Perturbations on a cosmological model with non-null Weyl tensor

Grasiele B. Santos[1]

University of Rome "La Sapienza"
and ICRANet

Hot Topics in General Relativity and Gravitation

Quy Nhon, Vietnam, August 2015.

[1] In collaboration with E. Bittencourt and J. Salim, *JCAP* 06 (2015) 013.

Outline

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- We consider a class of Friedmann-type metrics with constant spatial curvature and with a stochastic magnetic field as matter content.
- An anistropic pressure component sourced by this field is considered and it is found to be related to a non-null Weyl tensor.
- We analyse the gravitational stability of this model under **linear scalar perturbations** using the covariant gauge-invariant approach in order to understand the role of the Weyl tensor in structure formation in this context.

Outline

- Let's consider

$$ds^2 = dt^2 - a^2(t)[d\chi^2 + \sigma^2(\chi)d\Omega^2], \quad (1)$$

where t represents the cosmic time, $a(t)$ is the scale factor and $\sigma(\chi)$ is an arbitrary function.

- We then take as source the EM field with

$$\overline{E_i} = 0, \quad \overline{B_i} = 0, \quad \overline{E_i B_j} = 0, \quad \overline{E^i E_i} = 0 \quad (2)$$

$$\overline{B^i B_j} = -\frac{1}{3} B^2 h^i{}_j - \pi^i{}_j. \quad (3)$$

Therefore,

$$T_{\mu\nu} = (\rho + p) V_\mu V_\nu - p g_{\mu\nu} + \pi_{\mu\nu}, \quad (4)$$

with $p = \frac{1}{3}\rho$ and $\rho = \frac{B^2(t)}{2}$.

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with $p = \frac{1}{3}\rho$ and $\rho = \dfrac{B^2(t)}{2}$.

- Einstein equations admit a solution with constant spatial curvature and $\pi^{\mu}{}_{\nu}$ only if

$$\pi^2{}_2 = \pi^3{}_3, \qquad \pi^1{}_1 = -2\pi^2{}_2, \quad \text{where} \quad \pi^1{}_1 = \frac{2k}{a^2\,\sigma^3}, \tag{5}$$

where k is an integration constant[2]. We can rewrite the metric as

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-\epsilon r^2 - \frac{2k}{r}} + r^2 d\Omega^2\right). \tag{6}$$

- FLRW is regained whenever $2k \ll r$. From the evolution equation for the shear tensor and $V^{\mu} = \delta^{\mu}_{0}$ we get[3]

$$E_{\mu\nu} \doteq -W_{\mu\alpha\nu\beta}V^{\alpha}V^{\beta} = -\frac{1}{2}\pi_{\mu\nu}. \tag{7}$$

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- The remaining equations are

$$\dot{\theta} + \frac{\theta^2}{3} = -\frac{1}{2}(\rho + 3p), \tag{8a}$$

$$\dot{\rho} + (\rho + p)\,\theta = 0, \tag{8b}$$

$$E^{\alpha}{}_{\mu;\alpha} = 0, \tag{8c}$$

$$h^{\epsilon}{}_{\mu} h^{\nu}{}_{\lambda} \dot{E}^{\mu}{}_{\nu} + \frac{2}{3}\,\theta\, E^{\epsilon}{}_{\lambda} = 0. \tag{8d}$$

- The model can be extended to any equation of state (EOS) of the form $p = (\gamma - 1)\rho$, which is also valid for a mixture of non-interacting fluids.

Outline

- We take into account only the spatial scalar harmonic functions $Q_{(m)}(x^k)$ and its derived vector and tensor quantities:

$$Q_i \doteq Q_{,i}, \quad Q_{ij} \doteq Q_{,i||j} = Q_{,i;j}.$$

- These functions satisfy

$$\nabla^2 Q_{(m)} = m^2 Q_{(m)}, \tag{9}$$

where m is a constant (the wave number) and

$$\nabla^2 Q \doteq \gamma^{ij} Q_{,i||j} = \gamma^{ij} Q_{,i;j}, \tag{10}$$

defines the 3-dimensional Laplace-Beltrami operator.

