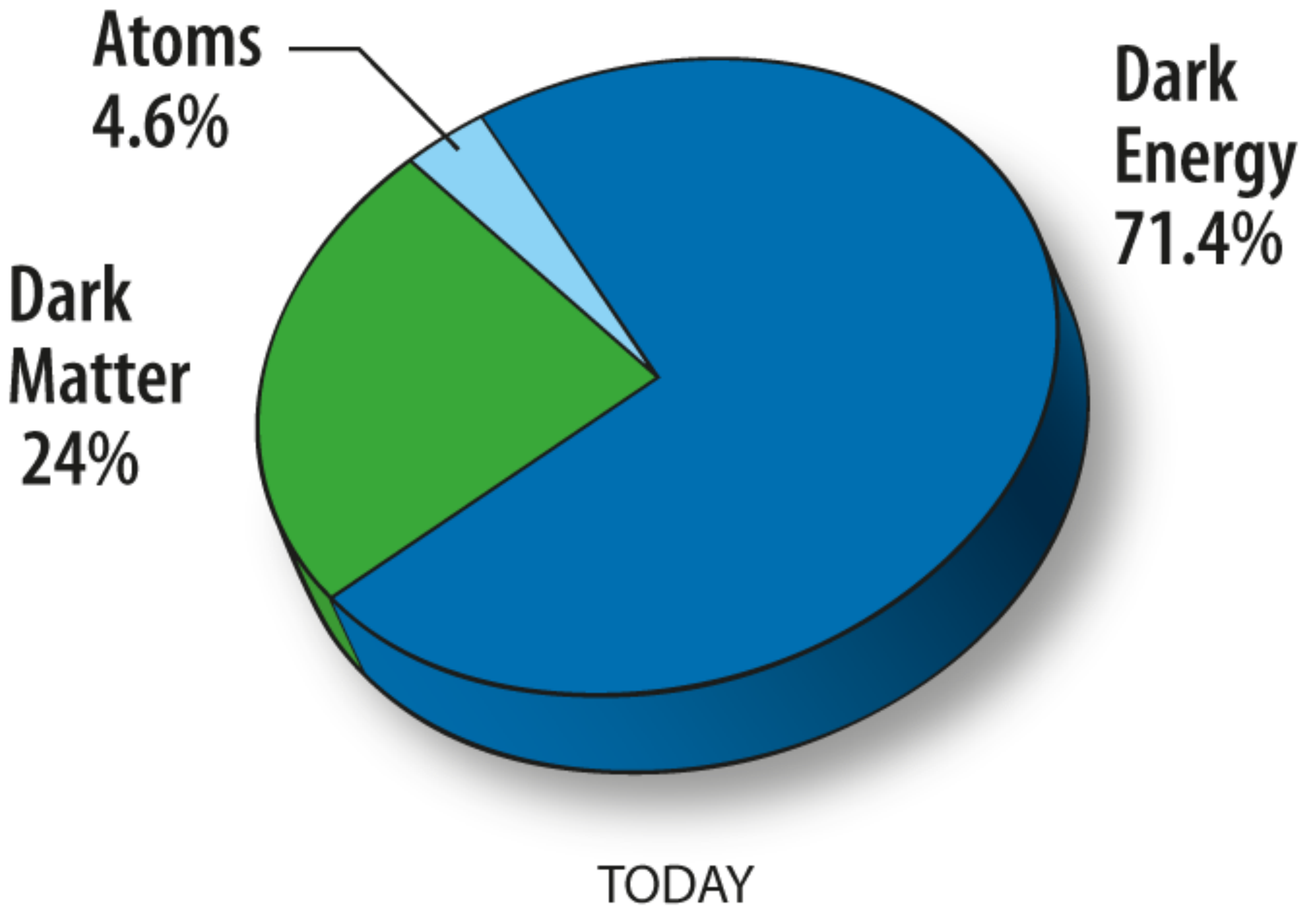
ASTRO@TS - 25 JUNE 2019 - SISSA

CONSTRAINTS ON EARLY DARK ENERGY

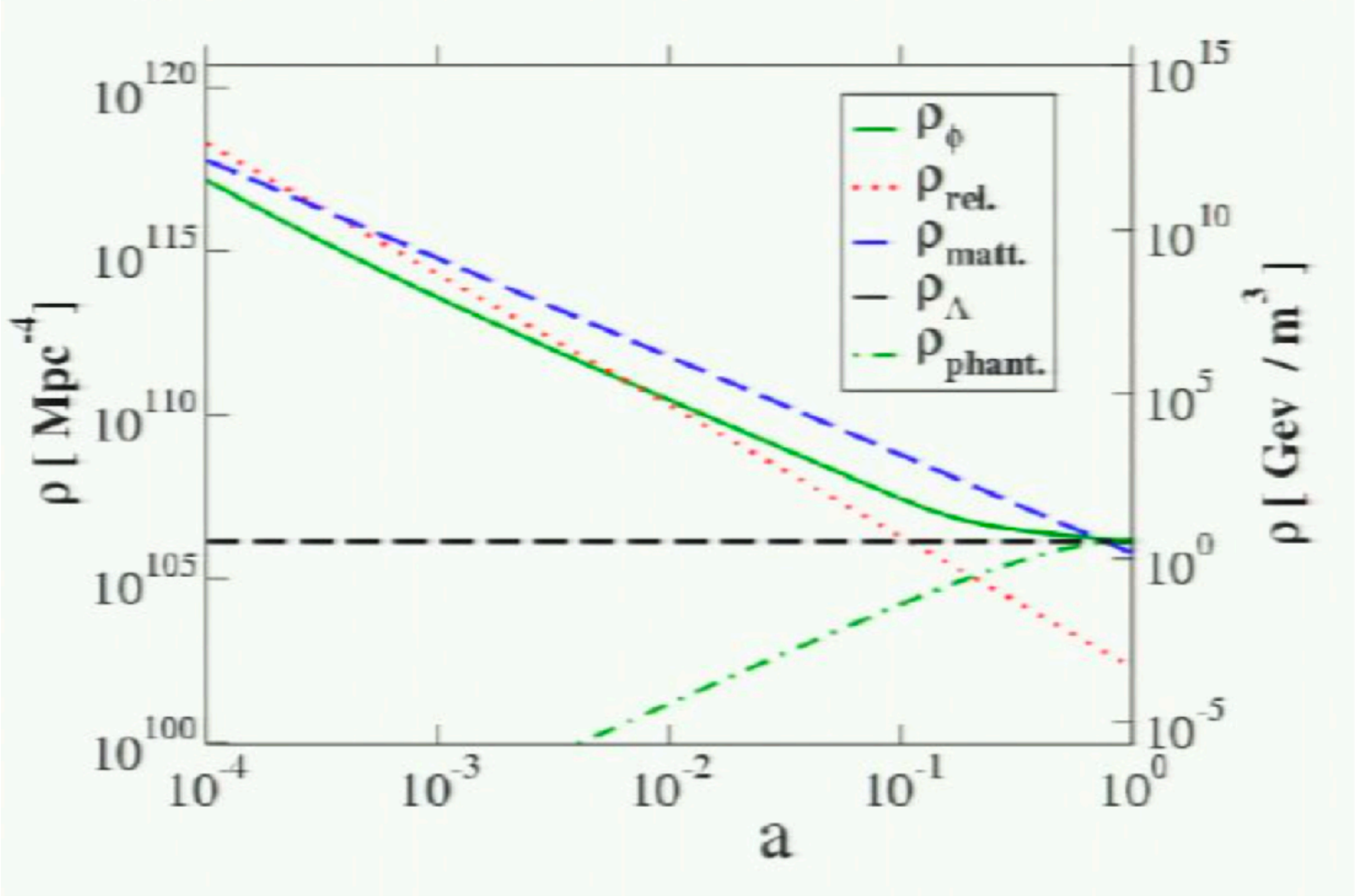
Hasti Khoraminezhad

Supervisors: Matteo Viel and Carlo Baccigalupi

THE ENERGY BUDGET OF THE UNIVERSE



ENERGY DENSITIES IN THE UNIVERSE



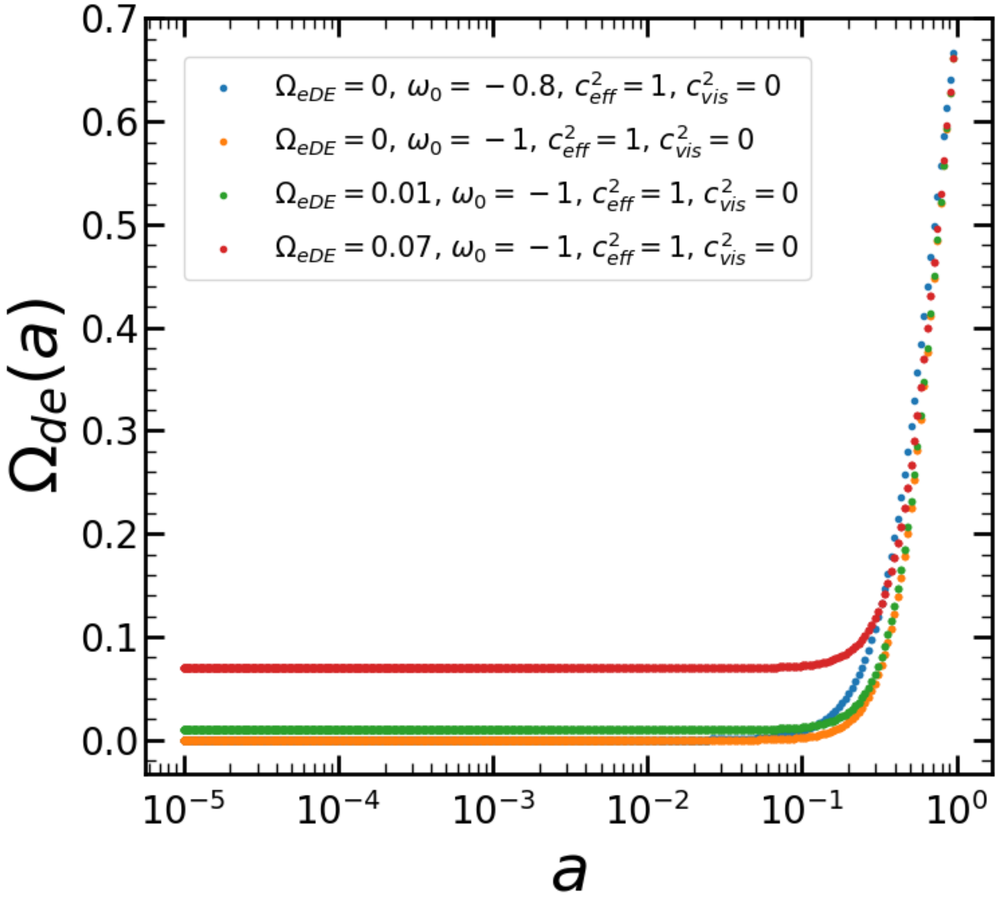
Georg Robbers (2008)

