Cosmological case study of a tower of neutrino states

Subhajit Ghosh

Postdoctoral Scholar
Weinberg Institute
Department of Physics

The University of Texas at Austin

..with Saurabh Bansal, Matthew Low, Yuhsin Tsai

(2409.xxxxx)

sghosh@utexas.edu

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Probing Neutrinos via cosmology

DESI puts strong constraint on 'standard' neutrino

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

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

Planck2018+BAO

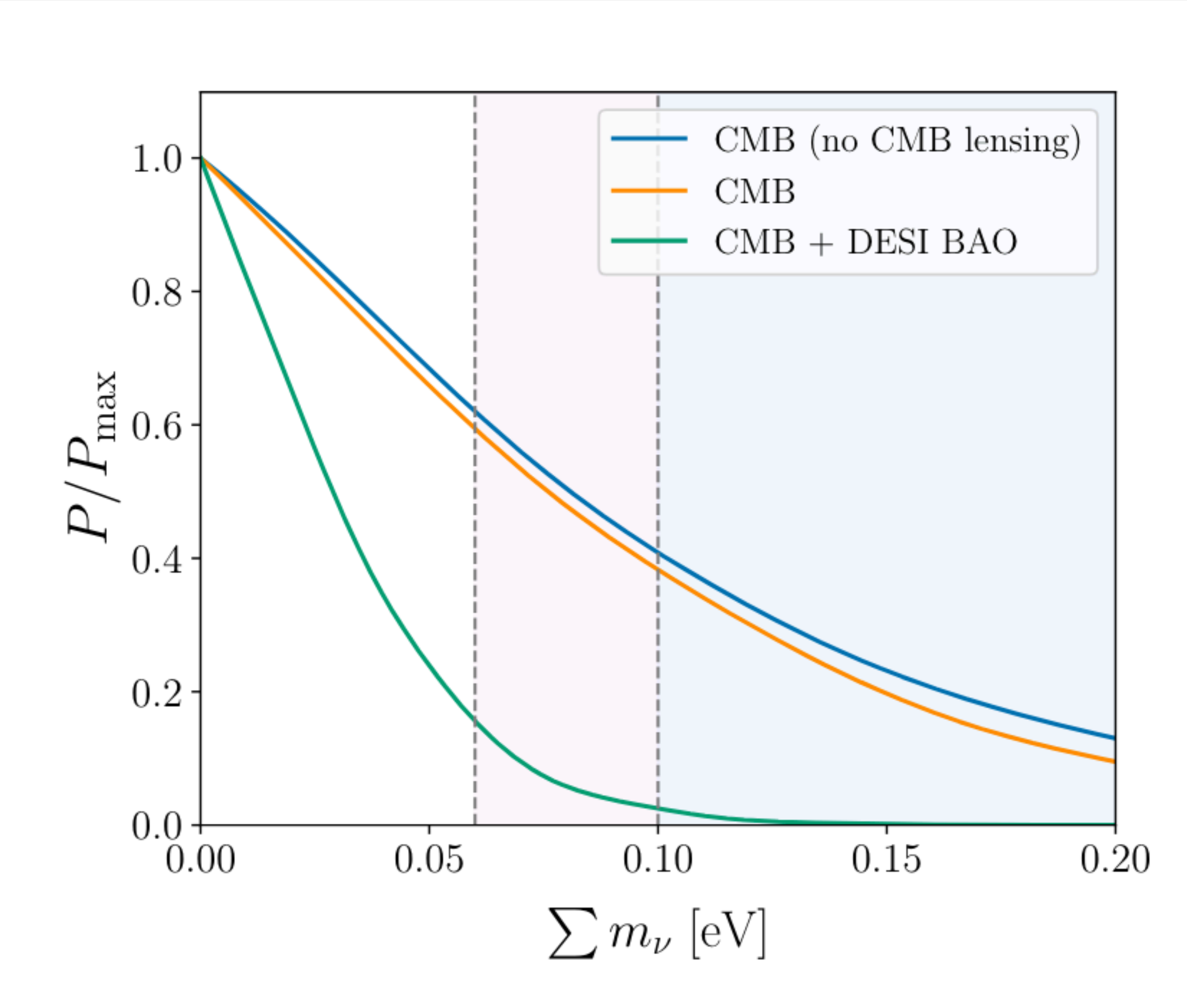
Neutrino mass

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

Planck2018 + DESI

$$\sum m_\nu > 0.10\ \text{eV} : \text{IH}$$

$$\sum m_\nu > 0.059\ \text{eV} : \text{NH}$$



How cosmology probes Neutrinos?

Non-relativistic (matter) m_ν Relativistic (radiation)

