Interacting dark matter-dark energy

Laura Lopez Honorez

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based on

`Dark Coupling`: JCAP 0907:034
`Dark Coupling and Gauge Invariance`: JCAP11(2010)044
`Coupled dark matter-dark energy in light of near Universe observations`: JCAP 1009:029.

in collaboration with B. Gavela, D. Hernandez, O. Mena, S. Rigolin, L.Verde, R. Jimenez and B. Reid

Service de Physique Théorique

What is our Universe made of ?

Several sources converges for 95% of unknown material

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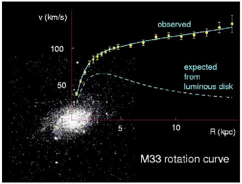

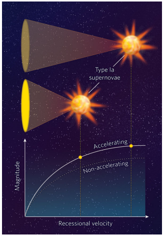

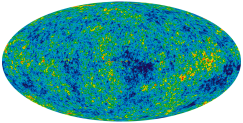

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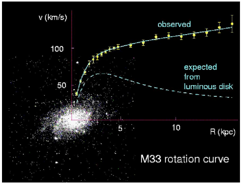
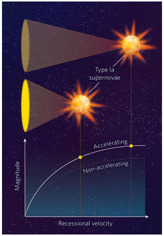
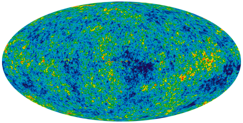
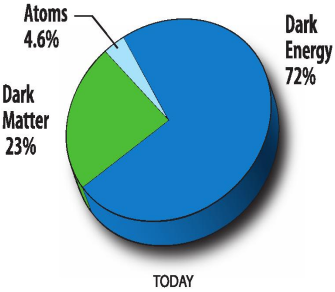
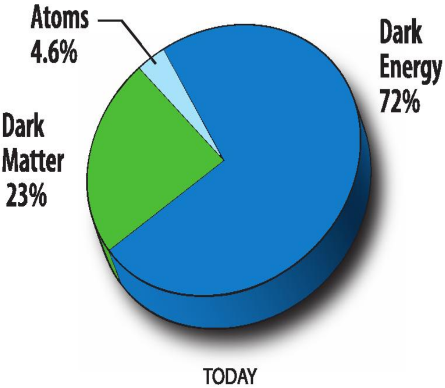


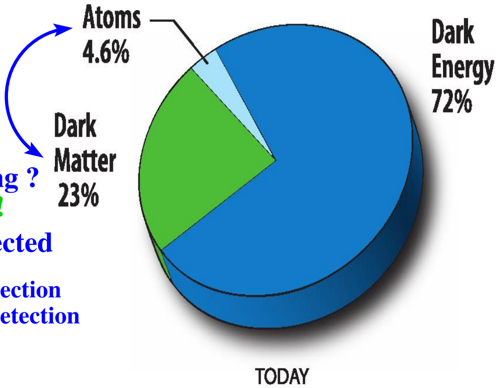




Universe content from WMAP7




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



Interacting ?

Allowed!

To be detected

Colliders

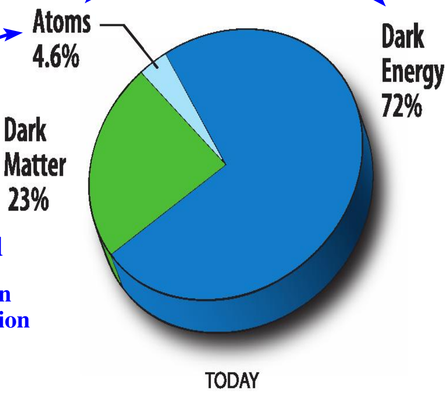
Direct detection

Indirect detection

Interacting ?

