Can kinetic Sunyaev-Zel'dovich effect be used to detect the interaction between DE and DM?

Bin Wang

Shanghai Jiao Tong University

Outline:

- The interaction model between DE&DM
- The ISW effect as a probe of the interaction
- Probing the interaction with peculiar velocities
- The kinetic Sunyaev-Zel'dovich effect as a new

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)

95% Unknown: 25% DM+70% DE

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?

Λ is not the end story to account for the cosmic acceleration

Reason for proposing Quintessence, tachyon field, Chaplygin gas models etc.

No clear winner in sight

Suffer fine-tuning

Why do we need the interaction between DE&DM?

- A phenomenological generalization of the LCDM model is

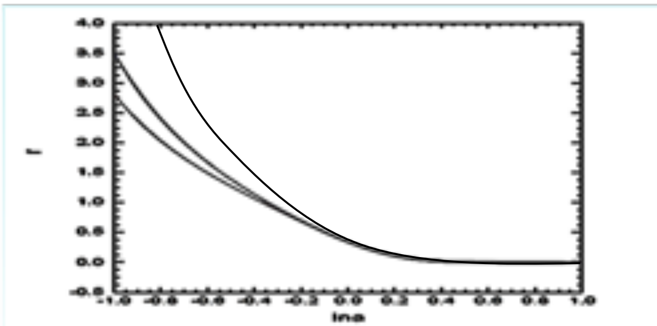
$$\frac{\rho_M}{\rho_X} = r_0 \left(\frac{a_0}{a}\right)^{\beta}$$

$\beta = 3$ LCDM model,

$\beta = 0$ Stationary ratio of energy densities

$\beta < 3$ 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

$\beta < 3$ 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

 $-1.5 \leq w_{eff} \leq -0.7$

 WMAP: 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 a**

 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

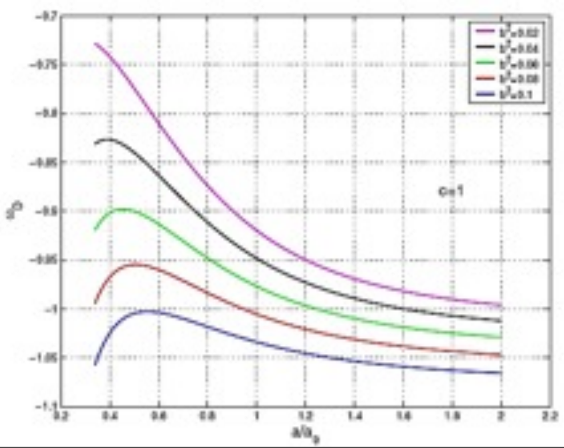
2) Another option: Interaction between DE and DM

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.



Interaction

70% DE

25% DM

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25% DM

Motivations to introduce the interaction between DE and DM:

1. Alleviate the coincidence problem
2. Accommodate the DE with w<-1
3. Relate to the study of the modified gravity

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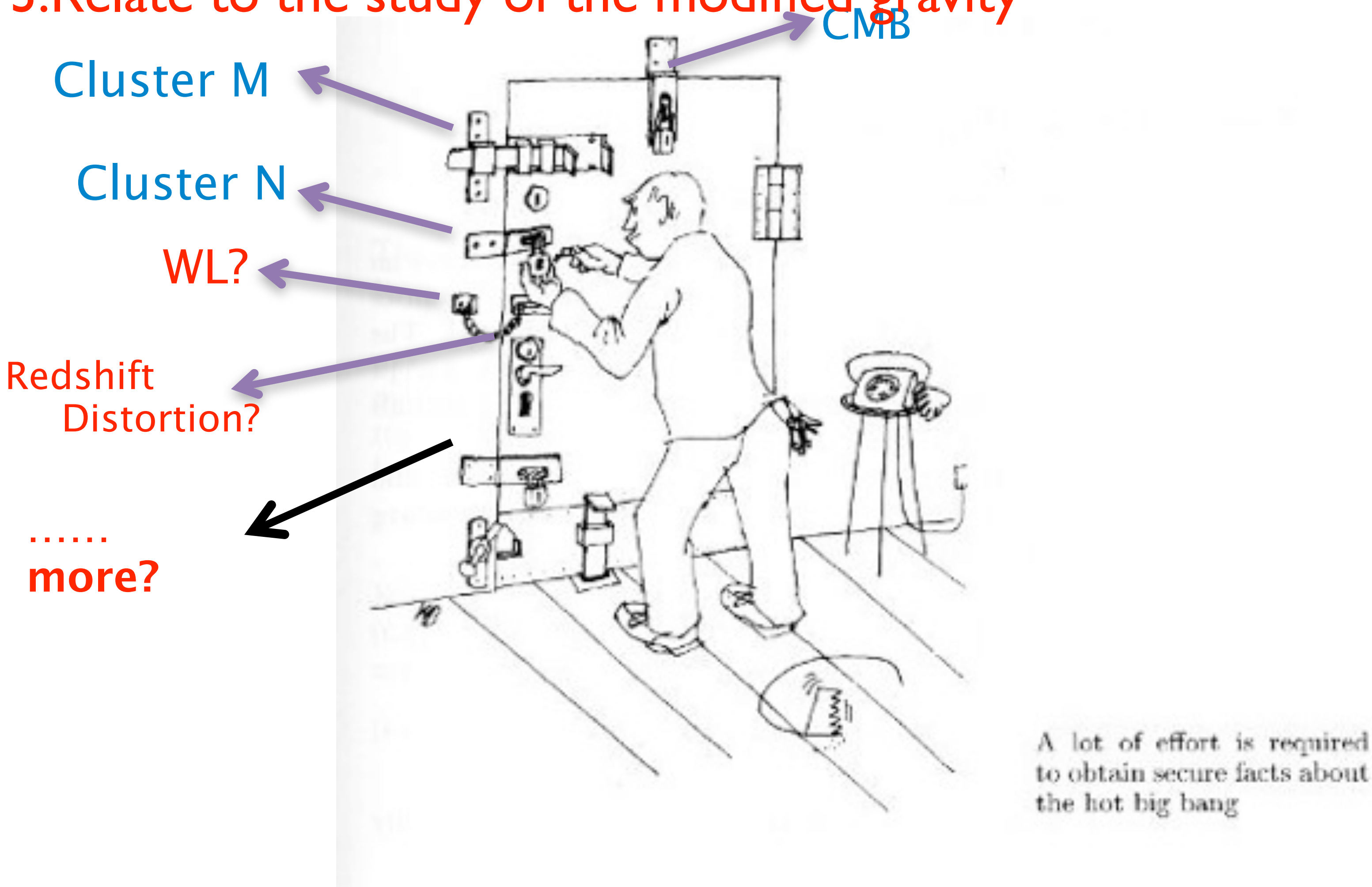

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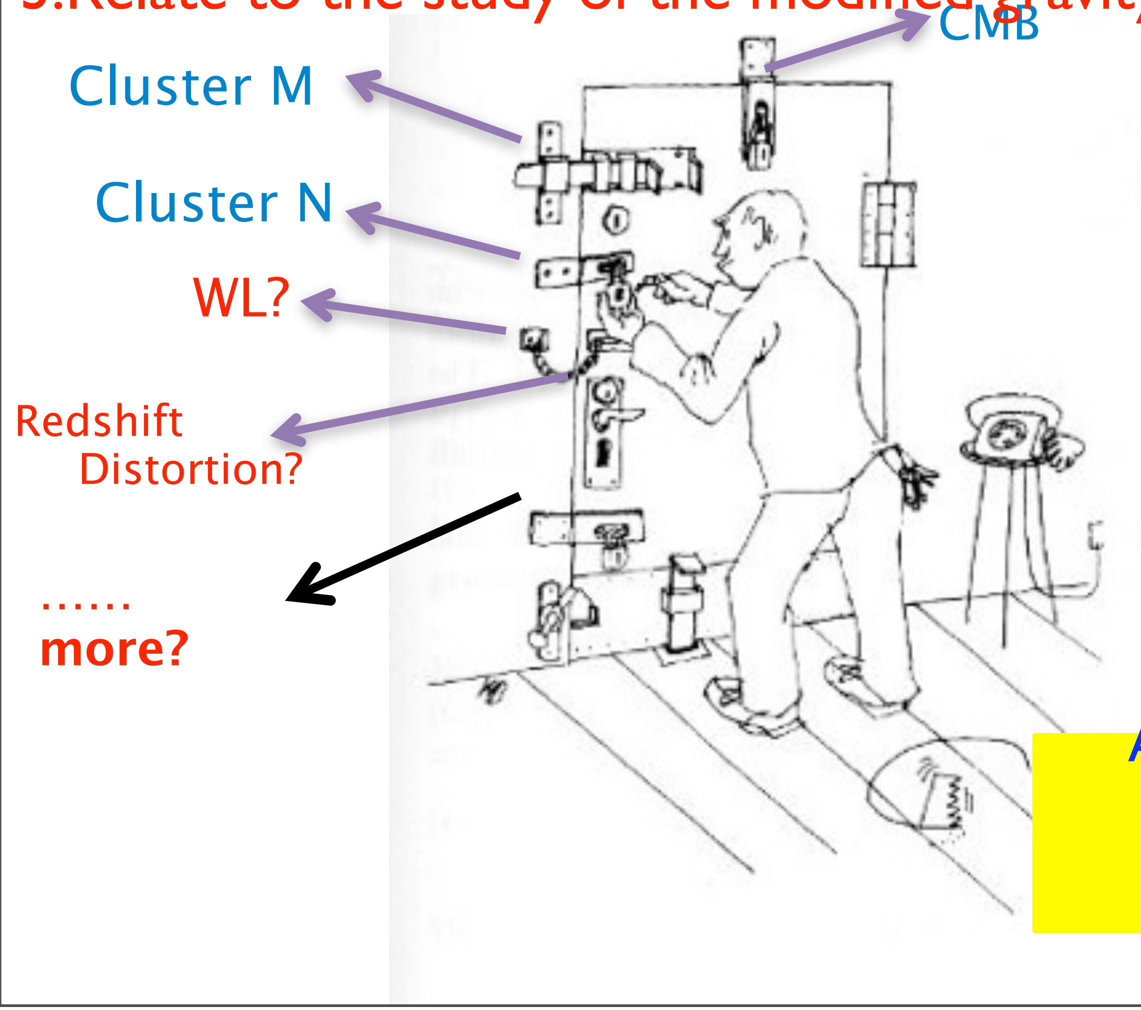


A lot of efforts have been spent to detect the interaction
Still more are needed

The interaction model between DE & DM

Phenomenological interaction forms:

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

For Q > 0 the energy proceeds from DE to DM

Phenomenological forms of Q

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

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 ten $T^{\mu\nu}_{(\lambda);\mu} = Q^{\nu}_{(\lambda)}$

$Q^{\nu}_{(\lambda)}$ 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

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

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

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

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

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

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,

Perturbation Theory

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

DM:

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

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

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

DE:

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

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

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

He, Wang, Jing, JCAP(09);
He, Wang, Abdalla, PRD(11)

We have not specified the form o the interaction between dark sectors.

Perturbation Equations

Phenomenological interaction forms:

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

$$a^2 Q_m^0 = 3\mathcal{H}(\lambda_1 \rho_m + \lambda_2 \rho_d)$$
$$a^2 Q_d^0 = -3\mathcal{H}(\lambda_1 \rho_m + \lambda_2 \rho_d)$$

Perturbation equations:

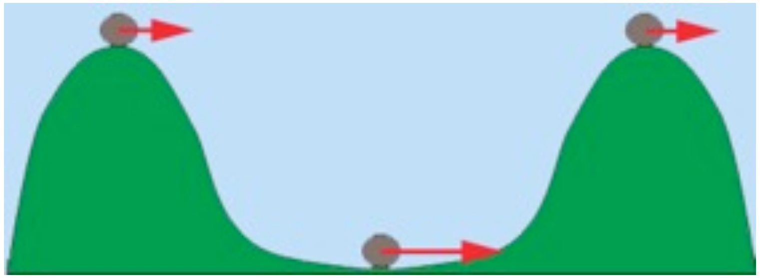
$$\begin{aligned}
D'_m &= -kU_m + 6\mathcal{H}\Psi(\lambda_1 + \lambda_2/r) - 3(\lambda_1 + \lambda_2/r)\Phi' + 3\mathcal{H}\lambda_2(D_d - D_m)/r \quad , \\
U'_m &= -\mathcal{H}U_m + k\Psi - 3\mathcal{H}(\lambda_1 + \lambda_2/r)U_m \quad , \\
D'_d &= -3\mathcal{H}C_e^2 \left\{D_d - [3(\lambda_1 r +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

Signature of the interaction in the CMB

Sachs–Wolfe effects:

- non-integrated — photons' initial conditions
- integrated
  - Early ISW
  - Late ISW

has the unique ability to probe the **"size"** of DE: **EOS,** the speed of sound



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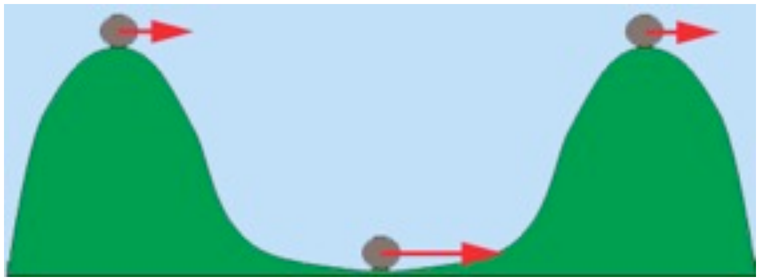
Signature of the interaction between DE and DM?



