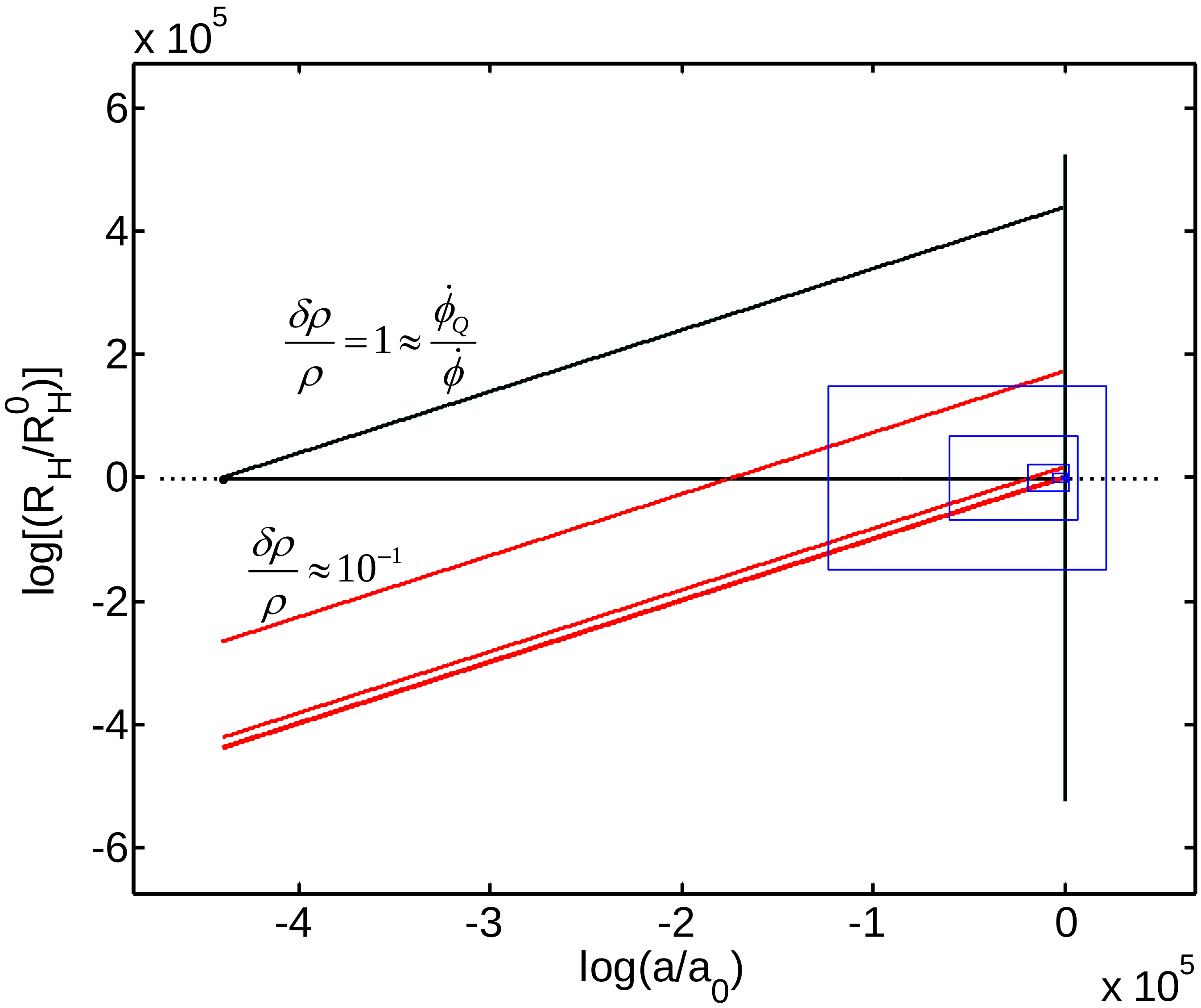

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