Cosmological case study of a tower of neutrino states

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(To appear soon)

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DPF-PHENO, 2024

May 13, 2024

Probing Neutrinos via cosmology

Effective number of Neutrino ($N_{\rm eff}$)

Neutrino mass

$$\sum m_\nu < 0.09 \text{ eV} \qquad (95\% \text{ C.L.})$$

Planck2018+BAO+Lyman$-\alpha$

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \qquad (95\% \text{ C.L.})$$

Planck2018+BAO

$$\boxed{\sum m_\nu < 0.072 \text{ eV } (95\,\%\,\text{C . L.})}$$

Planck2018 + DESI(BAO)

Probing Neutrinos via cosmology

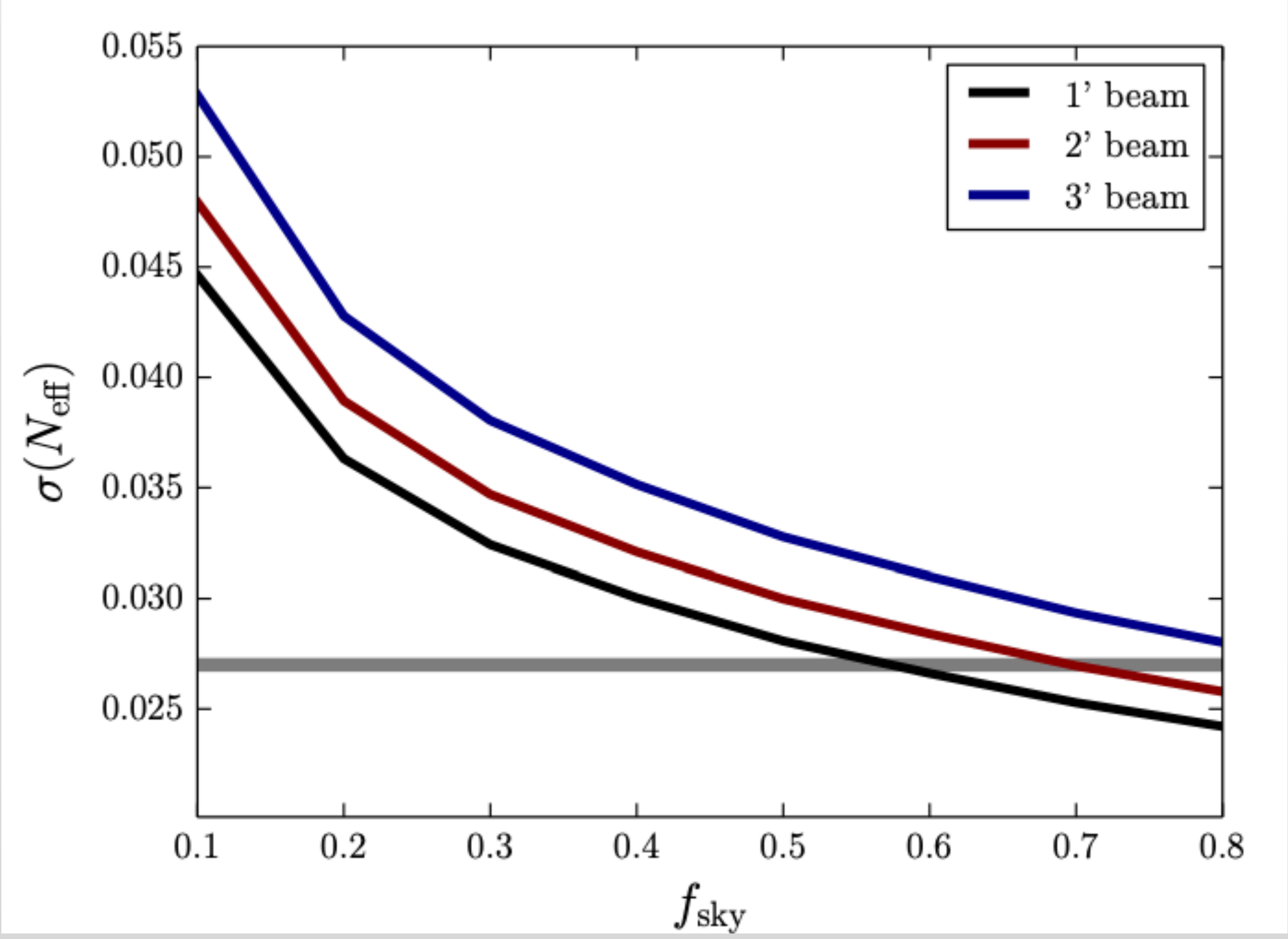
DESI puts strong constraint on ‘standard’ neutrino

Effective number of Neutrino ($N_{\rm eff}$)

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad \text{(95\% C.L.)}$$

Planck2018+BAO

Projection

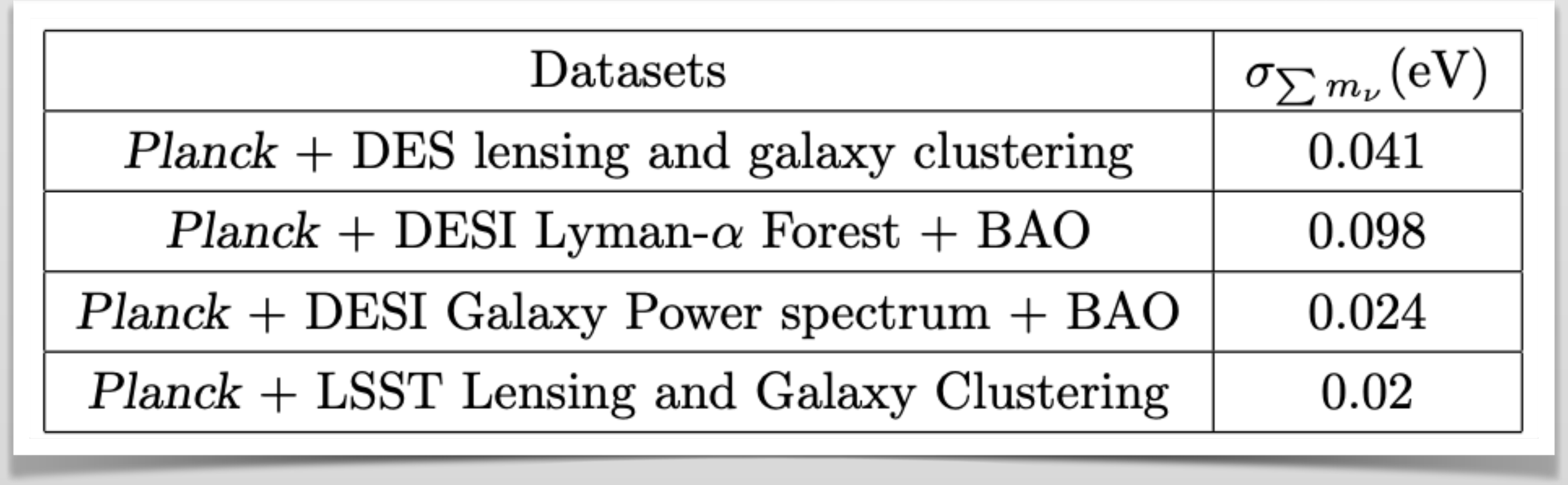


Neutrino mass

$$\sum m_\nu < 0.072 \text{ eV} \quad \text{(95\% C.L.)}$$

Planck2018 + DESI

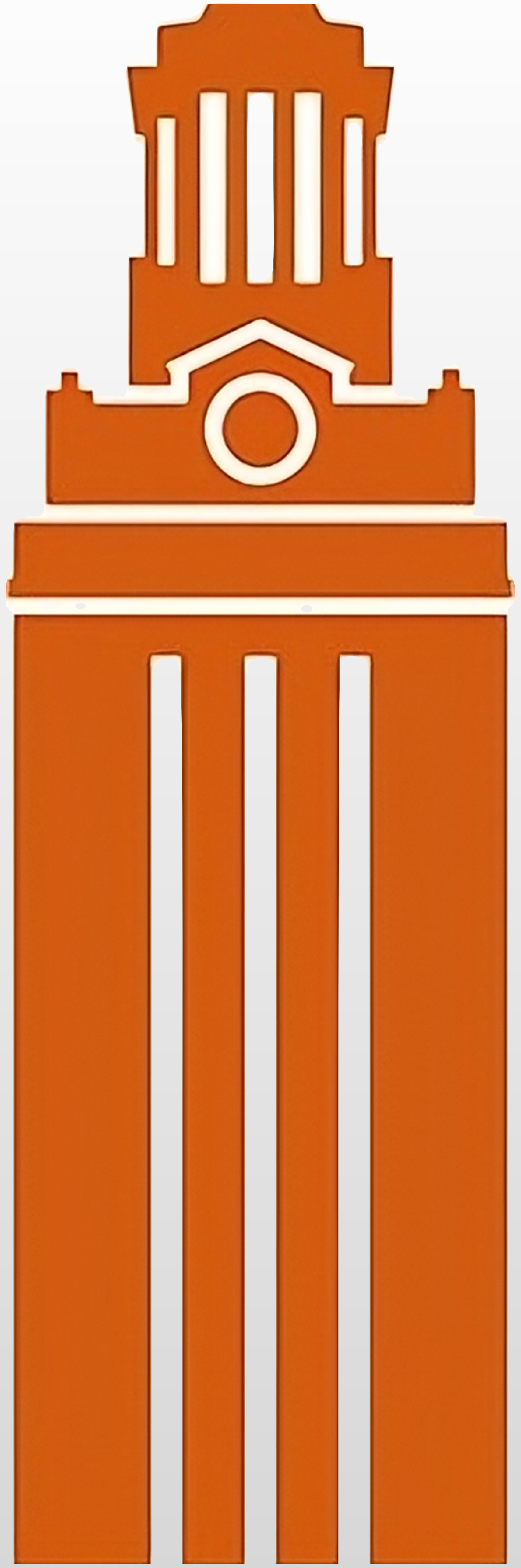
$$\boxed{\begin{array}{l}\sum m_\nu > 0.10 \text{ eV : IH} \\ \sum m_\nu > 0.059 \text{ eV : NH}\end{array}}$$



