The Universe and Black Holes in Gravity with Spin and Torsion

Nikodem J. Popławski

Department of Physics, Indiana University
Bloomington, IN

Department of Physics & Department of Mathematics
University of New Haven, West Haven, CT

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Outline

1. Problems of general relativity and cosmology
2. Gravity with spin: Einstein-Cartan theory
3. Cosmology with torsion
   • Nonsingular big bounce instead of big bang
   • Torsion as alternative to inflation
   • Matter-antimatter asymmetry
4. Black holes with torsion
   • Wormholes to new universes and arrow of time
5. Observational status and research directions
Problems of general relativity

• Singularities: points with infinite density of matter.

• Incompatible with quantum mechanics. We need quantum gravity – a dream of theoretical physicists. It may resolve the singularity problem.

• Field equations contain the conservation of angular momentum without intrinsic angular momentum (spin).

• Spin is quantum-mechanical: extending GR to include spin of elementary particles is a natural first step towards quantum gravity. Simplest extension: Einstein-Cartan theory.
Problems of big-bang cosmology

- Big-bang singularity: resolution from quantum gravity?

- 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).

- Flatness problem: the Universe is nearly flat. The initial conditions of the Universe must have been fine-tuned.

- What is dark energy? What is dark matter? What happened to antimatter? What does time flow in one direction?
Problems of big-bang cosmology

• Inflation (extremely rapid, exponential expansion of the early Universe) solves the flatness/horizon problems, and predicts the observed spectrum of CMB perturbations. It does not solve the singularity problem and does not explain the big bang.

• Bouncing cosmologies avoid the big-bang singularity, and also explain the flatness/horizon problems.

• What caused inflation or bounce – hypothetical fields? Why did inflation end?

• Simple solution: Einstein-Cartan theory.
Gravity with spin requires torsion

- The correct generalization of the conservation law for the total (orbital plus spin) angular momentum to the presence of the gravitational field requires spacetime with both curvature and 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 very early Universe).

arXiv.org > gr-qc > arXiv:1304.0047
Gravity with spin: Einstein-Cartan-Sciama-Kibble theory

Simplest theory of spacetime with torsion.

This talk:
Big-bang and black hole singularities, flatness/horizon problems, and several other puzzles are naturally solved by torsion.
### ECSK gravity

- Einstein equations:
  Ricci tensor *(curvature)* is proportional to the energy and momentum density.
  Bianchi identities give the conservation law for the energy and momentum.

- Cartan equations:
  Torsion tensor is proportional to the spin density. ECSK in vacuum reduces to GR and obeys the equivalence principle.
  Cyclic identities give the conservation law for the spin angular momentum.

GR: only Einstein equations. Bianchi identities give the conservation laws for the energy and momentum without spin.
Matter-antimatter asymmetry

• The observable Universe has imbalance in baryonic matter and antibaryonic matter.

Dirac equation for a fermion:

\[ i\gamma^k \psi_{;k} + eA_k \gamma^k \psi = m\psi - \frac{3\kappa}{8} (\bar{\psi}\gamma^5 \gamma_k \psi) \gamma^5 \gamma^k \psi \]

Dirac equation for an antifermion:

\[ i\gamma^k \psi^c_{;k} - eA_k \gamma^k \psi^c = m\psi^c + \frac{3\kappa}{8} (\bar{\psi}^c\gamma^5 \gamma_k \psi^c) \gamma^5 \gamma^k \psi^c \]

• Torsion generates charge-conjugation asymmetry. Particles and antiparticles behaves differently in the very early Universe, which may have led to their present imbalance.

Fermions are spatially extended

- To satisfy the conservation law for the spin density, Dirac particles cannot be points in the presence of torsion.

Spatial extension of a fermion is at Cartan radius:

\[
\frac{m}{r_C^3} \sim \frac{G}{c^4} \left( \frac{\hbar}{r_C^3} \right)^2
\]

For an electron, \( r_C \approx 10^{-27} \text{ m} \gg \) Planck length and 5 orders of magnitude smaller than experimental upper limits on its radius.

- Torsion may provide a natural ultraviolet cutoff in quantum field theory, avoiding divergent integrals arising from treating fermions as points.

What is torsion?