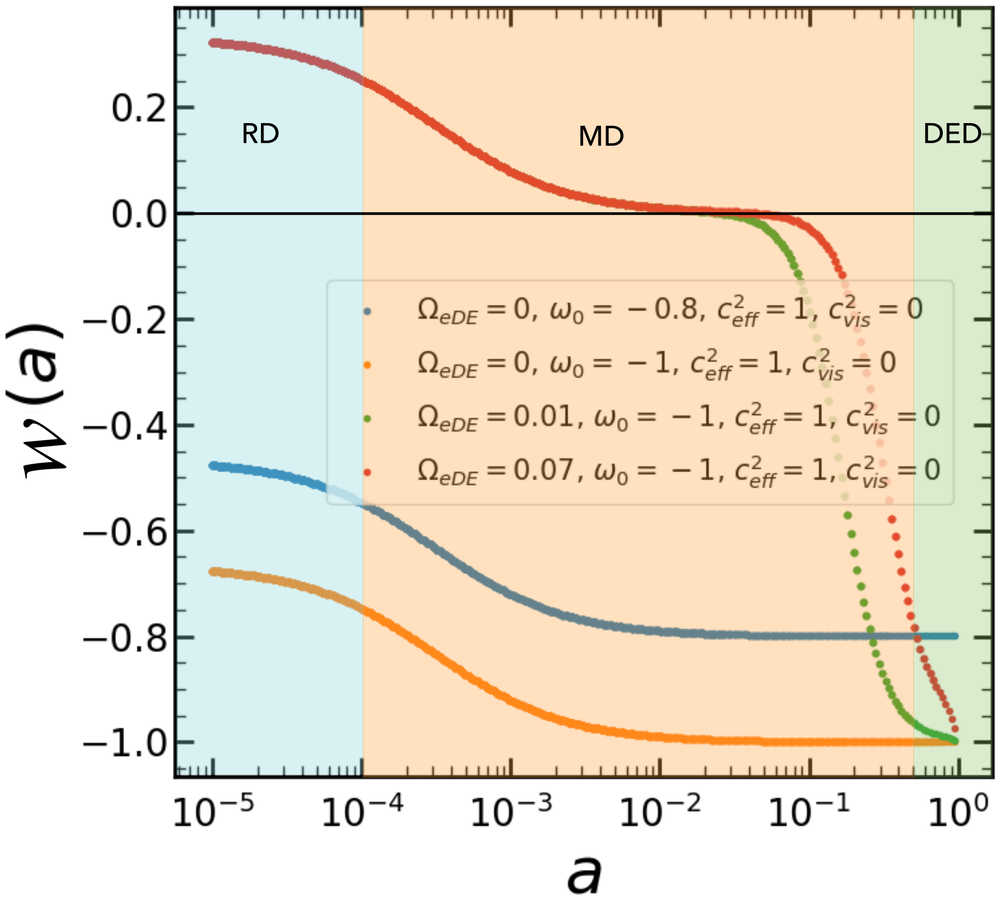
ONE MODEL OF EARLY DARK ENERGY

Michael Doran & Georg Robbers (2006)

$$\Omega_{DE}(a) = \frac{\Omega^0_{DE} - \Omega_{eDE}(1 - a^{-3w_0})}{\Omega^0_{DE} + \Omega^0_m a^{3w_0}} + \Omega_{eDE}(1 - a^{-3w_0})$$

$$w(a) = -\frac{1}{3[1 - \Omega_{DE}(a)]}\frac{d\,ln\,\Omega_{DE}(a)}{d\,ln\,a} + \frac{a_{eq}}{3(a + a_{eq})}$$





synchronous gauge - energy momentum conservation $T^{\nu}_{\mu;\nu} = 0$

PERTURBATIONS – DARK ENERGY STRESSED PARAMETRIZATION

The trace of the synchronous metric perturbation

DE density perturbation

$$\frac{\dot{\delta}}{1+w} = -\left[k^2 + 9\left(\frac{\dot{a}}{a}\right)^2\left(c^2_{eff} - w + \frac{\dot{w}}{3(1+w)(\dot{a}/a)}\right)\right]\frac{\theta}{k^2} - \frac{\dot{h}}{2} - 3\frac{\dot{a}}{a}(c^2_{eff} - w)\frac{\delta}{1+w}$$

Velocity potential

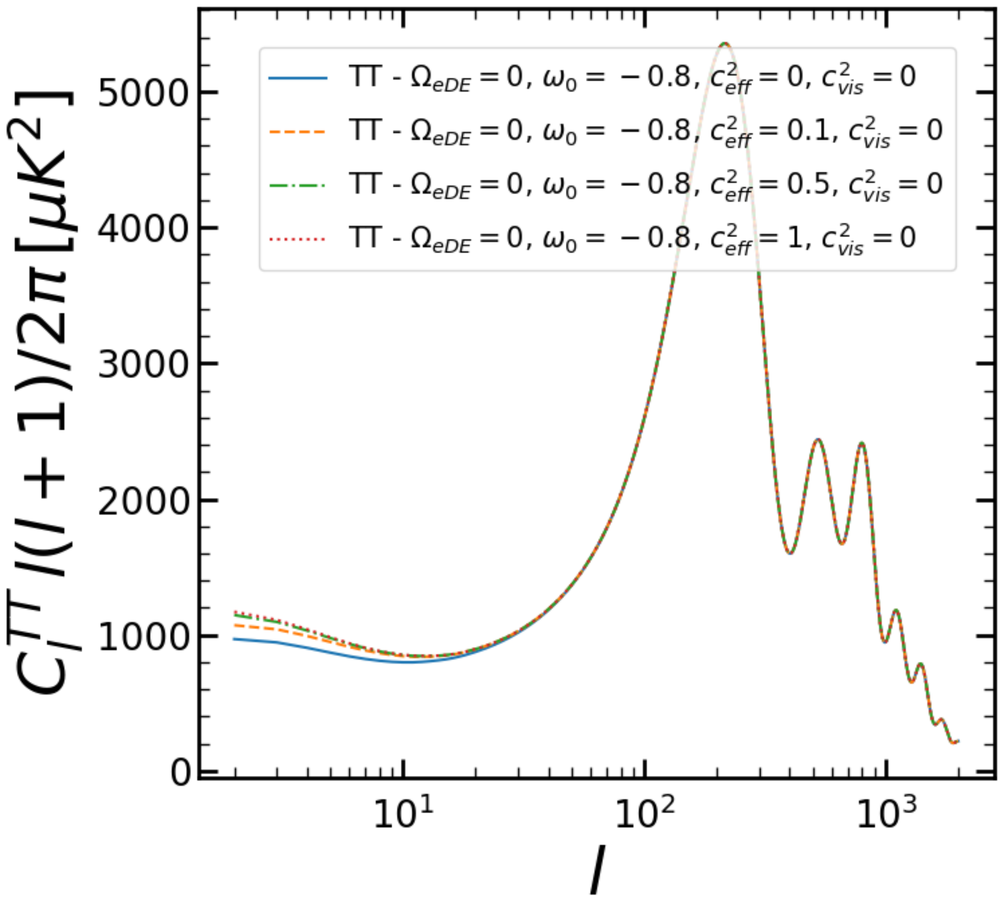
$$\dot{\theta} = -\frac{\dot{a}}{a}(1 - 3c^2_{eff})\theta + \frac{\delta}{1+w}c^2_{eff}k^2 - k^2\sigma \longrightarrow$$ Anisotropic stress of DE

$$\dot{\sigma} = -3\frac{\dot{a}}{a}\left[1 - \frac{\dot{w}}{3w(1+w)(\dot{a}/a)}\right]\sigma + \frac{8c^2_{vis}}{3(1+w)}\left[\theta + \frac{\dot{h}}{2} + 3\dot{\eta}\right]$$

Ma and Bertschinger (1995)

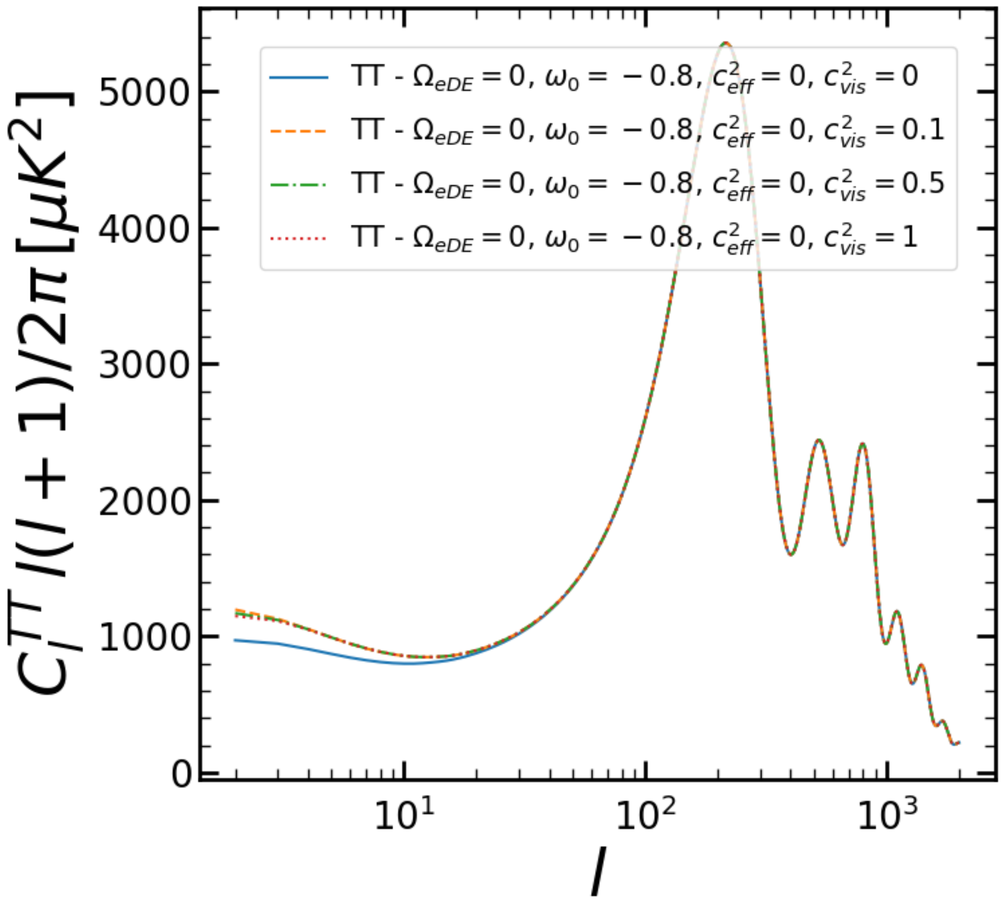
arXiv:astro-ph/9506072

EFFECTS ON CMB



Effect of the effective sound speed on the CMB spectrum

wCDM



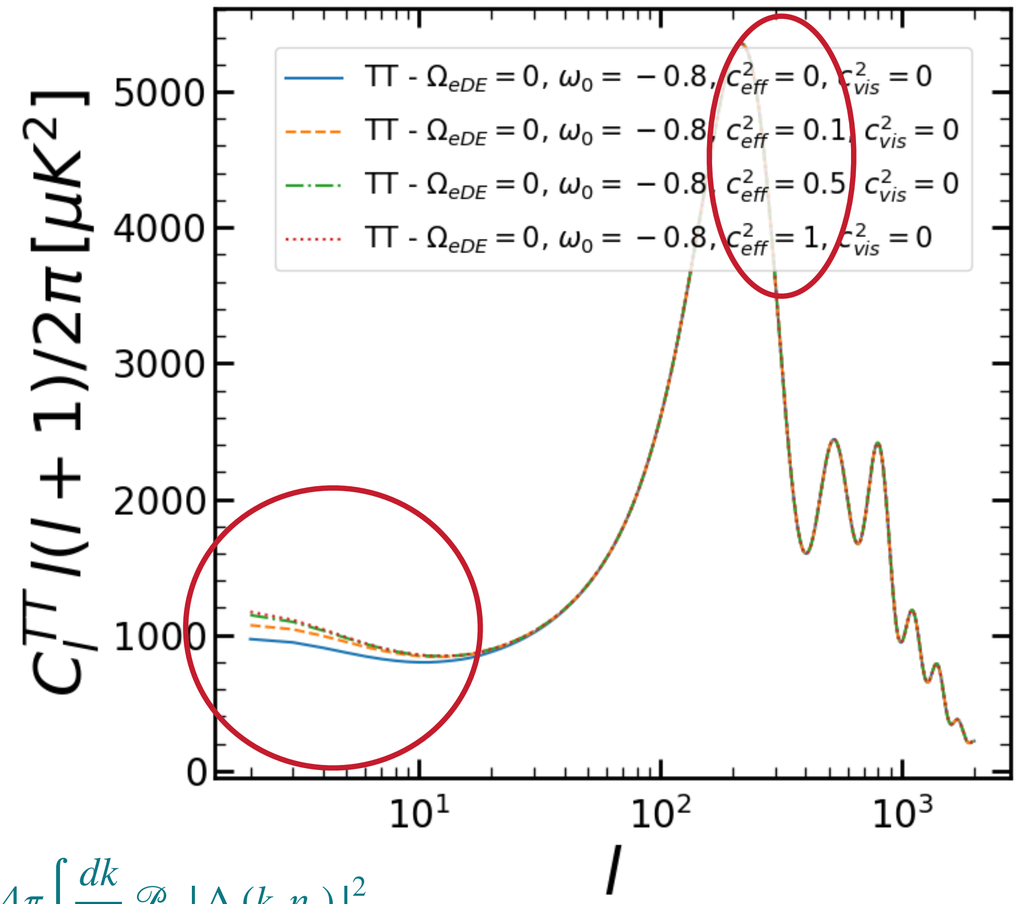
Effect of the viscose sound speed on the CMB spectrum

