# Massive neutrinos and LSS beyond linear approximation

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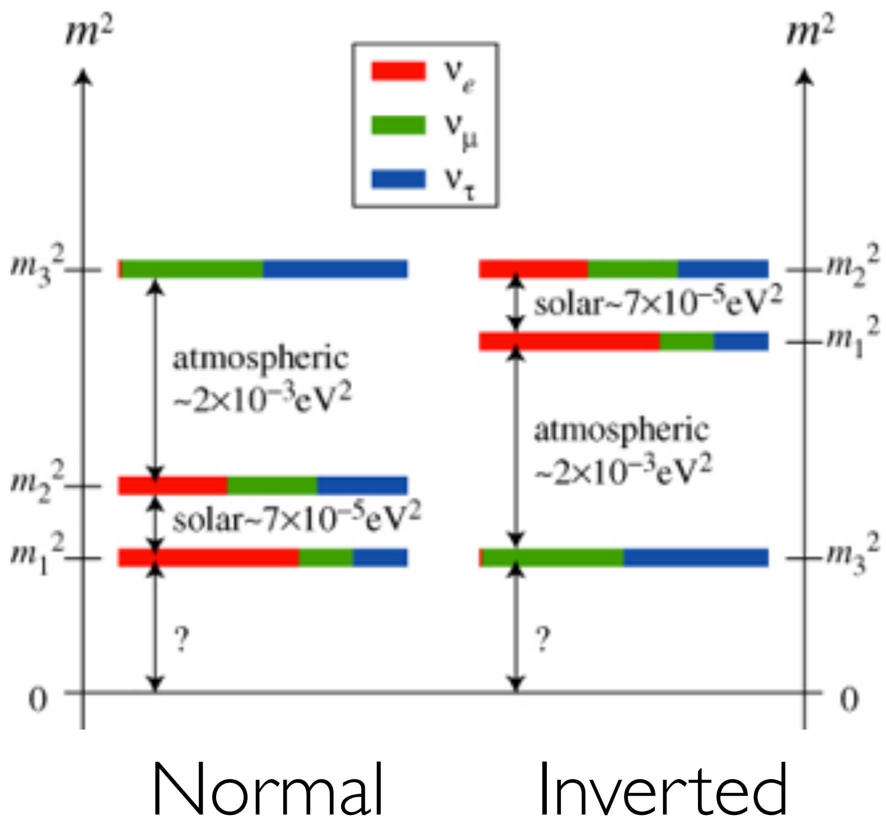
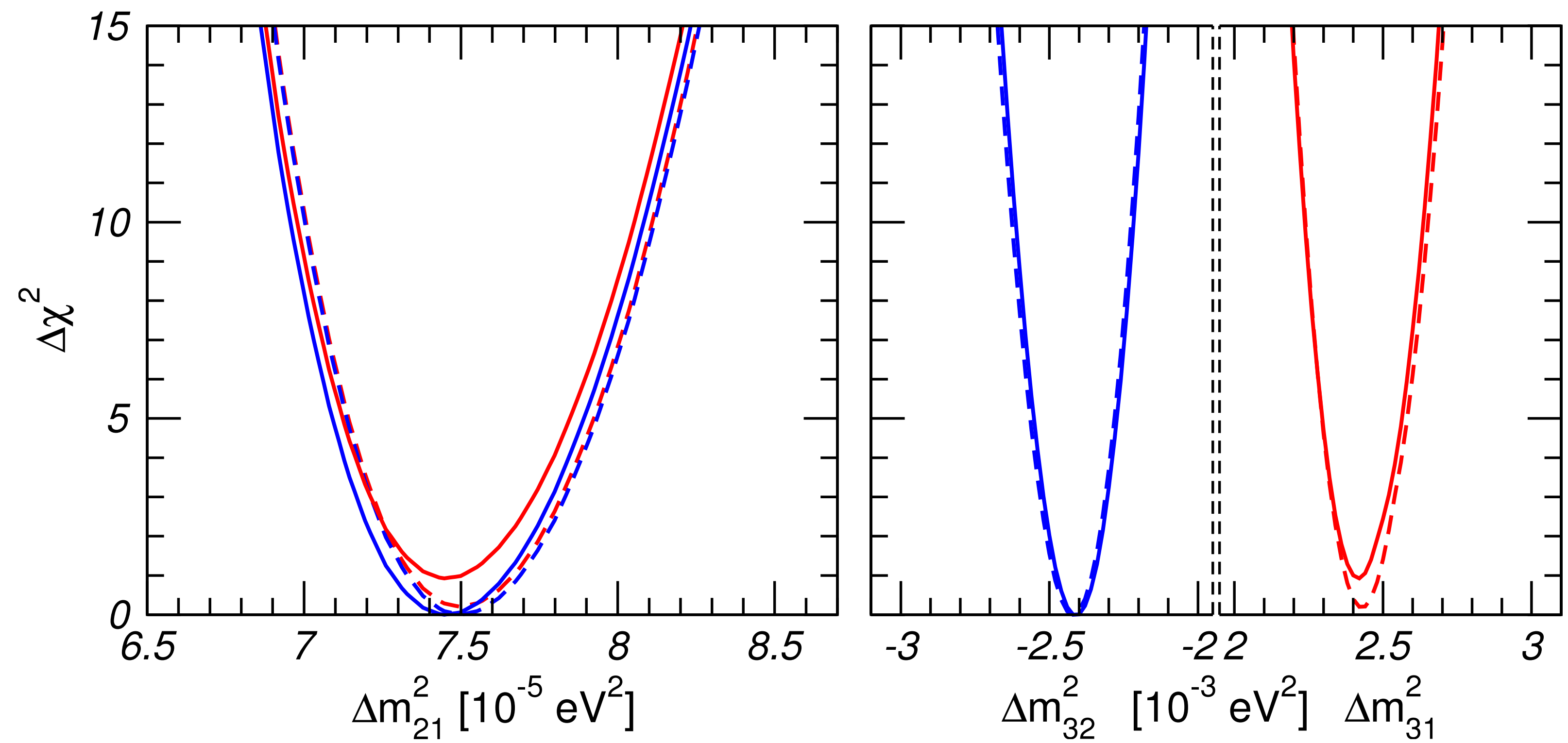
w/ M. Garny, T. Konstandin and J. Lesgourgues
arXiv:1408.2995 [astro-ph.CO]

w/ V. Desjacques, H. Dupuy, M. Garny, M. Ivanov, and S. Sibiryakov
arXiv:16xx.xxxx

# Particle physics constraints on $m_\nu$




M.C. Gonzalez-Garcia / Physics of the Dark Universe 4 (2014) 1–5




$$0.06 \text{ eV} < \sum_{\psi=e,\mu,\tau} m_{\nu_\psi}$$

the sum can be constrained by decaying processes

$$^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_k$$

PDG 2014

$$\sum_{\psi=e,\mu,\tau} m_{\nu_\psi} < 2 \text{ eV } (95\%\ CL)$$

This **number** may be the door to physics BSM!

(and cosmology has the key!)