Very constrained!

unobserved 5th force
solar system test



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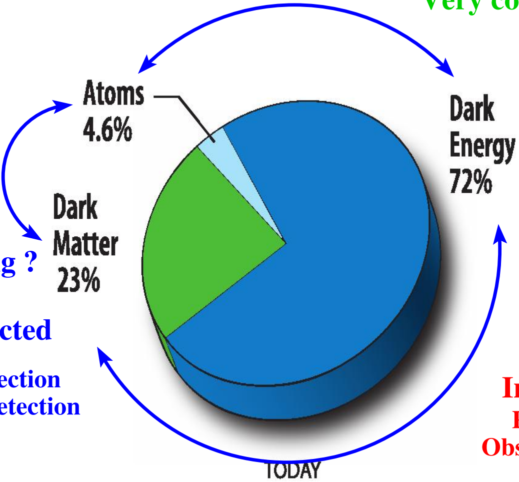

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Interacting ?
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In this TALK!
- **Parametrizations**
- **Observational constraints**

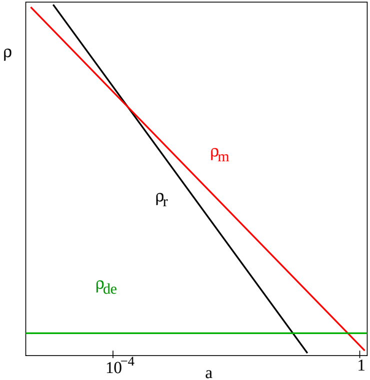
Energy exchange - Background

- Evolution equations for a Interacting DM-DE System :

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

$p_i = w_i \rho_i$

ΛCDM model $w_{de} = -1$



uncoupled $Q = 0$

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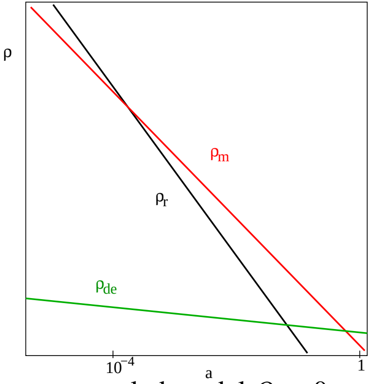
DE model $w_{de} = -0.9$



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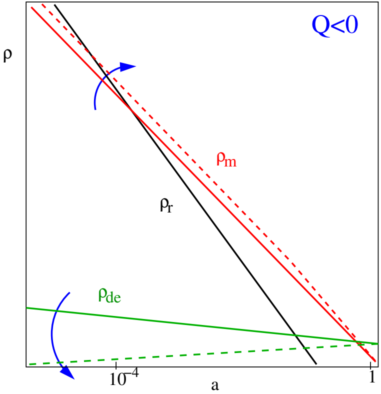
  - $Q < 0 \equiv$ DM decaying into DE
  - for accel : $w < -1/3$ as the deceleration param is still : $q = -\dot{\mathcal{H}}/\mathcal{H}^2 = 1/2(1+3w)\Omega_{de}$

DE-dm Coupled model



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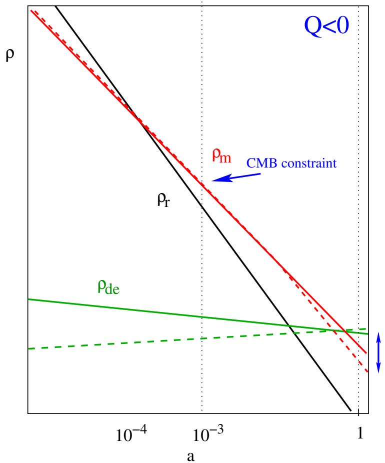
- Hint of cosmological constraints : CMB data constrains *e.g.* $\rho_{dm}(a_{\rm rec})$

$\rightsquigarrow \rho_{dm}(a_0)|_{Q<0} < \rho_{dm}(a_0)|_{Q=0}$
more dark matter in the past

DE-dm Coupled model



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What is the interaction like : Background

From the Background : Energy exchange...