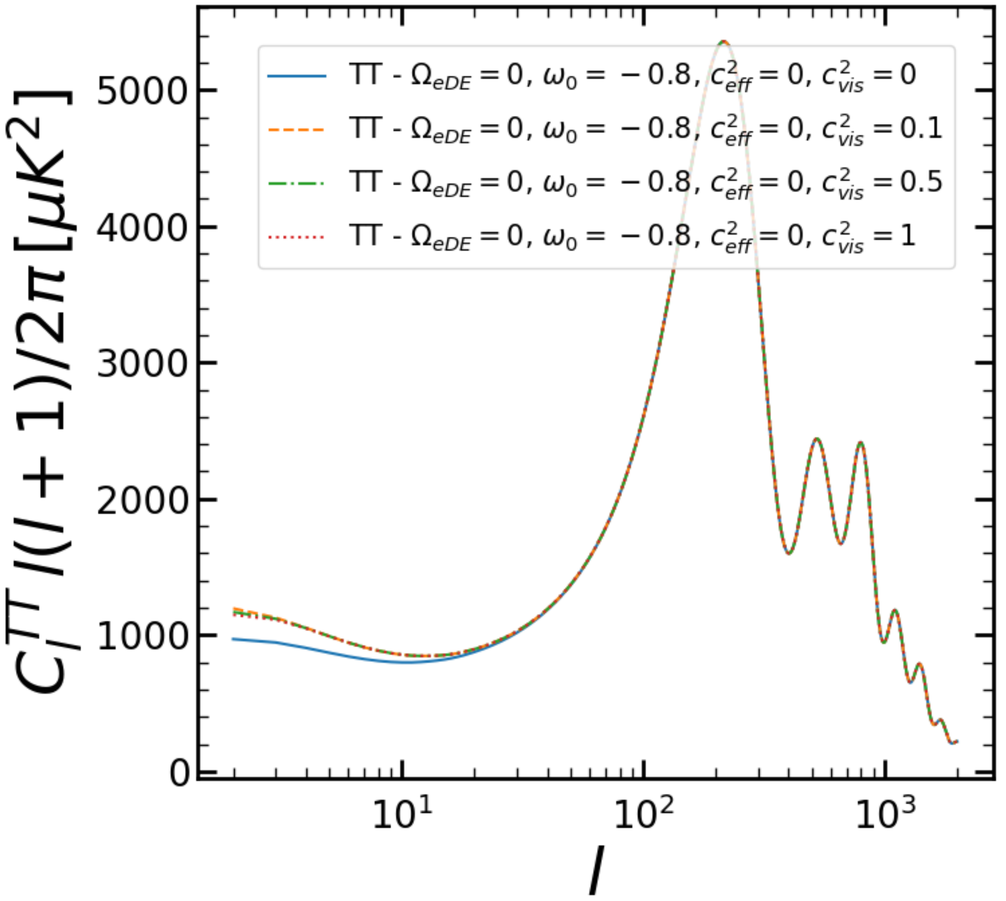
wCDM

$$\frac{\dot{\delta}}{1+w} = -\left[k^2 + 9\left(\frac{\dot{a}}{a}\right)^2\left(c_{eff}^2 - w + \frac{\dot{w}}{3(1+w)(\dot{a}/a)}\right)\right]\frac{\theta}{k^2} - \frac{\dot{h}}{2} - 3\frac{\dot{a}}{a}(c_{eff}^2 - w)\frac{\delta}{1+w}$$

EFFECTS ON CMB

$$\dot{\theta} = -\frac{\dot{a}}{a}(1 - 3c_{eff}^2)\theta + \frac{\delta}{1+w}c_{eff}^2 k^2 - k^2\sigma \qquad \dot{\sigma} = -3\frac{\dot{a}}{a}\left[1 - \frac{\dot{w}}{3w(1+w)(\dot{a}/a)}\right]\sigma + \frac{8c_{vis}^2}{3(1+w)}\left[\theta + \frac{\dot{h}}{2} + 3\dot{\eta}\right]$$





$$C_l = 4\pi\int\frac{dk}{k}\mathcal{P}_\chi\,|\,\Delta_l(k,\eta_0)\,|^2$$

$$\Delta_l(k,\eta_0) = \Delta_l^{LSS}(k) + \Delta_l^{ISW}(k)$$

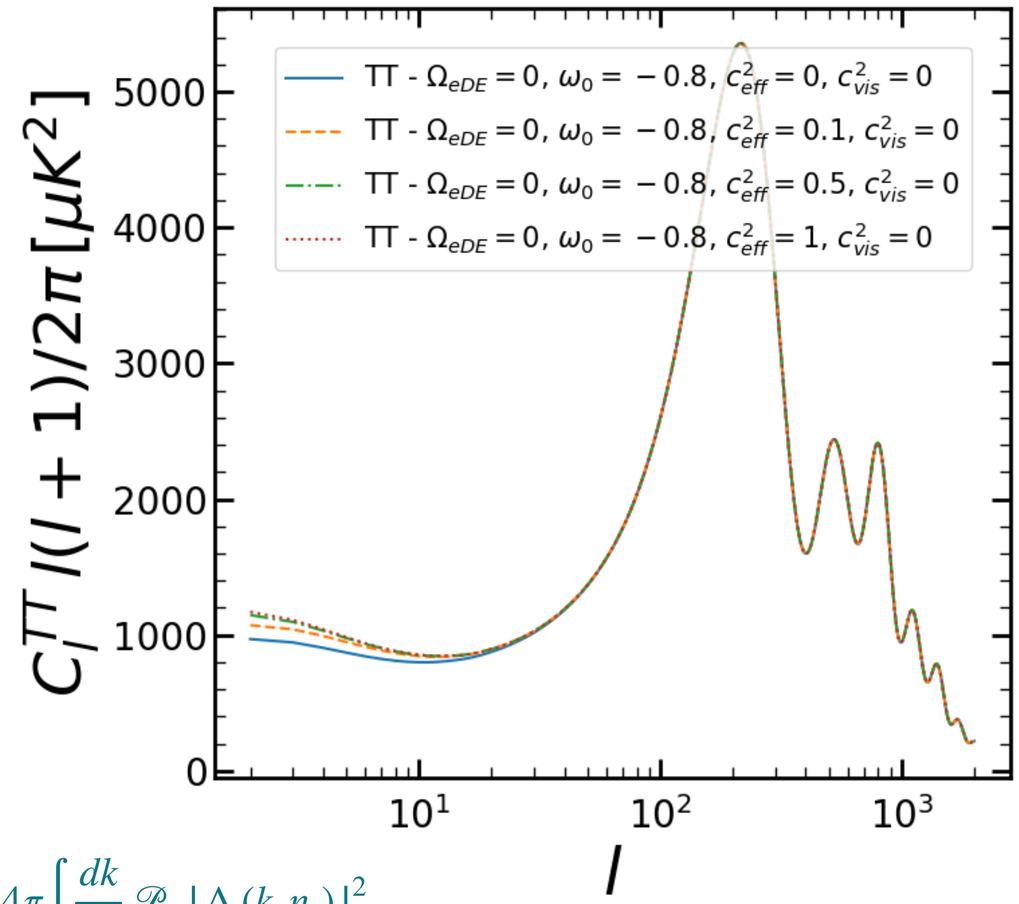
$$\Delta_l^{ISW}(k) = 2\int d\eta\, e^{-\tau(\eta)}\,\phi'\, j_l[k(\eta-\eta_0)]$$

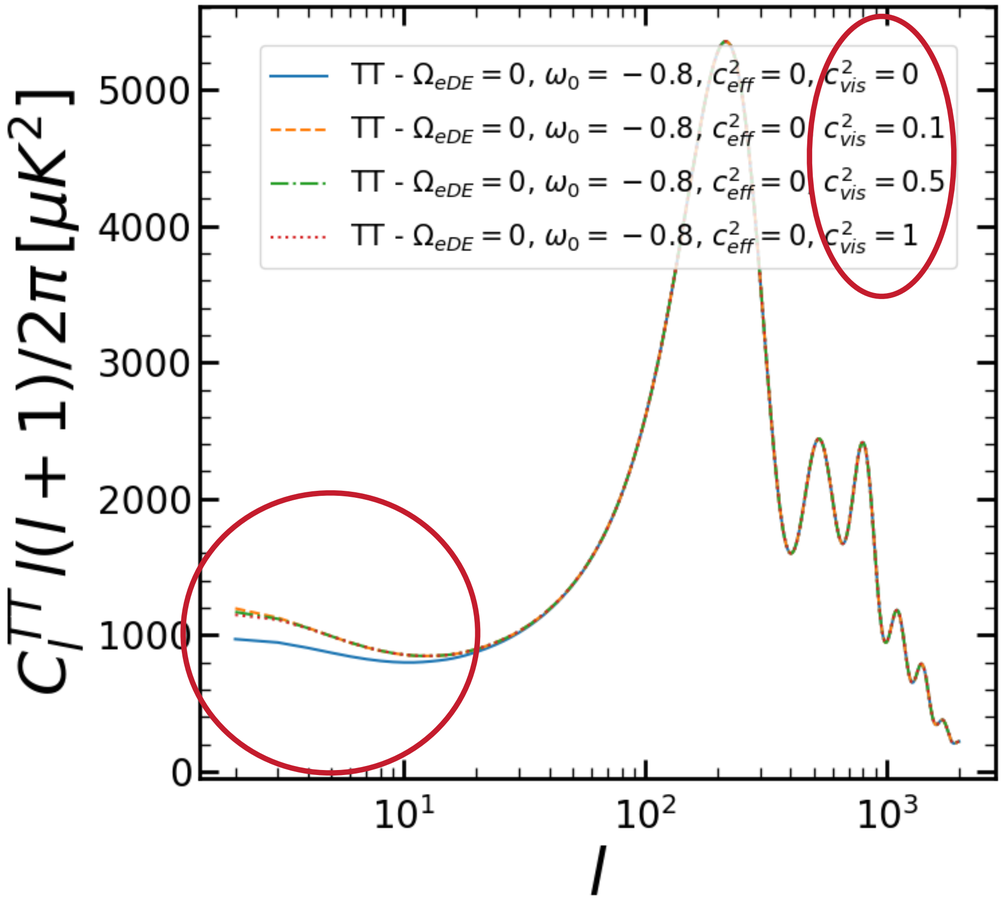
$$\frac{\dot{\delta}}{1+w} = -\left[k^2 + 9\left(\frac{\dot{a}}{a}\right)^2\left(\cancel{c_{eff}^2}^{\,0} - w + \frac{\dot{w}}{3(1+w)(\dot{a}/a)}\right)\right]\frac{\theta}{k^2} - \frac{\dot{h}}{2} - 3\frac{\dot{a}}{a}(\cancel{c_{eff}^2}^{\,0} - w)\frac{\delta}{1+w}$$

EFFECTS ON CMB

$$\dot{\theta} = -\frac{\dot{a}}{a}(1 - 3\cancel{c_{eff}^2}^{\,0})\theta + \frac{\delta}{1+w}\cancel{c_{eff}^2}^{\,0}k^2 - k^2\sigma$$

$$\dot{\sigma} = -3\frac{\dot{a}}{a}\left[1 - \frac{\dot{w}}{3w(1+w)(\dot{a}/a)}\right]\sigma + \frac{8c_{vis}^2}{3(1+w)}\left[\theta + \frac{\dot{h}}{2} + 3\dot{\eta}\right]$$





