CMB Power Spectrum in Delta Gravity

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Outline

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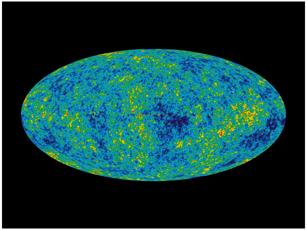
The CMB

- The Cosmic Microwave Backgroung (CMB) are photons which we can detect from all directions of space, whose distribution of temperature is practically isotropic: $T_{\textbf{CMB}} \sim 2,725K$.

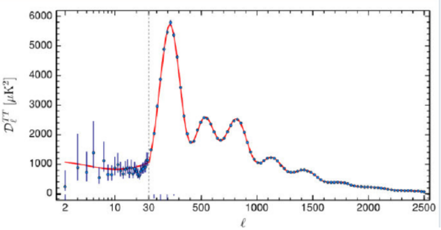
- The CMB is a "photograph" of the early universe, which corresponds with the period in which the photons decoupled from matter. This time corresponds to a Red-shift: $z \sim 1100$.



- Its small anisotropies, $\Delta T \sim 10^{-4}$, provide valuable information about the formation and evolution of the universe.

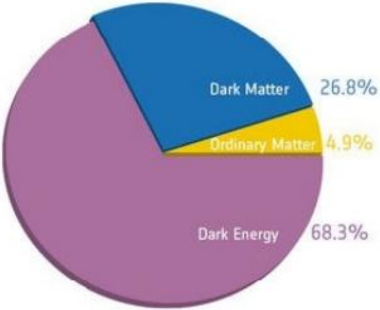
- This information is mainly extracted from the multipolar distribution of correlations in temperature anisotropies T, polarization E and B, ...

$$\langle \delta T_l, \delta T_l \rangle \propto D_l^{TT}$$



What do we know about the components of our Universe?

- Last discoveries in cosmology have revealed that most part of matter is in form of unknown matter, dark matter, and that the dynamics of the expansion of the Universe is governed by a mysterious component that accelerates its expansion, the so called dark energy.



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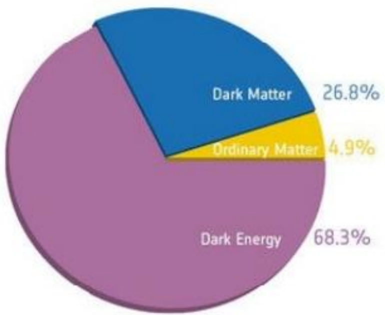

- Although General Relativity (GR) is able to accommodate both dark matter and dark enegy, the interprepation of the dark sector in terms of fundamental theories of elementary particles is problematic.

What do we know about our Universe?

- There are some candidates that could play the role of dark matter, however none have been detected yet.

- In GR, dark energy can be explained if a small cosmological constant (Λ) is present. At early times, this constant is irrelevant, but at the later stages of the evolution of the Universe Λ will dominate the expansion, explaining the observed acceleration.

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- Such small Λ is very difficult to generate in quantum field theory (QFT) models, because Λ is the vacuum energy, which is usually predicted to be very large.

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- Such small Λ is very difficult to generate in quantum field theory (QFT) models, because Λ is the vacuum energy, which is usually predicted to be very large.

- In order to understand the nature of dark energy in the context of a fundamental physical theory is that there has been various proposals to explain the observed acceleration of the Universe.

$\tilde{\delta}$ Gravity

- $\tilde{\delta}$ Gravity is a model of gravitation based on two symmetric tensors.
- In its construction, we consider two different points.
    - The first is that GR is finite on shell at one loop in vacuum, so renormalization is no necessary at this level.

$\tilde{\delta}$ Gravity

- $\tilde{\delta}$ Gravity is a model of gravitation based on two symmetric tensors.
- In its construction, we consider two different points.
  - The first is that GR is finite on shell at one loop in vacuum, so renormalization is no necessary at this level.
  - The second is a type of gauge theories, $\tilde{\delta}$ gauge theories (DGT), which main properties are:
    - A new kind of field $\tilde{\phi}_I$ is introduced, different from the original set ϕ_I.
    - The classical equation of motion of ϕ_I are satisfied in the full quantum theory.
    - The model lives at one loop.
    - The action is obtained through the extension of the original gauge symmetry of the model, introducing an extra symmetry that we call $\tilde{\delta}$ symmetry, since it is formally obtained as the variation of the original symmetry.
- When we apply this prescription to GR we obtain $\tilde{\delta}$ Gravity.

