

Cosmic Inflation: Open questions and perspectives on future surveys

Andreas Albrecht

UC Davis Center for Quantum Mathematics and Physics (QMAP)

CosKASI Conference

Daejeong

April 2017

Cosmic Inflation: Open questions and perspectives on future surveys

Thank you CosKASI
Organizers!

...cs and Physics (QMAP)

CosKASI Conference
Daejeong
April 2017

Outline

A) Open Questions

i) Tuning

- Entropy perspective
- Bunch Davies Vacuum

ii) Measures

B) Connections to modern research topics, and ultimately surveys

What is the point of cosmic inflation?

Guth (1981) The point of cosmic inflation is to solve cosmological tuning problems

PHYSICAL REVIEW D

VOLUME 23, NUMBER 2

15 JANUARY 1981

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.

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, England¹
and The Landau Institute for Theoretical Physics, The Academy of Sciences, Moscow, 117334, USSR²*

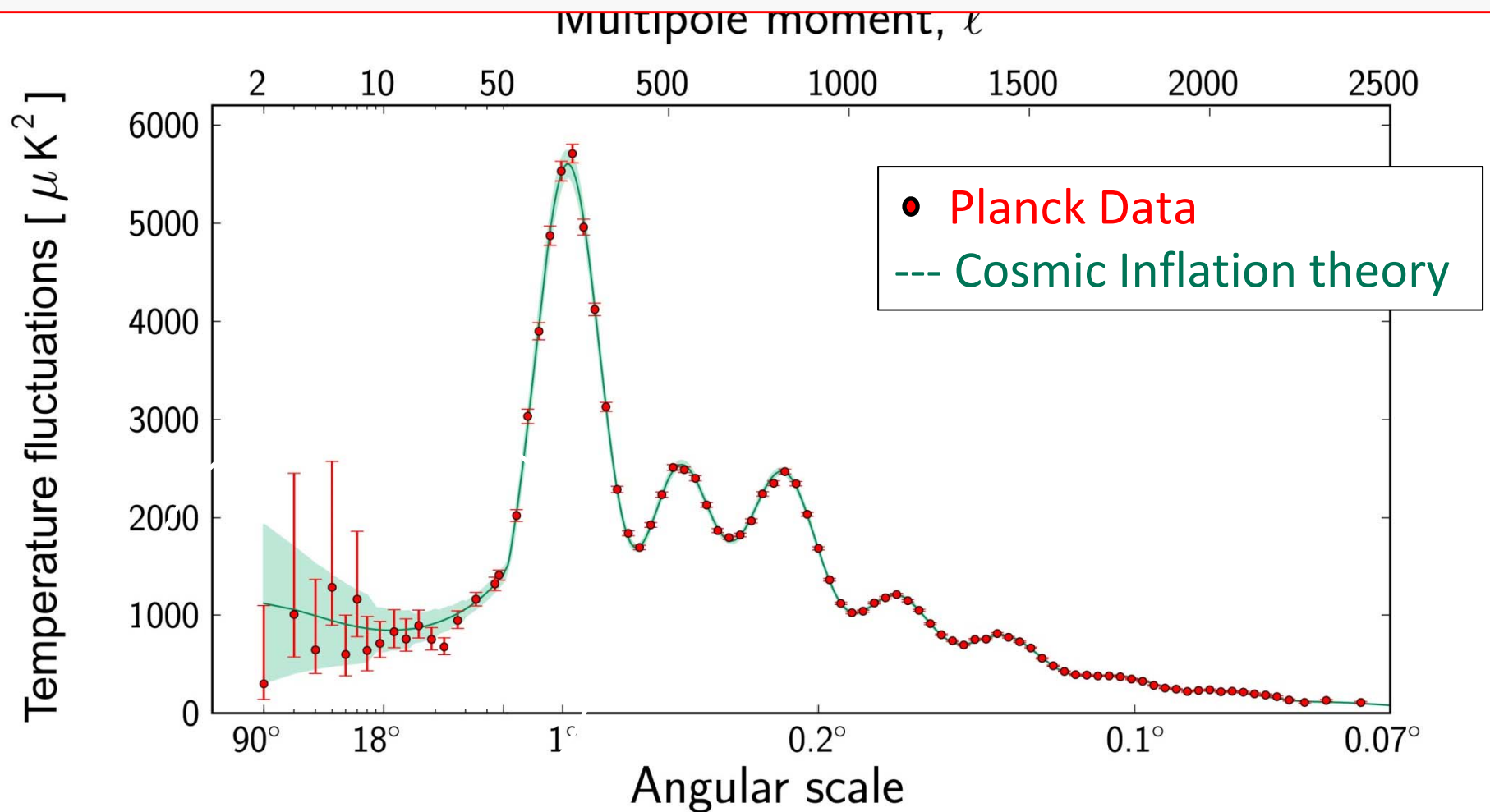
Received 11 January 1980

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.

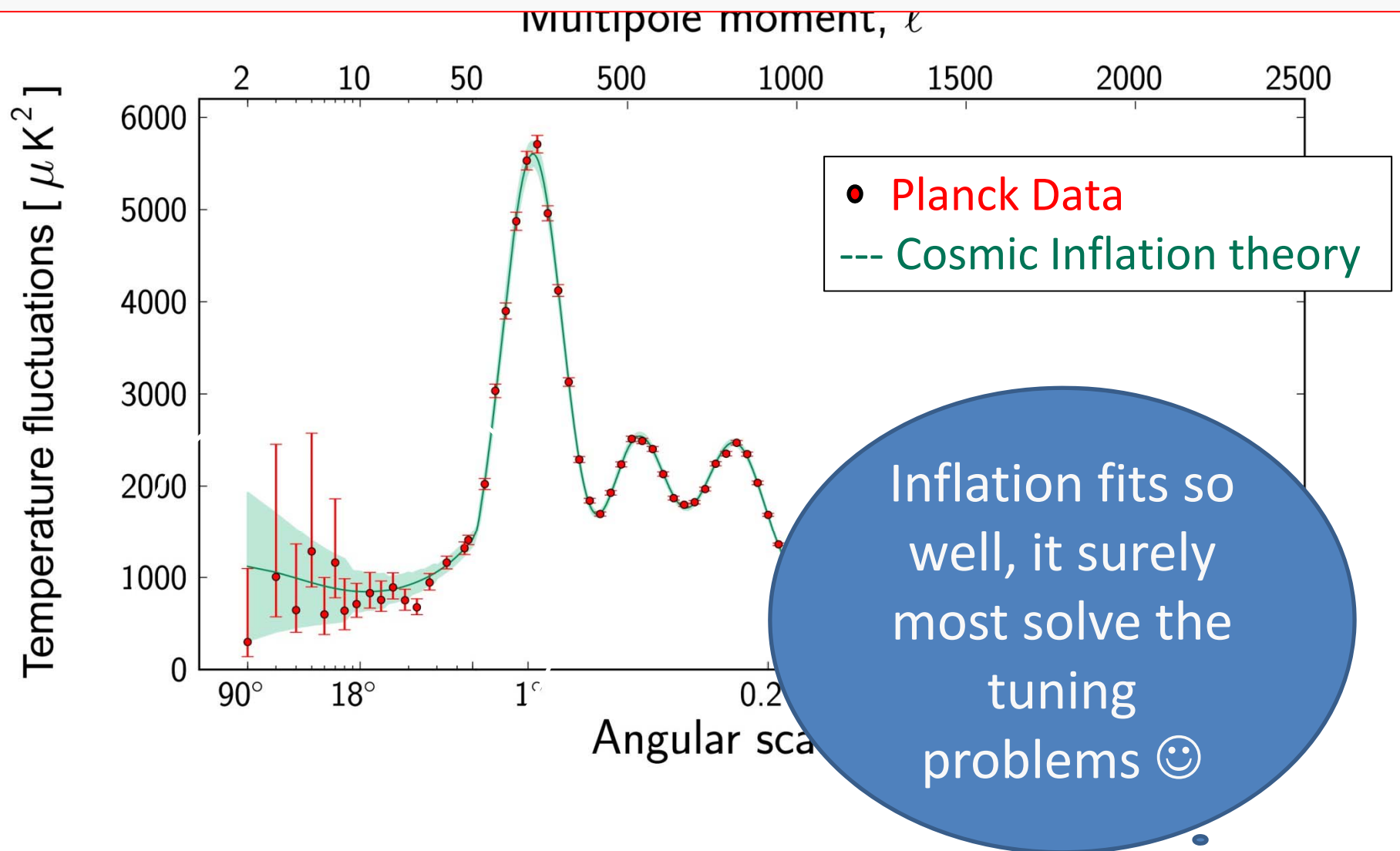
the above mentioned condition then we shall obtain one possible answer to the fundamental question stated in the first paragraph of this paper. It is worth noting that the evolution of the Universe need not follow a “generic” solution, it may well be described just by this unique one, at least initially.

Eqs. (2), (3) were first considered in ref. [1] and then investigated in detail in ref. [2] in the case $K = 0$.
The conclusion was that they have no singularities

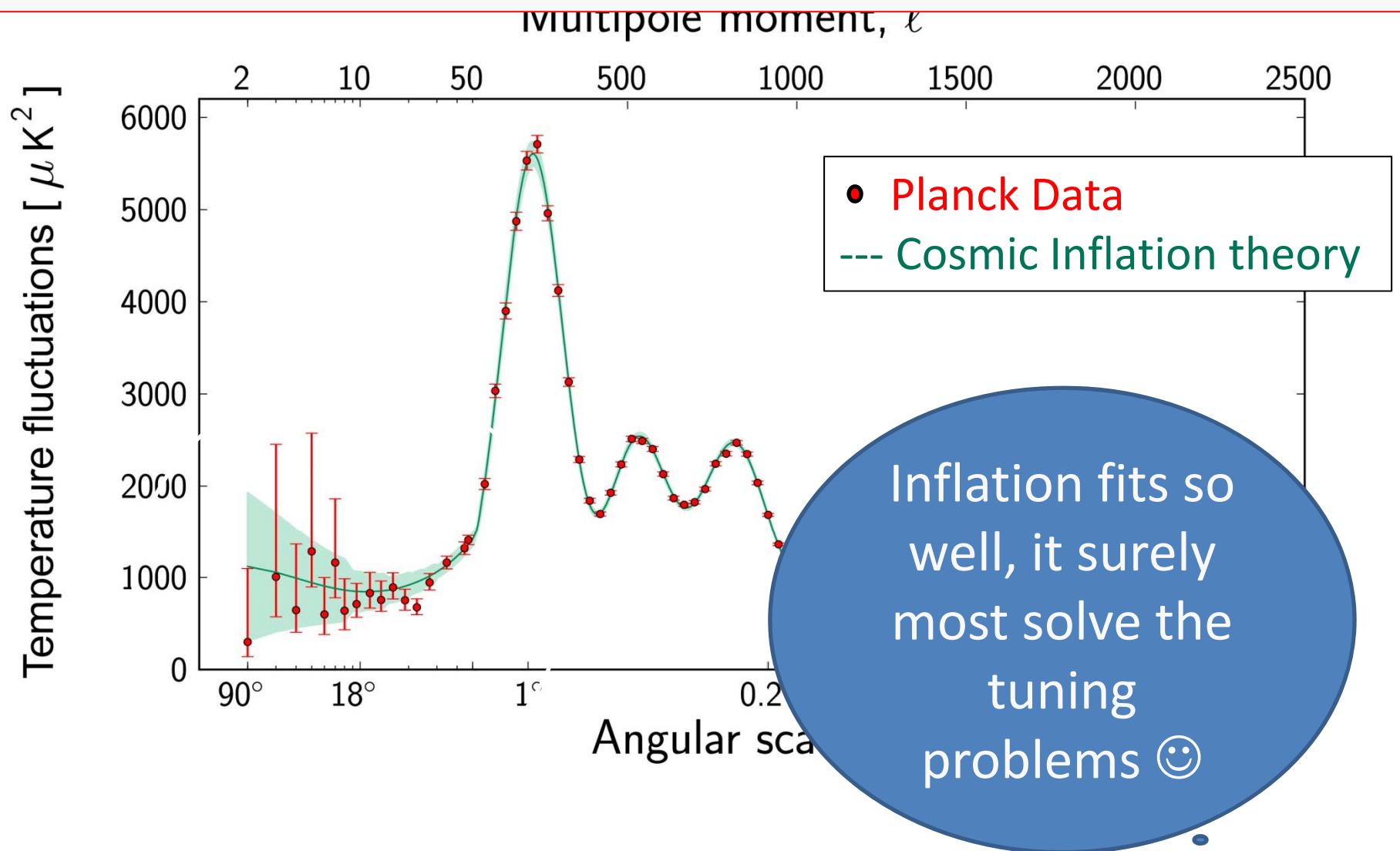
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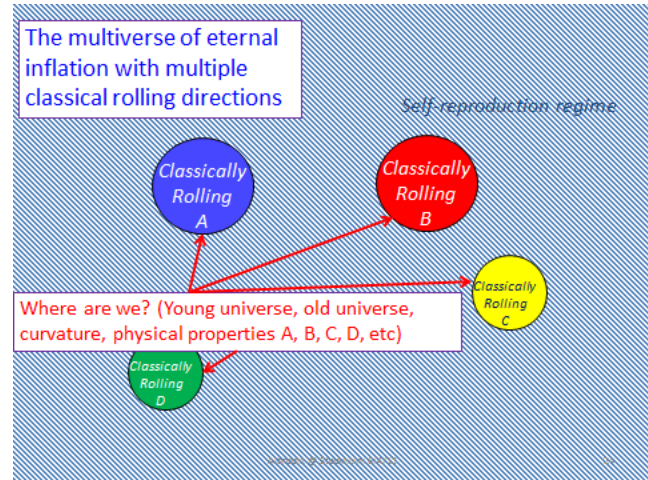
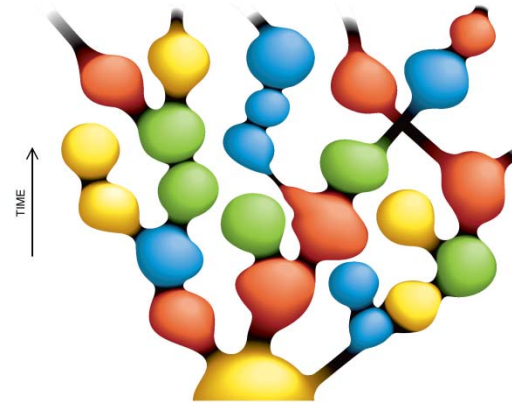
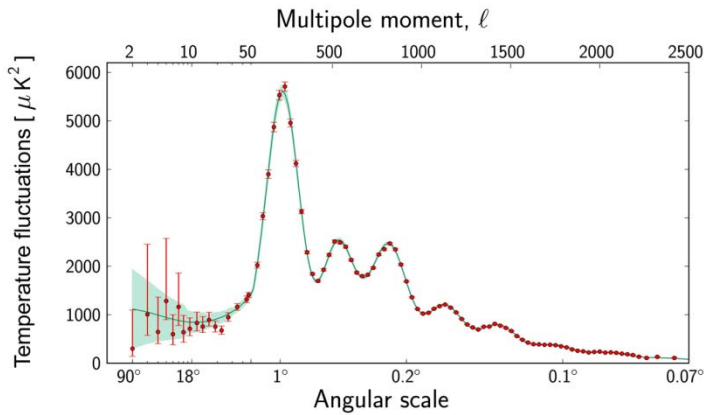


Cosmic Inflation:

Consumers

&

Producers

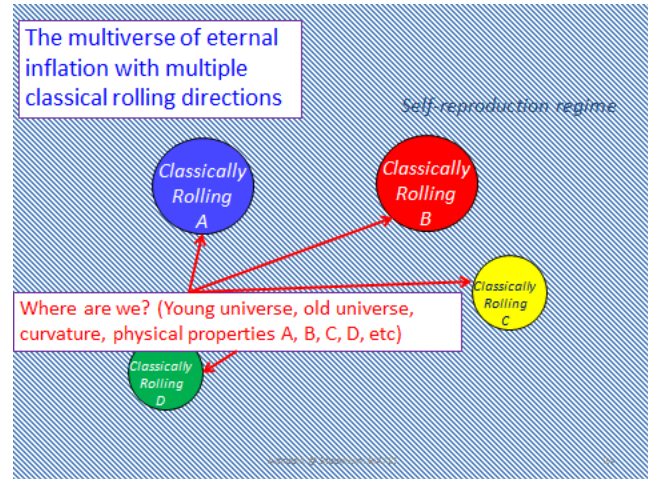
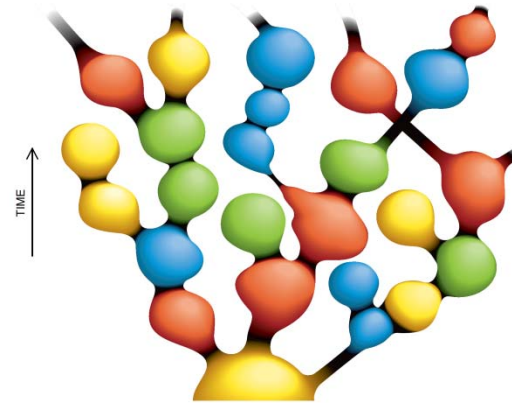
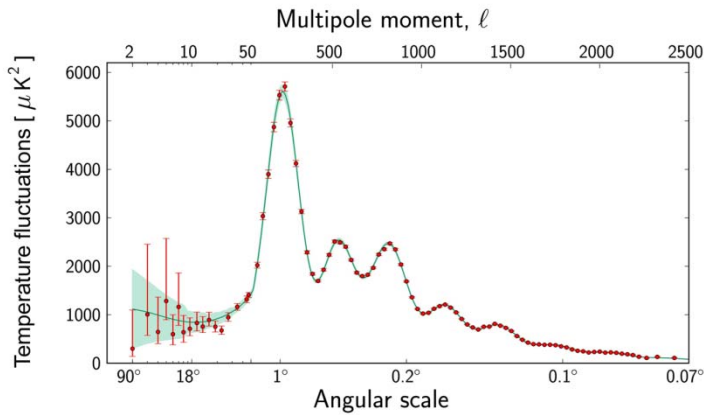


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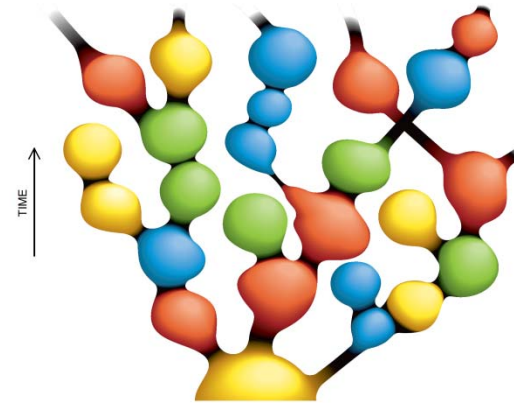
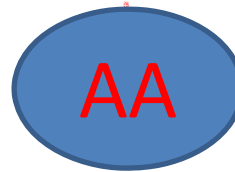
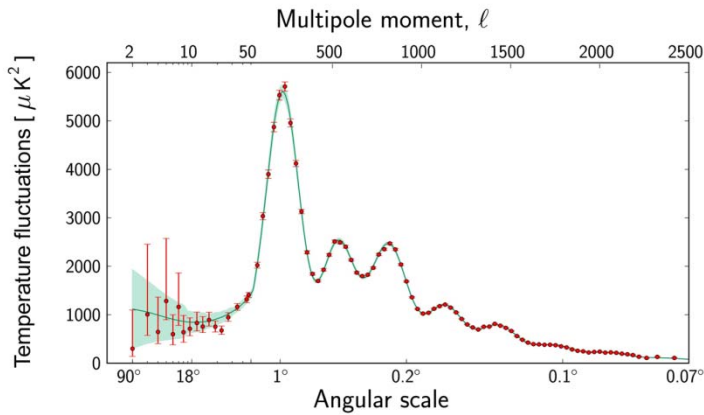


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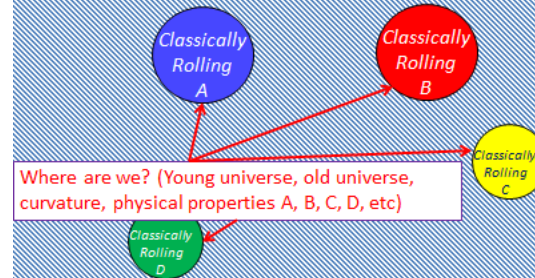
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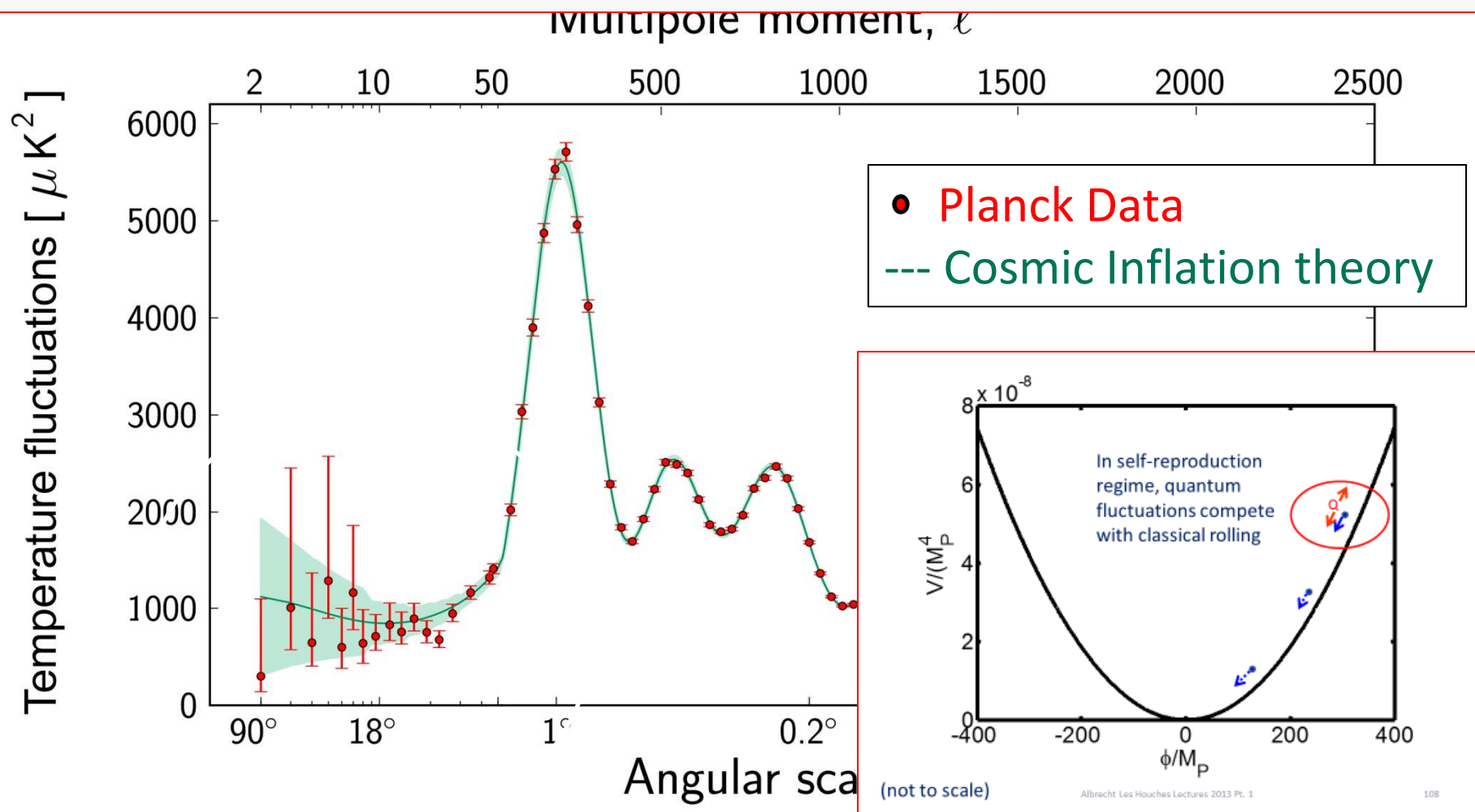


