Les Houches Lectures on Cosmic Inflation

Four Parts

1) Introductory material

2) Entropy, Tuning and Equilibrium in Cosmology

3) Classical and quantum probabilities in the multiverse

4) de Sitter equilibrium cosmology

Andreas Albrecht; UC Davis
Les Houches Lectures; July-Aug 2013

Part 4 Outline

1. de Sitter Equilibrium cosmology

2. Cosmic curvature from de Sitter Equilibrium cosmology

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de Sitter Equilibrium (dSE) cosmology

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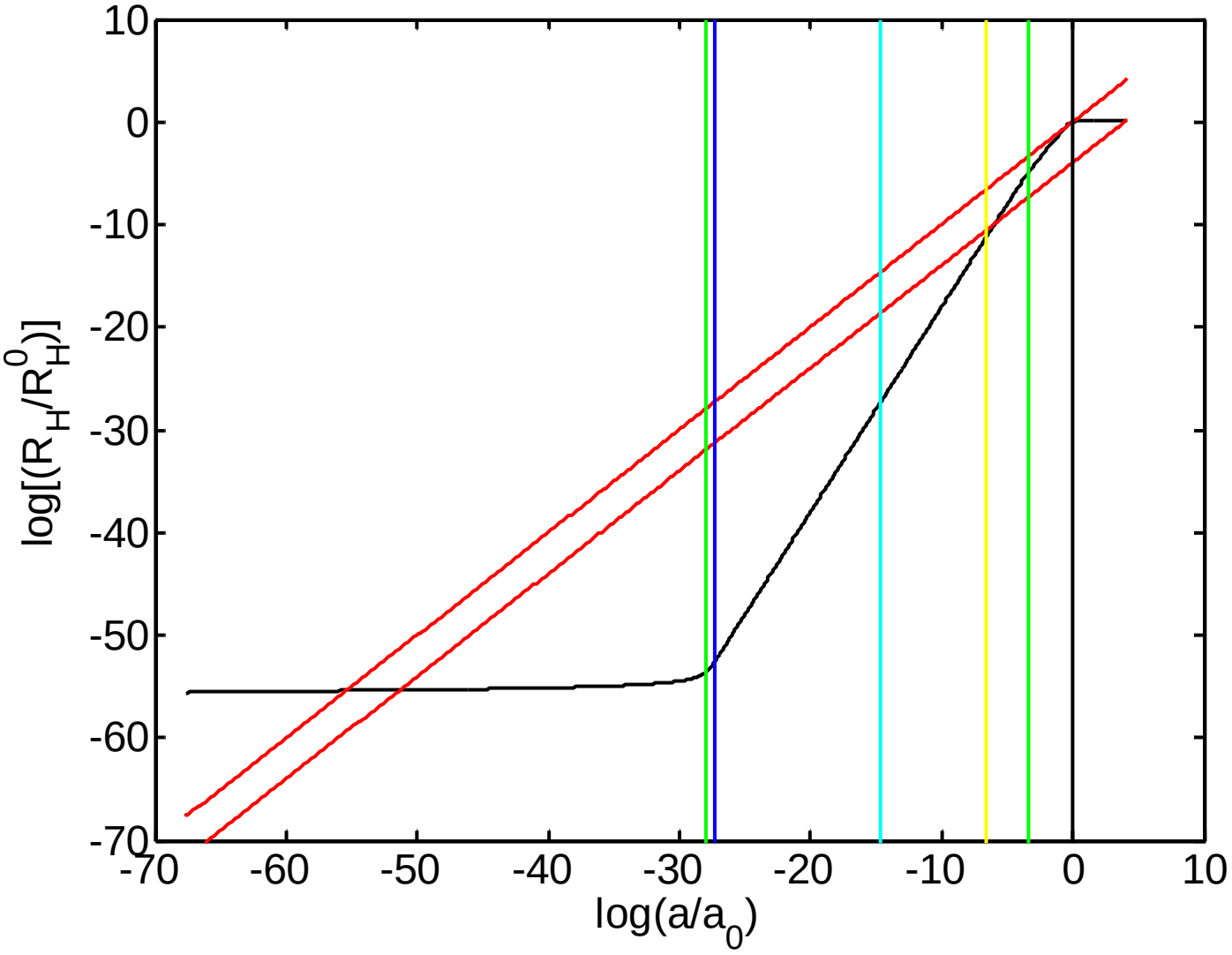
AA: arXiv:1104.3315
AA: arXiv:0906.1047
AA & Sorbo: hep-th/0405270

Evolution of Cosmic Length



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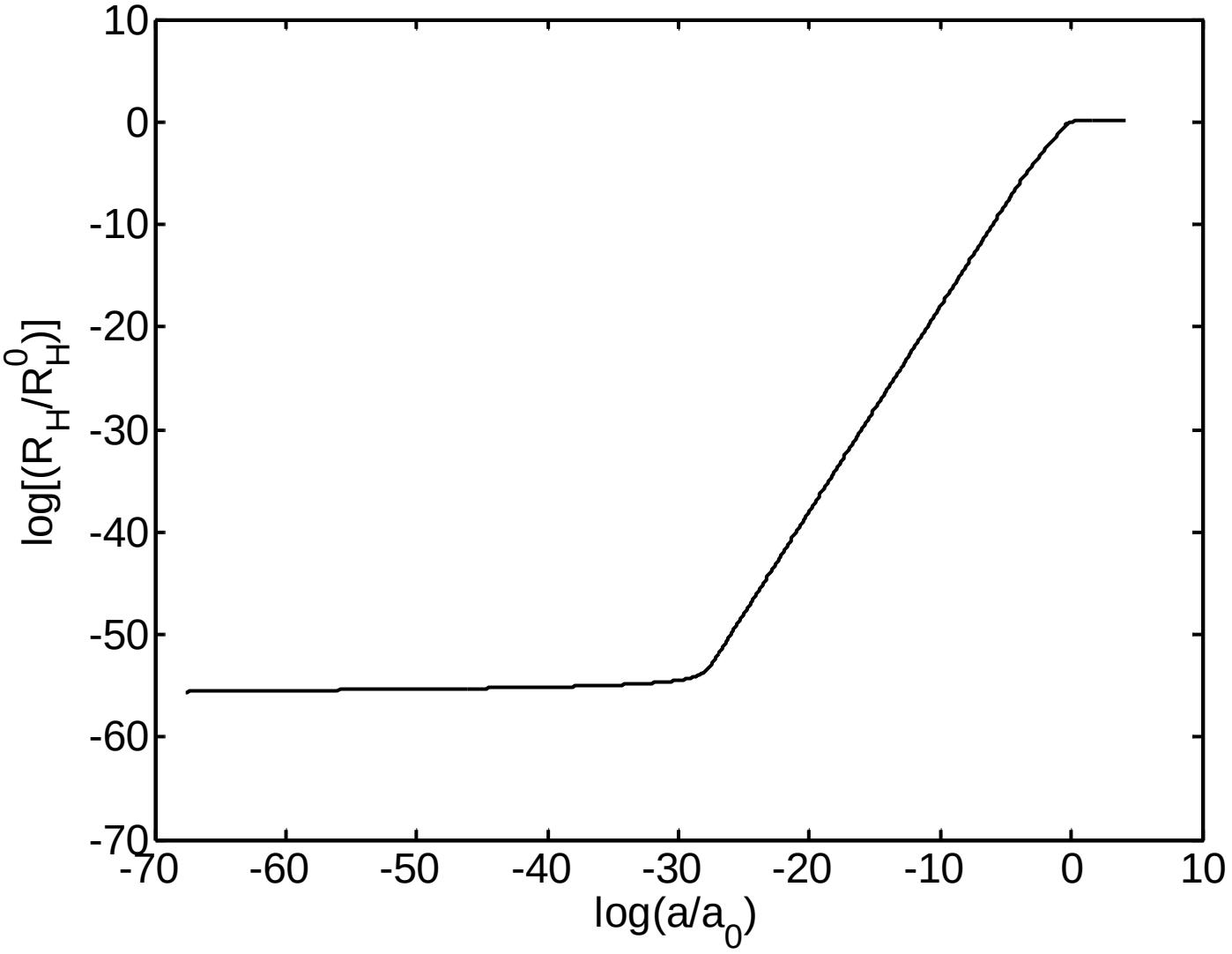

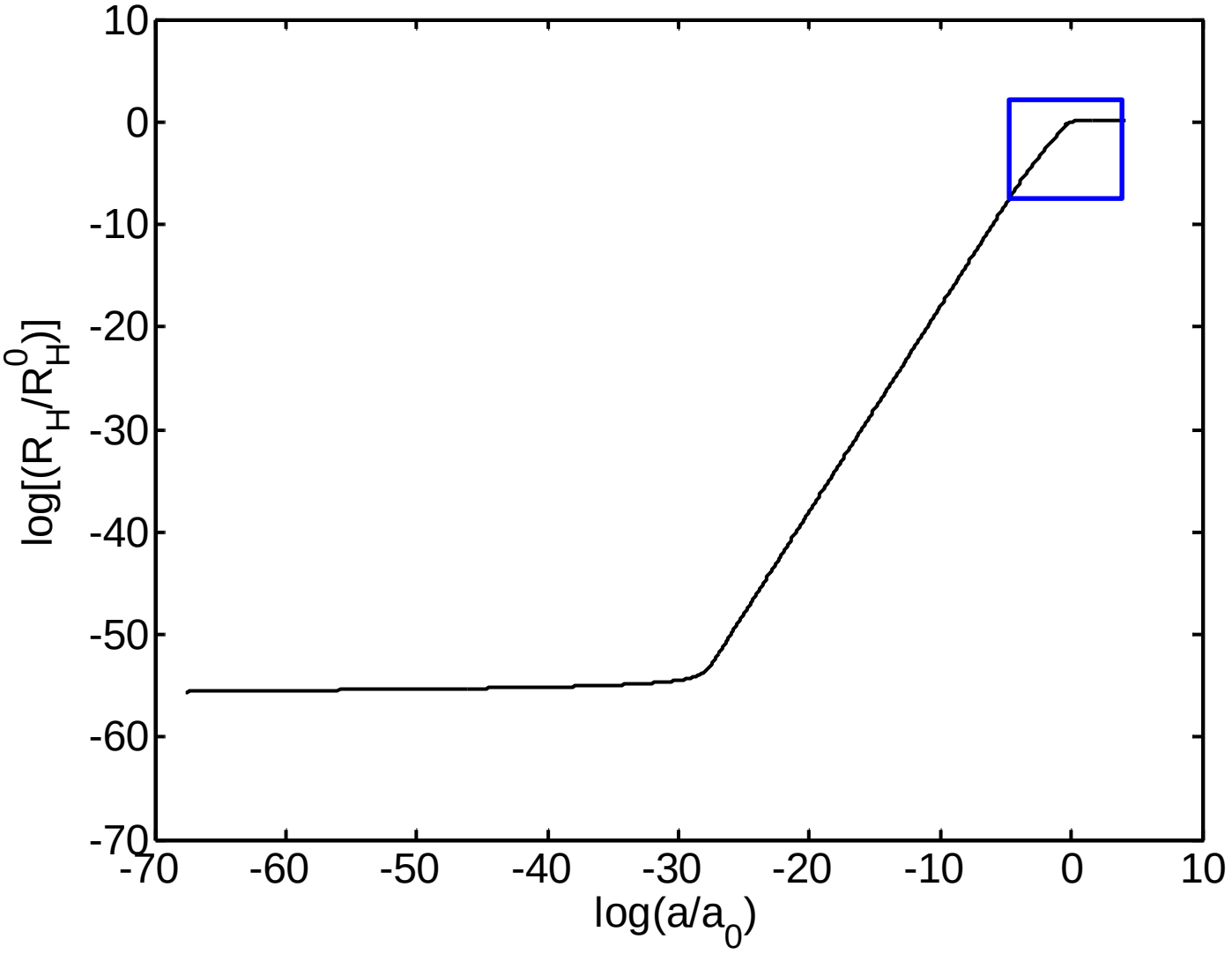
10
0
-10
-20
-30
-40
-50
-60
-70
-70
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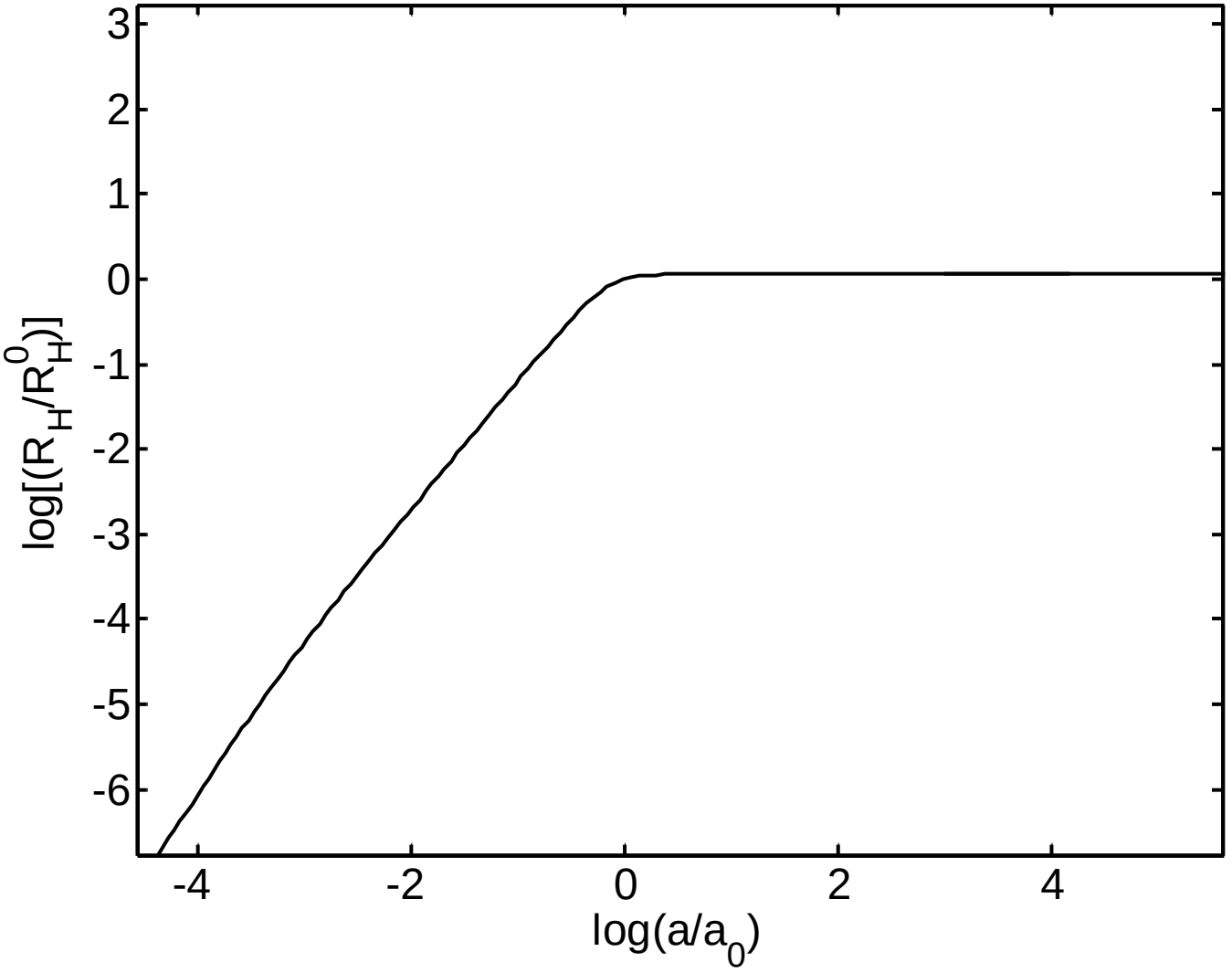
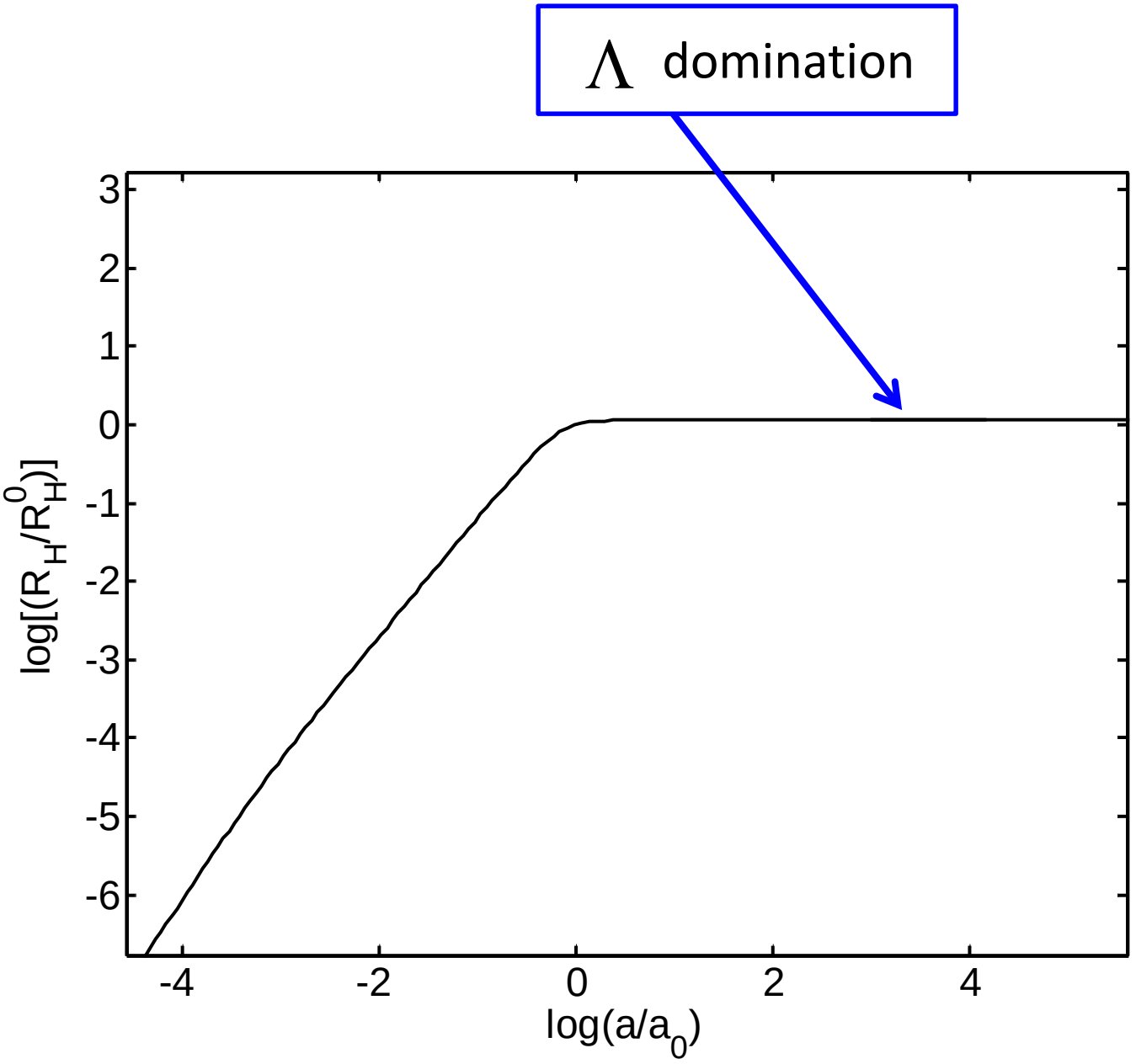
-50
-40
-30
-20
-10
0
10
log[(R_H/R_H^0)]
log(a/a_0)