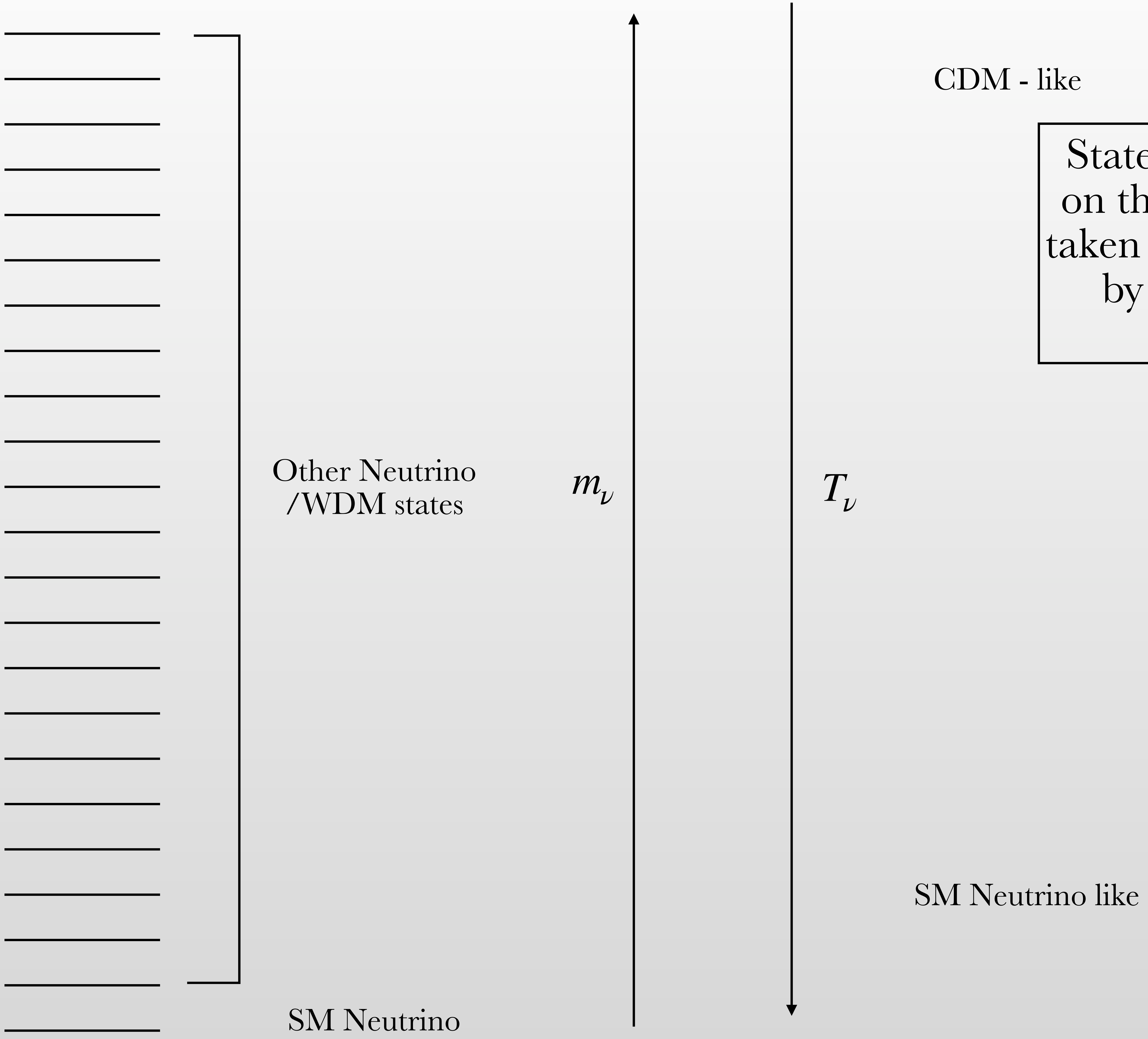
Datasets	$\sigma_{\sum m_\nu}$(eV)
Planck + DES lensing and galaxy clustering	0.041
Planck + DESI Lyman-α Forest + BAO	0.098
Planck + DESI Galaxy Power spectrum + BAO	0.024
Planck + LSST Lensing and Galaxy Clustering	0.02

CMB S4 science book (arXiv: 1610.02743)

Tower of neutrinos



*UT Tower



CDM - like

Other Neutrino
/WDM states

m_ν

T_ν

SM Neutrino like

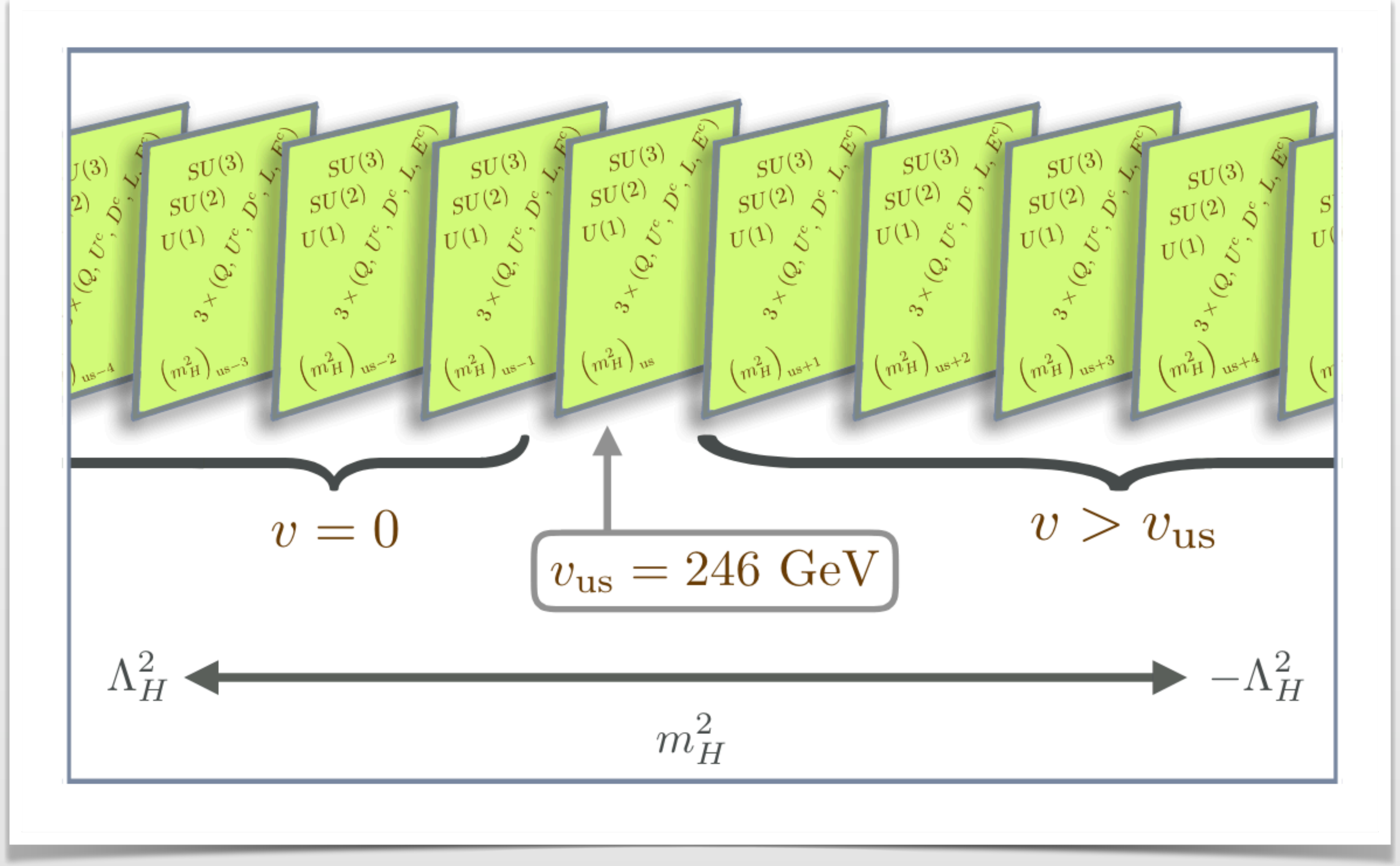
SM Neutrino

States higher up on the tower can taken into account by adjusting Ω_{CDM}

Arkani-Hamed+, arXiv:1607.06821

N-Naturalness : a Model for Neutrino Tower

A proposed solution to Hierarchy problem



$$\left(m_H^2\right)_i = -\frac{\Lambda_H^2}{N}\left(2\,i + r\right), \qquad -\frac{N}{2} \le i \le \frac{N}{2}$$

$$\mathcal{L}_\phi \supset -a\,\phi \sum_i |H_i|^2 - \frac{1}{2}\,m_\phi^2\,\phi^2,$$

