Tools to predict non-adiabatic instabilities in coupled DE-DM models

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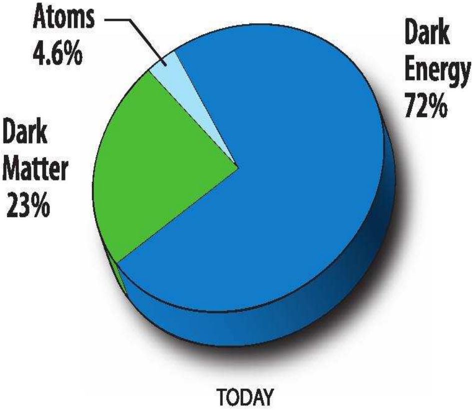
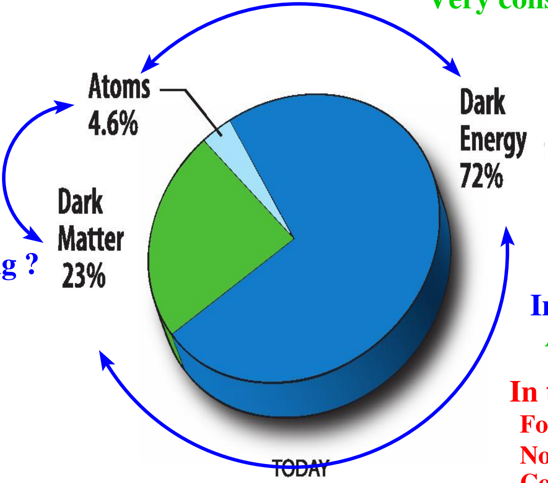
based on *Dark Coupling*
astro-ph/0901.1611- accepted for publication in JCAP

in collaboration with B. Gavela, D. Hernandez, O. Mena, S. Rigolin

Invisible Universe 2009 - Paris


Atoms
4.6%
Dark
Energy
72%
Dark
Matter
23%
TODAY

Interacting ?
Very constrained!



Interacting ?
Allowed!

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Allowed!

In this TALK!

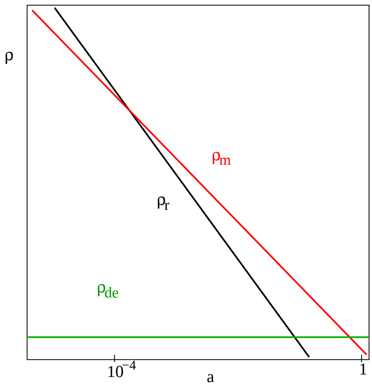
For one parametrization
Non adiabatic instabilities
Cosmological constraints

Background equations - The coupling

- Evolution equation for cosmological fluids :

$$\dot{\rho}_i + 3H(\rho_i + p_i) = 0$$
$$p_i = w_i \rho_i$$

ΛCDM model $w_{de} = -1$



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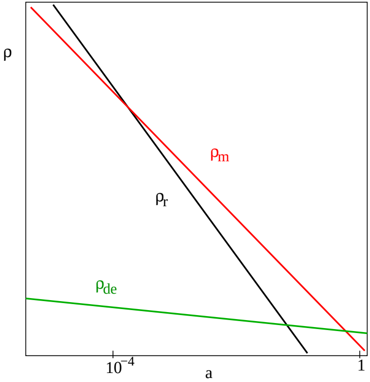
DE model $w_{de} = -0.9$



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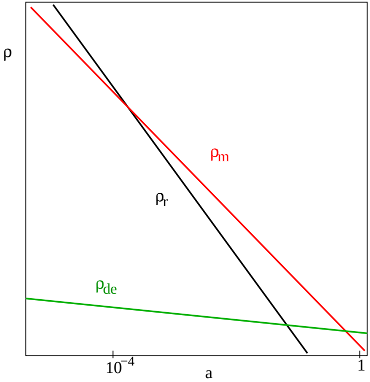

