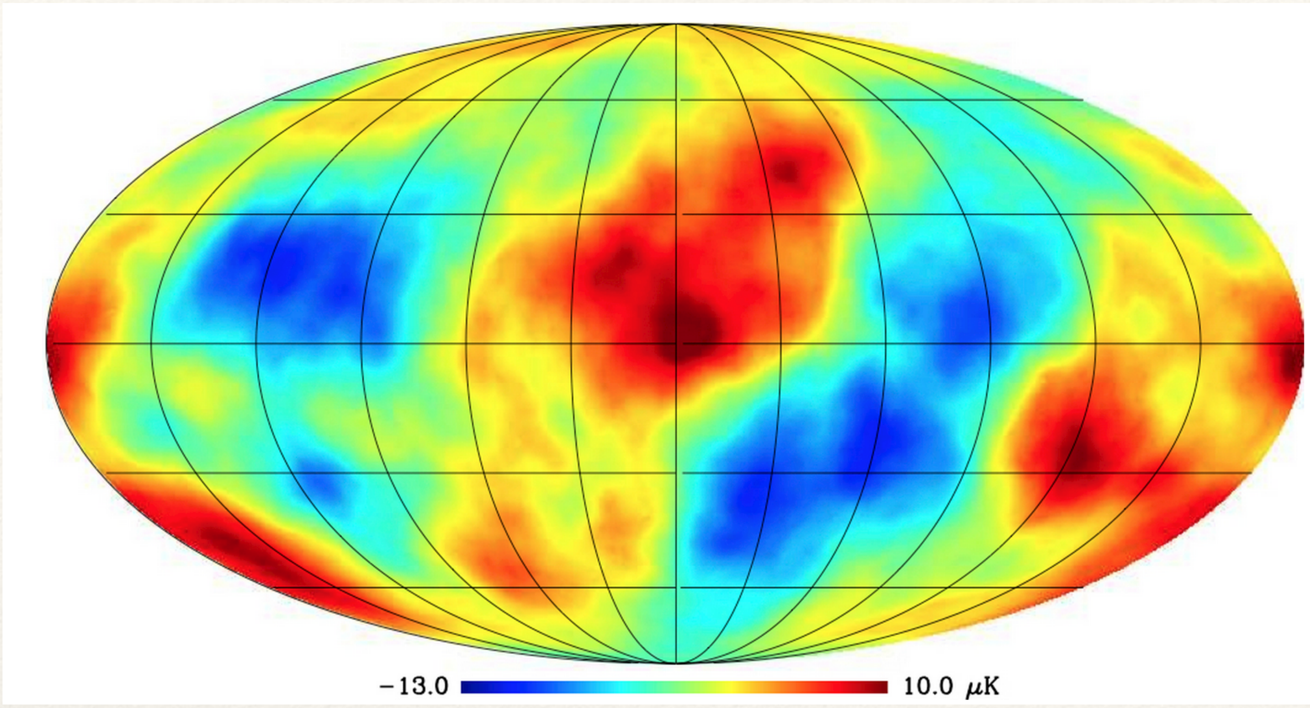
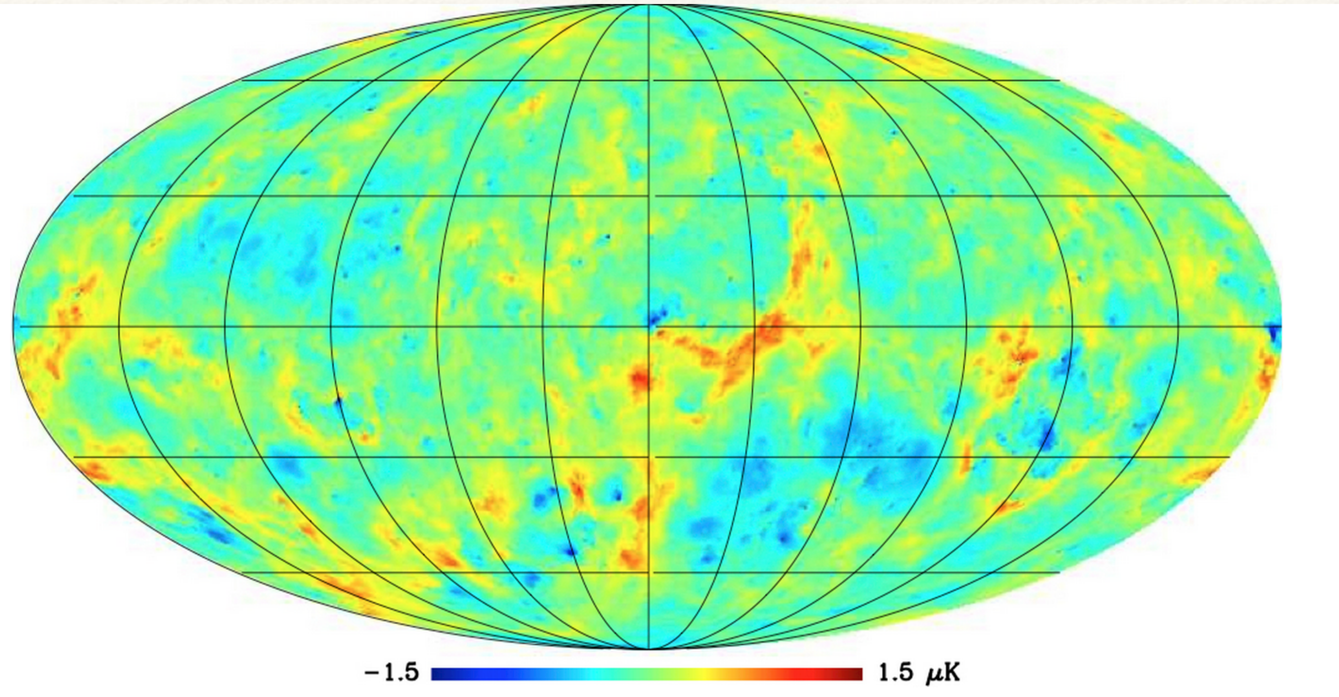
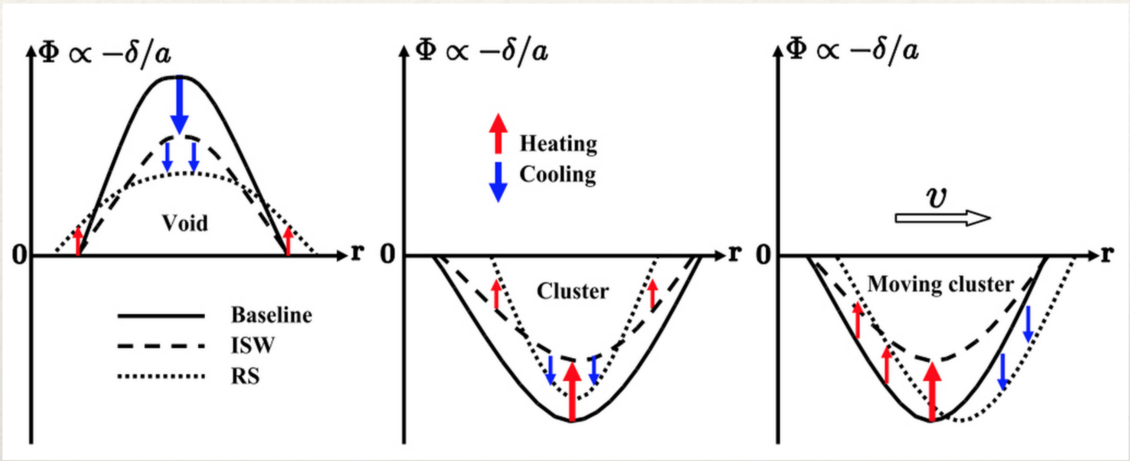






CosPA 2015 Oct.12-16. 2015 (IBS)