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,

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

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

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

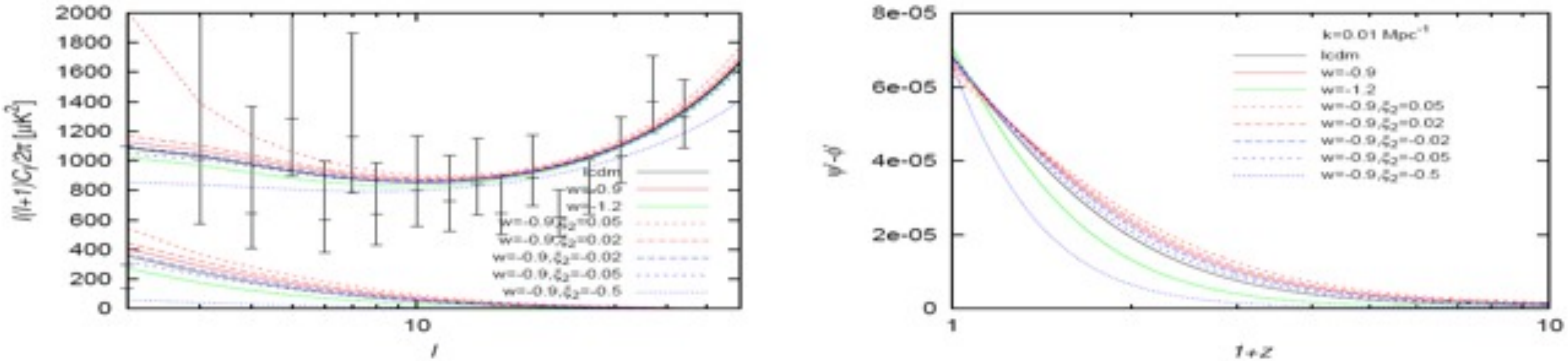
ISW effect is not simply due to the change of the CDM perturbation. The interaction enters each part of gravitational potential.

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

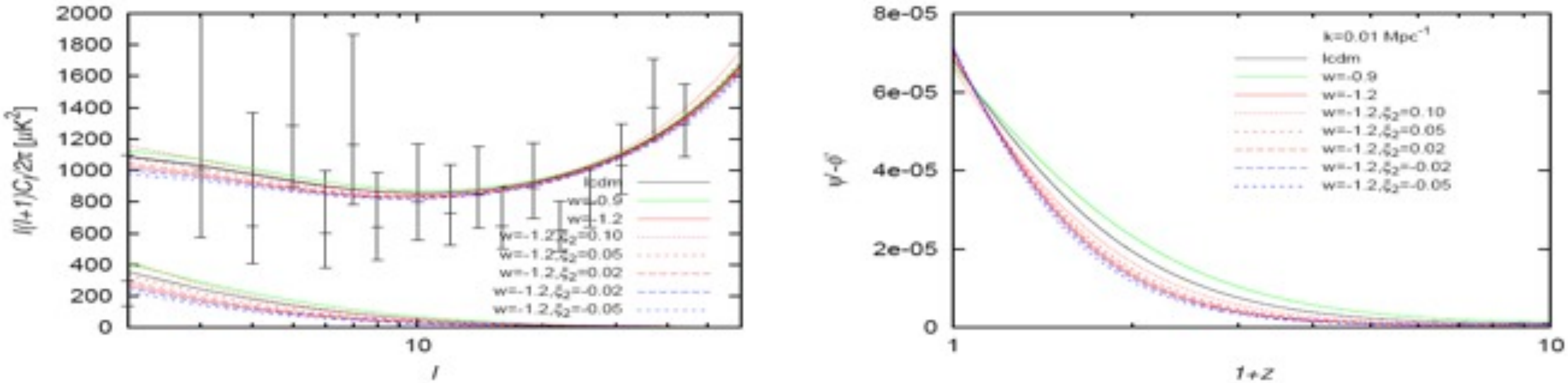
J.H.He, B.Wang, E.Abdalla, PRD(11)

The ISW effect as a probe of the interaction

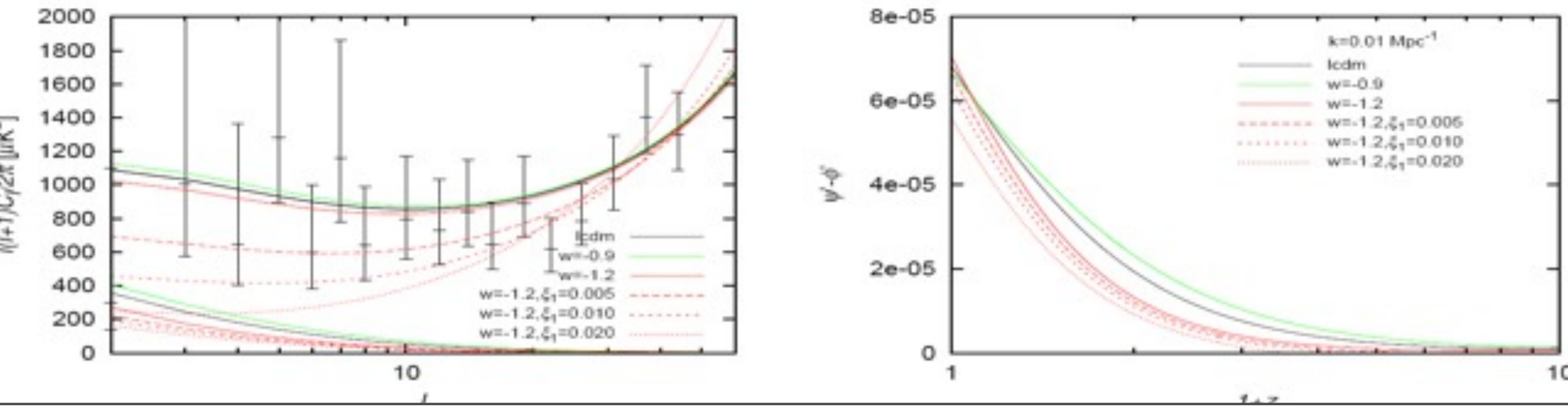
~DE, w>-1



~DE, w<-1



~DM, w<-1

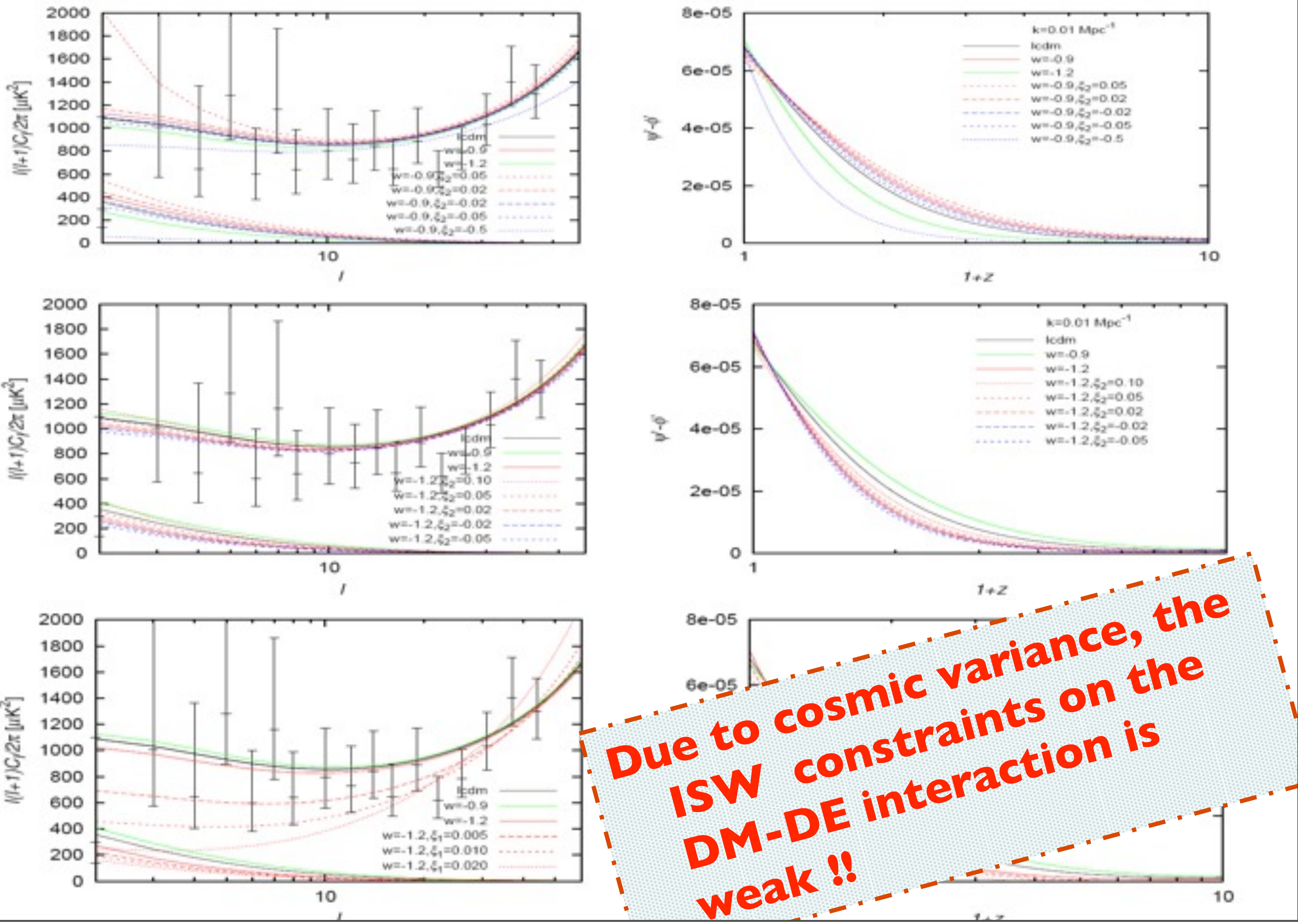


The ISW effect as a probe of the interaction

~DE, w>-1

~DE, w<-1

~DM, w<-1



Due to cosmic variance, the ISW constraints on the DM-DE interaction is weak !!

The peculiar velocities

The evolution equation for the velocity of baryons

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

We compute the root mean square velocity dispersion of the baryon velocity field, smoothed on a sphere of radius *r*,

