Title: Weak Gravity and the Arrow of Time

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Abstract: CMB measurements reveal a very smooth early universe. We propose a mech- anism to make this smoothness natural by weakening the strength of gravity at early times, and therefore altering which initial conditions have low entropy.

Weak Gravity and the Arrow of Time

arXiv:0911.0693

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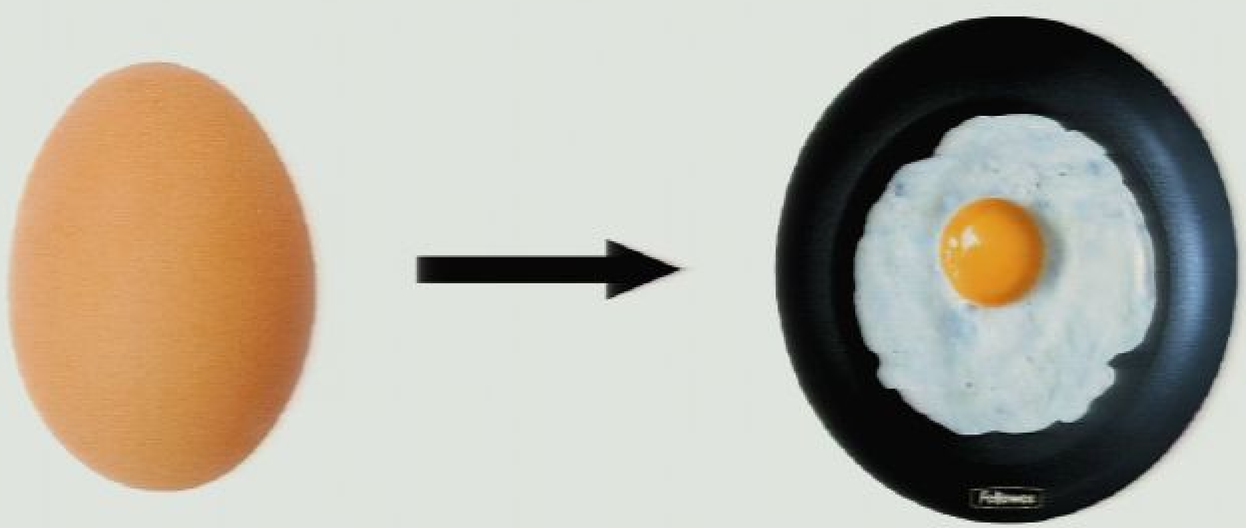
The Arrow of Time

Traditional Formulation of Problem

The laws of physics are (almost) time–reversal symmetric.

1. Given non–maximal entropy S at time t_1, why is the entropy larger at $t > t_1$ and smaller at $t < t_1$?
2. Given decreasing entropy gradient into the past, why was the *initial* entropy so low?



