How to relax the comological neutrino mass bound

Isabel M. Oldengott*,

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

***University of Valencia, IFIC**

arXiv: 1901.04352 [astro-ph]

JCAP 1904 (2019) no.04, 049

Neutrino oscillations → neutrinos massive

PMNS matrix:

Mass splittings:

Mass hierarchy:

Absolute mass scale:

Neutrino oscillations → neutrinos massive

PMNS matrix: ✓

Mass splittings: ✓

Mass hierarchy: ←

Absolute mass scale: ←

Neutrino oscillations → neutrinos massive

PMNS matrix: ✓

Mass splittings: ✓

Mass hierarchy: ←

Absolute mass scale: ←

→ minimal mass:

$\sum m_\nu \geq 0.06$ eV

Neutrino oscillations → neutrinos massive

PMNS matrix: ✓

Mass splittings: ✓

Mass hierarchy: ←

Absolute mass scale: ←

minimal mass:
$\sum m_\nu \geq 0.06$ eV

Holy grail of neutrino physics:

Determination of the neutrino mass scale

Neutrino oscillations → neutrinos massive

PMNS matrix: ✓

Mass splittings: ✓

Mass hierarchy: ←

Absolute mass scale: ←

minimal mass:
$\sum m_\nu \geq 0.06$ eV

Holy grail of neutrino physics:

Determination of the neutrino mass scale

Troitzk (1994-2004): $m_{\nu_e} < 2.05$ eV

Mainz (1997-2001): $m_{\nu_e} < 2.3$ eV

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

Laboratory: Tritium β decay

Neutrino oscillations → neutrinos massive

PMNS matrix: ✓

Mass splittings: ✓

Mass hierarchy:

Absolute mass scale:

minimal mass: $\sum m_\nu \geq 0.06$ eV

Holy grail of neutrino physics:

Determination of the neutrino mass scale

Troitzk (1994-2004): $m_{\nu_e} < 2.05$ eV

Mainz (1997-2001): $m_{\nu_e} < 2.3$ eV

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

Laboratory: Tritium β decay

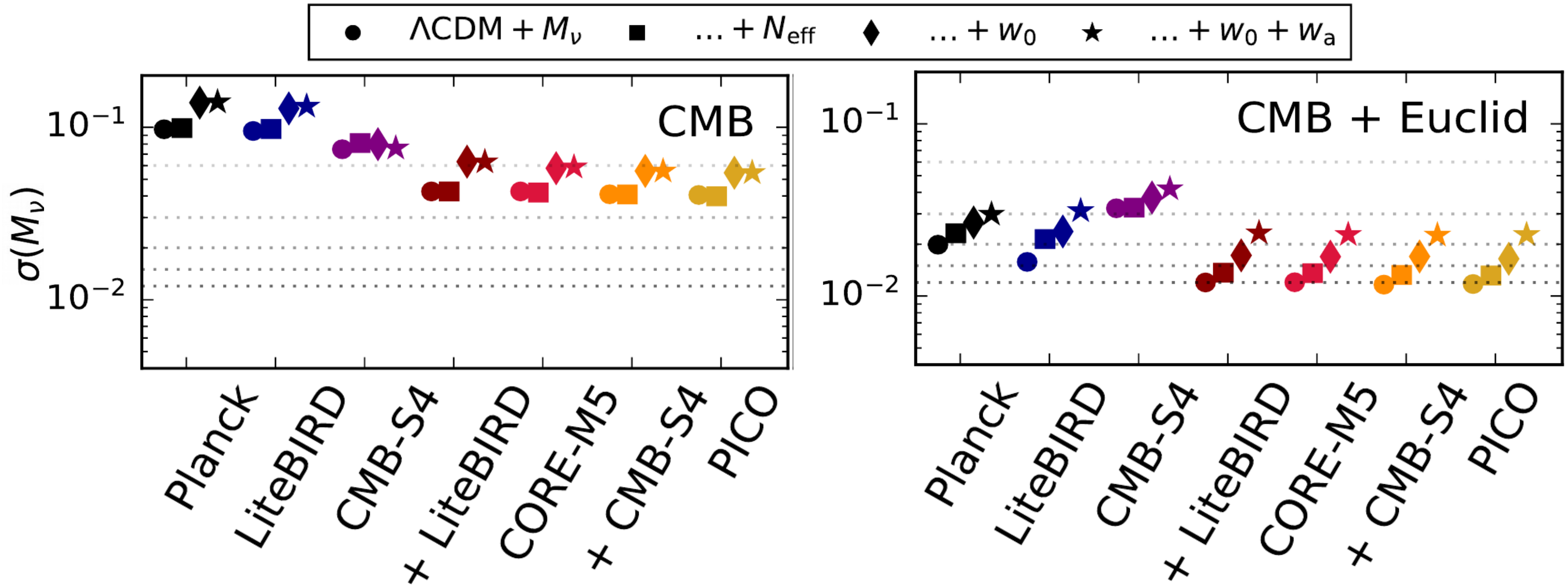
Cosmology (Planck 2018):

$\sum m_\nu < 0.54$ eV (TT+lowP)

$\sum m_\nu < 0.16$ eV (TT+lowP+BAO)

$\sum m_\nu < 0.12$ eV (TT,TE,EE+lowP+lensing+BAO)

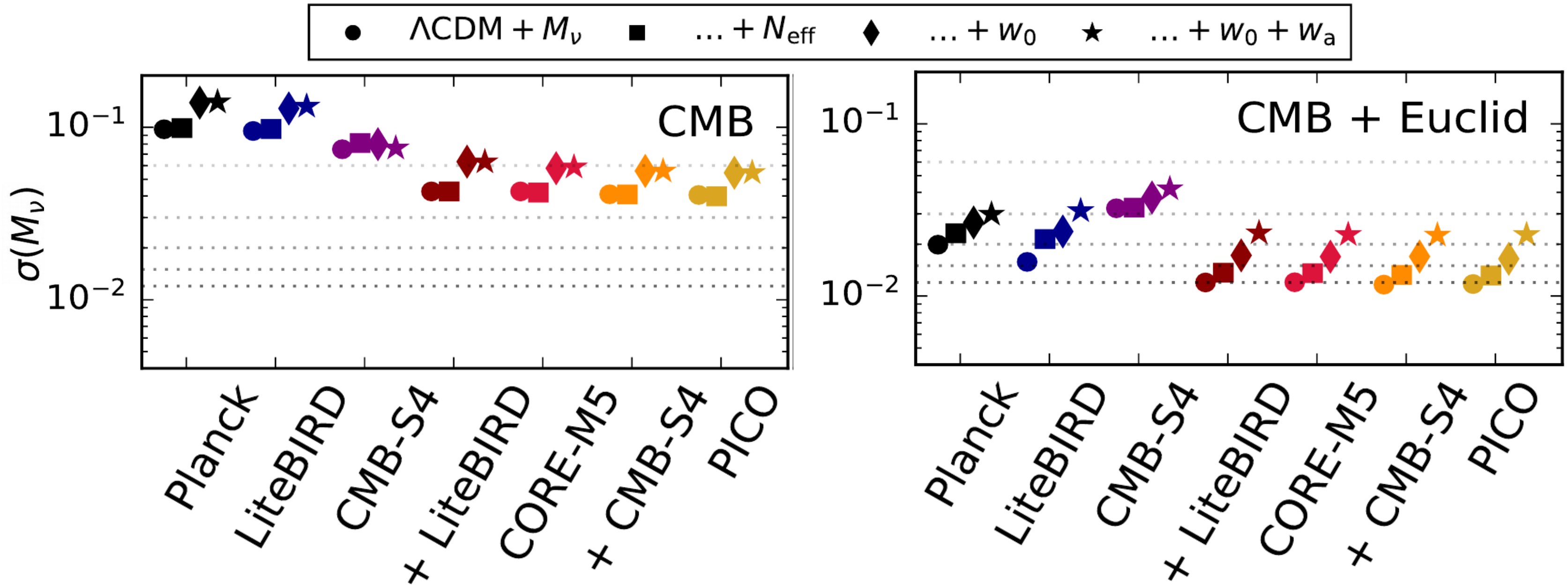
… and the future looks even brighter:



+ DESI + SKA

(fig. from Brinckmann et al., arXiv:1808.05955)

… and the future looks even brighter:

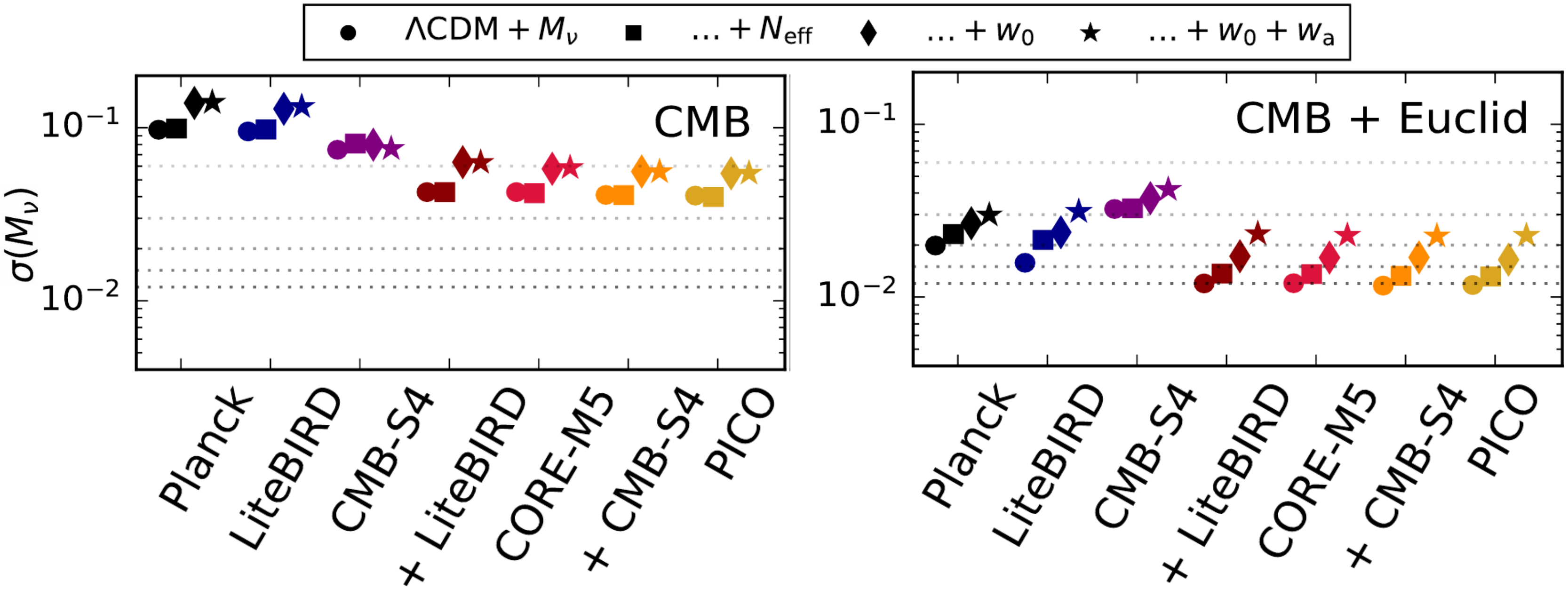


+ DESI + SKA

(fig. from Brinckmann et al., arXiv:1808.05955)

But how robust are those constraints?

