A possible explanation for phantom dark energy

Hermano Velten (UFES)

based on
HV, Jiaxin Wang (Nankai) and Xinhe Meng (Kavli/Beijing)
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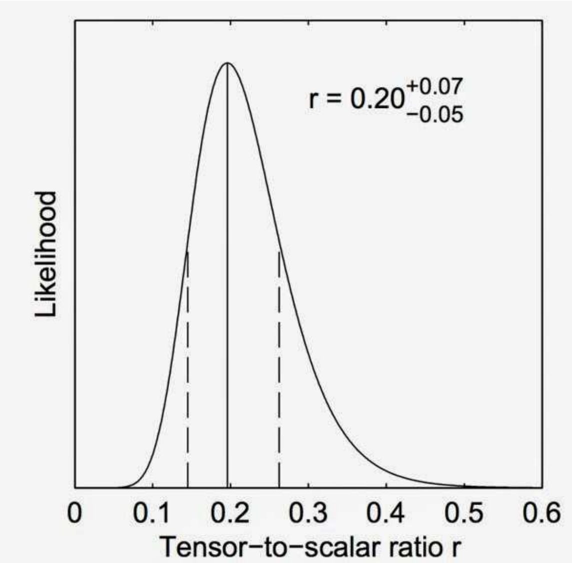
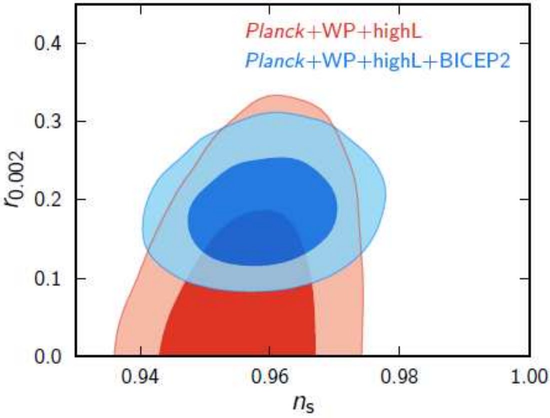


$r = 0.20^{+0.07}_{-0.05}$
Likelihood
0
0.1
0.2
0.3
0.4
0.5
0.6
Tensor−to−scalar ratio r


Planck+WP+highL
Planck+WP+highL+BICEP2
0.4
0.3
0.2
0.1
0.0
$r_{0.002}$
0.94
0.96
0.98
1.00
n_s

Dealing with gravity: Einstein equations

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = T_{\mu\nu} \tag{1}$$

$$T_{\mu\nu} = \rho u_\mu u_\nu + p(g_{\mu\nu} + u_\mu u_\nu) \tag{2}$$

An expanding, homogeneous and isotropic background is described by the FLRW metric:

$$ds^2 = -dt^2 + a(t)^2 \left(\frac{dr^2}{\sqrt{1-kr^2}} + r^2(d\theta^2 + sin^2\theta d\phi^2)\right) \tag{3}$$

Bianchi Identitities $\rightarrow \nabla^\mu G_{\mu\nu} = 0 \rightarrow \nabla^\mu T_{\mu\nu} = 0$.
Then we have matter-energy conservation:

$$\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + p) = 0 \tag{4}$$

Friedmann's equation and cosmic fluids

$$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \tag{5}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \tag{6}$$

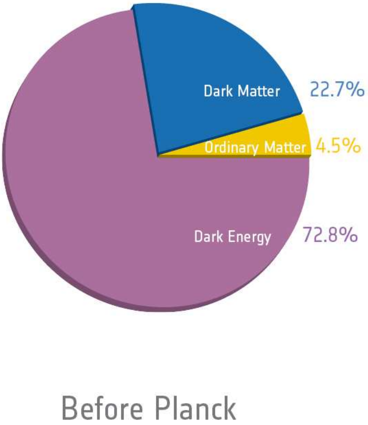
- Baryonic matter e.g. stars and gases. Non-relativistic components: $p_b = 0 \rightarrow \rho_m = \frac{\rho_{b0}}{a^3} = \rho_{b0}(1+z)^3$
- Photons and "primordial" neutrinos. Relativistic components: $p_r = \frac{\rho_r}{3} \rightarrow \rho_r = \frac{\rho_{r0}}{a^4} = \rho_{r0}(1+z)^4$
- Cold Dark Matter (CDM). Non-relativistic components: $p_{dm} = 0 \rightarrow \rho_{dm} = \frac{\rho_{dm0}}{a^3} = \rho_{dm0}(1+z)^3$
- Cosmological constant Λ: $p_\Lambda = -\rho_\Lambda \rightarrow \rho_\Lambda = \rho_\Lambda$ or some kind of dark energy $p_{de} = w\rho_{de}$, with $w < -\frac{1}{3}$, $\rightarrow \rho_{de} = \rho_{de0}(1+z)^{3(1+w)}$