Two free parameters : r and m_ϕ

Tower of N-Neutrino

Mass

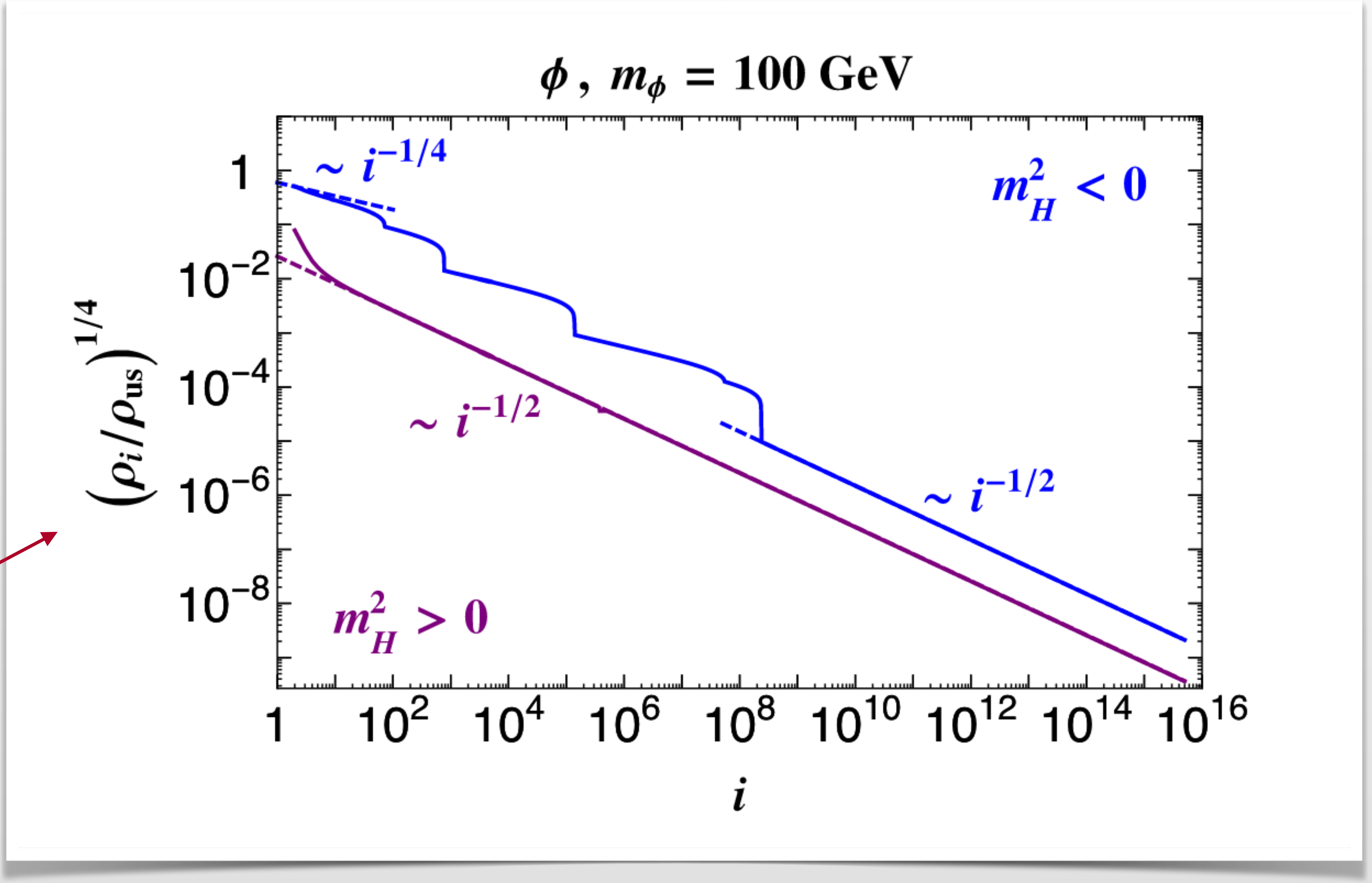
$$v_i = v^{\mathrm{SM}}\sqrt{\frac{2i+r}{r}}.$$

The spectrum depends of SM neutrino masses

$$m_{\nu,i}^{(\mathrm{Maj})} = m_{\nu,\mathrm{SM}}\frac{v_i^2}{v_{\mathrm{SM}}^2}.$$

$$m_{\nu,i}^{(\mathrm{Dir})} = m_{\nu,\mathrm{SM}}\frac{v_i}{v_{\mathrm{SM}}},$$

Temperature

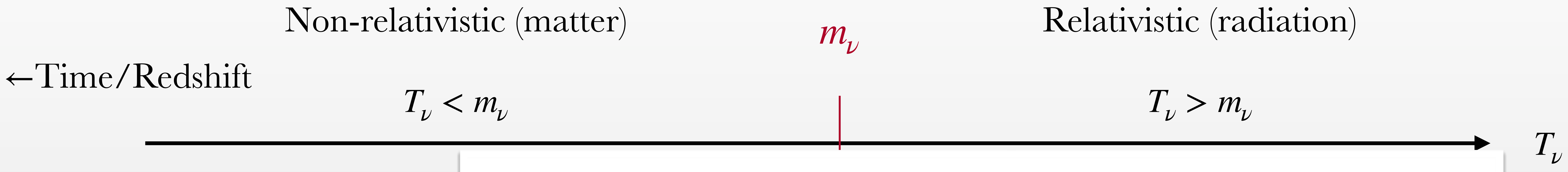


$$\frac{T_i}{T_{\mathrm{SM}}}$$

$$\boxed{\sum_{f=1}^{3} m_{\nu,\mathrm{SM}}^{(f)} = 0.12\ \mathrm{eV}\ \ \&\ \text{Normal Hierarchy}}$$

The bounds will depends on the choice of SM Neutrino mass

How cosmology probes Neutrinos?



Non-relativistic (matter)

m_ν

Relativistic (radiation)