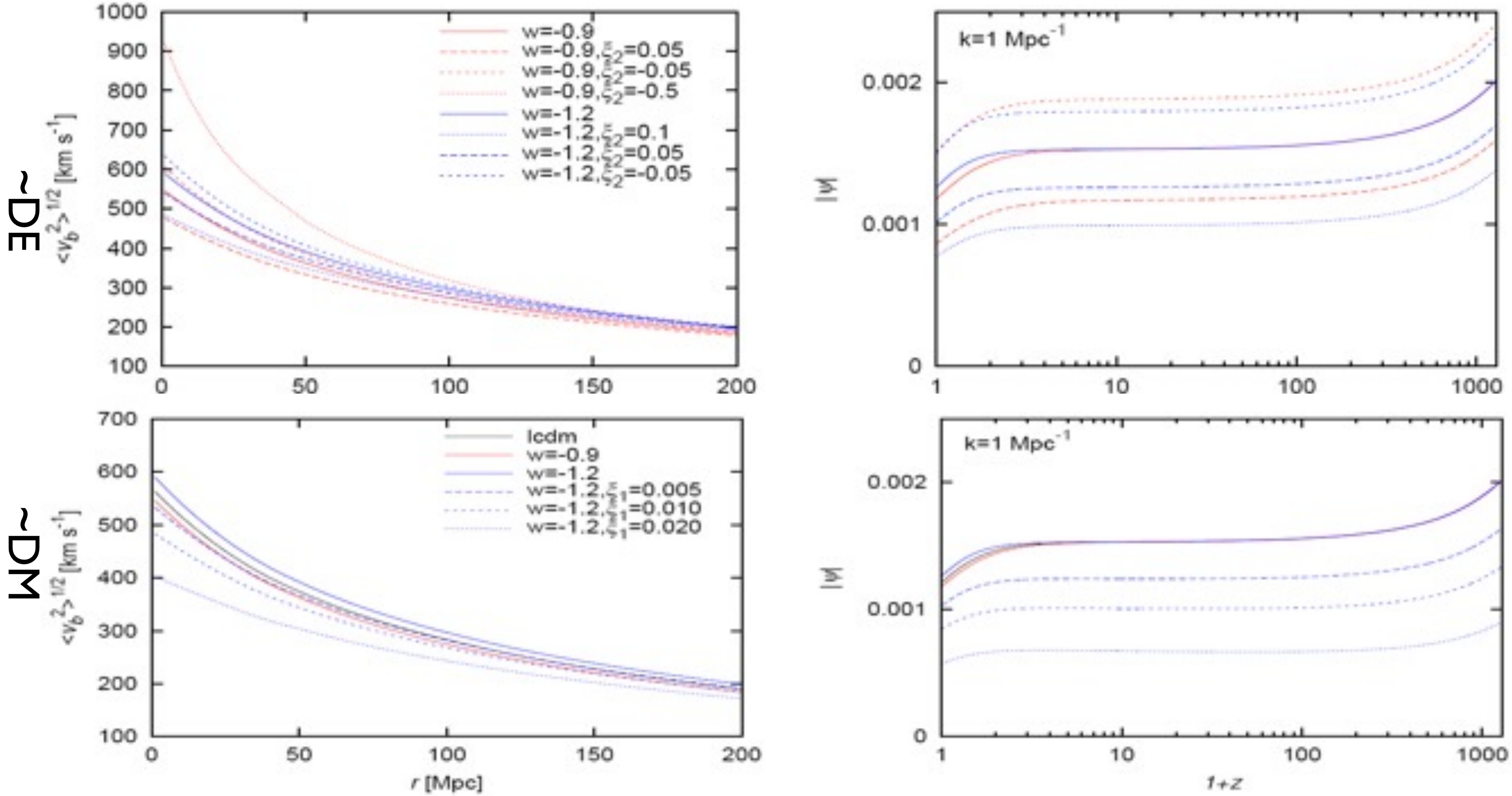
$$\langle v_b^2 \rangle = \int d^3k W_r^2(k) P_v(k)$$

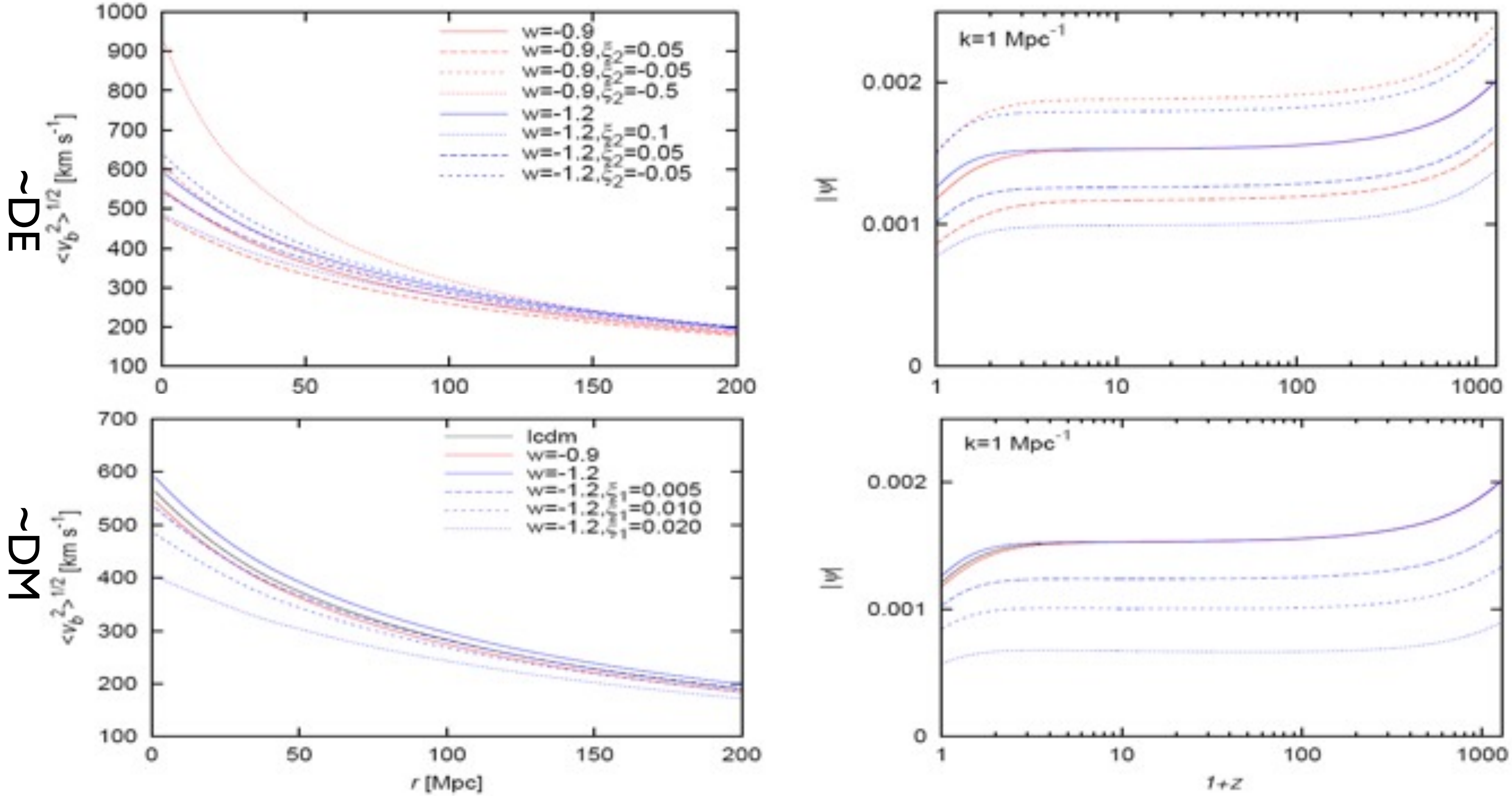
Wr(k) is a top hat window function of radius r

Pv(k) is the power spectrum of the baryon velocity field

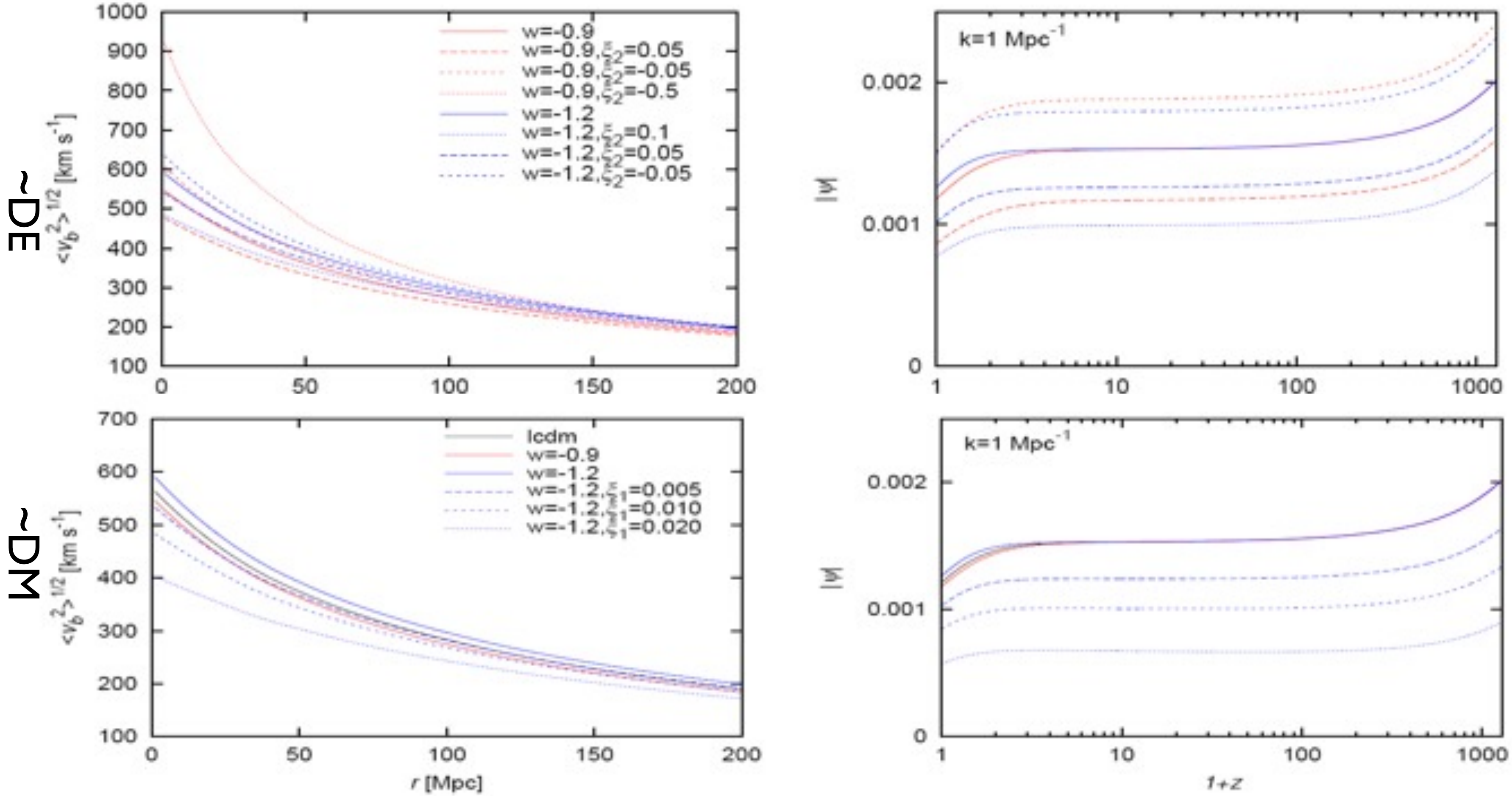
Interaction $\longrightarrow$ $\Phi = -\Psi$ $\longrightarrow$ v_b

Planck intermediate results. XIII. Constraints on peculiar velocities
1303.5090: radial velocity at z=0.15 to be below 800km/s at 95%C.L., 3 times of LCDM prediction


~DE
~DM
<v_b^2>^1/2 [km s^-1]
w=-0.9
w=-0.9,ξ2=0.05
w=-0.9,ξ2=-0.05
w=-0.9,ξ2=-0.5
w=-1.2
w=-1.2,ξ2=0.1
w=-1.2,ξ2=0.05
w=-1.2,ξ2=-0.05
k=1 Mpc^-1
|ψ|
lcdm
w=-0.9
w=-1.2
w=-1.2,ξ1=0.005
w=-1.2,ξ1=0.010
w=-1.2,ξ1=0.020
r [Mpc]
1+z



• No interaction, w influence φ at small z, suppression of the velocity for w > −1, enhancement for w < −1, compared with w=-1