Probe of Dark Energy with CMB correlation with WL

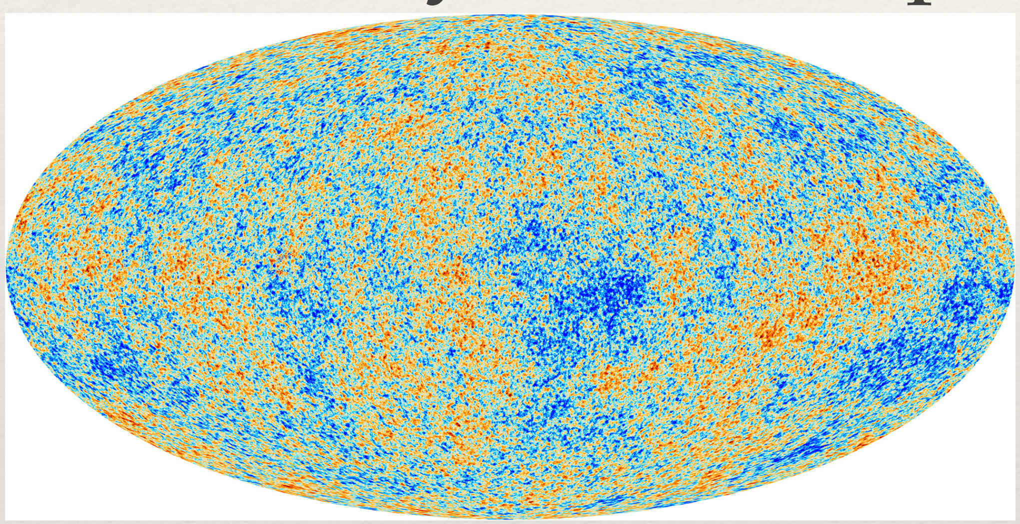
Seokcheon Lee (KIAS)

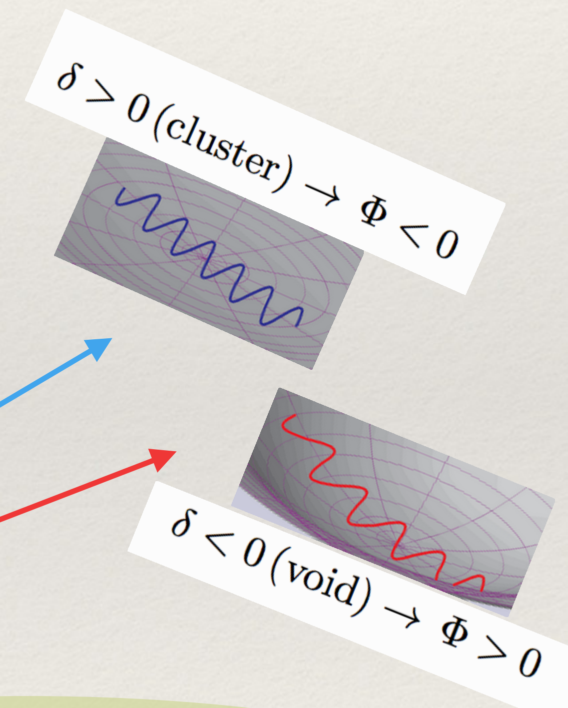
OUTLINE

- Large scale CMB anisotropy
- ISW vs RS
- Integrated Sachs-Wolfe effect (linear)
- Rees-Sciama effect (non-linear)
- Standard Perturbation Theory
- As a new probe for dark energy models
- Cross-correlation between RS and Weak Lensing
- Conclusions

LARGE SCALE CMB ANISOTROPY

- Time variation of gravitational Potential energy induces secondary CMB temperature fluctuation





$$\frac{\delta T}{T}(\hat{n}) = \left[\frac{1}{4}\delta_\gamma + \vec{v}\cdot\hat{n} + \Phi\right]_{\eta_*}^{\eta_0} + \int_{\eta_*}^{\eta_0} d\eta \left[\Phi'\Big(\eta, \hat{n}(\eta_0 - \eta_*)\Big) + \Psi'\Big(\eta, \hat{n}(\eta_0 - \eta_*)\Big)\right]$$

ISW VS RS

- Time variation of Φ induces
  - Integrated Sachs-Wolfe (ISW) effect (67) : linear regime (conserve primordial Gaussianity, no mode mixing)
  - Rees-Sciama (RS) effect (68) : non-linear regime (break Gaussianity, mode mixing)
- Capture the dynamics of the Univ

ISW EFFECT I

linear overdensity

$$\Phi = -\frac{3}{2}\Omega_{m0}H_0^2\frac{\delta}{ak} < 0$$

$$\Phi' = -\frac{3}{2}\Omega_{m0}H_0^2\frac{1}{ak}(\delta' - \mathcal{H}\delta) = -\frac{3}{2}\Omega_{m0}H_0^2\frac{1}{ak}\mathcal{H}\delta(f-1) > 0$$

- During the journey of γ from last scattering to the present, γ experiences the gravitational redshifts due to the time variation of Φ.

$$\Theta^{\rm ISW} \equiv \frac{\delta T}{T}^{\rm ISW}(\hat{n}) = 2\int_{\eta_*}^{\eta_0} d\eta \Phi'\Big(\eta, \hat{n}(\eta_0 - \eta_*)\Big)$$

- Contrary to γ, δ can grow and becomes non-linear
- From Poisson equation,

$$\Phi'(\vec{k},\eta) \simeq_{k \gg aH} -\frac{3}{2}\Omega_{m0}\left(\frac{H_0}{k}\right)^2\left(\frac{\delta(\vec{k},\eta)}{a}\right)' = -\frac{3}{2}\Omega_{m0}\left(\frac{H_0}{k}\right)^2\frac{1}{a}(\delta' - \mathcal{H}\delta)$$

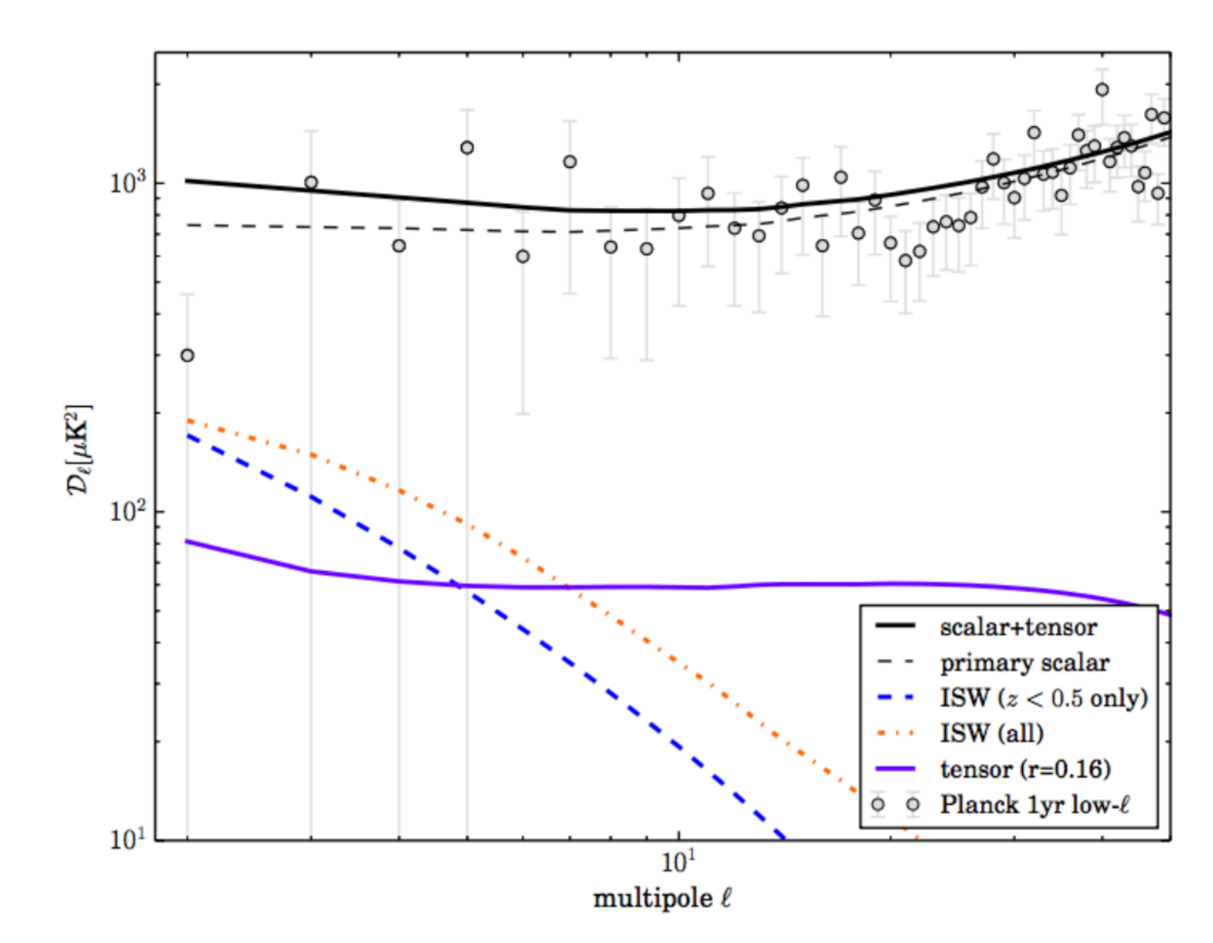
$$\simeq_{\rm lin} -\frac{3}{2}\Omega_{m0}\left(\frac{H_0}{k}\right)^2\frac{1}{a}(f-1)\mathcal{H}\delta$$

