Repulsive gravity model for dark energy

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

Foundational Aspects of Cosmology
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Outline

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The ΛCDM model of cosmology

- 4.6% visible matter.

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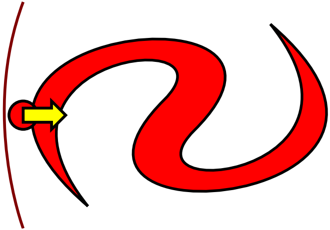

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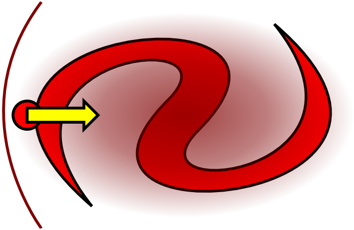

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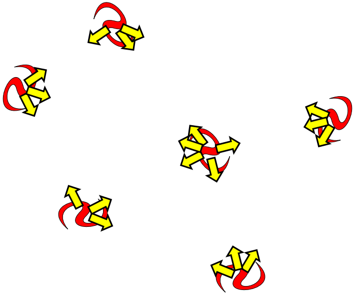

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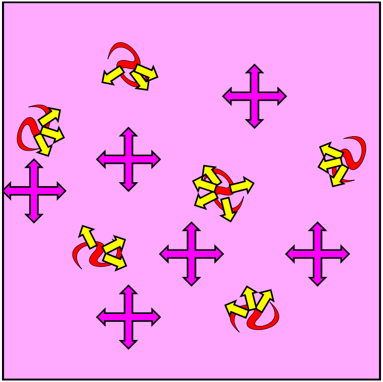

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$\Rightarrow$ Problem: What are dark matter and dark energy?

Explanations for the dark universe

- Particle physics:
  - Dark matter: [Bertone, Hooper, Silk '05]
    - Weakly interacting massive particles (WIMPs). [Ellis *et al.* '84]
    - Axions. [Preskill, Wise, Wilczek '83]
    - Massive compact halo objects (MACHOs). [Paczynski '86]
  - Dark energy: [Copeland, Sami, Tsujikawa '06]
    - Quintessence. [Peebles, Ratra '88]
    - K-essense. [Chiba, Okabe, Yamaguchi '00; Armendariz-Picon, Mukhanov, Steinhardt '01]
    - Chaplygin gas. [Kamenshchik, Moschella, Pasquier '01]
- Gravity:
  - Modified Newtonian dynamics (MOND). [Milgrom '83]
  - Tensor-vector-scalar theories. [Bekenstein '04]
  - Curvature corrections. [Schuller, Wohlfarth '05; Sotiriou, Faraoni '05]
  - Dvali-Gabadadze-Porrati (DGP) model. [Dvali, Gabadadze, Porrati '00, Lue '06]
  - Non-symmetric gravity. [Moffat '95]
  - Area metric gravity. [Punzi, Schuller, Wohlfarth '07]

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  - New idea: repulsive gravity $\Leftrightarrow$ negative mass!

Mass in Newtonian gravity

- Three types of mass! [Bondi '57]
  - Active gravitational mass m_a - source of gravity: $\phi = -G_N \frac{m_a}{r}$.
  - Passive gravitational mass m_p - reaction on gravity: $\vec{F} = -m_p \vec{\nabla} \phi$.
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- Convention: unit ratios and signs such that $m_a = m_p = m_i > 0$.
- Observations exist for visible matter only.

Dark universe from negative mass

- Idea for dark universe: standard model with $m_a = m_p = -m_i < 0$.
- Both copies couple only through gravity $\Rightarrow$ “dark”.

$\Rightarrow$ Preserves momentum conservation.

$\Rightarrow$ Breaks weak equivalence principle only for cross-interaction.

