Nonsingular Big-Bounce Cosmology without Inflation from Torsion

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218th Meeting of American Astronomical Society, Boston, MA

24 May 2011

What is Torsion?

- Differentiation of tensors in 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
$R^{\rho}{}_{\sigma\mu\nu} = \partial_{\mu}\Gamma^{\rho}{}_{\sigma\nu} - \partial_{\nu}\Gamma^{\rho}{}_{\sigma\mu} + \Gamma^{\rho}{}_{\tau\mu}\Gamma^{\tau}{}_{\sigma\nu} - \Gamma^{\rho}{}_{\tau\nu}\Gamma^{\tau}{}_{\sigma\mu}$

- **Torsion tensor** – antisymmetric part of affine connection
(Cartan – 1921)

$$S^{k}{}_{ij} = \Gamma^{\;k}_{[i\,j]}$$

arXiv.org > gr-qc > arXiv:0911.0334

Einstein-Cartan-Sciama-Kibble gravity

Special Relativity - no curvature & no torsion
Dynamical variables: matter fields

$g_{ik} = \eta_{ik}$ $\qquad$ $S^k{}_{ij} = 0$

More degrees of freedom

General Relativity - no torsion
Dynamical variables: matter fields + metric tensor g_{ik}

$S^k{}_{ij} = 0$

ECSK Gravity (same Lagrangian as GR, simplest theory with torsion)
Dynamical variables: matter fields + metric g_{ik} + torsion $S^k{}_{ij}$

Why ECSK gravity?

❖ Takes into account intrinsic angular momentum (spin)
(Sciama; Kibble – 1961)

❖ Avoids curvature singularities from fermionic matter
(Kopczyński; Trautman; Hehl, von der Heyde & Kerlick; Kuchowicz)

❖ Generates effective four-fermion interaction for Dirac fields
(Kibble; Hehl & Datta)
-> self-regulation of UV behavior of fermions in QFT? (van der Merve)

❖ No free parameters

❖ Different from GR only at densities > 10^{45} g/cm^3
-> ECSK passes all tests of GR

Big-bounce cosmology

- Origin of Universe?
- Nature of black-hole interiors?

Torsion combines both problems

NJP, Phys. Lett. B **694**, 181 (2010)

Torsion in ECSK gravity averts big-bang singularity and singularities in black holes via **gravitational repulsion at high densities**

⬇

Big bounce instead of big bang
(Kuchowicz; Gasperini)

Loop quantum gravity -> big bounce too

Universe in a black hole

Our Universe was contracting before bounce – from what?

Idea: **every black hole produces a nonsingular, closed universe**

Our Universe born in a black hole existing in another universe
(Pathria; Frolov, Markov & Mukhanov; Smolin; Stuckey)

- Can explain the arrow of time
- Torsion provides a simple and natural mechanism for this scenario -> Einstein-Rosen bridges connect universes
  NJP, Phys. Lett. B **694**, 181 (2010)

Spin fluids

- Macroscopic matter with spin -> spin fluid

(Nomura, Shirafuji & Hayashi)

- Dynamical energy-momentum tensor for unpolarized spins

$$T^{ij} + U^{ij} = \underbrace{\boxed{\left(\epsilon - \frac{1}{4}\kappa s^2\right)}}_{\textbf{Energy density}} u^i u^j - \underbrace{\boxed{\left(p - \frac{1}{4}\kappa s^2\right)}}_{\textbf{Pressure}} (g^{ij} - u^i u^j)$$

(Hehl et al.)