- Curved spacetime requires geometrical structure: affine connection $\Gamma^\rho_{\mu\nu}$

- Covariant derivative
  $$\nabla_\nu V^\mu = \partial_\nu V^\mu + \Gamma^\mu_{\rho\nu} V^\rho$$

- Curvature tensor
  $$R^\rho_{\sigma\mu\nu} = \partial_\mu \Gamma^\rho_{\sigma\nu} - \partial_\nu \Gamma^\rho_{\sigma\mu} + \Gamma^\rho_{\tau\mu} \Gamma^\tau_{\sigma\nu} - \Gamma^\rho_{\tau\nu} \Gamma^\tau_{\sigma\mu}$$

Measures the change of a vector parallel-transported along a closed curve:

change = curvature $\times$ area $\times$ vector
What is torsion?

- **Torsion tensor** – antisymmetric part of affine connection
  \[ S^k_{ij} = \Gamma^k_{[ij]} \]

- **Contortion tensor**
  \[ C^i_{jk} = S^i_{jk} + S^j_{ik} + S^k_{ij} \]

Measures noncommutativity of parallel transports

GR – affine connection restricted to be **symmetric** in lower indices

ECSK – no constraint on connection: more natural?

[arXiv.org > gr-qc > arXiv:0911.0334]
What is torsion?

Note on the torsion tensor

March 2007, page 16

In commenting on letters responding to his Einstein article (PHYSICS TODAY, November 2005, page 31, and April 2006, page 10), Steven Weinberg states that he "never understood what is so important physically about the possibility of torsion in differential geometry." He basically argues that torsion "is just a tensor" and could be treated like any additional tensor field in the context of general relativity.

In my opinion, however, a decisive point was overlooked. Torsion is not just a tensor, but rather a very specific tensor that is intrinsically related to the translation group, as was shown by Élie Cartan\(^1\) in 1923–24. In fact, in the Yang–Mills sense, it is the field strength of the translations. Torsion is related to translations and curvature to Lorentz rotations. As one consequence, torsion cracks an infinitesimal parallelogram in the spacetime continuum and gives rise to a closure failure described by a vector (in dislocation theory in solids in three dimensions, it is the Burgers vector).

The simplest gravitational theory with torsion, the Einstein–Cartan theory, is a viable one.\(^2\) Incidentally, torsion could be measured by the precession of nuclear spins, even though the effects are expected to be minute in the present-day cosmos.\(^3\)
What is torsion?

**Weinberg replies:** Sorry, I still don't get it. Is there any physical principle, such as a principle of invariance, that would require the Christoffel symbol to be accompanied by some specific additional tensor? Or that would forbid it? And if there is such a principle, does it have any other testable consequences?

**Steven Weinberg**
(weinberg@physics.utexas.edu)
University of Texas at Austin
Theories of spacetime

**Special Relativity** – flat spacetime (no curvature)
Dynamical variables: matter fields

$$g_{ik} = \eta_{ik}$$

**General Relativity** – (curvature, no torsion)
Dynamical variables: matter fields + metric tensor $$g_{ik}$$

$$S^k_{ij} = 0$$

**ECSK Gravity** (simplest theory with curvature & torsion)
Dynamical variables: matter fields + metric $$g_{ik}$$ + torsion $$S^k_{ij}$$
Why ECSK gravity?

<table>
<thead>
<tr>
<th>GR</th>
<th>ECSK</th>
<th>MTG</th>
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<tbody>
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<td>NO</td>
<td>YES</td>
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Intrinsic angular momentum (spin) of matter couples to spacetime

Ordinary matter can form singular configurations

Additional free parameters (relative to GR)

ECSK gravitational repulsion at densities $\gg$ nuclear:
- Nonsingular black holes
- Big bounce instead of big bang
- Cosmic inflation not needed

$E = mc^2$
## Why ECSK gravity?

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<td>Intrinsic angular momentum (spin) of matter couples to spacetime</td>
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<td>?</td>
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<tr>
<td>Dirac equation linear</td>
<td>YES</td>
<td>NO</td>
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Cubic term may explain:

- Dark energy
- Matter-antimatter asymmetry
- Dark matter

*Astrophysics/relativity seminar tomorrow*
Why ECSK gravity?