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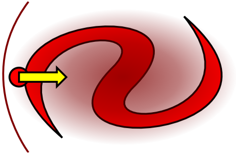

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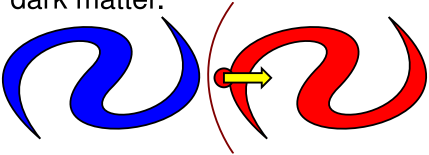

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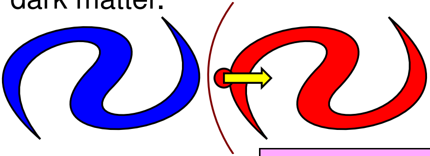

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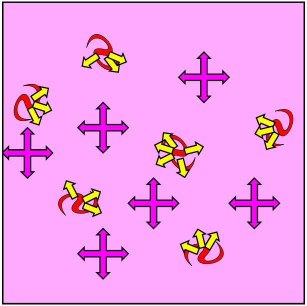

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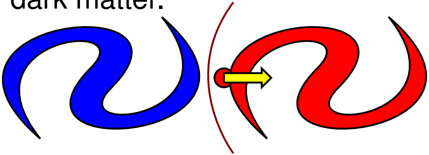

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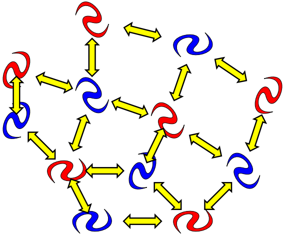

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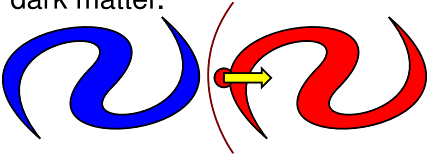
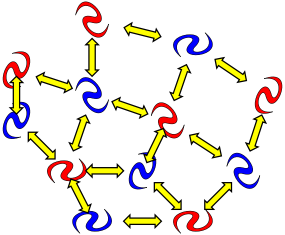


- Explanation of dark energy.

$\Rightarrow$ Advantage: Dark copy Ψ^- of well-known standard model Ψ^+:
  - No new parameters.
  - No unknown masses.
  - No unknown couplings.



Repulsive Einstein gravity

- Positive and negative test masses follow different trajectories.
- Two types of test mass trajectories $\Rightarrow$ two types of observers.
- Observer trajectories are autoparallels of two connections $\nabla^{\pm}$.
- Observers attach parallely transported frames to their curves.
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- Frames are orthonormalized using two metric tensors $g^{\pm}_{ab}$.
- No-go theorem forbids bimetric repulsive gravity. [MH, M. Wohlfarth '09]
- Solution: $N \geq 3$ metrics g^{I}_{ab} and standard model copies Ψ^{I}.

Outline

Construction principles

1. $N \geq 3$ copies of standard model matter Ψ^I, $I = 1, \ldots, N$.
2. N metric tensors g^I_{ab}.
3. Each standard model copy Ψ^I couples only to its metric g^I.

$$\Rightarrow \quad S_M[g^I, \Psi^I] = \int d^4x \sqrt{g^I} \mathcal{L}_M[g^I, \Psi^I]\,.$$

4. Different sectors couple only gravitationally.

$$\Rightarrow \quad S = S_G[g^1, \ldots, g^N] + \sum_{I=1}^{N} S_M[g^I, \Psi^I]\,.$$

5. Field equations contain at most second derivatives of the metrics.
6. Symmetric with respect to permutations of the sectors (g^I, Ψ^I).

Action and equations of motion

- Gravitational action:

$$S_G[g^1,\ldots,g^N] = \frac{1}{2}\int d^4x\sqrt{g_0}\left[\sum_{I,J=1}^{N}(x+y\delta^{IJ})g^{Iij}R^J_{ij} + F(S^{IJ})\right].$$

- Symmetric volume form $g_0 = (g^1 g^2 \ldots g^N)^{1/N}$.
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$\Rightarrow$ Equations of motion:

$$T^I_{ab} = \sqrt{\frac{g_0}{g^I}}\left[-\frac{1}{2N}g^I_{ab}\sum_{J,K=1}^{N}(x+y\delta^{JK})g^{Jij}R^K{}_{ij} + \sum_{J=1}^{N}(x+y\delta^{IJ})R^J{}_{ab}\right]$$
$$+ \text{ terms linear in } \nabla^I S^{JK}$$
$$+ \text{ terms quadratic in } S^{IJ}.$$

$\Rightarrow$ Repulsive Newtonian limit for $N \geq 3$.