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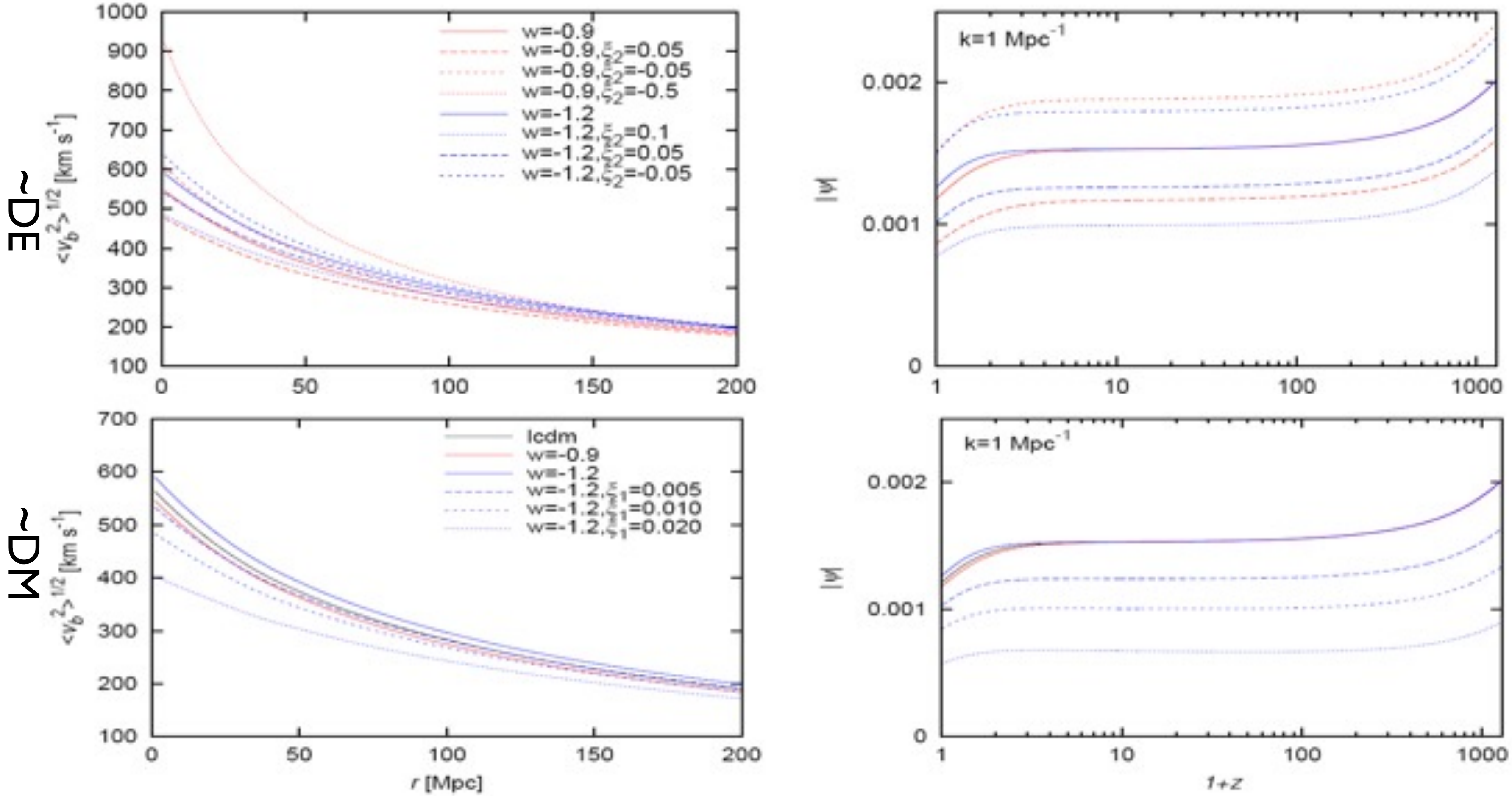
• With interaction, φ evolves during a longer period than in non-interacting models. Larger couplings give smaller peculiar velocities. The peculiar velocities changes larger when the coupling is proportional to the DM than to the DE.



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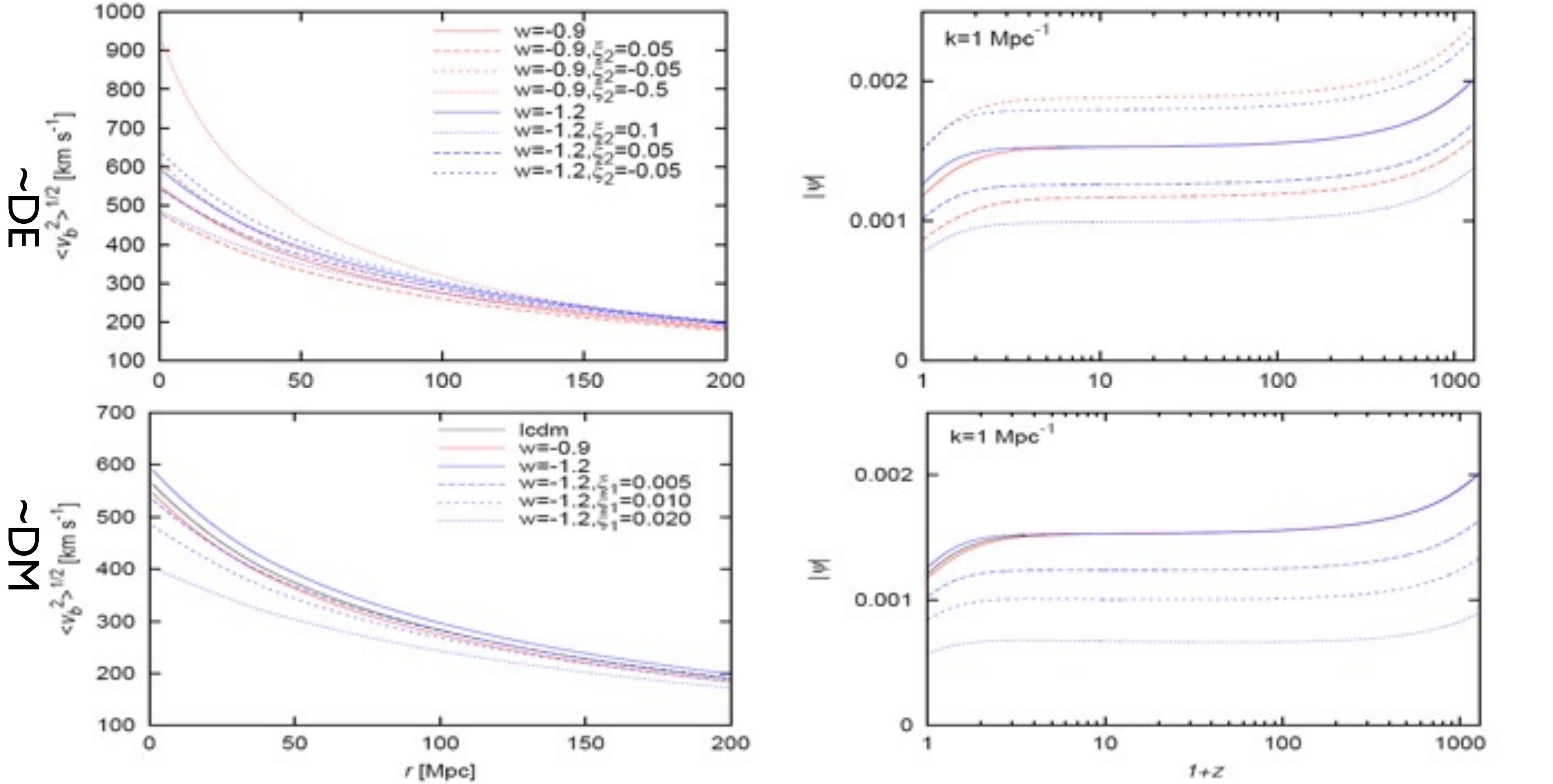

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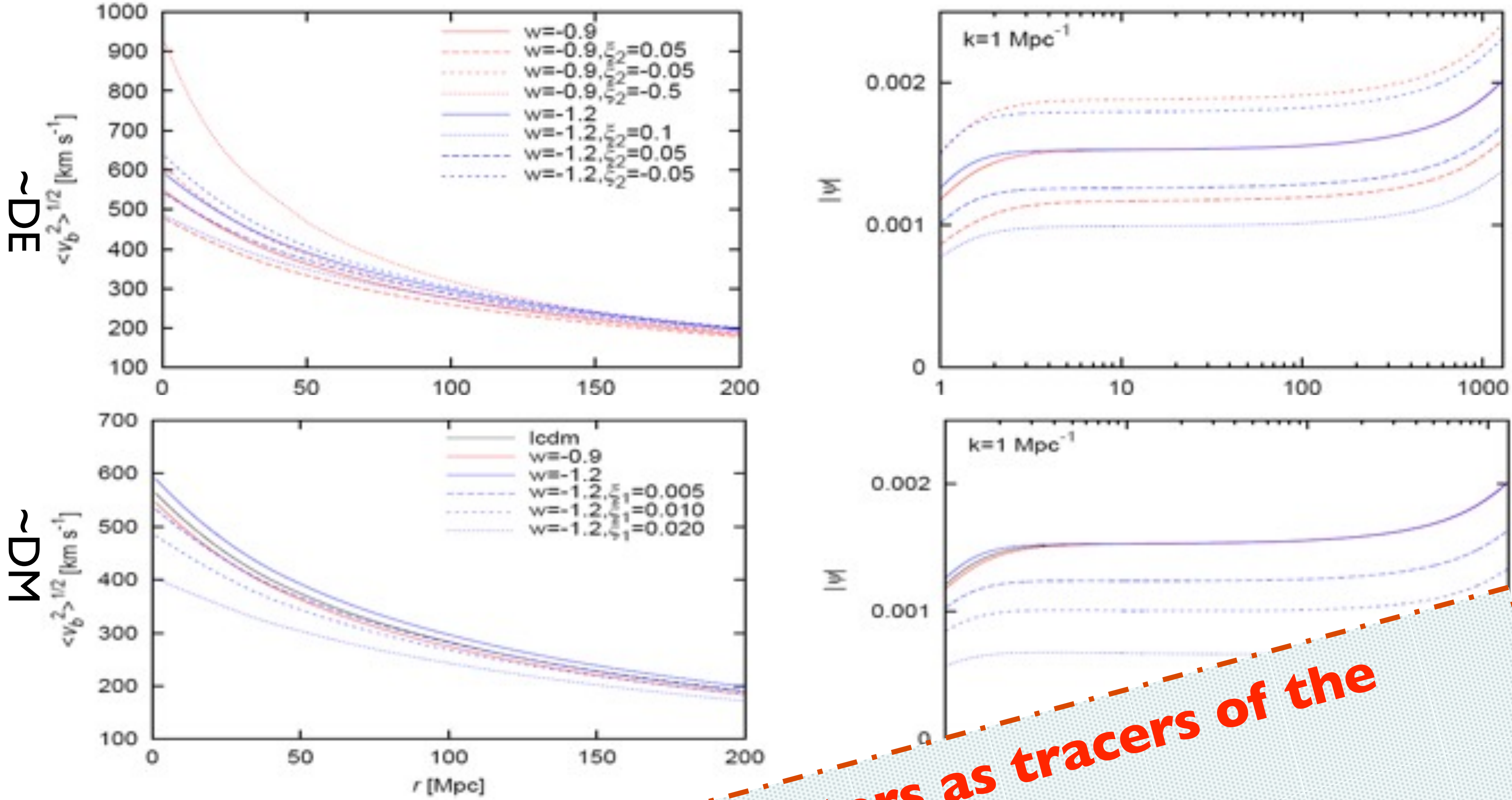
• For negative coupling and with w<-1, the peculiar velocity could be larger than in the LCDM model by a factor of two.

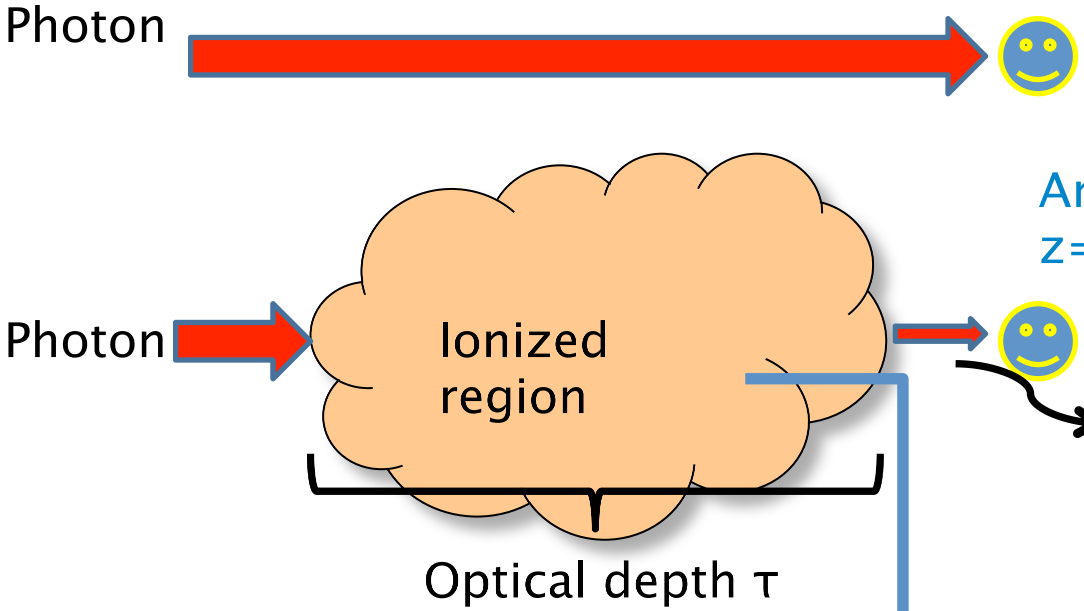


•No interaction, w influence φ at sm
for w < −1, compared with w=-1
• With interaction, φ evolves during
couplings give smaller peculiar velocit
coupling is proportional to the DM tha
• For negative coupling and with w<-1, ... larger than in the
LCDM model by a factor of two.

Use clusters as tracers of the velocity field.

The velocity can be directly measured by the Kinematic Sunyaev-Zel'dovich effect

Change in CMB spectrum



Mean temperature

Temperature: $T(1+\Theta)$, T background, Θ is the perturbation

Anisotropy, primordial set up at z=1100

Only a fraction of photon, $\exp(-\tau)$, escapes, contribution to temperature $T(1+\Theta)\exp(-\tau)$.

