Title

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1 Objectives

For LCDM, interacting models, and CPL, calculate

- ξ range for varying EoS while fixing $\Omega m0$
- ξ range for varying $\Omega m0$ or r, while fixing ω
- Does $\xi > 0$ means energy transfer to dark energy in this method?

2 Background

Deceleration parameter reads

$$q(z) = -1 + \frac{1+z}{H}\frac{\mathrm{d}H}{\mathrm{d}z} \tag{1}$$

For interaction models, the Friedmann equaitons,

$$\dot{\rho}_c + 3H\rho_c = Q_c \tag{2a}$$
$$\dot{\rho}_d + 3H(1+w)\rho_d = -Q_c \tag{2b}$$

$Q_c = \xi H \rho_c$ Background equations,

$$\Omega m = \Omega m0(1+z)^{3-\xi} \tag{3a}$$
$$\Omega d = (\Omega d0 + \frac{\xi}{3w+\xi}\Omega m0)(1+z)^{3(1+w)} + \frac{-\xi}{\xi+3w}\Omega m = \Omega \bar{d}0(1+z)^3 + \frac{-\xi}{\xi+3w}\Omega m \tag{3b}$$

$Q_c = \xi H \rho_d$

$$\Omega m = (\Omega m0 + \frac{\xi}{\xi+3w}\Omega d0)(1+z)^3 + \frac{-\xi}{\xi+3w}\Omega d = \omega \bar{m}0(1+z)^3 + \frac{-\xi}{\xi+3w}\Omega d \tag{4a}$$
$$\Omega d = \Omega d0(1+z)^{3(1+w)+\xi} \tag{4b}$$

Eqn **??** and eqn **??** shows that the coupling constant has two effects,

1. Change the amplitude of the evolution of matter or dark energy energy density.
2. Transfer energy between DE and DM.

2.1 Some definitions

1. For short

$$r = \frac{\Omega m0}{\Omega d0}$$

CPL EoS is

$$w = w0 + w1\frac{z}{1+z}$$

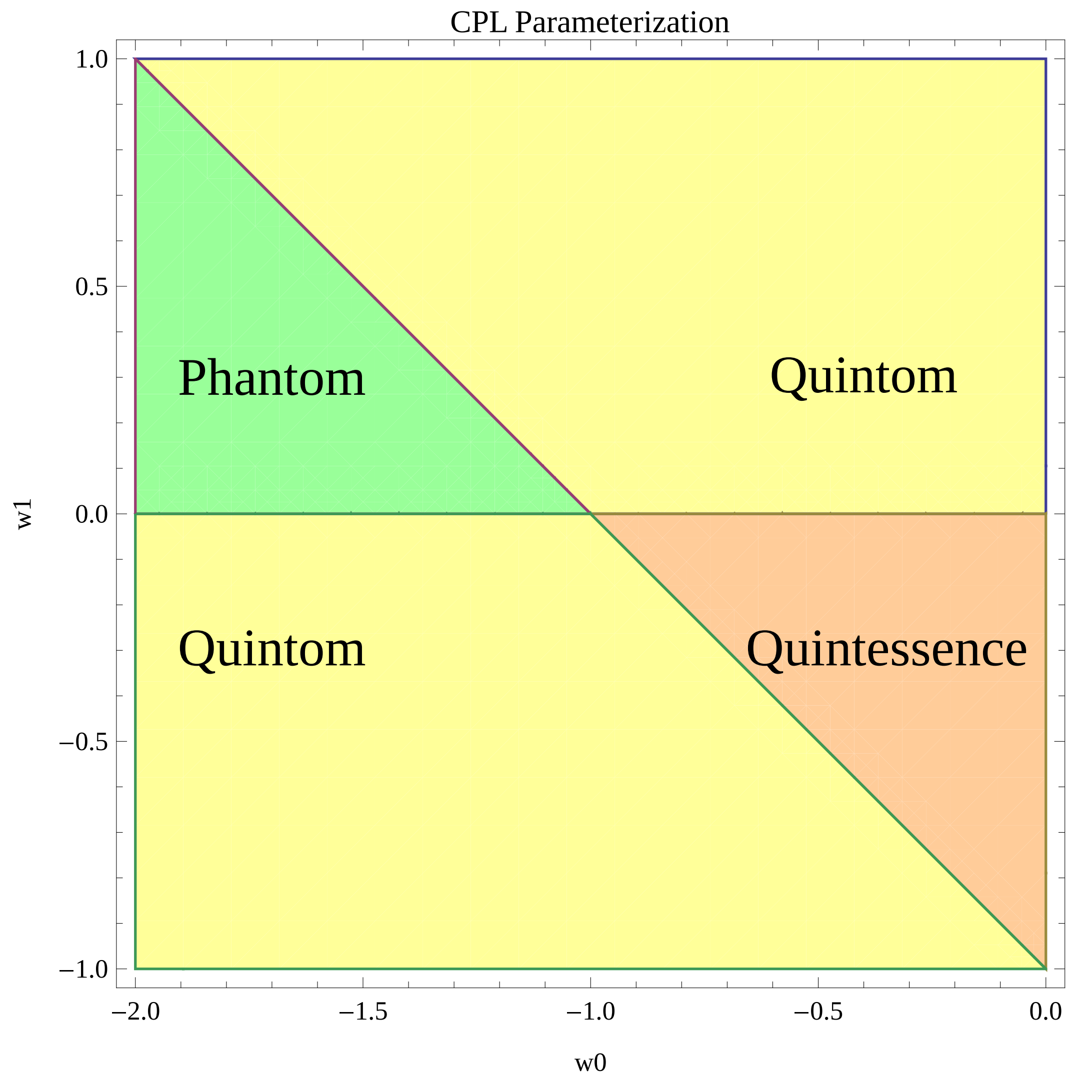


Figure 1: CPL classification

Classification Figure **??** shows how to category the dark energy models in CPL parametrization.

3 Data & Method

3.1 Data

LCDM Parameters From WMAP, $\Omega m0 = 0.265$

Constraints $\Omega m0 = 0.247(+0.013, -0.013)$; Transition redshift 0.426 (+0.082, -0.050).(arXiv:1205.4688, arXiv:astro-ph/0611572).

In ($\Omega m0$, Transition redshift) plane, allowed region is a rectangle centred at (0.274, 0.426) with two diagonal points (0.261, 0.376) and (0.287, 0.508).

CPL $\Omega m0 = 0.269(+0.017, -0.008)$, $w0 = -0.97(+0.12, -0.07)$, $w1 = 0.03(+0.26, -0.75)$

4 Results

Check the files in files folder.

4.1 $Q_c = \xi H \rho_c$

Results table

$Q_c=\xi H \rho_c$, constant ξ, constant w=-1: Results for ξ			
Ωm0/Ωd0\Transition	z_t=0.376	z_t=0.426	z_t=0.508
r=0.358	-1.25282	-0.965436	-0.617444
r=0.378	-1.15011	-0.875189	-0.542347
r=0.398	-1.05453	-0.791252	-0.472561

Figure 2: ICC Result table

Figure **??** shows that

ρ_c**-Dec-1** The universe decelerates faster at the early stage for smaller interaction constant ξ even they have the same matter fraction.

ρ_c**-Dec-2** For the same ξ, the deceleration converge ($q = (1 - \xi)/2$ with $3w + \xi < 0$) at early time.

Figure **??** shows

ρ_c**-Trans-1** Transition happens earlier when matter fraction is smaller. Matter is against DE's pressure.

ρ_c**-Trans-2** Transition is later when ξ is smaller.Energy transfers to DE when ξ is negative, then why later transition? [1]

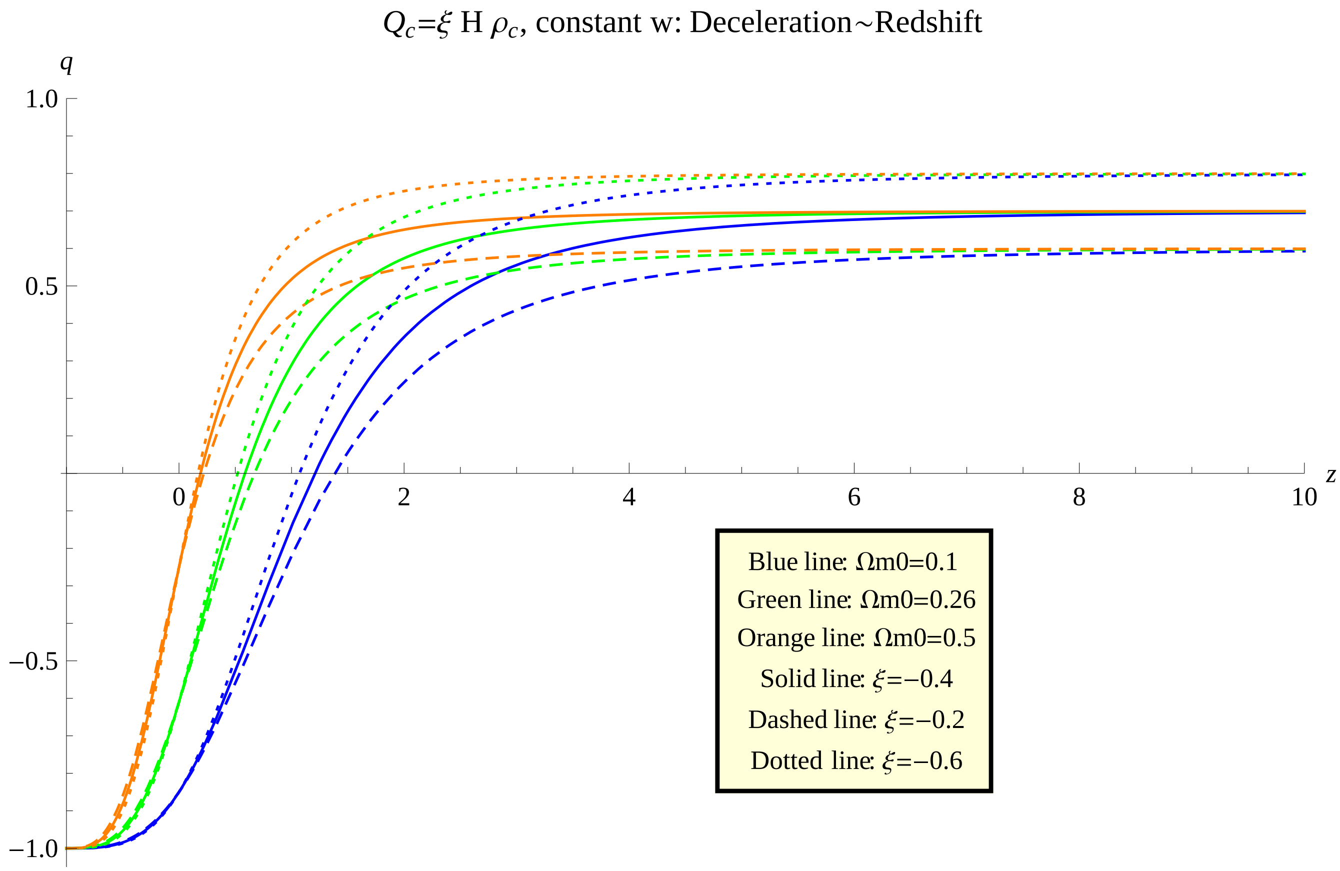


Figure 3: Deceleration parameter

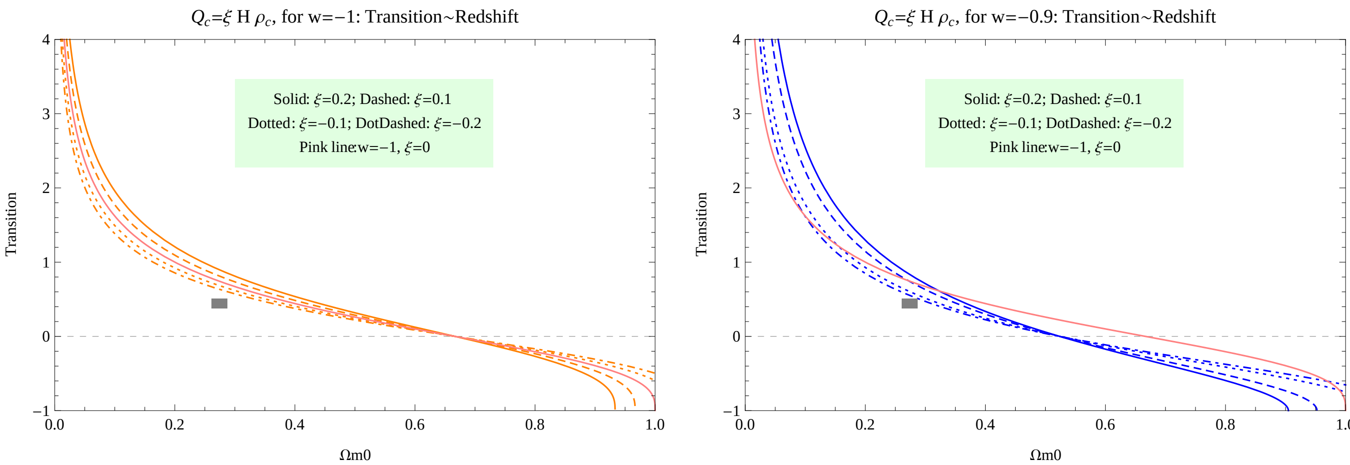


Figure 4: Transition redshift.