Outline

Cosmological symmetry

- Standard cosmology: Robertson–Walker metrics

$$g^I = -n_I^2(t)dt \otimes dt + a_I^2(t)\gamma_{\alpha\beta}dx^\alpha \otimes dx^\beta\,.$$

  - Lapse functions n_I.
  - Scale factors a_I.
  - Spatial metric $\gamma_{\alpha\beta}$ of constant curvature $k \in \{-1, 0, 1\}$ and Riemann tensor $R(\gamma)_{\alpha\beta\gamma\delta} = 2k\gamma_{\alpha[\gamma}\gamma_{\delta]\beta}$.
- Perfect fluid matter:

$$T^{I\,ab} = (\rho_I + p_I)u^{Ia}u^{Ib} + p_I g^{Iab}\,.$$

- Normalization: $g^I_{ab}u^{Ia}u^{Ib} = -1$.

Simple cosmological model

- Early universe: radiation; late universe: dust.
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$\Rightarrow$ Single effective energy-momentum tensor $T^I_{ab} = T_{ab}$.

$\Rightarrow$ Single effective metric $g^I_{ab} = g_{ab}$.

$\Rightarrow$ Common scale factors $a^I = a$ and lapse functions $n^I = n$.

$\Rightarrow$ Rescale cosmological time to set $n \equiv 1$.

$\Rightarrow$ Ricci tensors $R^I_{ab} = R_{ab}$ become equal.

$\Rightarrow$ Connection differences $S^{IJ\,i}{}_{jk} = 0$ vanish.

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$\Rightarrow$ Equations of motion simplify for repulsive Newtonian limit:

$$(2 - N)T_{ab} = R_{ab} - \frac{1}{2}Rg_{ab}\,.$$

$\Rightarrow$ Negative effective gravitational constant for early / late universe.

Cosmological equations of motion

- Insert Robertson–Walker metric into equations of motion:

$$\rho = \frac{3}{2-N}\left(\frac{\dot{a}^2}{a^2} + \frac{k}{a^2}\right),$$
$$p = -\frac{1}{2-N}\left(2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2}\right).$$

$\Rightarrow$ Positive matter density $\rho > 0$ requires $k = -1$ and $\dot{a}^2 < 1$.

$\Rightarrow$ No solutions for $k = 0$ or $k = 1$.

Accelerating expansion

- Acceleration equation:

$$\frac{\ddot{a}}{a} = \frac{N-2}{6}(\rho + 3p)\,.$$

- Factor $N - 2 > 0$ for multimetric gravity.
- Strong energy condition

$$\left(T_{ab} - \frac{1}{2}Tg_{ab}\right)t^a t^b \geq 0$$

  for all timelike vector fields t^a implies $\rho + 3p \geq 0$.

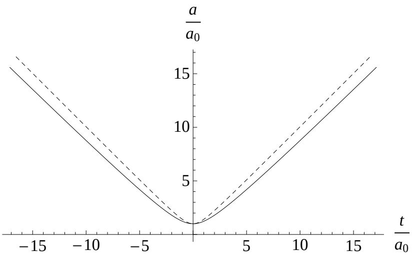
$\Rightarrow$ Acceleration must be positive.

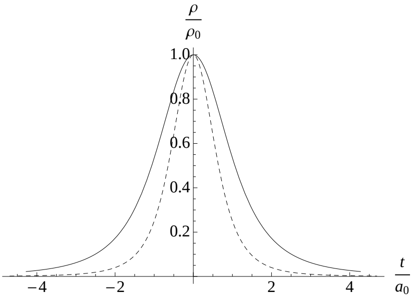
Explicit solution

- Equation of state: $p = \omega\rho$; dust: $\omega = 0$, radiation: $\omega = 1/3$.
- General solution using conformal time η defined by $dt = a\,d\eta$:

$$a = a_0 \left(\cosh\left(\frac{3\omega+1}{2}(\eta-\eta_0)\right)\right)^{\frac{2}{3\omega+1}},$$

$$\rho = \frac{3}{(N-2)a_0^2}\left(\cosh\left(\frac{3\omega+1}{2}(\eta-\eta_0)\right)\right)^{-\frac{6\omega+6}{3\omega+1}}.$$





