The Second Law and the Multiverse

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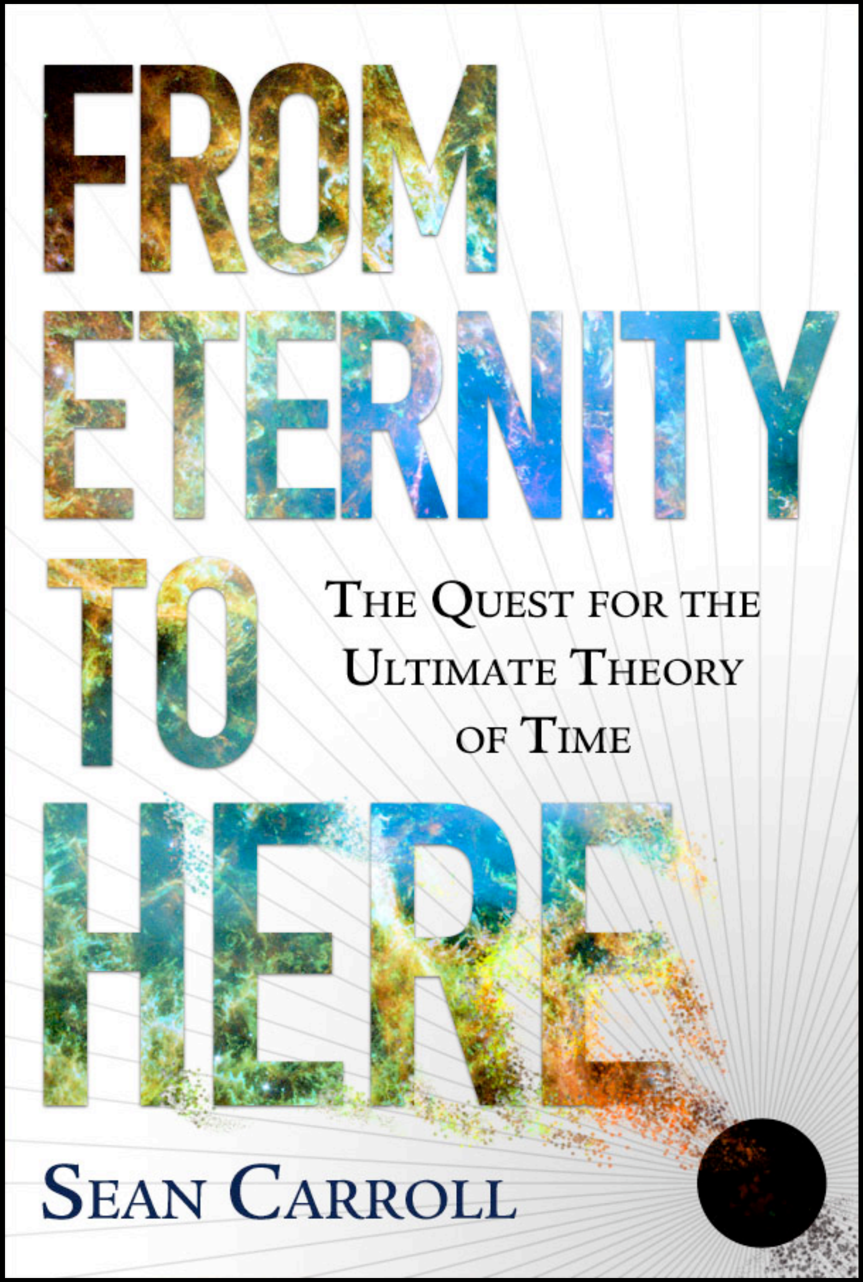


The earliest scientific proposal of a multiverse:

Boltzmann (1895): thermal fluctuations around equilibrium.

> “There must then be in the universe, which is in thermal equilibrium as a whole and therefore dead, here and there relatively small regions of the size of our galaxy (which we call *worlds*), which during the relatively short time of eons deviate significantly from thermal equilibrium.

