Imperfect Dark Matter

Alexander Vikman

26.03.15
This talk is mostly based on

e-Print: arXiv: 1403.3961,
JCAP 1406 (2014) 017
with A. H. Chamseddine and V. Mukhanov

and

e-Print: arXiv: 1412.7136
with L. Mirzagholi
Inflation
no vorticity
on large scales

DM
27%

SM
5%

DE
DM

27%

SM

5%

DE

Inflation

no vorticity on large scales

\[ u_\mu \propto \partial_\mu \phi \]
normalized velocity  \[ u_\mu = \partial_\mu \varphi / m \]
normalized velocity

Newton law

\[ u_\mu = \partial_\mu \varphi / m \]

\[ ma_\mu = \nabla^\lambda_\mu \nabla_{\lambda} m \]
normalized velocity \[ u_\mu = \frac{\partial_\mu \varphi}{m} \]

Newton law \[ ma_\mu = \downarrow_\mu^\lambda \nabla_\lambda m \]

with projector \[ \downarrow_{\mu\nu} = g_\mu\nu - u_\mu u_\nu \]
normalized velocity

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the dynamical part of dark sector moves along timelike geodesics

\[ u_\mu = \frac{\partial_\mu \varphi}{m} \]

\[ m a_\mu = \perp_\mu^\lambda \nabla_\lambda m \]

\[ \perp_{\mu\nu} = g_{\mu\nu} - u_\mu u_\nu \]

\[ m = m(\varphi) \]
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\[ \varphi \rightarrow \phi \quad d\phi = d\varphi/m(\varphi) \quad u_\mu = \partial_\mu \phi \]

\[ g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi = 1 \]

Constraint or the Hamilton-Jacobi equation
How to implement this constraint?
Mimetic Matter

Chamseddine, Mukhanov (2013)
One can encode the conformal / scalar part of the physical metric $g_{\mu\nu}$ in a scalar field $\phi$:

$$g_{\mu\nu} (\tilde{g}, \phi) = \tilde{g}_{\mu\nu} \tilde{g}^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi$$
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auxiliary metric

$$S [\tilde{g}_{\mu\nu}, \phi, \Phi_m] = \int d^4 x \left[ \sqrt{-g} \left( -\frac{1}{2} R (g) + \mathcal{L} (g, \Phi_m) \right) \right]_{g_{\mu\nu} = g_{\mu\nu} (\tilde{g}, \phi)}$$
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The theory becomes invariant with respect to Weyl transformations:

$$\tilde{g}_{\mu\nu} \rightarrow \Omega^2(x) \tilde{g}_{\mu\nu}$$
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- The scalar field obeys a constraint (Hamilton-Jacobi equation):

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with

\[ g_{\mu\nu}(\tilde{g}, \phi) = \tilde{g}_{\mu\nu} \tilde{g}^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi \]
\[ S [\bar{g}_{\mu \nu}, \phi, \Phi_m] = \int d^4 x \left[ \sqrt{-g} \left( -\frac{1}{2} R (g) + \mathcal{L} (g, \Phi_m) \right) \right] \]

\[ g_{\mu \nu} = g_{\mu \nu} (\bar{g}, \phi) \]

with \[ g_{\mu \nu} (\bar{g}, \phi) = \bar{g}_{\mu \nu} \bar{g}^{\alpha \beta} \partial_\alpha \phi \partial_\beta \phi \]

is not in the Horndeski (1974) construction of the most general scalar-tensor theory with second order equations of motion.
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is not in the Horndeski (1974) construction of the most general scalar-tensor theory with second order equations of motion.