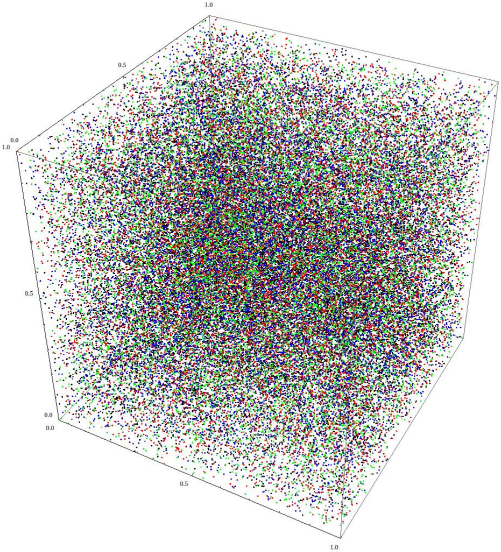
$\Rightarrow$ Big bounce at $\eta = \eta_0$. [MH, M. Wohlfarth '10]

Outline

Ingredients

1. Metrics $g^I_{ab} = g^0_{ab} + h^I_{ab}$ with
$$g^0 = -dt \otimes dt + a^2(t)\gamma_{\alpha\beta} dx^\alpha \otimes dx^\beta$$
and $a(t)$ determined by cosmology.
2. Scale for structure formation $\ll$ curvature radius of the universe:
   - Cubic volume $0 \leq x^\alpha \leq \ell$.
   - Approximate $\gamma_{\alpha\beta}$ by $\delta_{\alpha\beta}$.
   - Periodic boundary conditions.
3. Matter content: n point masses M for each sector.
   - Model for dust matter: $p = 0$.
   - Matter density:
$$\rho = \frac{Mn}{(a\ell)^3}\,.$$
4. Large mean distance $a\ell/\sqrt[3]{Nn} \gg 2GM$.
5. Small velocities $|v^\alpha_{Ii}| = |a\dot{x}^\alpha_{Ii}| \ll 1$.

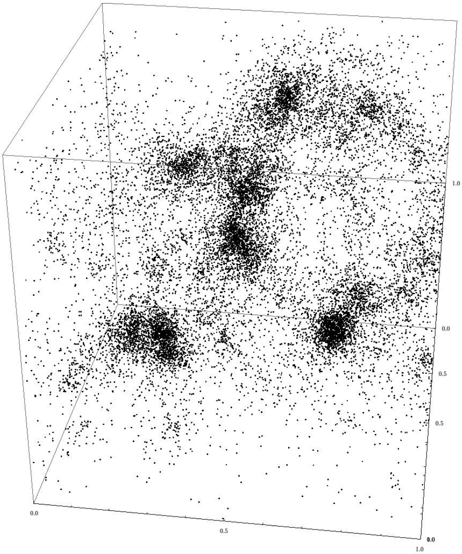
Evolution of structures for all matter types



- $N = 4$.
- $n = 16384$.
- 7.5 days CPU time.

Final state for one matter type

- Galactic clusters.
- Empty voids.



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Physical situation in the solar system

- Consider only repulsive gravity between different sectors.
  - $\Rightarrow$ Different matter types should separate.
  - $\Rightarrow$ Energy-momentum tensor contains only visible matter:
    - $\Rightarrow$ $T^{+}_{ab} = T^{1}_{ab} \neq 0$.
    - $\Rightarrow$ $T^{-}_{ab} = T^{2}_{ab} = \ldots = T^{N}_{ab} = 0$.

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    - $\Rightarrow$ $T^{-}_{ab} = T^{2}_{ab} = \ldots = T^{N}_{ab} = 0$.
- Permutation symmetry between sectors.
  - $\Rightarrow$ Visible matter has equal effects on all dark sectors.
  - $\Rightarrow$ Metric:
    - $\Rightarrow$ $g^{+}_{ab} = g^{1}_{ab}$.
    - $\Rightarrow$ $g^{-}_{ab} = g^{2}_{ab} = \ldots = g^{N}_{ab}$.

Parametrized post-Newtonian formalism

- Characterize single-metric gravity theories by 10 parameters.
  [Thorne, Will ’71; Will ’93]
- 2 parameters can be obtained from linearized field equations.
- Values constrained by experiment, e.g., $\gamma = 1 \pm 2.3 \cdot 10^{-5}$.

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- Values constrained by experiment, e.g., $\gamma = 1 \pm 2.3 \cdot 10^{-5}$.
- Extension of PPN formalism for multimetric gravity theories.
  [MH, M. Wohlfarth '10]
- Extended set of 26 PPN parameters.
- 8 parameters can be obtained from linearized field equations.
- 10 parameters correspond to single-metric parameters $\Rightarrow$ experimentally measured.