he Arrow of Time

Problem 1

1. Given non–maximal entropy S at time t_1, why is the entropy larger at $t > t_1$ and smaller at $t < t_1$?

Clearly not true for *any* state with entropy S at t_1

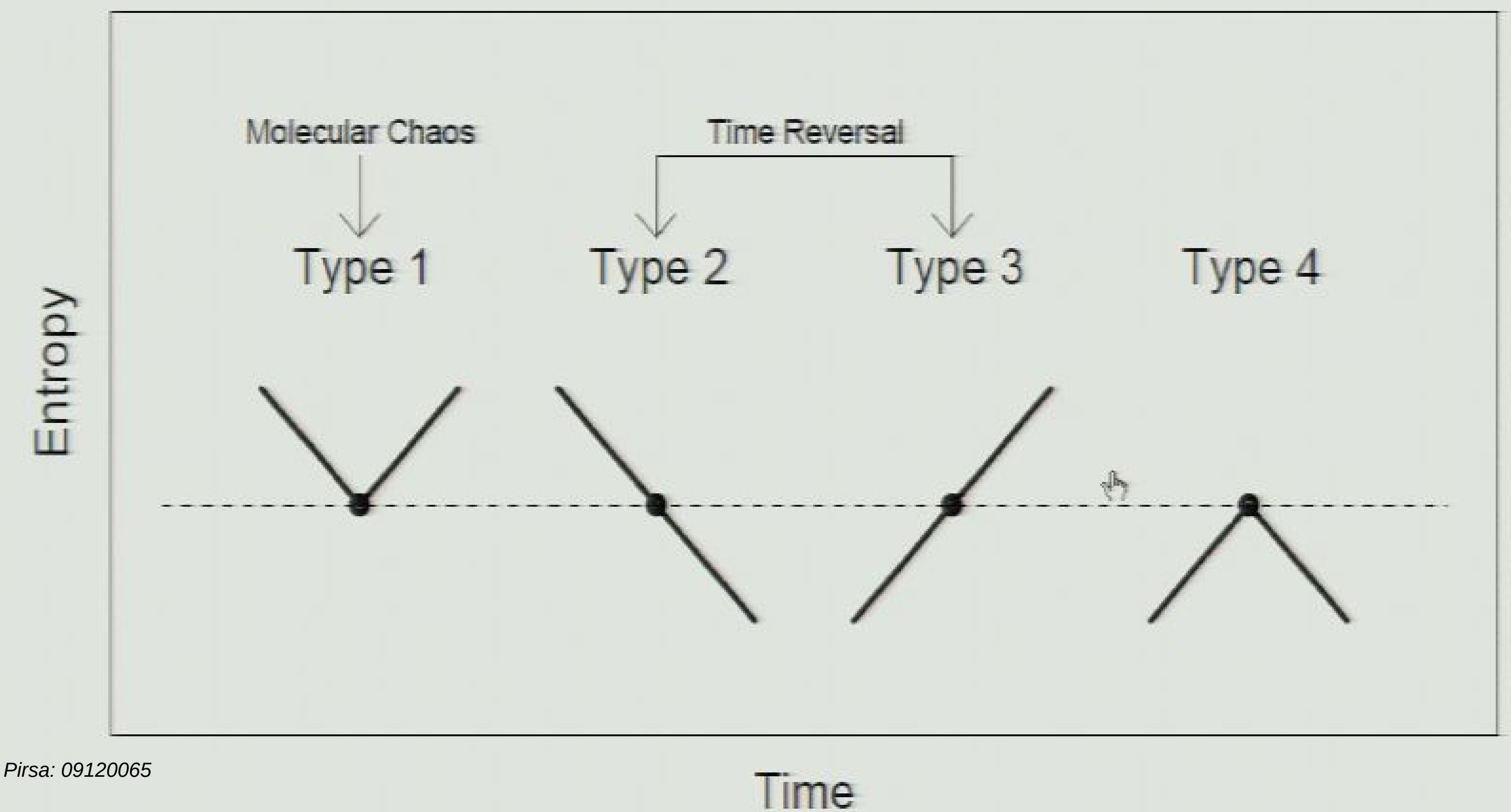
$\longrightarrow$ two options:

Restrict to some physically motivated subset of states with entropy S (molecular chaos, H–theorem) ▸ H–Theorem

Choose probability measure over states of entropy S (*Statistical Hypothesis, typicality*)

he H–Theorem and the 2nd Law

- H–Theorem requires molecular chaos (MC): at a given position the velocities of the molecules there are uncorrelated.
- MC is *time–reversible* $\longrightarrow$ states satisfying it are type 1 ▸ back



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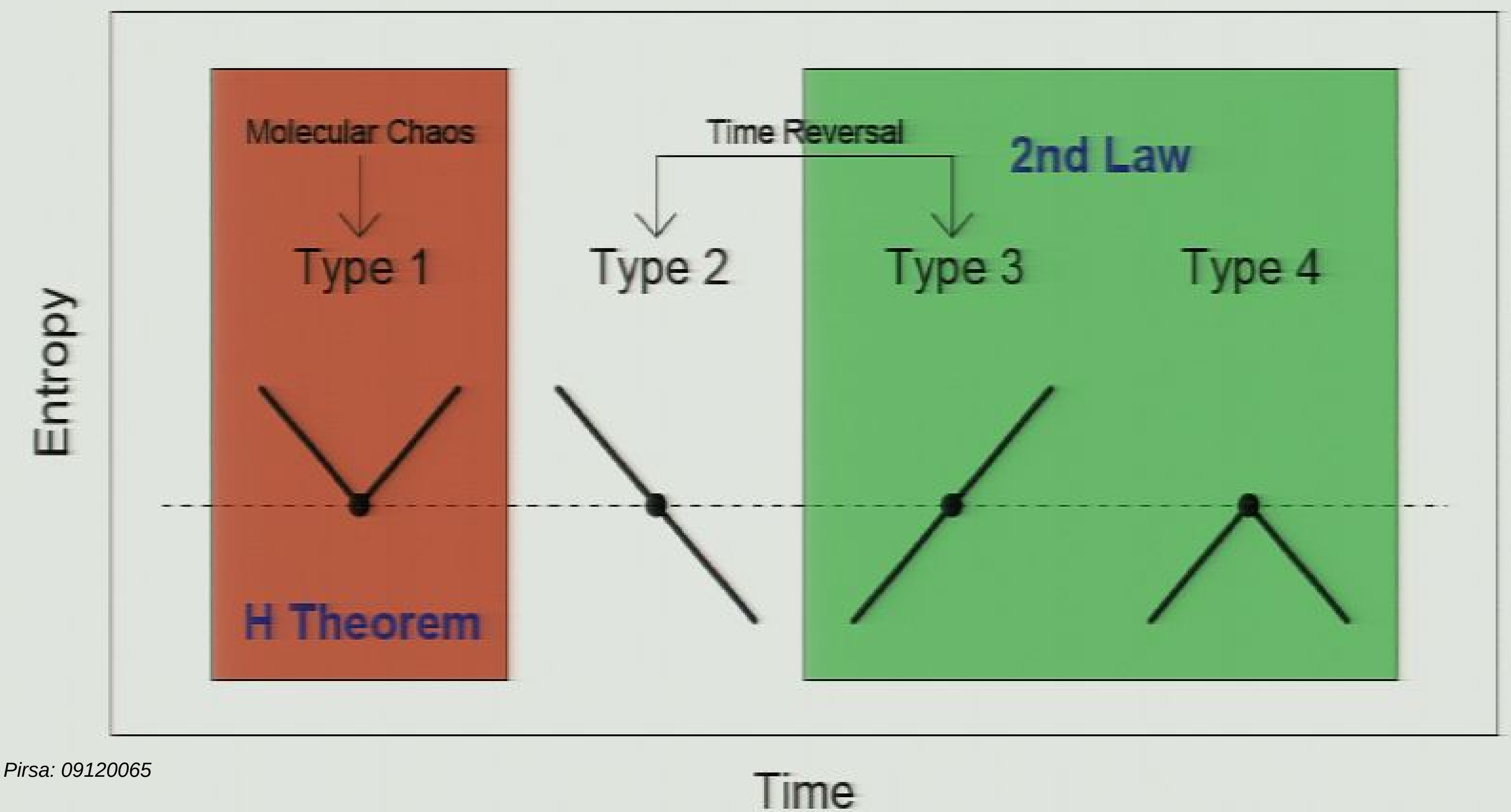

