

Big Bounce and Inflation from Spin and Torsion

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Abstract

The conservation law for the total (orbital plus spin) angular momentum of a Dirac particle in the presence of gravity requires that spacetime is not only curved, but also has a nonzero torsion.

The coupling between the spin and torsion in the Einstein-Cartan theory of gravity generates gravitational repulsion at extremely high densities, which prevents a singularity in a black hole and may create there a new, closed, baby universe undergoing one or more nonsingular bounces.

We show that quantum particle production caused by an extremely high curvature near a bounce creates enormous amounts of matter and can generate a finite period of inflation.

Our scenario has only one parameter, does not depend significantly on the initial conditions, does not involve hypothetical scalar fields, avoids eternal inflation, and predicts plateau-like inflation that is supported by the Planck observations of the cosmic microwave background.

This scenario suggests that our Universe may have originated from a nonsingular bounce in a black hole existing in another universe.

Cosmic Microwave Background

**Afterglow Light
Pattern
380,000 yrs.**

Dark Ages

**Development of
Galaxies, Planets, etc.**

**Dark Energy
Accelerated Expansion**

Inflation

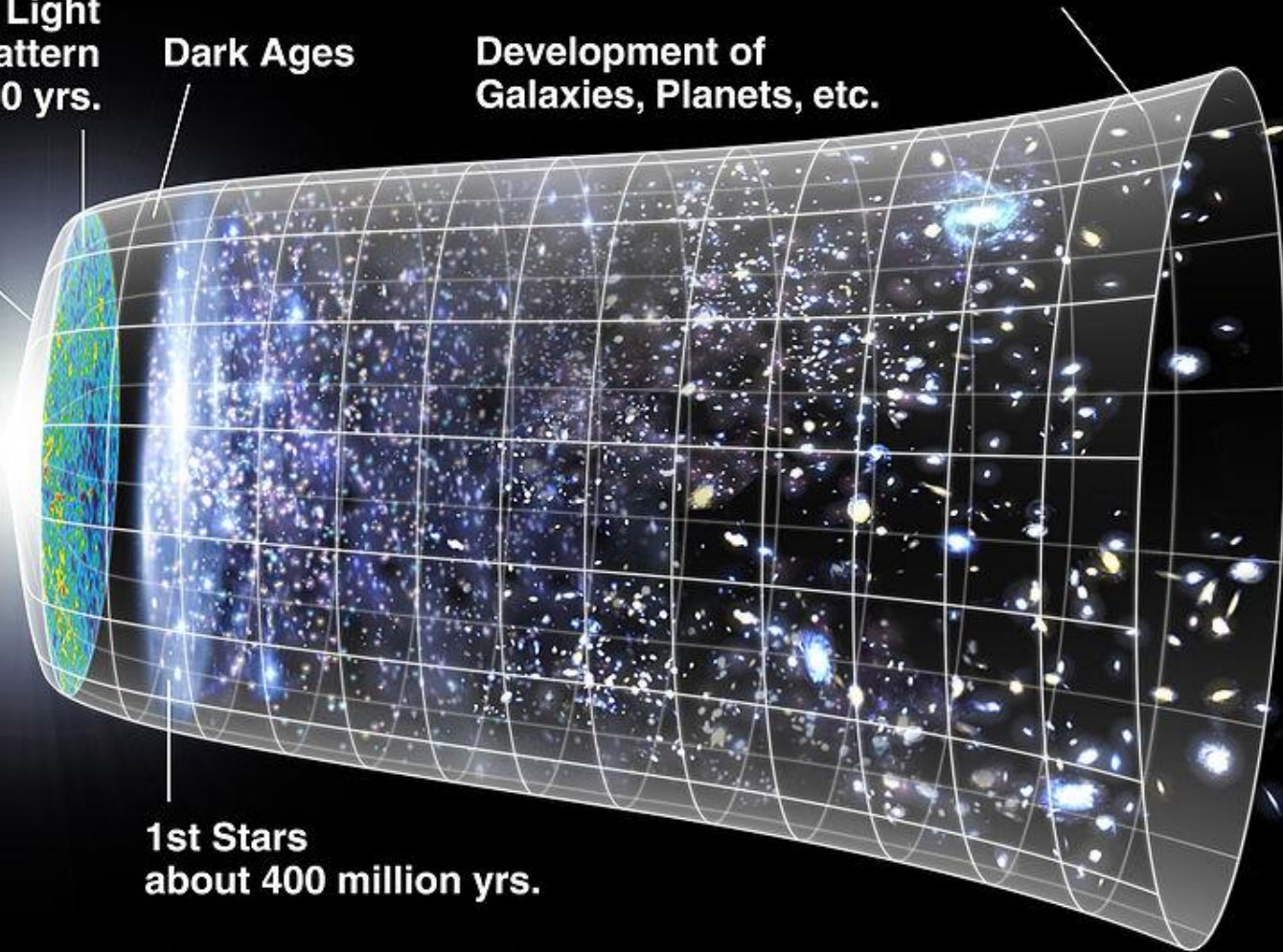
Big Bounce

**Quantum
Fluctuations**

**1st Stars
about 400 million yrs.**

Big Bang Expansion

13.7 billion years



How do we know the Big Bang happened?

