# N-Naturalness Cosmology


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WORK IN PROGRESS

# Introduction

Precision Cosmology

Probing nuanced Phenomenological Model

Simplified Models

Probing Interactions/Distributions of dark sector species

Atomic DM

N-naturalness

Dark QCD

....

Extra relativistic d.o.f

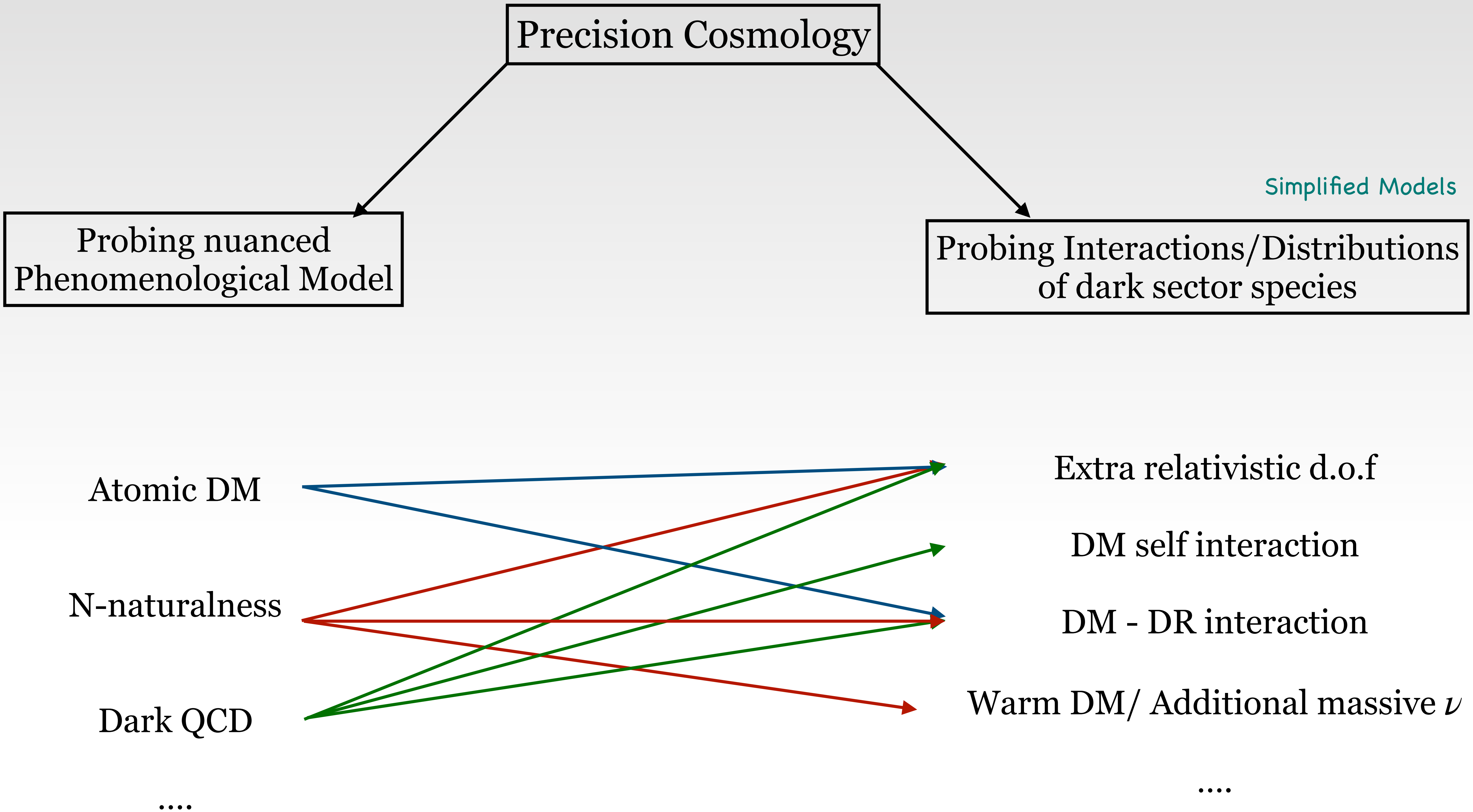
DM self interaction

DM - DR interaction

Warm DM/ Additional massive $\nu$

....

