Cosmic Inflation

Reflections on Motivations, Accomplishments and future opportunities

Andreas Albrecht
Center for Quantum Mathematics and Physics (QMAP)
and
Department of Physics
UC Davis

Advances in Theoretical Cosmology in Light of Data
NORDITA
July 21, 2017

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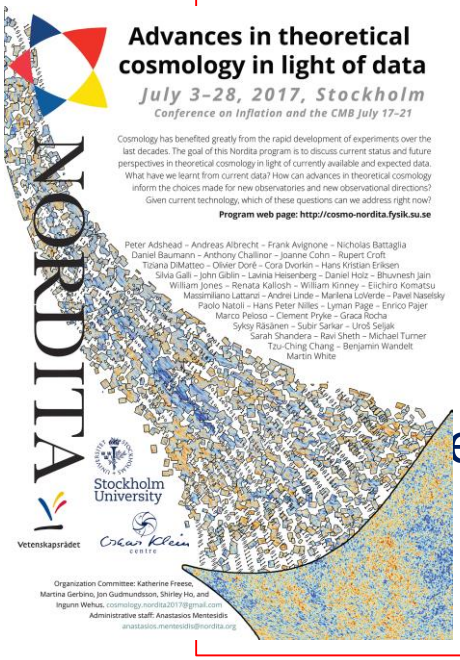

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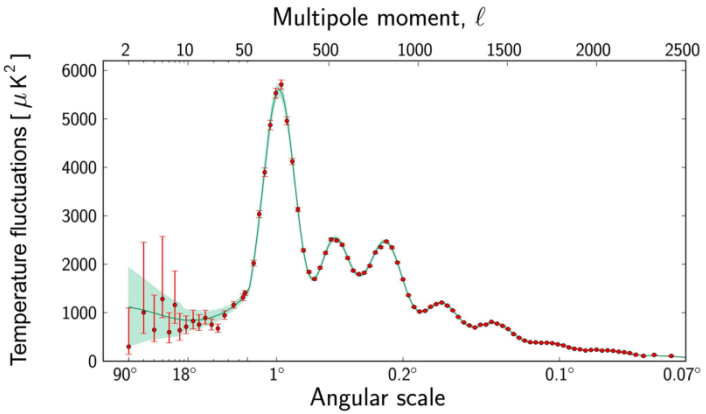
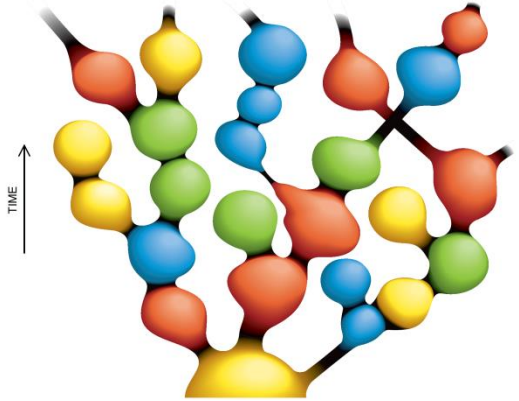
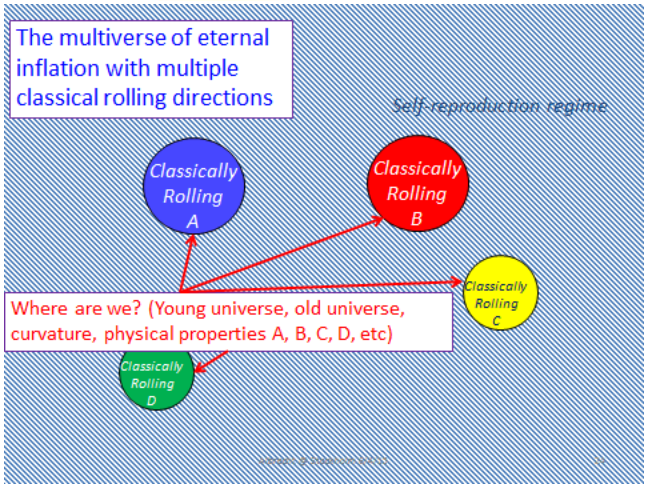
Cosmic Inflation:

Consumers & Producers







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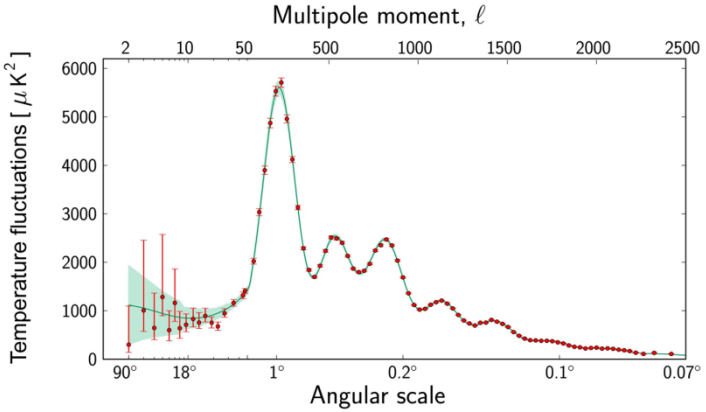

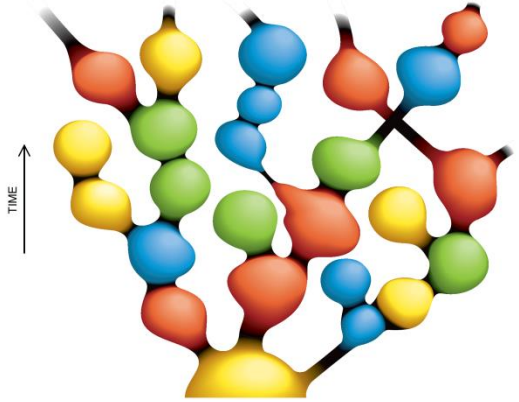

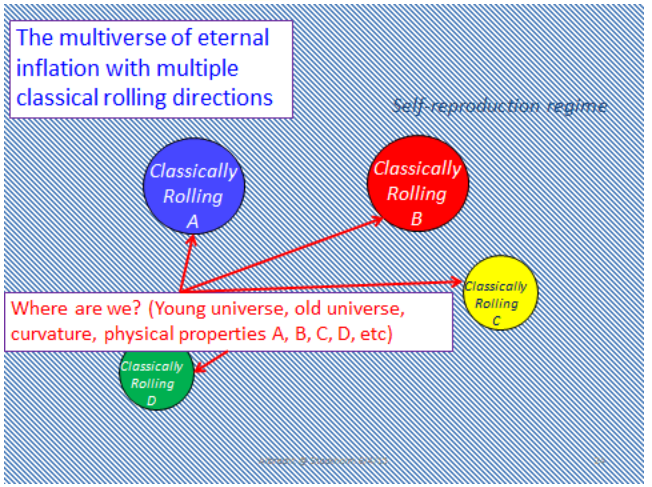

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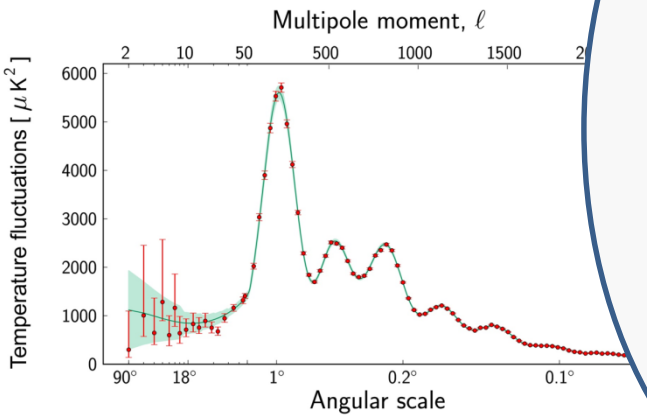

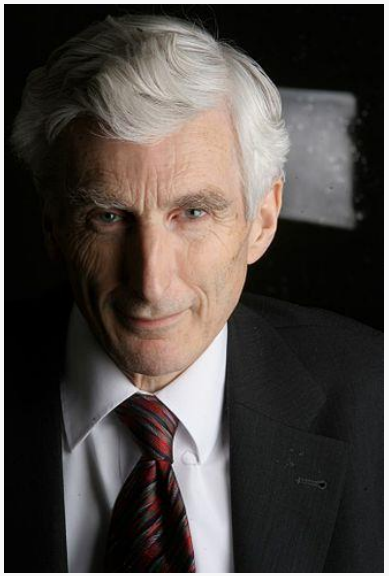

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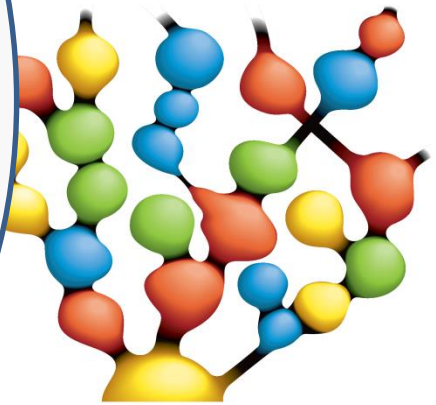

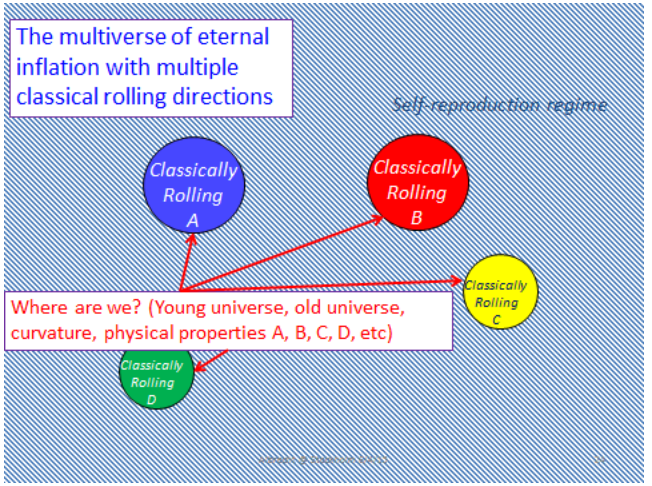

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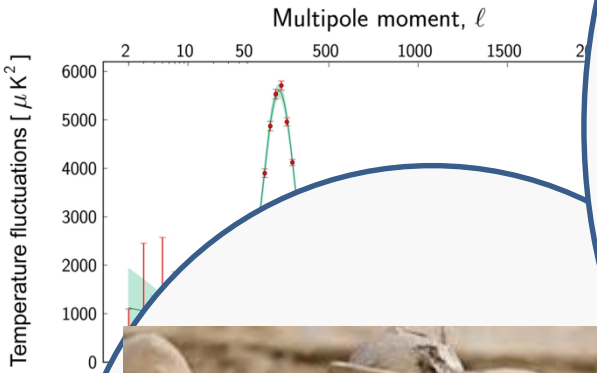

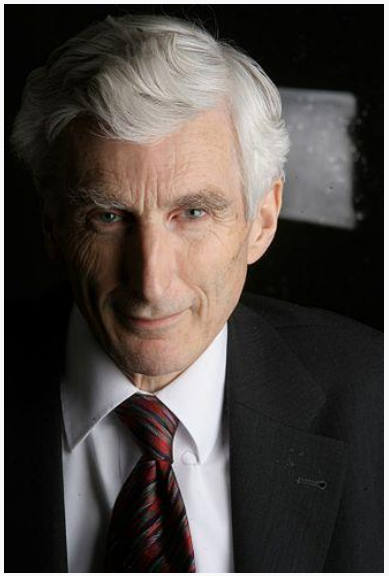

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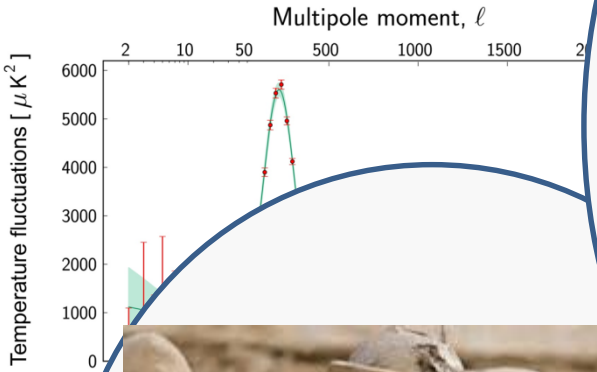

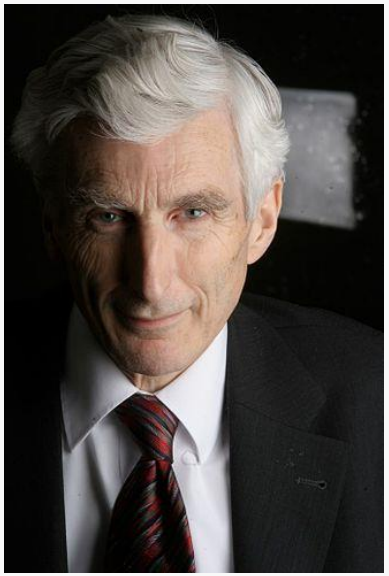

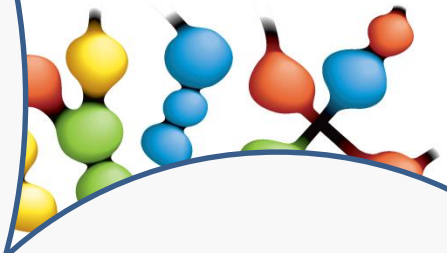

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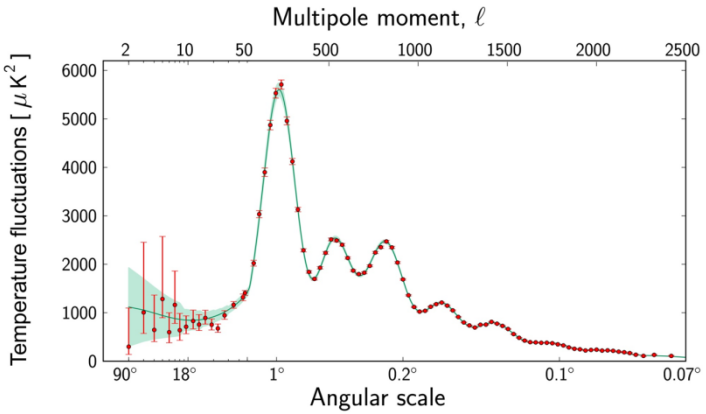
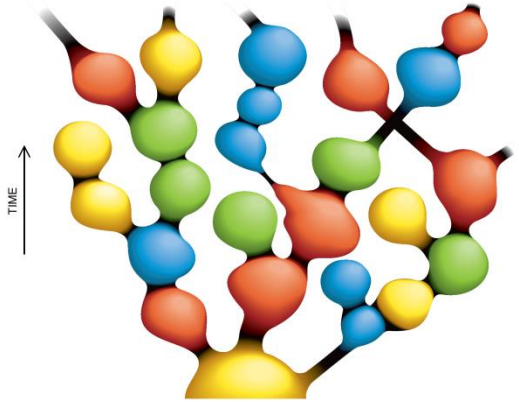
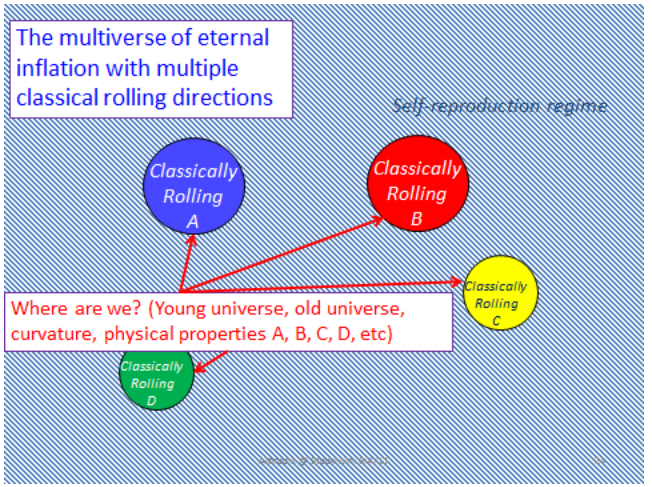
Cosmic Inflation:

Consumers & Producers







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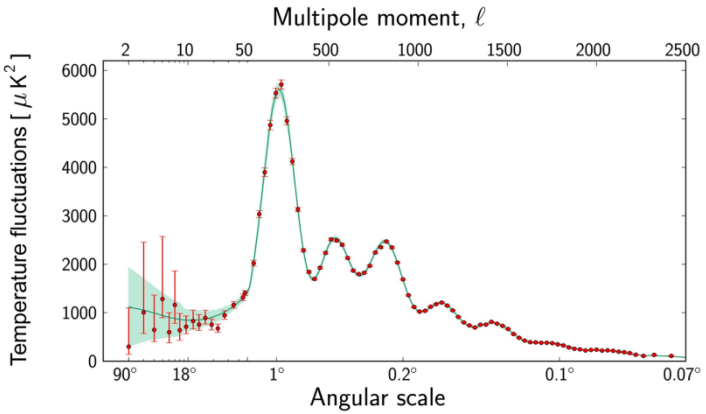

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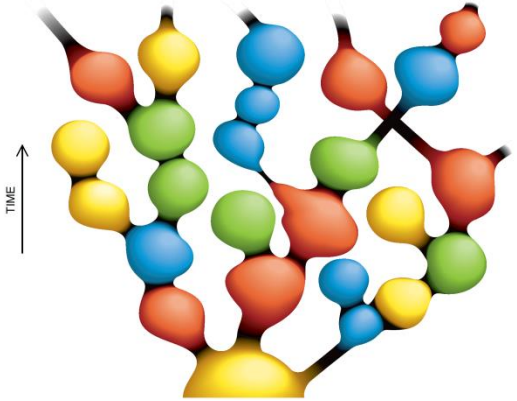

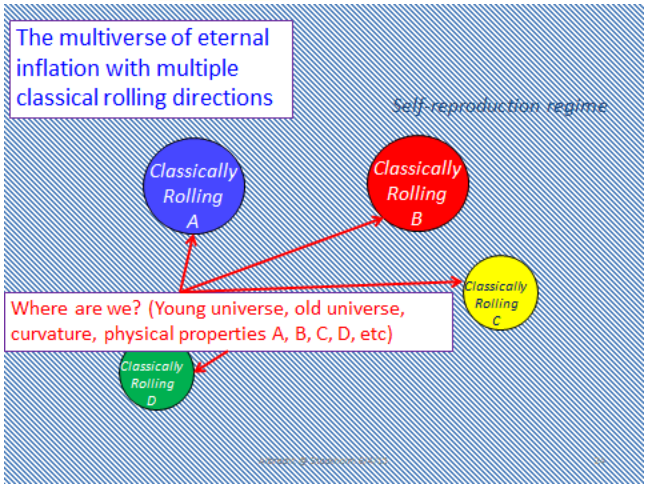

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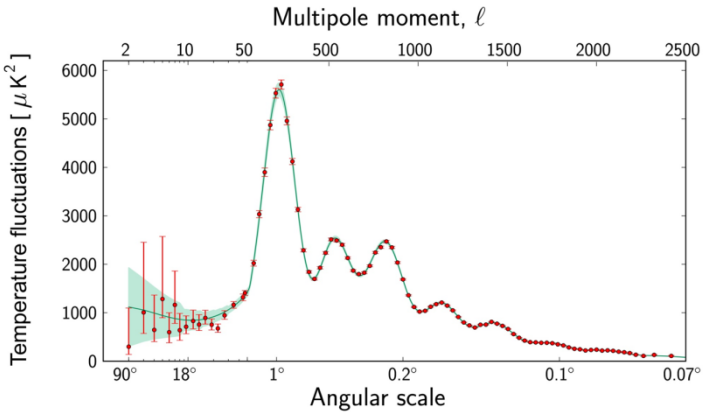

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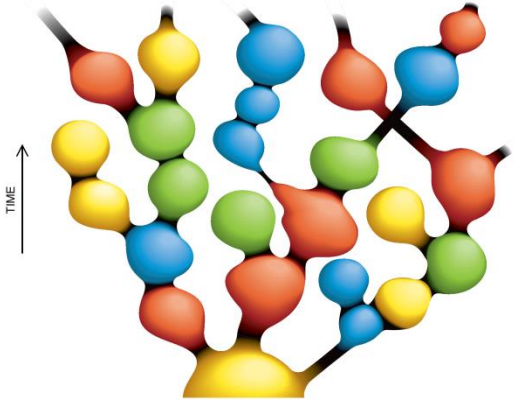

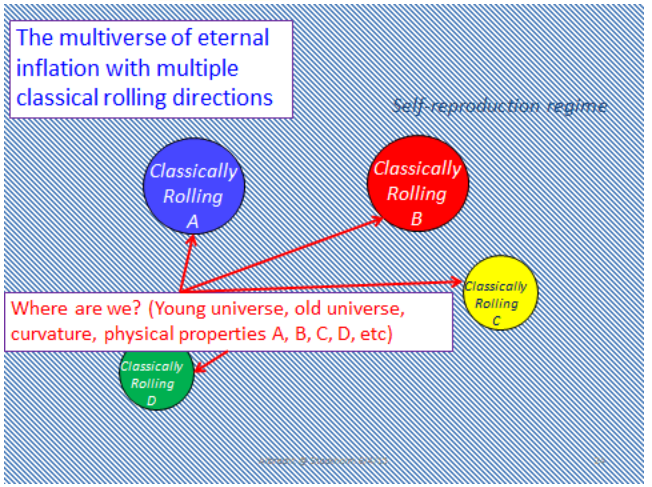

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Outline

A) Big questions about the cosmos

B) Open questions about cosmic inflation
   i) Tuning
      - Entropy perspective
      - Bunch Davies Vacuum
   ii) Measures

C) Connections to modern research into quantum gravity/fundamental physics

D) Connections to cosmological observations

E) Great opportunities ahead!!

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What is a good theory of cosmic initial conditions?

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➔ Something that makes us feel happy (!)

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(priors)

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e.g. the inflation story so far (re "cosmological puzzles")

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Historical note: Dicke and the cosmological puzzles: https://www.aip.org/history-programs/niels-bohr-library/oral-histories/33931

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We are just groping our way through this

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(compare with particle physicists and "naturalness")

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What is the point of cosmic inflation?

Guth (1981) The point of cosmic inflation is to solve cosmological tuning problems (and the monopole problem)

PHY 981

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

Alan H. Guth*
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 11 August 1980)

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

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Starobinsky (1981) The point of cosmic inflation is to "help find" a unique highly symmetric (highly tuned!) initial state with no singularity

A NEW TYPE OF ISOTROPIC COSMOLOGICAL MODELS WITHOUT SINGULARITY

A.A. STAROBINSKY

Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, England [1]
and The Landau Institute for Theoretical Physics, The Academy of Sciences, Moscow, 117334, USSR [2]

Received 11 January 1980

The Einstein equations with quantum one-loop contributions of conformally covariant matter fields are shown to admit a class of nonsingular isotropic homogeneous solutions that correspond to a picture of the Universe being initially in the most symmetric (de Sitter) state.

the above mentioned condition then we shall obtain one possible answer to the fundamental question stated in the first paragraph of this paper. It is worth noting that the evolution of the Universe need not follow a "generic" solution, it may well be described just by this unique one, at least initially.

Eqs. (2), (3) were first considered in ref. [1] and then investigated in detail in ref. [2] in the case $K = 0$.

Volume 108B, number 6 PHYSICS LETTERS 4 February 1982

A NEW INFLATIONARY UNIVERSE SCENARIO: A POSSIBLE SOLUTION OF THE HORIZON, FLATNESS, HOMOGENEITY, ISOTROPY AND PRIMORDIAL MONOPOLE PROBLEMS

A.D. LINDE
Lebedev Physical Institute, Moscow 117924, USSR

Received 29 October 1981

A new inflationary universe scenario is suggested, which is free of the shortcomings of the previous one and provides a possible solution of the horizon, flatness, homogeneity and isotropy problems in cosmology, and also a solution of the primordial monopole problem in grand unified theories.

There is now considerable interest in the cosmological consequences of symmetry breaking phase transitions, which occur in grand unified theories (GUTs) with the decrease of temperature at the very early stages of the evolution of the universe [1–3]. These phase transitions typically are strongly first order [4,5]. The lifetime of the supercooled symmetry tained in a very interesting paper of Guth [12], where it is shown that the existence of a sufficiently long period of exponential expansion (inflation) in the early universe would provide a natural solution of the horizon and flatness problems in cosmology and of the primordial monopole problem in grand unified theories [13].

VOLUME 48, NUMBER 17 PHYSICAL REVIEW LETTERS 26 APRIL 1982

Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking

Andreas Albrecht and Paul J. Steinhardt
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 25 January 1982)

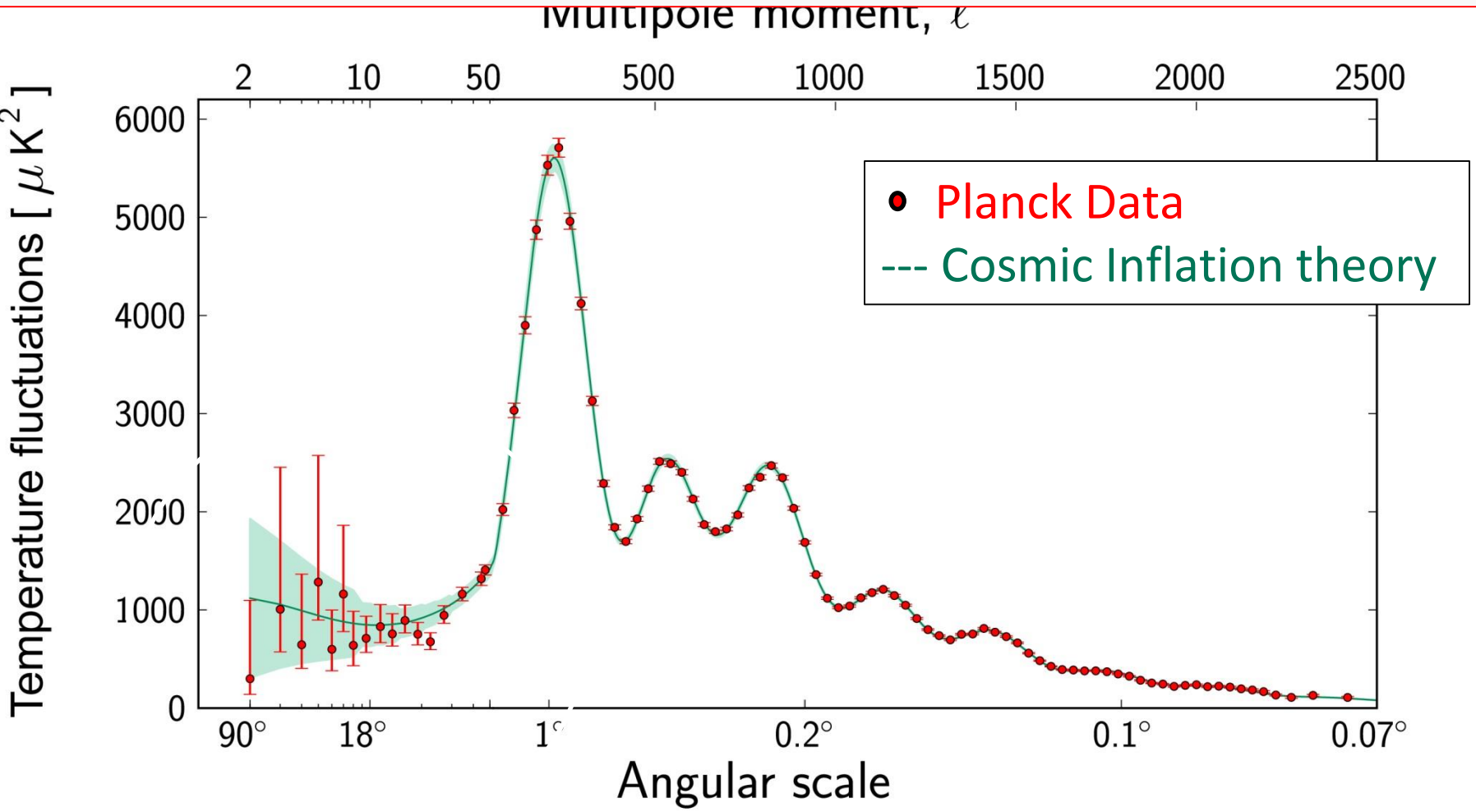
The treatment of first-order phase transitions for standard grand unified theories is shown to break down for models with radiatively induced spontaneous symmetry breaking. It is argued that proper analysis of these transitions which would take place in the early history of the universe can lead to an explanation of the cosmological homogeneity, flatness, and monopole puzzles.

PACS numbers: 98.80.Bp, 11.15.Ex, 12.10.En

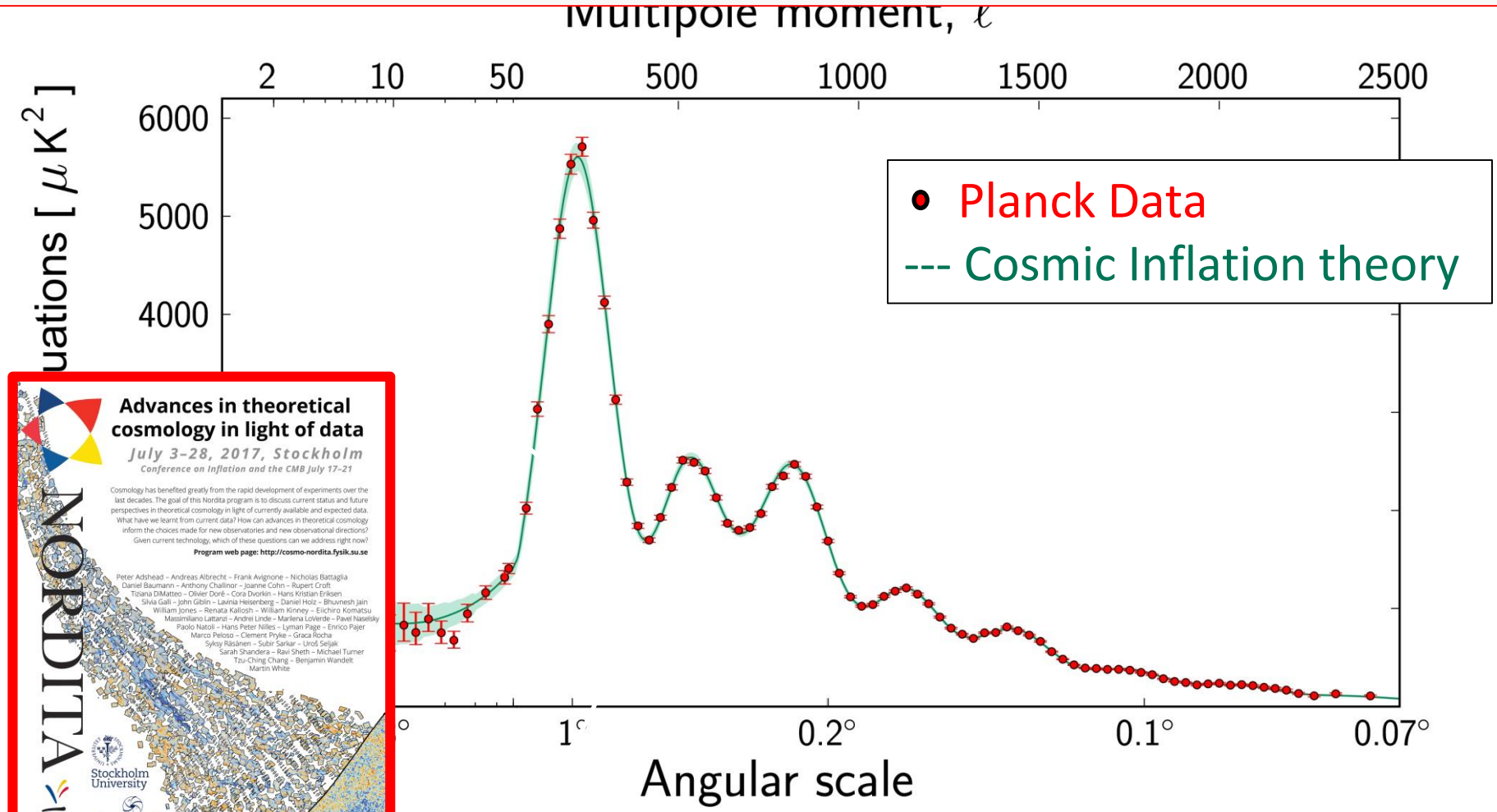
Hot big-bang cosmology depends upon special conditions for the early universe to explain the high degree of homogeneity (the "homogeneity puzzle")[1] and the nearly critical mass density (the "flatness puzzle")[2] found in the universe today. In addition, it has been shown that in typical grand unified theories (GUT's) phase transitions should occur in the early history of the universe which lead to many more magnetic monopoles being produced and surviving to the present epoch than are consistent with experiment (the "monopole puzzle").[3]

In this paper we will argue that first-order phase transitions in a special class of GUT's —models in which the GUT symmetry is broken by radiatively induced corrections to the tree approximation to the effective potential—can lead to a solution to these and other cosmological puzzles. (Models with radiatively induced symmetry breaking, a mechanism discovered by Coleman and Weinberg,[4] will be referred to as CW models.) In particular, we will present results for the standard GUT with a finite-temperature effective (scalar) potential:

Generic Cosmologist (2017): The point of cosmic inflation is to have a theory to fit the data



Generic Cosmologist (2017): The point of cosmic inflation is to have a **new** theory to fit **new** data



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Model Building Paradise ☺

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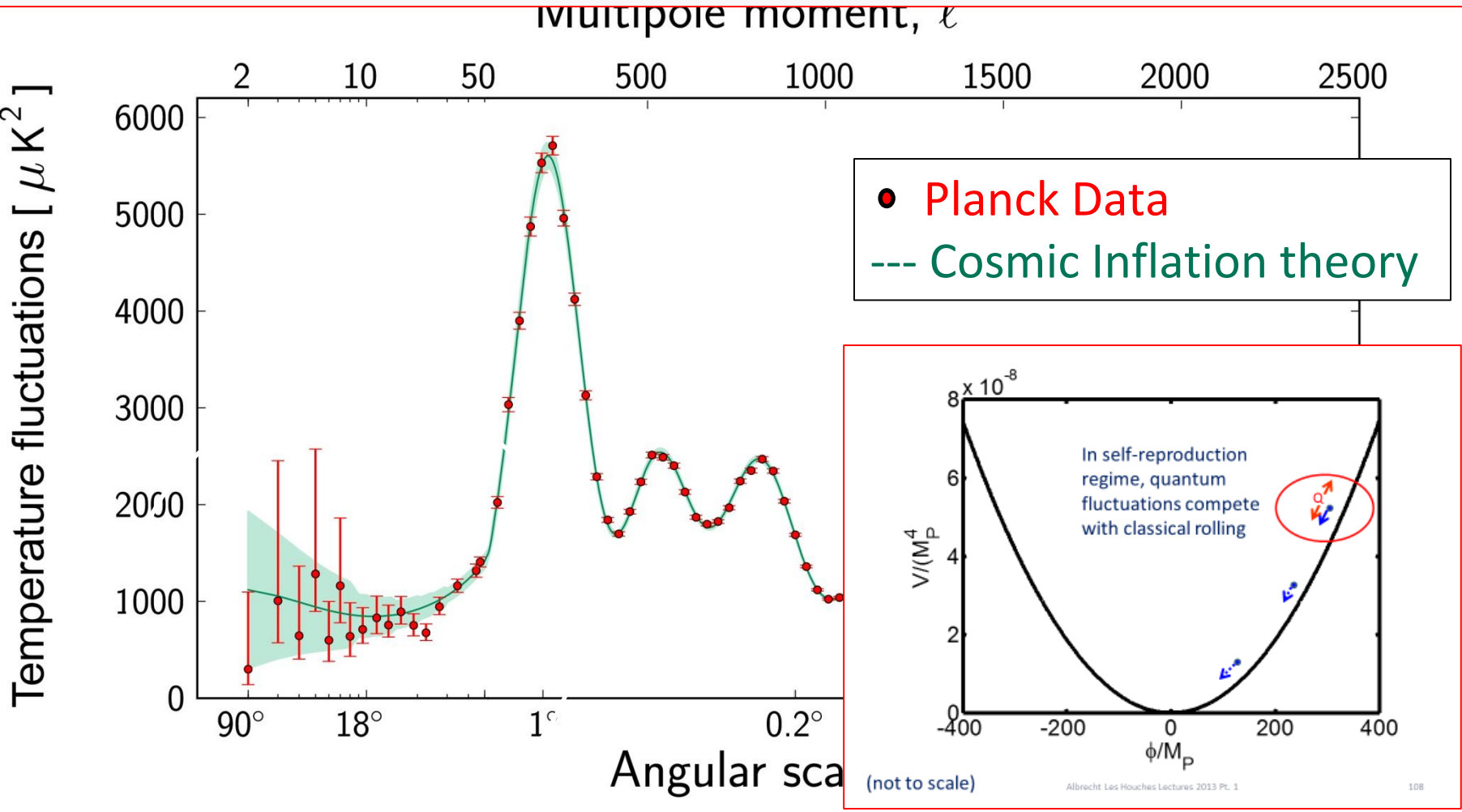
Model Building Paradise ☺

Insturment Building Paradise ☺

Data Analysis Paradise ☺

Starobinsky (2015): Inflation is a way to connect cosmic structure with fundamental physics



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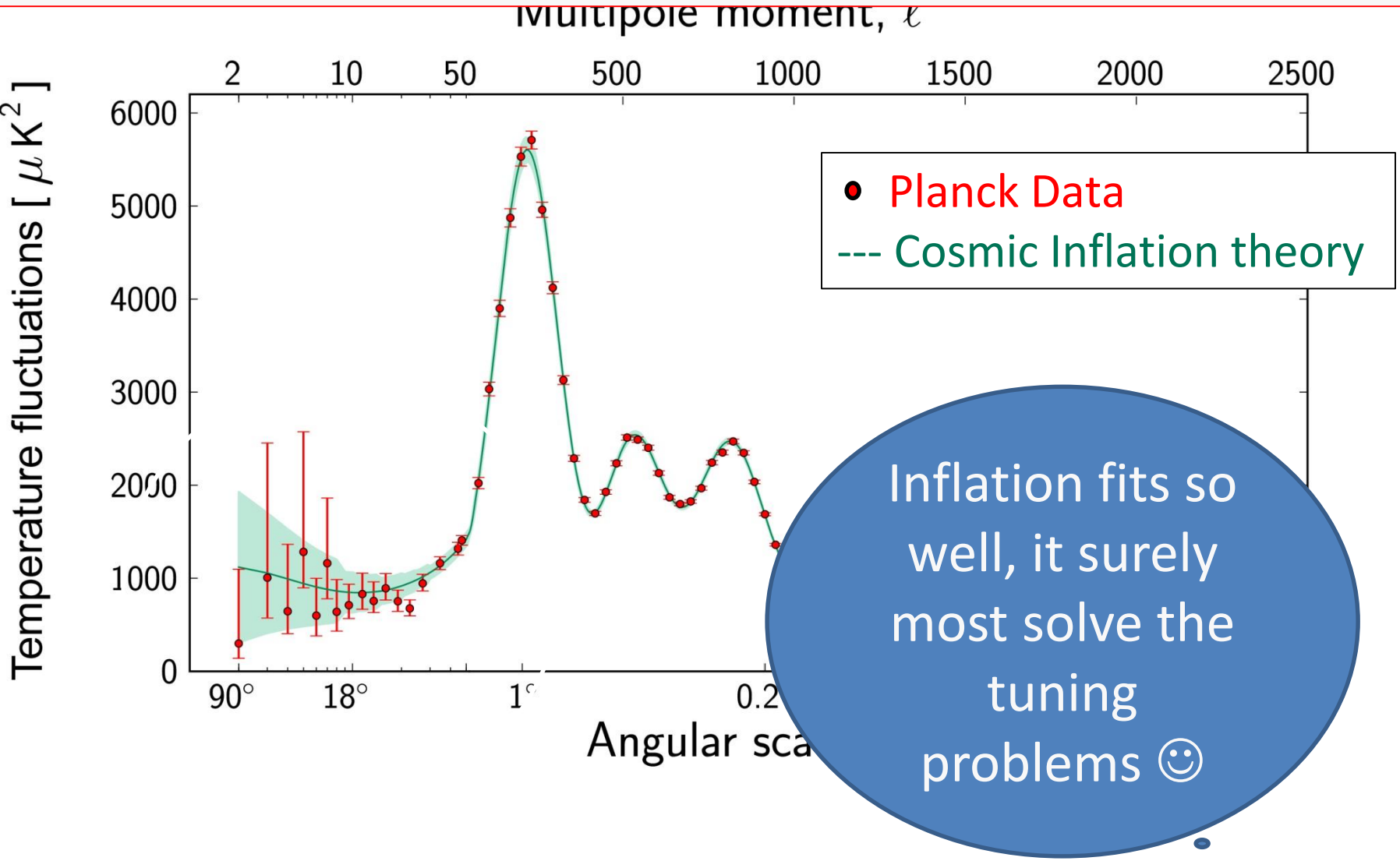

