Cosmology with torsion - an alternative to cosmic inflation

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The Einstein-Cartan-Kibble-Sciama theory of gravity provides a simple scenario in early cosmology which is alternative to standard cosmic inflation and does not require scalar fields. The torsion of spacetime prevents the appearance of the cosmological singularity in the early Universe filled with Dirac particles averaged as a spin fluid. Instead, its expansion starts from a state at which the Universe has a minimum but finite radius. We show that the dynamics of the closed Universe immediately after this state naturally solves the flatness and horizon problems in cosmology because of an extremely small and negative torsion density parameter, $\Omega_S \approx -10^{-69}$. This scenario also suggests that the contraction of our Universe preceding the state of minimum radius could correspond to the dynamics of matter inside the event horizon of a newly formed black hole existing in another universe.

ECKS gravity. The Einstein-Cartan-Kibble-Sciama (ECKS) theory of gravity naturally extends Einstein's general relativity to include matter with intrinsic angular momentum, providing a more complete account of local gauge invariance with respect to the Poincaré group [1–4]. It is a viable theory, which differs significantly from general relativity only at densities of matter much larger than the density of nuclear matter. This theory is advantageous over general relativity because torsion appears to prevent the formation of singularities from matter composed of particles with half-integer spin and averaged as a spin fluid [5–7], and to introduce an effective ultraviolet cutoff in quantum field theory for fermions [8].

The ECKS gravity is based on the Lagrangian density of the gravitational field that is proportional to the Ricci scalar R, as in general relativity. However, this theory removes the general-relativistic restriction of the symmetry of the affine connection $\Gamma^{k}_{\ ij}$, that is, of the vanishing of the torsion tensor $S^{k}_{\ ij} = \Gamma^{k}_{\ [ij]}$. Instead, the torsion tensor is regarded as a dynamical variable, in addition to the metric tensor g_{ij}. Varying the total action for the gravitational field and matter with respect to the metric gives the Einstein field equations that relate the curvature of spacetime to the canonical energy-momentum tensor of matter $\sigma_{ij} = \mathfrak{T}_{ij}/\sqrt{-g}$ (we use the notation of [4]):

$$R_{ik} - \frac{1}{2}Rg_{ik} = \kappa\sigma_{ik}, \tag{1}$$

where R_{ik} is the Ricci tensor of the Riemann-Cartan connection

$$\Gamma^{k}_{\ ij} = \{^{\ k}_{i\ j}\} + C^{k}_{\ ij}. \tag{2}$$

Here $\{^{\ k}_{i\ j}\}$ are the Christoffel symbols of the metric and

$$C^{k}_{\ ij} = S^{k}_{\ ij} + 2S_{(ij)}^{\ \ k} \tag{3}$$

is the contortion tensor. Varying the total action with respect to the torsion gives the Cartan field equations that relate (algebraically) the torsion of spacetime to the canonical spin tensor of matter $s_{ij}^{\ \ k} = \mathfrak{S}_{ij}^{\ \ k}/\sqrt{-g}$:

$$S^{j}_{\ ik} - S_i\delta^{j}_{k} + S_k\delta^{j}_{i} = -\frac{1}{2}\kappa s_{ik}^{\ \ j}, \tag{4}$$

where $S_i = S^{k}_{\ ik}$.

The conservation law for the spin tensor is

$$\nabla^{*}_{k} s_{ij}^{\ \ k} = \sigma_{ij} - \sigma_{ji}, \tag{5}$$

where $\nabla^{*}_{k} = \nabla_k - 2S_k$ and ∇_k denotes the covariant derivative with respect to the affine connection $\Gamma^{k}_{\ ij}$. The canonical energy-momentum tensor can be symmetrized using the Belinfante-Rosenfeld relation

$$T_{ik} = \sigma_{ik} - \frac{1}{2}\nabla^{*}_{j}(s_{ik}^{\ \ j} - s_{k\ i}^{\ j} + s^{j}_{\ ik}), \tag{6}$$

where T_{ik} is the symmetric energy-momentum tensor of general relativity [9]. Substituting (2) and (3) into (1) and using (4) and (6) gives

$$P_{ik} - \frac{1}{2}Pg_{ik} = \kappa(T_{ik} + U_{ik}), \tag{7}$$

where P_{ik} is the general-relativistic Ricci tensor of the Christoffel connection and

$$U^{ik} = \kappa\Big(-s^{ij}_{\ \ [l}s^{kl}_{\ \ j]} - \frac{1}{2}s^{ijl}s^{k}_{\ jl} + \frac{1}{4}s^{jli}s_{jl}^{\ \ k}$$
$$+\frac{1}{8}g^{ik}(4s_{j\ [m}^{\ l}s^{jm}_{\ \ l]} + s^{jlm}s_{jlm})\Big) \tag{8}$$

is the correction to the energy-momentum tensor from the intrinsic spin [2, 6].

