Interaction between dark energy and dark matter

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Known? *Unknown!*

5% 95%

知之為知之， ← 5% → Present your understanding when you understand;

不知為不知， ← 95% → recognize your not understanding when you don't understand;

是知也。 that's the true meaning of understanding.

—論語為政篇

— By Confucius

(Analects of Confucius)

相互作用

暗能量

暗物质

理论及实验

Concordance Cosmology

- DE-- Λ ?
  1. QFT value 123 orders larger than the observed
  2. Coincidence problem:

     Why the universe is accelerating just now?

     In Einstein GR: Why are the densities of DM and DE of precisely the same order today?
- Reason for proposing Quintessence, tachyon field, Chaplygin gas models etc.

  No clear winner in sight

  Suffer fine-tuning

Scaling behavior of energy densities

- A phenomenological generalization of the LCDM model is

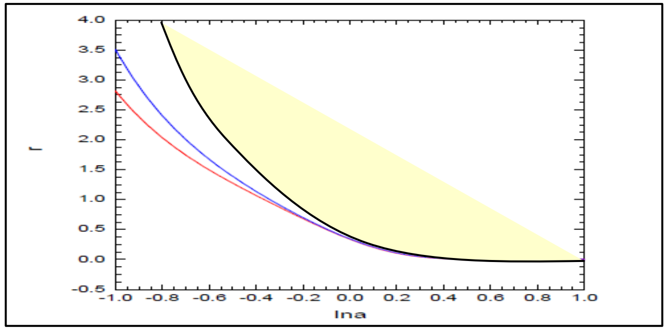
$$\frac{\rho_M}{\rho_X} = r_0 \left(\frac{a_0}{a}\right)^{\xi}$$

$\xi = 3$ LCDM model,

$\xi = 0$ Stationary ratio of energy densities

$\xi < 3$ Coincidence problem less severe than LCDM

The period when energy densities of DE and DM are comparable is longer



The coincidence problem is less acute

$\xi < 3$ can be achieved by a suitable interaction between DE & DM

$$\dot{\rho}_M + 3H\rho_M = Q\,, \quad \dot{\rho}_X + 3H\,(1+w_X)\,\rho_X = -Q\,.$$

Do we need to live with Phantom?

- Degeneracy in the data.

SNe alone however are consistent with w in the range, roughly
$-1.5 \leqslant w_{eff} \leqslant -0.7$ Hannestad et al, Melchiorri et al, Carroll et al

WMAP 3Y(06) w=-1.06{+0.13,-0.08}

w<-1 from data is strong!

- One can try to model w<-1 with scalar fields like quintessence. But that requires **GHOSTS**: fields with negative kinetic energy, and so with a Hamiltonian not bounded from below:

$$3\,M_4^2\,H^2 = -\,(\phi')^2/2 + V(\phi)$$

\`Phantom field′ , Caldwell, 2002

- **Phantoms and their ills: instabilities, negative energies ... ,**

Theoretical prejudice against w<-1 is strong!

MAYBE NOT!

- *Conspiracies are more convincing if they* ***DO NOT*** *rely on supernatural elements!*
- Ghostless explanations:

1) Modified gravity affects **EVERYTHING,** with the effect to make w<-1.

S. Yin, B. Wang, E.Abdalla, C.Y.Lin, arXiv:0708.0992, PRD (2007)

A. Sheykhi, B. Wang, N. Riazi, Phys. Rev. D 75 (2007) 123513

R.G. Cai, Y.G. Gong, B. Wang, JCAP 0603 (2006) 006

2) Another option: Interaction between DE and DM

Super-acceleration (w<-1) as signature of dark sector interaction

B. Wang, Y.G.Gong and E. Abdalla, Phys.Lett.B624(2005)141

B. Wang, C.Y.Lin and E. Abdalla, Phys.Lett.B637(2006)357.

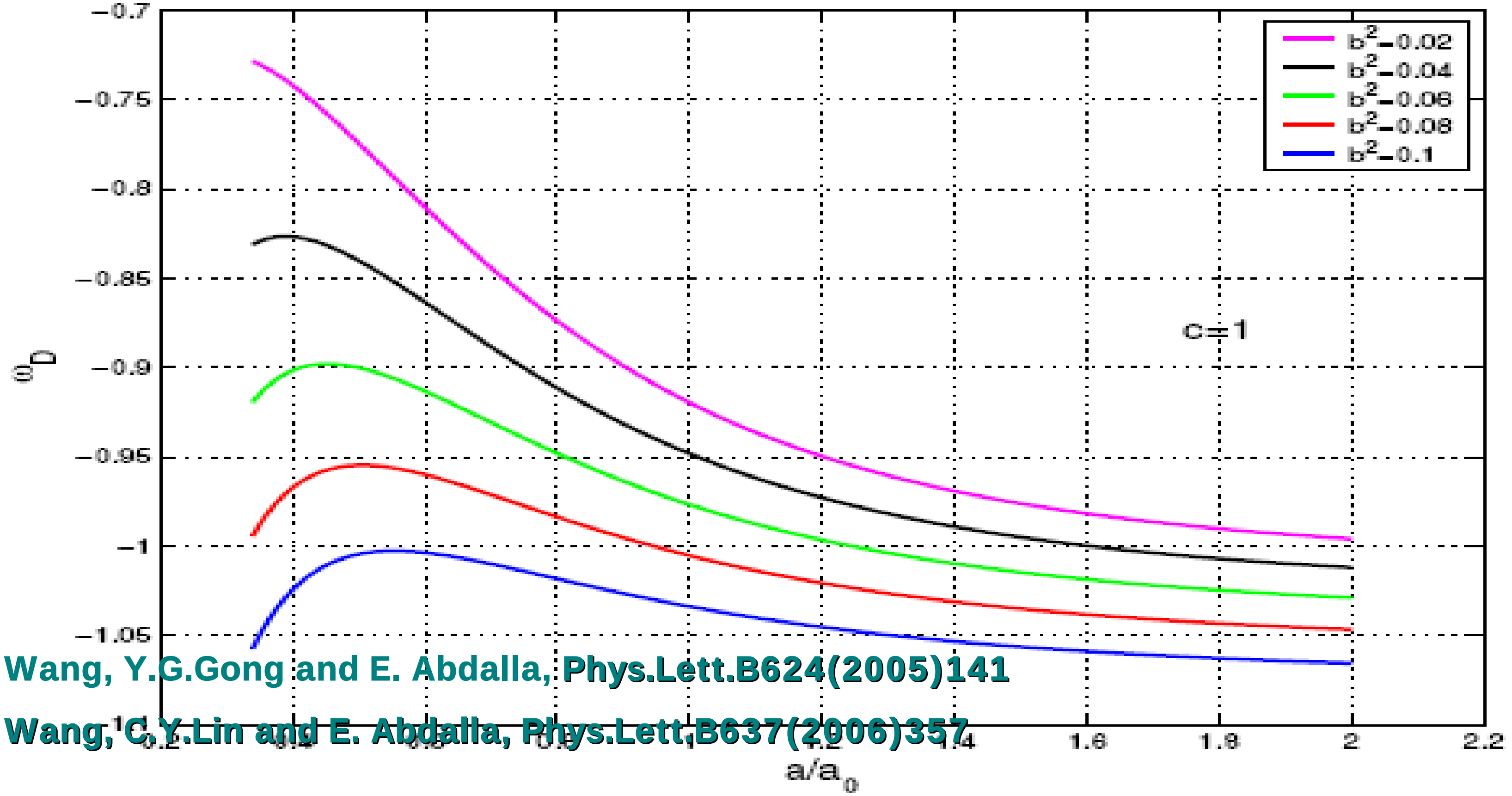
S. Das, P. S. Corasaniti and J. Khoury, Phys.Rev. D73 (2006) 083509.

Evolution of the equation of state of DE

$$w_D = -1/3 - 2\sqrt{\Omega_D}/(3c) - b^2/\Omega_D$$

- **Crossing -1 behavior** $\sqrt{\Omega_D} < c < 1.255$

$$1.4(1-\sqrt{0.7}/c)/3 < b^2 < 8c^2/81$$



B. Wang, Y.G.Gong and E. Abdalla, Phys.Lett.B624(2005)141

B. Wang, C.Y.Lin and E. Abdalla, Phys.Lett.B637(2006)357

The Interaction Between DE & DM

In the framework of field theory, the interaction between 70%DE and 30%DM is nature, could be even more general than uncoupled case.

(Pavon, Almendola et al)

$$\dot{\rho}_M + 3H\rho_M = Q \ , \quad \dot{\rho}_X + 3H\,(1+w_X)\,\rho_X = -Q \ .$$

Q>0 $\longrightarrow$ accelerated scaling attractor to alleviate the coincidence problem

S.Chen, Bin Wang, J.Liang, arXiv:0808.3482; D.Pavon et al, arXiv:0806.2116 etc.

For Q > 0 the energy proceeds from DE to DM

Phenomenological interaction forms:

$$(1)\ Q = \delta H(\rho_{DM} + \rho_{DE}),\ (2)\ Q = \delta H\rho_{DM}\ \text{and}\ (3)\ Q = \delta H\rho_{DE}$$

- Is the interaction between DE & DM allowed by observations?