Ionized region contribution to the temperature $T(1-\exp(-\tau))$

Equilibrated temperature T

Temperature we see today:

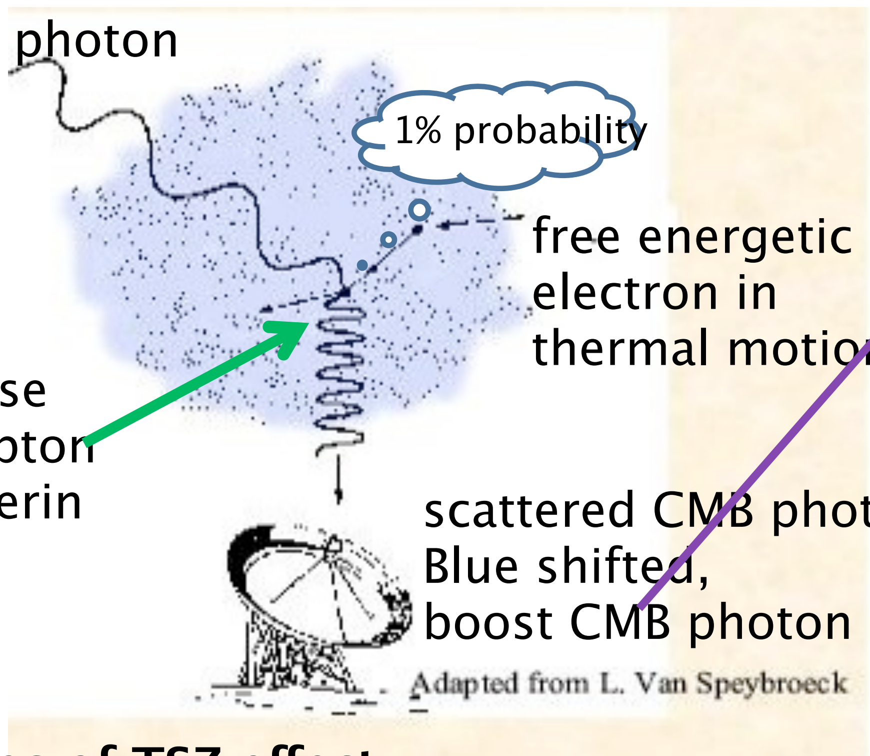
$$T(1+\Theta)\exp(-\tau) + T(1-\exp(-\tau)) = T[1+\Theta\exp(-\tau)]$$

Only those scale within the horizon at the time of reionization get suppressed by $\exp(-\tau)$, $l > \eta_0/\eta_{reion}$, small l will not be affected

Sunyaev Zel'dovich effec

The thermal SZ effect

CMB photon

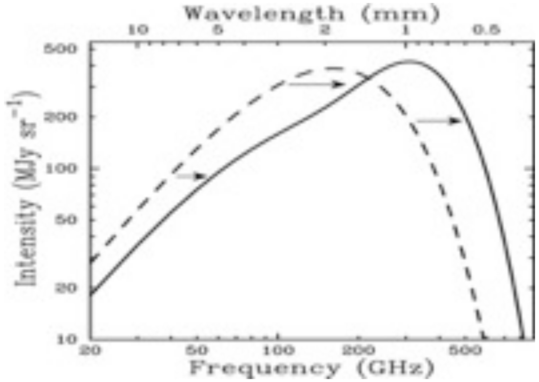


1% probability

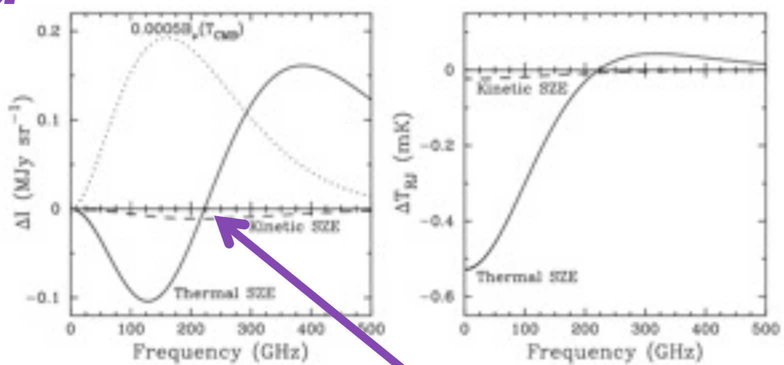
free energetic electron in thermal motion

Inverse Compton scatterin g

scattered CMB photon Blue shifted, boost CMB photon ≤1



distortion in the CMB spectrum



218GHz

Features of TSZ effect:

1. CMB ↓ at frequency <218GHz, ↑CMB at frequency>218GHz
2. TSZ depends on the depth of the cluster gas, distortion strong at the center, weak at the edge

- Independent of the redshift
- Intensity of TSZ depends on the cluster mass

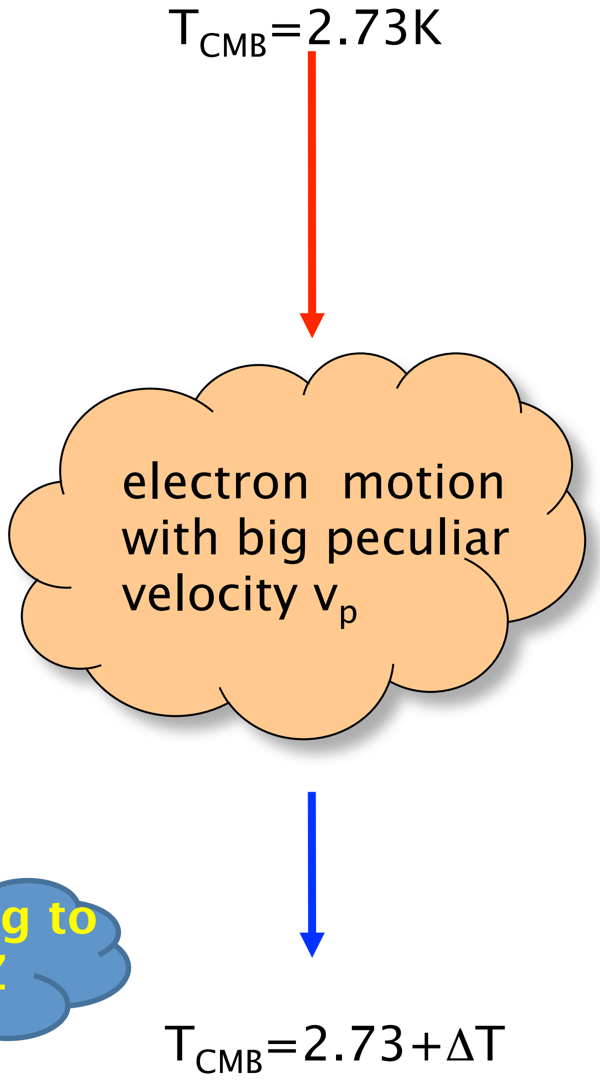
The kinetic SZ effect

$$\frac{\Delta T}{T}|_{CMB} = \int v_p n_e \sigma_T dl$$

v_p: peculiar velocity

scattering probability

Interesting to study KSZ effect



PLANCK result: the upper limit of the peculiar velocity can be three times of the LCDM prediction

The KSZ effect

$$\frac{\Delta T(\hat{\boldsymbol{n}})}{T_{CMB}} = \int_{t_{re}}^{t_0} n_e \sigma_T e^{-\kappa} (\boldsymbol{v} \cdot \hat{\boldsymbol{n}}) \mathrm{d}t,$$

n_e: the electron density,
σ_T: the Thomson cross section
k: the Thomson optical depth
v: the peculiar velocity of the electrons
***n**: the unit vector along the l.o.s.*

Using the comoving distance x and neglecting any interaction of electrons with other particles,

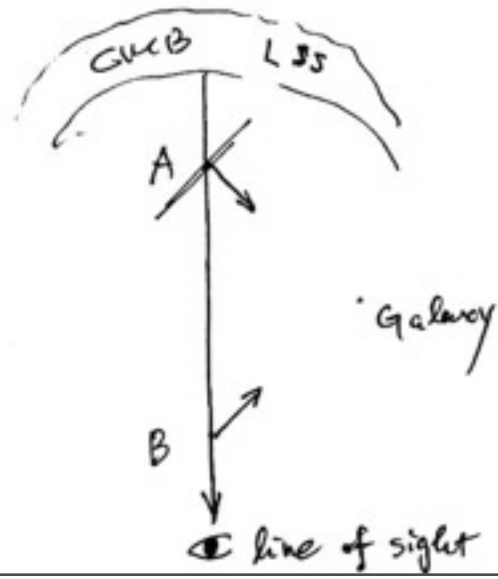
$$n_e(x, z) = \chi_e \bar{n}_e(0) a^{-3} [1 + \delta_e(x, z)]$$

$\bar{n}_e(0)$ the mean electron number density at present

$$\frac{\Delta T(\hat{\boldsymbol{n}})}{T_{CMB}} = \bar{n}_e(0)\sigma_T \int a^{-2} \chi_e e^{-\kappa} (\boldsymbol{p} \cdot \hat{\boldsymbol{n}}) \mathrm{d}x,$$

χ_e is the ionization fraction

peculiar momentum $\boldsymbol{p} \equiv (1 + \delta_e)\boldsymbol{v}$



p_E : gradient component
p_B: curl component

p_E: no contribution to KSZ,
cancels out when integrating along the l.o.s.
p_B: contributes to KSZ

$$\nabla \times \boldsymbol{p} = (1+\delta_e)\nabla \times \boldsymbol{v} + \nabla \delta_e \times \boldsymbol{v},$$

the rotational mode of ***v***

the cross-talk between the density and the velocity

In the linear regime, only the irrotational component of the velocity fields couples to gravity,

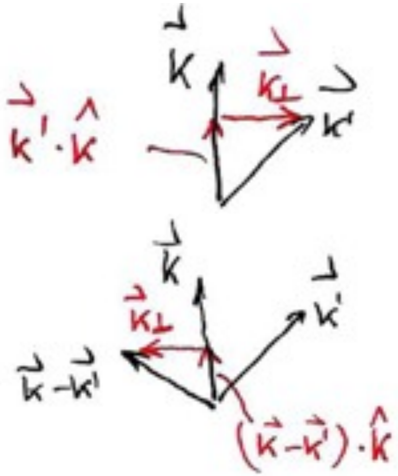
The KSZ effect is due to the cross-talk between the density gradient and the velocity.

$$C_l^{KSZ} = \frac{16\pi^2}{(2l+1)^3}(\bar{n}_e(0)\sigma_T)^2 \int_0^{z_{re}} (1+z)^4 \chi_e^2 \frac{1}{2} \Delta_B^2(k,z)|_{k=l/x} e^{-\kappa} x(z) \frac{dx(z)}{dz} dz$$

This formula is in the same form as the KSZ effect of the LCDM model

$$\Delta_B^2(k,z) = \frac{k^3}{2\pi^2} P_B(k,z)$$ Where,

$$P_B(k) = \langle \boldsymbol{p}_B^*(\boldsymbol{k}) \boldsymbol{p}_B(\tilde{\boldsymbol{k}}) \rangle = \int \frac{d^3\boldsymbol{k}'}{(2\pi)^3} \int \frac{d^3\tilde{\boldsymbol{k}}'}{(2\pi)^3} \langle \delta_e^*(\boldsymbol{k}-\boldsymbol{k}') \delta_e(\tilde{\boldsymbol{k}}-\tilde{\boldsymbol{k}}') \boldsymbol{v}^*(\boldsymbol{k}') \boldsymbol{v}(\tilde{\boldsymbol{k}}') \rangle$$
$$\times |\boldsymbol{k}'||\tilde{\boldsymbol{k}}'| \beta(\boldsymbol{k}, \boldsymbol{k}') \beta(\tilde{\boldsymbol{k}}, \tilde{\boldsymbol{k}}'),$$



$$\beta_2(\vec{k}, \vec{k}') = \frac{1}{|\vec{k}'|^2}\left[\vec{k}' - \vec{k}' \cdot \hat{k}\hat{k}\right] = \frac{1}{|\vec{k}'|}\left[\hat{k}_\perp\right]$$

$$\beta_1(\vec{k}, \vec{k}-\vec{k}') = \frac{1}{|\vec{k}-\vec{k}'|^2}\left[(\vec{k}-\vec{k}') - (\vec{k}-\vec{k}') \cdot \hat{k}\hat{k}\right] = \frac{1}{|\vec{k}-\vec{k}'|}\left[\hat{k}_\perp\right]$$

In the linear perturbation theory and for subhorizon perturbations,

$$v = -\delta_e'/k = -aHf_e(a)\delta_e/k,$$

$$aHf_e = a\dot{D}_e/D_e \qquad D_e(z) \equiv \delta_e(z)/\delta_e(0)$$

Thus:

$$P_B(k,z) = \frac{a^2}{2} \int \frac{d\boldsymbol{k}'^3}{(2\pi)^3} \left(\frac{\dot{D}_e}{D_e}\right)^2 P(k',z) P(k-k',z)$$
$$\times [W_g(k-k')\beta(\boldsymbol{k},\boldsymbol{k}') + W_g(k')\beta(\boldsymbol{k},\boldsymbol{k}-\boldsymbol{k}')]^2$$

