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

Les Houches Lectures Part 2

Entropy, Tuning and Equilibrium in Cosmology

Andreas Albrecht
UC Davis
Les Houches Lectures
July 2013

Part 2 outline

1. Entropy and tuning

2. Equilibrium (& toy models)

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2. Equilibrium (& toy models)

Intro

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

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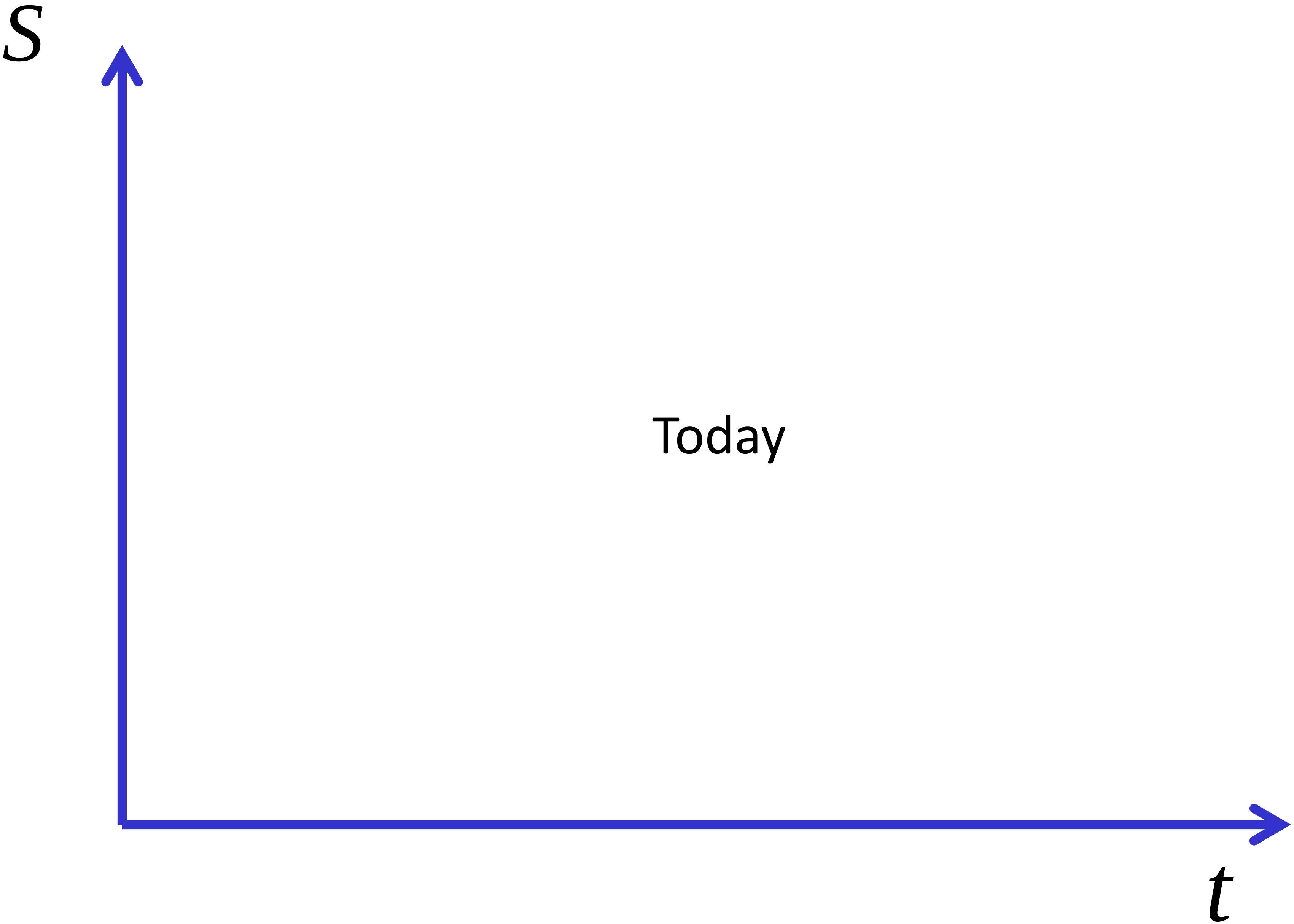
- 2^{nd} law tells us that the early universe was dynamically "unusual" (low entropy, past hypothesis)
- Inflation is supposed to teach us that the early universe was dynamically "typical"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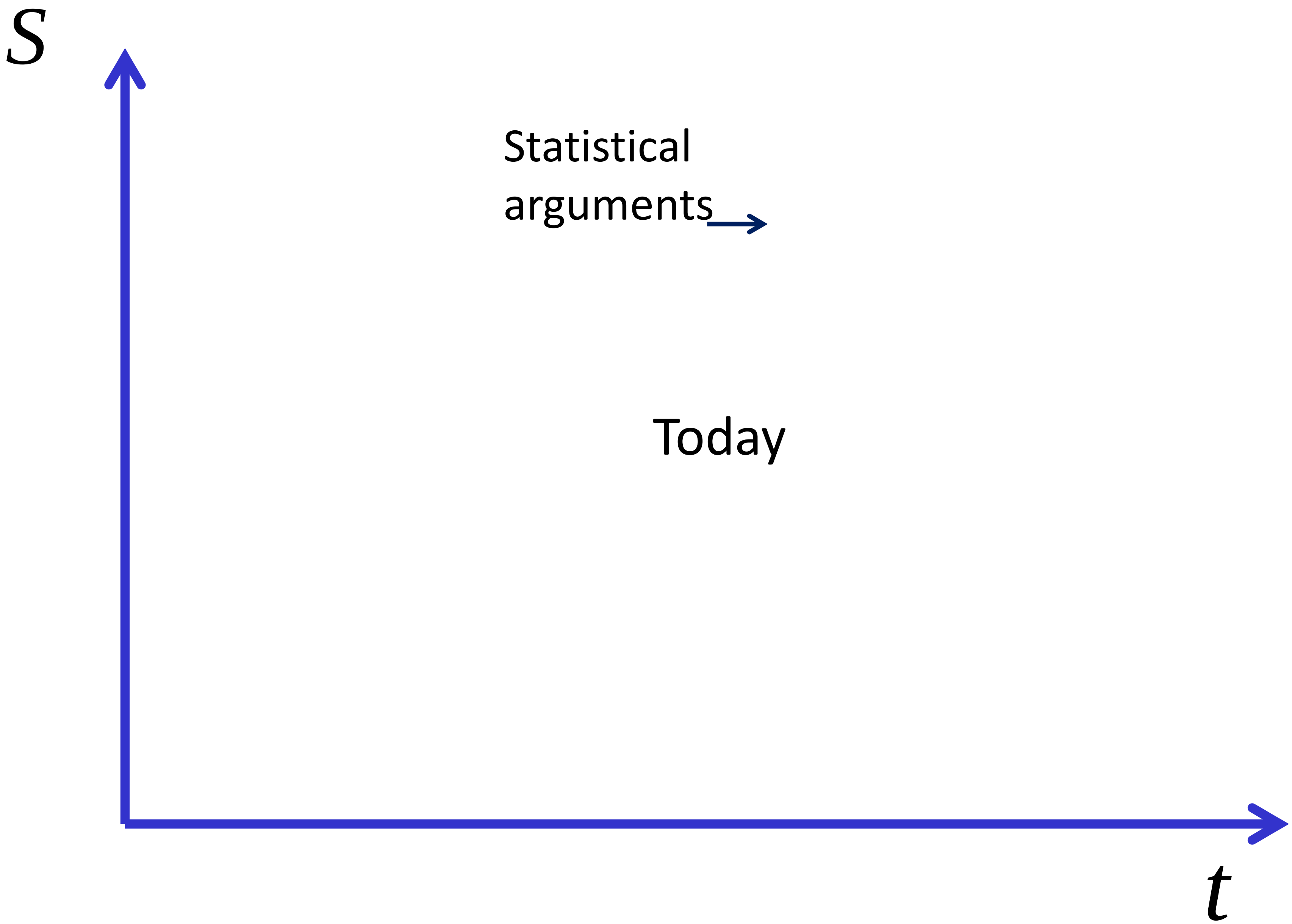
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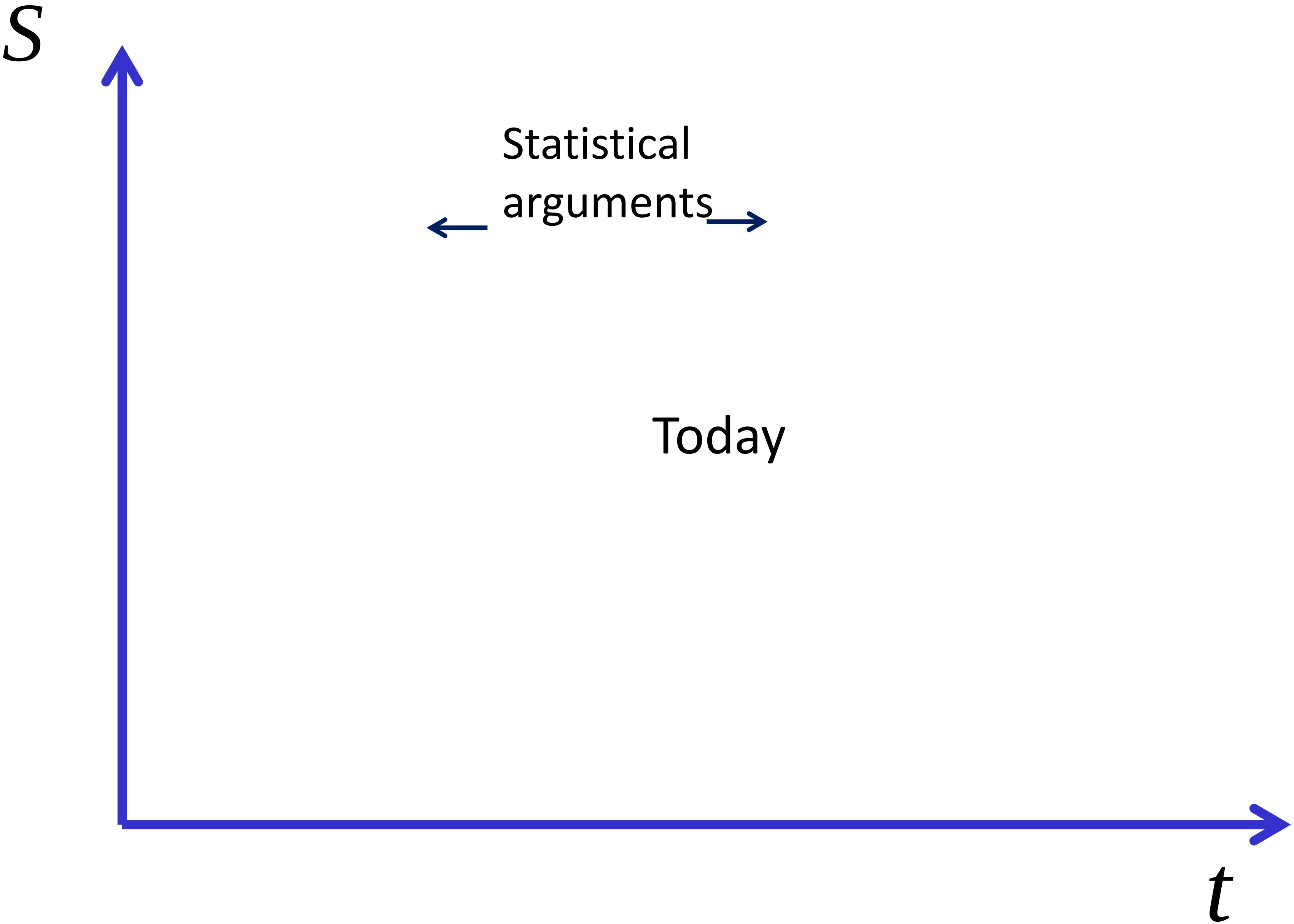
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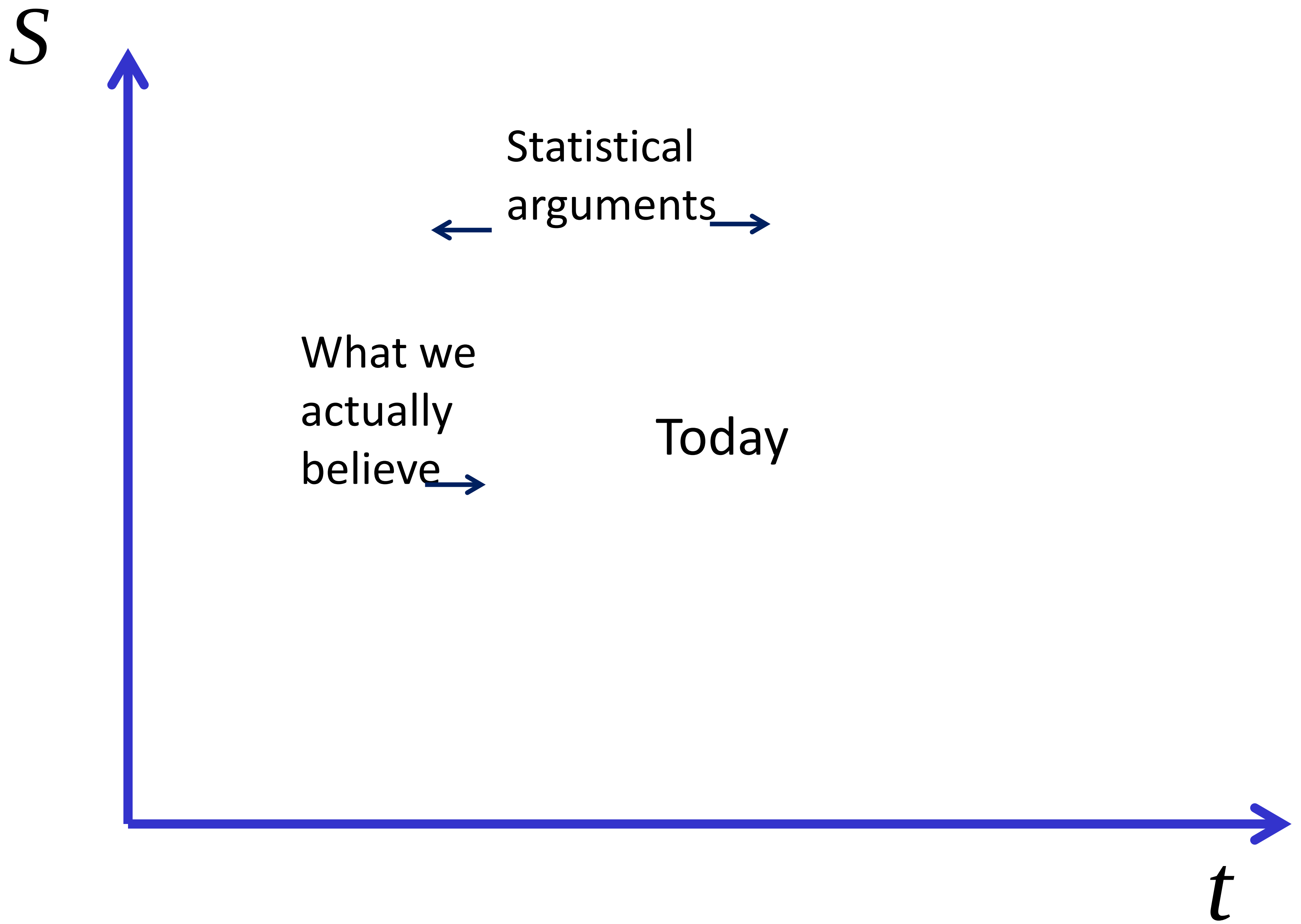
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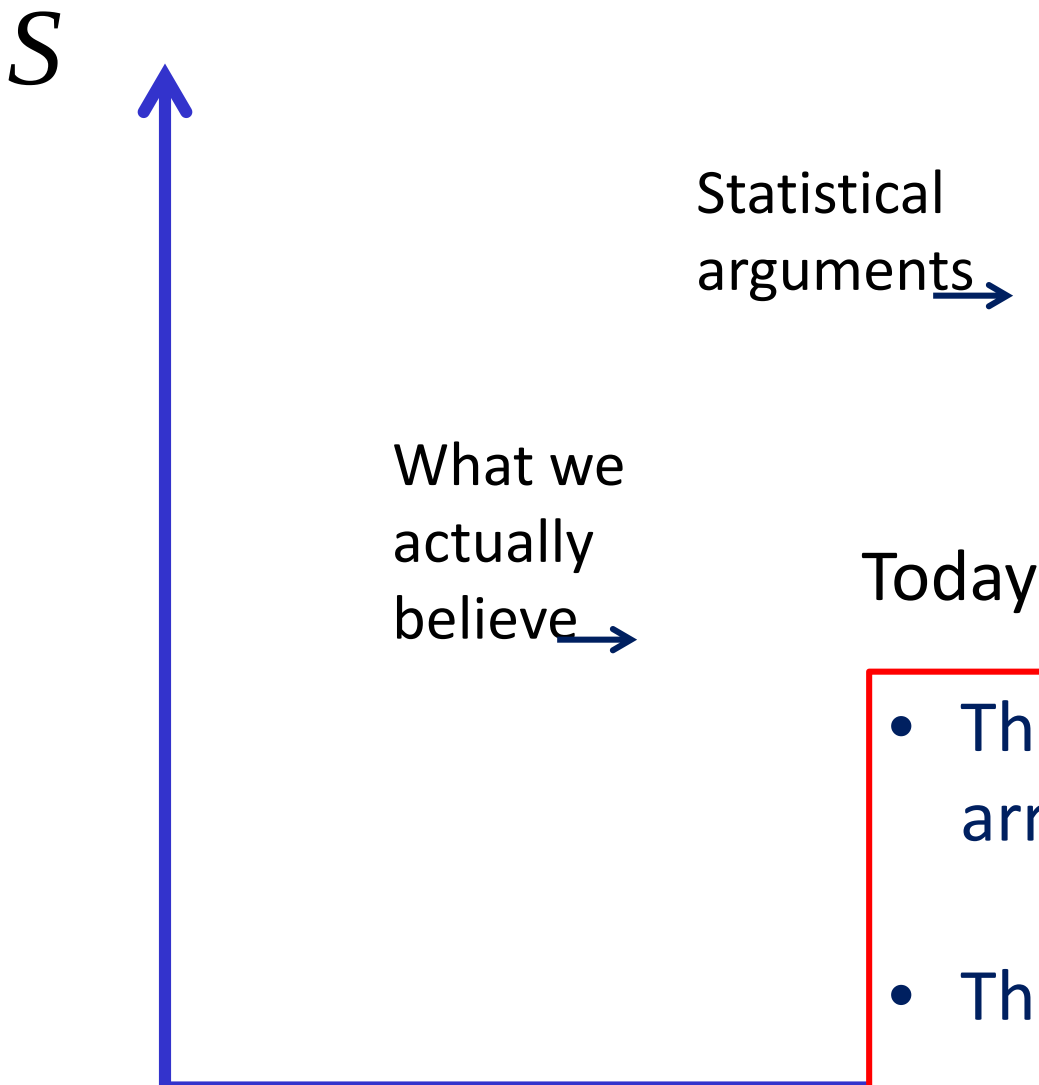
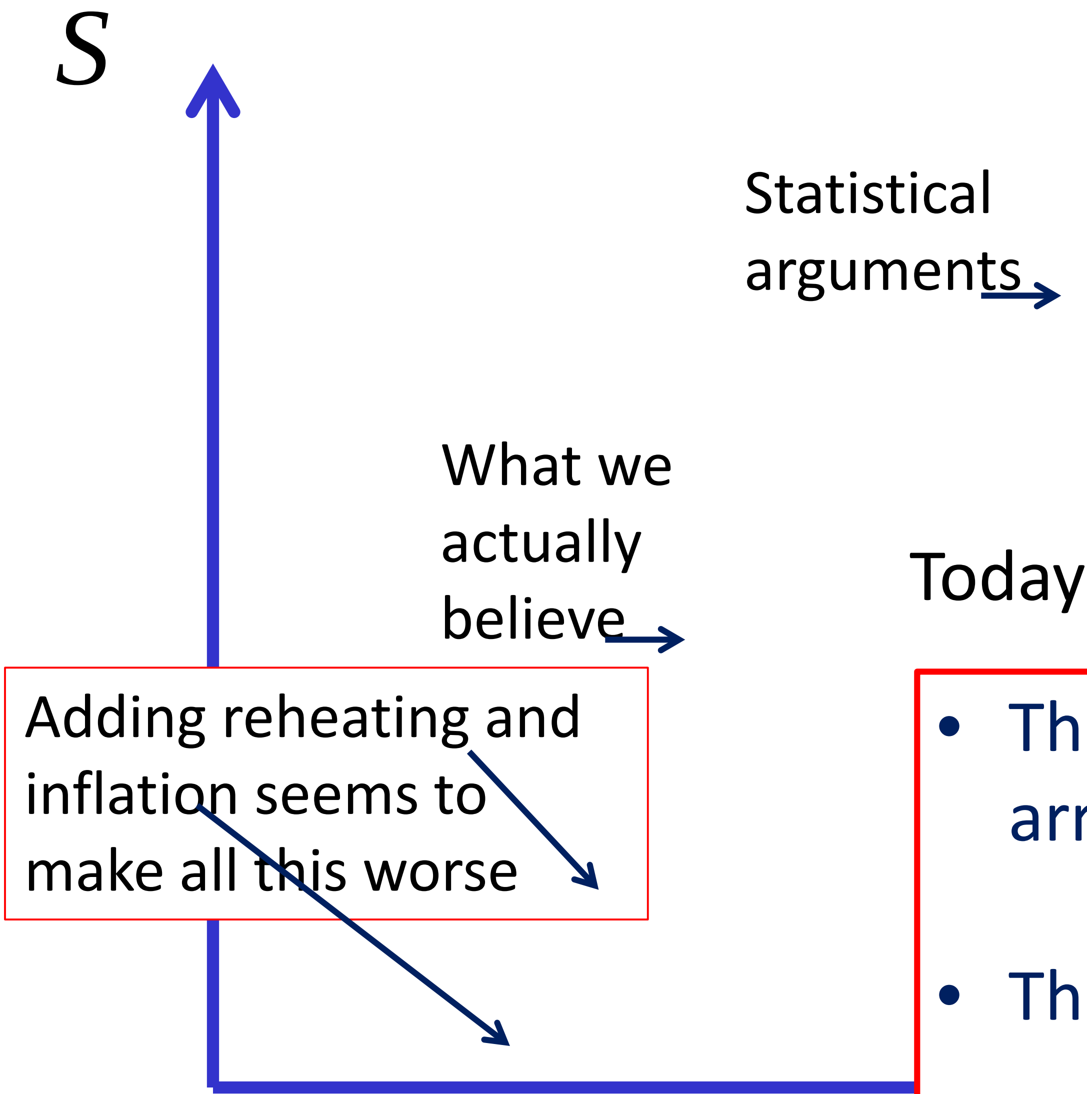