- Analogy : decaying dark matter e.g. $\chi_1 \to \chi_2$

$$\begin{aligned} \dot{n}_2 - 3Hn_2 &= \Gamma_{12} n_1 \\ \dot{n}_1 - 3Hn_1 &= -\Gamma_{12} n_1 \end{aligned}$$

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  - Interaction rate : Γ can be taken $\propto H, H_0, \dot{\phi}$
  - Energy density involved $\rho_{dark} = \rho_{dm}$ Class I, or $\rho_{dark} = \rho_{de}$ Class II

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...Up to the perturbations level : What would be the evolution of the density and velocity perturbations ?

Coupled models at the level of $T_{\mu\nu}$

- Geometry : Newtonian potential
  $ds^2 = g_{\mu\nu}dx^\mu dx^\nu = a^2\left[-(1+2\Psi)d\tau^2 + (1+2\Phi)dx^i dx^j\right]$

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$$\begin{aligned} \dot\delta_{dm} &= -(kv_{dm} - \dot\Phi) \\ \dot v_{dm} &= -\mathcal{H}v_{dm} + k\Psi\ , \end{aligned}$$

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- Momentum exchange : $Q_\nu = Q\, u_\nu^{(dm)} / a \rightsquigarrow v_Q = v_{dm}$ DM vel

  $Q_\nu = Q\, u_\nu^{(de)} / a \rightsquigarrow v_Q = v_{de}$ DE vel

Tracking instability in the Dark Energy sector

Limitations due to Instabilities in the DE sector :

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

Limitations due to Instabilities in the DE sector :

leads when A,B negligible

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Exponential Growth or Oscillations

(Anti)Damping

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δ_{de}'' gets contributions from :

$$\delta P_{de} = \hat{c}^2_{s\,de}\delta\rho_{de} - (\hat{c}^2_{s\,de} - c^2_{a\,de})3(1+w)\,(1+\mathbf{d})\,\frac{\theta_{de}}{k^2}\mathcal{H}\rho_{de}$$

where $\hat{c}^2_{s\,de} = \delta P_{de}/\delta\rho_{de}$ and $c^2_{a\,de} = \dot{P}_{de}/\dot{\rho}_{de}$

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

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In strongly coupled regime, ($|\mathbf{d}| > 1$ ie δP_{de} is Q dominated) instabilities in DE perturbations can arise from the δP_{de} sector Valiviita '08, He '09, Jackson '09

Indeed at early time and large scale A_{de} & B_{de} $\propto$ $\mathbf{d}$ when w =cst

$\rightsquigarrow$ $\mathbf{d} > 1$ Instability ! ! Gavela '09

What coupling on the market ?

$Q \propto \rho_{de}$: stable for $w < -1$ and w cst and $Q < 0$

$Q_\nu = \xi \mathcal{H} \rho_{de} u^\nu_{de}$ and $= \xi \mathcal{H} \rho_{de} u^\nu_{dm}$ with $\xi < 0$ DEvel/DMvel ClassII

$Q^\nu \propto u^\nu_{de}$, $\propto u^\nu_{dm}$ same background, fith force present or not on DM

He '09, Gavela '09, Jackson '09

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- coupled quintessence well studied in literature Damour '90, Wetterich '95, Amendola '00,...

  $Q^\nu \propto \alpha \rho_{dm} \nabla_\nu \phi / M_p$ DEvel ClassI

  from WMAP, SDSS, HST : $\alpha < 0.08$ Bean '08

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- Recent studies with $\Sigma, w_0, w_e =$ cst Valviita '09, Majerotto'09

  $Q^\nu = -a \Gamma \rho_{dm} u^\mu_{dm}$ and $w = w_0 a + w_e(1-a)$, DMvel ClassI

Constraints from data : In the light of the Dark Matter sector

δ''_{dm} growth equation - late time - small scales

leads when A,B negligible

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

Exponential Growth or Oscillations

(Anti)Damping

- In the standard cosmology :