… and the future looks even brighter:



+ DESI + SKA

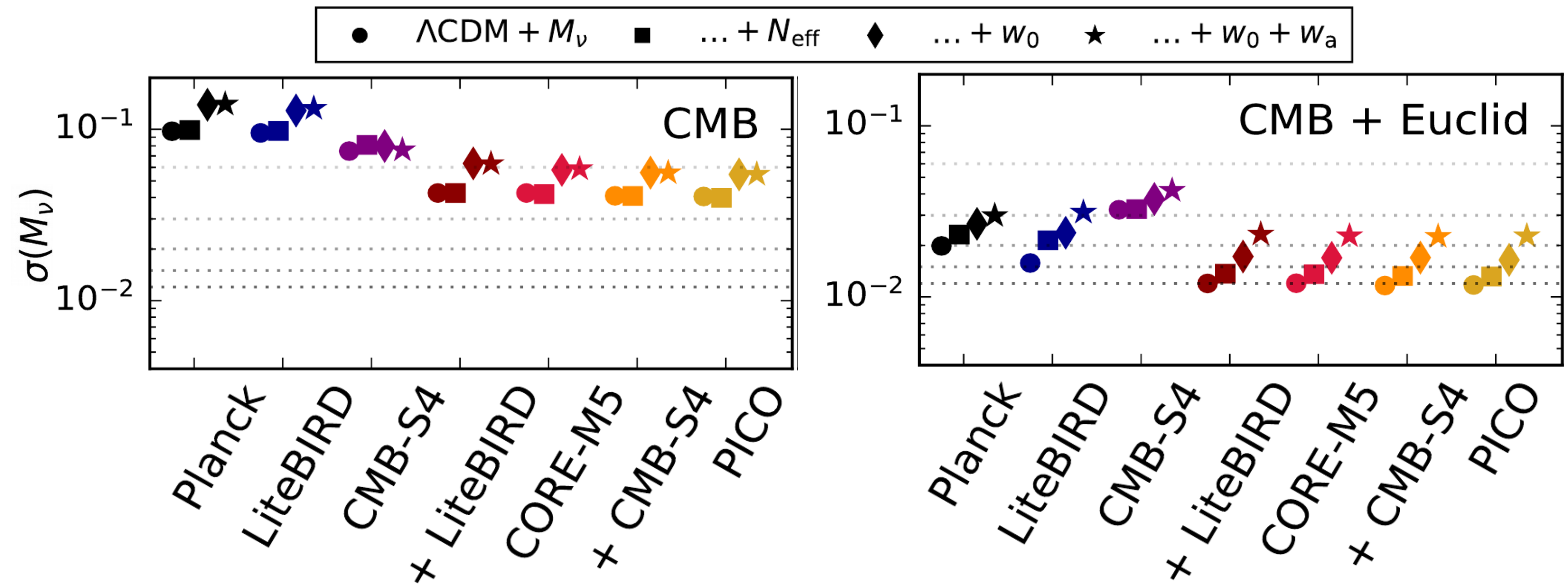
(fig. from Brinckmann et al., arXiv:1808.05955)

But how robust are those constraints?

Tightest constraints assume ΛCDM base model

→ parameter degeneracies (w, A_{lens}, τ_{reio}, N_{eff}…)

… and the future looks even brighter:



+ DESI + SKA

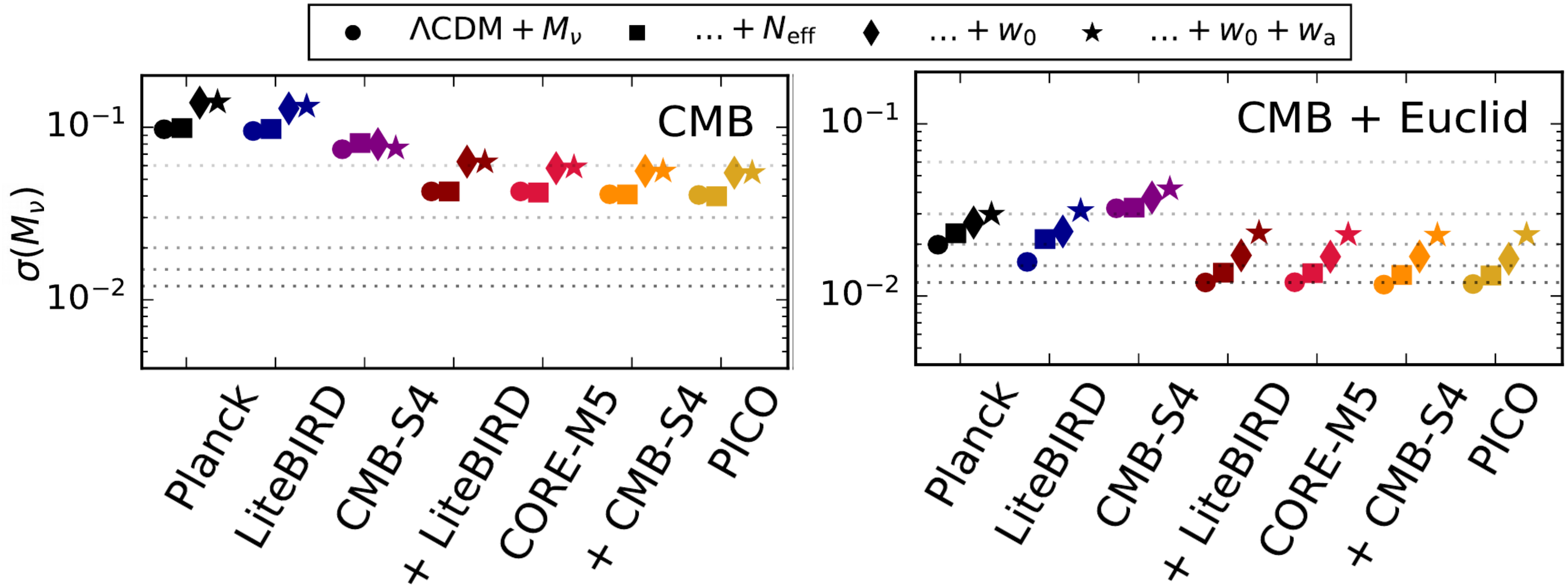
(fig. from Brinckmann et al., arXiv:1808.05955)

But how robust are those constraints?

Tightest constraints assume ΛCDM base model
→ parameter degeneracies (w, $A_{\rm lens}$, $\tau_{\rm reio}$, $N_{\rm eff}$ …)

Marginalizing over different models relaxes bounds *(Gariazzo, Mena 2018)*

… and the future looks even brighter:



+ DESI + SKA

(fig. from Brinckmann et al., arXiv:1808.05955)

But how robust are those constraints?

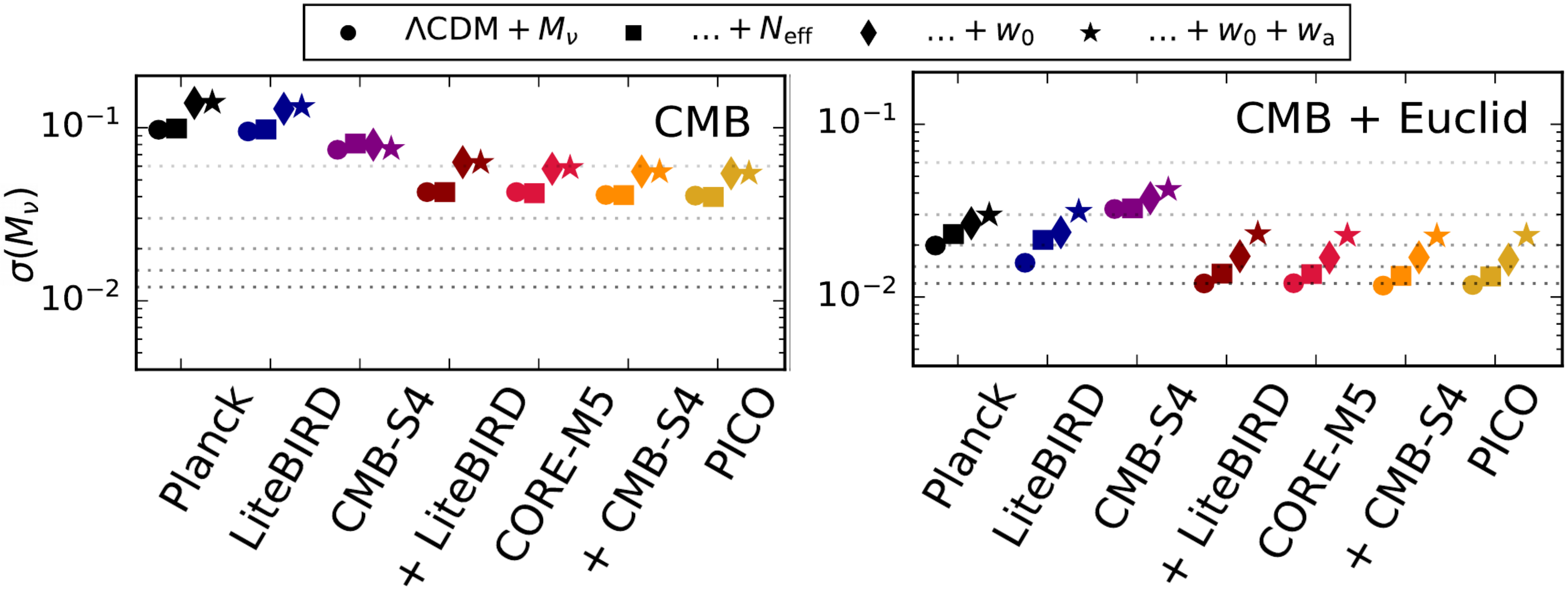
Tightest constraints assume ΛCDM base model

→ parameter degeneracies (w, A_{lens}, τ_{reio}, N_{eff} …)

Marginalizing over different models relaxes bounds *(Gariazzo, Mena 2018)*

→ mass bounds usually claimed to be very robust…

… and the future looks even brighter:



+ DESI + SKA

(fig. from Brinckmann et al., arXiv:1808.05955)

But how robust are those constraints?