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


Λ domination
3
2
1
0
-1
-2
-3
-4
-5
-6
-4
-2
0
2
4
log[(R_H/R_H^0)]
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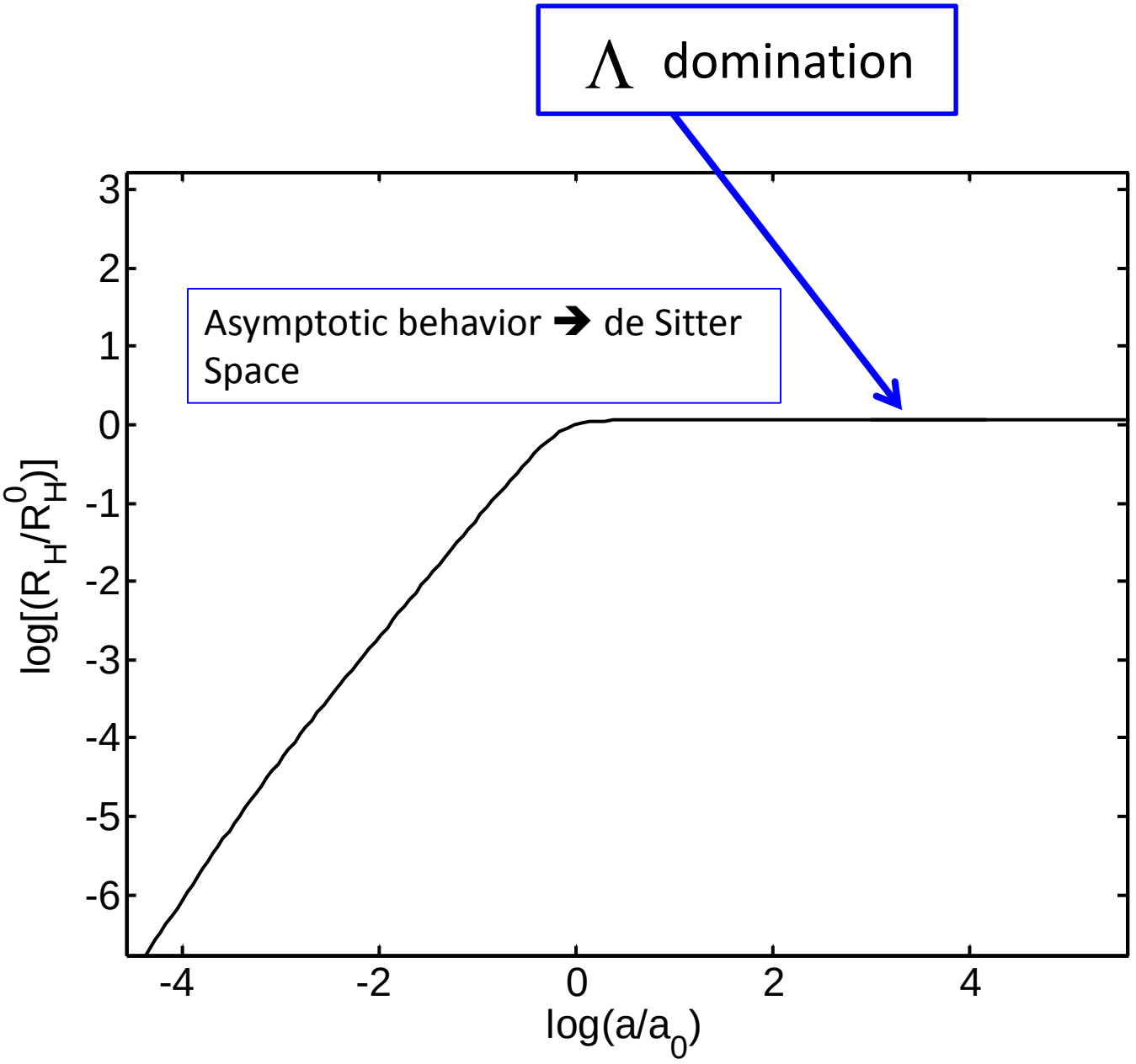
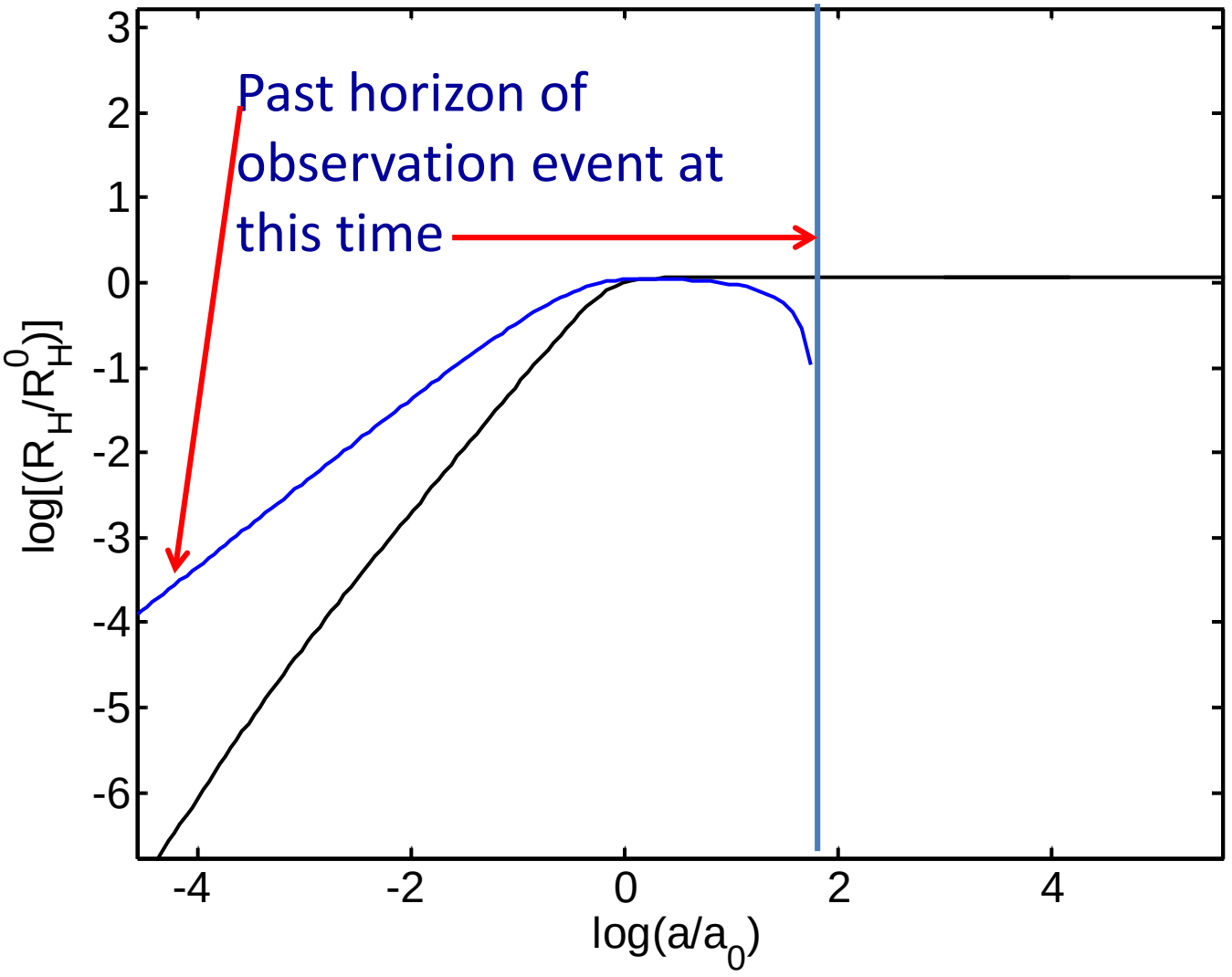
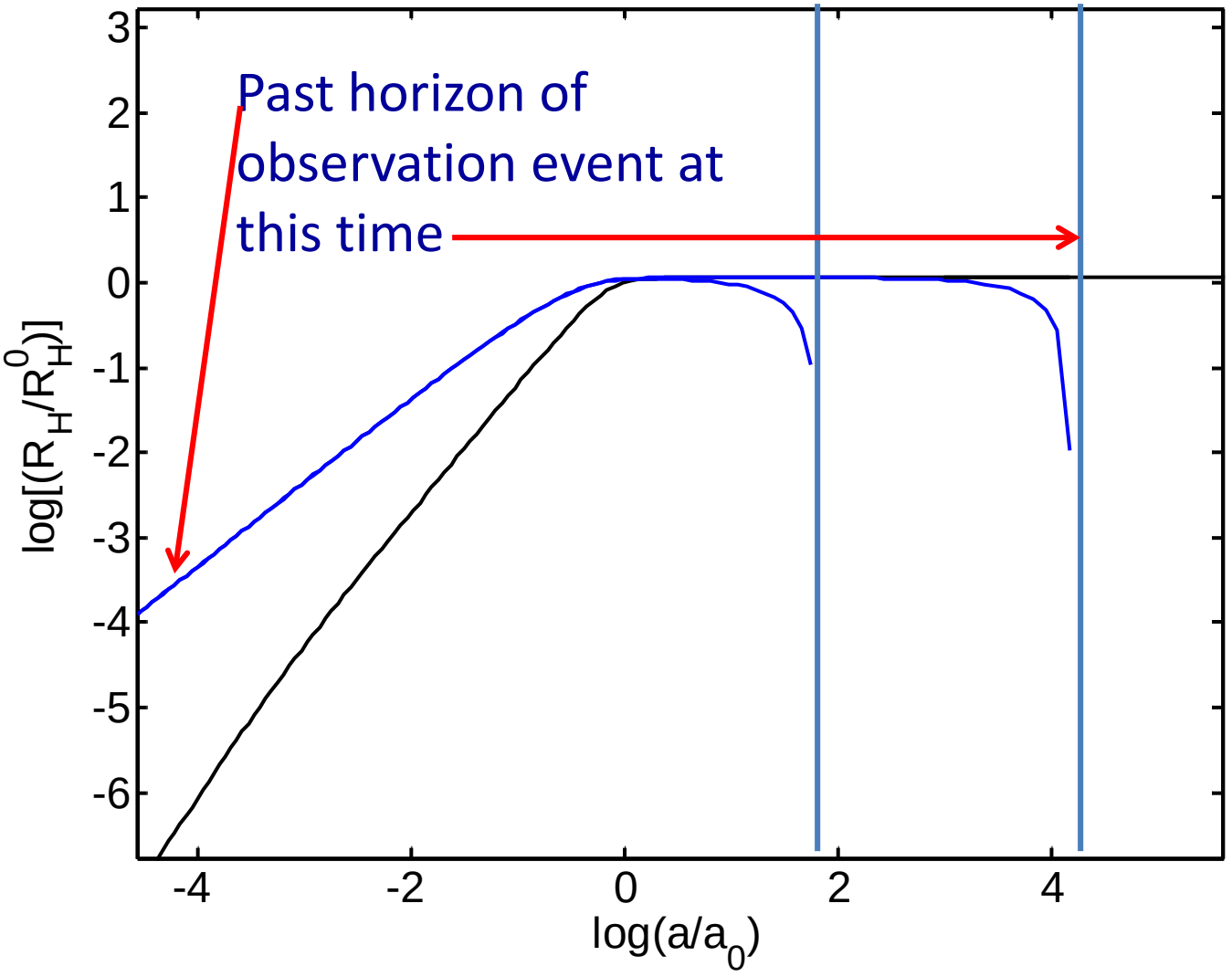

Λ domination
Asymptotic behavior ➔ de Sitter Space
log[(R_H/R_H^0)]
log(a/a_0)
3
2
1
0
-1
-2
-3
-4
-5
-6
-4
-2
0
2
4

The de Sitter horizon



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

The de Sitter horizon



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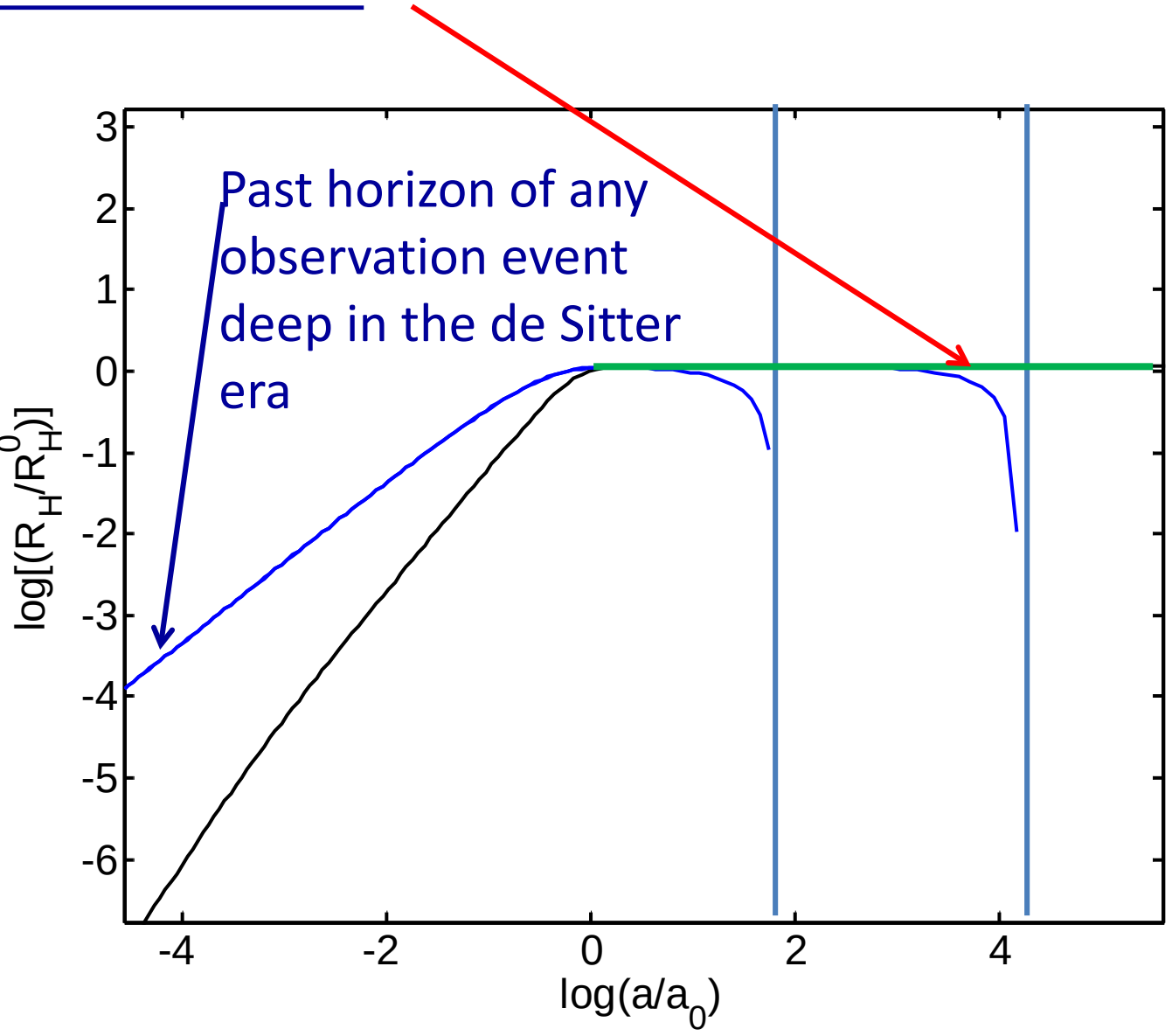