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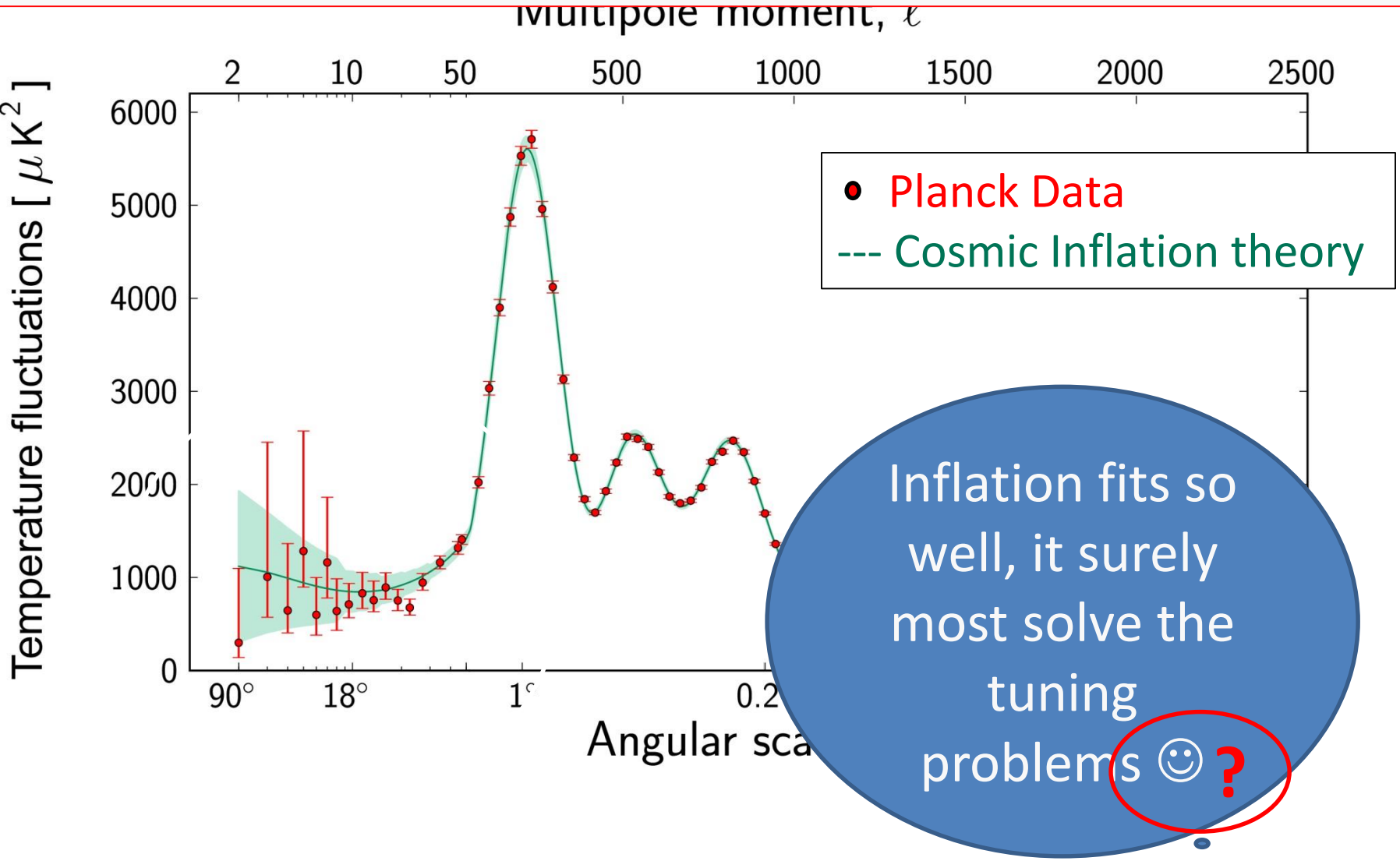

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Reflections on fine tuning

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Use entropy to get some perspective

- 2nd law tells us that the early universe was dynamically “unusual” (low entropy, past hypothesis)

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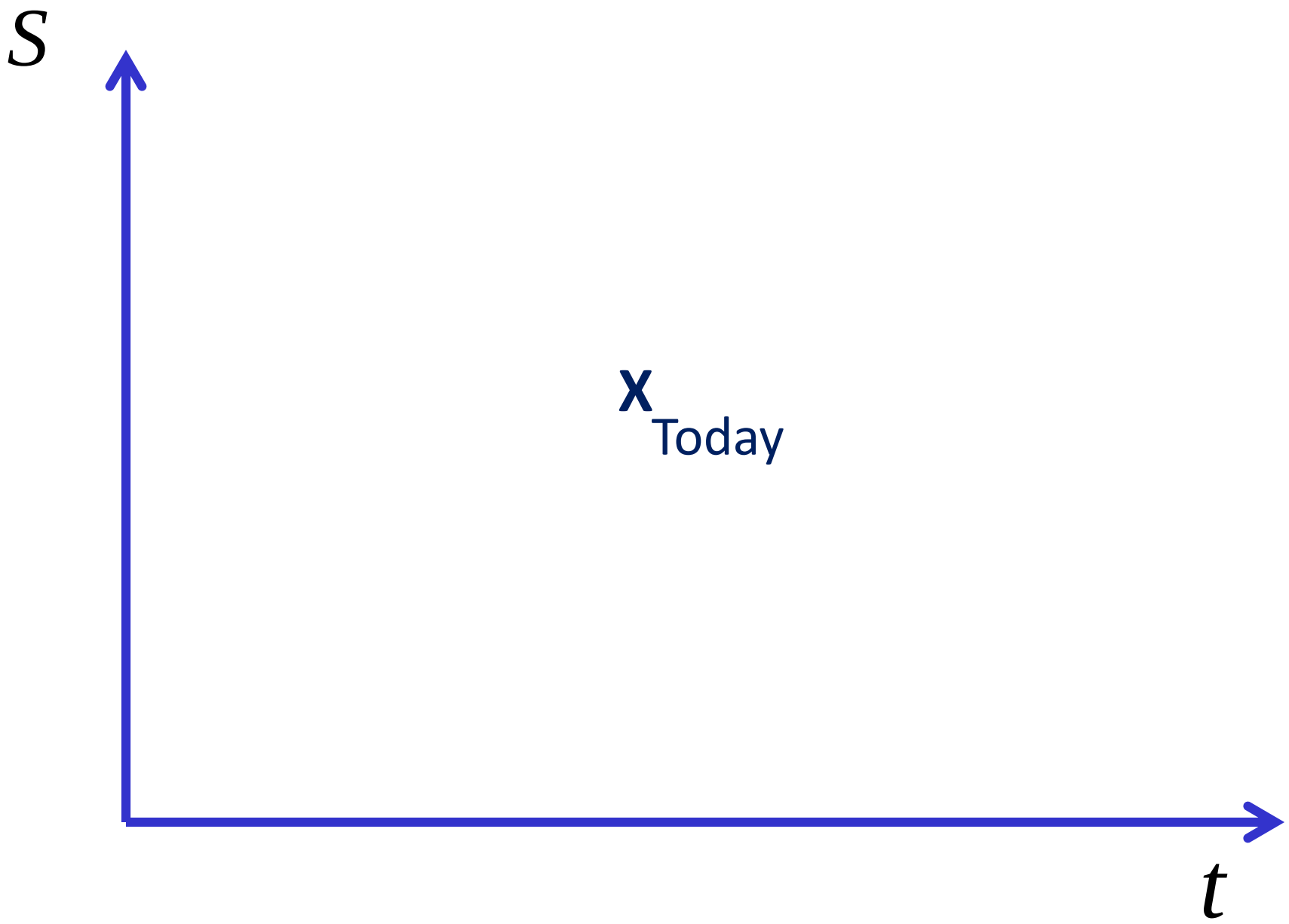
- Inflation is supposed to teach us that the early universe was dynamically “typical”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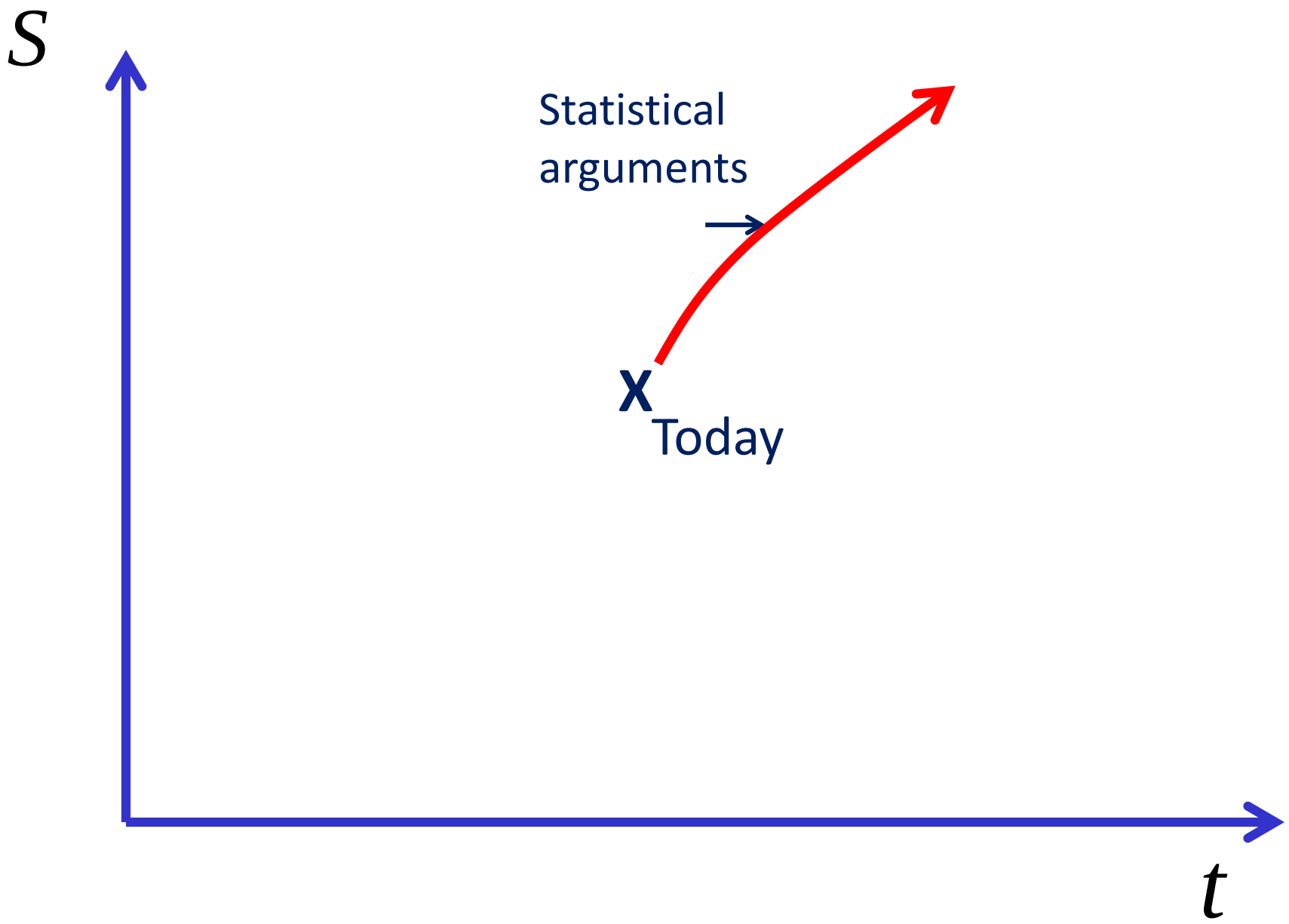
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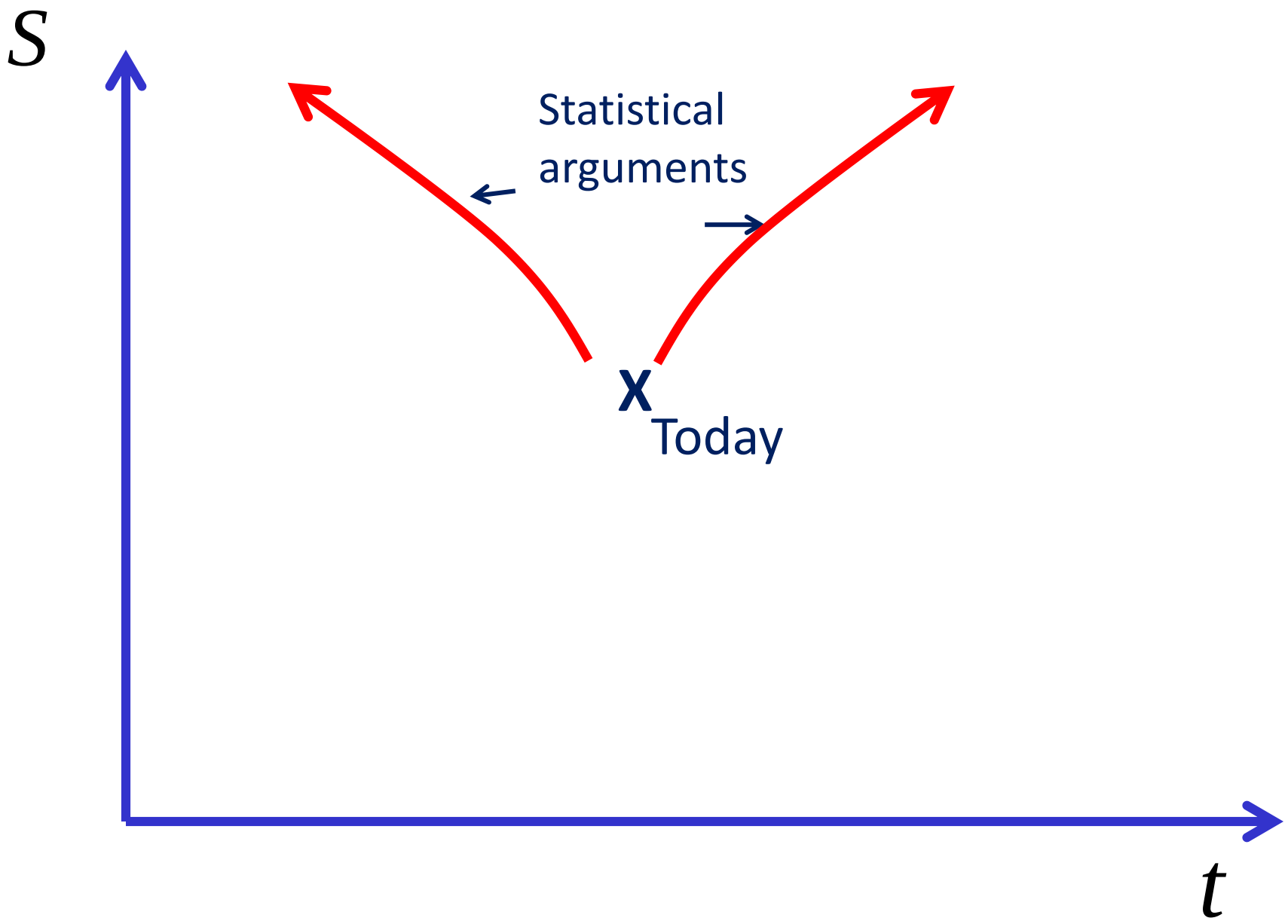
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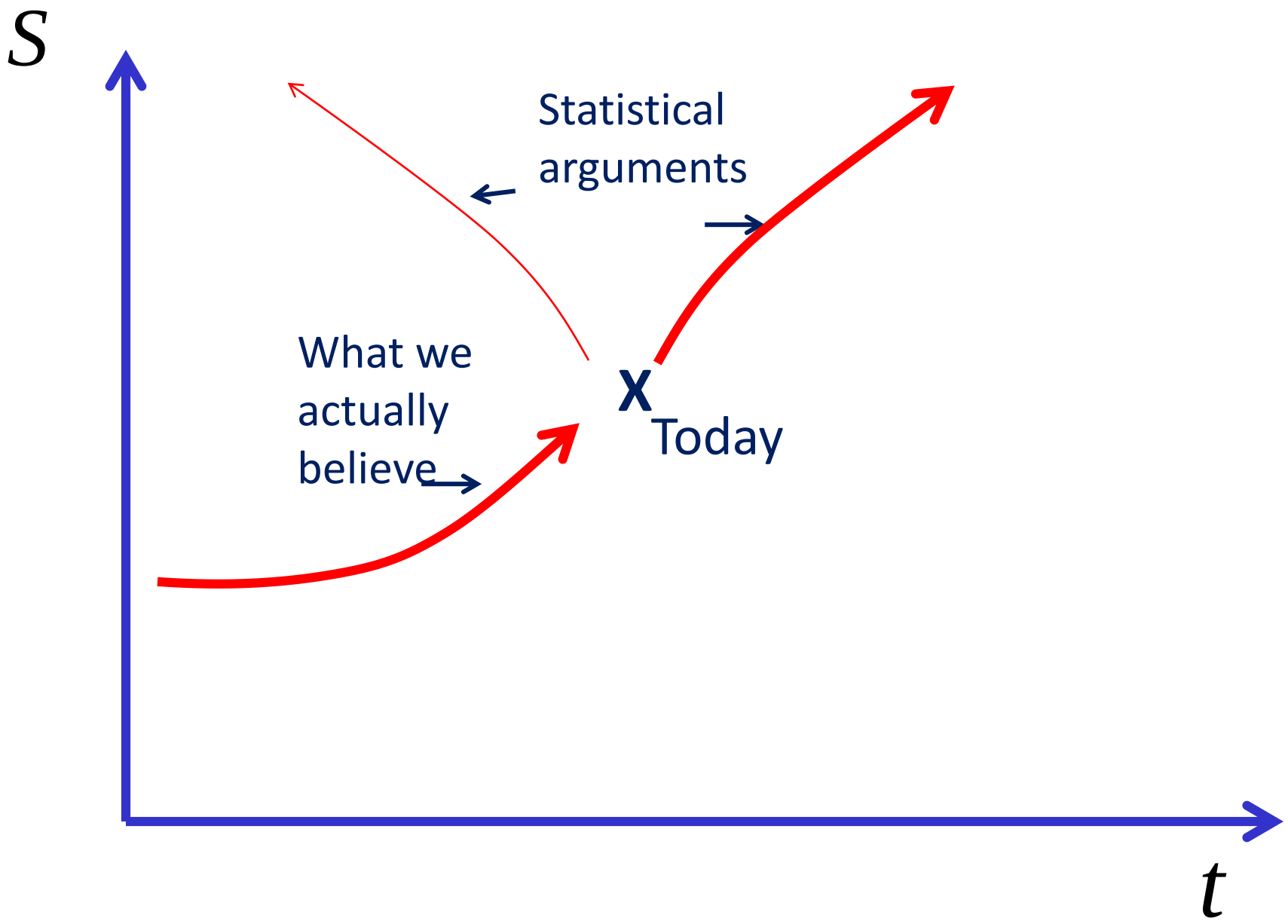
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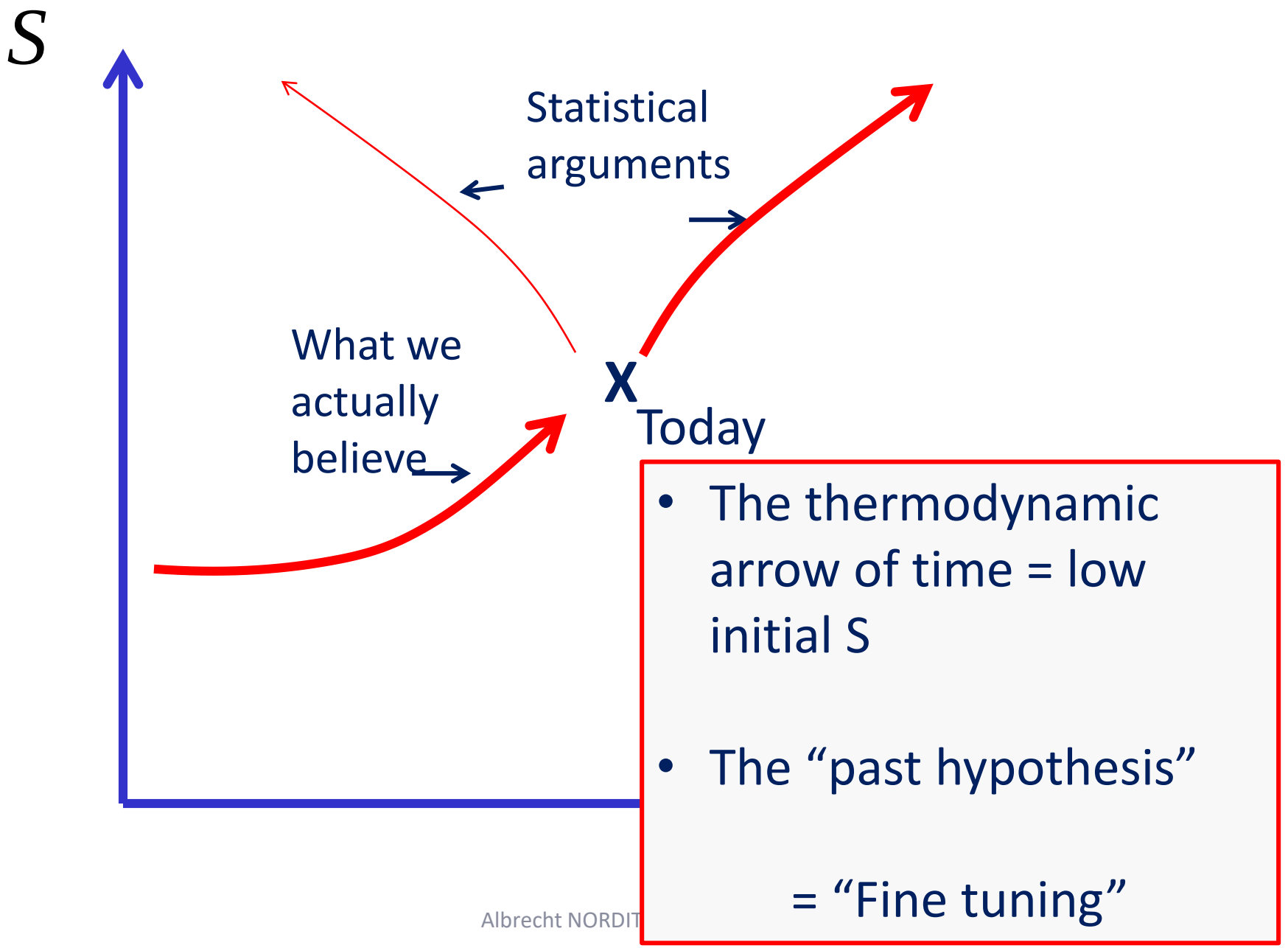
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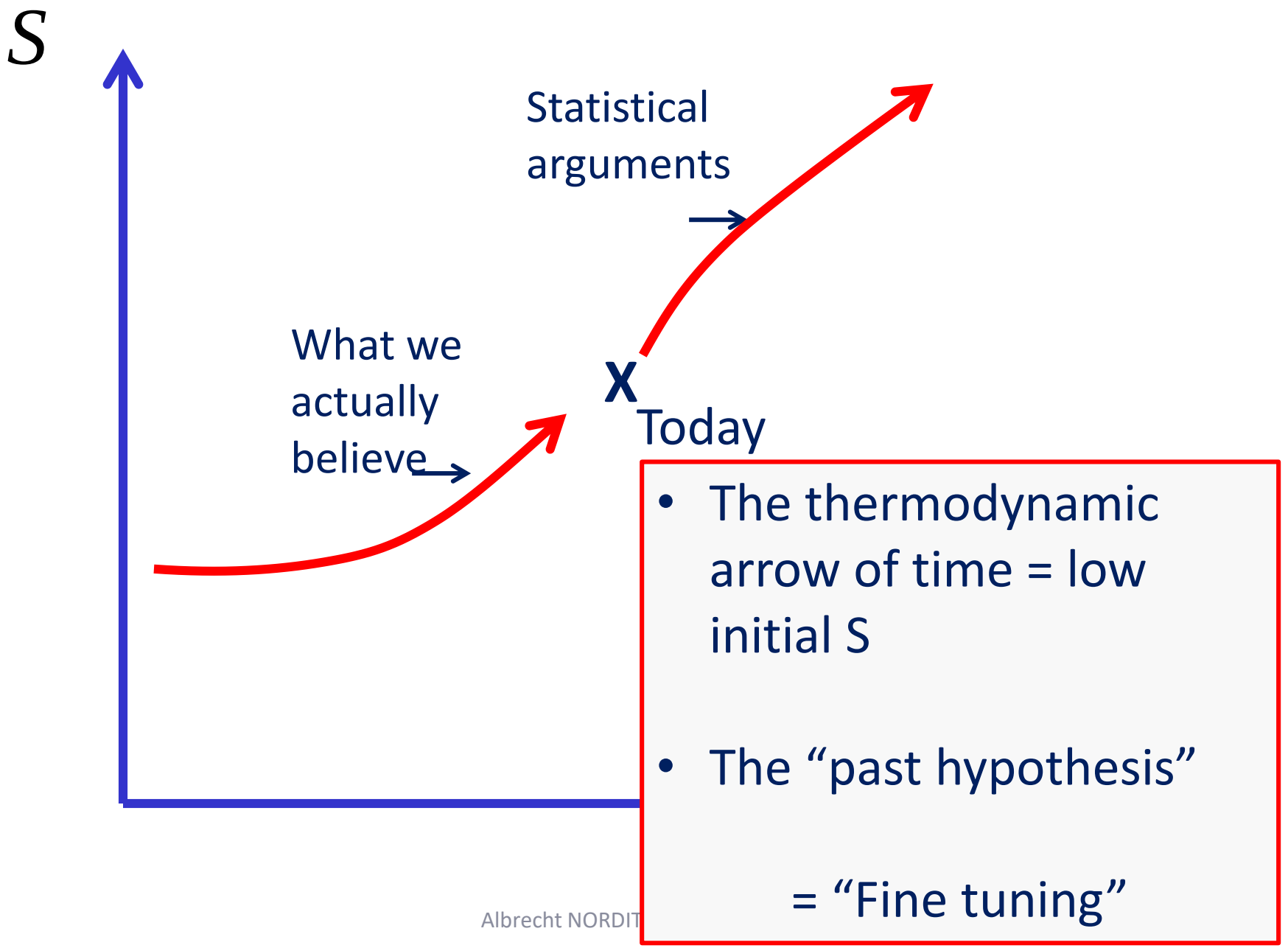
Today
• The thermodynamic arrow of time = low initial S
• The "past hypothesis"
= "Fine tuning"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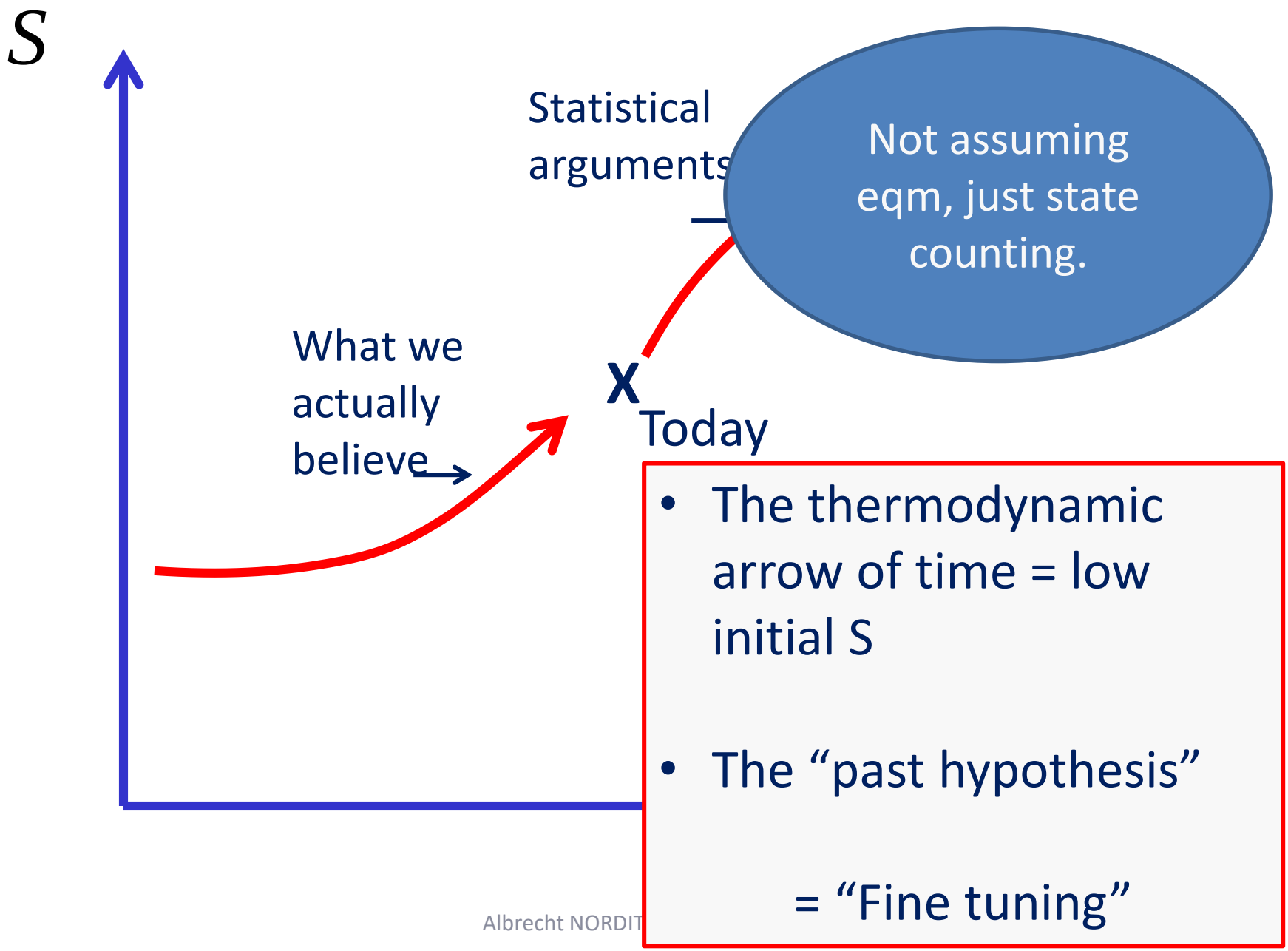
S
Statistical arguments
Not assuming eqm, just state counting.
What we actually believe
X
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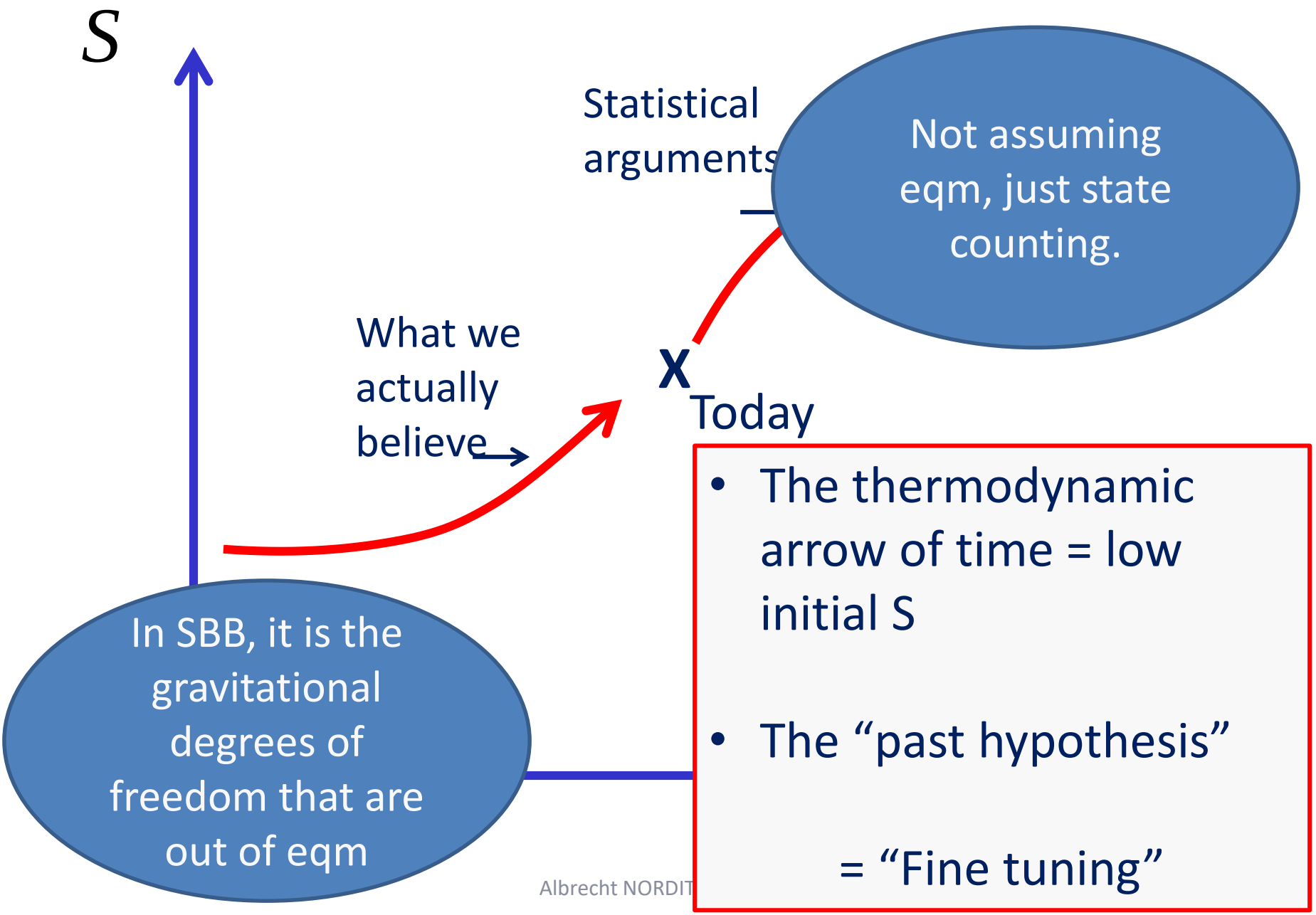
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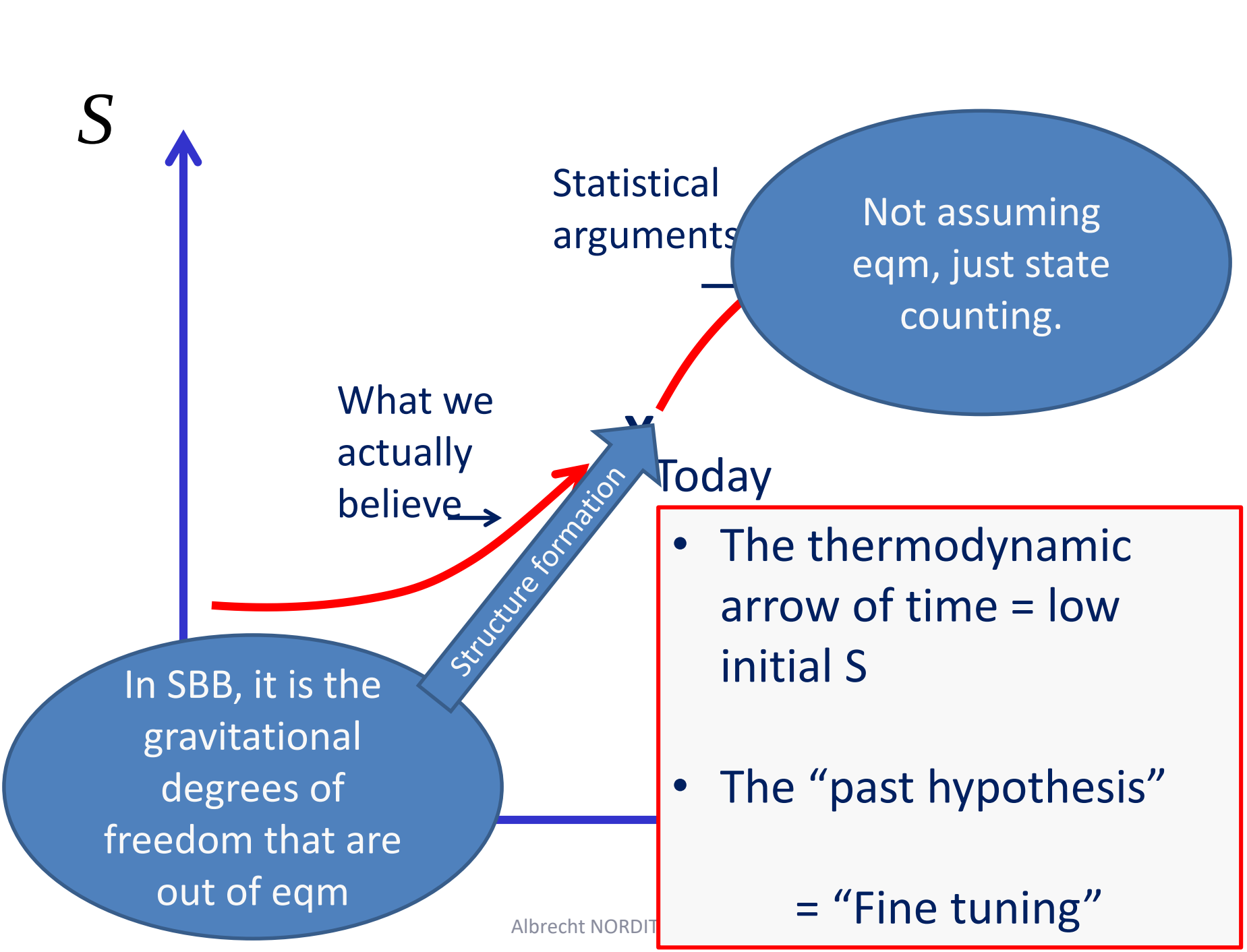
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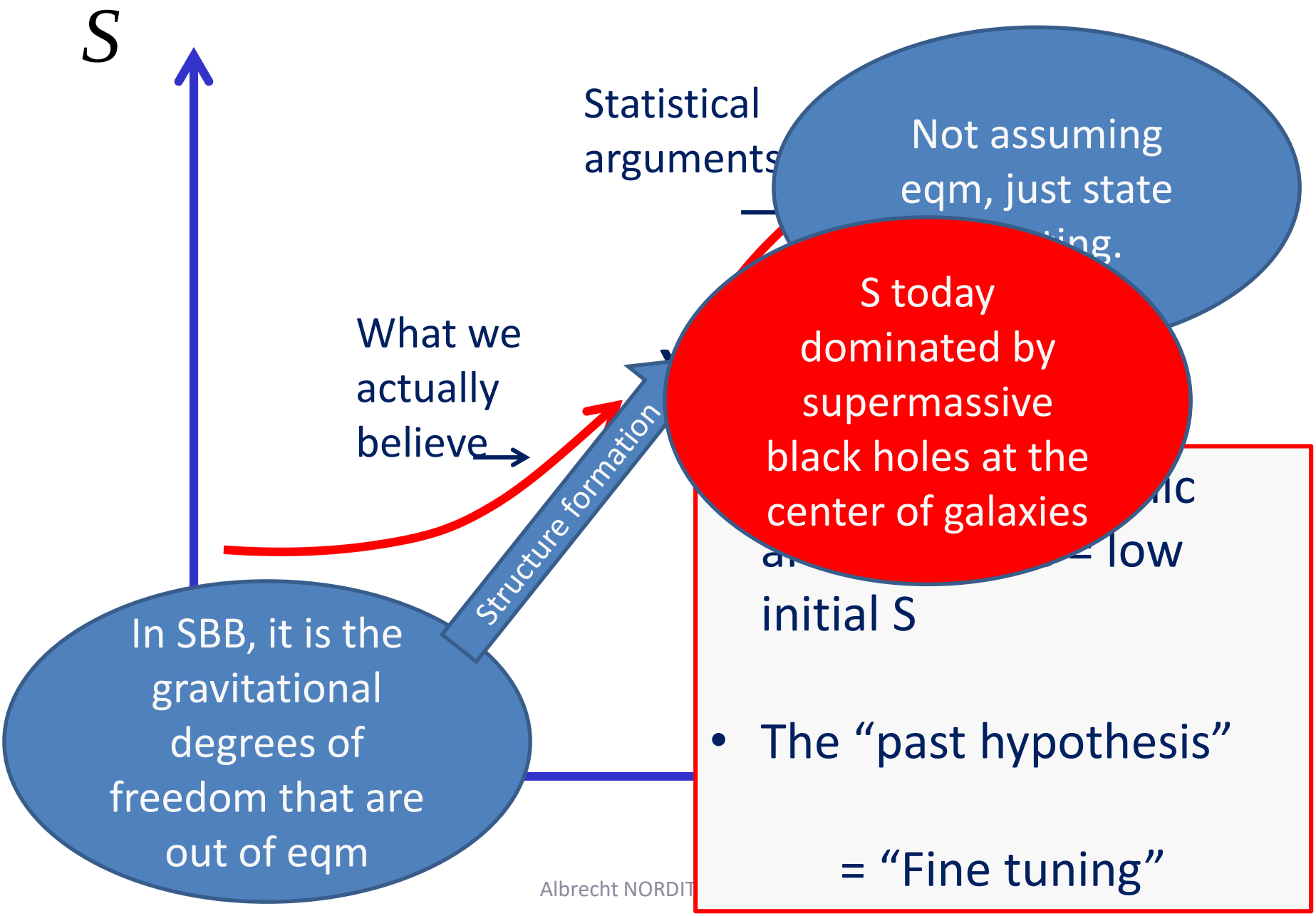
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S today dominated by supermassive black holes at the center of galaxies
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The thermodynamic arrow of time originates with the very special initial conditions of the cosmos:

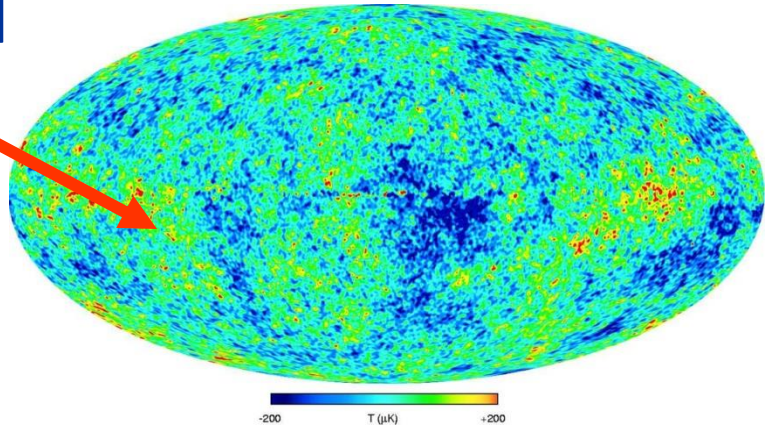
The early universe is very homogeneous on scales $l > l_{Jeans}$

➔ very far from Eqm. (= black hole)

Penrose

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

Cosmic Microwave Background uniform to one part in 10^5



Entropy increase is realized mainly through gravitational collapse (destruction of homogeneity)

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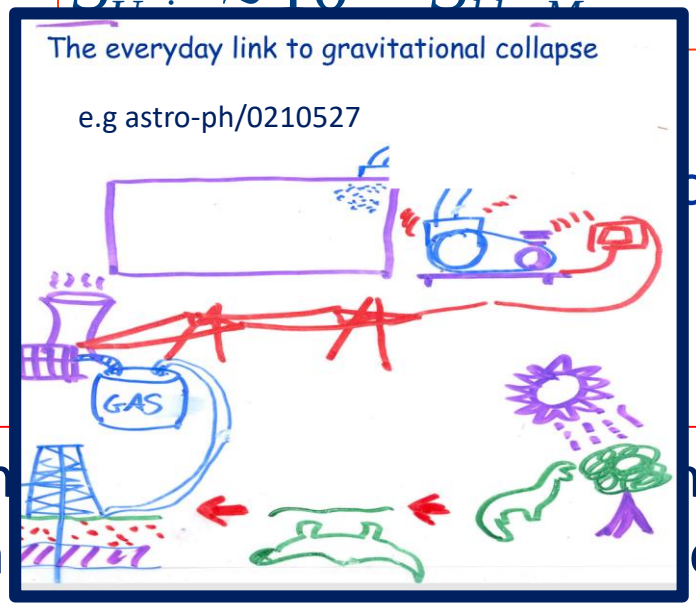

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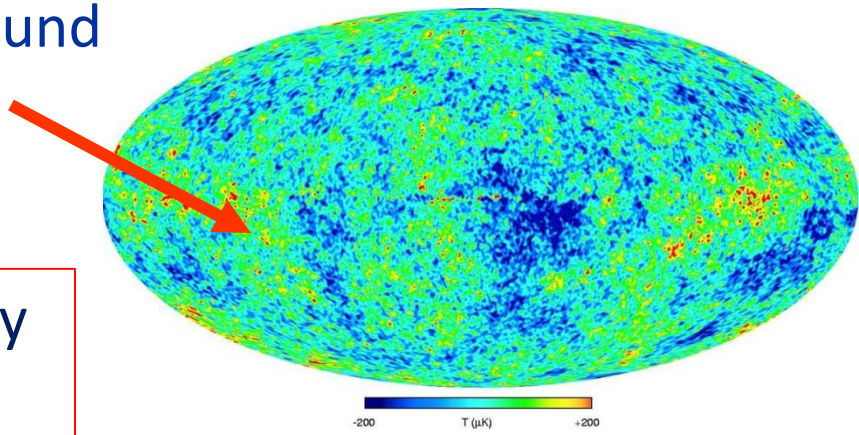
10^5



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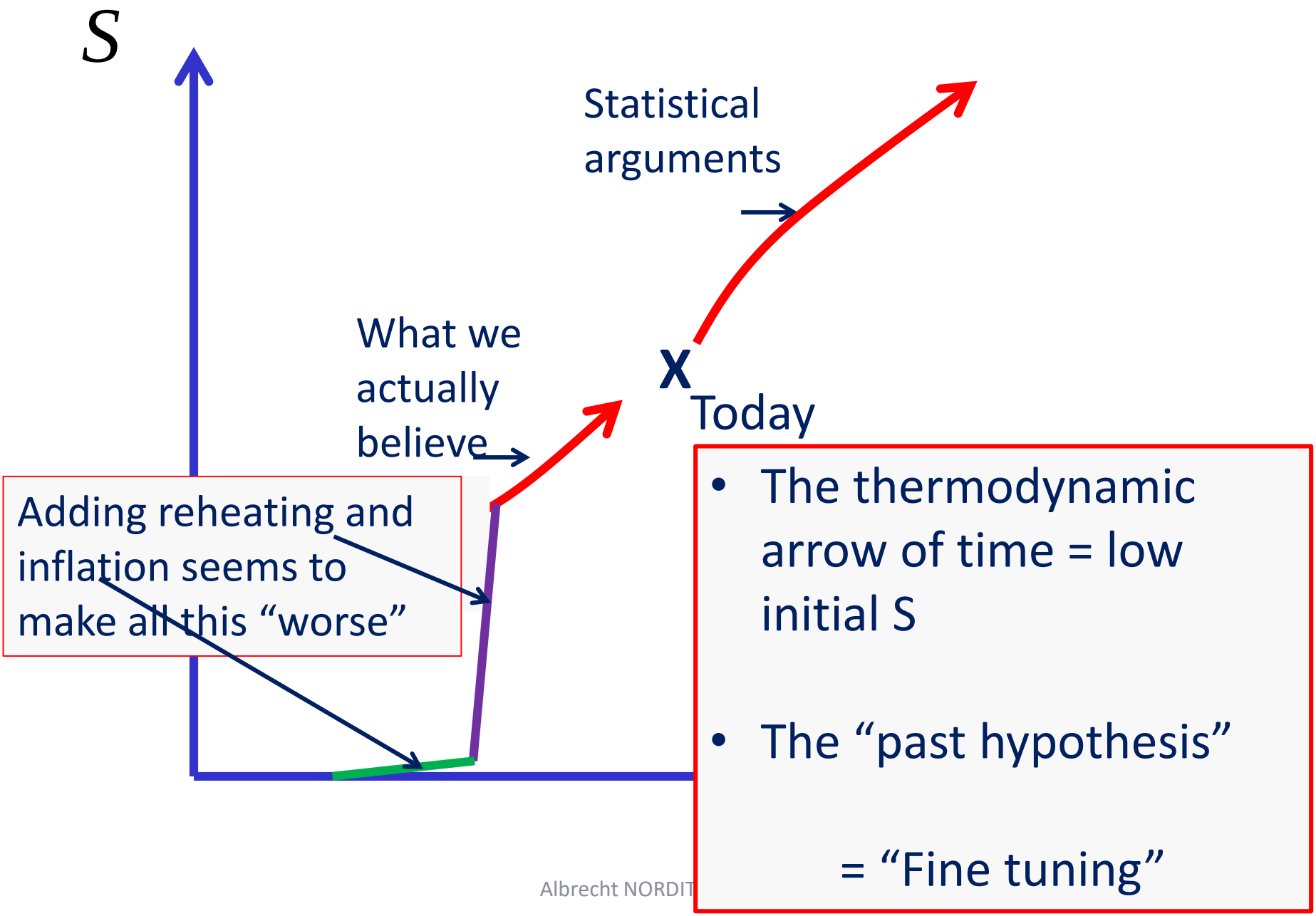
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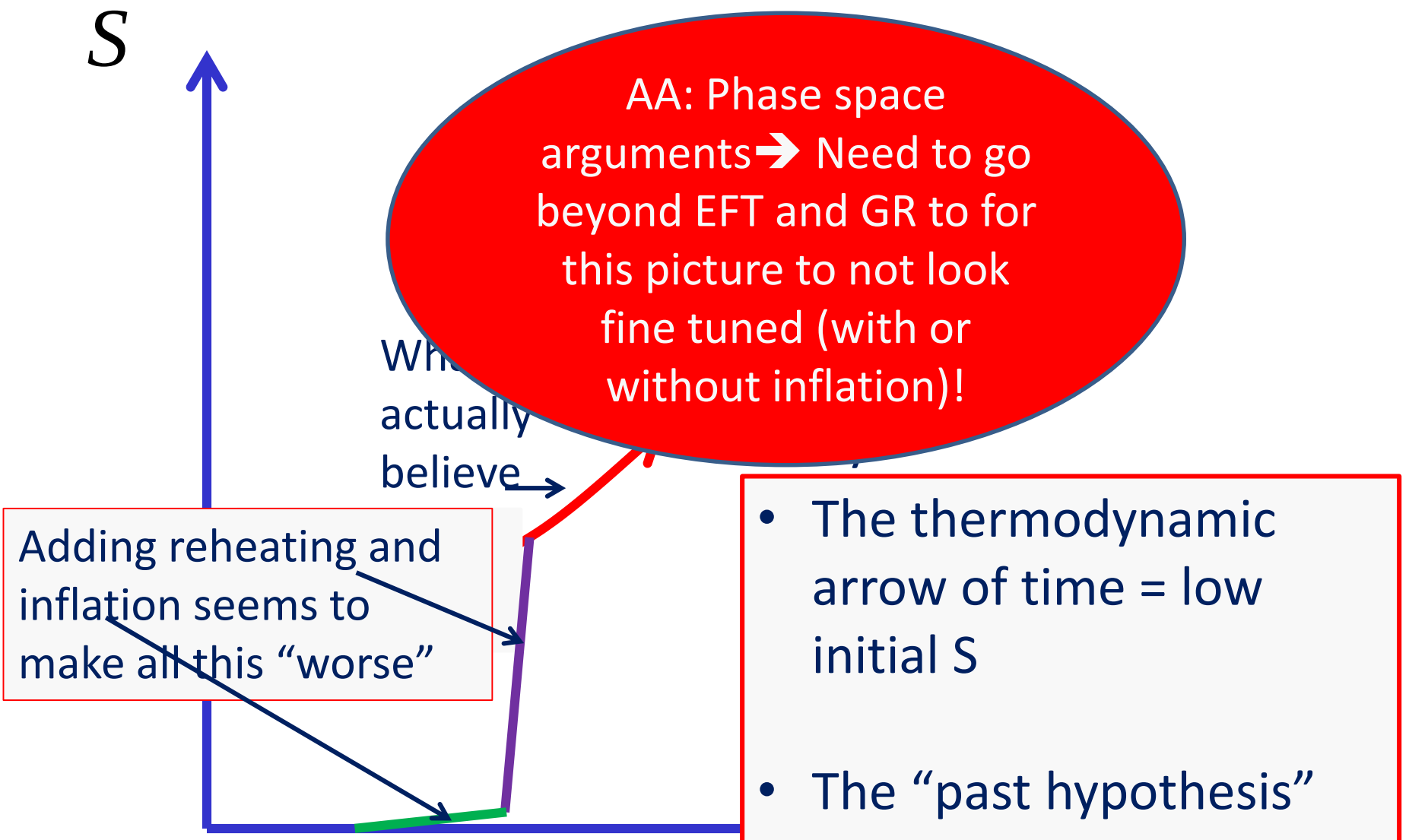

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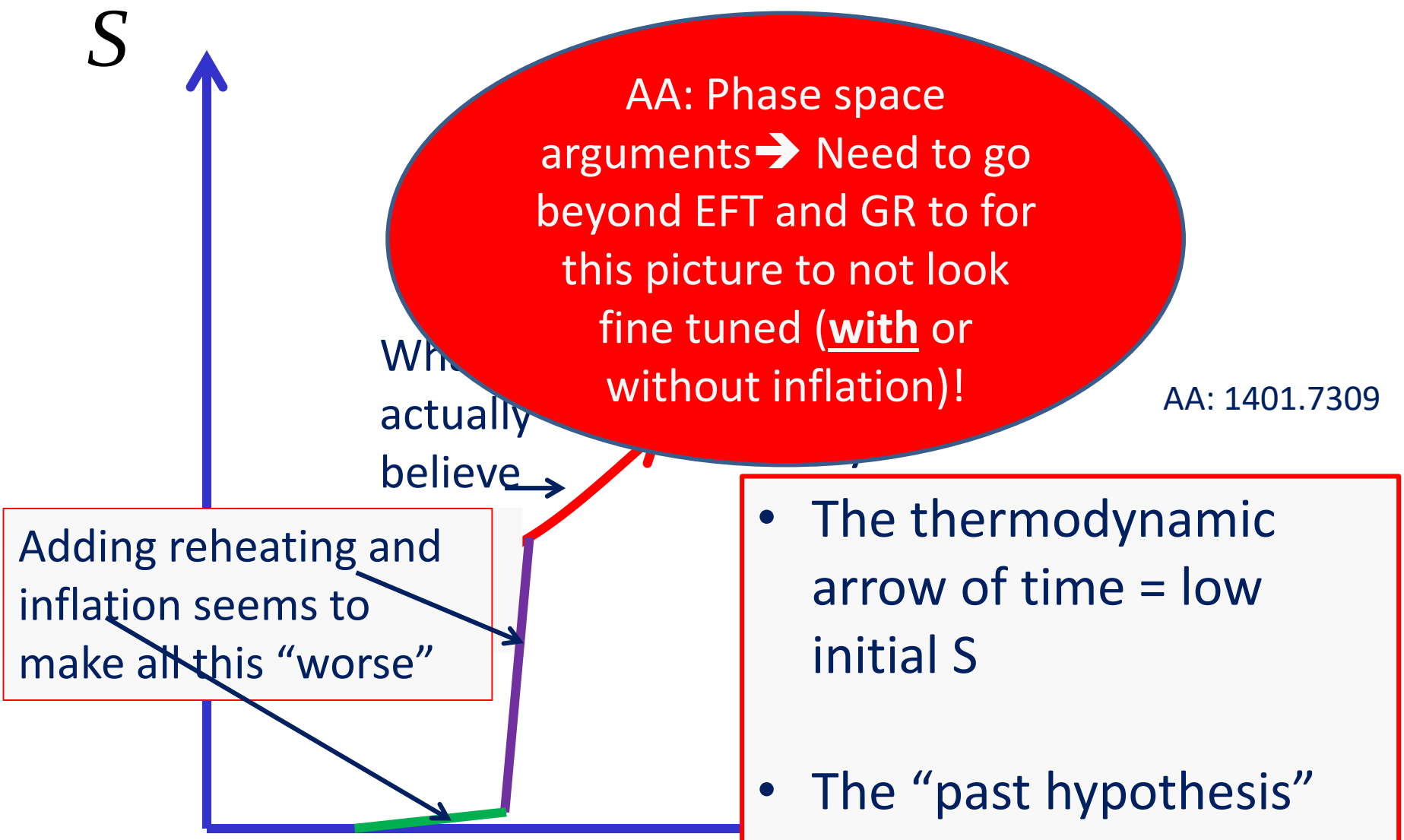

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Beware “temporal provincialism*”:

The tendency to slip in assumptions about $\dot{S} > 0$ (and thus tunings of initial conditions) without even realizing it

Related issues:

- Arrival Terminals

* L. Susskind

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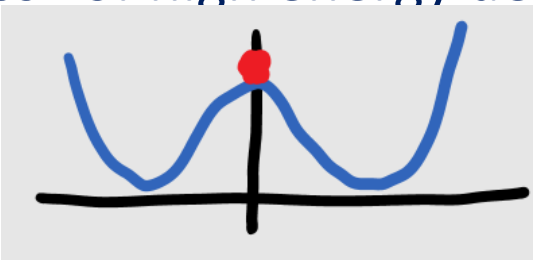

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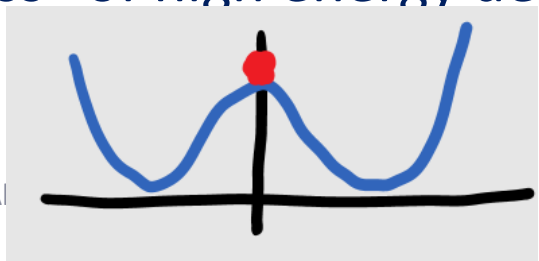

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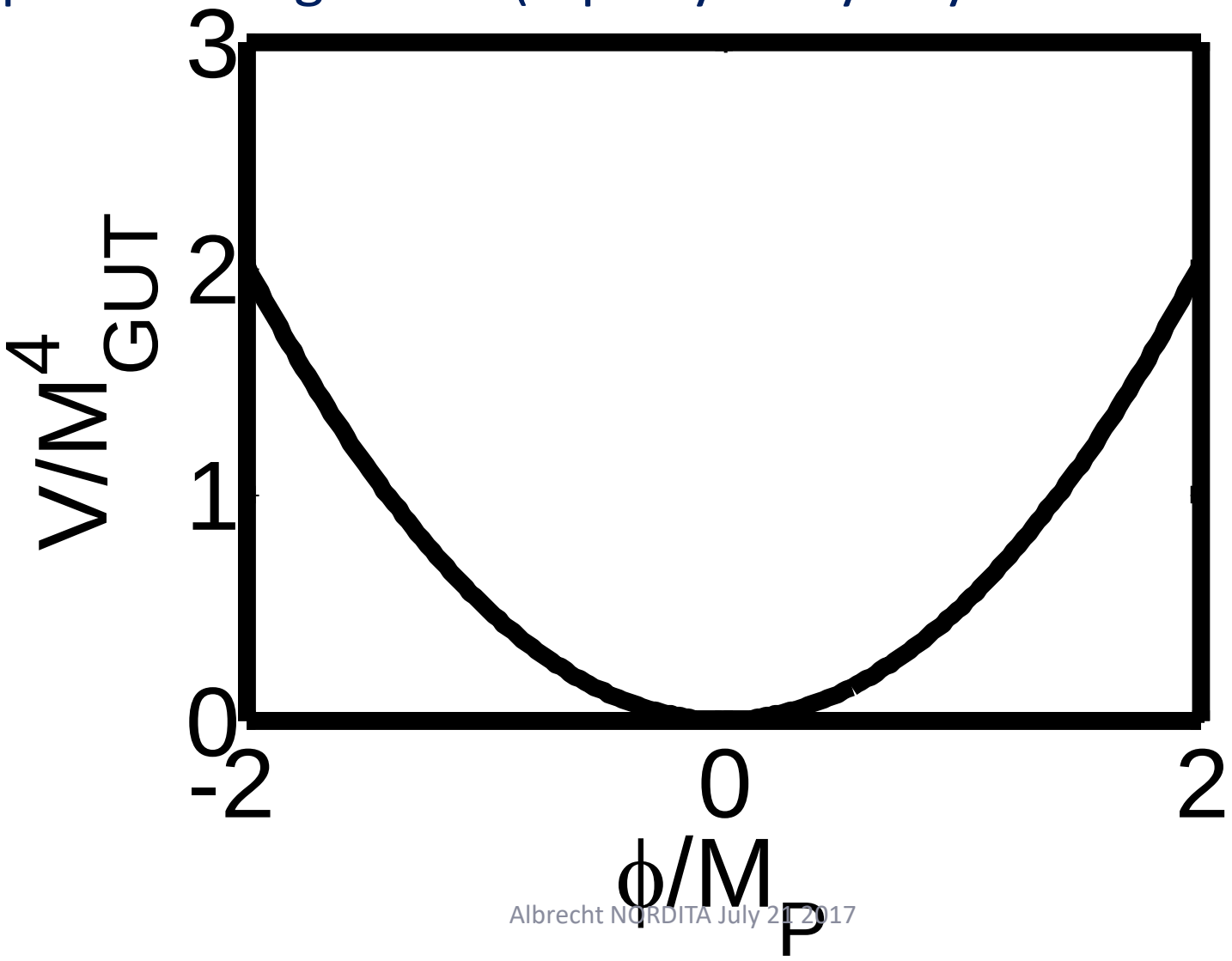
Equipartition argument (equally likely anywhere on potential)



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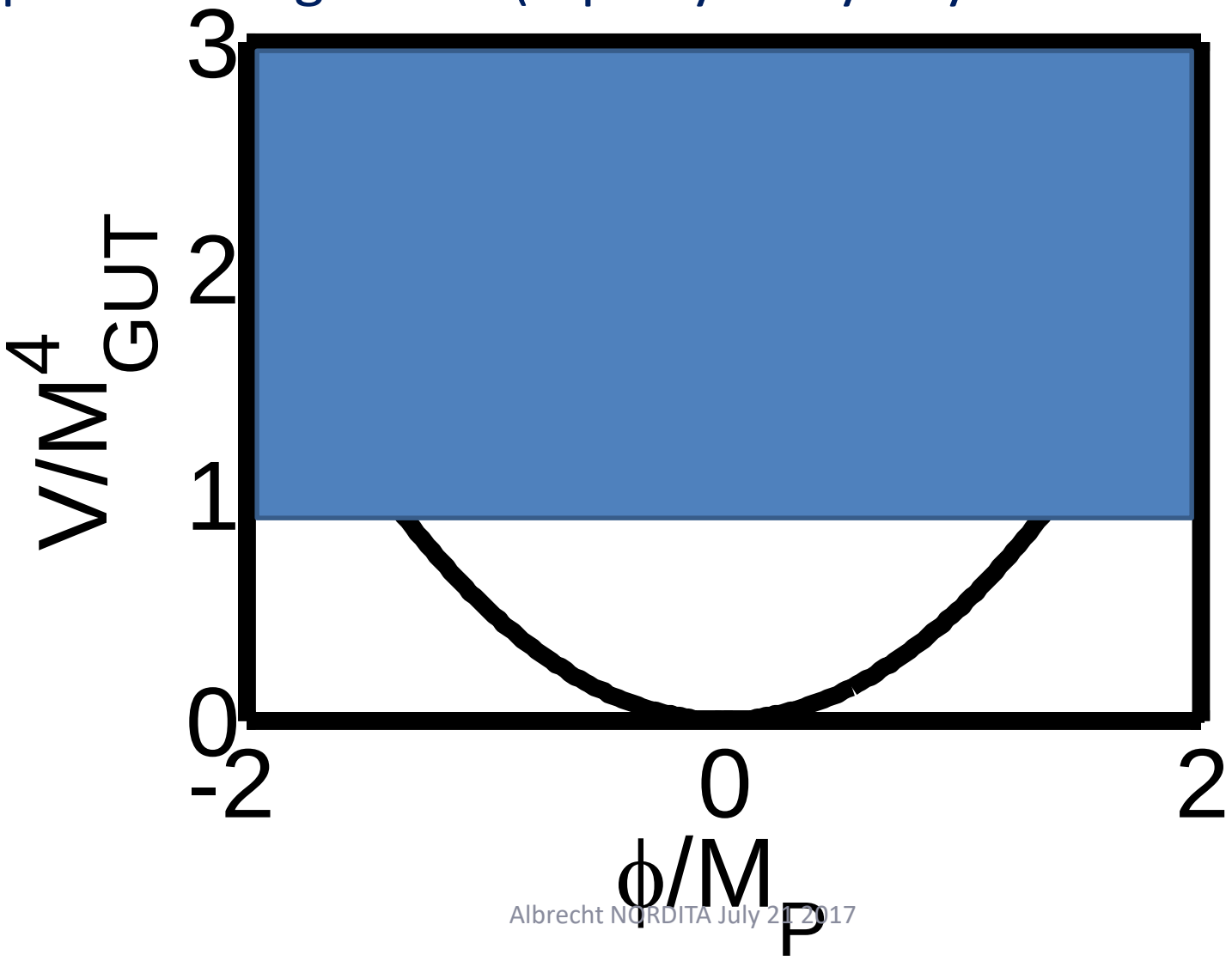

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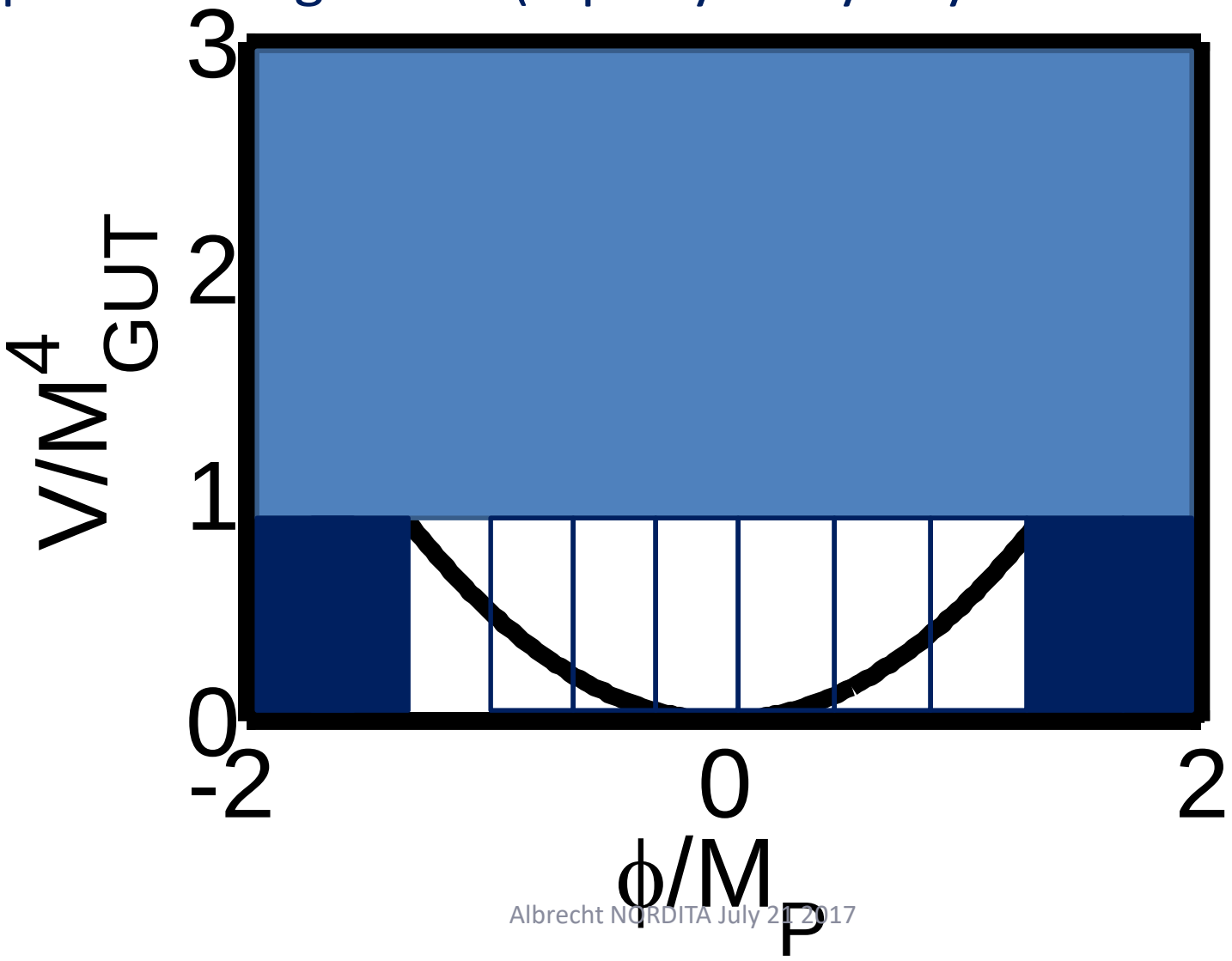

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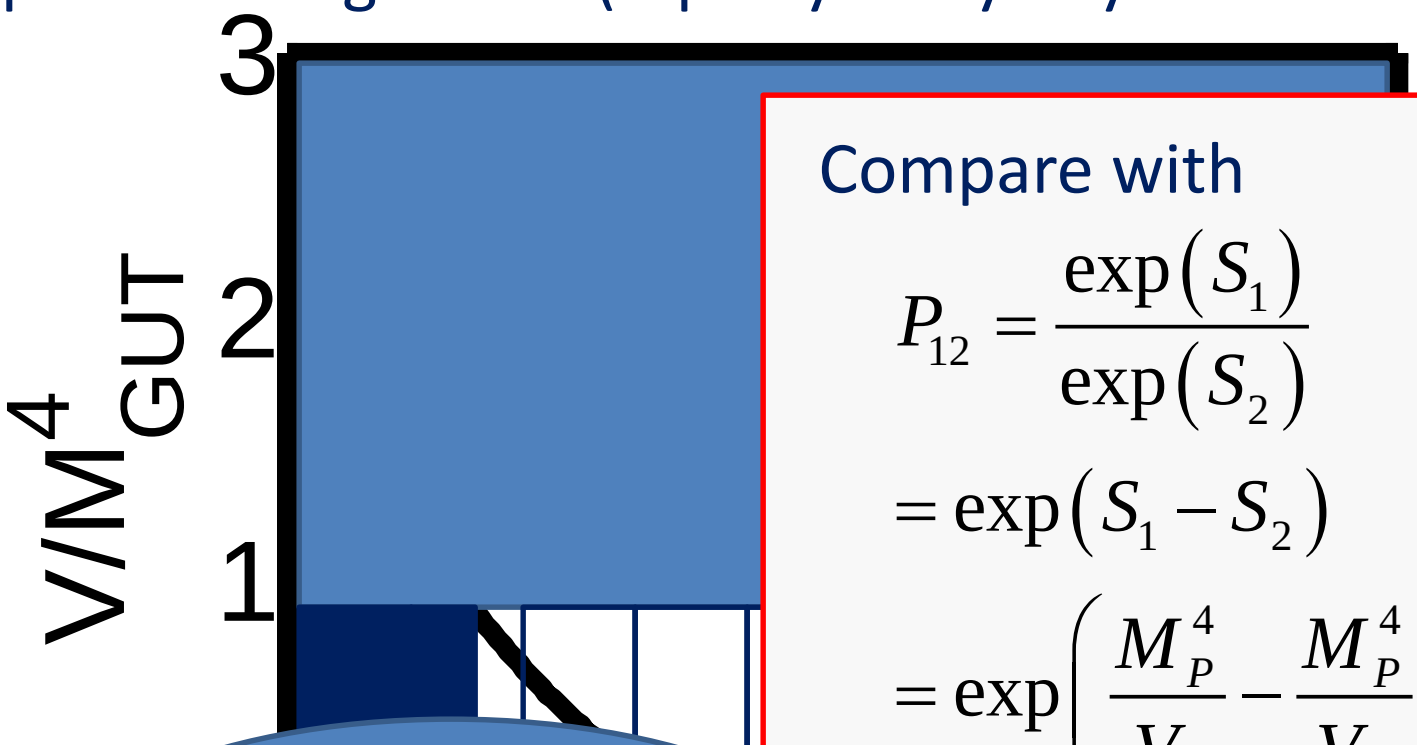

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$$P_{12} = \frac{\exp(S_1)}{\exp(S_2)}$$

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

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

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

Entropy arguments give exponential suppression of higher V values

AA and Sorbo, hep-th/0405270

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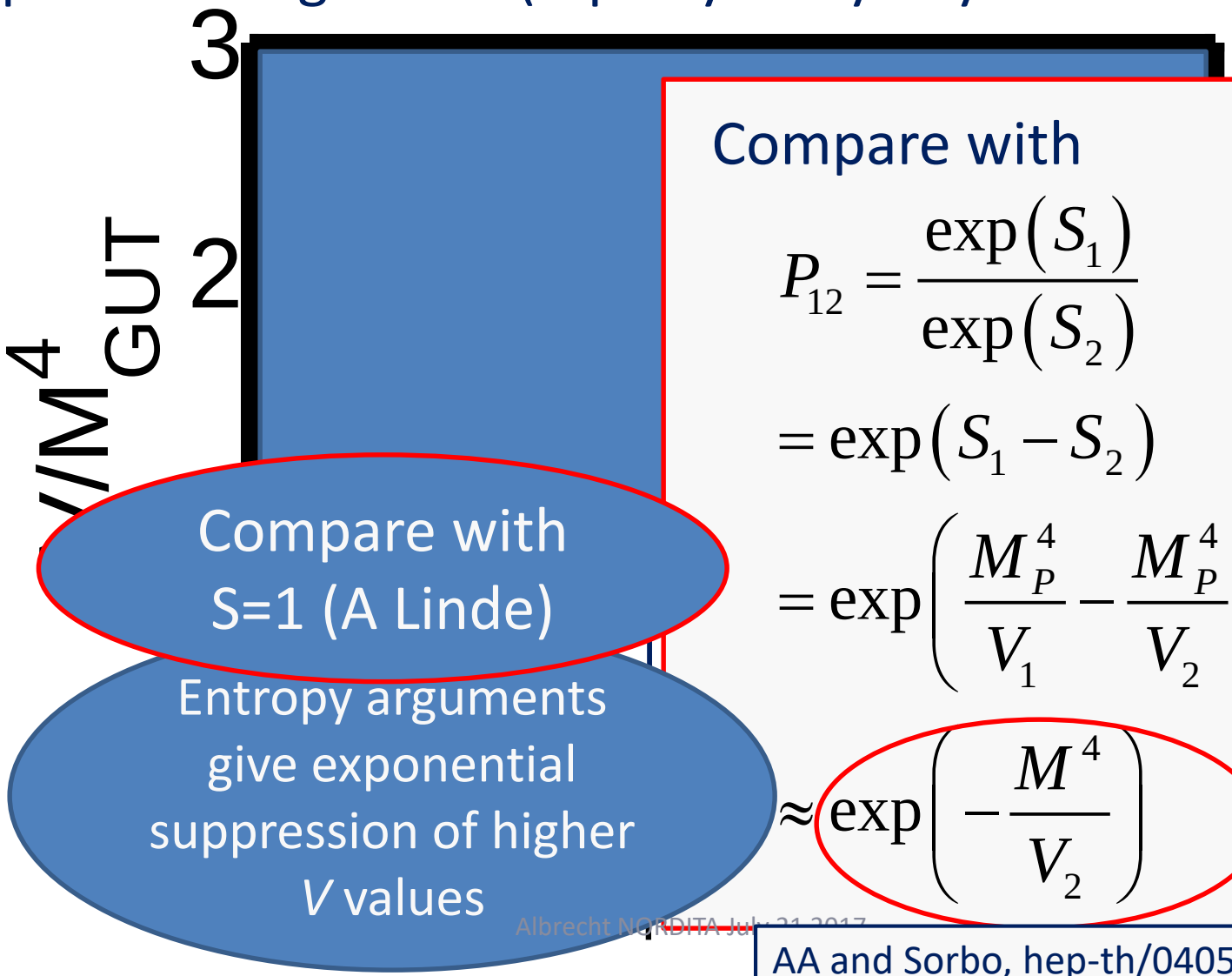

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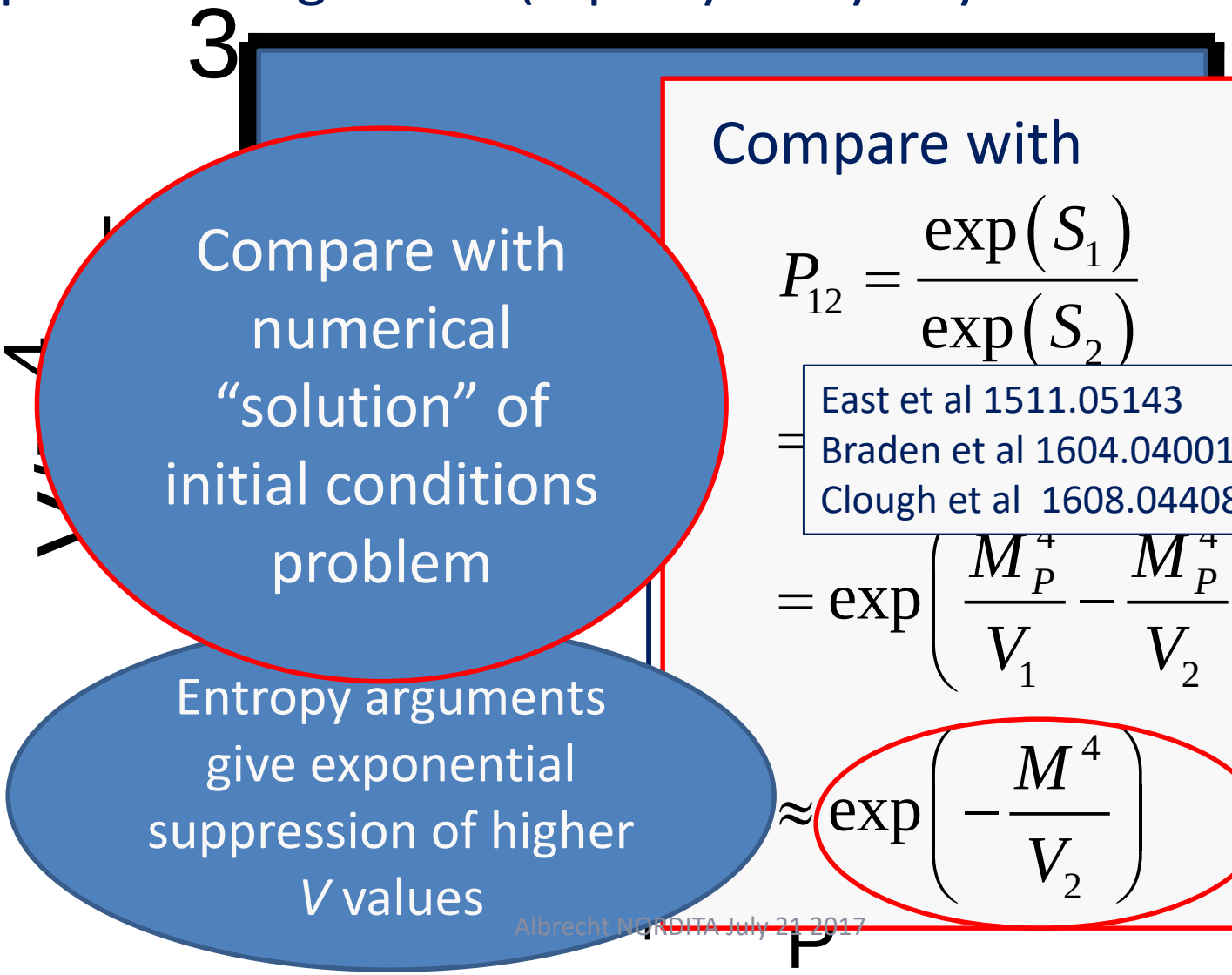