- We can see the Universe expanding: galaxies look **redder** as they speed away (just as sirens sound lower pitched).
Hubble's law: speed of receding galaxies is proportional to their distances.
- Big Bang Nucleosynthesis (Gamow).

If the Universe is closed, the 2-dimensional surface of the balloon is an analog to our 3-dimensional space.

The 3-dimensional space in which the balloon expands is not analogous to any higher dimensional space. Points off the surface of the balloon are not in the Universe in this simple analogy.

The balloon radius = the **scale factor a** .

The Universe may be finite (closed) or infinite (flat or open).

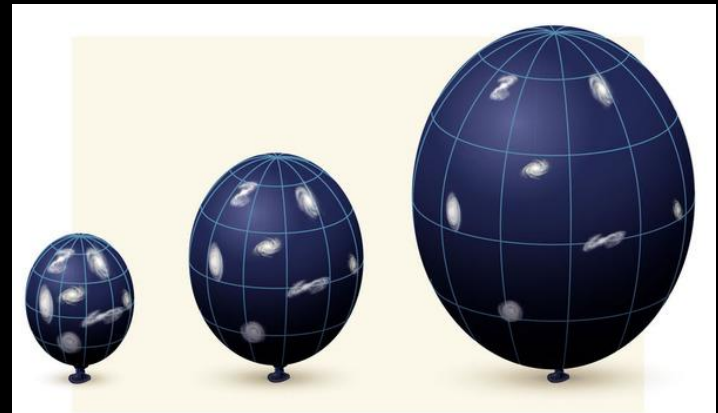


Image credit: One-Minute Astronomer

How do we know the Big Bang happened?

- We can observe the Cosmic Microwave Background. This electromagnetic radiation is a remnant from an early stage of the Universe. When protons and electrons combined (recombination) to form neutral hydrogen atoms that could not absorb photons, photons decoupled and the Universe became transparent. Currently, the CMB comes to us from all directions in the sky and has a temperature 2.725 K.
- The temperature anisotropy, about 2×10^{-5} , provides information about the dynamics of the early Universe.

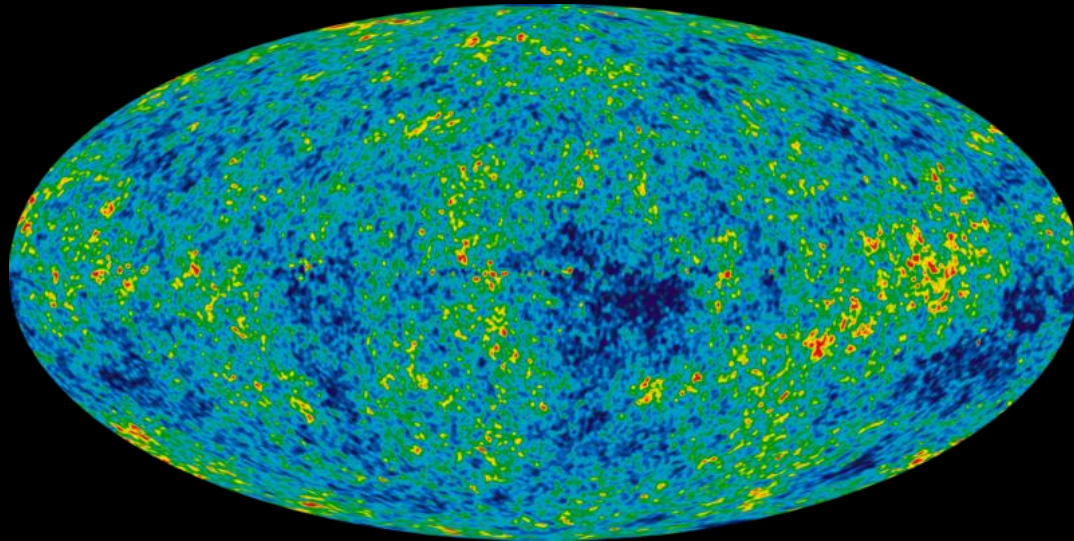


Image credit: Wikipedia

Problems of General Relativity

Cosmology is based on General Relativity, which describes gravity as curvature of spacetime.

- Singularities: points with infinite density of matter.
- Incompatible with quantum mechanics. We need quantum gravity. It may resolve the singularity problem.
- Field equations contain the conservation of orbital angular momentum, contradicting Dirac equation which gives the conservation of total angular momentum (orbital + spin) and allows spin-orbit exchange in QM.

Simplest extension of GR to include QM spin:

Einstein-Cartan theory. It also resolves the singularity problem.

Problems of cosmology

- Big-Bang singularity.
- What caused the Big Bang? What existed before?
- Horizon problem: different regions of the Universe have not contacted each other because of large distances between them, but they have the same physical properties (the Universe is homogeneous and isotropic). The temperature of the CMB is almost isotropic.
- Flatness problem: the Universe is nearly flat. The initial conditions of the Universe must have been fine-tuned.
- What was the initial condition for structure formation?