$A^{\mathrm{SC}}_{dm} > 0 \rightsquigarrow$ exponential growth
$B^{\mathrm{SC}}_{dm} < 0 \rightsquigarrow$ damping by Hubble friction

$\rightsquigarrow$ polynomial rise of δ_{dm}

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- In coupled models with :

  with negative $Q < 0$

  $\rightsquigarrow A_{dm}(Q) > A^{SC}_{dm}$ & $B_{dm}(Q) < B^{SM}_{dm}$

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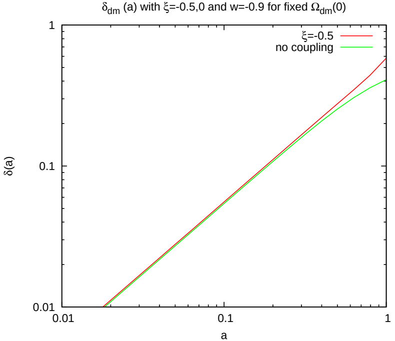


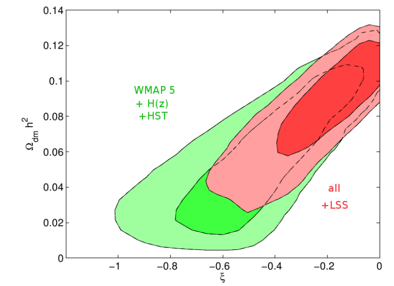
$$Q = \xi \mathcal{H} \rho_{de} u^{dm}_\nu$$

see also Caldera-Cabral '09

Constraints and Degeneracies : Current data

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

$Q_\nu = \xi \mathcal{H} \rho_{de} u_{dm}^{\nu}$ Gavela '09



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

For $Q < 0$, $|Q|$ large

$\rightsquigarrow$ more growth

$\rightsquigarrow$ more clustering

$\rightsquigarrow$ less $\Omega_{dm}^{(0)}$ needed in the source term of δ''_{dm}

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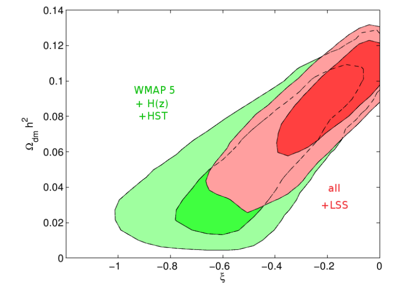

LSS data $\rightsquigarrow$ stringent constraint

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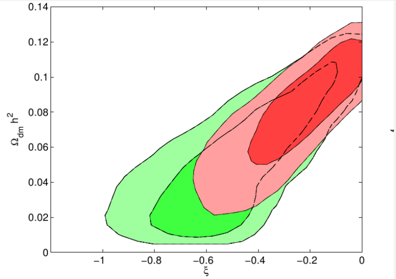

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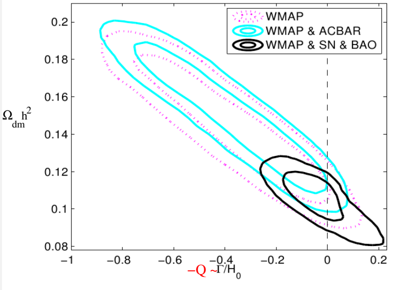
$Q^{\nu} = -a\Gamma \rho_{dm} u^{\mu}_{dm}$ Valiviita '10