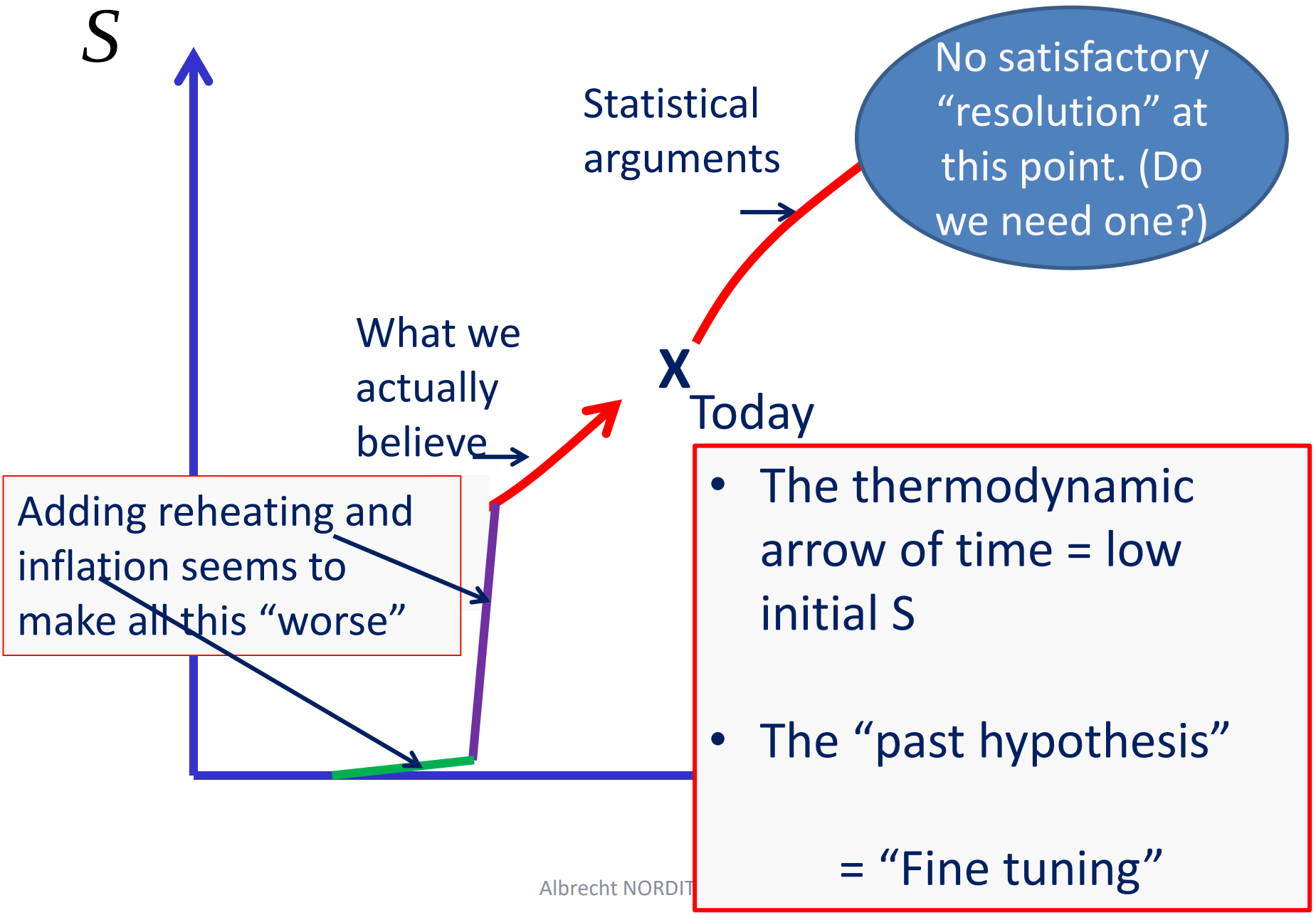
S
Statistical arguments
No satisfactory "resolution" at this point. (Do we need one?)
What we actually believe
X
Today
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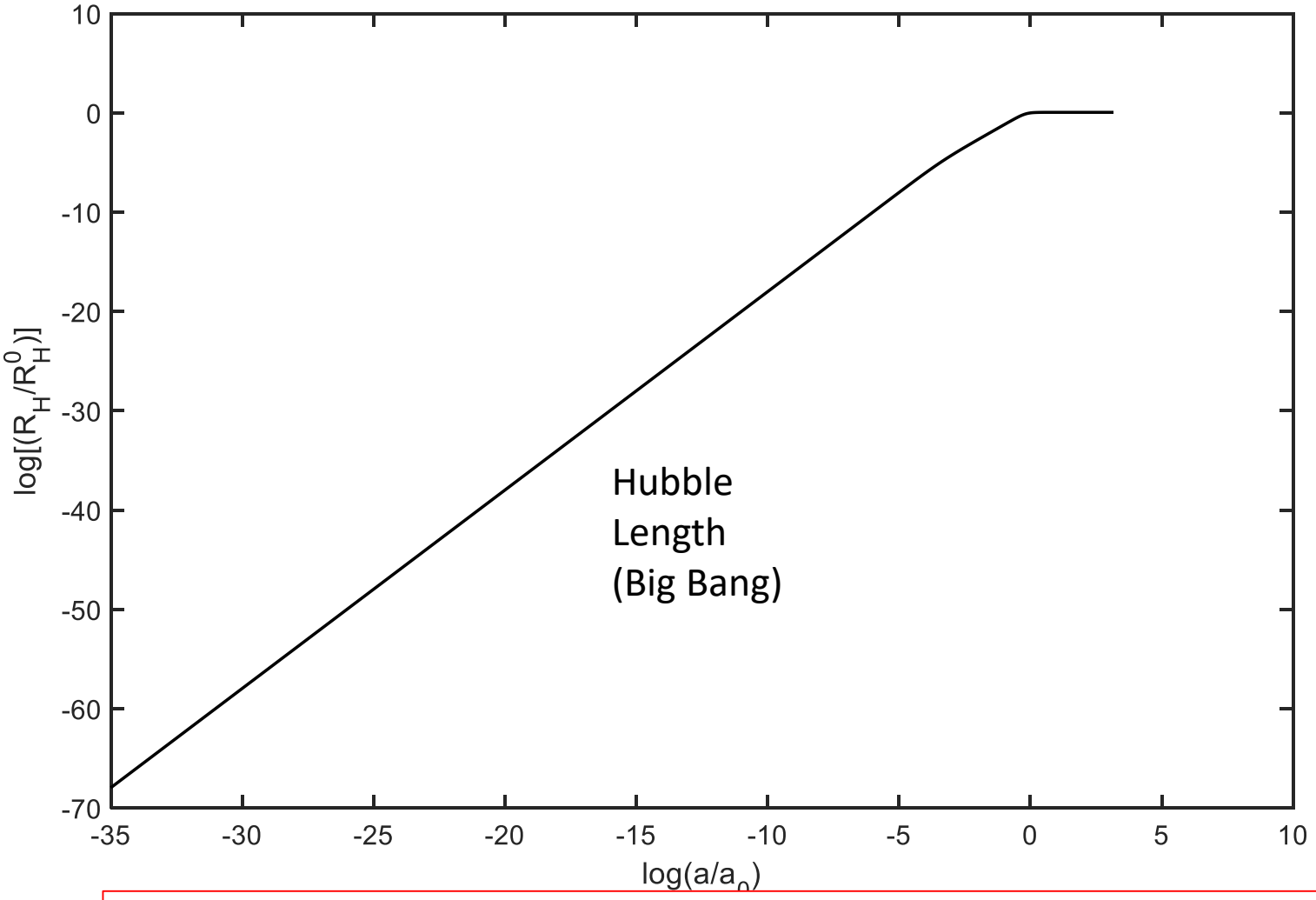
Reflections on fine tuning

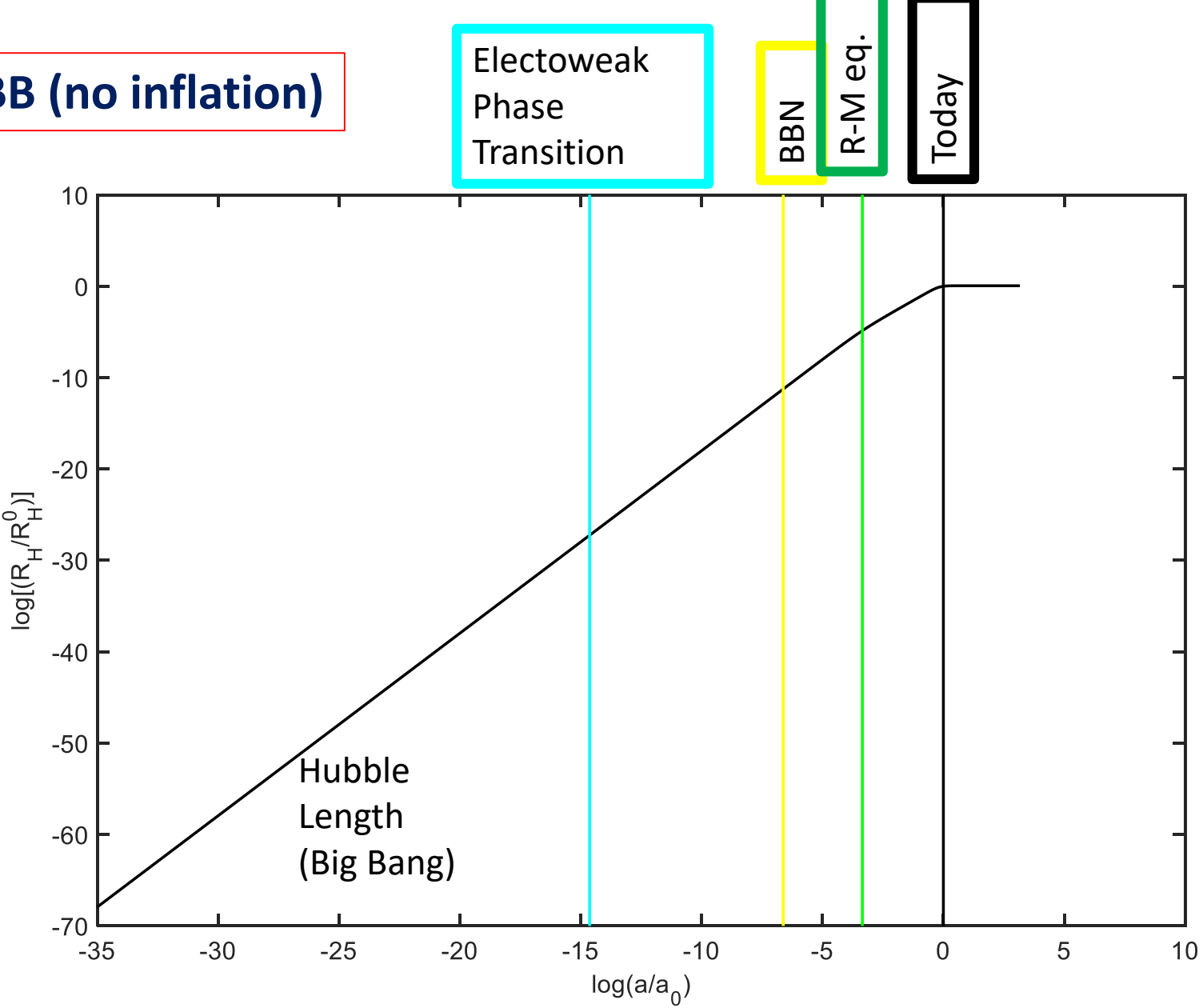
Use the evolution of length scales to get some perspective

Log length over Hubble length today



Log scale factor over scale factor today

SBB (no inflation)



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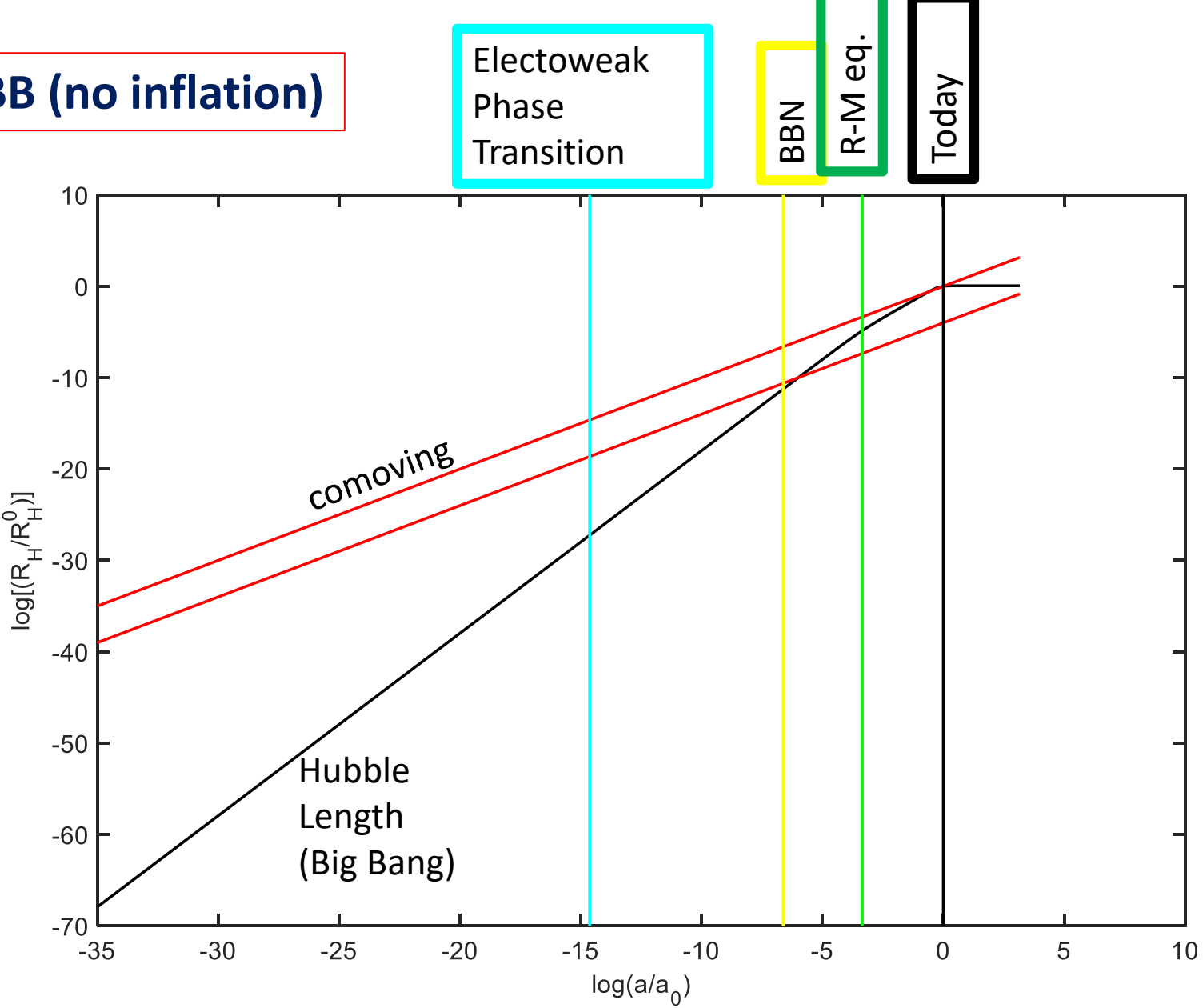

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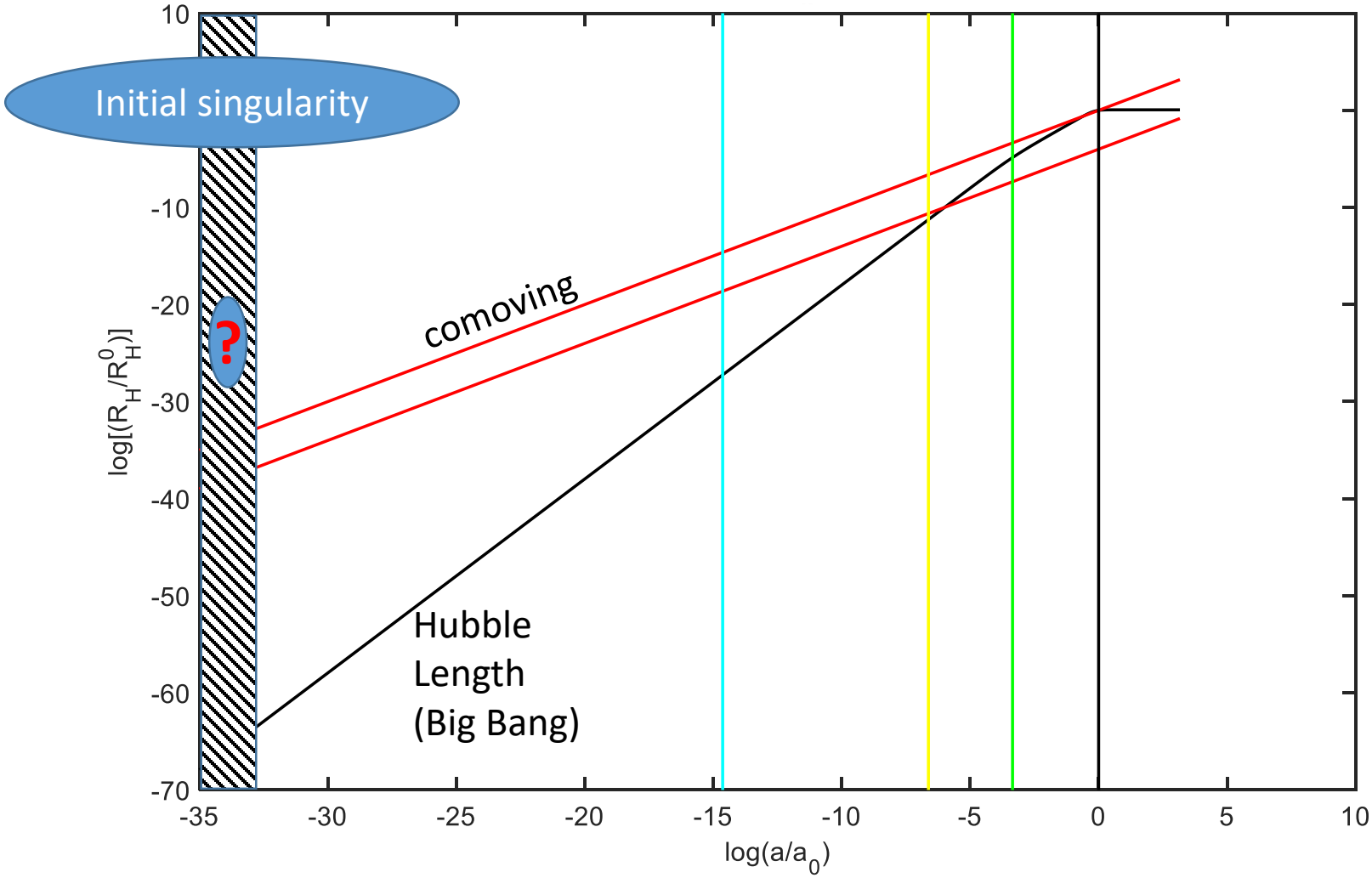

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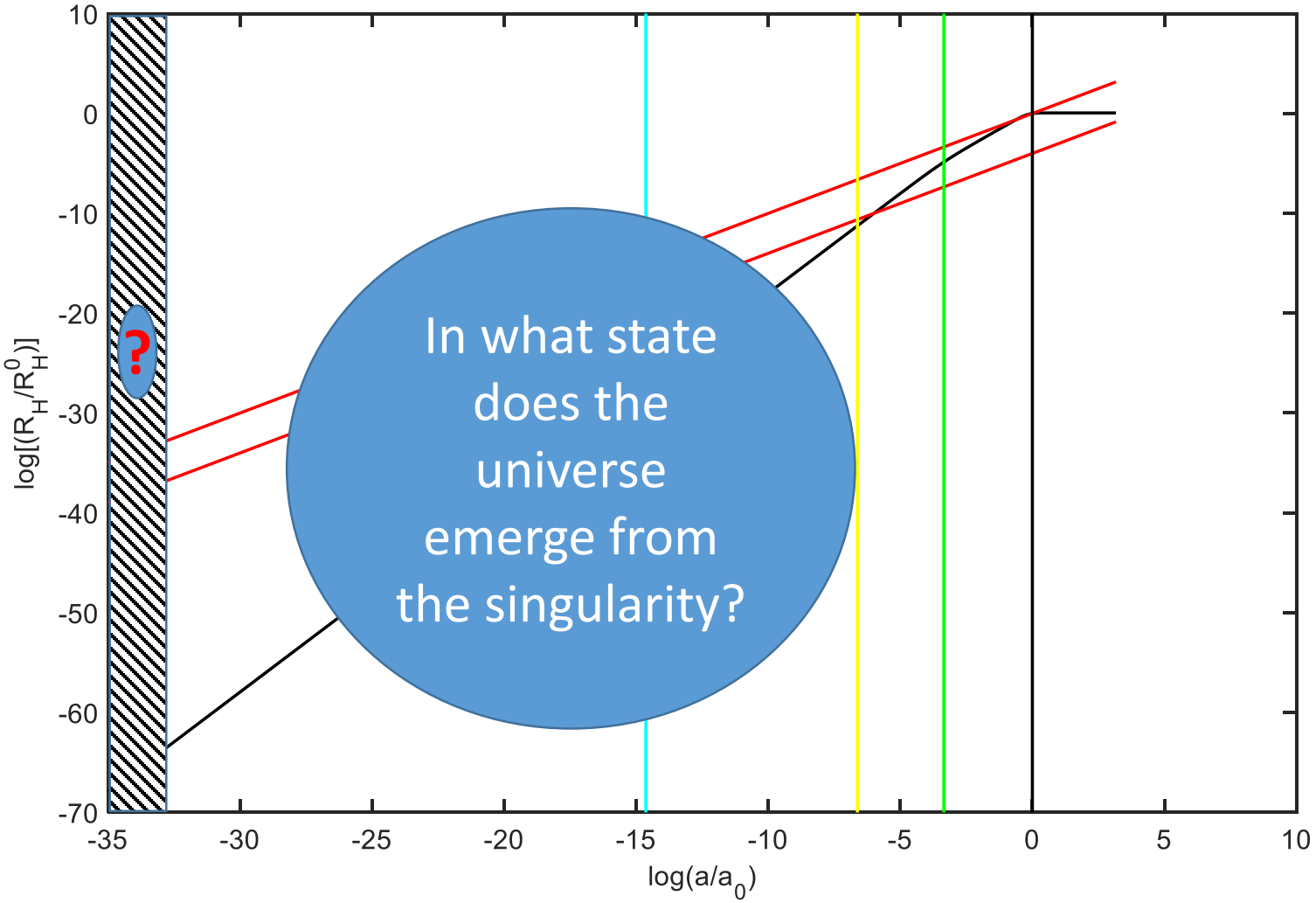
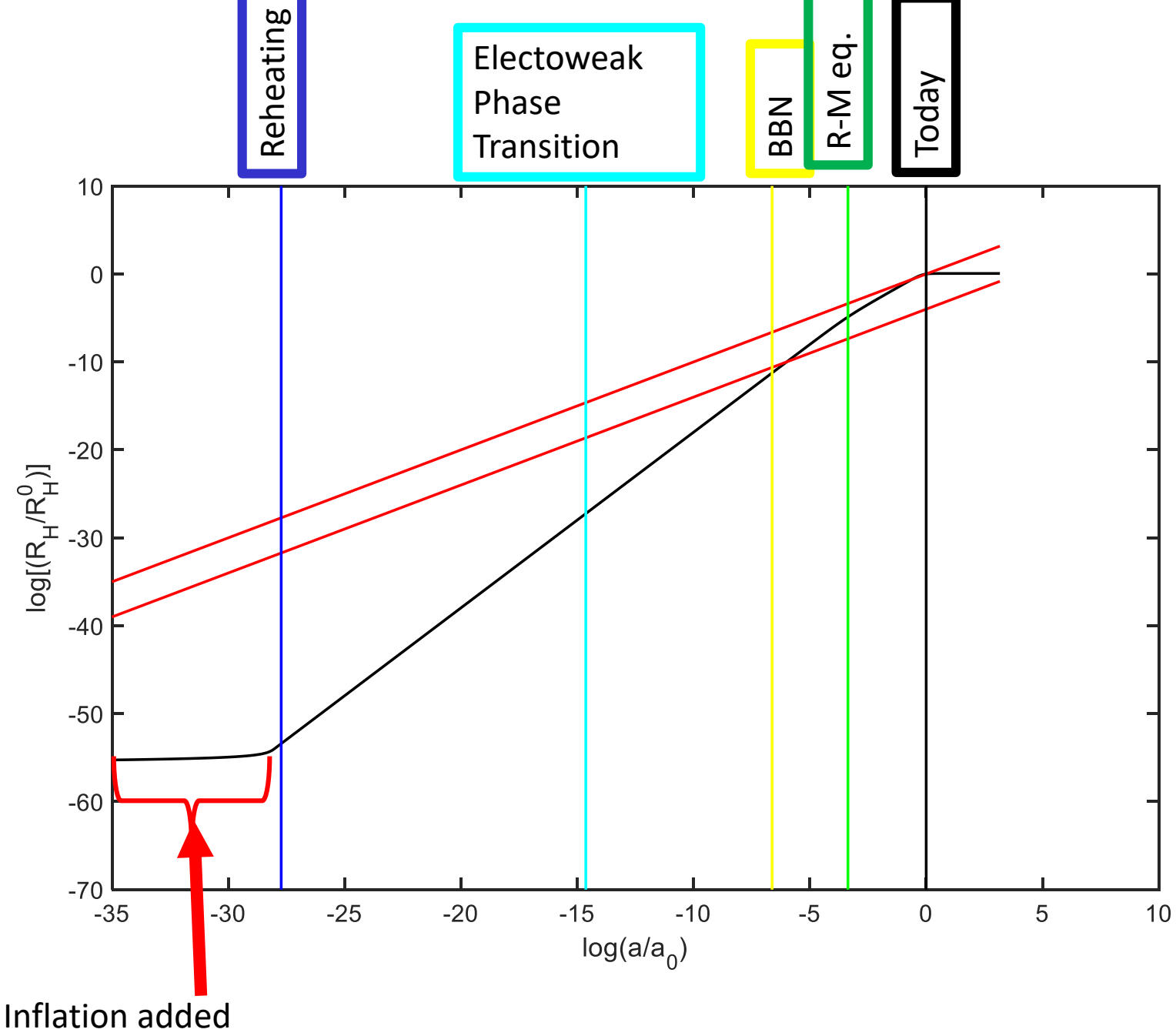
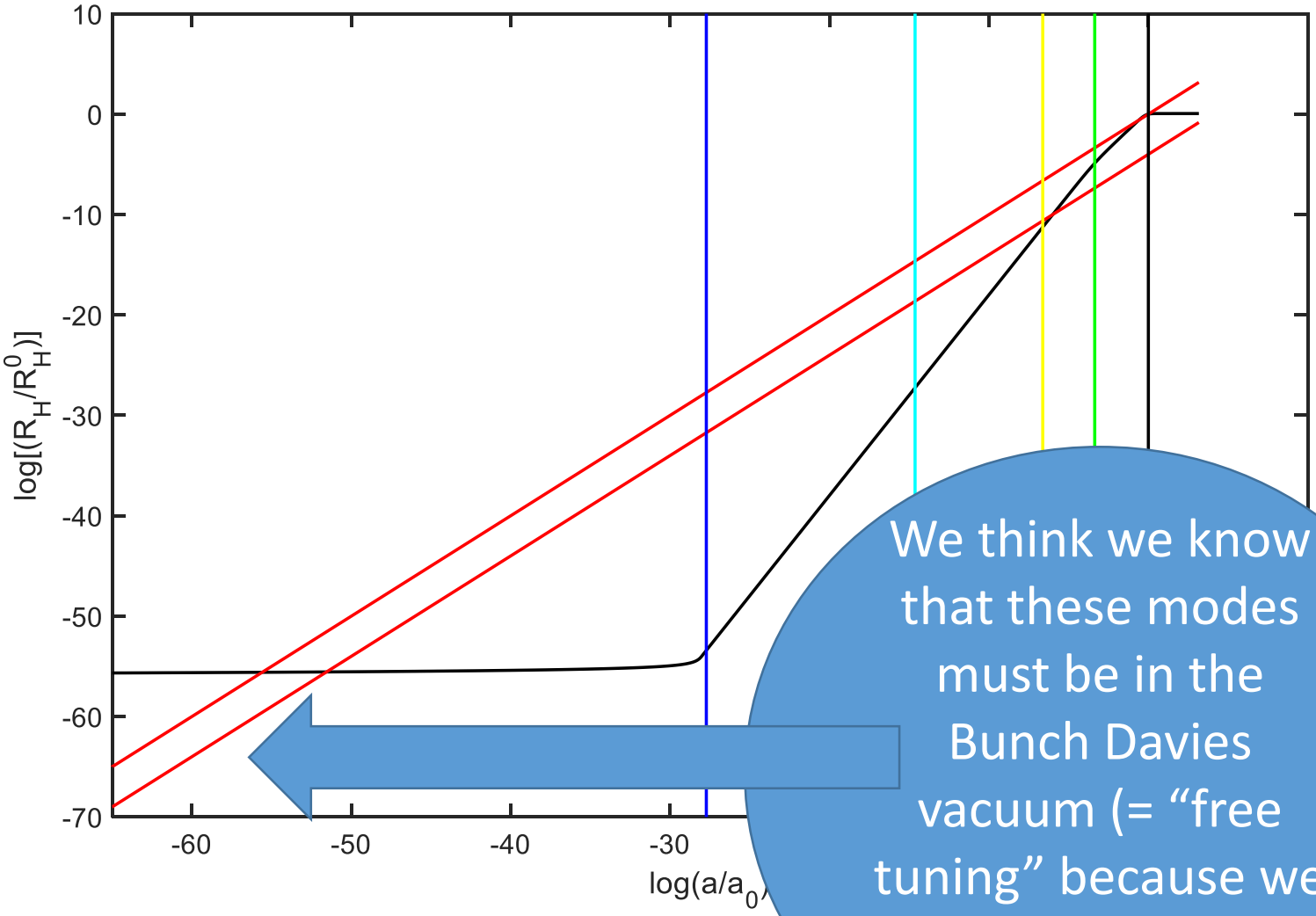



Reheating
Electoweak
Phase
Transition
BBN
R-M eq.
Today
10
0
-10
-20
-30
-40
-50
-60
-70
log[(R_H/R_H^0)]
-35
-30
-25
-20
-15
-10
-5
0
5
10
log(a/a_0)
Inflation added



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Compare with formal debate about tuning (see Hernley, AA and Dray 2013)

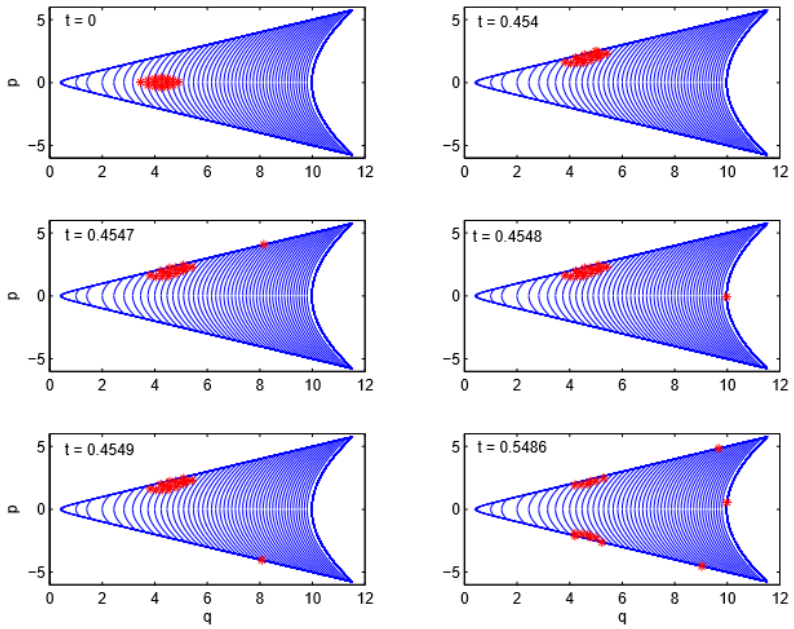

FIG. 10. Short squeeze duration in the BPS model: A patch started at $t = 0$ (as shown in upper-left) will spend most of its time away from squeezed and barrier regions. As the squeezed region is approached small parts of the patch will move rapidly through to the other side. The time marked on each panel shows the different time scales involved. The patch is represented by a finite collection of points. A more continuous treatment would show the patch stretched very thinly along the trajectories followed by the isolated points.

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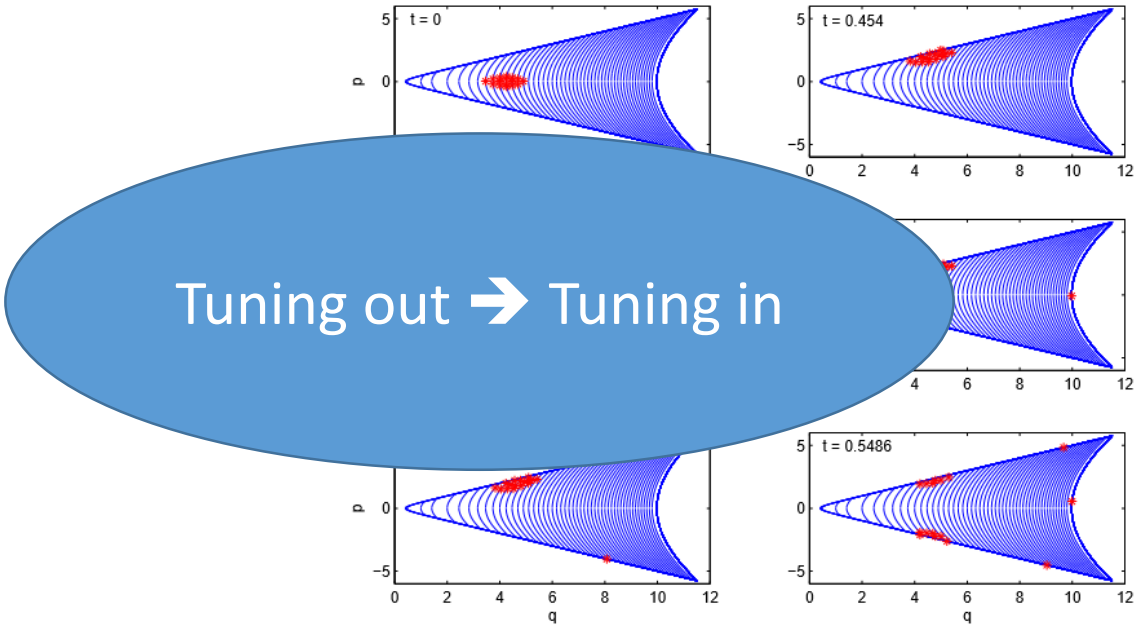

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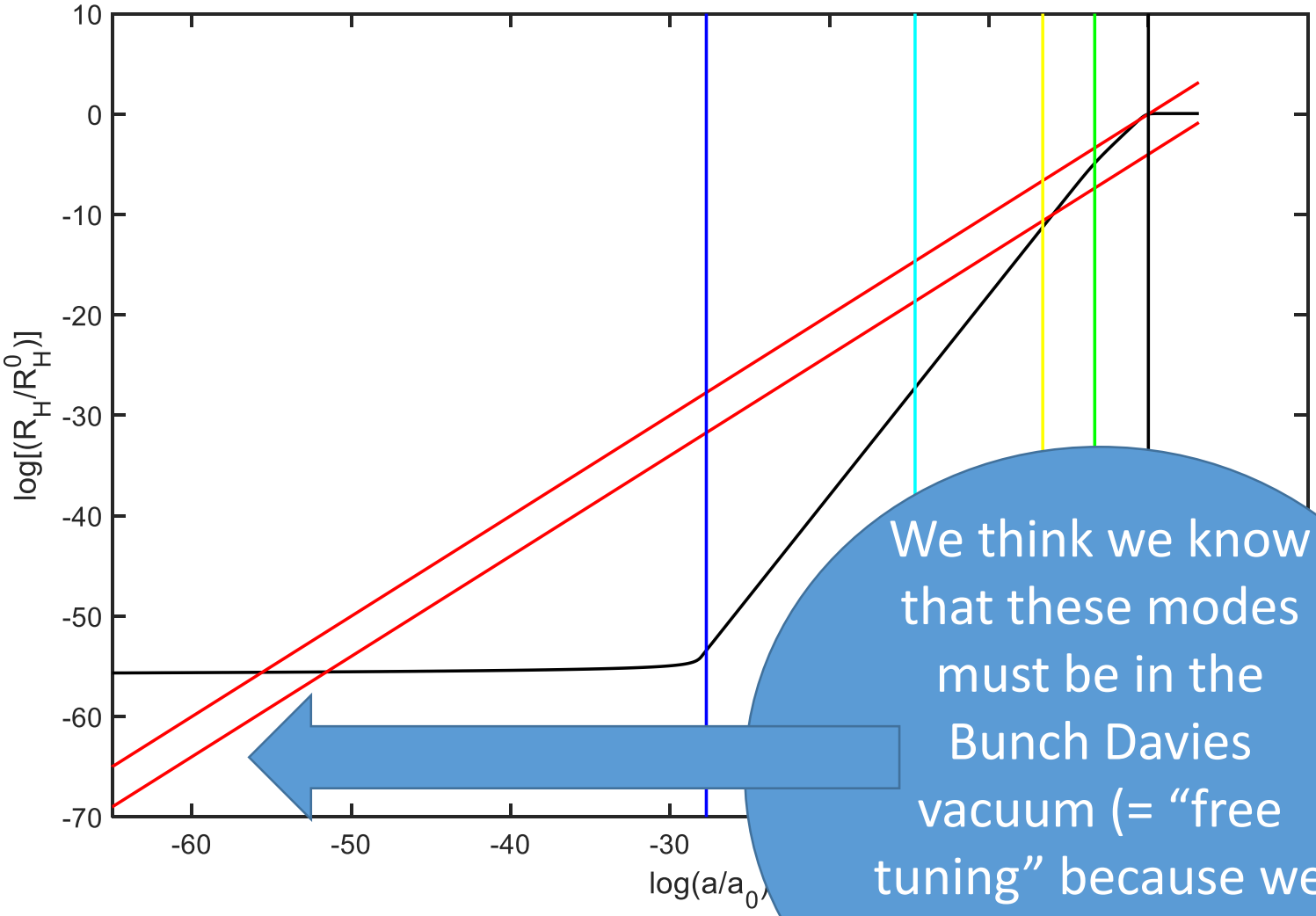

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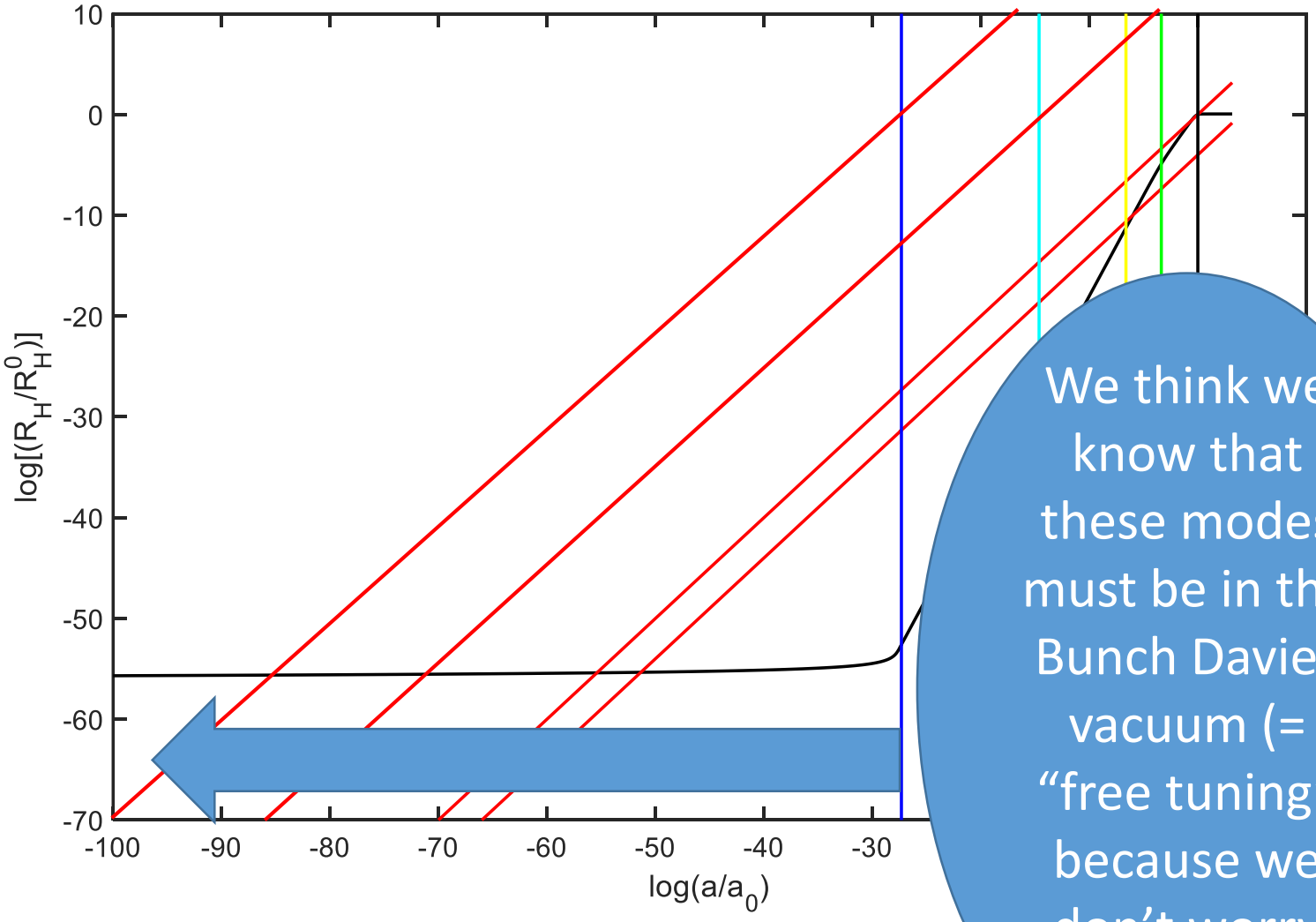