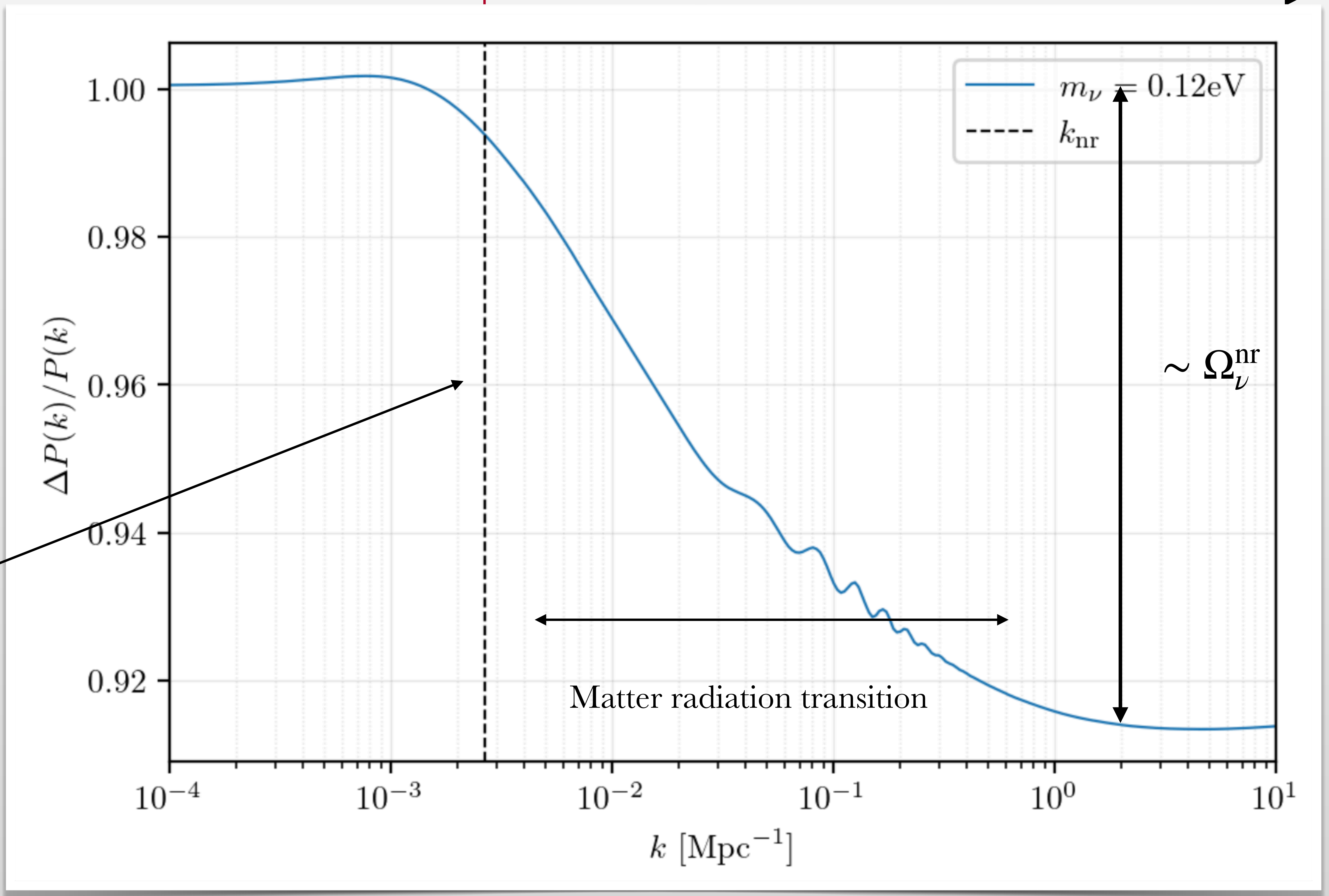
←Time/Redshift

$T_\nu < m_\nu$ $T_\nu > m_\nu$ T_ν

CMB & BBN constraints $N_{\rm eff}$

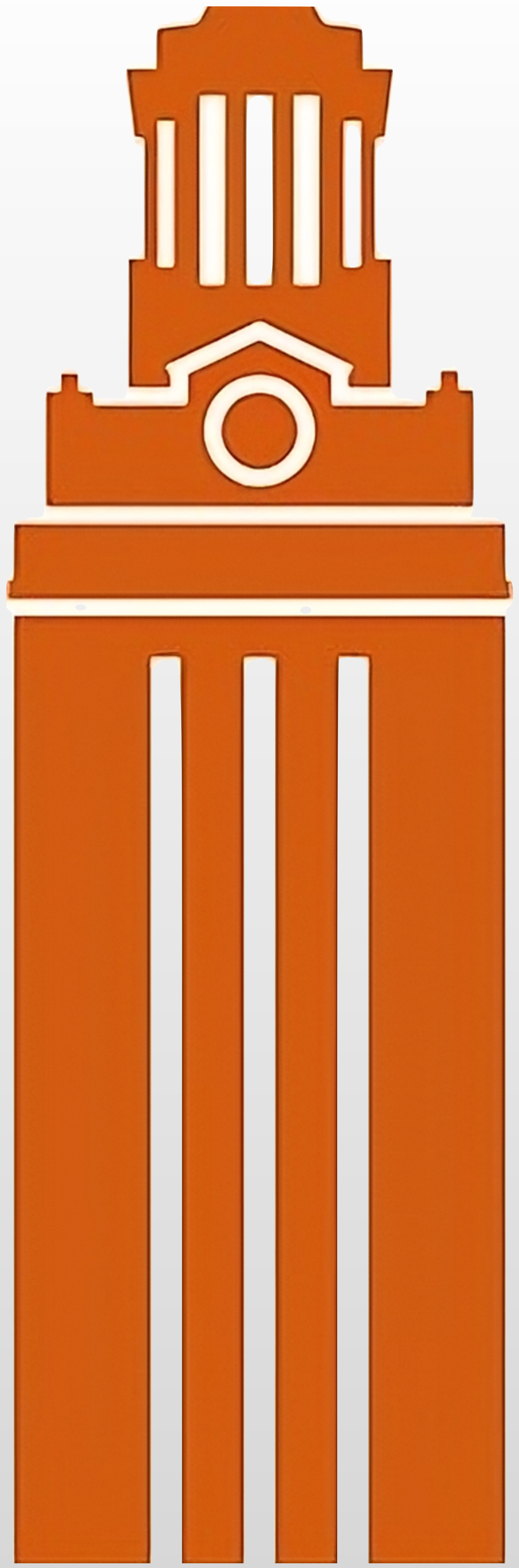
CMB & LSS probes matter power spectrum

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

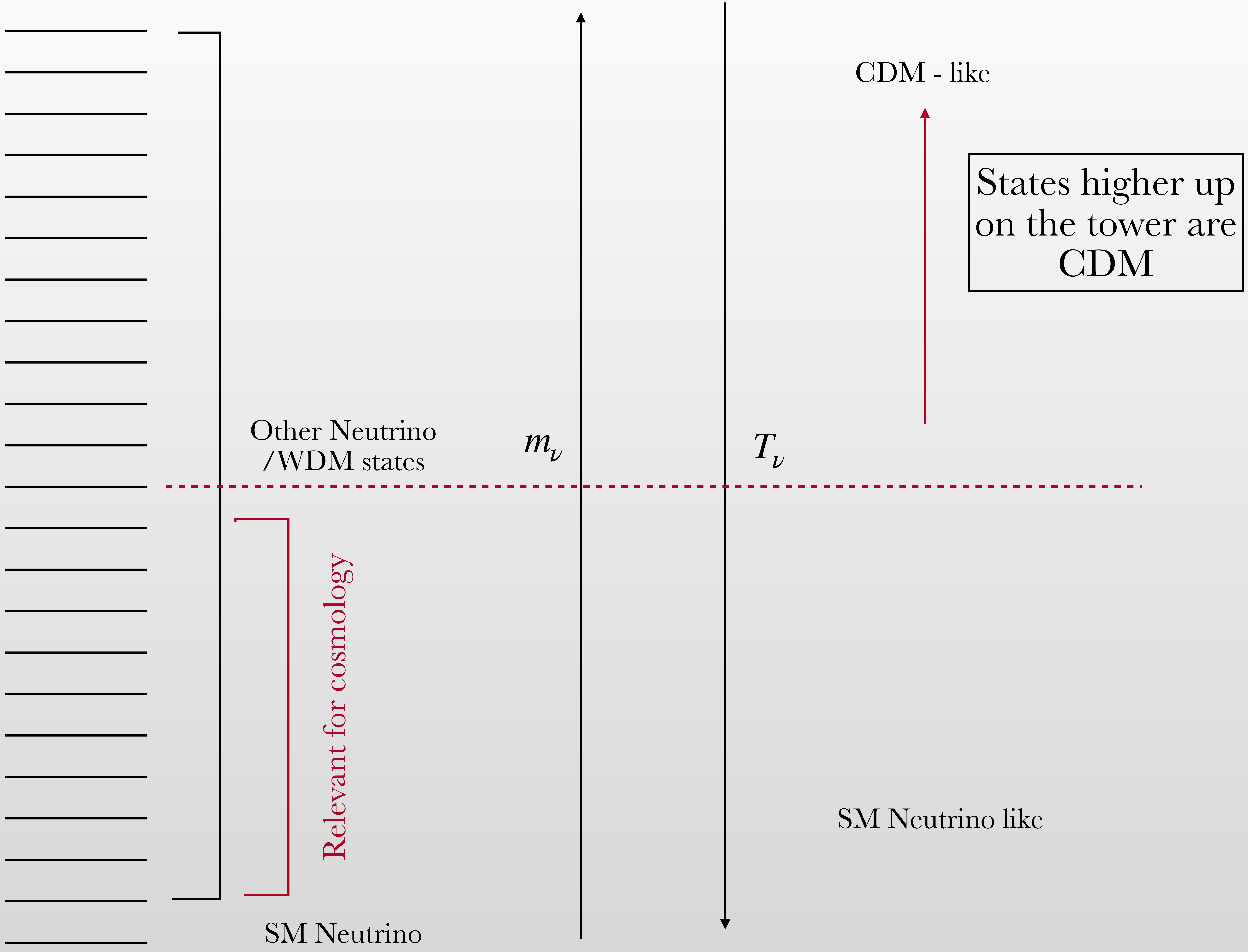


Same Ω_m and $N_{\rm eff}$ for both models

Tower of neutrinos



*UT Tower

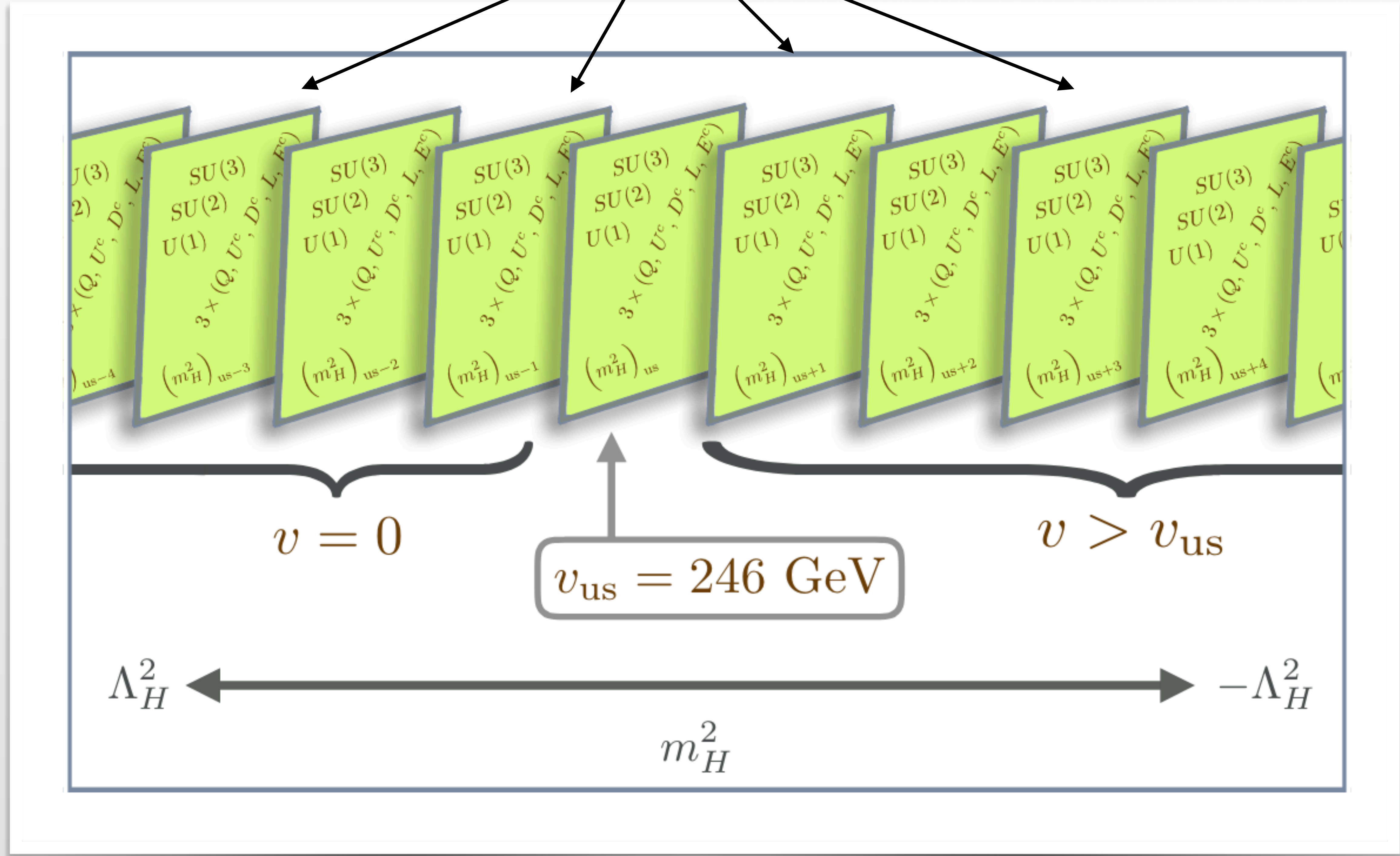


Arkani-Hamed+, arXiv:1607.06821

N-Naturalness : a Model for Neutrino Tower

A proposed solution to Hierarchy problem

Reheaton: ϕ



Total number of sectors: N

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

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