# (Massive) neutrinos in cosmology

Cosmology is very sensitive to neutrinos properties


CUP 2013


all neutrino species are relativistic

Mostly sensitive to **massless** properties $N_{eff}$

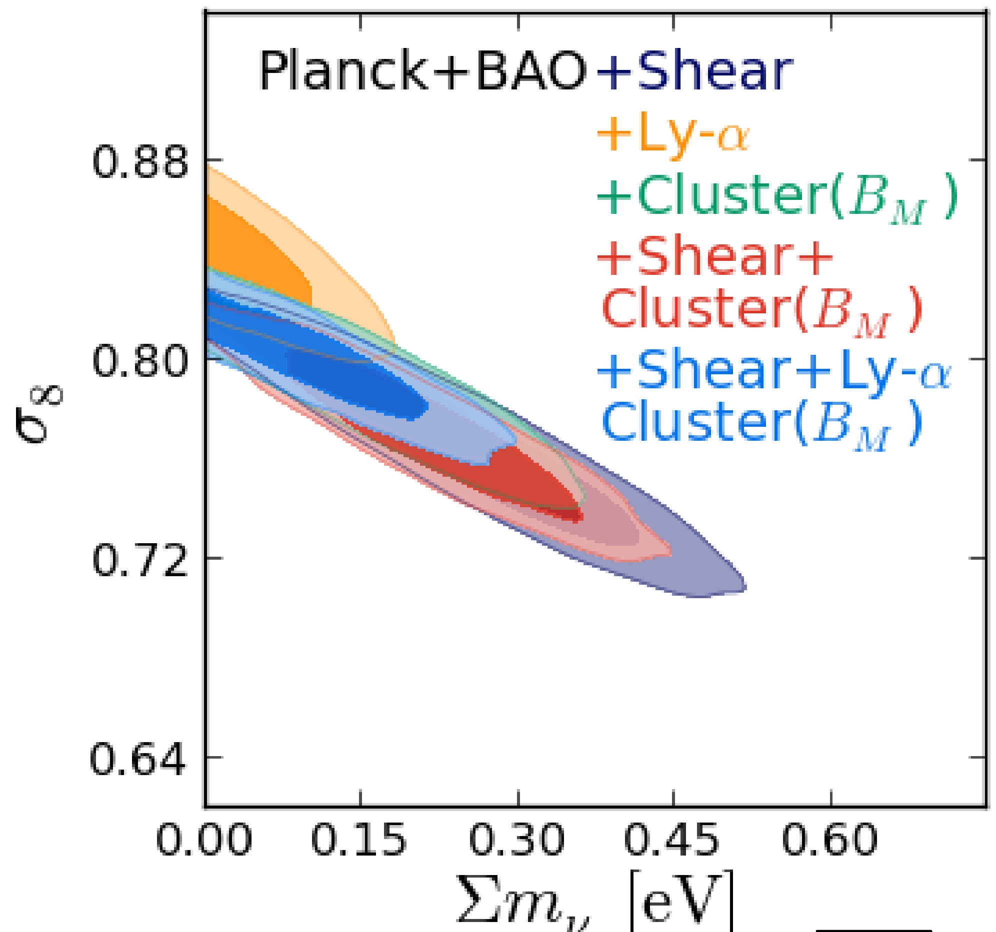
# Bounds

CMB: $\sum m_\nu < 0.49 \text{ eV } (95\% \; Planck \; TT, \; TE, \; EE + lowP)$

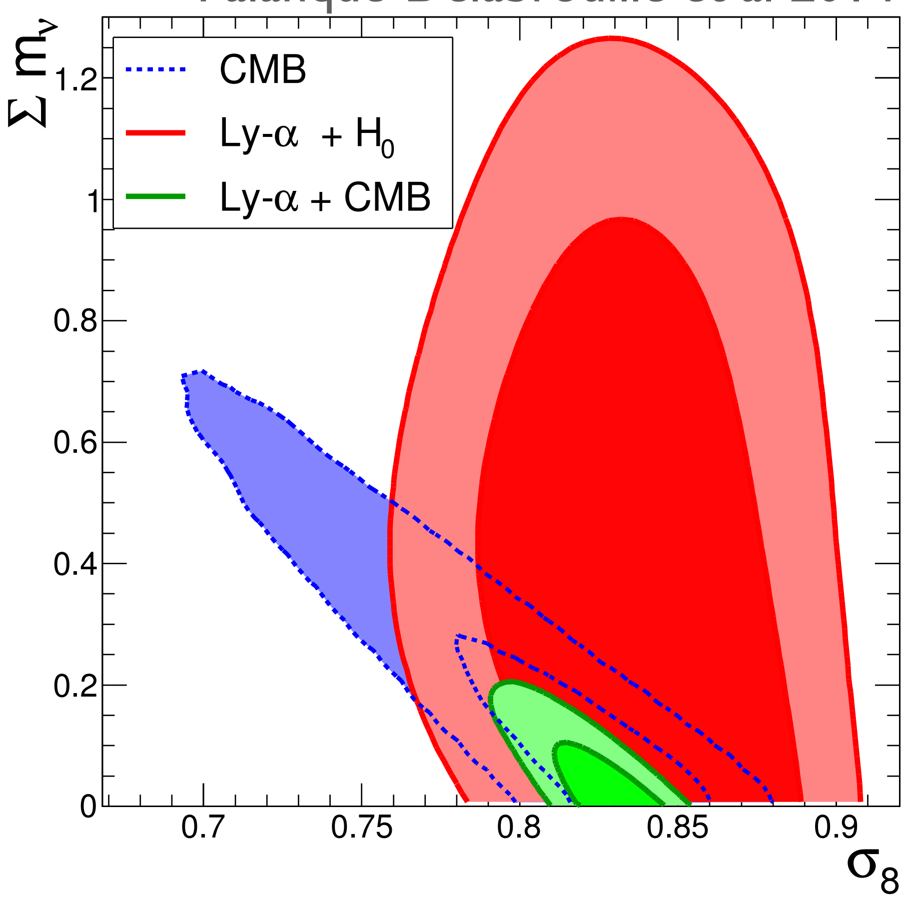
Neutrino mass and $N_{eff}$ affect many other LSS observables

Ly-α, Shear, Mass function,…

Costanzi et al 2014

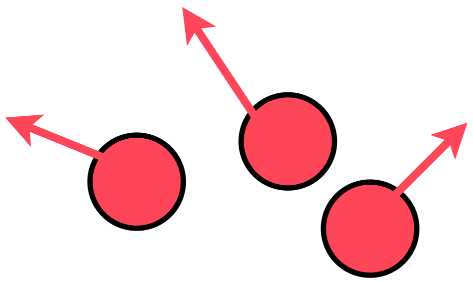



Palanque-Delabrouille et al 2014




$$\sum m_i < 0.14 \; (95\%)$$

# Description of neutrinos



thermal background $f_{\nu 0}(\eta, p) \equiv \left(e^{p/T_\nu} + 1\right)^{-1}$

distribution function $\Psi_\nu(\eta; \bar{x}, \bar{p}) = \frac{f_\nu(\eta; \bar{x}, \bar{p})}{f_{\nu 0}(\eta, p)} - 1$

(linear) Boltzmann equation ( $E(p) = \sqrt{p^2 + m_\nu^2}$ )

**Massless** neutrinos $E(p) = p$ free-stream and do not cluster

$$\delta\rho_\nu = \int d^3p E(p) f_\nu(\eta, \bar{x}, \bar{p}) \,, \qquad \delta\rho_\nu(k)'' = (c^2(\eta)k^2 - 3a^2H^2/2)\delta\rho_\nu(k) + \ldots$$

$\nwarrow 1/3$

**Massive:** when $p \ll E(p) \sim m$, neutrinos become **cold (cluster)**

$$k_{fs} \sim aH/c \quad , \qquad c(\eta) \sim T_\nu(\eta)/m_\nu$$

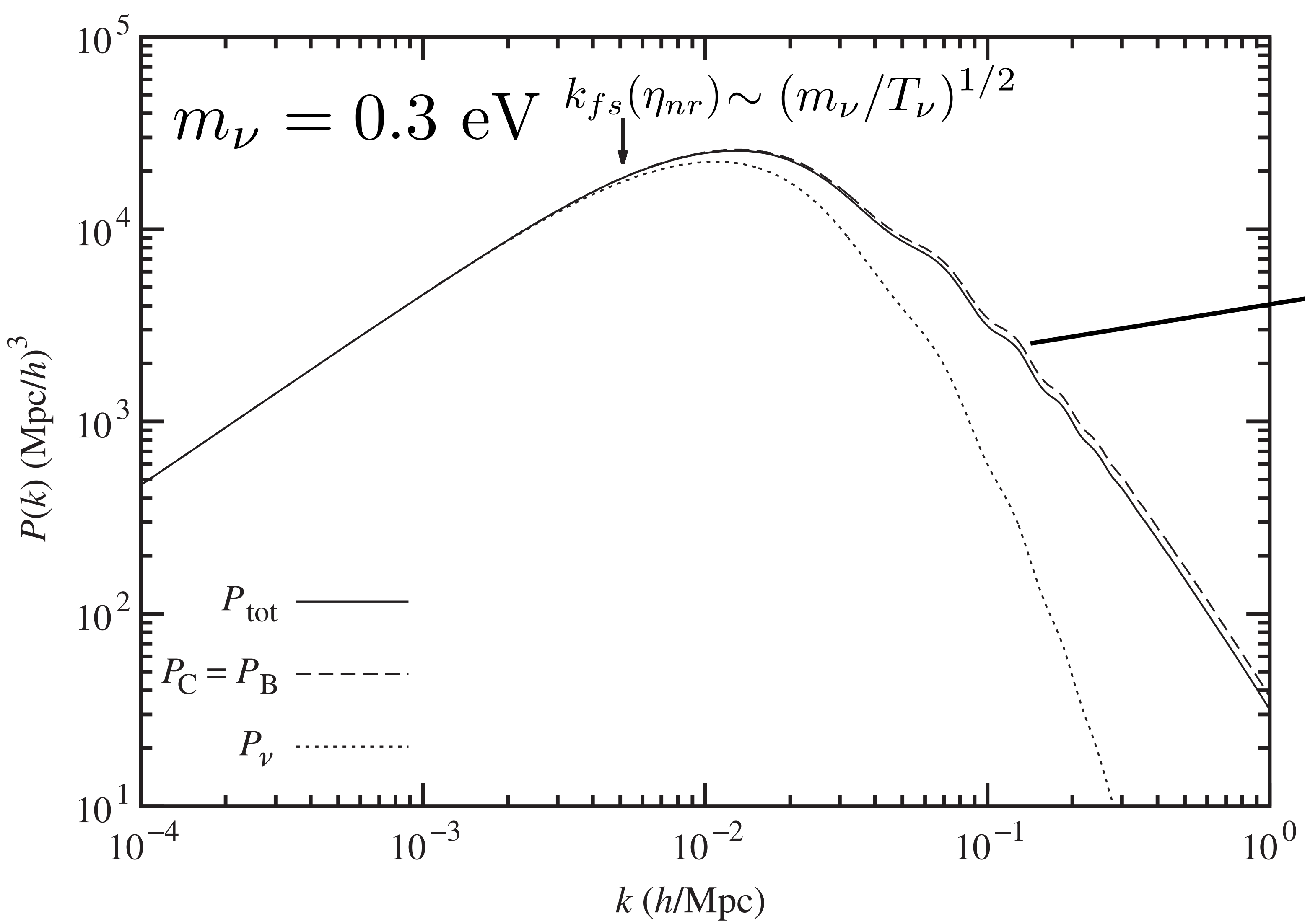
they fall into DM potentials!

known law e.g. Shoji, Komatsu 2010

# Effects of $m_\nu$ on the linear power spectrum

$$\delta \equiv \frac{\sum_{i=b,c,\nu} \delta\rho_i}{\sum_{i=b,c,\nu} \bar{\rho}_i}$$

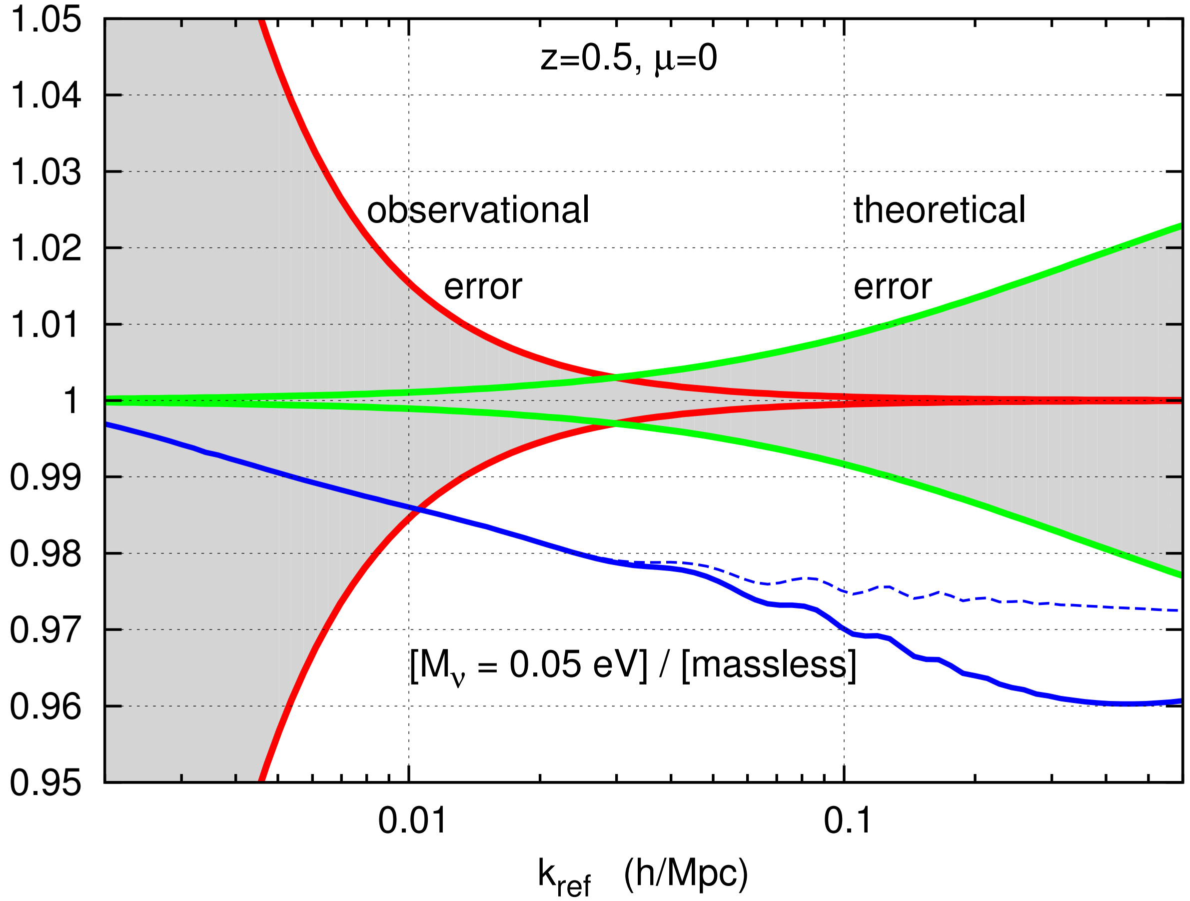
Lesgourgues, Mangano, Miele, Pastor CUP 2013