But it is still a system with one degree of freedom + standard two polarizations for the graviton!
Mimetic Dark Matter

Chamseddine, Mukhanov; Golovnev; Barvinsky (2013)
Lim, Sawicki, Vikman; (2010)
Mimetic Dark Matter

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- Weyl-invariance allows one to fix $g_{\mu\nu} = \tilde{g}_{\mu\nu}$
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- Weyl-invariance allows one to fix $g_{\mu\nu} = \tilde{g}_{\mu\nu}$
- one implements constraint through $\lambda \left( g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - 1 \right)$

\[
S \left[ g_{\mu\nu}, \phi, \lambda, \Phi_m \right] = \int d^4 x \sqrt{-g} \left( -\frac{1}{2} R(g) + \mathcal{L}(g, \Phi_m) + \lambda \left( g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - 1 \right) \right)
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- The system is equivalent to standard GR + irrotational dust, moving along timelike geodesics with the velocity $u_\mu = \partial_\mu \phi$ and energy density $\rho = 2\lambda$
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Dark Matter
Mimicking any cosmological evolution, but always with zero sound speed

Lim, Sawicki, Vikman; (2010)
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Just add a potential $V(\phi)$!
Mimicking any cosmological evolution, but always with zero sound speed

Lim, Sawicki, Vikman; (2010)
Chamseddine, Mukhanov, Vikman (2014)

1. Just add a potential $V(\phi)$!

2. $g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi = 1$ → Convenient to take $\phi$ as time
Mimicking any cosmological evolution,
But always with zero sound speed

Lim, Sawicki, Vikman; (2010)
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- Just add a potential $V(\phi)$!
- $g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi = 1 \quad \text{Convenient to take } \phi \text{ as time}$
- Adding a potential = adding a function of time in the equation
  $2\dot{H} + 3H^2 = V(t)$
Mimicking any cosmological evolution, But always with zero sound speed

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Enough freedom to obtain any cosmological evolution!
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Adding a potential = adding a function of time in the equation

$$2\dot{H} + 3H^2 = V(t)$$

**Enough freedom to obtain any cosmological evolution!**

In particular $V(\phi) = \frac{1}{3} \frac{m^4 \phi^2}{e^\phi + 1}$ gives the same cosmological inflation as $\frac{1}{2} m^2 \phi^2$ potential in the standard case.
Even with potential, the energy still moves along the timelike geodesics.
Perturbations I

Lim, Sawicki, Vikman; (2010)
Chamseddine, Mukhanov, Vikman (2014)

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\[ c_S = 0 \]
Perturbations I

Even with potential, the energy still moves along the timelike geodesics.

$$c_S = 0$$

Newtonian potential:

$$\Phi = C_1(x) \left( 1 - \frac{H}{a} \int a \, dt \right) + \frac{H}{a} C_2(x)$$

*Here on all scales but in the usual cosmology it is an approximation for superhorizon scales*
Next term in the gradient expansion

Chamseddine, Mukhanov, Vikman (2014)
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\[ \gamma (\Box \phi)^2 \]

“unique” quadratic term
Next term in the gradient expansion

Chamseddine, Mukhanov, Vikman (2014)

\[ \gamma (\Box \phi)^2 \]

“unique” quadratic term

\[ \nabla_\mu \nabla_\nu \phi \nabla^\mu \nabla^\nu \phi \]

is not that useful:

\[ \int d^4 x \sqrt{-g} \, \phi_{;\mu;\nu} \phi^{;\mu;\nu} = \int d^4 x \sqrt{-g} \left( (\Box \phi)^2 - R^{\mu\nu} \phi_{;\mu} \phi_{;\nu} \right) \]
Next term in the gradient expansion

Chamseddine, Mukhanov, Vikman (2014)

\[ \gamma \left( \Box \phi \right)^2 \]

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\[ \int d^4 x \sqrt{-g} \phi_{\mu;\nu} \phi^{\mu;\nu} = \int d^4 x \sqrt{-g} \left( (\Box \phi)^2 - R^{\mu\nu} \phi_{\mu;\nu} \phi^{\mu;\nu} \right) \]

\[ \theta = \Box \phi = \nabla_\mu \mathcal{U}^\mu \]
The scalar field still obeys a constraint (Hamilton-Jacobi equation)

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Higher time derivatives can be eliminated just by the differentiation of this Hamilton-Jacobi equation
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Higher time derivatives can be eliminated just by the differentiation of this Hamilton-Jacobi equation.