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Problem 2

2. Given decreasing entropy gradient into the past, why was the *initial* entropy so low?

Is there really a problem here?

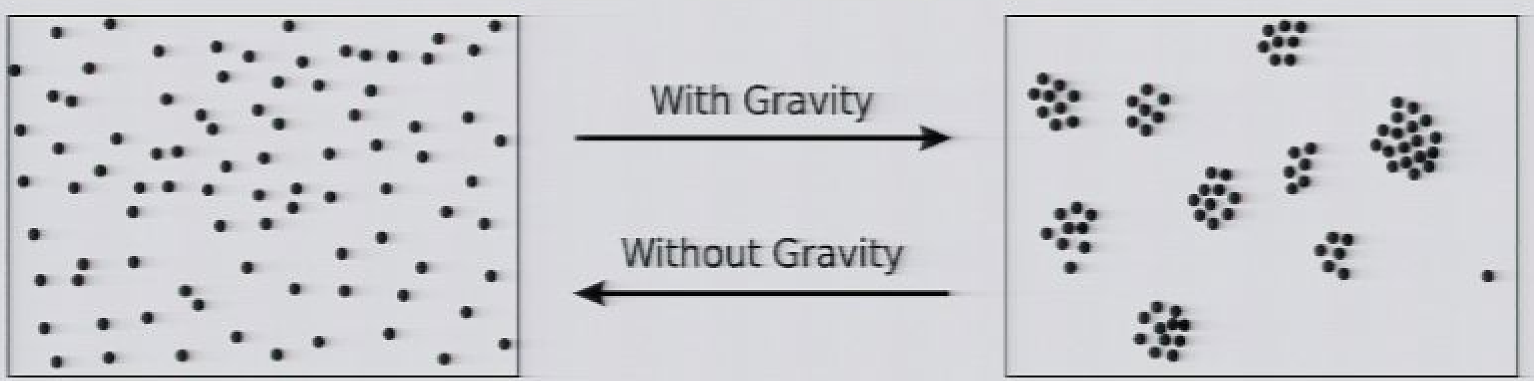
- Low entropy initial conditions are not *unlikely*
- They are a feature of the world we want to understand better
- Analogy: three generations of standard model is not *unlikely*, but any insight into why three would be great.

osmology

How is low entropy manifest in the Early Universe?

- The early universe was very homogeneous: $\delta\rho/\rho \sim 10^{-5}$
- For a gravitational system this is low entropy
  - Almost all such states clump
  - Only very special clumped states smooth out

A Gas in a Box



flation

Common claim: inflation naturally produces a smooth universe.