at least 5% effect

Audren et al. 2013

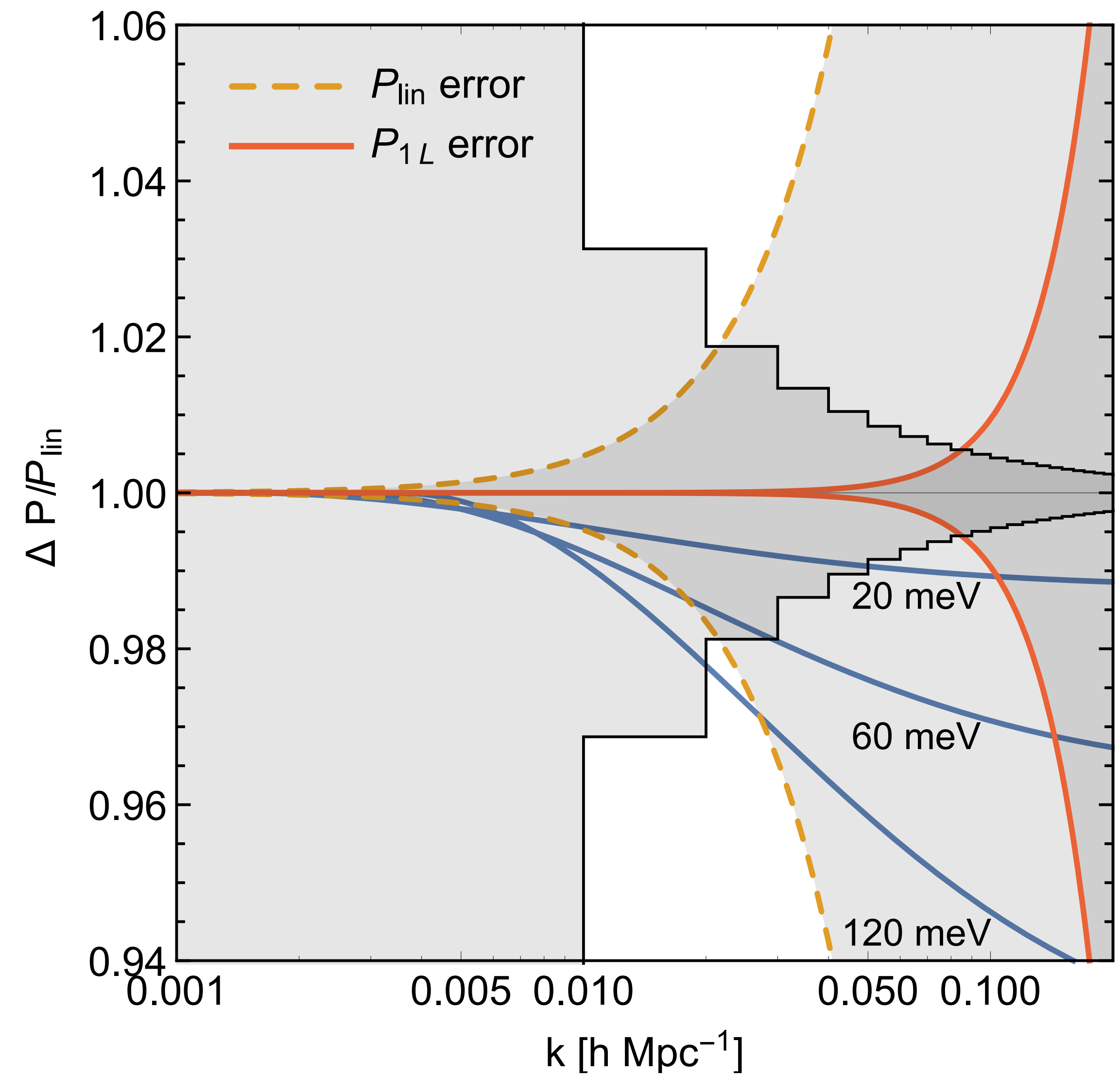
# Forecasts PS




relative error

Audren et al. 2013 EUCLID Forecast
based on HALOFIT

Baldauf et al 2016



# Beyond linear theory

N-body (with warm components)
Demanding (hard for MC)
Halo model (~10% precision)

The effect is 5% at BAO scales
(mildly non-linear regime):
Non-linear perturbation theory

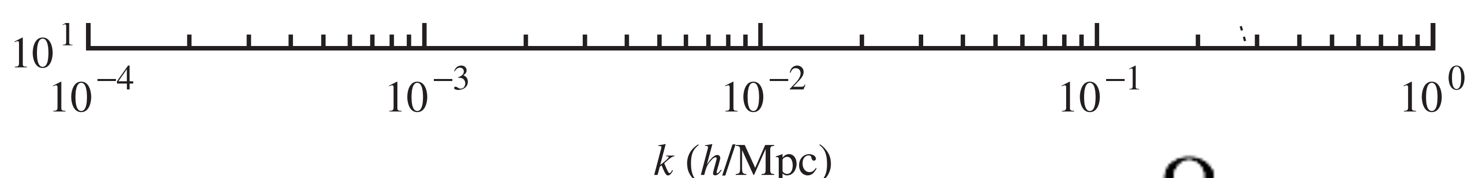
DB, Garny, Konstandin, Lesgourgues'14
(also Führer-Wong'14, Dupuy-Bernardeau'14
Archidiacono-Hannestad'15)

**DM** as a **non-linear** pressureless perfect fluid
(SPT or 'beyond')

**Neutrinos**

CDM-like

Phase-space

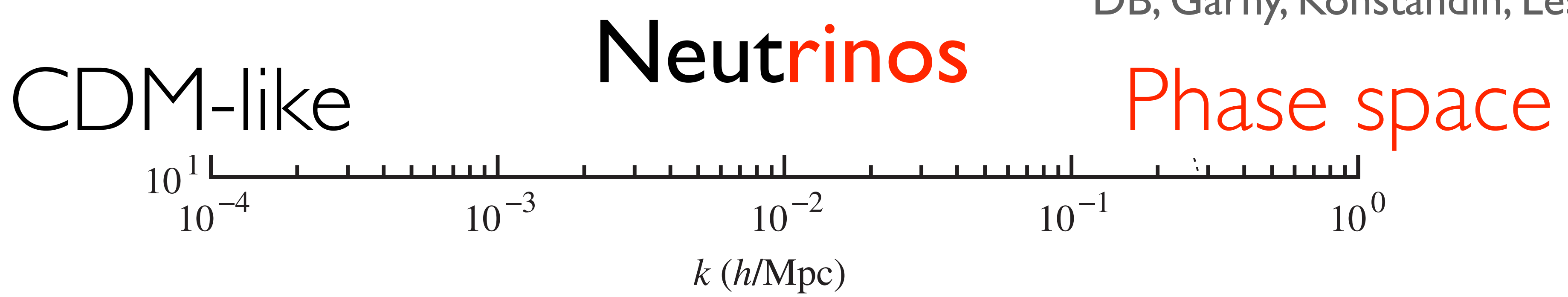



$$\Delta\phi = \frac{3}{2}\mathcal{H}^2\Omega_m[f_\nu\delta_\nu + (1-f_\nu)\delta_{cb}]$$

$$f_\nu \equiv \frac{\Omega_\nu}{\Omega_m} = \frac{1}{\Omega_m^0 h^2}\frac{\sum_i m_{\nu,i}}{93.14\,\mathrm{eV}}$$

# Massive neutrinos in SPT

DB, Garny, Konstandin, Lesgourgues 2014




Q1: Since $\delta_\nu$ is small, can it be treated as **linear**?

$$\dot{\theta}_{cb} + \mathcal{H}\theta_{cb} + \frac{3}{2}\mathcal{H}^2\Omega_m[f_\nu\delta_\nu^L + (1-f_\nu)\delta_{cb}] = -\beta\delta_{cb}\theta_{cb} \quad (+\text{ UV})$$

⚠ violates conservation of momentum!

$\delta_k \sim k^2$ at low $k$ from loops spoiled!

A1: **NO!** (it introduces a spurious large effect at NLO)

(Dupuy talk, or wait for a few slides)

# Linear vs Non-linear $\nu$'s II

Q2: How to include $\nu$ non-linearities?

(even linear order is **NOT** a fluid at **all redshift**)

Shoji, Komatsu 2009

Blas, Lesgourgues, Tram 2011

A2: At low-redshift ( $z < z_{nr} \sim 10^2$ ) the fluid is very cold non-cold corrections are $O(T_\nu/m_\nu)$