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

Two free parameters : r and m_ϕ

Tower of N-Neutrino

Mass

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

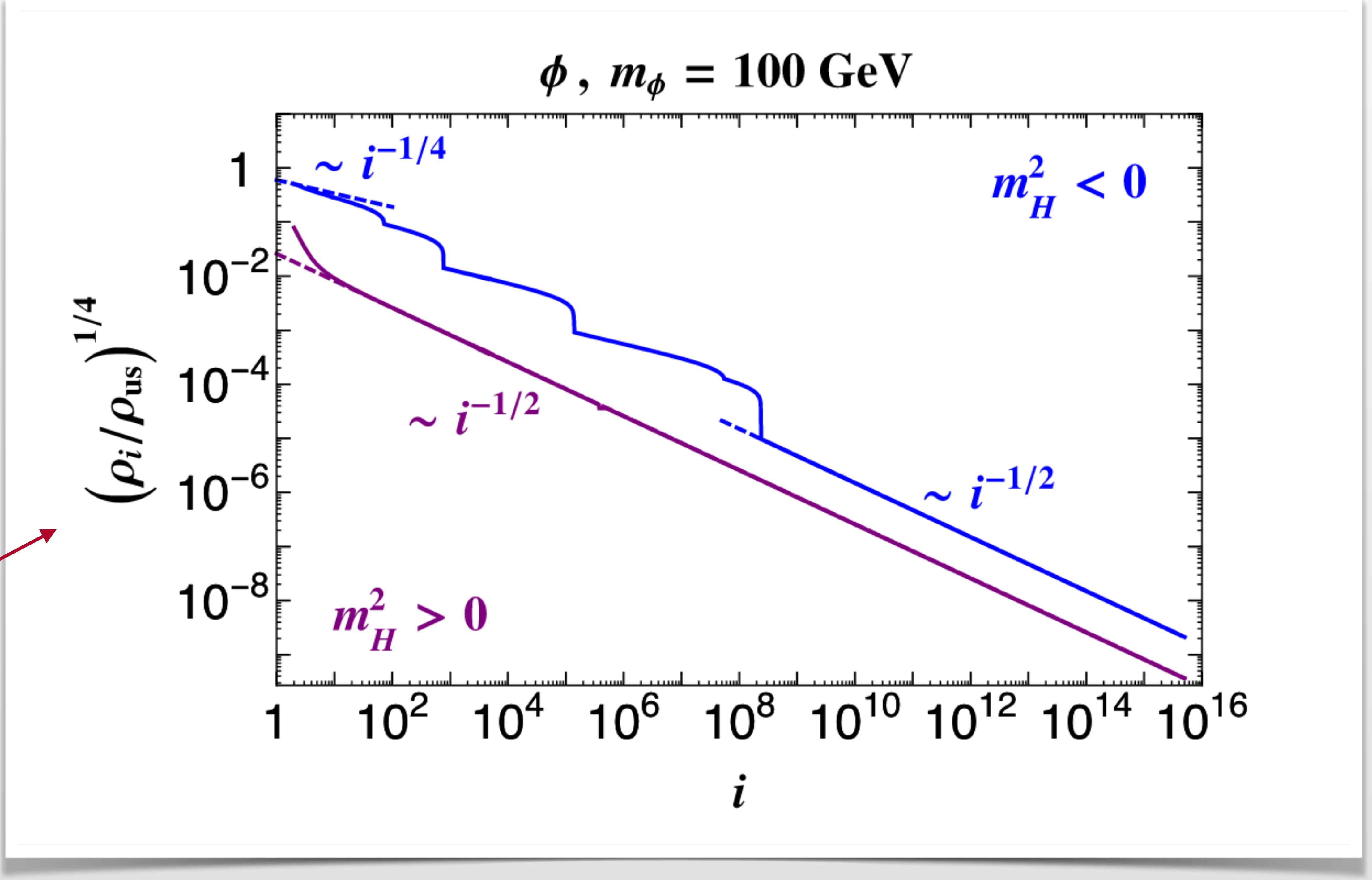
The spectrum depends of SM neutrino masses

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

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

Temperature

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

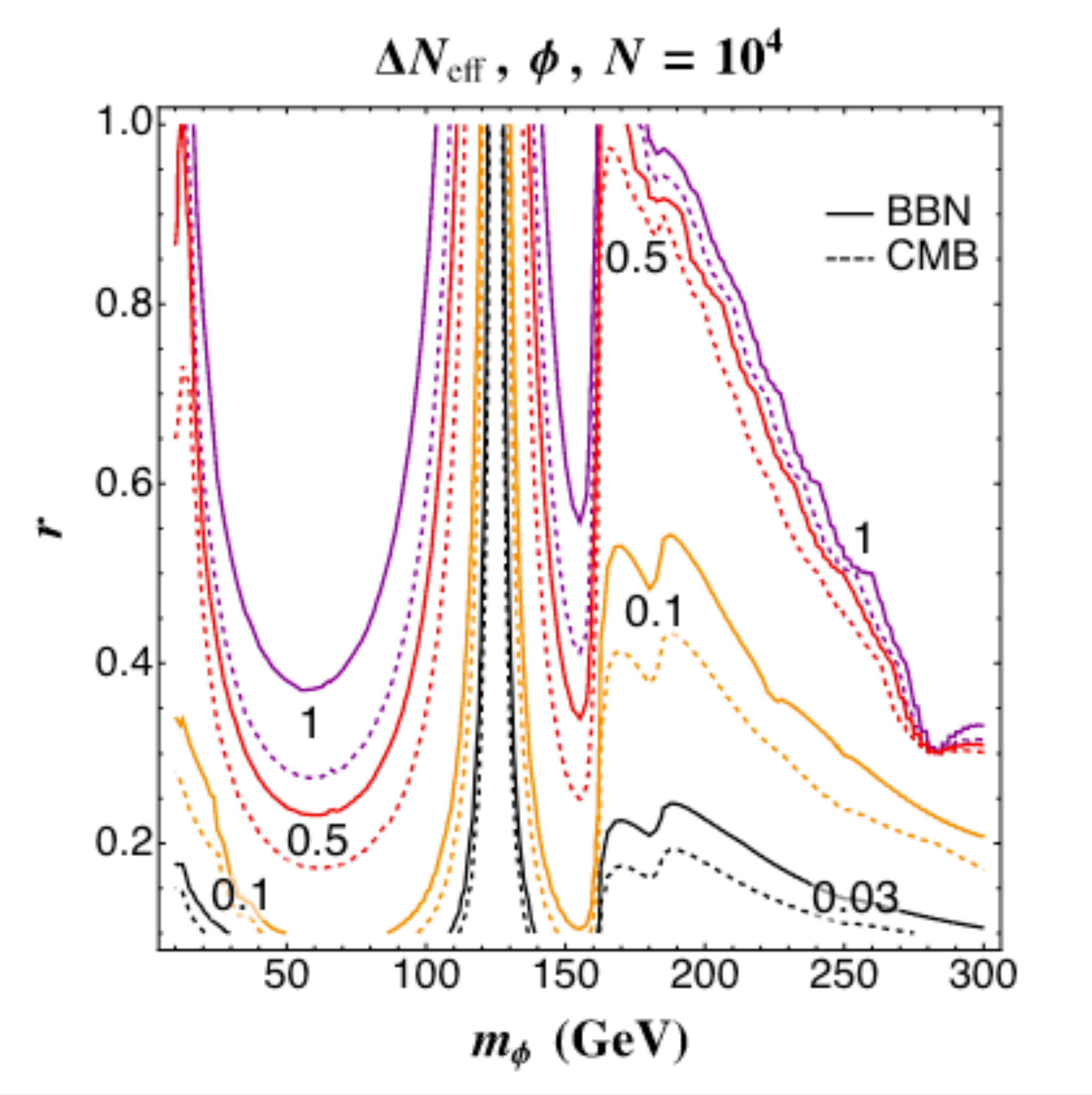


$$\sum_{f=1}^{3} m_{\nu,\rm SM}^{(f)} = 0.12 \text{ eV} \quad \& \text{ Normal Hierarchy}$$

The bounds will depends on the choice of SM Neutrino mass

N-naturalness Cosmology

Arkani-Hamed+, arXiv:1607.06821



N-Neutrinos

(WDMs)