- Problem: inflation itself requires very special initial conditions to get going
- In the simplest case of a single scalar field, inflation requires:

$$w = \frac{\frac{1}{2}\left(\dot{\phi}^2 + (\nabla\phi)^2\right) - V}{\frac{1}{2}\left(\dot{\phi}^2 + (\nabla\phi)^2\right) + V} < -1/3$$

  ϕ must be smooth so that V dominates over kinetic terms
- Inflation "passes the buck" on smoothness to the inflaton
- Possible solution: chaotic inflation
  - Measure problem
  - Analog of Boltzmann brain problem

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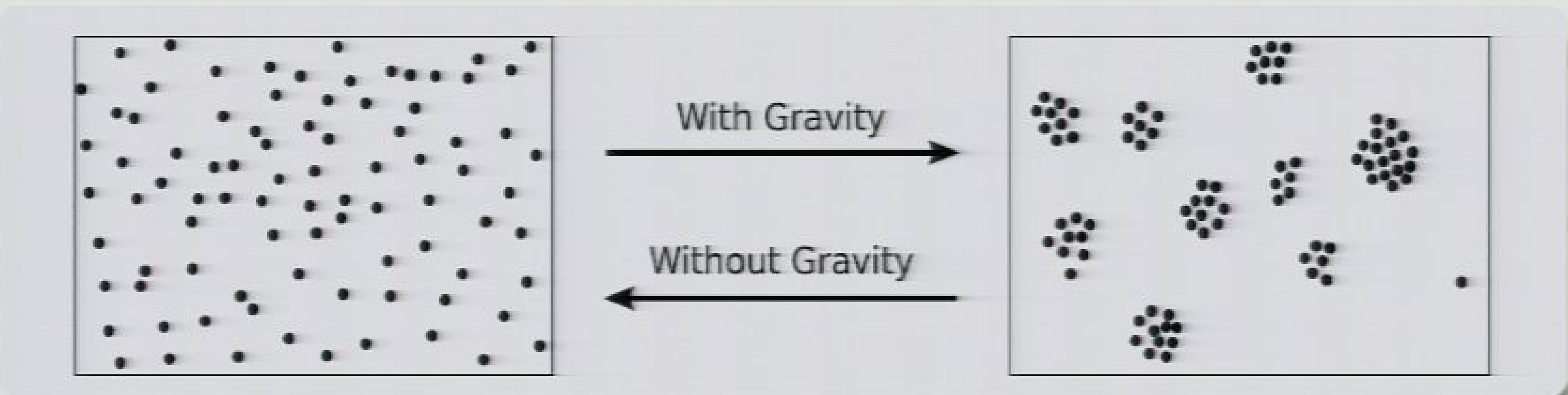

- In the absence of attractive forces, smooth initial conditions are equilibrium states.
- Idea: phase transition from weak to strong gravity
- Universe starts out in a homogeneous state — natural for a system with only weak attractive forces
- Immediately after the phase transition, the universe is still homogeneous, but no longer in equilibrium.

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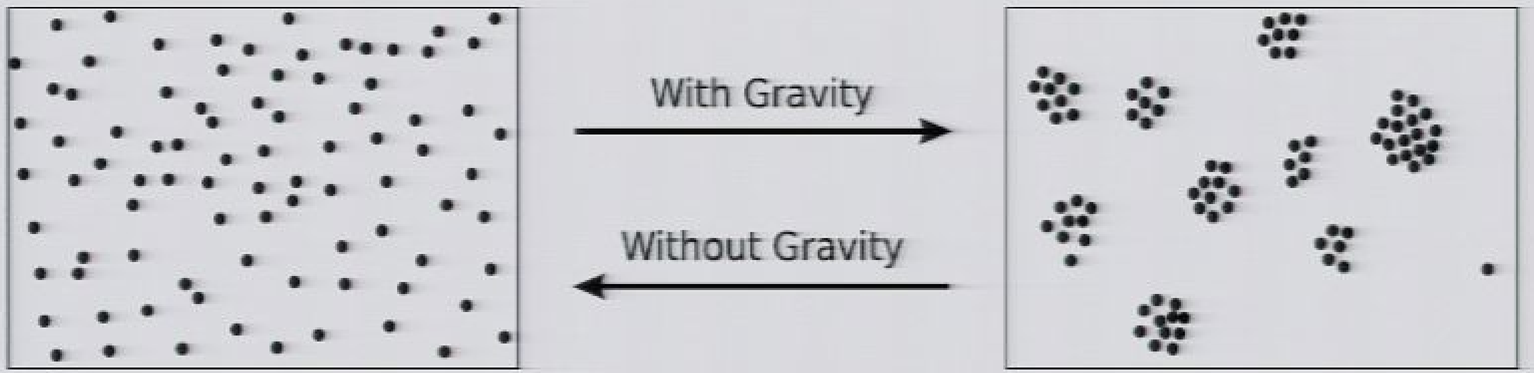

