# Inflation, Tuning and Measures

Andreas Albrecht; UC Davis
Cosmocruise Sep 5 2015

# Infl d Measures

THANKS!

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Infl d

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# Inflation, Tuning and Measures

A complement to
Alexei's talk

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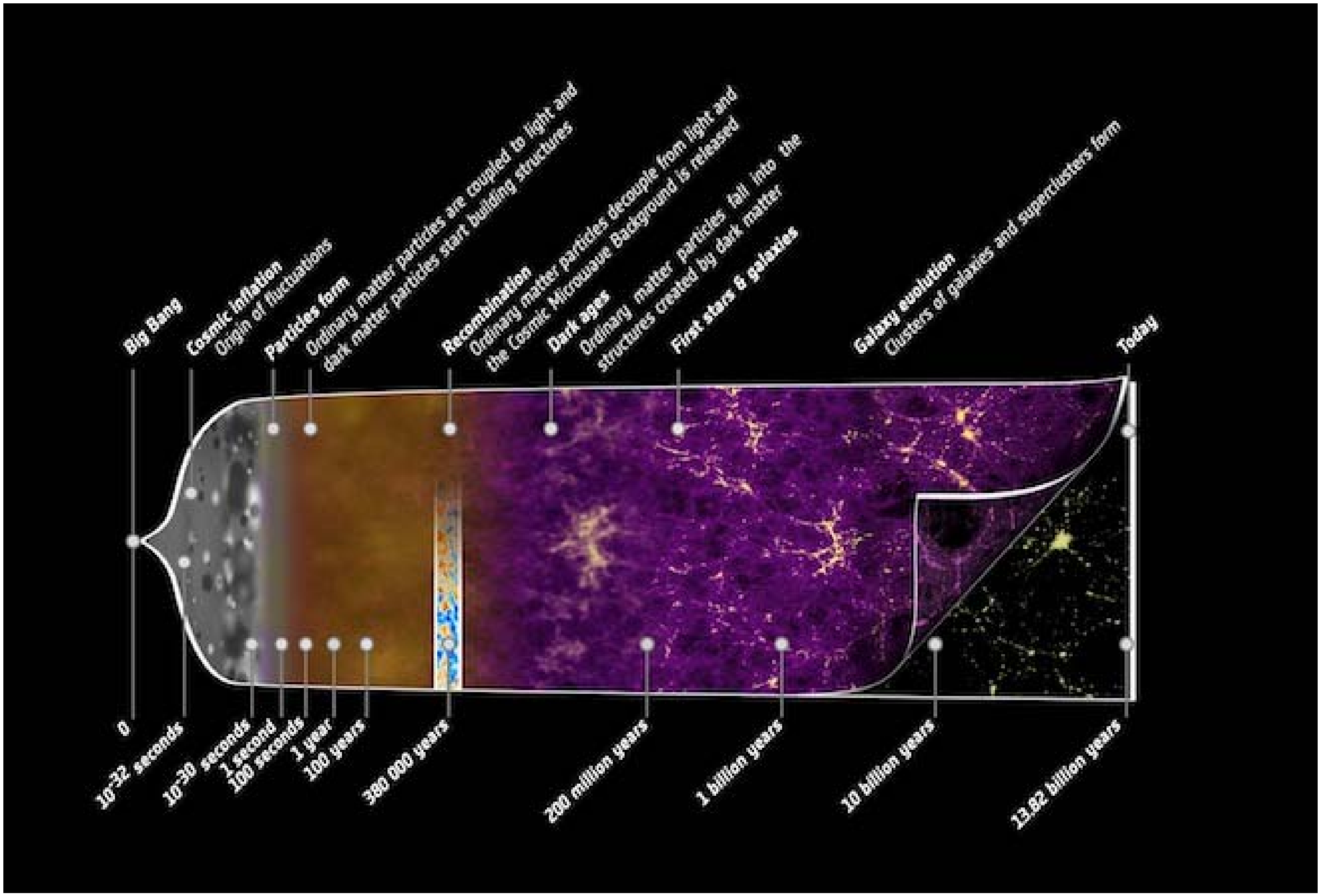
# The History of the Universe



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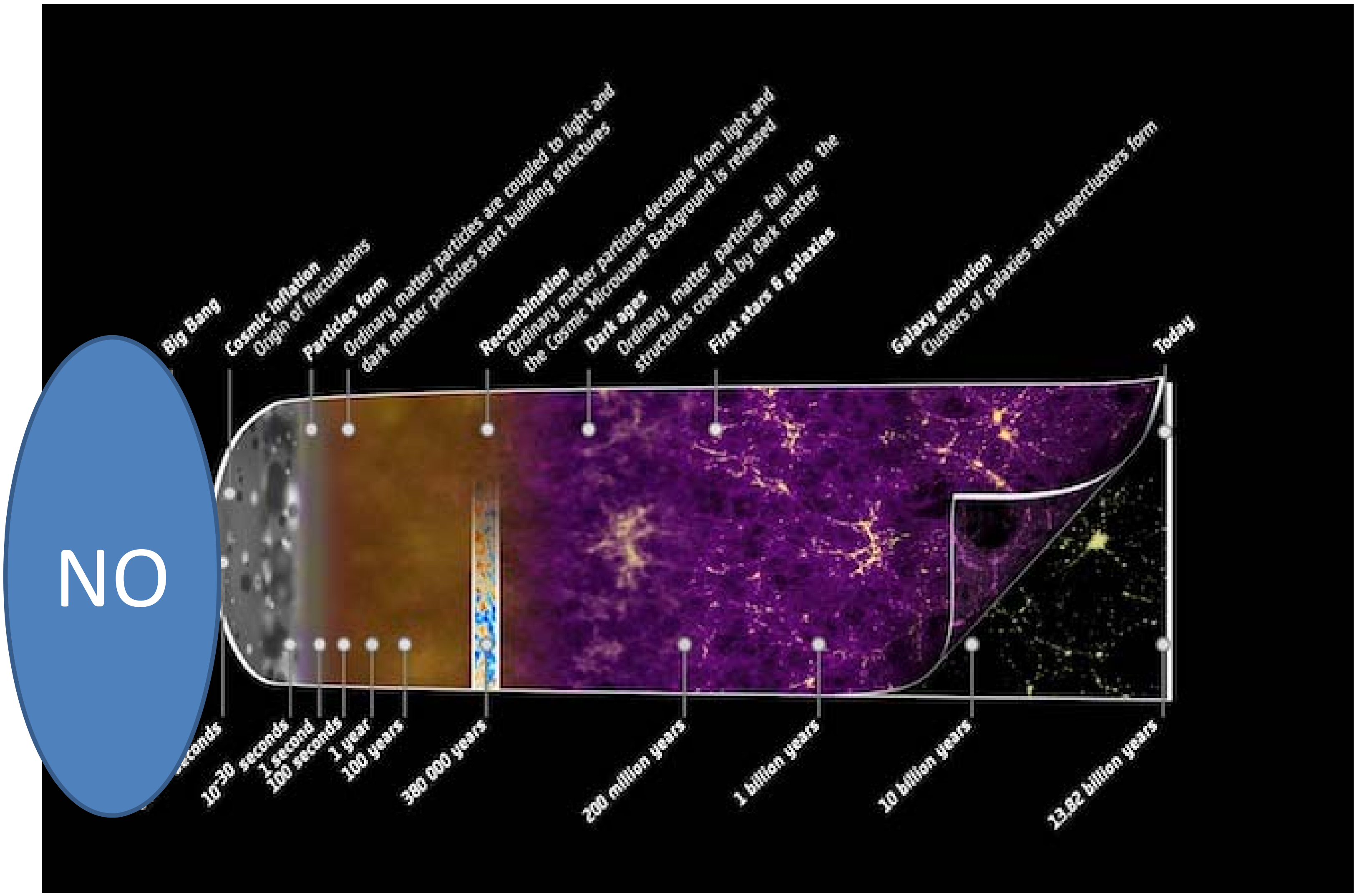

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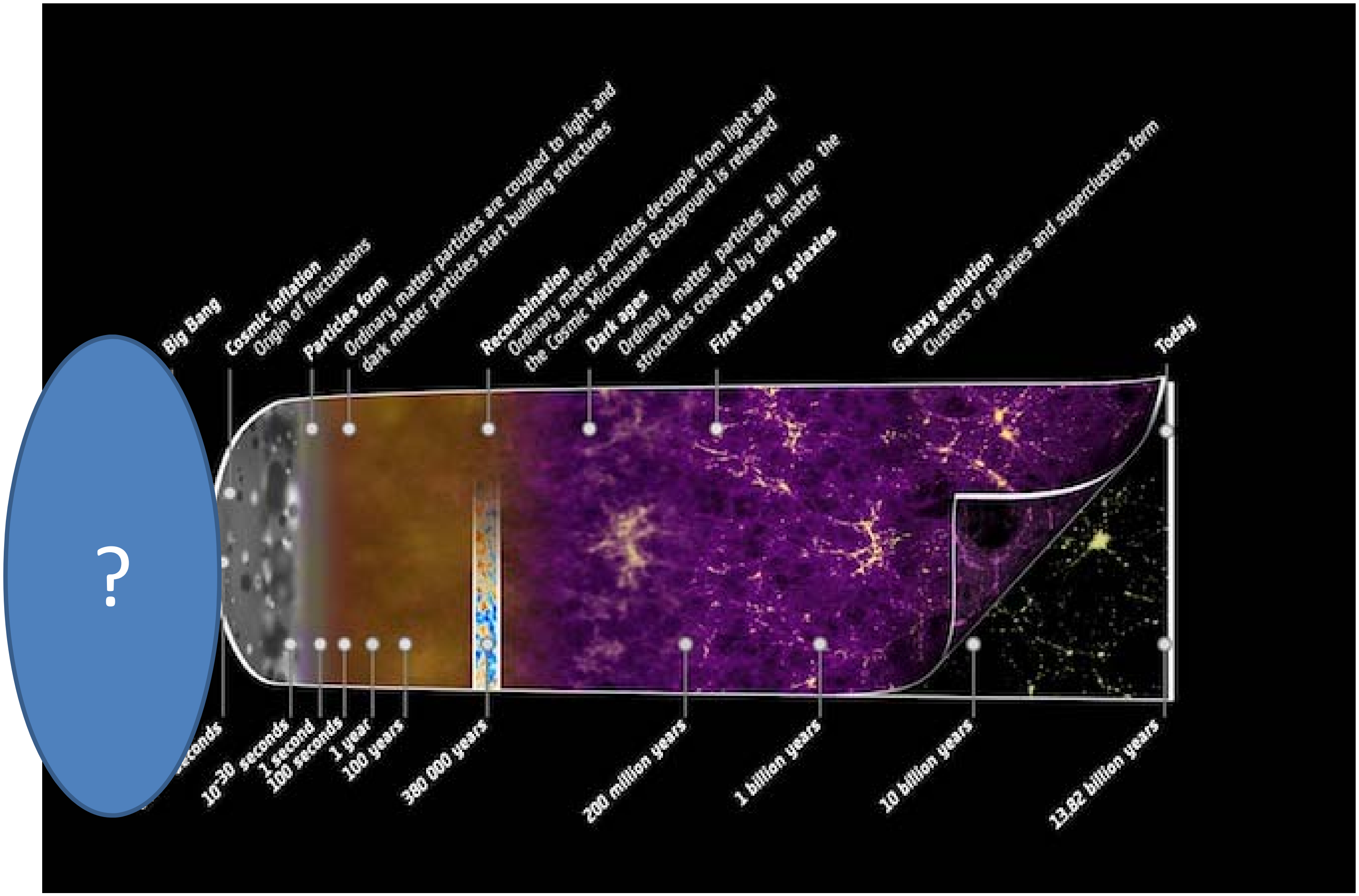

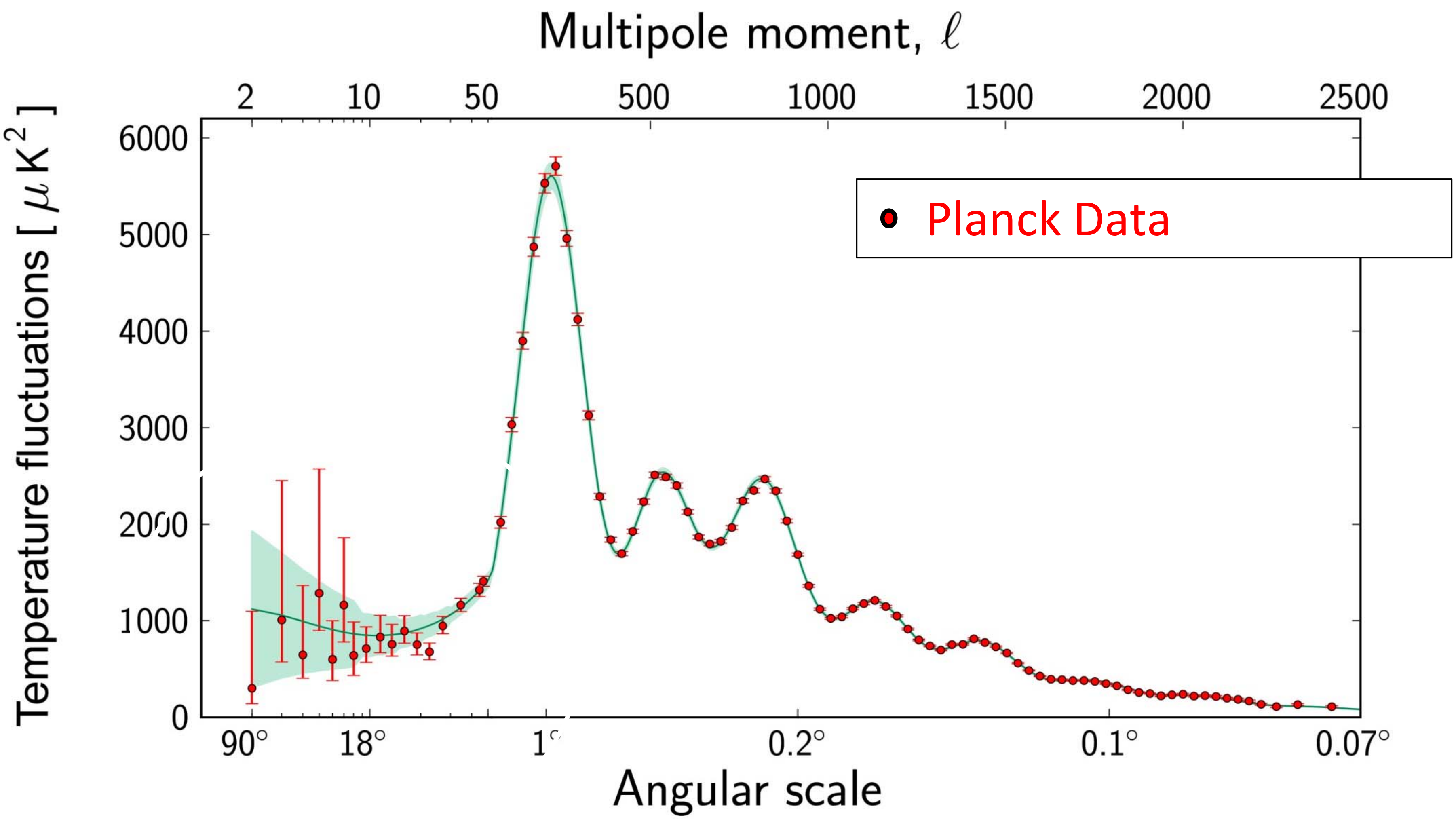

Multipole moment, $\ell$
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10
50
500
1000
1500
2000
2500
Temperature fluctuations [ $\mu K^2$ ]
6000
5000
4000
3000
2000
1000
0
Planck Data
90°
18°
1°
0.2°
0.1°
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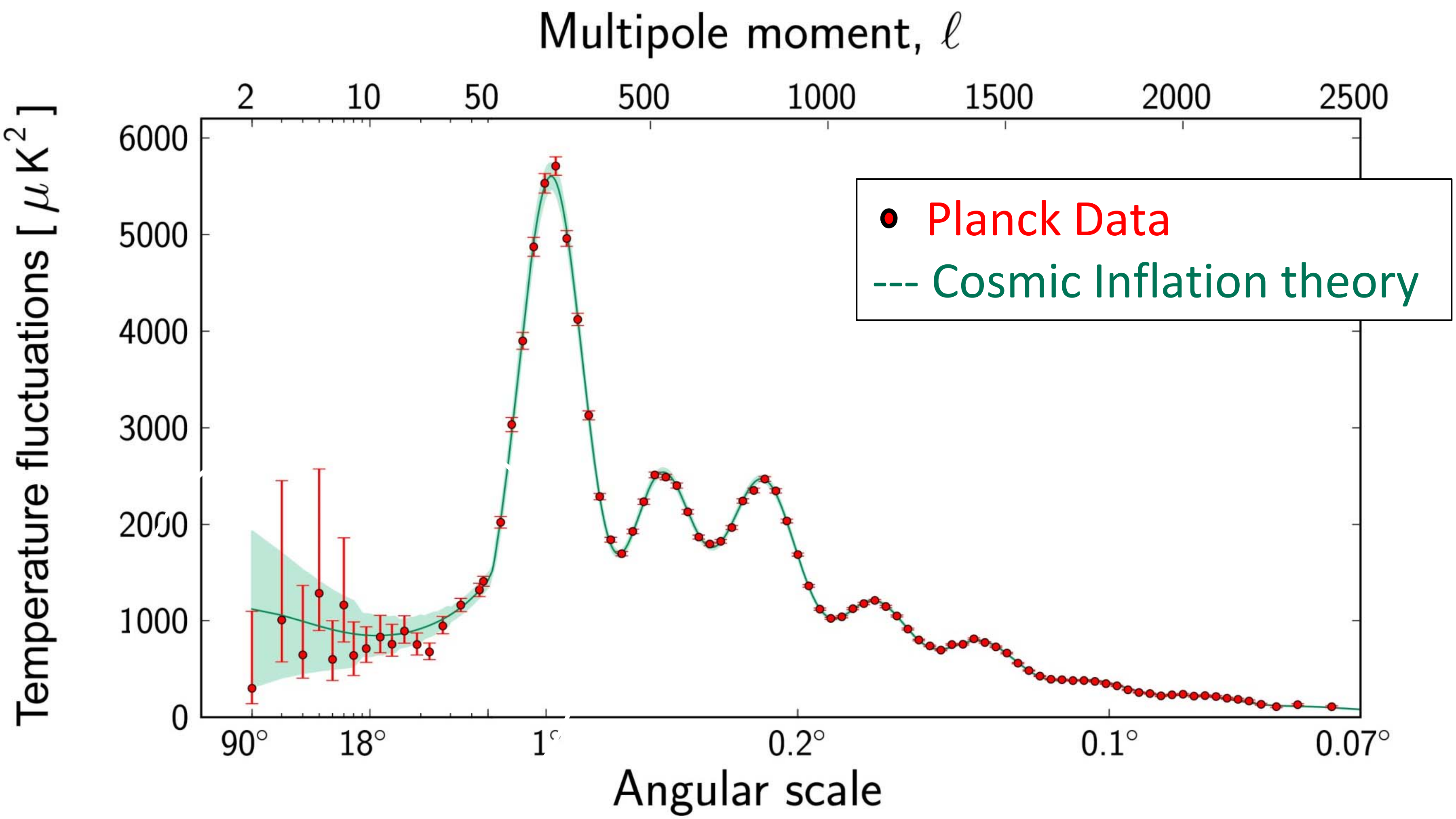
Angular scale



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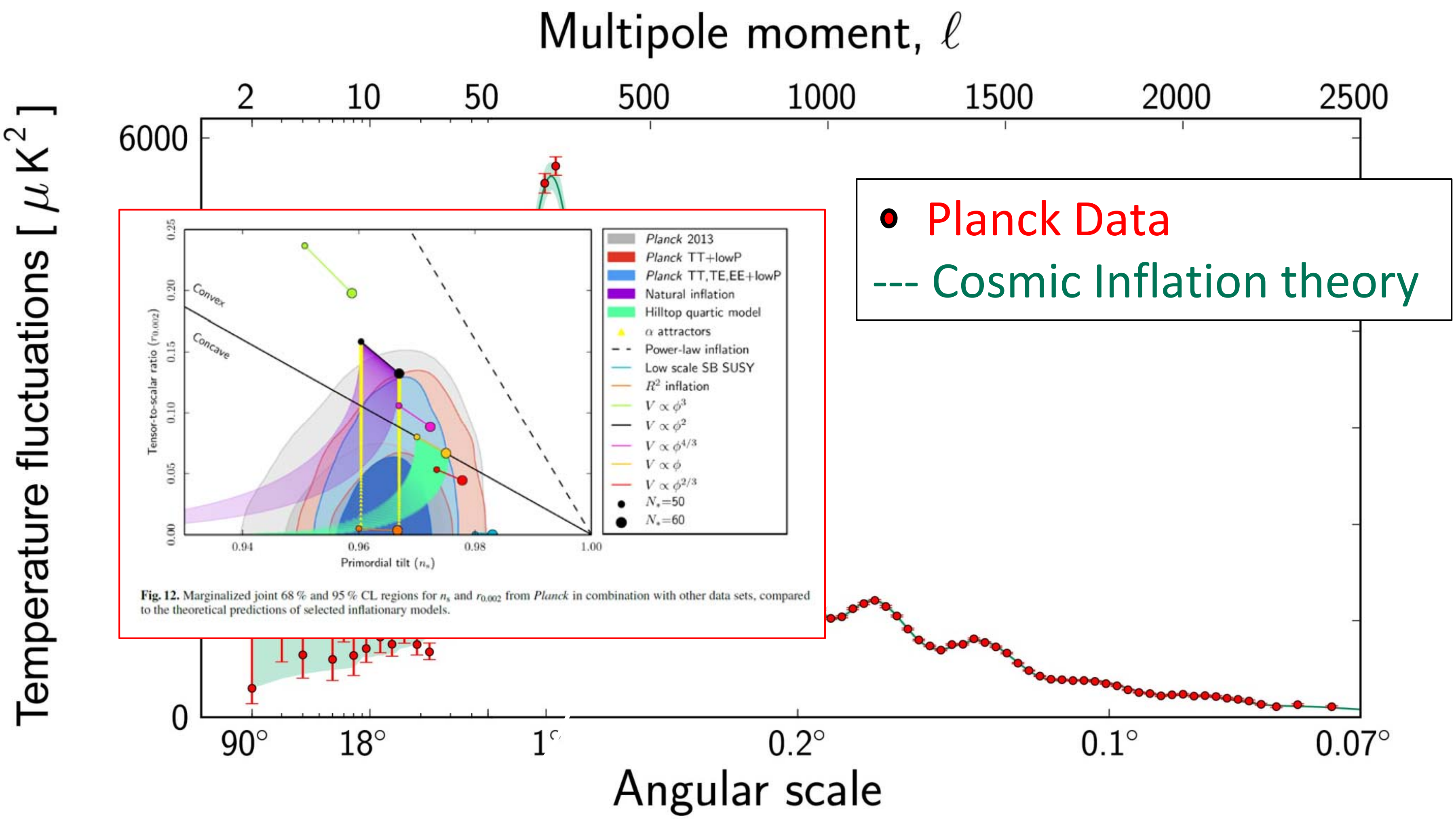

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--- Cosmic Inflation theory
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt ($n_s$)
Convex
Concave
Planck 2013
Planck TT+lowP
Planck TT,TE,EE+lowP
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
Low scale SB SUSY
$R^2$ inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
$N_*$=50
$N_*$=60
Fig. 12. Marginalized joint 68 % and 95 % CL regions for $n_s$ and $r_{0.002}$ from Planck in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

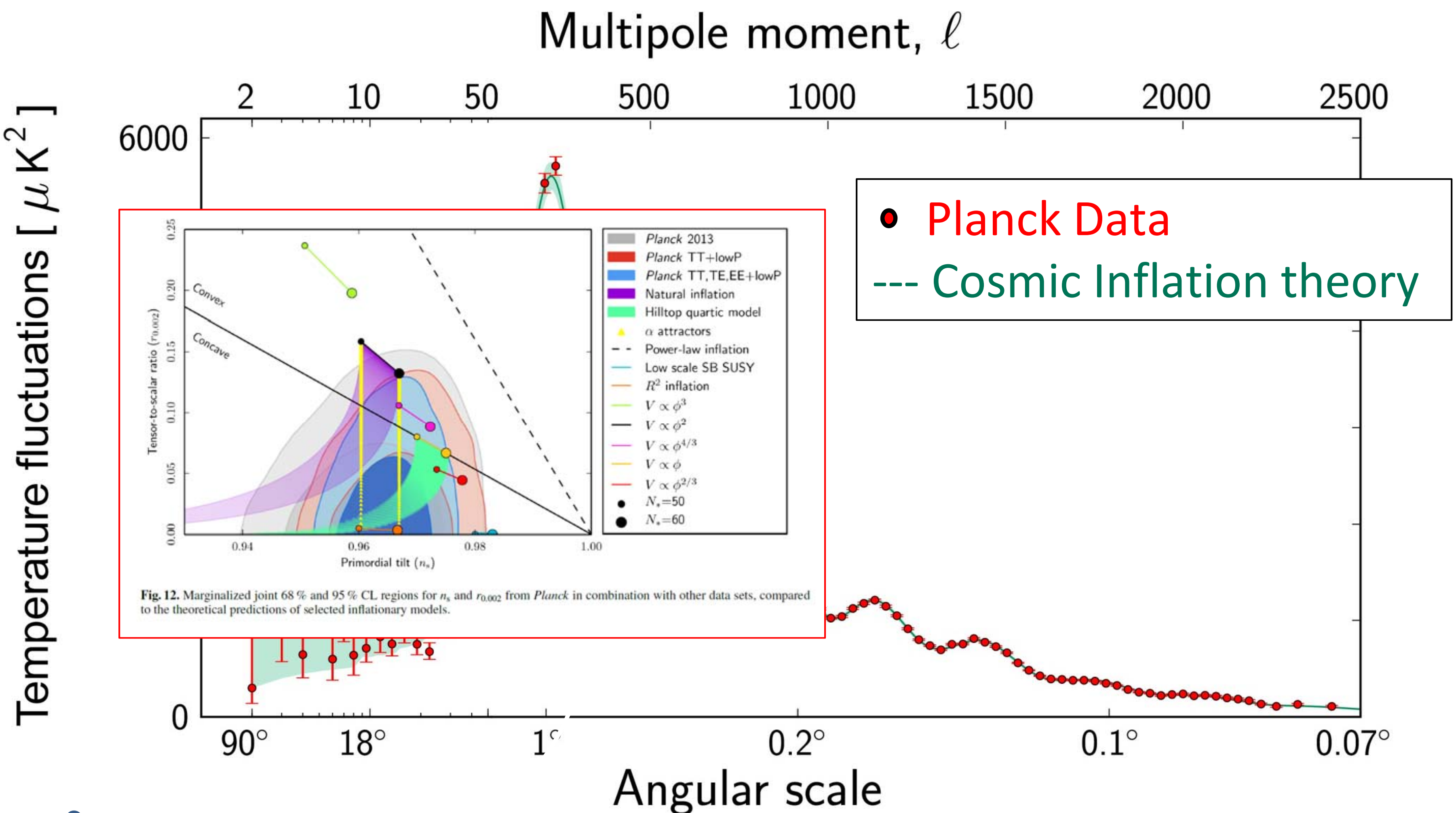


**Fig. 12.** Marginalized joint 68 % and 95 % CL regions for $n_s$ and $r_{0.002}$ from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.


A recent application of inflation (IAU 2015)

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➔ Great phenomenology of cosmic structure, but:

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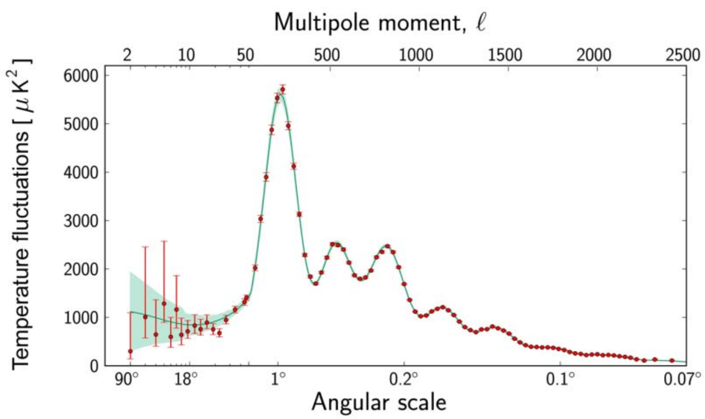
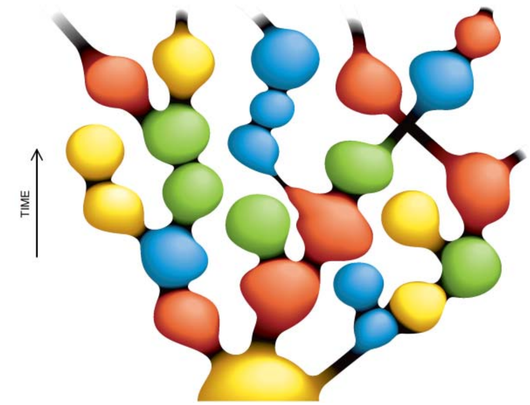
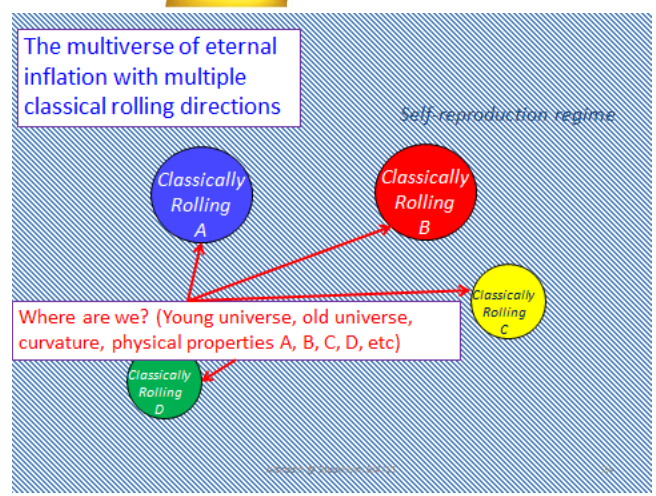
# Cosmic Inflation:

## Consumers & Producers



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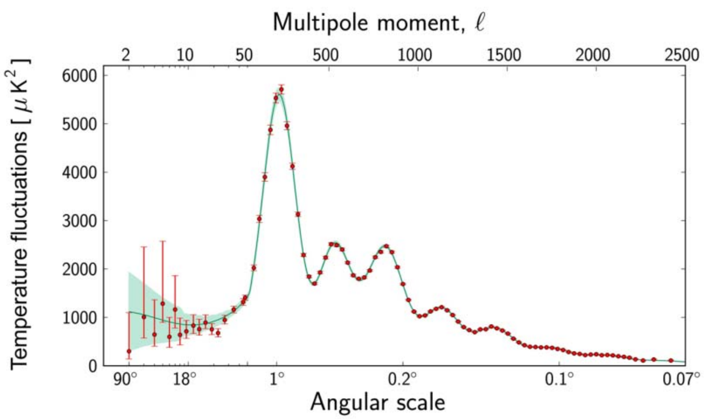


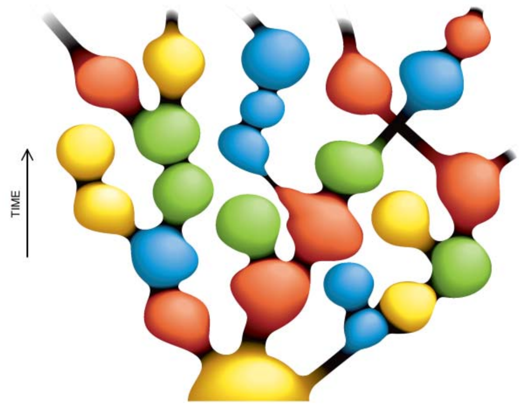


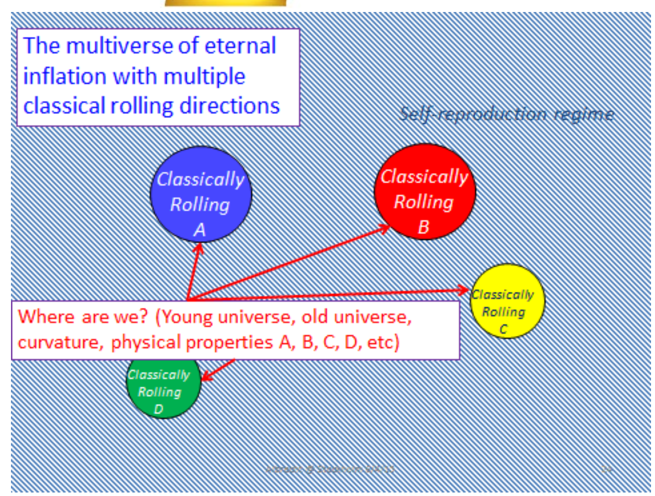

Goal of resolving tuning inspired by Guth's paper:

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.

An alternate perspective in Starobinsky's famous paper:

Volume 91B, number 1 PHYSICS LETTERS 24 March 1980

## 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 ho
most symmetric (de Sitter) state.

It is well known that many solut
Einstein equations, in particular, th
Robertson–Walker isotropic homog
logical model, contain singularities
ytically continued beyond them. S

Volume 91B, number 1 PHYSICS LETTERS

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 nonsingular solutions. We shall show that the only reason for this result is that an additional term describing classical isotropic radiation (i.e. a certain number of initially

number of quantum fields is large

Let $u = a^2\dot{a}^2$, $v = u + Ka^2$. Th
we have:

$$v = \frac{v^2}{H^2a^4} - \frac{1}{M^2}\left(\frac{vv''}{a^2} - \frac{2vv'}{a^3} - \frac{v'}{4a}\right.$$

where a prime denotes a derivativ

Another useful representation
tained by letting $f = u^{3/4}$, $\xi = (1$
$d^2f/d\xi^2 + M^2\xi^{-2/3}f^{-1/3} - M^2f$

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# Outline

1. Introduction
2. Tuning & Entropy
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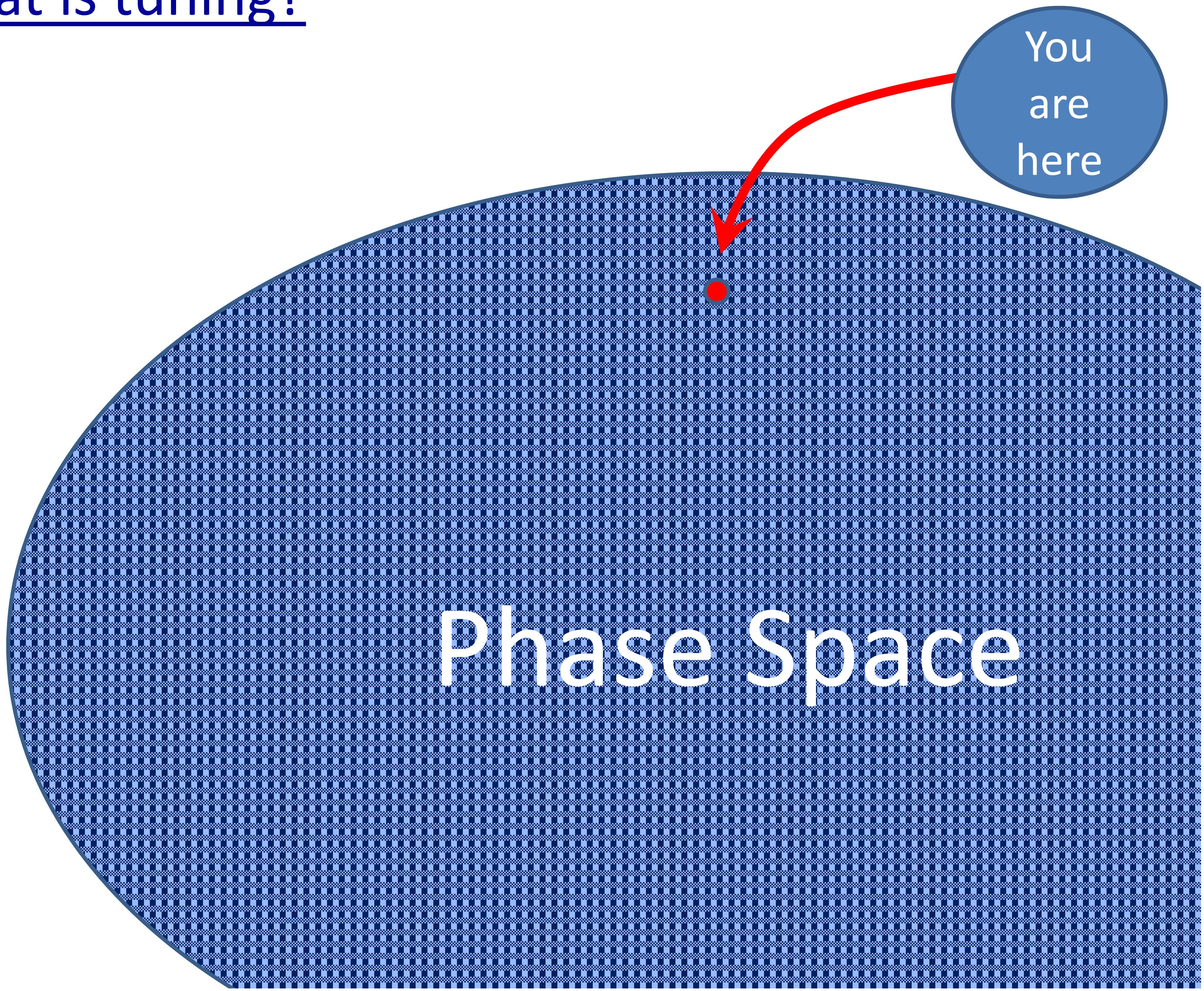

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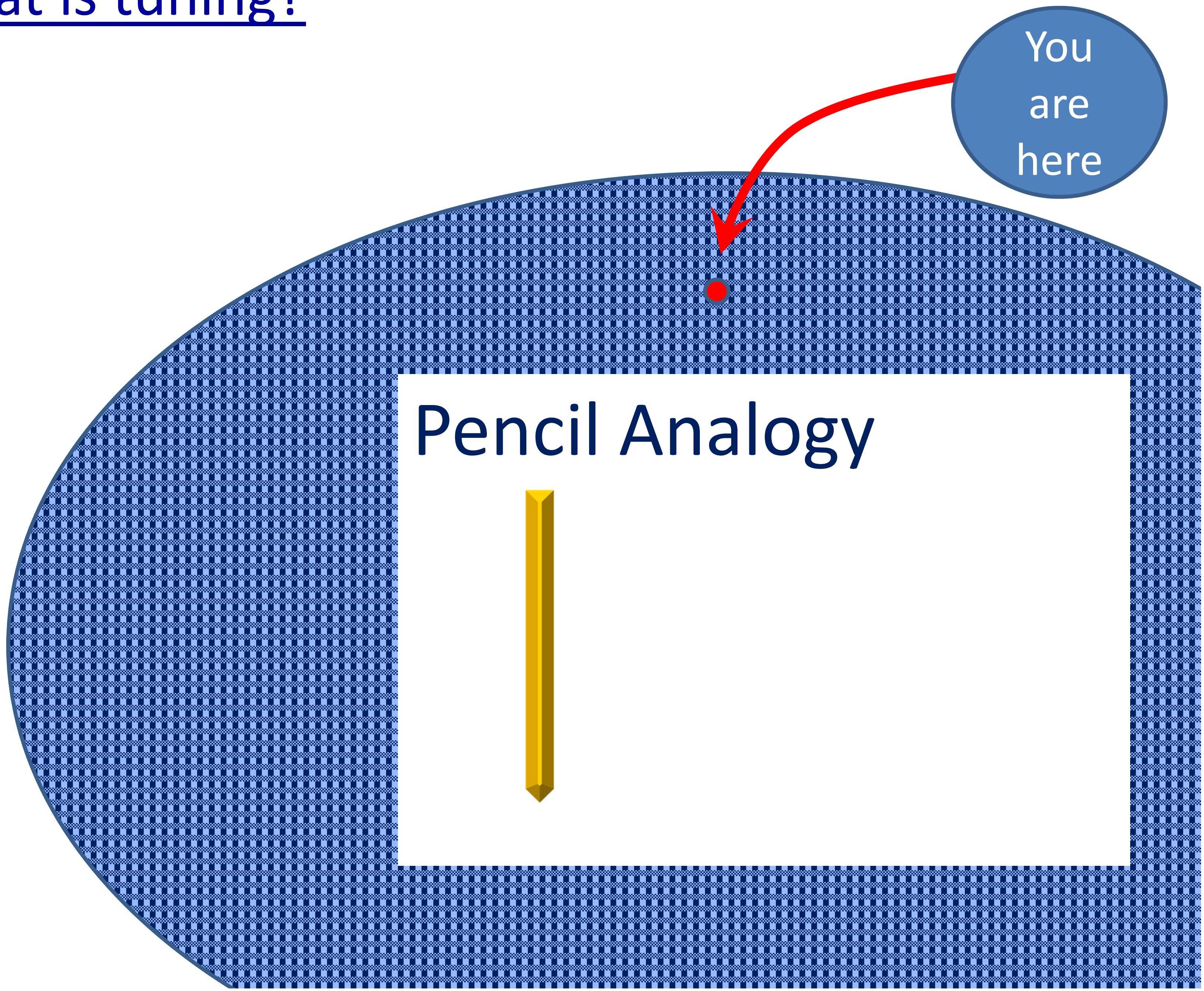