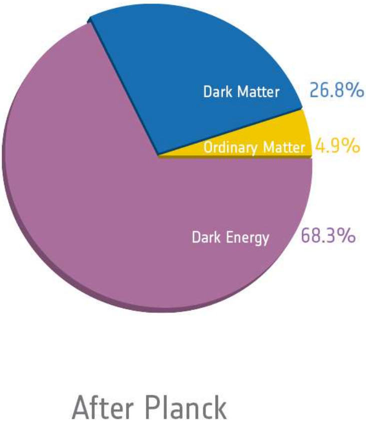
One can also define the fractionary density parameter: $\Omega_i = \frac{\rho_i}{\rho_{crt}}$, where $\rho_{crt} = 3H_0^2/8\pi G$

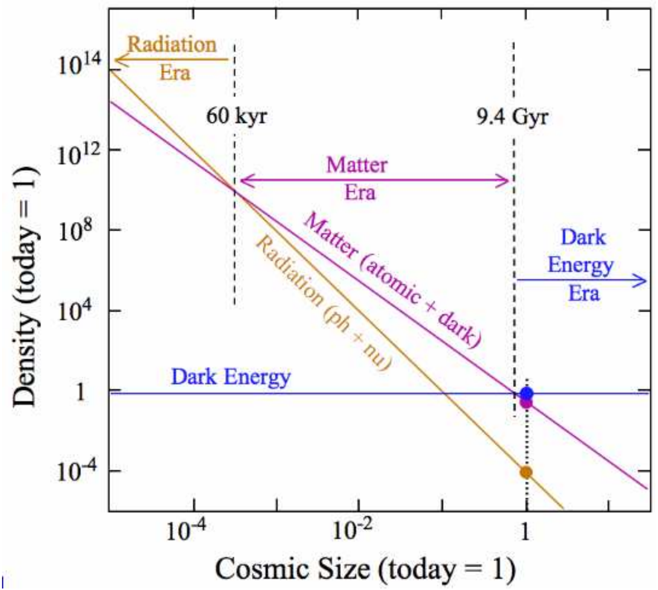
$$\frac{H^2}{H_0^2} = \Omega_{b0}(1+z)^3 + \Omega_{dm0}(1+z)^3 + \Omega_\nu(z) + \Omega_{r0}(1+z)^4 + \Omega_{de0}(1+z)^{3(1+w)} \quad (7)$$

For a flat universe: $k = 0$:

- In a first approach te neutrino background contribution can de discarded, i.e., $\Omega_\nu = 0$.
- Ω_{b0} is well constrained by nucleosynthesis: $\Omega_{b0} \sim 0.04$
- Ω_{r0} is determined by the temperature of the CMB photons. $\Omega_{r0} \sim 10^{-5}$
- Our task is to determine the today's dark matter density Ω_{dm0} (equivalently the dark energy density Ω_{de0}) and the EoS parameter w.


Dark Matter
22.7%
Ordinary Matter
4.5%
Dark Energy
72.8%
Before Planck


Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%
After Planck


Radiation
Era
60 kyr
9.4 Gyr
Matter
Era
Matter (atomic + dark)
Radiation (ph + nu)
Dark
Energy
Era
Dark Energy
Density (today = 1)
10^{14}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-4}
10^{-2}
1
Cosmic Size (today = 1)

DE equation of state

Energy conditions

- The weak energy condition $\rho \geq 0, \rho + p \geq 0$
- The null energy condition $\rho + p \geq 0$
- The strong energy condition $\rho + p \geq 0, \rho + 3p \geq 0$
- The dominant energy condition $\rho \geq |p|$

DE equation of state

One of the biggest questions in cosmology is the actual value of $w_{\rm de}$.
Phantom dark energy models have been preferred by most of the observations! The inferred value for the equation of state parameter being slightly bellow $w_{\rm de} = -1$.
(W. Godlowski M. Szydlowski, Phys.Lett.B**623**, 10 (2005); R. Amanullah, *et al*, Astrophys. J. **716**, 712 (2010))

Current notable results are

- $w_{\rm de} = -1.04^{+0.09}_{-0.10}$ (K. Nakamura *et al*, [Particle Data Group], J. Phys. G **37**, 075021 (2010).);
- $w_{\rm de} = -1.10^{+0.14}_{-0.14}$ (E. Komatsu et al., Astrophys. J. Suppl. **192**, 18 (2011).);
- and the recent results from Planck satellite $w_{\rm de} = -1.49^{+0.65}_{-0.57}$ (Planck Collaboration, arXiv:1303.5076v1, Submitted to Astronomy & Astrophysics.).