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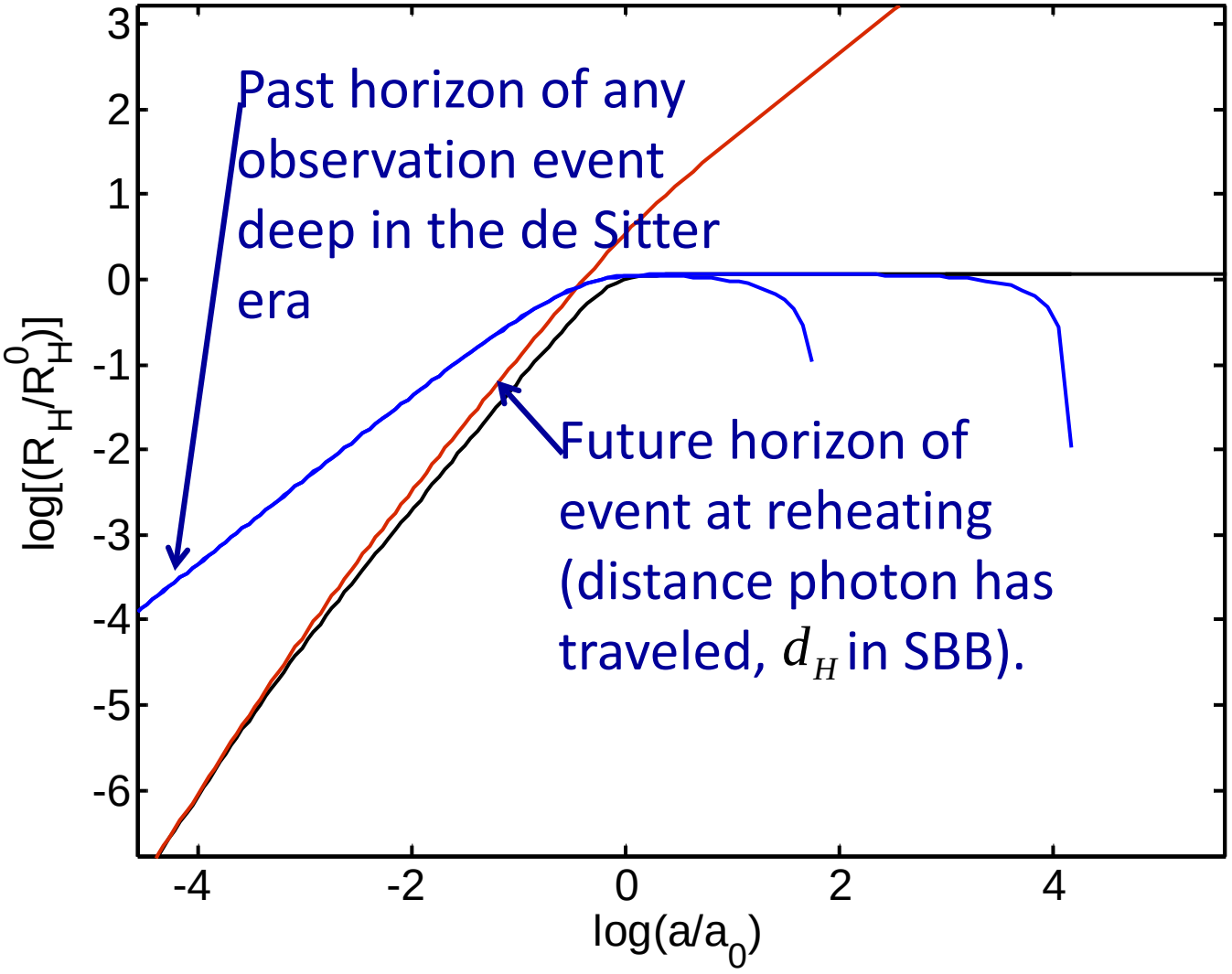


Past Horizon: Physical distance from (comoving) observer of a photon that will reach the observer at the time of the observation.

Implications of the de Sitter horizon

- Maximum entropy

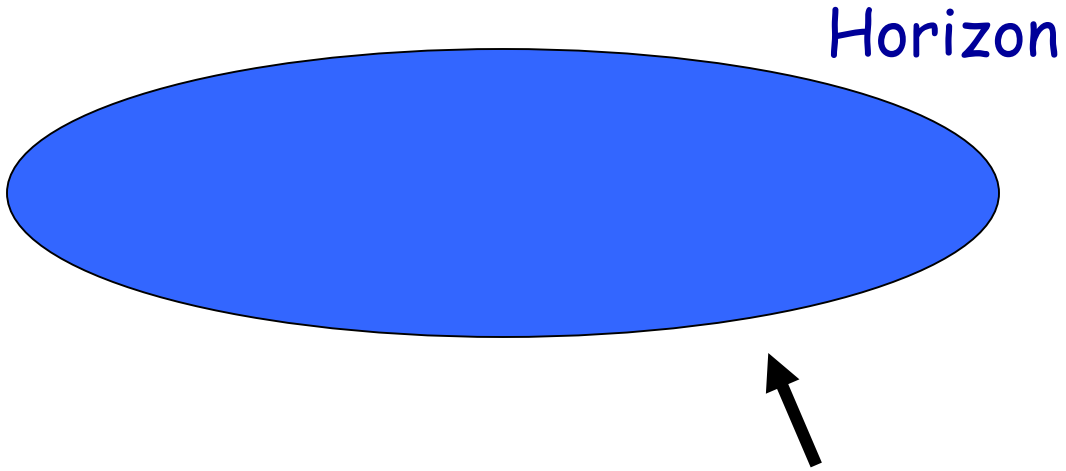
$$S_\Lambda \propto A = H_\Lambda^{-2} = \left(\frac{\Lambda}{3}\right)^{-1}$$

- Gibbons-Hawking Temperature

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

Gibbons & Hawking 1977

"De Sitter Space: The ultimate equilibrium for the universe?



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

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

Implications of the de Sitter horizon

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- Only a finite volume ever observed

- If Λ is truly constant: Cosmology as fluctuating Eqm.

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

Banks & Fischler & Dyson et al.

Implications of the de Sitter horizon

- Maximum entropy

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dSE cosmology

- ✓ Only a finite volume ever observed
- ✓ If Λ is truly constant: Cosmology as fluctuating Eqm.?
- ✓ Maximum entropy $\xrightarrow{?}$ finite Hilbert space of dimension $N = e^{S_\Lambda}$

Banks & Fischler & Dyson et al.

