Constraints on the dark matter and dark energy interactions from weak lensing bispectrum tomography

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Outline

- Dark Matter and Dark Energy Interaction
- Weak Lensing
- Fisher Matrix Analysis
- Conclusions

Dark matter and dark energy interaction

- Background

$$\dot{\rho}_{dm} + 3H\rho_{dm} = Q$$

$$\dot{\rho}_{de} + 3H(1+\omega)\rho_{de} = -Q$$

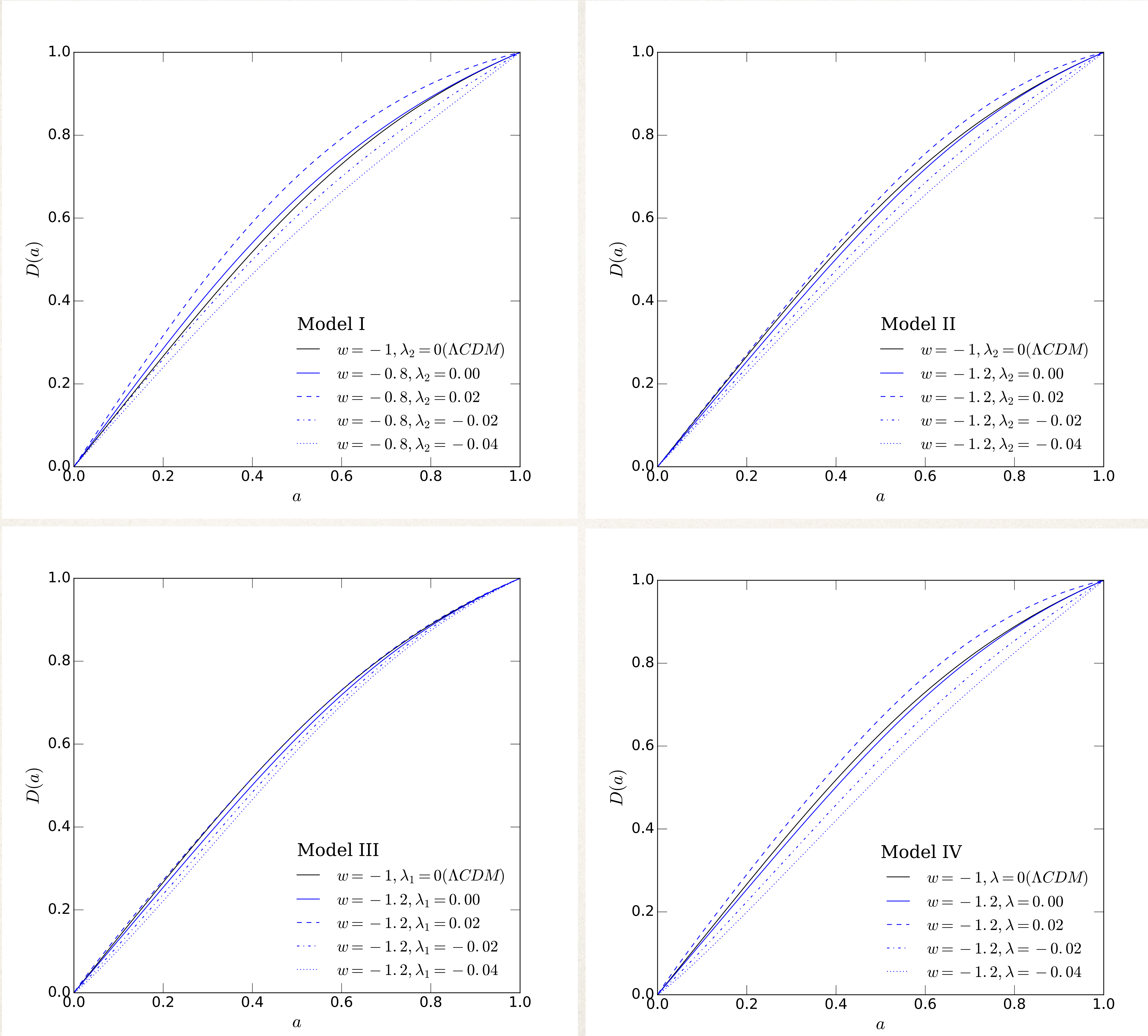
where

$$Q = 3\lambda_1 H\rho_{dm} + 3\lambda_2 H\rho_{de}$$

Model	Q	ω
I	$3\lambda_2 H\rho_{de}$	$-1 < \omega < -1/3$
II	$3\lambda_2 H\rho_{de}$	$\omega < -1$
III	$3\lambda_1 H\rho_{dm}$	$\omega < -1$
IV	$3\lambda H(\rho_{dm} + \rho_{de})$	$\omega < -1$
V	0	$\omega < -1/3$