There are only minor changes (rescaling) in the background evolution equations e.g.

\[ 2\dot{H} + 3H^2 = \frac{2}{2 - 3\gamma} V(t) \]
\[ \ddot{\delta \phi} + H \dot{\delta \phi} - \frac{c_s^2}{a^2} \Delta \delta \phi + \dot{H} \delta \phi = 0 \]

with the sound speed

\[ c_s^2 = \frac{\gamma}{2 - 3\gamma} \]
\[ \delta \ddot{\phi} + H \dot{\delta \phi} - \frac{c_s^2}{a^2} \Delta \delta \phi + \dot{H} \delta \phi = 0 \]

with the sound speed

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Newtonian potential:

\[ \Phi = \delta \dot{\phi} \]
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Imperfect Dark Matter

Mirzagholi, Vikman (2014)
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(no potential)

\[ T_{\mu\nu} = \varepsilon u_\mu u_\nu - p \perp_{\mu\nu} + q_\mu u_\nu + q_\nu u_\mu \]
Imperfect Dark Matter

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(no potential)

\[ T_{\mu\nu} = \varepsilon u_\mu u_\nu - p \bot_{\mu\nu} + q_\mu u_\nu + q_\nu u_\mu \]

\[ \bot_{\mu\nu} = g_{\mu\nu} - u_\mu u_\nu \]

expansion \[ \theta = \nabla_\mu u^\mu \]
Imperfect Dark Matter

(no potential)

\[ T_{\mu\nu} = \varepsilon u_{\mu} u_{\nu} - p \, \perp_{\mu\nu} + q_{\mu} u_{\nu} + q_{\nu} u_{\mu} \]

energy flow \[ q_{\mu} = -\gamma \perp_{\mu} \nabla \lambda \theta \]

expansion \[ \theta = \nabla_{\mu} u^{\mu} \]

Mirzagholi, Vikman (2014)
Imperfect Dark Matter

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energy density \[ \varepsilon = 2\lambda - \gamma \left( \dot{\theta} - \frac{1}{2} \theta^2 \right) \]
Imperfect Dark Matter

Mirzagholi, Vikman (2014)

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\[ T_{\mu\nu} = \varepsilon u_\mu u_\nu - p \downarrow_{\mu\nu} + q_\mu u_\nu + q_\nu u_\mu \]

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expansion \[ \theta = \nabla_{\mu} u^\mu \]

energy density \[ \varepsilon = 2\lambda - \gamma \left( \dot{\theta} - \frac{1}{2} \theta^2 \right) \]

pressure \[ p = -\gamma \left( \dot{\theta} + \frac{1}{2} \theta^2 \right) \]
CHARGE CONSERVATION

Mirzgholi, Vikman (2014)
**CHARGE CONSERVATION**

Mirzagholi, Vikman (2014)

no potential  \[ \phi \rightarrow \phi + C \]  symmetry
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$\nabla_\mu J^\mu = 0$
no potential \[ \phi \rightarrow \phi + c \]
symmetry

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Noether current:

\[ J_\mu = nu_\mu + q_\mu \]
**CHARGE CONSERVATION**

*Mirzagholi, Vikman (2014)*

no potential  \[ \phi \rightarrow \phi + c \]  symmetry

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charge density  \[ n = 2\lambda - \gamma \dot{\theta} \]
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Noether current:

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\[ n \propto a^{-3} \]
Vorticity for a single scalar dof DM?
Vorticity for a single scalar dof DM?