Outline

Equation of motion

Let's consider the Einstein-Hilbert Action:

$$S_0 = \int d^4x\sqrt{-g}\left(\frac{R}{2\kappa} + L_M\right), \tag{1}$$

where $L_M = L_M(\phi_I, \partial_\mu)$ is the lagrangian of the matter fields ϕ_I. Using the δ theories, this action becomes:

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{2\kappa} + L_M - \frac{\kappa_2}{2\kappa}\left(G^{\alpha\beta} - \kappa T^{\alpha\beta}\right)\tilde{g}_{\alpha\beta} + \kappa_2\tilde{L}_M\right), \tag{2}$$

where $\kappa = \frac{8\pi G}{c^2}$, $\tilde{g}_{\mu\nu} = \tilde{\delta}g_{\mu\nu}$ and:

$$T^{\mu\nu} = \frac{2}{\sqrt{-g}}\frac{\delta}{\delta g_{\mu\nu}}\left[\sqrt{-g}L_M\right] \tag{3}$$

$$\tilde{L}_M = \tilde{\phi}_I\frac{\delta L_M}{\delta\phi_I} + (\partial_\mu\tilde{\phi}_I)\frac{\delta L_M}{\delta(\partial_\mu\phi_I)}, \tag{4}$$

where $\tilde{\phi}_I = \tilde{\delta}\phi_I$ are the $\tilde{\delta}$ matter fields. From this action, we can obtain the equations of motion of $g_{\mu\nu}$ and $\tilde{g}_{\mu\nu}$.

$\tilde{\delta}$ Gravity action and equation of motion

It is easy to see that the Einstein's equations are still valid. Besides, the equation for $\tilde{g}_{\mu\nu}$ is:

$$\begin{aligned} F^{(\mu\nu)(\alpha\beta)\rho\lambda} D_\rho D_\lambda \tilde{g}_{\alpha\beta} &+ \frac{1}{2} R^{\alpha\beta} \tilde{g}_{\alpha\beta} g^{\mu\nu} + \frac{1}{2} R \tilde{g}^{\mu\nu} - R^{\mu\alpha} \tilde{g}^{\nu}_{\alpha} - R^{\nu\alpha} \tilde{g}^{\mu}_{\alpha} + \frac{1}{2} \tilde{g}^{\alpha}_{\alpha} G^{\mu\nu} \\ &= \frac{\kappa}{\sqrt{-g}} \frac{\delta}{\delta g_{\mu\nu}} \left[\sqrt{-g} \left(T^{\alpha\beta} \tilde{g}_{\alpha\beta} + 2\tilde{L}_M \right) \right], \end{aligned} \quad (5)$$

with:

$$\begin{aligned} F^{(\mu\nu)(\alpha\beta)\rho\lambda} &= P^{((\rho\mu)(\alpha\beta))} g^{\nu\lambda} + P^{((\rho\nu)(\alpha\beta))} g^{\mu\lambda} - P^{((\mu\nu)(\alpha\beta))} g^{\rho\lambda} - P^{((\rho\lambda)(\alpha\beta))} g^{\mu\nu} \\ P^{((\alpha\beta)(\mu\nu))} &= \frac{1}{4} \left(g^{\alpha\mu} g^{\beta\nu} + g^{\alpha\nu} g^{\beta\mu} - g^{\alpha\beta} g^{\mu\nu} \right), \end{aligned} \quad (6)$$

where $(\mu\nu)$ denotes that μ and ν are in a totally symmetric combination. An important fact to notice is that our equations are of second order in derivatives which is needed to preserve causality.

$\tilde{\delta}$ Gravity action and equation of motion

- The equations of motion are:

$$G^{\mu\nu} = \kappa T^{\mu\nu} \qquad (7)$$

$$F^{(\mu\nu)(\alpha\beta)\rho\lambda} D_\rho D_\lambda \tilde{g}_{\alpha\beta} + \frac{1}{2} g^{\mu\nu} R^{\alpha\beta} \tilde{g}_{\alpha\beta} - \frac{1}{2} \tilde{g}^{\mu\nu} R = \kappa \tilde{T}^{\mu\nu}. \qquad (8)$$

On the other side, it is possible to demonstrate that:

$$\tilde{\delta}\left[G_{\mu\nu}\right] = F_{(\mu\nu)}^{(\alpha\beta)\rho\lambda} D_\rho D_\lambda \tilde{g}_{\alpha\beta} + \frac{1}{2} g_{\mu\nu} R^{\alpha\beta} \tilde{g}_{\alpha\beta} - \frac{1}{2} \tilde{g}_{\mu\nu} R. \qquad (9)$$

This means that $(8)_{\mu\nu} = \tilde{\delta}\left[(7)_{\mu\nu}\right]$.

