Cosmic Inflation Tutorial

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Quantum Information in Cosmology
Niels Bohr Institute
April 2018

Cosmic Inflation:

- ➔ Concrete technical idea with great phenomenology
- ➔ Couched in the language of "solving tuning problems"
- ➔ Big open questions

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Conclusions

A) Inflation is a technical tool for connecting cosmological observables with high energy physics. Impressive successes.

B) However, without a meta theory about how inflation started (and how it "competes" with other scenarios, such as the Standard Big Bang) big questions are unresolved.

C) Complex sociology as different individuals choose to give A) and B) different weight.

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Priors!!

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Priors!!

Q

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- Big open questions

OUTLINE

1. Big Bang basics
2. Inflation basics
3. Eternal inflation
4. An alternative to Eternal Inflation
5. Further thoughts

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Einstein equation + Homogeneity & Isotropy ➔

Friedmann Eqn.

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

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Hubble parameter
("constant", because
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"Scale factor"

Friedmann Eqn.

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

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Curvature

"Scale factor"

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Curvature

Relativistic Matter

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

$\rho_r \propto a^{-4}$

$\rho_m \propto a^{-3}$

Curvature

Relativistic Matter

Non-relativistic Matter

"Scale factor"

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$\rho_k \propto a^{-2}$, $\rho_r \propto a^{-4}$, $\rho_m \propto a^{-3}$, $\rho_{DE} \propto a^{\approx 0}$

Curvature (ρ_k)

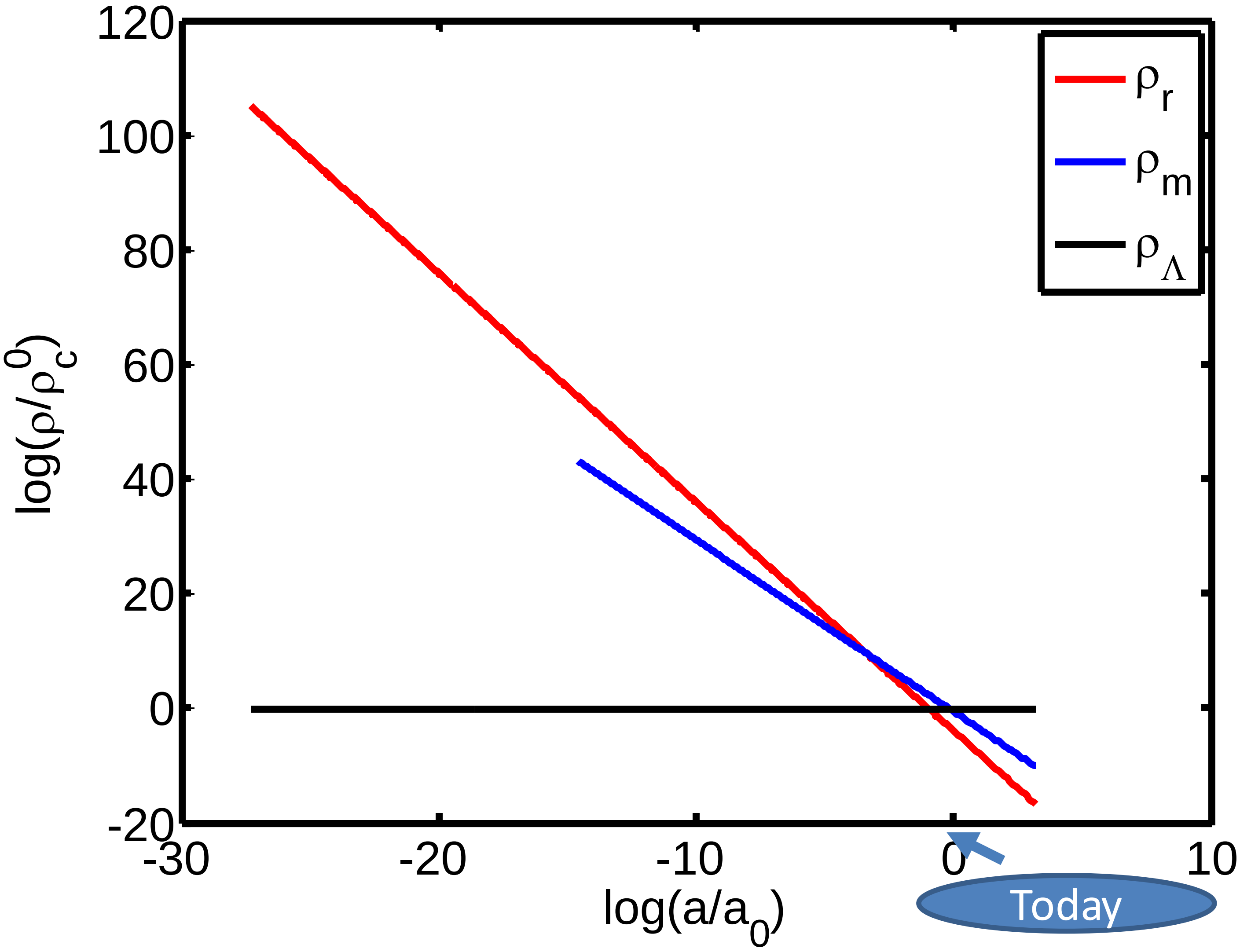
Relativistic Matter (ρ_r)

Non-relativistic Matter (ρ_m)

Dark Energy (ρ_{DE})

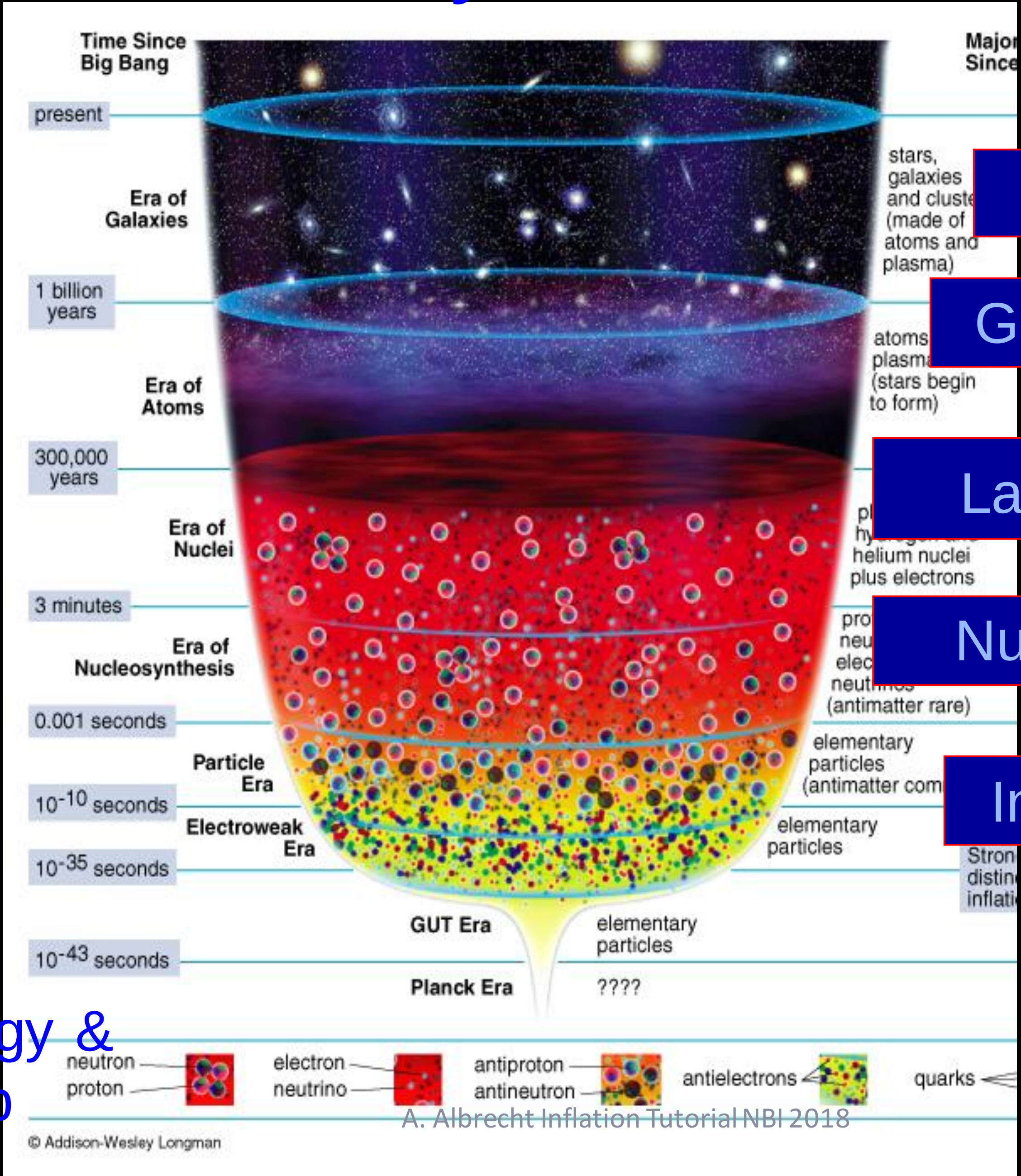
“Scale factor” (a)

Evolution of Cosmic Matter



Time

The History of the Universe



Today

Dark Energy

Galaxy Formation

Last Scattering

Nuclear & HEP

Inflation?

Extra Dimensions?

High Energy & Temp

The History of the Universe

Time

High Energy & Temp

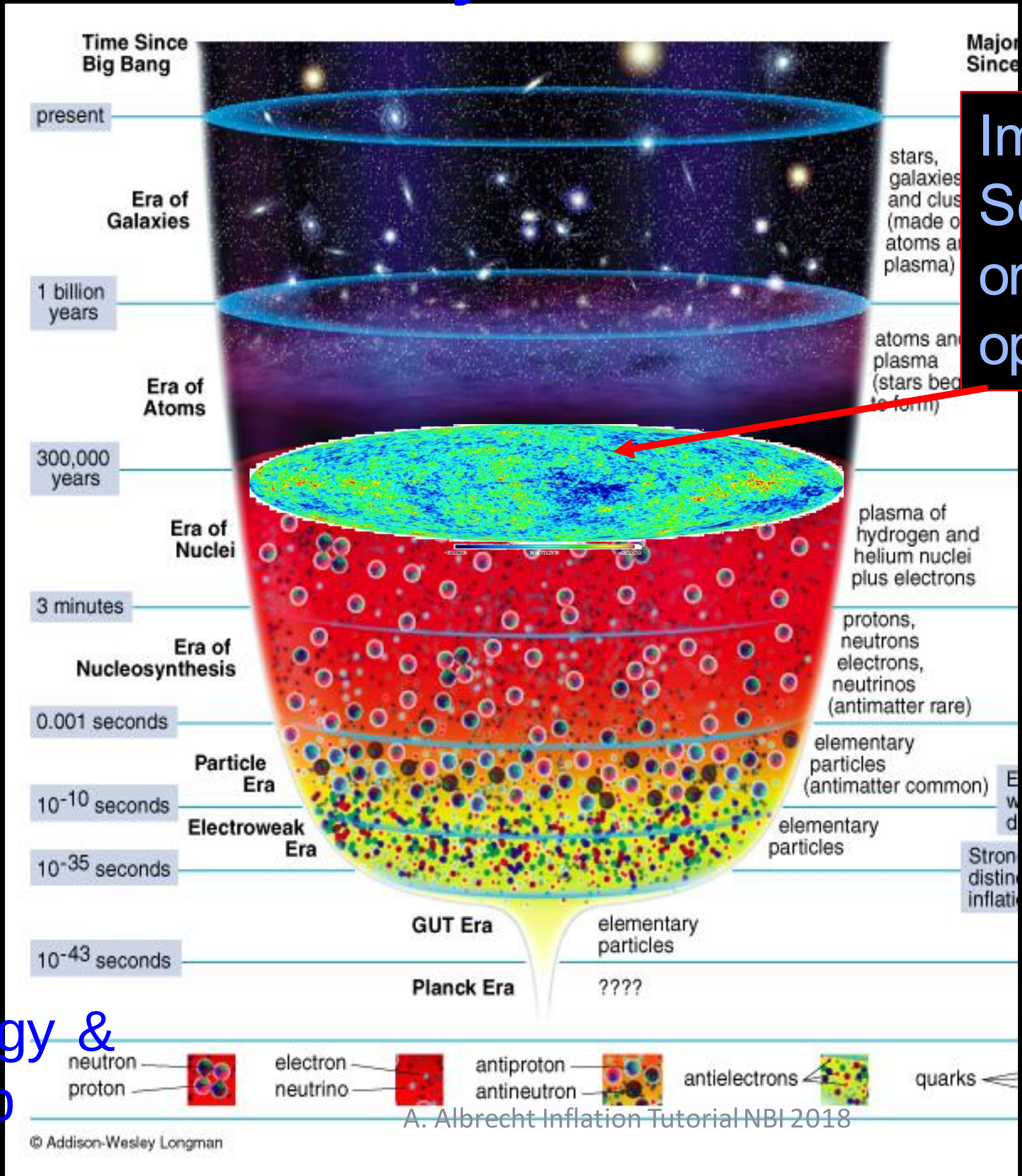
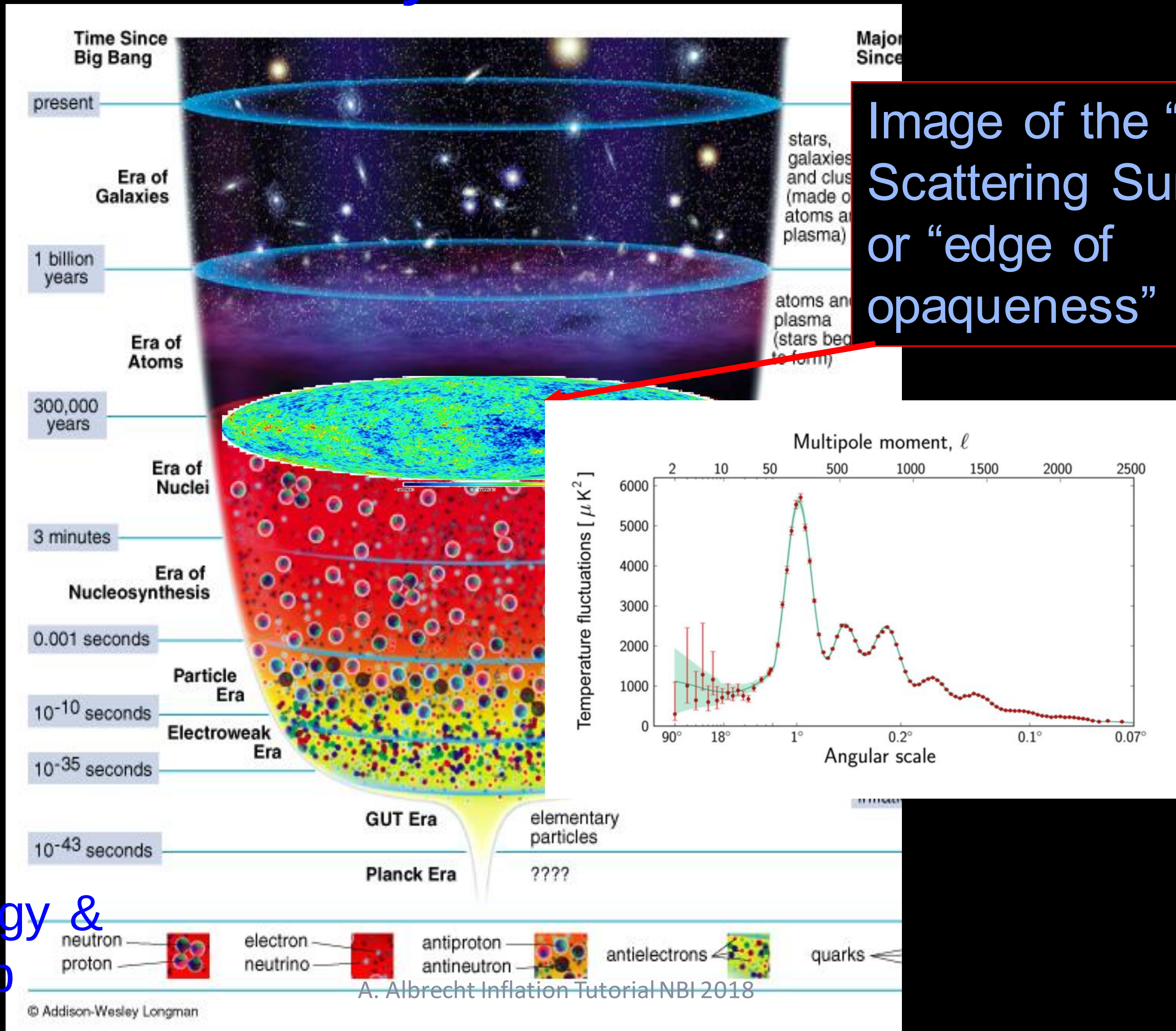


Image of the "Last Scattering Surface" or "edge of opaqueness"

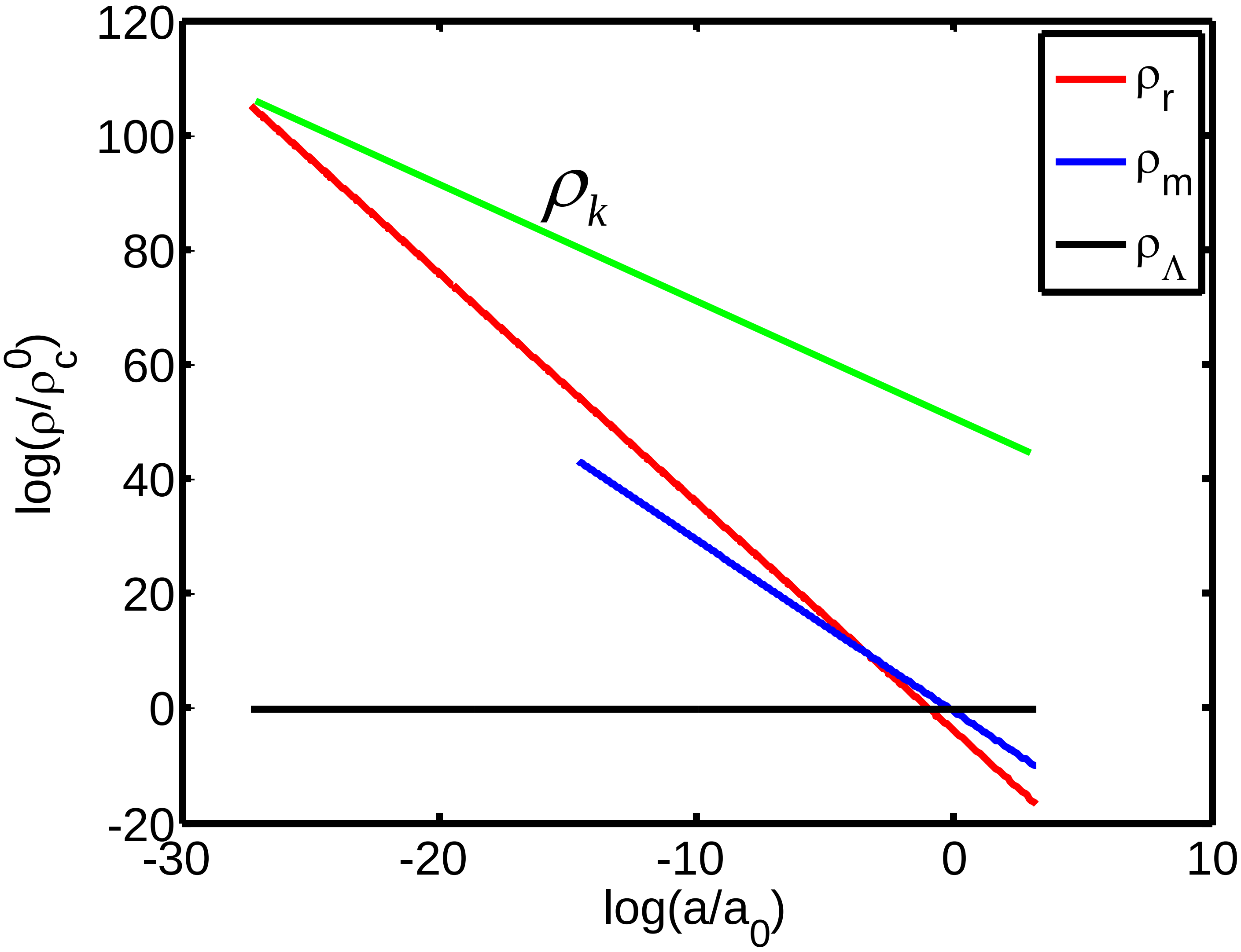
Time

The History of the Universe



High Energy & Temp

The curvature feature/"problem"



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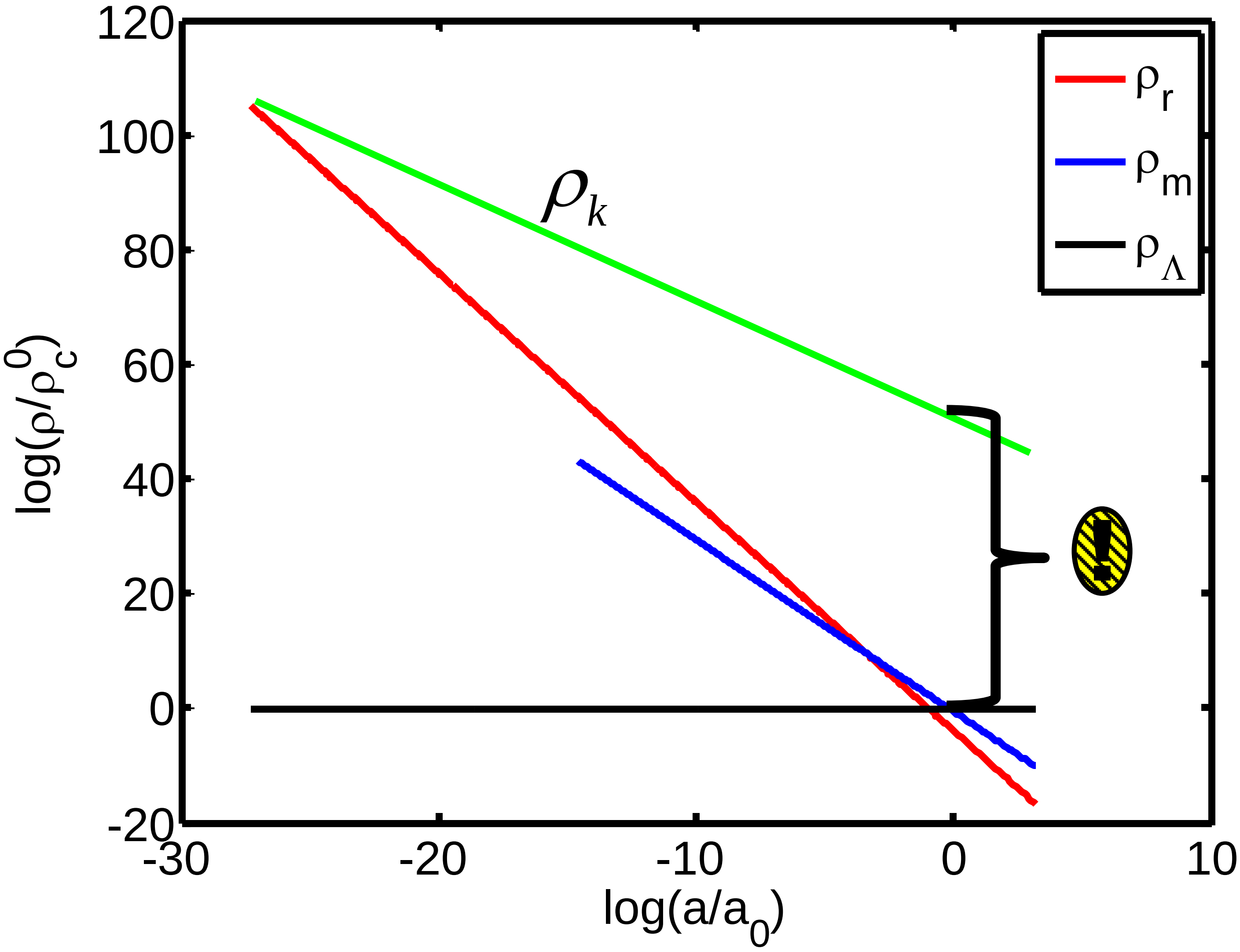

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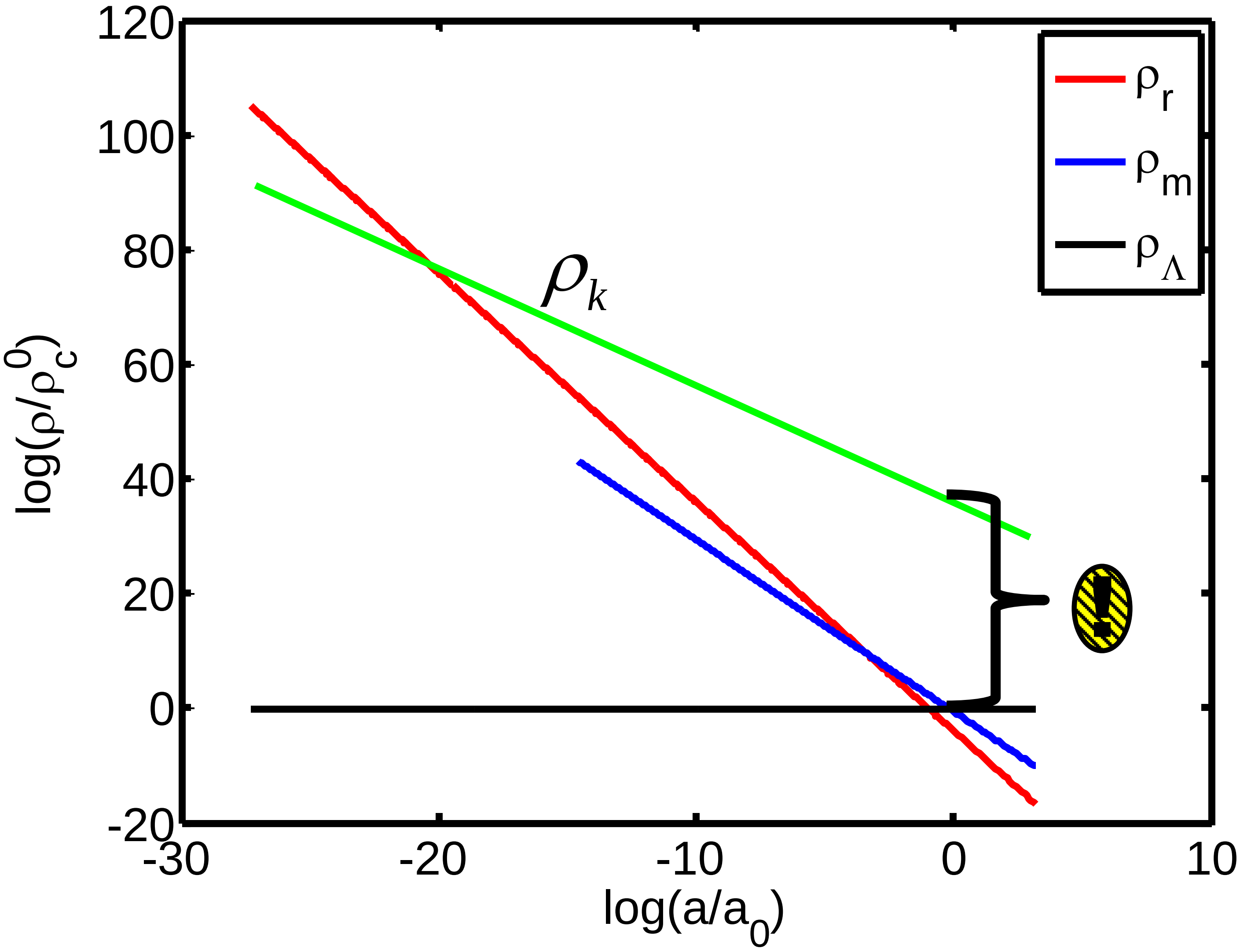

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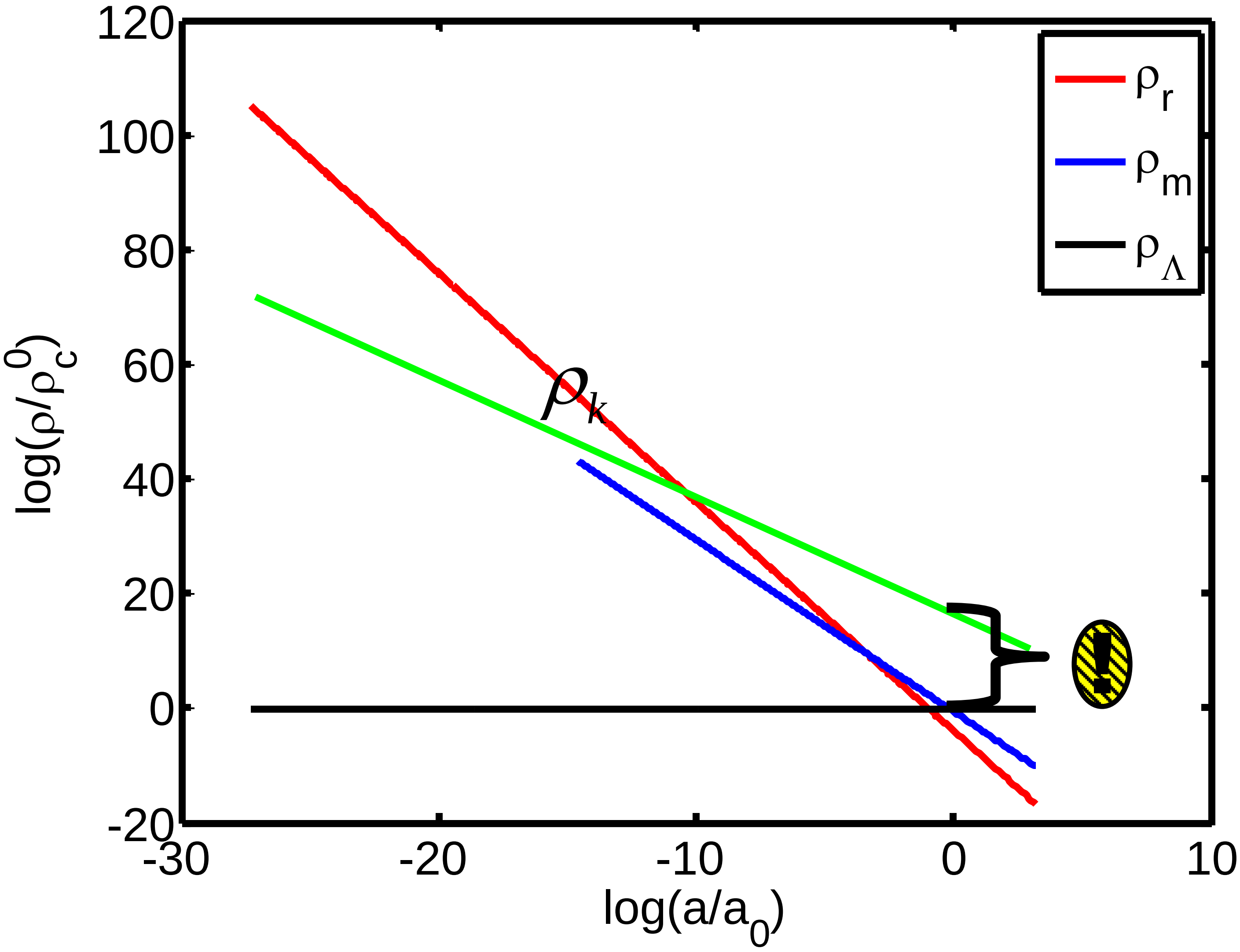

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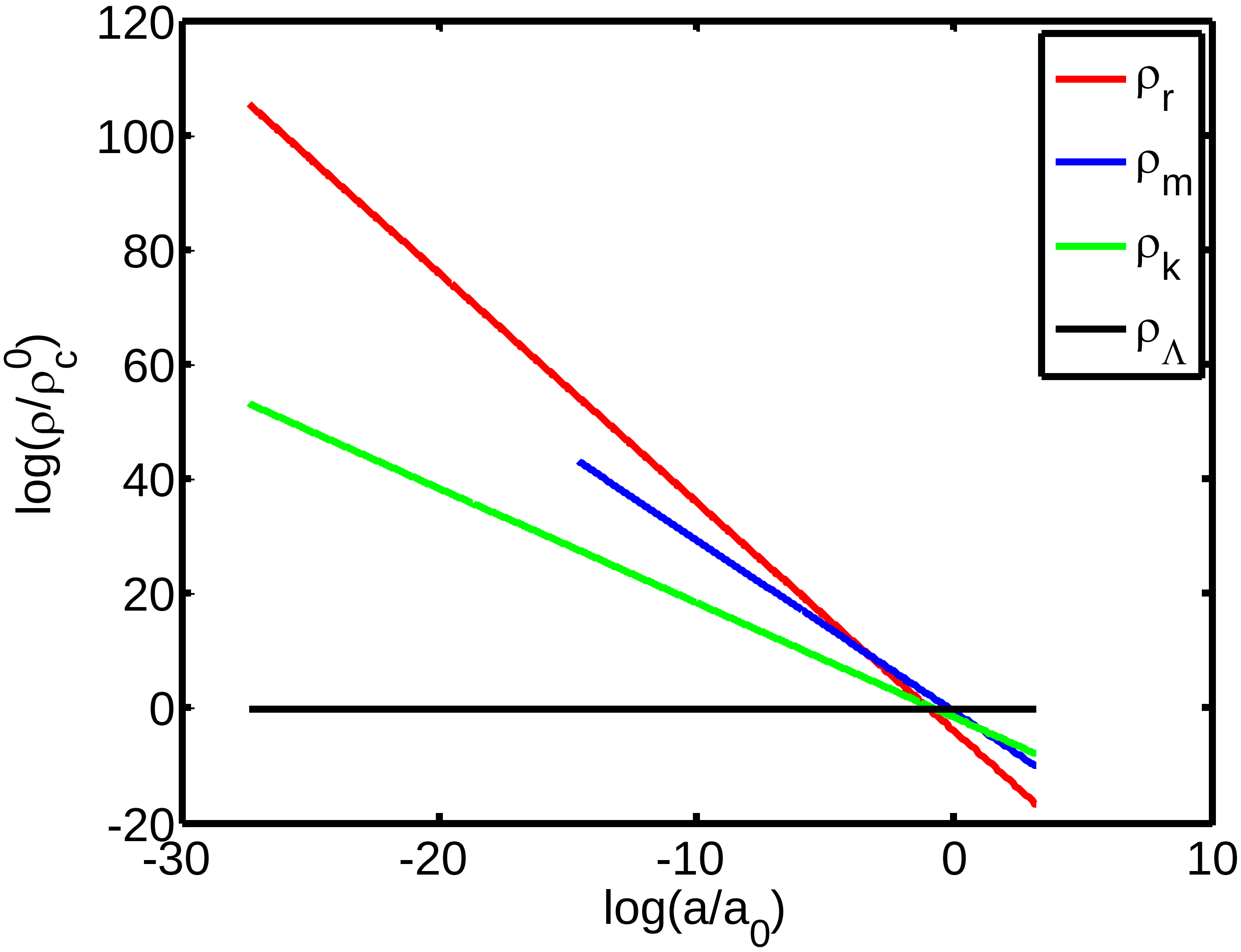

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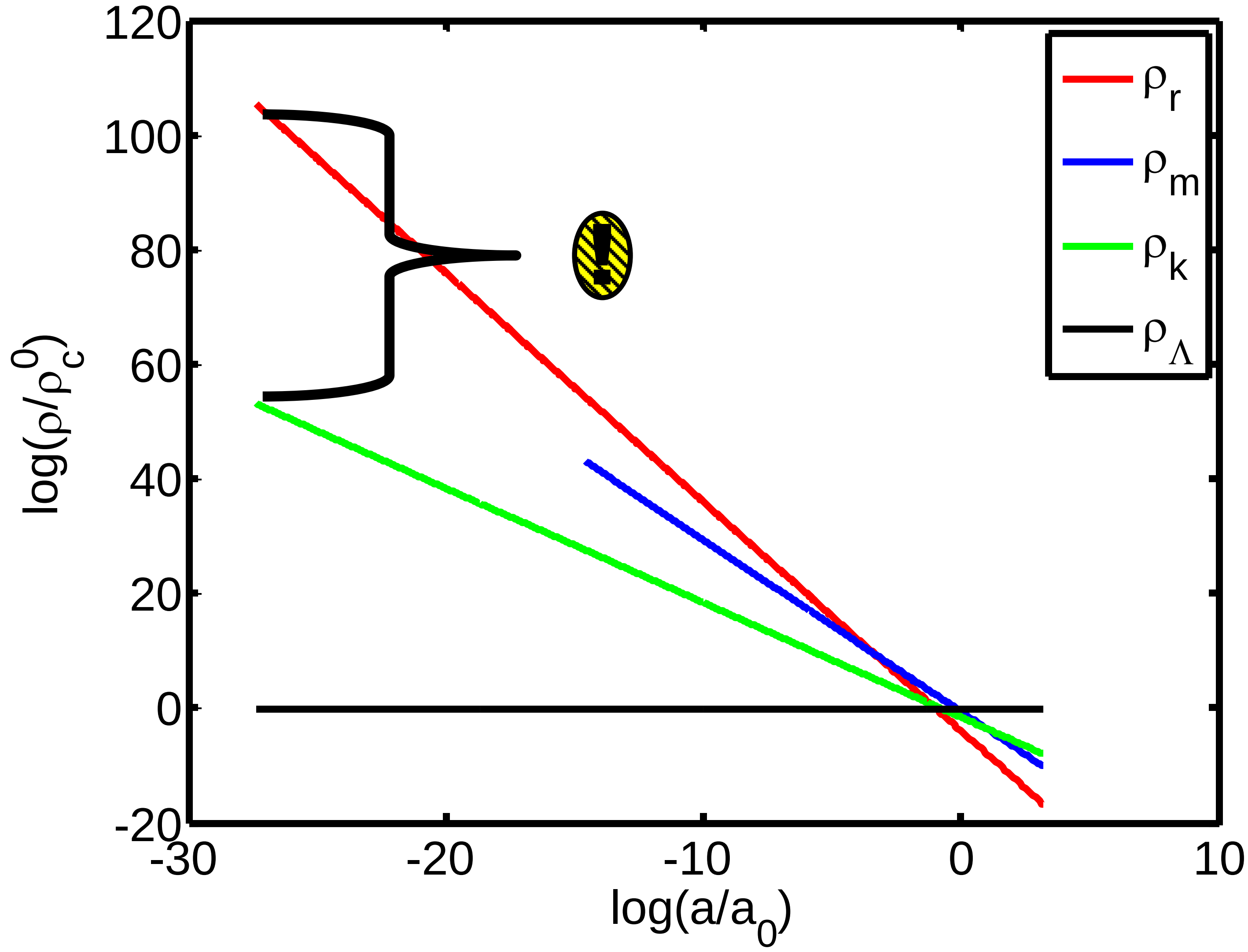
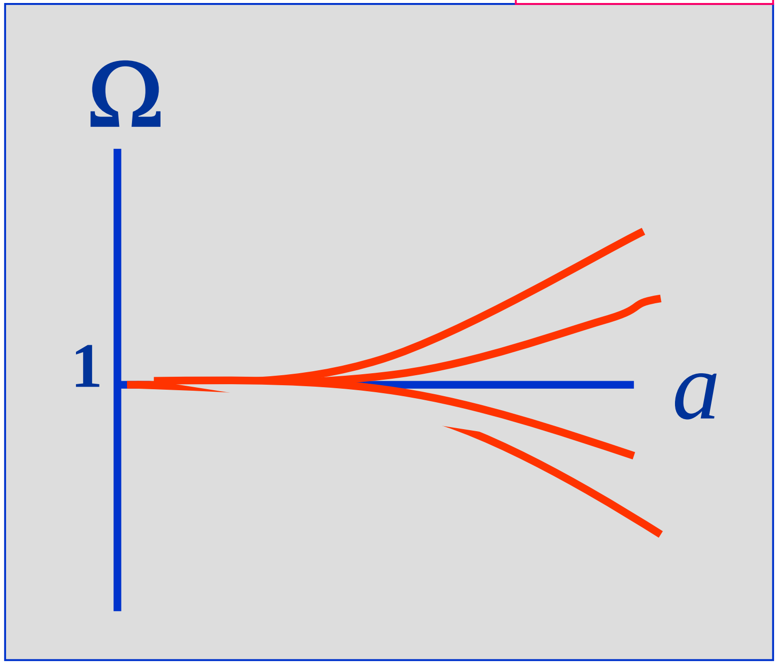


In the SBB, flatness is an "unstable fixed point":



$$\Omega \equiv \frac{\rho}{\rho_c}$$

$$\rho_c \equiv \frac{3H^2}{8\pi}$$

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi}{3}\rho - \frac{k}{a^2}$$

$\propto a^{-3}, a^{-4}$

Dominates with time

At $T = 10^{16}\, GeV$

or $\dfrac{a}{a_0} = 10^{-28}$ The "GUT scale"

Require $\rho = \rho_c$ to 55 decimal places to get $\rho \approx \rho_c$ today

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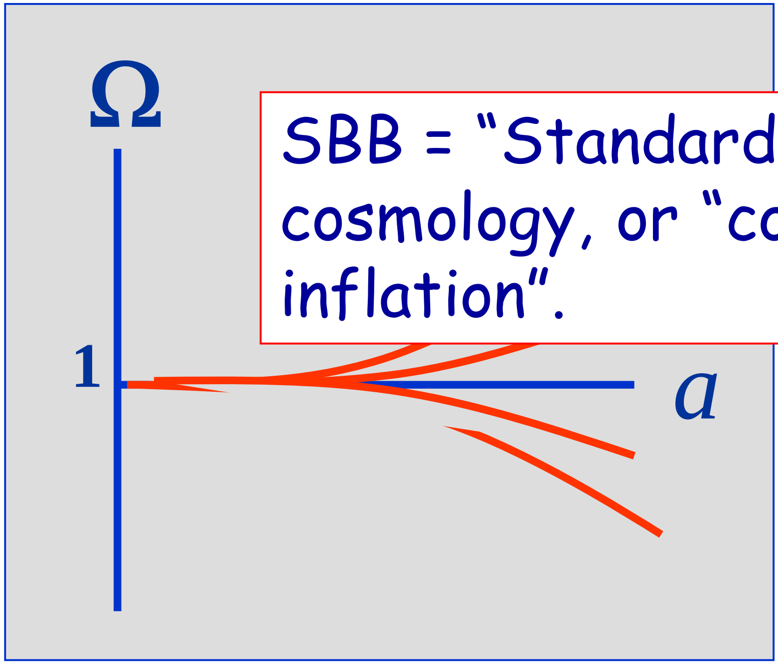

SBB = “Standard Big Bang” cosmology, or “cosmology without inflation”.

$$\rho_c \equiv \frac{3H^2}{8\pi}$$

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Gravitational instability: The Jeans Length

$$R_{Jeans} \equiv \lambda_J \equiv c_s \left(\frac{\pi c^2}{G\bar{\rho}} \right)^{1/2}$$

Sound speed

Average energy density

• Overdense regions of size $> R_{Jeans}$ collapse under their own weight.