## Neutrinos at late times

$$\dot{\delta}_\nu + \theta_\nu = -\alpha\theta_\nu\delta_\nu$$

$$\dot{\theta}_\nu + \mathcal{H}\theta_\nu + \frac{3}{2}\mathcal{H}^2\Omega_m[f_\nu\delta_\nu + (1-f_\nu)\delta_{cb}] - k^2 c_s(t)^2\delta_\nu = -\beta\delta_\nu\theta_\nu$$

$$+O(T_\nu/m_\nu)$$

i.c. from the Boltzmann equations at $10 > z > 10^2$

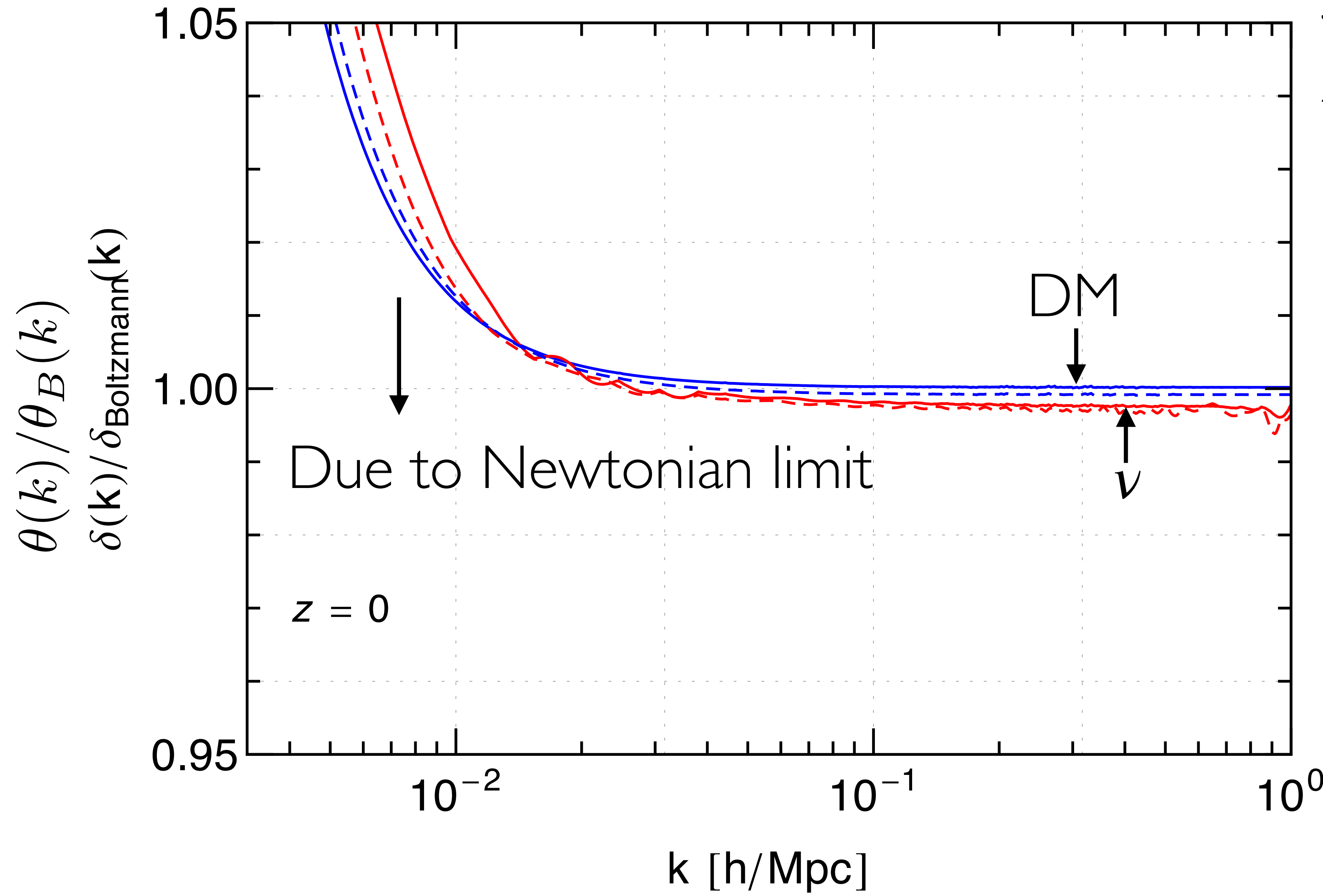
linear physics

# Accuracy of linear approximations

DB, Garny, Konstandin, Lesgourgues 2014

CLASS CODE, Blas, Lesgourgues, Tram, 2011

Linear Fluid vs Boltzmann equation




$\sum m_\nu = 0.21$ eV

$z = 0$

# Results at NLO

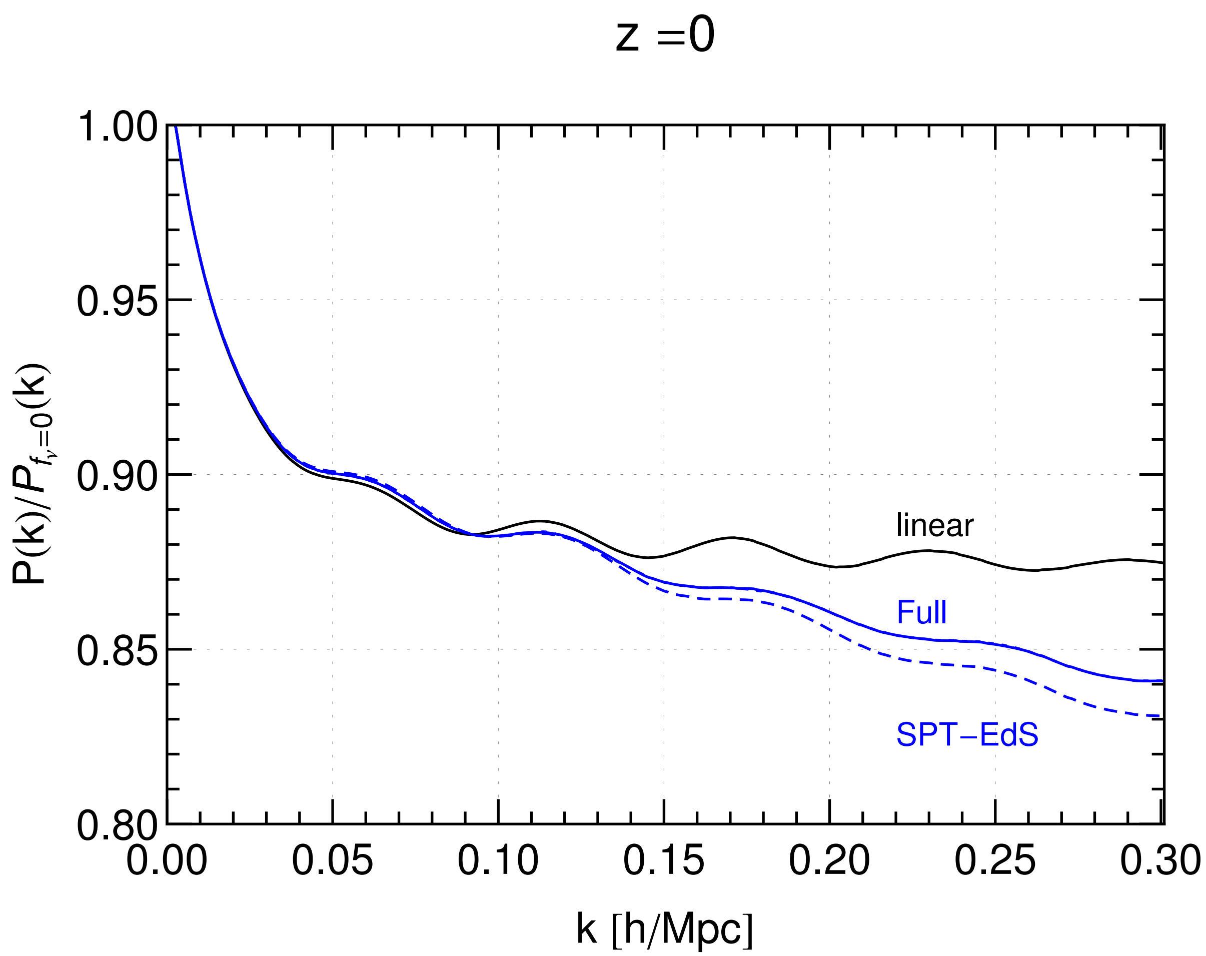
DB, Garny, Konstandin, Lesgourgues 2014

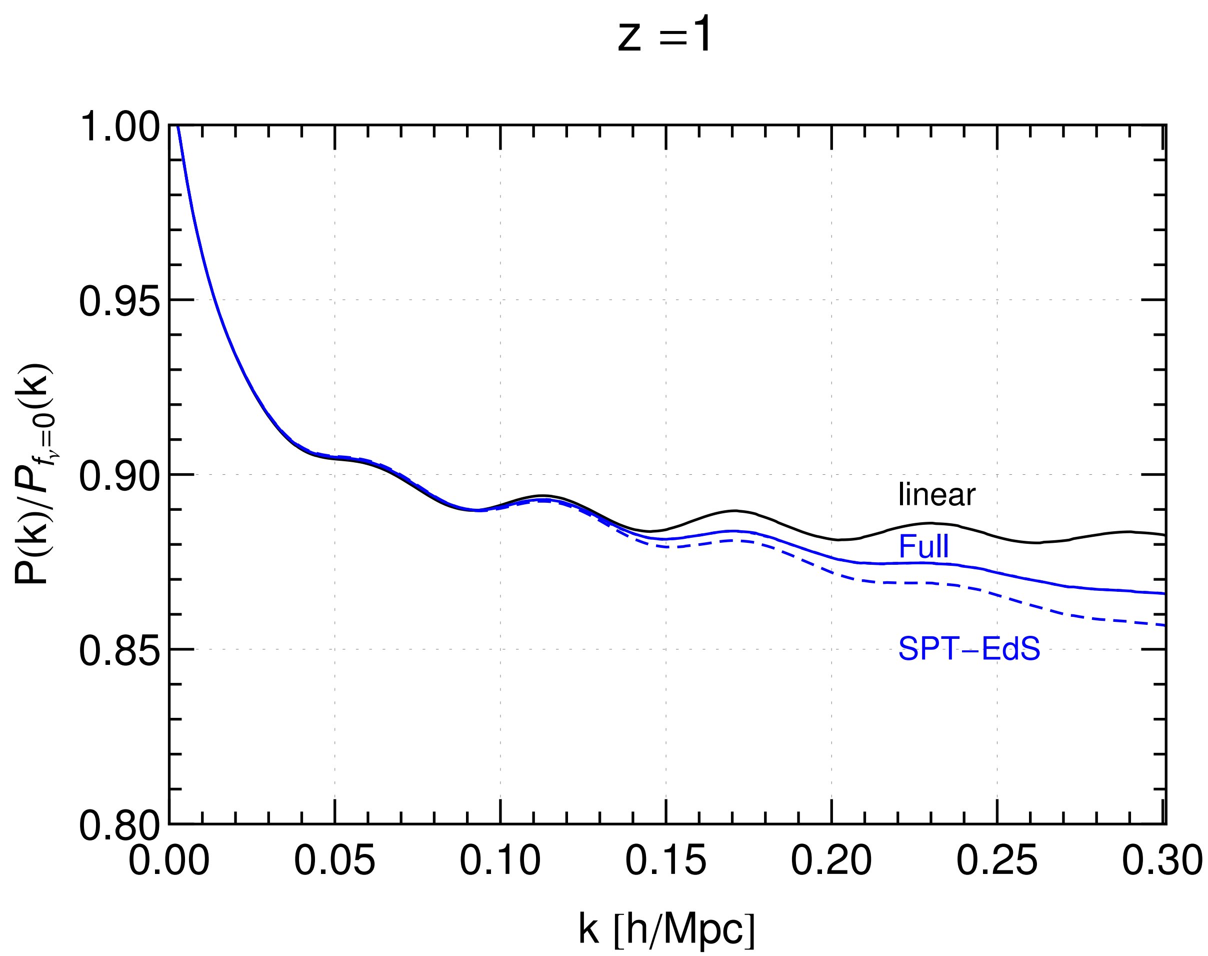
Scale dependent growth factor: better solved with

