Extension to the standard cosmological model with scalar graviton as a unified dark matter and energy

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Content

ER

- Extra Relativity (ER):
  GC and GR on an extended gravity set

$$S = \int L_G(g_{\mu\nu}, X^a)\sqrt{-g}d^4x$$

- Affine variables: $a = 0, \ldots, 3$. Global internal $SO(1,3)$.
  Piece-wise $X^a(x^\mu)$. Inverse $x^\mu(X^a)$.
  Affine connection: $\gamma^\lambda_{\mu\nu}(X^a)$
- Distinguished affine coordinates: $\bar{x}^\alpha = \delta^\alpha_a X^a$, $\bar{\gamma}^\gamma_{\alpha\beta} = 0$
- A remnant of the Affine Nonlinear Model (NM)
  $G/H = GL(4,R)/ISO(3,1)$
  Emergent gravity

ER (con't 1)

- DOFs
  ER: $10 + 4 - 4 = 10 = 1 + 3 + 6$
  Vacuum ER: $10 - 4 = 6$
  Scalar-vector-tensor gravity

  Minimal ER: $10 - 3 = 1 + 6$
  Vacuum Minimal ER: $1 + 6 - 4 = 3 = 1 + 2$
  Scalar-tensor gravity

Minimal ER

- Minimal ER Lagrangian

$$L_{sg} \equiv L_g + L_s = -\frac{1}{2}\kappa_g^2 R + \frac{1}{2}\kappa_s^2 g^{\kappa\lambda}\partial_\kappa\sigma\partial_\lambda\sigma - V_s(\sigma)$$

- Scalar graviton

$$\sigma = \ln \sqrt{-g}/\sqrt{-\gamma}$$

- Affine scalar density

$$X = \det(\partial_\lambda X^a) \equiv \sqrt{-\gamma}$$

- Matter: $\varsigma = \kappa_s \sigma, \quad \kappa_s \sim 10^{15}$ GeV

Minimal ER (cont'd 1)

- Field equations (FEs)

$$
\begin{aligned}
G_{\mu\nu} &\equiv R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{1}{\kappa_g^2} T_{\mu\nu}, \\
\frac{\delta}{\delta X^a}(L_s + L_m) &\equiv -\nabla_\lambda \Big(\big(\frac{\delta L_s}{\delta \sigma} + \frac{\delta L_m}{\delta \sigma} \big) X_a^\lambda \Big) = 0, \\
\frac{\delta L_m}{\delta \Phi^I} &\equiv \frac{\partial L_m}{\partial \Phi^I} - \nabla^\kappa \frac{\partial L_m}{\partial \nabla_\kappa \Phi^I} = 0
\end{aligned}
$$

- Conventional matter

$$\delta L_m / \delta \sigma = 0$$

Minimal ER (cont'd 2)

- Energy-momentum tensors

$$T_{s\mu\nu} = \kappa_s^2 \nabla_\mu \sigma \nabla_\nu \sigma - \Big(\frac{1}{2}\kappa_s^2 \nabla^\lambda \sigma \nabla_\lambda \sigma - (V_s + W_s)\Big) g_{\mu\nu},$$

$$T_{m\mu\nu} = 2\frac{\partial L_m}{\partial g^{\mu\nu}} - \Big(L_m + \frac{\delta L_m}{\delta \sigma}\Big) g_{\mu\nu}$$

- Wave operator

$$W_s \equiv -\delta L_s / \delta\sigma = \kappa_s^2 \nabla^\lambda \nabla_\lambda \sigma + \partial V_s / \partial \sigma$$

Minimal ER (cont'd 3)

- Bianchi identity

$$\partial_\mu W_s + W_s \partial_\mu \sigma + \nabla_\nu T_{m\mu}^{\ \nu} = 0$$

$$\nabla_\nu T_{m\mu}^{\ \nu} = 0 \Rightarrow W_s = W_0 e^{-\sigma}$$

- Effective potential

$$\tilde{V}_s \equiv V_s + W_0 e^{-\sigma}$$

- Scalar-graviton effective FE

$$\kappa_s^2 \nabla^\lambda \nabla_\lambda \sigma + \partial \tilde{V}_s / \partial \sigma = 0 \qquad (1)$$

- Affine FE

$$\partial_\lambda(\sqrt{-g} e^{-\sigma} X_a^\lambda) = \partial_\lambda(\sqrt{-\gamma} X_a^\lambda) = 0 \qquad (2)$$