- ECSK torsion significant only at densities $\gg$ nuclear
- ECSK torsion vanishes in vacuum
  - ECSK in vacuum = GR
  - ECSK passes all current GR tests
  - Cosmology of very early Universe can test ECSK

ECSK in vacuum obeys equivalence principle
History of torsion

- Élie Cartan (1921)
  - asymmetric affine connection → torsion

- Dennis Sciama and Tom Kibble (1960s)
  - spin generates torsion (energy & momentum generate curvature)
    
    D. W. Sciama, Rev. Mod. Phys. 36, 463 (1964)

- (1970s)
  - torsion may avert cosmological singularities (polarized spins)
    
    W. Kopczyński, Phys. Lett. A 39, 219 (1972); 43, 63 (1973)
    J. Tafel, Phys. Lett. A 45, 341 (1973)
History of torsion

- Hehl and Datta (1971)
  - Dirac equation with torsion is nonlinear (cubic in spinors) → Fermi-like four-fermion interaction
  

- (1970s)
  - torsion averts cosmological singularities (spin fluids with unpolarized spins) → bounce cosmology

  B. Kuchowicz, Gen. Relativ. Gravit. 9, 511 (1978)

- (1991)
  - macroscopic matter with torsion has spin-fluid form

Universe in a black hole

Department of Physics, University of Waterloo, Waterloo, Ontario
Received June 19; revised September 20, 1972.

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LETTERS TO NATURE

PHYSICAL SCIENCES
The Universe as a Black Hole

Since Einstein applied his general theory of relativity to study the structure of the universe as a whole, cosmologists have wondered if the universe is geometrically closed or open. Neither theory nor observation has been able to settle this question unambiguously. Several authors have hoped that the universe may after all be a closed, yet unbounded, system. This would solve many problems regarding the nature and origin of the universe, and would fit many of the observations of distant sources made at radio, optical and other wavelengths. Here I demonstrate that the universe may not only be a closed structure (as perceived by its inhabitants at the present epoch) but may also be a black hole, confined to a localized region of space which cannot expand without limit.

Is the universe itself a black hole? To investigate this question, the customary view of the universe, which is necessarily internal, is not sufficient; it has to be supplemented with an external view—I assume that there exists, outside our universe, an external world from which one may take a "detached" look at our universe. It turns out that these two views are not only mutually compatible but also show considerable similarities. Both views are presented here.

implications as well. For instance, we are now faced with several questions: How did the universe come to be a black hole—through a gravitational collapse, followed by a phase of expansion? In the cosmos, which includes the exterior as well as the interior of the universe, can our universe be unique? If not, what would its status be vis-a-vis other such structures in the cosmos? Investigation of these and other related questions, including the possible existence of an hierarchy of black holes, is clearly a matter of some importance.
Every black hole forms a new universe

Did the universe evolve?

Lee Smolin
Department of Physics, Syracuse University, Syracuse, NY 13244-1130, USA

Received 9 May 1991

The mechanism is contained in the following two postulates concerning the physics near spacetime singularities.

(i) Each final singularity is followed by an initial singularity, which evolves into a universe which is spatially closed. An alternative hypothesis, which is equivalent as far as its consequences for the subject of this paper, is that instead of an ending in a final singularity, the interior of a black hole tunnels into a new spatially compact universe. We may note that this hypothesis has been advocated as a resolution for the problem of information loss in black hole evaporation [9] and has also been discussed recently in connection with the baby universe scenario [10].
Black holes as Einstein-Rosen bridges

Radial motion into an Einstein–Rosen bridge

Nikodem J. Popławski

Department of Physics, Indiana University, Swain Hall West, 727 East Third Street, Bloomington, IN 47405, USA

