Cosmic Inflation

Phy 262
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Andreas Albrecht

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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.

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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

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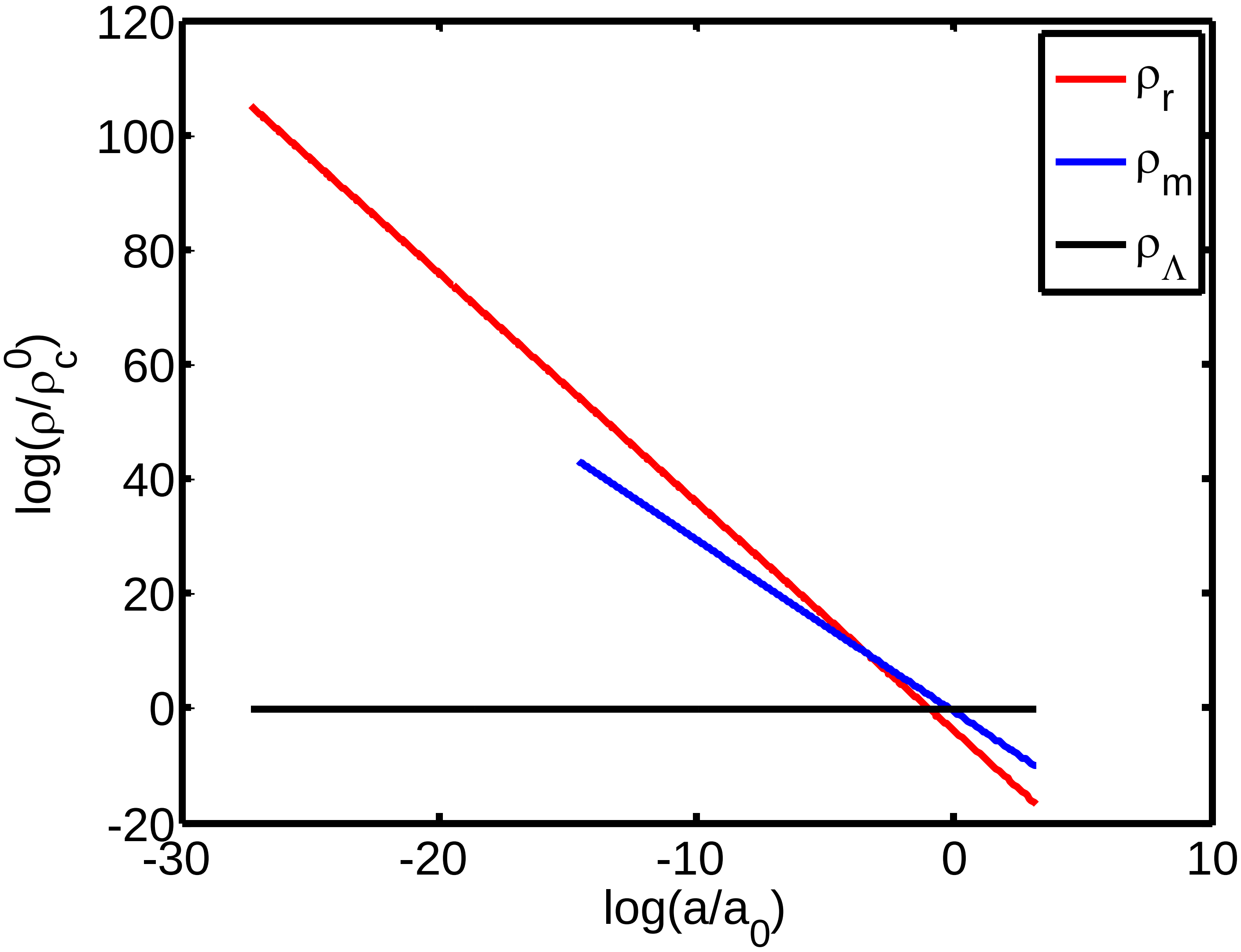
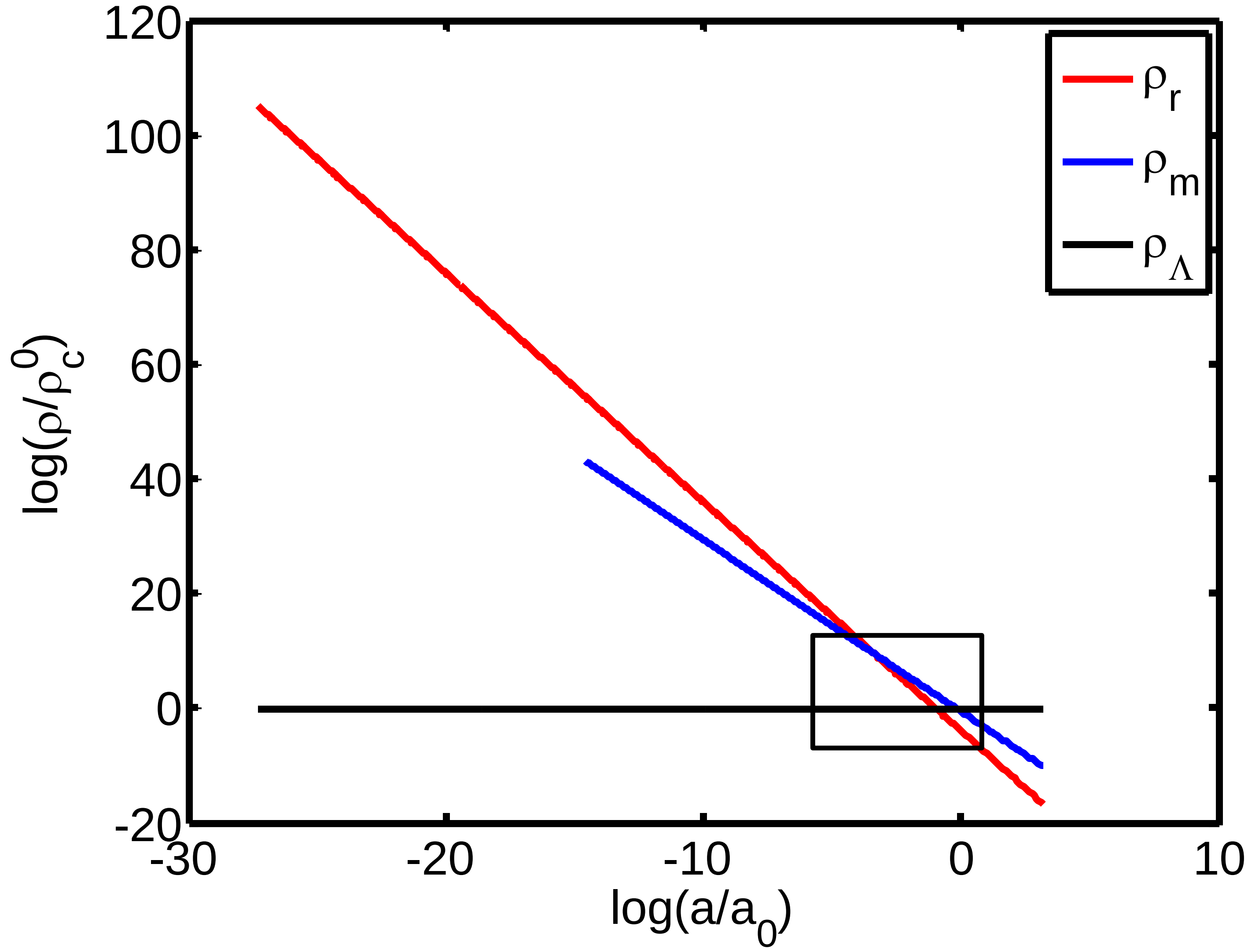
Evolution of Cosmic Matter



Evolution of Cosmic Matter



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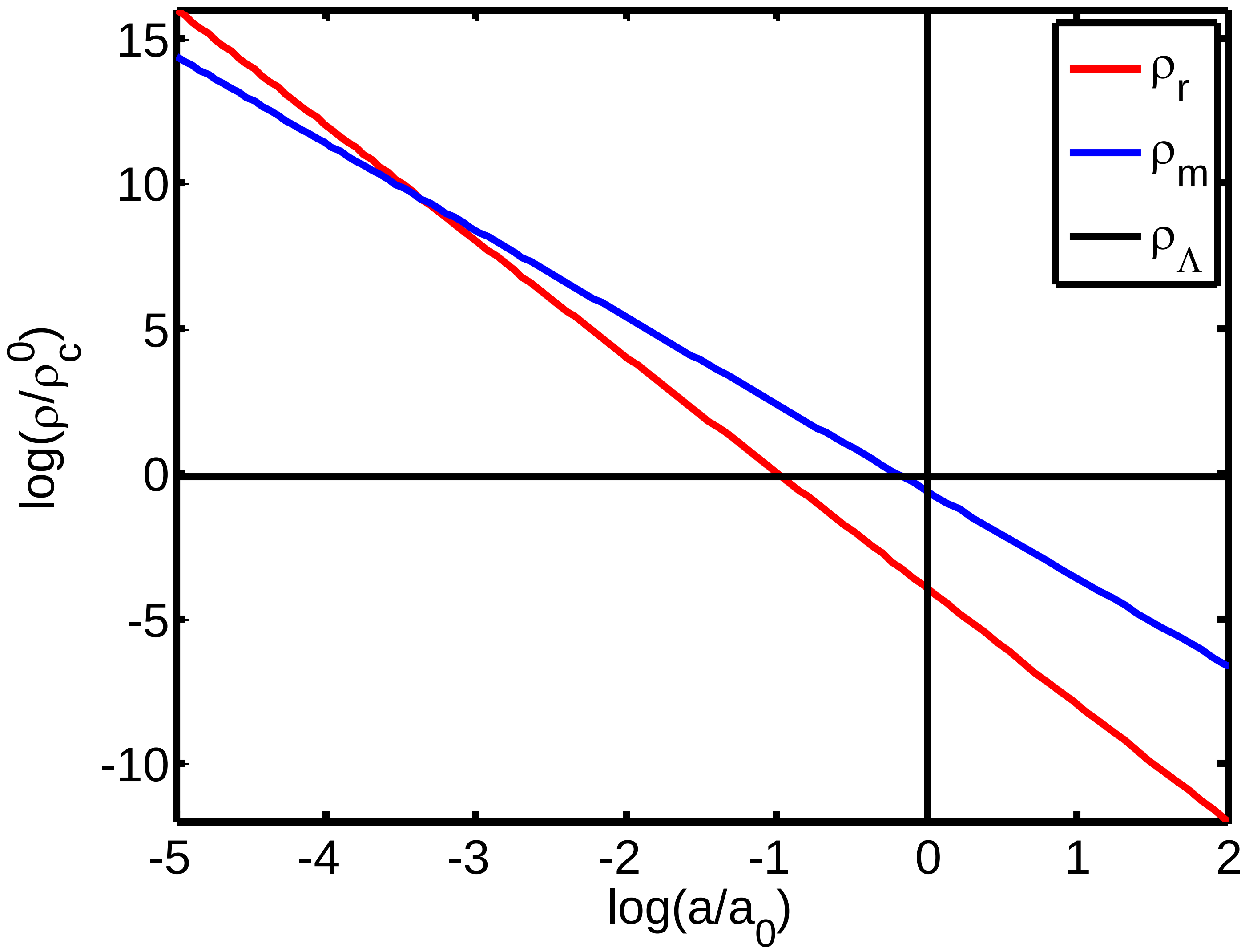
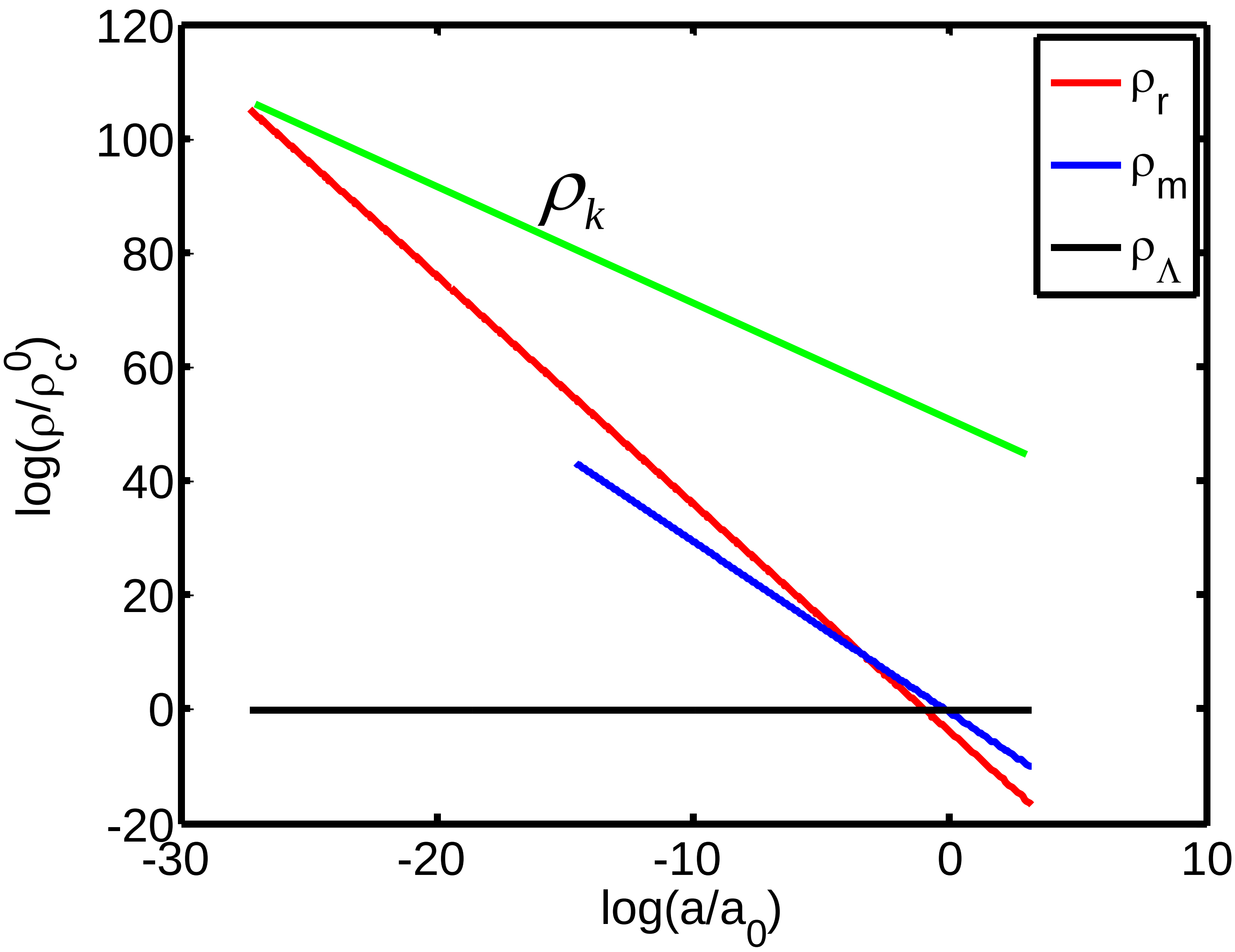


The curvature feature/“problem”



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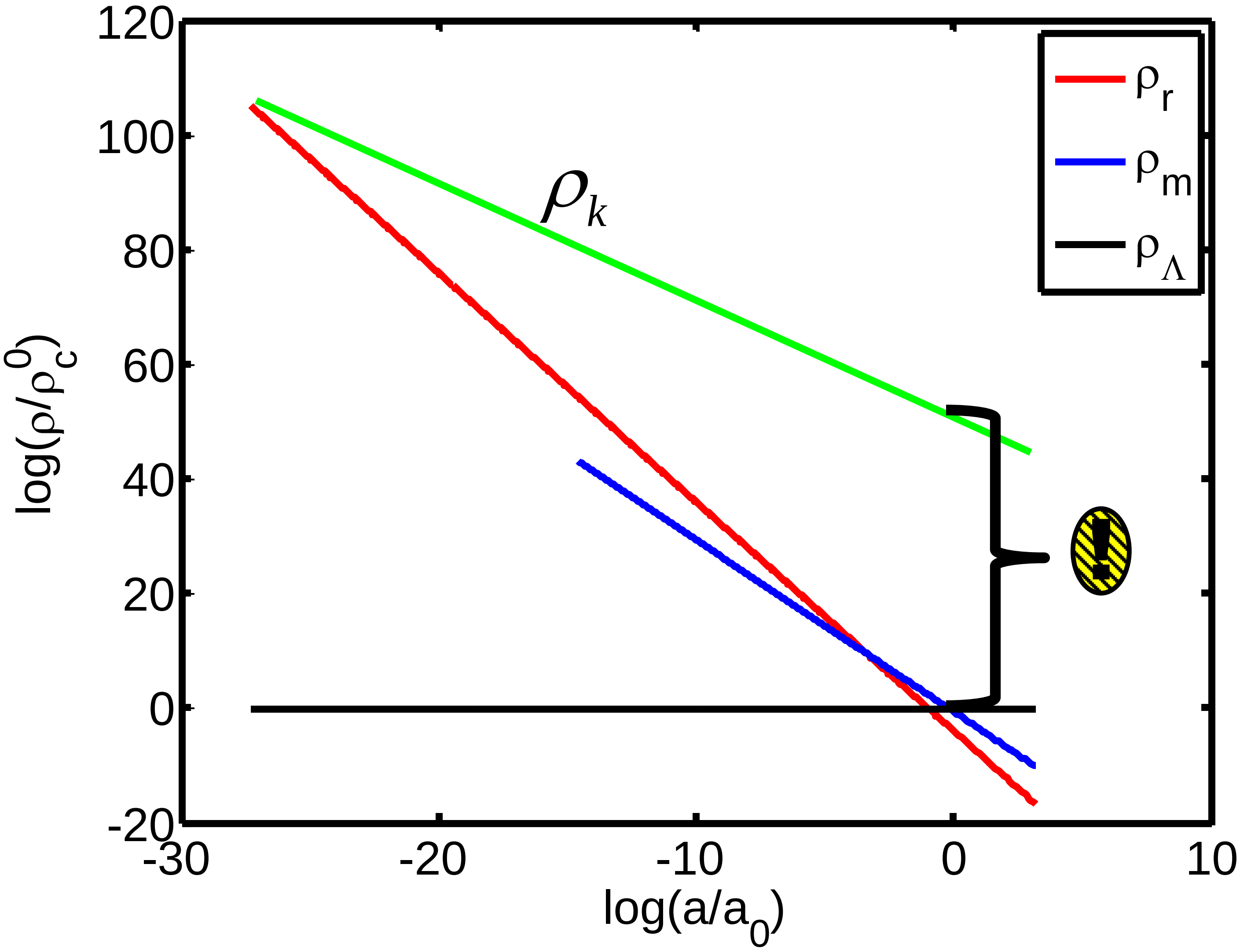

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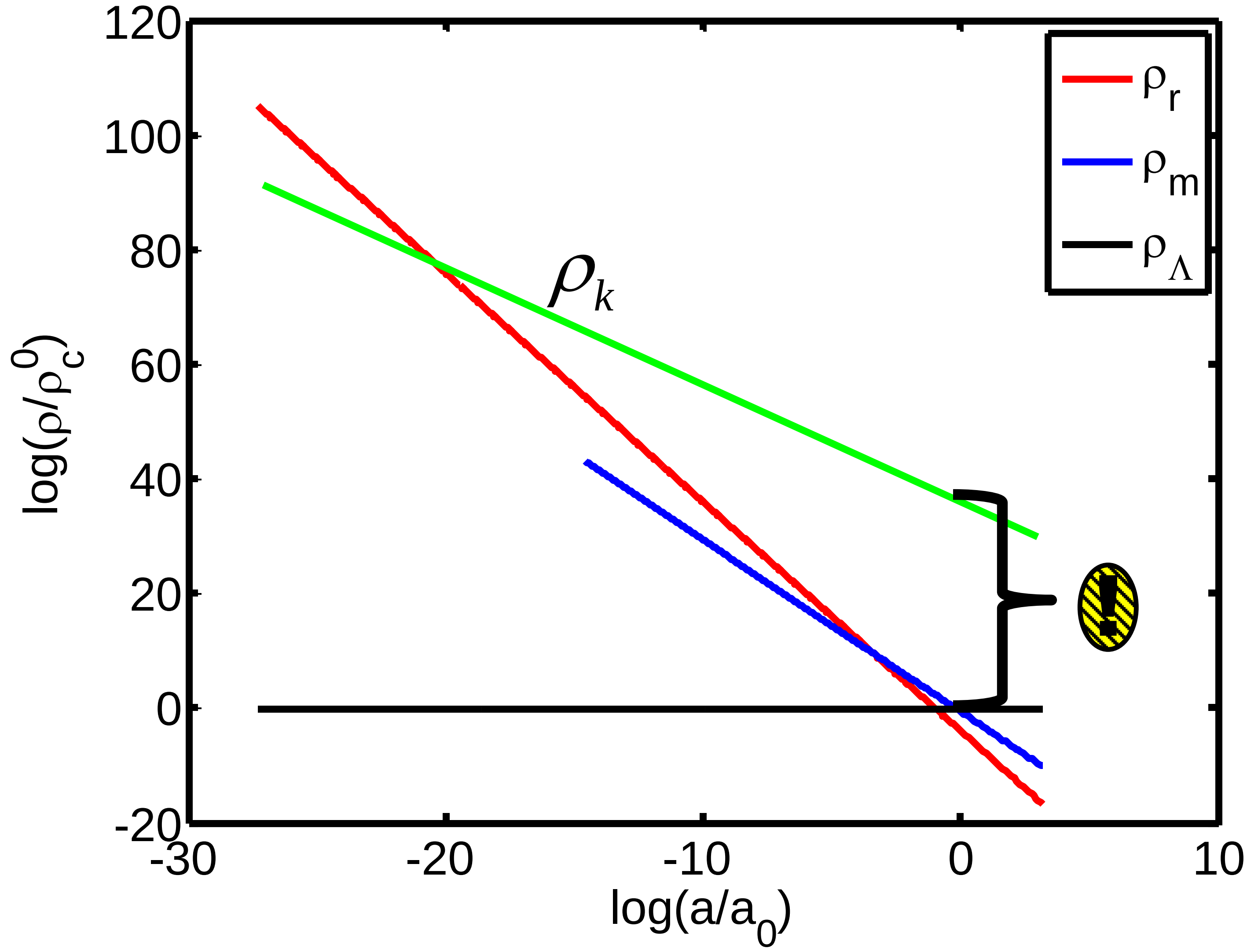

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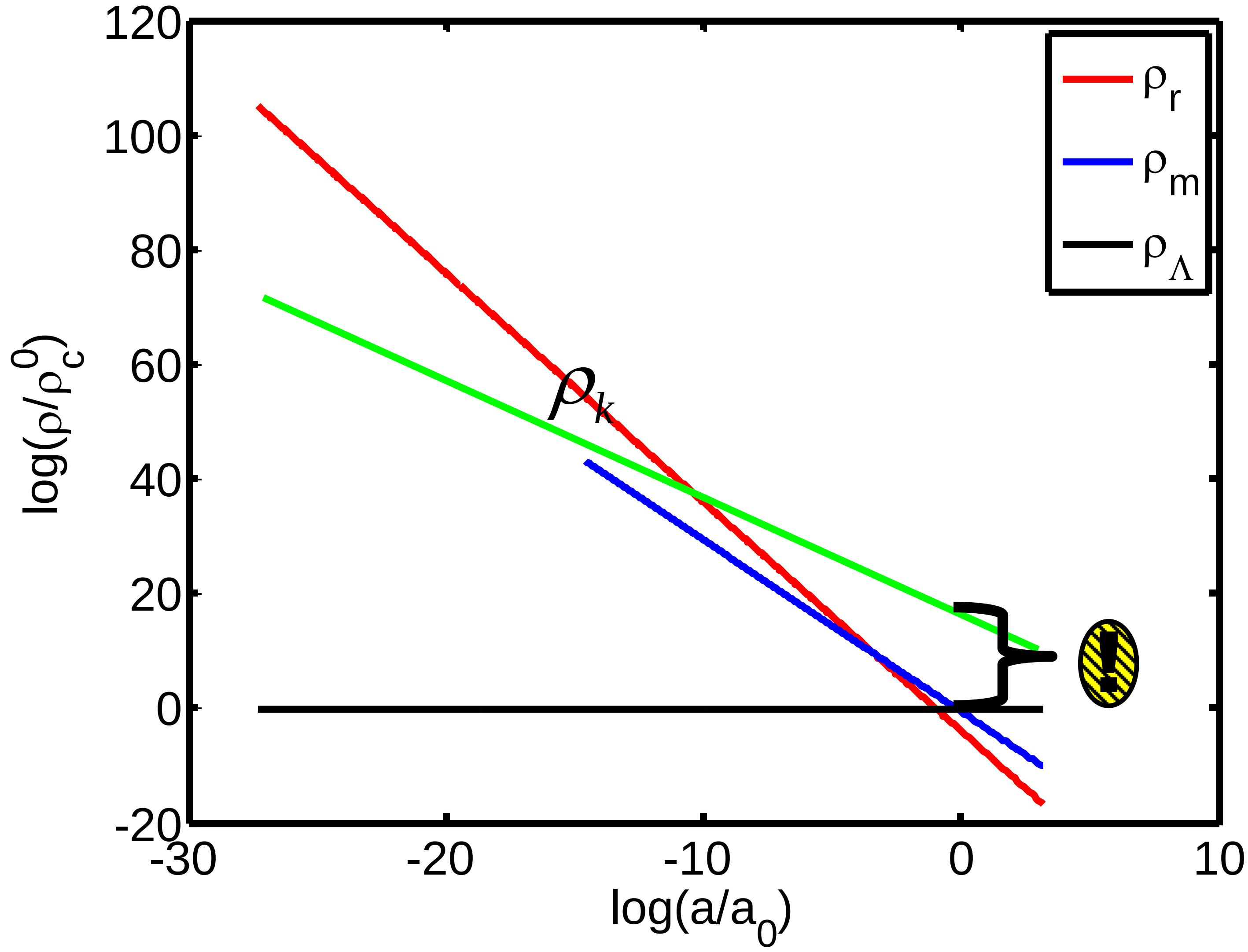

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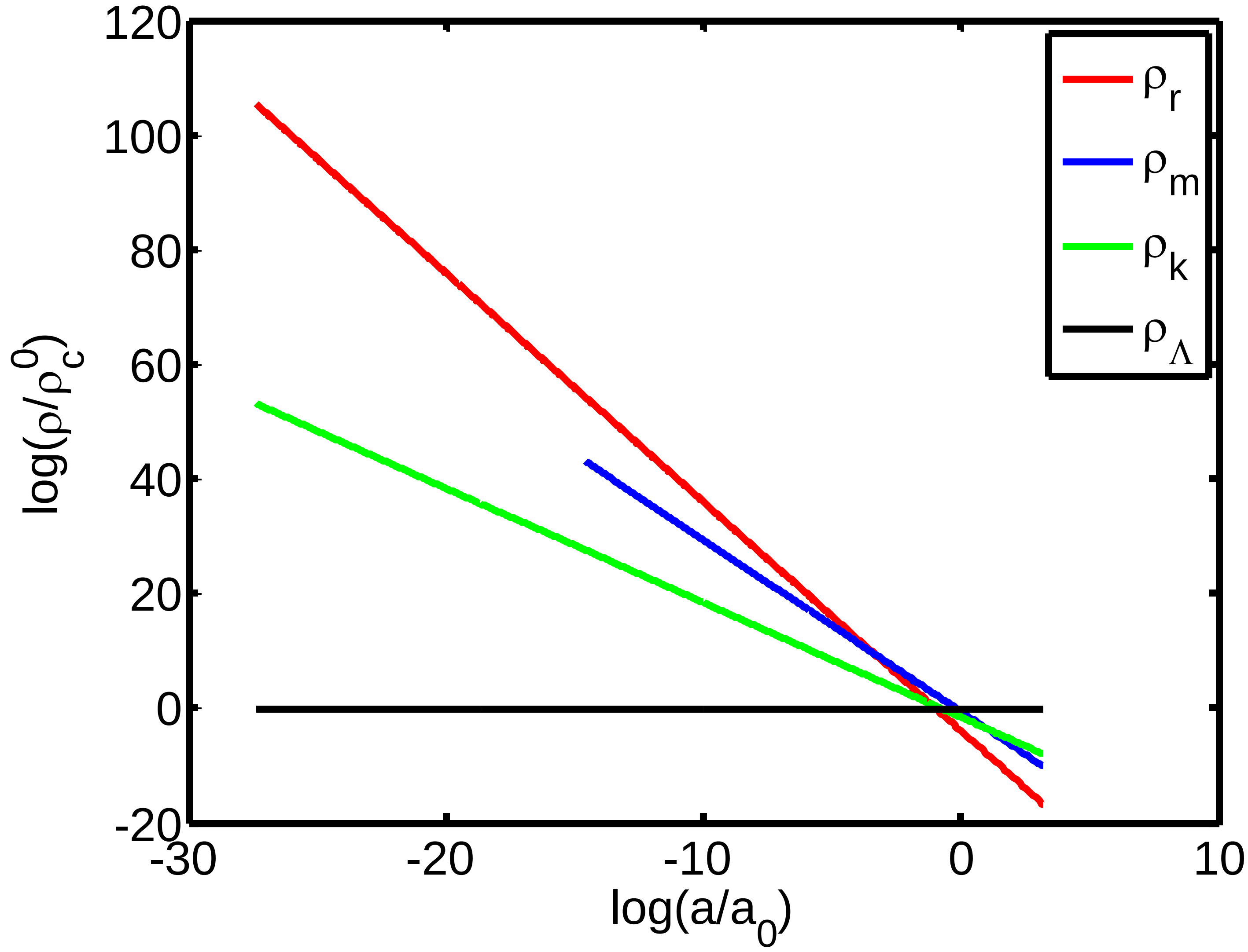

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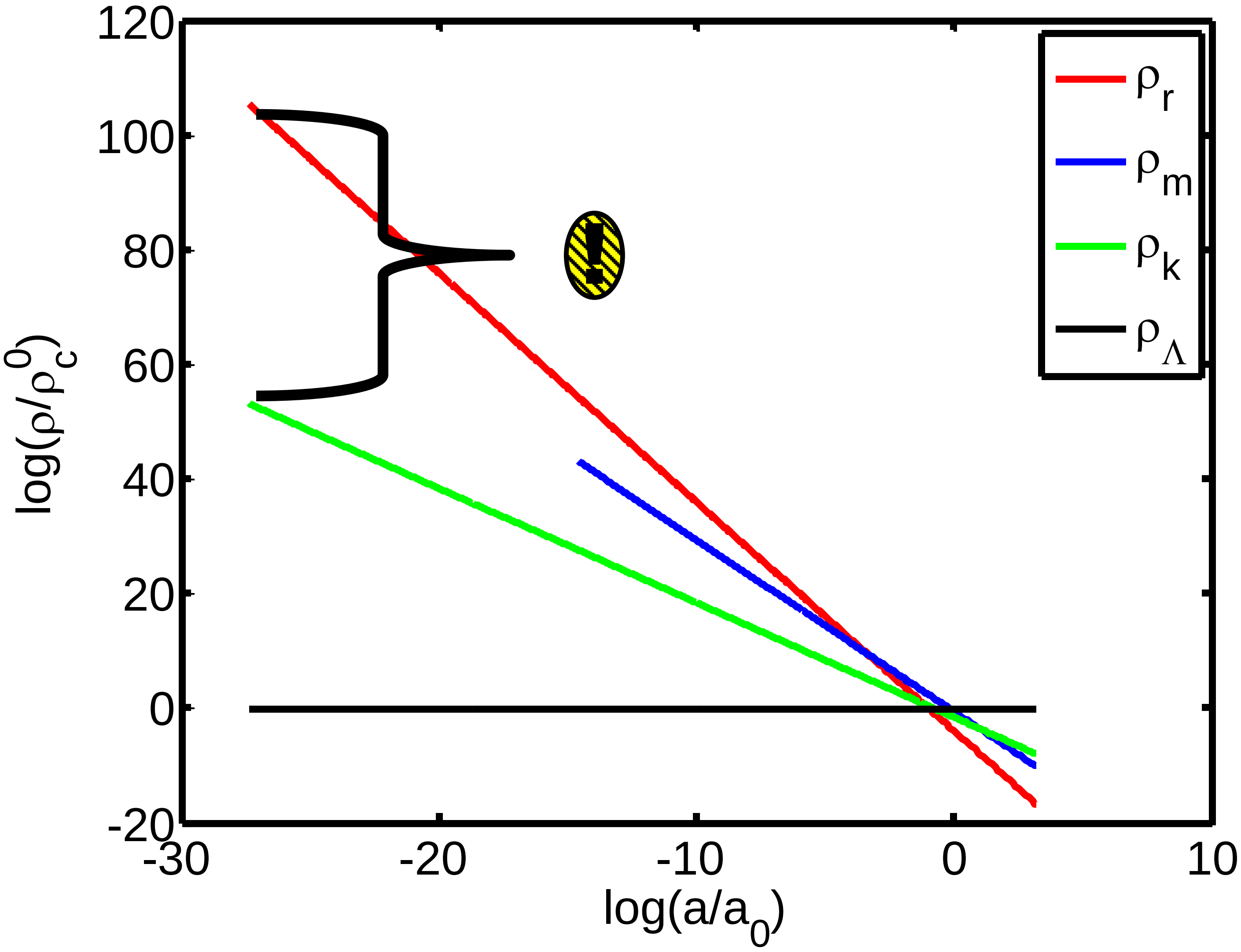
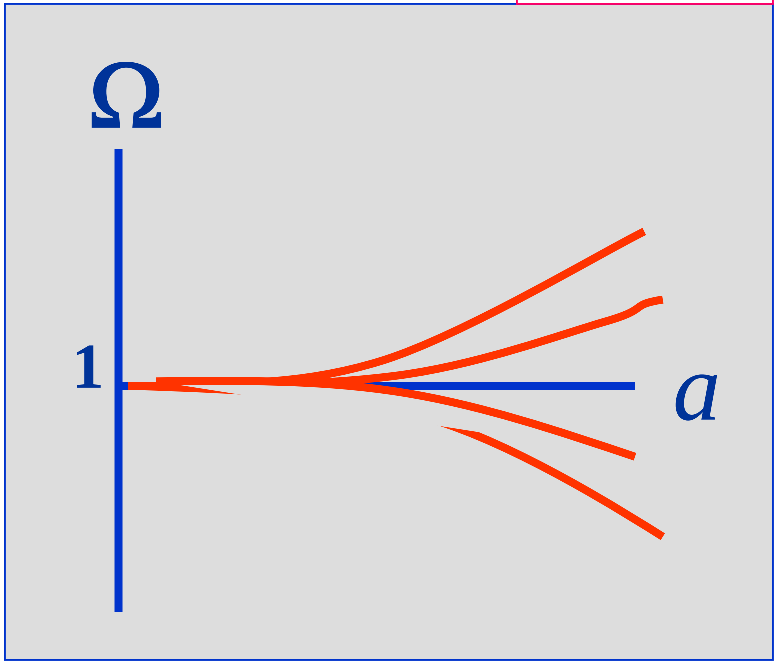


In the SBB, flatness is an "unstable fixed point":



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

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

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

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

Dominates with time

At $T = 10^{16} GeV$

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

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

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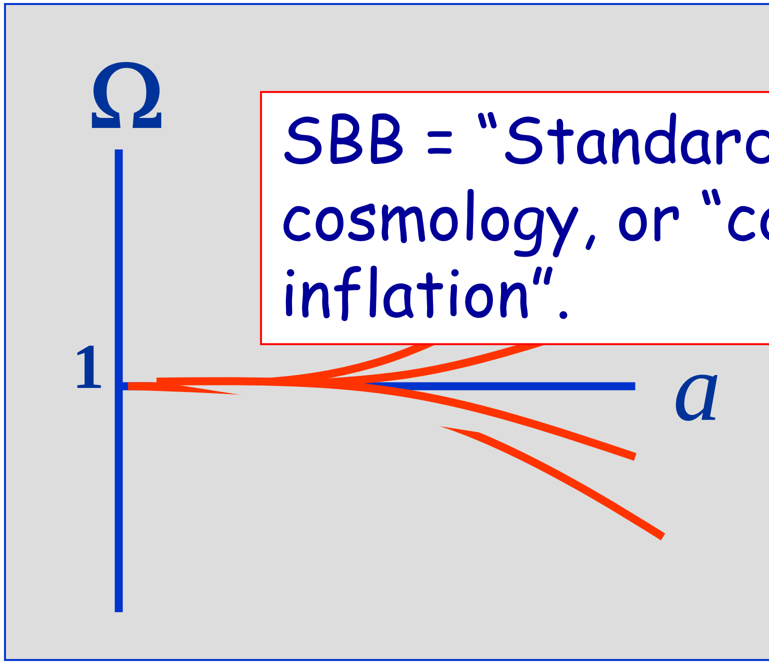

SBB = “Standard Big Bang” cosmology, or “cosmology without inflation”.

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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.

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

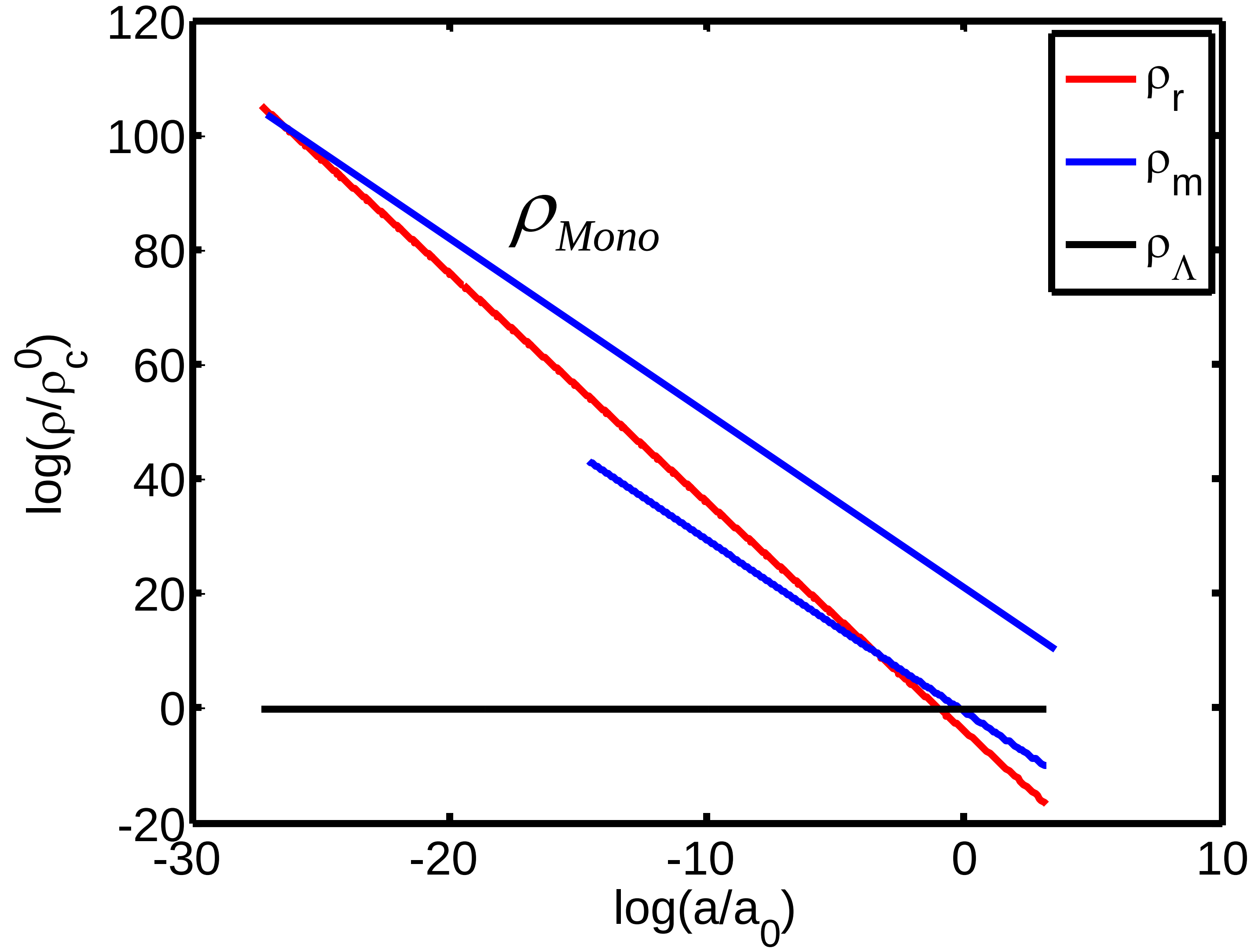
SBB Monopoles

- 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:

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

Monopole dominated Universe

The monopole "problem"



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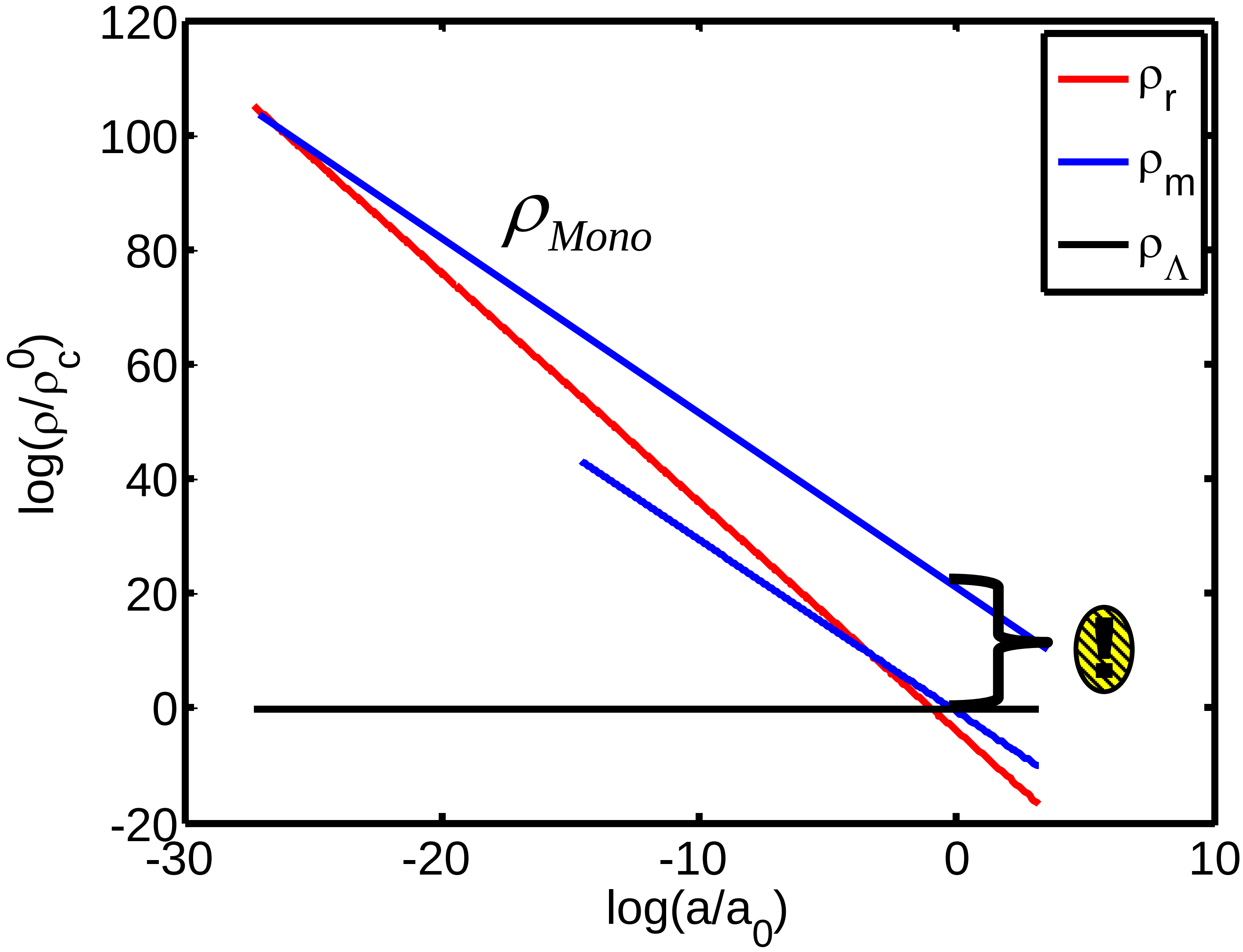
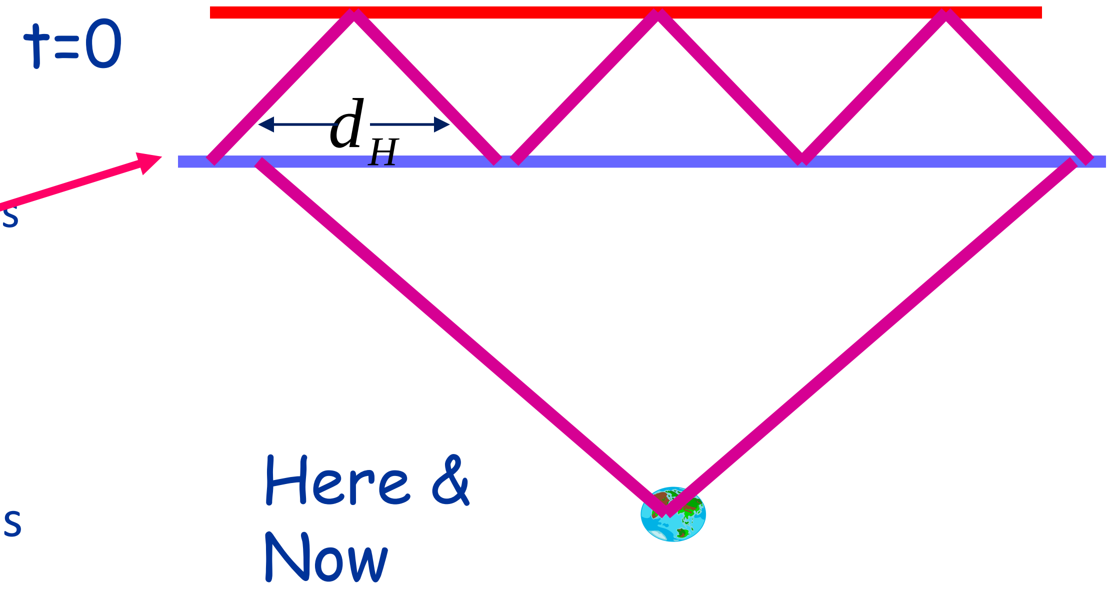


SBB Horizon



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"

Friedmann Eqn.

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

$\rho_k \propto a^{-2}$ — 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.

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

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

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

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

Now add cosmic inflation

Friedmann Eqn.

$\propto a^{\approx 0}$

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Inflaton

Curvature

Relativistic Matter

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The inflaton:

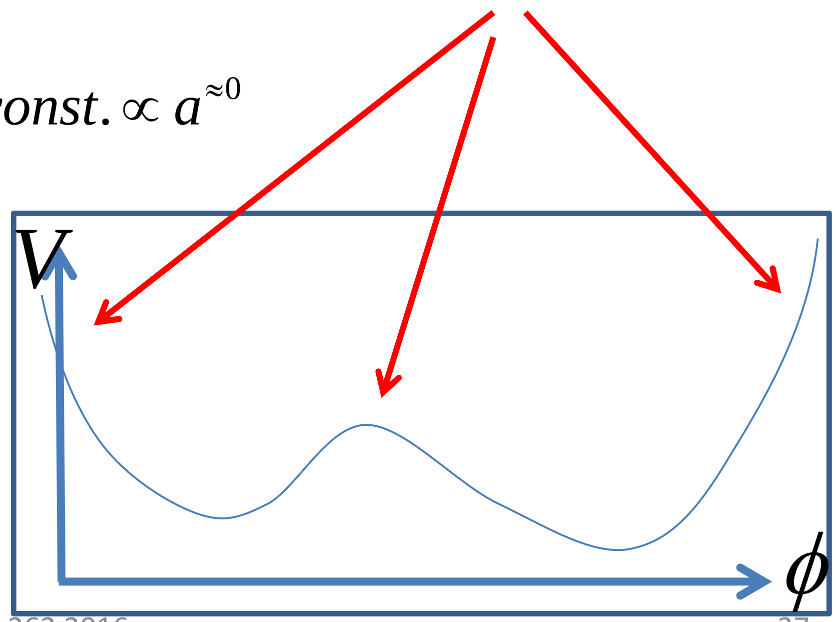
~Homogeneous scalar field ϕ obeying

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

Cosmic damping *Coupling to ordinary matter*

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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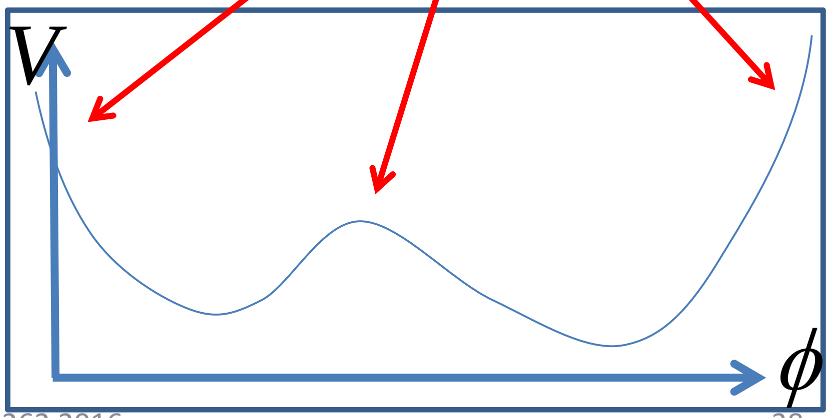
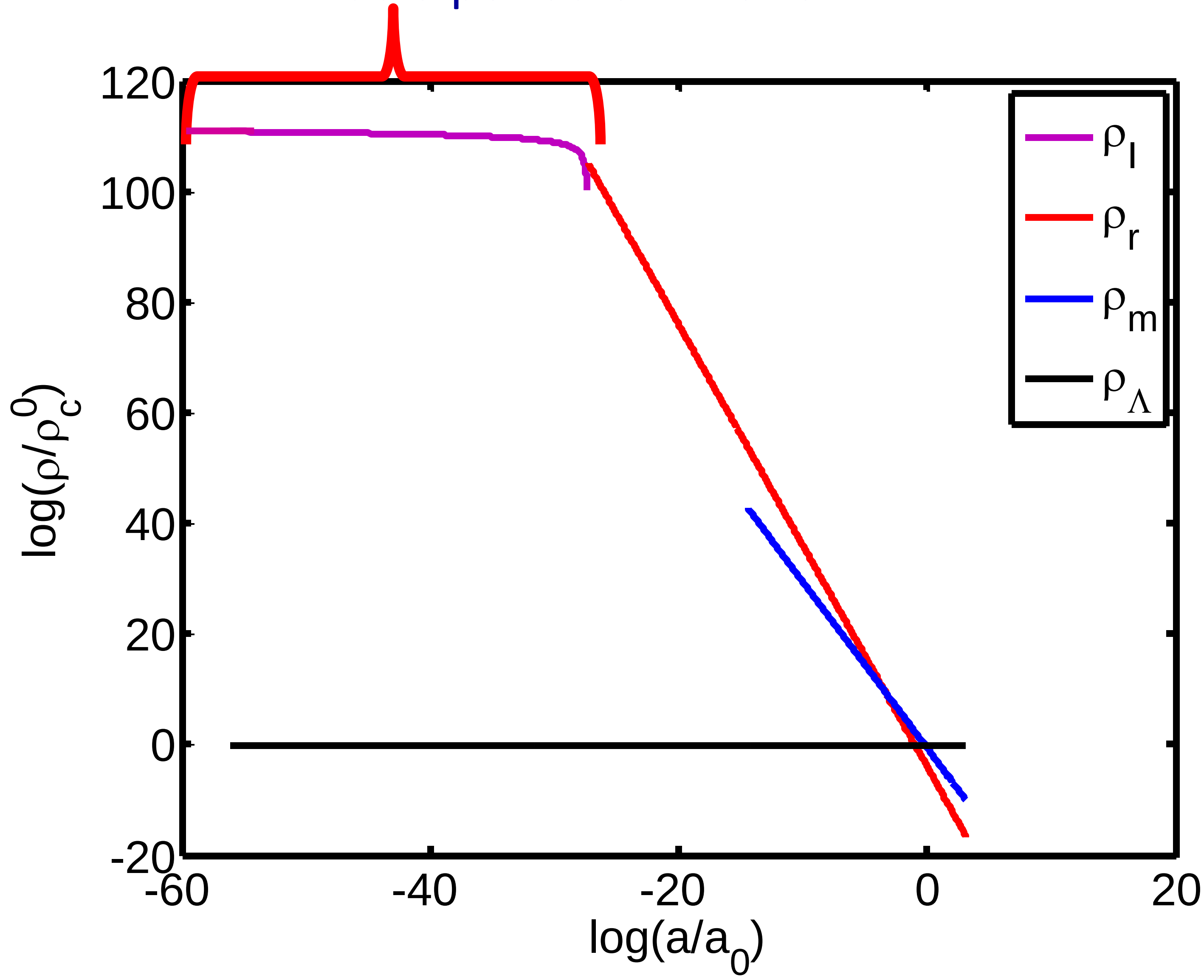
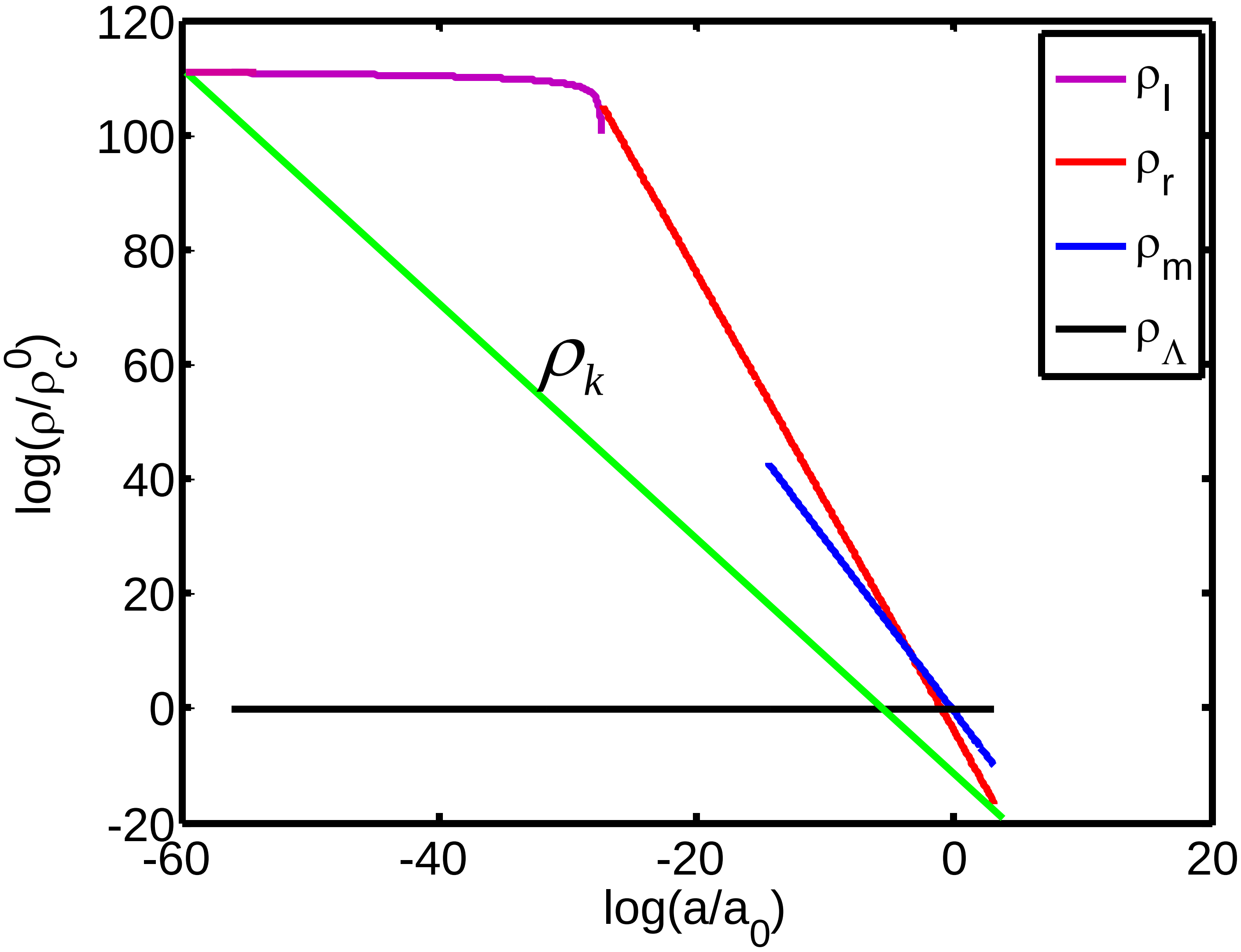


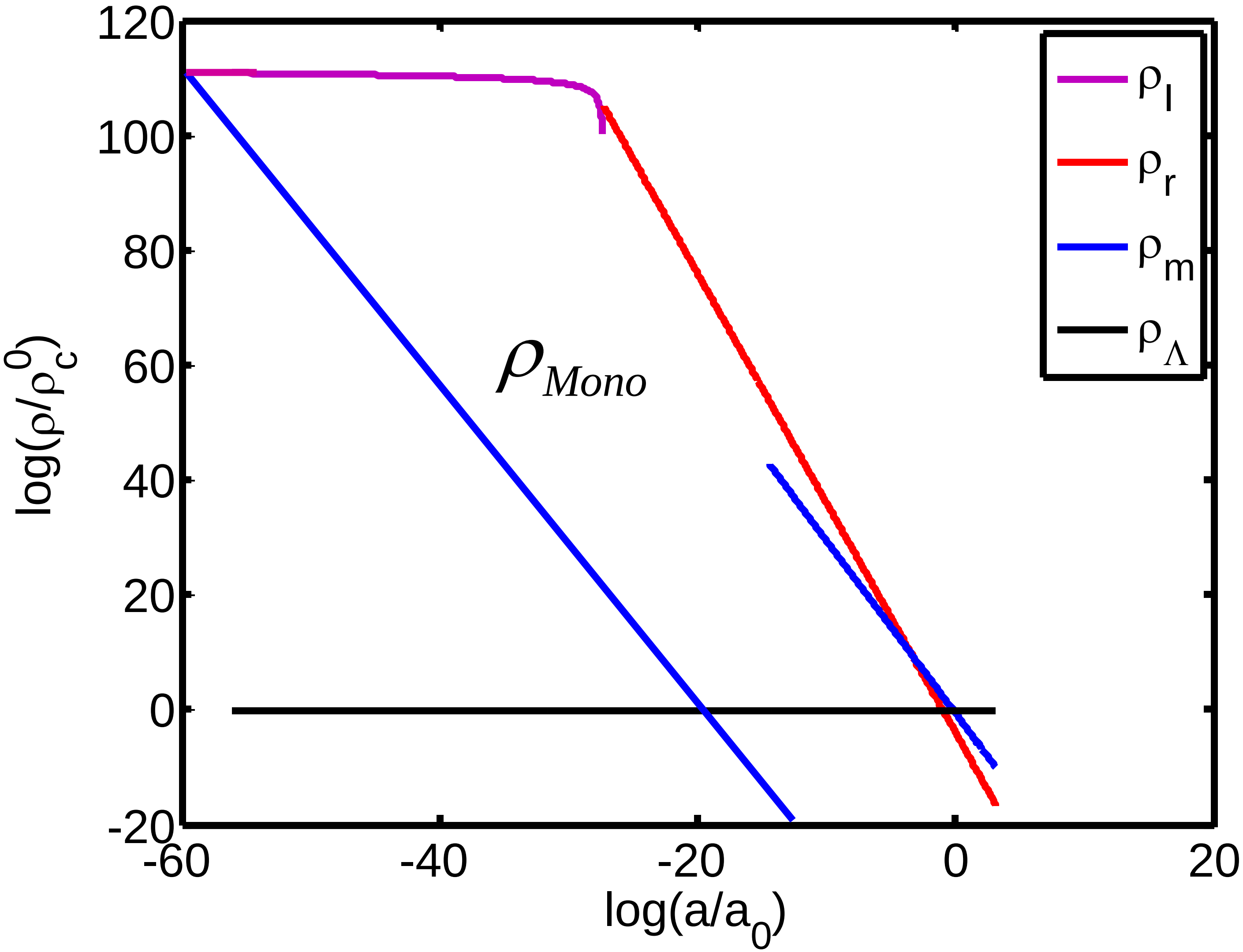
Add a period of Inflation:



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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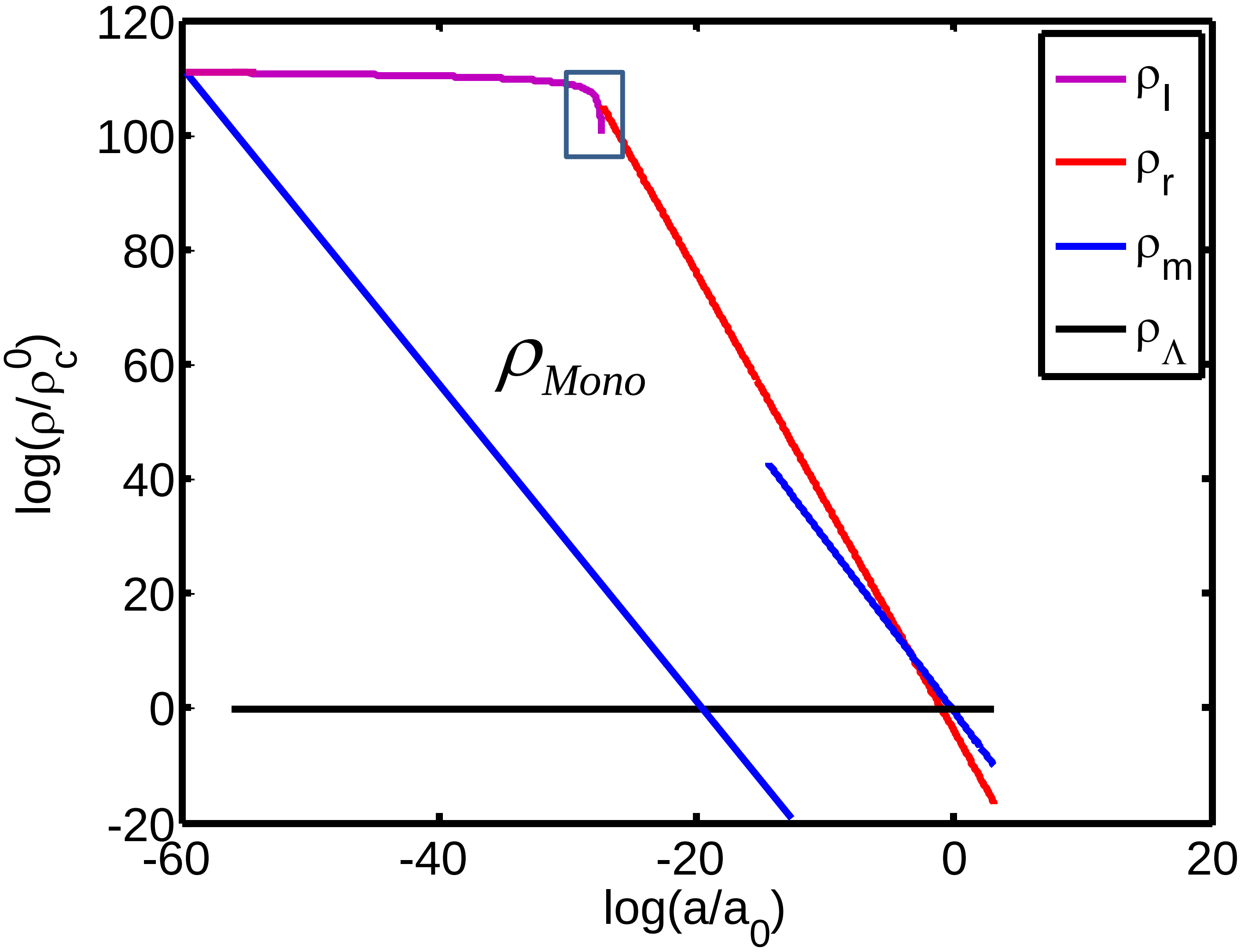
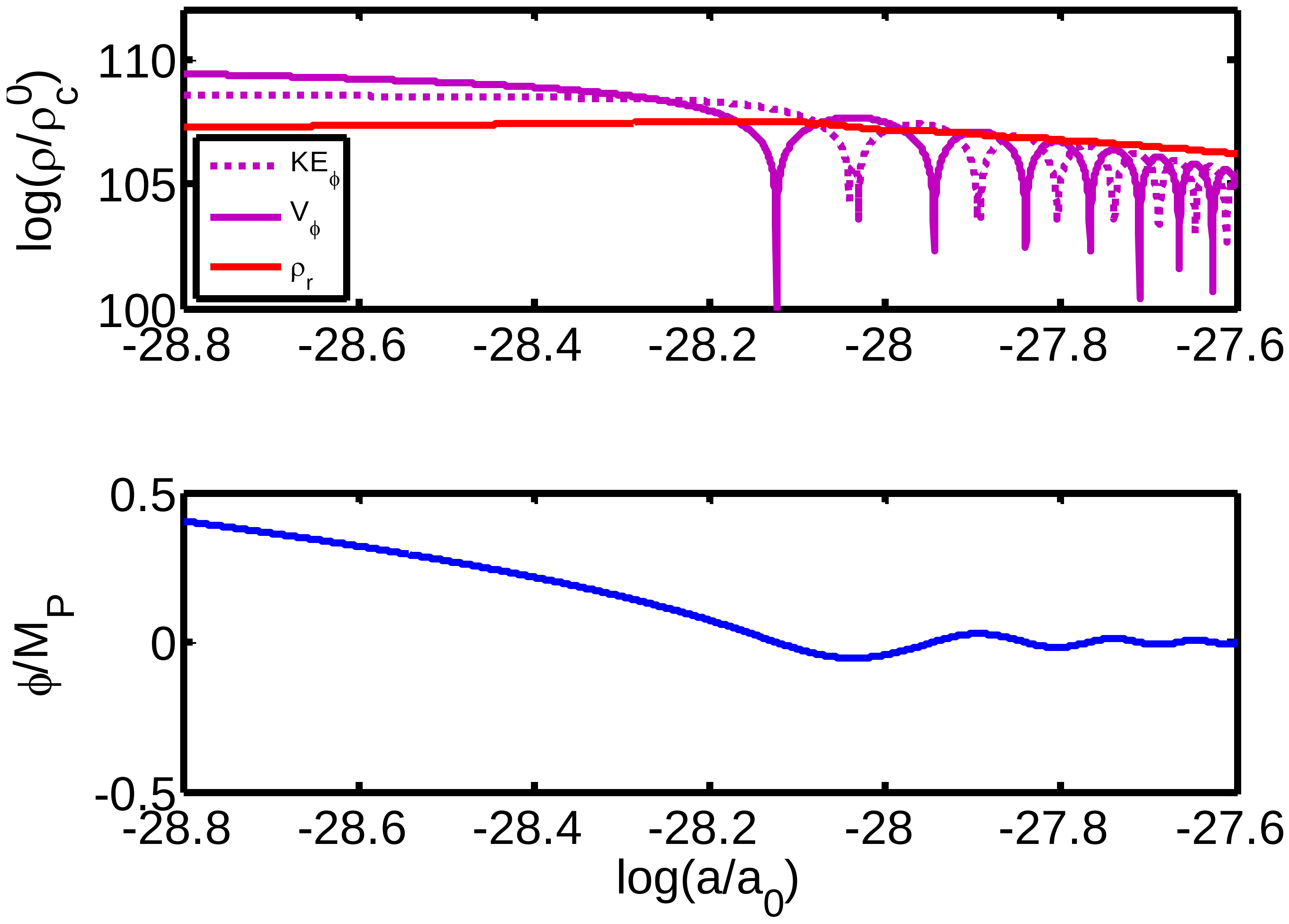


Inflation detail:



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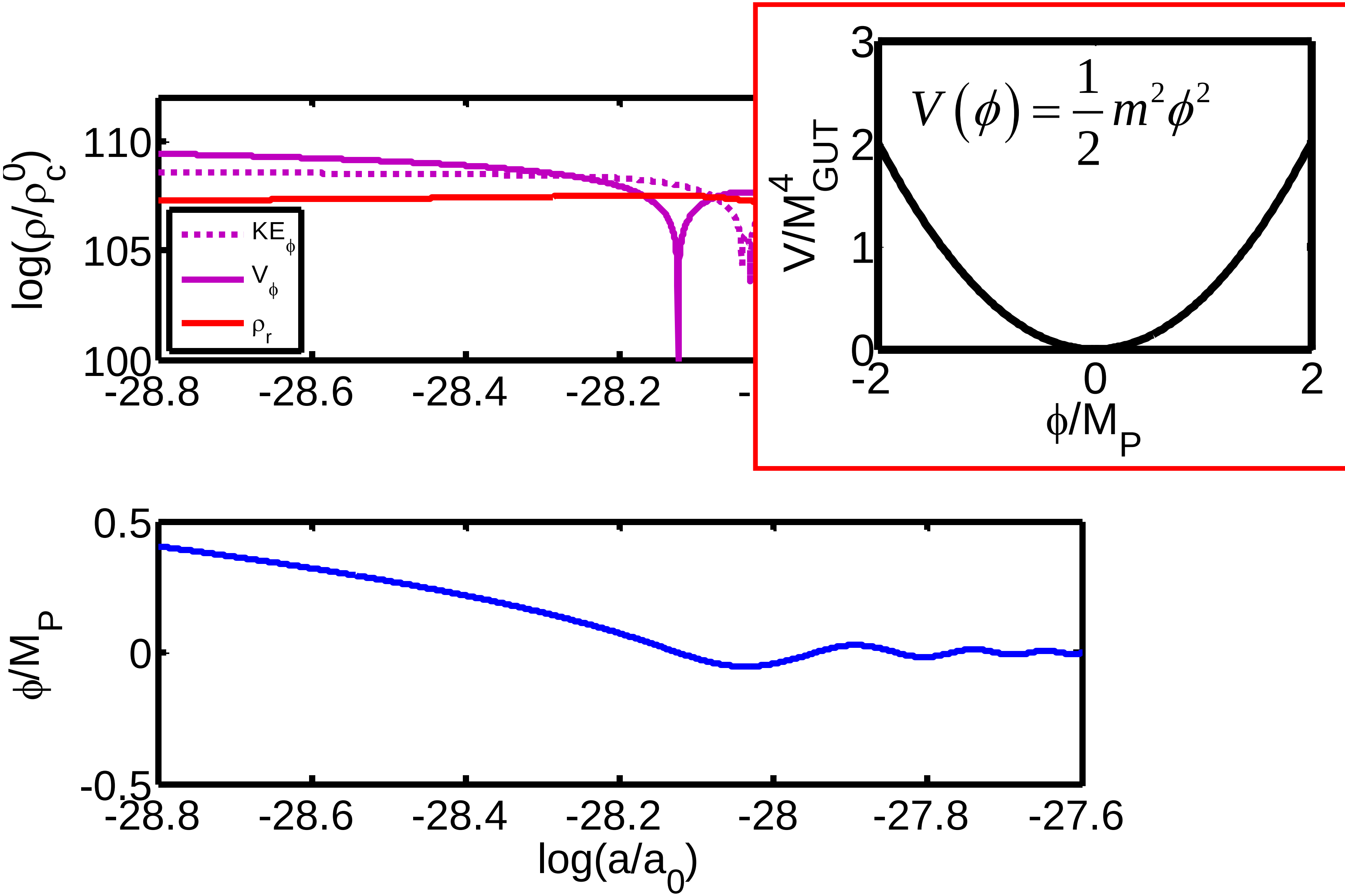

Hubble Length

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

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

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(aka ρ_c)

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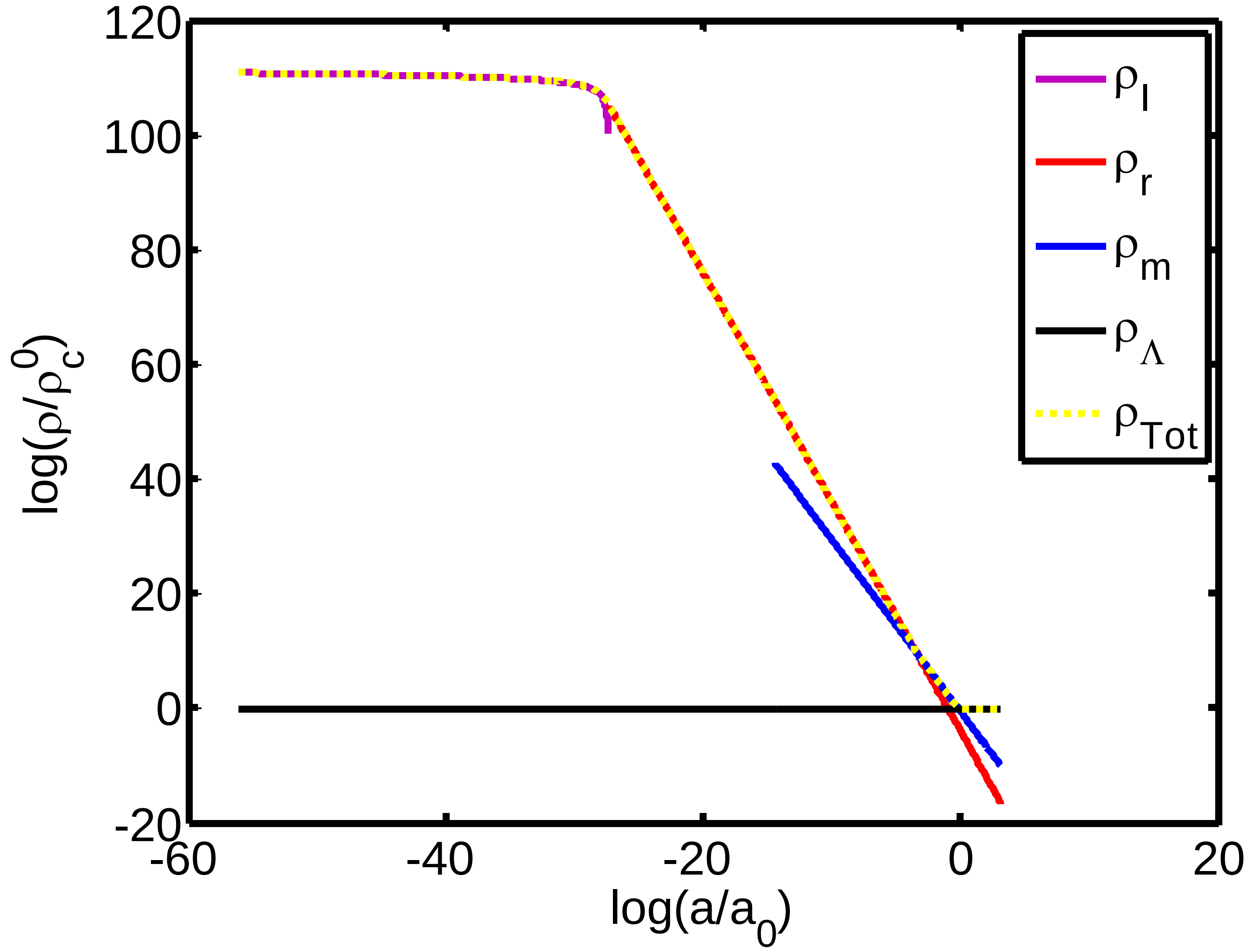
120
100
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0
-20
-60
-40
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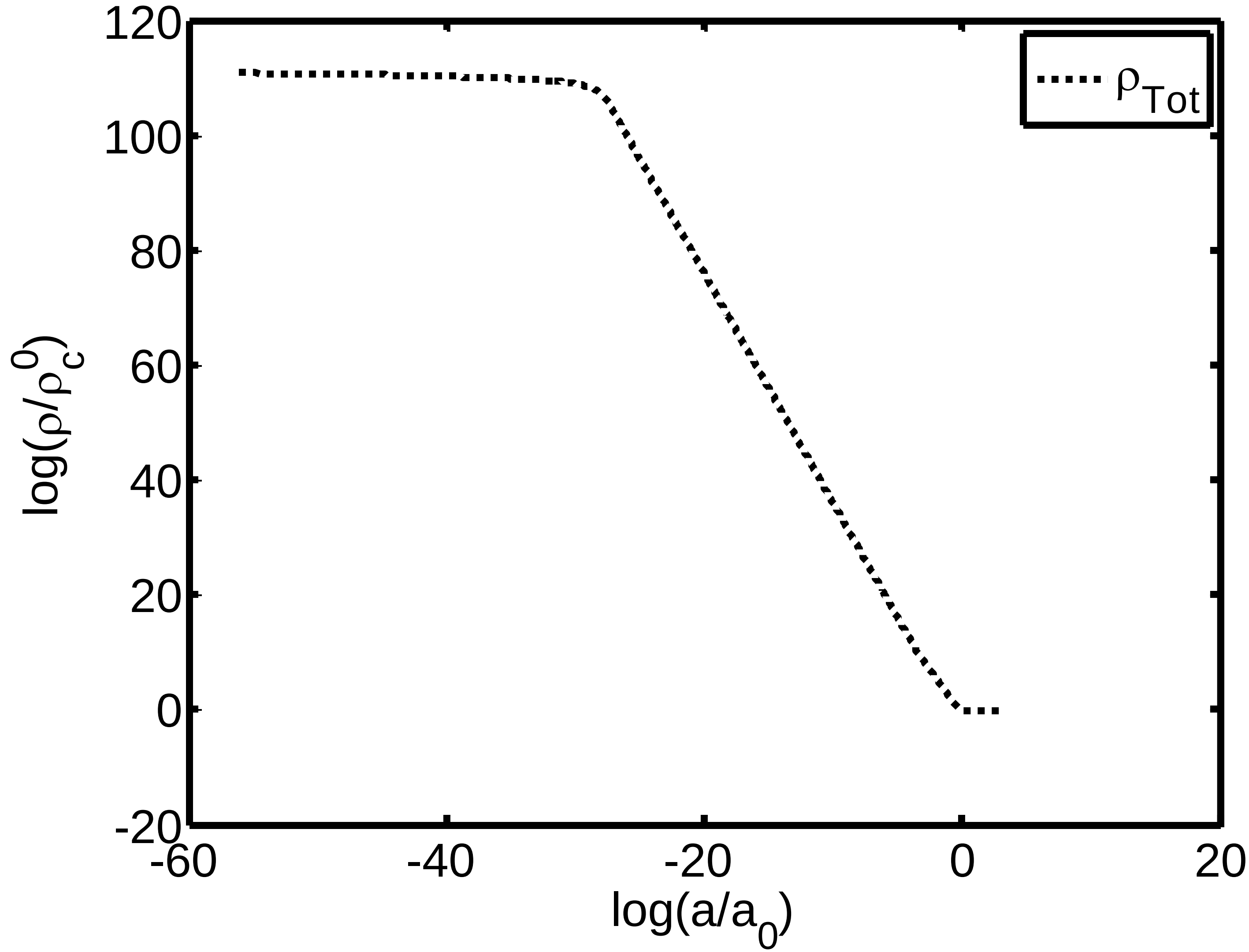
0
20
log(ρ/ρ_c^0)
log(a/a_0)
ρ_I
ρ_r
ρ_m
ρ_Λ
ρ_Tot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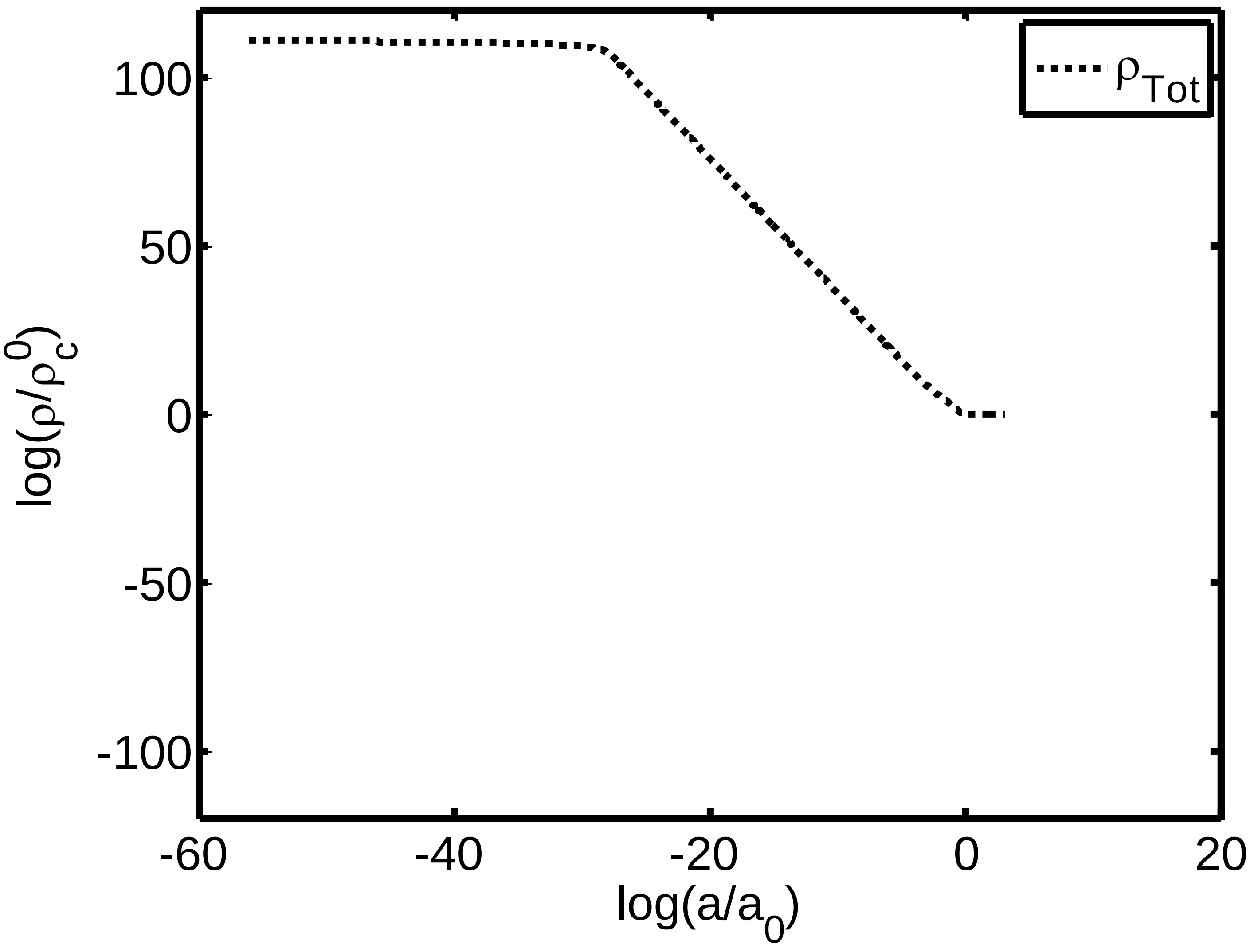

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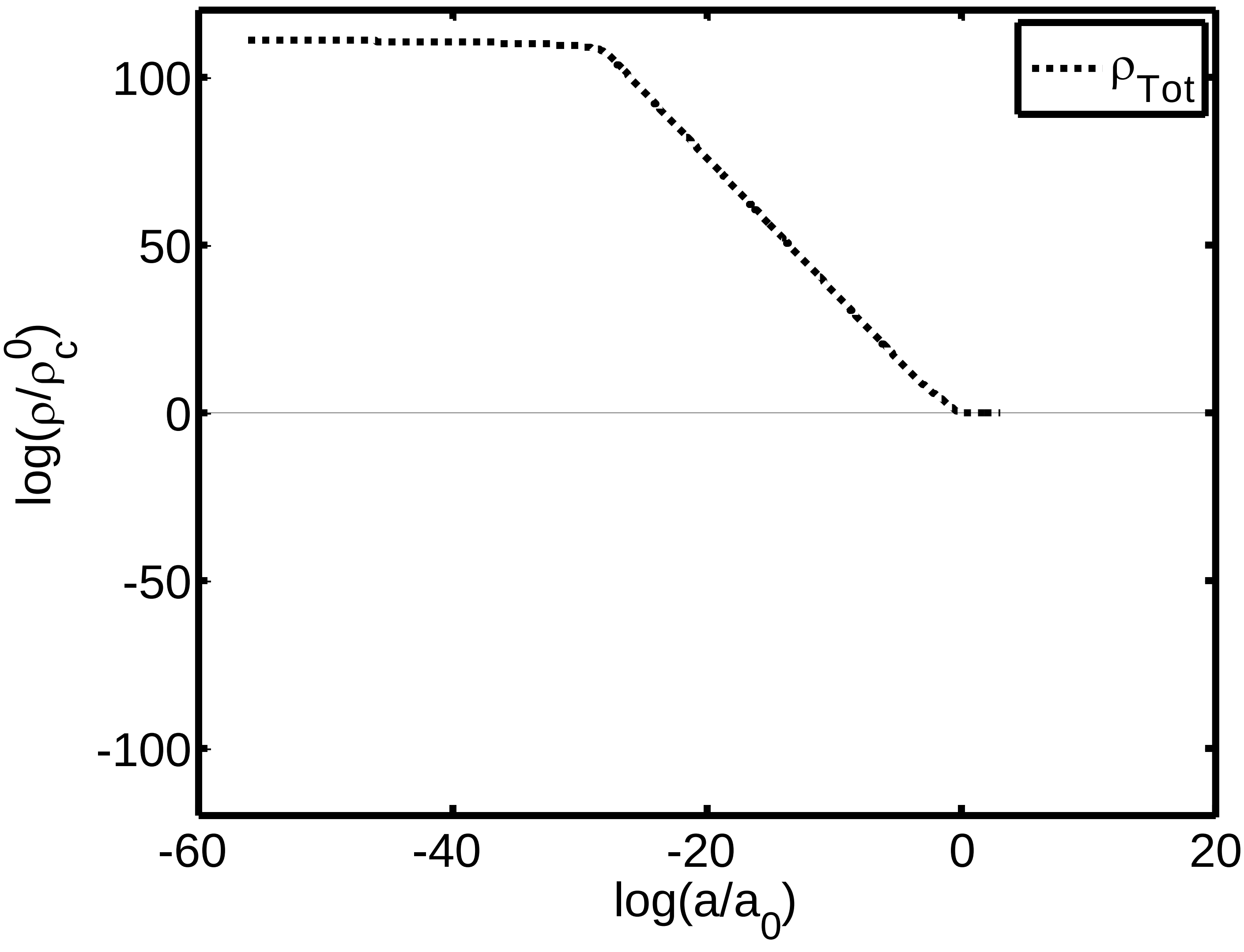
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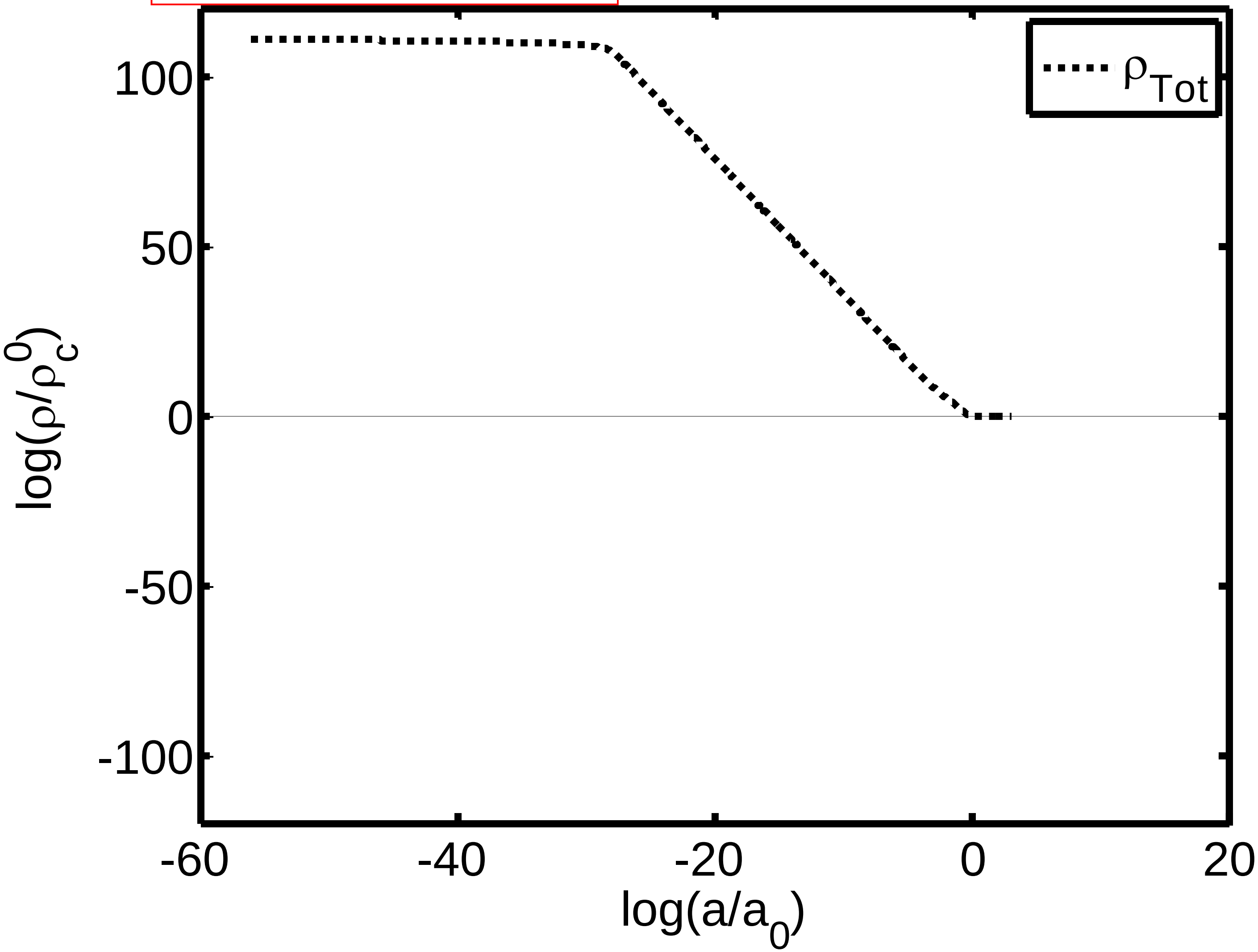

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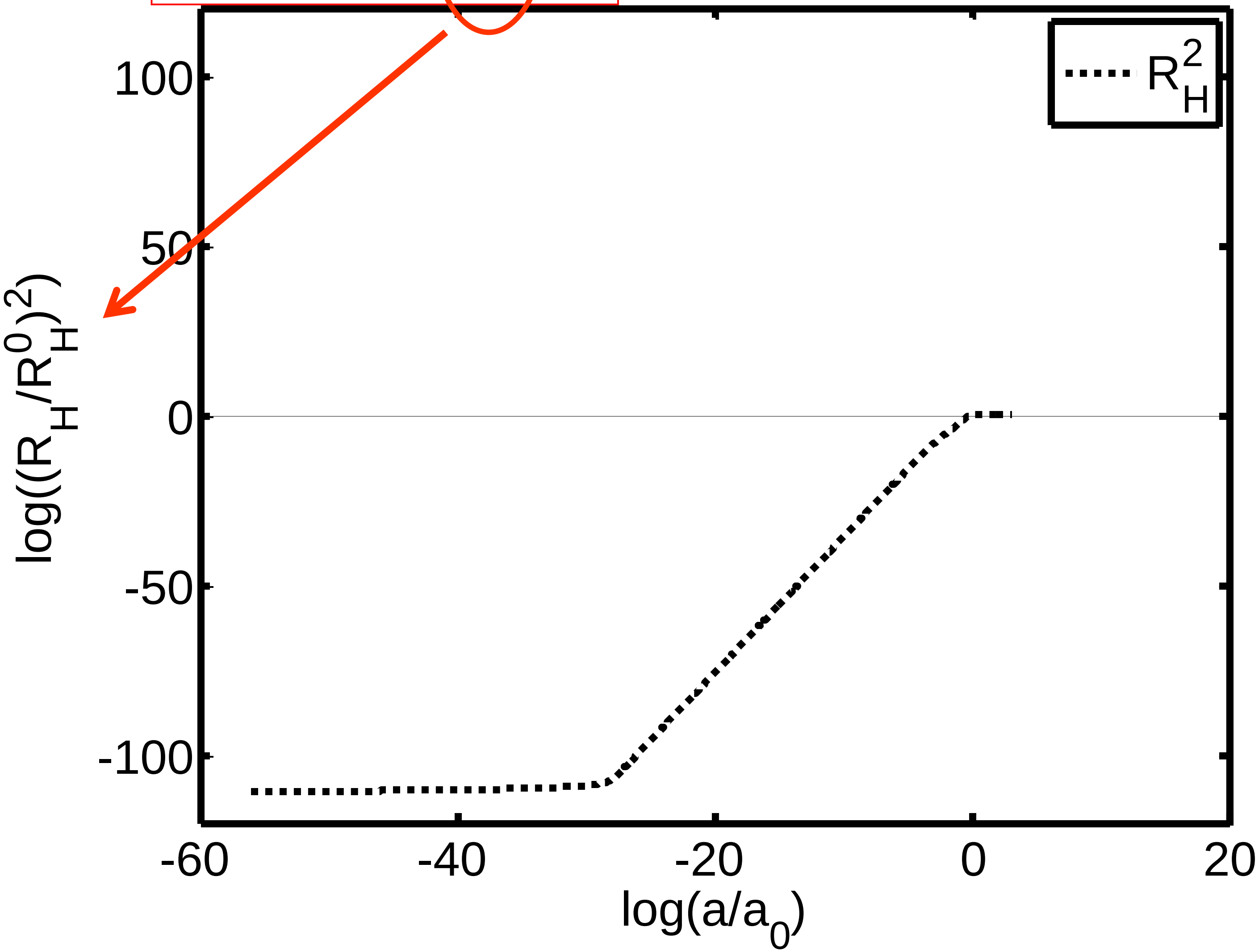

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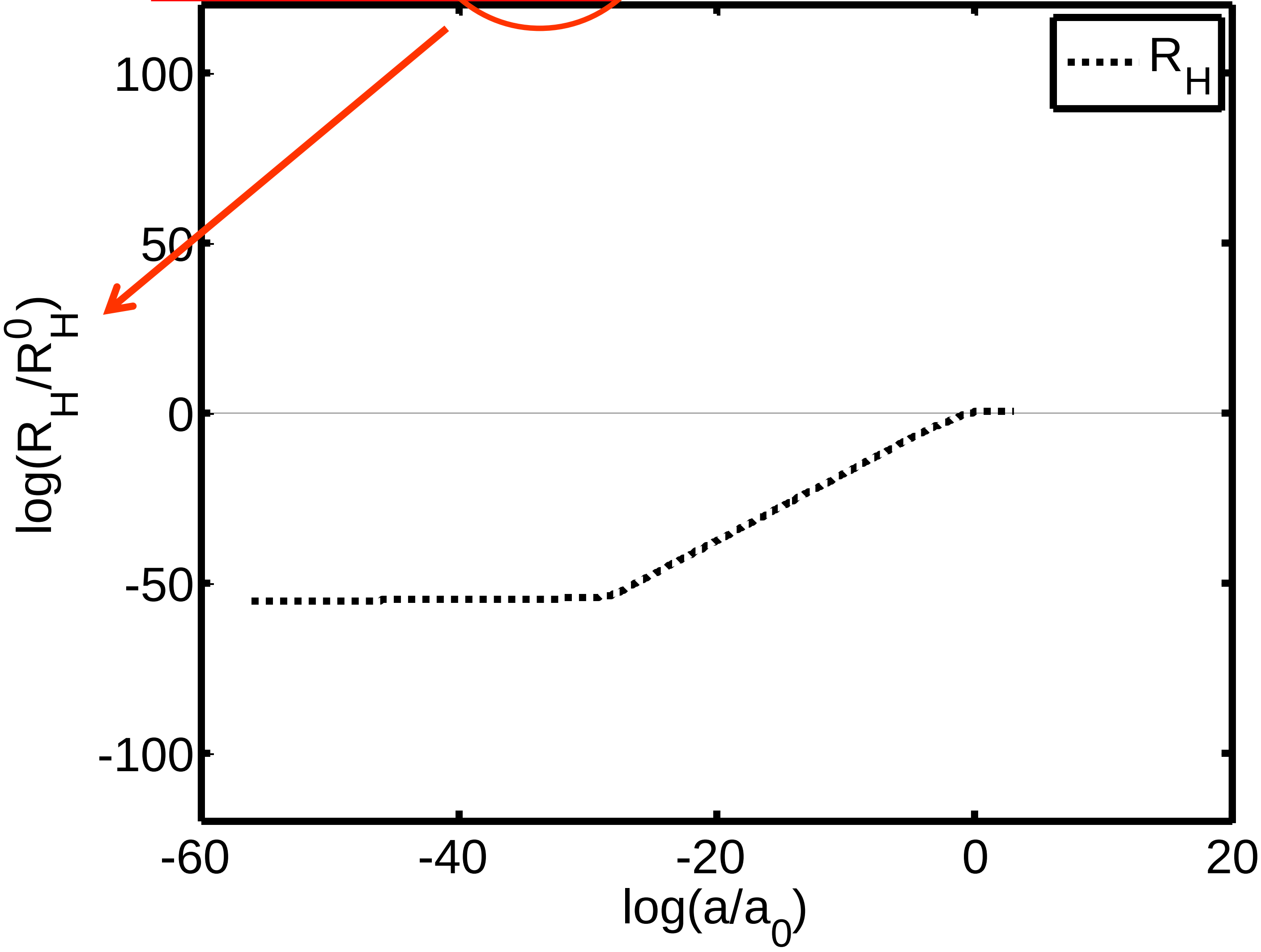

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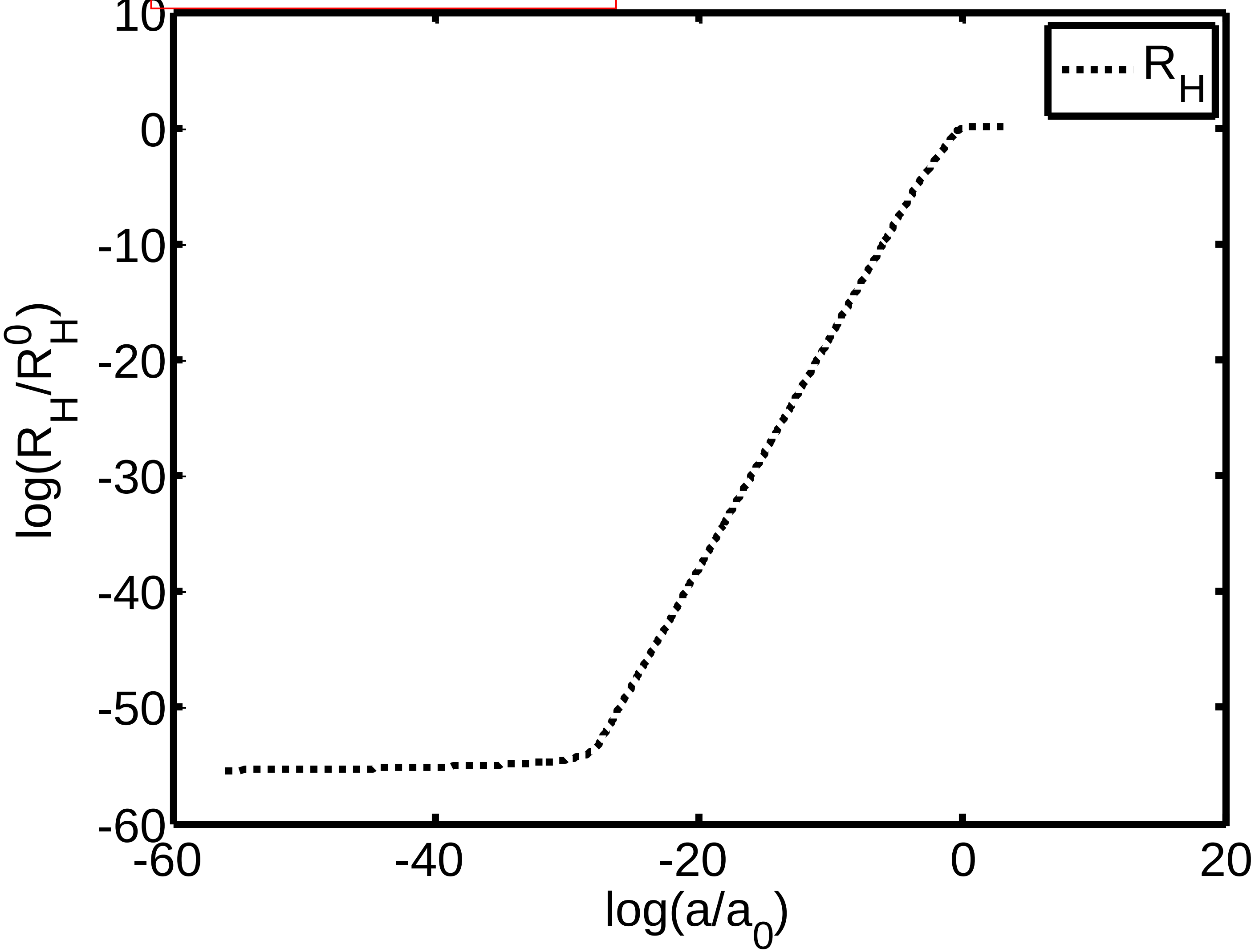

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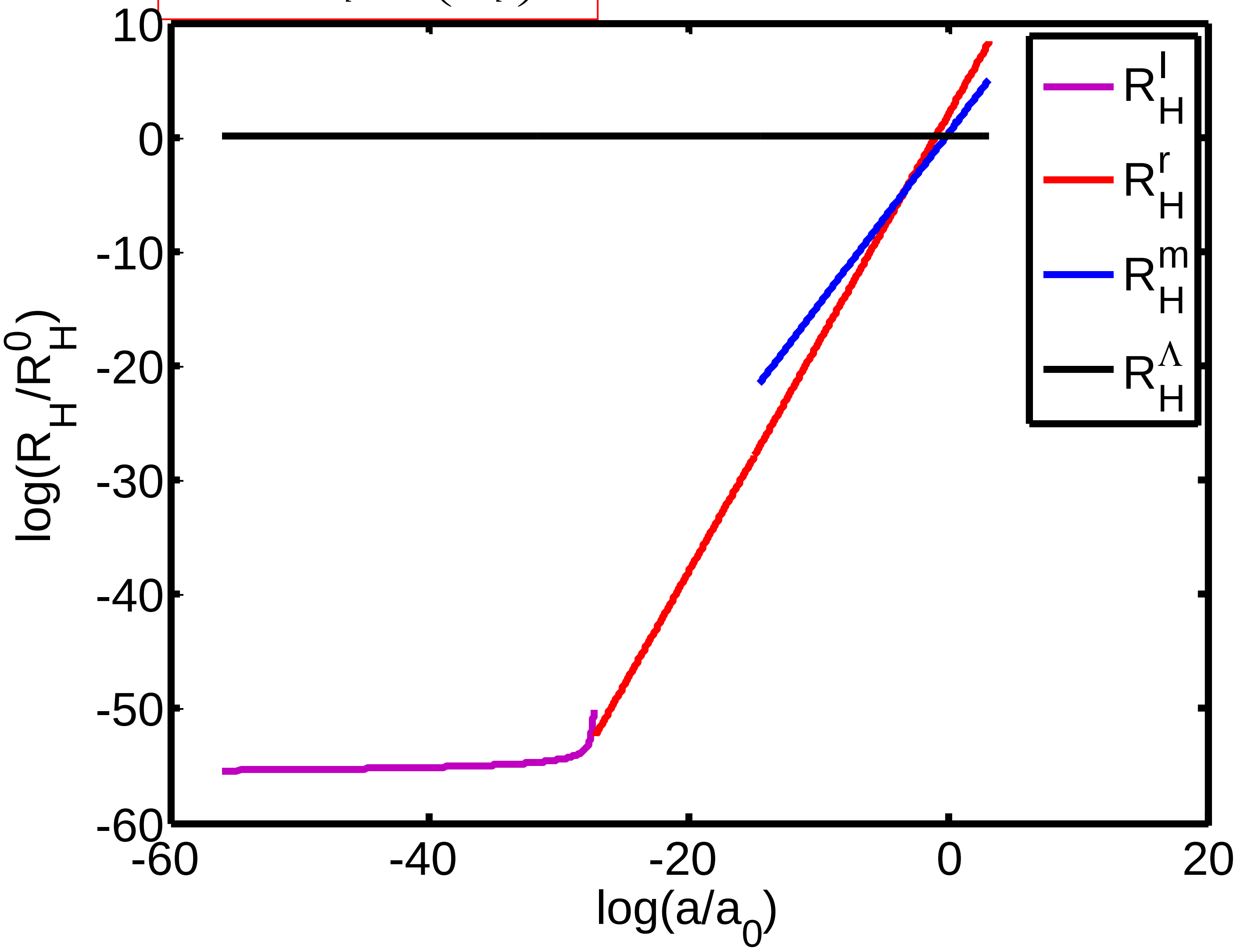

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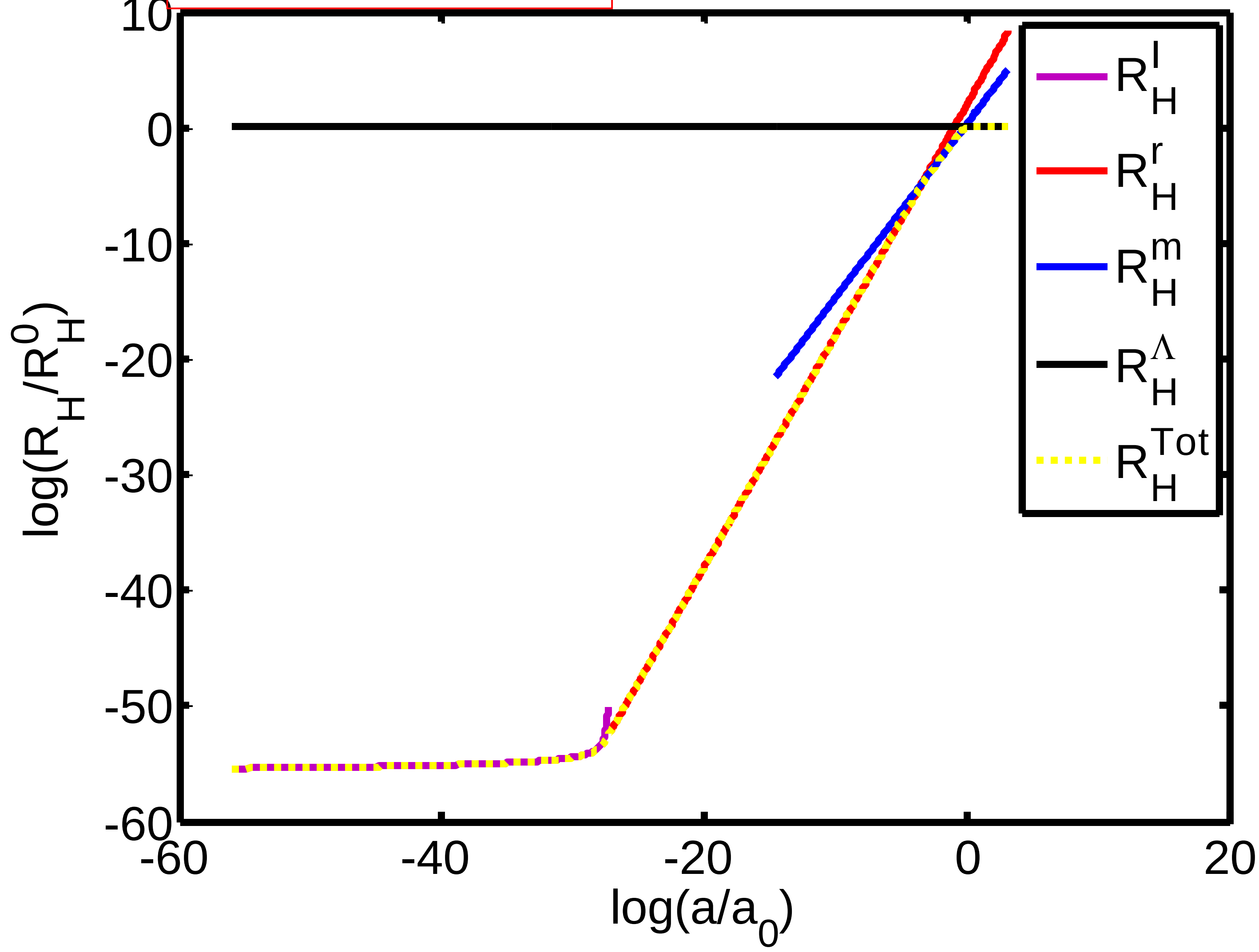

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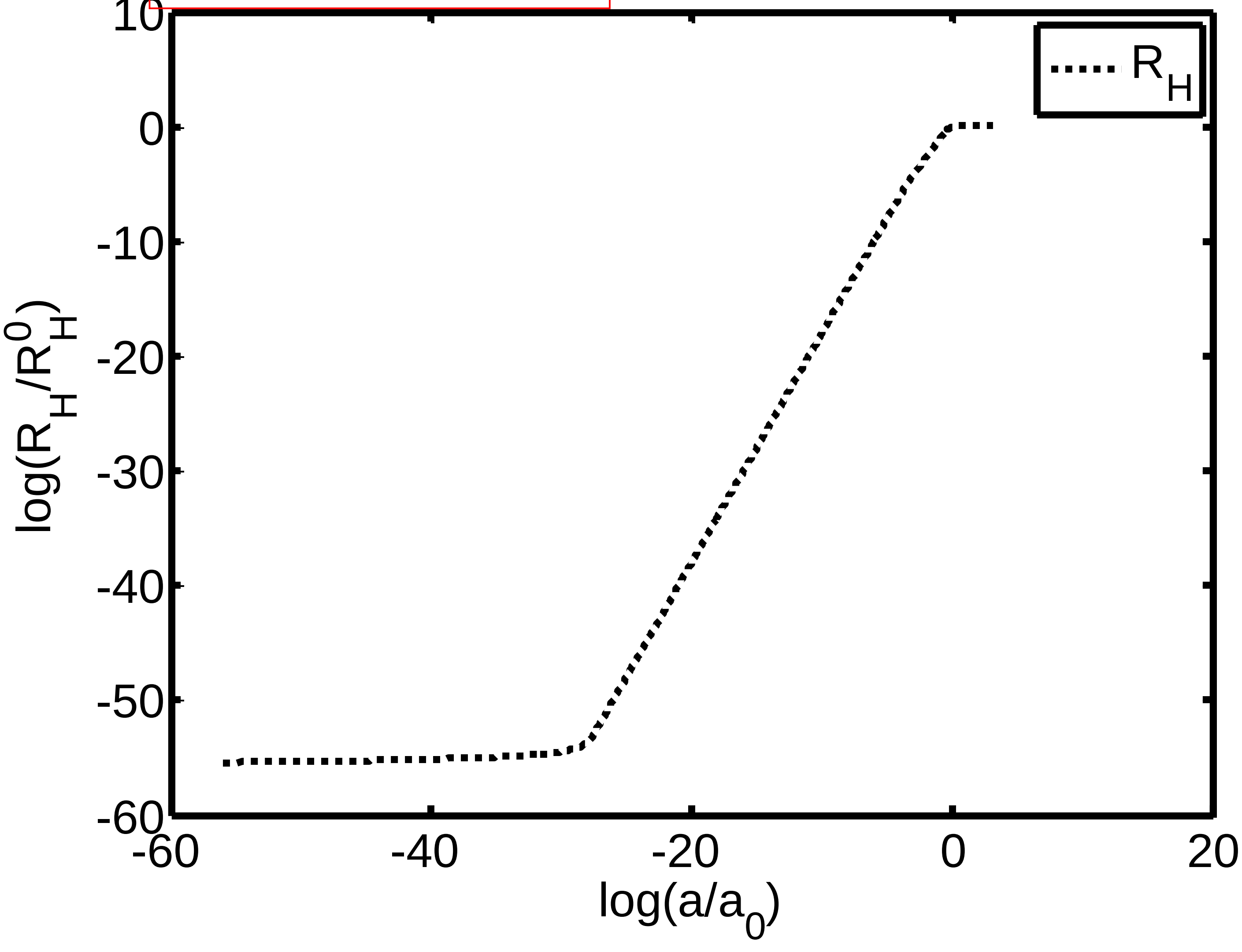
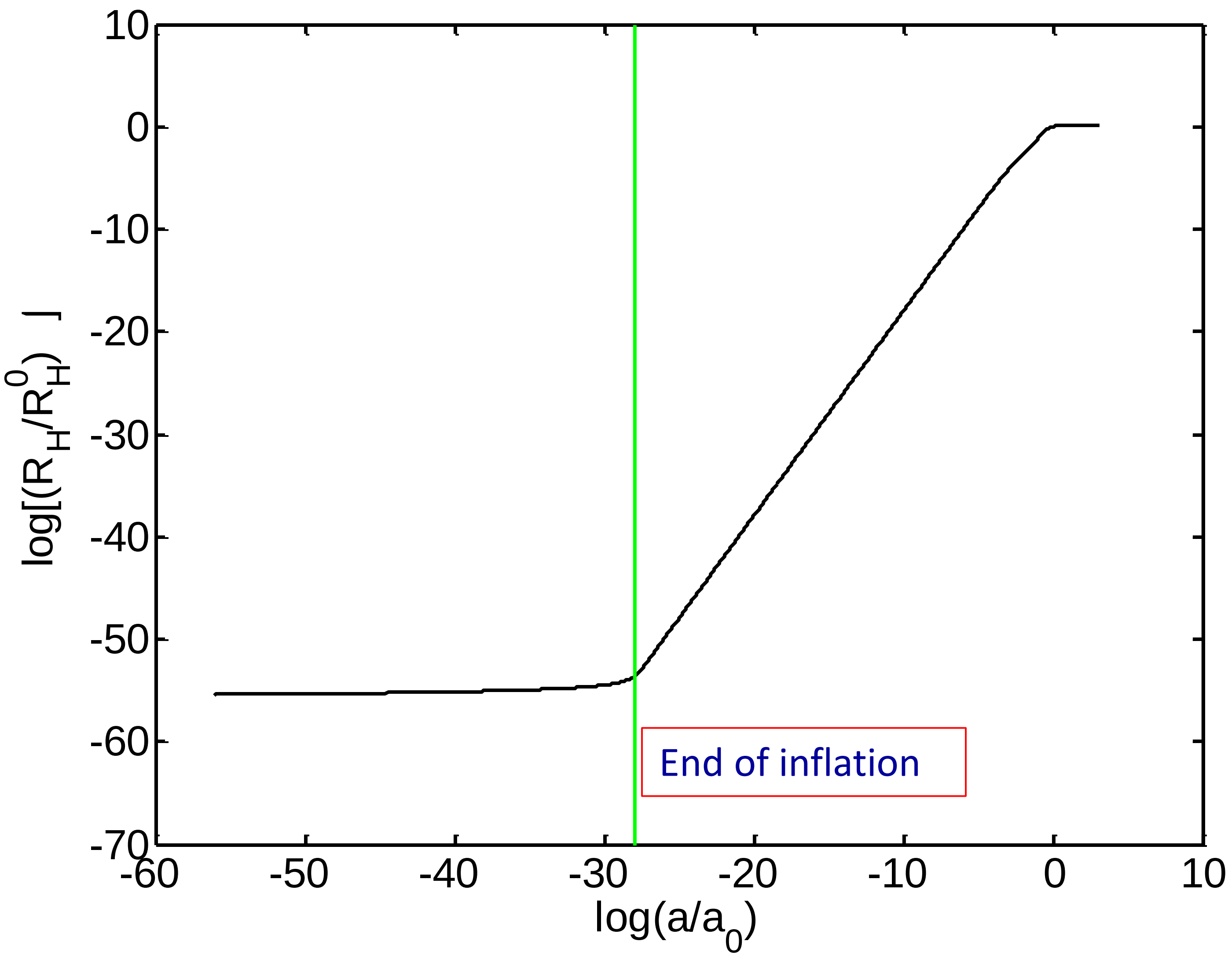


Evolution of Cosmic Length



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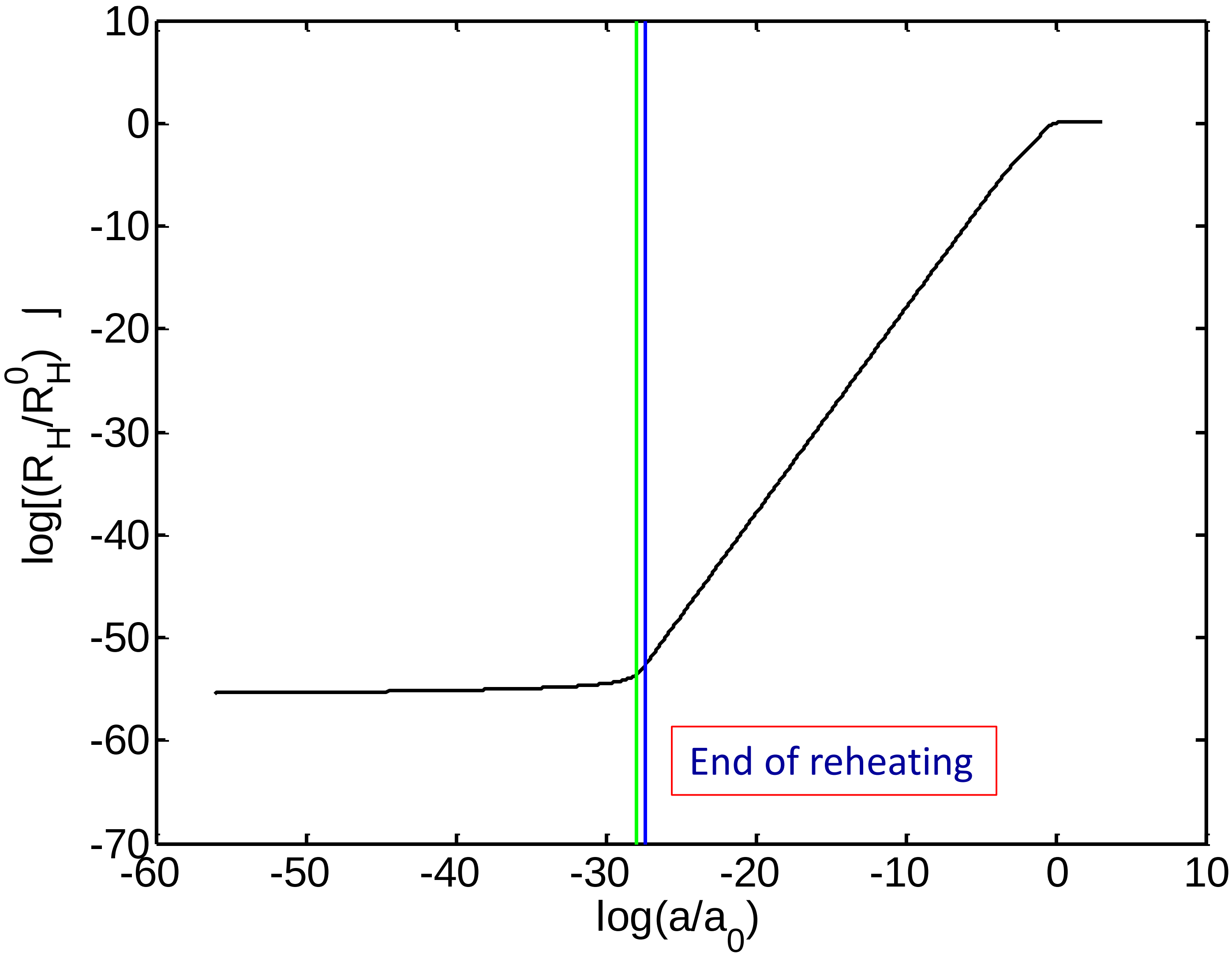

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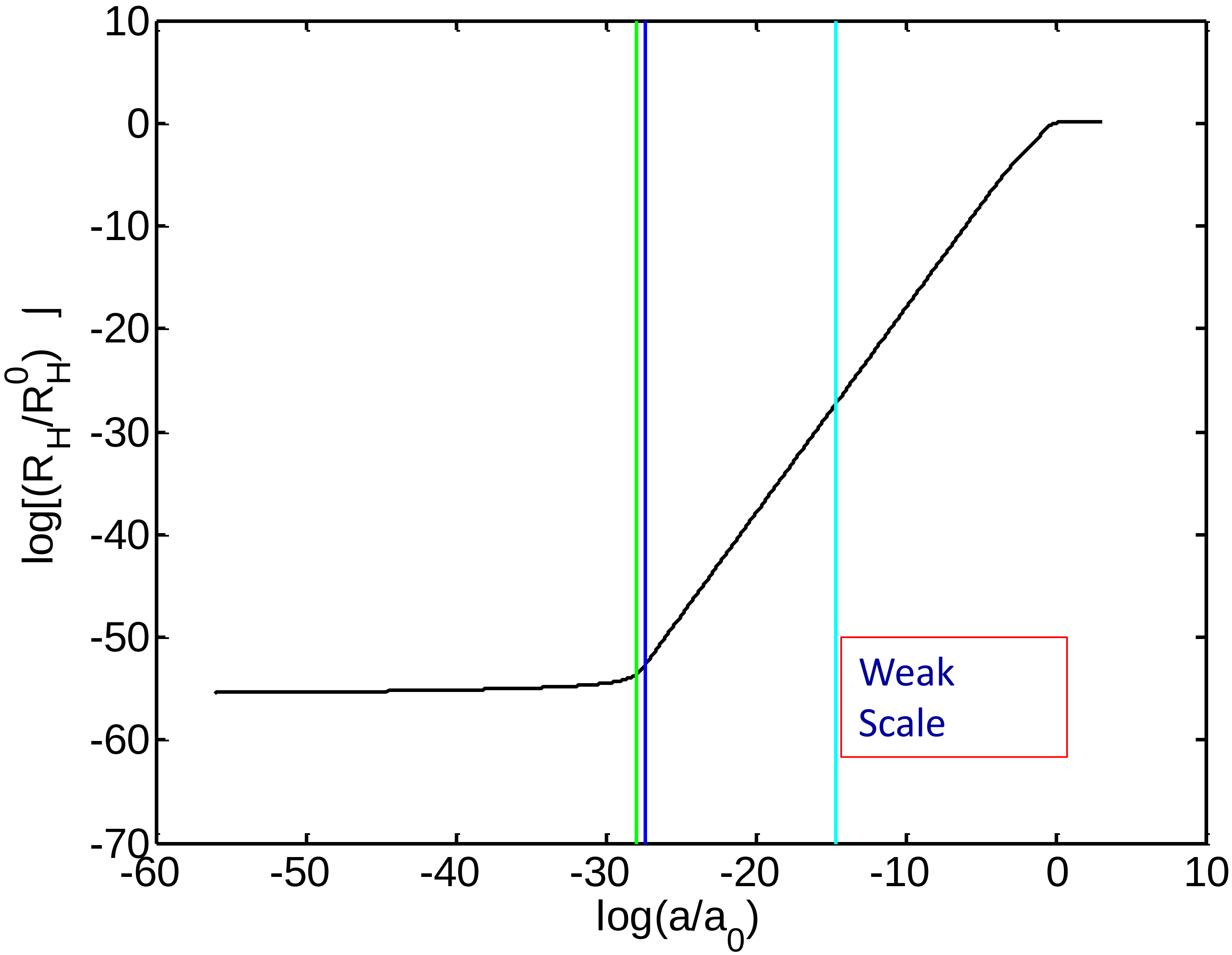