PPN consistent theory

- Consider gravitational action of the form:

$$S_G = \frac{1}{2}\int d^4x\sqrt{g_0}\sum_{I=1}^{N} g^{I\,ij}\left[z\tilde{S}^I{}_k\tilde{S}^{I\,k}{}_{ij} + u\tilde{S}^I{}_i\tilde{S}^I{}_j + \sum_{J=1}^{N}(x + y\delta^{IJ})R^J_{ij}\right].$$

- Parameters in the action:

$$x = \frac{1}{8-4N}\,, \quad y = \frac{4-N}{8-4N}\,, \quad z = -\frac{4-N}{8-4N}\,, \quad u = -\frac{12-3N}{8-4N}\,.$$

$\Rightarrow$ PPN parameters from linearized formalism:

- $\alpha^+ = 1$, $\theta^+ = 0$: standard PPN gauge choice.
- $\gamma^+ = 1$, $\sigma^+_+ = -2$: experimental consistency.
- $\alpha^- = -1$: repulsive Newtonian limit.
- $\gamma^- = -1$, $\theta^- = 0$, $\sigma^-_+ = 2$: additional "dark" PPN parameters.

Outline

Propagation velocity

- Write linearized vacuum field equations as:

$$\sum_{J=1}^{N} \mathcal{D}^{IJ}{}_{ab}{}^{cd} h^J_{cd} = 0 \,.$$

- Differential operator $\mathcal{D}$.
- Consider wavelike solution:

$$h^I_{ab} = h^{I\,0}_{ab} e^{ik_a x^a} \,.$$

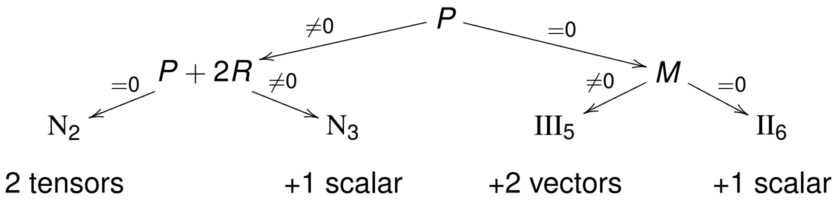
- Multiplication operator $\hat{\mathcal{D}}$.
- Non-vanishing solution require zero eigenvalue of $\hat{\mathcal{D}}$.
- $\det \hat{\mathcal{D}} \propto (k^a k_a)^{10}$.

$\Rightarrow$ Solutions exist only for $k^a k_a = 0$.

$\Rightarrow$ Gravitational waves are null.

Polarization and E(2) class

- Up to 6 polarizations in general metric theories.
- Theories classified by representations of E(2).
- E(2) class of multimetric gravity depends on 3 parameters:



- PPN consistent theory shown before of class N_2.

⇒ Same class as general relativity.

Outline

Summary

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- Constituents of dark matter & dark energy are unknown.
- Idea here: Dark universe might be explained by repulsive gravity.

$\Rightarrow$ Repulsive gravity requires an extension of general relativity.

$\Rightarrow$ No-go theorem: bimetric repulsive gravity is not possible.

$\Rightarrow$ Multimetric repulsive gravity with $N \geq 3$ by explicit construction.

$\Rightarrow$ Cosmology features late-time acceleration and big bounce.

$\Rightarrow$ Structure formation features clusters and voids.

$\Rightarrow$ Repulsive gravity is consistent with solar system experiments.

$\Rightarrow$ Gravitational waves are null.

Outlook

- Remaining PPN parameters should be determined from full multimetric PPN formalism.
- Restrict multimetric gravity theories by additional PPN bounds.
- Establish further construction principles, e.g., continuous symmetry between sectors.
- Examine initial-value problem.
- Determine further exact solutions (single point mass. . .).
- Advanced simulation of structure formation including thermodynamics using GADGET-2 (Millenium Simulation).
- Search for repulsive gravity sources in the galactic voids through gravitational lensing.
- Application to binaries: gravitational radiation should be emitted in all sectors, but only one type is visible.

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- Application to binaries: gravitational radiation should be emitted in all sectors, but only one type is visible. Prediction!