Hint of
Interacting dark matter-dark energy Cosmologies

Laura Lopez Honorez

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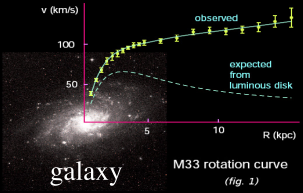
based on

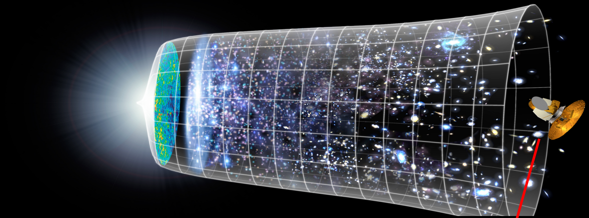
`Dark Coupling`: JCAP 0907:034
`Dark Coupling and Gauge Invariance`: JCAP11(2010)044
`Coupled dark matter-dark energy in light of near Universe observations`: JCAP 1009:029.

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

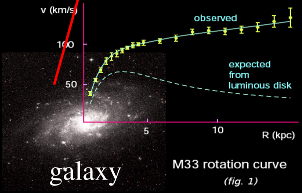
Séminaire - IIHE - ULB & VUB



The Quest to determine the Composition of our Universe

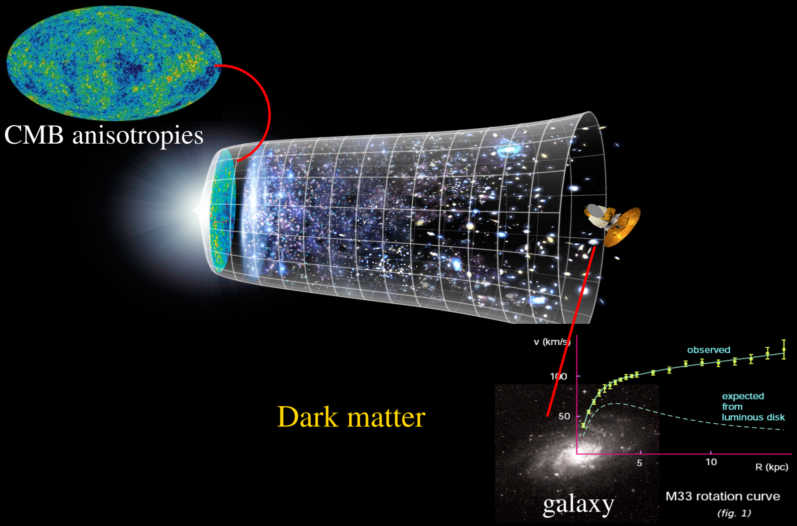


Dark matter



M33 rotation curve
(fig. 1)

The Quest to determine the Composition of our Universe



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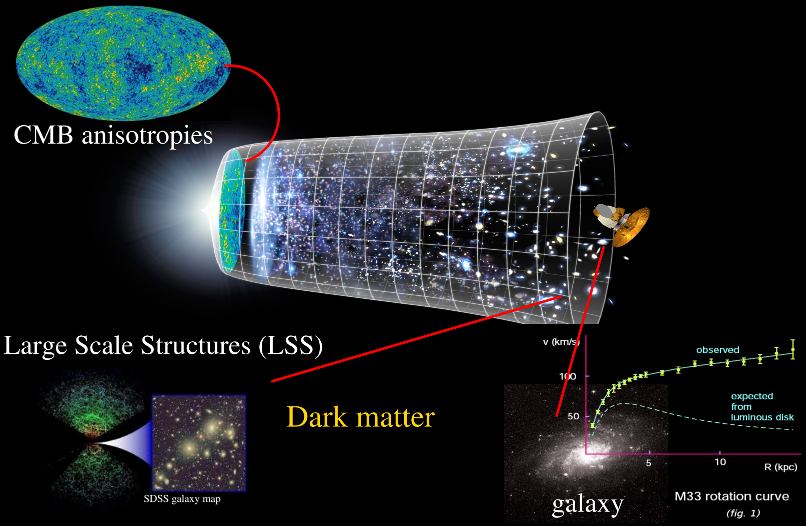

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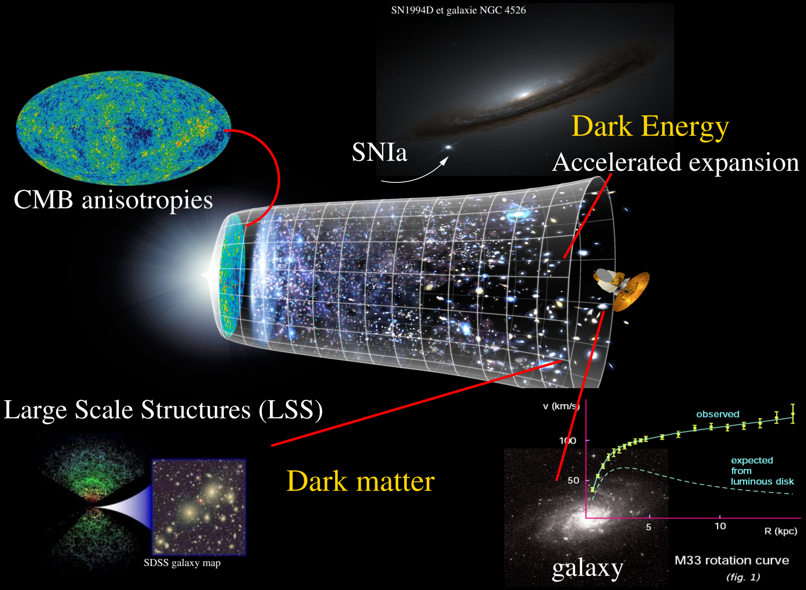

