Acceptable Inverse Power Law Potential 
Quintessence with $n = 18/7$

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ABSTRACT

We present a particle physics quintessence model which agrees well with existing cosmological data, including the position of the acoustic peaks. This model has an inverse power law potential (IPL) with $n = 18/7 \sim 2.57$ and it gives $w_{eff} = -0.75$, an acoustic scale $l_A = 307$ and a density contrast $\sigma_8 = 0.95$.

Models with $n > 1$ have been said to be disfavored by the analysis of the acoustic peaks. However, the results are not correct. The main reason is that the tracker approximation has been used in deriving the IPL constrains and for $n < 5$ the scalar field has not reached its tracker value by present day.

The model can be derived from particle physics, using Affleck-Dine-Seiberg ”ADS” superpotential, for a non-abelian gauge group with $N_c = 8, N_f = 1$. The advantage of having $N_f = 1$ is that there is only one degree of freedom below the condensation scale given by the condensate (quintessence) $\phi^2 = < Q\bar{Q} >$ field. The condensation scale is at 1GeV a very interesting scale since it connects the quintessence "Q" with the standard model "SM" scale. The similarity in energy scales between $Q$ and $SM$ scale gives an ”explanation” to the coincidence problem. The fact that only recently the universe is accelerating is a natural consequence of the Q scale and the evolution of $\phi$.

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The Maxima and Boomerang [1] observations on the cosmic radiation microwave background ("CMBR") and the superonovae project SN1a [2] have lead to conclude that the universe is flat and it is expanding with an accelerating velocity. These conclusions show that the universe is now dominated by an energy density $\Omega_{\phi o} = 0.7 \pm 0.1$ (the subscript "o" refers to present day quantities) with negative pressure. The SN1a data requires an equation of state $w_{\phi o} < -2/3$ [4] while recent analysis on the CMBR peaks constrains the models to have $w_{\text{eff}} = -0.82_{-0.11}^{+0.14}$ [5, 6], where $w_{\text{eff}}$ is an average equation of state. This energy is generically called the cosmological constant. Structure formation also favors a non-vanishing cosmological constant consistent with SN1a and CMBR observations [3]. An interesting parameterization of this energy density is in terms of a scalar field with gravitationally interaction only called quintessence [10]. The evolution of scalar field has been widely studied and some general approach can be found in [14, 15, 16]. The evolution of the scalar field $\phi$ depends on the functional form of its potential $V(\phi)$ and a late time accelerating universe constrains the form of the potential [15].

One of the simplest and most interesting quintessence potentials are the inverse power law (IPL) [11]. In some special cases they can be derived from non-abelian gauge theories [12, 13, 18] and we can also have consistent models with a gauge coupling unified with the standard model (SM) couplings [13].

From the CMBR analysis it has been inferred that IPL with $n < 1$ are disfavored [3, 7]. However, in most cases one assumes a constant $w$ given by the tracker value $w_{tr} = -2/(2+n)$ and for IPL models with $n < 5$ the tracker solution [11] is not a good approximation to the numerical (exact) solution since the field has not reached its tracker value by present time. This fact implies that we cannot use the tracker solution (i.e. the constant $w_{tr}$) for the evolution of $\phi$ in determining the acoustic peaks. It is no surprise that the values of the acoustic peaks differ greatly if we use the tracker solution approximation or we evolve the quintessence field from its initial conditions. Models with $1 < n < 2.5$ (for $\Omega_{\phi i} \geq 0.25$) are therefore still phenomenologically viable.

Tracker fields have the advantage that the value of $w_{\phi o}$ does not depend on the initial condition. In fact one can have more then 100 orders of magnitude on the initial conditions $\Omega_{\phi i}$ [23] and the value of $w_{\phi o}$ will not change. In our case this is no longer so since the scalar field has not reached its tracker value and $w_{\phi o}$ depends slightly on $\Omega_{\phi i}$, so there is a dependence on $\Omega_{\phi i}$ but there is no fine tuning required on the initial conditions (we do not need to adjust the initial condition more than one significant figure). Furthermore, in our model, derived from non-abelian gauge theories, we can determine the initial conditions in terms of the number of degrees of freedom of the system. So we do not need 100 orders of magnitude independence of initial conditions since they are well motivated and given within one order of magnitude at most. Of course, any model which requires a fine tuning on the initial conditions would not be theoretically acceptable but this is not our case. In both cases, tracker and our model, one still has the coincidence problem since the scale $\Lambda_0$ has to be tuned so that $\Omega_\phi \simeq 0.7$ with $h_o \simeq 0.7$ today.