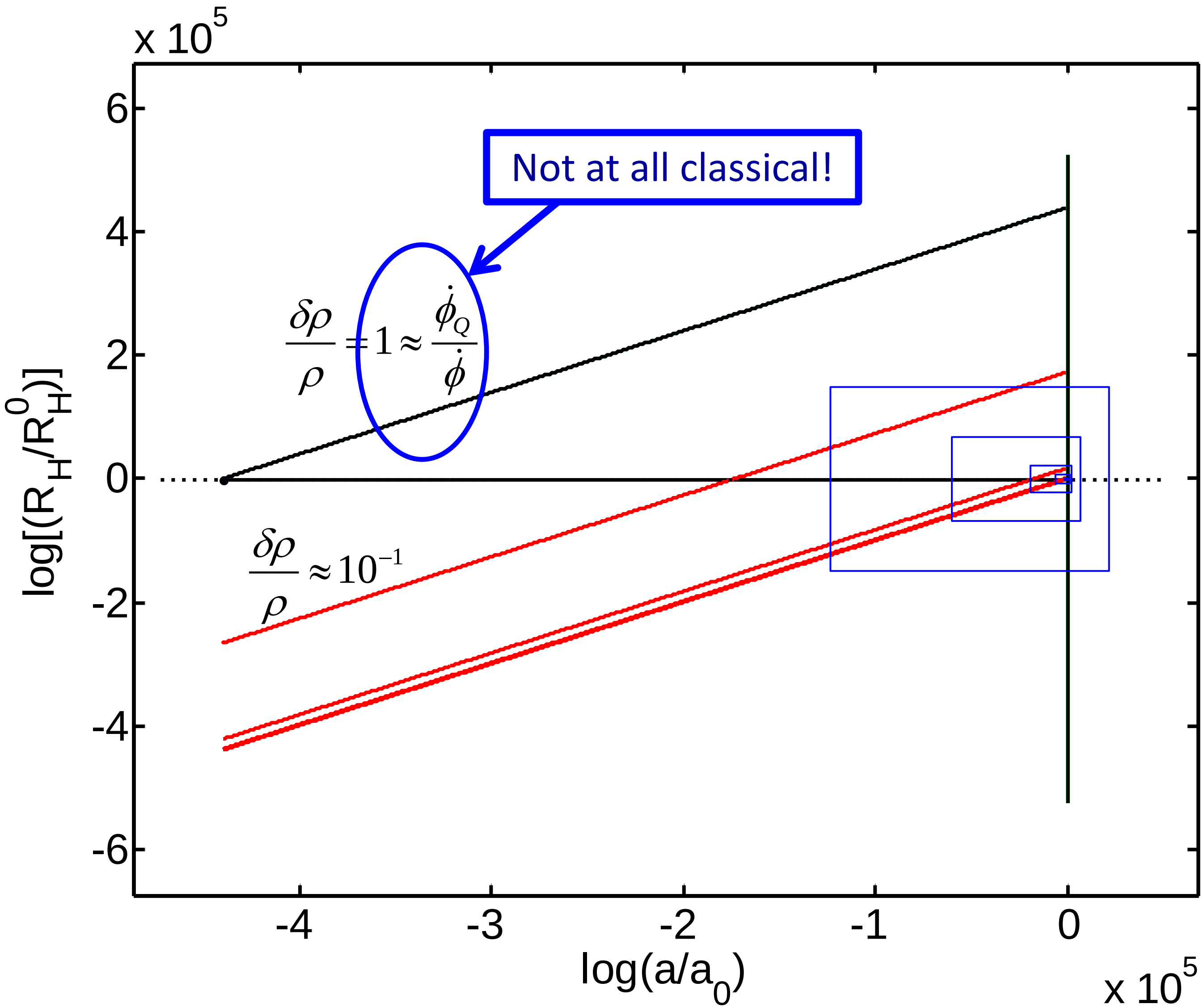
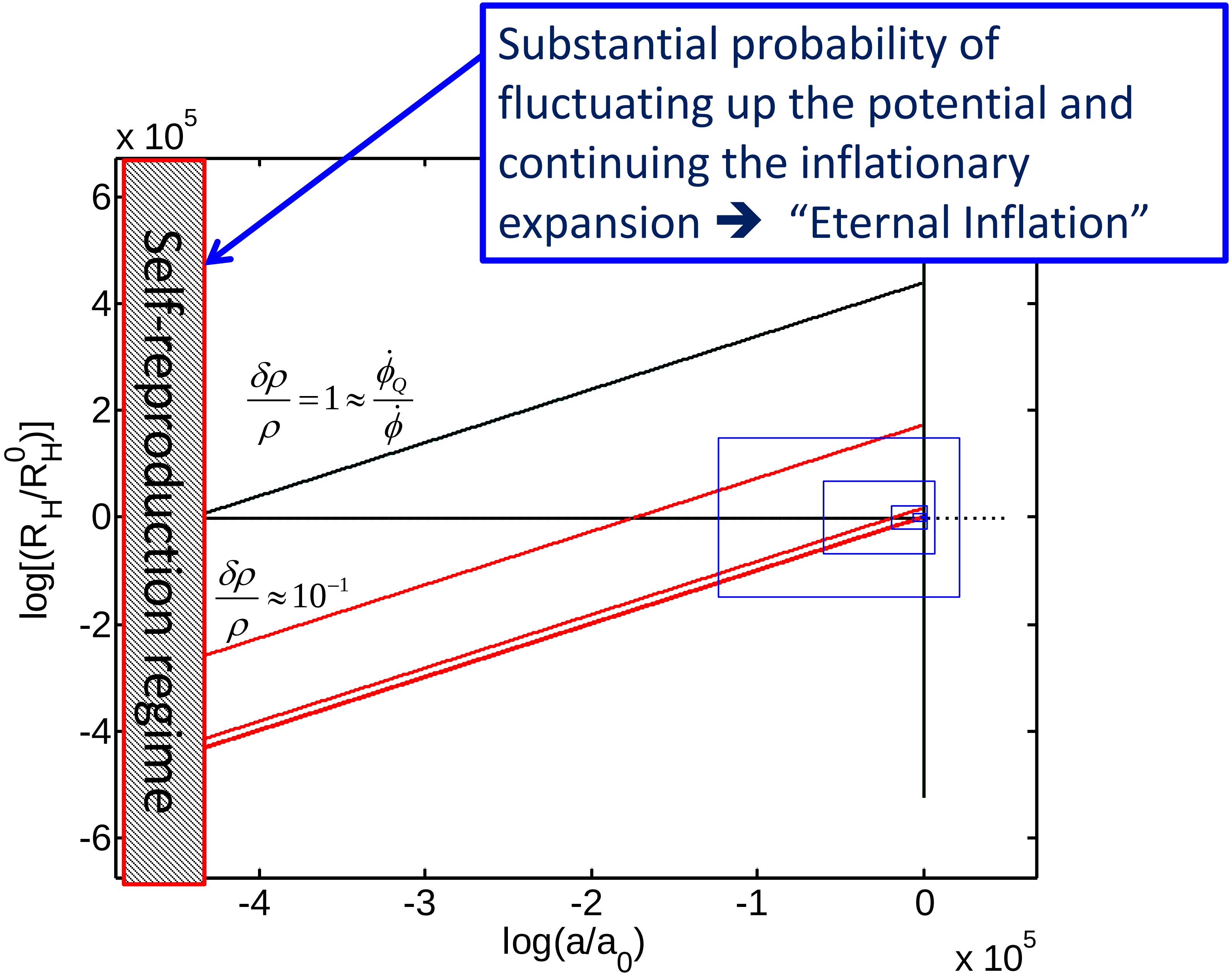
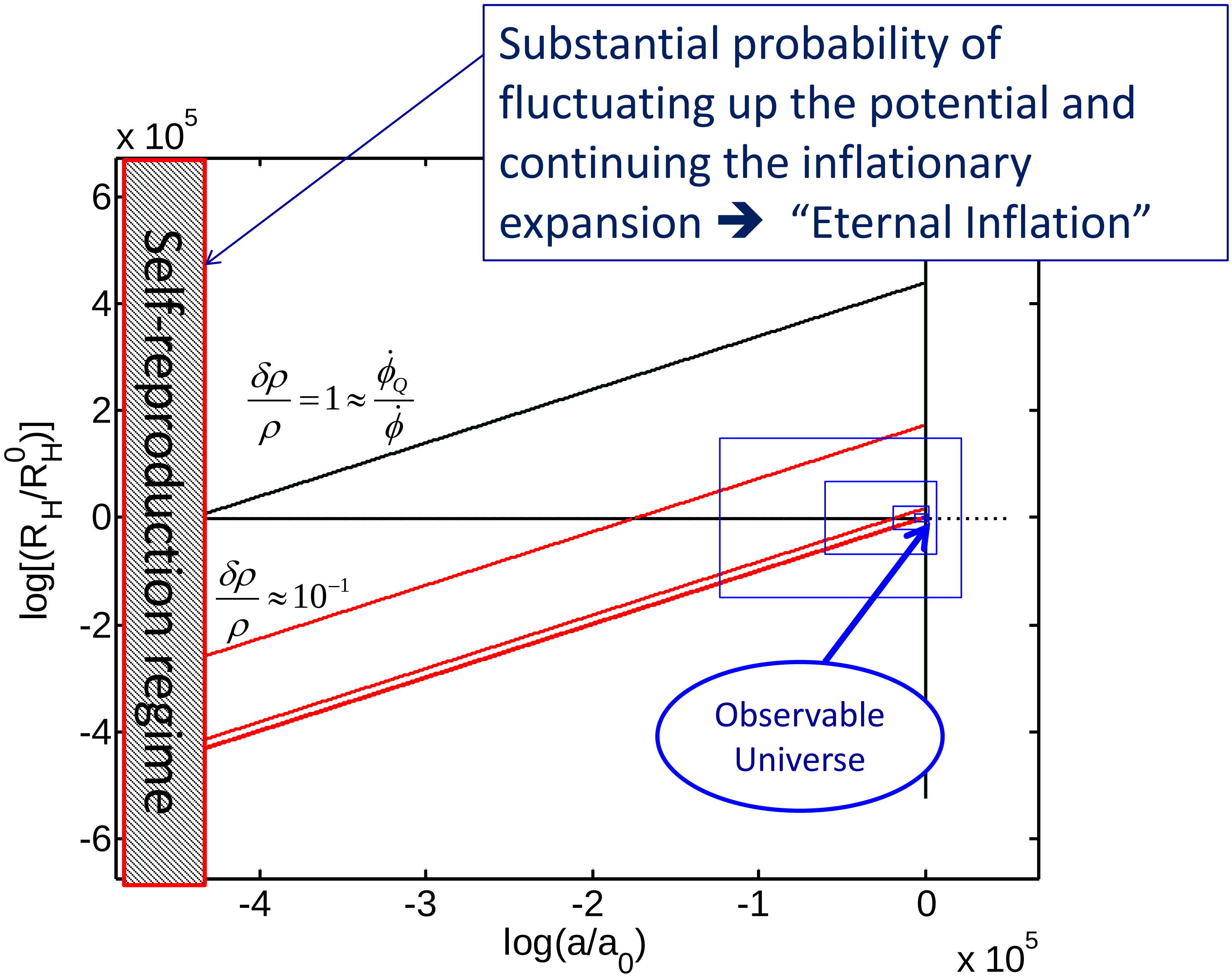




Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others



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

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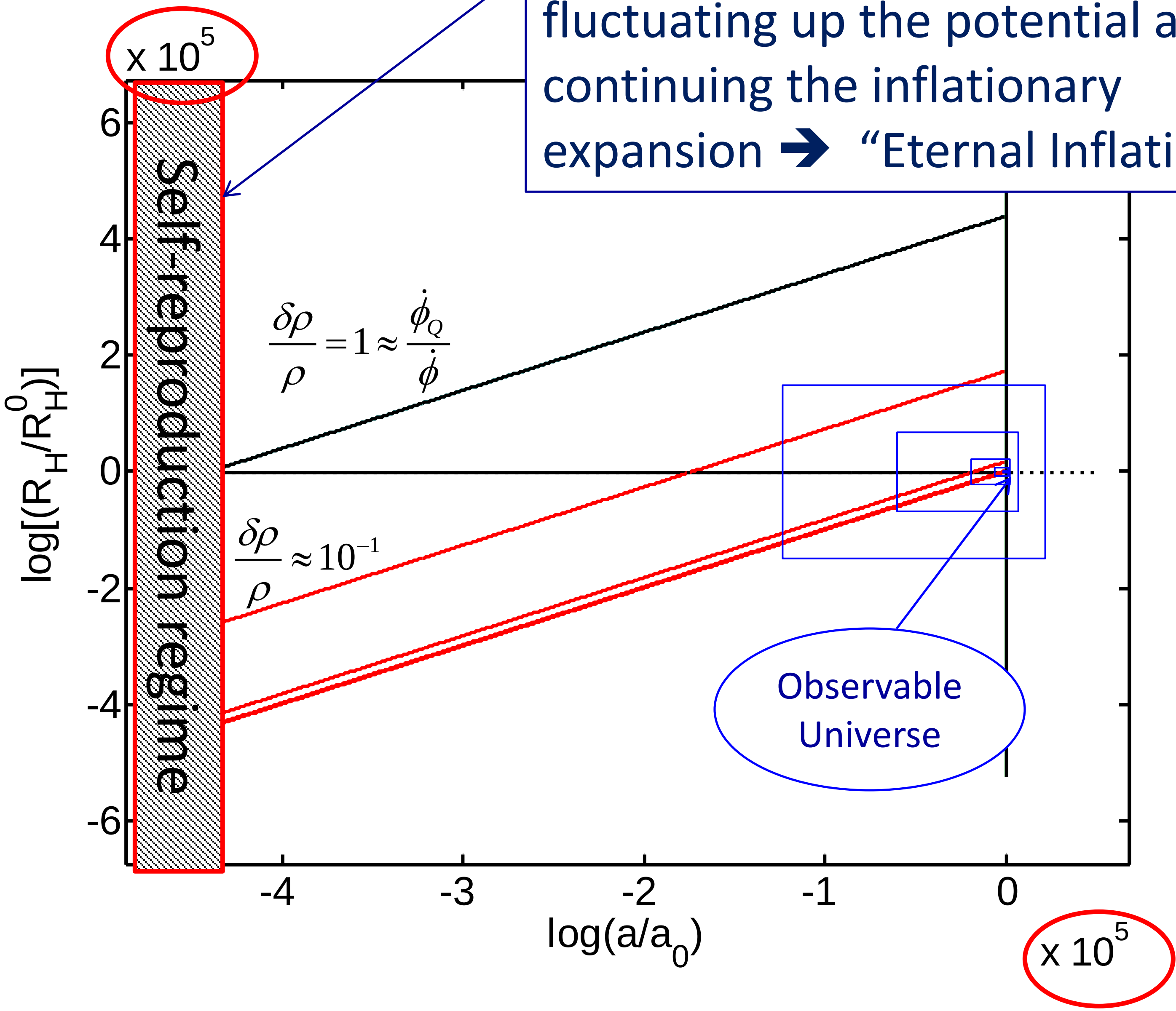
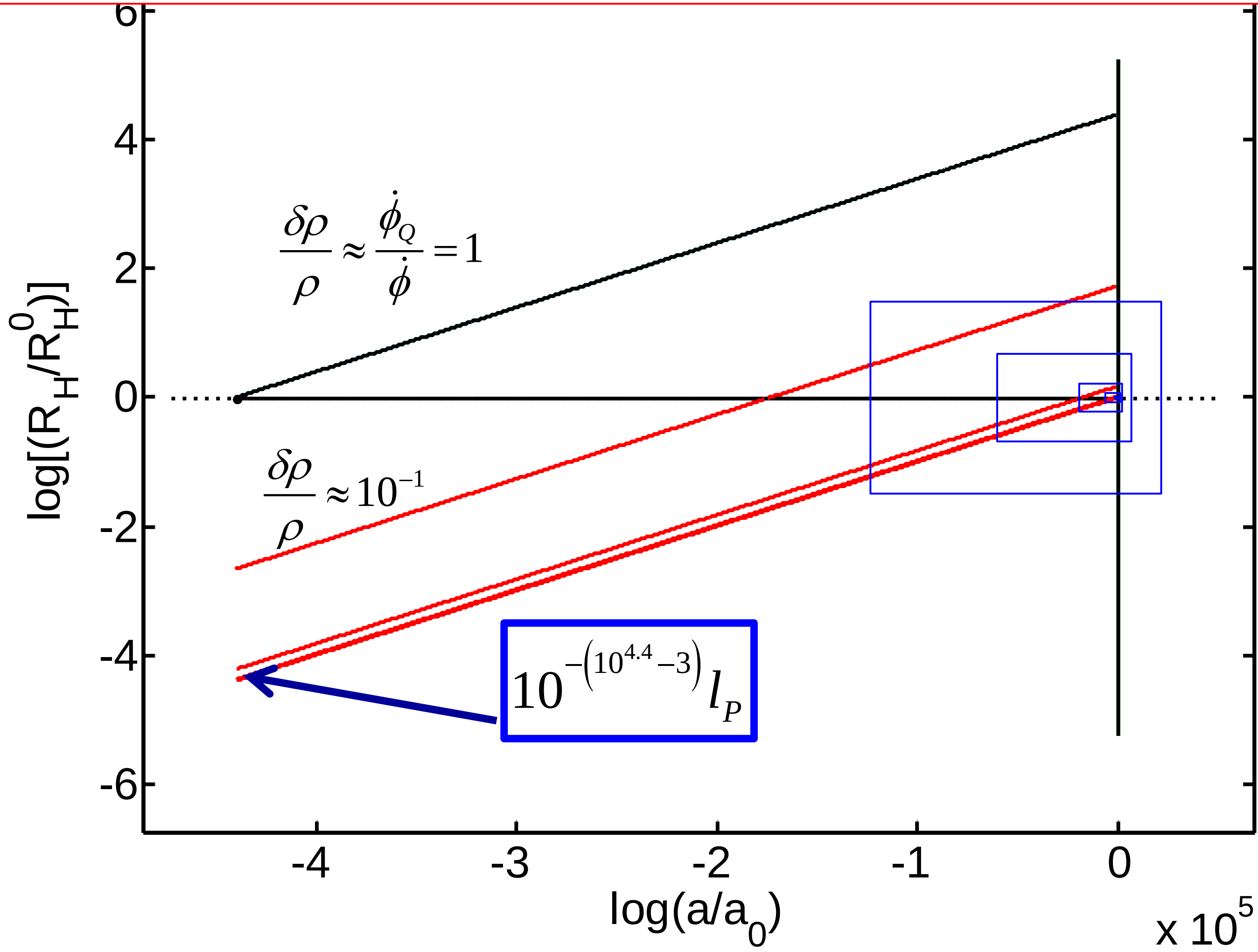
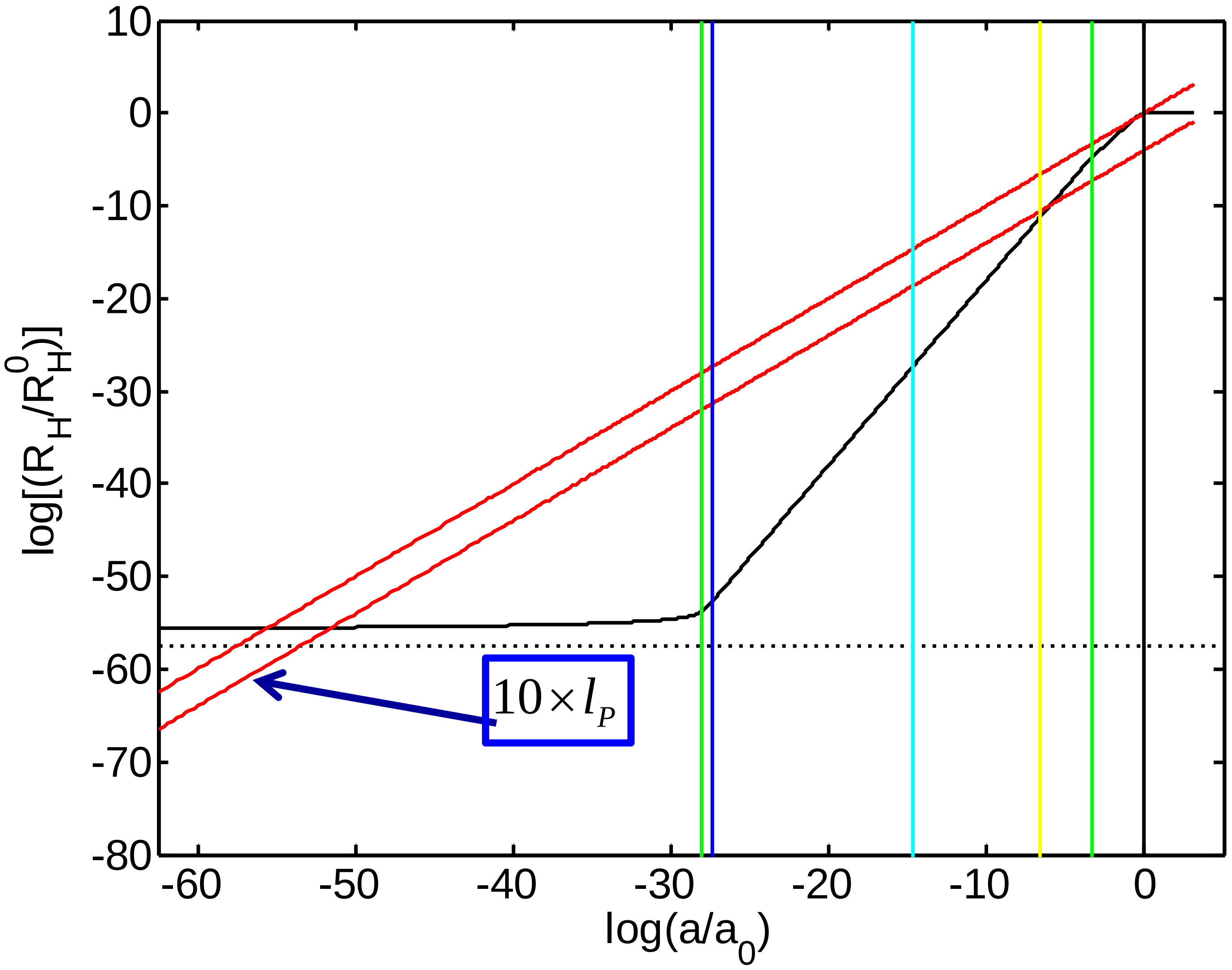


At end of self-reproduction our observable length scales were exponentially below the Plank length (and much smaller than that *during* self-reproduction)!