- The thermodynamic arrow of time
- The “past hypothesis”

= “Fine tuning”



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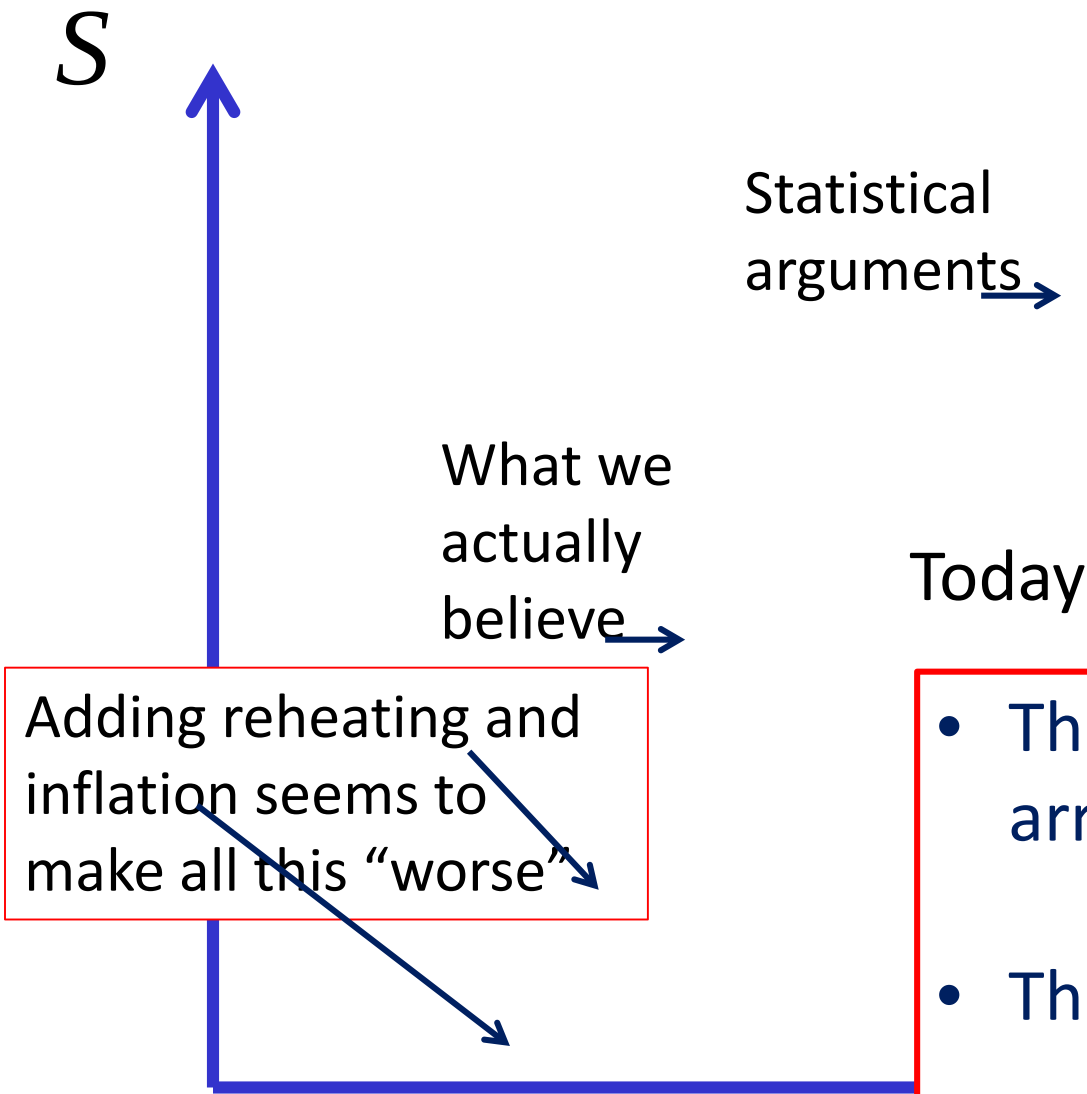


- The thermodynamic arrow of time
- The "past hypothesis"

= "Fine tuning"

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

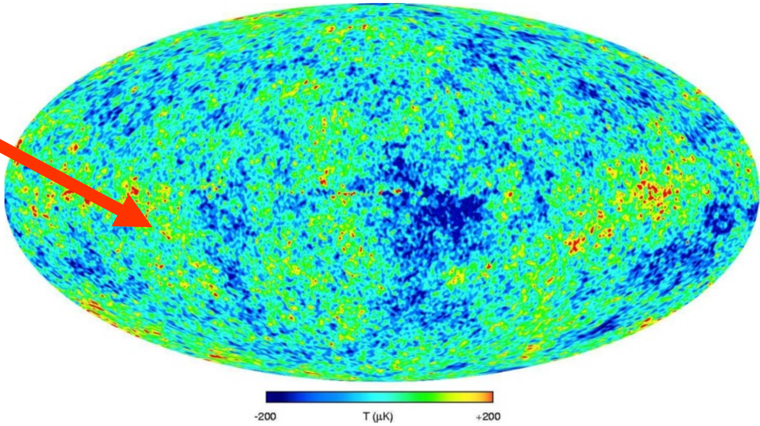
The early universe is very homogeneous on scales $l > l_{Jeans}$

→ very far from Eqm. (= black hole)