Tightest constraints assume ΛCDM base model
→ parameter degeneracies (w, A_{lens}, τ_{reio}, N_{eff} …)

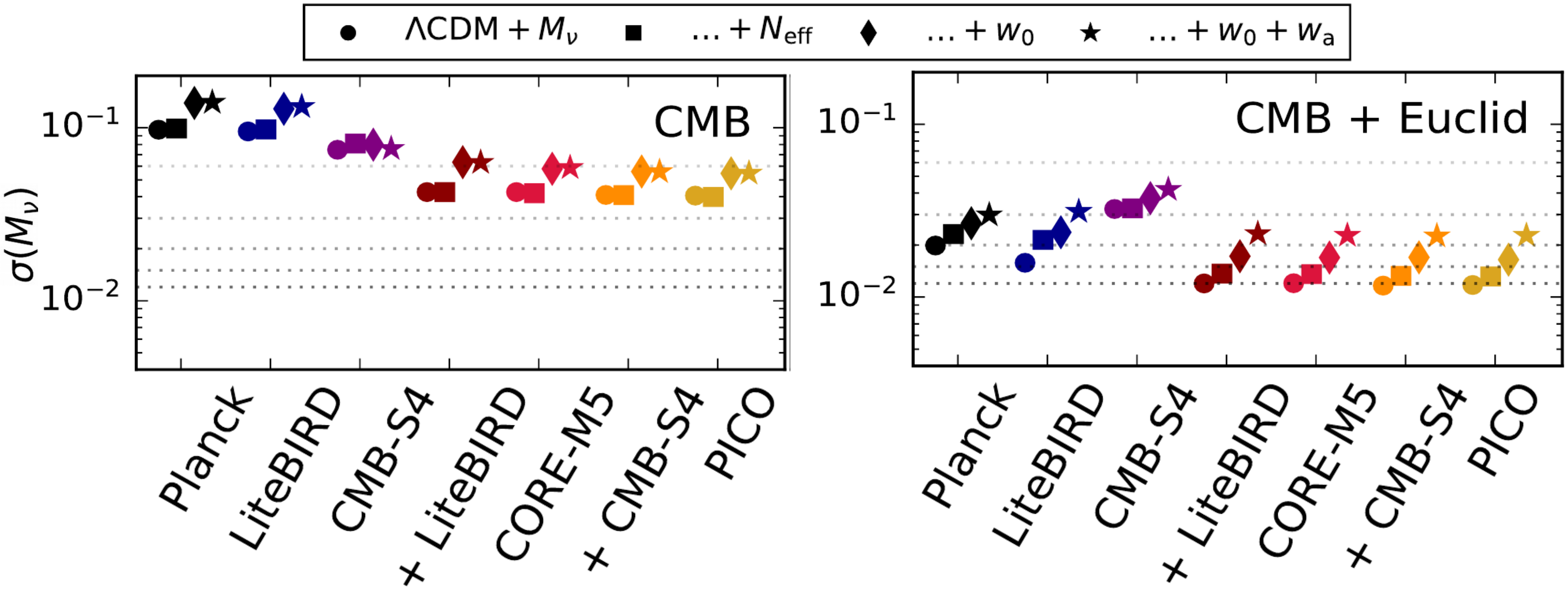
Marginalizing over different models relaxes bounds *(Gariazzo, Mena 2018)*

→ mass bounds usually claimed to be very robust…

Often mentioned caveat: → „neutrinoless Universe“ *(Beacom et al. 2004)*

→ time-varying neutrino masses *(e.g. Lorenz 2018)*

… and the future looks even brighter:



+ DESI + SKA

(fig. from Brinckmann et al., arXiv:1808.05955)

But how robust are those constraints?

Tightest constraints assume ΛCDM base model
→ parameter degeneracies (w, $A_{\rm lens}$, $\tau_{\rm reio}$, $N_{\rm eff}$ …)

Marginalizing over different models relaxes bounds *(Gariazzo, Mena 2018)*

→ mass bounds usually claimed to be very robust…

Often mentioned caveat: → „neutrinoless Universe“ *(Beacom et al. 2004)*
→ time-varying neutrino masses *(e.g. Lorenz 2018)*

This work:
Less extreme scenario

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

…**but** all cosmological bounds 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:

→ neutrino decouple at ~1 MeV (when still ultra-relativistic)

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

Cosmic perturbation theory:

→ neutrino decouple at ~1 MeV (when still ultra-relativistic)

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

Many exotic scenarios can alter the standard distribution:

Cosmic perturbation theory:

→ neutrino decouple at ~1 MeV (when still ultra-relativistic)

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 *(e.g. Hannestad et al. 2012)*

Cosmic perturbation theory:

→ neutrino decouple at ~1 MeV (when still ultra-relativistic)

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 *(e.g. Hannestad et al. 2012)*

Model-independent parameterization for non-thermal distributions:

→ expansion in orthonormal 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:

→ neutrino decouple at ~1 MeV (when still ultra-relativistic)

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 *(e.g. Hannestad et al. 2012)*

<u>Model-independent parameterization for non-thermal distributions:</u>

→ expansion in orthonormal 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

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

Impact on cosmological observables?

Impact on cosmological observables?

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

Impact on cosmological observables?

$$\to \text{modify } N_{\text{eff}}$$

But that's a
well-known fact…

Impact on cosmological observables?

$\rightarrow$ modify N_{eff}

But that's a well-known fact...

Eliminate degeneracy by fixing energy density at early times:

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

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

Impact on cosmological observables?

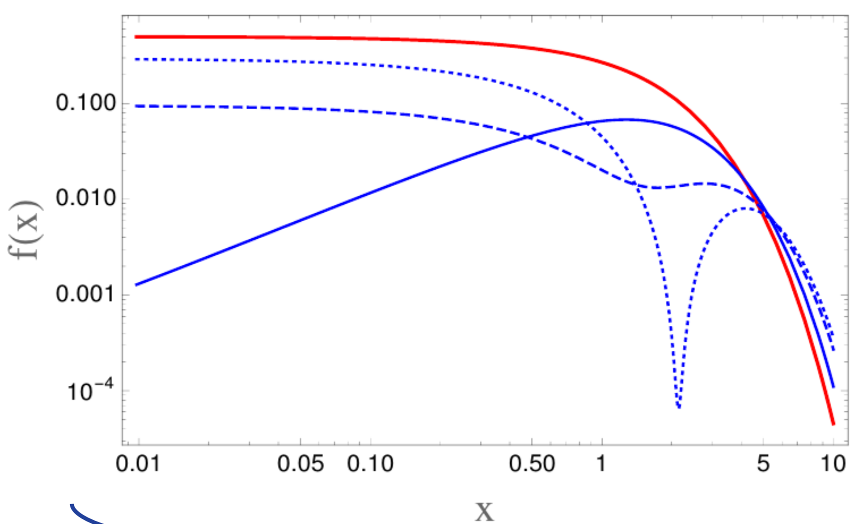
$$\to \text{modify } N_{\text{eff}}$$

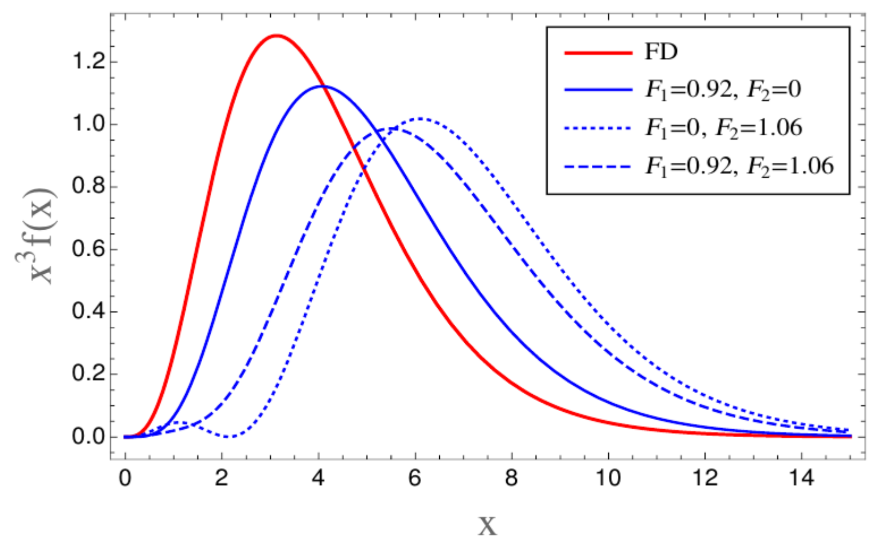
But that's a well-known fact...

