Scalar field dark matter – dark energy

a viable approach ?

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Some questions

- Discussion in A3 led to question the strict dichotomy between dark matter and alternative gravitational approach to dark matter phenomena (Martens/Lehmkuhl 2021).
- Here “dark matter” is seen from a generalized point of view: any field/object with (general relativistic) energy tensor.
- In this sense also electromagnetic field is considered as “matter” and also “dark” energy (I guess), with vacuum energy tensor $\sim g$.
- Scalar fields (classical view) carry energy, can be candidates for "dark sector".
- Main question here: can MOND-like dynamics be generated by a relativistic scalar field (or several)?

\+ Answer: Yes, at least if studied in Weyl geometric framework (geometry with local scale (conformal) symmetry.

++ In this approach also new types of cosmological models arise.

1. Astrophysical example (galaxies, clusters)

MOND

- Milgrom 1983: flat rotation curves in outer regions of galaxies can be explained by a modification of Newtonian mechanics (MOND), acting if Newtonian acceleration is below a universal threshold:

  $$a_N < a_0\,[c] \qquad (a_0 \textit{ Milgrom constant})$$

  $$a_0\,[c] \approx 1.2 \cdot 10^{-8}\, cm\, s^{-2} \quad \longleftrightarrow \quad a_0 \approx 3.9 \cdot 10^{-19}\, s^{-1}$$

- Diverse phenomena on galactic level derivable from this assumption: Tully-Fisher law (relating luminosity and maximal rotation velocity), Faber-Jackson relation (between mass of elliptic galaxies and velocity dispersion),
  mass discrepancy acceleration relation (between baryonic mass and observed acceleration):

  "Keplerian laws" of galactic dynamics (Famaey/McGaugh)

- Problem: general relavistic extension/underpinning:

  R-MOND theory ?!

- Diverse proposals often with strange modification of geometry or (too) many new fields $\leftrightarrow$ d.o.f.

  RAQUAL, TeVeS, Einstein-Aether, superfluid theory, emergent gravity, "new" RMOND (Skordis/Złośnik)

R-MOND – WdST

- Here considered: "simple" modification of geometry supposing — well founded modification of Riemannian geometry: *integrable Weyl geometry* (IWG) with (" weakly broken") conformal symmetry — and only one ("gravitational") *scalar field* ϕ + Riem. metric g

  $\rightarrow$ Weyl geometric dark scalar field theory (WdST)

- ... with "strange" kinetic term of scalar field (conformally coupled quadratic term + cubic term similar to RAQUAL + 2nd order derivative term from Novello et al. 1996)

- and quartic potential $V(\phi) = \lambda\phi^4$,
  plus, perhaps, in cosmology biquadratic coupling to (expectation value of) Higgs field (Bars/Turok/Steinhardt, Shapovnikov et al.).

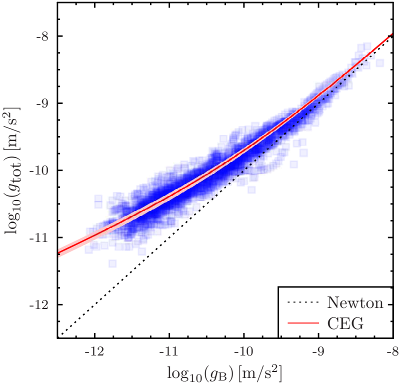
Properties of WdST

- Generalized Einstein equation for g_E (Riem. metric Einstein gauge), covariant "Milgrom equation" for $\sigma = \log \phi$.
- *Weak field approximation* and *flat space limit*:
  Newton approx. for Riemannian metric,
  (deep) MOND equation for σ
  both sourced by baryonic matter only.
- Particle acceleration in flat space limit

  $a = a_N + a_\phi = -(\partial \Phi_N + \partial \sigma), \qquad \sigma$ "scalar field *potential*".
- Gravitational light refraction with total potential $\Phi_N + \sigma$ relativistic, i.e. with factor 2, consistent with acceleration.
- Effects: special type of MOND with acceleration like in Hosssenfelder/Mistele's "covariant emergent gravity (CEG)"

Illustration of (baryonic) mass discepancy-acceleration relation

Newtonian acceleration (here g_B) from the observed baryonic mass (on x-axis) in relation to observed acceleration (here g_{tot} – y-axis) in 2693 measured data points from 153 galaxies (Hossenfelder/Mistele 2018)



"CEG" corresponds to MOND acceleration with $a = \left(1 + \sqrt{\frac{a_0}{a_N}}\right) a_N$
the same ("interpolation function") in WdST.

Energy-stress of the scalar field

- Superposition of "*dark energy*" (de) with variable coefficient and "*dark +matter* (fluid)" (dm):
  $T^{(\phi)} = T^{(de)} + T^{(dm)}\,, \qquad T^{(de)}(x) = \tilde{\Lambda}(x)\, g(x)$
  dm-contribution often with strange (negative) stresses.
- For R-MOND ("Milgrom regime"), *central symmetric* case.
  solution $\sigma = C_1 \log r,\ C_1 = \sqrt{a_o\, M}$.