Contributes to

scale-dependent N_{eff}

Suppression of
Matter power spectrum

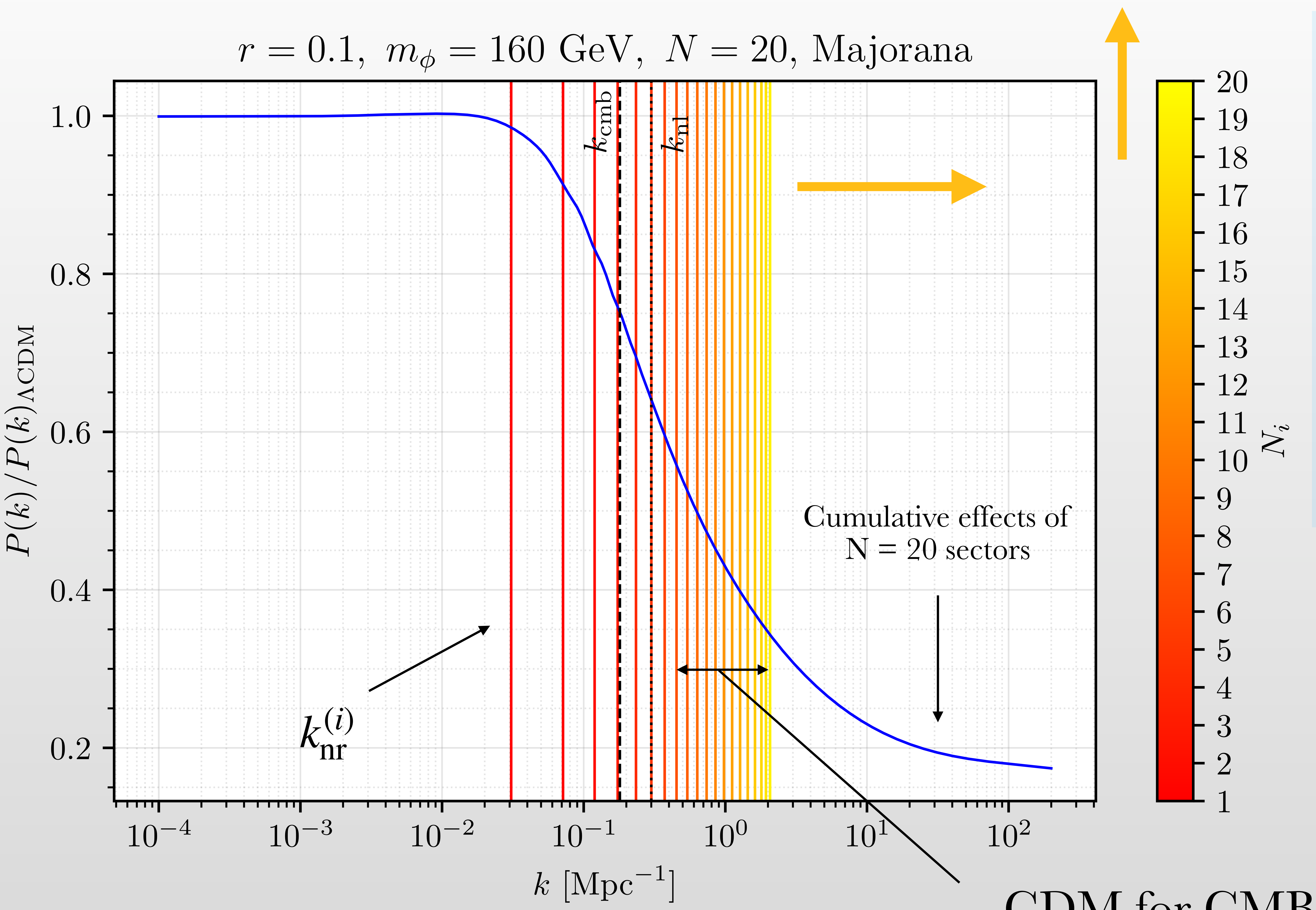
N-photons

(DR)

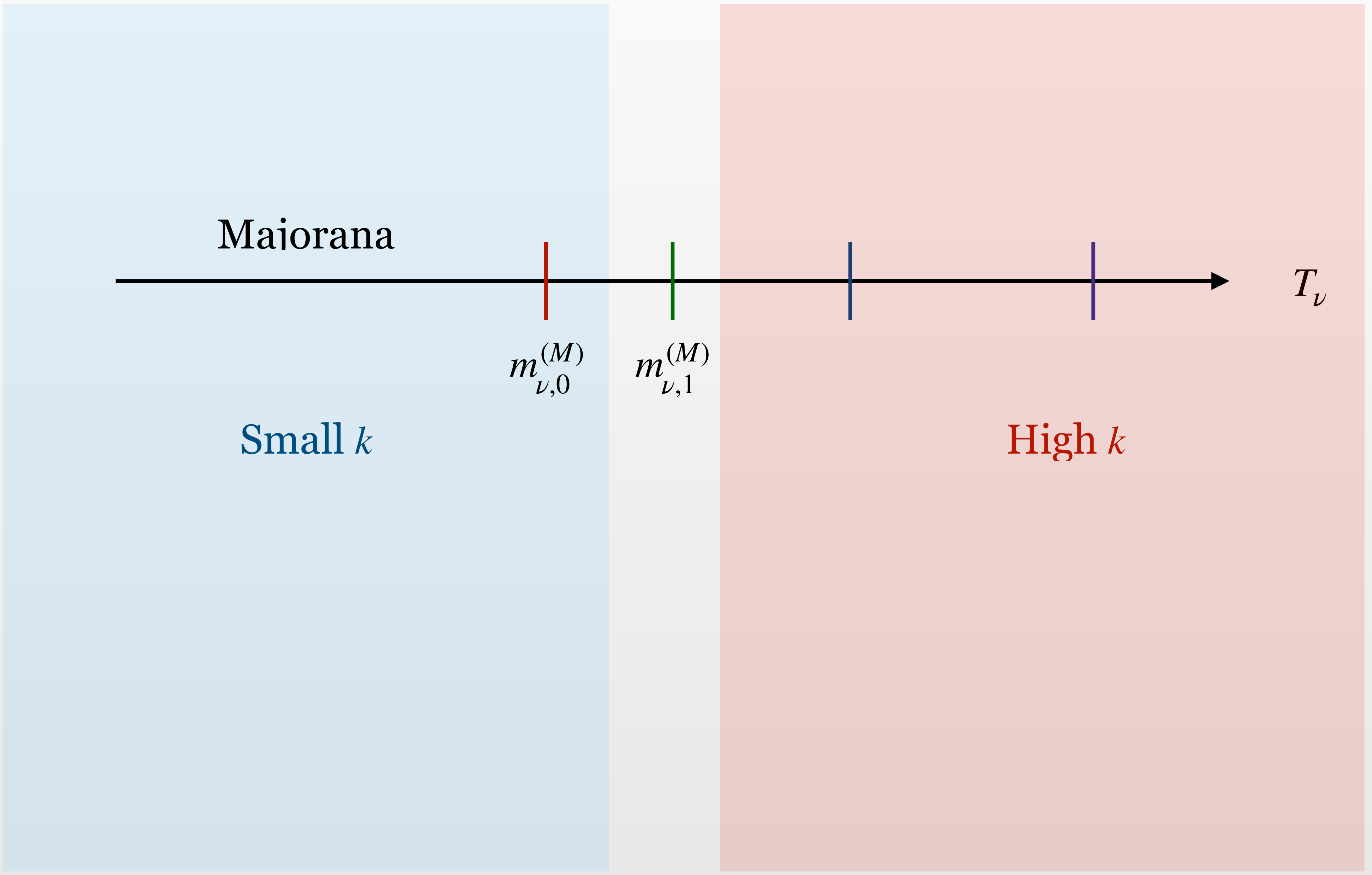
Contributes to N_{eff}

Assuming Baryon asymmetry for N>0 sectors for simplicity

Matter power spectrum suppression for N-Neutrino



CDM for CMB but WDM for Ly-α

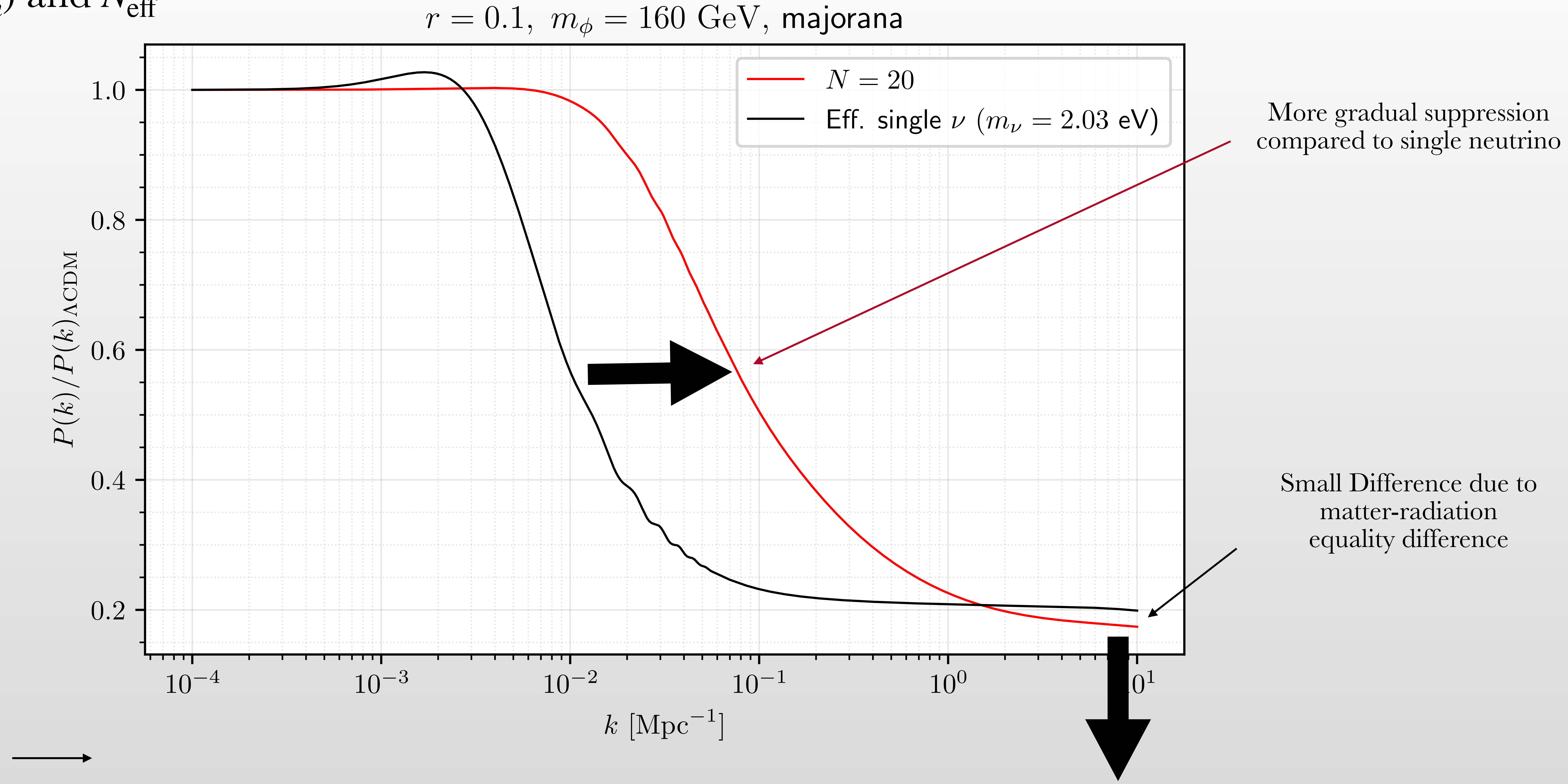


Cosmological observations are sensitive to finite number of lower rungs of the Neutrino tower

