Matter Creation and Cosmic Acceleration

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Summary

We investigate matter creation cosmology as a viable alternative to explain cosmic acceleration. Particular attention is given to the evolution of density perturbations and constraints coming from recent observations. Both neo-Newtonian and standard relativistic formalisms are compared and we show the former gives in general an inappropriate description.

What is causing the cosmic acceleration?

Main Possibilities

A new exotic component with negative pressure (DE) or modified gravity?

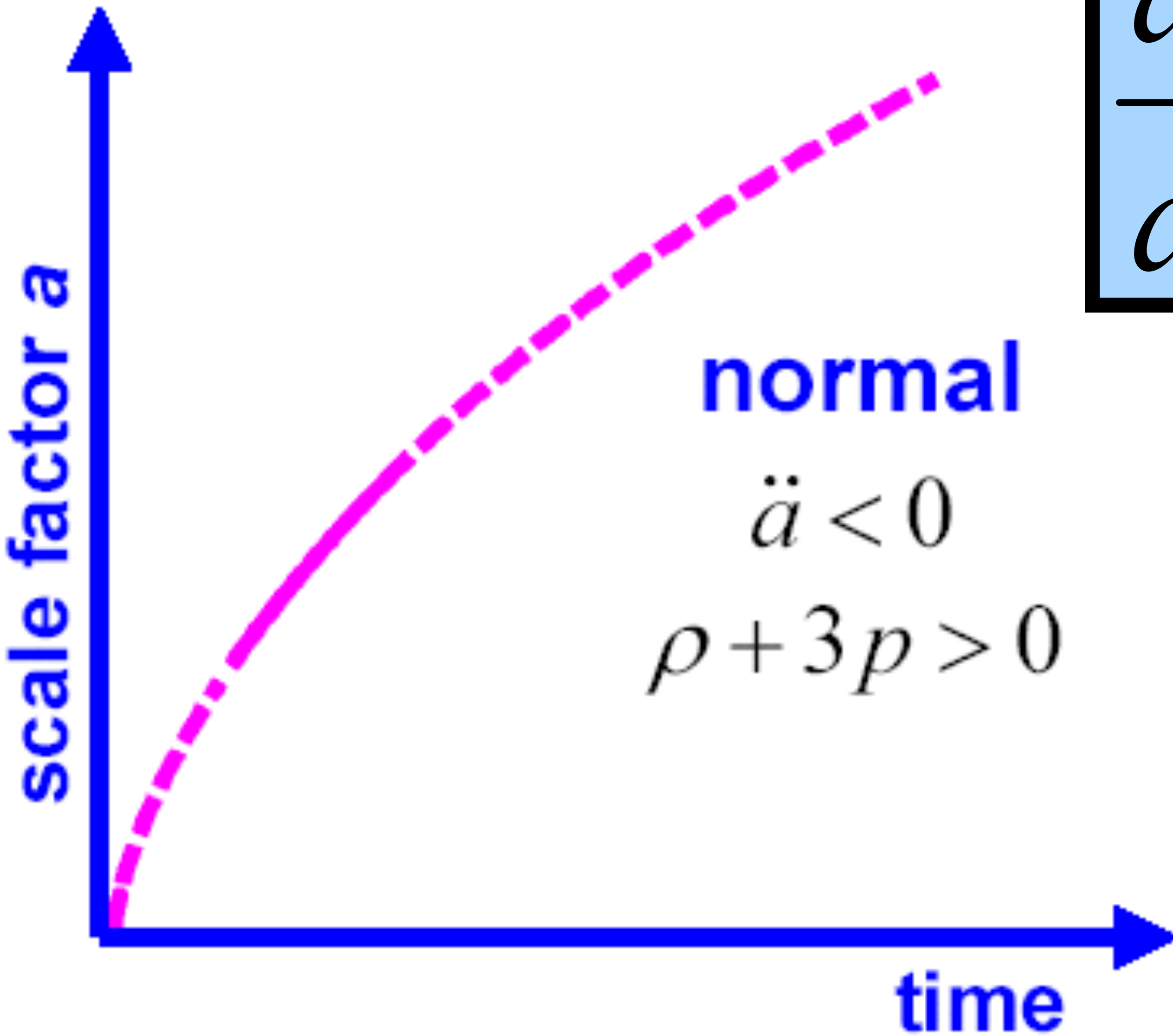
New Component

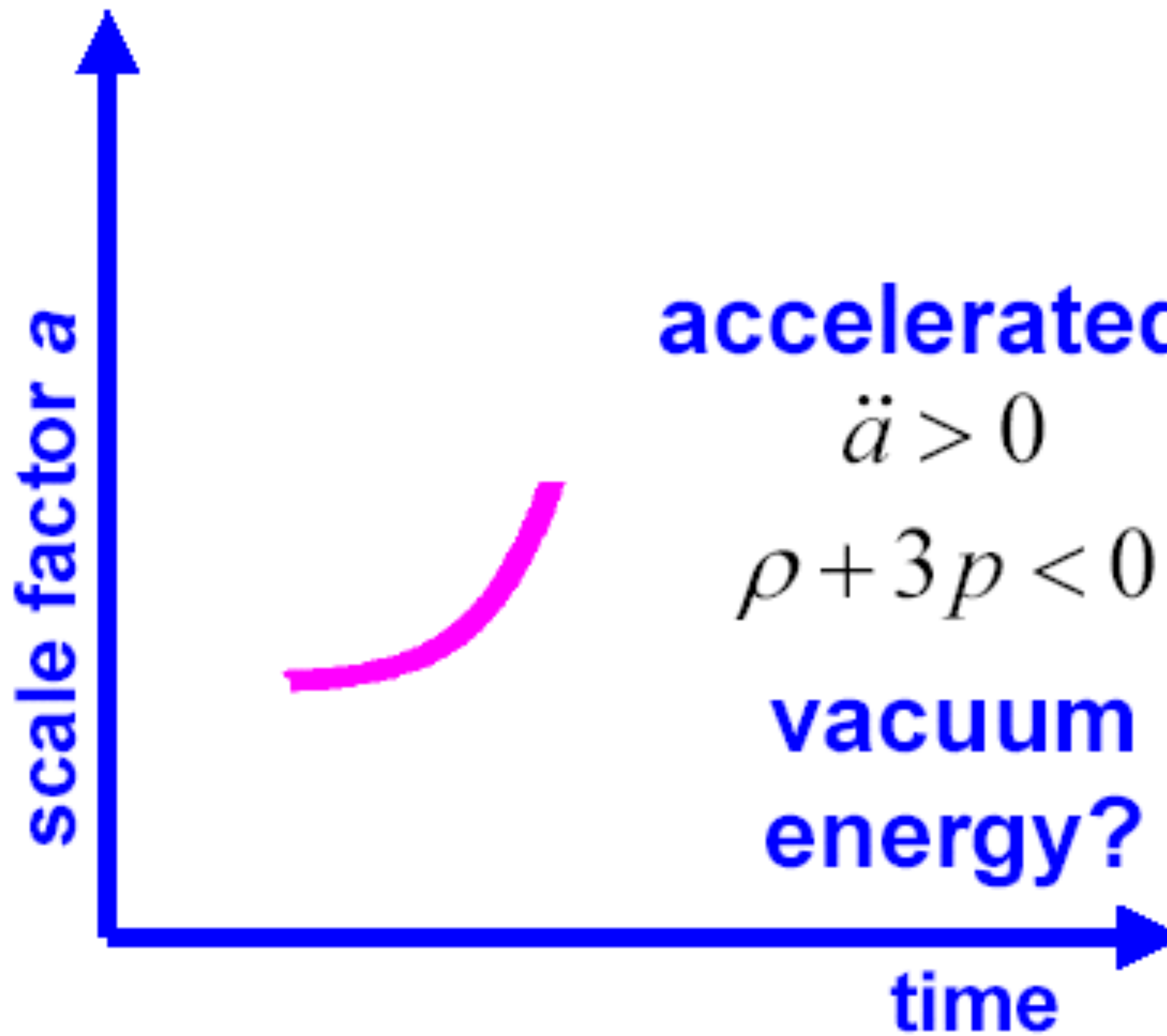
$$G_{\mu\nu} = \kappa T_{\mu\nu}^{(m)} + T_{\mu\nu}(\phi)$$

Modified Gravity

$$G_{\mu\nu} + L_{\mu\nu}(g_{\mu\nu}) = \kappa T_{\mu\nu}^{(m)}$$

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





Kolb

What is causing the cosmic acceleration?

Matter creation as an alternative to Dark Energy or Modified Gravity.

✳ **Thermodynamics of matter creation in a simple fluid**

$$T^{\alpha\beta} = (\rho + P)u^{\alpha}u^{\beta} - Pg^{\alpha\beta} \qquad N^{\alpha} = nu^{\alpha} \qquad s^{\alpha} = n\sigma u^{\alpha}$$

$$T^{\alpha\beta}{}_{;\beta} = 0 \qquad N^{\alpha}{}_{;\alpha} = n\Gamma \qquad s^{\alpha}{}_{;\alpha} \geq 0$$

$$\boxed{P = p + \Pi} \qquad \Gamma > 0 \ \text{(source)}$$

- **p is the equilibrium (thermostatic) pressure**
- **Π is present in scalar dissipative processes (bulk viscosity)**
- **Π is also relevant when there is particle creation (Π=p_c) -> There is no restriction**

adiabatic matter creation $\rightarrow \sigma$=const.

