Towards creating a universe in the laboratory

V.A. Rubakov

Institute for Nuclear Research
of the Russian Academy of Sciences

Department of Particle Physics and Cosmology,
Physics Faculty
Moscow State University

Preface

When discussing with organizers, I suggested several topics.

They have chosen this one.

Now I understand: they wanted a contemporary illustration of Sheldon Glashow’s statement that a crazy theory may after long time become a technology.

Hmm...

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}

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:

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

- Gradient instabilities:

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

- Superluminal propagation of excitations

Today: YES

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 $\pi(x^\mu)$,

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

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

Deffayet, Pujolas, Sawicki, Vikman' 2010

Kobayashi, Yamaguchi, Yokoyama' 2010

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

Homogeneous solution in Minkowski space (attractor)

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

For it $Y \equiv e^{-2\pi_c} \cdot (\partial_\mu \pi_c)^2 = Y_* =$ 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.

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 $\Longrightarrow$ $dH/dt > 0, \quad d\rho/dt > 0$.

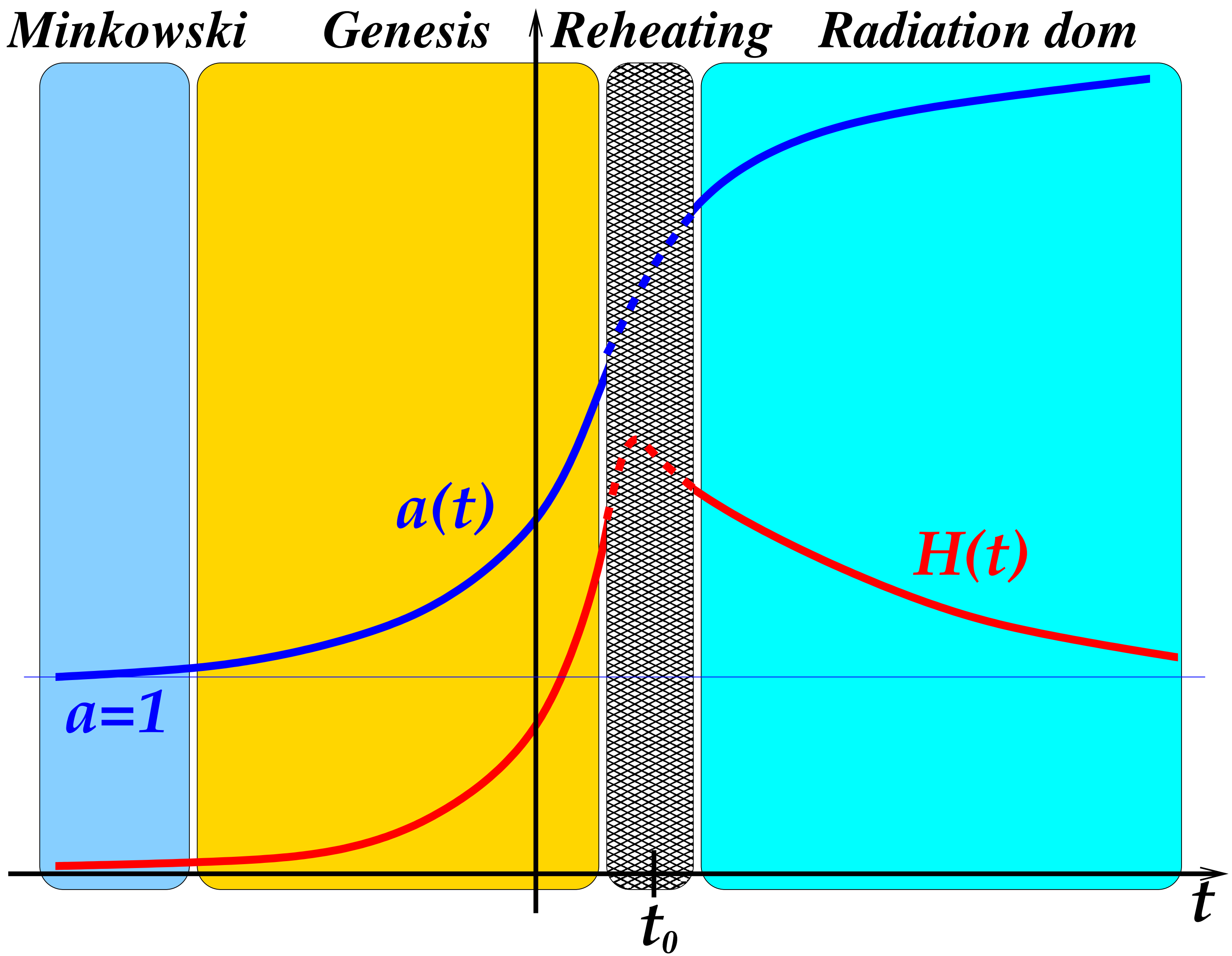
  The Universe starts from Minkowski,

  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, $\pi =$ 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: $\pi(x) \to \pi'(x) = \pi(\lambda x) + \ln \lambda$.