Figure **??** and figure **??** (vertical lines are $w = -1 \pm 0.05$) show the value of ξ for different EoS. Results from this figure:

(EoS is -1 within 5w=-1 (-1.279,-0.457) center:-0.878 ; w=-1.05 (-1.293,-0.461) center:-0.887 ; w=-0.95 (-1.255,-0.447) center:-0.860 ;

ρ_c-xiVSw-1 NOT monotonic. The result of ξ is greatly affected by $\Omega m0$. In correspondence with another

ρ_c-xiVSw-2 For different $\Omega m0$, ξ values deviate greatly form each other at small w.

Figures **??** show how do we constrain ξ and how do EoS change our constrain results with the transition fixed.

ρ_c-xiVS$\Omega m0$-1 The smaller, the more difference among ξ values of different EoS. Reason for this is less matter has less effect on the evolution thus the property of dark energy determines more about the transition.

ρ_c-xiVS$\Omega m0$-2 Second figure shows

+ System with smaller w needs smaller coupling to achieve the same transition time, as expected.
+ So we give the result that $w \in (-0.58406, -0.3334)$ if we constrain $\Omega m0 = 0.2603$ and transition redshift 0.426.

[1] Reasons below. All solutions of equation **??** have the same value at $z = 0$, i.e. now. Equation **??**a tells us a positive ξ leads to smaller energy density of dark matter at early time of the universe, thus dark energy takes over quickly if the transition happens before today. (For more details, calculation are shown in supplement_ 08-10.pdf file.)

ξ results for $Q_c=\xi\ H\ \rho_c$ (Fitting data: Data From, 2)			
w	Center	Lower	Upper
-1.183	-0.881565	-1.29687	-0.443589
-1.087	-0.88948	-1.29859	-0.459135
-0.991	-0.875238	-1.27522	-0.456176

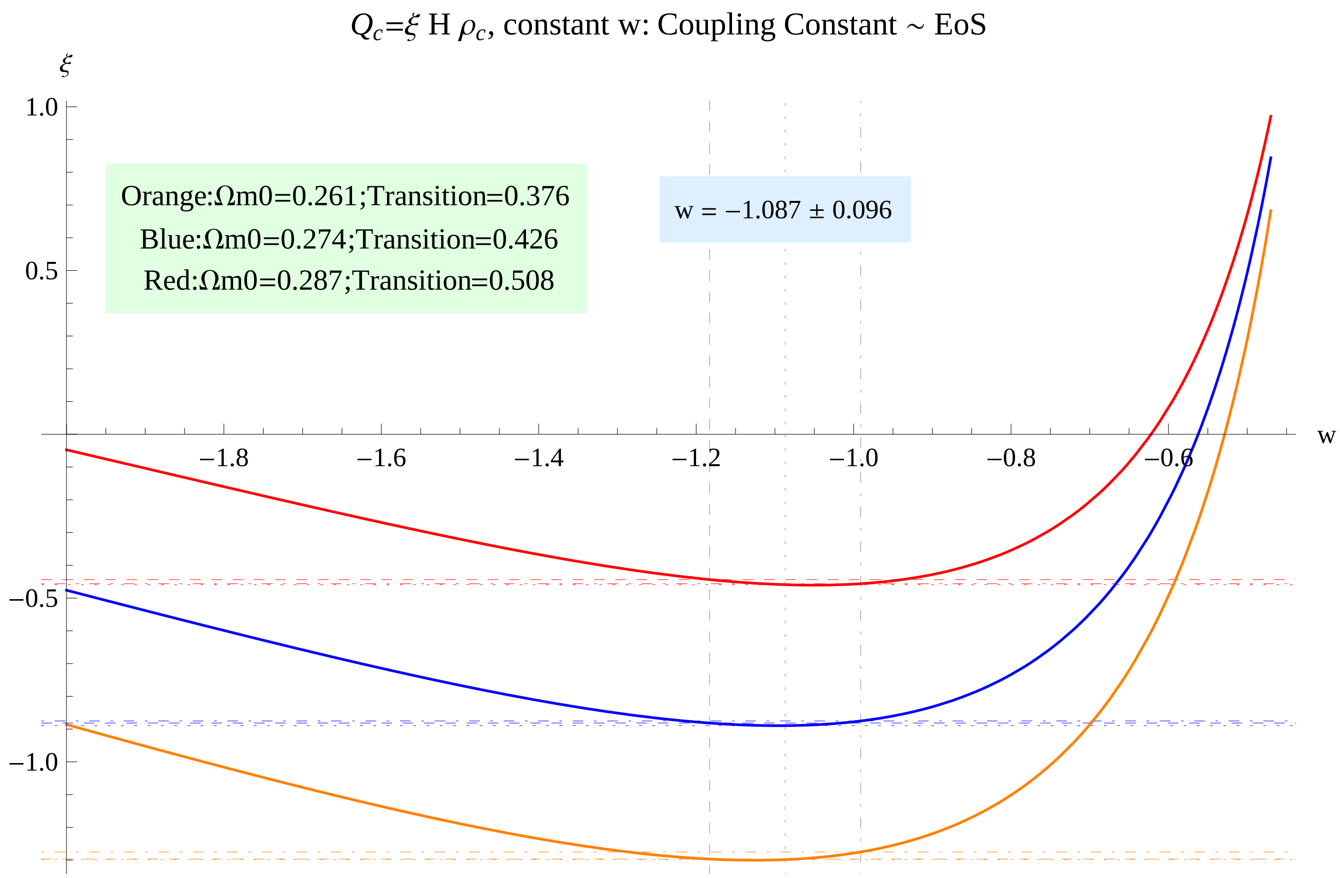


Figure 5: Interacting coefficient for $Q_c = \xi H \rho_c$

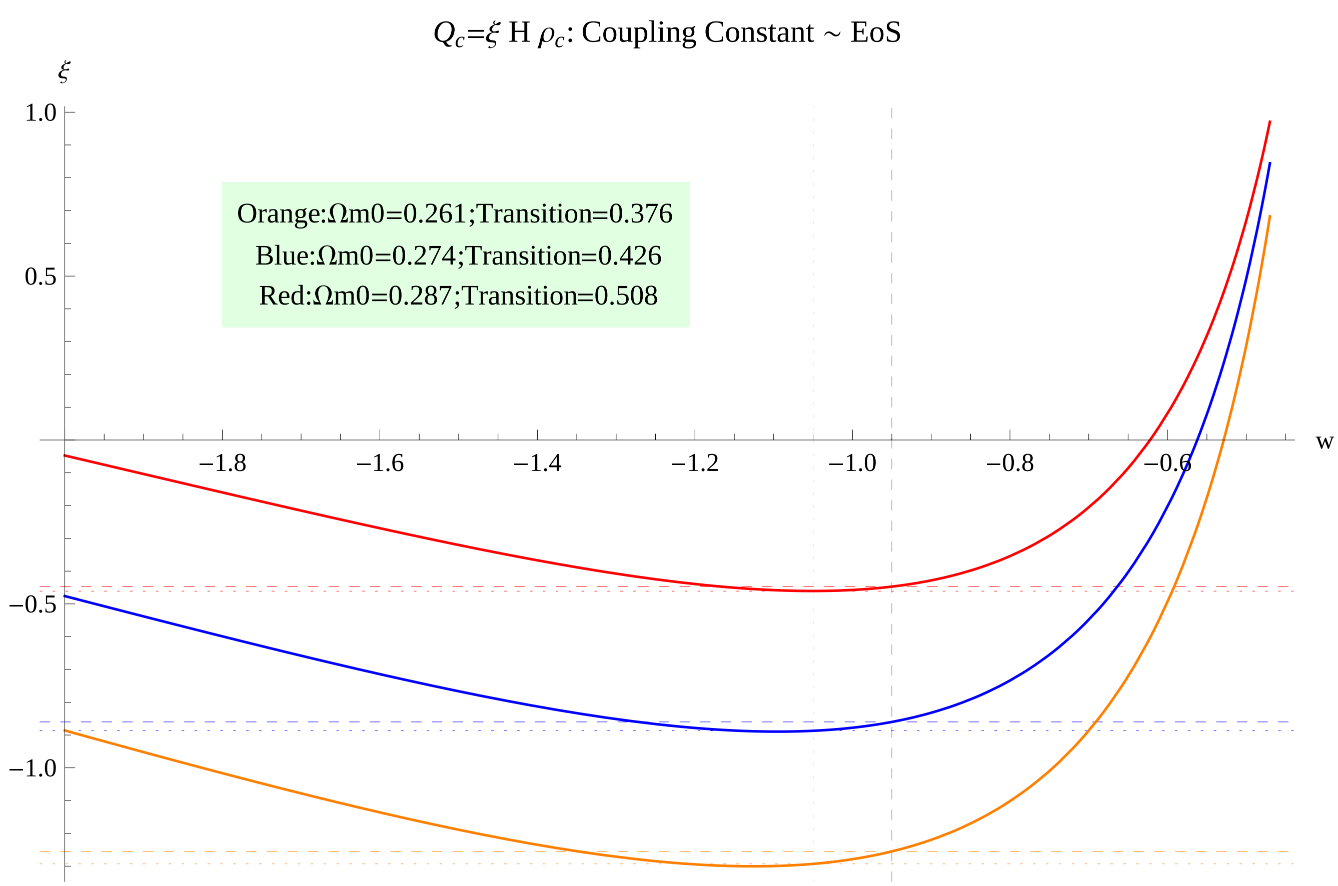
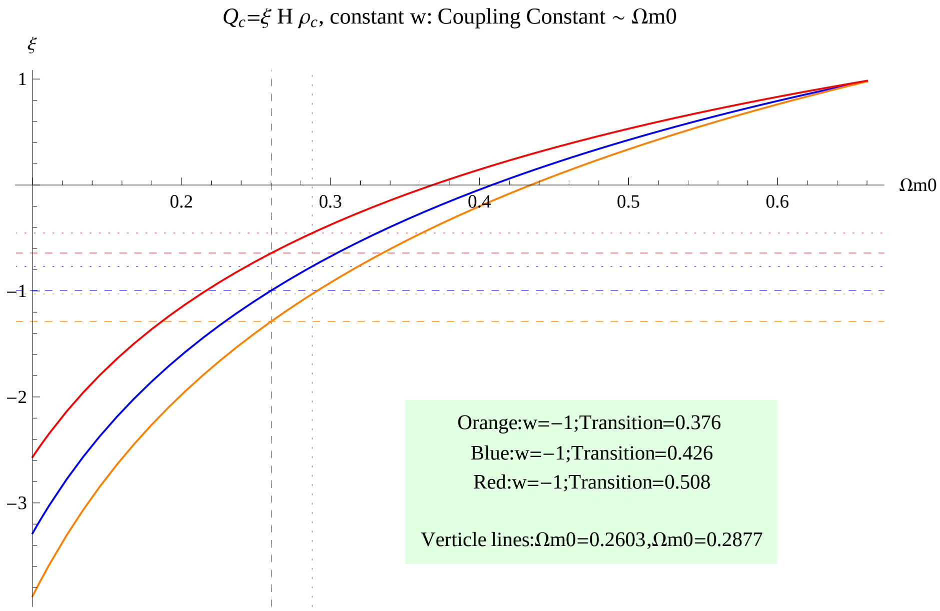


Figure 6: Interacting coefficient for $Q_c = \xi H \rho_c$

For Ωm0∈0.274 (1 ± 0.05) Table of ξ for different Ωm0~Transition combination			
Ωm0\Transition	0.426	0.376	0.508
0.2603	-0.994339	-1.28571	-0.641508
0.274	-0.877755	-1.15303	-0.544482
0.2877	-0.767582	-1.02756	-0.452892



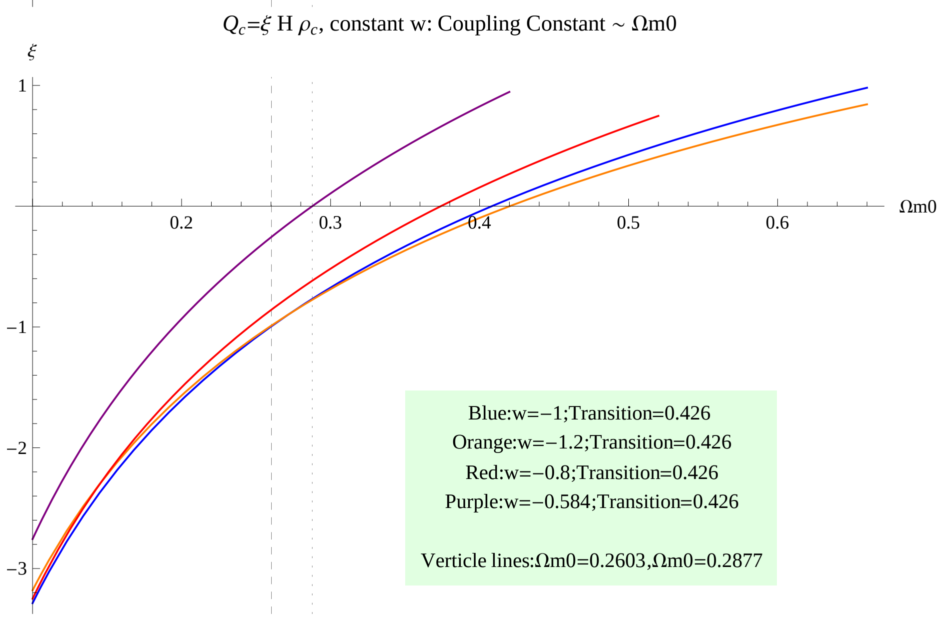


Figure 7: Interacting coefficient changing with $\Omega m0$ for $Q_c = \xi H \rho_c$

4.2 $Q_c = \xi H \rho_c$, CPL

For a flat universe, choose the parameters w0=-1.02,w1=0.6, the region for interation cosntant ξ should be (-1.04,-0.21) with a center at -0.64, derived from the (transition redshift, $\Omega m0$) plane, while a result of (-1.01, -0.23) with a center at -0.63, derived from (transition redshift, $\Omega m0/$

First let's have a look at the deceleration parameter.