Universe expansion history observations:

SN constraint

CMB

BAO

Age constraints

B. Wang, Y.G.Gong and E. Abdalla, Phys.Lett.B(2005),

B. Wang, C. Lin, E. Abdalla, PLB (06)

B.Wang, J.Zang, C.Y.Lin, E.Abdalla, S.Micheletti, Nucl.Phys.B(2007)

C.Feng, B.Wang, Y.G.Gong, R.Su, JCAP (2007);

C.Feng, B.Wang, E.Abdalla, R.K.Su, PLB(08),

J.He, B.Wang, JCAP(08)

$$\omega_I(z) = w_0 + \frac{w_1 z}{(1+z)},$$

$$\omega_{II}(z) = w_0 + \frac{w_1 z}{(1+z)^2}.$$

Galaxy cluster scale test

E. Abdalla, L.Abramo, L.Sodre, B.Wang, PLB(09) arXiv:0710.1198

……..

The Sachs-Wolfe Effect

The Sachs-Wolfe effect is an imprint on the cosmic microwave background(CMB) that results from gravitational potentials shifting the frequency of CMB photons as they leave the surface of last scattering and are eventually observed on Earth.

Two categories of Sachs-Wolfe effects alters the CMB:

non-integrated

integrated

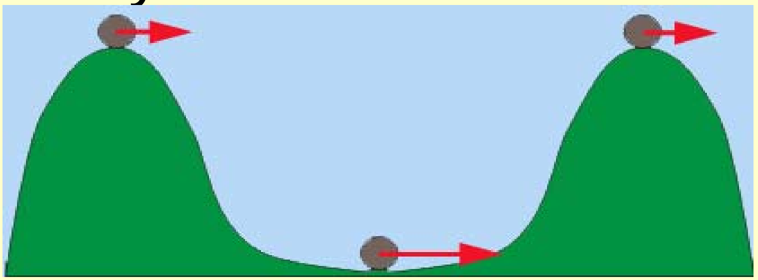
The Non-Integrated Sachs-Wolfe Effect

- The non-integrated Sachs-Wolfe effect takes place at the surface of last scattering and is a primary anisotropy.
- The photon frequency shifts result from the photons climbing out of the potential wells at the surface of last scattering created by the energy density in the universe at that point in time.
- The effect is not constant across the sky due to the perturbations in the energy density of the universe at the time the CMB was formed.

The non-integrated Sachs-Wolfe effect reveals information about the photons’ initial conditions

The Integrated Sachs-Wolfe Effect

- It appears as the photons pass through the universe on their way to Earth.



the photons encounter additional gravitational potentials and gain & lose energy.

one would expect these changes to cancel out over time, but the wells themselves can evolve, leading to a net change in energy for the photons as they travel.

- Why this is the integrated Sachs-Wolfe effect: the effect is integrated over the photon's total passage through the universe.

The integrated Sachs-Wolfe effect leaves evidence of the change of space as the photon traveled through it

The Integrated Sachs-Wolfe Effect

- **The early ISW effect:** takes place from the time following recombination to the time when radiation is no longer dominant

  The early ISW gives clues about what is happening in the universe at the time when radiation ceases to dominate the energy in the universe.

- **The late ISW effect:** gives clues about the end of the matter dominated era.

When matter gives way to DE, the gravitational potentials decay away. Photons travel much farther.

During the potential decay, the photons pass over many intervening regions of low and high density, effectively cancelling the late integrated Sachs-Wolfe effect out except at the very largest scales.

The late ISW effect has the unique ability to probe the

"size" of DE: **EOS,** the speed of sound …… **Bean, Dore, PRD(03)**

Perturbation theory when DE&DM are in interaction

Choose the perturbed spacetime

$$ds^2 = a^2\Big\{ -(1+2\phi)d\tau^2 + 2\partial_i B\, d\tau dx^i + \Big[(1-2\psi)\delta_{ij} + 2\partial_i\partial_j E\Big]dx^i dx^j\Big\}.$$

DE and DM, each with energy-momentum tensor $T^{\mu\nu}_{(\lambda);\mu} = Q^{\nu}_{(\lambda)}$

$Q^{\nu}_{(\lambda)}$ denotes the interaction between different components.

The perturbed energy-monentum tenser reads

$$\begin{aligned}
\delta T^{00} &= \frac{1}{a^2}(\delta\rho - 2\psi\rho) \\
\delta T^{i0} &= \frac{1}{a^2}[(p+\rho)V^i + p\partial^i B] \\
\delta T^{ij} &= \frac{1}{a^2}[\delta p\delta^{ij} - p(2\phi\delta^{ij} + D^{ij}E)] \\
\delta T^{0i} &= \delta T^{i0}
\end{aligned}$$

,

Perturbation Theory

The perturbed Einstein equations

$$\delta g_\mu^\nu \Longrightarrow \delta R_\mu^\nu \Longrightarrow \delta G_\mu^\nu \qquad\qquad \delta T_\mu^\nu$$

$$\Downarrow \qquad\qquad\qquad \Downarrow$$

$$\nabla^2\phi + 3\mathcal{H}\left(\mathcal{H}\psi - \phi'\right) + \mathcal{H}\nabla^2 B - \frac{1}{6}[\nabla^2]^2 E = -4\pi G a^2 \delta\rho$$

$$\mathcal{H}\nabla^2\psi - \nabla^2\phi' + 2\mathcal{H}^2\nabla^2 B - \frac{a''}{a}\nabla^2 B + \frac{1}{6}[\nabla^2]^2 E' = -4\pi G a^2(\rho + p)\theta$$

$$-\partial^i\partial_j\psi - \partial^i\partial_j\phi + \frac{1}{2}\partial^i\partial_j E'' + \mathcal{H}\partial^i\partial_j E' + \frac{1}{6}\partial^i\partial_j\nabla^2 E - 2\mathcal{H}\partial^i\partial_j B - \partial^i\partial_j B' = 8\pi G a^2 \Pi^i_j$$

$$2\mathcal{H}\psi' + 4\frac{a''}{a}\psi - 2\mathcal{H}^2\psi + \frac{2}{3}\nabla^2\psi + \frac{2}{3}\nabla^2\phi - 4\mathcal{H}\phi' - 2\phi'' + \frac{4}{3}\mathcal{H}\nabla^2 B + \frac{2}{3}\nabla^2 B' - \frac{1}{9}[\nabla^2]^2 E = 8\pi G a^2 \delta p$$

Perturbation Theory

The perturbed equations of motion

$$\delta\nabla_\mu T^{\mu\nu} = \partial_\mu \delta T^{\mu\nu} + \delta\Gamma^\mu_{\mu\tau} T^{\tau\nu} + \Gamma^\mu_{\mu\tau}\delta T^{\tau\nu} + \delta\Gamma^\nu_{\mu\tau} T^{\mu\tau} + \Gamma^\nu_{\mu\tau}\delta T^{\mu\tau} = \delta Q^\nu$$

Zeroth component

$$\begin{aligned}\delta\nabla_\mu T^{\mu 0}_{(\lambda)} &= \frac{1}{a^2}\{-2[\rho'_\lambda + 3\mathcal{H}(p_\lambda+\rho_\lambda)]\psi + \delta\rho'_\lambda + (p_\lambda+\rho_\lambda)\theta_\lambda + 3\mathcal{H}(\delta p_\lambda + \delta\rho_\lambda) + 3(p_\lambda+\rho_\lambda)\phi'\} \\ &= \delta Q^0_\lambda\end{aligned}$$

i-th component

$$\begin{aligned}\partial_i\delta\nabla_\mu T^{\mu i}_{(\lambda)} &= \frac{1}{a^2}\{[p'_\lambda + \mathcal{H}(p_\lambda+\rho_\lambda)]\nabla^2 B + [(p'_\lambda+\rho'_\lambda) + 4\mathcal{H}(p_\lambda+\rho_\lambda)]\theta_\lambda \\ &\quad +(p_\lambda+\rho_\lambda)\nabla^2 B' + \nabla^2\delta p_\lambda + (p_\lambda+\rho_\lambda)\theta'_\lambda + (p_\lambda+\rho_\lambda)\nabla^2\psi\} = \partial_i\delta Q^i_{(\lambda)}\end{aligned}$$

The perturbed pressure of DE:

$$\delta p_d = C_e^2\delta_d\rho_d + (C_e^2 - C_a^2)\left[\frac{3\mathcal{H}(1+w)V_d\rho_d}{k} - a^2 Q_d^0\frac{V_d}{k}\right]$$

C_e^2 is the sound speed in the rest frame, C_a^2 is the adiabatic sound speed,

(He, Wang, Jing JCAP0907,030(2009))

Perturbation Theory

$$\delta\nabla_\mu T^\mu_\nu = \delta Q_\nu$$

DM:

$$D'_{gc} + \left\{ \left(\frac{a^2 Q_c^0}{\rho_c \mathcal{H}} \right)' + \frac{\rho'_c}{\rho_c \mathcal{H}} \frac{a^2 Q_c^0}{\rho_c} \right\} \Phi + \frac{a^2 Q_c^0}{\rho_c} D_{gc} + \frac{a^2 Q_c^0}{\rho_c \mathcal{H}} \Phi'$$

$$= -kV_c + 2\Psi \frac{a^2 Q_c^0}{\rho_c} + \frac{a^2 \delta Q_c^{0I}}{\rho_c} + \frac{a^2 Q_c^{0'}}{\rho_c \mathcal{H}} \Phi - \frac{a^2 Q_c^0}{\rho_c} \left(\frac{\Phi}{\mathcal{H}} \right)'$$

$$V'_c + \mathcal{H} V_c = k\Psi - \frac{a^2 Q_c^0}{\rho_c} V_c + \frac{a^2 \delta Q_{pc}^I}{\rho_c}$$