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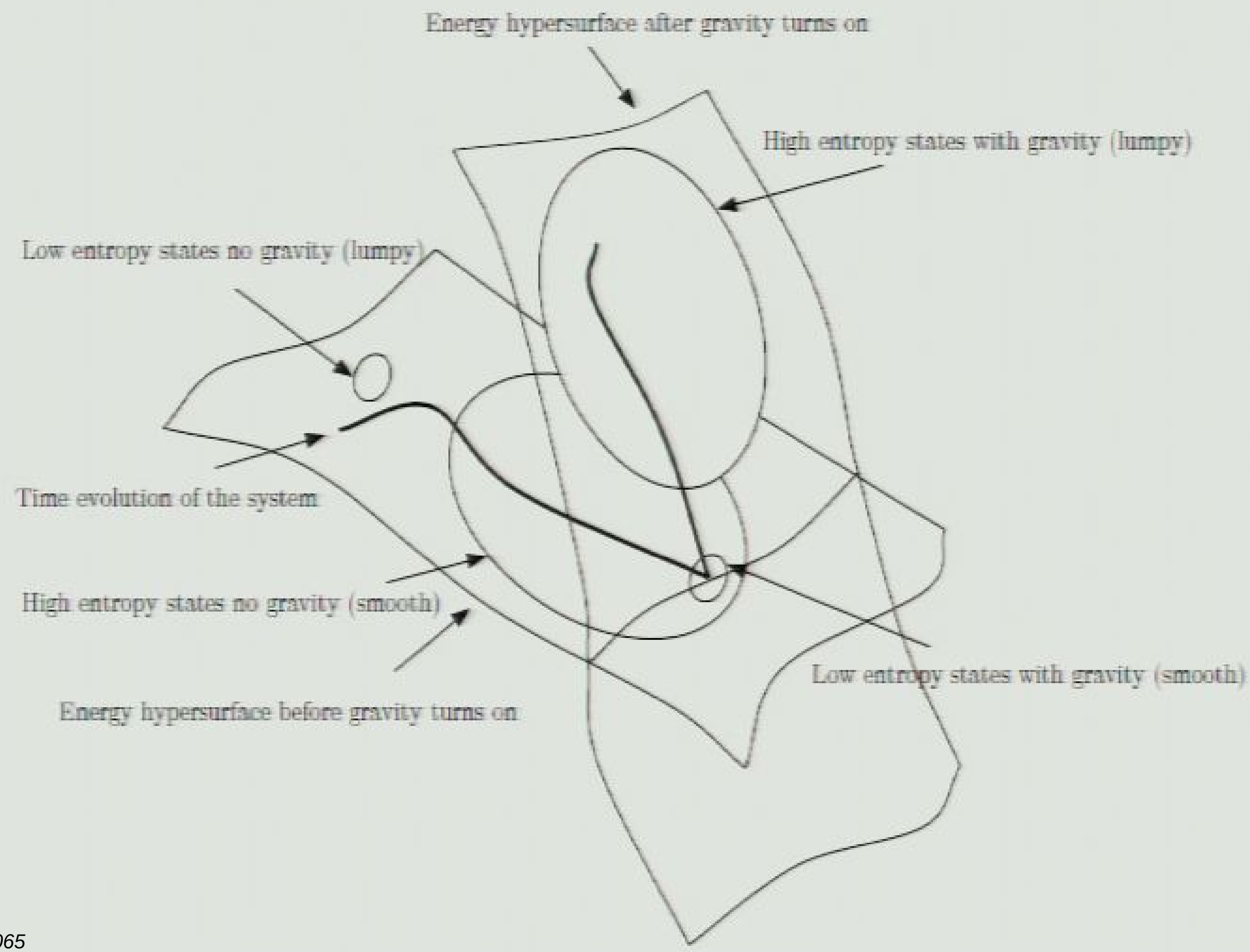

oy Model

- Idea: promote Newtom's contant to a dynamical field: ϕ

$$S = \int d^4x \sqrt{-g}\left(f(\phi)R - \frac{1}{2}g(\phi)g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - U(\phi)\right) + \mathcal{L}_{\mathrm{Matter}}$$

$$f(\phi) = \frac{1}{16\pi G_{\mathrm{effective}}}$$

Choose $f(\phi)$, $g(\phi)$, and $U(\phi)$ so that the Einstein–frame potential $V(\phi)$ has:

- 1 unstable extremum with small $G_{\mathrm{effective}}$ ($\phi = \lambda$)
- 1 minimum with large $G_{\mathrm{effective}}$ ($\phi = 0$)

Phase transition is $\langle\phi\rangle$ rolling from unstable to stable vacuum.