Eliminate degeneracy by fixing energy density at early times:

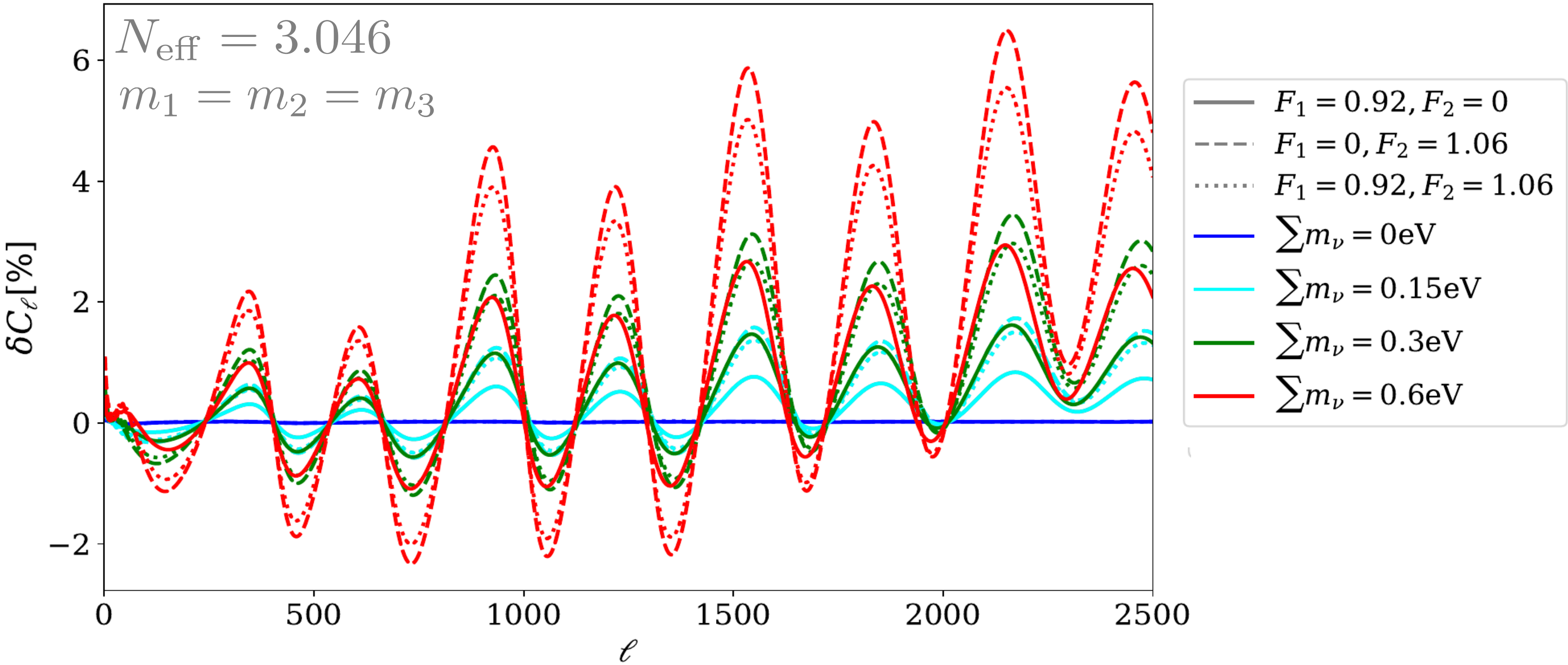
$$N \cdot \int \mathrm{d}x \frac{x^3}{e^x+1}\Big(p_0(x) + F_1 p_1(x) + F_2 p_2(x)\Big) \stackrel{!}{=} \int \mathrm{d}x \frac{x^3}{e^x+1}$$

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

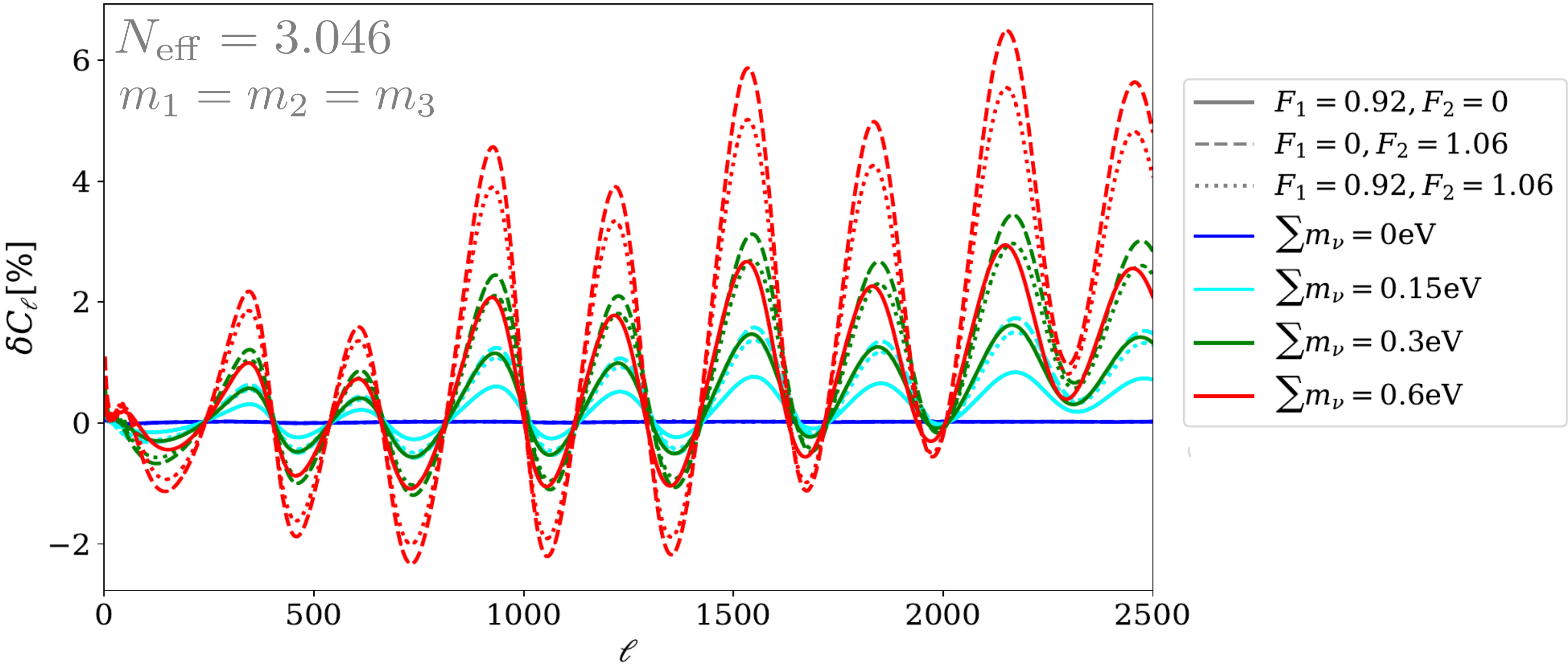


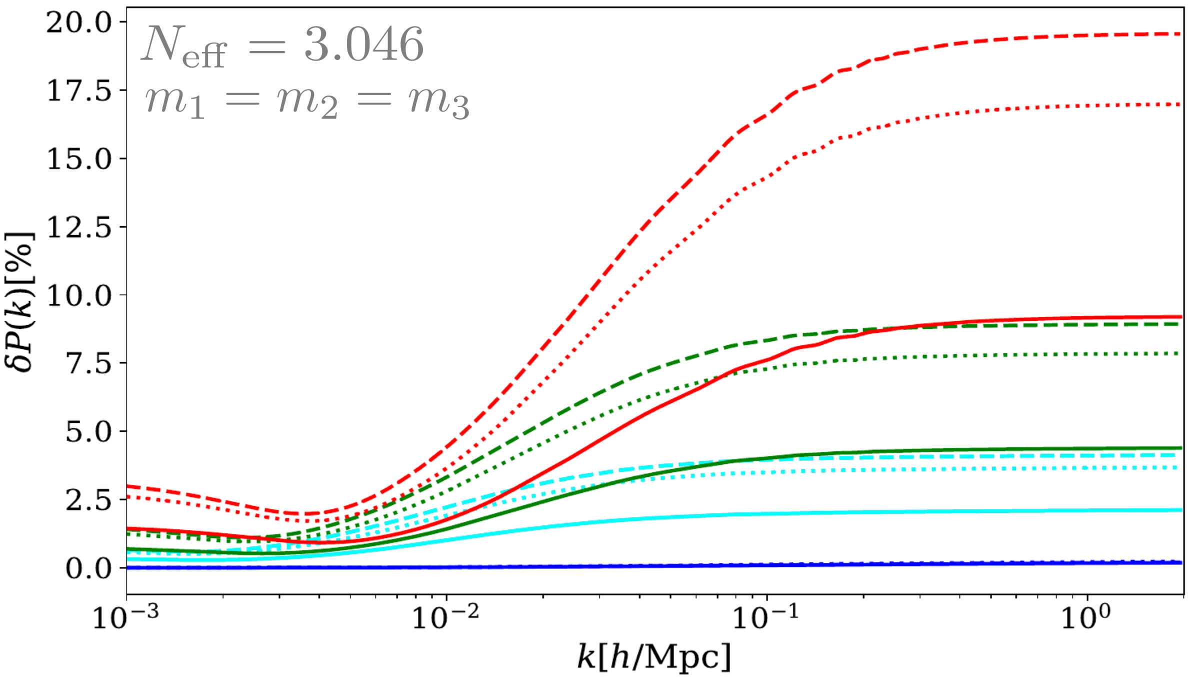


Model independent parameterization allows some variation,
but all distributions still relatively close to Fermi-Dirac...