$$nTd\sigma = d\rho - \frac{\rho + p}{n}dn$$

$$p_c = -\frac{\rho + p}{3H}\Gamma$$

Cosmological models with particle creation

$$ds^2 = dt^2 - a^2(t)\left(\frac{1}{1-kr^2}dr^2 + r^2(d\theta^2 + \mathrm{sen}^2\theta\, d\phi^2)\right)$$

- We assume flat space (k=0)
- We are mainly interested in processes that occurred after radiation domination.
- First approximation: we neglect radiation and baryons, considering only the presence (and creation) of pressureless (p=0) dark matter particles.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\frac{\ddot{a}}{a} = \dot{H} + H^2 = -\frac{4\pi G}{3}(\rho + 3p_c)$$

$$p_c = -\frac{\rho}{3H}\Gamma$$

$$\dot{\rho} + 3H\rho = \rho\Gamma$$

$$\Gamma = 3\beta H_0\left(\frac{H}{H_0}\right)^\alpha$$

$$\frac{dH}{dz}(1+z) = \frac{3}{2}H_0\left[\frac{H}{H_0} - \beta\left(\frac{H}{H_0}\right)^\alpha\right]$$

$$z = \frac{1}{a} - 1$$

Cosmological models with particle creation

$$H = \begin{cases} H_0 \left[\beta + (1-\beta)\,(1+z)^{\frac{3}{2}(1-\alpha)}\right]^{\frac{1}{1-\alpha}}, & \text{if } \alpha \neq 1\,, \\ H_0\,(1+z)^{\frac{3}{2}(1-\beta)}, & \text{if } \alpha = 1\,. \end{cases}$$

Lima, Jesus, Oliveira JCAP 1011, 027, 2010
Basilakos & Lima PRD 82, 0235, 2010
Jesus, Oliveira, Basilakos, Lima PRD 84, 063511 2011
Lima, Basilakos, Costa PRD 86, 103534, 2012

Creation of Cold Dark Matter (CCDM) $\boxed{\alpha = -1}$

$$\frac{H^2}{H_0^2} = (1-\beta)\,(1+z)^3 + \beta$$

Zimdahl, Schwarz, Balakin & Pavon
PRD 64, 063501 (2001)
Freaza, de Souza & Waga
PRD 66, 103502 (2002)

flat ΛCDM $\quad \beta \Rightarrow \Omega_{\Lambda 0}$

$p_c = -\beta\rho_{c0}$ **(constant)**

$$\rho = \rho_{c0}\left[(1-\beta)\,(1+z)^3 + \beta\right]$$

$$\rho = \rho_{\text{conserved}} + \rho_{\text{created}} \qquad \begin{cases} \rho_{\text{conserved}} = \rho_{c0}\,(1-\beta)\,(1+z)^3 \\ \rho_{\text{created}} = \rho_{c0}\beta \end{cases}$$

Evolution of linear density perturbations: neo-Newtonian versus relativistic approach

- The idea of a Newtonian expanding universe was developed by Milne (GRG 32, 1939 (2000)) and also by McCrea and Milne (GRG 32, 1949 (2000)) in the 1930's. By considering a pressureless fluid and assuming Newtonian dynamics and gravitation, it was shown that the governing Newtonian differential equations are identical in form to the relativistic ones.

$$\nabla_r^2 \phi = 4\pi G \rho \,,$$

$$\left(\frac{\partial \mathbf{u}}{\partial t}\right)_r + (\mathbf{u}\cdot\nabla_{\mathbf{r}})\mathbf{u} + \nabla_{\mathbf{r}}\phi = \mathbf{0} \,,$$

$$\left(\frac{\partial \rho}{\partial t}\right)_r + \nabla_{\mathbf{r}}\cdot(\rho\mathbf{u}) = \mathbf{0} \,.$$

- The NC equations were generalized to include uniform pressure by McCrea (1951) in a paper in which the hypothesis of continuous creation of matter was investigated. The same equations were re-obtained later by Harrison (1965) in a different context.

$$\nabla_r^2 \phi = 4\pi G (\rho + 3P) \,,$$

$$\left(\frac{\partial \mathbf{u}}{\partial t}\right)_r + (\mathbf{u}\cdot\nabla_{\mathbf{r}})\mathbf{u} = -\nabla_{\mathbf{r}}\phi - (\rho + P)^{-1}\nabla_{\mathbf{r}} P \,,$$

$$\left(\frac{\partial \rho}{\partial t}\right)_r + \nabla_{\mathbf{r}}\cdot[(\rho + P)\mathbf{u}] = \mathbf{0} \,.$$

Evolution of linear density perturbations: neo-Newtonian versus relativistic approach

- However, as pointed out by Sachs and Wolfe, although the Newtonian background evolution equations with pressure are identical in form to the relativistic ones (assuming zero spatial curvature), at the perturbative level they are only equivalent when pressure is zero. To circumvent this difficulty, Lima, Zanchin and Brandenberger (1997) suggested a modification of the continuity equation.