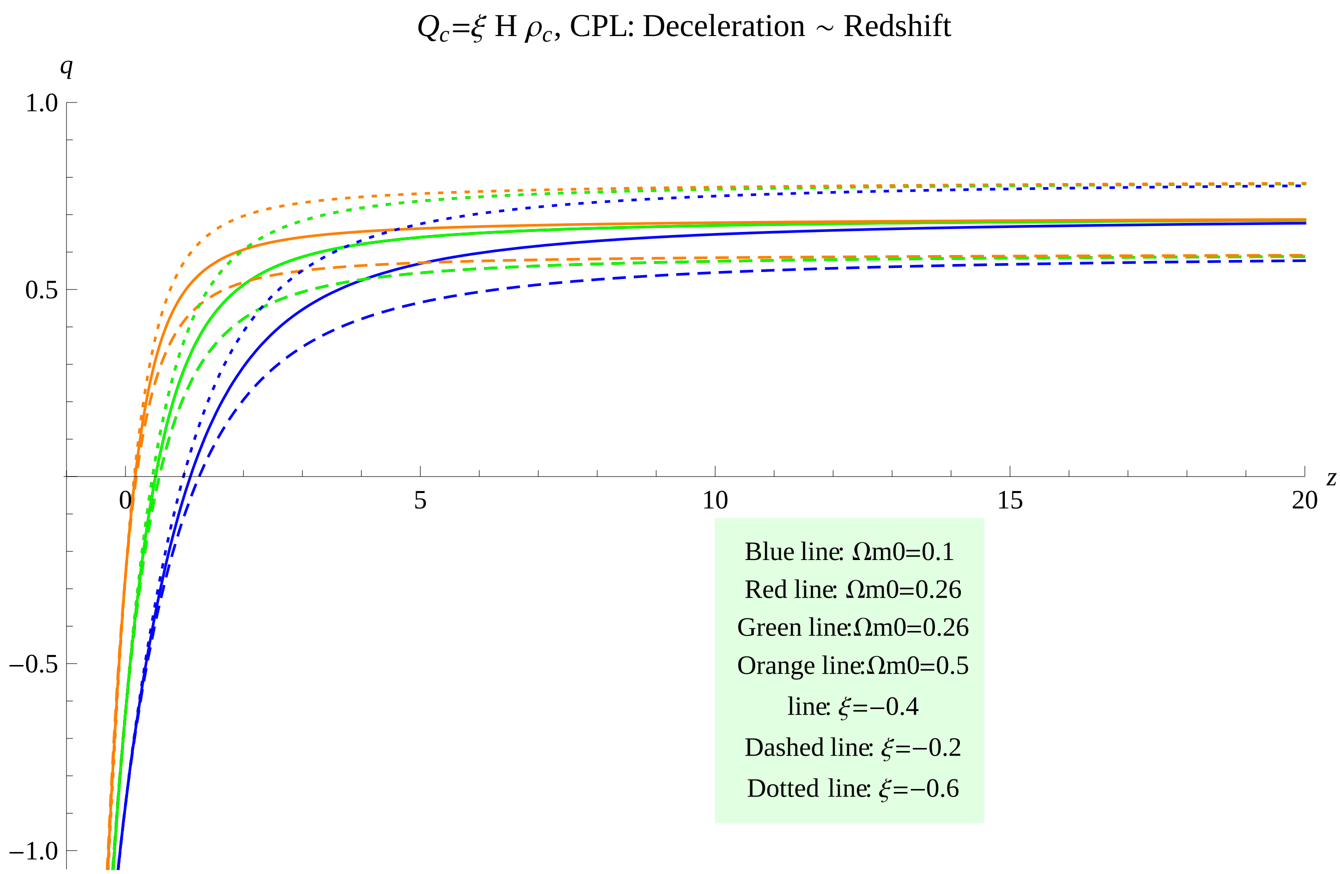


Figure 8: Deceleration parameters for ICCPL ($Q_c = \xi H \rho_c$ with CPL parametrized EoS)

Figure **??** is right similar to constant EoS situation.

Figures **??** show

ρ_c-ICCPL-TVS$\Omega m0$-1 Coupling acts on these model similar to constant EoS model.

ρ_c-ICCPL-TVS$\Omega m0$-2 The change in $w1$ has a similar effect with the change of ξ. Larger $w1$ corresponds to smaller ξ. The reason for this is both negative ξ and larger $w1$ enhances the energy density of dark energy (check using the CPL EoS).

The dots in figure **??** are the data set of $\xi = 0$. If we need $\xi < 0$, i.e., energy transfers from dark matter to dark energy, the allowed parameter space is the striped area.