- Matter density perturbation $\delta_{dm}(k,a) = \frac{\rho_{dm} - \langle\rho_{dm}\rangle}{\langle\rho_{dm}\rangle} = D(a)\delta_{dm}(k,1)$

$$\frac{\mathrm{d}^2 D}{\mathrm{d}a^2} + \frac{1}{a}\left[\frac{3}{2} - \frac{3}{2}\omega(1-\Omega_{dm}) + 3\lambda_1 + 6\frac{\lambda_2}{r}\right]\frac{\mathrm{d}D}{\mathrm{d}a}$$
$$= \frac{1}{a^2}\left[\frac{3}{2}\Omega_{dm} - 3\frac{\lambda_2}{r}\left(2 + 3\lambda_1 + 3\frac{\lambda_2}{r} - \frac{\ln r}{\ln a} + \frac{\mathrm{d}\ln H}{\mathrm{d}\ln a}\right)\right]D, \quad \text{where } r = \frac{\rho_{dm}}{\rho_{de}}$$



Model I
$w=-1, \lambda_2=0(\Lambda CDM)$
$w=-0.8, \lambda_2=0.00$
$w=-0.8, \lambda_2=0.02$
$w=-0.8, \lambda_2=-0.02$
$w=-0.8, \lambda_2=-0.04$
Model II
$w=-1, \lambda_2=0(\Lambda CDM)$
$w=-1.2, \lambda_2=0.00$
$w=-1.2, \lambda_2=0.02$
$w=-1.2, \lambda_2=-0.02$
$w=-1.2, \lambda_2=-0.04$
Model III
$w=-1, \lambda_1=0(\Lambda CDM)$
$w=-1.2, \lambda_1=0.00$
$w=-1.2, \lambda_1=0.02$
$w=-1.2, \lambda_1=-0.02$
$w=-1.2, \lambda_1=-0.04$
Model IV
$w=-1, \lambda=0(\Lambda CDM)$
$w=-1.2, \lambda=0.00$
$w=-1.2, \lambda=0.02$
$w=-1.2, \lambda=-0.02$
$w=-1.2, \lambda=-0.04$
$D(a)$
a

Weak lensing

- Weak lensing convergence field

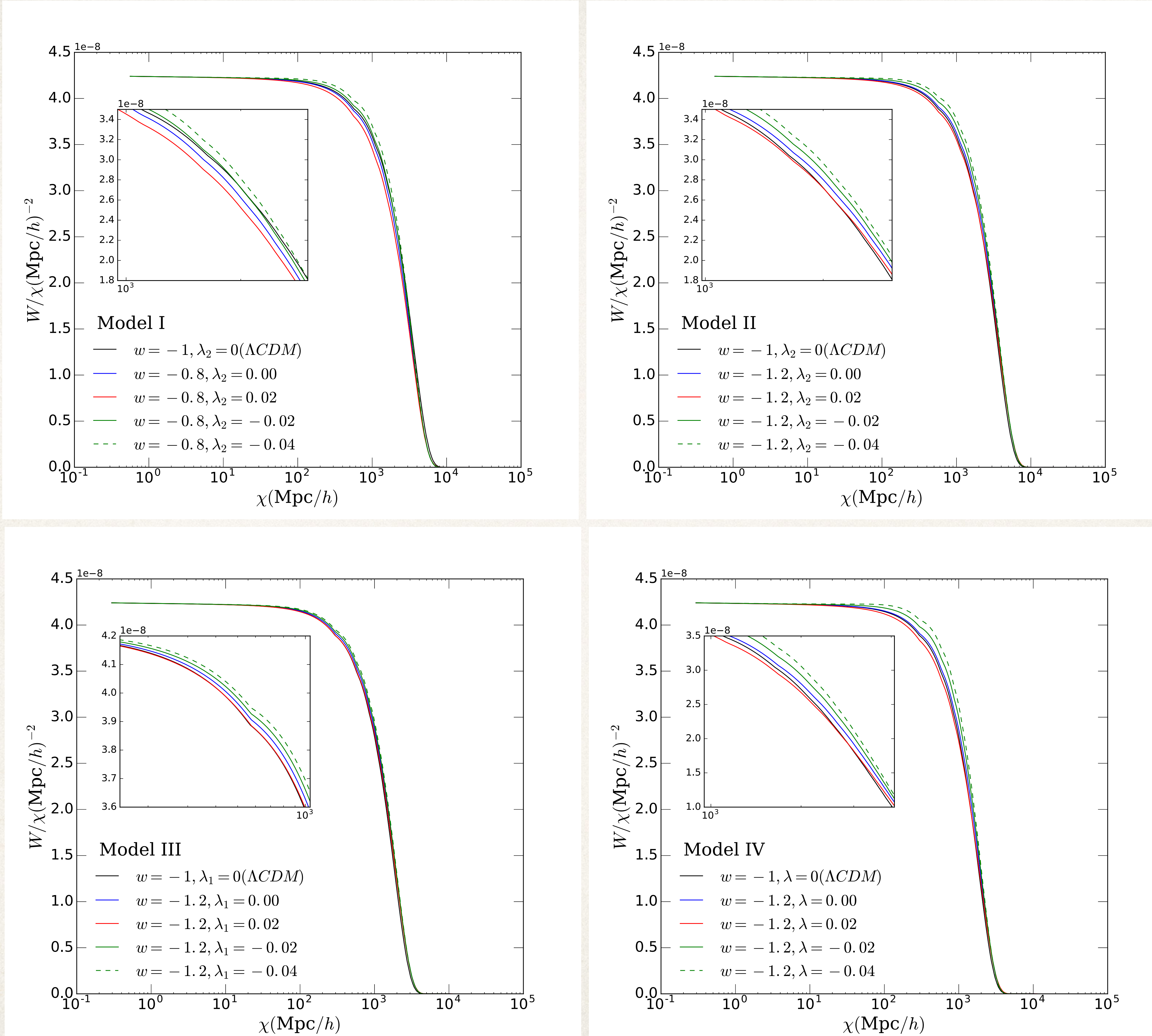
$$\kappa(\boldsymbol{\theta}) = \int_0^{\chi_H} d\chi W(\chi)\delta[\chi\boldsymbol{\theta}, \chi]$$