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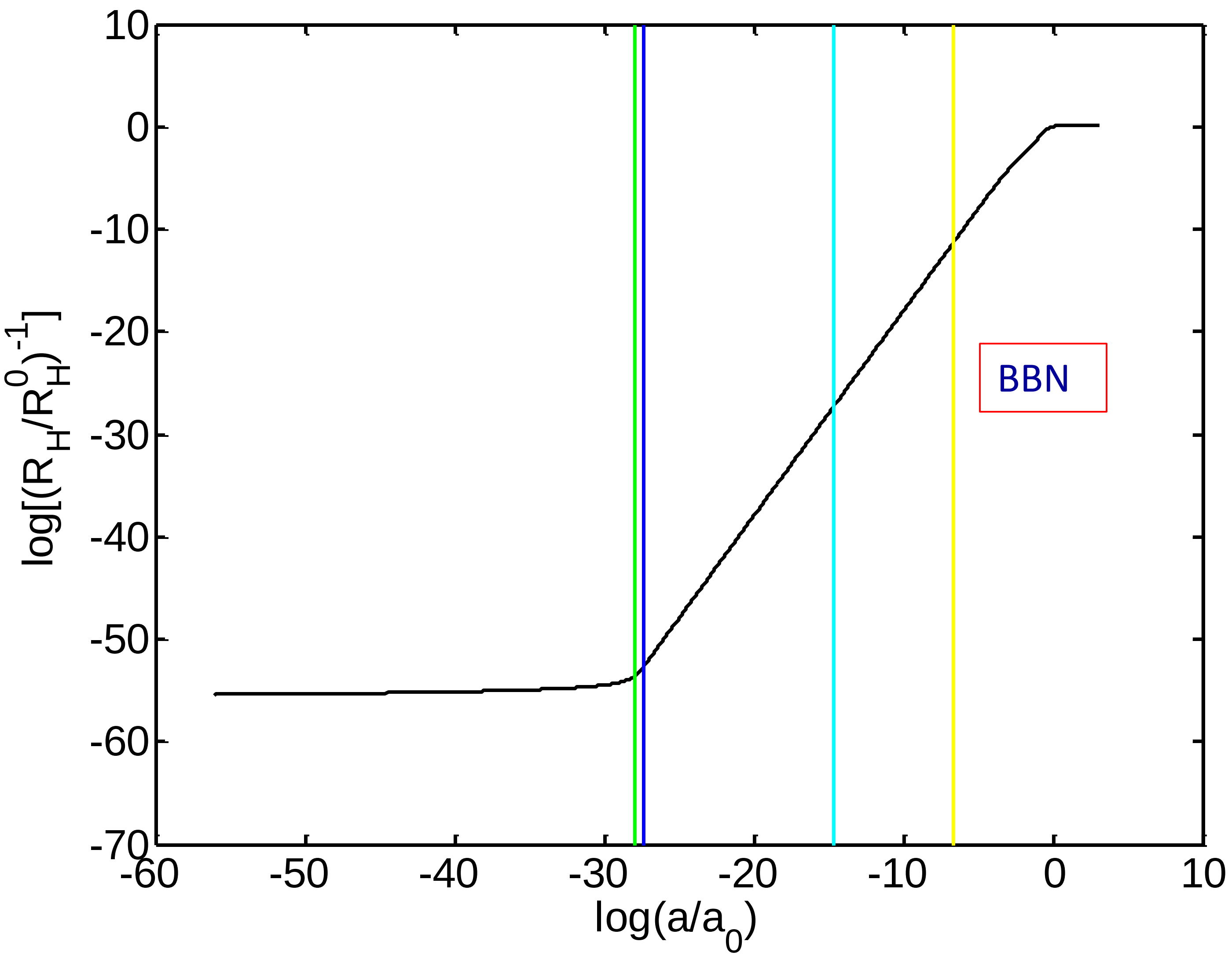

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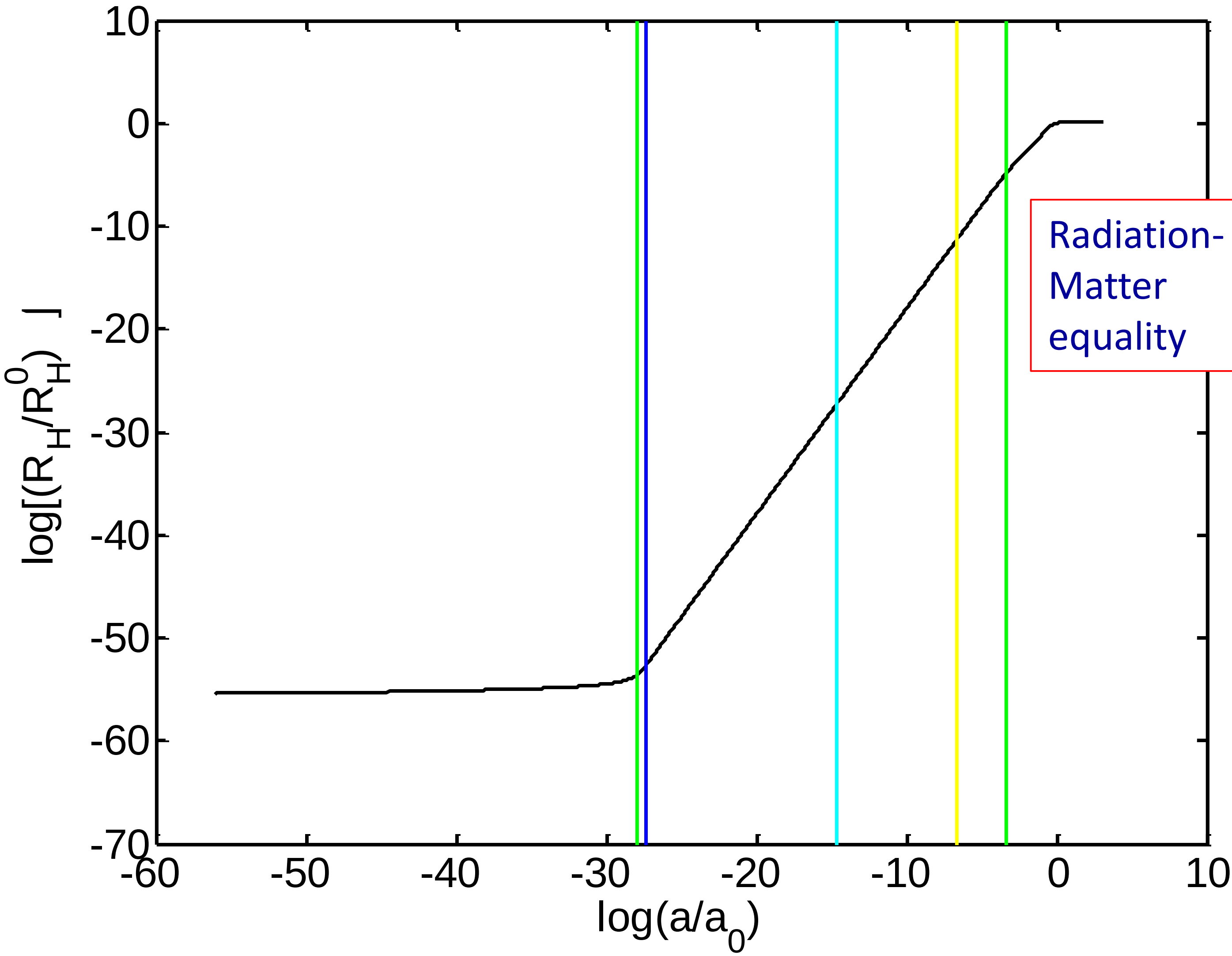

Radiation-Matter equality

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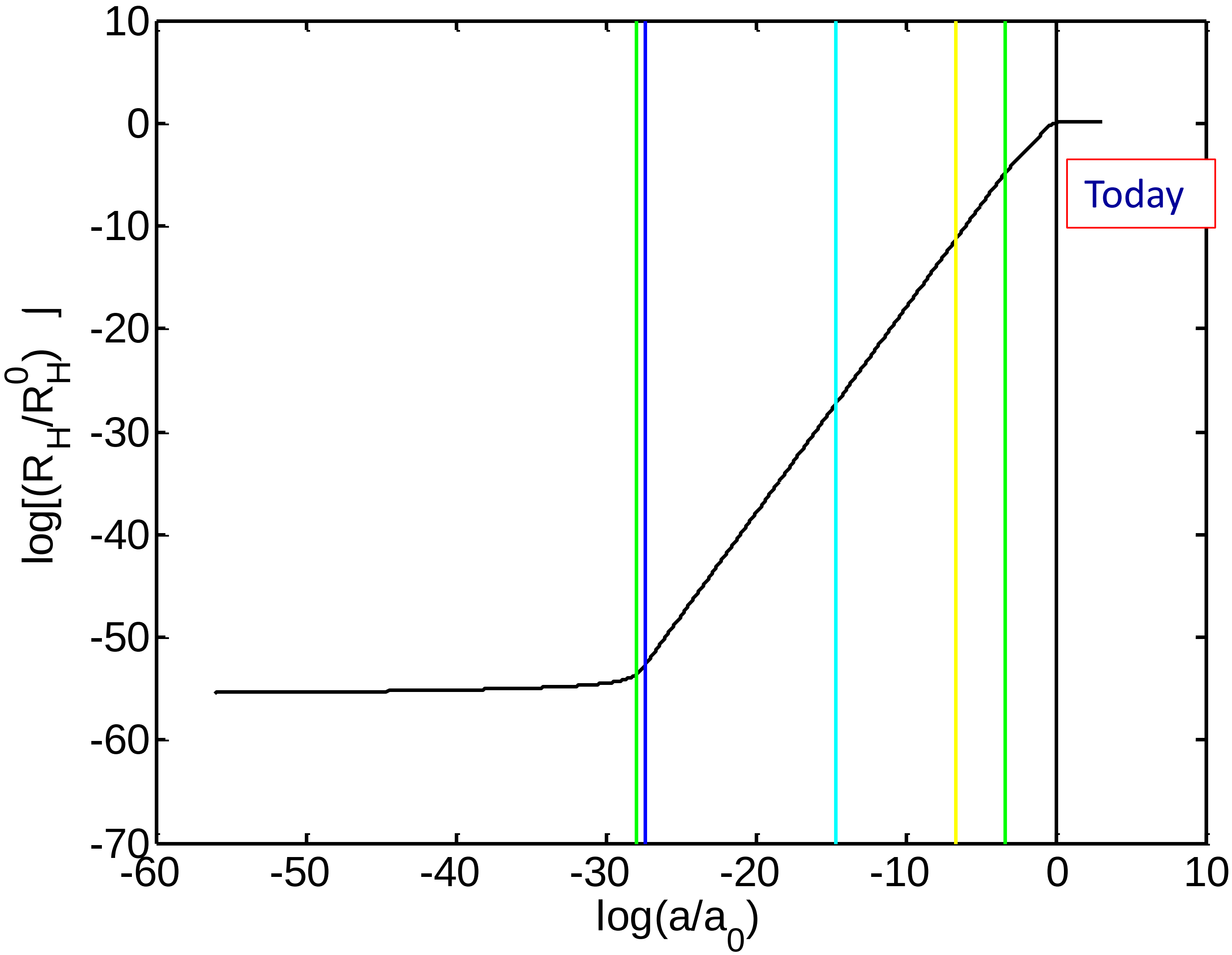

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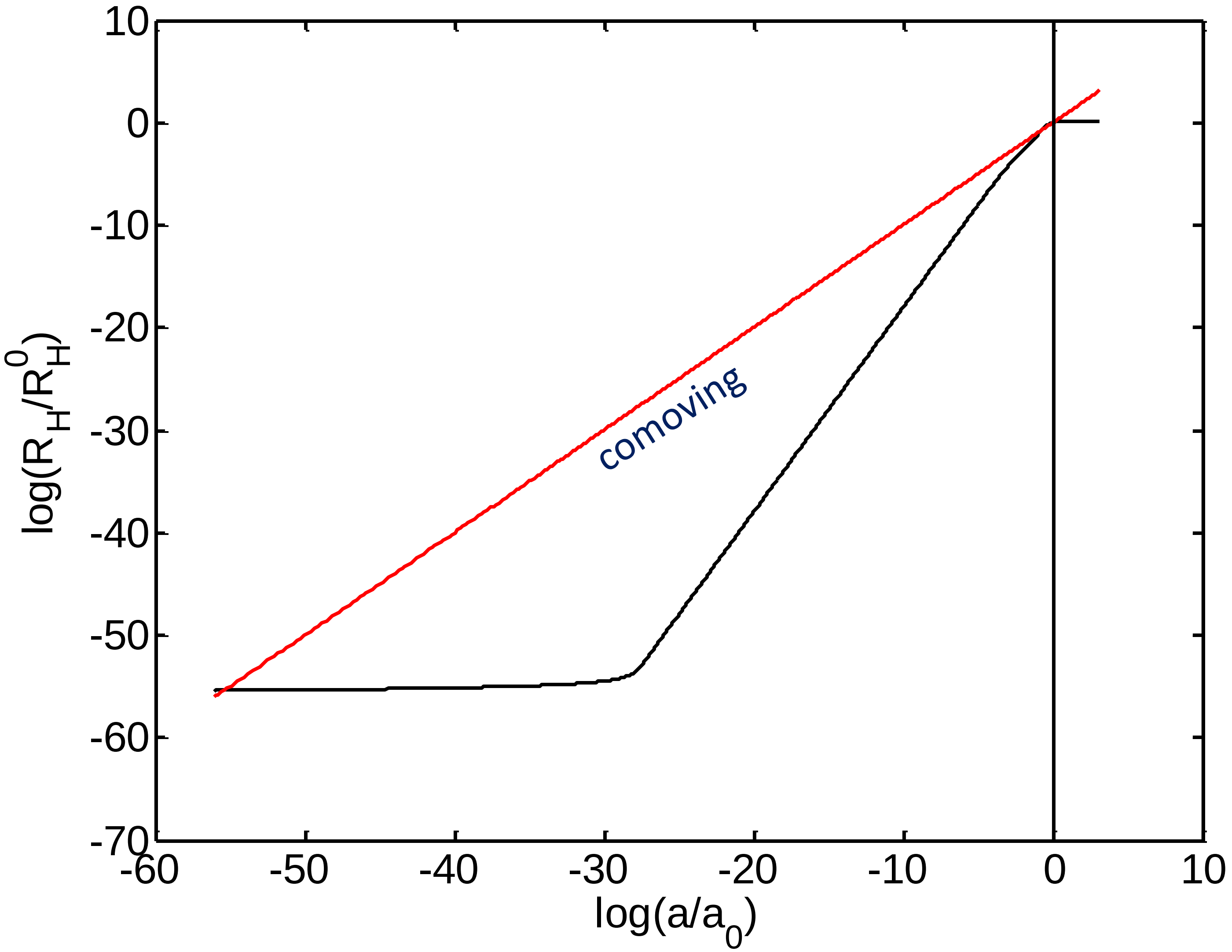

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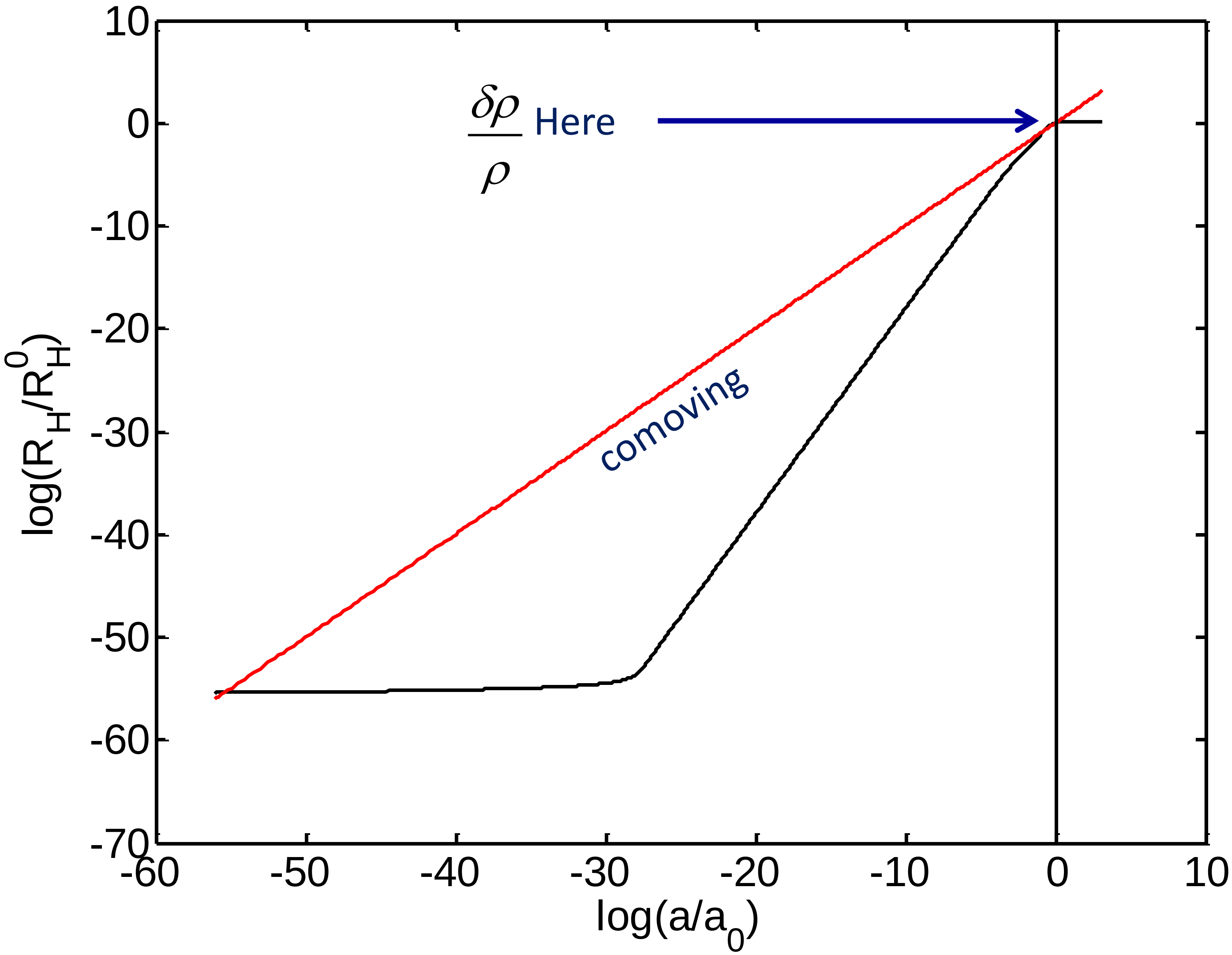
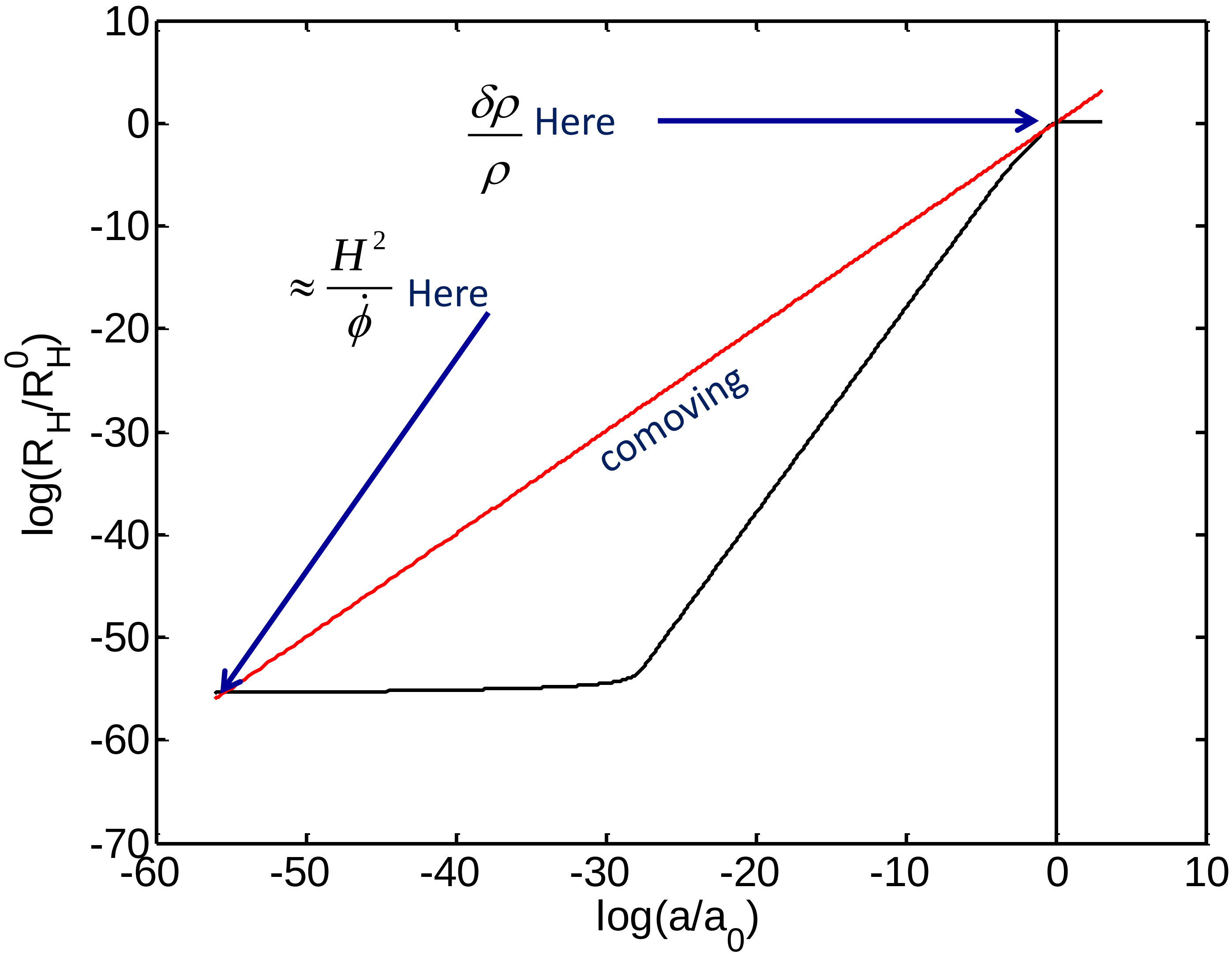
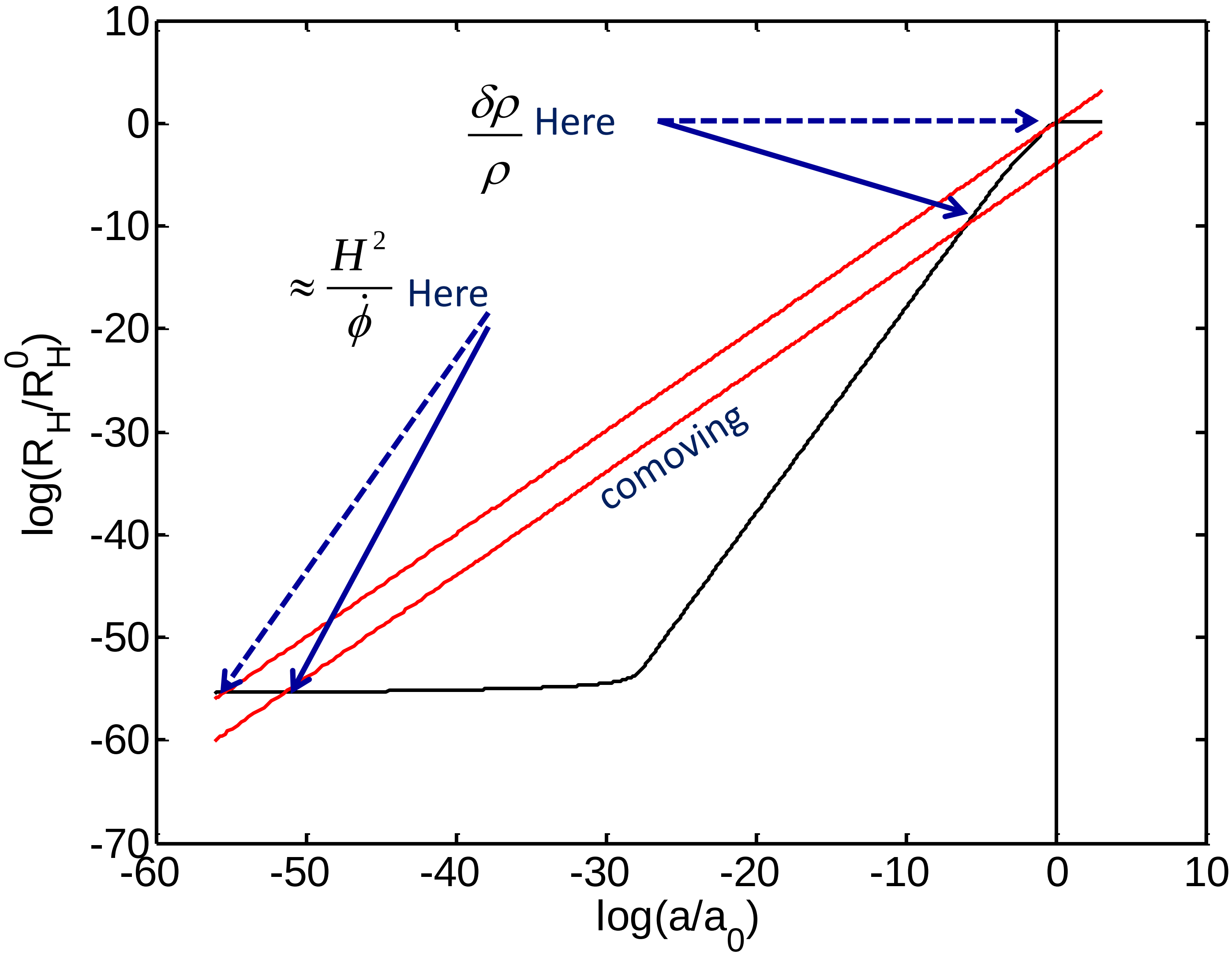
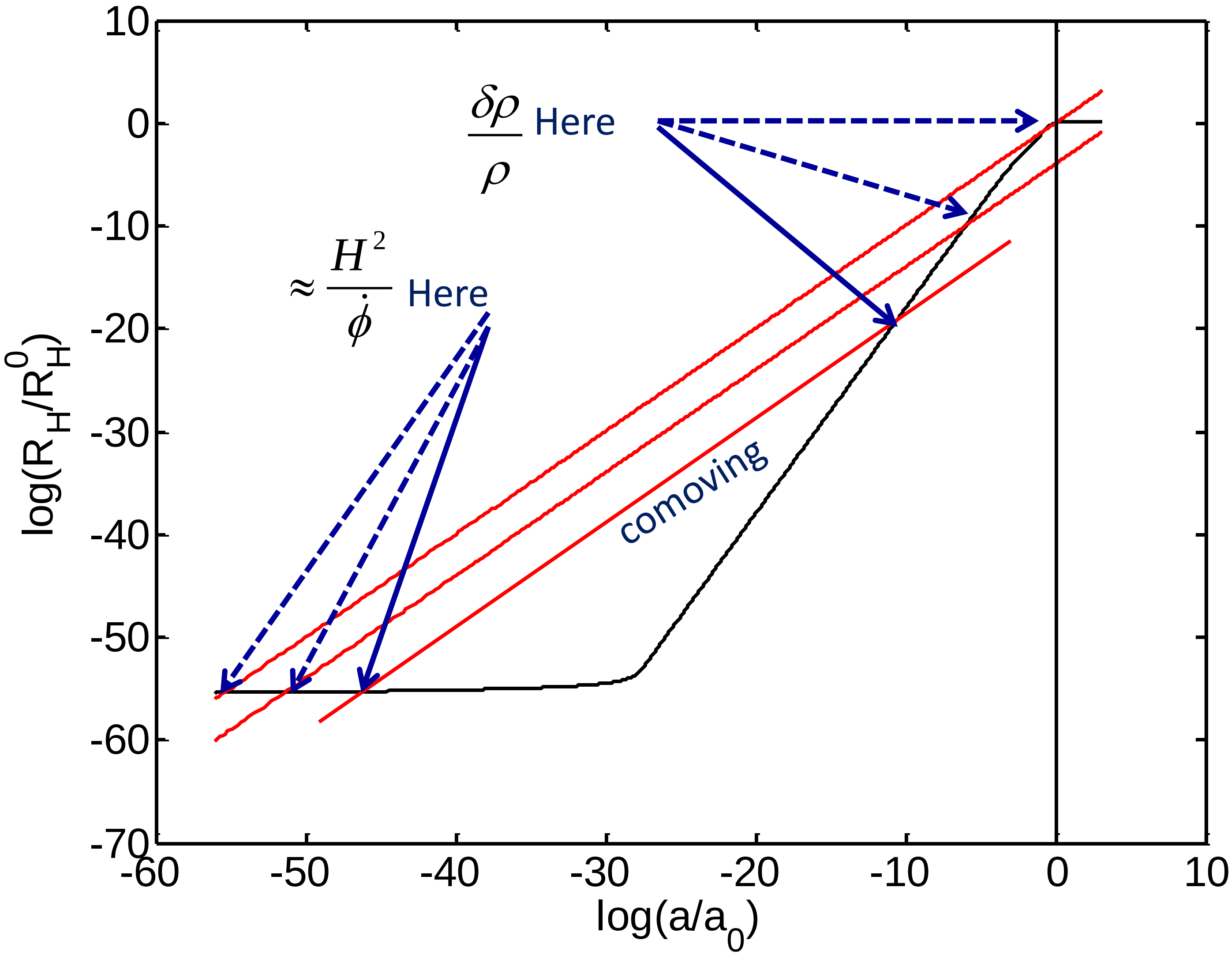


Perturbations from inflation



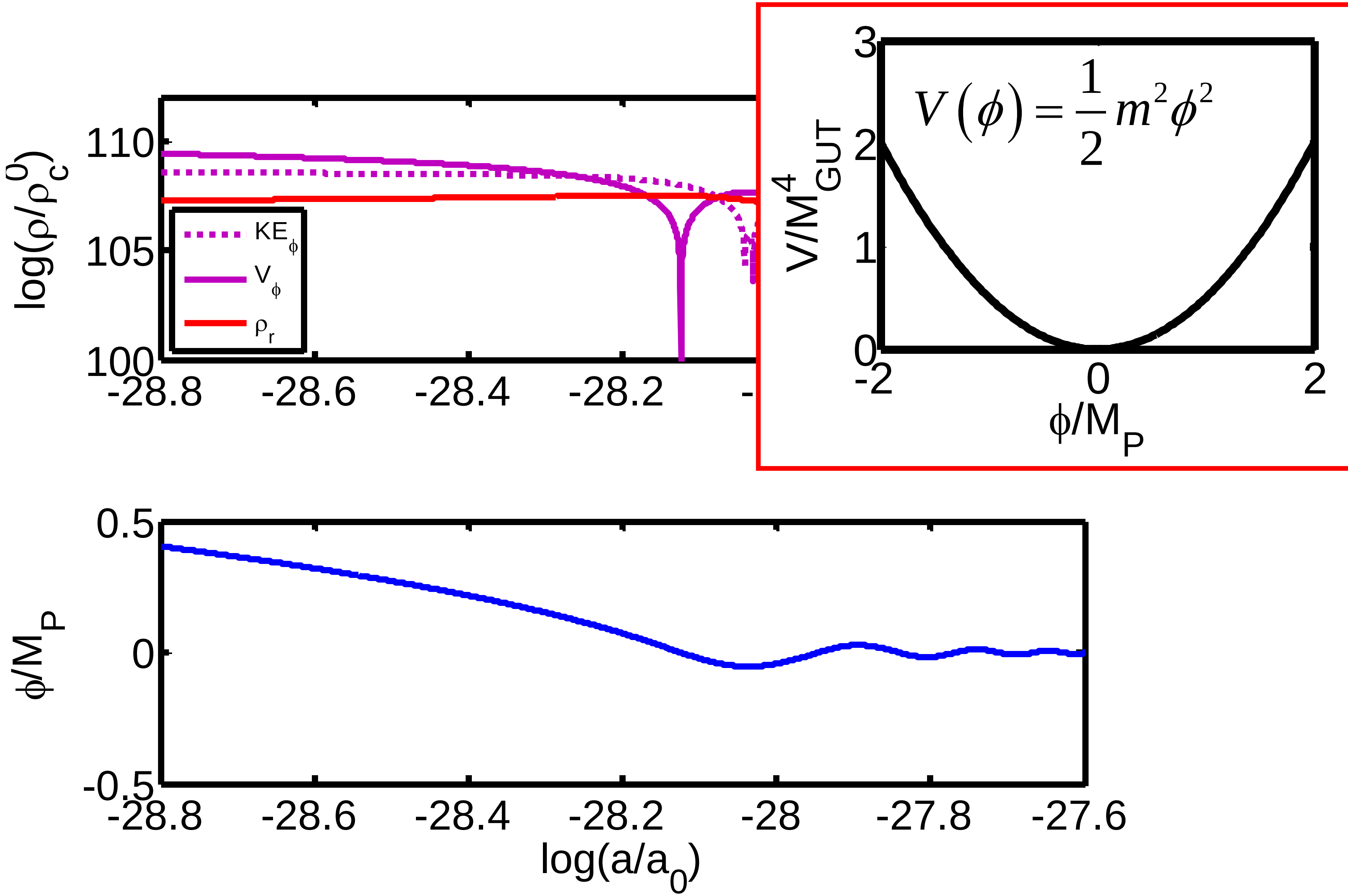


$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}}$ Here
comoving
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10
$\log(R_H/R_H^0)$
$\log(a/a_0)$

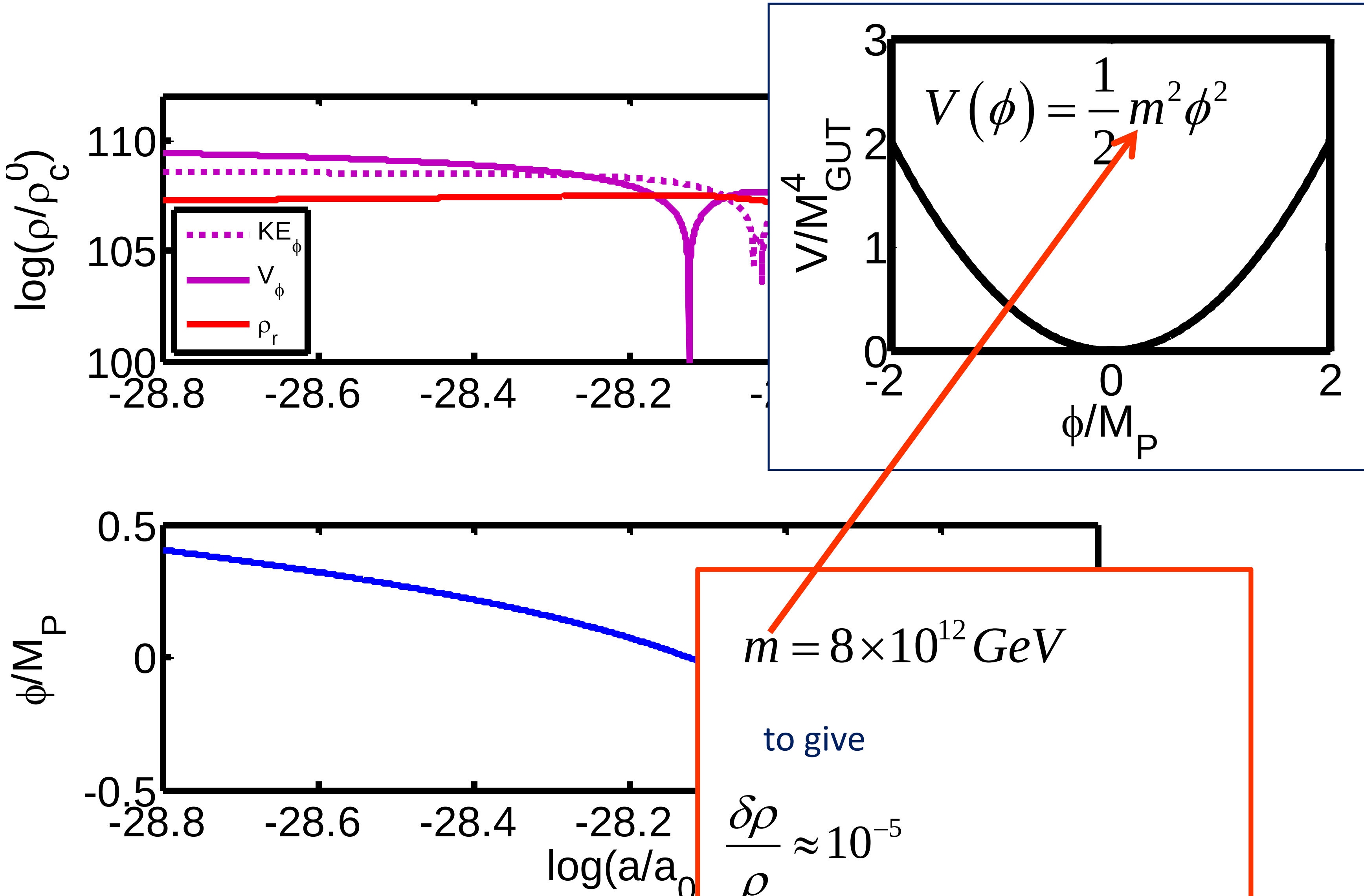


$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}}$ Here
comoving
log(R_H/R_H^0)
log(a/a_0)
10
0
-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10

Inflation detail:



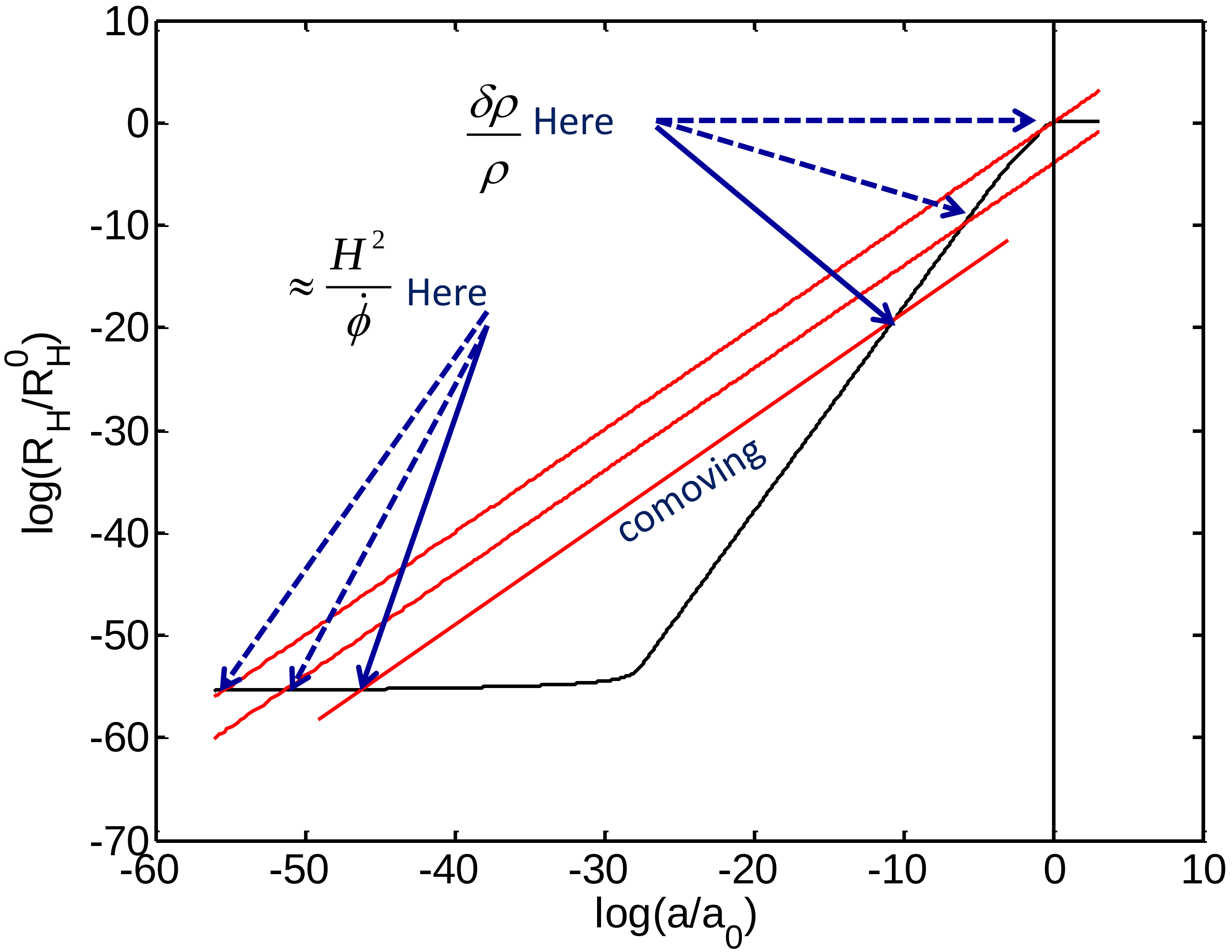
Inflation detail:



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

to give

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



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

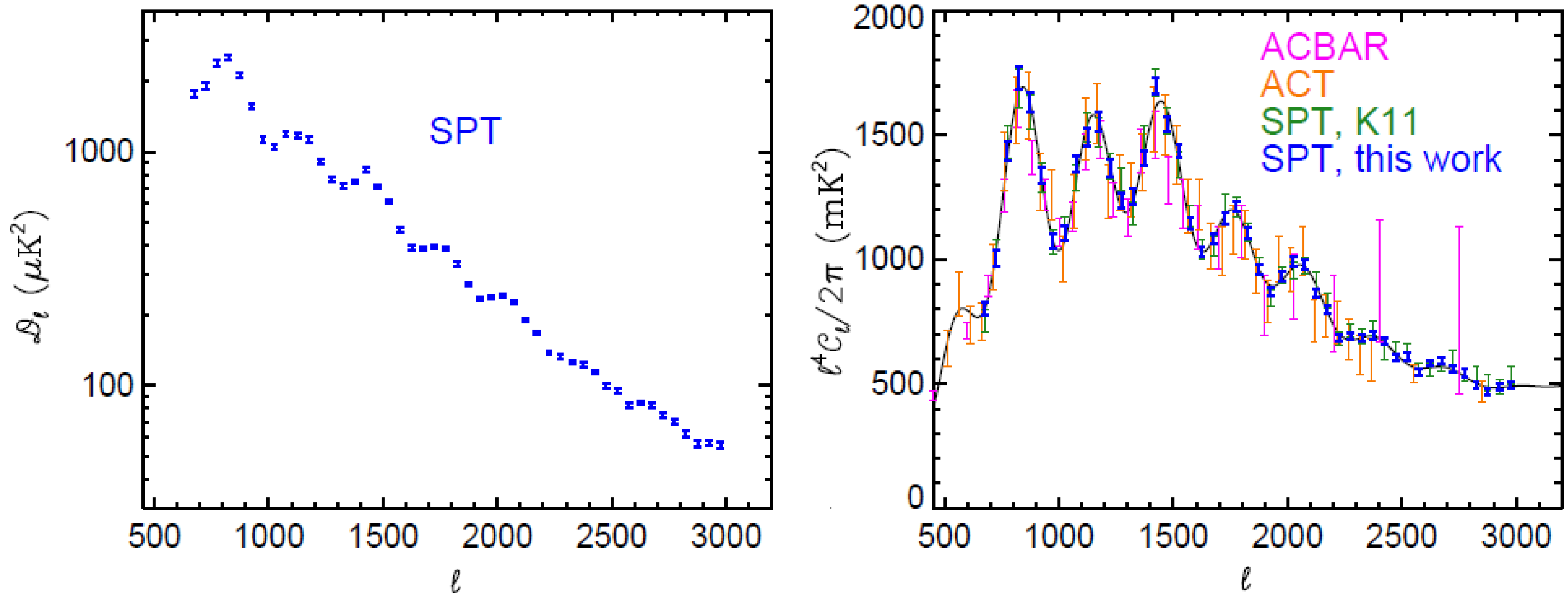


FIG. 3.— ***Left panel:*** The SPT power spectrum. The leftmost peak at $\ell \sim 800$ is the third acoustic peak. ***Right panel:*** A comparison of the new SPT bandpowers with other recent measurements of the CMB damping tail from ACBAR (Reichardt et al. 2009), ACT (Das et al. 2011b), and SPT (K11). 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

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Submitted to ApJ

arXiv:1210.7231v1

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:

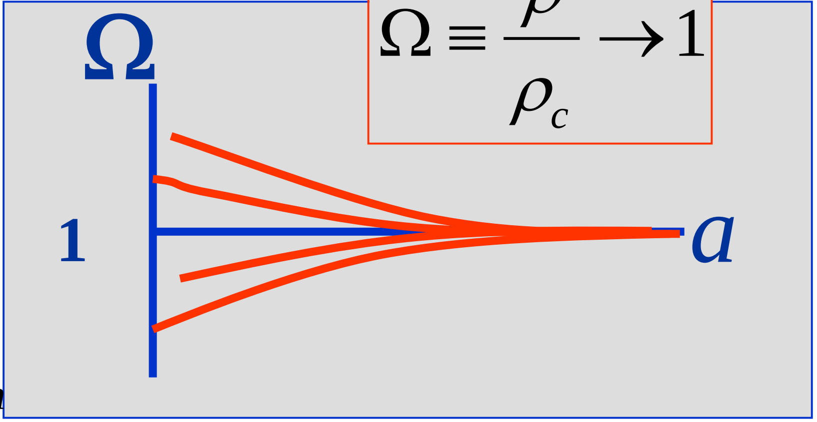
Flatness:

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

$\rho_\varphi = const.$

Dominates over ρ_r & ρ_m during inflation

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



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 : $\delta_H \approx 10^{-5}$

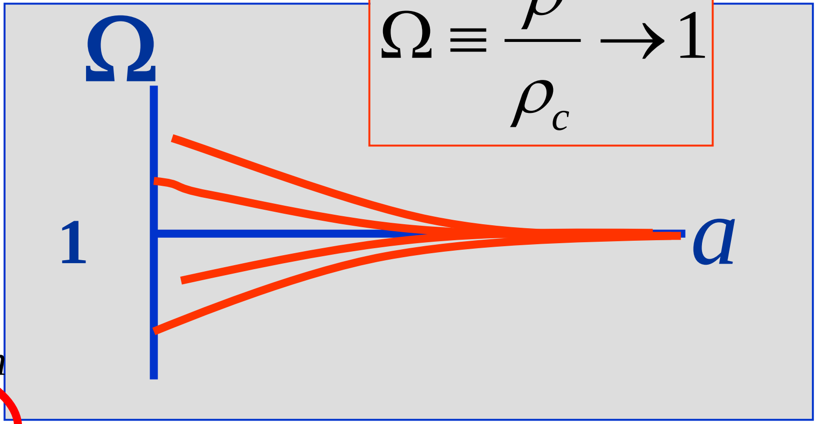
A period of early inflation gives:

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)

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

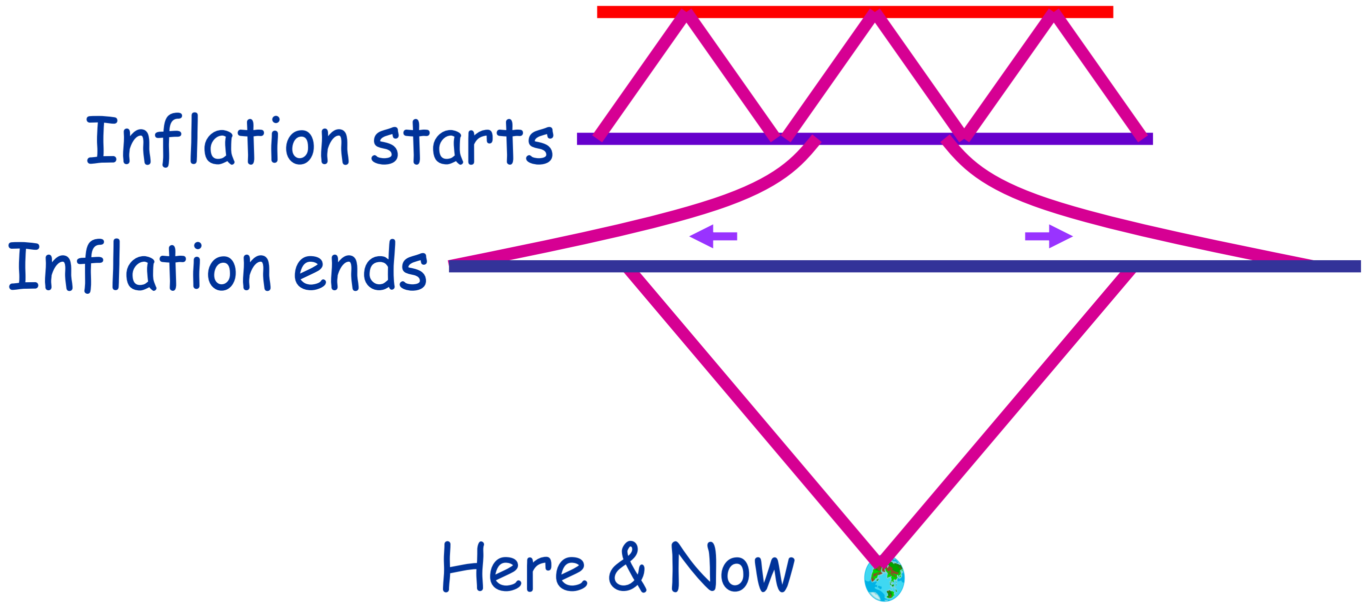


$$a \sim e^{Ht}$$

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

Monopoles are erased

Inflation Horizon:



I) Inflation in the era of WMAP

I.0 What is Cosmic Inflation?

I.1 Successes

II) Inflation and the arrow of time

II.1 Introduction

II.2 Arrow of time basics

II.3 Inflation and the arrow of time

II.4 Implications

II.5 Can the Universe Afford Inflation?

III) Conclusions

- Inflation:
  - An early period of nearly exponential ("superluminal") 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 ✓

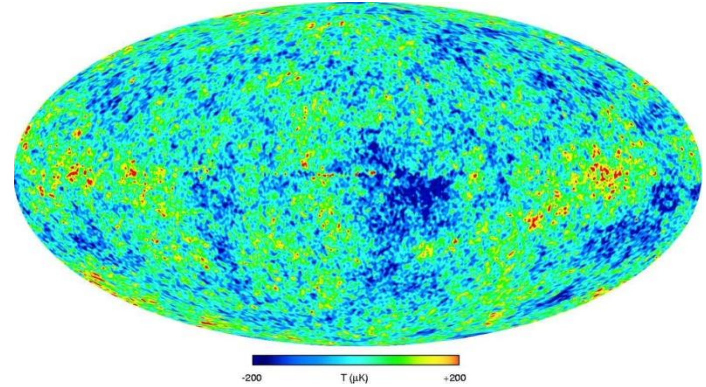


Table 3. "Best" Cosmological Parameters

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	—

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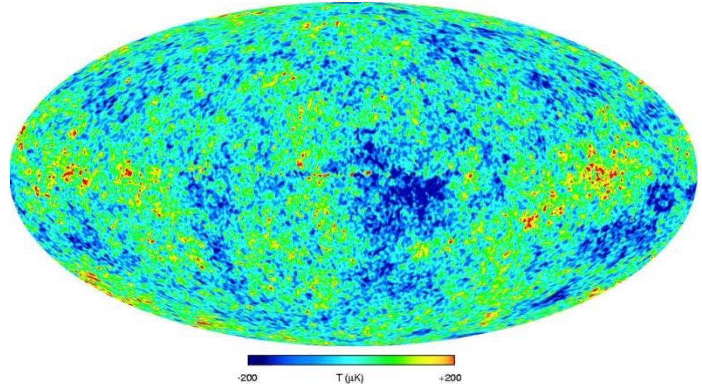
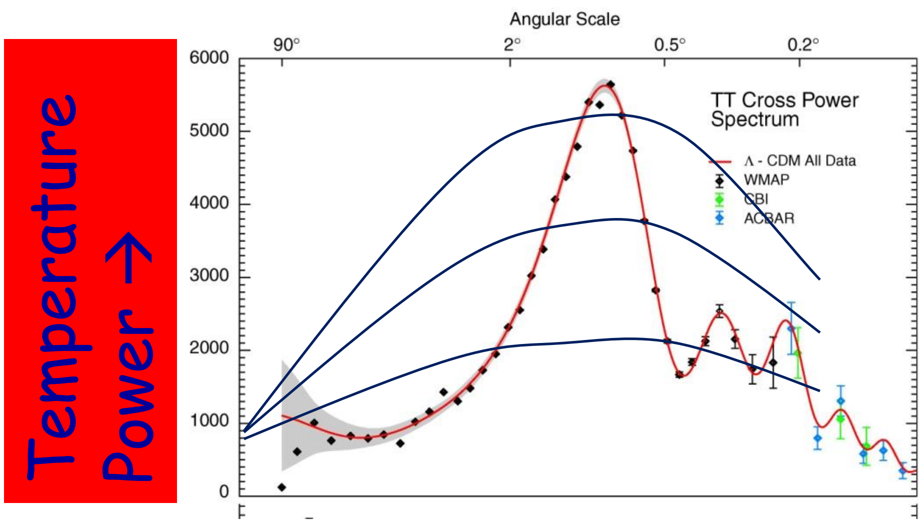
WMAP

- Characteristic oscillations in the CMB power





Inflation

"Active" models

← Angular scale

Adapted from

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WMAP

- Nearly scale invariant perturbation spectrum

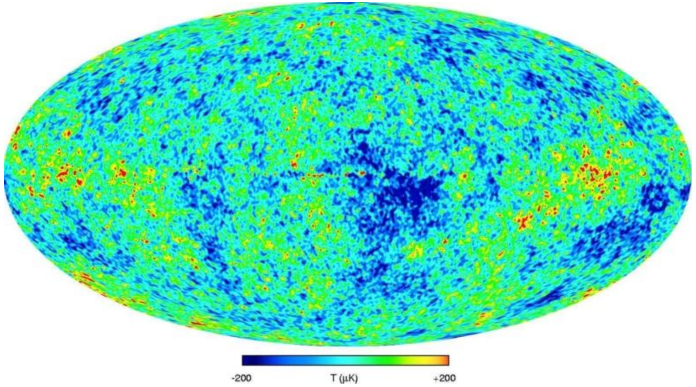

Table 3. "Best" Cosmological Parameters

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

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

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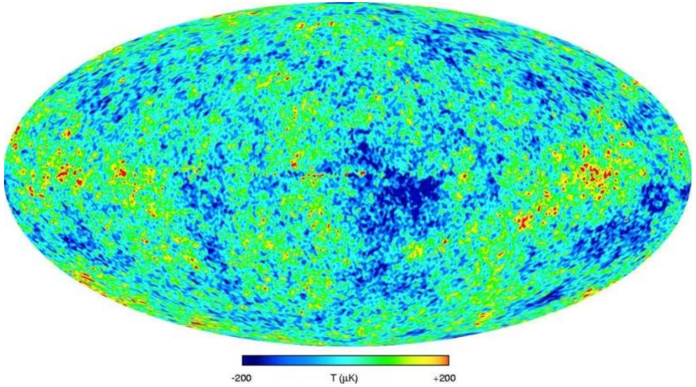
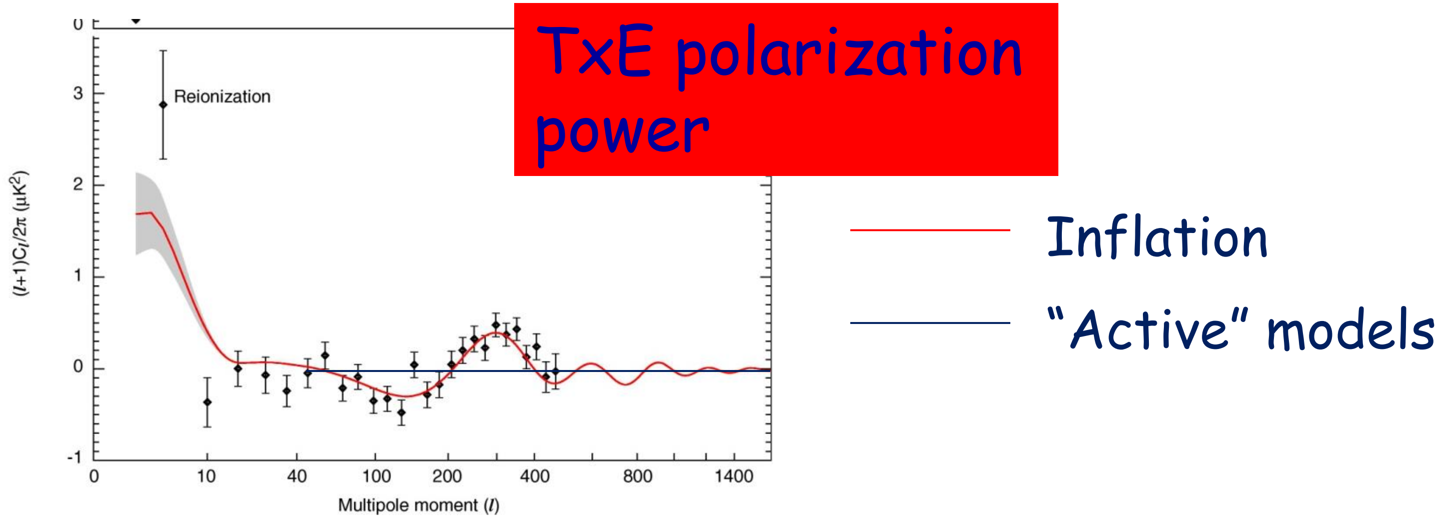
WMAP

- Characteristic Gravity wave, CMB Polarization etc





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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

OUTLINE

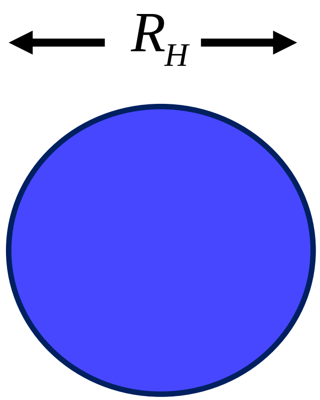
1. Big Bang & inflation basics
2. Eternal inflation ⇦
3. de Sitter Equilibrium cosmology
4. Cosmic curvature from de Sitter Equilibrium cosmology

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:

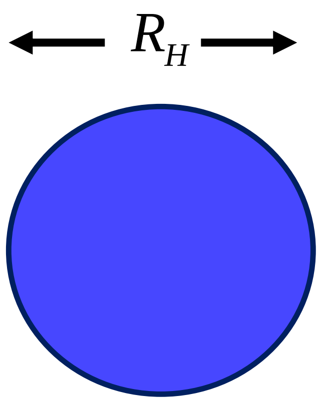
$$\frac{\Delta\phi}{\Delta t} \equiv \dot{\phi}_Q = H^2$$

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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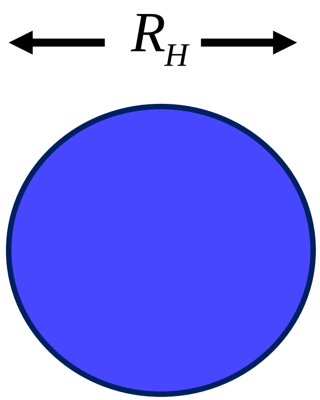
Thus

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

measures the importance of quantum fluctuations in the field evolution

Quantum fluctuations during slow roll:



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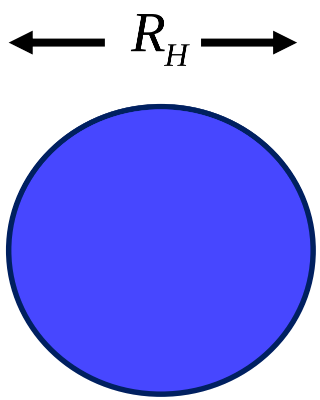
Thus

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

measures the importance of quantum fluctuations in the field evolution

For realistic perturbations the evolution is very classical

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:

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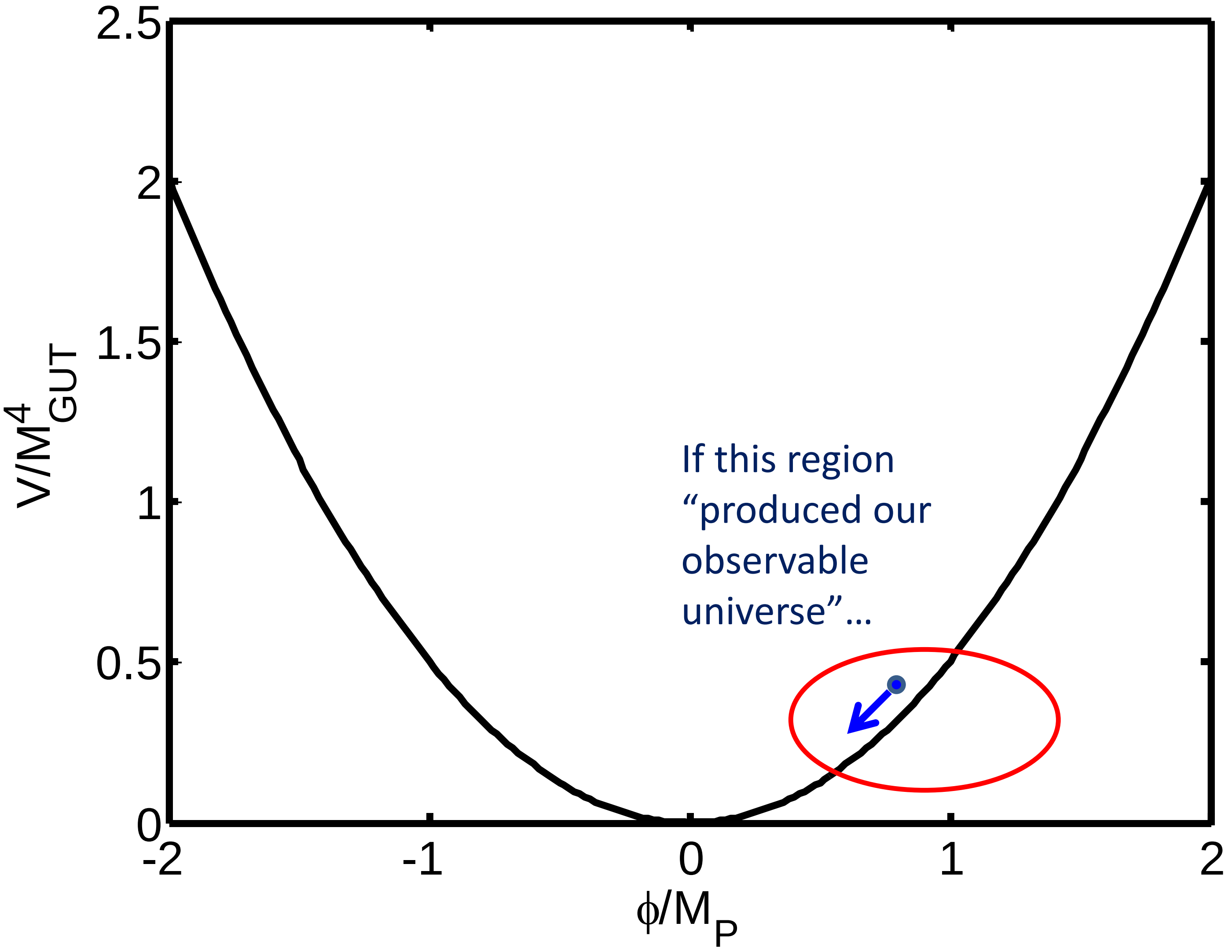
Thus

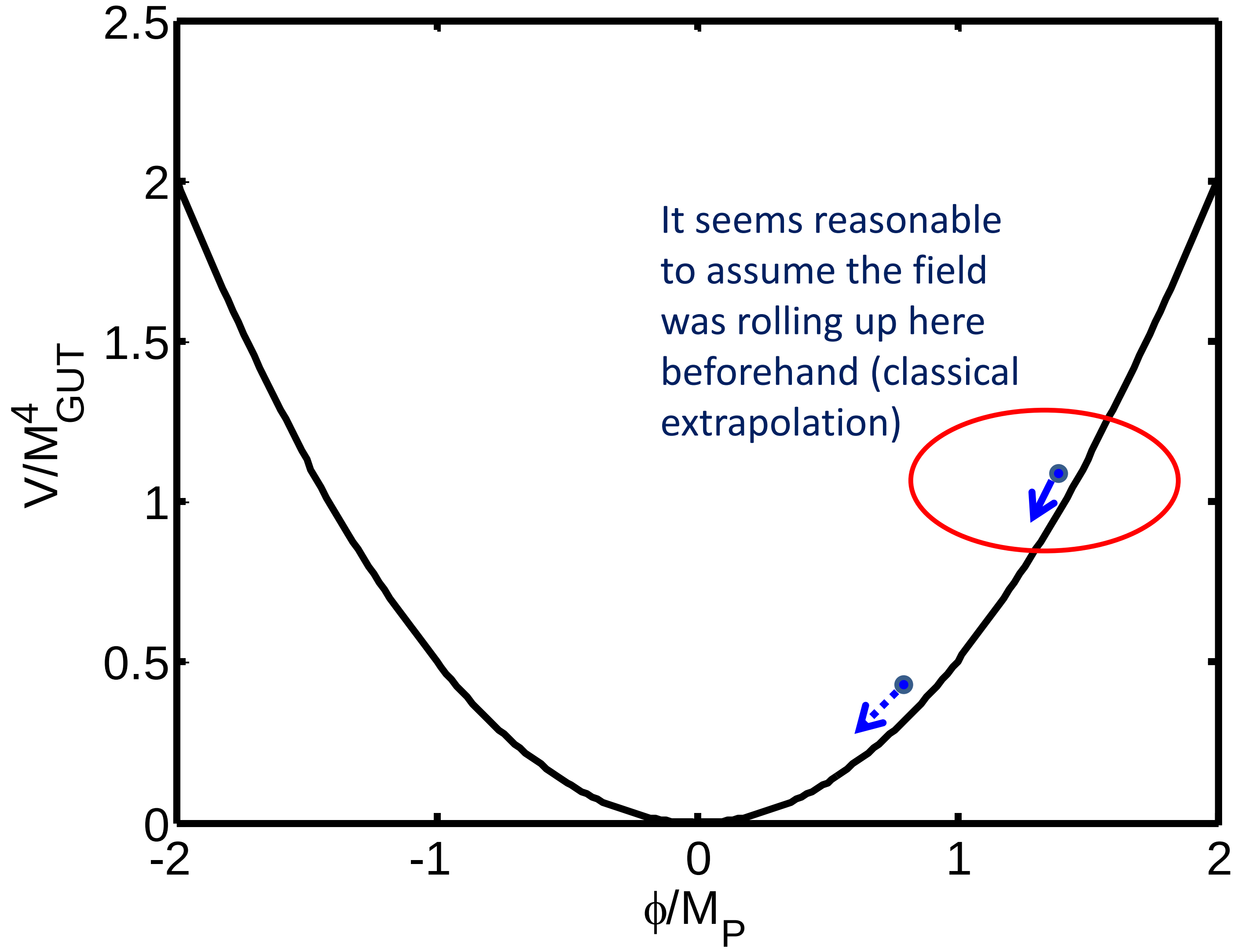
$$\frac{\dot{\phi}_Q}{\dot{\phi}} = \frac{H^2}{\dot{\phi}} \quad \left(= \frac{\delta\rho}{\rho} \approx 10^{-5} \right)$$

measures the importance of quantum fluctuations in the field evolution

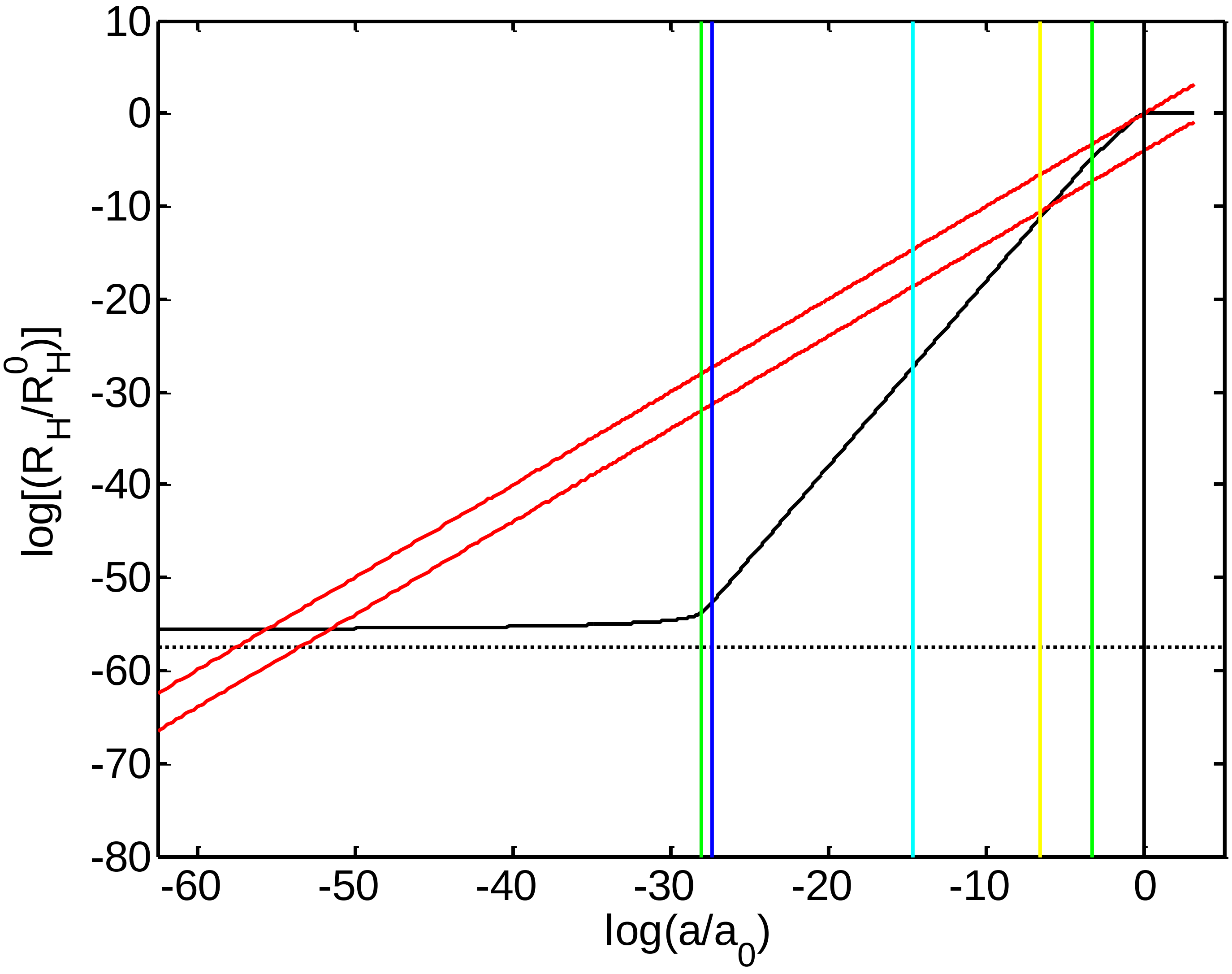
For realistic perturbations the evolution is very classical

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

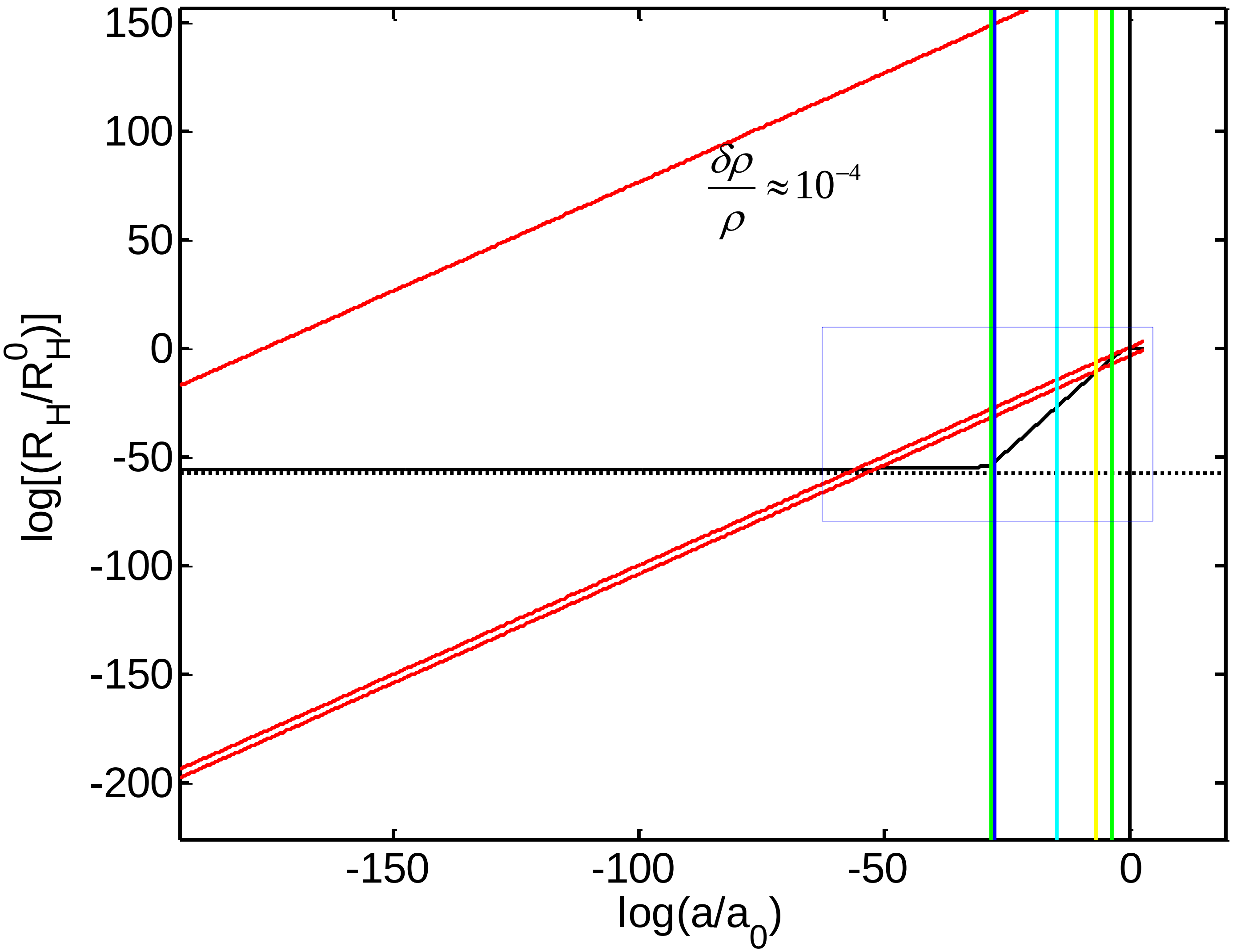

2.5
2
1.5
1
0.5
0
V/M^4_{GUT}
-2
-1
0
1
2
ϕ/M_P
If this region
"produced our
observable
universe"…


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

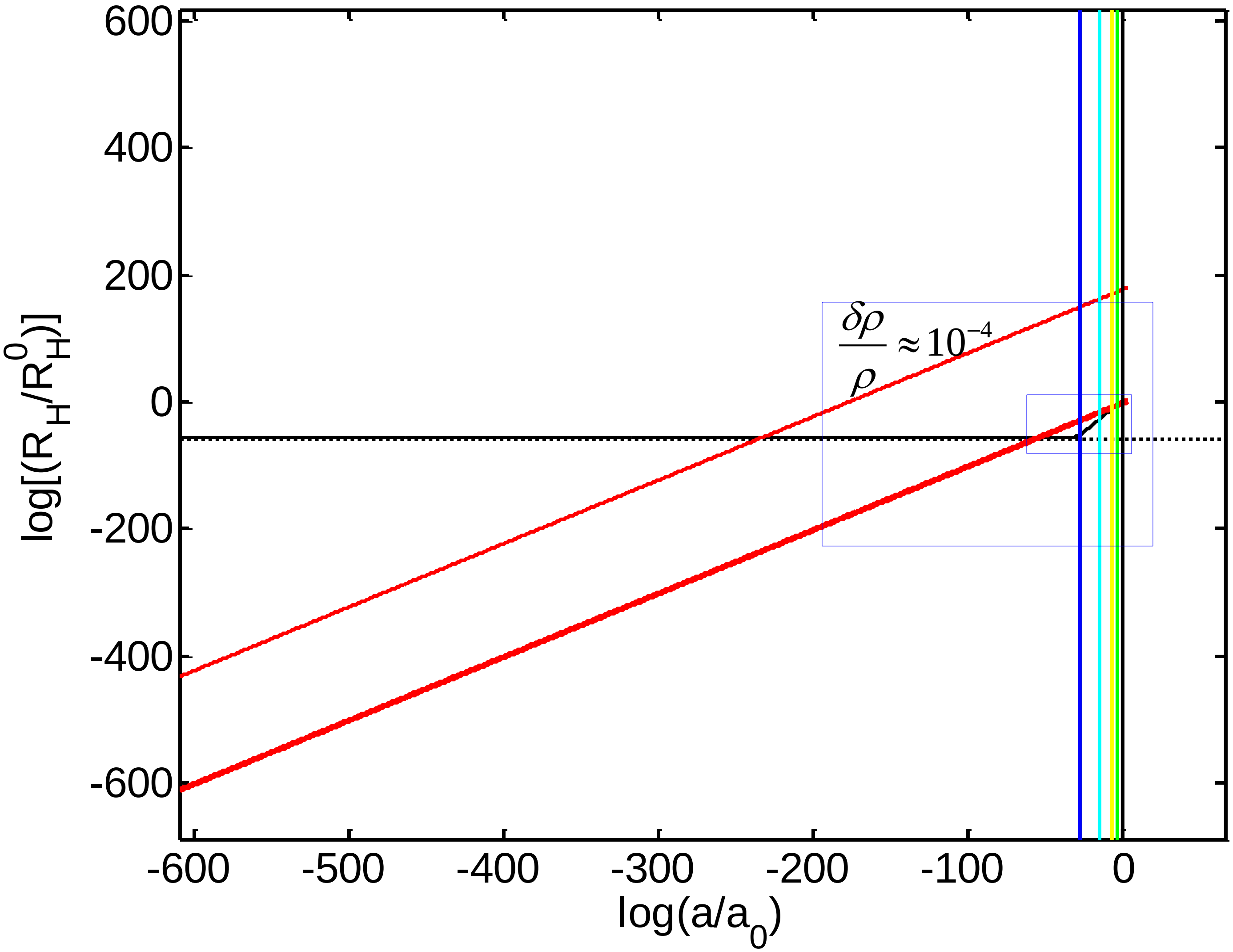
Evolution of Cosmic Length



Evolution of Cosmic Length (zooming out)



Evolution of Cosmic Length (zooming out)



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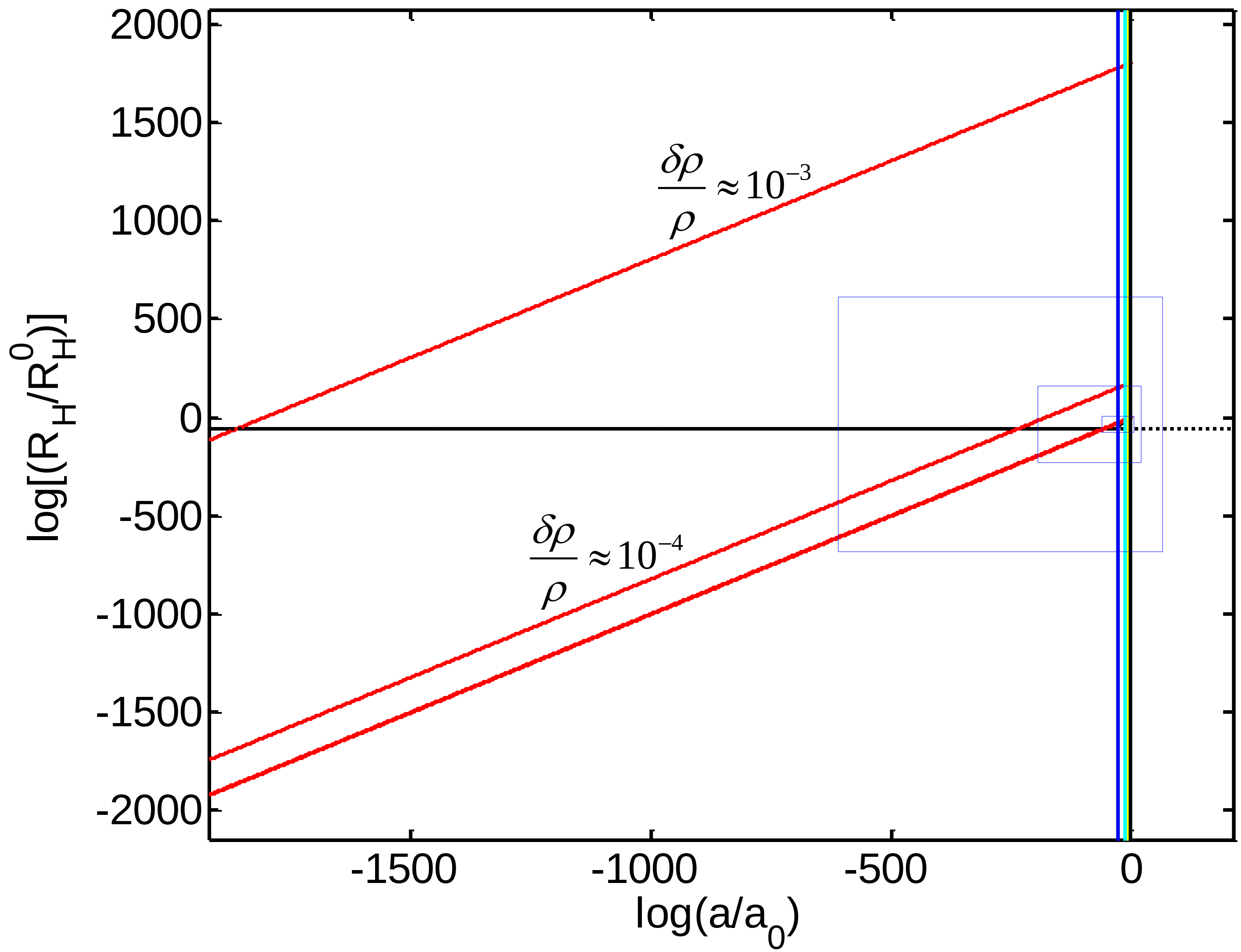

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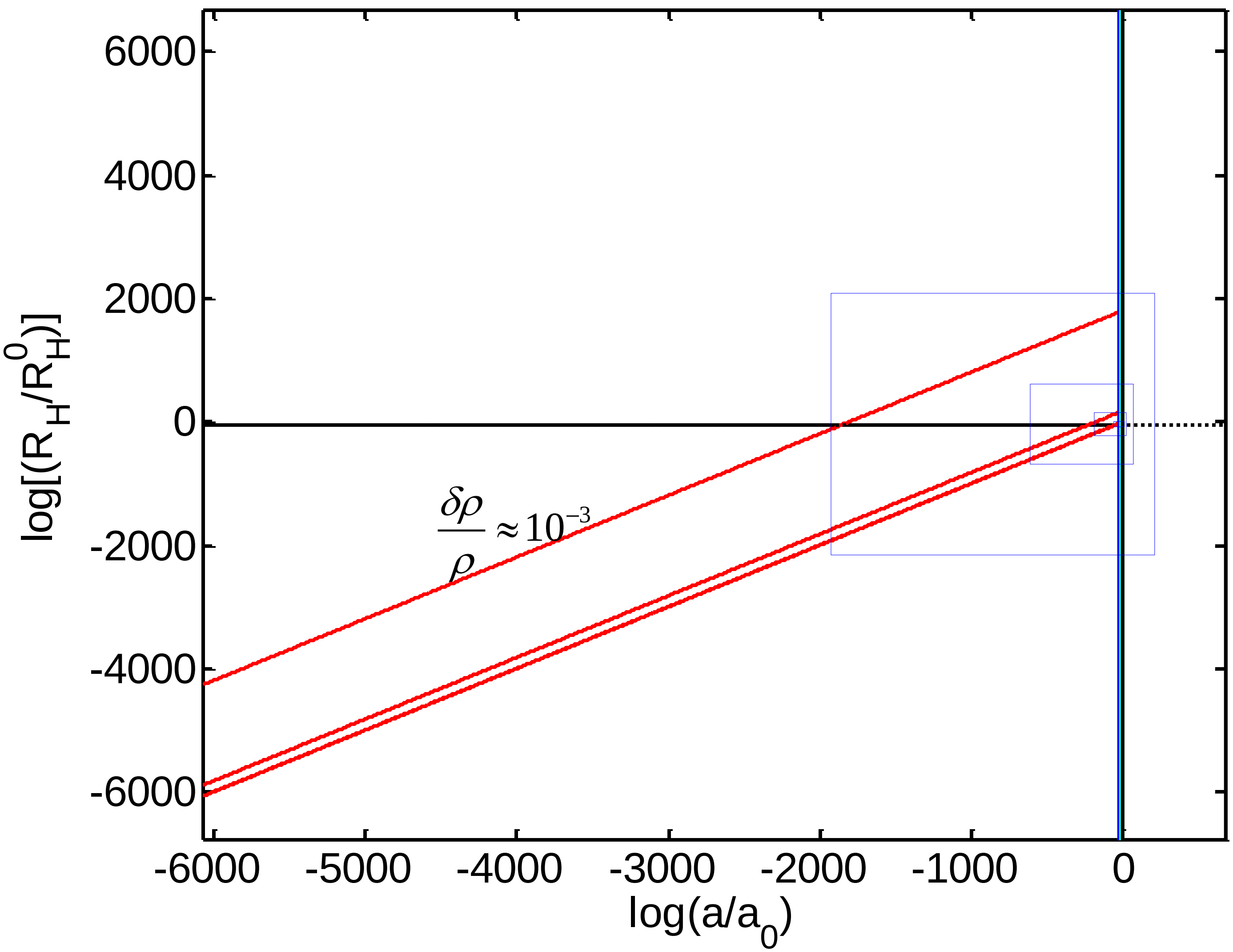
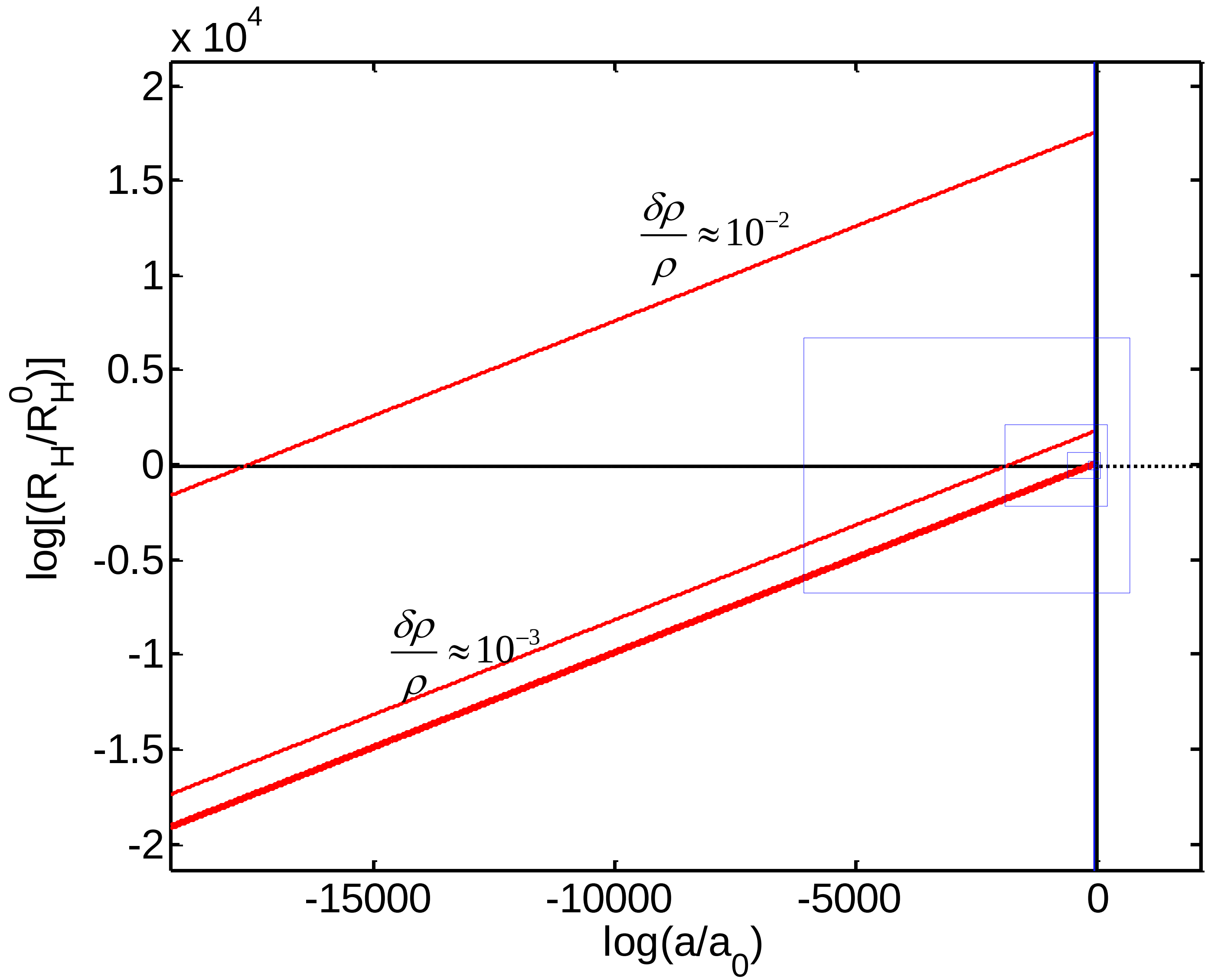
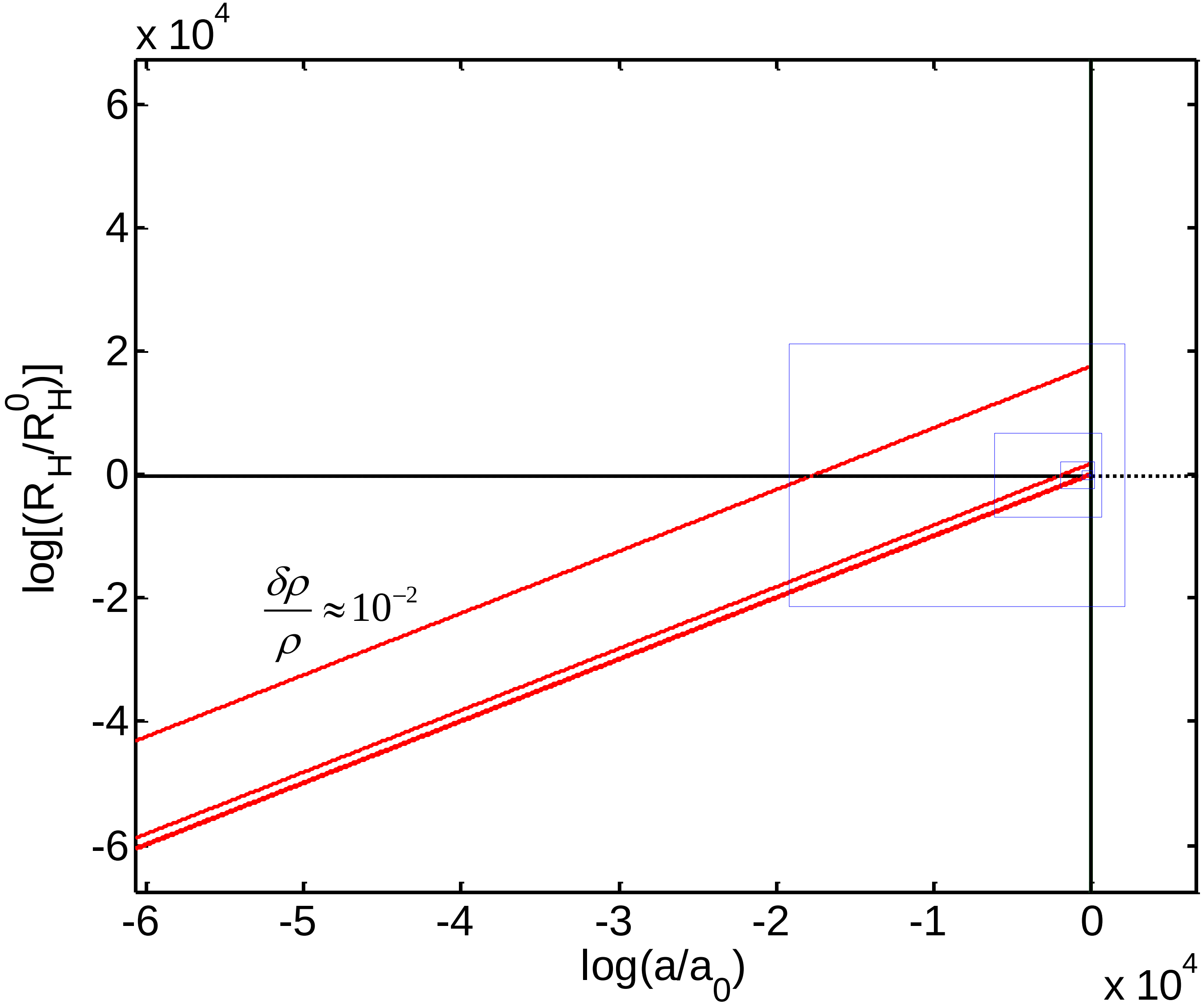


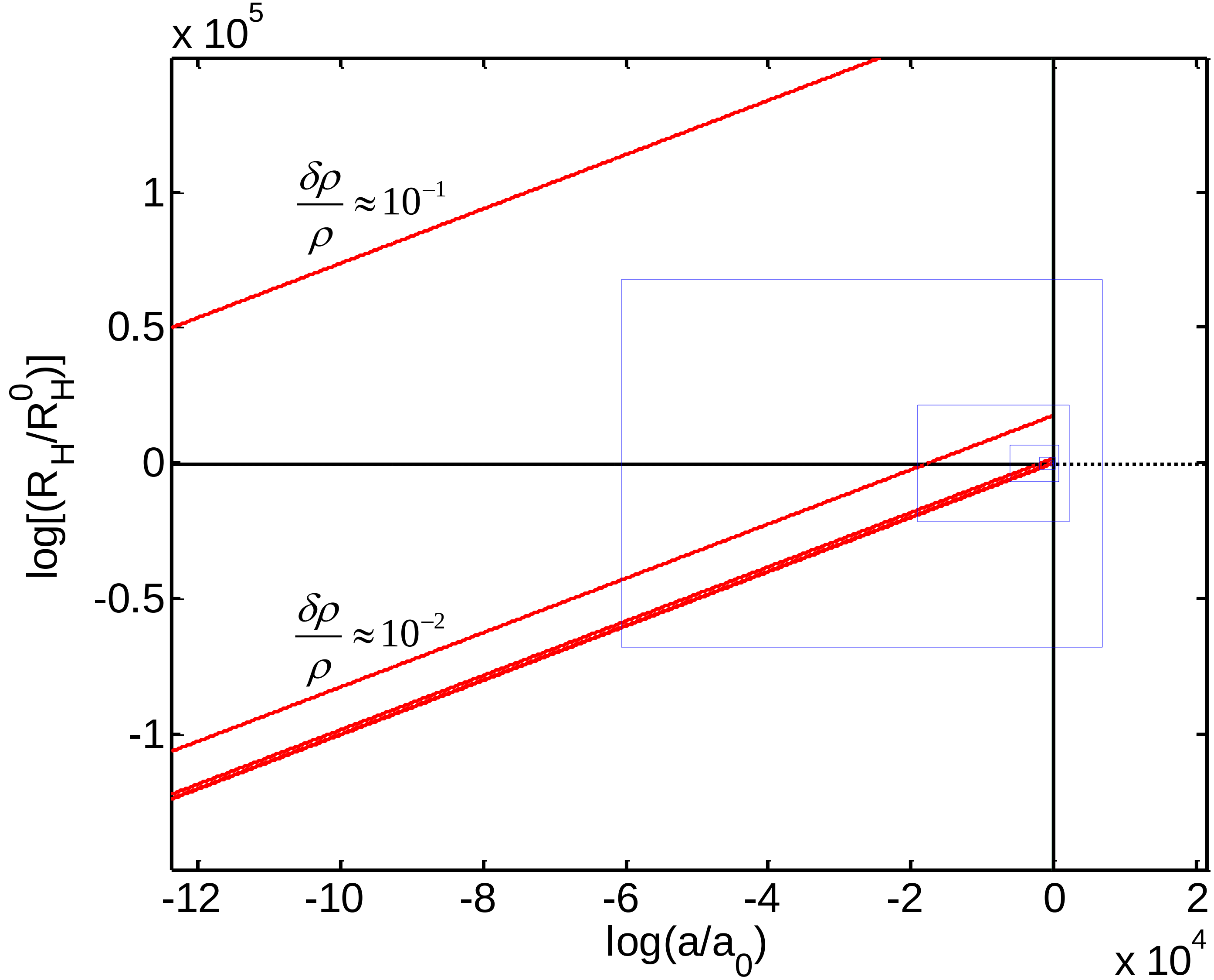
Evolution of Cosmic Length (zooming out)



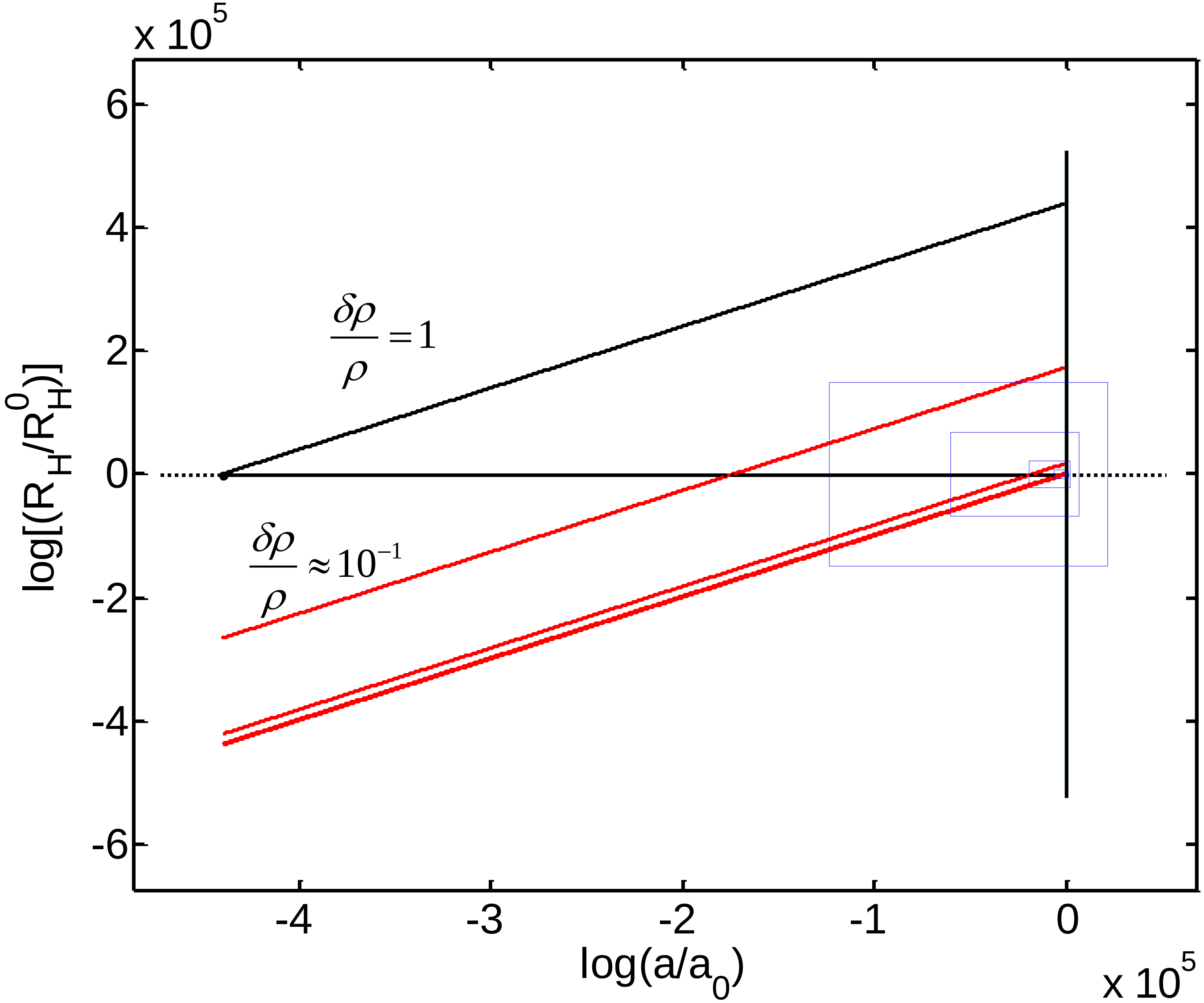
Evolution of Cosmic Length (zooming out)



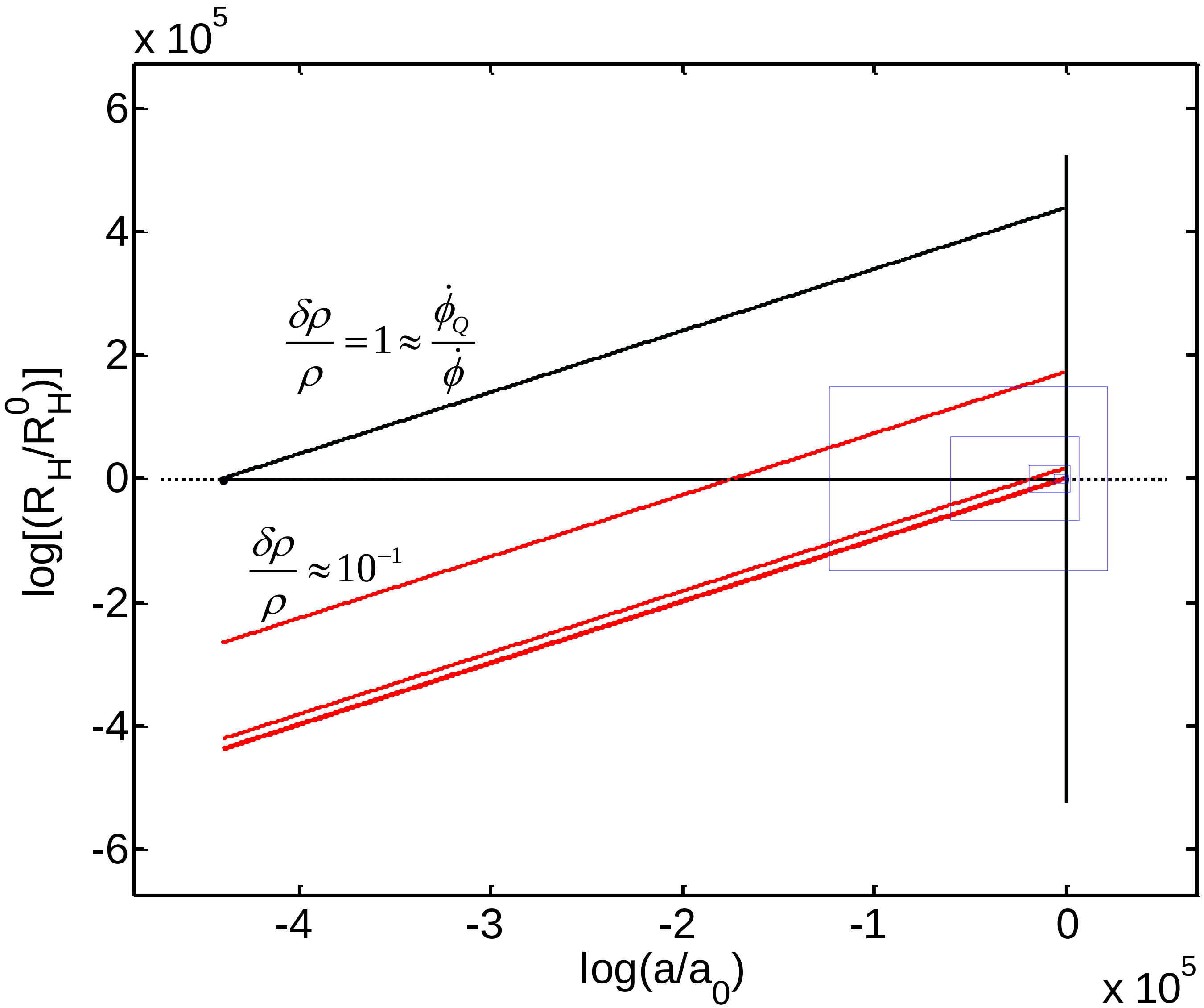
Evolution of Cosmic Length (zooming out)



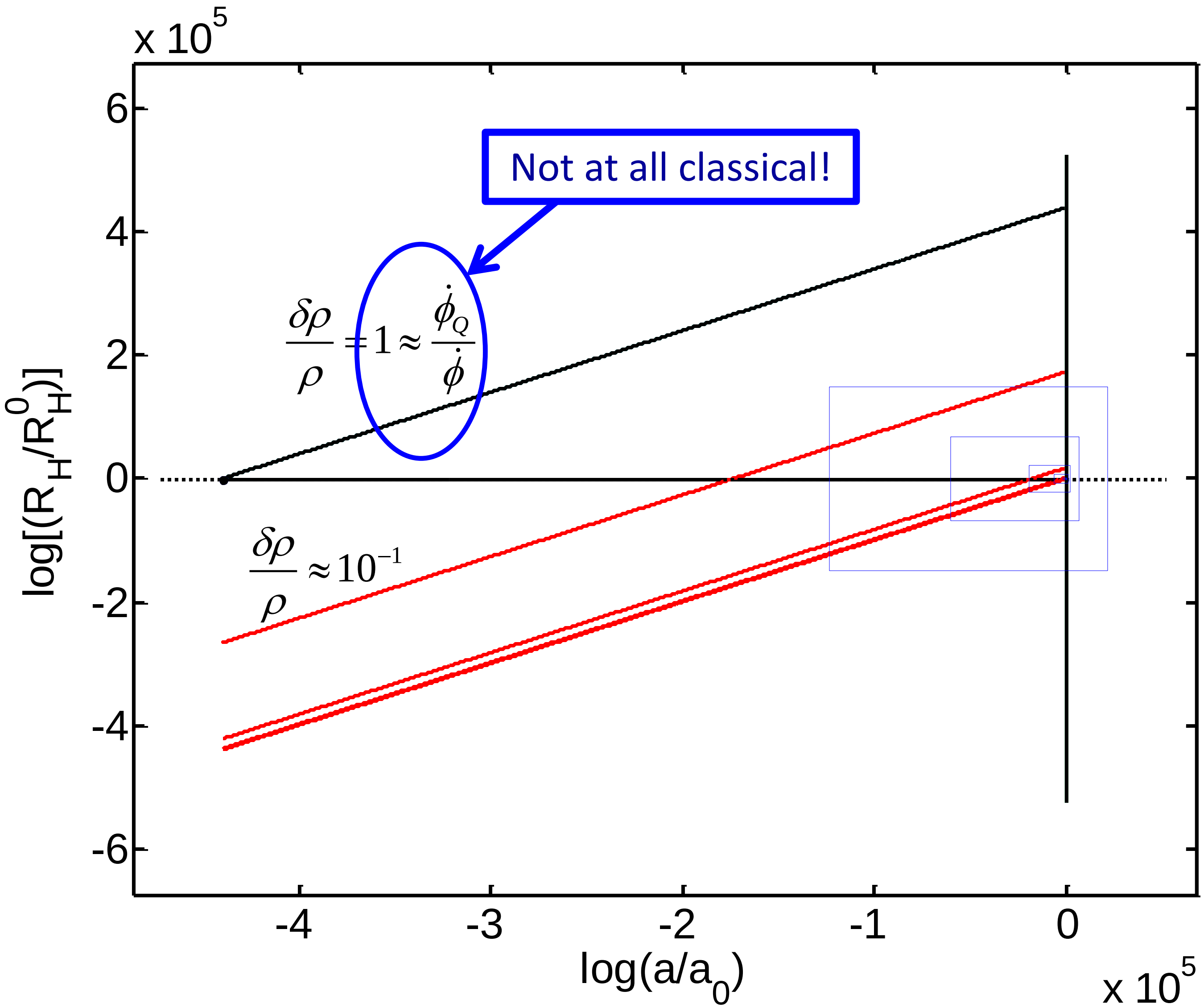
Evolution of Cosmic Length (zooming out)



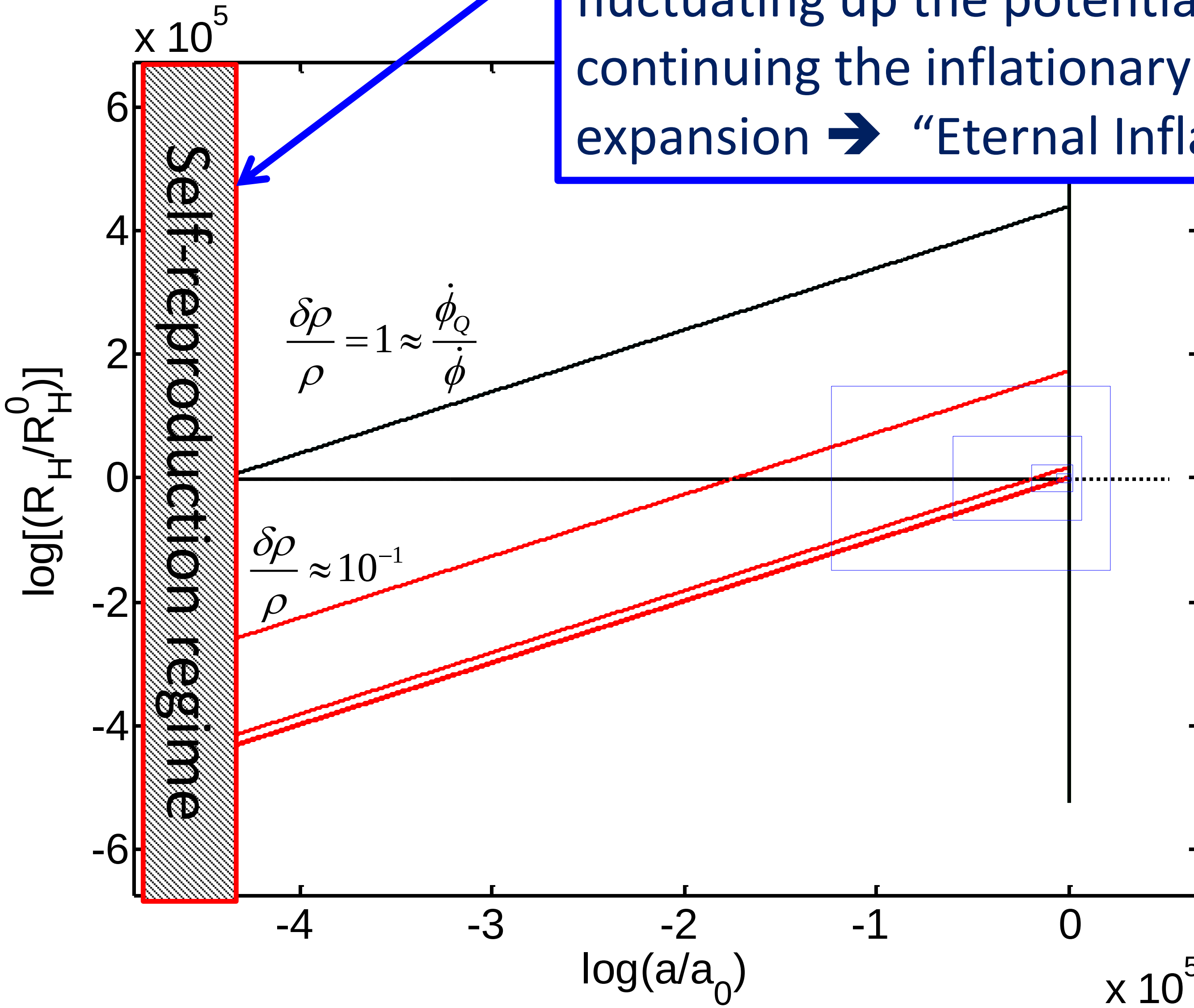
Evolution of Cosmic Length (zooming out)



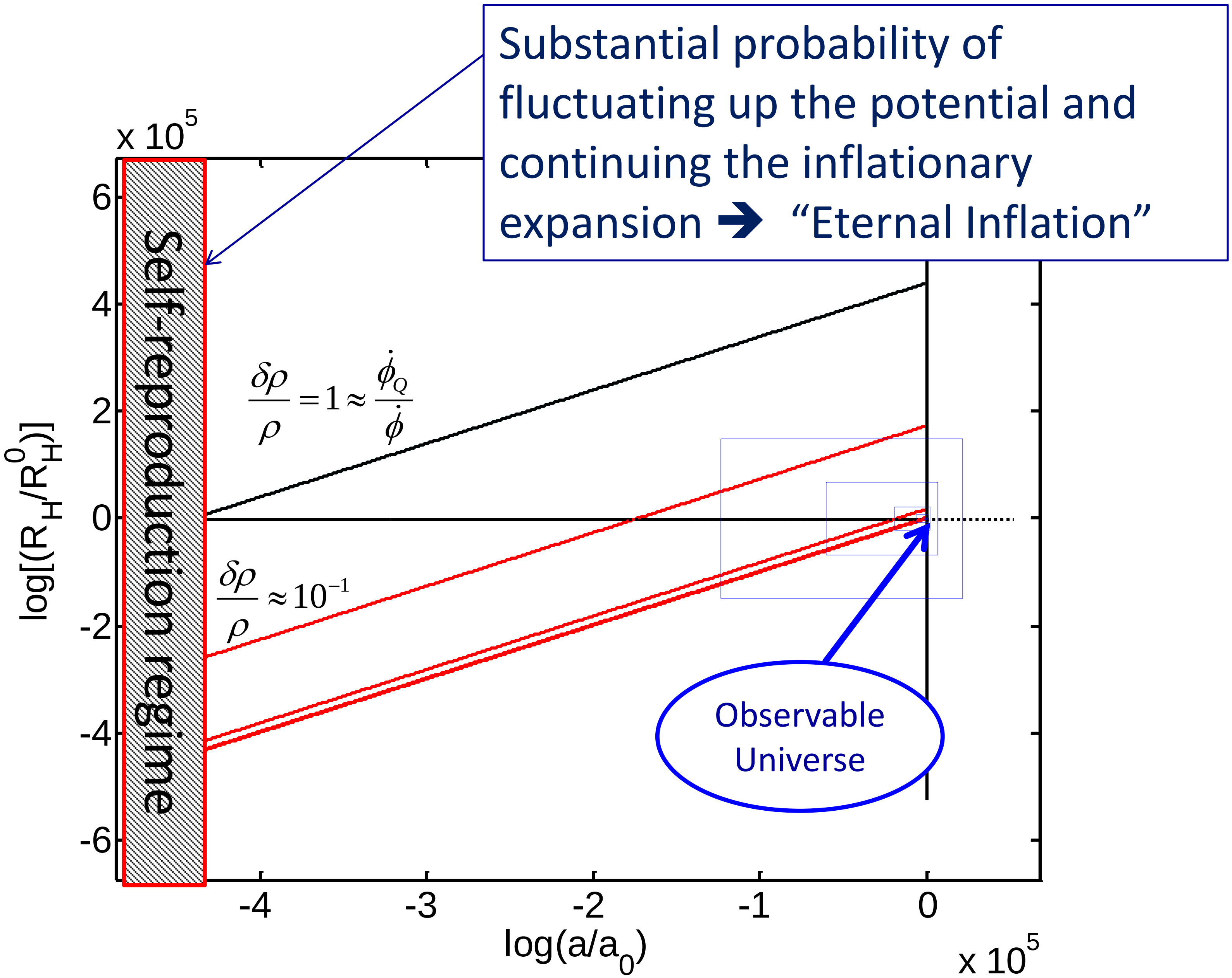
Evolution of Cosmic Length (zooming out)



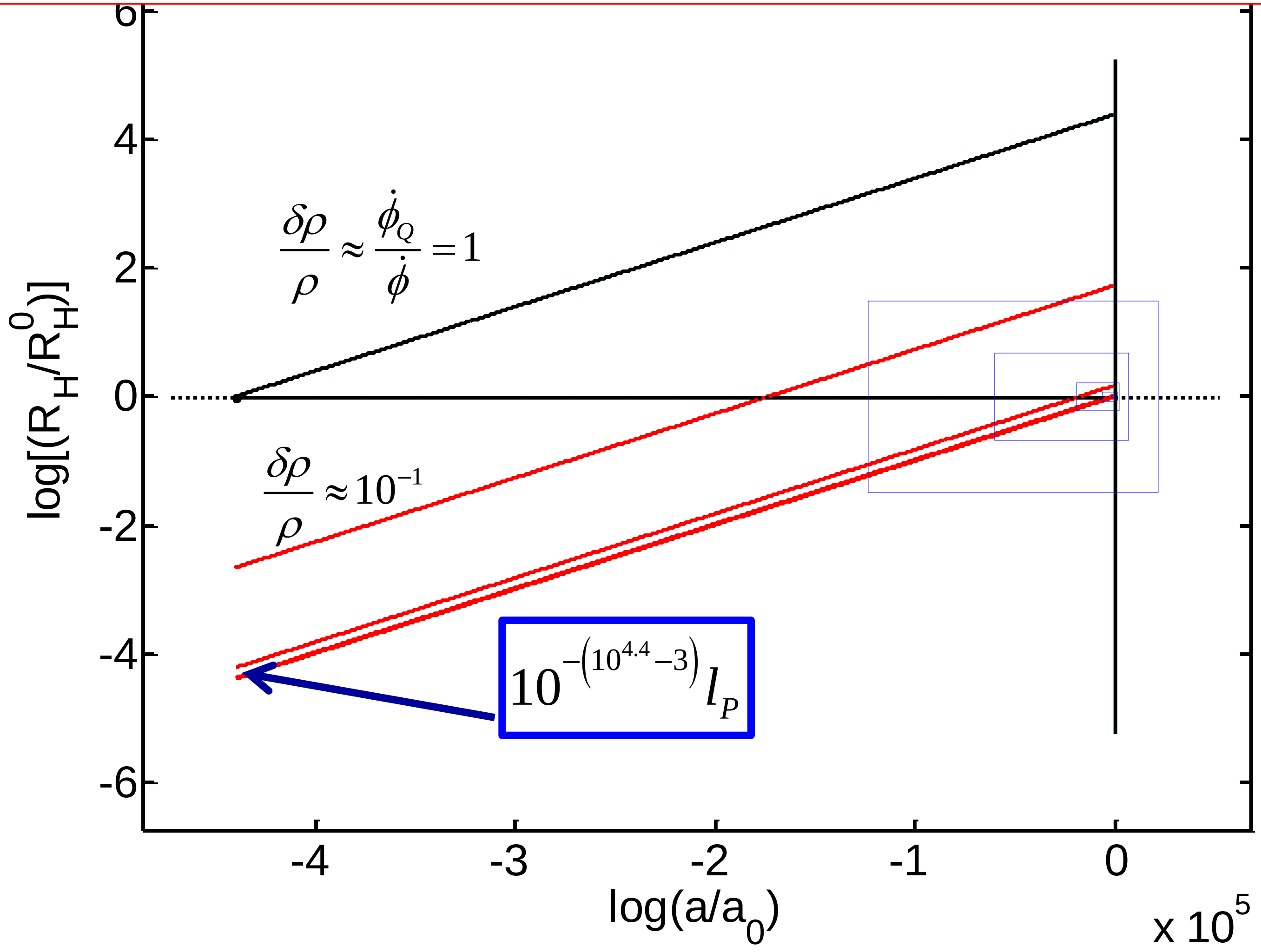
Substantial probability of fluctuating up the potential and continuing the inflationary expansion ➔ "Eternal Inflation"



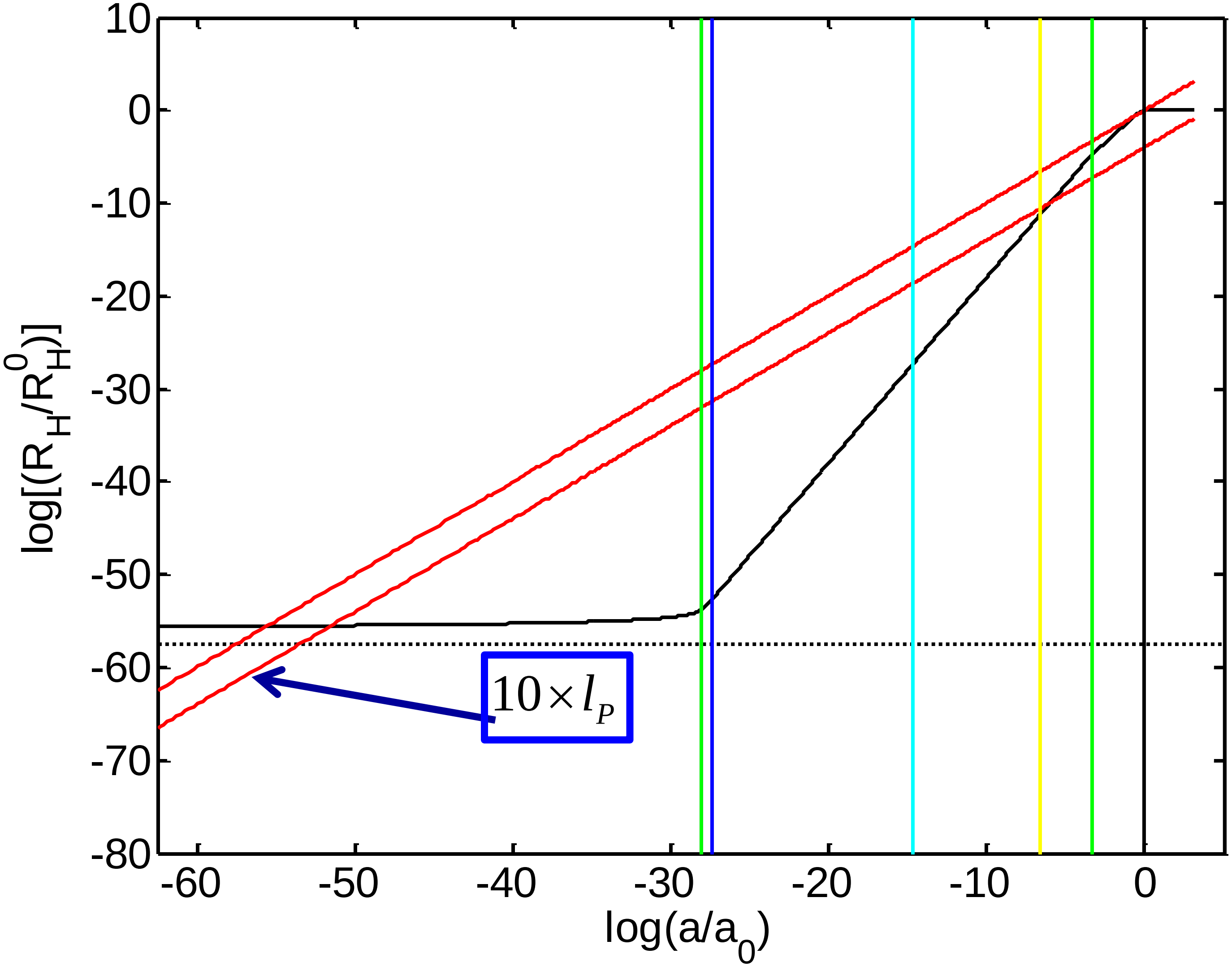
Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others


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

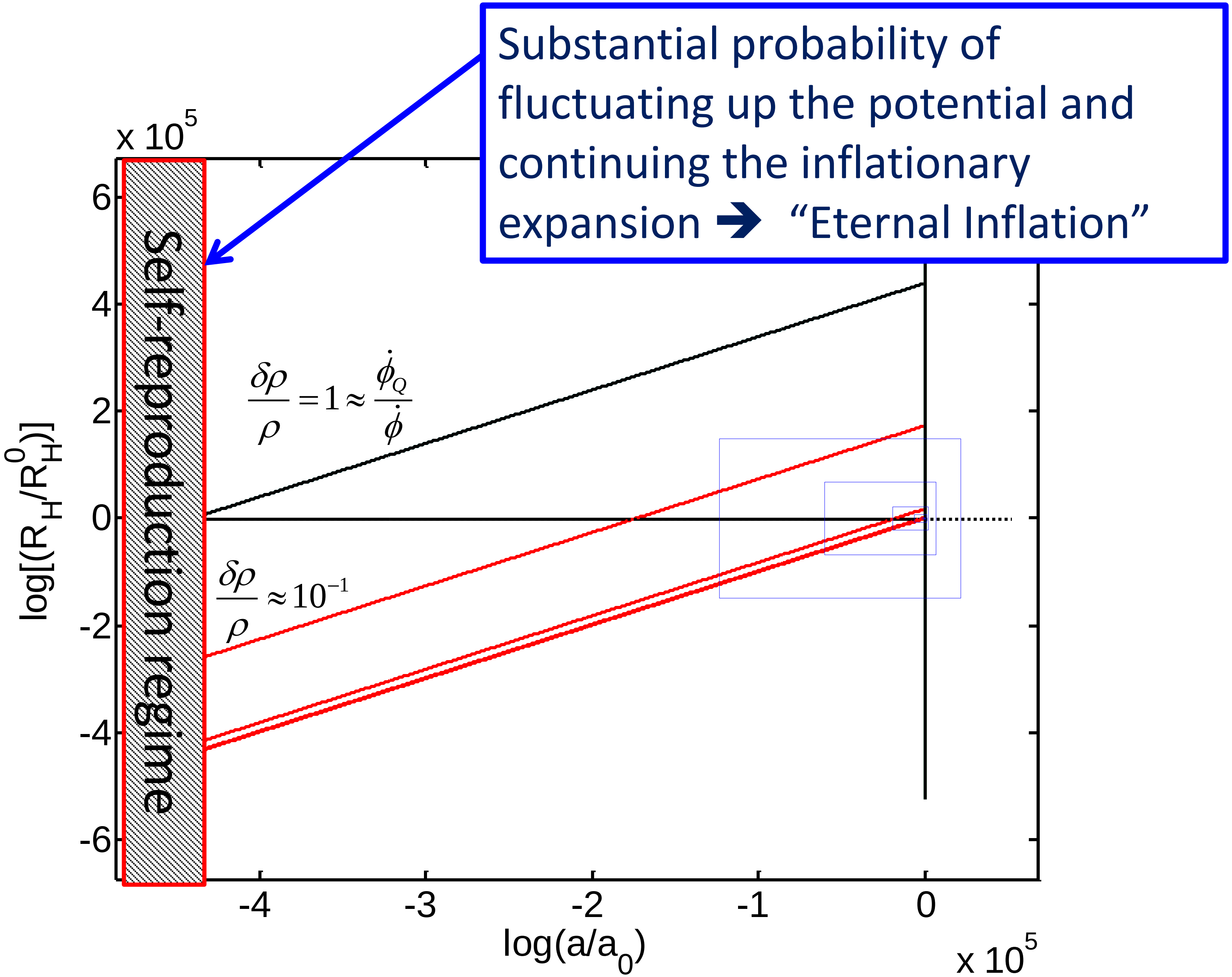
At end of self-reproduction our observable length scales were exponentially below the Plank length (and much smaller than that *during* self-reproduction)!