There are two constrains on the equation of state parameter $w_{\phi}$, one coming from direct obser-
vations SN1a which sets an upper limit, \( w_{\phi_0} < -2/3 \) [8] and the other is indirect and comes from numerical analysis of the CMBR data and gives a smaller value \( w_{eff} = -0.82^{+0.14}_{-0.11} \) [8]. Notice that the CMBR data gives a more negative \( w_\phi \) than the SN1a one but it is an average equation of state (from last scattering to present day) while the SN1a result gives an \( w_\phi \) in recent times. In IPL with \( n < 5 \), where the quintessence field has not reached its tracker value yet, one has always \( w_{\phi_0} \) larger than \( w_{eff} \) in good agreement with SN1a and CMBR data. For IPL models it was shown [8] that \( w_{\phi_0} \) depends on \( n \) and the initial condition \( \Omega_{\phi_i} \). If we want \( w_{\phi_0} < -2/3 \) assuming an \( \Omega_{\phi_i} \geq 0.25 \) IPL models require an \( n \) to be less 2.74 [8] assuming no contribution from radiation at present time. If we include radiation with \( \Omega_{r_0} = 4.17 \times 10^{-5} h_o^2 \) then the value of \( n \) will decrease slightly, e.g. for \( \Omega_{\phi_i} = 0.25 \) we have \( w_{\phi_0} \leq -2/3 \) for \( n \leq 2.5 \). Larger values of \( \Omega_{\phi_i} \) allow larger values of \( n \), however we would not expect to have \( \Omega_{\phi_i} \) much larger since a ”reasonable” amount of energy must go into the standard model of elementary particles ”SM". These results set an upper value of \( n \) but there is still room for models with \( 1 < n < 2.5 \) and if we take \( \Omega_{\phi} \geq 0.3 \) then the value of \( n \) can be as large as \( n \leq 2.66 \).

The CMBR constrain on \( w_\phi \) can be studied from the position of the third acoustic peak. The position of the third CMBR peak has been found to be not very sensitive to the different cosmological parameters and it is a good quantity to obtain the acoustic scale \( l_A \) [8]. The acoustic scale \( l_A \), which sets the scale of the peaks, derived from the third acoustic peak is

\[
l_A = 316 \pm 8
\]

were we have taken \( l_3 = 845^{+12}_{-25} \) [8] (see below for the definition of \( l_A \)).

Here we will present a model with the largest value of \( n \) that is still in agreement with the observational cosmological data [8] and that can be nicely derived from particle physics. Since, for a non-abelian gauge group (see below) we have \( n = 2 + 4N_f/(N_c - N_f) = 2 + 4/(z - 1) \), where \( N_f \) is the number of flavors of the gauge group \( SU(N_c) \) and \( z = N_c/N_f \), we can see that \( n \) decreases with increasing \( z \). The requirement on \( n \) to be smaller than 2.66 (2.5) for \( \Omega_{\phi_i} \geq 0.3 \) (0.25), in order to give the correct phenomenology and the observed values of the acoustic scale and present day \( w_{\phi_0} \), implies that \( z > 9 \) (7) or \( z N_f < N_c \). As we will see later the number of condensates of the gauge group \( SU(N_c) \) is given in terms of \( N_f \). Therefore, the model with the least number of condensates has \( N_f = 1 \) and the smallest gauge group would be \( N_c = 8 \). Furthermore, in string compactification for the heterotic string, the gauge group has at most rank 8 (as \( SU(8) \)). The value of \( n \) for \( SU(8) \) with \( N_f = 1 \) is \( n = 18/7 = 2.57 \). This model represents the limiting acceptable model.