DM

- Static scalar field $\sigma = \sigma(\mathbf{x})$
  Decoupling: $W_s = W_0 e^{-\sigma(\mathbf{x})}, \quad W_0 \leq 0$
- Dark fractures (singular core)
- Dark halos (soft-core) $\sigma = \sigma(r)$

$$W_0 \equiv -\kappa_s^2/R_0^2$$

$$\sigma \sim \ln(r/R_0)^2, \quad r > R_0$$

- Stationary objects $\rho_{DM} = \rho_s + 3p_s$

$$\rho_{DM} \sim \kappa_s^2/r^2 > 0$$

- Transverse rotation velocity $(\kappa_s/\kappa_g)^2/R \sim v^2/R$

$$v|_\infty \sim \kappa_s/\kappa_g$$

- Dark Lacunas (singular core)

DE

- Homogeneous and isotropic Universe: $M = (m, DM)$
- Homogeneous scalar field $\sigma = \sigma(t)$
- FRW metric

$$ds^2 = dt^2 - a^2\Big(\frac{1}{1-kr^2}dr^2 + r^2 d\Omega^2\Big)$$

- Flat, closed or open Universe: $k = 0, \pm 1$

$$\begin{aligned}\rho_{DE} &= \frac{1}{2}\kappa_s^2\dot{\sigma}^2 + U_s,\\ p_{DE} &= \frac{1}{2}\kappa_s^2\dot{\sigma}^2 - U_s.\end{aligned}$$

$$U_s = V_s + W_s$$

- Wave operator

$$W_s = \kappa_s^2(\ddot{\sigma} + 3H\dot{\sigma}) + \partial V_s/\partial\sigma$$

DE (cont'd 1)

- Friedman equations

$$\begin{aligned} \ddot{a}/a &= -(\rho + 3p)/6\kappa_g^2, \\ H^2 + k/a^2 &= \rho/3\kappa_g^2 \end{aligned}$$

- Hubble parameter $H \equiv \dot{a}/a$
- Total distributions

$$\begin{aligned} \rho &= \rho_m + \rho_{DM} + \rho_{DE} \equiv \rho_M + \rho_{DE}, \\ p &= p_m + p_{DM} + p_{DE} \equiv p_M + p_{DE} \end{aligned}$$

- Continuity condition

$$\dot{W}_s + W_s\dot{\sigma} = -(\dot{\rho}_M + 3H(\rho_M + p_M))$$

- Affine variables ($k = 0$)

$$X^{(0)} = \int \sqrt{-\gamma}dt, \quad X^A = \delta_I^A x^I, \quad A = 1, 2, 3$$

$$\bar{t} = X^{(0)}(t), \quad \sqrt{-\bar{\gamma}} = 1$$

DE (cont'd 2)

- Scalar-graviton effective FE

$$\kappa_s^2(\ddot{\sigma} + 3H\dot{\sigma}) + \partial\tilde{V}_s/\partial\sigma = 0$$

$$\tilde{V}_s = V_s + W_0 e^{-\sigma}$$

$$\partial\tilde{V}_s/\partial\sigma|_{\bar{\sigma}} = 0$$

- Restriction: $\sigma = \tilde{\sigma}$
- Effective LCDM

$$\tilde{V}_s|_{\tilde{\sigma}} \equiv \kappa_g^2\tilde{\Lambda}_s$$

$$\rho_{DE} = -p_{DE} = \kappa_g^2\tilde{\Lambda}_s$$

CC problem

- ER $\Rightarrow$ Extended SCM
- Extended SCM $\Rightarrow$ Effective LCDM
- Caveats:
  (i) $t \sim \tilde{t}$: $\sigma(\tilde{t}) \sim \tilde{\sigma}$
  (ii) $\tilde{\Lambda}_s = \tilde{\Lambda}(V_s, W_s)$
  Lagrangian plus spontaneous contributions
- CC problem
  (i) GR: Lagrangian Λ.
  Why $\Lambda \simeq 0$? If so, why not exactly $\Lambda = 0$?.
  (ii) UR: $\Lambda = 0$, but $\Lambda_0 \simeq 0$ an integration constant as it is.
  (iii) ER: $\Lambda_s \neq 0$, $W_0 \neq 0$, but $\tilde{\Lambda}_s \simeq 0$ due to dynamical screening.
- ER: Time will tell.