Problems of cosmology

- Inflation (Guth, Linde): exponential expansion of the early Universe explains why the Universe appears flat, homogeneous, and isotropic.
- What caused inflation? Hypothetical scalar field: inflaton.
- Quantum fluctuations of inflaton are stretched to macroscopic scales and freeze in upon leaving the horizon. At the later stages of radiation- and matter-domination, they re-enter the horizon and set the initial condition for structure formation. Inflation predicts the observed spectrum of CMB anisotropies.
- How did inflation end? The large inflaton potential energy decays into Standard Model particles. Poorly understood. Eternal inflation may occur.

Einstein-Cartan-Sciama-Kibble gravity

- Einstein-Cartan theory replaces the Big Bang by a nonsingular **Big Bounce**. The dynamics after the bounce explains the flatness and horizon problems.
- Spacetime is equipped with torsion.
 - Curvature – “bending” of spacetime
 - Torsion – “twisting” of spacetime
- Bending a thin rod is more apparent than twisting. Effects of torsion are important only in extreme situations (in black holes and in the very early Universe).

Einstein-Cartan-Sciama-Kibble gravity

- Torsion tensor is a variable in addition to the metric.

$$S^k{}_{ij} = \Gamma_{[ij]}^k$$

- Lagrangian density is proportional to curvature scalar (as in GR).
- Cartan equations:

Torsion is proportional to **spin** density of fermions. ECSK differs significantly from GR at densities $> 10^{45}$ kg/m³; passes all tests.

$$S_{jik} - S_i g_{jk} + S_k g_{ji} = -\frac{1}{2} \kappa S_{ikj}$$

[arXiv.org > gr-qc > arXiv:0911.0334](https://arxiv.org/abs/gr-qc/0911.0334)

- Einstein equations:

Curvature is proportional to **energy and momentum** density.

$$G^{ik} = \kappa T^{ik} + \frac{1}{2} \kappa^2 \left(s^{ij}{}_j s^{kl}{}_l - s^{ij}{}_l s^{kl}{}_j - s^{ijl} s^k{}_{jl} + \frac{1}{2} s^{jli} s_{jl}{}^k + \frac{1}{4} g^{ik} (2s_j{}^l{}_m s^{jm}{}_l - 2s_j{}^l{}_l s^{jm}{}_m + s^{jlm} s_{jlm}) \right)$$

Universe with spin fluid

Dirac particles can be averaged macroscopically as a spin fluid.

$$S^{\mu\nu\rho} = S^{\mu\nu}u^\rho \quad S^{\mu\nu}u_\nu = 0 \quad S^2 = S^{\mu\nu}S_{\mu\nu}/2$$

Einstein-Cartan equations for a (closed) FLRW Universe become Friedmann equations for the scale factor a .

$$\frac{\dot{a}^2}{c^2} + 1 = \frac{1}{3}\kappa\left(\epsilon - \frac{1}{4}\kappa s^2\right)a^2$$
$$\frac{\dot{a}^2 + 2a\ddot{a}}{c^2} + 1 = -\kappa\left(p - \frac{1}{4}\kappa s^2\right)a^2$$

$$s^2 = \frac{1}{8}(\hbar cn)^2$$

Spin and torsion modify the energy density and pressure with a **negative** term proportional to the square of the fermion number density n , which acts like **repulsive gravity**.

Universe with spin fluid

For relativistic matter, Friedmann equations can be written in terms of temperature: $\varepsilon \approx 3p \sim T^4$, $n \sim T^3$.

$$\frac{\dot{a}^2}{c^2} + 1 = \frac{1}{3}\kappa(h_*T^4 - \alpha h_{nf}^2T^6)a^2$$
$$\frac{\dot{a}}{a} + \frac{\dot{T}}{T} = 0 \quad \alpha = \kappa(\hbar c)^2/32$$

Using nondimensional quantities:

$$\dot{y}^2 + 1 = (3x^4 - 2x^6)y^2$$
$$xy = C > 0$$

$$x = \frac{T}{T_{\text{cr}}} \quad y = \frac{a}{a_{\text{cr}}} \quad \tau = \frac{ct}{a_{\text{cr}}}$$

$$T_{\text{cr}} = \left(\frac{2h_*}{3\alpha h_{nf}^2}\right)^{1/2} \quad a_{\text{cr}} = \frac{9\hbar c}{8\sqrt{2}} \left(\frac{\alpha h_{nf}^4}{h_*^3}\right)^{1/2}$$

NP, ApJ 832, 96 (2016); G. Unger & NP, ApJ 870, 78 (2019)

