Instability in coupled dark sectors

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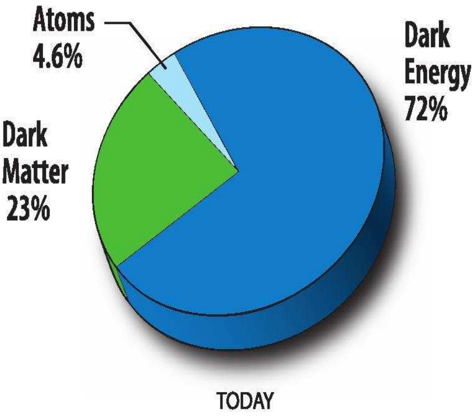
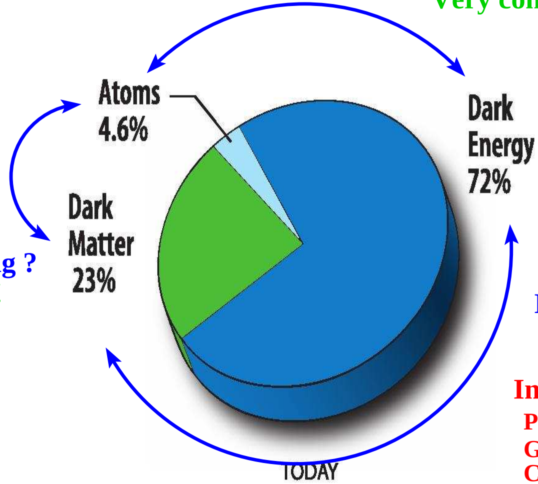
based on *Dark Coupling*
astro-ph/0901.1611

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

Moriond EW 2009


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

Interacting ?
Very constrained!



Interacting ?
Allowed!

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In this TALK!

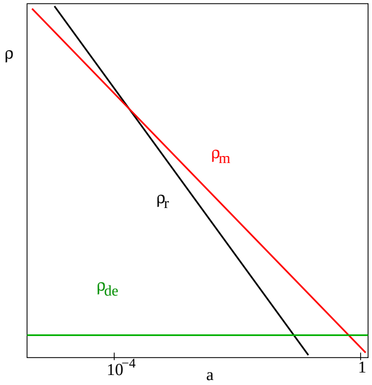
Parametrization
Growth instability study
Cosmological constraints

Evolution equation - 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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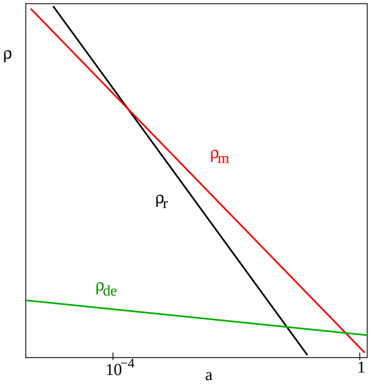
DE model $w_{de} = -0.9$



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- Evolution equations for a Interacting DM-DE System :

$$\begin{aligned} \dot{\rho}_{dm} + 3H\rho_{dm} &= 0 \\ \dot{\rho}_{de} + 3H\rho_{de}(1+w) &= 0 \end{aligned}$$

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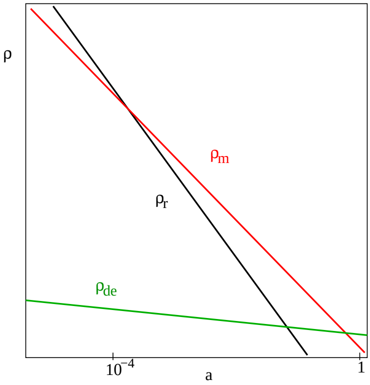

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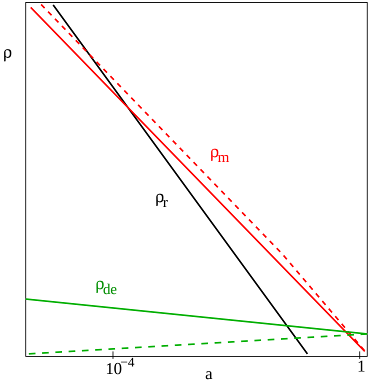
- Evolution equations for a Interacting DM-DE System :

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

  - Q encodes the interaction
  - for $e.g.$ $Q < 0$
    $\rightsquigarrow$ M-Rad equ appears earlier

DE-dm Coupled model



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

Linear perturbations treatment

To deduce the evolution of perturbations,
we need 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 $\nabla_\mu T^\mu_{(TOT)\nu} = 0$,
- $u^{(dm)}_\nu$ is the 4-velocity of dark matter $u^{(dm)}_\nu = a(-1, v^i_{dm})$
  $\rightsquigarrow$ no momentum exchange in the rest frame of dark matter.