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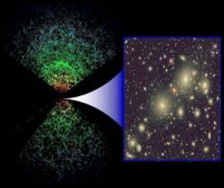
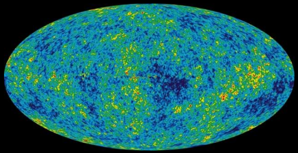
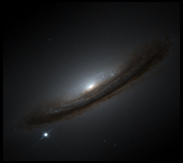
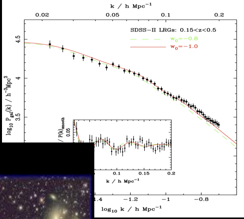
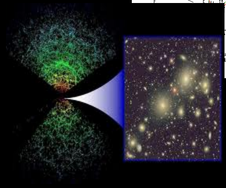
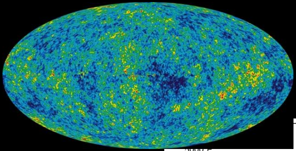


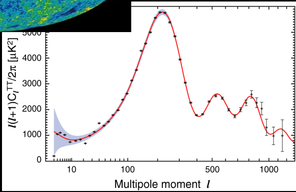


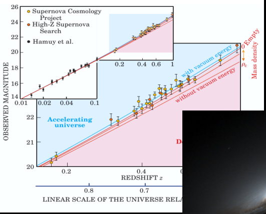


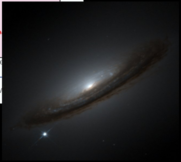

k / h Mpc^{-1}
0.02
0.05
0.1
0.2
SDSS−II LRGs: 0.15<z<0.5
w_0=−0.8
w_0=−1.0
$\log_{10} P_{gal}(k)$ / h^{-3}Mpc^3
4.5
4
3.5
0.1
0.15
0.2
k / h Mpc^{-1}
−1.2
−1
−0.8
$\log_{10}$ k / h Mpc^{-1}





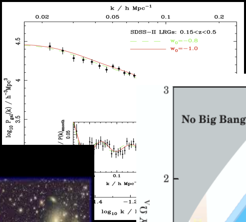

$l(l+1)C_l^{TT}/2\pi$ [μK^2]
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l

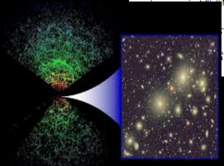

Supernova Cosmology Project
High-Z Supernova Search
Hamuy et al.
OBSERVED MAGNITUDE
26
24
22
20
18
16
14
0.01
0.02
0.04
0.1
0.2
0.4
0.6
1
with vacuum energy
without vacuum energy
Empty
Mass density
Accelerating universe
22
21
20
0.2
0.4
REDSHIFT z
0.8
0.7
LINEAR SCALE OF THE UNIVERSE REL