- Besides, we have two conservation rules:

$$D_\nu T^{\mu\nu} = 0 \qquad (10)$$

$$D_\nu \tilde{T}^{\mu\nu} = \frac{1}{2} T^{\alpha\beta} D^\mu \tilde{g}_{\alpha\beta} - \frac{1}{2} T^{\mu\beta} D_\beta \tilde{g}^\alpha_\alpha + D_\beta (\tilde{g}^\beta_\alpha T^{\alpha\mu}). \qquad (11)$$

It is easy to see that (11) is $\tilde{\delta}\left(D_\nu T^{\mu\nu}\right) = 0$. In conclusion, the equations of our model are (7), (8), (10) and (11).

Outline

Perfect Fluid

- The energy-momentum tensors are

$$T_{\mu\nu} = p(\rho)g_{\mu\nu} + (\rho + p(\rho))\, U_\mu U_\nu \tag{12}$$

$$\tilde{T}_{\mu\nu} = p(\rho)\tilde{g}_{\mu\nu} + \frac{\partial p}{\partial \rho}(\rho)\tilde{\rho} g_{\mu\nu} + \left(\tilde{\rho} + \frac{\partial p}{\partial \rho}(\rho)\tilde{\rho}\right) U_\mu U_\nu + (\rho + p(\rho))\left(\frac{1}{2}\left(U_\nu U^\alpha \tilde{g}_{\mu\alpha} + U_\mu U^\alpha \tilde{g}_{\nu\alpha}\right) + U^T_\mu U_\nu + U_\mu U^T_\nu\right) \tag{13}$$

  with $U_\alpha = e^a{}_\alpha u_a$ and $U^\alpha_T = e^{\alpha a}\tilde{u}_a$, where $e^a{}_\alpha$ is the Veirbein.
- Now, we can use (12) and (13) to solve (7), (8), (10) and (11) for a perfect fluid.

Outline

Test Particles and Harmonic Gauge

- When we apply $\tilde{\delta}$ prescription to study test particles we found:
  - Free massive particles do not follow a geodesic.
  - Massless particles trajectories are null geodesics of an effective metric $\mathbf{g}_{\mu\nu} = g_{\mu\nu} + \kappa_2 \tilde{g}_{\mu\nu}$.
- Beside, in this prescription the harmonic gauge is extended, and for FLRW the effective metric for photons is

$$\begin{aligned} \mathbf{g}_{\mu\nu} &= g_{\mu\nu} + \kappa_2 \tilde{g}_{\mu\nu} \\ &= -(1 + 3\kappa_2 F_a(t))c^2 dt^2 + R^2(t)(1 + \kappa_2 F_a(t))(dx^2 + dy^2 + dz^2) \,. \end{aligned} \quad (14)$$

Outline

Photon Trajectory, Luminosity Distance and Angular Distance

When a photon emitted from a supernova travels to the Earth, the Universe is expanding. This means that the photon is affected by the cosmological Doppler effect. For this, let's use a null geodesic in a radial trajectory from r_1 to $r = 0$. So we have

$$-(1 + 3\kappa_2 F_a(t))c^2 dt^2 + R^2(t)(1 + \kappa_2 F_a(t))dr^2 = 0.$$

In GR, we have that $cdt = -R(t)dr$. So, in the $\tilde{\delta}$ Gravity case, we can define the effective scale factor:

$$\tilde{R}(t) = R(t)\sqrt{\frac{1 + \kappa_2 F_a(t)}{1 + 3\kappa_2 F_a(t)}} \tag{15}$$

such that $cdt = -\tilde{R}(t)dr$ now. If we integrate this expression from r_1 to 0, we obtain:

$$r_1 = c\int_{t_1}^{t_0} \frac{dt}{\tilde{R}(t)}, \tag{16}$$

Photon Trajectory, Luminosity Distance and Angular Distance

If a second wave crest is emitted at $t = t_1 + \Delta t_1$ from $r = r_1$, it will reach $r = 0$ at $t = t_0 + \Delta t_0$, so:

$$r_1 = c \int_{t_1+\Delta t_1}^{t_0+\Delta t_0} \frac{dt}{\tilde{R}(t)}. \tag{17}$$