$$\nabla_r^2 \phi = 4\pi G(\rho + 3P) \ ,$$
$$\left(\frac{\partial \mathbf{u}}{\partial t}\right)_r + (\mathbf{u}\cdot\nabla_{\mathbf{r}})\mathbf{u} = -\nabla_{\mathbf{r}}\phi - (\rho + P)^{-1}\nabla_{\mathbf{r}} P \ ,$$
$$\left(\frac{\partial \rho}{\partial t}\right)_r + \nabla_{\mathbf{r}}\cdot(\rho\mathbf{u}) + P\nabla_{\mathbf{r}}\cdot\mathbf{u} = \mathbf{0} \ .$$

- This formulation, known as neo-Newtonian approach, has also limitations (Reis (2003)) as we now discuss.
- As usual in perturbation theory, we assume small perturbations around the homogeneous background solution in the form:

$$\rho = \tilde{\rho} + \delta\rho = \tilde{\rho}(1+\delta) \quad ; \quad P = \tilde{P} + \delta P$$
$$\phi = \tilde{\phi} + \varphi \quad ; \quad \vec{u} = H\vec{r} + \vec{v}$$

Introducing comoving coordinates $\vec{x} = \dfrac{\vec{r}}{a}$, neglecting shear and vorticity

and taking into account the background equations, we obtain for δ

Evolution of linear density perturbations: neo-Newtonian versus relativistic approach

$$\boxed{\begin{aligned}&\ddot{\delta} - \left[3\left(2w - c_s^2 - c_{eff}^2\right) - 2\right] H\dot{\delta}\\ &+3H^2\left\{\left[\frac{3}{2}w^2 - 4w - \frac{1}{2} + 3c_s^2\right] + c_{eff}^2\left(3c_s^2 - 6w - 1\right) + \frac{(c_{eff}^2)^{\cdot}}{H} + \frac{k^2}{a^2}\frac{c_{eff}^2}{3H^2}\right\}\delta = 0,\end{aligned}}$$

$$\boxed{\delta(\mathbf{x}, t) = \sum_k \delta_k(t) e^{i\mathbf{k}\cdot\mathbf{x}}}$$

$$\boxed{w = \tilde{P}/\tilde{\rho}} \qquad \boxed{c_{eff}^2 = \delta P/\delta\rho} \qquad \boxed{c_s^2 = \dot{\tilde{P}}/\dot{\tilde{\rho}} = w - \dot{w}/[3H(1+w)]}$$

In a general-relativistic framework, assuming zero anisotropic pressure perturbations, besides flat space, we obtain (Kodama & Sasaki)

$$\ddot{\Delta} - \left[3\left(2w - c_s^2\right) - 2\right] H\dot{\Delta} + 3H^2\left\{\left[\frac{3}{2}w^2 - 4w - \frac{1}{2} + 3c_s^2\right] + \frac{k^2}{a^2}\frac{c_s^2}{3H^2}\right\}\Delta = -\frac{k^2}{a^2}w\hat{\Gamma},$$

$$\hat{\Gamma} \equiv \delta P/\tilde{P} - c_s^2\delta/w = (c_{eff}^2 - c_s^2)\delta/w$$

$$\Delta = \delta + 3(1+w)H\frac{a}{k}(v - B)$$

$$\boxed{\ddot{\delta} - \left[3\left(2w - c_s^2\right) - 2\right] H\dot{\delta} + 3H^2\left\{\left[\frac{3}{2}w^2 - 4w - \frac{1}{2} + 3c_s^2\right] + \frac{k^2}{a^2}\frac{c_{eff}^2}{3H^2}\right\}\delta = 0}$$

Creation of Cold Dark Matter: Theory versus observations

Let us now consider observational constraints on the α = -1 CCDM model from the linear growth of energy density perturbation data. $\tilde{p}_c = -\beta\rho_{c0} = const \rightarrow c_s^2 = 0$