At “formation” (Hubble length crossing) observable scales were just above the Planck length



(Bunch Davies Vacuum)

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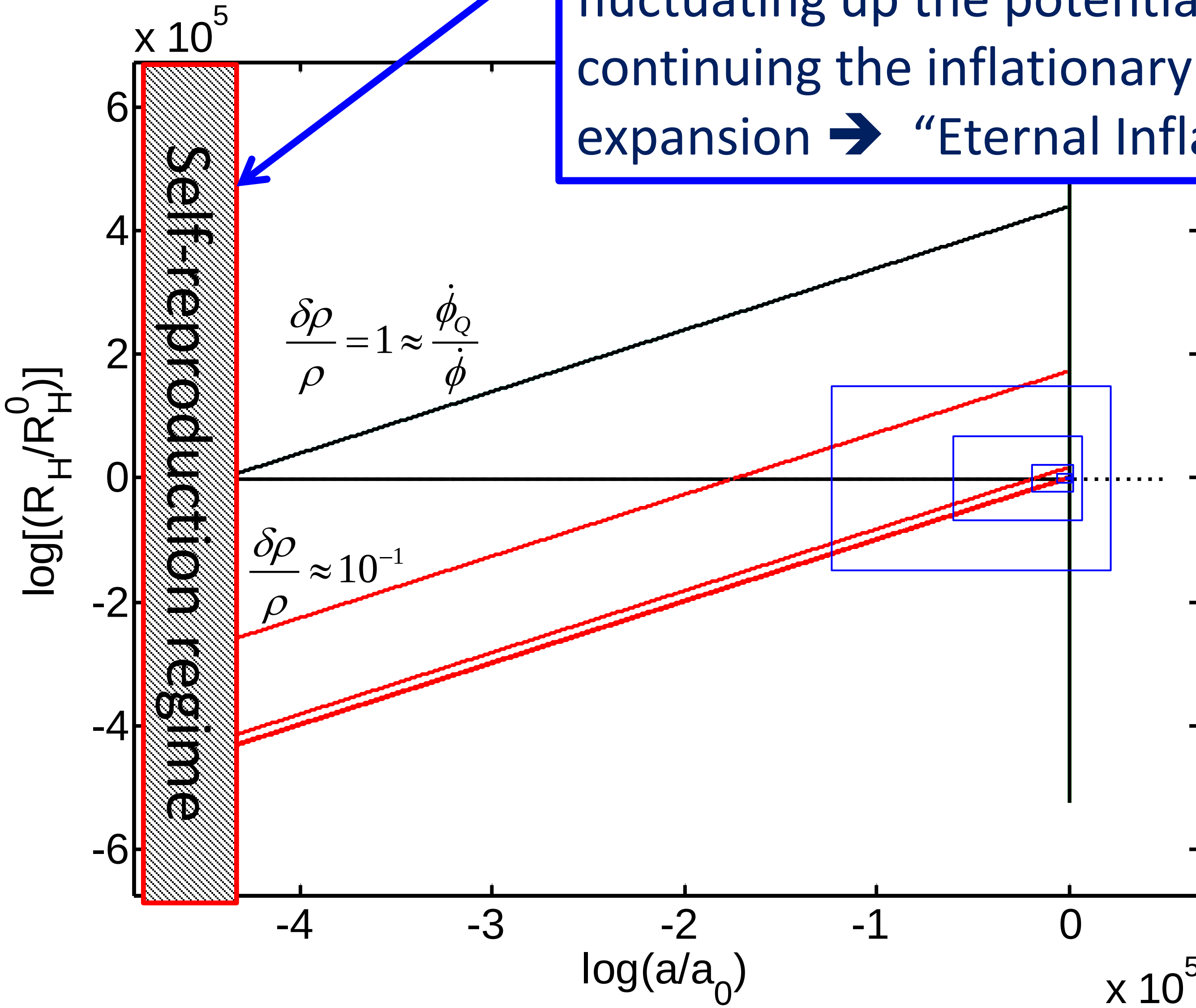

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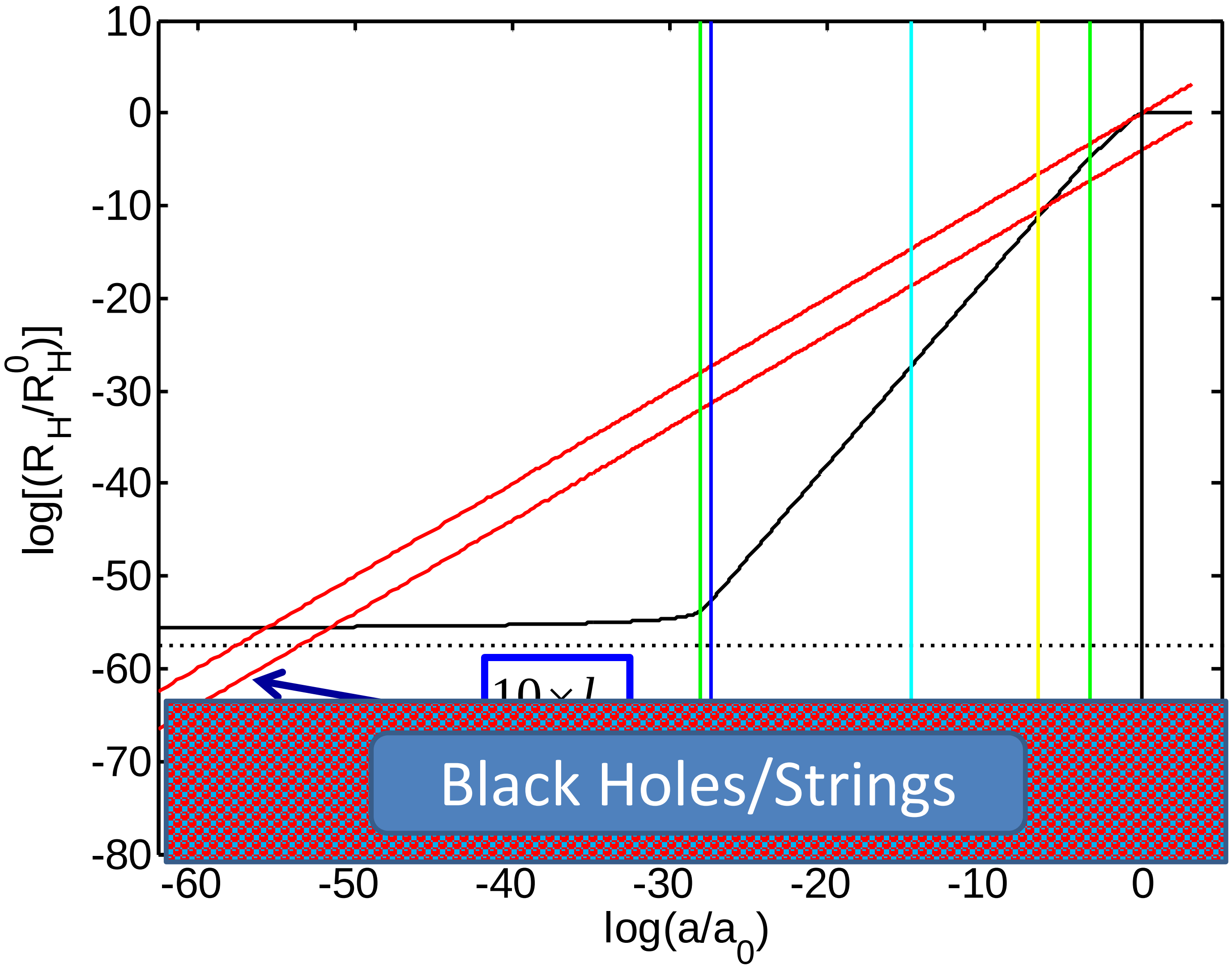