- CMB Power spectrum

$$C_l^{\rm ISW} = \left\langle \Theta_{lm}^{\rm ISW}\Theta_{lm}^{\rm ISW*}\right\rangle = \frac{18}{\pi}\Omega_{m0}^2 H_0^4 D^2(f-1)^2(H)^2\int dk P_{\rm lin}(k)\left[\int dr j_l(kr)\right]^2$$

ISW EFFECT II

- ISW contributes only at large angle (l < 50 = θ > 3 deg)



Nishizawa : 14

- Measuring ISW effect is limited by cosmic variance

RS EFFECT I

- Same as ISW effect, but one needs to consider non-linearity of δ

- There exits several ways to deal with non-linearity of δ (N-body sim, Standard Perturbation Theory, LPT, etc)

$$\Phi'(\vec{k},\eta) \simeq_{k\gg aH} -\frac{3}{2}\Omega_{m0}\left(\frac{H_0}{k}\right)^2\left(\frac{\delta(\vec{k},\eta)}{a}\right)' = -\frac{3}{2}\Omega_{m0}\left(\frac{H_0}{k}\right)^2\frac{1}{a}(\delta' - \mathcal{H}\delta)$$

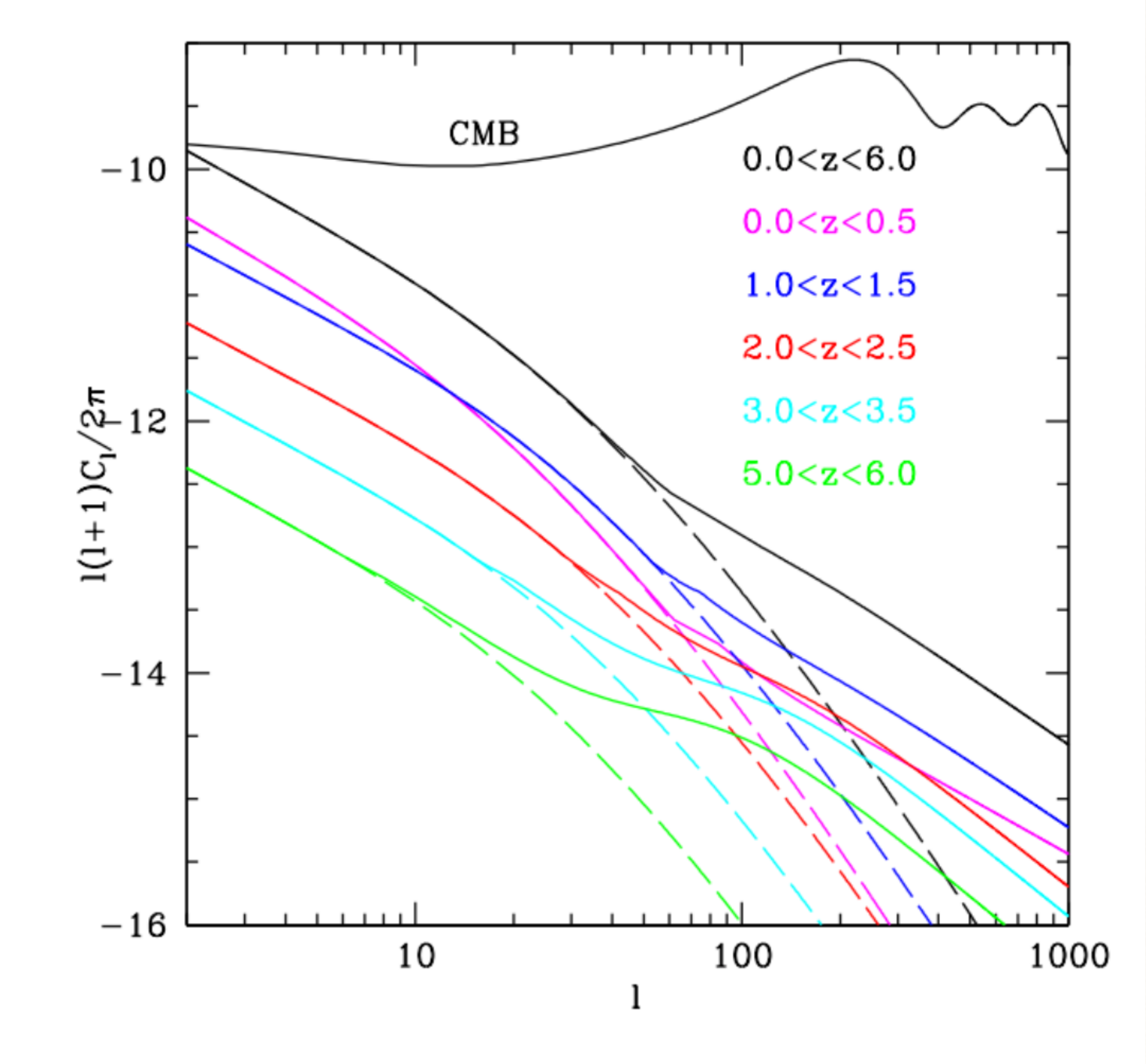
$$\simeq_{\rm SPT} -\frac{3}{2}\Omega_{m0}\left(\frac{H_0}{k}\right)^2\frac{1}{a}\sum_i^n(\delta^{(i)\prime} - \mathcal{H}\delta^{(i)})$$

- We adopt SPT which can investigate various DE model without too much time consuming

$$\delta^{(i)\prime}(\vec{k},\tau) = -\theta^{(i)}(\vec{k},\tau) - \sum_{j+k=i}\int d^3q_1\int d^3q_2\delta_{\rm D}(\vec{q}_{12}-\vec{k})\alpha(\vec{q}_1,\vec{q}_2)\theta^{(j)}(\vec{q}_1,\tau)\delta^{(k)}(\vec{q}_2,\tau)$$

RS EFFECT II

- RS effect on CMB power spectrum is too small to be measured



Cai et.al 08

CROSS-CORRELATION I

- Thus, CMB power spectrum is not good probe to measure ISW and RS effects.
- Angular cross-correlation power spectrum between the ISW and any tracers of the density field is rather promising.

$$P_{\Phi'\Phi} \equiv \left\langle \Phi'\Phi \right\rangle = \frac{9}{4}\Omega_{\rm m0}^2 \left(\frac{H_0}{k}\right)^4 \frac{1}{a^2} \left\langle \delta(\delta' - \mathcal{H}\delta) \right\rangle$$

$$= \frac{9}{4}\Omega_{\rm m0}^2 \left(\frac{H_0}{k}\right)^4 \frac{1}{a^2} \left(P_{\delta'\delta} - \mathcal{H} P_{\delta\delta} \right)$$

CROSS-CORRELATION II

$$
\begin{aligned}
F_2^{(s)}(a,\vec{k}_1,\vec{k}_2) &= \frac{1}{2}\left[c_{21}\left(\frac{\vec{k}_{12}\cdot\vec{k}_1}{k_1^2}+\frac{\vec{k}_{12}\cdot\vec{k}_2}{k_2^2}\right)-2c_{22}\frac{k_{12}^2(\vec{k}_1\cdot\vec{k}_2)}{k_1^2k_2^2}\right] \\
&= c_{21}-2c_{22}\left(\frac{\vec{k}_1\cdot\vec{k}_2}{k_1k_2}\right)^2+\frac{1}{2}\left(c_{21}-2c_{22}\right)\vec{k}_1\cdot\vec{k}_2\left(\frac{1}{k_1^2}+\frac{1}{k_2^2}\right), \\
G_2^{(s)}(a,\vec{k}_1,\vec{k}_2) &= \frac{1}{2}\left[-c_{\theta 21}\left(\frac{\vec{k}_{12}\cdot\vec{k}_1}{k_1^2}+\frac{\vec{k}_{12}\cdot\vec{k}_2}{k_2^2}\right)+2c_{\theta 22}\frac{k_{12}^2(\vec{k}_1\cdot\vec{k}_2)}{k_1^2k_2^2}\right] \\
&= -c_{\theta 21}+2c_{\theta 22}\left(\frac{\vec{k}_1\cdot\vec{k}_2}{k_1k_2}\right)^2-\frac{1}{2}\left(c_{\theta 21}-2c_{\theta 22}\right)\vec{k}_1\cdot\vec{k}_2\left(\frac{1}{k_1^2}+\frac{1}{k_2^2}\right)
\end{aligned}
$$