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Origin of instabilities : pressure sector of DE perturbation equations.
The sound speed velocity is involved :

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- non adiabatic processes, in the DM rest frame :

$$\begin{aligned} c_s^2 &= \frac{\delta P_{de}}{\delta \rho_{de}} \neq c_a^2, \\ \delta P_{de} &= \delta P_{de}(\hat{c}^2_{s\,de}, \delta\rho_{de}, c^2_{a\,de}, w, \mathbf{d}) \quad \text{where} \quad \hat{c}^2_{s\,de} = \left.\frac{\delta P_{de}}{\delta \rho_{de}}\right|_{DE\,rf} \end{aligned} \tag{1}$$

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

Growth equation

- The evolution of a perturbation depends on three contributions :

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

Growth equation

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leads when A,B negligible

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Exponential
Growth or Oscillations

(Anti)Damping

Growth equation

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- In the Strongly Coupled case (*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 $\hat{c}^2_{sde} > 0$: $\mathbf{d} > \mathbf{1} \rightsquigarrow$ INSTABILITY

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

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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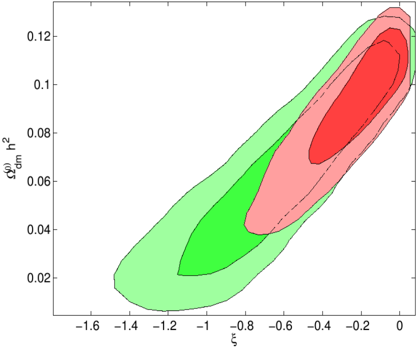
  - H(z) data
  - Supernovae
  - Matter Power spectrum (or LSS data from SDSS LRGs)

$$\Omega_{dm}^{(0)} = \frac{\rho_{dm}^{(0)}}{\rho_{cr}}$$



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

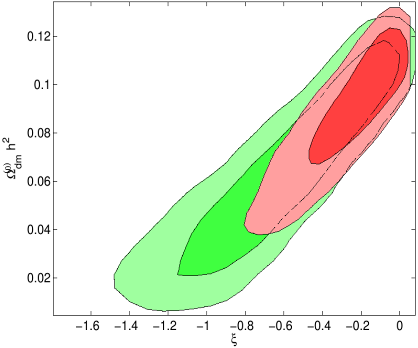
$\rightsquigarrow$ more $\Omega_{dm}(a)$ in the past

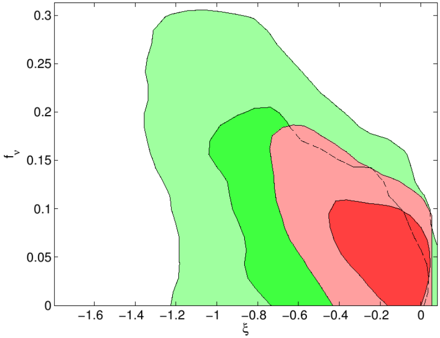
$\rightsquigarrow$ degeneracies $\xi - \Omega_{dm}^{(0)}$

LSS data give stringent constraint

$$\Omega^{(0)}_{dm} = \frac{\rho^{(0)}_{dm}}{\rho_{cr}}$$

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





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Conclusion

For DM-DE Coupled Models

- We have clarified the origin of early time non-adiabatic instabilities :

  The doom factor characterizes the (un)stable regime :

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

  - **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 ($B = 0$) :

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

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

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 : $\quad \nabla_\mu T_M^{\mu\nu} = 0$
we get in the Einstein frame coupled DE-DM system :

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

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 :

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

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 :

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

Which instability ?

In coupled DM-DE models

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- Adiabatic Instability (late time)
    - see *e.g.* Bean, Flanagan and Trodden '07
    - source : negative sound speed $c^2_{s\,de} \to c^2_{a\,de} < 0$

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- Adiabatic Instability (late time)
  - see *e.g.* Bean, Flanagan and Trodden '07
  - source : negative sound speed $c^2_{s\,de} \to c^2_{a\,de} < 0$
- Non-adiabatic Instability (early time and large scales)
  - pointed out in Valiviita, Majorotto & Maartens '08
  - source : δP_{de} get an extra huge contrib from **d**

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.