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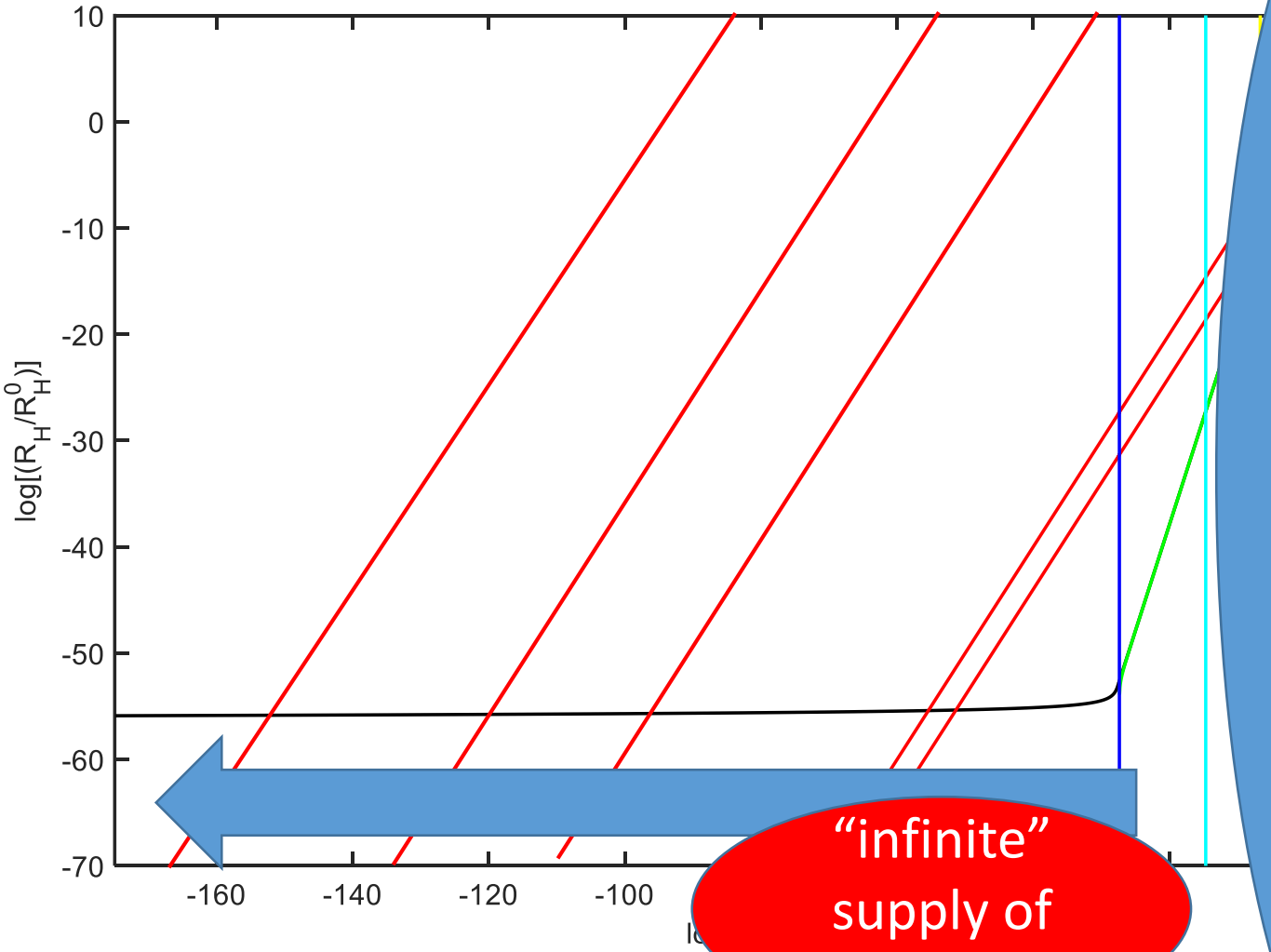

"infinite" supply of tuning

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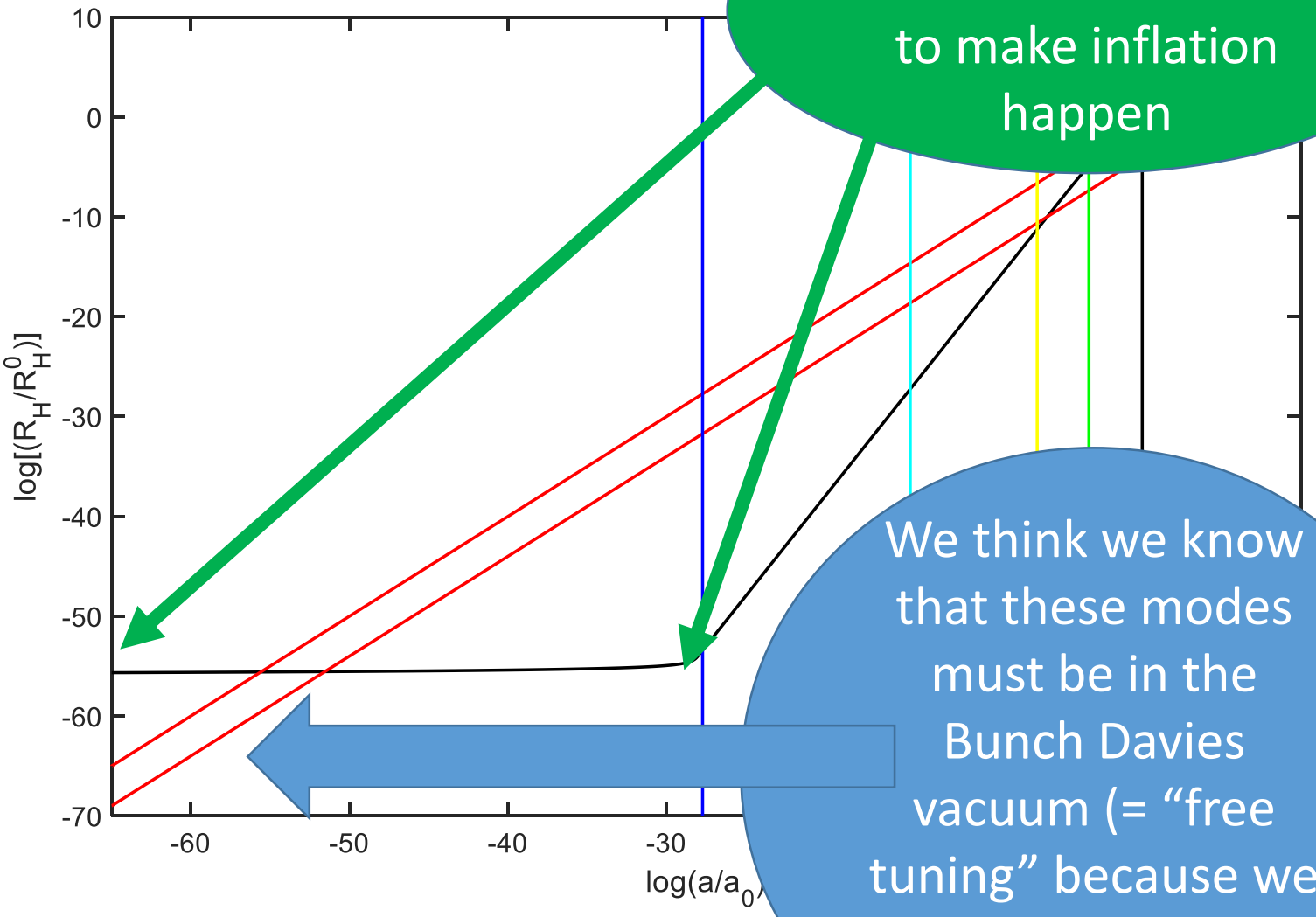
VOLUME 48, NUMBER 17 PHYSICAL REVIEW LETTERS 26 APRIL 1982

Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking

Andreas Albrecht and Paul J. Steinhardt
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 25 January 1982)

isfied. Because the observed universe would be only a small portion of the total universe resulting from the extreme expansion of a small homogeneous region, the homogeneity puzzle is solved.



Entropy arguments still an issue re how to make inflation happen

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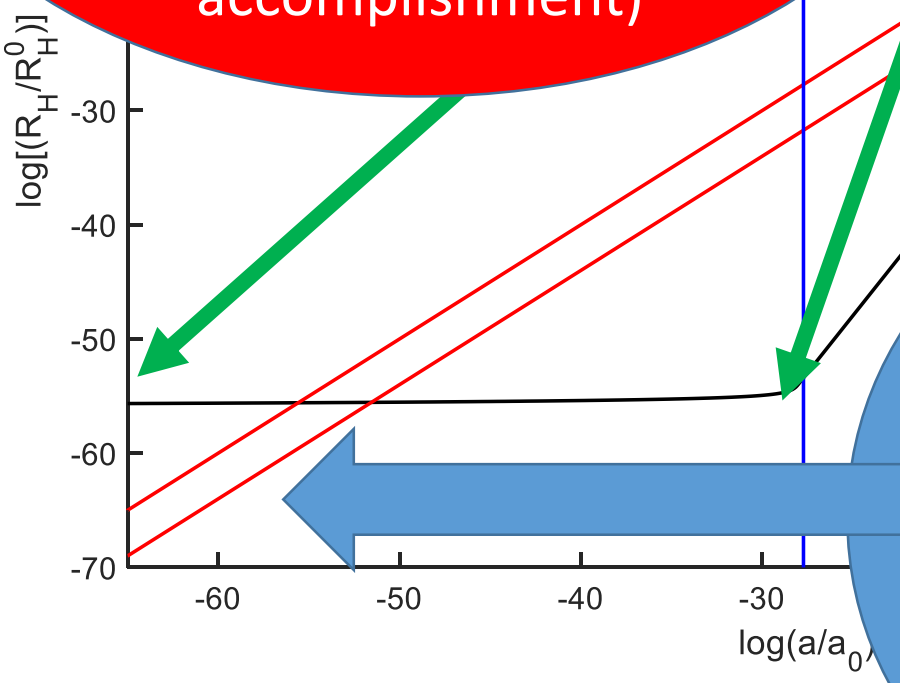

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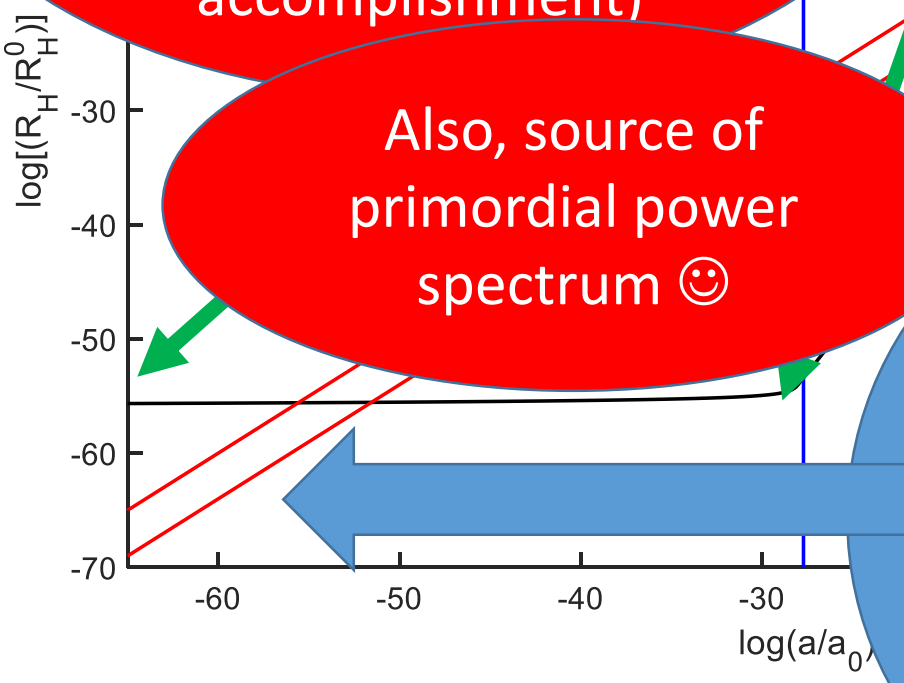

Also, source of primordial power spectrum ☺

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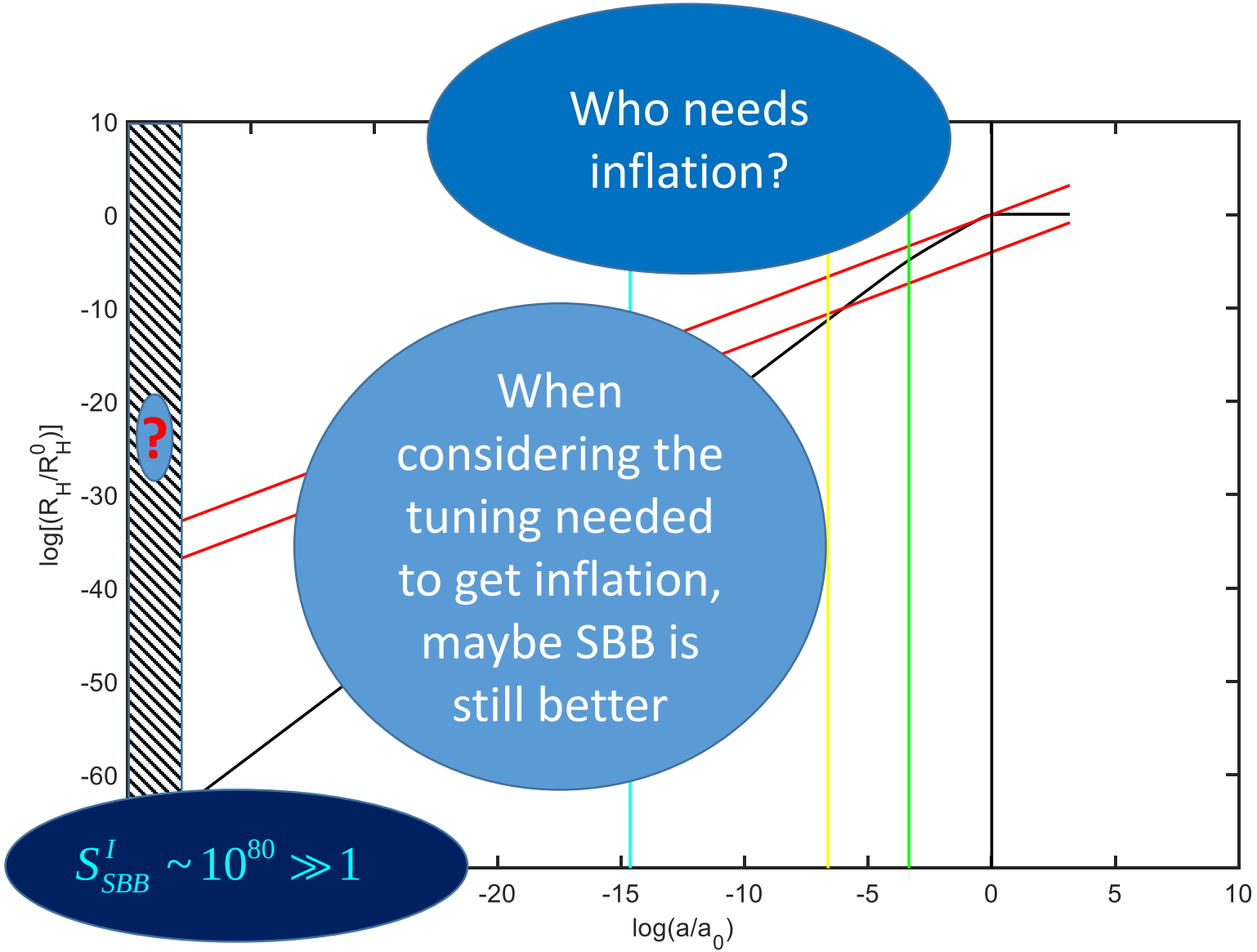
Who needs inflation?
When considering the tuning needed to get inflation, maybe SBB is still better
?
$S^{I}_{SBB} \sim 10^{80} \gg 1$
10
0
-10
-20
-30
-40
-50
-60
log[(R_H/R_H^0)]
-20
-15
-10
-5
0
5
10
log(a/a_0)

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- Bunch Davies Vacuum

ii) Measures

C) Connections to modern research into quantum gravity/fundamental physics

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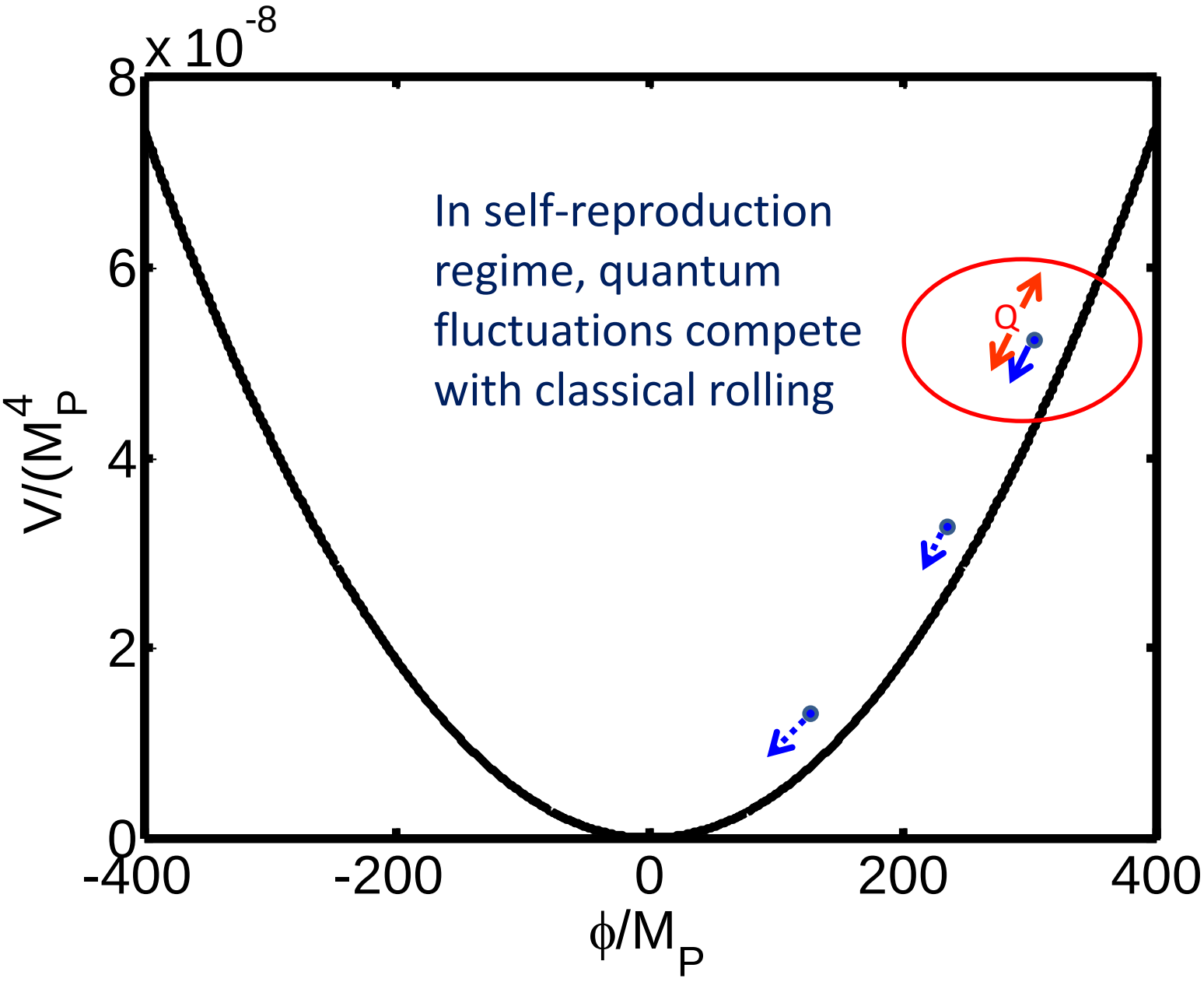
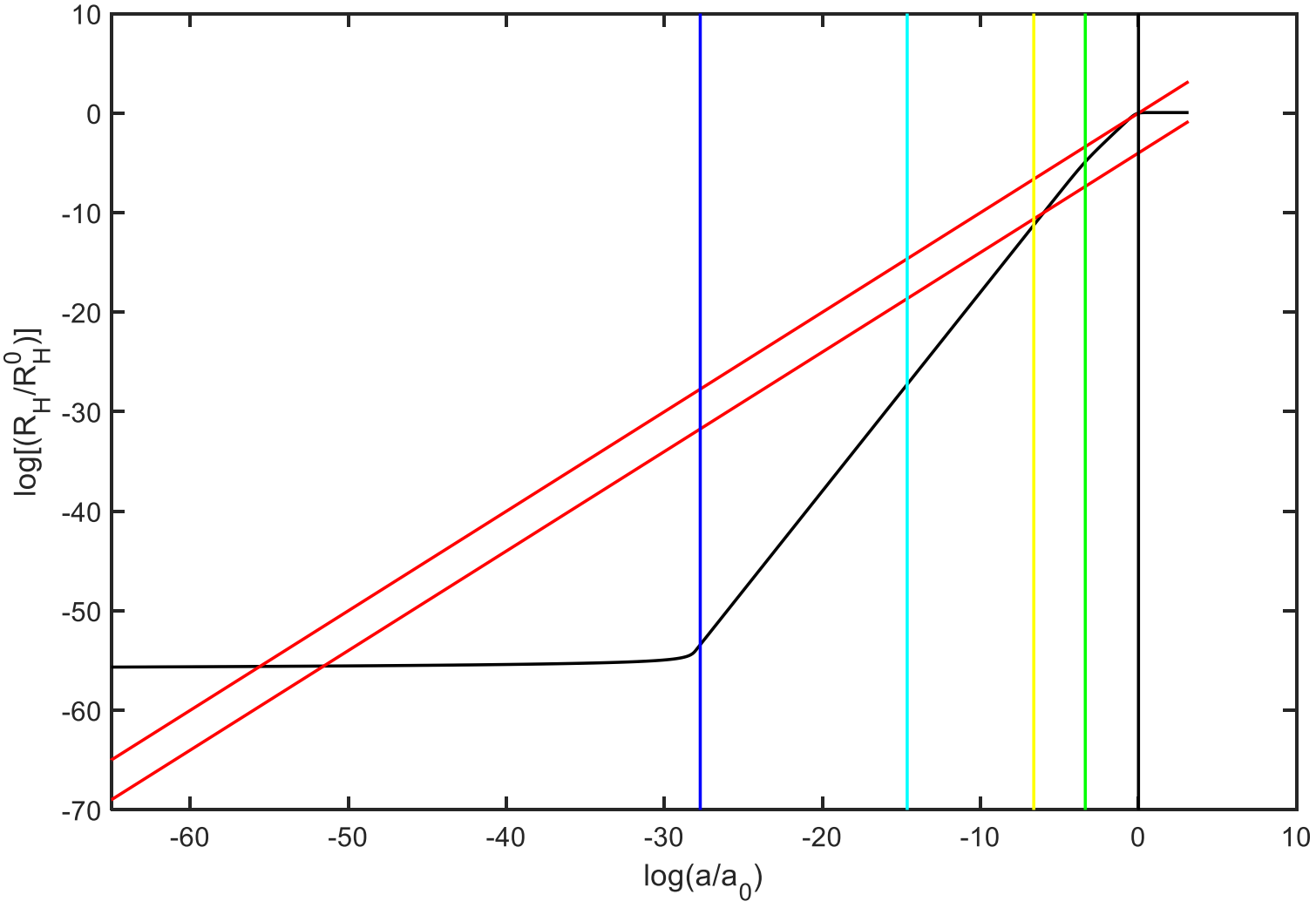
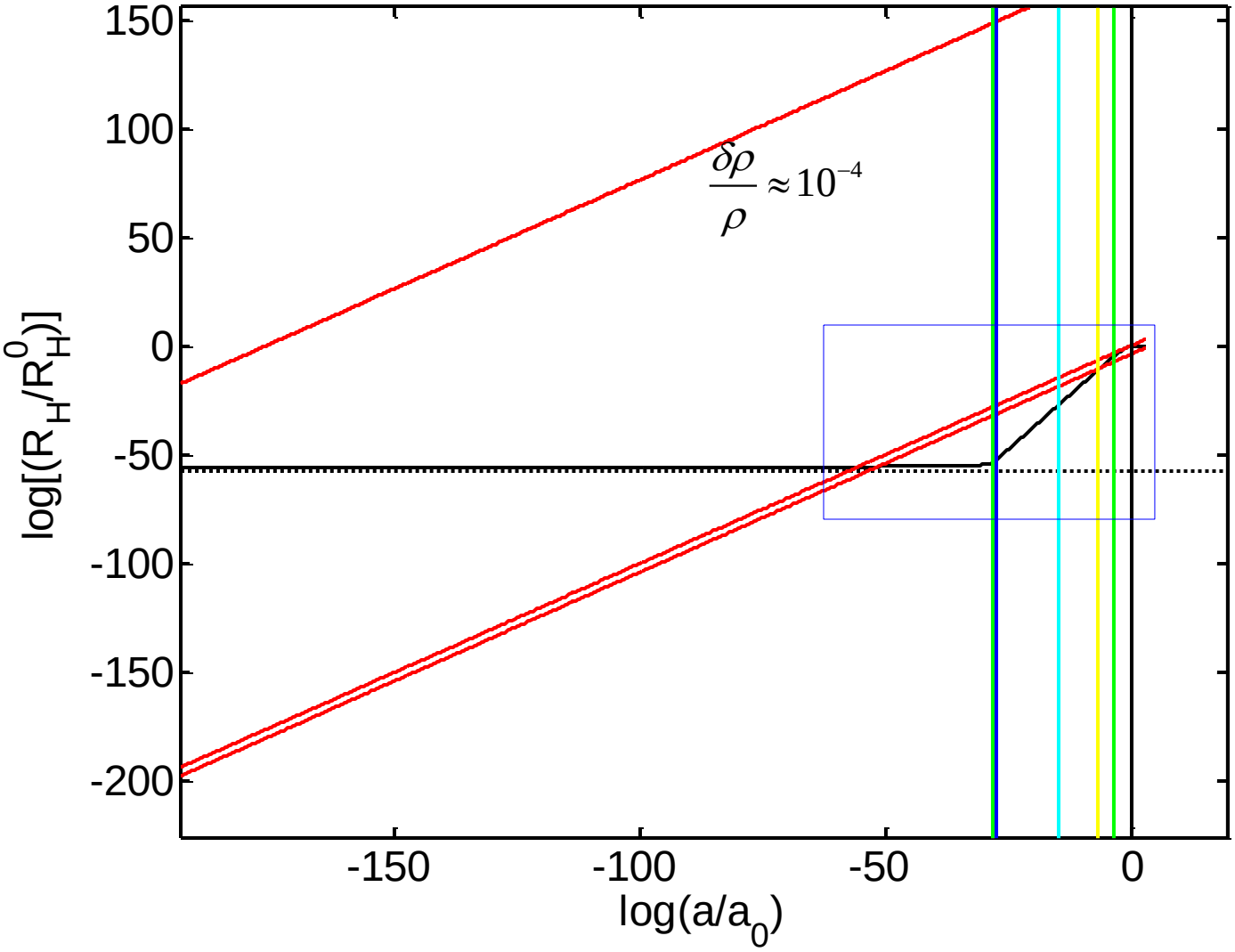

x 10^-8
8
6
4
2
0
V/(M_P^4)
-400
-200
0
200
400
φ/M_P
In self-reproduction regime, quantum fluctuations compete with classical rolling
Q

(not to scale)


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)

Evolution of Cosmic Length (zooming out)



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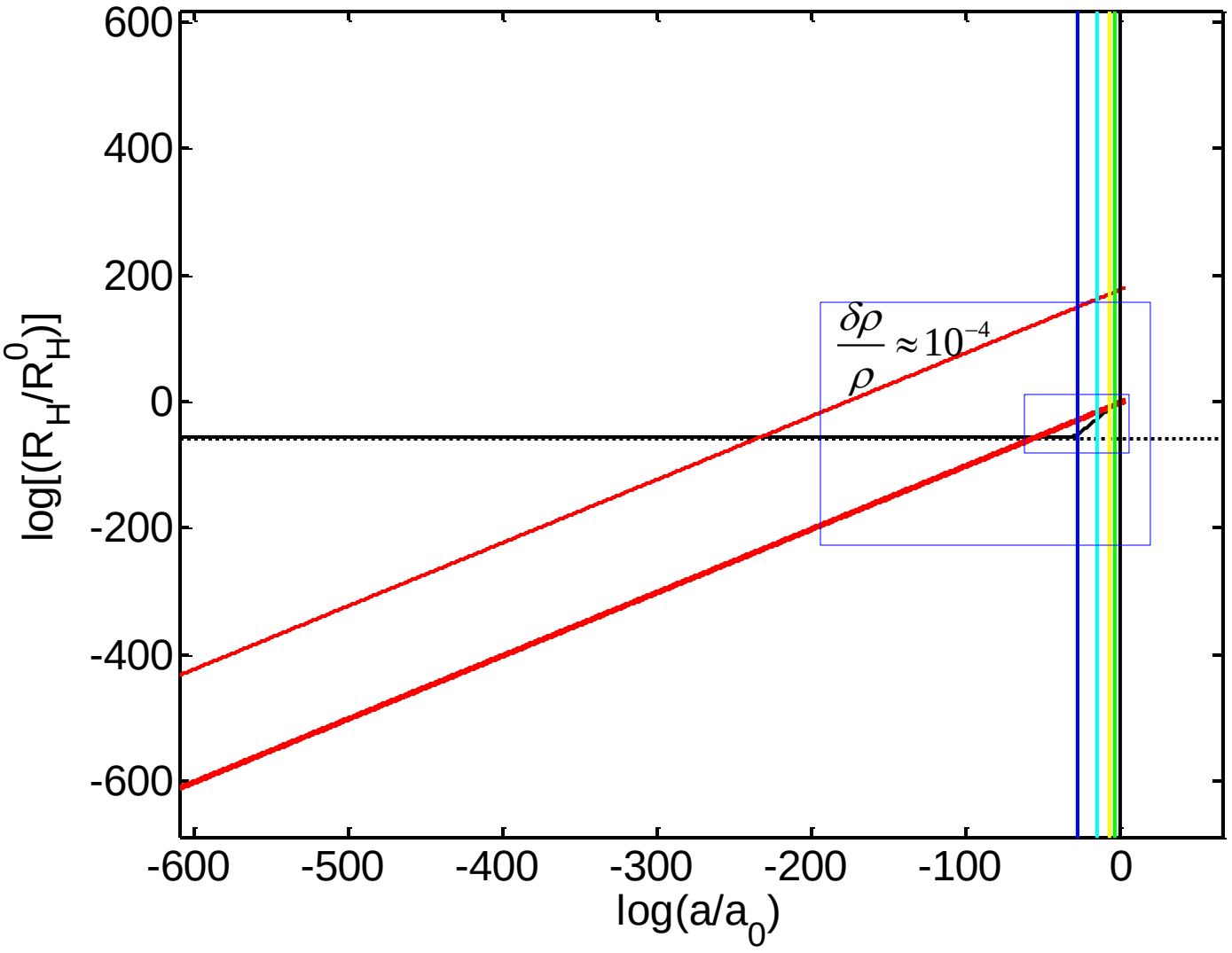

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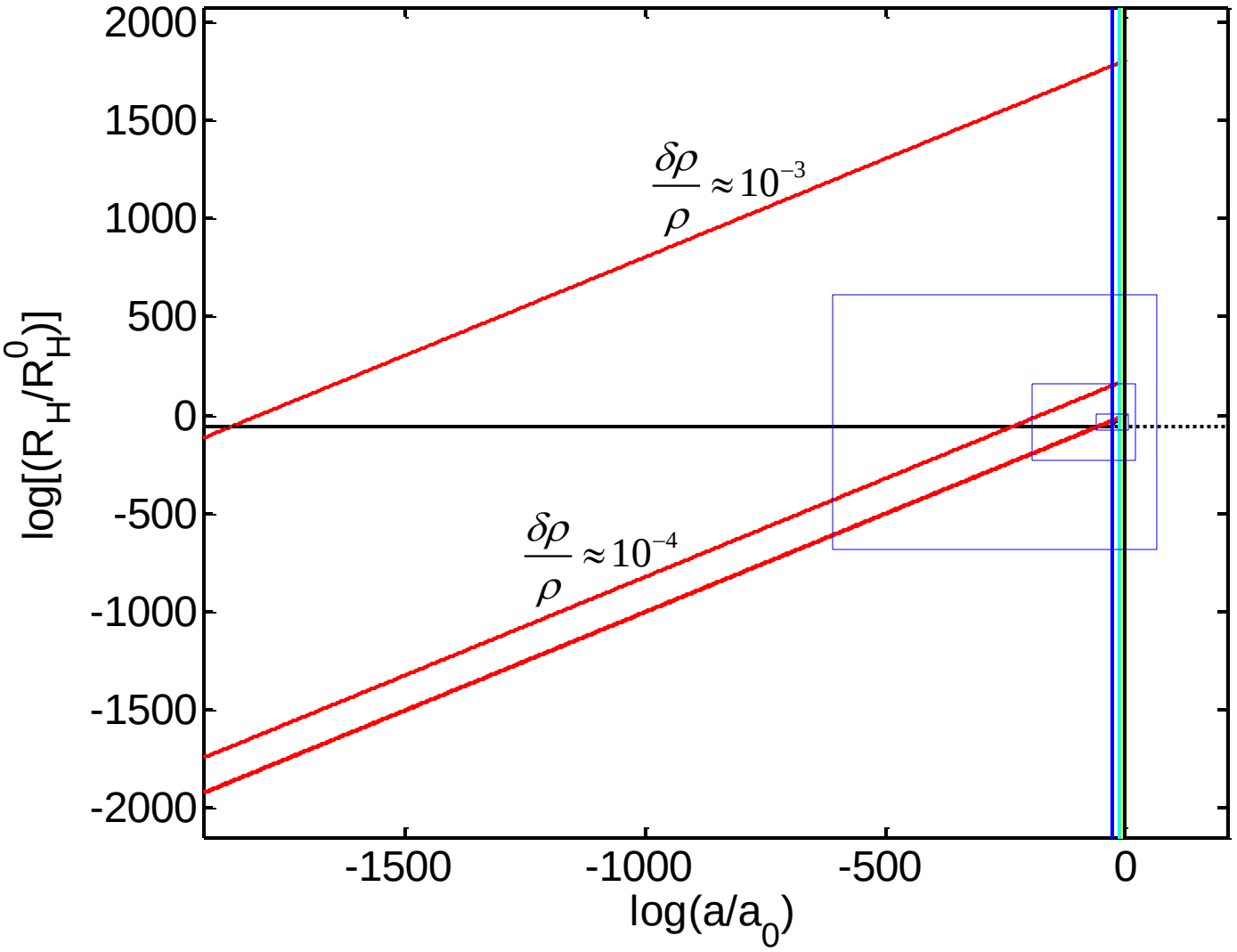

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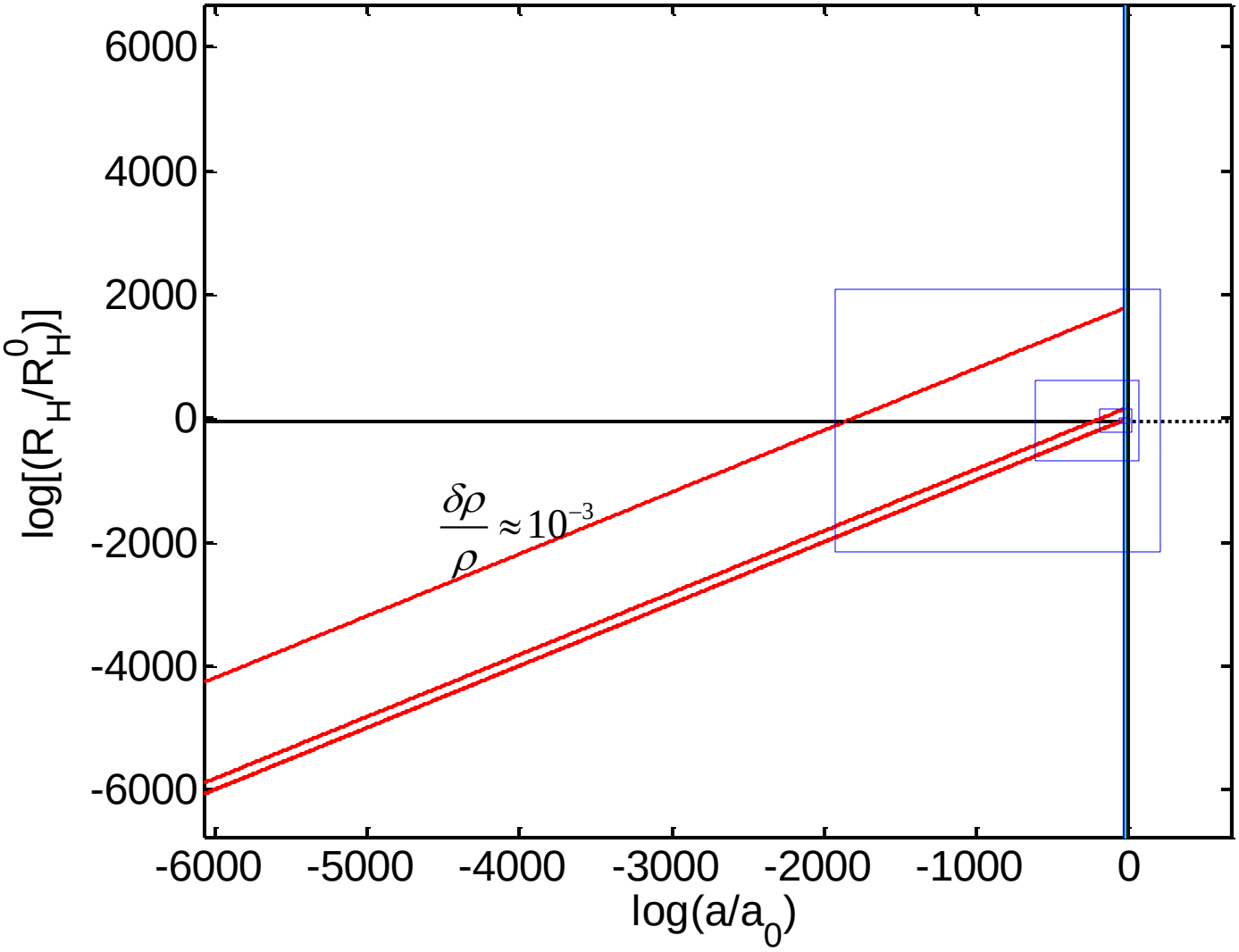