If the size is $< R_{Jeans}$ they just oscillate

SBB Homogeneity:

On very large scales the Universe is highly homogeneous, despite the fact that gravity will clump matter on scales greater than $\mathbf{R_{Jeans}}$

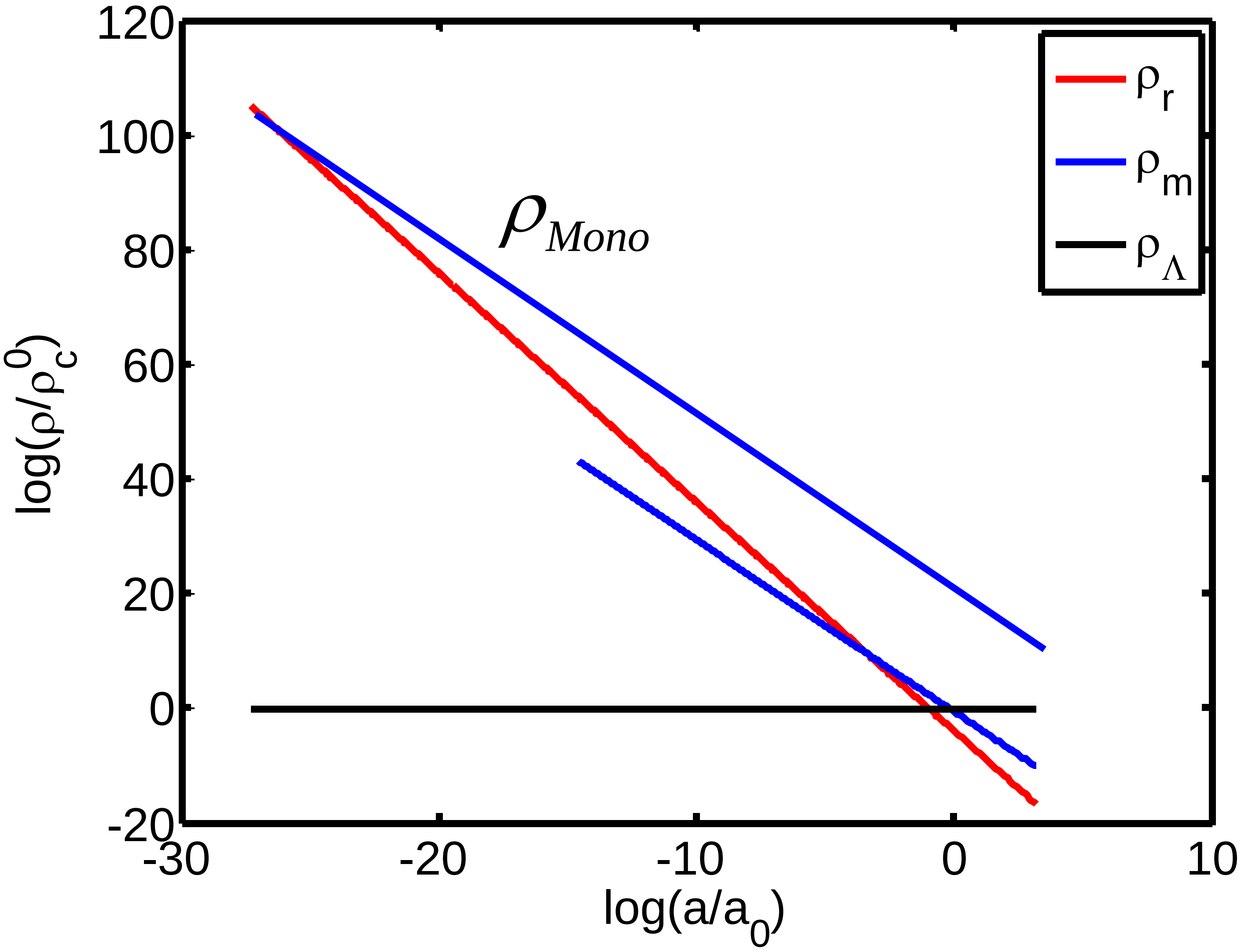
At the GUT epoch the observed Universe consisted of $\mathbf{10^{79}}$ $\mathbf{R_{Jeans}}$ sized regions.

→ The Universe was *very* smooth to start with.

NB: Flatness & Homogeneity → SBB Universe starts in highly *unstable* state.

$$S_{Univ} \approx 10^{-35} S_{bh-Max} = 10^{-35} 4\pi M_{Univ}^{2}$$

The monopole "problem"



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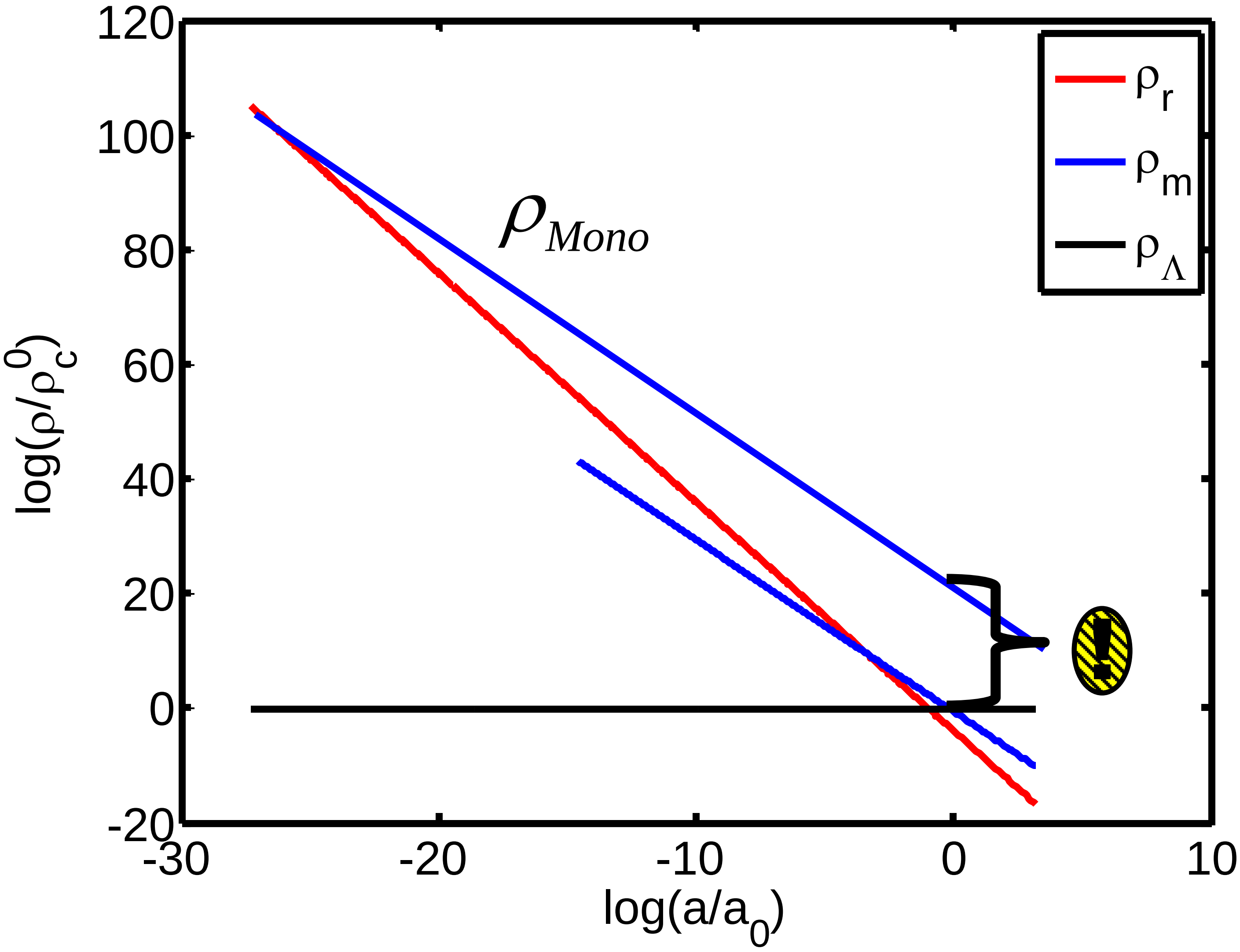


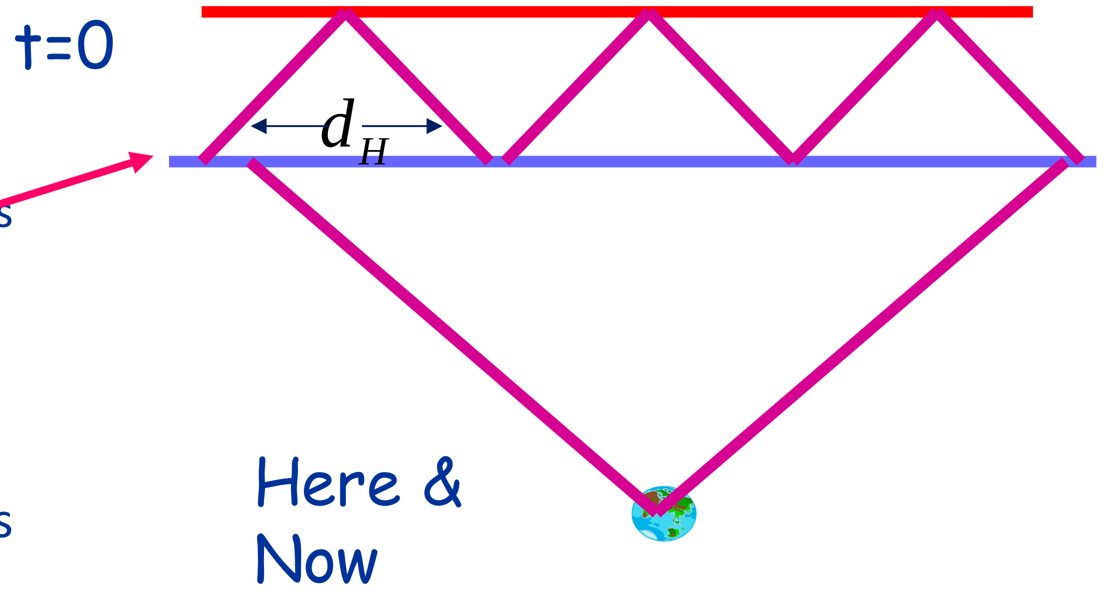
SBB Monopoles

- A GUT phase transition (or any other process) that injects stable non-relativistic matter into the universe at early times (deep in radiation era, ie $T_i = 10^{16}$ GeV) will *ruin* cosmology:

$$\left.\frac{\rho_M}{\rho_{Normal}}\right|_T = \frac{\rho_M(T_i)\left(\frac{T}{T_i}\right)^3}{\rho_{Normal}(T_i)\left(\frac{T}{T_i}\right)^4} = \left(\frac{\rho_M(T_i)}{\rho_{Normal}(T_i)}\right)\times\left(\frac{T_i}{T}\right) \longrightarrow "\infty"$$

Monopole dominated Universe

SBB Horizon



10^{80} causally disconnected regions at the GUT epoch

Horizon: The distance light has traveled since the big bang:

$$d_H = a(t)\int_0^t \frac{dt'}{a(t')}dt'$$

The flatness, homogeneity & horizon features become "problems" if one feels one must <u>explain</u> initial conditions.

Basically, the SBB says the universe must start in a highly balanced (or "fine tuned") state, like a pencil on its point.

Must/can one explain this?

Inflation says "yes"

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

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

Now add cosmic inflation

Friedmann Eqn.

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$\propto a^{\approx 0}$ (Inflaton, ρ_I)

$\propto a^{-2}$ (Curvature, ρ_k)

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

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

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

Now add cosmic inflation

Fried

Just suppose!

$\propto a^{\approx 0}$

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Inflaton

Curvature

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Dark Energy

The inflaton:

~Homogeneous scalar field ϕ obeying

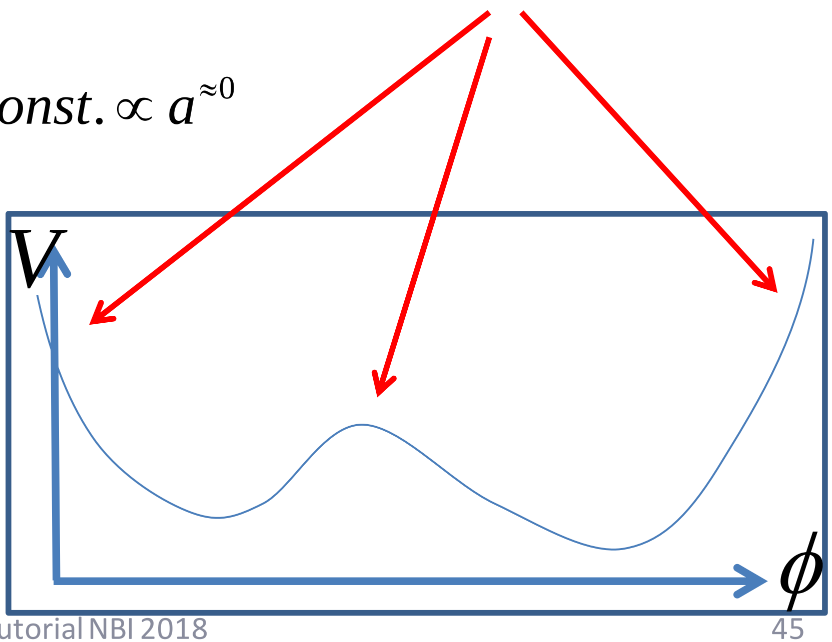
$$\ddot{\phi} + 3H\dot{\phi} = -\Gamma_{\phi}\dot{\phi} - V'(\phi)$$

Cosmic damping

Coupling to ordinary matter

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

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



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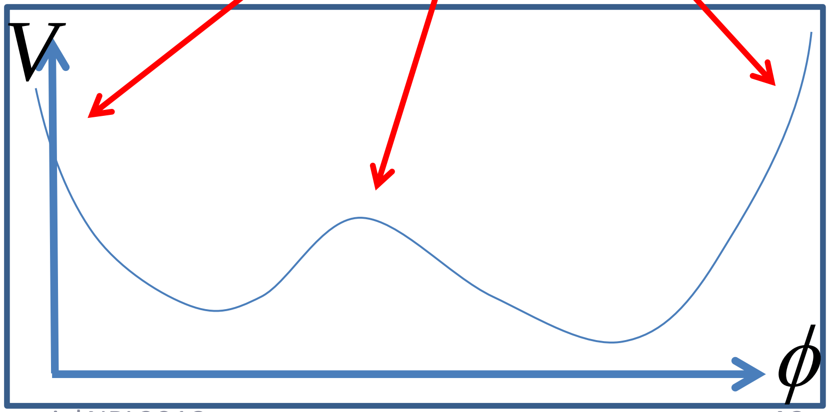
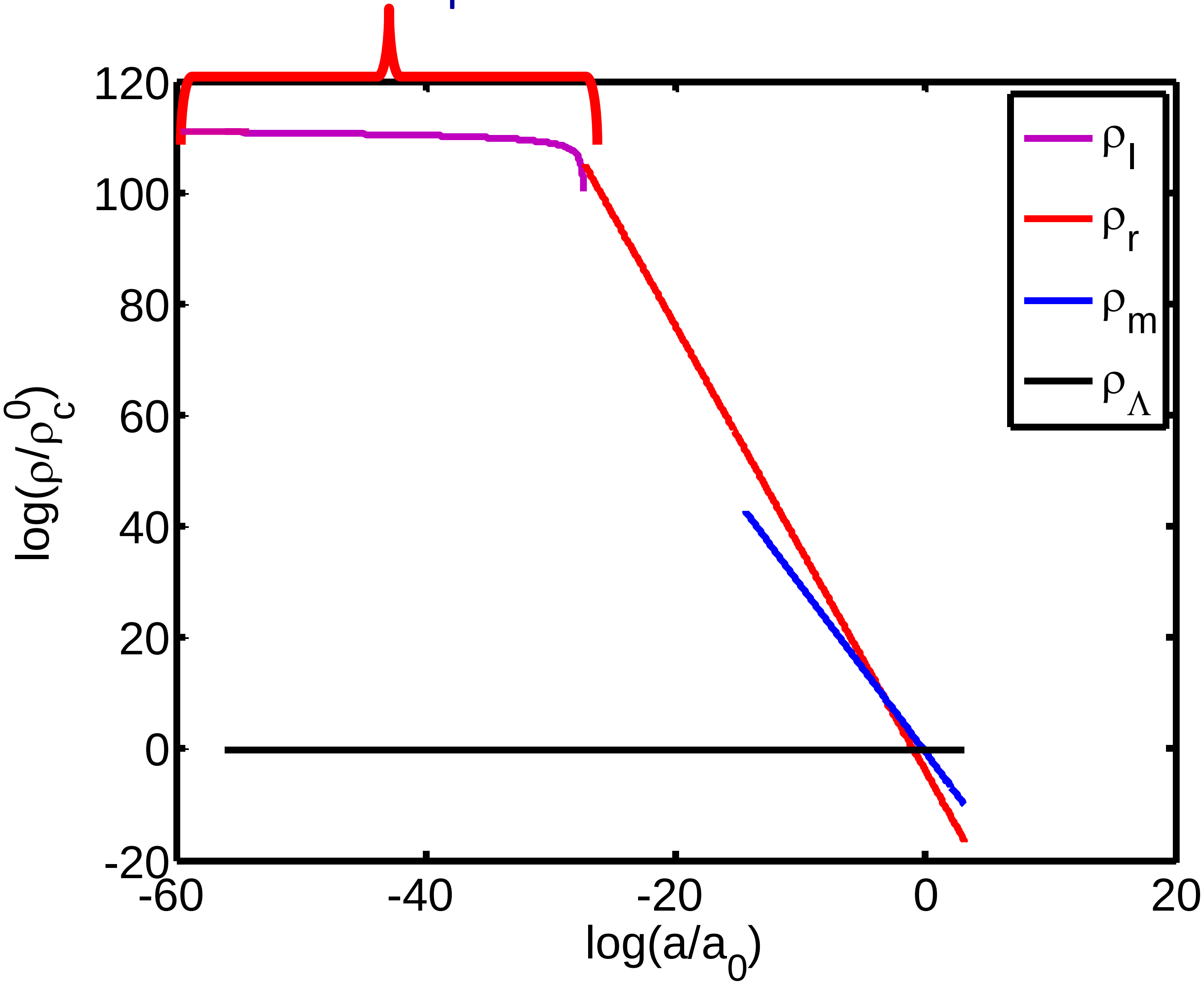
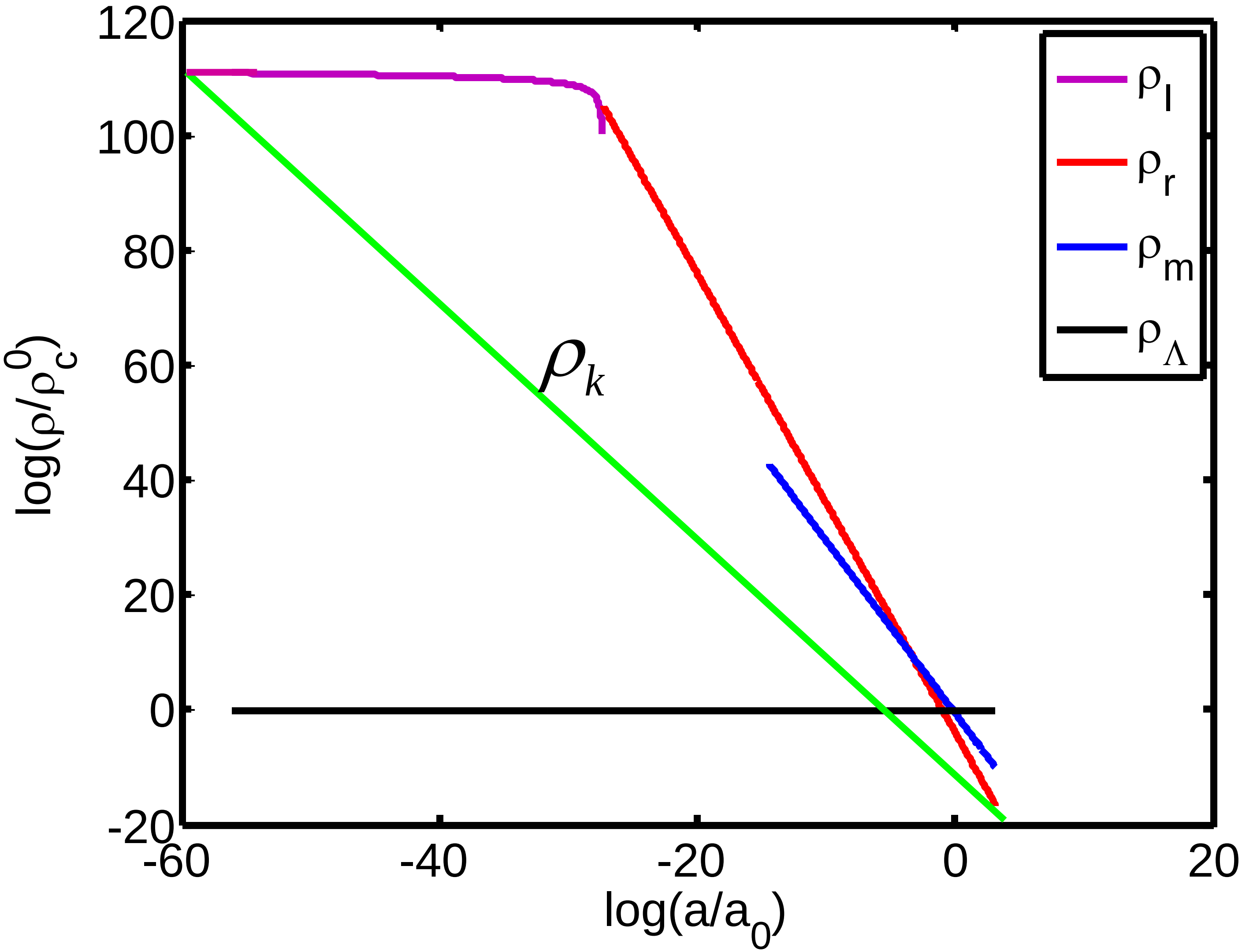


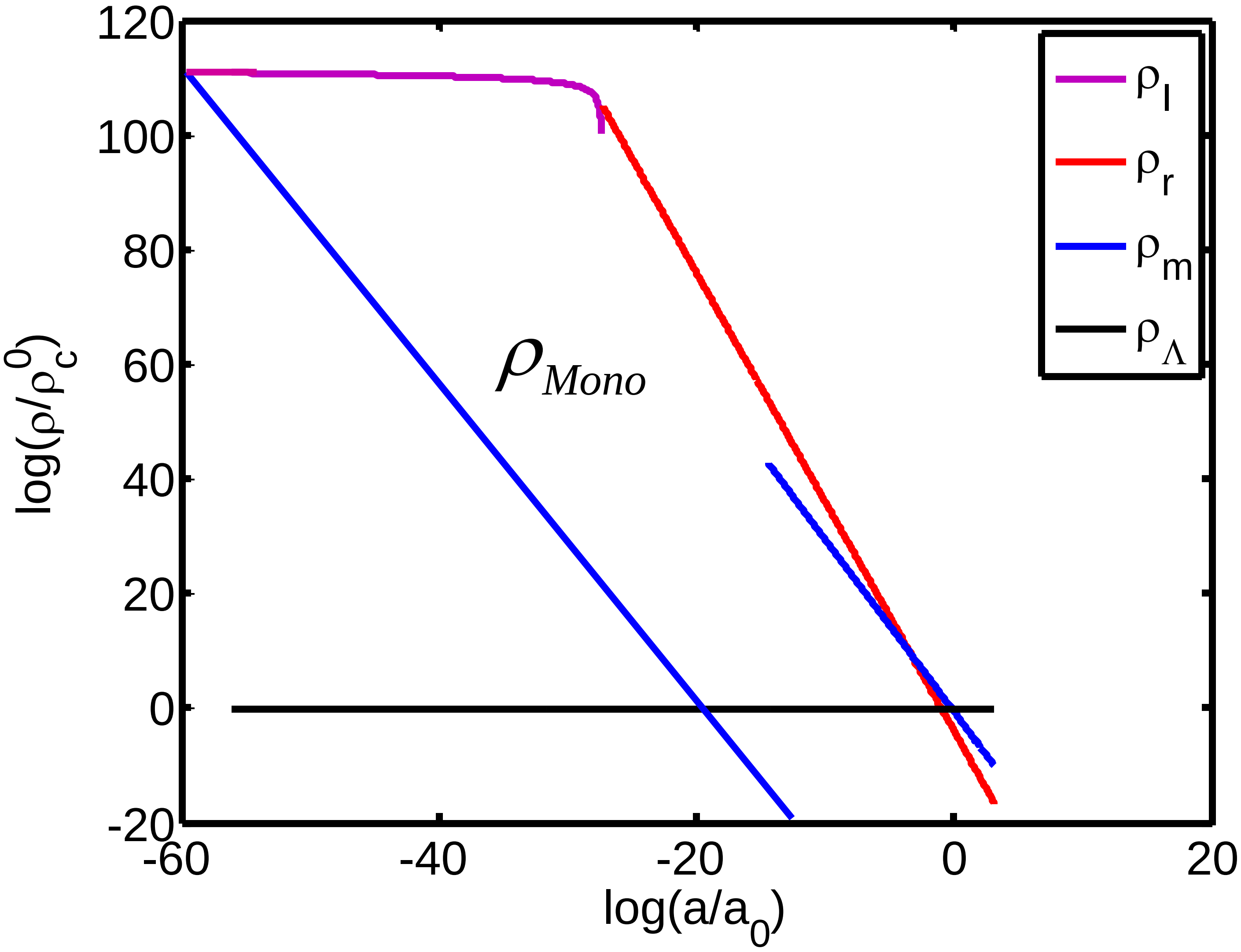
Add a period of Inflation:



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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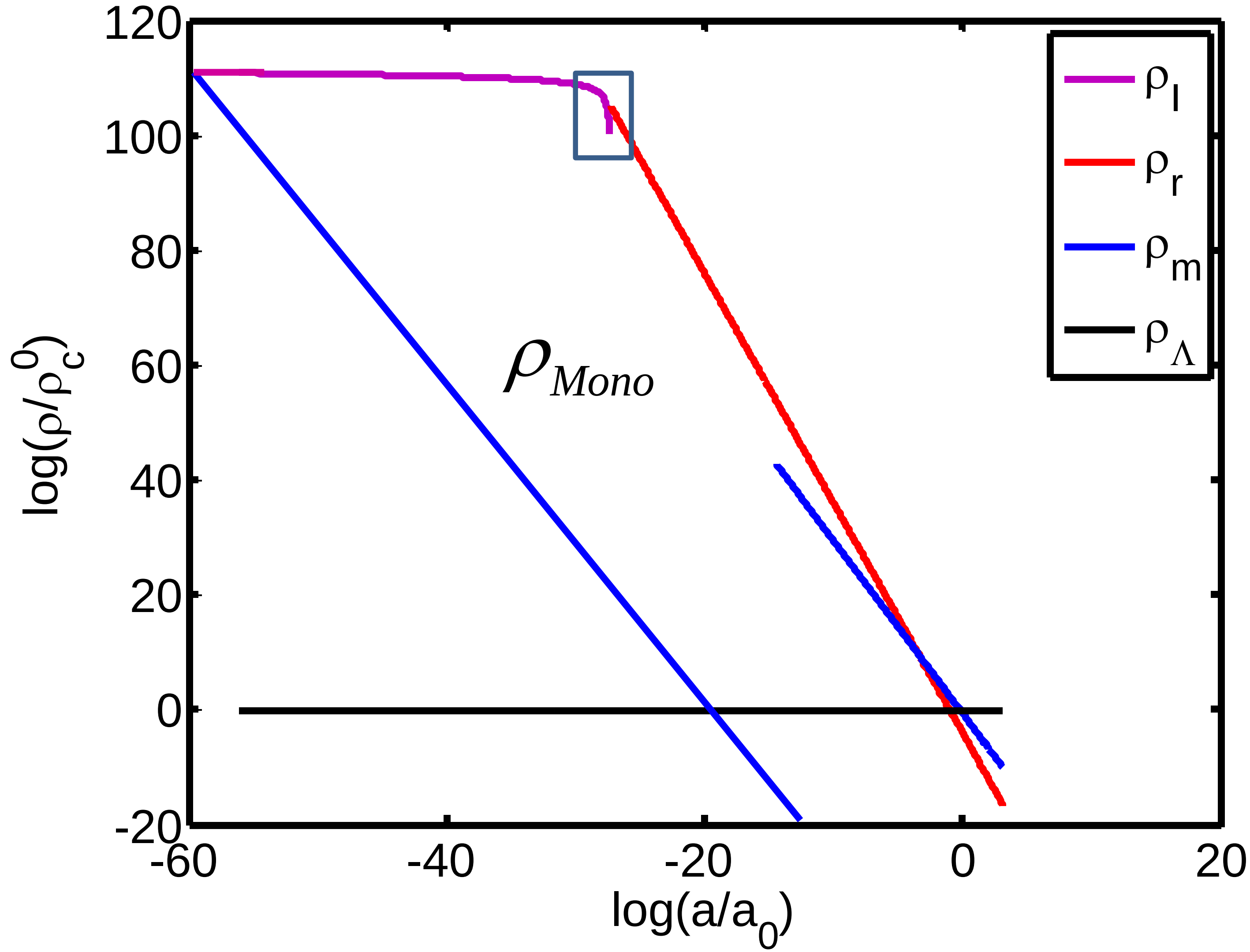
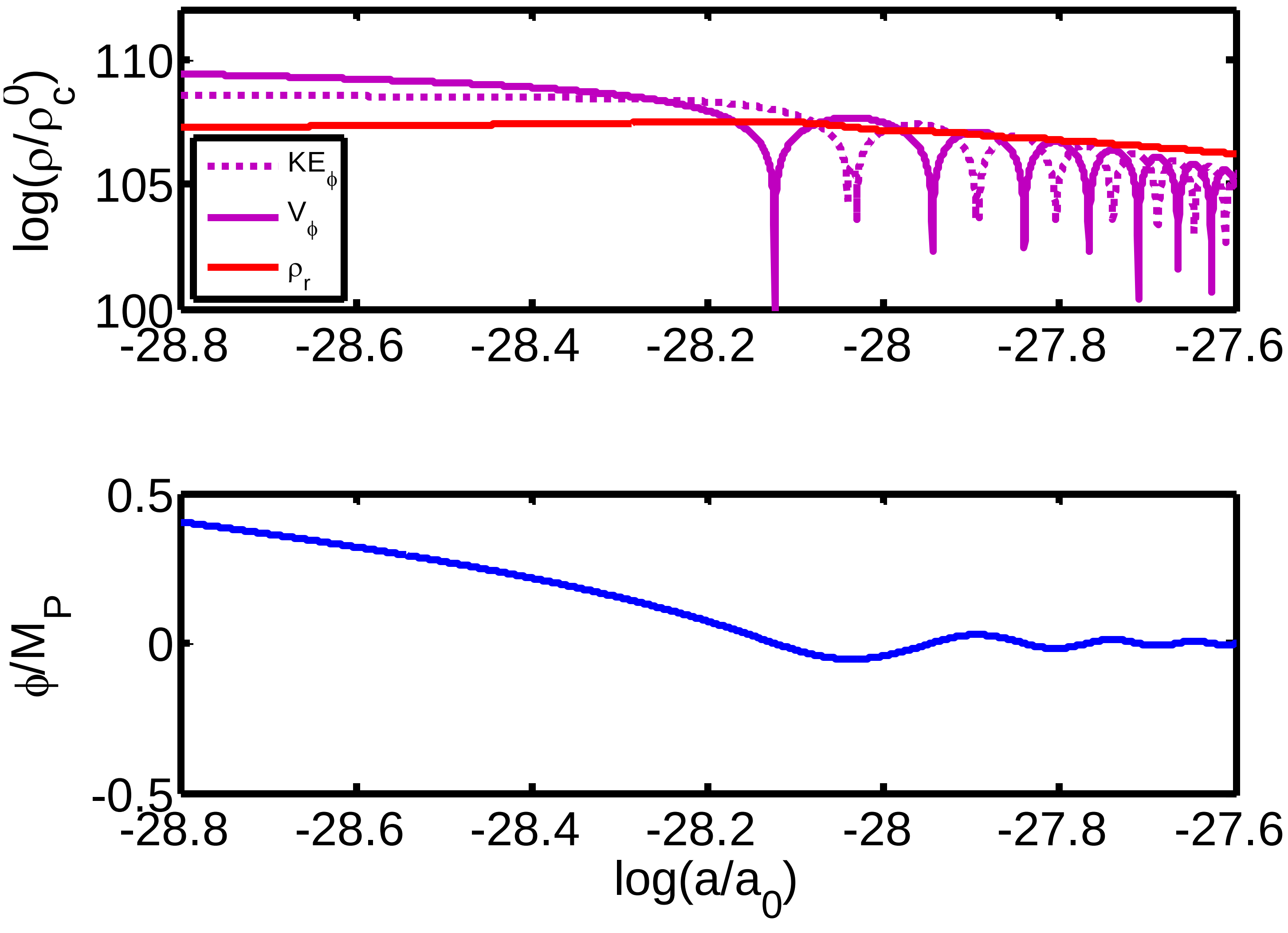


Inflation detail:



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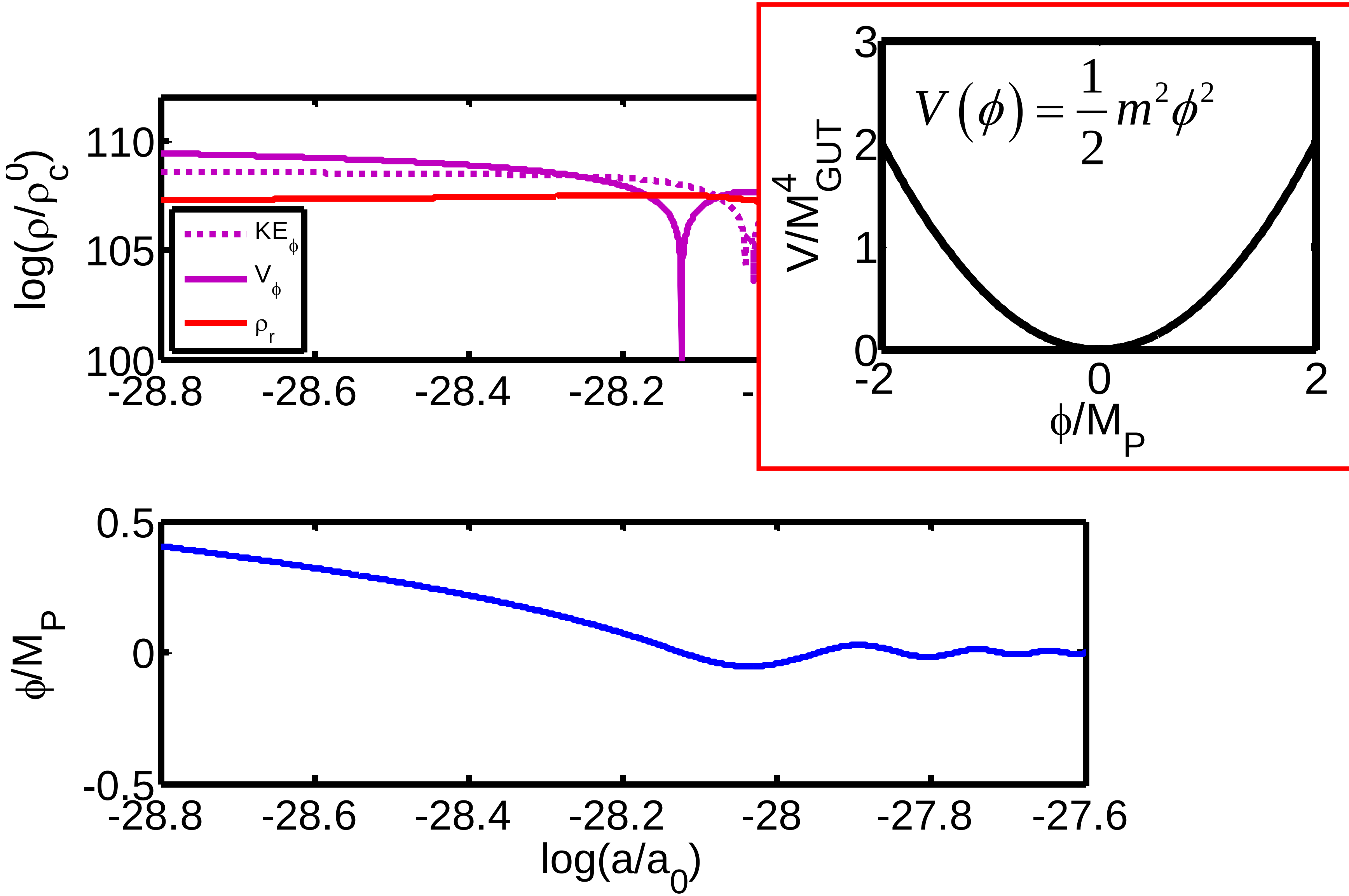

Hubble Length

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

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

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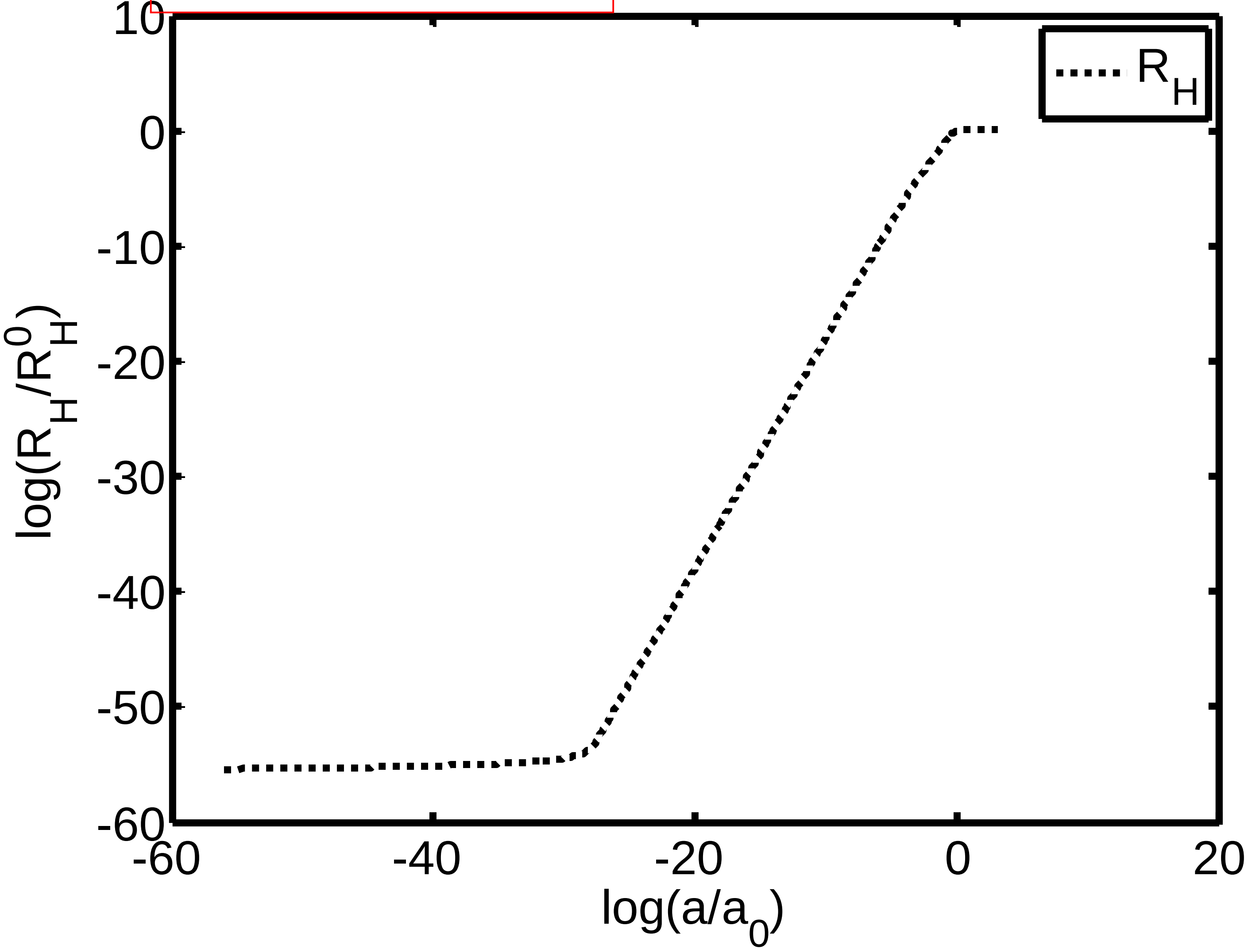
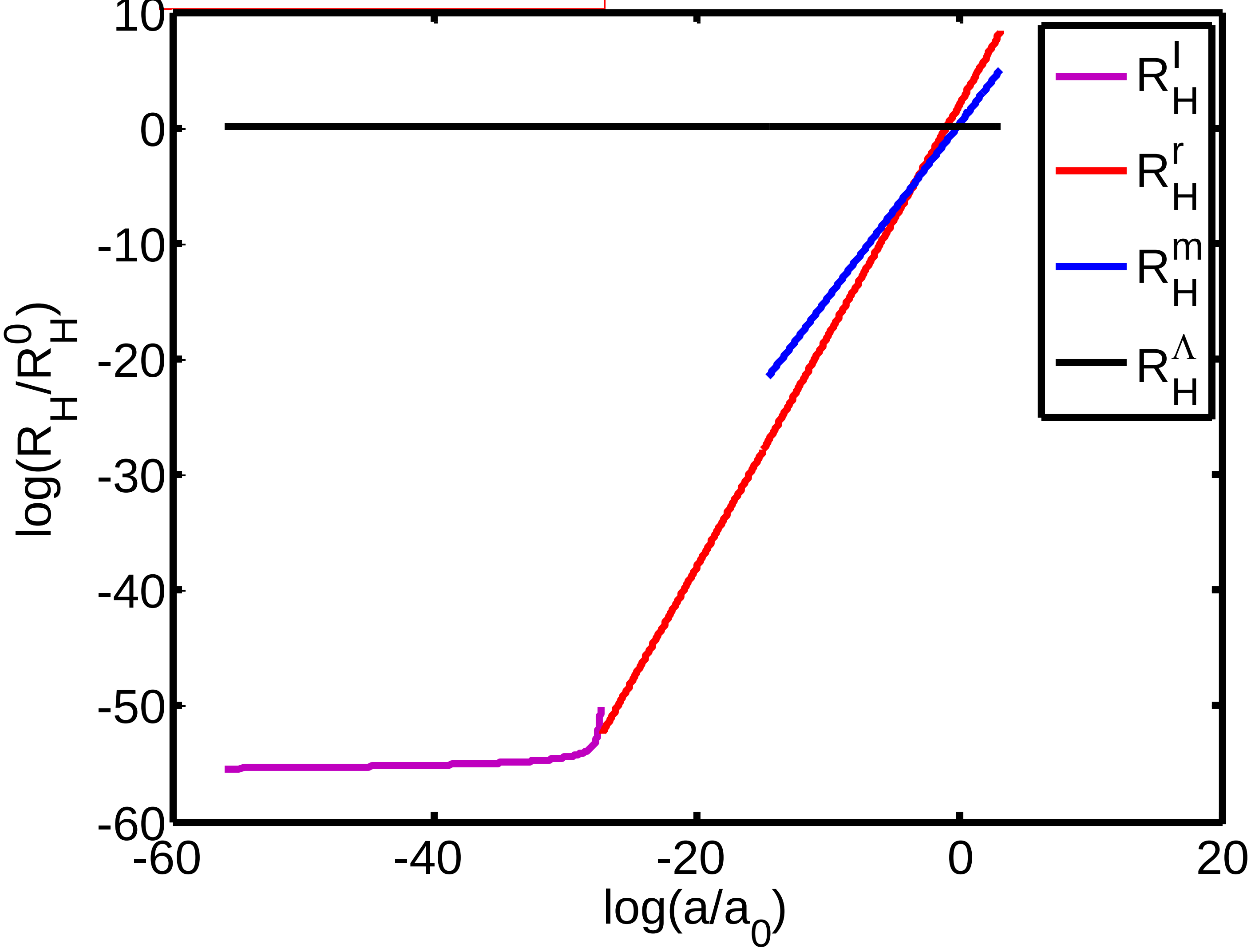


$$R_H^i \equiv \frac{c}{H_i} \propto \left(\frac{1}{\rho_i}\right)^{1/2}$$



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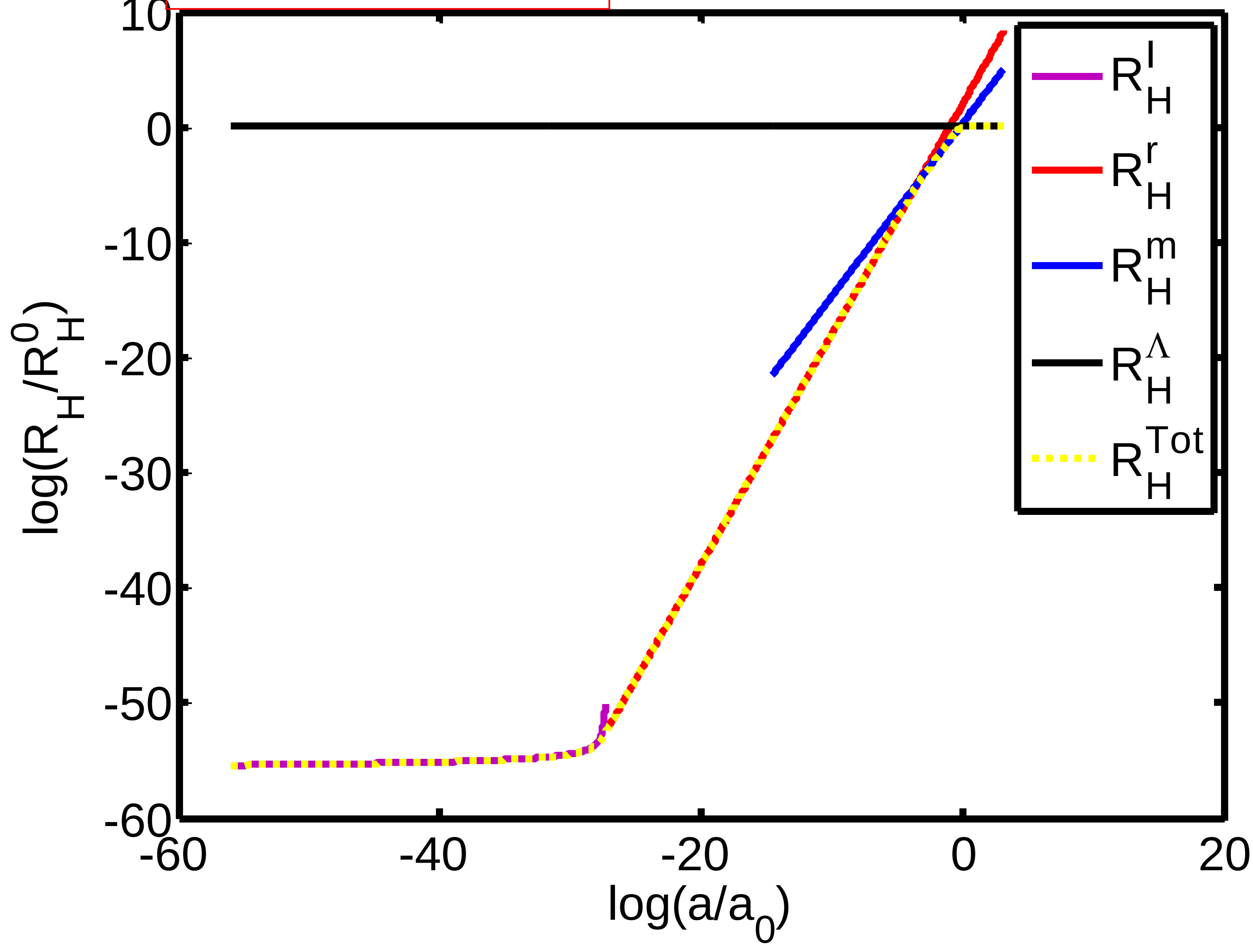