Spin fluid. Since Dirac fields couple minimally to the torsion tensor, the torsion of spacetime at microscopic scales is nonzero in the presence of fermions. At macroscopic scales, such particles can be averaged and described as a spin fluid [10]. If the spin orientation of particles is random then the macroscopic spacetime average of the spin and of the spin gradients vanish. On

the contrary, the terms in U_{ik} are quadratic in the spin tensor and they do not vanish after averaging [6]. The tensor U_{ik} differs significantly from zero only at densities of matter much larger than the density of nuclear matter. We show now the steps in [6] that lead to the combined energy-momentum tensor of a spin fluid $T^{ij} + U^{ij}$. The macroscopic canonical energy-momentum tensor of a spin fluid is given by

$$\sigma_i{}^j = \Pi_i c u^j - p h_i^j, \tag{9}$$

while its macroscopic canonical spin tensor is given by

$$s_{ij}{}^k = s_{ij} u^k, \tag{10}$$

$$s_{ij} u^j = 0, \tag{11}$$

where Π_i is the four-momentum density of the fluid, u^i its four-velocity, s_{ij} its spin density, p its pressure, and $h_{ij} = g_{ij} - u_i u_j$ is the projection tensor [6]. Substituting (10) into (4) and using (11) gives $S_i = 0$ and $\nabla_i^* = \nabla_i$. Accordingly, the torsion tensor is

$$S^j{}_{ik} = -\frac{1}{2} \kappa s_{ik} u^j. \tag{12}$$

Putting (9) into (5) gives $c(\Pi_i u_j - \Pi_j u_i) = \nabla_k(s_{ij} u^k)$, which leads to

$$c \Pi_i = \epsilon u_i + \nabla_k s_{ij} u^k u^j, \tag{13}$$

where $\epsilon = c \Pi_i u^i$ is the rest energy density of the fluid.

Substituting (13) into (9) and using (6) gives $T_{ij} = \epsilon u_i u_j - p h_{ij} - \nabla_k(s^k{}_{(i} u_{j)}) + \nabla_k(s_{il} u^k) u^l u_j - \frac{1}{2} \nabla_k(s_{ij} u^k)$. The last two terms on the right of this equation are equal to $-\nabla_k(s_{l(i} u^k) u^l u_{j)} = -\nabla_l(s^k{}_{(i} u_{j)}) u_k u^l$, so the tensor T^{ij} becomes

$$T^{ij} = \epsilon u^i u^j - p h^{ij} - (\delta_k^l + u_k u^l) \nabla_l(s^{k(i} u^{j)}). \tag{14}$$

The last term on the right of (14) can be decomposed according to (2) into $-(\delta_k^l + u_k u^l) D_l((s^{k(i} u^{j)}) - (\delta_k^l + u_k u^l)(C^k{}_{ml} s^{m(i} u^{j)} + C^i{}_{ml} s^{k(m} u^{j)} + C^j{}_{ml} s^{k(i} u^{m)})$, where D_k denotes the general-relativistic covariant derivative with respect to the Christoffel symbols. This term reduces, using (3), (11) and (12), to $-(\delta_k^l + u_k u^l) D_l((s^{k(i} u^{j)}) - C^i{}_{mk} s^{k(m} u^{j)} - C^j{}_{mk} s^{k(i} u^{m)}) = -(\delta_k^l + u_k u^l) D_l((s^{k(i} u^{j)}) - \frac{1}{2} \kappa(s_{kl} s^{kl} u^i u^j - s^{ik} s^j{}_k)$. Thus (14) becomes

$$T^{ij} = \epsilon u^i u^j - p h^{ij} - (\delta_k^l + u_k u^l) D_l(s^{k(i} u^{j)})$$
$$-\kappa s^2 u^i u^j + \frac{1}{2} \kappa s^{ik} s^j{}_k, \tag{15}$$

where

$$s^2 = \frac{1}{2} s^{ij} s_{ij} > 0 \tag{16}$$

is the square of the spin density.

