How to weaken the comological neutrino mass bound

Isabel M. Oldengott*,

Gabriela Barenboim*, Jordi Salvadó-Serra, Dominik J. Schwarz, Sarah Kahlen

***University of Valencia**

arXiv: 1812.XXXX [astro-ph]

Holy grail of neutrino physics: Determination of the neutrino mass scale

Holy grail of neutrino physics: Determination of the neutrino mass scale

KATRIN (forecast): $m_{\nu_e} < 0.2 \text{ eV}$

Holy grail of neutrino physics: Determination of the neutrino mass scale

KATRIN (forecast): $m_{\nu_e} < 0.2$ eV

Cosmology (Planck 2015):

$$\sum m_\nu < 0.72 \text{ eV} \qquad (\text{TT+lowP})$$

$$\sum m_\nu < 0.21 \text{ eV} \qquad (\text{TT+lowP+BAO})$$

Holy grail of neutrino physics: Determination of the neutrino mass scale

KATRIN (forecast): $m_{\nu_e} < 0.2$ eV

Cosmology (Planck 2015):

$$\sum m_\nu < 0.72 \text{ eV} \quad \text{(TT+lowP)}$$

$$\sum m_\nu < 0.21 \text{ eV} \quad \text{(TT+lowP+BAO)}$$

Cosmology (Planck 2018):

$$\sum m_\nu < 0.54 \text{ eV} \quad \text{(TT+lowP)}$$

$$\sum m_\nu < 0.16 \text{ eV} \quad \text{(TT+lowP+BAO)}$$

Holy grail of neutrino physics: Determination of the neutrino mass scale

KATRIN (forecast): $m_{\nu_e} < 0.2$ eV

Cosmology (Planck 2015):	$\sum m_\nu < 0.72$ eV	(TT+lowP)
	$\sum m_\nu < 0.21$ eV	(TT+lowP+BAO)
Cosmology (Planck 2018):	$\sum m_\nu < 0.54$ eV	(TT+lowP)
	$\sum m_\nu < 0.16$ eV	(TT+lowP+BAO)

Holy grail of neutrino physics: Determination of the neutrino mass scale

KATRIN (forecast): $m_{\nu_e} < 0.2$ eV

Cosmology (Planck 2015):	$\sum m_\nu < 0.72$ eV	(TT+lowP)
	$\sum m_\nu < 0.21$ eV	(TT+lowP+BAO)
Cosmology (Planck 2018):	$\sum m_\nu < 0.54$ eV	(TT+lowP)
	$\sum m_\nu < 0.16$ eV	(TT+lowP+BAO)

→ usually claimed to be **very robust…**

Holy grail of neutrino physics: Determination of the neutrino mass scale

KATRIN (forecast): $m_{\nu_e} < 0.2$ eV

Cosmology (Planck 2015):	$\sum m_\nu < 0.72$ eV	(TT+lowP)
	$\sum m_\nu < 0.21$ eV	(TT+lowP+BAO)
Cosmology (Planck 2018):	$\sum m_\nu < 0.54$ eV	(TT+lowP)
	$\sum m_\nu < 0.16$ eV	(TT+lowP+BAO)

→ usually claimed to be **very robust…**

…**but** cosmological measurements all rely on the question when neutrinos become non-relativistic.

Simple (!) take-home message:

Neutrinos can be much heavier if they have a larger average-momentum

Cosmic perturbation theory:

$\rightarrow$ for massive neutrinos dependent on neutrino distribution

Cosmic perturbation theory:

$\rightarrow$ for massive neutrinos dependent on neutrino distribution

Standard assumption: $f_\nu(x) = \dfrac{1}{e^x + 1}$

Cosmic perturbation theory:

$\rightarrow$ for massive neutrinos dependent on neutrino distribution

Standard assumption: $f_\nu(x) = \dfrac{1}{e^x + 1}$

Many exotic scenarios can alter the standard distribution:

Cosmic perturbation theory:

→ for massive neutrinos dependent on neutrino distribution

Standard assumption: $f_\nu(x) = \dfrac{1}{e^x + 1}$

Many exotic scenarios can alter the standard distribution:

- particle decay into neutrinos *(e.g. Cuoco et al. 2005, Gonzalez-Garcia et al. 2012)*
- non-standard neutrino interactions *(Basboll et al. 2009, Starkmann et al. 1994)*
- oscillations to sterile neutrinos *(Barbieri & Dolgov 1990, Foot et al. 1996)*

Cosmic perturbation theory:

→ for massive neutrinos dependent on neutrino distribution

Standard assumption: $f_\nu(x) = \dfrac{1}{e^x + 1}$

Many exotic scenarios can alter the standard distribution:

- particle decay into neutrinos *(e.g. Cuoco et al. 2005, Gonzalez-Garcia et al. 2012)*
- non-standard neutrino interactions *(Basboll et al. 2009, Starkmann et al. 1994)*
- oscillations to sterile neutrinos *(Barbieri & Dolgov 1990, Foot et al. 1996)*

Model-independent parameterization for non-thermal distributions:

→ expansion in othonormal polynomials $\int \mathrm{d}x \frac{1}{e^x + 1} p_n(x) p_m(x) = \delta_{nm}$

$$\Rightarrow f_\nu(x) = \frac{1}{e^x + 1} \sum_{n=0}^{\infty} C_n p_n(x)$$

(similar to Esposito, Miele, Pastor, Peloso, Pisanti 2000)

Cosmic perturbation theory:

→ for massive neutrinos dependent on neutrino distribution

Standard assumption: $f_\nu(x) = \dfrac{1}{e^x + 1}$

Many exotic scenarios can alter the standard distribution:

- particle decay into neutrinos *(e.g. Cuoco et al. 2005, Gonzalez-Garcia et al. 2012)*
- non-standard neutrino interactions *(Basboll et al. 2009, Starkmann et al. 1994)*
- oscillations to sterile neutrinos *(Barbieri & Dolgov 1990, Foot et al. 1996)*

Model-independent parameterization for non-thermal distributions:

→ expansion in othonormal polynomials $\int \mathrm{d}x \frac{1}{e^x+1} p_n(x) p_m(x) = \delta_{nm}$

$$\Rightarrow f_\nu(x) = \frac{1}{e^x + 1} \sum_{n=0}^{\infty} C_n p_n(x)$$

(similar to Esposito, Miele, Pastor, Peloso, Pisanti 2000)

Here: only n<3

$$f_\nu(x) = N \cdot \frac{1}{e^x + 1} \left(p_0(x) + F_1 p_1(x) + F_2 p_2(x) \right)$$

Which impact has the neutrino distribution function on the CMB and LSS?