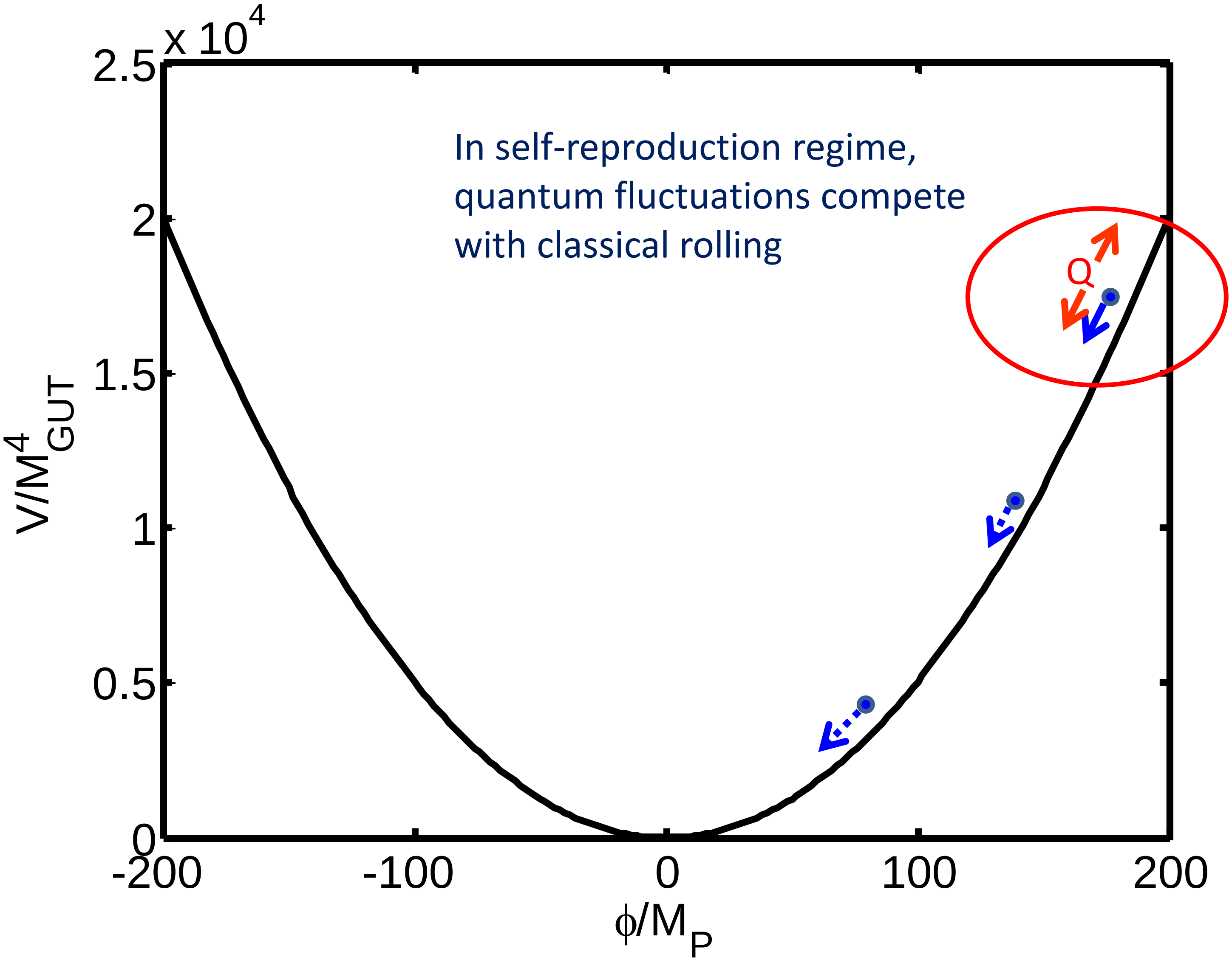


At “formation” (Hubble length crossing) observable scales were just above the Planck length



(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
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)]
-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 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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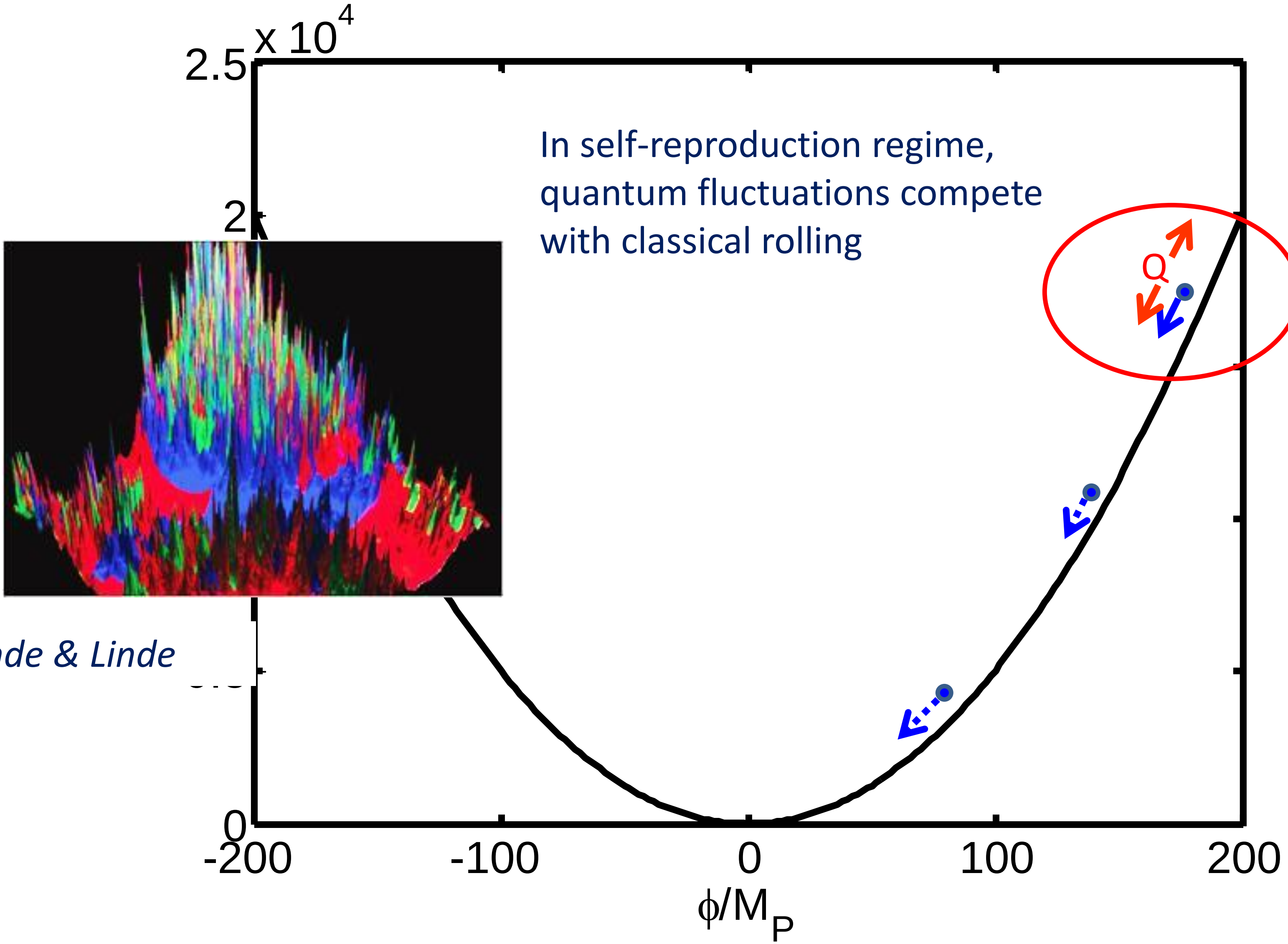
≥ 1 for self-reproduction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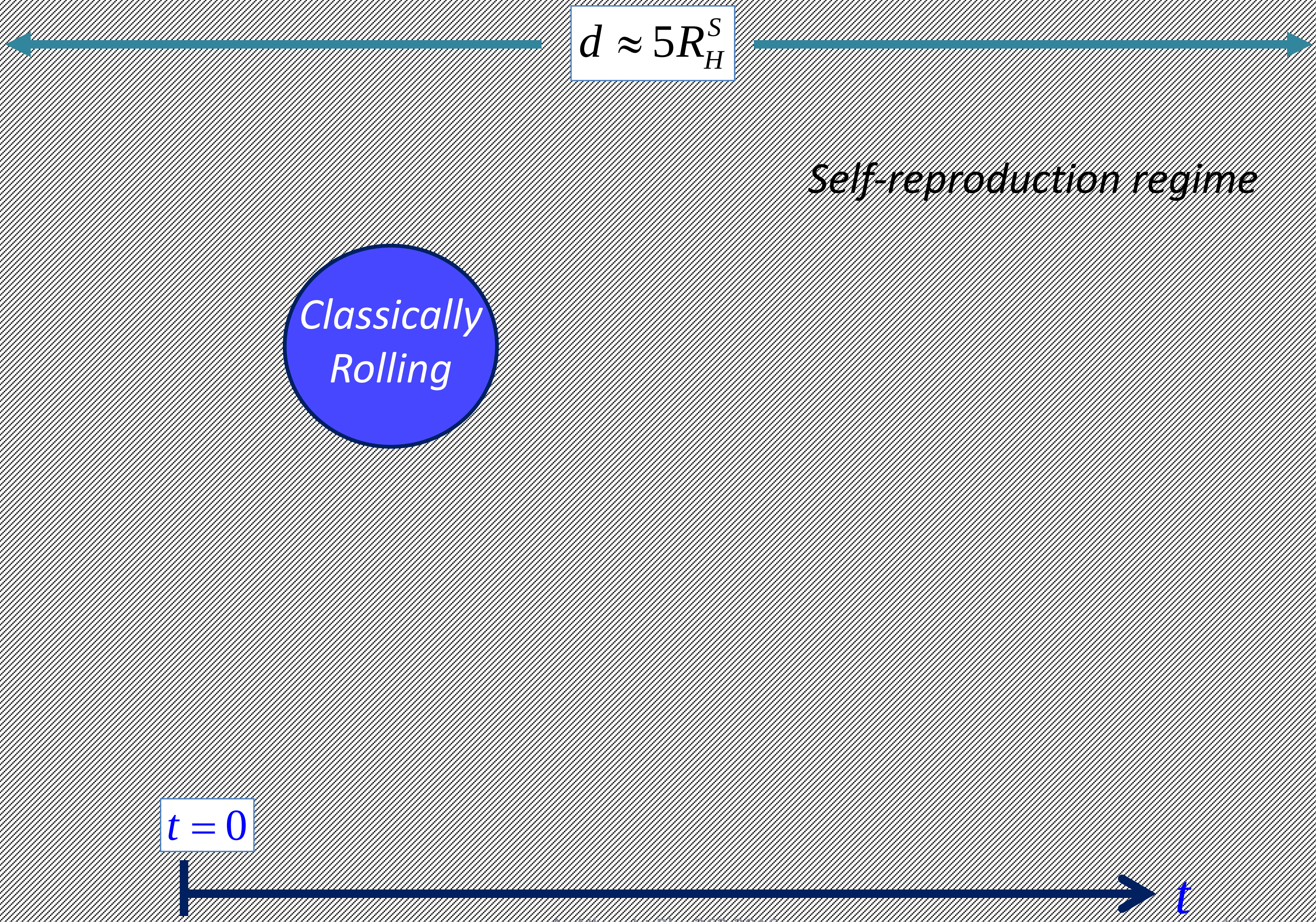
Linde & Linde


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

$d \approx 5R_H^S$

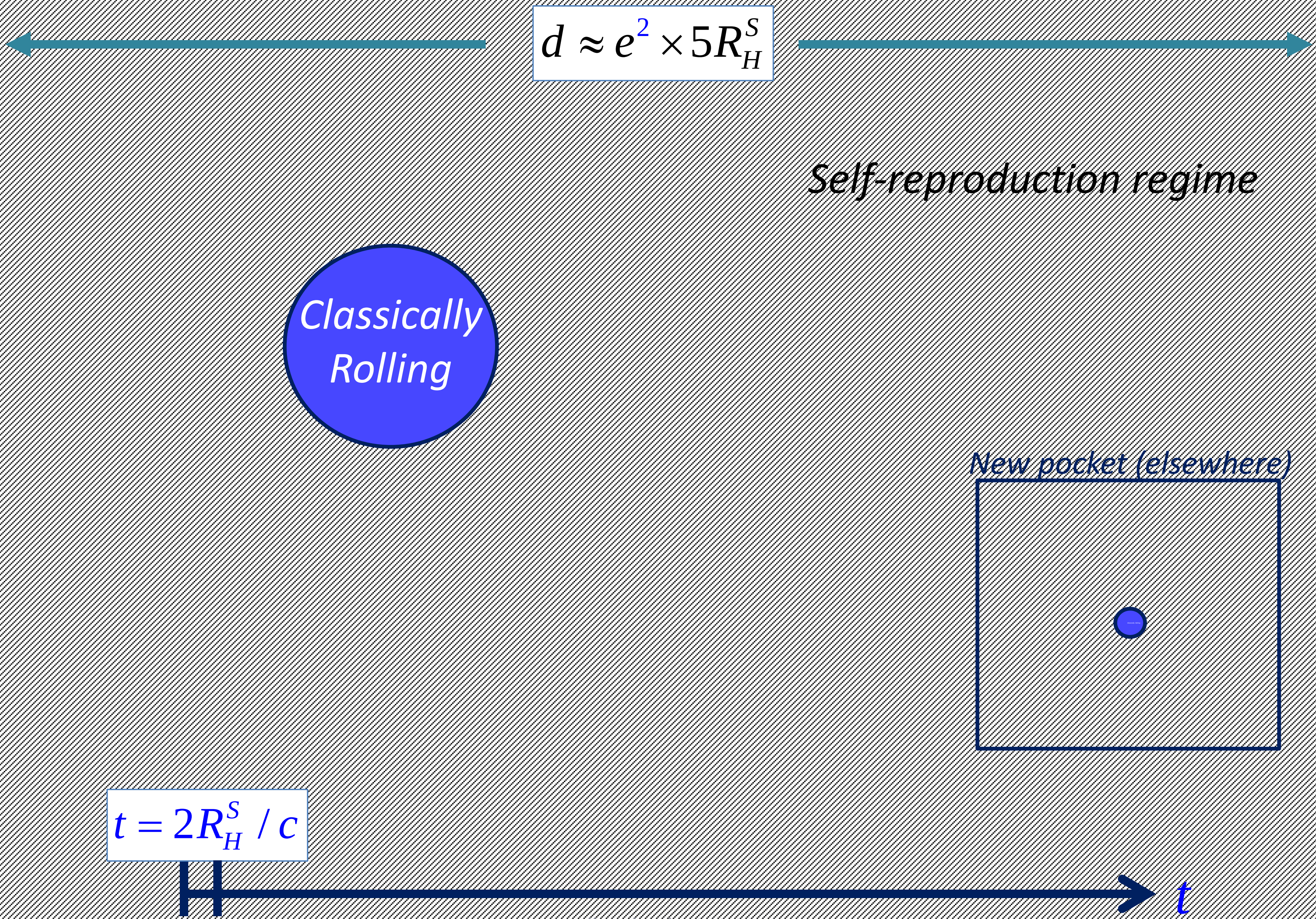
Self-reproduction regime

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

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

Self-reproduction regime

Classically Rolling

New pocket (elsewhere)

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

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

t

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

Self-reproduction regime

New pocket (elsewhere)

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

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

t

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

Self-reproduction regime

New pocket (elsewhere)

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

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

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

Self-reproduction regime

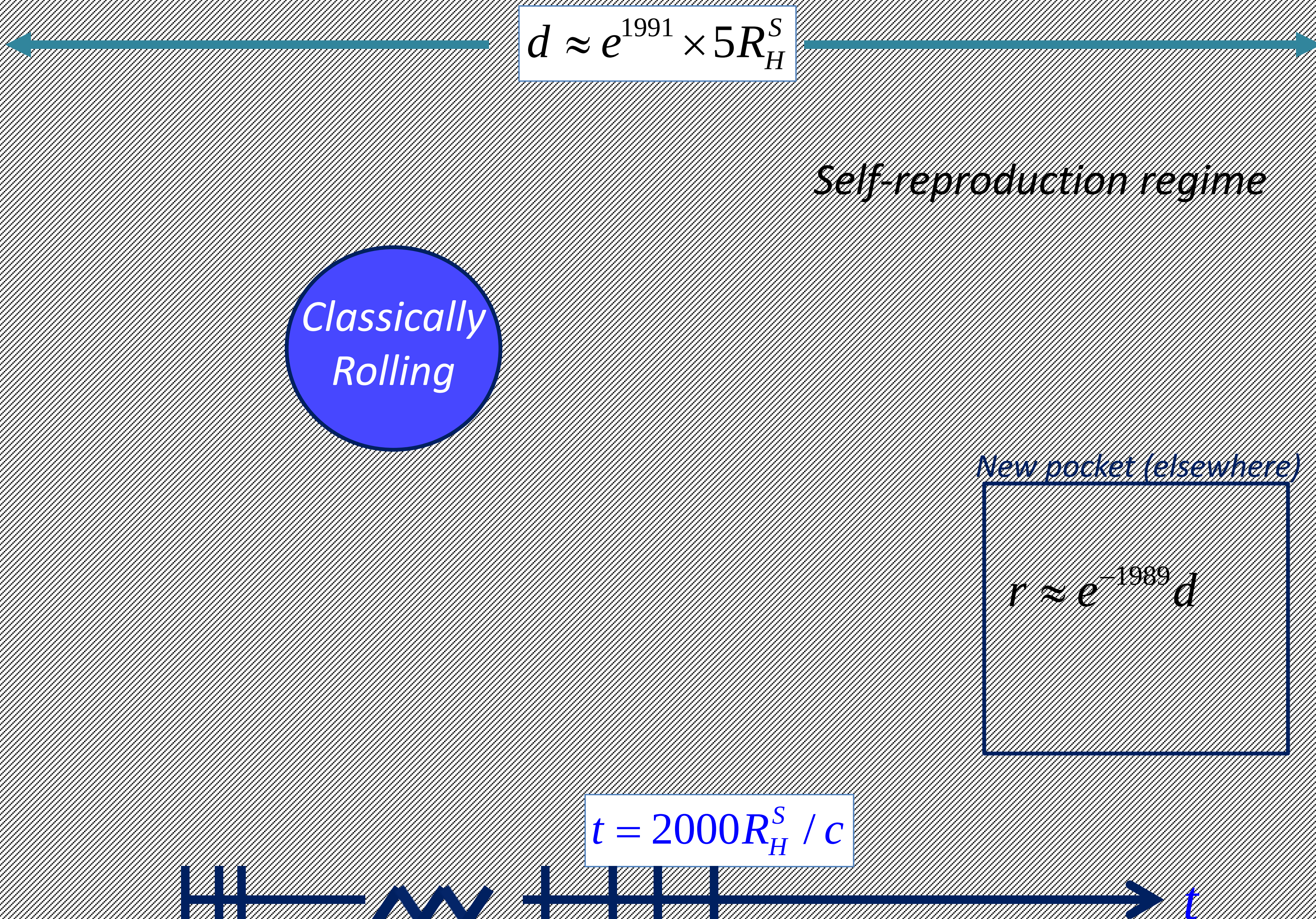
Classically Rolling

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)

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

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

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

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

Radiation Era

New pocket (elsewhere)

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

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

Eternal inflation features

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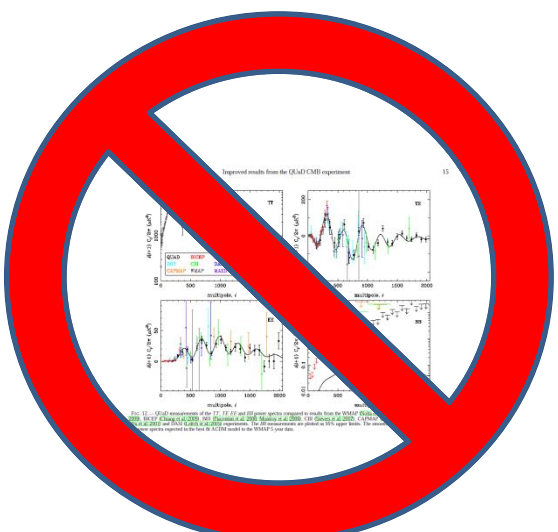

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Eternal inflation features

"True infinity" needed here

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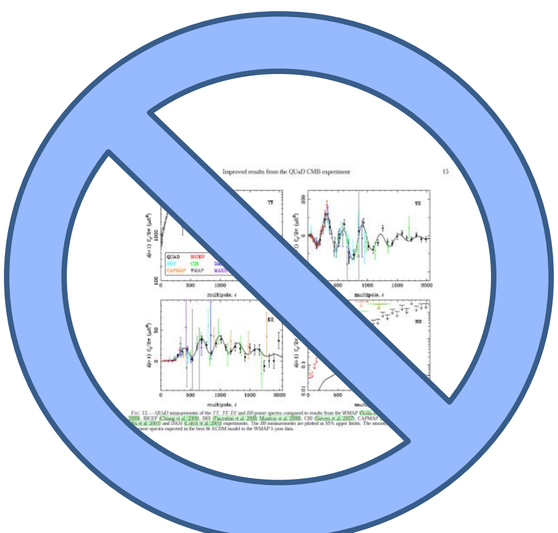

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Hernley, AA & Dray in prep

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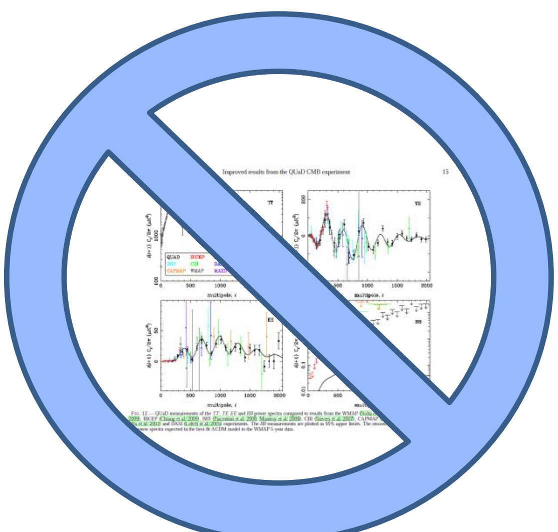

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Eternal inflation

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

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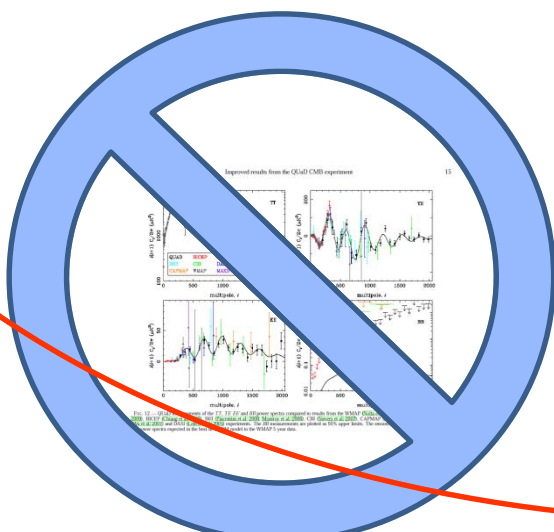

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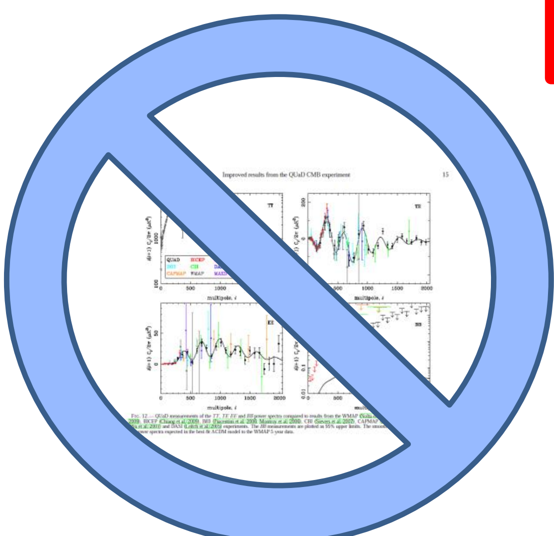
> ➢ Multiple (∞) copies of "you" in the wavefunction ➔ Page's "Born Rule Problem"

em

> ➢ Measure problems



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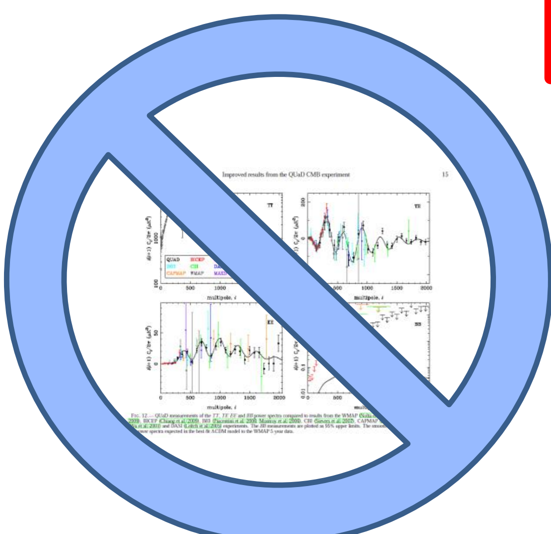
AA & Phillips 2012: "All probabilities are quantum"



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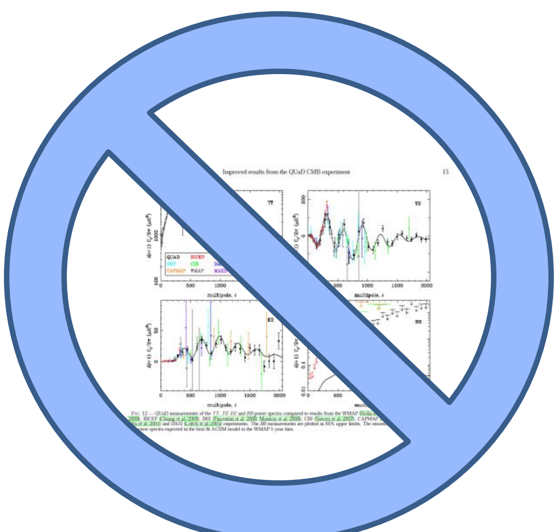

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A problem has been detected and your calculation has been shut down to prevent damage

RELATIVE_PROBABILITY_OVERFLOW

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

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

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

Eternal inflation features

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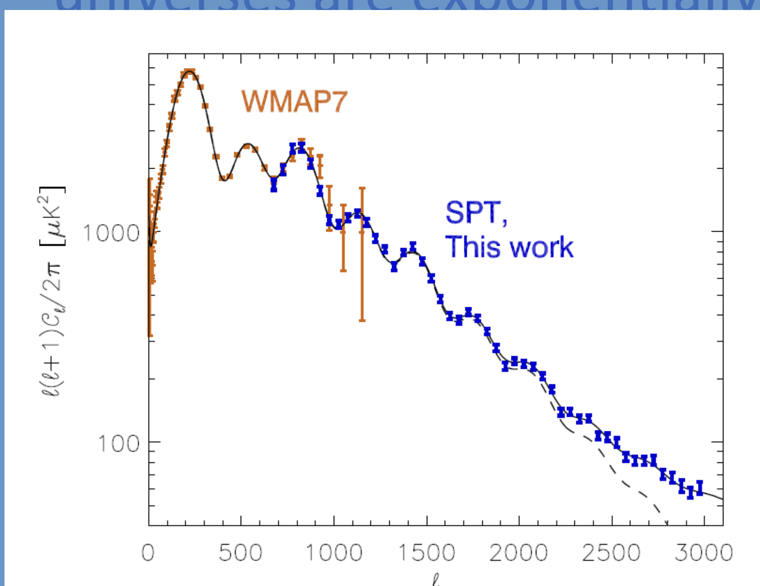

Or, just be happy we have equations to solve?

➢ State
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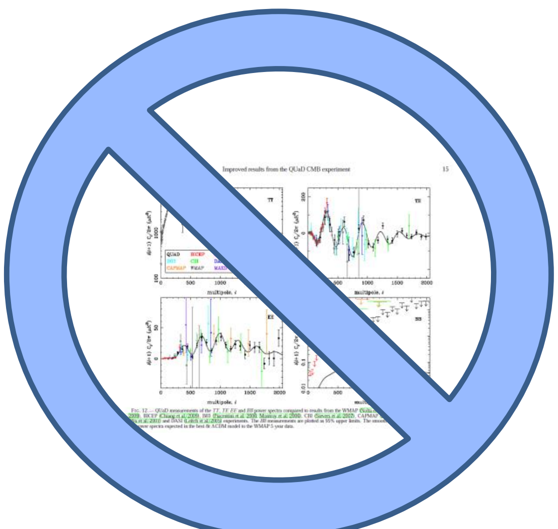


- ➢ State of the ... ad of making ... experts are usin... r the “correct m...

See upcoming discussion of probabilities for new angle

OUTLINE

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

- Macroscopic (or thermodynamic) arrow of time emerges from a combination of:

  - Dynamical trends or "attractors"
  - Special initial conditions
  - Choice of coarse graining

- Despite a completely reversible microscopic world

NB: Not about "T symmetry"

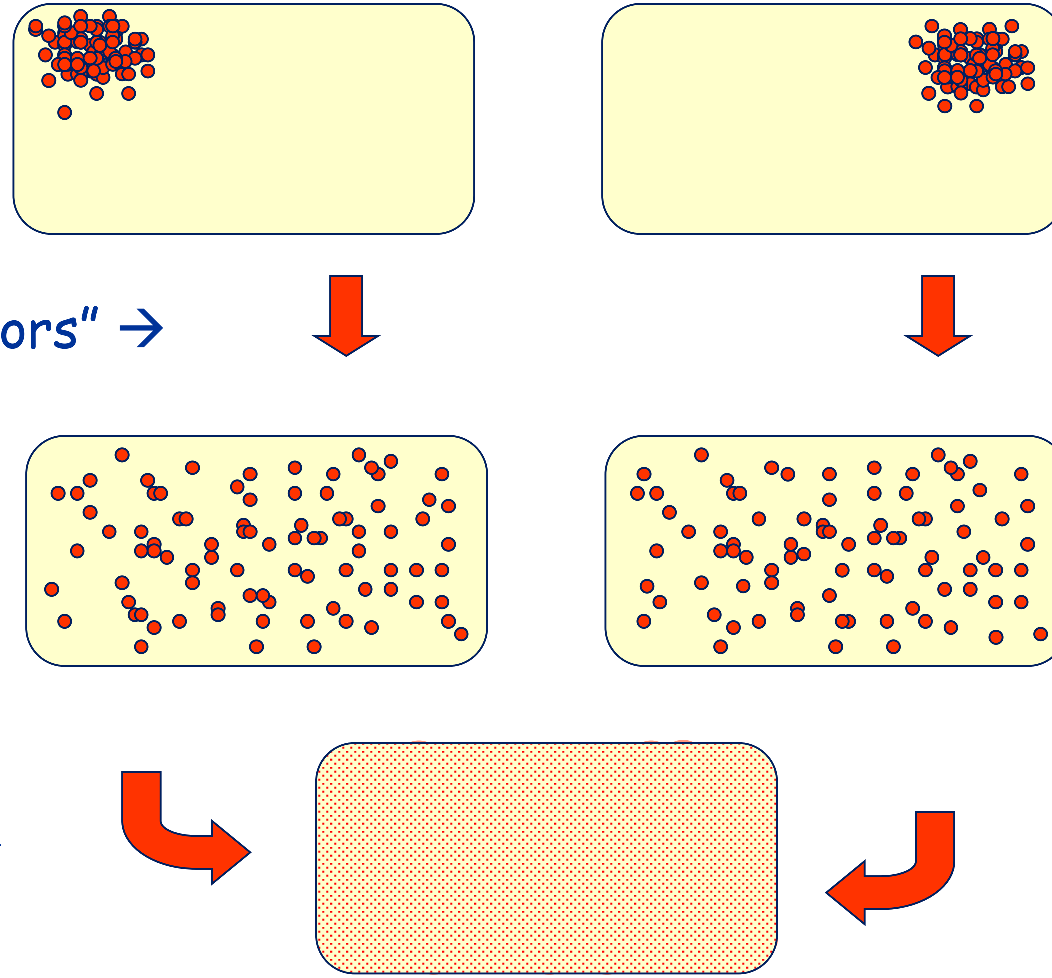
See H.D. Zeh *The physical basis of the direction of time*

An Example:

Special initial conditions →

Dynamical trends or "attractors" →

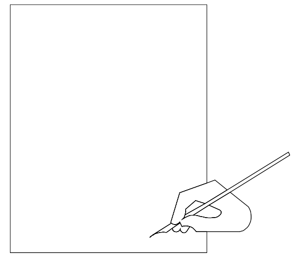
Choice of coarse graining →



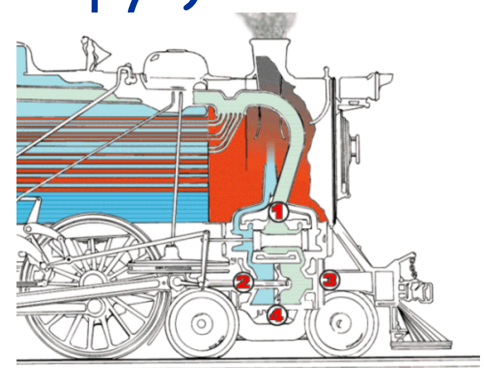
(Taking $l < l_{Jeans}$, gravity unimportant)

Key roles of the arrow of time:

- Recording/Learning

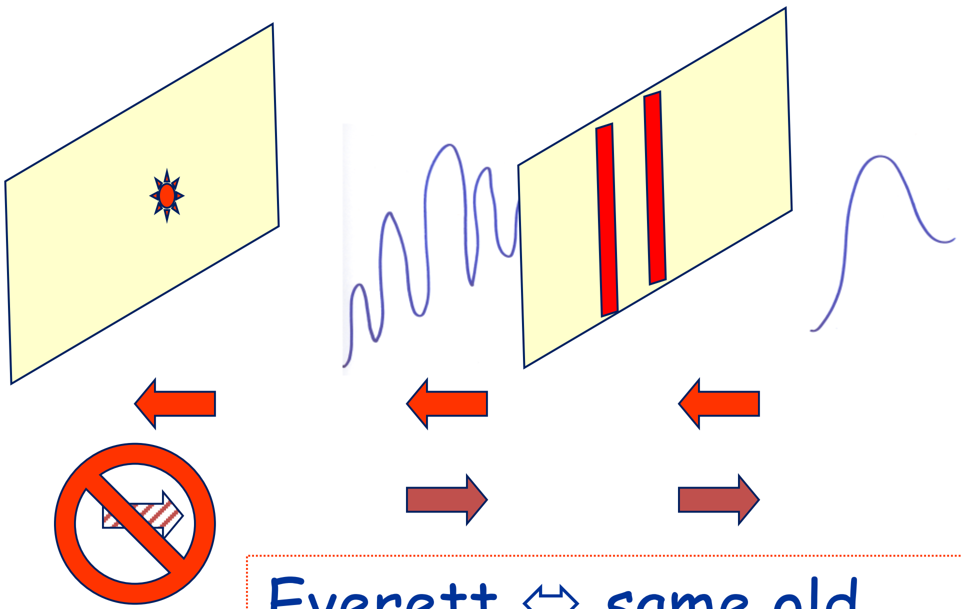


- Harnessing energy (actually "low entropy")



Key roles of the arrow of time (cont.):

- Quantum Measurement



Everett ⇔ same old "thermodynamic" arrow of time

- Macroscopic (or thermodynamic) arrow of time emerges from a combination of:

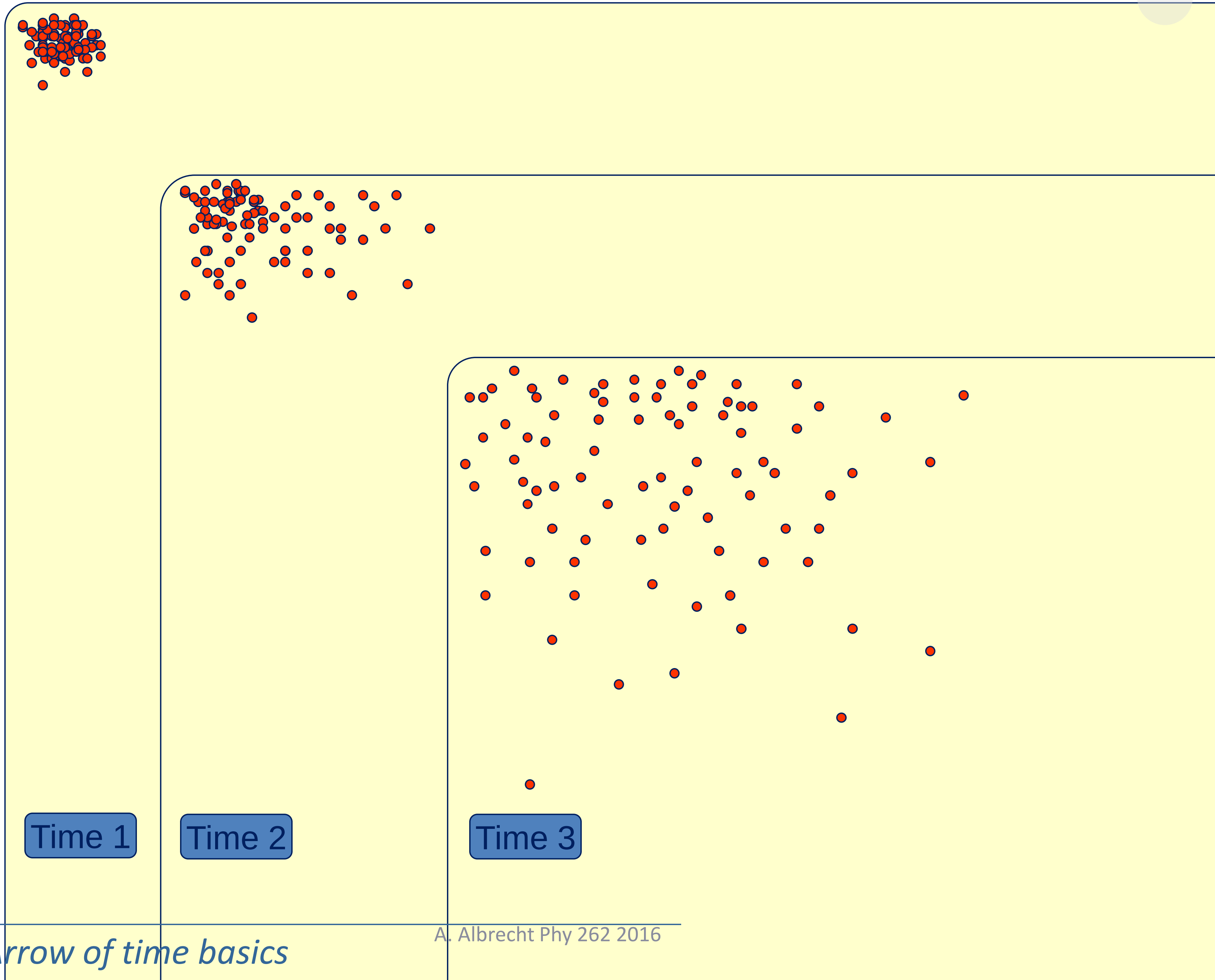
- Dynamical trends or "attractors"
- Special initial conditions
- Choice of coarse graining

} Most Fundamental

Entropy, laws of thermodynamics, counting number of states etc:

-Ways to quantify the above

- "Icing on the cake"


Time 1
Time 2
Time 3

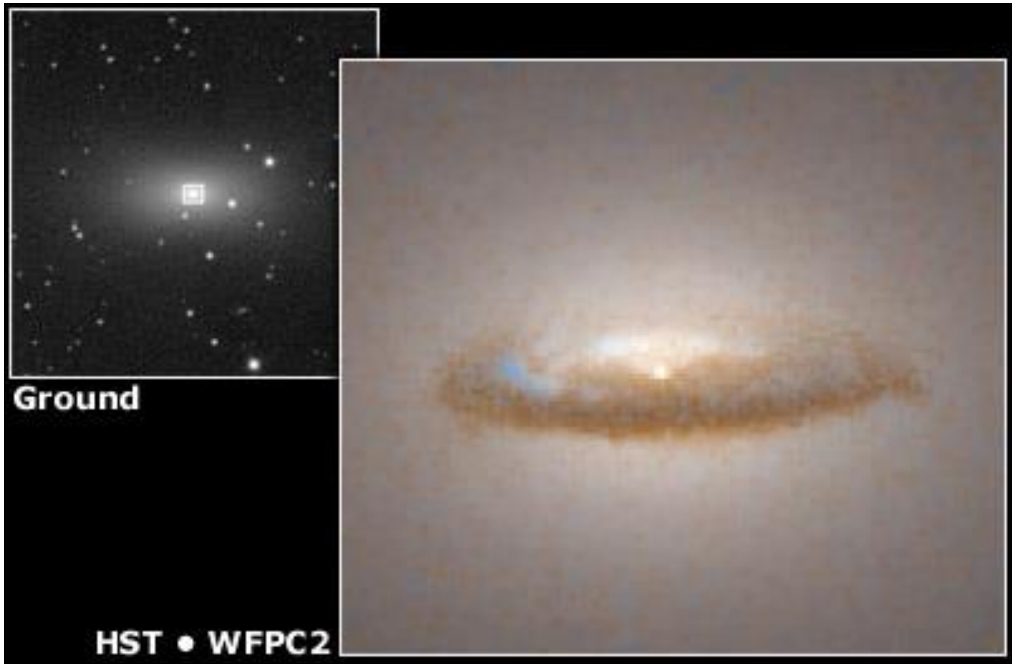
Now consider $l > l_{Jeans}$: gravity very important

A completely different trend/attractor:

Gravitational Collapse

$l > l_{Jeans}$: gravity very important

Equilibrium under gravitational collapse:



<u>Black Hole</u>

(the state of ultimate collapse)

$$S_{bh} = 4\pi M^2$$

(S_{bh} not as well developed as ordinary entropy, but good enough for our purposes as a way to quantify a dynamical trend.)

The Punch Line:

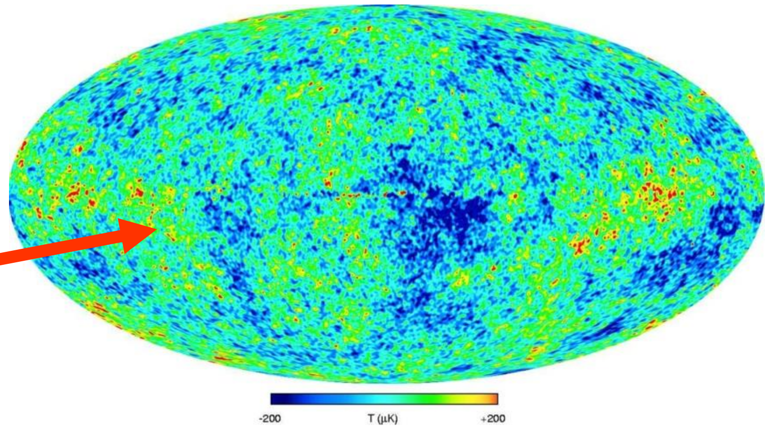
The thermodynamic arrow of time originates with the very special initial conditions of the cosmos:

The early universe is very homogeneous on scales $l > l_{Jeans}$
➔ very far from Eqm. (= black hole)

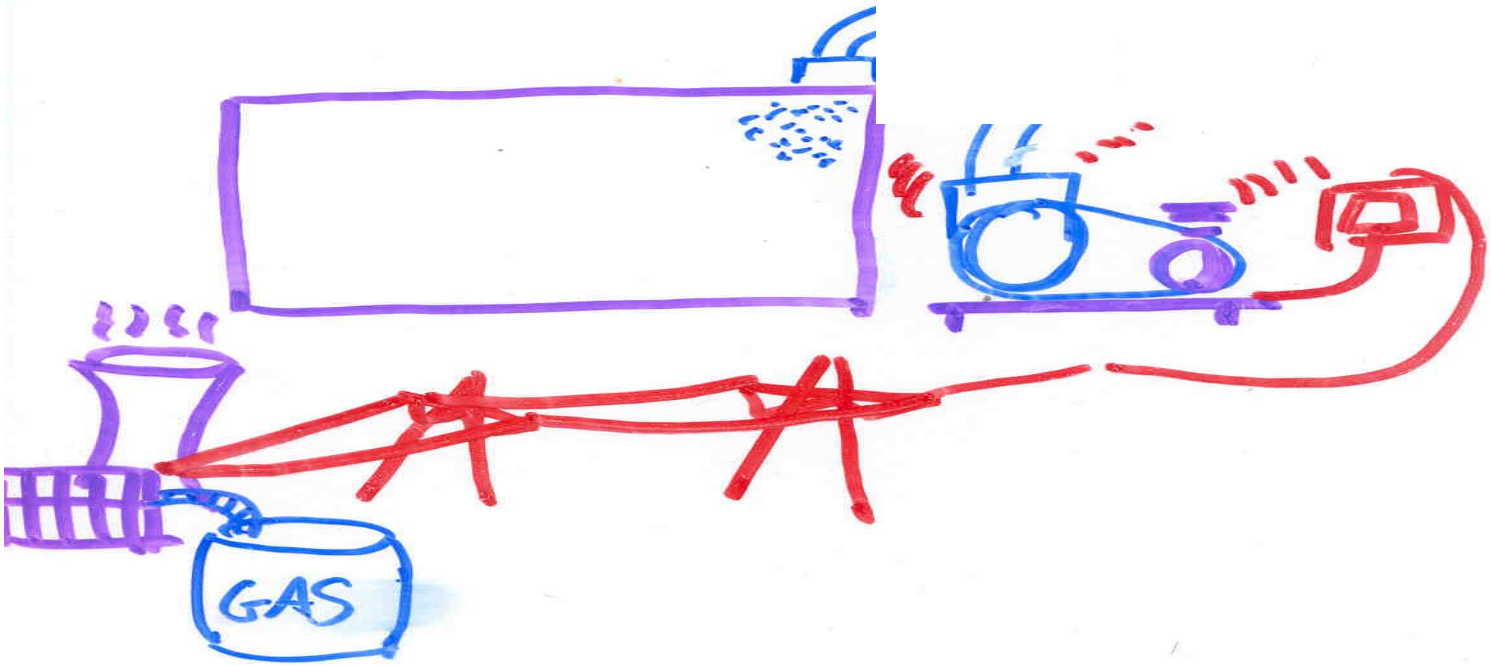
$$S_{Univ} \approx 10^{-35} S_{bh-Max} = 10^{-35} 4\pi M_{Univ}^{2}$$

Penrose

Cosmic Microwave Background uniform to one part in 10^5



- The everyday link to gravitational collapse



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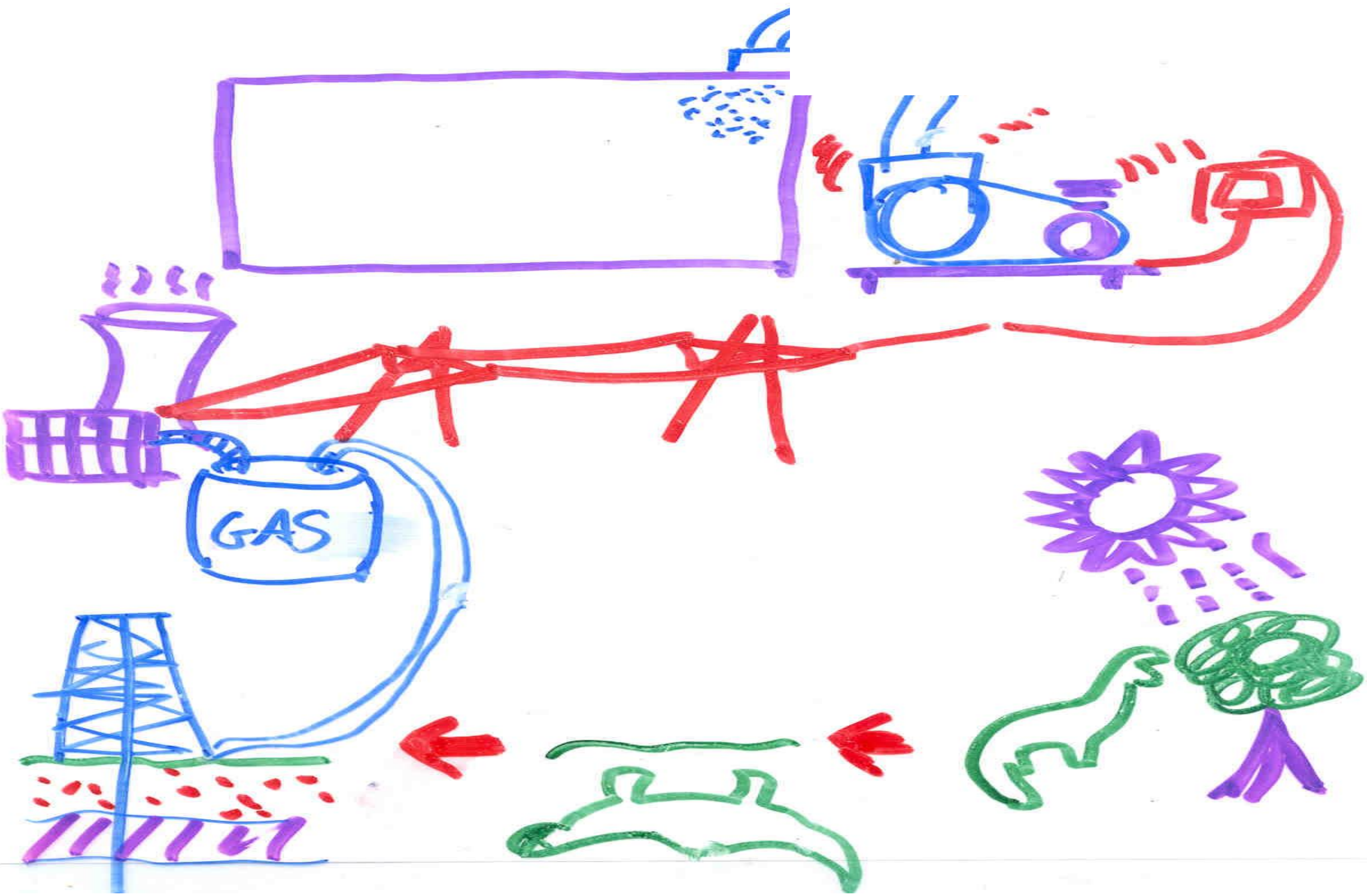


Standard inflation spiel begins:

Cosmological problems of standard big bang:

Universe starts far from dynamical trend:

- -Flat
- -Homogeneous
- -Horizons prevent dynamical explanation

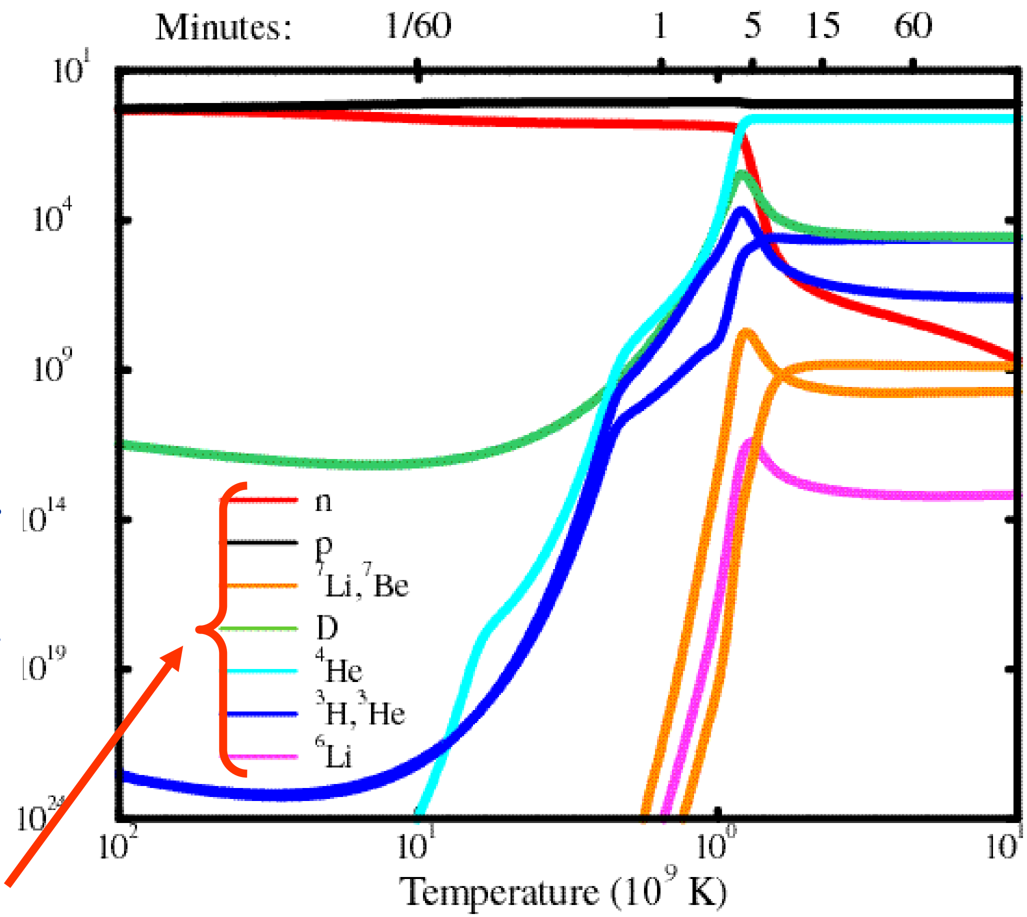
Q: How can this fact be explained?

But isn't starting far from the dynamical trend exactly what is required to explain the arrow of time?

And when do we ever explain initial conditions anyway?

Warm up 1: Big Bang Nucleosynthesis

Prediction of abundances.



Mass Fraction →

Species

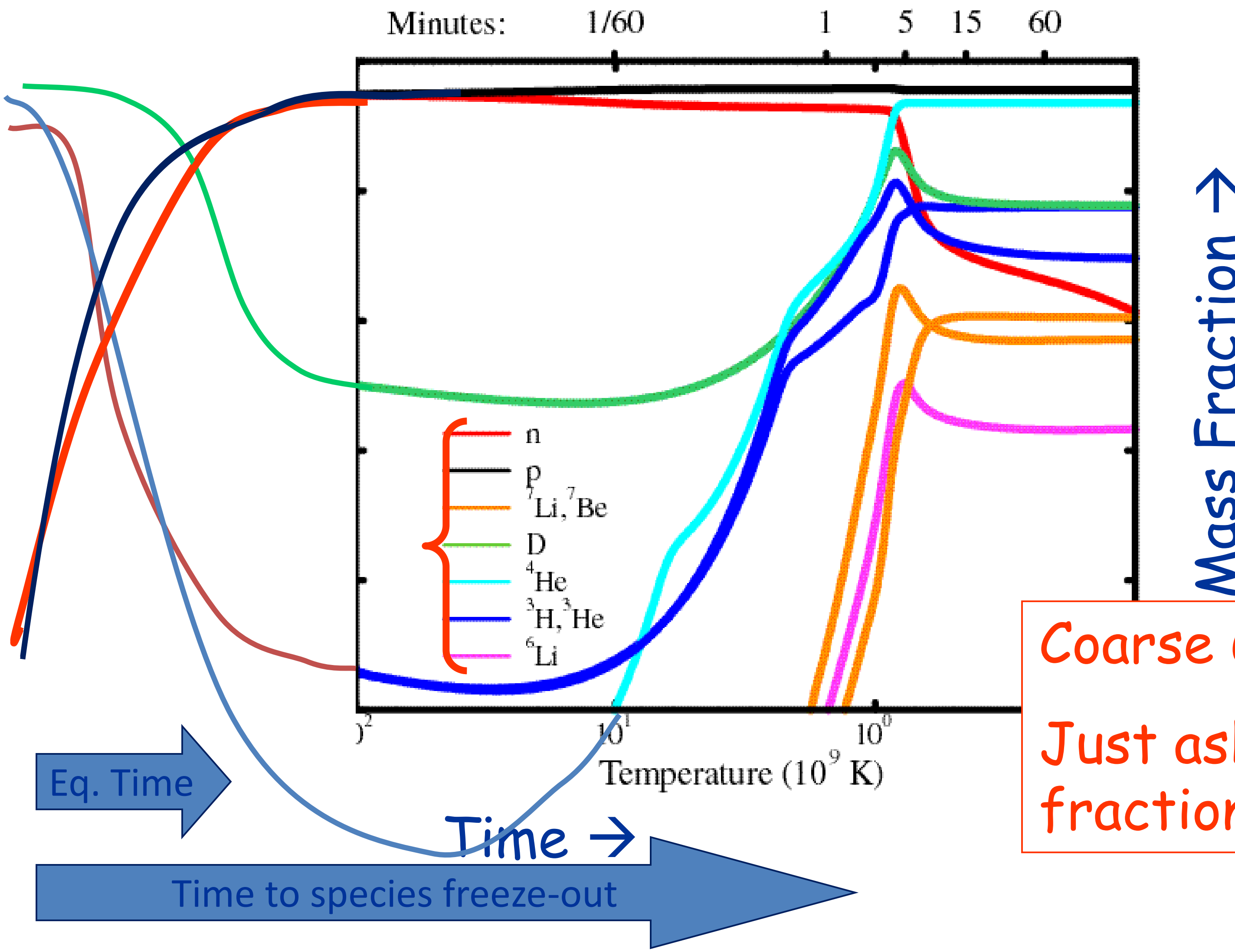
Time →

But doesn't the answer just depend on the initial state?