Substituting (12) into (8) gives

$$U^{ij} = \frac{1}{2} \kappa s^2 u^i u^j + \frac{1}{4} \kappa s^2 g^{ij} - \frac{1}{2} \kappa s^{ik} s^j{}_k. \tag{17}$$

Adding (15) and (17) brings the combined energy-momentum tensor $T^{ij} + U^{ij}$ in the Einstein field equations (7) to the form obtained in [6]:

$$T^{ij} + U^{ij} = \left(\epsilon - \frac{1}{4} \kappa s^2\right) u^i u^j - \left(p - \frac{1}{4} \kappa s^2\right) h^{ij}$$
$$-(\delta_k^l + u_k u^l) D_l(s^{k(i} u^{j)}). \tag{18}$$

If the spin orientation of particles in a spin fluid is random then the last term in (18) vanishes after averaging. Thus the combined energy-momentum tensor of such a spin fluid describes a perfect fluid with the effective energy density $\epsilon - \frac{1}{4} \kappa s^2$ and the effective pressure $p - \frac{1}{4} \kappa s^2$ [6, 11, 12].

Friedman equations with torsion. A closed, homogeneous and isotropic universe is described by the Friedman-Lemaître-Robertson-Walker (FLRW) metric which, in the isotropic spherical coordinates, is given by

$$ds^2 = c^2 dt^2 - \frac{a^2(t)}{(1 + kr^2/4)^2}(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2), \tag{19}$$

where $a(t)$ is the scale factor and $k = 1$, and the energy-momentum tensor in the rest frame: $u^0 = 1$, $u^\alpha = 0$ ($\alpha = 1, 2, 3$) [9]. The Einstein field equations (7) for this metric and for the combined energy-momentum tensor (18) turn into the Friedman equations [5, 7, 11]:

$$\dot{a}^2 + 1 = \frac{1}{3} \kappa \left(\epsilon - \frac{1}{4} \kappa s^2\right) a^2, \tag{20}$$

$$\dot{a}^2 + 2a\ddot{a} + 1 = -\kappa \left(p - \frac{1}{4} \kappa s^2\right) a^2, \tag{21}$$

where the dot denotes the differentiation with respect to ct. These equations yield the conservation law

$$\left((\epsilon - \kappa s^2/4) a^3\right)^{\cdot} + (p - \kappa s^2/4)\left(a^3\right)^{\cdot} = 0, \tag{22}$$

which can be used instead of the second Friedman equation (21).

The energy density is the sum $\epsilon = \epsilon_R + \epsilon_M + \epsilon_\Lambda$ of the energy density of radiation ϵ_R, energy density of matter ϵ_M, and energy density associated with the cosmological constant $\epsilon_\Lambda = \Lambda/\kappa$. The pressure is the sum $p = p_R + p_M + p_\Lambda$ of the pressure of radiation $p_R = \epsilon_R/3$, pressure of matter $p_M = 0$, and pressure associated with the cosmological constant $p_\Lambda = -\epsilon_\Lambda$. Applying (22) to each component of the energy density and pressure separately leads to $\epsilon_R \propto a^{-4}$, $\epsilon_M \propto a^{-3}$, $\epsilon_\Lambda \propto a^0$, and

$$\epsilon_S = -\frac{1}{4} \kappa s^2 \propto a^{-6}, \tag{23}$$

which is consistent with the conservation of the particle number because

$$s^2 = \frac{1}{8}(\hbar c n)^2, \tag{24}$$

where $n \propto a^{-3}$ is the particle number density [11, 12]. Thus the total effective energy density is given by

$$\epsilon + \epsilon_S = \epsilon_{R0}\hat{a}^{-4} + \epsilon_{M0}\hat{a}^{-3} + \epsilon_\Lambda + \epsilon_{S0}\hat{a}^{-6}, \qquad (25)$$

where $\hat{a} = a/a_0$ is the normalized scale factor and the subscripts 0 denote quantities measured at the present time (when $\hat{a} = 1$).