DE:

$$D'_{gd} + \left\{ \left(\frac{a^2 Q_d^0}{\rho_d \mathcal{H}} \right)' - 3w' + 3(C_e^2 - w) \frac{\rho'_d}{\rho_d} + \frac{\rho'_d}{\rho_d \mathcal{H}} \frac{a^2 Q_d^0}{\rho_d} \right\} \Phi + \left\{ 3\mathcal{H}(C_e^2 - w) + \frac{a^2 Q_d^0}{\rho_d} \right\} D_{gd} + \frac{a^2 Q_d^0}{\rho_d \mathcal{H}} \Phi'$$

$$= -(1+w)kV_d + 3\mathcal{H}(C_e^2 - C_a^2) \frac{\rho'_d}{\rho_d} \frac{V_d}{k} + 2\Psi \frac{a^2 Q_d^0}{\rho_d} + \frac{a^2 \delta Q_d^{0I}}{\rho_d} + \frac{a^2 Q_d^{0'}}{\rho_d \mathcal{H}} \Phi - \frac{a^2 Q_d^0}{\rho_d} \left(\frac{\Phi}{\mathcal{H}} \right)'$$

$$V'_d + \mathcal{H}(1-3w) V_d = \frac{kC_e^2}{1+w} D_{gd} + \frac{kC_e^2}{1+w} \frac{\rho'_d}{\rho_d \mathcal{H}} \Phi - (C_e^2 - C_a^2) \frac{V_d}{1+w} \frac{\rho'_d}{\rho_d} - \frac{w'}{1+w} V_d + k\Psi - \frac{a^2 Q_d^0}{\rho_d} V_d + \frac{a^2 \delta Q_{pd}^I}{\rho_d}$$

Perturbation Theory

$$\delta G_\mu^\nu = 8\pi G \delta T_\mu^\nu$$

The curvature perturbation relates to density contrast

$$\Phi = \frac{4\pi G a^2 \sum \rho_i \{D_g^i + 3\mathcal{H}U^i/k\}}{k^2 - 4\pi G a^2 \sum \rho_i'/\mathcal{H}}$$

We assume the phenomenological description of the interaction Between dark sectors in the comoving frame as,

$$Q_c^\nu = \left[\frac{3\mathcal{H}}{a^2}(\xi_1\rho_c + \xi_2\rho_d), 0, 0, 0\right]^T$$

$$Q_d^\nu = \left[-\frac{3\mathcal{H}}{a^2}(\xi_1\rho_c + \xi_2\rho_d), 0, 0, 0\right]^T$$

Perturbations

Special cases:

$$(1)\ Q=\delta H(\rho_{DM}+\rho_{DE}),\ (2)\ Q=\delta H\rho_{DM}\ \text{and}\ (3)\ Q=\delta H\rho_{DE}$$

Perturbation equations:

$$\begin{aligned}
D_m' &= -kU_m+6\mathcal{H}\Psi(\lambda_1+\lambda_2/r)-3(\lambda_1+\lambda_2/r)\Phi'+3\mathcal{H}\lambda_2(D_d-D_m)/r \quad ,\\
U_m' &= -\mathcal{H}U_m+k\Psi-3\mathcal{H}(\lambda_1+\lambda_2/r)U_m \quad ,\\
D_d' &= -3\mathcal{H}C_e^2\left\{D_d-[3(\lambda_1 r+\lambda_2)+3(1+w)]\,\Phi\right\}-3\mathcal{H}(C_e^2-C_a^2)\left[\frac{3\mathcal{H}U_d}{k}-a^2Q_d^0\frac{U_d}{(1+w)\rho_d k}\right]\\
&\quad -3\mathcal{H}w\,[3(\lambda_1 r+\lambda_2)+3(1+w)]\,\Phi+3\mathcal{H}wD_d+3w'\Phi+3(\lambda_1 r+\lambda_2)\Phi'-kU_d-6\Psi\mathcal{H}(\lambda_1 r+\lambda_2)\\
&\quad +3\mathcal{H}\lambda_1 r(D_d-D_m)\\
U_d' &= -\mathcal{H}(1-3w)U_d+kC_e^2\left\{D_d-3[(\lambda_1 r+\lambda_2)+(1+w)]\Phi\right\}\\
&\quad -(C_e^2-C_a^2)a^2Q_d^0\frac{U_d}{(1+w)\rho_d}+3(C_e^2-C_a^2)\mathcal{H}U_d+(1+w)k\Psi+3\mathcal{H}(\lambda_1 r+\lambda_2)U_d.
\end{aligned}$$

Perturbations

Assuming: $C_e^2 = 1,\ C_a^2 = w,$

$$
\begin{aligned}
D_d' &= (-1 + w + \lambda_1 r) 3\mathcal{H} D_d - 9\mathcal{H}^2 (1-w)(1 + \frac{\lambda_1 r + \lambda_2}{1+w}) \frac{U_d}{k} - kU_d + 9\mathcal{H}(1-w)(\lambda_1 r + \lambda_2 + 1 + w)\Phi \\
&\quad + 3(\lambda_1 r + \lambda_2)\Phi' - 6\Psi\mathcal{H}(\lambda_1 r + \lambda_2) - 3\mathcal{H}\lambda_1 r D_m \quad , \\
U_d' &= 2\left\{1 + \frac{3}{1+w}(\lambda_1 r + \lambda_2)\right\}\mathcal{H} U_d + kD_d - 3k(\lambda_1 r + \lambda_2 + 1 + w)\Phi + (1+w)k\Psi \quad .
\end{aligned}
$$

By using the gauge-invariant quantity $\zeta = \phi - \mathcal{H}\delta\tau$ and letting $\zeta_m = \zeta_d = \zeta$

the adiabatic initial condition, $$\frac{D_m}{1 - \lambda_1 - \lambda_2/r} = \frac{D_d}{1 + w + \lambda_1 r + \lambda_2}$$

The curvature perturbation relates to density contrast

$$\Phi = \frac{4\pi G a^2 \sum \rho_i \{D_g^i - \rho_i' U_i/\rho_i(1+w_i)k\}}{k^2 - 4\pi G a^2 \sum \rho_i'/\mathcal{H}}$$

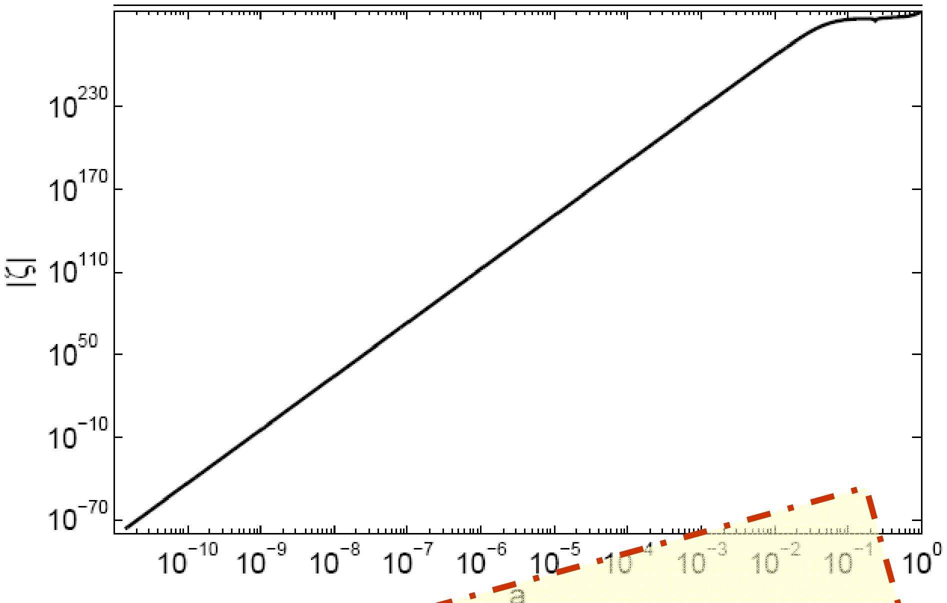
Perturbations

Choosing interactions

$$(1)\ Q = \delta H(\rho_{DM} + \rho_{DE}),\ (2)\ Q = \delta H \rho_{DM}$$

W>-1

Maartens et al, JCAP(08)



Curvature perturbation is not stable!

Is this result general?

How about the other forms of the interaction? Stable??

How about the case with w<-1?