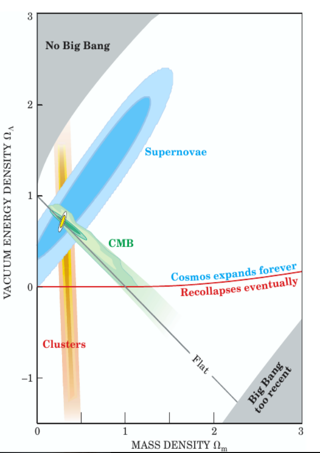


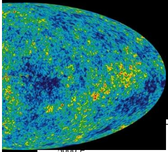
SDSS

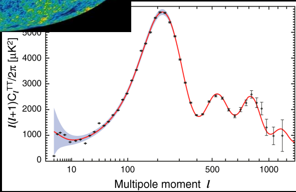
Percival et al 2010



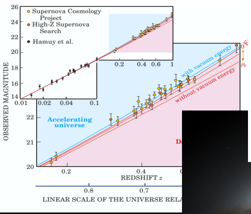




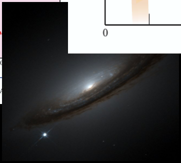




WMAP7, Larson et al 2010



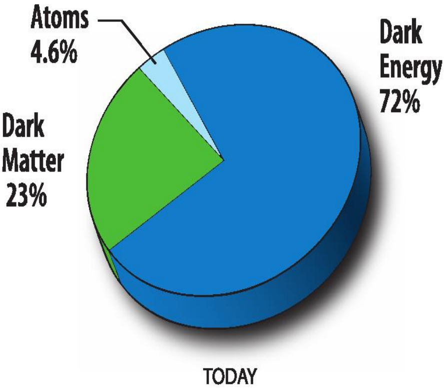
Pelmutter 2003

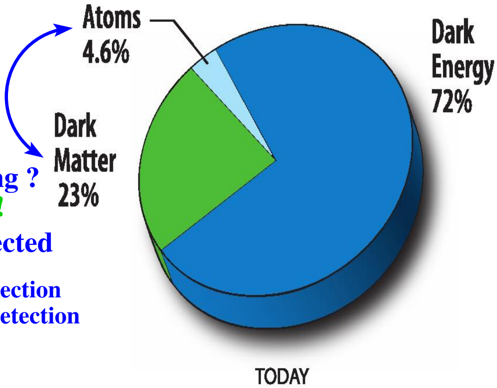


Concordance for a flat Universe today made of

~ 70% of dark energy

~ 30% of matter

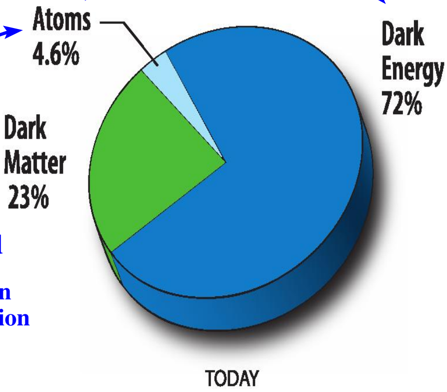

Atoms
4.6%
Dark
Energy
72%
Dark
Matter
23%
TODAY



Interacting ?
Allowed!

To be detected
- **Colliders**
- **Direct detection**
- **Indirect detection**

Interacting ?
Very constrained!



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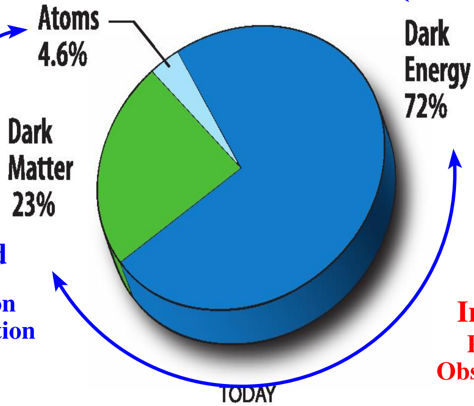

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To be detected
Colliders
Direct detection
Indirect detection

Interacting ?
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In this TALK!
Parametrizations
Observational constraints

Conclusion Preview

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

Background : Evolution Equations

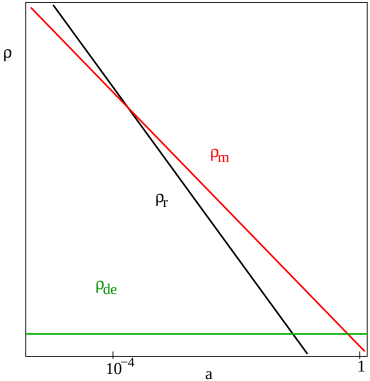
... for cosmological fluids in an homogeneous and isotropic space time :

- $T_{\mu\nu} = diag(-\rho, p, p, p)$

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

$w_m = 0,\ w_r = 1/3,\ w_{de} = w < -1/3$

ΛCDM model $w_{de} = -1$



uncoupled $Q = 0$

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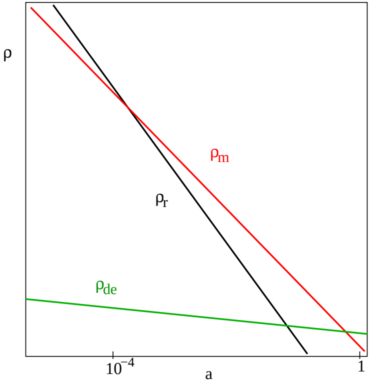

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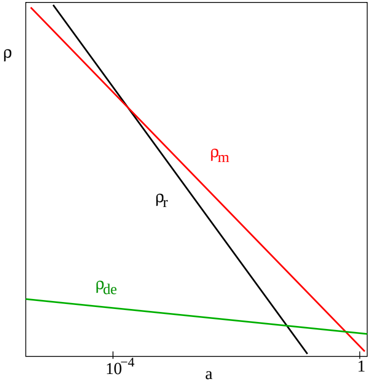

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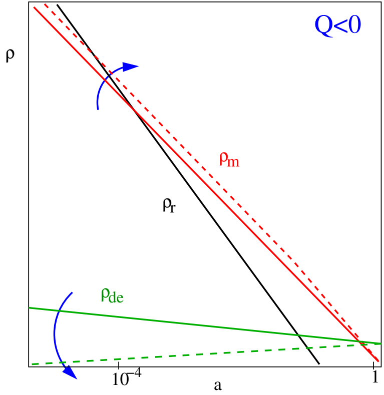
  - Q encodes the interaction
  - for $e.g.$ $Q < 0$
    $\rightsquigarrow$ more DM in the past

DE-dm Coupled model



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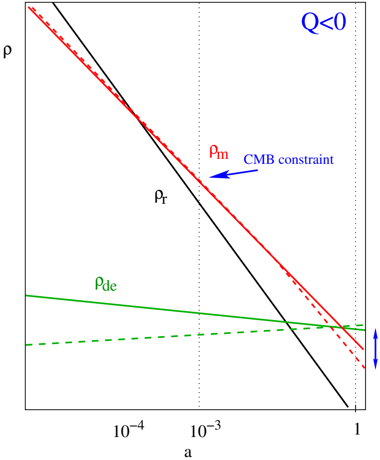

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What is the interaction like : Background

From the Background : Energy exchange...

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

- 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, remember :

$$T^0_0 = \rho(1+\delta),\ T^0_i = (\rho+p)v_i, T^i_j = p + \delta p$$

What is the evolution of the overdensities δ and velocity perturbations v ?