Penrose

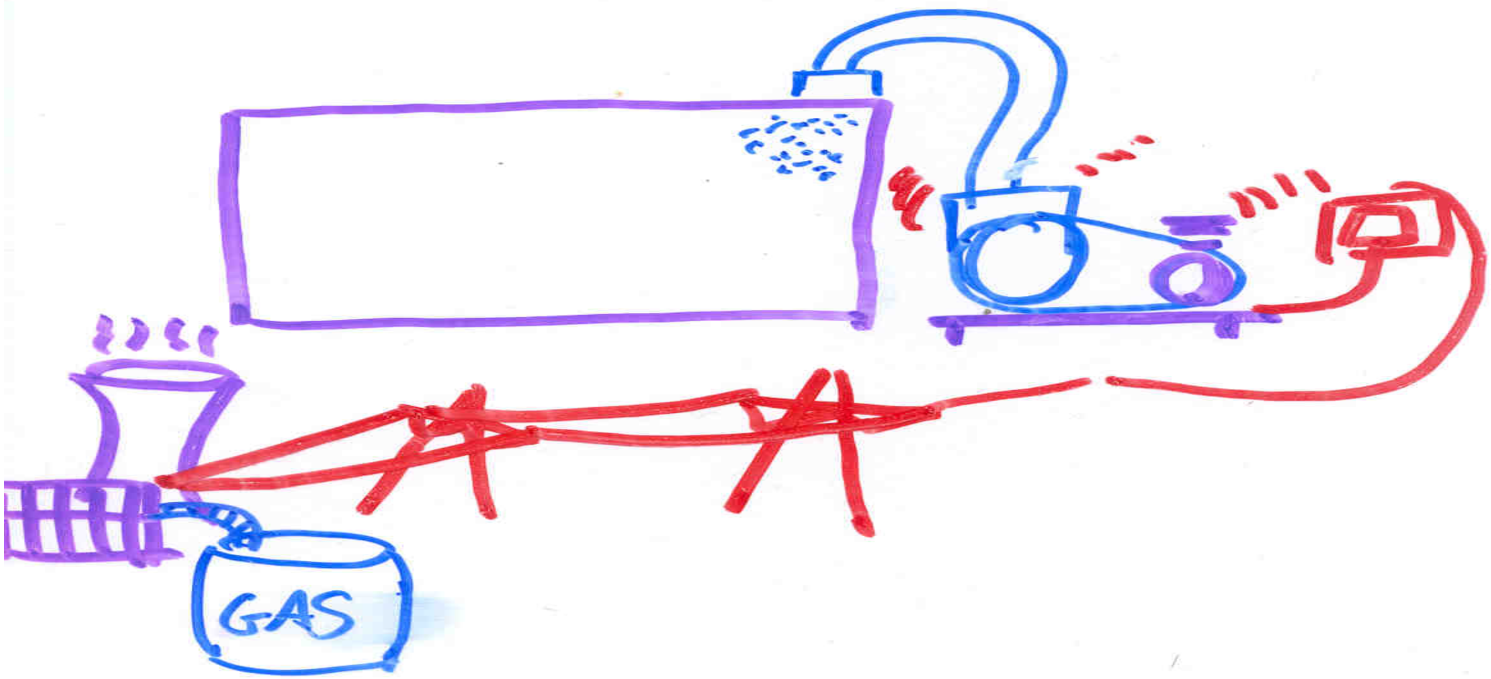
$$\boxed{S_{Univ} \approx 10^{-35} S_{bh-Max} = 10^{-35} 4\pi M_{Univ}^{2}}$$

Cosmic Microwave Background uniform to one part in 10^5

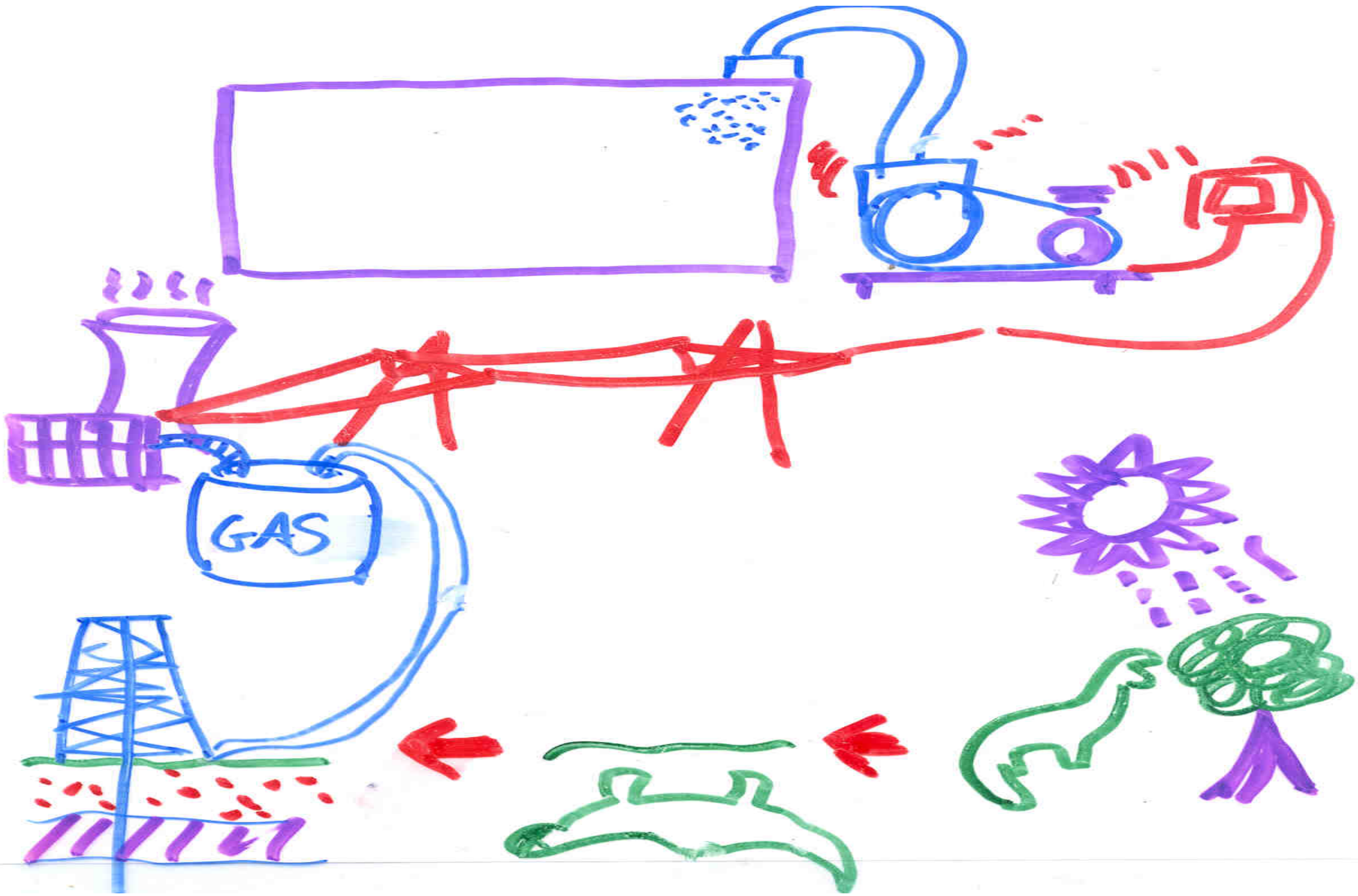


Entropy increase is realized mainly through gravitational collapse (destruction of homogeneity)

- The everyday link to gravitational collapse



The everyday link to gravitational collapse



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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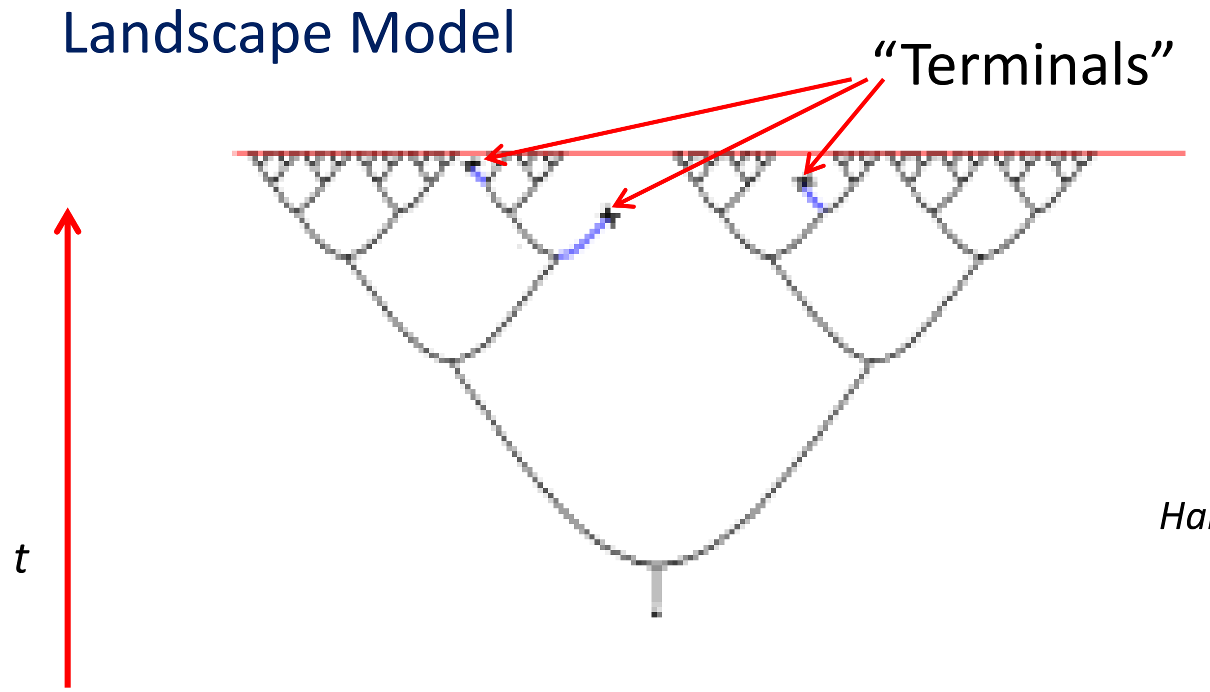
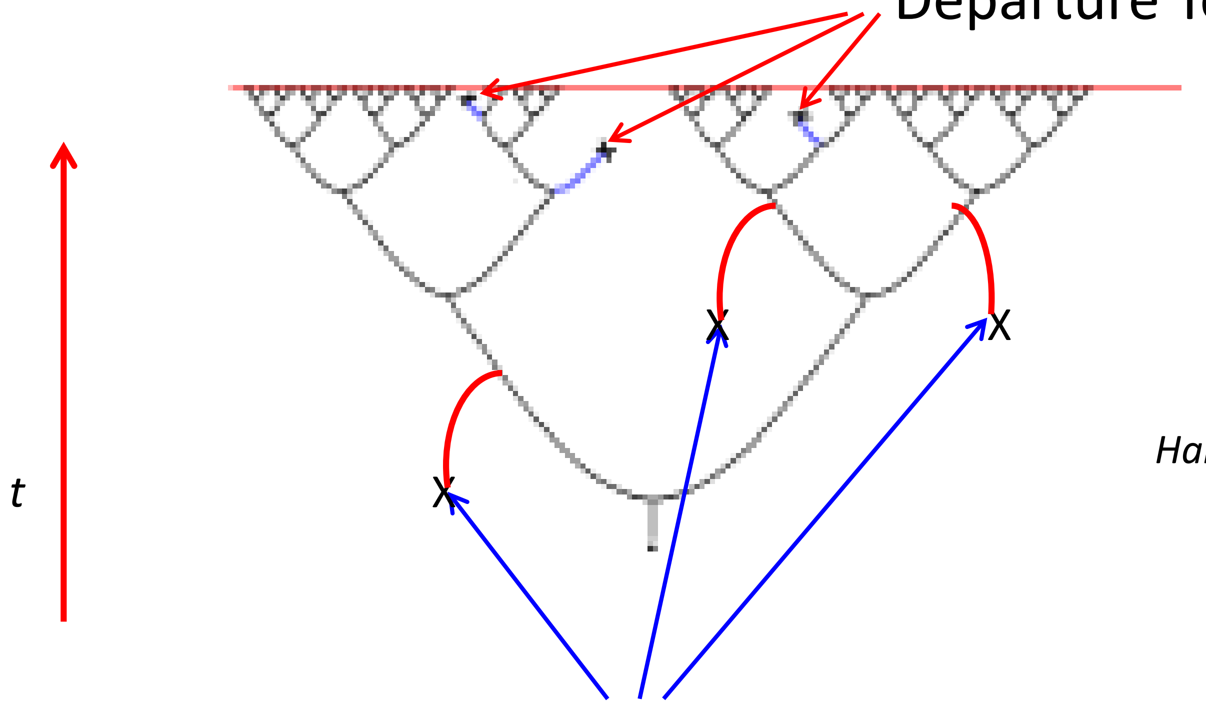


Harlow et al 2012

Beware “temporal provincialism”:

Landscape Model

“Departure Terminals”



Harlow et al 2012

Neglecting “arrival terminals” ➔ extreme fine tuning of initial conditions (AA & Stoltenberg in prep)

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- Tuning assumptions in infinite universes (eternal)

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Hernley, AA & Dray
2013

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Dyson et al.
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Shiffren & Wald
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NB Same issues with cyclic models: $\dot{S} > 0$ “but it’s infinite” (!)

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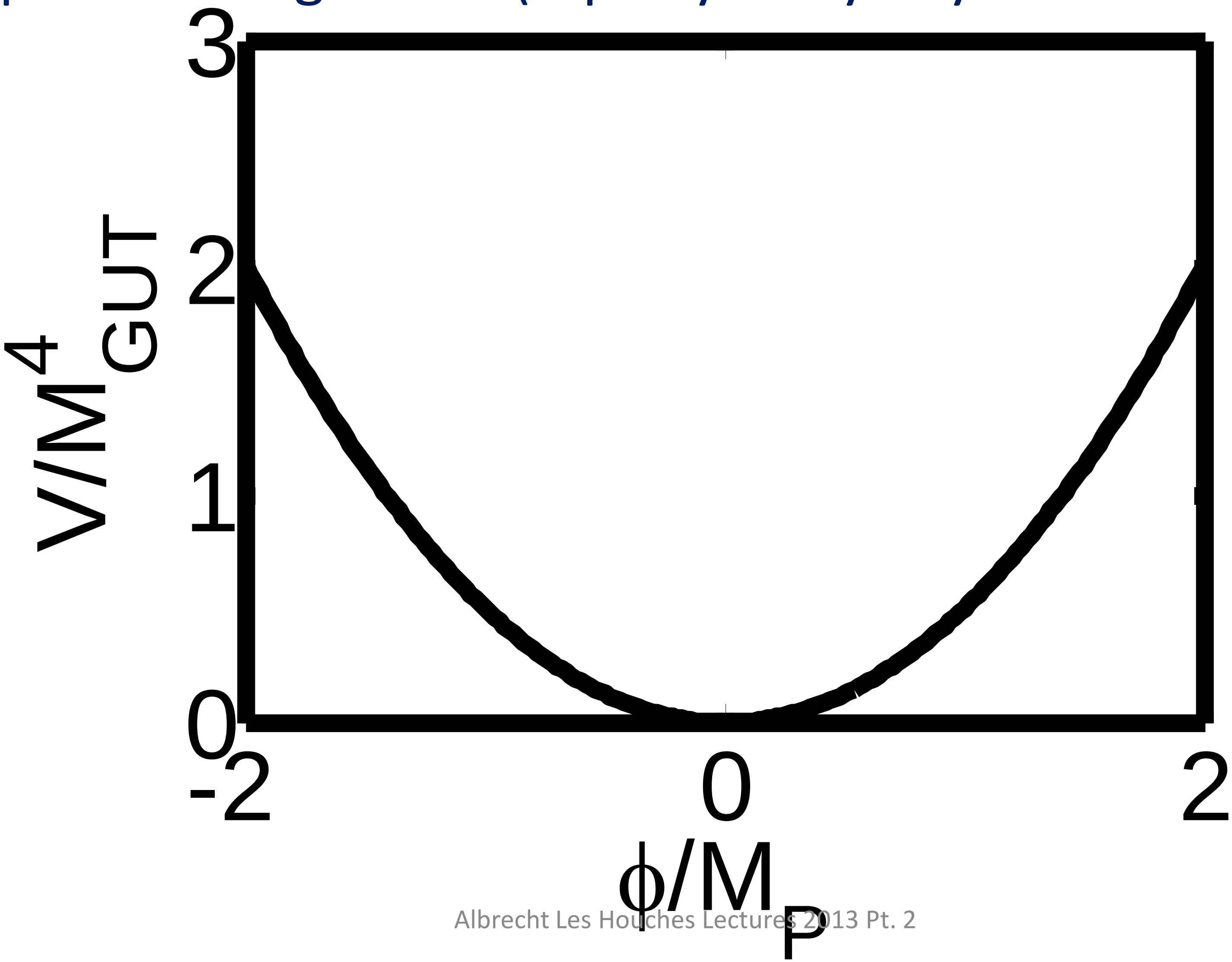
- Belief in "naturalness" of high energy density starts