$$C_l = 4\pi\int\frac{dk}{k}\mathcal{P}_\chi\,|\,\Delta_l(k,\eta_0)\,|^2$$

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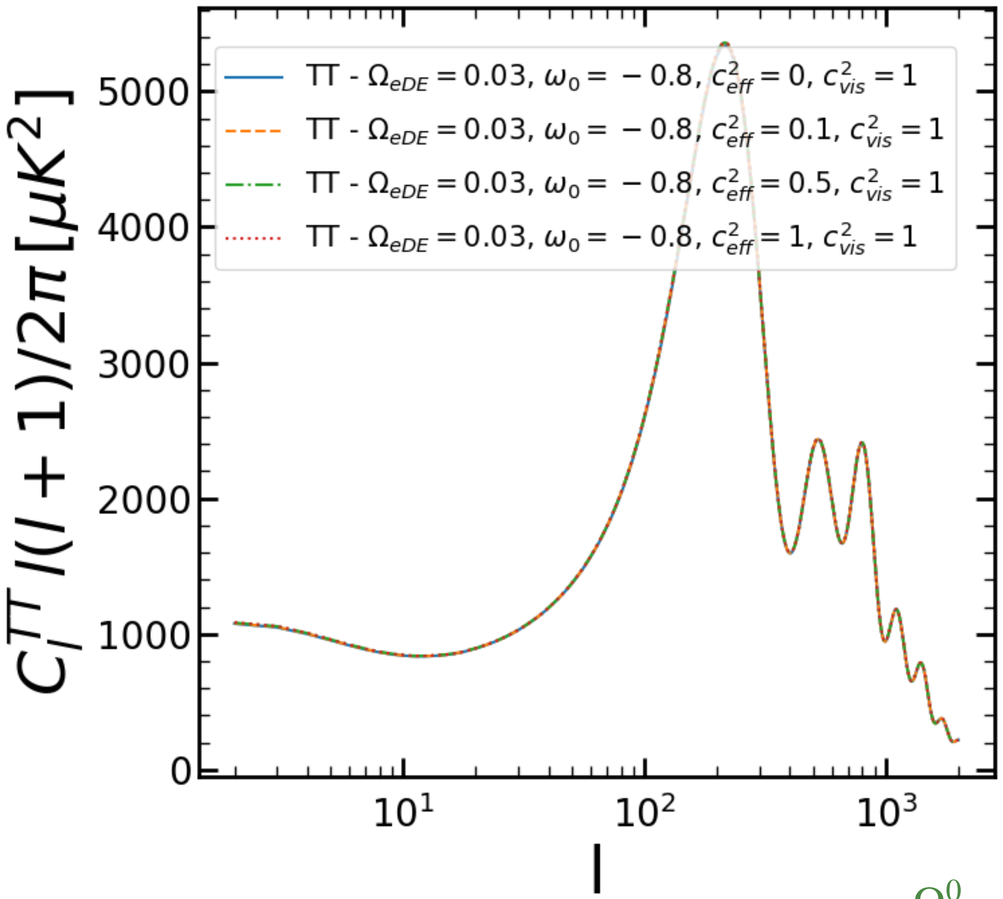
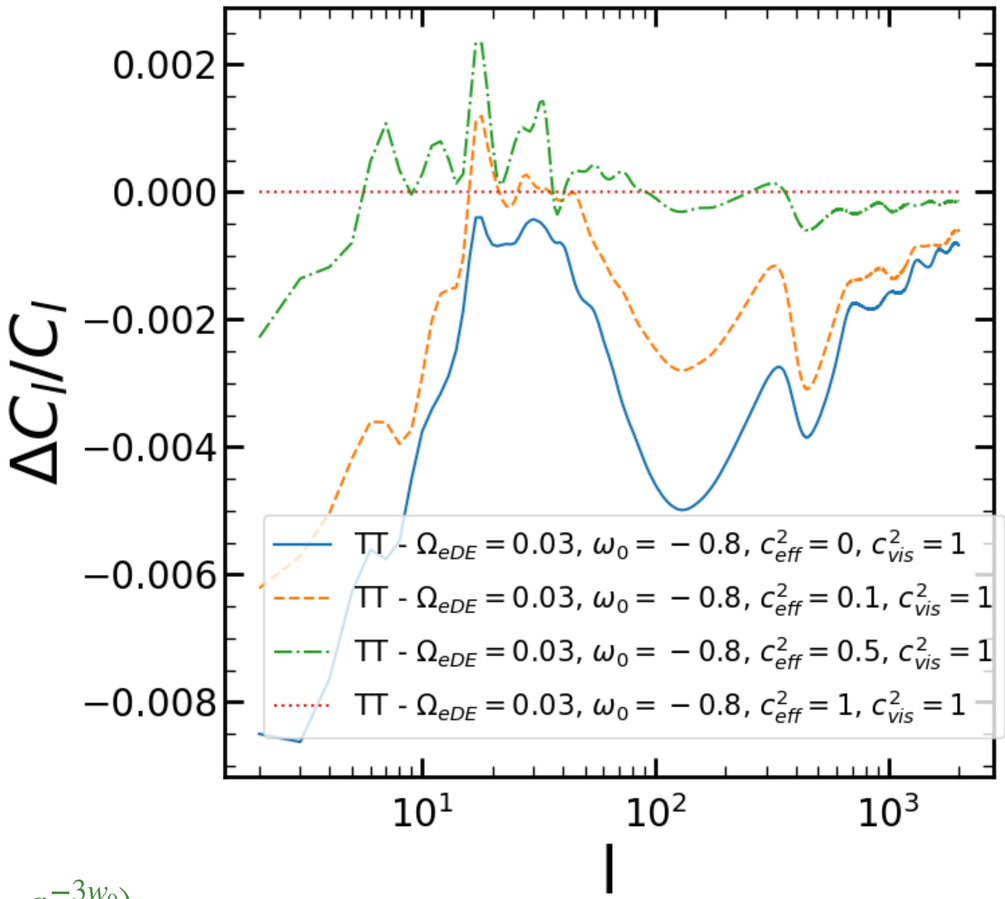
$$\Delta_l^{ISW}(k) = 2\int d\eta\, e^{-\tau(\eta)}\,\phi'\, j_l[k(\eta-\eta_0)]$$

EFFECTS OF SOUND SPEED ON CMB





$$\Omega_{DE}(a) = \frac{\Omega^0_{DE} - \Omega_{eDE}(1 - a^{-3w_0})}{\Omega^0_{DE} + \Omega^0_m a^{3w_0}} + \Omega_{eDE}(1 - a^{-3w_0})$$

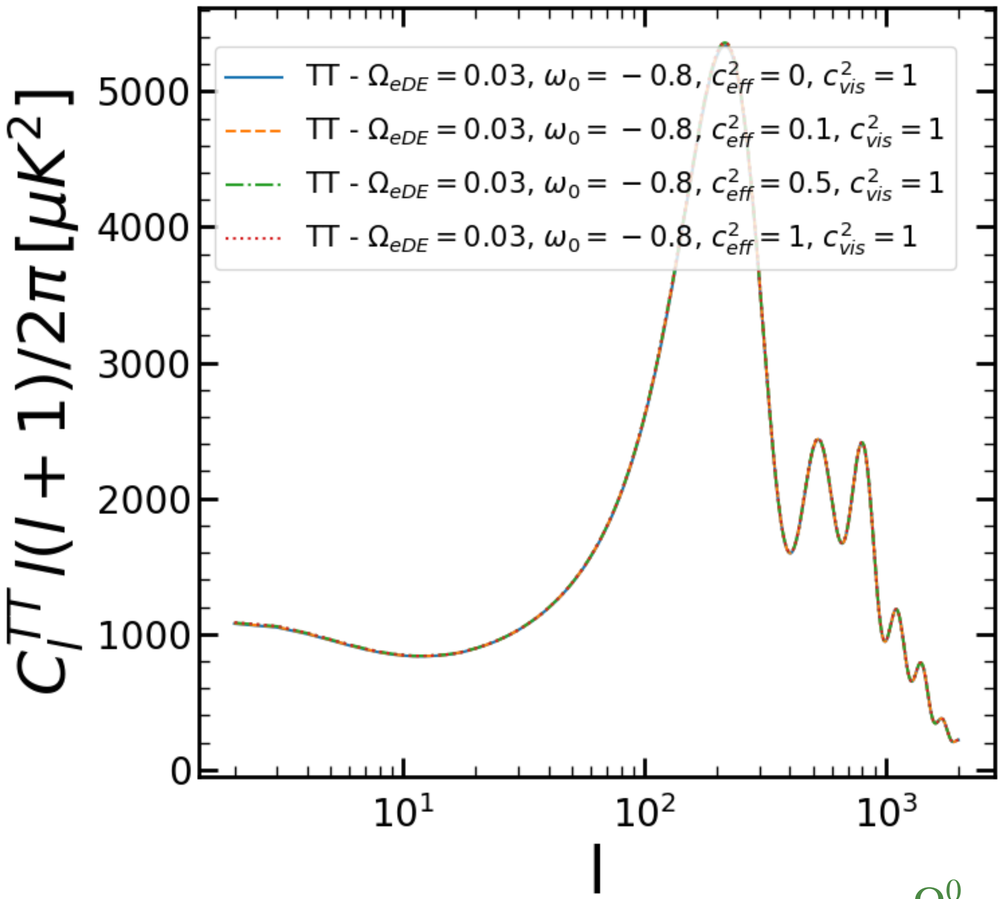
EDE

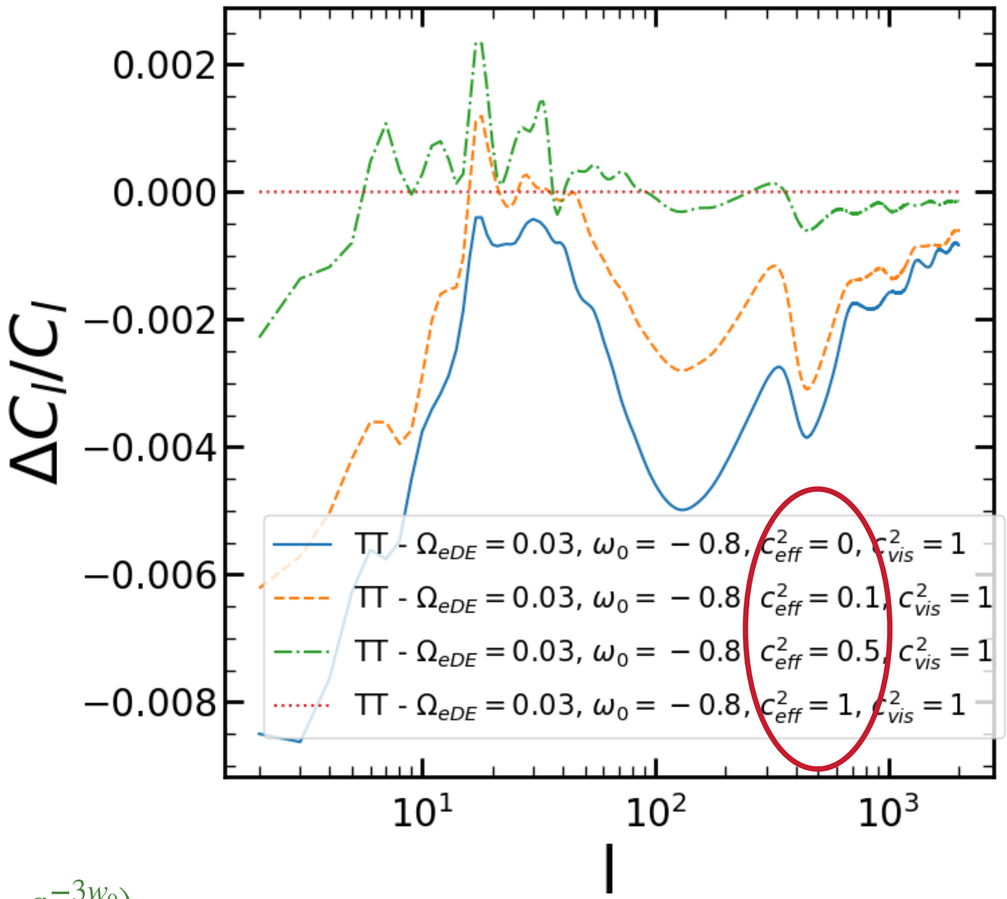
$$\frac{\dot{\delta}}{1+w} = -\left[k^2 + 9\left(\frac{\dot{a}}{a}\right)^2\left(c_{eff}^2 - w + \frac{\dot{w}}{3(1+w)(\dot{a}/a)}\right)\right]\frac{\theta}{k^2} - \frac{\dot{h}}{2} - 3\frac{\dot{a}}{a}(c_{eff}^2 - w)\frac{\delta}{1+w}$$

EFFECTS OF SOUND SPEED ON CMB

$$\dot{\theta} = -\frac{\dot{a}}{a}(1 - 3c_{eff}^2)\theta + \frac{\delta}{1+w}c_{eff}^2 k^2 - k^2\sigma$$

$$\dot{\sigma} = -3\frac{\dot{a}}{a}\left[1 - \frac{\dot{w}}{3w(1+w)(\dot{a}/a)}\right]\sigma + \frac{8c_{vis}^2}{3(1+w)}\left[\theta + \frac{\dot{h}}{2} + 3\dot{\eta}\right]$$