Perturbations

$$
\begin{aligned}
D'_d &= (-1+w+\lambda_1 r)3\mathcal{H}D_d - 9\mathcal{H}^2(1-w)\left(1+\frac{\lambda_1 r+\lambda_2}{1+w}\right)\frac{U_d}{k} - kU_d + 9\mathcal{H}(1-w)(\lambda_1 r+\lambda_2+1+w)\Phi \\
&+3(\lambda_1 r+\lambda_2)\Phi' - 6\Psi\mathcal{H}(\lambda_1 r+\lambda_2) - 3\mathcal{H}\lambda_1 r D_m \quad , \\
U'_d &= 2\left\{1+\frac{3}{1+w}(\lambda_1 r+\lambda_2)\right\}\mathcal{H}U_d + kD_d - 3k(\lambda_1 r+\lambda_2+1+w)\Phi + (1+w)k\Psi \quad .
\end{aligned}
$$

$\lambda_1 \neq 0$ divergence

$\lambda_1 = 0,\ \lambda_2 \neq 0$ divergence disappears

the interaction proportional to DE density

W>-1

W<-1, always

Stable perturbation

couplings	DE	DM	Total
W>-1	Stable	Unstable	Unstable
W<-1	Stable	Stable	Stable

J.He, B.Wang, E.Abdalla, PLB(09)

ISW imprint of the interaction

The analytical descriptions for such effect

$$C_l^{ISW} = 4\pi \int \frac{d^3k}{(2\pi)^3} P_\psi(k) \mid \int_{\tau_i}^{\tau_0} d\tau j_l(k[\tau_0 - \tau]) e^{\kappa(\tau_0)-\kappa(\tau)} [\Psi' - \Phi'] \mid^2$$

where $P_\psi(k)$ is the power spectrum of the primordial coverture perturbation. j_l is the spherical Bessel functions. κ denotes the optical depth for Thompson scattering.From Einstein's equations,we obtain,

$$\Psi' - \Phi' = -2\Phi' - \mathcal{T}' = 2\mathcal{H}\left\{\Phi + 4\pi G a^2 \sum V^i(p^i + \rho^i)/(\mathcal{H}k) + \mathcal{T}\right\} - \mathcal{T}'$$

$$\Phi' = -\mathcal{H}\Phi - \mathcal{H}\mathcal{T} - 4\pi G a^2 \sum V^i(p^i + \rho^i)/k$$

$$\Phi = \frac{4\pi G a^2 \sum \rho_i \{D_g^i + 3\mathcal{H}U^i/k\}}{k^2 - 4\pi G a^2 \sum \rho_i'/\mathcal{H}}$$

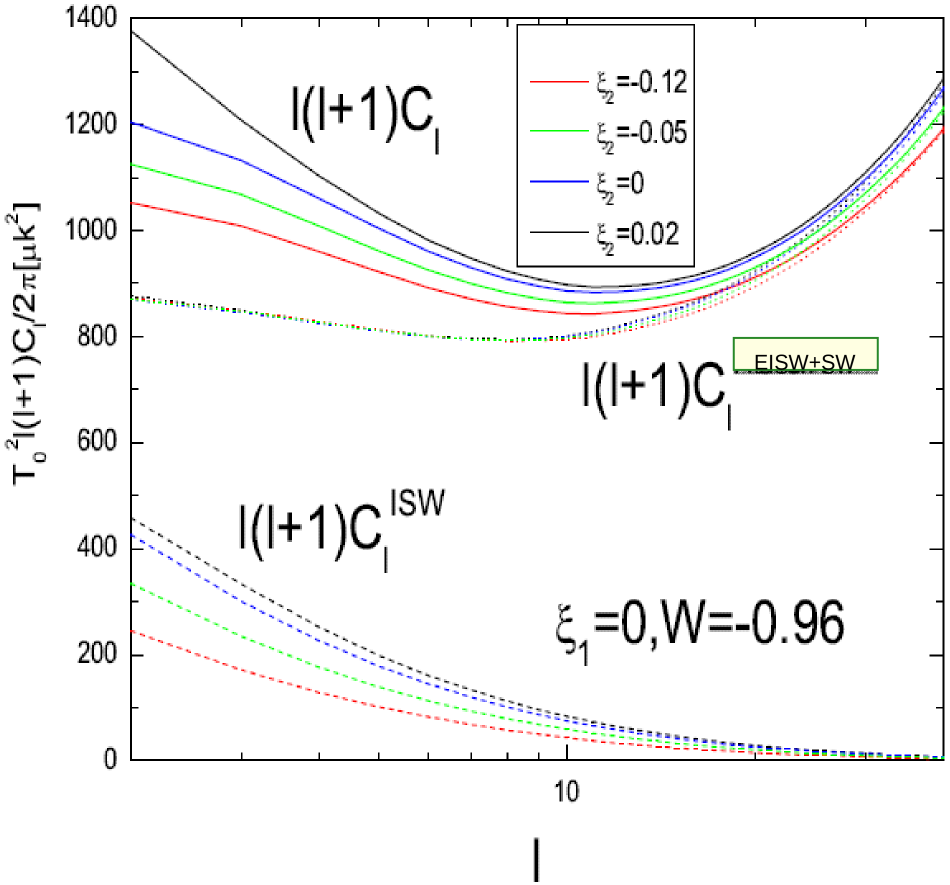
ISW effect is not simply due to the change of the CDM perturbation. The interaction enters each part of gravitational potential.

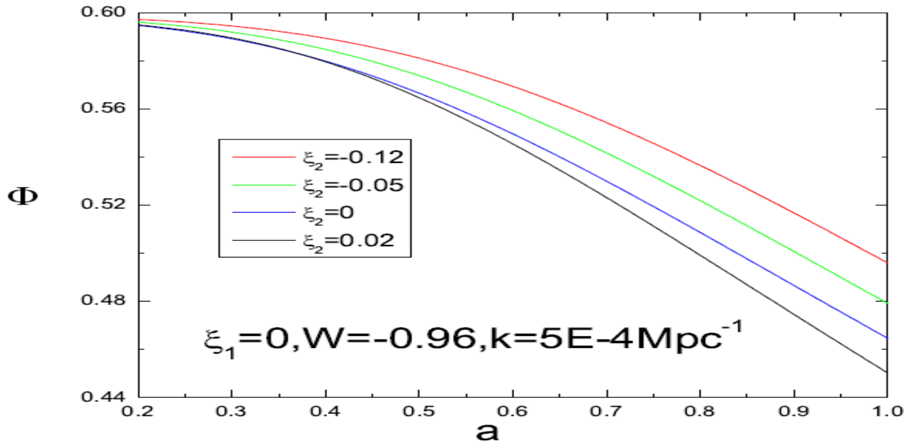
J.H. He, B.Wang, P.J.Zhang, PRD(09)