The first Friedman equation (20) can be written as

$$H^2 + \frac{c^2}{a^2} = \frac{1}{3}\kappa(\epsilon + \epsilon_S)c^2, \qquad (26)$$

where $H = c\dot{a}/a$ is the Hubble parameter. The present-day total density parameter, $\Omega = (\epsilon_0 + \epsilon_{S0})/\epsilon_c$, where $\epsilon_c = 3H_0^2/(\kappa c^2)$ is the present-day critical energy density, gives $a_0 H_0 \sqrt{\Omega - 1} = c$, as in general-relativistic cosmology [13]. The total density parameter at any instant,

$$\Omega(\hat{a}) = \frac{\kappa c^2}{3H^2}(\epsilon + \epsilon_S), \qquad (27)$$

satisfies

$$a|H|\sqrt{\Omega(\hat{a}) - 1} = c, \qquad (28)$$

Using the present-day density parameters for each component, $\Omega_a = \epsilon_{a0}/\epsilon_c$, in (25) brings (26) to

$$|H| = H_0\Big(\Omega_R\hat{a}^{-4} + \Omega_S\hat{a}^{-6} + \Omega_M\hat{a}^{-3} + \Omega_\Lambda - (\Omega-1)\hat{a}^{-2}\Big)^{\frac{1}{2}}. \qquad (29)$$

The relations (28) and (29) give

$$\Omega(\hat{a}) = 1 + \frac{(\Omega - 1)\hat{a}^4}{\Omega_R\hat{a}^2 + \Omega_S + \Omega_M\hat{a}^3 + \Omega_\Lambda\hat{a}^6 - (\Omega-1)\hat{a}^4}. \qquad (30)$$

Since the energy-density contribution from torsion ϵ_S is negative, so is the torsion density parameter

$$\Omega_S = \epsilon_{S0}/\epsilon_c. \qquad (31)$$

Density parameters. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations show that our Universe may be indeed closed, with $\Omega = 1.002$ and $\Omega_M = 0.27$ [14]. The WMAP data give also $H_0^{-1} = 4.4 \times 10^{17}\,\text{s}$ and $\Omega_R = 8.8 \times 10^{-5}$. Thus $a_0 = 2.9 \times 10^{27}\,\text{m}$. To estimate Ω_S, we use the relic background neutrinos which are the most abundant fermions in the Universe, with $n = 5.6 \times 10^7\,\text{m}^{-3}$ for each type (out of 6) [13]. Equations (23) and (24) then give

$$\Omega_S = -8.6 \times 10^{-70}. \qquad (32)$$

While in general relativity the torsion density parameter Ω_S vanishes, the ECKS theory of gravity gives Ω_S a nonzero, though extremely small, negative value.

Flatness problem. For the early Universe, $\hat{a} \ll 1$. Thus we can neglect the terms with Ω_M, Ω_Λ and $\Omega - 1$ in (29), simplifying it to

$$|H| = H_0(\Omega_R\hat{a}^{-4} + \Omega_S\hat{a}^{-6})^{\frac{1}{2}}. \qquad (33)$$

This equation shows that the expansion of the Universe started when $H = 0$, at which $\hat{a} = \hat{a}_m$, where

$$\hat{a}_m = \sqrt{-\frac{\Omega_S}{\Omega_R}} = 3.1 \times 10^{-33}, \qquad (34)$$

corresponding to the minimum but finite scale factor (radius of a closed universe) $a_m = 9 \times 10^{-6}\,\text{m}$. Before reaching its minimum size, the Universe was contracting with $H < 0$. The total density parameter corresponding to (33) is

$$\Omega(\hat{a}) = 1 + \frac{(\Omega - 1)\hat{a}^4}{\Omega_R\hat{a}^2 + \Omega_S}. \qquad (35)$$

If we choose $t = 0$ at $\hat{a} = \hat{a}_m$ then integrating (33) for $t > 0$ gives

$$-\frac{\Omega_R^{3/2}H_0}{\Omega_S}t = f(x) = \frac{x}{2}\sqrt{x^2 - 1} + \frac{1}{2}\ln|x + \sqrt{x^2 - 1}|, \qquad (36)$$

where $x = \hat{a}/\hat{a}_m$. When $x \gg 1$, $f(x) \approx x^2/2$, yielding the usual evolution of the radiation-dominated Universe, $a \sim t^{1/2}$.