LSS data $\rightsquigarrow$ stringent constraint

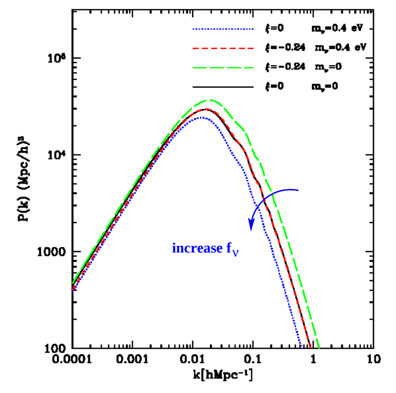
$\xi - m_\nu$ degeneracy

$$Q_\nu = \xi \mathcal{H} \rho_{de} u^\nu_{dm}$$ Gavela '09

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

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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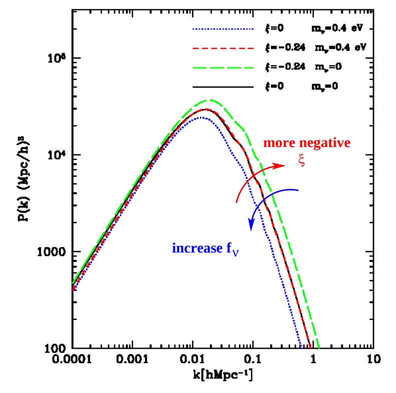

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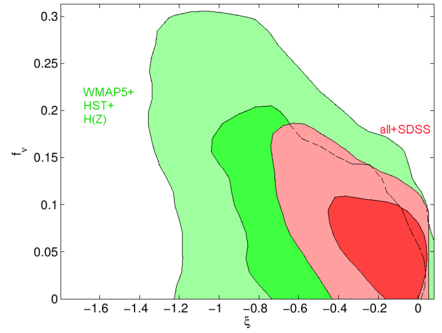

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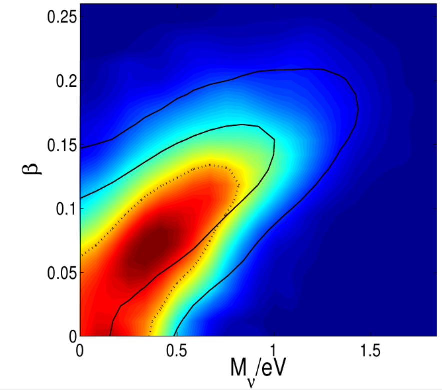
$Q_\nu \propto -\beta \rho_{dm} \nabla_\nu \phi / M_p$ La Vacca -Colombo '08



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Constraints from near universe observation data
Peculiar velocities

`Coupled dark matter-dark energy in light of near Universe observations` : JCAP 1009 :029.

Newtonian Limit

Low Redshifts, small scales $(k \gg \mathcal{H})$, Newtonian limit :

$$\begin{aligned}\dot{\delta}_{dm} &= -(kv_{dm} - \dot{\Phi}) + \frac{Q}{\bar{\rho}_{dm}}\left[\delta_Q - \delta_{dm} + \Psi\right] \\ \dot{v}_{dm} &= -\mathcal{H}v_{dm} + k\Psi + \frac{Q}{\bar{\rho}_{dm}}\left[v_Q - v_{dm}\right] \ ,\end{aligned}$$

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Linear growth function : $v = f\,(\mathcal{H}/k)\,\delta$

- Uncoupled and Class I : $f = d\ln\delta/d\ln a$
- Class II models, 2d contrib $f = d\ln\delta/d\ln a + Q/(\rho_{dm}\mathcal{H})$

Bulk flows : large scale galaxy motion

Watkins '09 : anomalously large averaged velocities @ $100h^{-1}$ Mpc scales
$\langle u^2 \rangle^{1/2} = 407 \pm 81$ km/s while $\langle u^2_{\Lambda CDM} \rangle^{1/2} \sim 200$ km/s

$$\langle u^2 \rangle = \frac{1}{2\pi^2} \int_0^\infty \mathrm{d}k\, k^2 P_v(k) |\tilde{W}(k)|^2 = \frac{1}{2\pi^2} \int_0^\infty \mathrm{d}k\, \mathcal{H}^2 f^2 P_\delta(k)\, |\tilde{W}(k)|^2$$