We consider the radial geodesic motion of a massive particle into a black hole in isotropic coordinates, which represents the exterior region of an Einstein–Rosen bridge (wormhole). The particle enters the interior region, which is regular and physically equivalent to the asymptotically flat exterior of a white hole, and the particle’s proper time extends to infinity. Since the radial motion into a wormhole after passing the event horizon is physically different from the motion into a Schwarzschild black hole, Einstein–Rosen and Schwarzschild black holes are different, physical realizations of general relativity. Yet for distant observers, both solutions are indistinguishable. We show that timelike geodesics in the field of a wormhole are complete because the expansion scalar in the Raychaudhuri equation has a discontinuity at the horizon, and because the Einstein–Rosen bridge is represented by the Kruskal diagram with Rindler’s elliptic identification of the two antipodal future event horizons. These results suggest that observed astrophysical black holes may be Einstein–Rosen bridges, each with a new universe inside that formed simultaneously with the black hole. Accordingly, our own Universe may be the interior of a black hole existing inside another universe.
Fig. 2. Infalling radial geodesic motion of a massive particle into a Schwarzschild black hole (ABE) and an Einstein–Rosen black hole (ABCD) in the Kruskal coordinates. For the Einstein–Rosen black hole, the events on the segment OF are identified with the events on the segment OG, e.g., points B and C represent the same spacetime event.
Einstein-Cartan-Sciama-Kibble

theory of gravity

prevents singularities:
black hole interiors become new universes
T. Kibble, G. Guralnik, C. Hagen, F. Englert, R. Brout & P. Higgs:

relativistic Anderson-Higgs mechanism

2010 APS Sakurai Prize
ECSK gravity

- Riemann-Cartan spacetime – metricity $\nabla_\rho g_{\mu\nu} = 0$

$\rightarrow$ connection $\Gamma^\rho_{\mu\nu} = \{\rho_{\mu\nu}\} + C^\rho_{\mu\nu}$

Christoffel symbols \hspace{1cm} contortion tensor

- Lagrangian density for matter $\mathcal{L}$

Metrical energy-momentum tensor \hspace{1cm} Spin tensor

$$T_{ik} = \frac{2}{\sqrt{-g}} \frac{\delta \mathcal{L}}{\delta g^{ik}}$$
$$s^{ijk} = \frac{2}{\sqrt{-g}} \frac{\delta \mathcal{L}}{\delta C_{ijk}}$$

Spin tensor $\neq 0$ for fermions:

$$s^{ijk} = \frac{i}{2} \bar{\psi} \gamma^{[i} \gamma^j \gamma^k] \psi = s^{[ijk]} = -e^{ijkl} s_l$$

Total Lagrangian density $-\frac{R\sqrt{-g}}{2\kappa} + \mathcal{L}$ (like in GR)
ECSK gravity

- Curvature tensor = Riemann tensor + tensor quadratic in torsion + total derivative

- Stationarity of action under $\delta g^\mu\nu \rightarrow$ Einstein equations

$$R^\emptyset_{\mu\nu} - R^\emptyset_{g\mu\nu}/2 = k(T_{\mu\nu} + U_{\mu\nu})$$

$$U_{\mu\nu} = [C_\rho^{\mu\rho} C_\sigma^{\nu\sigma} - C_\rho^{\mu\sigma} C_\sigma^{\nu\rho} - (C_\rho^{\rho\sigma} C_\tau^{\tau\sigma} - C_\sigma^{\sigma\tau} C_\tau^{\tau\sigma})g_{\mu\nu}/2] / k$$

- Stationarity of action under $\delta C^\mu\nu_{\rho} \rightarrow$ Cartan equations

$$S_\rho^\mu_{\mu\nu} - S_\mu^\rho_{\delta^\rho_{\nu}} + S_\nu^\delta^\rho_{\mu} = -k S_{\mu\nu}^\rho / 2$$

$$S_\mu = S^\nu_{\mu\nu}$$

Same coupling constant $k$

- Cartan equations are algebraic and linear
- Contributions to energy-momentum from spin are quadratic
ECSK gravity

- Stationarity of action under metric $\rightarrow$ Einstein equations

\textbf{Curvature} = k \cdot \text{(energy-momentum density)}

- Stationarity of action under torsion $\rightarrow$ Cartan equations

\textbf{Torsion} = k \cdot \text{spin density}

\text{Same coupling constant } k

- Cartan equations are algebraic and \textit{linear}
- Contributions to energy-momentum from spin are \textit{quadratic}

D. W. Sciama, Rev. Mod. Phys. \textbf{36}, 463 (1964)
ECSK gravity

- No spinors -> torsion vanishes -> ECSK reduces to GR

- Torsion significant when $U_{\mu\nu} \sim T_{\mu\nu}$ (at Cartan density)

