Can one create a universe in the laboratory

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Can one in principle create a universe in the laboratory?

- Question raised in mid-80’s, right after invention of inflationary theory

Berezin, Kuzmin, Tkachev’ 1984;
Guth, Farhi’ 1986

Idea: create, in a finite region of space, the conditions such that this region enters inflationary regime $\Longrightarrow$ this region will inflate to enormous size and in the end will look like our Universe.

- Do not need much energy: pour little more than Planckian energy into little more than Planckian volume. But
At that time: negaive answer!
[In the framework of classical General Relativity]

Guth, Farhi’ 1986;
Berezin, Kuzmin, Tkachev’ 1987

- Need inflationary conditions in a region larger than Hubble volume.

- Sphere of the Hubble size is antitrapped surface: all light rays are directed outwards.
Opposite to black hole interior.

- Penrose theorem:

Penrose' 1965

There must be singularity in the past

Assumption of the theorem: Null Energy Condition, NEC

$$T_{\mu\nu}n^{\mu}n^{\nu} > 0$$

for any null vector n^{μ}, such that $n_{\mu}n^{\mu} = 0$.

$T_{\mu\nu}$ = energy-momentum tensor

Meaning:

- Homogeneous and isotropic region of space: metric

$$ds^2 = dt^2 - a^2(t)d\mathbf{x}^2 \ .$$

Local Hubble parameter $H = \dot{a}/a$.
Wish to create region with large H , whose size is larger than H^{-1}

This is the definition of a universe

Hubble size regions evolve independently of each other

$\Longrightarrow$ Legitimate to use eqs. for FLRW universe

- A combination of Einstein equations:

$$\frac{dH}{dt} = -4\pi G(\rho + p)$$

$\rho = T_{00}$ = enrgy density
$p = T_{11} = T_{22} = T_{33}$ = effective pressure.

- Null Energy Condition:
$T_{\mu\nu} n^\mu n^\nu \geq 0$, $n^\mu = (1,1,0,0) \Longrightarrow \rho + p > 0 \Longrightarrow dH/dt < 0$,

Hubble parameter was greater early on.

At some moment in the past, there was a singularity, $H = \infty$.

Side remark

- Null Energy Condition, $\rho + p > 0 \Longrightarrow dH/dt < 0 \Longrightarrow$ impossibility of a bounce in cosmology, transition from collapse ($H < 0$) to expansion ($H > 0$)

- Another side of the NEC

  Covariant energy-momentum conservation:

$$\frac{d\rho}{dt} = -3H(\rho + p)$$

  NEC: energy density decreases during expansion, except for $p = -\rho$, cosmological constant.

Can Null Energy Condition be violated?

- Folklore until recently: NO!

Pathologies:

- Ghosts:

$$E = -\sqrt{p^2 + m^2}$$

Example: theory with wrong sign of kinetic term,

$$\mathscr{L} = -(\partial\phi)^2 \quad \Longrightarrow \quad \rho = -\dot{\phi}^2 - (\nabla\phi)^2 \,, \qquad p = -\dot{\phi}^2 + (\nabla\phi)^2$$

$$\rho + p = -2\dot{\phi}^2 < 0$$

Catastrophic vacuum instability

NB: Can be cured by Lorentz-violation

(but hard! – even though Lorentz-violation is inherent in cosmology)

Other pathologies

- Gradient instabilities:

$$E^2 = -(p^2 + m^2) \implies \varphi \propto \mathrm{e}^{|E|t}$$

- Superluminal propagation of excitations

Today: YES,

Null Energy Condition can be violated in a healthy way

Senatore' 2004;
V.R.' 2006;
Creminelli, Luty, Nicolis, Senatore' 2006

General properties of non-pathological NEC-violating field theories:

- Non-standard kinetic terms
- Non-trivial background, instability of Minkowski space-time

Example: scalar field $\pi(x^\mu)$,

$$L = F(Y) \cdot e^{4\pi} + K(Y) \cdot \Box\pi \cdot e^{2\pi}$$

$$Y = e^{-2\pi} \cdot (\partial_\mu \pi)^2$$

Deffayet, Pujolas, Sawicki, Vikman' 2010

Kobayashi, Yamaguchi, Yokoyama' 2010

- Second order equations of motion
- Scale invariance: $\pi(x) \to \pi'(x) = \pi(\lambda x) + \ln \lambda$.