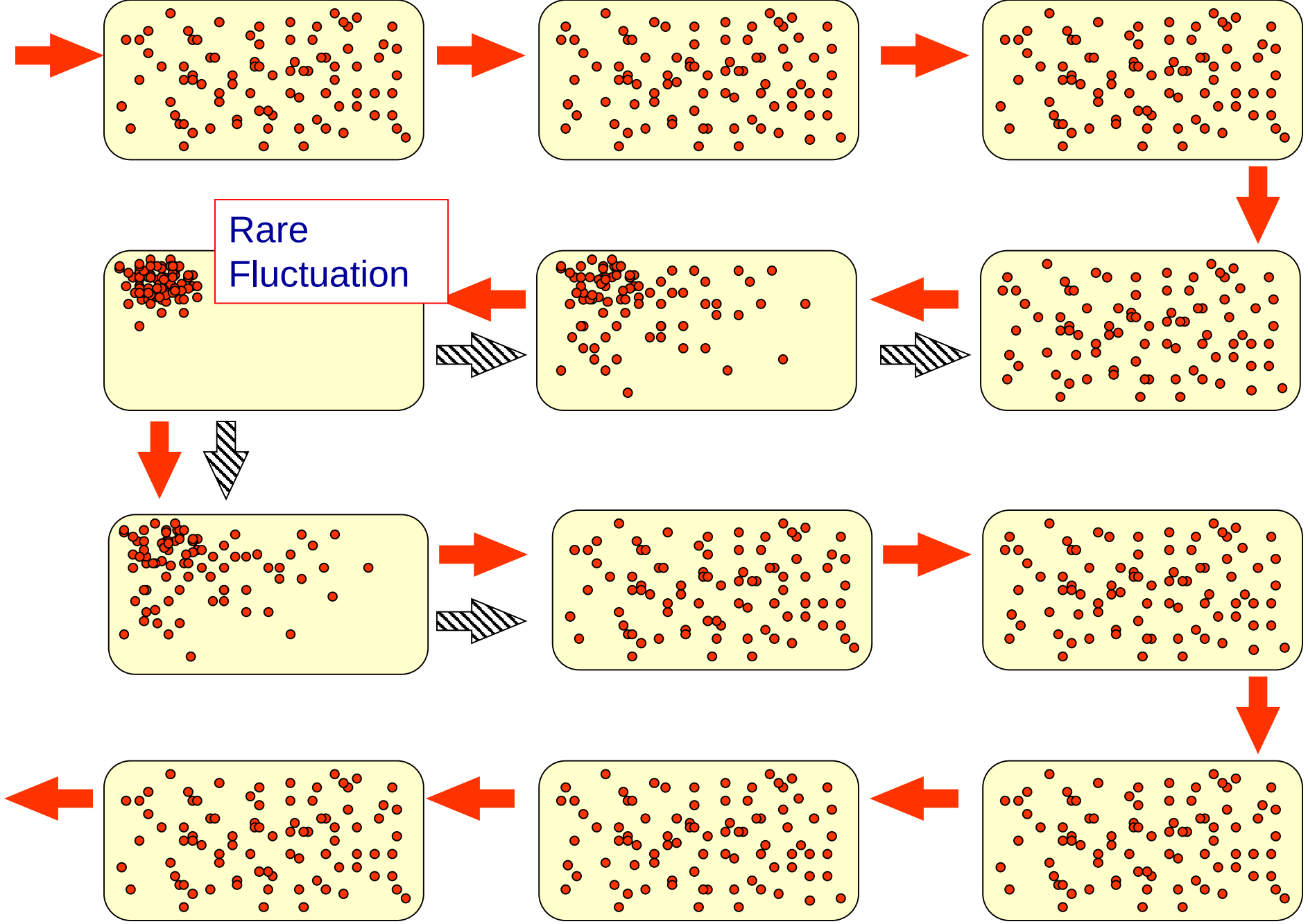
Equilibrium Cosmology

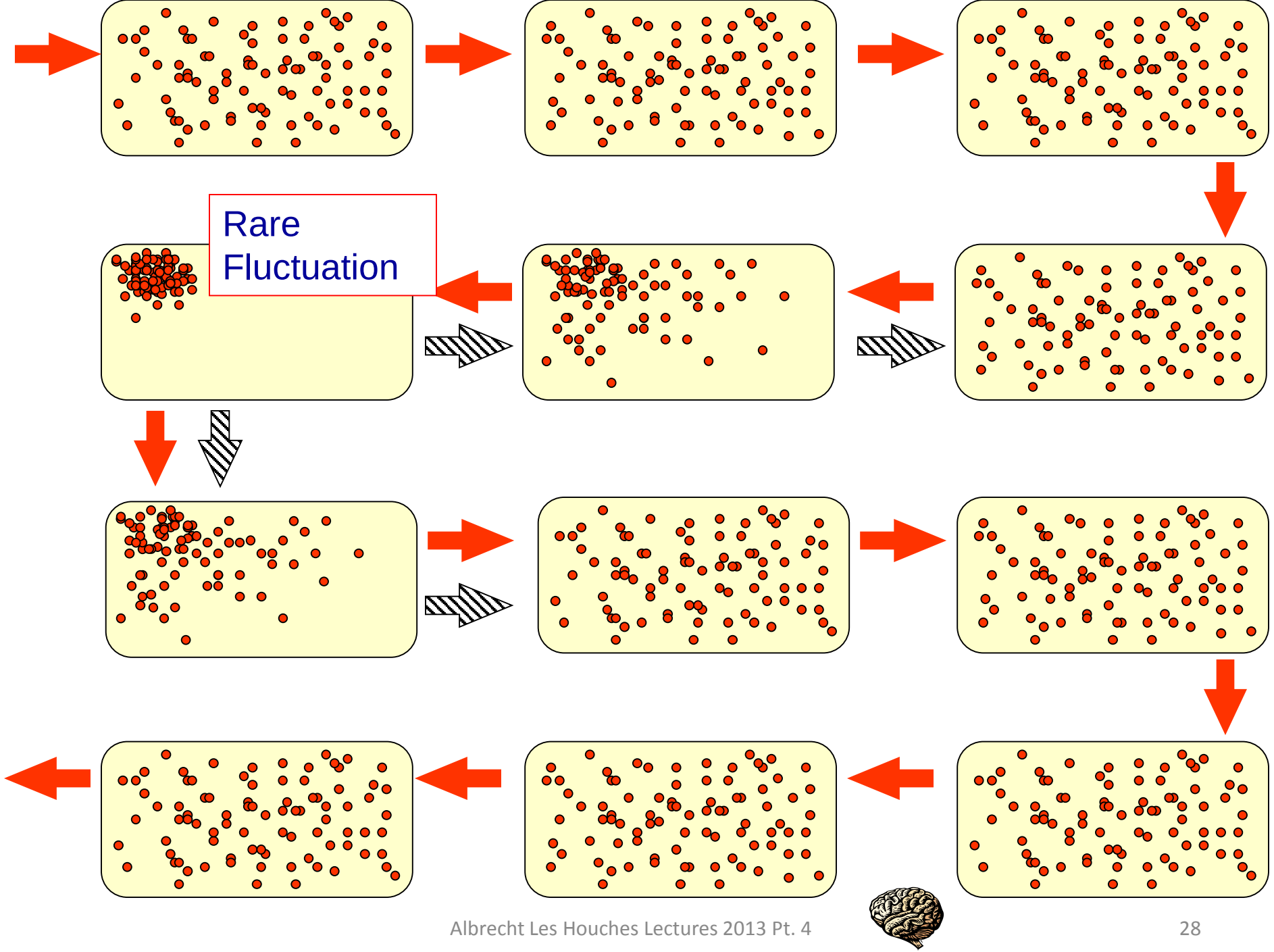
Equilibrium Cosmology

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

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

Dyson et al 2002


Rare
Fluctuation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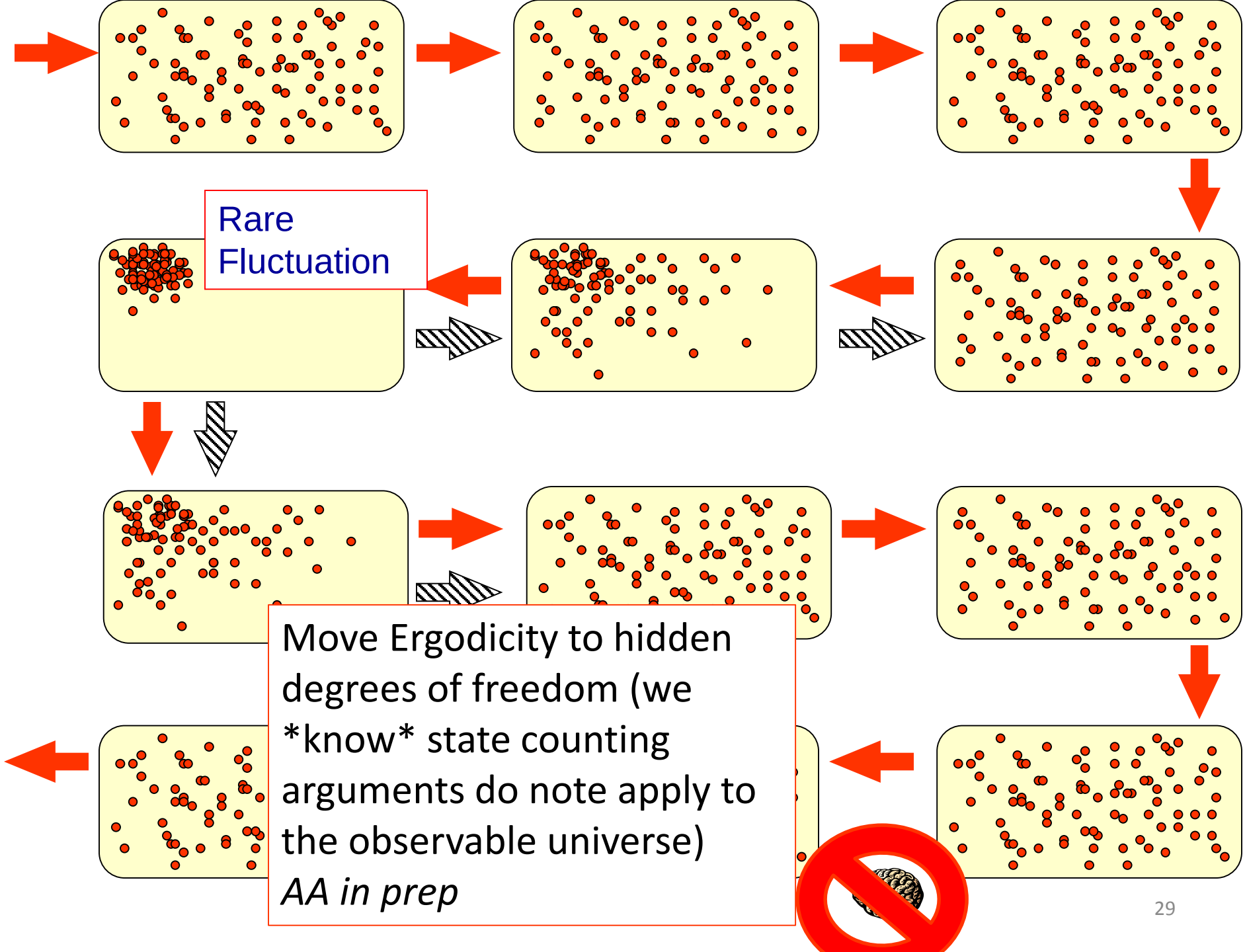
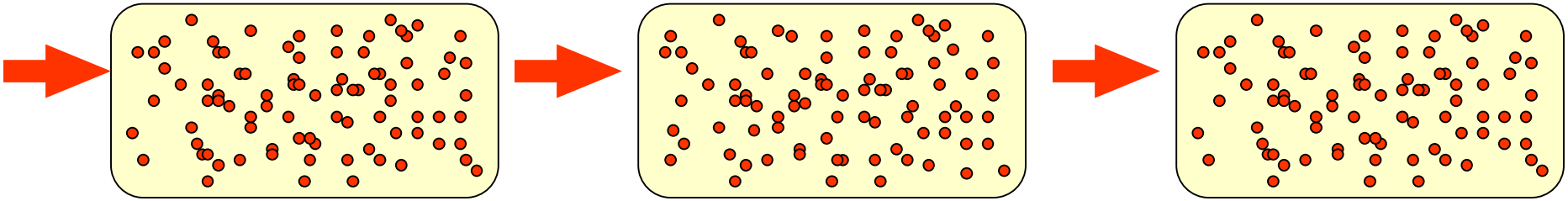


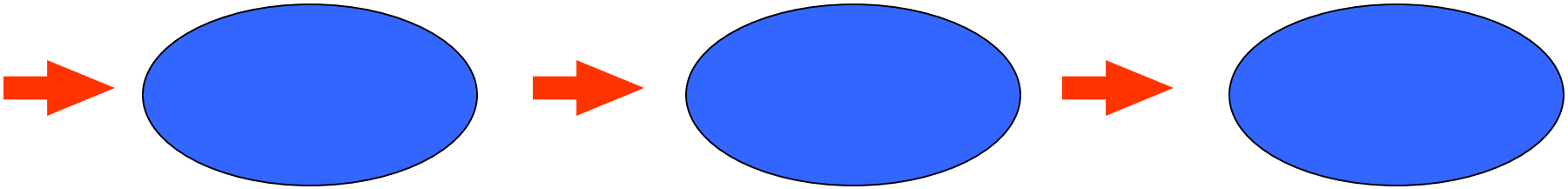
Move Ergodicity to hidden degrees of freedom (we *know* state counting arguments do note apply to the observable universe)

AA in prep

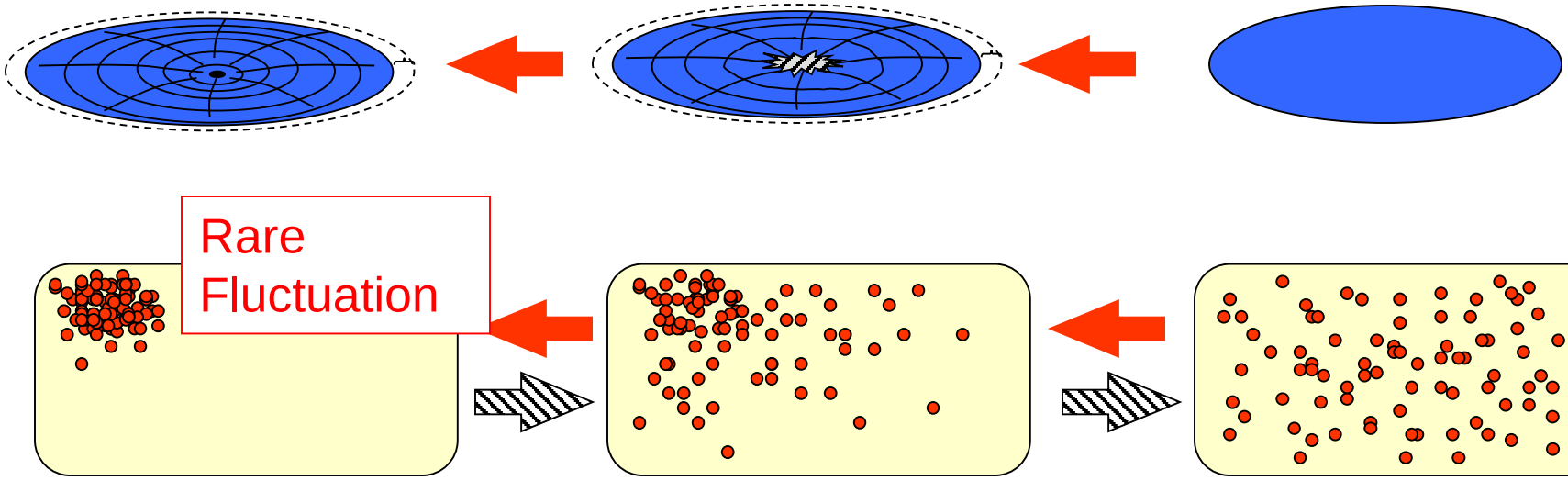
Concept:



Realization:



"de Sitter Space"


Rare
Fluctuation

Fluctuating from dSE to inflation:

- The process of an inflaton fluctuating from late time de Sittter to an inflating state is dominated by the "Farhi-Guth Guven" (FGG) process
- A "seed" is formed from the Gibbons-Hawking radiation that can then tunnel via the Guth-Farhi instanton.
- Rate is well approximated by the rate of seed formation:

$$\propto e^{-\frac{m_s}{T_{GH}}} = e^{-\frac{m_s}{H_\Lambda}}$$

- Seed mass:

$$m_s = \rho_I \left(cH_I^{-1}\right)^3 = 0.0013kg \left(\frac{\left(10^{16} GeV\right)^4}{\rho_I} \right)^{1/2}$$

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Small seed can produce an entire universe ➔
Evade "Boltzmann Brain" problem

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

See also Freivogel et al 2006, Banks 2002

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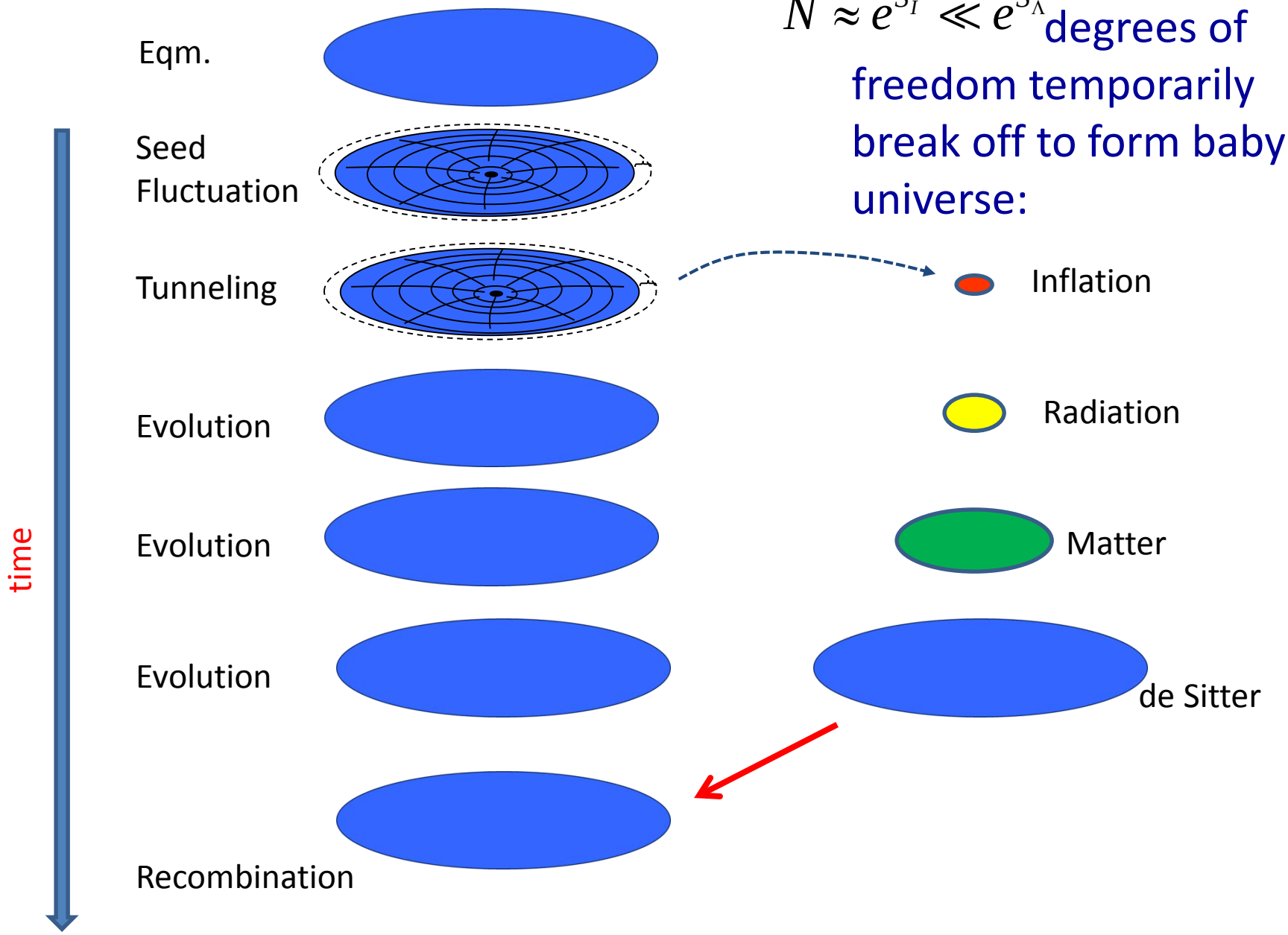
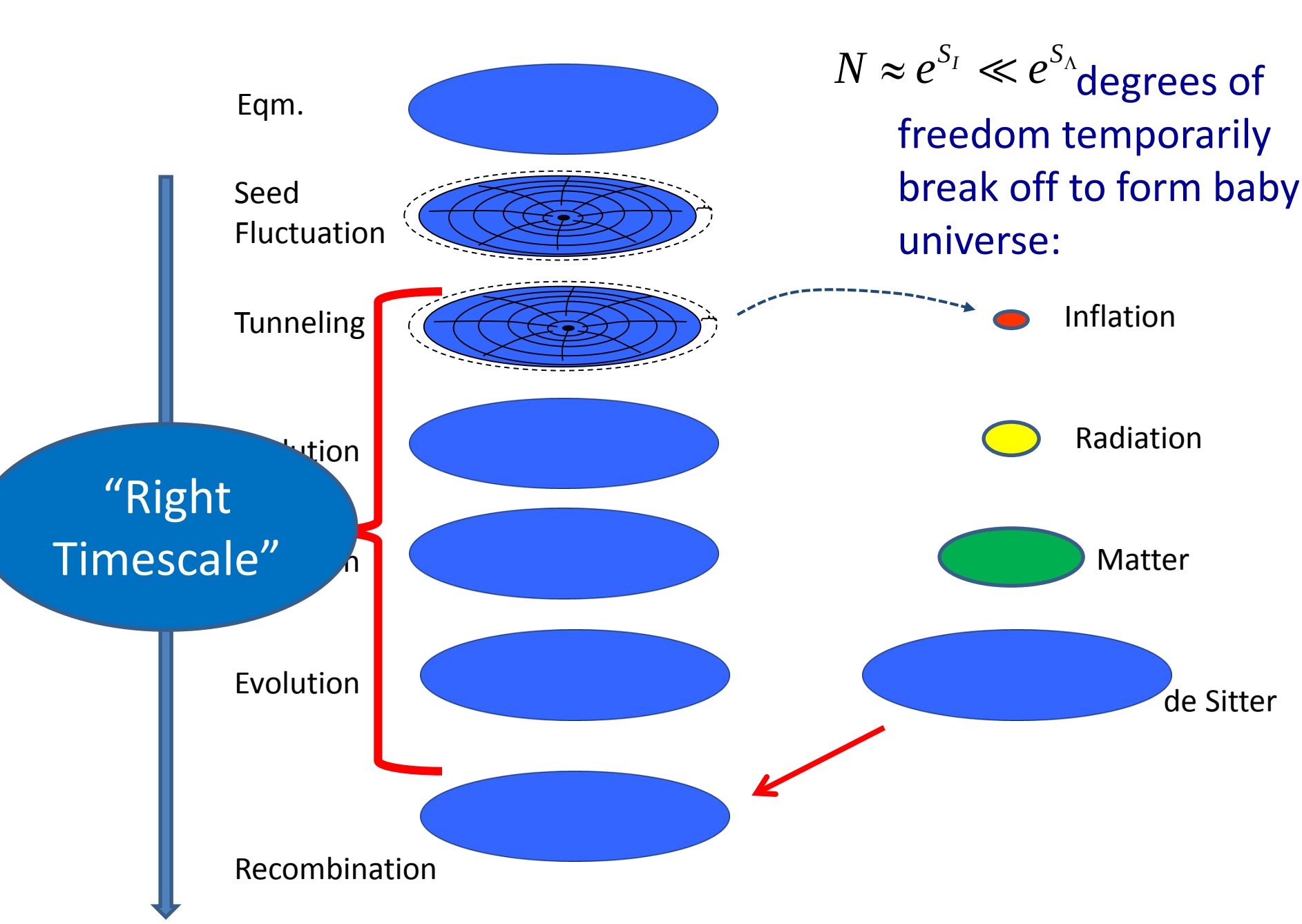

$N \approx e^{S_I} \ll e^{S_\Lambda}$ degrees of freedom temporarily break off to form baby universe:
Eqm.
Seed Fluctuation
Tunneling
Inflation
Evolution
Radiation
Evolution
Matter
Evolution
de Sitter
Recombination
time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Eqm.
Seed Fluctuation
Tunneling
Inflation
Radiation
Matter
de Sitter
"Right Timescale"
Evolution
Recombination