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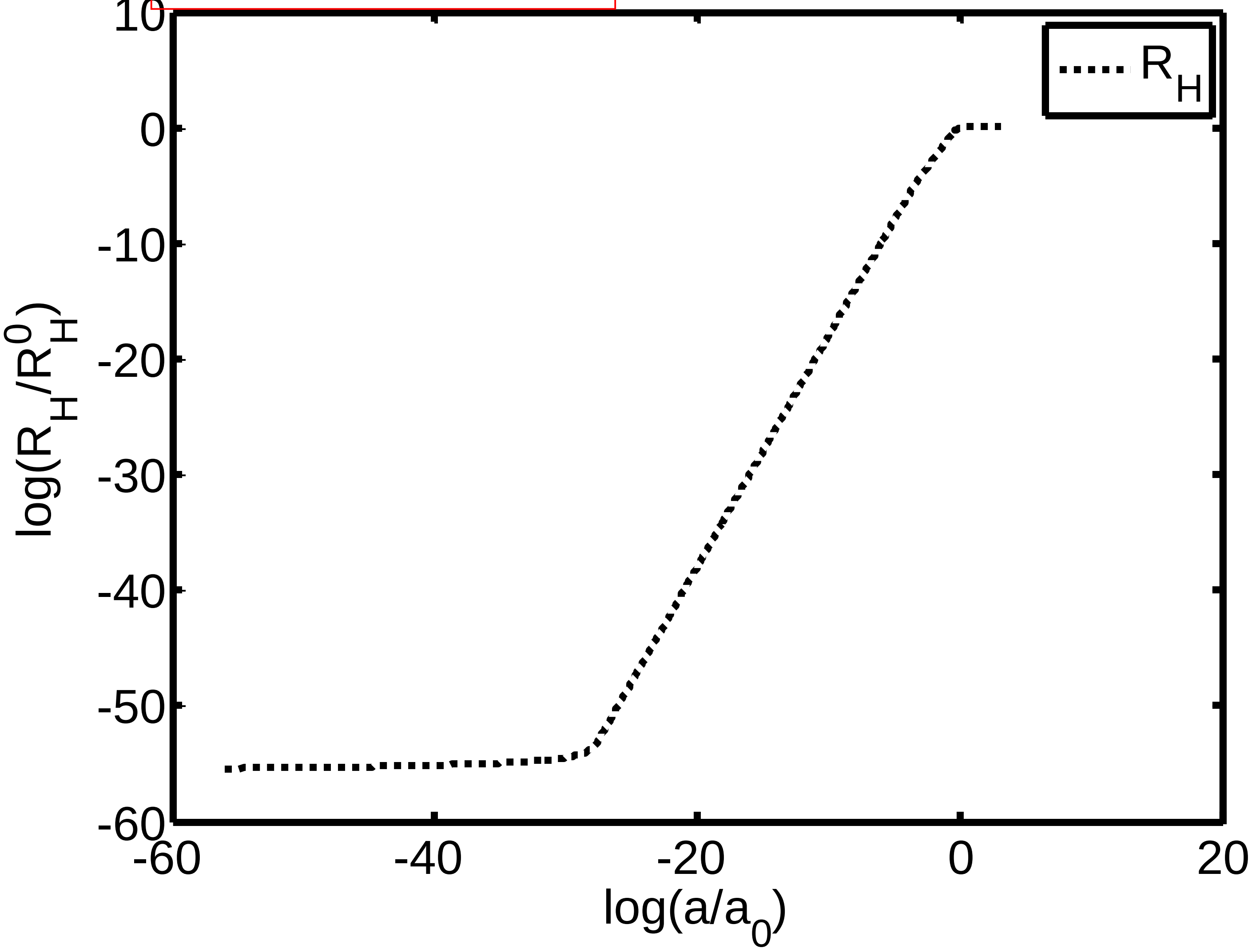
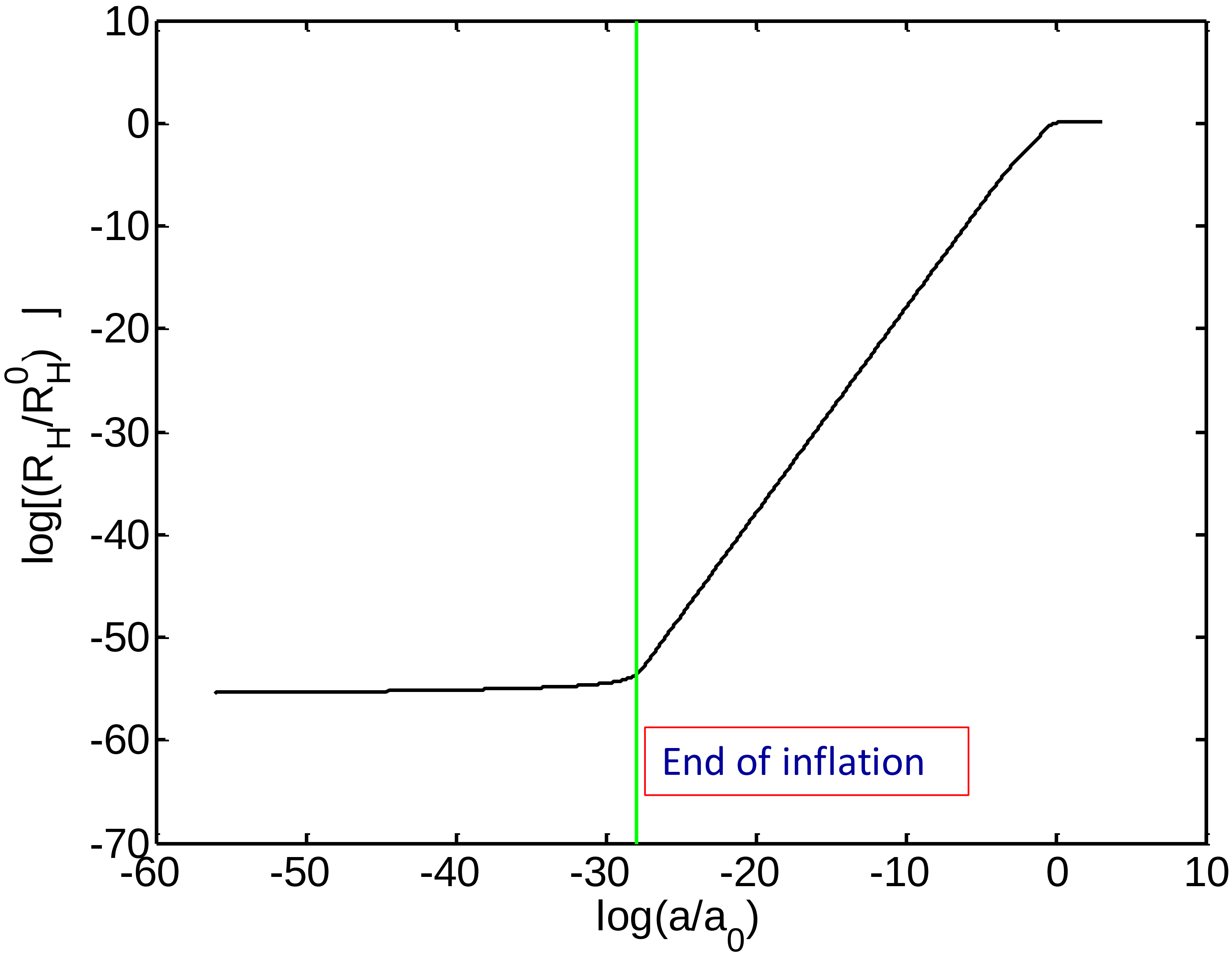


Evolution of Cosmic Length



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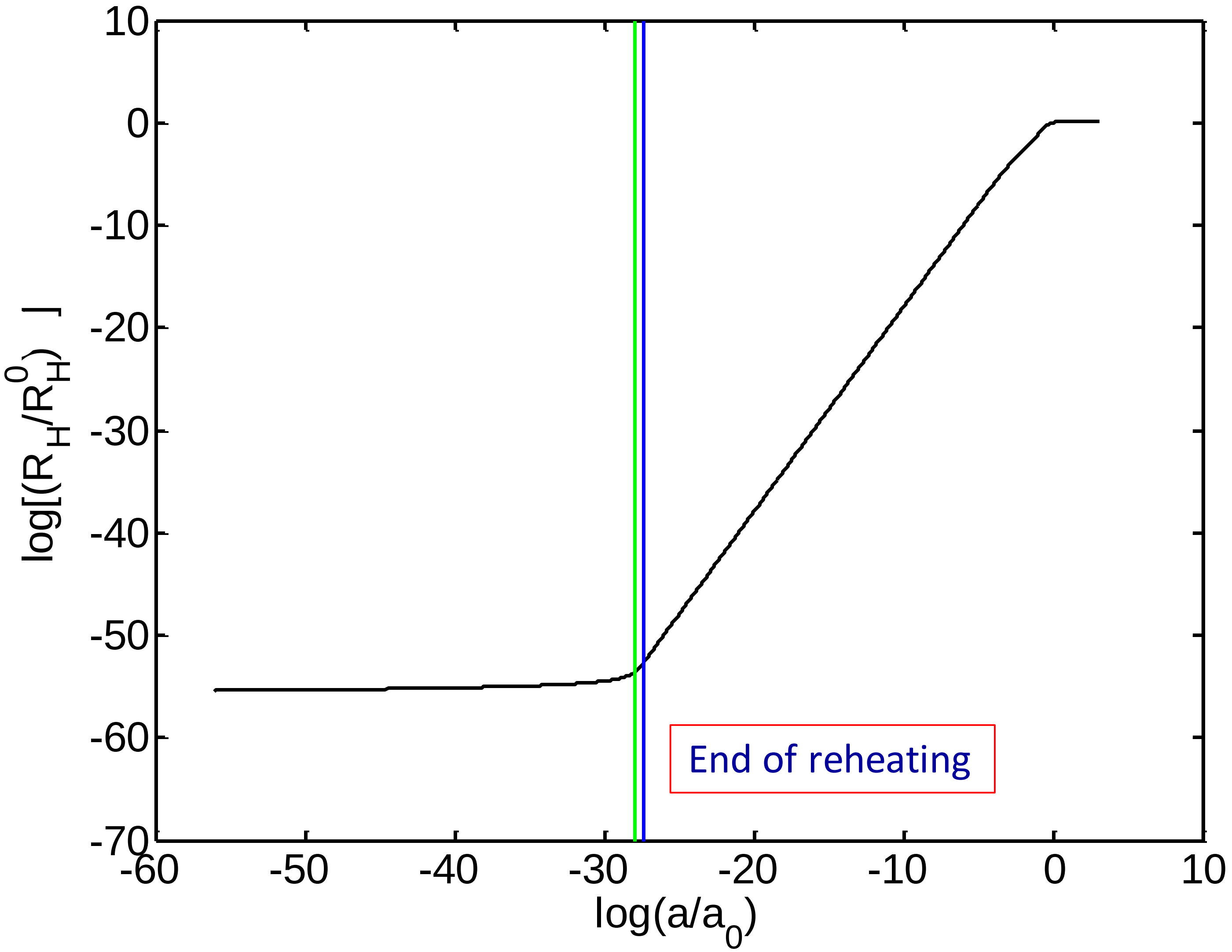

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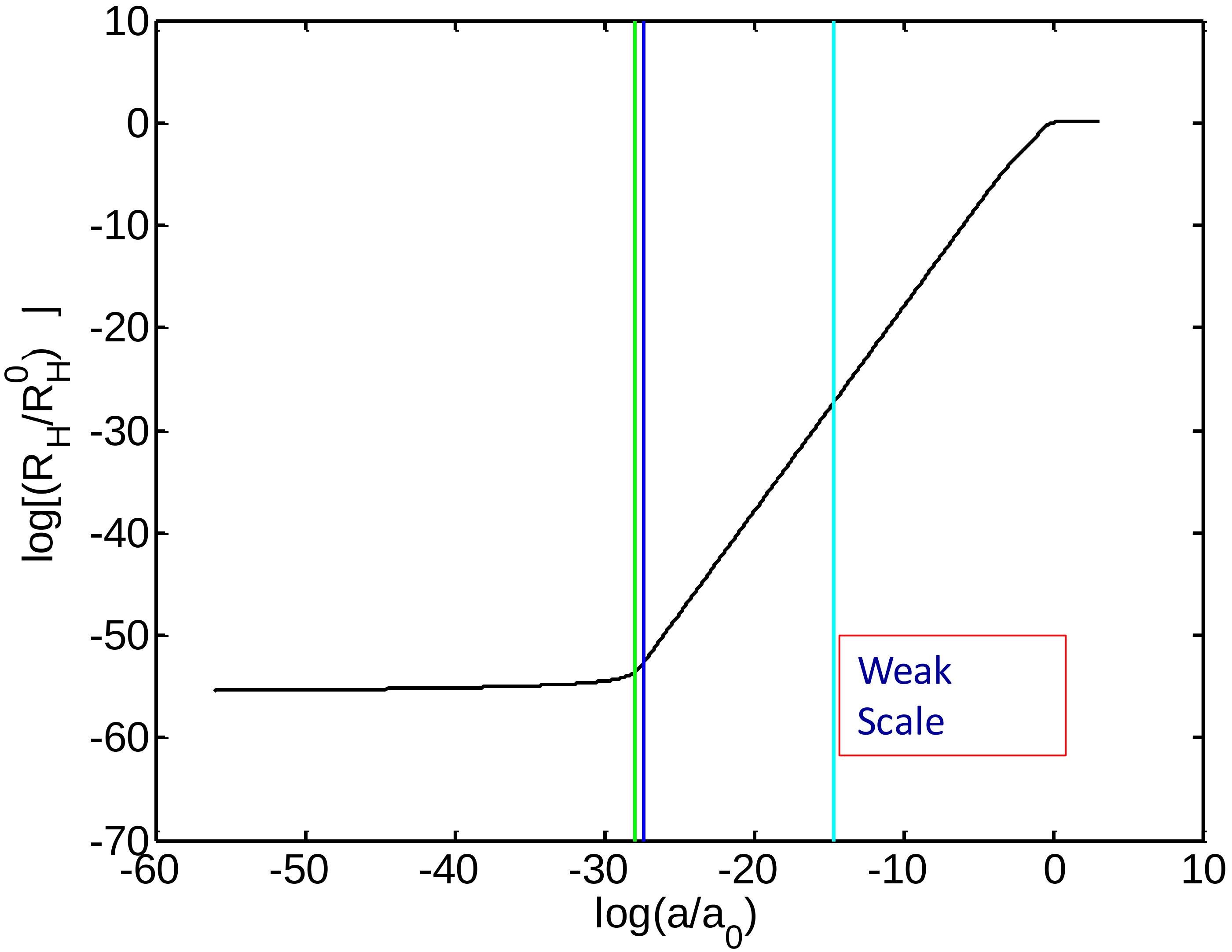

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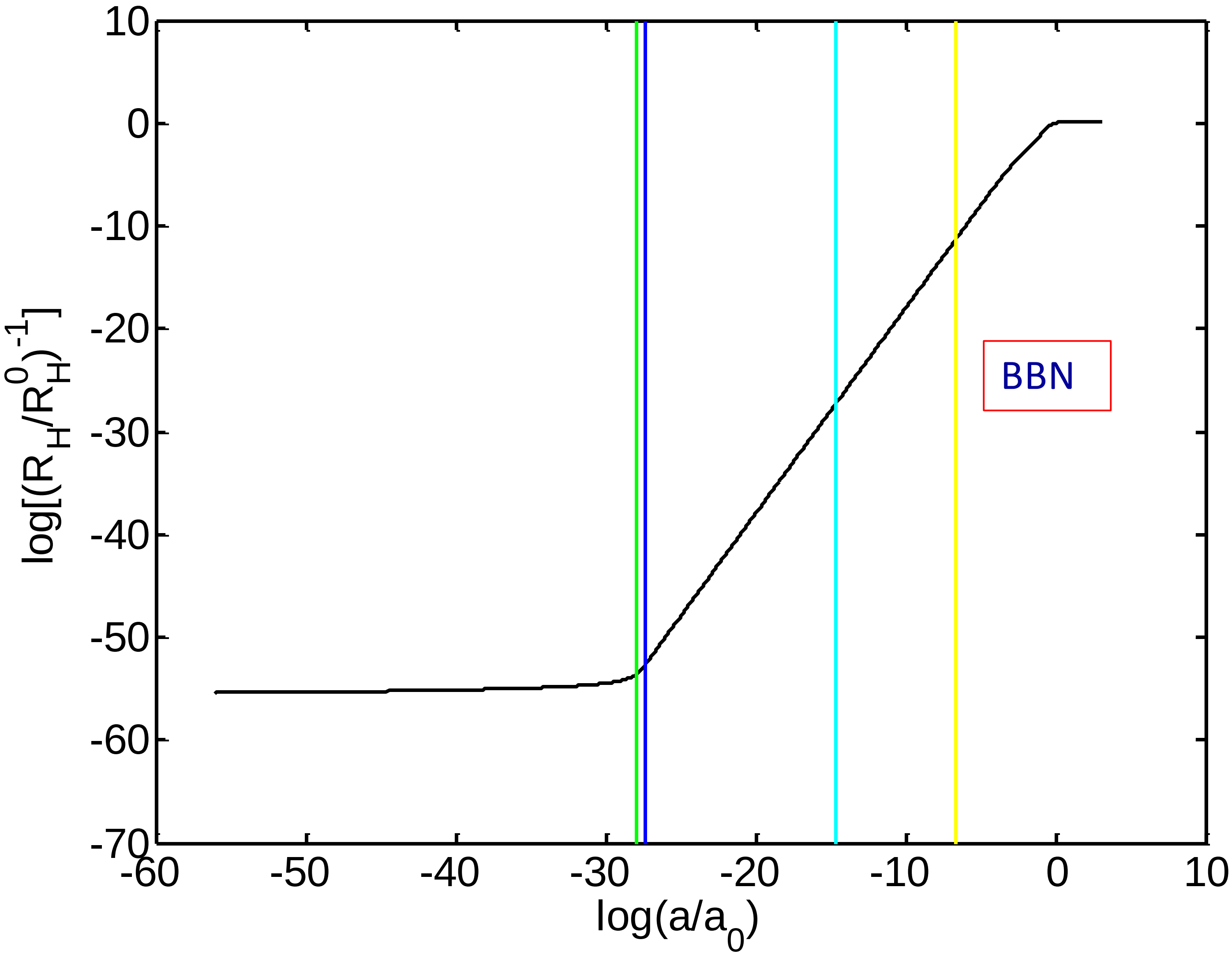

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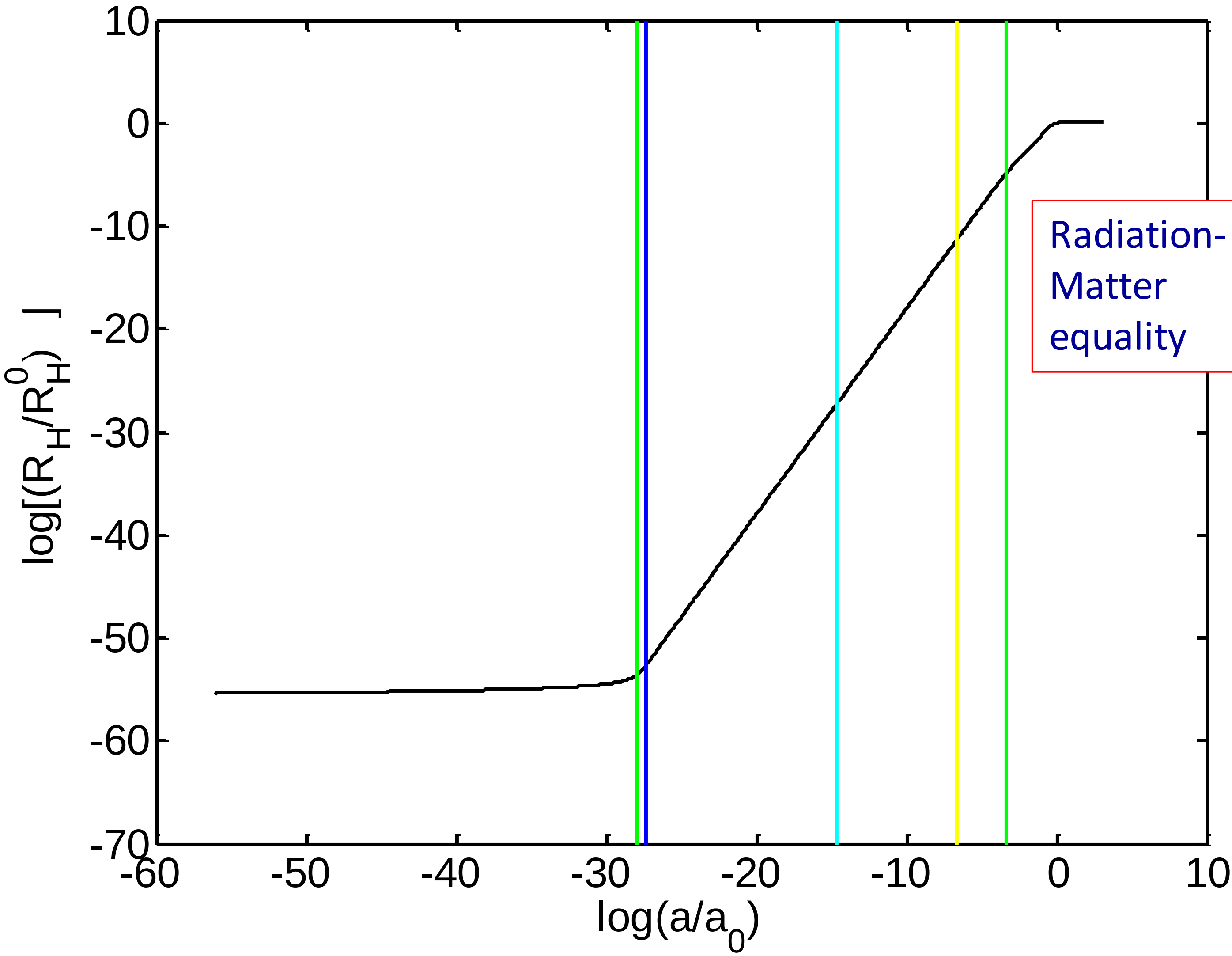
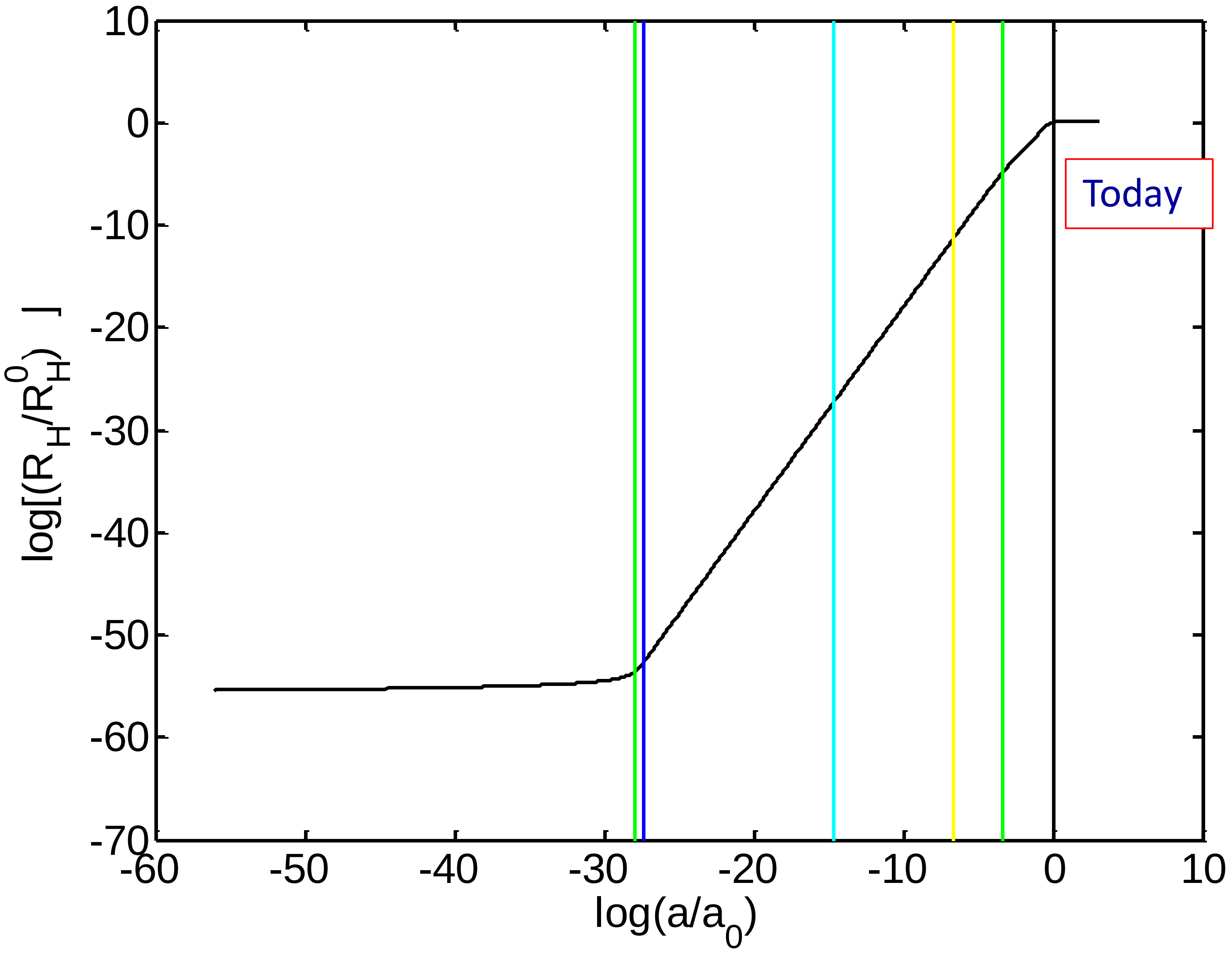
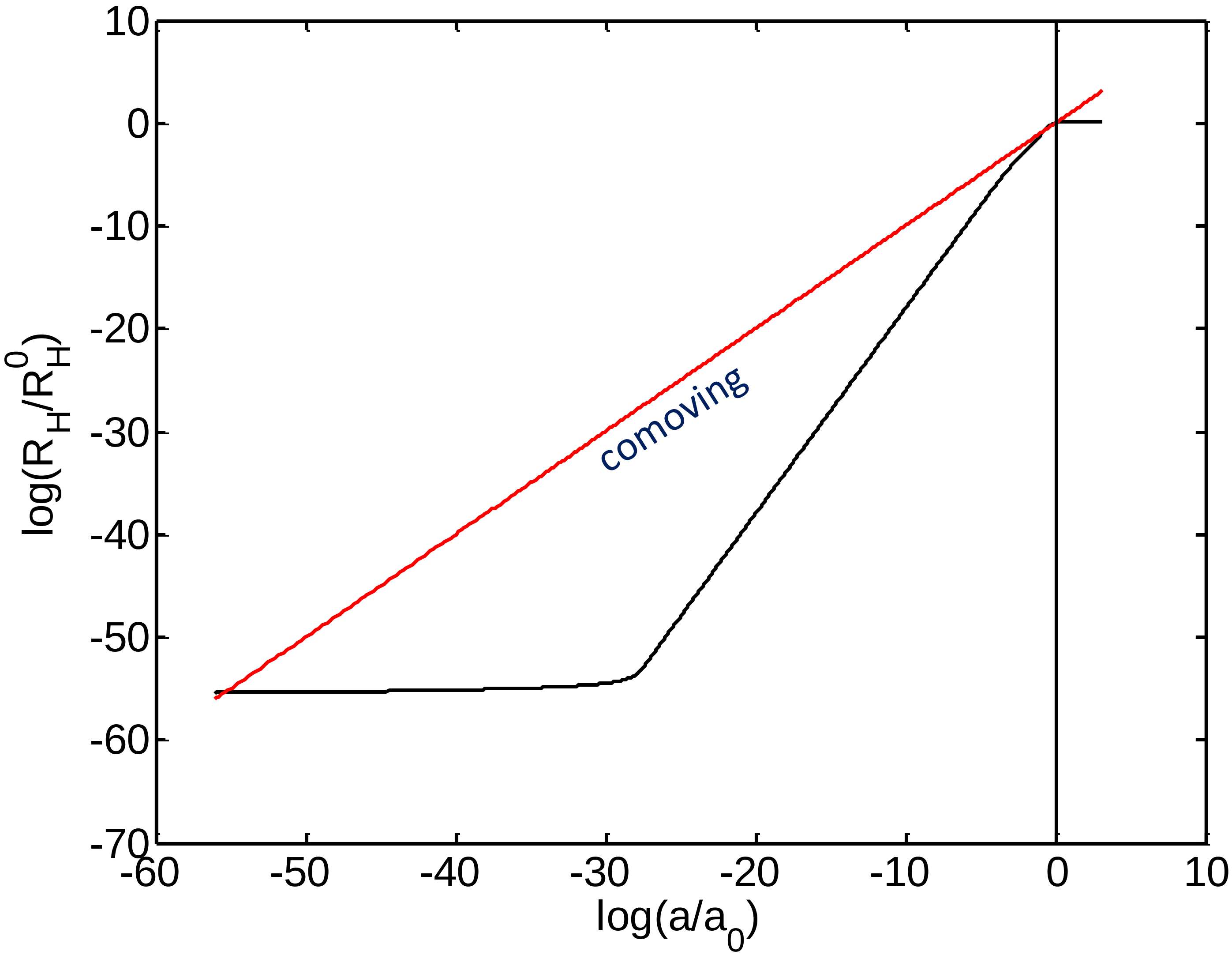


Radiation-
Matter
equality

Evolution of Cosmic Length



Perturbations from inflation



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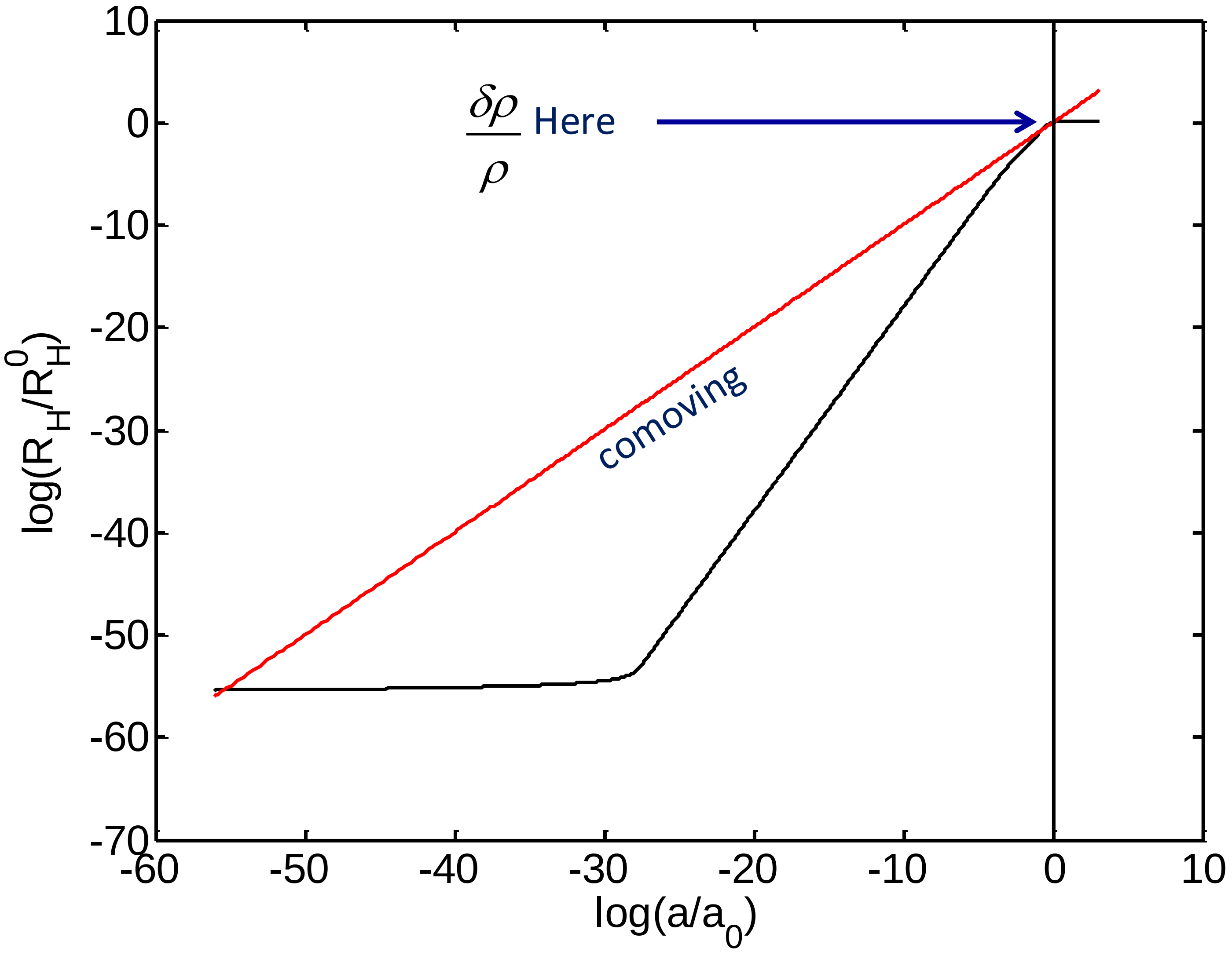

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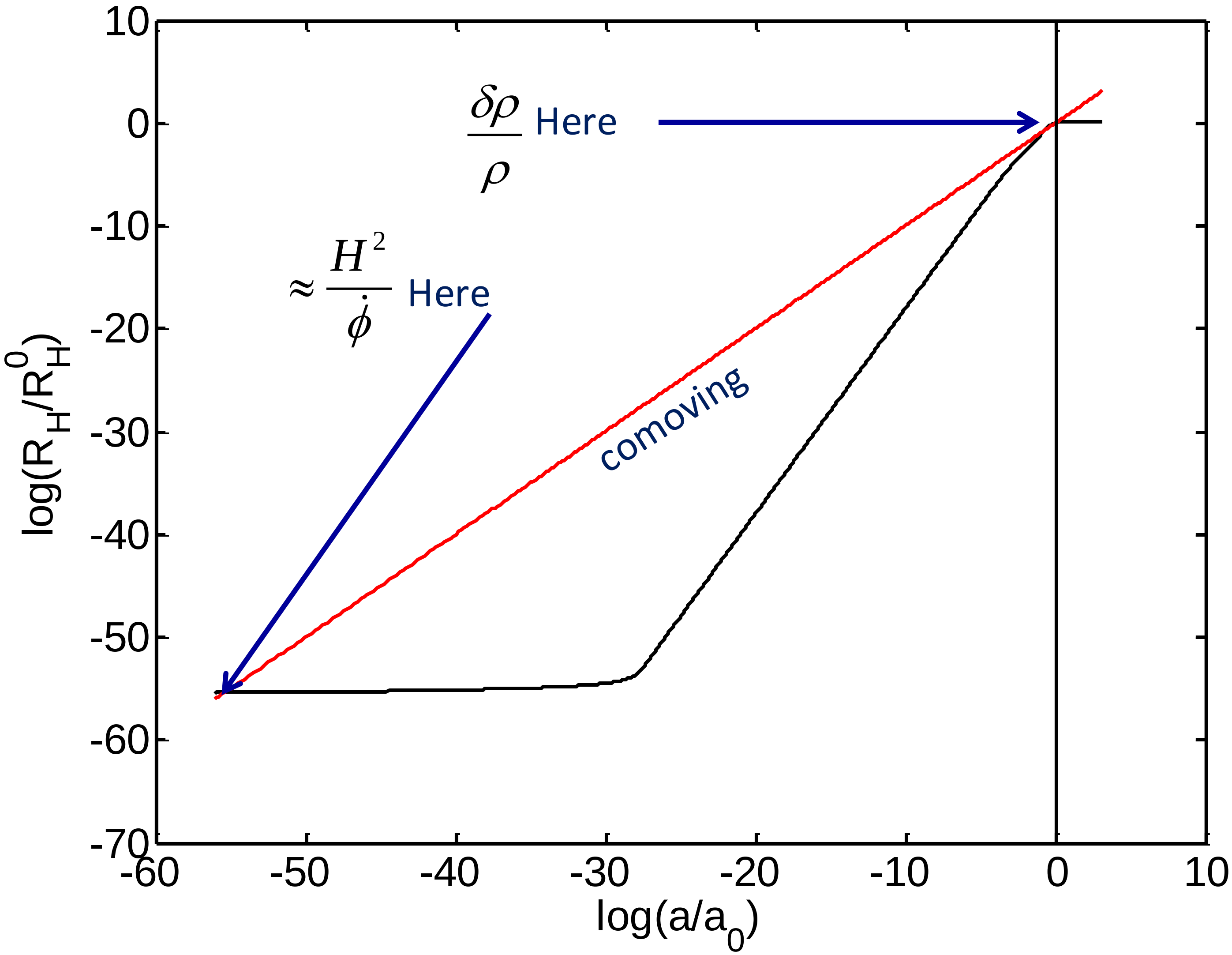
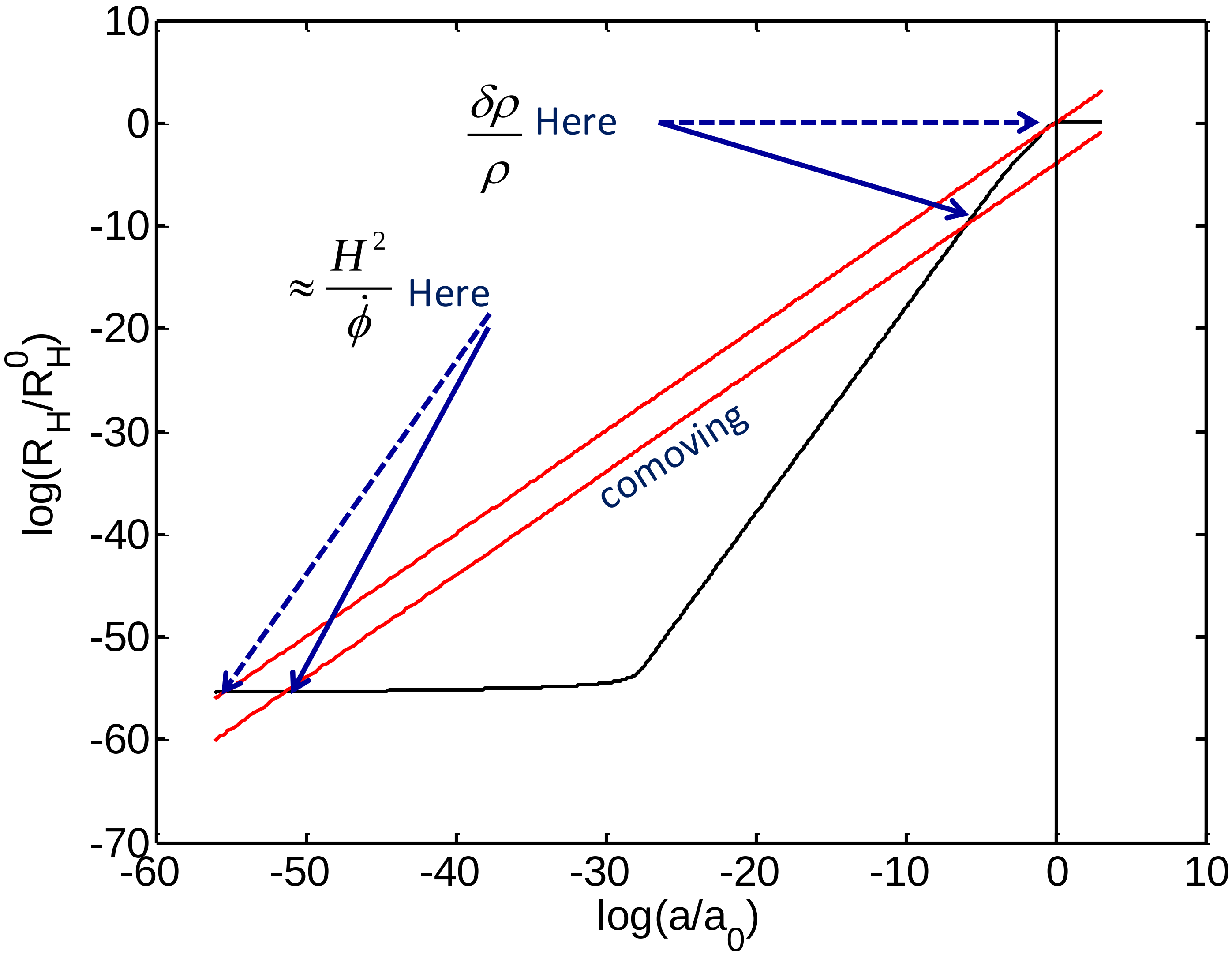
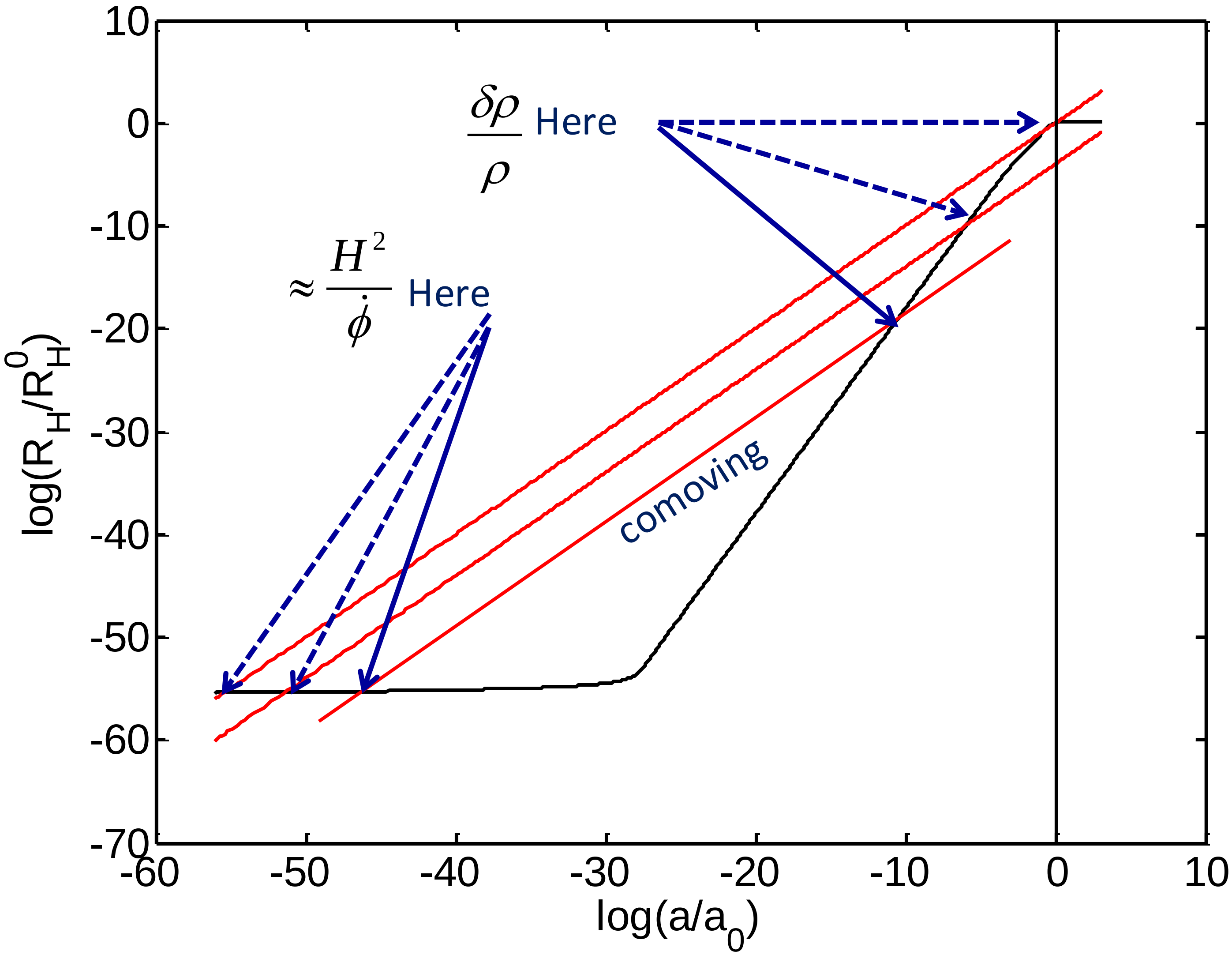