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

(Nurgaliev & Ponomariev; Gasperini)

Closed universe with torsion

Spin-torsion contribution to energy density

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

$$\hat{a} = a/a_0$$

negative & dominant at small *a*

gravitational repulsion

Friedman equations -> Universe begins to expand from nonsingular state (bounce)

$$\hat{a}_m = \sqrt{-\frac{\Omega_S}{\Omega_R}}$$

$\mathbf{\Omega_S = -8.6 \times 10^{-70}}$ (negative, extremely small in magnitude)

Cosmology with torsion

Density parameter

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

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

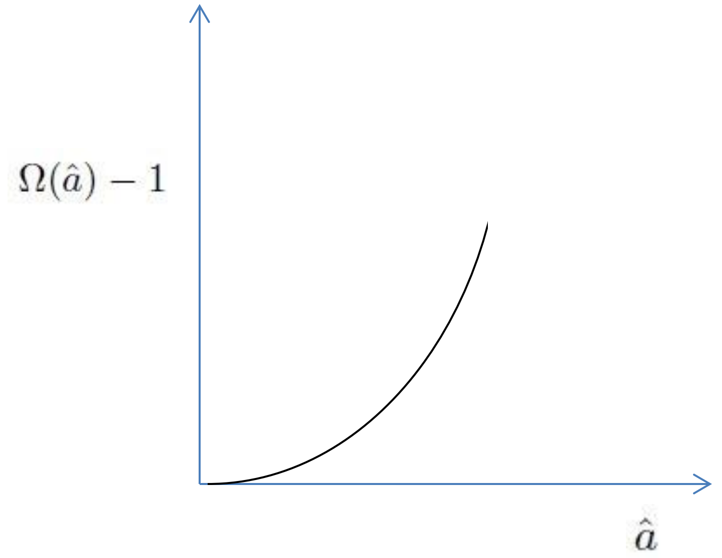
Velocity of antipode

$$v_a = \pi c \dot{a}$$

Standard cosmology

GR

Ω_S = 0 and a_m = 0



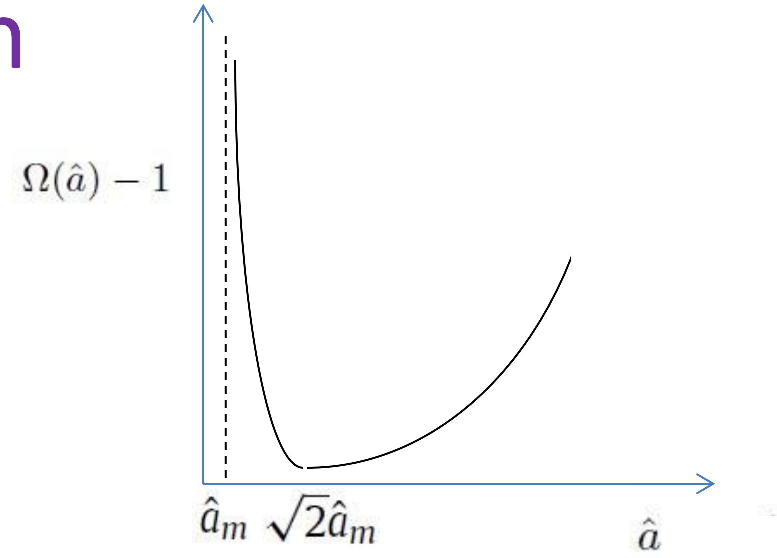
$\Omega \sim$ 1 today -> $\Omega(a)$ at GUT
must be tuned to 1 to a precision of > 52 decimal places

Solved by cosmic inflation – consistent with cosmic perturbations

Problems:

- Initial (big-bang) singularity
- Needs additional (scalar) fields, specific forms of potential (to stop inflation), free parameters
- Why $\Omega \sim$ 1 before inflation?