  $\tilde{\Lambda} = -2\, \nabla^2 \sigma\ [+\Lambda] = \frac{2C_1}{r^2}$ (cosmological Λ negligible),
  $T^{(dm)}_{\mu\nu} = \frac{3}{4\pi G}\, \partial_\mu \partial_\nu \sigma\,, \qquad p_1^{(dm)} = \frac{3}{4\pi G}\, 6\, \sigma''$, else 0.

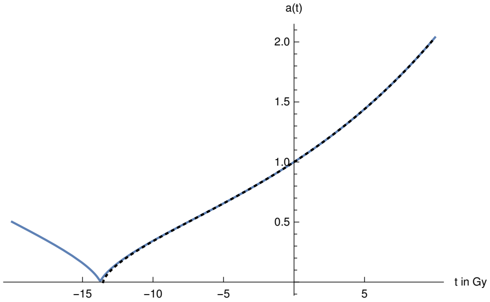
  Energy density $\rho^{(\phi)} = (4\pi G)^{-1} \frac{C_1}{r^2}$ "real" not "phantom"
  induces (fictitious?) Newtonian acceleration $a_N^{(\phi)} = a_\phi$ above (equal to MOND addition to baryonic $a_N^{(bar)}$) ...

  But: this energy density is not "seen" by the Newton approximation of the Einstein equation; it comes into the play through the *additional acceleration due to the scalar field* (scale connection).

2. Cosmological example

A bouncing cosmological model

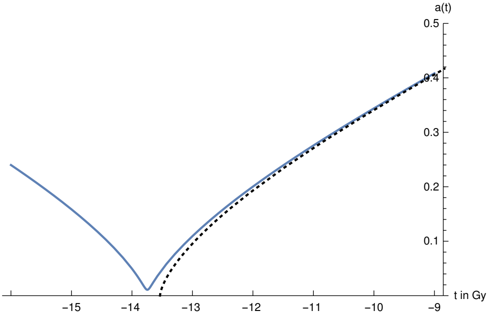
Because of “varying vacuum tensor” of scalar fields, such models can lead to unexpected behaviour in the FRW-cosmological context. Here is one:



Blue: scalar field model, black dashed: standard ΛCDM

$\Omega_m = 0.23$, $\Omega_\Lambda \approx 0.773$, initial conditions at present time $t_0 = 0$: $a(0) = 1$, $H(0) = \frac{a'(0)}{a(0)} = H_0$, acceleration $-q(t) = \frac{\ddot{a}a}{\dot{a}^2} = 0.067$

Closer look near the bounce



Bounce $\approx 200\, My$ earlier than time of "big bang" (in ΛCDM)

Maximal redshift $z_{max} \approx 100 \longrightarrow$ either physically nonsense or CMB resulting from thermalized background radiation at throat (kind of "Olbers" effect).

Dynamical assumptions of this model

- Two scalar fields, ϕ, s. ϕ (gravitational) scalar field,
- s real valued classical companion of the Higgs field,
  "expectation" value $s(x) = |H(x)| = \left(H^{\dagger}(x)H(x)\right)^{\frac{1}{2}}$
  similar to Bars/Turok/Steinhardt $\sim$ 2010ff.
- ϕ conformally coupled to Hilbert term and important for the Weylian scale connection (in Einstein gauge): gravitational scalar field.
- Common biquadratic potential of the two fields:
  $V(\phi, s) = \frac{\lambda_H}{4}(s^2 - (\omega\phi)^2)^2$
  This allows (baryonic) matter even with conformal coupling of ϕ.

Energy-stress of the scalar field

- Like above superposition:
  $T^{\phi} = T^{(de)} + T^{(dm)}\,, \qquad T^{(de)}(x) = \tilde{\Lambda}(x)\, g(x)$
- For FRW-cosmology:
  $\tilde{\Lambda} = 4\dot{\sigma}^2 + 2(\ddot{\sigma} + 3\frac{\dot{a}}{a}\dot{\sigma}) + \Lambda$
  $(8\pi G)\, T^{(dm)}_{00} = -6\dot{\sigma}^2 \;(!)\,, \qquad (8\pi G)\, p^{(dm)}_j = 2\frac{\dot{a}}{a}$
  In the example above $\rho^{(\phi)} = (8\pi G)^{-1}\, T^{\phi}_{00} > 0$,
  with the exception of a cosmologically "short" time about the bounce.

A final question:

What does all this mean?

A “funny” model only . . .

or, perhaps, a step towards a viable alternative to particle dark matter ?

. . . and the paper behind the talk:
http://arxiv.org/abs/2202.13467