Generating nonsingular bounce

$$\dot{y}^2 + 1 = \frac{3C^4}{y^2} - \frac{2C^6}{y^4}$$

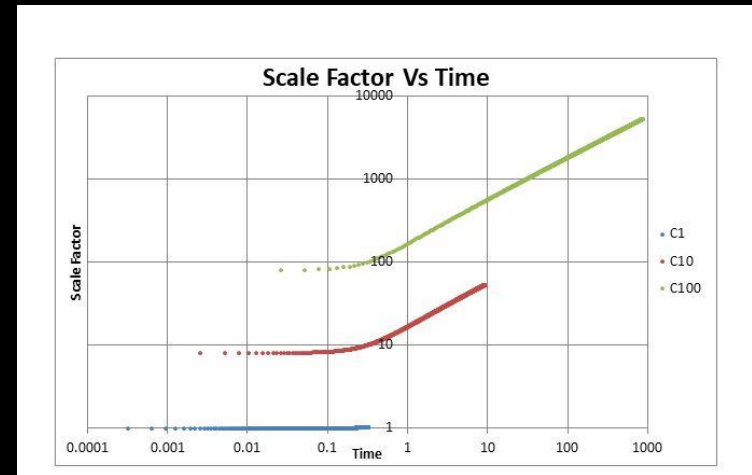
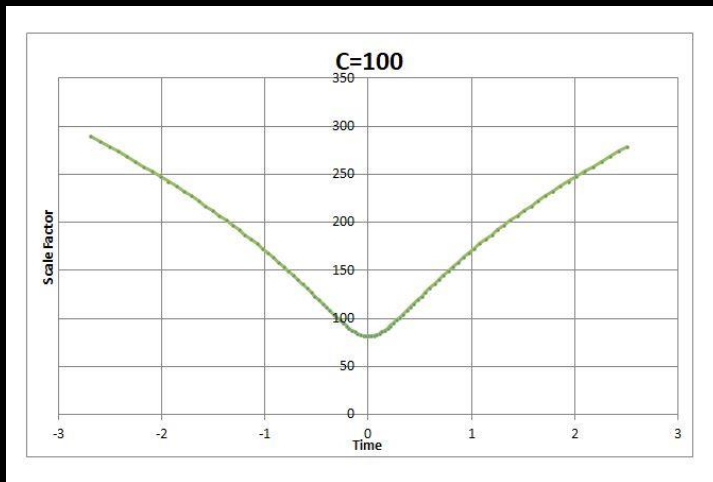
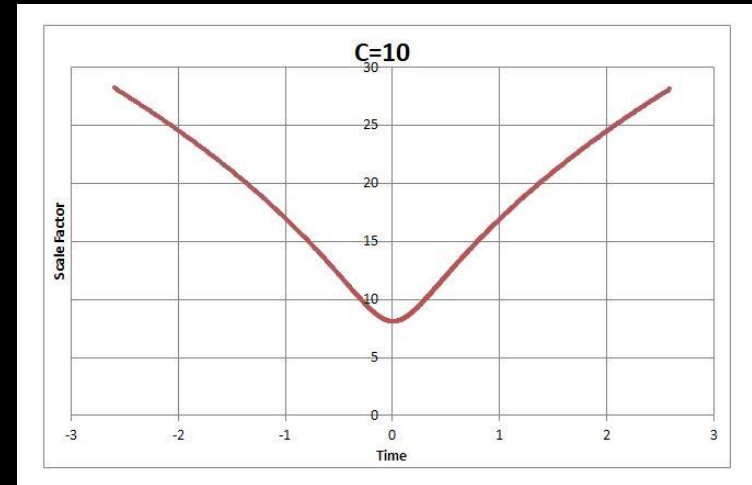
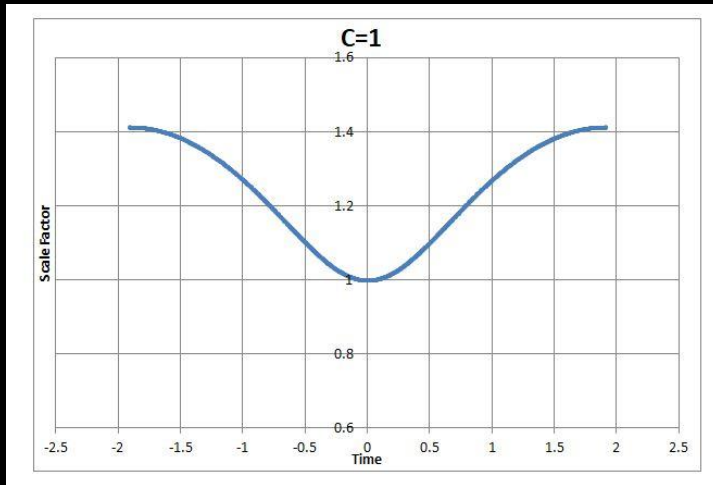
$$y_{\pm}^2 = 3C^4 \left[\frac{1 \pm \sqrt{1 - \frac{8}{9C^2}}}{2} \right]$$

Turning points ($\dot{y} = 0$) for the closed Universe with torsion are positive – **no cosmological singularity!**

- 2 points if $C > (8/9)^{1/2}$ (absolute $y_{\min} = 1$ for $C = 1$)
- 1 point if $C = (8/9)^{1/2}$ -> stationary Universe
- 0 points if $C < (8/9)^{1/2}$ -> Universe cannot exist (form)