←Time/Redshift

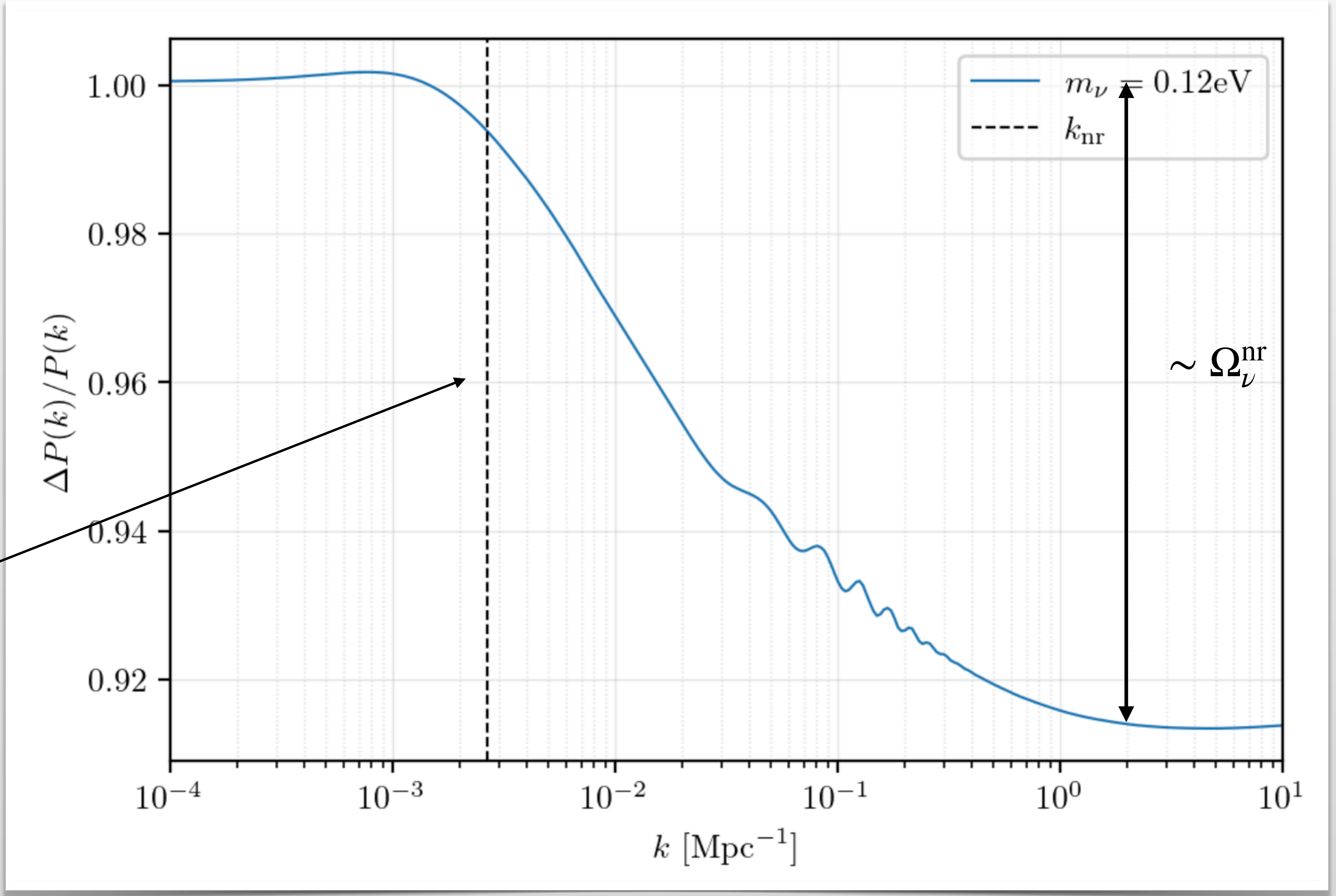
$T_\nu < m_\nu$

$T_\nu > m_\nu$

T_ν

CMB & BBN constraints N_{eff}

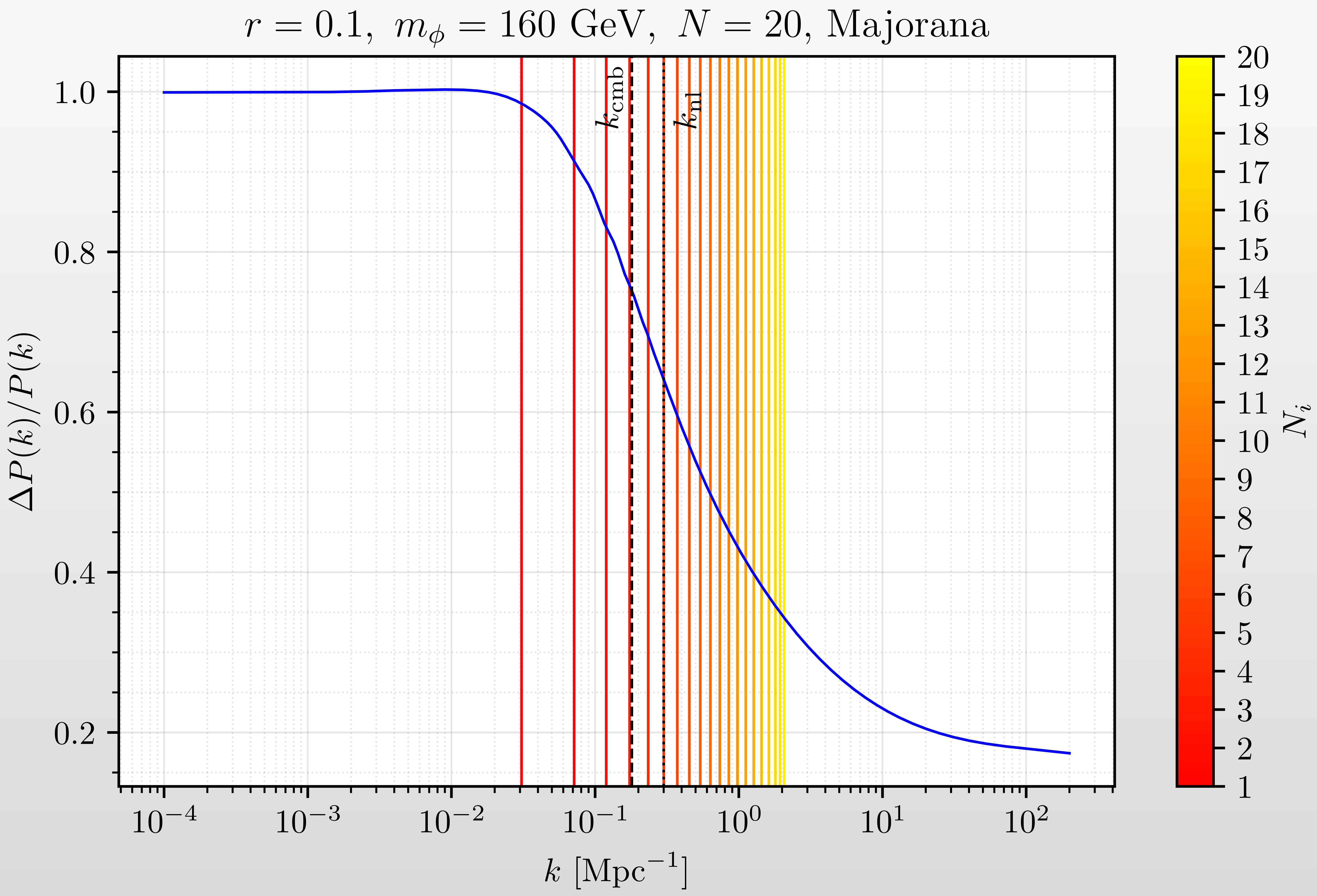
CMB & LSS probes matter power spectrum

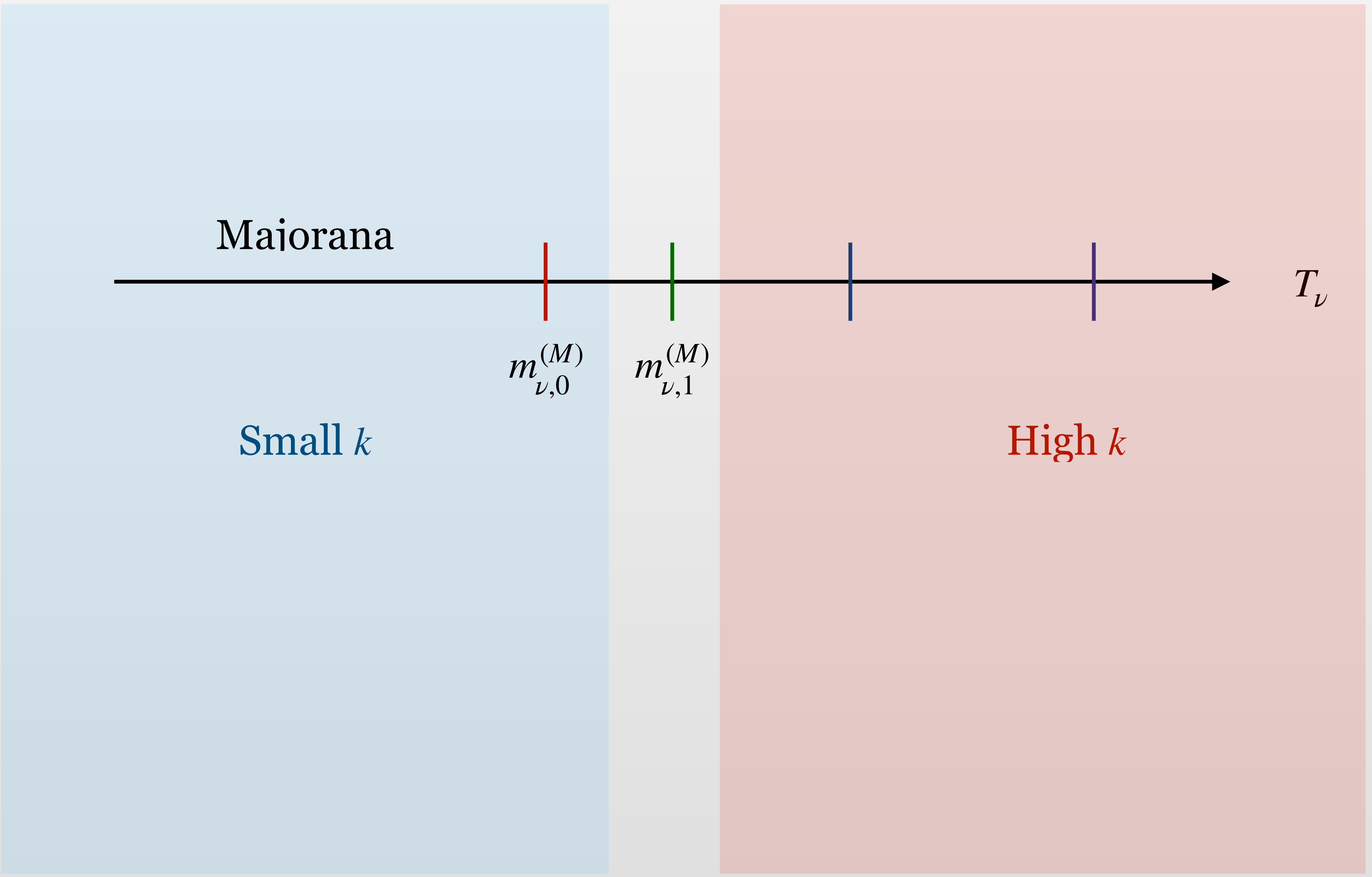


$k_{\text{nr}} = 1/\eta_{\text{nr}}$ where $T_\nu(\eta_{\text{nr}}) = m_\nu$