- Lensing weighting function

$$W(\chi) = \frac{3}{2c^2} a(\chi)^2 H(\chi)^2 \Omega_{dm}(\chi)\chi \int_\chi^{\chi_H} d\chi' p(z) \frac{dz}{d\chi'} \frac{\chi' - \chi}{\chi'}$$

- Normalized redshift distribution of lensing galaxies

$$p(z) = \frac{\beta}{\Gamma\left(\frac{3}{\beta}\right)} \left(\frac{z^2}{{z_0}^3}\right) \exp[-(\frac{z}{z_0})^\beta] \text{ with } \beta = \frac{3}{2}, z_0 = 0.64$$



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$w=-1.2, \lambda=0.00$
$w=-1.2, \lambda=0.02$
$w=-1.2, \lambda=-0.02$
$w=-1.2, \lambda=-0.04$
$W/\chi(\mathrm{Mpc}/h)^{-2}$
$\chi(\mathrm{Mpc}/h)$
1e−8

Weak lensing

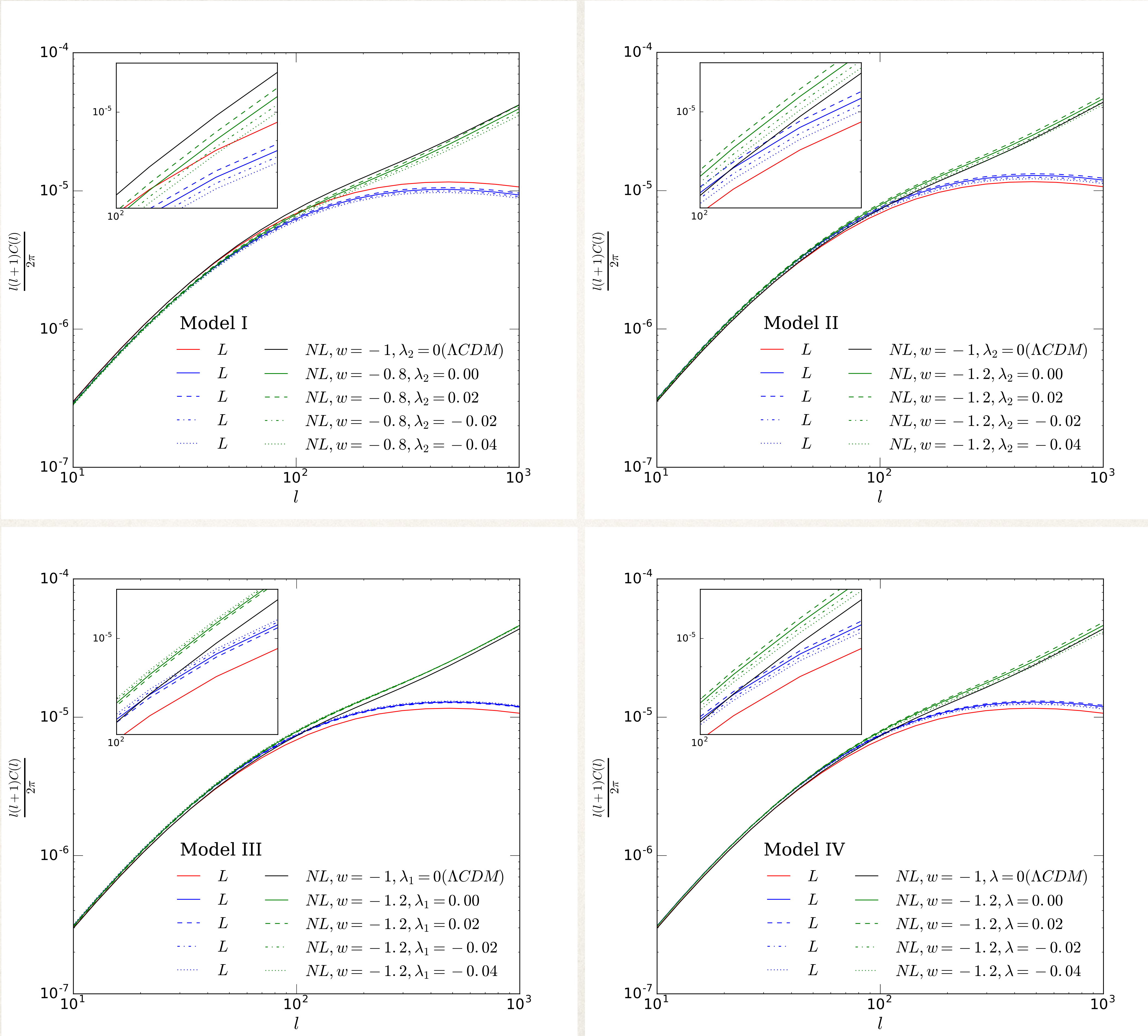
- Weak lensing convergence power spectrum

$$\left\langle \kappa^{(i)}_{l_1 m_1} \kappa^{(j)}_{l_2 m_2} \right\rangle = \delta_{l_1 m_1} \delta_{l_2 m_2} C^{(ij)}_{l_1}, \text{ where } \kappa_{lm} = \int d\boldsymbol{\theta} \kappa(\boldsymbol{\theta}) Y^*_{lm}$$