$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}}$ Here
comoving
log(R_H/R_H^0)
log(a/a_0)
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10



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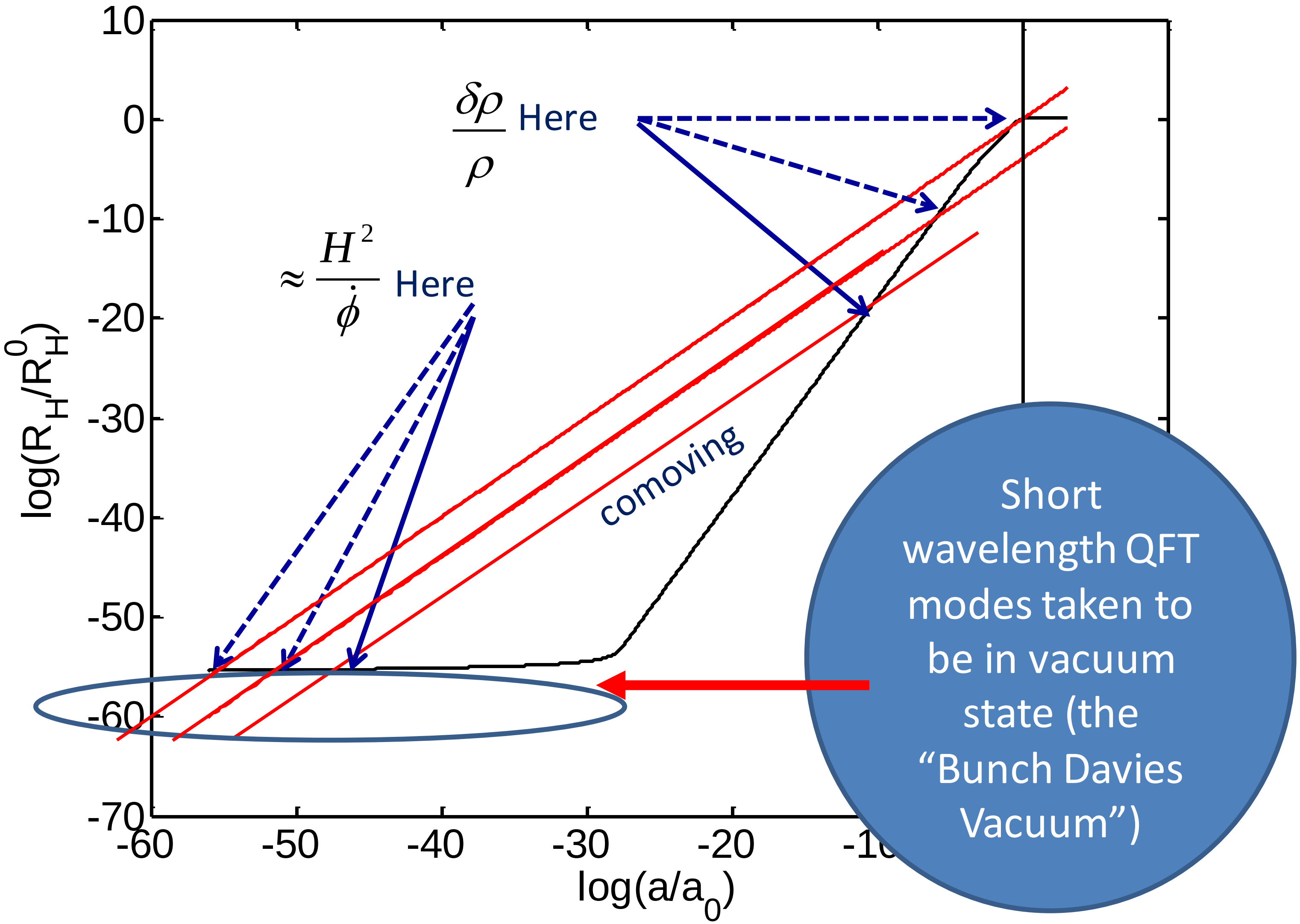
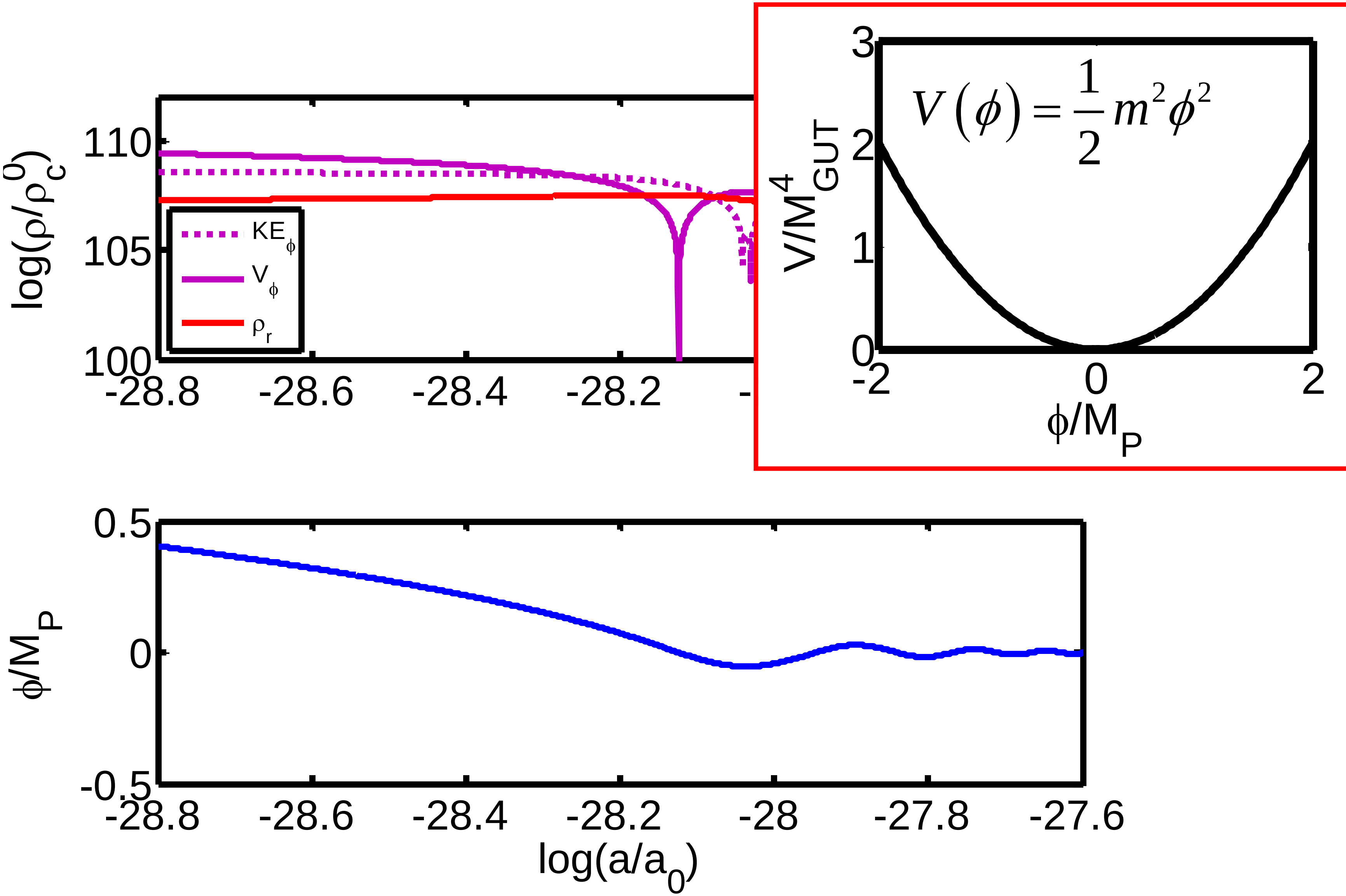
-10
0
10
$\log(R_H/R_H^0)$
$\log(a/a_0)$

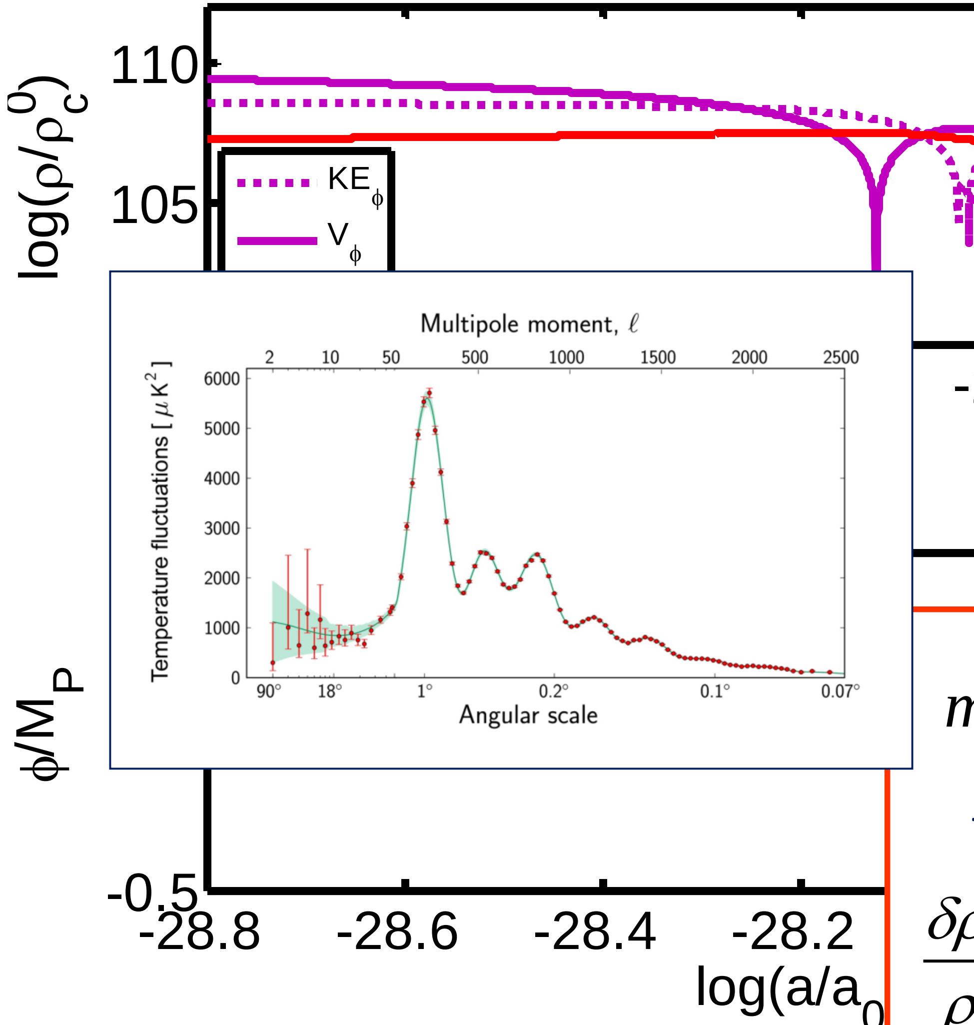


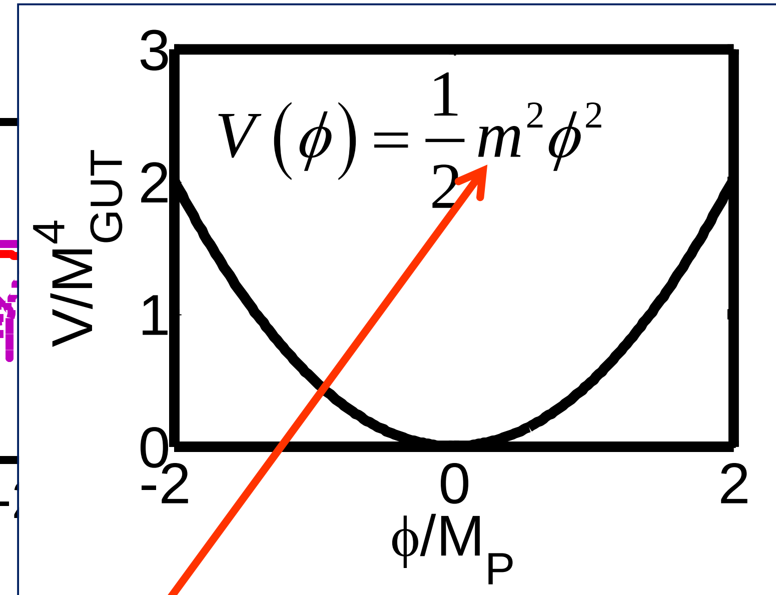
$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}}$ Here
comoving
Short wavelength QFT modes taken to be in vacuum state (the "Bunch Davies Vacuum")
log(R_H/R_H^0)
log(a/a_0)
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20

Inflation detail:



Inflation detail:



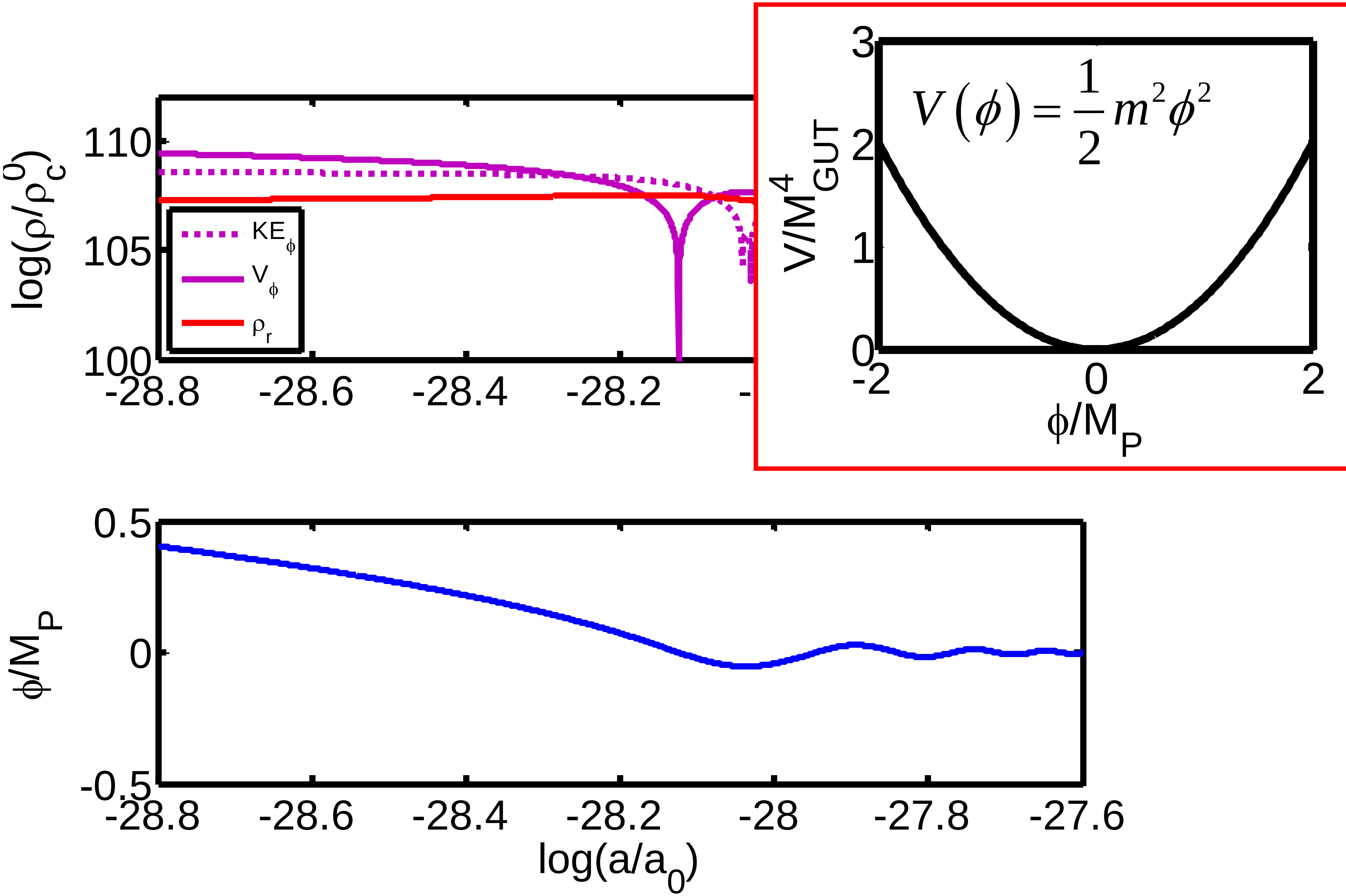


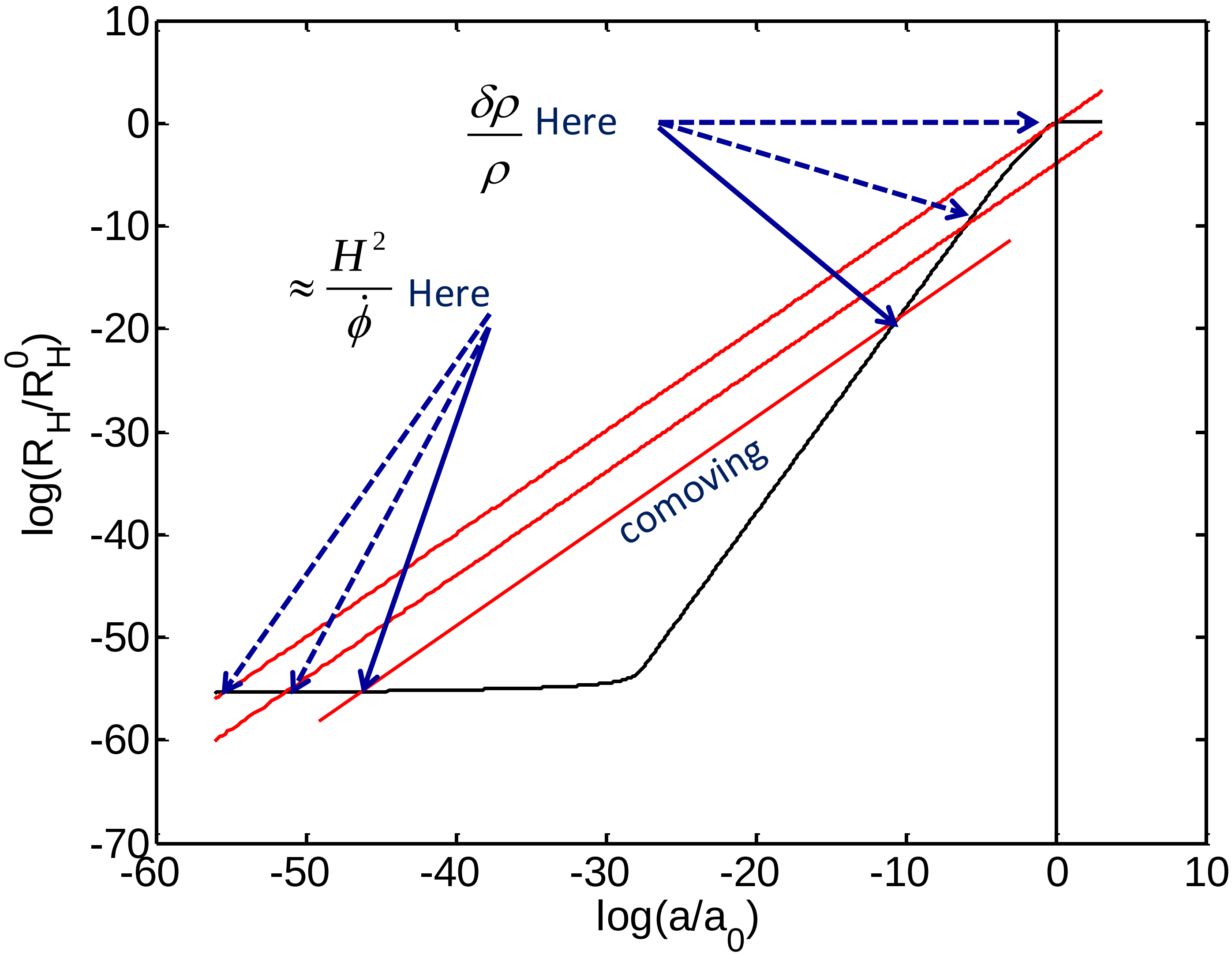
$$m = 8 \times 10^{12}\, GeV$$

to give

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

Inflation detail:




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

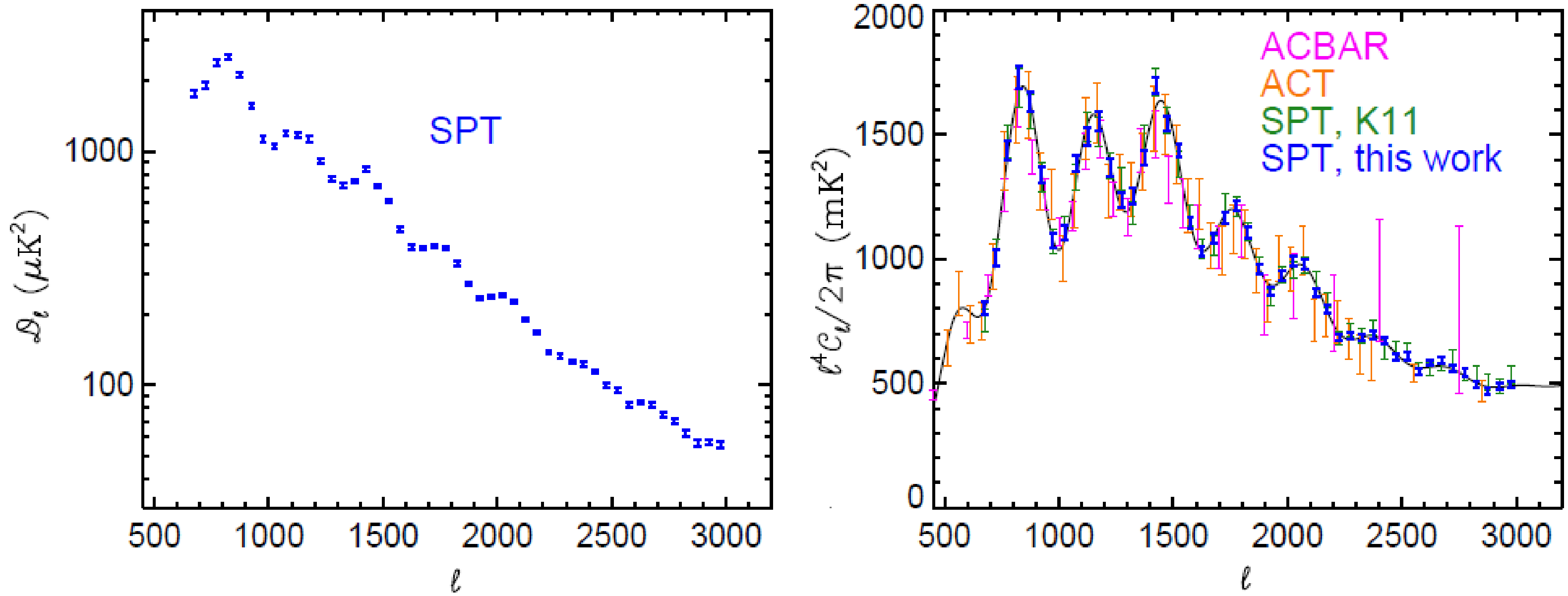


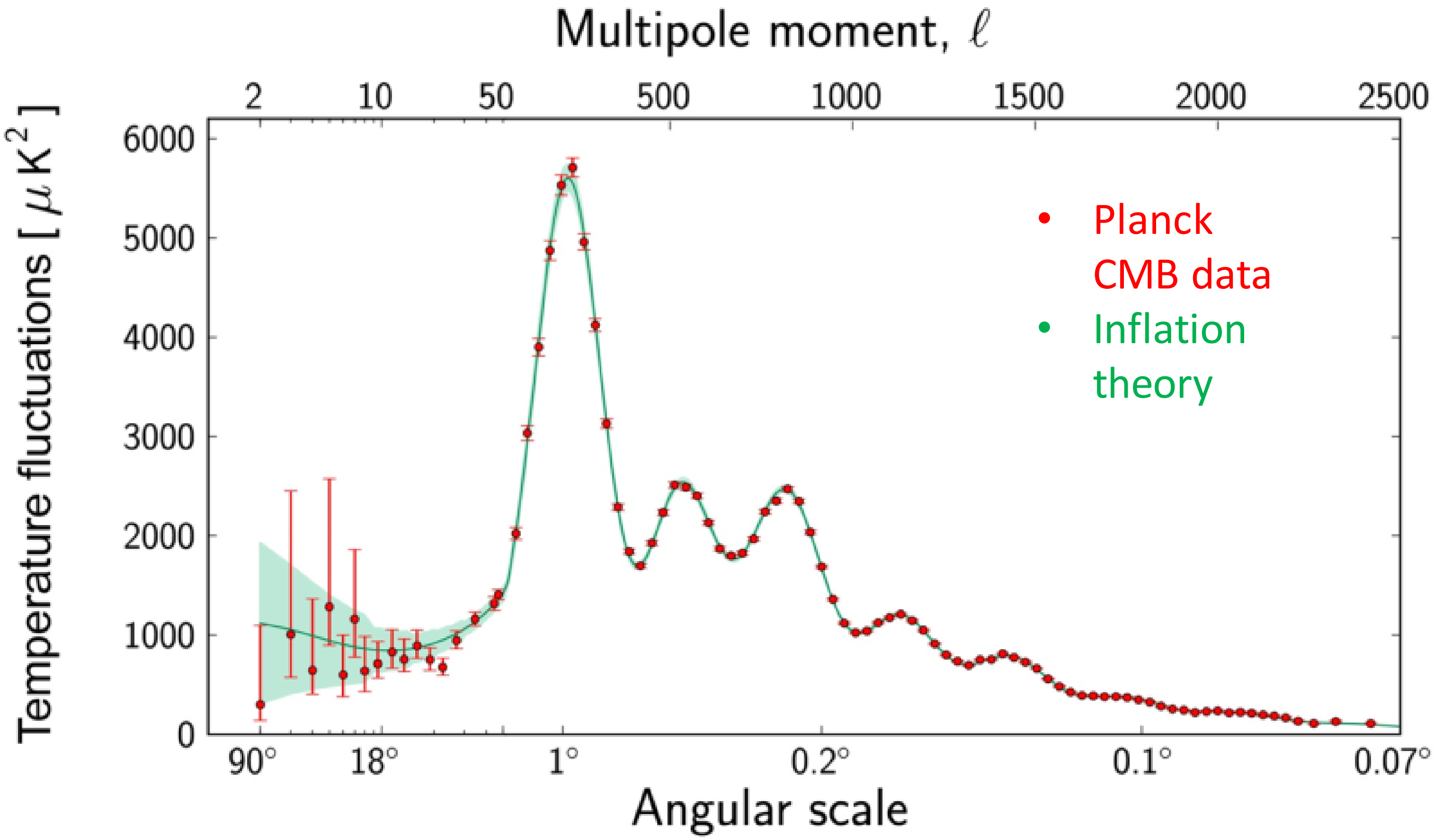
FIG. 3.— ***Left panel:*** The SPT power spectrum. The leftmost peak at $\ell \sim 800$ is the third acoustic peak. ***Right panel:*** A comparison of the new SPT bandpowers with other recent measurements of the CMB damping tail from ACBAR (Reichardt et al. 2009), ACT (Das et al. 2011b), and SPT (K11). Note that the point source masking threshold differs between these experiments which can affect the power at the highest multipoles. In order to highlight the acoustic peak structure of the damping tail, we plot the bandpowers in the right panel as $\ell^4 C_\ell/(2\pi)$, as opposed to $D_\ell = \ell(\ell+1)C_\ell/(2\pi)$ in the left panel. The solid line shows the theory spectrum for the ΛCDM model + foregrounds that provides the best fit to the SPT+*WMAP7* data. The bandpower errors shown in these plots contain sample and noise variance terms only; they do not include beam or calibration uncertainties.

A MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND DAMPING TAIL FROM THE 2500-SQUARE-DEGREE SPT-SZ SURVEY

K. T. Story,[1,2] C. L. Reichardt,[3] Z. Hou,[4] R. Keisler,[1,2] K. A. Aird,[5] B. A. Benson,[1,6] L. E. Bleem,[1,2] J. E. Carlstrom,[1,2,6,7,8] C. L. Chang,[1,6,8] H-M. Cho,[9] T. M. Crawford,[1,7] A. T. Crites,[1,7] T. de Haan,[10] M. A. Dobbs,[10] J. Dudley,[10] B. Follin,[4] E. M. George,[3] N. W. Halverson,[11] G. P. Holder,[10] W. L. Holzapfel,[3] S. Hoover,[1,2] J. D. Hrubes,[5] M. Joy,[12] L. Knox,[4] A. T. Lee,[3,13] E. M. Leitch,[1,7] M. Lueker,[14] D. Luong-Van,[5] J. J. McMahon,[15] J. Mehl,[8,1] S. S. Meyer,[1,2,6,7] M. Millea,[4] J. J. Mohr,[16,17,18] T. E. Montroy,[19] S. Padin,[1,7,14] T. Plagge,[1,7] C. Pryke,[20] J. E. Ruhl,[19] J.T. Sayre[19] K. K. Schaffer,[1,6,21] L. Shaw,[10] E. Shirokoff,[3] H. G. Spieler,[13] Z. Staniszewski,[19] A. A. Stark,[22] A. van Engelen,[10] K. Vanderlinde,[10] J. D. Vieira,[14] R. Williamson,[1,7] and O. Zahn[23]

Submitted to ApJ

arXiv:1210.7231v1


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK²]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
• Planck CMB data
• Inflation theory

The Basic Tools of Inflation:

Consider a scalar field with:

$$\mathcal{L}(\varphi) = \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - V(\varphi)$$

⇨ If $V(\varphi) >>$ all space and time derivative (squared) terms

⇨ Then

$$T_\mu^\nu \approx \begin{pmatrix} V(\varphi) & 0 & 0 & 0 \\ 0 & -V(\varphi) & 0 & 0 \\ 0 & 0 & -V(\varphi) & 0 \\ 0 & 0 & 0 & -V(\varphi) \end{pmatrix}$$

⇨ Which implies $p = -\rho$ $w=-1$ ⇨ $\frac{d\rho}{da} \approx 0$

⇨ $a \sim e^{Ht}$ } **Inflation**

A period of early inflation gives:

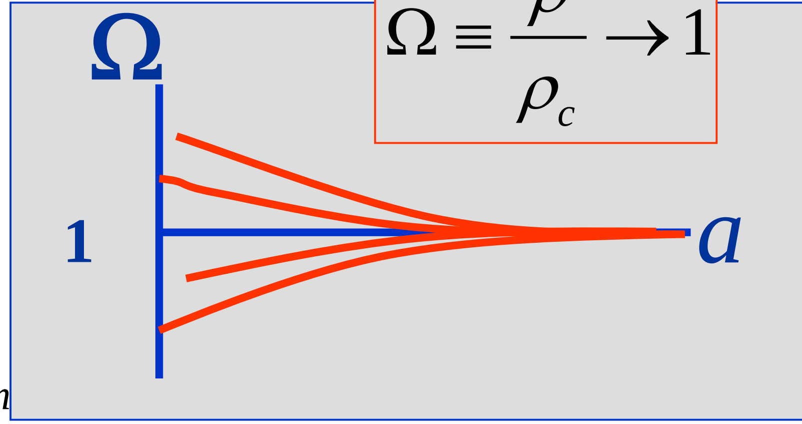
Flatness:

$$\left(\frac{\dot a}{a}\right)^2 \equiv H^2 = \frac{8\pi}{3}\rho - \frac{k}{a^2}$$

$\rho_\varphi = const.$

Dominates over ρ_r & ρ_m during inflation

$$\Omega \equiv \frac{\rho}{\rho_c} \to 1$$



Homogeneity

At horizon crossing:

$$\left.\frac{\delta\rho}{\rho}\right|_H \equiv \delta_H \approx \left(\frac{H^2}{\dot\phi}\right) \approx \left(\frac{HV'}{2\pi\dot\varphi^2}\right) \approx const$$

Evaluate when k=H during inflation

A suitably adjusted potential will give : $\delta_H \approx 10^{-5}$

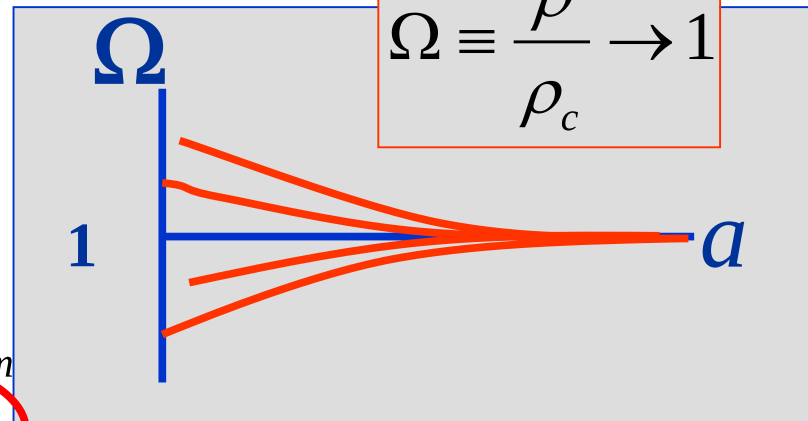
A period of early inflation gives:

Monopoles:

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi}{3}\rho - \frac{k}{a^2}$$

ρ_φ Dominates over ρ_r & ρ_m during inflation (and ρ_M)

$$\Omega \equiv \frac{\rho}{\rho_c} \rightarrow 1$$

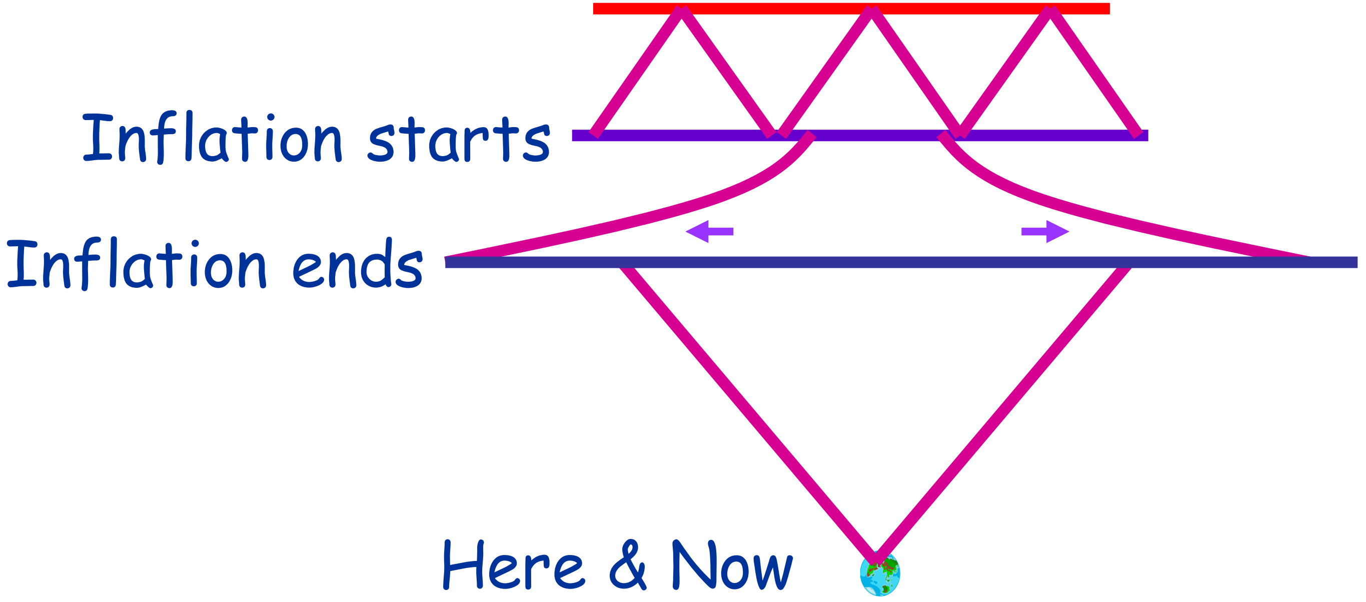


$$a \sim e^{Ht}$$

$$\left.\frac{\rho_M}{\rho_\varphi}\right|_a = \frac{\rho_M(a_1)\left(\frac{a_1}{a}\right)^3}{\rho_\varphi(a) = Const} = \left(\frac{\rho_M(a_1)}{\rho_\varphi(a_1)}\right) \times e^{-3Ht} \longrightarrow 0$$

Monopoles are erased

Inflation Horizon:



I) Inflation in the era of WMAP

I.0 What is Cosmic Inflation?

I.1 Successes

Inflation and the arrow of time

Introduction

Arrow of time basics

Inflation and the arrow of time

Implications

Can the Universe Afford Inflation?

- Inflation:
    - An early period of nearly exponential expansion set up the “initial” conditions for the standard big bang

- Predictions:
    - Ω_{total}=1 (to one part in 100,000 as measured)
    - Characteristic oscillations in the CMB power
    - Nearly scale invariant perturbation spectrum
    - Characteristic Gravity wave, CMB Polarization etc
    - etc

WMAP

- Ωtotal=1

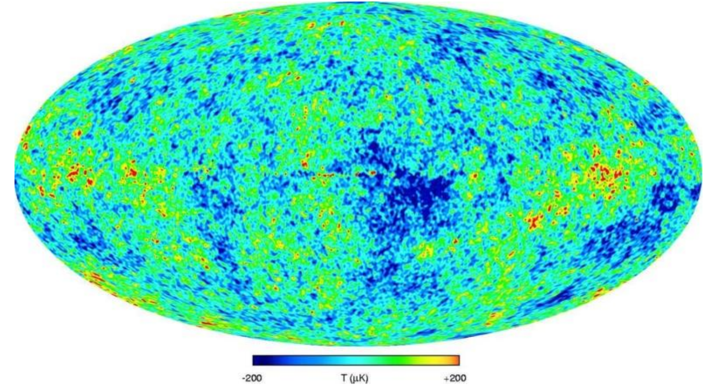


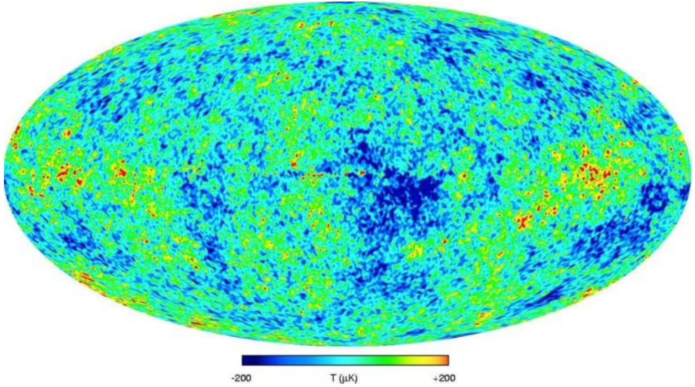
Table 3. "Best" Cosmological Parameters

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—

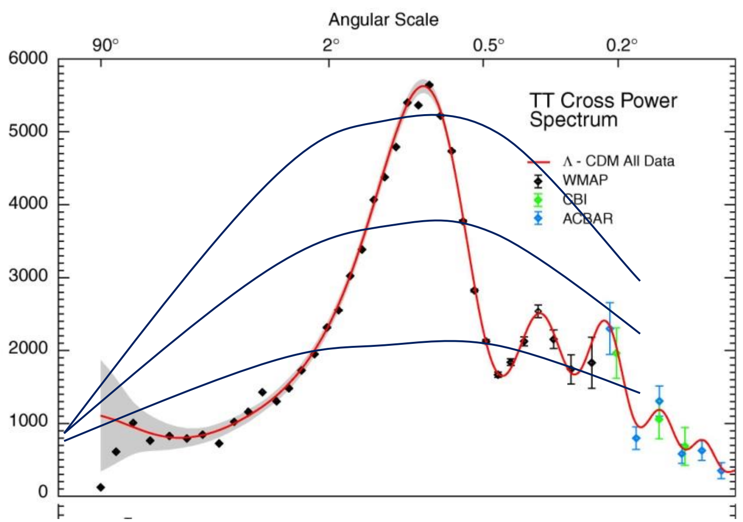
Bennett et al Feb 11 '03

- Characteristic ✓ oscillations in the CMB power

WMAP



Temperature Power →



← Angular scale

Inflation

"Active" models

Adapted from

Bennett et al Feb 11 '03

- Nearly scale invariant perturbation spectrum

WMAP

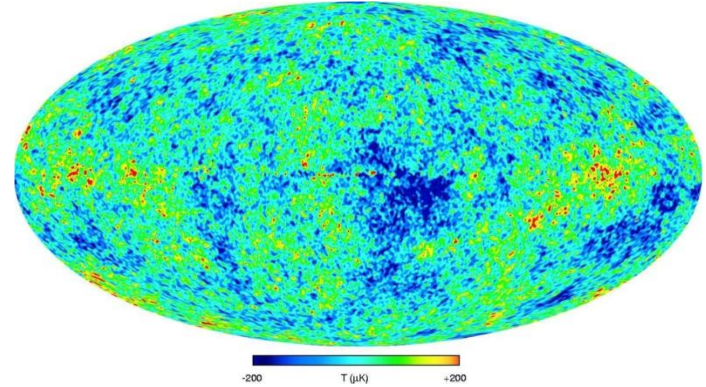


Table 3. "Best" Cosmological Parameters

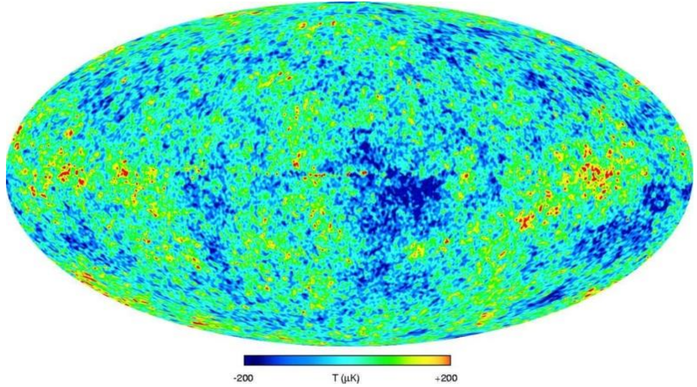
Description	Symbol	Value	+ uncertainty	− uncertainty
Power spectrum normalization (at $k_0 = 0.05$ Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05$ Mpc^{-1})[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05$ Mpc^{-1})[c]	$dn_s/d\ln k$	−0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc^{-1})	r	< 0.71	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
T	Δz_{dec}	195	2	2
H	h	0.71	0.04	0.03

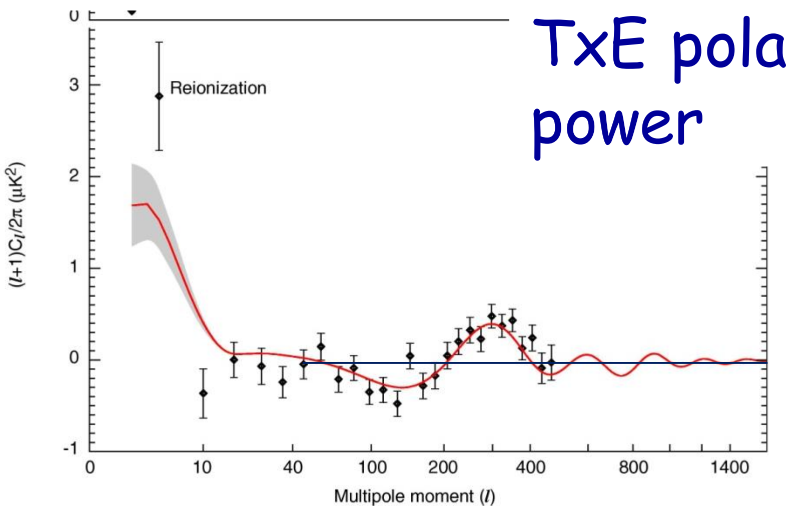
$$\frac{\delta\rho}{\rho}(k)\Big|_{H=k} = Ak^{1-n_s}$$

Bennett et al Feb 11 '03

WMAP

- Characteristic Gravity wave, CMB Polarization etc



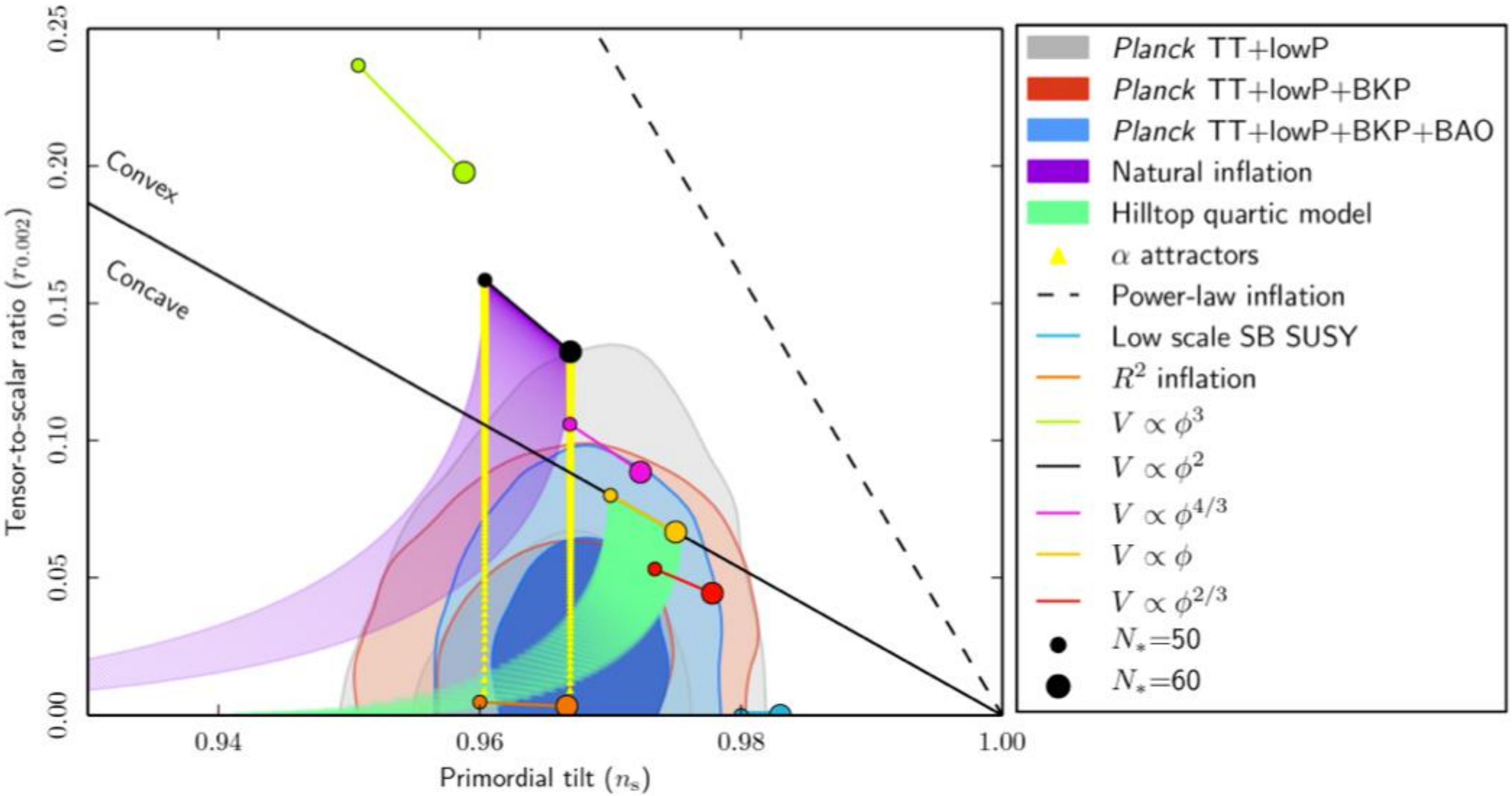


TxE polarization power

Inflation

"Active" models

Bennett et al Feb 11 '03



https://www.aanda.org/articles/aa/full_html/2016/10/aa25898-15/aa25898-15.html
fig 55

What happened before inflation?