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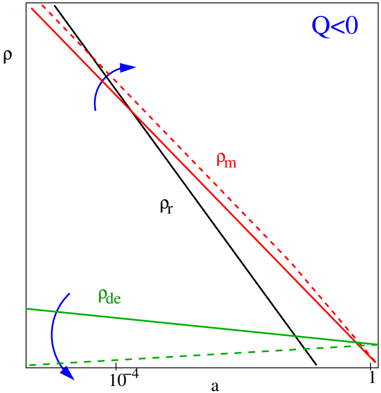
$$\begin{aligned} \dot{\rho}_{dm} + 3H\rho_{dm} &= Q \\ \dot{\rho}_{de} + 3H\rho_{de}(1+w) &= -Q \end{aligned}$$

  - we took w constant and $w < -1/3$
  - Q encodes the interaction
  - Q changes the time of M-Rad equ

DE-dm Coupled model



$w_{de} = -0.9$ and $Q < 0$

Density perturbation equations

The growth of a perturbation $\delta_i = \delta\rho_i/\rho_i$ depends on three contributions :

$$\delta_i'' = A_i \frac{\delta_i}{a^2} + B_i \frac{\delta_i'}{a} + \mathcal{F}(\rho_j, \delta_j, \delta_j'; j \neq i)$$

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Exponential
Growth or Oscillations

(Anti)Damping

A and $B \gg 0$ can give rise to unstable growth of δ_i.

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In the case of DE-DM coupled models :

- δ_{de} and δ_{dm} growth are NOT independent
- A and B depend on Q through $\rho_i(Q)$ and $\delta P(Q)$ contributions

Origin of instabilities in coupled models - δP sector

- Adiabatic processes :

$$\delta P_{de} \longrightarrow c^2_{a\,de}\delta\rho_{de}$$

$$c^2_{a\,de} = \frac{\dot{P}_{de}}{\dot{\rho}_{de}} \qquad \text{which for } w = cst, c^2_{a\,de} = w$$

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$\rightsquigarrow$ Instability as $c^2_{a\,de} < 0$, pressure no more counteract gravity

see *e.g.* Bean, Flanagan and Trodden '07 AND
slow-roll suppression see Corasaniti talk

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In the rest frame of I : $\delta P_I = \hat{c}^2_{s\,I}\delta\rho_I \neq c^2_{a\,I}\delta\rho_I,$

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In any frame for coupled DE-DM :

$$\delta P_{de} = \delta P_{de}(\hat{c}^2_{s\,de}, \delta\rho_{de}, c^2_{a\,de}, w, \mathbf{d})$$

where $\mathbf{d} \equiv \frac{Q}{3\mathcal{H}\rho_{de}(1+w)}$ is the DOOM FACTOR

Linear perturbations treatment- Model Parametrisation

To deduce the evolution of perturbations, we need a lagrangian or a parametrization at the level of the stess-energy tensor

$$\begin{aligned} \nabla_\mu T^\mu_{(dm)\nu} &= Q\, u_\nu^{(dm)}/a\ , \\ \nabla_\mu T^\mu_{(de)\nu} &= -Q\, u_\nu^{(dm)}/a\ , \end{aligned}$$

Valiviita, Majorotto & Maartens '08

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Valiviita, Majorotto & Maartens '08

- Conservation of the total stress-energy tensor $\nabla_\mu T^\mu_{(TOT)\nu} = 0$,
- $u_\nu^{(dm)}$ is the 4-velocity of dark matter $u_\nu^{(dm)} = a(-1, v^i_{dm})$ $\rightsquigarrow$ no momentum exchange in the rest frame of dark matter.

