The Origin of the Universe and the Arrow of Time

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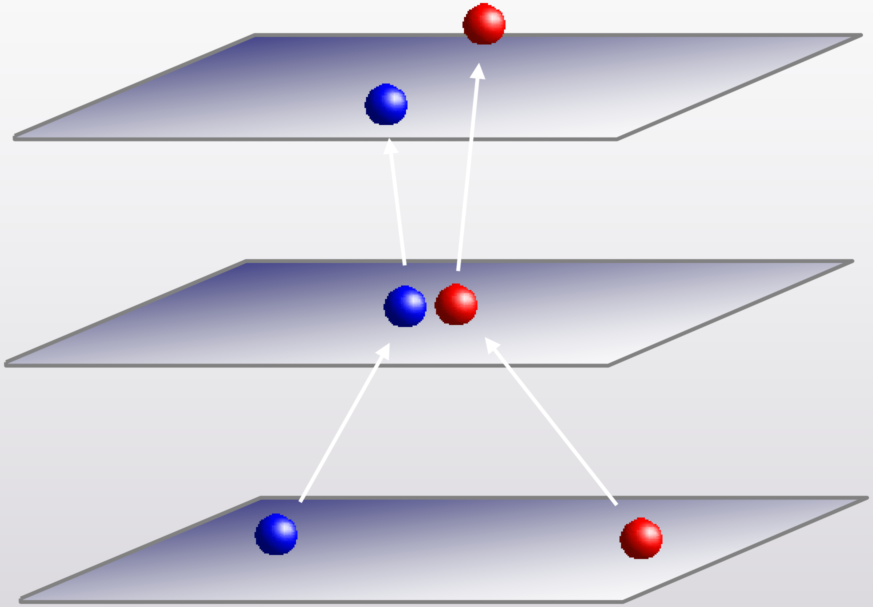
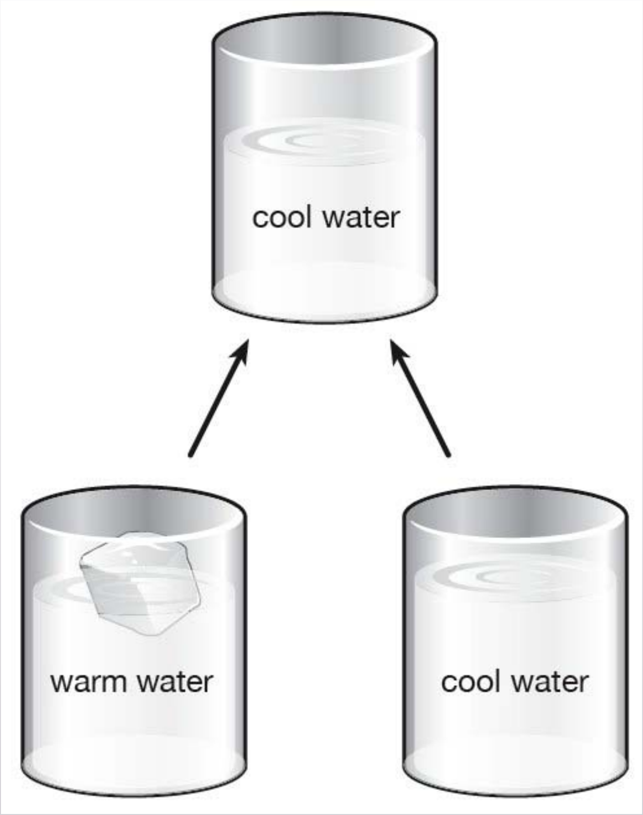
The arrow of time -- the difference between past and future -- is one of reality's most blatant features.

The fundamental laws of nature have no arrow of time.

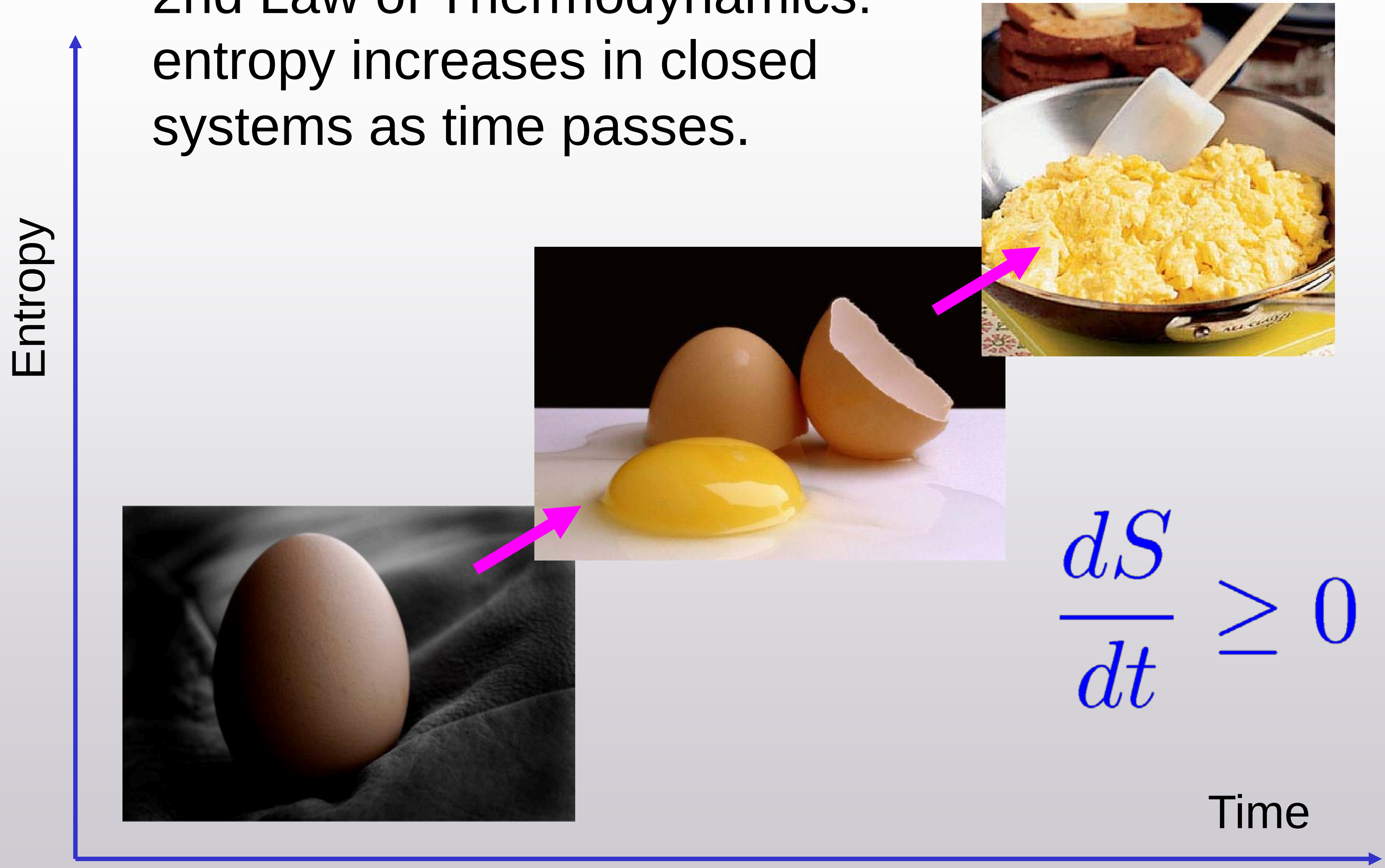




Simple ("fundamental") motions are reversible.

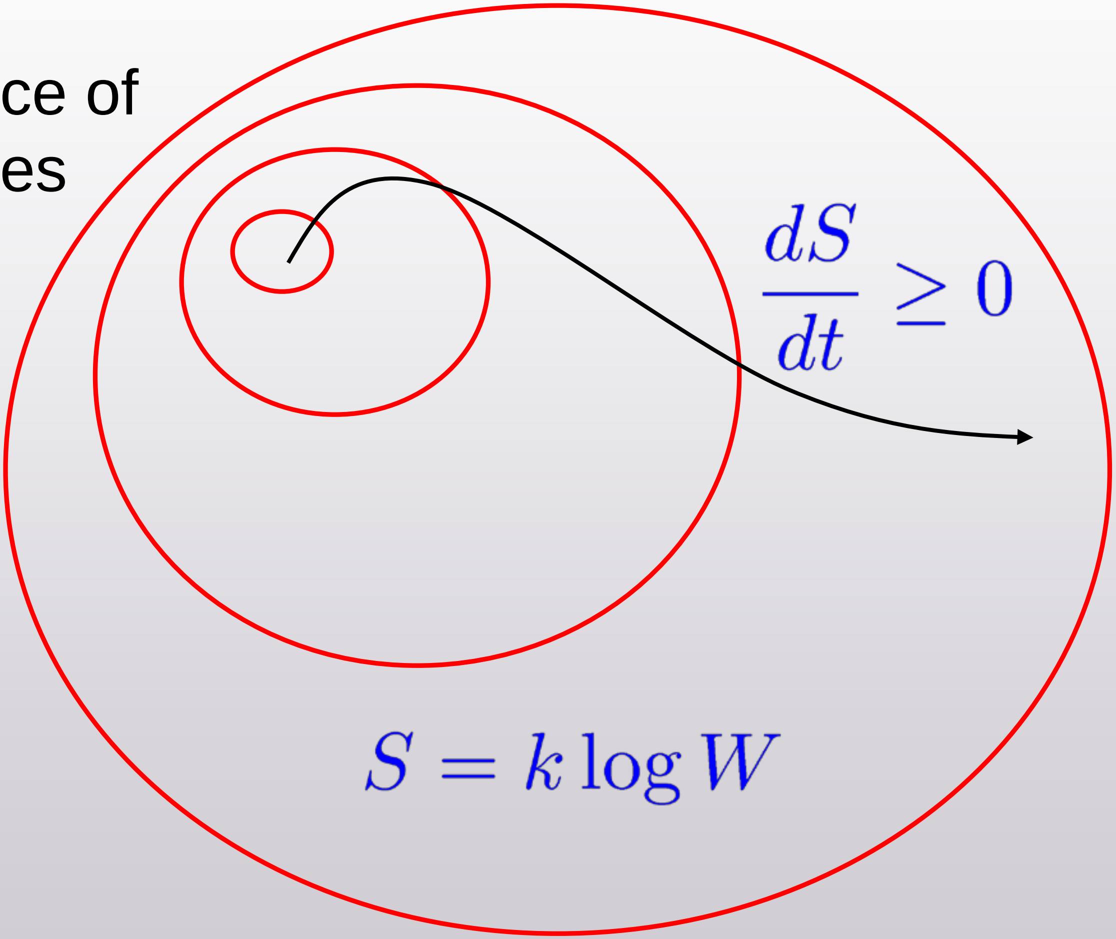
Macroscopic evolution is irreversible.