In general relativity, $\Omega_S = 0$, from which it follows that $\Omega(\hat{a}) - 1$ tends to zero as $\hat{a} \to 0$ according to $\Omega(\hat{a}) - 1 = (\Omega - 1)\hat{a}^2/\Omega_R$, which introduces the flatness problem in Big-Bang cosmology. $\Omega(\hat{a})$ at the GUT epoch must have been tuned to 1 to a precision of more than 52 decimal places in order for Ω to be near 1 today. This problem can be solved by cosmic inflation, according to which the Universe in the very early stages of its evolution exponentially expanded (which involved false vacuum or scalar fields) by a factor of at least 10^{26}, making $\Omega(\hat{a})$ sufficiently close to 1 at the GUT epoch [15].

In the ECKS gravity, where $\Omega_S < 0$, $\Omega(\hat{a})$ is infinite at $\hat{a} = \hat{a}_m$. The function (35) has a local minimum at $\hat{a} = \sqrt{2}\hat{a}_m$, where it is equal to

$$\Omega(\sqrt{2}\hat{a}_m) = 1 + \frac{4\Omega_S(\Omega - 1)}{\Omega_R^2} = 1 + 8.9 \times 10^{-64}. \qquad (37)$$

As the Universe expands from $\hat{a}_m$ to $\sqrt{2}\hat{a}_m$, $\Omega(\hat{a})$ rapidly decreases from infinity to the value (37) which *appears* to be tuned to 1 to a precision of about 63 decimal places. This stage takes

$$t = -\frac{\Omega_S}{\Omega_R^{3/2}H_0}f(\sqrt{2}) = 5.3 \times 10^{-46}\,\text{s}. \qquad (38)$$

During this time, the Universe expands only by a factor of $\sqrt{2}$ which is much less than 10^{26} in the inflationary scenario. Thus the apparent fine tuning of $\Omega(\hat{a})$

in the very early Universe is naturally caused by the *extremely small and negative torsion density parameter* (32) originating from the torsion of spacetime in the ECKS gravity, without needing the inflationary dynamics. As the Universe expands further, $\Omega_R \hat{a}^2$ becomes much greater than $|\Omega_S|$ and $\Omega(\hat{a}) - 1$ increases according to $\Omega(\hat{a}) - 1 = (\Omega - 1)\hat{a}^2/\Omega_R$, until the Universe becomes dominated by matter and the full (30) must be used.

Horizon problem. The relations (28) and (37) give

$$\dot{a} = \frac{1}{\sqrt{\Omega(\hat{a}) - 1}}. \qquad (39)$$

The velocity of the point that is antipodal to the coordinate origin, $v_a = \pi c \dot{a}$ [9, 13], has a local maximum at $\hat{a} = \sqrt{2}\hat{a}_m$, where it is equal to

$$v_a = \frac{\Omega_R}{2\sqrt{\Omega_S(\Omega - 1)}}c = 1.1 \times 10^{32}\, c. \qquad (40)$$

As the closed Universe expands from $\hat{a}_m$ to $\sqrt{2}\hat{a}_m$, v_a rapidly increases from zero to the enormous value (40). During this time, the Universe is accelerating: $\ddot{a} > 0$. As the Universe expands further, v_a decreases according to $v_a = \sqrt{\pi c \Omega_R}\hat{a}^{-1}/\sqrt{\Omega - 1}$, until the Universe becomes dominated by matter and the full (29) must be used. During this time, the Universe is decelerating: $\ddot{a} < 0$, until the cosmological constant becomes dominant.

If the closed Universe was causally connected at some instant $t < 0$, then it remains causally connected during its contraction until $t = 0$ and also during the subsequent expansion until v_a reaches c. After that moment, the point at the origin cannot communicate with points in space receding with velocities greater than c. That is, the Hubble radius $d_H = c/H$ becomes smaller than the physical distance to the antipodal point $d_a = \pi a$. The Universe contains $N \approx (v_a/c)^3 = (d_a/d_H)^3$ causally disconnected volumes. At t given by (38), d_a is 32 orders of magnitude greater than d_H and $N \approx 10^{96}$. Again, it is the *extremely small and negative torsion density parameter* (32) that naturally causes how such a large number of causally disconnected volumes arises from a single causally connected region of spacetime, without needing the inflationary dynamics. As the Universe expands further, $|\Omega_S|$ becomes negligible and N decreases according to standard cosmology. For example, at recombination, $\hat{a} = 9.2 \times 10^{-4}$ [14] gives $d_a/d_H = 1.4 \times 10^3$.