- By using SPT, we obtain

$$
\begin{aligned}
\sum_{i,j}\left\langle\delta^{(i)}(a,\vec{k})\delta^{(j)}(a,\vec{k}')\right\rangle &\equiv P_{\delta\delta}\delta_{\rm D}(\vec{k}+\vec{k}')=\left\langle\delta^{(1)}\delta^{(1)}\right\rangle+\left\langle\delta^{(2)}\delta^{(2)}\right\rangle+\left\langle\delta^{(1)}\delta^{(3)}\right\rangle+\left\langle\delta^{(3)}\delta^{(1)}\right\rangle \\
&\equiv P_{\rm lin}+P_{(22)}+P_{(13)}+P_{(31)} \\
\sum_{i,j}\left\langle\delta^{(i)\prime}(a,\vec{k})\delta^{(j)}(a,\vec{k}')\right\rangle &\equiv P_{\delta'\delta}\delta_{\rm D}(\vec{k}+\vec{k}')=-\left\langle\theta^{(1)}\delta^{(1)}\right\rangle-\left\langle\theta^{(2)}\delta^{(2)}\right\rangle-\left\langle\theta^{(3)}\delta^{(1)}\right\rangle \\
&-\left\langle\delta^{(3)}\theta^{(1)}\right\rangle-\left\langle\delta^{(1)}\theta^{(1)}\delta^{(2)}\right\rangle-\left\langle\delta^{(1)}\theta^{(2)}\delta^{(1)}\right\rangle-\left\langle\delta^{(2)}\theta^{(1)}\delta^{(1)}\right\rangle
\end{aligned}
$$

$$
P_{\delta'\delta}=-\left\langle\left(\theta^{(i)}(\vec{k},\tau)+\sum_{l+m=i}\int d^3q_1\int d^3q_2\delta_{\rm D}(\vec{q}_{12}-\vec{k})\alpha^{(l)}(\vec{q}_1,\vec{q}_2)\theta^{(m)}(\vec{q}_1,\tau)\delta(\vec{q}_2,\tau)\right)\delta^{(j)}(a,\vec{k}')\right\rangle
$$

- ISW cross-correlation : anti-correlated

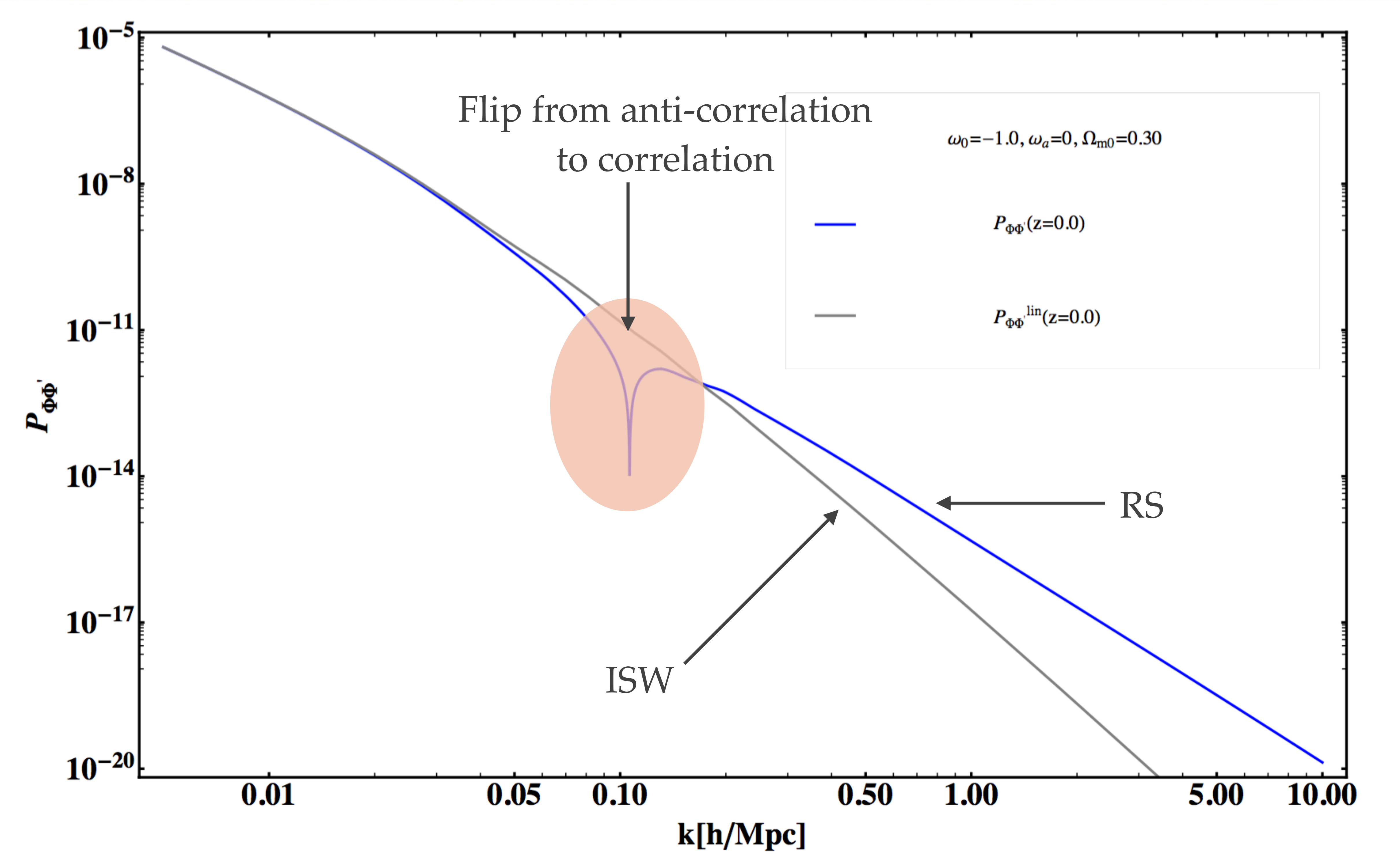
$$
P^{\rm ISW}_{\Phi'\Phi}=\frac{9}{4}\Omega_{\rm m0}^2\left(\frac{H_0}{k}\right)^4\frac{1}{a^2}\left(P^{\rm lin}_{\theta\delta}-\mathcal{H}P^{\rm lin}_{\delta\delta}\right)=\frac{9}{4}\Omega_{\rm m0}^2\left(\frac{H_0}{k}\right)^4\frac{1}{a^2}(f-1)\mathcal{H}P^{\rm lin}_{\delta\delta}
$$

$$
f\equiv\frac{d\ln\delta}{d\ln a}\simeq\Omega_{\rm m}(a)^\gamma\leq 1\;\rightarrow\;P^{\rm ISW}_{\Phi'\Phi}\leq 0
$$