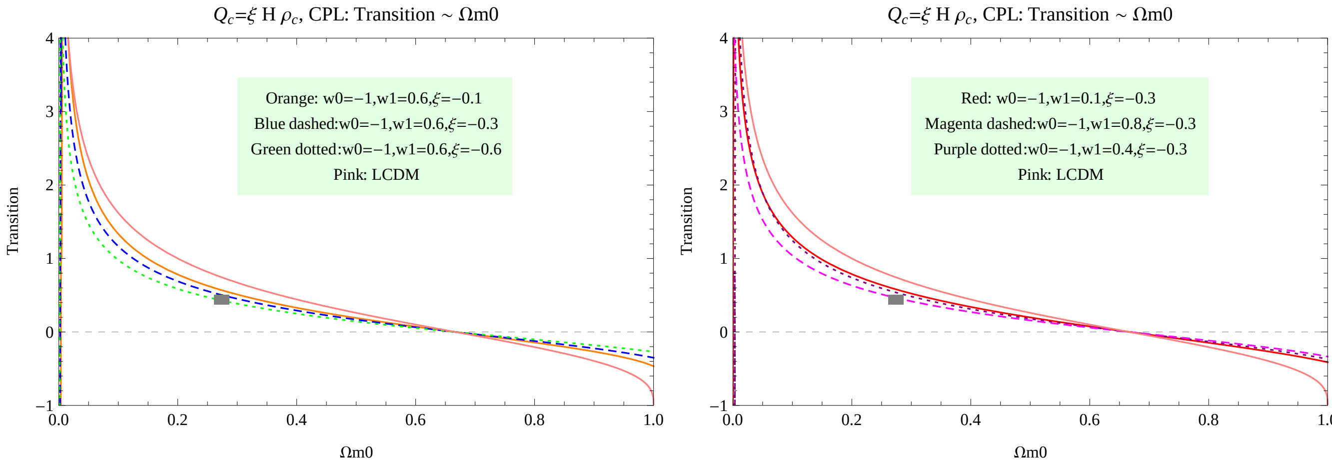


Figure 9: The effect of EoS parameters on Transition and $\Omega m0$

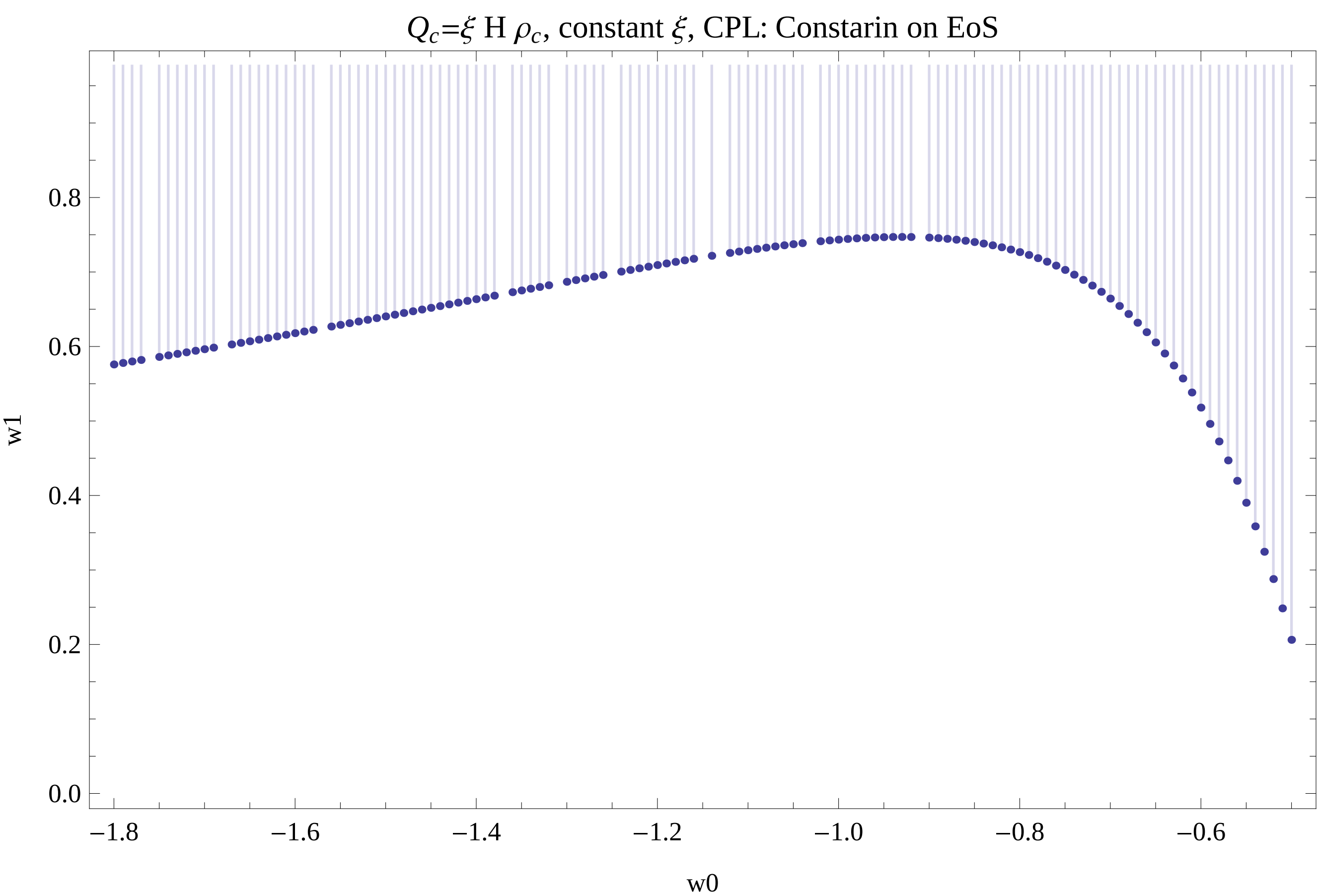


Figure 10: Lower bound in the W1 w0 parameter space

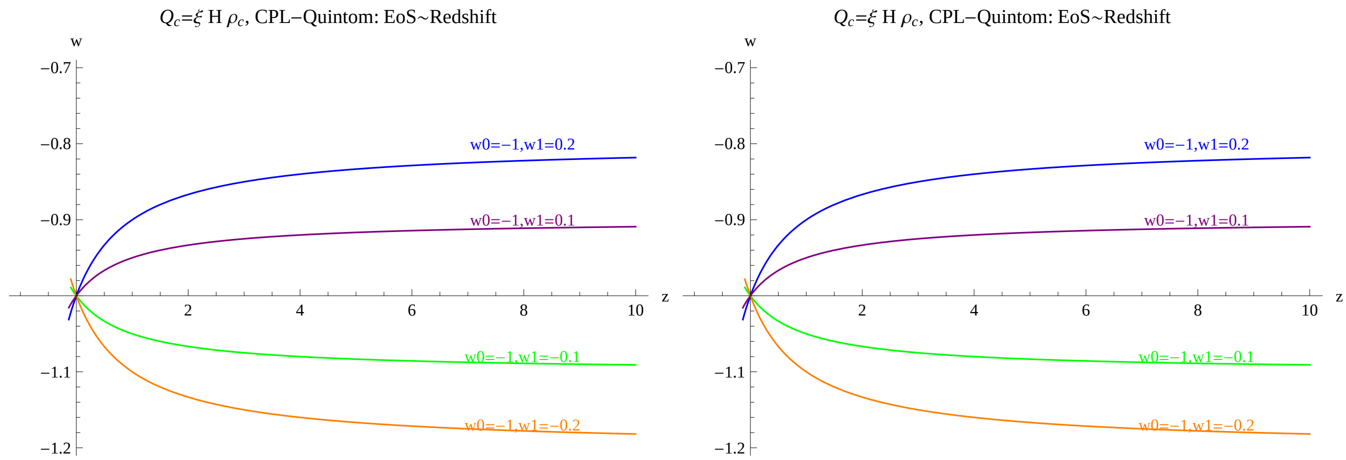


Figure 11: The EoS

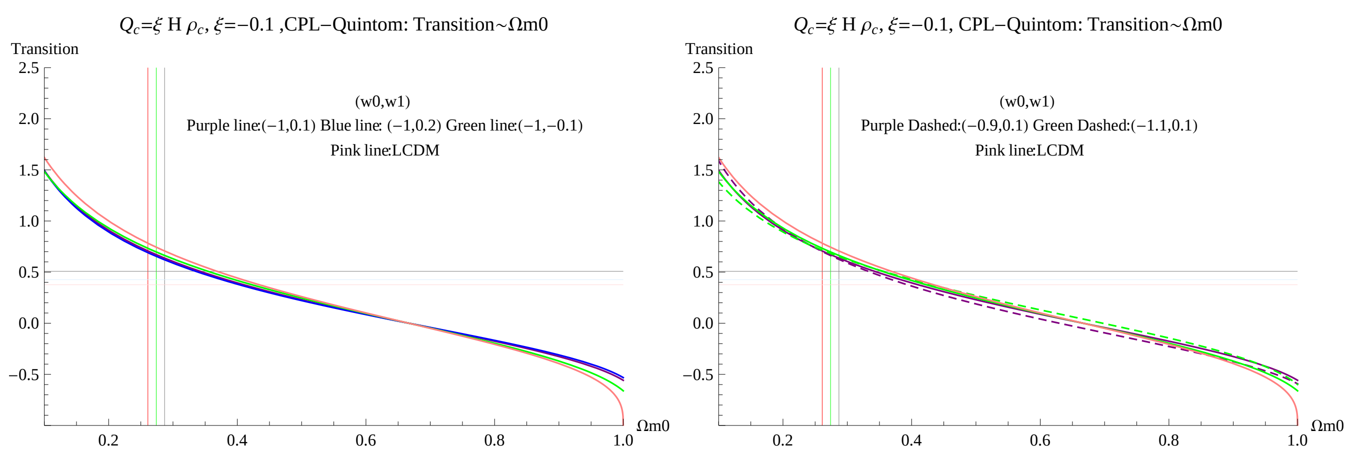


Figure 12: Transition vs $\Omega m0$

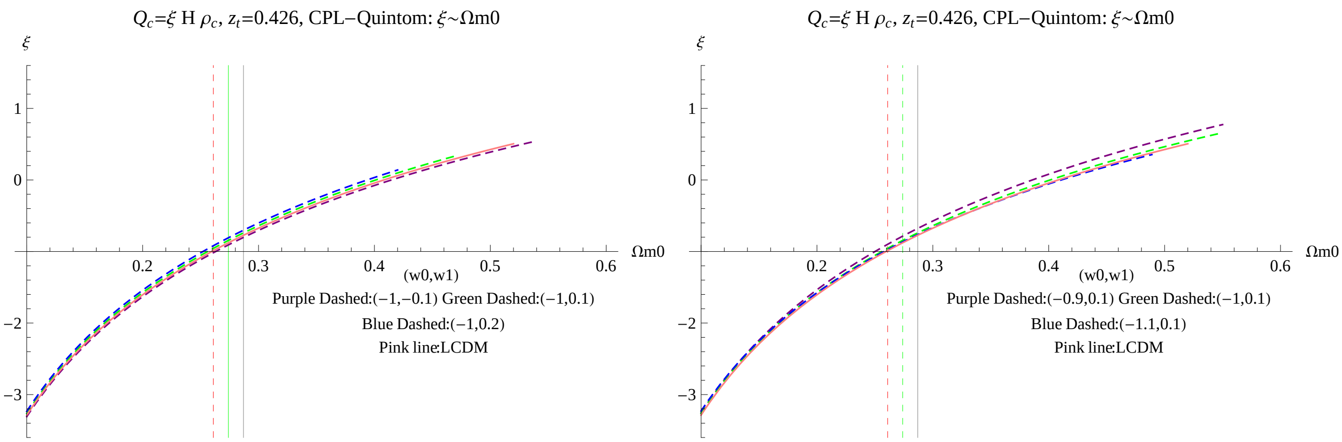


Figure 13: ξ vs $\Omega m0$

4.2.1 Quintom

(Figures **??**, **??**, **??**)
The left figure in **??** indicates a possible stationary point.[2]
(Other results are shown on the complete results files.)

4.2.2 Quintessence

(Figures **??**, **??** and **??**.)

4.2.3 Phantom

(Figures **??**, **??**, **??**, **??**)

4.3 $Q_c = \xi H \rho_d$

(Figures **??**, **??**, **??**, **??**)

4.4 I2CCPL

(Figures **??**, **??**)
Figure **??** shows the all the deceleration are the same at very early time.

4.4.1 Quintom

(Figures **??**, **??**)

4.4.2 Quintessence

(Figures **??**, **??**)

[2]Only possible because I can only partially prove there is a nearly stationary. This is on my *Cosmologia Notebook*.