Although for all these results the error bars cover the case $w_{\rm de} = -1$, it is worth noting a tendency for phantom values for the dark energy equation of state.

Phantom or Quintessence?

- B. Novosyadlyj, O. Sergijenko, R. Durrer and V. Pelykh, Phys. Rev. **D86**, 083008 (2012)
- B. Novosyadlyj, O. Sergijenko, R. Durrer, V. Pelykh, Journal of Cosmology and Astroparticle Physics, Issue 06, 042 (2013)

Degeneracy in bulk viscous cosmologies

As a consequence of the Bianchi identities the total energy-momentum tensor is conserved $\nabla_{\mu} T^{\mu\nu} = 0$, then

$$\dot{\rho}_{\rm eff} + 3\mathrm{H} \left(\rho_{\rm eff} + P_{\rm eff}\right) = 0. \quad (8)$$

Degeneracy in bulk viscous cosmologies

Let us assume that bulk viscosity in the universe is a collective phenomena acting on the global dynamics such that we rewrite (8) as

$$\dot{\rho}_{eff} + 3H\left(\rho_{eff} + P_{per} + \Pi\right) = 0, \tag{9}$$

where the effective pressure is now decomposed into perfect-fluid pressure p_{per} and the viscous pressure, which in the Eckart formalism reads $\Pi = -3H\xi$.

Degeneracy in bulk viscous cosmologies

Now, we turn our attention to the fact that the real universe is made of different i components. Assuming that
$\rho_{\rm eff} = \rho_{\rm r} + \rho_{\rm m} + \rho_{\rm de}$
equation (9) is then written as

$$\dot{\rho}_{\rm m} + \dot{\rho}_{\rm r} + \dot{\rho}_{\rm de} + 3H\left(\rho_{\rm m} + \frac{4}{3}\rho_{\rm r} + \rho_{\rm de} + p_{\rm de} - 3H\xi\right) = 0. \quad (10)$$

Degeneracy in bulk viscous cosmologies: $\xi \equiv \xi(H)$

The degeneracy appears in bulk viscous models with $\xi \equiv \xi(H)$ because we have the freedom to further decompose the above equation mathematically either into the system

$$\dot{\rho}_{\rm m}+3H\left(\rho_{\rm m}-3H\xi\right)=0, \quad \dot{\rho}_{\rm r}+4H\rho_{\rm r}=0, \quad \dot{\rho}_{\rm de}+3H\left(\rho_{\rm de}+p_{\rm de}\right)=0; \tag{11}$$

or into the system

$$\dot{\rho}_{\rm m}+3H\rho_{\rm m}=0, \quad \dot{\rho}_{\rm r}+3H\left(\frac{4}{3}\rho_{\rm r}-3H\xi\right)=0, \quad \dot{\rho}_{\rm de}+3H\left(\rho_{\rm de}+p_{\rm de}\right)=0; \tag{12}$$

or even into

$$\dot{\rho}_{\rm m}+3H\rho_{\rm m}=0, \quad \dot{\rho}_{\rm r}+4H\rho_{\rm r}=0, \quad \dot{\rho}_{\rm de}+3H\left(\rho_{\rm de}+p_{\rm de}-3H\xi\right)=0. \tag{13}$$