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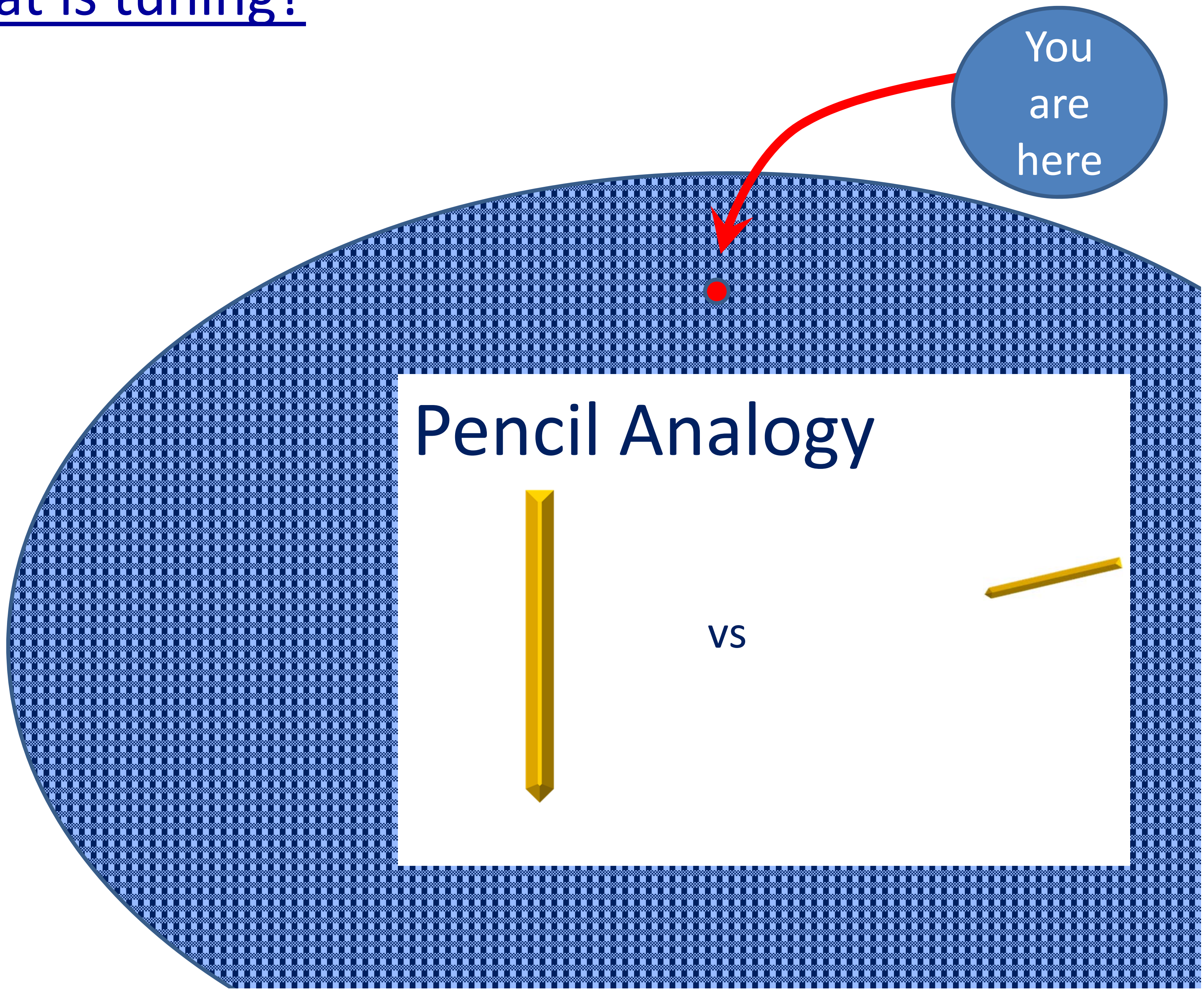

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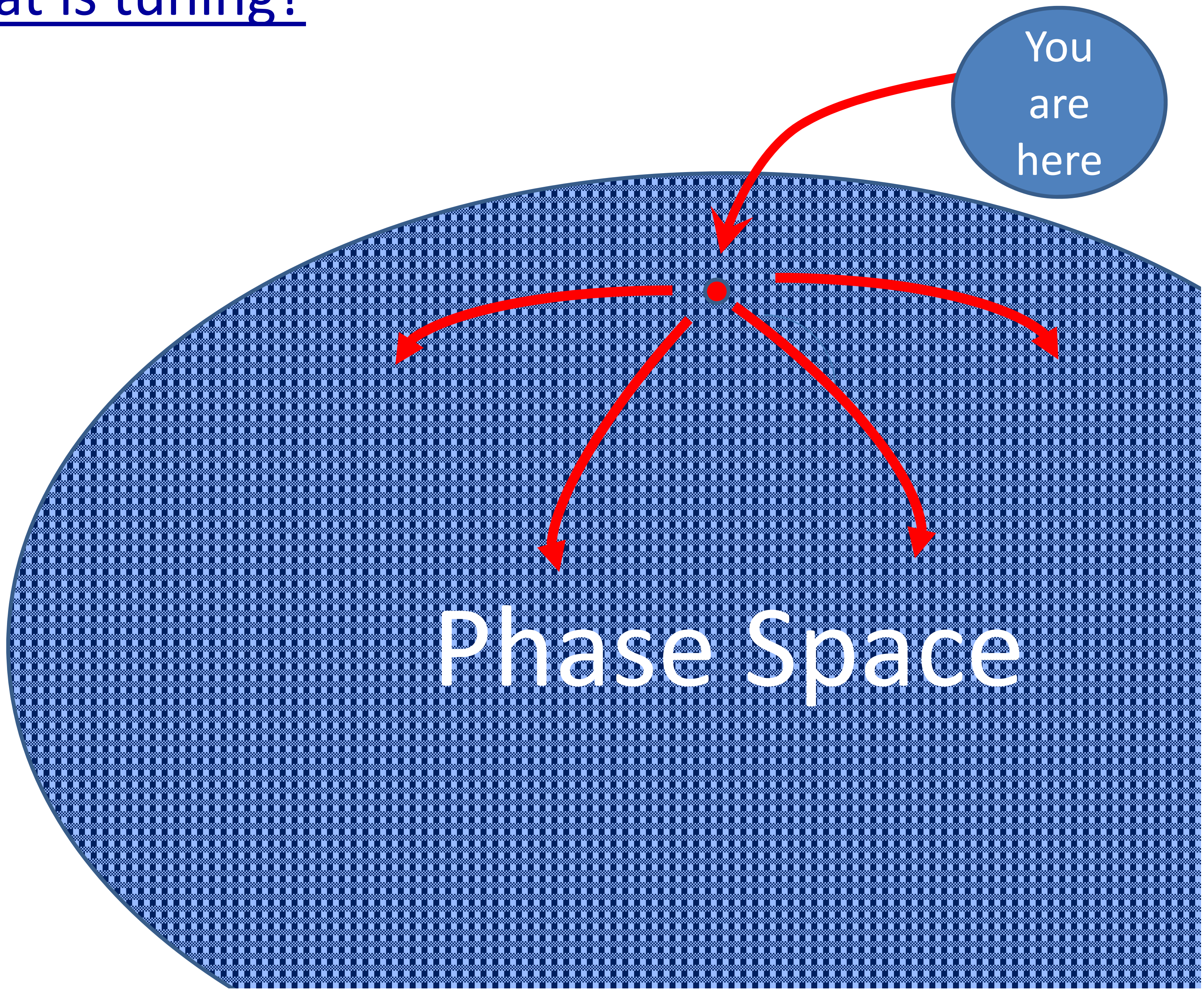

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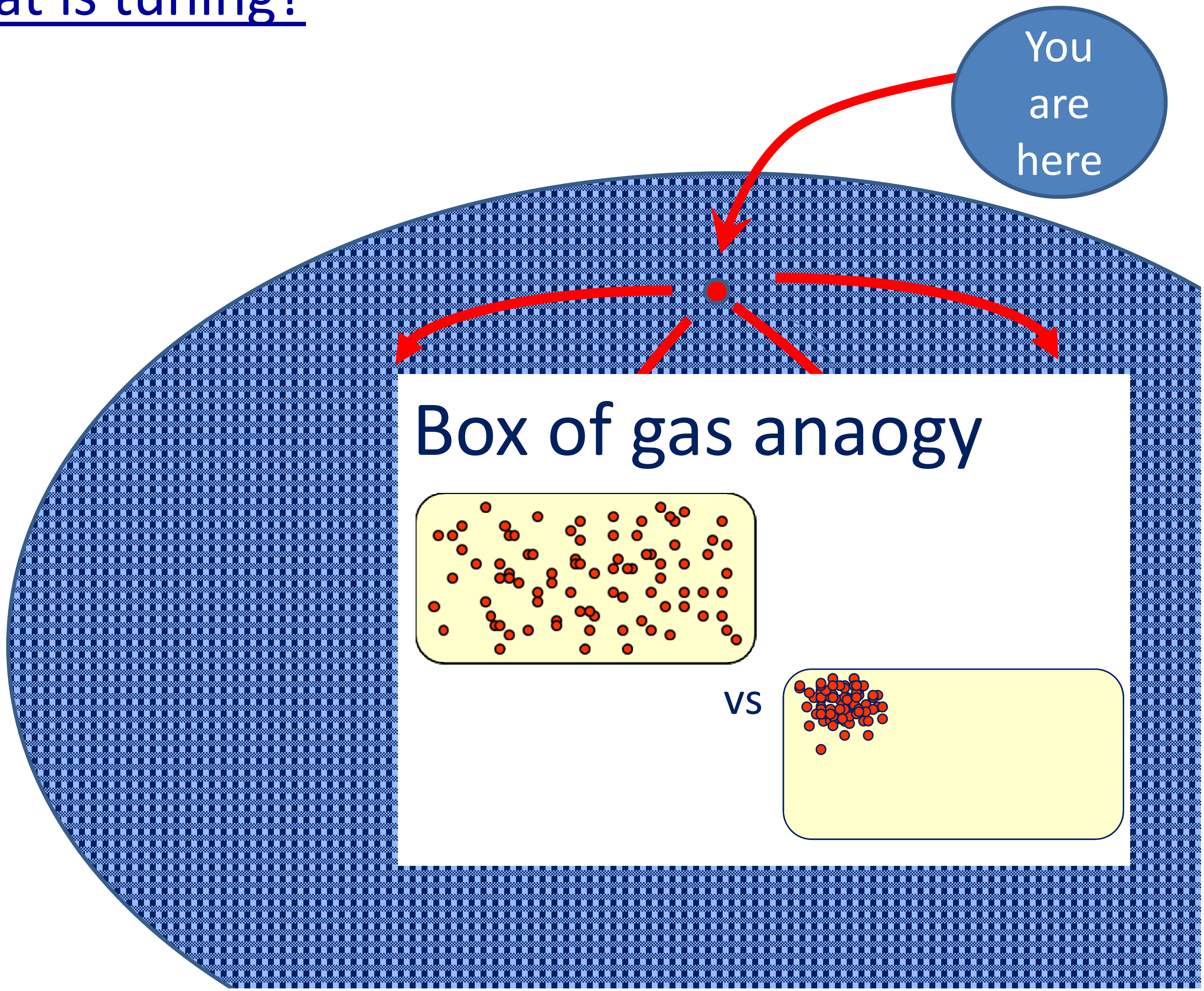
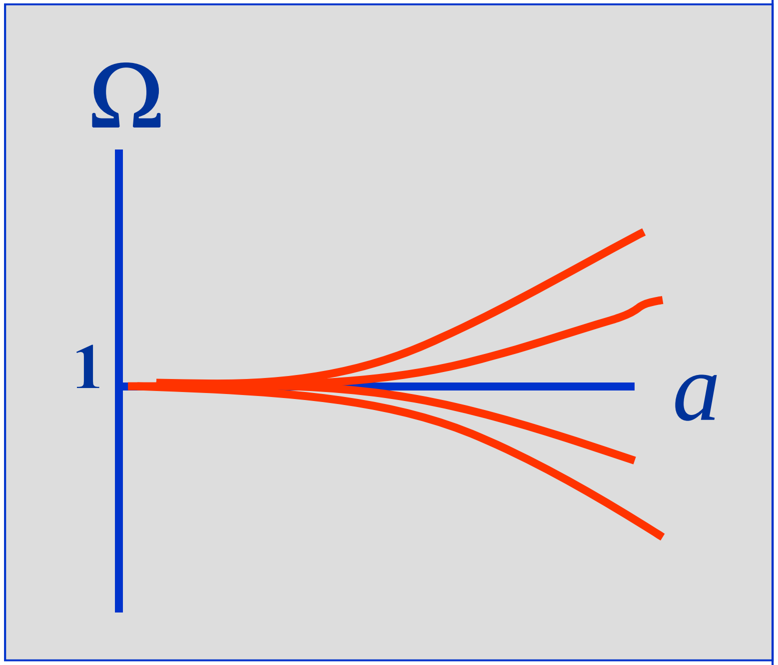


In the SBB, flatness & homogeneity are "unstable fixed points":




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

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

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

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

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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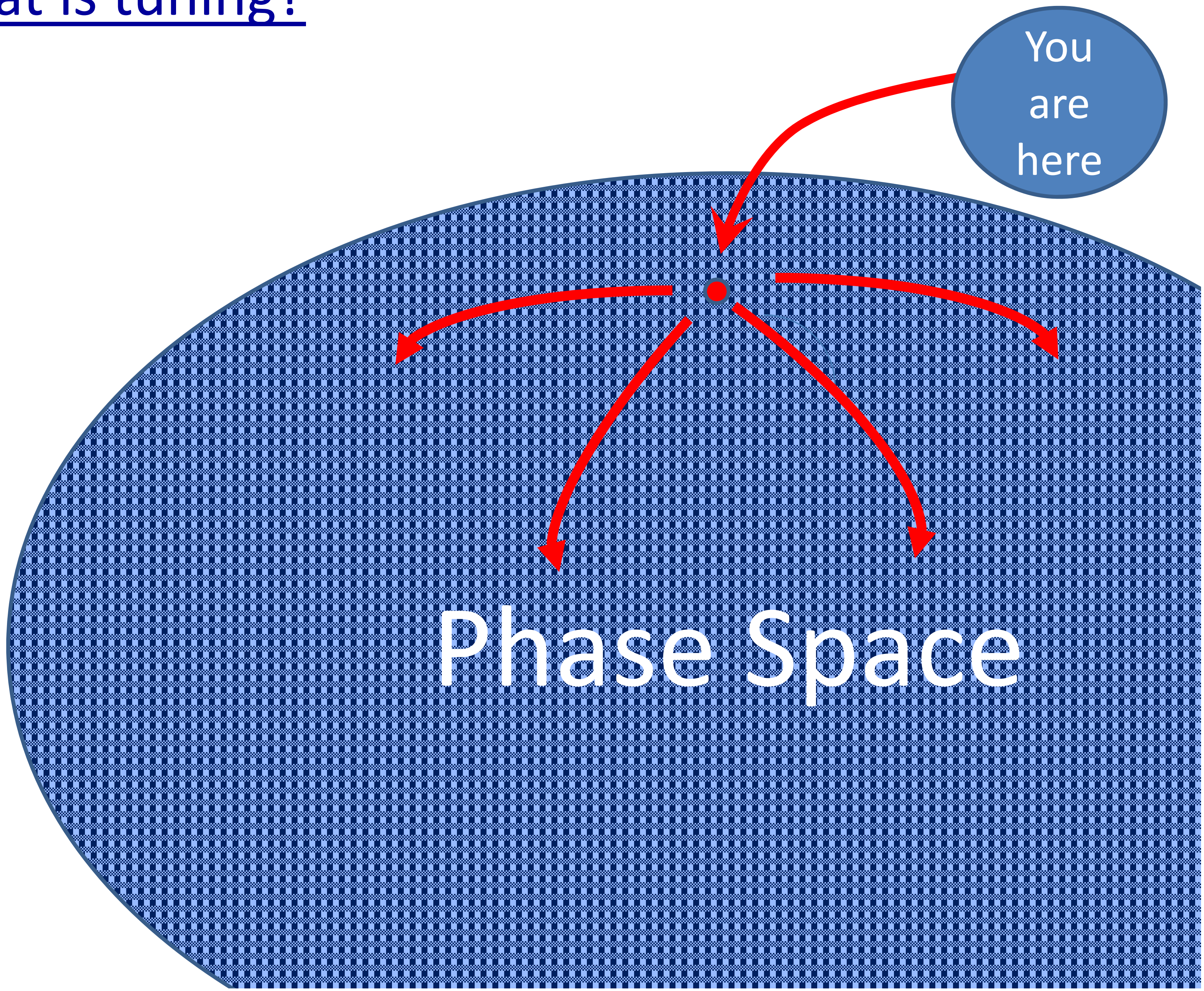

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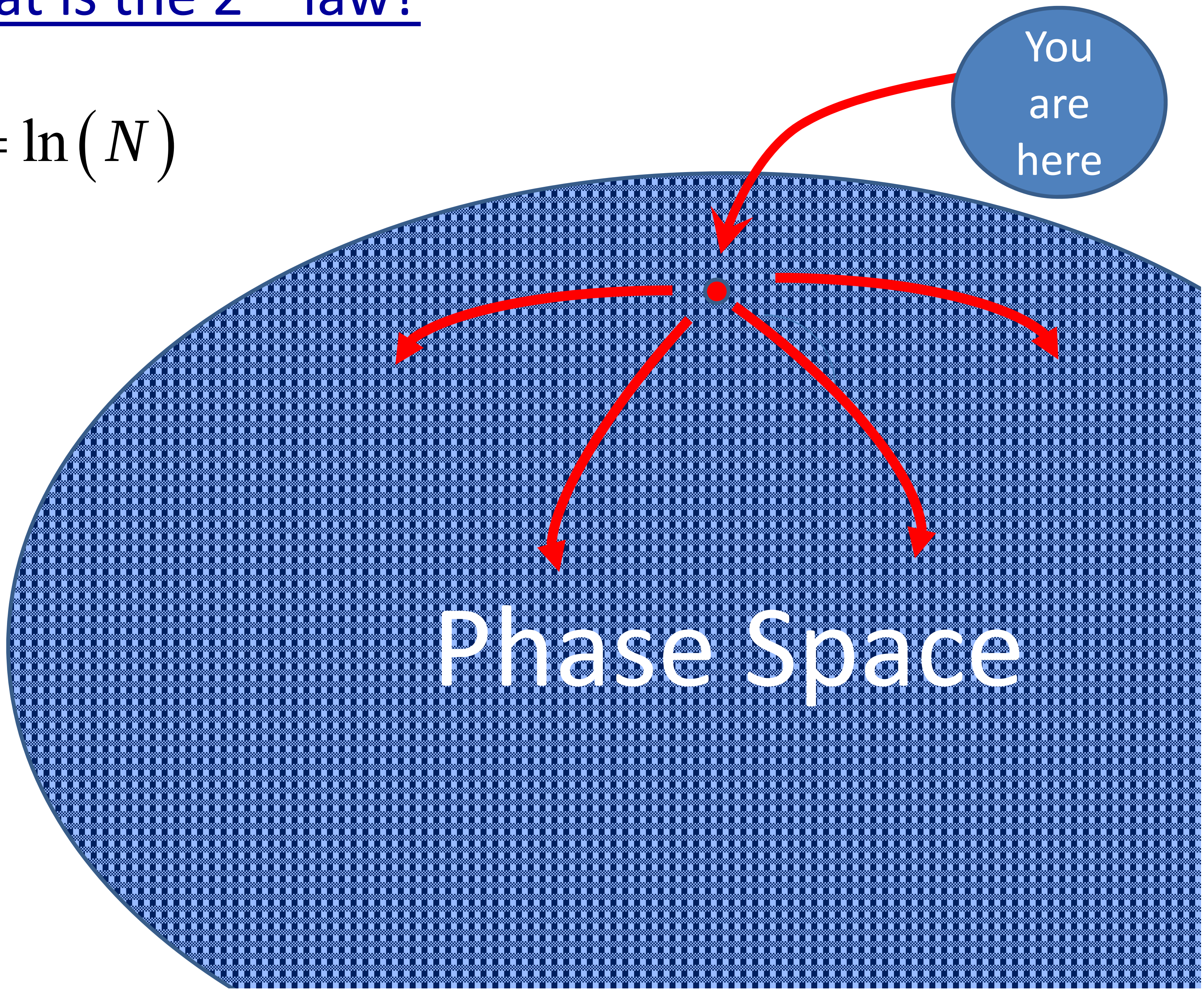
$$S = \ln(N)$$



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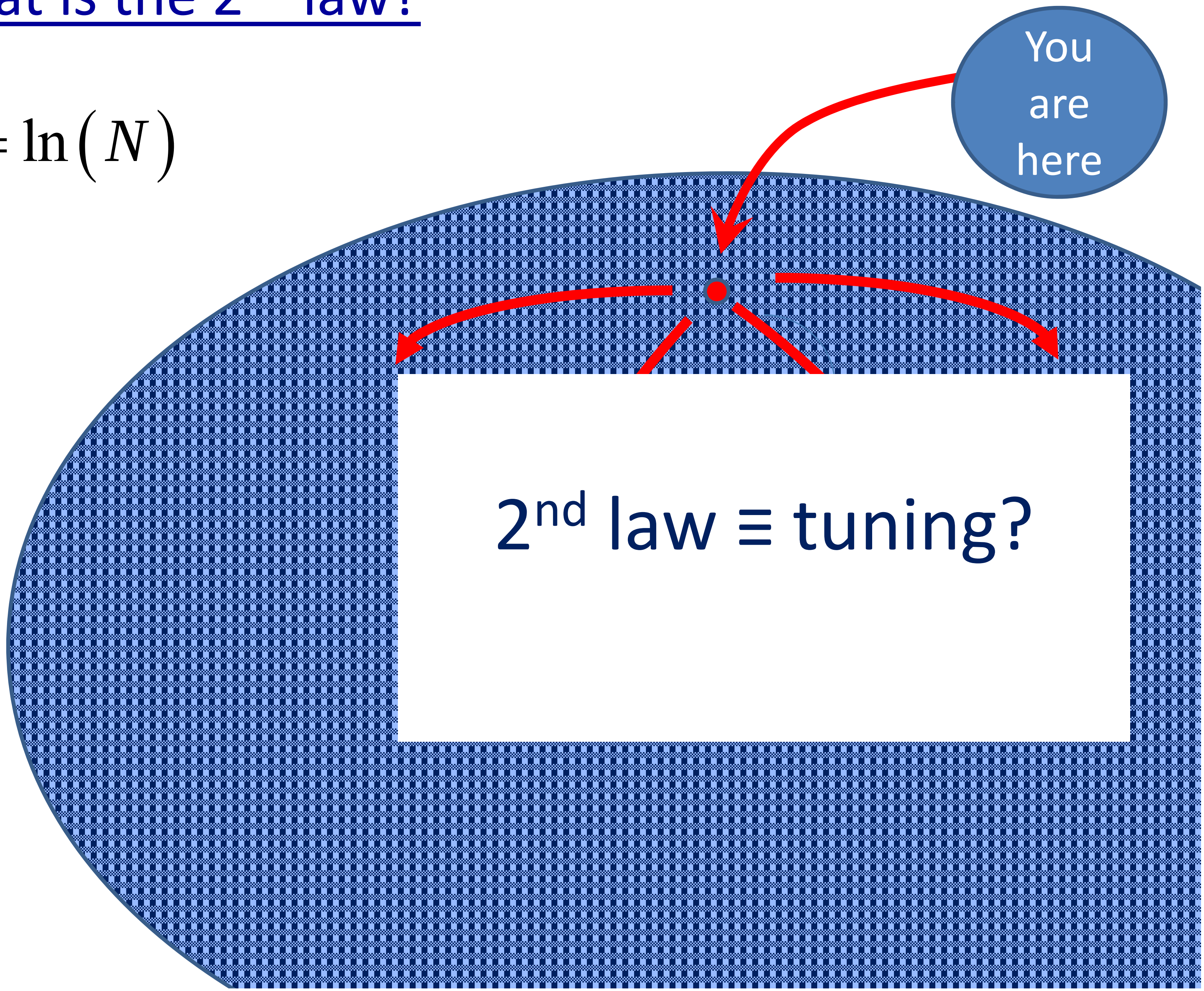

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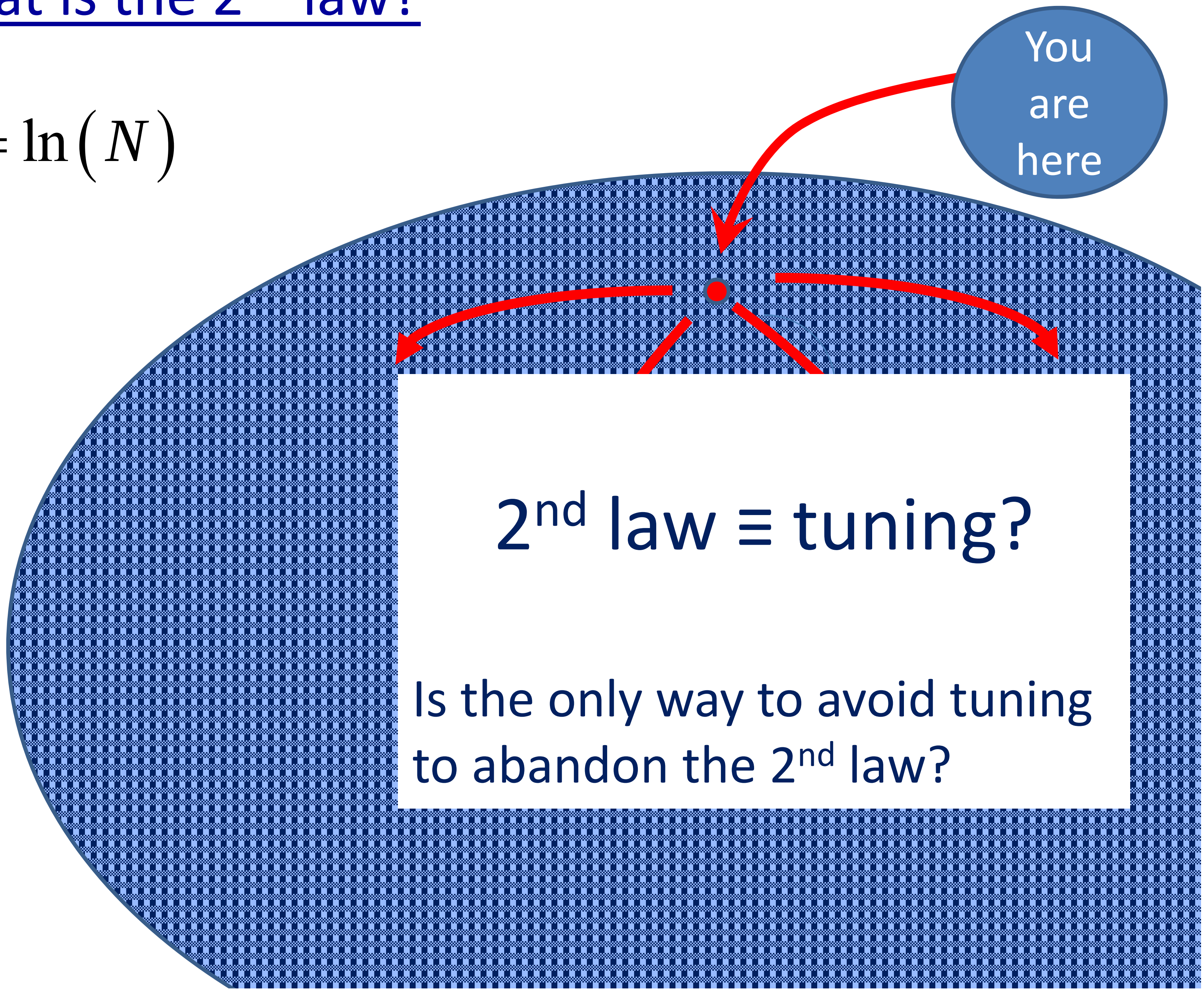

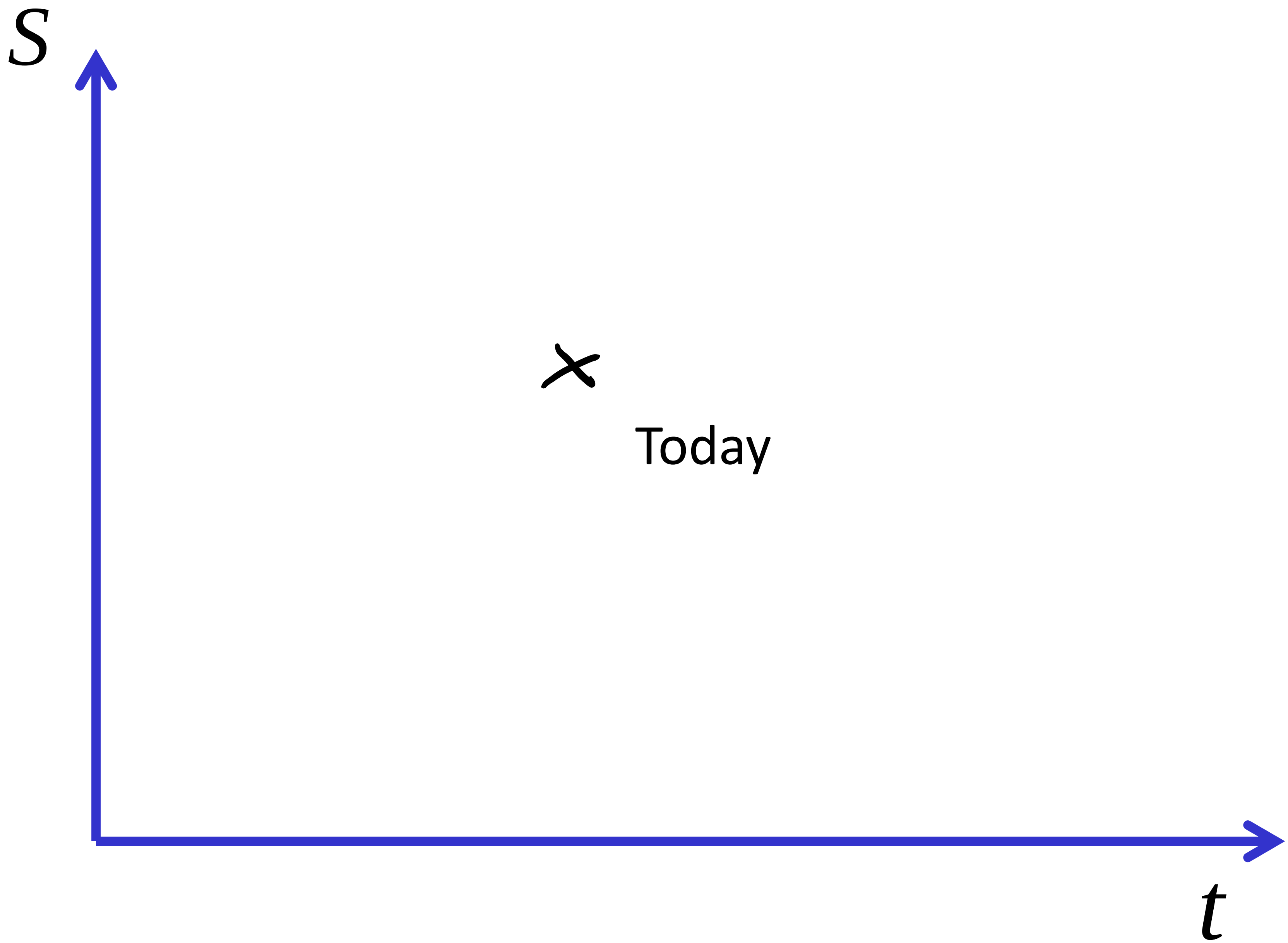
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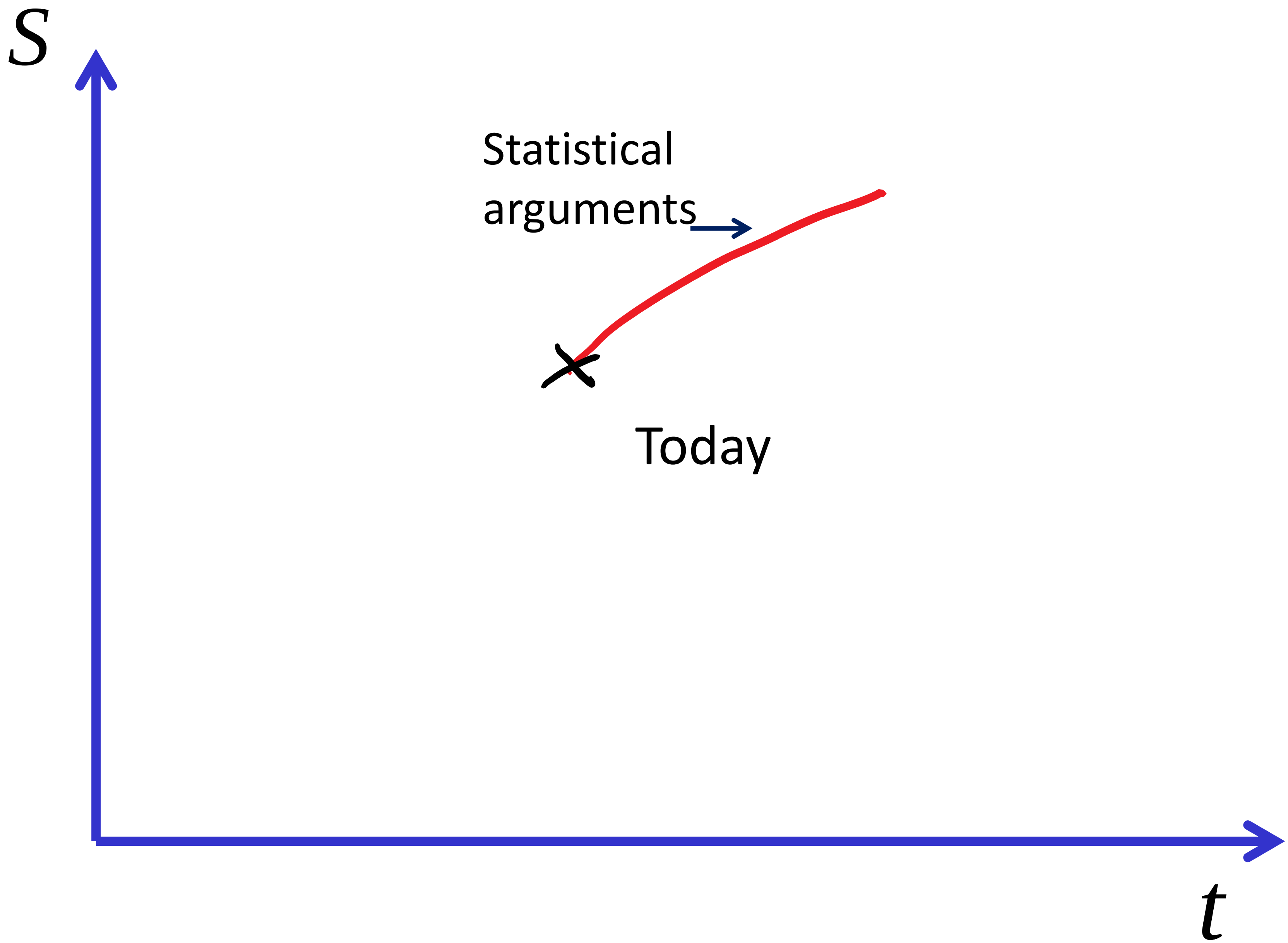
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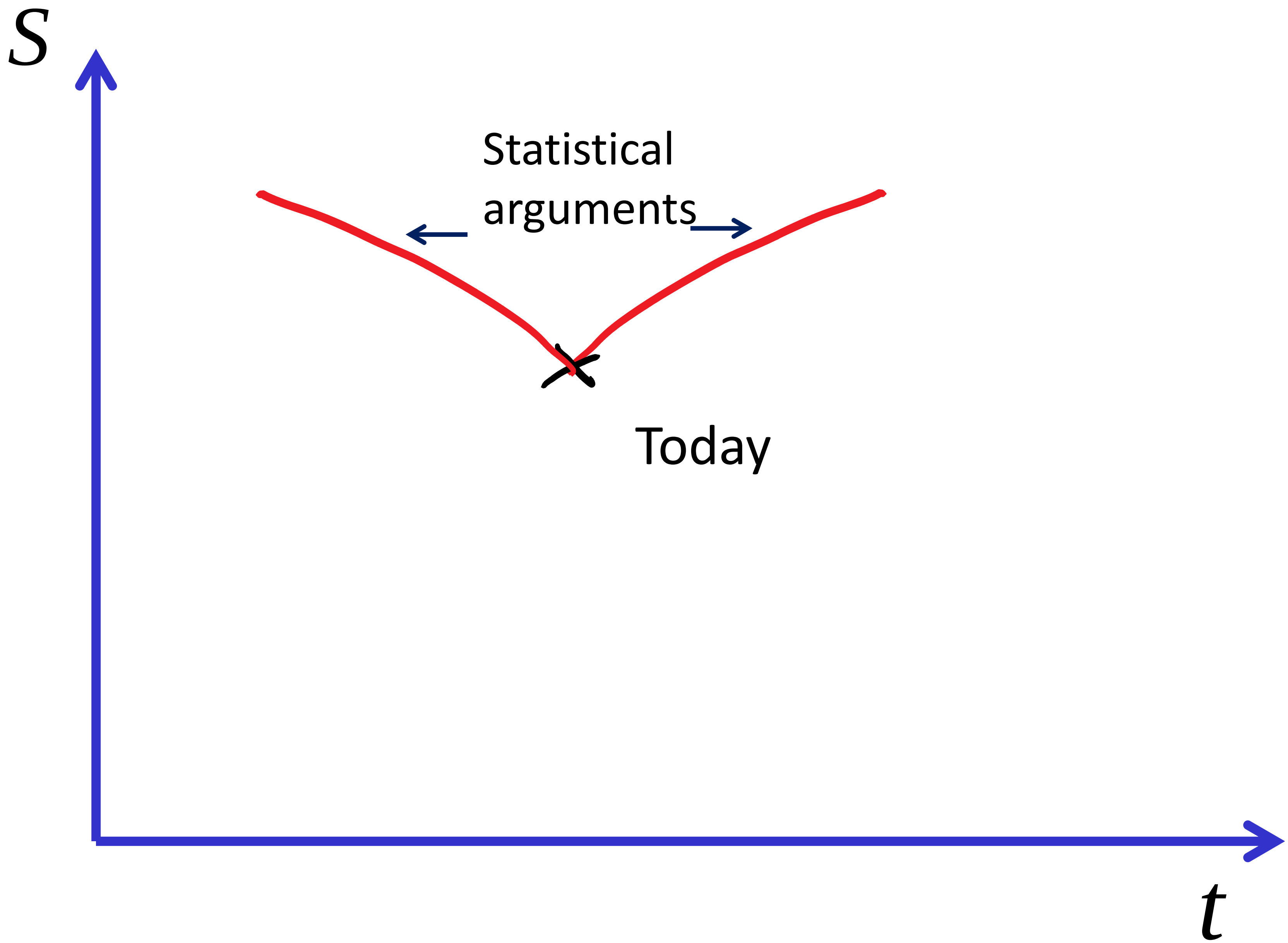
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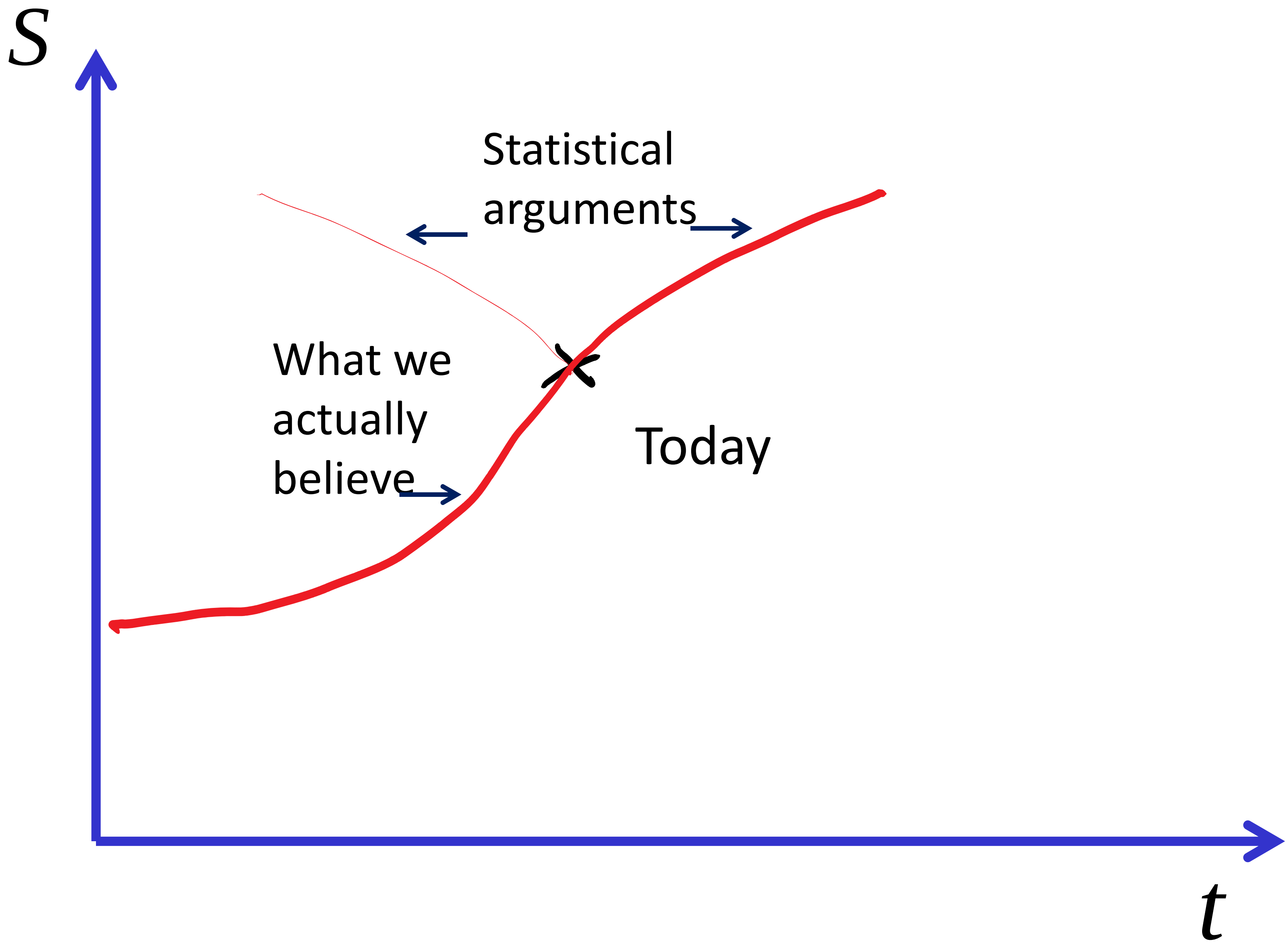
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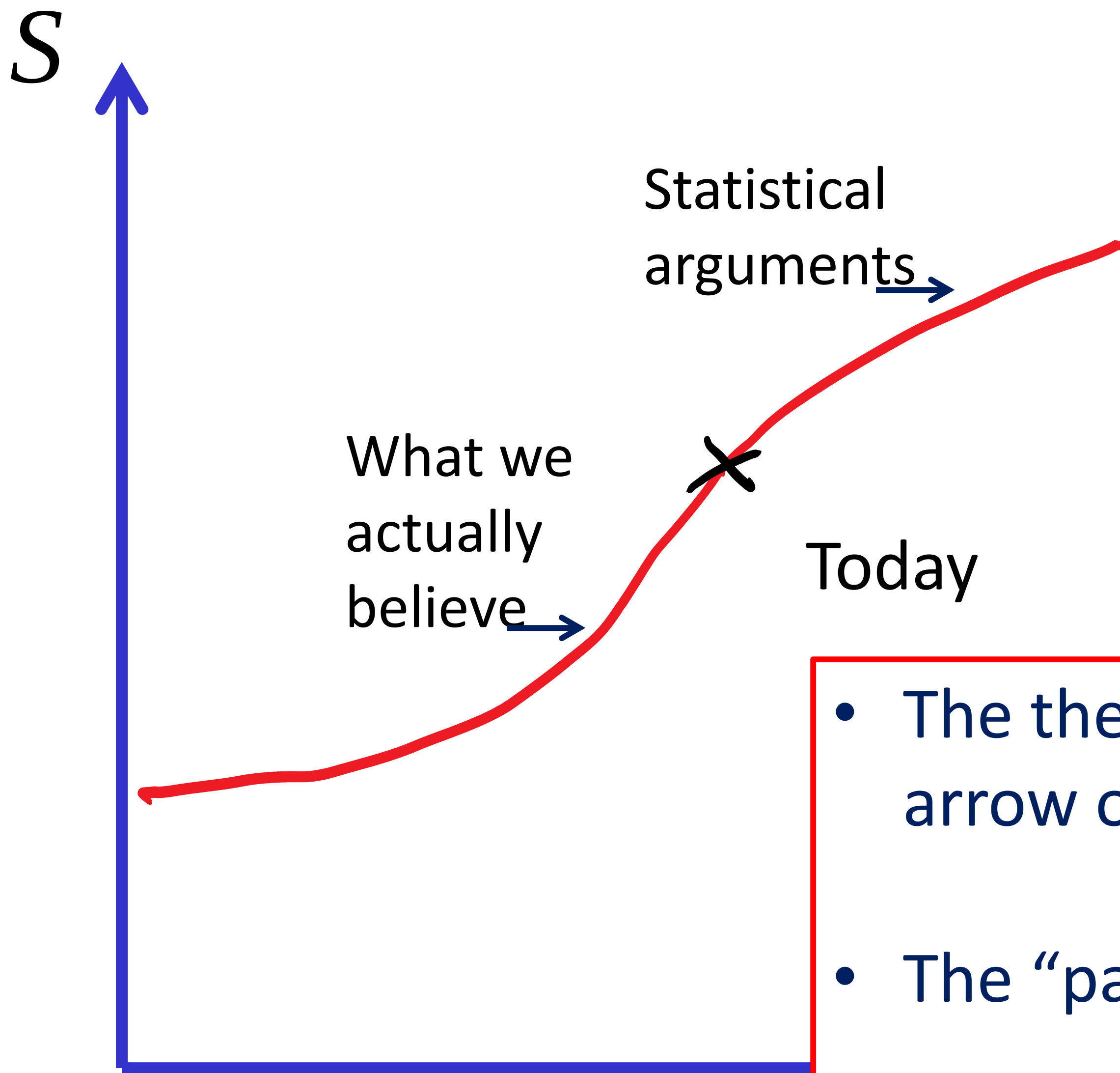