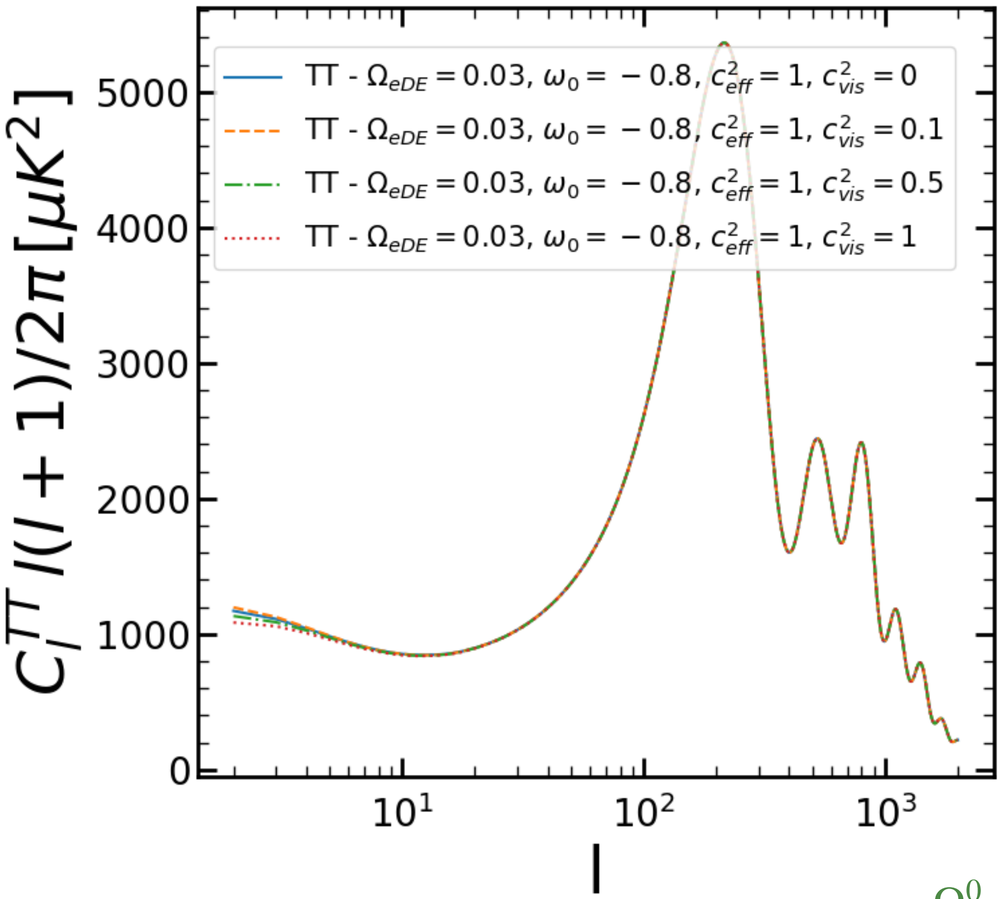


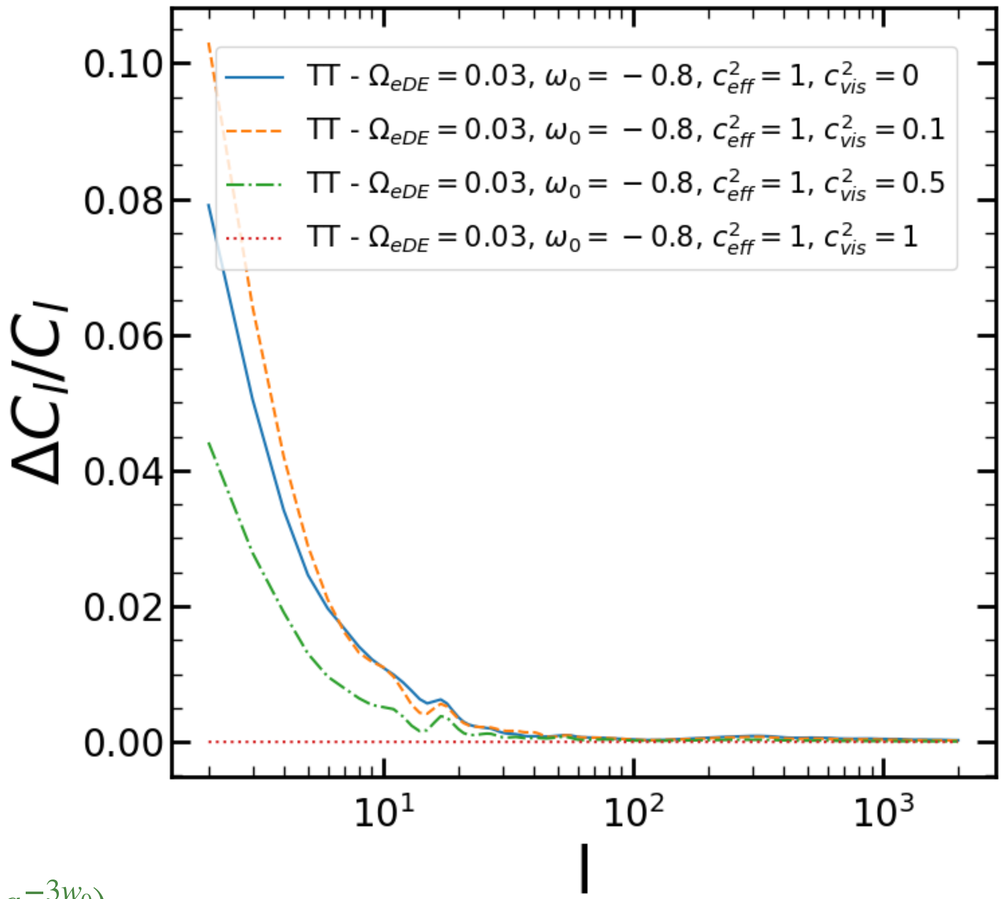


$$\Omega_{DE}(a) = \frac{\Omega_{DE}^0 - \Omega_{eDE}(1 - a^{-3w_0})}{\Omega_{DE}^0 + \Omega_m^0 a^{3w_0}} + \Omega_{eDE}(1 - a^{-3w_0})$$

EDE

EFFECTS OF VISCOSITY ON CMB





EDE

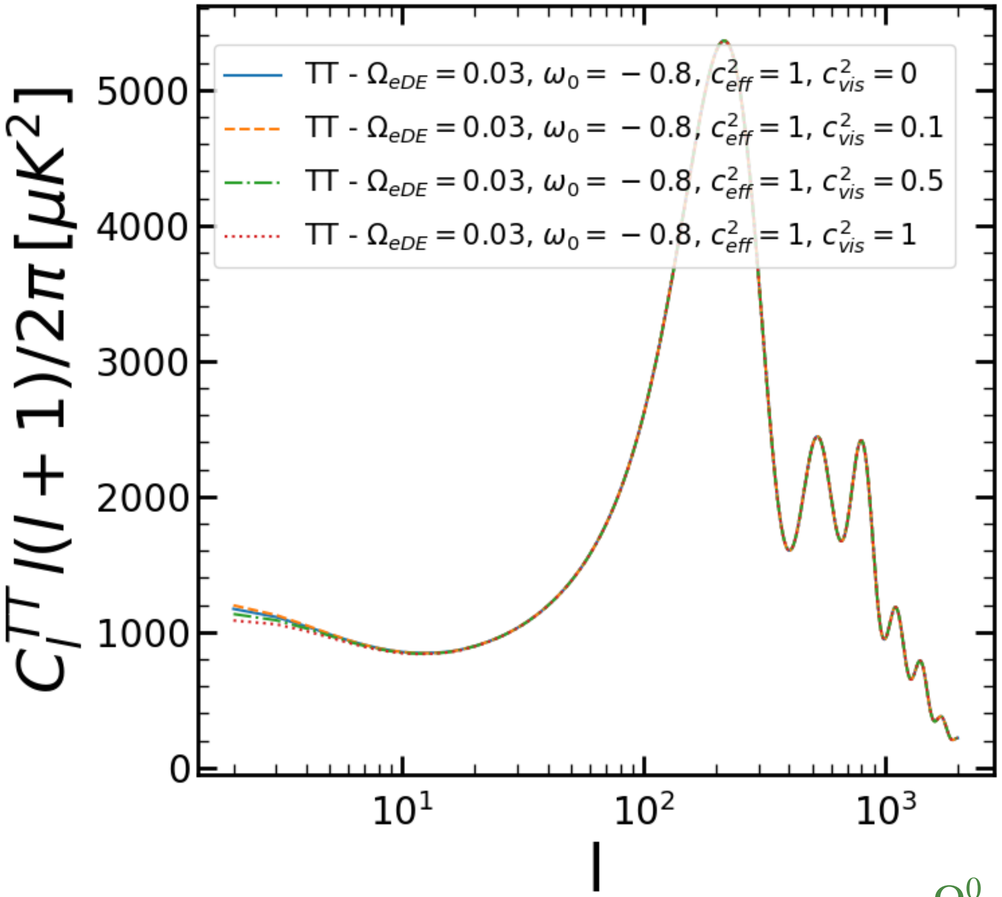
$$\Omega_{DE}(a) = \frac{\Omega^0_{DE} - \Omega_{eDE}(1 - a^{-3w_0})}{\Omega^0_{DE} + \Omega^0_m a^{3w_0}} + \Omega_{eDE}(1 - a^{-3w_0})$$

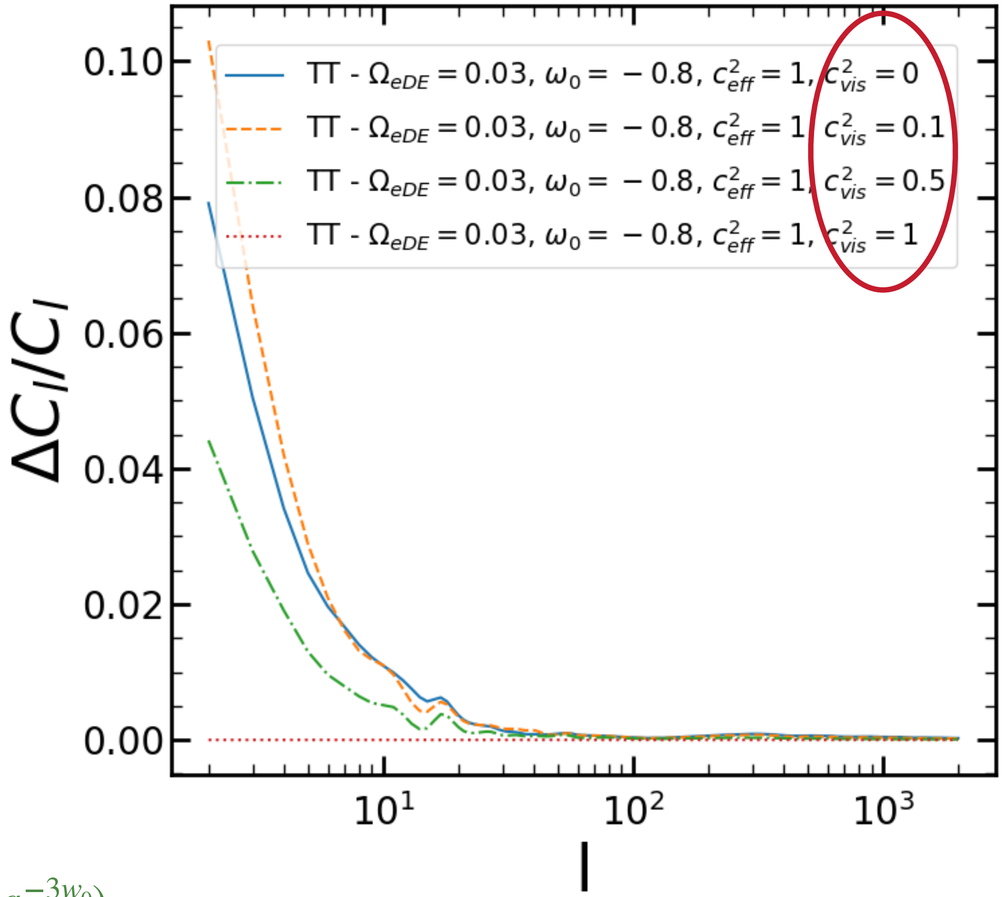
$$\frac{\dot{\delta}}{1+w} = -\left[k^2 + 9\left(\frac{\dot{a}}{a}\right)^2\left(c_{eff}^2 - w + \frac{\dot{w}}{3(1+w)(\dot{a}/a)}\right)\right]\frac{\theta}{k^2} - \frac{\dot{h}}{2} - 3\frac{\dot{a}}{a}(c_{eff}^2 - w)\frac{\delta}{1+w}$$

EFFECTS OF VISCOSITY ON CMB

$$\dot{\theta} = -\frac{\dot{a}}{a}(1 - 3c_{eff}^2)\theta + \frac{\delta}{1+w}c_{eff}^2 k^2 - k^2\sigma$$

$$\dot{\sigma} = -3\frac{\dot{a}}{a}\left[1 - \frac{\dot{w}}{3w(1+w)(\dot{a}/a)}\right]\sigma + \frac{8c_{vis}^2}{3(1+w)}\left[\theta + \frac{\dot{h}}{2} + 3\dot{\eta}\right]$$