Beware "temporal provincialism":

Equipartition argument (equally likely anywhere on potential)



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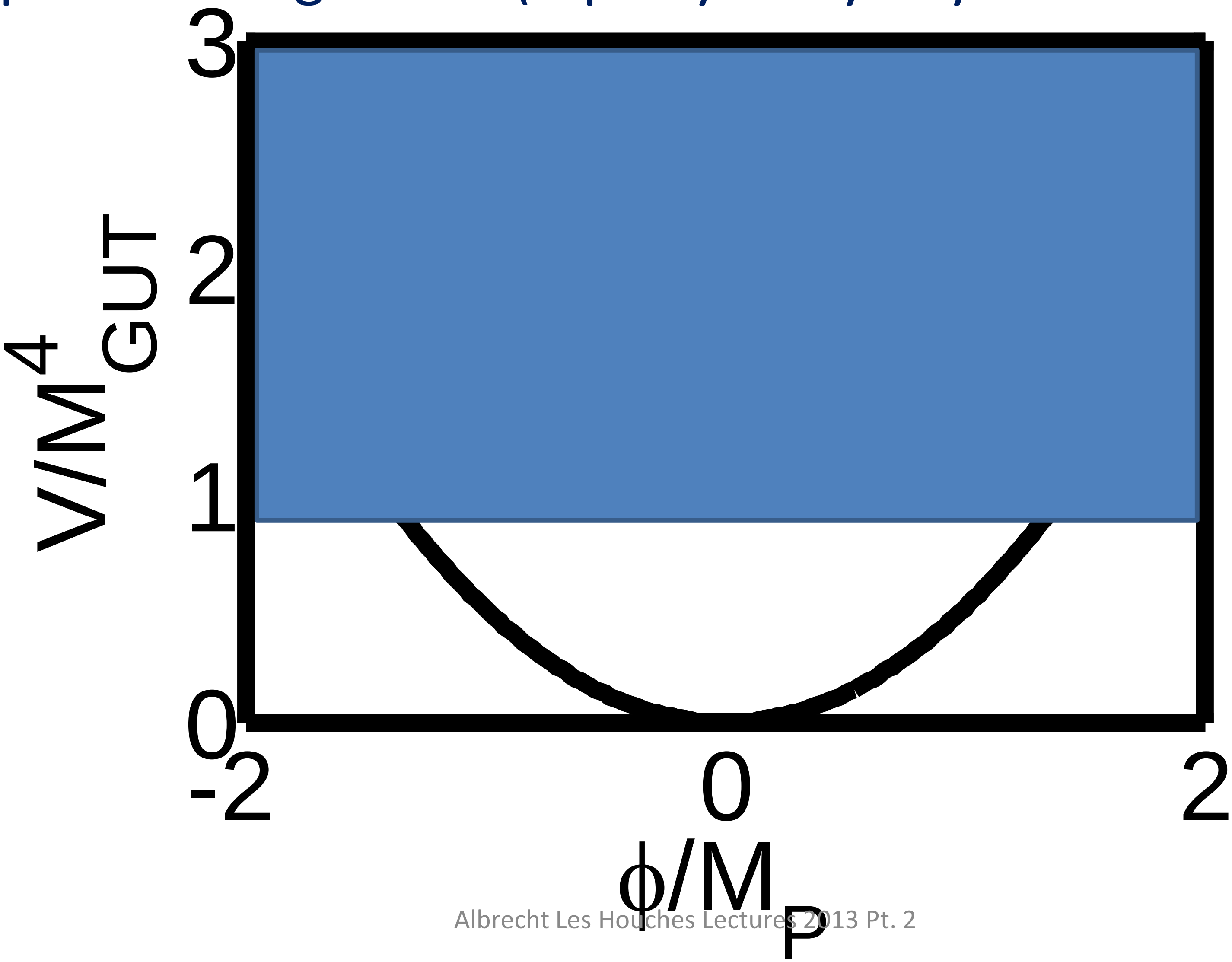

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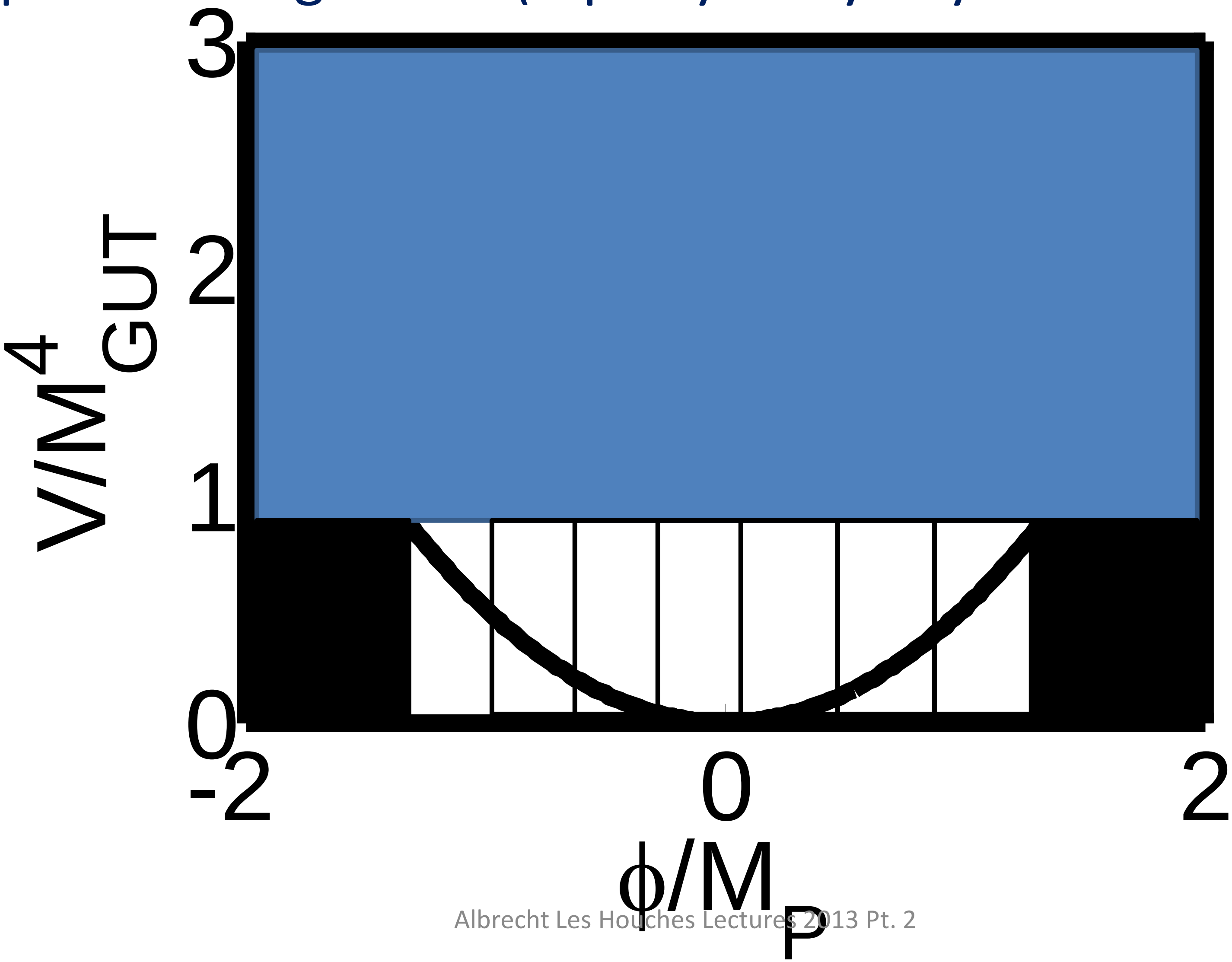

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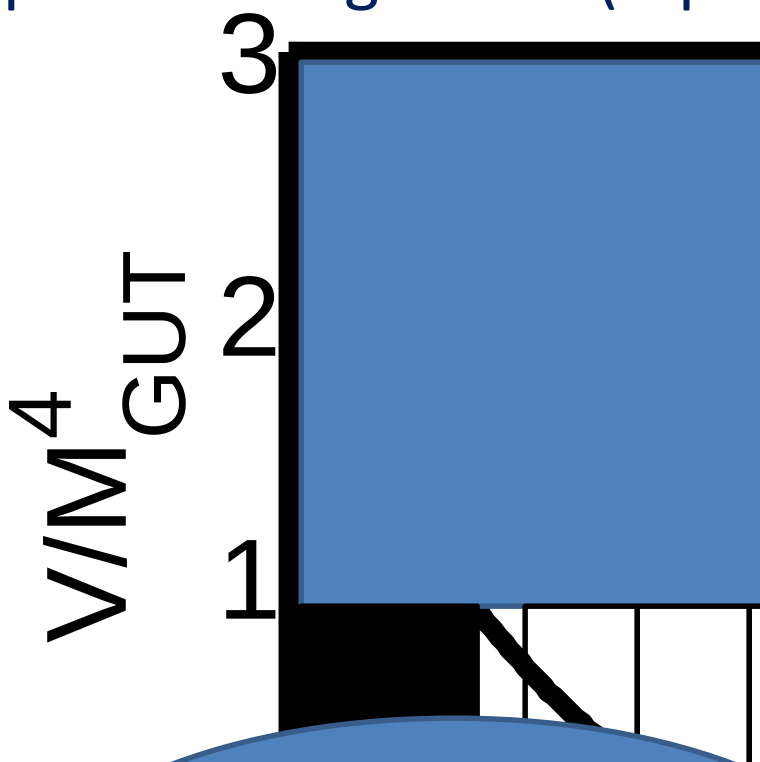

Compare with

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

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

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

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

Entropy arguments give exponential suppression of higher *V* values

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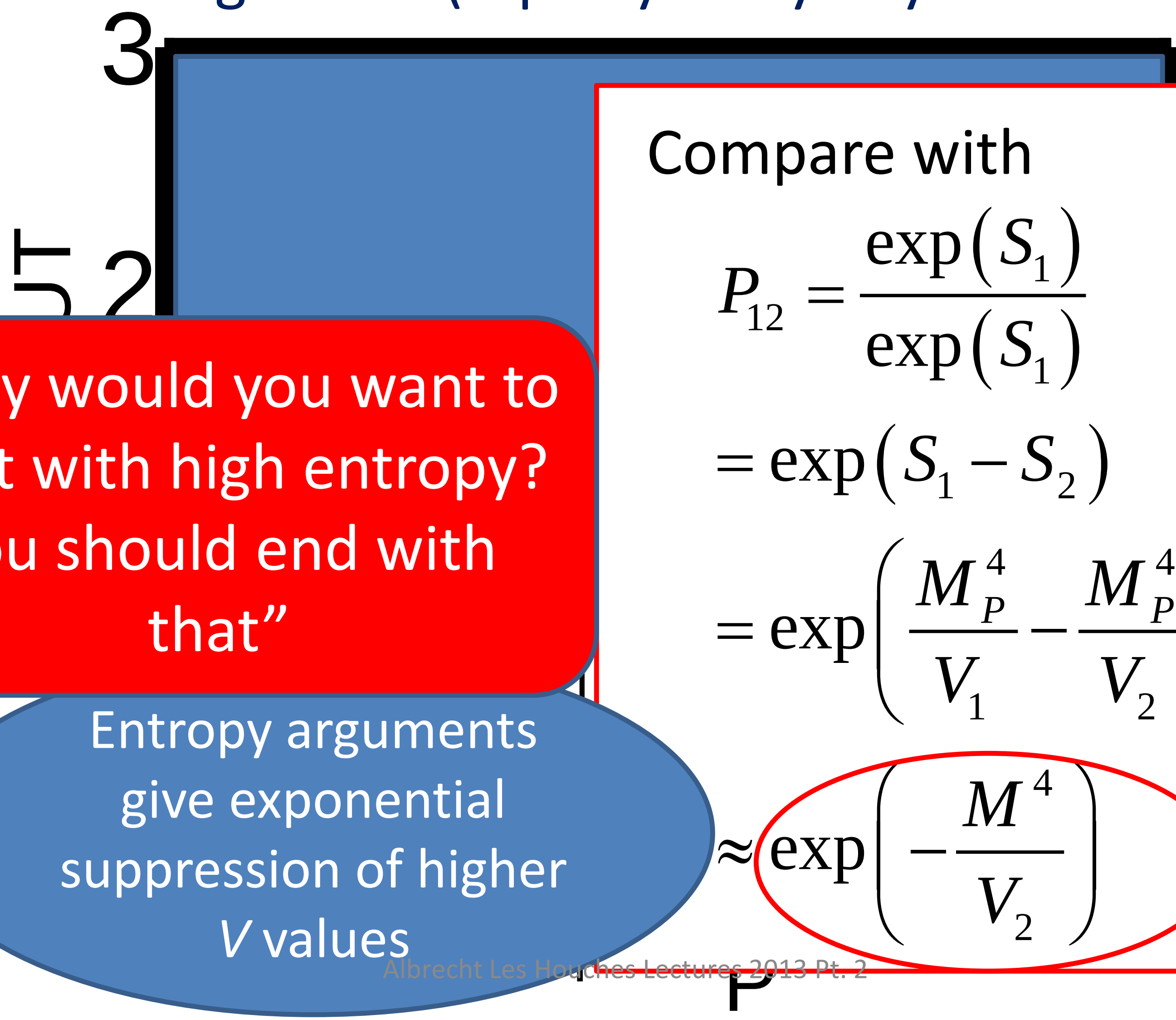