What happened before inflation?

Related to some more contentious topics:

- How well does inflation “solve” tuning problems?
- Eternal inflation

OUTLINE

1. Big Bang basics
2. Inflation basics
3. Eternal inflation
4. An alternative to Eternal Inflation
5. Further thoughts

OUTLINE

1. Big Bang basics
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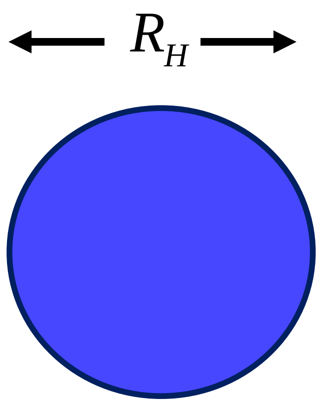
3. Eternal inflation
4. An alternative to Eternal Inflation
5. Further thoughts

- Eternal 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:

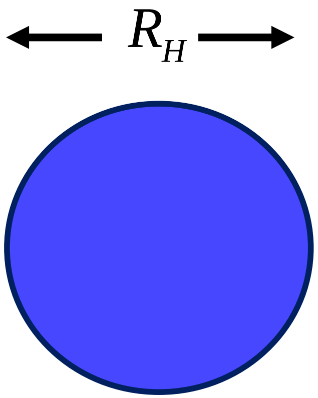
$$\frac{\Delta\phi}{\Delta t} \equiv \dot{\phi}_Q = H^2$$

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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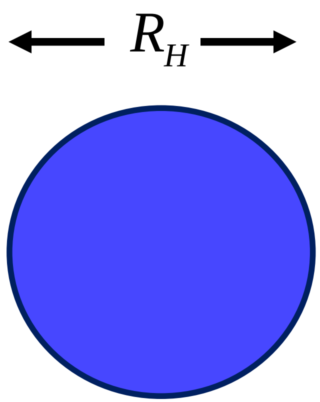
Thus

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

measures the importance of quantum fluctuations in the field evolution

Quantum fluctuations during slow roll:



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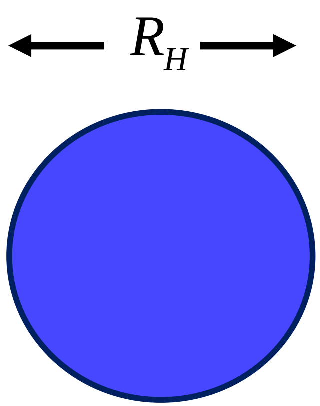
measures the importance of quantum fluctuations in the field evolution

For realistic perturbations the evolution is very classical

Quantum fluctuations during slow roll:



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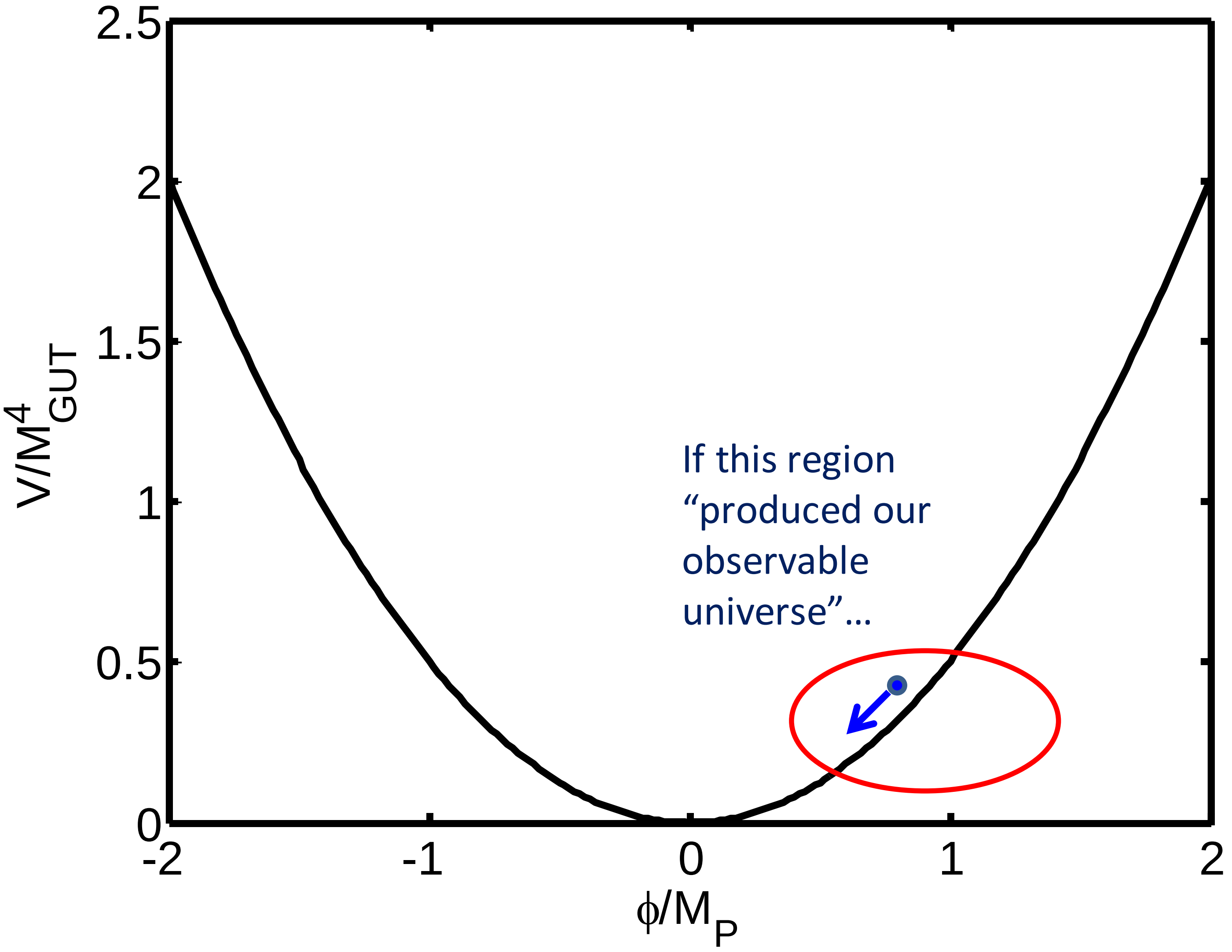
Thus

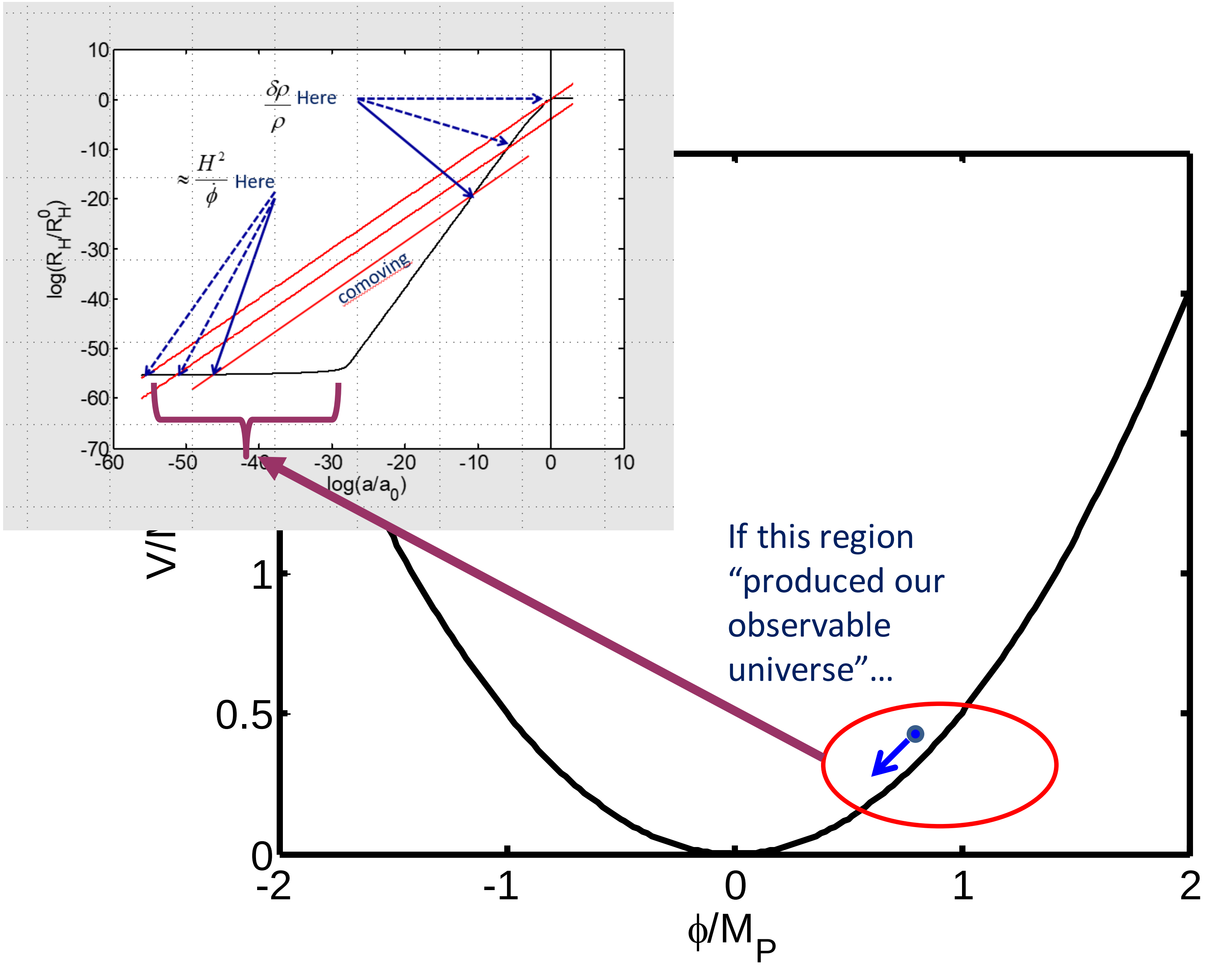
$$\frac{\dot{\phi}_Q}{\dot{\phi}} = \frac{H^2}{\dot{\phi}} \quad \left(= \frac{\delta\rho}{\rho} \approx 10^{-5} \right)$$

measures the importance of quantum fluctuations in the field evolution

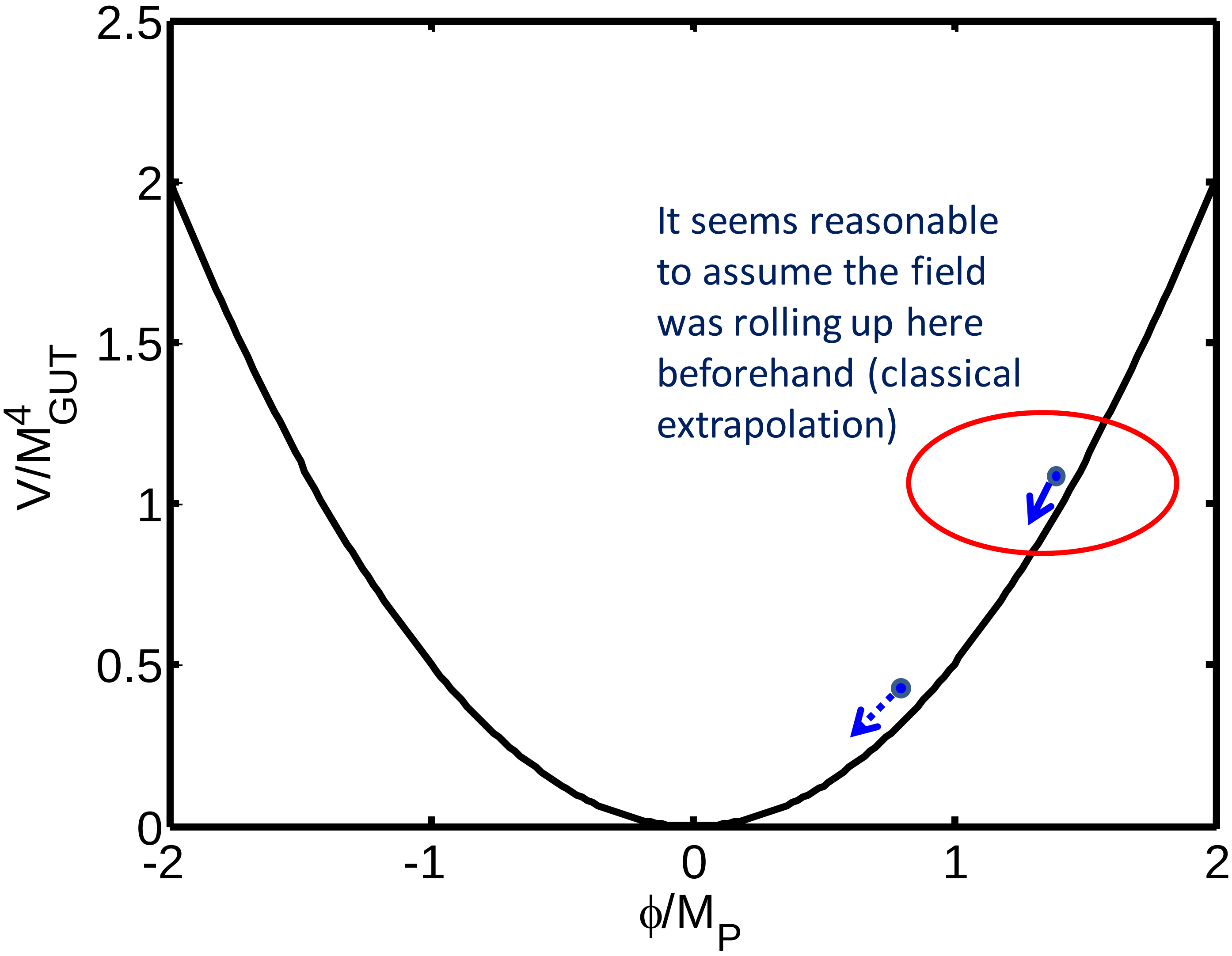
For realistic perturbations the evolution is very classical

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

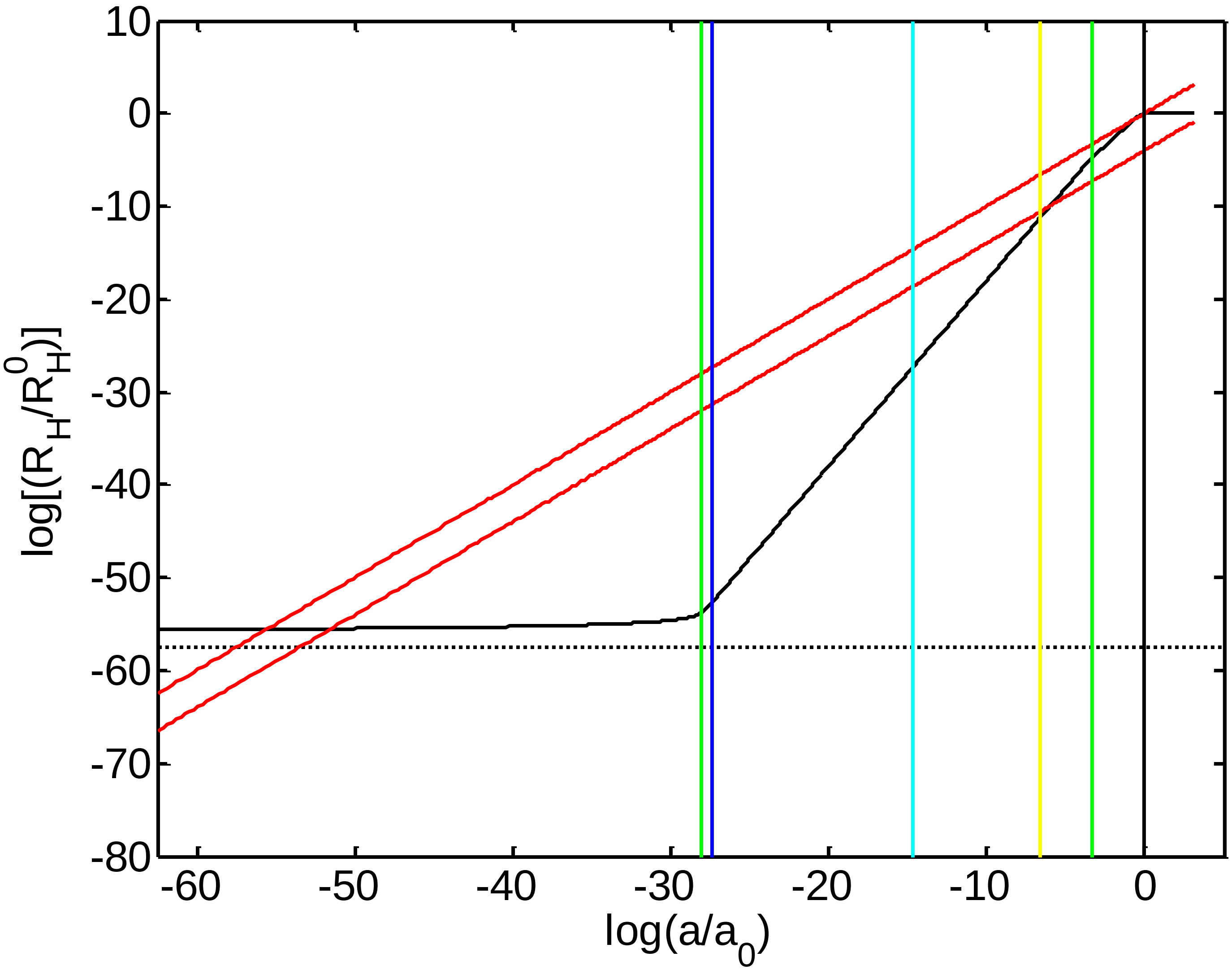

2.5
2
1.5
1
0.5
0
-2
-1
0
1
2
V/M^4_{GUT}
ϕ/M_P
If this region
"produced our
observable
universe"…



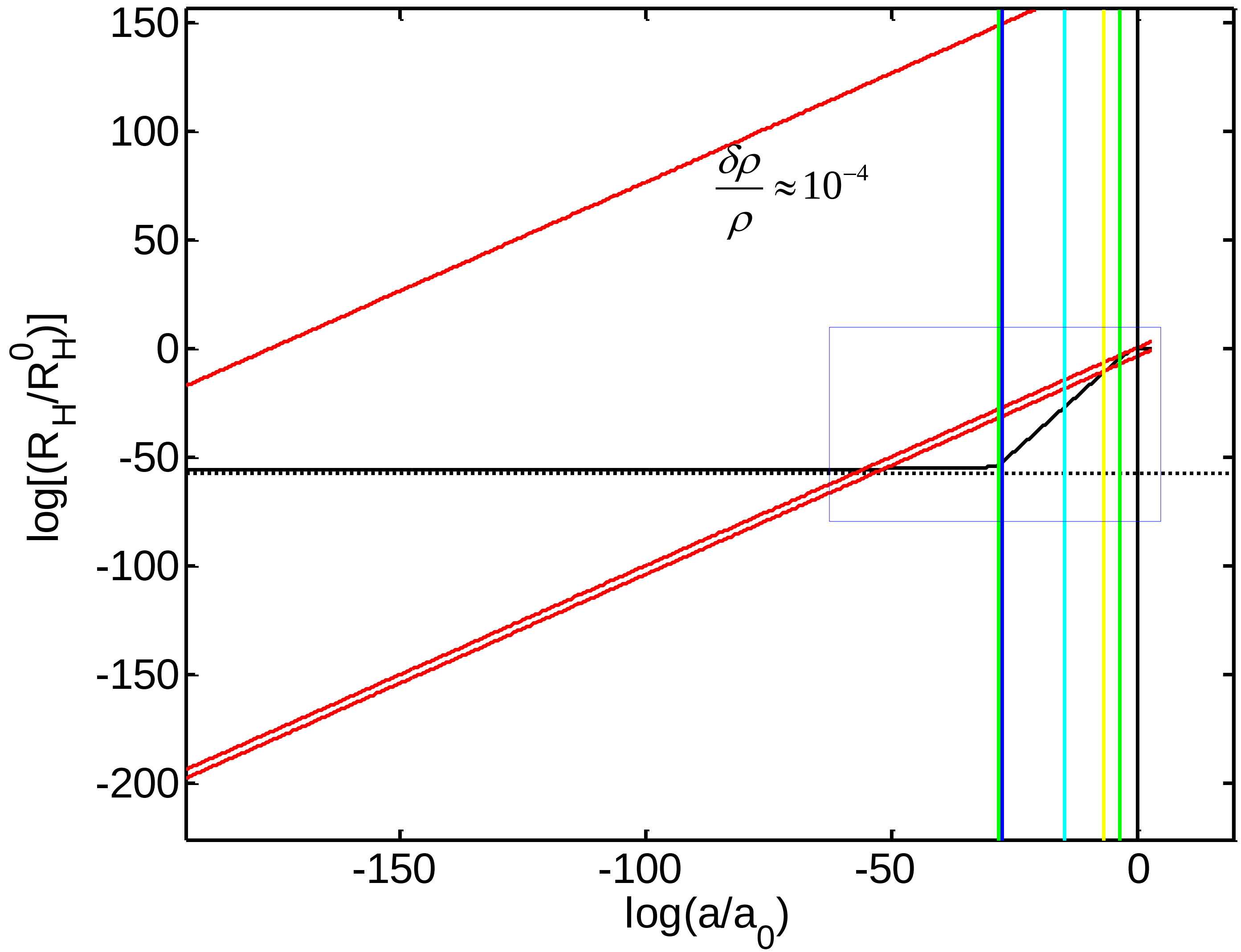
log(R_H/R_H^0)
log(a/a_0)
δρ/ρ Here
≈ H²/φ̇ Here
comoving
V/M
ϕ/M_P
If this region "produced our observable universe"…


2.5
2
1.5
1
0.5
0
-2
-1
0
1
2
V/M^4_{GUT}
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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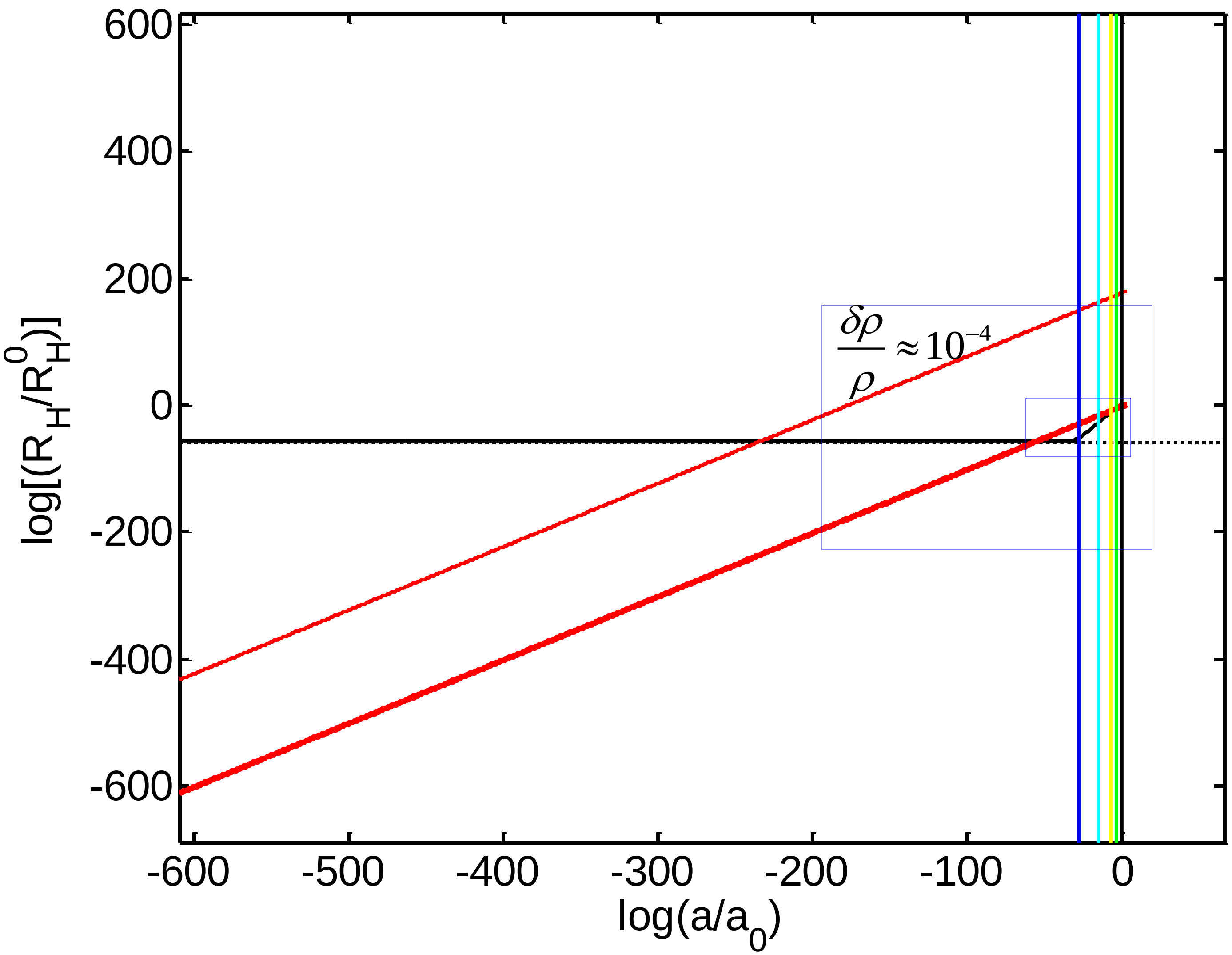
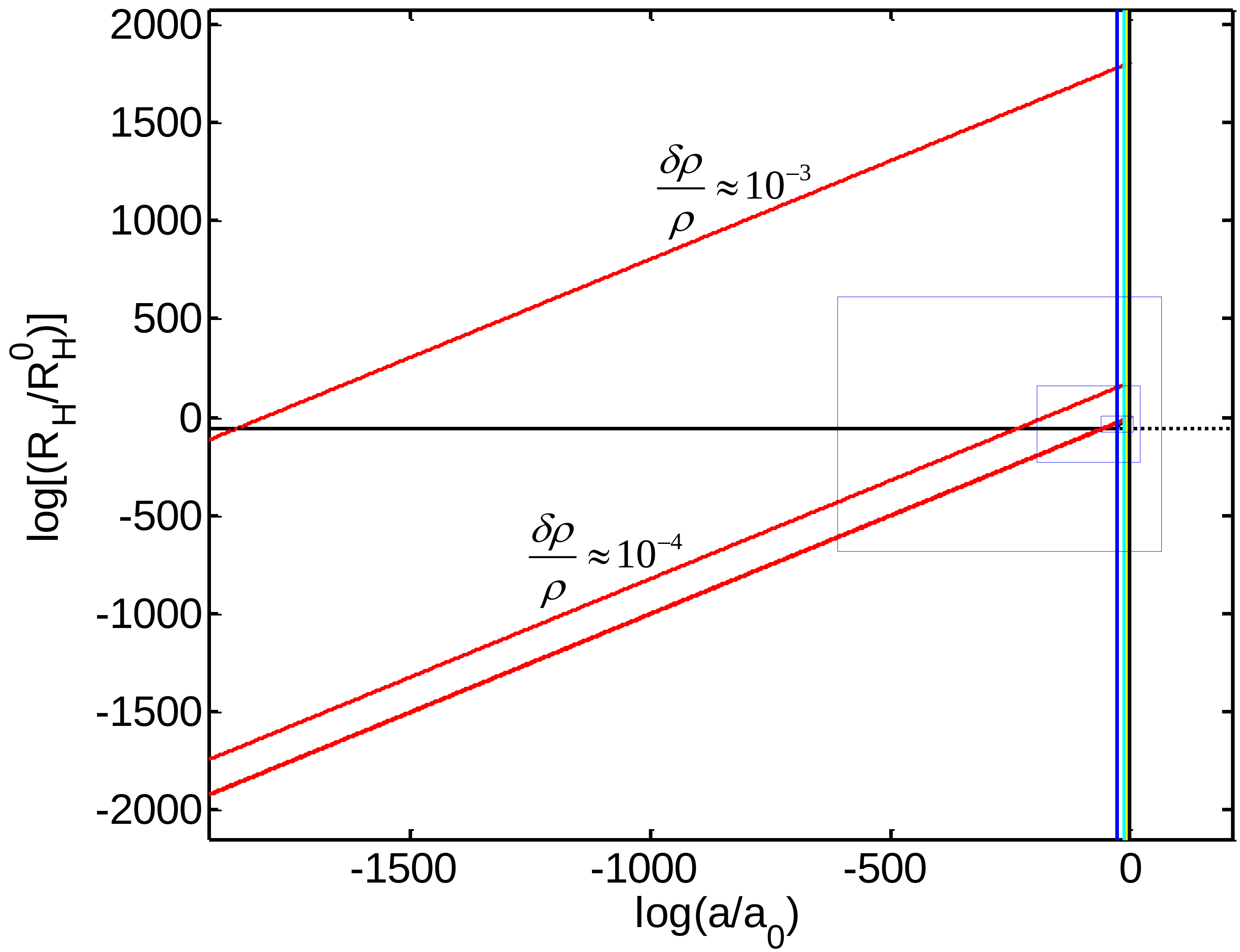
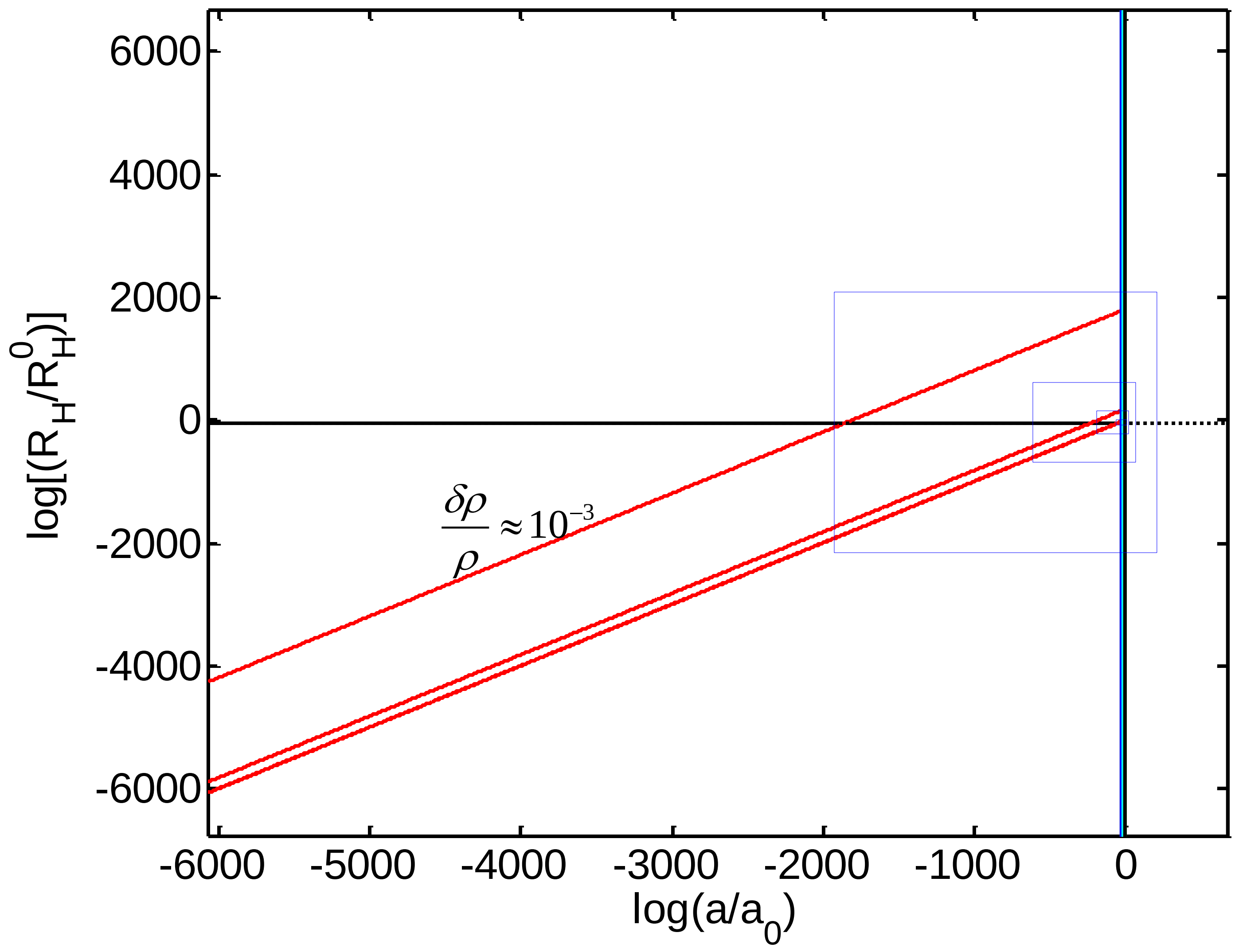


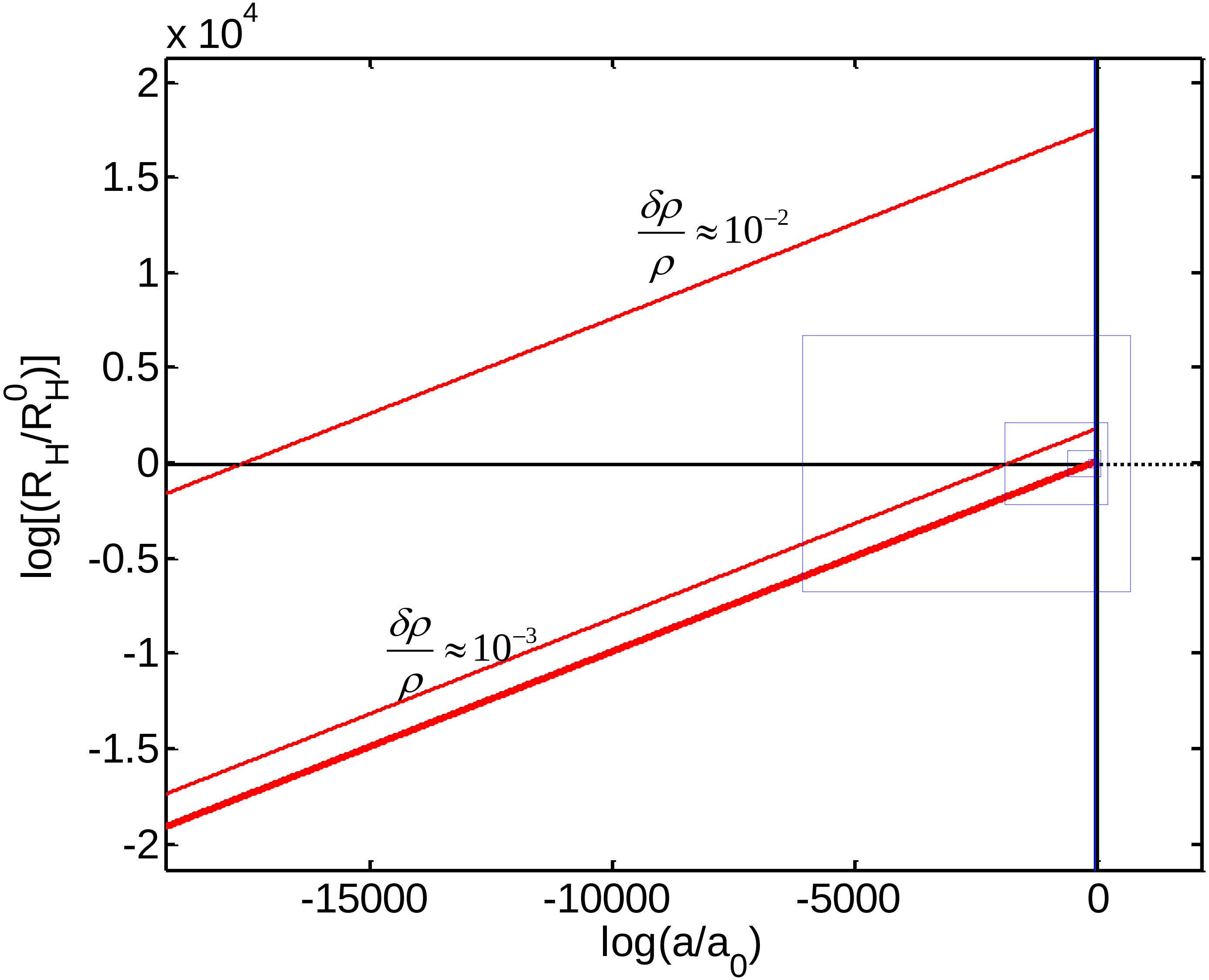
Evolution of Cosmic Length (zooming out)



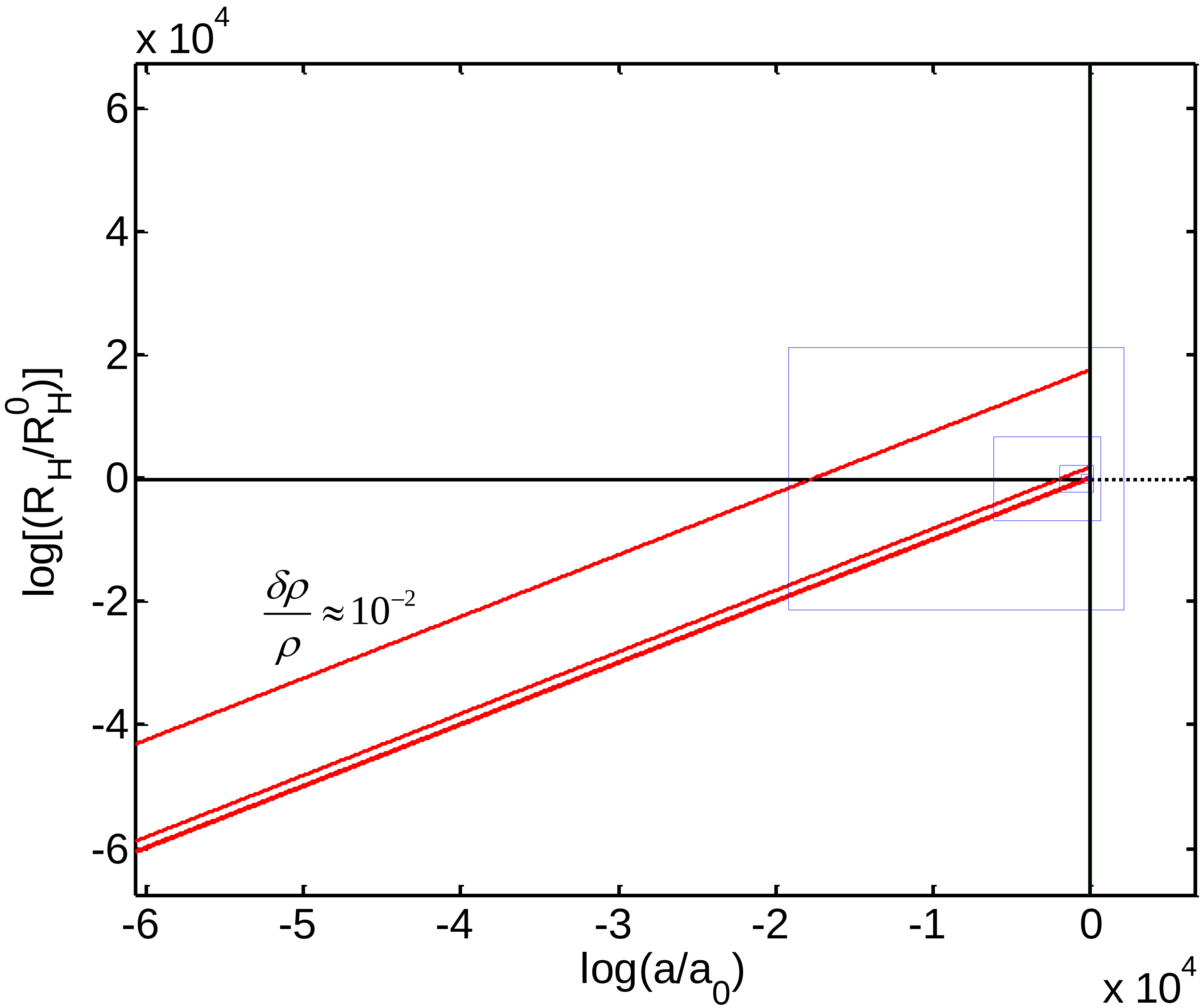
Evolution of Cosmic Length (zooming out)