$$\partial_\eta P_{ab}[k,\eta] \sim -\Omega(k,\eta)_{ac} P_{cb} + \int \gamma_{acd} B_{cdb}(k-q,-k,q)$$

$$\partial_\eta B_{abc} \sim -\Omega(k,\eta)_{ad} B_{dbc} + \int \gamma P P$$

Pietroni 2008
Audren Lesgourgues 2011



# Comparison of NLO Results

DB, Garny, Konstandin, Lesgourgues 2014

$$\Delta P = P - P_L$$

Schemes with linear $\nu$

Wong 2008

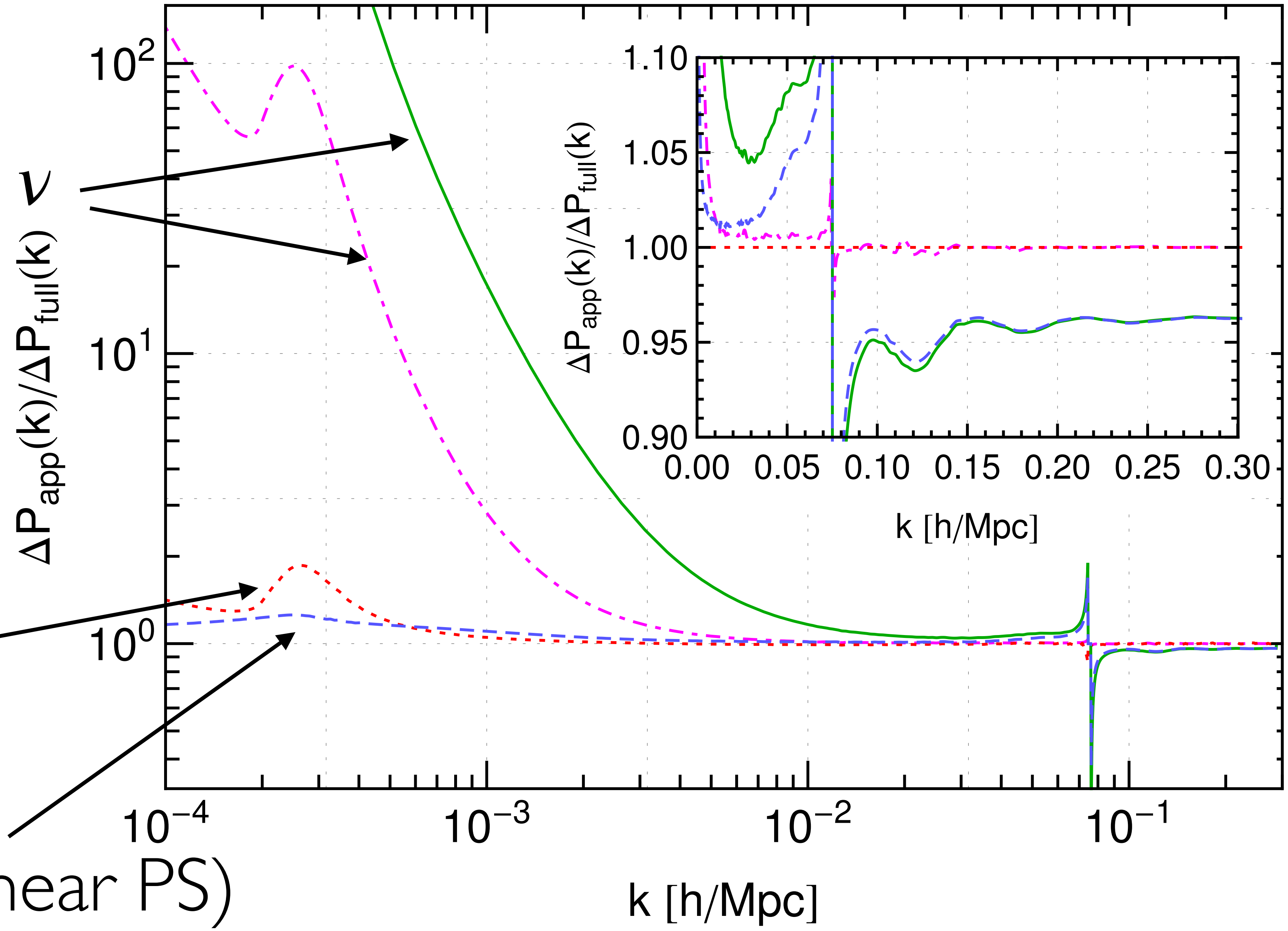
no momentum conservation

Ansatz $\delta_\nu \to \delta_{cb} \frac{\delta_\nu^L}{\delta_{cb}}$

Lesgourgues et al 2009

No $\delta_\nu$ (modified Linear PS)

Saito et al 2008, Beutler et al 2014




$P_c(0, k)$

NNLO?

# Does it matter?

NLO-SPT is not enough for 5% accuracy at BAO

NNLO and resummations/EFT more sensitive
to the short mode/long mode (de)coupling

Predictive descriptions require a good $\sim k^2$ behaviour

Zhu et al. 2013

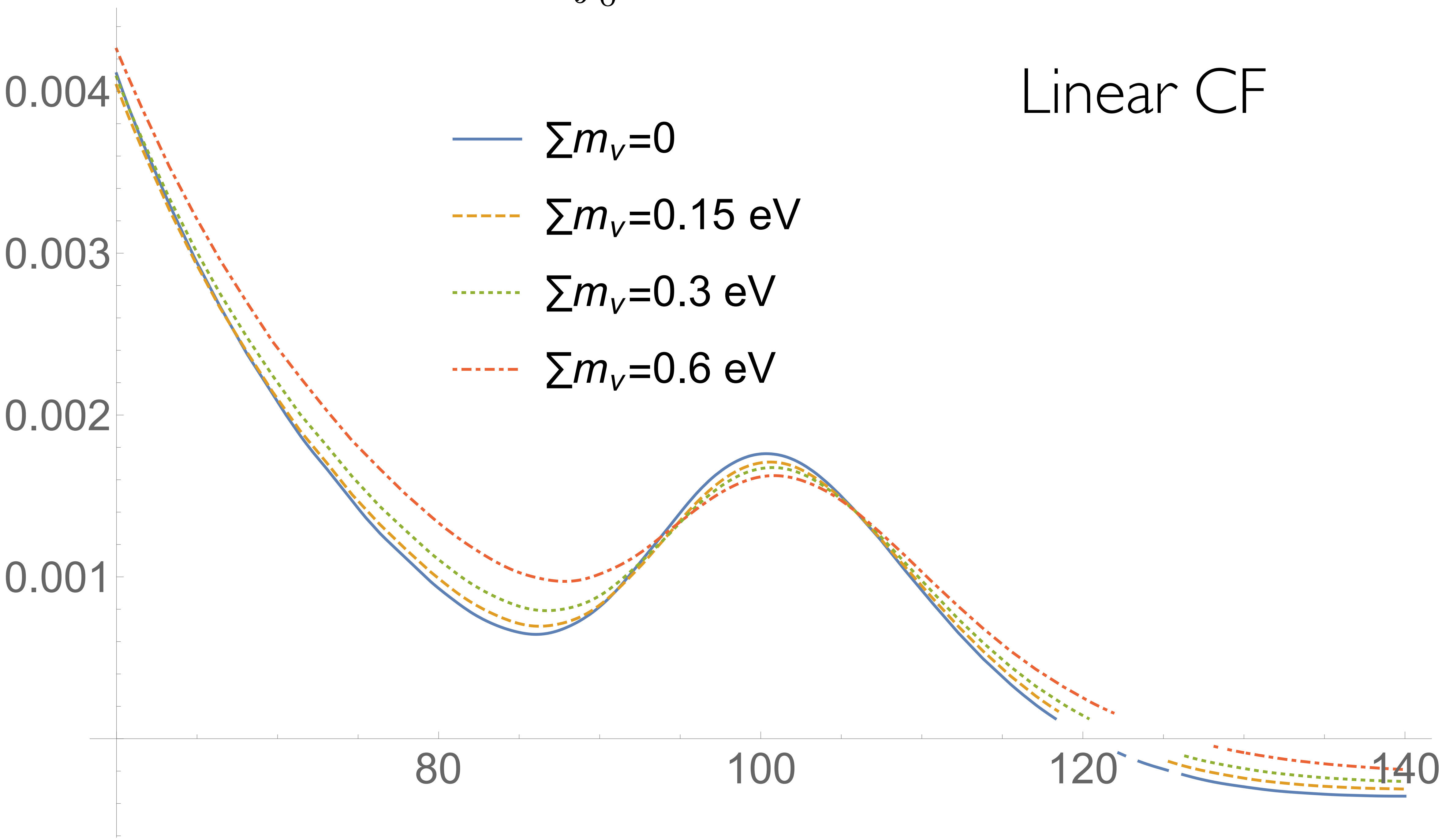
Neutrino Masses from Relative Velocities