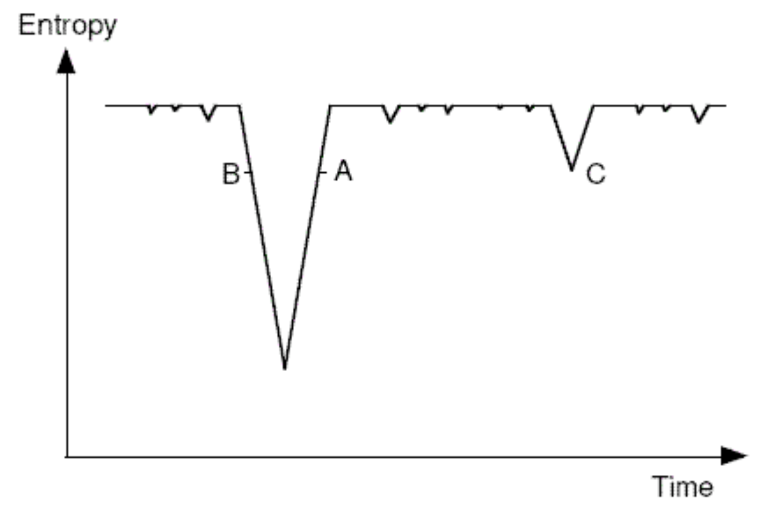
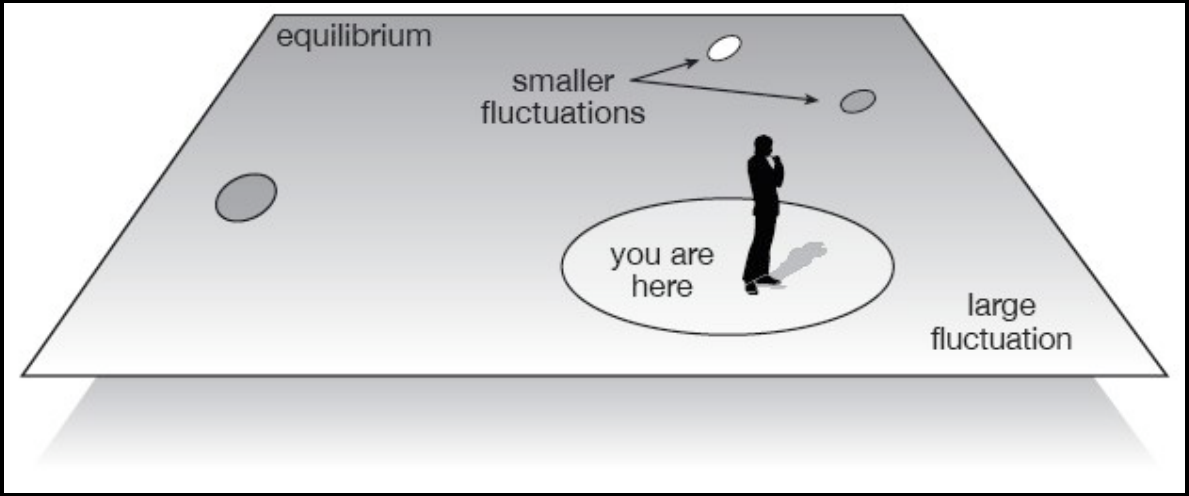
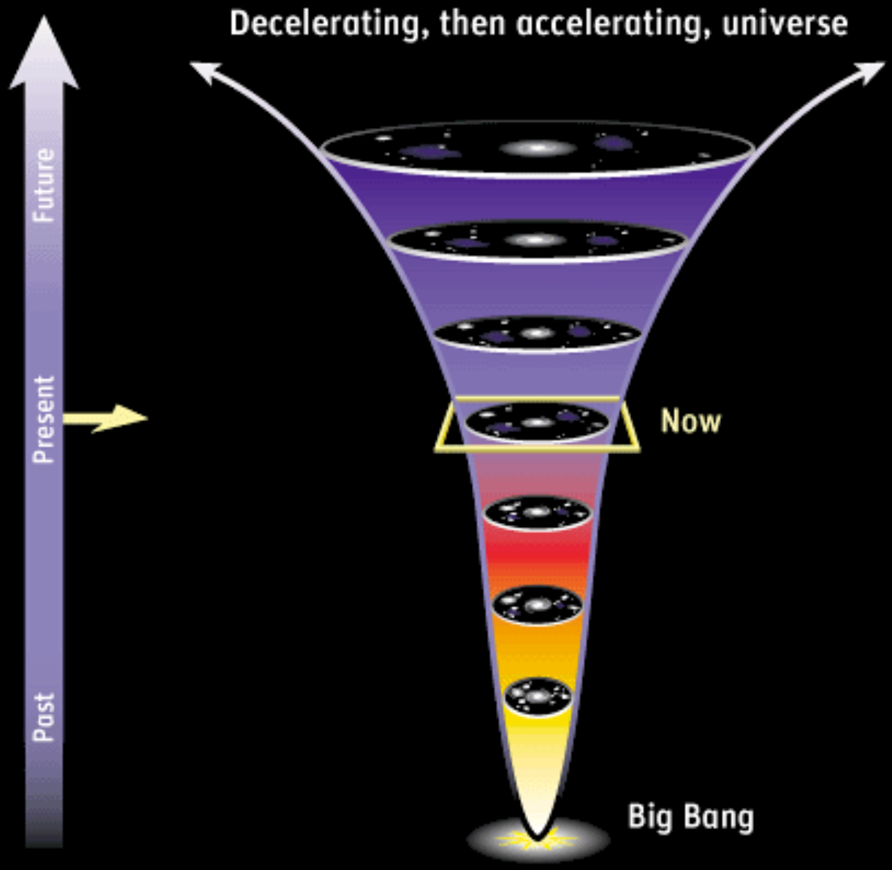