Heavier states can be approximated as CDM

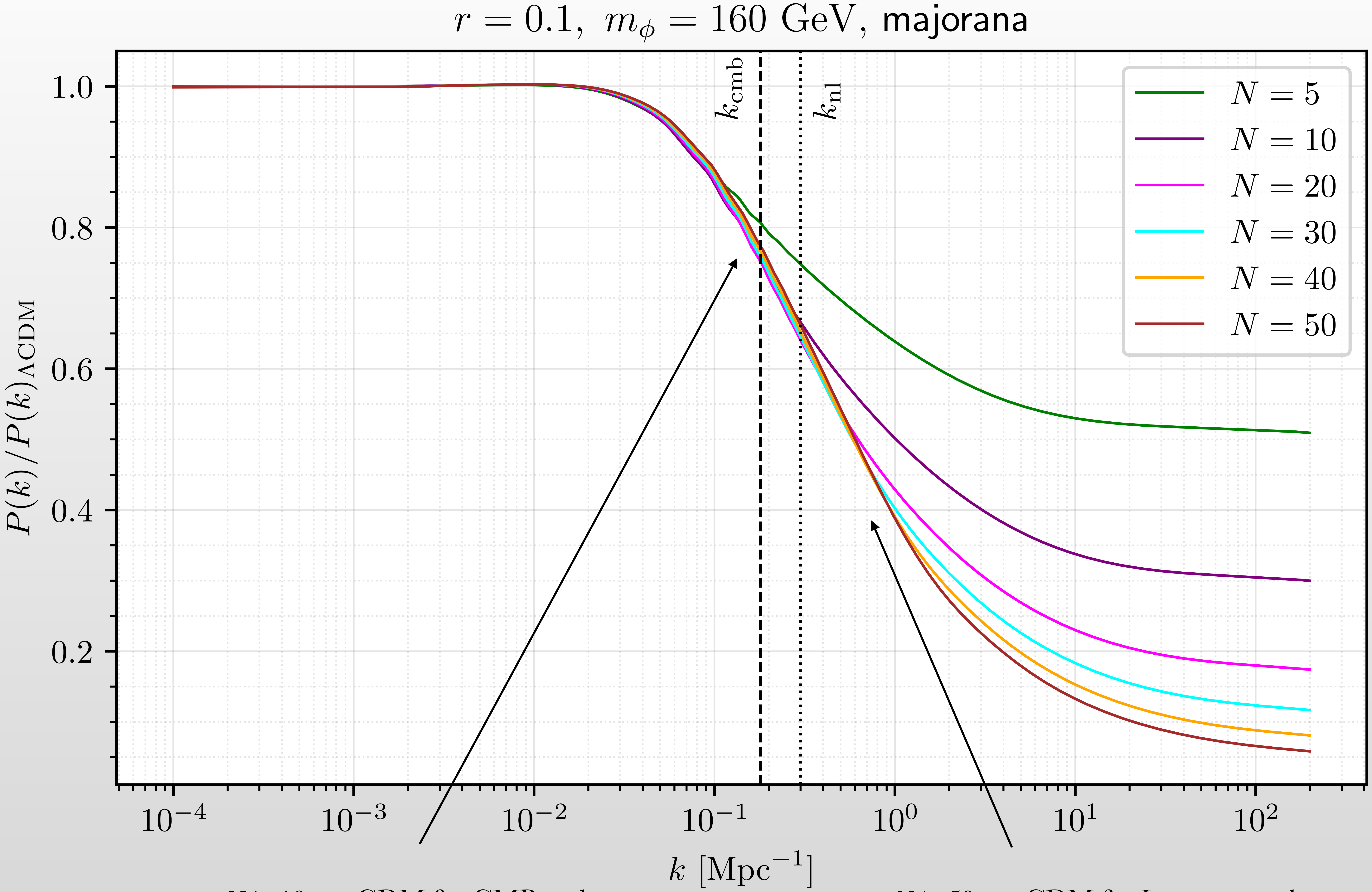
N neutrino vs 1 neutrino

Same $\boldsymbol{\Omega}_\nu(\boldsymbol{\Omega}_m)$ and N_{eff}



k_{nr} and Ω_ν both increase with m_ν

Matter power spectrum suppression along N

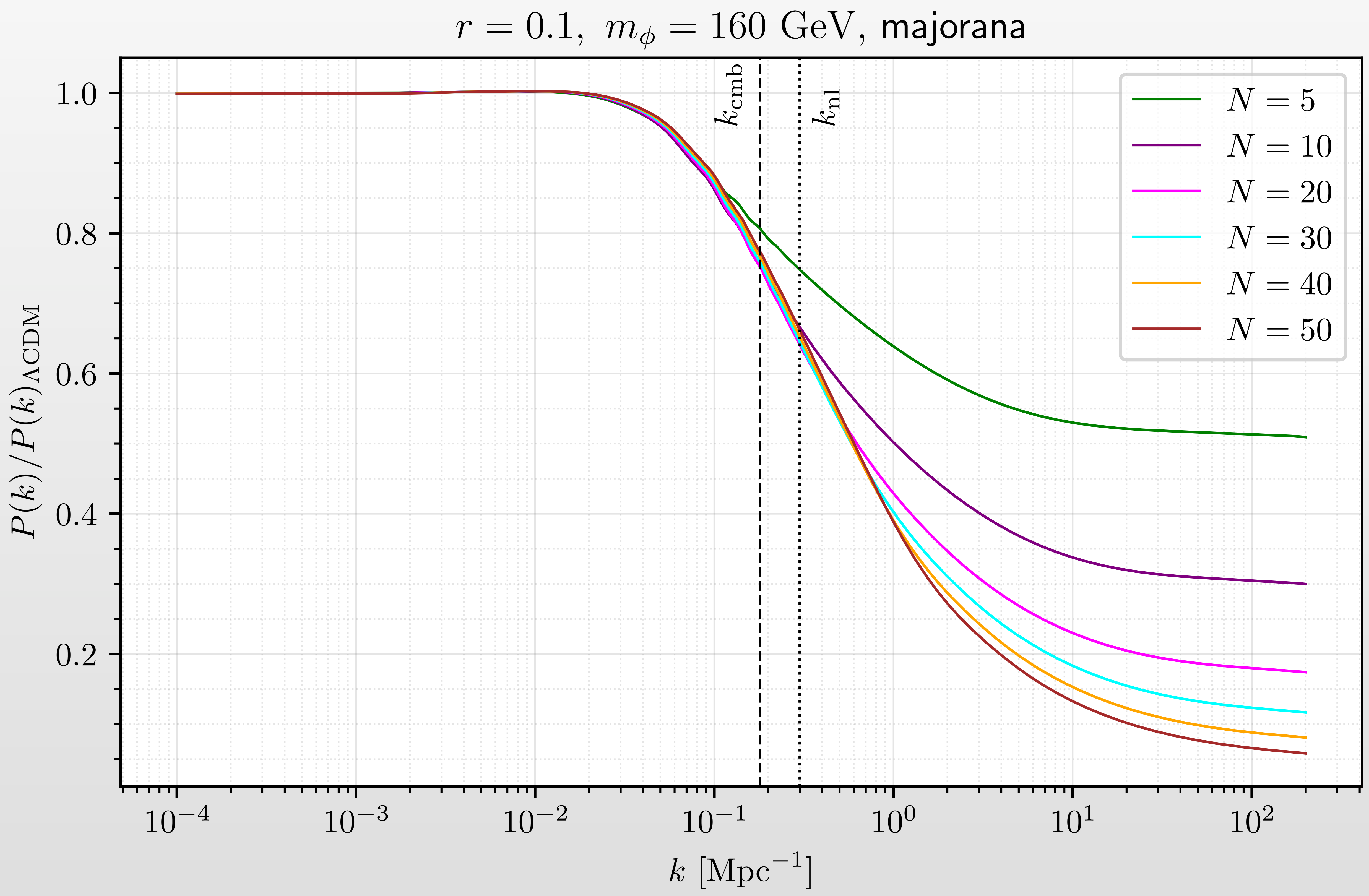


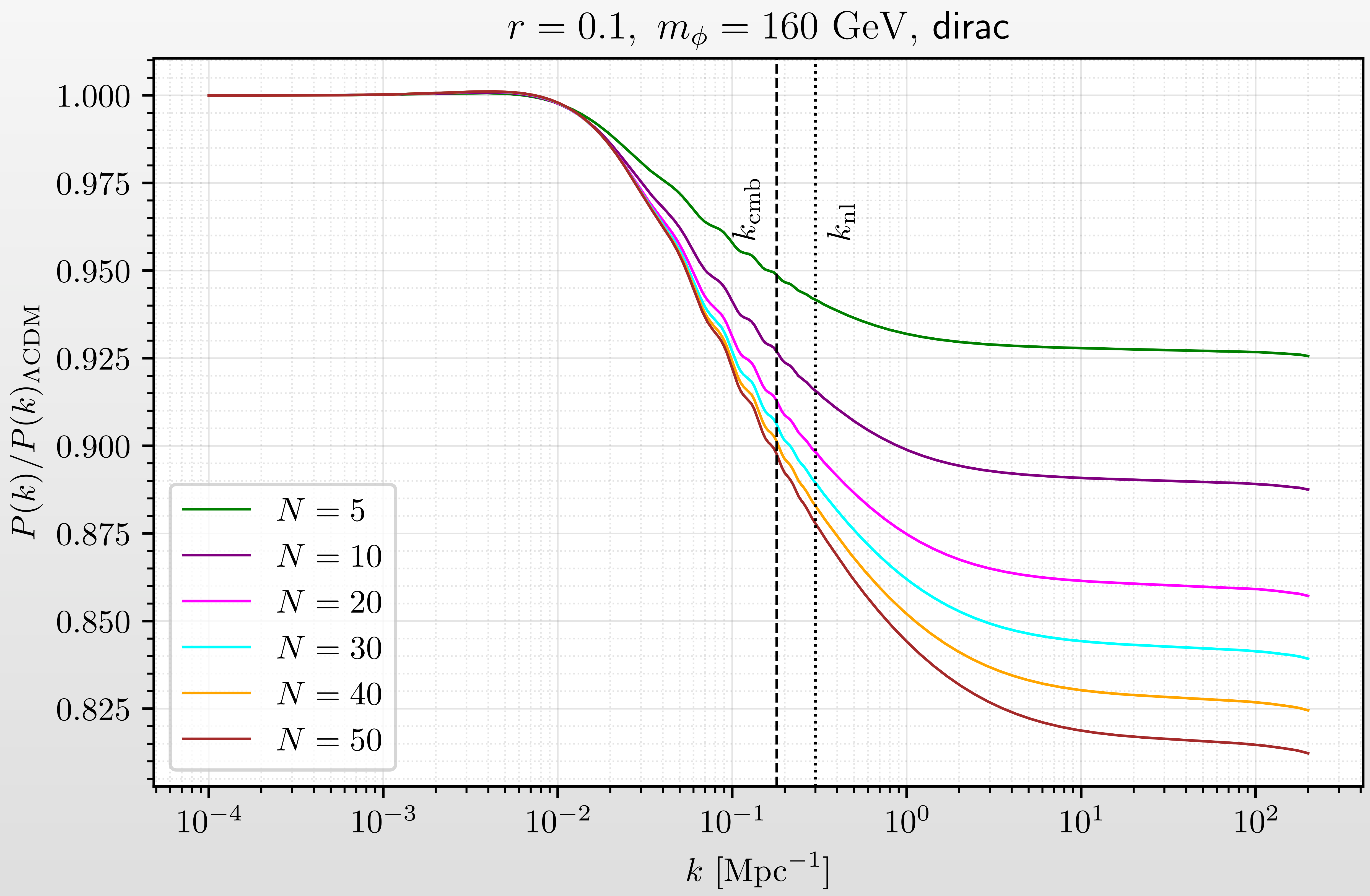
$N \gtrsim 10$ are CDM for CMB scale

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

Same Ω_m and N_{eff} for all models

Matter power spectrum suppression along N

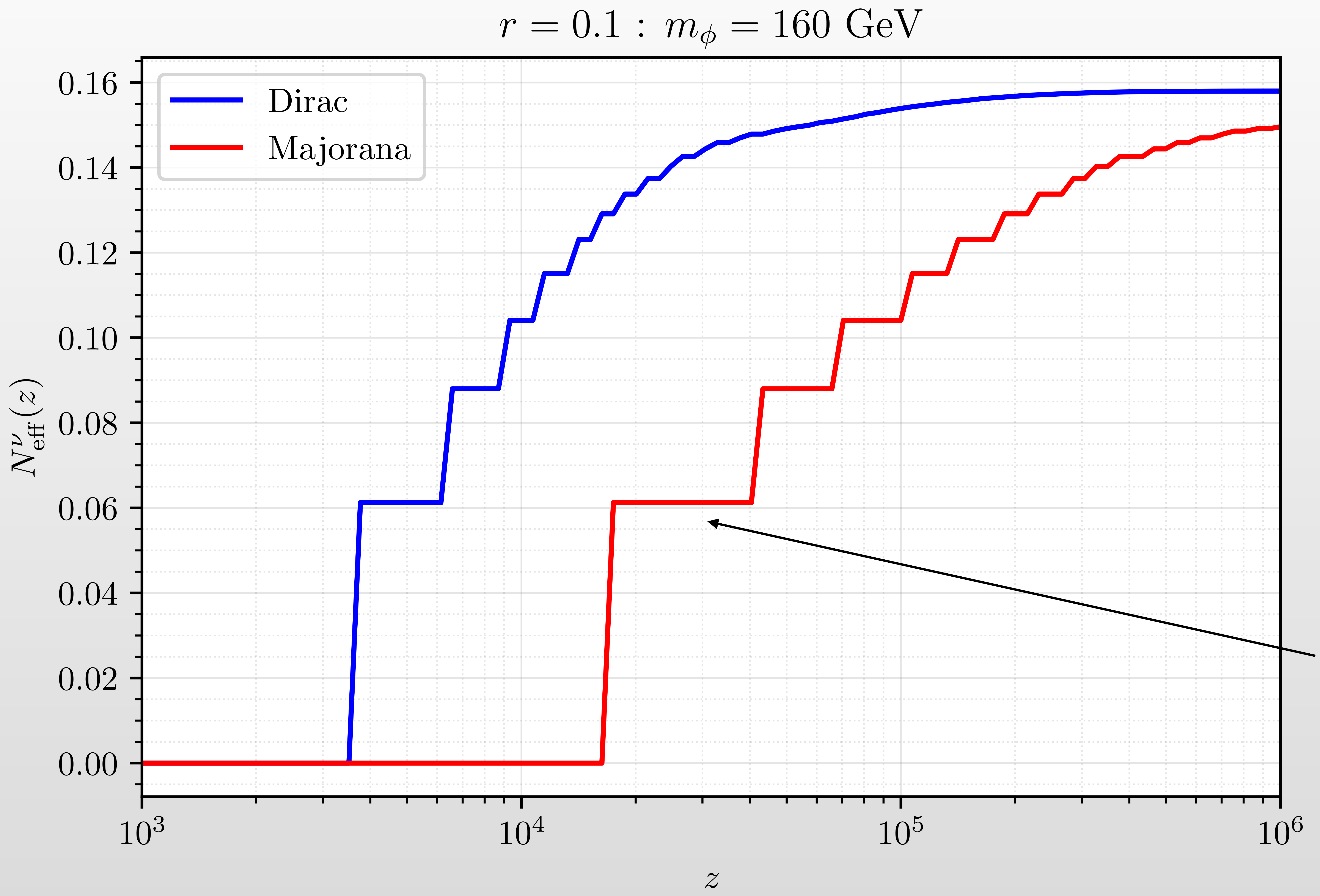