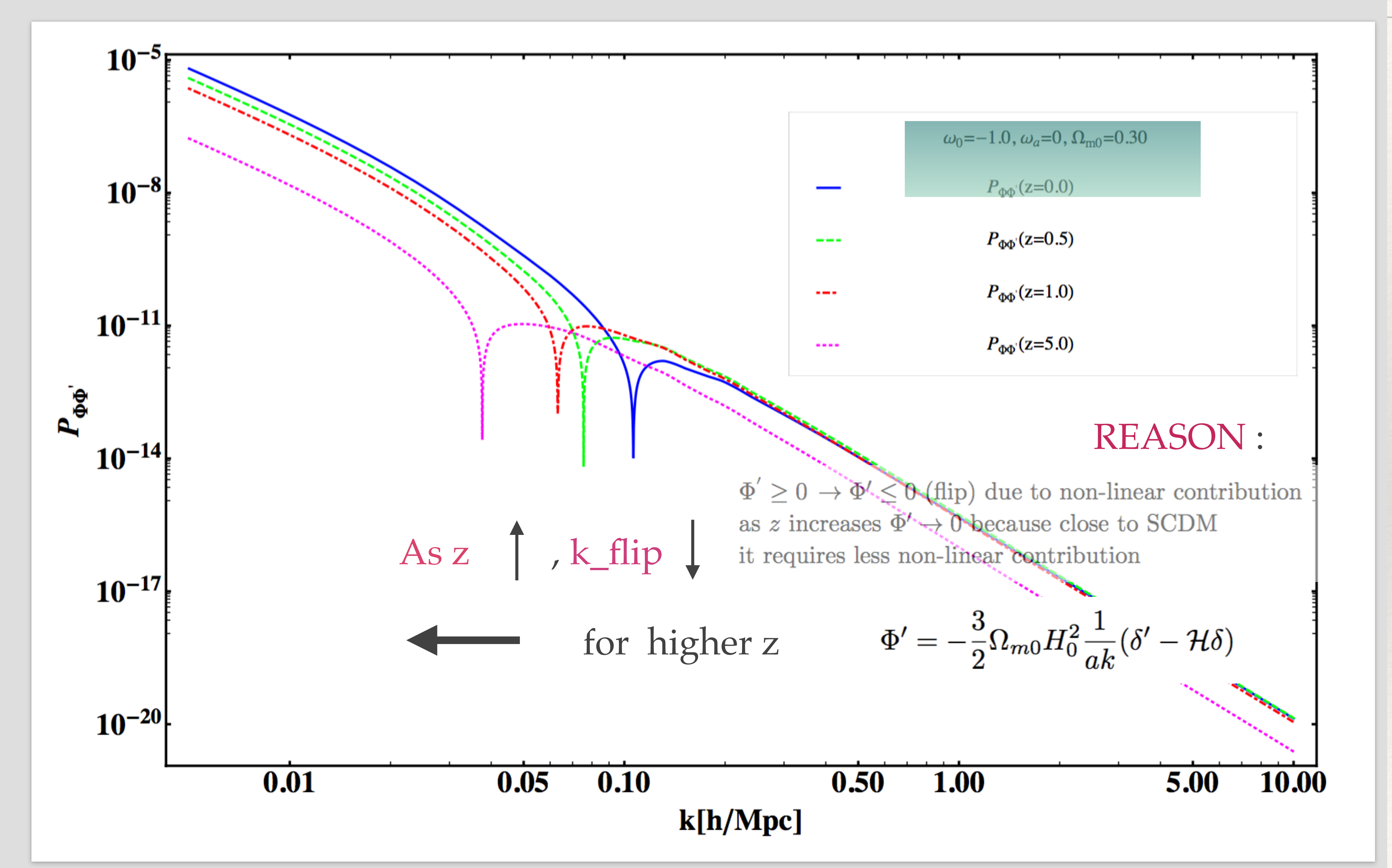
CROSS-CORRELATION III

- Full non-linear cross-correlation (we just consider up to two loops though, need N-body simulation. k ~ 1Mpc/h @ z= 0 is good approximation), sign of cross-correlation can be changed
- From anti-correlation to correlation
- We obtain cross-correlation for ΛCDM model

CROSS-CORRELATION III



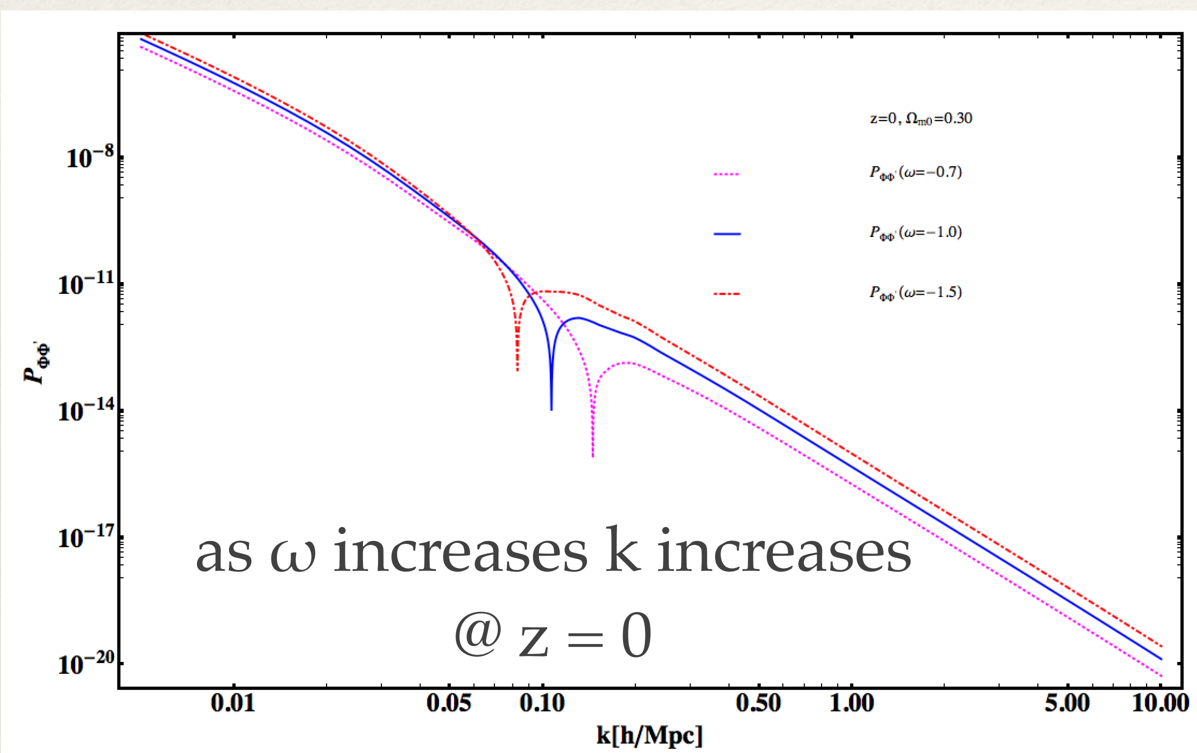
CROSS-CORRELATION III

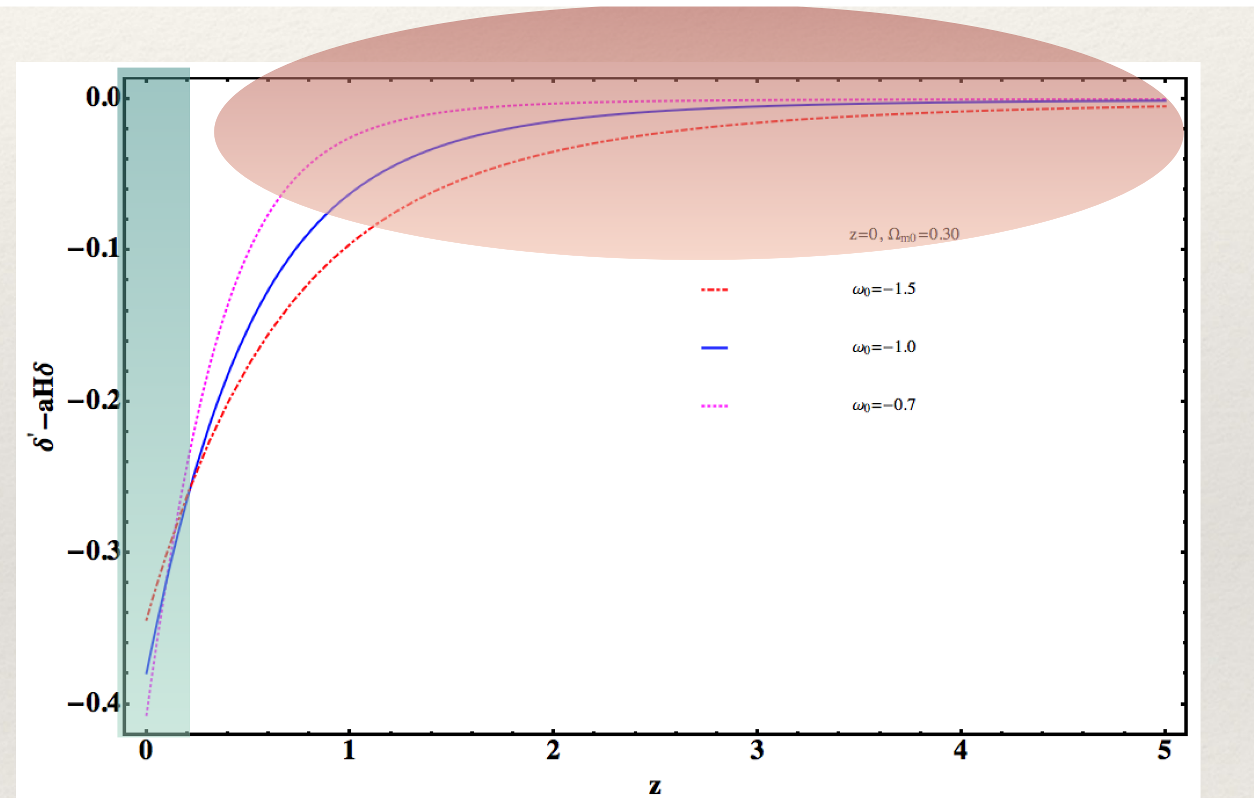


CROSS-CORRELATION IV

@ high z

$\omega \uparrow \Rightarrow \delta' - \mathcal{H}\delta \uparrow : k_{\text{flipping}} \downarrow =$ (need less non − linear contribution)