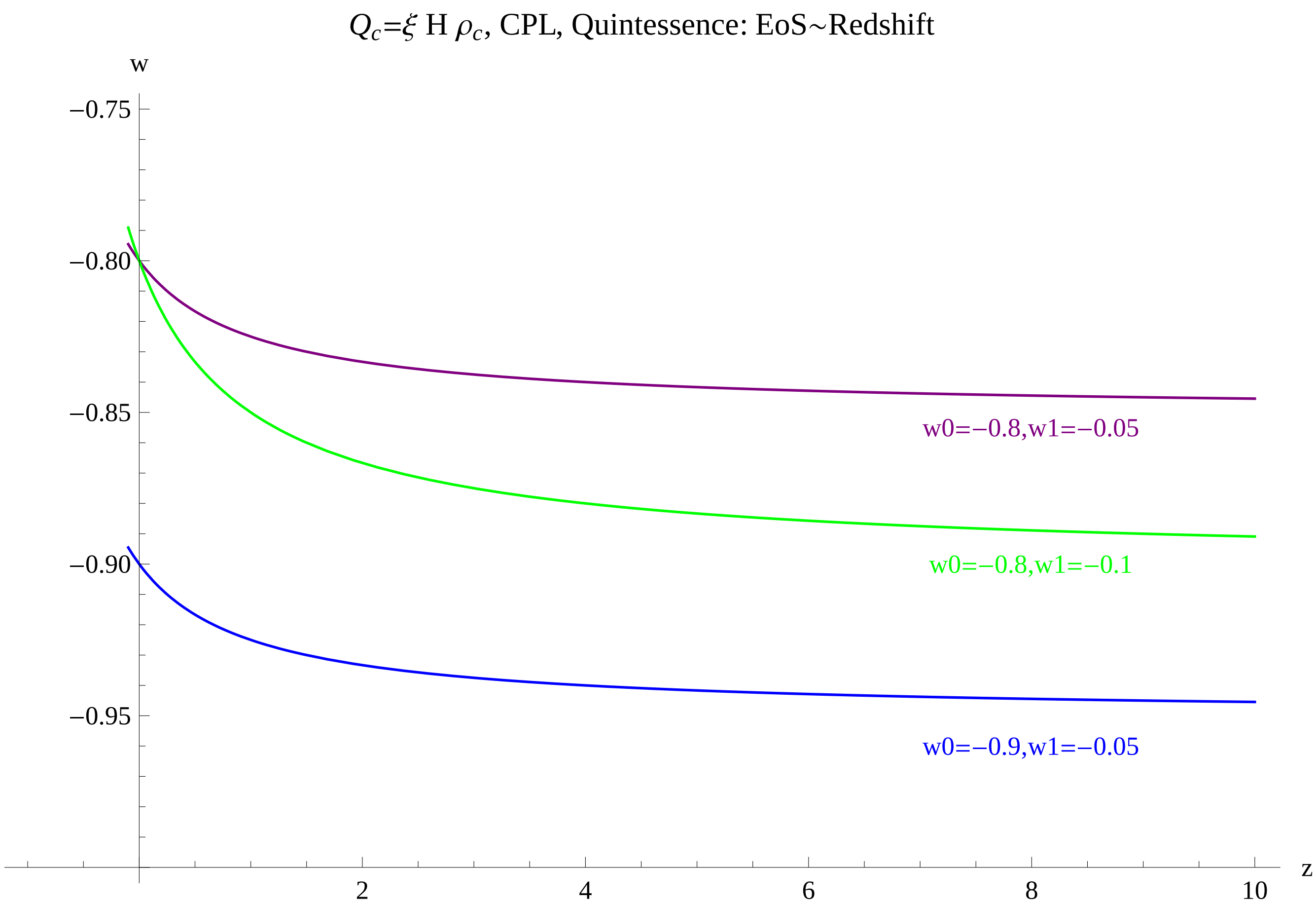


Figure 14: The EoS

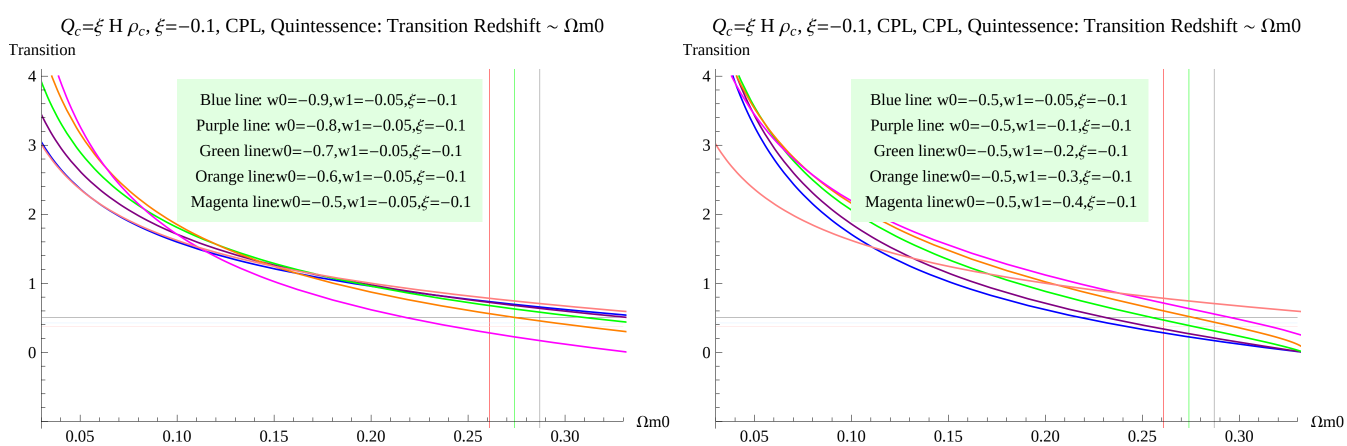


Figure 15: Transition vs $\Omega m0$

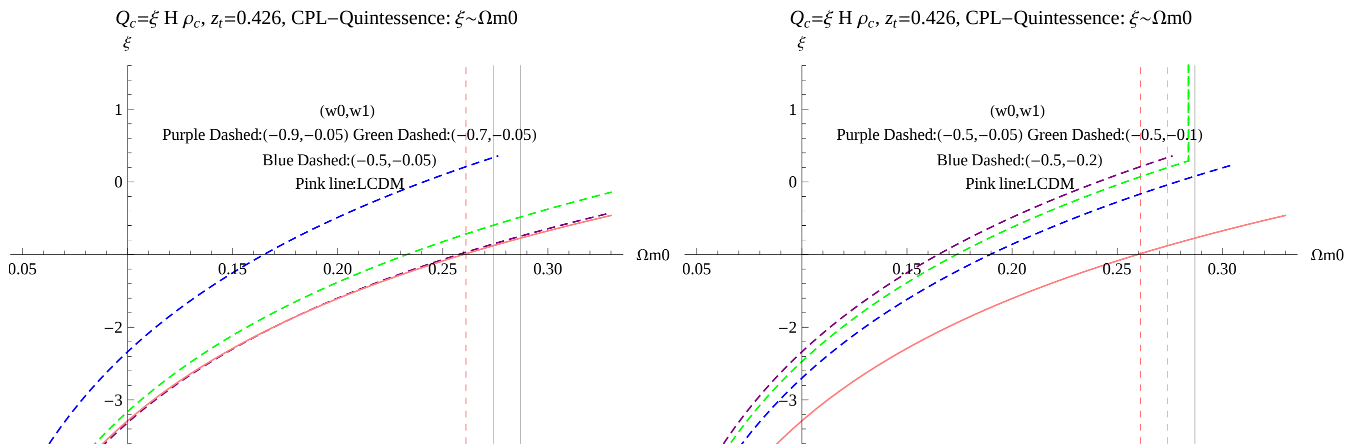


Figure 16: ξ vs $\Omega m0$

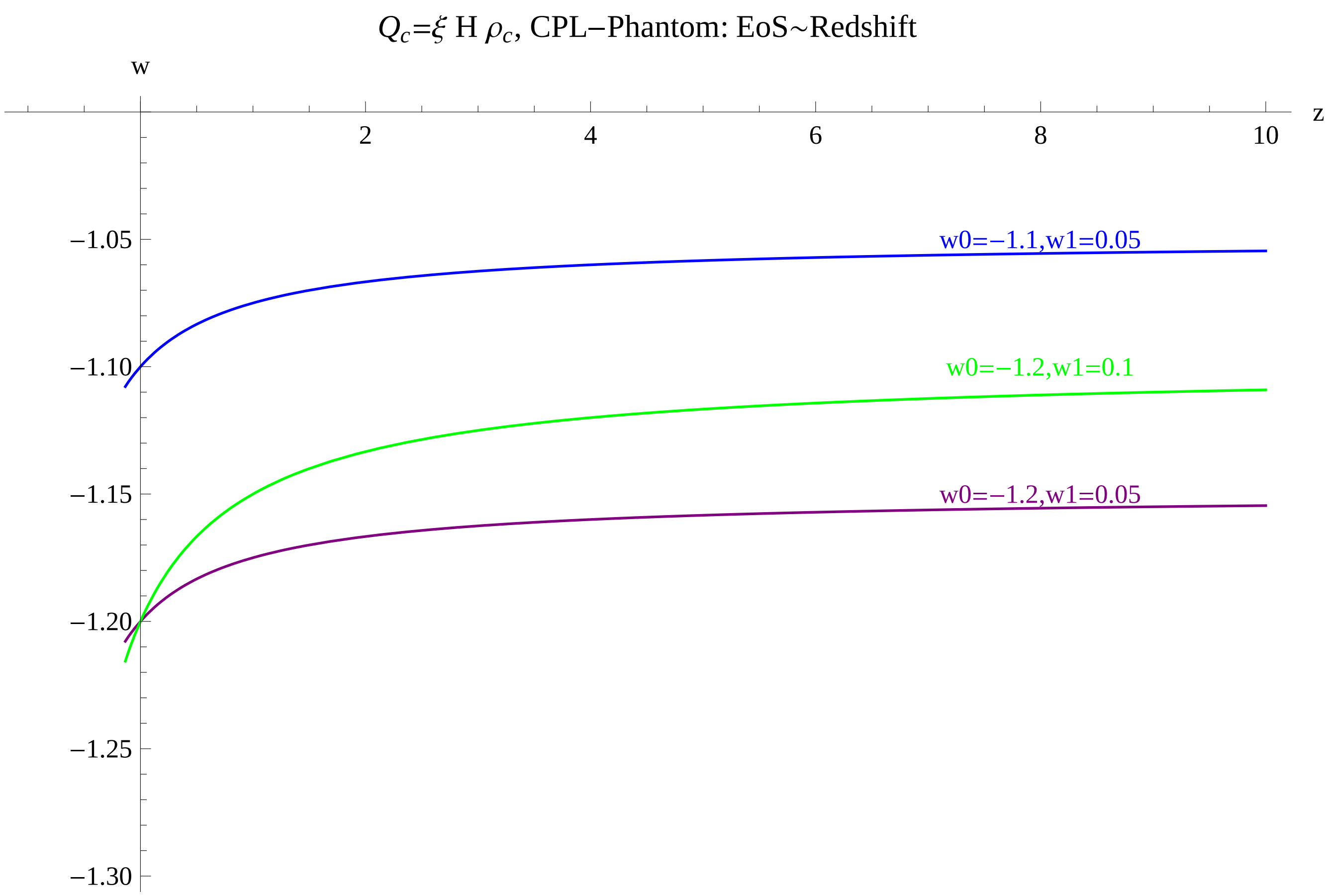


Figure 17: The EoS

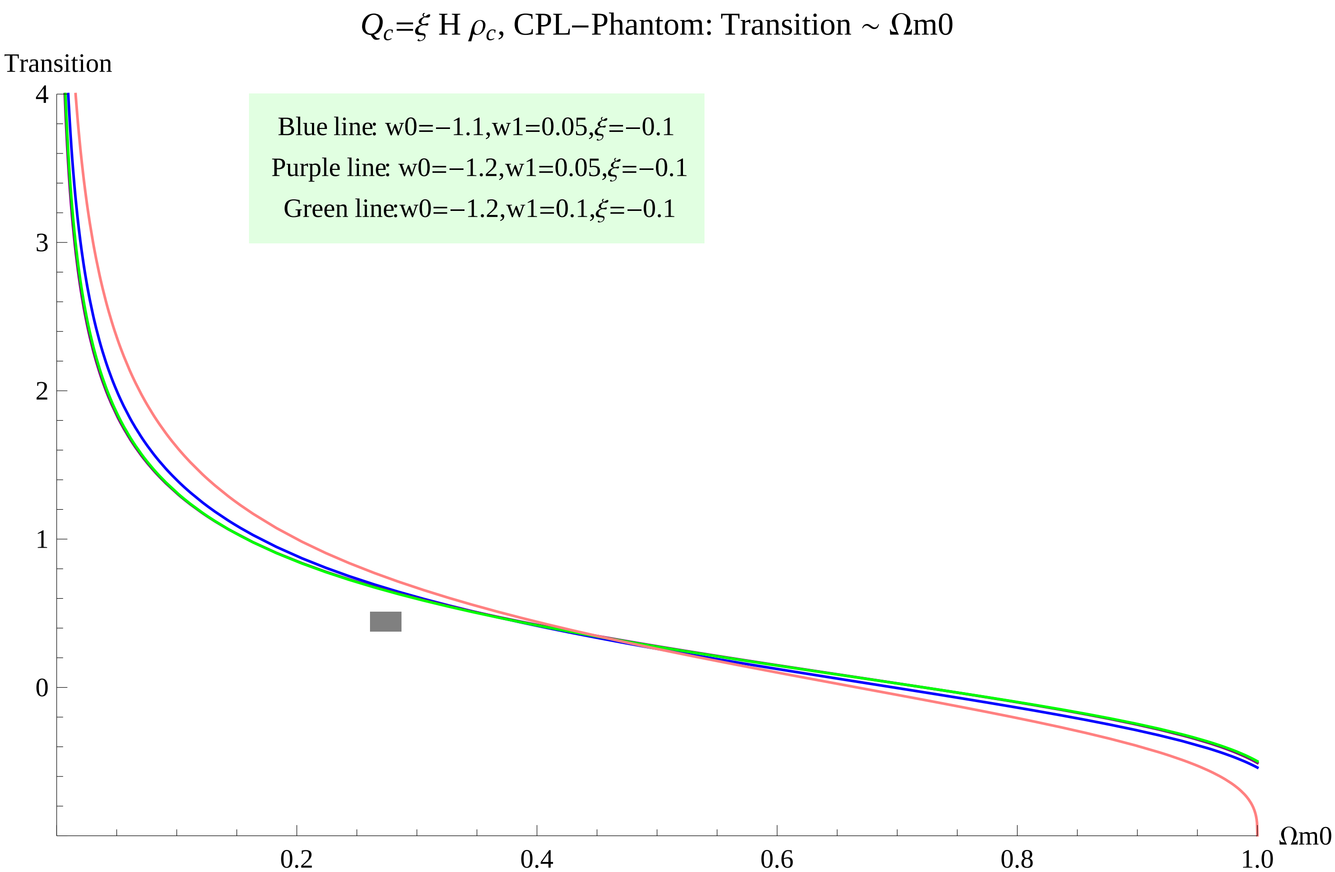


Figure 18: Transition vs $\Omega m0$

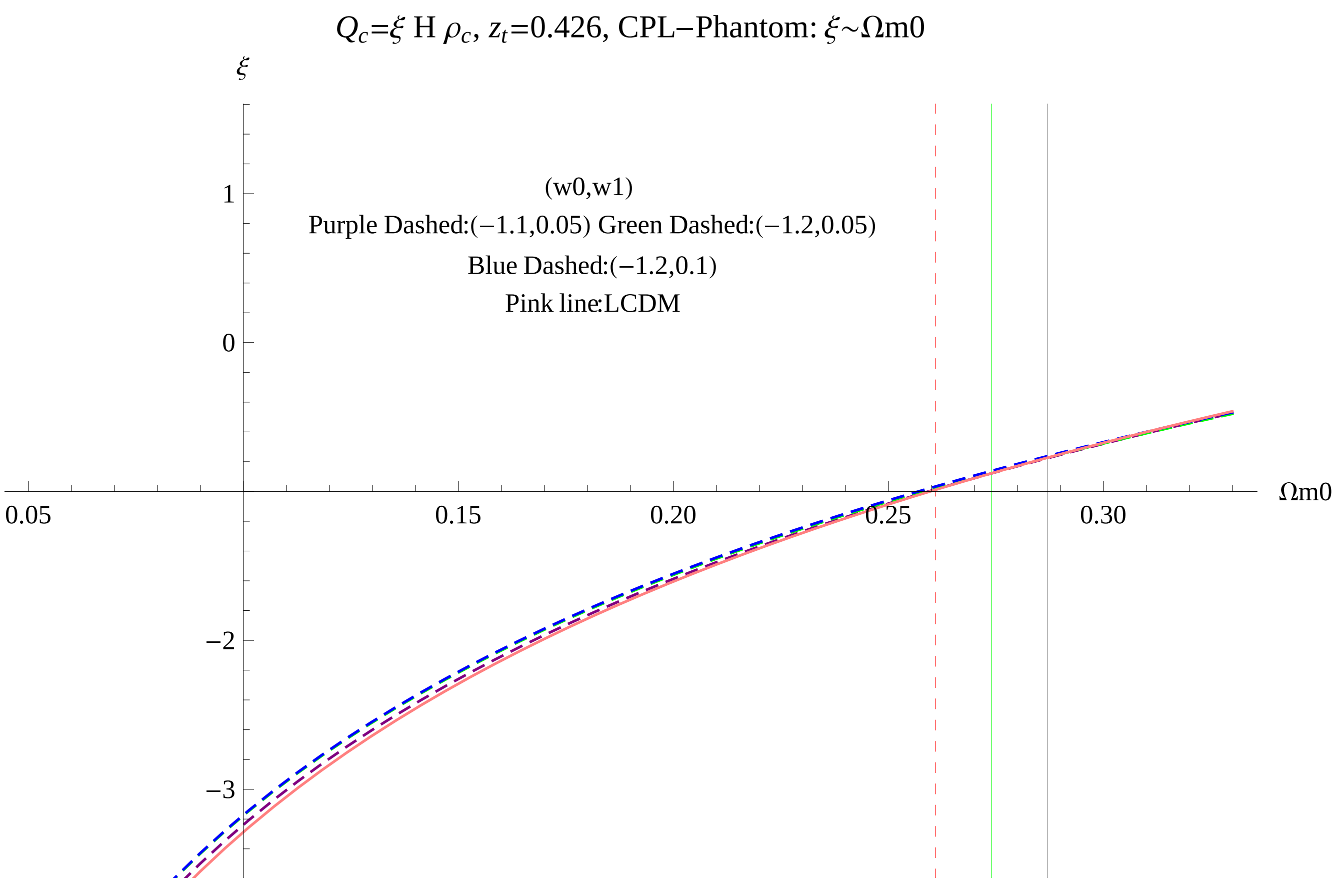


Figure 19: ξ vs $\Omega m0$

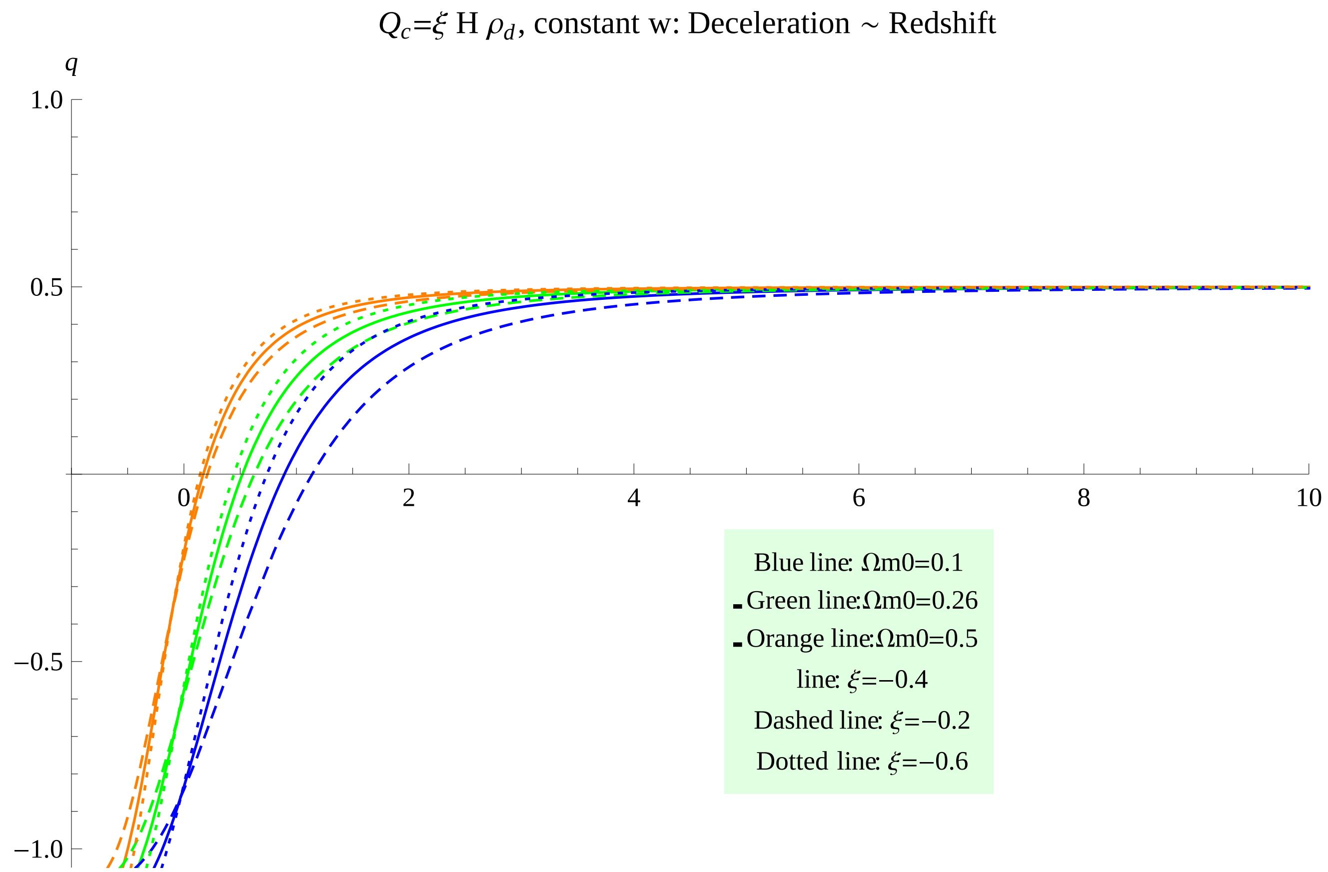


Figure 20: Deceleration parameter

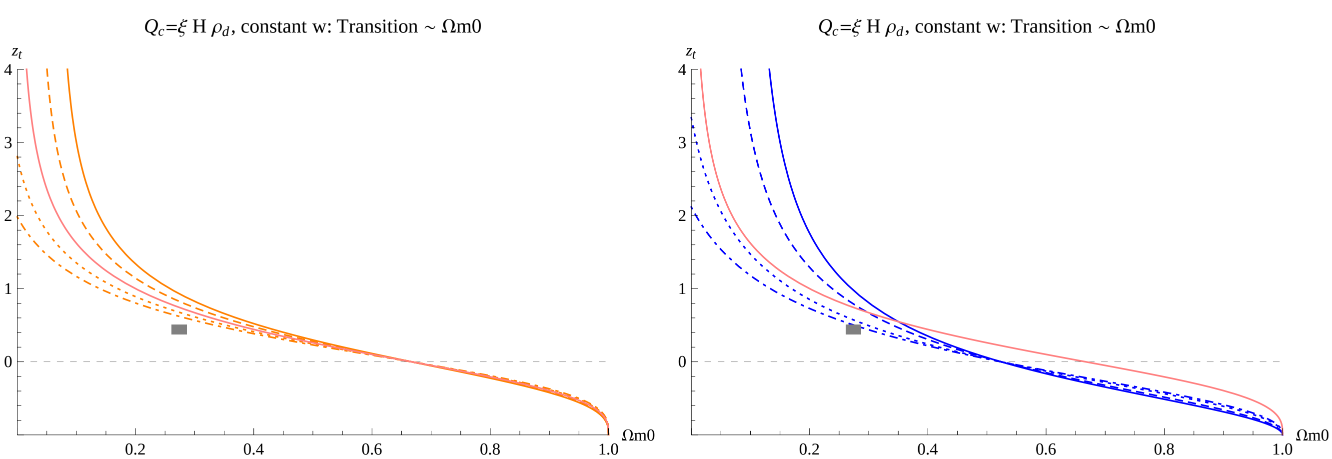