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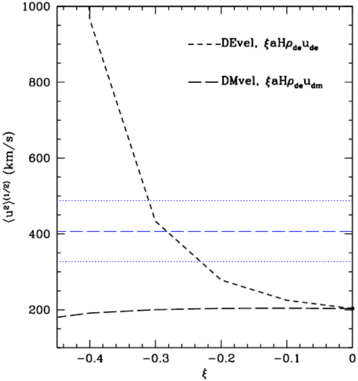
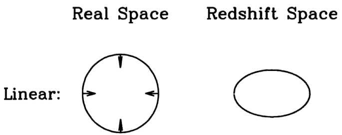


Imposing agrement with WMAP5 $d_A(z_{rec})$

- DMvel can't account for large $\langle u^2 \rangle^{1/2}$
- DEvel suffer from WEPV ! ! ! $\rightsquigarrow$ bulk flows are constraining $\xi < -0.35$

Peculiar velocities and Redshift space distortions



$$z_{obs} = z_{true} + \vec{v}_{pec}.\hat{x}$$

Neglecting v_{pec} $\rightsquigarrow$ distortion in redshift space

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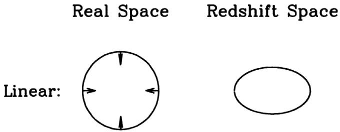

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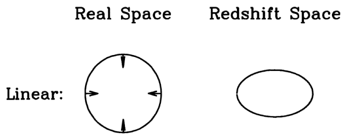
Redshift space distortions seen in galaxy surveys carry an imprint of the rate of growth of LSS

(Kaiser 1987, Song & Percival ’10)

Galaxy surveys offer a measure of $f\sigma_8$! ! Applied to coupled cosmologies :

Peculiar velocities and Redshift space distortions



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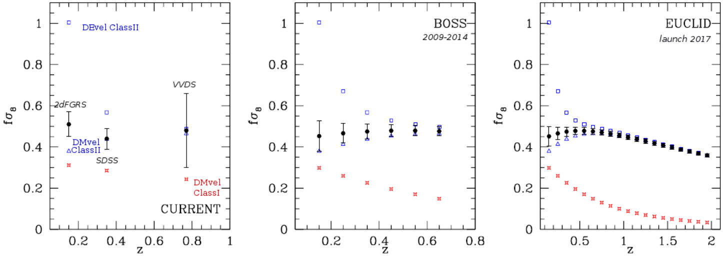

for DMvel & DEvel Class II $Q = \xi \mathcal{H} \rho_{de}$ with $\xi = -0.5$ and DMvel Class I $Q = -a\Gamma\rho_{dm}$ and $\Gamma = -0.3 H_0$ (best fit point Valiviita '09)

Violation of the Weak Equivalence Principle -DMvel test

Kesden & Kamionkowsi : Extra force between DM can lead to an asymmetry in the leading compared to the trailing tidal stream of a DM dominated satellite orbiting in the halo of a much larger host galaxy.

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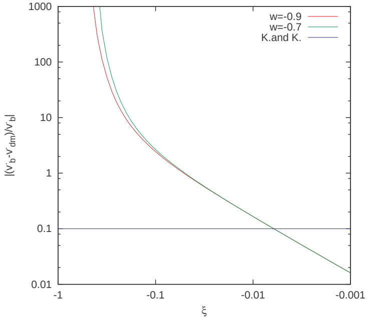


for $Q_\nu = \beta \rho_{dm} \nabla_\nu \phi / M_p$

$$G_{dm} = G_N(1+\beta^2) \rightsquigarrow |\beta| < 0.22 \text{ K\&K '06}$$

for $Q_\nu = \xi H \rho_{de} u_\nu^{de}$

$$k\dot{v}_{\rm b} = \mathcal{H}\dot{\delta}_{\rm b} + k^2\Psi .$$

$$k\dot{v}_{\rm dm} = \mathcal{H}\left(1+\xi\frac{\rho_{\rm de}}{\rho_{\rm dm}}\right)\left(\dot{\delta}_{\rm dm} + \xi\mathcal{H}\delta_{\rm dm}\frac{\rho_{\rm de}}{\rho_{\rm dm}}\right) + k^2\Psi ,$$

$$k^2\Psi = -\frac{3}{2}\mathcal{H}^2(\Omega_{\rm b}\delta_{\rm b} + \Omega_{\rm dm}\delta_{\rm dm})$$