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"Why would you want to start with high entropy? You should end with that"

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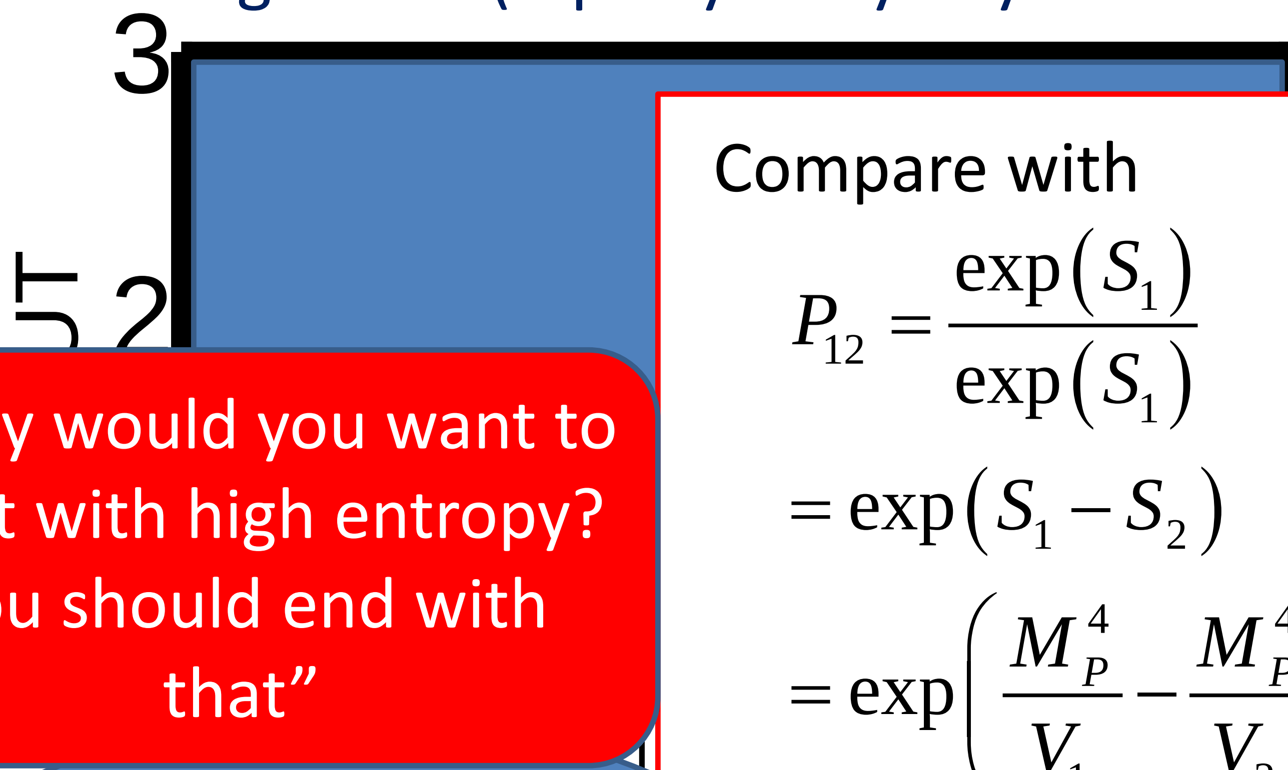

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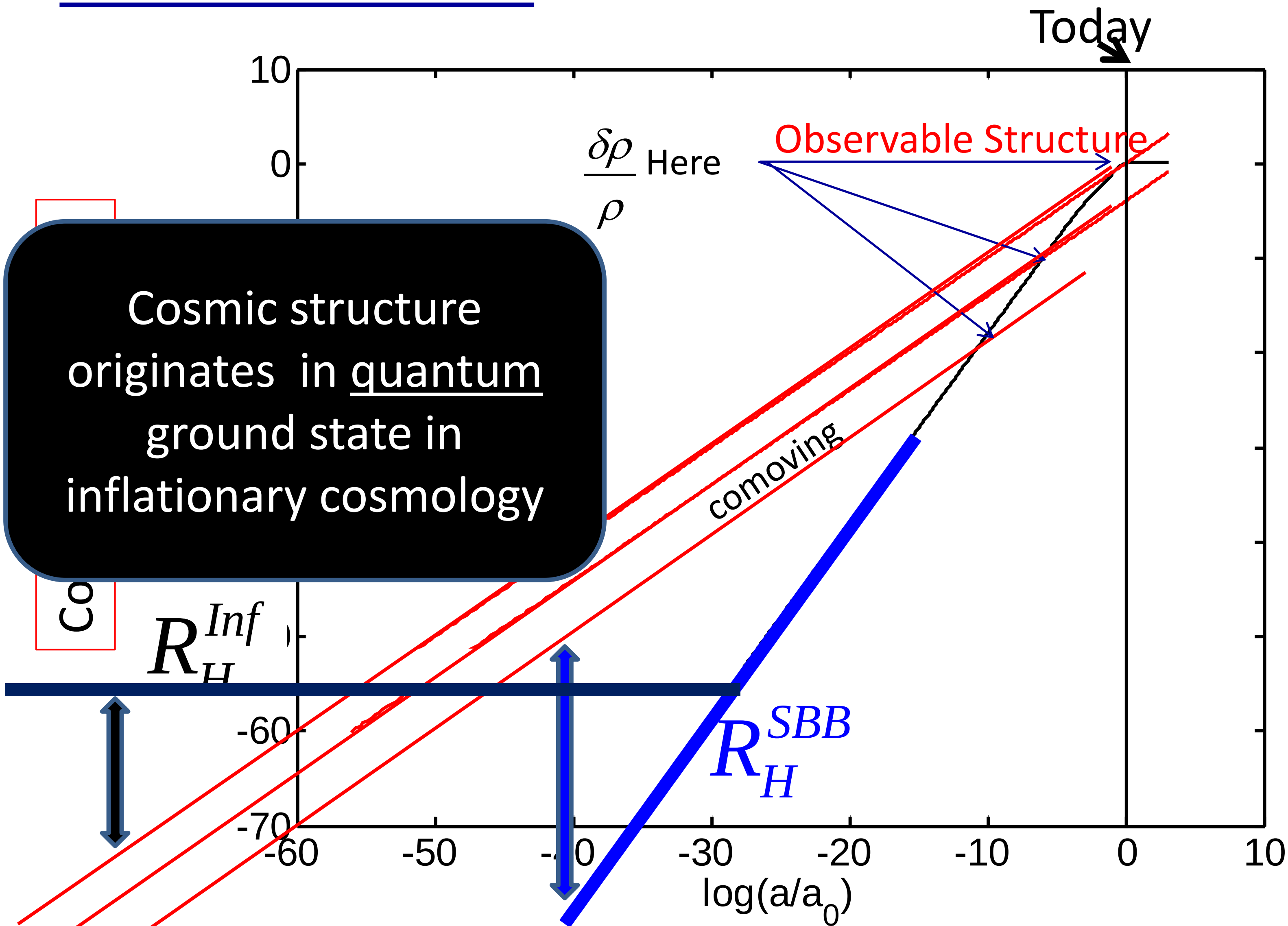
- And what about those short wavelength modes in their ground states?

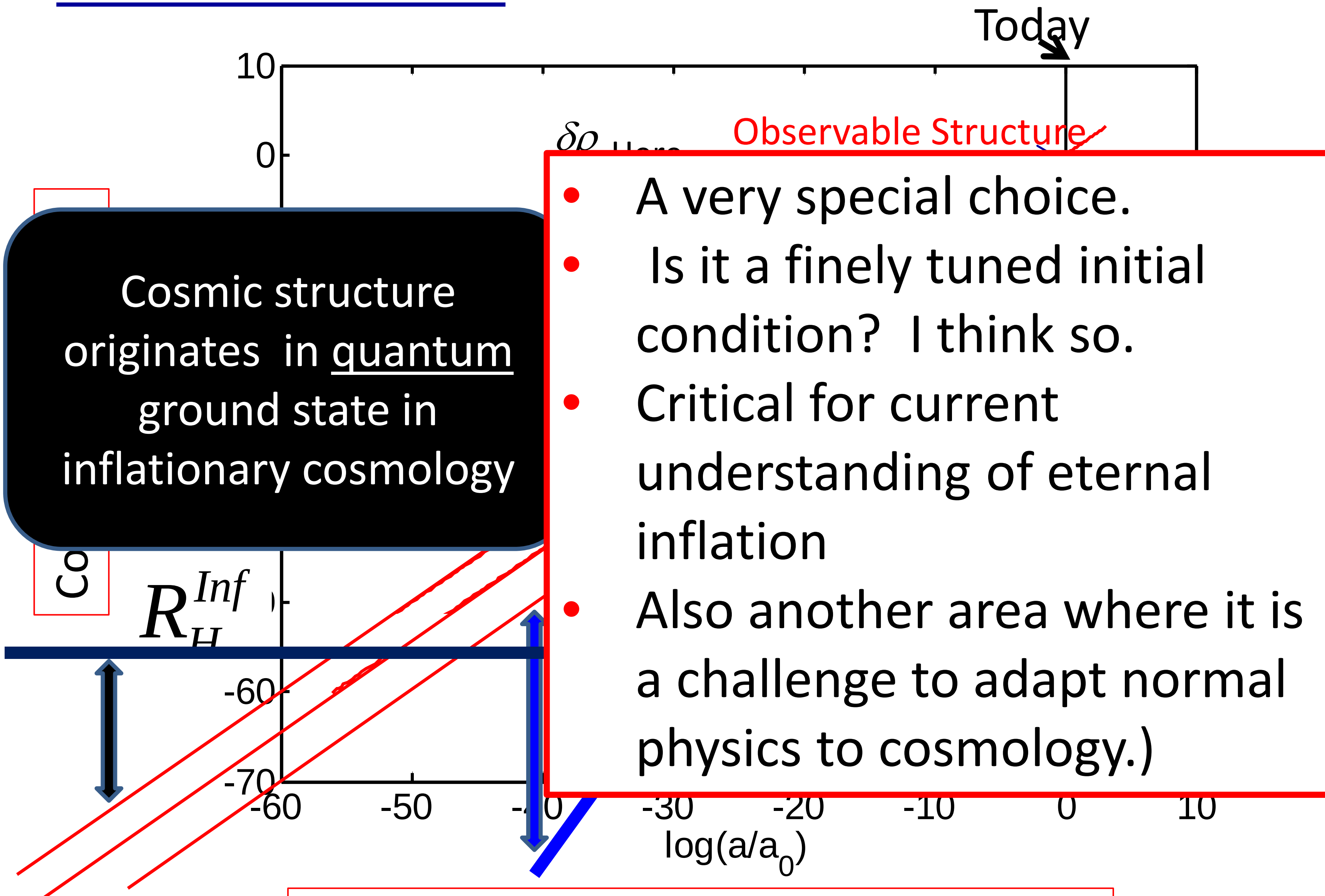
Cosmic structure

Cosmic structure originates in quantum ground state in inflationary cosmology



Scale factor (measures expansion, time)

Cosmic structure

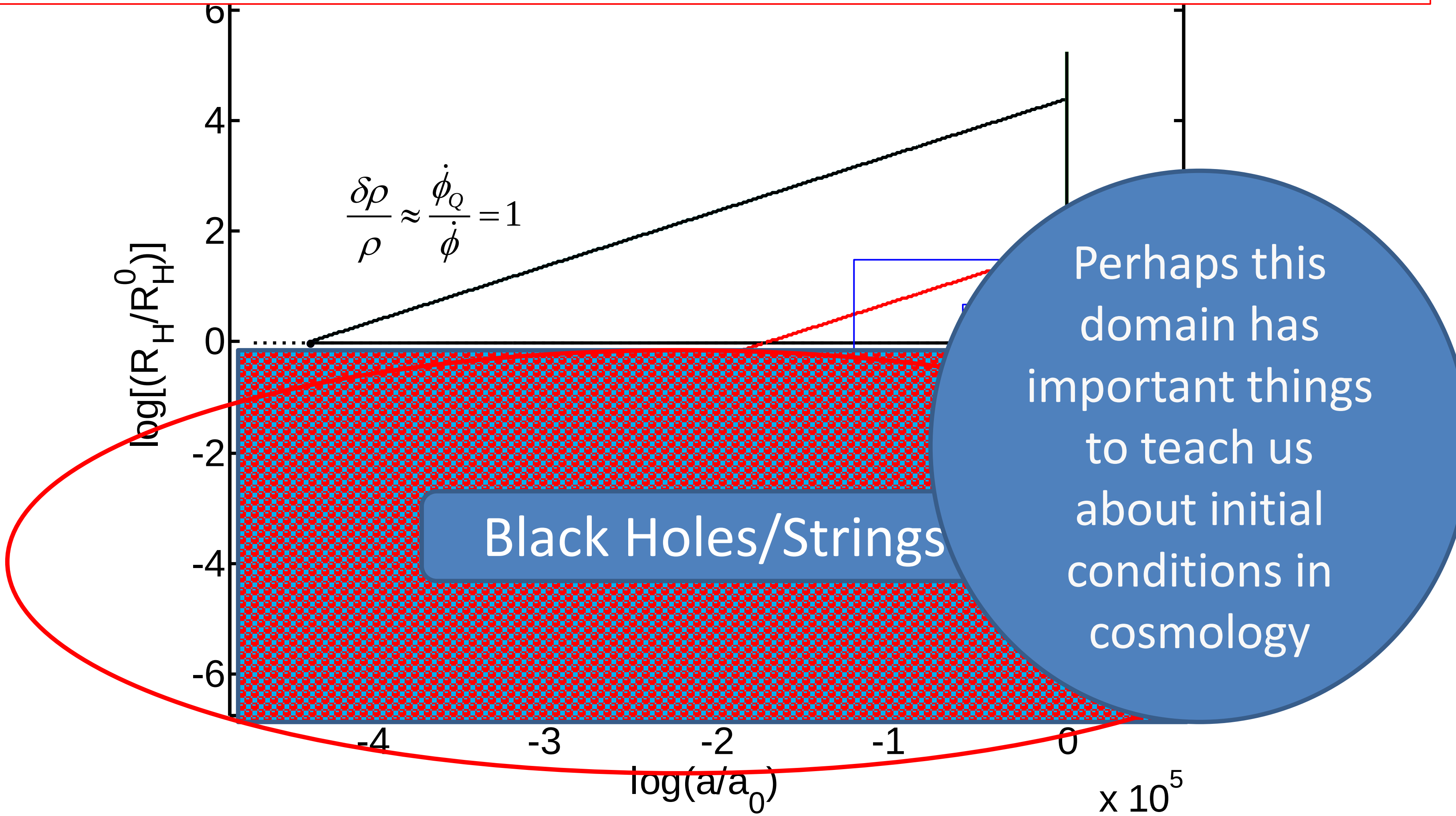


Cosmic structure originates in quantum ground state in inflationary cosmology

- A very special choice.
- Is it a finely tuned initial condition? I think so.
- Critical for current understanding of eternal inflation
- Also another area where it is a challenge to adapt normal physics to cosmology.)