2nd Law of Thermodynamics: entropy increases in closed systems as time passes.



$$\frac{dS}{dt} \geq 0$$

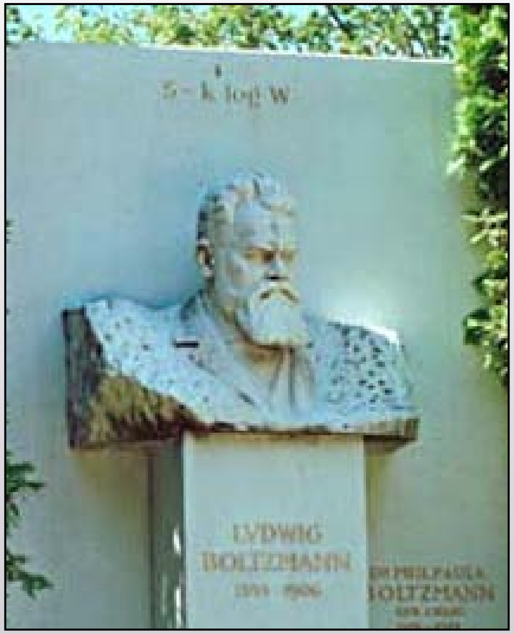
Boltzmann, 1870s: entropy counts the number of states that look the same macroscopically.



space of states

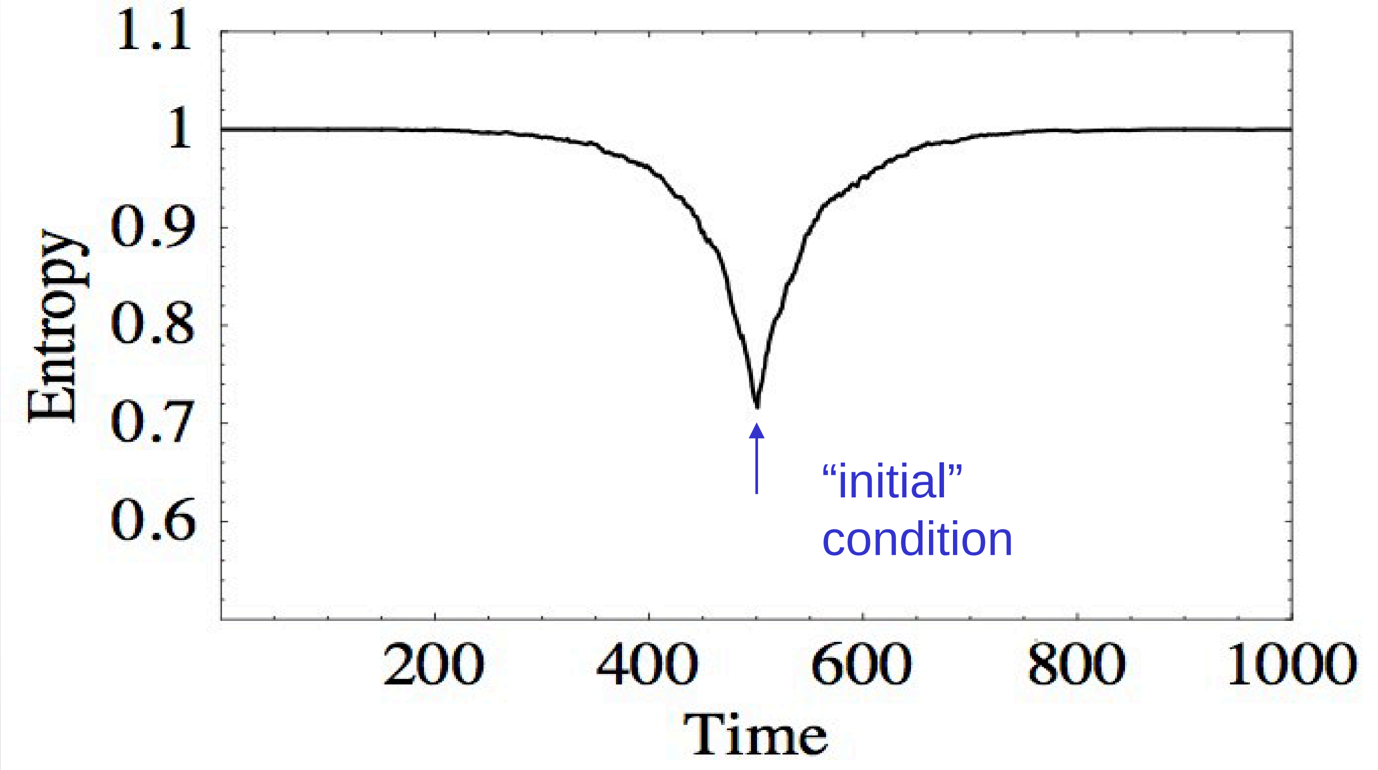
$$\frac{dS}{dt} \geq 0$$

$$S = k \log W$$



“macrostates” = sets of macroscopically indistinguishable microstates

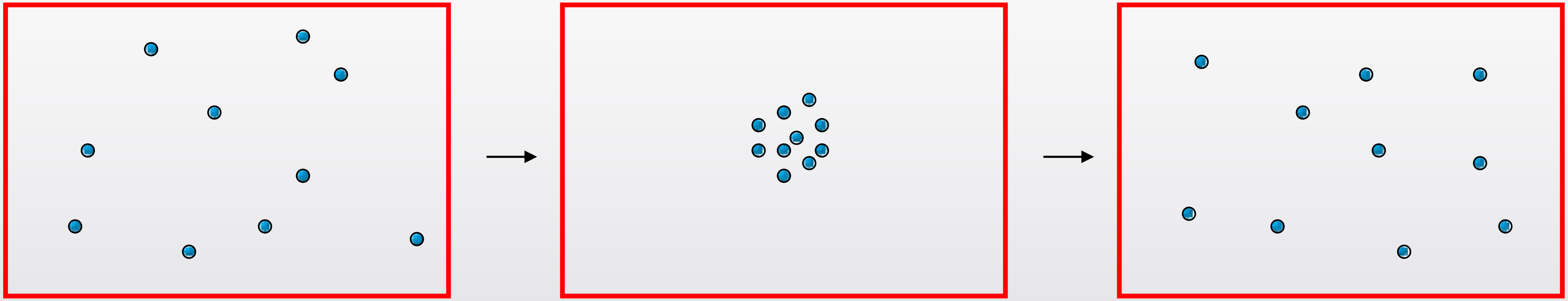
Boltzmann’s formalism explains why entropy will probably be higher in the future.

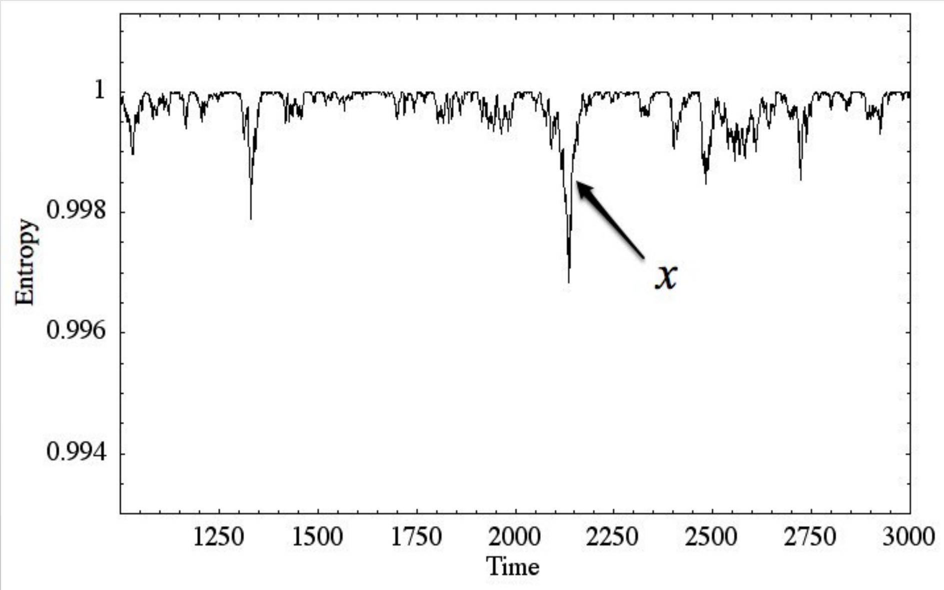


“initial” condition

Why was it lower in the past?

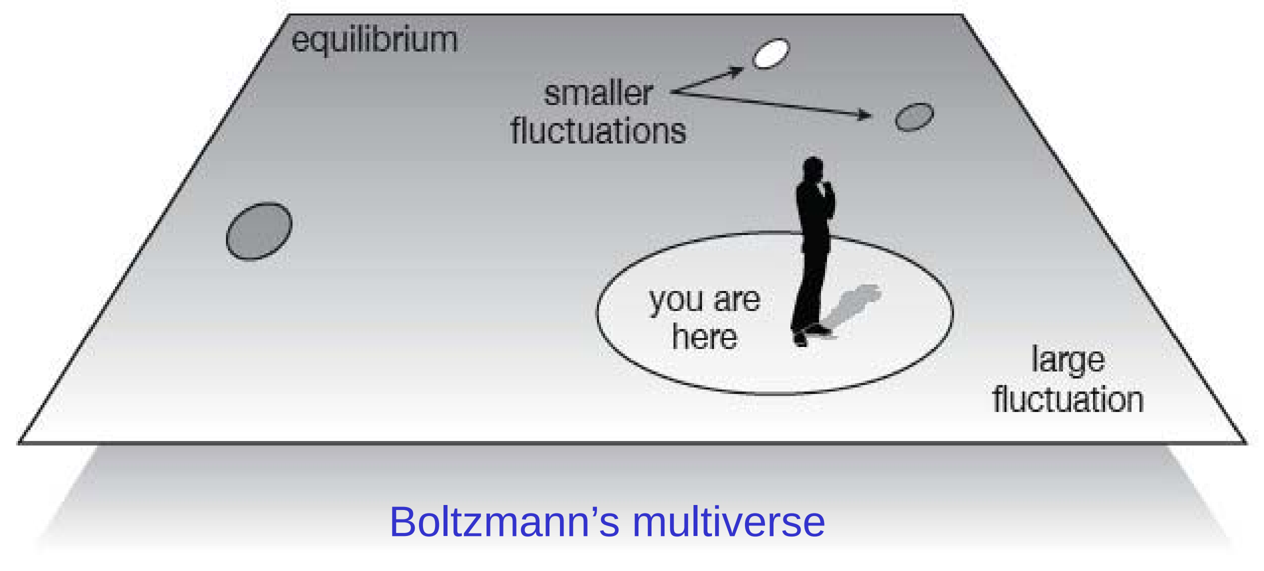
Could our local region be a random fluctuation in a mostly-equilibrium universe?





Entropy of a box of gas, fluctuating around equilibrium.

Boltzmann, 1895: maybe there is a multiverse mostly in high-entropy equilibrium, and our galaxy is just a random fluctuation.