Conclusions

Interactions between DM and DE can be present

Neglecting them can lead to a misinterpretation of observational data

- Carrefull choice of the Q_ν parametrization in order to avoid Instabilities
- Large values of the coupling are still allowed by LSS and CMB data
- Degeneracies $Q - \Omega_{dm}$ and $Q - m_\nu$ shows up
- Velocity constraints put stringent bounds on Q in DEvel models

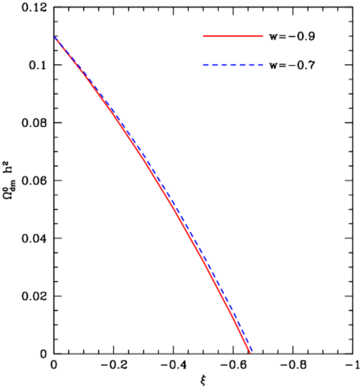
This is the End

Thank you for your attention ! !

Backup

Values of Ω_{dm} that fit CMB

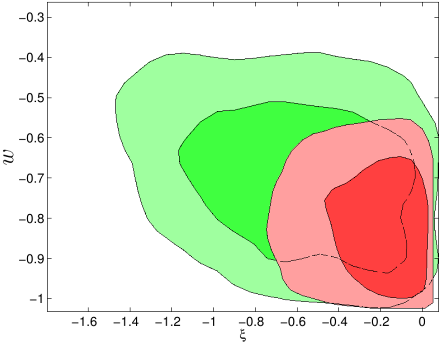
We use the values of Ω_{dm} giving rize to the $d_A(z_{rec})$ in agreement with WMAP5 :
For e.g. $Q = \xi \mathcal{H} \rho_{de}$



Background dependent ! !
quite independent of w

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

Origin of instabilities in coupled models - δP sector

- Adiabatic processes :

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

$$c^2_{a\,de} = \frac{\dot{P}_{de}}{\dot{\rho}_{de}} \qquad \text{which for } w = cst,\, c^2_{a\,de} = w < 0$$

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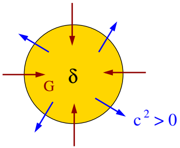
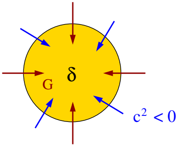


$$\Rightarrow$$



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

$\rightsquigarrow$ Exponential growth from the A-term contribution

see *e.g.* Bean, Flanagan and Trodden '07 AND
slow-roll suppression see Corasaniti '09

Origin of instabilities in coupled models - δP sector

- Non adiabatic processes :

$$\delta P_I \neq c^2_{a\,I}\delta\rho_I,$$

In any frame for coupled DE-DM :

$$\delta P_{de} = \hat{c}^2_{s\,de}\delta\rho_{de} - (\hat{c}^2_{s\,de} - c^2_{a\,de})\dot{\rho}_{de}\frac{\theta_{de}}{k^2} \qquad \text{where} \qquad \hat{c}^2_{s\,de} = \left.\frac{\delta P_{de}}{\delta\rho_{de}}\right|_{DE\,rf}$$

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

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$|\mathbf{d}| > 1 \rightsquigarrow$ strongly growing non-adiabatic mode
at early time-large scales (*i.e.* $k \ll \mathcal{H}$)
$\rightsquigarrow$ drive NON-ADIABATIC instabilities

see also Valiviita *et* all '08, He *et* all '08 and Jackson *et* all '09

Analytical treatment of Perturbations

$$Q_\nu = Q\, u_\nu^{(dm)} \text{ with } Q = \xi H \rho_{de}$$

no fith force effects and $\xi < 0$ with $w > -1$ to avoid instabilities

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- Gauge invariant formalism $\rightsquigarrow$ δH must be included in Δ_Q
- Derive initial conditions