Figure 1. Boltzmann’s entropy curve.



Boltzmann’s multiverse

The observable universe:

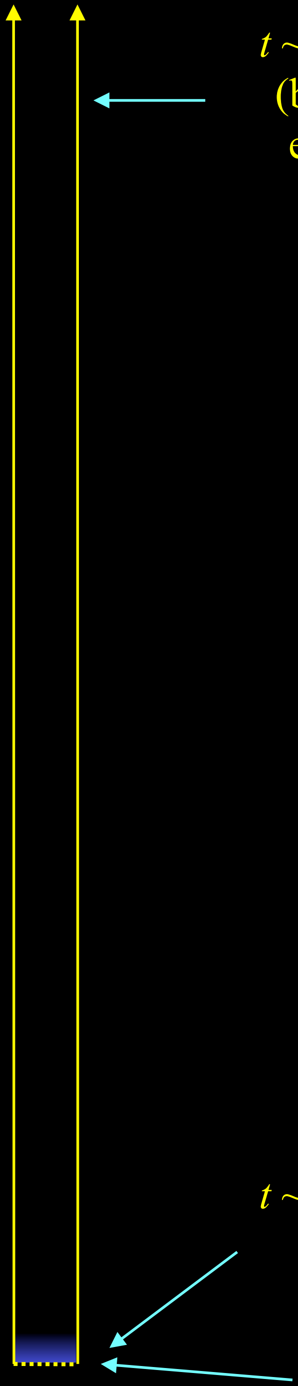


Rescaled view of the observable universe (comoving patch):

$t \sim 10^{10}$ years

$t \sim 0$

Extend into the future:

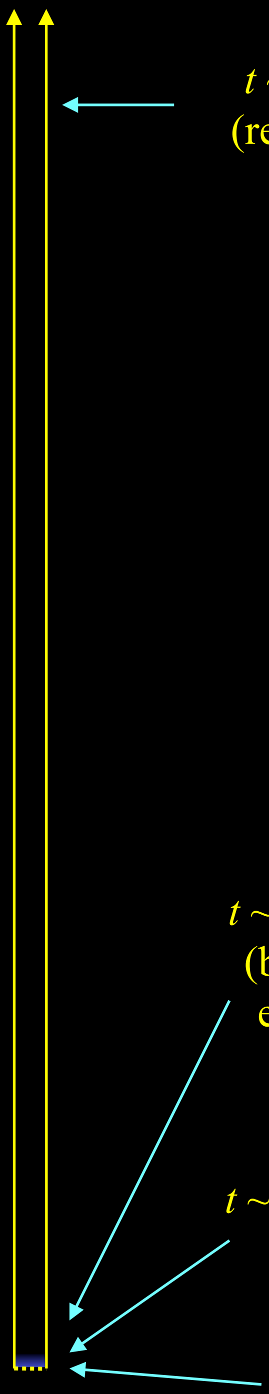


$t \sim 10^{100}$ years
(black holes
evaporate)