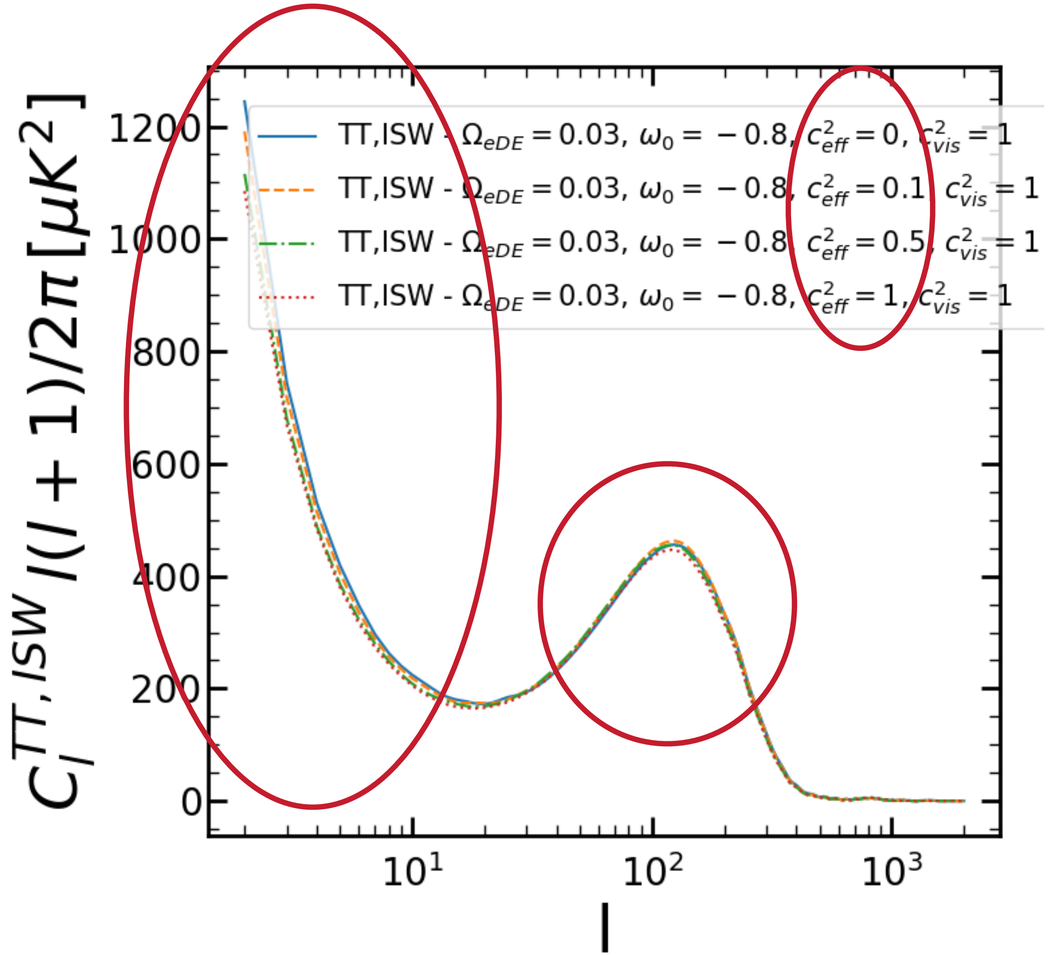




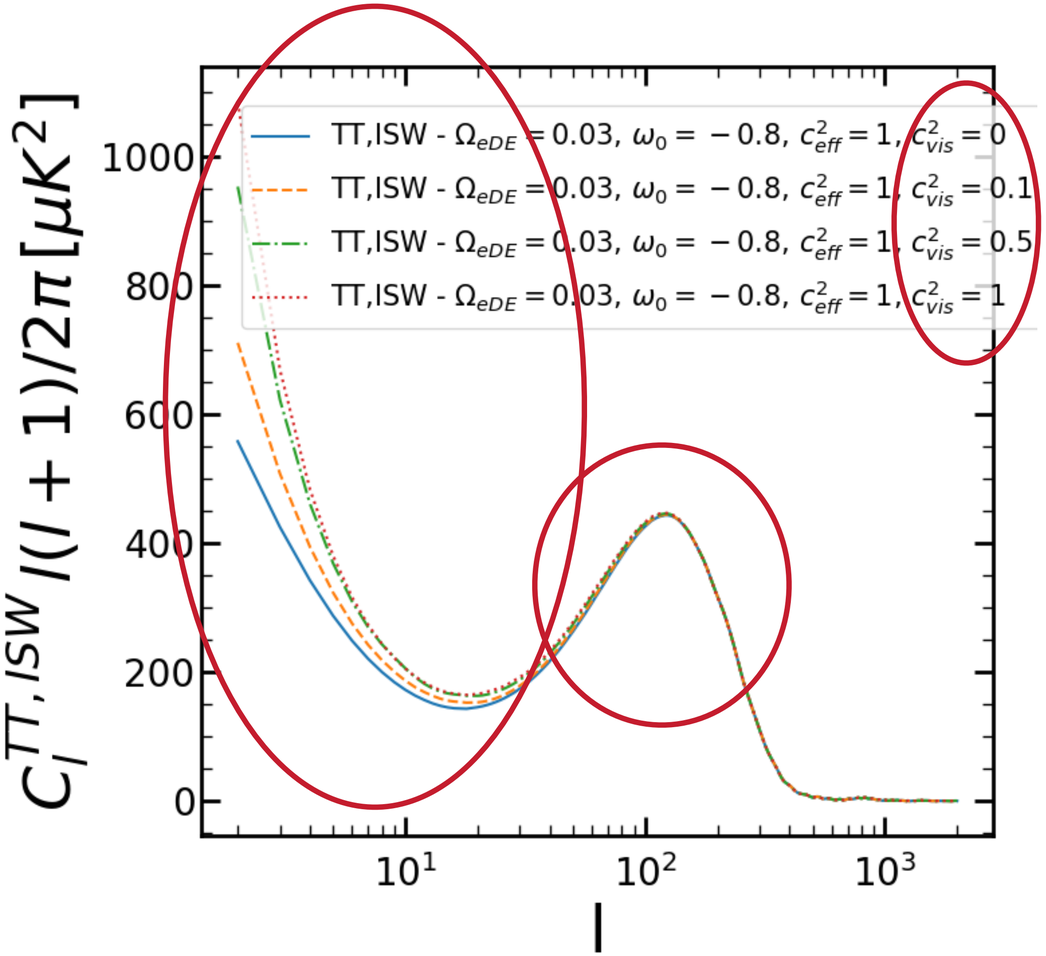
EDE

$$\Omega_{DE}(a) = \frac{\Omega_{DE}^0 - \Omega_{eDE}(1 - a^{-3w_0})}{\Omega_{DE}^0 + \Omega_m^0 a^{3w_0}} + \Omega_{eDE}(1 - a^{-3w_0})$$