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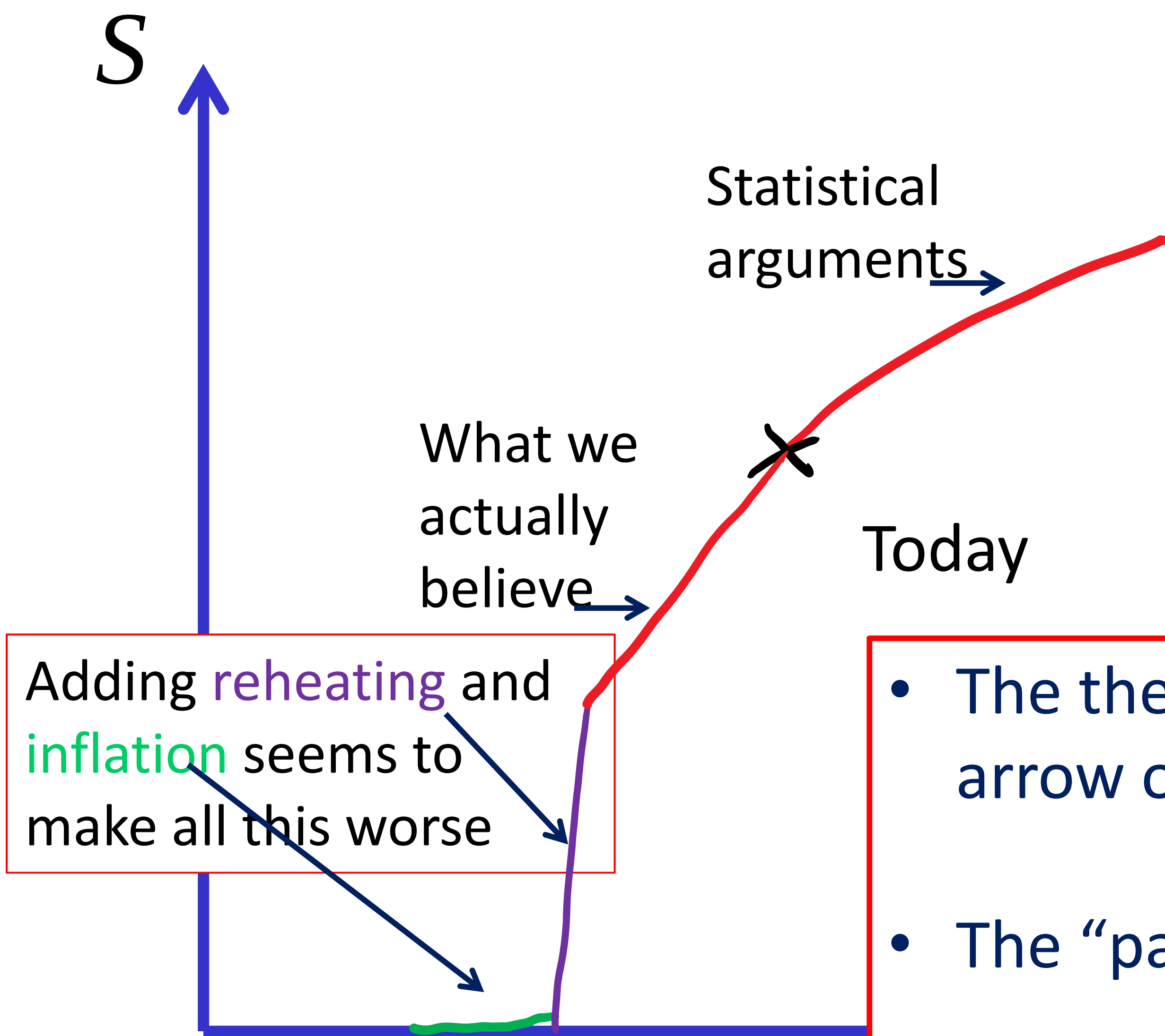
- The "past hypothesis"

  = "Fine tuning"

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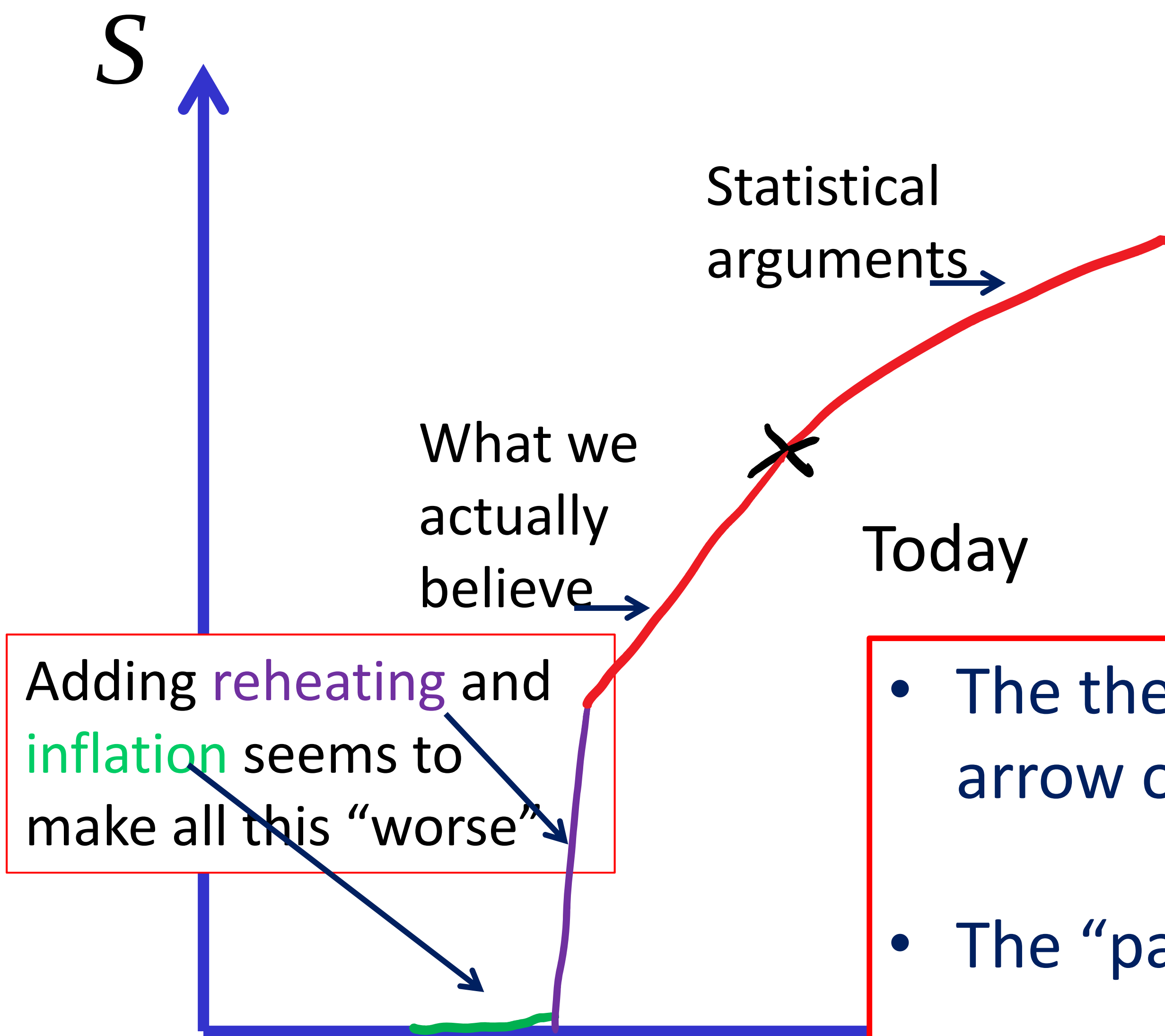


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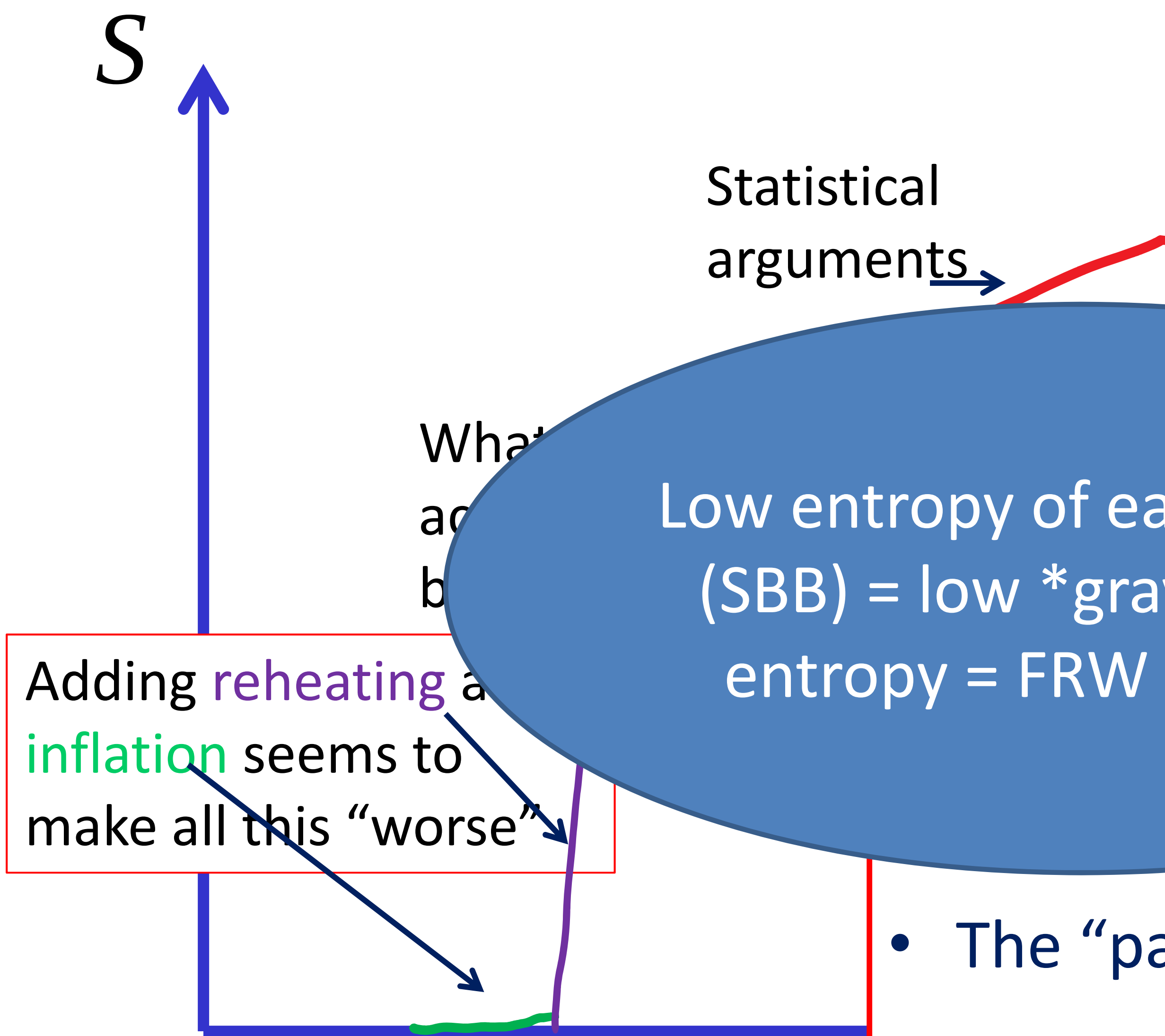


Low entropy of early universe (SBB) = low *gravitational* entropy = FRW (Penrose)

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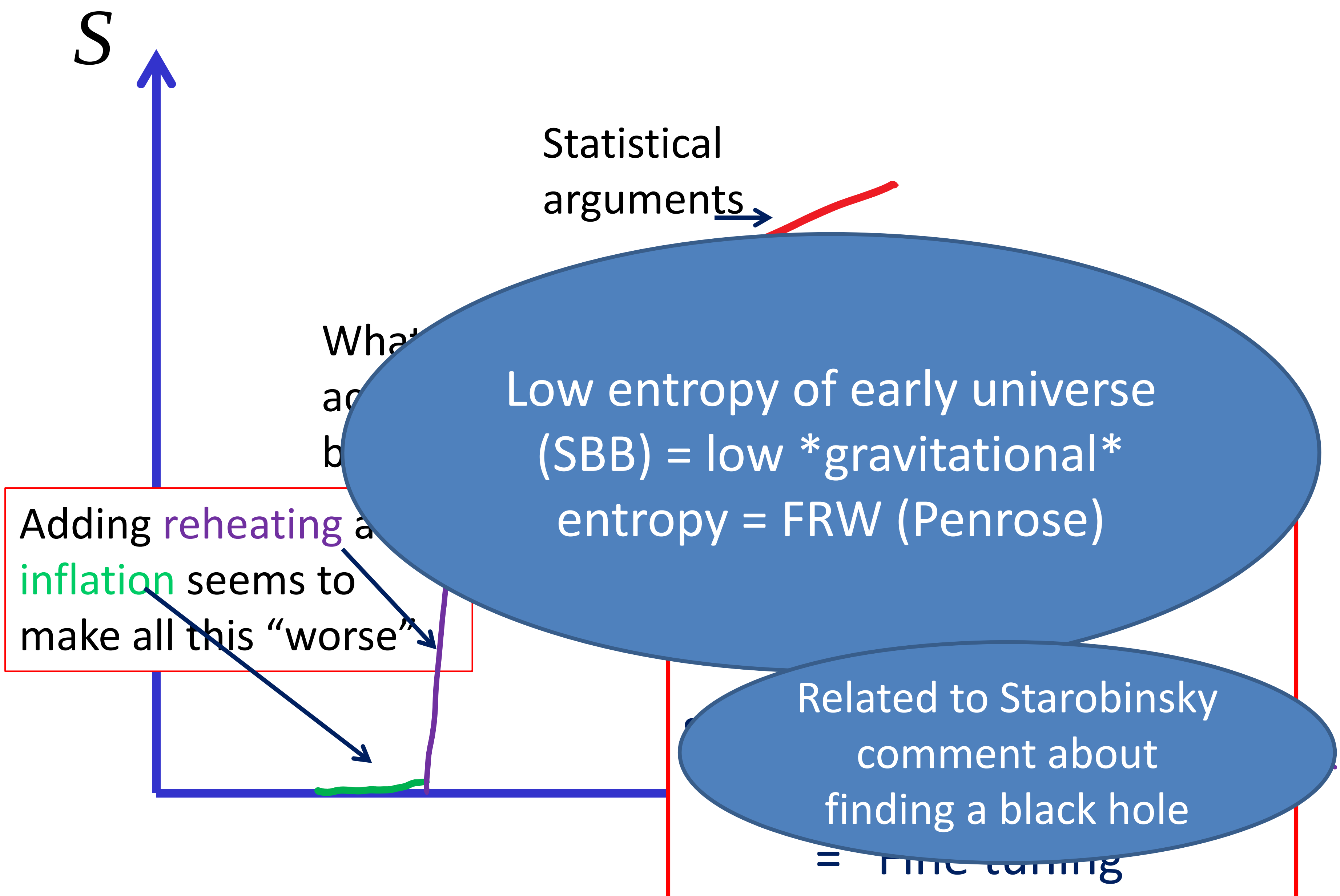
S
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Low entropy of early universe (SBB) = low *gravitational* entropy = FRW (Penrose)
Related to Starobinsky comment about finding a black hole

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Stoltenberg & AA 2015

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Hernley, AA & Dray
2013

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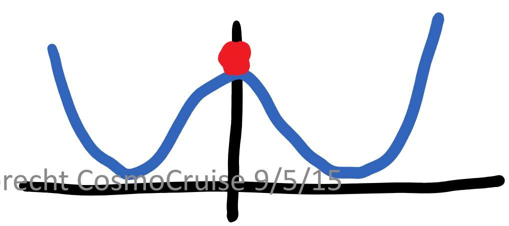
- Various discussions about tuning in SBB (with or without inflation)
- Belief in "naturalness" of high energy density starts



- "Std inflation"
- Landscape

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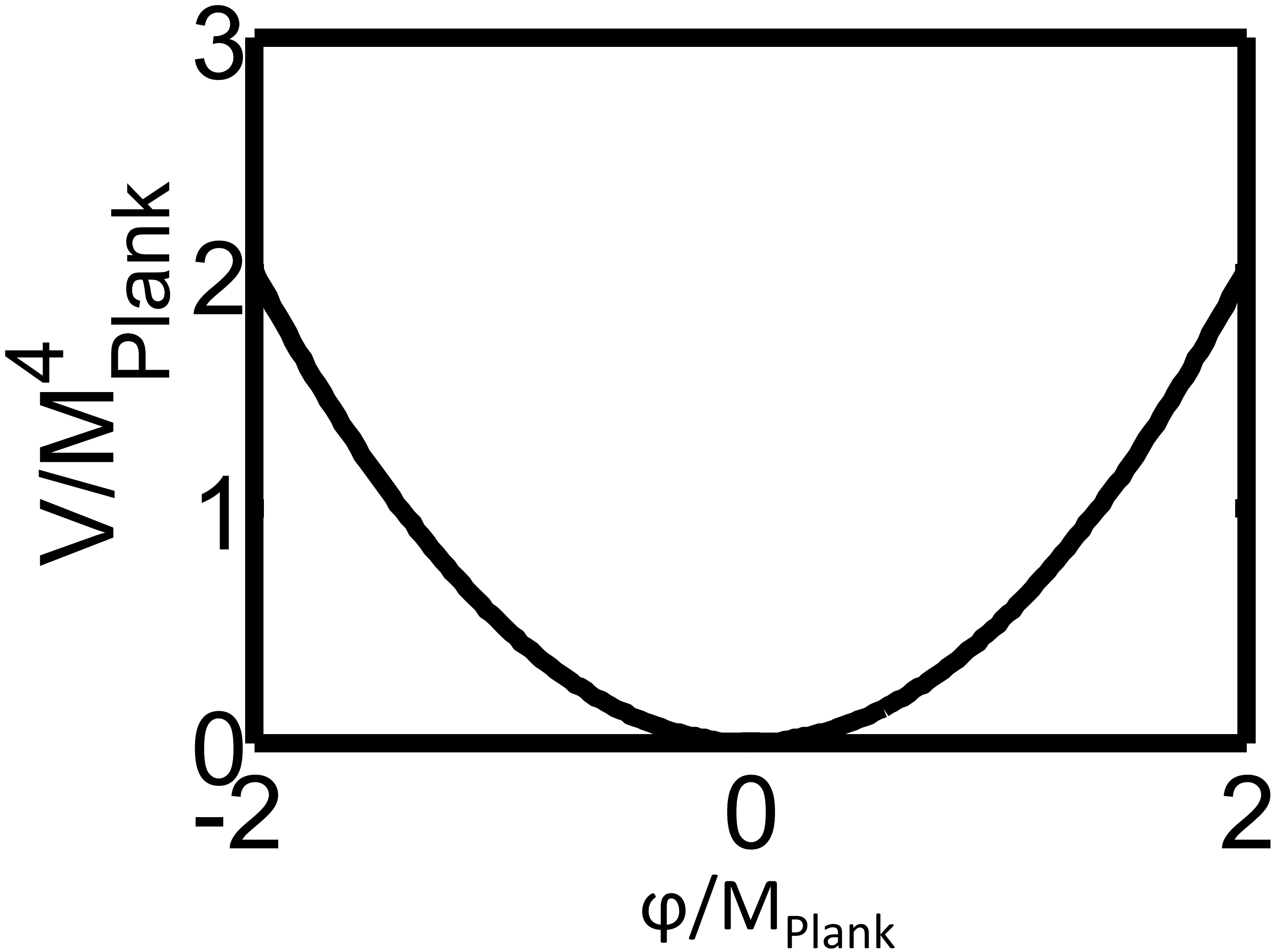
Equipartition argument
(equally likely anywhere on potential)



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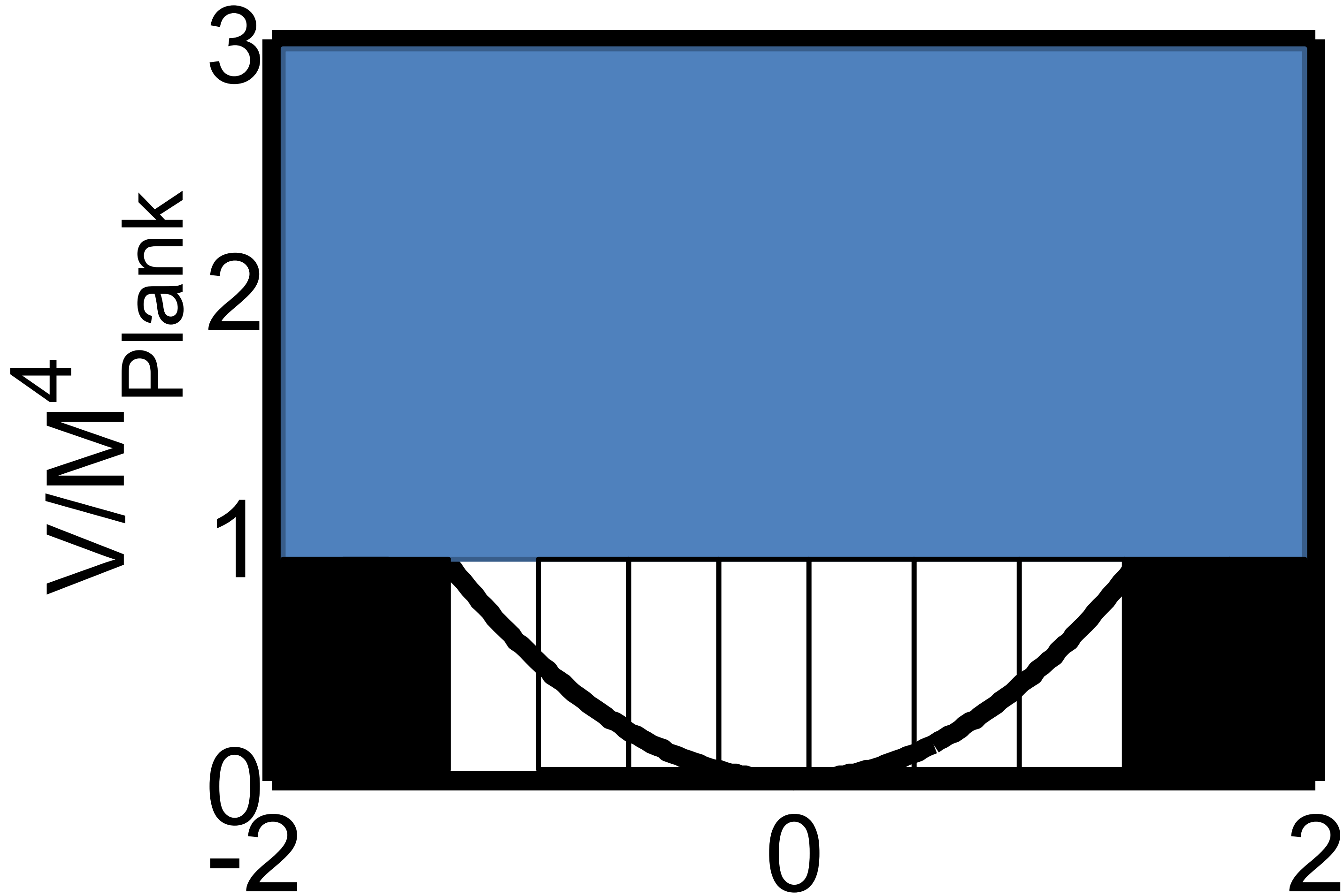

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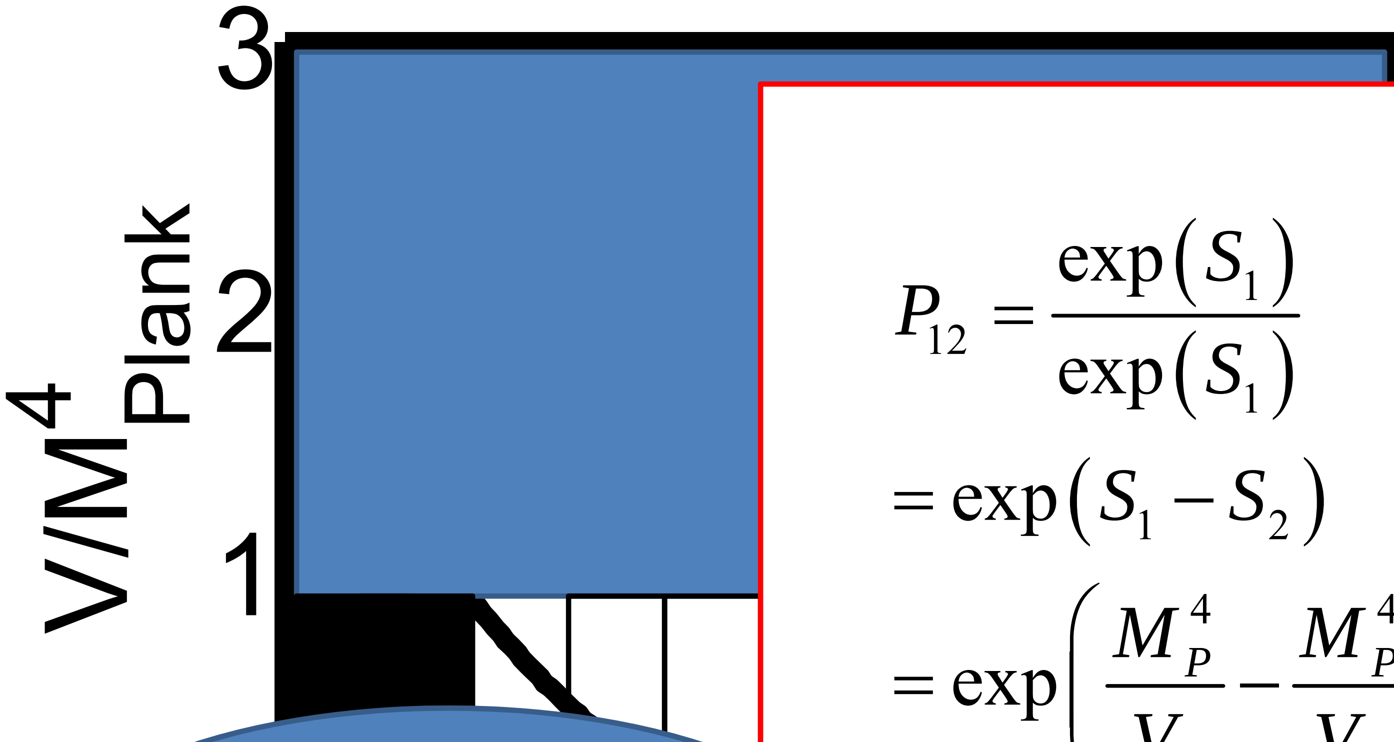



$$P_{12} = \frac{\exp(S_1)}{\exp(S_1)}$$

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

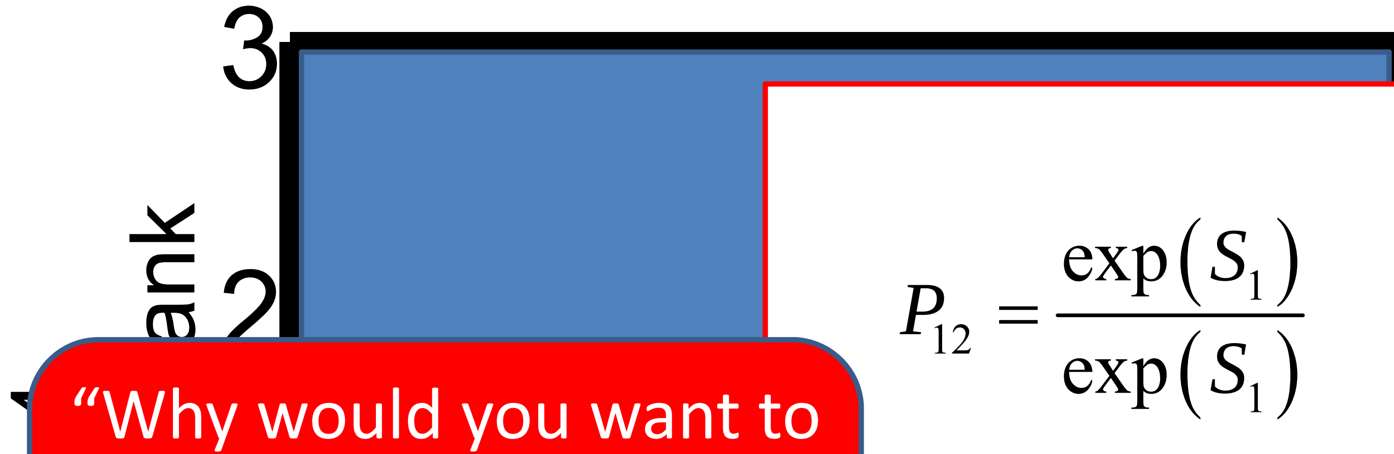
$$= \exp\left(\frac{M_P^4}{V_1} - \frac{M_P^4}{V_2}\right)$$

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

Entropy arguments give exponential suppression of higher *V* values

# Beware "temporal provincialism":

Equipartition argument
(equally likely anywhere on potential)

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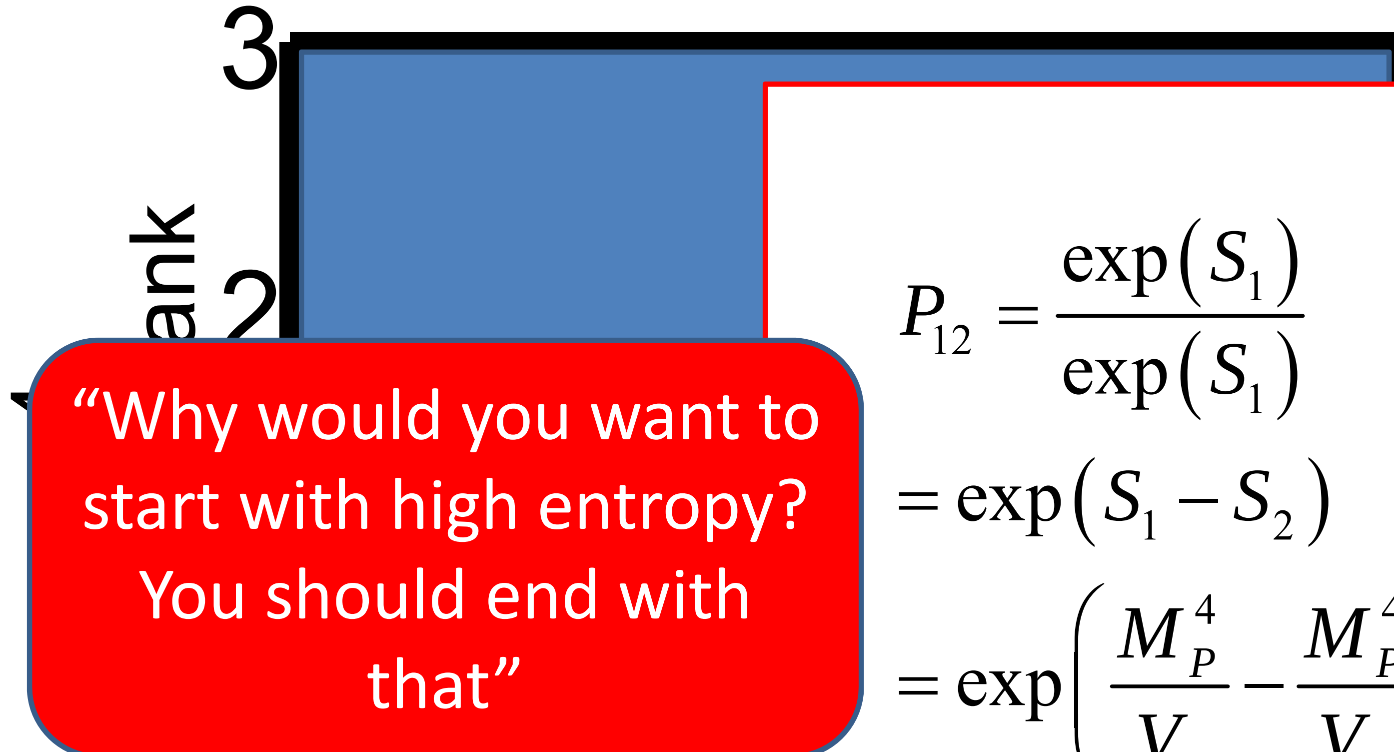


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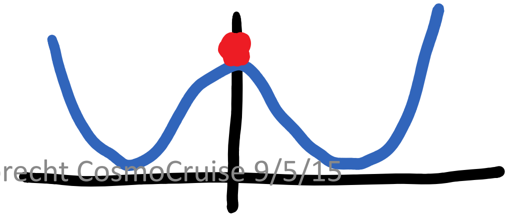
Entropy arguments give exponential suppression of higher *V* values

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



“But if eternal inflation produces an infinite universe surely it does not matter if the start of inflation is very improbable”

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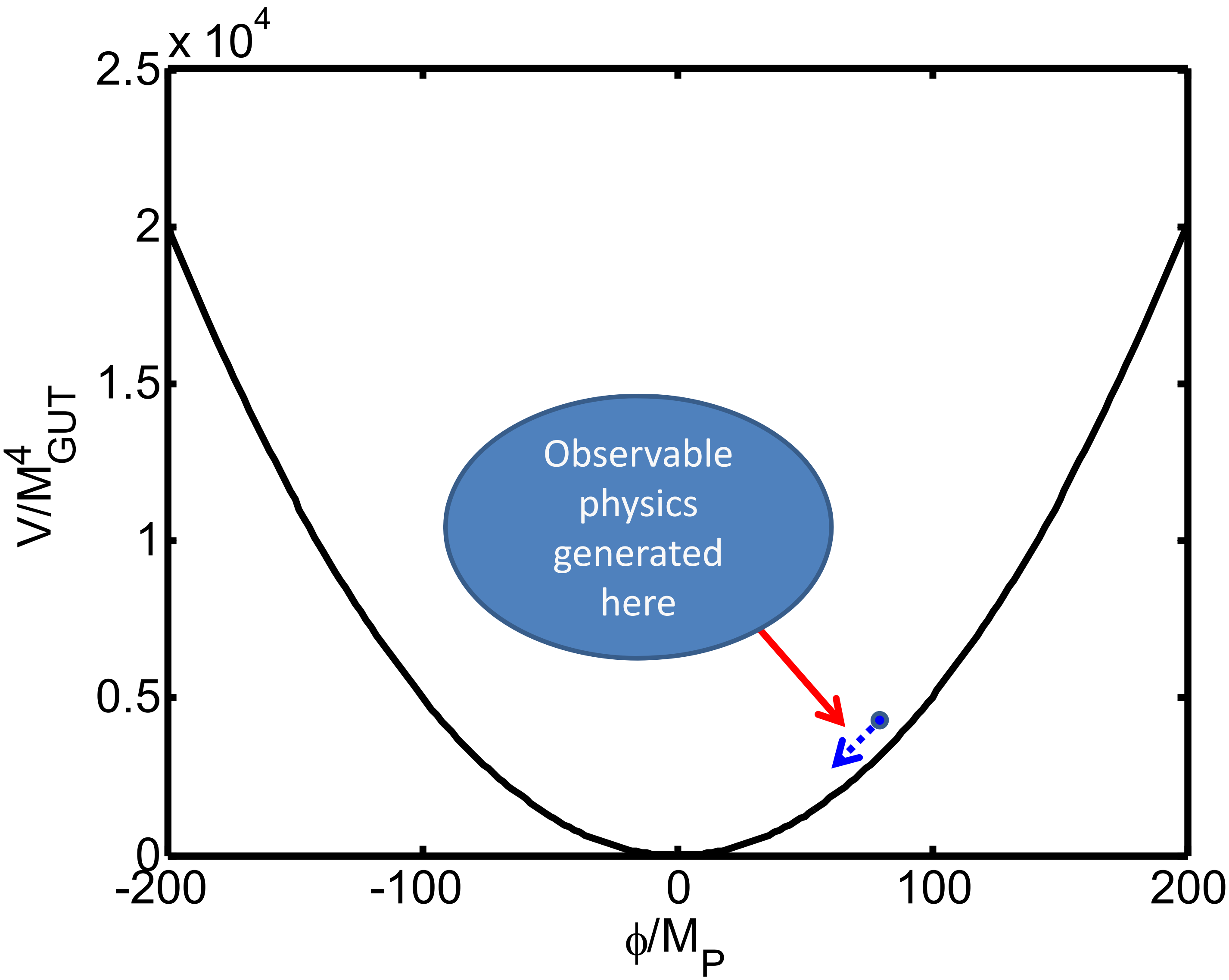
# Slow rolling of inflaton