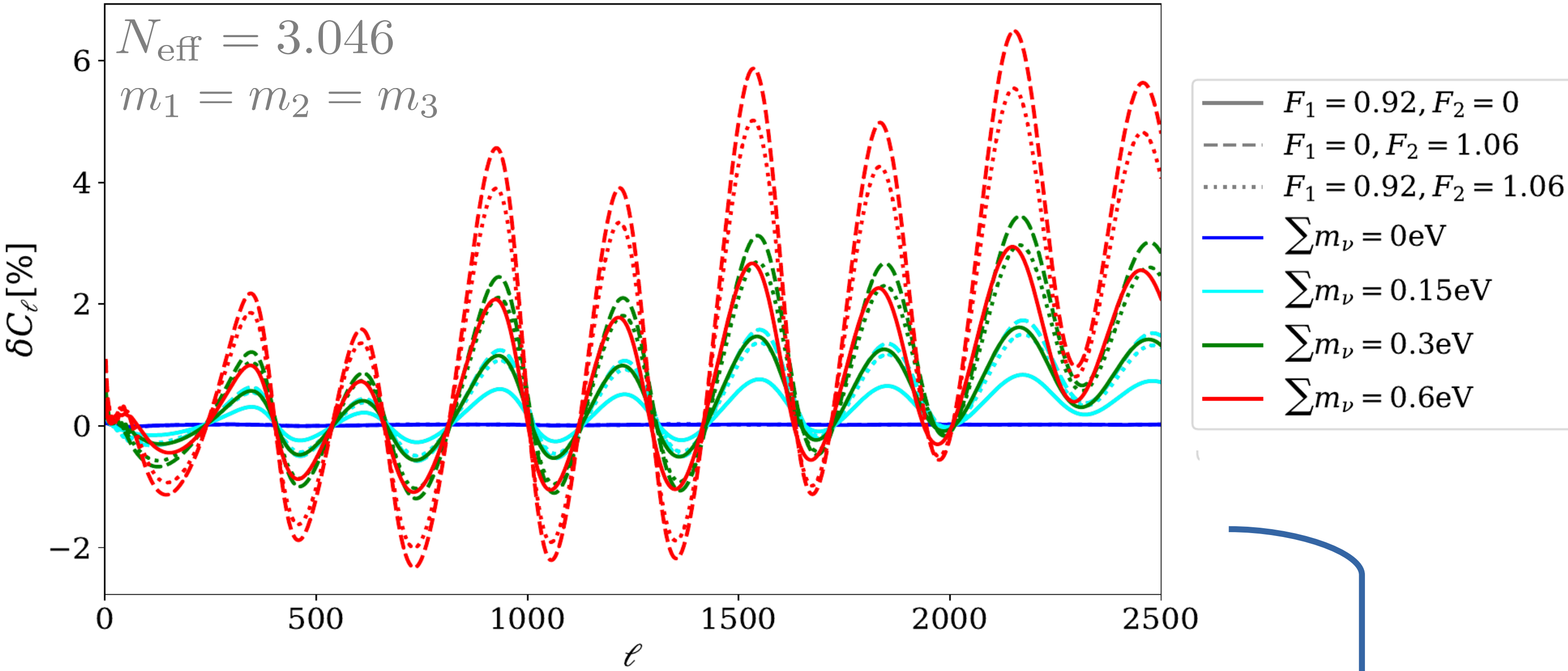


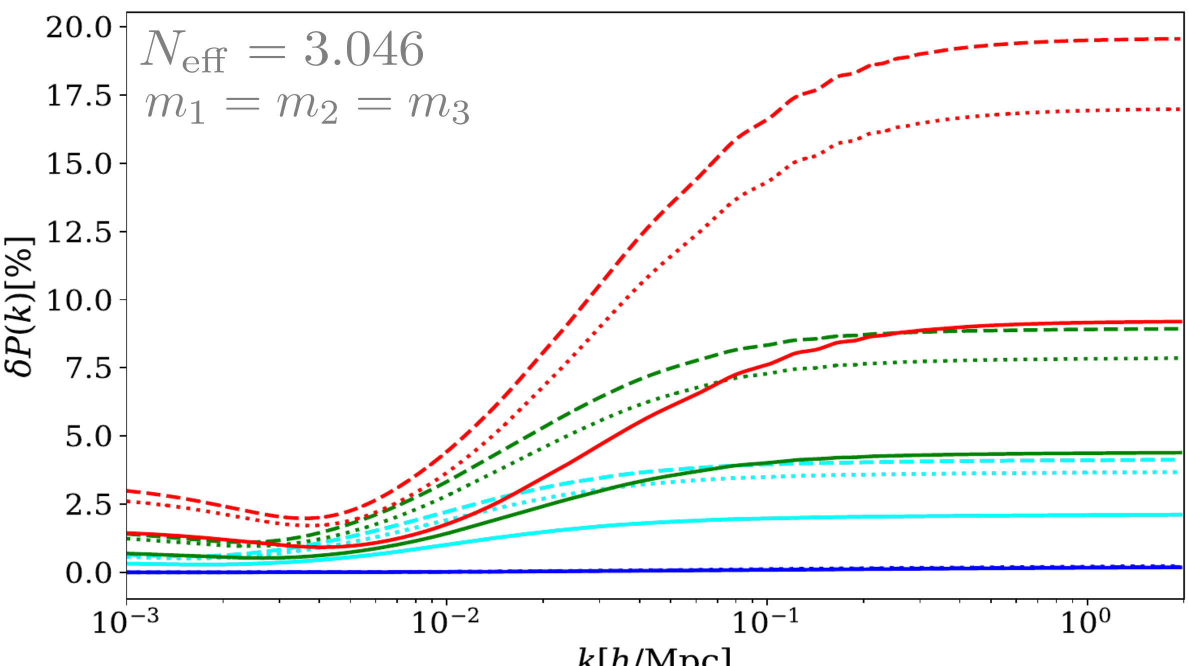
Using CLASS
(Blas, Lesgourgues, Tram 2011)





Using CLASS
(Blas, Lesgourgues, Tram 2011)





Is this a <u>unique</u> feature of the distribution function???

Using CLASS
(Blas, Lesgourgues, Tram 2011)

Normalization → fixed neutrino energy density at *early times*

Normalization → fixed neutrino energy density at *early times*

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

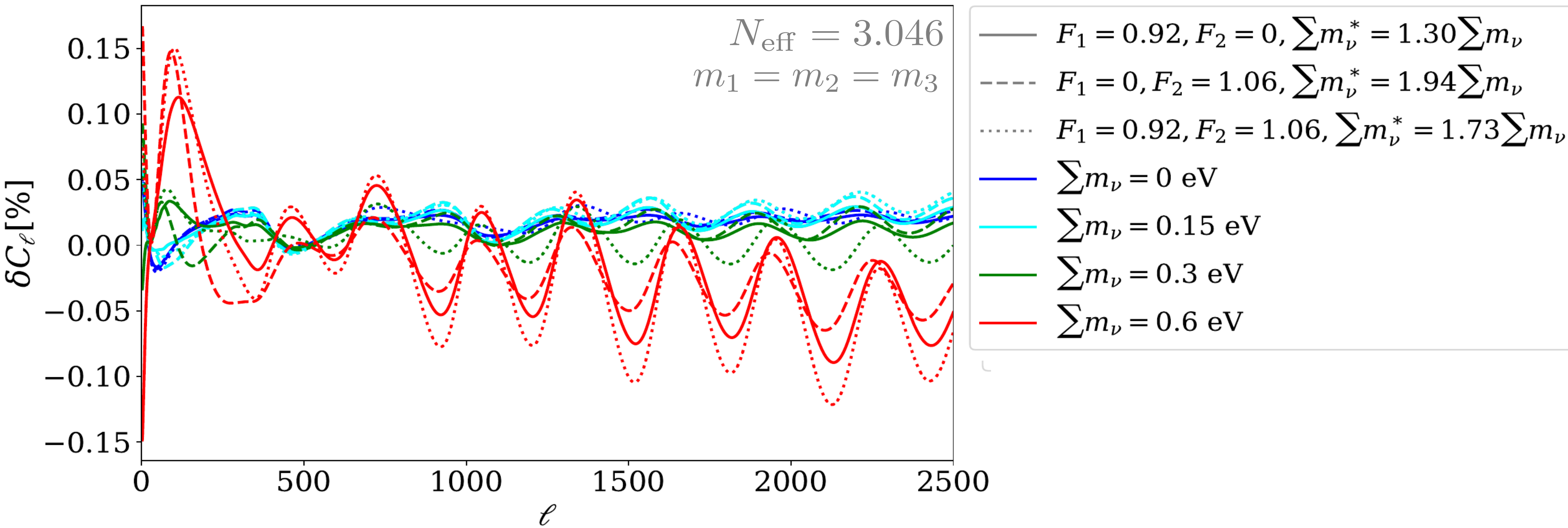
$$\int \mathrm{d}x\, x^2 \sqrt{x^2 + \frac{m_\nu^2}{T_{\nu 0}^2}} \left(\frac{1}{e^x+1}\right) \stackrel{!}{=} N \int \mathrm{d}x\, x^2 \sqrt{x^2 + \frac{m_\nu^{*\,2}}{T_{\nu 0}^2}}\, \frac{1}{e^x+1} \Big(p_0(x) + F_1 p_1(x) + F_2 p_2(x)\Big)$$