Growth equation - Doom factor - Instability

leads when A,B negligible

$$\delta_i'' = A_i \frac{\delta_i}{a^2} + B_i \frac{\delta_i'}{a} + \boxed{\mathcal{F}(\rho_j, \delta_j, \delta_j'; j \neq i)}$$

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Exponential Growth or Oscillations

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In the Strongly Coupled case of $\nabla_\mu T^\mu_{(de)\nu} = -Q\, u_\nu^{(dm)}/a$ (*i.e.* when $|\mathbf{d}| > 1$) at large scale-early time in an unstable scenario :

$$\delta_{de}'' \simeq 3\,\mathbf{d}\,(\hat{c}^2_{s\,de} + 1)\left(\frac{\delta_{de}'}{a} + 3\frac{\delta_{de}}{a^2}\frac{(\hat{c}^2_{s\,de} - w)}{\hat{c}^2_{s\,de} + 1} + \frac{3(1+w)}{a^2}\delta[\,\mathbf{d}\,]\right) + \ldots$$

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Assuming $\hat{c}^2_{sde} > 0$: $\mathbf{d} > \mathbf{1} \rightsquigarrow$ Non adiabatic source of instability

see also Valiviita - Majerotto - Maartens ’08 & He - Wang - Abdalla ’08 & Jackson - Taylor - Berera ’09

One example : $Q = \xi \mathcal{H} \rho_{de}$

- Doom factor : $\mathbf{d} = \frac{\xi}{3(1+w)} \rightsquigarrow$ strong coupling regime $\equiv |\xi|$ large

STABLE when ξ and $1 + w$ have opposite signs
see also He - Wang - Abdalla '08 & Jackson - Taylor - Berera '09

For Cosmological constraints, we consider $\xi < 0$ and $1 + w > 0$

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- Datasets considered for constraints : Run 0
  - WMAP 5-year
  - prior on the Hubble parameter of $72 \pm 8 km\, s^{-1} Mpc^{-1}$ from HST
  - H(z) data
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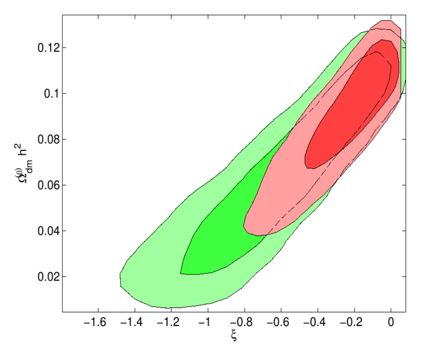
- Datasets considered for constraints : Run 1
  - WMAP 5-year
  - prior on the Hubble parameter of $72 \pm 8 km\, s^{-1} Mpc^{-1}$ from HST
  - H(z) data
  - Supernovae
  - Matter Power spectrum (or LSS data from SDSS LRGs)

$\xi - \Omega_{dm}^{(0)}$ degeneracy



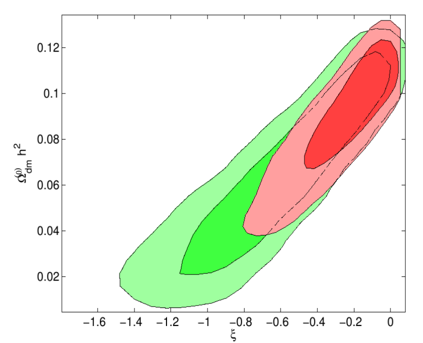
$\xi - \Omega_{dm}^{(0)}$ degeneracy

For $\xi < 0$, $|\xi|$ large

$\rightsquigarrow$ more $\Omega_{dm}(a)$ in the past for the same value of $\Omega_{dm}^{(0)}$

$\rightsquigarrow$ more clustering

$\rightsquigarrow$ less $\Omega_{dm}^{(0)}$ needed



LSS data $\rightsquigarrow$ stringent constraint

due to enormous galaxy clustering for $\xi < -0.5$

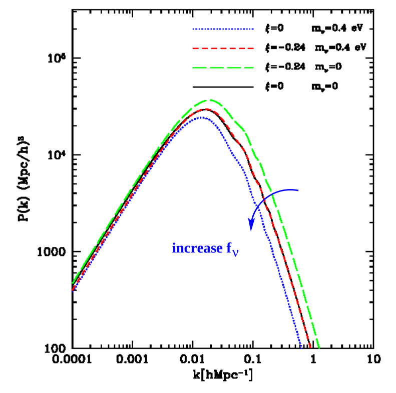
(up to $\sigma_8 > 2$ compared to WMAP5 analysis $\sigma_8 = 0.812 \pm 0.026$)

$\xi - f_\nu$ degeneracy

$$f_\nu = \frac{\Omega_\nu^{(0)} h^2}{\Omega_{dm}^{(0)} h^2} = \frac{\sum m_\nu}{93.2\text{eV}} \cdot \frac{1}{\Omega_{dm}^{(0)} h^2}$$

Non relativistic neutrinos suppress the growth of δ_{dm} at small scales

For $f_\nu \neq 0$ the power spectrum is reduced with respect to $f_\nu = 0$.