Same Ω_m and N_{eff} for both models

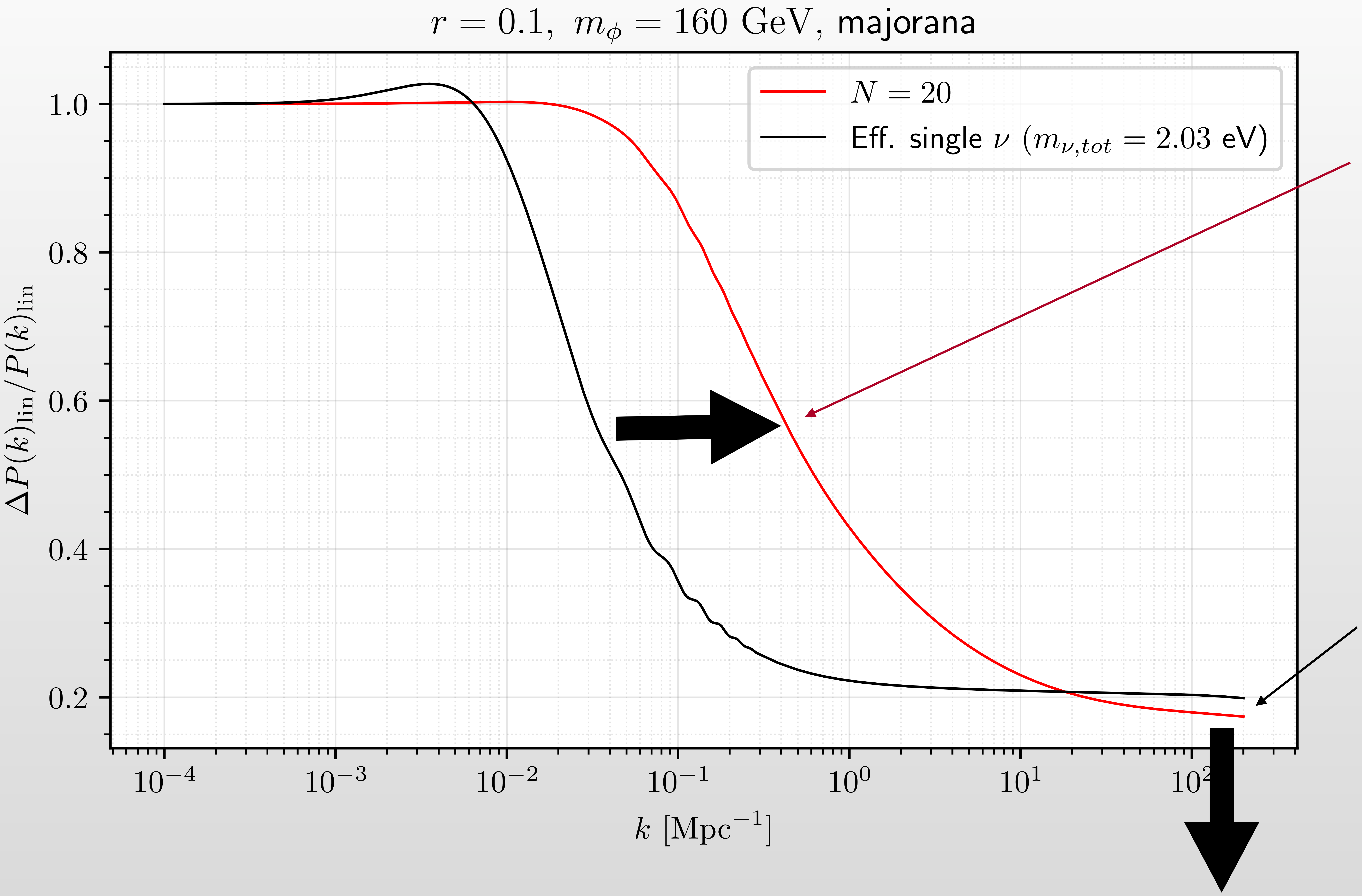
Matter power spectrum suppression for N-Neutrino





$$m_{\nu,i}^{(D)} \sim i^{1/2}, m_{\nu,i}^{(M)} \sim i$$

N neutrino vs 1 neutrino



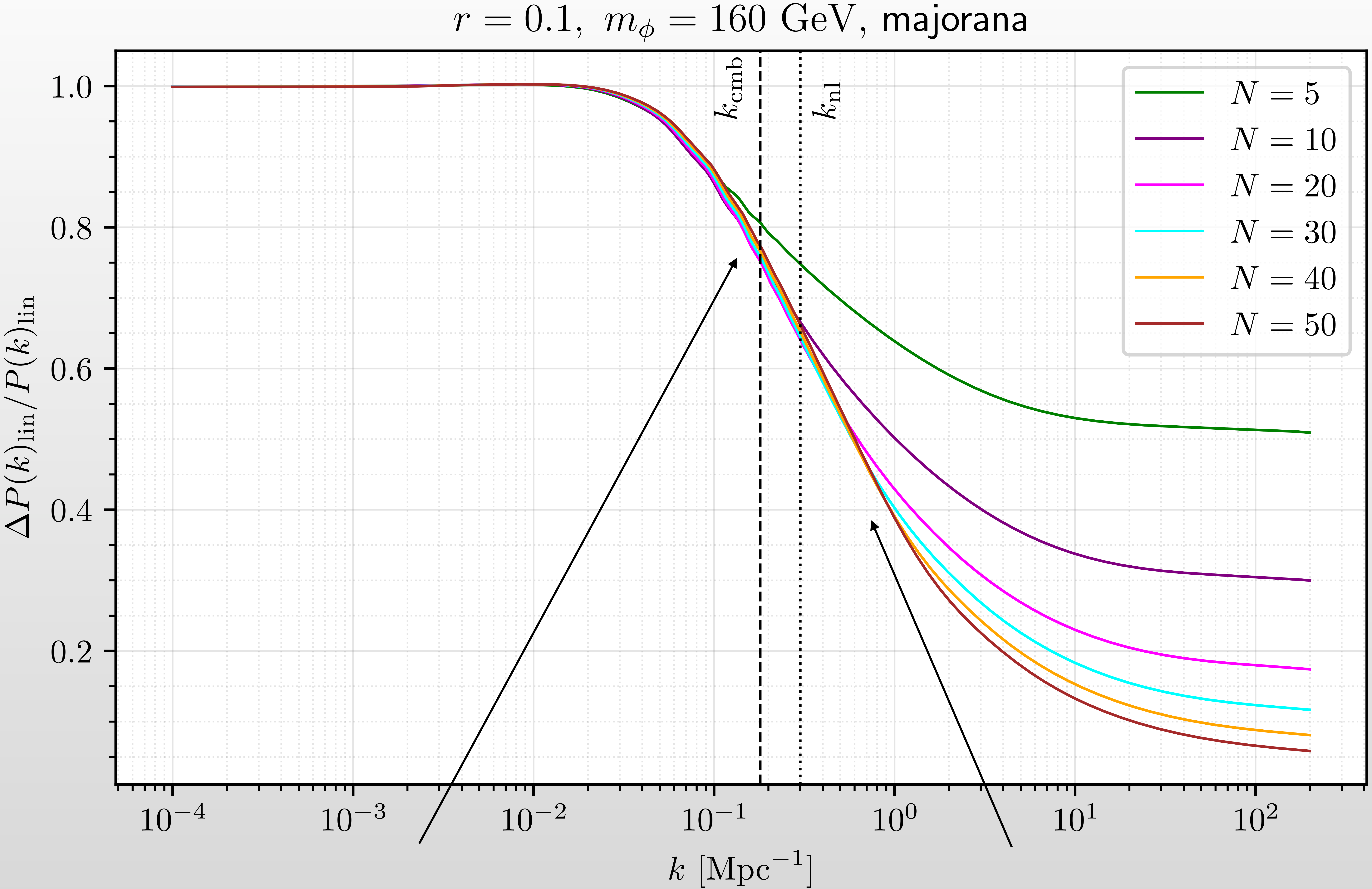
More gradual suppression compared to single neutrino