Which impact has the neutrino distribution function on the CMB and LSS?

$\rightarrow$ modify $N_{\rm eff}$

Which impact has the neutrino distribution function on the CMB and LSS?

$\rightarrow$ modify $N_{\rm eff}$ ← But that's a well-known fact...

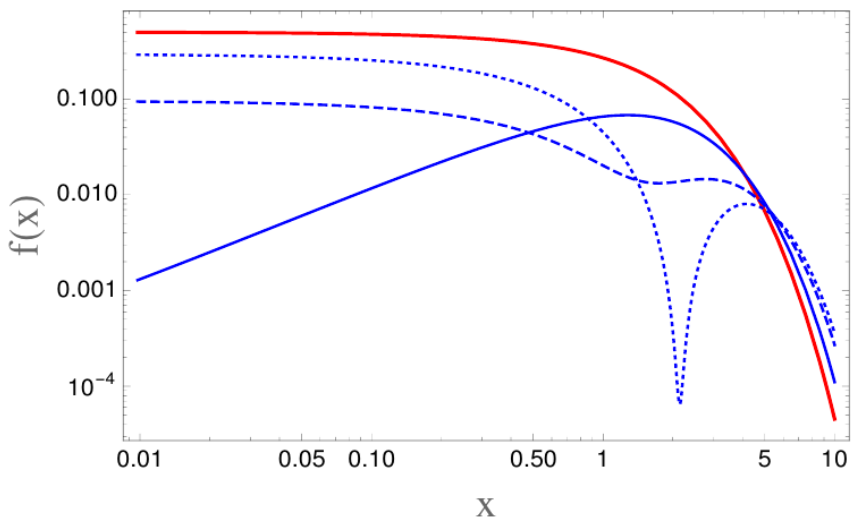
Which impact has the neutrino distribution function on the CMB and LSS?

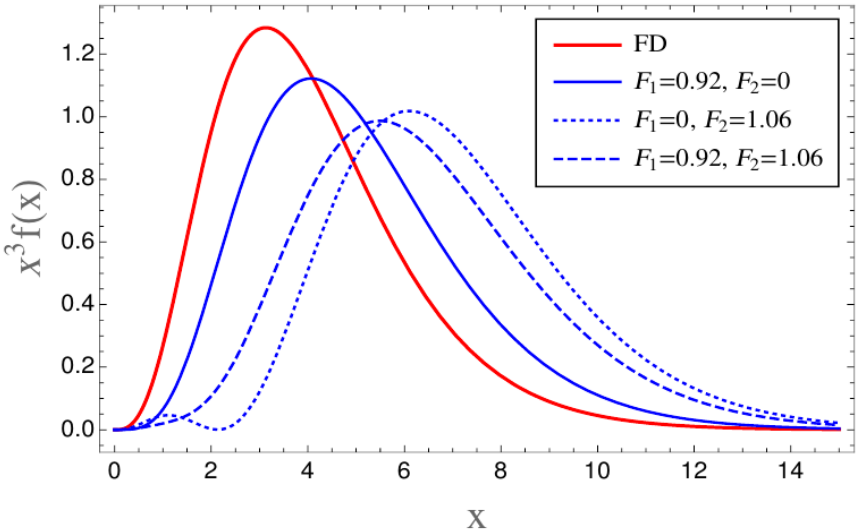
$\rightarrow$ modify $N_{\rm eff}$ ← But that's a well-known fact…

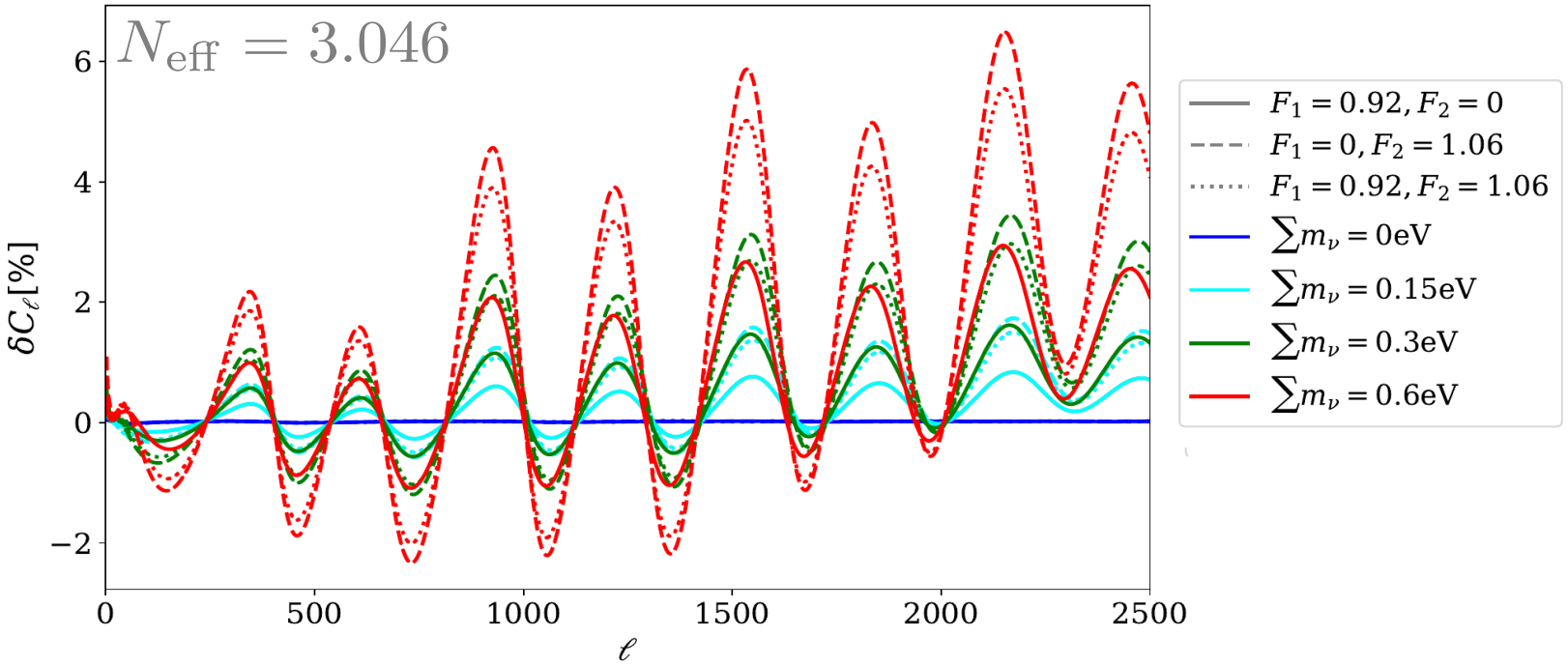
Eliminate degeneracy by fixing energy density at early times:

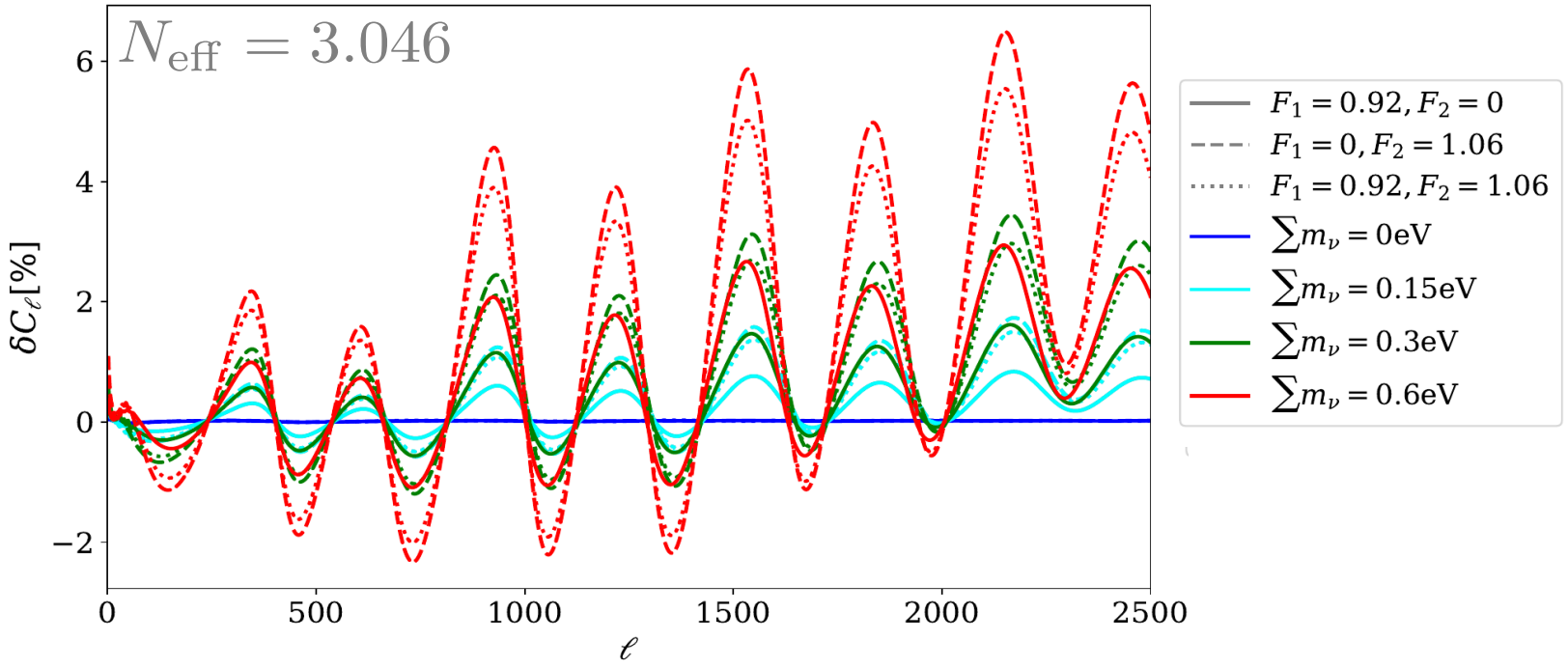
$$N \cdot \int \mathrm{d}x \frac{x^3}{e^x+1}\Big(p_0(x) + F_1 p_1(x) + F_2 p_2(x)\Big) \stackrel{!}{=} \int \mathrm{d}x \frac{x^3}{e^x+1}$$