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

- Recurrences
- Eqm.
- Breakdown of continuum field theory

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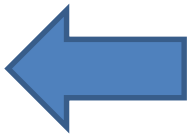
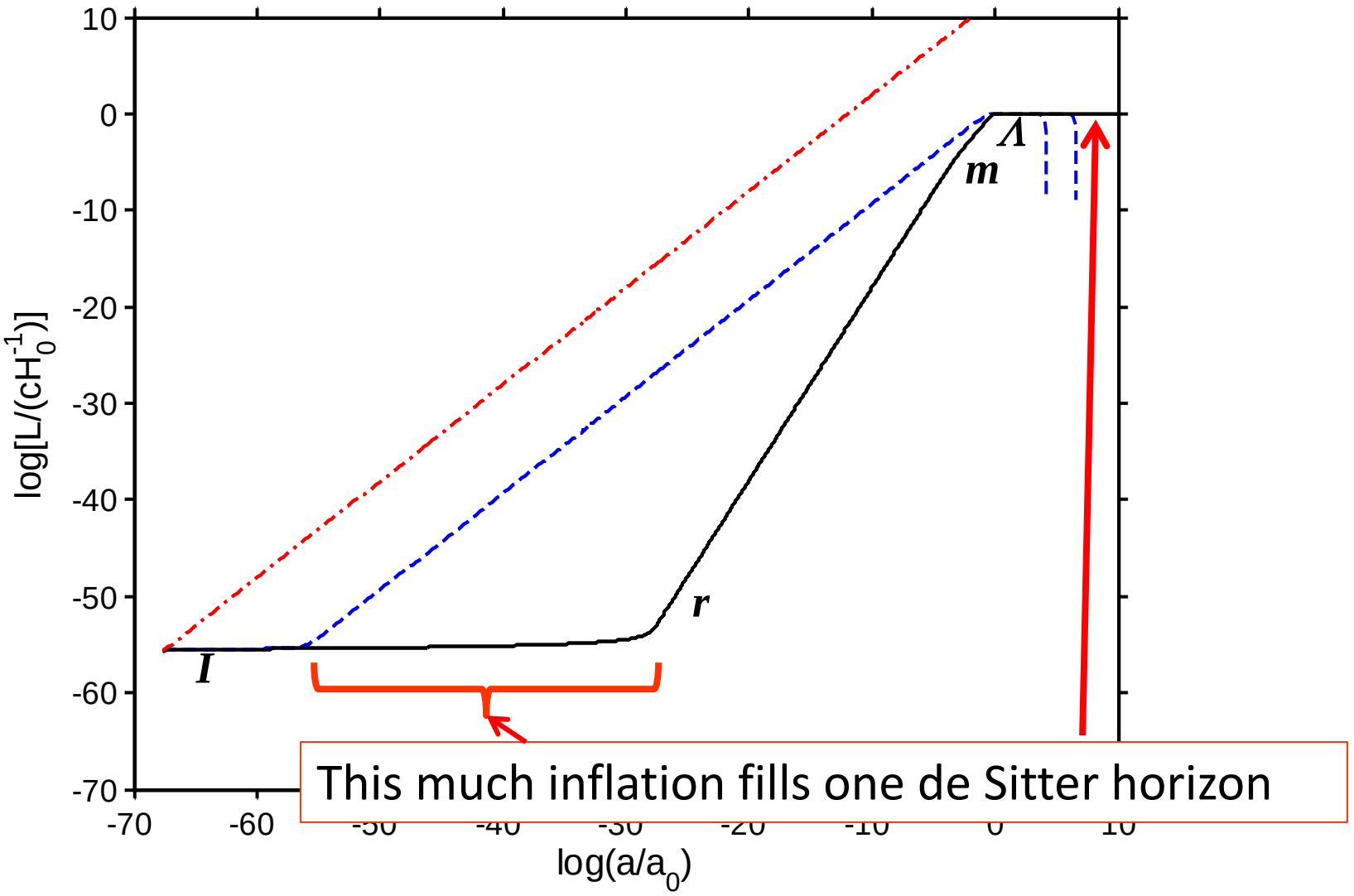
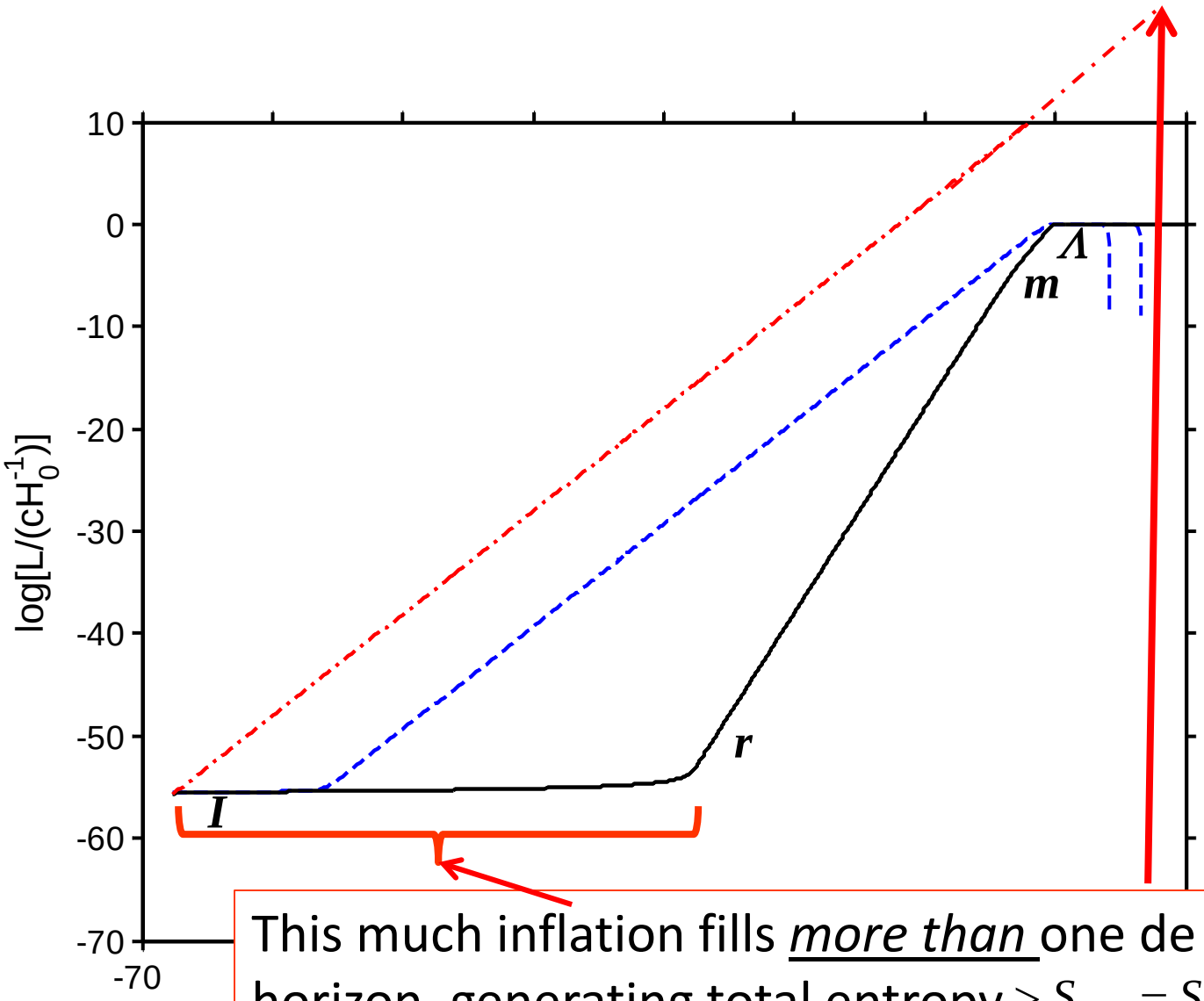
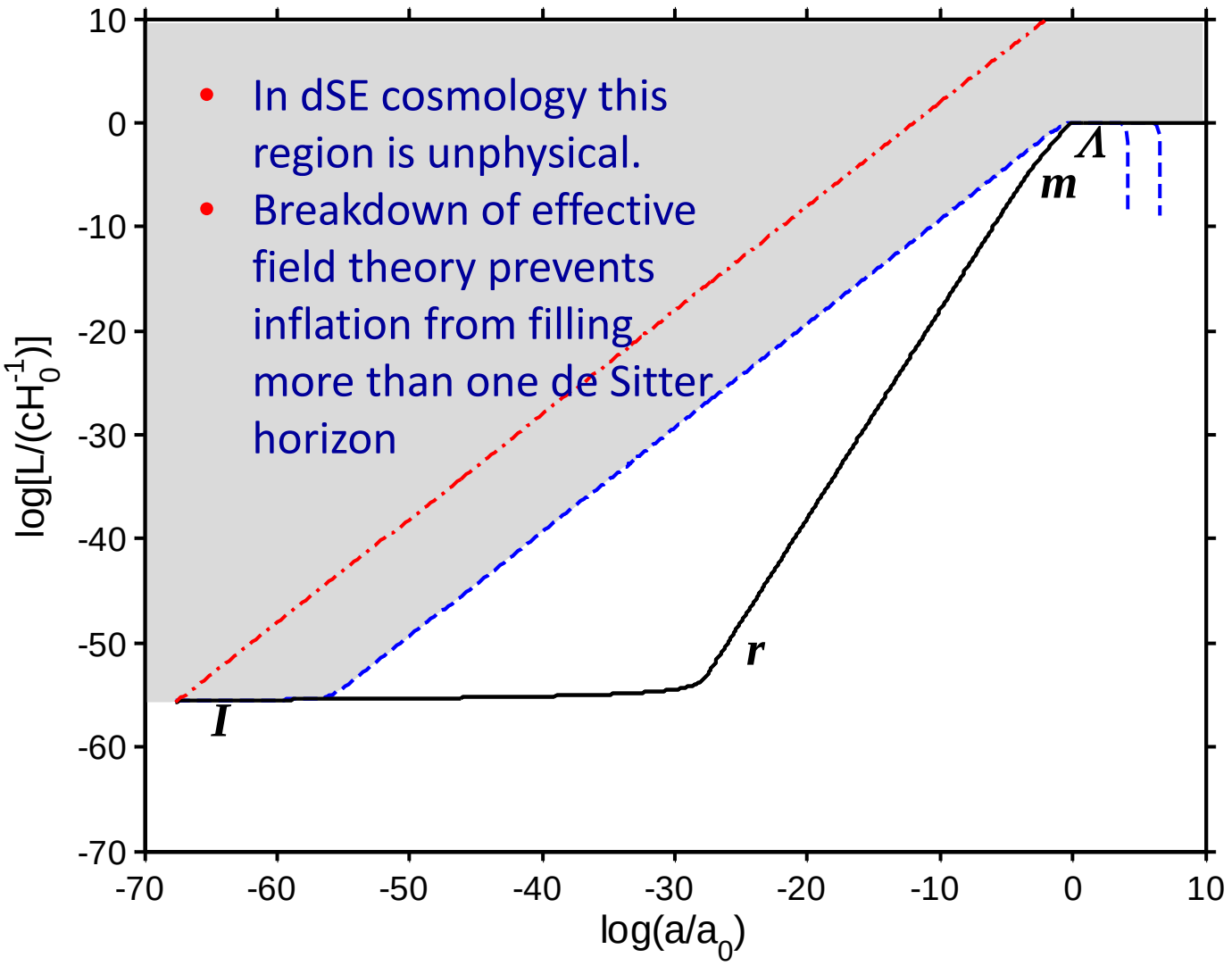
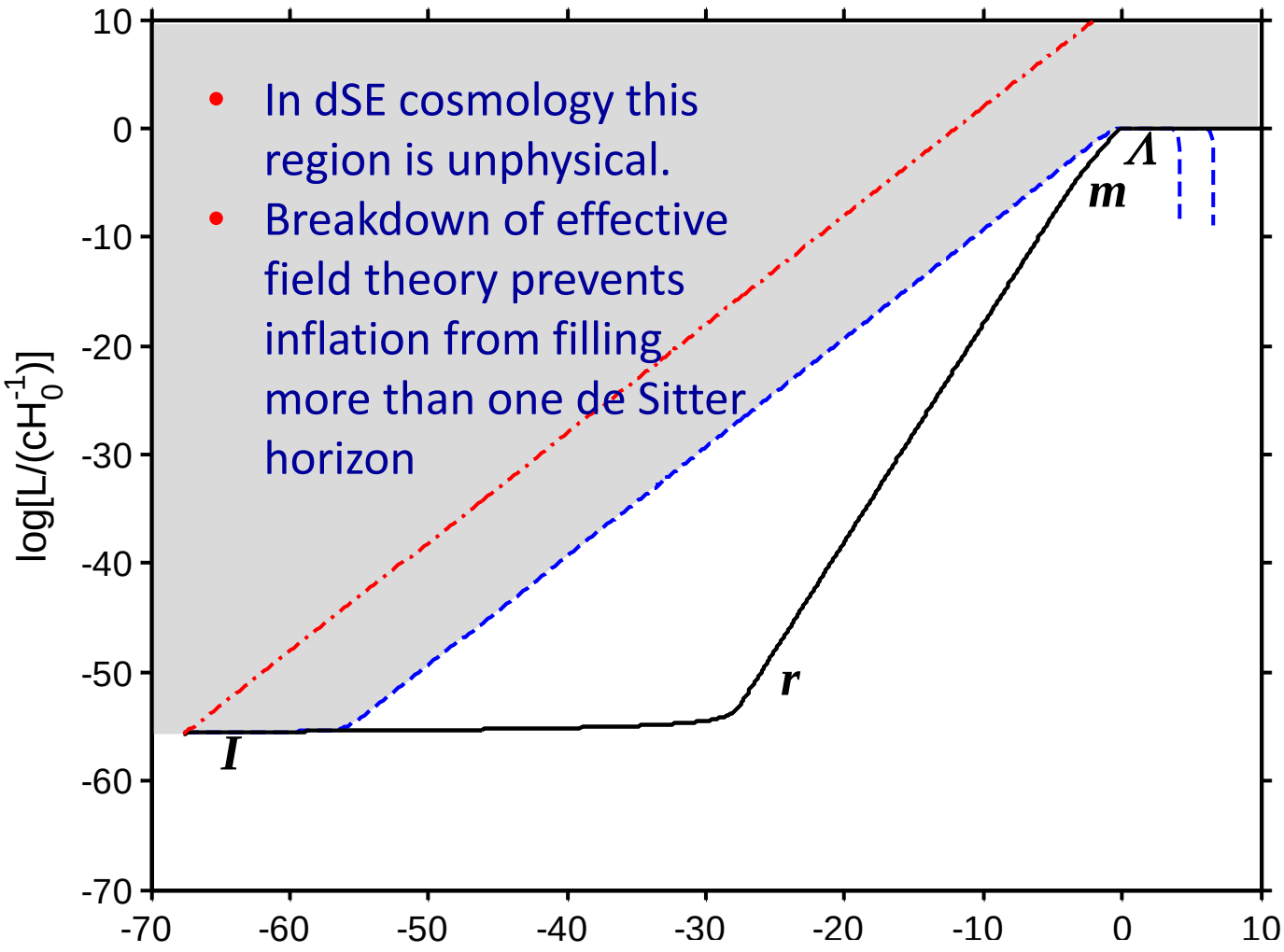



10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
log[L/(cH0-1)]
log(a/a0)
Λ
m
r
I
This much inflation fills one de Sitter horizon

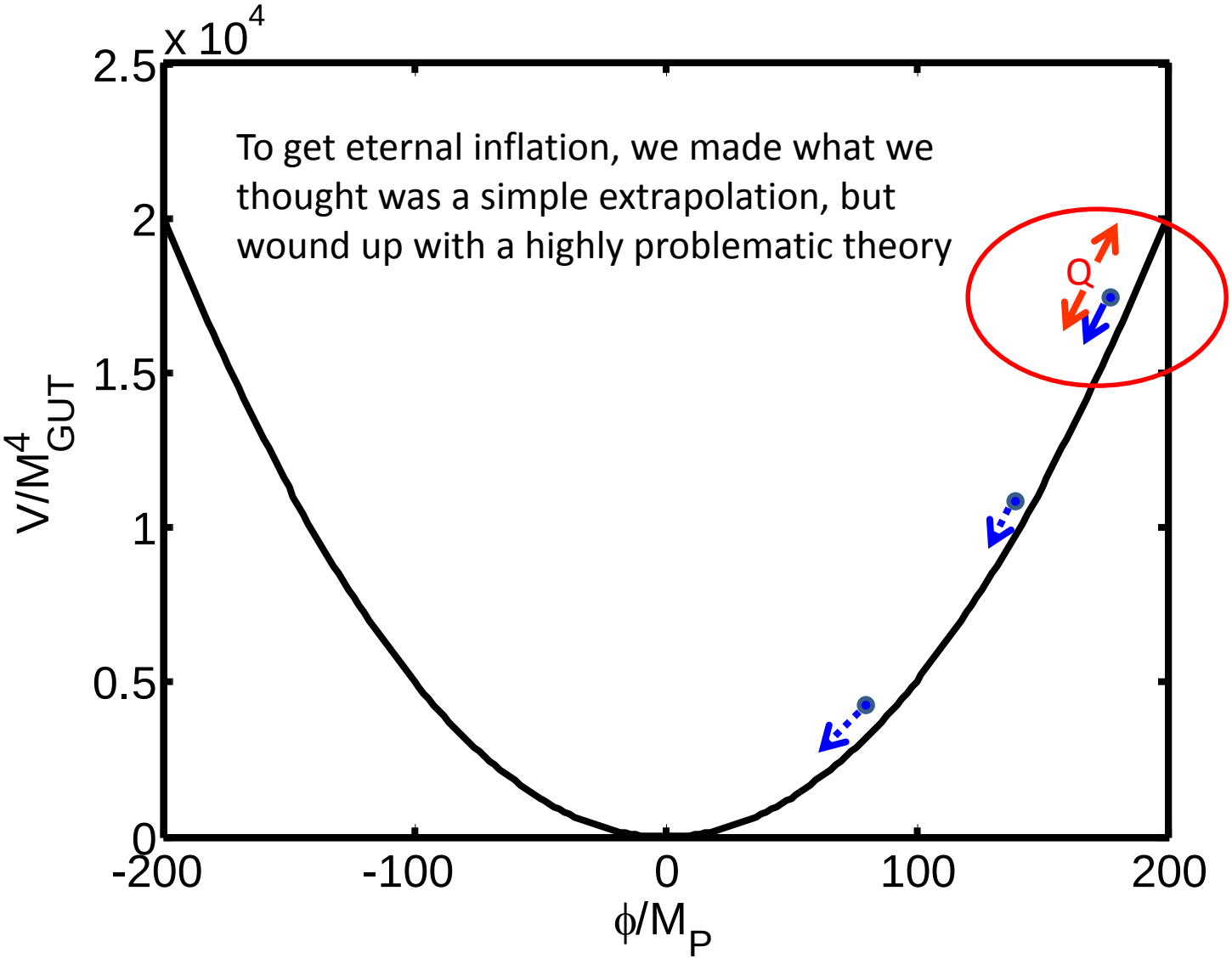


This much inflation fills *more than* one de Sitter horizon, generating total entropy $> S_{Max} = S_{\Lambda}$ and affecting regions beyond the horizon of the observer