Therefore, for Δt_1, Δt_0 small, which is appropriate for light waves, we get:

$$\frac{\Delta t_0}{\Delta t_1} = \frac{\tilde{R}(t_0)}{\tilde{R}(t_1)} \tag{18}$$

Photon Trajectory, Luminosity Distance and Angular Distance

or:

$$\frac{\Delta\nu_1}{\Delta\nu_0} = \frac{\tilde{R}(t_0)}{\tilde{R}(t_1)}, \tag{19}$$

where ν_0 is the light frequency detected at $r = 0$, corresponding to a source emission at frequency ν_1. So, the redshift is now:

$$1 + z(t_1) = \frac{\tilde{R}(t_0)}{\tilde{R}(t_1)}. \tag{20}$$

We see that $\tilde{R}(t)$ replaces the usual scale factor $R(t)$ to compute z.

Photon Trajectory, Luminosity Distance and Angular Distance

One can show that the luminosity distance is given by:

$$d_L = c\frac{\tilde{R}^2(t_0)}{\tilde{R}(t_1)}\int_{t_1}^{t_0}\frac{dt}{\tilde{R(t)}}\,. \qquad (21)$$

And the angular distance is:

$$\begin{aligned} d_A &= \frac{\tilde{R}^2(t_1)}{\tilde{R}^2(t_0)}d_L \\ &= \frac{d_L}{(1+z_1)^2}\,. \end{aligned} \qquad (22)$$

Therefore, the relation between d_A and d_L is the same to GR.

Einstein's Equations

- The usual cosmological solution is still valid. So, if we use $U_\mu = (c, 0, 0, 0)$, the equations for $g_{\mu\nu}$ are reduced to:

$$\left(\frac{\dot{R}(t)}{R(t)}\right)^2 = \frac{\kappa c^2}{3}\sum_i \rho_i(t) \quad (23)$$

$$\dot{\rho}_i(t) = -\frac{3\dot{R}(t)}{R(t)}(\rho_i(t) + p_i(t)). \quad (24)$$

Einstein's Equations

- To solve (23) and (24), we need equations of state which relate $\rho_i(t)$ and $p_i(t)$, for which we take $p_i(t) = \omega_i \rho_i(t)$. With this we get the exact solutions:

$$\rho(Y) = \rho_M(Y) + \rho_R(Y) = \frac{3H_0^2\Omega_R}{\kappa c^2 C}\frac{Y+C}{Y^4} \tag{25}$$

$$p(Y) = \frac{1}{3}\rho_R(t) = \frac{H_0^2\Omega_R}{\kappa c^2}\frac{1}{Y^4} \tag{26}$$

$$t(Y) = \frac{2\sqrt{C}}{3H_0\sqrt{\Omega_R}}\left(\sqrt{Y+C}(Y-2C) + 2C^{\frac{3}{2}}\right) \tag{27}$$

$$Y = \frac{R(t)}{R_0}, \tag{28}$$

where $t(Y)$ is the time variable, R_0 is the scale factor in the present, $C = \frac{\Omega_R}{\Omega_M}$, and Ω_R and Ω_M are the radiation and non-relativistic matter density in the present respectively, with $\Omega_M = 1 - \Omega_R$. We know that $\Omega_R \ll 1$, so $\Omega_M \sim 1$ and $C \ll 1$. We can see that it is convenient to use Y like our independent variable. By definition $Y \gg C$ describes the non-relativistic era and $Y \ll C$ describes the radiation era.

$\tilde{\delta}$ Gravity with $\tilde{\delta}$ Matter

- In this case we have a new energy-momentum tensor $\tilde{T}_{\mu\nu}$, so we have $\tilde{\delta}$ non-relativistic matter and radiation densities, given by $\tilde{\rho}_M$ and $\tilde{\rho}_R$ respectively. The solutions are:

$$
\begin{aligned}
F_a(Y) &= \frac{3}{2}(2C_2 - C_1)\frac{Y}{C}\left(\sqrt{\frac{Y}{C}+1}\ln\left(\frac{\sqrt{\frac{Y}{C}+1}+1}{\sqrt{\frac{Y}{C}+1}-1}\right)-2\right) \\
&\quad -2C_2 + C_3\frac{Y}{C}\sqrt{\frac{Y}{C}+1} \qquad (29) \\
\tilde{\rho}_M(Y) &= \frac{9H_0^2\Omega_R}{2\kappa c^2 C}\frac{(C_1 - F_a(Y))}{Y^3} \qquad (30) \\
\tilde{\rho}_R(Y) &= \frac{6H_0^2\Omega_R}{\kappa c^2}\frac{(C_2 - F_a(Y))}{Y^4}, \qquad (31)
\end{aligned}
$$

where C_1, C_2 and C_3 are integration constants.