(technically convenient)

Homogeneous solution in Minkowski space (attractor)

$$e^{\pi_c} = \frac{1}{\sqrt{Y_*}(t_* - t)}$$

- $Y \equiv e^{-2\pi_c} \cdot (\partial_\mu \pi_c)^2 = Y_* = \text{const}$, a solution to

$$Z(Y_*) \equiv -F + 2Y_* F' - 2Y_* K + 2Y_*^2 K' = 0$$

$$' = d/dY \; .$$

Energy density

$$\rho = e^{4\pi_c} Z = 0$$

Effective pressure T_{11}:

$$p = e^{4\pi_c}(F - 2Y_* K)$$

Can be made negative by suitable choice of $F(Y)$ and $K(Y)$
$\Longrightarrow \rho + p < 0$, violation of Null Energy Condition.

Switching on gravity

$$p = \mathrm{e}^{4\pi_c}\,(F - 2Y_* K) \propto -(t_* - t)^4\,, \qquad \rho = 0$$

- Use $\dot{H} = -4\pi G(p+\rho) \Longrightarrow$

$$H = \frac{4\pi}{3}\frac{1}{M_{Pl}^2 (t_* - t)^3}$$

NB:

$$\rho \sim M_{Pl}^2 H^2 \sim \frac{1}{M_{Pl}^2 (t_* - t)^6}$$

Early times $\Longrightarrow$ weak gravity, $\rho \ll p$

Perturbations about homogeneous solution

$$\pi(x^\mu) = \pi_c(t) + \delta\pi(x^\mu)$$

- Qudratic Lagrangian for perturbations:

$$L^{(2)} = \mathrm{e}^{2\pi_c} Z' (\partial_t \delta\pi)^2 - V(\vec{\nabla}\delta\pi)^2 + W(\delta\pi)^2$$

Absence of ghosts:

$$Z' \equiv dZ/dY > 0$$

Absence of gradient instabilities and superluminal propagation

$$V > 0 \, ; \qquad V < \mathrm{e}^{2\pi_c} Z'$$

Can be arranged.

Digression: What is this good for?

- Non-standard scenario of the start of cosmological expansion: Genesis, alternative to inflation

  Creminelli, Nicolis, Trincherini' 2010

  Have $\rho + p < 0$ and GR $\Longrightarrow dH/dt > 0, \quad d\rho/dt > 0$.