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

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

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

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\end{aligned}
$$

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

To deduce the evolution of perturbations,
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$$\nabla_\mu T^\mu_{(dm)\nu} = Q\, u^{dark}_\nu,$$
$$\nabla_\mu T^\mu_{(de)\nu} = -\, Q\, u^{dark}_\nu,$$

- Conservation of the total energy momentum : $\nabla_\mu T^\mu_{(tot)\nu} = 0$
- Parametrization of DM-DE energy-momentum exchange : $Q_\nu = Q\, u^{dark}_\nu$

$$u^\nu = \frac{P^\nu}{P^0} : \quad \text{bgd} \quad u^\nu = a^{-1}(1, \vec{0}), \quad \text{perturb} \quad u^i \propto v^i$$

u_ν is the 4-velocity and P_μ the 4-momentum ($\neq p = w\rho$! !)

Perturbations evolution equations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- Geometry $g_{\mu\nu} \rightsquigarrow$ Newtonian potential Ψ, Φ

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

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$$\dot{v}_{dm} = -\mathcal{H}v_{dm} + k\Psi + \frac{Q}{\bar{\rho}_{dm}}\left[v_Q - v_{dm}\right] \, ,$$

- For a DE $\delta p_{de} \neq 0$ and is a function of

$\hat{c}^2_{s\,de} = \delta p_{de}/\delta\rho_{de}|_{rf}$, $c^2_{a\,de} = \dot{p}_{de}/\dot{\rho}_{de}$, and **d** $\equiv \frac{Q}{3\mathcal{H}\rho_{de}(1+w)}$

$\rightsquigarrow$ more complicated expressions for $\dot{\delta}_{de}, \dot{v}_{de}$

Growth equations

For any fluid-component the first order differential evolution equations can be combined in second order growth equation with 3 main contributions :

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

NB :X' denotes $\partial X/\partial a$, $\dot{X}$ denotes $\partial/\partial\tau$

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Rapid Growth or Oscillations

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Rapid Growth or Oscillations (A_i)

(Anti)Damping (B_i)

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Growth equations

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leads when A,B negligible

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Rapid Growth or Oscillations

(Anti)Damping

NB :X' denotes $\partial X/\partial a$, $\dot{X}$ denotes $\partial/\partial\tau$

Some examples : The Uncoupled Case (late time)

ΛCDM Cosmology ($w = -1$)$\Rightarrow$ NO DE perturbations

- $\dot{\delta}_{de} = \dot{\theta}_{de} = 0$
- $\dot{\delta}_{dm}$ and $\dot{\theta}_{dm}$ + Matter Dominated Era :

$$\delta''_{dm} = \frac{3}{2}\Omega_{dm}\frac{\delta_{dm}}{a^2} - \frac{3}{2}\frac{\delta'_{dm}}{a}$$

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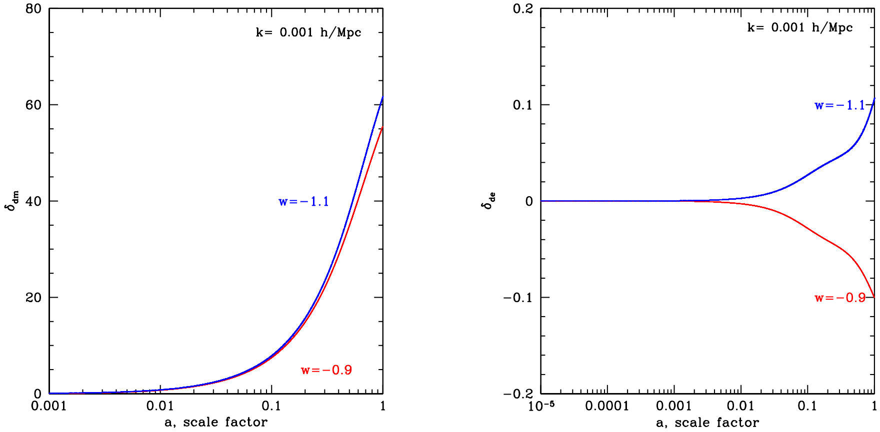
$w \neq -1 \Rightarrow$ DM-DE perturbations are NOT independent

$$\begin{aligned} \delta''_{dm} &= \frac{3}{2}\Omega_m\frac{\delta_{dm}}{a^2} - \frac{3}{2}\frac{\delta'_{dm}}{a} + \mathcal{F}(\delta_{de}) \\ \delta''_{de} &= -\frac{9}{2}(\hat{c}^2_{s\,de} - w)\frac{\delta_{de}}{a^2} - (\frac{5}{2} - 3w)\frac{\delta'_{de}}{a} + \mathcal{G}(\delta_{dm})\,. \end{aligned}$$

$\rightsquigarrow$ $\delta_{de} \neq 0$ and δ_{dm} can be affected by w, $\hat{c}^2_{s\,de}$

The Uncoupled Case : $w \neq -1$



Even for Q=0 DM and DE interact at the perturbation level ! !

see *e.g.* Bean and Doré ' 03, Lewis and Weller '03

Ballesteros and Riotto '08

Growth equations-General

leads when A,B negligible

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

Rapid Growth or Oscillations

(Anti)Damping

Growth equations-General

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leads when A,B negligible ($\mathcal{F}$ term)