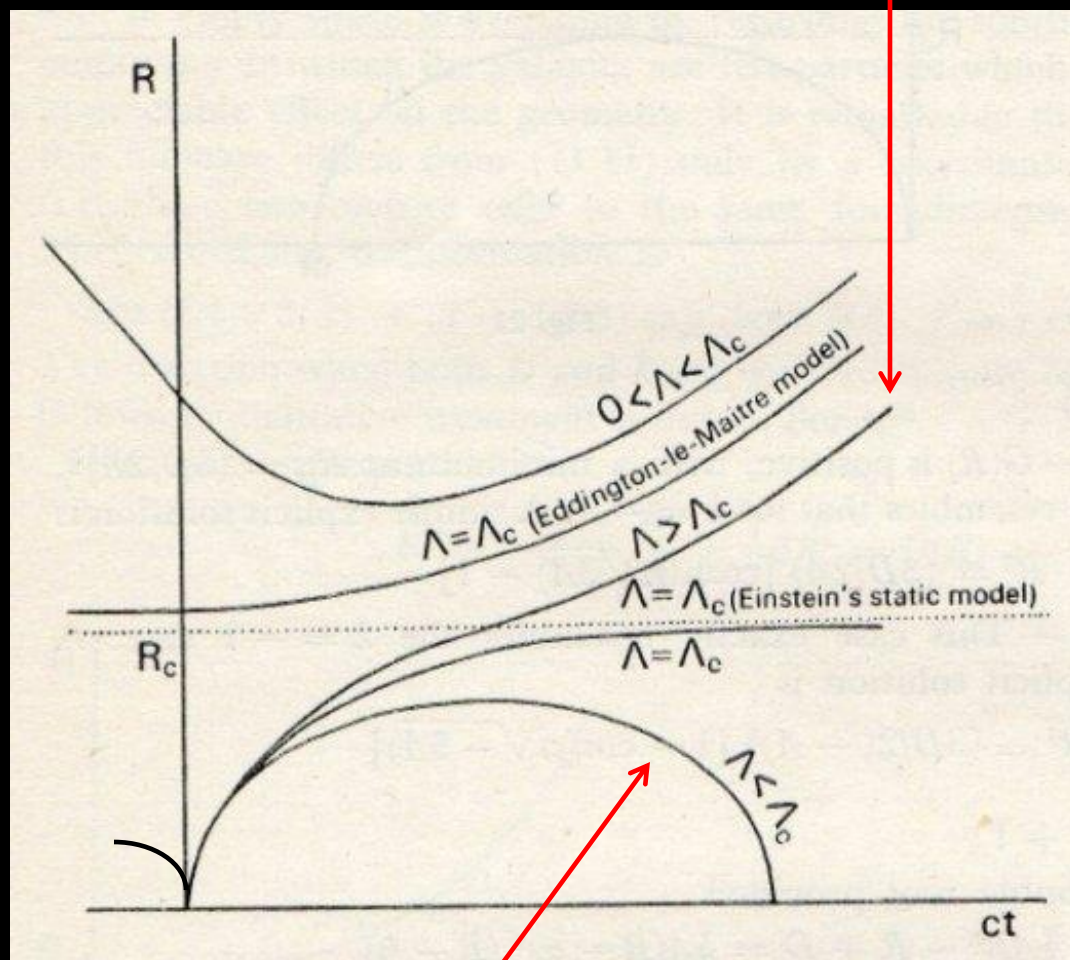
C	y_{\min}^2	y_{\max}^2	x_{\max}^2	x_{\min}^2
$\sqrt{8/9}$	$\frac{32}{27}$	$\frac{32}{27}$	$\frac{3}{4}$	$\frac{3}{4}$
1	1	2	1	$\frac{1}{2}$
$\gg 1$	$\frac{2C^2}{3}$	$3C^4$	$\frac{3}{2}$	$\frac{1}{3C^2}$

Generating nonsingular bounce



Proposal: the Universe has begun at $a \sim a_{cr}$ and $T \sim T_{cr}$ with $C \sim 1$.
Quantum matter production: C increased to the current $> 10^{30}$.

If quantum effects in the gravitational field near a bounce produce enough matter, then the closed Universe can reach a size at which dark energy becomes dominant and expands to infinity.



Otherwise, the Universe contracts to another bounce (with larger scale factor) at which it produces more matter, and expands again.

(Image: Lord, *Tensors, Relativity, and Cosmology*.)

Matter production causing inflation

Near a bounce, Parker-Starobinsky-Zel'dovich particle production enters through a term $\sim H^4$, with β as a production parameter.

$$\frac{\dot{a}}{a} \left[1 - \frac{3\beta}{c^3 h_{n1} T^3} \left(\frac{\dot{a}}{a} \right)^3 \right] = -\frac{\dot{T}}{T}$$

To avoid eternal inflation: the β term $< 1 \rightarrow \beta < \beta_{cr} \approx 1/929$.

For $\beta \approx \beta_{cr}$ and during an expansion phase, when $H = \dot{a}/a$ reaches a maximum, the β term is slightly lesser than 1 and:

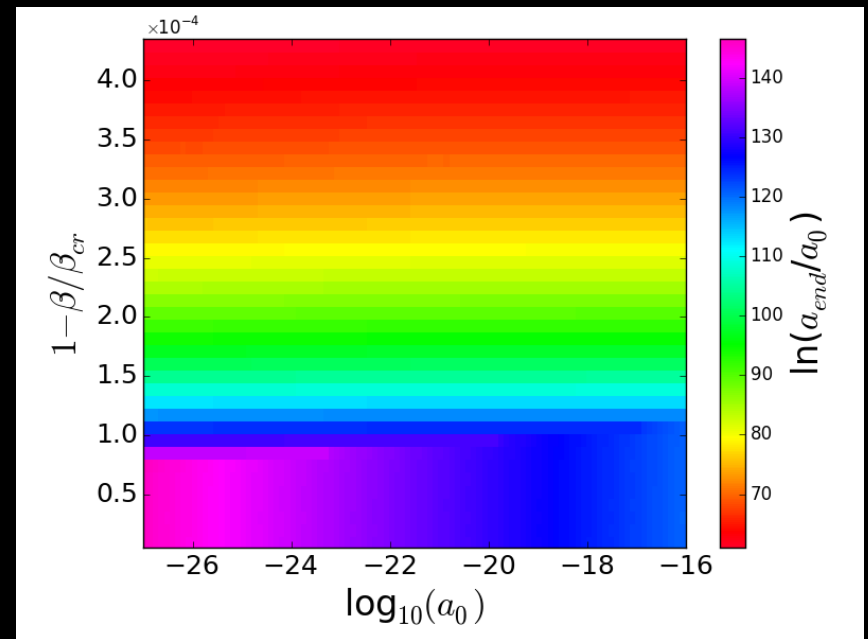
$$T \sim \text{const}, \quad H \sim \text{const}, \quad \varepsilon \sim \text{const}.$$

Exponential expansion and mass increase last about t_{Planck} , then H and T decrease. Torsion becomes weak, inflation ends, and radiation dominated era begins. No scalar fields needed.

NP, ApJ 832, 96 (2016)

- The numbers of e-folds and bounces (until the Universe reaches the radiation-matter equality) depend on the particle production but are not too sensitive to the initial scale factor.
- The Big Bang was the last bounce (Big Bounce).

β/β_{cr}	Number of bounces
0.996	1
0.984	2
0.965	3
0.914	5
0.757	10

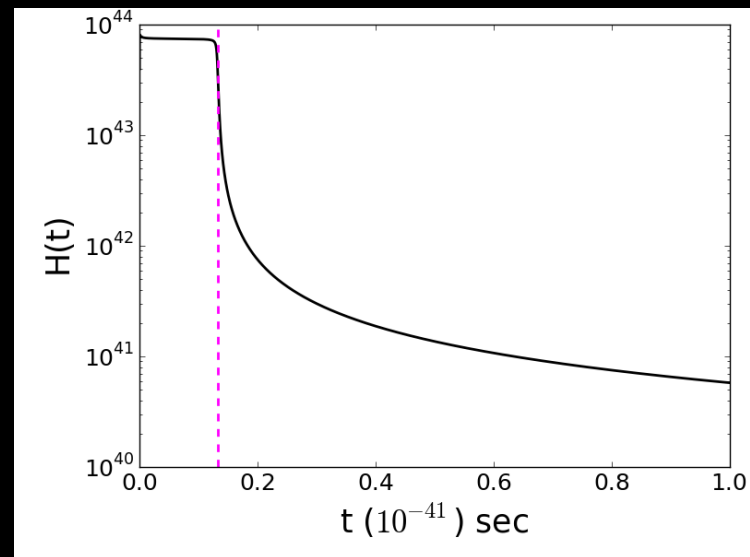
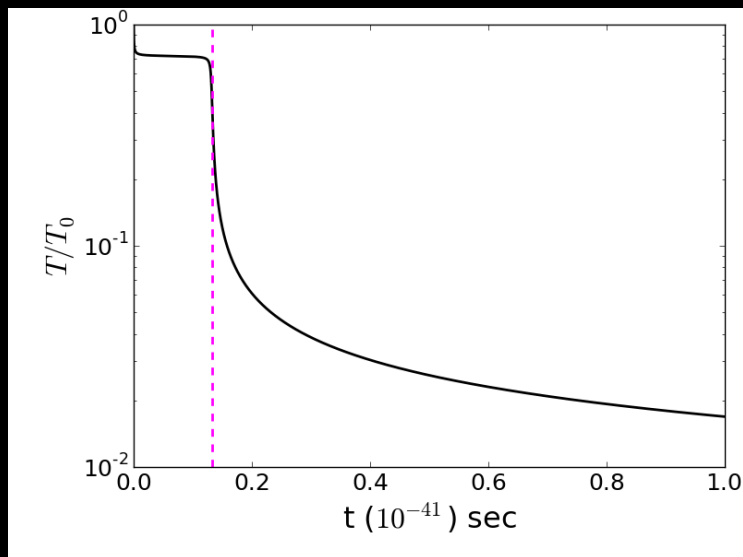
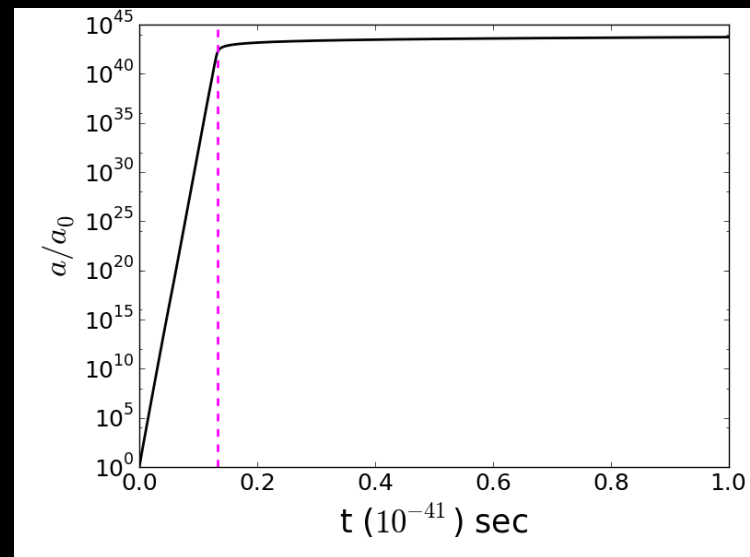