Figure: Burles, Nollett, &Turner

Warm up 1: Big Bang Nucleosynthesis:

Nuclear Statistical ("chemical") equilibrium (attractor) erases initial conditions dependence.

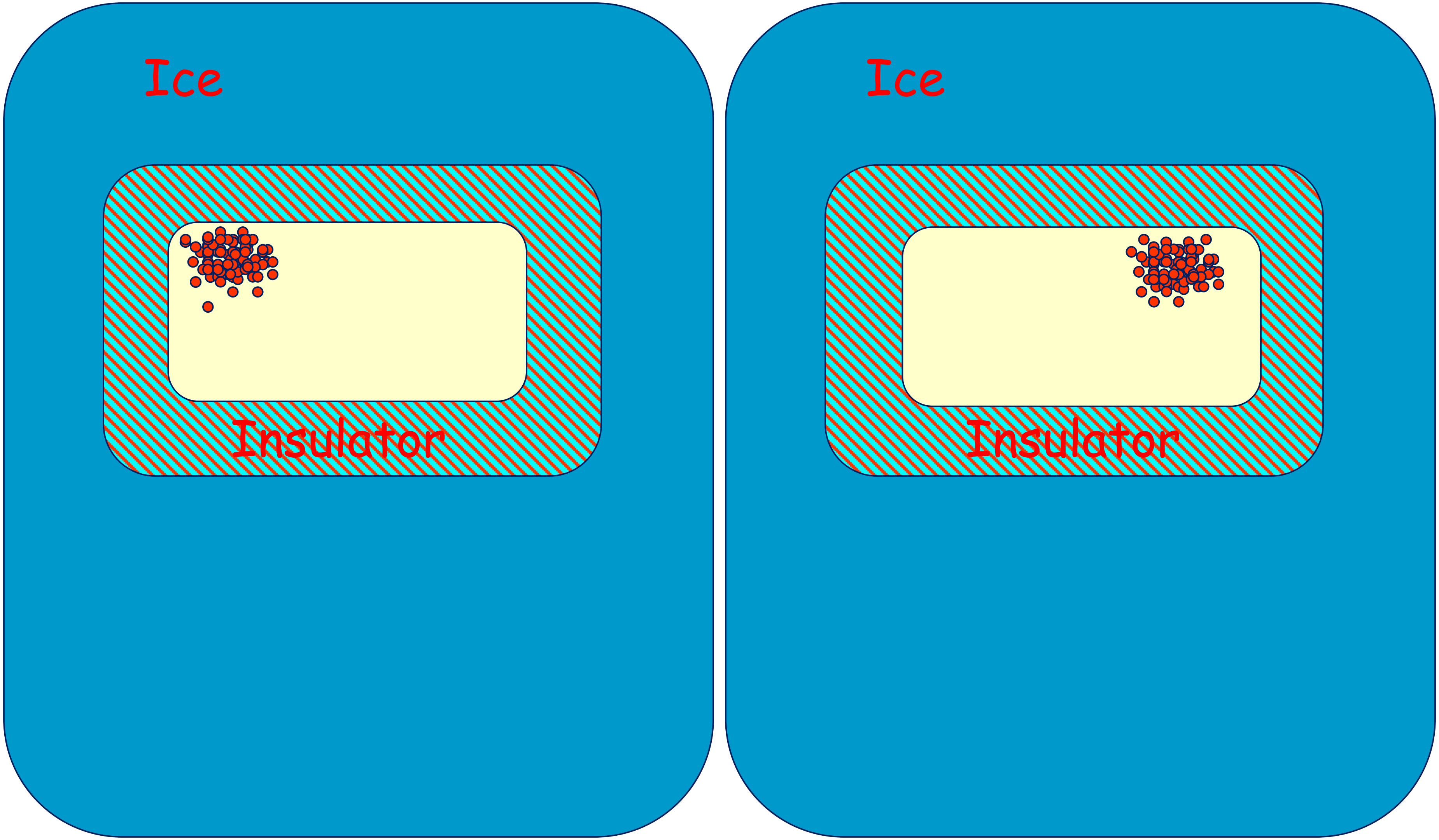


Coarse Graining:

Just ask about mass fractions

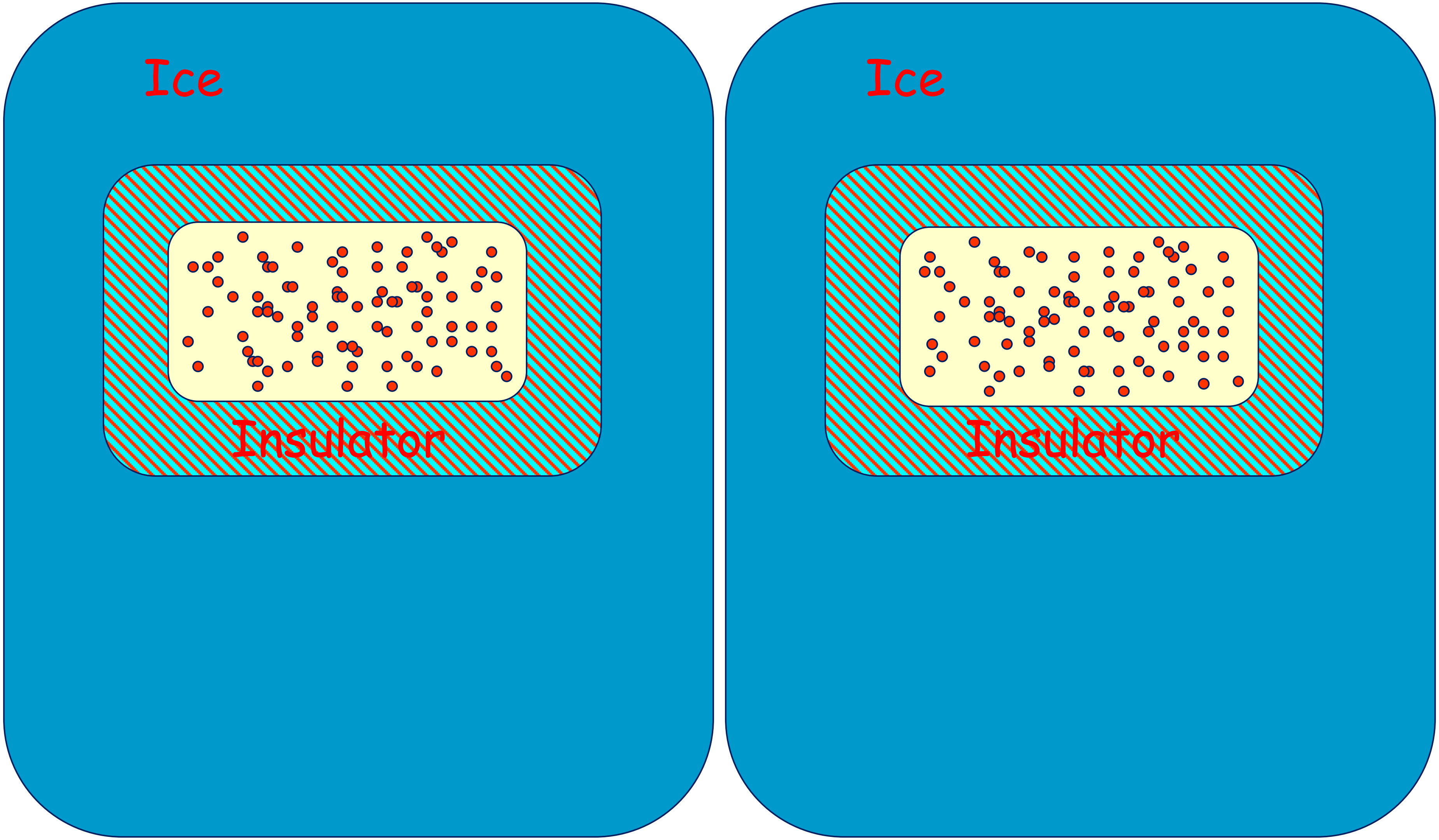
Warm up 2: Gas in ice

Time 1



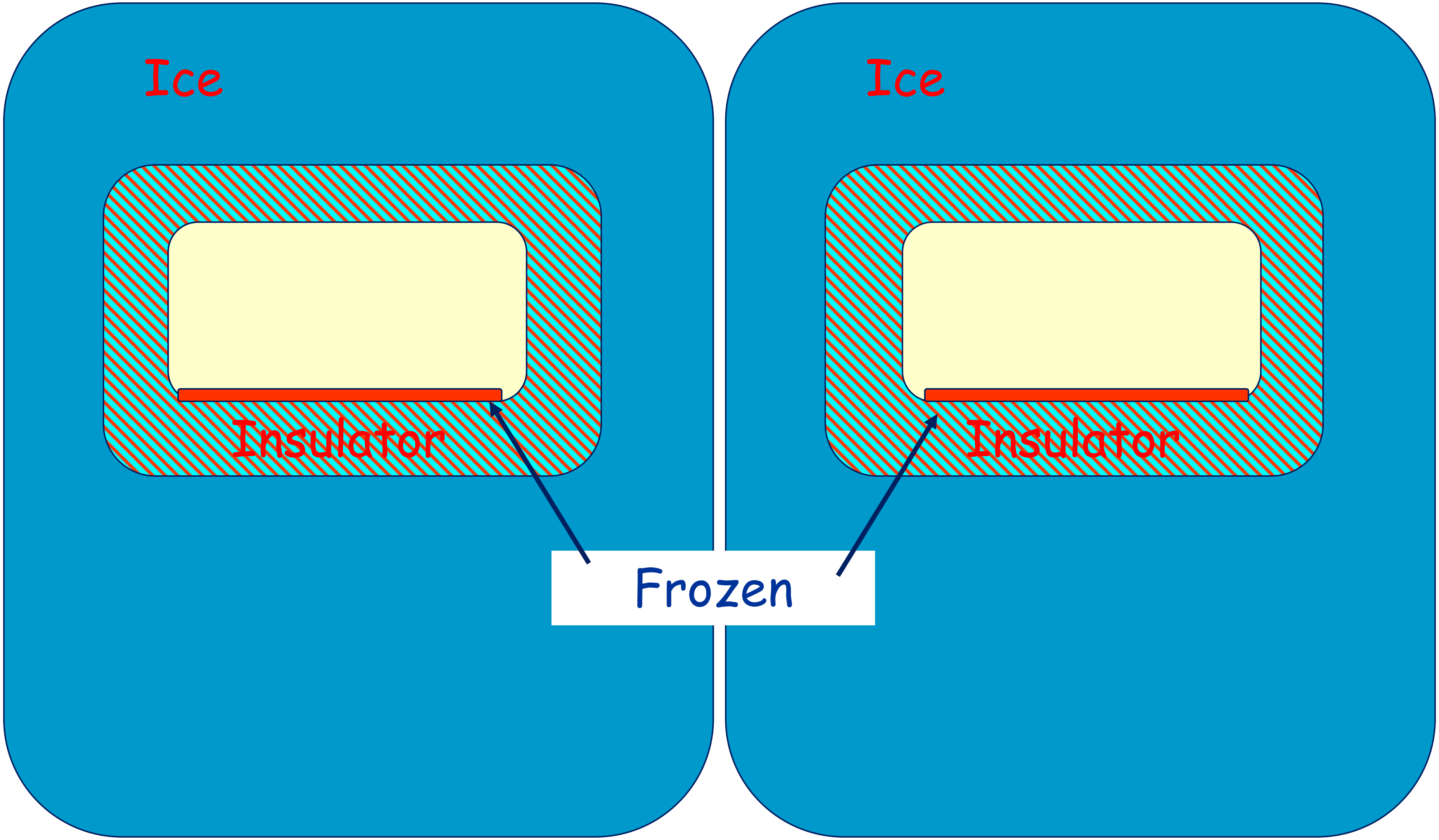
Warm up 2: Gas in ice

Time 2

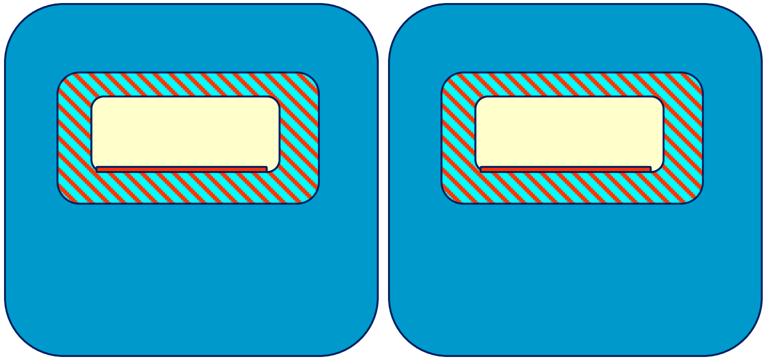


Warm up 2: Gas in ice

Time 3



Warm up 2: Gas in ice



Internal eqm time « freezing time

➔ Internal eqm. set initial conditions for condensation & final frozen state.

End warm up… now the real thing:

Key ingredient:

Equivalent to "perfect" potential dominated state

$$G + \Lambda = 8\pi T$$

Cosmological constant => different gravitational at attractor:

de Sitter space

- Perfectly flat, homogeneous, exponentially expanding

Properties of Big Bang initial state

$$S_{dS} = \frac{3\pi}{\Lambda}$$

Gibbons & Hawking, See also Bousso

Λ Can be mimicked by a scalar field in a special "potential dominated state"

↓

Inflaton field φ can turn Λ_{eff} on and off

Inflation: Let the inflaton field turn Λ_{eff} on and leave it on for *many* de Sitter equilibration times, then decay into ordinary matter.

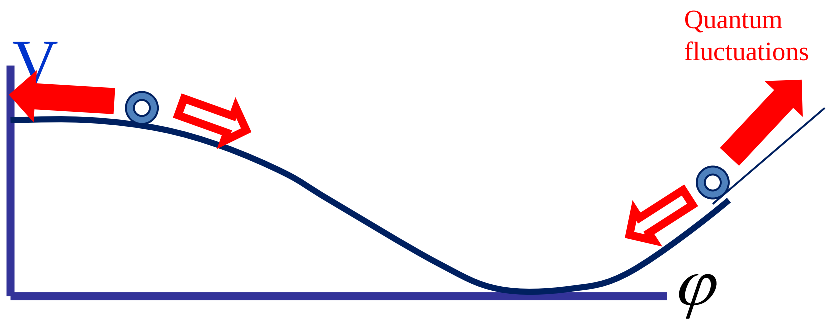
A standard "big bang" (arrow of time and all) is created.

The Inflaton:

Consider a scalar field with:

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

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



⇨ $\frac{\partial \rho}{\partial a} = 0$

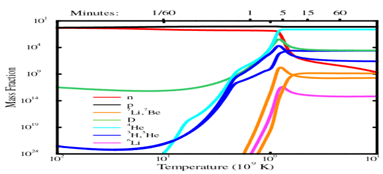
⇨ $a \sim e^{Ht}$

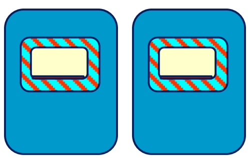
Inflation

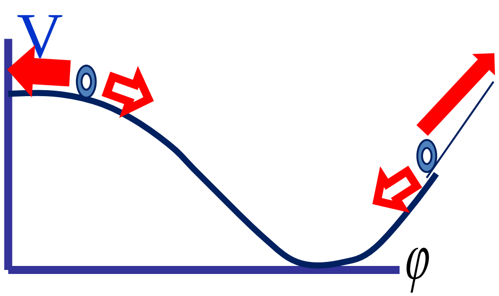
$$8\pi G V(\varphi) \approx \Lambda$$

Comparisons:

System	Initial Conditions
•Nucleosynthesis	Created by early time attractor (eqm)
•Slow Freeze	Created by early time attractor (eqm)
•Inflation	Created by early time attractor (eqm)



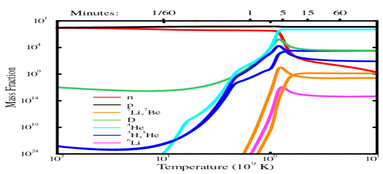


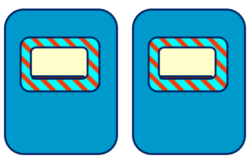


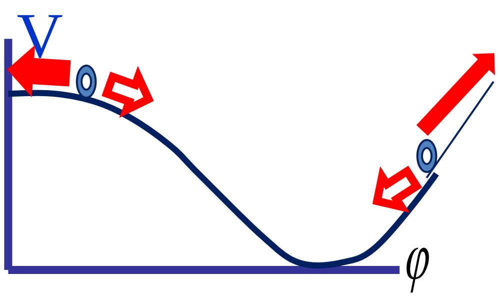
Comparisons:

But driven by non-eqm degree of freedom

System	Initial Conditions	
•Nucleosynthesis	Created by early time attractor (eqm) in subspace	Background Spacetime
•Slow Freeze	Created by early time attractor (eqm) in subspace	Out of eqm ice
•Inflation	Created by early time attractor (eqm) in subspace	Special Inflaton field configuration







Issues with very small scales!

I) Inflation in the era of WMAP

I.0 What is Cosmic Inflation?

I.1 Successes

I.2 Future tests

I.3 Theoretical advances

II) Inflation and the arrow of time

II.1 Introduction

II.2 Arrow of time basics

II.3 Inflation and the arrow of time

II.4 Implications

II.5 Can the Universe Afford Inflation?

III) Conclusions

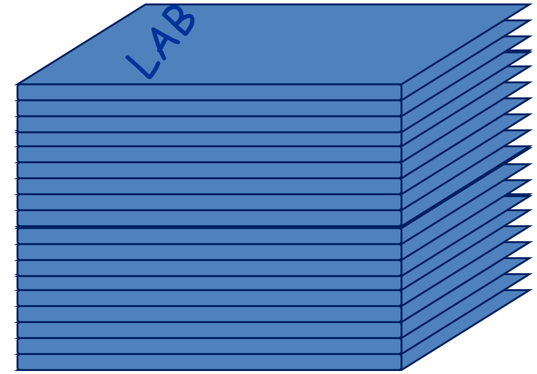
Does inflation

-Predict the arrow of time? (Sets up IC's for Big Bang)

-Depend on the arrow of time? (Requires special initial state of inflaton etc.)

Comment on how we use knowledge ("A" word!)

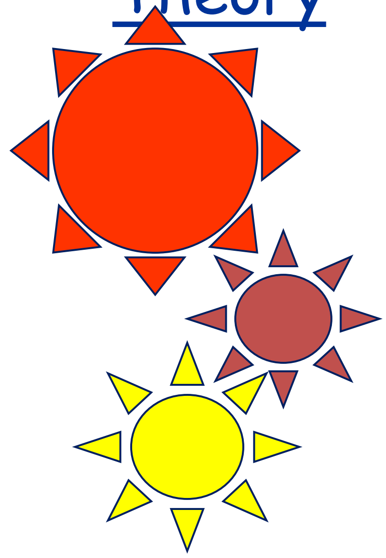
Total knowledge about the universe→



Input

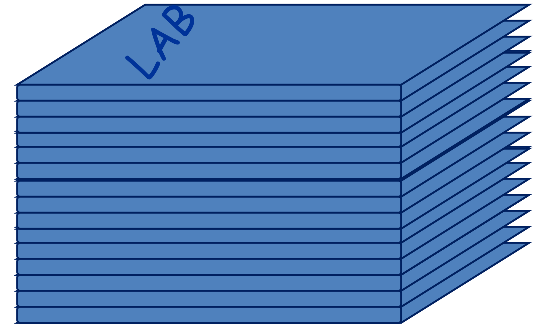
Theory

Output



Comment on the "A" word:

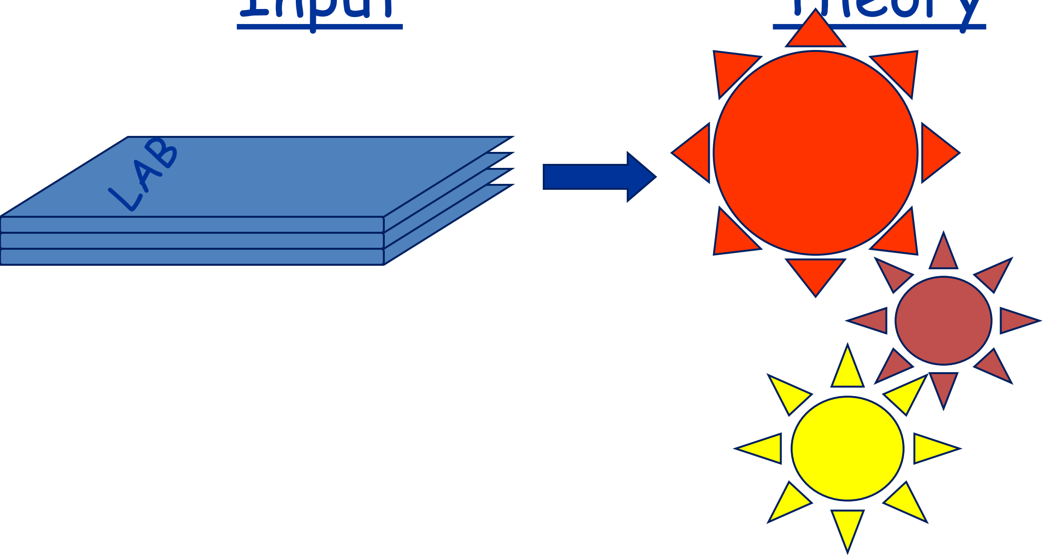
Total knowledge about the universe→



Input

Theory

Output



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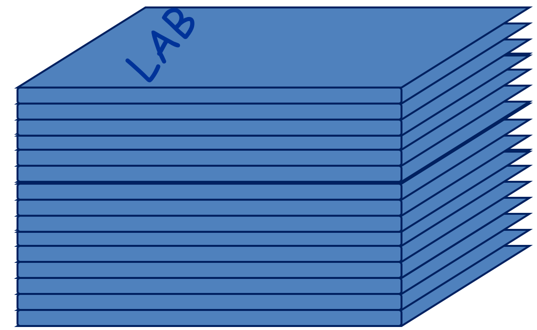
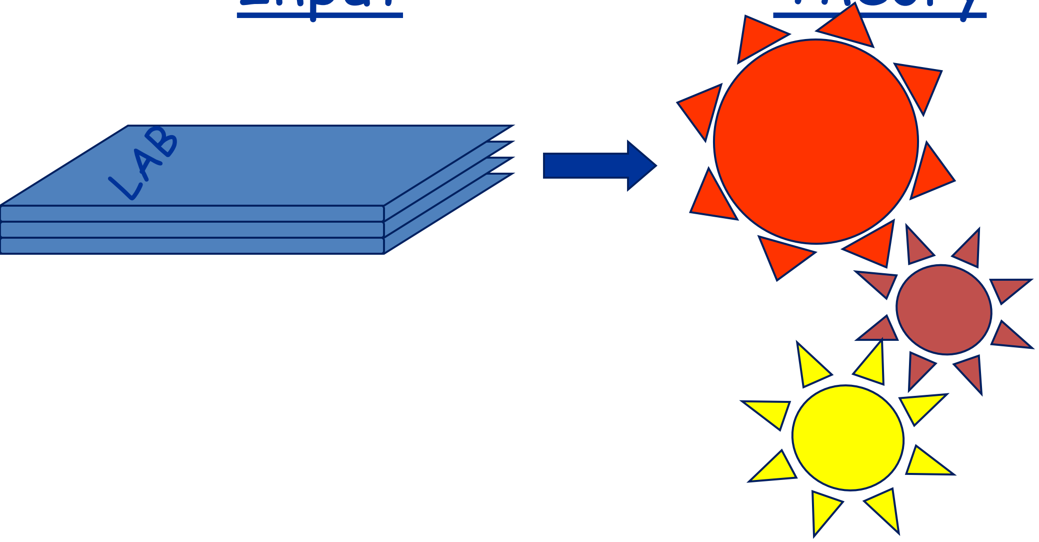


Input Theory Output



Comment on the "A" word:

Total knowledge about
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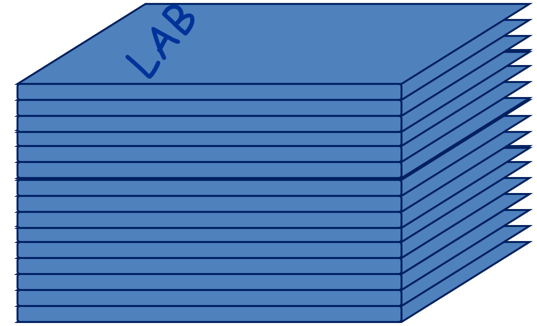
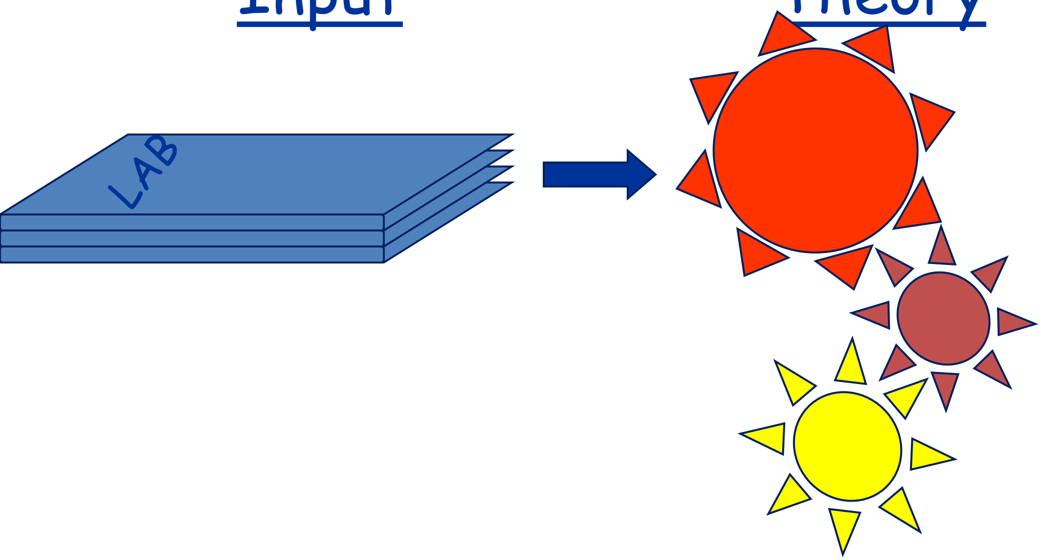


Input Theory Output



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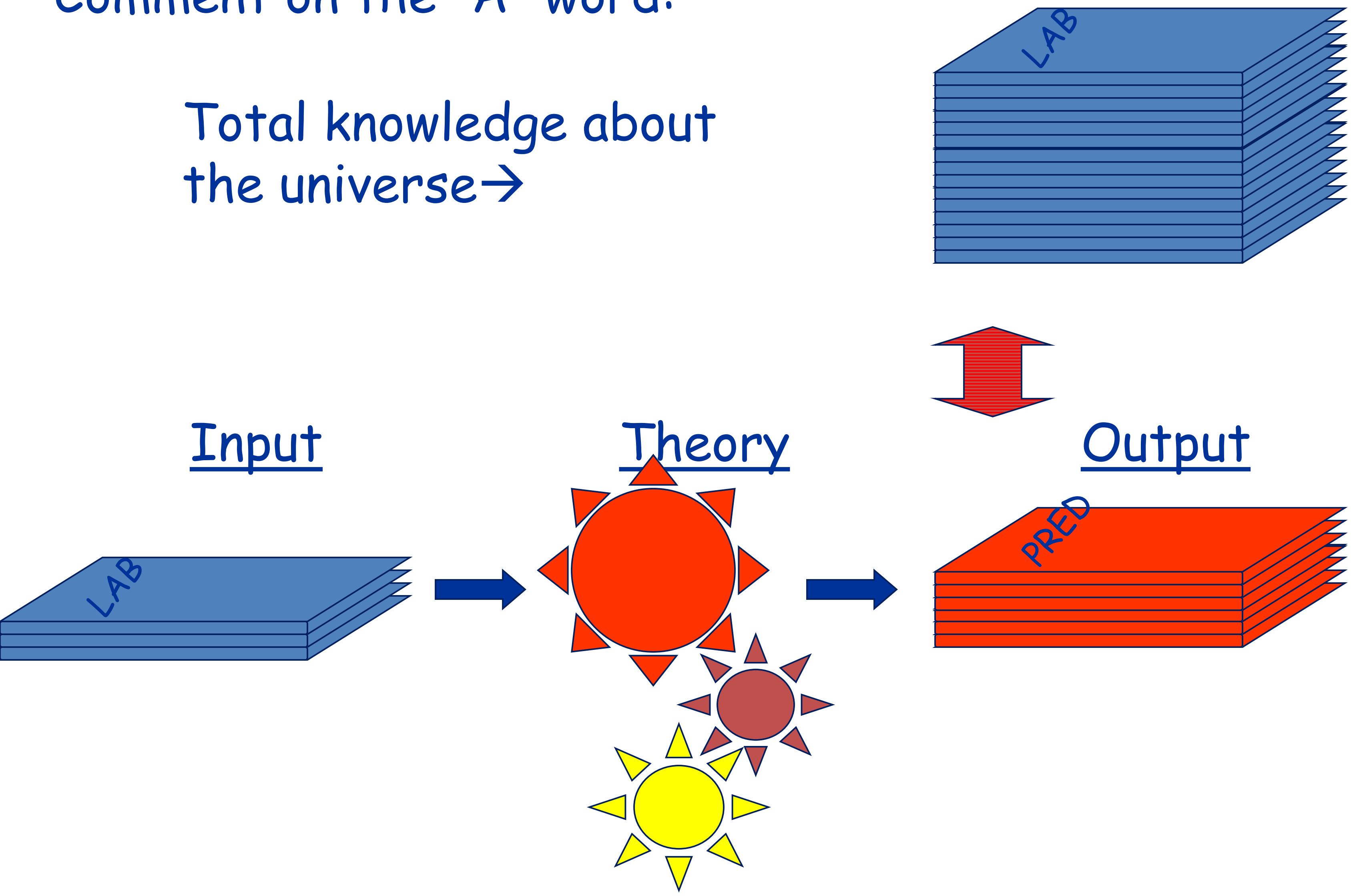
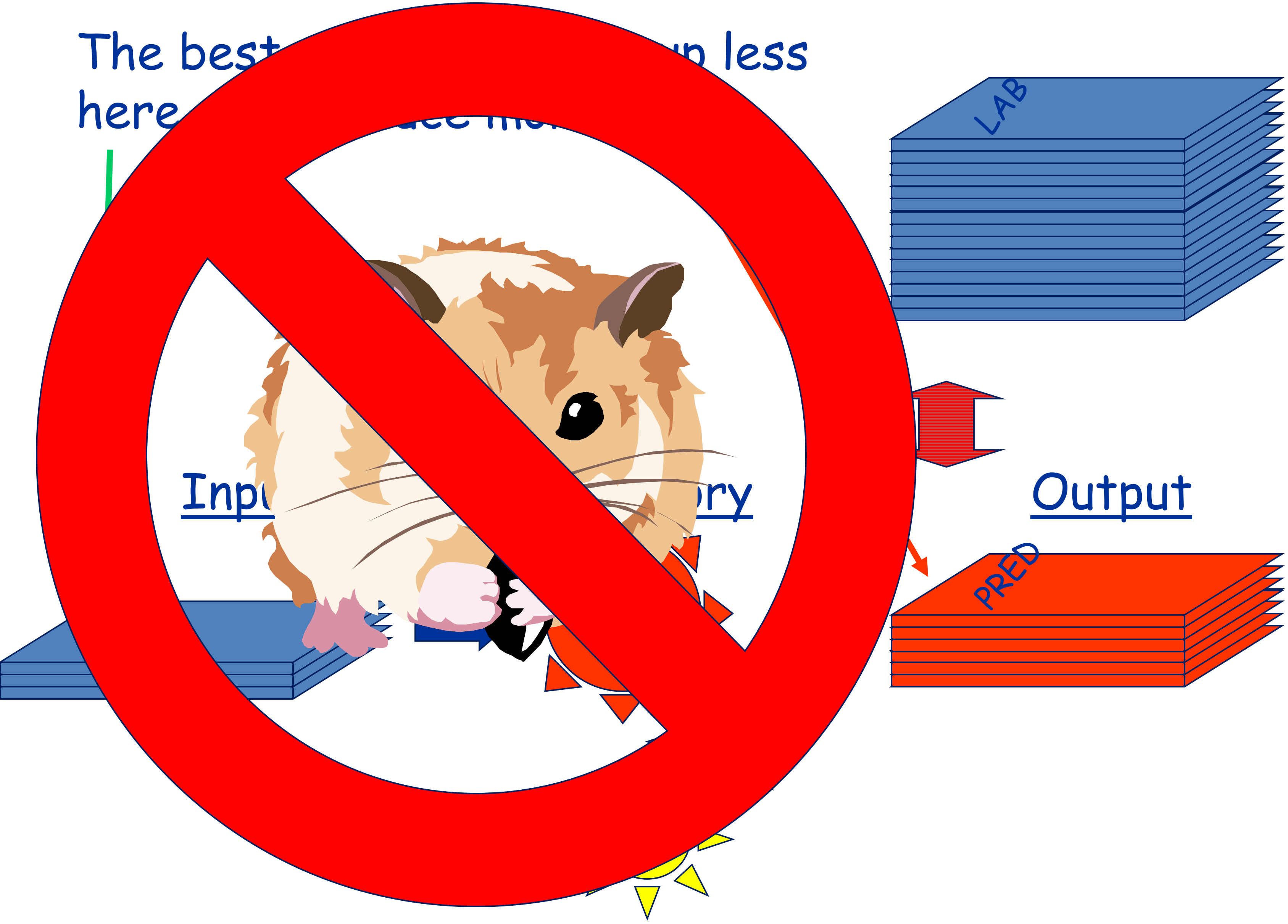


The best ... less
here ...



Q: To what extent should our arrow of time (smooth initial state of Big Bang) best used as INPUT, rather than OUTPUT?

A: The arrow of time (smooth initial state of Big Bang) can NOT be 100% output.

The very nature of the arrow of time requires initial conditions that are not completely generic

What Role

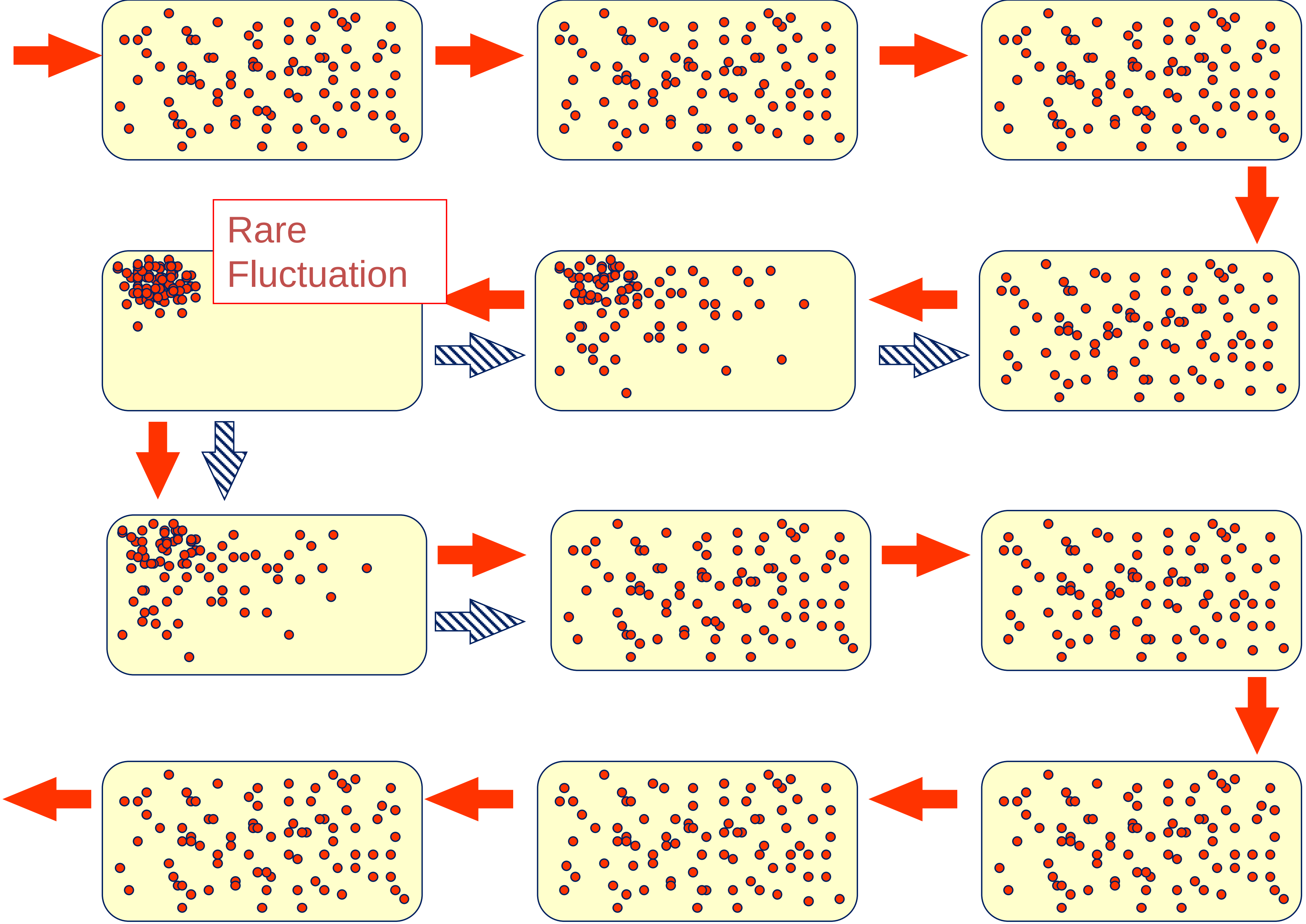
-"Dominant channel" into Big Bang (Uses attractor behavior and exponential volume factors to maximize impact)

-Gives package deal: Universe very large, flat, and with particular perturbations (falsifiable!).

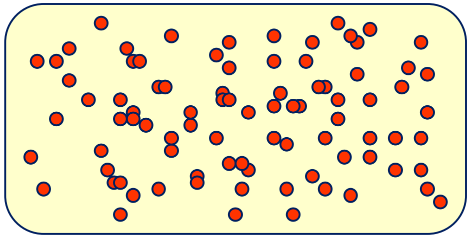
-Answers Boltzmann's concerns about typical regions with arrow of time being much smaller and "shorter" then we experience. (inflation as amplifier). [Also modern cosmological version.]

- Answers "How did our Universe come about?"

NB: In the spirit of Linde's "chaotic inflation"


Rare
Fluctuation

Boltzmann's "cosmology":



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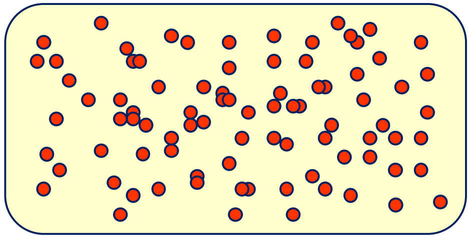

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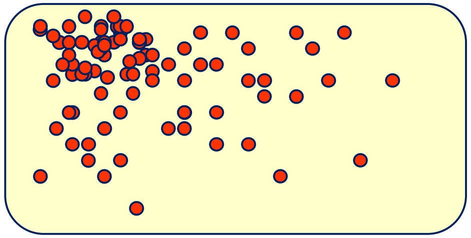

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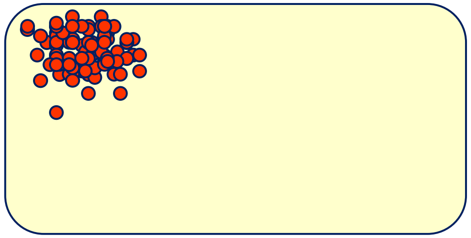

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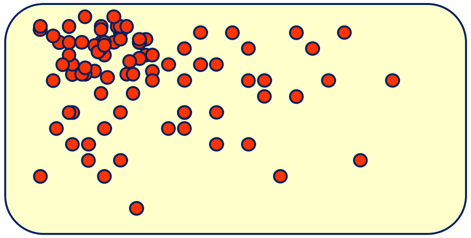

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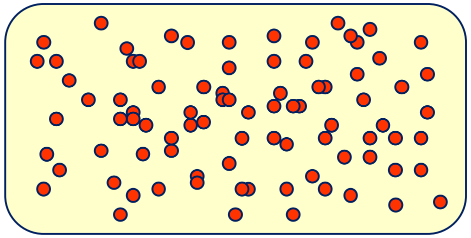

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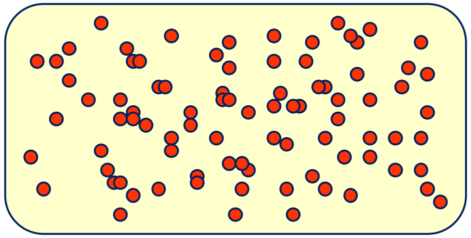

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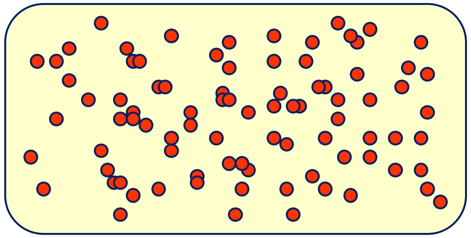

Boltzmann's “cosmology” appeared to make very strange predictions:

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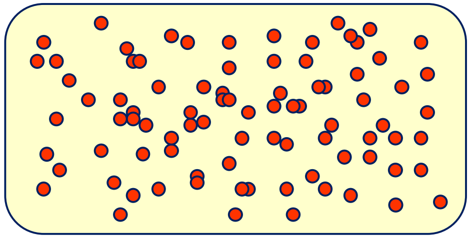

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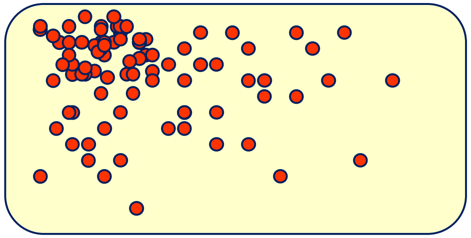

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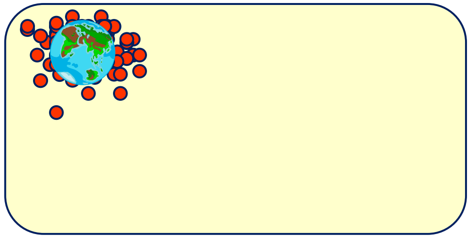
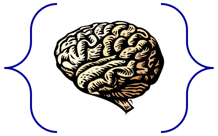


(Boltzmann's brain)



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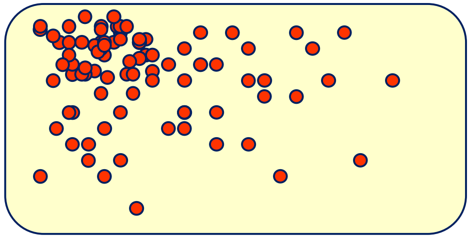

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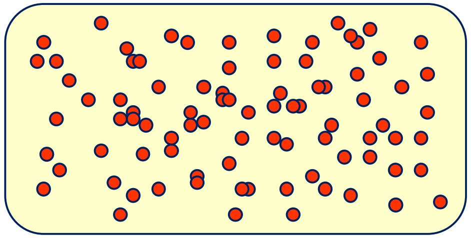

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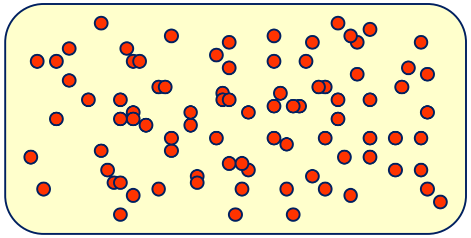
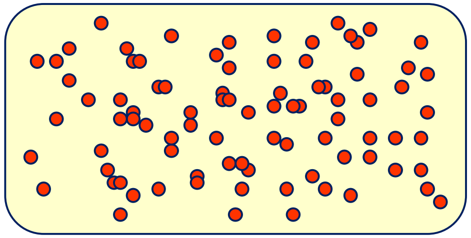


Inflation (**schematic**):



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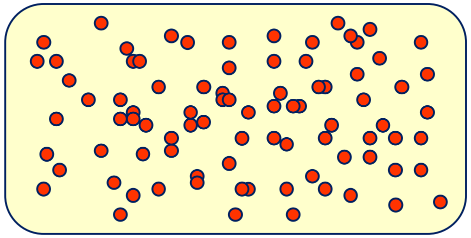
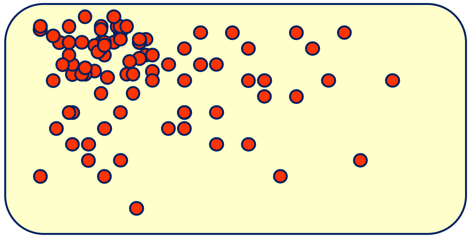
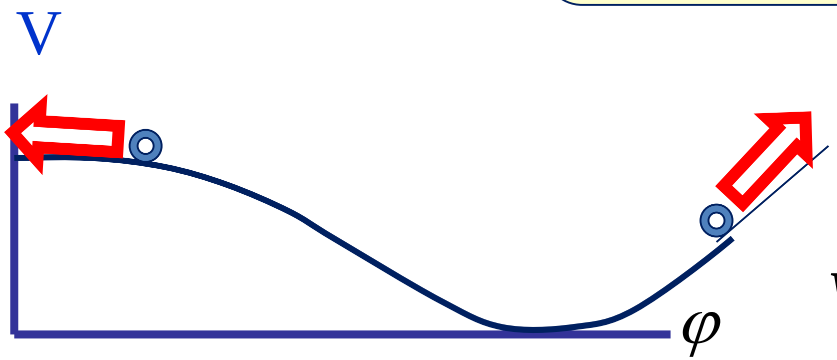


Inflation (**schematic**):

The "rare fluctuation" is in the inflaton field

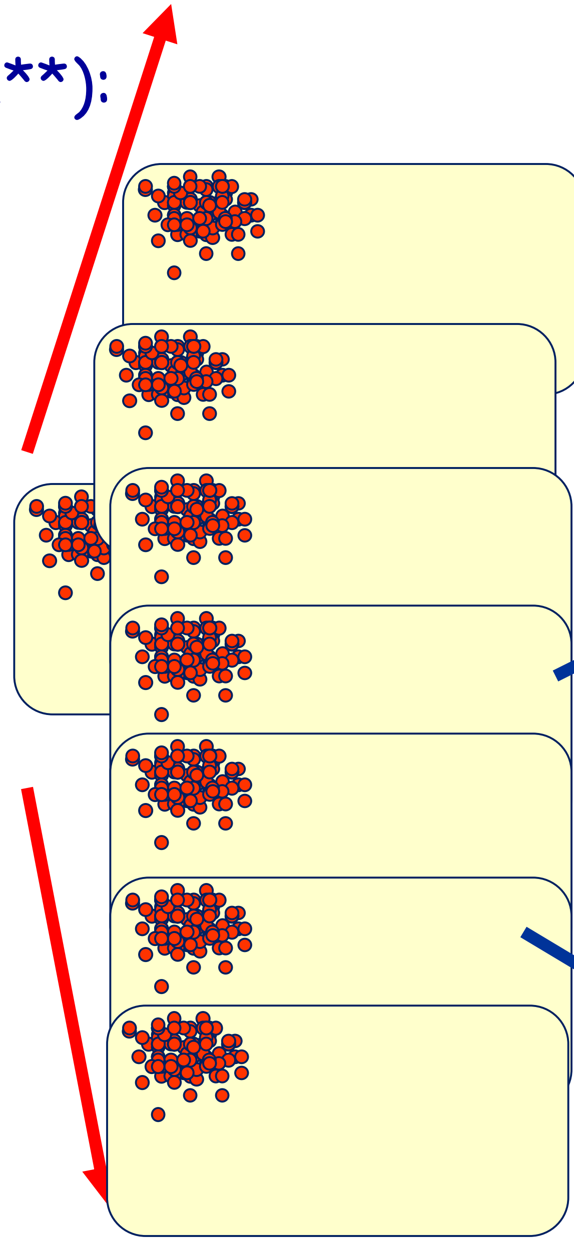




$V(\varphi) >>$ all space and time derivative (squared) terms

Inflation (**schematic**):

Inflation exponentially expands the volume



Special package of features predicted by inflation

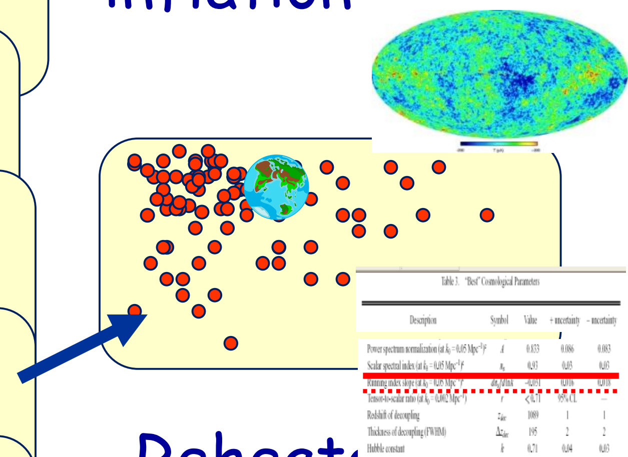


Table 3. "Best" Cosmological Parameters

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

Reheated regions give big bang

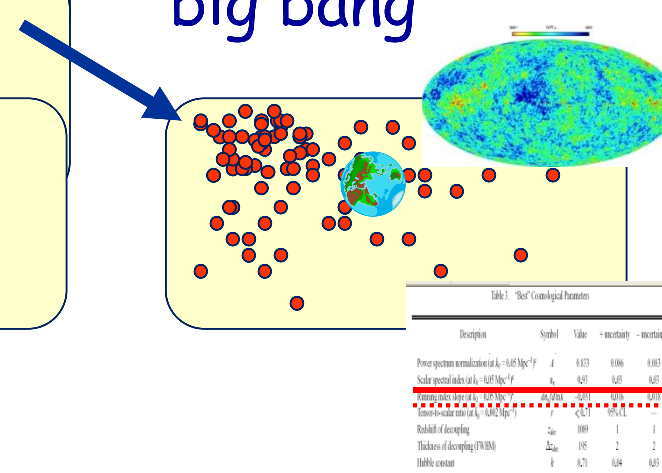


Table 3. "Best" Cosmological Parameters

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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2. Eternal inflation
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de Sitter Equilibrium (dSE) cosmology

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

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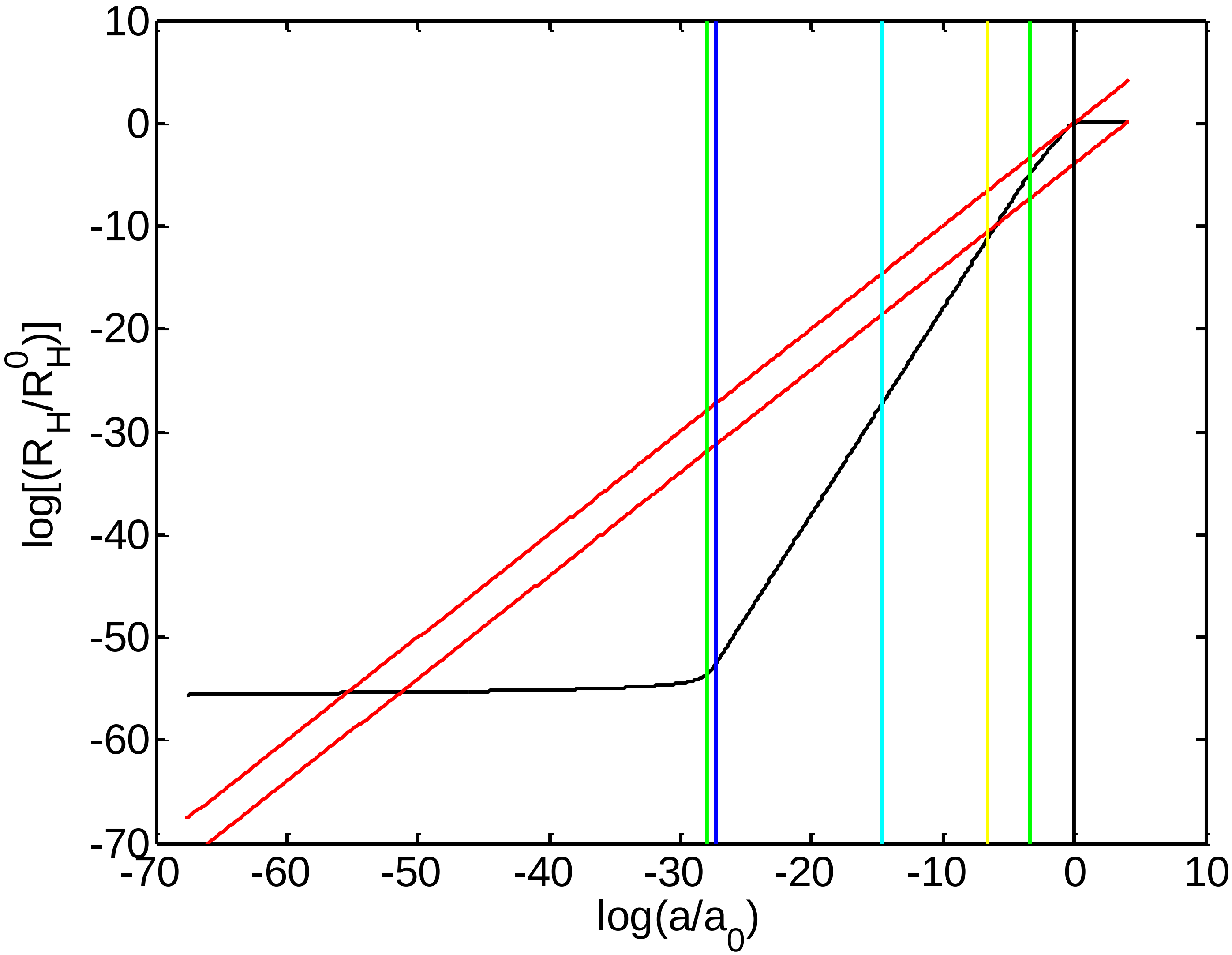
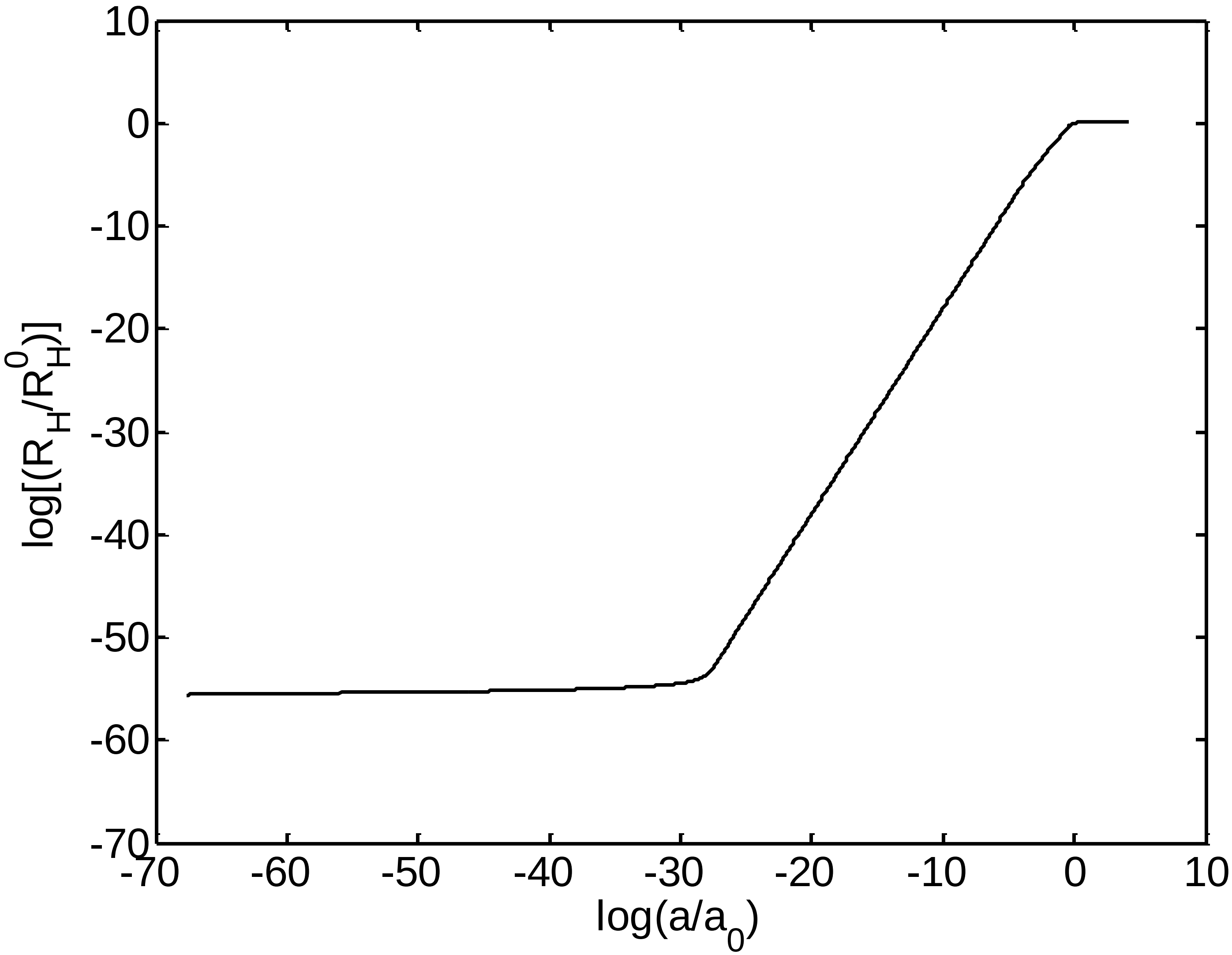
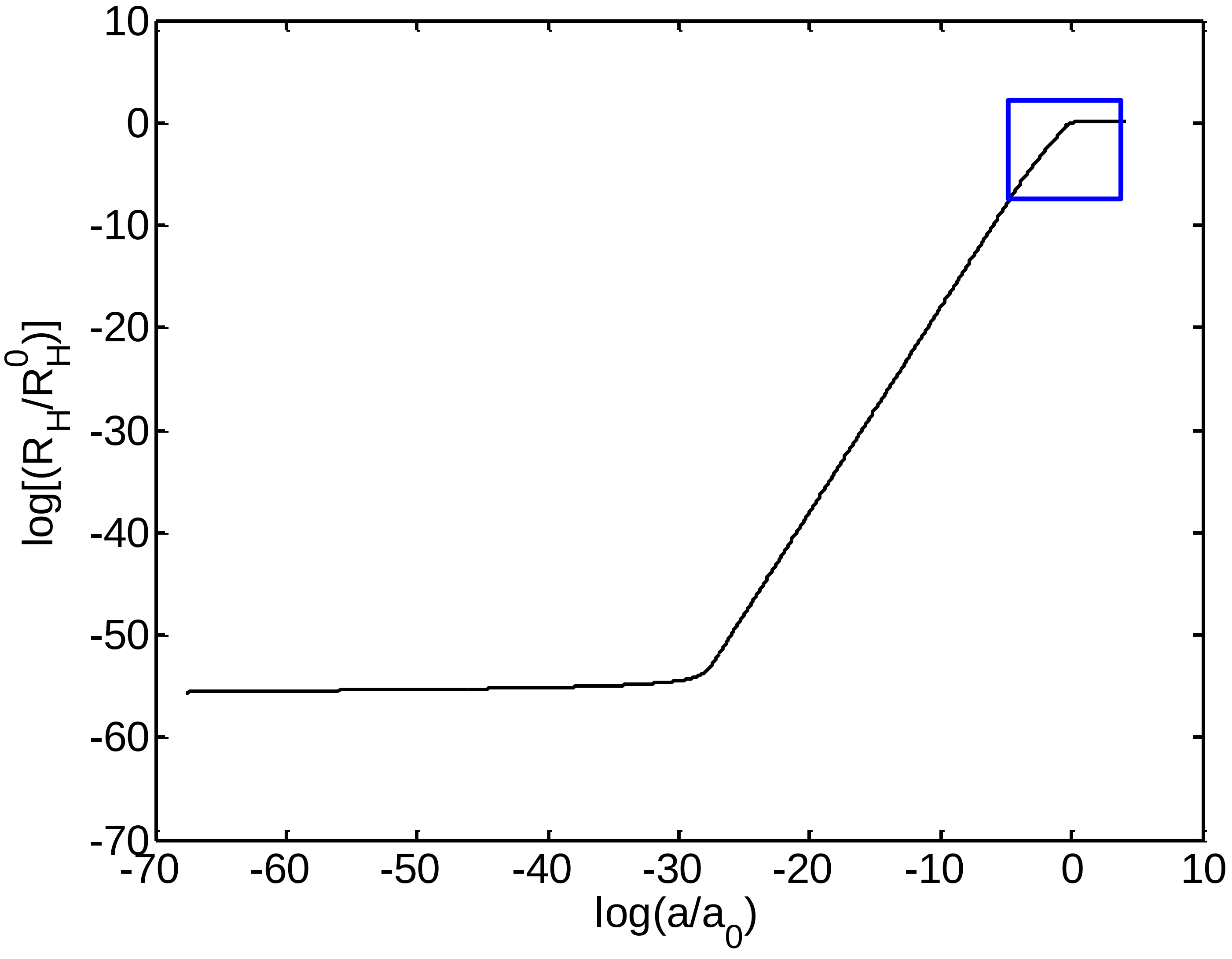
AA: arXiv:1104.3315
AA: arXiv:0906.1047
AA & Sorbo: hep-th/0405270