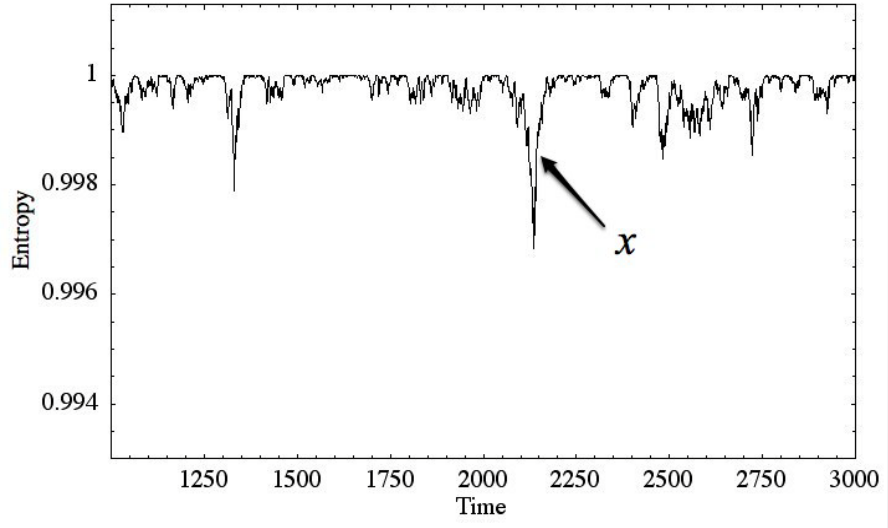


Boltzmann's multiverse

The anthropic principle: in a big universe, we will only observe those parts that are hospitable to the existence of intelligent life.

This idea doesn't work.
Entropy fluctuations are exponentially suppressed,

$$P(\Delta S) \sim e^{-\Delta S}$$

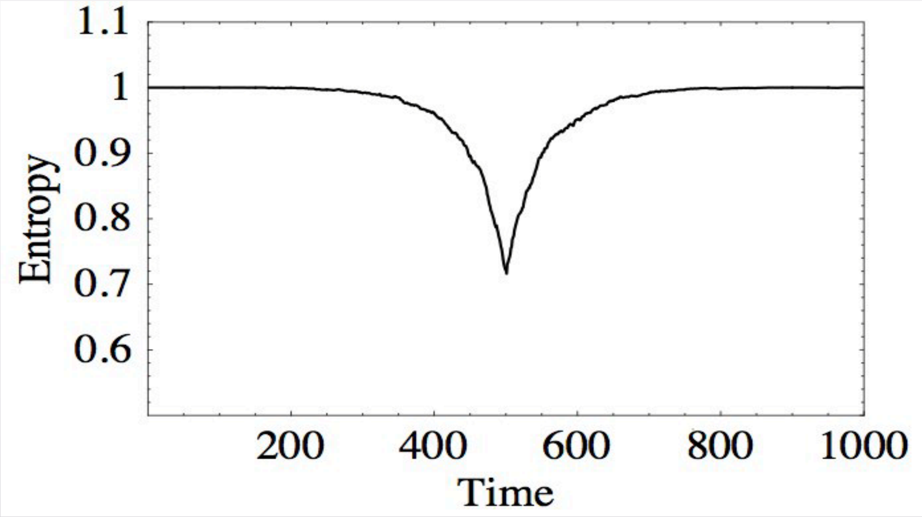


Prediction: we should observe the smallest deviation from equilibrium consistent with anthropic requirements.

Albrecht & Sorbo (2004):
"Boltzmann Brains."

The real problem is not Boltzmann brains.
You’re not a typical observer, deal with it.

The real problem is a “Boltzmann you.”

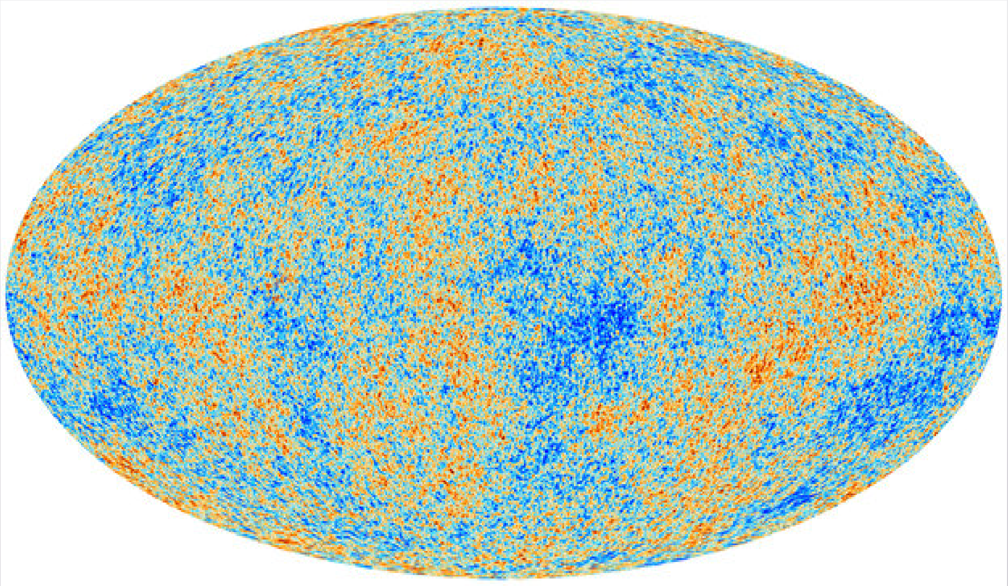


Cognitive instability:
in a fluctuation scenario, it’s easier to fluctuate a copy of you with false memories than to fluctuate the whole world.

If this scenario were correct, you would have no good reason to believe it.

How can we escape from cognitive instability?

"The Past Hypothesis":
our universe started in a low-entropy state.
(At high density, smooth = low entropy.)



Compatible with observation -- but necessarily an assumption.

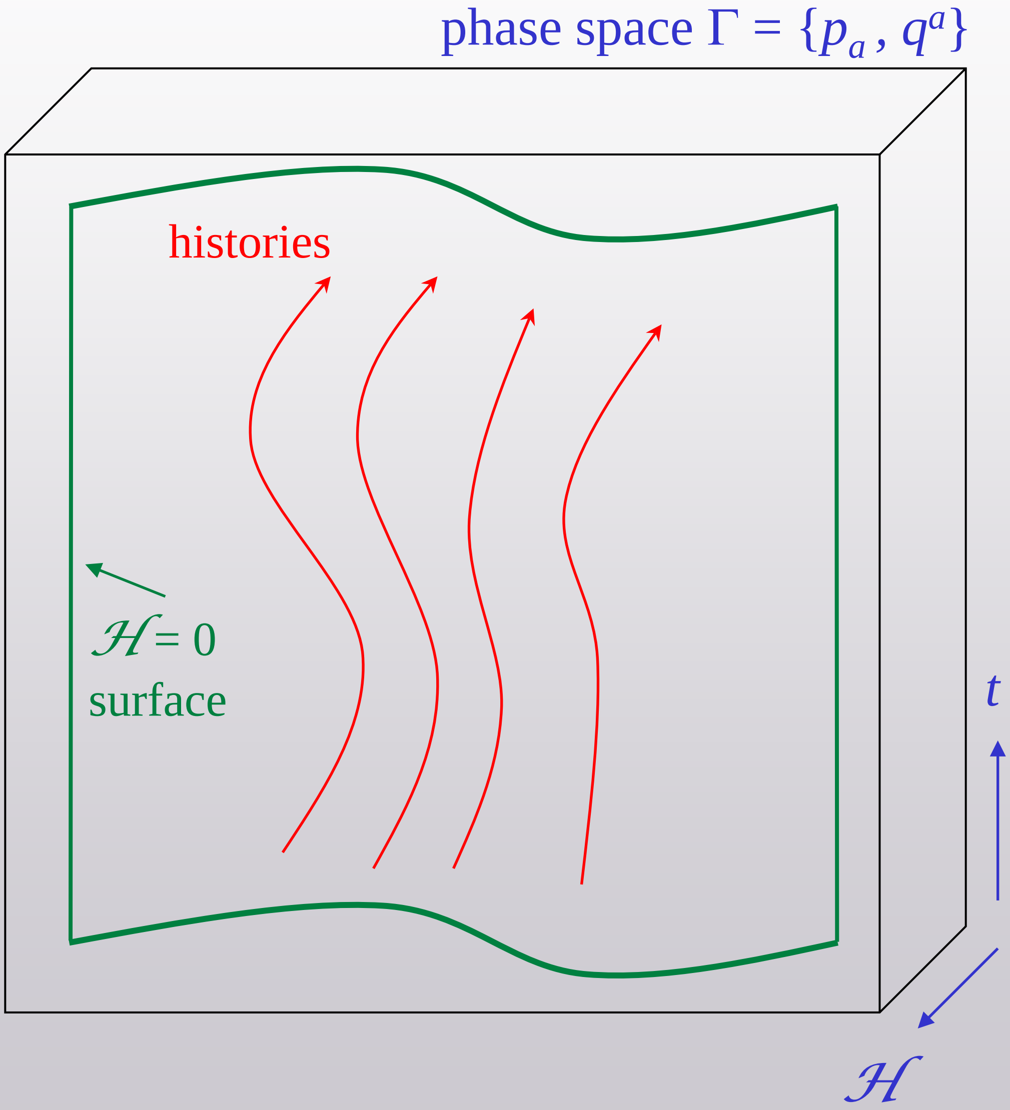
The measure on cosmological histories

[Carroll & Tam]

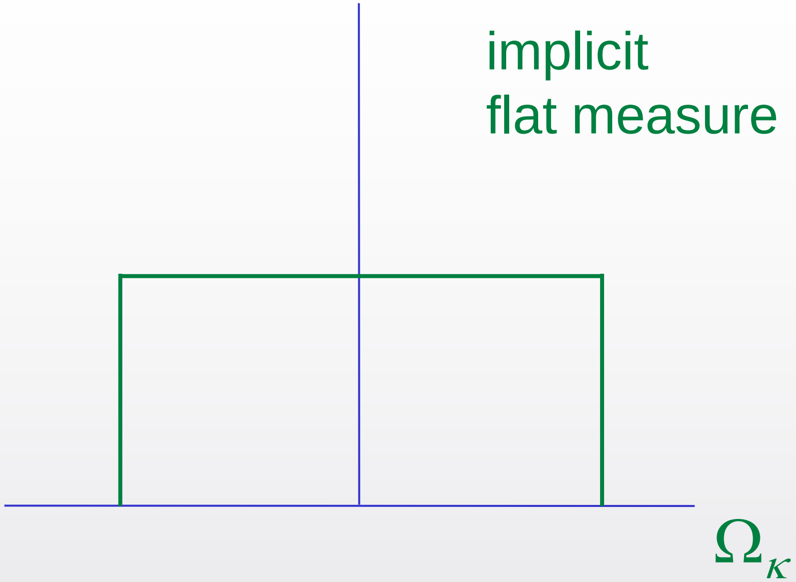
Classical GR has a phase space and a Hamiltonian $\mathcal{H}$, therefore a conserved Liouville measure.

Gibbons, Hawking and Stewart (86) derived an invariant measure on the space of trajectories.