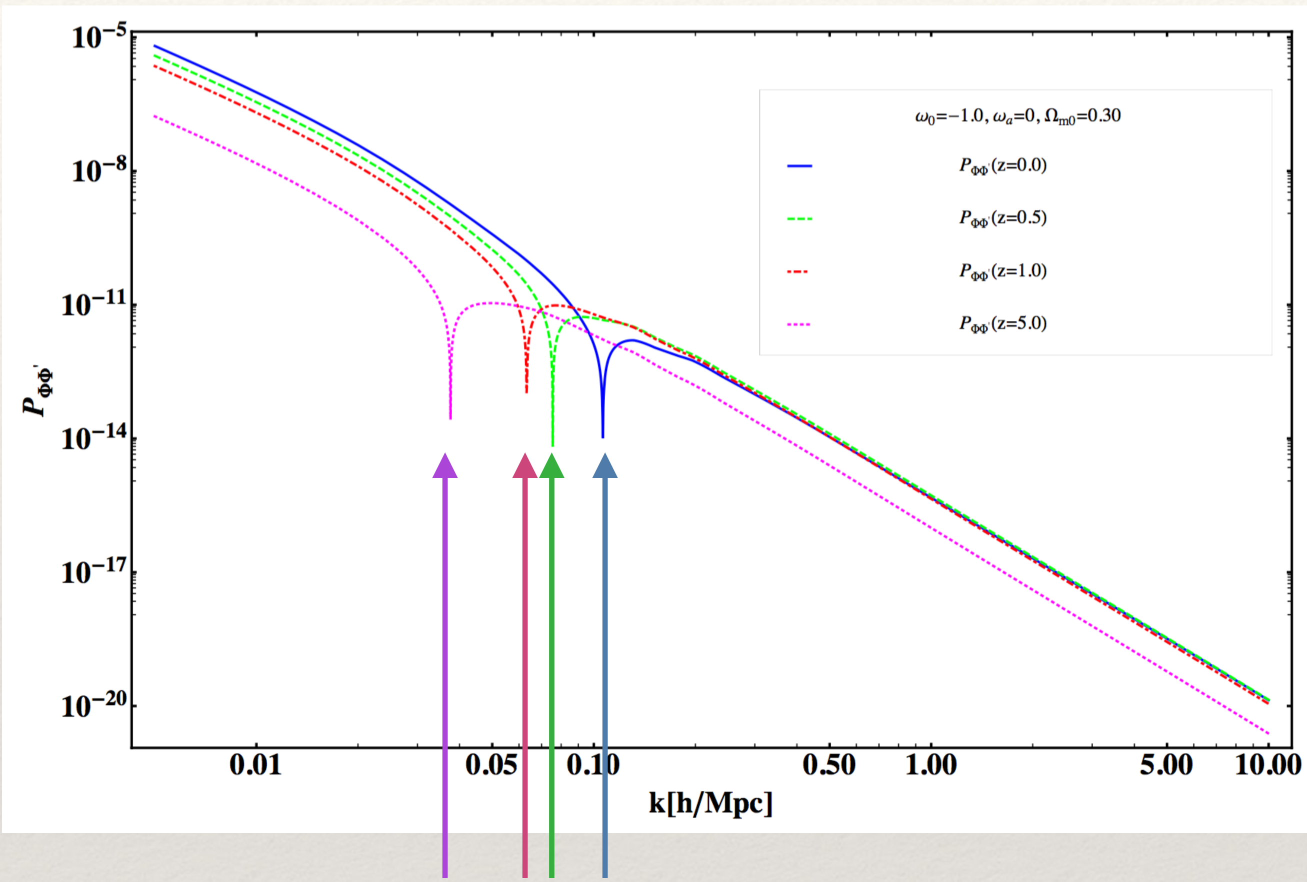


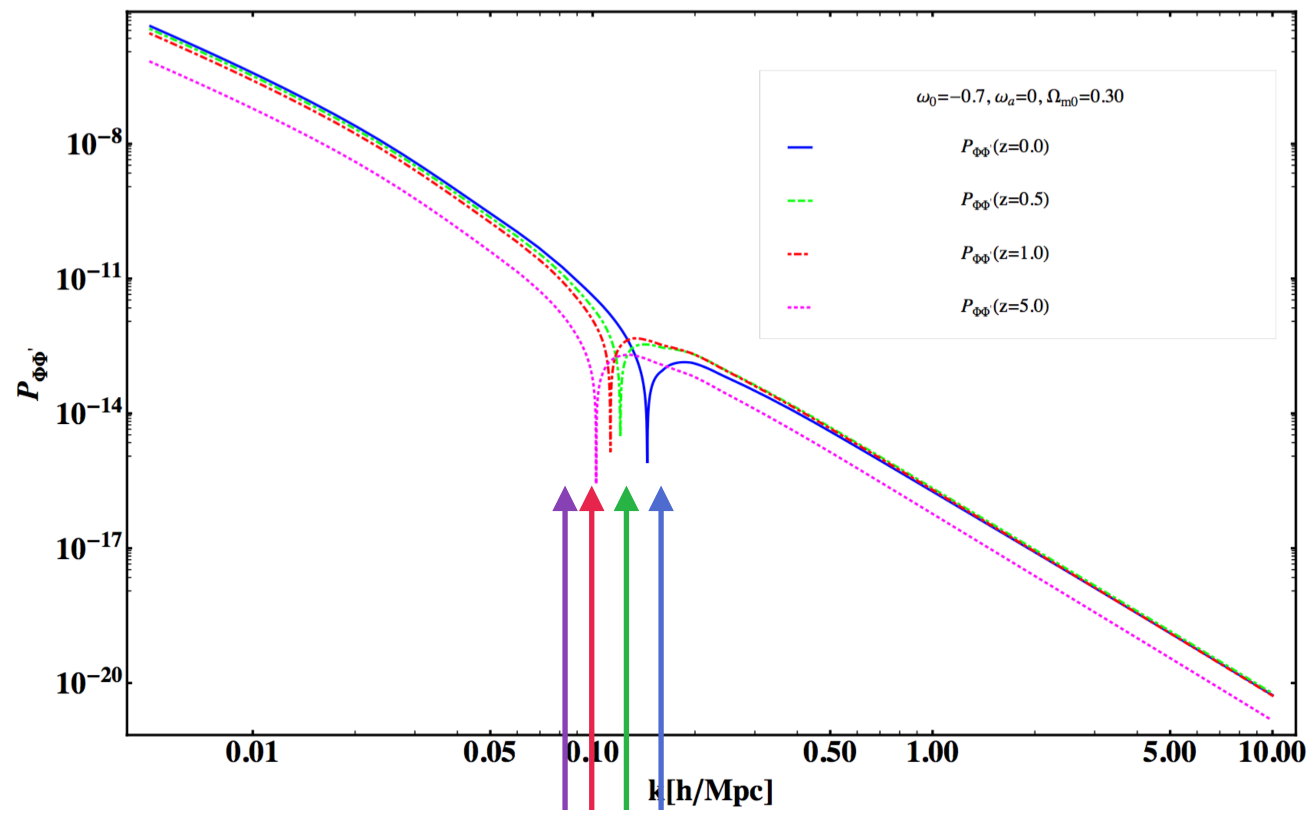


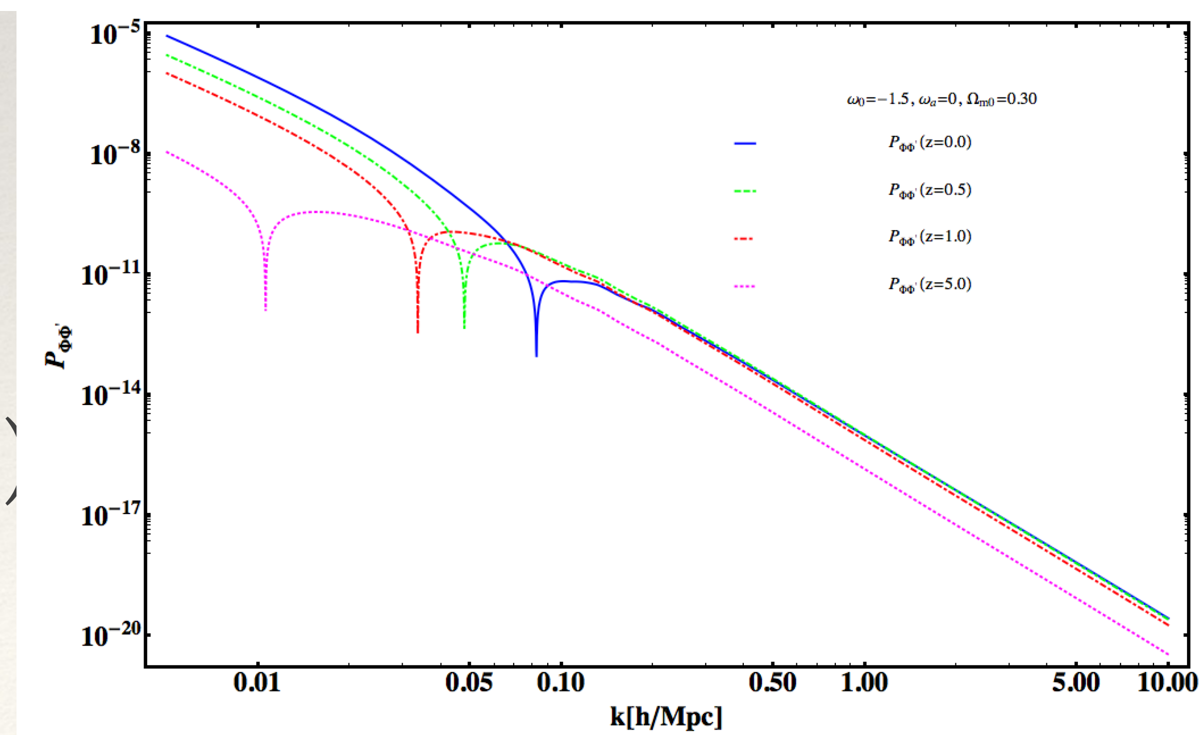
@ low z

$\omega \uparrow \Rightarrow \delta' - \mathcal{H}\delta \downarrow : k_{\text{flipping}} \uparrow =$ (need more non − linear contribution)

DE DEPENDENCE







- at z=0, k(w=-1.0) < k(w=-0.7)
- at z > 0.3, k(w=-.10) > k(w=-0.7)

OBSERVATION

- ISW effect was first detected in CMB measured by WMAP cross-correlated with LSS data traced by X-ray background radiation and radio galaxies (*Boughn & Critteden 04*)
- Planck 2015 : measure the correlation btw ISW and mass tracer $\left\langle \Theta \delta_{\rm LSS} \right\rangle = \left\langle \left(\Theta_{\rm ISW} + \Theta_{\rm dec} + \Theta_{\rm fg} + \Theta_{\rm SZ} + \Theta_{\rm lens} + \cdots \right) \delta_{\rm LSS} \right\rangle$ Not trivial

Weak Lensing

- As a tracer, it's good to use the weak lensing
- Thus, one needs to investigate the cross-correlation between RS and Weak Lensing (convergence, κ)

$$\kappa(z_s, \hat{n}) = \int_0^{r_s} W(r)\delta(r)dr \text{ , where } W(r) = \frac{3}{2}\Omega_m H_0^2 \int_0^{r_s} dr \frac{r(r_s - r)}{r_s}\frac{1}{a}$$

$$\kappa(\hat{n}) = \int_0^{z_s} dz_s n(z_s)\kappa(\hat{n}, z_s)$$

$$n(z) = Az^2 \exp[-(z/z_0)^\beta]$$

$$C_l^{\text{RS}-\kappa}(z_s) = \left\langle a_{lm}^{\text{ISW}}(\vec{k}) a_{l'm'}^{\kappa *}(\vec{k}', z_s) \right\rangle = \frac{4}{\pi}\int dk k^4 \int_0^{r_*} dr \int_0^{r_s} dr' \frac{r'(r_s - r')}{r_s} P_{\Phi\Phi'}(k, r, r') j_l(kr) j_l(kr')$$

$$\simeq 2l^2 \int_0^{r_s} dr' \frac{r_s - r}{r^3 r_s} P_{\Phi\Phi'}(k = \frac{l}{r}, r)\Big|_{k=l/r}$$

$$C_l^{\text{RS}-\kappa} = \int_0^{z_s} dz_s n(z_s) C_l^{\text{RS}-\kappa}(z_s)$$