$$C^{(ij)}_l = \int_0^{\chi_H} d\chi \, W^{(i)}(\chi) W^{(j)}(\chi) \chi^{-2} P_\delta(\frac{l}{\chi}, \chi)$$

- Lensing weighting function in redshift bin *i*

$$W^{(i)}(\chi) = \begin{cases} \frac{3}{2c^2} a(\chi)^2 H(\chi)^2 \Omega_c(\chi) \chi \int_{\max(\chi, \chi_i)}^{\chi_{i+1}} d\chi' p(z) \frac{dz}{d\chi'} \frac{\chi' - \chi}{\chi'}, & \chi \le \chi_{i+1} \\ 0, & \chi > \chi_{i+1} \end{cases}$$



Model I
L
$NL, w=-1, \lambda_2=0(\Lambda CDM)$
$NL, w=-0.8, \lambda_2=0.00$
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Model III
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$NL, w=-1.2, \lambda_1=0.00$
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$NL, w=-1.2, \lambda_1=-0.02$
$NL, w=-1.2, \lambda_1=-0.04$
Model IV
$NL, w=-1, \lambda=0(\Lambda CDM)$
$NL, w=-1.2, \lambda=0.00$
$NL, w=-1.2, \lambda=0.02$
$NL, w=-1.2, \lambda=-0.02$
$NL, w=-1.2, \lambda=-0.04$
$\frac{l(l+1)C(l)}{2\pi}$
l