Figure 21: Transition vs $\Omega m0$. For a flat universe, choose the parameters w0=-1.02,w1=0.6, the region for interation cosntant ξ should be (-1.04,-0.21) with a center at -0.64, derived from the (transition redshift, $\Omega m0$) plane, while a result of (-1.01, -0.23) with a center at -0.63, derived from (transition redshift, $\Omega m0/\Omega d0$) plane.

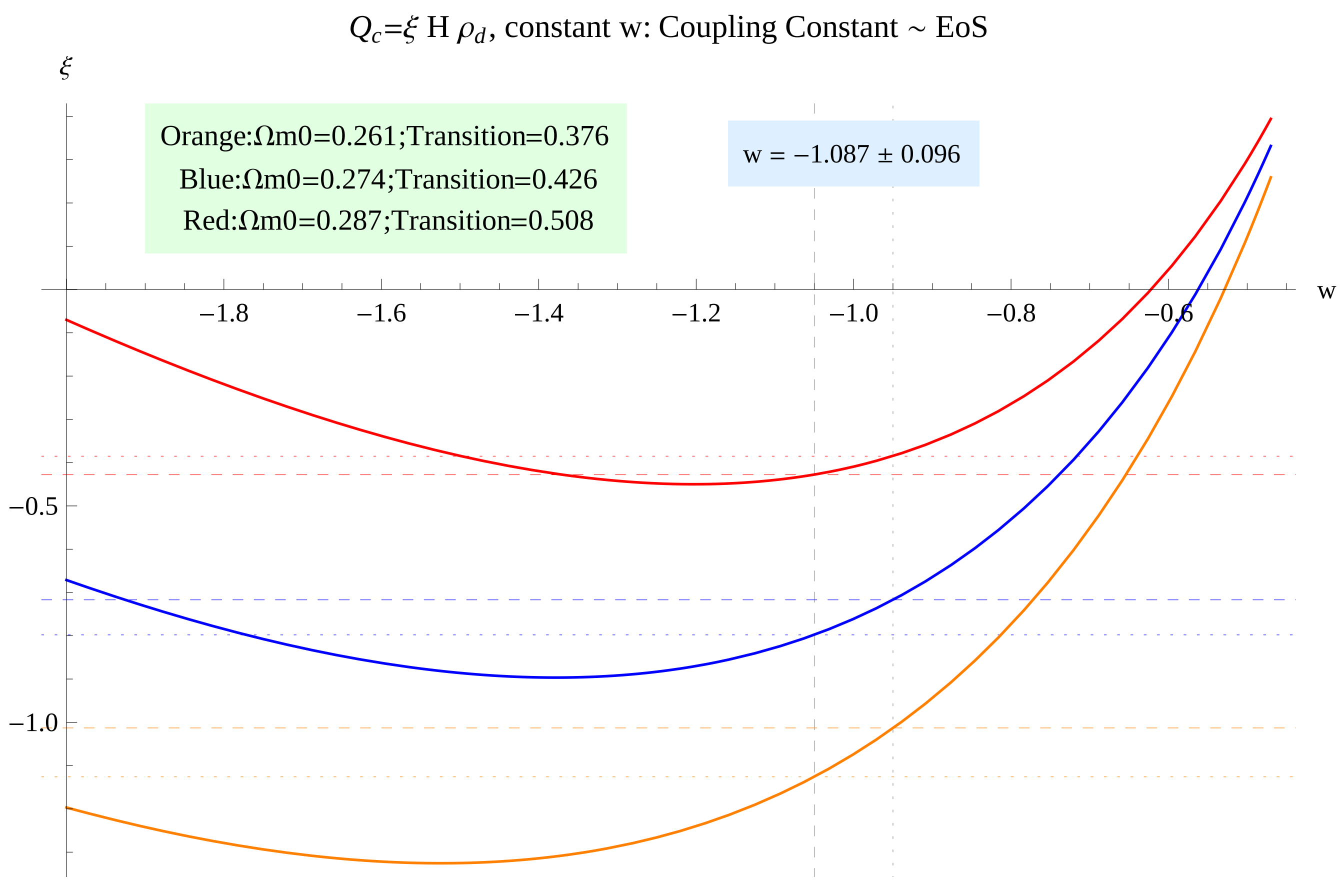


Figure 22: ξ VS w

$Q_c = \xi$ H ρ_d, Constant w. (Data used:Data From, 2)			
w	Center	Lower	Upper
-1.183	-0.864289	-1.22984	-0.449552
-1.087	-0.820486	-1.15946	-0.437339
-0.991	-0.753634	-1.06346	-0.405262