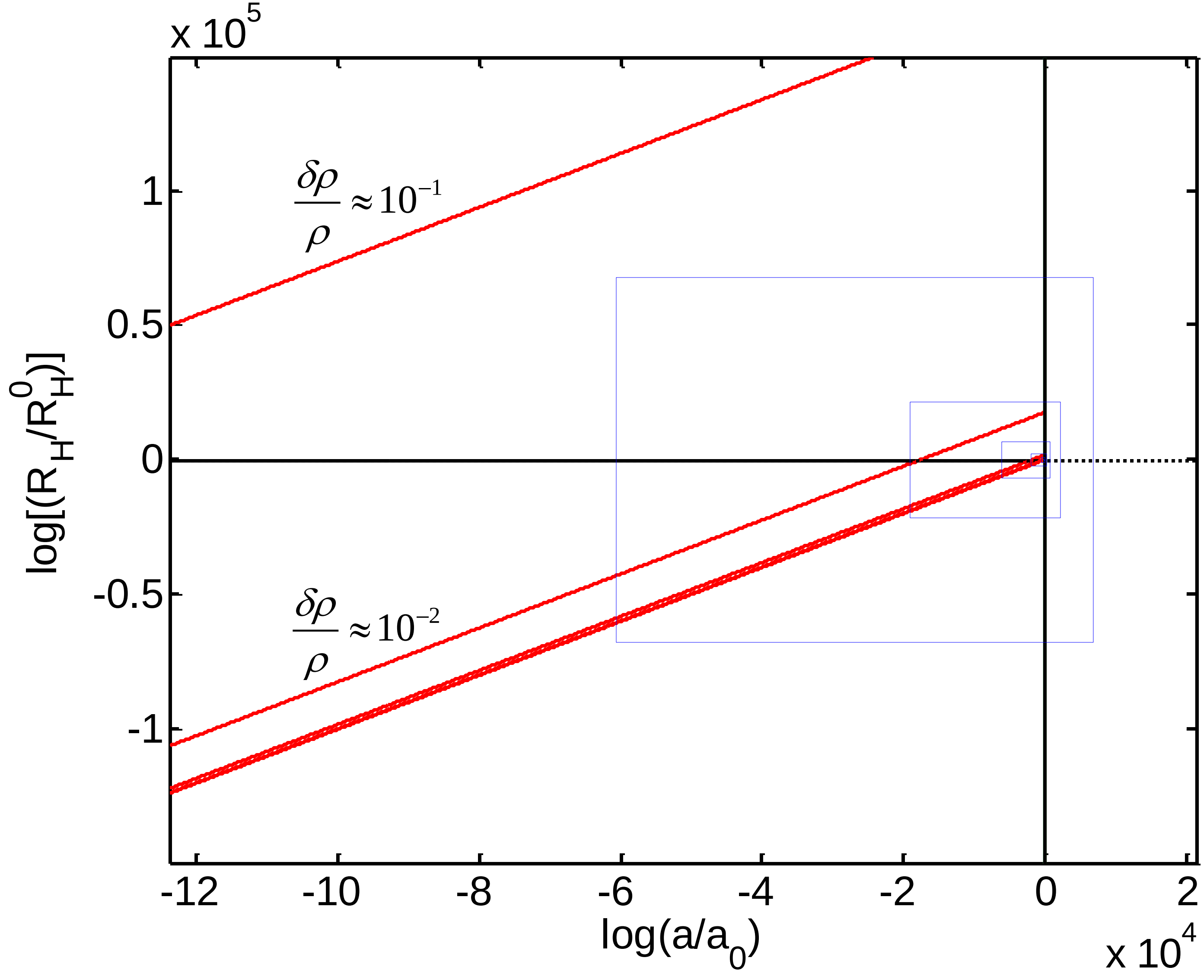
Evolution of Cosmic Length (zooming out)



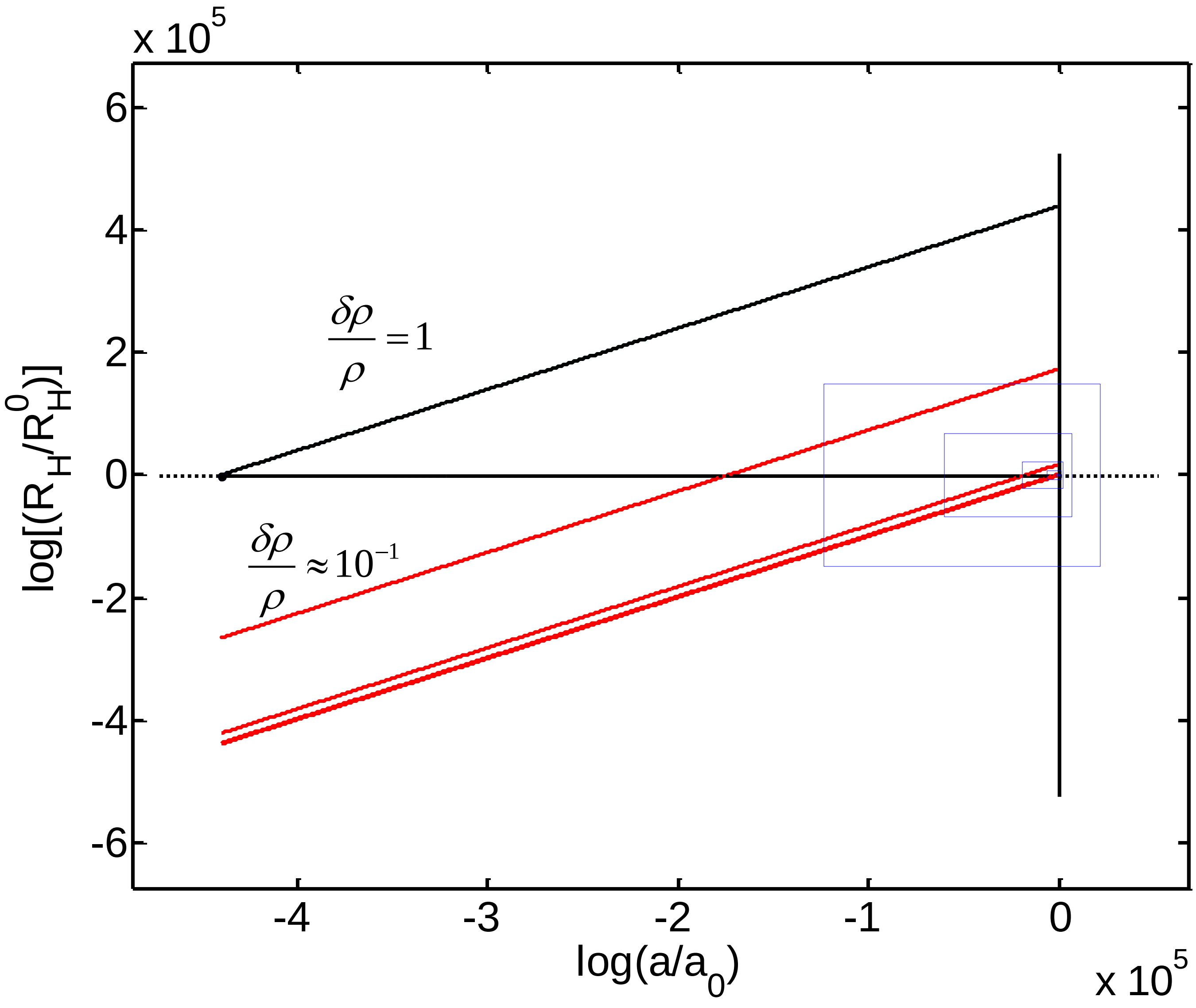
Evolution of Cosmic Length (zooming out)



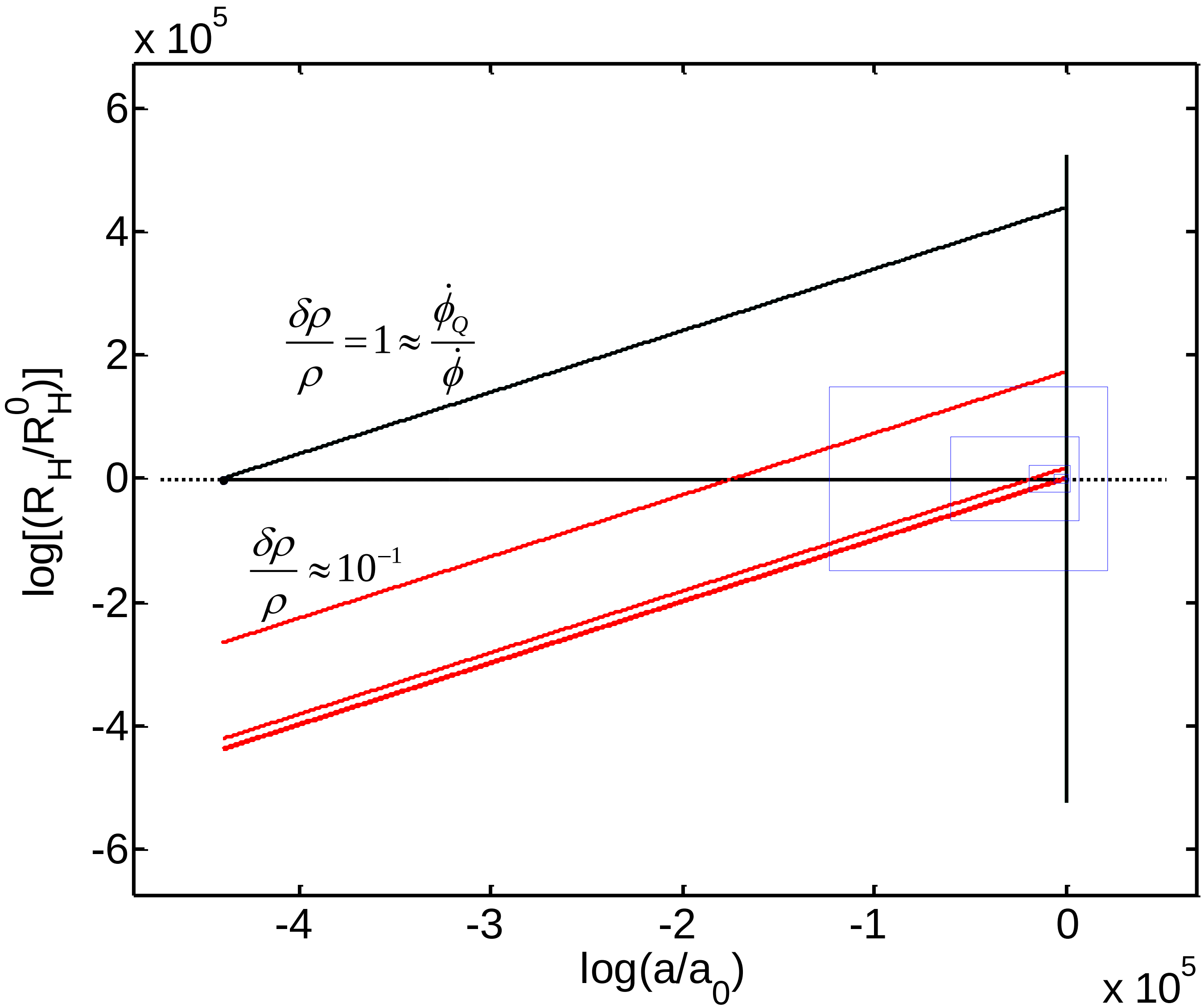
Evolution of Cosmic Length (zooming out)



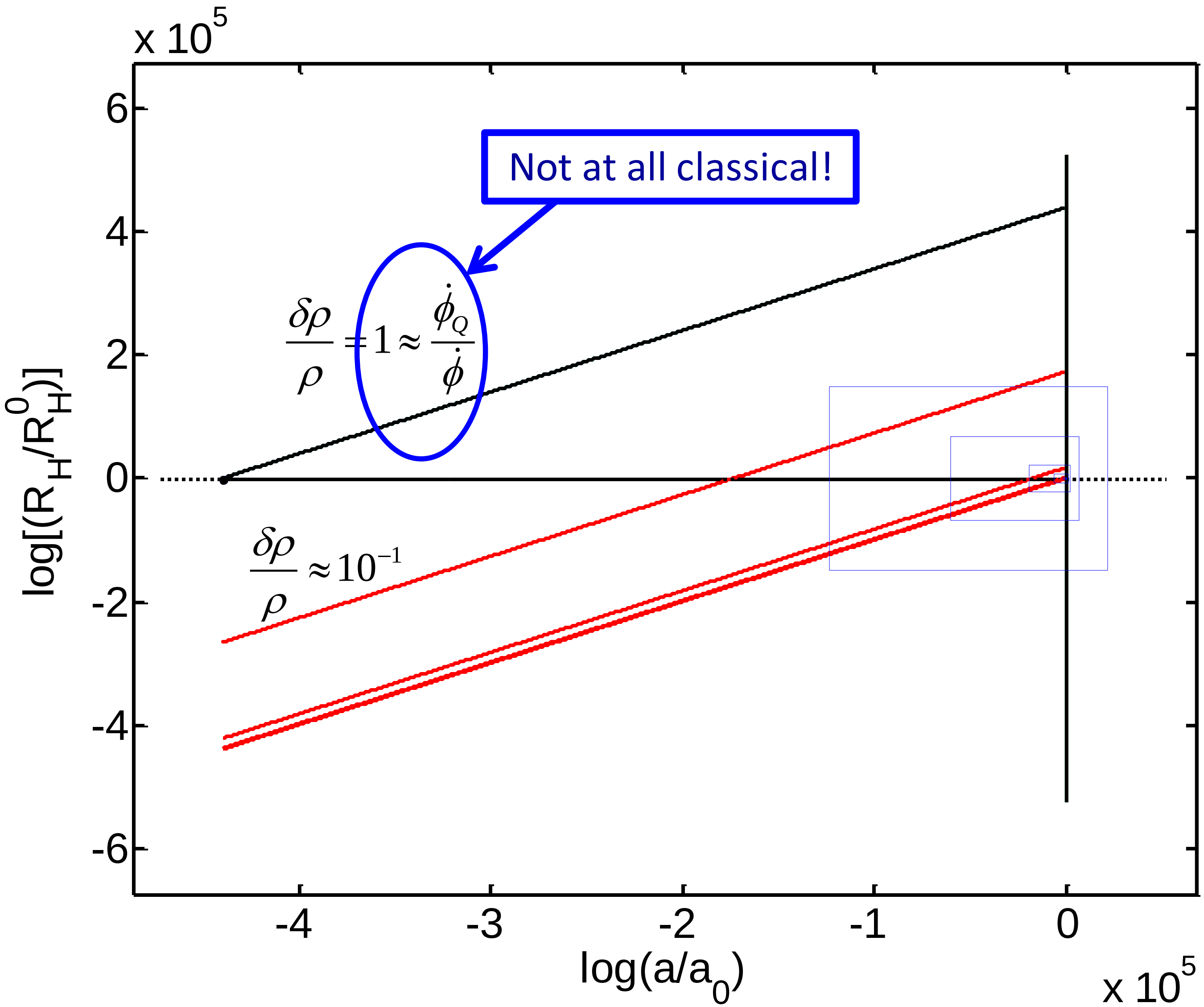
Evolution of Cosmic Length (zooming out)



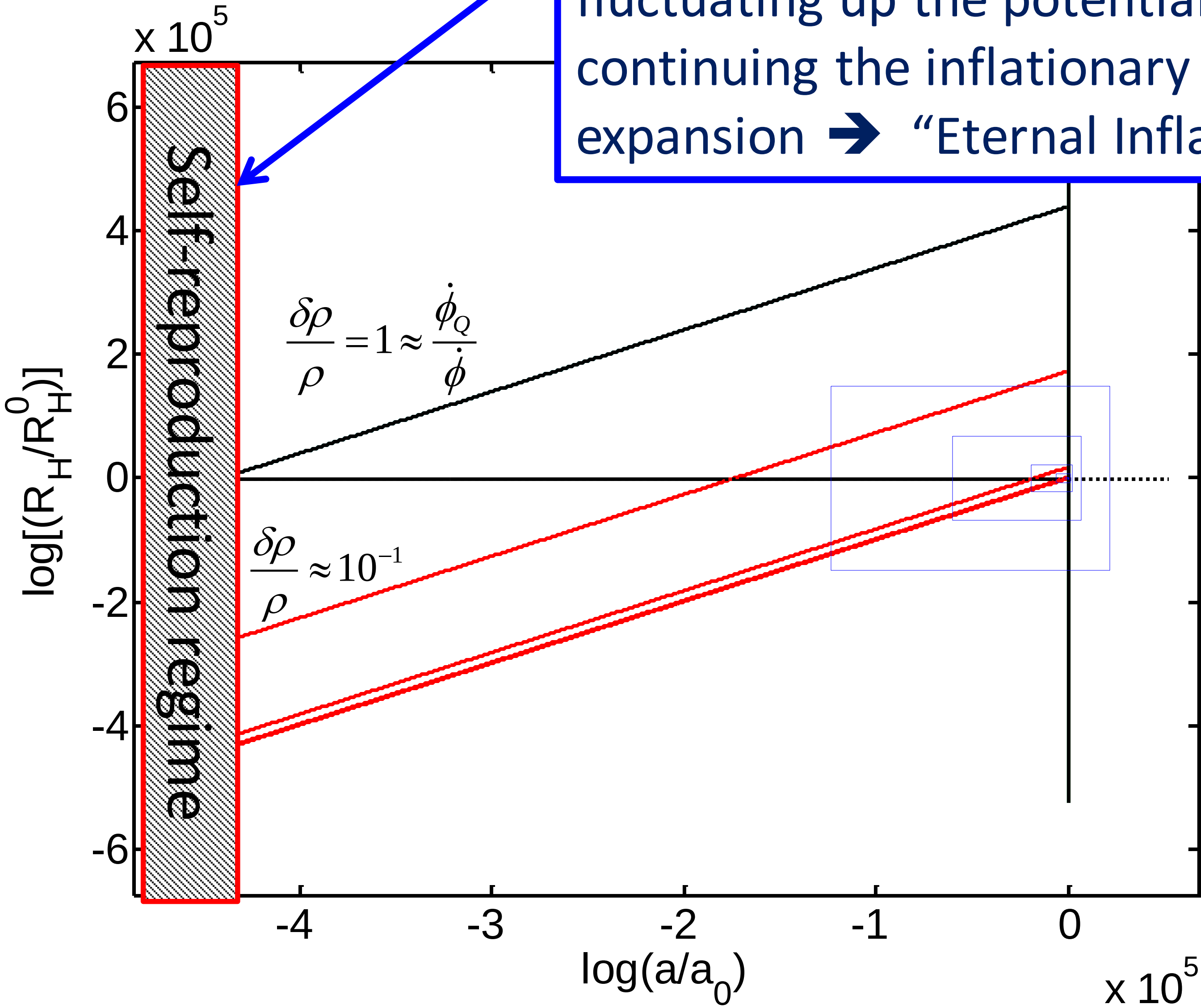
Evolution of Cosmic Length (zooming out)



Evolution of Cosmic Length (zooming out)

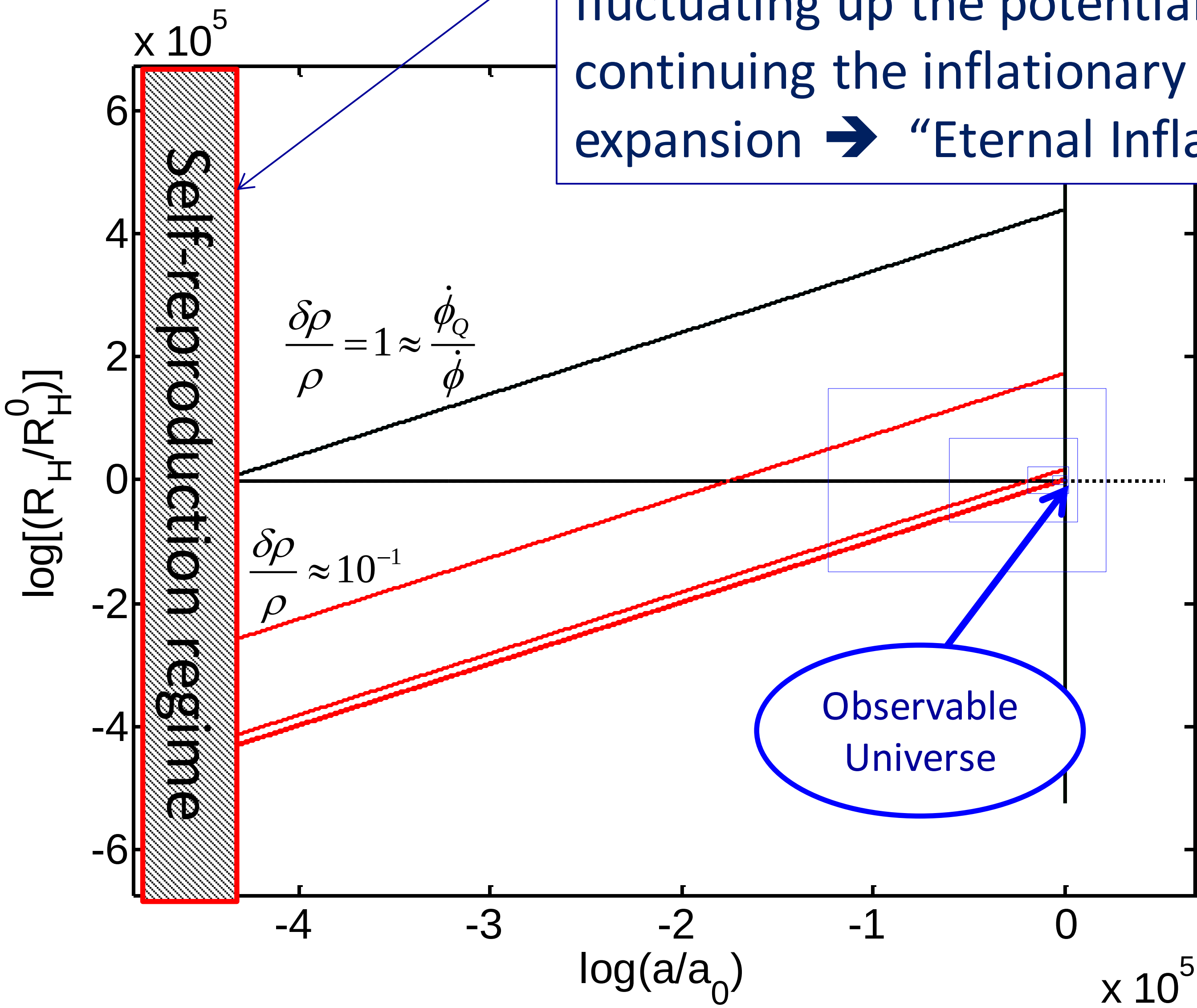


Substantial probability of fluctuating up the potential and continuing the inflationary expansion ➔ "Eternal Inflation"

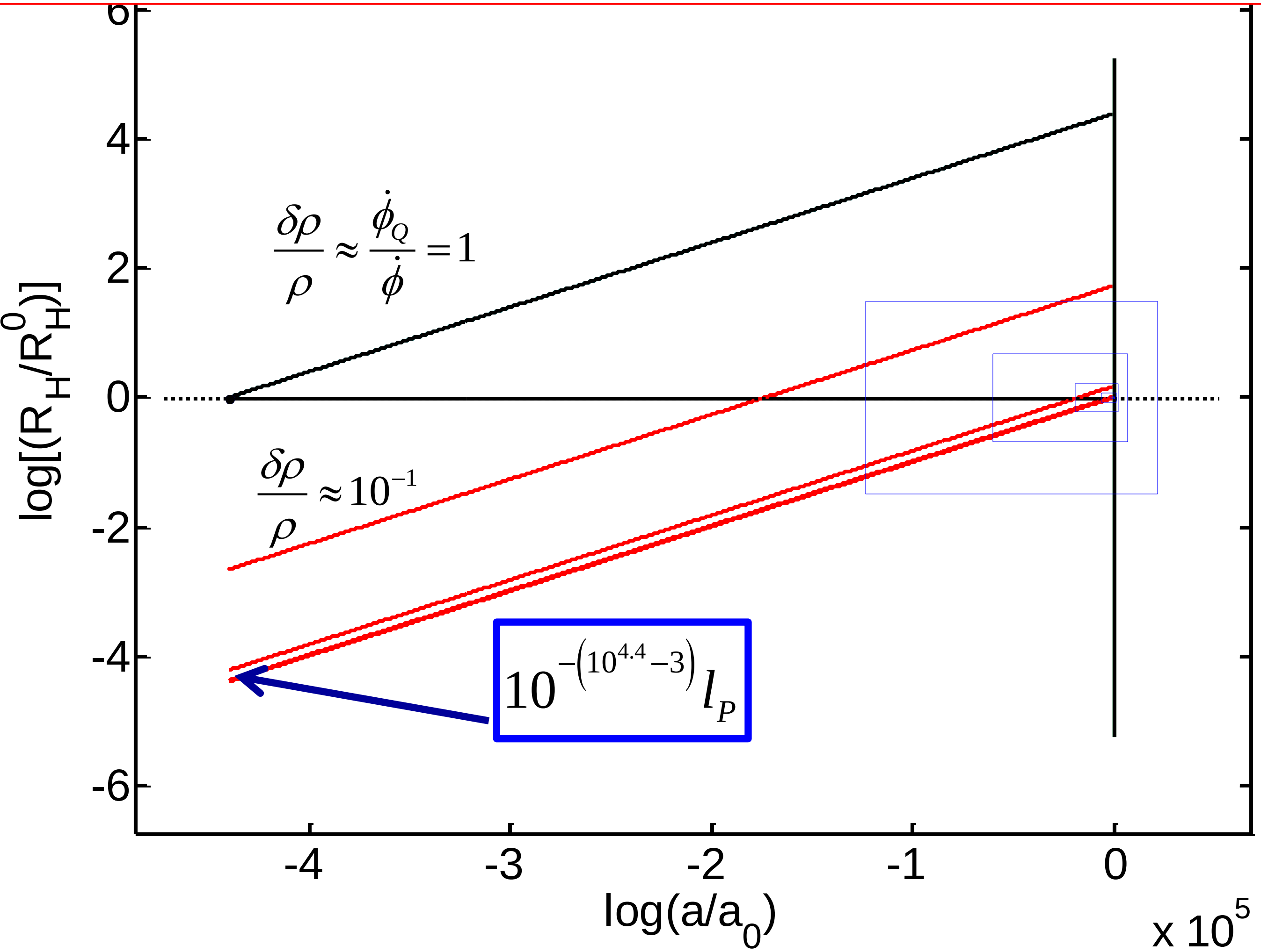


Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others

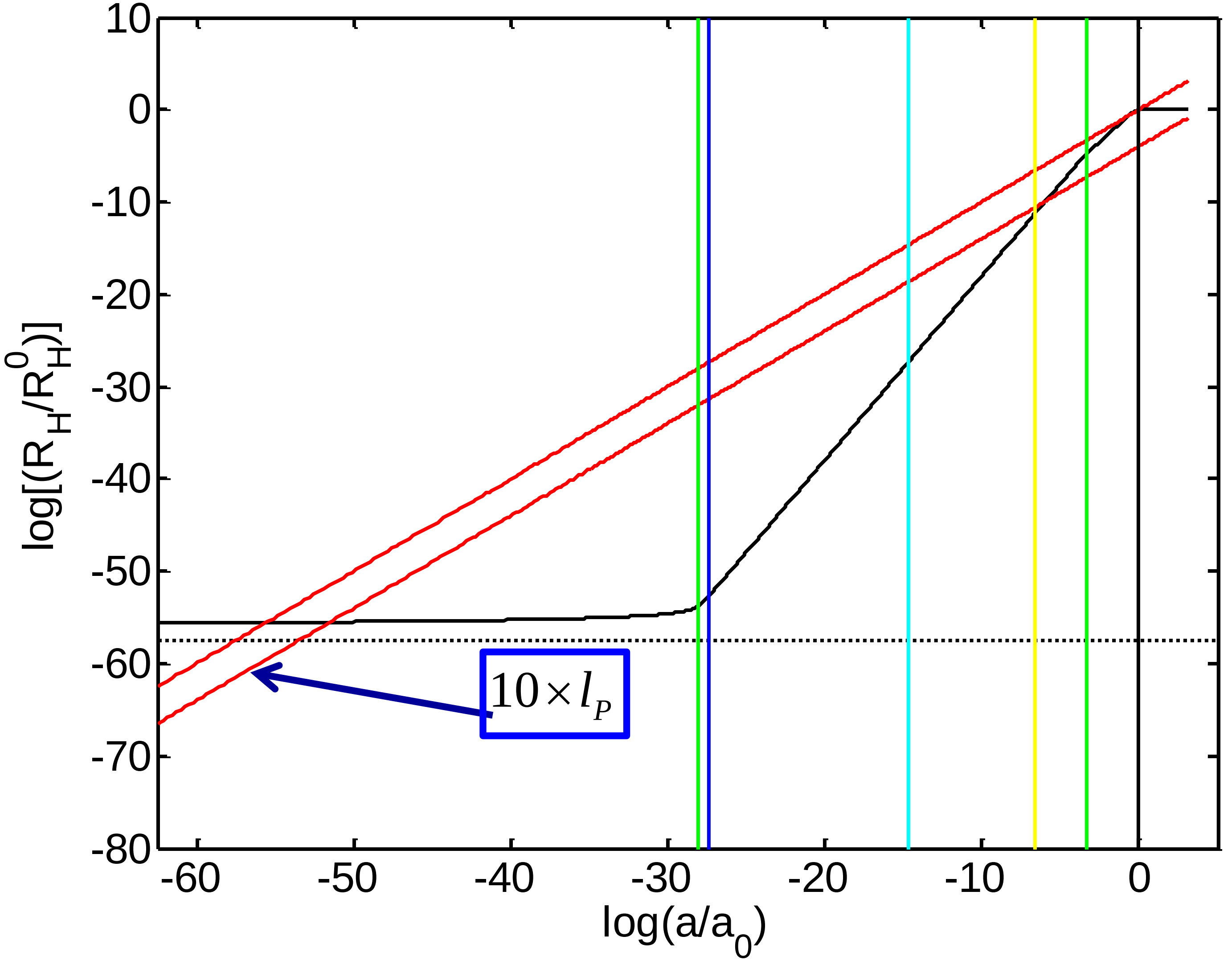
Substantial probability of fluctuating up the potential and continuing the inflationary expansion ➔ “Eternal Inflation”



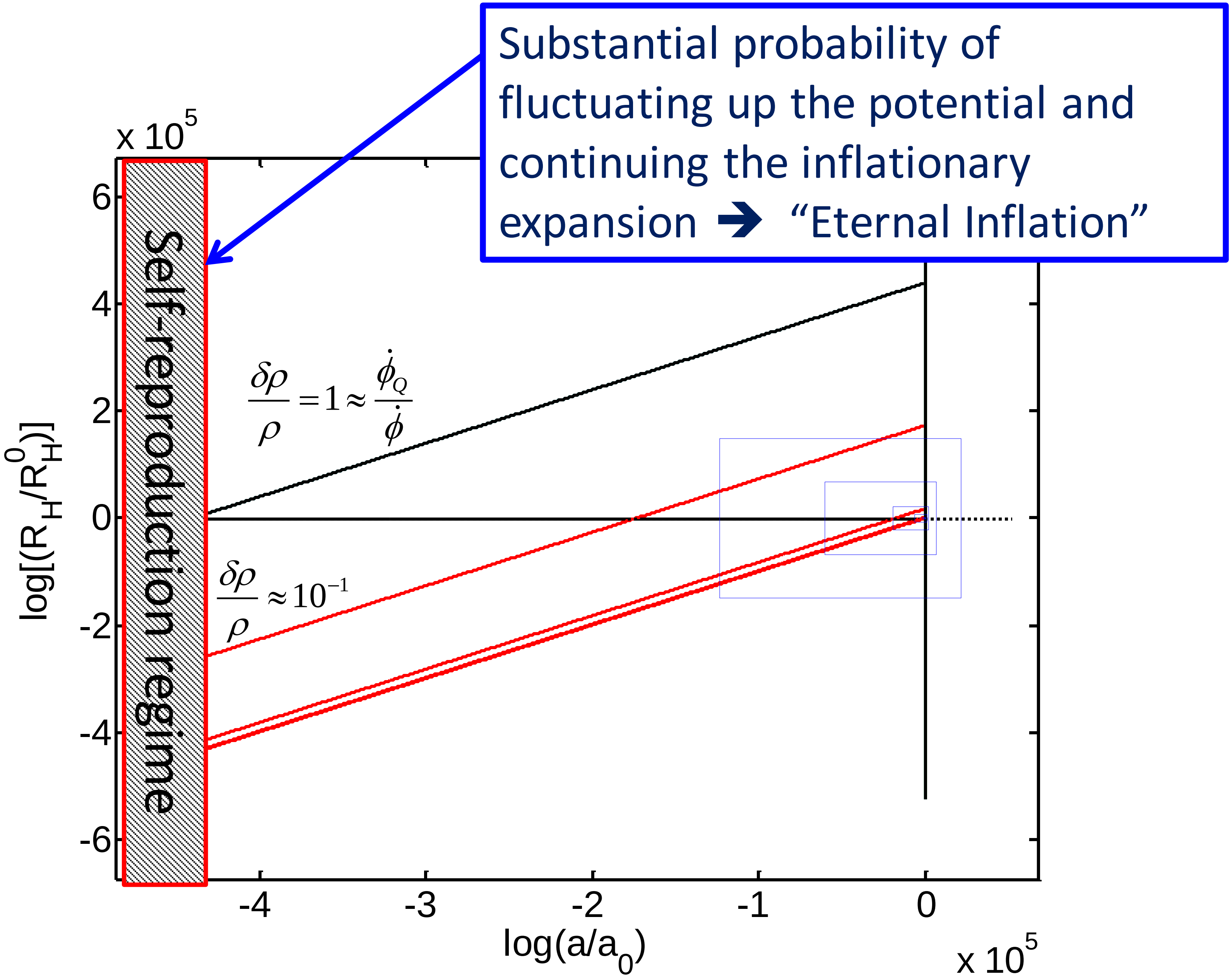
At end of self-reproduction our observable length scales were exponentially below the Plank length (and much smaller than that *during* self-reproduction)!

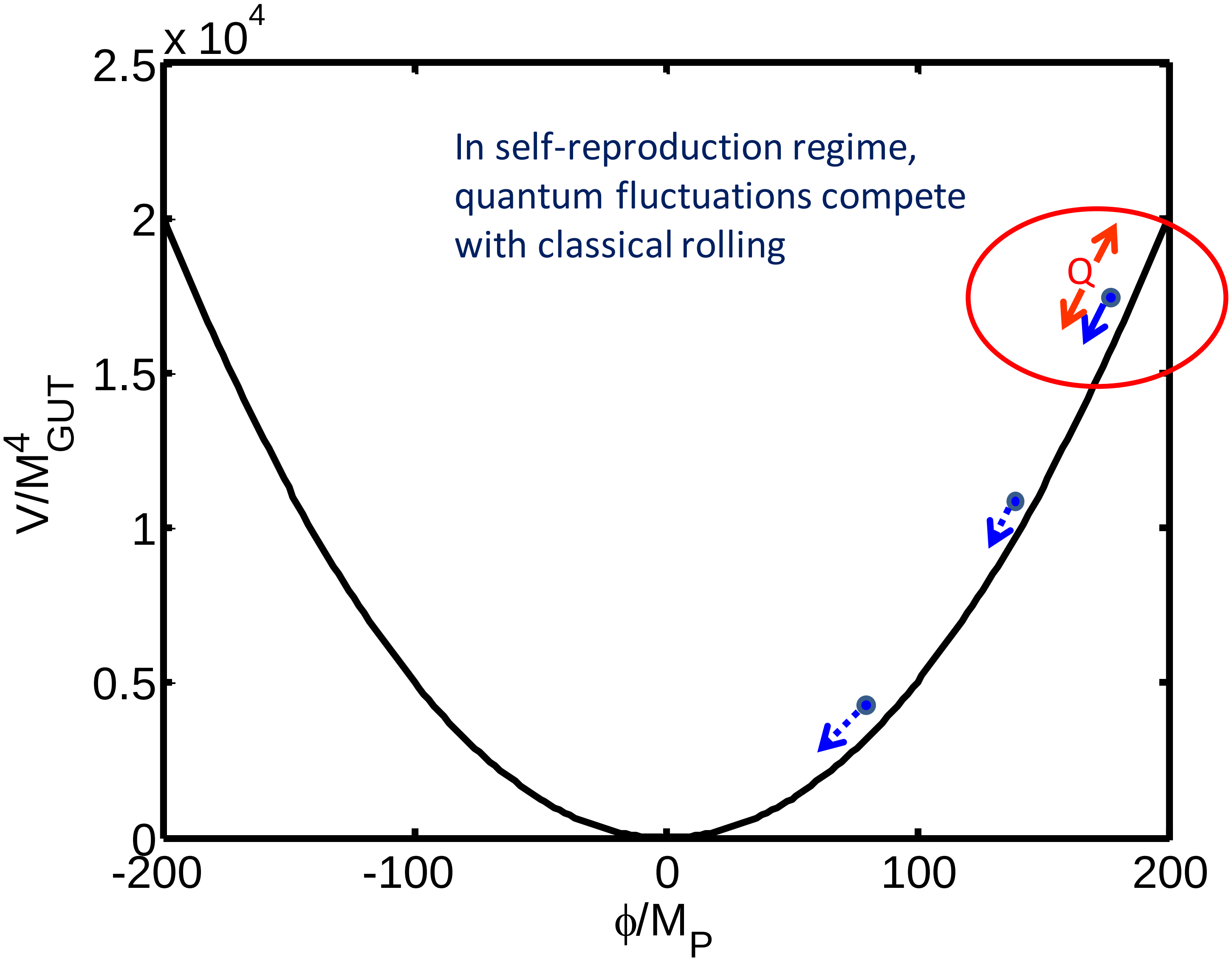


At “formation” (Hubble length crossing) observable scales were just above the Planck length



(Bunch Davies Vacuum)


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
-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
-200
-100
0
100
200
ϕ/M_P
In self-reproduction regime,
quantum fluctuations compete
with classical rolling
Q

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

During inflation

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

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

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

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

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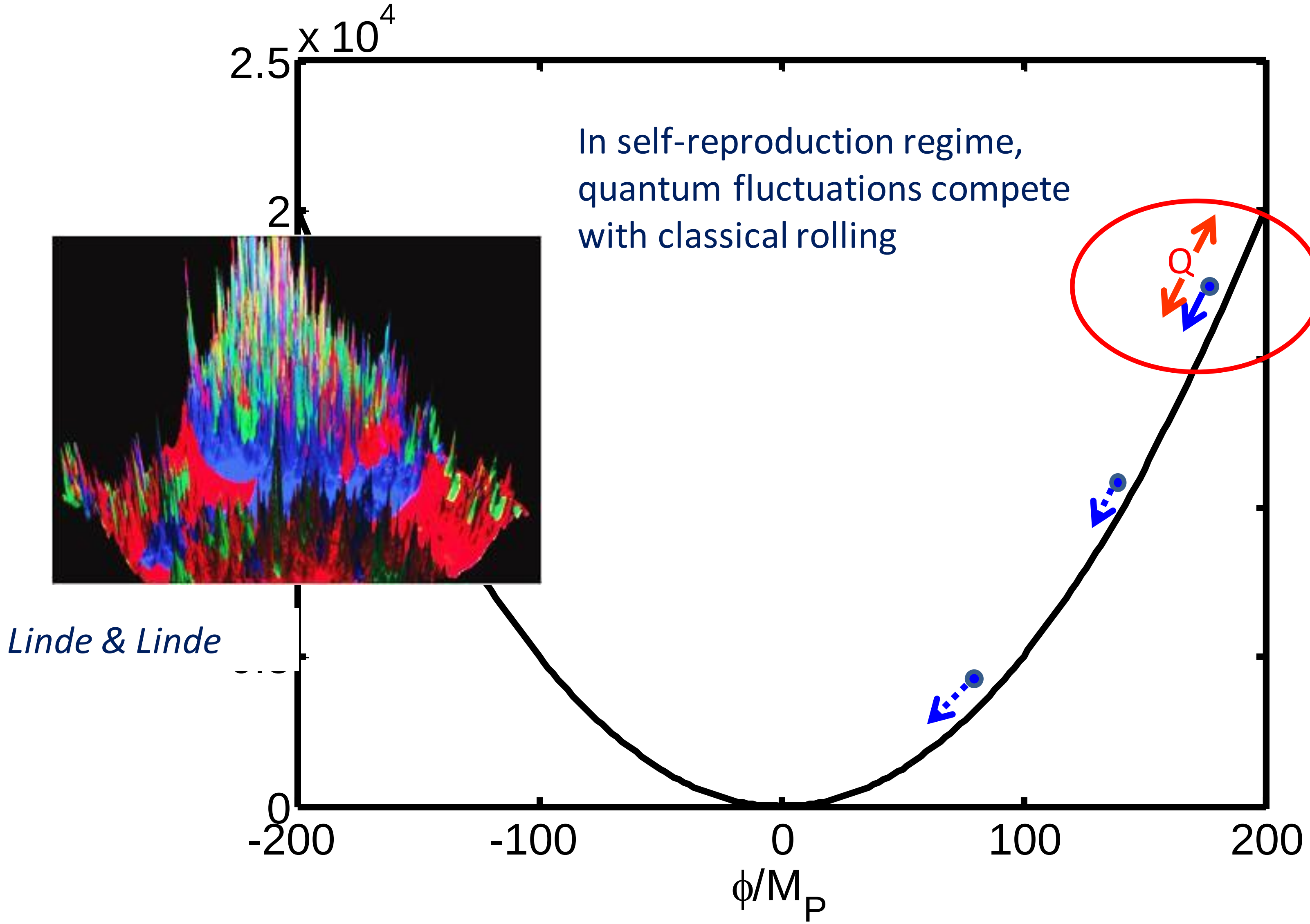
≥ 1 for self-reproduction