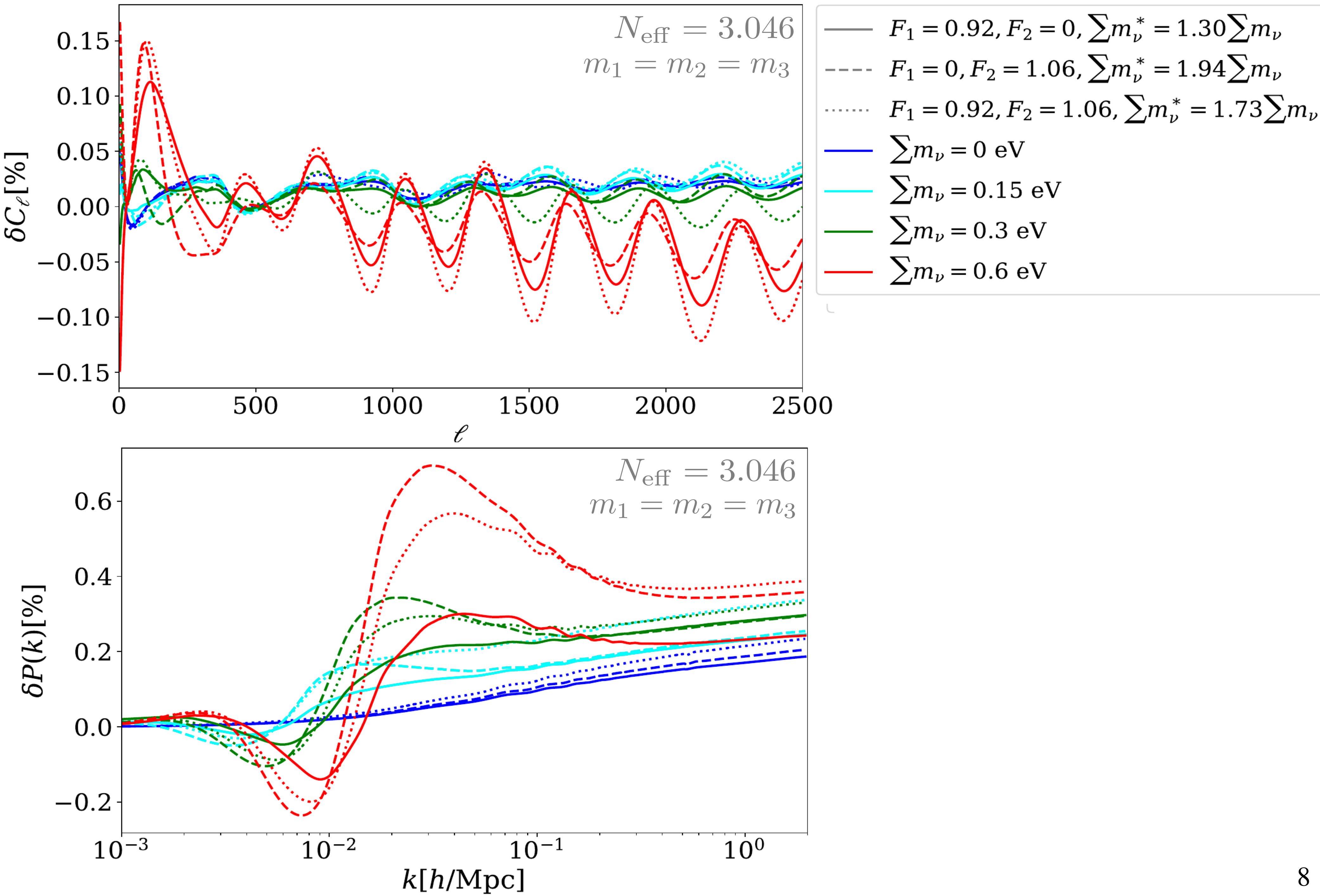
Normalization → fixed neutrino energy density at *early times*

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

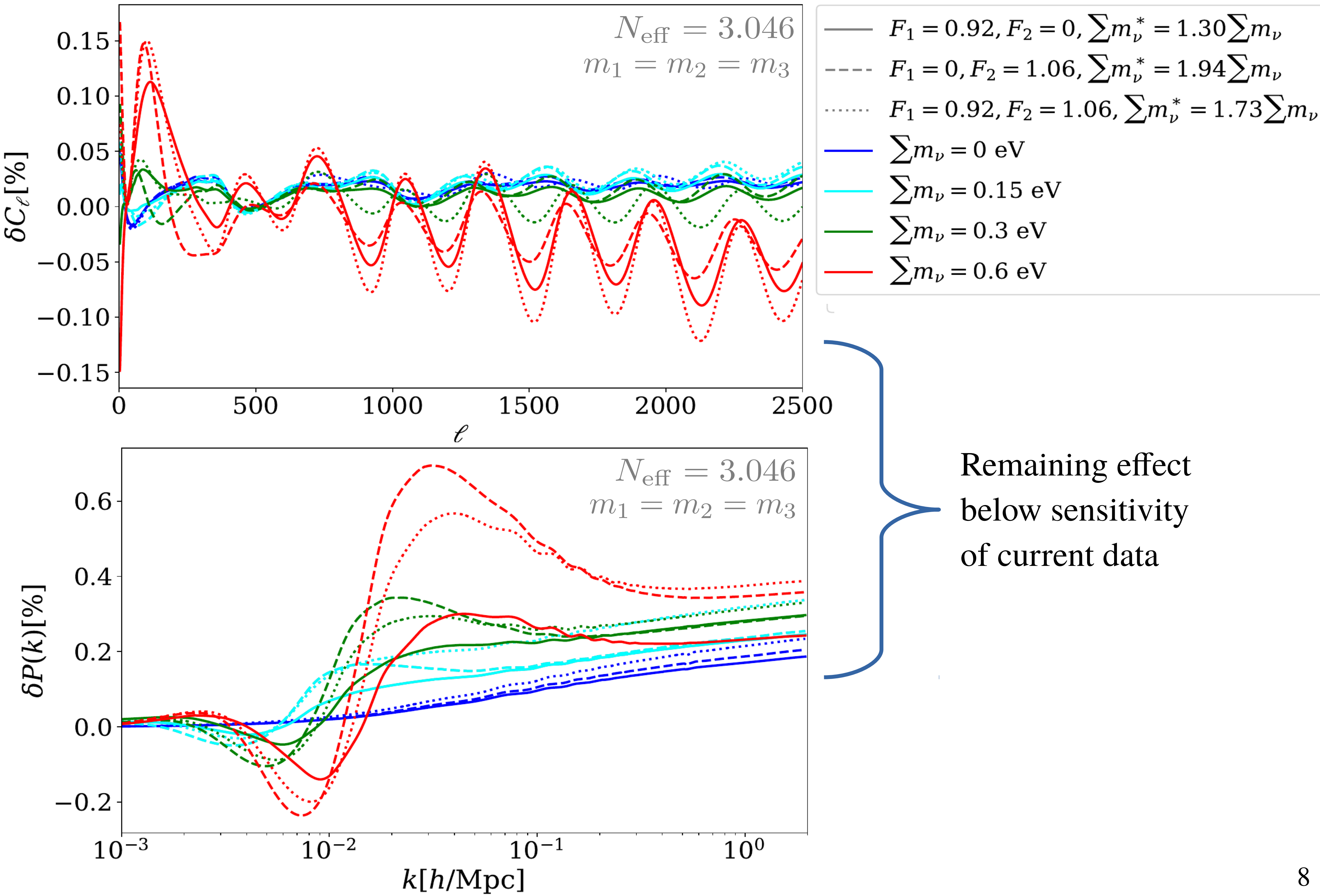
$$\int \mathrm{d}x\, x^2 \sqrt{x^2 + \frac{m_\nu^2}{T_{\nu 0}^2}} \left(\frac{1}{e^x + 1} \right) \stackrel{!}{=} N \int \mathrm{d}x\, x^2 \sqrt{x^2 + \frac{m_\nu^{*\,2}}{T_{\nu 0}^2}}\, \frac{1}{e^x + 1} \Big(p_0(x) + F_1 p_1(x) + F_2 p_2(x) \Big)$$

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

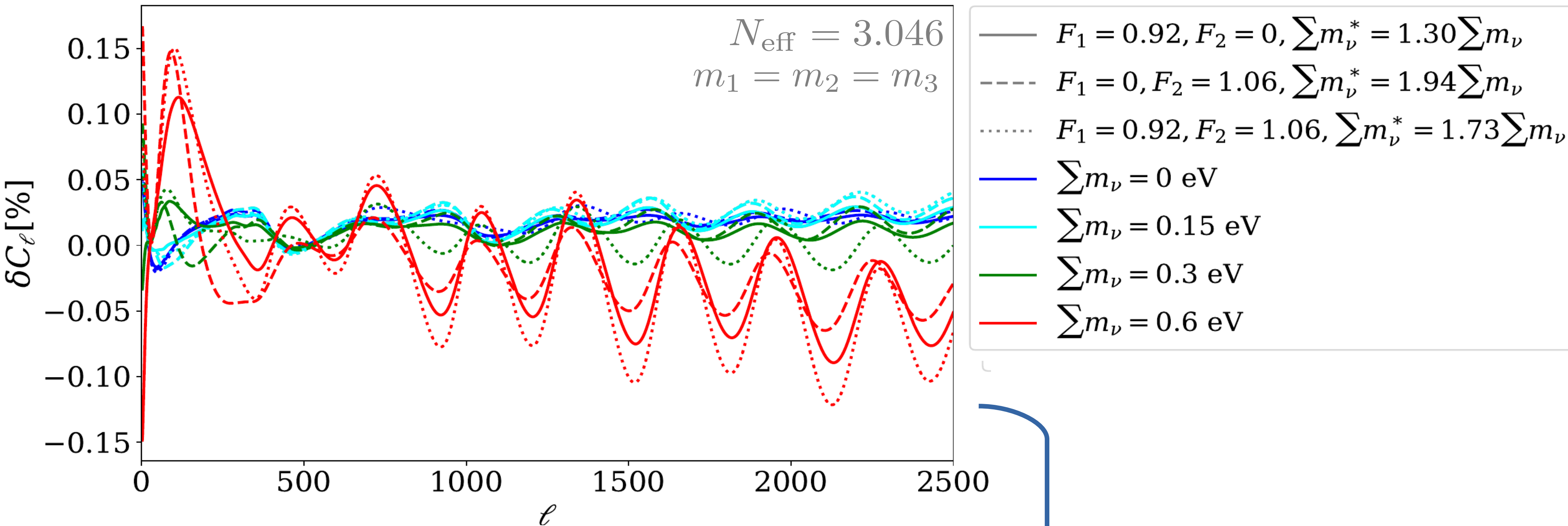

$N_{\rm eff} = 3.046$
$m_1 = m_2 = m_3$
$F_1 = 0.92, F_2 = 0, \sum m_\nu^* = 1.30 \sum m_\nu$
$F_1 = 0, F_2 = 1.06, \sum m_\nu^* = 1.94 \sum m_\nu$
$F_1 = 0.92, F_2 = 1.06, \sum m_\nu^* = 1.73 \sum m_\nu$
$\sum m_\nu = 0$ eV
$\sum m_\nu = 0.15$ eV
$\sum m_\nu = 0.3$ eV
$\sum m_\nu = 0.6$ eV
$\delta C_\ell [\%]$
ℓ
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
0
500
1000
1500
2000
2500