Small Difference due to matter-radiation equality difference

$k_{\rm nr}$ and Ω_ν both increase with m_ν

Same Ω_m and $N_{\rm eff}$ for ΛCDM, 1-ν and N-ν

Matter power spectrum suppression along N

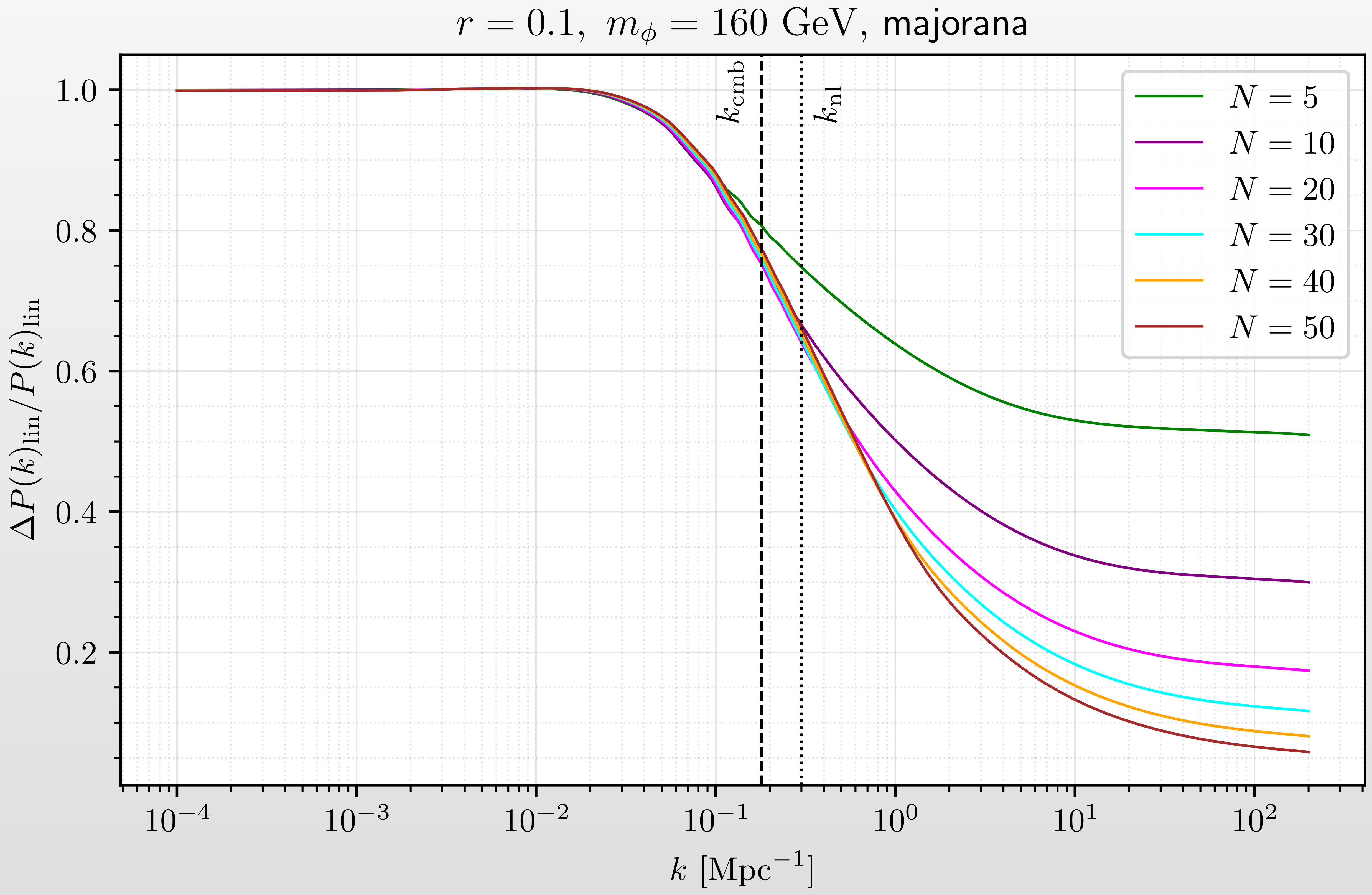


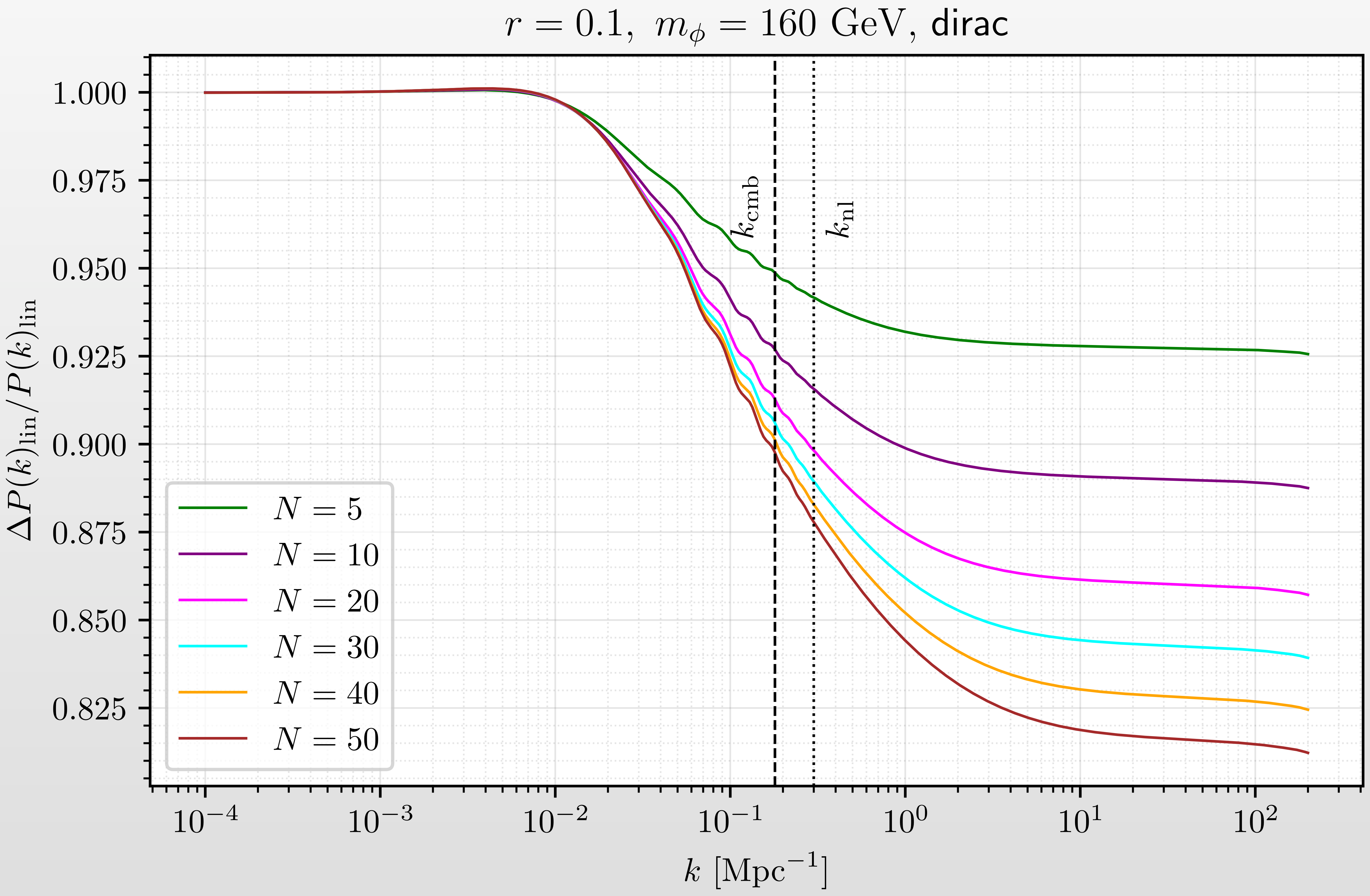
$N \gtrsim 10$ are CDM for CMB scale

$N \gtrsim 50$ are CDM for Lyman-α scale

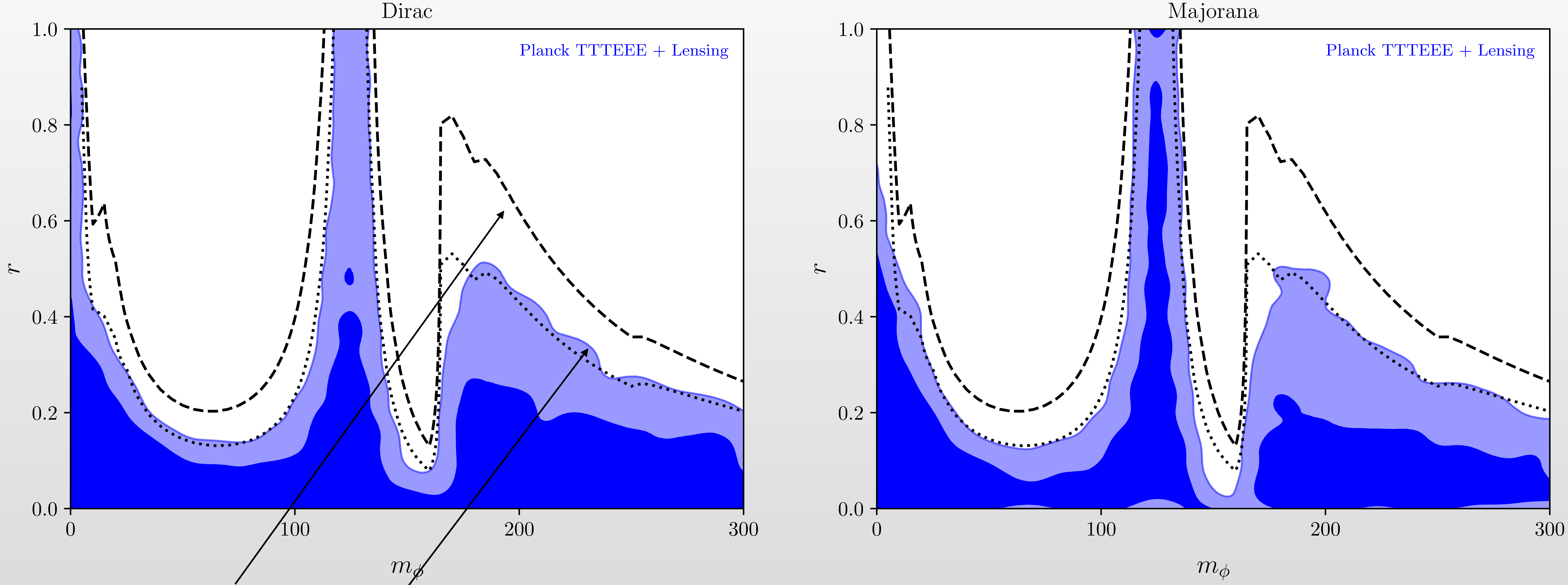
Same Ω_m and $N_{\rm eff}$
for all models