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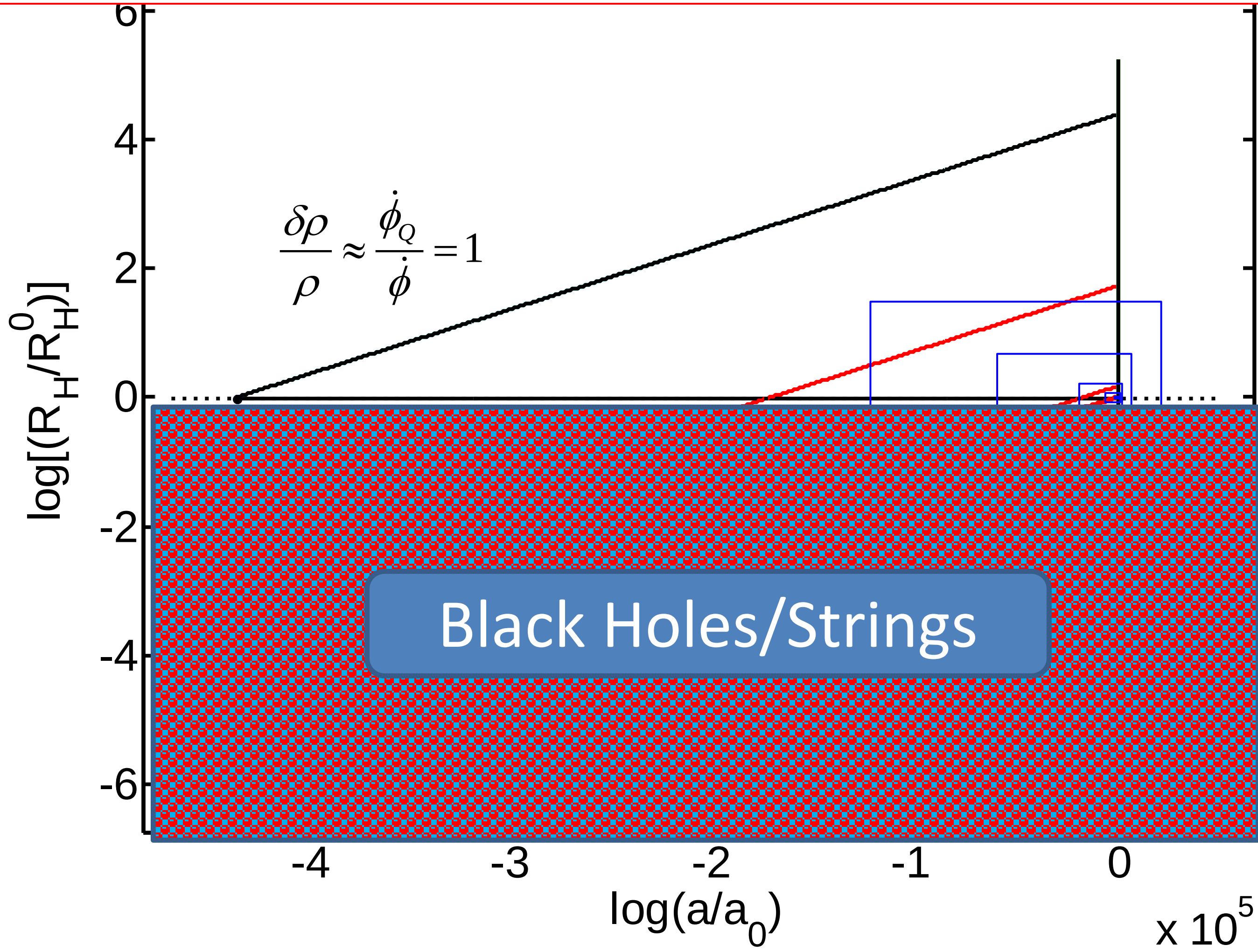
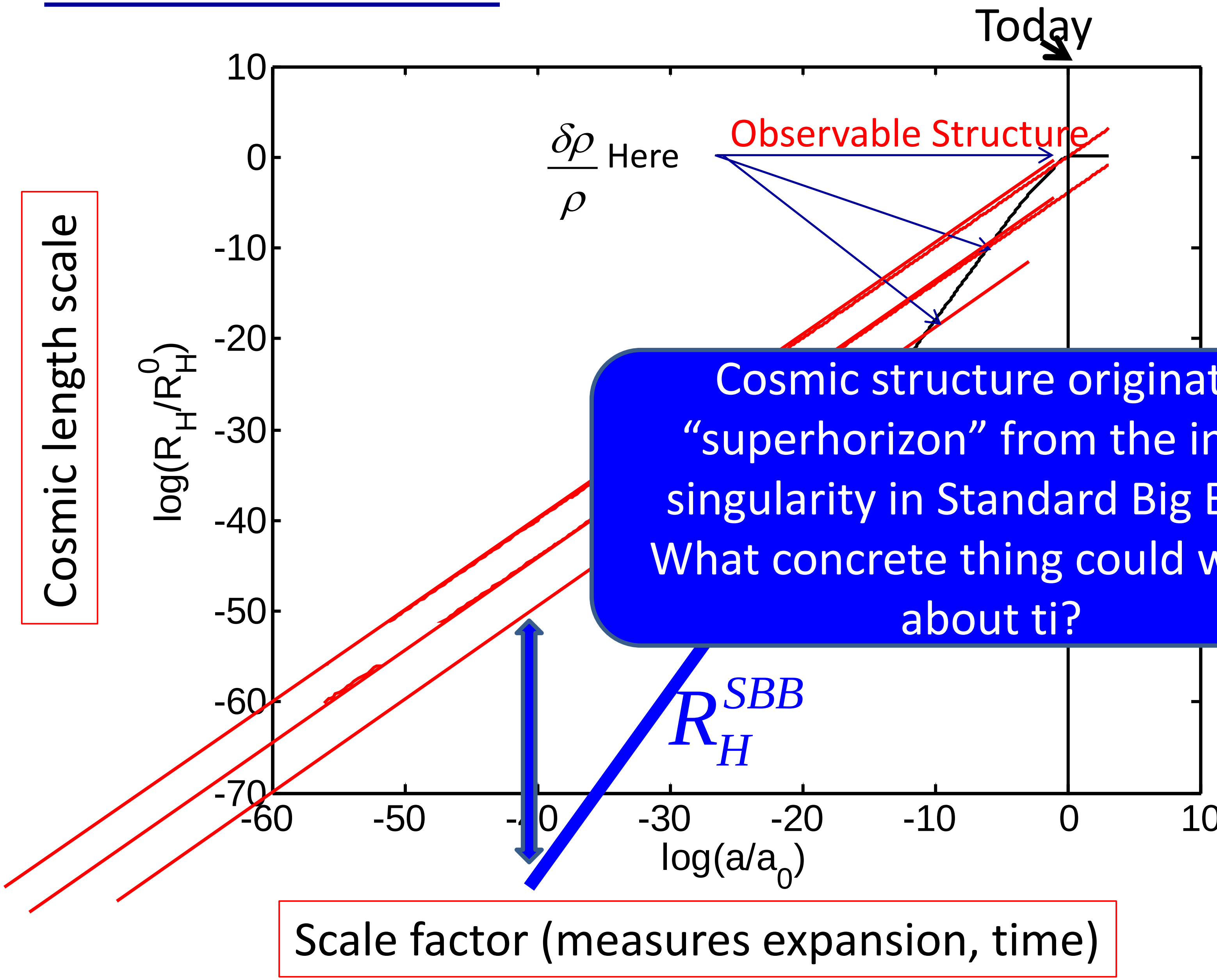
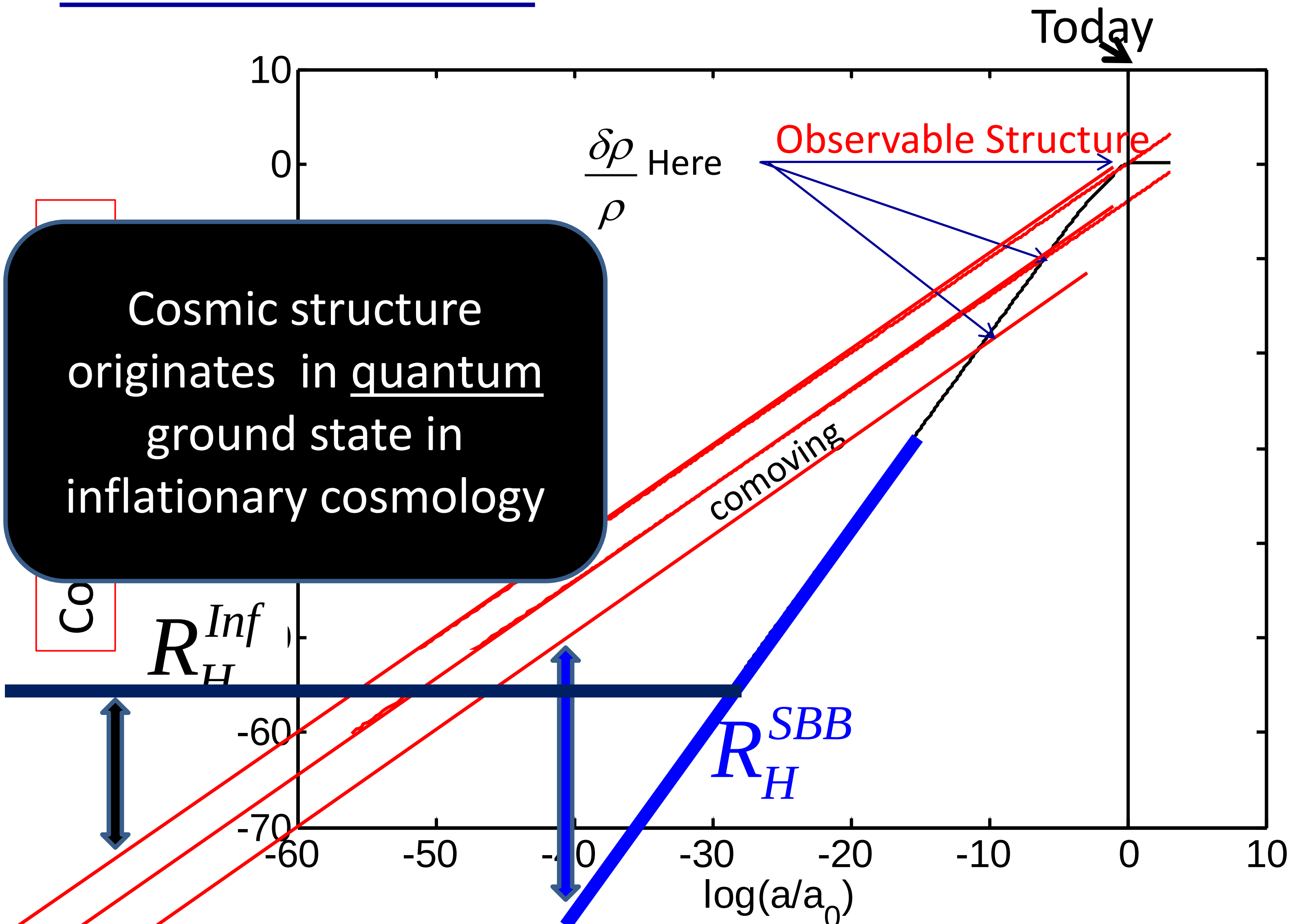