Imposing adiabatic initial conditions $S_{ab} \equiv \frac{\Delta_a^0}{\dot\rho_a/\rho_a} - \frac{\Delta_b^0}{\dot\rho_b/\rho_b} = 0$ for dm, b, γ, ν, automatically implies :

$$\rightsquigarrow \Delta_{de}^0 = \frac{3}{4}\left(1 + w + \frac{\xi}{3}\right)\Delta_\gamma^0$$

Adiabatic initial conditions for dark energy (depend on ξ ! !)

for uncoupled Doran'03, for coupled also Majerotto'10

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

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

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

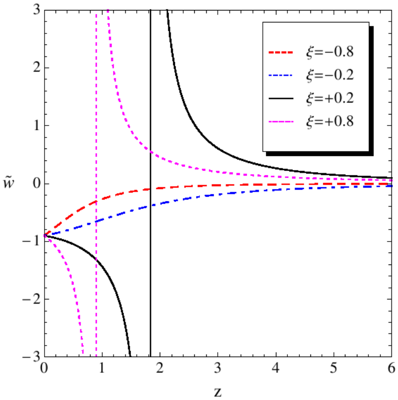
$$\Rightarrow \tilde{w}(z) = \frac{1}{3}\,\frac{R'_H(1+z) - 3R_H}{R_H - \Omega_{dm}^{(0)}(1+z)^3}\,.$$

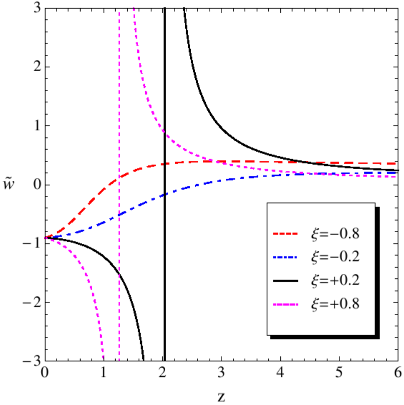
However in presence of dark couplings :

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

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

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





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

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

Future Constraints : from CMB lensing Martinelli'10

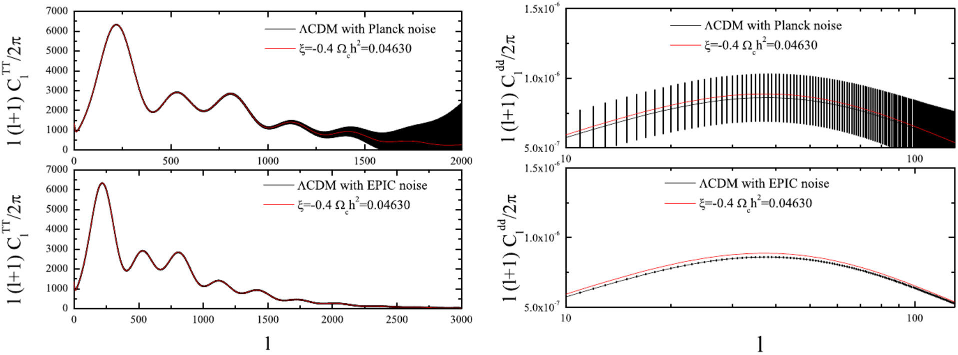
Lensing deflection $d = \nabla\Phi$ whit Φ the lensing potential. In harmonic space, multipoles follows $d_l^m = -i\sqrt{l(l+1)}\phi_l^m$,

For $C_l^{dd} \equiv \langle d_l^m d_l^{m*}\rangle$ and $C_l^{\phi\phi} \equiv \langle \phi_l^m \phi_l^{m*}\rangle$, we have $C_l^{dd} = l(l+1)C_l^{\phi\phi}$.

$\rightsquigarrow$ breaking of $\Omega_{dm} - \xi$ degeneracy with EPIC that will greatly reduce its noise on CMB lensing

Temperature power spectra

Lensing deflection power spectra



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