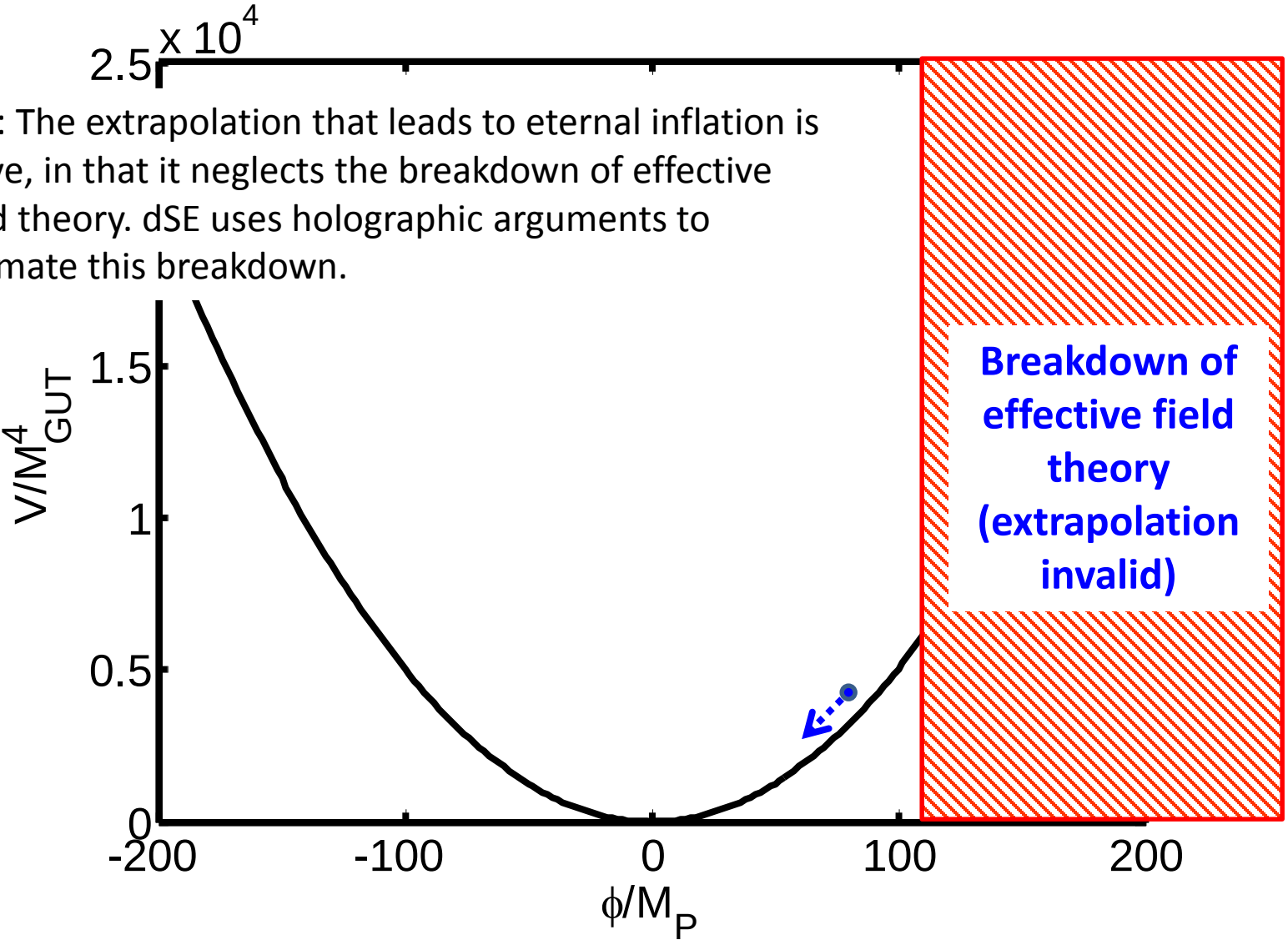

In dSE cosmology this region is unphysical.
Breakdown of effective field theory prevents inflation from filling more than one de Sitter horizon
I
r
m
Λ
log[L/(cH0^-1)]
log(a/a0)
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10



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


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

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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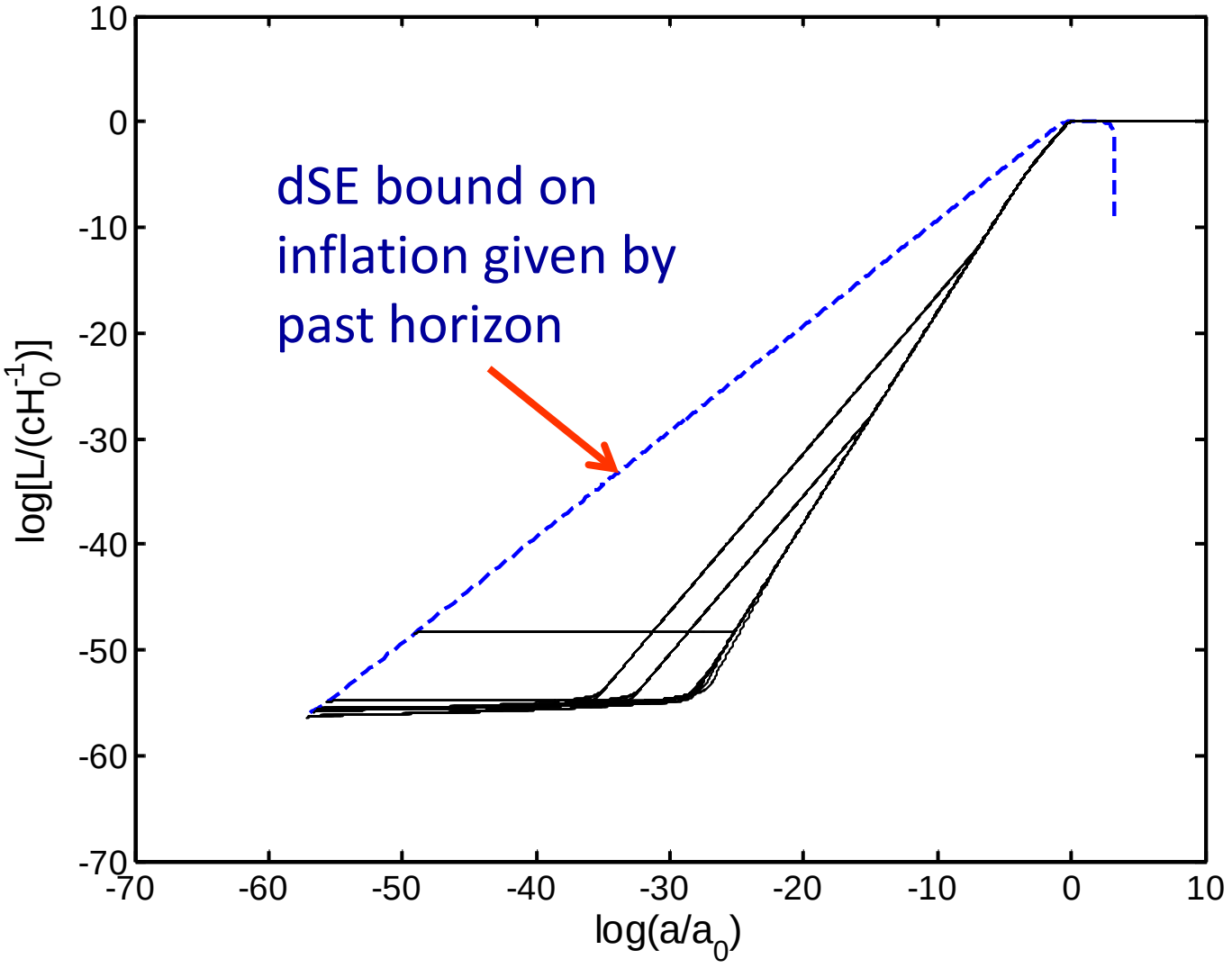
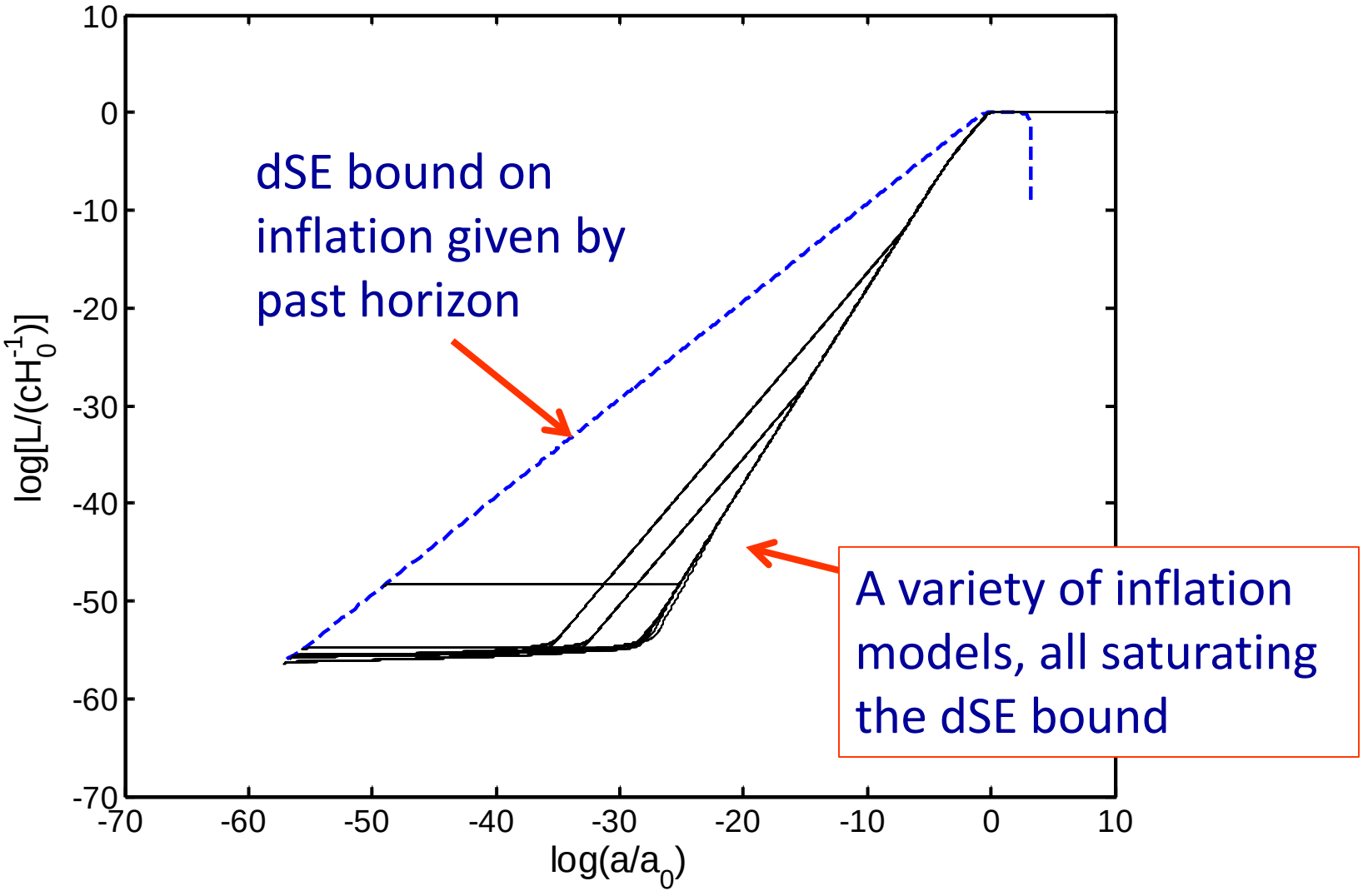
Large ρ_I exponentially favored ➔ saturation of dSE bound


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


dSE bound on inflation given by past horizon
A variety of inflation models, all saturating the dSE bound
log[L/(cH0^-1)]
log(a/a0)
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10

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2. Cosmic curvature from de Sitter Equilibrium cosmology