The acoustic scale gives \( l_A = 307 \) and \( w_{\phi_0} = -0.68 \), which gives a good prediction of the acoustic peaks within observational limits. This acoustic scale should be compared with the tracker solution \( l_{Atr} = 281 \) and \( w_{tr} = -2/(2 + n) = -0.44 \) and the cosmological constant \( l_{ACte} = 315 \) (i.e. \( w_{Cte} = -1 \)) for the same initial conditions. We see that the tracking solution is not a good approximation since \( w_{\phi_0} \) differs by more than 38% and the acoustic scale \( l_A \) by 9% from the numerical solution of the scalar field, discrepancy large enough to rule out the model.
Since our model has \( n < 5 \) the quintessence field has not reached its tracker value yet and the coincidence problem is not solved. However, there is a clear connection between the model condensation scale \( \Lambda_c = 1 GeV \) and the standard model scale. So, we could think of the "solution" to the coincidence problem as the following: The scale of quintessence should not be given by today’s energy density but by the condensation scale \( \Lambda_c \). The natural value of this scale is that of the standard model. The subsequent evolution of the quintessence field is determined by the solution of the Friedmann-Robertson-Walker equations and the fact that only recently the universe is accelerating is a natural consequence of the quintessence dynamics starting at \( \Lambda_c \).

The model with \( n = 18/7 \) can be easily obtained from a \( SU(8) \) non-abelian gauge group with \( N_f = 1 \) number of (chiral + antichiral) fields in the fundamental representation and with a condensation scale \( \Lambda_c = 1 GeV \), quite an interesting scale. Above the condensation scale the gauge coupling constant is small and the elementary fields are massless. At the condensation scale there is a phase transition, the gauge coupling constant becomes strong, and binds the elementary fields together forming meson fields. In this model there is only one degree of freedom, \( \phi \), in the confined phase and the Affleck-Dine-Seiberg "ADS" superpotential \[^{17}\] obtained is therefore exact.

At the beginning we have particles of the standard model (SM) and the quintessence model (Q). All fields, SM and Q model, are massless and redshift as radiation until we reach the condensation scale \( \Lambda_c \) of Q group. Below this scale the fields of the quintessence gauge group will dynamically condense and we use ADS potential to study its cosmological evolution. The ADS potential is non-perturbative and exact (it receives no quantum corrections) \[^{20}\] and it is given for a non-abelian \( SU(N_c) \) gauge group with \( N_f \) (chiral + antichiral) massless matter fields by \[^{17}\]

\[
W = (N_c - N_f)(\frac{\Lambda^b_o}{det < Q\bar{Q} >})^{1/(N_c-N_f)}
\]

where \( b_o = 3N_c - N_f \) is the one-loop beta function coefficient. The scalar potential in global supersymmetry is \( V = |W_\phi|^2 \), with \( W_\phi = \partial W/\partial \phi \), giving \[^{12}\]

\[
V = c^2\Lambda^4\phi^{2+n}\phi^{-n}
\]

where we have taken \( det < Q\bar{Q} > = \Pi_{j=1}^{N_f} \phi_j^3 \), \( c = 2N_f \), \( n = 2 + 4\frac{N_f}{N_c-N_f} \) and \( \Lambda_c \) is the condensation scale of the gauge group \( SU(N_c) \). Our model has \( N_f = 1, N_c = 8 \) and \( n = 18/7 \).

There are no baryons since \( N_f < N_c \) and there is only one degree of freedom below \( \Lambda_c \) which is the condensate \( \phi = < Q\bar{Q} > \).

The cosmological evolution of \( \phi \) with an arbitrary potential \( V(\phi) \) can be determined from a system of differential equations describing a spatially flat Friedmann–Robertson–Walker universe in the presence of a barotropic fluid energy density \( \rho_\gamma \) that can be either radiation or matter, are

\[
\dot{H} = -\frac{1}{2}(\rho_\gamma + p_\gamma + \dot{\phi}^2),
\]
\[ \dot{\rho} = -3H(\rho + p), \]
\[ \ddot{\phi} = -3H\dot{\phi} - \frac{dV(\phi)}{d\phi}, \]

where \( H \) is the Hubble parameter \( (H = 100h \text{ km Mpc}^{-1}s^{-1}) \), \( \dot{f} = df/dt, \rho \) (\( p \)) is the total energy density (pressure) and we are setting the reduced Planck mass \( m_p^2 = 1/8\pi G \equiv 1 \).

Solving eqs.(4) we have that the energy density of the Q group \( \Omega_\phi \) drops quickly, independently of its initial conditions, and it is close to zero for a long period of time, which includes nucleosynthesis (NS) if \( \Lambda_c \) is larger than the NS energy \( \Lambda_{NS} \) (or temperature \( T_{NS} = 0.1 - 10 MeV \)), and becomes relevant only until very recently [18]. On the other hand, if \( \Lambda_c < \Lambda_{NS} \) then the NS bounds on relativistic degrees of freedom must be imposed on the models. Finally, the energy density of Q grows and it dominates at present time the total energy density with the \( \Omega_{\phi_0} \approx 0.7 \) and a negative pressure \( w_{\phi_0} < -2/3 \) leading to an accelerating universe [4].