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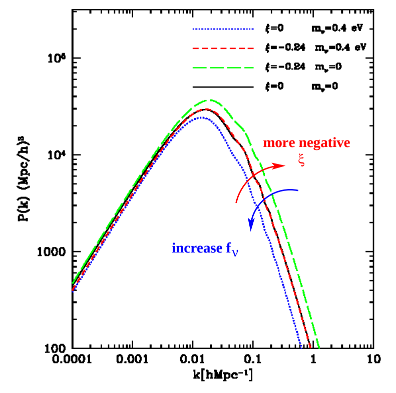

$\rightsquigarrow$ Can be compensated with more negative ξ

see also Bonometto talk

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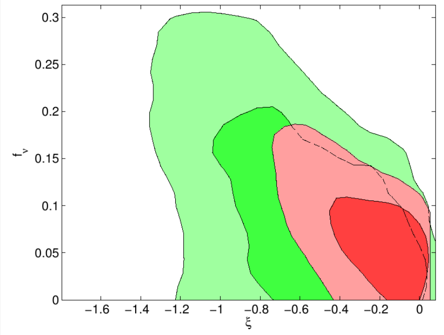

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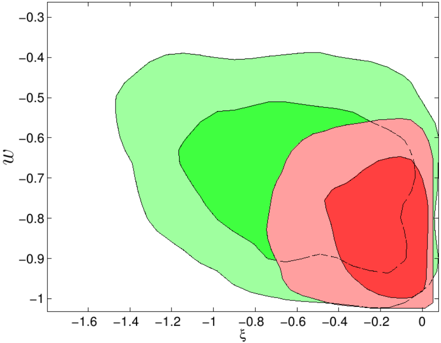
Viable parameter space in $\xi - w$ plane

In the instability-free region $\xi < 0$ and $w > -1$:



$\rightsquigarrow$ Present data are unable to set strong constraints on ξ - w, and large values for both parameters, near -0.5, are easily allowed

Conclusion for $\nabla_\mu T^\mu_\nu = \pm Q\, u_\nu^{(dm)}/a$ models

- We have identified the source of non-adiabatic instability as a function of Q independently of its specific form :

  The doom factor characterizes the (un)stable regime :

  $$\mathbf{d} = \frac{Q}{3\mathcal{H}\rho_{de}\,(1+w)}$$

  - $\mathbf{d}$ >1 $\Rightarrow$ unstable growth
  - in the other cases, Coupled Models are still viable !

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- Confrontation to data for $Q = \xi H \rho_{de}$

  - both w and ξ are not very constrained from data.
    large values for both parameters, near -0.5, are easily allowed ! !
  - ξ positively correlated with both $\Omega_{dm} h^2$
  - m_ν -ξ degeneracy : *i.e.* f_ν increases for more negative ξ

This the End

Thank you for your attention ! !

Backup

Gauge transformations

1. There is always some freedom in the way we do the correspondence between the background and the physical perturbed universe $\equiv$ Gauge Freedom
2. Some quantities are gauge invariant like ($v^j = ik^j v$ and $c_s^2 = \delta P/\delta\rho$) :

$$\begin{aligned} w\Gamma &= (c_s^2 - c_a^2)\delta \\ \Delta &= \delta + \dot{\rho}/\rho(v - B) \end{aligned}$$