ISW COMPONENT OF THE TEMPERATURE CMB ANISOTROPIES

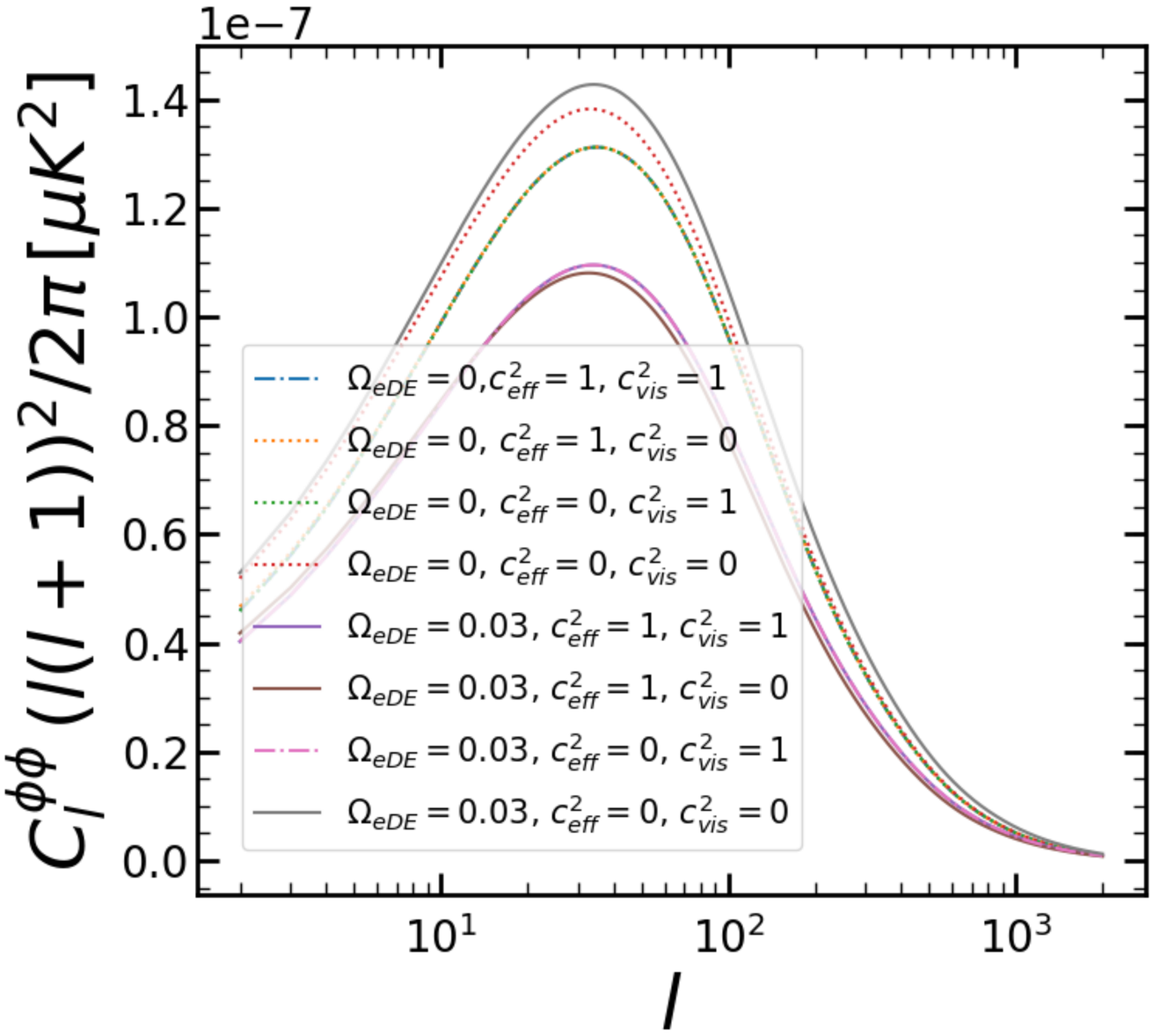


$l < 30$ $l \sim 120$

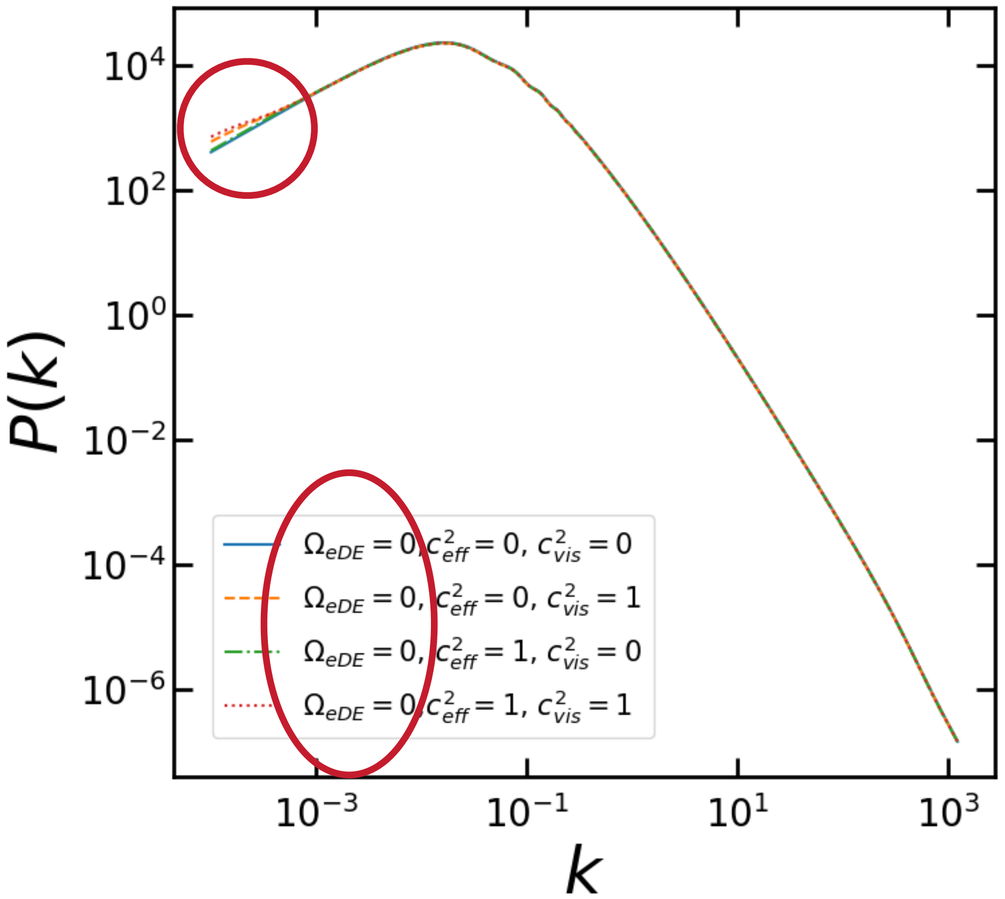


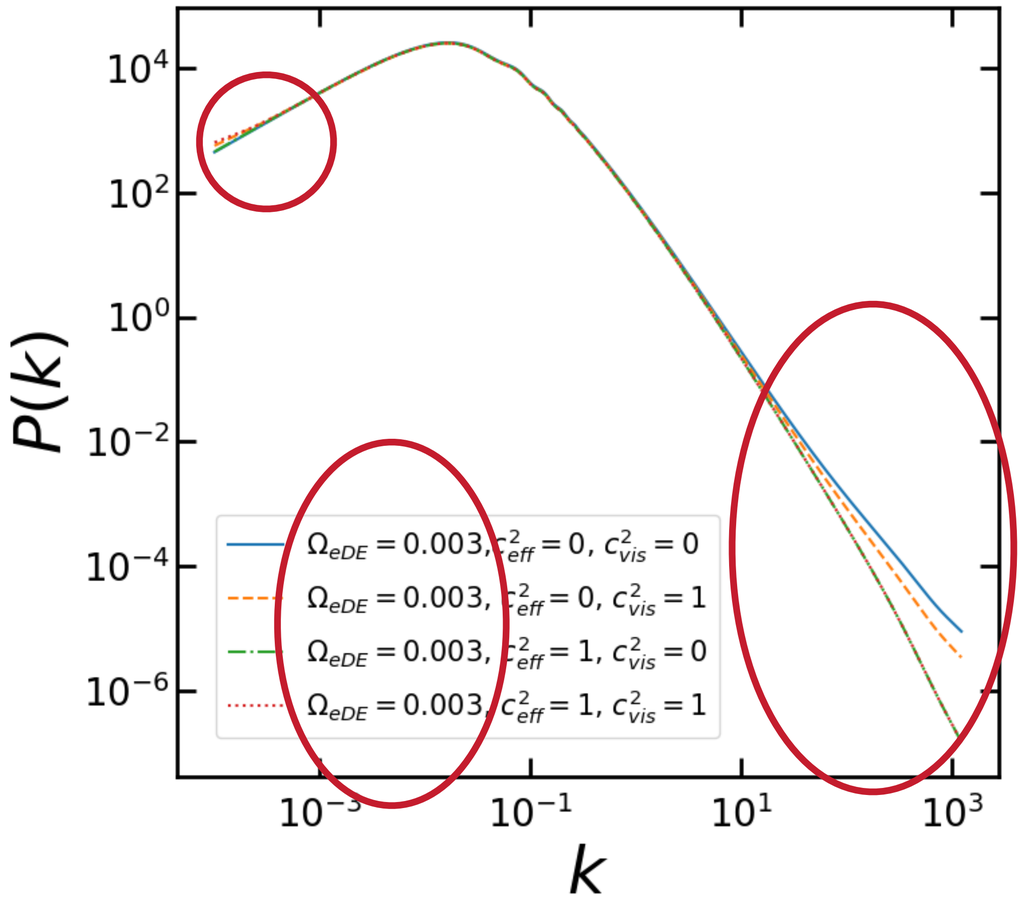
$l < 30$ $l \sim 120$

CMB LENSING


1e−7
$C_l^{\phi\phi}\,(l(l+1))^2/2\pi\,[\mu K^2]$
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^1
10^2
10^3
l
$\Omega_{eDE}=0, c^2_{eff}=1, c^2_{vis}=1$
$\Omega_{eDE}=0, c^2_{eff}=1, c^2_{vis}=0$
$\Omega_{eDE}=0, c^2_{eff}=0, c^2_{vis}=1$
$\Omega_{eDE}=0, c^2_{eff}=0, c^2_{vis}=0$
$\Omega_{eDE}=0.03, c^2_{eff}=1, c^2_{vis}=1$
$\Omega_{eDE}=0.03, c^2_{eff}=1, c^2_{vis}=0$
$\Omega_{eDE}=0.03, c^2_{eff}=0, c^2_{vis}=1$
$\Omega_{eDE}=0.03, c^2_{eff}=0, c^2_{vis}=0$

EFFECTS ON MATTER POWER SPECTRUM





CONSTRAINTS ON EARLY DARK ENERGY

Planck

Params	bestfits	mean	2σ lower limit	2σ upper limit
Ω_{eDE}	0.000211574	0.00291269	0	0.00840509
w_0	−0.898016	−0.893396	−1	−0.716352
τ	0.0660344	0.0839135	0.0507459	0.117357
Σm_ν	0.0595693	0.202833	0.056	0.502911

Planck+BAO+SNe+H0

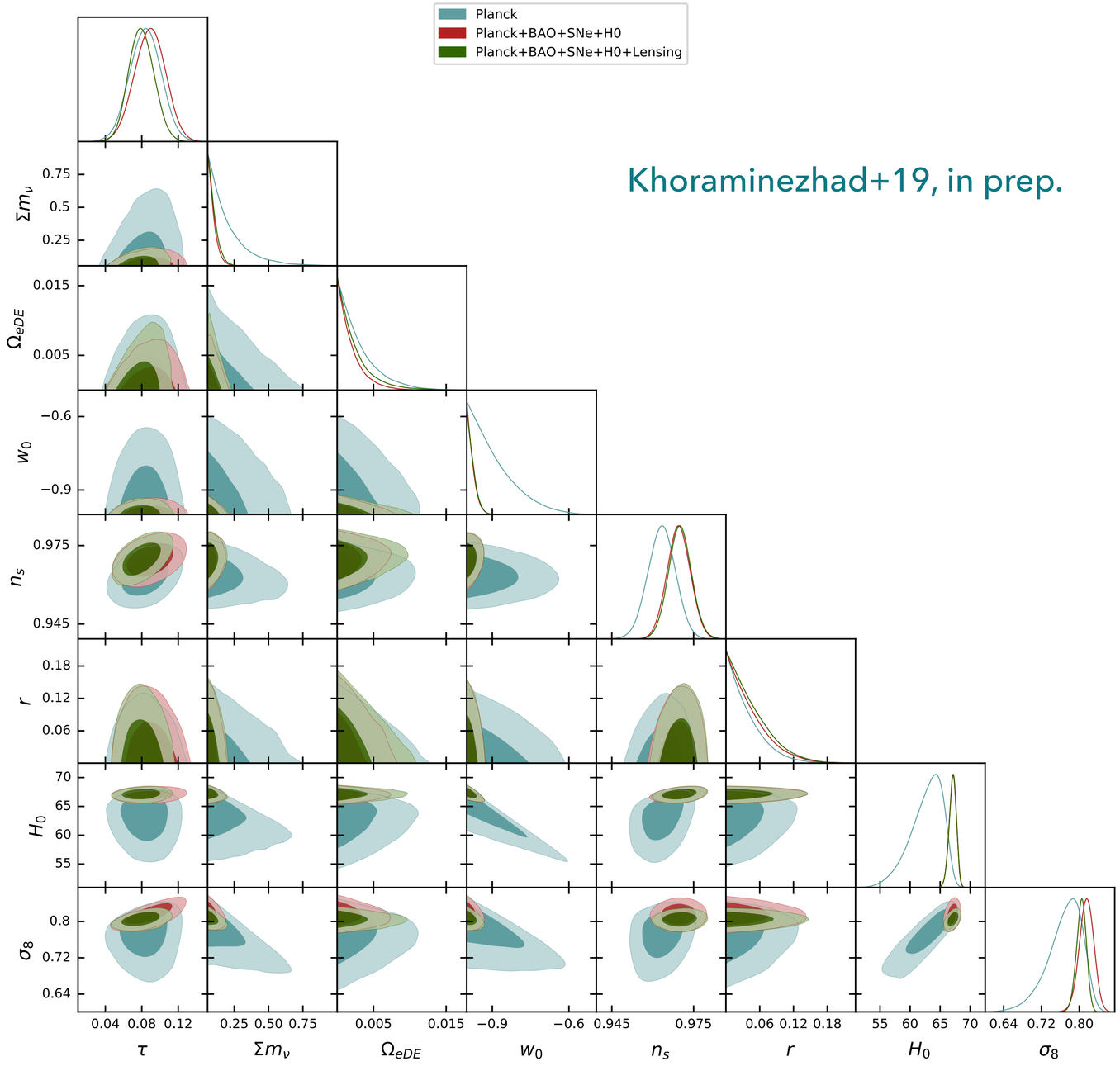
Params	bestfits	mean	2σ lower limit	2σ upper limit
Ω_{eDE}	0.00160501	0.00192165	0	0.00574627
w_0	−0.992979	−0.980116	−1	−0.946334
τ	0.0930969	0.0888891	0.055531	0.120996
Σm_ν	0.073089	0.0931285	0.056	0.158235

Planck+BAO+SNe+H0+Lensing

Params	bestfits	mean	2σ lower limit	2σ upper limit
Ω_{eDE}	0.00350455	0.00251735	0	0.00782563
w_0	−0.977624	−0.979581	−1	−0.946519
τ	0.0694712	0.0796277	0.0531697	0.107371
Σm_ν	0.0847083	0.0968175	0.056	0.166335

Planck: Planck TT, TE, EE + low TEB

$H_0 = (70.6 \pm 3.3)\ kms^{-1}\,Mpc^{-1}$



Khoraminezhad+19, in prep.

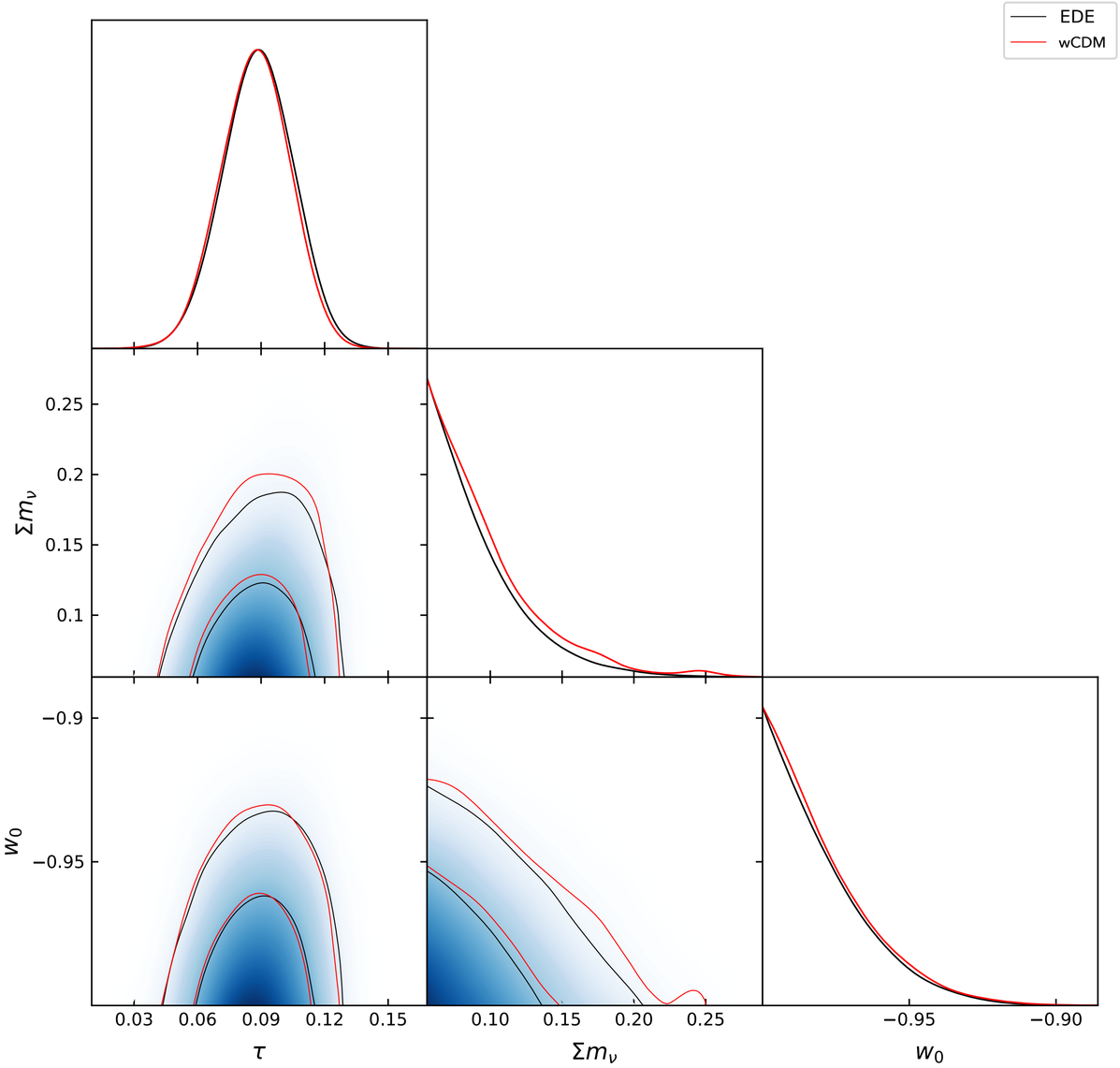
ARE τ OR Σm_ν AFFECTED BY EDE ?