The value of the condensation scale in terms of \( H_o \) is [12, 18]

\[ \Lambda_c = \left( \frac{3y_0^2 \phi_0^2 H_0^2}{4N_f^2} \right)^{1/4+n}. \] (5)

The approximated value can be obtained since one expects, in general, to have \( y_0^2 \phi_0^n \sim 1 \) for a model with \( \Omega_{\phi_0} = 0.7 \) and \( w_{\phi_0} < -2/3 \). The magnitude order of the condensation scale is therefore \( \Lambda_c = H_0^{2/(4+n)} \).

In our model, the cosmological evolution requires a condensation scale \( \Lambda_c = 1 GeV \) in order to give \( \Omega_{\phi_0} = 0.7 \pm 0.1 \) with a Hubble parameter \( h_o = .65 \pm .7 \) at present time. Since \( \Lambda_c \gg \Lambda_{NS} \) the energy density at NS is \( \Omega_\phi (NS) \ll 1 \) and there is no constrain from nucleosynthesis on the model.

In order to set the initial conditions for \( \phi \) we will assume that all relativistic degree of freedom (MSSM and Q) had the same fraction of energy density at high energies, when all fields were massless. The initial conditions could be set at the unification scale or at the reheating temperature \( T_{rh} \). If \( T_{rh} \) is larger then the supersymmetric mass (i.e. \( T_{rh} > 10^3 GeV \)), which is a natural assumption, then all degrees of freedom (MSSM and Q) would be relativistic at \( T_{rh} \) and each degree of freedom would have the same energy density (assuming the standard reheating process which is gauge blind). Therefore, the initial energy density conditions would be exactly the same at the unification scale or reheating temperature.

The MSSM has \( g_{sm} = 228.75 \) while the Q group has \( g_{Qi} = (1+7/8)(2(N_c^2-1)+2N_f N_c) = 266.25 \) degrees of freedom, where \( g_a = \Sigma_a Bosons + 7/8 \Sigma_a Fermions \). Taking into account that some fields become massive at lower energies, we can determine the energy density at an arbitrary energy scale \( \Lambda \) and it is given by [13]

\[ \Omega_Q(\Lambda) = \frac{g_{Qi}(g_{sm}f g_{Qi}/g_{sm}g_{Qi})^{4/3}}{g_{sm}f + g_{Qi}(g_{sm}f g_{Qi}/g_{sm}g_{Qi})^{4/3}} \] (6)
where $g_{smi}$, $g_{smf}$, $g_{Qi}$, $g_{Qf}$ are the initial (i.e. at high energy scale) and final (i.e. at $\Lambda$) standard model and $Q$ model relativistic degrees of freedom, respectively. Taking $\Lambda = \Lambda_c = 1 GeV$ the MSSM has $g_{smf} = 10.75$ and if the $Q$ group is still supersymmetric at $\Lambda_c$ it has $g_{Qf} = g_{Qi}$ and $\Omega_{\phi i}(\Lambda_c) = 0.29$. If $Q$ is no longer supersymmetric $g_{Qf} = g_{Qi}/2$ and $\Omega_{\phi i}(\Lambda_c) = 0.34$. So a reasonable choice for the initial conditions is $\Omega_{\phi i}(\Lambda_c) = 0.3$.

We show in fig.(1) the evolution of $\Omega_\phi$ and $w_\phi$ as a function of $N = \log(a)$, with $a$ the scale factor, for initial conditions $\Omega_{\phi i} = 0.5, 0.3, 0.2$ short-dashed, long-dashed and solid lines, respectively. We see that $w_{\phi o}$ decreases for larger initial condition $\Omega_{\phi i}$. For $\Omega_{\phi i} = 0.9, 0.5, 0.3, .2$ one finds $w_{\phi o} = -0.95, -0.8, -0.68, -0.61$ and an acoustic scale $l_A = 314, 313, 307, 303$, respectively. It is no surprise that for $\Omega_{\phi i} = 0.2$ the value of $w_{\phi o} = -0.61$ lies outside the observed range $w_{\phi o} < -2/3$. This is because the model we are working with (i.e. $n=18/7=2.57$) gives almost the limiting value of $w_{\phi o} = -2/3$ for $\Omega_{\phi i} = 0.3$ ( $w_{\phi o}$ increases for smaller $\Omega_{\phi i}$) and that was the reason for using this model. However, as long as we take $\Omega_{\phi i} \geq 0.27$ the model satisfies the cosmological constrains. For scalar fields that have reached its tracker value by present day (i.e. $n > 5$) the initial value of $\Omega_{\phi i}$ is not constrained since it can vary for more than 100 orders of magnitude and the value of $w_{\phi o}$ will be the same $w_{\phi o} = -2/(2 + n)$, however for $n > 5$ one has $w_{\phi o} \geq -0.28$ which is too large.