Cosmic structure



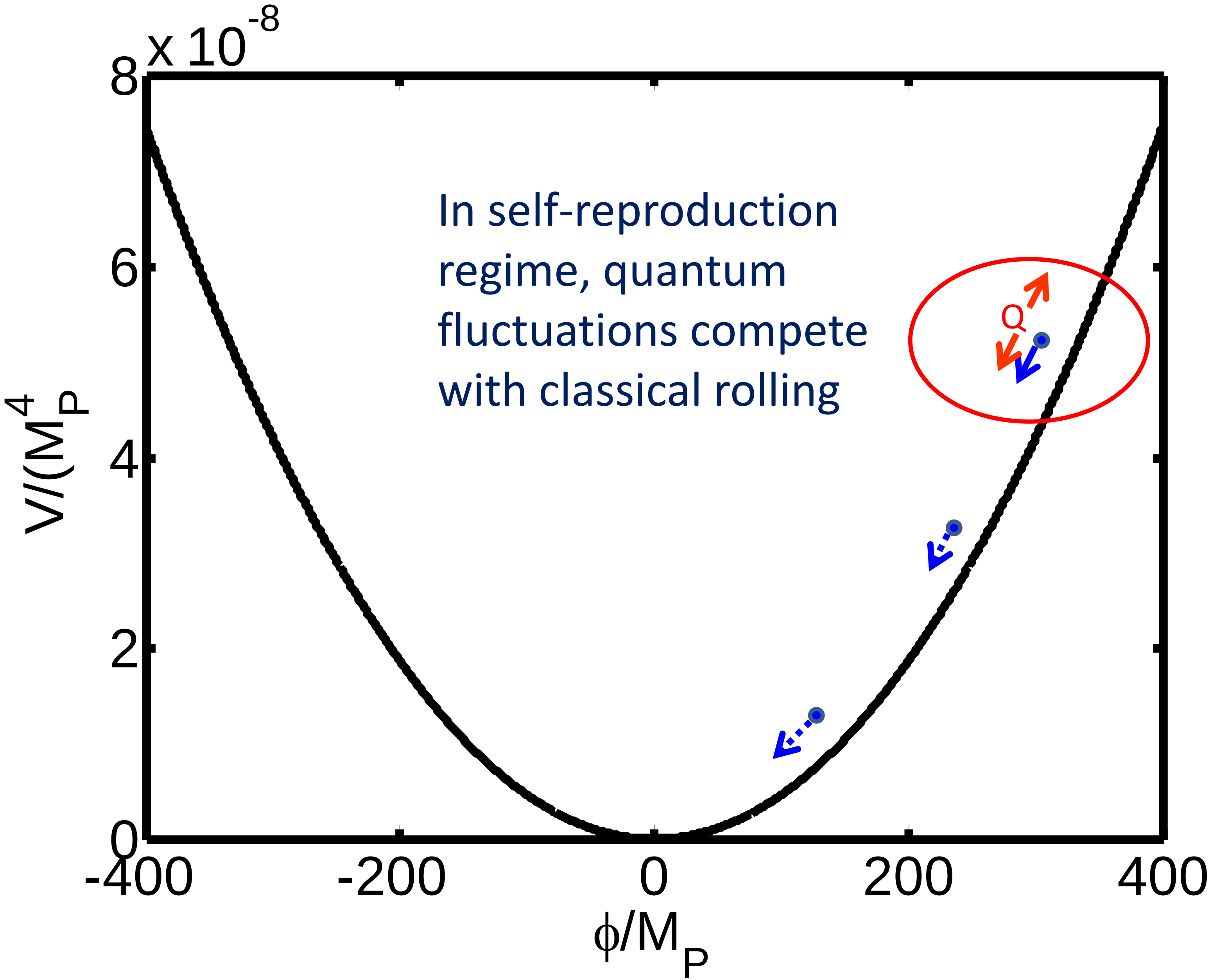
Cosmic structure originates "superhorizon" from the initial singularity in Standard Big Bang. What concrete thing could we say about ti?

Cosmic structure



Cosmic structure originates in quantum ground state in inflationary cosmology

Scale factor (measures expansion, time)


x 10^-8
8
6
4
2
0
V/(M_P^4)
In self-reproduction regime, quantum fluctuations compete with classical rolling
Q
-400
-200
0
200
400
ϕ/M_P

(not to scale)

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

During inflation

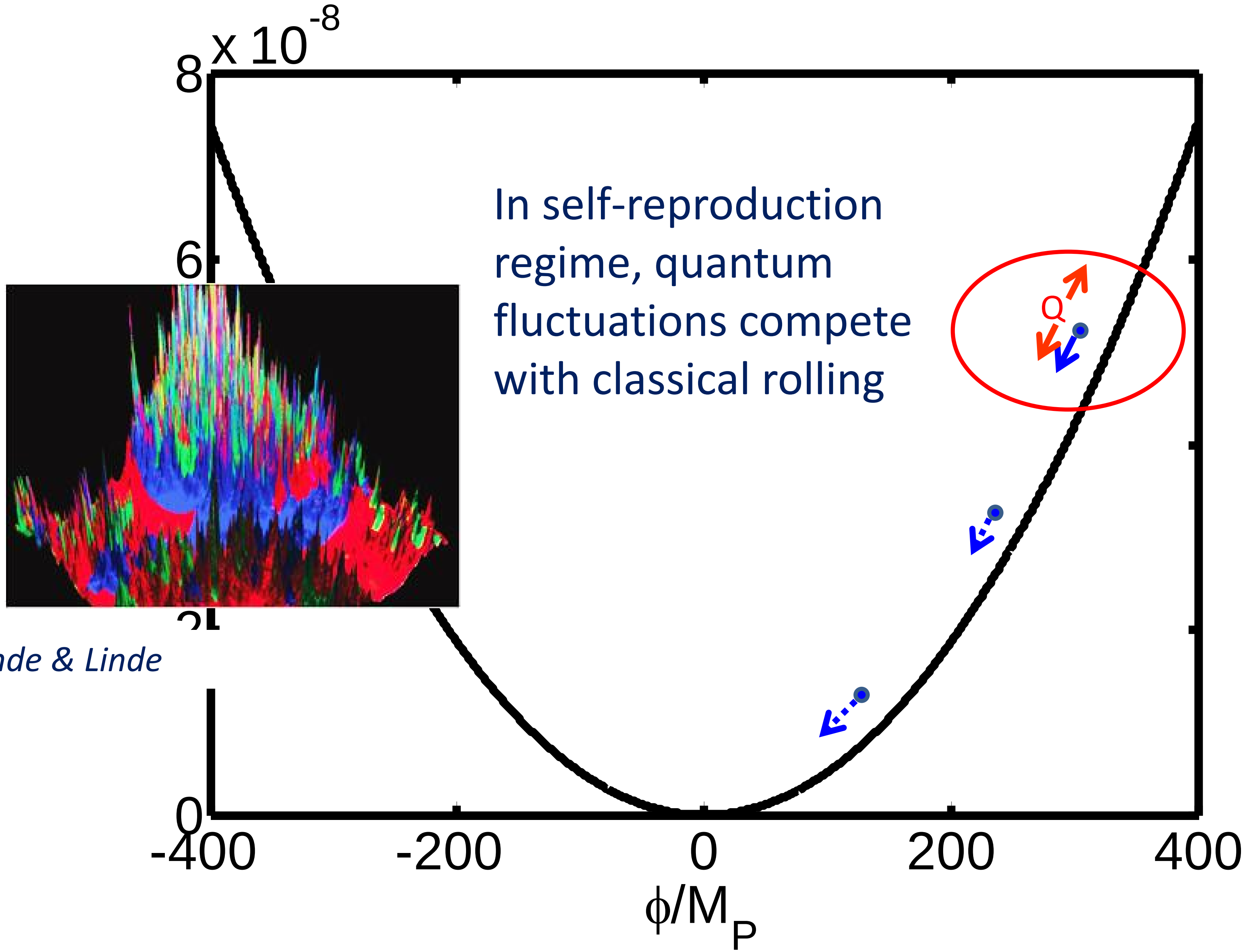
$$\ddot{\phi} + 3H\dot{\phi} = -\Gamma_{\phi}\dot{\phi} - V'(\phi)$$