$m_{\nu,i}^{\mathrm{Majorana}} \sim i$

$m_{\nu,i}^{\mathrm{dirac}} \sim i^{1/2}$

Effects of Neutrino tower on N_{eff}



Steps are for individual ν states going relativistic

Tower of neutrino produce scale dependent N_{eff}

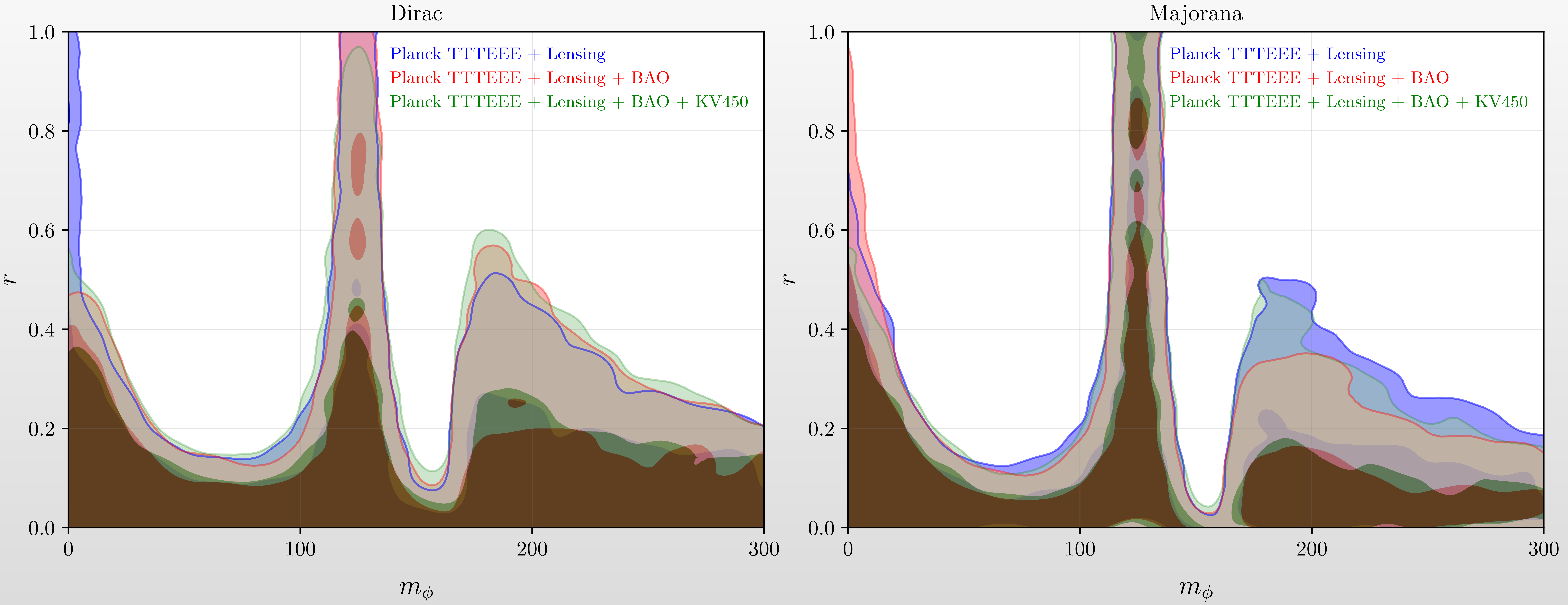
MCMC constraints: Role of Neutrinos

Constraint from N-photons

Neutrinos strengthen the constraints on the Model

Combined constraint from N-photons & N-Neutrinos

MCMC constraints: Role of LSS dataset



LSS strengthen the constraint

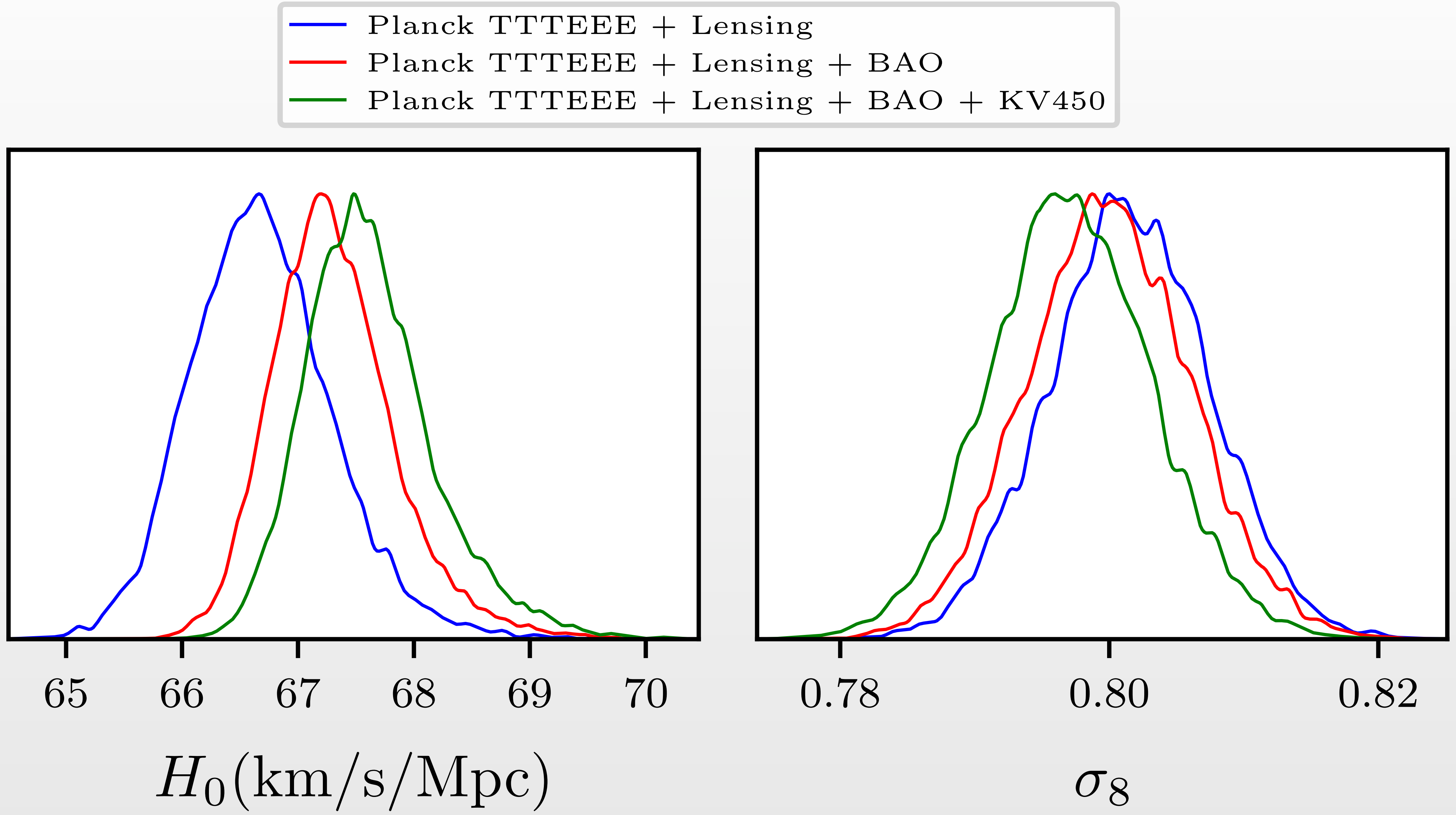
Estimated Constraints : e-BOSS (compressed) Lyman-α