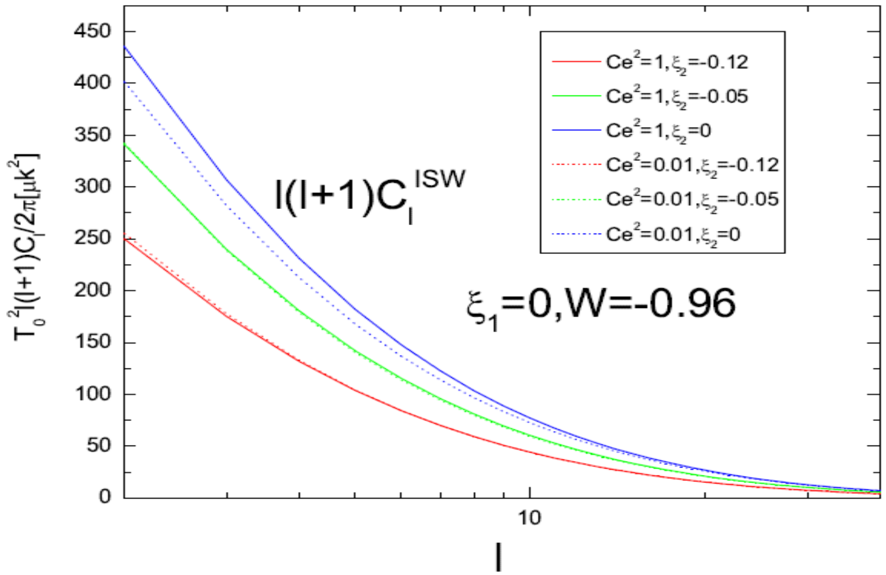
ISW imprint of the interaction

- Interaction proportional to the energy density of DE

W>-1



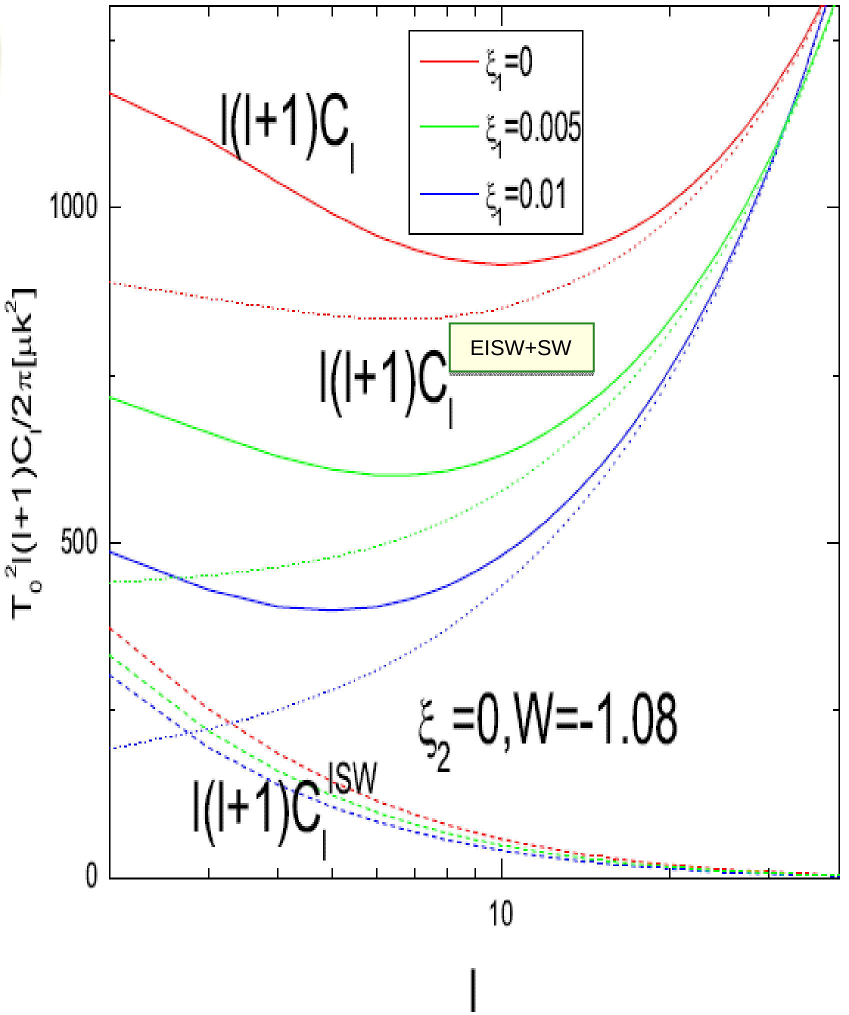


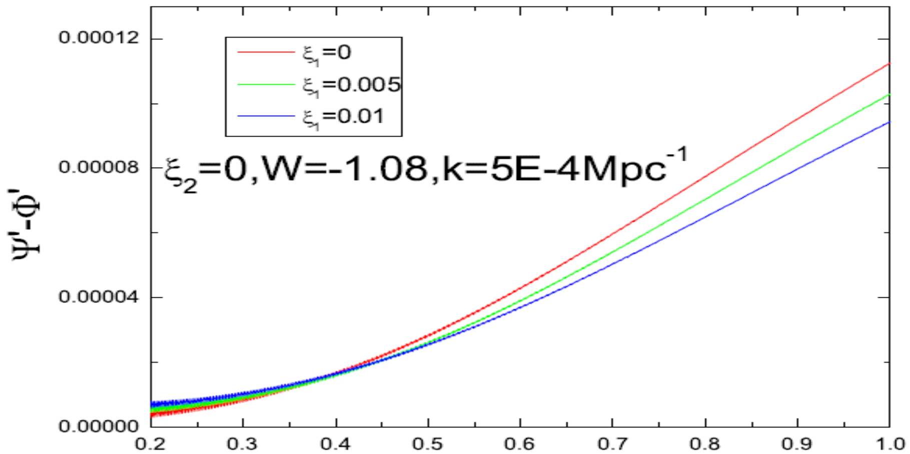


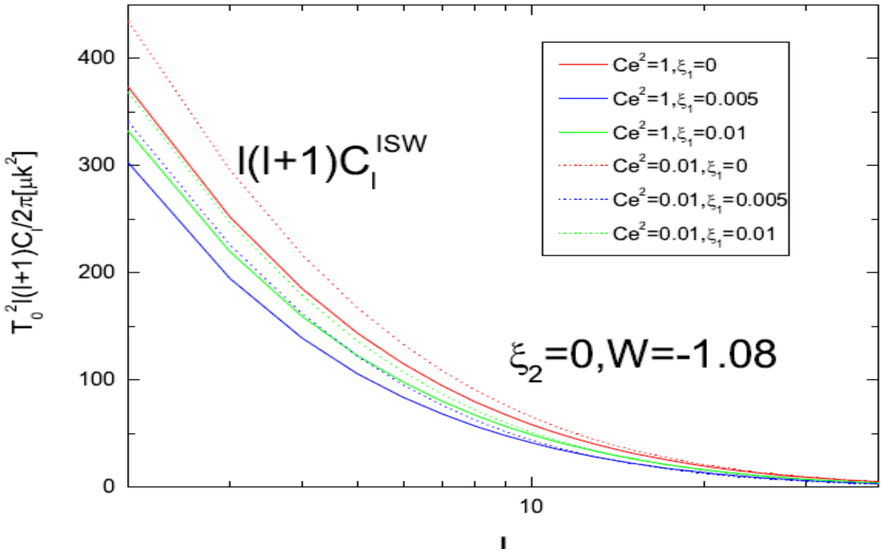
ISW imprint of the interaction

- Interaction proportional to the energy density of DM

W<-1



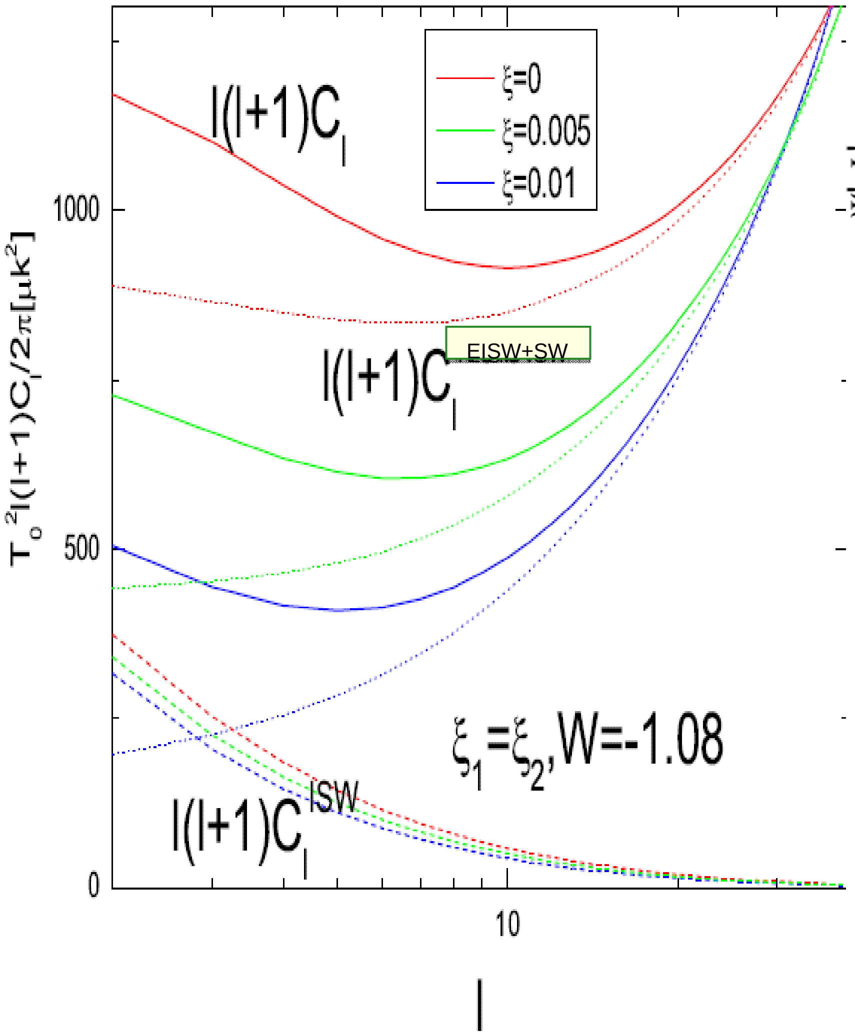


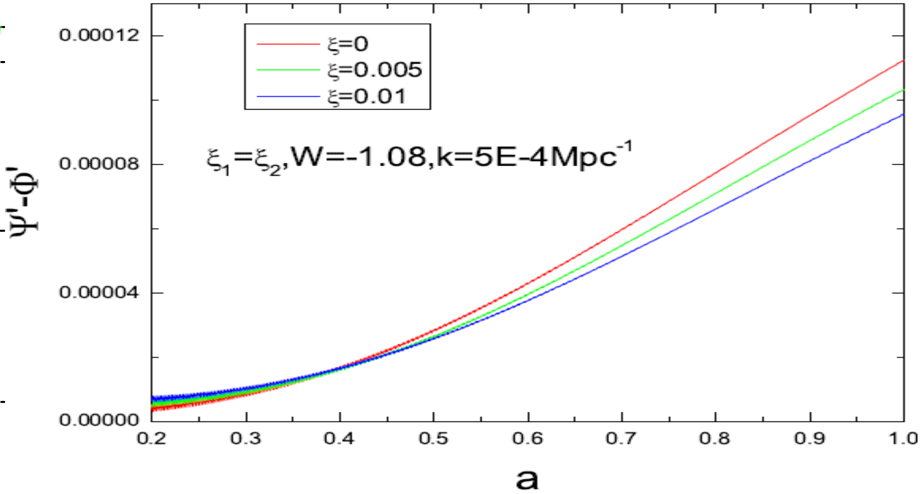


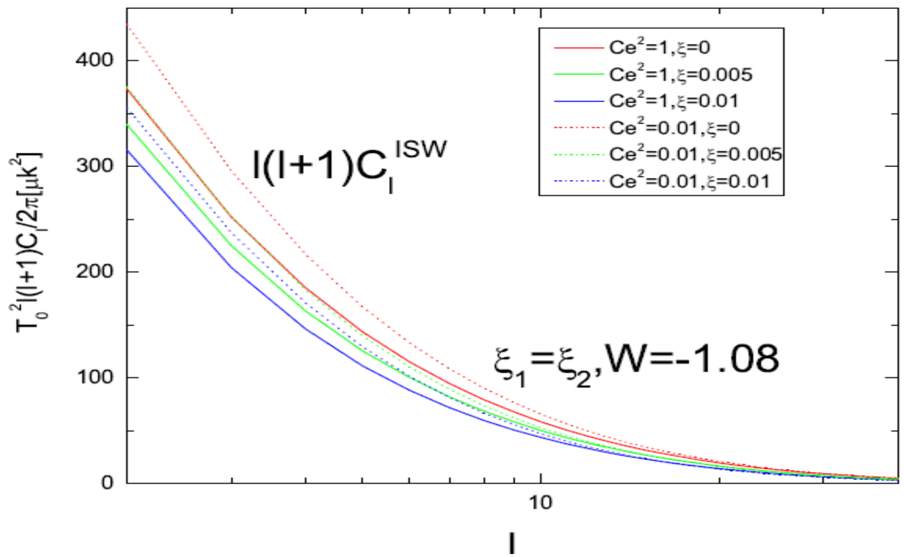
ISW imprint of the interaction

- Interaction proportional to the energy density of DE+DM

W<-1







Global fitting results

- WMAP5+BOOMERanG,CBI,VSA,ACBAR
- SDSS

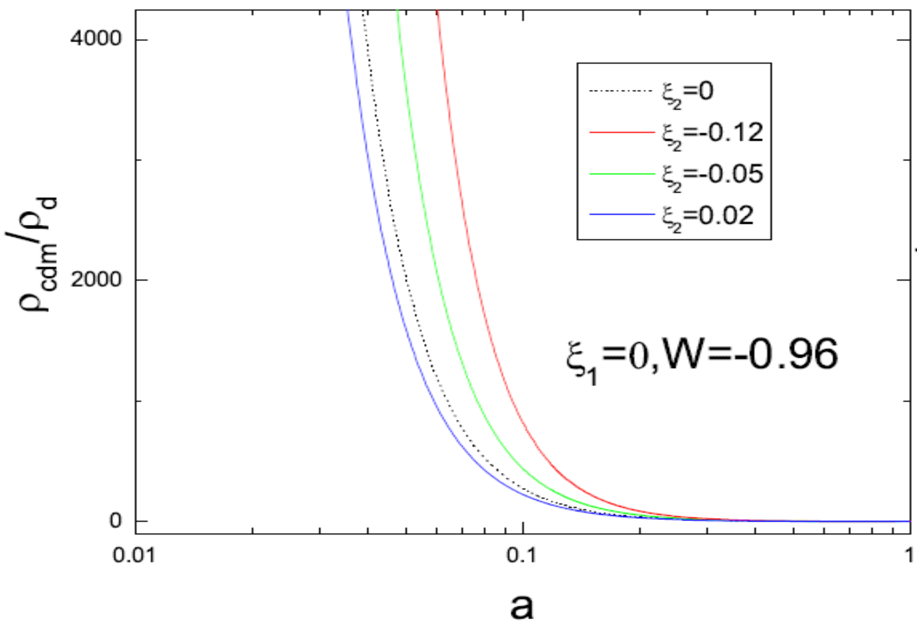
Interaction proportional to the energy density of DE

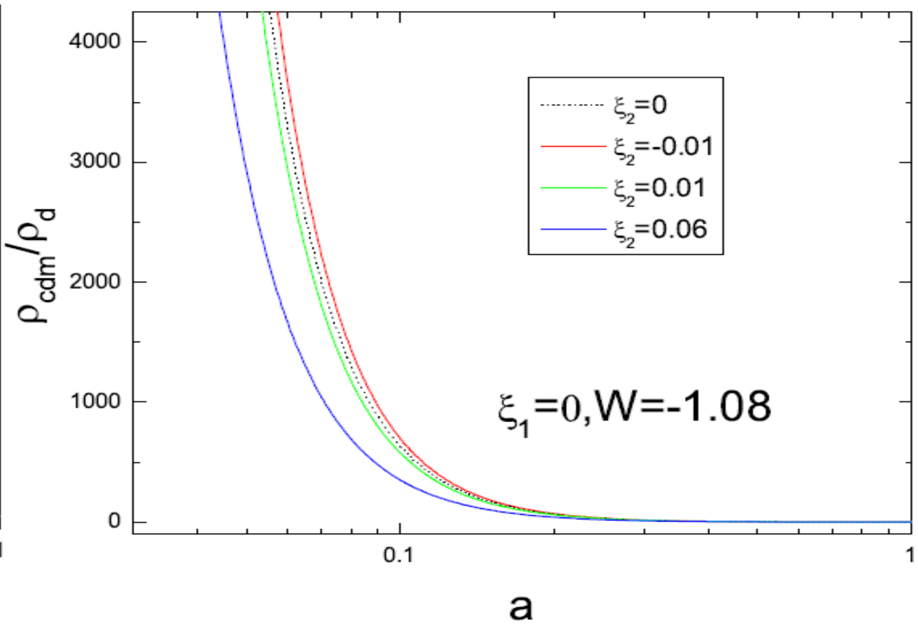
W>-1

h	$\Omega_b h^2$	$\Omega_{cdm} h^2$	τ	$\ln[10^{10}A_s]$	n_s	$\xi_1=0,\xi_2\neq 0$	$1+w>0$