$\tilde{\delta}$ Gravity with $\tilde{\delta}$ Matter

- Now, if we use (29) in the expression of $\tilde{R}$ and define $\tilde{Y} = \frac{\tilde{R}(t)}{R(t_0)}$, the effective scale factor is:

$$\tilde{Y}(Y, L_1, L_2, C) = Y \sqrt{\frac{1 - L_2 \frac{Y}{3}\sqrt{Y+C} + L_1 \frac{Y}{C}\left(\sqrt{\frac{Y}{C}+1}\ln\left(\frac{\sqrt{\frac{Y}{C}+1}+1}{\sqrt{\frac{Y}{C}+1}-1}\right) - 2\right)}{1 - L_2 Y\sqrt{Y+C} + 3L_1 \frac{Y}{C}\left(\sqrt{\frac{Y}{C}+1}\ln\left(\frac{\sqrt{\frac{Y}{C}+1}+1}{\sqrt{\frac{Y}{C}+1}-1}\right) - 2\right)}}, \quad (32)$$

  where we used $C_1 = -\frac{2L_1}{3\kappa_2}$, $C_3 = -\frac{C^{\frac{3}{2}} L_2}{3\kappa_2}$. L_1 and L_2 are new constants.

- We have that $\tilde{Y} \sim Y$ in the radiation era, that is $Y \ll C$, so the Universe evolves normally at its beginning, without differences with GR. But, when $Y \gg C$, and accelerated expansion is produced, ending in a Big-Rip when the denominator is null.

Outline

Important results in DG

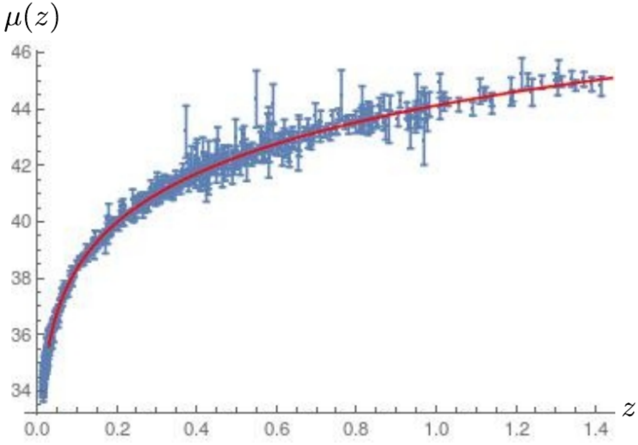

Figure: Distance modulus vs Redshift. We have fitted 580 supernovae with $\chi^2 = 0.99998$.

Important results in DG

- When we fix the model with supernovae data we get the free parameters

	Estimate	Standard Error
L1	0.497656	0.0152317
L2	0.976514	0.0150707
C	0.000182913	4.18236×10^{-6}

- With the parameters fixed, we can get important results, as the age of the universe

$$t_0 = 1.36889 \times 10^{10} \pm 1.56417 \times 10^{8} \text{ years}, \tag{33}$$

- also we get the Hubble constant

$$\tilde{H}_0 = 70.43 \pm 1.45 \text{ km/(s Mpc)}, \tag{34}$$

- and the deceleration parameter $\tilde{q}(t)$, defined as

$$\tilde{q}(t) = -\frac{\ddot{\tilde{Y}}(t)\tilde{Y}(t)}{\dot{\tilde{Y}}^2(t)}, \tag{35}$$

- in particular we get $\tilde{q}_0 = -0.73 \pm 0.04$.