The multiverse of eternal inflation with multiple classical rolling directions

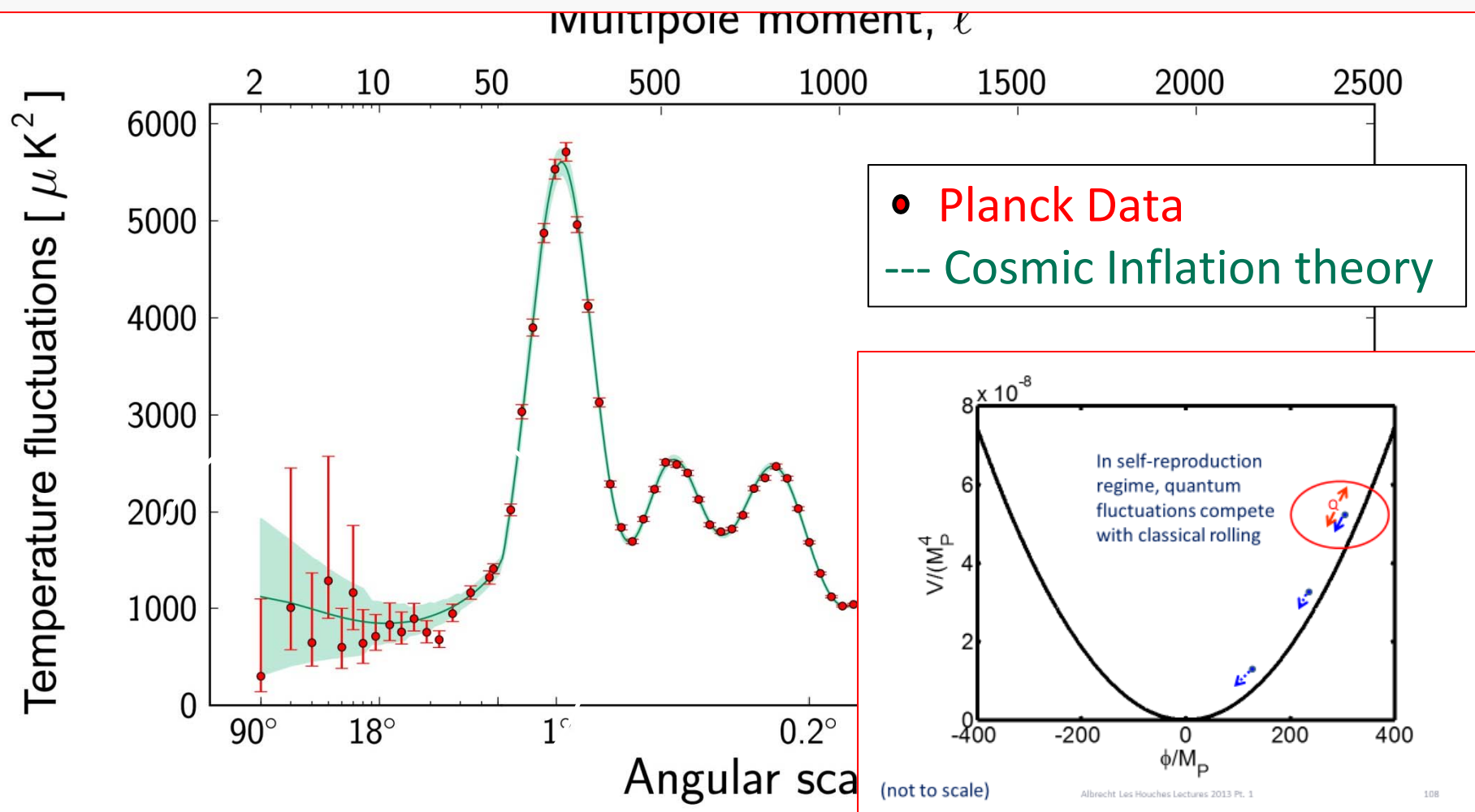
Self-reproduction regime



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



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Outline

A) Open Questions

i) Tuning

- Entropy perspective
- Bunch Davies Vacuum

ii) Measures

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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”

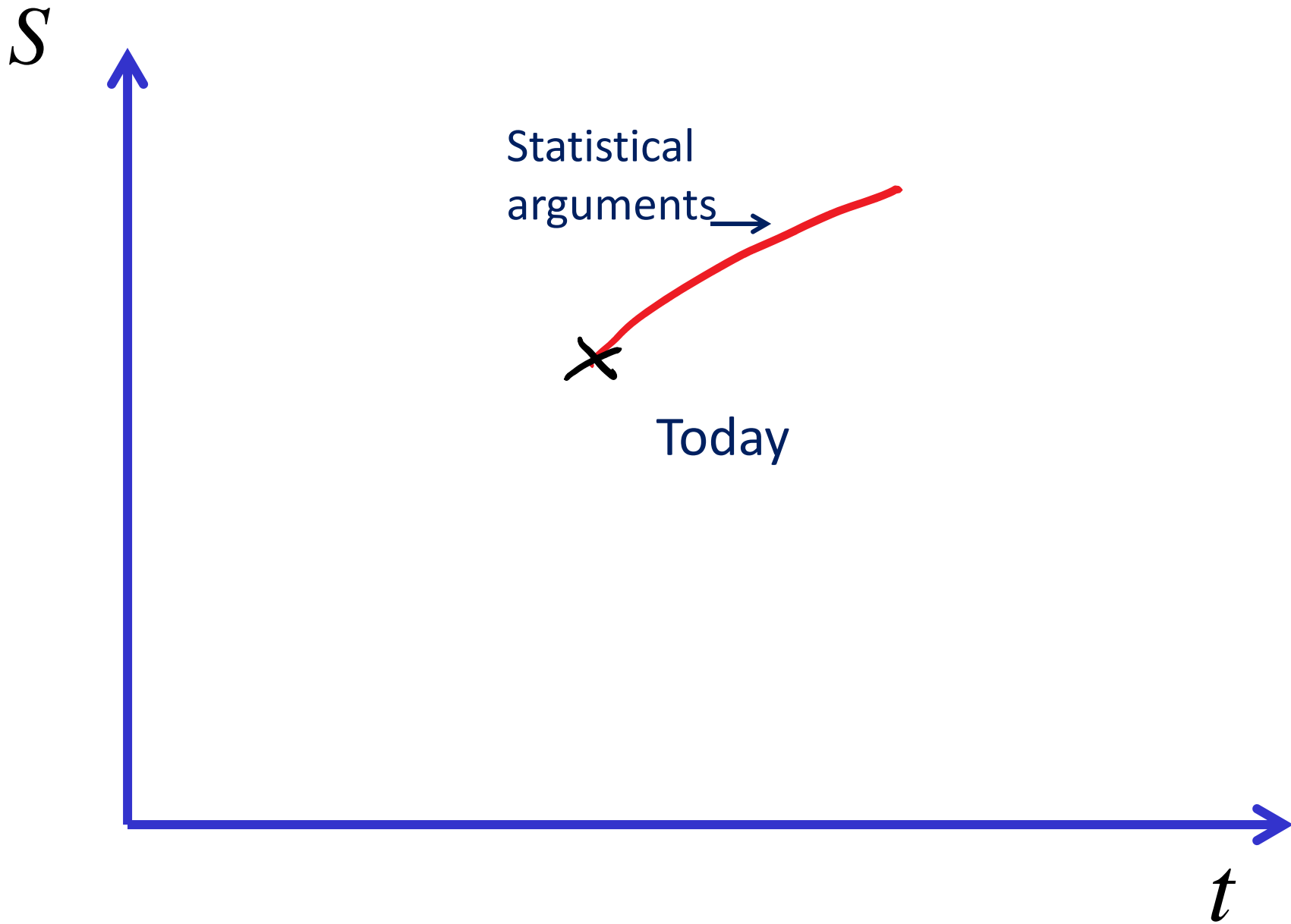
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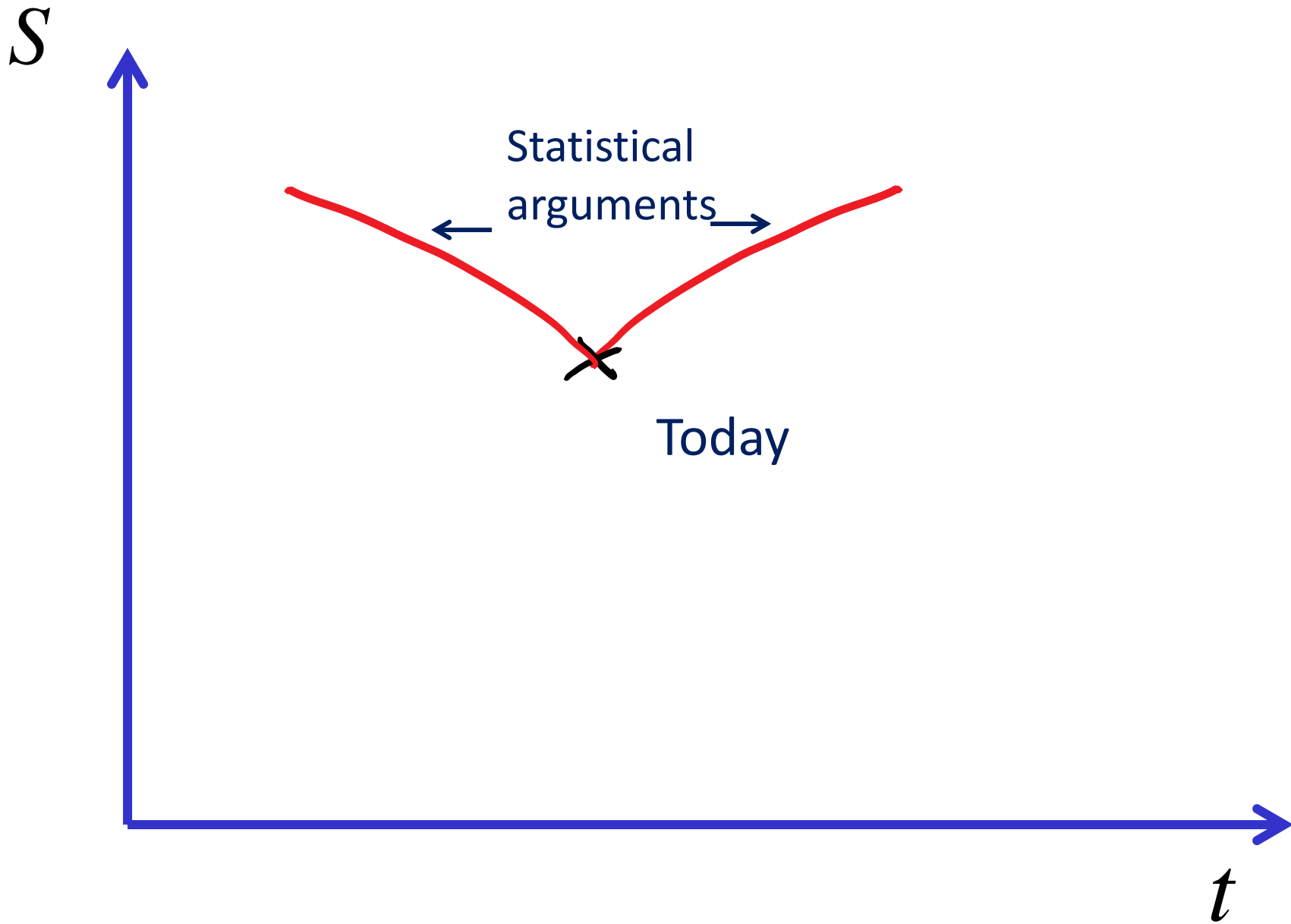


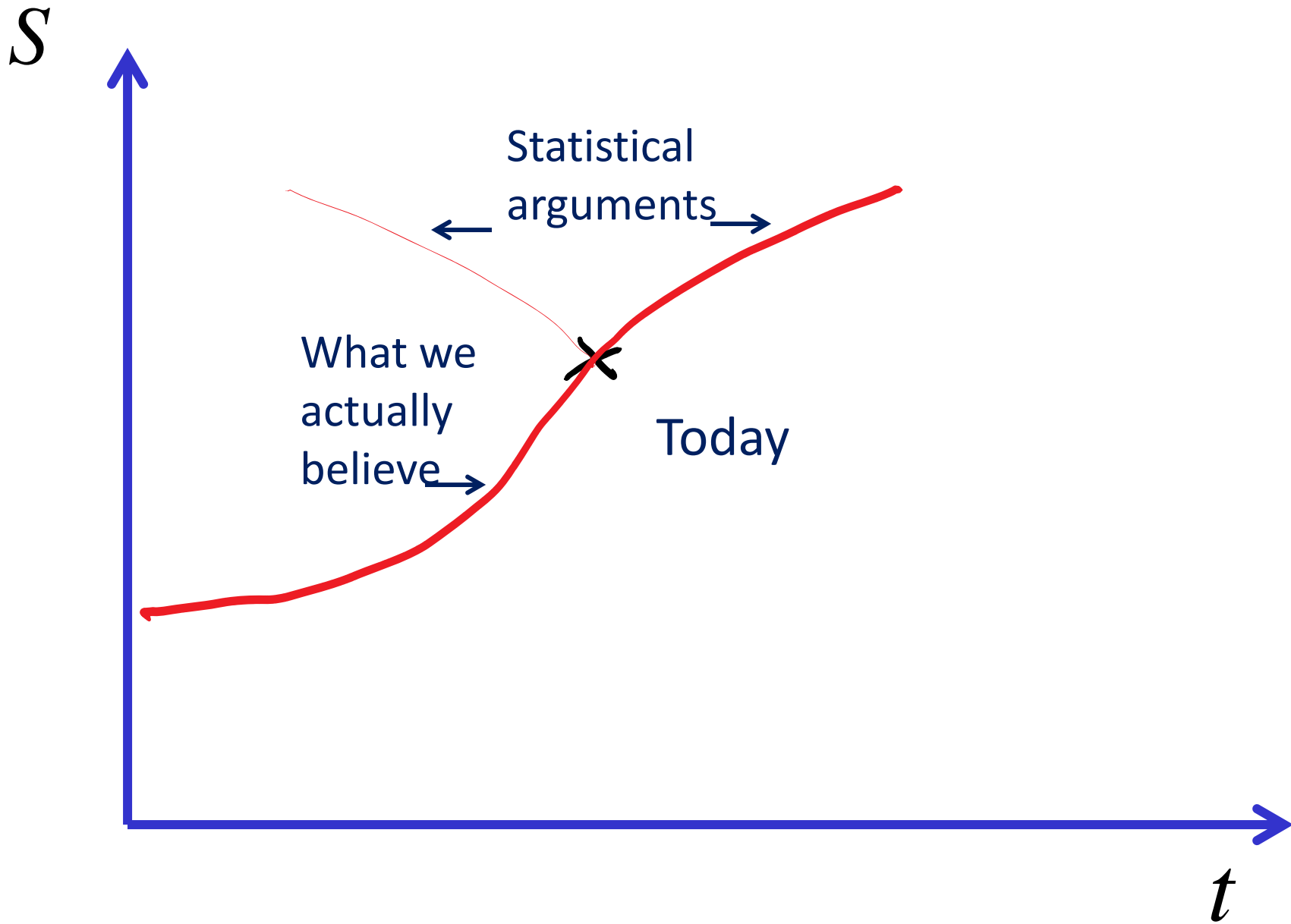
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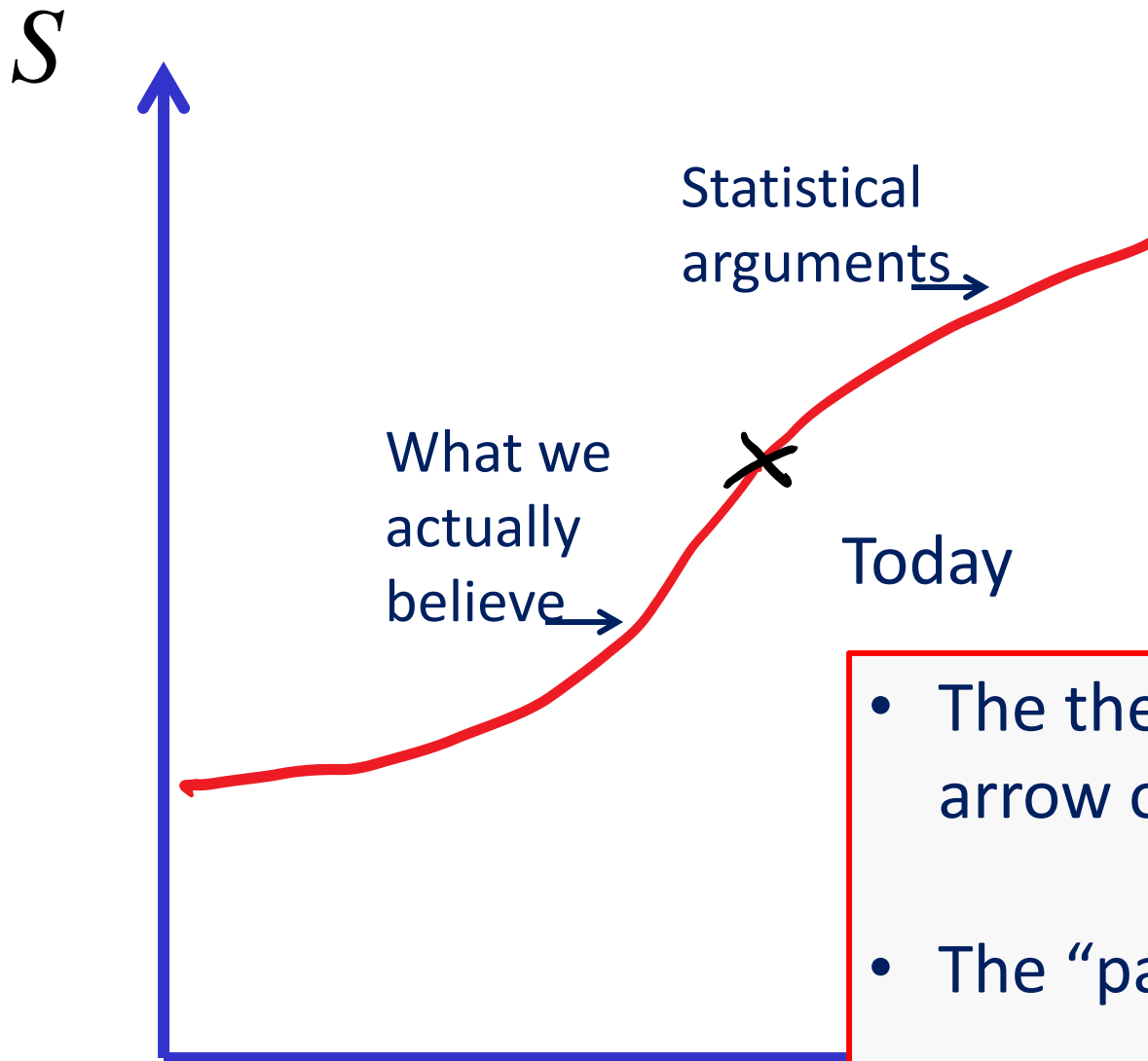
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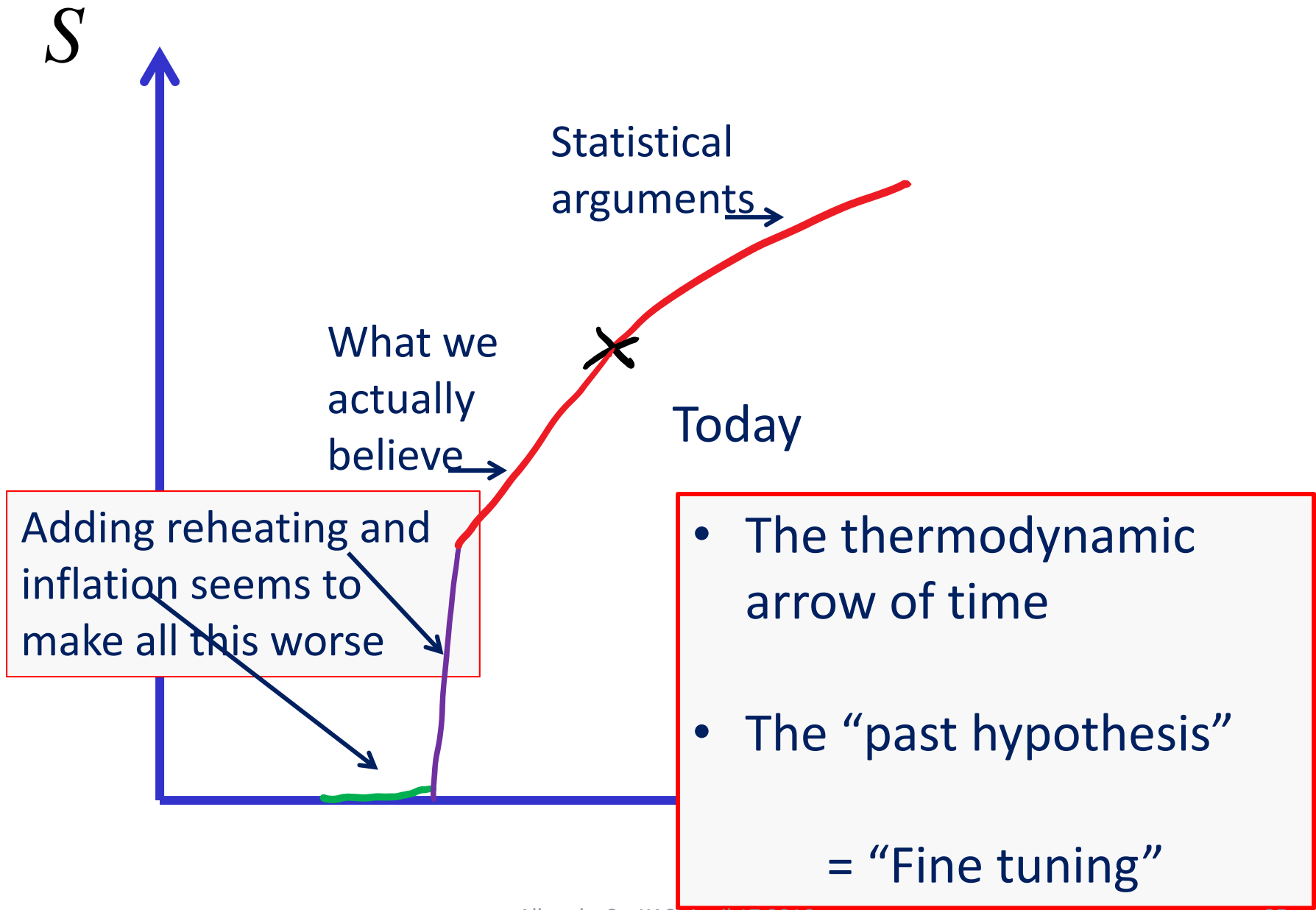








- The thermodynamic arrow of time
- The “past hypothesis”
= “Fine tuning”



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

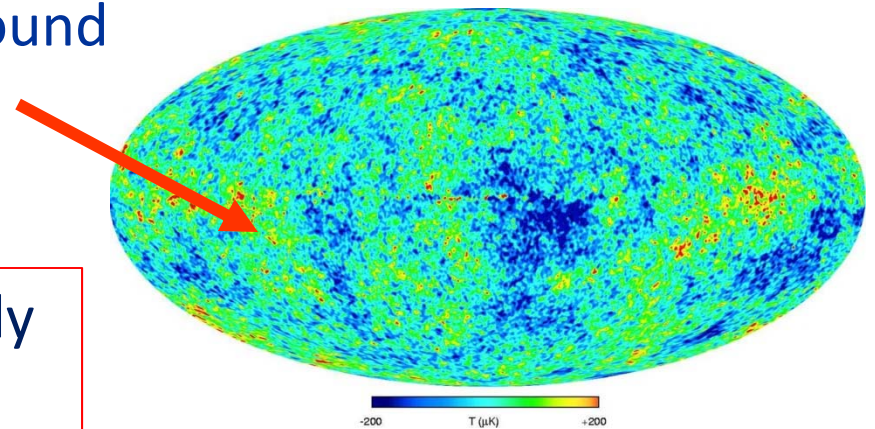
The early universe is very homogeneous on scales $l > l_{Jeans}$

→ 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



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

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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Gibbons & Turok

Dyson et al.