$0.687^{+0.013}_{-0.013}$	$0.0225^{+0.0006}_{-0.0005}$	$0.107^{+0.007}_{-0.009}$	$0.091^{+0.017}_{-0.016}$	$3.109^{+0.033}_{-0.031}$	$0.963^{+0.013}_{-0.013}$	$-0.028^{+0.023}_{-0.032}$	<0.052

W<-1

h	$\Omega_b h^2$	$\Omega_{cdm} h^2$	τ	$\ln[10^{10}A_s]$	n_s	$\xi_1=0,\xi_2\neq 0$	$1+w<0$
$0.700^{+0.012}_{-0.011}$	$0.0223^{+0.0006}_{-0.0005}$	$0.119^{+0.009}_{-0.006}$	$0.086^{+0.019}_{-0.016}$	$3.105^{+0.033}_{-0.032}$	$0.956^{+0.013}_{-0.014}$	$-0.010^{+0.025}_{-0.020}$	$-0.051^{+0.051}_{-0.043}$





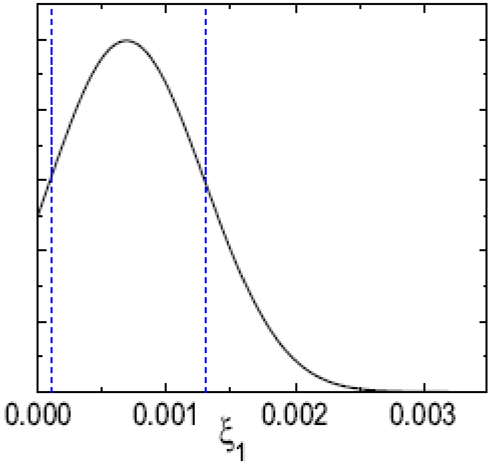
Global fitting results

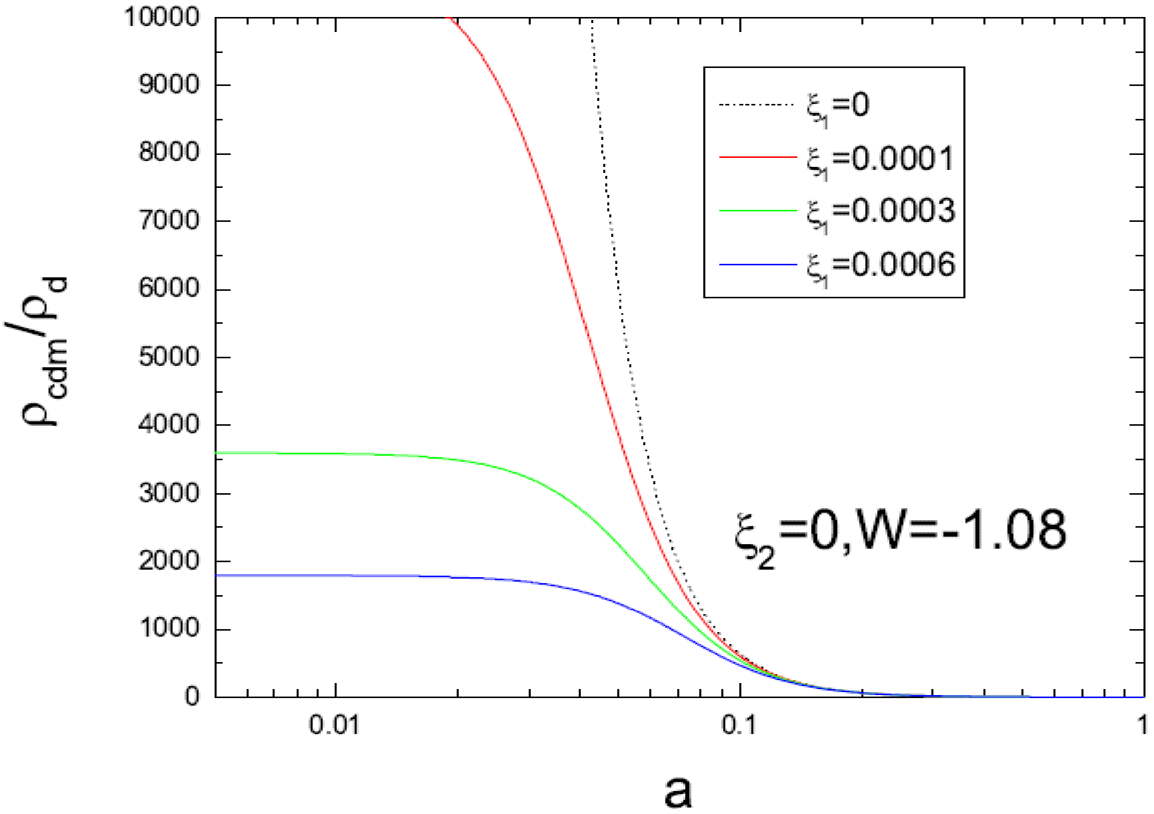
WMAP5+BOOMERanG,CBI,VSA,ACBAR

SDSS

Interaction proportional to the energy density of DM

h	$\Omega_b h^2$	$\Omega_{cdm} h^2$	τ	$\ln[10^{10} A_s]$	n_s	$\xi_1 > 0, \xi_2 = 0$	$1+w<0$
$0.690^{+0.015}_{-0.015}$	$0.0224^{+0.0005}_{-0.0005}$	$0.121^{+0.003}_{-0.003}$	$0.094^{+0.016}_{-0.017}$	$3.115^{+0.034}_{-0.033}$	$0.953^{+0.013}_{-0.013}$	$0.0007^{+0.0006}_{-0.0006}$	$-0.072^{+0.072}_{-0.053}$