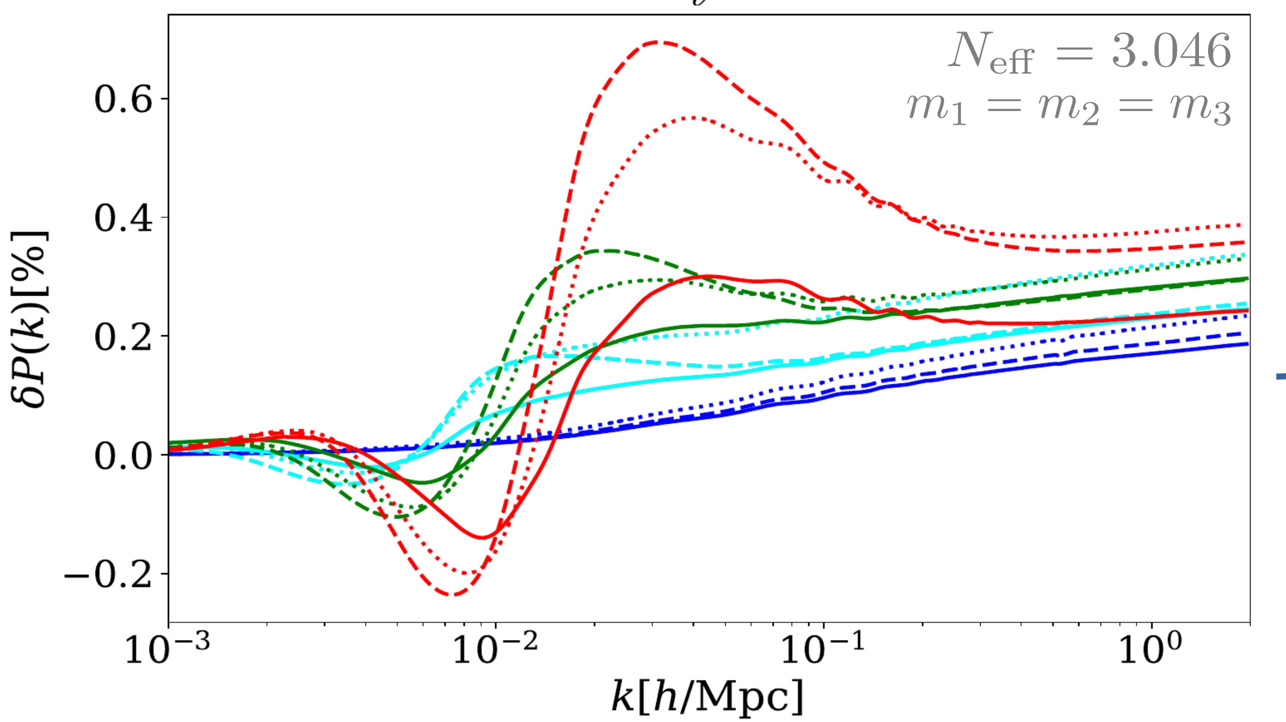


$N_{\rm eff} = 3.046$
$m_1 = m_2 = m_3$
$F_1 = 0.92, F_2 = 0, \sum m_\nu^* = 1.30 \sum m_\nu$
$F_1 = 0, F_2 = 1.06, \sum m_\nu^* = 1.94 \sum m_\nu$
$F_1 = 0.92, F_2 = 1.06, \sum m_\nu^* = 1.73 \sum m_\nu$
$\sum m_\nu = 0$ eV
$\sum m_\nu = 0.15$ eV
$\sum m_\nu = 0.3$ eV
$\sum m_\nu = 0.6$ eV
$\delta C_\ell [\%]$
ℓ
$\delta P(k) [\%]$
$k[h/\mathrm{Mpc}]$



Remaining effect below sensitivity of current data



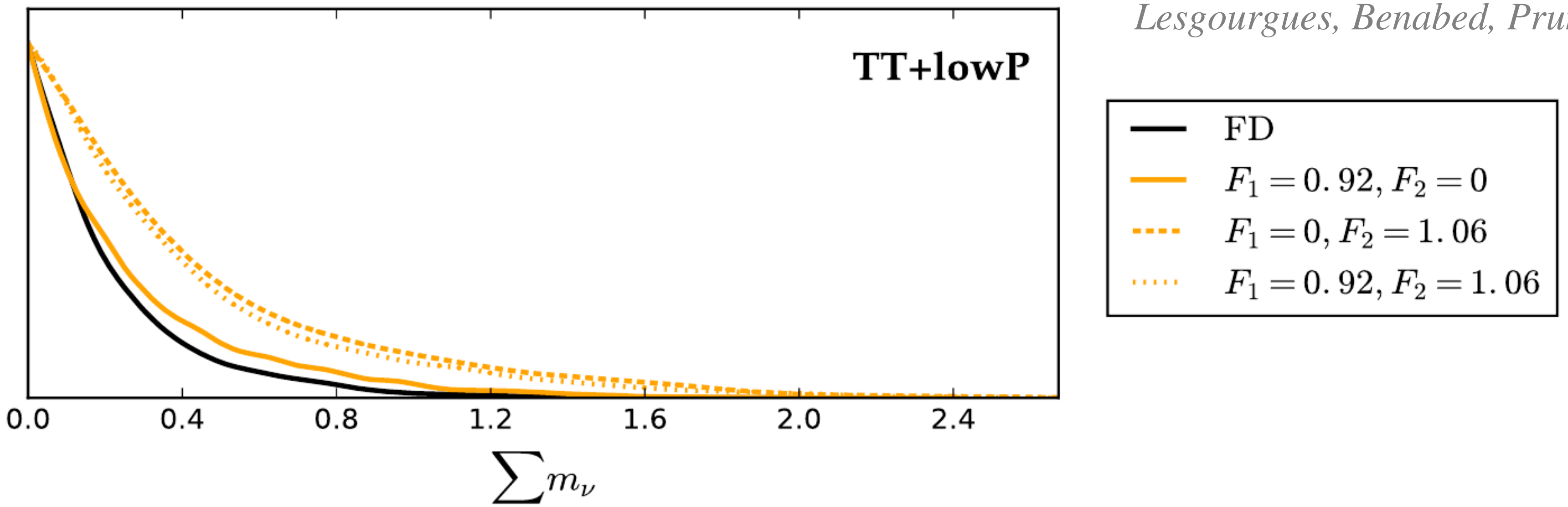


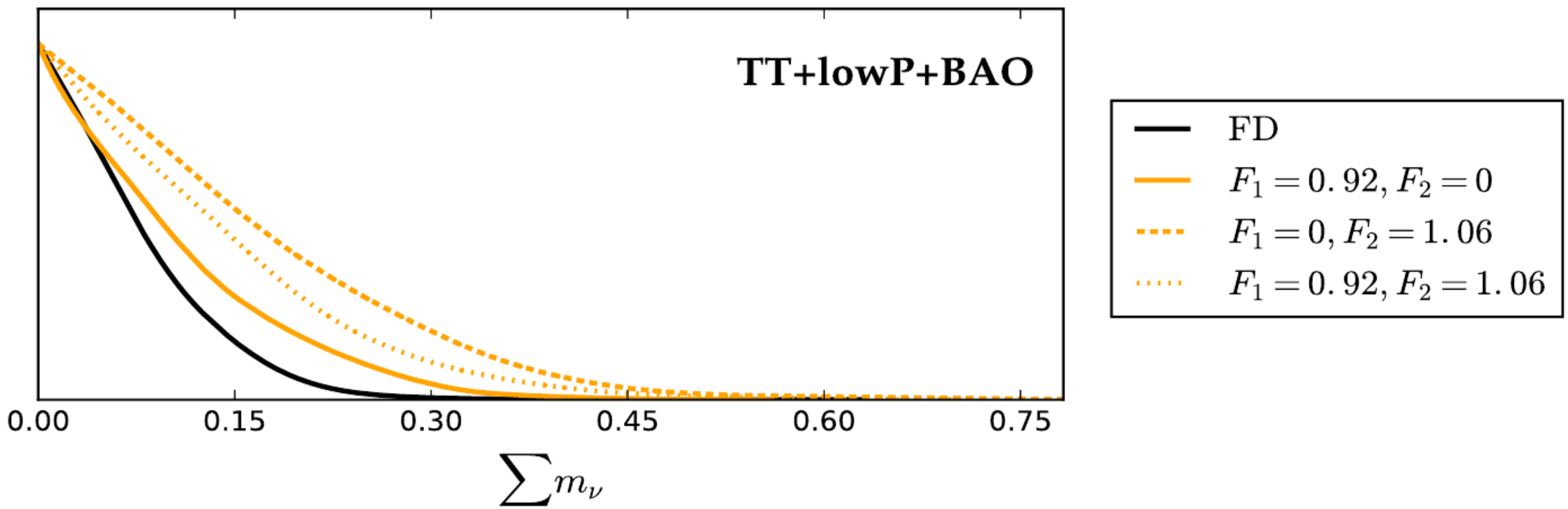
Remaining effect below sensitivity of current data

Intrinsic degeneracy between $\mathbf{m}_\nu$ and distribution

Monte-Carlo-Markov-Chain analysis

Using MontePython (Audren, Brinckmann, Lesgourgues, Benabed, Prunet)





Around 100% relaxed neutrino mass bounds

- Many scenarios could lead to a non-thermal neutrino distribution

- Many scenarios could lead to a non-thermal neutrino distribution

- Introduced a model-independent parameterization

- Many scenarios could lead to a non-thermal neutrino distribution

- Introduced a model-independent parameterization

→ Fixed relativistic neutrino energy density N_{eff}

- Many scenarios could lead to a non-thermal neutrino distribution

- Introduced a model-independent parameterization

→ Fixed relativistic neutrino energy density N_{eff}

Realistic?