Carroll & Tam

Shiffren & Wald

Penrose

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NB Same
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$$\dot{S} > 0$$

“but it’s
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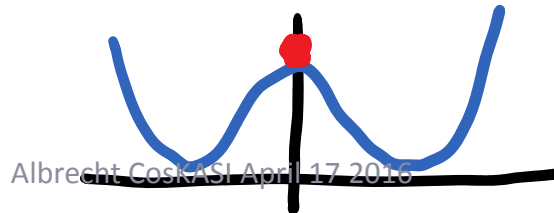
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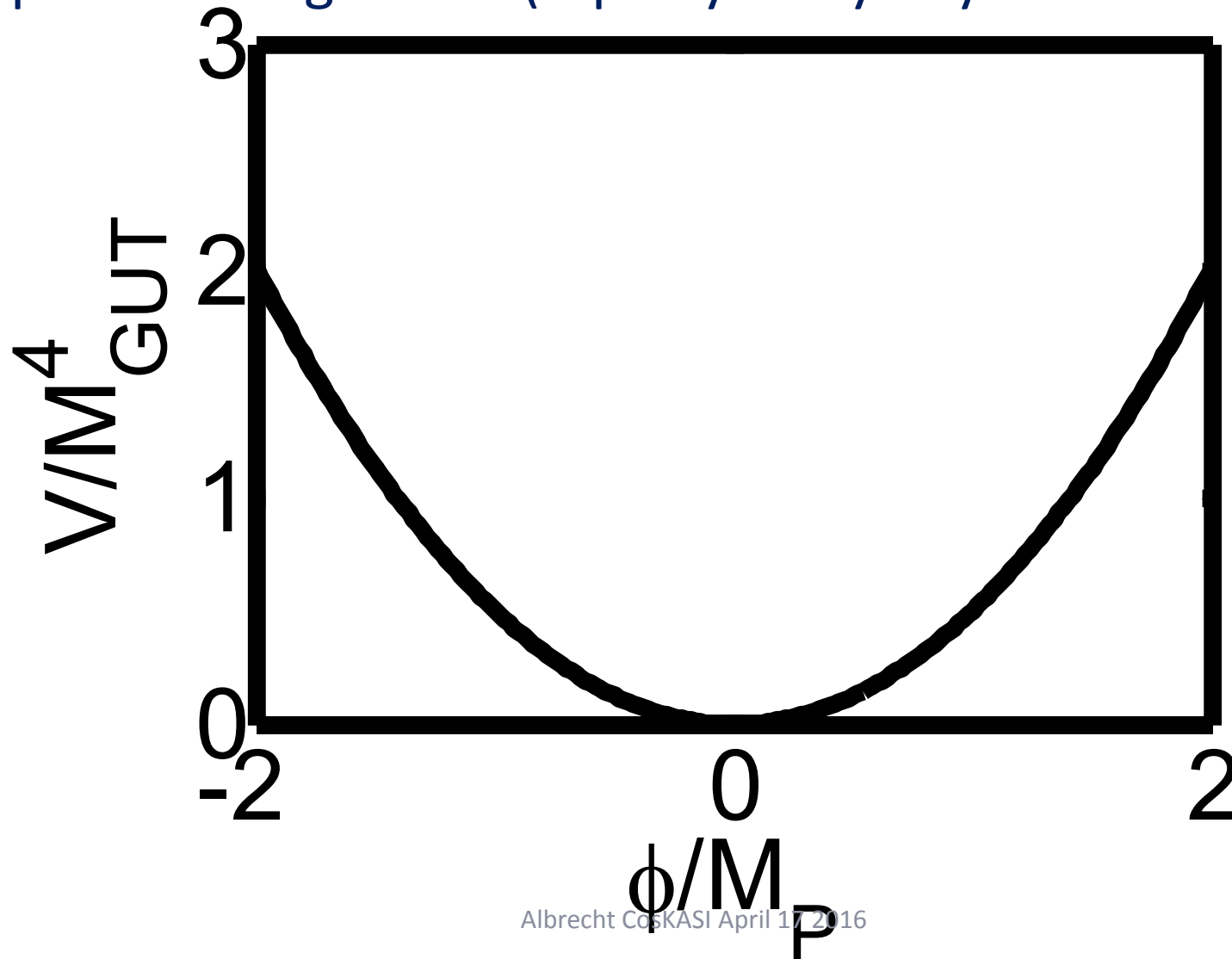
Related issues:

- Arrival Terminals
- Tuning assumptions in infinite universes (eternal)
- Various discussions about tuning in SBB (with or without inflation)
- Belief in “naturalness” of high energy density starts



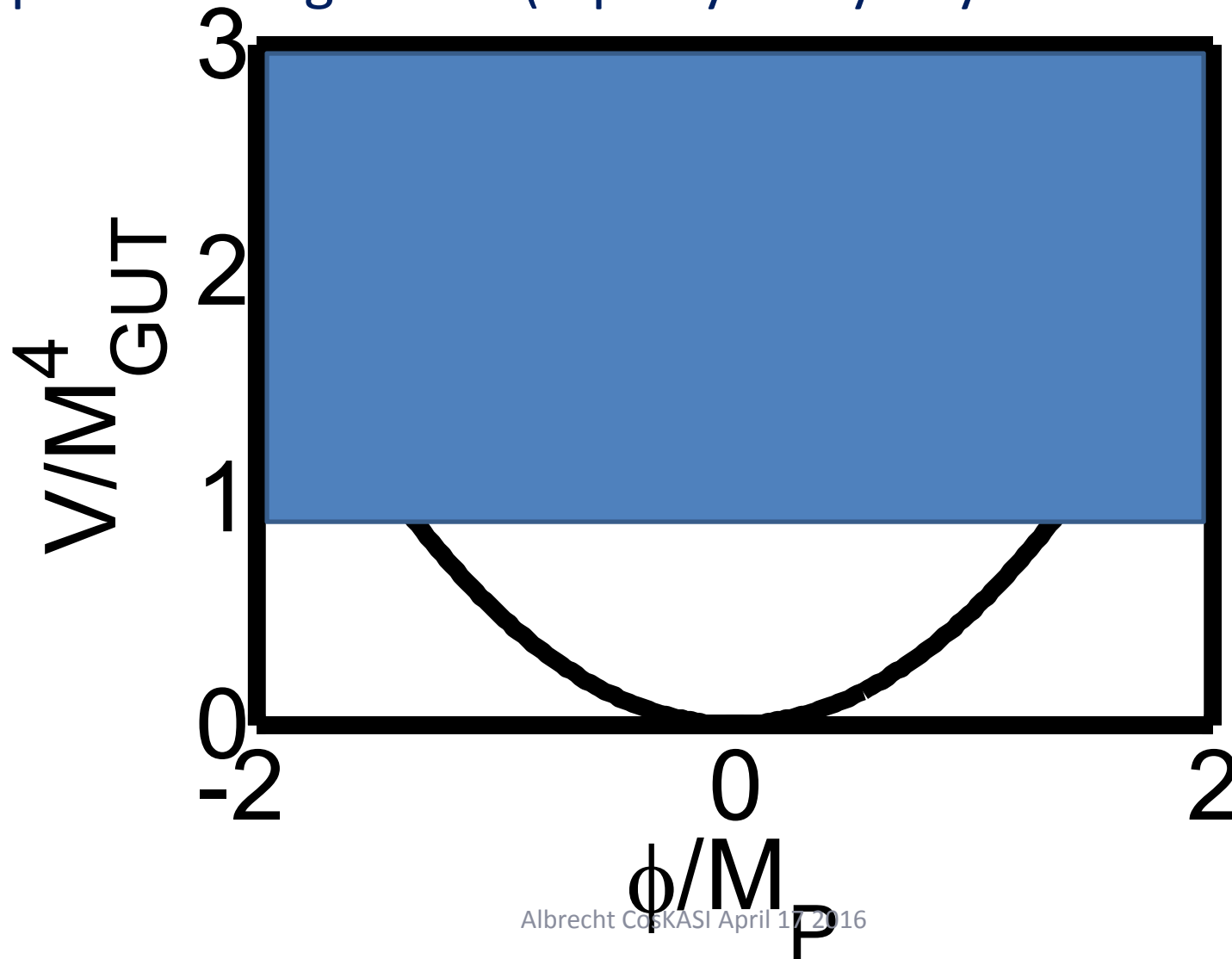
Beware “temporal provincialism”:

Equipartition argument (equally likely anywhere on potential)



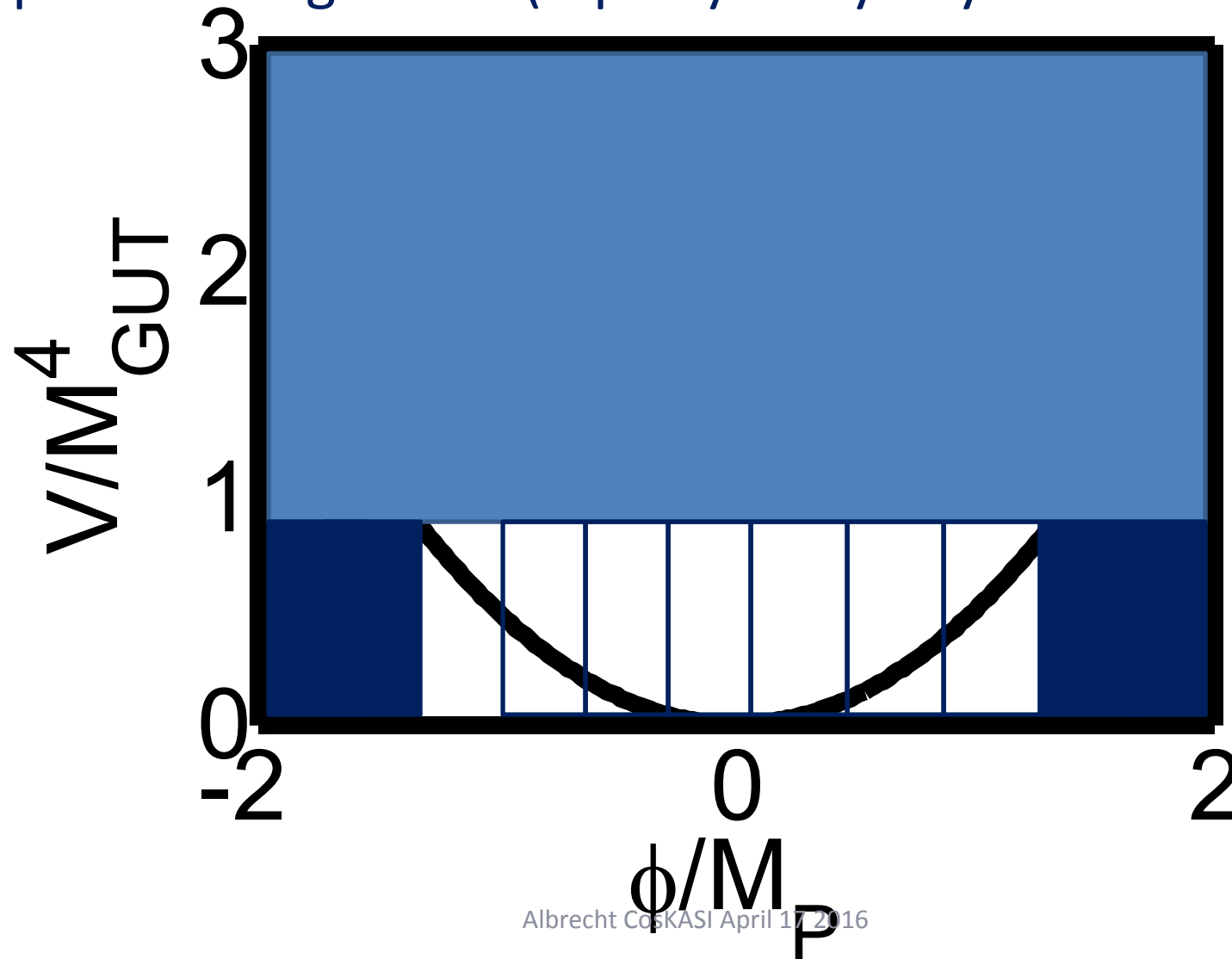
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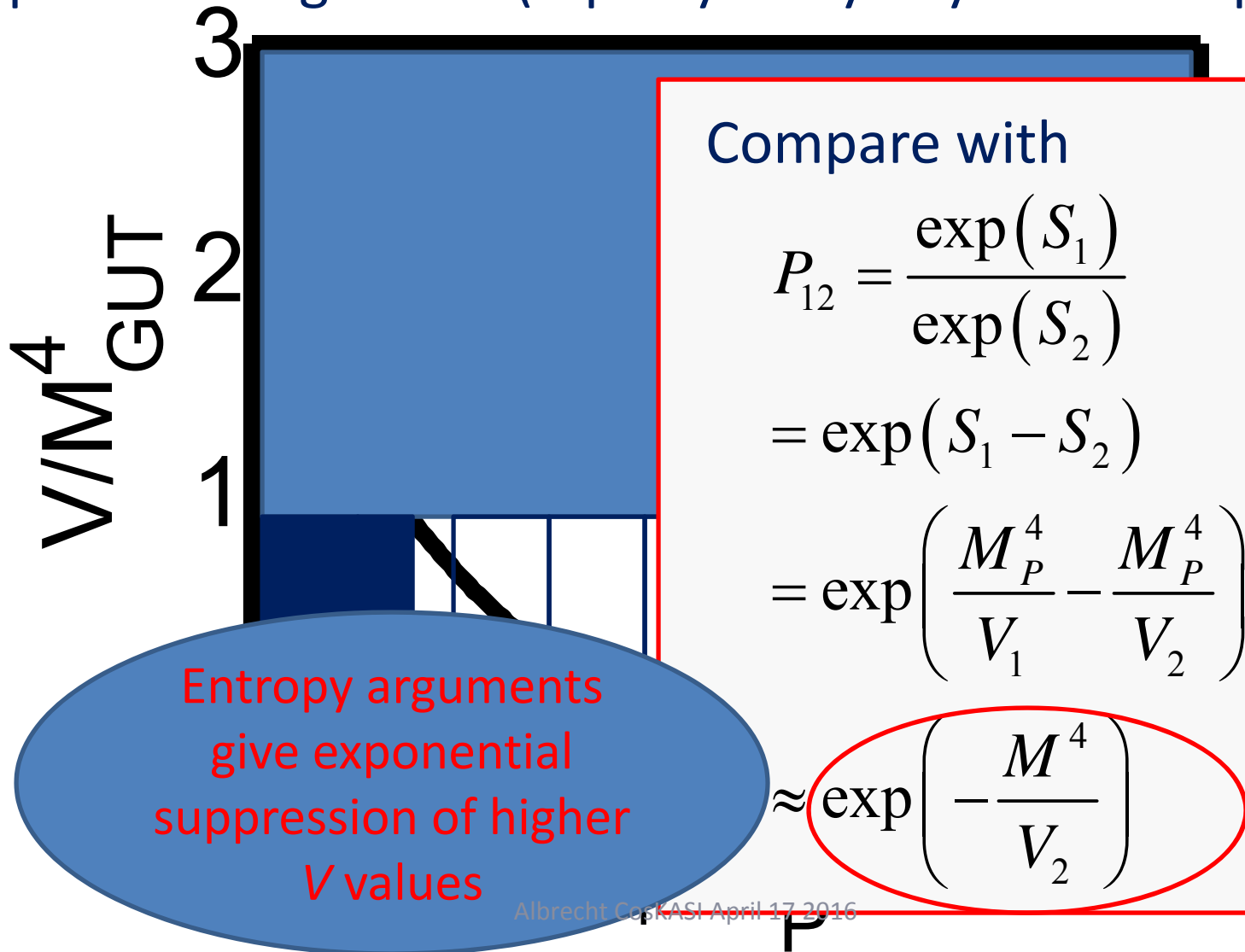
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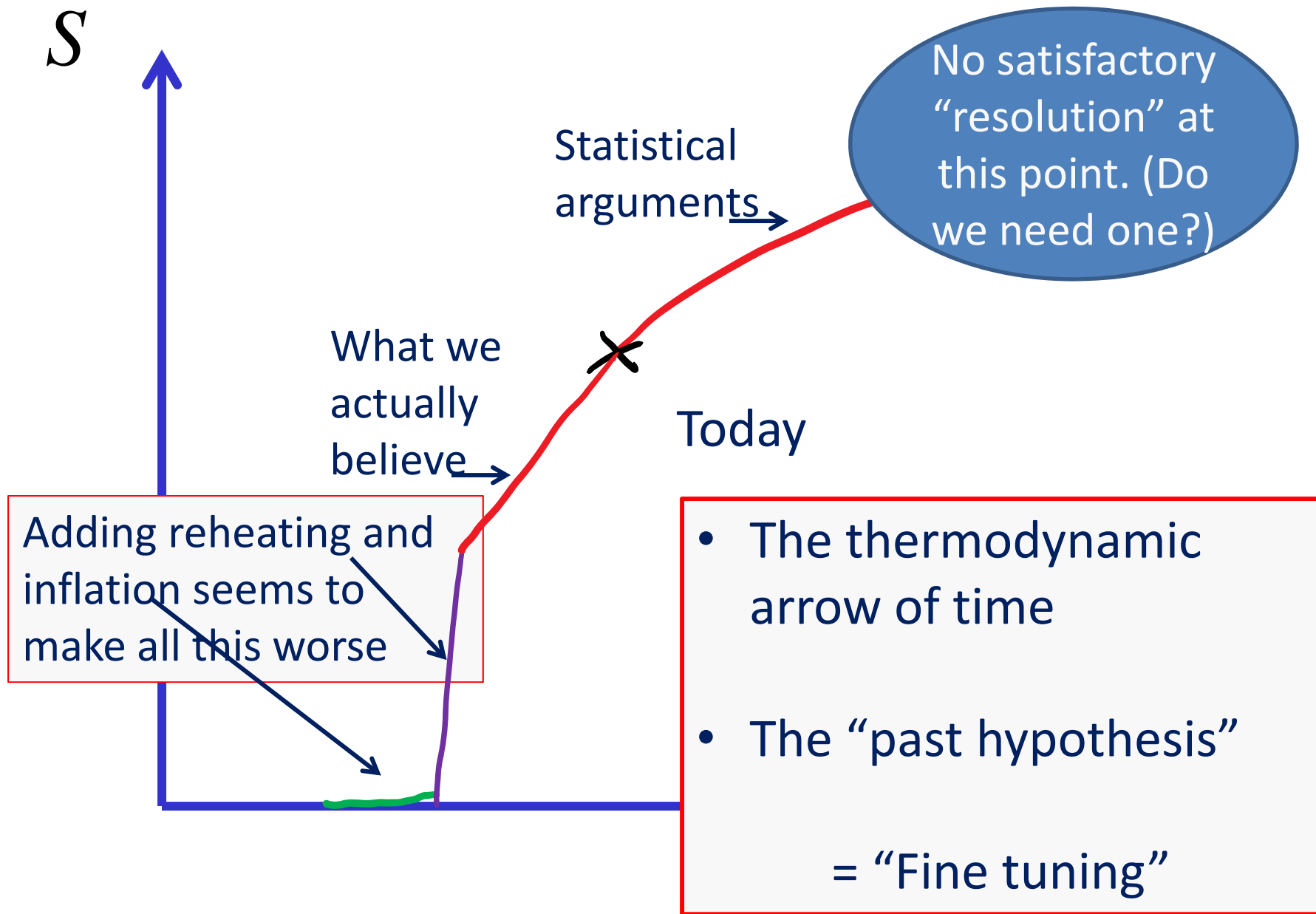
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- **Bunch Davies Vacuum**