For example in synchronous or Newtonian gauge ($B = 0$) :

$$\begin{aligned} w_{de}\Gamma_{de}|_{rf\,de} &= (\hat{c}_s^2 - c_a^2)\hat{\delta}_{de} = (c_s^2 - c_a^2)\delta_{de} = w_{de}\Gamma_{de}|_{any\,frame} \\ \Delta_{de}|_{rf\,de} &= \hat{\delta}_{de} = \delta_{de} + \frac{\dot{\rho}_{de}}{\rho_{de}} v_{de} = \Delta_{de}|_{any\,frame} \end{aligned}$$

$$\rightsquigarrow \delta P_{de} = \hat{c}_{s\,de}^2 \delta\rho_{de} - (\hat{c}_{s\,de}^2 - c_{a\,de}^2) 3(1 + w_{de})\,(1 + \mathbf{d})\, v_{de}\mathcal{H}\rho_{de}$$

What would be $\tilde{w}(z)$ reconstructed

...from $H(z)$ data assuming no coupling and dynamical DE :

$$R_H(z) = \frac{H^2(z)}{H_0^2} = \Omega_{dm}^{(0)}(1+z)^3 + \Omega_{de}^{(0)} \exp\left[3\int_0^z dz' \frac{1+\tilde{w}(z')}{1+z'}\right]$$

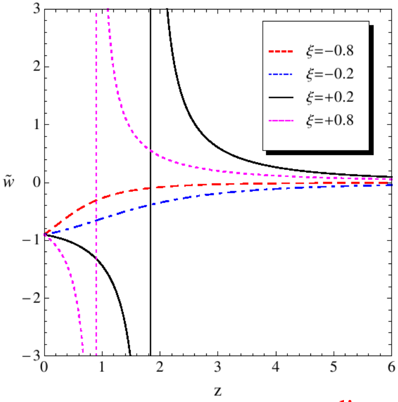
$$\Rightarrow \tilde{w}(z) = \frac{1}{3}\,\frac{R'_H(1+z) - 3R_H}{R_H - \Omega_{dm}^{(0)}(1+z)^3}\,.$$

However in presence of dark couplings :

$$R_H(z) = f(w, Q, \Omega_{dm}^{(0)}, \Omega_{de}^{(0)})$$

Reconstructing $\tilde{w}(z)$ as a function of w and ξ

For $Q = \xi H \rho_{de}$



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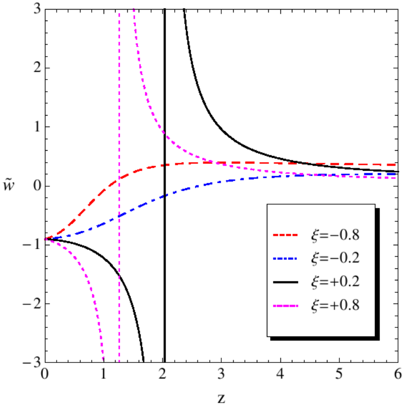

$\rightsquigarrow$ divergent $\tilde{w}(z)$ for $\xi > 0$

Similar behaviour in f(R) cosmologies see *e.g.* Amendola & Tsujikawa '07

Cosmo constraints

Parameter	Prior
ω_b	0.005-0.1
ω_{dm}	0.01-0.99
θ_{CMB}	0.5-10
τ	0.01-0.8
Ω_k	-0.1-0.1
f_ν	0-0.3
w	-1-0
ξ	-2-0
n_s	0.5-1.5
$\ln(10^{10}A_s)$	2.7-4.0

TAB.: *Priors for the cosmological fit parameters considered in this work. All priors are uniform in the given intervals.*

- $\omega_b = \Omega_b h^2$ and $\omega_{dm} = \Omega_{dm} h^2$
- θ_{CMB} is proportional to the ratio of the sound horizon to the angular diameter distance,
- τ is the reionisation optical depth,
- Ω_k is the spatial curvature,
- $f_\nu = \Omega_\nu/\Omega_{dm}$ refers to the neutrino fraction,
- n_s is the scalar spectral index
- A_s the scalar amplitude.

Cosmo ref

J. Dunkley et al. Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Likelihoods and Parameters from the WMAP data. 2008, 0803.0586.