Weak lensing

- Weak lensing convergence bispectrum

$$\left\langle \kappa^{(i)}_{l_1 m_1} \kappa^{(j)}_{l_2 m_2} \kappa^{(k)}_{l_3 m_3} \right\rangle = \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B^{(ijk)}_{l_1, l_2, l_3}$$

$$B^{(ijk)}_{l_1, l_2, l_3} \approx \begin{pmatrix} l_1 & l_2 & l_3 \\ 0 & 0 & 0 \end{pmatrix} \sqrt{\frac{\prod_{p=1}^{3}(2l_p + 1)}{4\pi}} B_{(ijk)}(\boldsymbol{l}_1, \boldsymbol{l}_2, \boldsymbol{l}_3)$$

$$B_{(ijk)}(\boldsymbol{l}_1, \boldsymbol{l}_2, \boldsymbol{l}_3) = \int_0^{\chi_H} d\chi\, W^{(i)}(\chi) W^{(j)}(\chi) W^{(k)}(\chi) \chi^{-4} B_\delta(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)$$

where $\boldsymbol{k} = \boldsymbol{l} / \chi$

Weak lensing

- Three-dimensional matter bispectrum

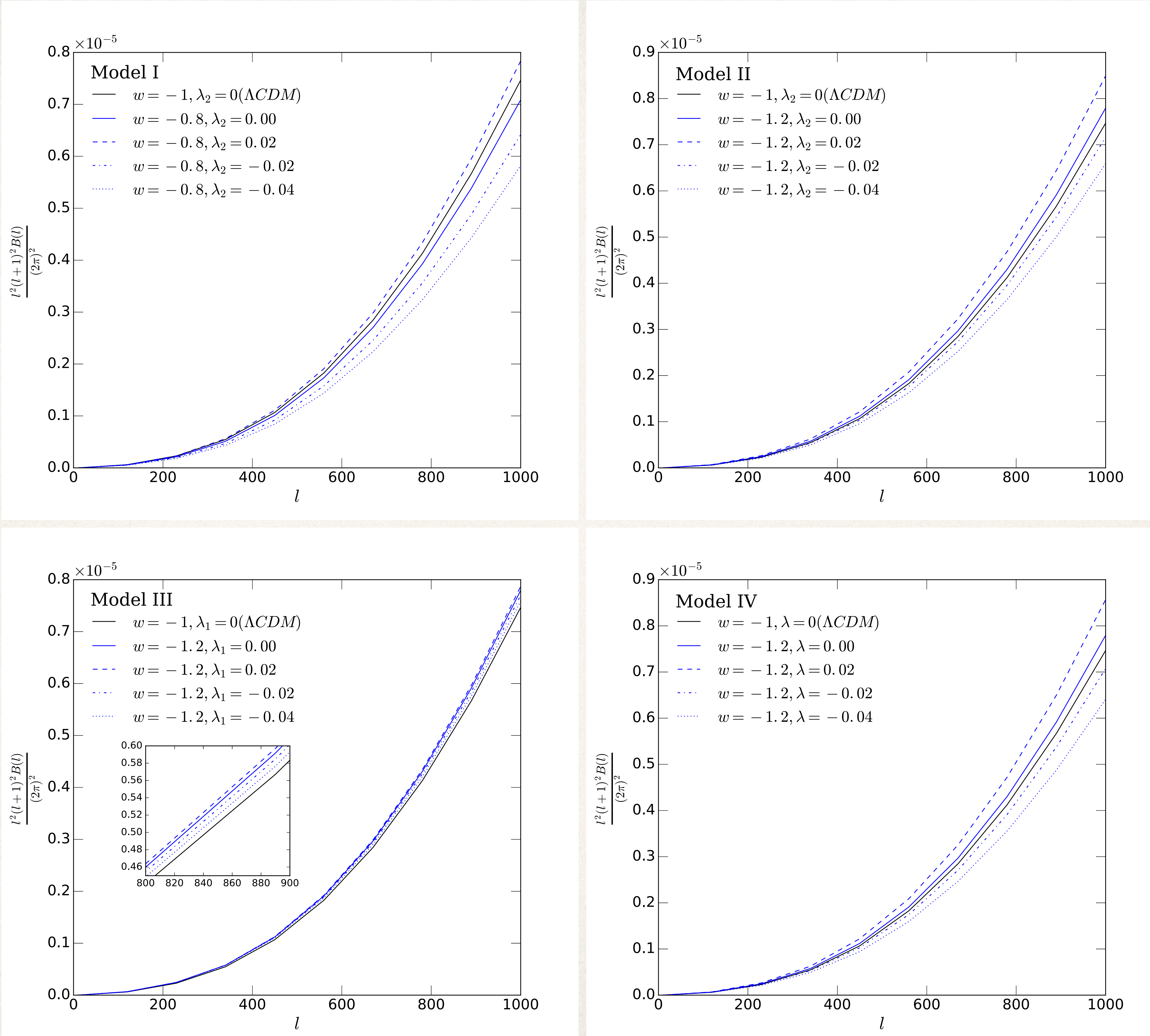
$$B_\delta(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3) = 2F_2(\boldsymbol{k}_1, \boldsymbol{k}_2)P_\delta(\boldsymbol{k}_1, z)P_\delta(\boldsymbol{k}_2, z) + 2perm$$