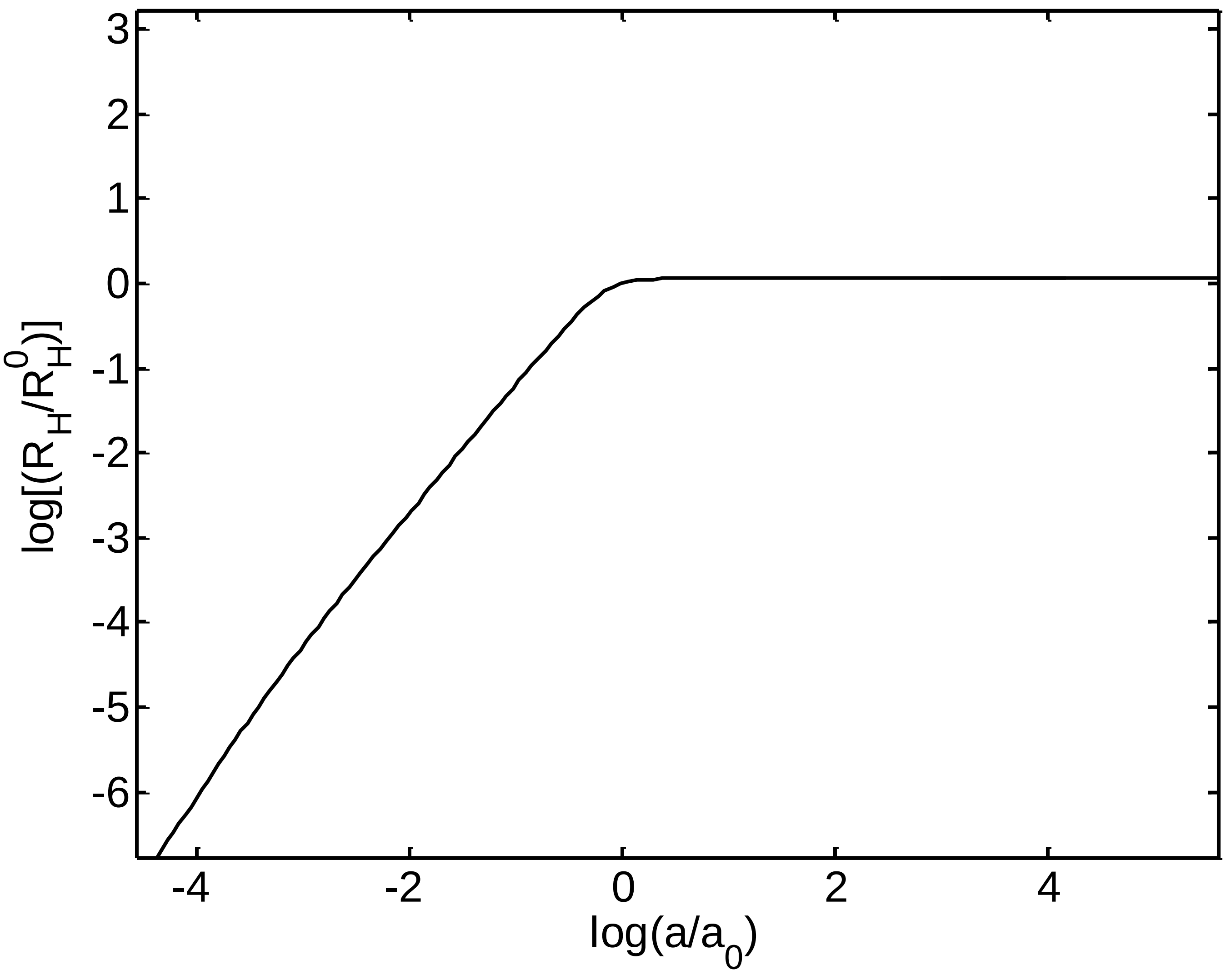
Evolution of Cosmic Length

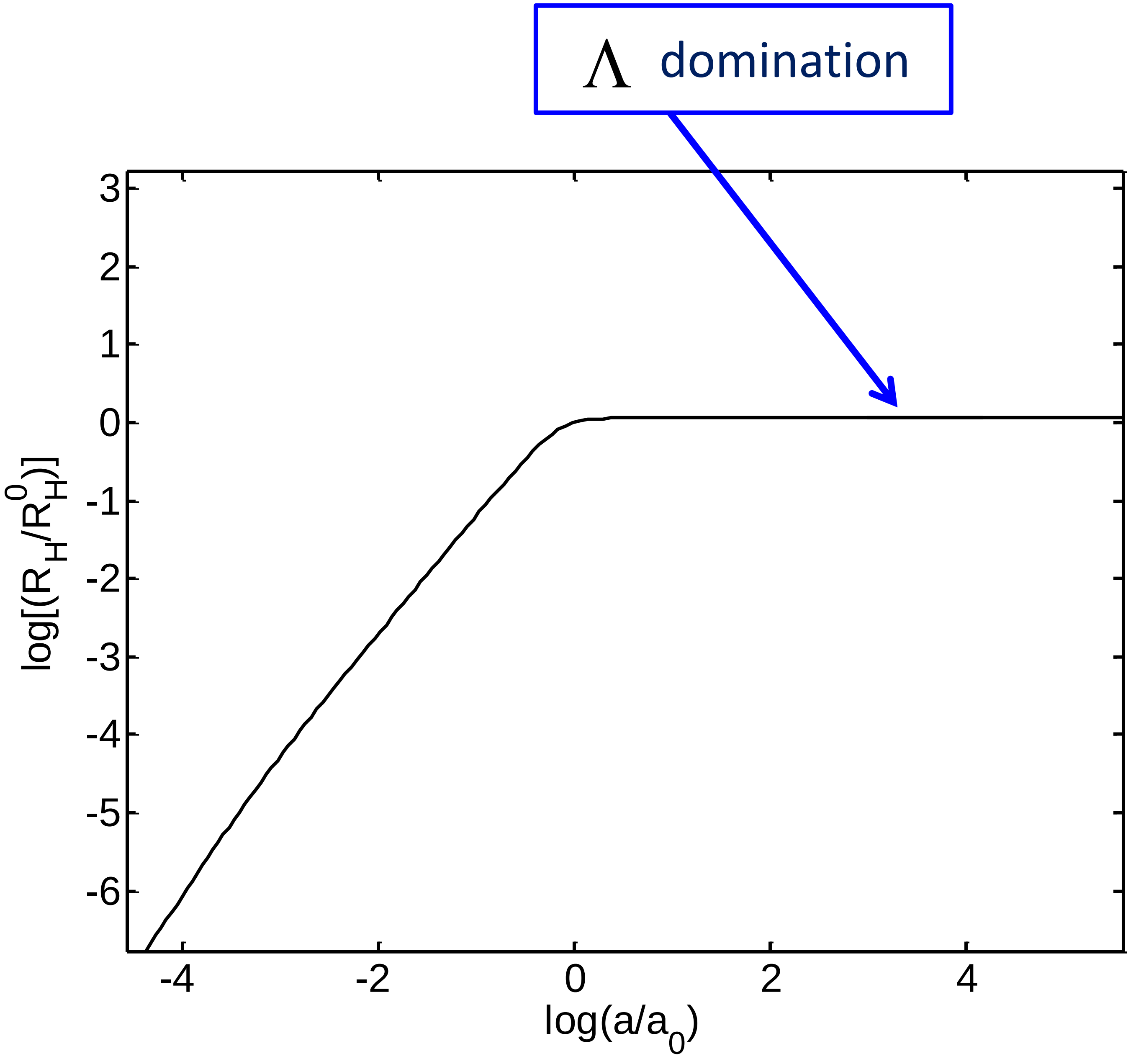


Evolution of Cosmic Length

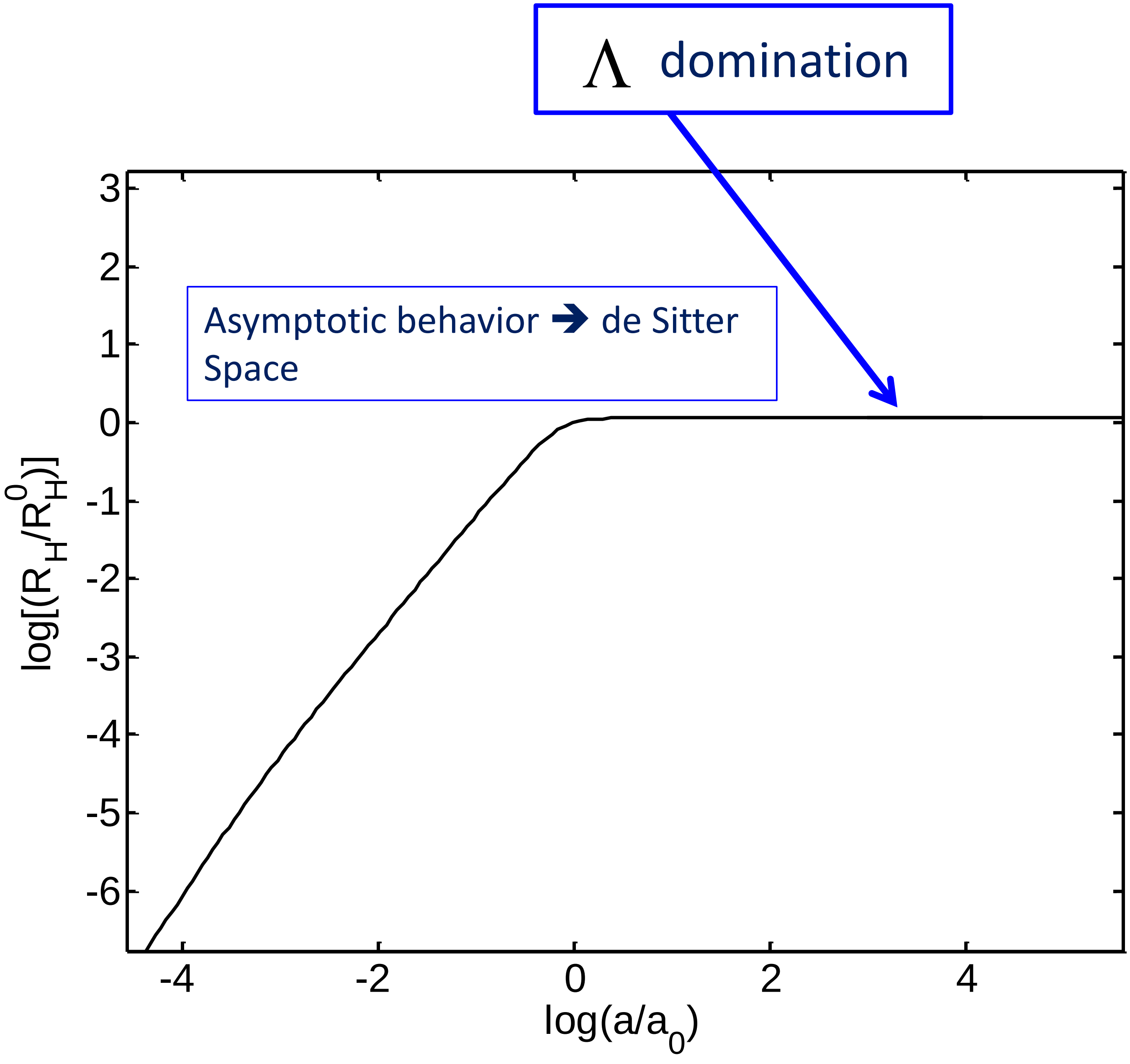



10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10
$\log[(R_H/R_H^0)]$
$\log(a/a_0)$

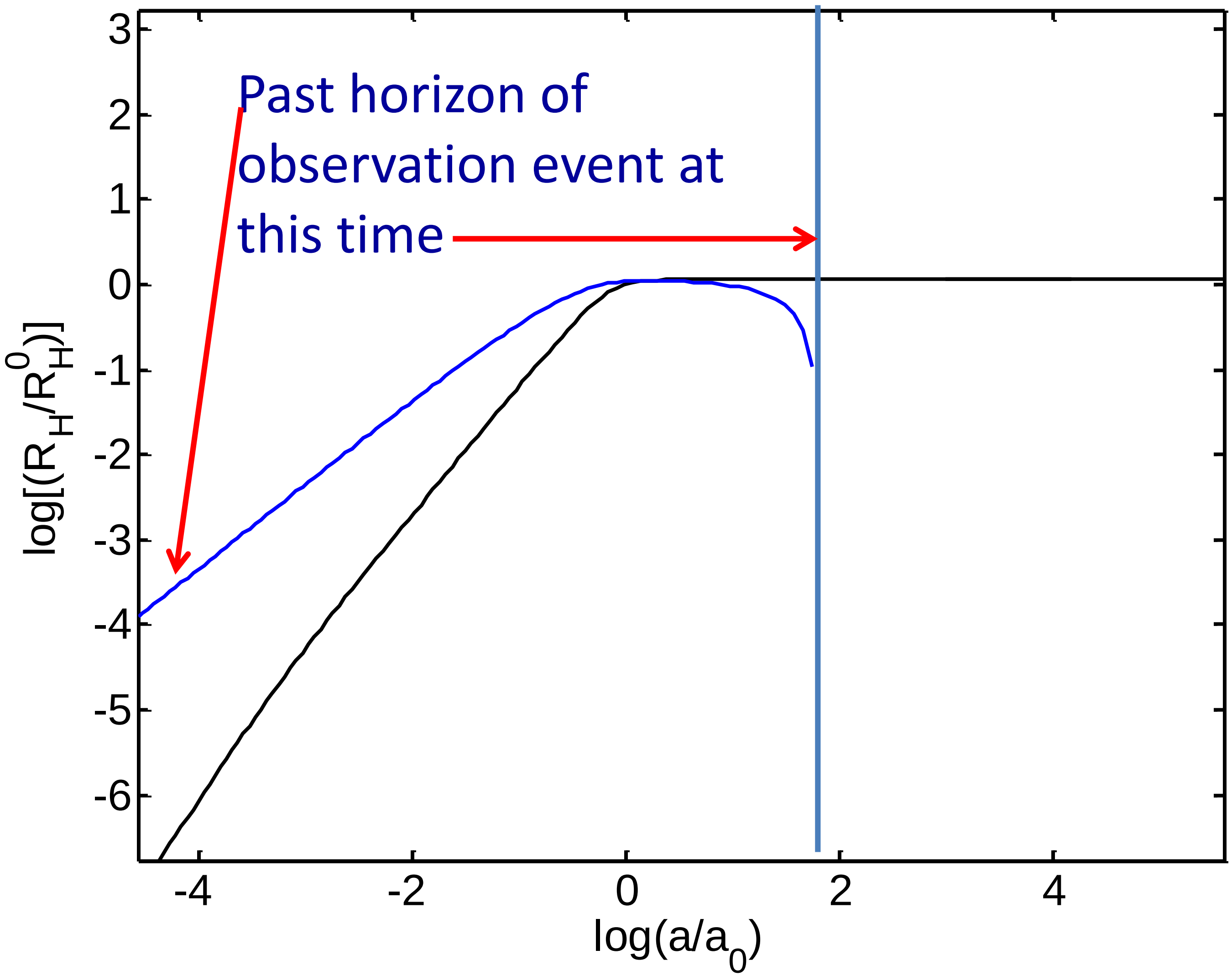

3
2
1
0
-1
-2
-3
-4
-5
-6
$\log[(R_H/R_H^0)]$
-4
-2
0
2
4
$\log(a/a_0)$



Λ domination
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)

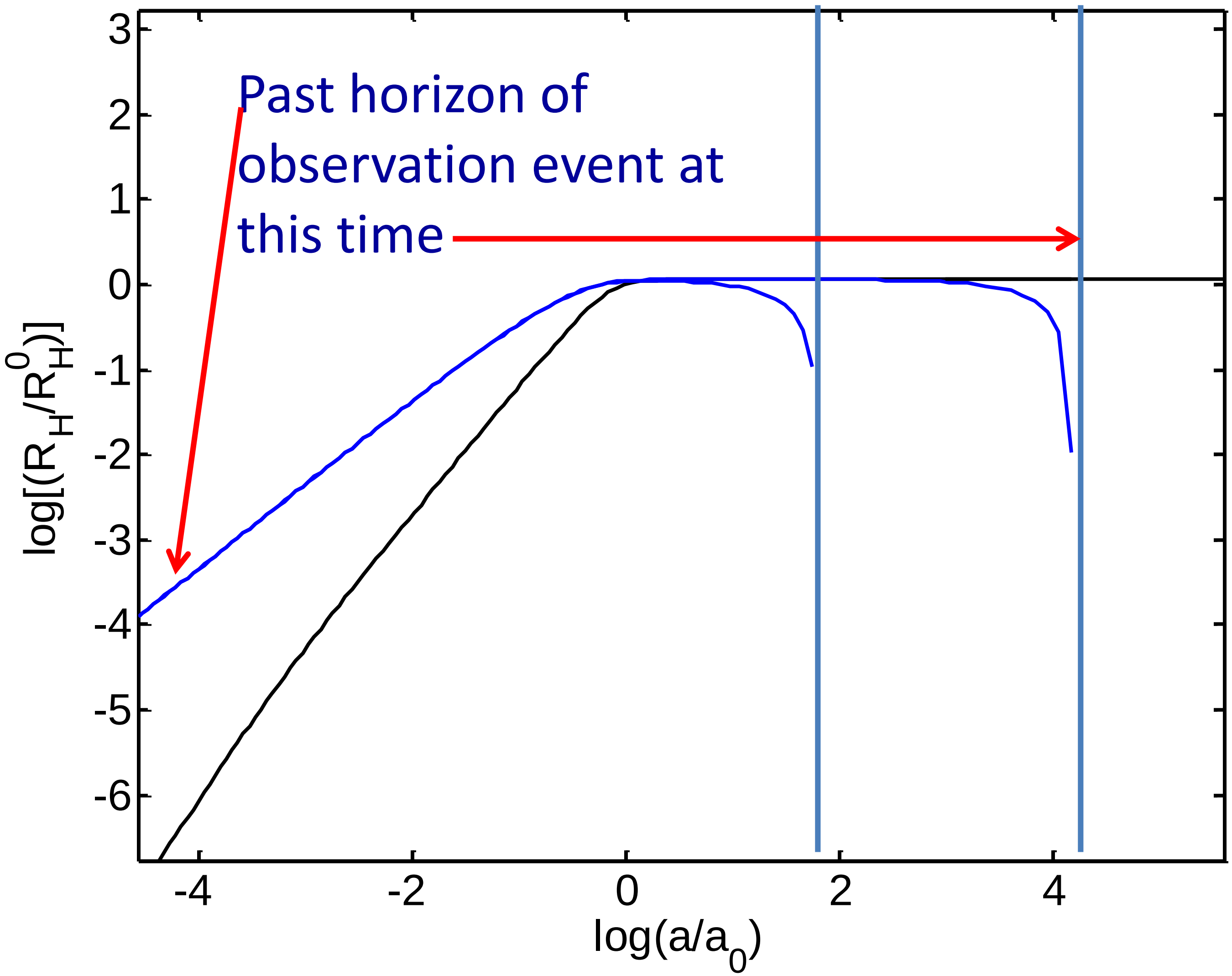

Λ domination
Asymptotic behavior → de Sitter Space
3
2
1
0
-1
-2
-3
-4
-5
-6
log[(R_H/R_H^0)]
-4
-2
0
2
4
log(a/a_0)

The de Sitter horizon



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

The de Sitter horizon



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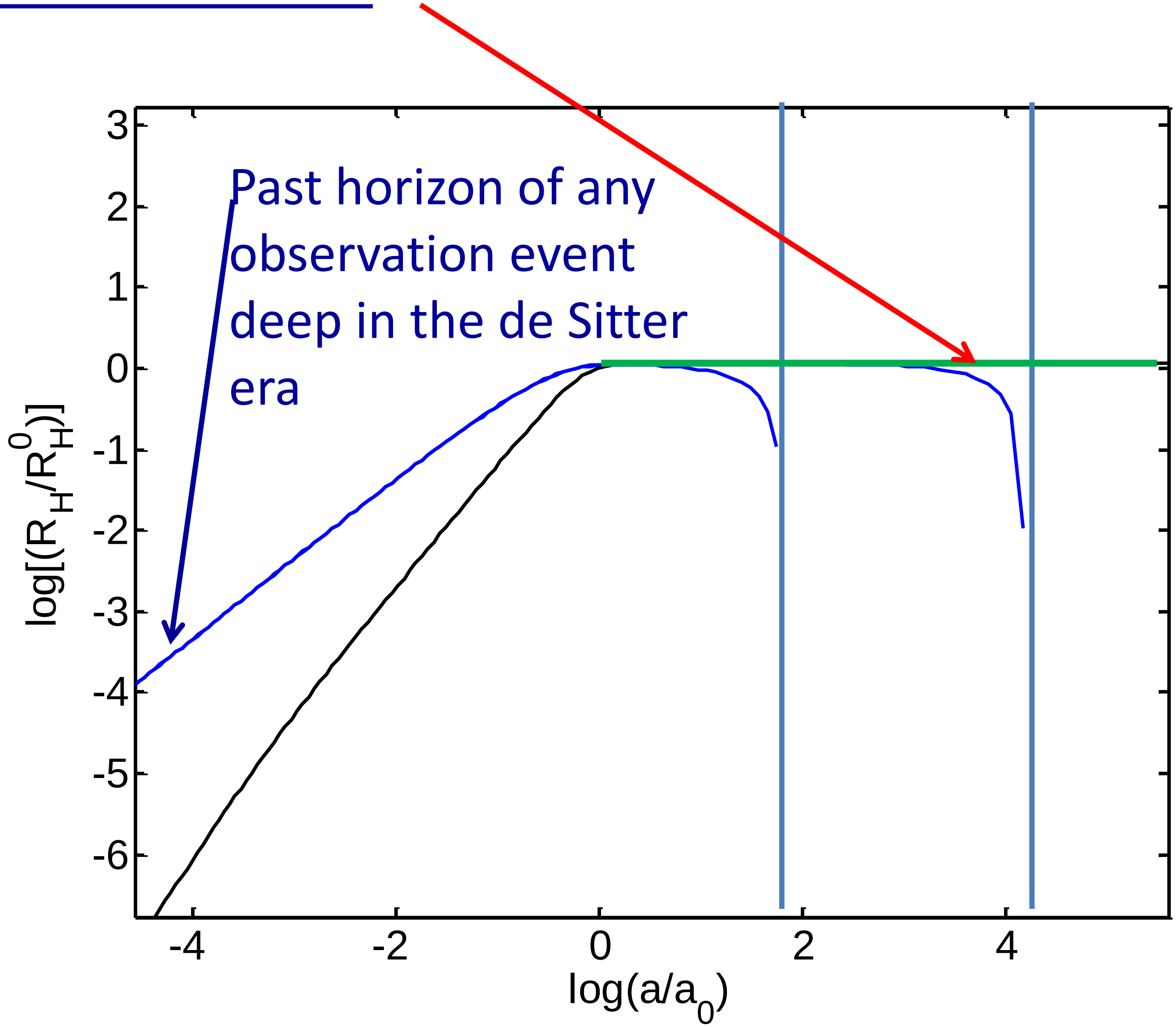

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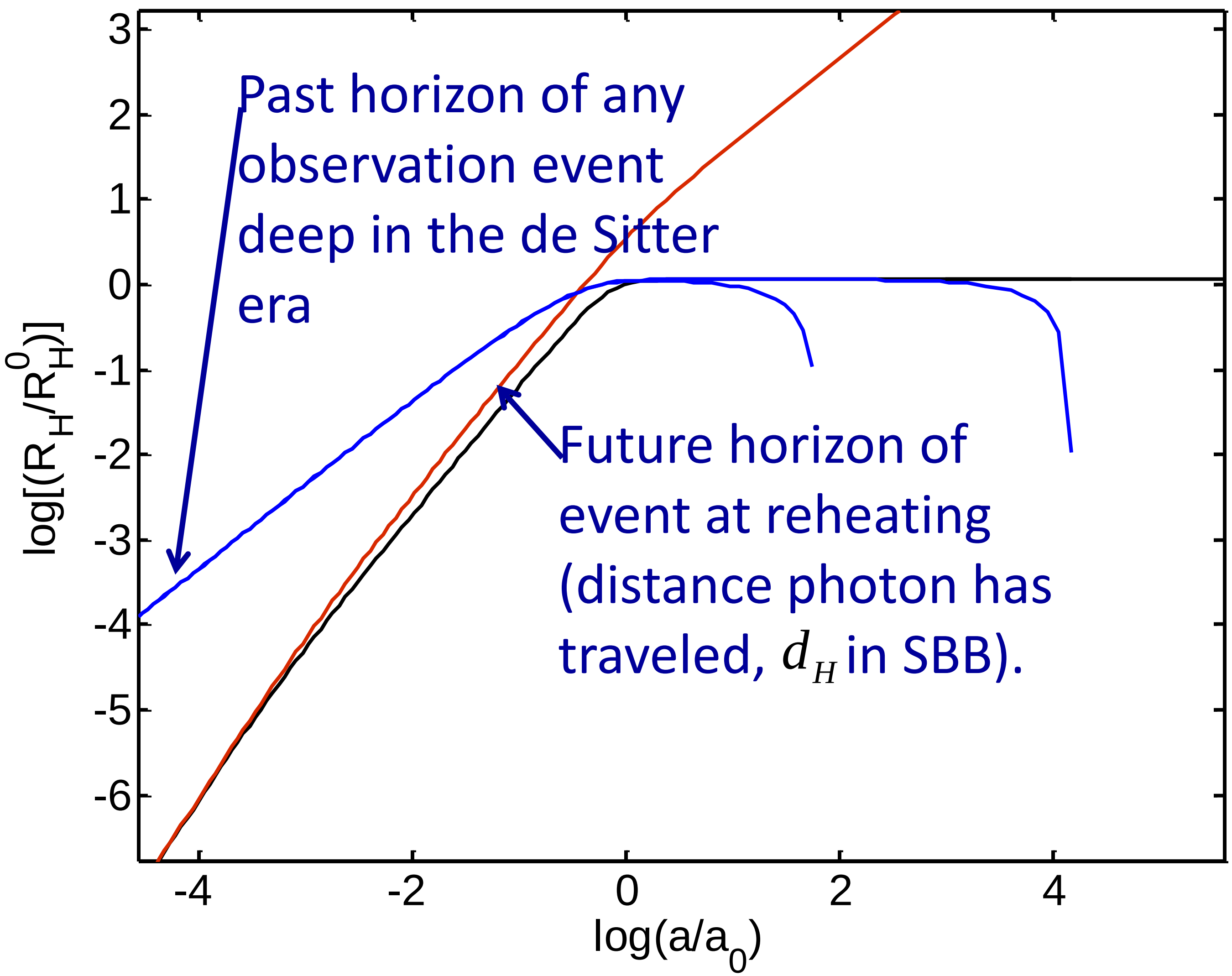

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Implications of the de Sitter horizon

- Maximum entropy

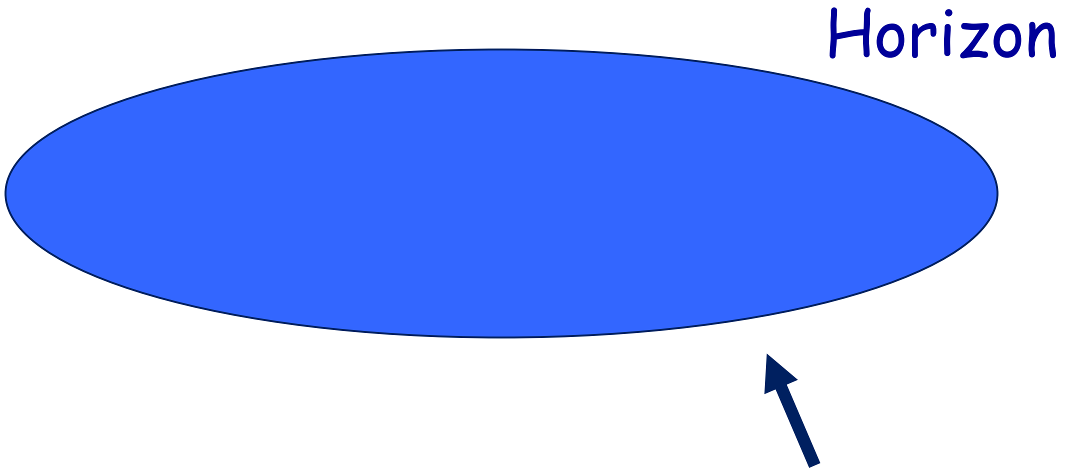
$$S_{\Lambda} \propto A = H_{\Lambda}^{-2} = \left(\frac{\Lambda}{3}\right)^{-1}$$

- 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?



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

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

Implications of the de Sitter horizon

- Maximum entropy $$S_\Lambda \propto A = H_\Lambda^{-2} = \left(\frac{\Lambda}{3}\right)^{-1}$$
- Gibbons-Hawking Temperature $$T_{GH} = H_\Lambda = \sqrt{\frac{8\pi G}{3}\rho_\Lambda}$$
- 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.

Implications of the de Sitter horizon

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✓ • Only a finite volume ever observed

✓ • If Λ is truly constant: Cosmology as fluctuating Eqm.?

✓ • Maximum entropy $\xrightarrow{?}$ finite Hilbert space of dimension $N = e^{S_\Lambda}$

Banks & Fischler & Dyson et al.

dSE cosmology

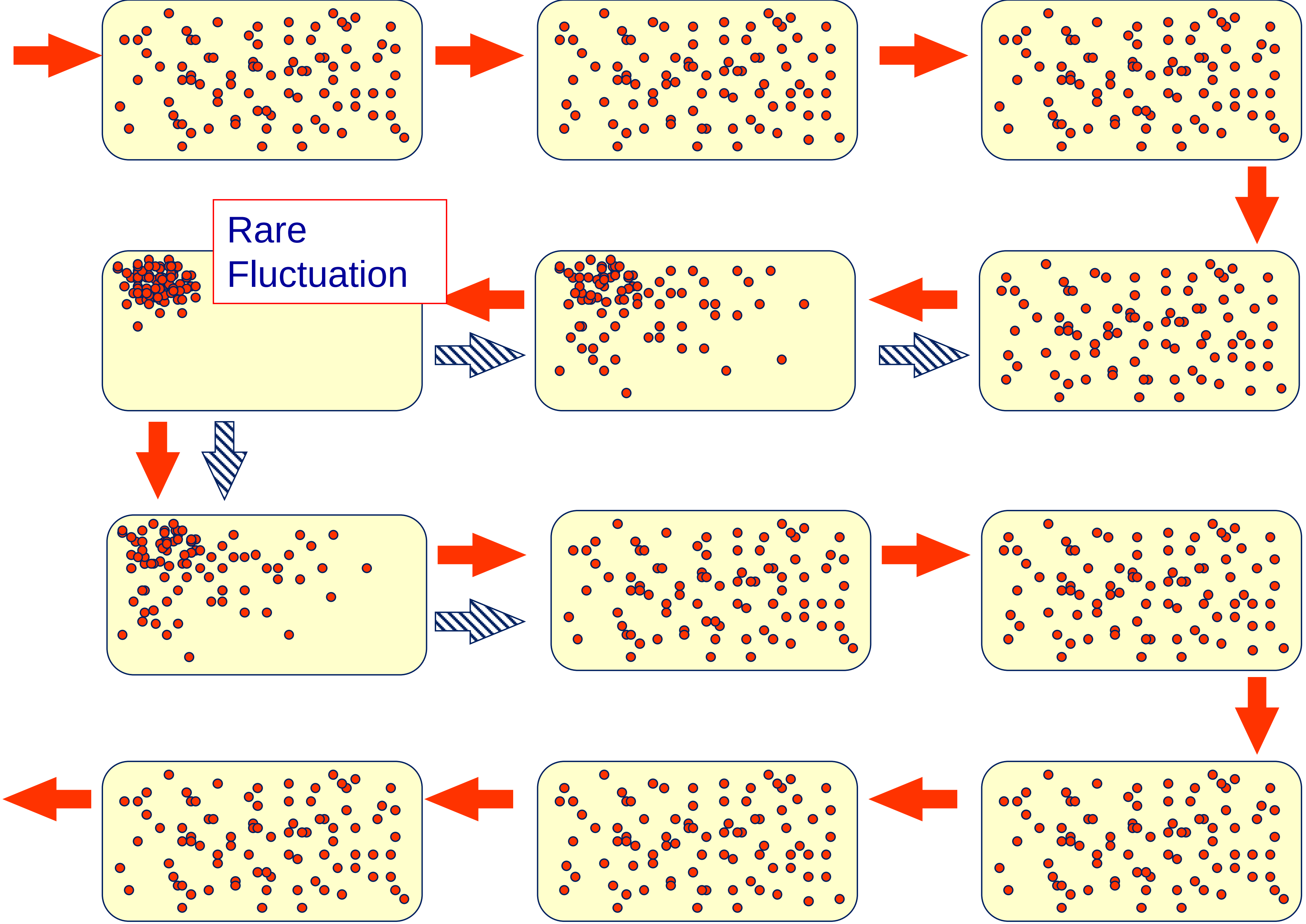
Equilibrium Cosmology

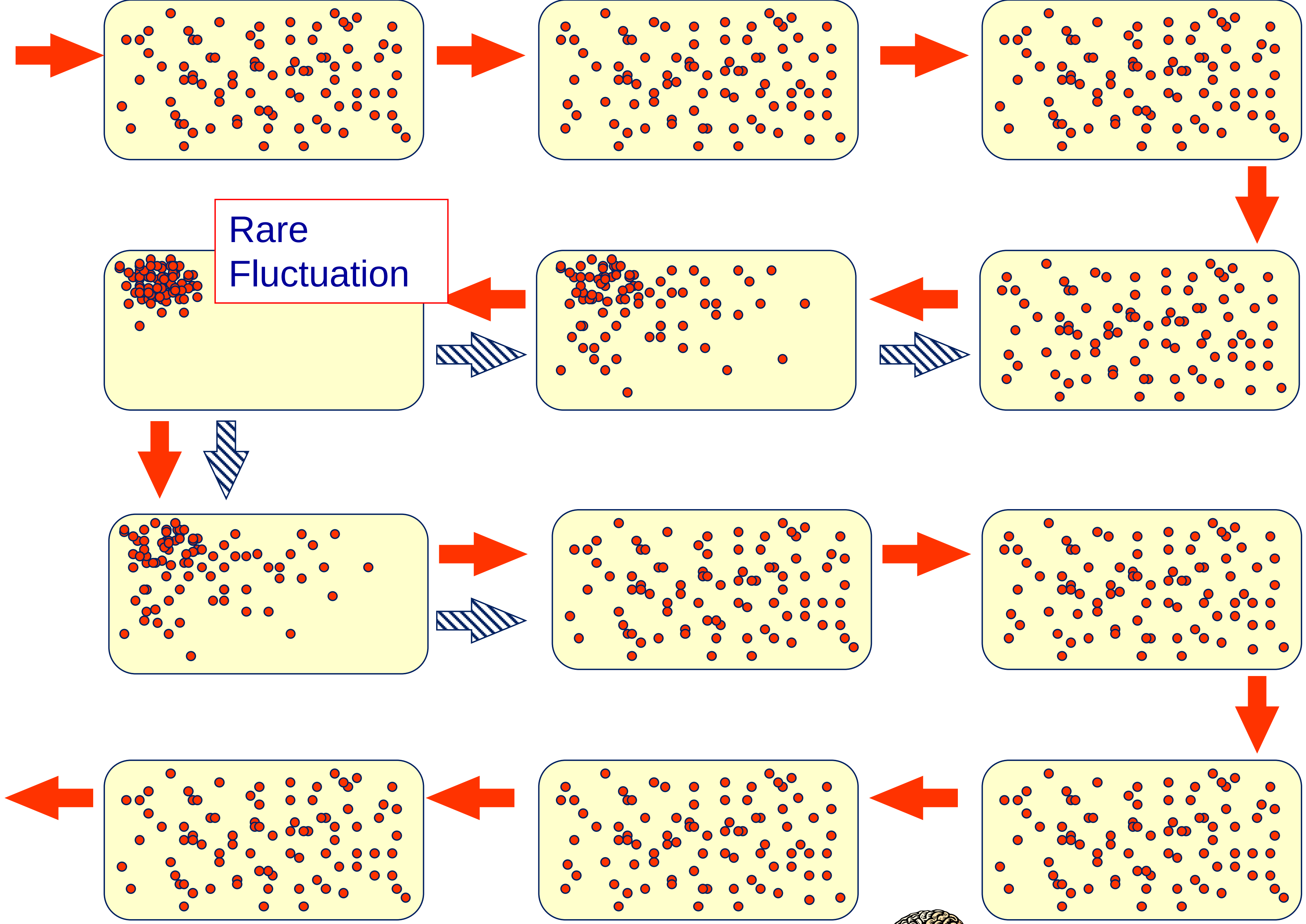
Equilibrium Cosmology

➔ An eqm. theory does not require any theory of initial conditions.   The probability of appearing in a given state is given entirely by stat mech, and is thus “given by the dynamics”.

➔ If you know the Hamiltonian you know how to assign probabilities to different states without any special theory of initial conditions.

Dyson et al 2002


Rare
Fluctuation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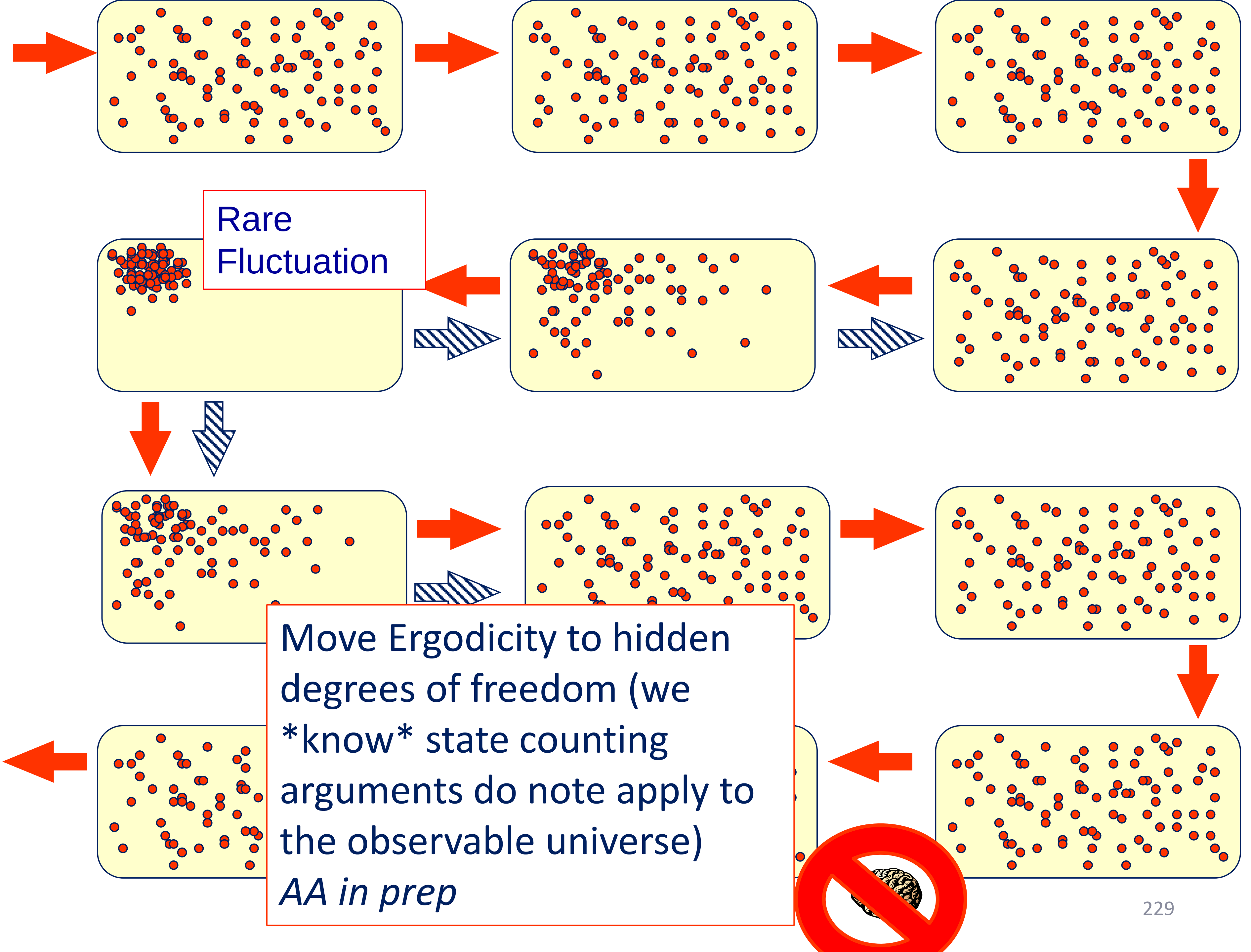
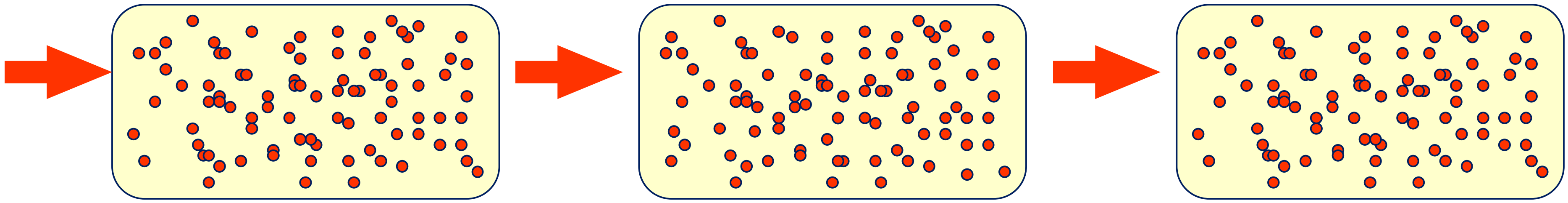
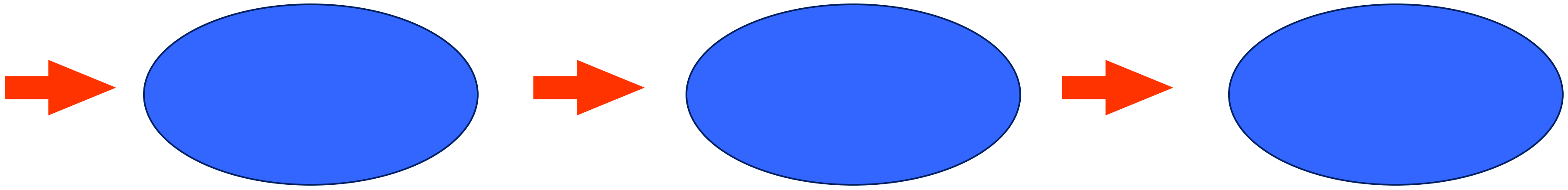

Rare Fluctuation
Move Ergodicity to hidden degrees of freedom (we *know* state counting arguments do note apply to the observable universe)
AA in prep

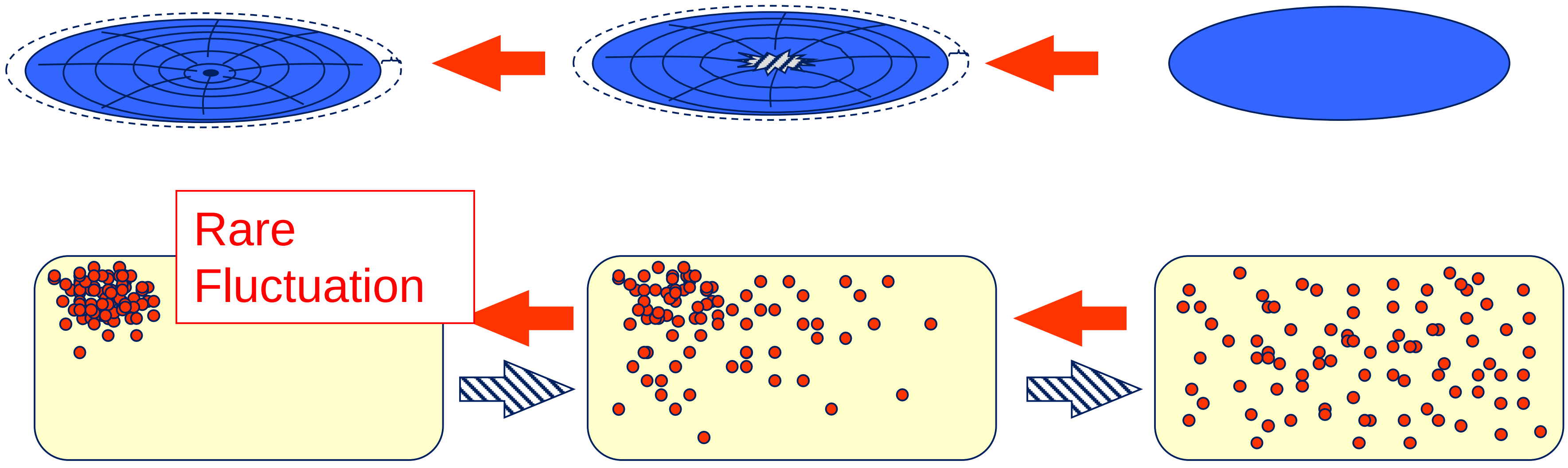
Concept:



Realization:



"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 "Farhi-Guth Guven" (FGG) 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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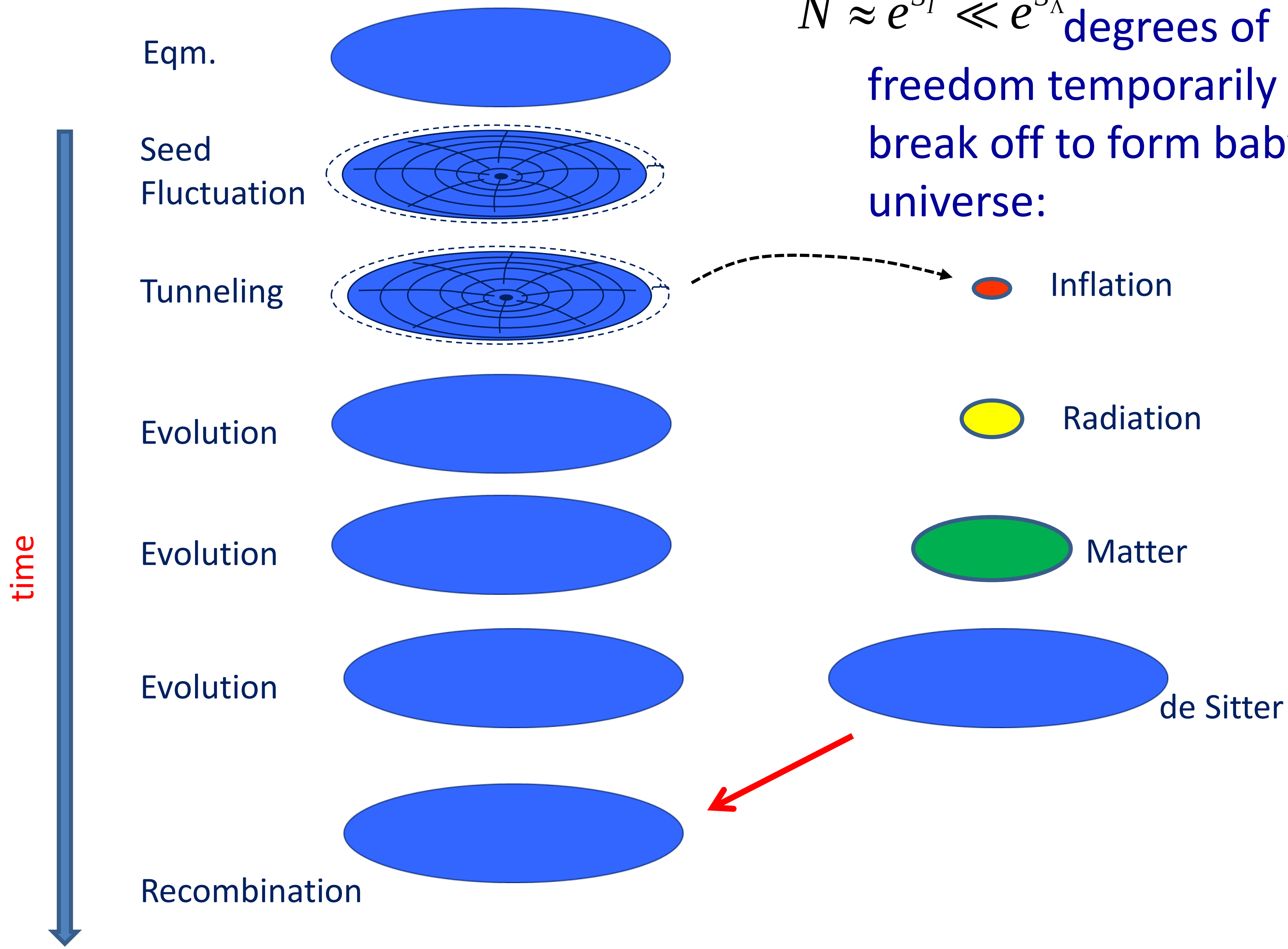
M → 0 not a problem for G-F process (A. Ulvestad & AA 2012)

See also Freivogel et al 2006, Banks 2002

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



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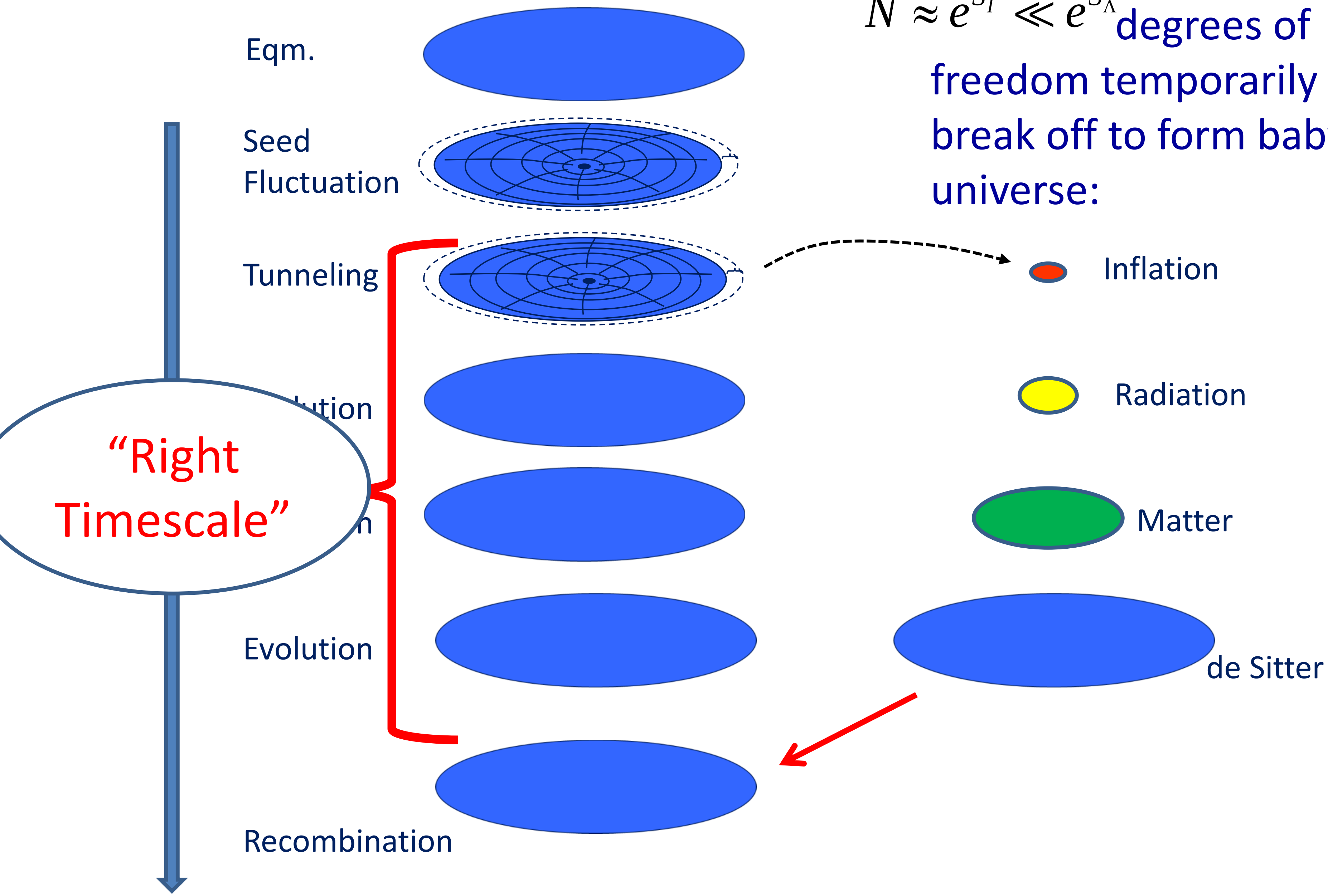

Implications of finite Hilbert space $N = e^{S_\Lambda}$

- Recurrences

- Eqm.