Rapid Growth or Oscillations (A_i term)

(Anti)Damping (B_i term)

- In the standard cosmology :

  $A_{dm}^{SC} > 0 \rightsquigarrow$ rapid growth
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Growth equations-General

leads when A,B negligible

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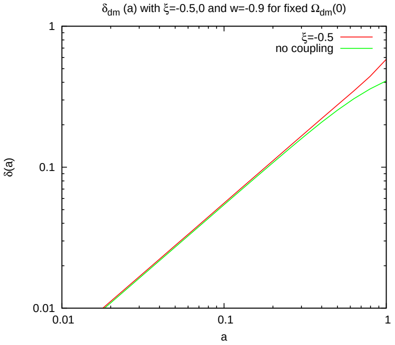
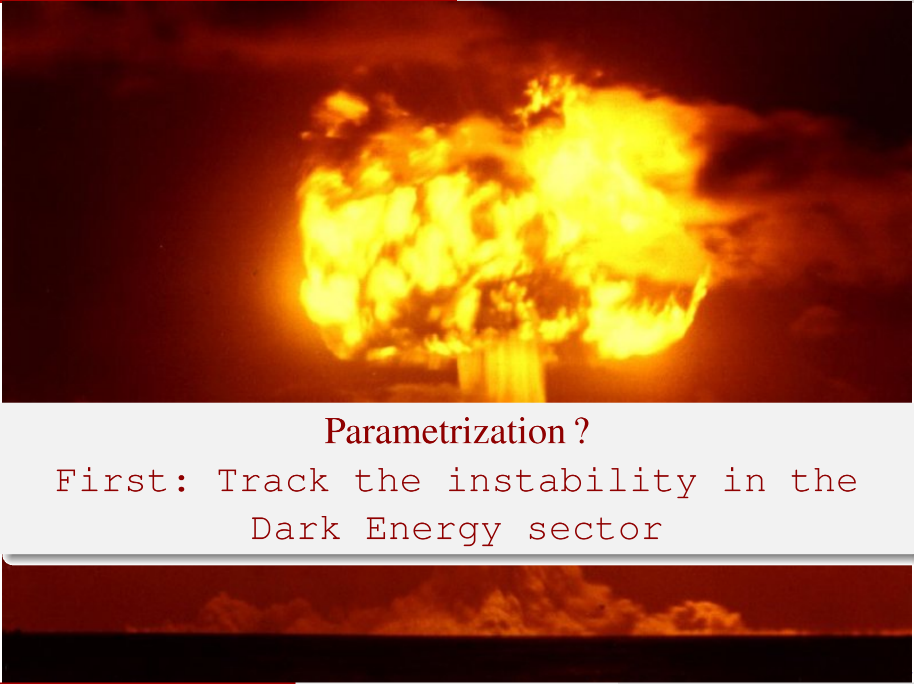


$$Q = \xi \mathcal{H} \rho_{de} u_\nu^{dm}$$

see also Caldera-Cabral '09



Parametrization ?

`First: Track the instability in the Dark Energy sector`

Limitations due to Instabilities in the DE sector :

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

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

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At early time, 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

As a rule of thumb : at early time and large scale when w =cst

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

What Coupling on the Market ?

$$\nabla_\mu T^\mu_{(dm,de)\nu} = \pm Q_\nu$$

$$Q_\nu = \pm Q \quad u_\nu$$

$$\propto \rho_{dm} \; u_\nu^{(dm)}$$

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Damour 90, Wetterich 95, Amendola 2000

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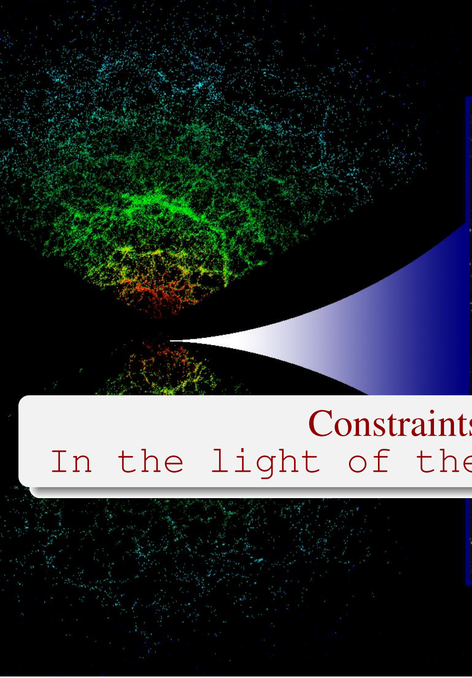
ξ must be negative for $w =$ cst, Γ and α are positive or negative $w \neq$ cst



Constraints from data :

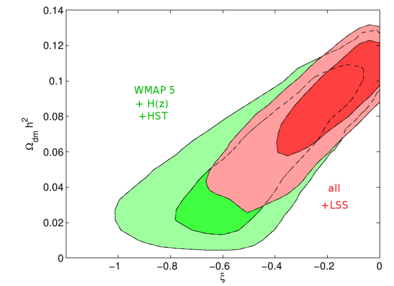
In the light of the Dark Matter sector

Constraints and Degeneracies : Current data

`Dark Coupling` : JCAP 0907 :034

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

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



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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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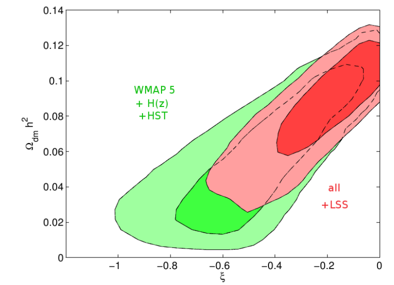