where

$$F_2(\boldsymbol{k}_1, \boldsymbol{k}_2) = \frac{5}{7}a(n, k_1)a(n, k_2) + \frac{1}{2}\left(\frac{k_1}{k_2} + \frac{k_2}{k_1}\right)\frac{\boldsymbol{k_1} \cdot \boldsymbol{k_2}}{k_1 k_2}b(n, k_1)b(n, k_2)$$

$$+\frac{2}{7}\left(\frac{\boldsymbol{k_1} \cdot \boldsymbol{k_2}}{k_1 k_2}\right)^2 c(n, k_1)c(n, k_2)$$

$a(n, k)$,$b(n, k)$ and $c(n, k)$ are fitting functions given by H. Gil-Marin 2012



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$w=-1.2, \lambda=0.02$
$w=-1.2, \lambda=-0.02$
$w=-1.2, \lambda=-0.04$
$\times 10^{-5}$
$\frac{l^2(l+1)^2 B(l)}{(2\pi)^2}$
l

Fisher matrix analysis

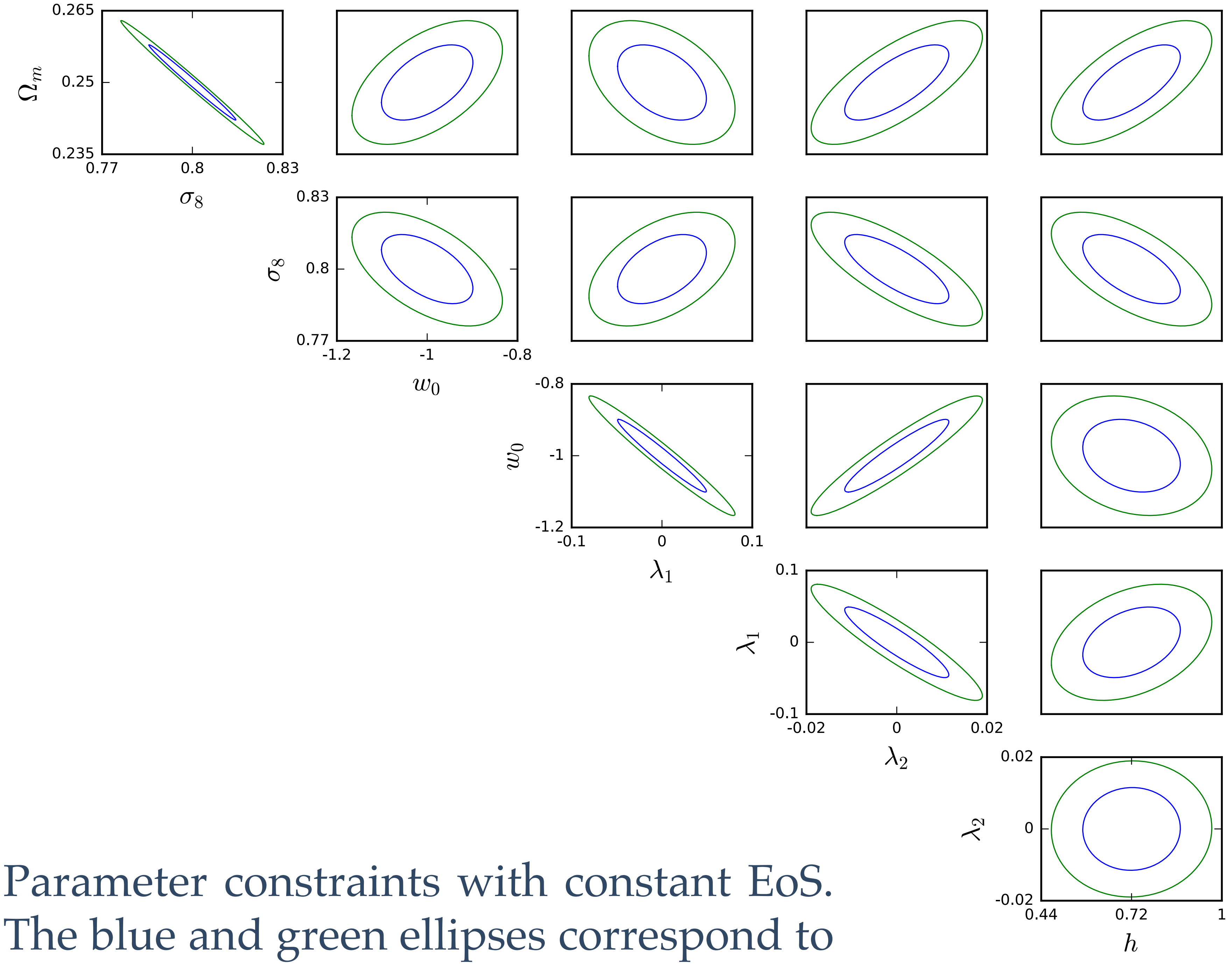
- Comparisons between different weak lensing probes