In previous works we have studied quintessence models that are unified with the standard model gauge groups, i.e. the gauge coupling constant of all gauge groups is the same at the unification scale. In the model we are working here, $N_f = 1$, $N_c = 8$, the renormalization group equation given by $\Lambda_{RG} = \Lambda_{Gut} \exp[-16\pi^2/2b_o g_{Gut}^2] = 9 \times 10^{12} GeV$ with $\Lambda_{Gut} = 10^{16} GeV$, $g_{Gut}^2 = 4\pi/25.7$ the unification scale and coupling, respectively, and $b_o = 3N_c - N_f = 23$ the one-loop beta function coefficient. It is clear that $\Lambda_{RG} \neq \Lambda_c$ and so the model cannot be unified with the SM groups. If we insist in gauge coupling unification we would need, on top of the original 1 chiral + 1 antichiral fields, 37 extra chiral fields. If all extra fields are chiral then they would not contribute to the ADS superpotential in eq.(3). Of course, we think that such a model is not natural but it is possible (4-D string models can have different number of chiral and antichiral fields).

The acoustic scale, that sets the scale of acoustic peaks, for a flat universe is given by

$$l_A = \pi \frac{\tau_o - \tau_{ls}}{\bar{c}_s \tau_{ls}}$$

(7)

where $\tau_o$ and $\tau_{ls}$ are the conformal time today and at last scattering ($\tau = \int dt/a(t)$, $a(t)$ the scale factor) and $\bar{c}_s \equiv \tau_{ls}^{-1} \int_0^{\tau_{ls}} d\tau c_s$ is the average sound speed before last scattering ($c_s^{-2} = 3 + (9/4) w_b(t)/w_r(t)$ with $w_b = \Omega_b h^2$, $w_r = \Omega_r h^2$ the fraction of baryon and radiation energy density, respectively). The acoustic $m$-th peak $l_m$ is then given in terms of $l_A$ and a peak and model dependent phase shift $\varphi_m$, $l_m = l_A(m - \varphi_m)$. It has been observed in that the third peak is quite insensitive to different cosmological parameters that enter in determining $\varphi_3 \simeq 0.341$ and so the position of the third peak is a good quantity to extract the acoustic scale
\[ l_A. \] The data from Boomerang and Maxima set the first three acoustic peaks, (the first through \( l_{3/2} \)) and the acoustic scale at \[ l_1 = 213^{+10}_{-13}, \quad l_2 = 541^{+20}_{-32}, \quad l_3 = 845^{+12}_{-25}, \quad l_{3/2} = 416^{+22}_{-32}, \quad l_A = 316^{+8}_{-9}, \] \hspace{1cm} (8)

We have solved eqs. (4) numerically with initial conditions \( \Omega_{\phi}(\Lambda_c) = 0.3 \) at \( \Lambda_c = 1 \text{GeV} \) imposing \( h_o = 0.65, \Omega_{\phi_0} = 0.75 \) and we obtain

\[ l_A = 307, \quad w_{\phi_0} = -0.68, \quad w_{\text{eff}} = -0.75, \] \hspace{1cm} (9)

where \( w_{\text{eff}} \equiv \int da \Omega(a)w_\phi(a)/\int da \Omega(a). \) The energy density at last scattering (LS) is negligible \( (\Omega_{\phi}(LS) = 10^{-9}) \) and the average sound speed at LS is \( \bar{c}_s = 0.52. \) The result is not highly sensitive to the initial conditions and a change in \( \Omega_{\phi_0} \) of 50% will still be ok \[ \text{(8)}. \]