- Breakdown of continuum field theory

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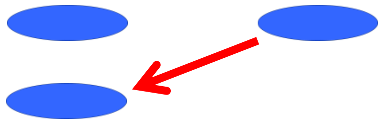
- Recurrences



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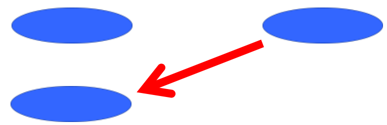
- Recurrences



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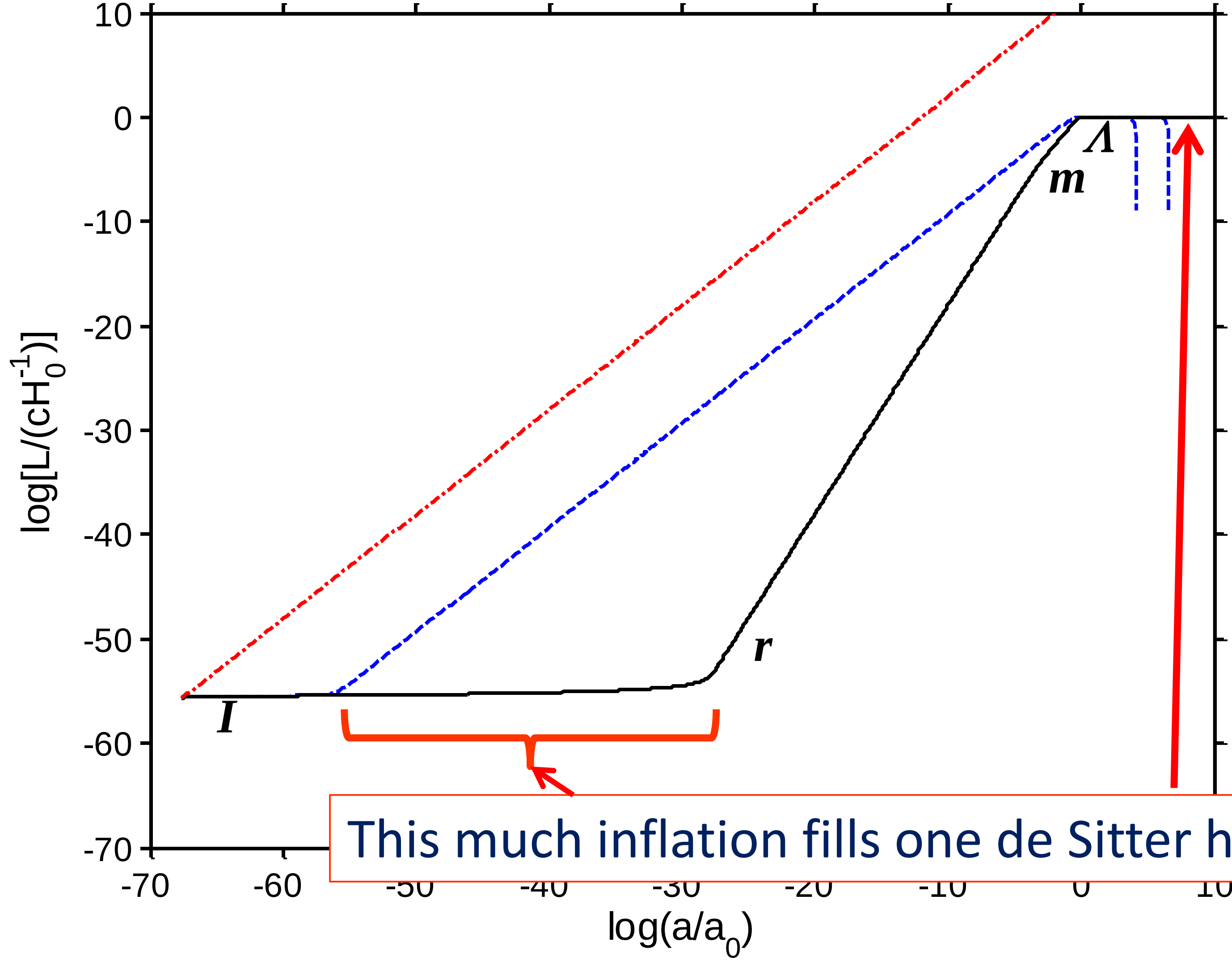
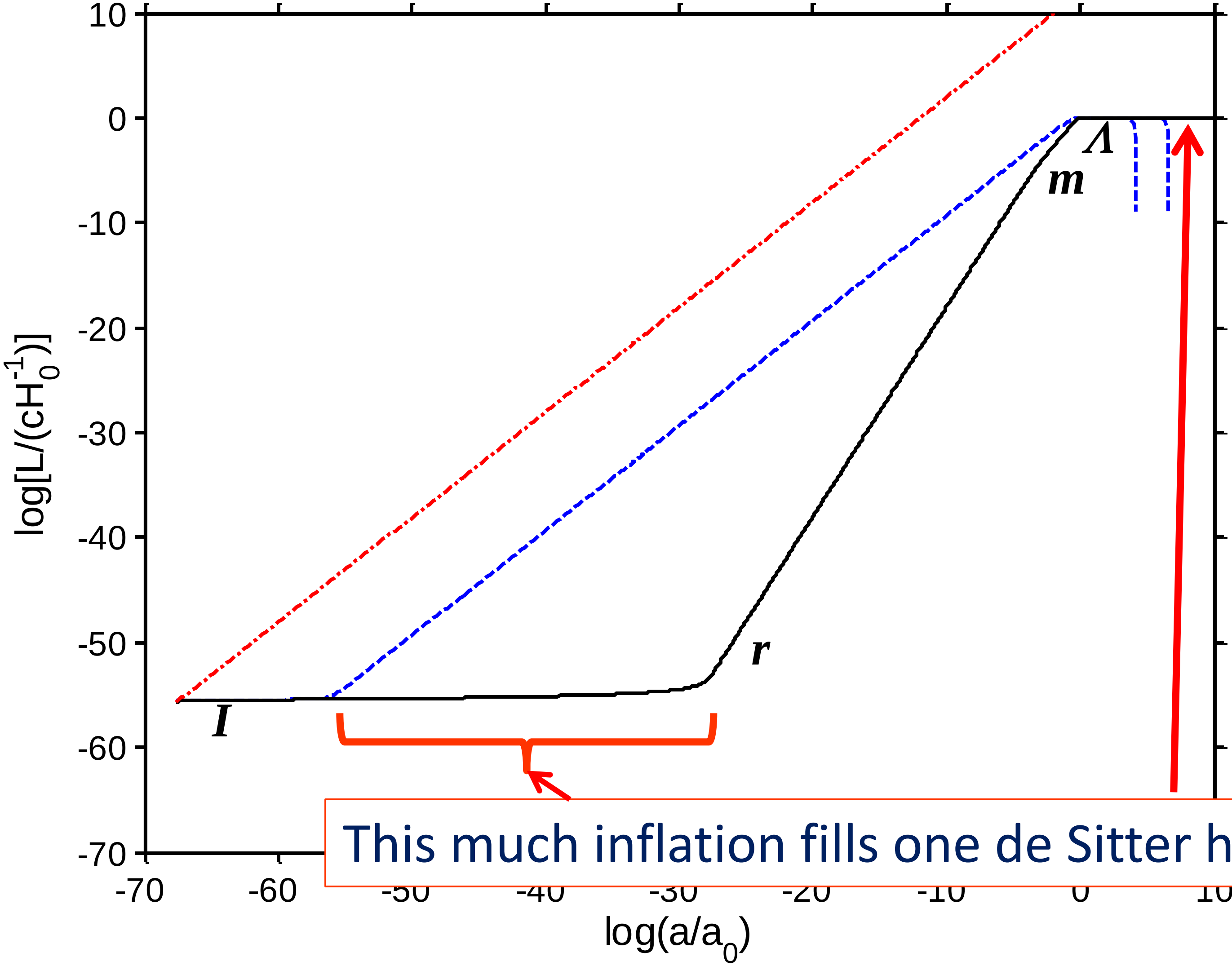


This much inflation fills one de Sitter horizon

(discuss "superluminal expansion")



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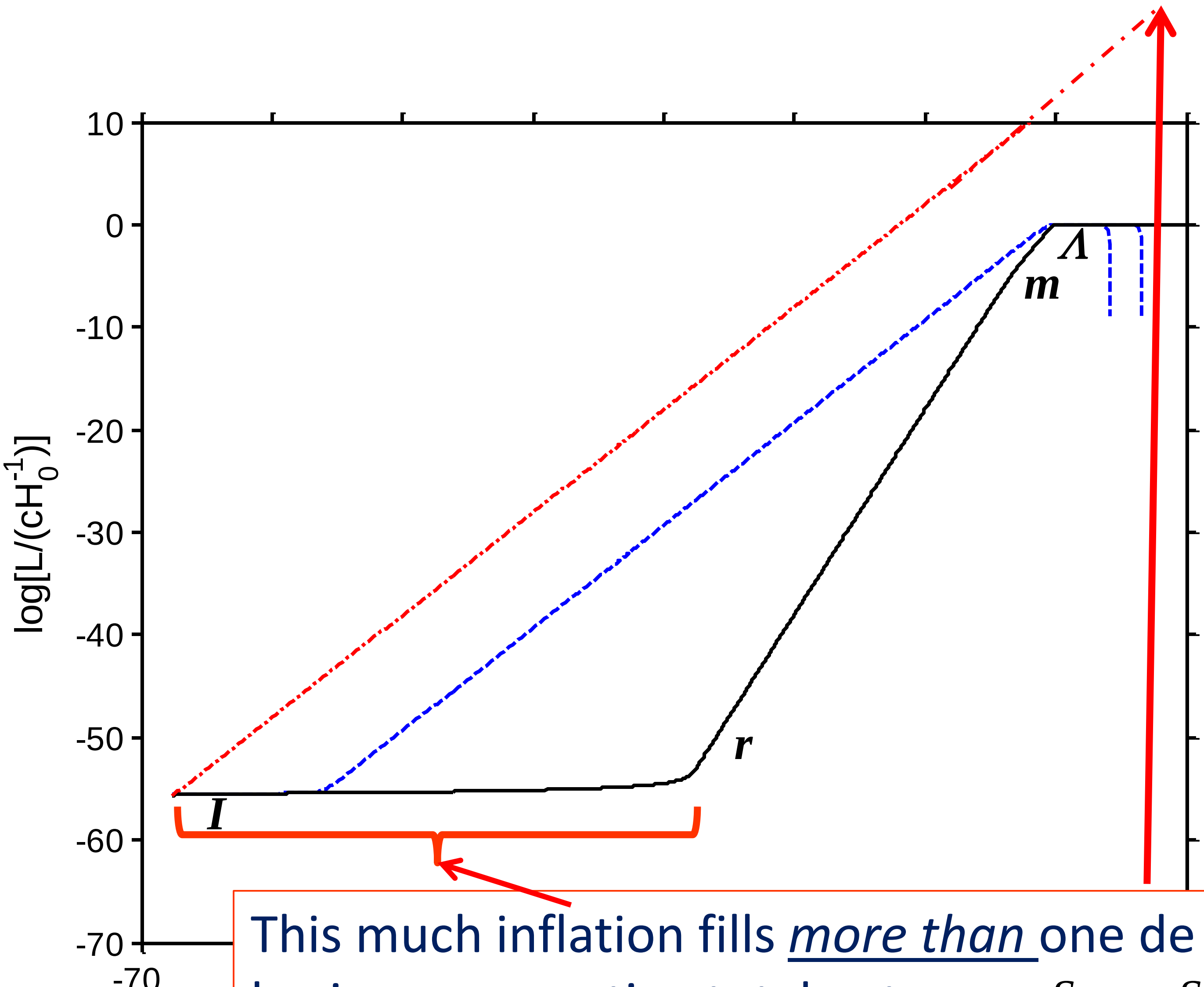
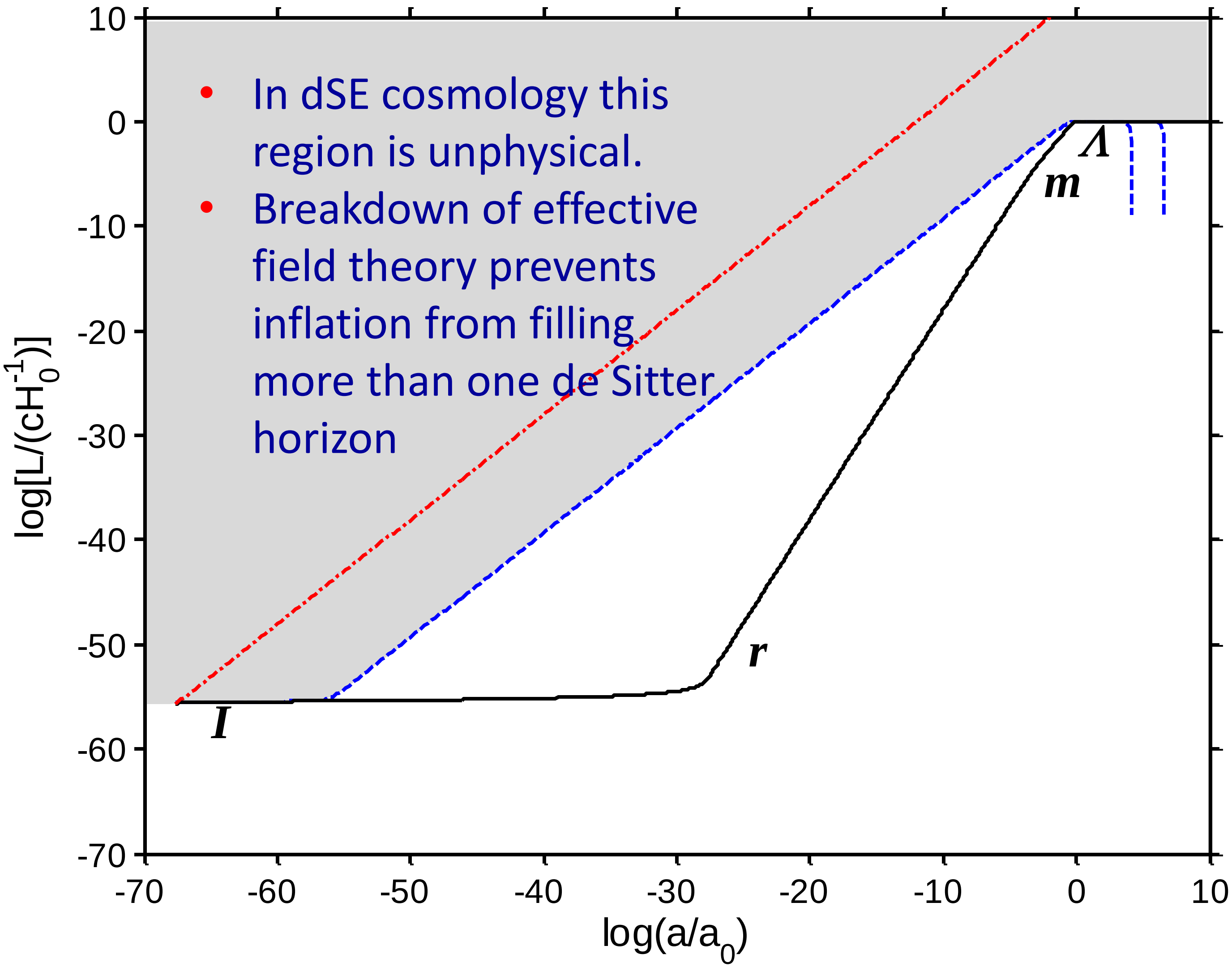
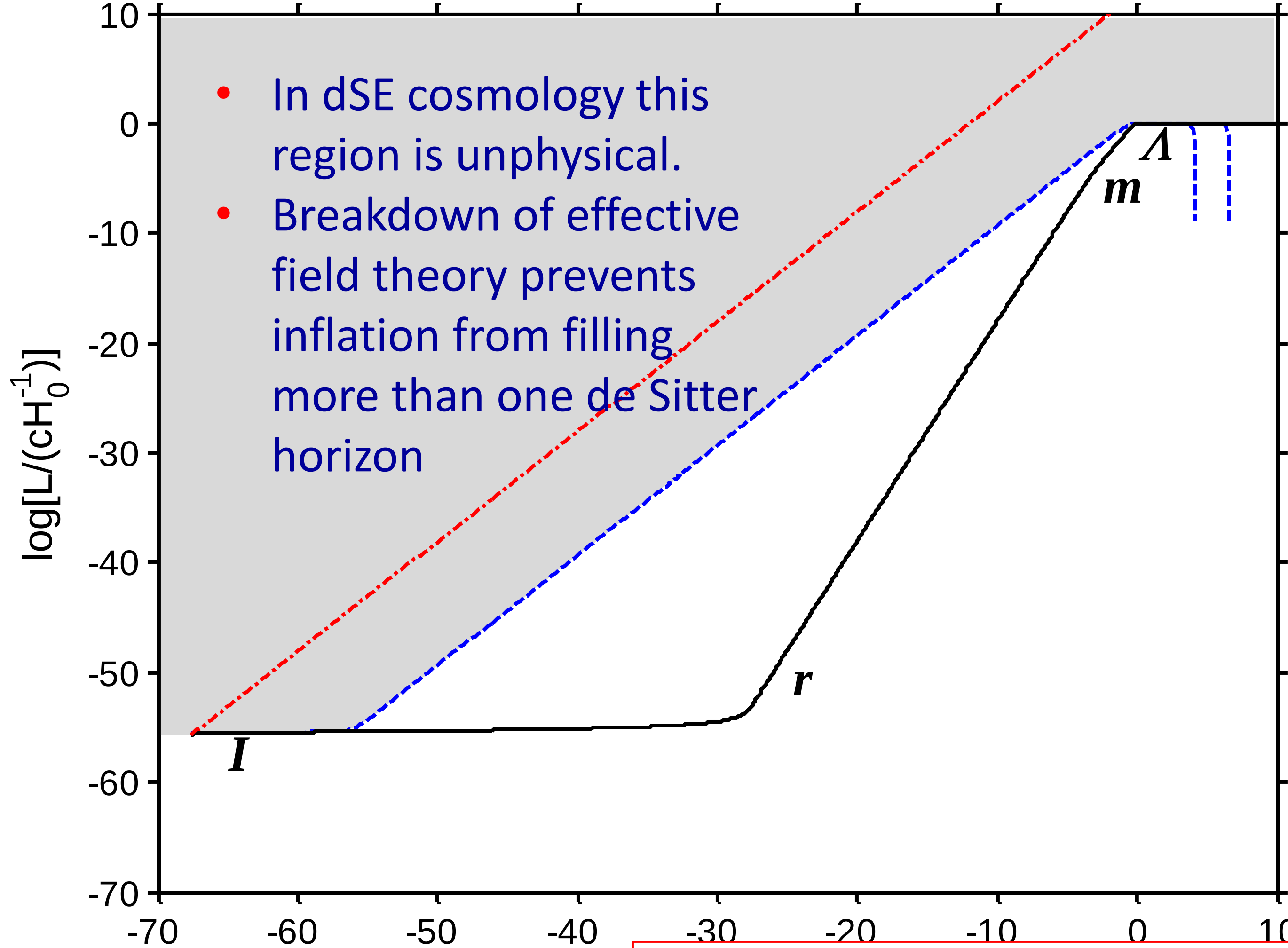


This much inflation fills *more than* one de Sitter horizon, generating total entropy $> S_{Max} = S_{\Lambda}$ and affecting regions beyond the horizon of the observer



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



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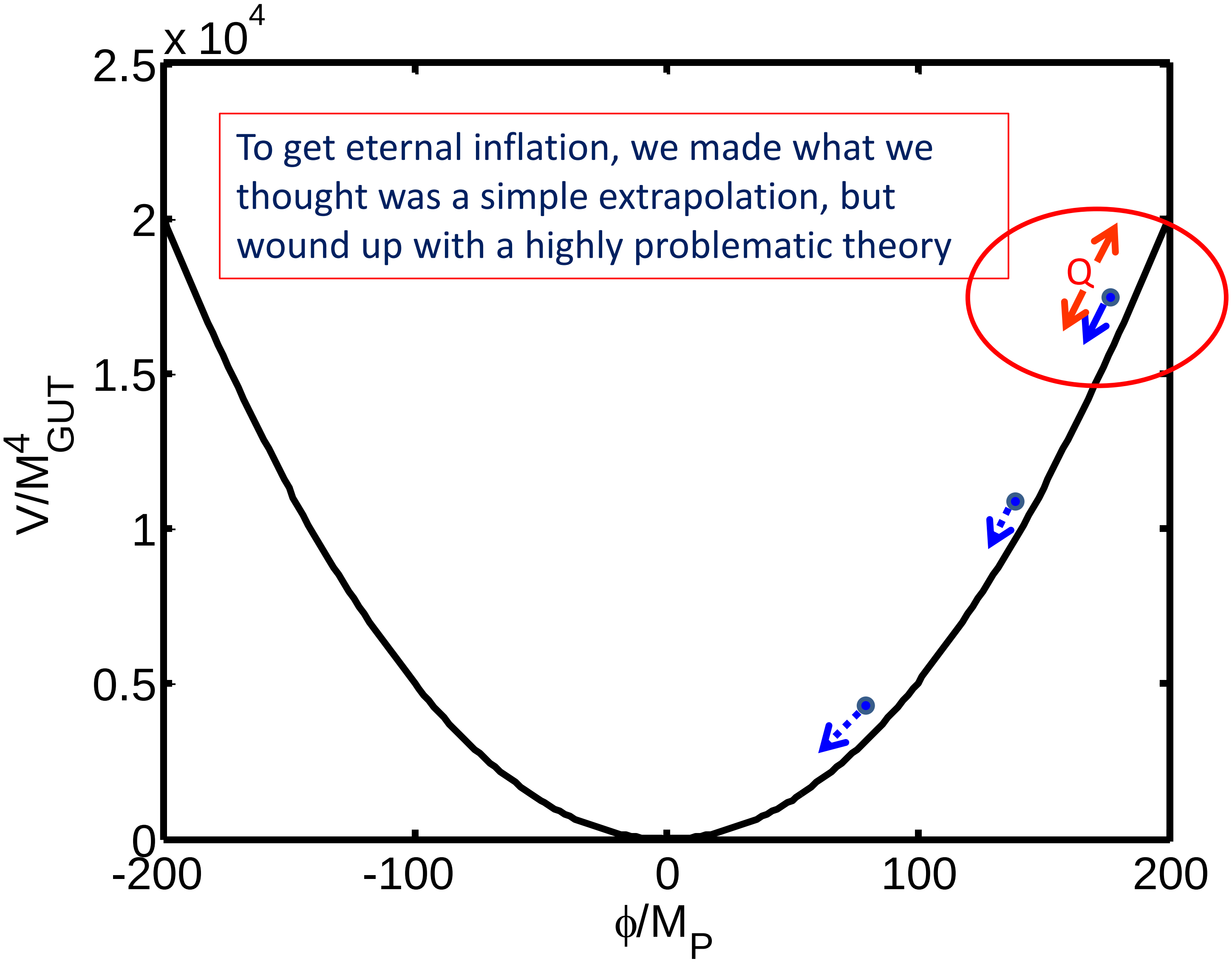
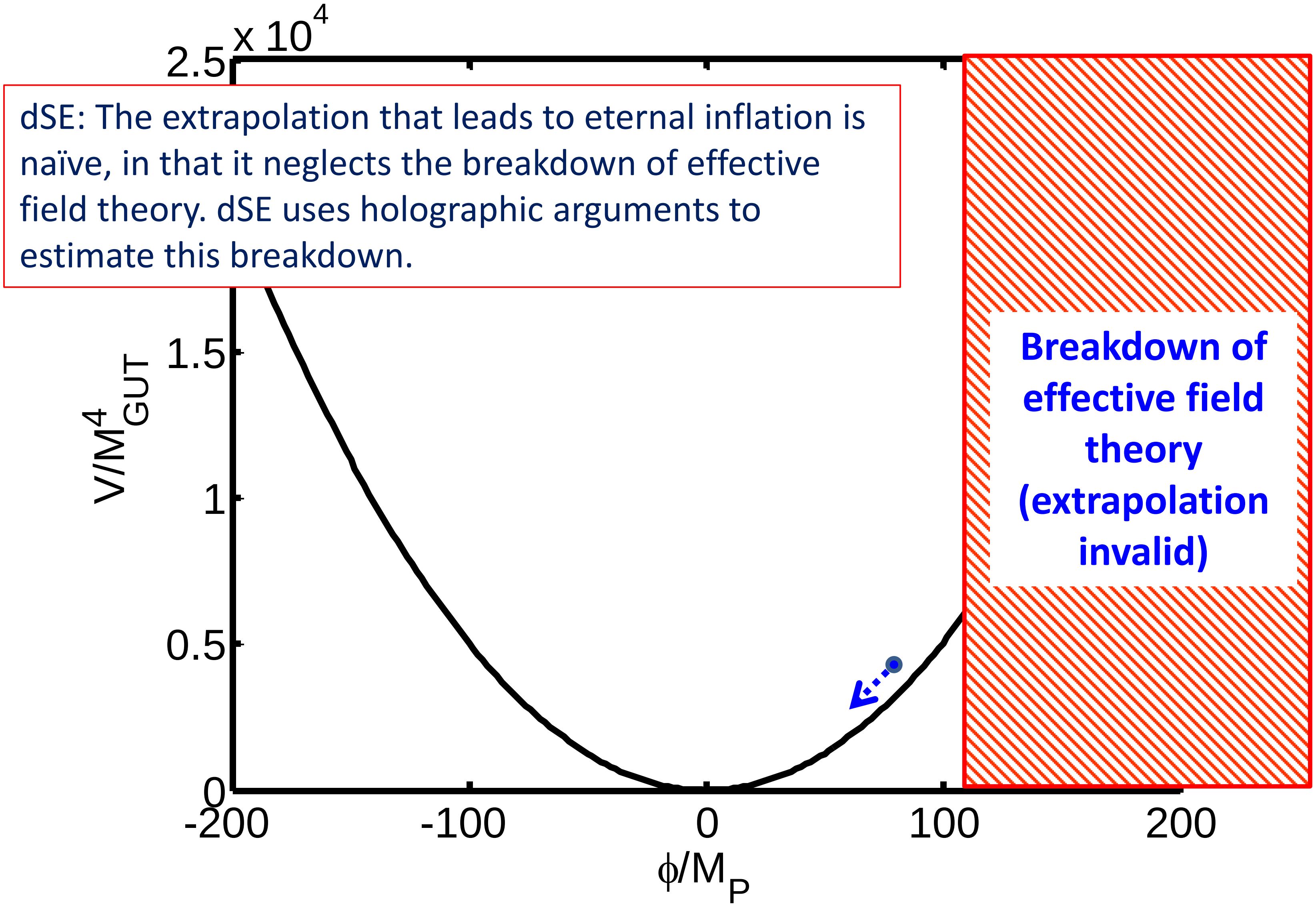
- Breakdown of effective field theory prevents inflation from filling more than one de Sitter horizon

"Equivalent" to Banks-Fischler holographic constraint on number of e-foldings of inflation (D Phillips & AA in prep)


To get eternal inflation, we made what we thought was a simple extrapolation, but wound up with a highly problematic theory
x 10^4
2.5
2
1.5
1
0.5
0
V/M^4_GUT
-200
-100
0
100
200
φ/M_P
Q


x 10^4
2.5
1.5
1
0.5
0
V/M^4_GUT
-200
-100
0
100
200
ϕ/M_P
dSE: The extrapolation that leads to eternal inflation is naïve, in that it neglects the breakdown of effective field theory. dSE uses holographic arguments to estimate this breakdown.
Breakdown of effective field theory (extrapolation invalid)

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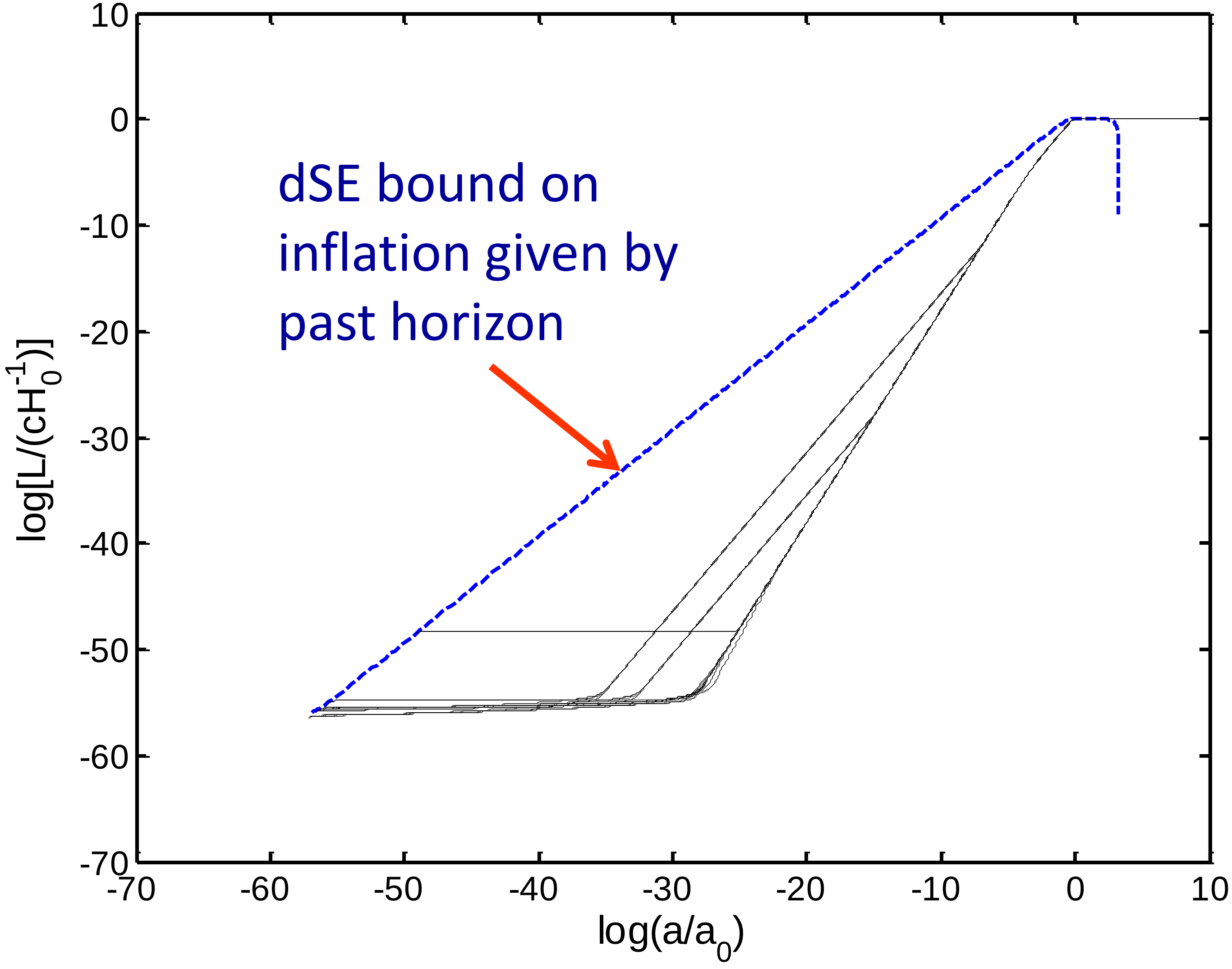
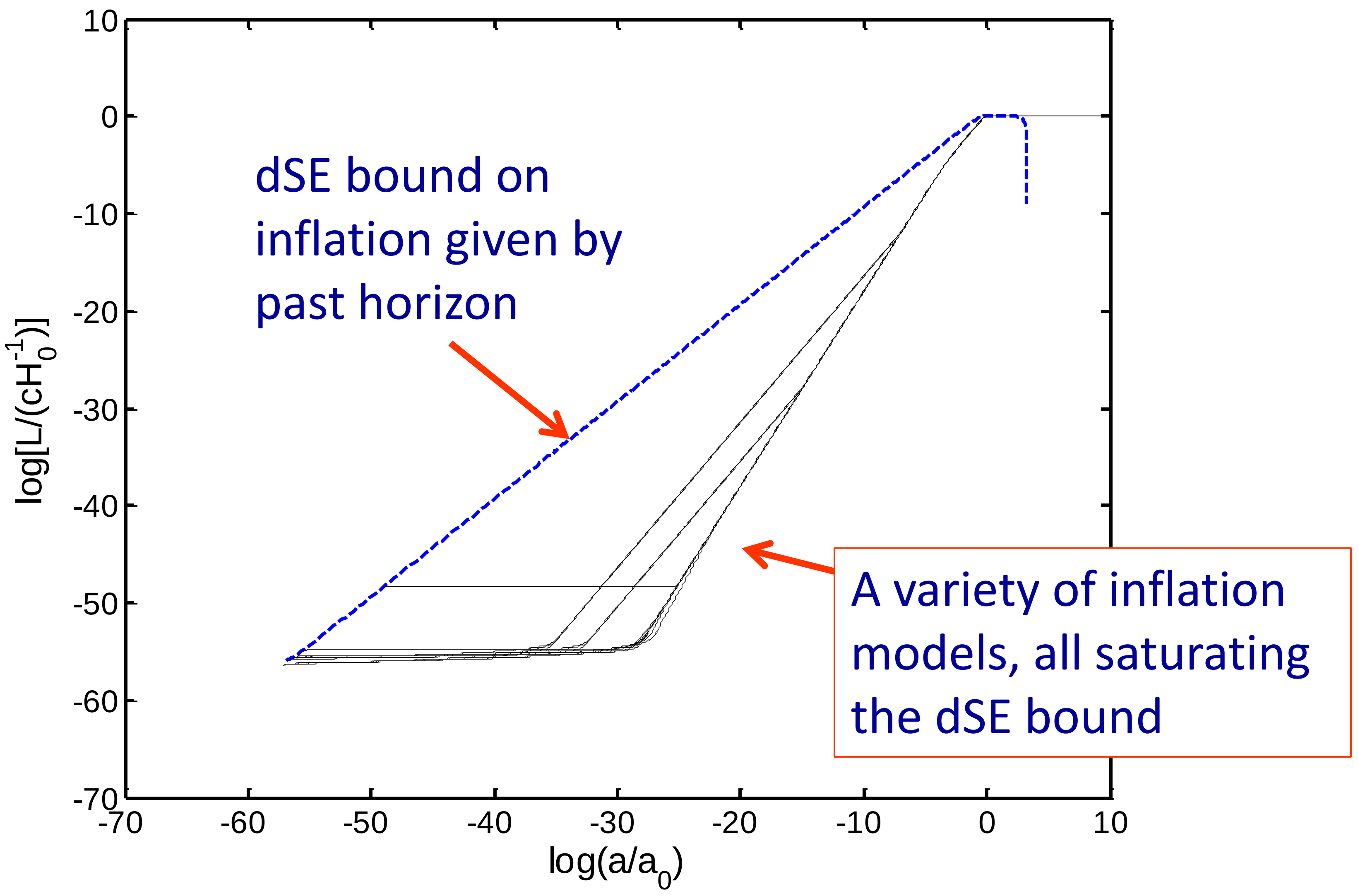
Large ρ_I exponentially favored ➔ saturation of dSE bound



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


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

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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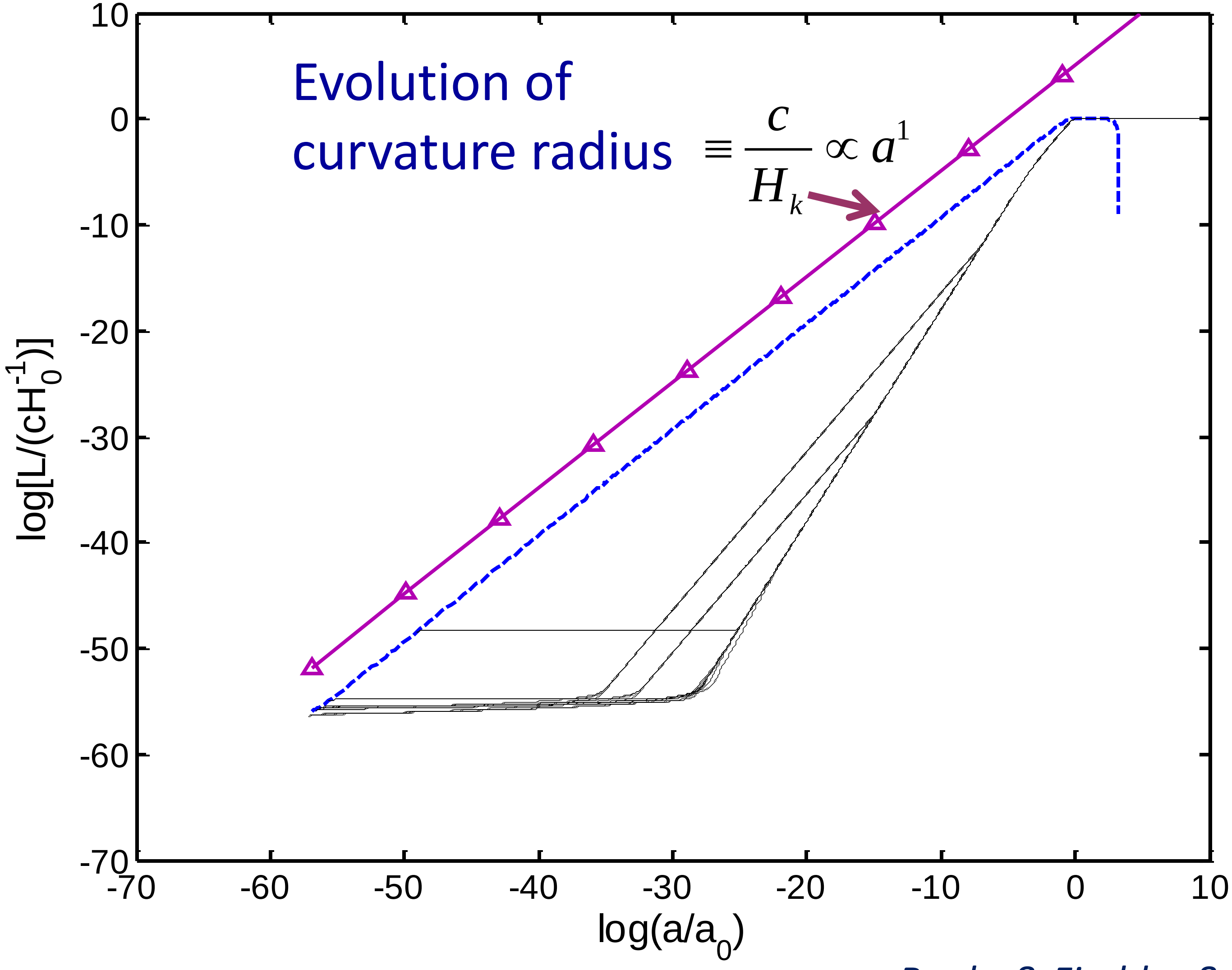
dSE Cosmology and cosmic curvature

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

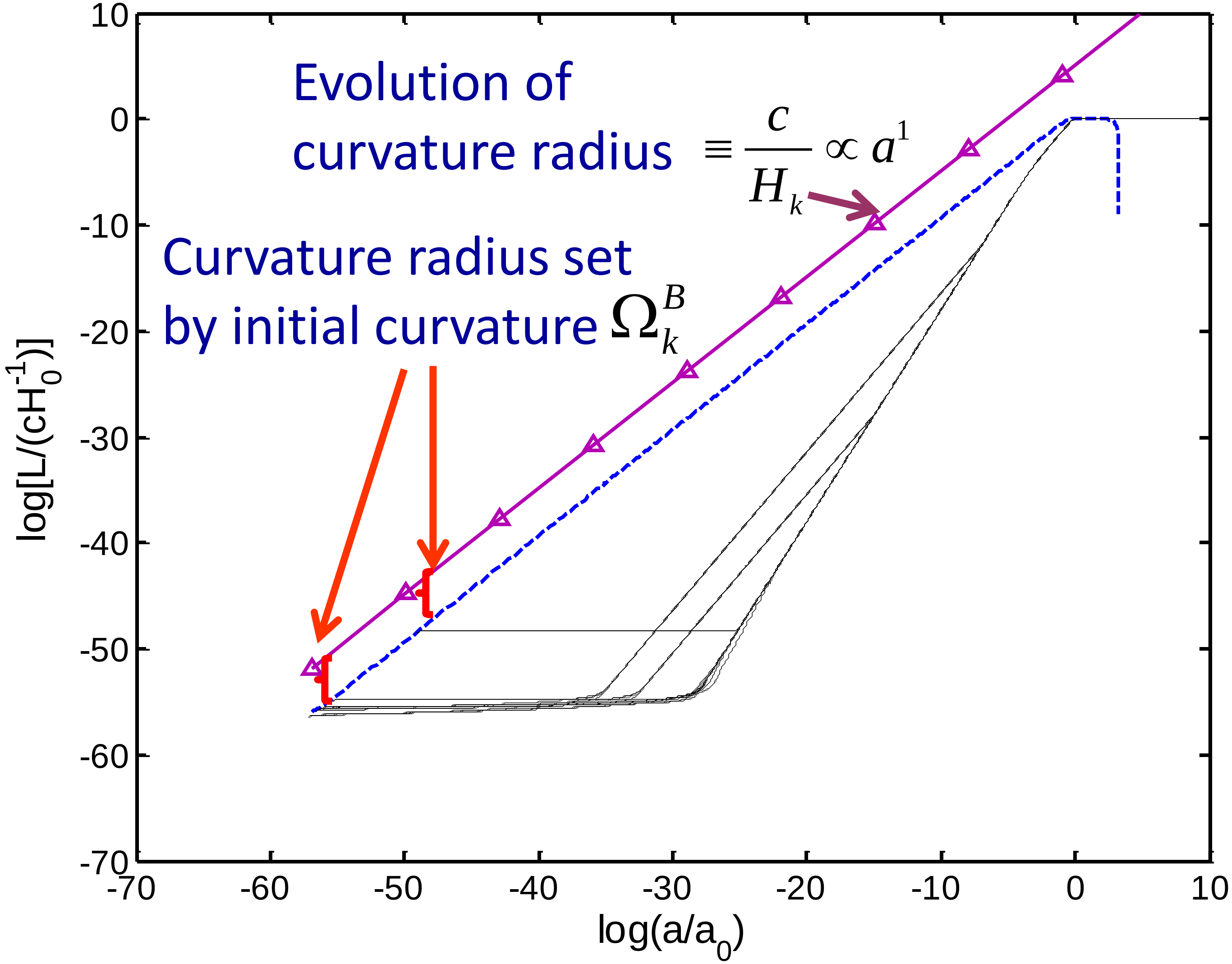
Friedmann Eqn.

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

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



Banks & Fischler & Dyson et al.



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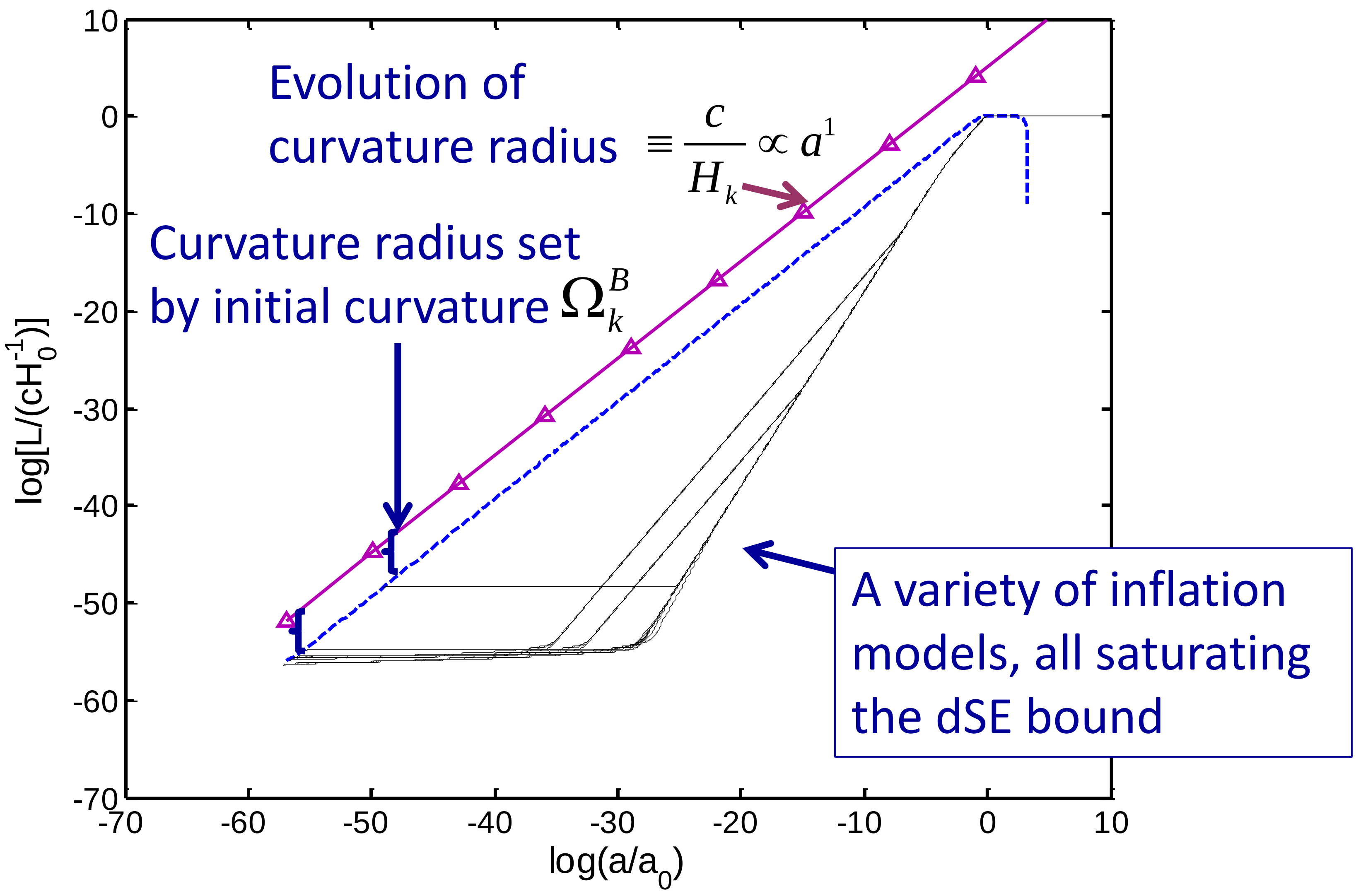

Evolution of
curvature radius $\equiv \frac{c}{H_k} \propto a^1$
Curvature radius set
by initial curvature Ω_k^B
A variety of inflation
models, all saturating
the dSE bound
log[L/(cH$_0^{-1}$)]
log(a/a$_0$)
10
0
-10
-20
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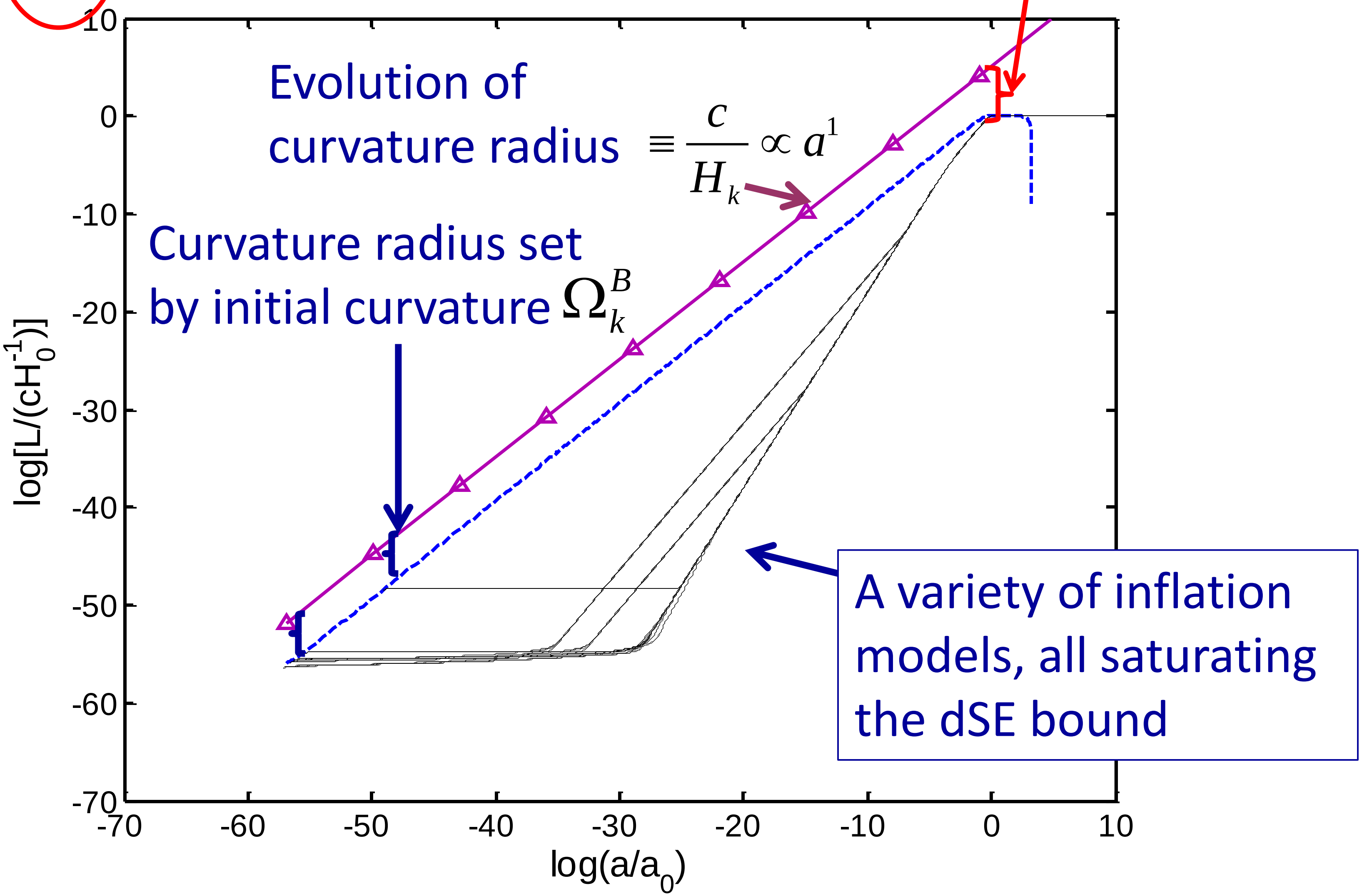
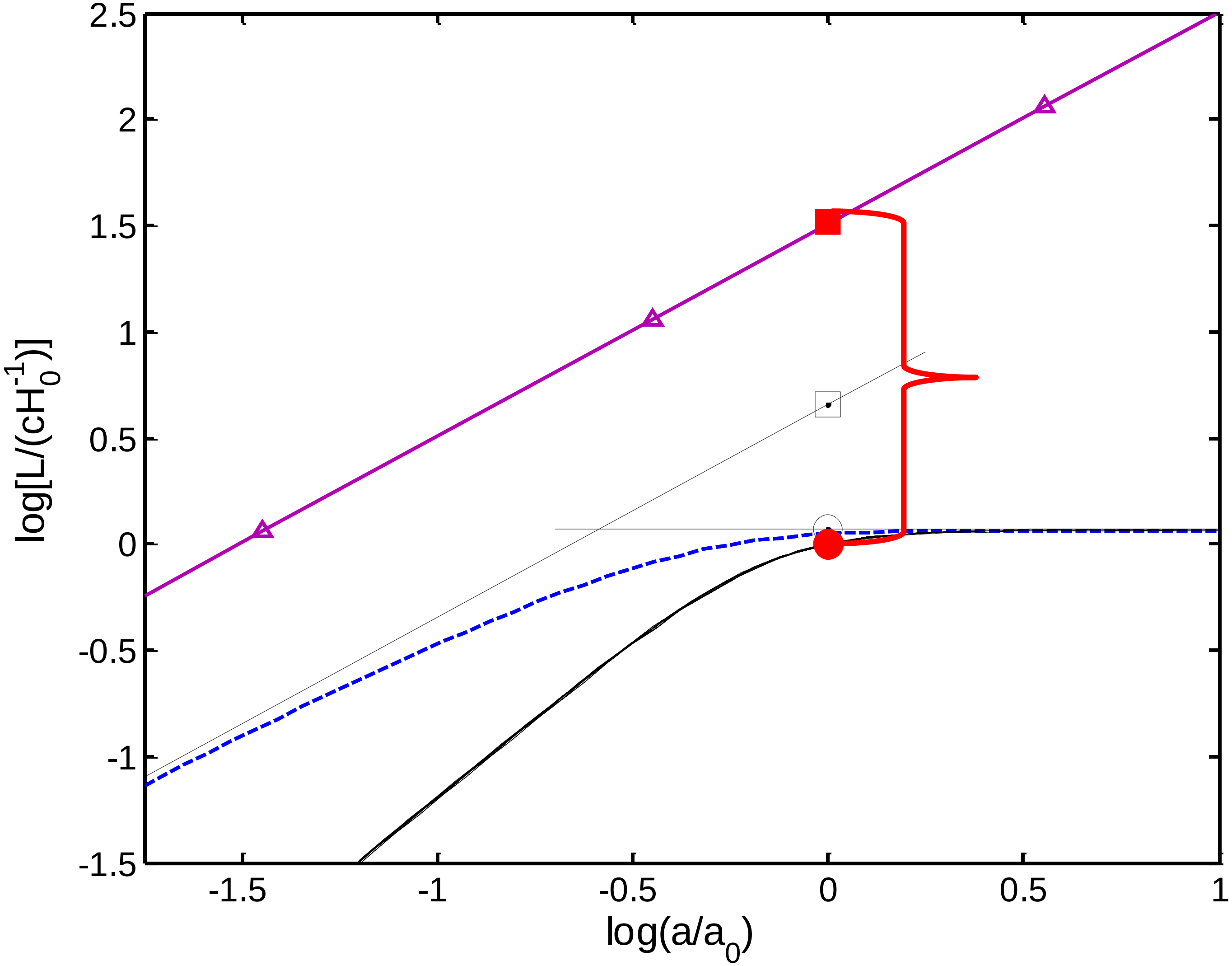
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10

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





AA: arXiv:1104.3315

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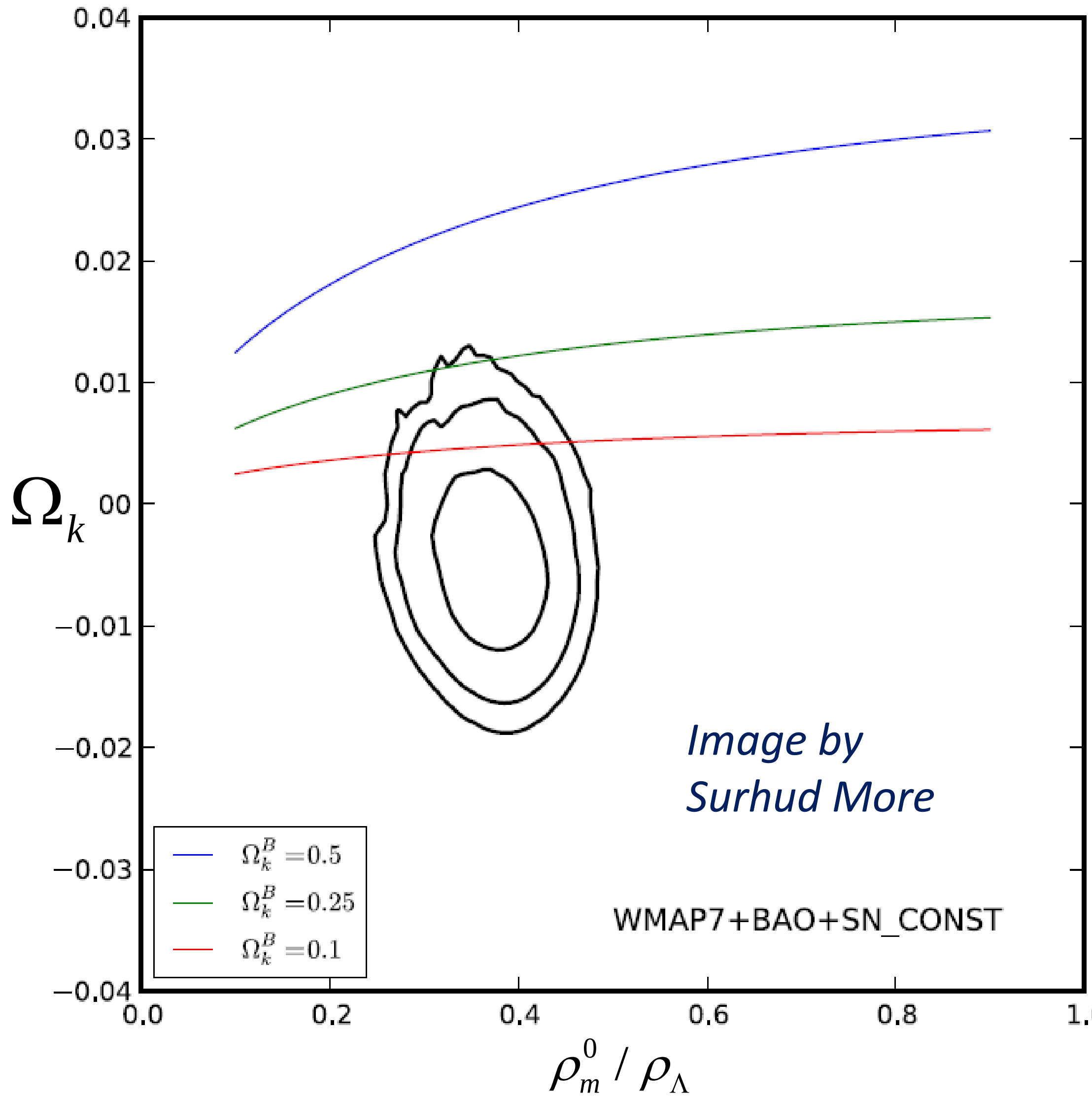
$$\Omega_k = \frac{1}{g^2} \frac{\Omega_k^B}{\left(\frac{\rho_m^0}{\rho_\Lambda} + \frac{\rho_k^0}{\rho_\Lambda} + 1\right)}$$

where

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

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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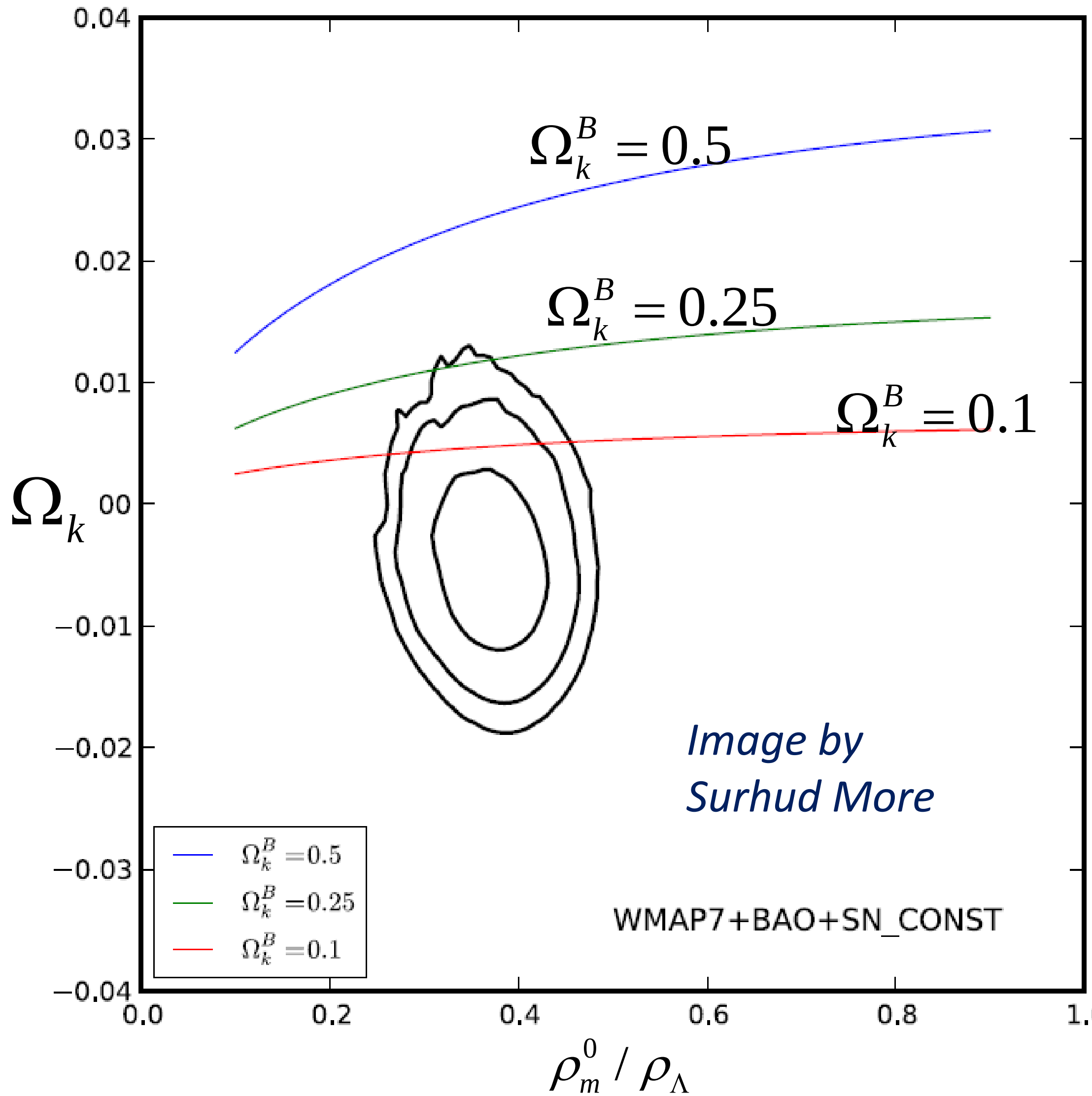

Image by Surhud More

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

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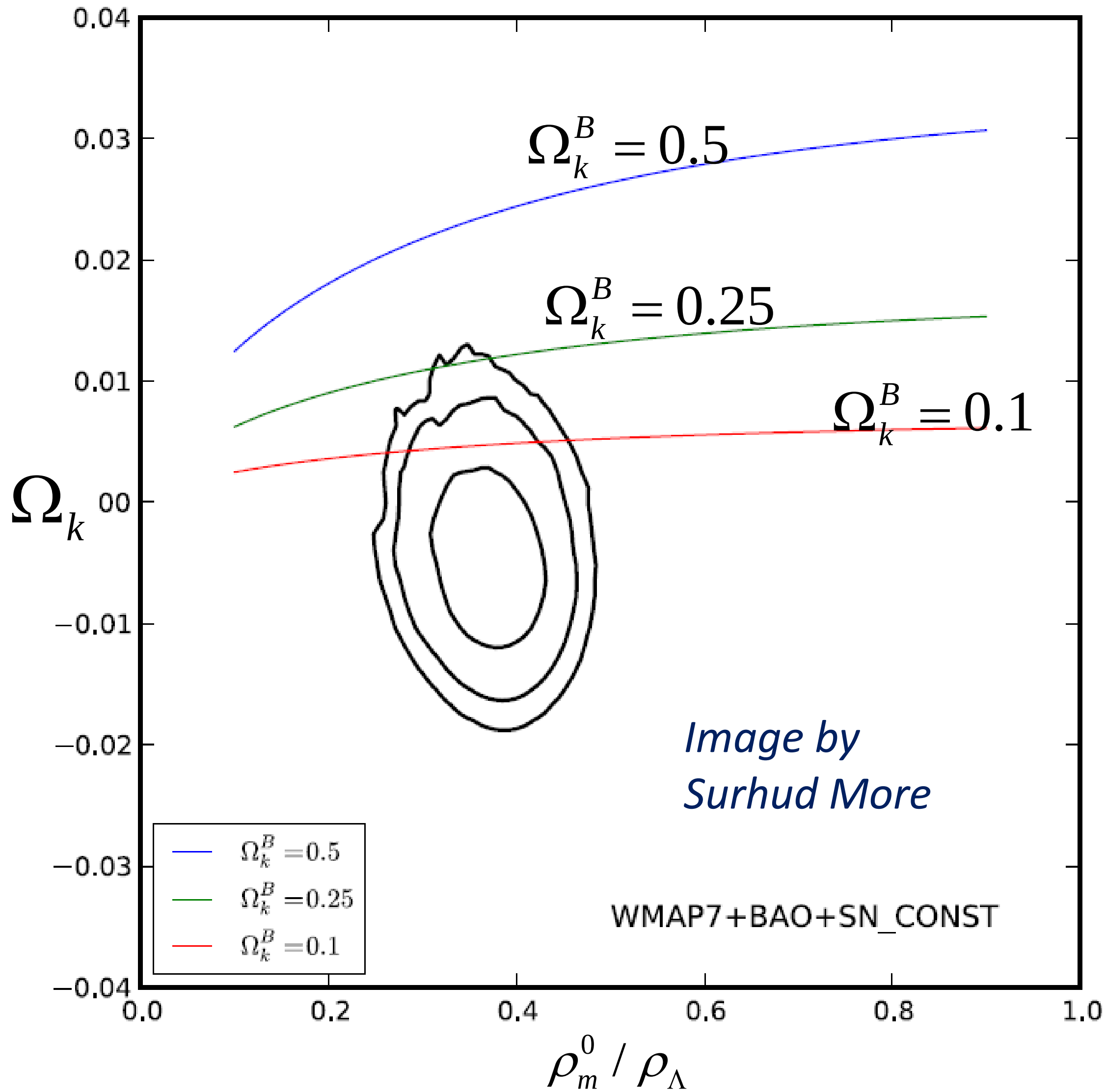

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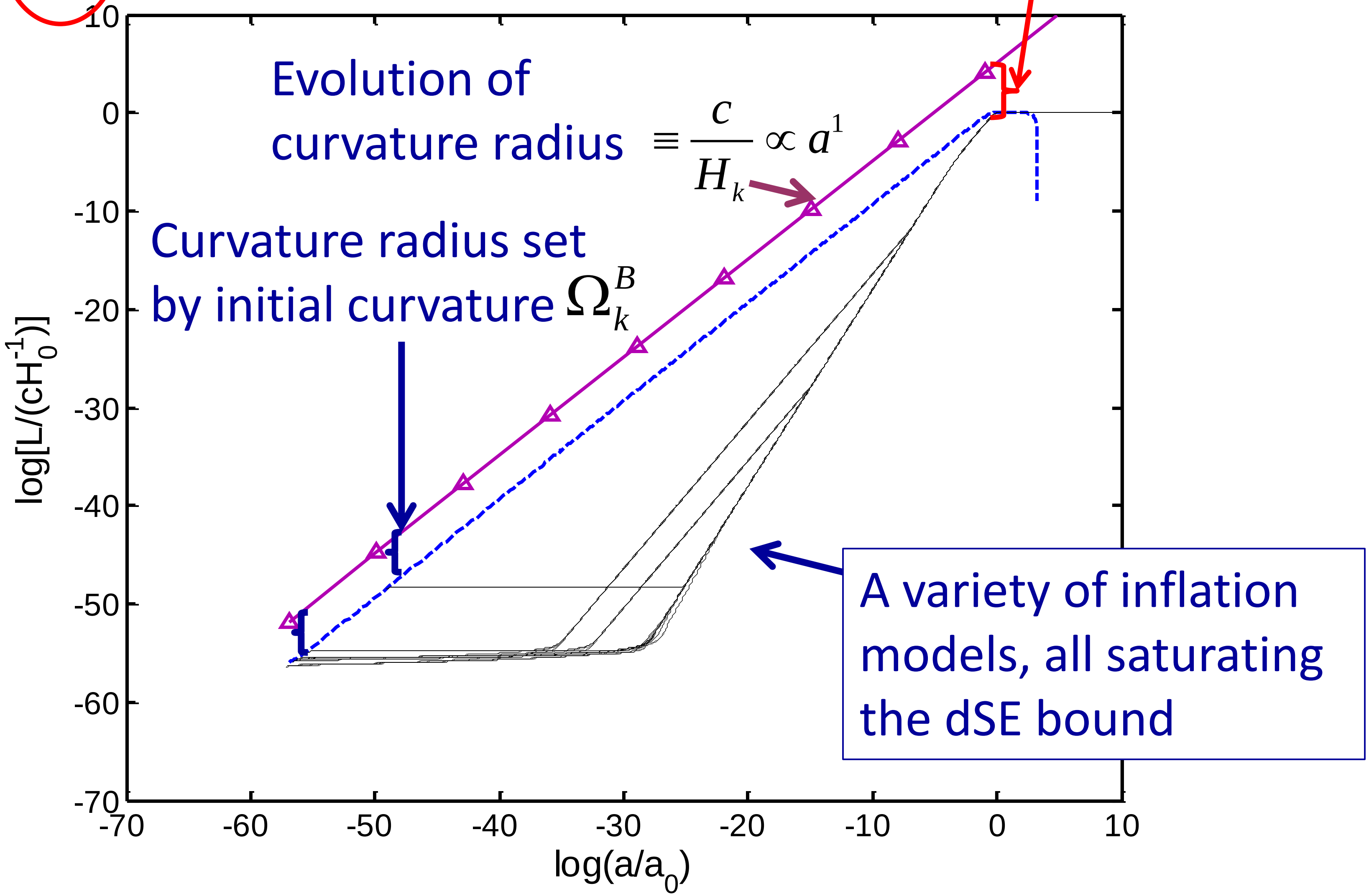

Conclusions

- 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 (plus, no initial conditions problem)
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