# Two point correlation function

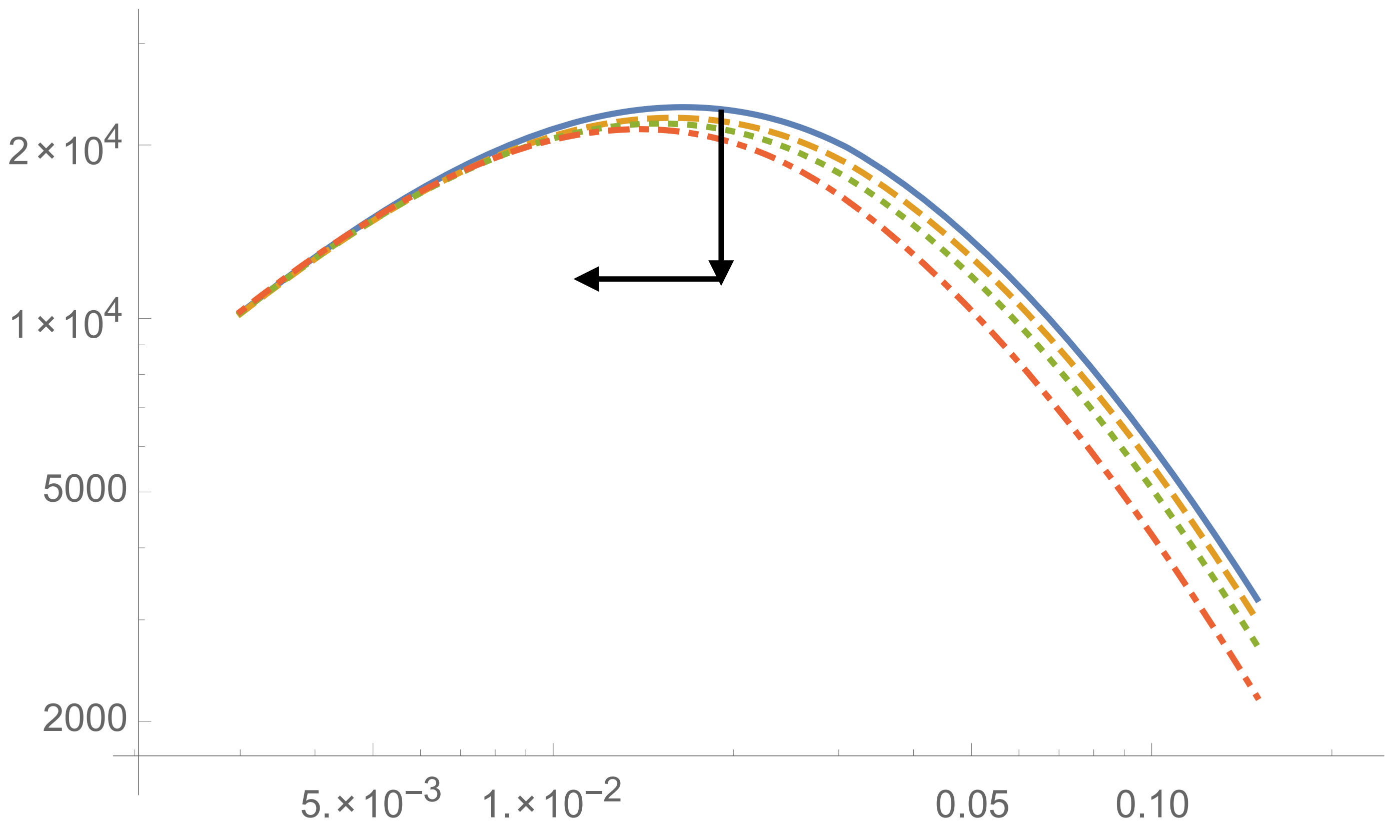
DB, Dupuy, Desjacques, Garny, Ivanov, Sibiryakov (under study)

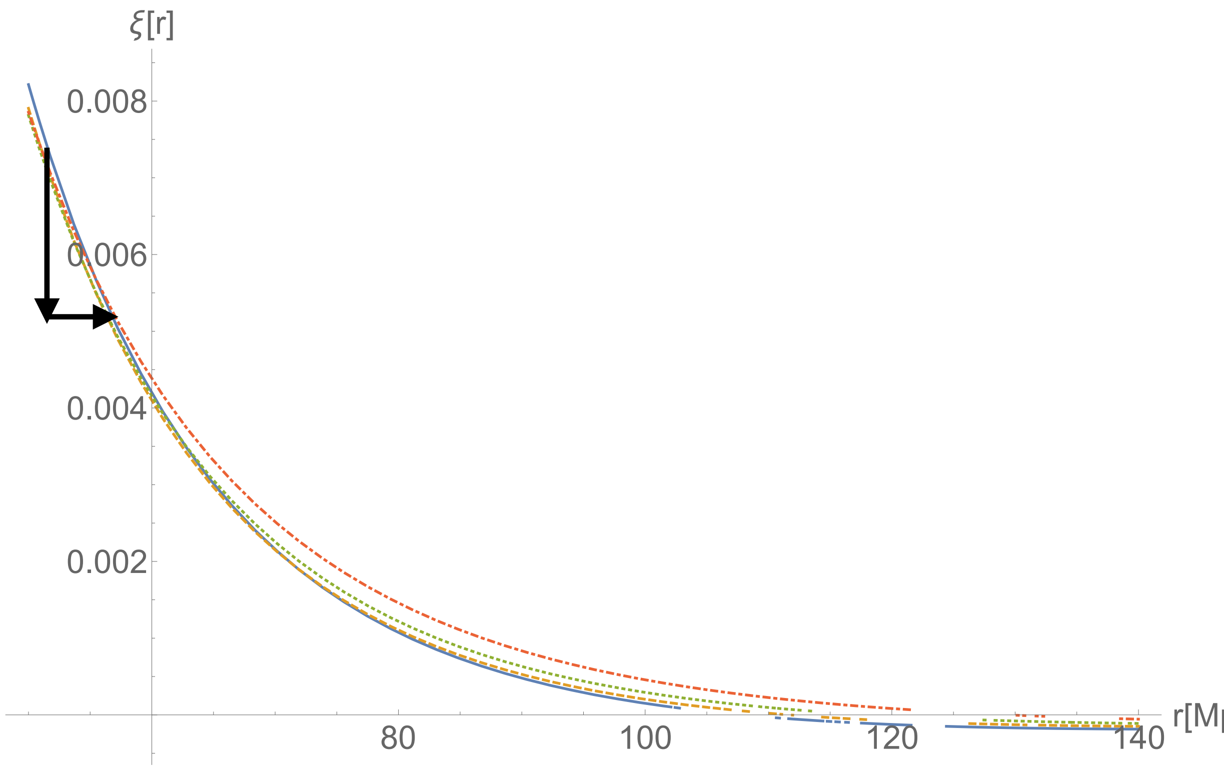
Peloso et al 2015

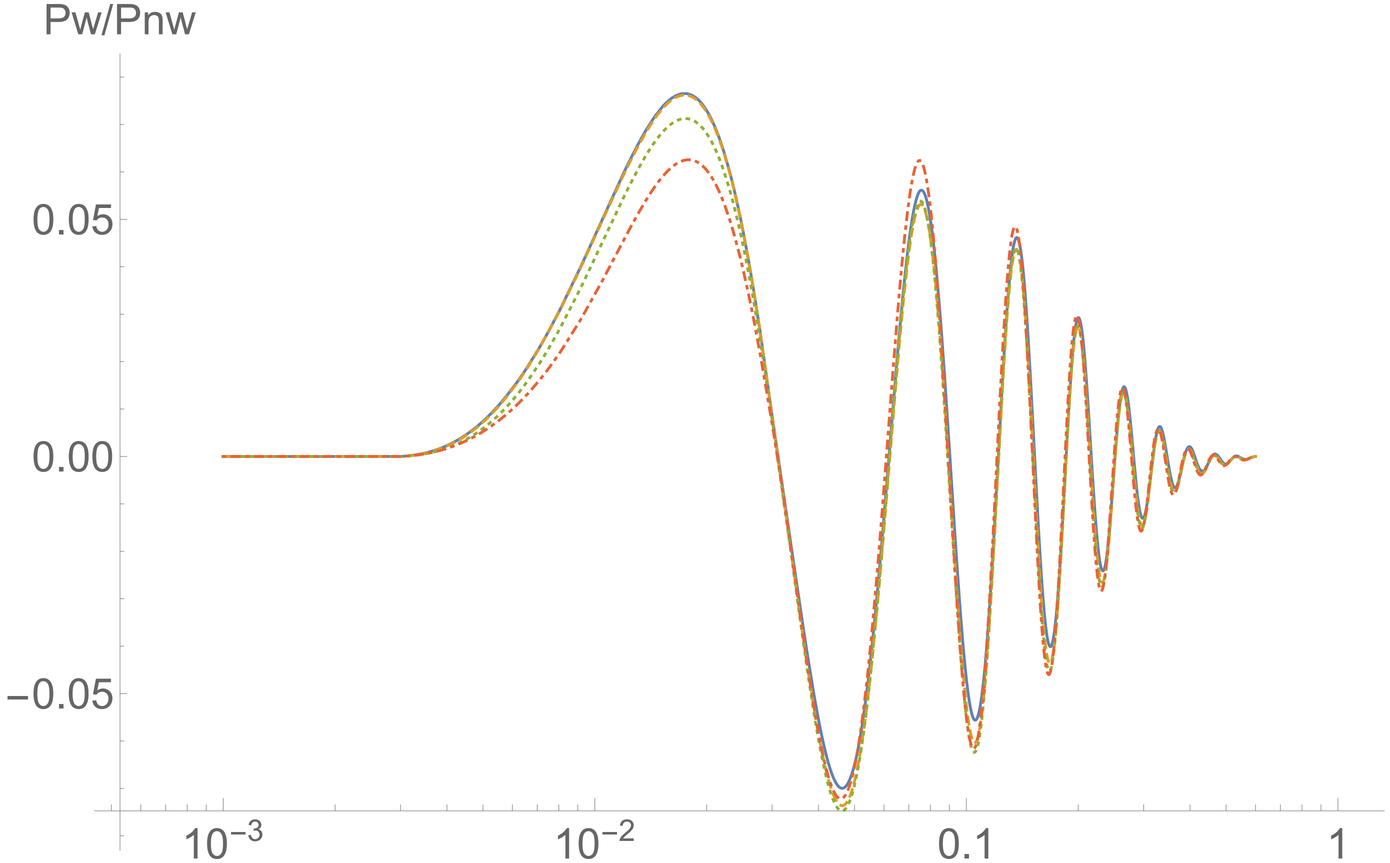
$$\xi(x,z) = \frac{4\pi}{x}\int_0^\infty dk\, kP(k,z)\sin(kx)$$