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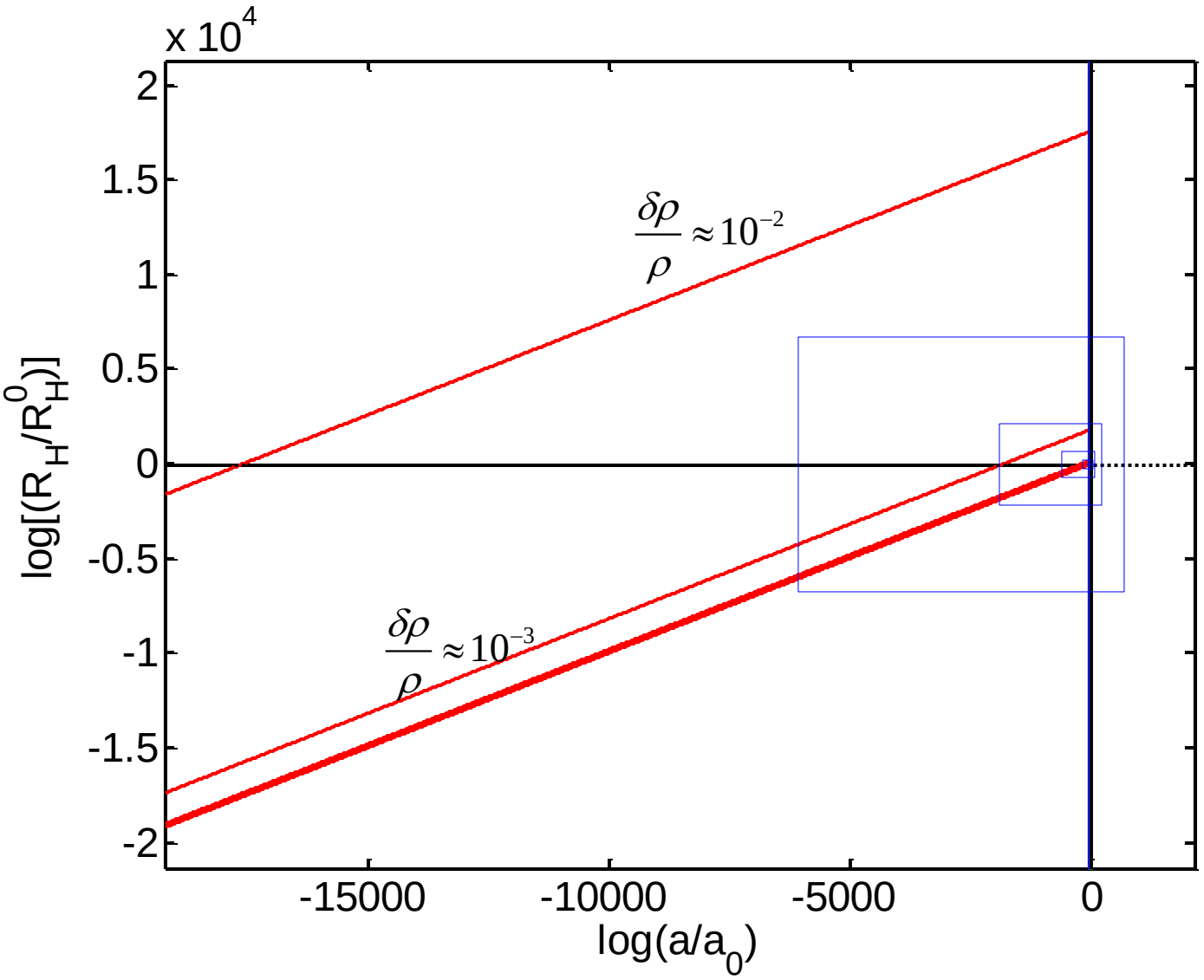

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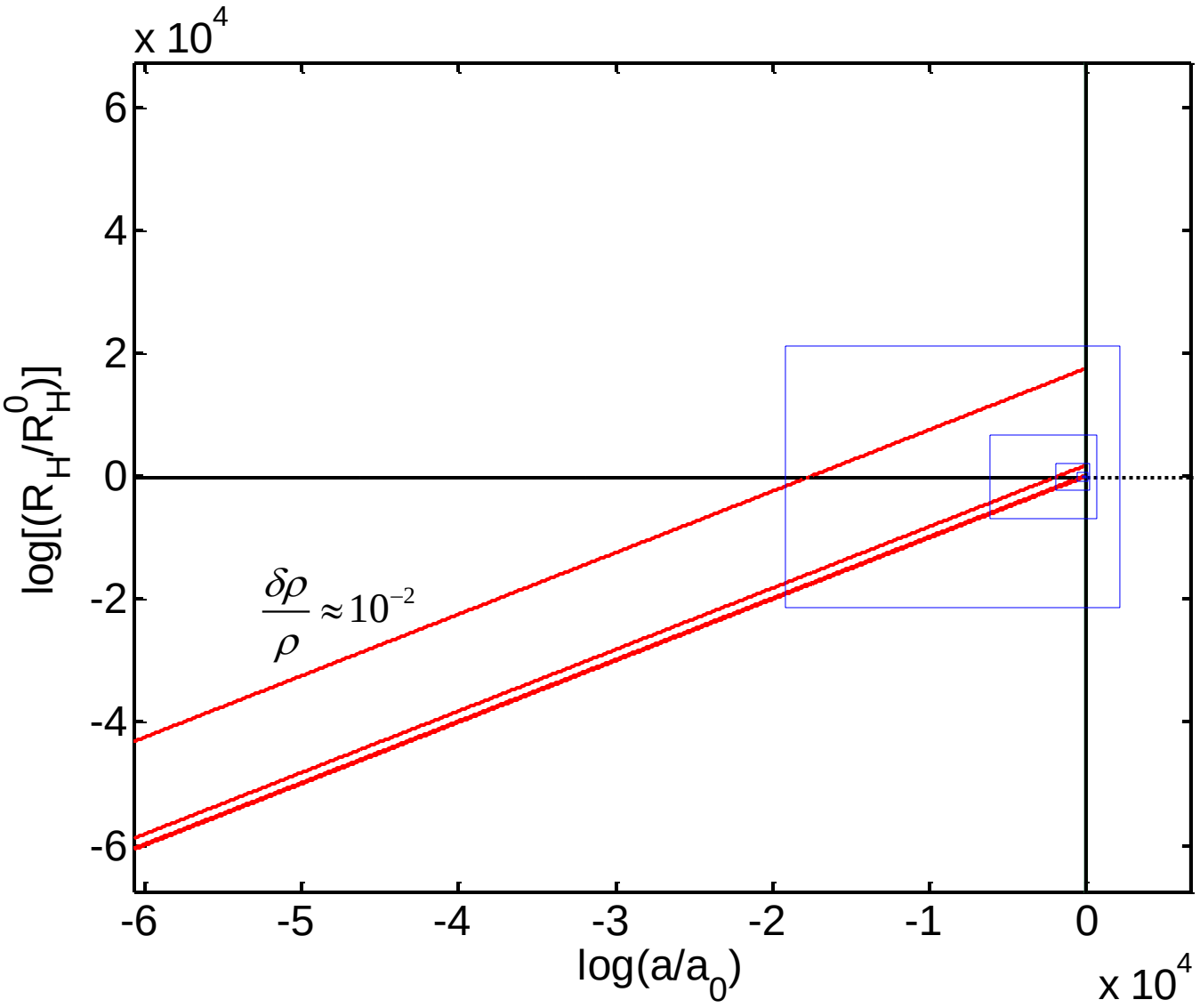

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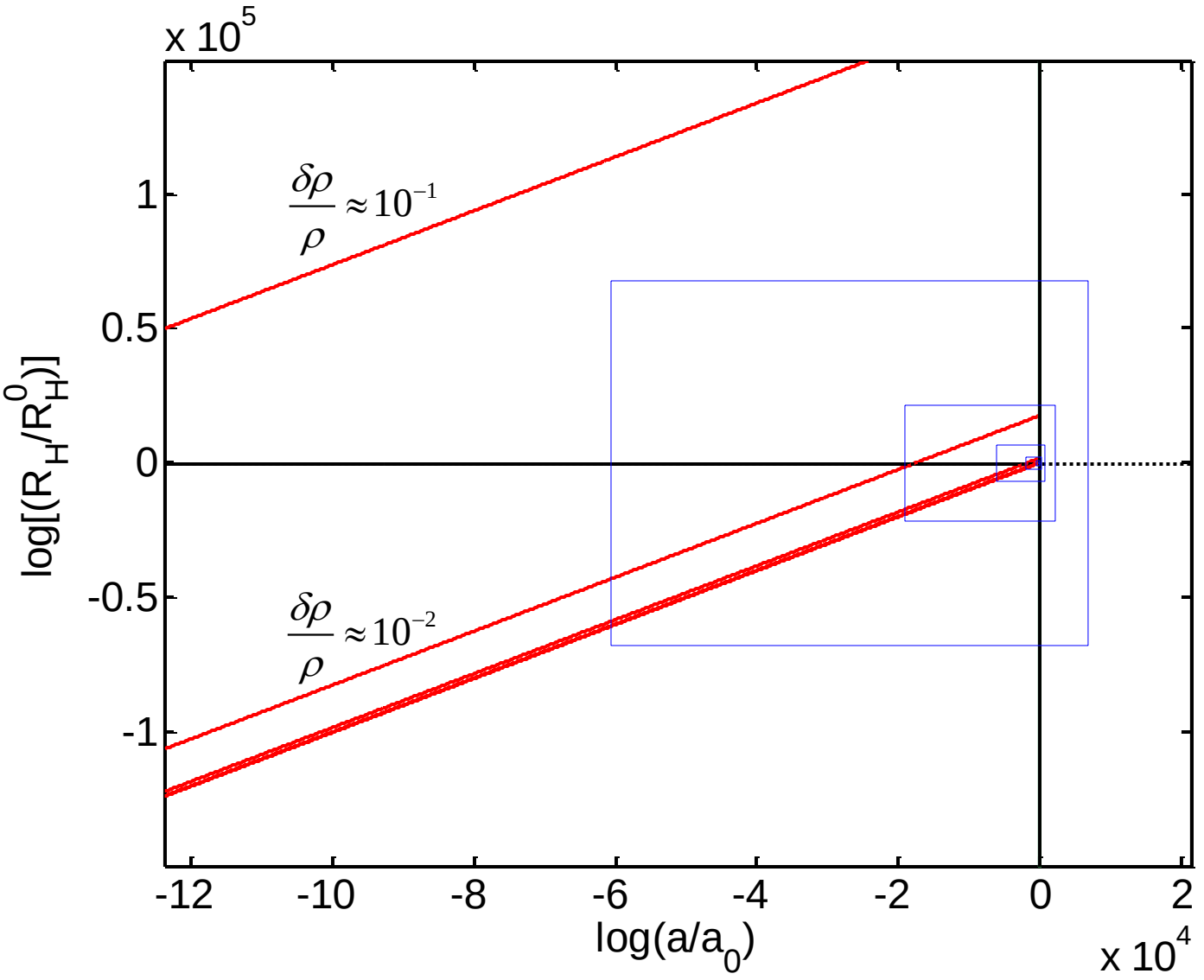

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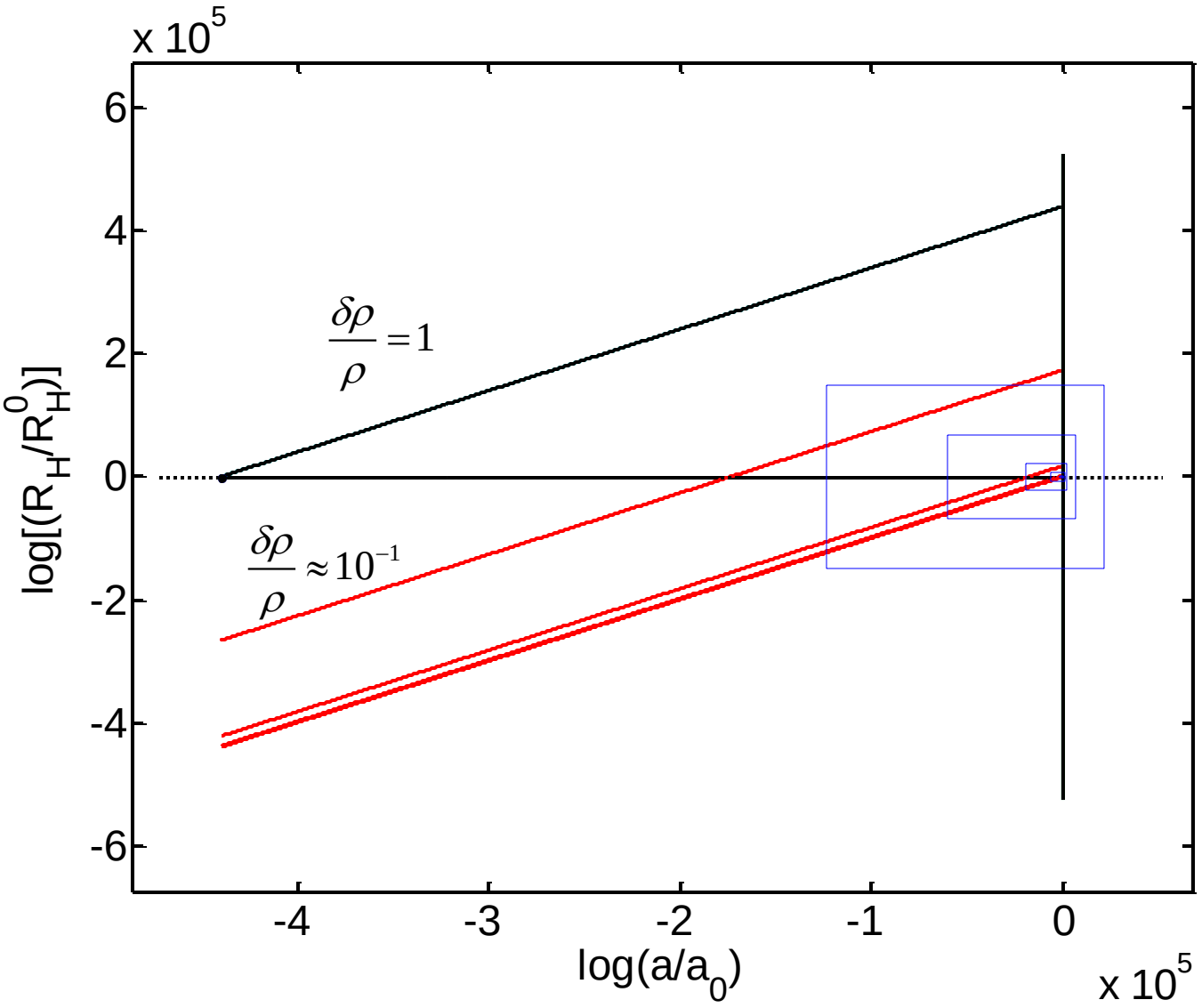

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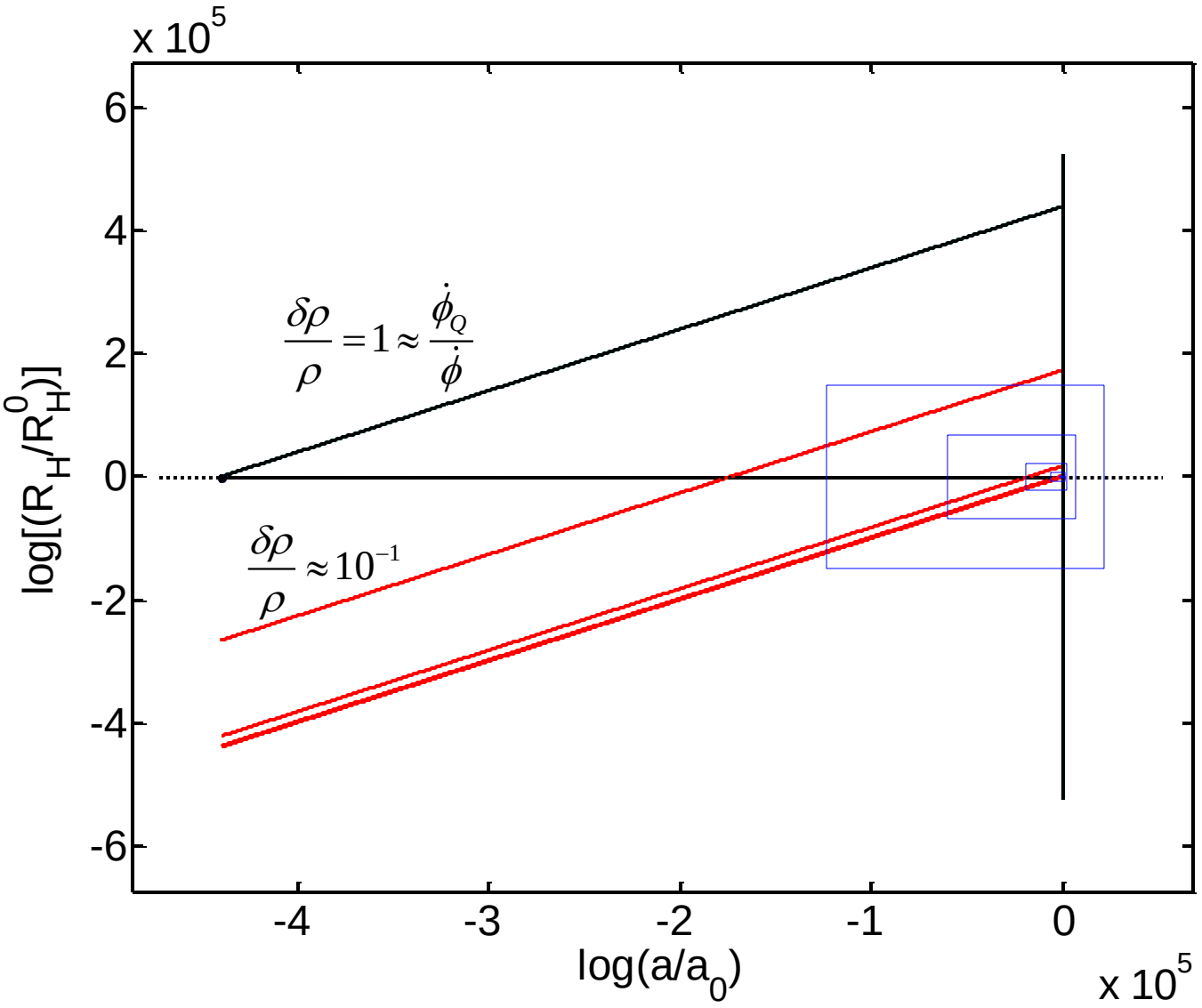

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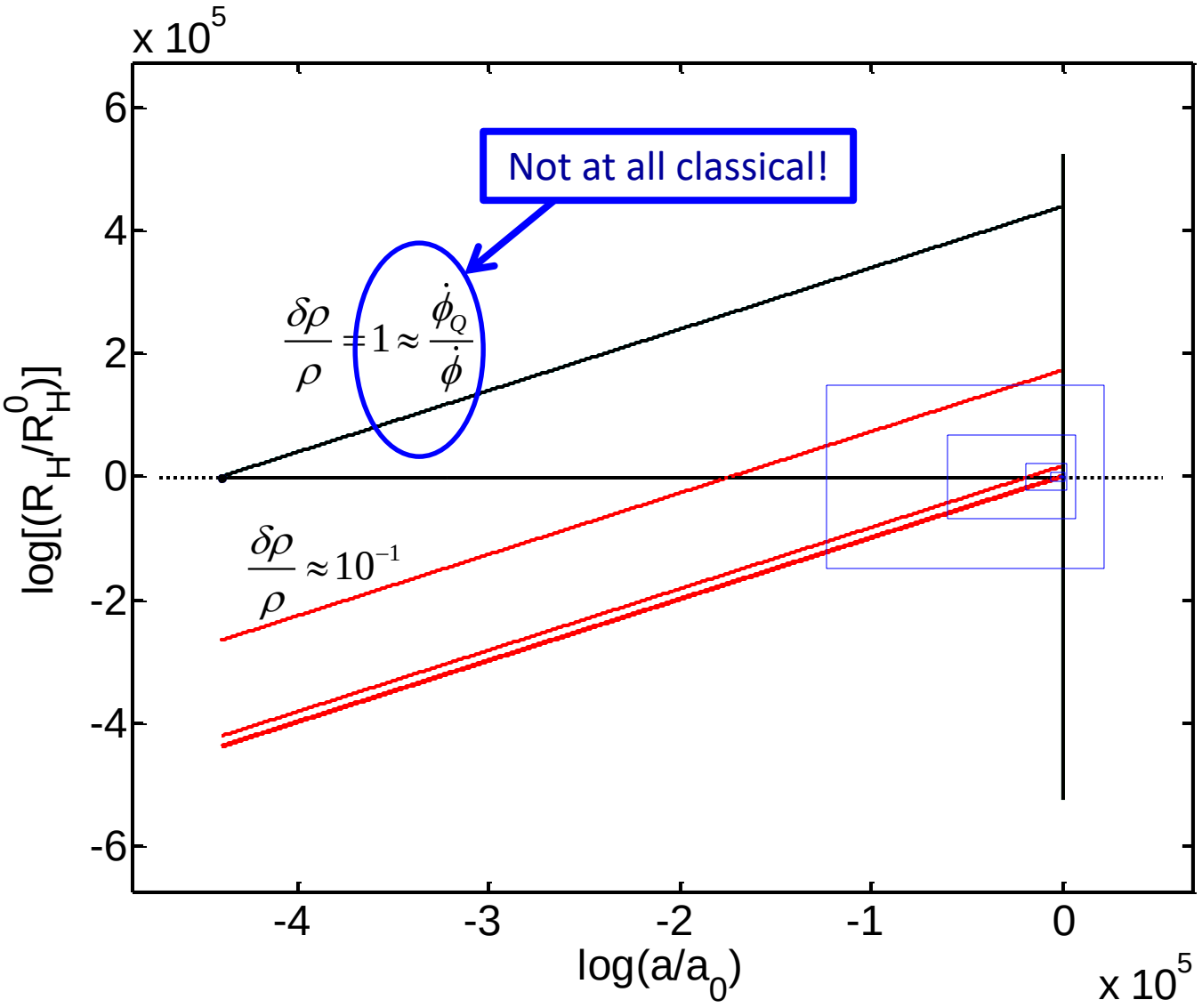
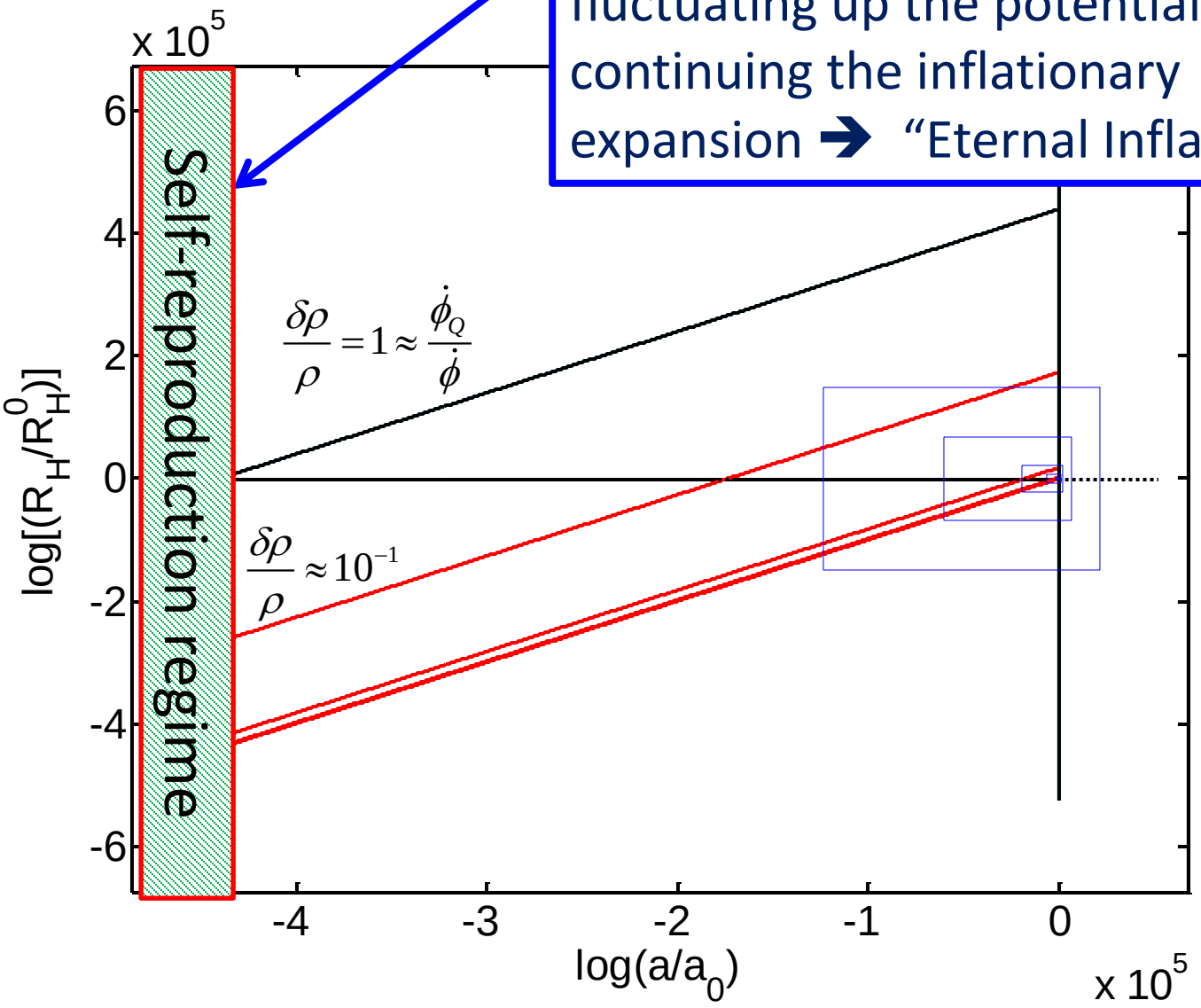
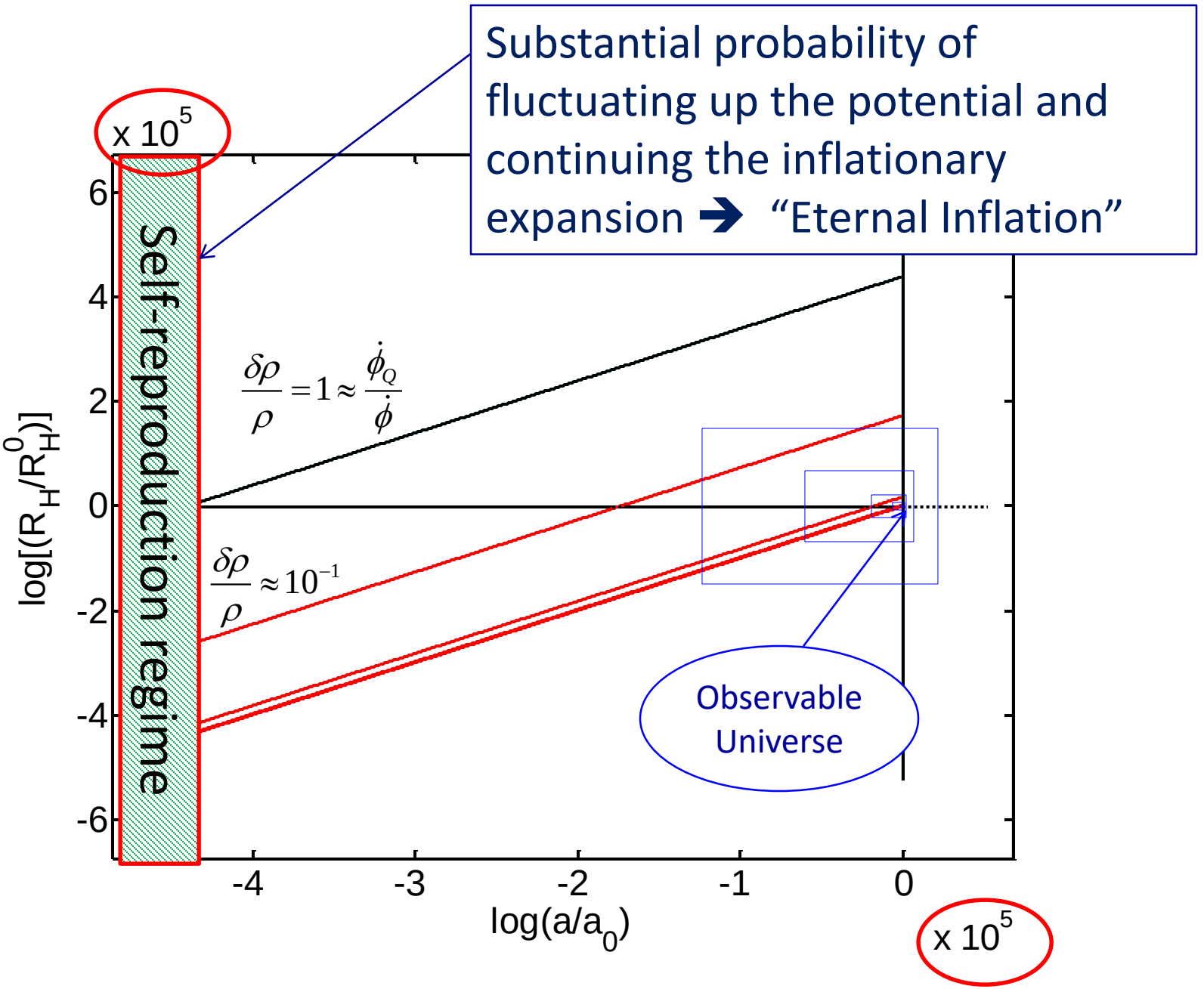


Substantial probability of fluctuating up the potential and continuing the inflationary expansion ➔ "Eternal Inflation"



Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others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6
4
2
0
-2
-4
-6
-4
-3
-2
-1
0
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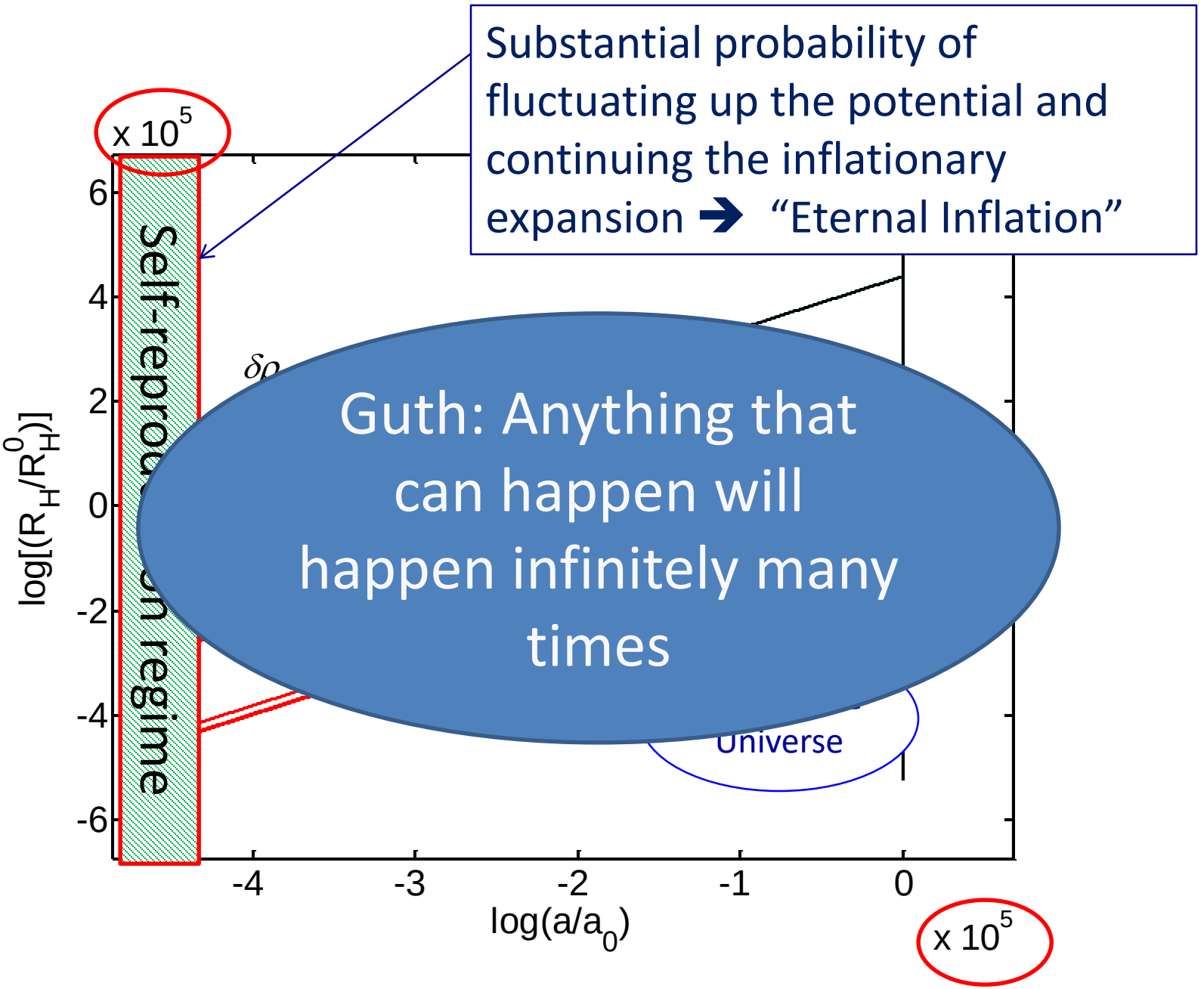

Guth: Anything that can happen will happen infinitely many times

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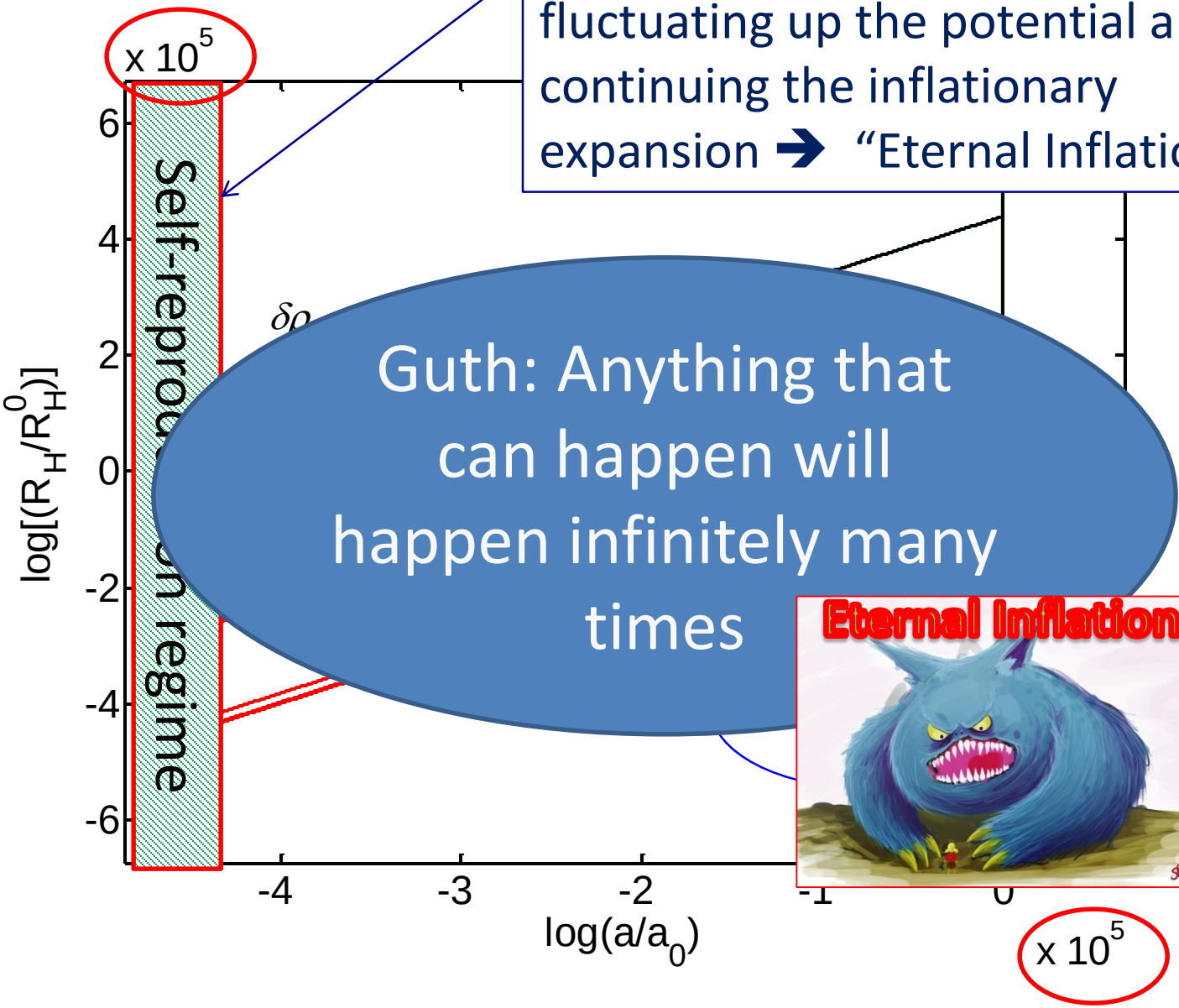

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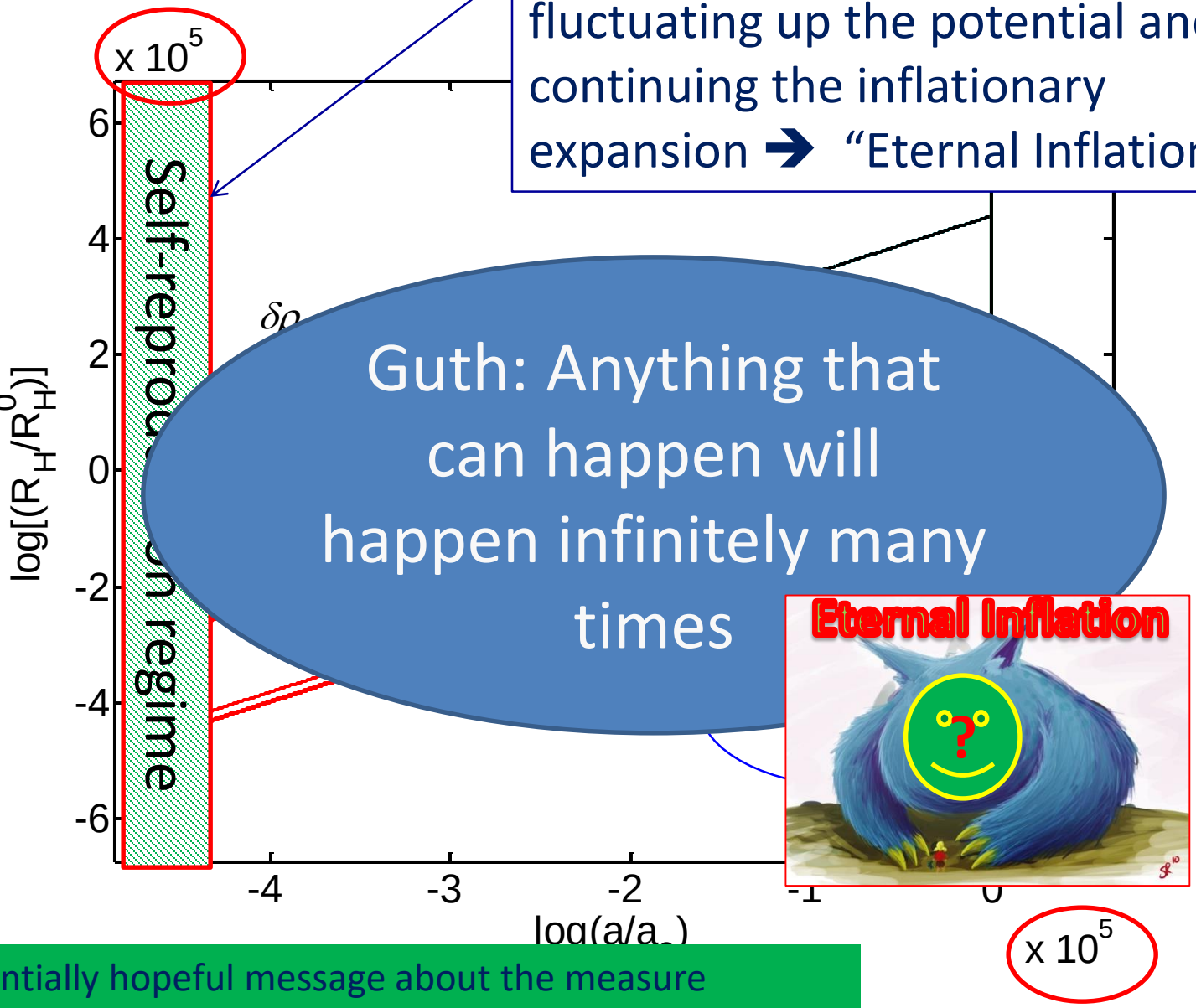