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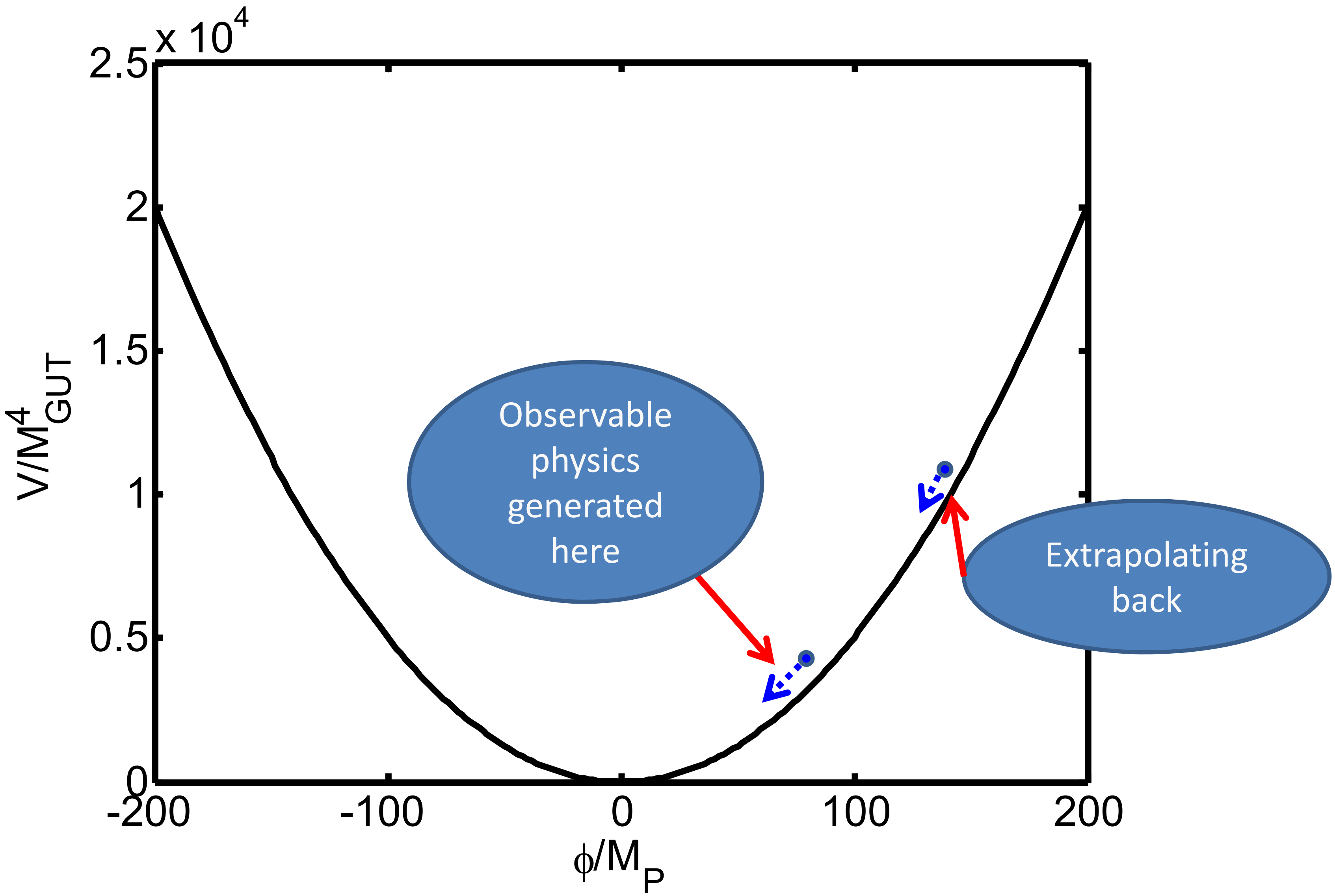

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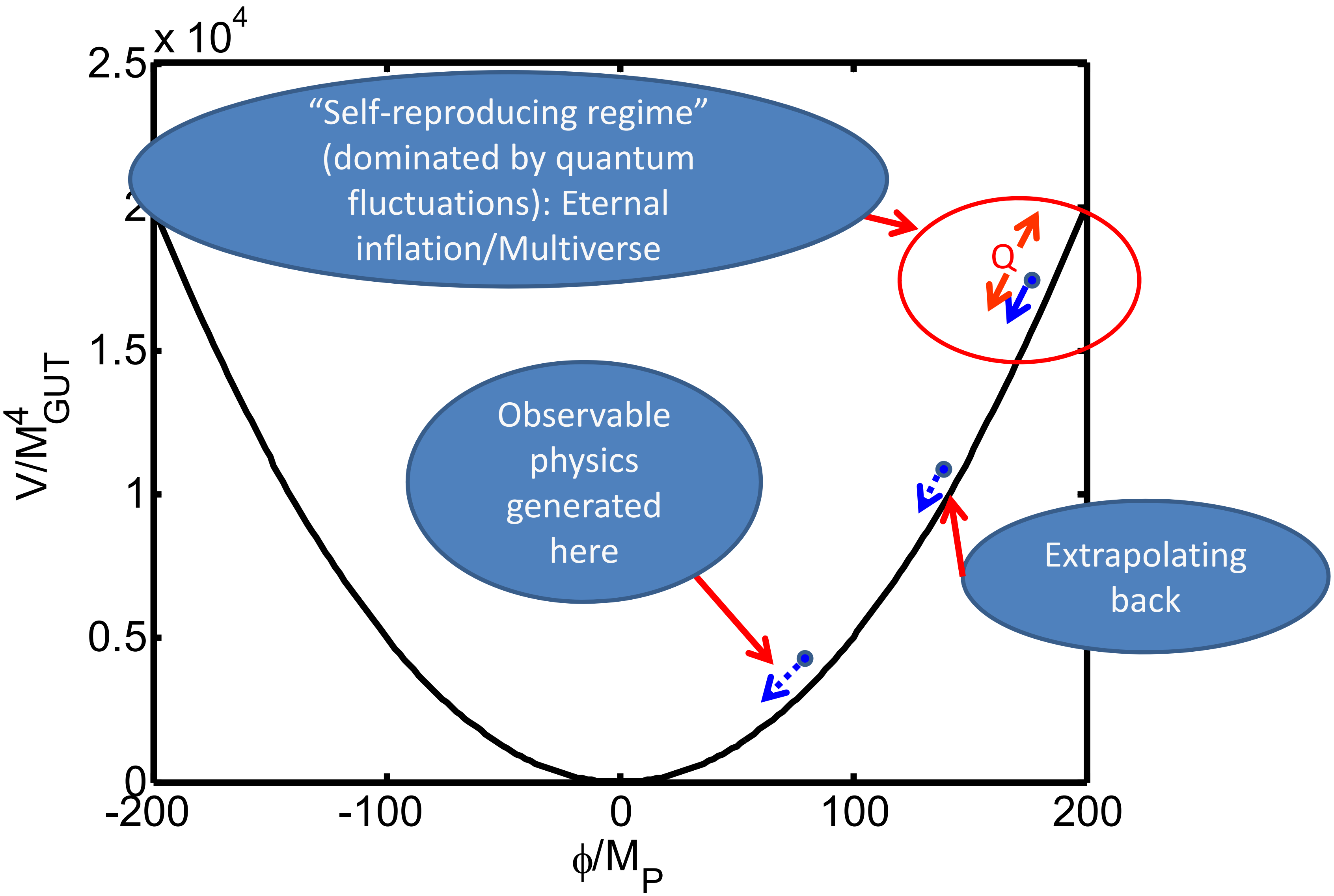

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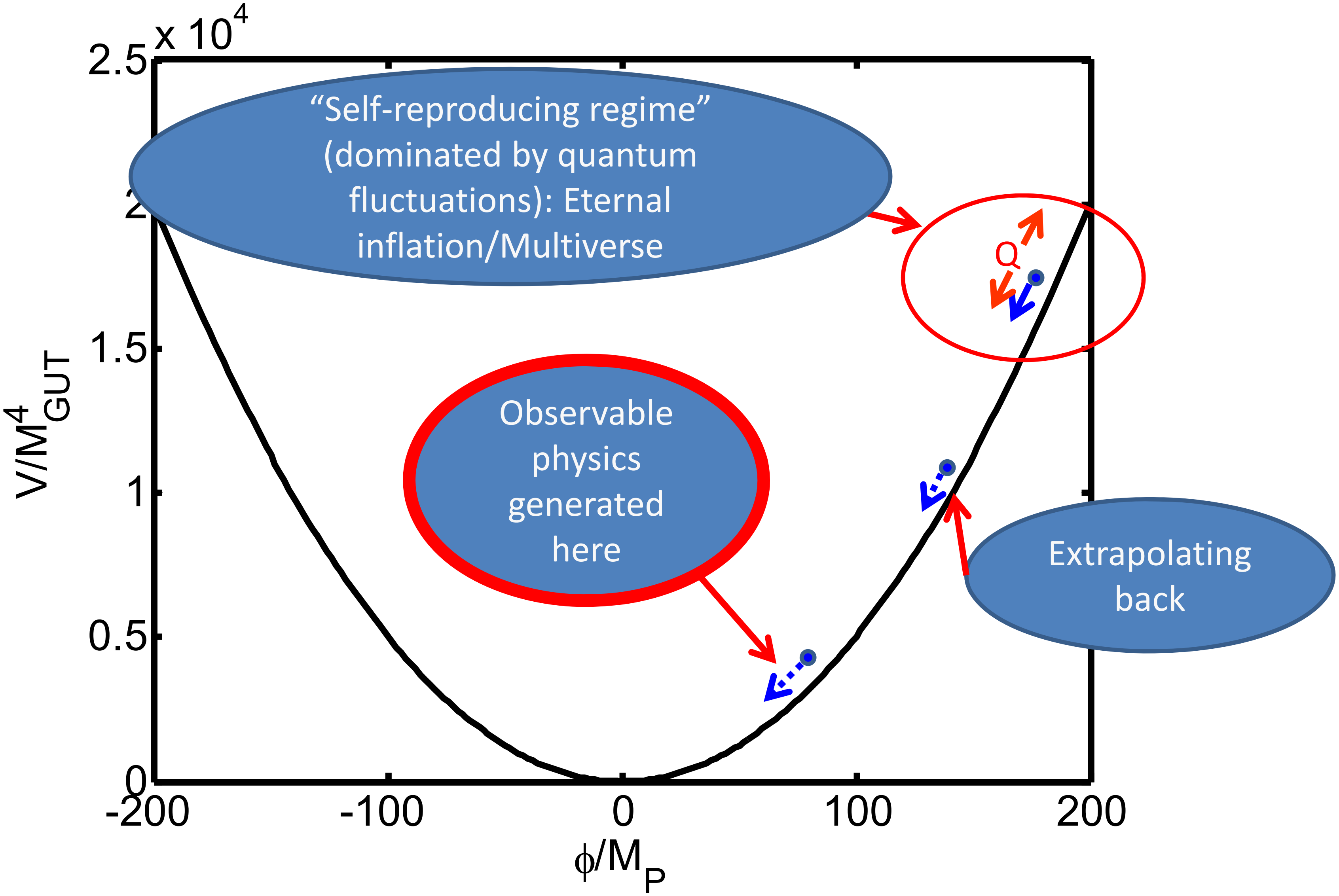
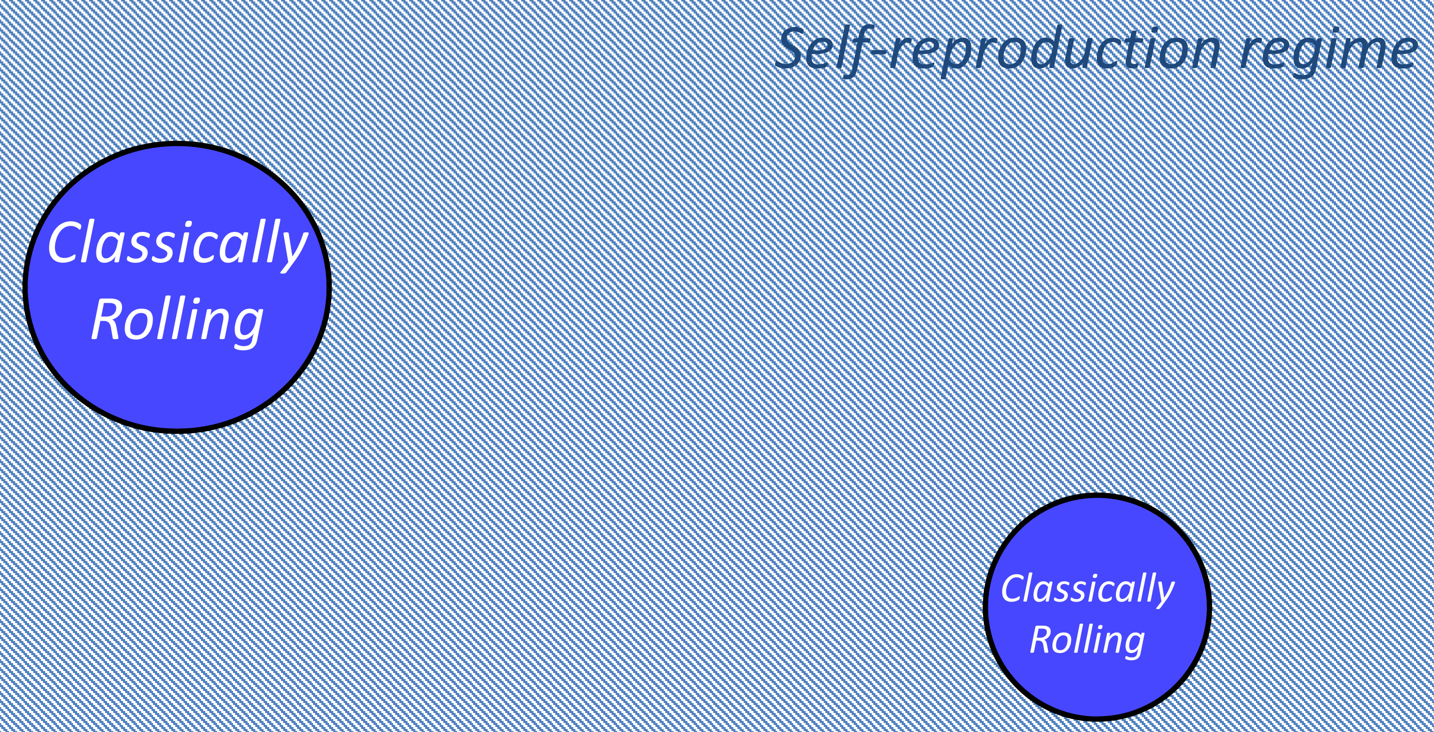


# The multiverse of eternal inflation



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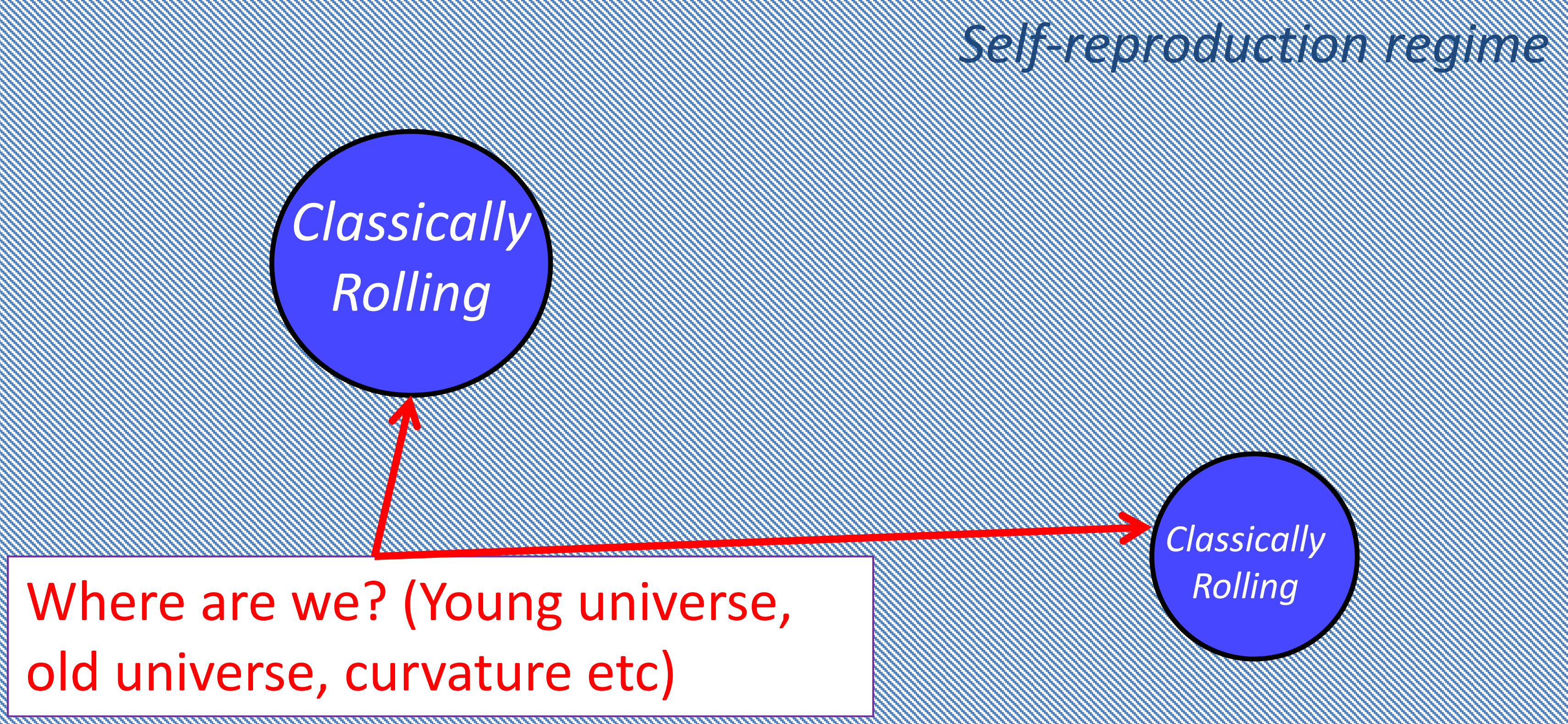

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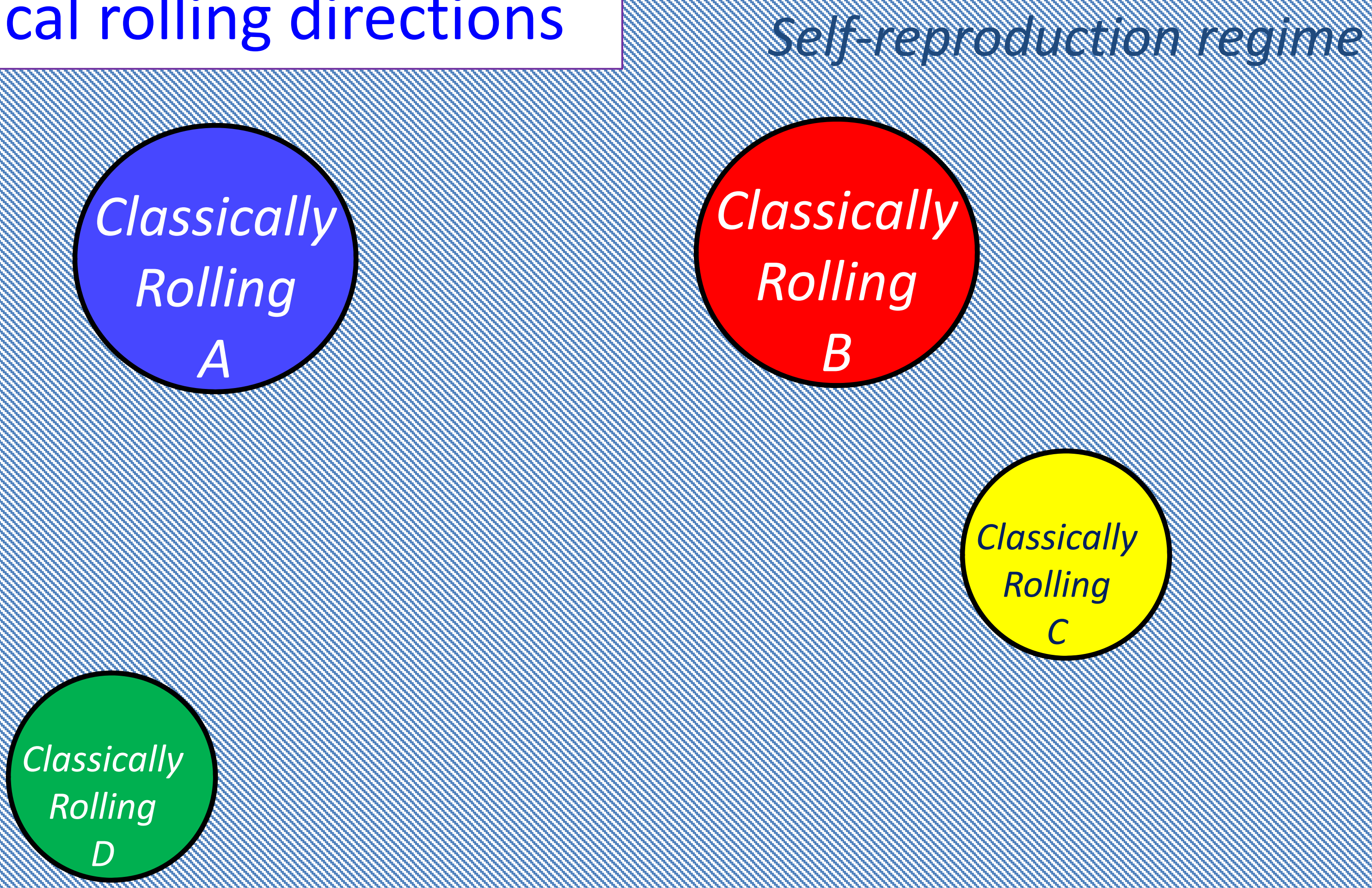

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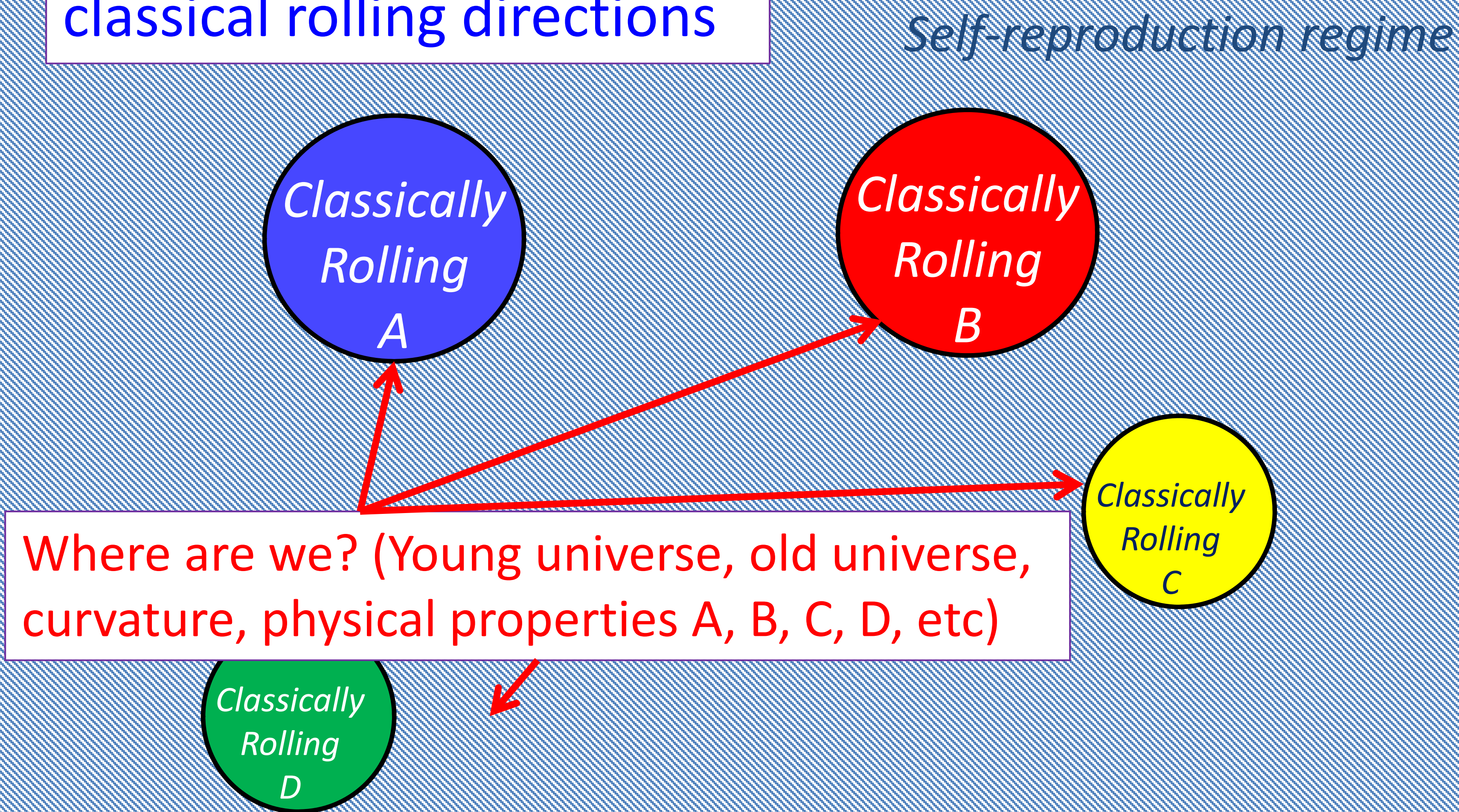
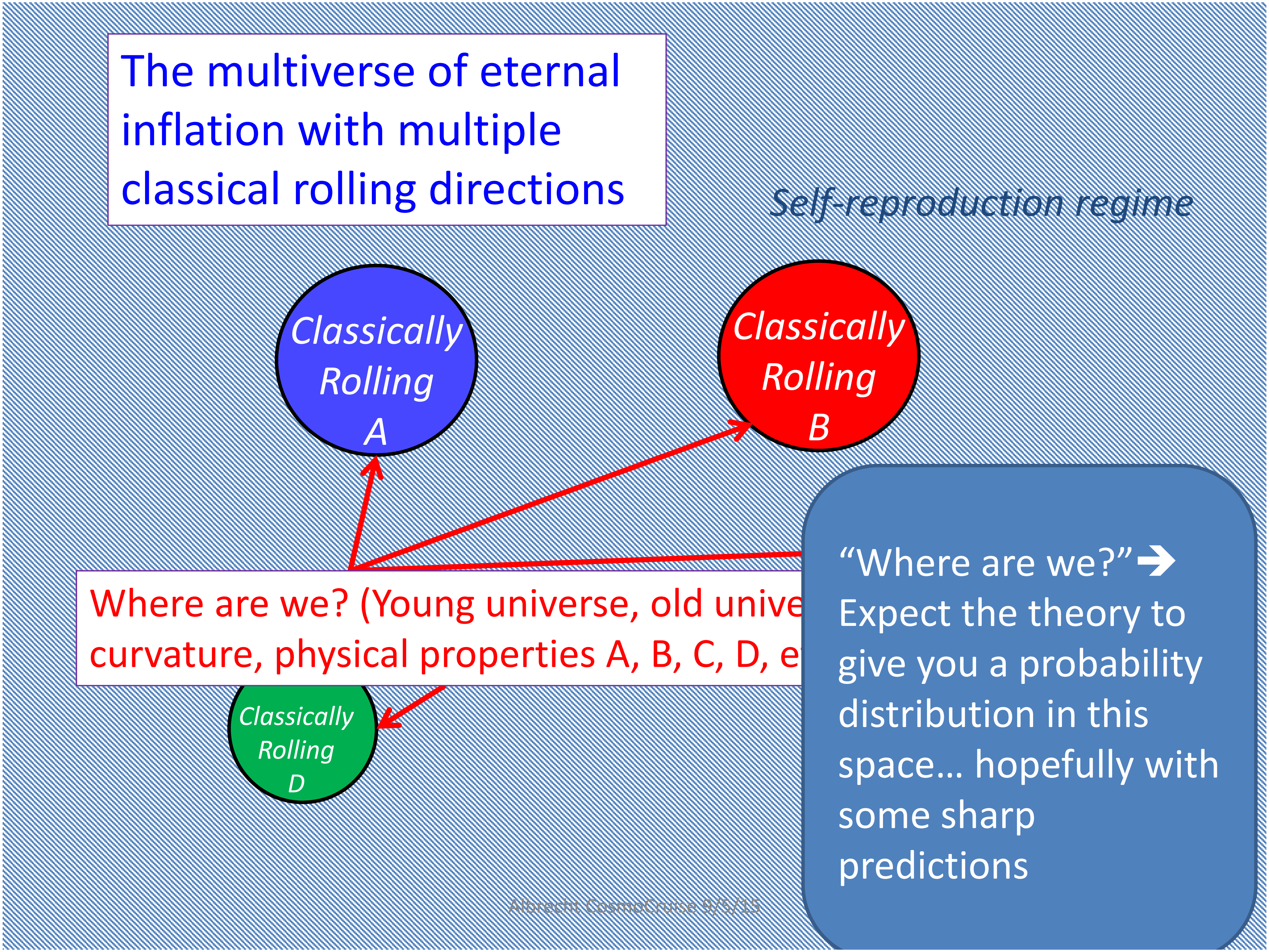
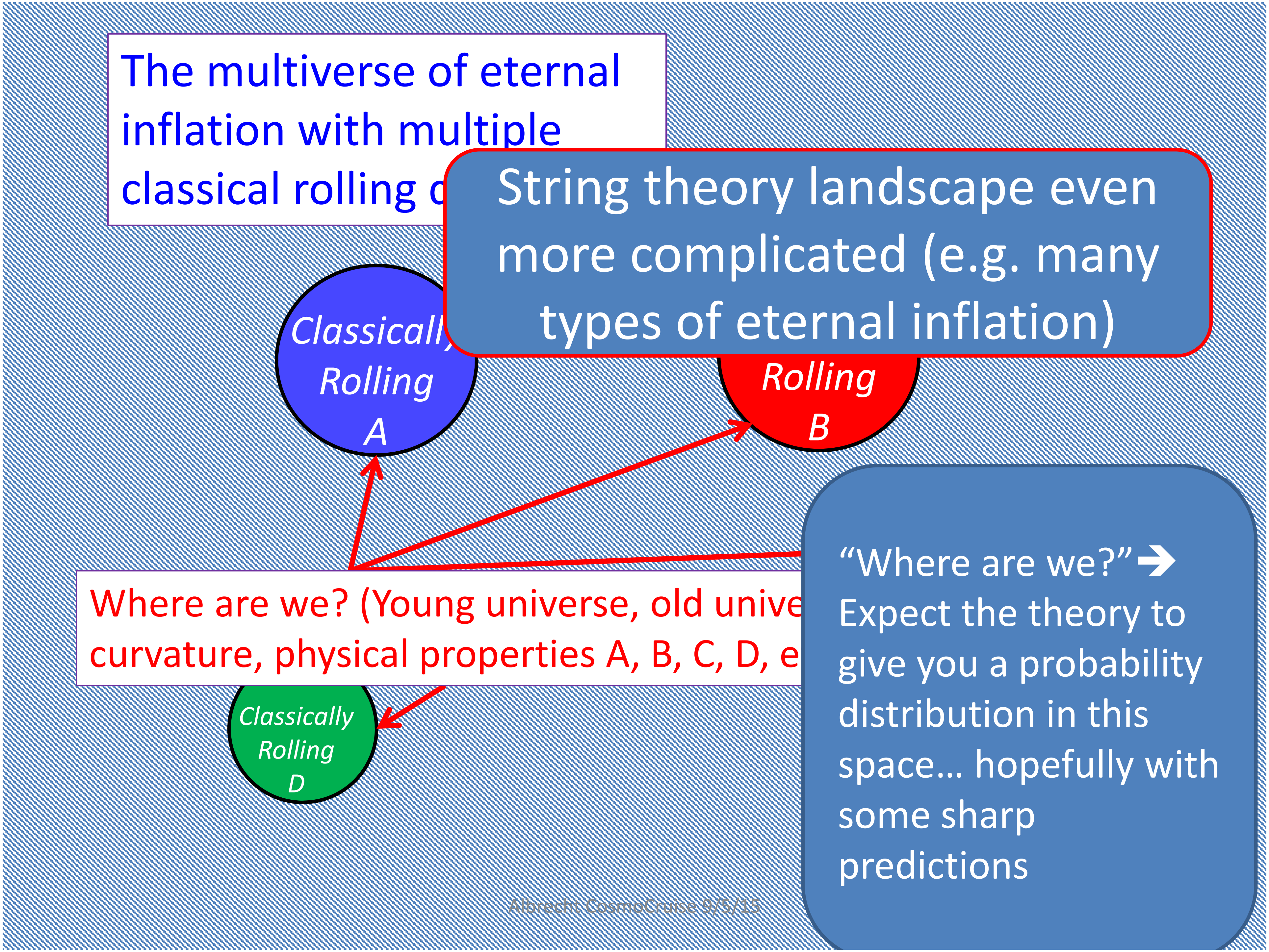



The multiverse of eternal inflation with multiple classical rolling directions
Self-reproduction regime
Classically Rolling A
Classically Rolling B
Classically Rolling D
Where are we? (Young universe, old unive
curvature, physical properties A, B, C, D, e
"Where are we?"→ Expect the theory to give you a probability distribution in this space… hopefully with some sharp predictions
Albrecht CosmoCruise 9/5/15


The multiverse of eternal inflation with multiple classical rolling c
String theory landscape even more complicated (e.g. many types of eternal inflation)
Classically Rolling A
Rolling B
Where are we? (Young universe, old unive
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# Challenges for eternal inflation

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

1) Measure Problems (**∞/∞**)

2) Problems defining probabilities

3) Problems/hidden assumptions re initial conditions
   - ➔ problem claiming generic predictions about state
     - ➔ cannot claim "solution to cosmological problems"
       - ➔ Related to $2^{nd}$ law, low *S* start

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Inflation ≠ Eternal Inflation

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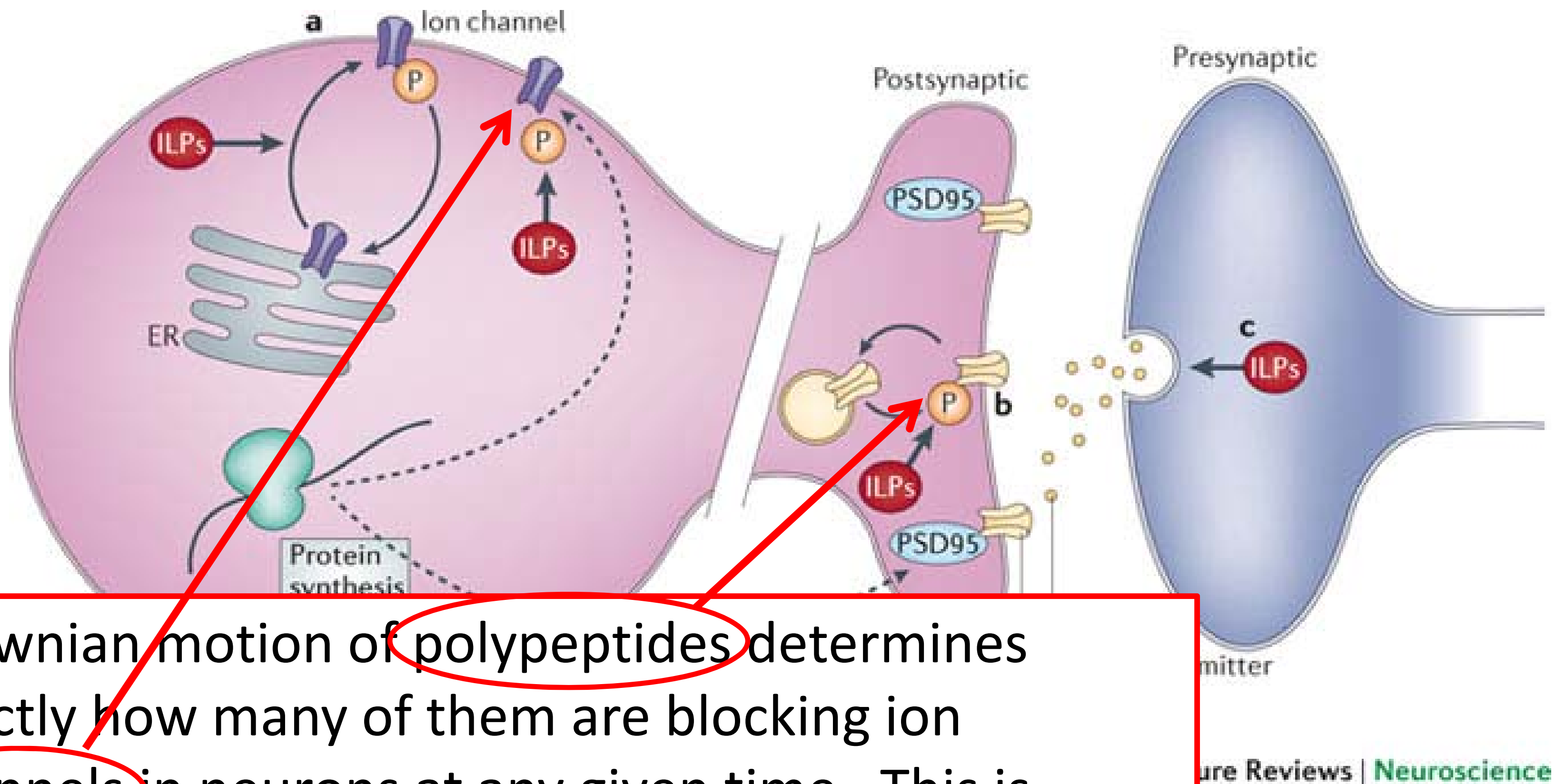
An important role for Brownian motion: Uncertainty in neuron transmission times

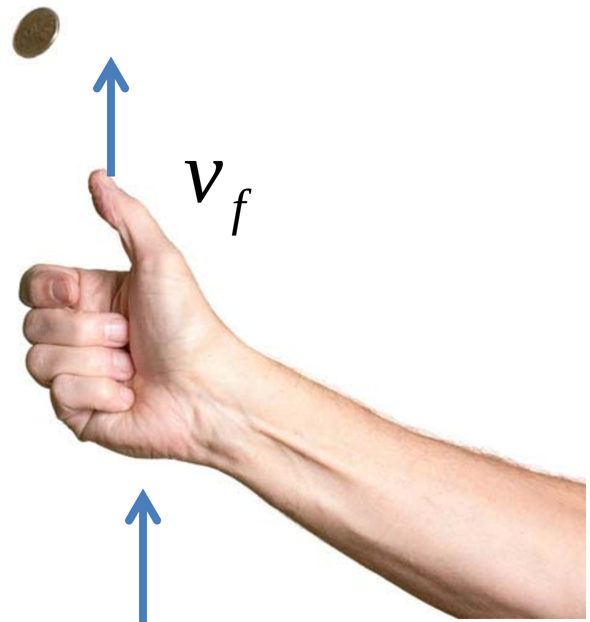
**QUANTUM**




Brownian motion of polypeptides determines exactly how many of them are blocking ion channels in neurons at any given time. This is believed to be the dominant source of *neuron transmission time uncertainties* $\delta t_n \approx 1 ms$

Image from http://www.nature.com/nrn/journal/v13/n4/full/nrn3209.html

# Analysis of coin flip



$v_f$

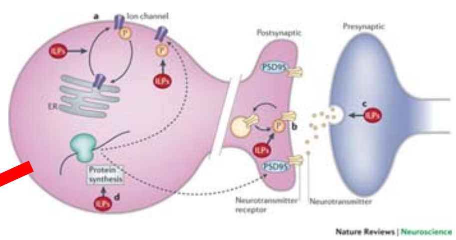
$v_h$

$$\delta t_f = \delta t_n \times \left( \frac{v_h}{v_h + v_f} \right)$$

$$\delta t_t = \sqrt{2}\,\delta t_f$$

$$f = \frac{4 v_f}{\pi d}$$

$$\delta N = f\,\delta t_t = 0.5$$




Coin diameter $= d$

Using:

$\delta t_n \approx 1ms$ $\quad v_h = v_f = 5m/s$

$d = 0.01m$

No "Principle of indifference"

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Possible discussion/surprise talk topic

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NO

Hernley, AA & Dray 2013

AA & Sorbo 2004

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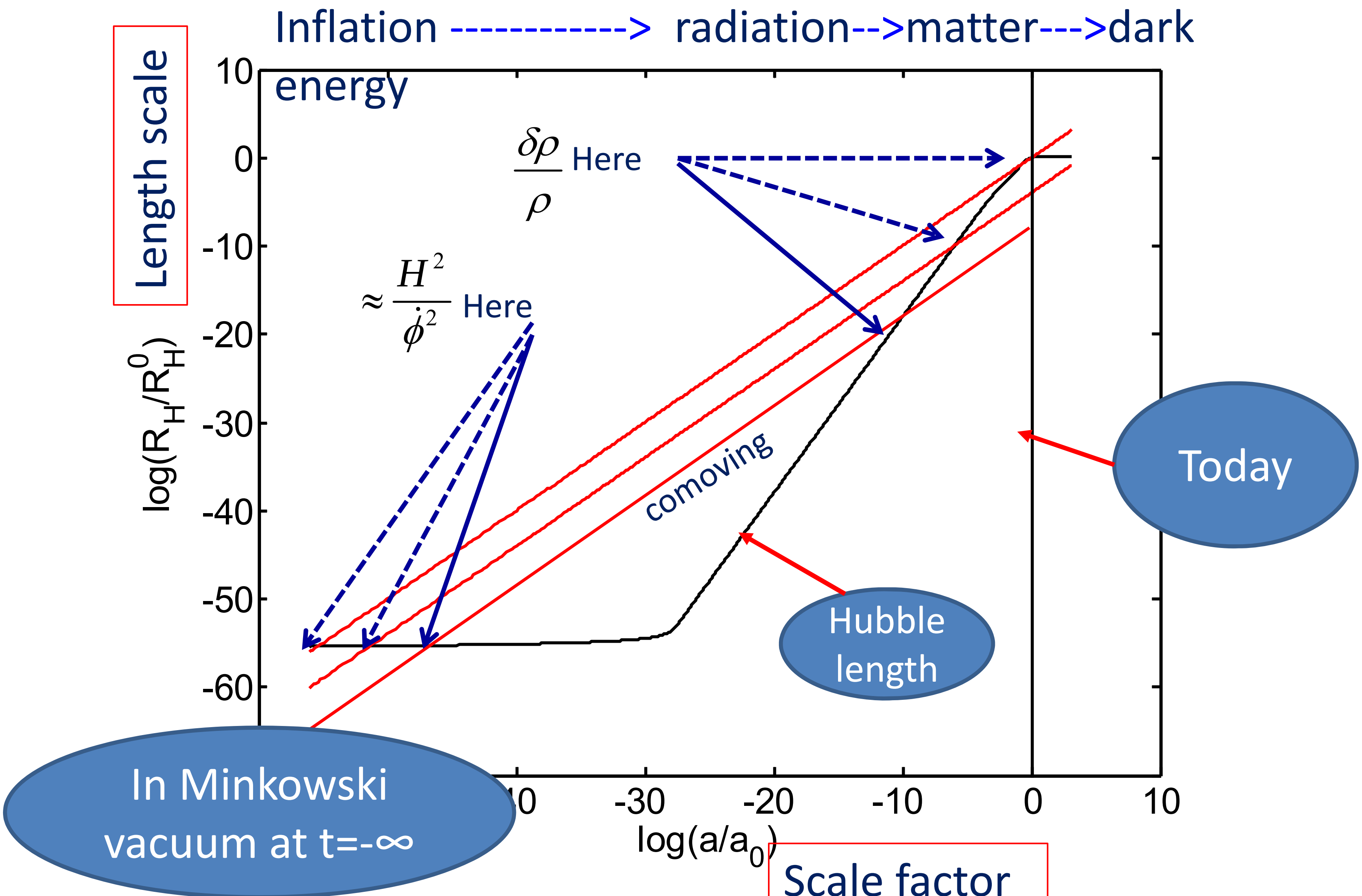
Inflation -----------> radiation-->matter--->dark energy
Length scale
$\log(R_H/R_H^0)$
10
0
-10
-20
-30
-40
-50
-60
$\frac{\delta\rho}{\rho}$ Here
$\approx \frac{H^2}{\dot{\phi}^2}$ Here
comoving
Today
Hubble length
In Minkowski vacuum at t=-∞
-30
-20
-10
0
10
$\log(a/a_0)$
Scale factor

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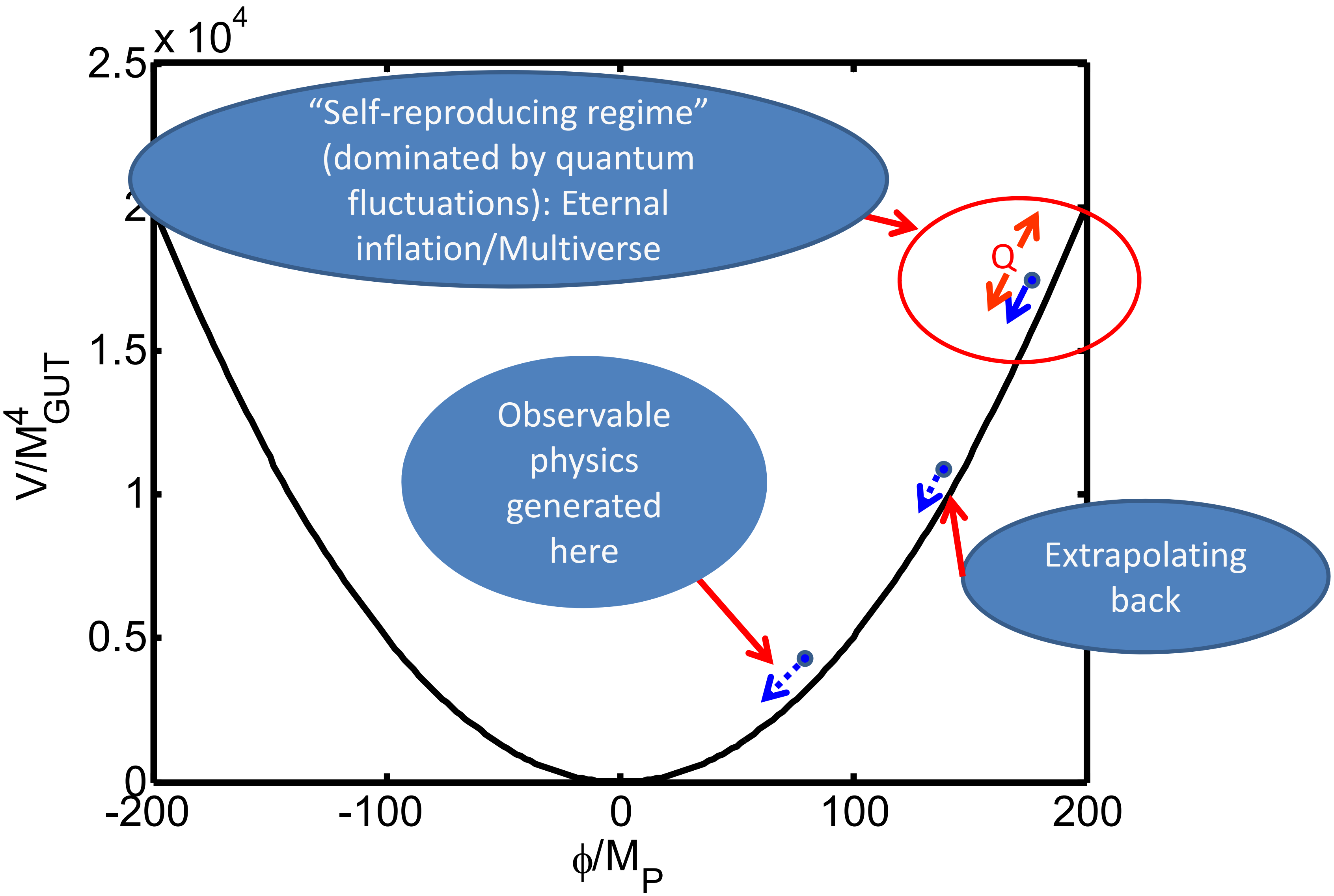
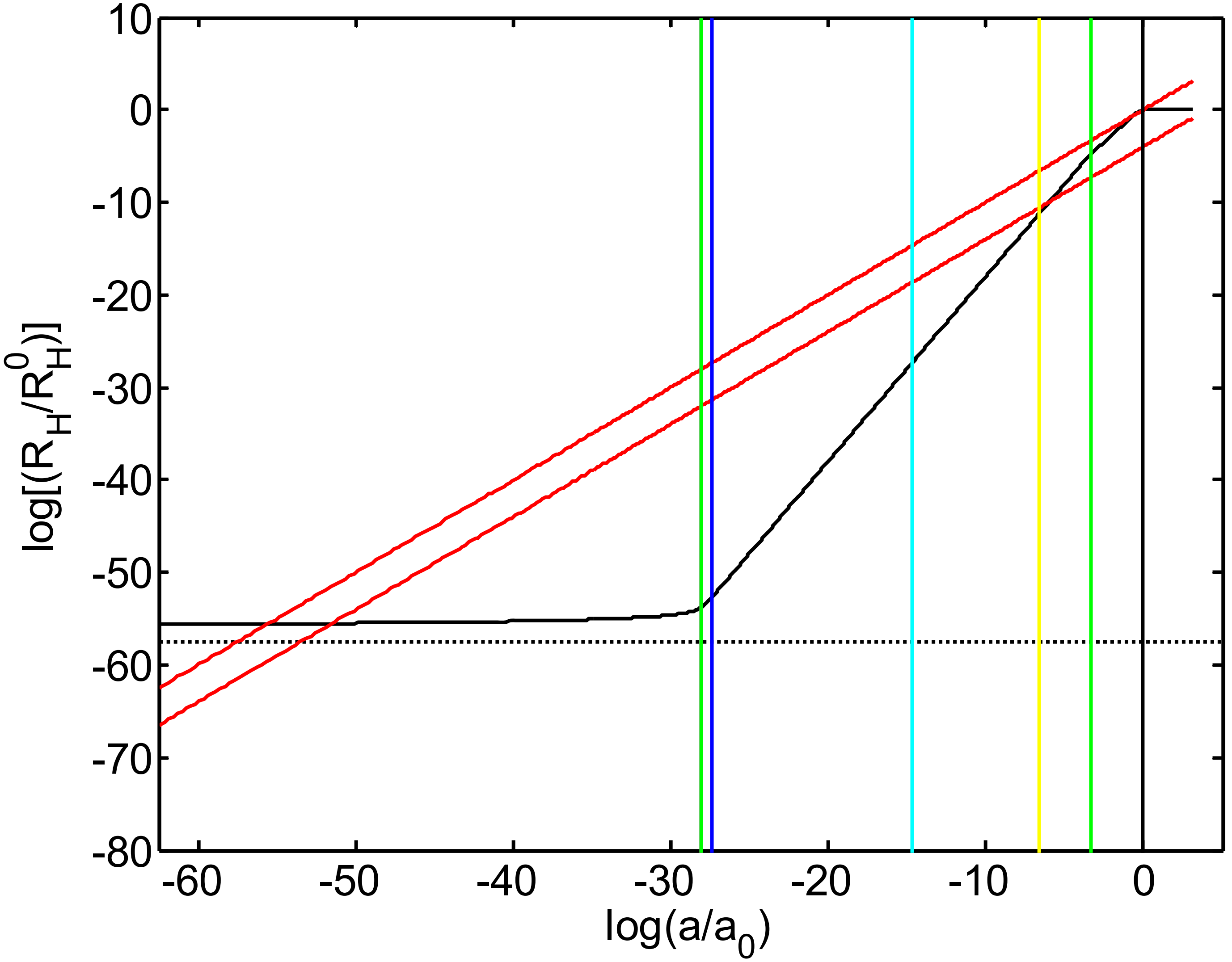
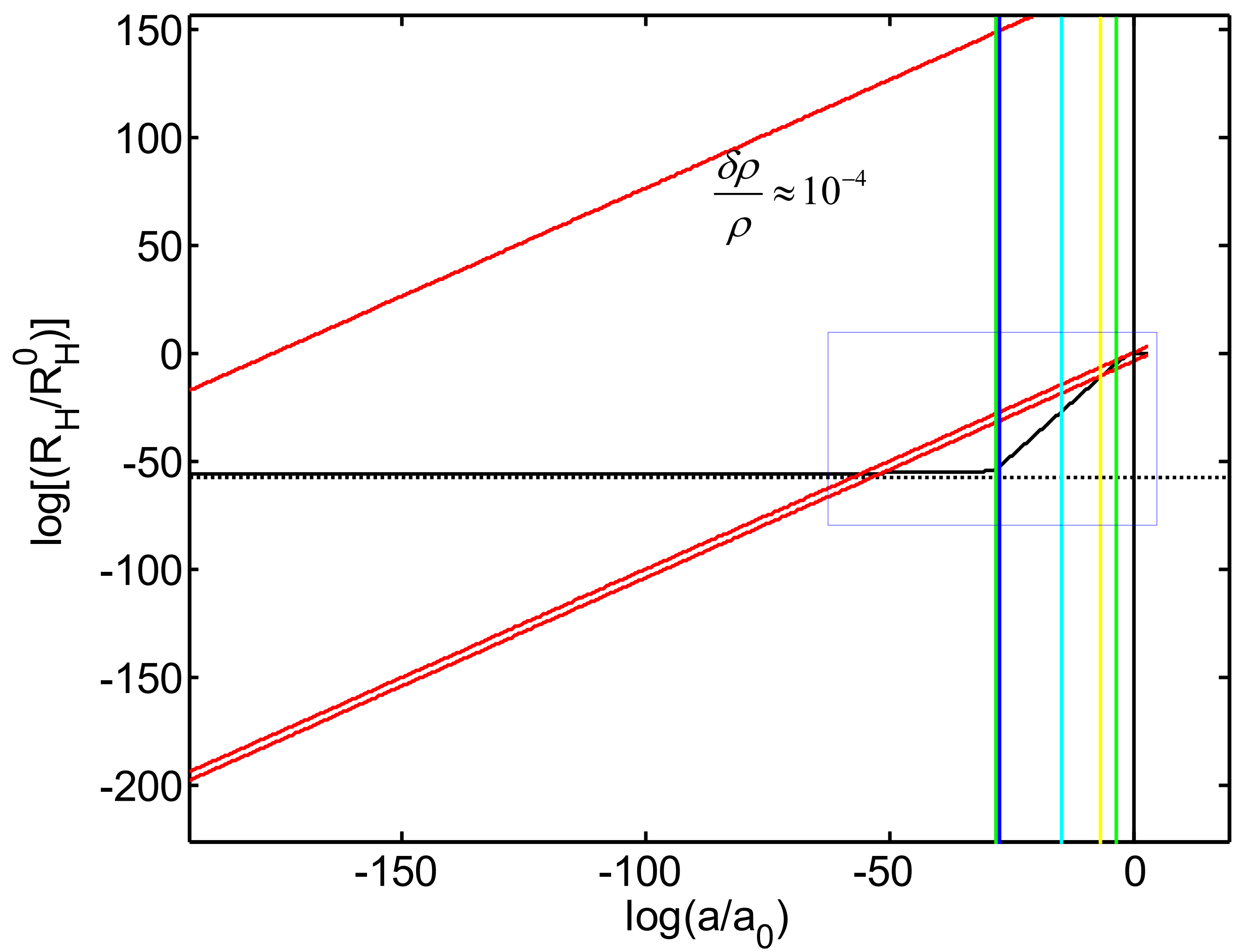


# Evolution of Cosmic Length



# Evolution of Cosmic Length (zooming out)



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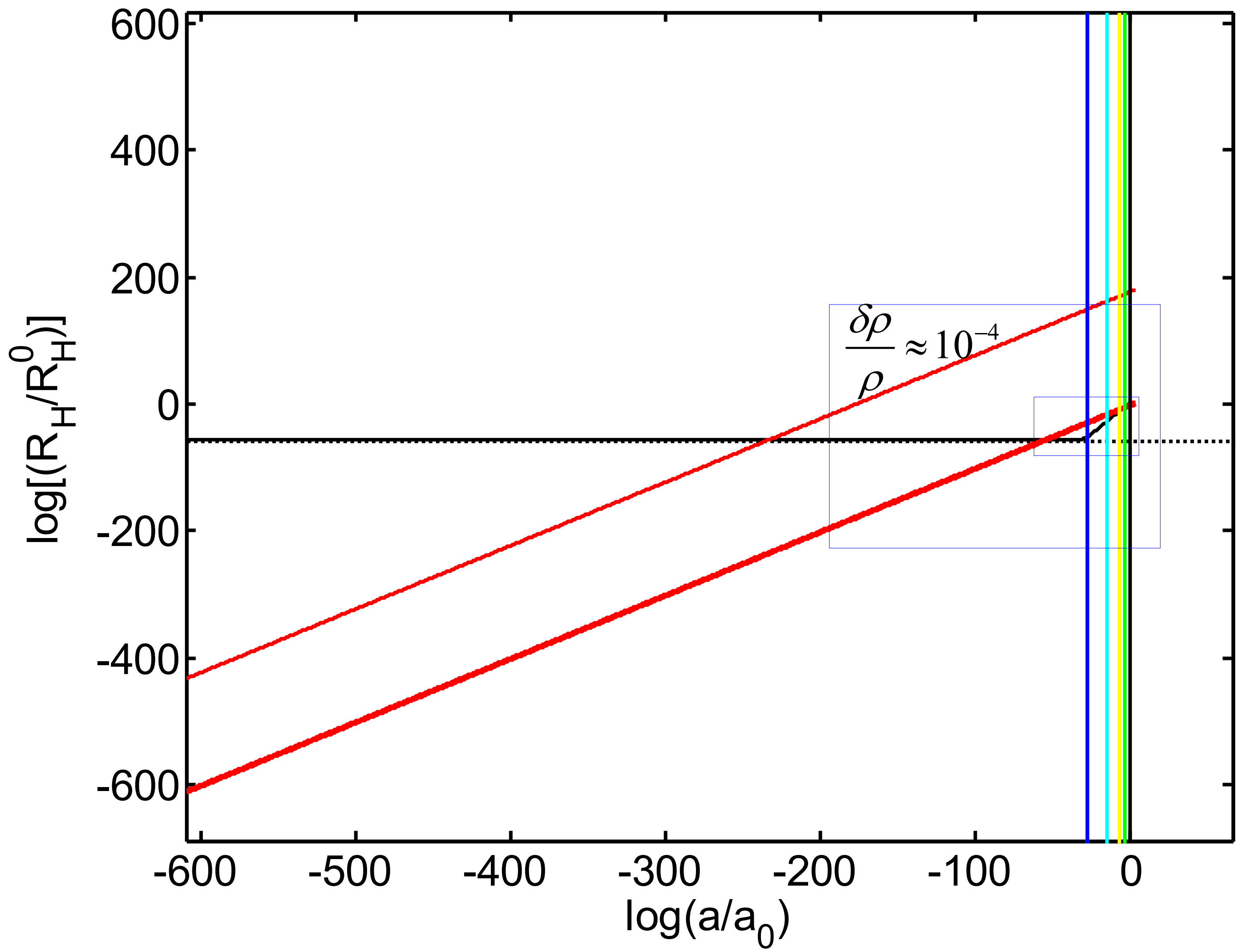

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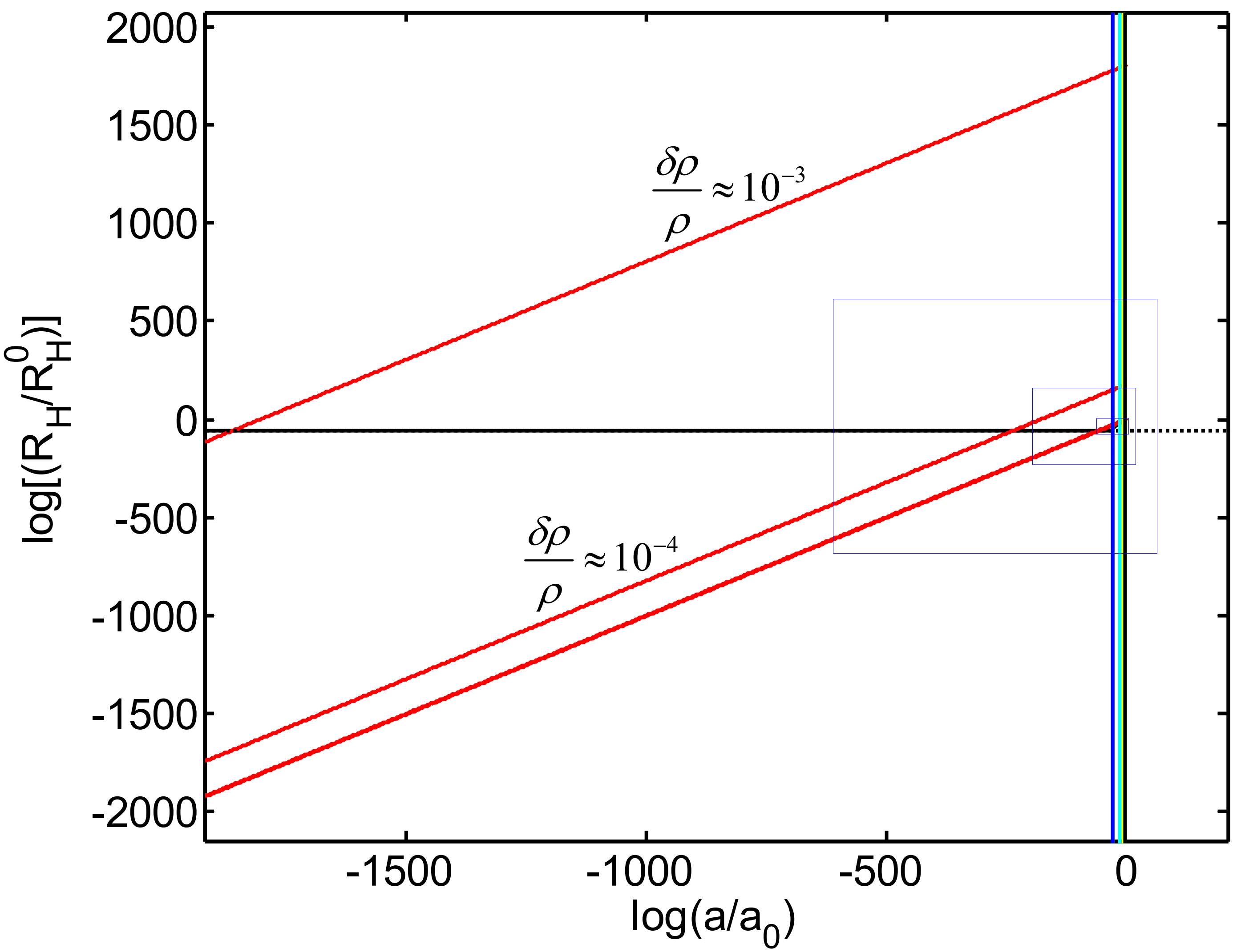

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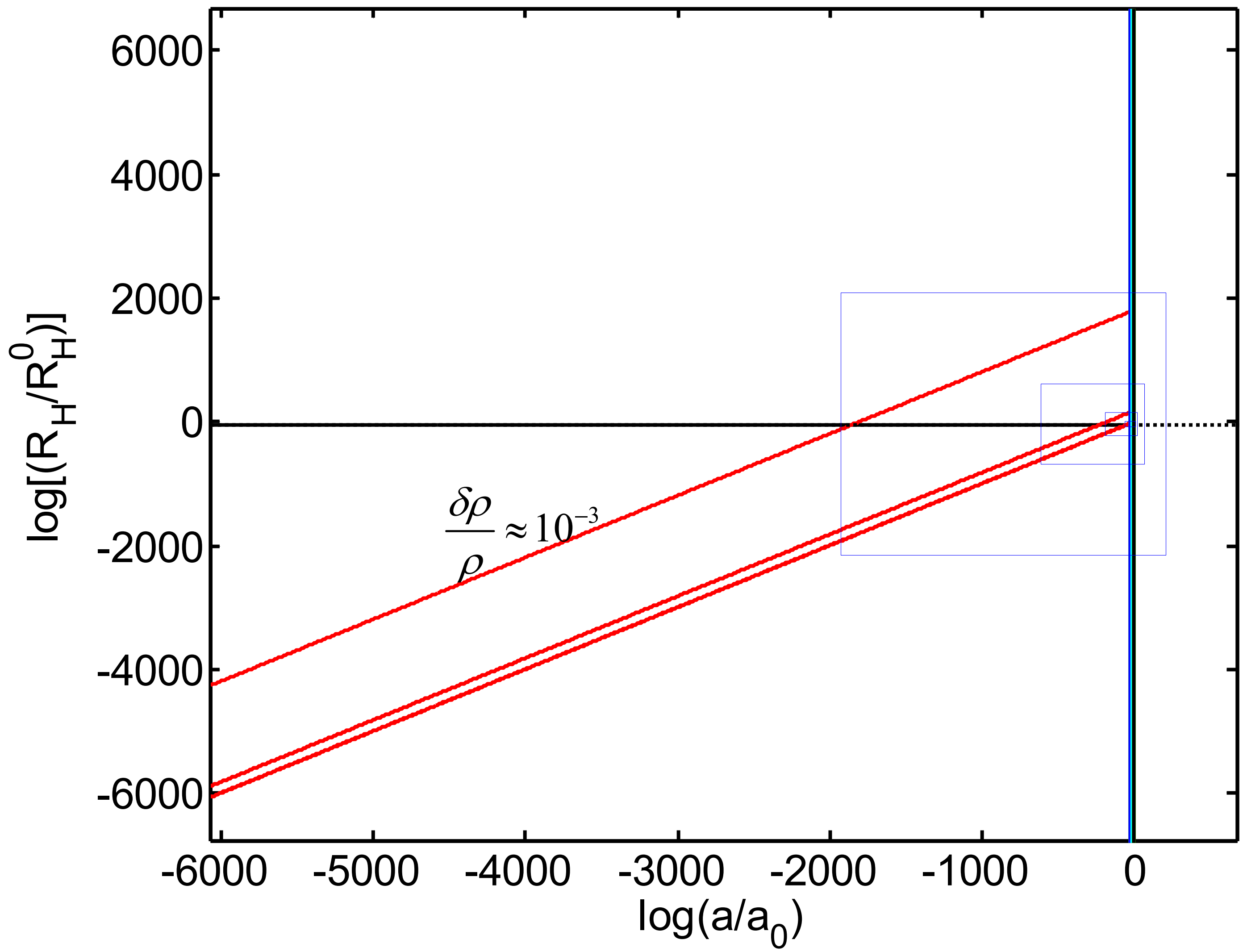

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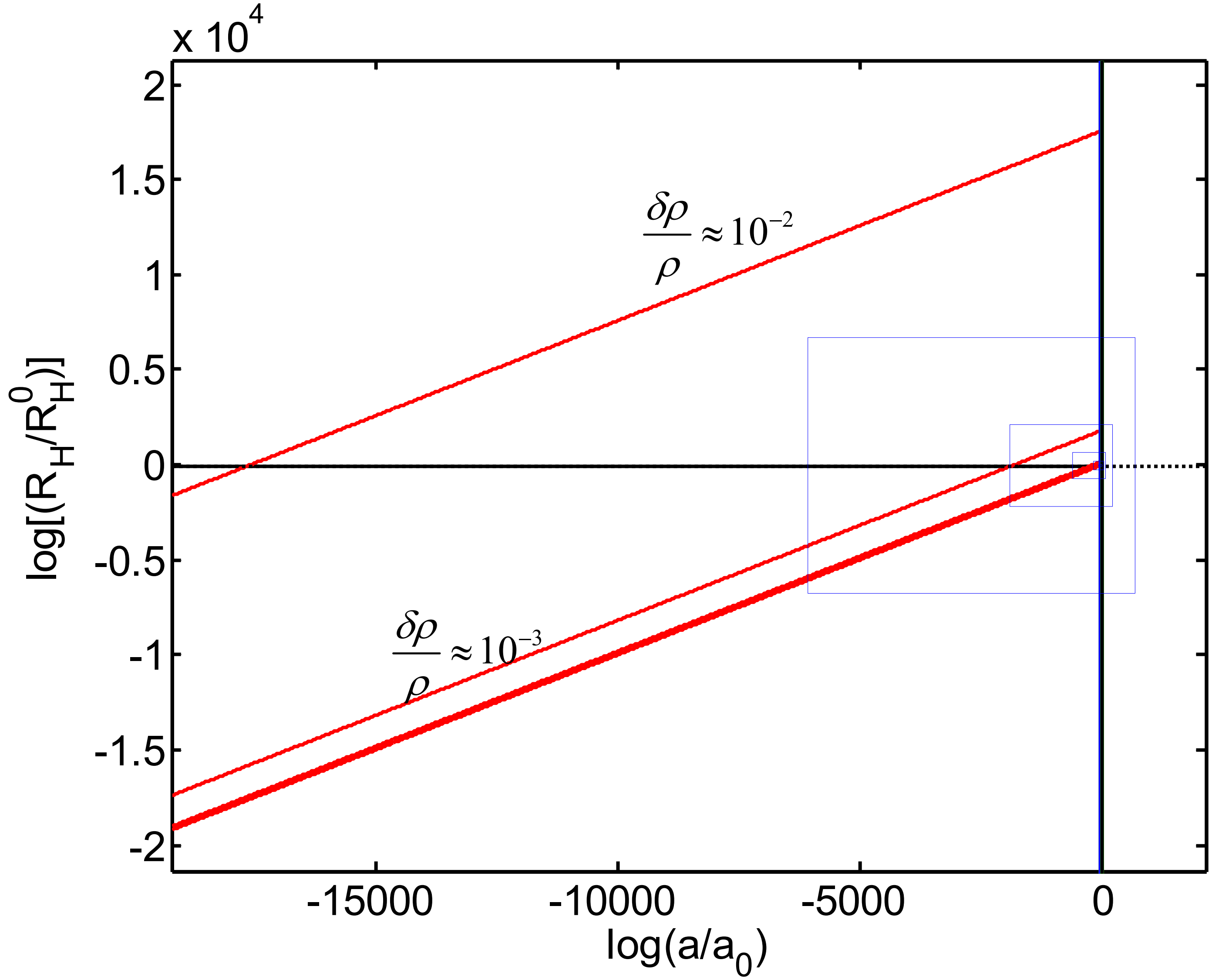

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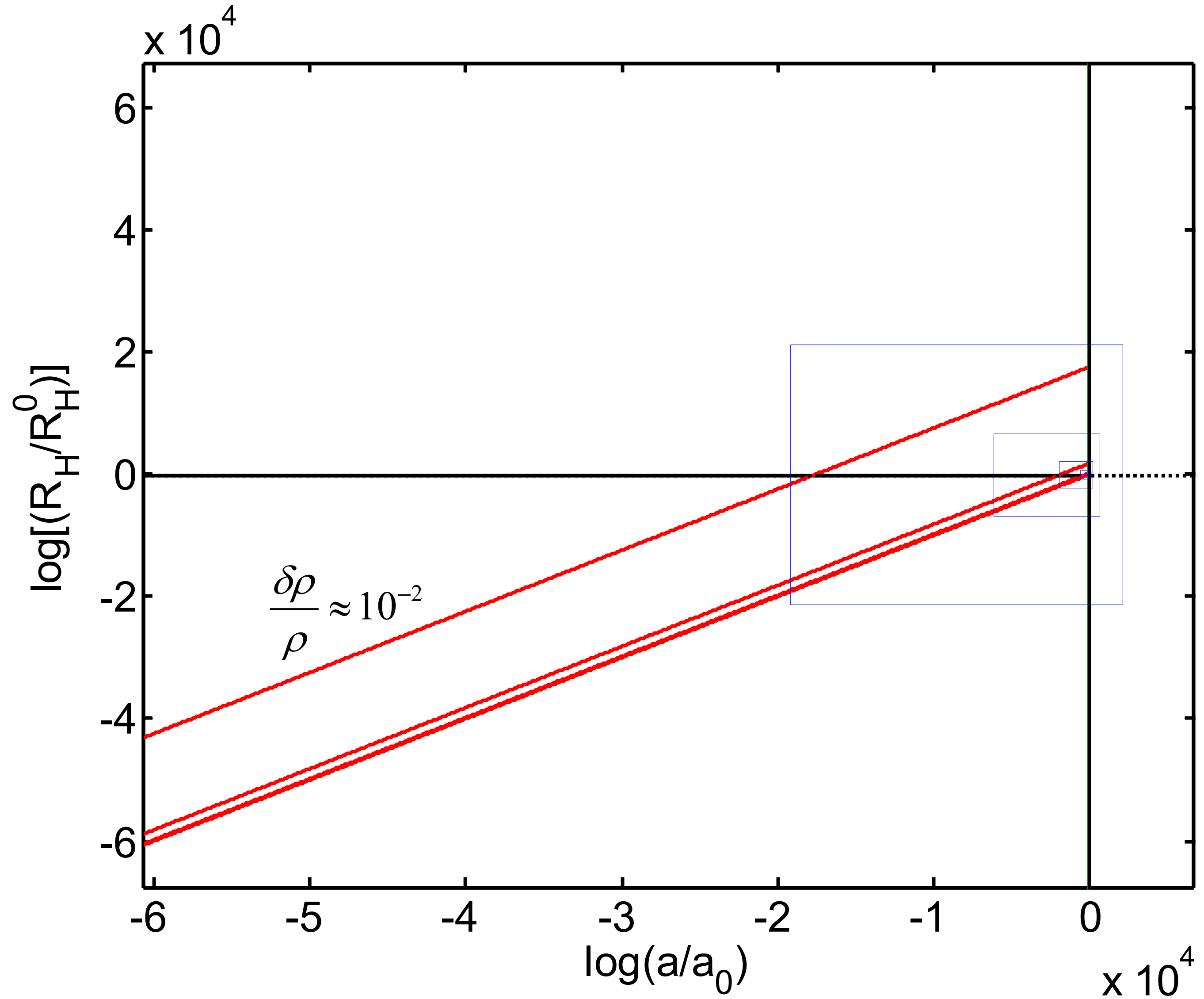

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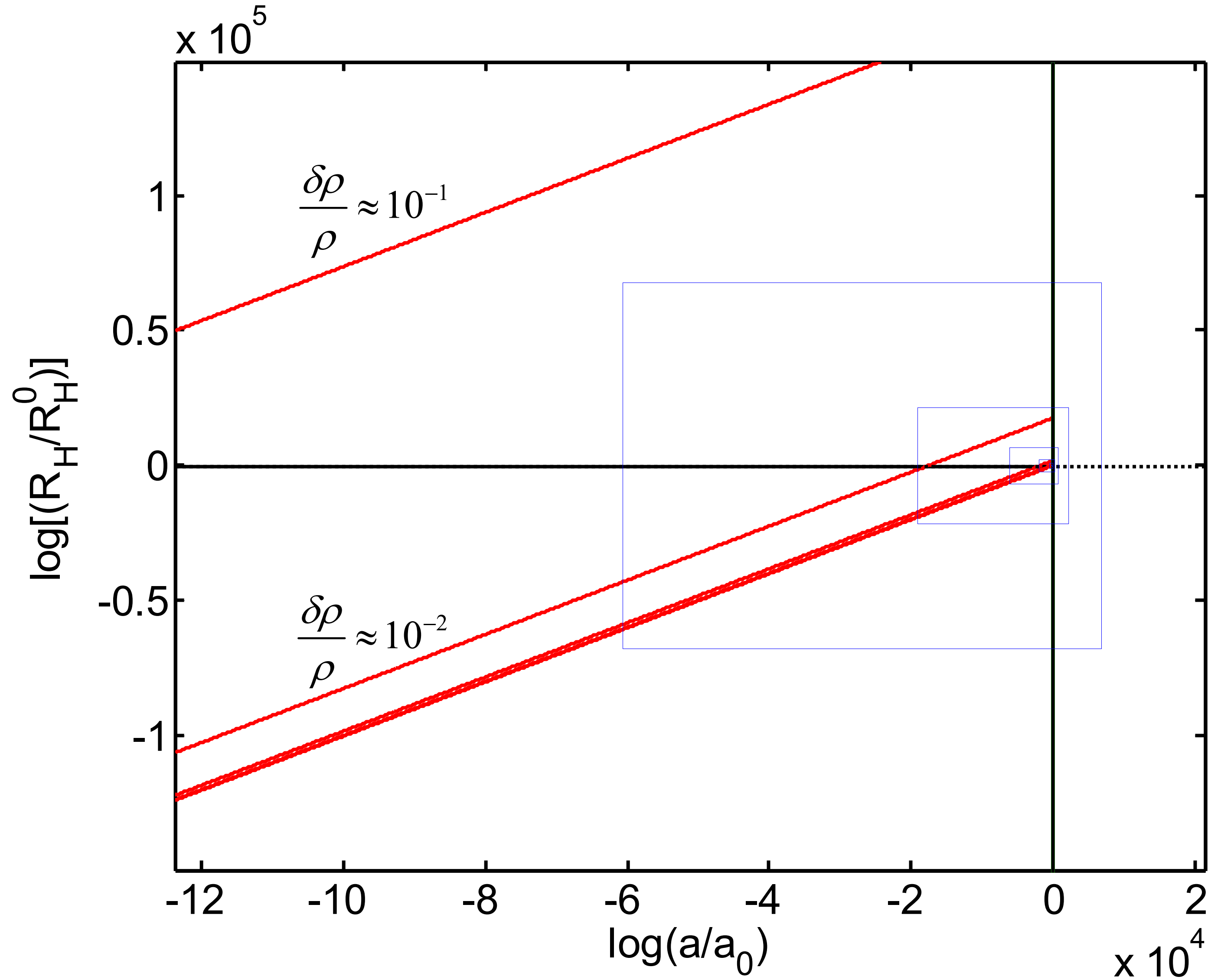

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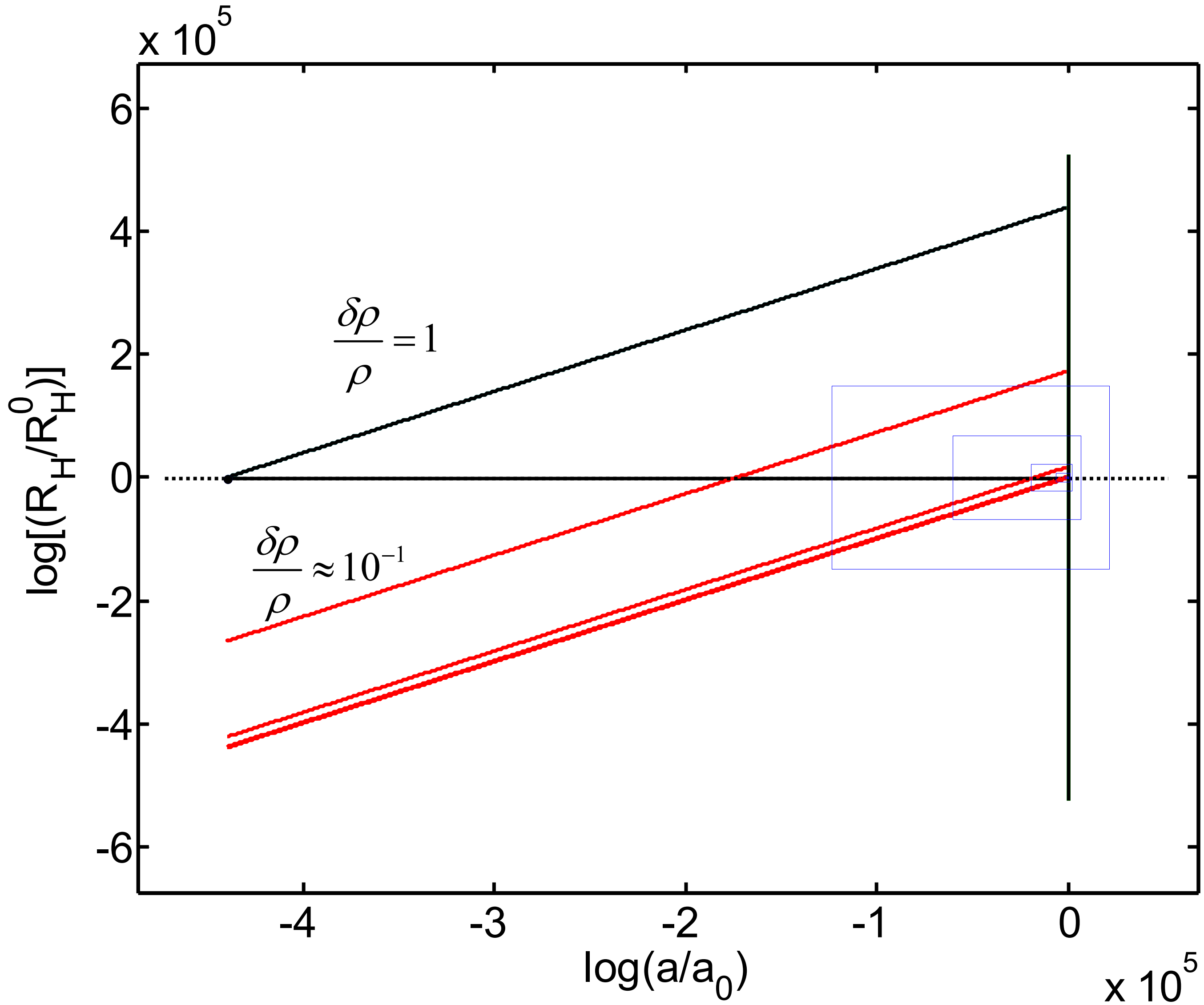