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

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

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

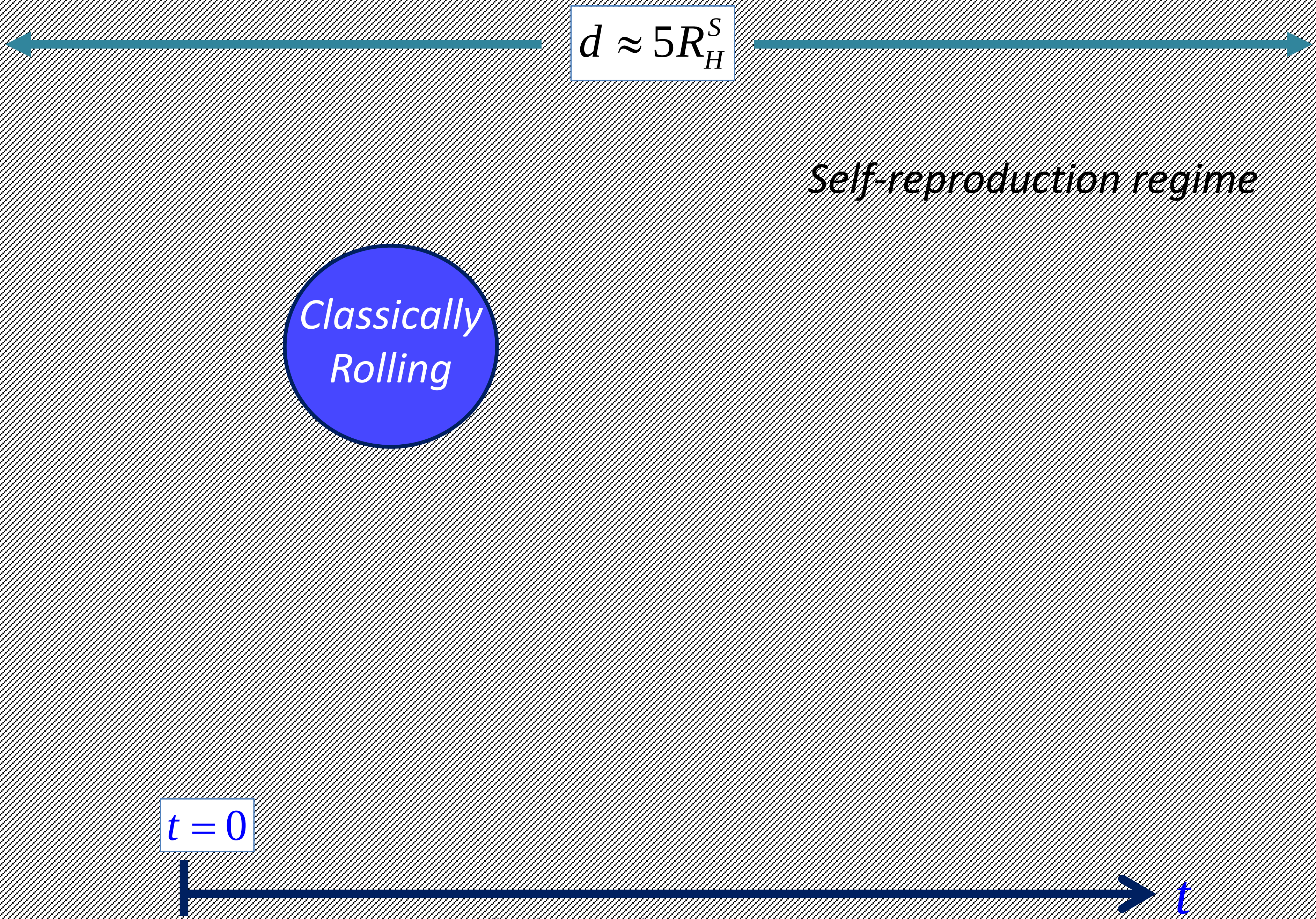
≥ 1 for self-reproduction



In self-reproduction regime, quantum fluctuations compete with classical rolling

Linde & Linde

(not to scale)


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

$d \approx 5R_H^S$

Self-reproduction regime

Classically Rolling

NB: shifting focus to $l(t)$

$t = 0$

t

$$d \approx e^{2} \times 5R_H^S$$

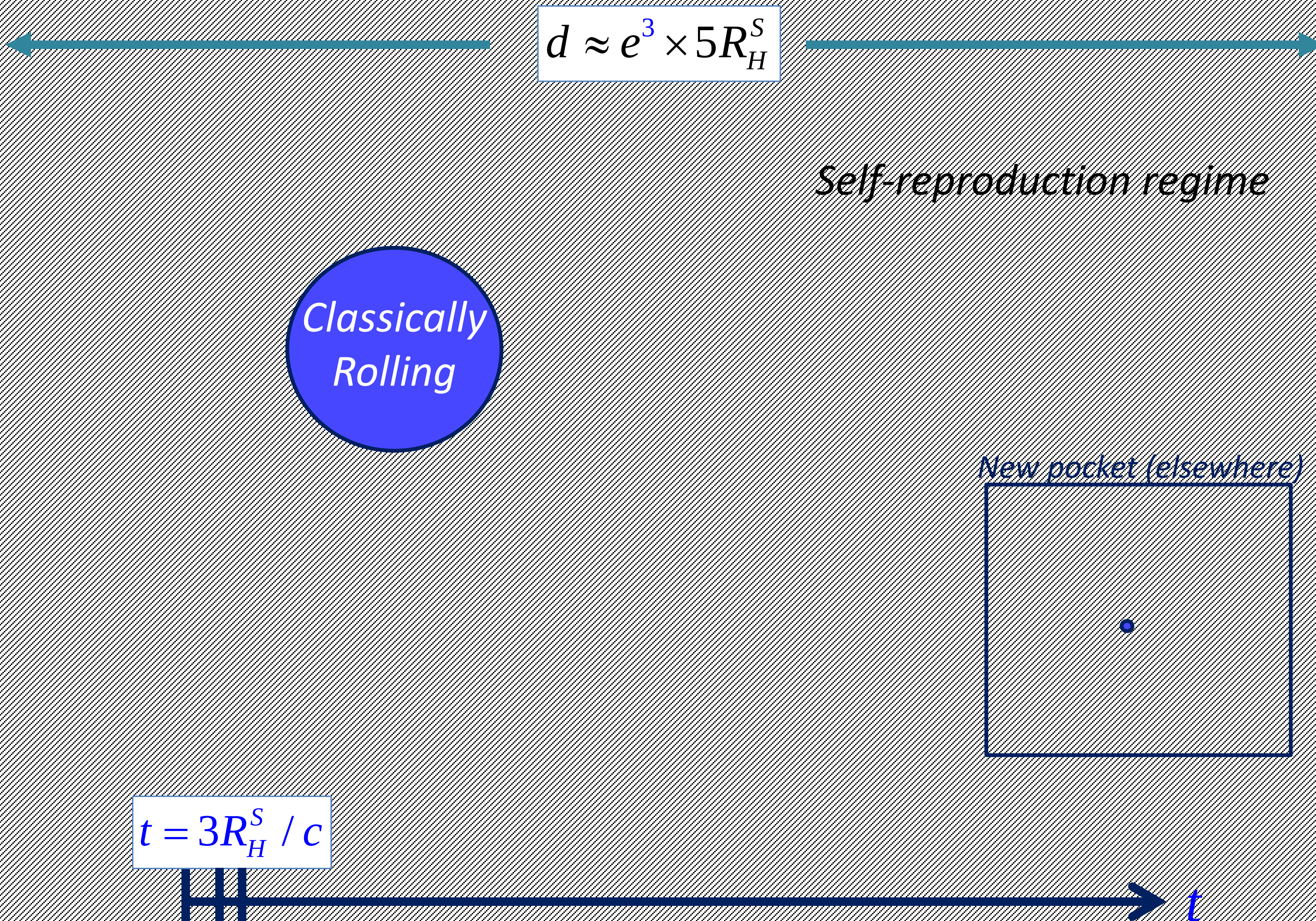
Self-reproduction regime

Classically Rolling

New pocket (elsewhere)

$$t = 2R_H^S / c$$

t


$d \approx e^{3} \times 5R_H^S$
Self-reproduction regime
Classically Rolling
New pocket (elsewhere)
$t = 3R_H^S / c$
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

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

Self-reproduction regime

New pocket (elsewhere)

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

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

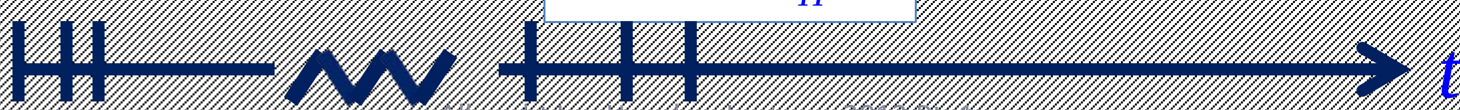
$$d \approx e^{1400} \times 5R_H^S$$

Self-reproduction regime

New pocket (elsewhere)

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

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



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

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)

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

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

t

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

Self-reproduction regime

Reheating

New pocket (elsewhere)

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

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

t

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

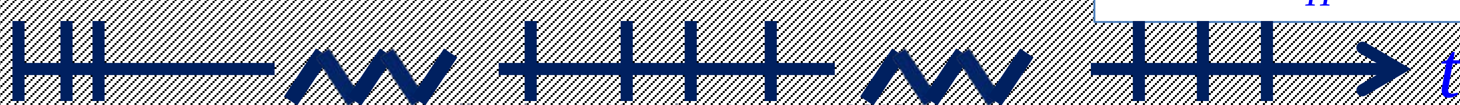
Self-reproduction regime

Radiation Era

New pocket (elsewhere)

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

$$t = 3.2 R_H^{Iend} / c$$



Eternal inflation features

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- Leads to infinite Universe, infinitely many pocket universes. The self-reproduction phase lasts forever.

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> - State of the art: Instead of making predictions, experts are using the data to infer the "correct measure"

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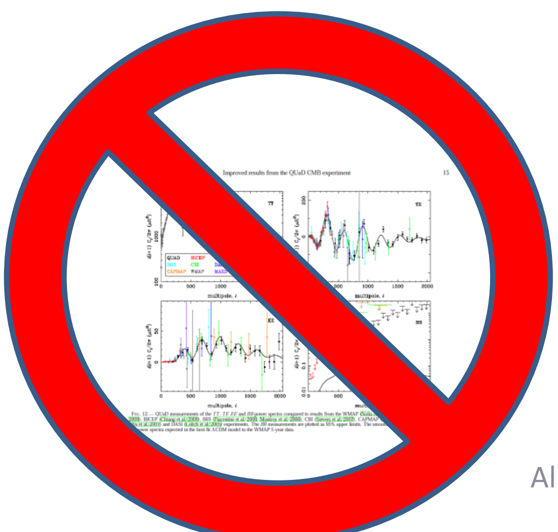
- For a specific time cutoff, the most recently produced pocket universes are exponentially favored (produced in an exponentially larger region).