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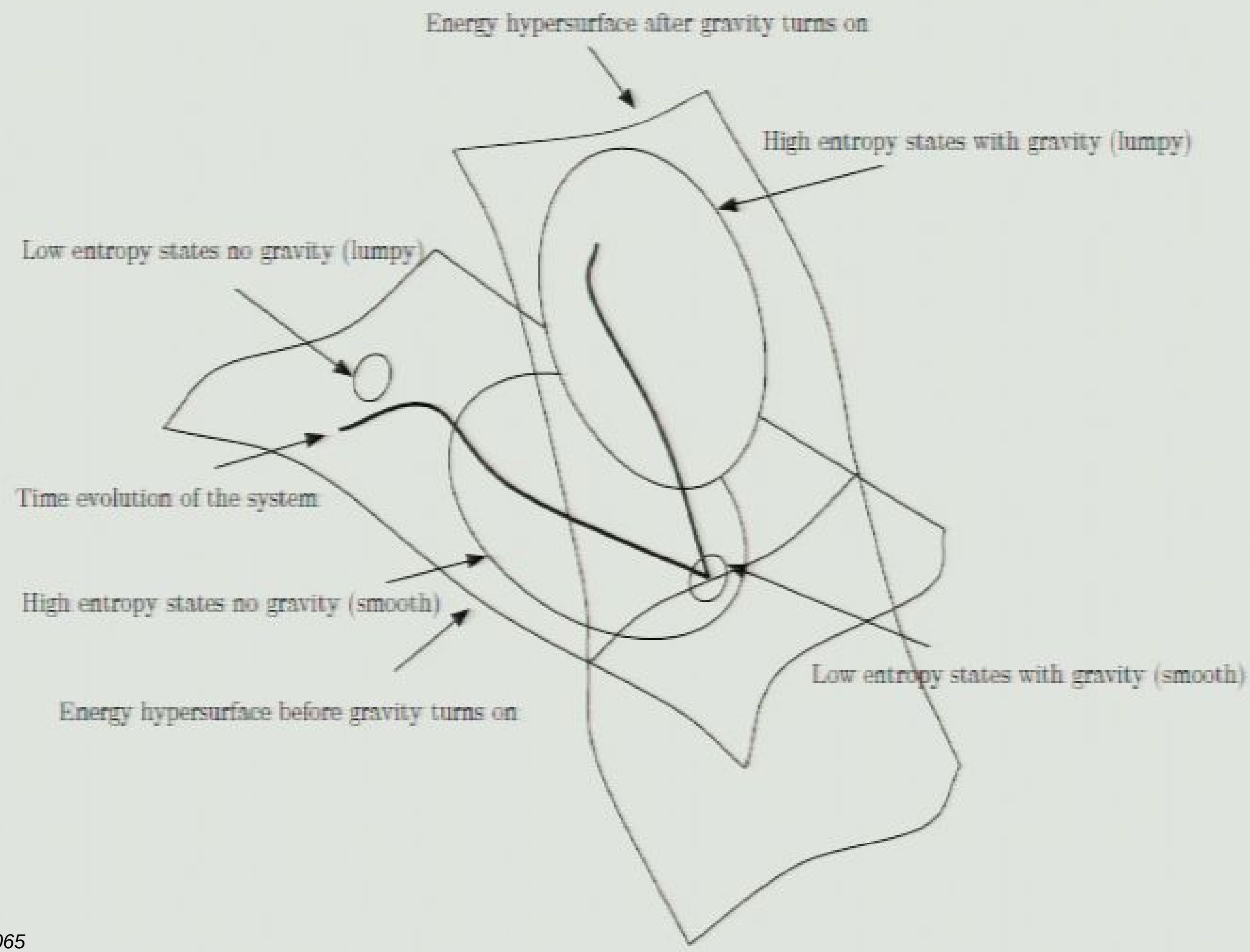

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Our model: $f(\phi) = \frac{1}{2\kappa^2} \left(1 + 2C\phi + \frac{2\phi^3}{\lambda^3} \right) = \frac{1}{16\pi G_{\text{effective}}}$

$$g(\phi) = 0$$

$$U(\phi) = \frac{1}{2\kappa^2} \left(C\phi^2 + \frac{3\phi^4}{2\lambda^3} \right)$$

C, λ arbitrary for now

$$\frac{G_{\text{effective}}(\phi = 0)}{G_{\text{effective}}(\phi = \lambda)} = 3 + 2C\lambda$$