We see from eq. (9) that the acoustic scale \( l_A \) is within the observational range given by eq. (10). The prediction of the first three acoustic peaks and first through \( (l_{3/2}) \) is

\[ l_1 = 223, \quad l_2 = 542, \quad l_3 = 829, \quad l_{3/2} = 414 \] \hspace{1cm} (10)

for a baryon density \( w_b = \Omega_b h_o^2 = 0.02 \) and \( n_s = 1 \) the index of power spectrum of primordial density fluctuations. The peak values in eq. (10) are consistent with the observational data in eq. (9) and we have used the phase shifts given in \[ \text{(9)}. \]

The value of \( l_A \) is sensitive to \( \Omega_{\phi_0} \) and even more to \( h_o. \) For increasing \( h_o \) (with \( \Omega_{\phi_0} \) fixed) we find a decreasing \( l_A, \) e.g. for \( h_o = 0.6, 0.65, 0.7, 0.8 \) one has \( l_A = 309, 307, 288, 272 \) respectively, while for an increasing energy density one has an increasing \( l_A, \) e.g. \( \Omega_{\phi_0} = 0.6, 0.7, 0.75, 0.8 \) one gets \( l_A = 291, 300, 307, 317 \) with fixed \( h_o = 0.65. \) Since \( \bar{c}_s \) depends on \( w_b \) and an increase in \( w_b \) makes \( \bar{c}_s \) smaller and we therefore have a slight increase in the acoustic scale, e.g. for \( w_b = .019, 0.020, 0.022, 0.026 \) one gets a value of \( l_A = 305, 307, 309, 314 \) with \( \Omega_{\phi_0} = 0.75, h_o = 0.65 \) fixed. A change in \( n_s \) does not affect \( l_A \) but it changes the acoustic peaks through the phase shifts \( \varphi_m \) slightly.

Another relevant cosmological quantity is the density contrast on scales of \( 8h^{-1}\text{Mpc}, \sigma_8, \) which is constraint by the galaxies cluster abundance. For a flat universe the empirical fit of different authors (which converge within one \( \sigma \)) are: Eke et al. have \( \sigma_8 = (0.52 \pm 0.08)\Omega_m^{-0.52+0.13\Omega_m} \) \[ \text{(21)}, \] while Steinhardt et al. \[ \text{(23)} \] have \( \sigma_8 = [(0.5 - 0.1 \Theta) \pm 0.1] \Omega_m^{-0.47}, \quad \Theta = (n - 1) + (h_o - 0.65), \gamma = 0.21 - 0.22w + 0.25\Theta. \) For \( n = 1, h_o = 0.65 \) one has \( \sigma_8 = 1.02 \pm .15, 1.07 \pm 0.03, 0.98 \pm 0.2 \) for Eke, Viana and Steinhardt respectively. Recent analysis give slightly lower values of \( \sigma_8 = (0.46^{+0.05}_{-0.07})\Omega_m^{-0.52} \) for \[ \text{(24)} \] (see also \[ \text{(23)} \]) and depends quite strongly on \( \Omega_m \) (for smaller \( \Omega_m \) one has a larger \( \sigma_8 \)). The central value for \( \Omega_m = 0.25 \) is \( \sigma_8 = 0.945 \) which agrees quite well with our the value obtained in our model \( \sigma_8 = 0.95. \)

To conclude, we have shown that inverse power law potentials with \( n > 1 \) are not disfavored with the existing cosmological data and we have shown an explicit example with \( n \approx 2.57. \) In
particular, the values of $w_{\phi_0}$, the acoustic scale and peaks and the density contrast $\sigma_8$ lie within the observed data. The model has been derived from particle physics, using ADS superpotential, from a non-abelian gauge group with $N_c = 8$, $N_f = 1$. Since $N_f = 1$ there is only one degree of freedom below the condensation scale, i.e. the condensate or quintessence field $\phi$. The condensation scale is at $1\text{GeV}$ a very interesting scale which connects quintessence with the standard model.

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Figure 1: Variations on $\Omega_{\phi_i}$ lead to different physical situations given by $w_{\phi_0}$ and $\Omega_{\phi_0}$. We have taken $\Omega_{\phi_i} = 0.5, 0.3, 0.2$ short-dashed, long-dashed and solid lines, respectively. The vertical line marks the time at $\Omega_{\phi_0} = 0.7$ with $h_0 = 0.67$. Notice that $w_{\phi_0}$ increases with decreasing $\Omega_{\phi_i}$. 