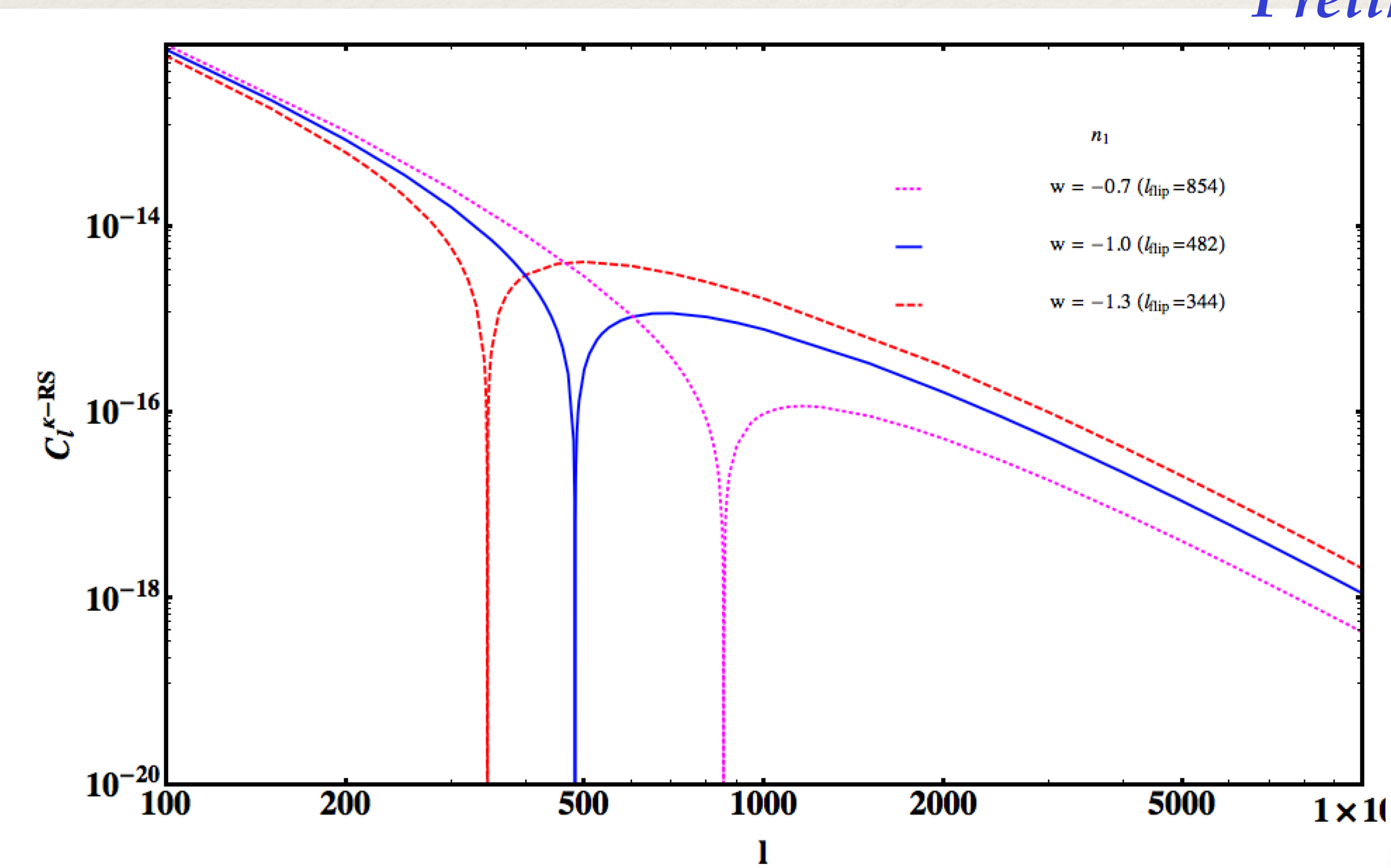
RS-WL Cross correlation

Weak point : no z-dependence
needs to integrate for z_s

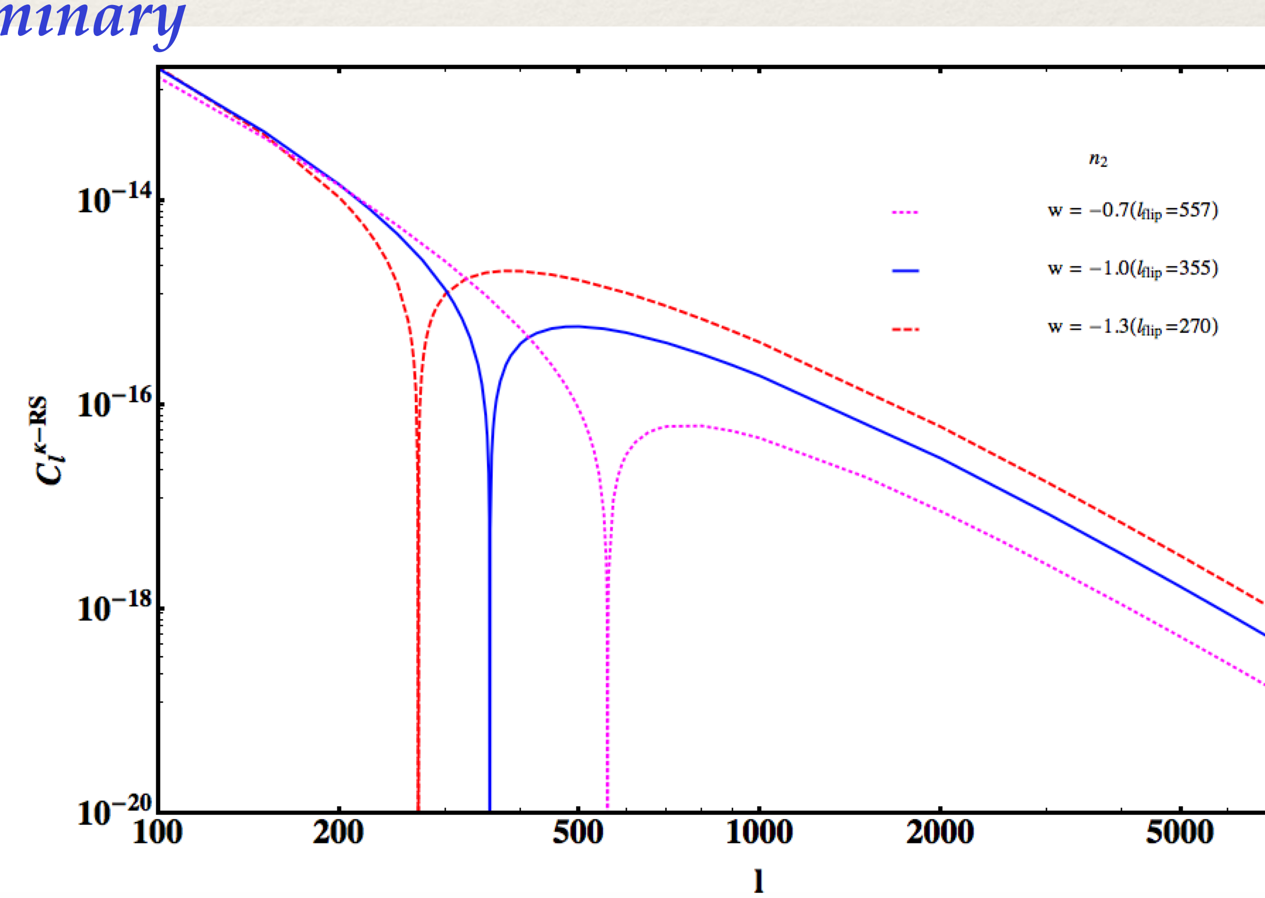
$$n(z) = Az^2 \exp[-(z/z_0)^\beta]$$

- Results for shallow and deep surveys

Preliminary



$n_1 : \beta = 0.7, z_0 = 0.5$(Deep survey)



$n_2 : \beta = 2.0, z_0 = 0.9$(Shallow survey)

RS-WL CC S/N

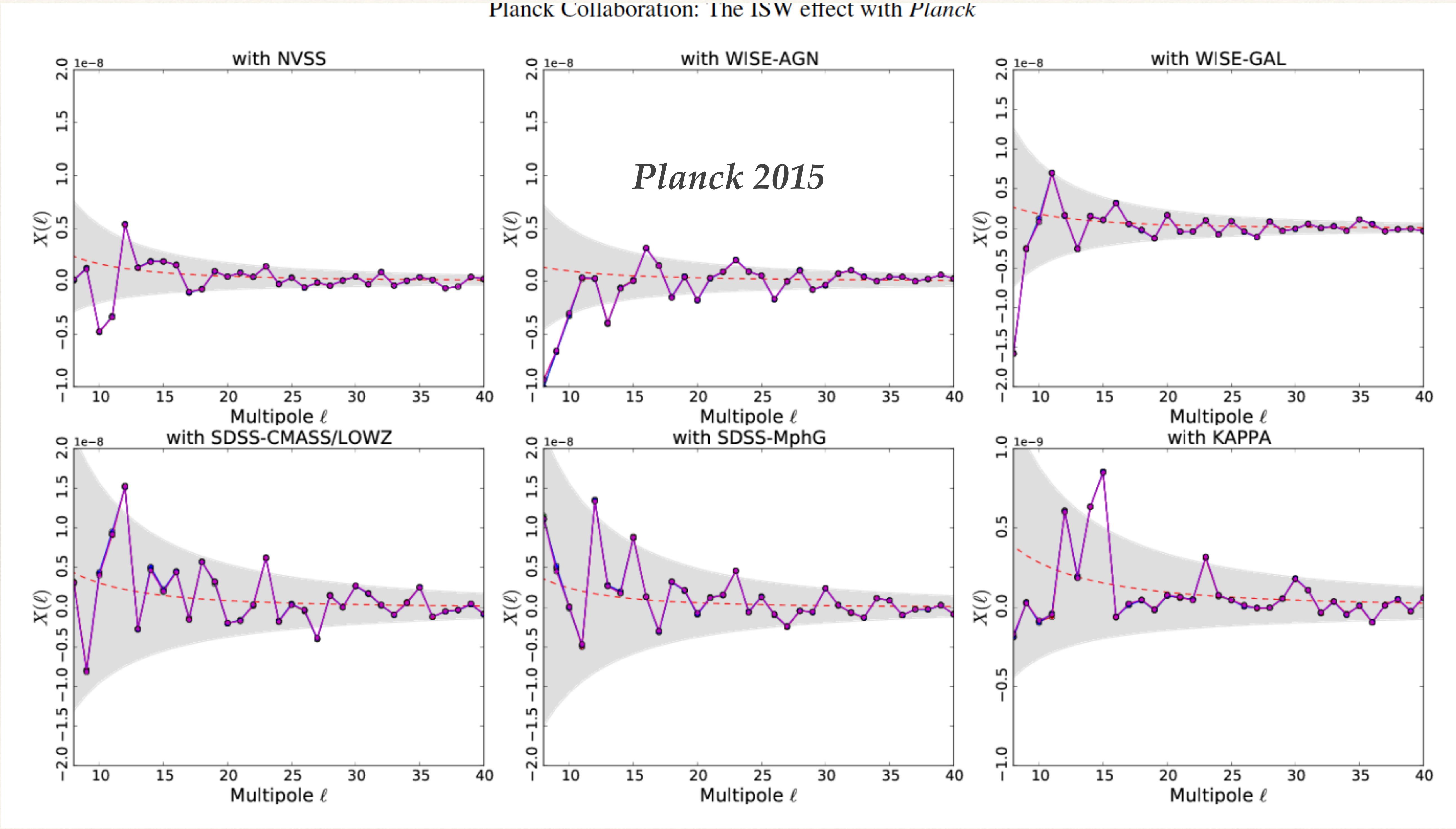
- To investigate the significance of detection, one needs to quantify the signal to noise ratio (S/N)

$$\left(\frac{S}{N}\right)^2_l \simeq f_{\rm sky} {\rm Cov}_l^{-1} (C_l^{{\rm RS}-\kappa})^2$$

$${\rm Cov}_l = \frac{\widetilde{C}_l^{\rm CMB} \widetilde{C}_l^{\kappa} + (C_l^{{\rm RS}-\kappa})^2}{2l+1}$$

- All sky CMB and WL : S/N ~ 50 (10) for Deep (shallow)
- 1000 sqdgr surveys : S/N ~ 7 (1) : *from Komatsu et.al (08)*

OBSERVATION



CONCLUSIONS

- RS effect (non-linear) can be distinguished from ISW effect (linear)
- ISW effect shows the anti-correlation between ISW and mass tracers
- RS effect gives the correlation between ISW and mass tracers
- This might be used as a new method to probe DE
- There exits dependences of flipping scale on galaxy distribution (weak / strong point?)