For fermionic matter (quarks and leptons)

\[ \rho > 10^{45} \text{ kg m}^{-3} \]

Nuclear matter in neutron stars

\[ \rho \sim 10^{17} \text{ kg m}^{-3} \]

Gravitational effects of torsion negligible even for neutron stars

Torsion significant only in very early Universe and in black holes
Spin fluids

- Field equations can be written for full Ricci tensor

\[ R_{\mu\nu} - Rg_{\mu\nu}/2 = \Theta_{\nu\mu} \]

Tetrad energy-momentum tensor

- Bianchi identities \(\rightarrow\) conservation law for energy and momentum & spin \(\rightarrow\) macroscopic fermionic matter is a spin fluid:

\[ s^{\mu\nu\rho} = s^{\mu\nu}u^\rho \quad s^{\mu\nu}u_\nu = 0 \]

\[ \Theta^{\mu\nu} = c\Pi^{\mu}u_\nu - p(g^{\mu\nu} - u^\mu u^\nu) \]

Four-momentum density

Pressure

\[ \epsilon = c\Pi_\mu u^\mu \]

Energy density

\[ s^2 = s^{\mu\nu}s_{\mu\nu}/2 \]


Spin fluids

- Dynamical energy-momentum tensor for a spin fluid with random spin orientation

\[
T^{ij} + U^{ij} = \left( \epsilon - \frac{1}{4} \kappa s^2 \right) u^i u^j - \left( p - \frac{1}{4} \kappa s^2 \right) (g^{ij} - u^i u^j)
\]

**Effective energy density**  **Effective pressure**


- Barotropic fluid

\[
dn/n = d\epsilon/(\epsilon+p)
\]

\[
p = w\epsilon \quad \rightarrow \quad n \propto \epsilon^{1/(1+w)}
\]

**Particle number density**

- Spin fluid of fermions with no spin polarization ->

\[
s^2 \propto \epsilon^{2/(1+w)}
\]

Cosmology with torsion

- A closed, homogeneous and isotropic Universe

Friedman-Lemaitre-Robertson-Walker metric \((k = 1)\)

\[
ds^2 = c^2 dt^2 - \frac{a^2(t)}{(1+kr^2/4)^2} \left( dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right)
\]

Distance from O to its antipodal point A: \(a\pi\)

- Friedman equations for scale factor \(a\)

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

\[
\dot{a}^2 + 2a\ddot{a} + 1 = -\kappa \left( p - \frac{1}{4} \kappa s^2 \right) a^2
\]

Conservation law

\[
\frac{d}{dt} \left( (\epsilon - \kappa s^2 / 4) a^3 \right) + (p - \kappa s^2 / 4) \frac{d}{dt} (a^3) = 0
\]

Cosmology with torsion

• Friedman conservation & \( s^2 \propto \epsilon^2/(1+w) \rightarrow \epsilon \propto a^{-3(1+w)} \)

Spin-torsion contribution to energy density

\[
\epsilon_S = -\frac{1}{4} \kappa s^2 \propto a^{-6}
\]

negative & dominant at small \( a \)

o Independent of \( w \)
o Consistent with the particle conservation \( n \propto a^{-3} \)

“spin fluid = perfect fluid + exotic fluid”  (with \( p = \epsilon = -\kappa s^2/4 < 0 \))

• Very early universe: \( w = 1/3 \) (radiation) \( \epsilon \approx \epsilon_R \sim a^{-4} \)

Total energy density

\[
\epsilon + \epsilon_S = \epsilon R_0 \hat{a}^{-4} + \epsilon S_0 \hat{a}^{-6}
\]

\( \hat{a} = a/a_0 \)
Big bounce from torsion

- Friedman equation

\[ |H| = H_0 \left( \Omega_R \dot{a}^{-4} + \Omega_S \dot{a}^{-6} \right)^{\frac{1}{2}} \]

- Gravitational repulsion from spin & torsion ($\Omega_S < 0$)

No singular big bang, but regular **big bounce!** ($t = 0$)

- Universe starts expanding from minimum radius (when $H = 0$):

\[ \dot{a}_m = \sqrt{-\frac{\Omega_S}{\Omega_R}} \]
Cosmology with torsion

\[ \Omega(\dot{a}) = 1 + \frac{(\Omega - 1)\dot{a}^4}{\Omega_R \dot{a}^2 + \Omega_S} \]