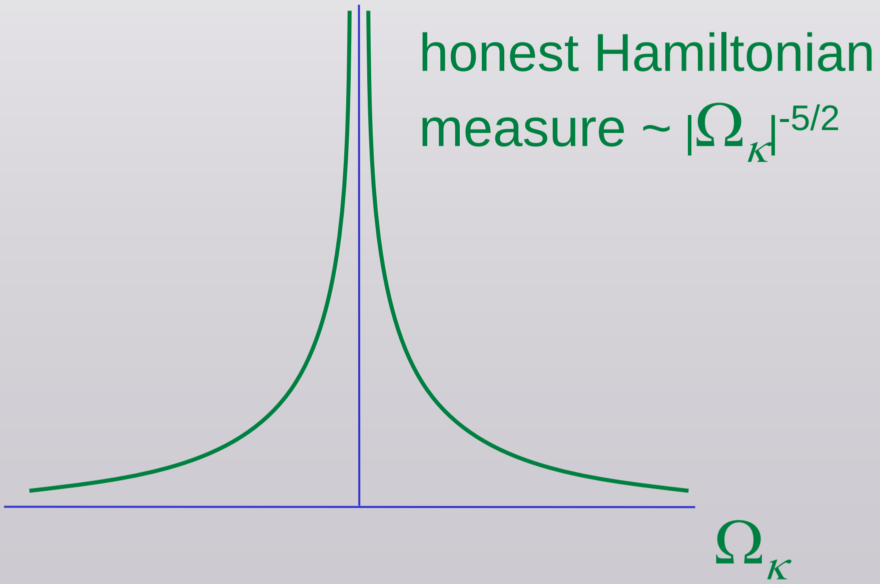
$$d\mu = \left(\sum_{a=1}^{n-1} \mathrm{d}p_a \mathrm{d}q^a \right)^{n-1}$$



The flatness problem implicitly assumes a uniform measure on curvature at early times.

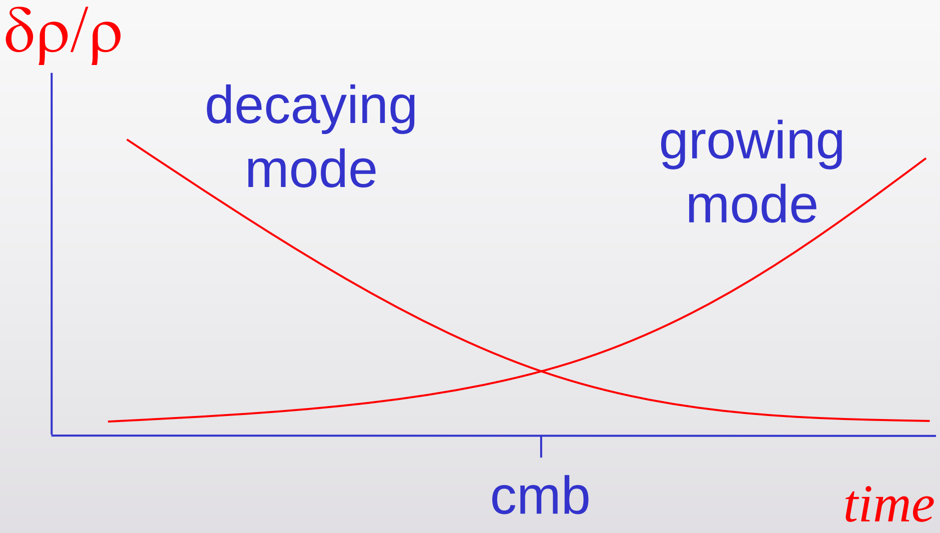


Totally wrong.
Well-defined measure is singular. Almost all FRW universes are spatially flat.
The flatness problem is fake.



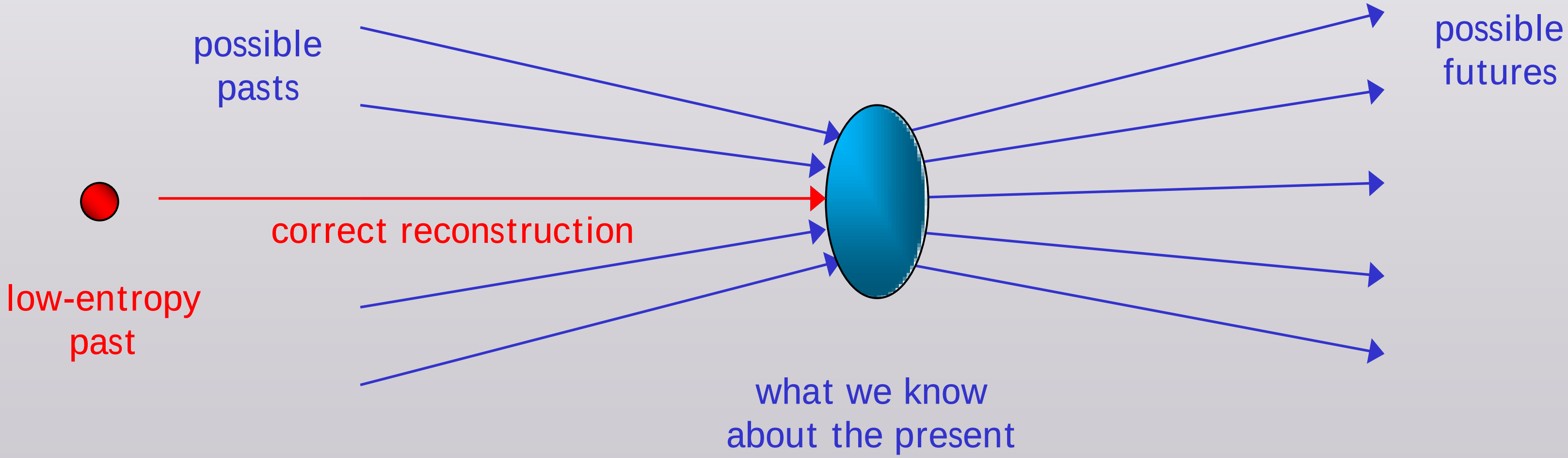
Applied to cosmological perturbations: early universe is incredibly finely-tuned.

$P(\text{early} \mid \text{cmb}) \sim 10^{-10^{17}}$



The horizon/homogeneity problem is frighteningly real.

The past hypothesis helps reconcile reversible microphysics with macroscopic directionality. Why do we remember the past and not the future?



possible
pasts

correct reconstruction

low-entropy
past

what we know
about the present

possible
futures

What we know:

1. Why entropy will increase toward the future. (Boltzmann)

2. Why entropy was lower in the past. (Big Bang)

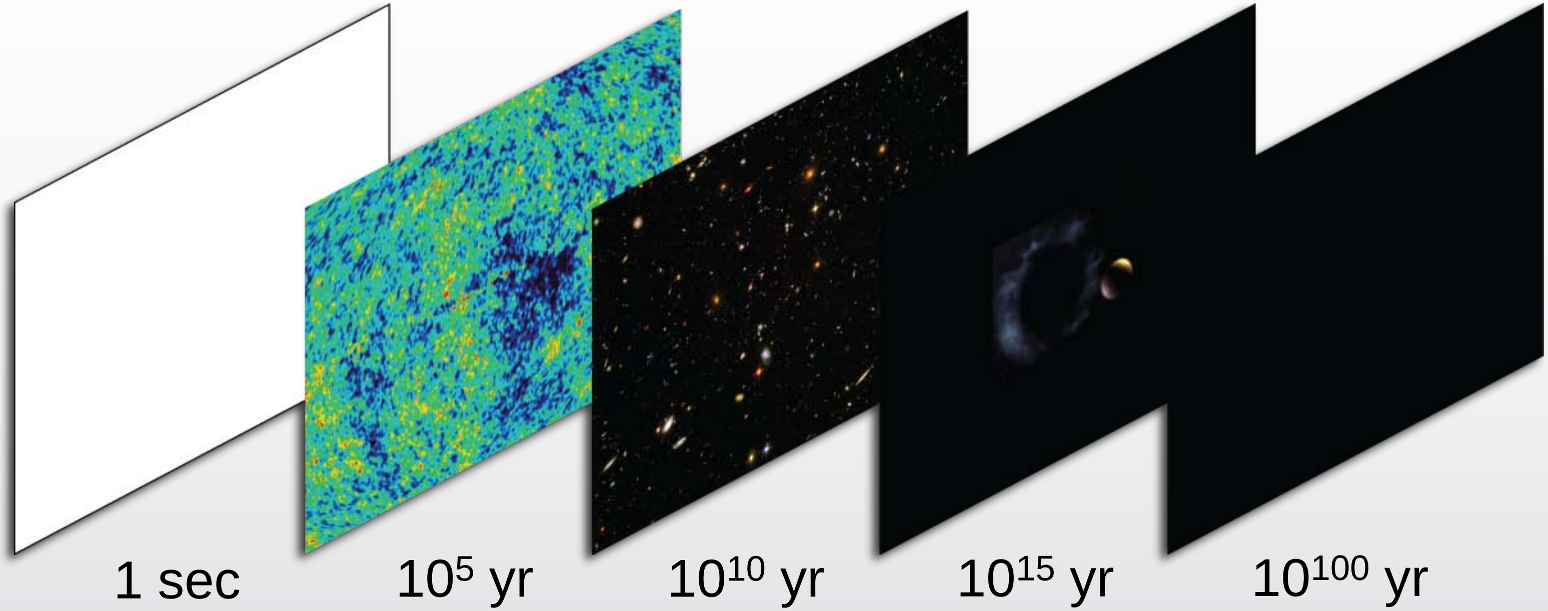
What we need to figure out:

1. Why the early universe had low entropy.

2. How increase of entropy undergirds all the manifestations of time’s arrow.

Aside: Entropy vs. Complexity

[Aaronson, Carroll, & Ouellette]

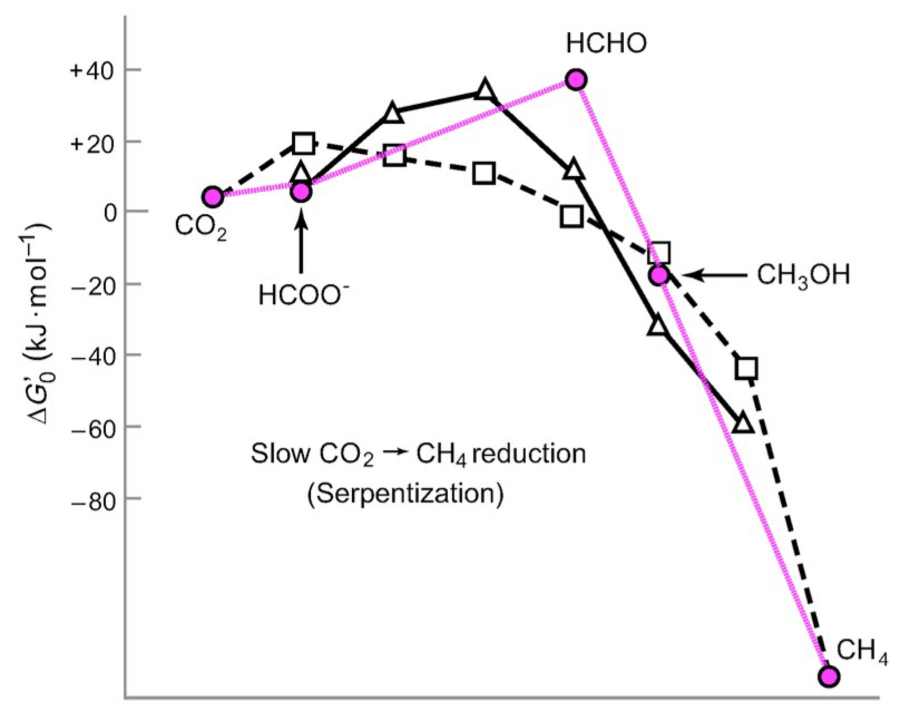


Entropy increases.
Complexity first increases,
then decreases.