We first assume $c_{eff}^2 = 0 \Rightarrow \hat{\Gamma} = 0$

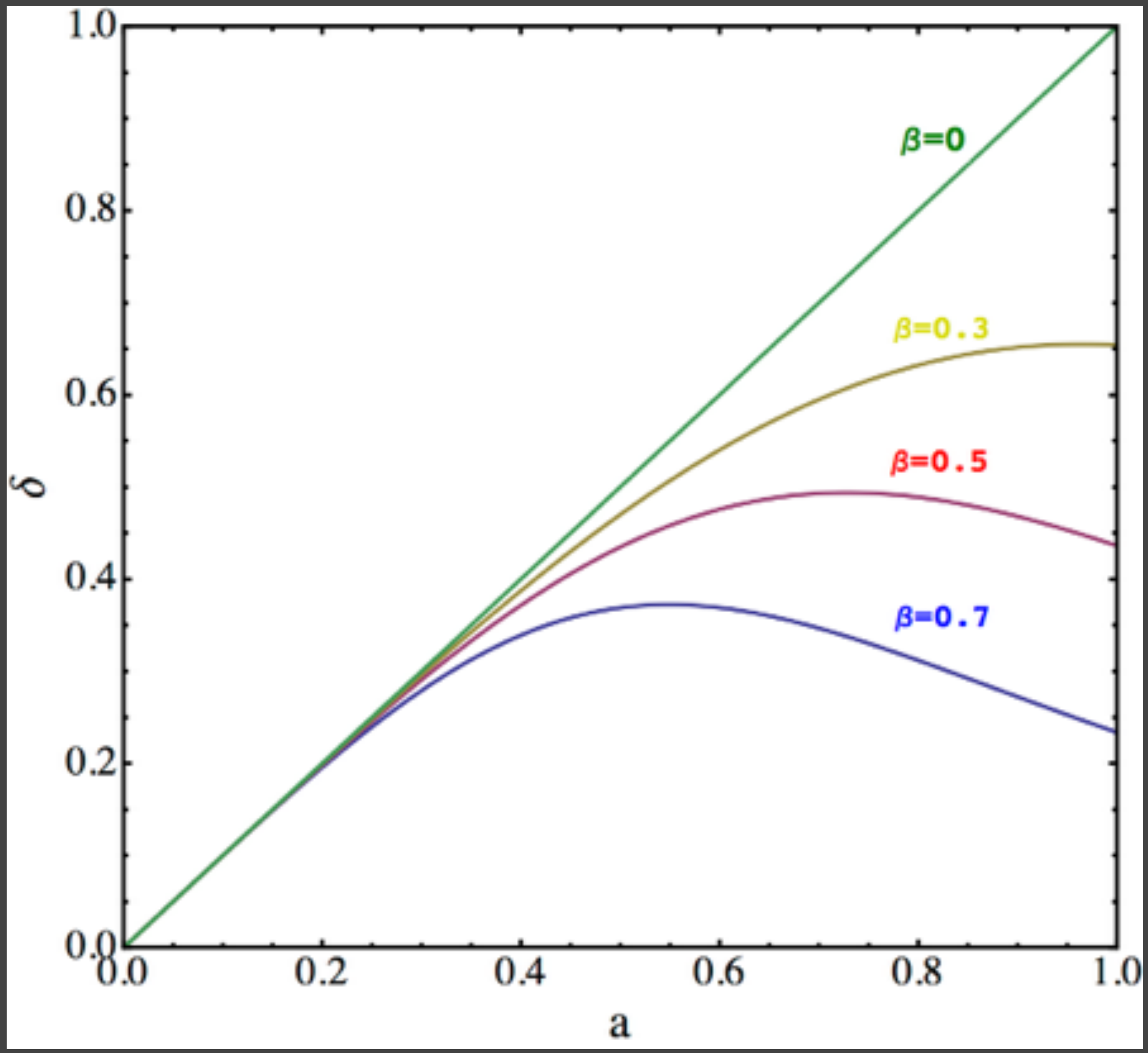
$$\boxed{\delta'' + \frac{3}{2a}\left(1 - 5w\right)\delta' + \frac{3}{2a^2}\left(3w^2 - 8w - 1\right)\delta = 0}$$

The prime denotes derivative with respect to the scale factor a and

$$w(a) = -\frac{\beta}{\beta + (1-\beta)a^{-3}}$$

$$\beta = 0 \rightarrow EdS$$
$$\beta = 1 \rightarrow \text{de Sitter}$$

To numerically integrate de above equation we have assumed, as initial condition, that at $a=10^{-4}$ we have δ=a, since at high redshifts ($a \ll 1$) the α=-1model behaves like the Einstein-de Sitter model, for which $\delta \propto a$.



Creation of Cold Dark Matter: Theory versus observations

To compare model predictions with observations we use redshift-space-distortion based f(z)σ$_8$(z) measurements [Song], which are displayed in the table bellow.