Q_c=ξ H ρ_d, constant w: Coupling Constant ~ EoS

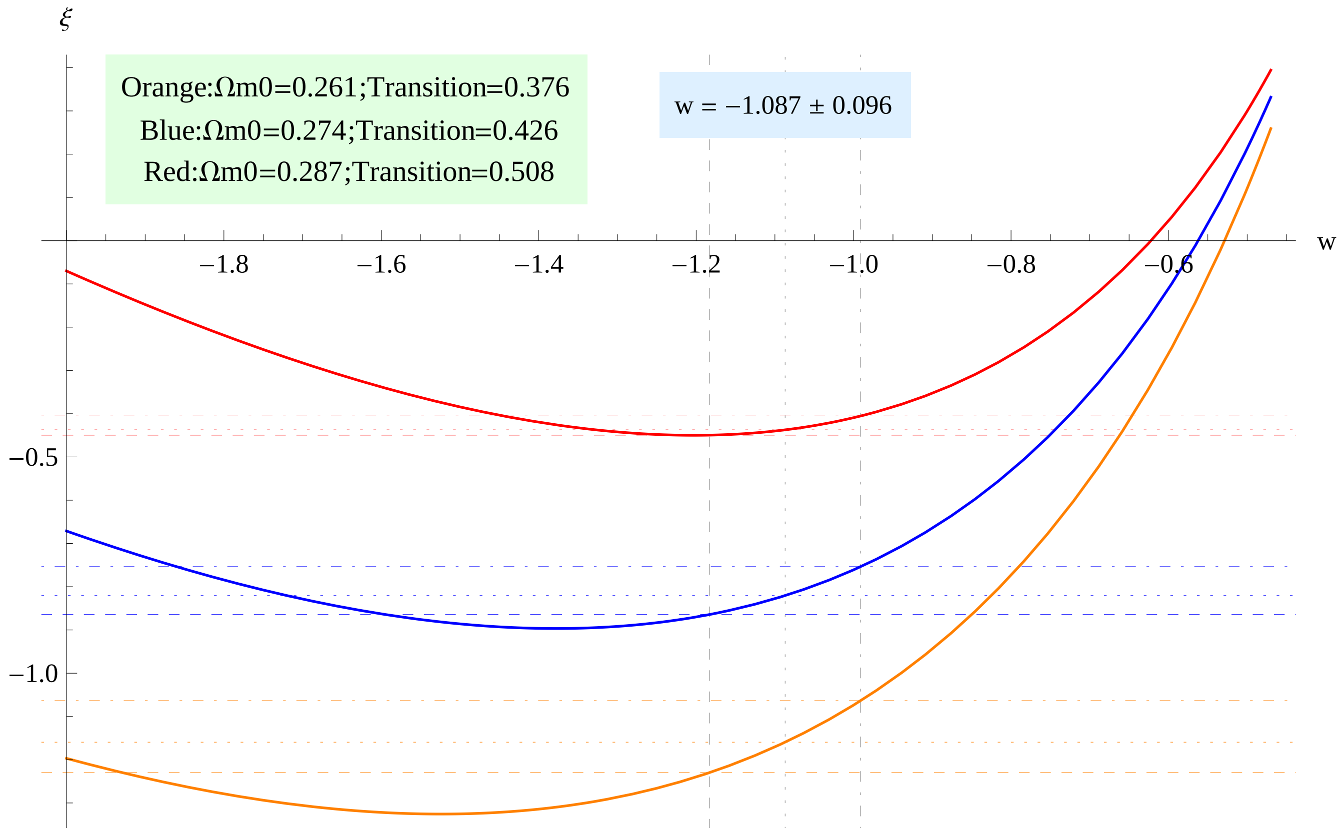


Figure 23: ξ VS w

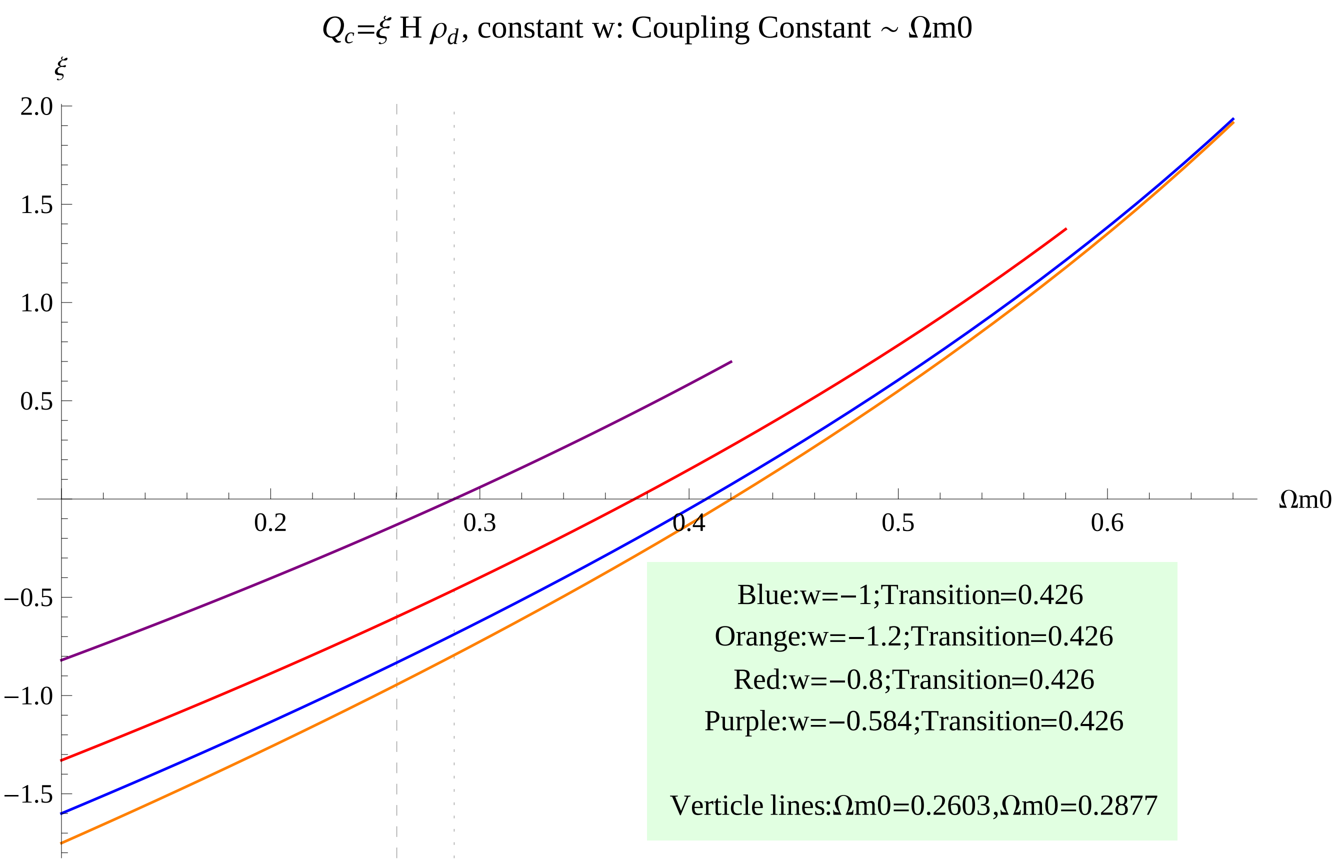


Figure 24: ξ VS $\Omega m0$

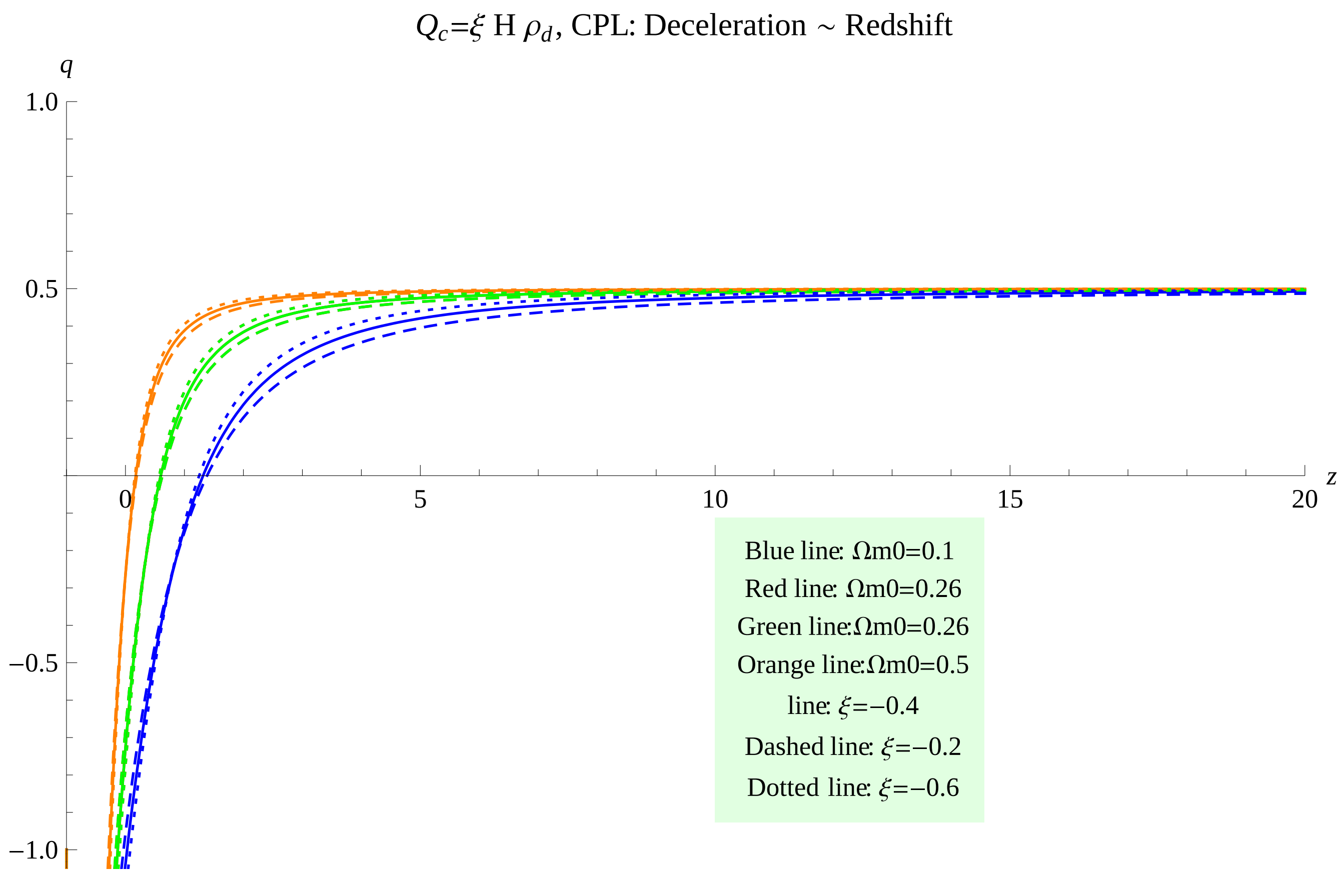
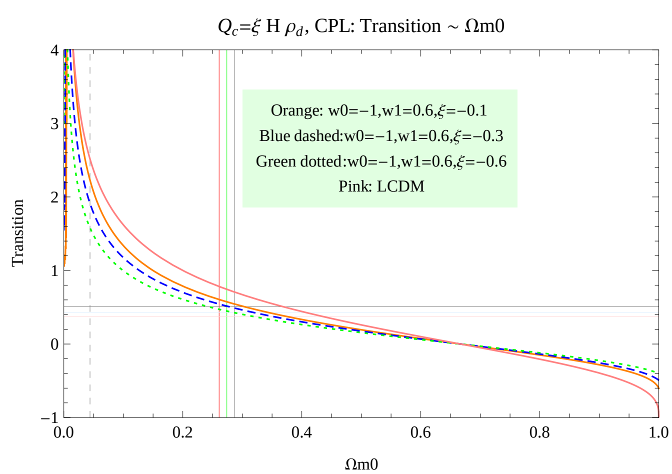