# Introduction



# Introduction

Precision Cosmology

Probing nuanced Phenomenological Model

Simplified Models

Probing Interactions/Distributions of cosmological species

N-naturalness

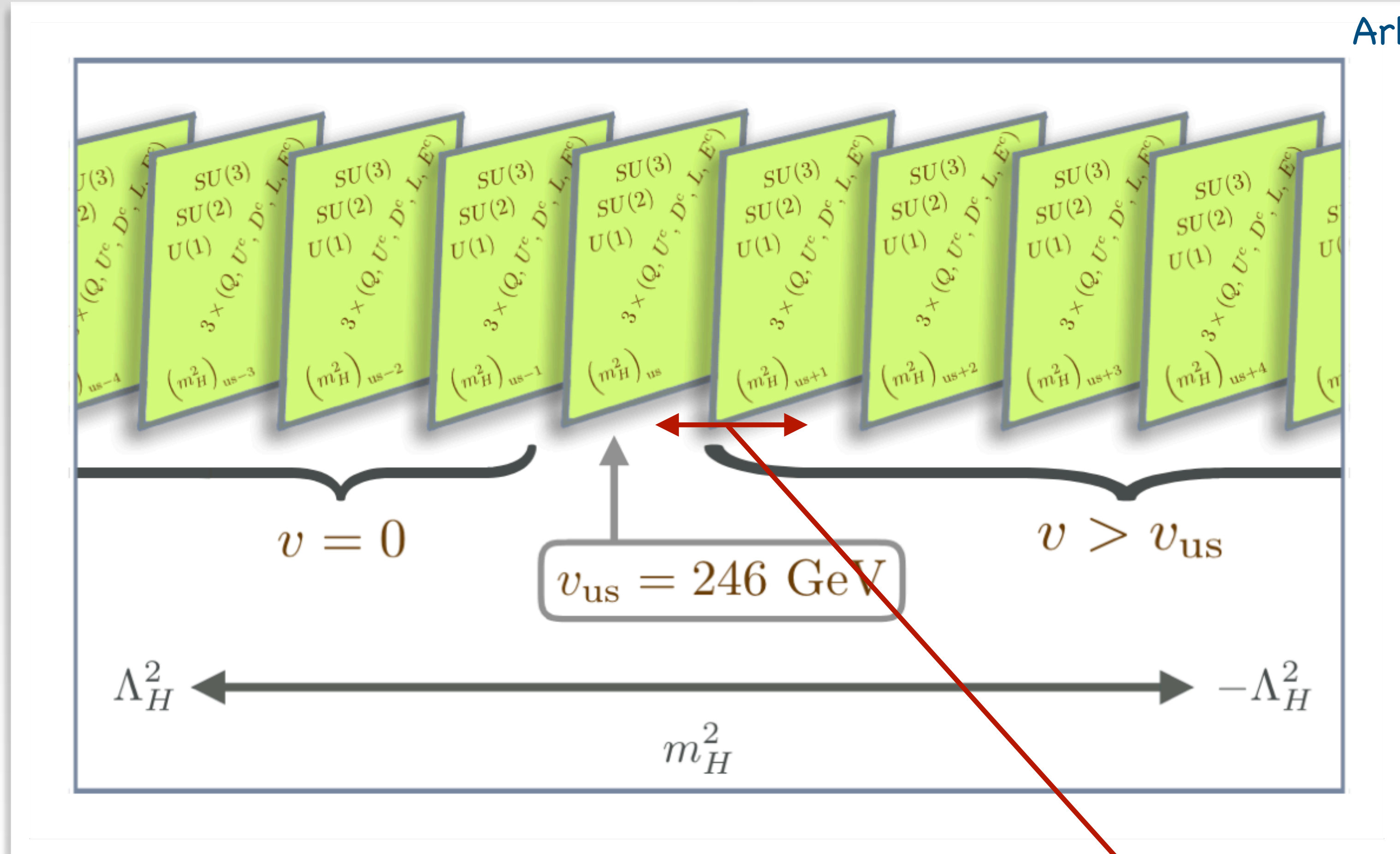
- Extra relativistic d.o.f
- Warm DM/ Additional massive $\nu$
- DM-DR interaction

Solution to the hierarchy problem

A Tower of massive neutrino states with gradually increasing $m_\nu$ and decreasing $T_\nu$

# N-Naturalness : N-copies of SM

Arkani-Hamed+, arXiv:1607.06821




High $N \sim 10^4$ naturally push the cutoff to $\sim 10$ TeV solving the Little hierarchy problem