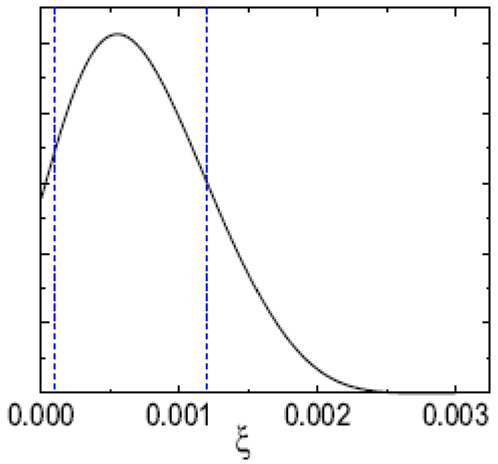


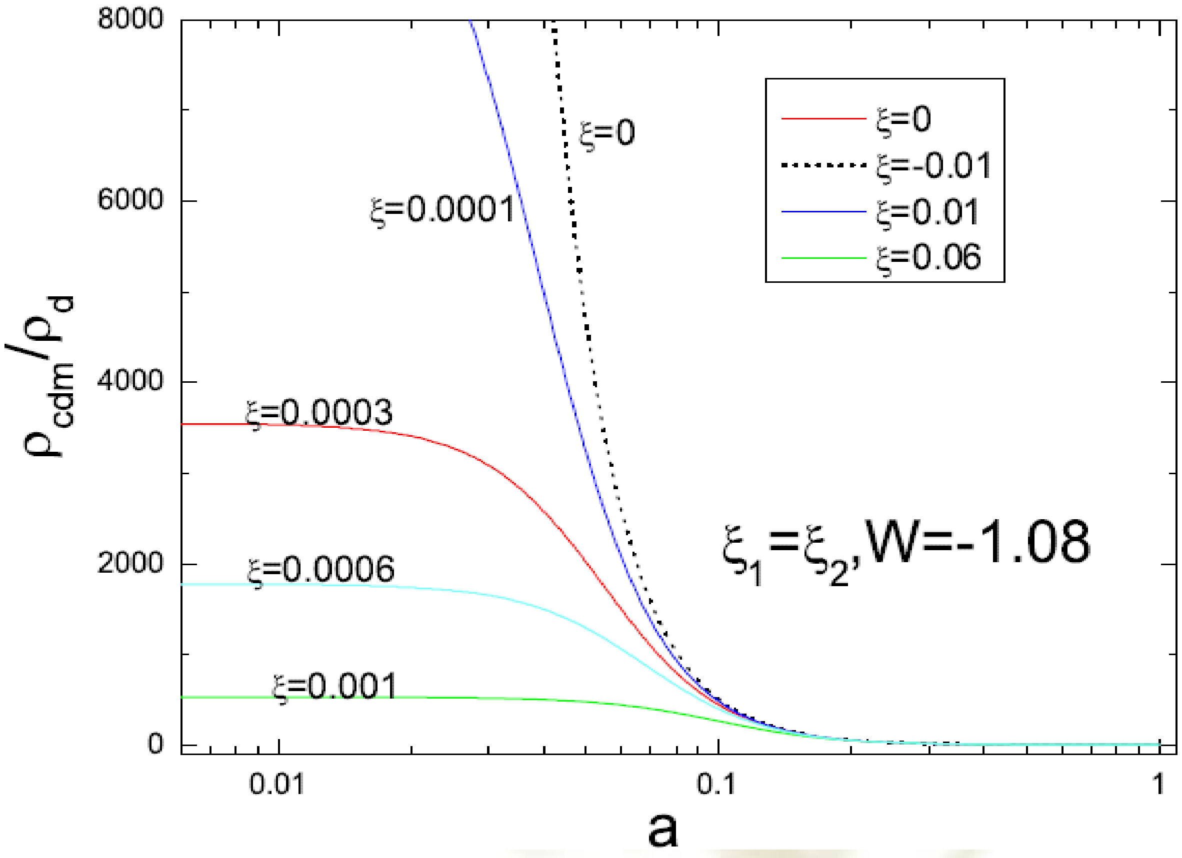
J.H. He, B.Wang, P.J.Zhang, PRD(09)

Global fitting results

Interaction proportional to the energy density of DE+DM

h	$\Omega_b h^2$	$\Omega_{cdm} h^2$	τ	$\ln[10^{10} A_s]$	n_s	$\xi = \xi_1 = \xi_2 > 0$	$1 + w < 0$
$0.690^{+0.014}_{-0.014}$	$0.0224^{+0.0006}_{-0.0006}$	$0.121^{+0.004}_{-0.003}$	$0.093^{+0.018}_{-0.017}$	$3.114^{+0.036}_{-0.033}$	$0.955^{+0.014}_{-0.014}$	$0.0006^{+0.0006}_{-0.0005}$	$-0.065^{+0.065}_{-0.054}$





To reduce the uncertainty and put tighter constraint on the value of the coupling between DE and DM, new observables should be added.

Galaxy cluster scale test

E. Abdalla, L.Abramo, L.Sodre, B.Wang, PLB(09) arXiv:0710.1198

Growth factor of the structure formation

J.He, B.Wang, Y.P.Jing, arXiv:0902.0660

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Argument from the dynamics of glaxay clusters for Q>0

- Phenomenology of coupled DE and DM

$$\begin{aligned} \dot{\rho}_{dm} + 3H\rho_{dm} &= \psi \\ \dot{\rho}_{de} + 3H\rho_{de}(1+w_{de}) &= -\psi\,, \end{aligned} \qquad \psi = \zeta H \rho_{tot}\,.$$

Collapsed structure: the local inhomogeneous density σ is far from the average homogeneous density ρ.

The continuity equation for DM reads

$$\dot{\sigma}_{dm} + 3H\sigma_{dm} + \vec{\nabla}\left(\sigma_{dm}\vec{v}_{dm}\right) = \zeta H\left(\sigma_{dm} + \sigma_{de}\right)$$

$\vec{v}_{dm}$ the peculiar velocity of DM particles.

Considering: $\sigma_{de} = b_{em}\sigma_{dm}$

the continuity equation with DM coupled to DE reads

$$\dot{\sigma}_{dm} + 3H\sigma_{dm} + \vec{\nabla}\left(\sigma_{dm}\vec{v}_{dm}\right) = \bar{\zeta} H \sigma_{dm}\,, \qquad \bar{\zeta} = \zeta(1+b_{em}).$$

Argument from the dynamics of glaxay clusters for Q>0

- Equilibrium condition for collapsed structure in the expanding universe ---Newtonian mechanics

The acceleration due to gravitational force is given by

$$(a\,\vec{v}_{dm})^{\cdot} = -a\,\vec{\nabla}\varphi\,,$$

φ is the (Newtonian) gravitational potential.

Multiplying both sides of this equation by $\sigma_{dm} a \vec{v}_{dm}$, integrating over the volume and using continuity equation,

LHS: $(a^2 K_{dm})^{\cdot} - a^2 \bar{\zeta} H K_{dm}\,,\quad K_{dm} = \frac{1}{2}\int \vec{v}^{\,2}_{dm}\sigma_{dm} dV$ kinetic energy of DM

RHS: $(1+b_{em})\left[-a^2\left(\dot{U}_{dm} + HU_{dm}\right) + 2\bar{\zeta} H a^2 U_{dm}\right]$

where $U_{dm} = -\frac{1}{2}G\int\int \frac{\sigma_{dm}(x)\sigma_{dm}(x')}{|x-x'|} dV\, dV'$

Potential energy of a distribution of DM particles

LHS=RHS the generalization of the Layzer-Irvine equation:
how a collapsing system reaches dynamical equilibrium in an expanding universe.