$$f(z) \equiv \frac{d\ln\delta}{d\ln a} = -(1+z)\frac{d\ln\delta}{dz}$$

$$\sigma_8(z) = \sigma_{80}\frac{\delta(z)}{\delta(z=0)}$$

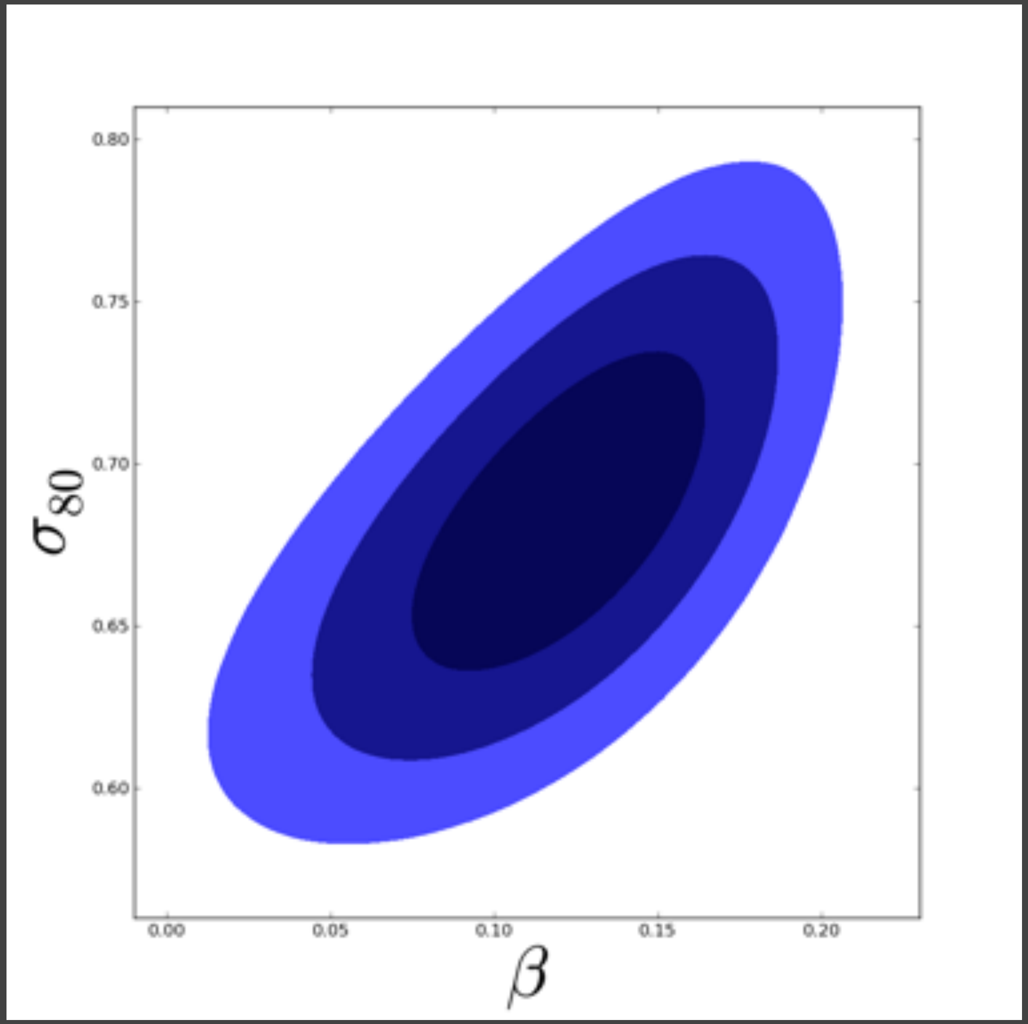
σ_8 is the redshift-dependent root-mean-square mass fluctuation in spheres with radius $R = 8h^{-1}$ Mpc.