Velocity of antipodal point \[ v_a = \pi c \dot{a} \]

- WMAP parameters of the Universe
\[ \Omega = 1.002 \quad H_0^{-1} = 4.4 \times 10^{17} \text{ s} \quad \Omega_R = 8.8 \times 10^{-5} \]
\[ \rightarrow a_0 = 2.9 \times 10^{27} \text{ m} \]

- Background neutrinos – most abundant fermions in the Universe
\[ n = 5.6 \times 10^7 \text{ m}^{-3} \text{ for each type} \]

- \[ \Omega_S = -8.6 \times 10^{-70} \text{ (negative, extremely small in magnitude)} \]
Cosmology with torsion

GR

$\Omega_S = 0$ and $a_m = 0$

$\Omega(\hat{a}) - 1 = (\Omega - 1)\hat{a}^2 / \Omega_R$

$\Omega \sim 1$ today $\rightarrow \Omega(\hat{a})$ at GUT epoch
must be tuned to 1 to a precision of $> 52$ decimal places

Flatness & horizon problems in big-bang cosmology

Solved by cosmic inflation – consistent with cosmic perturbations

Problems:
- Initial (big-bang) singularity unresolved
- Why $\Omega \sim 1$ before inflation?
- What ends inflation?
Cosmology with torsion

ECSK

$\Omega_S < 0$ and $a_m > 0$

\[
\Omega(\sqrt{2}\hat{a}_m) = 1 - \frac{4\Omega_S(\Omega - 1)}{\Omega_R^2}
\]

$\hat{a}_m = 3.1 \times 10^{-33}$, $a_m = 9 \times 10^{-6}$ m

\[
\Omega(\sqrt{2}\hat{a}_m) = 1 + 8.9 \times 10^{-64}
\]

Appears tuned to 1 to a precision of $\sim 63$ decimal places!

No flatness problem – advantages:
- Nonsingular bounce instead of initial singularity
- No new matter fields, additional assumptions, or free parameters
- Smooth transition: torsion epoch $\to$ radiation epoch
(torsion becomes negligible)

$\Omega(\hat{a}) - 1$

Minimum

\[
t = -\frac{\Omega_S}{\Omega_R^{3/2}H_0}f(\sqrt{2}) = 5.3 \times 10^{-46} \text{ s}
\]

Cosmology with torsion

ECSK

$\Omega_S < 0$ and $a_m > 0$

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

- Closed Universe causally connected at $t < 0$ remains causally connected through $t = 0$ until $v_a = c$
- Universe contains $N \sim (v_a/c)^3$ causally disconnected volumes
- $\Omega_S \sim -10^{-69}$ produces $N \approx 10^{96}$ from a single causally connected region – torsion solves horizon problem

Cosmology with torsion


Cosmology with torsion: An alternative to cosmic inflation

Nikodem J. Popławski

We propose a simple scenario which explains why our Universe appears spatially flat, homogeneous and isotropic. We use the Einstein–Cartan–Kibble–Sciama (ECKS) theory of gravity which naturally extends general relativity to include the spin of matter. The torsion of spacetime generates gravitational repulsion in the early Universe filled with quarks and leptons, preventing the cosmological singularity: the Universe expands from a state of 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, \( \Omega_5 \approx -10^{-69} \). Thus the ECKS gravity provides a compelling alternative to speculative mechanisms of standard cosmic inflation. This scenario also suggests that the contraction of our Universe preceding the bounce at the minimum radius may correspond to the dynamics of matter inside a collapsing black hole existing in another universe, which could explain the origin of the Big Bang.
Black holes with torsion

Q: Where does the mass of the Universe come from?
• Possible solution: **stiff equation of state** \( p = \varepsilon \)

• Strong interaction of nucleon gas
→ **ultradense matter has stiff EoS**


• Stiff matter – possible content of early Universe

J. D. Barrow, Nature **272**, 211 (1977)
Black holes with torsion

• Collapse of BH – truncated, closed FLRW metric

• Neutron-star mass measurements, X-ray emission from NS -> NS (and thus BH?) composed of matter with stiff EoS

• Friedman conservation law -> mass of collapsing BH increases (external observers do not see it)