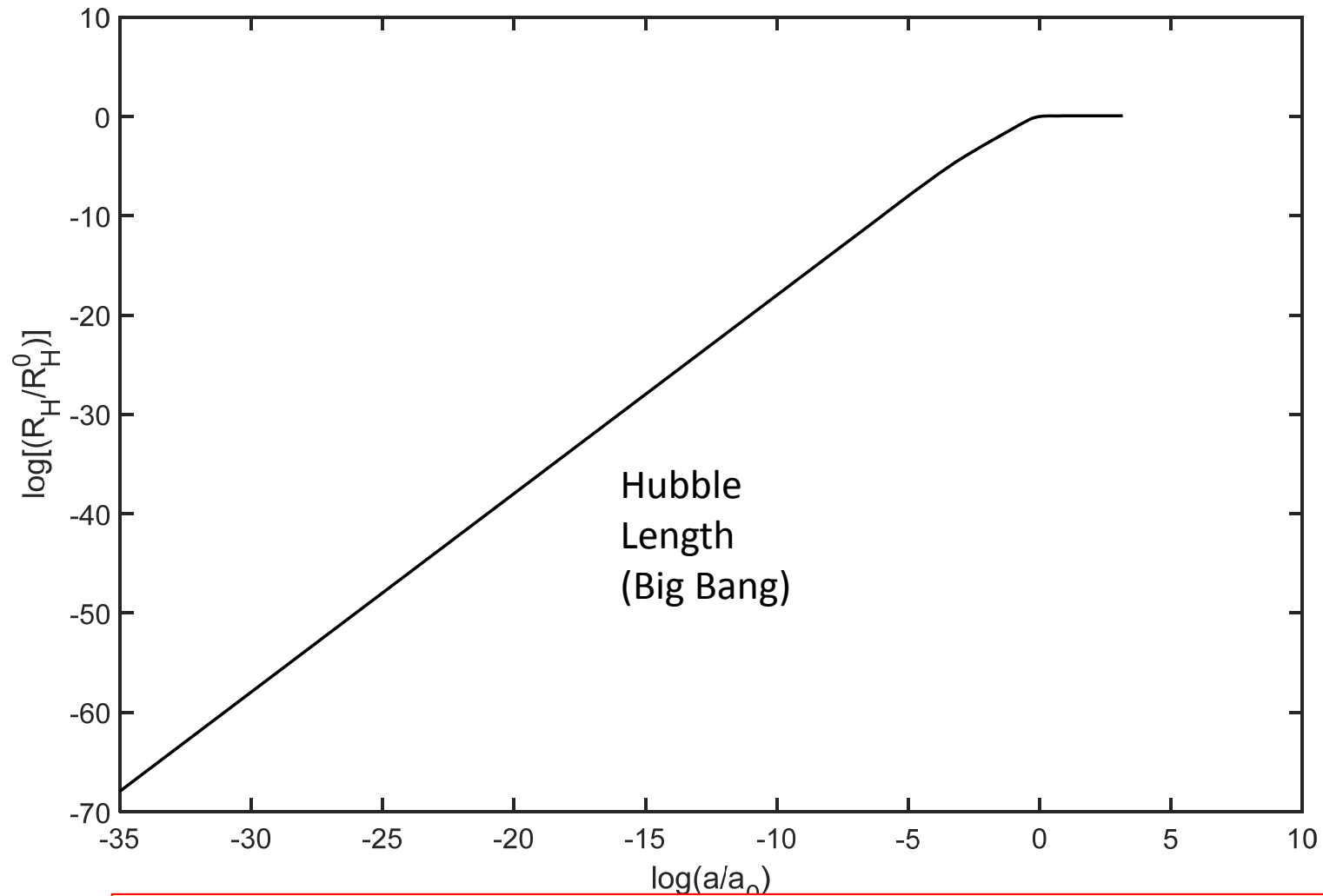
ii) Measures

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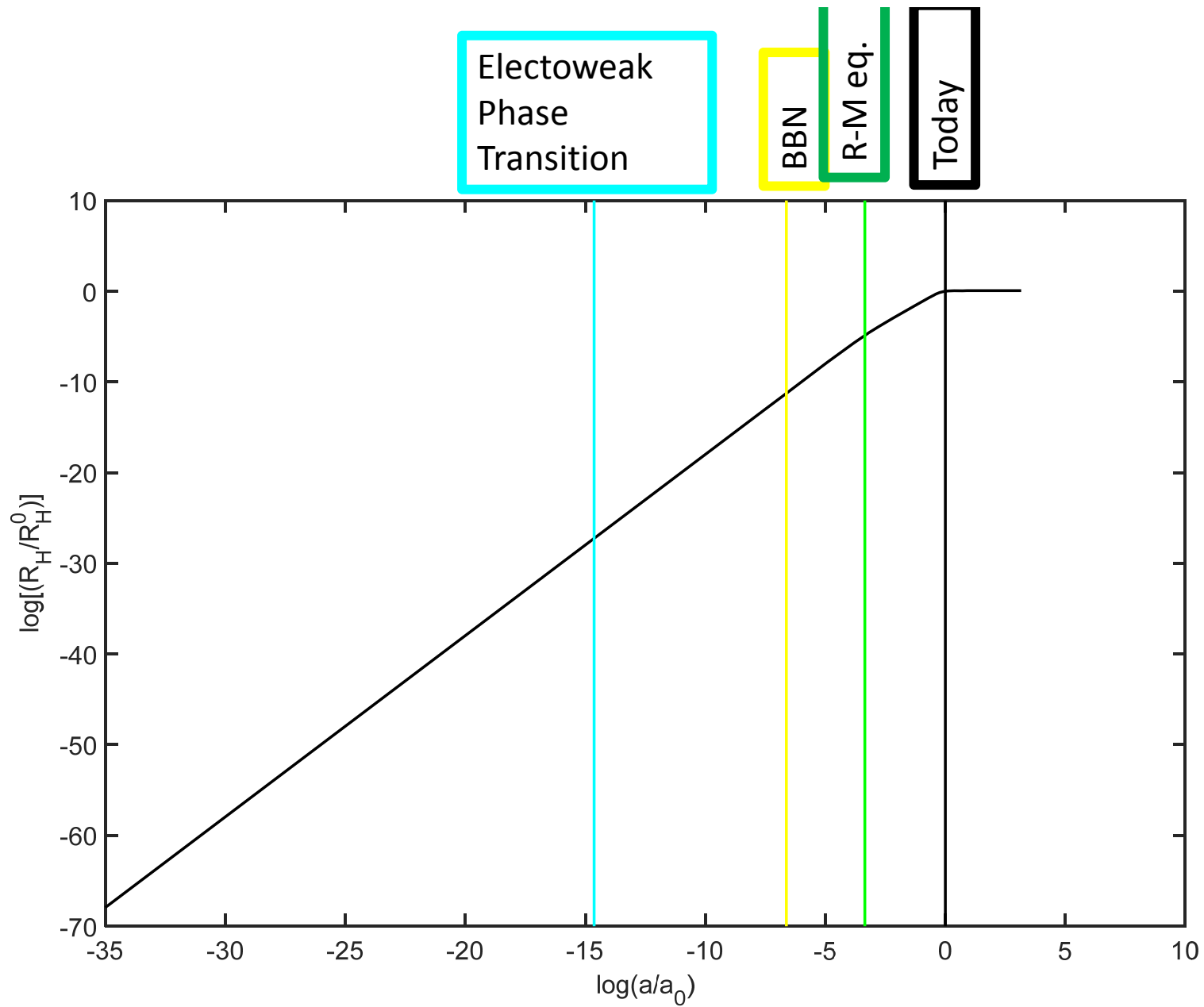
Reflections on fine tuning

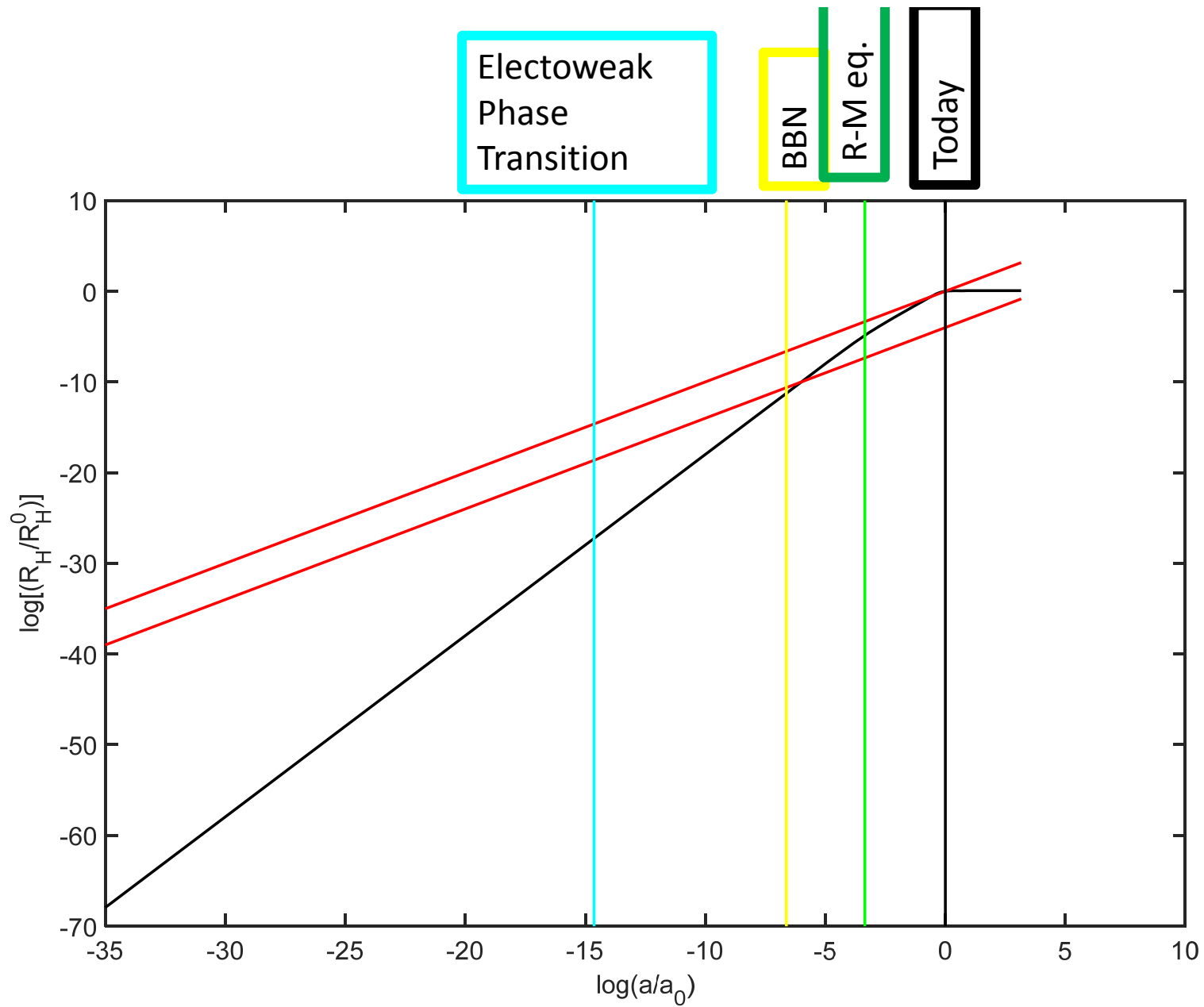
Use the evolution of length scales to get some perspective

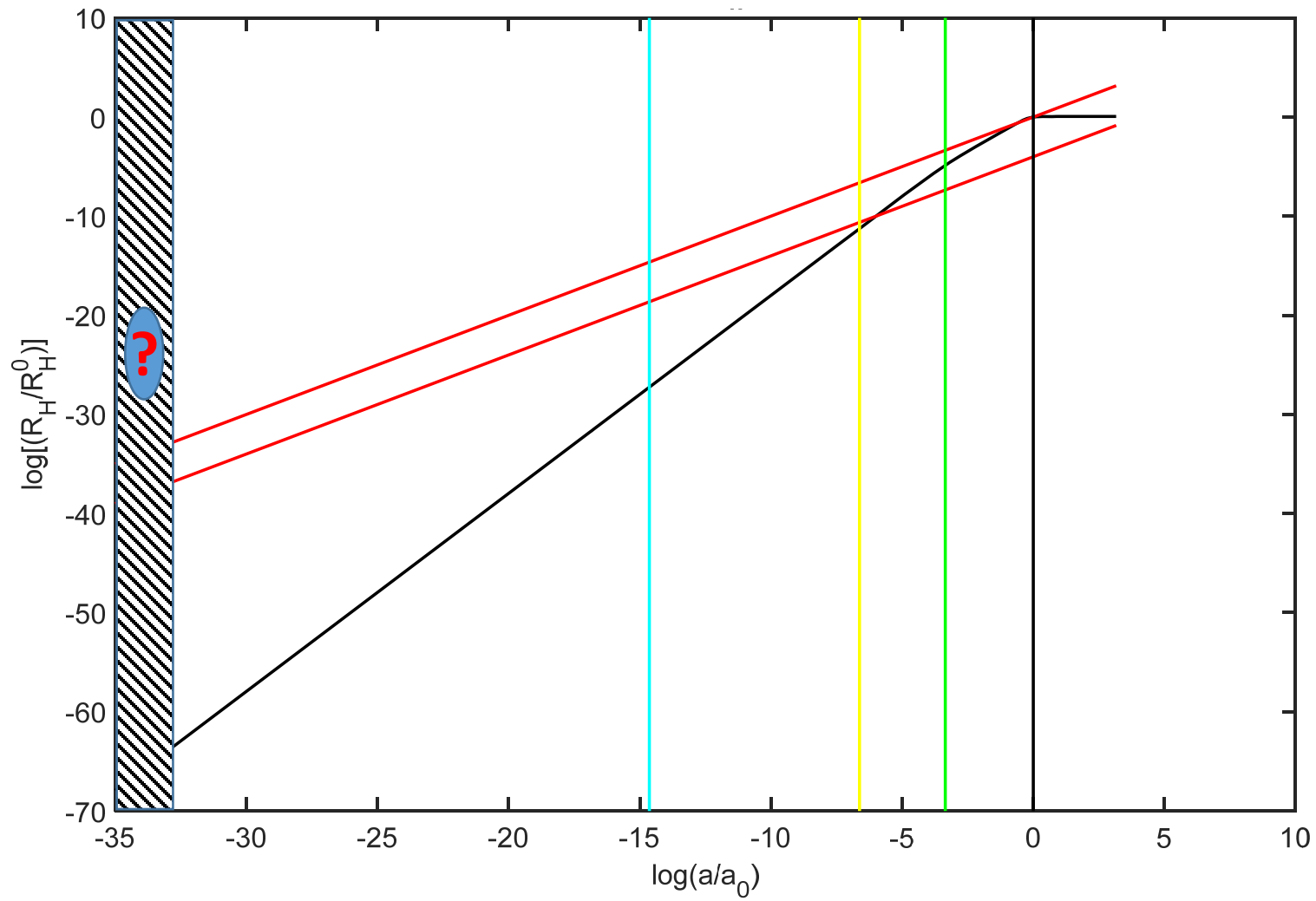
Log length over Hubble length today

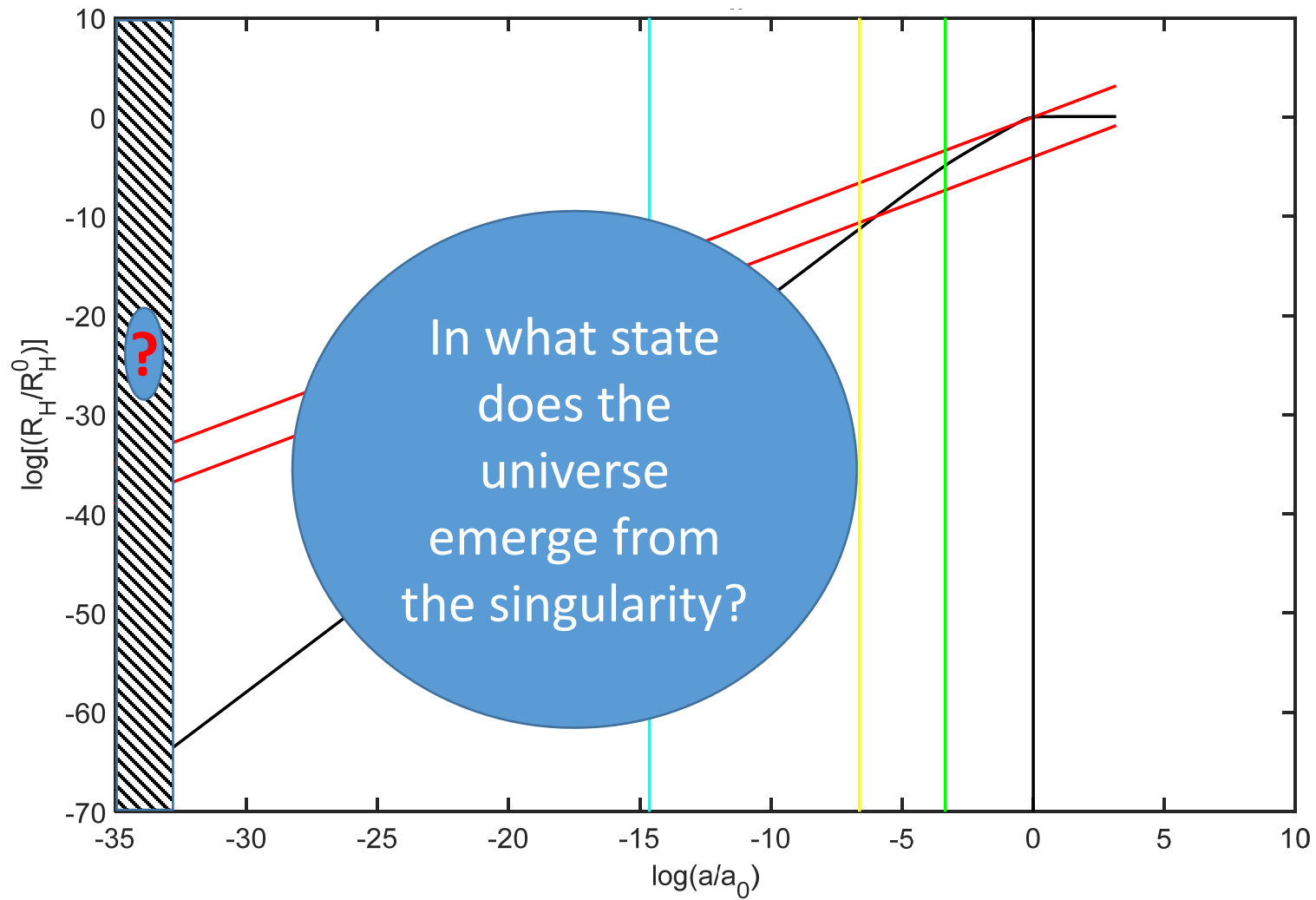


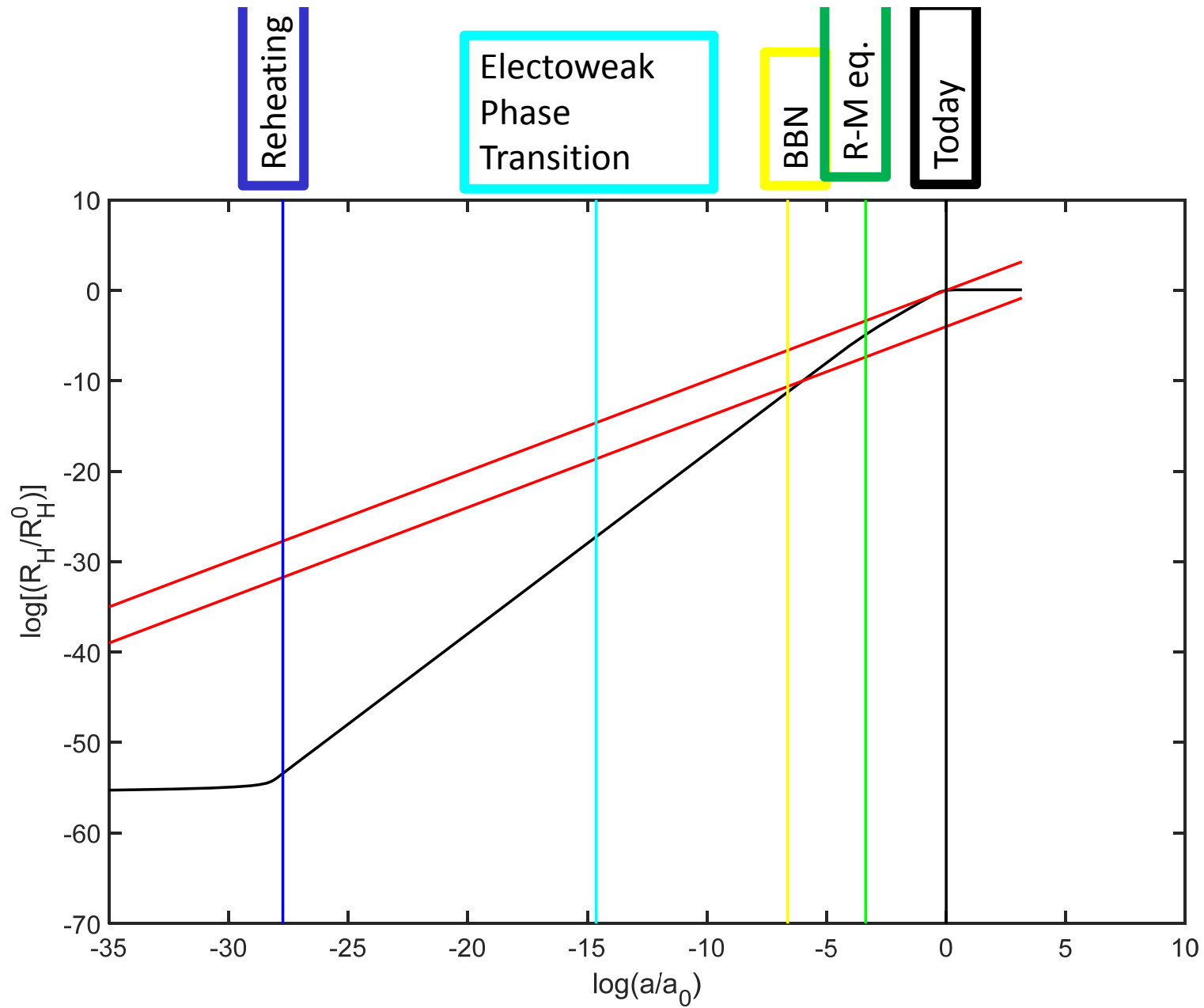
Log scale factor over scale factor today