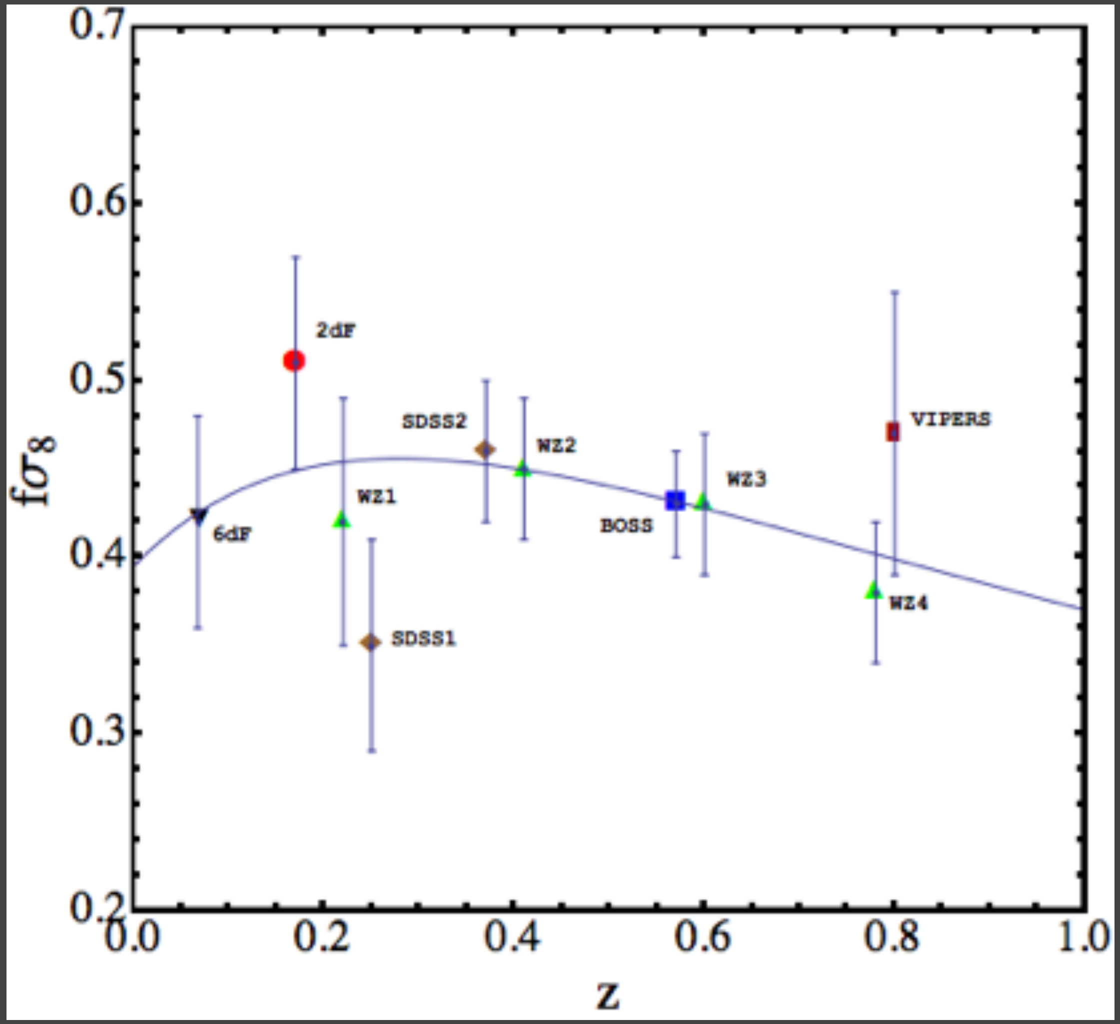
$$\sigma_R^2 = \frac{1}{2\pi^2}\int P(k)W_R^2(k)k^2\,dk$$

z	$f\sigma_8$	Survey	ref.
0.07	0.42 ± 0.06	6dFGRS	Beutler
0.17	0.51 ± 0.06	2dFGRS	Percival
0.22	0.42 ± 0.07	WiggleZ	Blake
0.25	0.35 ± 0.06	SDSS LRG	Samushia
0.37	0.46 ± 0.04	SDSS LRG	Samushia
0.41	0.45 ± 0.04	WiggleZ	Blake
0.57	0.43 ± 0.03	BOSS CMASS	Reid
0.60	0.43 ± 0.04	WiggleZ	Blake
0.78	0.38 ± 0.04	WiggleZ	Blake
0.80	0.47 ± 0.08	VIPERS	Delatorre

Table 1: Observational data for redshift-space-distortion based $f(z)\sigma_8(z)$ and the sources from where we have obtained them.

$$\chi^2_{f\sigma_8} = \sum_{i=1}^{10} \frac{[f\sigma_8^{obs}(z_i) - f(z_i,\beta)\sigma_8(z_i,\sigma_{80},\beta)]^2}{\sigma^2_{f\sigma_8}(z_i)}$$





$$\text{best fit} \rightarrow \beta = 0.12^{+0.04(0.07)}_{-0.04(0.06)}, \quad \sigma_{80} = 0.69 \pm 0.04(0.07)$$

