Trends in Theoretical Cosmology

The search for a gravitational solution of the Dark Matter and Dark Energy problem

Dirk Puetzfeld
(Iowa State University)

GNP Seminar, Iowa State University, Ames
November (2004)
Outline

- Broad brushed history of the universe
- Observational situation
- Theoretical landscape
- Why non-Riemannian gravity?
- Short history of non-Riemannian cosmology
- Conclusions & Outlook
History of the universe
interpreted within the cosmological standard model...
Parameter constraints within the standard model

Tegmark et al. (2004)
Dark energy equation of state

Tegmark et al. (2004)
What now?

Cosmologists are characterized by the following virtues:

- By her/his will to destruction
- By re-evaluating or destroying old ideals
- By overcoming nihilism GR (maybe)

(almost) Nietzsche (1885)
Some names...

- **Scalar fields / Quintessence**
  - Ratra & Peebles 1988, Wetterich 1988

- **Time varying cosmological constant**
  - Oezer & Taha 1987, Vishwakarma 2001

- **K-essence**

- **Phantom energy**
  - Caldwell 2002

- **Chaplygin gas**

- **Cardassian expansion**

- **Brane world models**
  - Randall & Sundrum 1999, Deffayet et al. 1999

- **NGT / Bimetric**
Some models...

- Brane world models
- Scalar tensor theories
- Non-symmetric models
- Bimetric models
- Topological models
- $f(R)$ models
- AdS/CFT inspired models
- Ad hoc add-on's
- Non-Riemannian models
Why go beyond Riemannian gravity?

- Curved spacetime (GR) ~ dynamics of masspoints and light
- Intrinsic properties of particles suggest couplings to new fields
- Simple analogy:

  1905 \quad \text{flat spacetime (SR)}

  1916 \quad \text{curved spacetime (GR)}

why not more complex?
Why cosmology?

- Local tests in rather good compliance with GR (maybe not on very small scales)

- New effects likely to show up on large scales and/or high energies

- Observations force us to introduce concepts like dark matter and dark energy within the standard cosmological model

- So far no direct detection of a dark matter particle

- So far no convincing theoretical explanation for the dark energy component
Why non-Riemannian gravity?

- Elementary particles may be classified by the Poincaré group by their mass and spin.
- Mass connected with the translational part of the Poincaré group.
- Spin connected with the rotational part of the Poincaré group.
- Mass and spin are elementary notions, each with an analogous standing not reducible to that of the other.
- Distributing mass-energy and spin over space-time leads to the field theoretical notions of an energy-momentum tensor and spin angular momentum tensor of matter.
- In macrophysical limit, mass or energy-momentum adds up because of its monopole character.
- Intrinsic spin has dipole character and usually averages out in the macroscopic limit (this is one of the reasons why GR is successful on macroscopic scales).
- In analogy to the coupling of the energy-momentum to the metric one expects that also spin angular momentum couples to a new quality which is linked to the geometry of spacetime.

Riemann-Cartan spacetime
The general MAG connection

\[ \Gamma_{\alpha\beta} = \tilde{\Gamma}_{\alpha\beta} + N_{\alpha\beta} = \]

\[ \frac{1}{2} dg_{\alpha\beta} + (e_{[\alpha}dg_{\beta]}) \varpi^\gamma + e_{[\alpha}[C_{\beta}] - \frac{1}{2} (e_{[\alpha}e_{\beta]}C_{\gamma}) \varpi^\gamma \]

\[ \text{Levi–Civita connection} \]

\[ -e_{[\alpha}[T_{\beta]} + \frac{1}{2} (e_{[\alpha}e_{\beta]}T_{\gamma}) \varpi^\gamma + \frac{1}{2} Q_{\alpha\beta} + (e_{[\alpha}Q_{\beta]}^\gamma) \varpi^\gamma \]

\[ \text{Distortion} \]
Spacetime types

Metric-affine

\[ Q_{\alpha\beta} - tr(Q_{\alpha\beta}) = 0 \]

Weyl-Cartan

\[ T^\alpha = 0 \]

\[ Q_{\alpha\beta} = 0 \]

Weyl

\[ Q_{\alpha\beta} = 0 \]

Riemann-Cartan

\[ T^\alpha = 0 \]

Riemann
Analogy with elasticity theory and theory of defects

In some cases torsion can be interpreted as the surface density of the Burgers vector, i.e. it is proportional to the dislocation density of an elastic medium.

$$b^i \sim \int \int dx^k \wedge dx^l T^i$$

Kröner 1958, Hehl 1967
### Metric-affine gravity (MAG)

<table>
<thead>
<tr>
<th>Potentials</th>
<th>Field strengths</th>
<th>Gauge currents</th>
<th>Excitations</th>
<th>Matter currents</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{\alpha \beta}$</td>
<td>$Q_{\alpha \beta}$</td>
<td>$m^{\alpha \beta}$</td>
<td>$M^{\alpha \beta}$</td>
<td>$\sigma^{\alpha \beta}$</td>
</tr>
<tr>
<td>$\varphi^\alpha$</td>
<td>$T^\alpha$</td>
<td>$E^\alpha$</td>
<td>$H_\alpha$</td>
<td>$\Sigma_\alpha$</td>
</tr>
<tr>
<td>$\Gamma^\alpha_{\beta \gamma}$</td>
<td>$R^\alpha_{\beta}$</td>
<td>$E^\alpha_{\beta}$</td>
<td>$H^\alpha_{\beta}$</td>
<td>$\Delta^\alpha_{\beta}$</td>
</tr>
</tbody>
</table>

\[
L = V_{\text{MAG}}(g_{\alpha \beta}, \varphi^\alpha, Q_{\alpha \beta}, T^\alpha, R^\alpha_{\beta}) + L_{\text{mat}}(g_{\alpha \beta}, \varphi^\alpha, \psi, D\psi)
\]
Field equations

\[ \frac{\delta L_{\text{mat}}}{\delta \psi} = 0 \]