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

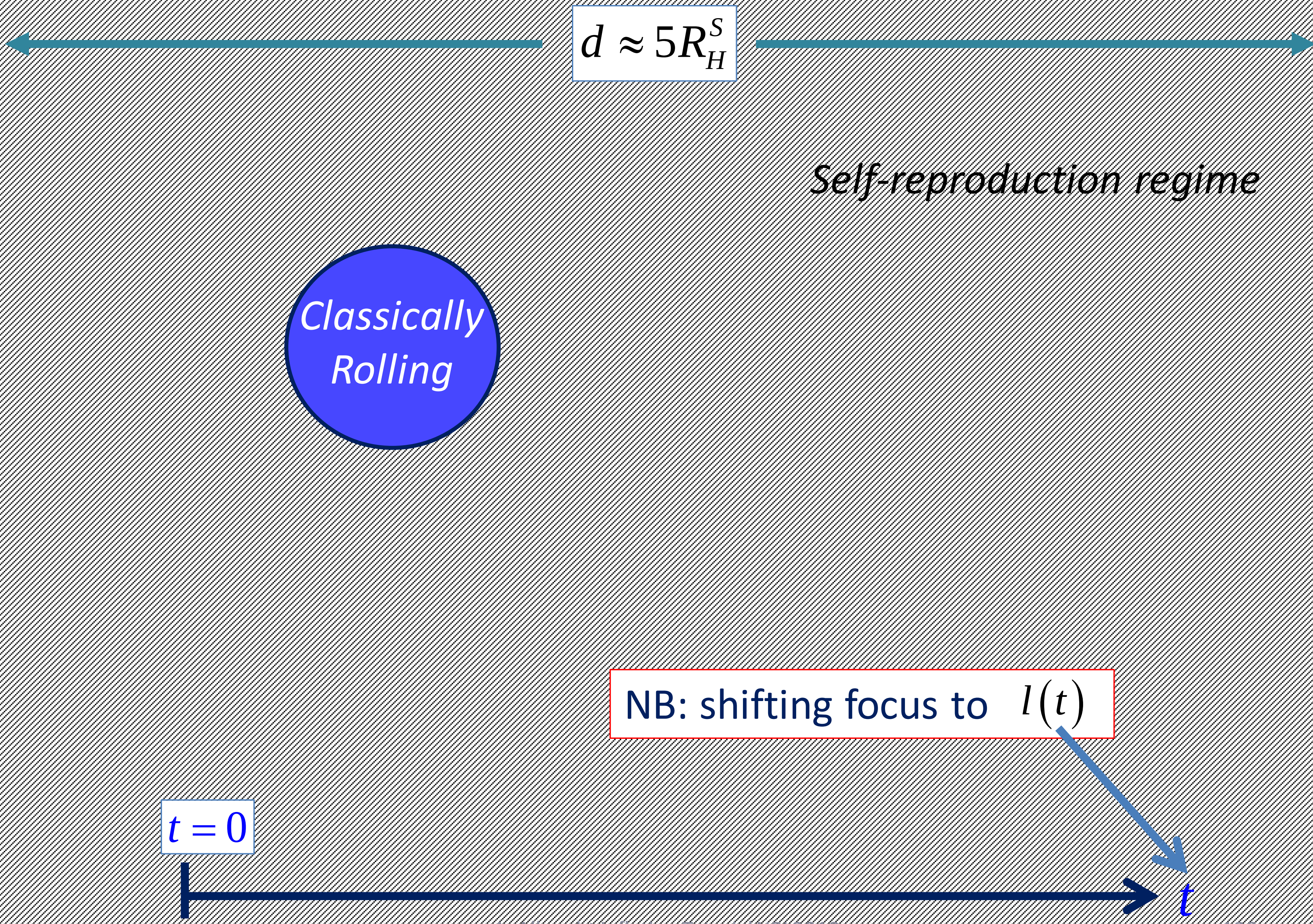
$d \approx 5R_H^S$

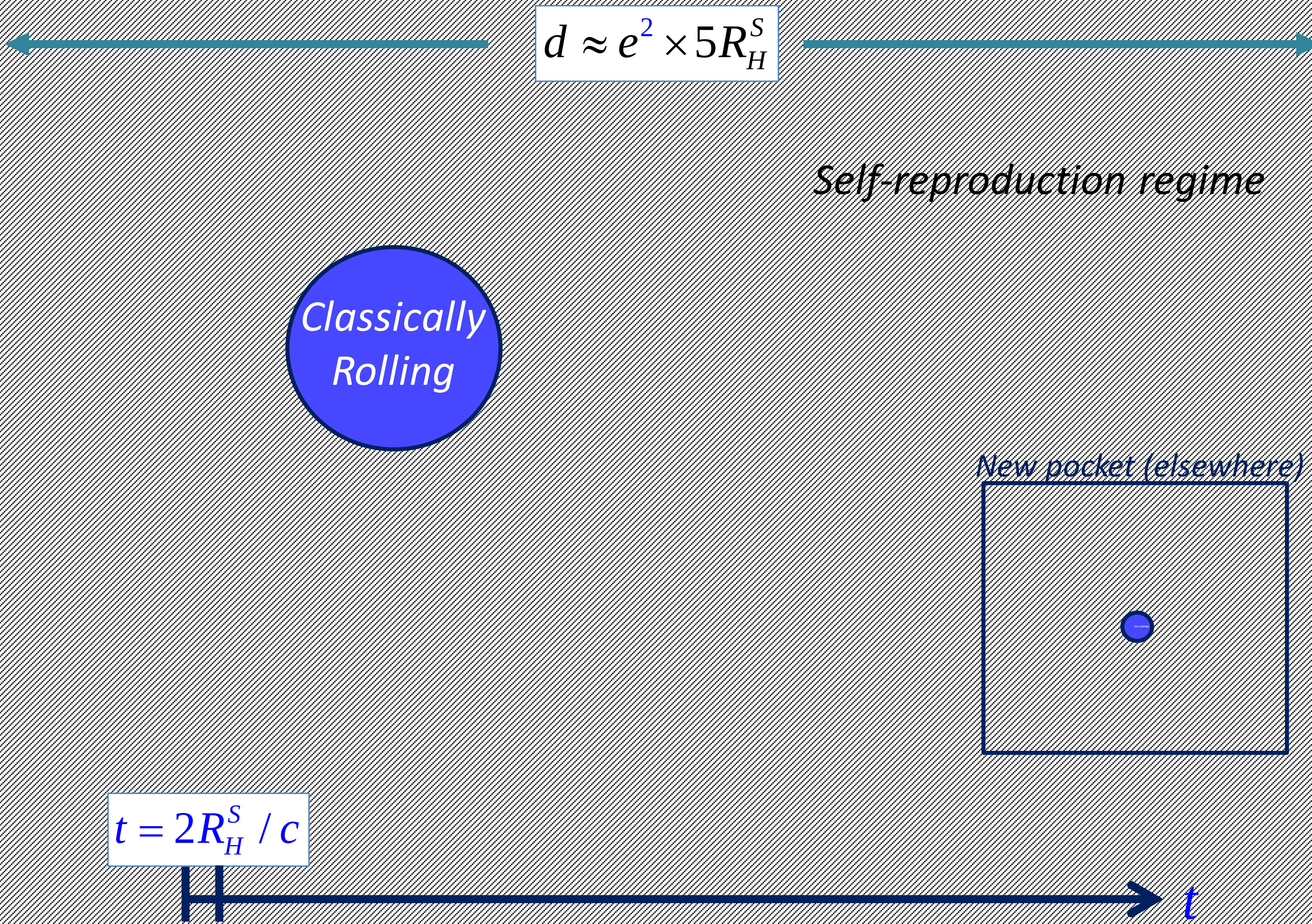
Self-reproduction regime

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

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

Self-reproduction regime

Classically Rolling

New pocket (elsewhere)

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

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

t

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

Self-reproduction regime

New pocket (elsewhere)

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

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

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

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

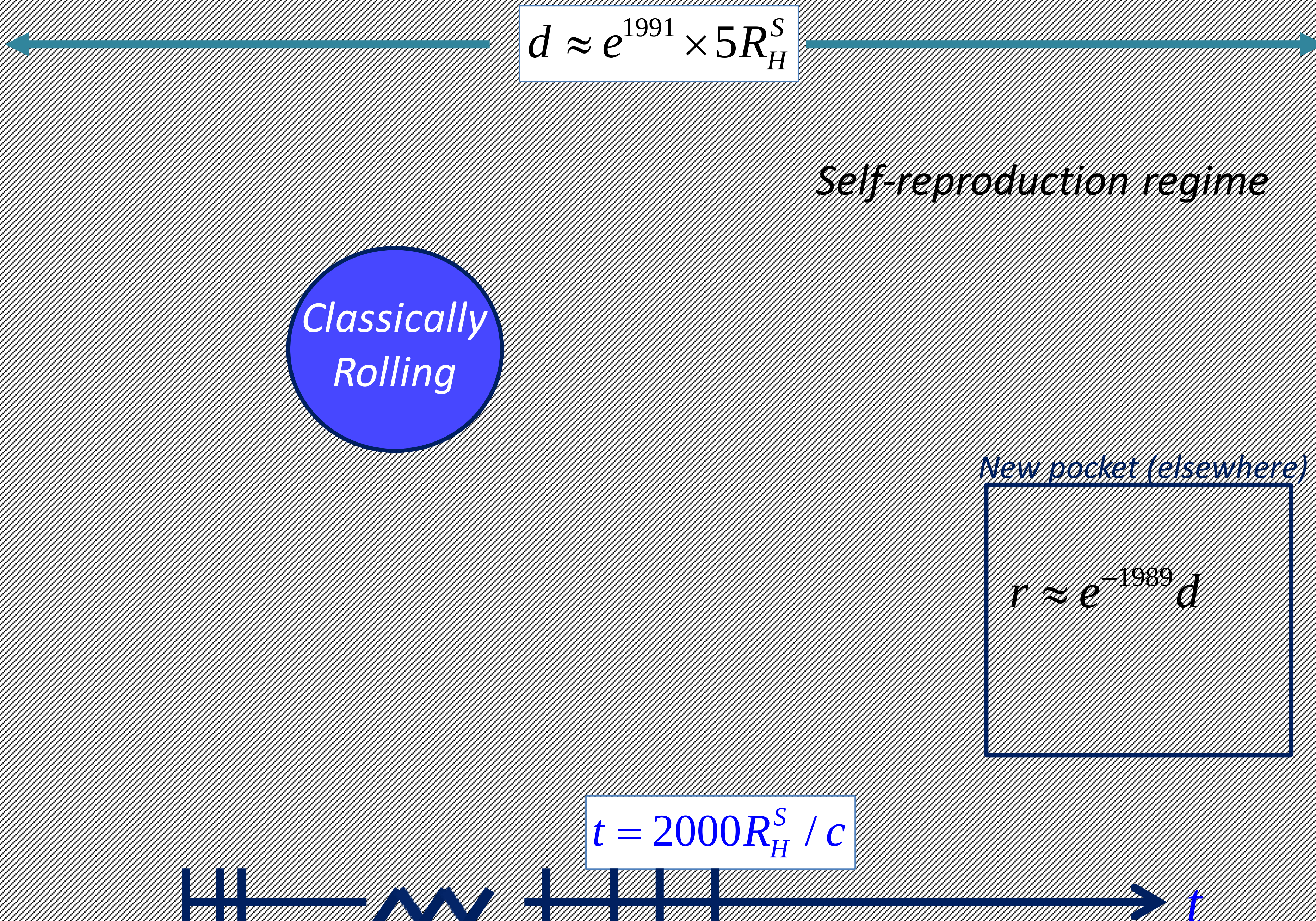
Classically Rolling

New pocket (elsewhere)

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

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

t


$d \approx e^{1991} \times 5 R_H^S$
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)

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

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

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

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

New pocket (elsewhere)

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

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

Eternal inflation features

- Most of the Universe is always inflating

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

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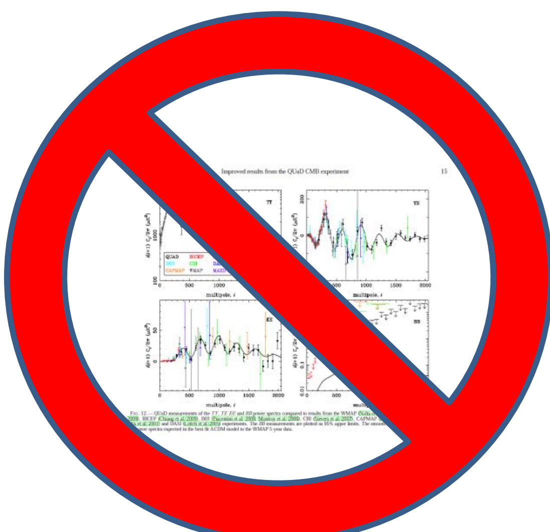

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"Anything that can happen will happened infinitely many times! (A. Guth)

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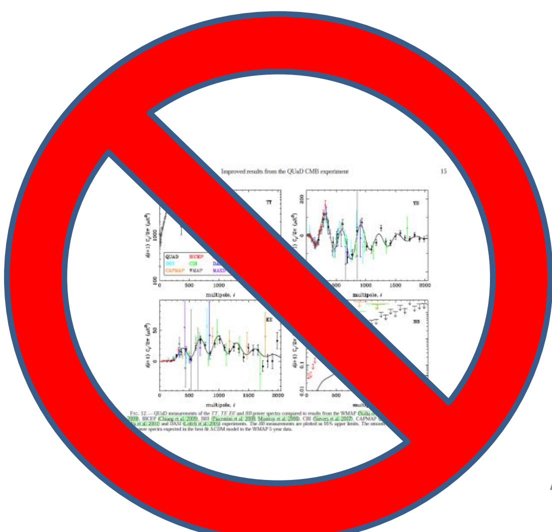

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Eternal inflation features

"True infinity" needed here

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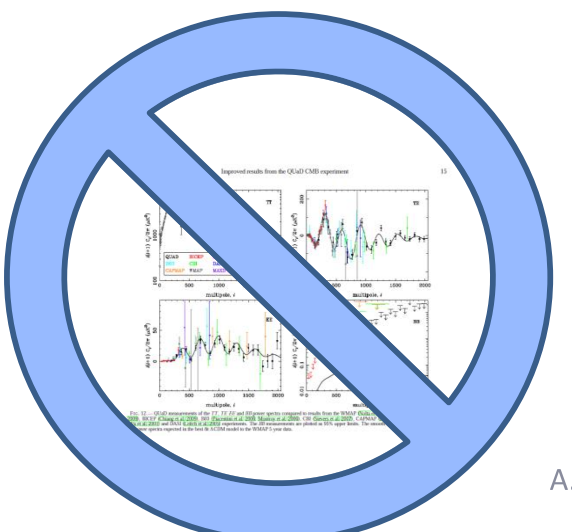

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Hernley, AA & Dray

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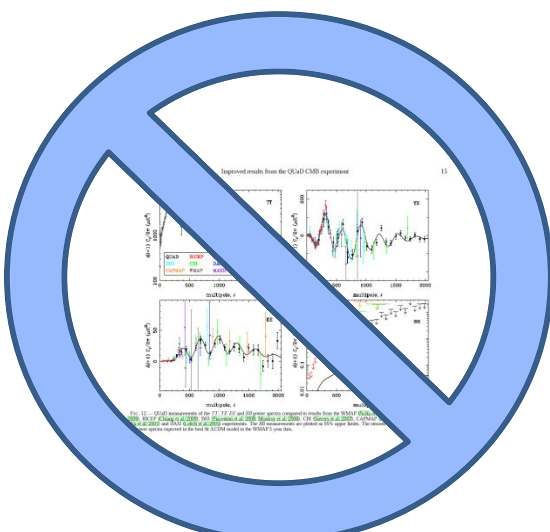

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Eternal inflation

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

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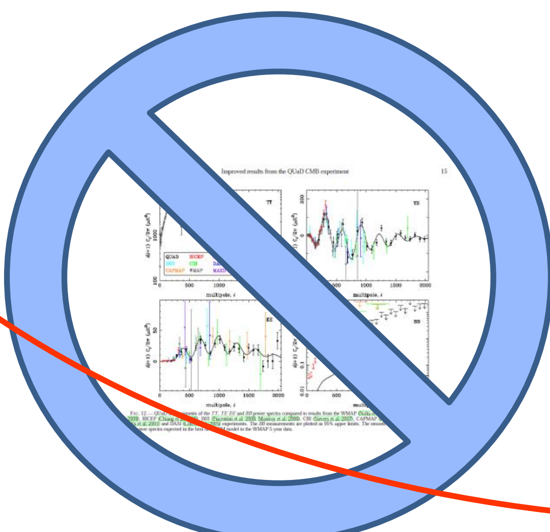

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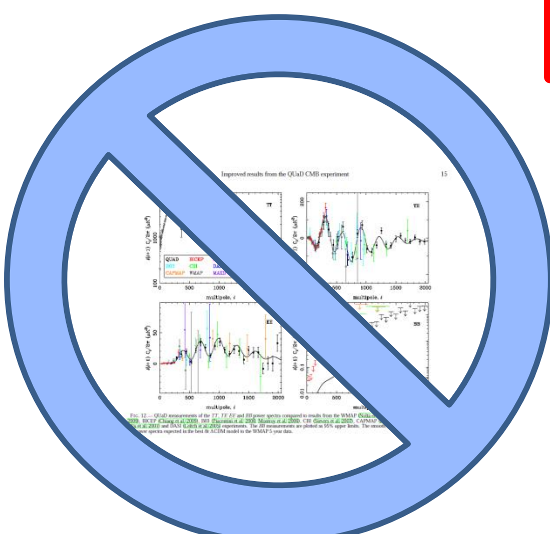
exponentially larger r

"True infinity" needed here

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

em

> Measure problems



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AA & Phillips 2012:
Be careful about
counting arguments.
Many are just wrong!

- Sta
makin
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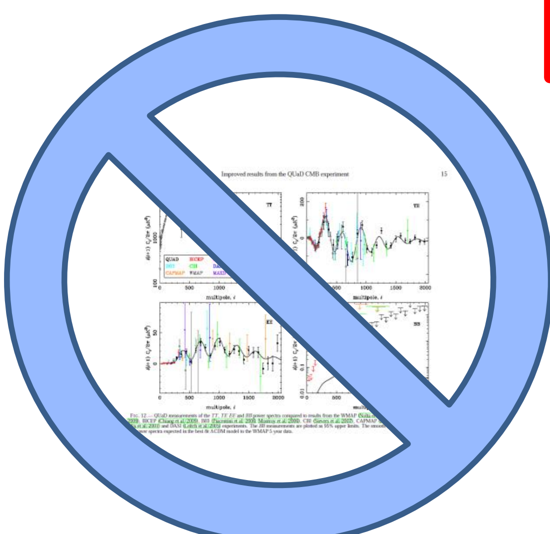

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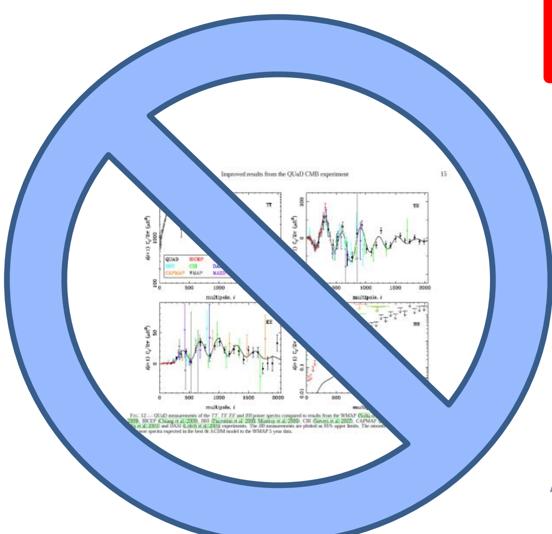

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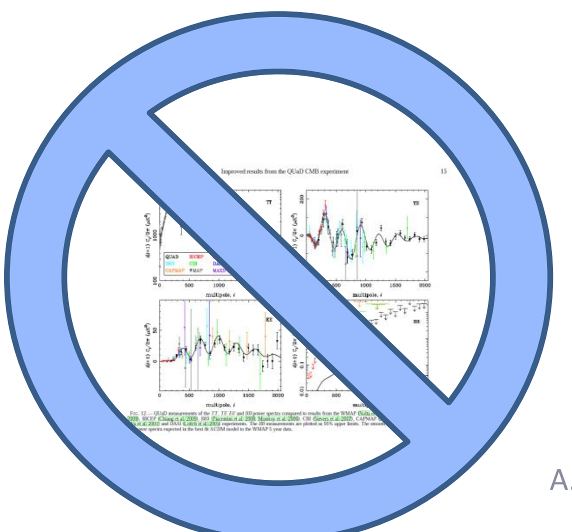

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OUTLINE

1. Big Bang basics
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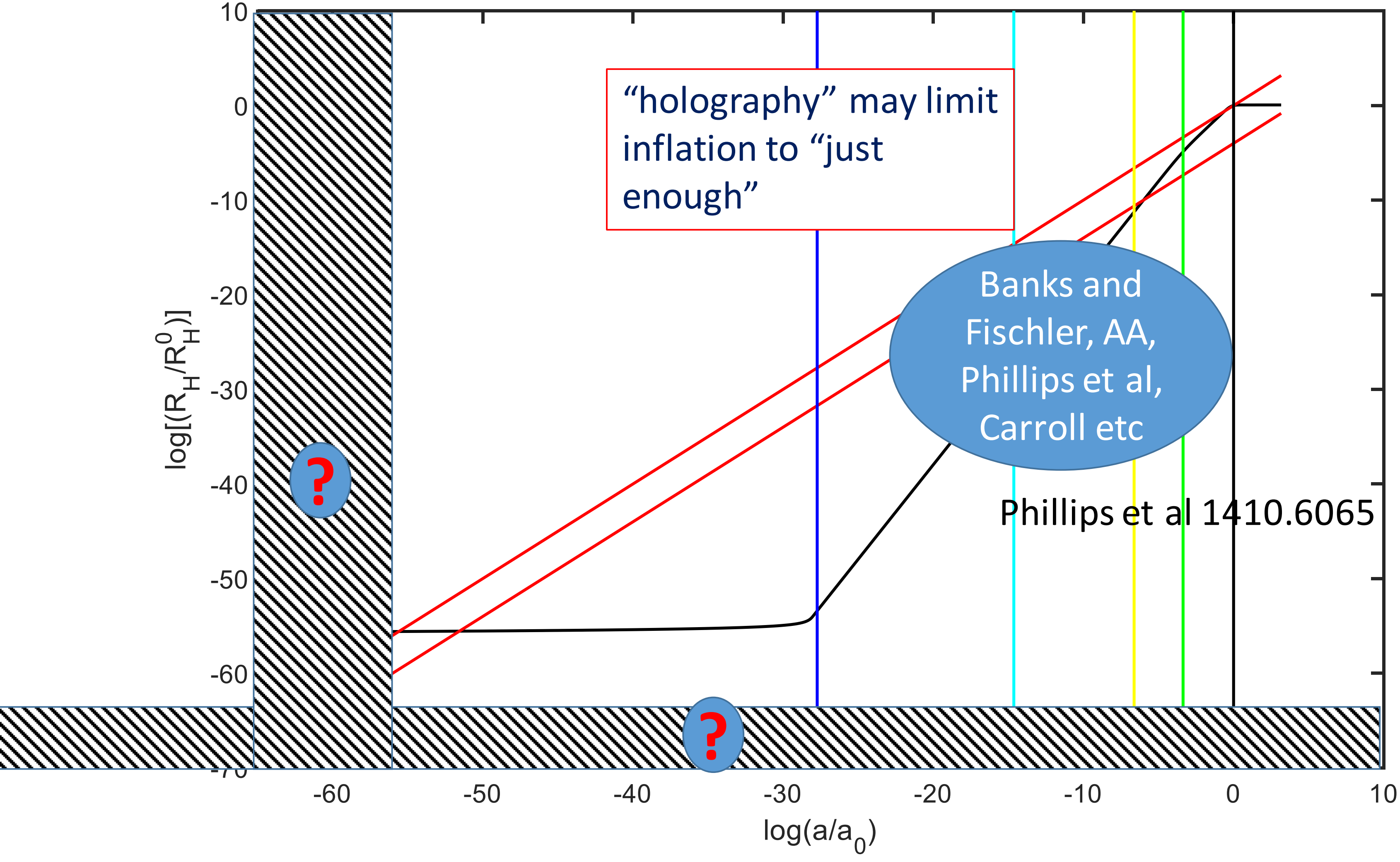
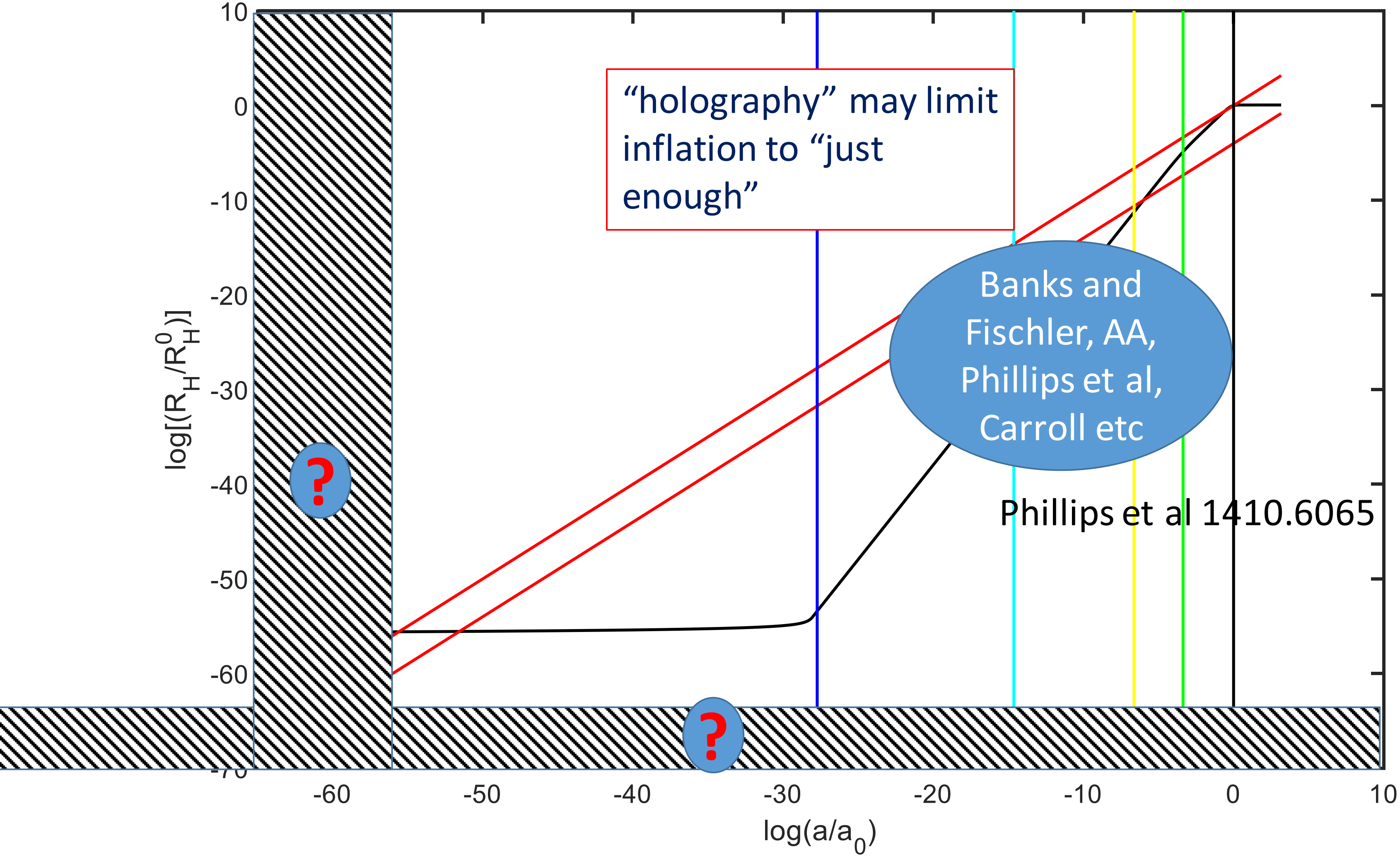


"holography" may limit inflation to "just enough"
Banks and Fischler, AA, Phillips et al, Carroll etc
Phillips et al 1410.6065
?
?
10
0
-10
-20
-30
-40
-50
-60
-70
$\log[(R_H/R_H^0)]$
-60
-50
-40
-30
-20
-10
0
10
$\log(a/a_0)$



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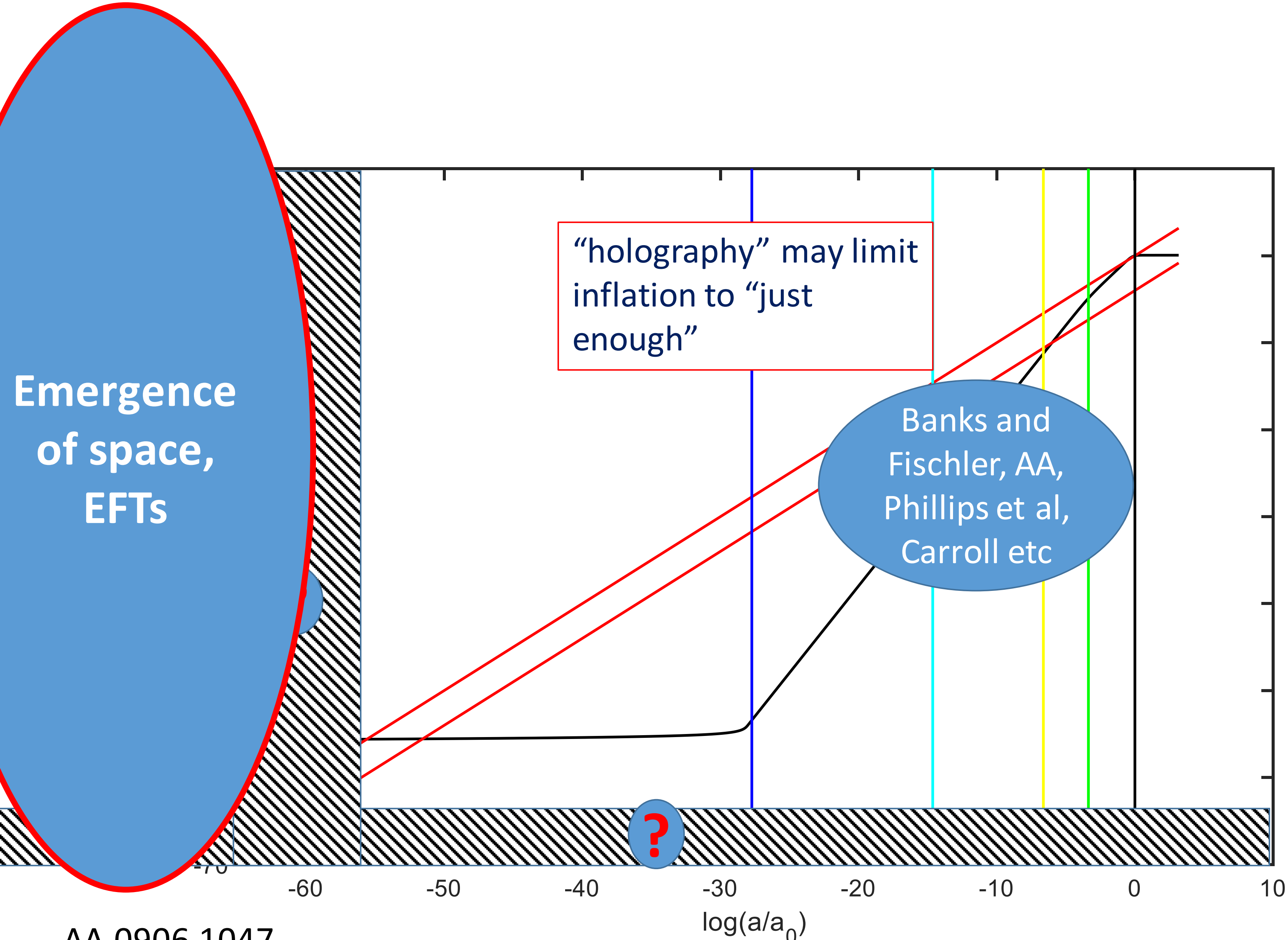
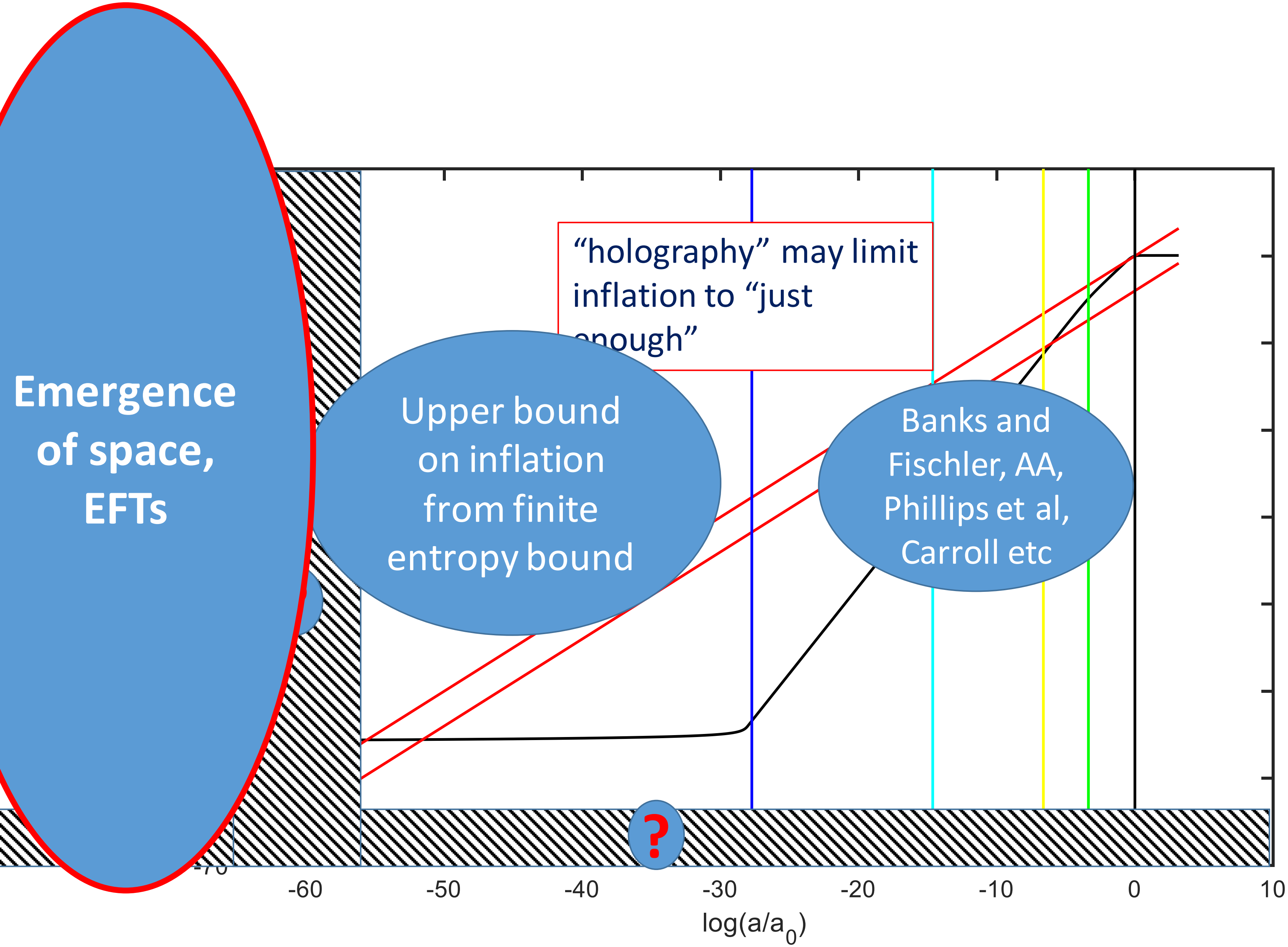
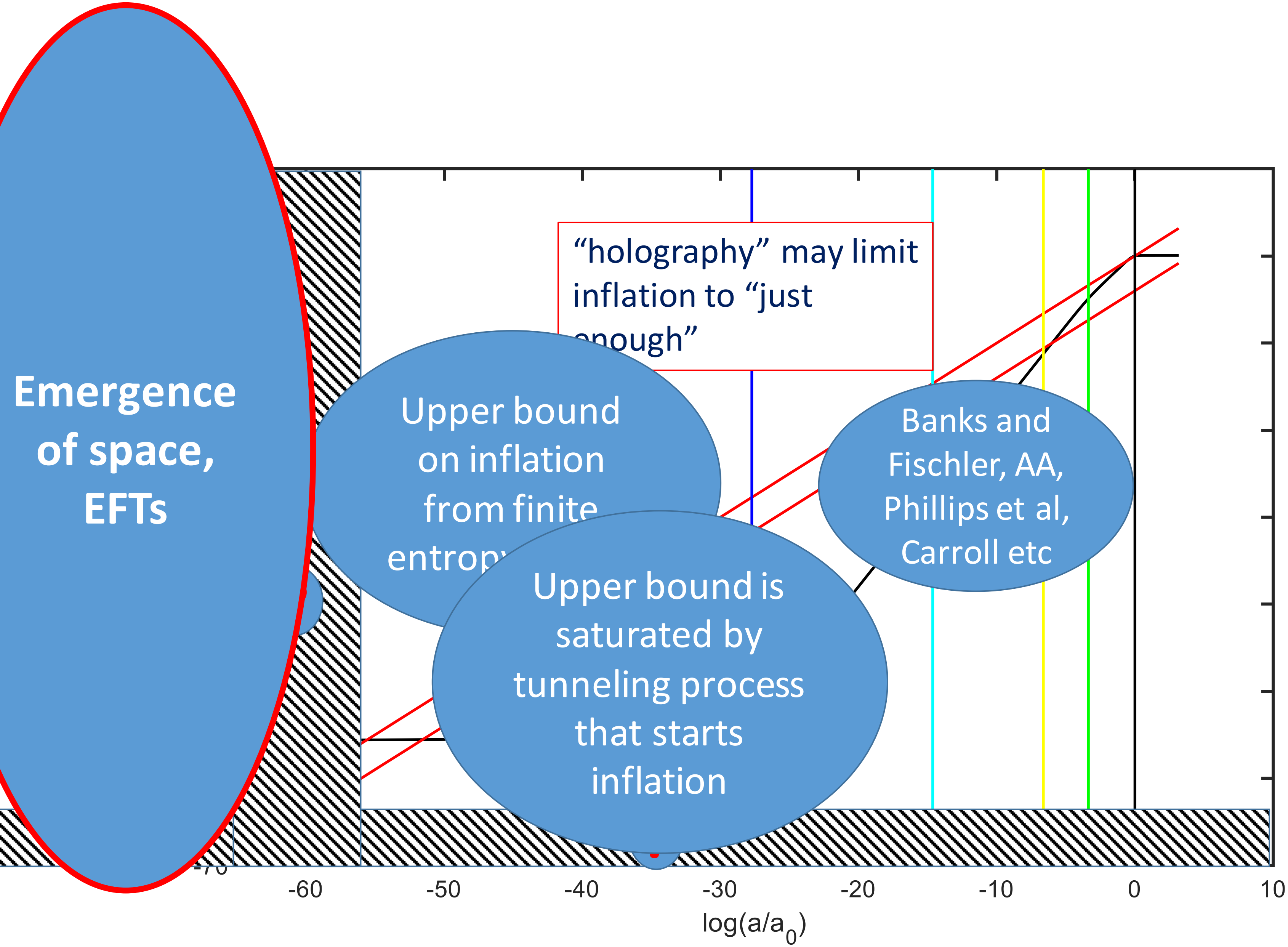


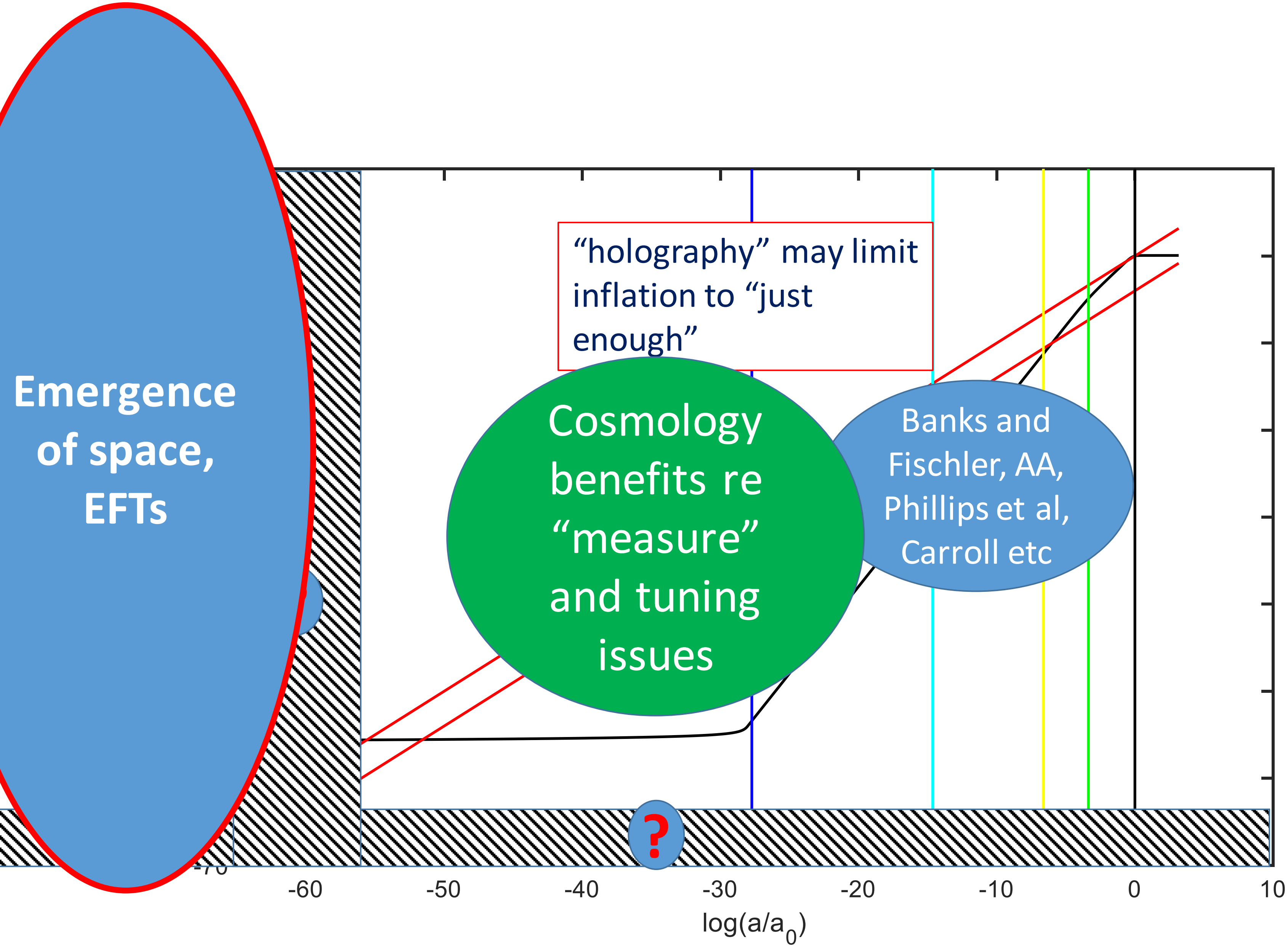
AA 0906.1047
AA and Sorbo, hep-th/0405270
AA 1401.7309



Emergence of space, EFTs
Upper bound on inflation from finite entropy bound
"holography" may limit inflation to "just enough"
Banks and Fischler, AA, Phillips et al, Carroll etc
?
-60
-50
-40
-30
-20
-10
0
10
log(a/a0)