• Occurs via quantum pair production in strong anisotropic fields

• Total energy (matter + gravity) remains constant
Black holes with torsion

- Friedman equations

\[ \dot{a}^2 + k = \frac{1}{3} \kappa \left( \epsilon - \frac{1}{4} \kappa s^2 \right) a^2 + \frac{1}{3} \Lambda a^2, \]
\[ s^2 = \frac{1}{8} (\hbar cn)^2 \]
\[ \frac{d}{dt} \left( (\epsilon - \kappa s^2 / 4) a^3 \right) + (p - \kappa s^2 / 4) \frac{d}{dt} (a^3) = 0 \]

- \( \Lambda \) negligible, initially \( s^2 \) negligible

As \( a \) decreases, \( k \) becomes less significant

- Stiff matter

\[ \epsilon \propto a^{-6} \rightarrow E \propto a^{-3} \rightarrow m \propto a^{-3} \rightarrow N \propto a^{-3} \rightarrow n \propto a^{-6} \]
\[ \rightarrow s^2 \propto a^{-12} \]

\[ \dot{a}^2 + k = \frac{1}{3} \kappa \epsilon_0 \frac{a_0^6}{a^4} - \frac{1}{96} (\hbar c \kappa)^2 n_0^2 \frac{a_0^{12}}{a^{10}} \]
Black holes with torsion

\[ \dot{a}^2 + k = \frac{1}{3} \kappa \epsilon_0 \frac{a_0^6}{a^4} - \frac{1}{96} (\hbar \kappa)^2 n_0^2 \frac{a_0^{12}}{a^{10}} \]

\[ \dot{a} = 0 \rightarrow 2 \text{ solutions for } a: \]

\[ a_0 = r_g = \frac{2GM}{c^2} \]

\[ a_{\text{min}} = \left( \frac{27}{128} \right)^{1/6} \frac{2G\tilde{M}}{c^2} \]

\[ \tilde{M} = \left( \frac{m_{\text{P1}}^2 M^2}{m_n^2} \right)^{1/3} \]

At bounce

\[ m_{\text{max}} = \left( \frac{a_0}{a_{\text{min}}} \right)^3 \tilde{M} \]

\[ m_{\text{max}} = \left( \frac{27}{128} \right)^{-1/2} M_* \]

\[ M_* = \frac{M^2 m_n}{m_{\text{P1}}^2} \]

Mass density \( \approx \) Cartan density (NR)

Mass of BH

\[ \epsilon_0 = \frac{Mc^2}{4\pi r_g^3/3} \]

Mass of neutron

\[ n_0 = \frac{3M}{4\pi m_n^3/3} \]

NJP, arXiv:1103.4192

must be refined
Black holes with torsion

The pairs produced via Parker-Zel’dovich-Starobinskii process annihilate to radiation

Stiff matter becomes a radiation fluid

Fermion number density decreases, gravitational repulsion weakens

Gravitational collapse proceeds further with $\epsilon \propto a^{-4}$ & $m \propto a^{-1}$ until the Planck energy

Scale factor at the bounce $\frac{2G}{c^2} \left( M_{BH}^{2/3} m_{Pl}^{1/6} m_n^{1/6} \right)$

Mass of the universe at the bounce $M_{BH}^2 m_{Pl}^{-3/2} m_n^{1/2}$

NJP, arXiv:1105.6127
Black holes with torsion

• After the bounce, the universe in BH expands
Torsion becomes negligible, $k = 1$ becomes significant
Expansion = time reversal of contraction?
Universe reaches $a_0$ and contracts $\rightarrow$ cyclic universe
(between $a_{\text{min}}$ and $a_0$)

• Pair production isotropizes the universe and ends
• Fermionic matter may be dominated by heavy, NR particles

$\rightarrow$ Expansion of Universe $\neq$ time reversal of contraction
$\rightarrow$ Mass of Universe should not dilute during expansion

Work in progress
Black holes with torsion

• Spin-torsion coupling replaces the singular big bang by a nonsingular big bounce.

• This coupling may also avoid the formation of singularities in black holes. The collapsing matter reaches a state of finite, extremely high density, and undergoes a bounce.