The wCDM cosmology

wCDM dynamics:

$$T^{\mu\nu}_{(\mathrm{eff})} = T^{\mu\nu}_{(\mathrm{r})} + T^{\mu\nu}_{(\mathrm{m})} + T^{\mu\nu}_{(\mathrm{de})}, \tag{14}$$

where for the pressure of the fluids we use

$$P_{\mathrm{eff}} = p_{\mathrm{r}} + p_{\mathrm{m}} + p_{\mathrm{de}} = \frac{\rho_{\mathrm{r}}}{3} + w_{\mathrm{de}}\rho_{\mathrm{de}}, \tag{15}$$

where w_{de} is a constant parameter. The background expansion for the wCDM model becomes

$$E^{\mathrm{w}}(z) = \left[\Omega^{\mathrm{w}}_{\mathrm{r0}}(1+z)^4 + \Omega^{\mathrm{w}}_{\mathrm{m0}}(1+z)^3 + \Omega^{\mathrm{w}}_{\mathrm{de0}}(1+z)^{3(1+w_{\mathrm{de}})}\right]^{1/2}, \tag{16}$$

$$(1+z)\frac{dE^{\mathrm{w}}(z)}{dz} = \frac{3}{2}E^{\mathrm{w}}(z)\left\{1 + \frac{w_{\mathrm{de}}\Omega^{\mathrm{w}}_{\mathrm{de0}}(1+z)^{3(1+w_{\mathrm{de}})} + \frac{1}{3}\Omega^{\mathrm{w}}_{\mathrm{r0}}(1+z)^4}{[E^{\mathrm{w}}(z)]^2}\right\} \tag{17}$$

where $E(z) = \mathrm{H}(z)/\mathrm{H}_0$ is the dimensionless expansion parameter. We use the superscript w to identify that the density parameters

Degeneracy in bulk viscous cosmologies: $\xi \equiv \xi(\rho_m)$

Let us now assume a cosmological background composed by standard radiation fluid, dark energy given by cosmological constant Λ and the matter component has bulk viscous pressure

$$T^{\mu\nu}_{(\mathrm{eff})} = T^{\mu\nu}_{(\mathrm{r})} + T^{\mu\nu}_{(\mathrm{vm})} + T^{\mu\nu}_{(\Lambda)}, \qquad (18)$$

where the subscript "vm" stands for viscous matter. The pressure of each component is given by

$$p_{\mathrm{r}} = \frac{\rho_{\mathrm{r}}}{3}, \qquad p_{\mathrm{vm}} = -3\mathrm{H}\xi_{\mathrm{vm}}, \qquad p_{\mathrm{de}} = -\rho_{\mathrm{de}}, \qquad (19)$$

where for the bulk viscous coefficient of the viscous matter we assume

$$\xi_{\mathrm{vm}} \equiv \xi_{\mathrm{vm}}(\rho_{\mathrm{vm}}) = \xi_{\mathrm{vm0}} \left(\frac{\rho_{\mathrm{vm}}}{\rho_{\mathrm{vm0}}} \right)^{\nu}. \qquad (20)$$

Note that for a constant bulk viscous coefficient ($\nu = 0$) the pressure p_{vm} does not depend explicitly on the energy density ρ_{vm}. We have $p_{\mathrm{vm}} \equiv p_{\mathrm{vm}}(\mathrm{H})$ and the previous analysis applies.

Viscosity in the matter fluid: $\xi \equiv \xi(\rho_m)$

$$T^{\mu\nu}_{(\mathrm{eff})} = T^{\mu\nu}_{(\mathrm{r})} + T^{\mu\nu}_{(\mathrm{vm})} + T^{\mu\nu}_{(\Lambda)}, \tag{21}$$

where the subscript "vm" stands for viscous matter. The pressure of each component is given by

$$p_{\mathrm{r}} = \frac{\rho_{\mathrm{r}}}{3}, \qquad p_{\mathrm{vm}} = -3\mathrm{H}\xi_{\mathrm{vm}}, \qquad p_{\mathrm{de}} = -\rho_{\mathrm{de}}, \tag{22}$$

where for the bulk viscous coefficient of the viscous matter we assume

$$\xi_{\mathrm{vm}} \equiv \xi_{\mathrm{vm}}(\rho_{\mathrm{vm}}) = \xi_{\mathrm{vm0}} \left(\frac{\rho_{\mathrm{vm}}}{\rho_{\mathrm{vm0}}}\right)^{\nu}. \tag{23}$$

From the above choice we note that for a constant bulk viscous coefficient ($\nu = 0$) the pressure p_{vm} does not depend explicitly on the energy density ρ_{vm}. Indeed we have $p_{\mathrm{vm}} \equiv p_{\mathrm{vm}}(\mathrm{H})$ and the previous analysis applies again.