in the frame moving with the charges (Eckart frame)

\[ \Omega_E^\mu = \frac{1}{2} \varepsilon^{\alpha \beta \gamma \mu} V_\gamma \nabla_\alpha V_\beta; \lambda \approx \frac{\gamma}{4 \lambda^2} \varepsilon^{\alpha \beta \gamma \mu} \nabla_\alpha \lambda \nabla_\beta \theta u_\gamma \]
Vorticity for a single scalar dof DM?

in the frame moving with the charges (Eckart frame)

\[ \Omega^\mu_E = \frac{1}{2} \varepsilon^{\alpha\beta\gamma\mu} V_\gamma \nabla_\alpha V_\beta; \lambda \simeq \frac{\gamma}{4\lambda^2} \varepsilon^{\alpha\beta\gamma\mu} \nabla_\alpha \lambda \nabla_\beta \theta u_\gamma \]

in the gradient expansion (without gravity)

\[ T_{\mu\nu} \simeq (\varepsilon + p) U_\mu U_\nu - pg_{\mu\nu} + O(\gamma^2) \]
\[ p \simeq c_S^2 \varepsilon + O(\gamma^2) \]
Raychaudhuri at work!

\[ \dot{\theta} = -\frac{1}{3} \theta^2 - \sigma^2 - R_{\mu\nu} u^\mu u^\nu \]
Raychaudhuri at work!

\[
\dot{\theta} = -\frac{1}{3} \theta^2 - \sigma^2 - R_{\mu\nu} u^\mu u^\nu
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\varepsilon = \frac{2}{2 - 3\gamma} n + 3c_S^2 \rho_{\text{ext}} \quad p = 3c_S^2 P_{\text{ext}}
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DM

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\[ n \propto a^{-3} \]

\[ G_{\text{eff}} = G_N \left( 1 + 3c_S^2 \right) \]
Mimetic construction and inflation

shift-symmetry breaking needed for DM
Mimetic construction and inflation

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\[ \gamma (\phi) : \nabla_\mu J^\mu = \frac{1}{2} \gamma' (\phi) \theta^2 \]
Mimetic construction and inflation

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easy to generate charge during radiation domination époque :

\[ n a^3 = \frac{9}{2} \int_{(t_{cr} - \Delta t)}^{t} \, dt' \, a^3 \dot{\gamma} H^2 \approx \frac{3}{2} a^3 \rho_{rad} (t_{cr}) \Delta \gamma \]
Mimetic construction and inflation

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\[ \Delta \gamma = \frac{2}{3} \left( \frac{a_{cr}}{a_{eq}} \right) \approx \frac{2}{3} \frac{z_{eq}}{z_{cr}} \quad T_{cr} \approx \frac{T_{eq}}{\Delta \gamma} \approx \frac{eV}{\Delta \gamma} \]
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Mimetic construction and inflation

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Rappaport, Schwab, Burles, Steigman (2007)

\[ \delta G_N \text{ bounds are mild:} \]

\[ c_S^2 \bigg|_{\text{BBN}} \lesssim 0.02 \]
Mimetic construction and inflation

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Rappaport, Schwab, Burles, Steigman (2007)

\[ c_S^2 \big|_{\text{BBN}} \lesssim 0.02 \]

Narimani, Scott, Afshordi (2014)

\[ 3 \left( c_S^2 \big|_{\text{matter}} - c_S^2 \big|_{\text{radiation}} \right) \lesssim 0.066 \pm 0.039 \]
Conclusions
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New large class of Weyl-invariant scalar-tensor theories beyond (but not in contradiction with) Horndeski
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- Can unite part of DM with DE, strongly decouples equation of state from the sound speed
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- Imperfect DM, with a small sound speed, transport of energy, vorticity and a perfect tracking of the external energy. Essentially only one free parameter.
Conclusions

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- Can unite part of DM with DE, strongly decouples equation of state from the sound speed

- Imperfect DM, with a small sound speed, transport of energy, vorticity and a perfect tracking of the external energy. Essentially only one free parameter.

Thanks a lot for attention!