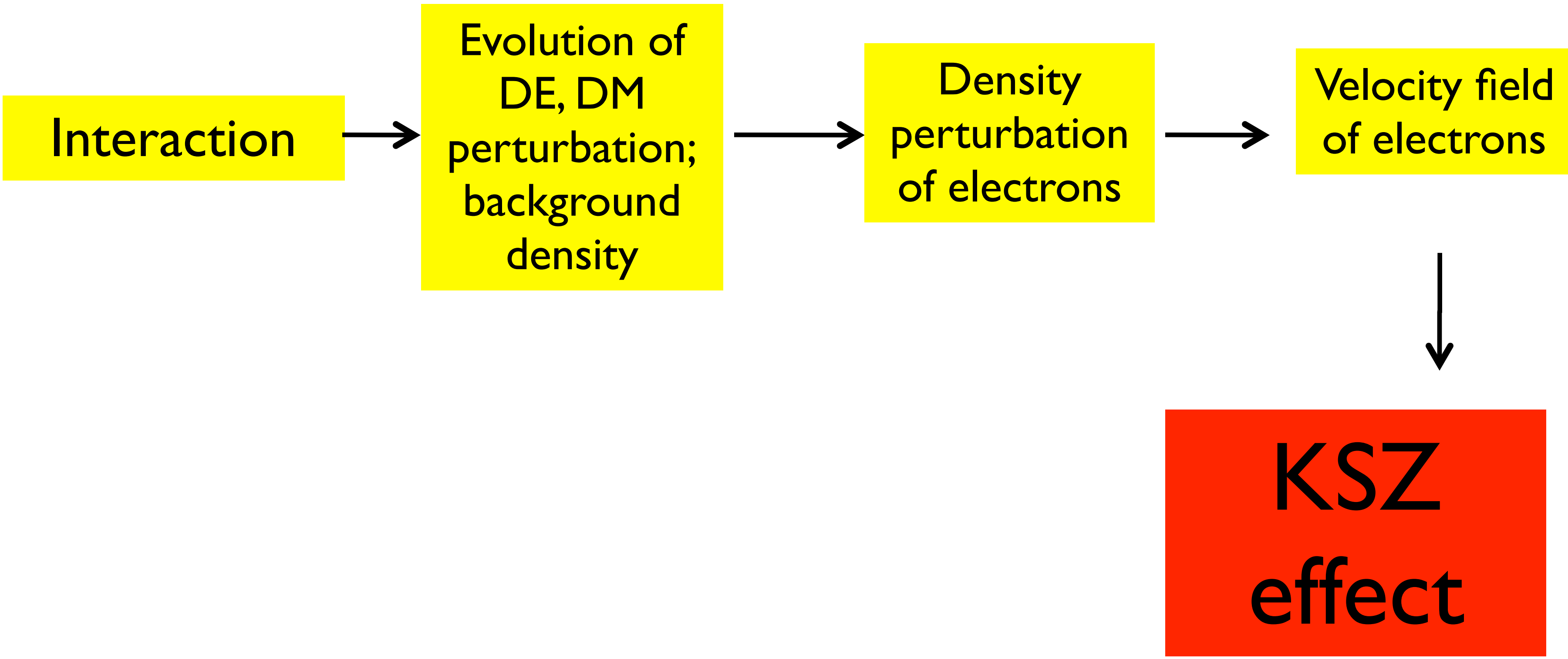
Wg(k) is the transfer function

These equations are formally identical to the KSZ contribution in the concordance ΛCDM model, **BUT…**

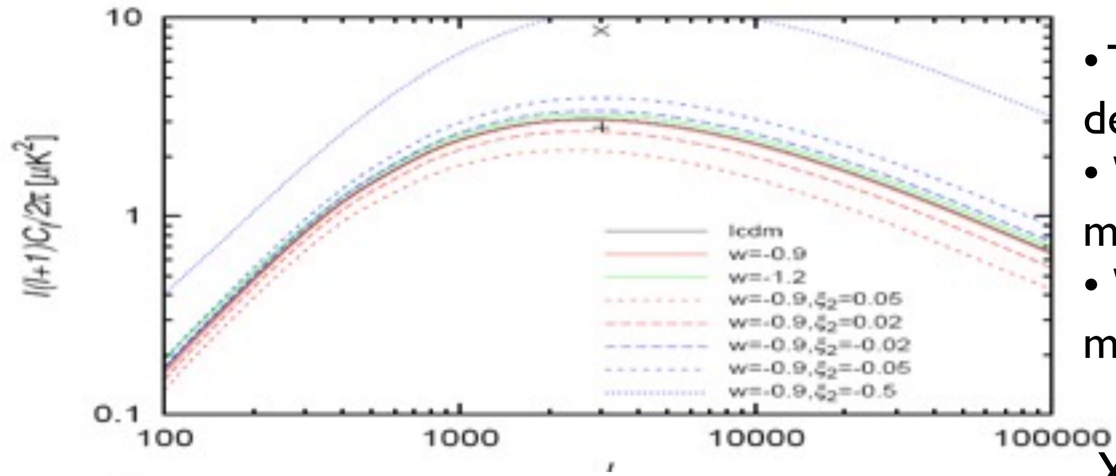
$$\delta_e'' + \frac{a'}{a}\delta_e' + 3\phi'' + 3H\phi' + k^2\psi = 0$$

In the small scale approximation k>>aH, neglect the time variation of the potential

$$\delta_e'' + \frac{a'}{a}\delta_e' - 4\pi G a^2(\rho_b\delta_b + \rho_c\delta_c + \rho_d\delta_d) = 0,$$



~DE, w>-1



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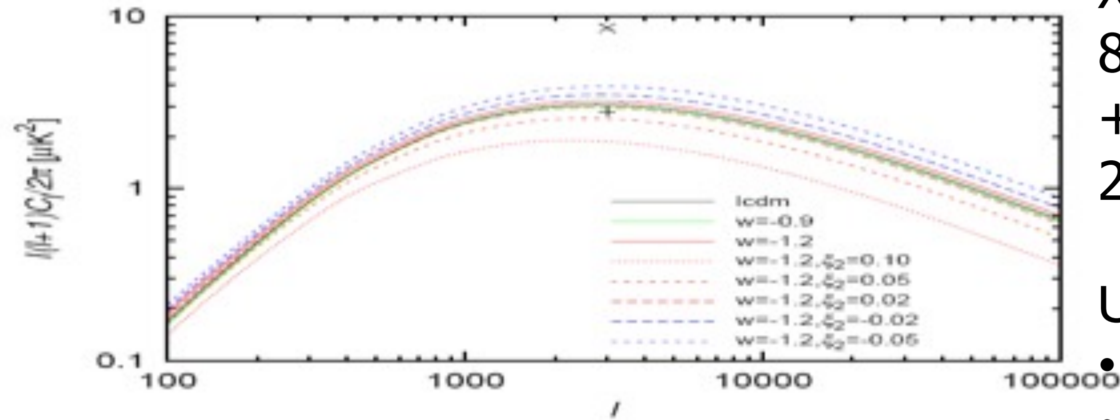
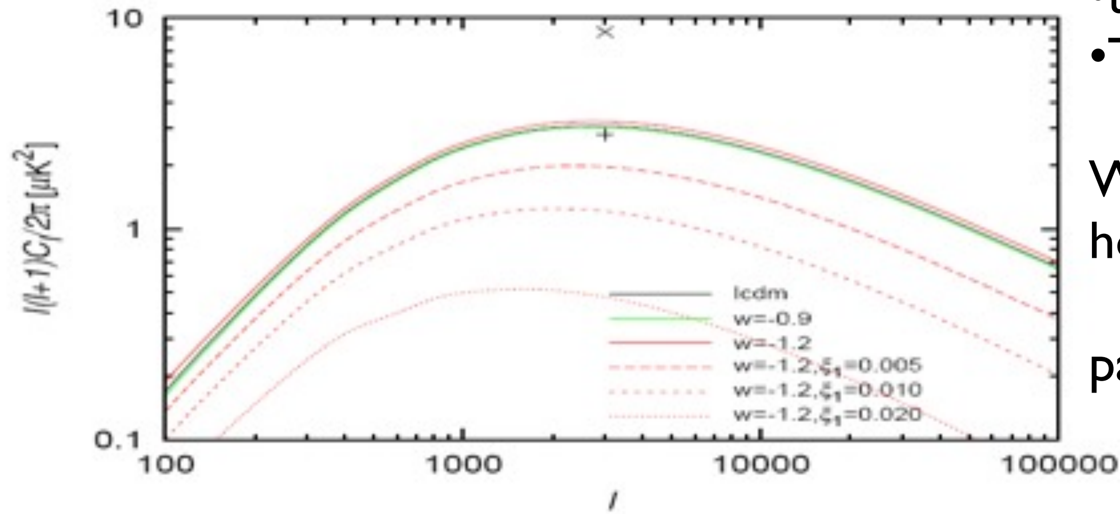


~DM, w<-1



- The amplitude increases with decreasing of coupling
- \xi>0, smaller than the LCDM model
- \xi<0, larger than the LCDM model

X: upper limit from ACT 8.6uk^2 at l=3000
+: upper limit from SPT 2.8uk^2 at l=3000

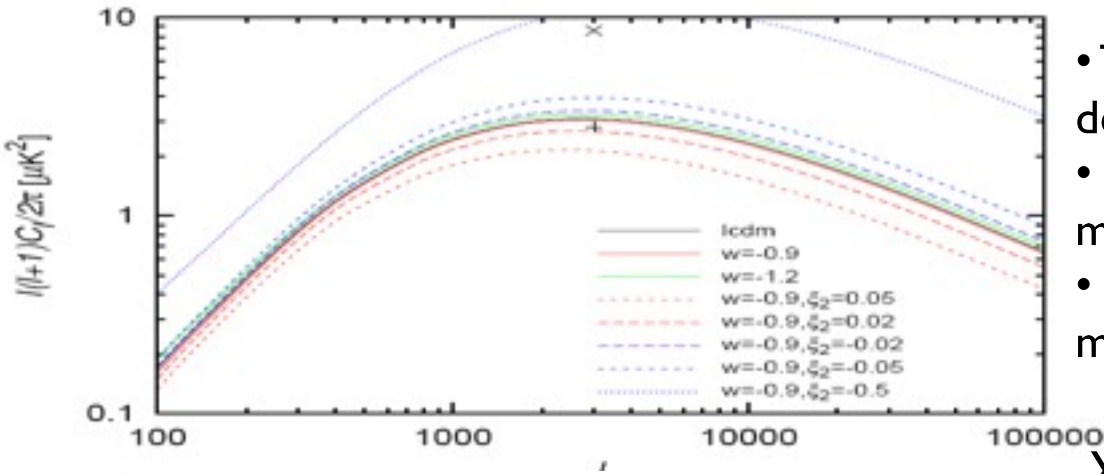
Upper limits depend on:

- reionization history
- the modeling of CIB
- TSZ contribution

We just consider: homogeneous, linear

patchy reionization, nonlinear

~DE, w>-1



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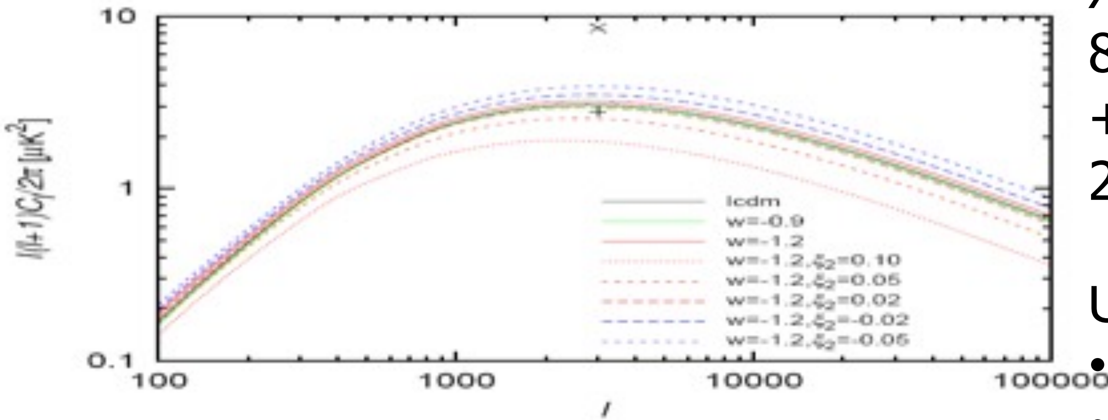