Scale factor (measures expansion, time)

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

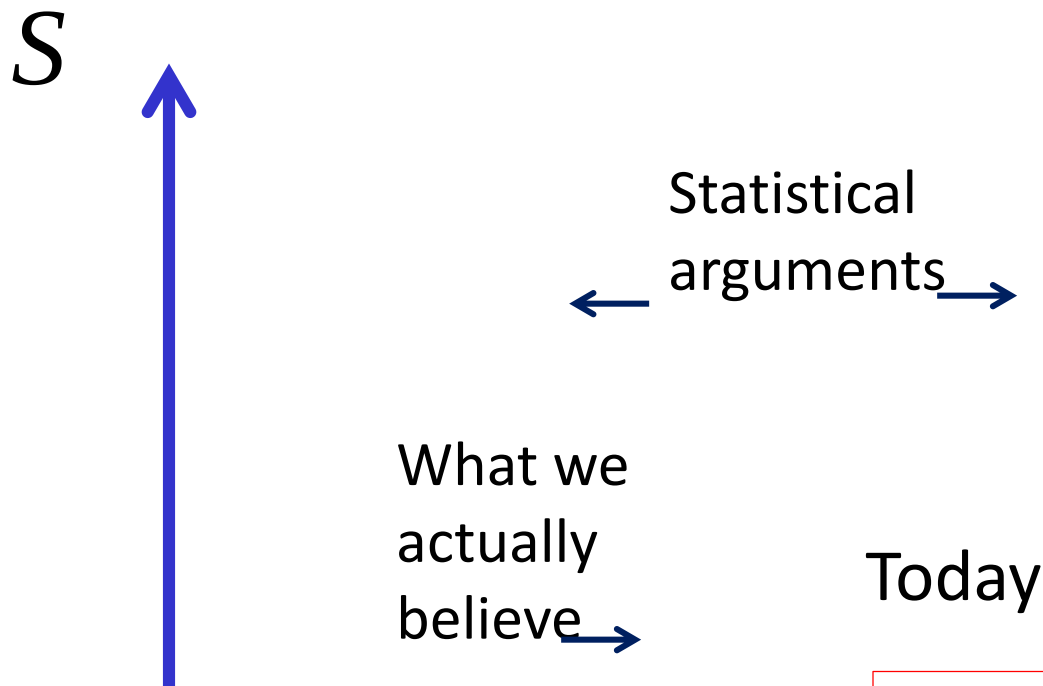


Start of day 2

Comment on Linde comment on anthropic selection of physical laws.

I have work that takes such an approach, and which actually makes some interesting predictions, such as Lorentz symmetry

http://arxiv.org/abs/arXiv:1003.2566



<u>For recap/clarification at start of 2nd day:</u> This discussion is just to point out that believing in the 2nd law involves believing that the universe is in a special state today (vs all possible microstates consistent with what we see).

- The thermodynamic arrow of time
- The "past hypothesis"

= "Fine tuning"

S

Statistical arguments

What we actually

...oday

The specialness of this state is directly equivalent to the homogeneity of the universe that Guth sought to explain (which is the origin of the thermodynamic arrow of time).

F...
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in...
a special state today (vs all possible microstates consistent with what we see).

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Beware "temporal provincialism":

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- For this discussion "Entropy" has just helped us assess tuning in phase space
- Could always embrace tuning (e.g. "wavefunction of the universe" or whatever just <u>gives</u> the initial state)
- These issues get much more serious if your model actually is in equilibrium. Then Entropy concrete physical facts about the universe

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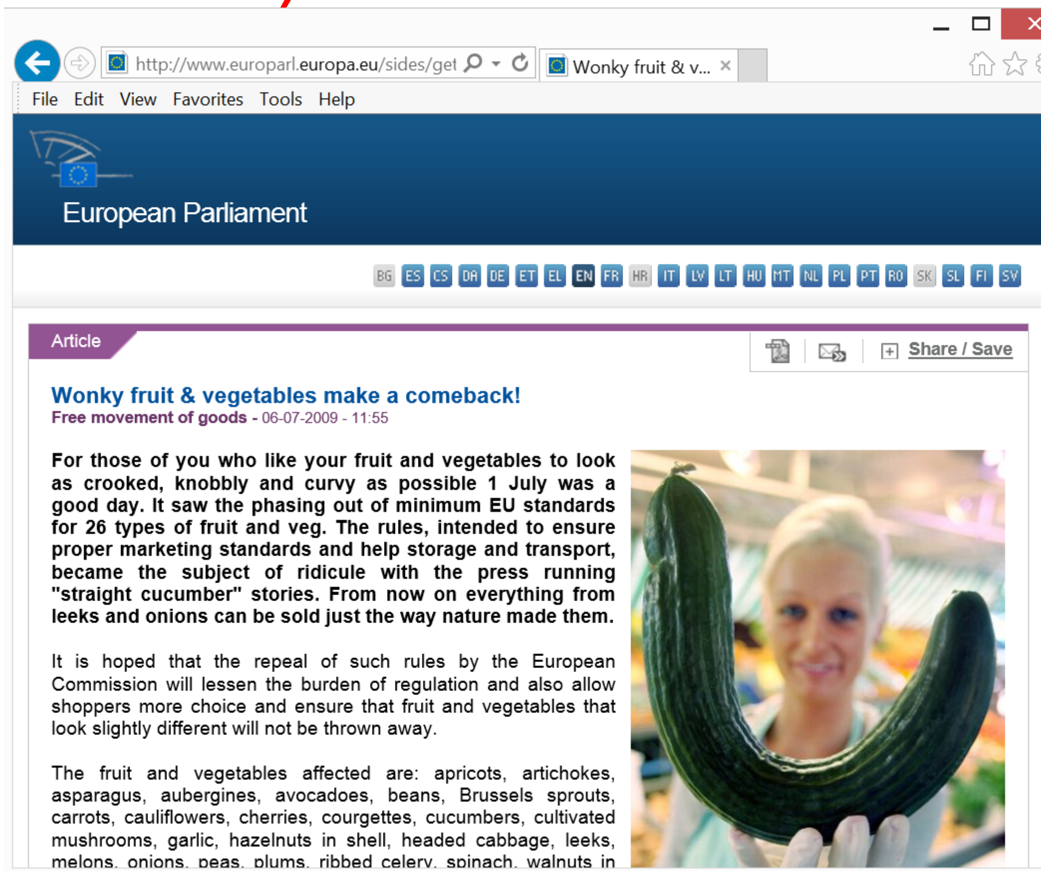

Wonky fruit & vegetables make a comeback!
Free movement of goods - 06-07-2009 - 11:55

For those of you who like your fruit and vegetables to look as crooked, knobbly and curvy as possible 1 July was a good day. It saw the phasing out of minimum EU standards for 26 types of fruit and veg. The rules, intended to ensure proper marketing standards and help storage and transport, became the subject of ridicule with the press running "straight cucumber" stories. From now on everything from leeks and onions can be sold just the way nature made them.

It is hoped that the repeal of such rules by the European Commission will lessen the burden of regulation and also allow shoppers more choice and ensure that fruit and vegetables that look slightly different will not be thrown away.

The fruit and vegetables affected are: apricots, artichokes, asparagus, aubergines, avocadoes, beans, Brussels sprouts, carrots, cauliflowers, cherries, courgettes, cucumbers, cultivated mushrooms, garlic, hazelnuts in shell, headed cabbage, leeks, melons, onions, peas, plums, ribbed celery, spinach, walnuts in

- And
  groun

Part 2 outline

1. Entropy and tuning

2. Equilibrium (& toy models)

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2. Equilibrium (& toy models) ⟸

Why consider an eqm system?

- I like finite: Better shot at controlling measures, more physical (we will never measure infinity).
- Finite systems are at risk of being eqm systems long-term.
- I *like* eqm because of its independence of initial conditions

But: Issues related to Boltzmann Brains seem problematic

Why consider an eqm system?

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  measures, mo
  measure infin
- Finite systems a
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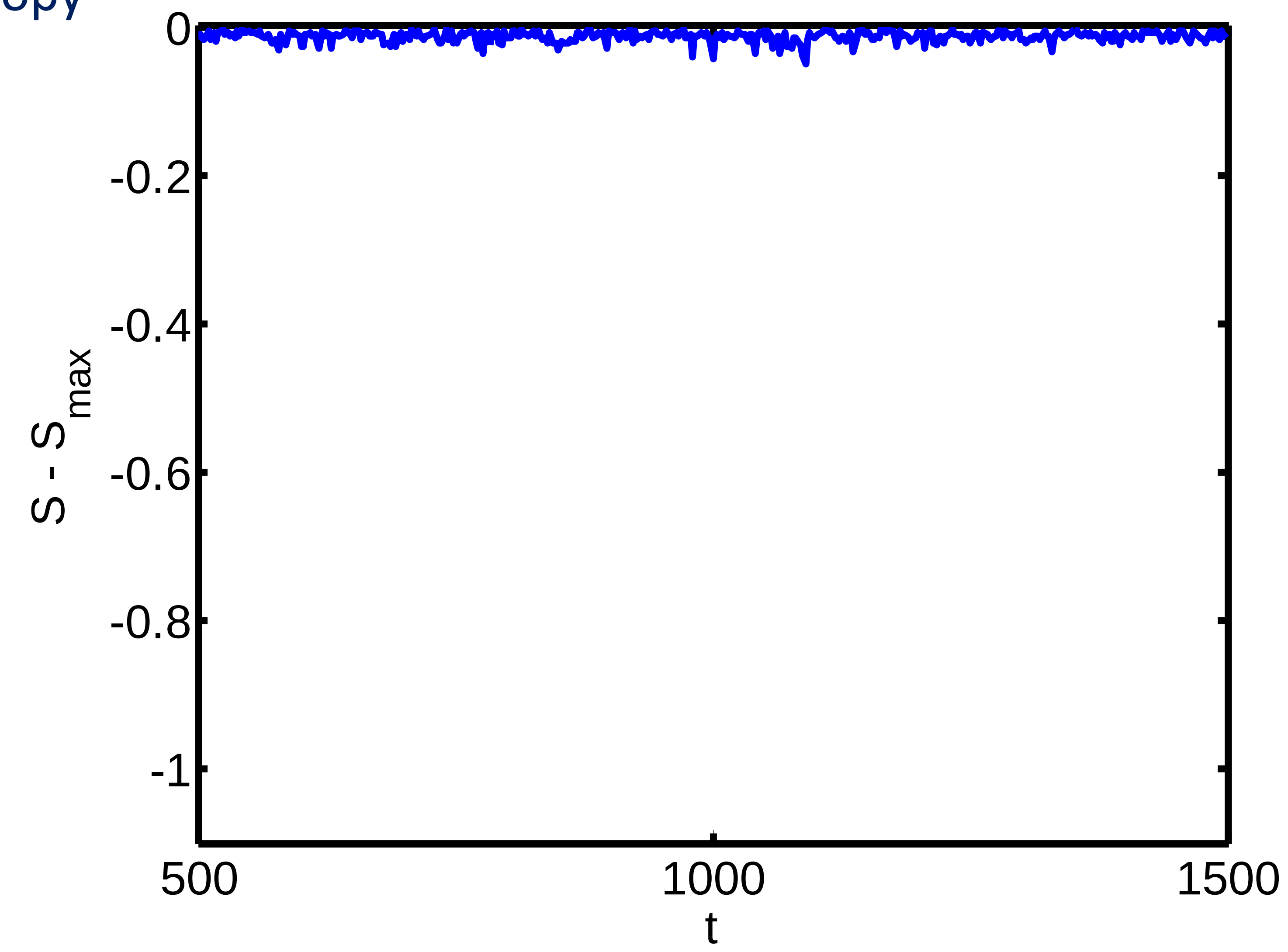
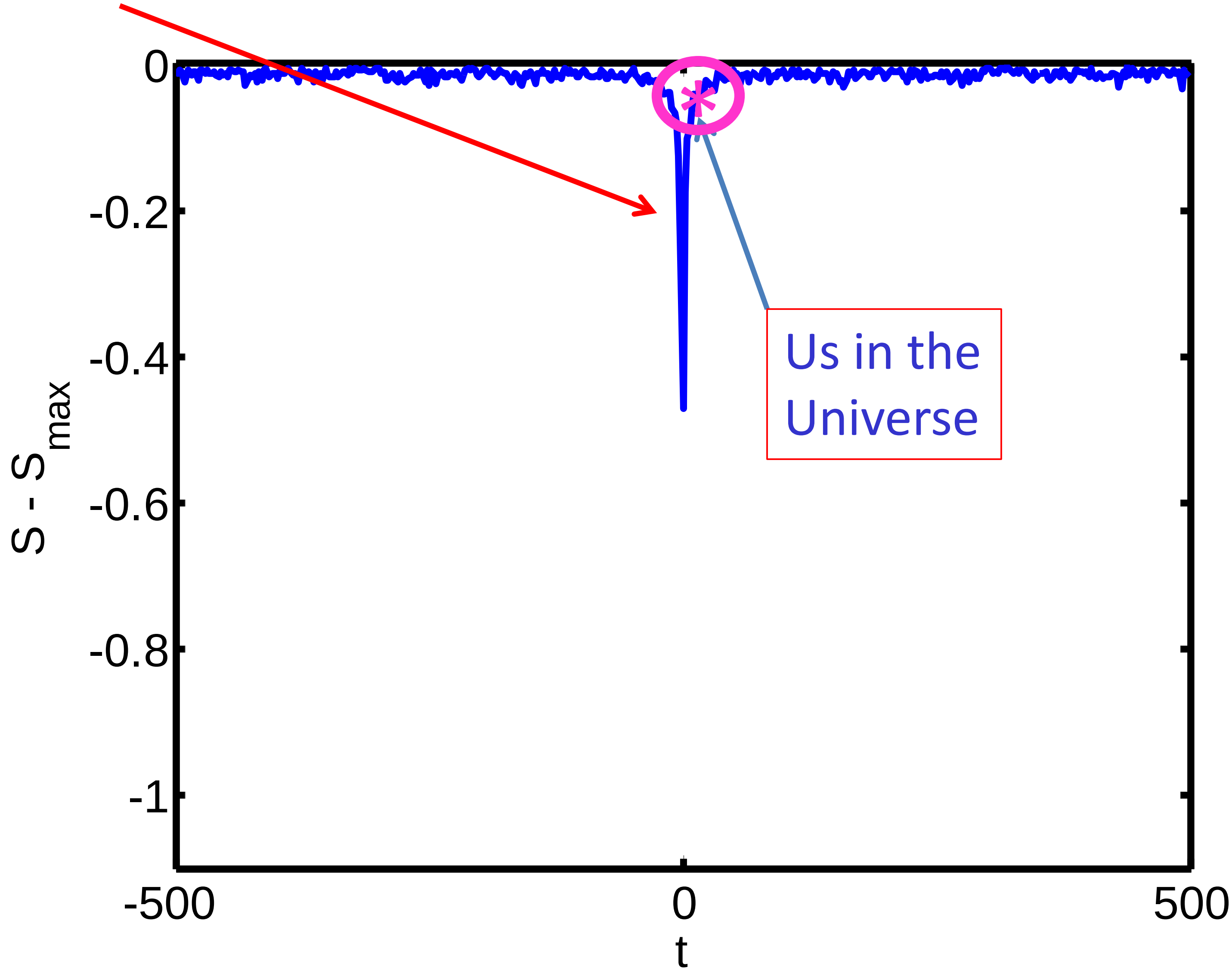
Essentially all the zillions of inflation models out there have unresolved measure problems..