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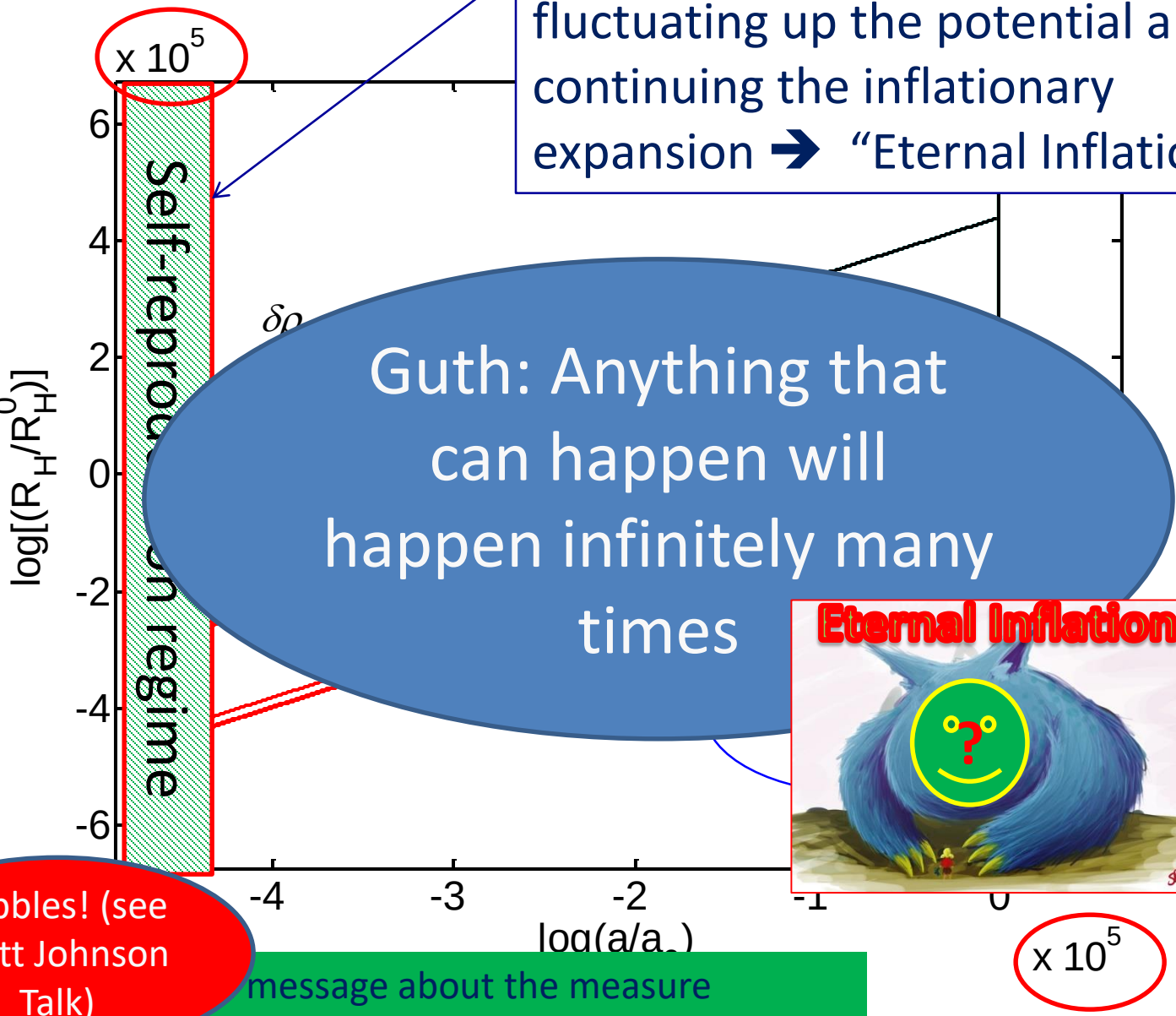
For a potentially hopeful message about the measure problem see arXiv:1212.0953 (More discipline about probabilities needed, counting not the answer)

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



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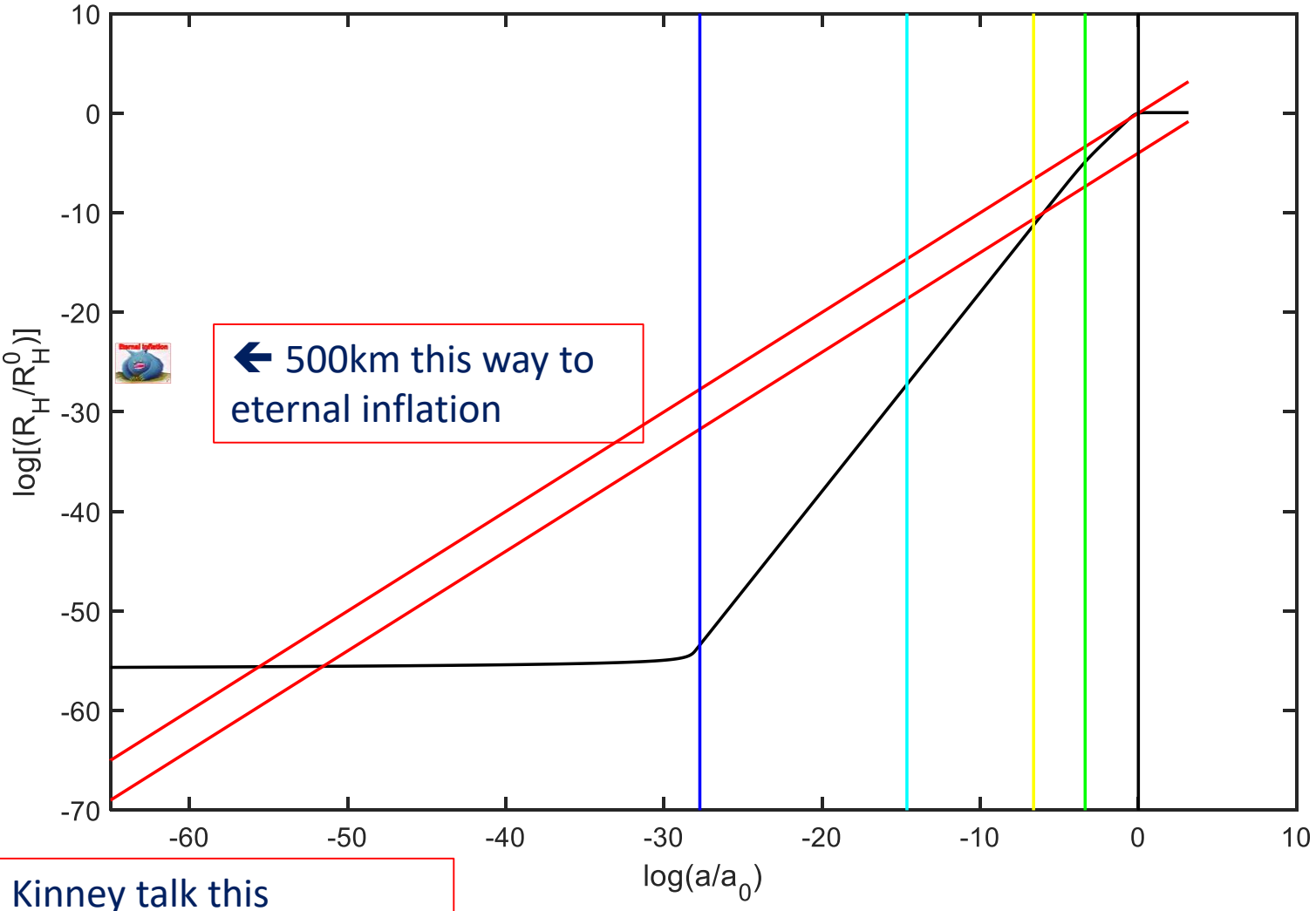
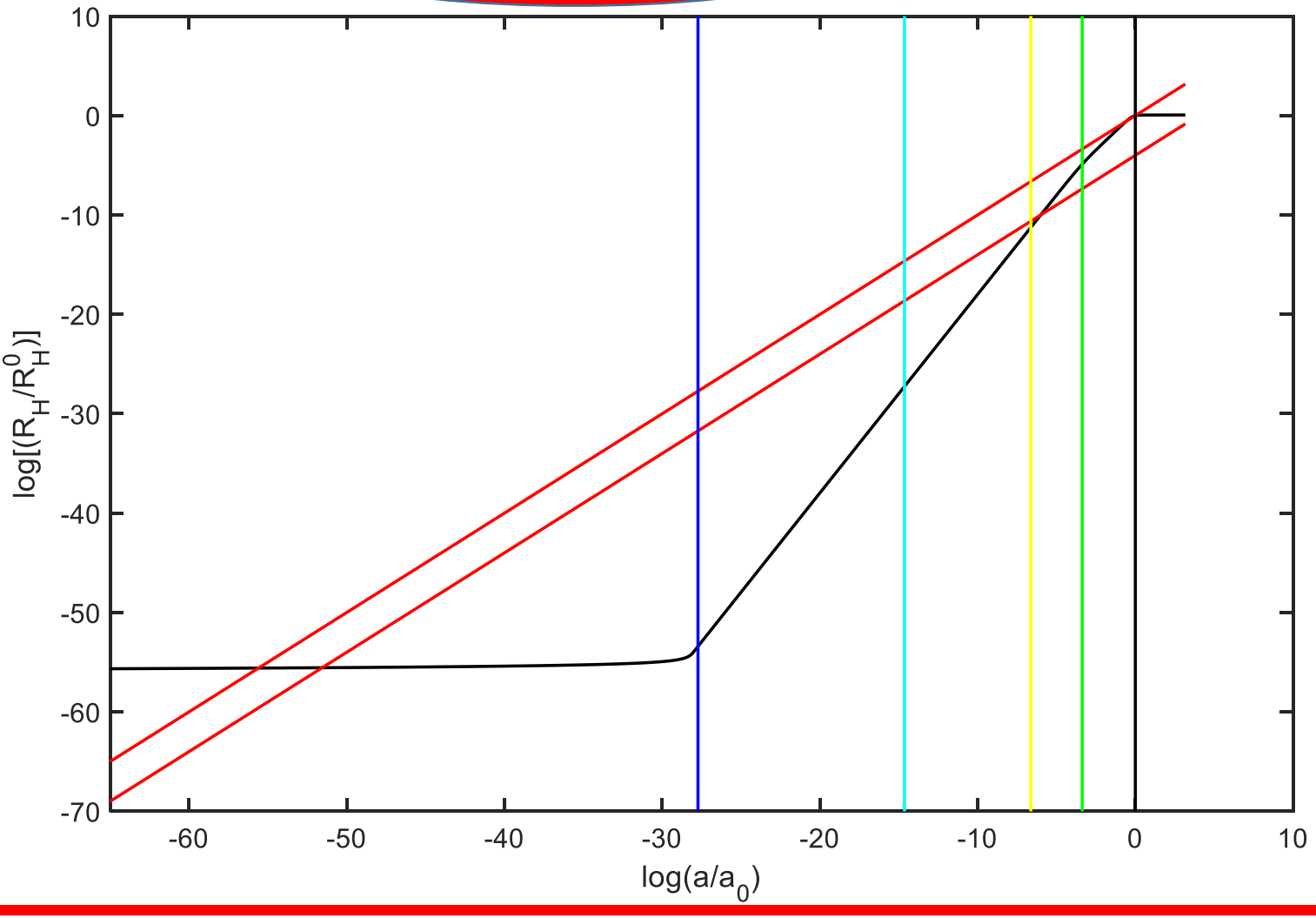
Bubbles! (see Matt Johnson Talk)

For message about the measure problem 1212.0953 (More discipline about probabilities needed, counting not the answer)



See Kinney talk this conference, Also comments by Katy Freese

Inflationary successes live here



Outline

A) Big questions about the cosmos

B) Open questions about cosmic inflation
   i) Tuning
      - Entropy perspective
      - Bunch Davies Vacuum
   ii) Measures

C) Connections to modern research into quantum gravity/fundamental physics

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Current questions

- What is the vacuum?, Firewalls
- Holography, AdS/CFT
- The nature of horizons, singularities
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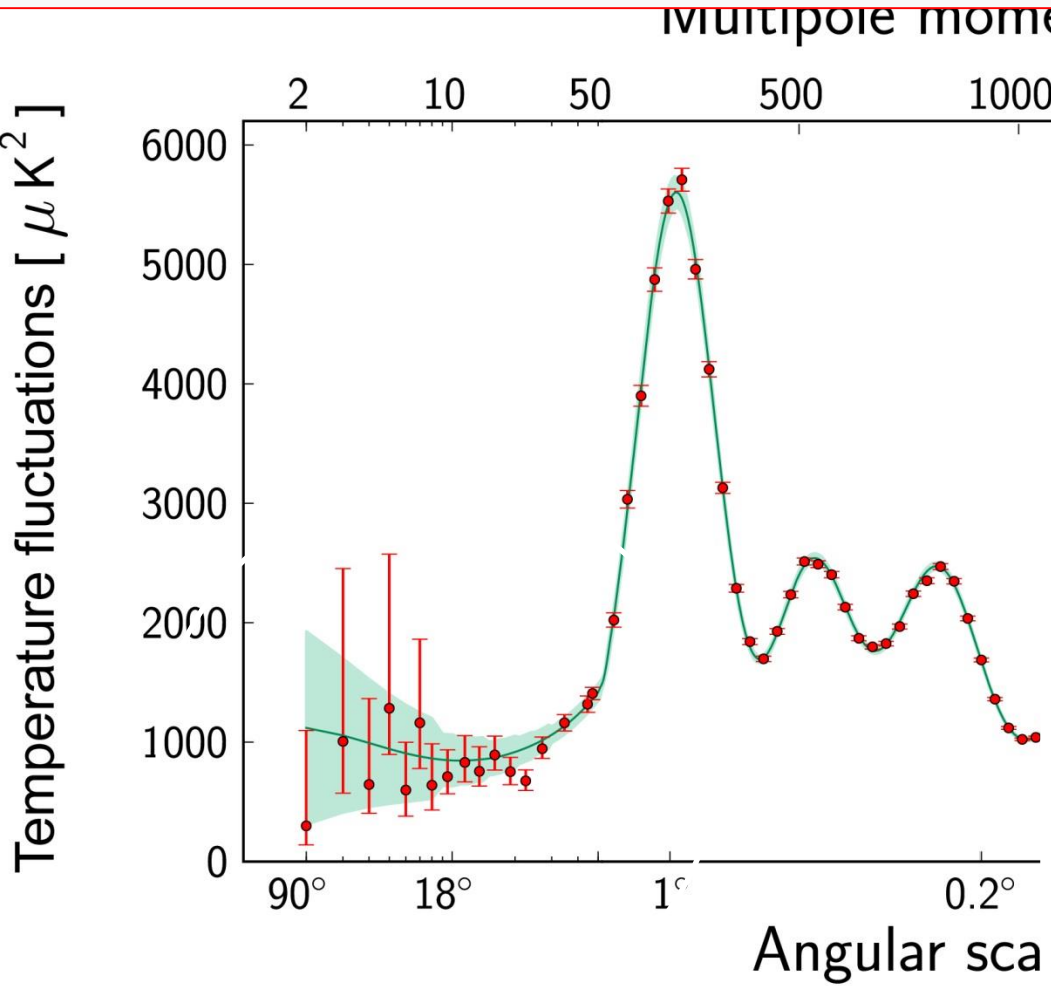
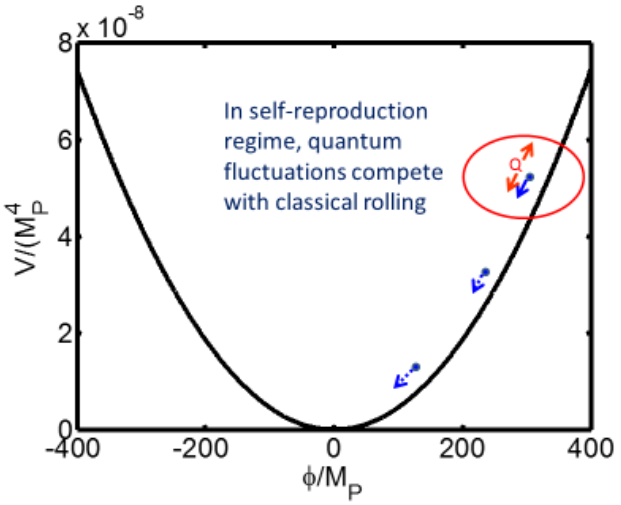
Inflation, and cosmology in general, have a deep capacity to link thes issues with observationa signatures.

Likely what is needed to resolve open questions with inflation

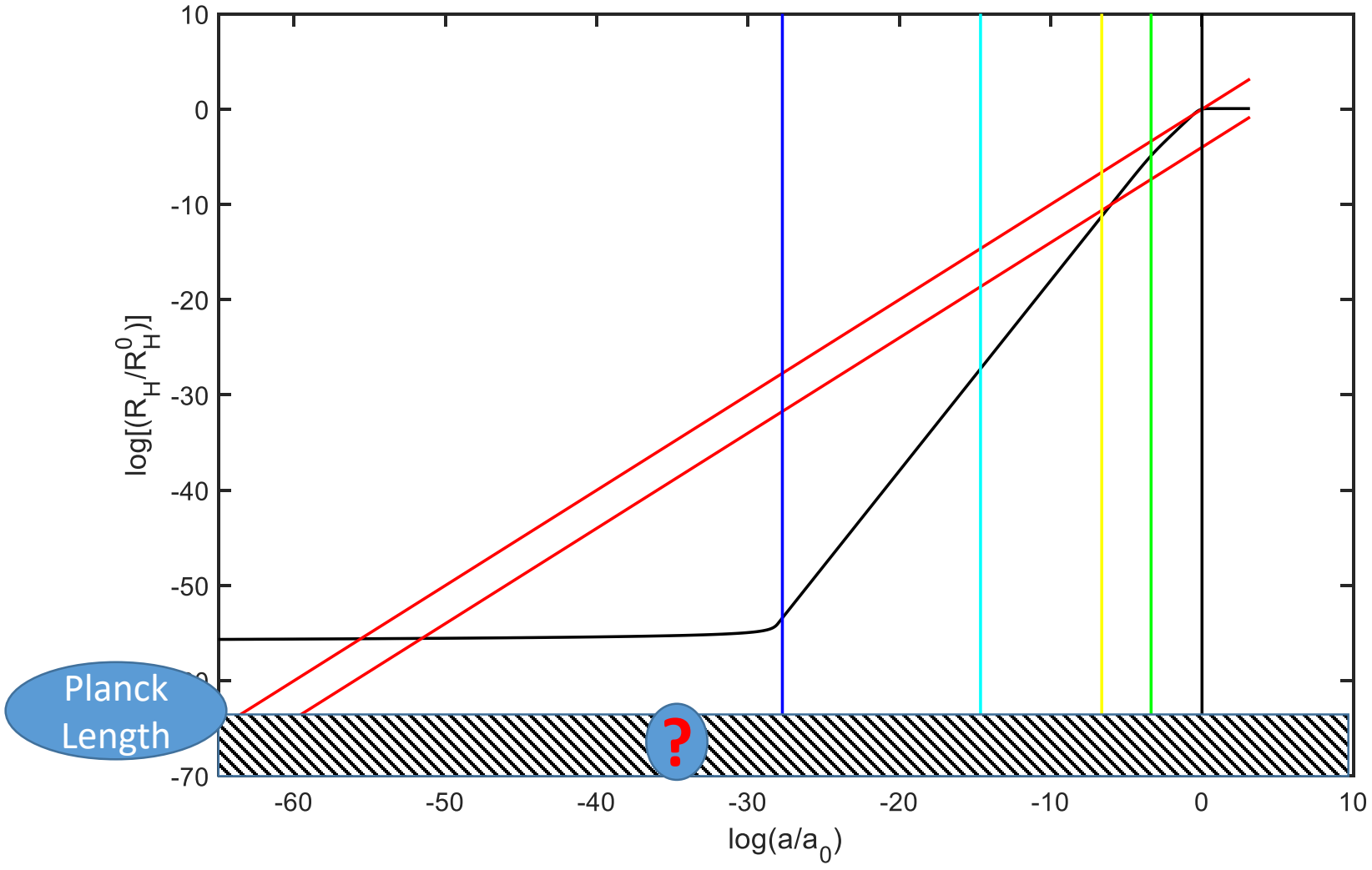
Starobinsky (2015): Inflation is a way to connect cosmic structure with fundamental physics



- Planck Data
--- Cosmic Inflation theory



(not to scale)


10
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-50
-70
-60
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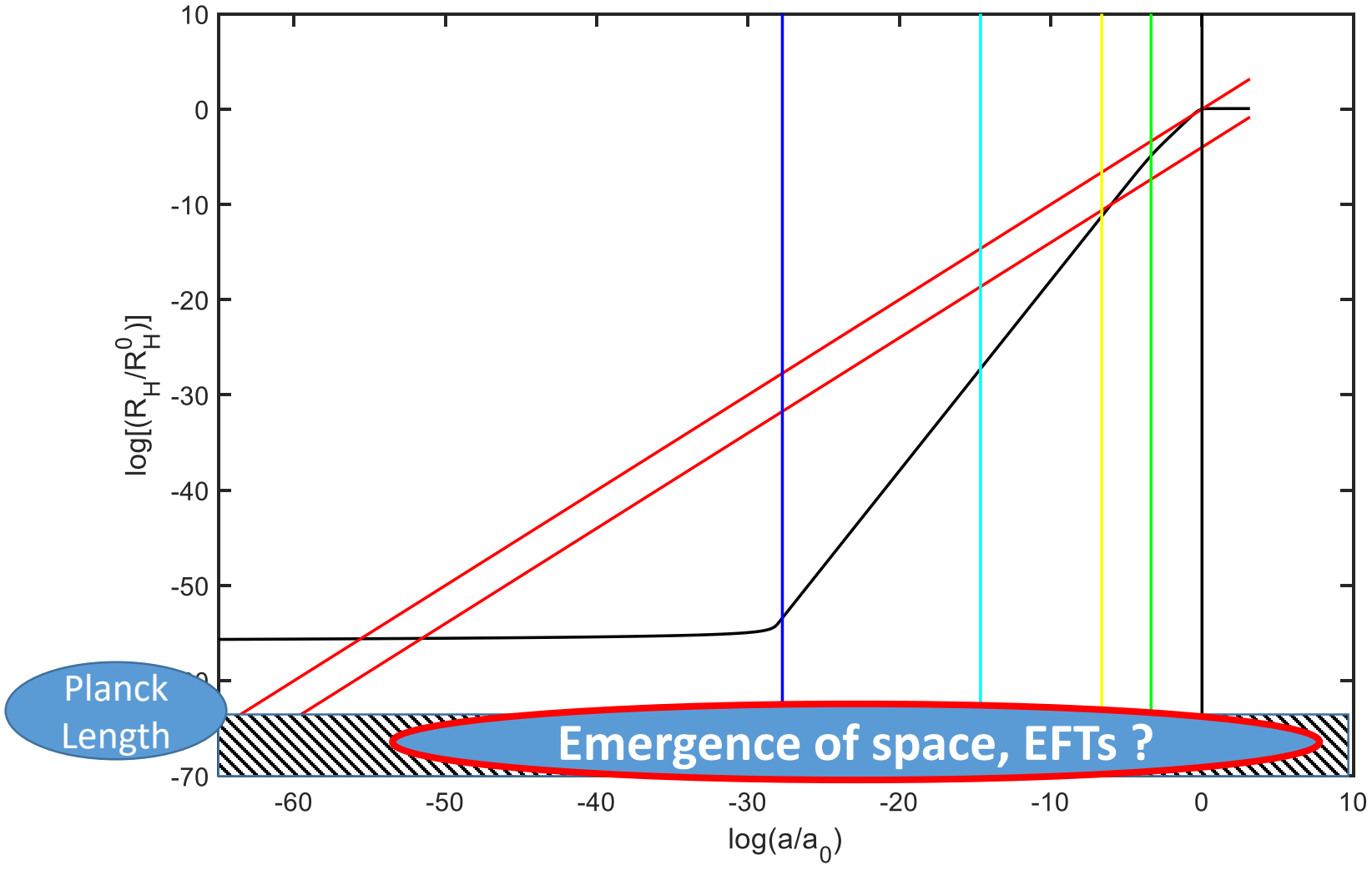
-30
-20
-10
0
10
log[(R_H/R_H^0)]
log(a/a_0)
Planck Length
?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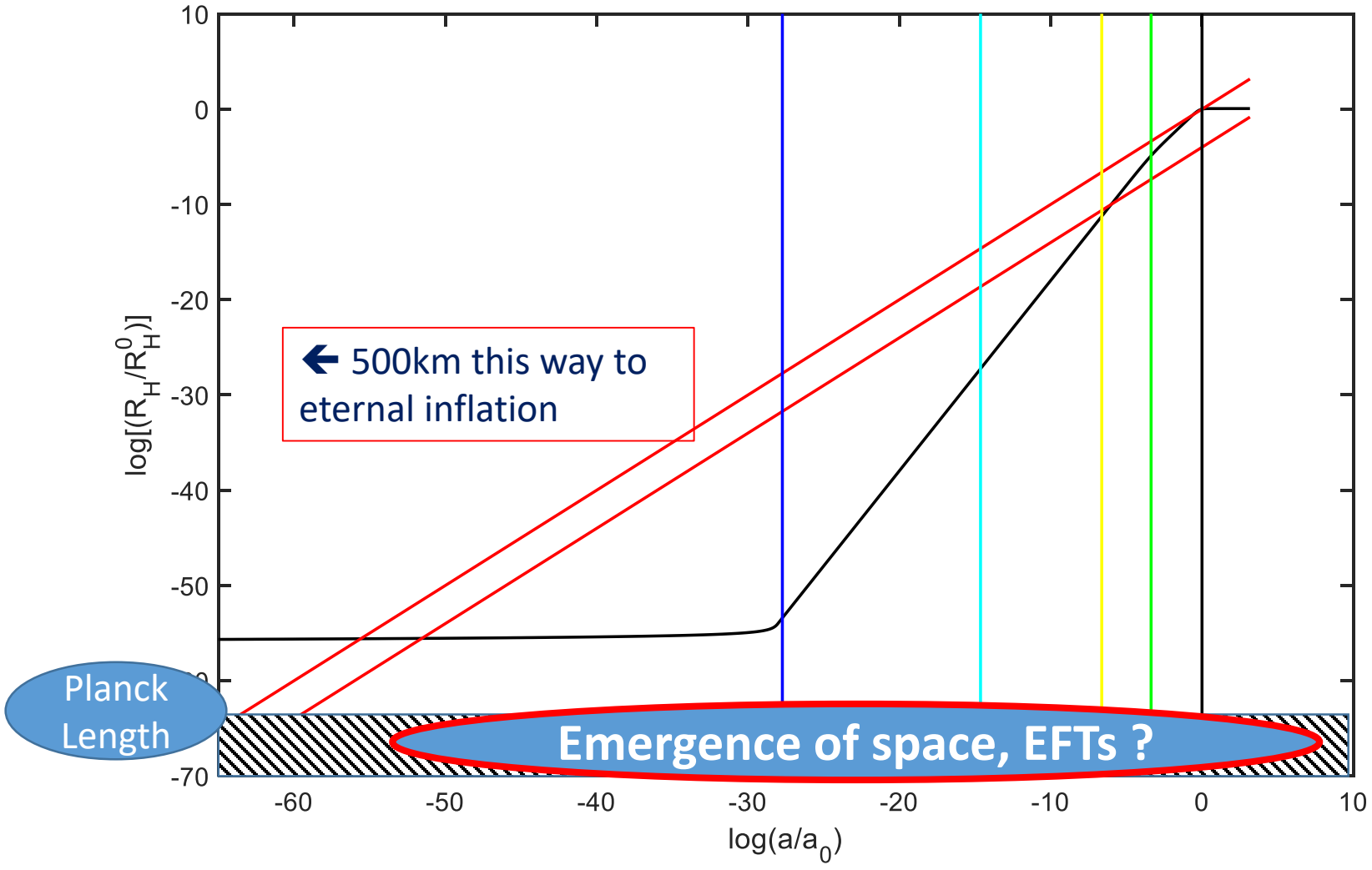
-20
-10
0
10
log[(R_H/R_H^0)]
log(a/a_0)
Planck Length
Emergence of space, EFTs ?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-70
-60
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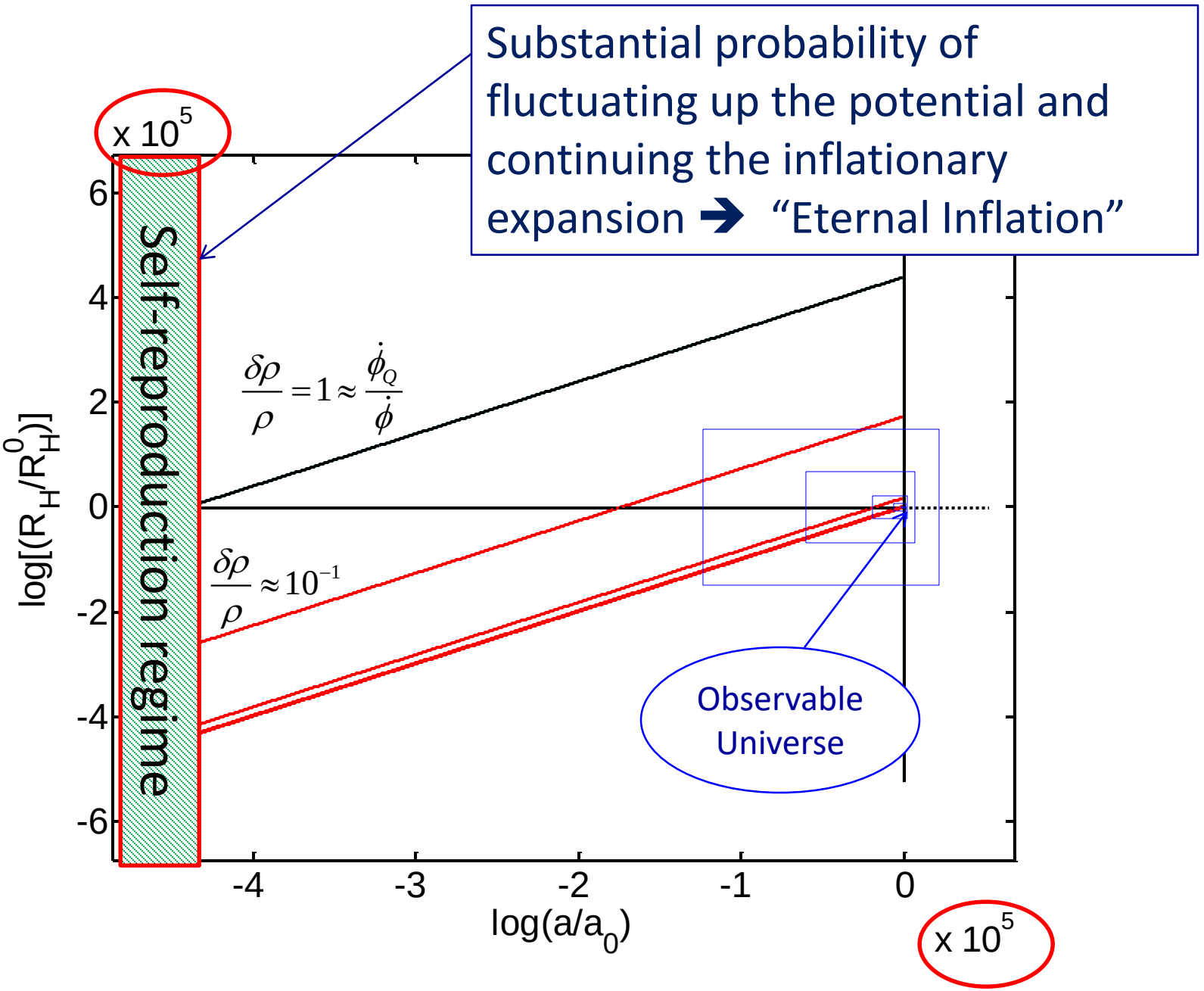
-40
-30
-20
-10
0
10
log[(R_H/R_H^0)]
log(a/a_0)
← 500km this way to eternal inflation
Planck Length
Emergence of space, EFTs ?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x 10^5
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6
4
2
0
-2
-4
-6
-4
-3
-2
-1
0
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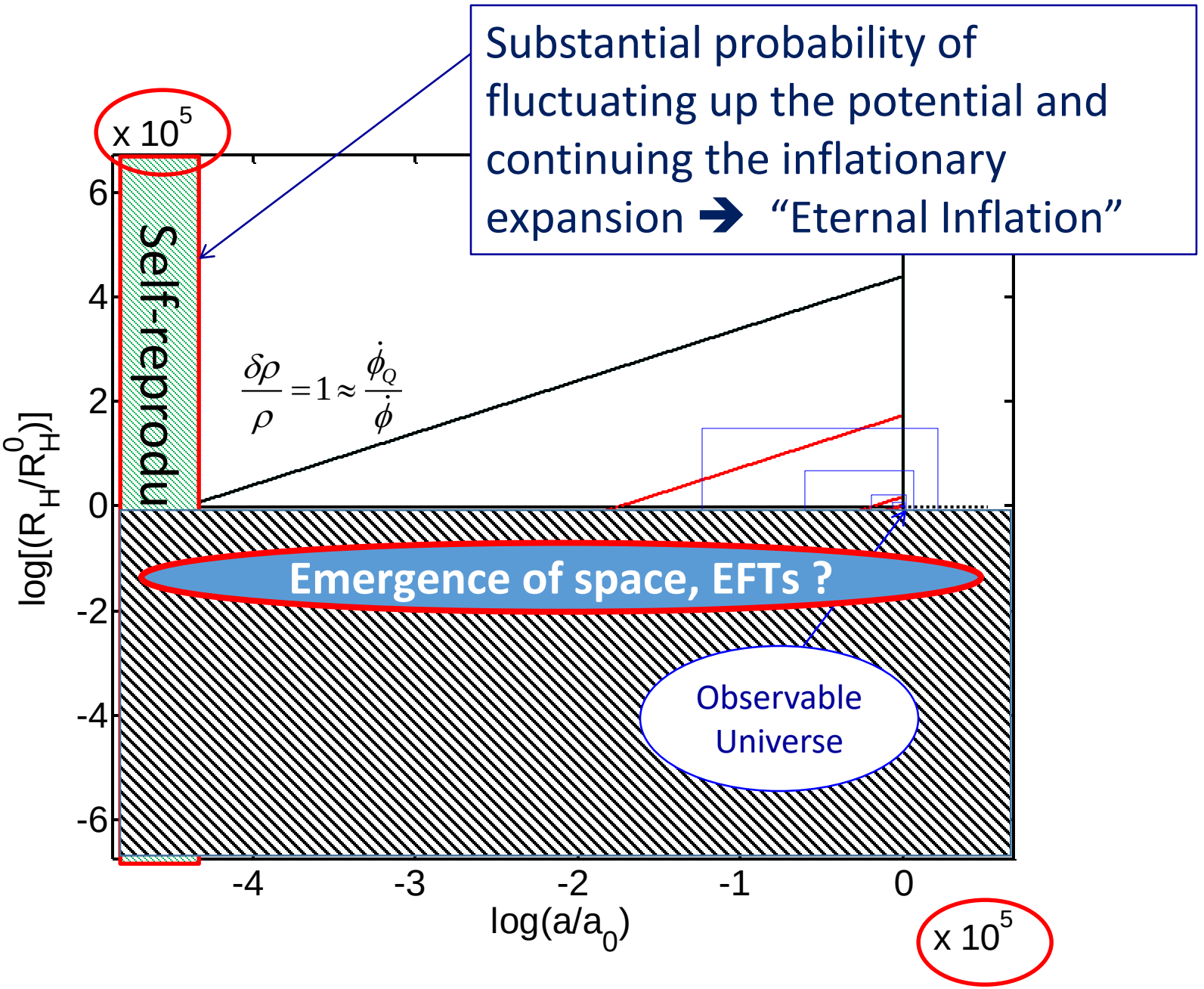
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6
4
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-3
-2
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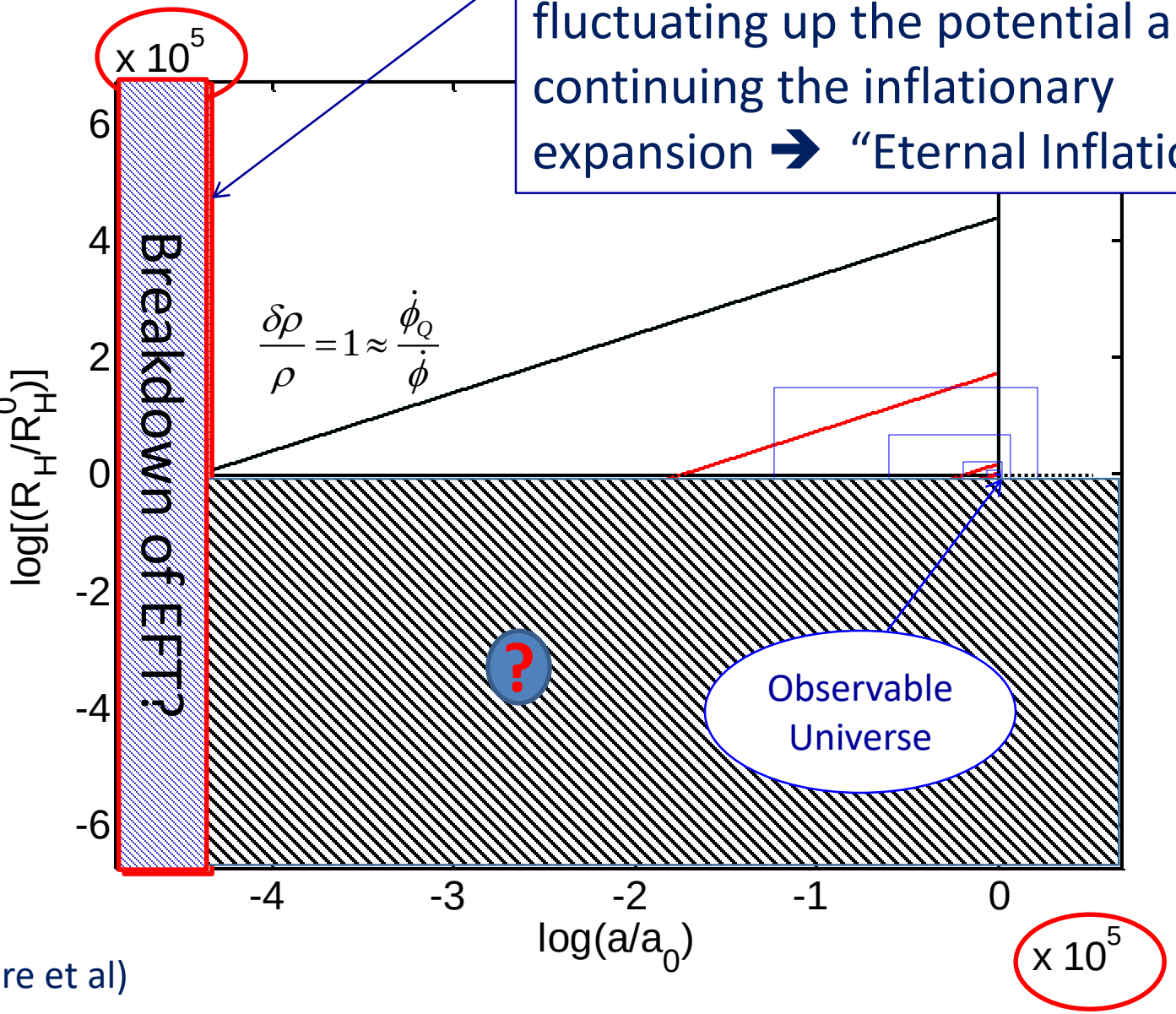
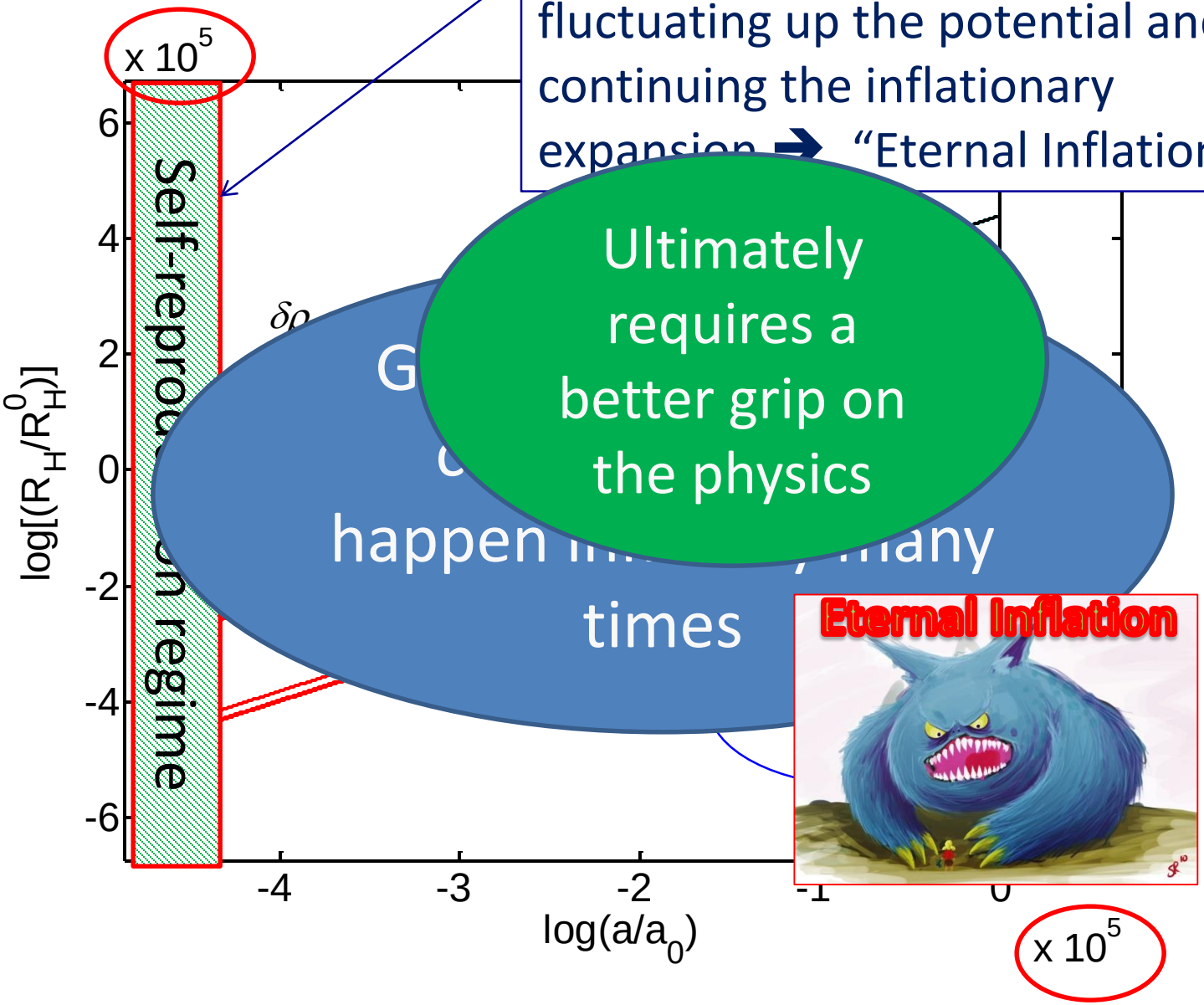