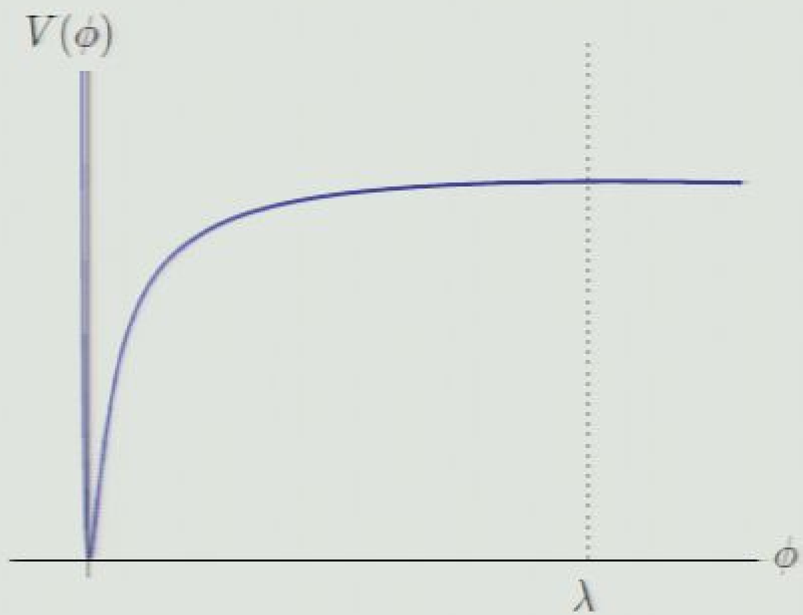
→ parametric control over the increase in the strength of gravity.

oy Model

Physical behavior is easier to see in Einstein frame:

$$S = \int d^4x \left[\frac{1}{2\kappa^2}\tilde{R} - \frac{1}{2}K(\phi)(\partial\phi)^2 - V(\phi) \right]$$

$$V(\phi) = \frac{\lambda^3\left[3\phi^4 + 2C\lambda^3\phi^2\right]}{4\kappa^2((2C\phi+1)\lambda^3 + 2\phi^3)^2}$$



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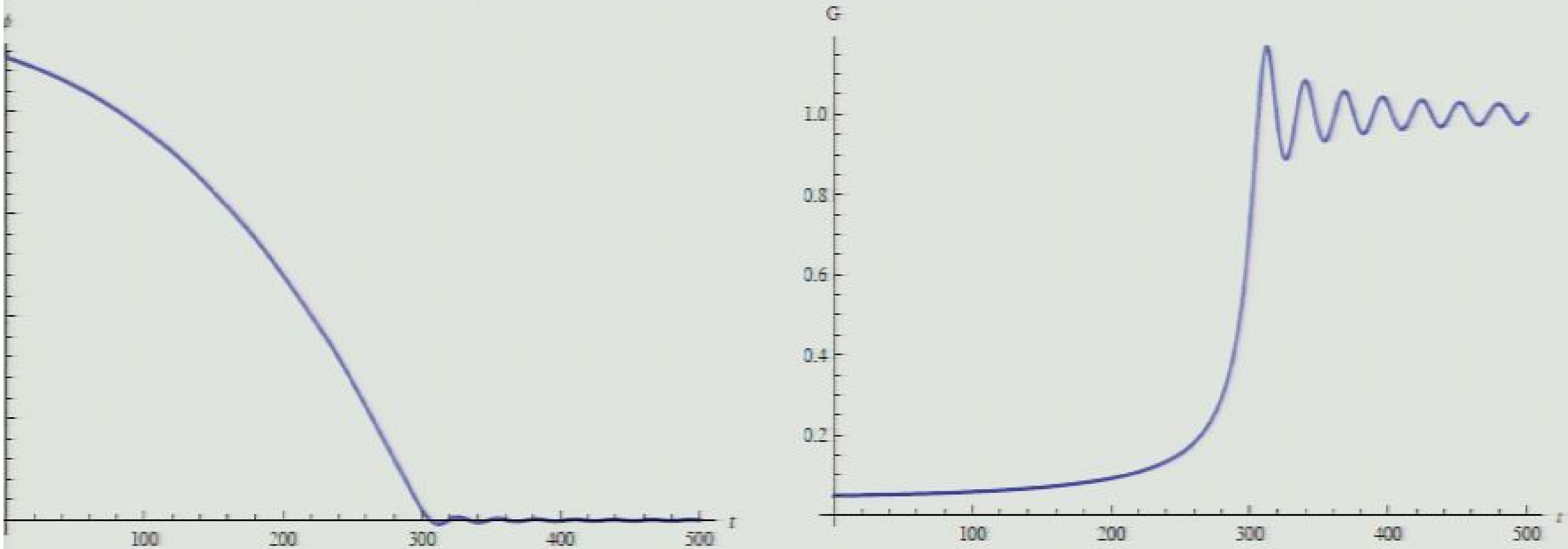
Example: $\lambda = 5, C = 2$

$\phi_0 = 5, \dot{\phi}_0 = -1$

Evolution of ϕ

Evolution of G



terpretation

Making smooth initial conditions natural is difficult
— it's easy to accidentally assume what you're trying to show.