Viscosity in the matter fluid: $\xi \equiv \xi(\rho_m)$

For a general value of the parameter ν the dynamics is given by the expression

$$E^{\rm vm}(z) = \left[\Omega_{\rm r0}^{\rm vm}(1+z)^4 + \Omega_{\rm vm}^{\rm vm}(z) + \Omega_{\rm de0}^{\rm vm}\right]^{1/2}, \qquad (24)$$

where the density of the viscous matter has to be determined from the energy balance

$$(1+z)\frac{d\Omega_{\rm vm}}{dz} - 3\Omega_{\rm vm} + \tilde{\xi}_{\rm vm} E^{\rm vm}(z)\left(\frac{\Omega_{\rm vm}}{\Omega_{\rm vm0}}\right)^{\nu} = 0, \qquad (25)$$

with

$$\tilde{\xi}_{\rm vm0} = \frac{24\pi G \xi_{\rm vm0}}{H_0}. \qquad (26)$$

Viscosity in the matter fluid: $\xi \equiv \xi(\rho_m)$

Of course, the degeneracy problem means two cosmological models which result in the same expansion of the universe. Assume that we have two solutions which are named $E_1(z;\theta)$ and $E_2(z;\gamma)$, where $E = \mathrm{H}/\mathrm{H}_0$, θ and γ represent two different parameter sets. If they are degenerate solutions,then $E_1(z;\theta) = E_2(z;\gamma)$. According to this

$$E^{\mathrm{w}}(z) = E^{\mathrm{vm}}(z) \tag{27}$$

should be satisfied. With the above equality we can map parameter-space of the matter viscous model into the parameter-space of wCDM model. Hence, we have

$$\Omega_{\mathrm{vm}}(z) = \Omega^{w}_{\mathrm{m0}}(1+z)^3 + (\Omega^{w}_{\mathrm{r0}} - \Omega_{\mathrm{r0}})(1+z)^4 + \Omega^{\mathrm{w}}_{\mathrm{de0}}(1+z)^{-3\delta} - \Omega_{\mathrm{de0}}, \tag{28}$$

where $\delta = -(1 + w_{\mathrm{de}})$.

Viscosity in the matter fluid: $\xi \equiv \xi(\rho_m)$

It is apparent that only if δ is positive, we can derive phantom wCDM model by the concept of model degeneracy. Substituting the above equation of $\Omega_{\rm vm}(z)$ into Eq. (25) we find

$$(\Omega_{r0}^{vm} - \Omega_{\rm r0}^{\rm w})(1+z)^4 + 3[\Omega_{\rm de0}^{w}(1+\delta)(1+z)^{-3\delta} - \Omega_{\rm de0}^{\rm vm}] = \tilde{\xi}_{\rm vm0} E^{\rm vm}(z) \left(\frac{\Omega_{\rm vm}(z)}{\Omega_{\rm vm0}}\right)^{\nu} . \quad (29)$$

Viscosity in the matter fluid: $\xi \equiv \xi(\rho_m)$

In what follows we will make two assumptions about the above equality.

- Since the density of radiation fluid can be directly obtained from the temperature of the CMB photons it is clear that this quantity is not model dependent and we can safely assume $\Omega_{\mathrm{r0}}^{\mathrm{vm}} = \Omega_{\mathrm{r0}}^{\mathrm{w}}$.
- Let us also assume that observations are able to establish the correct quantity of matter Ω_m independently of the model. This would imply $\Omega_{\mathrm{m0}}^{\mathrm{w}} = \Omega_{\mathrm{vm0}}$. As a consequence, the dark energy density parameter is also well determined for any cosmology therefore $\Omega_{\mathrm{de0}}^{\mathrm{w}} = \Omega_{\mathrm{de0}}^{\mathrm{vm}}$.

With these assumptions we can simplify (29) to

$$3\Omega_{\mathrm{de0}}^{w}\left[(1+\delta)(1+z)^{-3\delta}-1\right] = \tilde{\xi}_{\mathrm{vm0}}E^{\mathrm{vm}}(z)\left(\frac{\Omega_{\mathrm{vm}}(z)}{\Omega_{\mathrm{vm0}}}\right)^{\nu}. \quad (30)$$

Viscosity in the matter fluid: $\xi \equiv \xi(\rho_m)$

If the above condition is satisfied we can write the matter viscous cosmology Eqs. (24) and (25) in terms of the parameters of the phantom dark energy case, i.e., we have to solve

$$(1+z)\frac{d\Omega_{\rm vm}}{dz} - 3\Omega_{\rm vm} + 3\Omega_{\rm de0}\left[(1+\delta)(1+z)^{-3\delta} - 1\right] = 0, \quad (31)$$

for the density $\Omega_{\rm vm}$.