Cosmology with torsion



ECSK

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

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

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

NJP, Phys. Lett. **B** 694, 181 (2010)

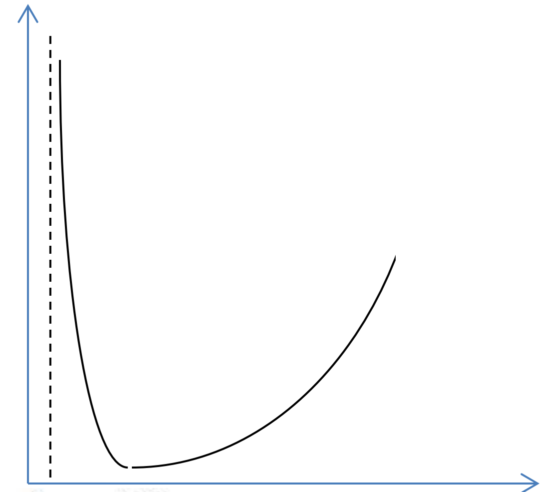
$$\boxed{\Omega(\sqrt{2}\hat{a}_m) = 1 + 8.9 \times 10^{-64}}$$

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

No flatness problem – advantages:

- Nonsingular bounce instead of initial singularity
- No additional fields & free parameters, values seem right
- Radiation epoch begins when torsion becomes negligible

Cosmology with torsion



ECSK

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

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

- 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
- $\mathbf{\Omega_S \sim -10^{-69}}$ produces $N \approx 10^{96}$ from a single causally connected region – torsion solves horizon problem
- Simpler than other bounce cosmologies that solve both problems

Black holes with torsion

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

(Zel'dovich; Walecka; Canuto)

- Stiff matter – possible content of early Universe

(Zel'dovich; Lin, Carr & Fall; Barrow)

- Stiff matter composes neutron stars

(Demorest et al.)

-> Expected in BH

Black holes with torsion

- Collapse of BH – truncated, closed FLRW metric
- Friedman conservation law -> mass of collapsing BH increases (external observers do not see it)
- Mass increase may be realized by intense particle production in strong fields

(Parker; Zel'dovich)

- Total energy (matter + gravity) remains constant

(Cooperstock & Israelit)

Cosmological perturbations

- Observed scale-invariant spectrum of cosmological perturbations produced by thermal fluctuations in a collapsing BH if

$$w_r = (w - 1)/4$$

Background

(Brandenberger et al.)

- Stiff matter w = 1 -> $w_r = 0$ (initially NR gas of fluctuating particles)