- Then

$$Q(r,\theta,\phi) = \sum_{l,n} R(r) Y_l^n(\theta,\phi),$$

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- We define the traceless operator

$$\hat{Q}_{ij} = \frac{1}{m^2} Q_{ij} - \frac{1}{3} Q \gamma_{ij}, \tag{11}$$

and its divergence can be computed yielding

$$\hat{Q}^j{}_{i||j} = 2\left(\frac{1}{3} - \frac{\epsilon}{m^2}\right) Q_i - \frac{\pi_{ij}}{m^2} Q^j. \tag{12}$$

- In this model, we also need to consider the expansion of the terms

$$\pi_{ij} \hat{Q}^{ij}_{(m)} = \sum_l a_{l(m)} Q_{(l)}, \tag{13}$$

$$\pi_{ij} Q^j_{(m)} = \sum_l b_{l(m)} Q_{i(l)}, \tag{14}$$

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and

$$\frac{1}{2}\pi_{k(i}\hat{Q}_{j)}{}^{k}{}_{(m)} = \sum_{l} c_{l(m)}\hat{Q}_{ij(l)} + \frac{\gamma_{ij}}{3}\sum_{l} a_{l(m)}Q_{(l)}, \qquad (15)$$

where the coefficients $a_{l(m)}$, $b_{l(m)}$ and $c_{l(m)}$ are constants for each of the modes m and l.

- Assuming small deviations of the metric given in (6) wrt to FLRW, the quantities

$$A_{(m)} \doteq \sum_{l} a_{l(m)}, \quad B_{(m)} \doteq \sum_{l} b_{l(m)}, \quad C_{(m)} \doteq \sum_{l} c_{l(m)},$$

should be bounded. They are determined through the full solution for the basis and depend on k.

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Outline

- According to the evolution equation for the shear tensor, we can define

$$X_{\mu\nu} \doteq E_{\mu\nu} + \frac{1}{2}\pi_{\mu\nu}, \tag{16}$$

which is a good variable as it is null in the background.

- Following Ellis & Bruni[4], we also consider the fractional energy density gradient

$$\chi_\alpha \doteq a(t) h_\alpha{}^\nu \frac{\rho_{,\nu}}{\rho}, \tag{17}$$

and the gradient of the expansion coefficient

$$Z_\alpha \doteq a(t) h_\alpha{}^\nu \theta_{,\nu}. \tag{18}$$

- To this set of variables we add: the acceleration a_μ, $\sigma_{\mu\nu}$ and the divergence of the anisotropic pressure $l_\mu \equiv h_\mu{}^\epsilon \pi_\epsilon{}^\nu{}_{;\nu}$.

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- The perturbed equation for X is given by

$$h^{\epsilon}_{\mu}h^{\lambda}_{\nu}\delta\dot{X}_{\epsilon\lambda} + \theta\delta X_{\mu\nu} + \frac{1}{2}\pi_{\alpha(\mu}\delta\sigma_{\nu)}{}^{\alpha} - \frac{1}{3}\pi_{\alpha\beta}\delta\sigma^{\alpha\beta}h_{\mu\nu} = -\frac{1}{2}\gamma_{ef}\rho\delta\sigma_{\mu\nu} + \delta D_{\mu\nu}, \quad (19)$$

where $\delta D_{\mu\nu} = \xi\theta\delta\sigma_{\mu\nu}$ comes from the causal thermodynamical relation[5]

$$\tau\dot{\pi}_{\mu\nu} + \pi_{\mu\nu} = \xi\sigma_{\mu\nu}$$

with $\tau \propto 1/\theta$.

- Using the basis just defined we set

$$\delta X_{ij} = X(t)\hat{Q}_{ij}, \quad \delta\sigma_{ij} = \sigma(t)\hat{Q}_{ij},$$
$$\delta\chi_i = \tilde{\chi}(t)Q_i, \quad \delta Z_i = Z(t)Q_i,$$
$$\delta a_i = \psi(t)Q_i \quad \delta I_i = I(t)\hat{Q}_i. \quad (20)$$

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The perturbed equations then result

$$\dot{X} + \theta X + \left(-\frac{C}{a^2} + \frac{1}{2}\gamma_{ef}\rho - \xi\theta \right) \sigma = 0, \tag{21}$$

$$\dot{\sigma} - m^2\psi + X = 0, \tag{22}$$

$$\dot{Z} + \left(a\,\dot{\theta} - \frac{m^2}{a^2} \right) \psi + \frac{2\theta}{3a} Z + \frac{1}{2}(3\gamma_{ef} - 1)\rho_t\tilde{\chi} = 0, \tag{23}$$

$$\dot{\tilde{\chi}} + \gamma_{ef} Z - \frac{1}{a^3}\frac{A}{\rho_t}\sigma - a\gamma_{ef}\theta\psi = 0. \tag{24}$$

Together with the constraints we get a system of dynamical equations that is closed in 3 variables.

Long wavelength regime

- We can use the local decomposition in irreducible parts of the projected covariant derivative of χ_μ as

$$a{h_\mu}^\lambda {h_\nu}^\epsilon \chi_{\lambda;\epsilon} = \frac{1}{3} h_{\mu\nu}\Delta + \Sigma_{\mu\nu} + W_{\mu\nu}, \qquad (25)$$

  where $W_{\mu\nu}$ gives the anti-symmetric part, $\Sigma_{\mu\nu}$ is the symmetric traceless part and the variable Δ is the scalar gauge invariant variable that represents the clumping of matter[6].