Figure 25: Deceleration parameter



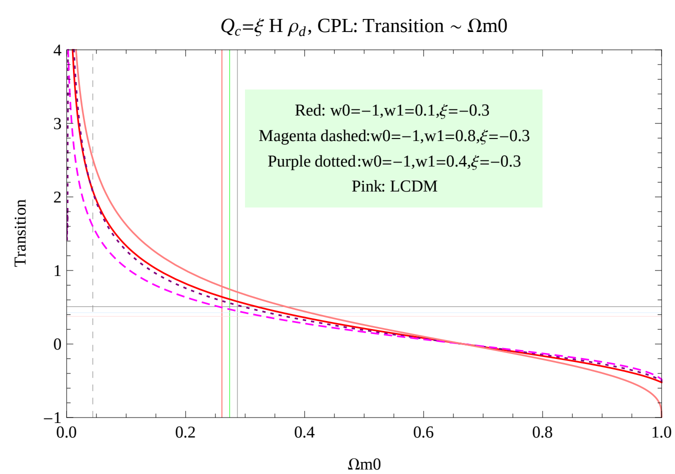


Figure 26: Transition VS $\Omega m0$

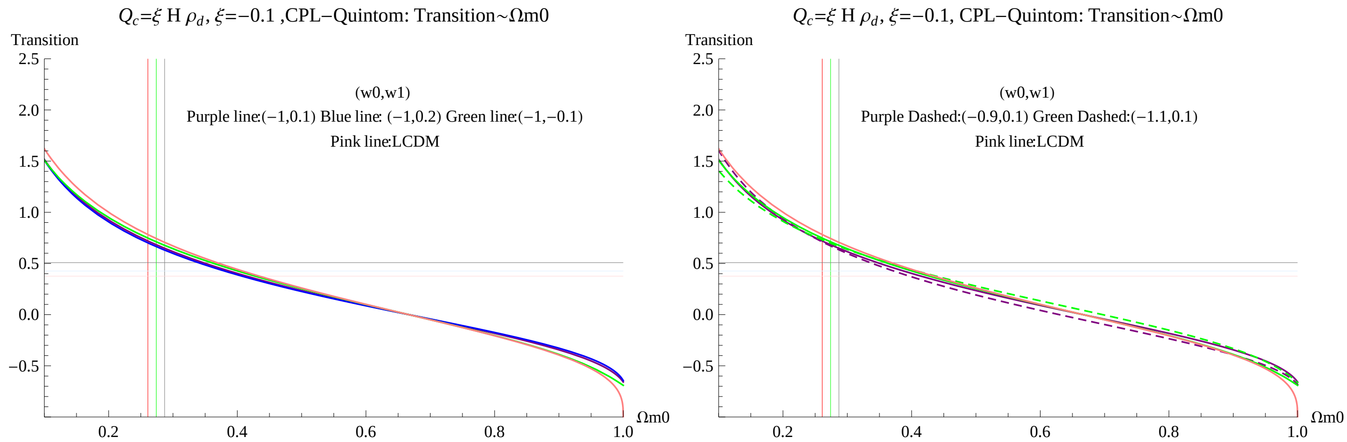


Figure 27: Transition VS $\Omega m0$

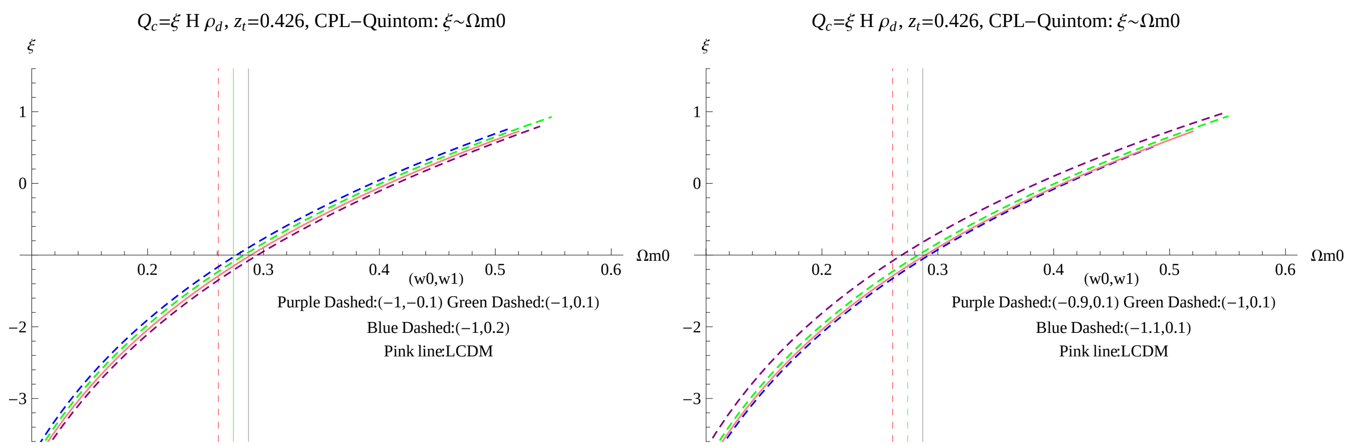


Figure 28: ξ VS $\Omega m0$

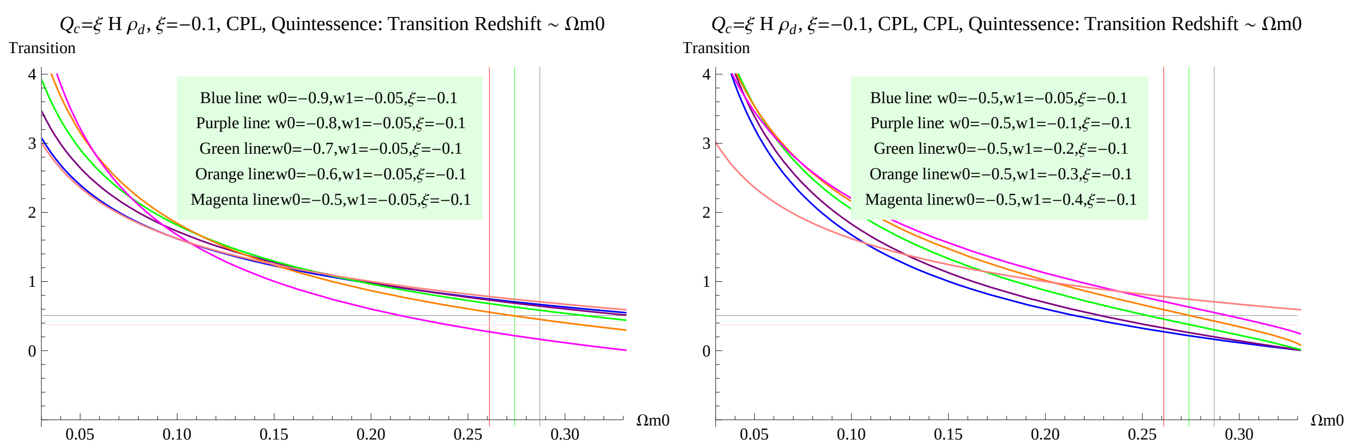


Figure 29: Transition VS $\Omega m0$

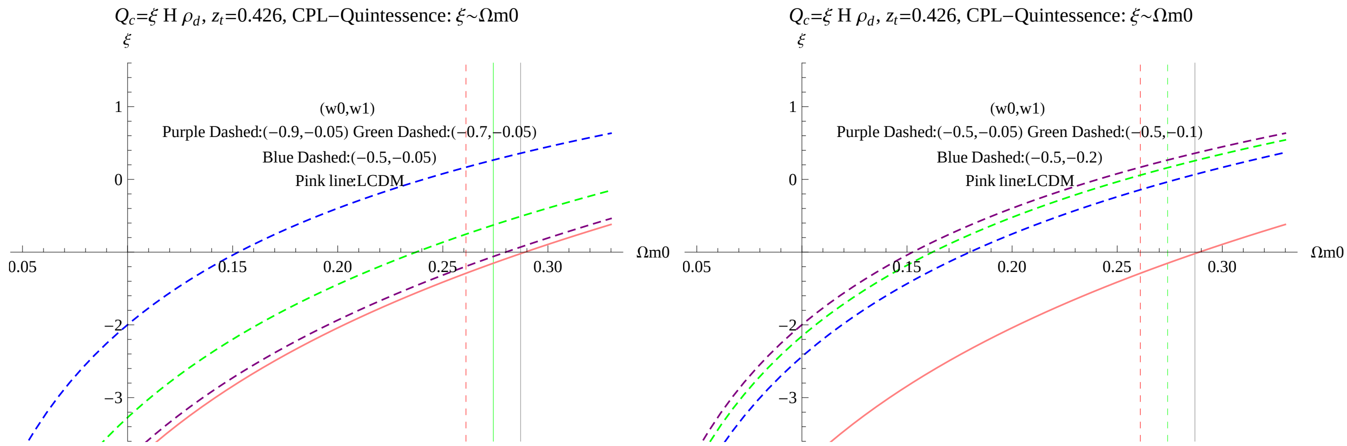


Figure 30: ξ VS $\Omega m0$

4.4.3 Phantom

(Figures ??, ??)

There is always a almost-stationary point.

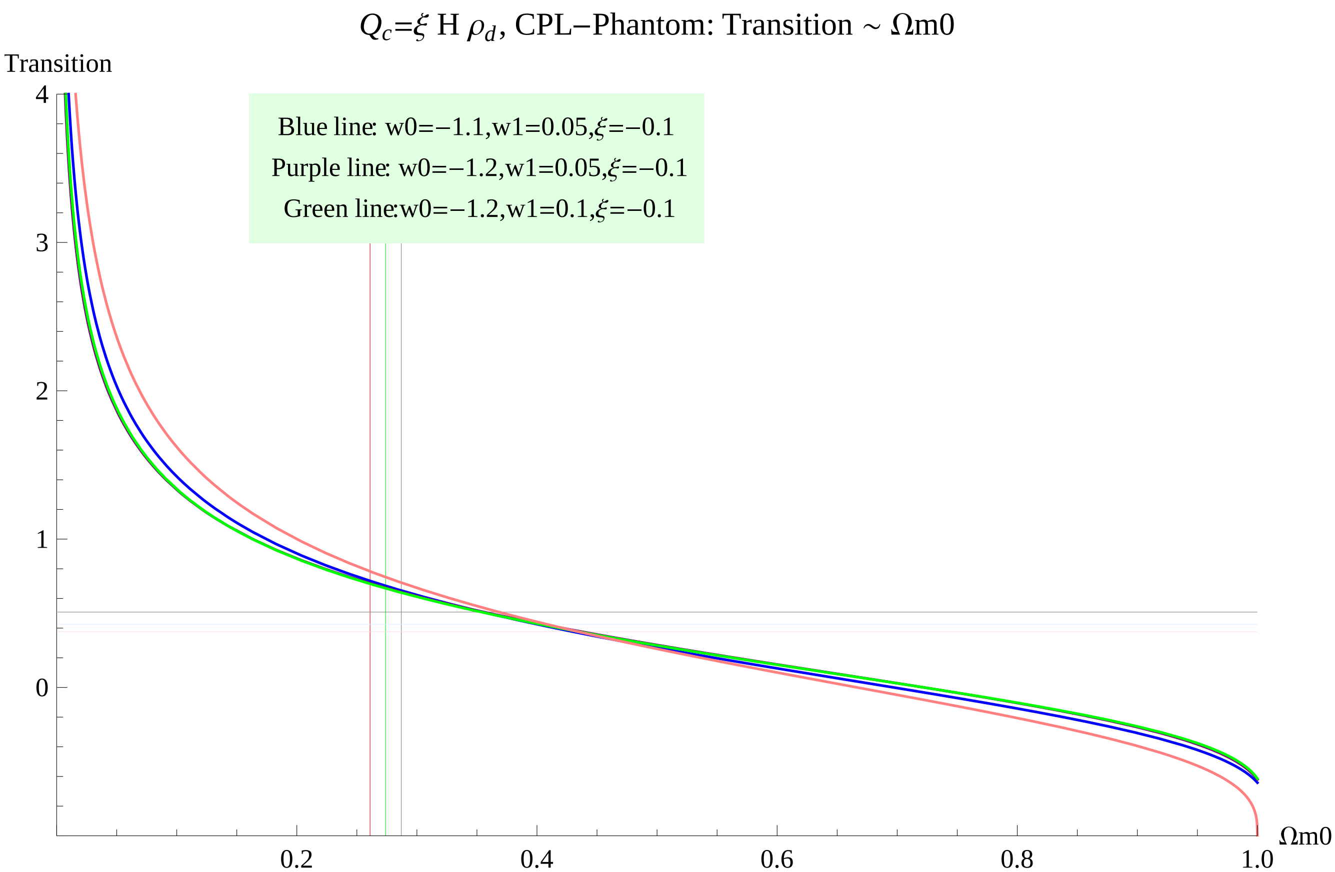


Figure 31: Transition VS $\Omega m0$

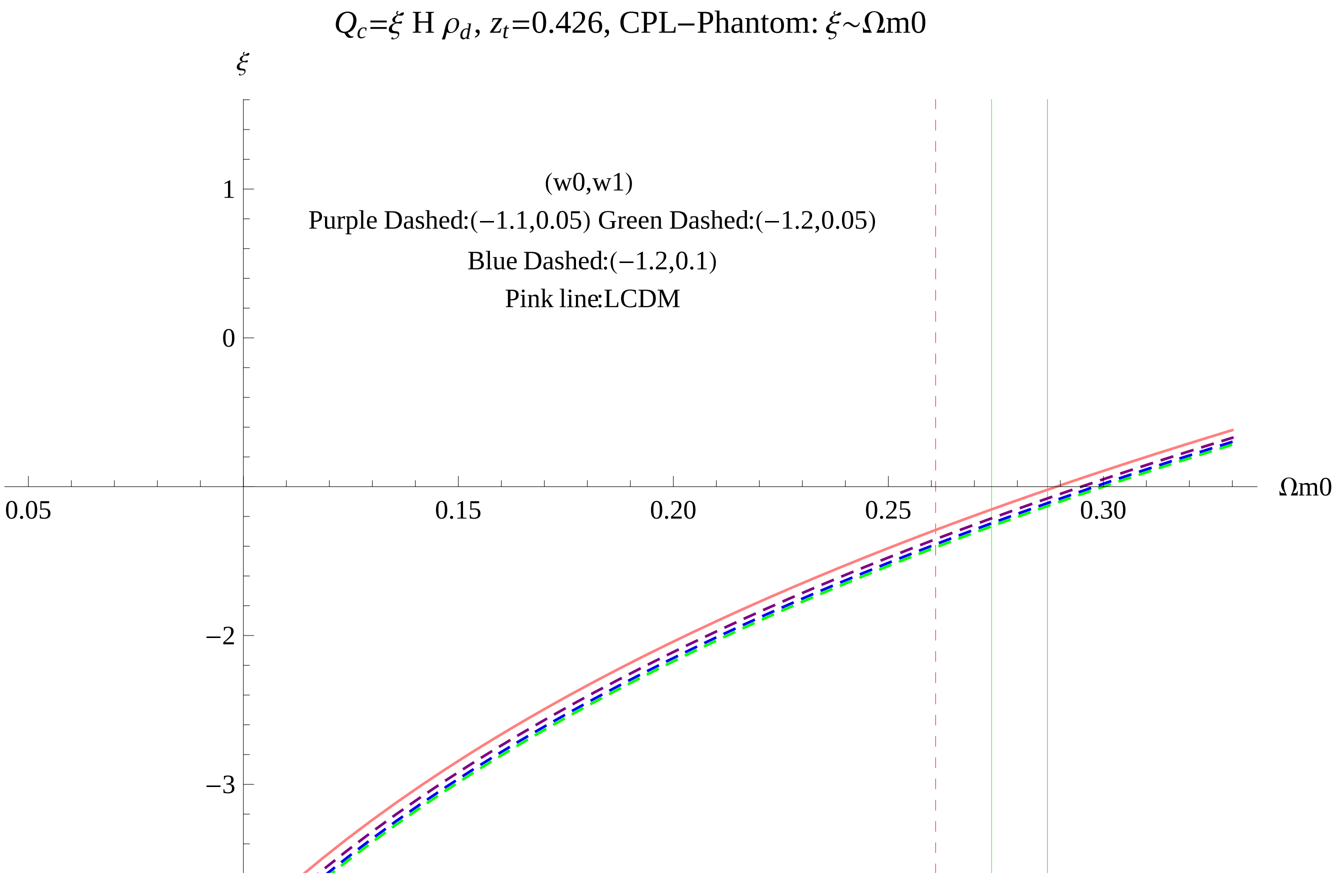


Figure 32: Transition VS $\Omega m0$