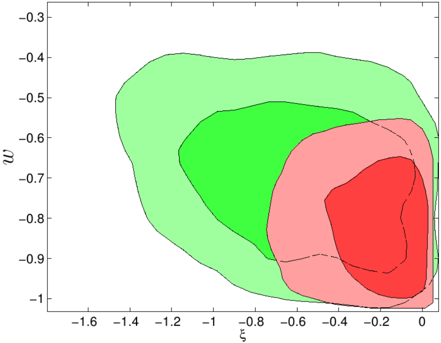
M. Kowalski et al. Improved Cosmological Constraints from New, Old and Combined Supernova Datasets. 2008, 0804.4142.

Max Tegmark et al. Cosmological Constraints from the SDSS Luminous Red Galaxies. *Phys. Rev.*, D74:123507, 2006, astro-ph/0608632.

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

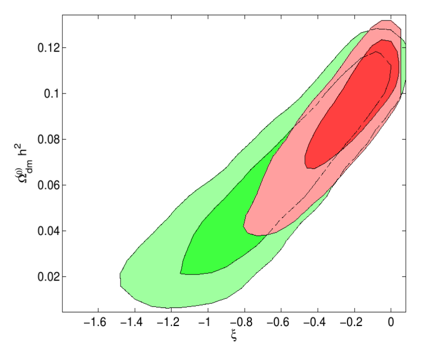
Viable parameter space in $\xi - w$ plane

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

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



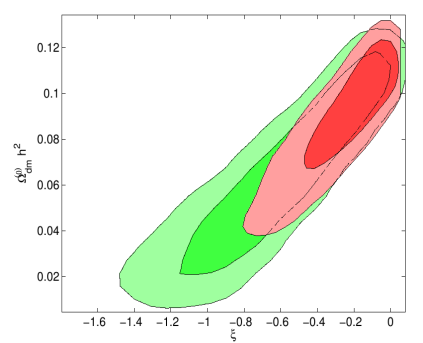
$\xi - \Omega_{dm}^{(0)}$ degeneracy

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

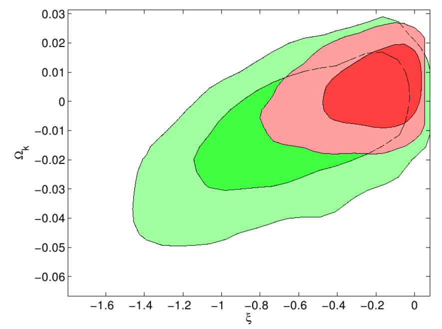


LSS data $\rightsquigarrow$ stringent constraint

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

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

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



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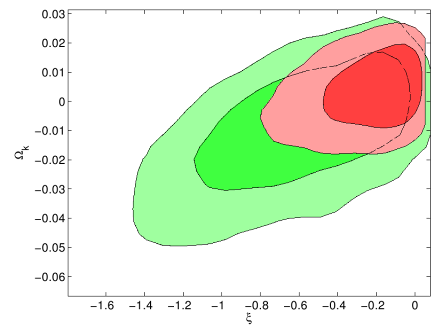


For $\xi < 0$, $|\xi|$ large

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

small negative Ω_K can compensate this effect

to describe well CMB data.

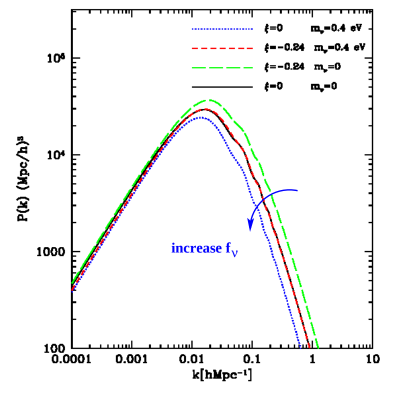
The degeneracy between ξ and Ω_k gets alleviated if one adds LSS data to the analysis.