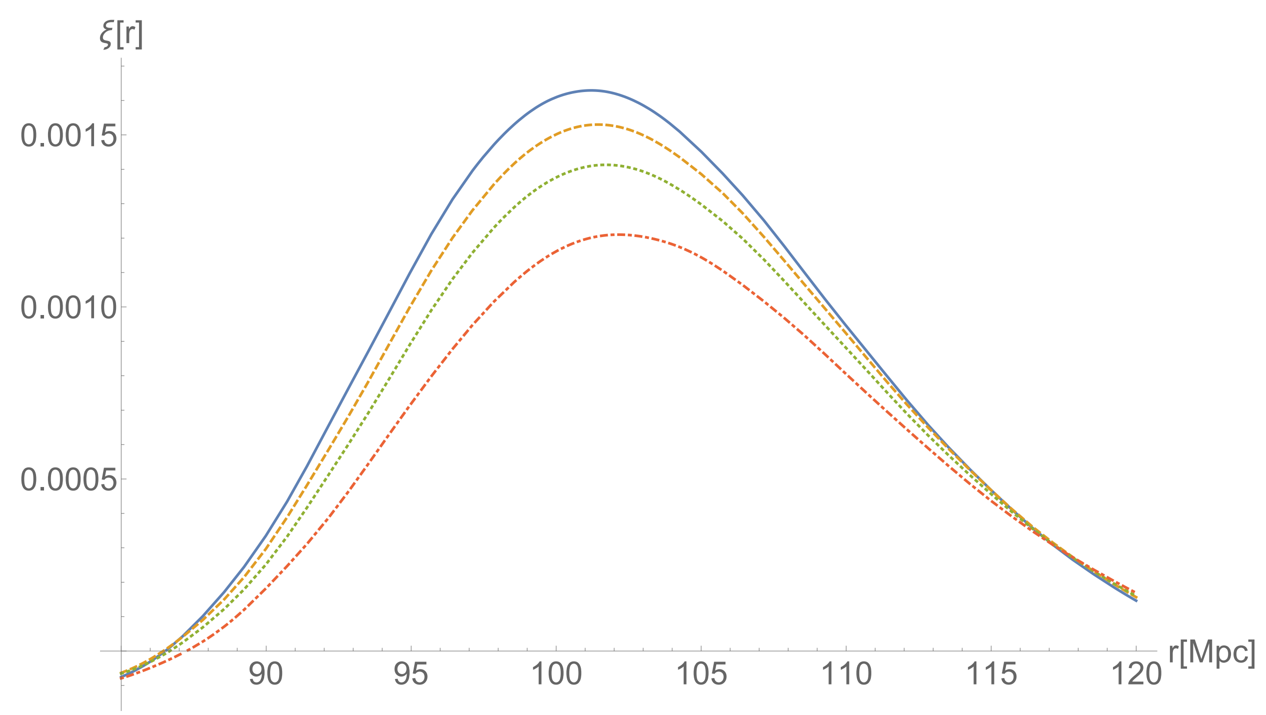


# Smooth vs wiggly linear CF



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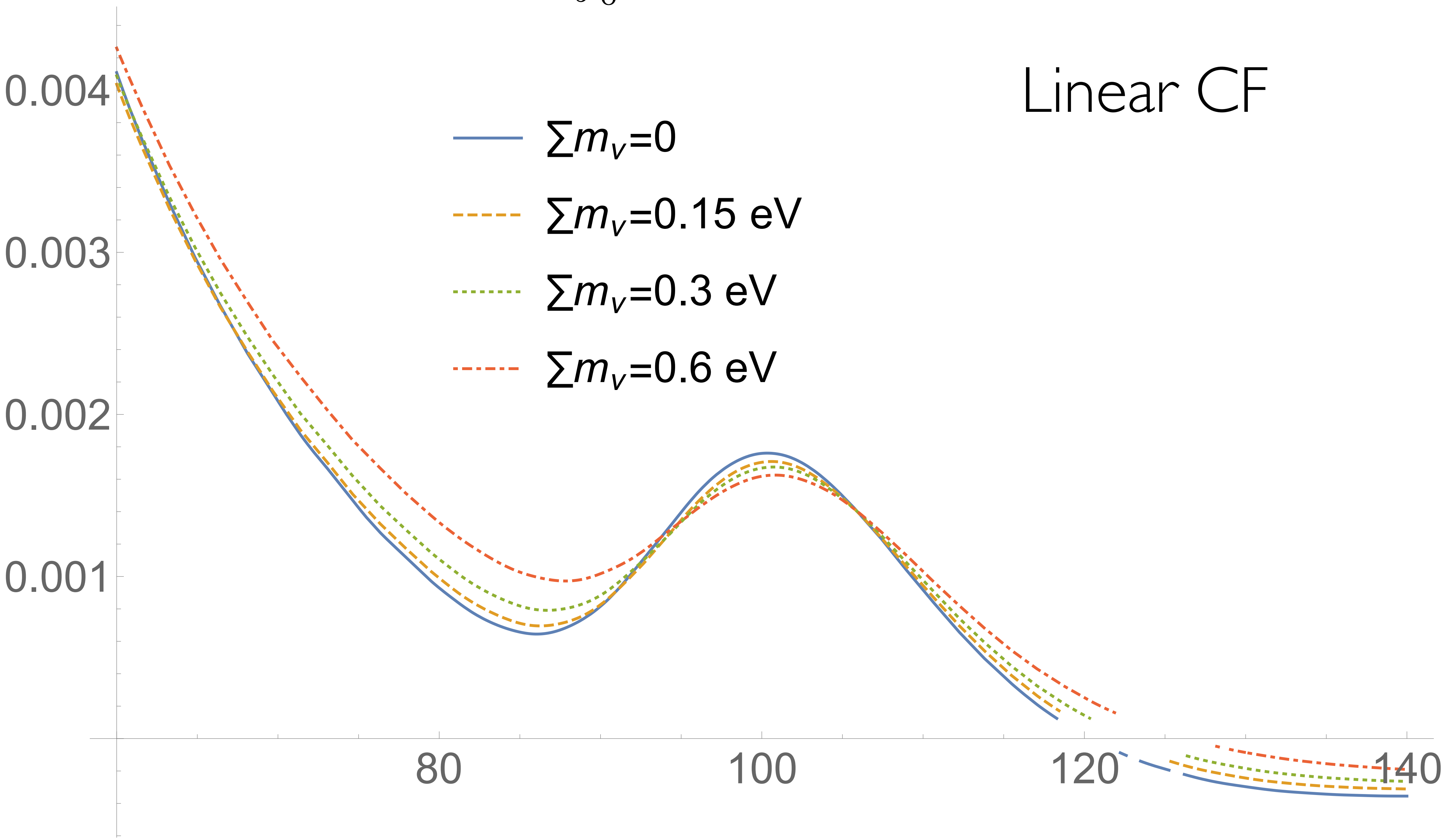