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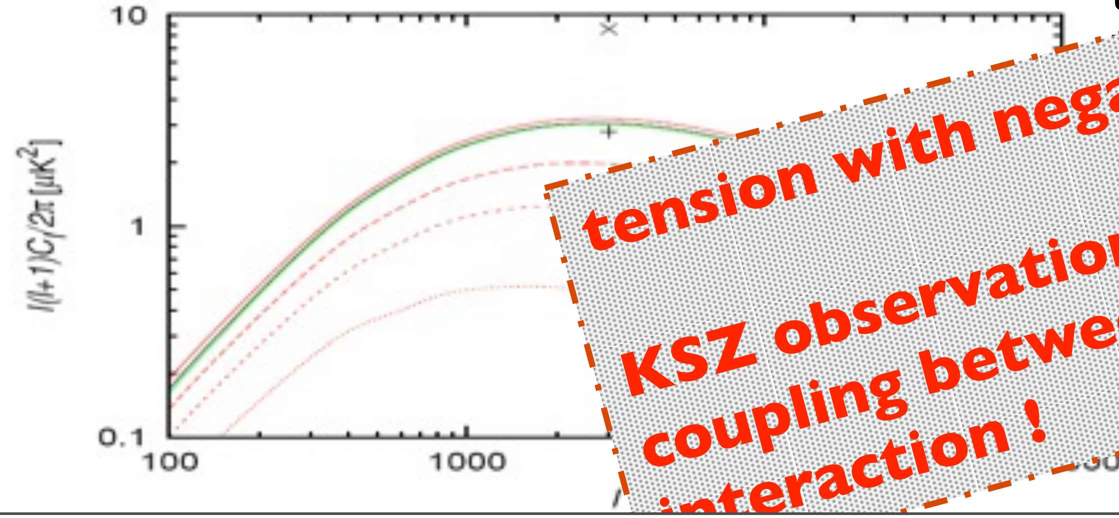

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- reionization histo...
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- ...ion, nonlinear

tension with negative coupling

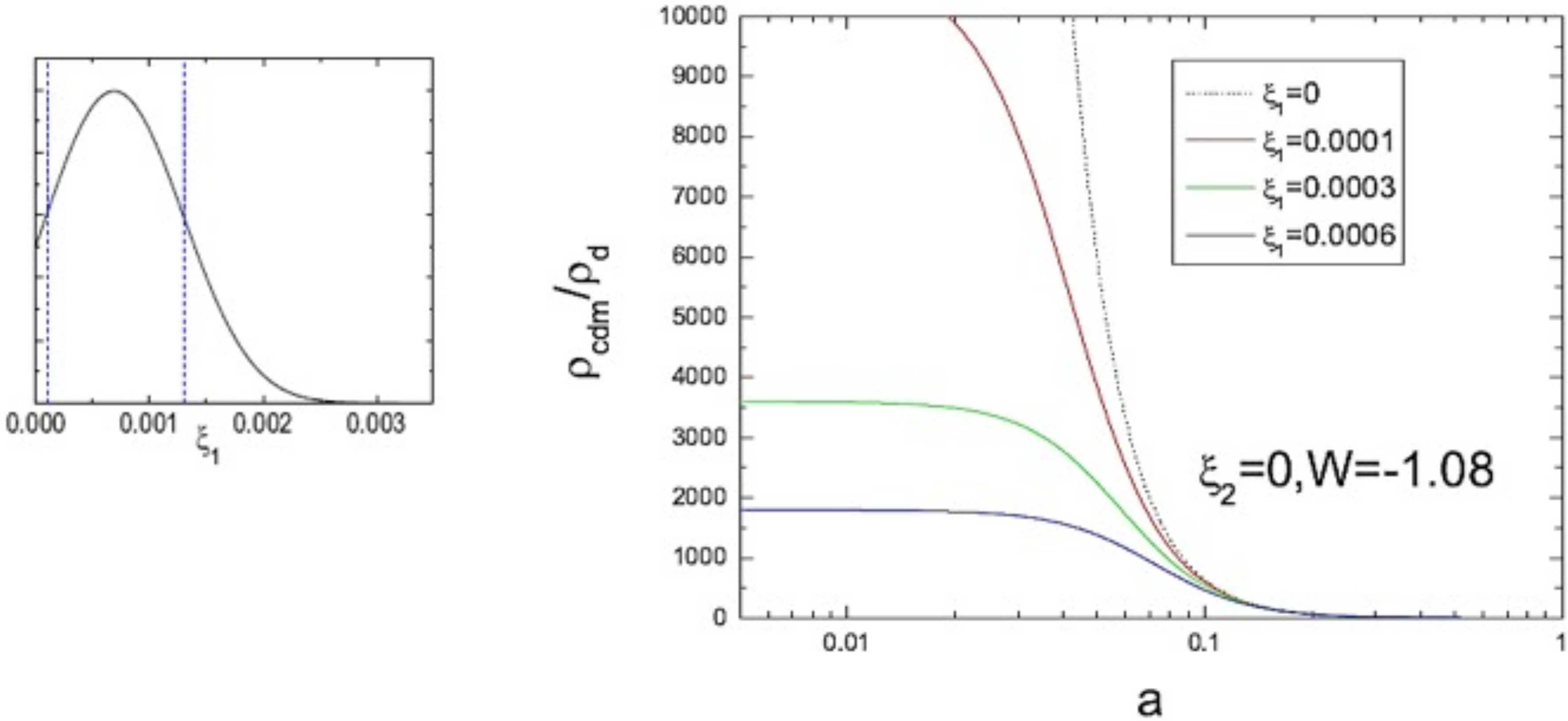
KSZ observations favor a positive coupling between DM-DE interaction !

KSZ observations favor a positive coupling between DM-DE interaction

Encouraging !! Consistent with CMB and galaxy cluster test

Alleviate the coincidence problem

Interaction proportional to the energy density of DM



J.H. He, B.Wang, P.J.Zhang, PRD(09); J.H.He, B.Wang, E.Abdalla, PRD(11)

Summary:

KSZ effect:

- potential,
- peculiar velocity,
- Large at big **l**,
- from the moment of reionization z ~10.

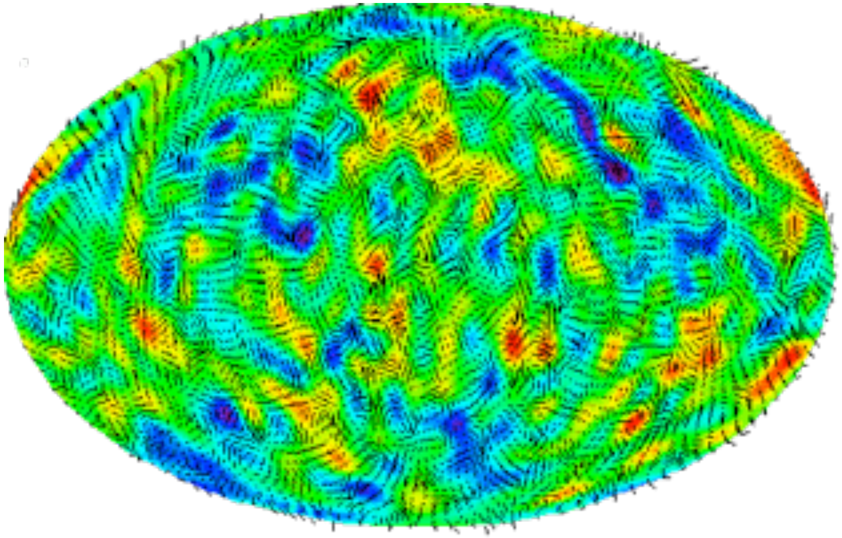
ISW effect:

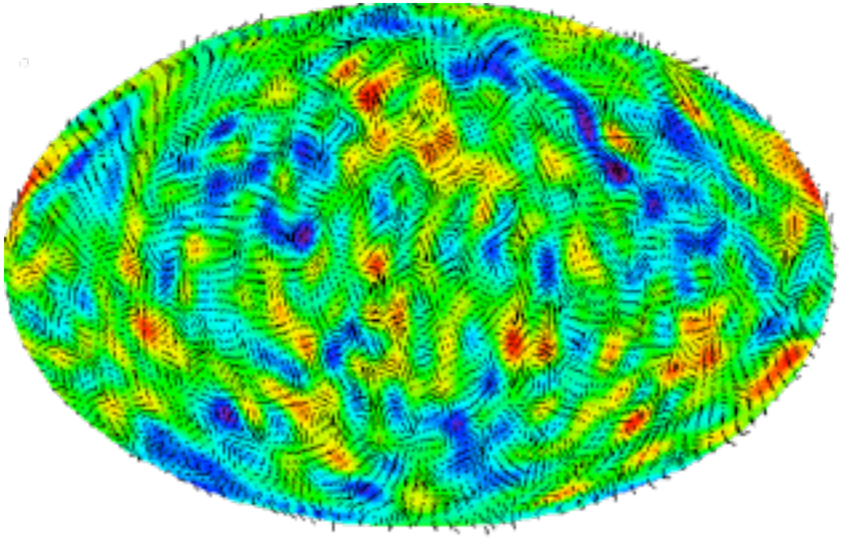
- time evolution of the potential,
- at large angular scales,
- during the period of acceleration

complementary

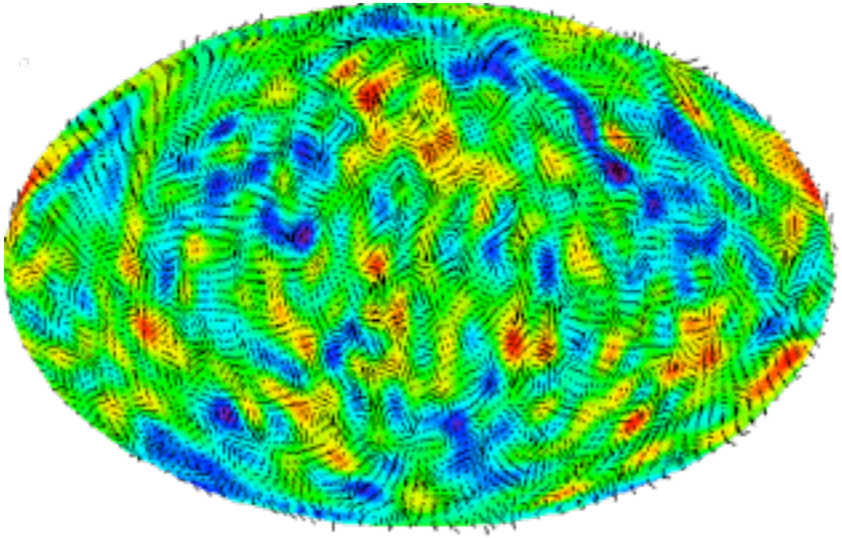
Alternatively:
The peculiar velocity - use clusters as tracers (DE&DM interaction)

Thanks!!!





1992 COBE satellite result 2006 Nobel Prize



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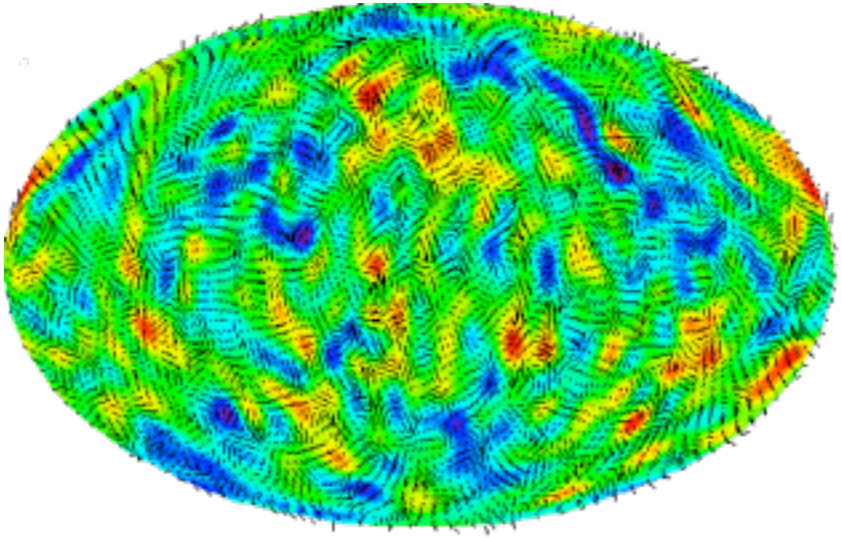