Argument from the dynamics of glaxay clusters for Q>0

- Virial condition:

For a system in equilibrium $(\dot{K}_{dm} = \dot{U}_{dm} = 0)$

$$(2 - \bar{\zeta})K_{dm} + (1 + b_{em})(1 - 2\bar{\zeta})U_{dm} = 0\ .$$

Taking $\bar{\zeta} = b_{em} = 0$ $\quad 2K + U = 0$

Layzer-Irvine equation describing how a collapsing system reaches a state of dynamical equilibrium in an expanding universe.

presence of the coupling between DE and DM changes the time required by the system to reach equilibrium,

Condition for a system in equilibrium

presence of the coupling between DE and DM changes the equilibrium configuration of the system

E. Abdalla, L.Abramo, L.Sodre, B.Wang, arXiv:0710.1198

Argument from the dynamics of glaxay clusters for Q>0

- Galaxy clusters are the largest virialized structures in the universe
- Ways in determining cluster masses:
  - Weak lensing: use the distortion in the pattern of images behind the cluster to compute the projected gravitational potential due to the cluster. D-cluster+D-background images $\longrightarrow$ mass cause the potential
  - X-ray: determine electrons number density and temperature. If the ionized gas is in hydrostatic equilibrium, M can be determined by the condition that the gas is supported by its pressure and gravitational attraction
  - Optical measurement: assuming cluster is virialized, M~U/K

$$(1 + b_{em})\frac{U_{dm}}{K_{dm}} = -2\frac{1-\bar{\zeta}/2}{1-2\bar{\zeta}}\,.$$

The M got by assuming $\bar{\zeta} = 0$ will be biased by a factor $(1 - 2\bar{\zeta})/(1 - \bar{\zeta}/2)$.

Argument from the dynamics of glaxay clusters for Q>0

- Comparing the mass estimated through naïve virial hypothesis with that from WL and X-ray, we get

$$M_{vir} = \frac{1-\bar{\zeta}/2}{1-2\bar{\zeta}} M_X = \frac{1-\bar{\zeta}/2}{1-2\bar{\zeta}} M_{WL}$$

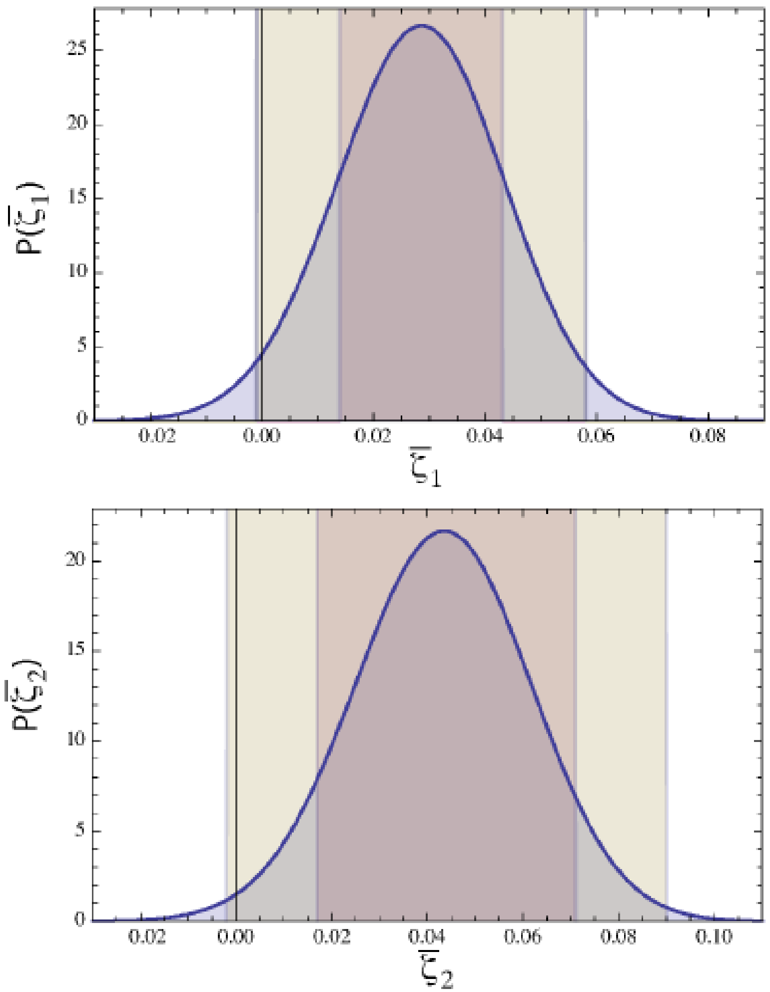
There are three tests one can make:

$$\begin{aligned} f_1 &= M_X / M_{vir} \ , \\ f_2 &= M_{WL} / M_{vir} \ , \\ f_3 &= M_X / M_{WL} \ . \end{aligned}$$

f1 and f2, should agree with each other, and put limits on the coupling parameter $\bar{\zeta}$.

f3, is a check on the previous two, and should be equal to one unless there are unknown systematics in the X-ray and weak lensing methods.

Argument from the dynamics of glaxay clusters for Q>0



Best-fit value $\bar{\zeta} \sim 0.03 - 0.04$

Indicating a weak preference for a small but positive coupling
DE → DM

Consistent with other tests

33 galaxy clusters optical, X-ray and weak lensing data

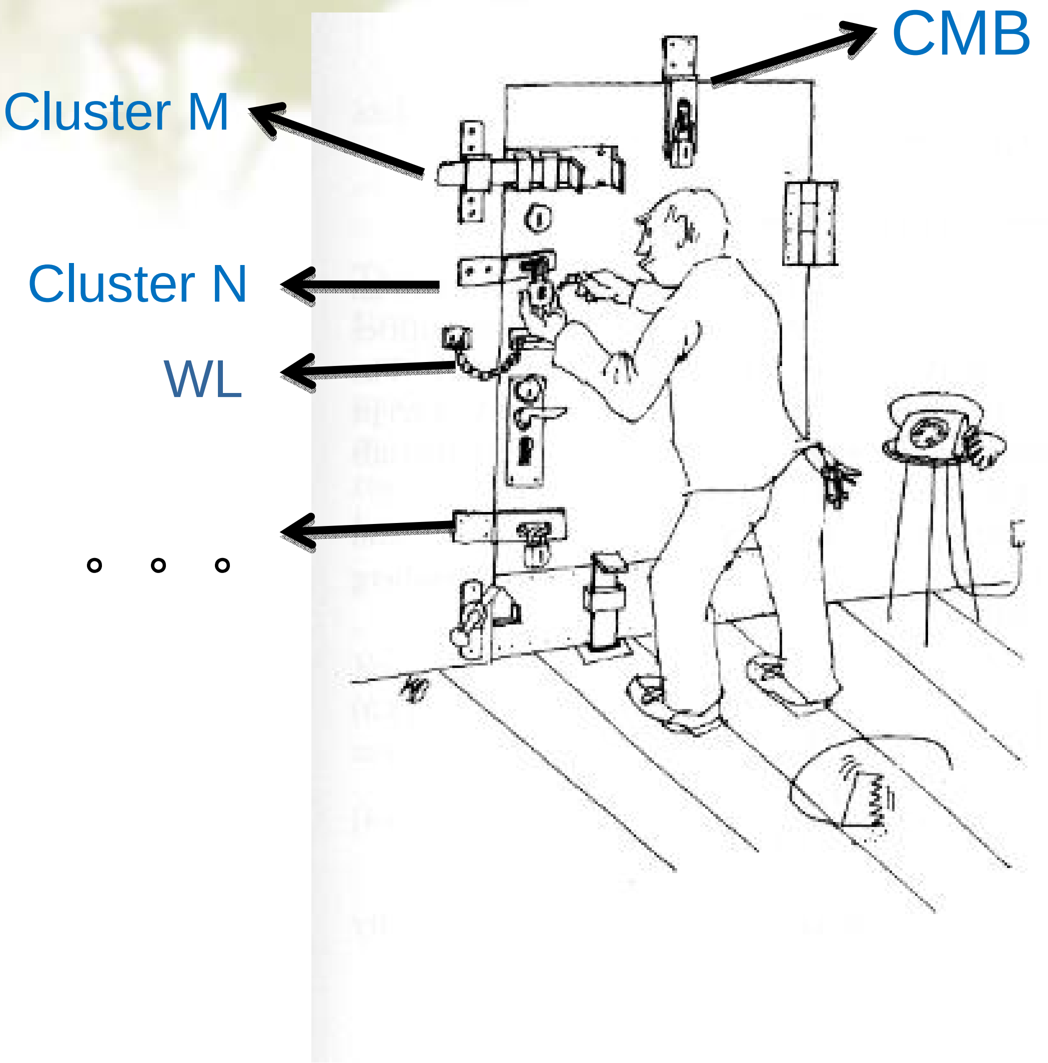
E. Abdalla, L.Abramo, L.Sodre, B.Wang, PLB (09) arXiv:0710.1198

DE interacting DM will influence:

- the dynamics of structure formation
- the number of galaxy clusters formed

The imprint of the interaction between dark sectors in galaxy clusters
Authors: Jian-Hua He, Bin Wang, Elcio Abdalla, Diego Pavon
arXiv:1001.0079

A lot of effort is required to disclose the signature on the interaction between DE and DM



Understanding the interaction between DE and DM from Field Theory

S. Micheletti, E. Abdalla, B. Wang, PRD(09)

Summary

- **Is there any interaction between DE & DM?**

  SN constraint

  CMB

  BAO

  Age constraints

  Galaxy cluster scale test

- **Q > 0 the energy proceeds from DE to DM**

  consistent with second law

  allowed by observations

- **Alleviate the coincidence problem**
- **Perturbation theory and growth of structure**
- **Understanding the interaction from field theory and thermodynamics**

- **Thanks!!!**