$\xi - f_\nu$ degeneracy

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

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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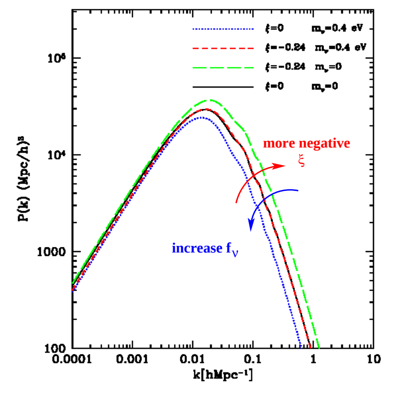

$\rightsquigarrow$ Can be compensated with more negative ξ

see also Vacca, Bonometto & Colombo '08

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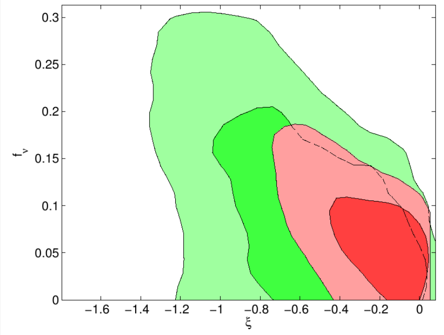

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The Very Coupled Case : $Q = \xi \mathcal{H} \rho_{de}$

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

$\rightsquigarrow$ 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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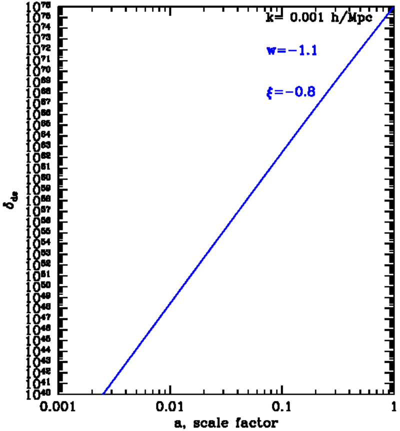

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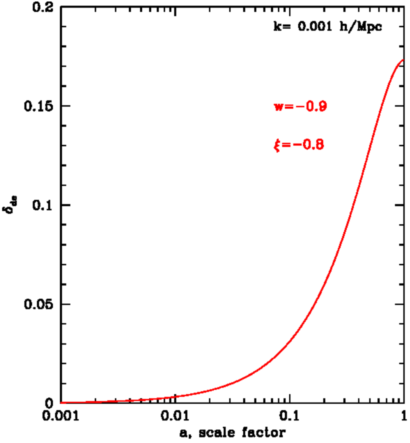
	$-$	$+$	$\mp$	$+$	$-$	No

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

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



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

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

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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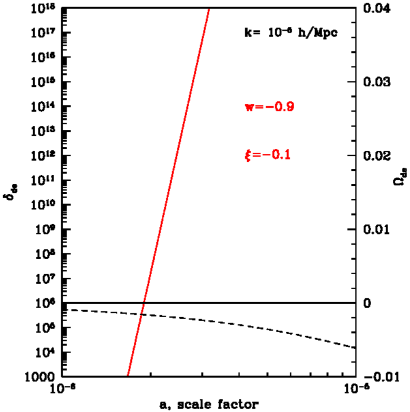
	$+$	$+$	$+$	$+$	$+$	Yes
	$-$	$+$	$+$	$+$	$-$	No
	$-$	$-$	$+$	$\mp$	$-$	No

$\frac{\rho_{dm}}{\rho_{de}}$ enhance **d** for small ξ

$\rightsquigarrow$ $|\xi| < 1$ always strong coupling regime

$\rightsquigarrow$ Ok with Valiviita *et al* analysis



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	$+$	$-$	$+$	$\mp$	$+$	Yes
	$+$	$+$	$+$	$+$	$+$	Yes
	$-$	$+$	$+$	$+$	$-$	No
	$-$	$-$	$+$	$\mp$	$-$	No

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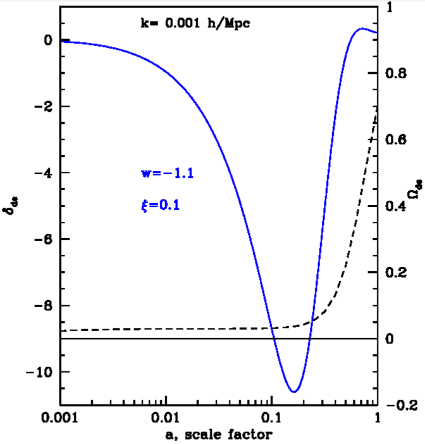

New : $Q = \xi \mathcal{H} \rho_{dm}$ model is free from early time non-adiabatic instabilities when $1 + w < 0$