$t \sim 10^{10}$ years
(today)

$t \sim 0$

Extend further:



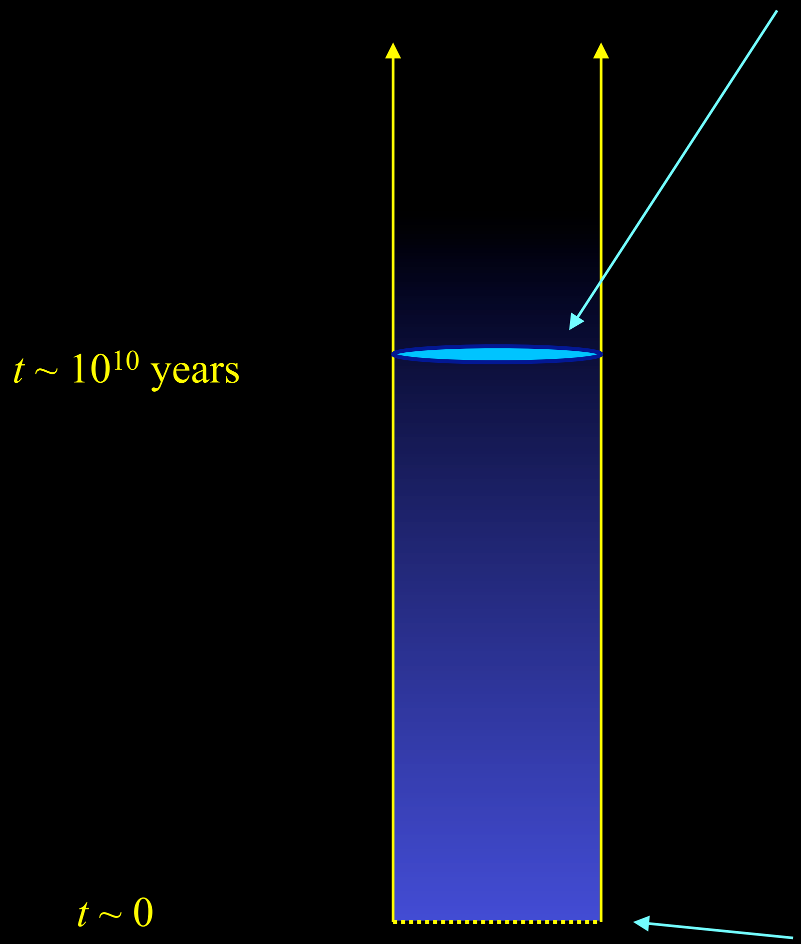
$t \sim 10^{10^{120}}$ years
(recurrence time)

$t \sim 10^{100}$ years
(black holes
evaporate)

$t \sim 10^{10}$ years
(today)

$t \sim 0$

Unitary evolution?



To a good approximation, the comoving patch evolves autonomously -- as a closed system, unaffected by outside influences.

The conservative assumption (consistent with ordinary quantum mechanics) is that this evolution is unitary -- reversible evolution within a fixed space of states.

The space of states described by quantum field theory on a smooth spacetime background is certainly not fixed -- it grows as the patch expands. $(L_P < \lambda < aH_0^{-1}.)$
Call these “smooth states.”

So: at early times, the vast majority of states are not smooth states.
They are wild, Planckian, stringy, etc.

The problem is that the actual early universe apparently was in a smooth state, even though very very few states are smooth.