Discussion. An extremely small and negative torsion density parameter $\Omega_S \approx -10^{-69}$, arising from a very weak and repulsive spin-spin interaction predicted by the ECKS theory of gravity, provides a simple mechanism for the apparent fine tuning of the total density parameter in the early closed Universe and for an enormous number of causally disconnected volumes in the Universe originating from a single causally connected region. The expansion of the Universe in the presence of torsion differs from that in Big-Bang cosmology only when the Universe is near its

minimum size; after that, the Universe smoothly enters the radiation-domination epoch. This mechanism, based on the geometrical effects of spin angular momentum, is thus a compelling alternative to the standard inflationary scenario because it does not require introducing false vacuum or scalar fields.

According to (29), the contraction of the Universe before $t = 0$ looks like the time reversal of the following expansion. However, the idea of a universe contracting from infinity in the past does not explain what caused such a contraction, just like Big-Bang cosmology cannot explain what happened before the Big Bang. Fortunately, two mechanisms can cause the dynamics asymmetry between the contraction and expansion. First, when the Universe has the minimum radius (34), the radiation energy density is $\epsilon_R = 1.1 \times 10^{116}\, \mathrm{J\,m^{-3}}$, which is greater than the Planck energy density by a few orders of magnitude. Thus it is also significantly greater than the density threshold for pair production [2, 16]. Such pair production would increase Ω_S. If the contracting Universe was anisotropic in the past, the pair production in the presence of extremely large tidal forces would also increase the energy density to the values sufficient for isotropization of the subsequent expansion [16]. Second, the electroweak interactions between fermions in the early Universe could cause their spins to align, making the last term on the right of (18) nonzero. This term would introduce in the Friedman equations a time asymmetry with respect to the transformation $t \to -t$, $H \to -H$. Also, the spin tensor in this term acts like viscosity, which would increase the entropy of the Universe.

We propose the following scenario. A massive star, that is causally connected, collapses gravitationally to a black hole and an event horizon forms. Inside the horizon, spacetime is nonstationary and matter contracts to an extremely dense, but because of torsion, finite-density state. In the frame locally moving with matter, this contraction looks like the contraction of a closed universe [9, 17]. Such a universe is initially causally connected and anisotropic. Extremely large tidal forces cause an intense pair production which generates the observed amount of mass and increases the energy density, resulting in isotropization of this universe [16]. Additional terms in the Lagrangian density containing torsion could also generate massive vectors [18]. The spin density increases, magnifying the repulsive spin-fluid forces due to the negative ϵ_S. The pair production does not change the total (matter plus gravitational field) energy of the resulting FLRW universe, which is zero if we neglect the cosmological constant [19]. After reaching its minimum size, the homogeneous and isotropic universe starts expanding. Such an expansion is not visible for observers outside the black hole, for whom the horizon's formation and all subsequent processes occur after infinite time [9]. The new universe is thus a separate spacetime branch with its own timeline; it can last infinitely long and grow

infinitely large if dark energy is present.

As the universe in a black hole expands to infinity, the boundary of the black hole becomes an Einstein-Rosen bridge connecting this universe with the outer universe [20]. We recently suggested that all astrophysical black holes may be Einstein-Rosen bridges (wormholes), each with a new univserse inside that formed simultaneously with the black hole [21]. Accordingly, our own Universe may be the interior of a black hole existing in another universe, and the time asymmetry of motion at the boundary of this black hole may cause the perceived arrow of cosmic time. This description is possible because the torsion of spacetime, which is produced by the intrinsic spin of fermions, prevents the formation of singularities. Thus the gravitational collapse of a star composed of quarks and leptons to a black hole does not create a singularity [8], allowing matter inside the event horizon to reexpand.