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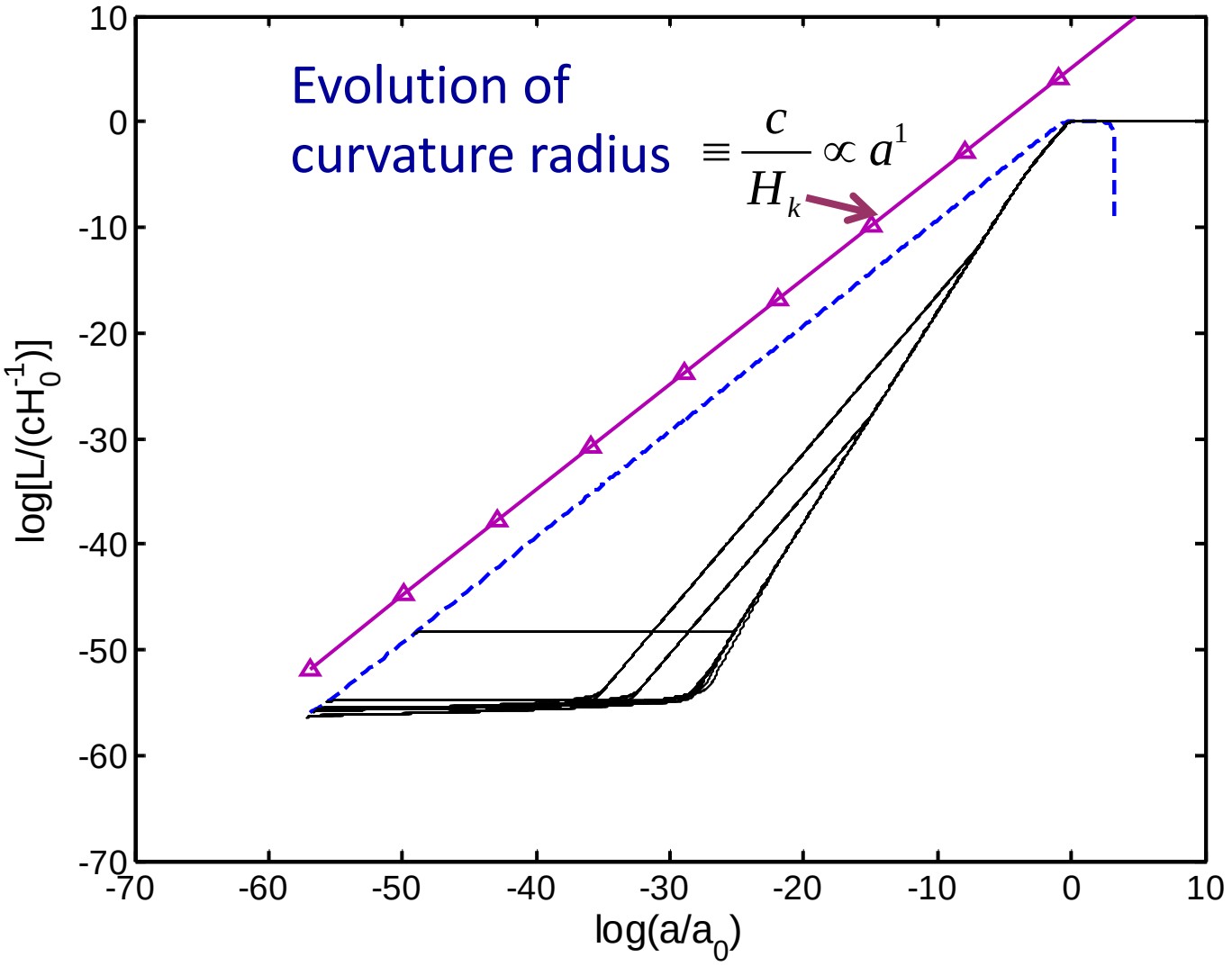
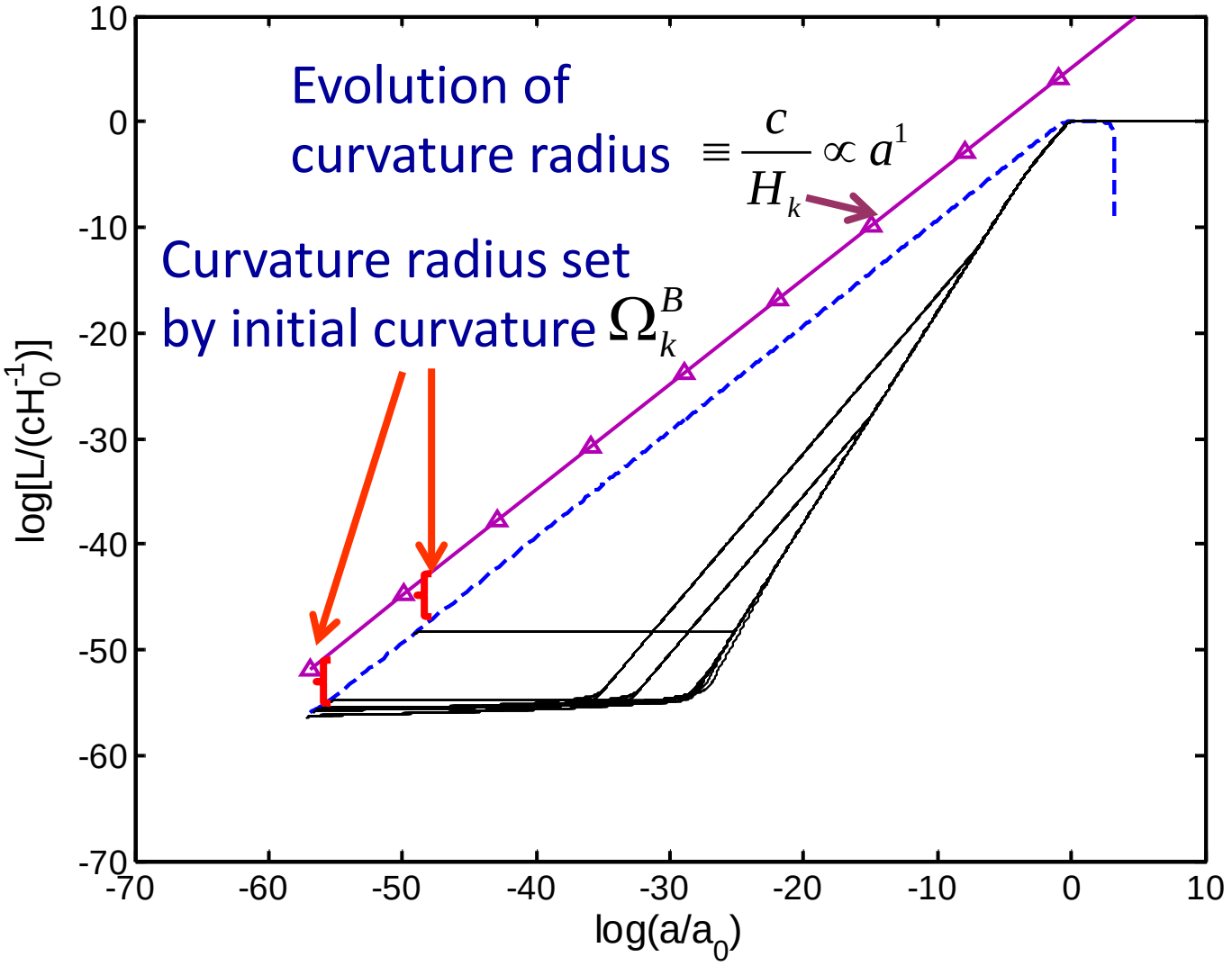
Friedmann Eqn.

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

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



Banks & Fischler & Dyson et al.



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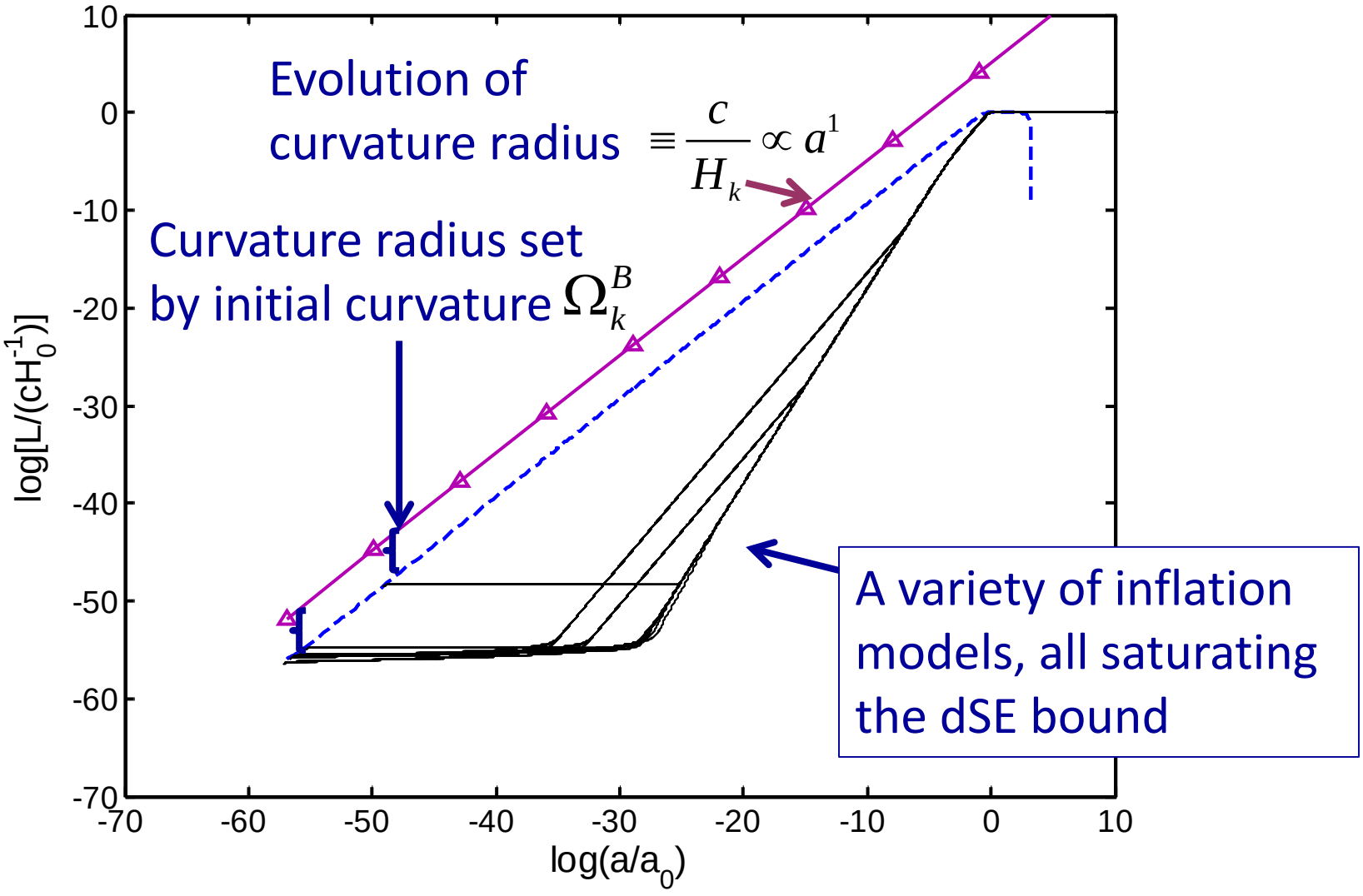
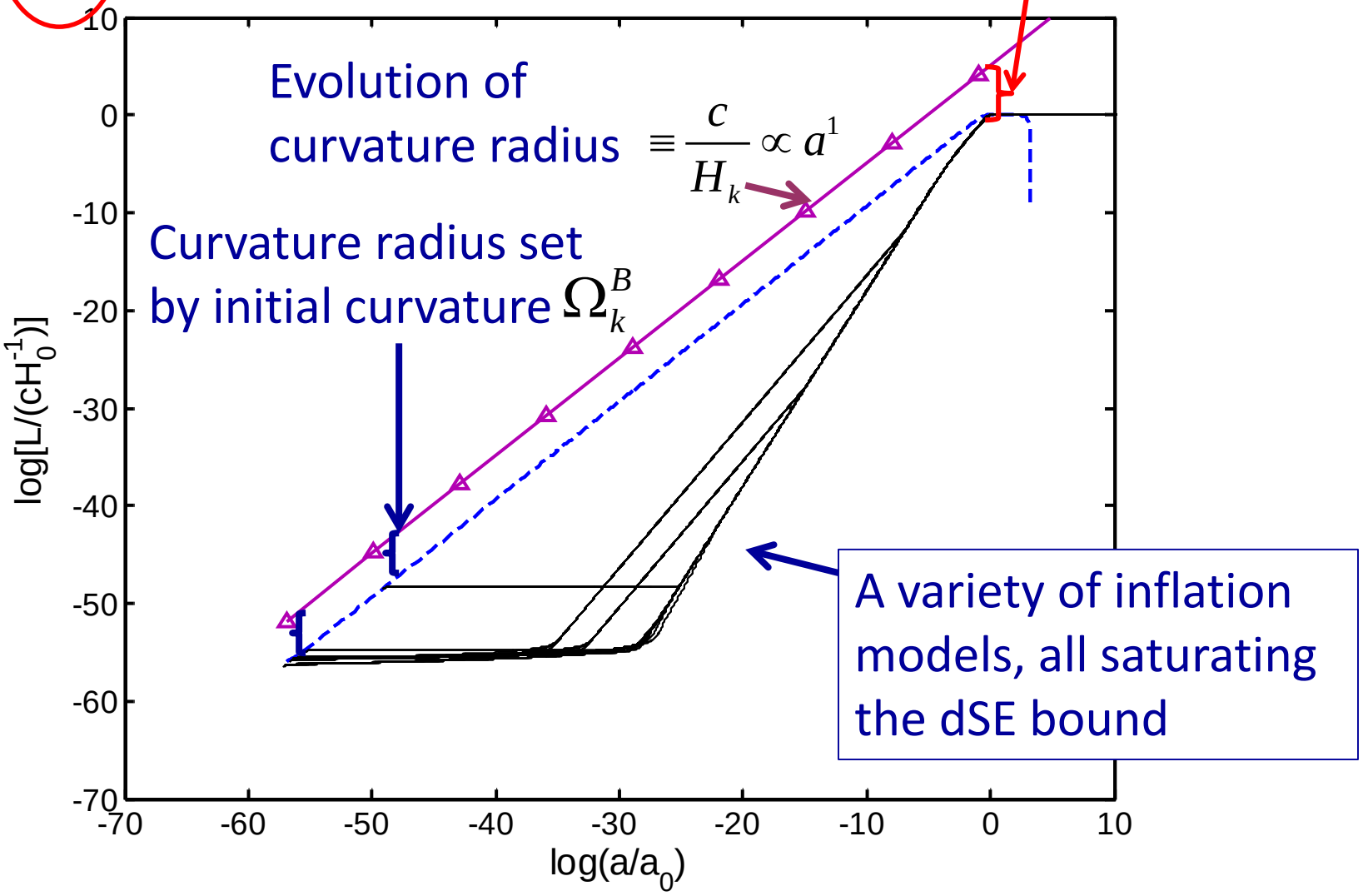
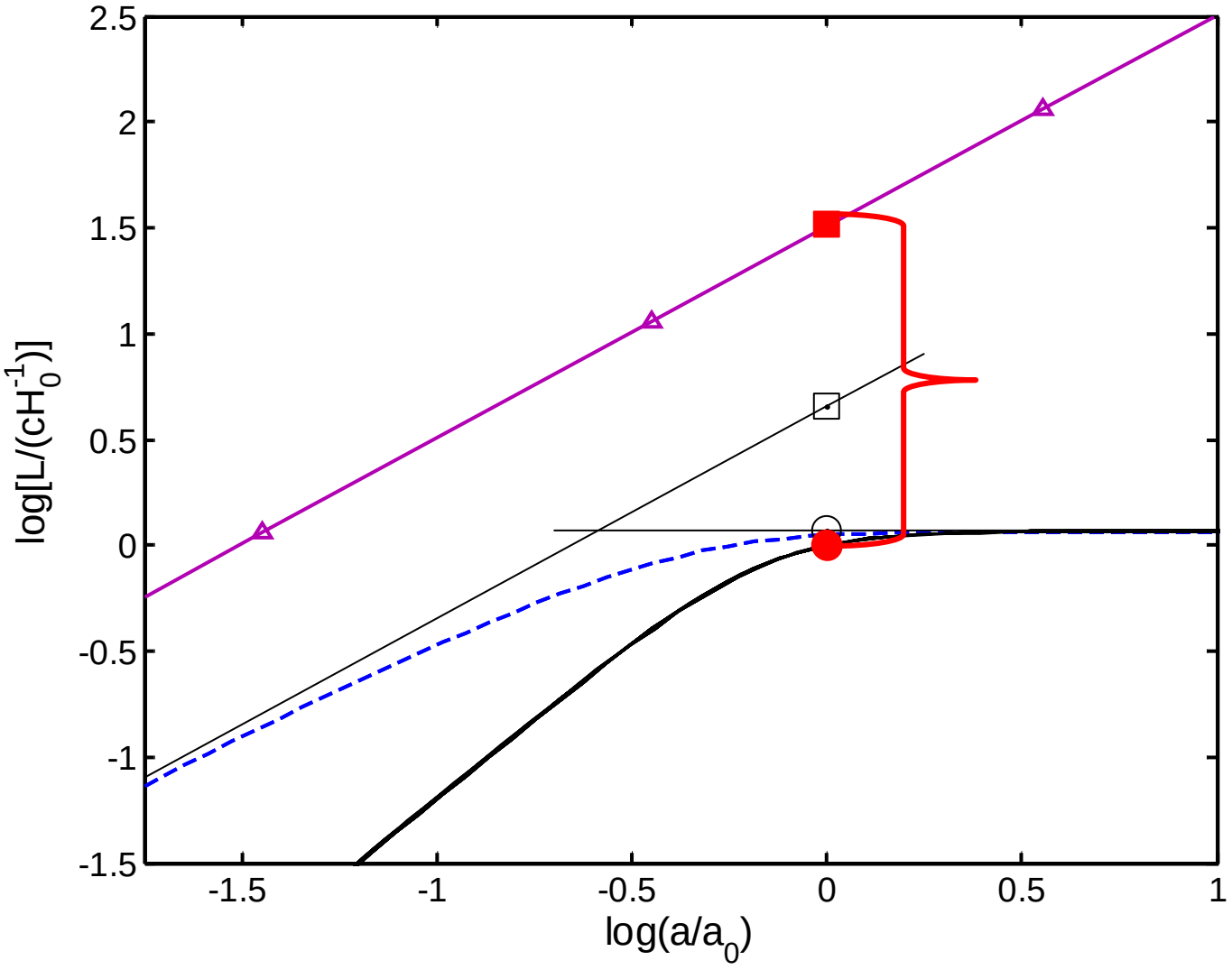

Evolution of
curvature radius $\equiv \frac{c}{H_k} \propto a^1$
Curvature radius set
by initial curvature Ω_k^B
A variety of inflation
models, all saturating
the dSE bound
log[L/(cH$_0^{-1}$)]
log(a/a$_0$)
10
0
-10
-20
-30
-40
-50
-60
-70
-70
-60
-50
-40
-30
-20
-10
0
10

$$\Omega_k \equiv \frac{\rho_k}{\rho_c} = \left(\frac{H_k}{H_0}\right)^2 \equiv \left(\frac{R_{H_0}}{R_k}\right)^2$$ 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 Ω_k^B
- Inflation dilutes the curvature, but dSE cosmology has a minimal amount of inflation