This is Penrose's entropy problem. The early universe has an entropy

$$S \sim 10^{88} \,.$$

The current universe has an entropy

$$S \sim 10^{101} \,.$$

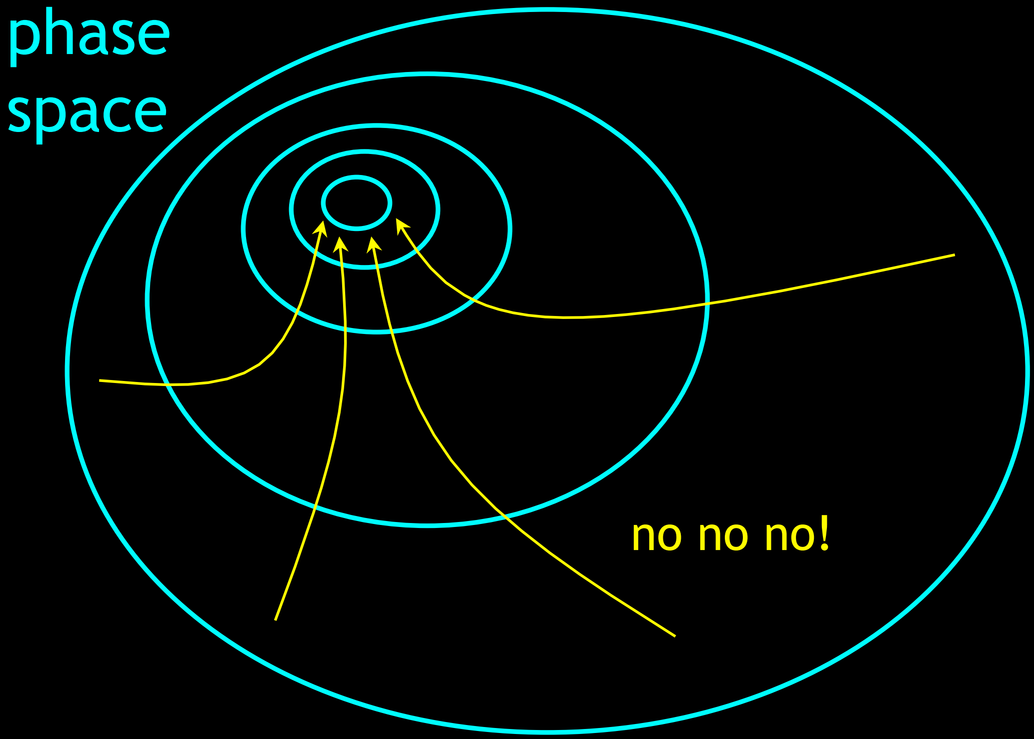
And the maximum entropy of our patch is something like

$$S \sim 10^{120} \,.$$

Remember that the number of macroscopically indistinguishable states is the exponential of the entropy.

There is no possible dynamical explanation of this state of affairs if we accept that:

1. The comoving patch evolves autonomously …
2. obeying unitary (reversible) dynamical laws …
3. for all time.

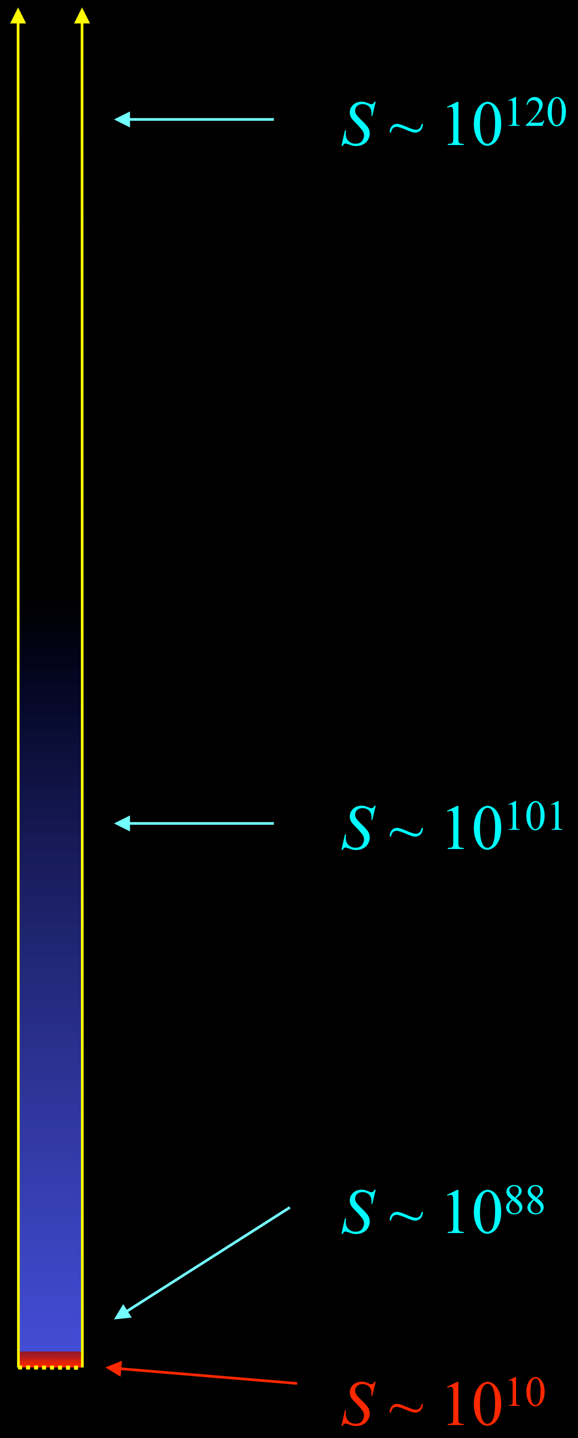


That's just Liouville's theorem: volume in phase space is conserved under reversible evolution.

Inflation, in particular, does not help, at least in a single universe; it just explains low entropy by invoking even lower entropy.

Inflation increases the fraction of smooth states at early times that evolve into universes like ours;

it does not change the fraction of all states that do so.



$S \sim 10^{120}$

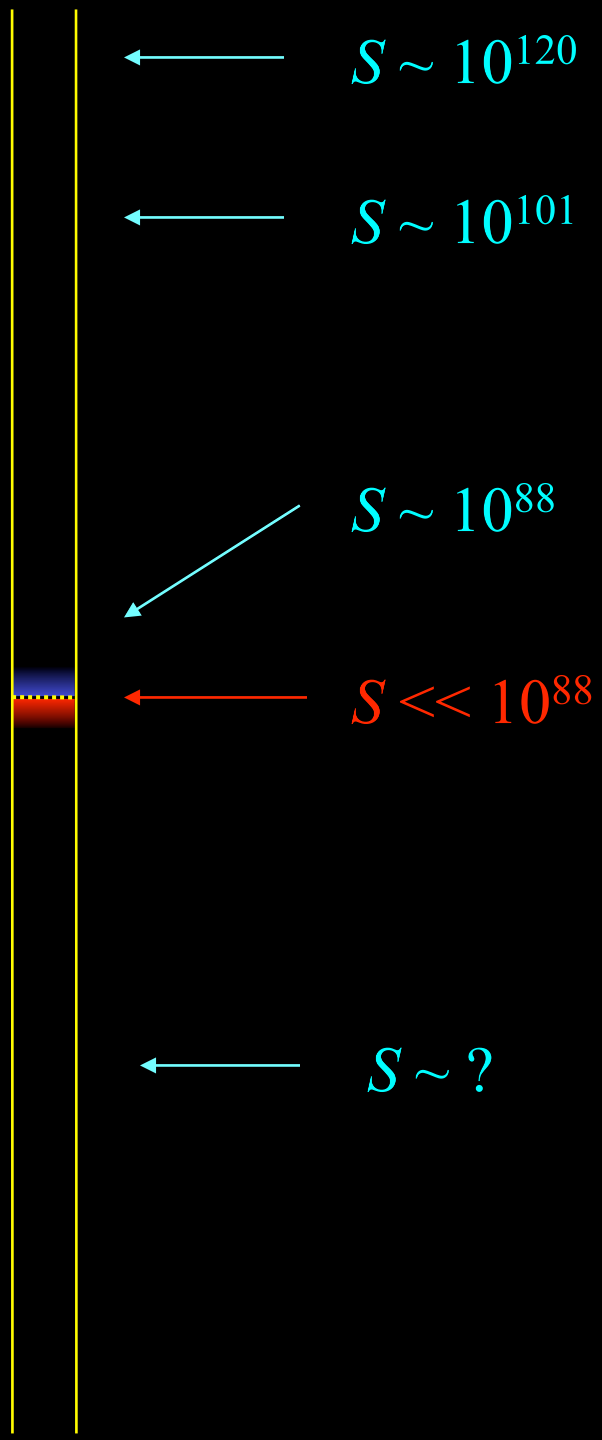
$S \sim 10^{101}$

$S \sim 10^{88}$

$S \sim 10^{10}$

Pre-Big-Bang models -- bouncing, ekpyrotic, cyclic, string gas -- don’t help either.

Either the entropy decreases in the contracting phase (for no good reason), or it increases for all time from an even more finely-tuned state in the very far past.