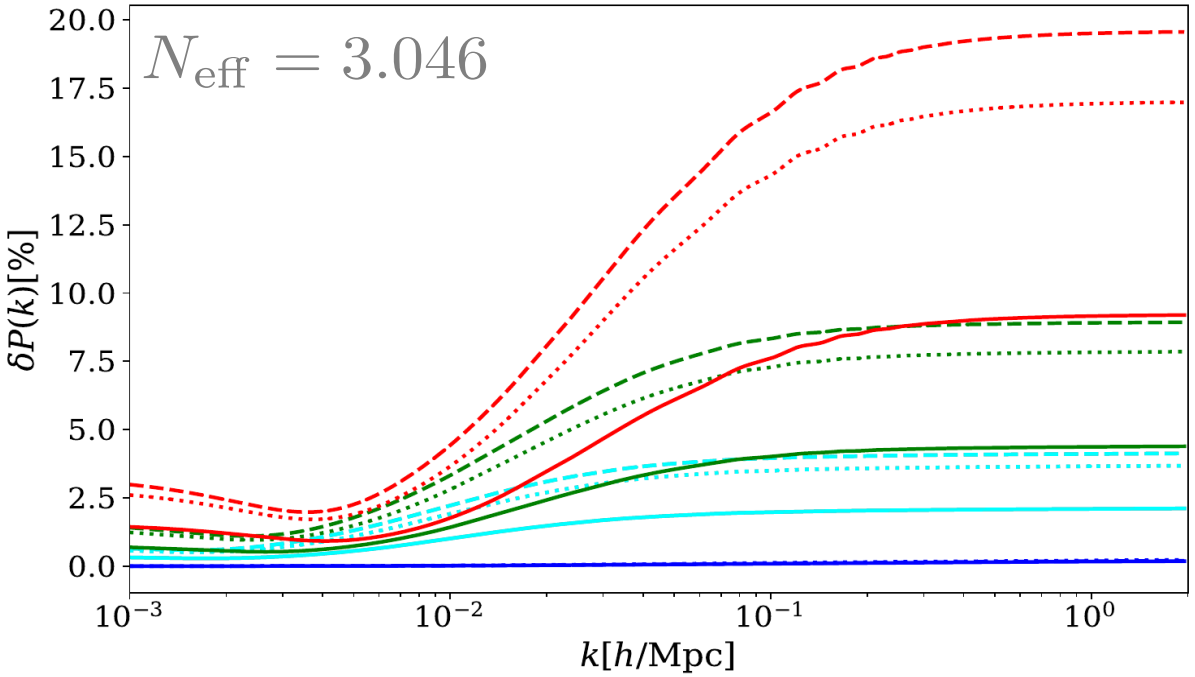
$$\Rightarrow \text{fix the normalization: } N = \frac{5.682197}{6.825012 + 18.239415 F_1 + 17.420046 F_2}$$