Origin of life:

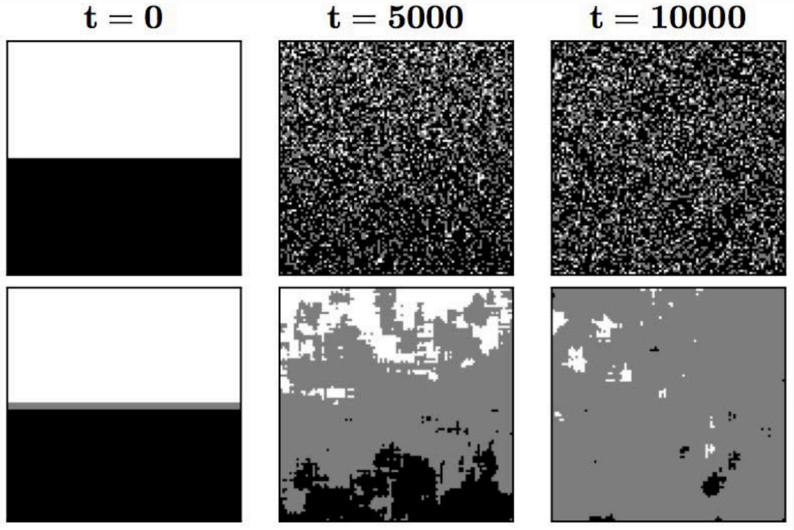
Complexity isn’t merely compatible with the Second Law, it’s a consequence of increasing entropy.

[Penrose]



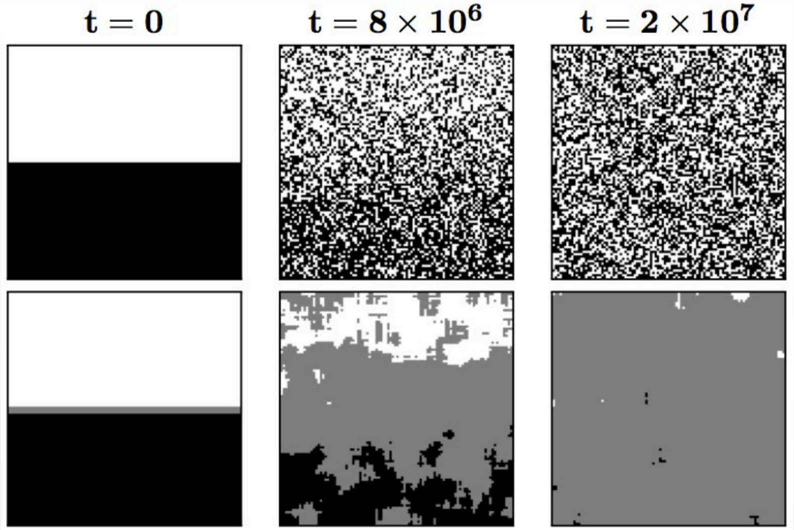
[Yung, Russell & Parkinson]

Simple model: the coffee-cup automaton.



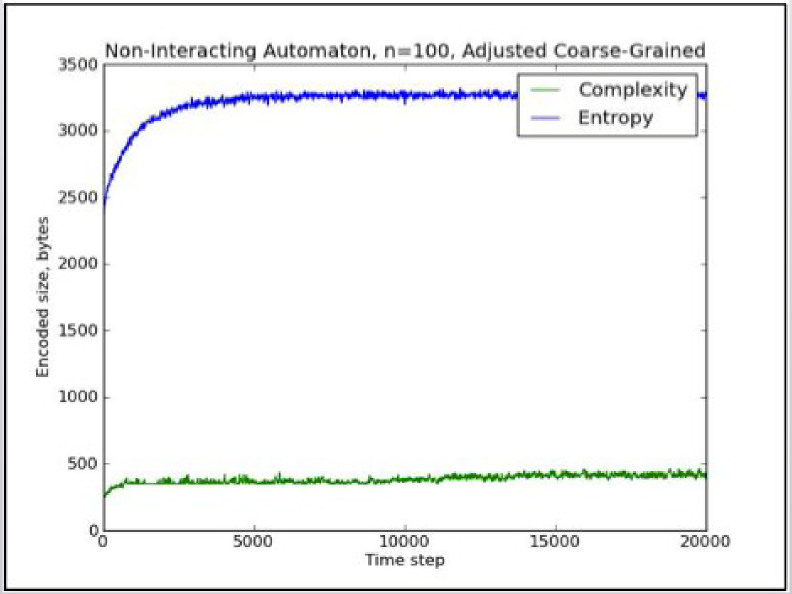
fine-grained

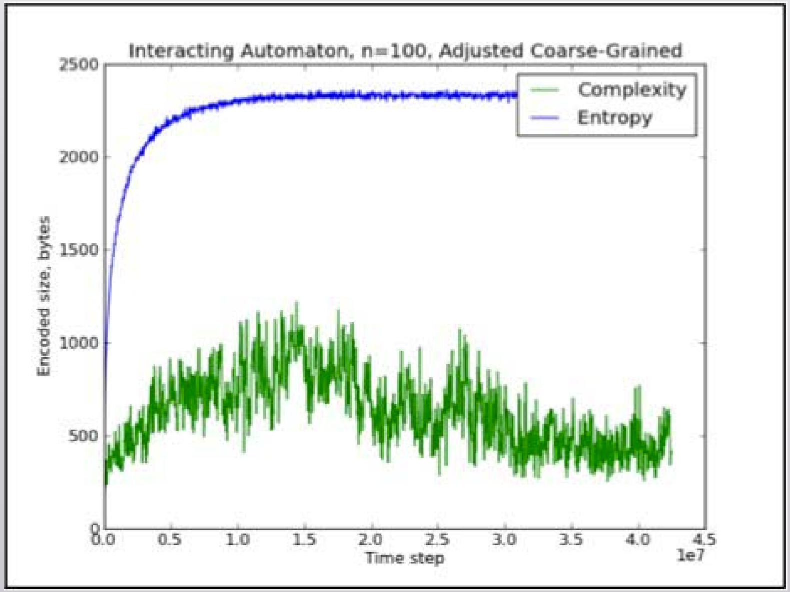
coarse-grained



non-interacting

interacting





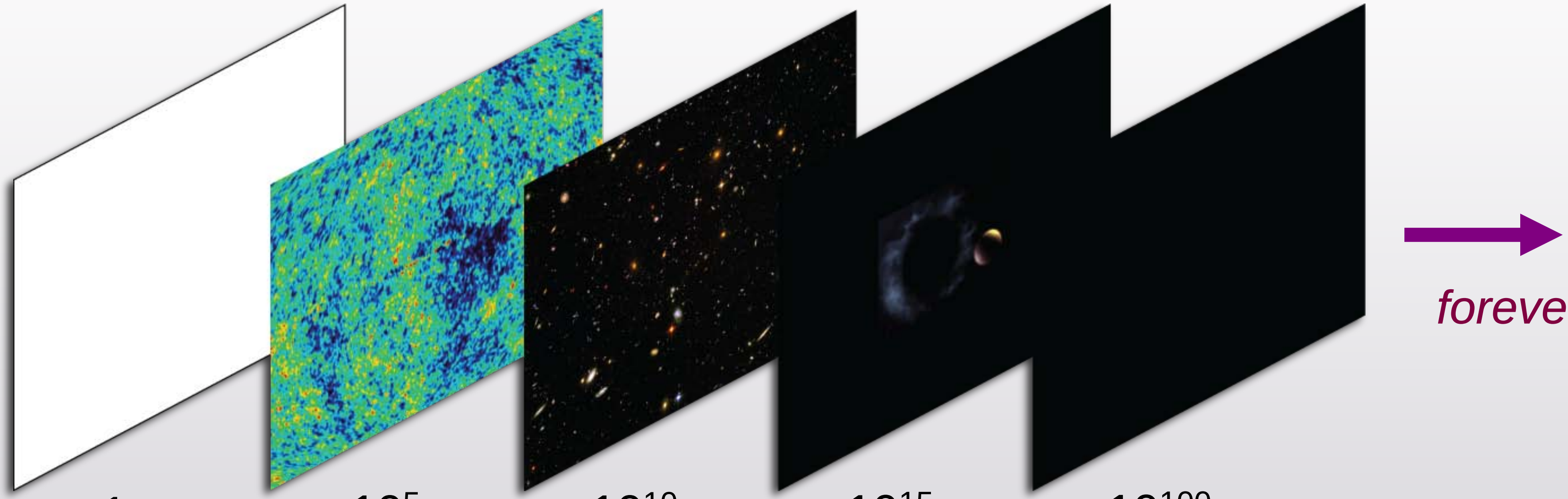
The challenge for theoretical cosmology:

The explanation for time asymmetry comes from cosmological initial conditions.

Therefore:

We can't *assume* time asymmetry when proposing new theories of cosmological initial conditions!