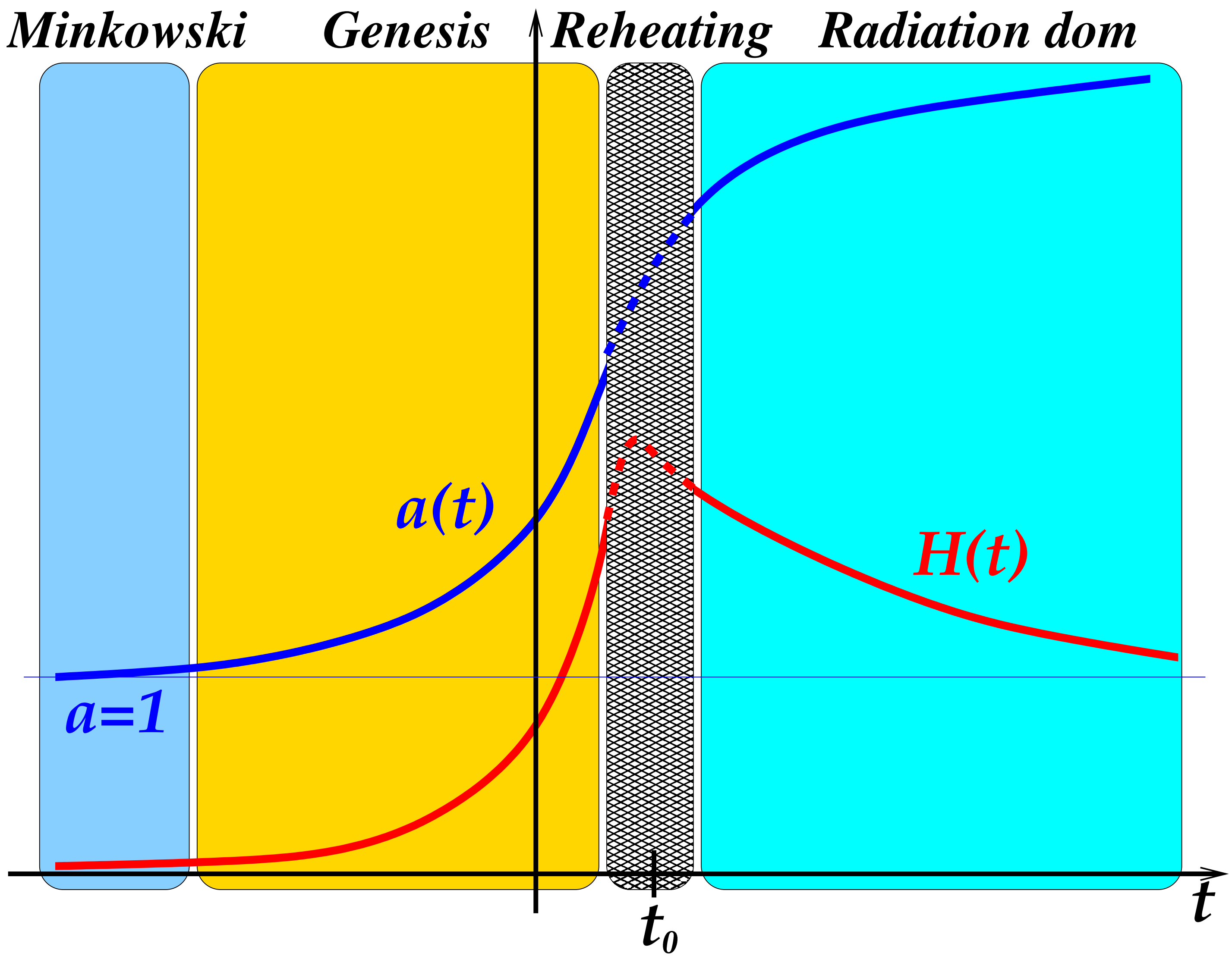
  The Universe starts from Minkowski,

  expansion slowly accelerates,

  energy density builds up.

  Expansion speeds up and at some point energy density of the field π is converted into heat (defrosting), hot epoch begins.

Genesis



- Another cosmological scenario: bounce
  Collapse $\longrightarrow$ expansion, also alternative to inflation

Qui et. al.' 2011;
Easson, Sawicki, Vikman' 2011;
Osipov, V.R.' 2013

- In either case: there may be enough symmetry to arrange for nearly flat power spectrum of density perturbations.

  Particularly powerful: conformal symmetry

  First mentioned by Antoniadis, Mazur, Mottola' 97
  Concrete models: V.R.' 09;
  Creminelli, Nicolis, Trincherini' 10

  What if our Universe started off from or passed through
  an unstable conformal state
  and then evolved to much less symmetric state we see today?

  Specific shapes of non-Gaussianity, statistical anisotropy.

  No gravity waves

Creating a universe: first attempt

- Prepare quasi-homogeneous initial configuration.

  Large sphere $Y = Y_*$ inside, $\pi = \text{const}$ (Minkowski) outside,

  smooth interpolation in between.

  Spatial derivatives small compared with time derivatives.

- Initial state: energy density and pressure small everywhere, geometry nearly Minkowskian. No antitrapped surface. Possible to create.

- Evolution: Genesis inside the sphere, Minkowski outside

Done?

Not quite!

Obstruction

- Energy density:

$$\rho = \mathrm{e}^{4\pi_c} Z$$

$Z = 0$ both outside the sphere and inside the sphere $\Longrightarrow$ dZ/dY is negative somewhere in between.

- On the other hand: absence of ghosts requires

$$dZ/dY > 0$$

Hence, there are ghosts somewhere in space $\equiv$ instability

- This is a general property of theories of one scalar field with
  - Second order field equations
  - Scale invariance: $\pi(x) \to \pi'(x) = \pi(\lambda x) + \ln \lambda$.

Proof

- Equation for homogeneous field always coincides with energy conservation (Noether theorem)

$$\frac{\delta S}{\delta \pi} \propto -\dot{\rho} = 0$$

This is second order equation, hence ρ contains first derivatives only, hence by scale invariance

$$\rho = \mathrm{e}^{4\pi} \cdot Z[\mathrm{e}^{-2\pi}(\partial\pi)^2]$$

- Write $\pi = \pi_c + \delta\pi$, then eqn. for $\delta\pi$ is

$$-Z' \ \partial_t^2 \delta\pi + \text{lower time derivatives} = 0$$

Hence

$$\mathscr{L}(\delta\pi) \propto Z'(\partial_t \delta\pi)^2 + \dots$$

QED

Possible ways out

- Give up Genesis inside the sphere, take $\rho \neq 0$ there.

  Hardly works. $Z = 0$ (Minkowski) is attractor.

- Give up scale invariance.

  A lot more technically demanding.

- Take initial data such that gravity is important

  Even more technically demanding.

- Give up single field, make model more complicated.

  But keep dynamics simple.

Second – and successful (?) attempt

- Make the Lagrangian for π explicitly dependent on radial coordinate r.