E. Komatsu et al. Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations:Cosmological Interpretation. 2008, 0803.0547.

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Will J. Percival et al. The shape of the SDSS DR5 galaxy power spectrum. *Astrophys. J.*, 657:645–663, 2007, astro-ph/0608636.

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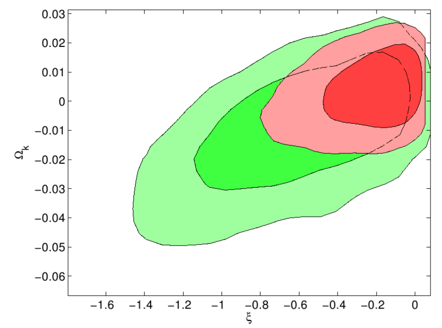
$\xi - \Omega_k^{(0)}$ degeneracy



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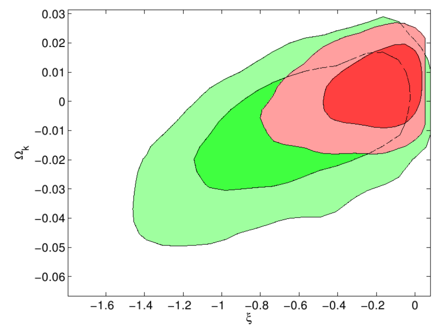

For $\xi < 0$, $|\xi|$ large

$\rightsquigarrow$ more Ω_{dm} in the past

small negative Ω_K can compensate this effect

to describe well CMB data.

The degeneracy between ξ and Ω_k gets alleviated if one adds LSS data to the analysis.

The Very Coupled Case : $Q = \xi \mathcal{H} \rho_{de}$

$$\mathbf{d} = \frac{\xi}{3(1+w)}\,.$$

$\rightsquigarrow$ strong coupling regime $\equiv |\xi|$ large

Model: $Q \propto \rho_{de}$	$1+w$	ξ	ρ_{dm}	ρ_{de}	$\mathbf{d}$	Early time instability?
	$+$	$+$	$\mp$	$+$	$+$	Yes
	$+$	$-$	$+$	$+$	$-$	No
	$-$	$-$	$+$	$+$	$+$	Yes
	$-$	$+$	$\mp$	$+$	$-$	No

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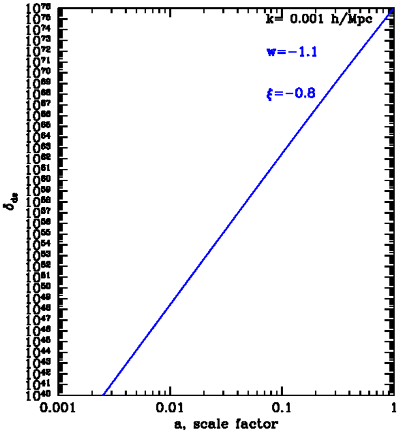

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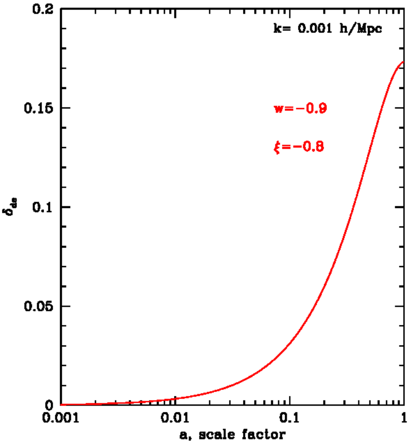
STABLE when ξ and $1+w$ have opposite signs

For Cosmological constraints, we consider $\xi < 0$ and $1+w > 0$



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$$\mathbf{d} = \frac{\xi}{3(1+w)} \frac{\rho_{dm}}{\rho_{de}} \,.$$

Model: $Q \propto \rho_{dm}$	$1+w$	ξ	ρ_{dm}	ρ_{de}	d	Early time instability?
	$+$	$-$	$+$	$\mp$	$+$	Yes
	$+$	$+$	$+$	$+$	$+$	Yes
	$-$	$+$	$+$	$+$	$-$	No
	$-$	$-$	$+$	$\mp$	$-$	No