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:

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

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

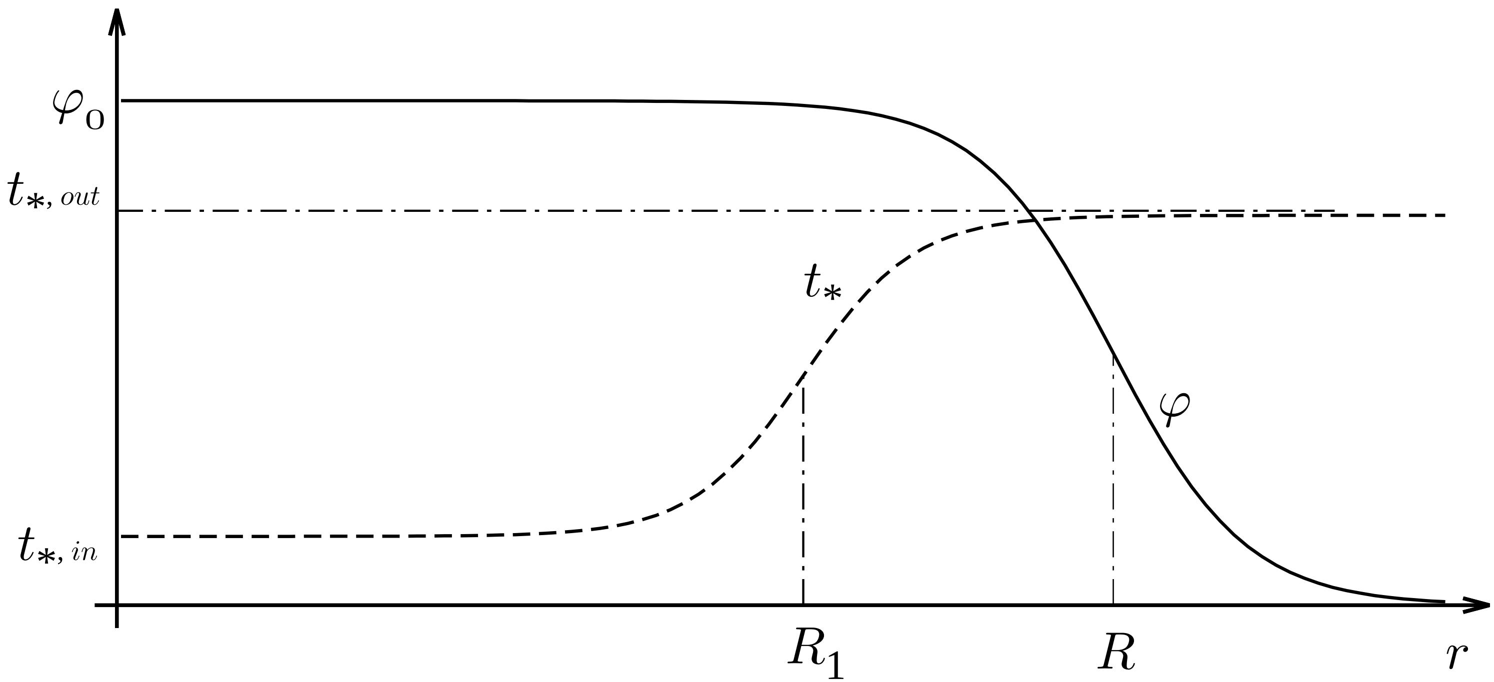
Choose functions $a(\varphi)$, ... in such a way that qusi-homogeneous solution is

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

Make sure that there are no pathologies about this solution.

Interior: $Y = \varphi_0 \Longrightarrow$ Genesis

Exterior $Y = 0 \Longrightarrow$ Minkowski



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. In that case one may try to use the appropriate fields for creating a universe in the laboratory.