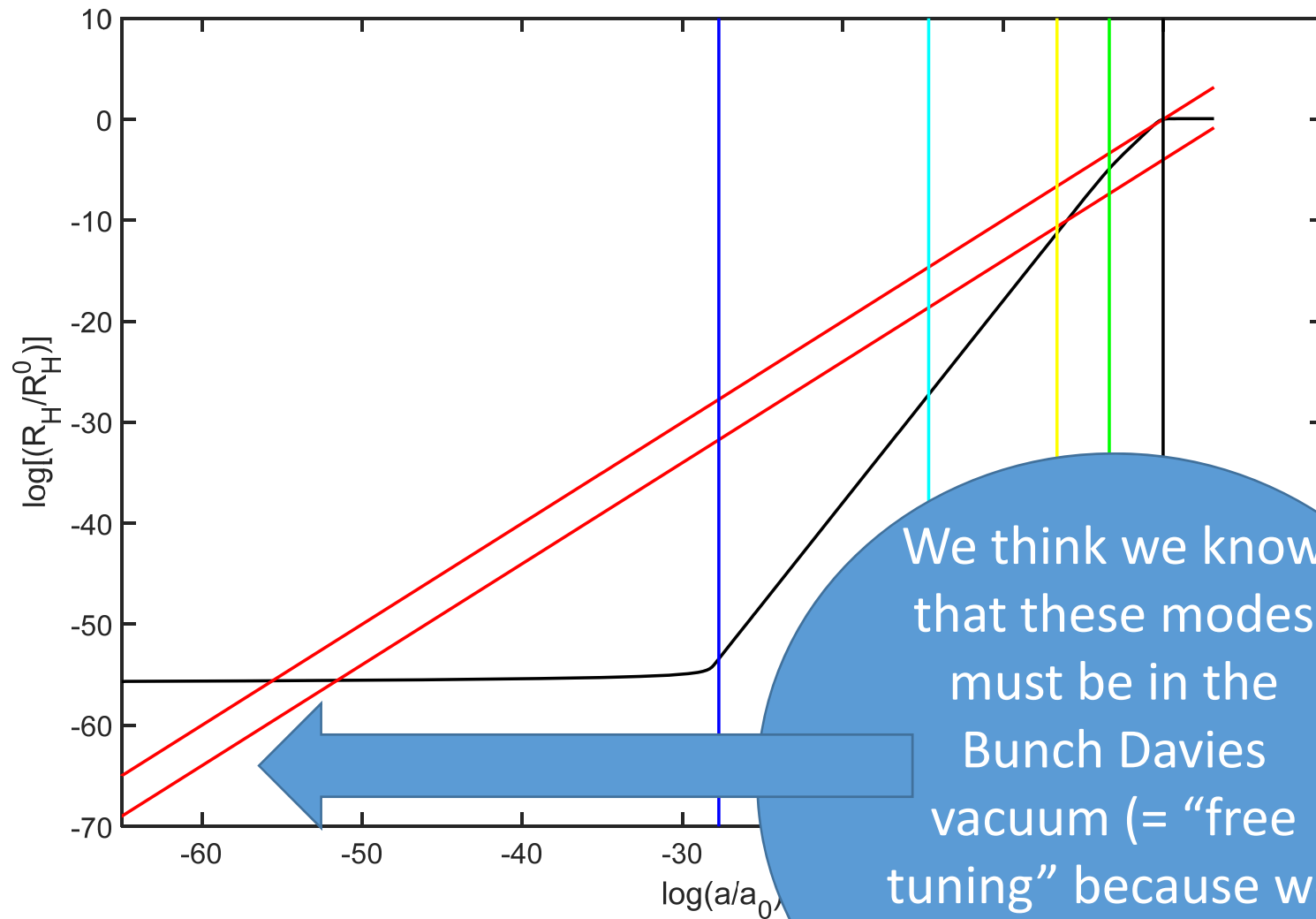


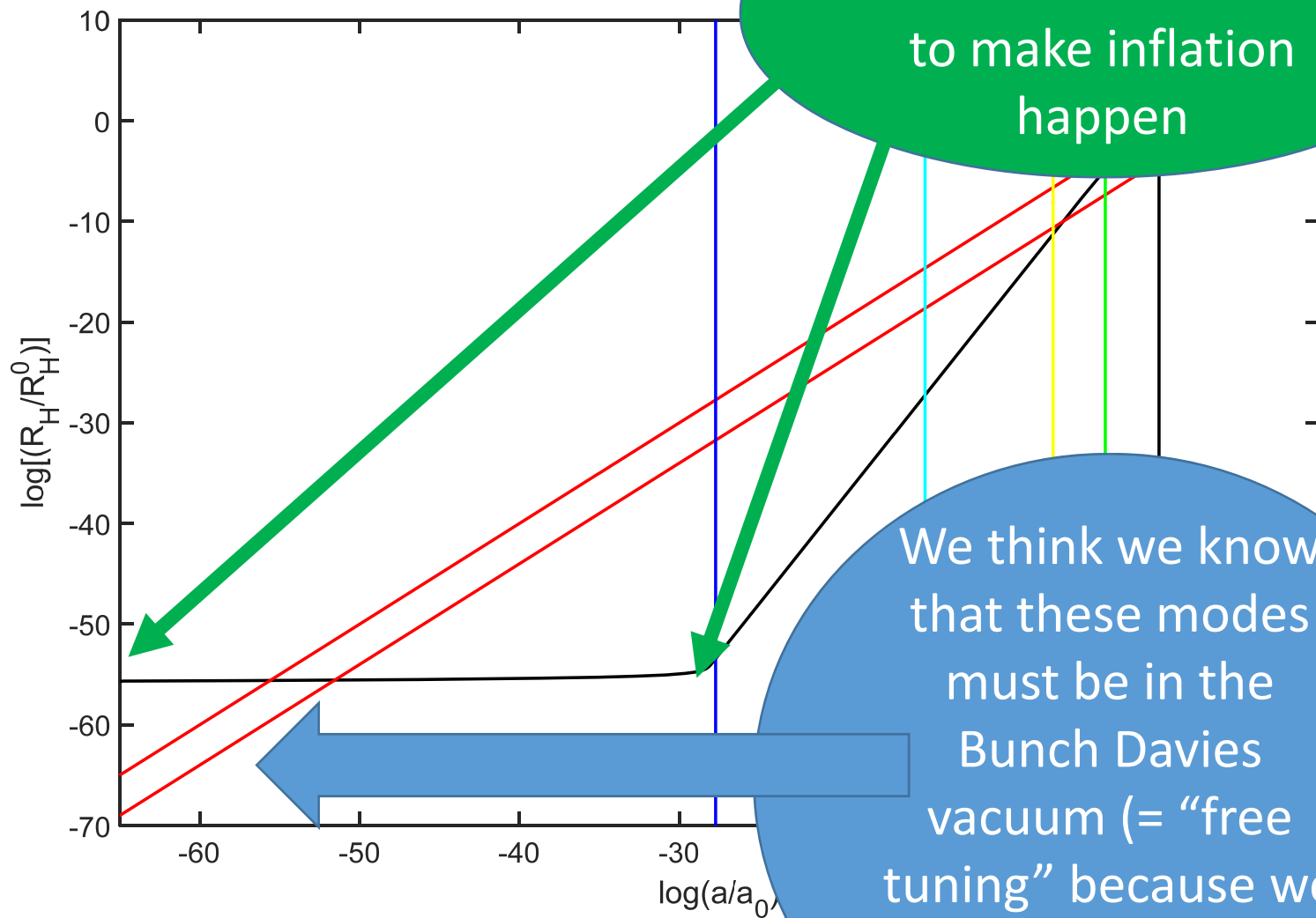






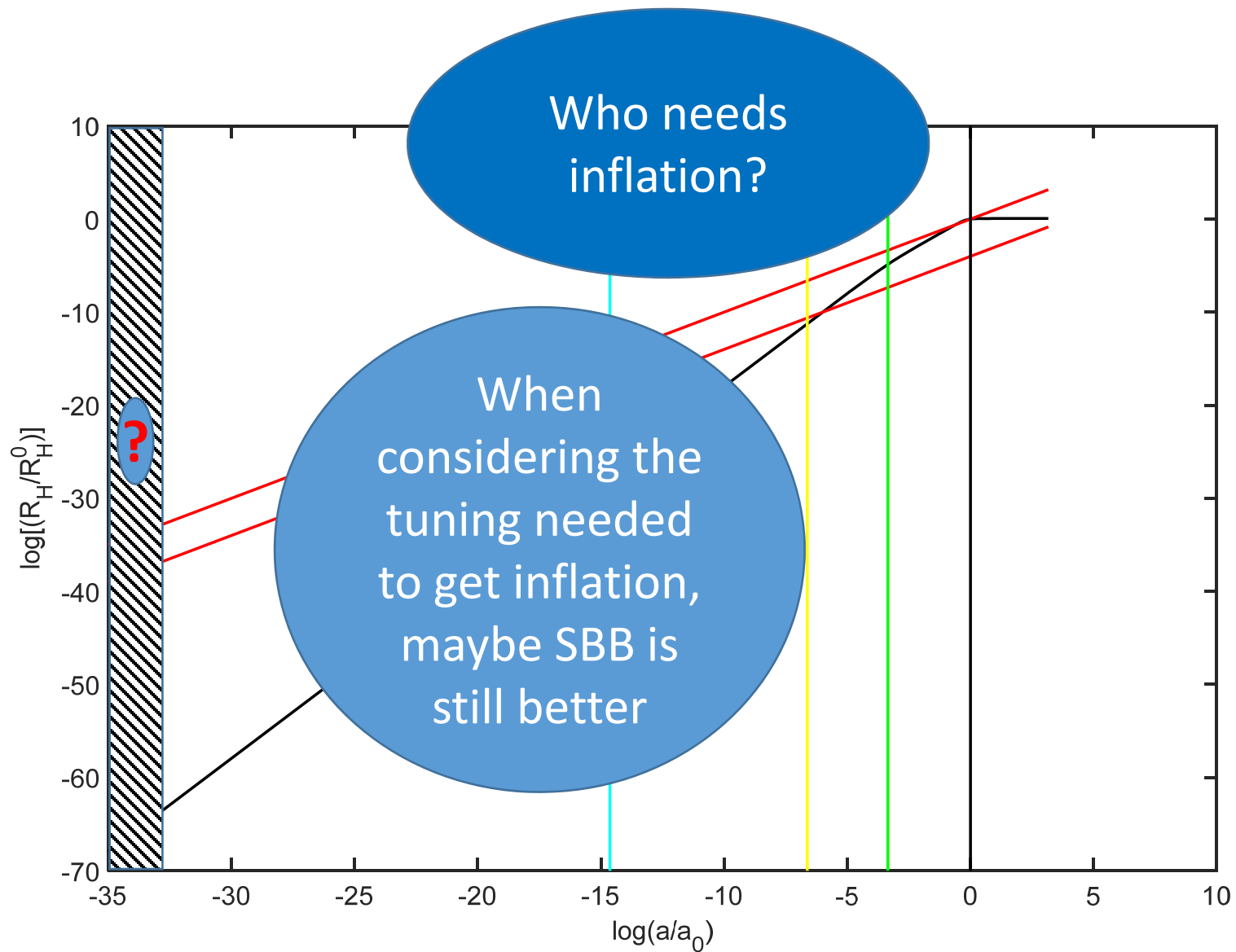






Entropy arguments still an issue re how to make inflation happen

We think we know that these modes must be in the Bunch Davies vacuum (= "free tuning" because we don't worry about it)



Outline

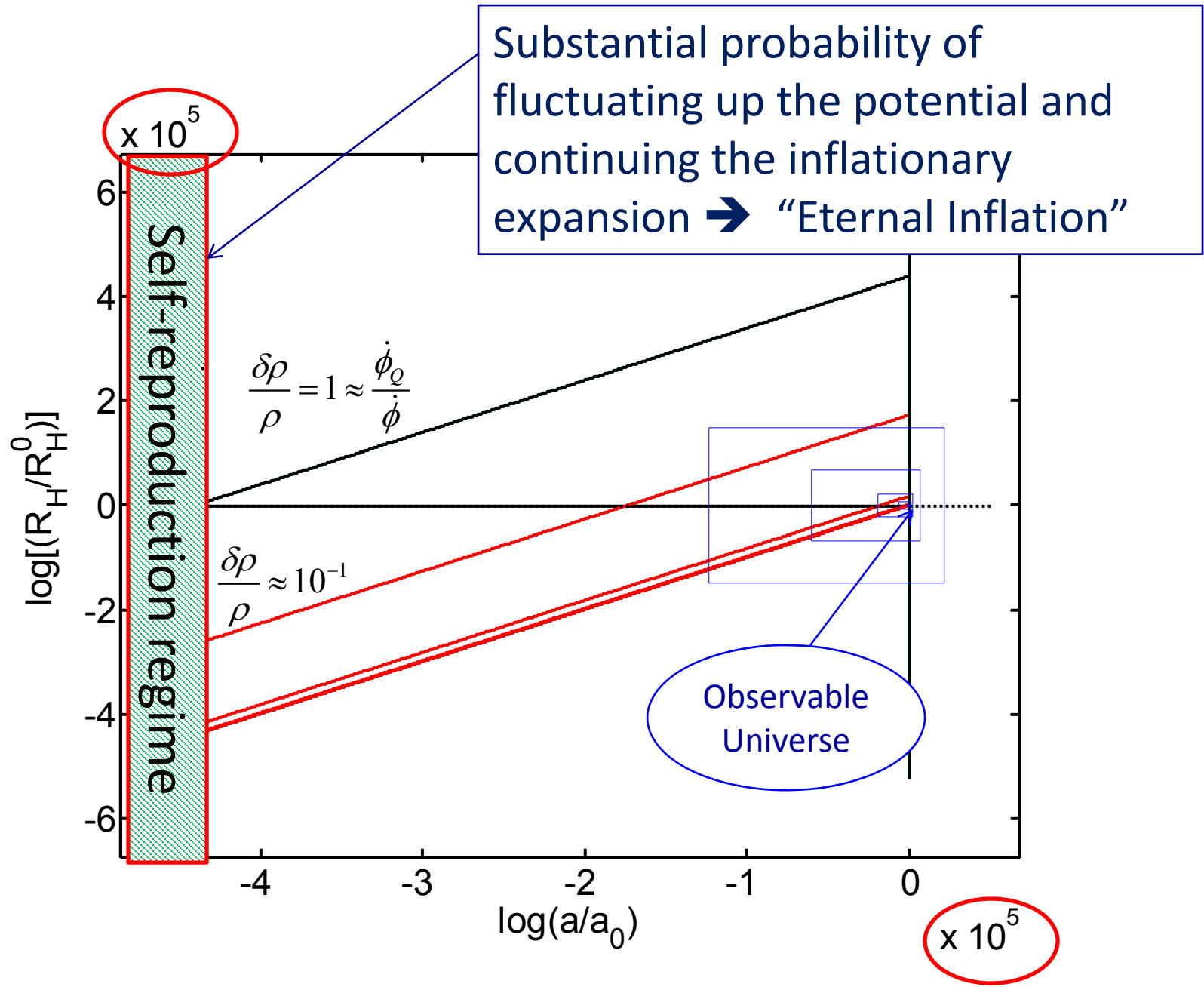
A) Open Questions

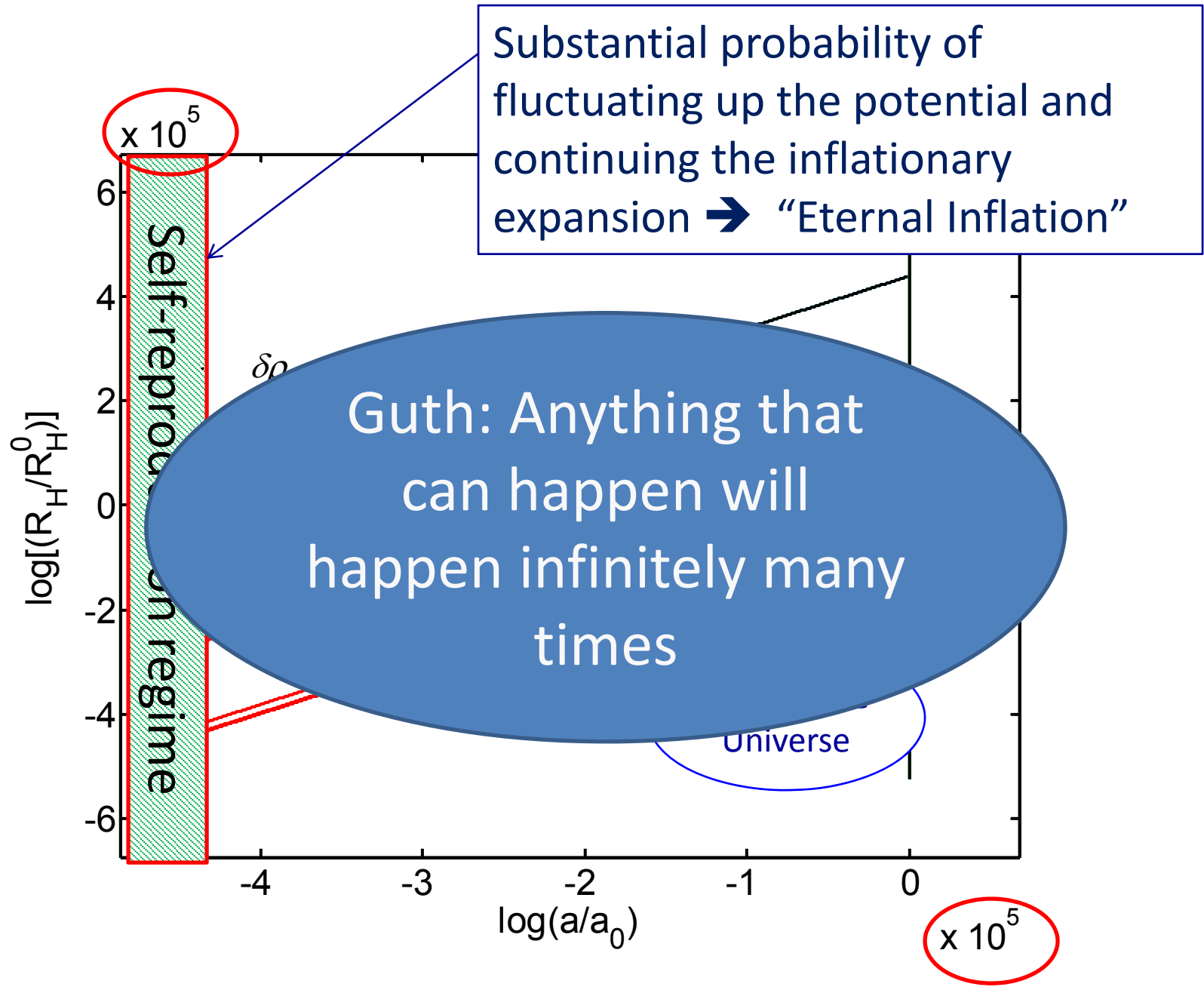
i) Tuning

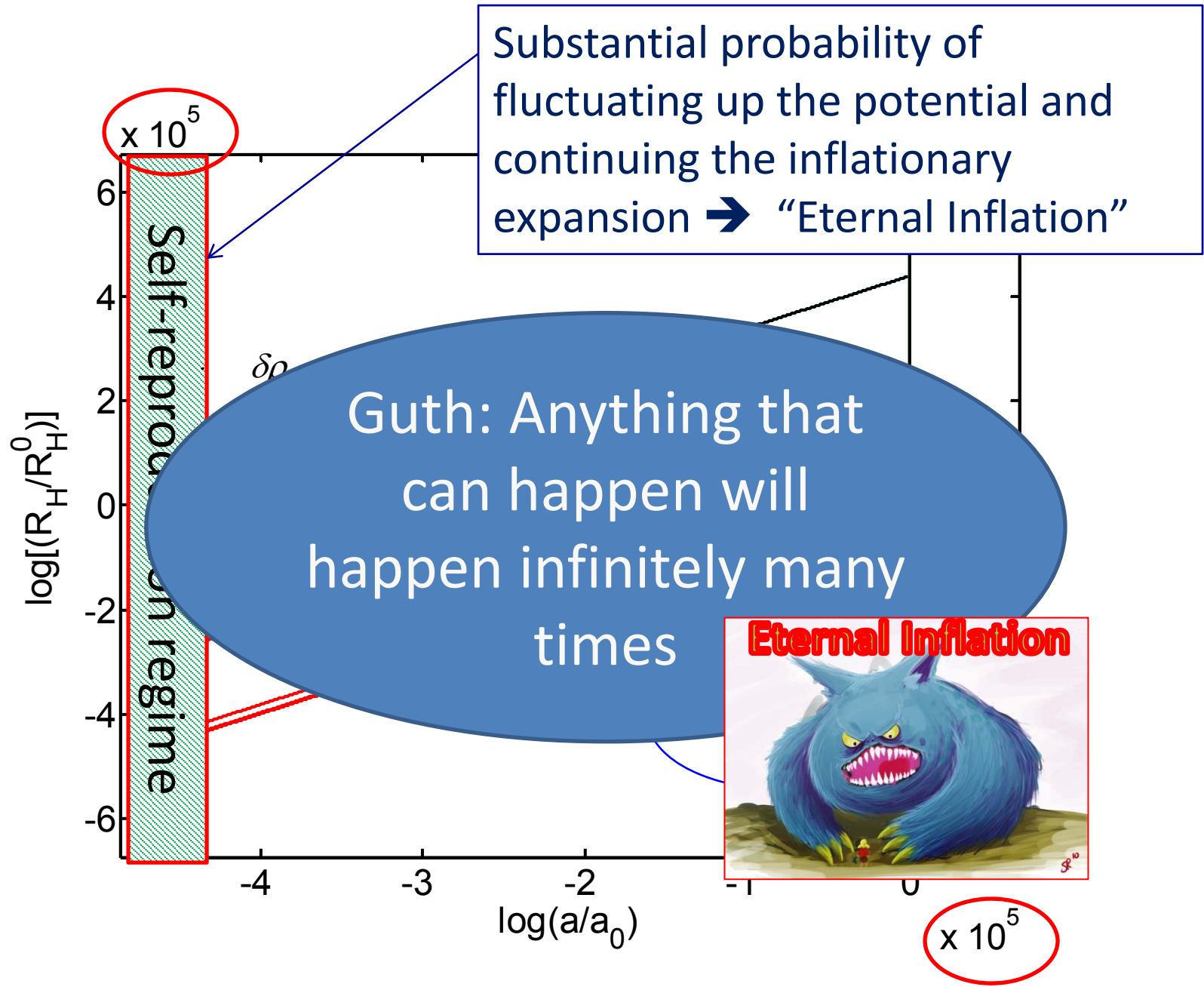
- Entropy perspective
- Bunch Davies Vacuum