Fiducial Model (ΛCDM)	**Power spectrum without any tomography**	**Bispectrum without any tomography**	**Bispectrum with a two-bin tomography**
$\Omega_{dm0} = 0.25$	$\Delta\Omega_{dm0} = 0.017674$	$\Delta\Omega_{dm0} = 0.010537$	$\Delta\Omega_{dm0} = 0.007350$
$\sigma_8 = 0.8$	$\Delta\sigma_8 = 0.030334$	$\Delta\sigma_8 = 0.023986$	$\Delta\sigma_8 = 0.013507$
$\omega_0 = -1$	$\Delta\omega_0 = 0.748681$	$\Delta\omega_0 = 0.182274$	$\Delta\omega_0 = 0.094660$
$\lambda_1 = 0$	$\Delta\lambda_1 = 0.119159$	$\Delta\lambda_1 = 0.093232$	$\Delta\lambda_1 = 0.045974$
$\lambda_2 = 0$	$\Delta\lambda_2 = 0.038550$	$\Delta\lambda_2 = 0.037720$	$\Delta\lambda_2 = 0.010776$
$h = 0.72$	$\Delta h = 0.481874$	$\Delta h = 0.236921$	$\Delta h = 0.141352$

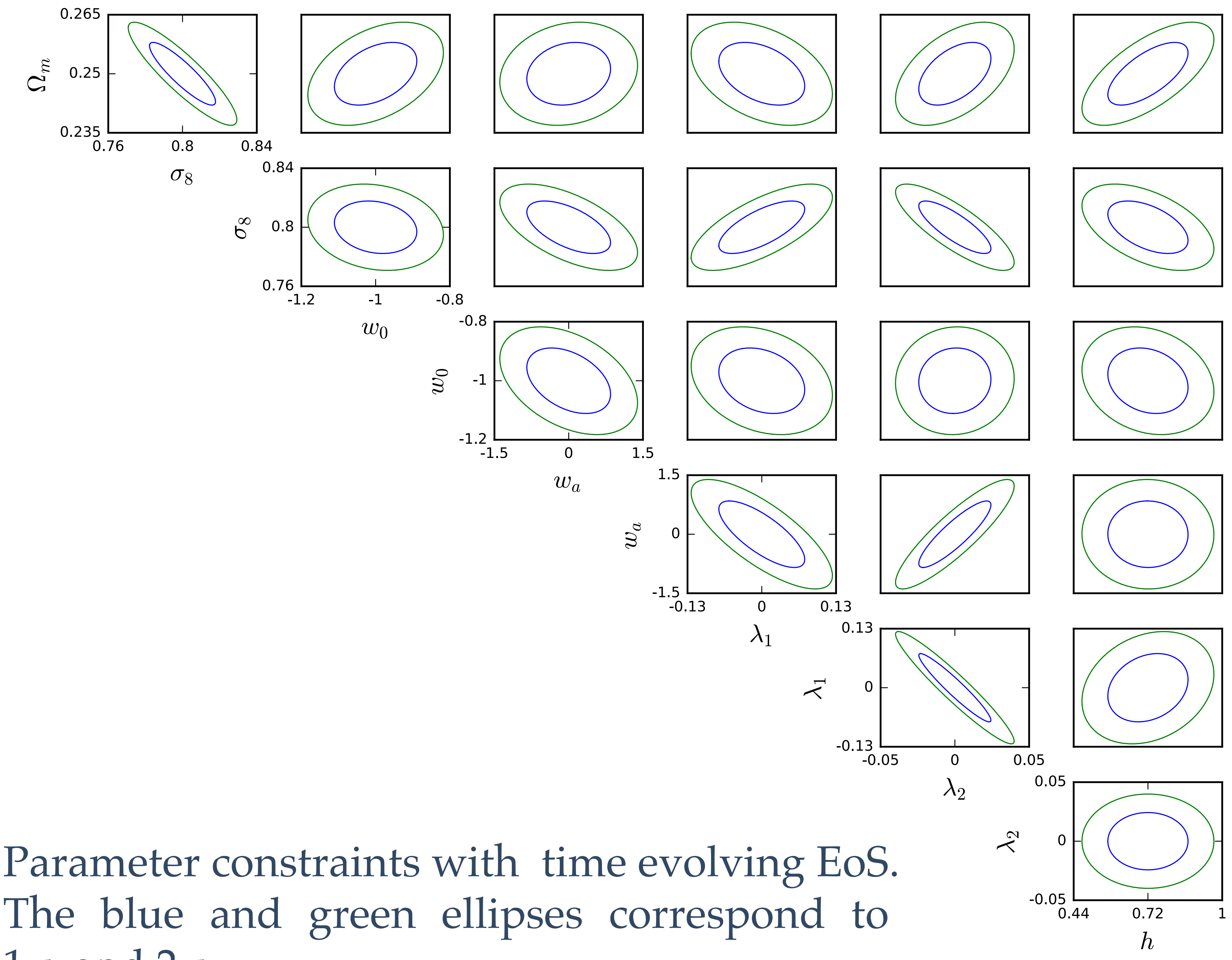
Fisher matrix analysis

- Expected accuracy on the parameters from two-bin weak lensing tomography

Fiducial Model (ΛCDM)	$\boldsymbol{\omega = \omega_0}$	$\boldsymbol{\omega = \omega_0 + \omega_a(1 - a)}$
$\Omega_{dm0} = 0.25$	$\Delta\Omega_{dm0} = 0.007350$	$\Delta\Omega_{dm0} = 0.007446$
$\sigma_8 = 0.8$	$\Delta\sigma_8 = 0.013507$	$\Delta\sigma_8 = 0.016626$
$\omega_0 = -1$	$\Delta\omega_0 = 0.094660$	$\Delta\omega_0 = 0.103739$
$\omega_a = 0$	$\Delta\omega_a = 0$	$\Delta\omega_a = 0.790401$
$\lambda_1 = 0$	$\Delta\lambda_1 = 0.045974$	$\Delta\lambda_1 = 0.070270$
$\lambda_2 = 0$	$\Delta\lambda_2 = 0.010776$	$\Delta\lambda_2 = 0.022699$
$h = 0.72$	$\Delta h = 0.141352$	$\Delta h = 0.141358$



Parameter constraints with constant EoS. The blue and green ellipses correspond to 1σ and 2σ.



Parameter constraints with time evolving EoS. The blue and green ellipses correspond to 1σ and 2σ.