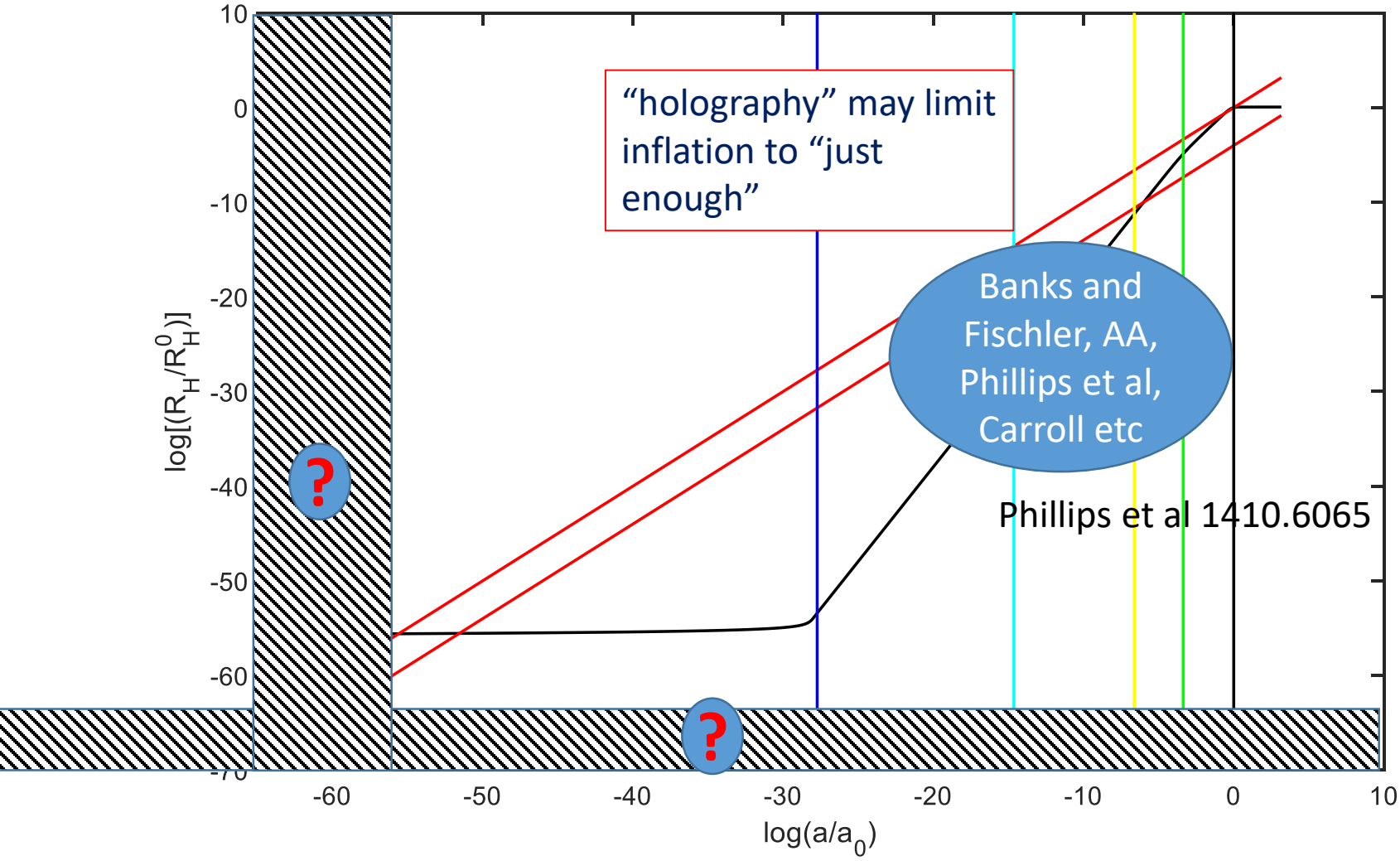
(Senatore et al)

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



Ultimately requires a better grip on the physics

G… c… happen in… many times


"holography" may limit inflation to "just enough"
Banks and Fischler, AA, Phillips et al, Carroll etc
Phillips et al 1410.6065
?
?
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-20
-30
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-10
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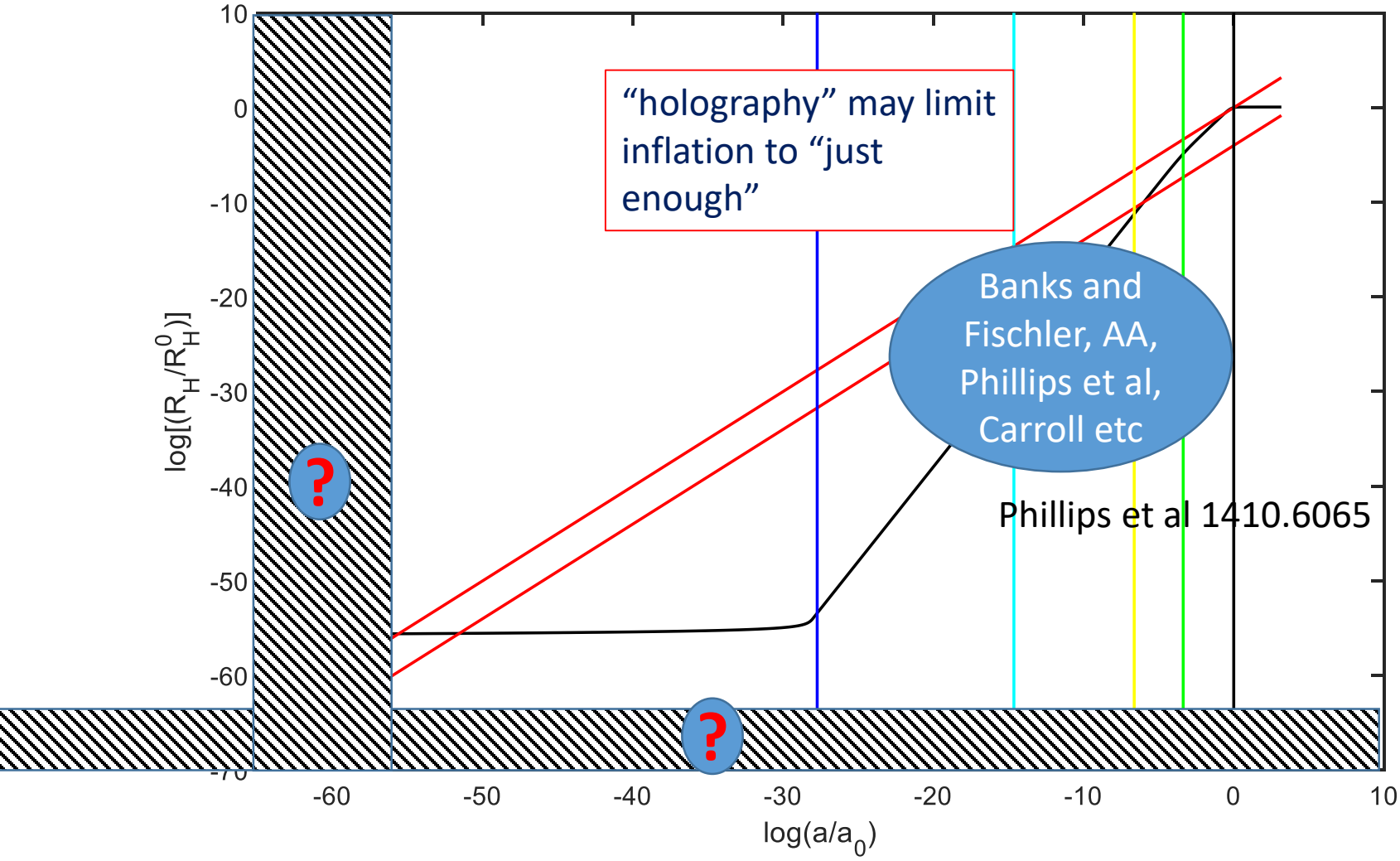
10
log[(R_H/R_H^0)]
log(a/a_0)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10
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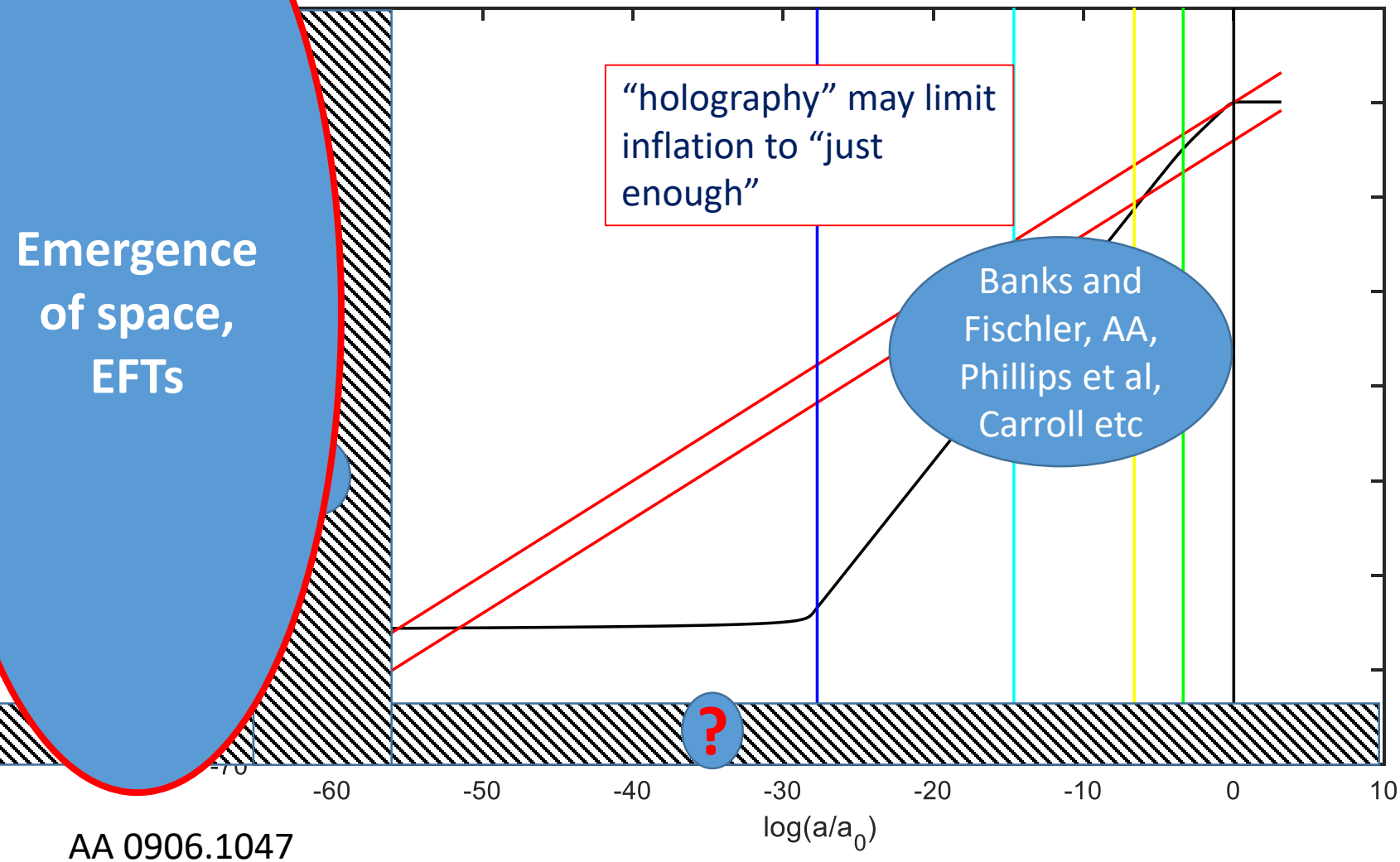
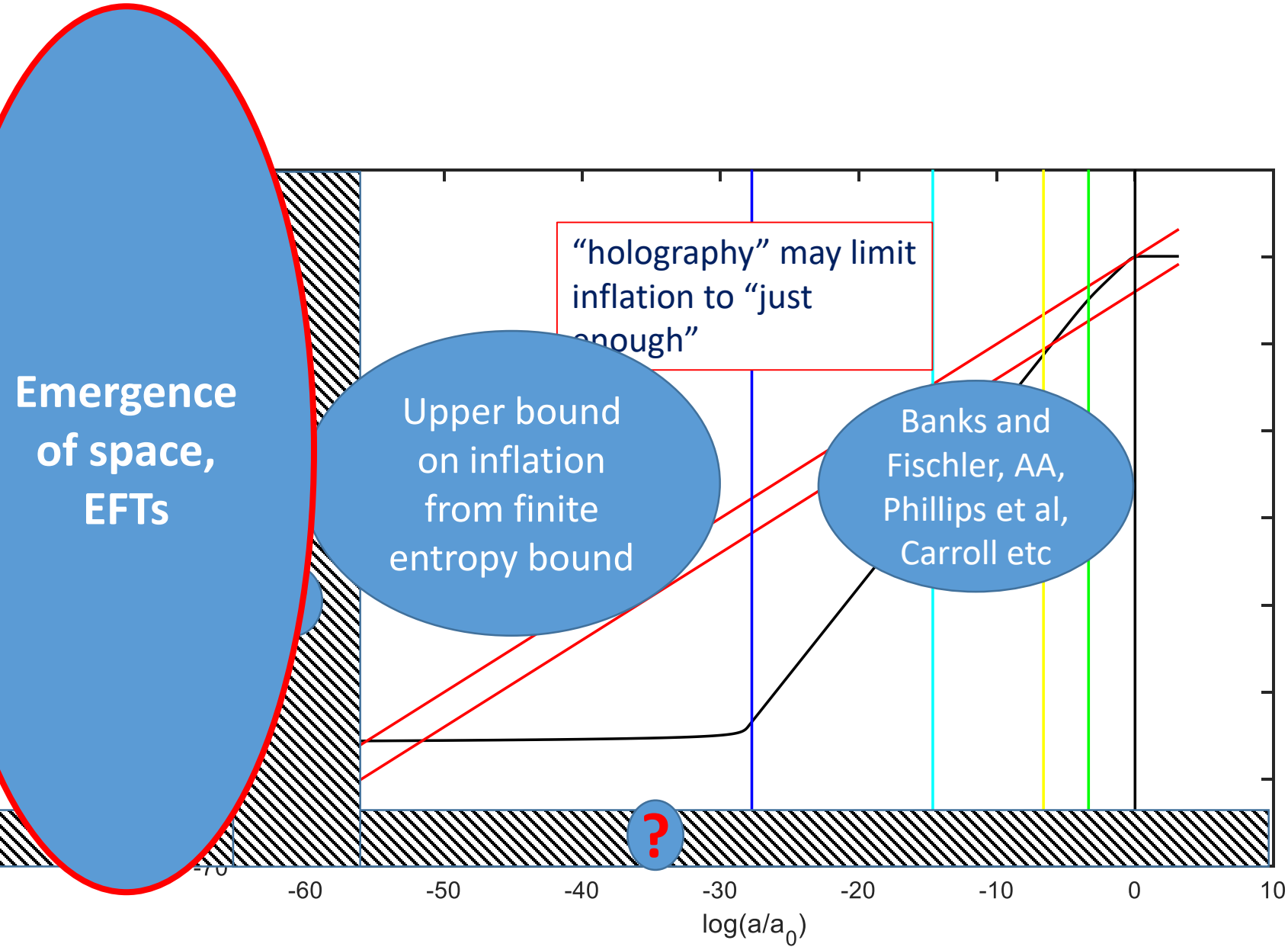
Emergence of space, EFTs



AA 0906.1047
AA and Sorbo, hep-th/0405270
AA 1401.7309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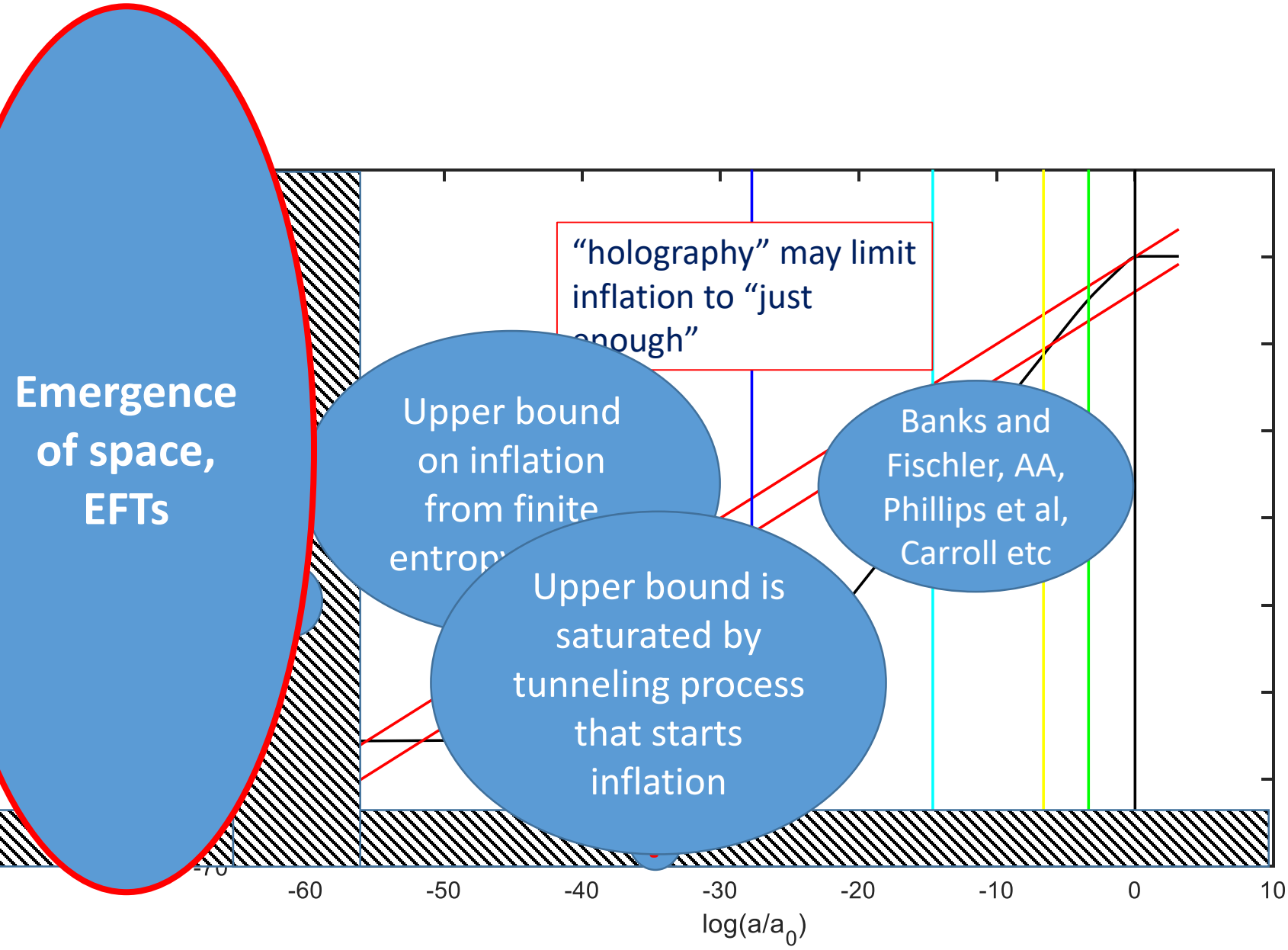
?
-60
-50
-40
-30
-20
-10
0
10
log(a/a0)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Banks and Fischler, AA, Phillips et al, Carroll etc
Upper bound is saturated by tunneling process that starts inflation
-60
-50
-40
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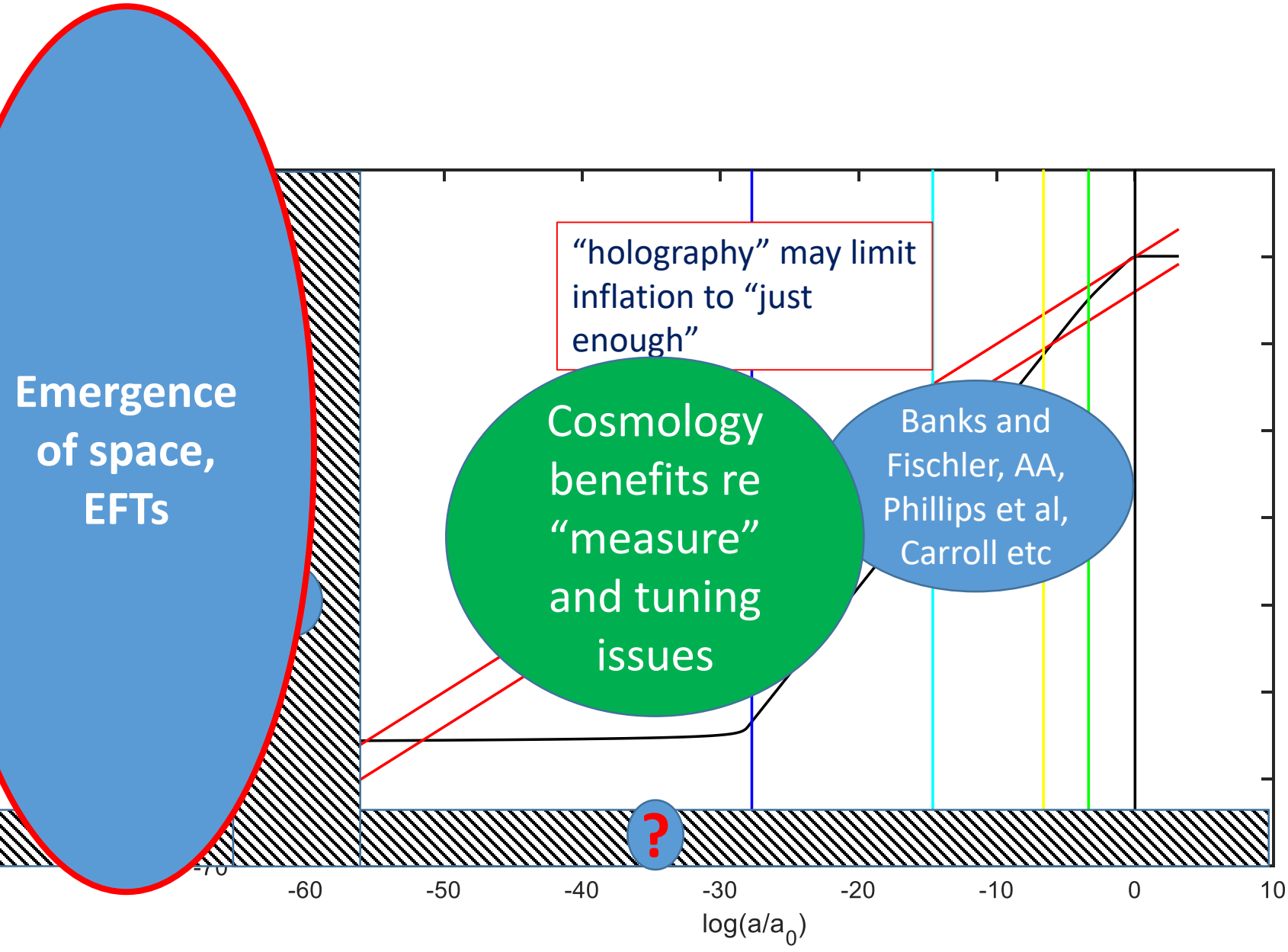
-20
-10
0
10
log(a/a0)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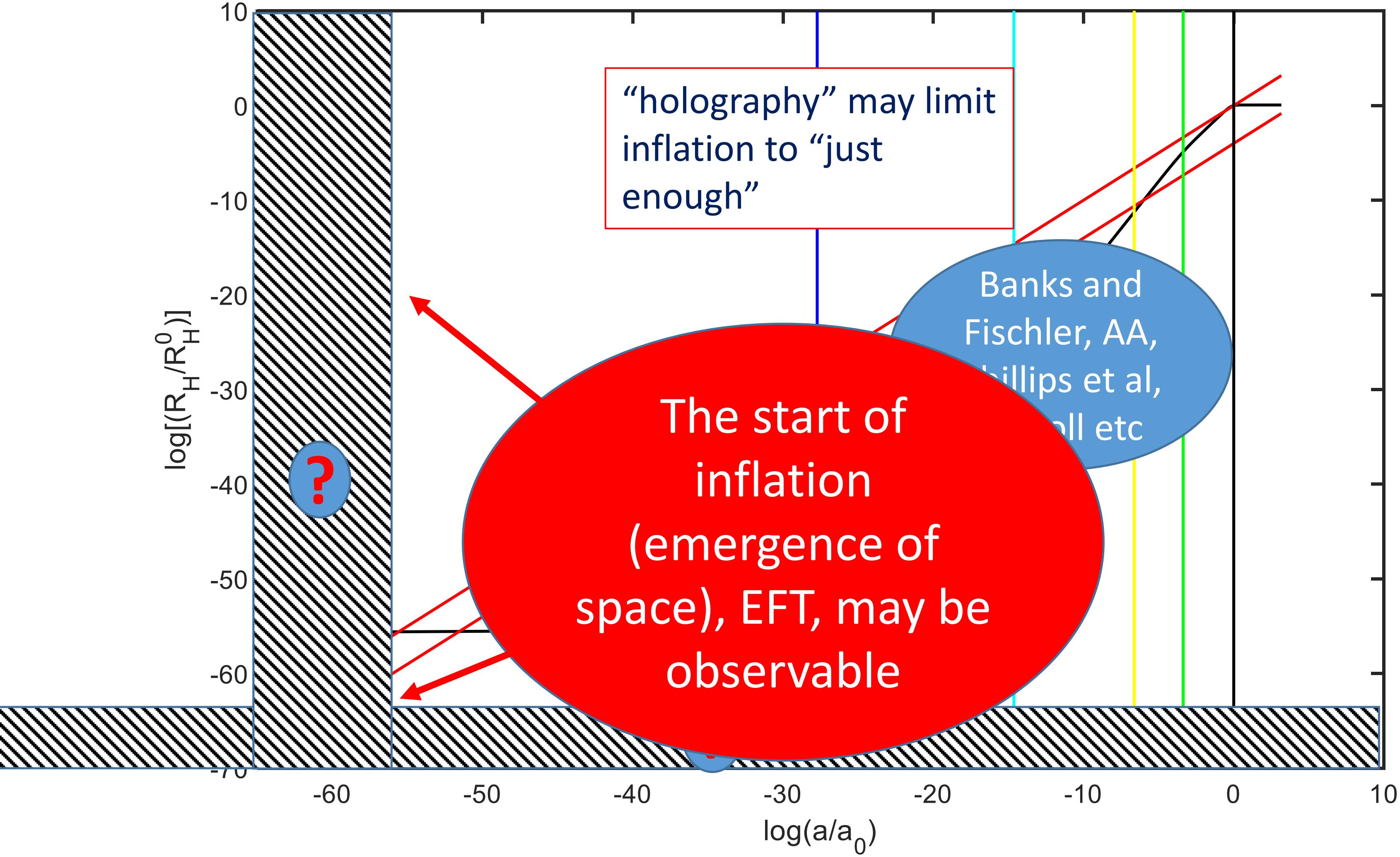
"holography" may limit inflation to "just enough"
Cosmology benefits re "measure" and tuning issues
Banks and Fischler, AA, Phillips et al, Carroll etc
?
-60
-50
-40
-30
-20
-10
0
10
log(a/a0)



"holography" may limit inflation to "just enough"
Banks and Fischler, AA,
hillips et al,
ll etc
The start of inflation (emergence of space), EFT, may be observable
?
10
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-10
-20
-30
-40
-50
-60
-70
-60
-50
-40
-30
-20
-10
0
10
log(a/a0)
log[(RH/RH0)]

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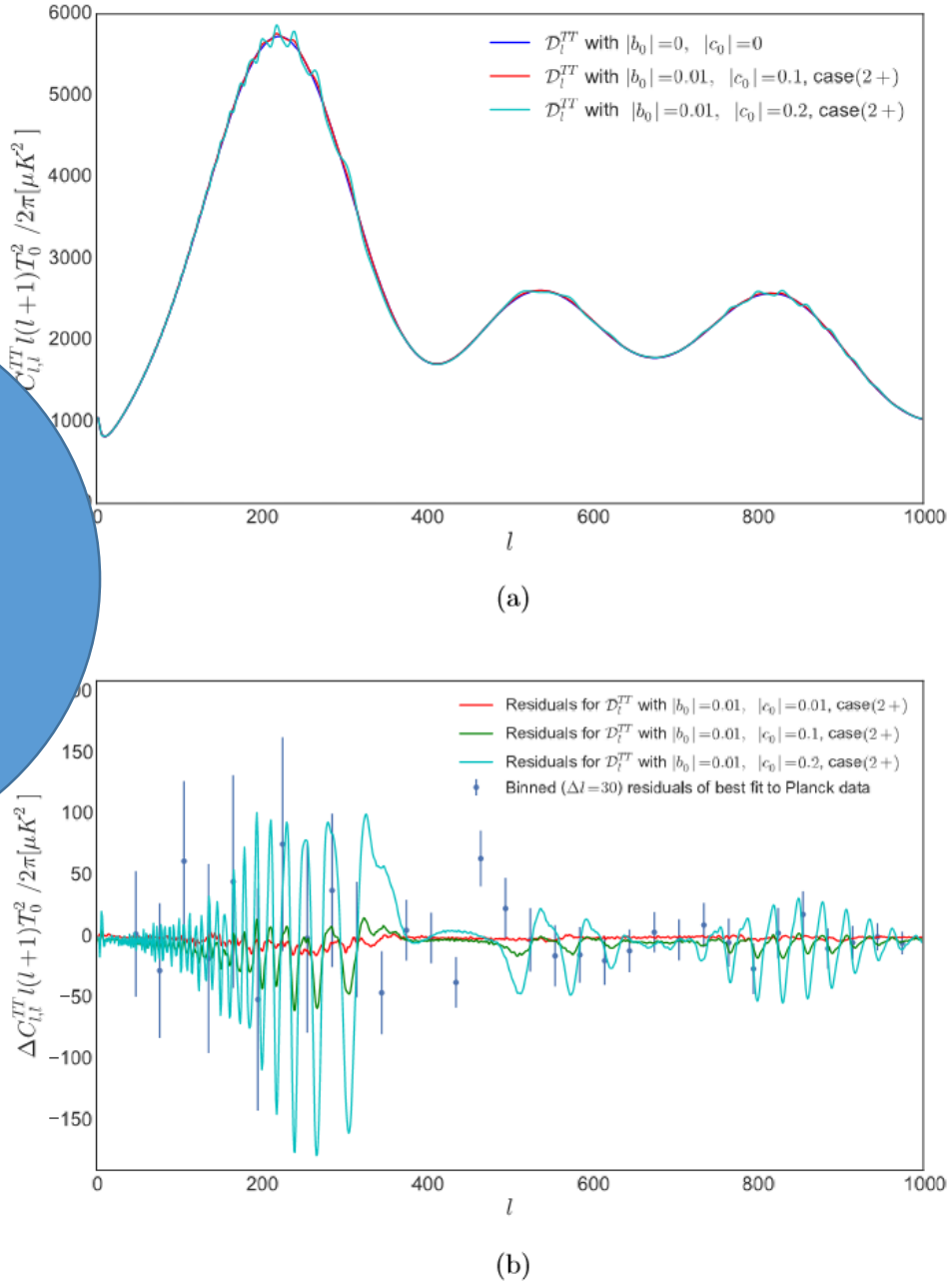
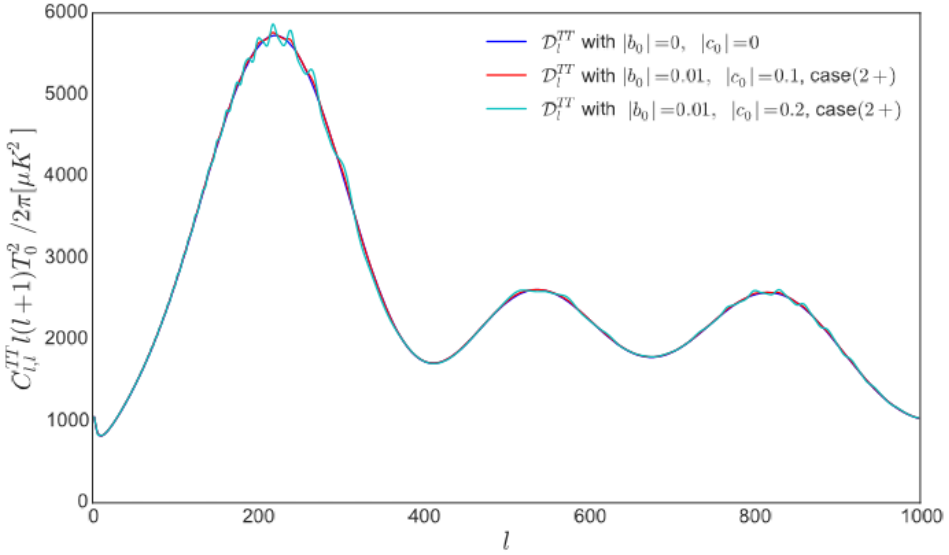
Possible signatures of "short inflation" and quantum entanglement

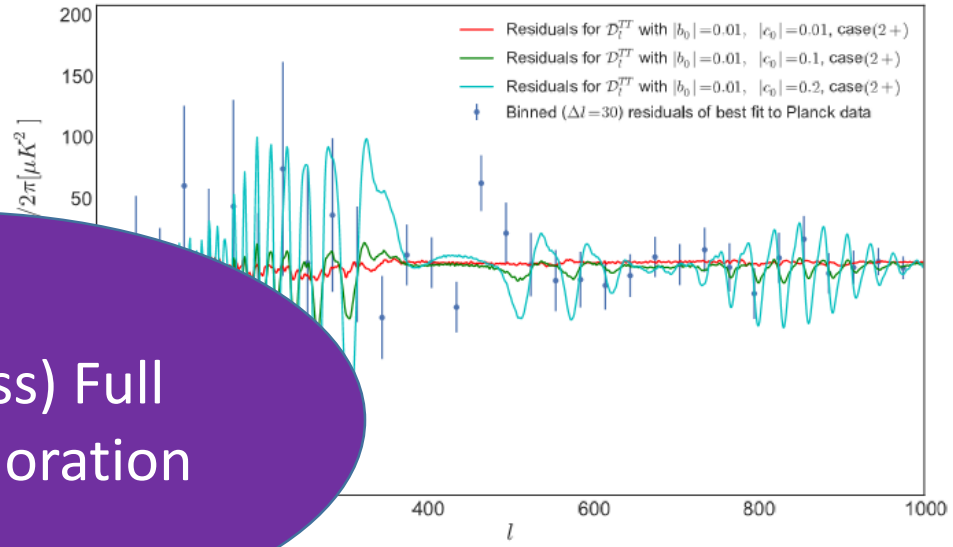


Bolis et al
arXiv:1605.01008

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-

See also

- Small observable curvature!! (AA, Linde, etc) arXiv:1104.3315 Knight & Knox (arXiv:1705.01178)
- Contaldi et al (astro-ph/0303636)
- Scacco & AA (arXiv:1503.04872),
- Easther et al hep-th/0104102
- Etc. (Bubbles)
- More to come!!

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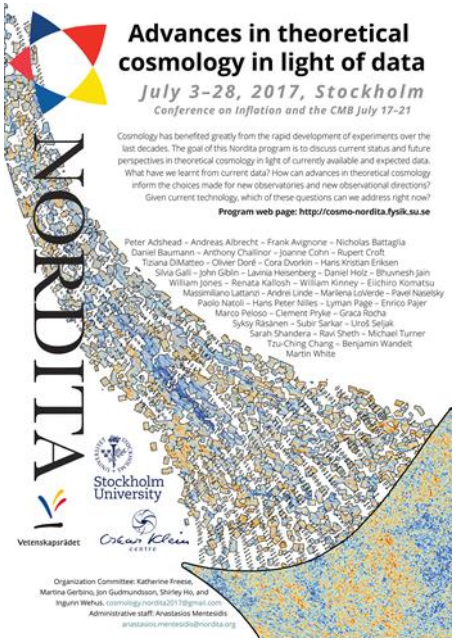

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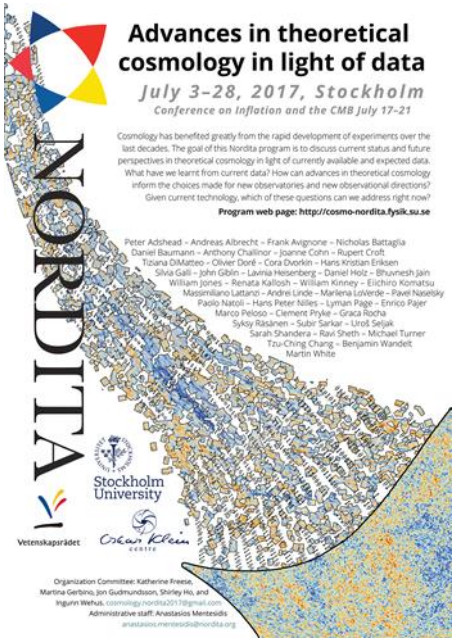

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B) Open questions about cosmic inflation
   i) Tuning
      - Entropy perspective
      - Bunch Davies Vacuum
   ii) Measures

C) Connections to modern research into qu
   gravity/fundamental physics

e.g.
Elena Pierpaoli, Matt Johnson, etc

D) Connections to cosmological observations

E) Great opportunities ahead!!

Outline

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- What is the vacuum?, Firewalls
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- The nature of horizons, singularities
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- Emergence of spacetime
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Inflation, and cosmology in general, have a deep capacity to link thes issues with observationa signatures.

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Exciting prospects for future data sets!

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➔ Takeaway 1: Theorists should not just build new models of inflation, but link to new physics beyond EFTs (some problems in cosmology will not be resolved without this)

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(*know where you stand)