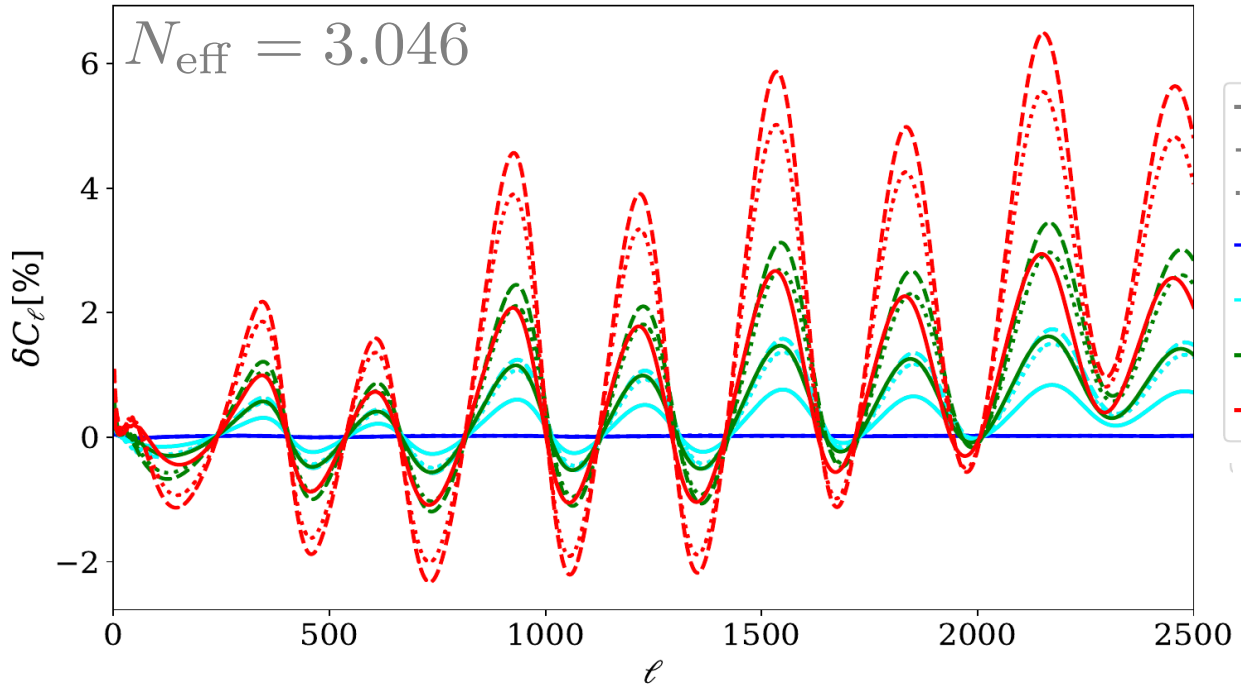


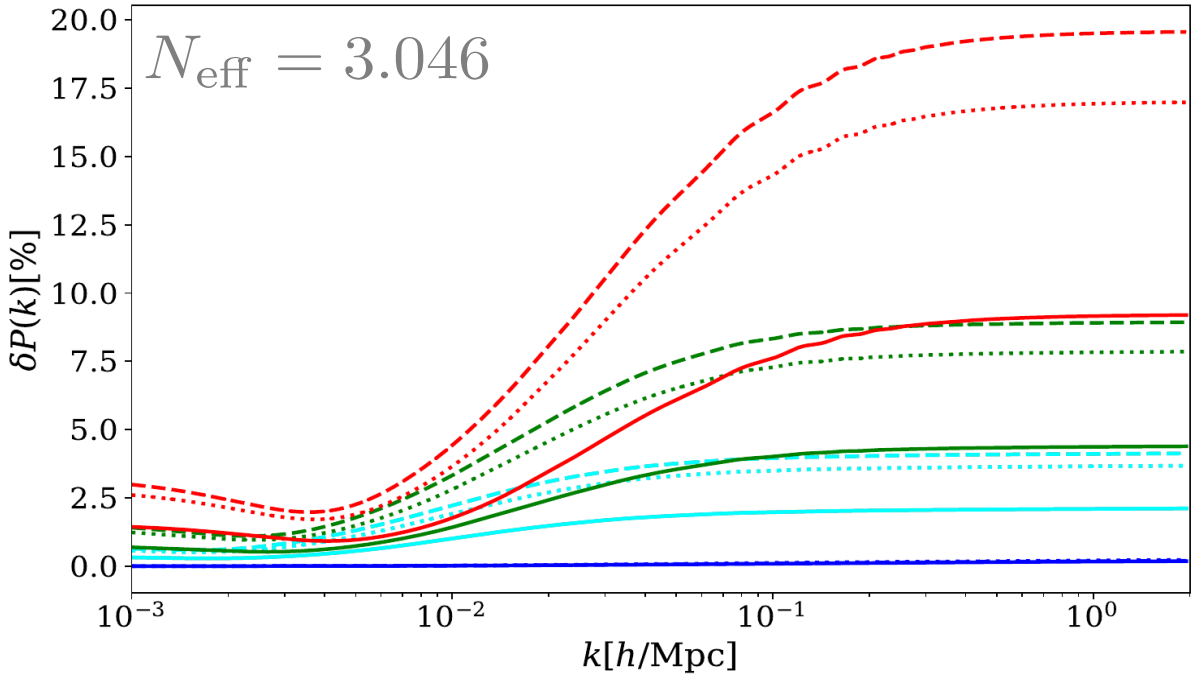



$N_{\rm eff} = 3.046$
δC_ℓ [%]
ℓ
$F_1 = 0.92, F_2 = 0$
$F_1 = 0, F_2 = 1.06$
$F_1 = 0.92, F_2 = 1.06$
$\sum m_\nu = 0$eV
$\sum m_\nu = 0.15$eV
$\sum m_\nu = 0.3$eV
$\sum m_\nu = 0.6$eV


$N_{\rm eff} = 3.046$
δC_ℓ[%]
ℓ
$F_1 = 0.92, F_2 = 0$
$F_1 = 0, F_2 = 1.06$
$F_1 = 0.92, F_2 = 1.06$
$\sum m_\nu = 0$eV
$\sum m_\nu = 0.15$eV
$\sum m_\nu = 0.3$eV
$\sum m_\nu = 0.6$eV


$N_{\rm eff} = 3.046$
$\delta P(k)$[%]
$k[h/\mathrm{Mpc}]$





Is this a unique feature of the distribution function???

Normalization $\rightarrow$ fixed neutrino energy density at *early times*

Normalization $\rightarrow$ fixed neutrino energy density at *early times*

Energy density at *late times* can be fixed by adopting the neutrino mass:

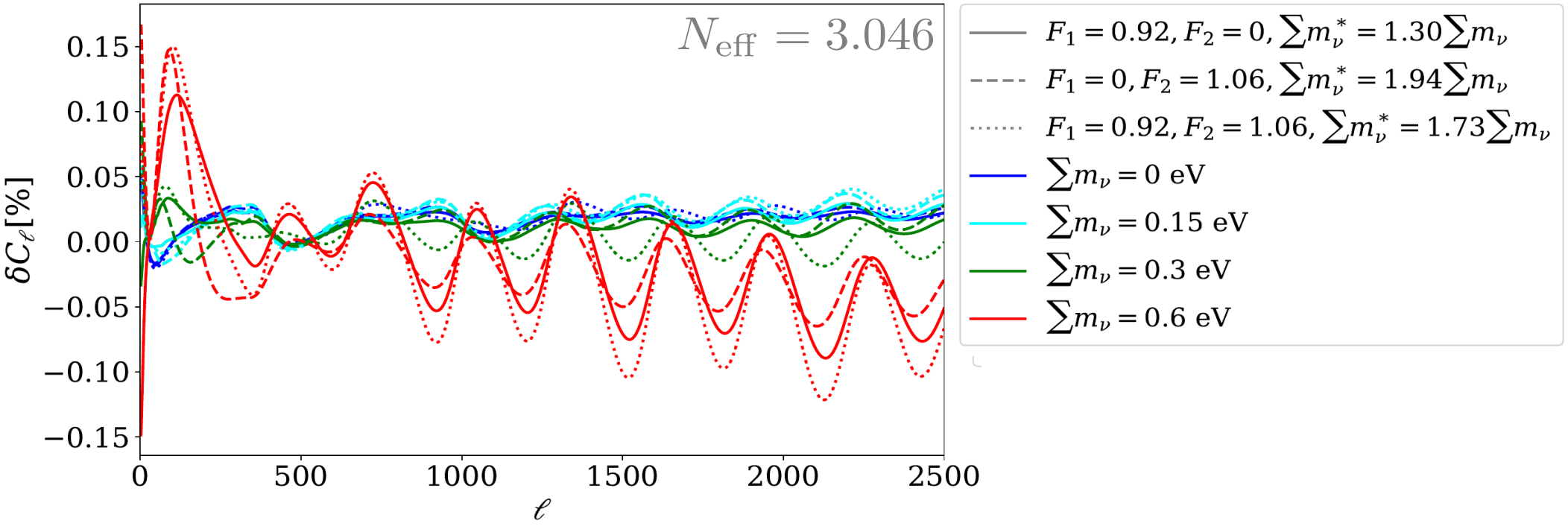
$$\int \mathrm{d}x\, x^2 \sqrt{x^2 + \frac{m_\nu^2}{T_{\nu 0}^2}} \left(\frac{1}{e^x + 1}\right) \stackrel{!}{=} N \int \mathrm{d}x\, x^2 \sqrt{x^2 + \frac{m_\nu^{*\,2}}{T_{\nu 0}^2}} \frac{1}{e^x + 1} \Big(p_0(x) + F_1 p_1(x) + F_2 p_2(x) \Big)$$