Fisher matrix analysis

- Cosmological implications from hypothetical models with interaction parameters being the upper bounds

Model	Age (Gyr)	$C_{l=1000}^{\kappa\kappa}$	$B_{l=1000}^{\kappa\kappa\kappa}$
ΛCDM	13.777	2.737×10^{-10}	2.941×10^{-16}
$\lambda_1 = 0.07$	14.362 (4.24%)	2.731×10^{-10} (0.19%)	2.986×10^{-16} (1.53%)
$\lambda_1 = -0.07$	13.215 (4.07%)	2.684×10^{-10} (1.91%)	2.802×10^{-16} (4.74%)
$\lambda_2 = 0.02$	13.937 (1.16%)	2.889×10^{-10} (5.56%)	3.227×10^{-16} (9.70%)
$\lambda_2 = -0.02$	13.630 (1.06%)	2.596×10^{-10} (5.14%)	2.684×10^{-16} (8.73%)

Conclusions

- We focus on the models with interactions between dark matter and dark energy, and show the how different forms of the interaction and equation of state can affect the weak lensing convergence power spectrum and bispectrum. Compared to the convergence power spectrum, the bispectrum can give more stringent constraints on the interactions between dark sectors.

- Employing the Fisher matrix analysis, we forecast parameter uncertainties derived from weak lensing bispectrum with a two-bin tomography and place upper bounds on strength of the interactions between the dark sectors, as well as other cosmological parameters. Our results show that the weak lensing bispectrum tomography is a sensitive probe to constraining the interaction models.

- The cosmic shear will be measured from upcoming weak lensing surveys with high sensitivity, thus it enables us to use the higher order correlation functions of weak lensing to constrain the interaction between dark sectors and will potentially provide more stringent results with other observations combined.

Thanks !