Note that as a consequence of the second law of thermodynamics $\xi \geq 0$. Then, from Eq. (31), positive values of $\tilde{\xi}$ should be mapped into positive δ.

In Eq. (31) we re-express the viscous DM model in terms of the wCDM's parameters. It is worth noting that $\tilde{\xi}$ and ν are characterized now only by δ which means the dimension of parameter-space has been reduced by one degree. Actually, this means that the degeneracy does not depend on the specific choice of the viscosity.

Observational tests

- SNIa data set UNION2.1 (Sukuzi *et al*, ApJ **746**, 85 (2012).)
- BAo data from the SDSS, WiggleZ and the 6dFGRS surveys.
- CMB distance priors which contains CMB-shift parameter $\mathcal{R}$, red-shift z_* at last scattering, and the position of the observed CMB peak $l_1 = 220.8 \pm 0.7$ obtained by the WMAP project (Komatsu et. al.)
- Observed Hubble parameter data-sets (OHD or H(z) data-sets which contains 29 measurement points) (J. Simon, L. Verde, R. Jimenez, Phys. Rev. **D71**, 123001 (2005); D. Stern, R. Jimenez, L. Verde, M. Kamionkowski, S. A. Standford, JCAP **02**, 008 (2010); M. Moresco, A. Cimatti, R. Jimenez, *et al.* arXiv:1201.3609v1; E. Gaztanaga, A. Cabre, L. Hui, MNRAS, **399**, 1663 (2009); C. Zhang, H. Zhang, S. Yuan, T.-J. Zhang, Y. C. Sun 2012, arXiv:1207.4541; C. Blake, S. Brough, M. Colless, *et al.*, Mon. Not. Roy. Astron. Soc., 425, 405 (2012).)

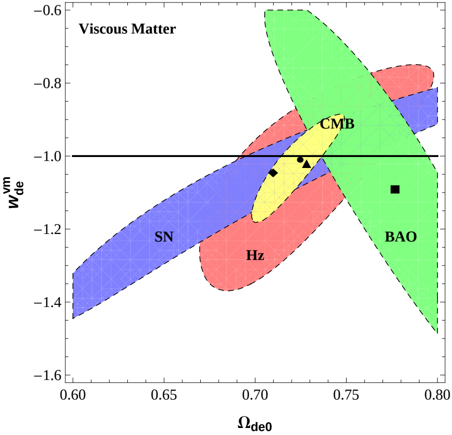


Abbildung: Viscous matter 2σ CL contours for different data sets. Yellow region corresponds to the CMB test.

Viscosity in the radiation fluid: $\xi \equiv \xi(\rho_r)$

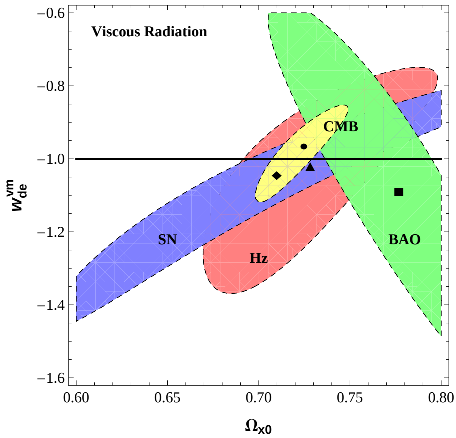
We also consider the ΛCDM model but taking into account the viscous pressure in the radiation fluid. This is the most likely scenario that can occur in the universe since it is well known that neutrinos do have bulk viscous properties (S. R. de Groot, W. A. van Leeuwen, C. G. vanWeert, Viscosity and heat conductivity of the primordial neutrino gas, Proc. K. Ned. Akad. Wet. Ser. B 82 (1979), 113.).
The pressure of each component is

$$p_{\rm vr} = \frac{\rho_{\rm vr}}{3} - 3H\xi_{\rm vr}, \qquad p_{\rm m} = 0, \qquad p_{\rm de} = -\rho_{\rm de}, \tag{32}$$

where for the bulk viscous coefficient of the viscous radiation we assume

$$\xi_{\rm vr} \equiv \xi_{\rm vr}(\rho_{\rm vr}) = \xi_{\rm r0}\left(\frac{\rho_{\rm vr}}{\rho_{\rm vr0}}\right)^{\nu}. \tag{33}$$

We proceed in the same way as the case of viscous matter cosmology



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- $f(R)$ theories realized via bulk viscosity? Soon in arxiv...