$S \sim 10^{120}$

$S \sim 10^{101}$

$S \sim 10^{88}$

$S << 10^{88}$

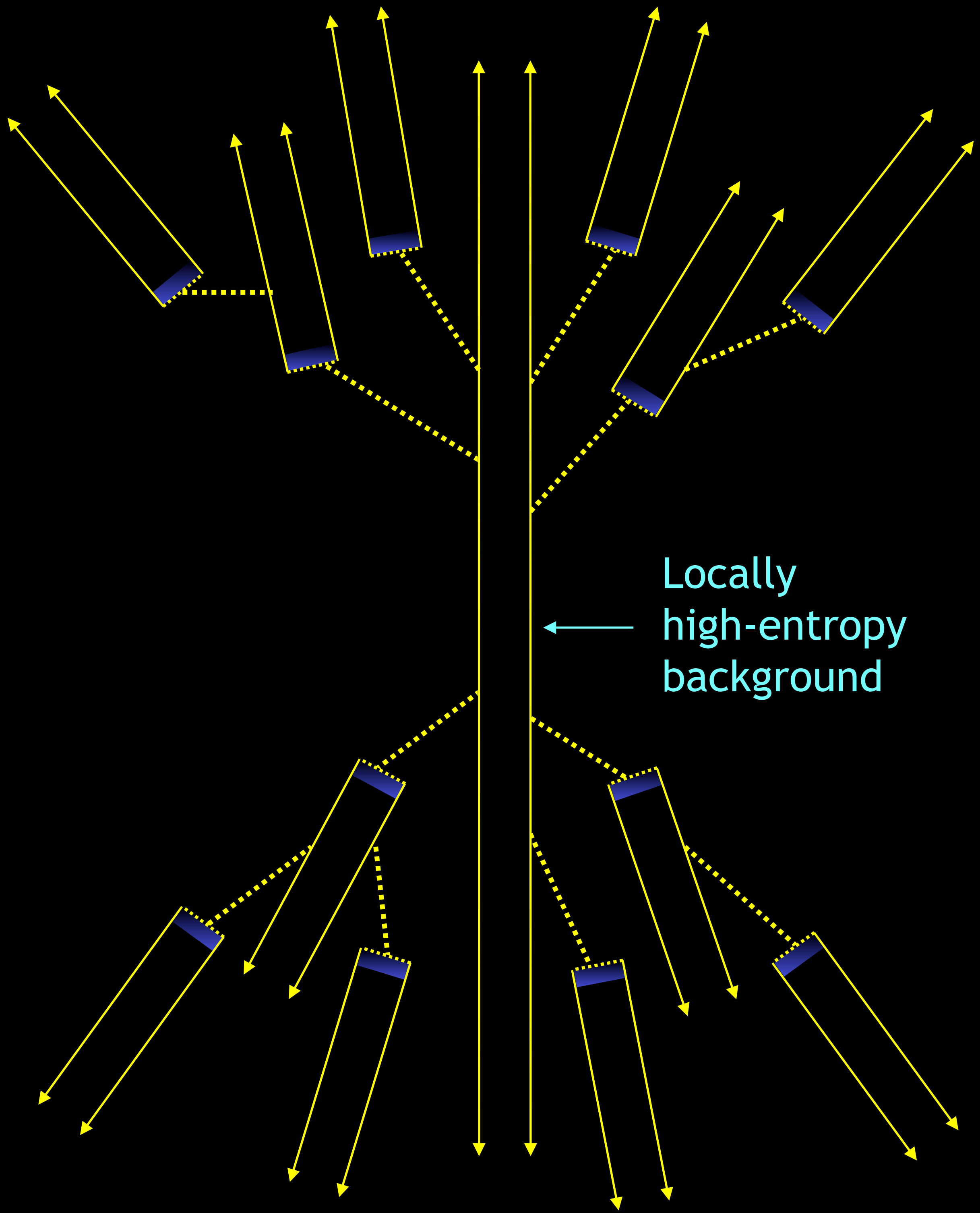
$S \sim ?$

The multiverse doesn’t automatically address this puzzle, but it offers a chance to do so.

We could be a baby universe born out of a (locally) high-entropy background.

There is no equilibrium state, because entropy can always increase.

And the multiverse is time-symmetric overall.



Locally high-entropy background