Creation of Cold Dark Matter: Theory versus observations

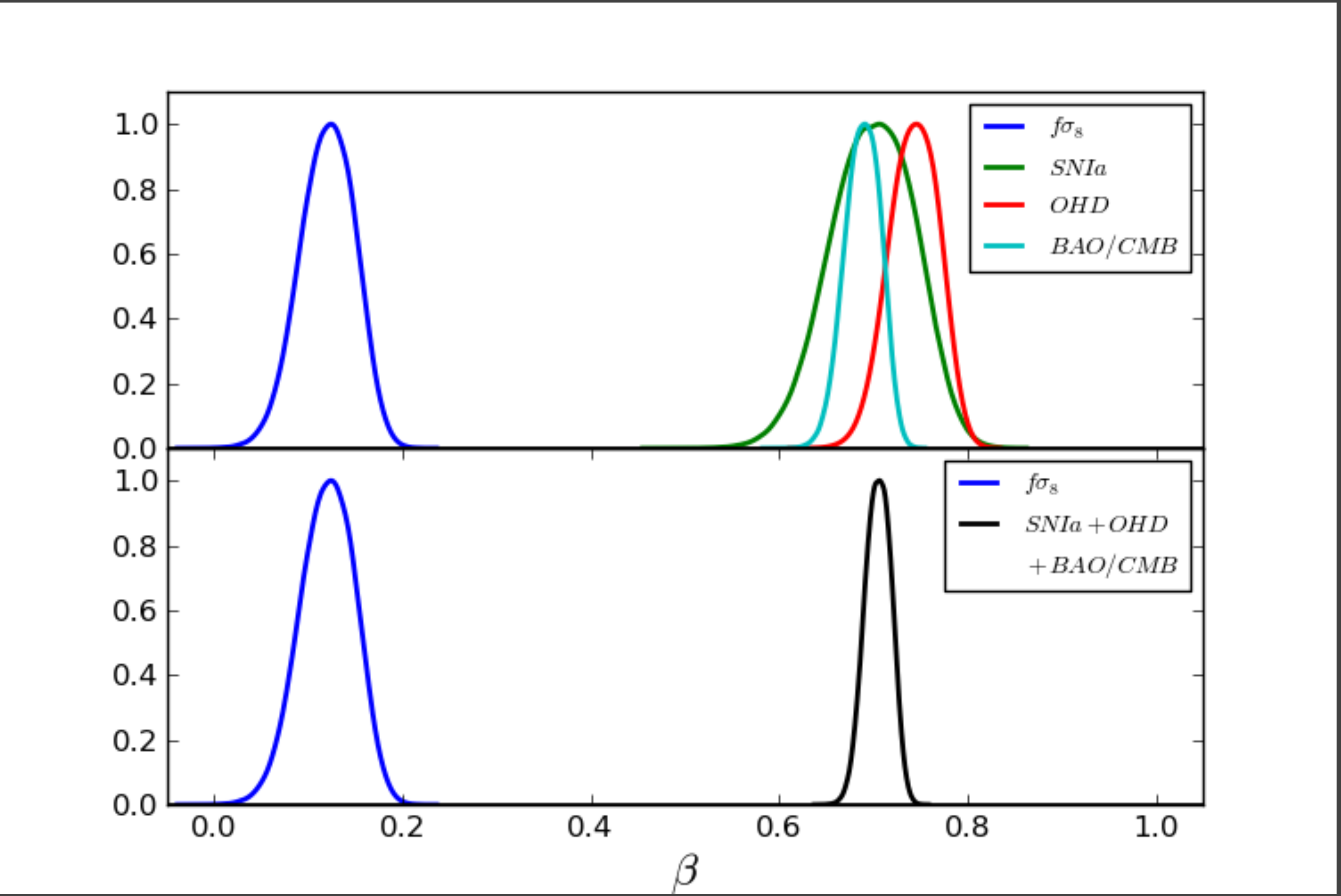
Background Tests

The Union 2.1 Type Ia Supernovae compilation [Suzuki]. This compilation is an update of the Union 2 [Amanullah] and include supernovae observed by the Hubble Space Telescope Cluster Survey. This compilation is composed of 580 selected supernovae fitted by the SALT2-1 lightcurve fitter and is available at http://supernova.lbl.gov/Union. In our approach we have considered the covariance matrix with systematics errors (available in the site mentioned above), obtaining: $\beta = 0.71^{+0.07(0.10)}_{-0.05(0.08)}$

The CMB/BAO test. We followed the procedure described in Section 3.2 of [Giostri], including one new data point from the BOSS survey [Anderson] and new data from WMAP-9yrs. With this test we get $\beta = 0.69^{+0.03(0.04)}_{-0.02(0.04)}$

Measurements of the Hubble parameter at different redshifts. For this observable we use the same data set and procedure as described in [Farook] and we obtain $\beta = 0.75^{+0.04(0.06)}_{-0.03(0.05)}$.

Creation of Cold Dark Matter: Theory versus observations



Conclusions

- We have studied CCDM scenario as a possible explanation for the late-time cosmic acceleration. We have compared the relativistic and neo-Newtonian differential equations for the density contrast for the CCDM model. Both relativistic and neo-Newtonian cases agree with each other only when the effective sound speed $c_{eff}^2 = 0$.

- We have compared the CCDM predictions at the perturbative level with those obtained from ΛCDM. We have used for this comparison redshift-space-distortion observational data. We have shown that the CCDM model produces results for the parameter β that largely underestimates the result expected from ΛCDM. Independent tests were also carried out at the background level. These tests show that the result for β predicted by the CCDM models seem consistent with the result from ΛCDM.

- We must, however, point out that in this work we have not accounted for the effect of baryons. This is a necessary next step to be carried out in the future. We should recall that observational data for the power spectrum, from which we obtain for example the results for σ_8, is in fact obtained from galaxies, thus dominated by baryons.

- In summary, dark matter creation models have attractive features. They in principle can provide a unified scenario for the dark sector and even provide a mechanism able to drive both the early-time cosmic acceleration, i.e., inflation, and the late-time one, i.e., dark energy, through some unified and single model. Though all these attractive features seem to be possible at the background level, these models present serious difficulties at the perturbative level when we account for different cosmological tests. Though future studies are still required to fully include the effect of baryons, these difficulties seem likely to persist. These problems pose a challenge for the feasibility of creation of cold dark matter in general as an alternative for dark energy.