0. \quad \delta M^{\alpha \beta} - m^{\alpha \beta} = \sigma^{\alpha \beta}

I. \quad D H_\alpha - E_\alpha = \Sigma_\alpha

II. \quad D H^{\alpha}_{\beta} - E^{\alpha}_{\beta} = \Delta^{\alpha}_{\beta}
The general MAG Lagrangian

\[ V_{\text{MAG}} = \frac{1}{2\kappa} \left[ -\sigma_0 R^{\alpha\beta} \wedge \eta_{\alpha\beta} - 2\lambda \eta + I^\alpha \wedge * \left( \sum_{l=1}^{3} a_l (I) I'_\alpha \right) \right] \]

\[ + Q_{\alpha\beta} \wedge * \left( \sum_{l=1}^{4} b_l (I) Q^{\alpha\beta} \right) \]

\[ + b_5 \left( Q_{\alpha\gamma} \wedge \vartheta^\alpha \right) \wedge * \left( Q_{\beta\gamma} \wedge \vartheta_\beta \right) \]

\[ + 2 \left( \sum_{l=2}^{4} c_l (I) Q_{\alpha\beta} \right) \wedge \vartheta^\alpha \wedge * \vartheta^\beta \]

\[ - \frac{1}{2\rho} R^{\alpha\beta} \wedge * \left[ \sum_{l=1}^{6} w_I (I) W_{\alpha\beta} + \sum_{l=1}^{5} z_I (I) Z_{\alpha\beta} + w_7 \vartheta_\alpha \wedge \left( e_\gamma \right) (5) W^{\gamma\beta} \right] \]

\[ + z_6 \vartheta_\gamma \wedge \left( e_\alpha \right) (2) Z^{\gamma\beta} + \sum_{l=7}^{9} z_l \vartheta_\alpha \wedge \left( e_\gamma \right) (1-4) Z^{\gamma\beta} \]

Hehl et al. 1999
**Timeline NRC models 1972-1985**

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>Kopczynski, Tafel</td>
</tr>
<tr>
<td>1973</td>
<td>Kerlick, Kopczynski, Trautman</td>
</tr>
<tr>
<td>1974</td>
<td>Kerlick</td>
</tr>
<tr>
<td>1975</td>
<td>Raychaudhuri, Hehl et al.</td>
</tr>
<tr>
<td>1976</td>
<td>Kerlick</td>
</tr>
<tr>
<td>1979</td>
<td>Kunststatter et al.</td>
</tr>
<tr>
<td>1980</td>
<td>Minkevich</td>
</tr>
<tr>
<td>1981</td>
<td>Tsamparlis</td>
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<tr>
<td>1983</td>
<td>Minkevich</td>
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<tr>
<td>1984</td>
<td>Canale</td>
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<tr>
<td>1985</td>
<td>Smalley</td>
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</tbody>
</table>

- **Field equations & exact solutions for EC scenarios**
- **Singularity avoidance**
- **Bouncing behavior investigated**
- **Class of solutions for PGT Lagrangian**
Timeline NRC models
1986-1999

Systematic study of Weyssenhoff fluid models
- Gasperini
- Minkowski
- Demianski et al.
- Obukhov et al.
- de Ritis et al.
- Fennelly et al.
- Kao
- Assad et al.
- Obukhov
- Garecki
- Chatterjee
- Tresguerres

1986
1987
1988
1990
1993

First Weyl & WC scenarios
- Savaria
- Maroto et al.
- Moffat
- Minkevich et al.
- de Oliveira et al.
- Gasperini
- Tucker et al.
- Garcia de Andrade
- Palle
- Brüggen
- Capozziello et al.

Hyperfluid approach
- Poberii
- Wolf
- Obukhov et al.
- Tucker et al.
- Minkevich et al.

1994
1995
1997
1998
1999

Nonmetricity driven inflation
First model within metric-affine gravity
Timeline NRC models 2001-2004

Models enter quantitative regime

First SNIa parameter estimates in WC model

NGT model

Puetzfeld et al.
Shapiro
Moffat
Puetzfeld
Capoziello

Extended WC model

Minkevich
Puetzfeld
Shapiro
Moffat
Capoziello
Puetzfeld et al.

Böhmer
Minkevich
Vereshchagin
Babourova et al.
Capoziello et al.

Scholz
Moffat
Miritzis
Puetzfeld et al.

2001 2002 2003 2004
Conclusion

- NRC models offer a very well motivated framework for cosmology

- So-far we have viable models which passed many of the cosmological tests (BBN, CMB*, SNIa, FRIIB, X-ray clusters)

- It possible to falsify these models! (Not necessarily true for DM paradigm)

- So-far no solution of the DM and DE problem
Challenge

- Find model which **removes** the need for any kind of DM and DE completely. Within the NRC framework such a model would provide an elegant geometric description of our spacetime.

- The model must pass **all** cosmological tests!