Matter power spectrum suppression along N





MCMC constraints: Role of Neutrinos

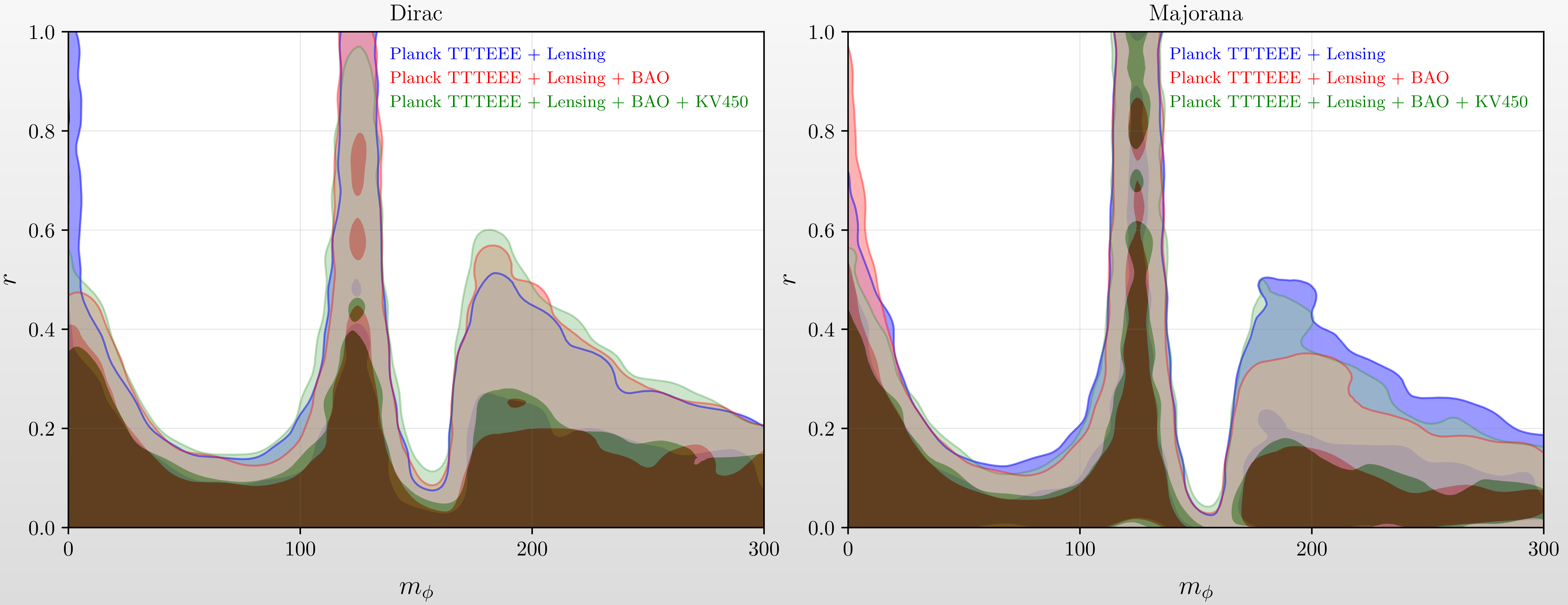


Constraint from N-photons

Combined constraint from N-photons & N-Neutrinos

Neutrinos strengthen the constraints on the Model

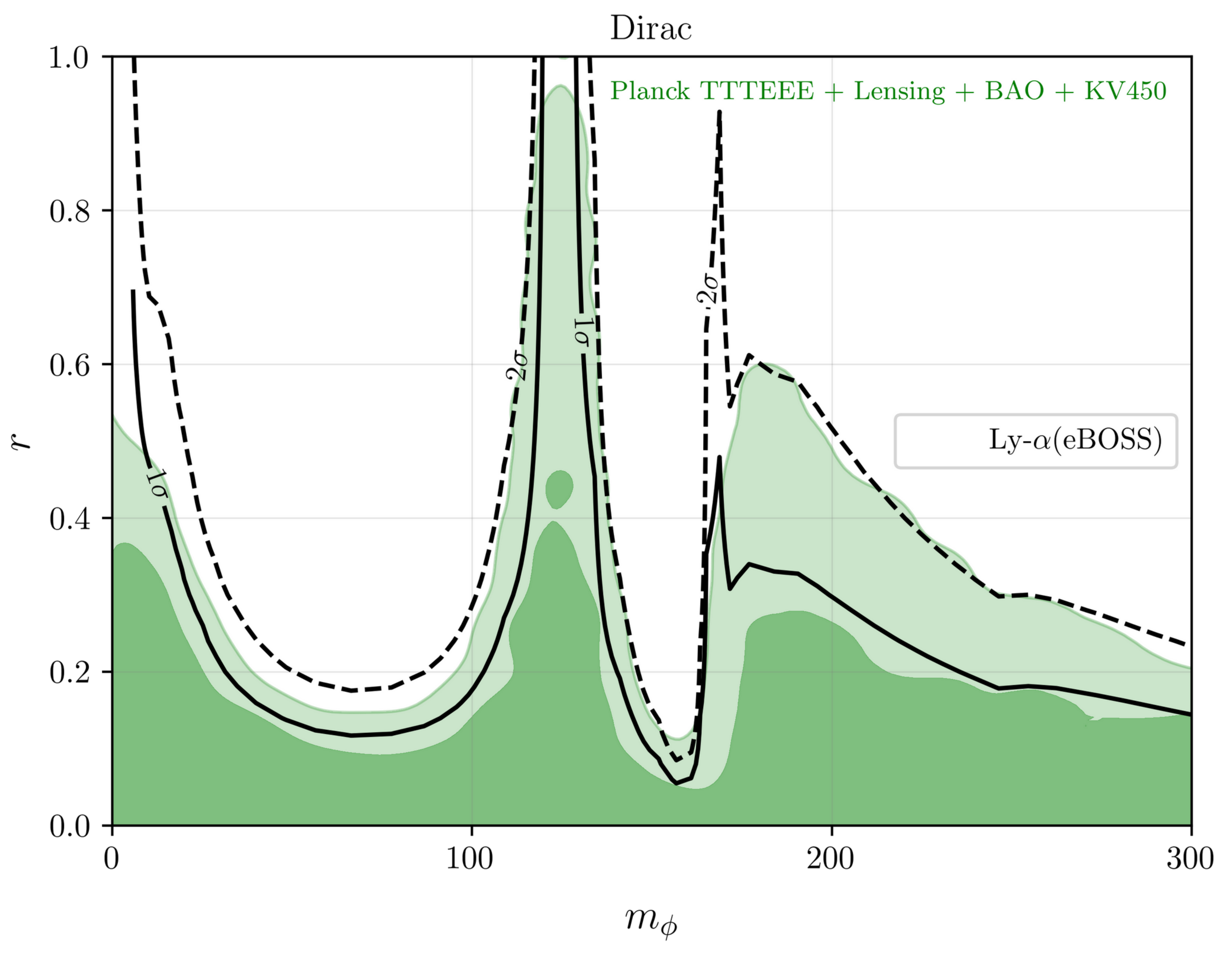
MCMC constraints: Role of LSS dataset

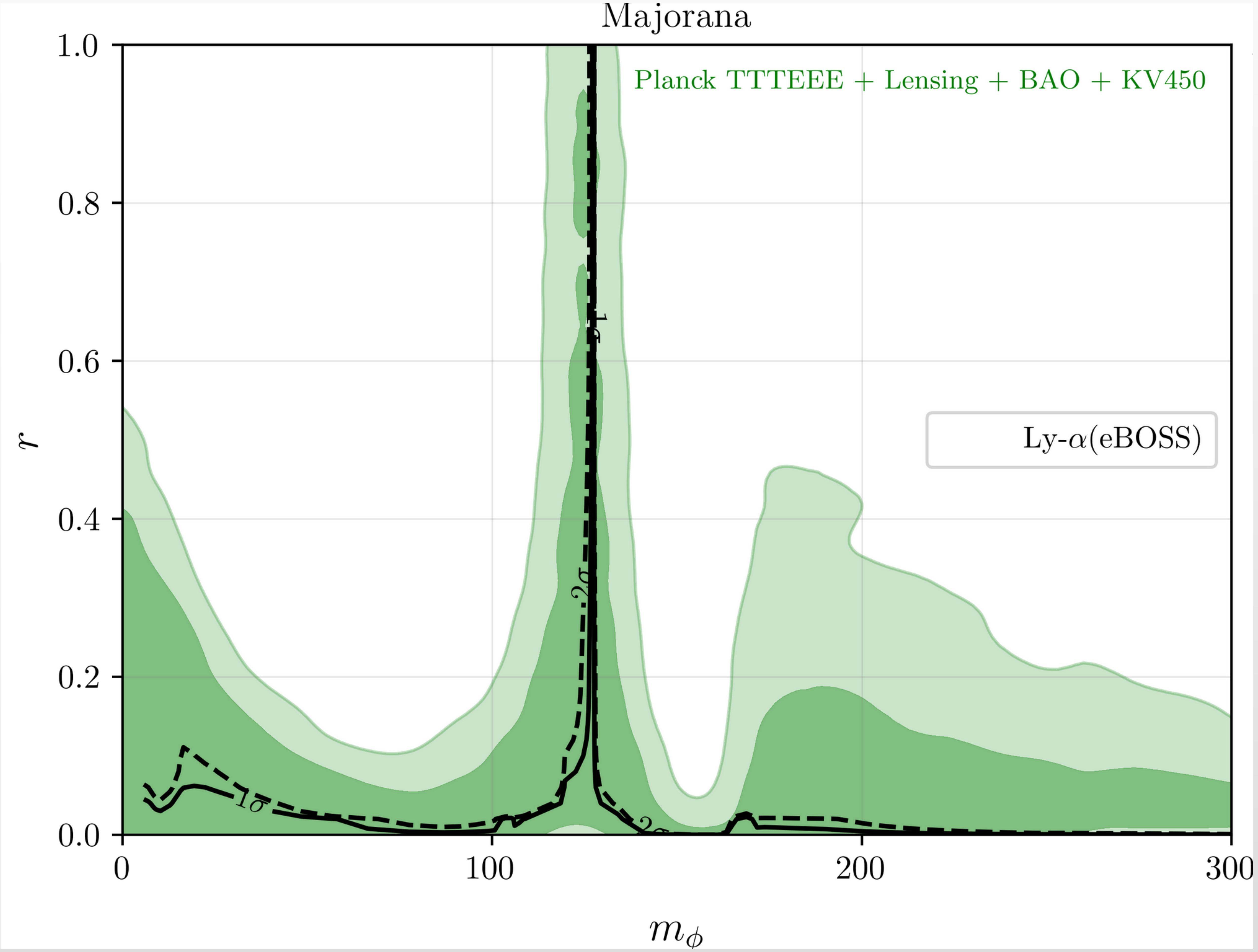


LSS strengthen the constraint

Rough Constraints : e-Boss Lyman-α

Preliminary



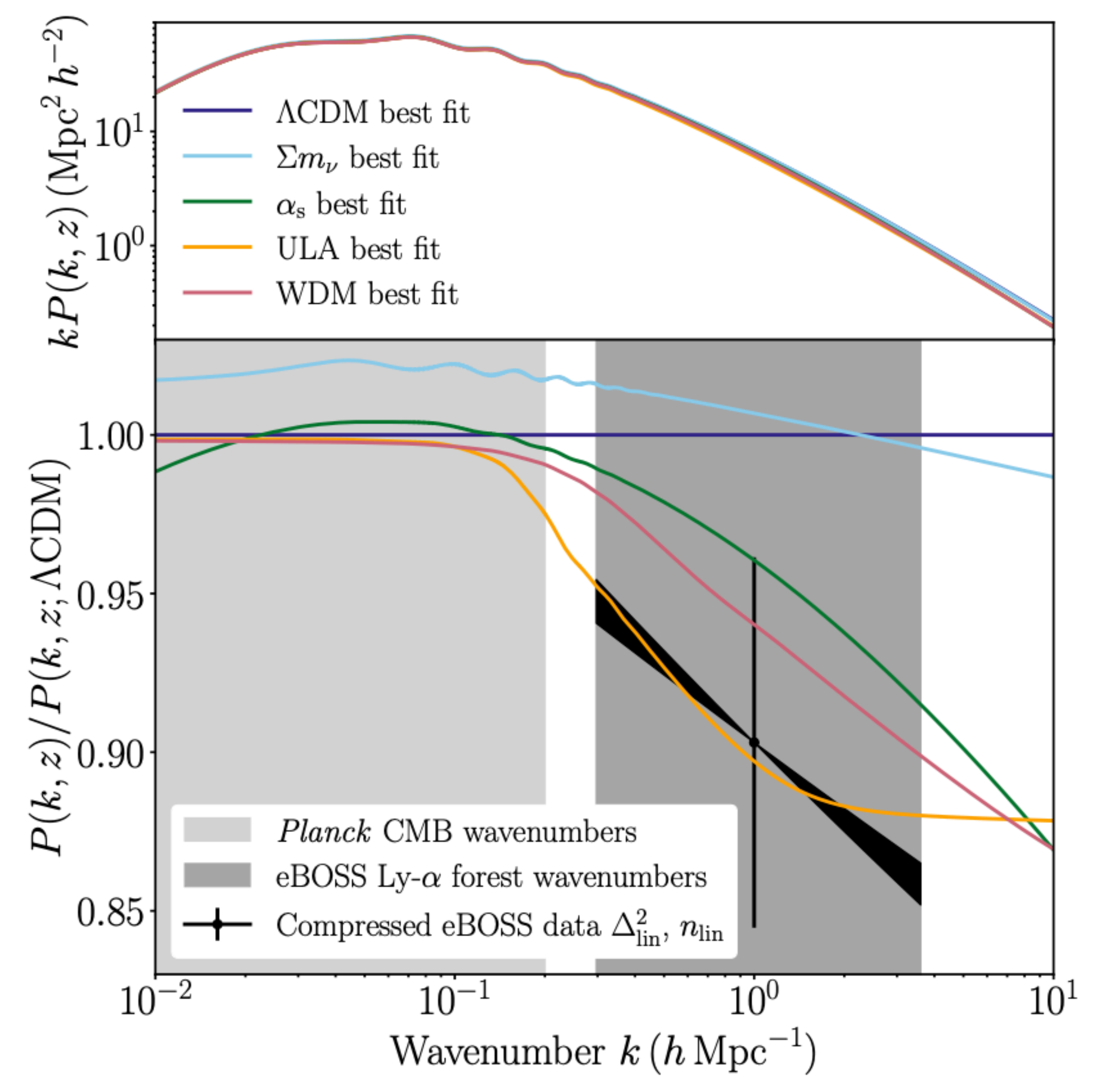


Constraints are **aggressive** . Will be relaxed in an MCMC analysis with varying SM neutrino mass

Conclusion

- Stricter constraints on neutrino mass will necessitate going beyond ‘standard neutrino’.
- 1-ν vs N-ν give distinguishable features in cosmology. The decoupling profile for a tower of neutrinos cannot be captured by a single neutrino species by adjusting its mass and temperature.
- Neutrino tower creates a more gradual suppression of power spectra is comparatively less constrained at large scale.
- Neutrino tower creates large suppression at smaller scale. LSS dataset is crucial to probe multiple neutrino state.
- Majorana neutrino in N-Naturalness is strongly constrained by LSS & Lyman-α data.
- Need of a faster and efficient Boltzmann code to study effects for neutrino/WDM tower.

Tension between Planck & e-Boss Ly-α in ΛCDM



Rogers+,arXiv:2311.16377

Effects on CMB anisotropy