> - Young universe problem
> - End of time problem
> - Measure problems



> - State of the art: Instead of making predictions, experts are using the data to infer the "correct measure"

Eternal inflation features

According to some: "True infinity" needed here

- Most of the Universe is always inflating
- Leads to infinite Universe, infinitely many pocket universes, self-reproduction phase lasts forever.
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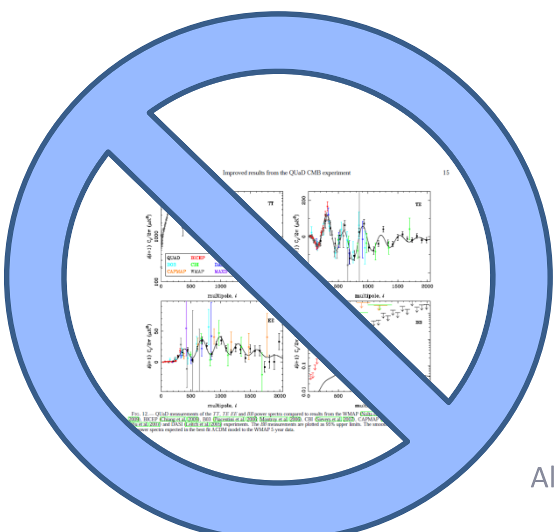

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Hernley, AA & Dray 2013

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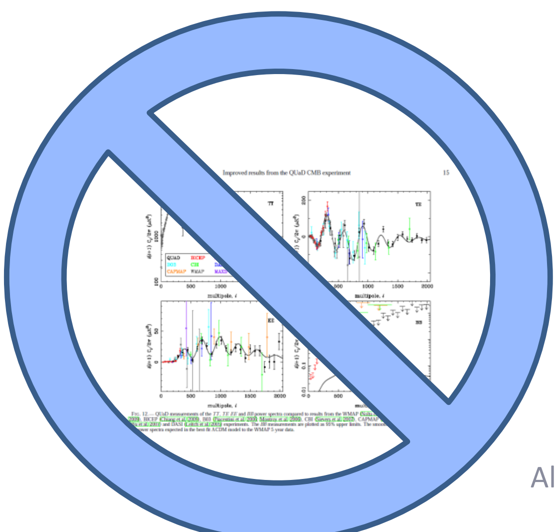

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Multiply by 10^{500} to get landscape story!

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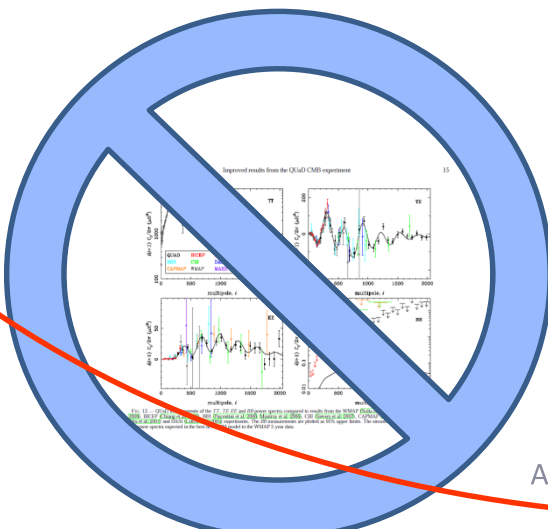

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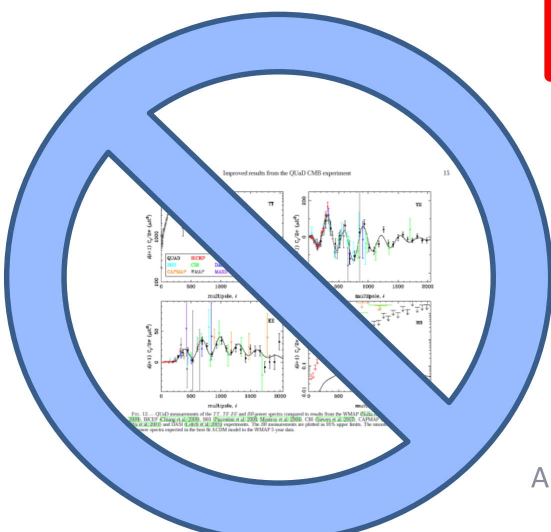
em

➢ Measure problems



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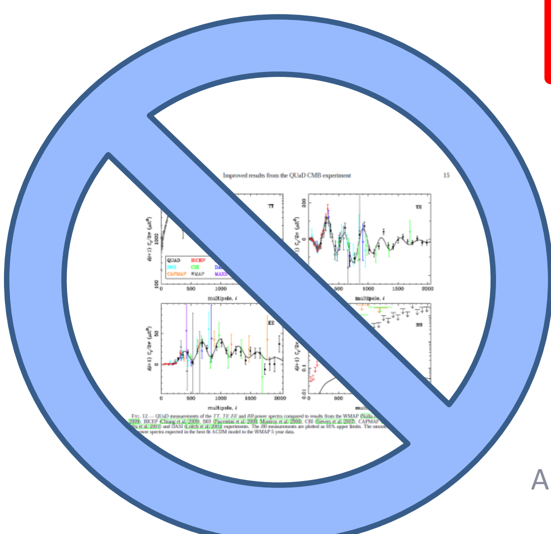

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See Part 3 of these lectures

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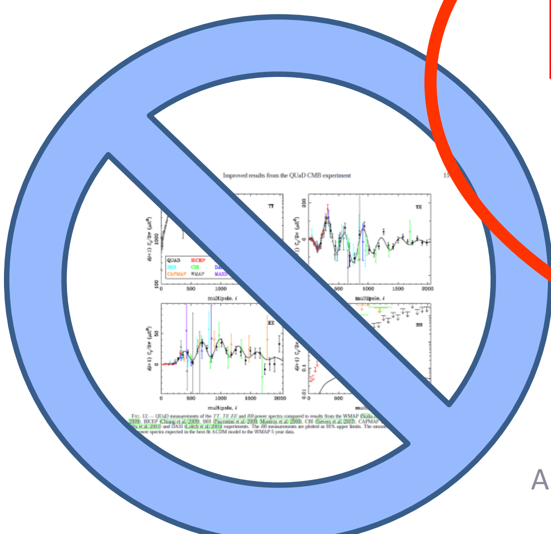

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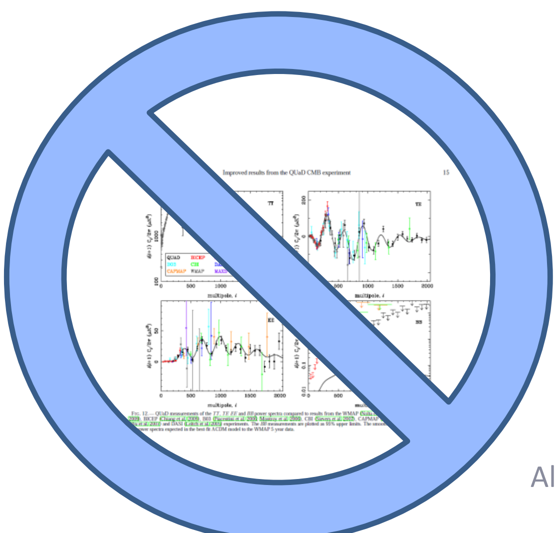

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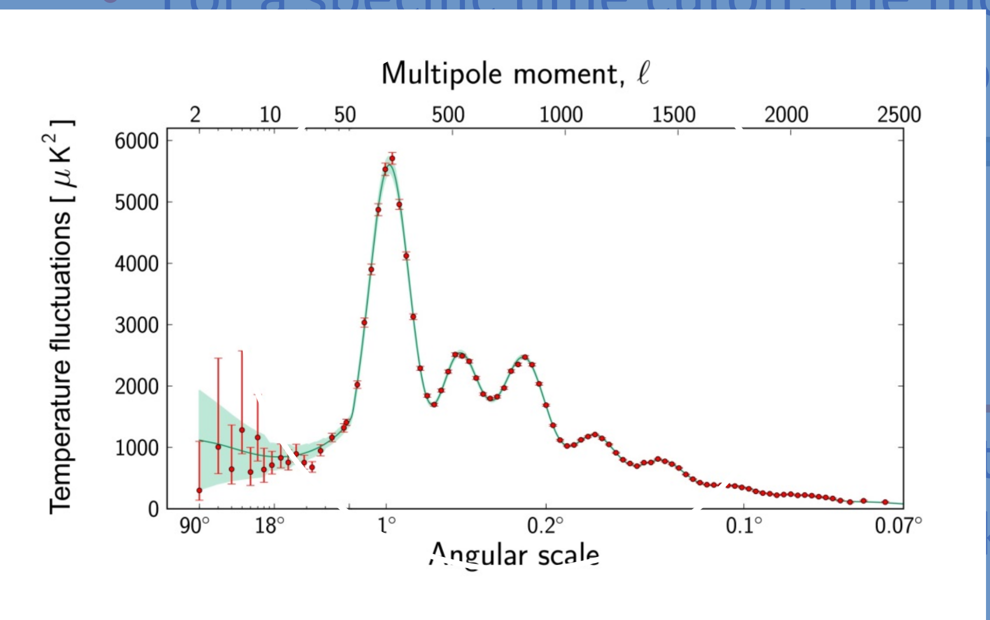

➢ Young universe problem

Or, just be happy we have equations to solve?

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Les Houches Lectures on Cosmic Inflation

Four Parts

1) Introductory material

End Part 1

2) Entropy, Tuning and Equilibrium in Cosmology

3) Classical and quantum probabilities in the multiverse

4) de Sitter equilibrium cosmology

Andreas Albrecht; UC Davis
Les Houches Lectures; July-Aug 2013