LSS data $\rightsquigarrow$ stringent constraint

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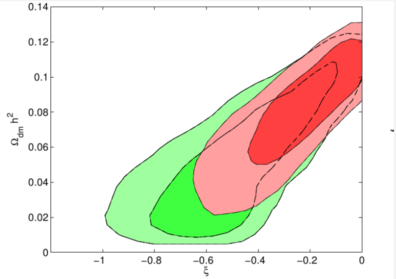

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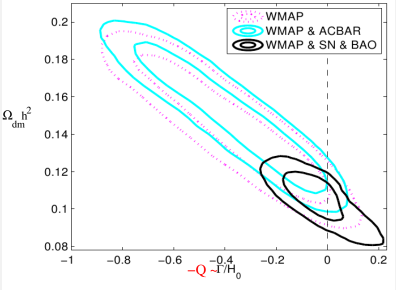

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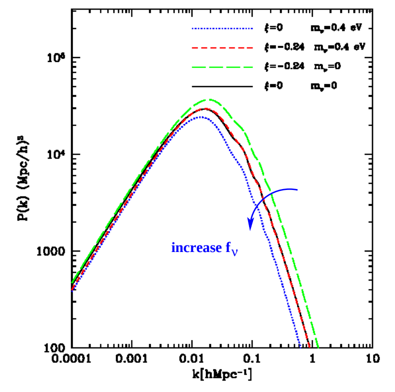
$$f_\nu = \frac{\Omega_\nu^{(0)} h^2}{\Omega_{dm}^{(0)} h^2} = \frac{\sum m_\nu}{93.2\text{eV}} \cdot \frac{1}{\Omega_{dm}^{(0)} h^2}$$

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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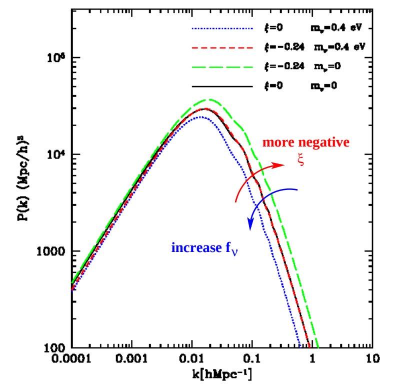

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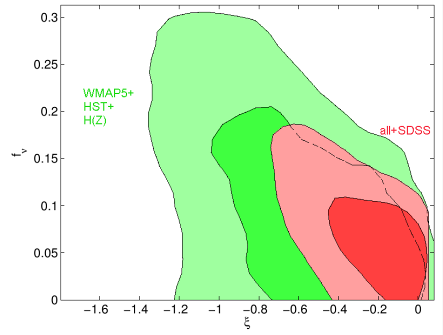

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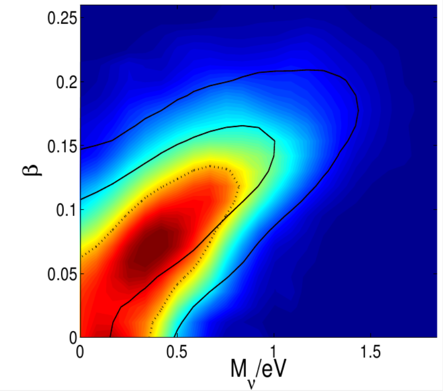

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Constraints from near universe observation data
Peculiar velocities

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] \ ,
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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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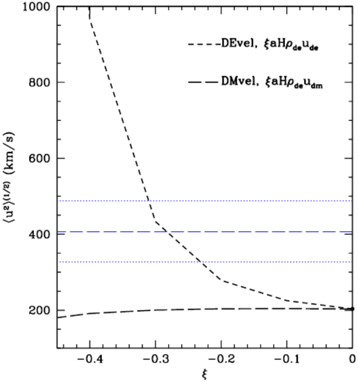

Imposing agrement with WMAP5 $d_A(z_{rec})$

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

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

One typical example : Coupled Quintessence

$$\mathcal{L}_{de-dm} = \frac{1}{2} D_\mu \phi_{de} D^\mu \phi_{de} - V(\phi_{de}) + \frac{1}{2} D_\mu \psi_{dm} D^\mu \psi_{dm} - \frac{1}{2} m_{dm}^2(\phi_{de}) \psi_{dm}^2$$

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$\rightsquigarrow$ Coupled Quintessence is a typical example of $Q_\nu \propto \rho_{dm}u^{(de)}_\nu$ ClassI DMvel model

What would be the other possible combinations ?