Some potential difficulties:

- Simulations assumed homogeneous scalar field ϕ — exactly the criticism of inflation!
  - Inflation *requires* smooth scalar field, this model does not.
  - Homogeneity only assumed for ease of computation.
- The action is highly contrived from the point of view of QFT — one expects higher order terms that will change the vacuum structure
  - The aim is not to solve the problem of fine–tuning in the Lagrangian
  - Idea is to explain smooth initial conditions

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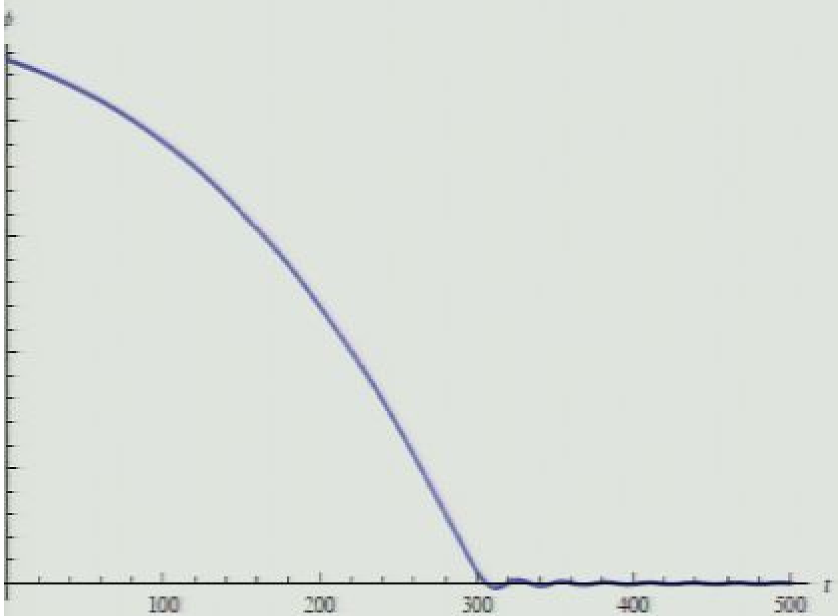

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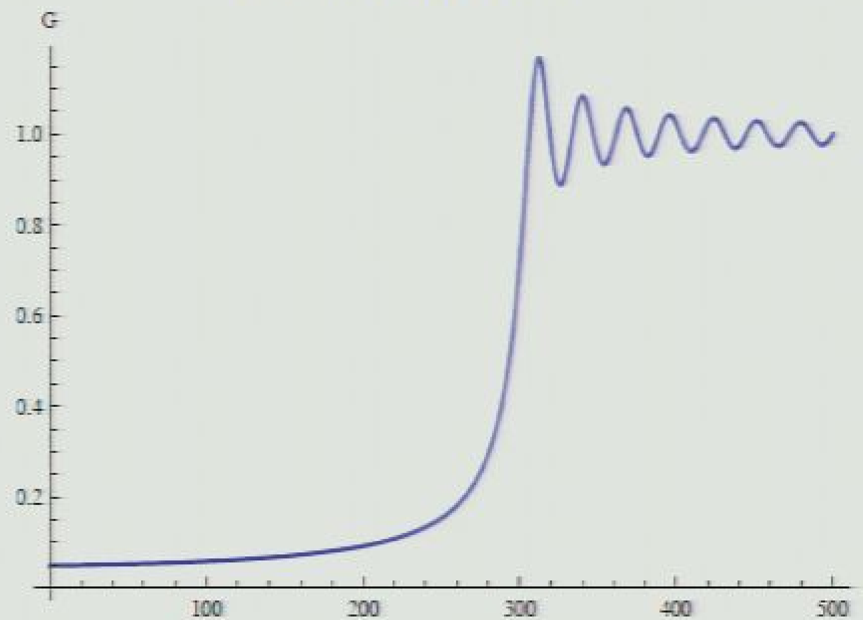

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- Smooth states of gravitational systems have low entropy.
- By engineering gravity to be very weak at early times, we can make give a smooth initial state high (equilibrium) entropy.
- This changes our perspective on the homogeneity of the early universe — it is now natural with respect to the dynamics at the time
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- Models where the strength of gravity can vary over time and space may have other interesting consequences
- For example, what if G_N can be made to depend on the local matter density, like a chameleon field?
- Future work: can we resolve a black hole singularity without a theory of quantum gravity?

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