- The equation for Δ can be derived from Eq. (24) and up to first order reads

$$\dot{\Delta} = \frac{a^2}{\rho_t} h^{\alpha\beta}(\pi_{\mu\nu}\sigma^{\mu\nu})_{,\alpha;\beta} - \gamma_{ef}\, a h^{\alpha\beta} Z_{\alpha;\beta} + a^2 \gamma_{ef}\theta h^{\alpha\beta} a_{\alpha;\beta}. \quad (26)$$

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- In terms of a 2nd order equation:

$$\sigma'' + 2\frac{a'}{a}\sigma' + \left(C - \frac{1}{2}\gamma_{ef}\, a^2 \rho_t\right)\sigma = 0, \qquad (27)$$

whose solution for a dust dominated phase ($\gamma_{ef} = 1$ and $a \propto \eta^2$) is

$$\sigma(\eta) = \frac{c_1}{\eta^{3/2}} \mathrm{J}\left(\frac{\sqrt{33}}{2}, \sqrt{C}\eta\right) + \frac{c_2}{\eta^{3/2}} \mathrm{Y}\left(\frac{\sqrt{33}}{2}, \sqrt{C}\eta\right), \qquad (28)$$

where J and Y are Bessel functions of first and second kind.

- Writing $\delta\Delta = \chi(\eta)Q(x^i)$ we have from Eq. (26)

$$\chi'(\eta) = -\frac{Am^2}{\rho\, a}\sigma(\eta) - \frac{3\gamma_{ef}\, m^2}{2}\left(\frac{2}{3}a - \frac{B}{am^2}\right)\sigma(\eta). \qquad (29)$$

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- Using the limit of small values of the argument in (28), $\sqrt{C}\eta \ll 1$, we explicitly obtain

$$\chi(\eta) = \frac{c_1}{\Gamma\left(\frac{\sqrt{33}}{2}\right)}\left[\frac{3(\sqrt{33}+5)}{8}B + \frac{(3-\sqrt{33})m^2\,\eta^4}{12\,{\eta_0}^4} + \right.$$
$$\left. + \frac{(\sqrt{33}-7)Am^2\,\eta^6}{96\,{\eta_0}^4}\right]\frac{\left(\sqrt{C}\eta\right)^{\frac{\sqrt{33}}{2}}}{(\eta/\eta_0)^{5/2}} \quad (30)$$

- The corresponding solution in a matter-dominated FLRW case is[7]

$$\chi(\eta) = \frac{c_1}{6}m^2\left(\frac{\eta}{\eta_0}\right)^2.$$

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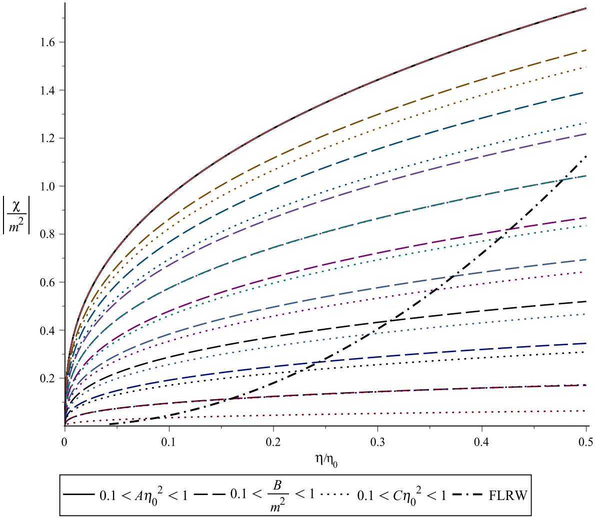

1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$\left|\frac{\chi}{m^2}\right|$
0
0.1
0.2
0.3
0.4
0.5
η/η_0
$0.1 < A\eta_0^2 < 1$
$0.1 < \frac{B}{m^2} < 1$
$0.1 < C\eta_0^2 < 1$
FLRW

Outline

- We have performed a perturbative analysis of a quasi-Friedmann model with a **non-null Weyl tensor**. We have adopted the **covariant and gauge-invariant approach** to perturbations and suitable gauge-invariant variables directly related to observational quantities were used.
- It is shown that, for a large range of values for the parameters involved, it is possible to have a **faster growing mode** for the perturbations, which could in principle play the role of dark matter in structure formation (preliminary analysis though!).
- We should understand and try to find explicit expressions for the quantities A, B and C which would also provide their dependence on the wavenumber that is needed to treat the issue of scale invariance (**Harrison-Zeldovich spectrum**) of the perturbations and the asymptotic behaviors for small wavenumbers.

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Thank you for your attention!