$\tilde{Y}(t)$ and $\tilde{q}(t)$

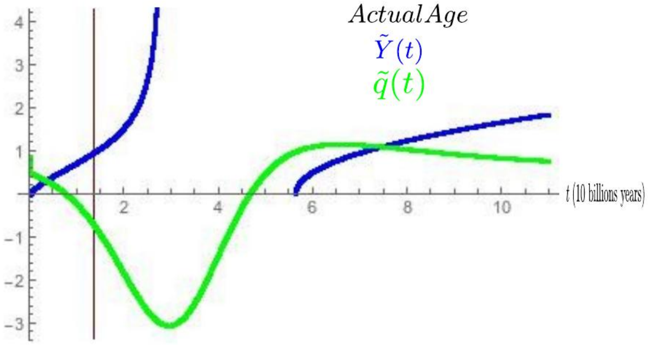

Figure: Effective scale factor and deceleration parameter.

Outline

Extended Newtonian and Synchronous Gauges

- **Extended Newtonian Gauge**.

  - In GR, Newtonian gauge is a perturbed form of the FLRW line element. The gauge freedom of GR is used to eliminate two scalar degrees of freedom of the metric, so that it can be written as

$$ds^2 = -(1+2\Phi)dt^2 + R^2(t)(1-2\Psi)\delta_{ij}dx^i dx^j \,. \tag{36}$$

  - However, in DG we still have gauge freedom. We can eliminate this new two scalar degrees of freedom in the same way. Both choices are unique, so that after choosing (Extended) Newtonian gauge, there is no remaining freedom to make gauge transformations and the metric is

$$d\tilde{s}^2 = -3F_a(t)(1+2\tilde{\Phi})dt^2 + F_a(t)R^2(t)(1-2\tilde{\Psi})\delta_{ij}dx^i dx^j \,. \tag{37}$$

- **Extended Synchronous gauge**.
  - Here the standard fixing is given by the metric

$$ds^2 = -dt^2 + R^2(t)\left[(1+A)\delta_{ij} + \frac{\partial B}{\partial x^i \partial x^j}\right] dx^i dx^j \,. \tag{38}$$

  - Nevertheless this choice do not fix the gauge completely and we have a residual gauge invariance given by an arbitrary function $\tau(\mathbf{x})$ of $\mathbf{x}$, but not of t.
  - In DG, the form of the perturbation is similar and also we have another residual gauge given by another arbitrary function $\sigma(\mathbf{x})$. The metrix is given by

$$d\tilde{s}^2 = -3F_a(t)dt^2 + F_a(t)R^2(t)\left[(1+\tilde{A})\delta_{ij} + \frac{\partial \tilde{B}}{\partial x^i \partial x^j}\right] dx^i dx^j \,. \tag{39}$$

- This arbitrary functions could be use to remove the cold dark matter velocity potential δu_D and the delta matter velocity potential $\delta\tilde{u}_D$ because one can prove that both are time-independent.

Outline

The CMB

- The study of the CMB in DG will be a great test for the theory. And it will help us to improve the estimation of the free parameters.

- The choice of the gauge will be important in order of implement this new equations in codes, such as CAMB or CLASS. Even one could try with a mixture of both gauges.

- For now we are trying to rewrite the equations *à la* standard form like Friedmann equations, this will be useful for an optimal modification of the codes.

- Preliminar estimation of the acoustic peak show a good concordance with the standard results, due it depends of the angular distance and DG has the same relation as GR ($d_A = d_L/(1+z)^2$).

Summary

- Due the problems in GR with the interpretation of the dark sector in terms of fundamental theories of elementary particles, is suggestive try new theories.

[1] Riess, A. *et al.* Astrophys. J. 826 (2016) no. 1, 56 axXiv:1604.01424

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- Due the problems in GR with the interpretation of the dark sector in terms of fundamental theories of elementary particles, is suggestive try new theories.
- We present a new theory, called Delta Gravity (DG), based in two symmetric tensors.

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Summary

- Due the problems in GR with the interpretation of the dark sector in terms of fundamental theories of elementary particles, is suggestive try new theories.
- We present a new theory, called Delta Gravity (DG), based in two symmetric tensors.
- DG does not need dark energy in order to explain the observed acceleration of the Universe. The age of the Universe is in accord with the accepted actual age of the Universe predicted by ΛCDM model. Also the Hubble constants are in accord with all the observed values until now, even with the last Hubble Space Telescope result $H_0 = 73.02 \pm 1.79$ km/(s Mpc)[1], where ΛCDM is out of error range.

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- In this way we are working in the computation of the CMB Power Spectrum, this will help us to fix the free parameters and compare with supernovae data. A great discordances between both test means that DG is not a good theory and we should start to work in other theories.

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This presentation was based in the following references:

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