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

$$m_{h,i} = m_h^{SM}\sqrt{\frac{2i+r}{r}}, \qquad v_i = v^{SM}\sqrt{\frac{2i+r}{r}}.$$

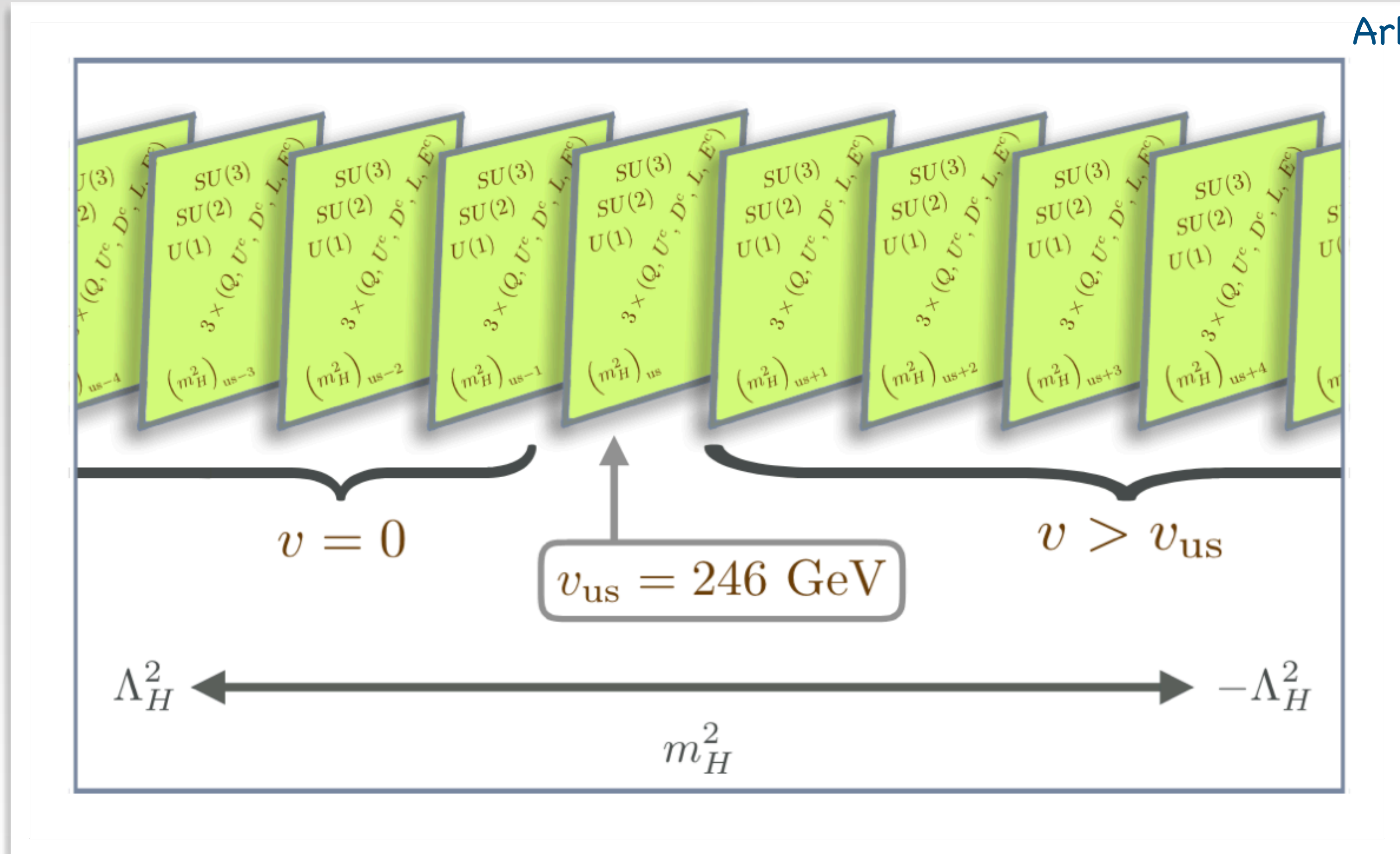
$$m_{f,i} = m_f^{SM}\frac{v_i}{v^{SM}}, \qquad m_{V,i} = m_V^{SM}\frac{v_i}{v^{SM}}.$$