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 ($\Phi = \Omega^{-1}$) :

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

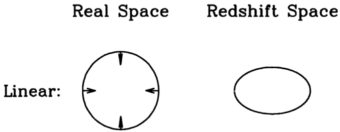
Using conformal transformation with

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

In that framework, assuming that in the Jordan Frame : $\nabla_\mu T_M^{\mu\nu} = 0$
we get in the Einstein frame coupled DE-DM system :

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

Peculiar velocities and Redshift space distortions



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Neglecting v_{pec} ⇝ distortion in redshift space

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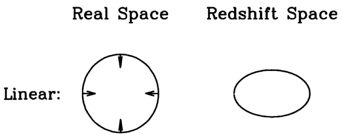

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Redshift space distortions seen in galaxy surveys carry an imprint of the rate of growth of LSS

(Kaiser 1987, Song & Percival '10)

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

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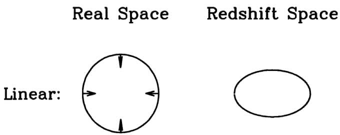

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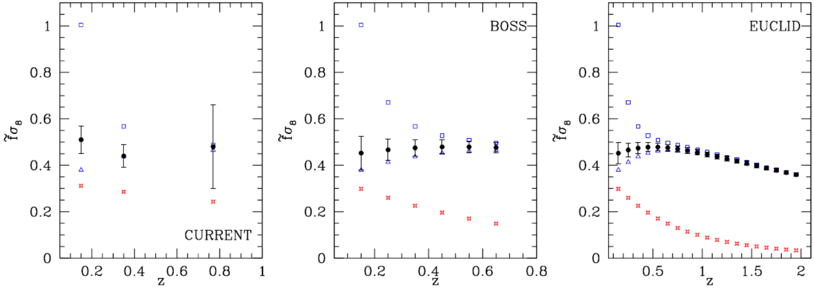

for DMvel & DEvel Class II $Q = \xi \mathcal{H} \rho_{de}$ with $\xi = -0.5$ and DMvel Class I $Q = -a\Gamma\rho_{dm}$ and $\Gamma = -0.3H_0$ (best fit point Valiviita '09)

Violation of the Weak Equivalence Principle -DMvel test

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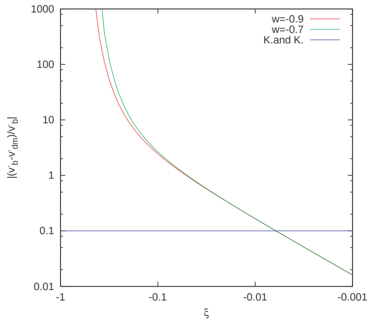

for $Q_\nu = \beta\rho_{dm}\nabla_\nu\phi/M_p$

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

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

$$k\dot{v}_{\rm b} = \mathcal{H}\dot{\delta}_{\rm b} + k^2\Psi .$$
$$k\dot{v}_{\rm dm} = \mathcal{H}\left(1+\xi\frac{\rho_{\rm de}}{\rho_{\rm dm}}\right)\left(\dot{\delta}_{\rm dm} + \xi\mathcal{H}\delta_{\rm dm}\frac{\rho_{\rm de}}{\rho_{\rm dm}}\right) + k^2\Psi ,$$
$$k^2\Psi = -\frac{3}{2}\mathcal{H}^2(\Omega_{\rm b}\delta_{\rm b} + \Omega_{\rm dm}\delta_{\rm dm})$$

Origin of instabilities in coupled models - δP sector

- Adiabatic processes :

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

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

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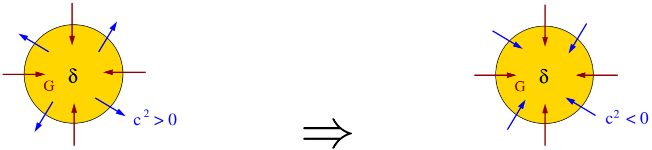

⇝ Instability as $c^2_{a\,de} < 0$, pressure no more counteract gravity

⇝ Exponential growth from the A-term contribution

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

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- 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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$|\mathbf{d}| > 1 \rightsquigarrow$ 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 :

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

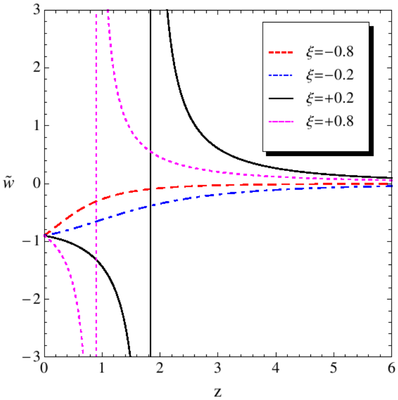
$$\Rightarrow \tilde{w}(z) = \frac{1}{3}\,\frac{R'_H(1+z) - 3R_H}{R_H - \Omega_{dm}^{(0)}(1+z)^3}\,.$$

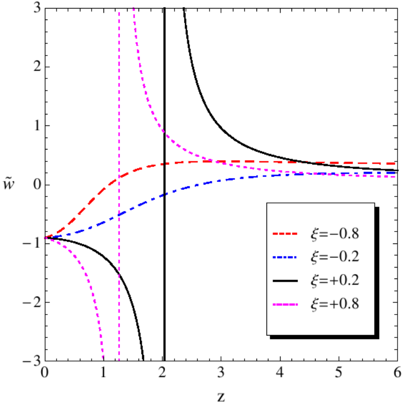
However in presence of dark couplings :