"holography" may limit inflation to "just enough"
Emergence of space, EFTs
Upper bound on inflation from finite entrop
Banks and Fischler, AA, Phillips et al, Carroll etc
Upper bound is saturated by tunneling process that starts inflation
-60
-50
-40
-30
-20
-10
0
10
log(a/a0)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Cosmology benefits re "measure" and tuning issues
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?
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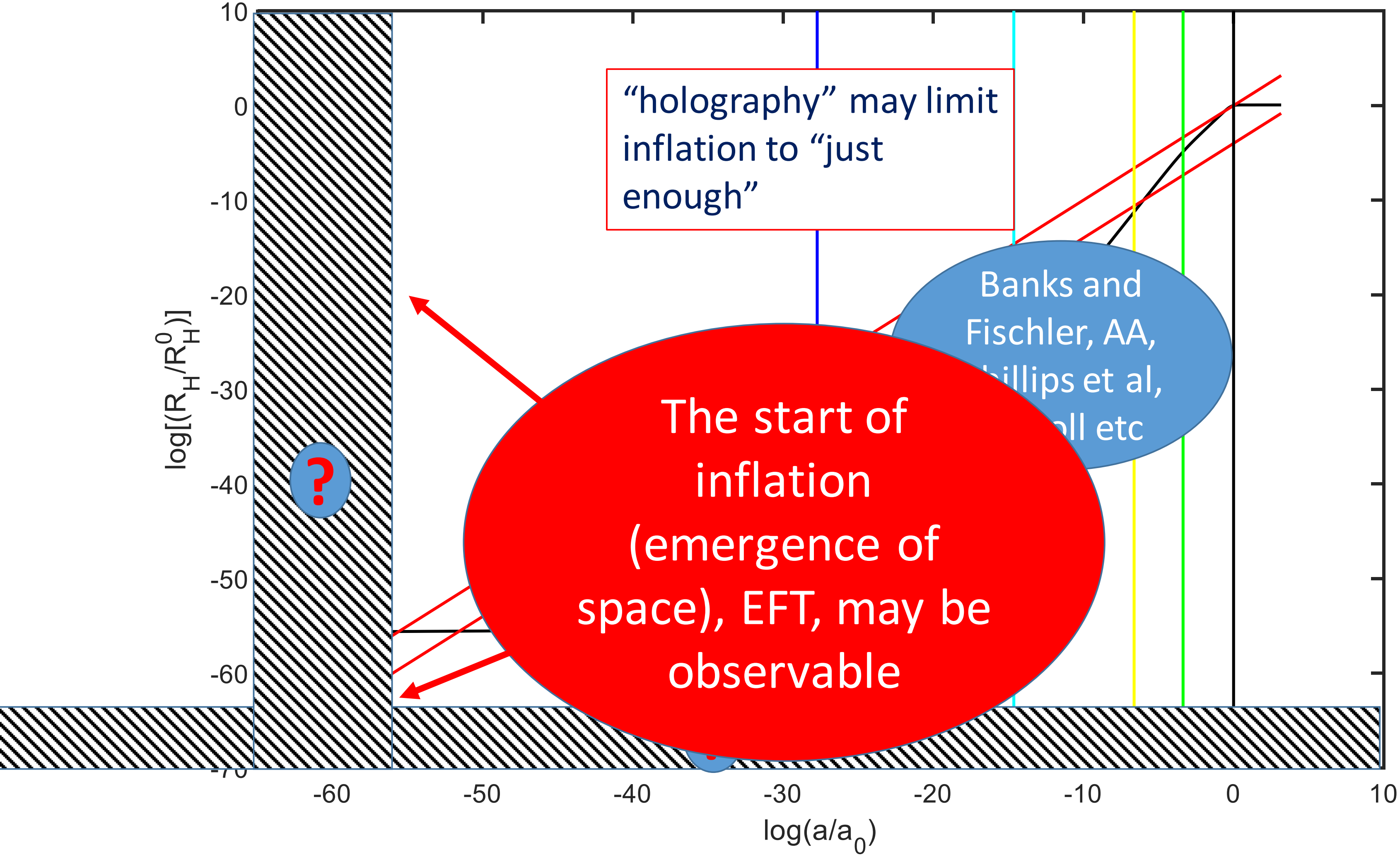
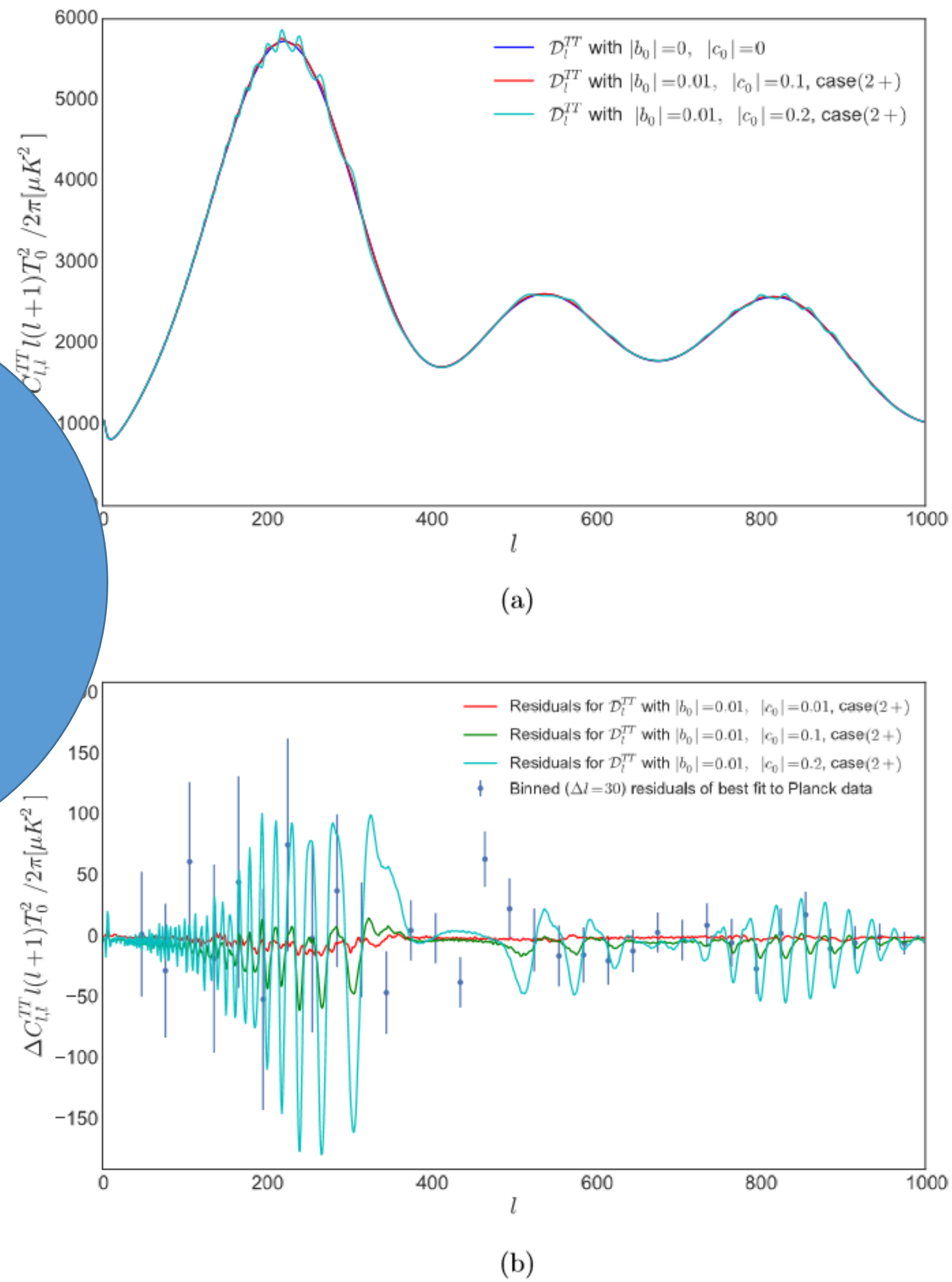


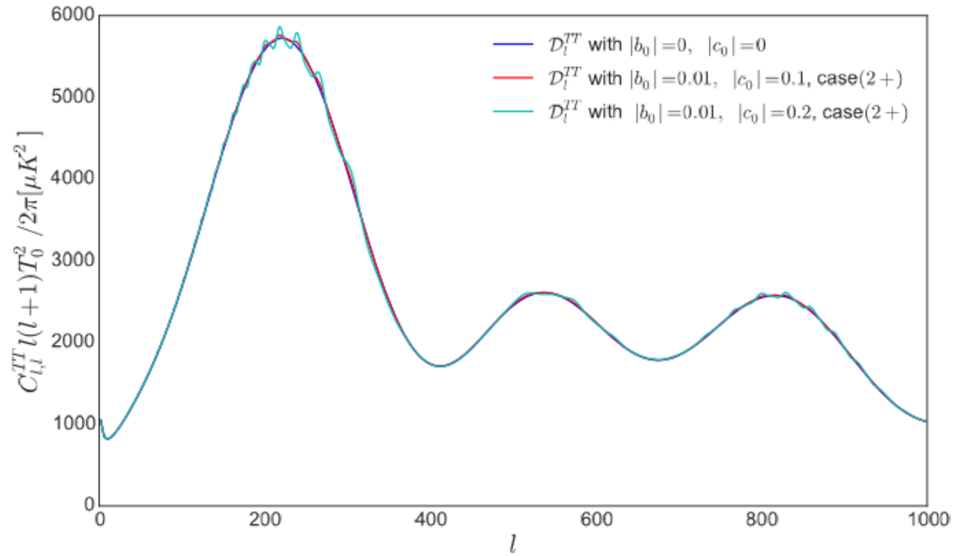
“holography” may limit inflation to “just enough”
Banks and Fischler, AA, Phillips et al, Carroll etc
The start of inflation (emergence of space), EFT, may be observable
?
log[(R_H/R_H^0)]
log(a/a_0)
10
0
-10
-20
-30
-40
-50
-60
-60
-50
-40
-30
-20
-10
0
10

Possible signatures of “short inflation” and quantum entanglement

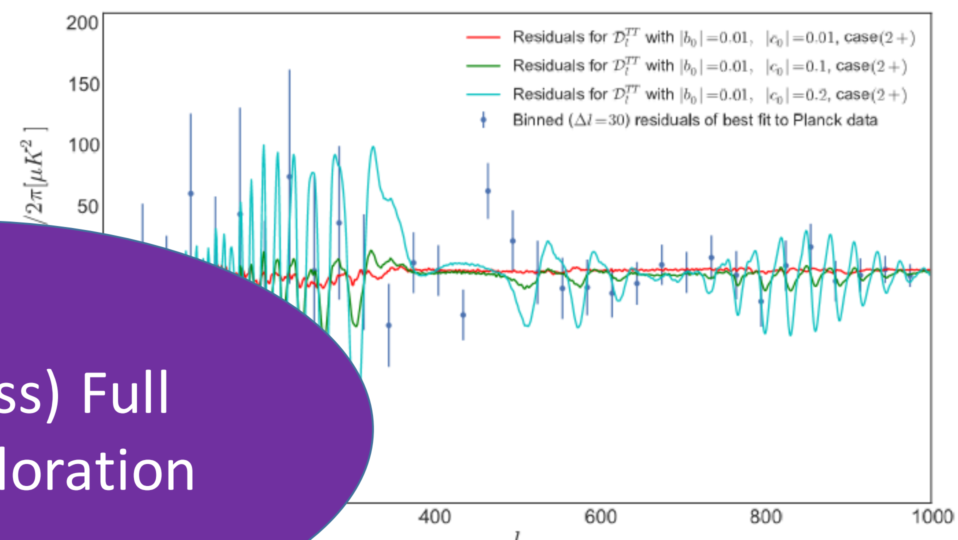


Bolis et al arXiv:1605.01008

Figure 1. (a) Temperature fluctuation angular power spectrum C_l^{TT} for different values of entanglement parameter $|\tilde{C}_{k0}^{+}|$ ($|c_0|$ on plot to simplify labeling), keeping $|\tilde{b}_{k3}(\tau_0)|$ ($|b_0|$ on plot) constant for



(a)



(In progress) Full MCMC exploration

arXiv

With Andrew Arrasmith

Figure 1. (a) Temperature fluctuation angular power spectrum C_l^{TT} for different values of entangle-

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What happened before inflation?

Related to some more contentious topics:

- How well does inflation “solve” tuning problems?
- Eternal inflation

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Need a meta-theory to answer this

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No good one so far

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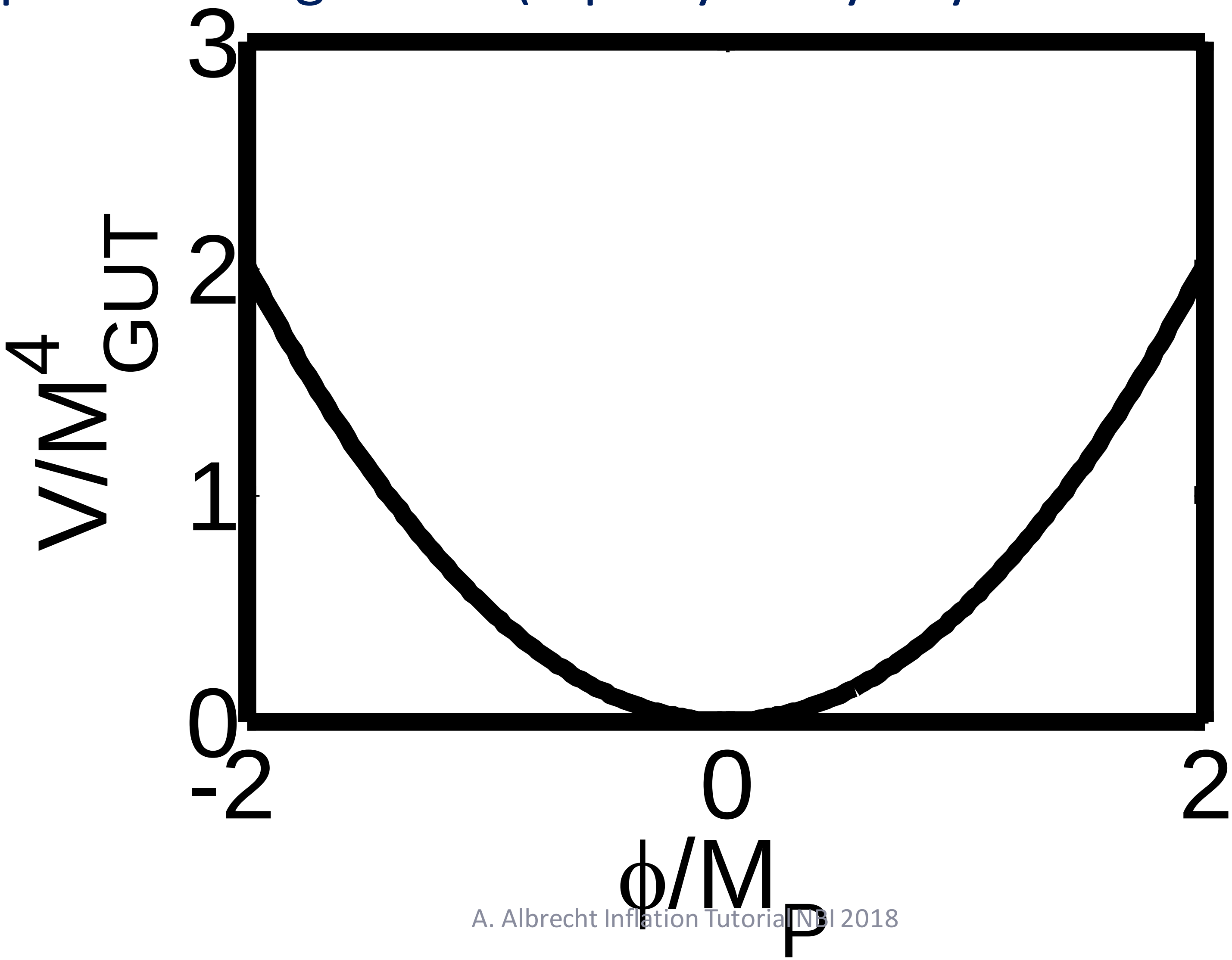
Need a meta-theory to answer

NEXT: A (popular) not good meta theory

No good one so far

Beware "temporal provincialism":

Equipartition argument (equally likely anywhere on potential)



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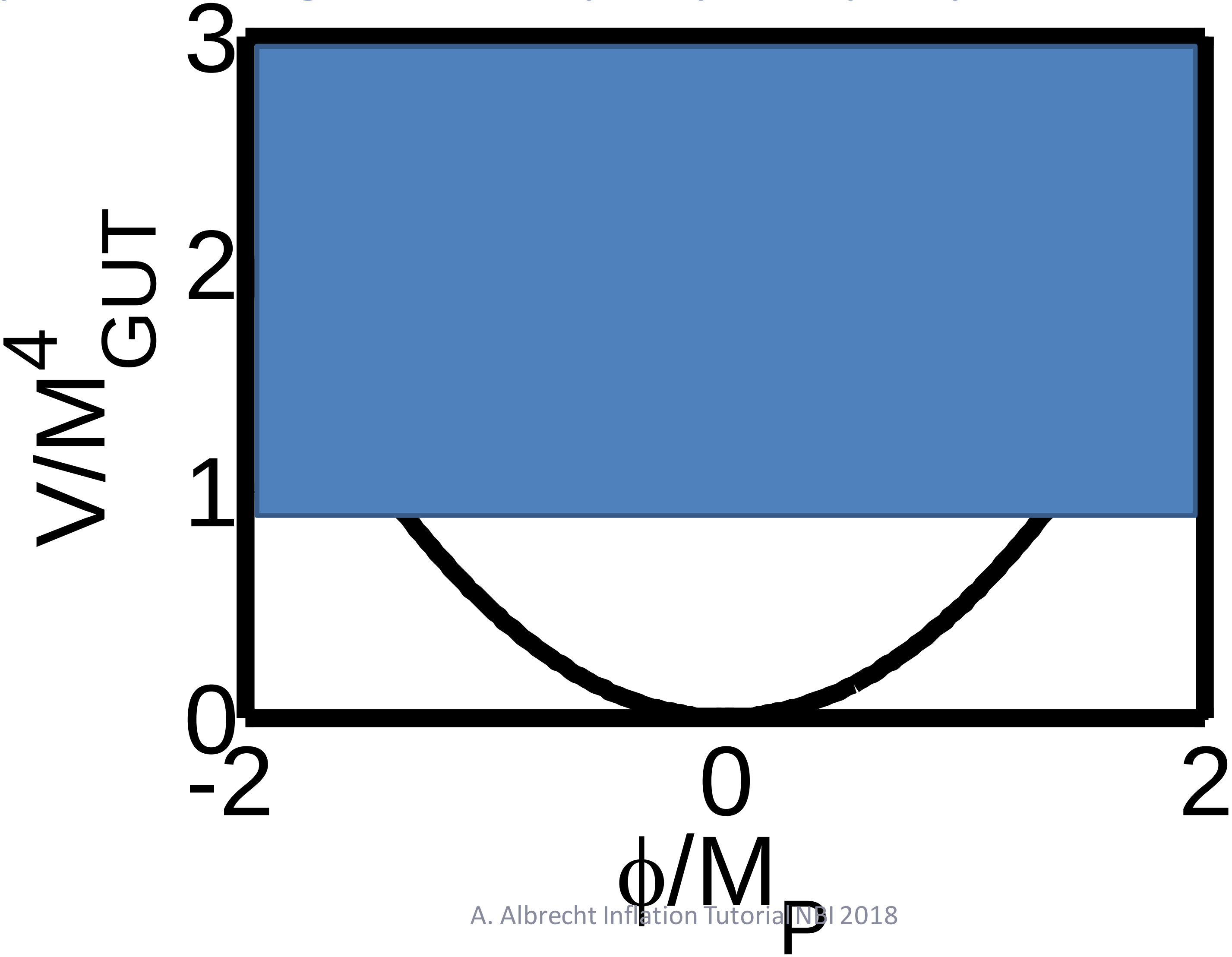

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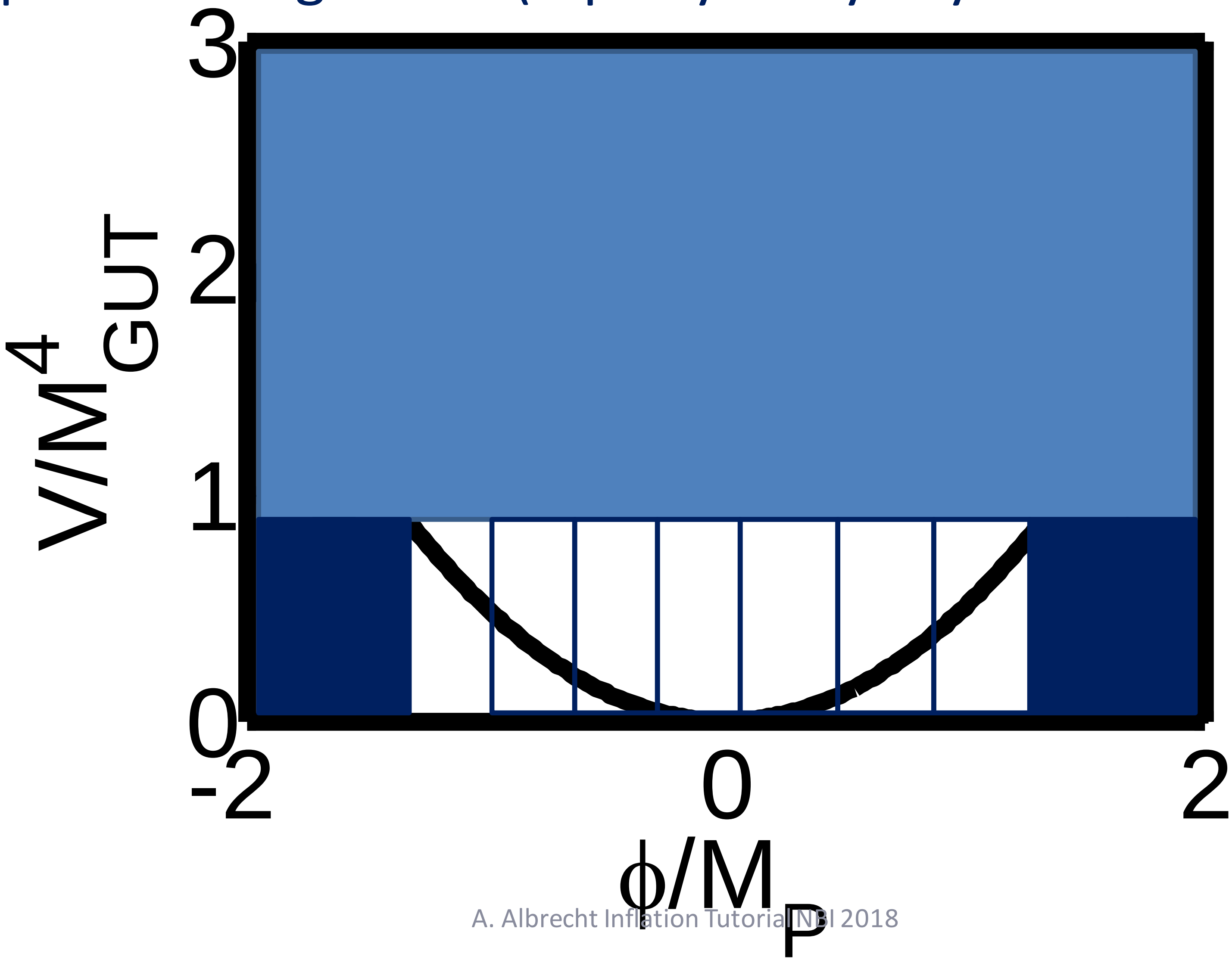

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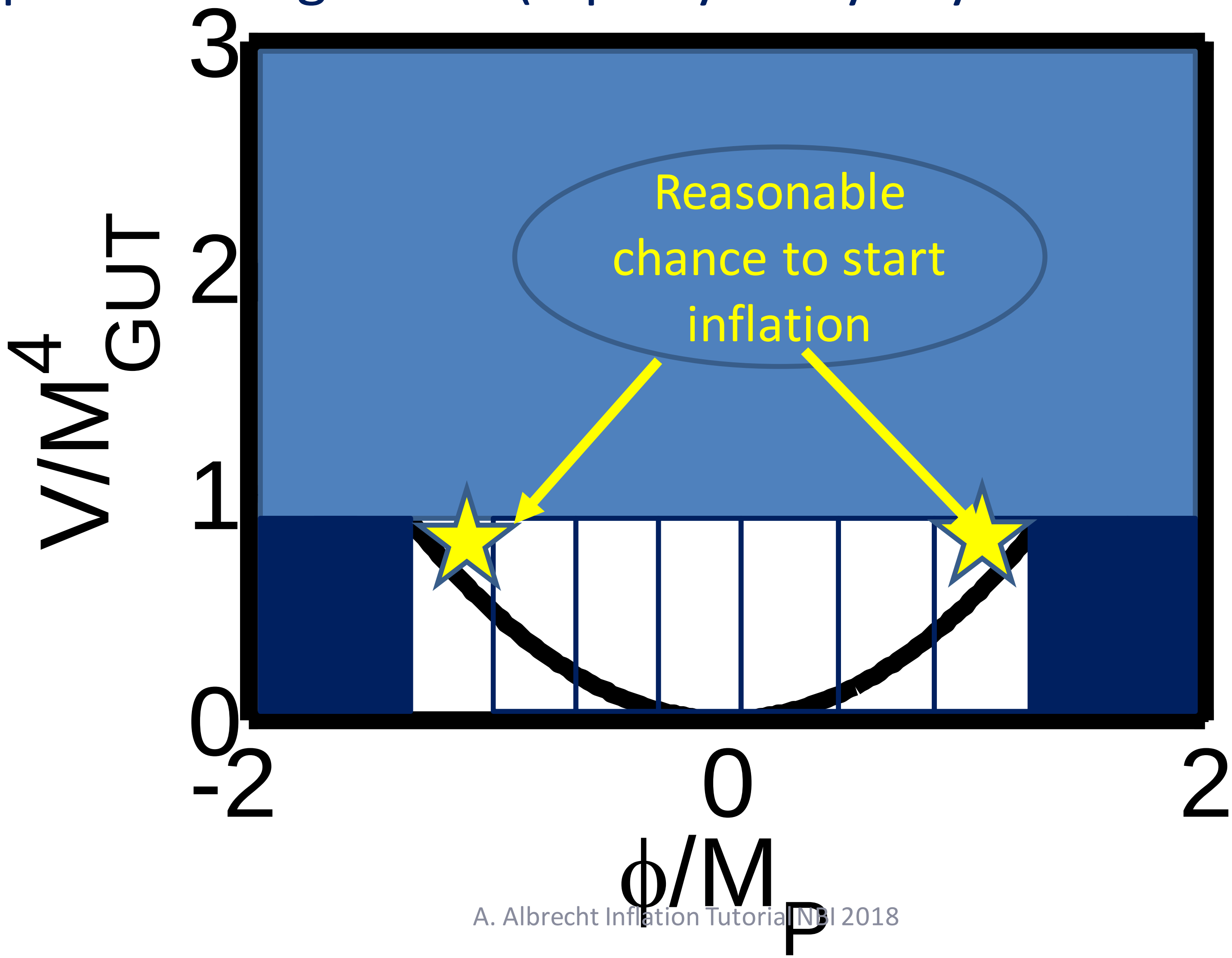

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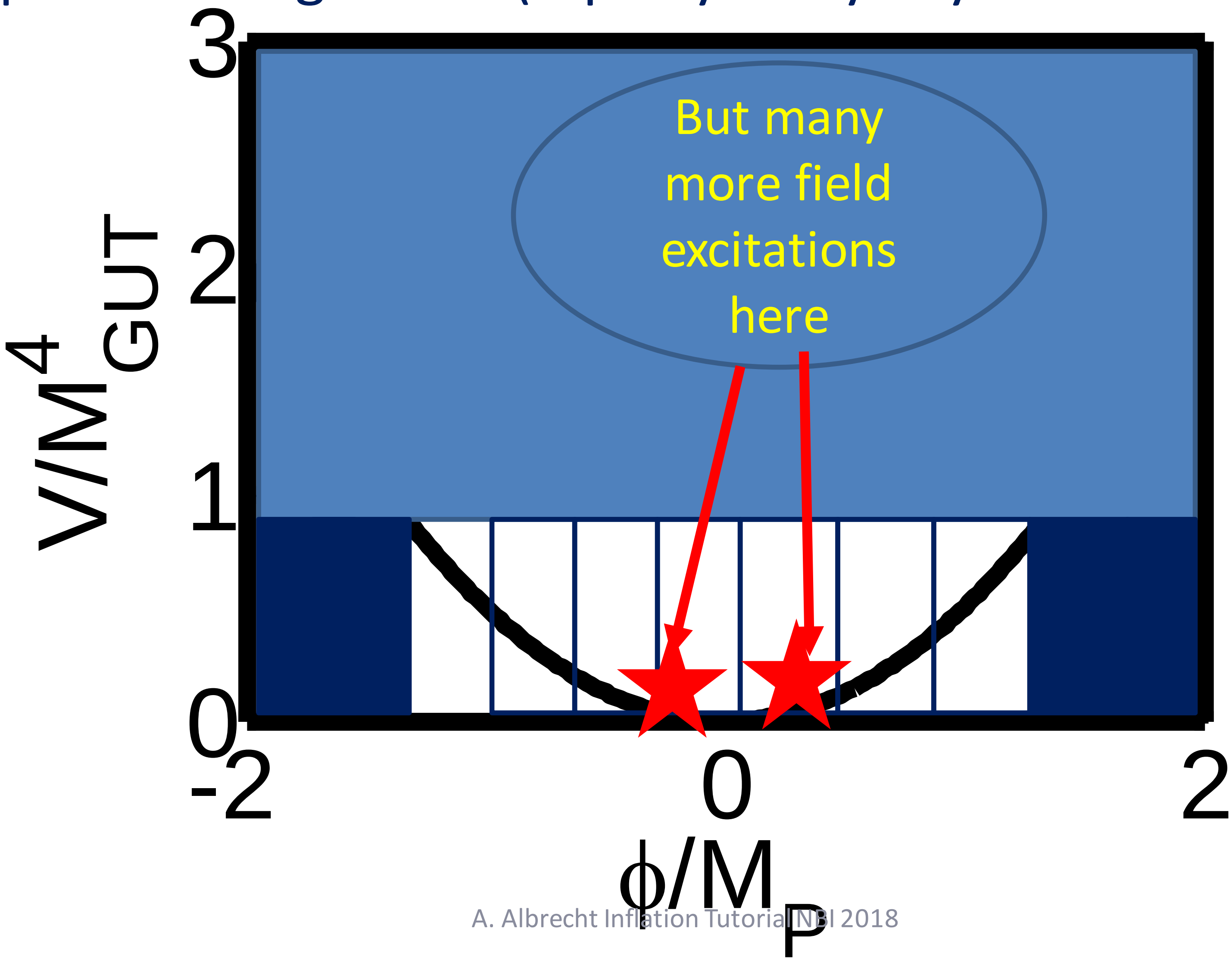

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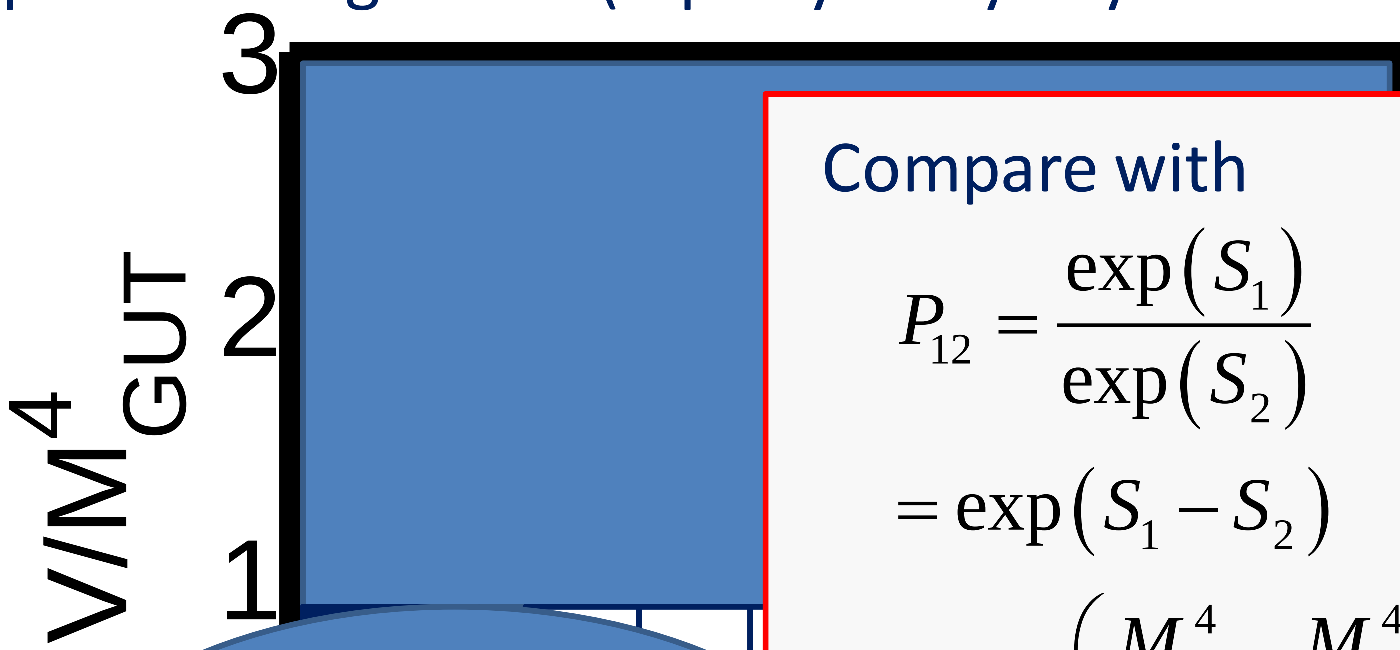

Compare with

$$P_{12} = \frac{\exp(S_1)}{\exp(S_2)}$$

$$= \exp(S_1 - S_2)$$

$$= \exp\left(\frac{M_P^4}{V_1} - \frac{M_P^4}{V_2}\right)$$

$$\approx \exp\left(-\frac{M^4}{V_2}\right)$$

Plus de Sitter entropy arguments give exponential suppression of higher *V* values

AA and Sorbo, hep-th/0405270

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Compare with numerical "solution" of initial conditions problem

Entropy arguments give exponential suppression of higher *V* values

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East et al 1511.05143
Braden et al 1604.04001
Clough et al 1608.04408

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All are temporally
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Entropy arguments
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What happened before inflation?

Related to some more contentious topics:

- How well does inflation “solve” tuning problems?
- Eternal inflation

Need a meta-theory to answer this

No good one so far

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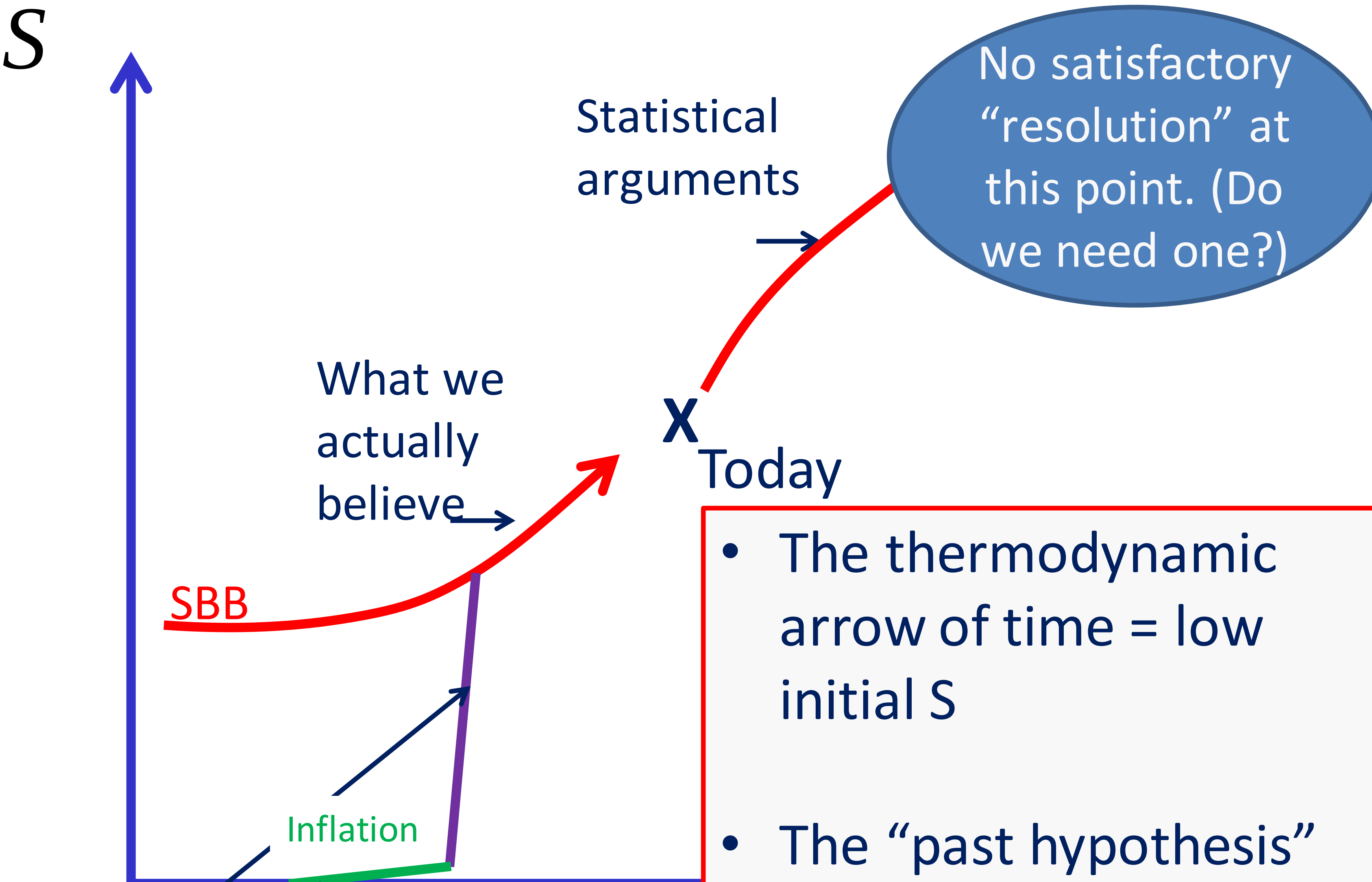
Not clear whether a good meta theory would favor inflation over just the SBB with correct initial conditions

No good one so far



- The thermodynamic arrow of time = low initial S

- The “past hypothesis”

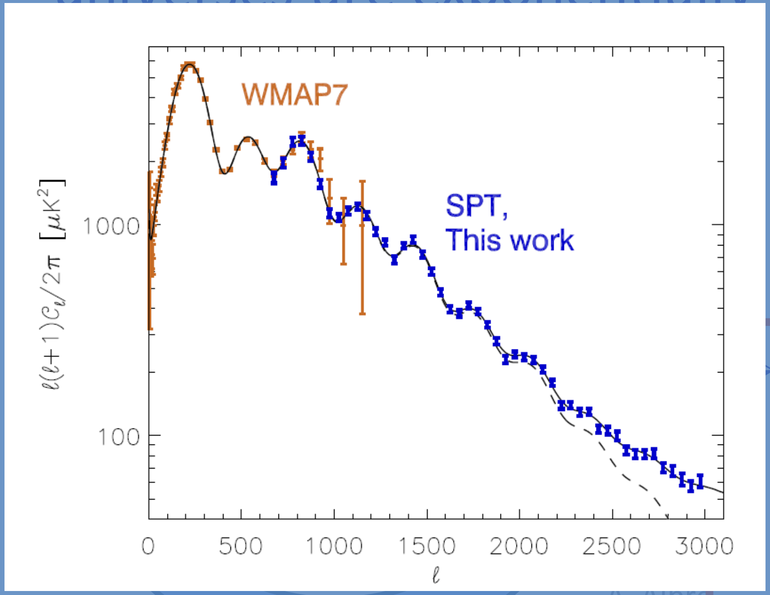
= “Fine tuning”

Adding reheating and inflation seems to make all this “worse”

Eternal inflation features

"True infinity" needed here

- Most of the Universe is always inflating
- Leads to infinite Universe, infinitely many pocke
  self-reproduction phase lasts forever.
- Inflation "takes over the Universe", seems like a good theory of initial conditions.
- Need to regulate ∞'s to make predictions, typically use a cutoff.
- For a specific time cutoff, the most recently produced pocket universes are exponentially favored (produced in an



➢ Young universe problem

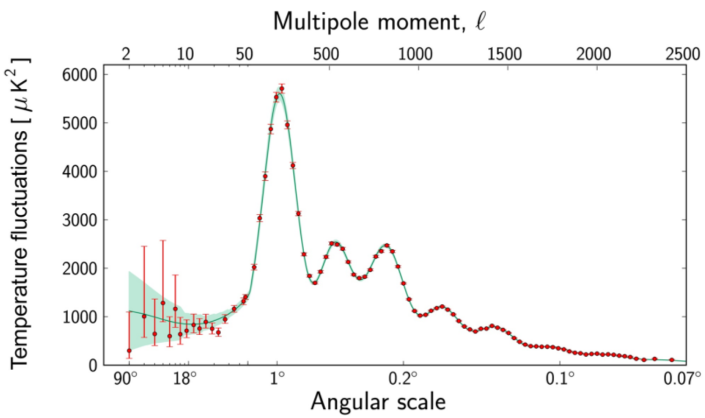
Or, just be happy we have equations to solve?

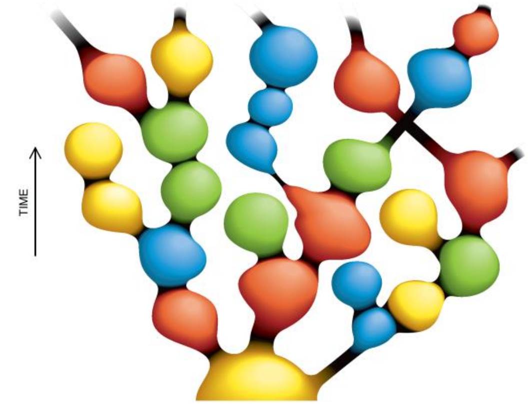
➢ State o

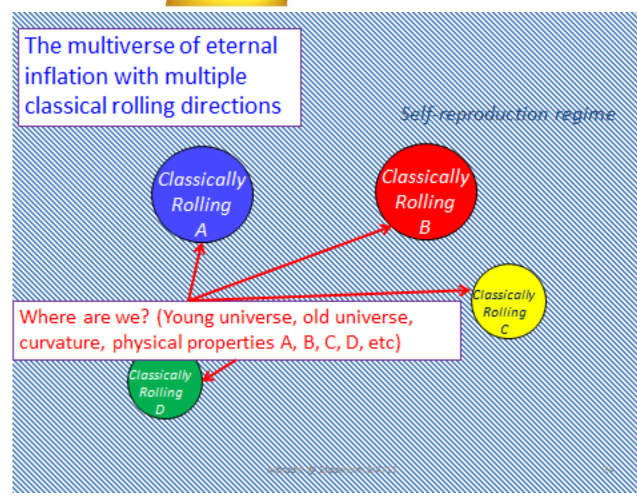
making predictions, the experts are using the data to infer the "correct measure"

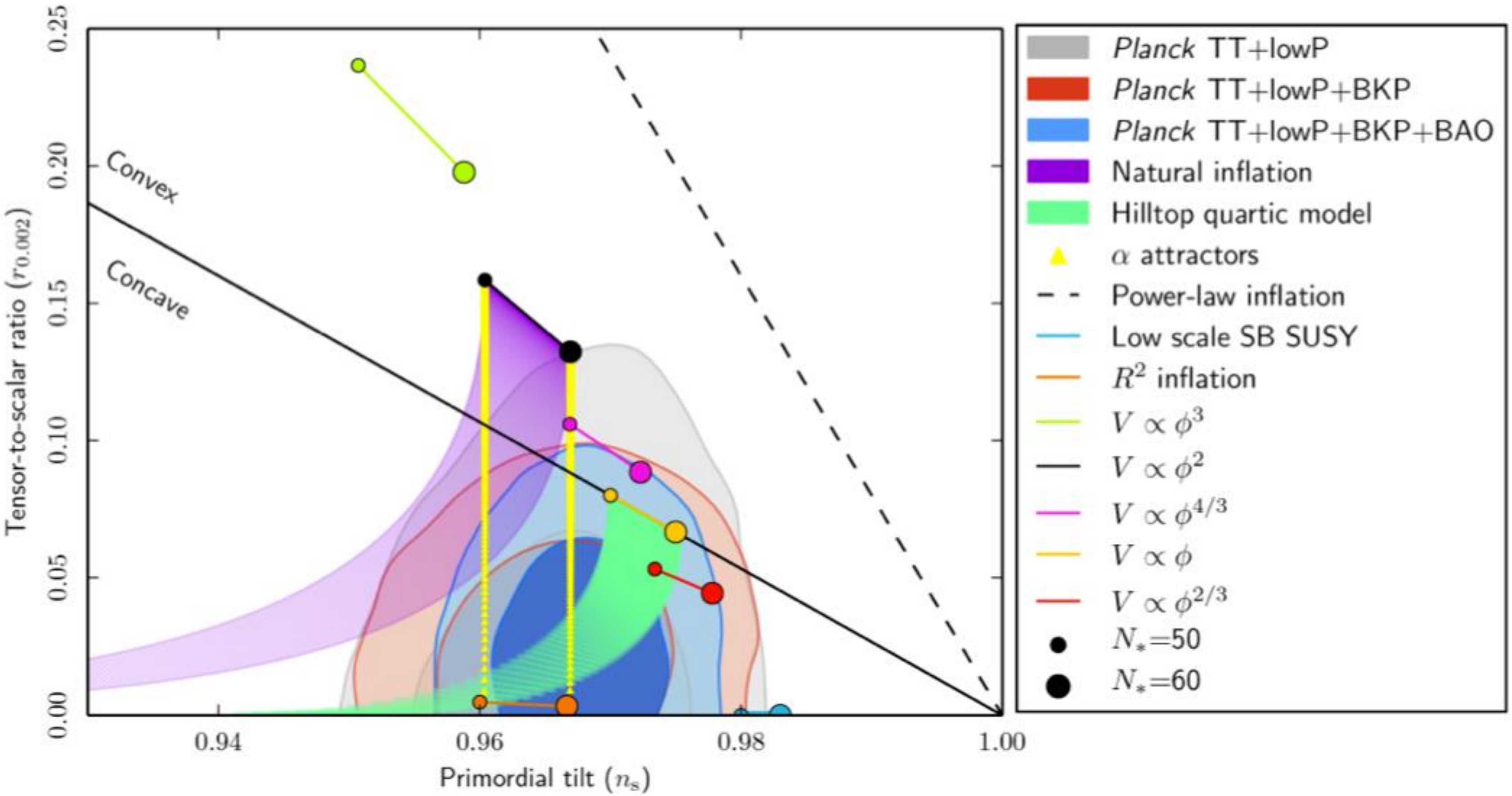
Cosmic Inflation:

Consumers & Producers









https://www.aanda.org/articles/aa/full_html/2016/10/aa25898-15/aa25898-15.html
fig 55

Conclusions

A) Inflation is a technical tool for connecting cosmological observables with high energy physics. Impressive successes.

B) However, without a meta theory about how inflation started (and how it "competes" with other scenarios, such as the SBB) big questions are unresolved.

C) Complex sociology as different individuals choose to give A) and B) different weight.

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My priors