Modern manifestation of Boltzmann’s scenario: ΛCDM



1 sec

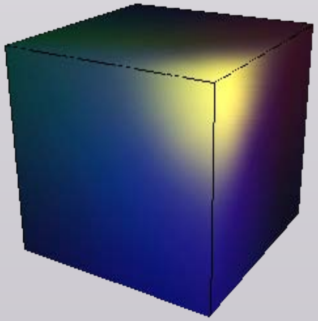
10^5 yr

10^{10} yr

10^{15} yr

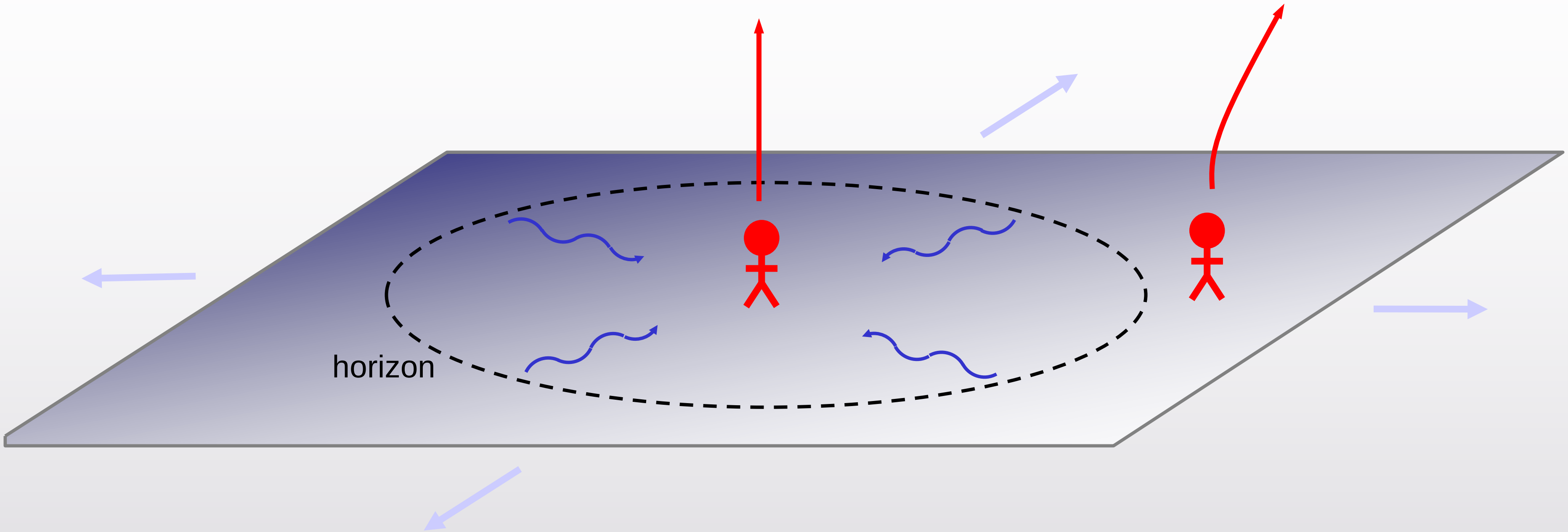
10^{100} yr

forever



vacuum energy, a/k/a
the cosmological constant

Consequences of Vacuum Energy

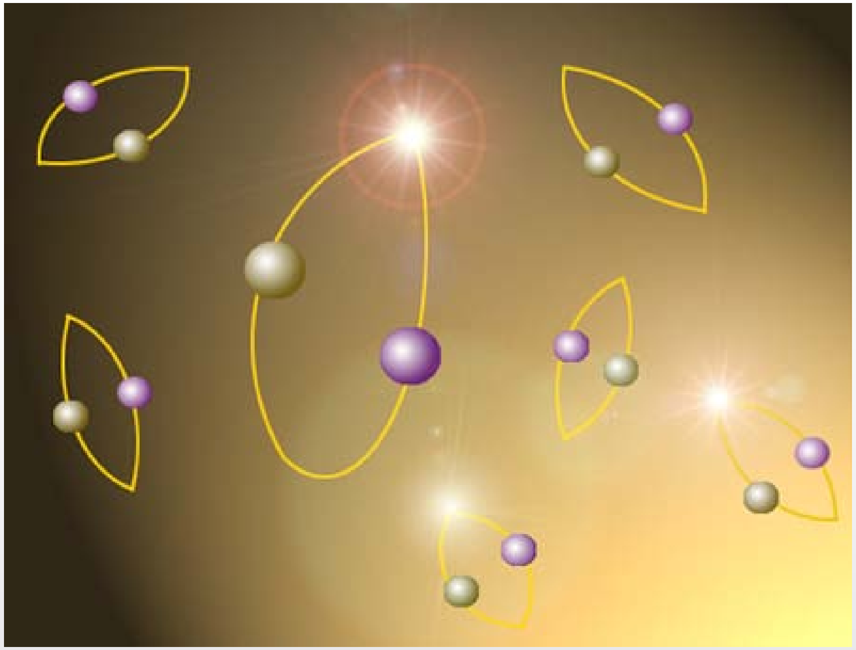


- the universe expands forever at a fixed rate
- distant objects disappear: we are surrounded by an horizon (recession velocity > c).
- our patch inside the horizon has:

  a temperature $T = (E_{vac})^2/E_{planck} \sim 10^{-30}\,\mathrm{K}$

  an entropy $S = (E_{planck}/E_{vac})^4 \sim 10^{120}$.

Vacuum fluctuations bring Boltzmann’s scenario back to life.



Our observable universe is like a box of gas at a fixed temperature that lasts forever.

Recurrence time: $10^{10^{120}}$ years.

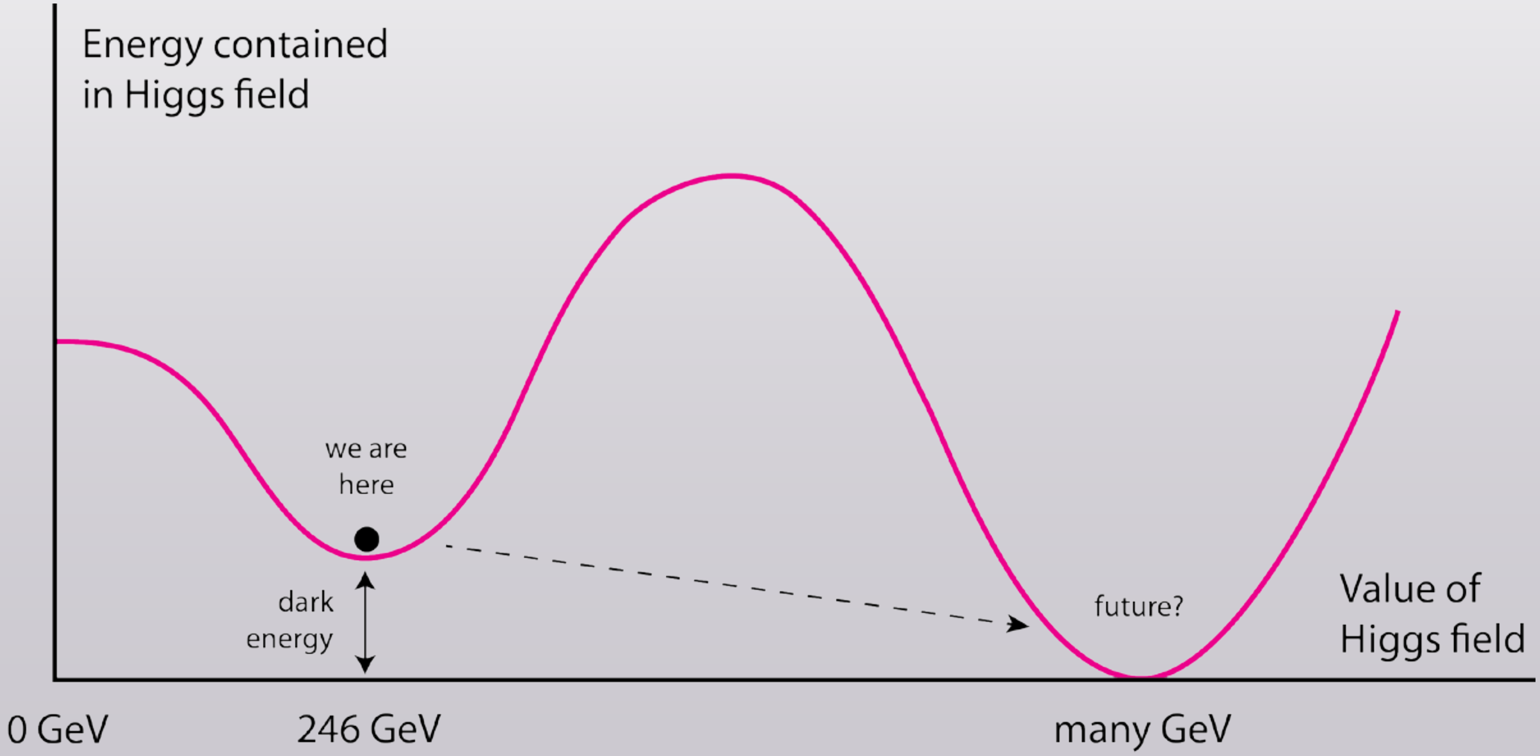
ΛCDM can’t be the whole story.

[Dyson, Kleban & Susskind;
Albrecht & Sorbo]

Getting rid of vacuum energy

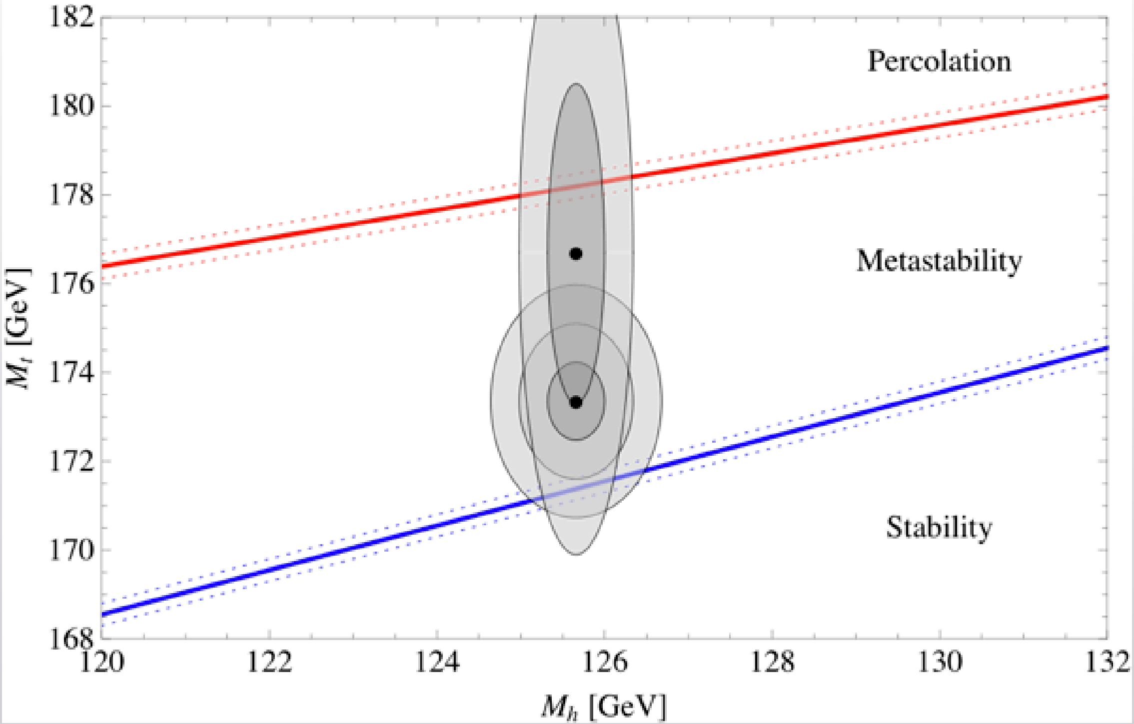
It’s quite plausible that we live in a false vacuum -- in the future we could convert to a different vacuum state via nucleation of bubbles.

Higgs field might even be responsible!



Worry: unless nucleation rate is pretty fast, eternal inflation kicks in, producing infinite volume of de Sitter.

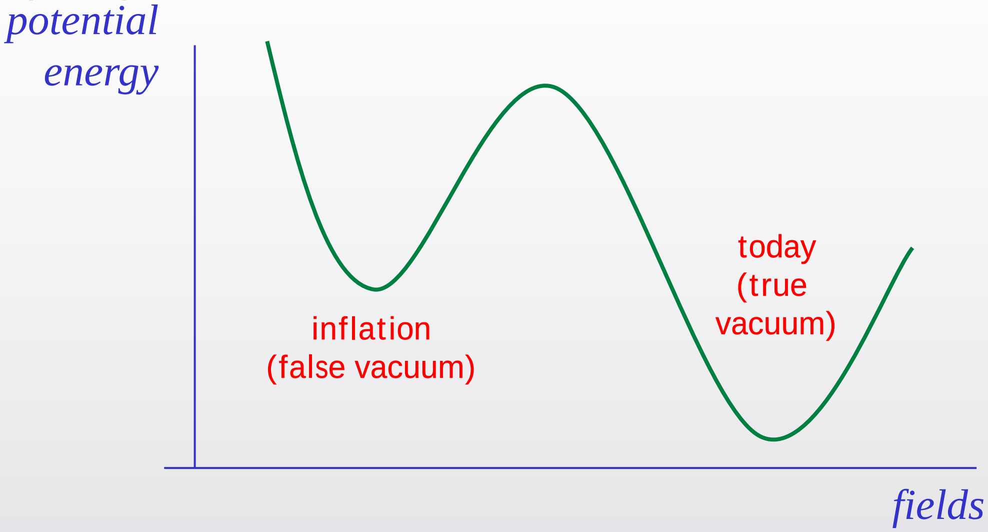
“Pretty fast” = of order 20 billion years!