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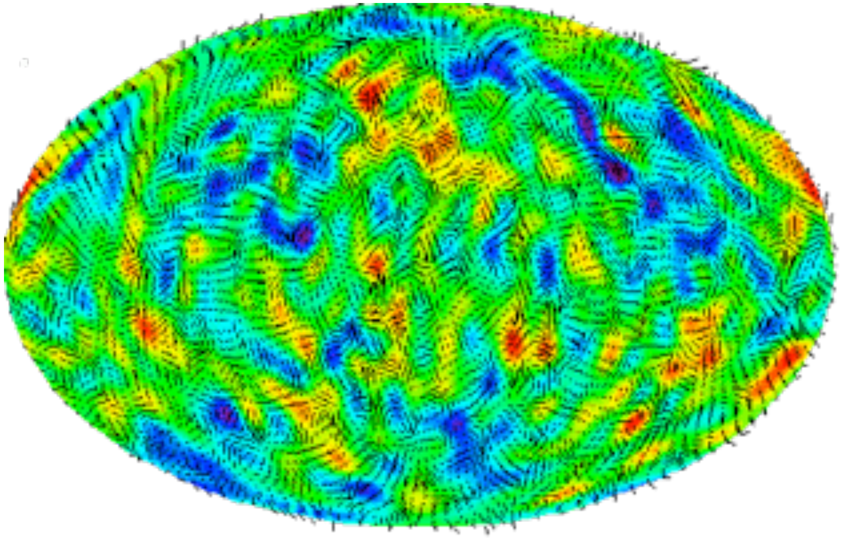

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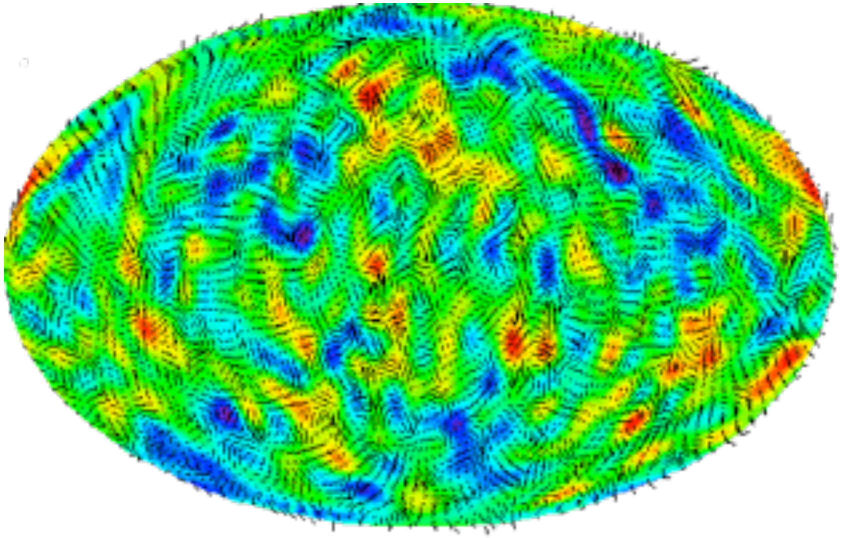

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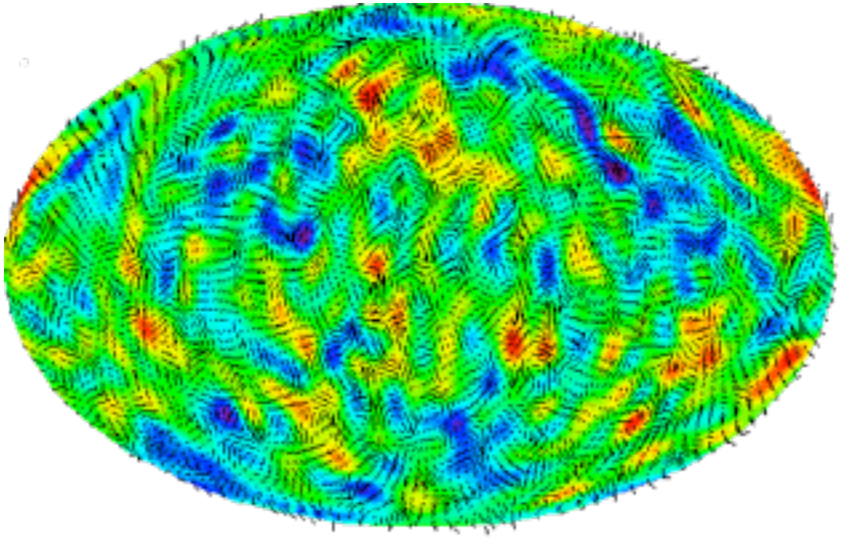

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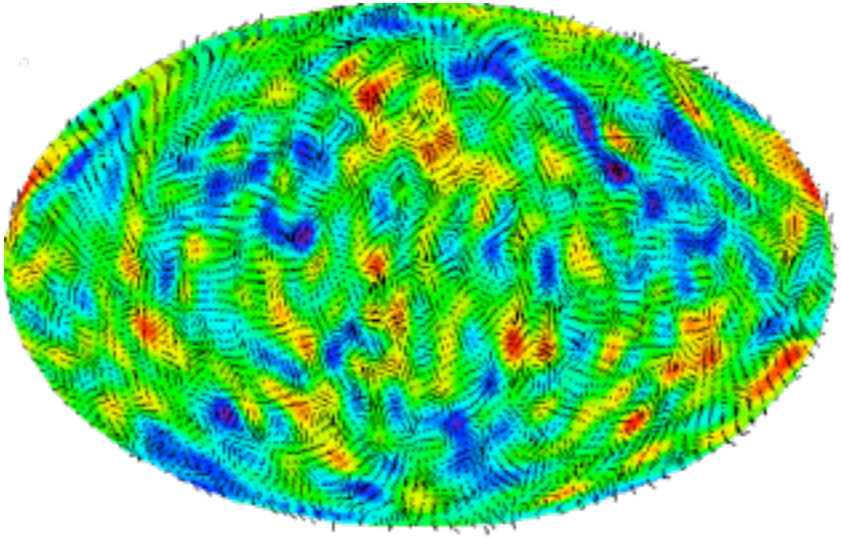

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Precision Cosmology

Problems in Cosmology

CMB

↑

Photons

1. Reionization time

The first phase change of hydrogen in the universe

→ **Plasma** Proton Electron → **Neutralization** Proton + Electron — **transparent** — **DARK AGE**

The second phase change of hydrogen in the universe

objects started to form in the early universe → ionize neutral hydrogen — radiate energy → **ionized Plasma**

Reionization

6 < z < 20, **exactly wh**

Important to the formation of stars, galaxies etc.

Observing the Reionization

CMB: ionized free electrons scatter photons, secondary anisotropies. WMAP: z 11

Quasars: brightest objects, energy absorbed by neutral hydrogen, Lyman transition

Gunn-Peterson trough

SDSS: z 6

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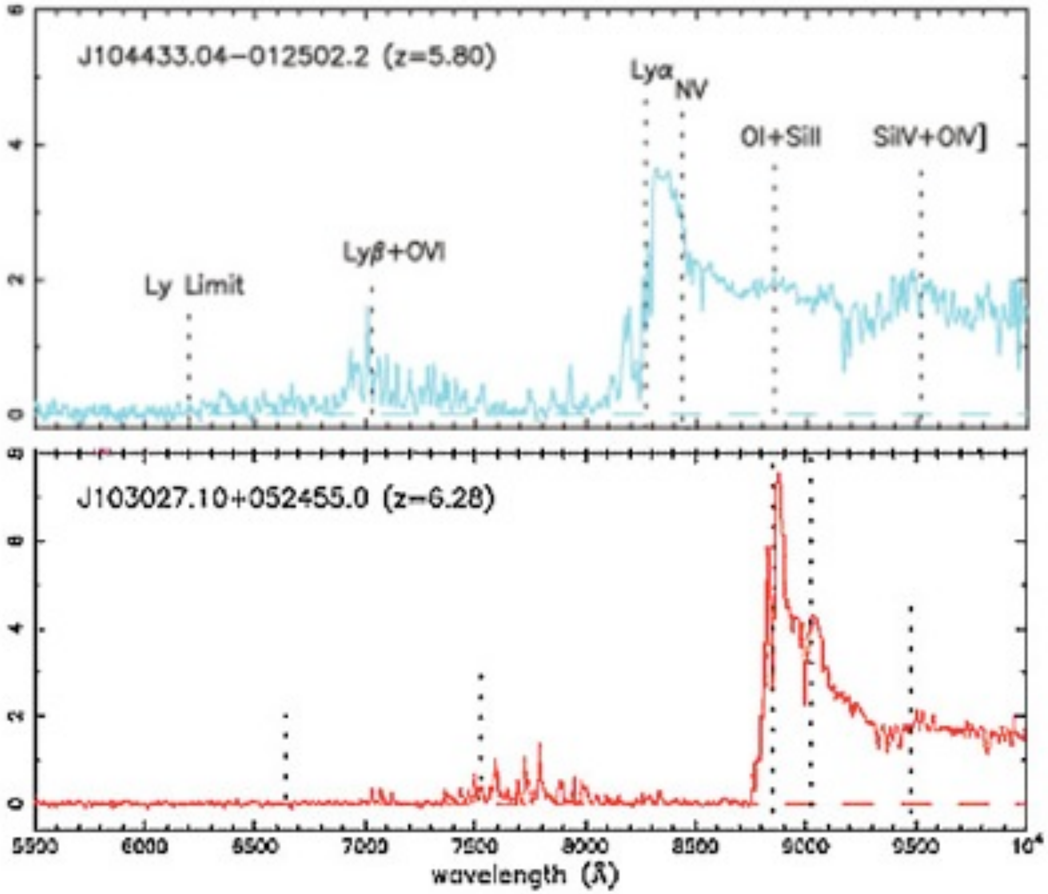
SDSS: z 6

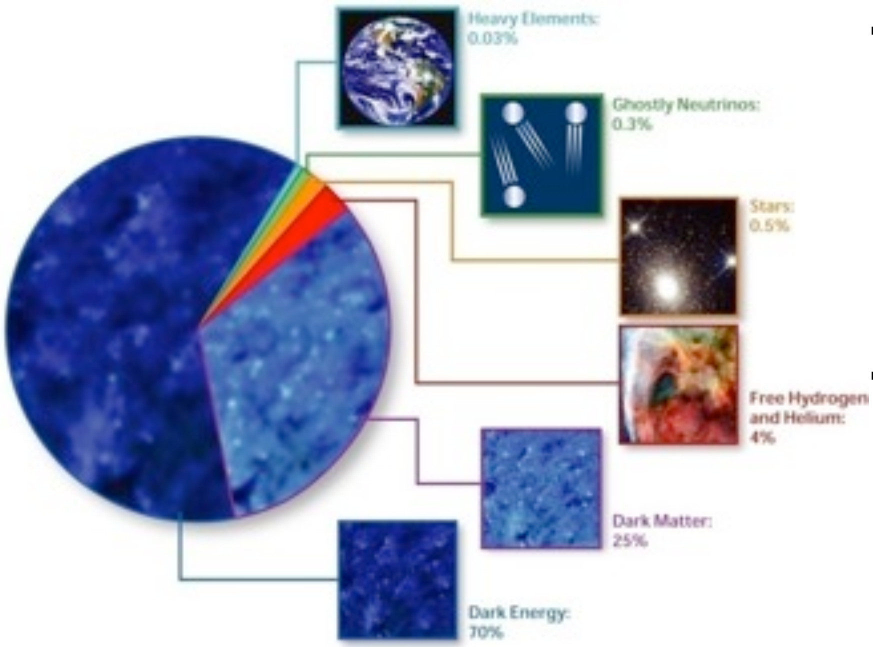
Gunn-Peterson trough in the quasar's spectrum

Quasars below a certain redshift will not show the Gunn-Peterson trough



quasars above z = 6 showed a Gunn-Peterson trough, indicating that the IGM was still at least partly neutral. The end of reionization around z=6.

2. Missing baryons



4-5% Baryons of total contents of the universe

50% baryons missing. WHY???

Direct measurement in local universe:
Stars
Interstellar medium
Intercluster medium

Structure formation model: Majority of baryons in IGM,
- hot (10^5k~10^7k), ionized, transparent to Lyman-alpha radiation, hard to trace by Lyman- alpha forest

- Not too hot, x-ray weak

Is TSZ effective to answer the above two problems?

The intensity of TSZ ~ n_e of free electrons, T,

1. **Missing baryons:** likely in less dense region with lower T
   TSZ effect is limited in answering the missing baryon problem.

2. **Reionization:** must know information about the fraction and dynamics of free electrons at high redshift z~10
   Lyman-alpha forest — effective to detect the last reionization

   At high redshift T is high, small change of n_e can result in the TSZ
   if we compare with usual CMB
   TSZ has the possibility to disclose the onset of the Reionization

Is KSZ effective to answer the above two problems?

The intensity of TSZ ~ n_e of free electrons, v_p

1. **Missing baryons:** likely in less dense region with lower T, but with n_e of free electrons, v_p

   KSZ effect is possible in answering the missing baryon problem.

2. **Reionization:** since the peculiar velocity three times the LCDM prediction in IGM from Planck, if the onset of Reionization happens at small redshift with low T,

   KSZ has the possibility to disclose the onset of the Reionization