• Such a bounce may form a new, closed universe on the other side of the event horizon of every black hole. Our Universe may have been born in a black hole existing in another universe.

• This idea is not new (Novikov 1966, Pathria 1972, Smolin 1992). Torsion provides the most natural theoretical foundation for it.

Universe in a black hole

• Universe forming and growing on the other side of the event horizon of a black hole is **closed**: finite but without boundaries. It is a 3-dimensional analogue of the 2-dimensional surface of a sphere.

• Extremely strong gravitational forces near the bounce cause an intense particle-antiparticle production, increasing the mass in the new universe by many orders of magnitude. The energy of the universe remains constant (mass and motion – positive, gravity – negative).

• Solving the dynamics of the collapse, bounce and expansion on the other side of the event horizon will require computational mathematics of PDEs. It could be an engaging **undergraduate project**.
Black holes with torsion

\[ \dot{a}^2 + k = \frac{b}{a} + \frac{1}{3} \Lambda a^2 \]

\[ b = \frac{2Gm_{\text{max}}}{c^2} \]

\[ \Lambda_c = \frac{4}{(9b^2)} \]

Expansion to infinity if:

\[ m_{\text{max}} > m_c = \frac{c^2}{3G\sqrt{\Lambda}} \]

Oscillations otherwise (or until then).

Cosmological models with \( k = 1, \Lambda \neq 0 \).
Black holes are wormholes

- A new universe in a BH invisible for observers outside the BH (EH formation and all subsequent processes occur after $\infty$ time).

- As the universe in a BH expands to infinity, the BH boundary becomes an **Einstein-Rosen bridge** connecting this (child) universe with the outer (parent) universe.

Parent universe appears for its child as the only white hole.

Black holes with torsion

Mathematical realizations of spherically symmetric, vacuum solutions of GR (& ECSK):

• **Schwarzschild black hole**
  Final stage of collapse of most massive stars in GR (singular).

• **Schwarzschild white hole**
  Cannot form physically (singular).

• **Einstein-Rosen bridge (wormhole)**
  Final stage of collapse of most massive stars in ECSK (regular).

GR & ECSK favor different mathematical solutions.
Arrow of time

• Why does time flow only in one direction?

• Laws of ECKS gravity (and GR) are time-symmetric.

• Boundary conditions of a universe in a BH are time-asymmetric: motion of matter through event horizon is **unidirectional** → defines arrow of time.

• Information is not lost: goes to a universe on the other side of EH.

How to test that every black hole contains a hidden universe?

To boldly go where no one has gone before
Cosmological perturbations

- Structure formation is seeded by density perturbations in the very early Universe.

- The observed nearly scale-invariant spectrum of density perturbations in CMB may be produced by thermal fluctuations during the contracting phase in a black hole (before the bounce).

- The formalism including the metric and torsion perturbations must be used. Calculations will require the knowledge of the dynamics of particle-antiparticle production.

Work in progress.
Preferred direction

- Stars rotate $\rightarrow$ Kerr black holes $\rightarrow$ rotating wormholes.
- A universe on the other side of a rotating wormhole inherits its preferred direction. Our Universe should have a preferred axis.

Another engaging undergraduate project.

Observational evidence for such an axis:

1) Large-scale bulk flows of X-ray luminous clusters of galaxies (dark flow).
2) Dipole asymmetry in the handedness of spiral galaxies.
3) Preferred direction in the CMB temperature inhomogeneities, recently reported by the Planck satellite.
Preferred direction

A preferred axis may be the source of preferred-frame parameters of the Standard Model Extension.

Possible experimental evidence for such parameters:

1) Neutrino oscillation signals inconsistent with the standard 3-neutrino massive model.
2) Matter-antimatter asymmetry in neutral-meson oscillations.

Anomalies in particle physics may thus be related to torsion.
Summary and research directions

• Quantum-mechanical, intrinsic spin equips spacetime with torsion.

• The simplest theory of gravity with torsion (Einstein-Cartan-Sciama-Kibble) avoids singularities which are the biggest problem in general relativity.

• Black holes are actually wormholes to new, growing, closed universes. The big bang was a bounce inside a black hole.

• Torsion may explain several major problems in cosmology and particle physics. Studying torsion may lead to breakthroughs.

• Future research:
Can torsion explain dark matter and dark energy?