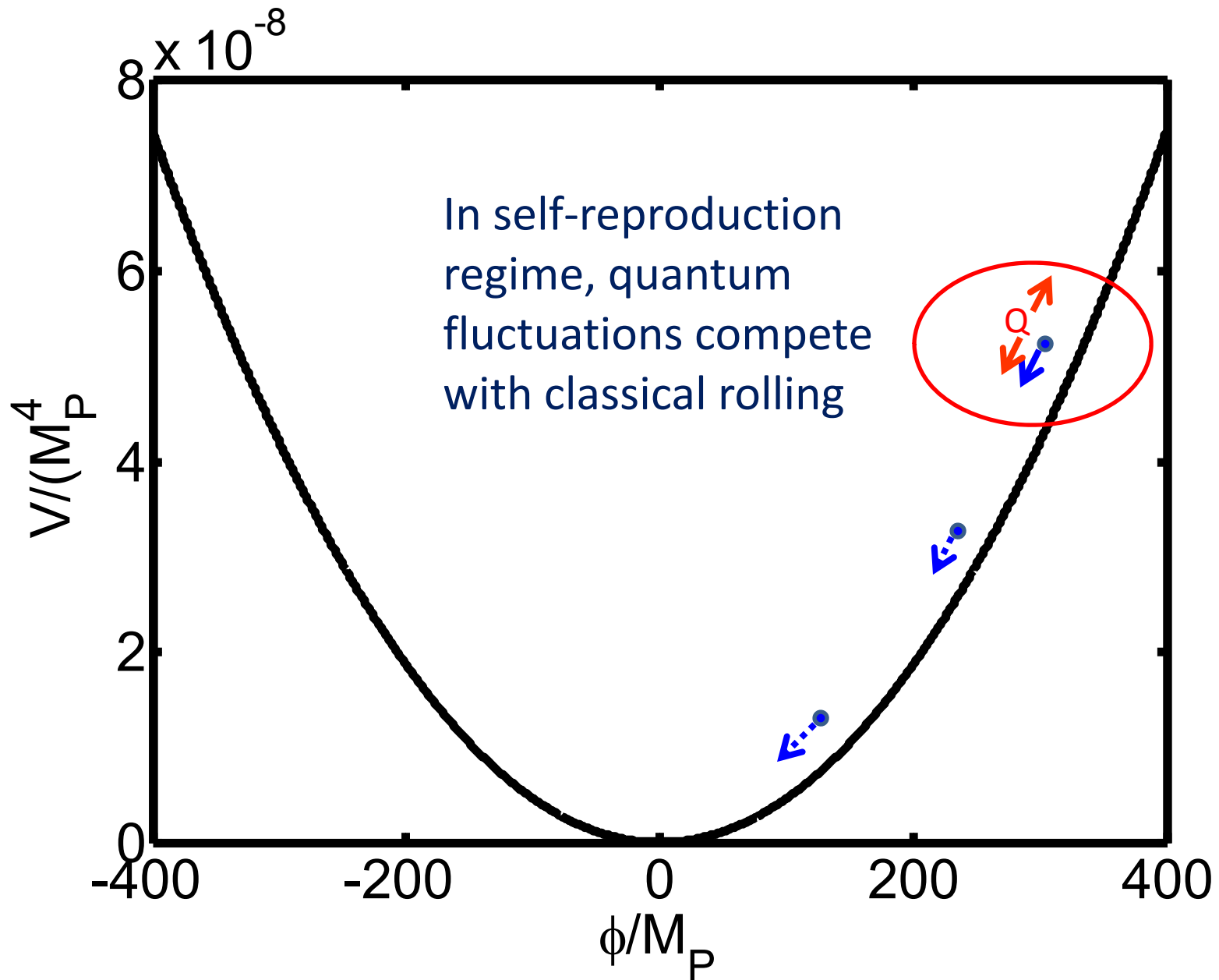
ii) Measures

B) Connections to modern research topics, and ultimately surveys

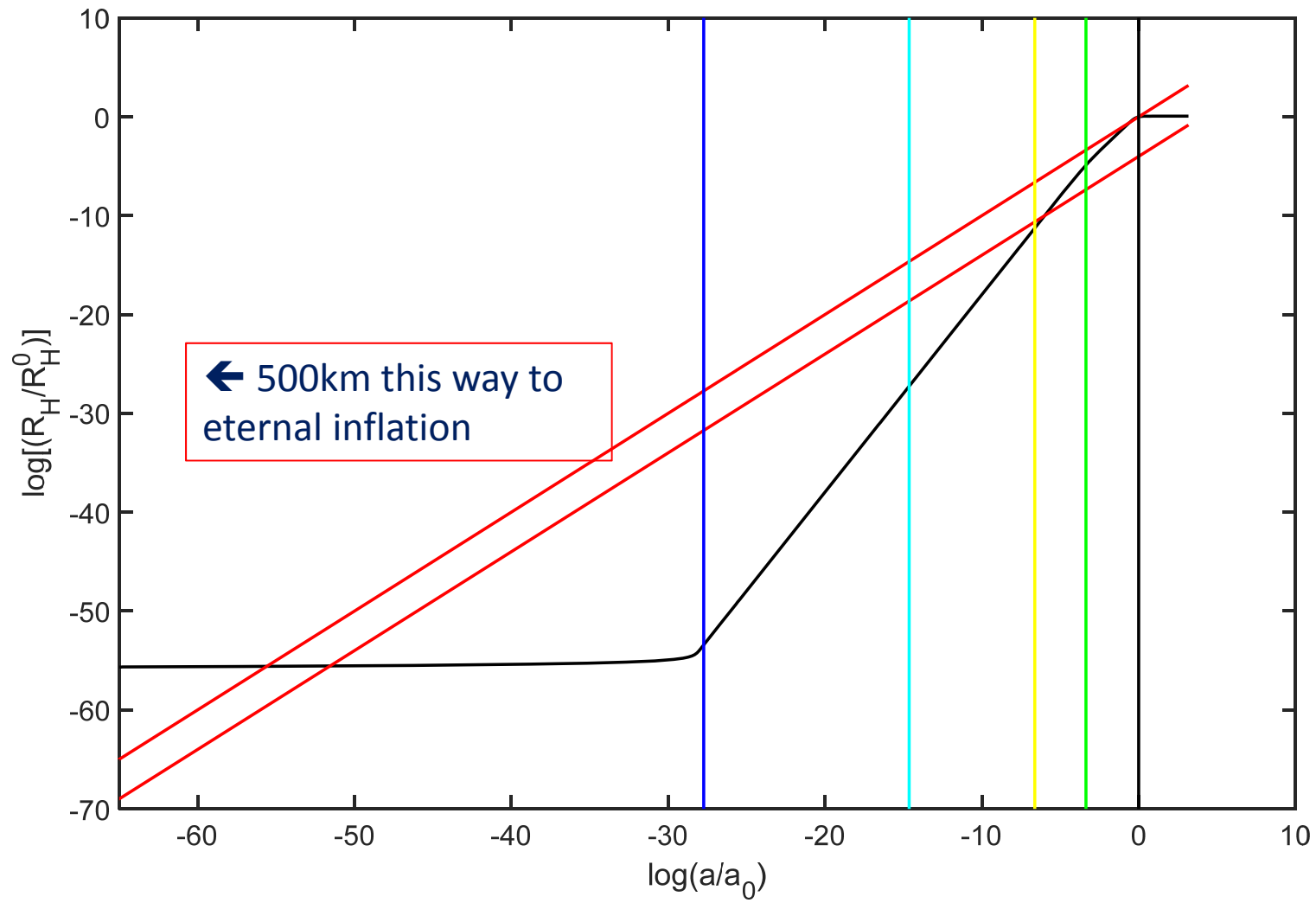








(not to scale)



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Current questions

- What is the vacuum?, Firewalls
- Holography, AdS/CFT
- The nature of horizons, singularities
- Entanglement/Geometry duality

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- Emergence of spacetime
- What is gravity?

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Inflation, and cosmology in general,
have a deep capacity to link these
issues with observational
signatures.

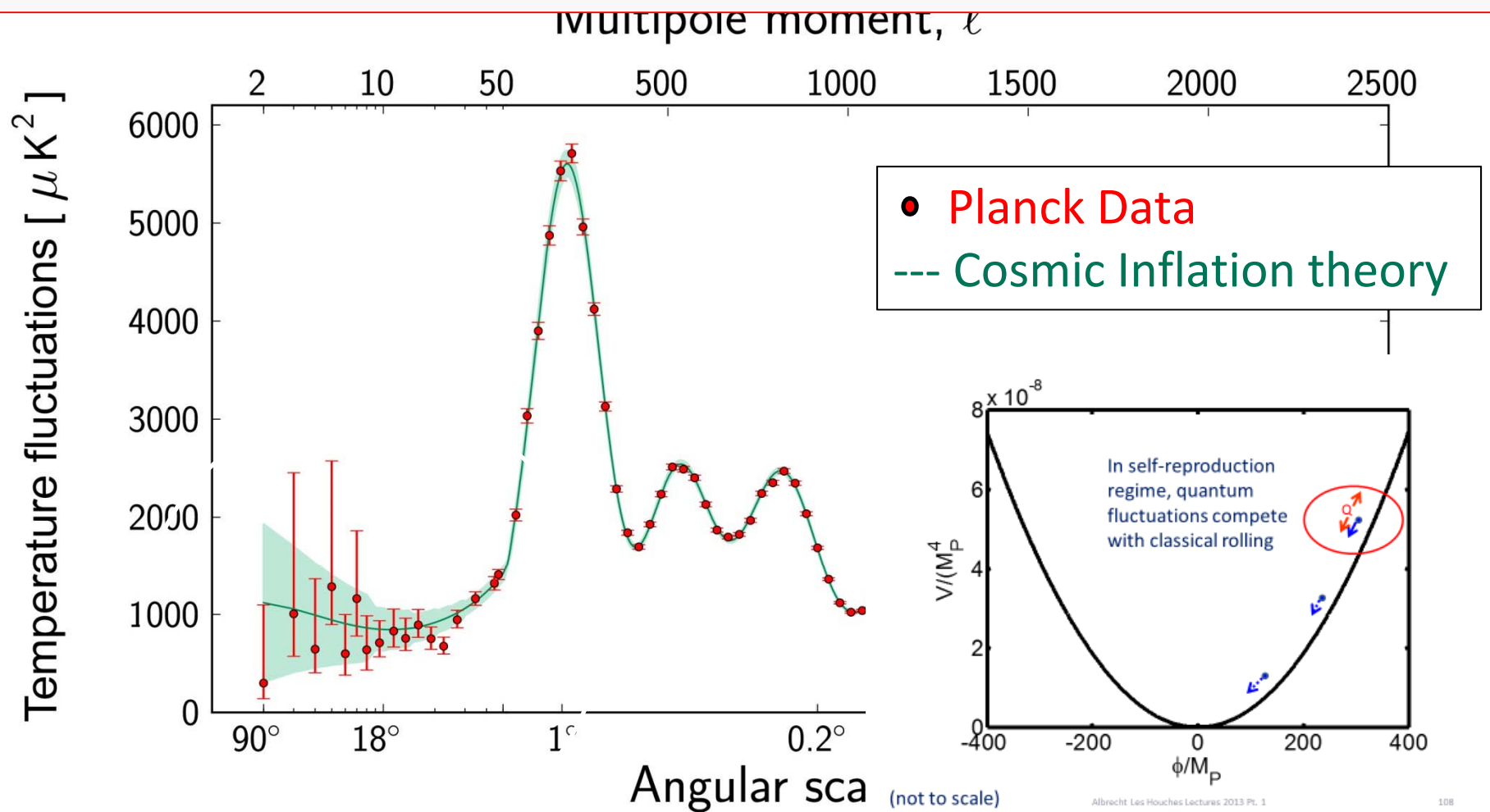
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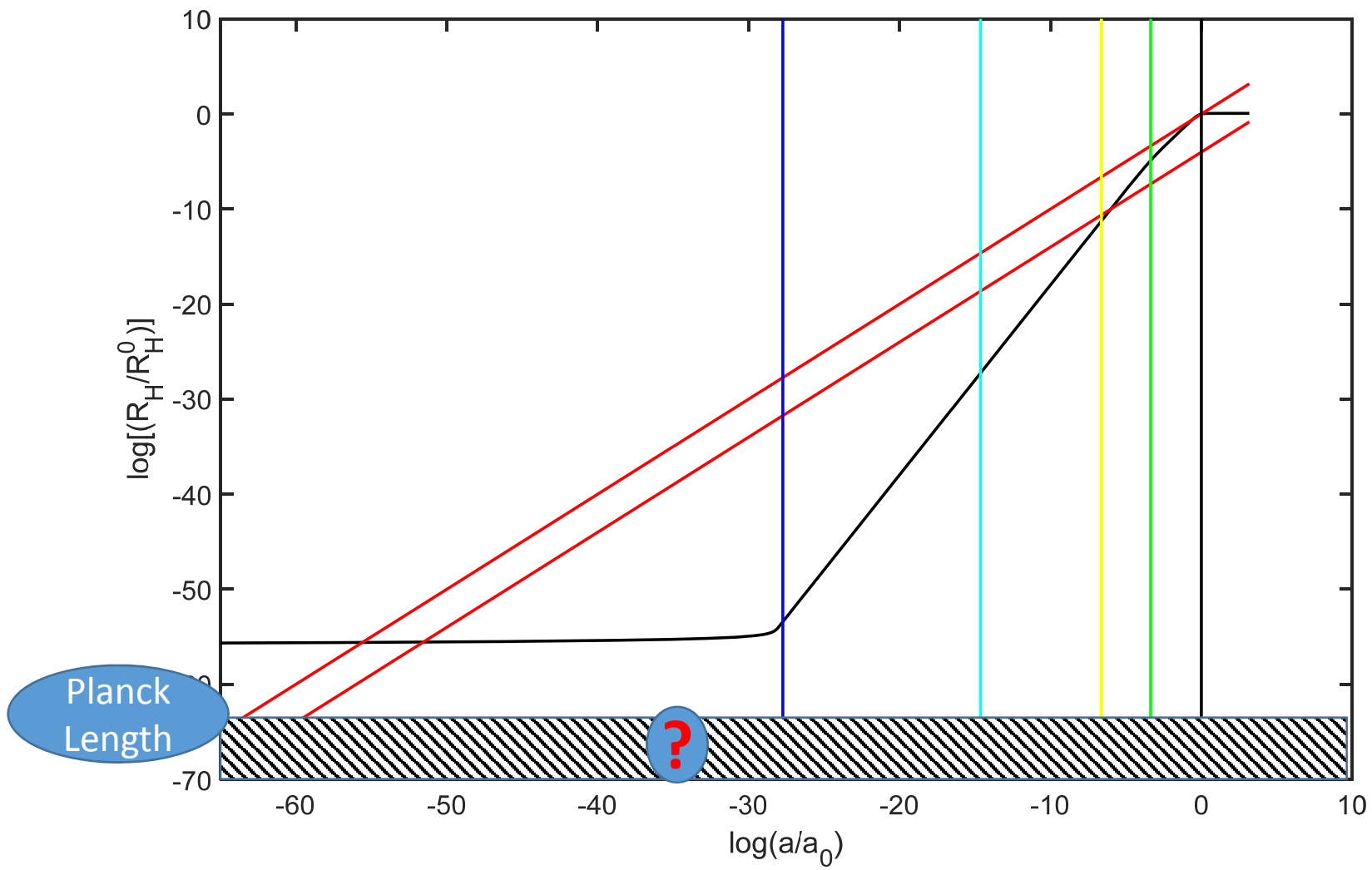
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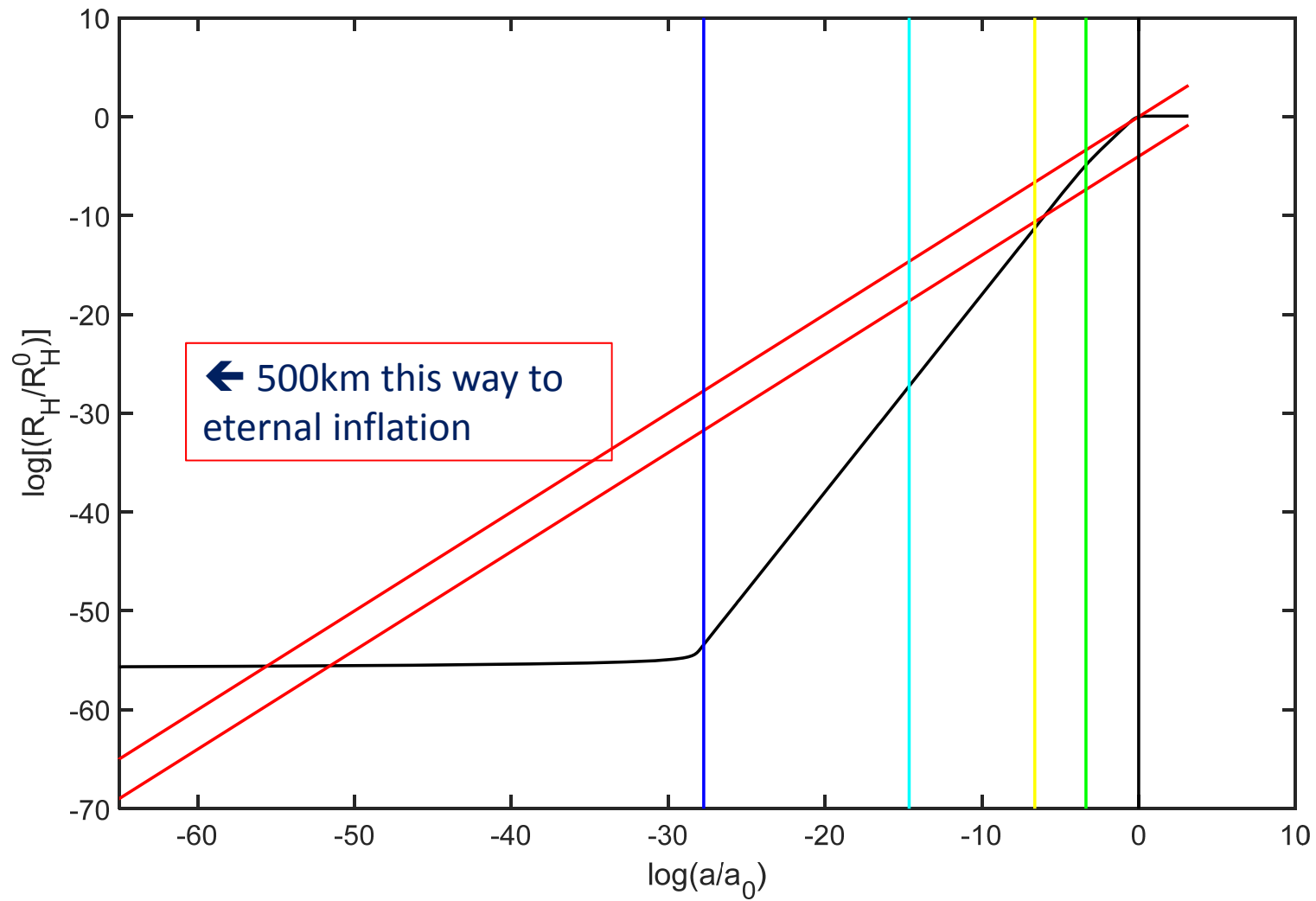
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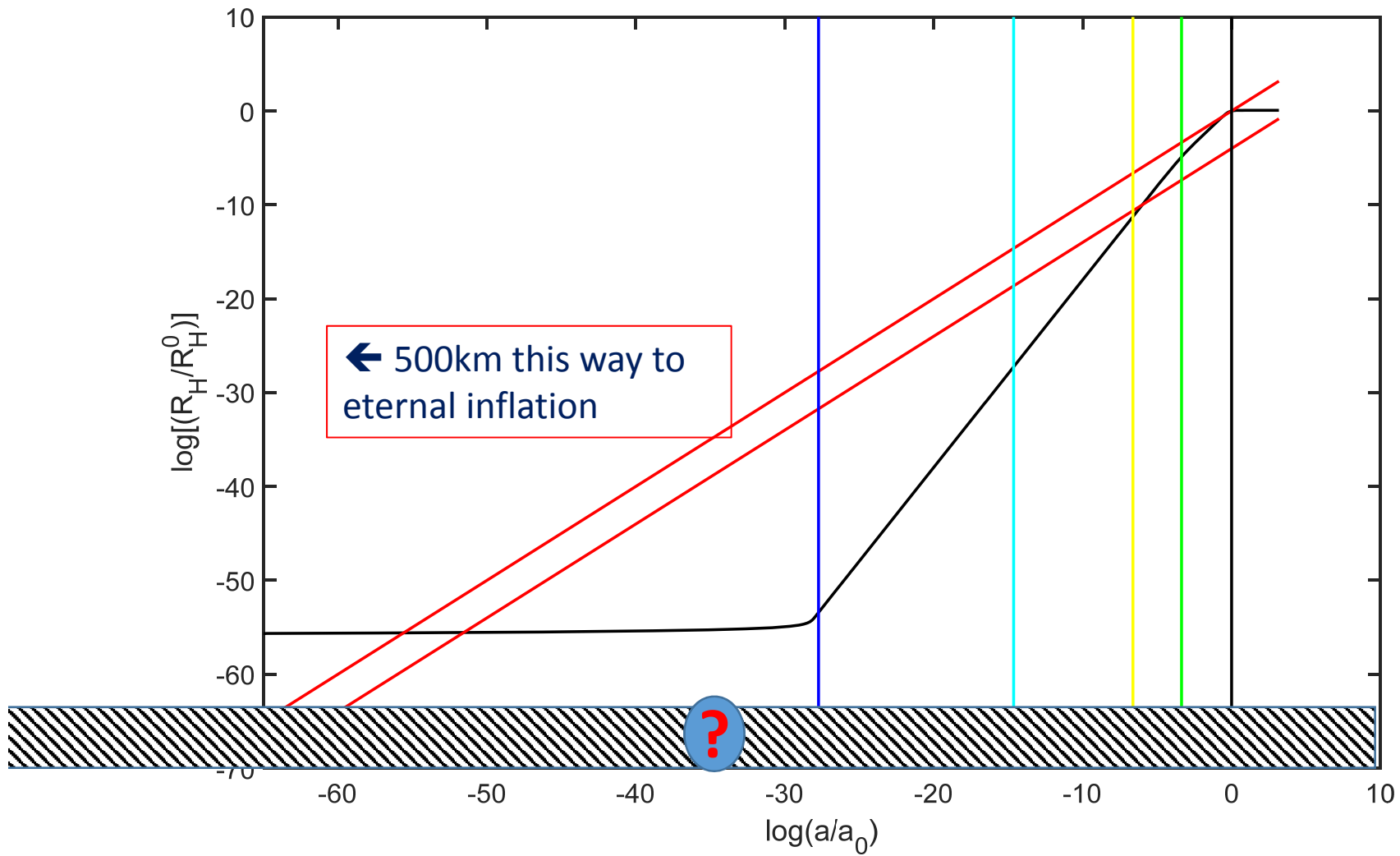
Likely what is needed to resolve open questions with inflation