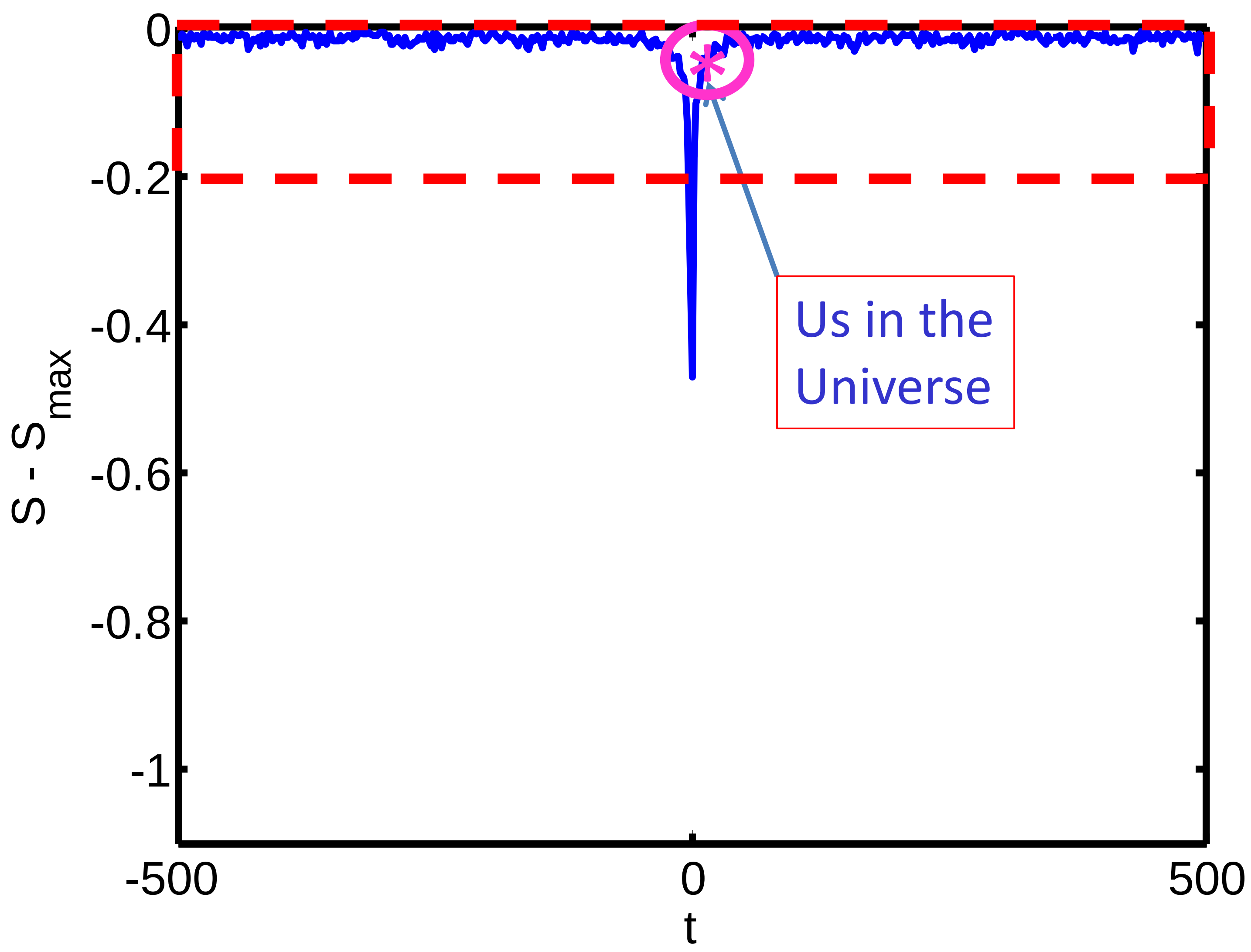
But: Issues related to Boltzmann Brains seem problematic

Eqm system with fluctuating entropy



Very rare fluctuation





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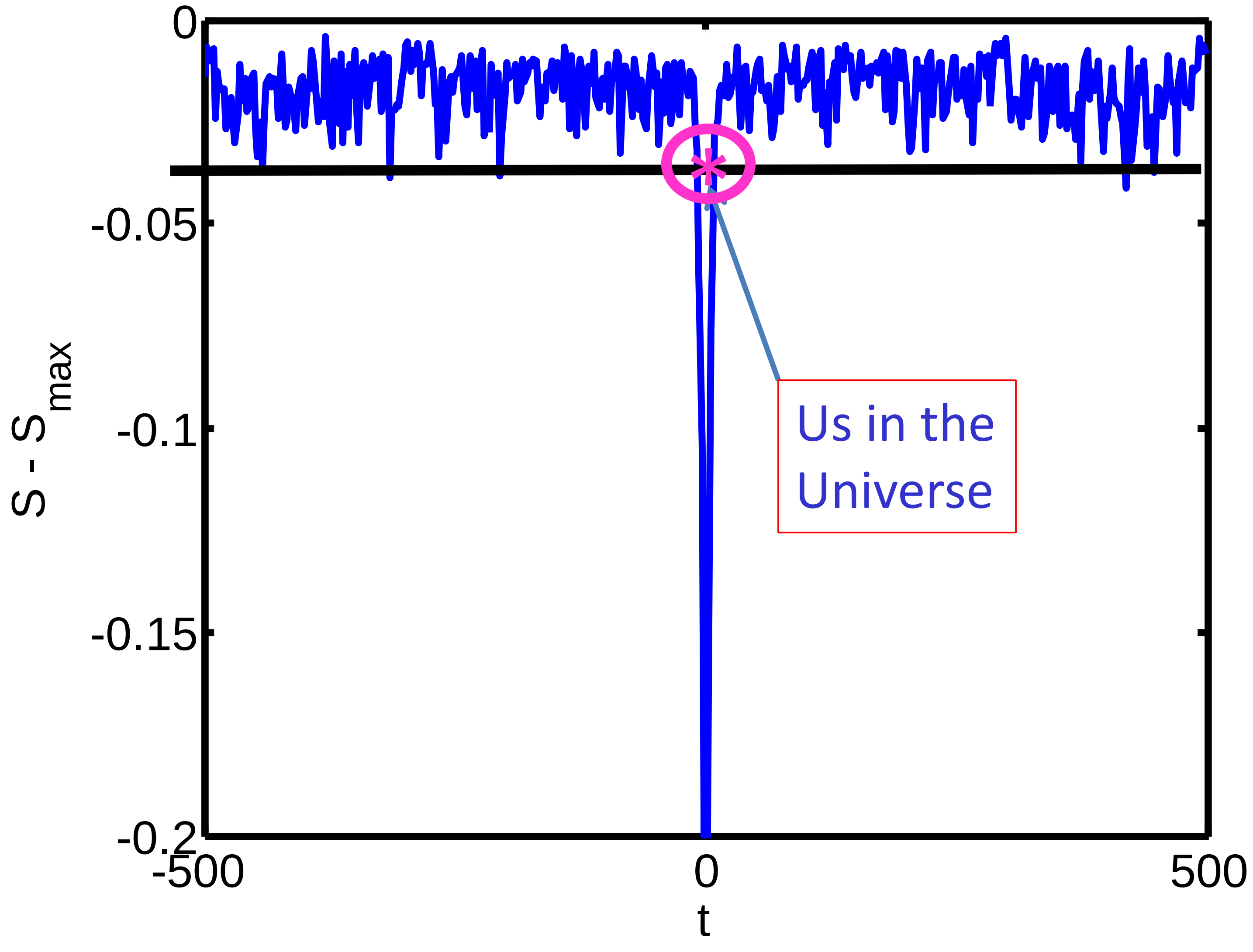
S - S_{max}
Us in the Universe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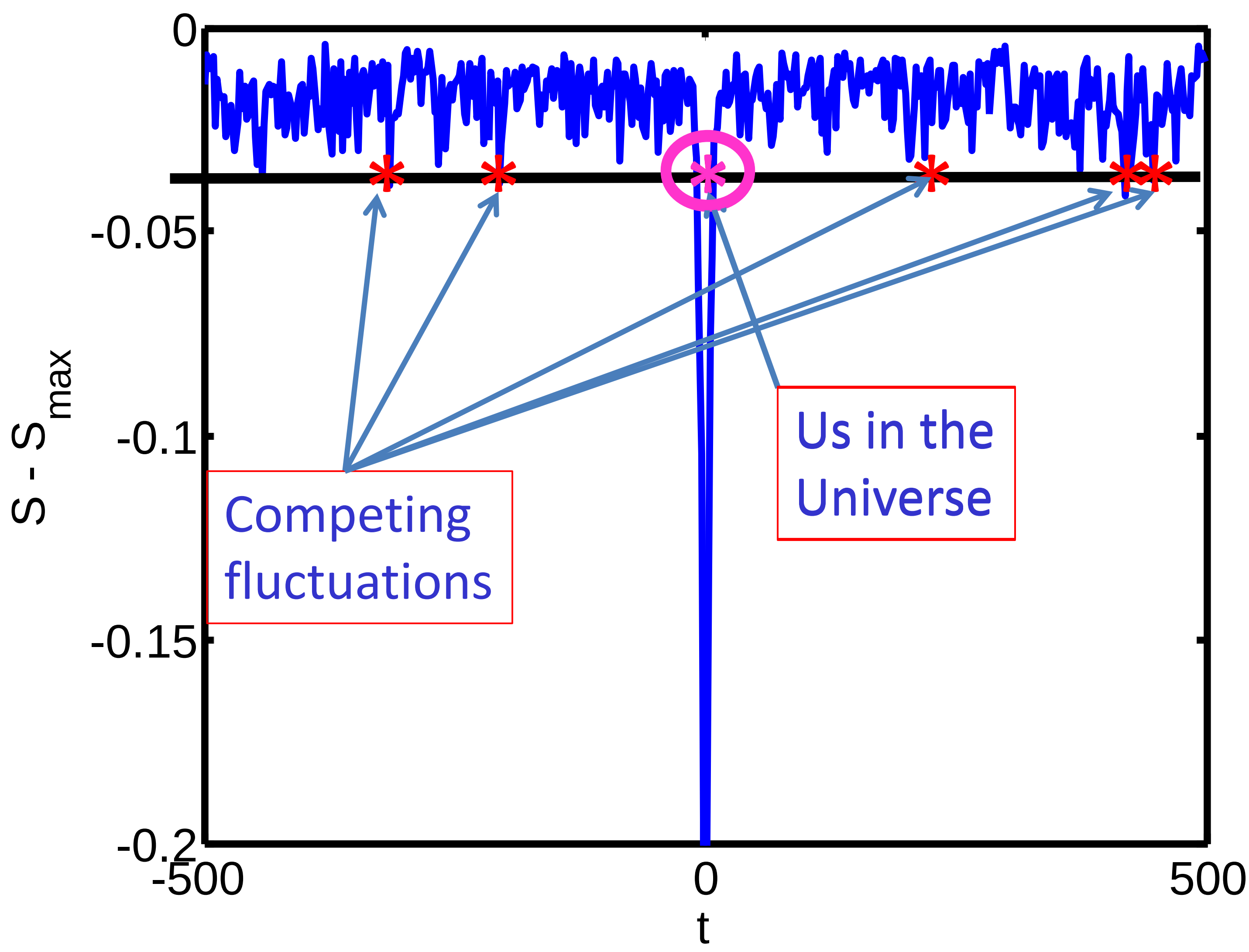
S - S_{max}
Us in the Universe