- Many scenarios could lead to a non-thermal neutrino distribution

- Introduced a model-independent parameterization

→ Fixed relativistic neutrino energy density N_{eff}

Realistic? ✓ (For mechanisms efficient after neutrino decoupling)

- Many scenarios could lead to a non-thermal neutrino distribution

- Introduced a model-independent parameterization

→ Fixed relativistic neutrino energy density N_{eff}

Realistic? ✓ (For mechanisms efficient after neutrino decoupling)

- Showed: **relic distribution and m_ν intrinsically degenerate**

- Many scenarios could lead to a non-thermal neutrino distribution

- Introduced a model-independent parameterization

→ Fixed relativistic neutrino energy density N_{eff}

Realistic? ✓ (For mechanisms efficient after neutrino decoupling)

- Showed: **relic distribution and m_ν intrinsically degenerate**

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

- Many scenarios could lead to a non-thermal neutrino distribution

- Introduced a model-independent parameterization

→ Fixed relativistic neutrino energy density N_{eff}

Realistic? ✓ (For mechanisms efficient after neutrino decoupling)

- Showed: **relic distribution and m_ν intrinsically degenerate**

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

- Here: Relaxed neutrino mass bounds by around **100%.**

→ More drastic scenarios may relax the mass bound in a more drastic way

- Many scenarios could in principle lead to a non-thermal neutrino distribution

- Introduced a model-independent parameterization

→ Fixed relativistic neutrino energy density N_{eff}

Realistic? ✓ (For mechanisms efficient after neutrino decoupling)

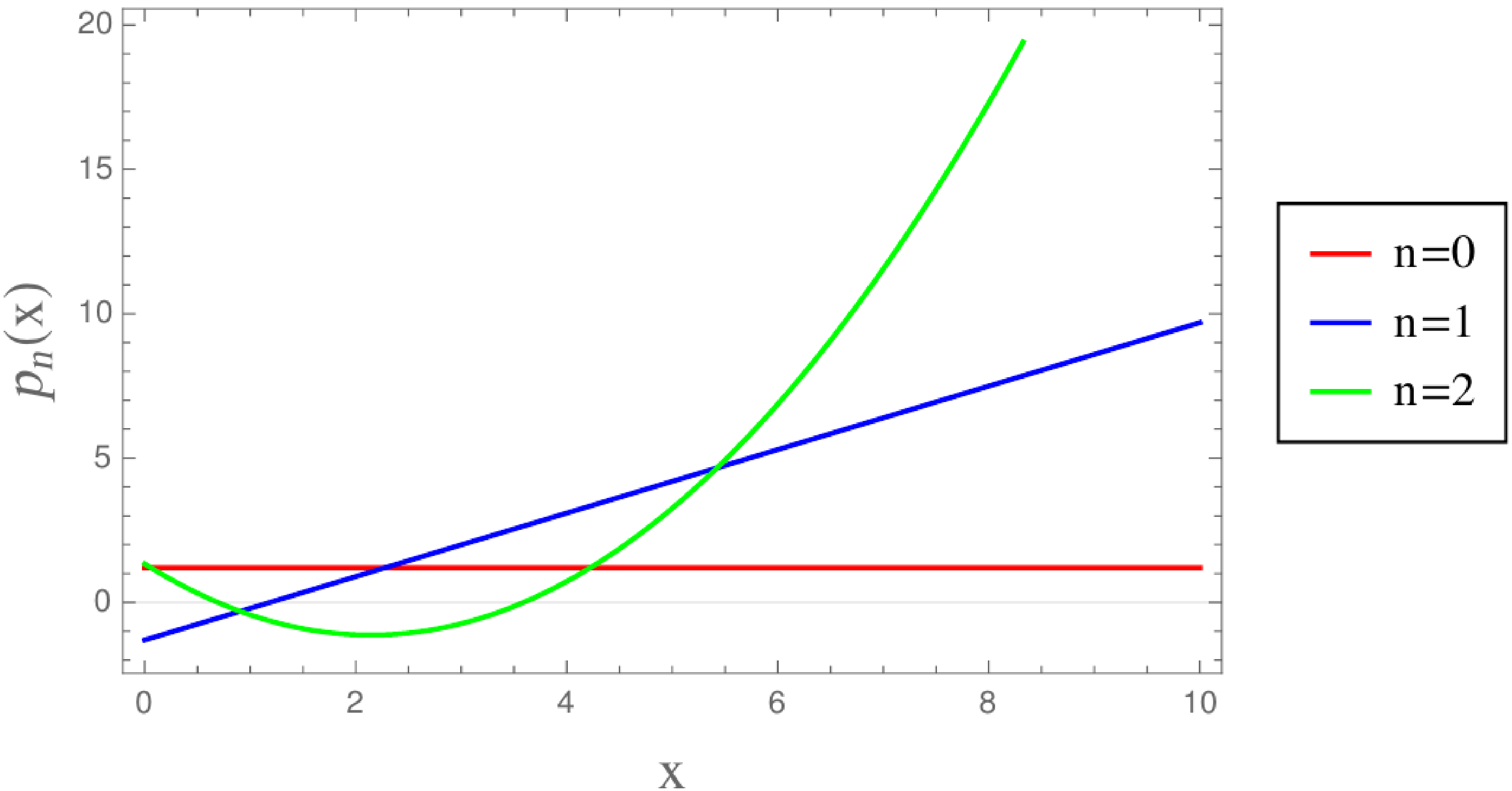
- Showed: **relic distribution and m_ν intrinsically degenerate**

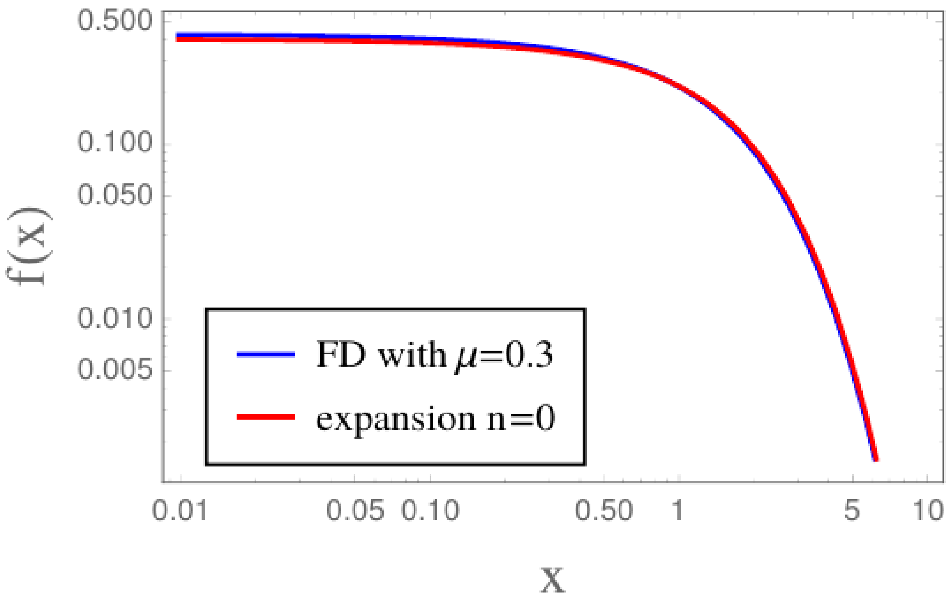
→ Cosmological neutrino mass bound strongly depends on our assumptions about the relic distribution function…

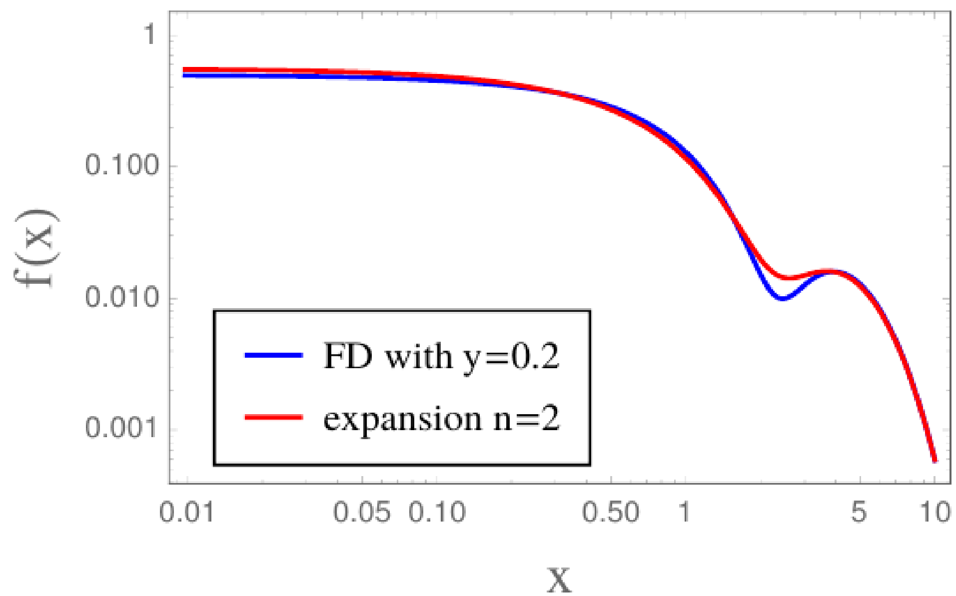
- Here: Relaxed neutrino mass bounds by around **100%.**

→ More drastic scenarios may relax the mass bound in a more drastic way

Thank you for your attention!


20
15
10
5
0
0
2
4
6
8
10
$p_n(x)$
x
n=0
n=1
n=2


0.500
0.100
0.050
0.010
0.005
f(x)
FD with μ=0.3
expansion n=0
0.01
0.05
0.10
0.50
1
5
10
x


1
0.100
0.010
0.001
f(x)
FD with y=0.2
expansion n=2
0.01
0.05
0.10
0.50
1
5
10
x

	TT+lowP (95 % CL)	TT+lowP+BAO (95 % CL)
FD	$\sum m_\nu < 0.73$ eV	$\sum m_\nu < 0.18$ eV
$F_1 = 0.92, F_2 = 0$	$\sum m_\nu < 0.95$ eV	$\sum m_\nu < 0.26$ eV
$F_1 = 0, F_2 = 1.06$	$\sum m_\nu < 1.45$ eV	$\sum m_\nu < 0.37$ eV
$F_1 = 0.92, F_2 = 1.06$	$\sum m_\nu < 1.34$ eV	$\sum m_\nu < 0.32$ eV