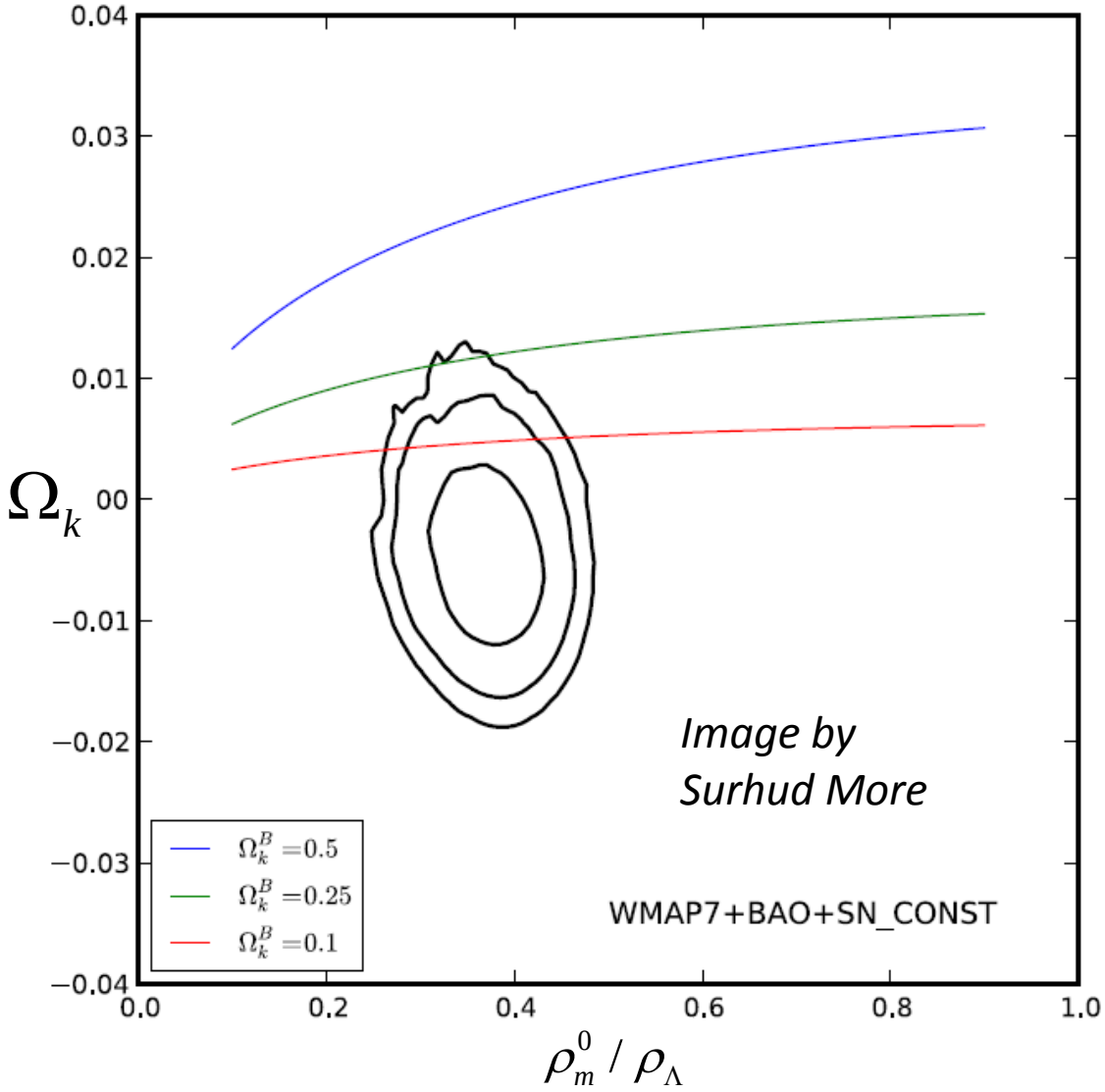
$$\Omega_k = \frac{1}{g^2} \frac{\Omega_k^B}{\left(\frac{\rho_m^0}{\rho_\Lambda} + \frac{\rho_k^0}{\rho_\Lambda} + 1 \right)}$$

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 Ω_k from dSE cosmology is:

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



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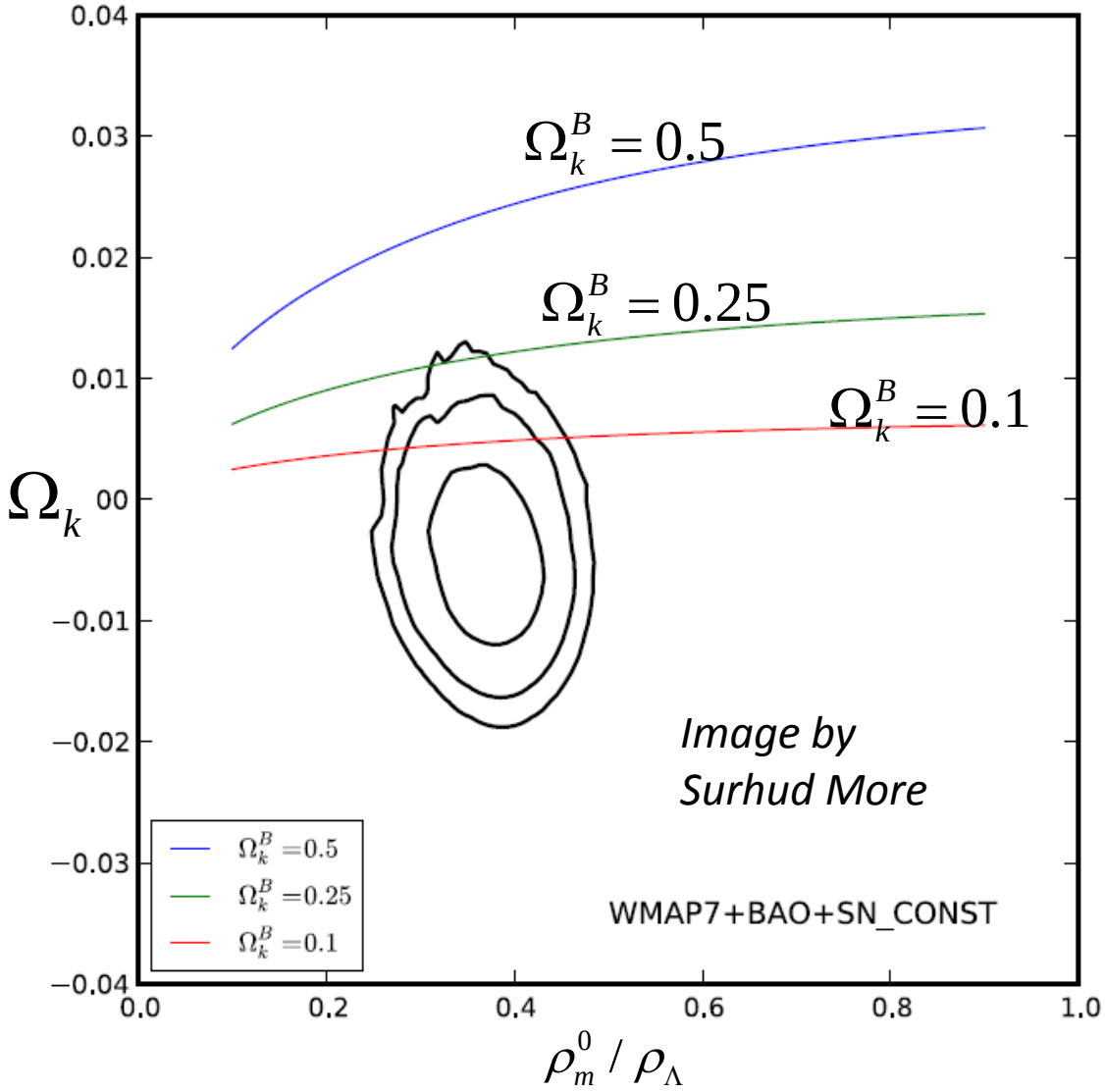

Work in progress on expected values of Ω_k^B (Andrew Ulvestad & AA)

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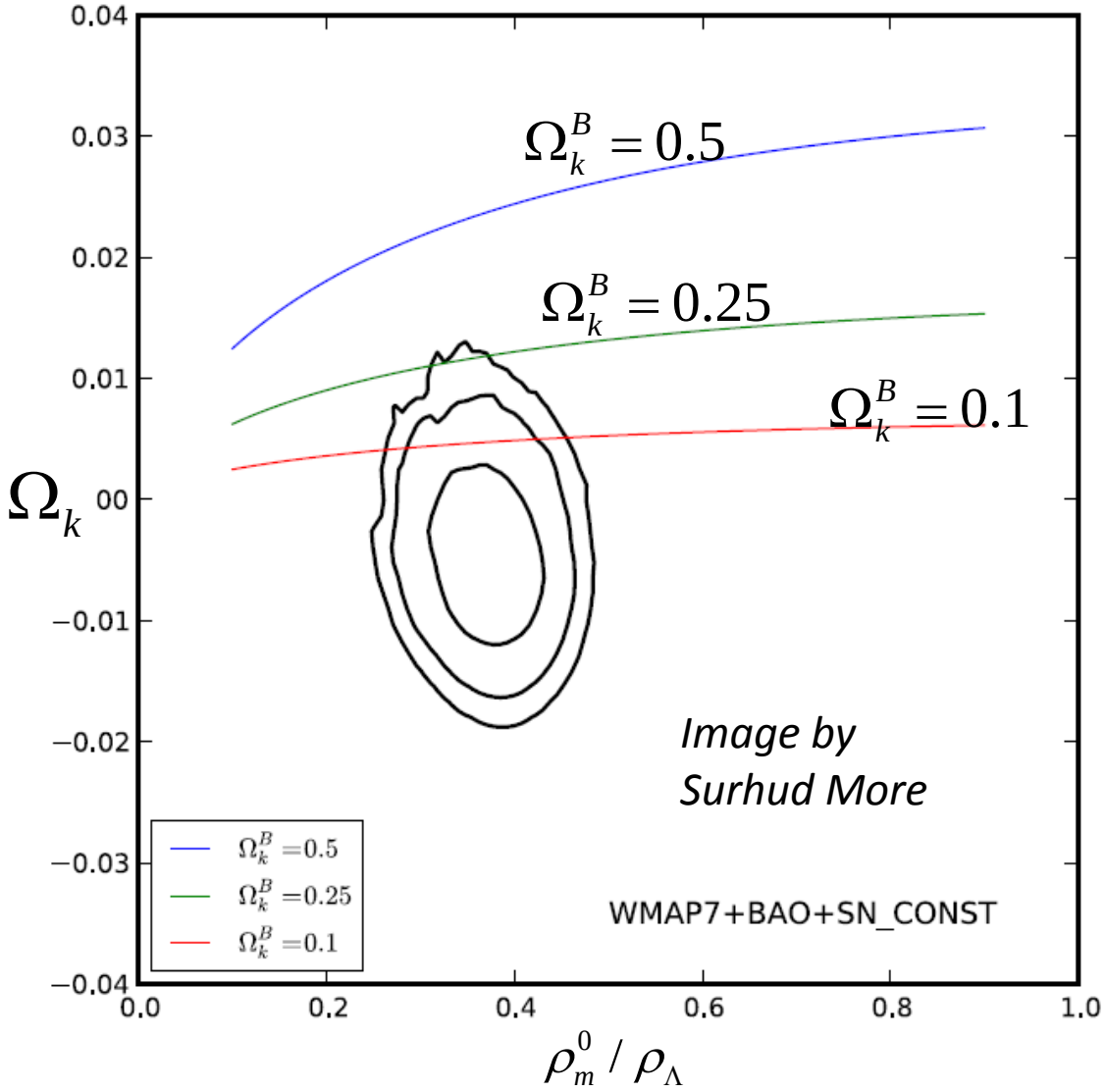
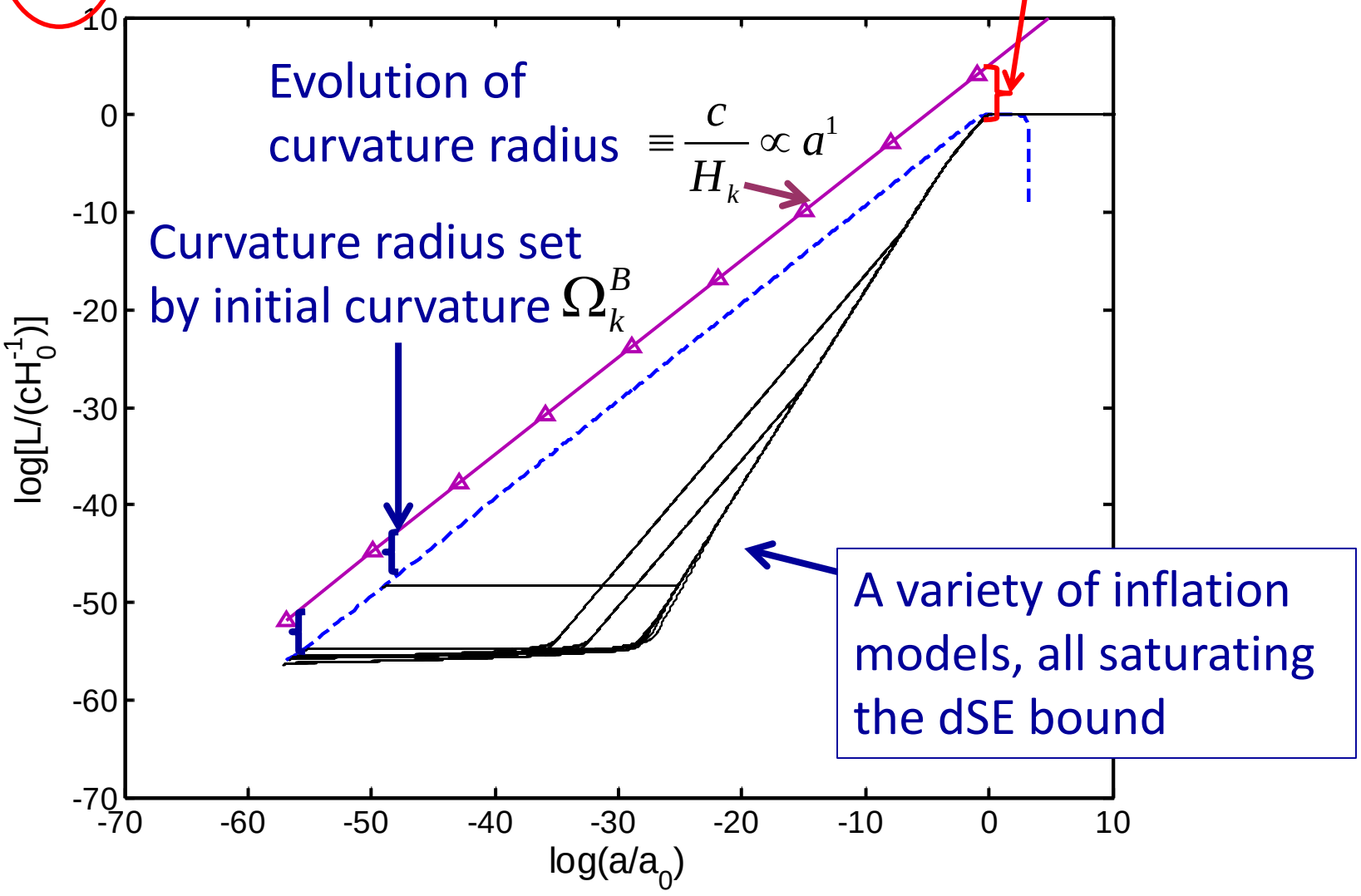


Work in progress on expected values of Ω_k^B (Andrew Ulvestad & AA)

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



Conclusions (Part 4)

- The search for a "big picture" of the Universe that explains why the region we observe should take this form has proven challenging, but has generated exciting ideas.
- We know we can do science with the Universe
- It appears that there is something right about cosmic inflation
- dSE cosmology offers a finite alternative to the extravagant (and problematic) infinities of eternal inflation (plus, no initial conditions problem)
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- dSE cosmology offers a finite alternative to the extravagant (and problematic) infinities of eternal inflation (plus, no initial conditions problem)
- Predictions of observable levels of cosmic curvature from dSE cosmology will give an important future test (also, alternative to bubble start)

Les Houches Lectures on Cosmic Inflation

Four Parts

1) Introductory material

2) Entropy, Tuning and Equilibrium in Cosmology

3) Classical and quantum probabilities in the multiverse

4) de Sitter equilibrium cosmology

End Part 4

Andreas Albrecht; UC Davis
Les Houches Lectures; July-Aug 2013

Some parting thoughts

- We are *so* fortunate to be doing cosmology in these times
- Fantastic successes (slow roll inflation & structure)
- Great puzzles and challenges (the Guth dream, dark energy)
- Which ideas to import from everyday physics, which to throw out?
- Which ideas are too radical, which not radical enough?
- Let us all make the most of these amazing opportunities, and navigate these difficult issues as bravely and energetically as possible!