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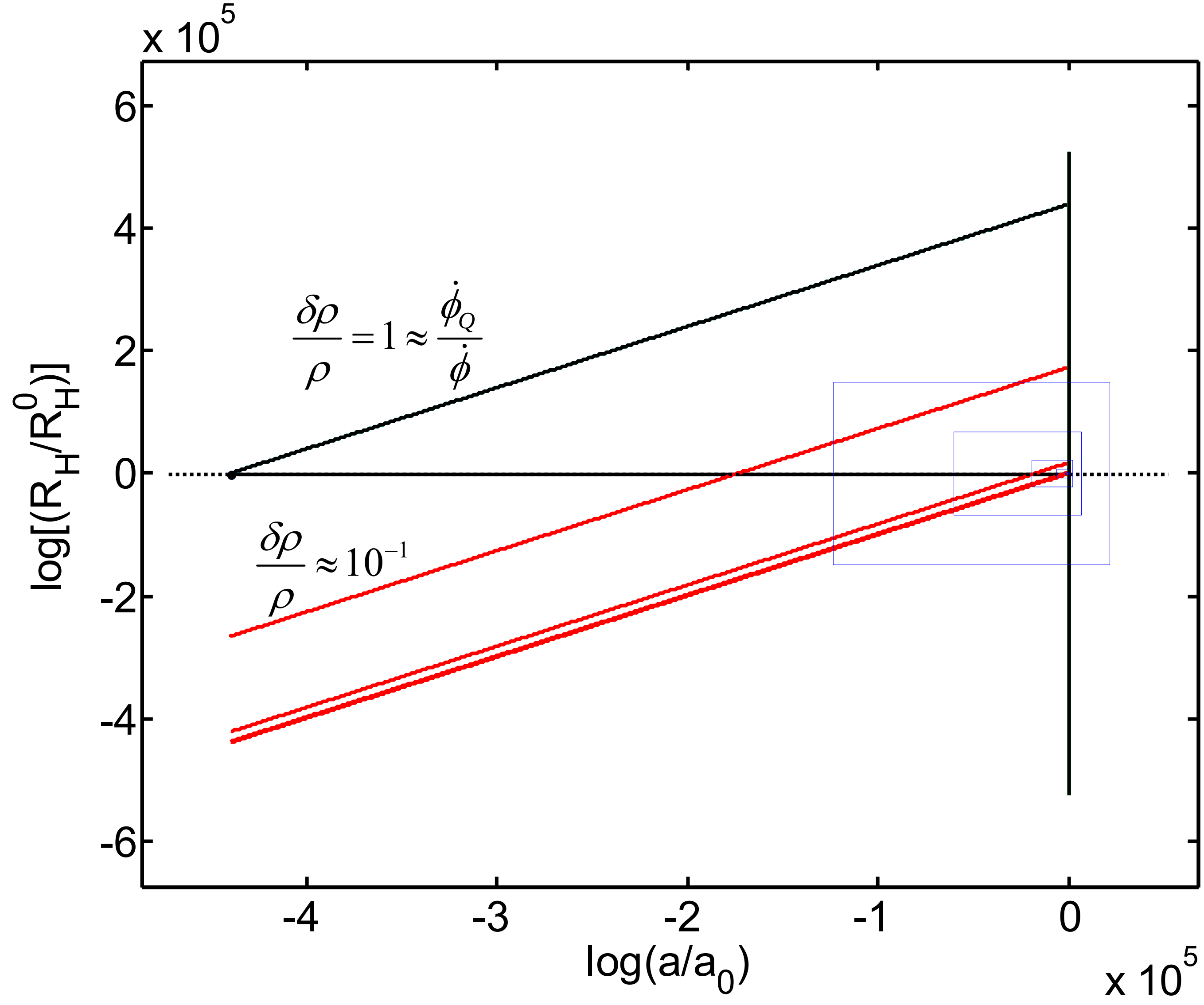

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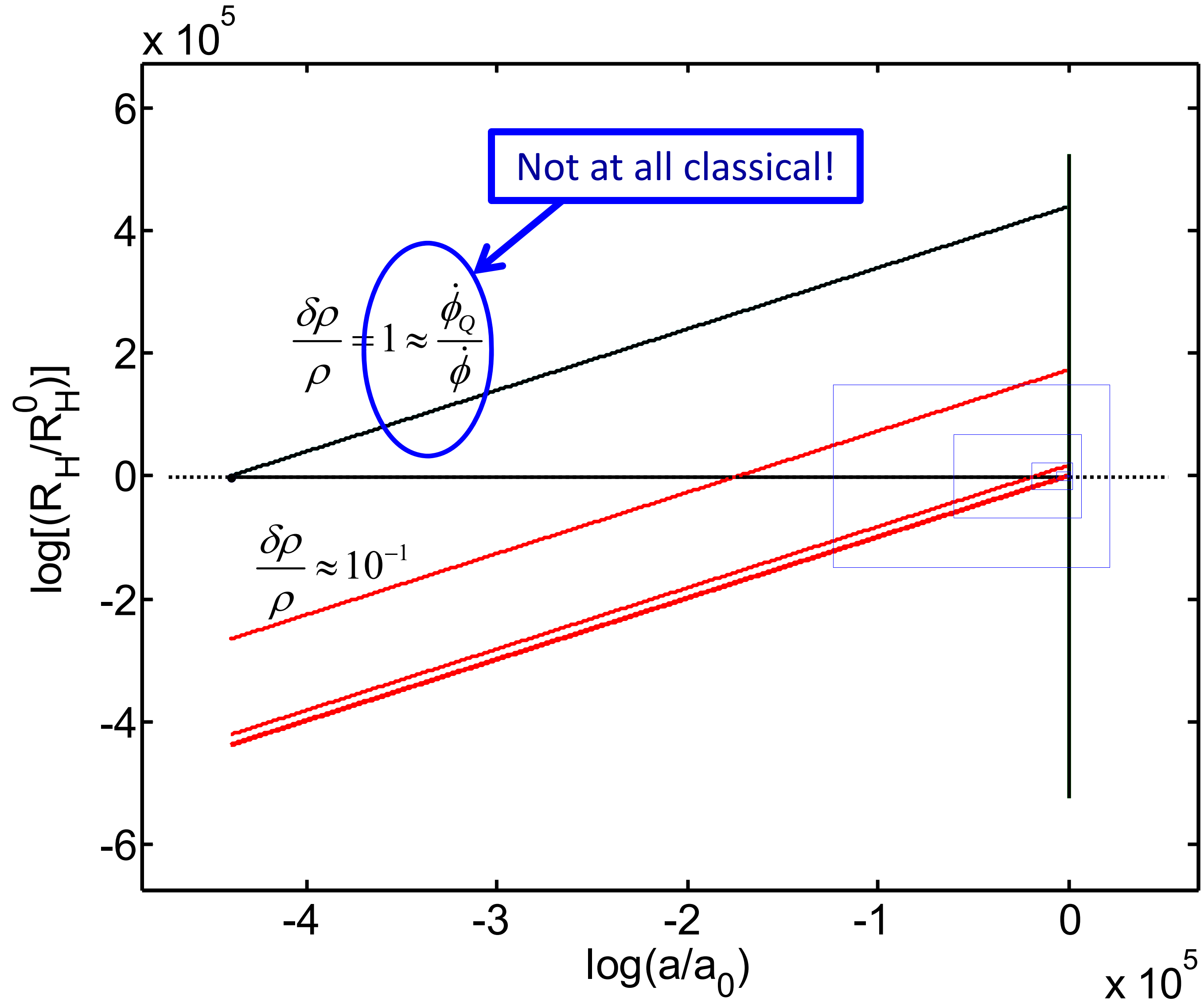
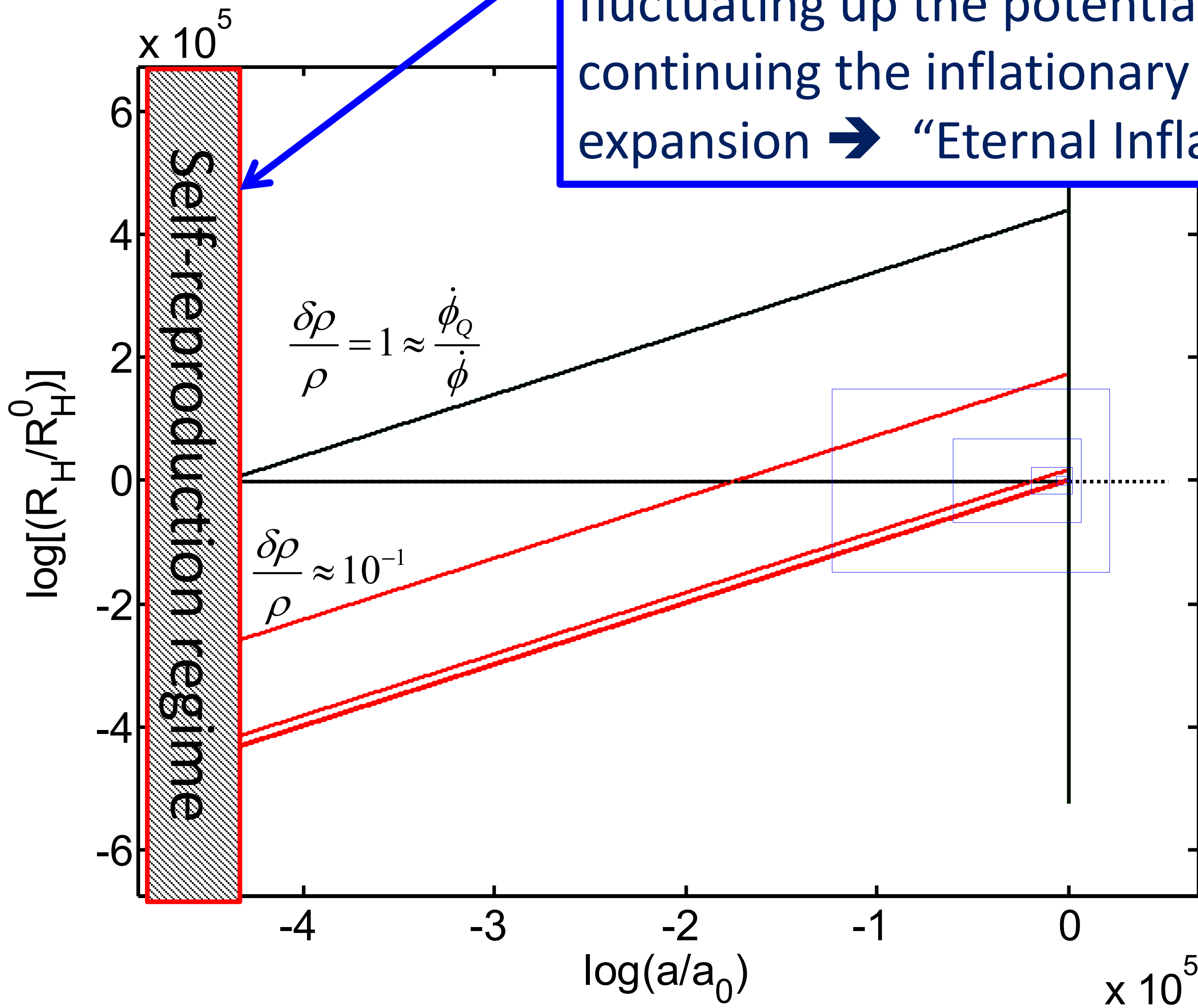
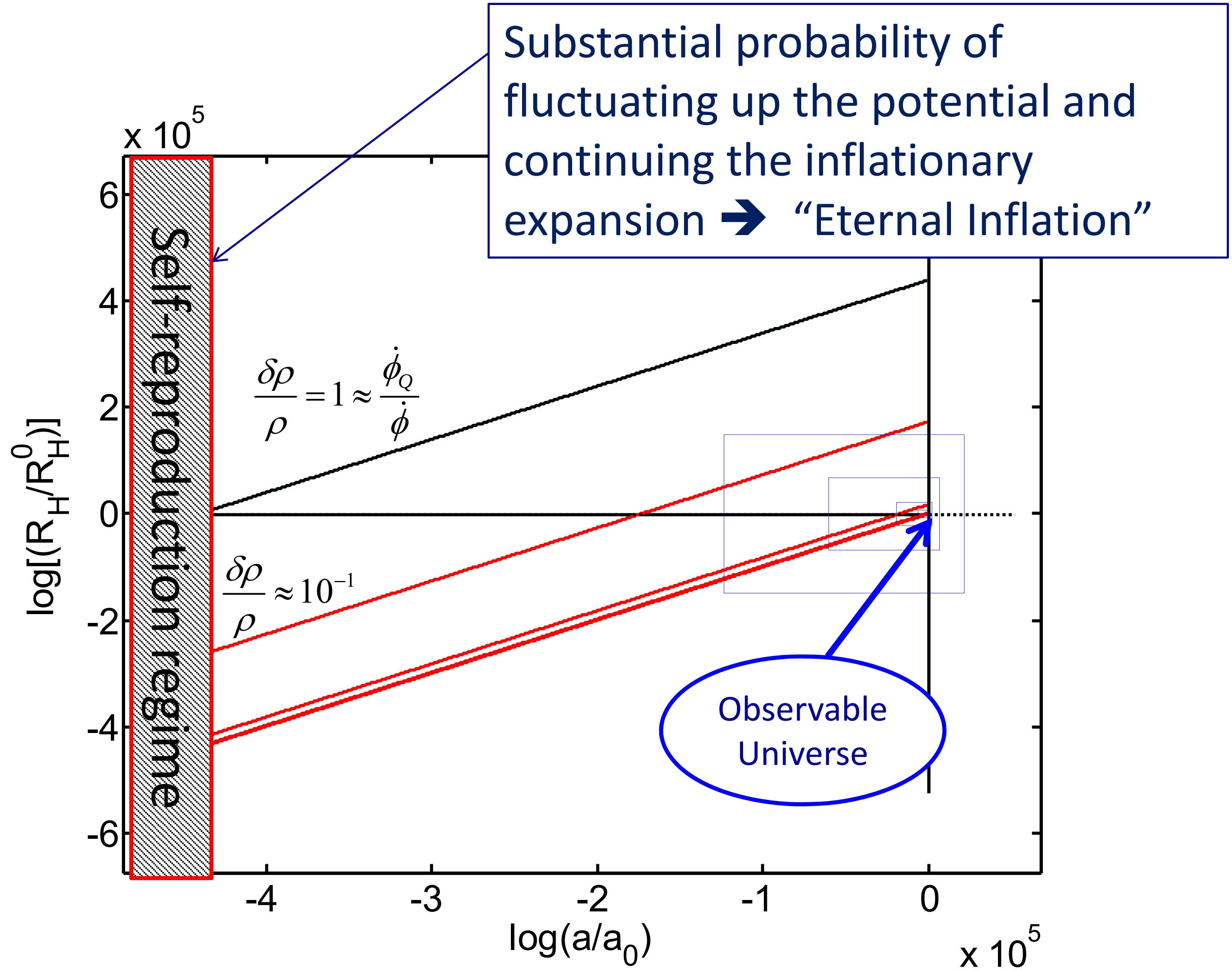


Substantial probability of fluctuating up the potential and continuing the inflationary expansion ➔ "Eternal Inflation"





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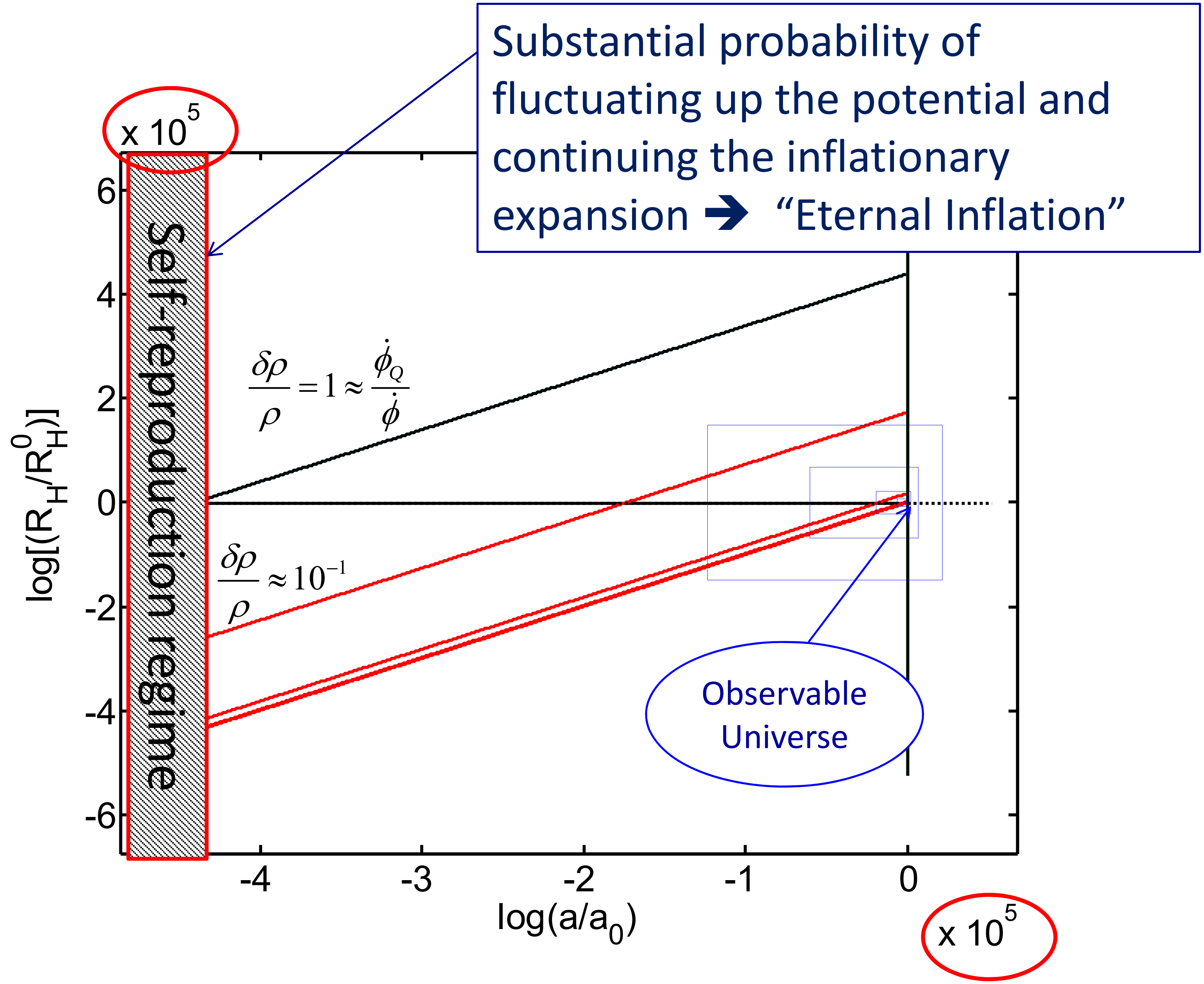
x 10^5
Self-reproduction regime
$\frac{\delta\rho}{\rho} = 1 \approx \frac{\dot{\phi}_Q}{\dot{\phi}}$
$\frac{\delta\rho}{\rho} \approx 10^{-1}$
Observable Universe
log[(R_H/R_H^0)]
log(a/a_0)
x 10^5



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x 10^5
6
4
2
0
-2
-4
-6
log[(R_H/R_H^0)]
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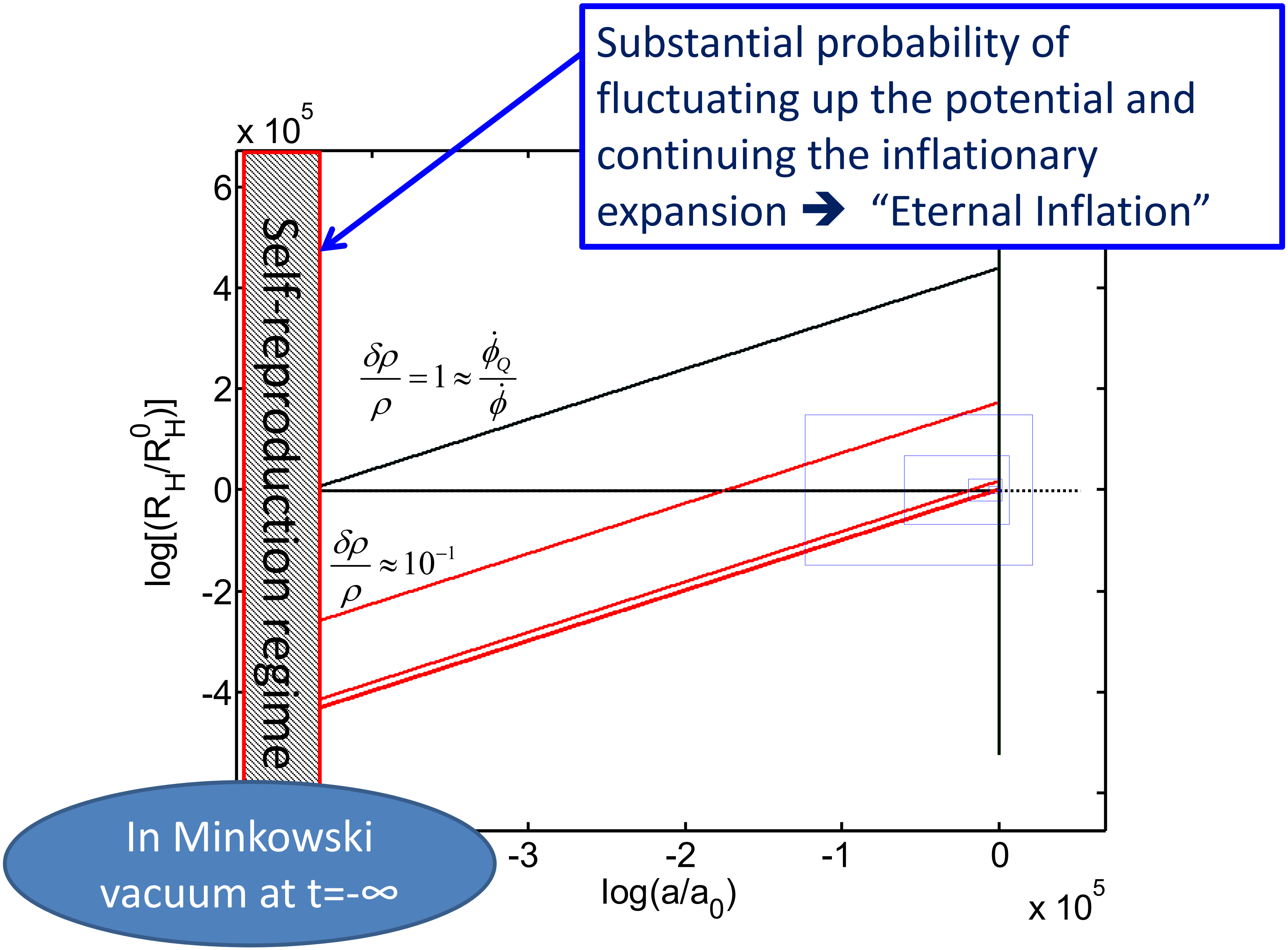
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In Minkowski vacuum at t=-∞

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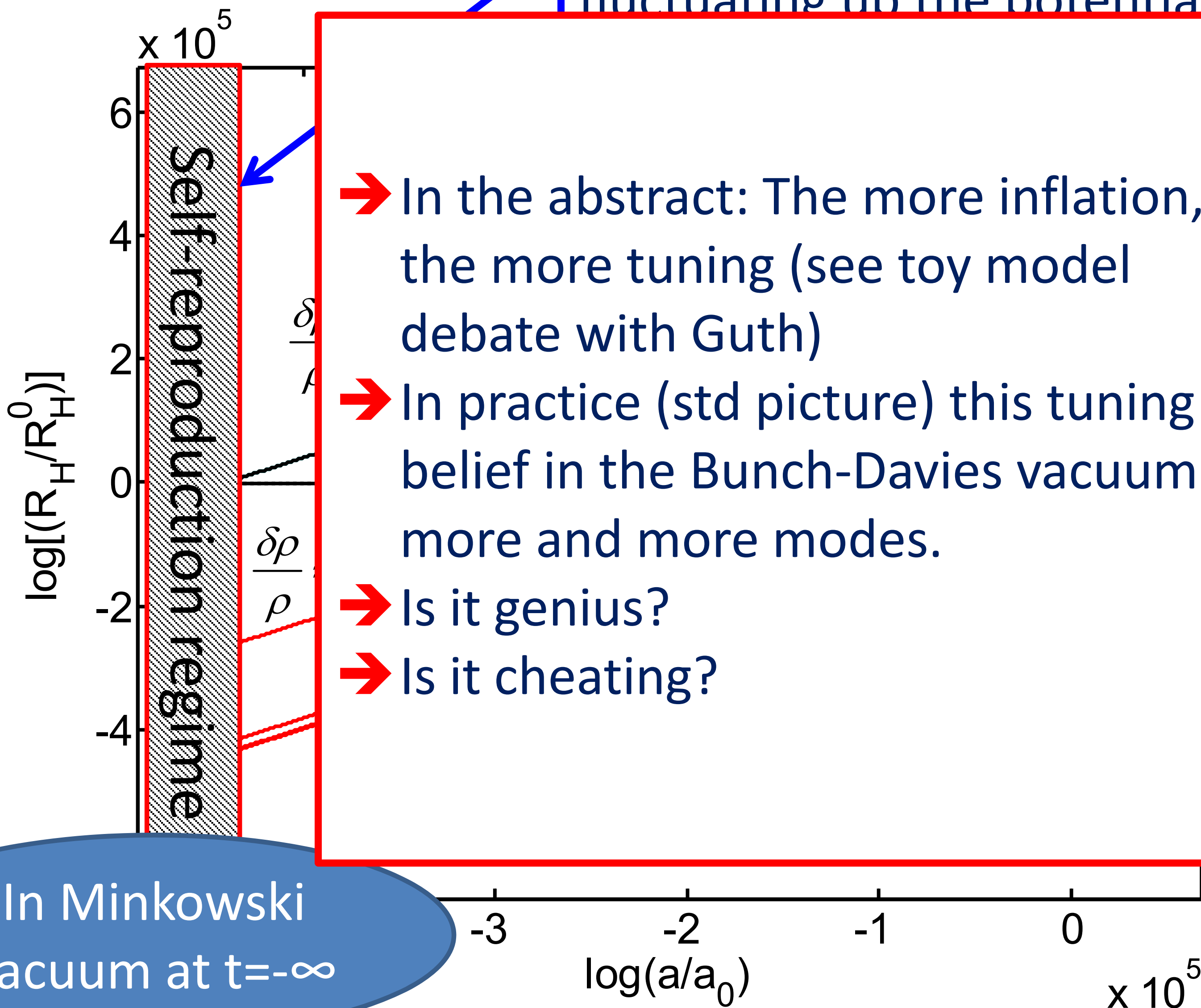


- In the abstract: The more inflation, the more tuning (see toy model debate with Guth)
- In practice (std picture) this tuning = belief in the Bunch-Davies vacuum for more and more modes.
- Is it genius?
- Is it cheating?

In Minkowski vacuum at t=-∞

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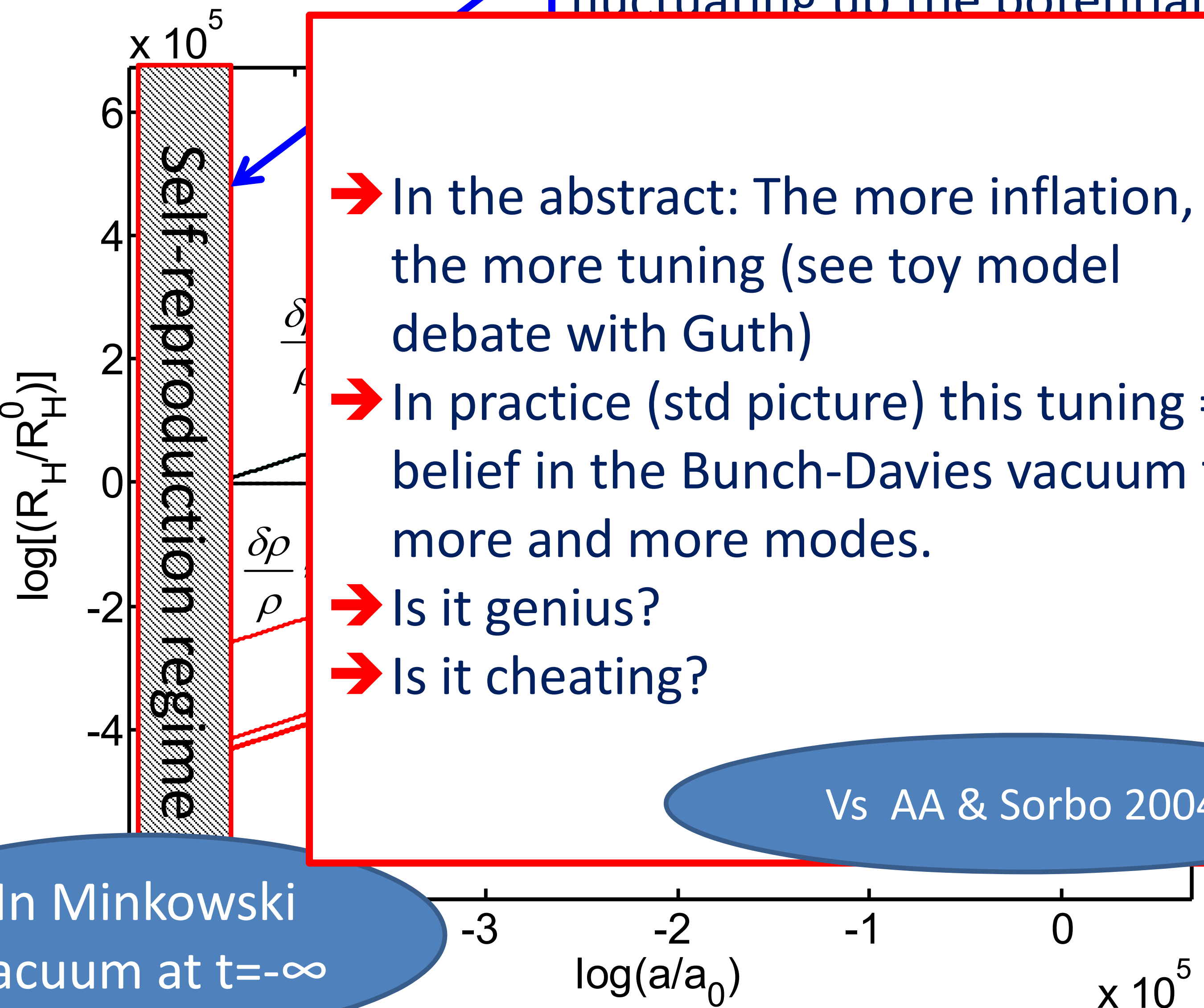


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> In our view, cosmologists should heed mathematician David Hilbert's warning: although infinity is needed to complete mathematics, it occurs nowhere in the physical Universe.
>
> *J Silk & J. Ellis Nature (2014)*

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*AA: arXiv:1401.7309*
*AA: arXiv:1104.3315*
*AA: arXiv:0906.1047*
*AA & Sorbo: hep-th/0405270*

# Implications of the de Sitter horizon

- Maximum entropy

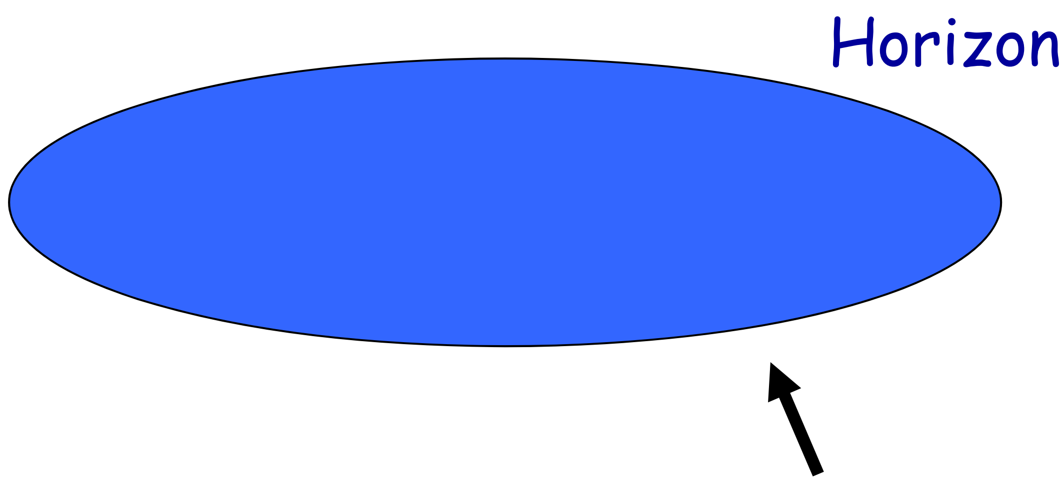
$$S_\Lambda \propto A = H_\Lambda^{-2} = \left(\frac{\Lambda}{3}\right)^{-1}$$

- 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?

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- Only a finite volume ever observed

- If $\Lambda$ is truly constant: Cosmology as fluctuating Eqm.

- Maximum entropy $\longrightarrow$ finite Hilbert space of dimension $N = e^{S_\Lambda}$

*Banks & Fischler & Dyson et al.*

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dSE cosmology

✓ • Only a finite volume ever observed

✓ • If $\Lambda$ is truly constant: Cosmology as fluctuating Eqm.?