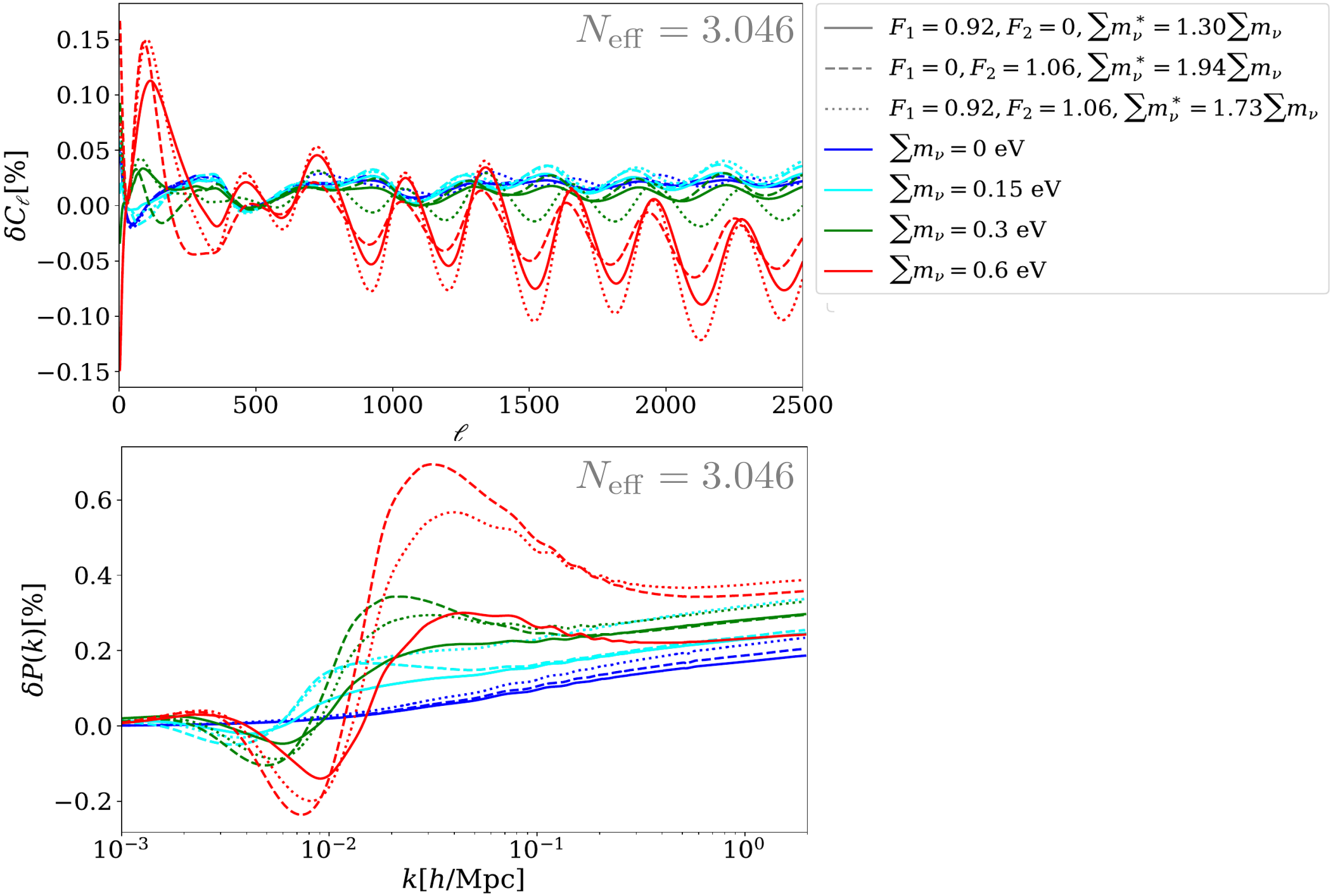
Normalization → fixed neutrino energy density at *early times*

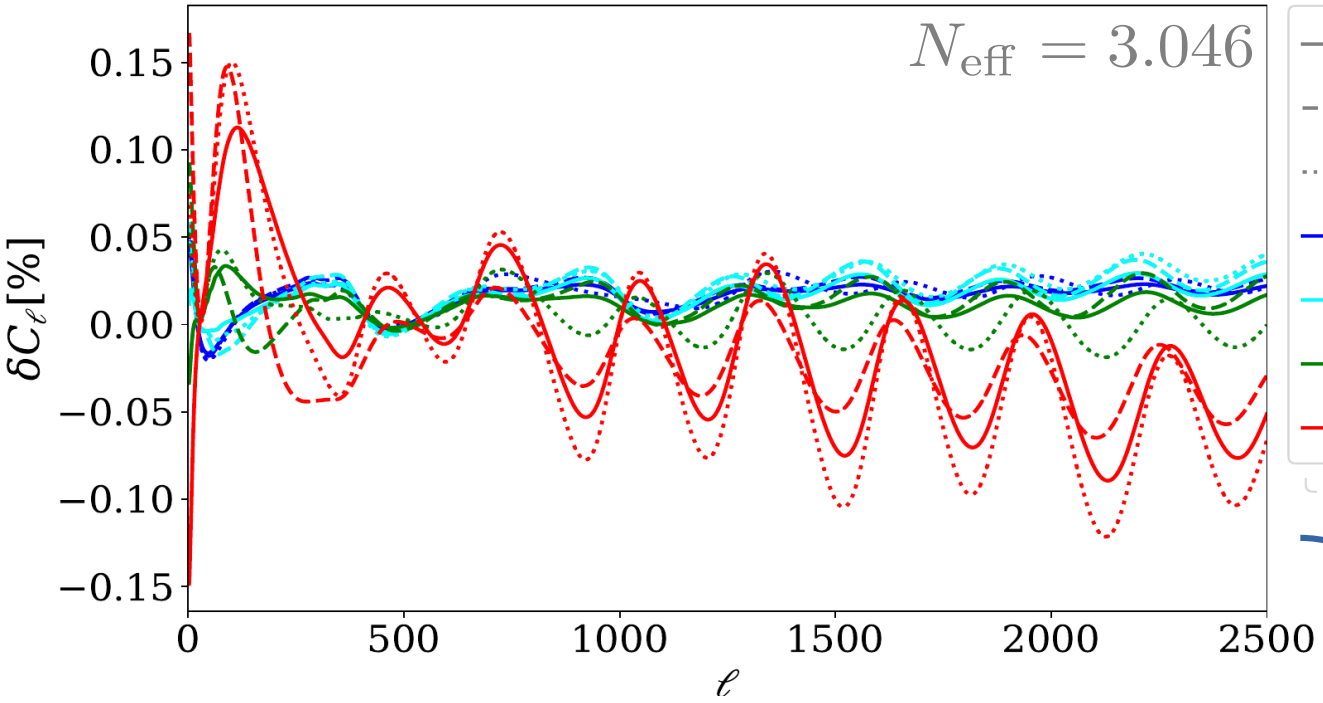
Energy density at *late times* can be fixed by adopting the neutrino mass:

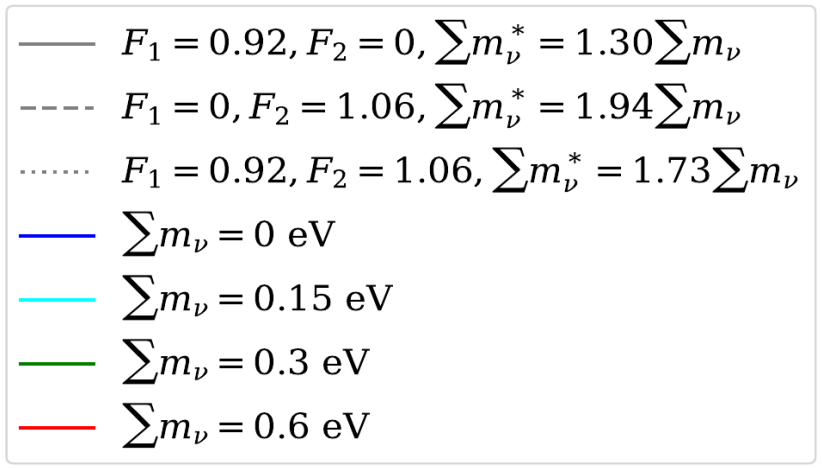
$$\int \mathrm{d}x\, x^2 \sqrt{x^2 + \frac{m_\nu^2}{T_{\nu 0}^2}} \left(\frac{1}{e^x + 1}\right) \stackrel{!}{=} N \int \mathrm{d}x\, x^2 \sqrt{x^2 + \frac{m_\nu^{*\,2}}{T_{\nu 0}^2}} \frac{1}{e^x + 1} \Big(p_0(x) + F_1 p_1(x) + F_2 p_2(x)\Big)$$

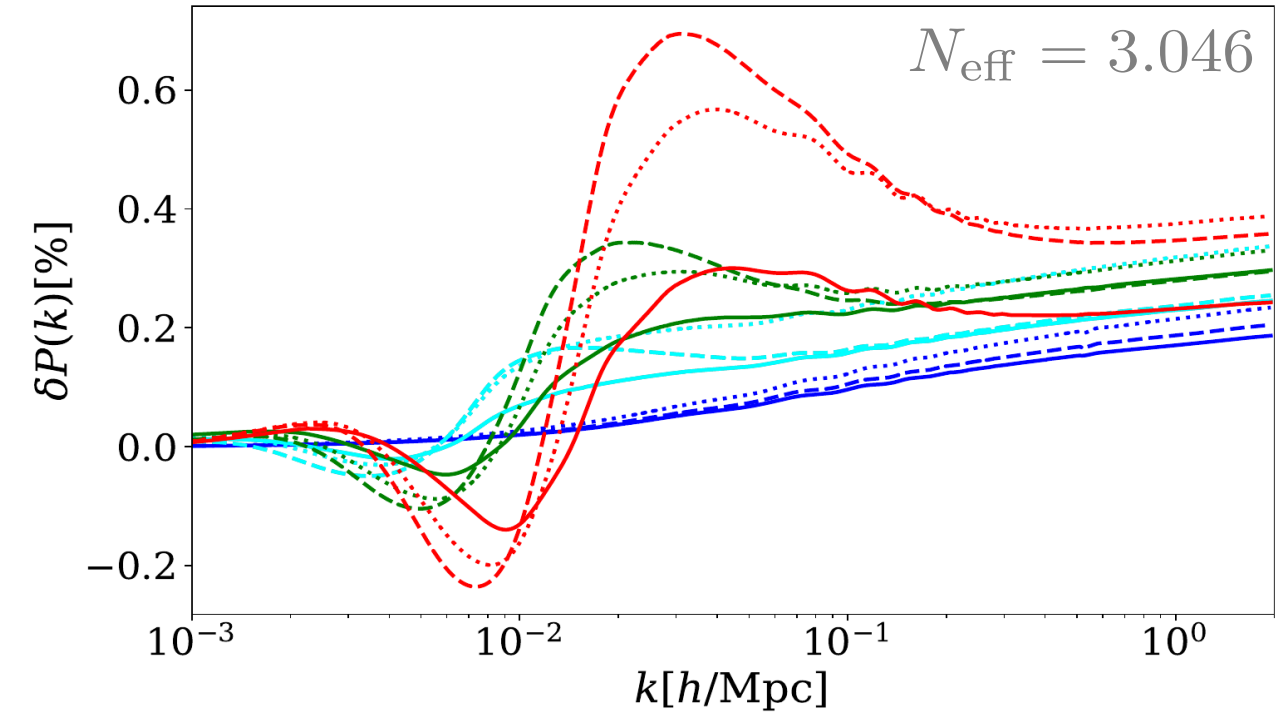
$$\begin{aligned} F_1 = 0.92, \quad F_2 = 0 \quad &: \quad m_\nu^* = 1.30 \cdot m_\nu \\ F_1 = 0, \quad F_2 = 1.06 \quad &: \quad m_\nu^* = 1.94 \cdot m_\nu \\ F_1 = 0.92, \quad F_2 = 1.06 \quad &: \quad m_\nu^* = 1.73 \cdot m_\nu \end{aligned}$$


$N_{\rm eff} = 3.046$
δC_ℓ [%]
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
0
500
1000
1500
2000
2500
ℓ
$F_1 = 0.92, F_2 = 0, \sum m_\nu^* = 1.30 \sum m_\nu$
$F_1 = 0, F_2 = 1.06, \sum m_\nu^* = 1.94 \sum m_\nu$
$F_1 = 0.92, F_2 = 1.06, \sum m_\nu^* = 1.73 \sum m_\nu$
$\sum m_\nu = 0$ eV
$\sum m_\nu = 0.15$ eV
$\sum m_\nu = 0.3$ eV
$\sum m_\nu = 0.6$ eV