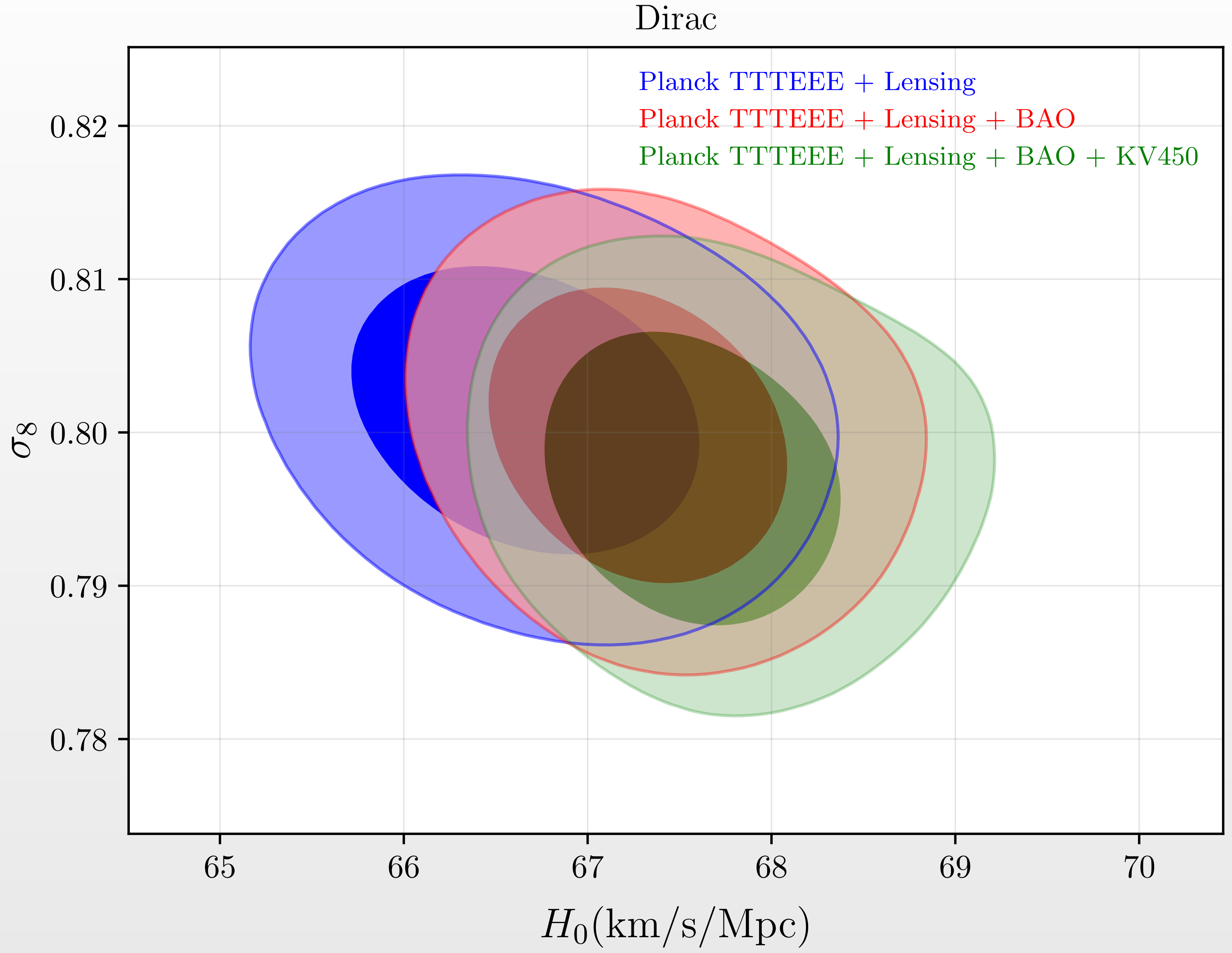
Preliminary

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

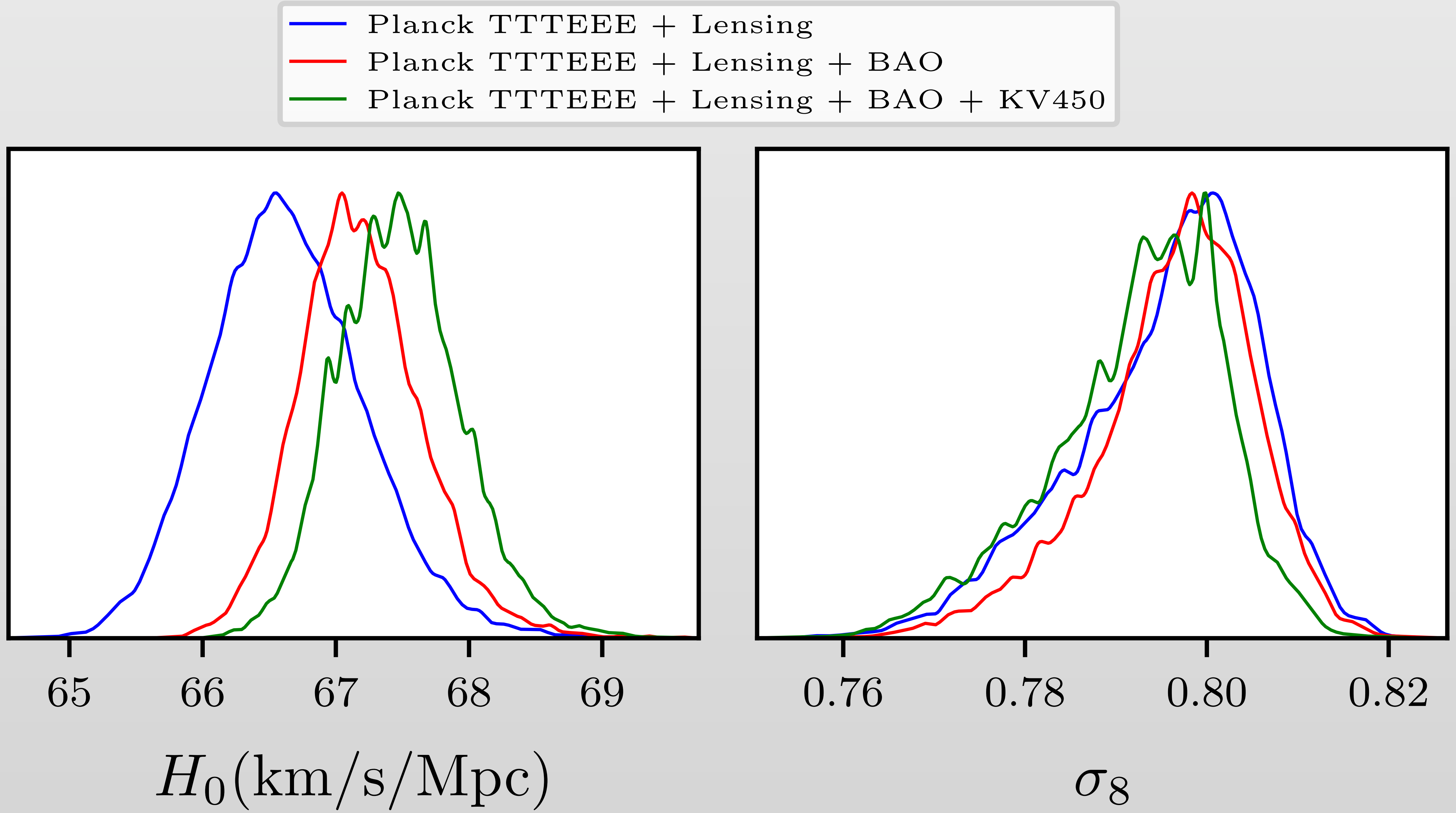
Neutrino tower on $\sigma 8$ tension

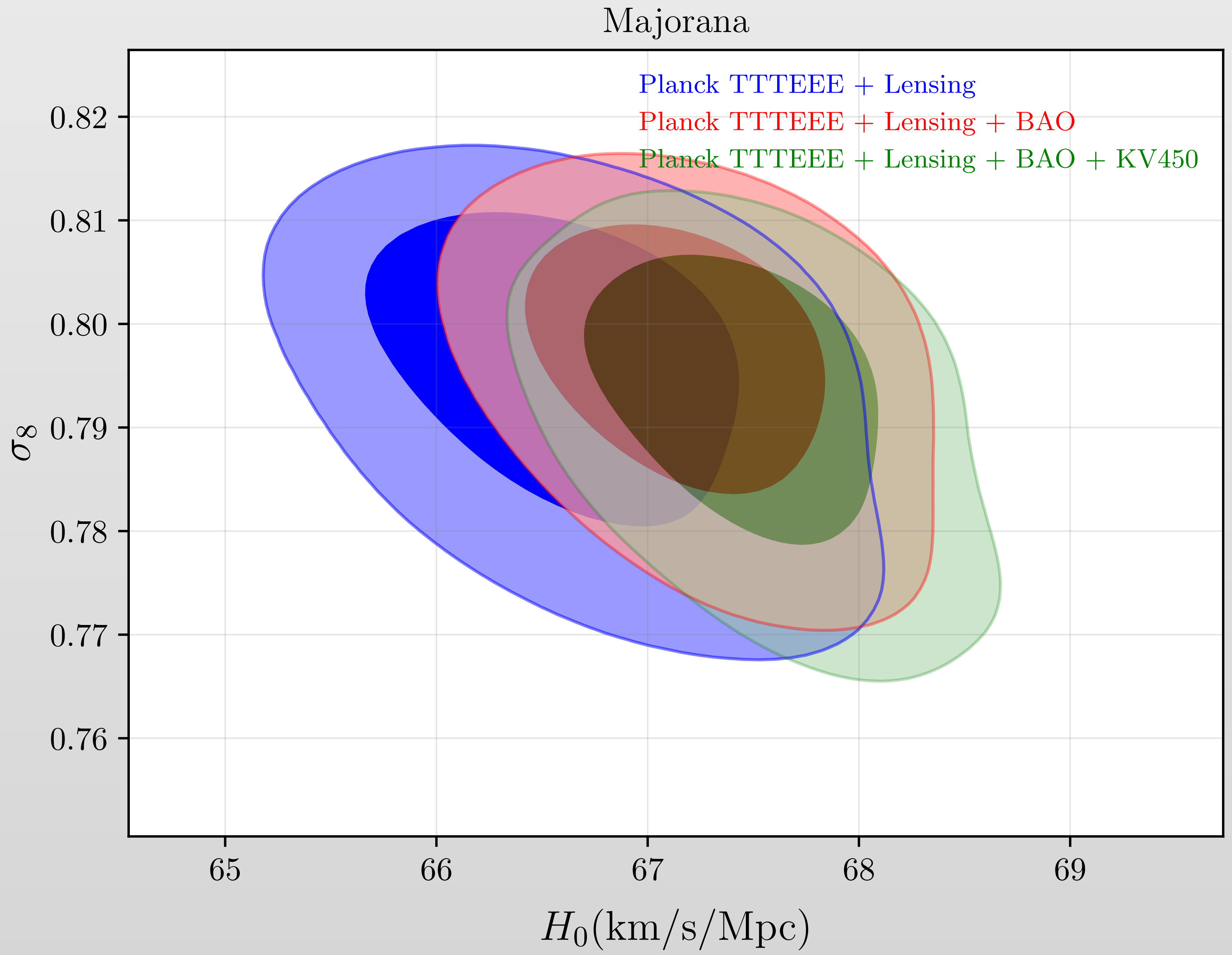
Dirac





Majorana





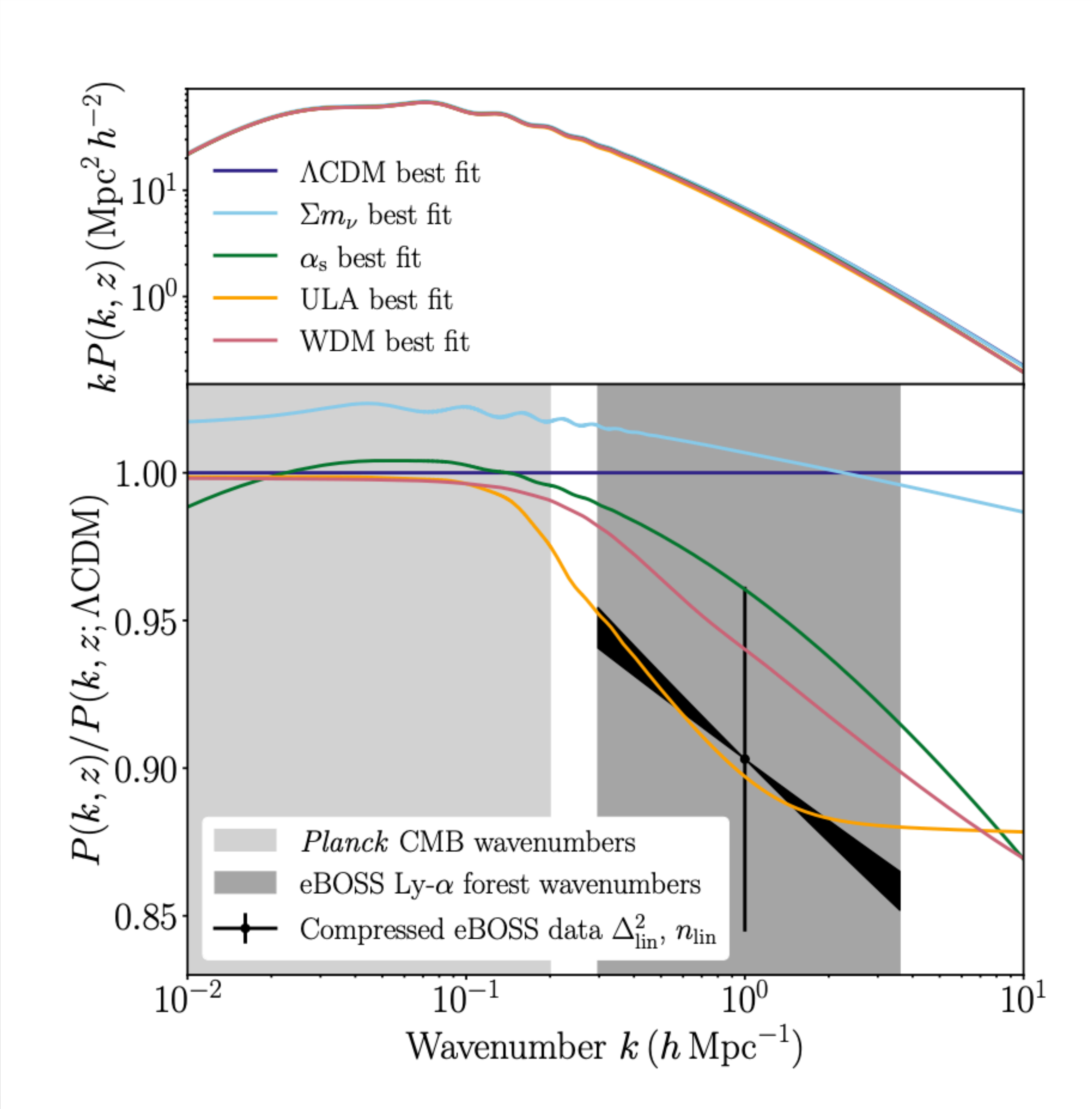
Conclusion

- The decoupling profile for a tower of neutrinos cannot be captured by a single neutrino species.
- 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.
- Majorana neutrino in N-Naturalness is strongly constrained by LSS & Lyman-α data.

Open questions!

- Can multiple neutrinos be used to reconcile ν mass measurement from Planck +BAO (no ν mass from large scale) with potential suppression observed in the small scale measurements?
- Prospect of small scale structure measurements to probe multiple neutrino/WDM scenarios?
- Other models that also predicts multiple neutrinos/WDM?

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



Rogers+,arXiv:2311.16377

Effects on CMB anisotropy