S. Desai & NP, PLB 755, 183 (2016)

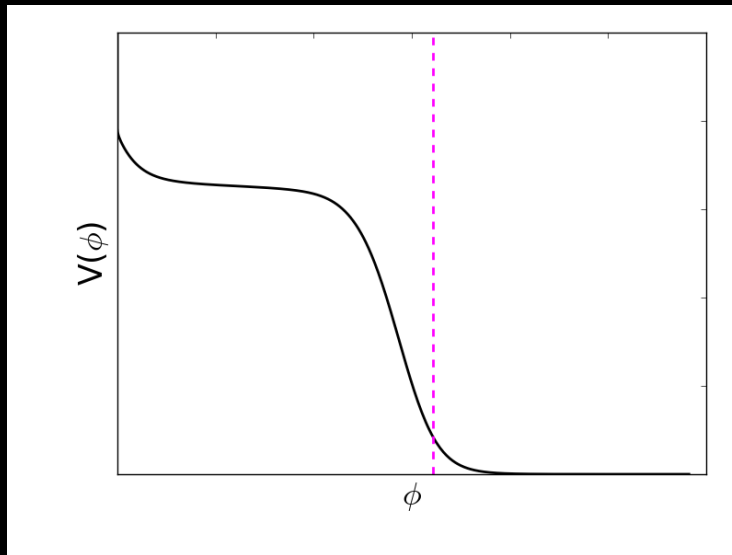
Dynamics of the very early Universe

$$\beta/\beta_{cr} = 0.9998$$

$$a_0 = 10^{-27} \text{ m}$$



It is possible to find a scalar field potential which generates the same time dependence of the scale factor.



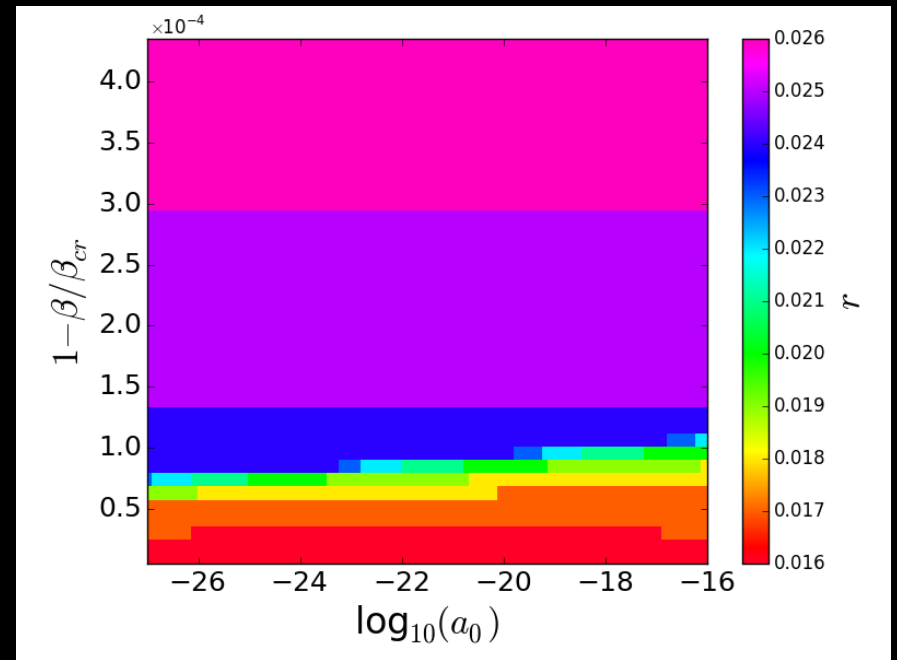
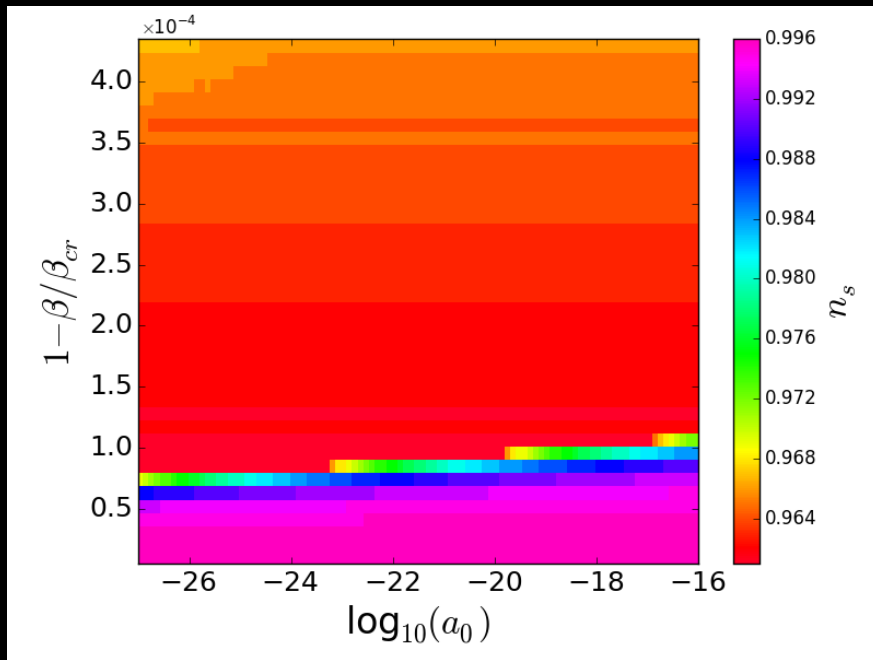
$$\beta/\beta_{cr} = 0.9998$$