  To this end, introduce a new field whose background configuration is $\varphi(r)$

- Example:

$$F = a(\varphi) + b(\varphi)(Y - \varphi) + \frac{c(\varphi)}{2}(Y - \varphi)^2$$

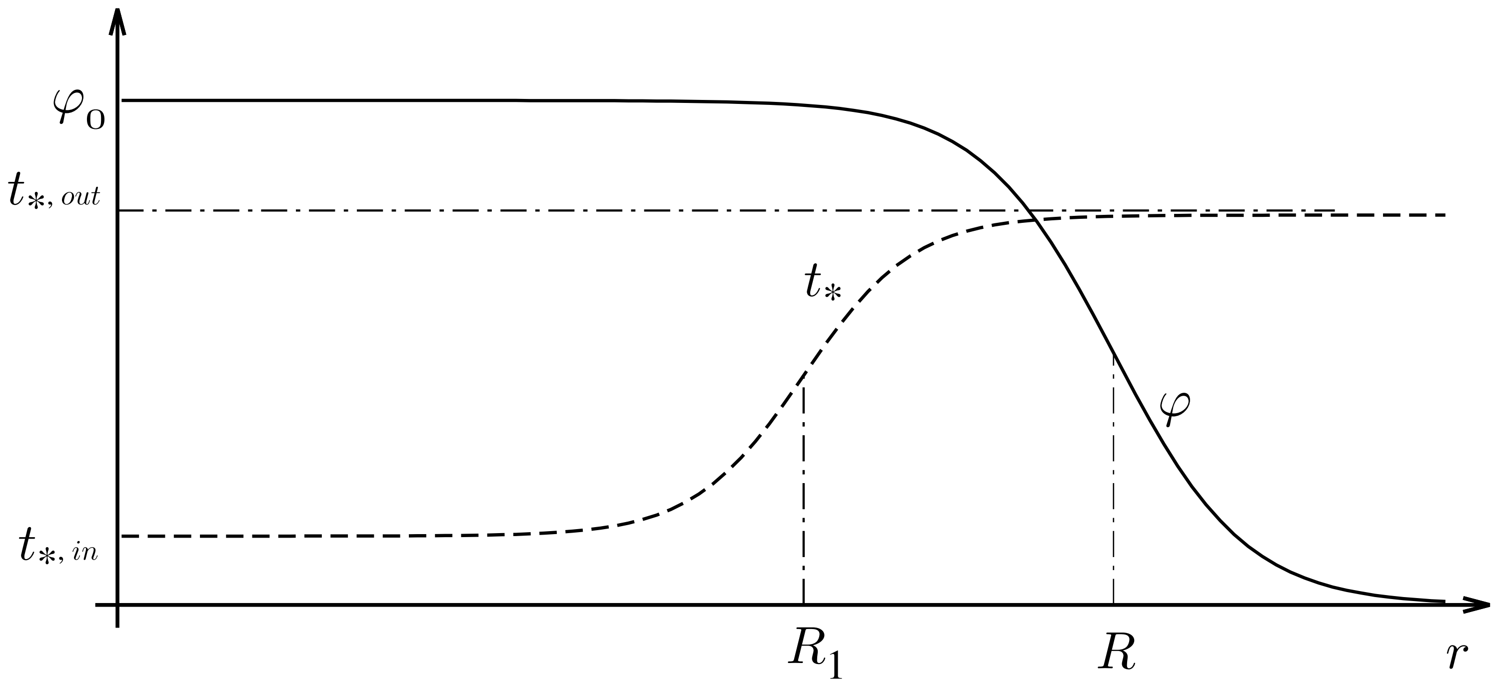
$$K = \kappa(\varphi) + \beta(\varphi)(Y - \varphi) + \frac{\gamma(\varphi)}{2}(Y - \varphi)^2$$

Choose functions $a(\varphi)$, ... in such a way that quasi-homogeneous solution is

$$e^{\pi} = \frac{1}{\sqrt{\varphi_0} t_*(r) - \sqrt{\varphi(r)} t}$$

Make sure that there are no pathologies about this solution.

- Interior: $Y = \varphi_0 \Longrightarrow$ Genesis $t_{*,in}$ small $\Longrightarrow$ quick start
  Exterior $\dot{\pi} = 0 \Longrightarrow Y = 0 \Longrightarrow$ Minkowski



Antitrapped surface (Hubble size) gets formed within weak gravity approximation

Why question mark?

- What do spatial gradients do?
- Where does the system evolve once gravity is turned on?
  What is the global geometry?
  Does a black hole get formed?
- Explicit (numerical) solution needed

To conclude

- There exist field theory models with healthy violation of the Null Energy Condition

- This removes obstruction for creating a universe in the laboratory

- A concrete scenario is fairly straightforward to design.

- Are there appropriate fields in Nature?

  Hardly. Still, we may learn at some point that our Universe went through Genesis or bounce phase. This will mean that Null Energy Condition was violated in the past by some exotic fields. In that case one may try to use the these fields for creating a universe in the laboratory.