Since most stars rotate, most astrophysical black holes are rotating black holes. A universe born from a rotating black hole should inherit its preferred direction, related to the axis of rotation. Such a preferred direction should introduce small corrections to the FLRW metric (19), containing the Kerr radius $a = M/(mc)$, where M is the angular momentum of a rotating black hole and m is its mass [9, 22]. These corrections could then couple to other fields, allowing to verify whether our Universe was born in a black hole. GRS 1915+105, which is the heaviest and fastest spinning, known stellar black hole in the Milky Way Galaxy, has $a < 26$ km [23]. Lighter or slower spinning black holes have smaller values of a. To compare, the preferred-frame parameter 2.4×10^{-19} GeV in a model for neutrino oscillations using Lorentz violation [24] corresponds to the length of 820 m.

The proposed description of the origin of our Universe may explain the arrow of time. Although the laws of the ECKS theory of gravity are time-symmetric, the boundary conditions of the Universe are not, because the motion of matter through the event horizon of a black hole is unidirectional and thus it can define the arrow of time. The arrow of cosmic time of a universe inside a black hole would then be fixed by the time-asymmetric collapse of matter through the event horizon, before the subsequent expansion. Such an arrow of time would also be entropic: although black holes are states of maximum entropy in the frame of outside observers, new universes expanding inside black holes would allow entropy to increase further.

[1] T. W. B. Kibble, J. Math. Phys. **2**, 212 (1961); D. W. Sciama, in *Recent Developments in General Relativity*, p. 415 (Pergamon, 1962); D. W. Sciama, Rev. Mod. Phys. **36**, 463 (1964).
[2] F. W. Hehl, P. von der Heyde, G. D. Kerlick, and J. M. Nester, Rev. Mod. Phys. **48**, 393 (1976).
[3] F. W. Hehl and B. K. Datta, J. Math. Phys. **12**, 1334 (1971); I. L. Shapiro, Phys. Rep. **357**, 113 (2002); R. T. Hammond, Rep. Prog. Phys. **65**, 599 (2002).
[4] N. J. Popławski, arXiv:0911.0334.
[5] A. Trautman, Nature (Phys. Sci.) **242**, 7 (1973).
[6] F. W. Hehl, P. von der Heyde, and G. D. Kerlick, Phys. Rev. D **10**, 1066 (1974).
[7] V. de Sabbata and C. Sivaram, Astrophys. Space Sci. **165**, 51 (1990); V. de Sabbata and C. Sivaram, *Spin and Torsion in Gravitation* (World Scientific, 1994).
[8] N. J. Popławski, Phys. Lett. B **690**, 73 (2010).
[9] L. D. Landau and E. M. Lifshitz, *The Classical Theory of Fields* (Pergamon, 1975).
[10] J. Weyssenhoff and A. Raabe, Acta Phys. Pol. **9**, 7 (1947).
[11] M. Gasperini, Phys. Rev. Lett. **56**, 2873 (1986).
[12] I. S. Nurgaliev and W. N. Ponomariev, Phys. Lett. B **130**, 378 (1983).
[13] J. Rich, *Fundamentals of Cosmology* (Springer-Verlag, 2001).
[14] D. Larson *et al.*, arXiv:1001.4635.
[15] A. H. Guth, Phys. Rev. D **23**, 347 (1981); A. D. Linde, Rep. Prog. Phys. **47**, 925 (1984).
[16] L. Parker, Phys. Rev. **183**, 1057 (1969); Ya. B. Zel'dovich, J. Exp. Theor. Phys. Lett. **12**, 307 (1970); G. D. Kerlick, Phys. Rev. D **12**, 3004 (1975).
[17] R. C. Tolman, *Relativity, Thermodynamics and Cosmology* (Clarendon, 1934).
[18] N. J. Popławski, Int. J. Theor. Phys. **49**, in press (2010), arXiv:0905.4284.
[19] F. I. Cooperstock and M. Israelit, Found. Phys. **25**, 631 (1995).
[20] A. Einstein and N. Rosen, Phys. Rev. **48**, 73 (1935).
[21] N. J. Popławski, Phys. Lett. B **687**, 110 (2010).
[22] R. P. Kerr, Phys. Rev. Lett. **11**, 237 (1963).
[23] J. E. McClintock, R. Shafee, R. Narayan, R. A. Remillard, S. W. Davis, and L.-X. Li, Astrophys. J. **652**, 518 (2006).
[24] T. Katori, V. A. Kostelecký, and R. Tayloe, Phys. Rev. D **74**, 105009 (2006).