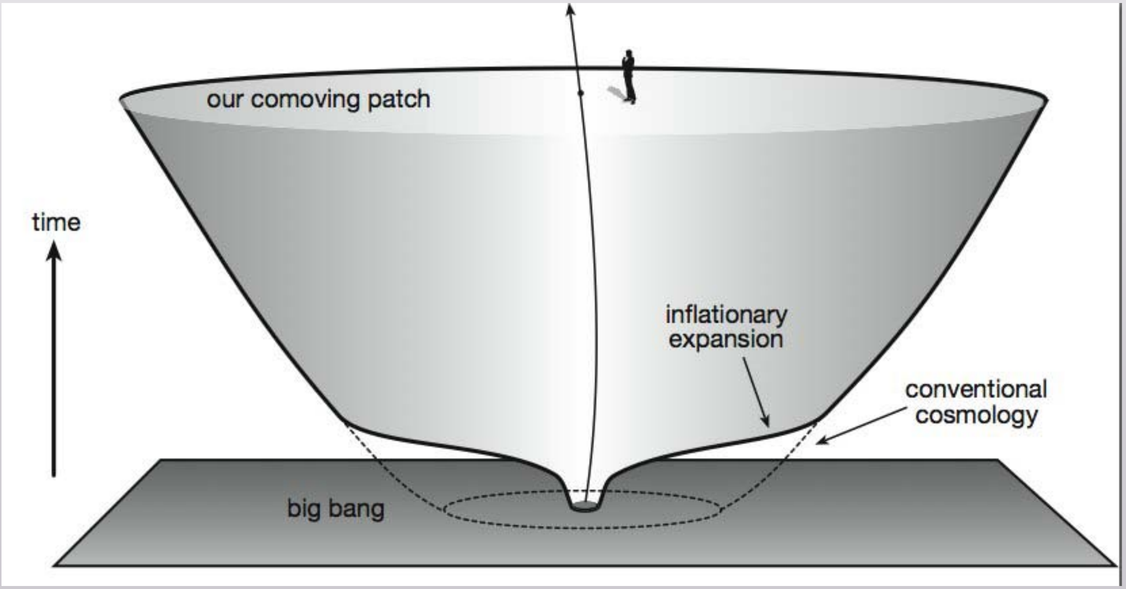
Higgs could produce rapid instability, but only if the top quark mass is ~ 178 GeV.

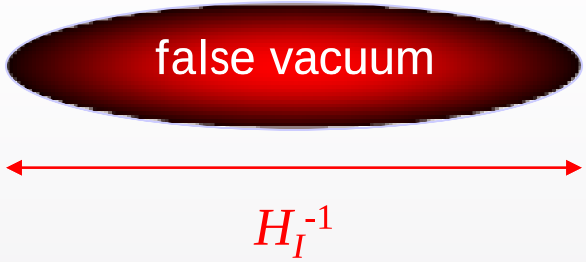
[Boddy & Carroll 2013]

Inflation by itself is not the answer.



Inflation: if a patch of space starts in a false vacuum, it naturally accelerates, creates energy, smooths out, and reheats into matter and radiation.





Starting inflation requires a lower-entropy initial condition than conventional Big-Bang cosmology. Every mode in its ground state.

$$S_{\text{inflation}} \sim (M_P/E_I)^3 \sim 10^{12} \;\; << S_{\text{ordinary Big Bang}} \sim 10^{88}$$

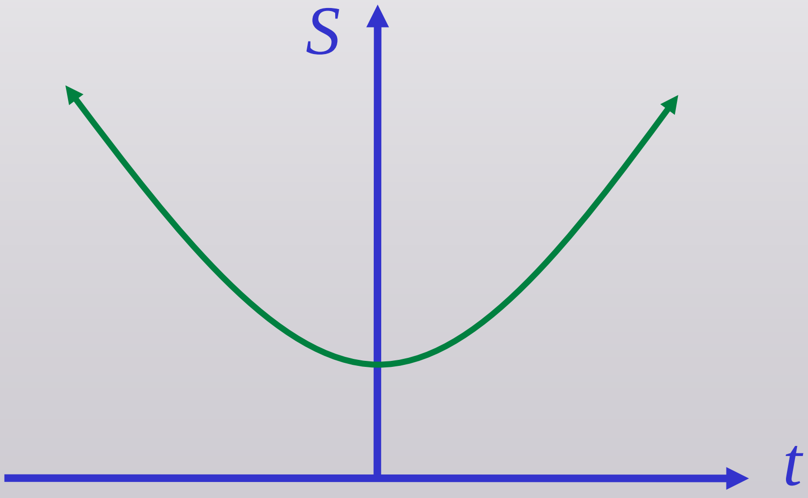
Why does inflation ever begin?

Our goal is to construct “Sagan-like” cosmologies:

if $S_n(t + \Delta t) > S_n(t)$,

then $S_n(t) > S_n(t - \Delta t)$ with high probability.

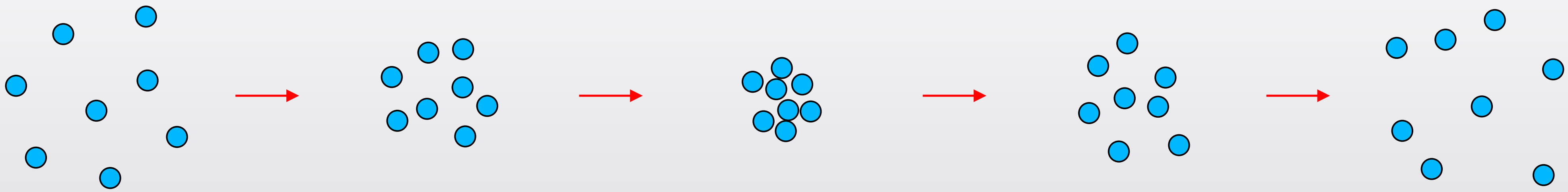
That is: if entropy is increasing, it’s probably been increasing for a while.



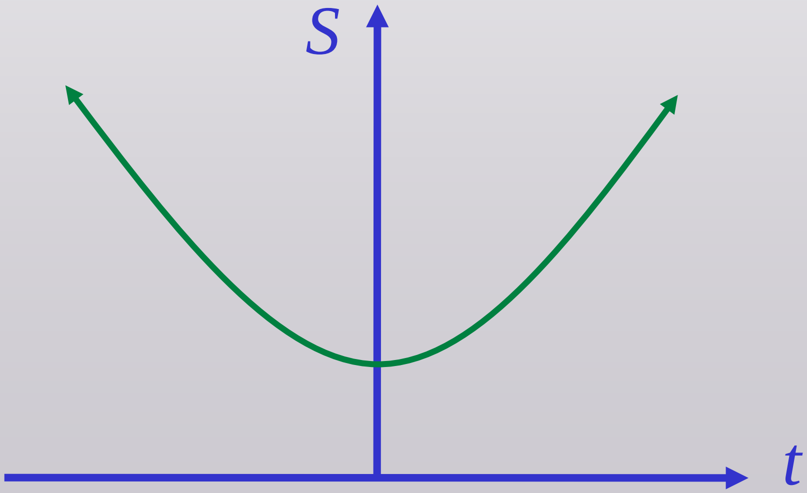
Impossible in a finite-entropy eternal universe. Possible if entropy is unbounded.

Toy model:
finitely many particles in an infinite space.

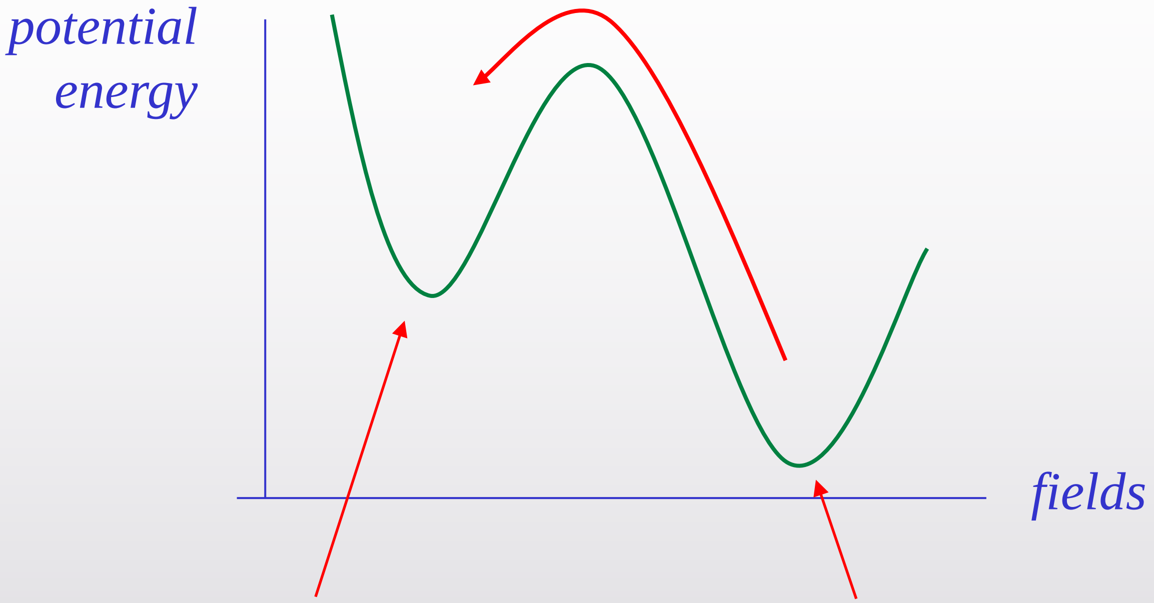
[Carroll, Guth & Tseng]



The trick is to make a realistic cosmology with this property: a restless universe.

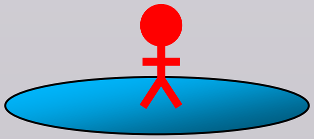


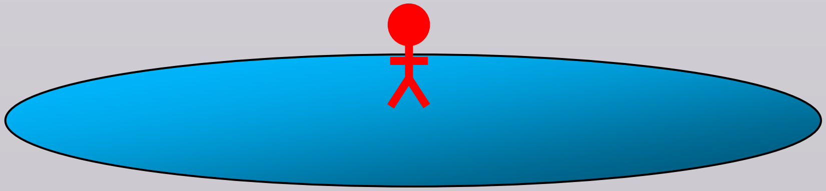
Can we tunnel upward to inflation?