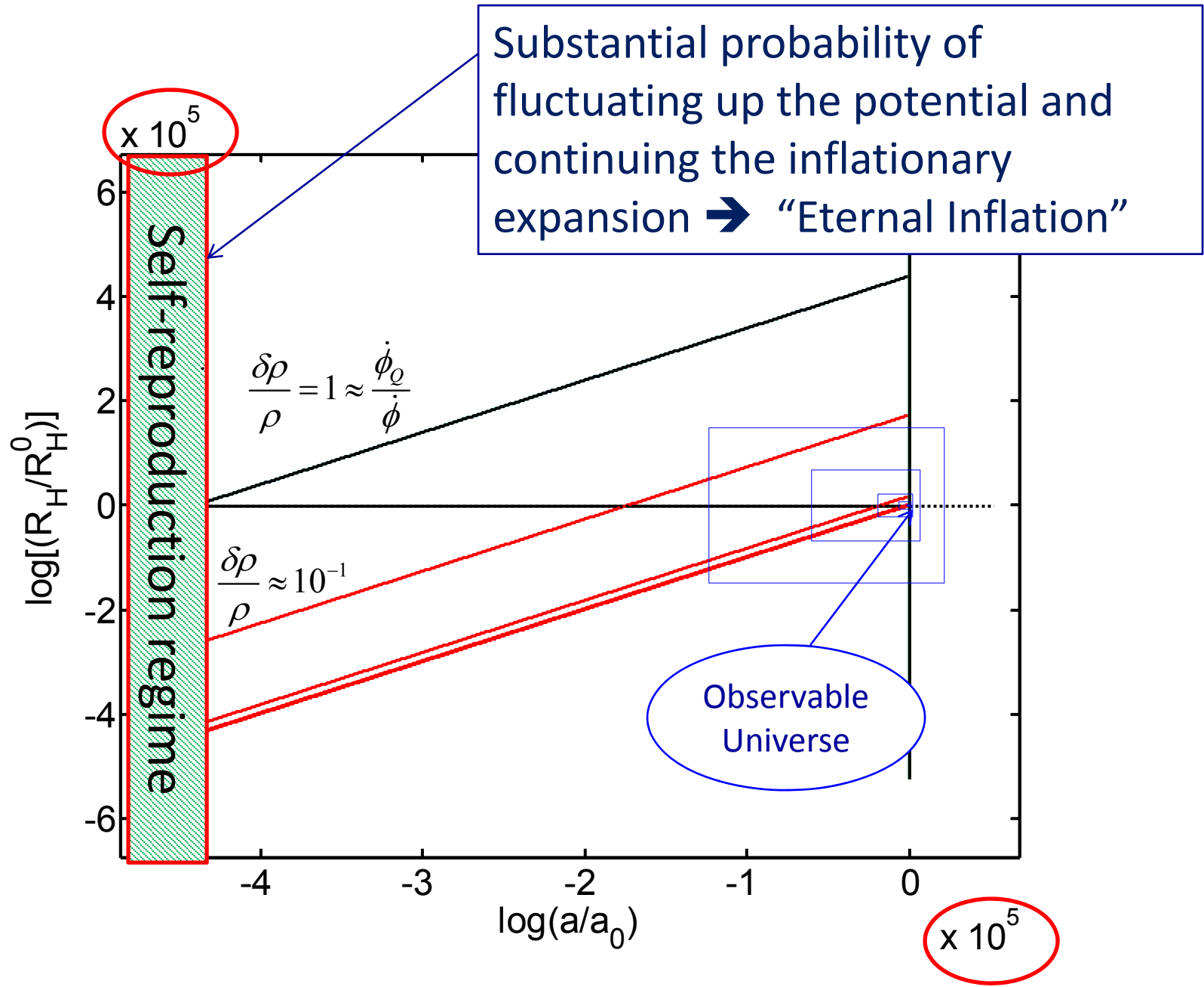
Starobinsky (2015): Inflation is a way to connect cosmic structure with fundamental physics