$N_{\rm eff} = 3.046$
δC_ℓ[%]
ℓ
$N_{\rm eff} = 3.046$
$\delta P(k)$[%]
k[h/Mpc]
$F_1 = 0.92, F_2 = 0, \sum m_\nu^* = 1.30 \sum m_\nu$
$F_1 = 0, F_2 = 1.06, \sum m_\nu^* = 1.94 \sum m_\nu$
$F_1 = 0.92, F_2 = 1.06, \sum m_\nu^* = 1.73 \sum m_\nu$
$\sum m_\nu = 0$ eV
$\sum m_\nu = 0.15$ eV
$\sum m_\nu = 0.3$ eV
$\sum m_\nu = 0.6$ eV





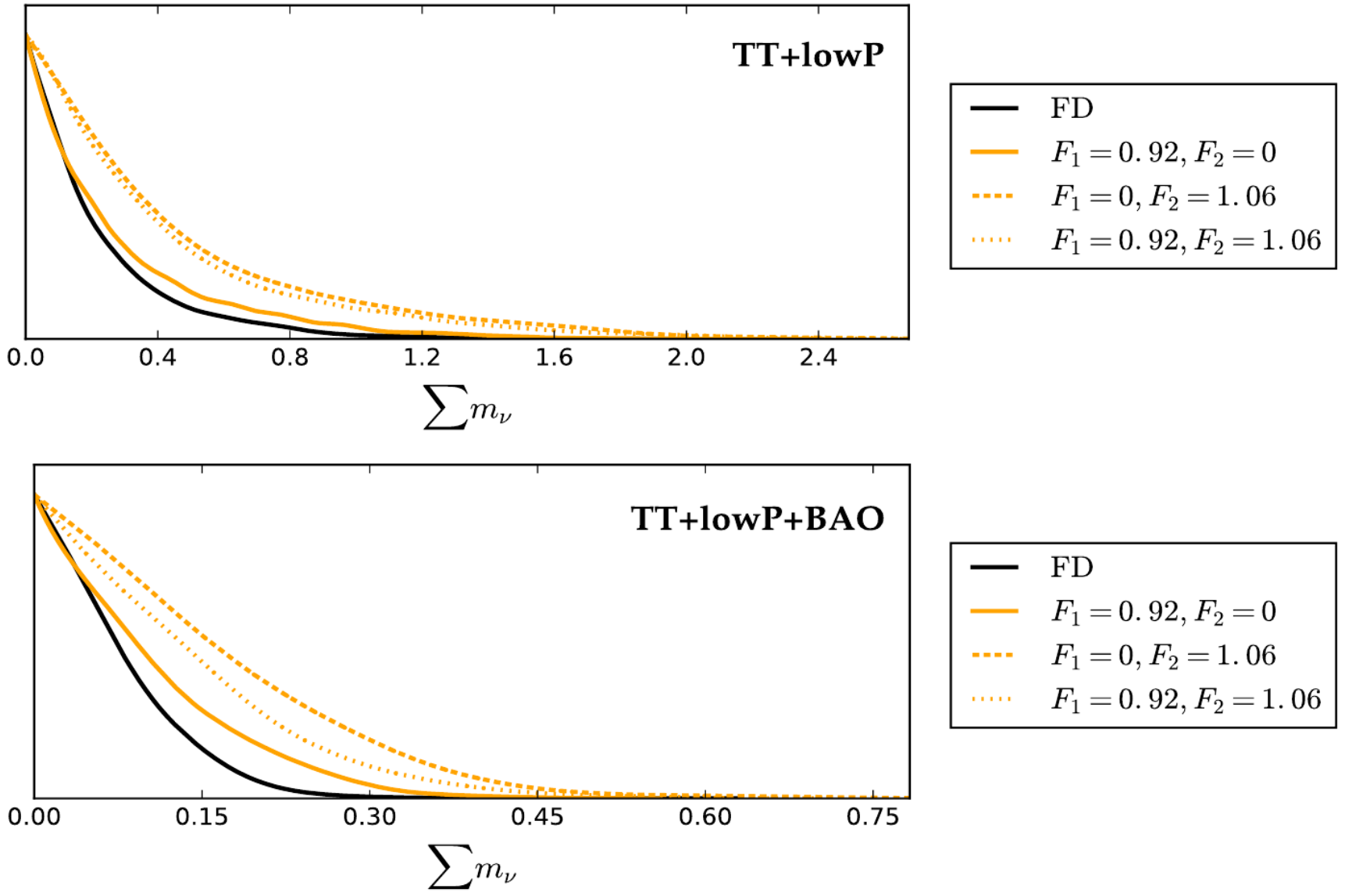


Remaining effect
below sensitivity
of current data

I. Almost no unique signature of the neutrino distribution function, large **intrinsic** degeneracy with $N_{\rm eff}$ **and** $\sum m_\nu$.

I. Almost no unique signature of the neutrino distribution function, large **intrinsic** degeneracy with $N_{\rm eff}$ **and** $\sum m_\nu$.

II. Non-thermal neutrino distributions can relax cosmological neutrino mass bounds significantly!



More than 90% relaxed neutrino mass bounds!!!

Cosmological neutrino mass bound strongly depends on our assumptions about the relic distribution function…

Cosmological neutrino mass bound strongly depends on our assumptions about the relic distribution function…

...**but** our intention is **not** to claim that the mass bounds are **not** robust…

Cosmological neutrino mass bound strongly depends on our assumptions about the relic distribution function…

...**but** our intention is **not** to claim that the mass bounds are **not** robust…

…**but** we should keep in mind that this assumption is behind all cosmological neutrino mass bounds.

Cosmological neutrino mass bound strongly depends on our assumptions about the relic distribution function…

...**but** our intention is **not** to claim that the mass bounds are **not** robust…

…**but** we should keep in mind that this assumption is behind all cosmological neutrino mass bounds.

Thank you for your attention!