Large vacuum energy
⇔ small horizon size
⇔ high temperature
⇔ low entropy

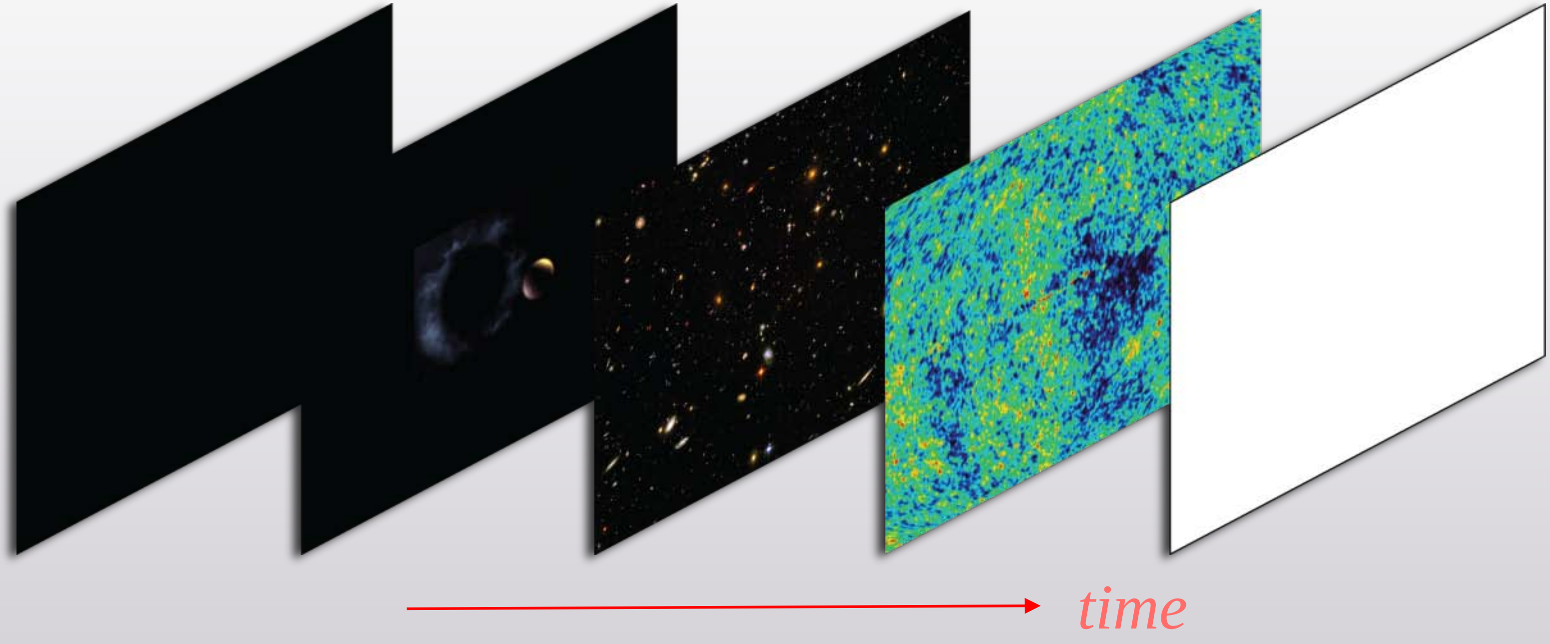
Small vacuum energy
⇔ large horizon size
⇔ low temperature
⇔ high entropy





Problem: fluctuating into inflation looks just like the time-reverse of our actual universe.

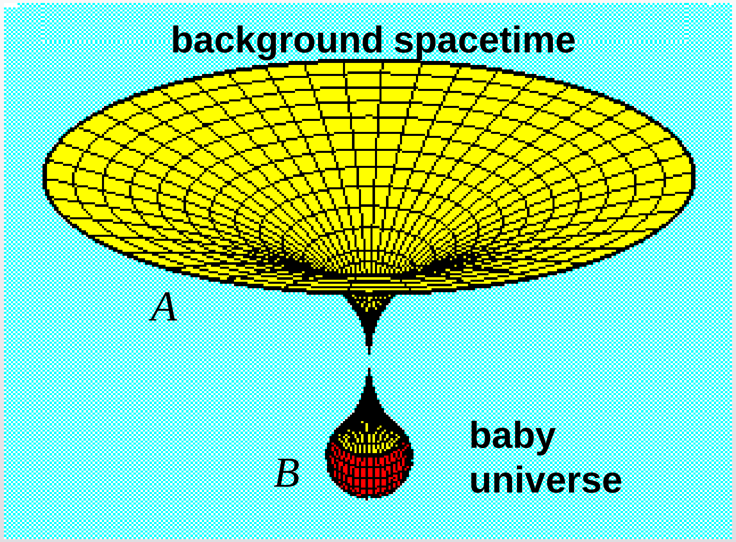
[Aguirre, Carroll & Johnson]



Fluctuating halfway and back is enormously more likely. Back to cognitive instability.

Potential loophole: disconnected baby universes.

[Carroll & Chen]



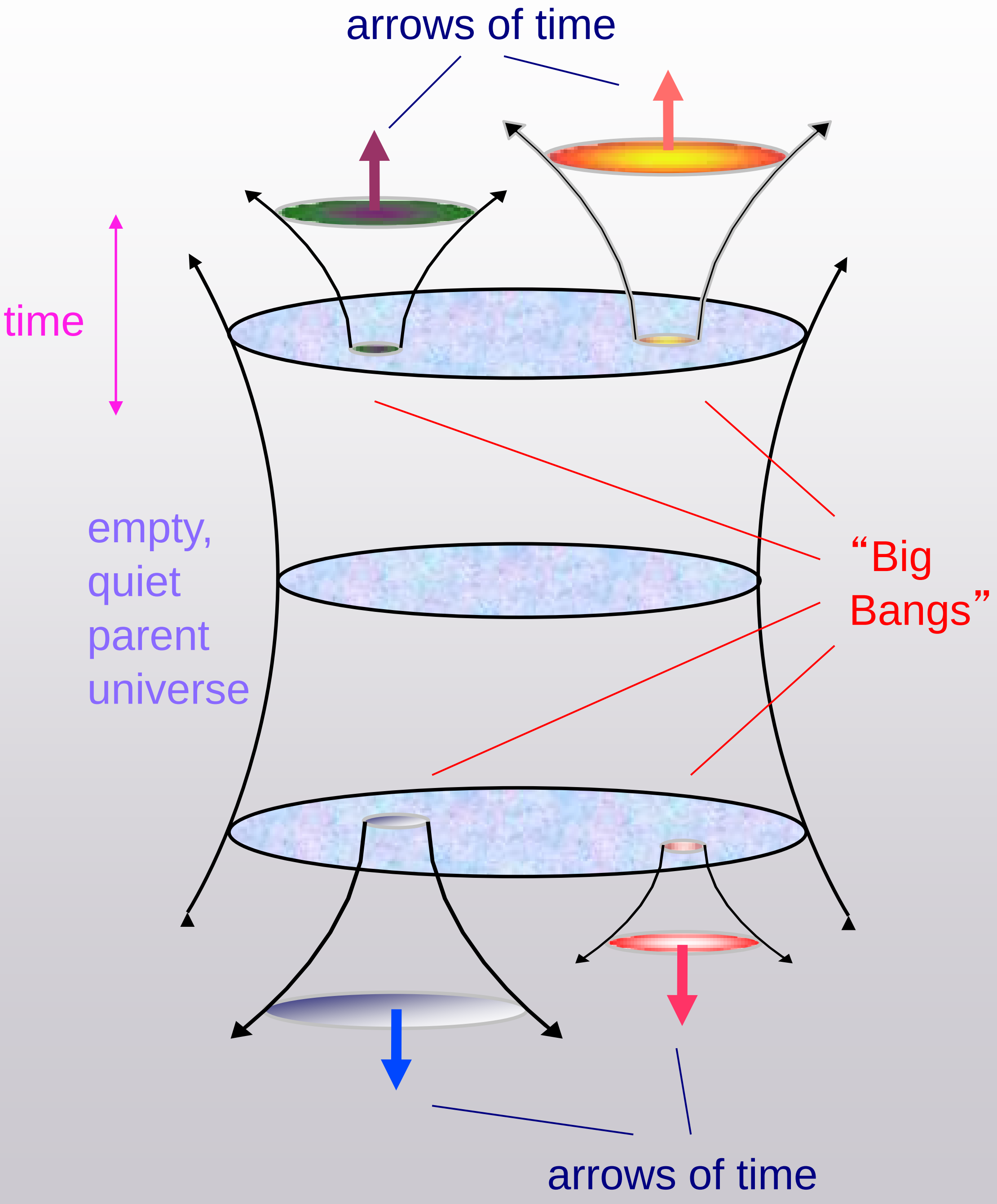
[Farhi & Guth, et al.]

If we're lucky, spacetime
may tunnel at the same time,
into a throat connecting
to a baby universe ready
to undergo inflation.

Baby universes are small: easier to make than brains.

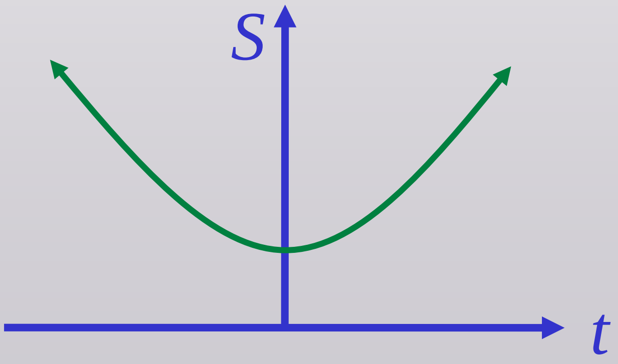
Entropy of the multiverse increases without bound.

This can happen in both directions in time.



Starting in the parent universe, babies are created toward the past as well as the future.

Crucial feature: a restless, time-symmetric multiverse.



[cf. Aguirre & Gratton; Garriga & Vilenkin;
Hartle, Hawking, & Hertog]

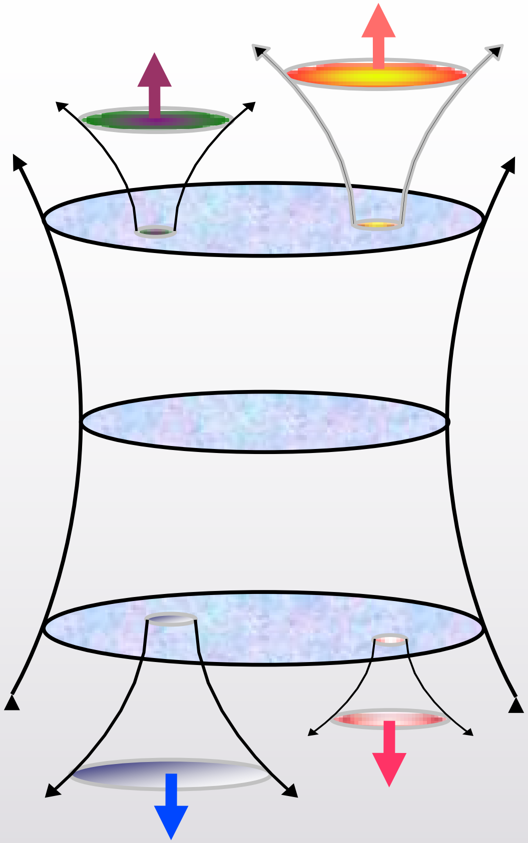
Advantages:

- Time asymmetry arises dynamically, not put in by hand.
- “Initial” conditions can be generic.
- Baby universes can be easier to make than people.
- Process continues forever; costs no energy.
- Origin of the universe, like the origin of life, is a side effect of increasing entropy.

Problems:

- Does baby-universe creation occur?
- Measure problem: how to compare universes to other fluctuations?

Baby universes are the most speculative – and least important! – part of this story.



The point is to develop models where the low entropy of the early universe is explained, not merely postulated.

Only then will we understand the arrow of time.