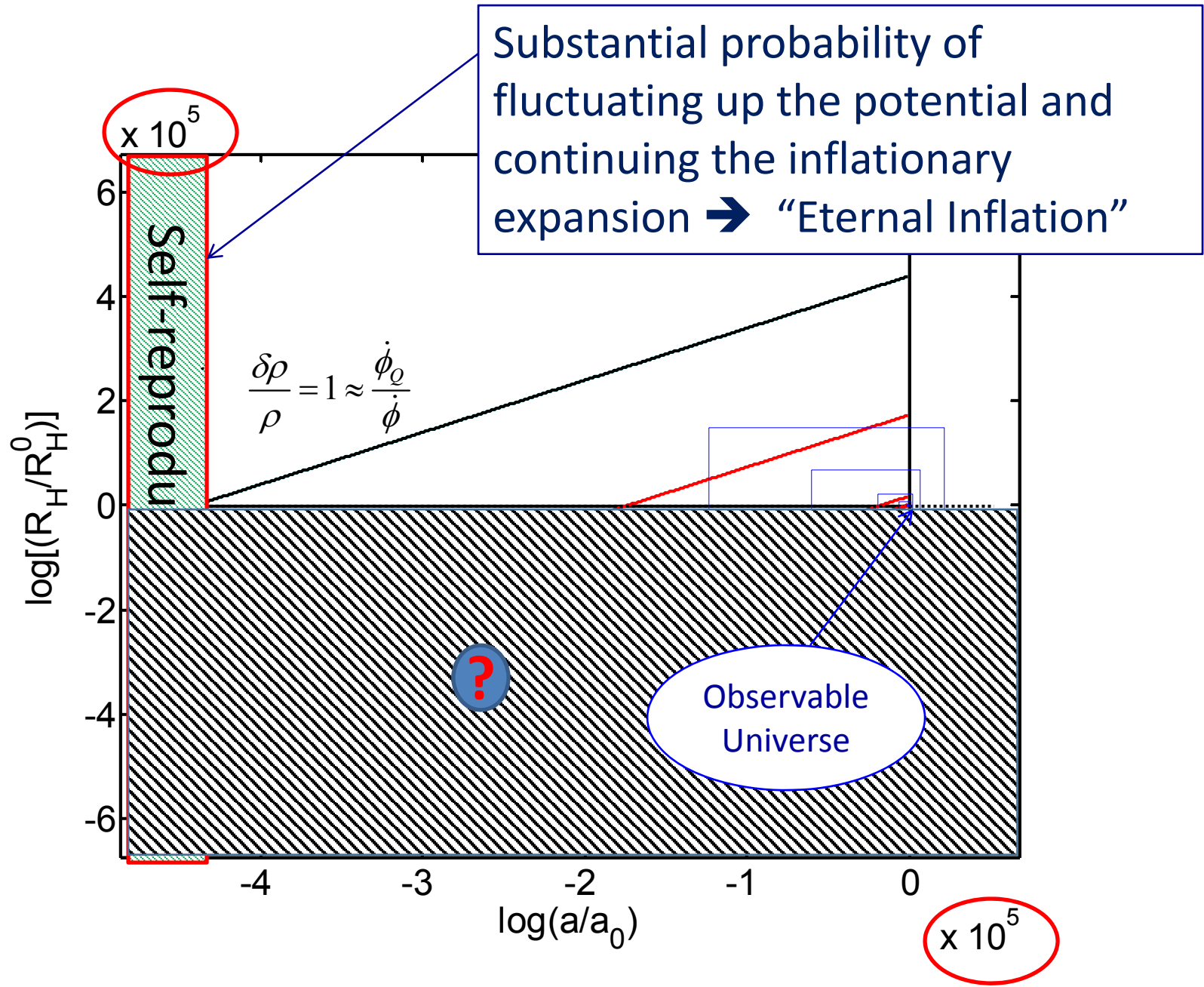


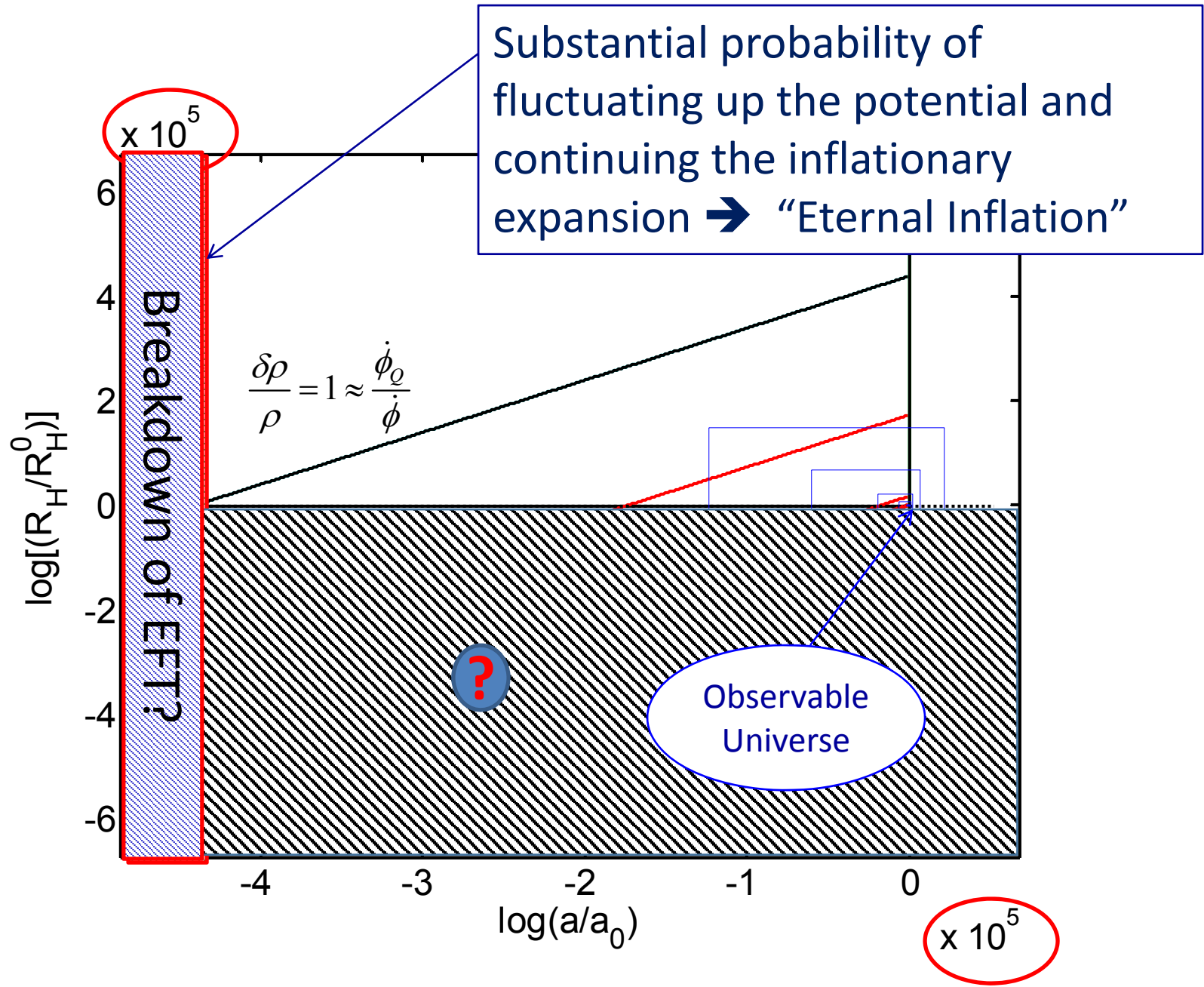


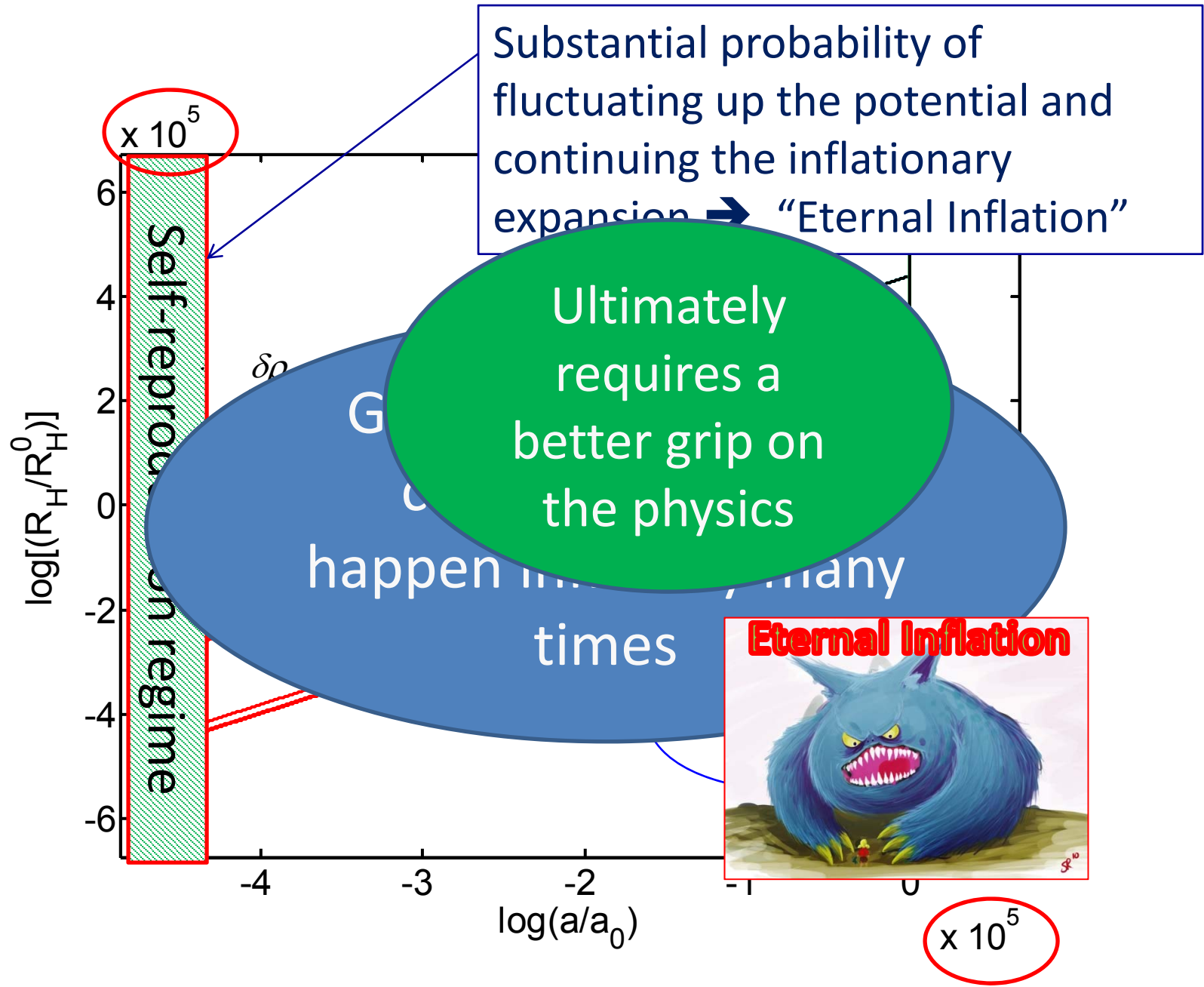


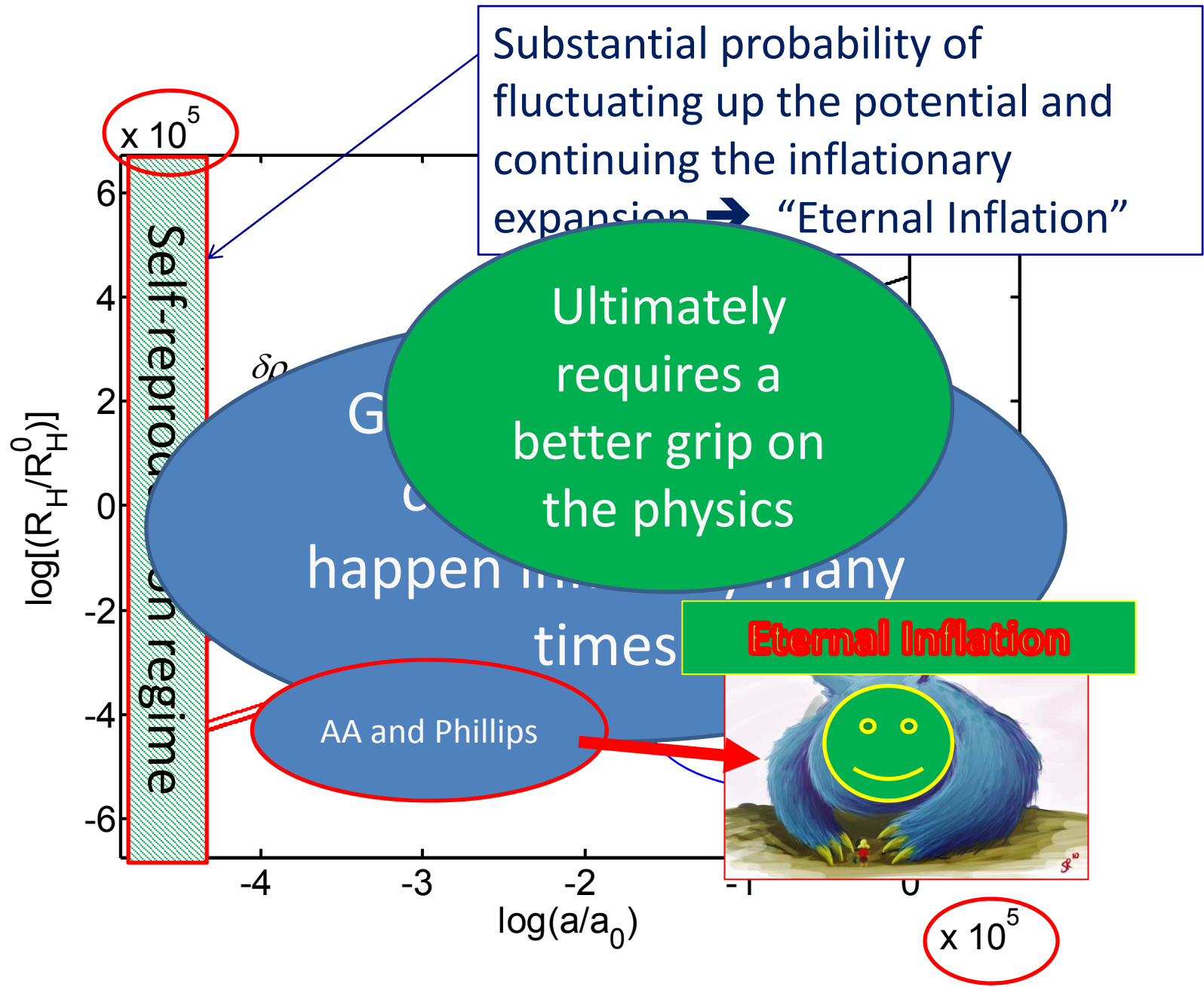


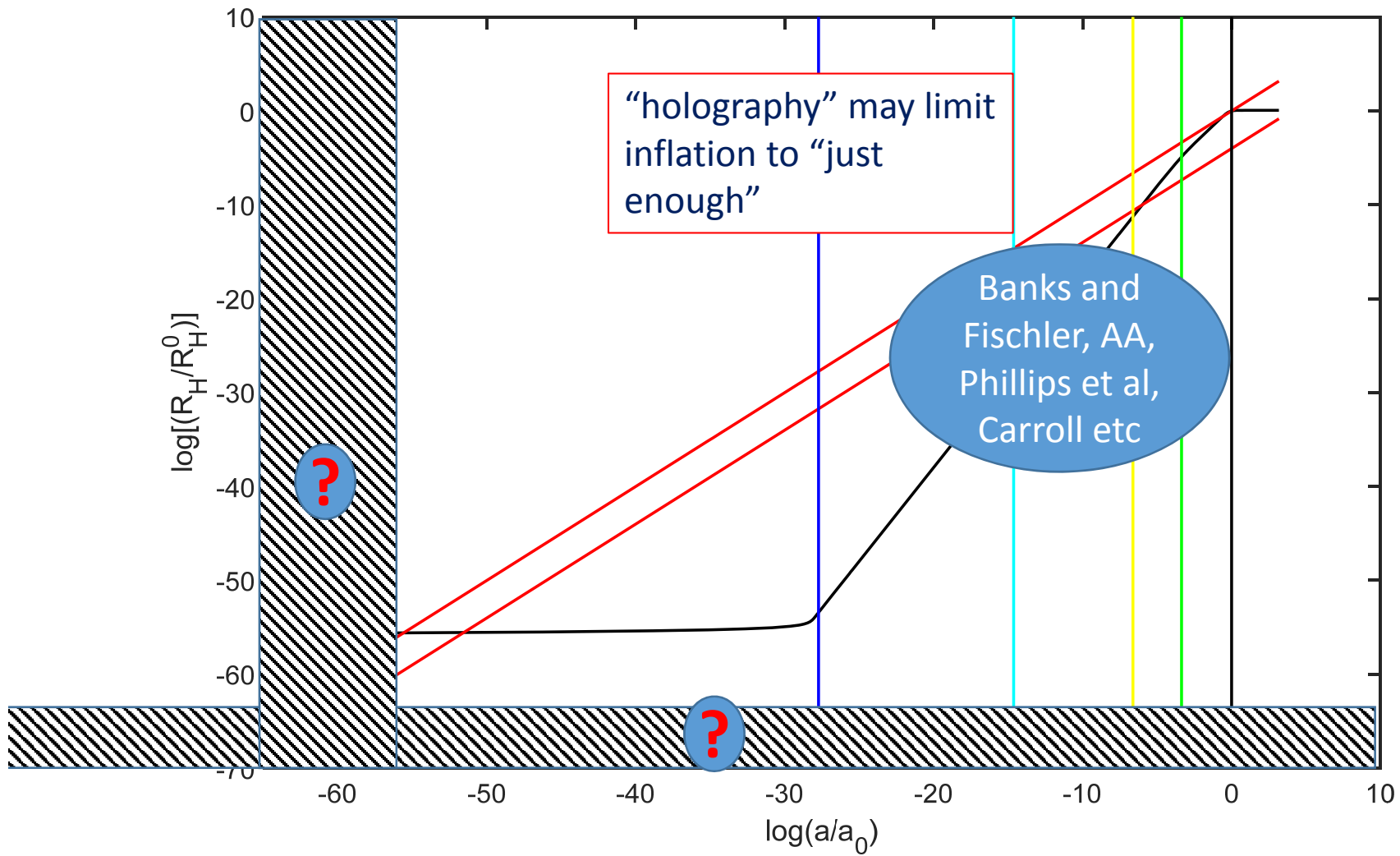


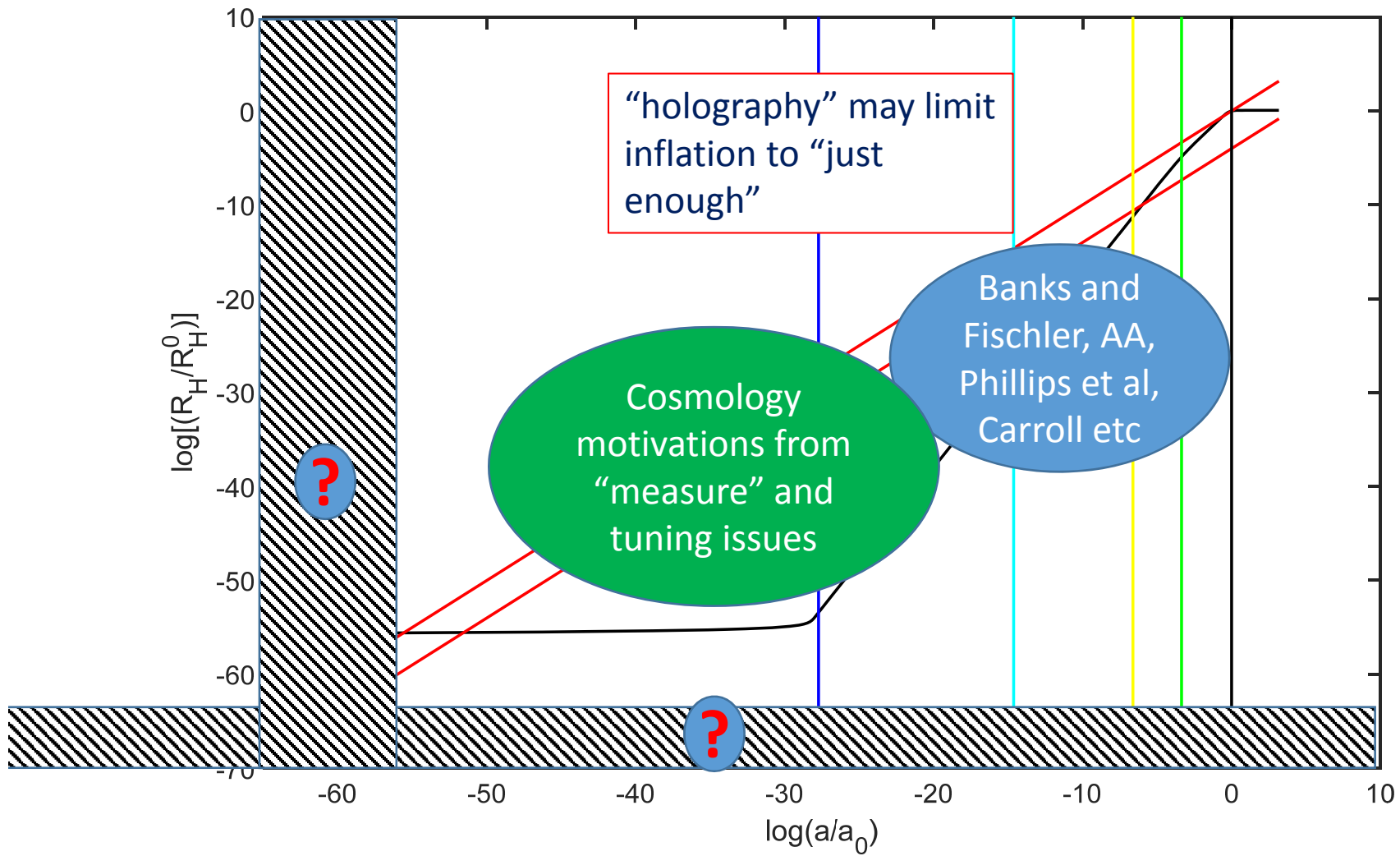




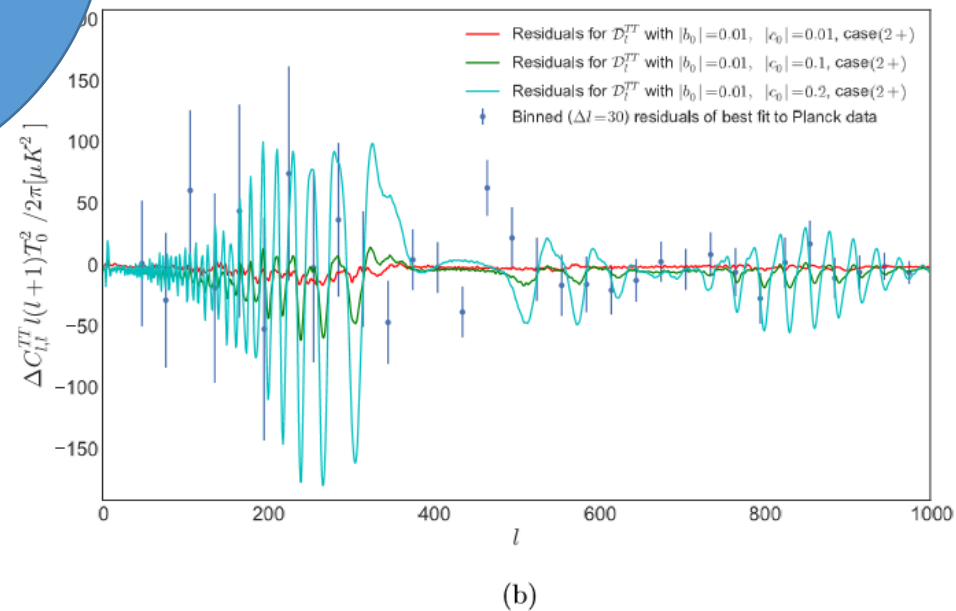
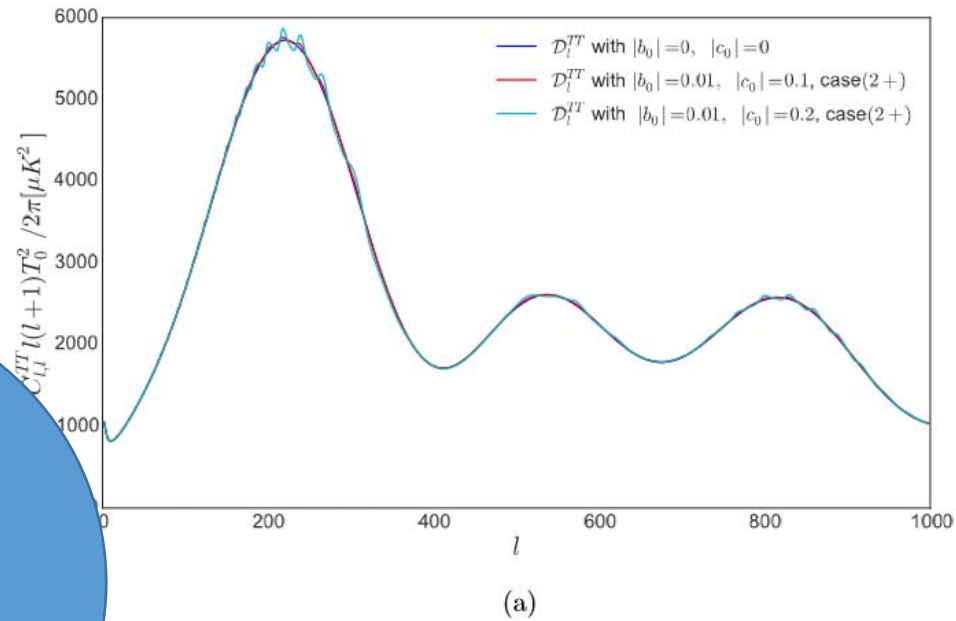






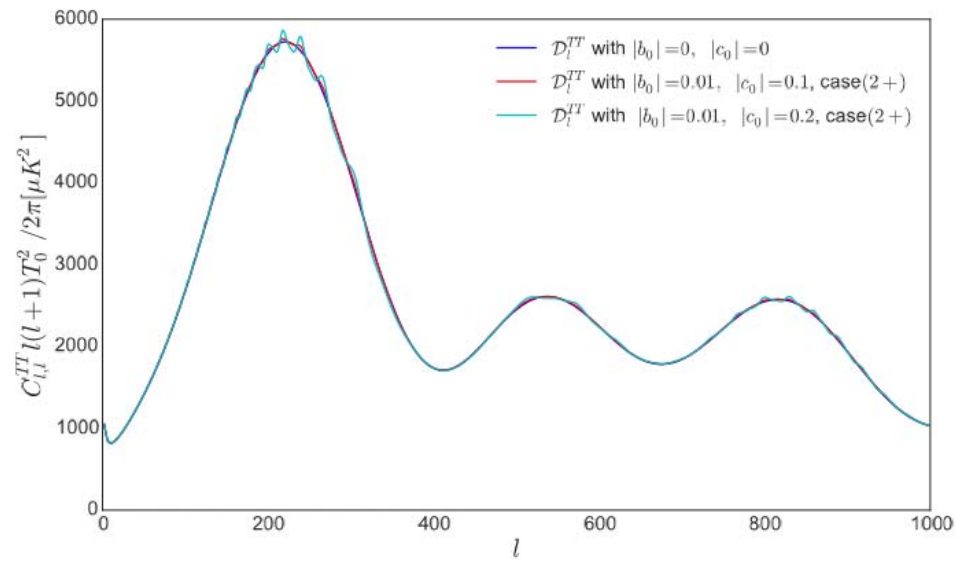


Possible signatures of “short inflation” and quantum entanglement

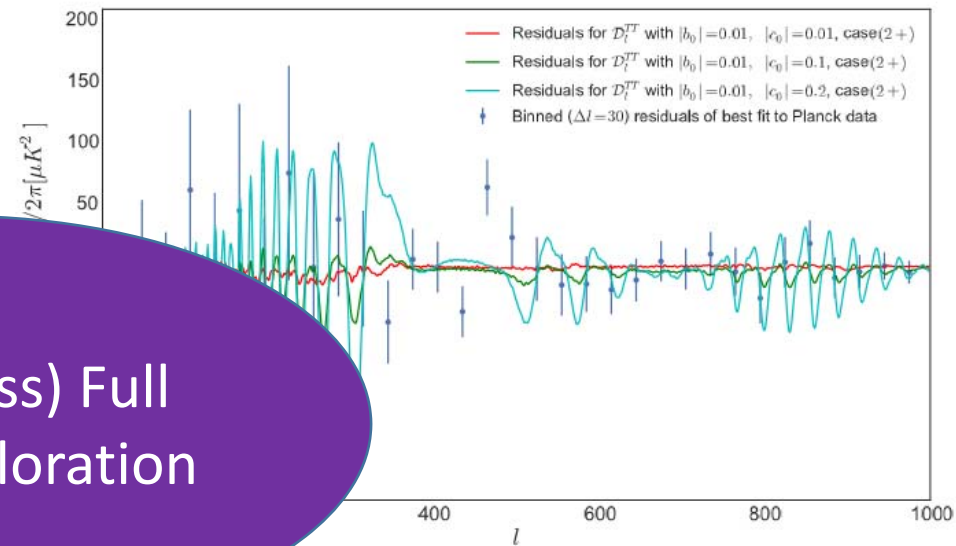


[Bolis et al](#)
[arXiv:1605.01008](#)

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)



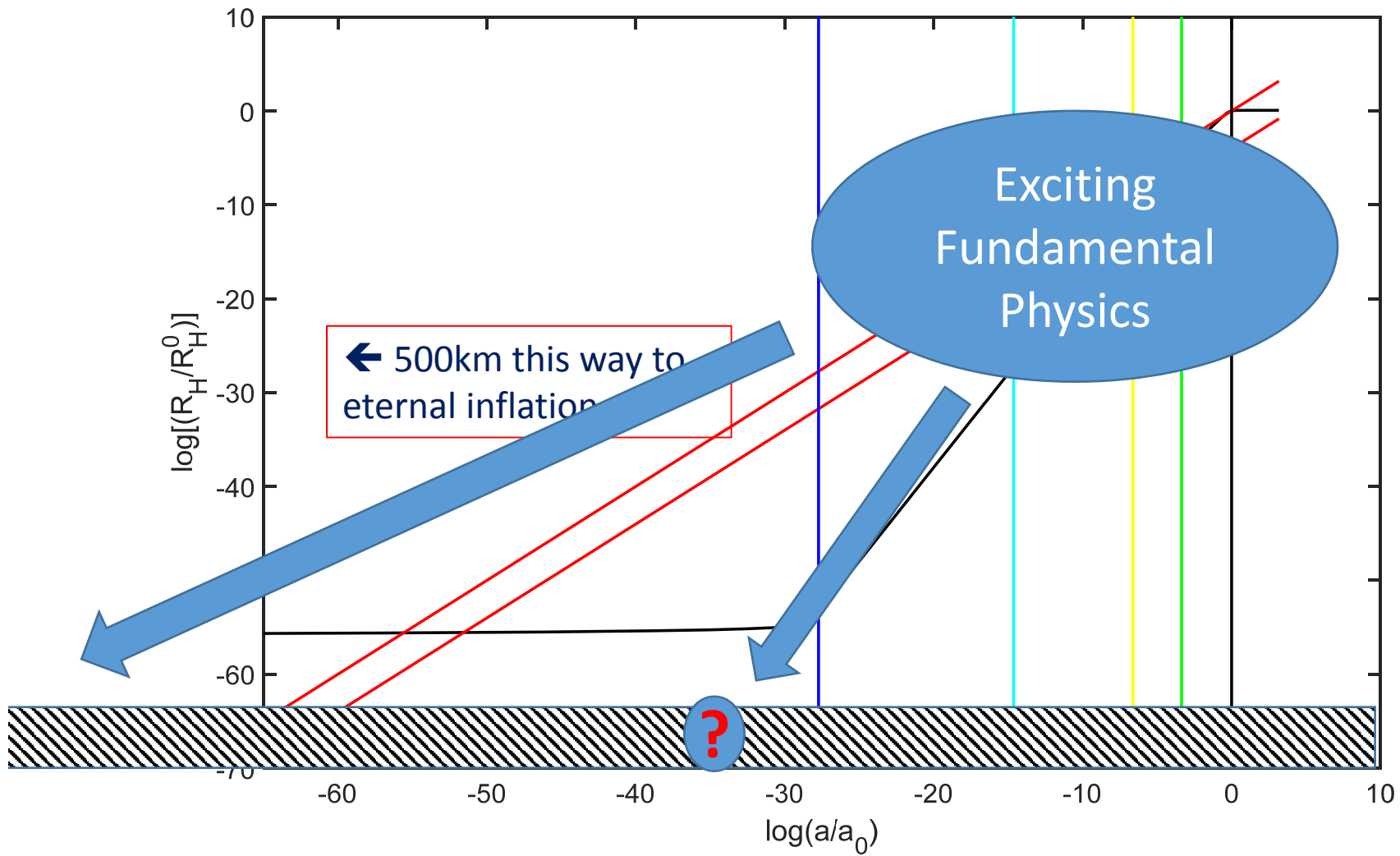
(In progress) Full
MCMC exploration

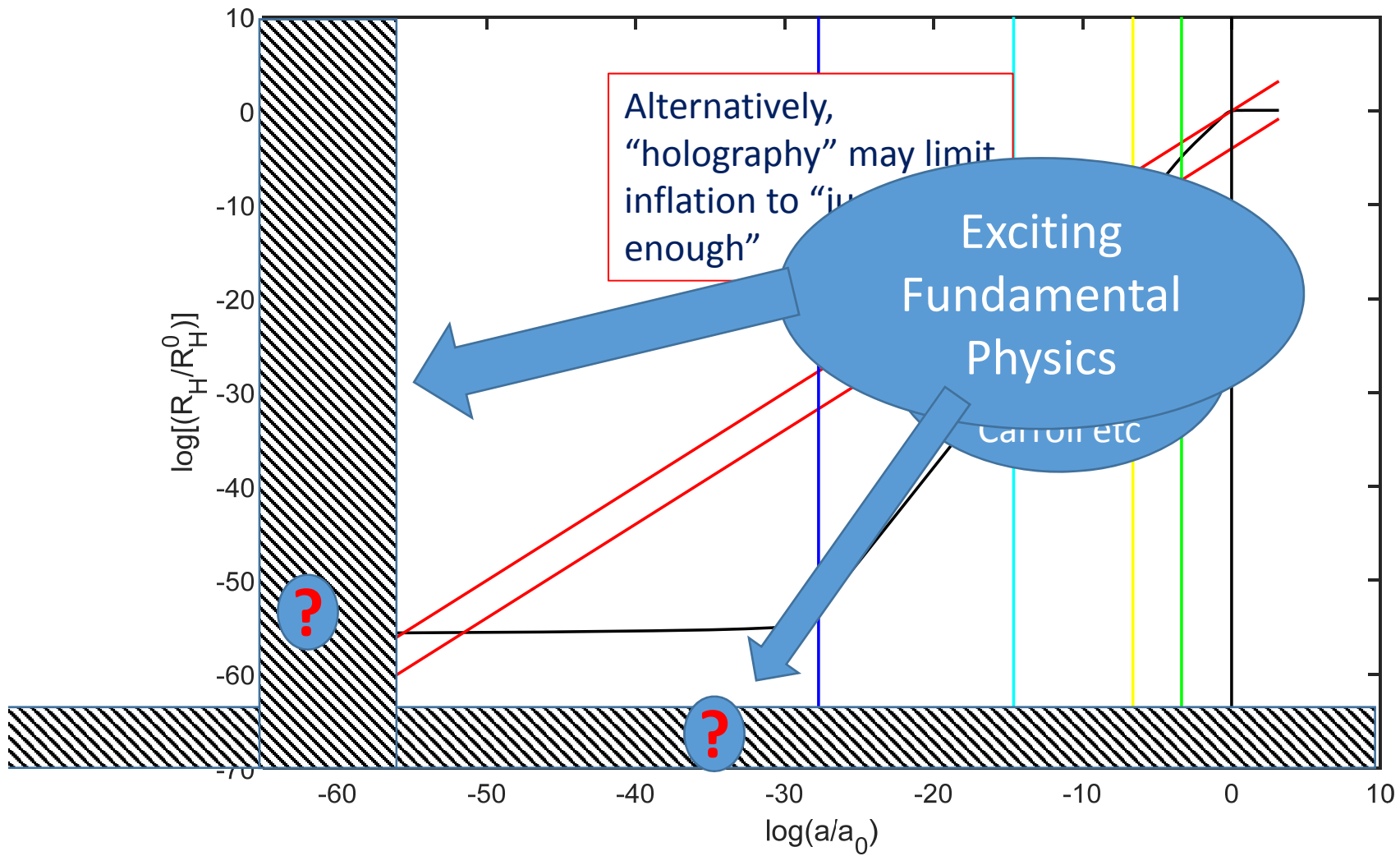
With Andrew Arrasmith

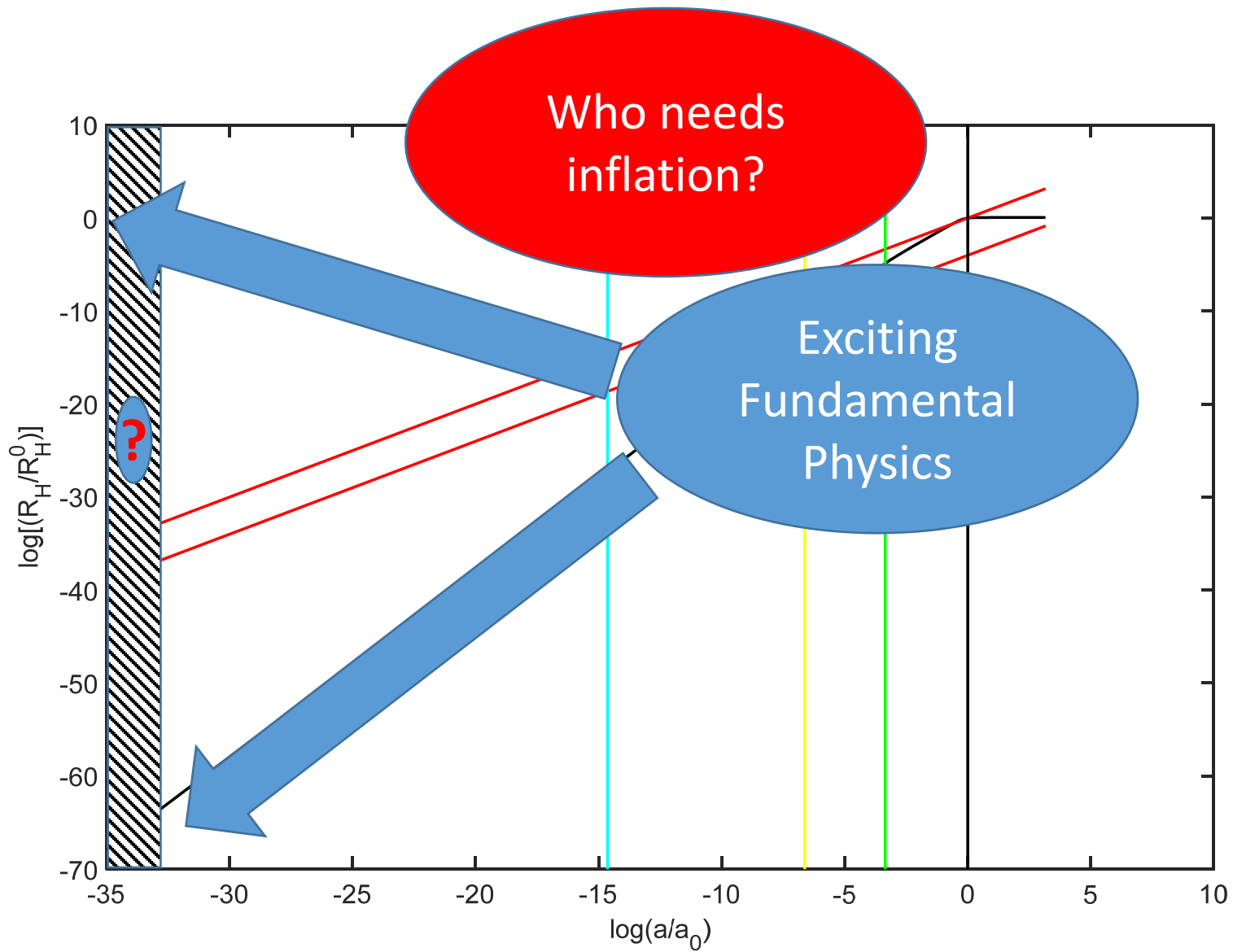
Figure 1. (a) Temperature fluctuation angular power spectrum $C_{l,l}^{TT}$ for different values of entangle-

See also

- Small observable curvature (AA, Linde, etc) !!
- L. Knox & Z. Knight, interpreting the large scale CMB power.
- More to come!!







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- Holography, AdS/CFT
- The nature of horizons, singularities
- Entanglement/Geometry duality
- Emergence of spacetime

Inflation, and cosmology in general, have a deep capacity to link these issues with observational signatures.

Likely what is needed to resolve open questions with inflation

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Exciting prospects for
future surveys!

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