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

*Banks & Fischler & Dyson et a*

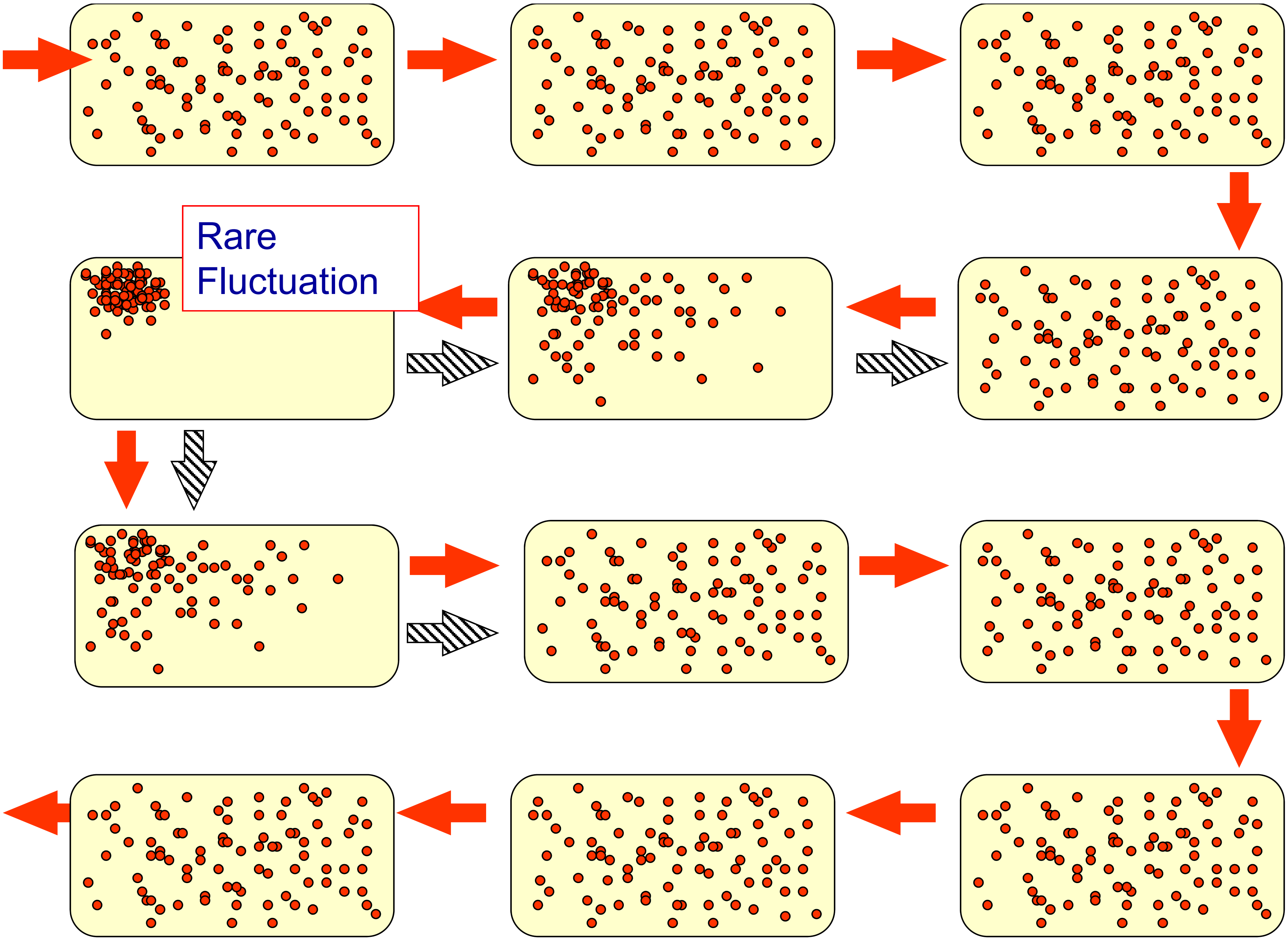
# Equilibrium Cosmology

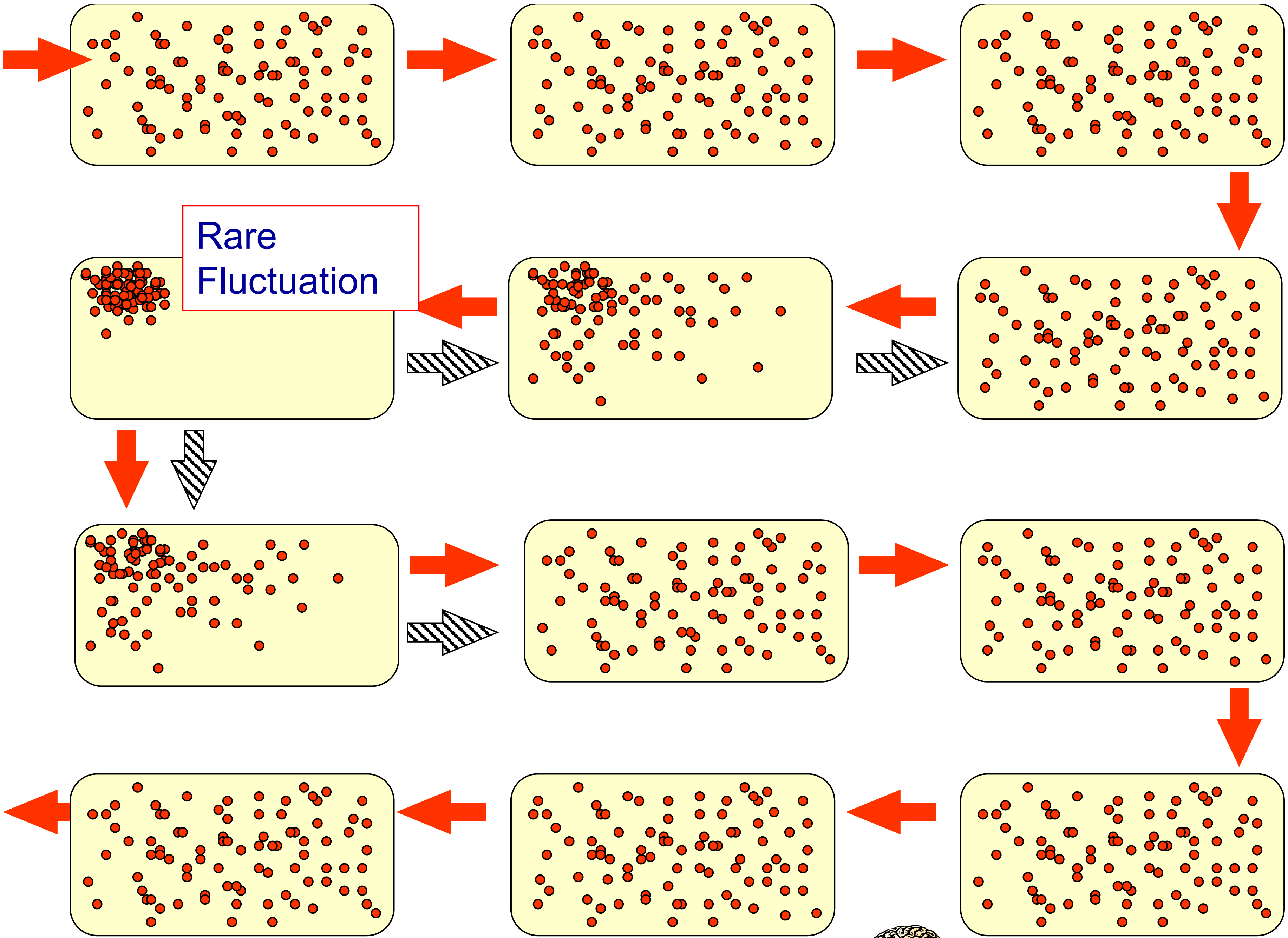
# Equilibrium Cosmology

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


Rare
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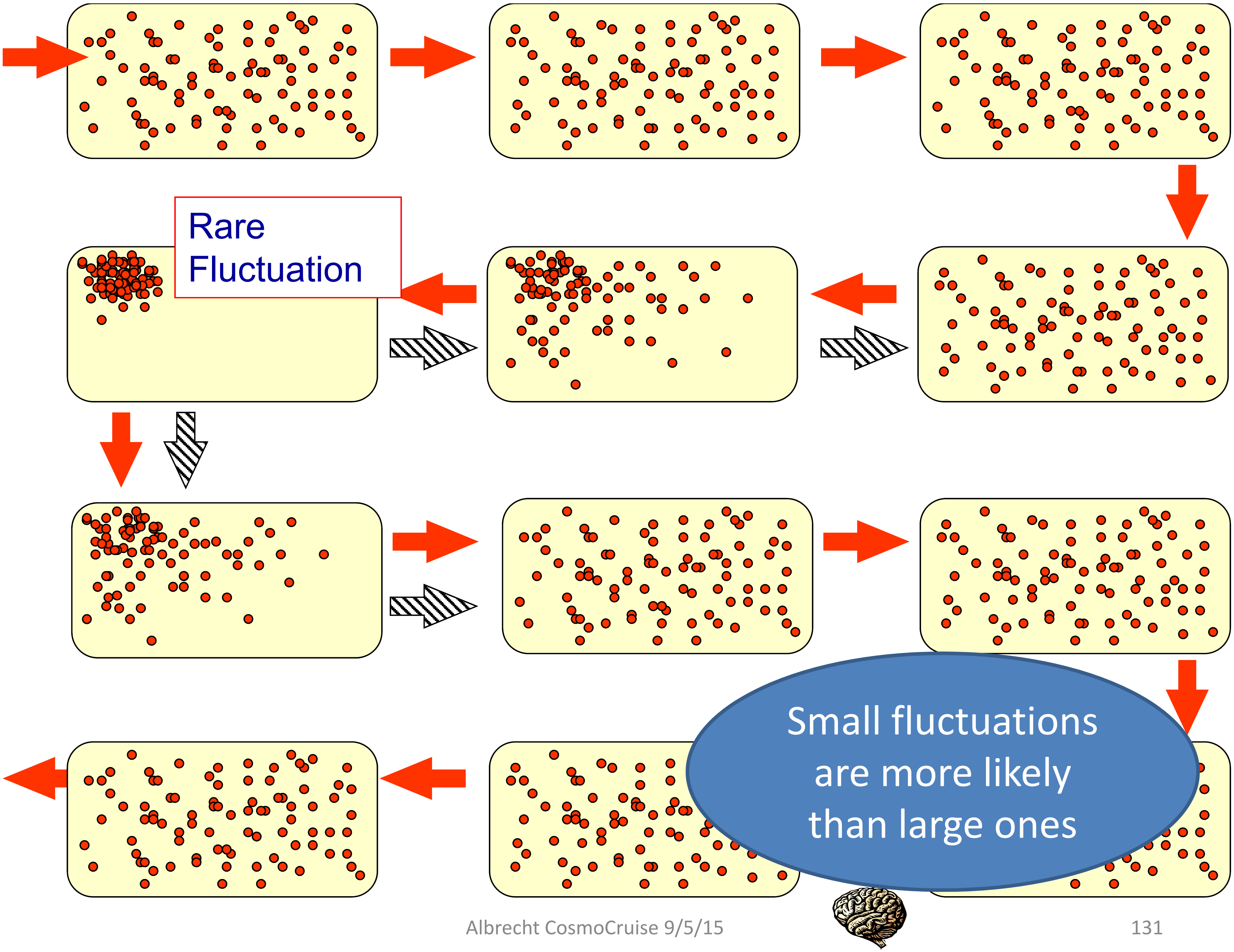
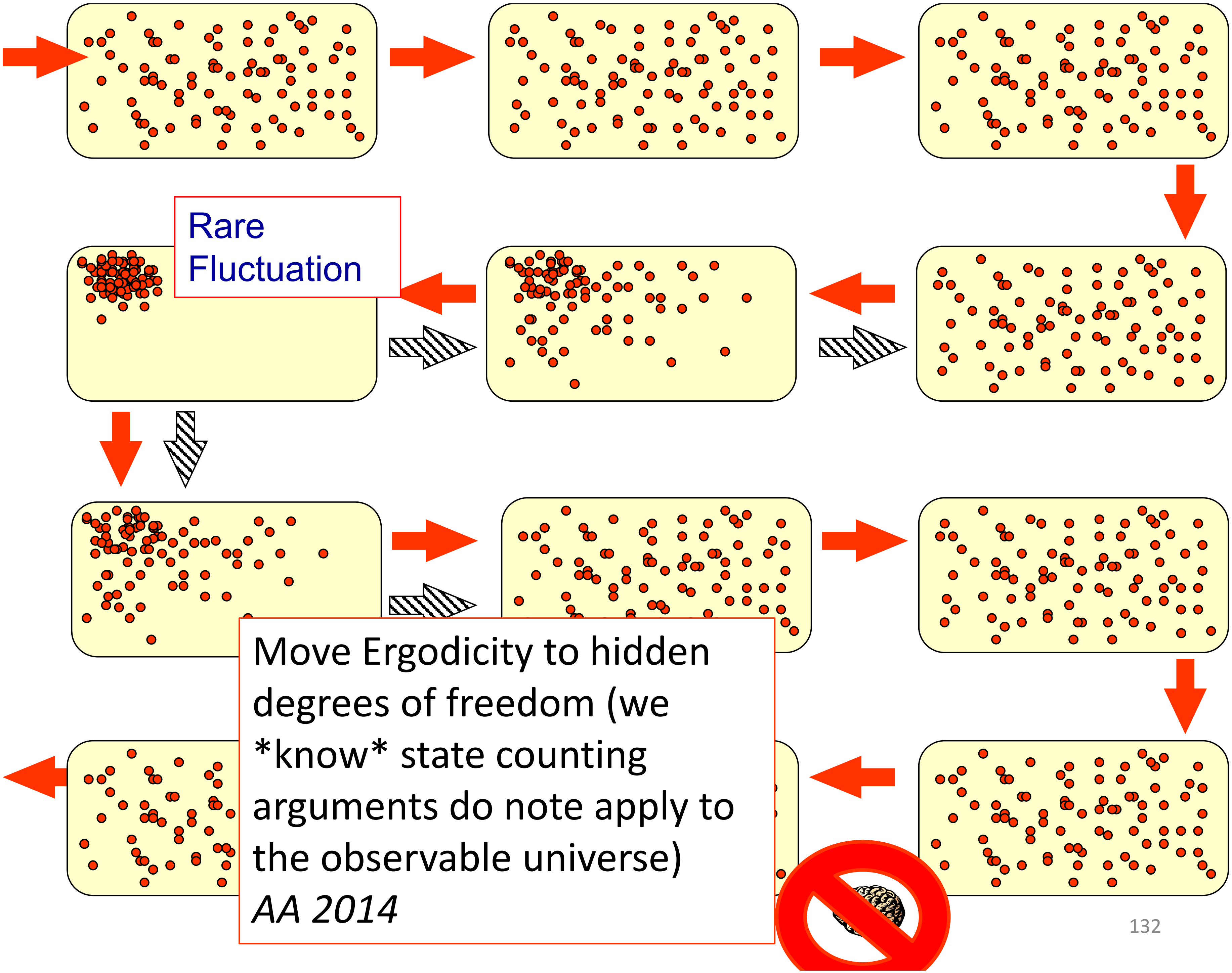
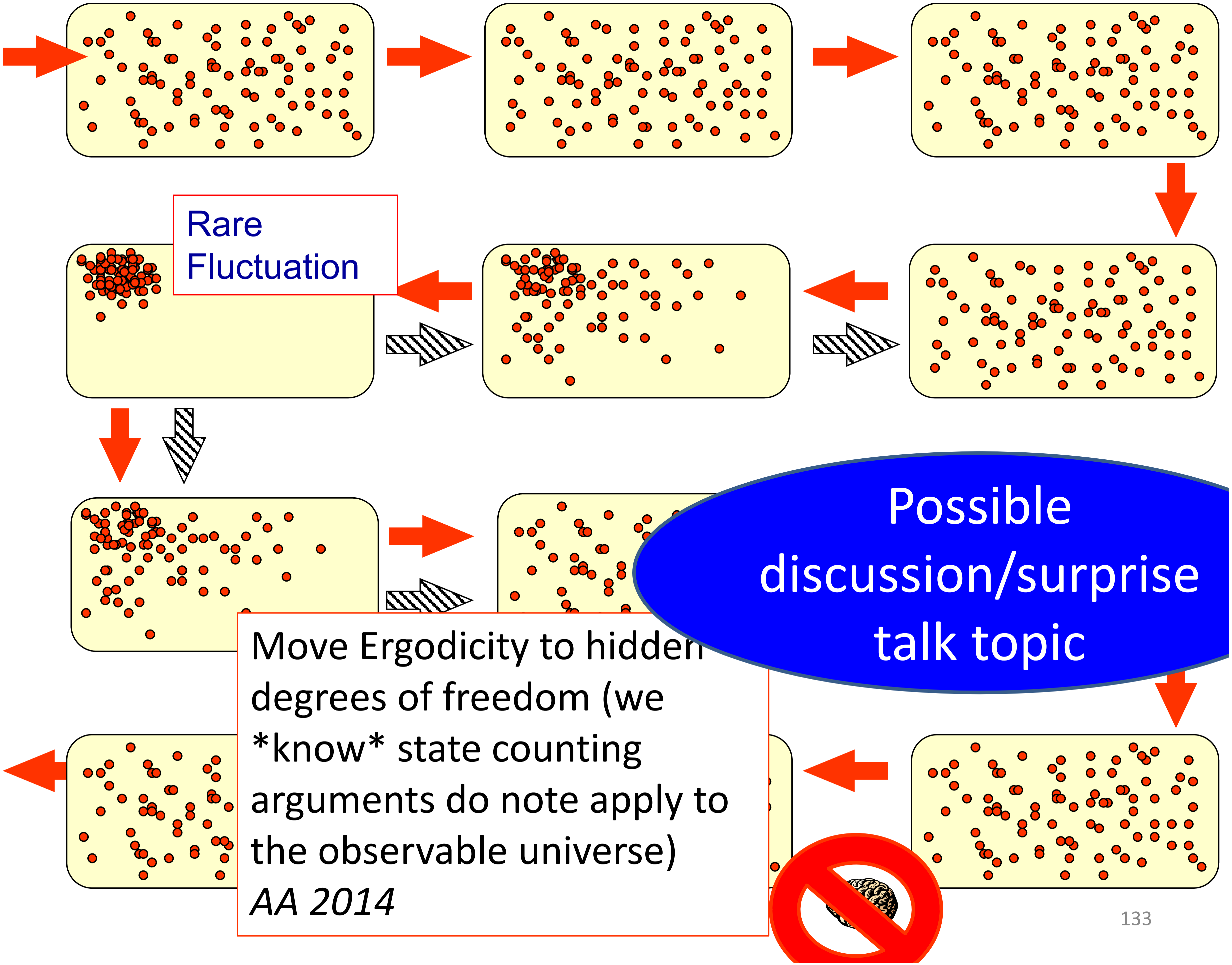

Rare
Fluctuation
Small fluctuations
are more likely
than large ones




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

*AA 2014*


Rare
Fluctuation
Possible
discussion/surprise
talk topic
Move Ergodicity to hidden
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*know* state counting
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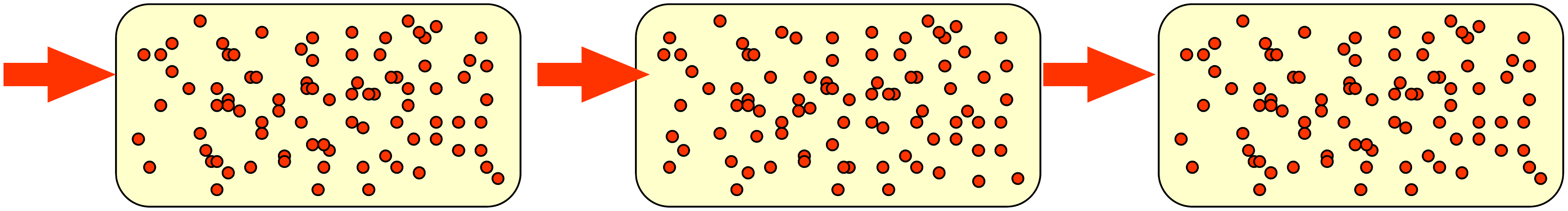
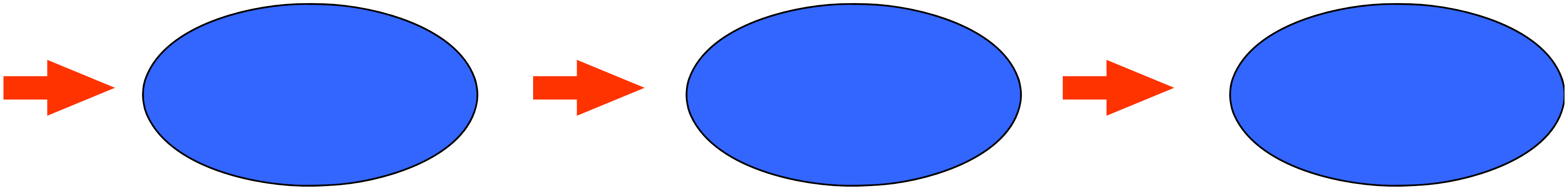
*AA 2014*

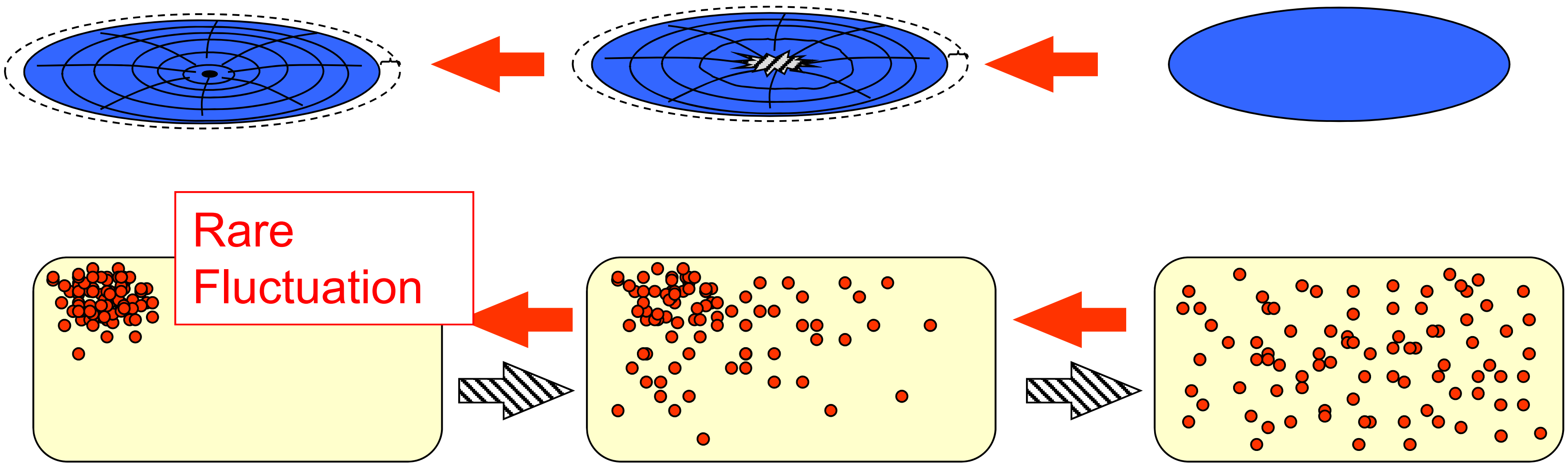
Concept:



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

## Fluctuating from dSE to inflation:

- The process of an inflaton fluctuating from late time de Sittter to an infl... ...te is dominated by the “Farhi G...
- A “... ...king ... ...arhi
- ...

Inflation plays the role we always thought it could play:
Makes a whole universe out of one easy to achieve fluctuation.

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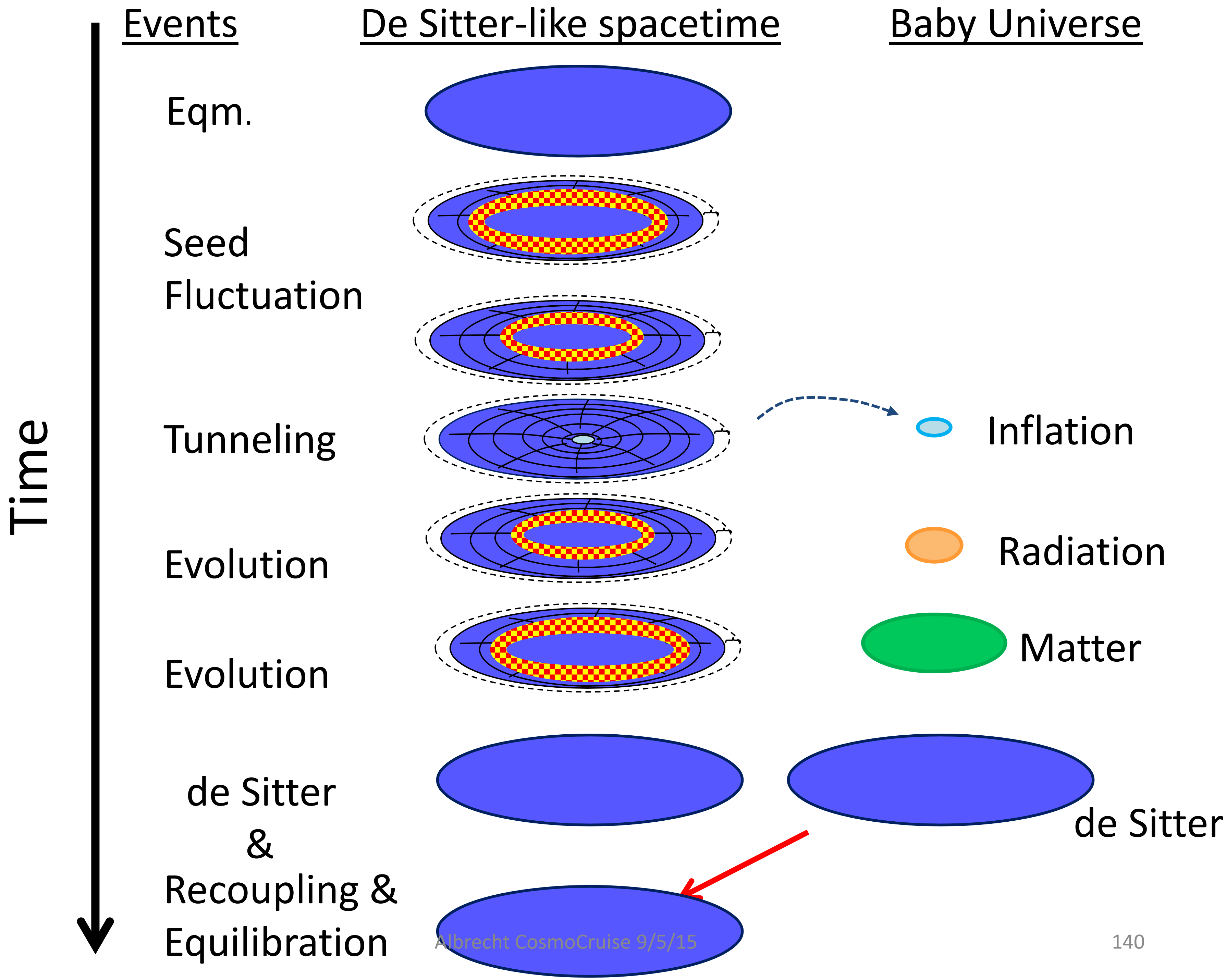
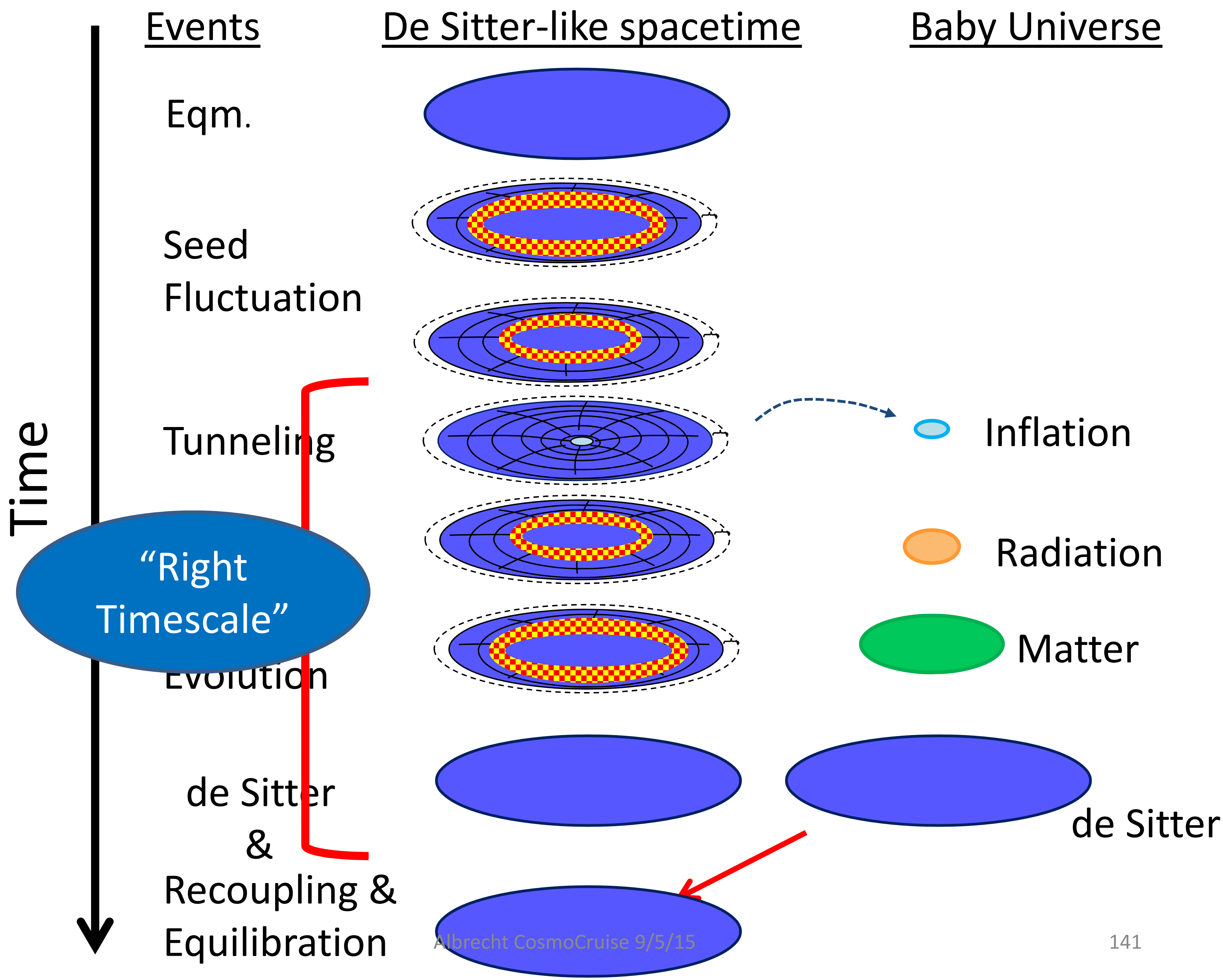
*M → 0 not a problem for G-F process (A. Ulvestad & AA 2012)*

*See also Freivogel et al 2006, Banks 2002*



Time
Events
De Sitter-like spacetime
Baby Universe
Eqm.
Seed
Fluctuation
Tunneling
Inflation
Evolution
Radiation
Evolution
Matter
de Sitter
&
Recoupling &
Equilibration
de Sitter


Events
De Sitter-like spacetime
Baby Universe
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Tunneling
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“Right
Timescale”
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de Sitter

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

- Recurrences

- Eqm.

- Breakdown of continuum field theory

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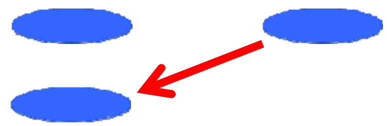

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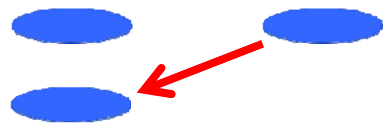

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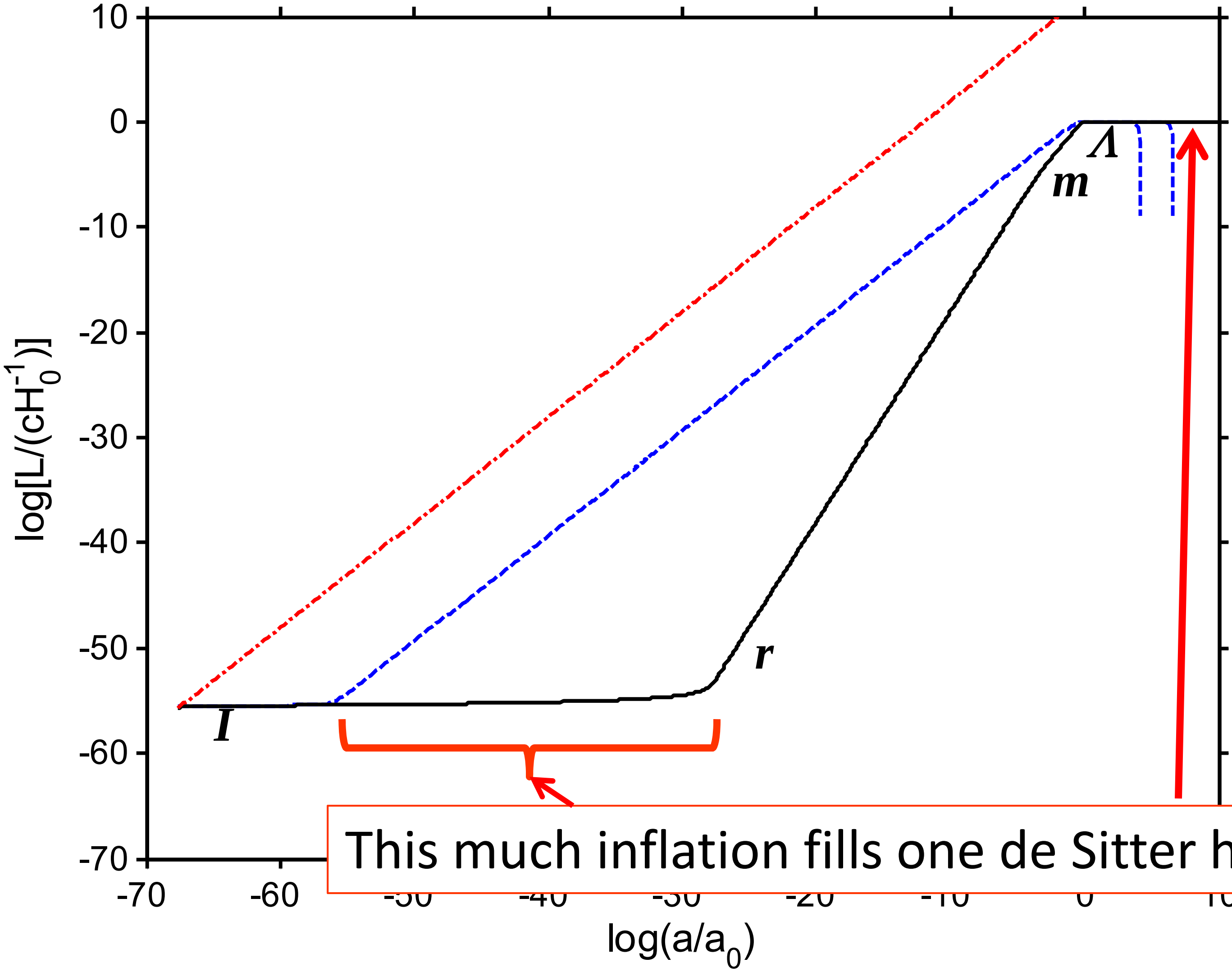
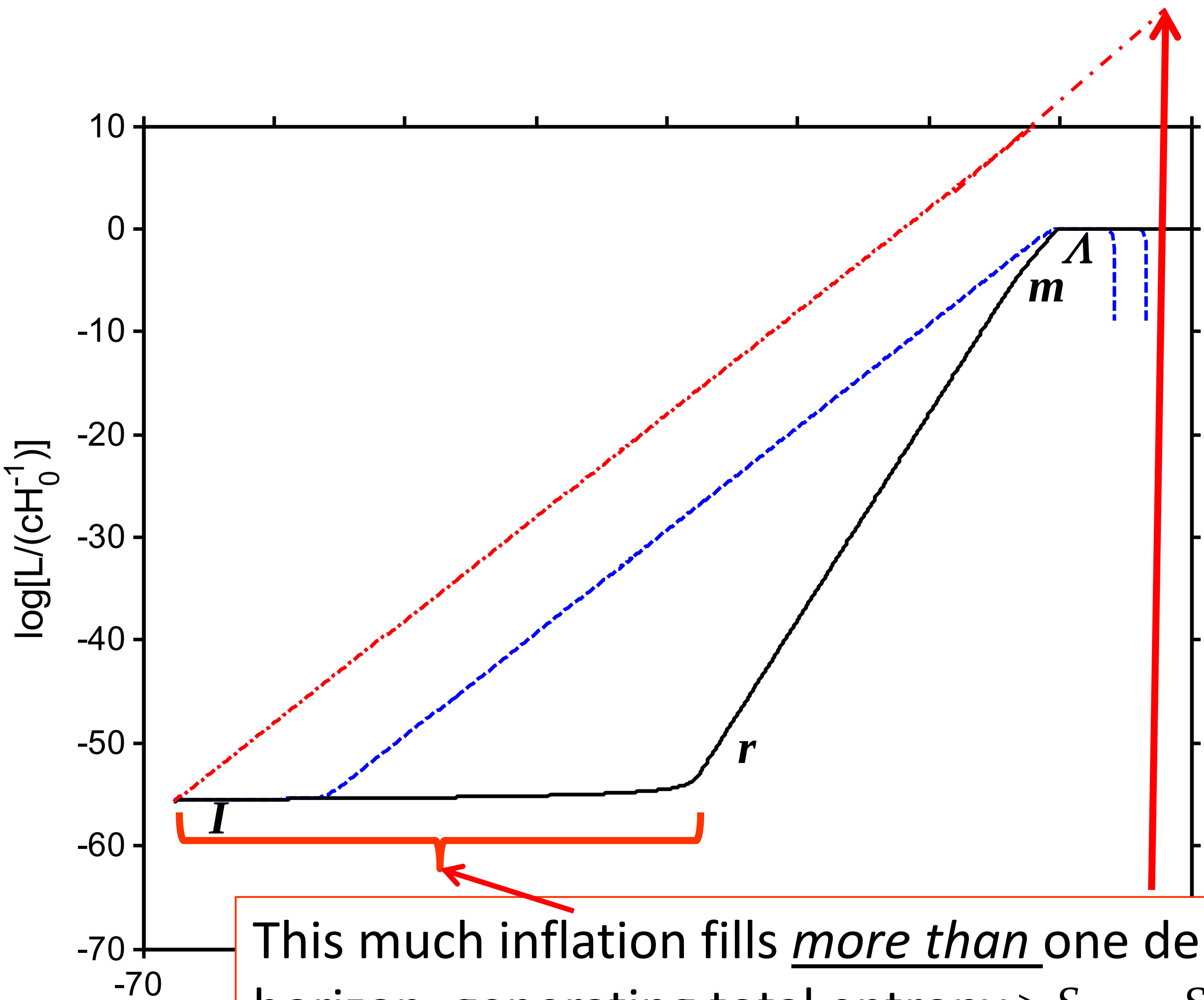
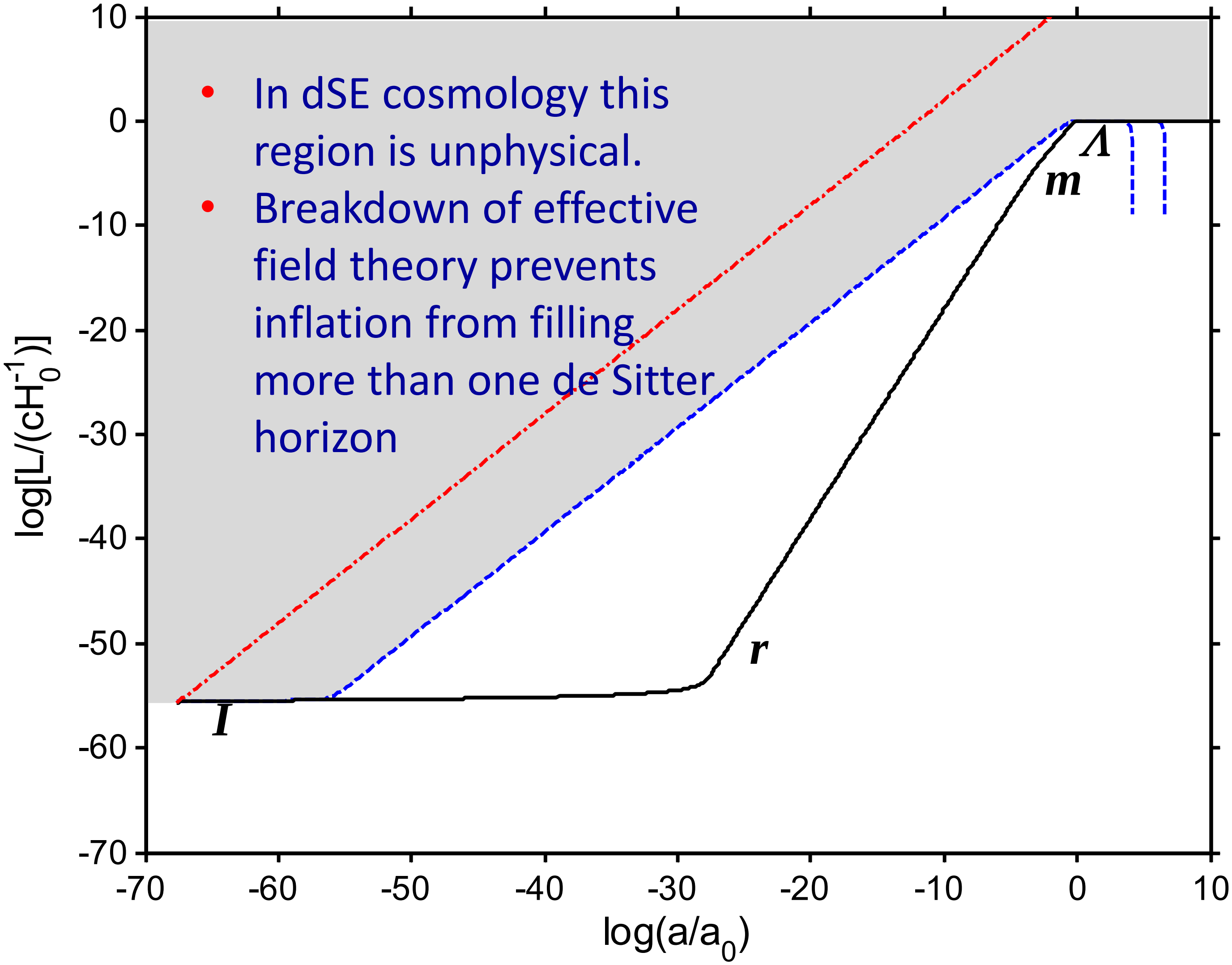
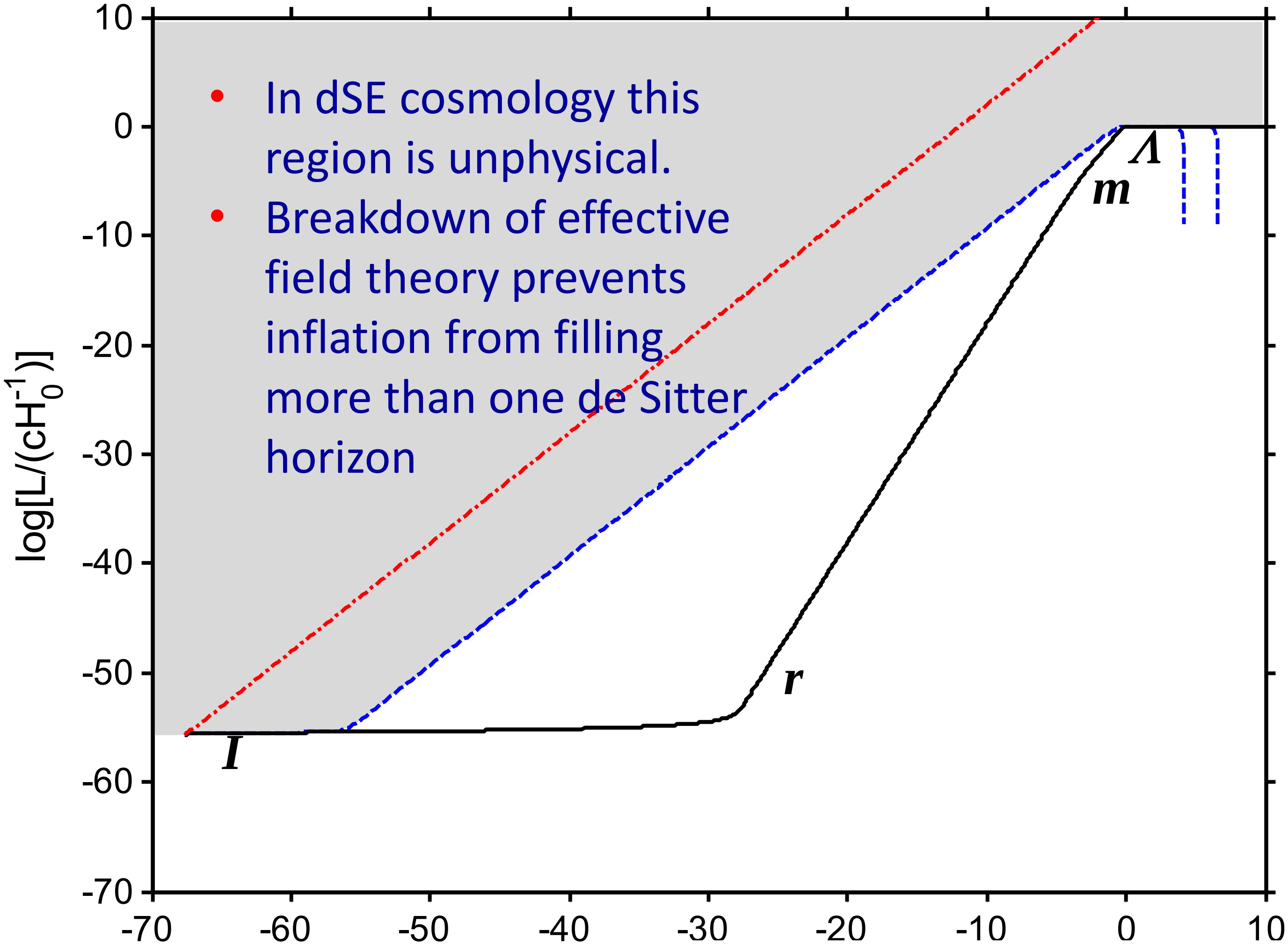