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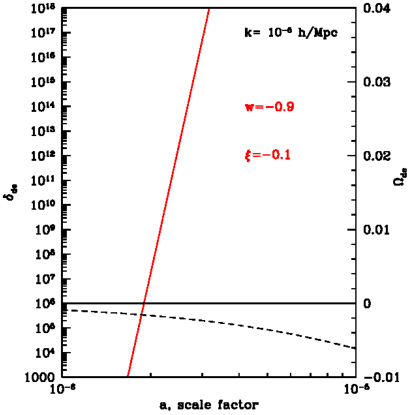

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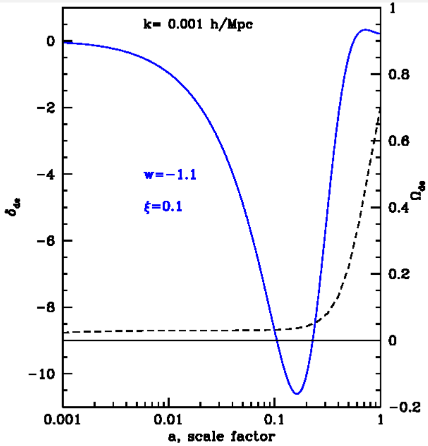

New : $Q = \xi \mathcal{H} \rho_{dm}$ model is free from early time non-adiabatic instabilities when $1 + w < 0$

Some coupling from conformal transformation

From a Brans-Dicke action (with $\omega = 0$) in the Jordan (string) frame :

$$S_J = \frac{M_{Pl}^2}{2} \int d^4x \sqrt{-g_J}\,\Phi R_J + S_M(\psi, g^J_{\mu\nu})$$

we get in the Einstein frame ($\Phi = \Omega^{-1}$) :

$$S_E = \int d^4x \sqrt{-g_E} \left\{ \frac{M_{Pl}^2}{2} R_E - \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi \right\} + S_M(\psi, \Omega^2 g^E_{\mu\nu})$$

Using conformal transformation with

$$\begin{aligned} g^E_{\mu\nu} &= \Omega^{-2} g^J_{\mu\nu} \\ \varphi / M_{Pl} &= -\sqrt{6} \ln \Omega . \end{aligned}$$

In that framework, assuming that in the Jordan Frame : $\nabla_\mu T^{\mu\nu}_M = 0$

we get in the Einstein frame coupled DE-DM system :

$$\nabla_\mu T^{\mu\nu}_M = T^{\mu}_{M\,\mu} g^{\mu\nu}_E \partial_\nu \ln \Omega = - \nabla_\mu\, T^{\mu\nu}_\varphi$$

Mass varying DM and Couplings

Non minimal couplings can appear for :

$$S_E = \int d^4x\sqrt{-g_E}\left\{\frac{M_{Pl}^2}{2}R_E - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi)\right\} + S_M(\psi, \Omega(\varphi)^2 g^E_{\mu\nu})$$

with :

$$\nabla_\mu T_M^{\mu\nu} = T^\mu_{M\ \mu} g_E^{\mu\nu}\partial_\nu \ln\Omega(\varphi) = -\nabla_\mu T_\varphi^{\mu\nu}$$

this implies for pressureless DM : $d\ln\rho_{dm} = d\ln\Omega(\varphi) - 3d\ln a$; such that :

$$m_{dm} \propto \Omega(\varphi)$$

In *e.g.* Amendola, Camargo & Rosenfeld '07 they parametrize the time variation of the m_{dm} as a function of the scale factor :

$$\begin{aligned} m(a) &= m_0 e^{\int_1^a \zeta(a') d\ln(a')} \\ &\rightsquigarrow \dot\rho_{dm} + 3H\rho_{dm} = \zeta\mathcal{H}\rho_{dm} \\ &\ \dot\rho_{de} + 3H\rho_{de}(1+w) = -\zeta\mathcal{H}\rho_{dm} \end{aligned}$$