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

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 $\xi > 0$

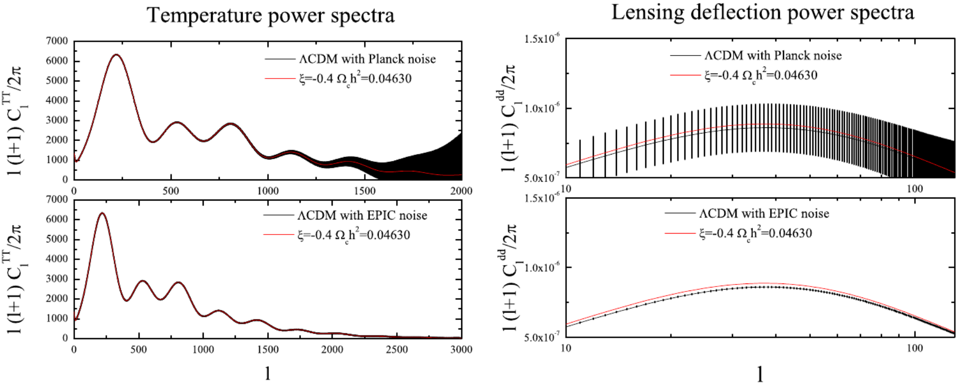
Similar behaviour in f(R) cosmologies see *e.g.* Amendola & Tsujikawa '07

Future Constraints : from CMB lensing Martinelli'10

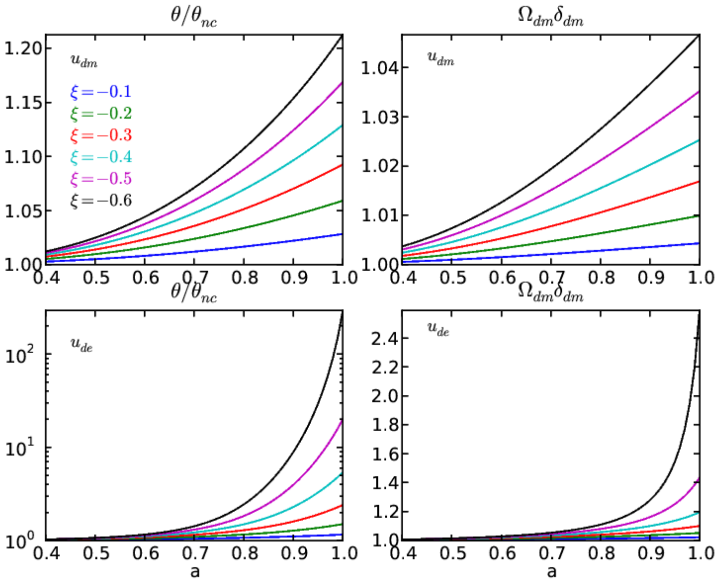
Lensing deflection $d = \nabla\Phi$ whit Φ the lensing potential. In harmonic space, multipoles follows $d_l^m = -i\sqrt{l(l+1)}\phi_l^m$,

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



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



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 ($B = 0$) :

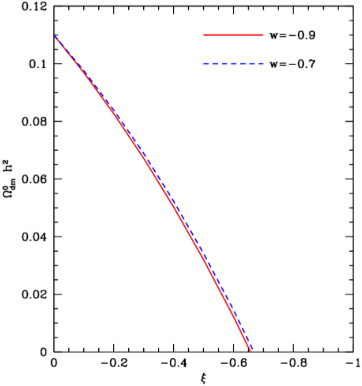
$$\begin{aligned} w_{de}\Gamma_{de}|_{rf\ de} &= (\hat{c}_s^2 - c_a^2)\hat{\delta}_{de} = (c_s^2 - c_a^2)\delta_{de} = w_{de}\Gamma_{de}|_{any\ frame} \\ \Delta_{de}|_{rf\ de} &= \hat{\delta}_{de} = \delta_{de} + \frac{\dot{\rho}_{de}}{\rho_{de}} v_{de} = \Delta_{de}|_{any\ frame} \end{aligned}$$

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

Values of Ω_{dm} that fit CMB

We use the values of Ω_{dm} with $d_A(z_{rec})$ in agreement with WMAP5 :

For e.g. $Q = \xi \mathcal{H} \rho_{de}$



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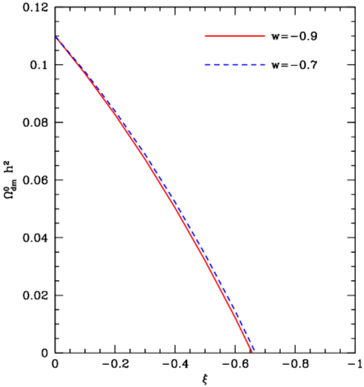

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- Constraints from voids :
  Voids are more empty than expected from Λ CDM (factor 10) :
  too few small galaxies with velocity below 35 km/s Thikonov & Klypin '08

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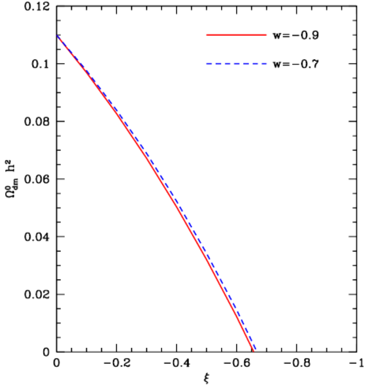

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Fitting obs. results : depletion of DM of at most 20%

$\rightsquigarrow \xi > -0.2$