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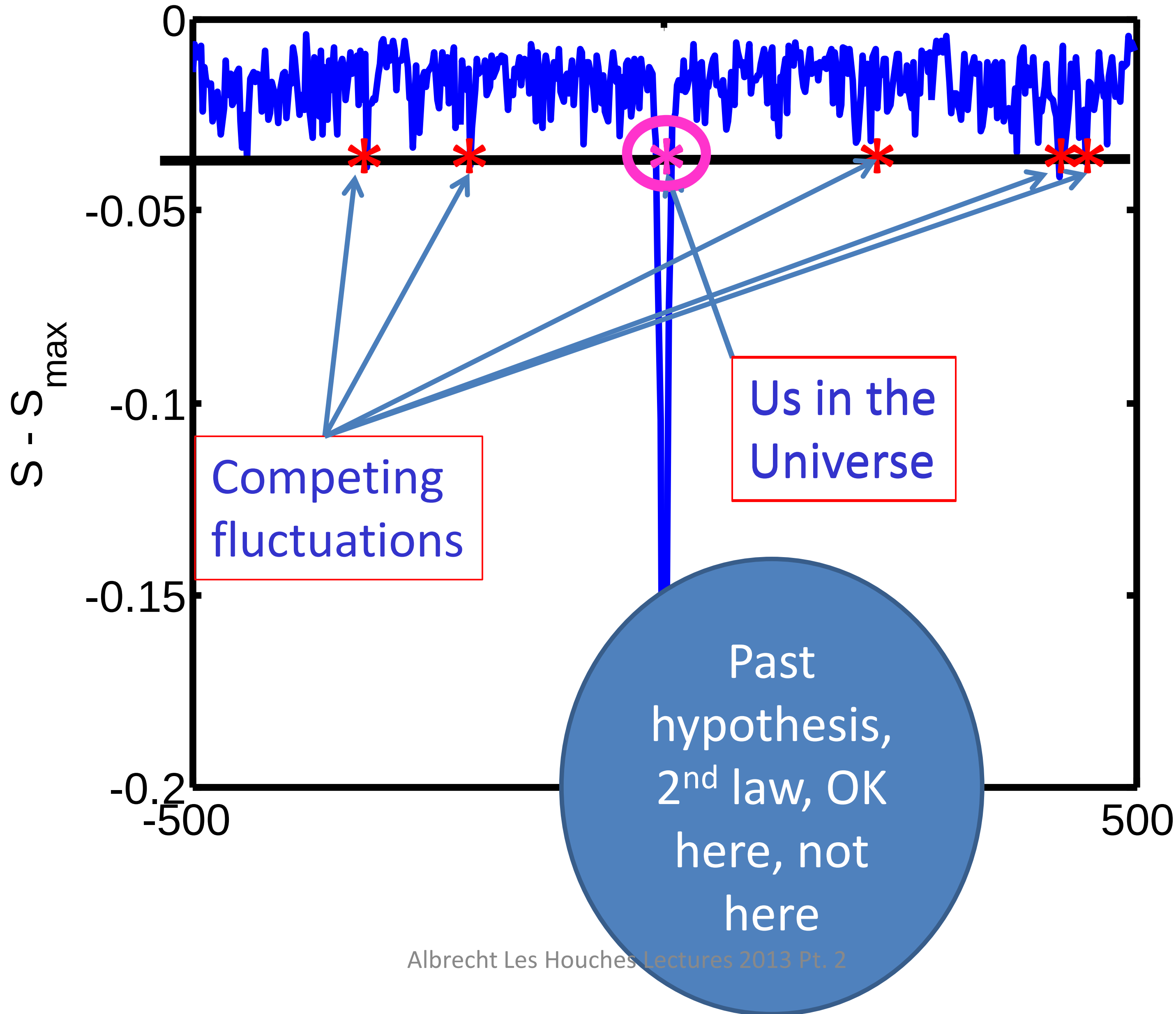
S - S
max
Competing fluctuations
Us in the Universe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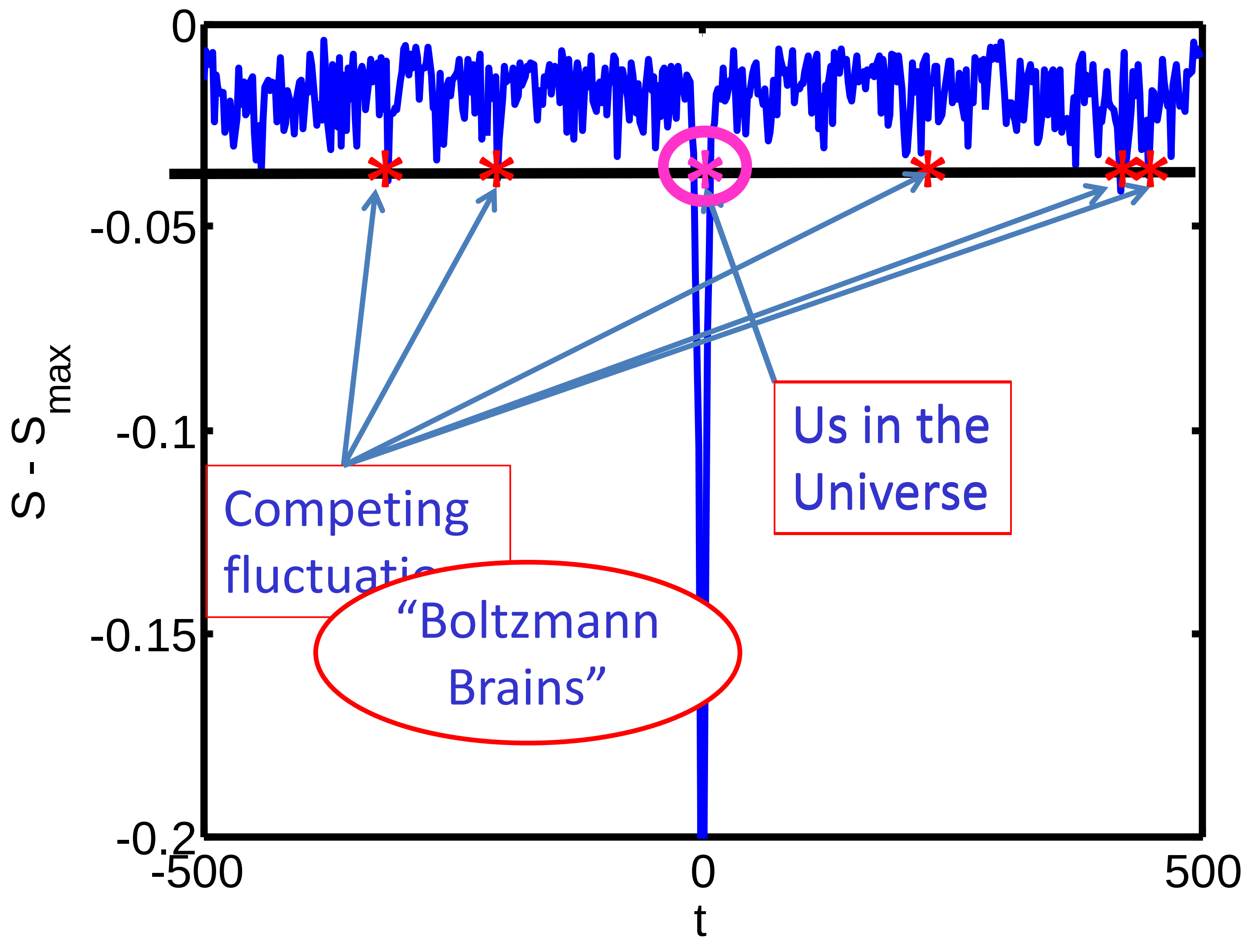
S - S max
Competing fluctuations
Us in the Universe
Past hypothesis, 2nd law, OK here, not here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"Boltzmann
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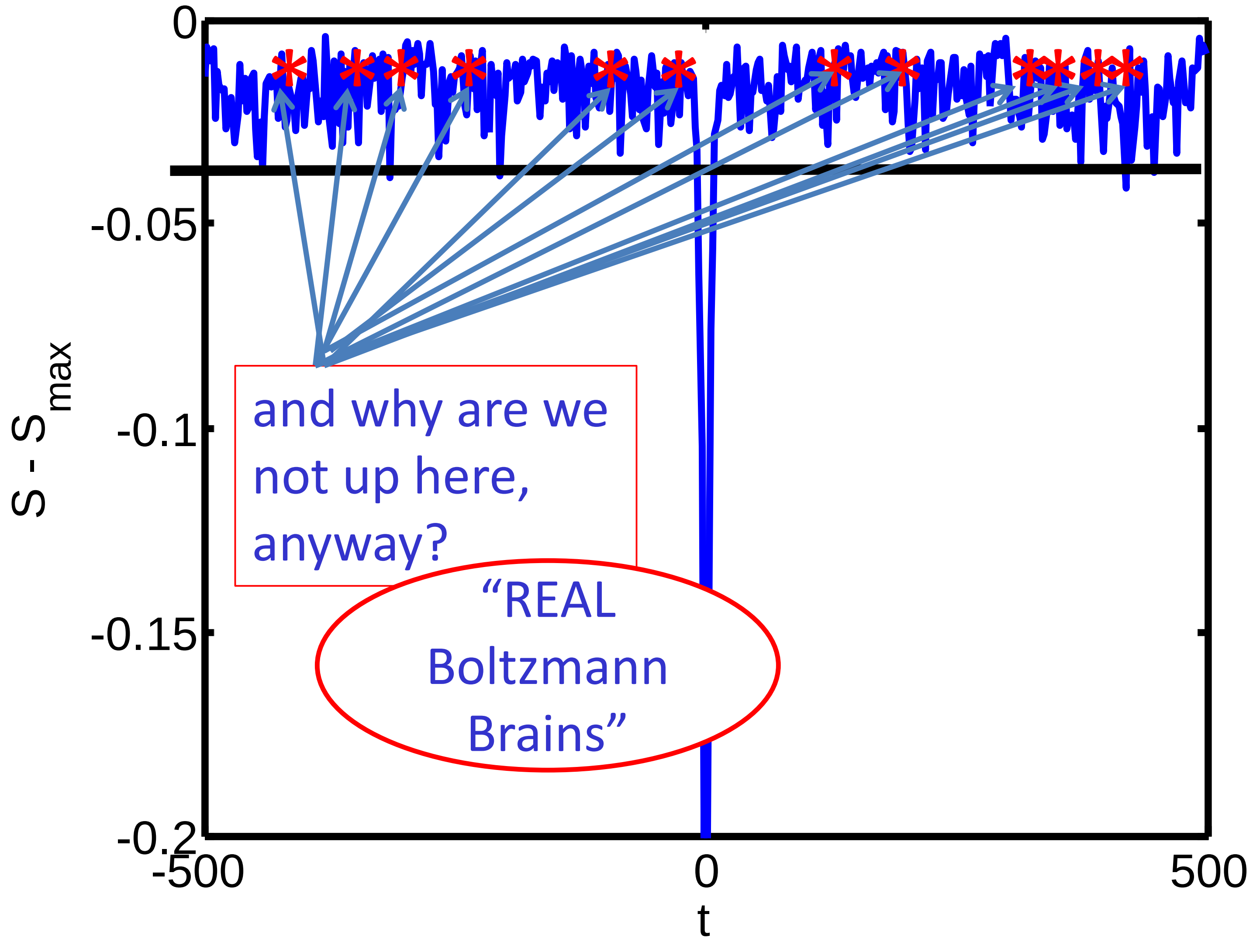
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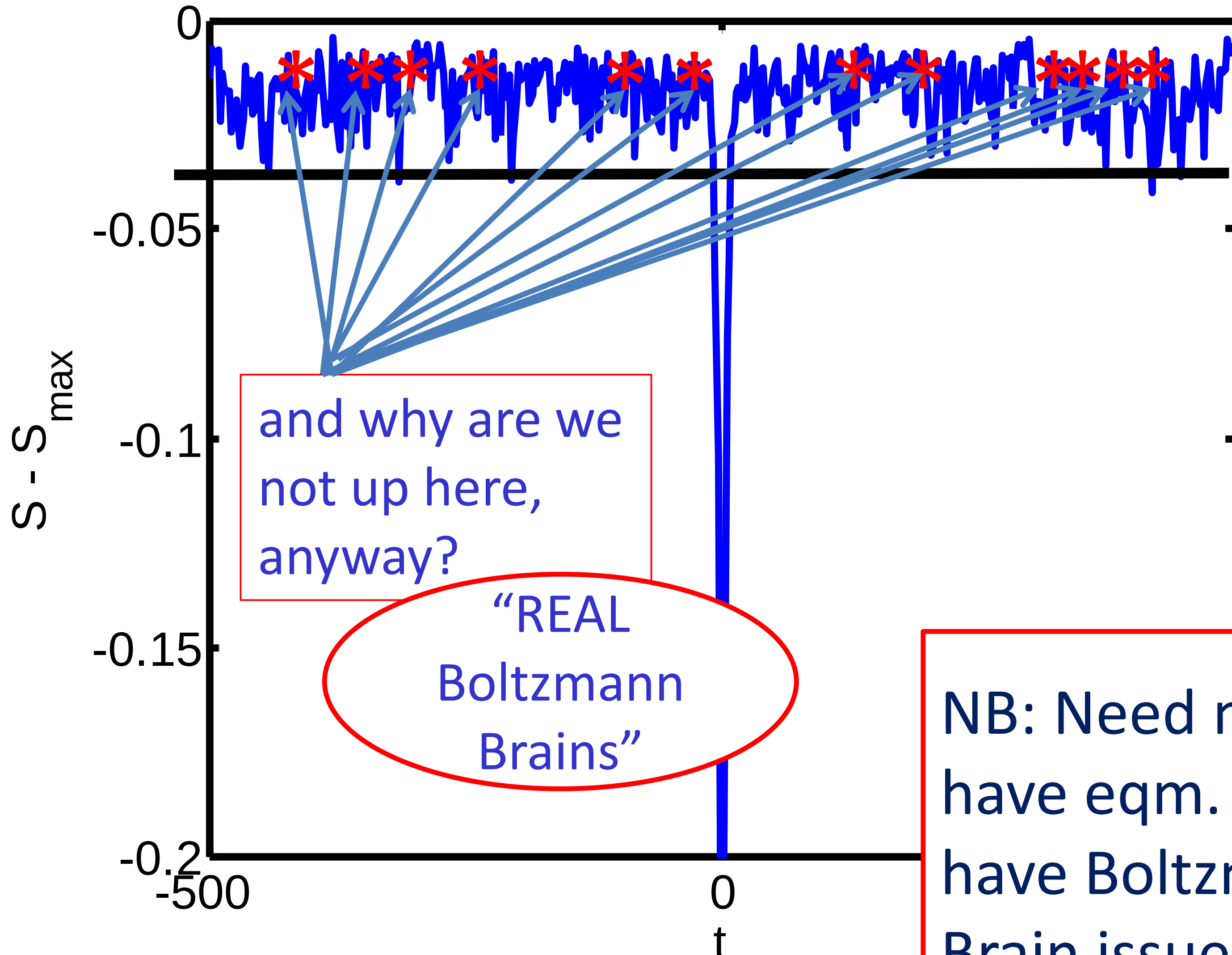
S - S max
and why are we not up here, anyway?
“REAL Boltzmann Brains”



NB: Need not have eqm. To have Boltzmann Brain issues

Where I stand:

- Still inspired by Guth idea of dynamics creating non-tuned picture
- Despite going up against the 2nd law
- Most arguments made so far for non-tuned scenarios are suspect in my view *(seem to depend too much on assumptions to do with arrow of time, wave function of the universe vs inflation dynamics)*
- Suspicious of infinite systems (hidden tunings)
- I like the way eqm. liberates you from issues with initial conditions
- Need to face BB problem etc. of finite eqm. systems

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Next: Address these issues in a toy model

Toy model A:

- Eqm state machine with “normal” behavior
- Small fluctuations more likely than large ones
- As a cosmological model, would have Boltzmann Brains, no 2^{nd} law.

Toy model B:

- ***Eqm*** state machine with proper *cosmological* behavior
- Small fluctuations *less* likely than large ones
- As a cosmological model, would have suppressed Boltzmann Brains,
- 2nd law, past hypothesis *OK*
- Achieved by introducing additional "trans-micro" degrees of freedom, which are the ones in eqm, and which course grain up to cosmologically correct behavior. ("familiar" Micro states are *not* in eqm.)

Part 2 Conclusions

1. Temporal provincialism is everywhere!
2. Rule of thumb: Find tuning by asking "why is the time reverse of this process not present?" (ie arrival terminals)
3. Should we accept tuning?
4. Eqm. cosmology possible in principle (can avoid Boltzmann Brains, have 2nd law). But in practice?

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End Part 2

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3) Classical and quantum probabilities in the multiverse

4) de Sitter equilibrium cosmology

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