Plateau-like potential – favored by Planck 2013.

Scalar-field plateau models of inflation: initial conditions problem, eternal inflation, unlikelihood (compared to power-law), several parameters: Ijjas, Steinhardt & Loeb, PLB 723, 261 (2013).

Torsion cosmology avoids those problems with only 1 parameter.

From the equivalent scalar field potential, one can calculate the parameters which are being measured in CMB.



Consistent with Planck 2015:

$$n_s = 0.968 \pm 0.006, r < 0.12$$



Scientific American (2017): debate about inflation.

Primordial fluctuations

The homogeneous and isotropic Universe can be viewed as a mechanical system described by a Lagrangian with the scale factor as a generalized coordinate – minisuperspace approximation.

$$L = \frac{6\pi^2}{\kappa} \left(\frac{-a\dot{a}^2}{c^2} + ka - \frac{1}{3}\kappa\epsilon a^3 \right)$$

The Lagrange equations for the scale factor give the second Friedmann equation.

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{a}} = \frac{\partial L}{\partial a}$$

Symmetry in time – conservation of energy.

The energy of the Universe = 0 gives the first Friedmann equation.

$$E = \frac{\partial L}{\partial \dot{a}} \dot{a} - L$$

Primordial fluctuations

The generalized momentum of the Universe.

$$p_a = \frac{\partial L}{\partial \dot{a}} = -\frac{12\pi^2 a \dot{a}}{\kappa c^2}$$

The uncertainty principle for the scale factor.

$$\Delta a \Delta \dot{a} \geq \frac{\hbar \kappa c^2}{24\pi^2 a}$$

Idea: quantum fluctuations of the scale factor, corresponding to quantum fluctuations of matter, are primordial fluctuations. Inflation, driven by torsion and particle production, increases them to macroscopic scales.

Cosmology without scalar fields.

NP, MPLA 33, 1850236 (2018)

Every black hole creates a new universe?

The closed Universe might have originated from the interior of a black hole existing in a parent universe when $C > (8/9)^{1/2}$.

Accordingly, every black hole may create a new, closed, baby universe (Novikov, Pathria, Hawking, Smolin, NP).

This hypothesis solves the black hole information paradox: the information goes through the Einstein-Rosen bridge to the baby universe on the other side of the black hole's event horizon.

The motion through an event horizon is one way only: it can define the past and future. Time asymmetry at the event horizon may induce time asymmetry everywhere in the baby universe. May explain why time flows in one direction?

Torsion as a solution to other problems

Torsion could also:

- Explain matter-antimatter asymmetry. The Dirac equation in the presence of torsion becomes cubic in spinor fields. The cubic terms for matter and for antimatter have different signs relative to the mass term. The asymmetry is significant only in the regime where torsion is significant.
- Explain a cosmological constant. If the metric tensor is proportional to the square of the torsion tensor, the field equations are the Einstein equations with the proportionality constant becoming the cosmological constant.
- Regularize Feynman diagrams in quantum field theory. In the presence of torsion, translations do not commute, so the momentum operator components do not commute. Integration in the momentum space must be replaced with summation over discrete momentum eigenvalues. The separation between adjacent eigenvalues increases with the momentum. The sum is convergent even if the original integral was UV divergent.

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Desai & NP, PLB 755, 183 (2016)

Unger & NP, ApJ 870, 78 (2019)

Summary

- The conservation law for total angular momentum (orbital + spin) in curved spacetime, consistent with Dirac equation, requires torsion.
- The simplest theory with torsion, Einstein-Cartan gravity, has the same Lagrangian as GR, but torsion is not set to zero.
- Torsion is strong only at extremely high densities and manifests itself as gravitational repulsion that avoids the formation of singularities. The Big Bang is replaced by a nonsingular Big Bounce.
- Particle production after a bounce can generate a finite period of inflation which ends when torsion becomes weak. No hypothetical fields or extra dimensions are needed. The dynamics is plateau-like and supported by the Planck data.
- EC gravity is the simplest and most natural explanation of the Big Bounce and inflation. Torsion could also explain other problems in cosmology and quantum field theory.