Parameters	mean value	standard deviation	2σ lower limit	2σ upper limit
Ω_{eDE}	$0.1249504E-02$	$0.1176688E-02$	$0.0000000E+00$	$0.3598433E-02$
w_0	$-0.9797396E+00$	$0.1678665E-01$	$-0.1000000E+01$	$-0.9464207E+00$
n_s	$0.9693165E+00$	$0.4160295E-02$	$0.9612642E+00$	$0.9775096E+00$
H_0	$0.6707394E+02$	$0.5978085E+00$	$0.6586974E+02$	$0.6824105E+02$
σ_8	$0.8162684E+00$	$0.1498472E-01$	$0.7862401E+00$	$0.8450923E+00$
τ	$0.8862058E-01$	$0.1665088E-01$	$0.5558448E-01$	$0.1204848E+00$
r	$0.4005223E-01$	$0.3364827E-01$	$0.0000000E+00$	$0.1068262E+00$
Σm_ν	$0.9284021E-01$	$0.3270721E-01$	$0.5600000E-01$	$0.1586265E+00$

EDE

Parameters	mean value	standard deviation	2σ lower limit	2σ upper limit
w_0	$-0.9791431E+00$	$0.1742040E-01$	$-0.1000000E+01$	$-0.9448148E+00$
n_s	$0.9691575E+00$	$0.4222589E-02$	$0.9609800E+00$	$0.9774636E+00$
H_0	$0.6707328E+02$	$0.6096638E+00$	$0.6584324E+02$	$0.6828242E+02$
σ_8	$0.8182037E+00$	$0.1534540E-01$	$0.7868118E+00$	$0.8468136E+00$
τ	$0.8733086E-01$	$0.1628956E-01$	$0.5530816E-01$	$0.1184659E+00$
r	$0.4128439E-01$	$0.3568493E-01$	$0.0000000E+00$	$0.1118276E+00$
Σm_ν	$0.9802247E-01$	$0.3812329E-01$	$0.5600000E-01$	$0.1752705E+00$

wCDM



Planck2015 (Planck TT, TE, EE + low TEB) +BAO+JLA+H0prior

ADDING QUASARS

Planck+BAO+SNe+QSOs+H0

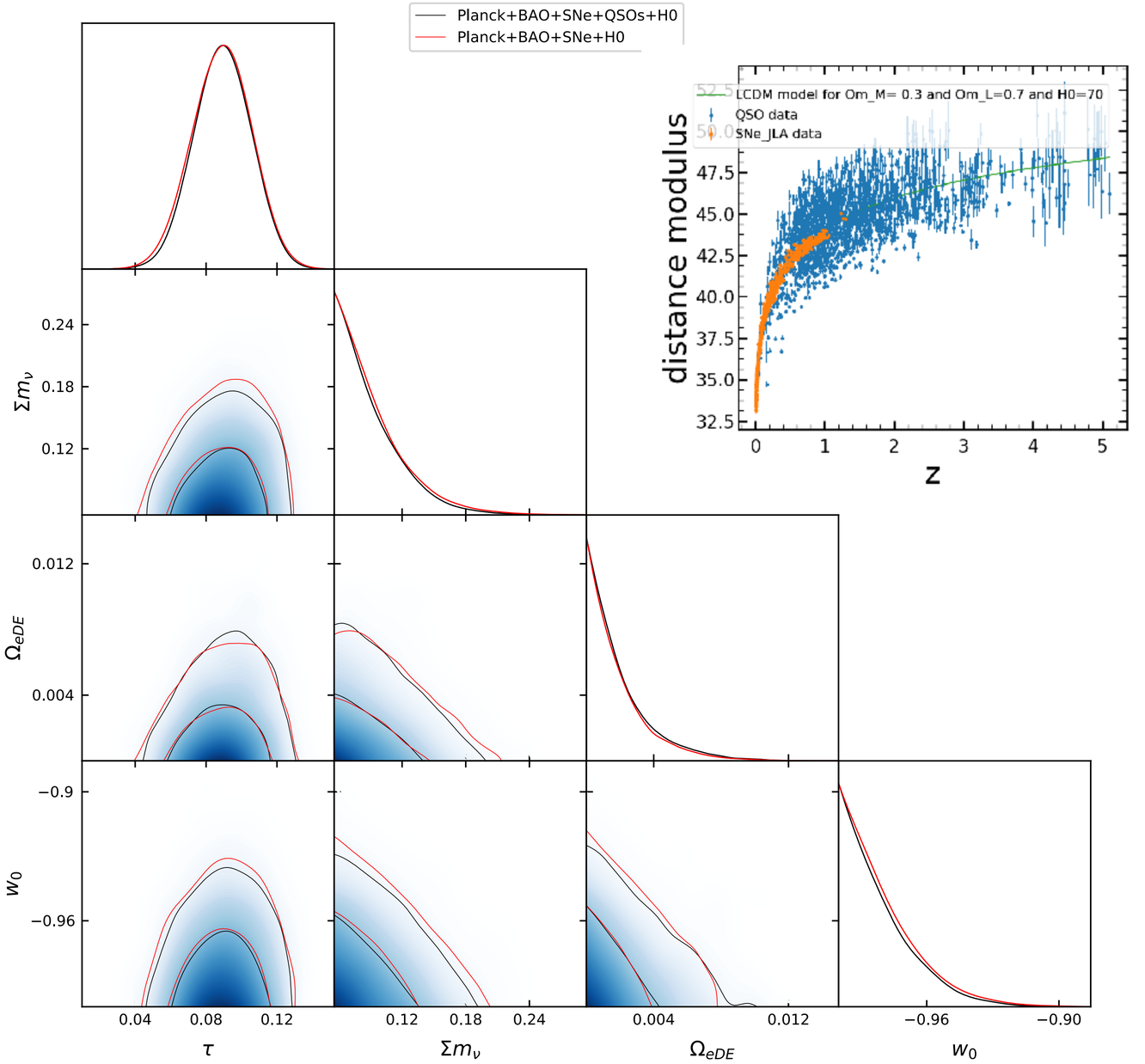
Params	bestfits	mean	2σ lower limit	2σ upper limit
Ω_{eDE}	0.00152123	0.00200005	0	0.00604808
w_0	−0.996865	−0.981194	−1	−0.949753
τ	0.0822686	0.0893285	0.0579568	0.120382
Σm_ν	0.0709065	0.0908281	0.056	0.149906

Planck+BAO+SNe+H0

Params	bestfits	mean	2σ lower limit	2σ upper limit
Ω_{eDE}	0.00160501	0.00192165	0	0.00574627
w_0	−0.992979	−0.980116	−1	−0.946334
τ	0.0930969	0.0888891	0.055531	0.120996
Σm_ν	0.073089	0.0931285	0.056	0.158235

$$log(L_X) = \beta + \gamma\, log(L_{UV})$$

$$ln(LF) = \Sigma_{i=1}^{N} \left\{ \frac{[log(F_X)_i - \Phi(F_{UV}, D_L)_i]}{s_i^2} + ln(s_i^2) \right\}$$



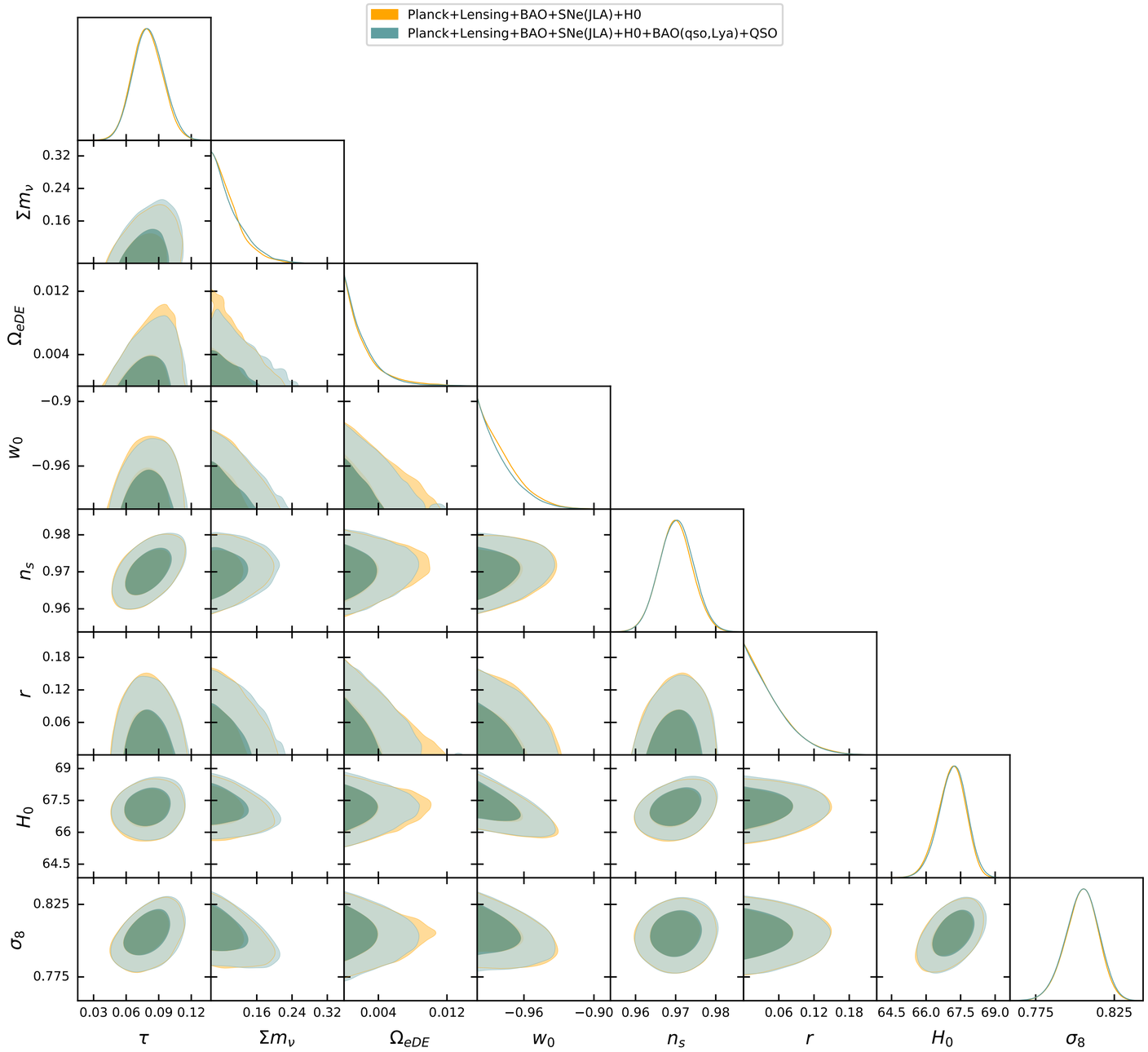
ADDING BAO DR14 (QSO,LYA) + QSO

Planck+Lensing+BAO+SNe(JLA)+H0

Params	bestfits	mean	2σ lower limit	2σ upper limit
Ω_{eDE}	0.00350455	0.00240698	0	0.00767044
w_0	−0.977624	−0.979299	−1	−0.945634
τ	0.0694712	0.0795518	0.0530791	0.107391
Σm_ν	0.0847083	0.0973397	0.056	0.166991

Planck+Lensing+BAO+SNe(JLA)+H0+BAO(qso,Lya)+QSOs

Params	bestfits	mean	2σ lower limit	2σ upper limit
Ω_{eDE}	0.000466991	0.00227519	0	0.00678934
w_0	−0.992498	−0.980544	−1	−0.947582
τ	0.0687274	0.0806523	0.0539031	0.108913
Σm_ν	0.0584204	0.101019	0.056	0.177641



CONCLUSION

- constraints on early dark energy (EDE) –> CMB, BAO, SNe and QSOs datasets (with CosmoMC code)
- Including the possibility of clustering through c^2_{eff} and c^2_{vis} (implemented in CAMB code)
- Perturbations in a DE component –> affect the CMB –> only on large scales –> ISW effect
- The net of increasing c^2_{eff} and c^2_{vis} –> making the ISW power higher
- Degeneracies between –> (r and Ω_{eDE}) , (r and w_0) , (Ω_{eDE} and w_0)
- Adding BAO Lya-qso dataset –> improving constraints on Ω_{eDE}
- QSOs do not seem to constrain much the EDE parameters but they constrain other models in which Ω_k is free
- The effect of EDE model on τ and Σm_ν –> No strong degeneracies

THANK YOU