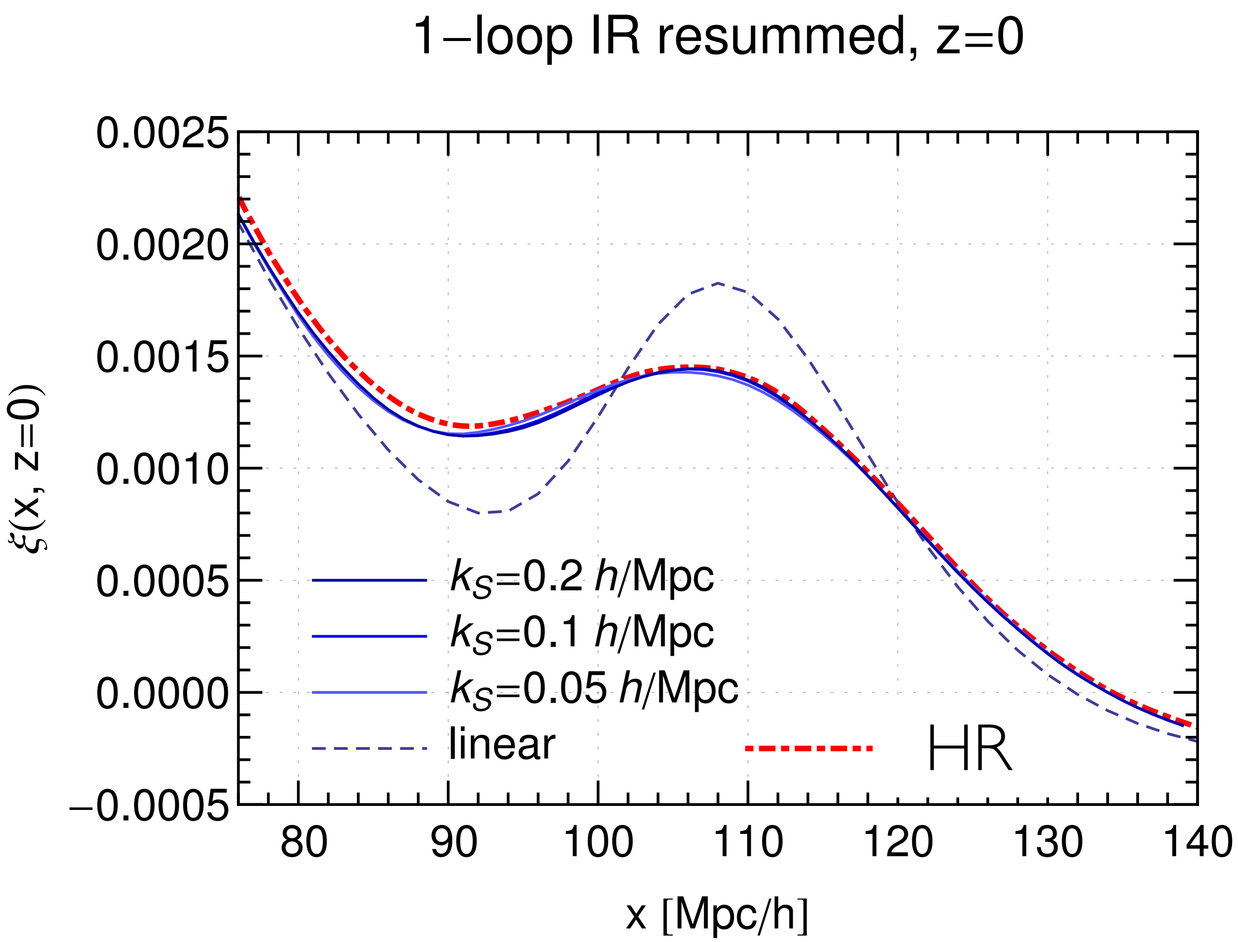
# IR-resummed CF

DB, Garny, Ivanov, Sibiryakov 2016

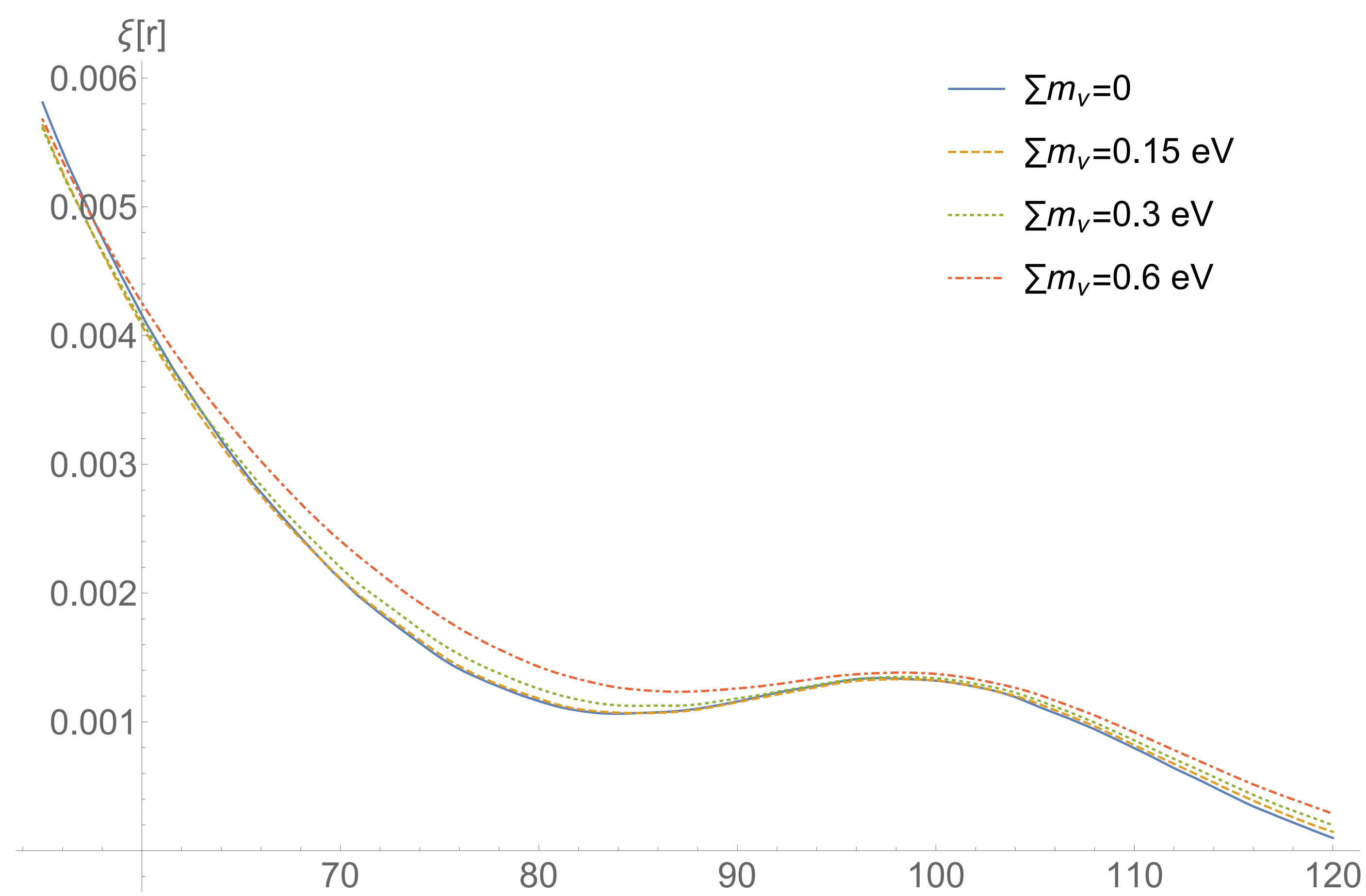
We use TSPT* final formula for the single fluid approach

RPT in Peloso et al 2015

(Senatore-Zaldarriaga 14, Baldauf et al 15 yield similar results)



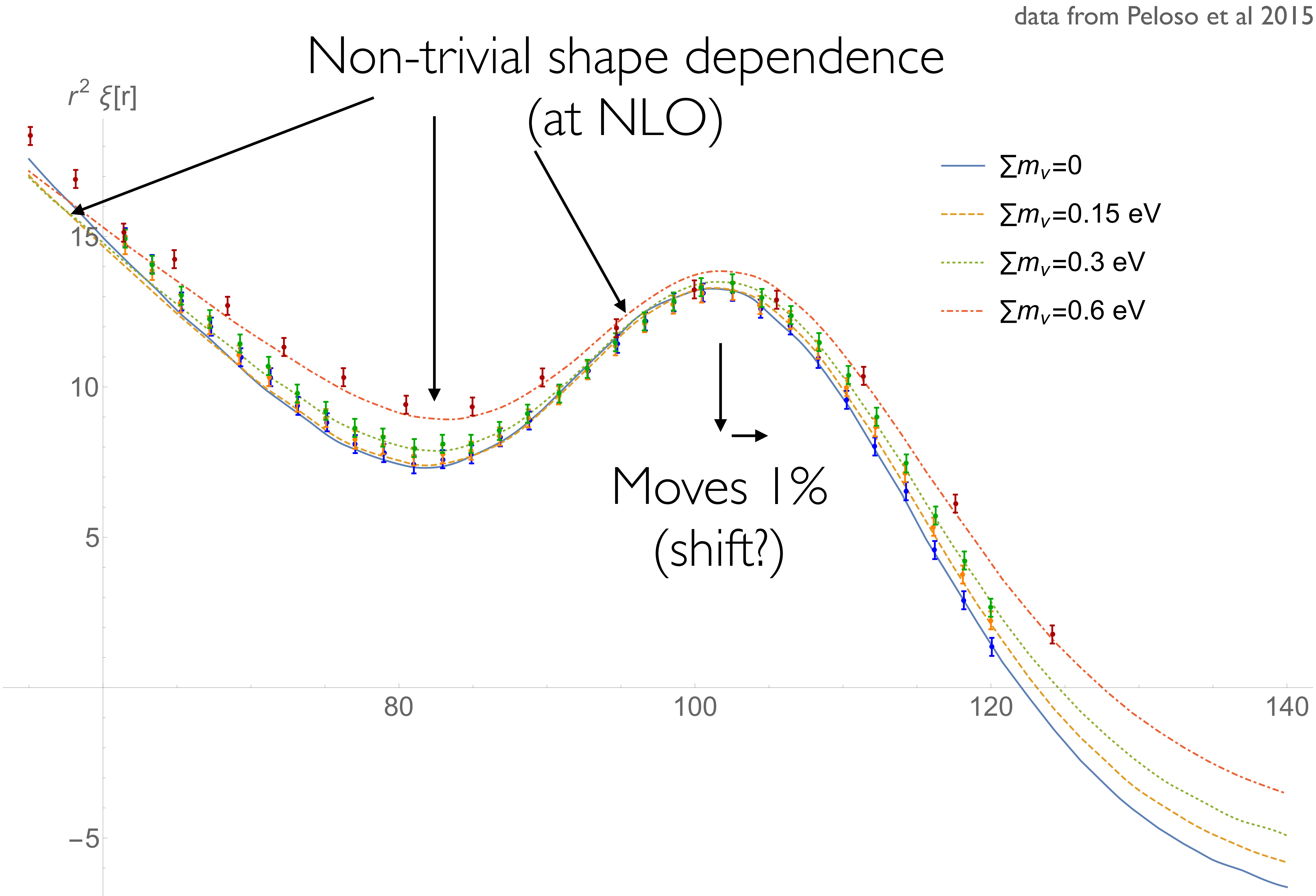

Massless case




* Perturbation theory based on the field PDF

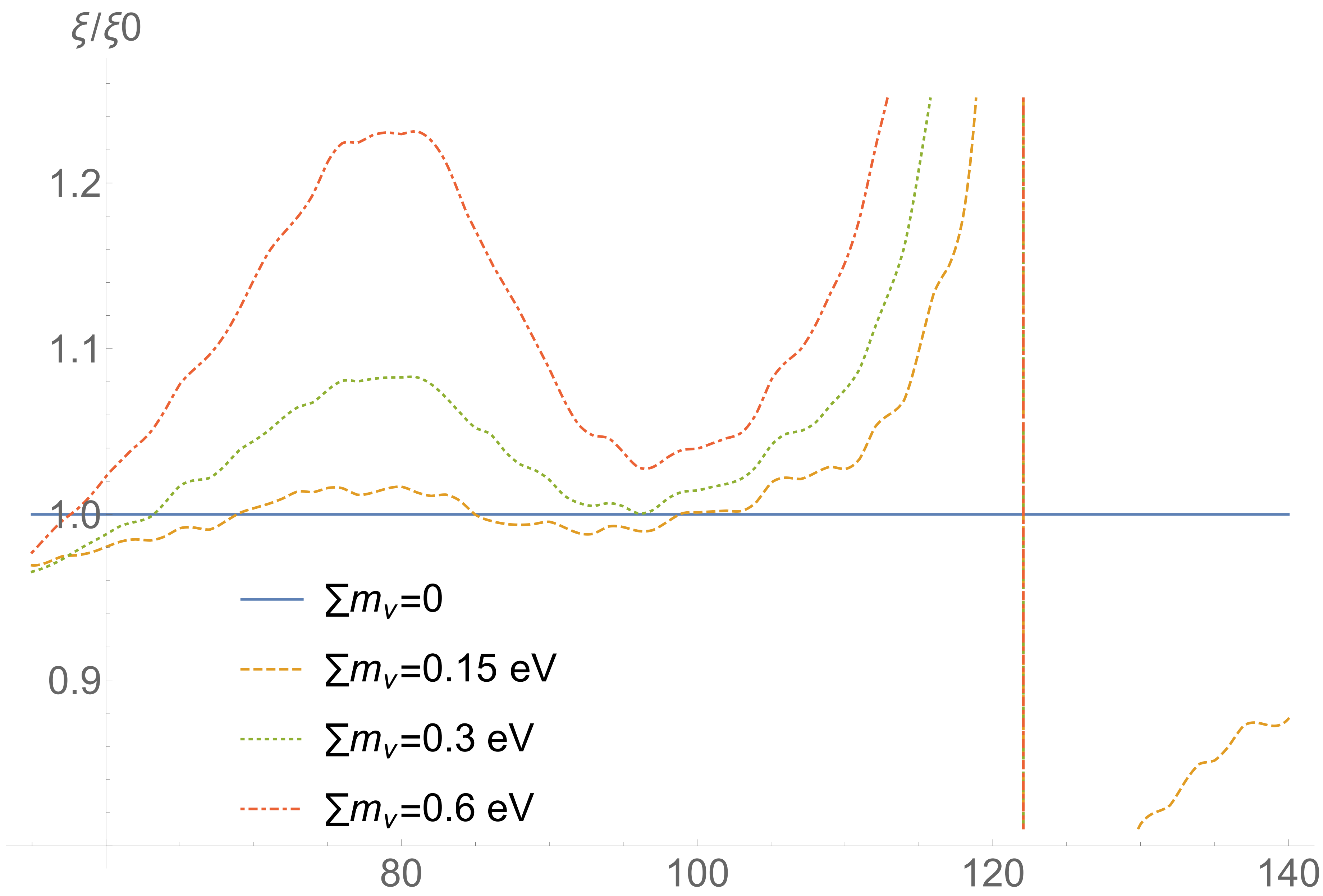
DB, Garny, Ivanov, Sibiryakov 2015

# IR-resummed CF



# IR-resummed CF

Non-trivial dependence (also at NNLO/EFT?)




Peloso et al 2015 also considered RSD and halos

# Conclusions

- LSS is in an advantageous situation to fix the mass of $\nu$ (missing parameter in the PDG)!

- Influence in LSS for whole mass range of $\nu$ at mildly non-linear scales

⚠ SPT with two fluids: required from precision and momentum conservation (relative velocities?)

- Large impact on CF close to BAO peak: peak height/position, dip height/position, and shape!

# Future

- NNLO/EFT/UV effects: impact on forecast!
- More comparison with N-body
- Understanding other observables/systematics (PS)
- Multi-fluids in TSPT, relative velocities