Work in progress

Black holes with torsion

Friedman equations

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

$$M = 10\, M_\odot$$

$$\boxed{m_{\max} \approx \frac{M^2 m_n}{m_{\mathrm{Pl}}^2}}$$

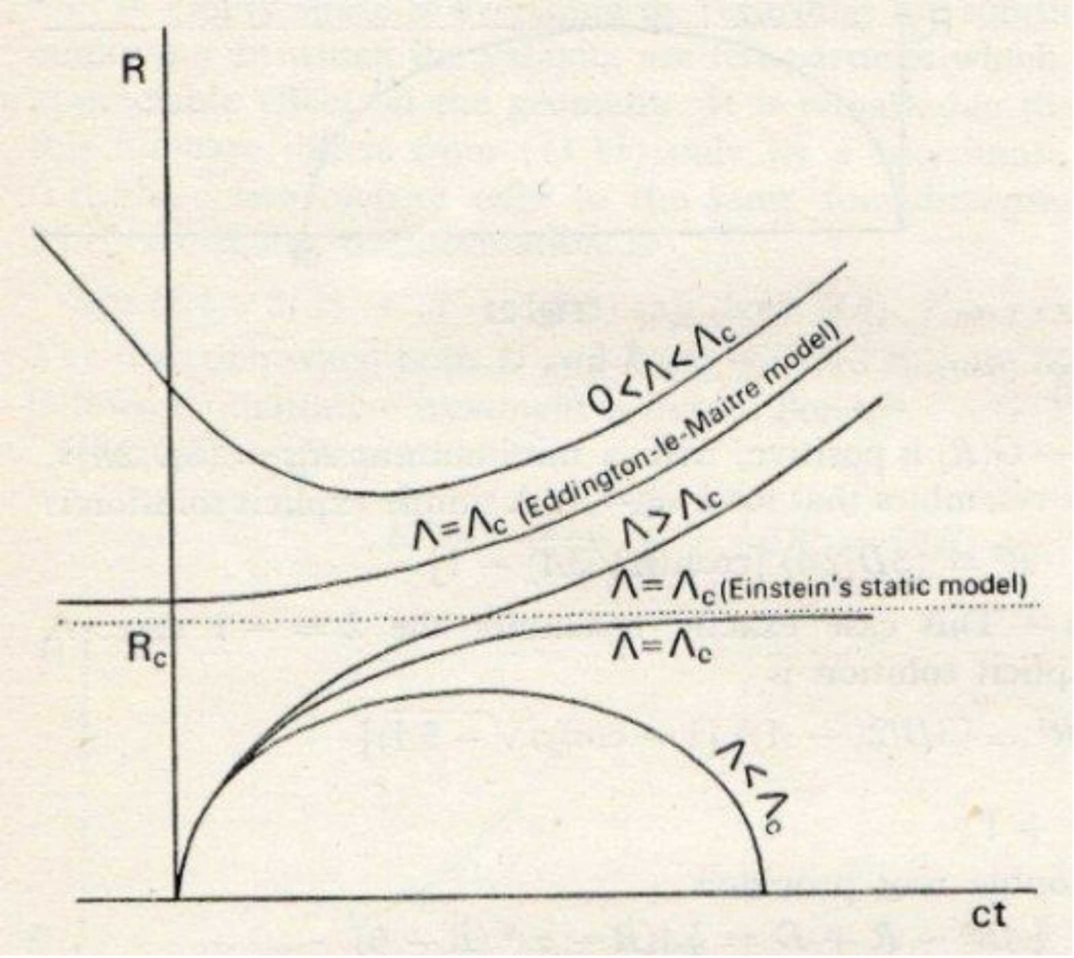
$$a_{\min} \approx 6 \times 10^{-3}\,\mathrm{m}$$

$$m_{\max} \approx 3.1 \times 10^{51}\,\mathrm{kg}$$

NJP, arXiv:1103.4192

- Mass of the Universe at the bounce
- This mass should not dilute -> due to four-fermion interaction?

Universe with cosmological constant



Cosmological models with k = 1, $\Lambda \neq 0$

E. A. Lord, *Tensors, Relativity and Cosmology*

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

$$b = \frac{2Gm_{\max}}{c^2}$$

Expansion to infinity if

$$m_{\max} > m_{\mathrm{c}} = \frac{c^2}{3G\sqrt{\Lambda}}$$

Possible oscillations until sufficient mass is generated

Black holes with torsion

$$\Lambda \approx 1.4 \times 10^{-52}\,\mathrm{m}^{-2}$$

$$M_c \approx 35\, M_\odot$$

(Binary IC 10 X-1 – 24-33 $M_\odot$)

Mass of our Universe $1.4 \times 10^{26}\, M_\odot$

Mass of our parent BH

$$\boxed{M \approx 3 \times 10^{3}\, M_\odot > M_c}$$

Why ECSK gravity?

- Not only avoids singularities but also solves flatness and horizon problems without inflation

- Torsion-induced four-fermion interaction may explain a small, positive cosmological constant

NJP, Annalen Phys. **523**, 291 (2011)

$$\Lambda = \frac{3\kappa^2}{16}(\bar{\psi}\gamma_j\gamma^5\psi)(\bar{\psi}\gamma^j\gamma^5\psi)$$

Condensing quarks -> $\langle 0|\rho_\Lambda|0\rangle = \frac{\kappa}{3}(\langle 0|\bar{\psi}\psi|0\rangle)^2$

$\rho_\Lambda \sim m^6/m_{\mathrm{Pl}}^2$

(Zel'dovich)

Energy scale only 8 times larger than observed

- Classical Dirac equation with this interaction is asymmetric under charge conjugation -> matter-antimatter asymmetry?

NJP, Phys. Rev. D **83**, 084033 (2011)