This much inflation fills one de Sitter horizon



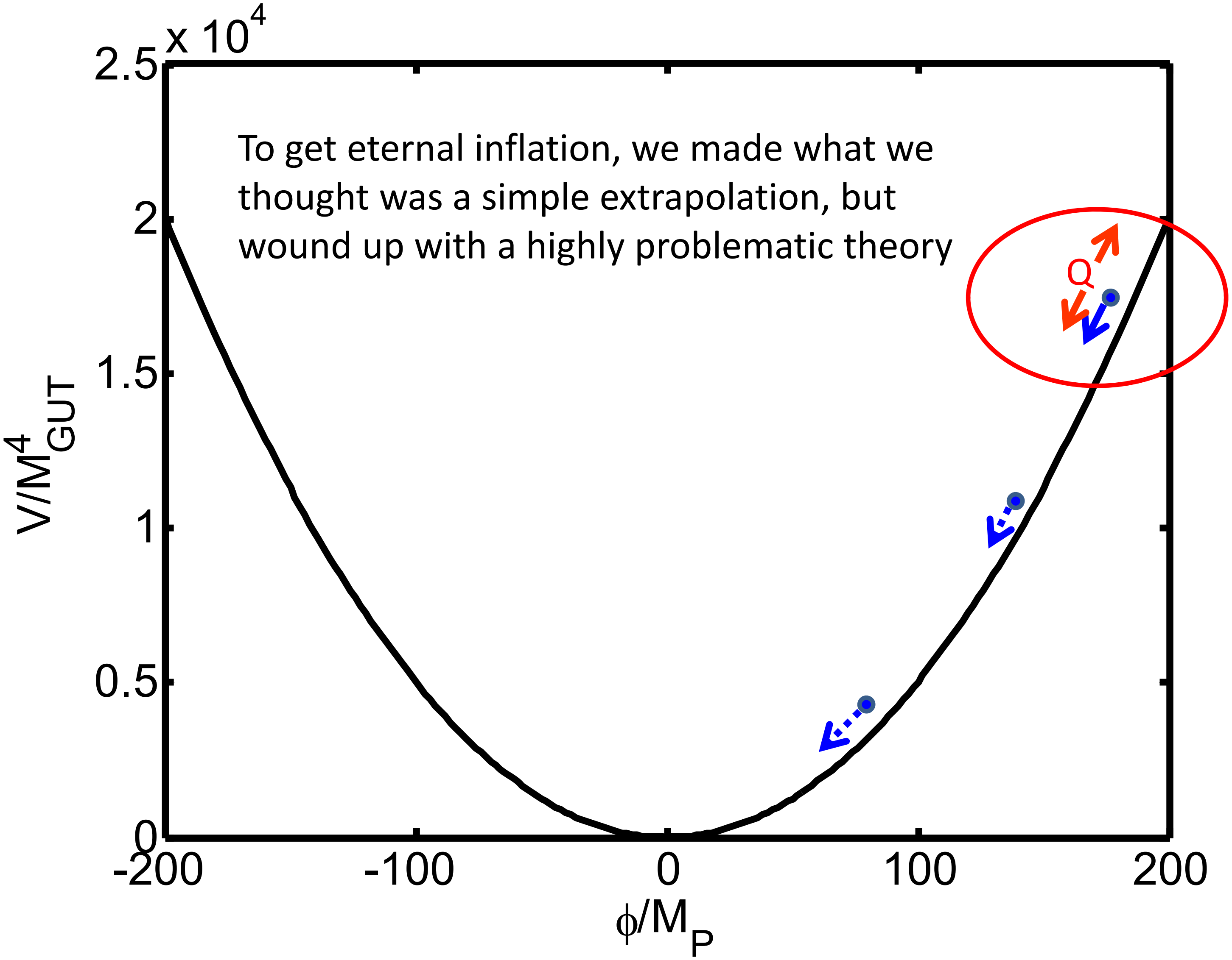

This much inflation fills <u>*more than*</u> one de Sitter horizon, generating total entropy $> S_{Max} = S_{\Lambda}$ and affecting regions beyond the horizon of the observer


In dSE cosmology this region is unphysical.
Breakdown of effective field theory prevents inflation from filling more than one de Sitter 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)
Λ
m
r
I



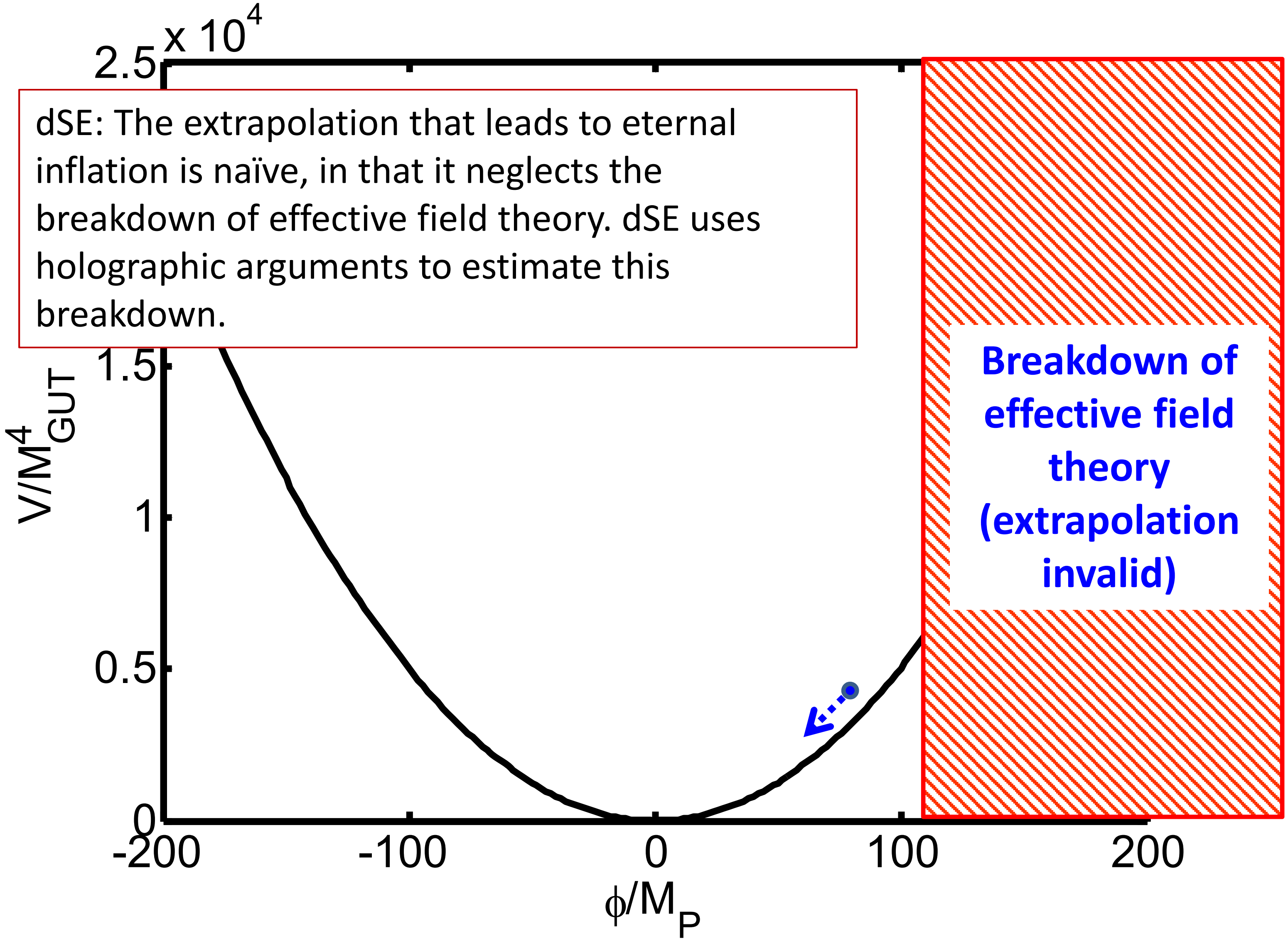

"Equivalent" to Banks-Fischler holographic constraint on number of e-foldings of inflation (D Phillips & AA in prep)

Albrecht (



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



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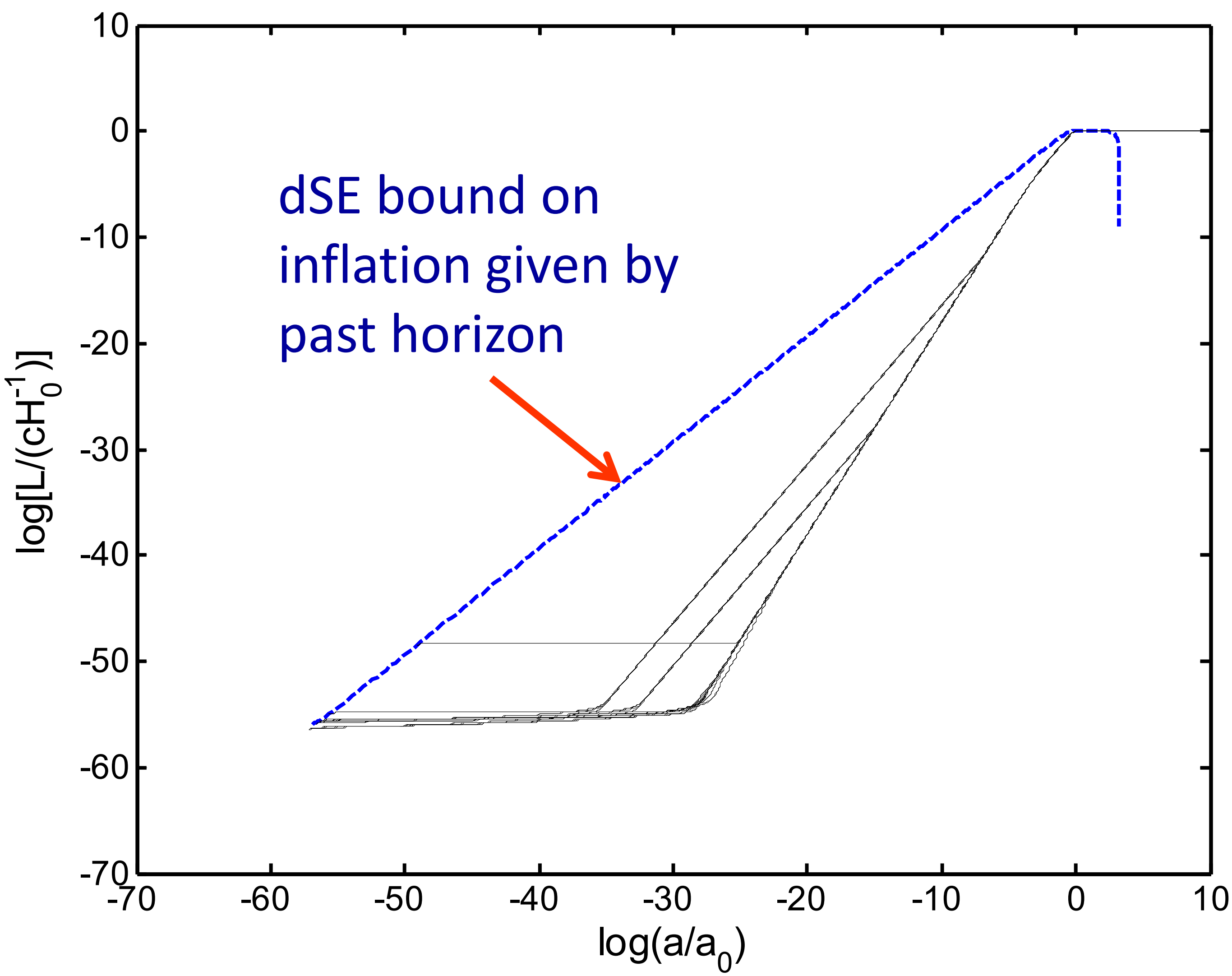
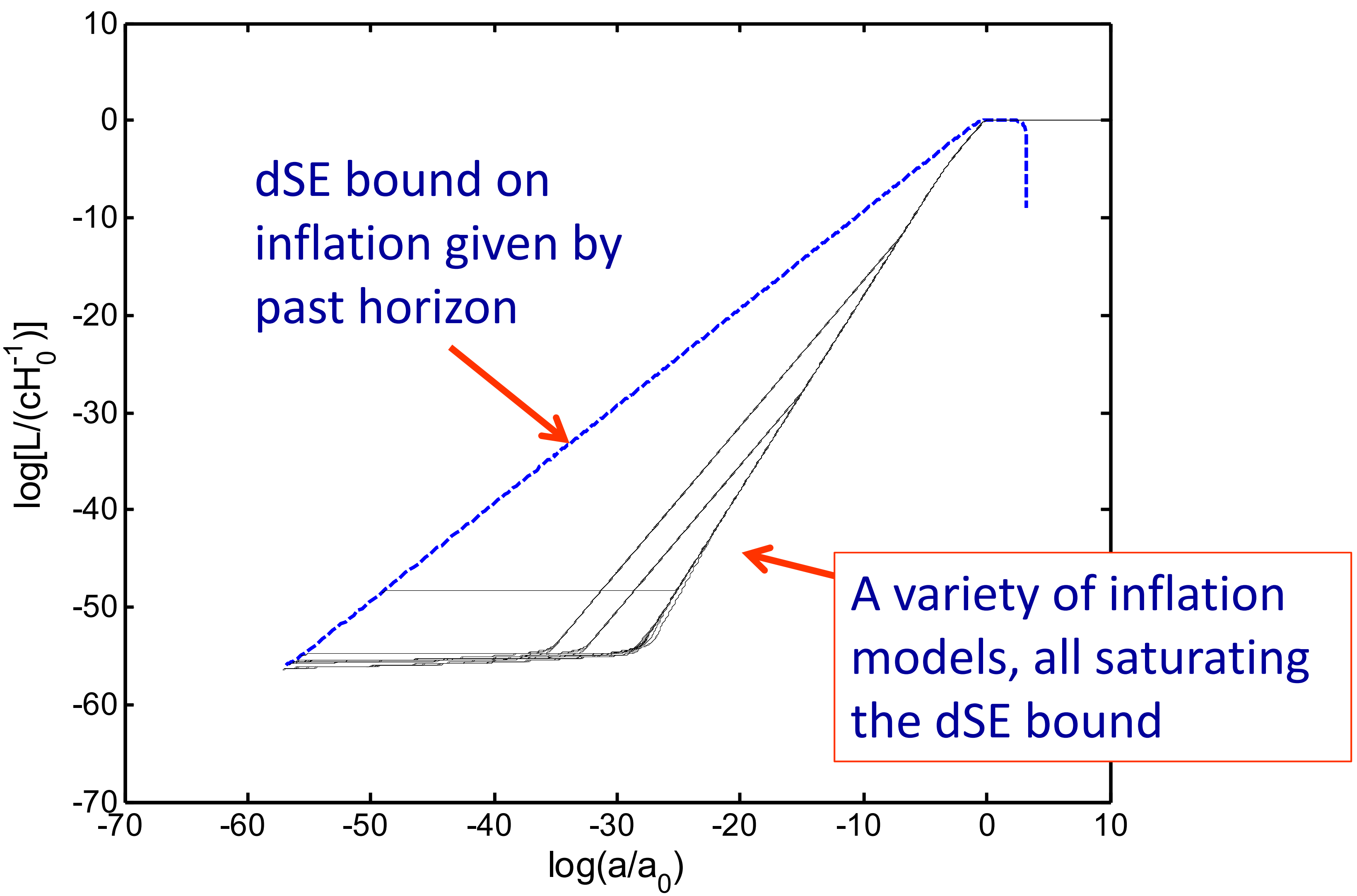
Large $\rho_I$ exponentially favored → saturation of dSE bound


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


10
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0
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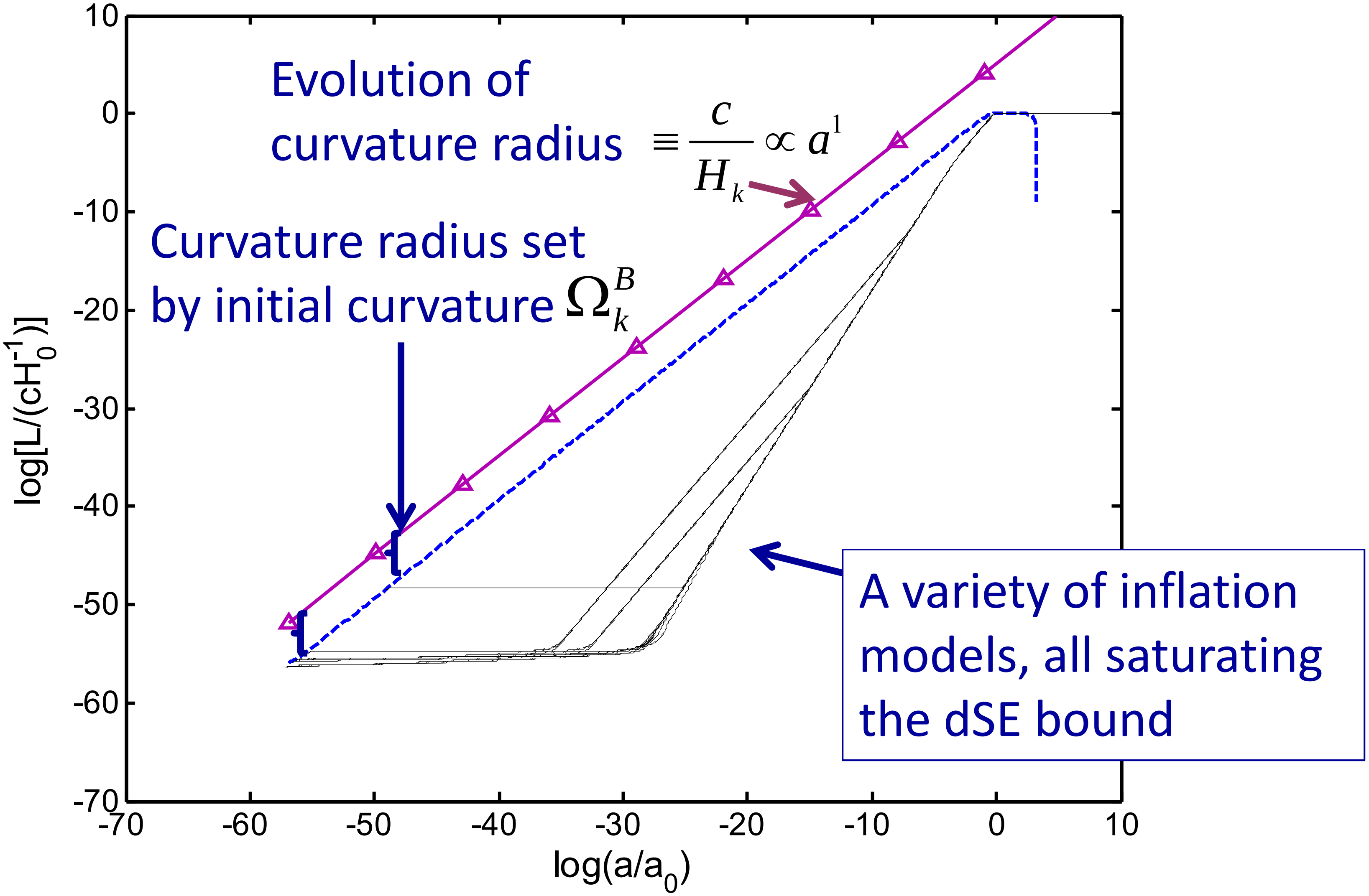
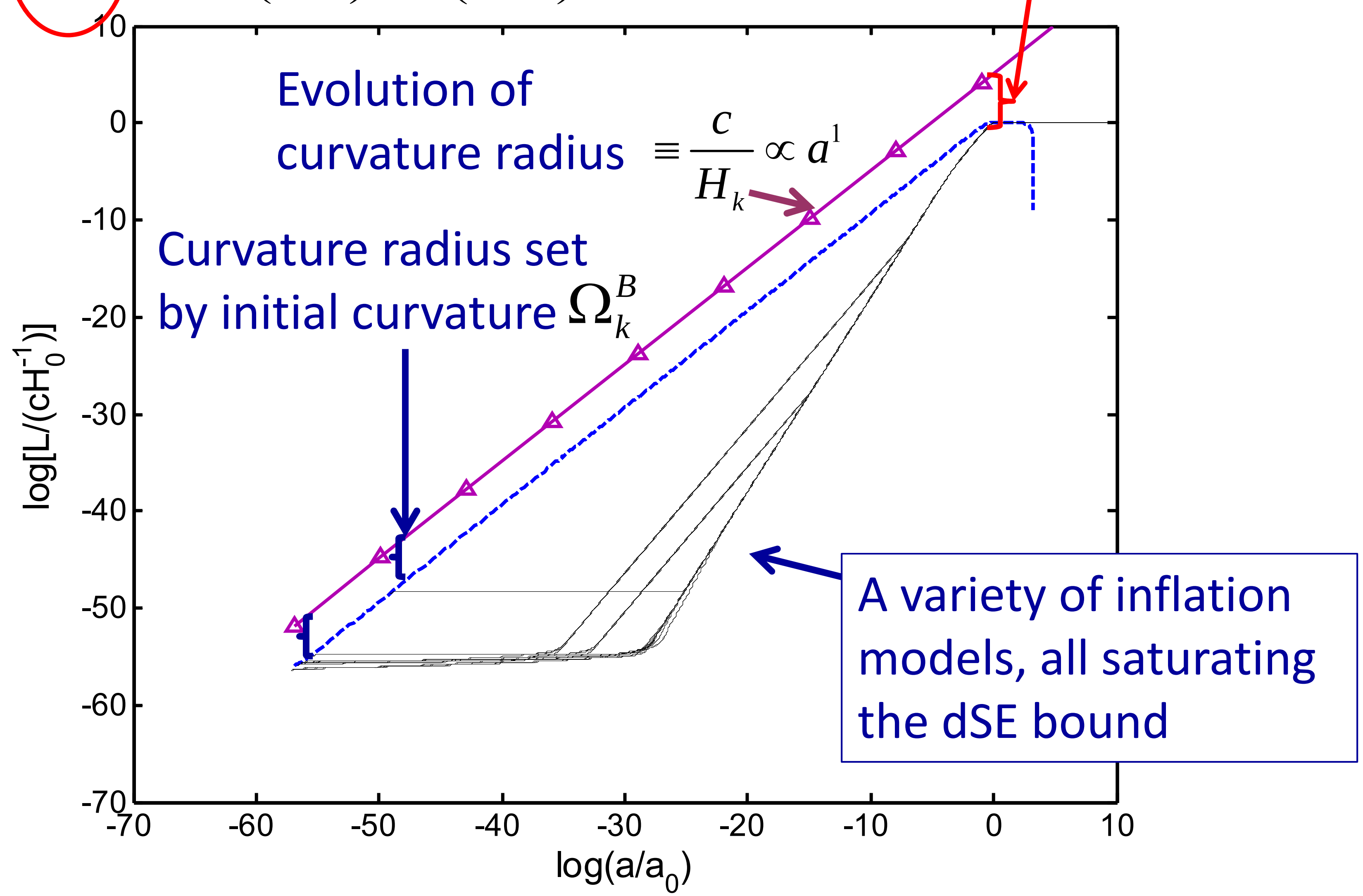
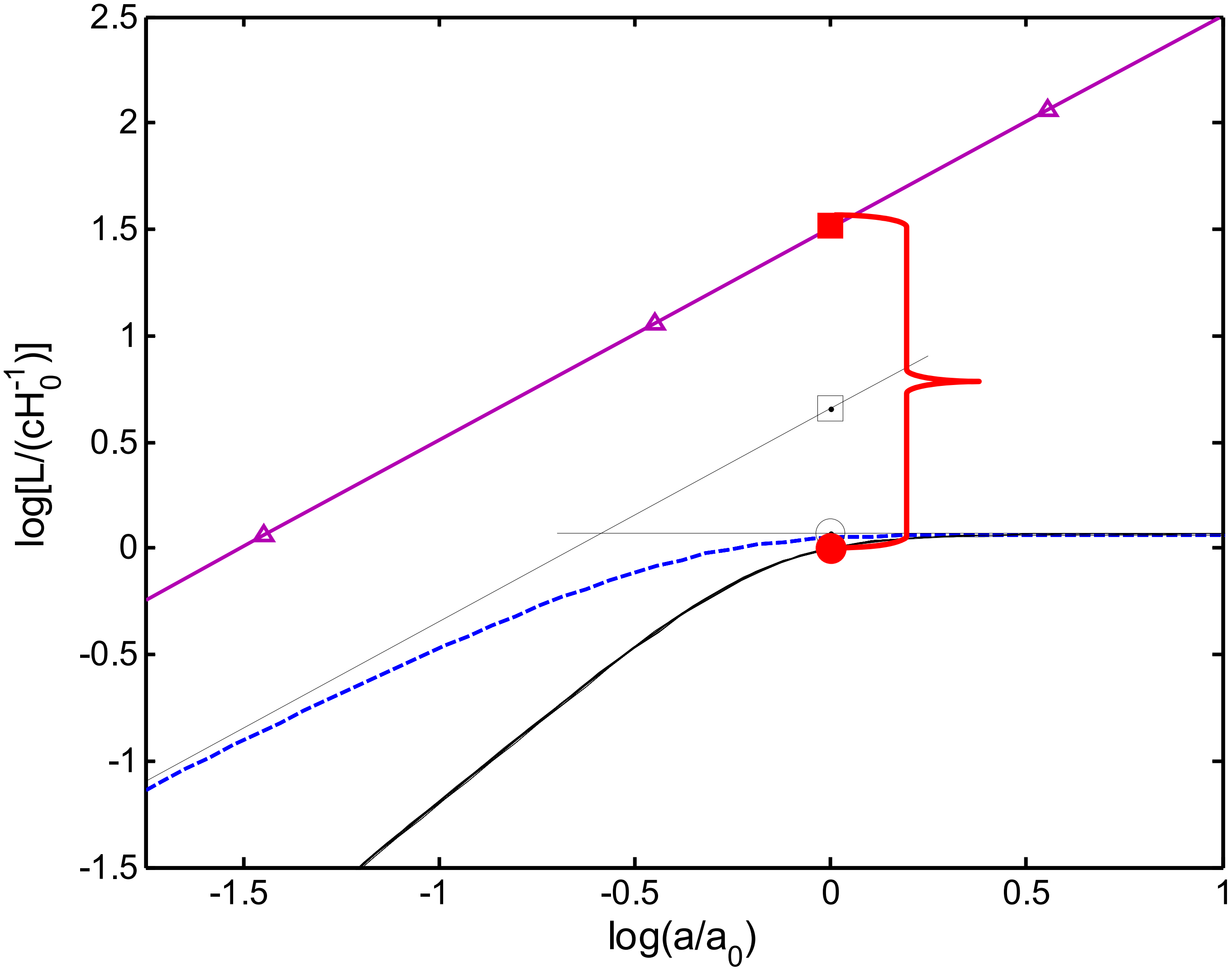
log(a/a$_0$)
dSE bound on inflation given by past horizon
A variety of inflation models, all saturating the dSE bound



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

# dSE Cosmology and cosmic curvature

- The Guth-Farhi process starts inflation with an initial curvature set by the curvature of the Guth-Farhi bubble $\Omega_k^B$
- Inflation dilutes the curvature, but dSE cosmology has a minimal amount of inflation

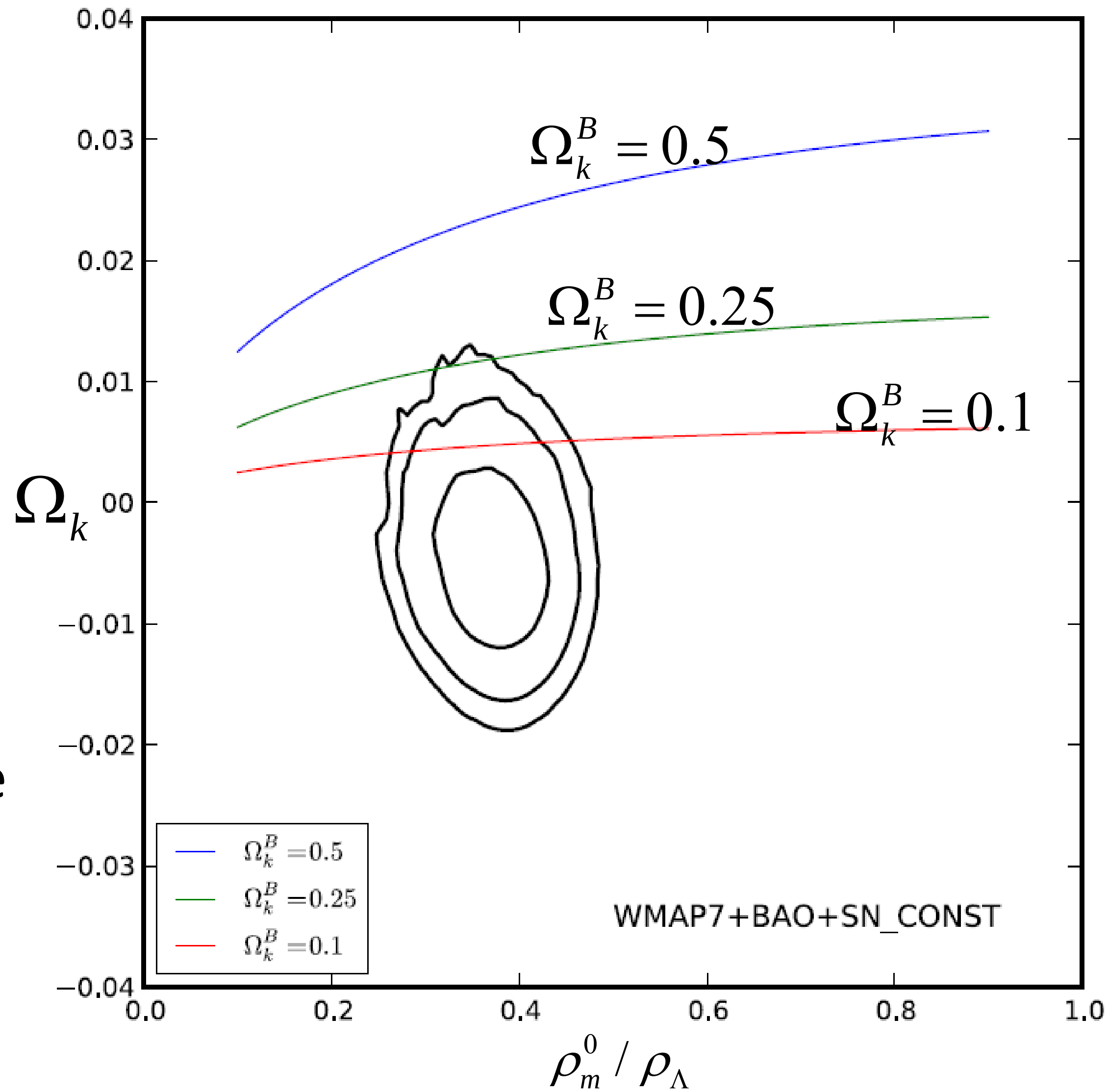
$$\Omega_k = \frac{1}{g^2} \frac{\Omega_k^B}{\left(\frac{\rho_m^0}{\rho_\Lambda} + \frac{\rho_k^0}{\rho_\Lambda} + 1\right)}$$

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 $\Omega_k$ from dSE cosmology is:

- Independent of almost all details of the cosmology
- Just consistent with current observations
- Will easily be detected by future observations




$\Omega_k^B$

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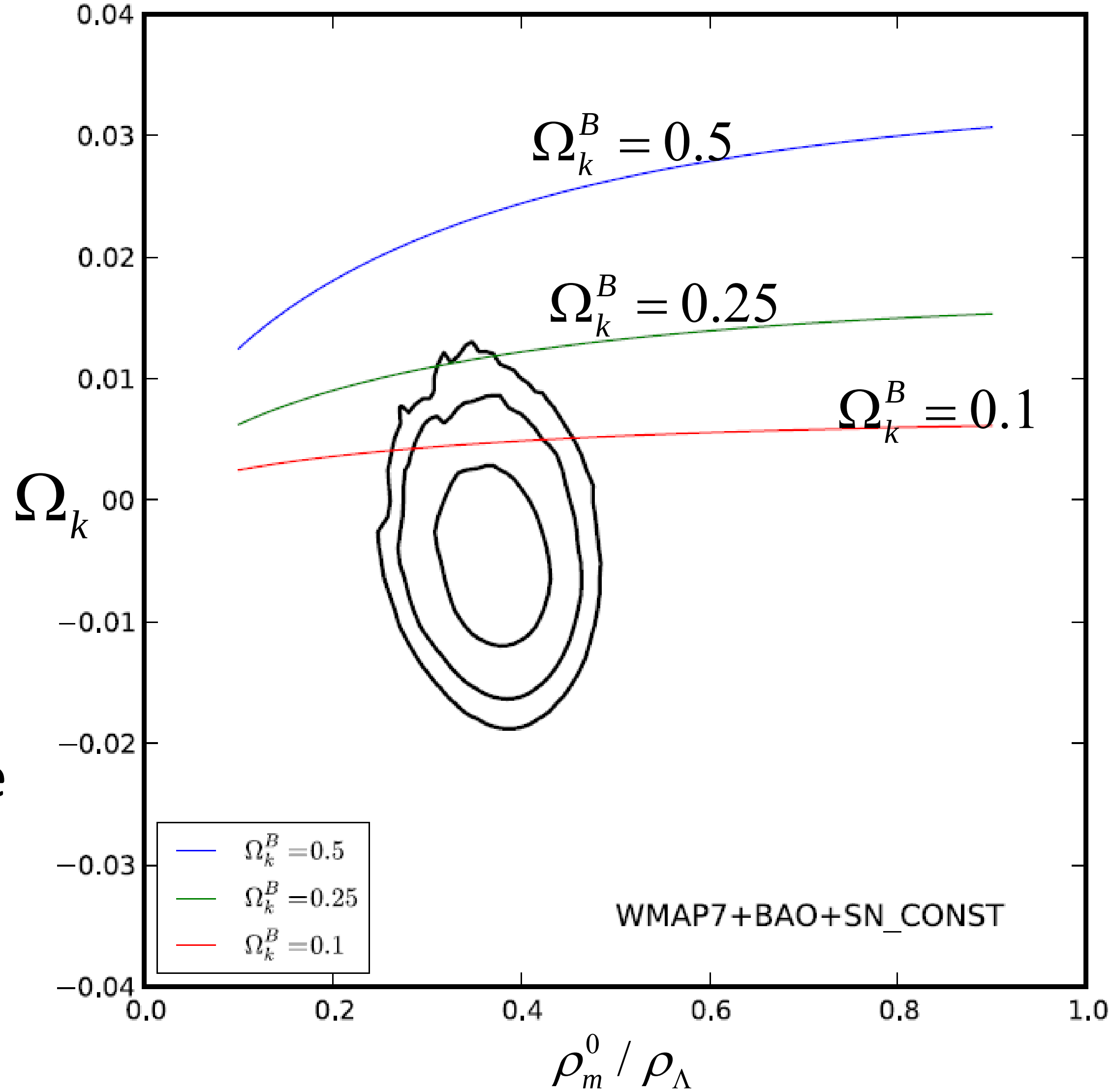


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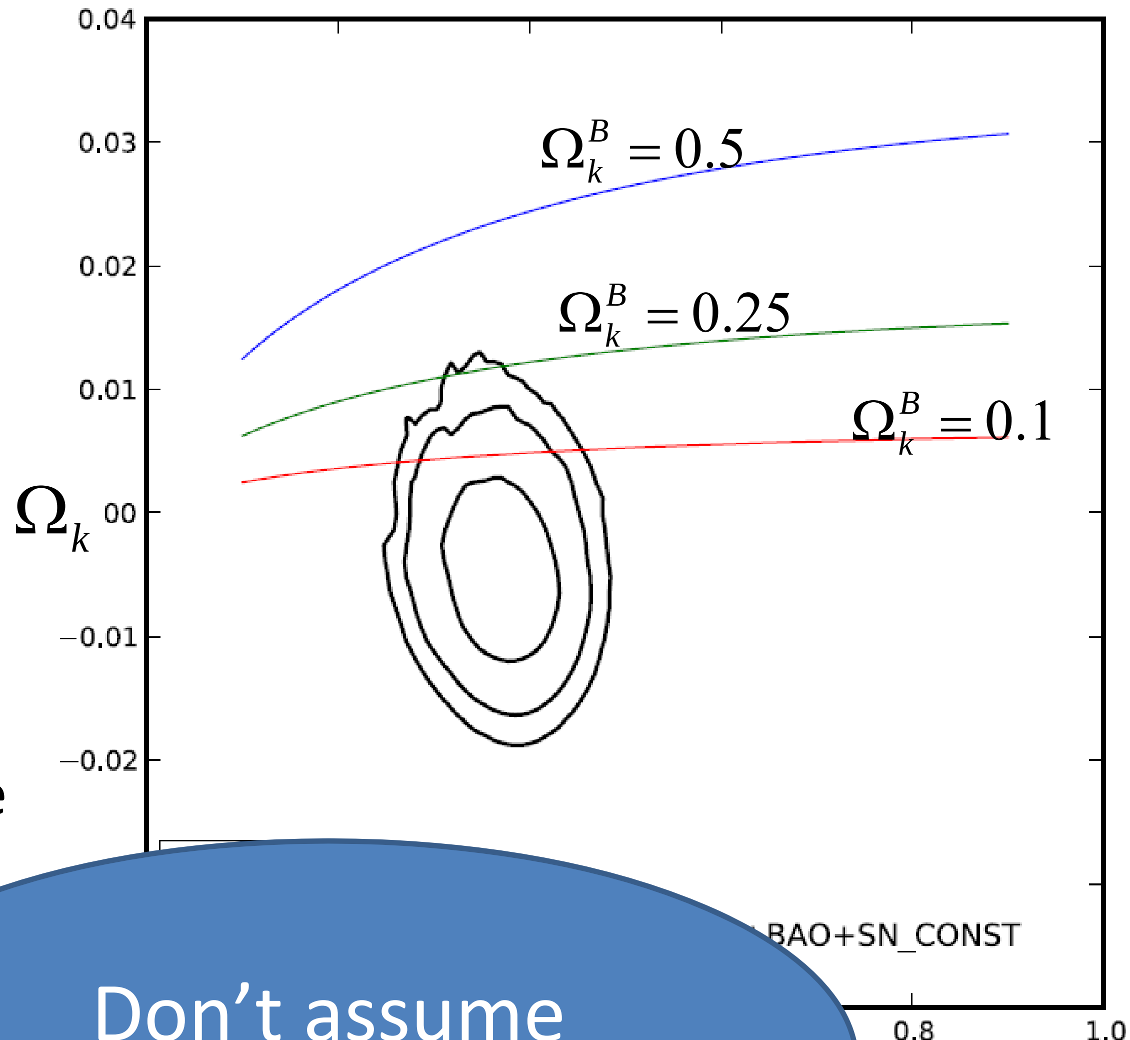


Don’t assume curvature = 0!

$\Omega_k^B$

# Outline

1. Introduction
2. Tuning & Entropy
3. Temporal Provincialism
4. Eternal Inflation, measures and probabilities
5. The Bunch Davies vacuum
6. de Sitter equilibrium cosmology
7. Conclusions

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Starobinsky talk

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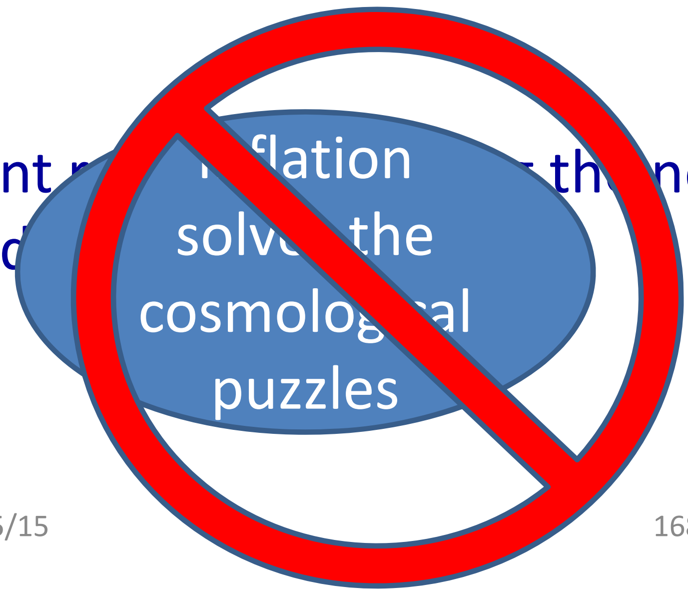

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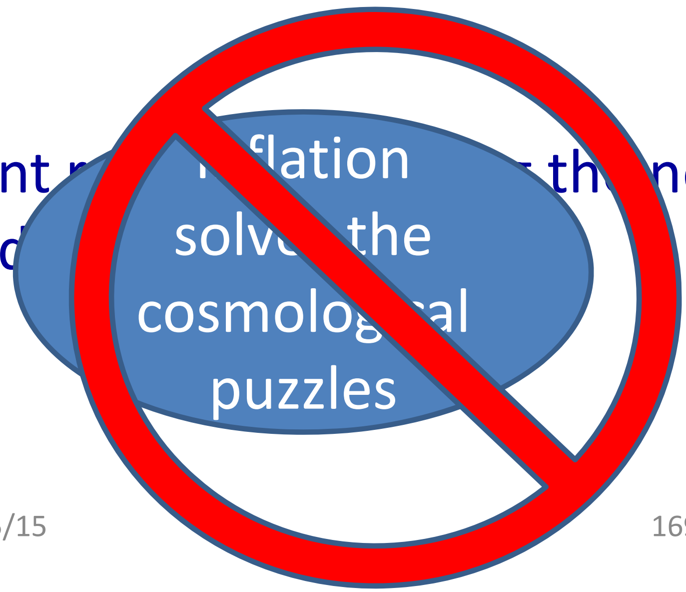

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5) Further progress will not be made using simply EFTs (thus dSE)

# How do ideas of dSE impact my research in practical terms:

- Search for finite quantum theory that looks approximately like de Sitter interior with finite thermal horizon (hard)
- Work on de Sitter equilibration
- Work on short inflation phenomenology.

1. *Transients in finite inflation*
Andrew Scacco, Andreas Albrecht
arXiv:1503.04872

3. *Holographic bounds and finite inflation*
Daniel Phillips, Andrew Scacco, Andreas Albrecht (UC, Davis).
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Next talk

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