$$\Delta m_H^2 = -\frac{2\Lambda_H^2}{N}r$$

Mass splitting increases with increasing $r$

# N-Naturalness : Reheating

Arkani-Hamed+, arXiv:1607.06821




$a \sim 1\text{MeV}$

No collider signal

Post inflationary reheating : Reheaton $\phi$ couples universally to N sectors

Dynamical mechanism ensures that SM sector is predominantly reheated

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

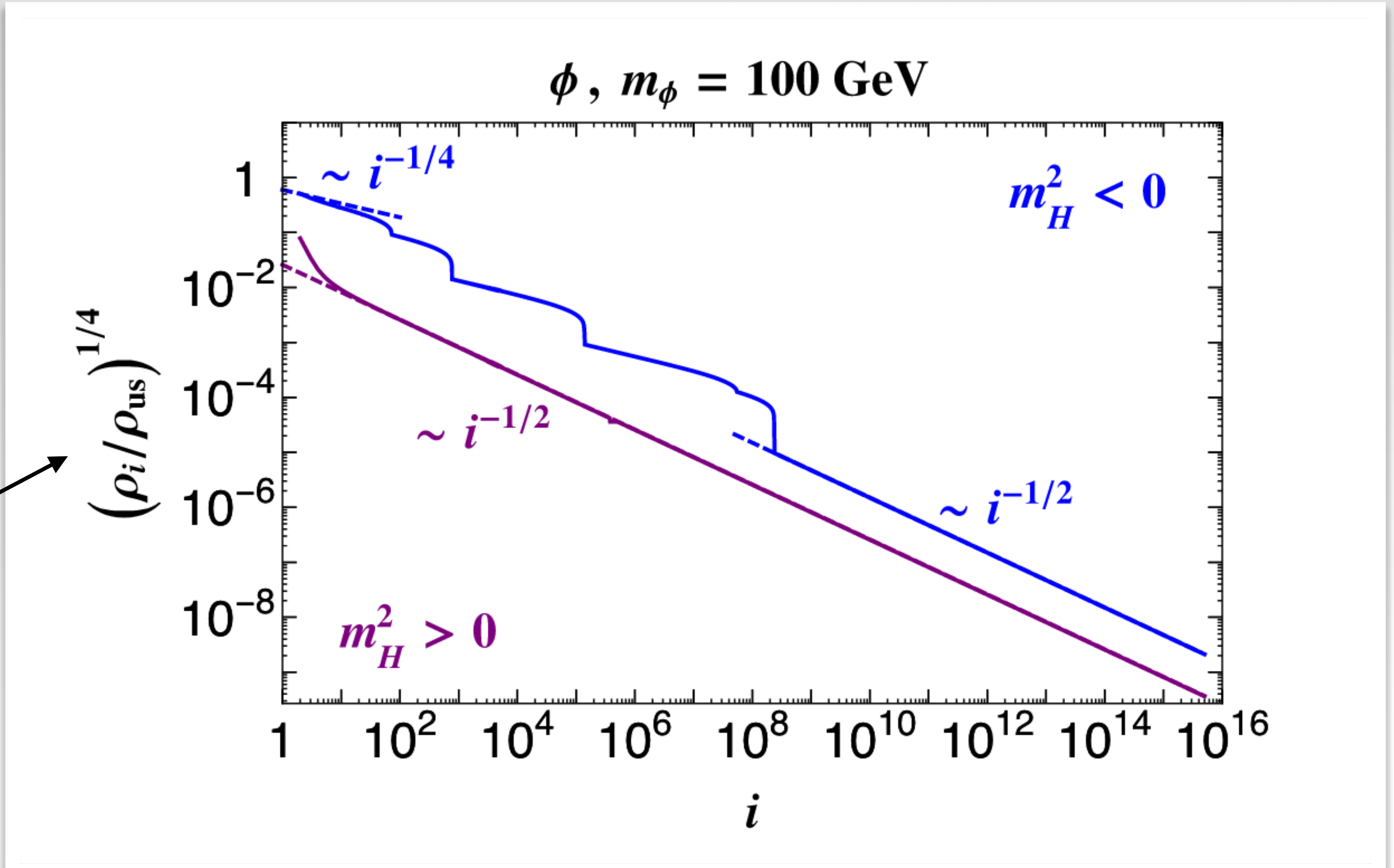
$$\Gamma_{m_H^2<0} \sim \frac{1}{m_{h_i}^2}$$

$$\Gamma_{m_H^2>0} \sim \frac{1}{m_{H_i}^4}$$

Reheaton predominantly decays (reheats) the sector with the lightest negative Higgs mass (SM sector)

# N-Naturalness : Reheating →Temperature of N Sectors

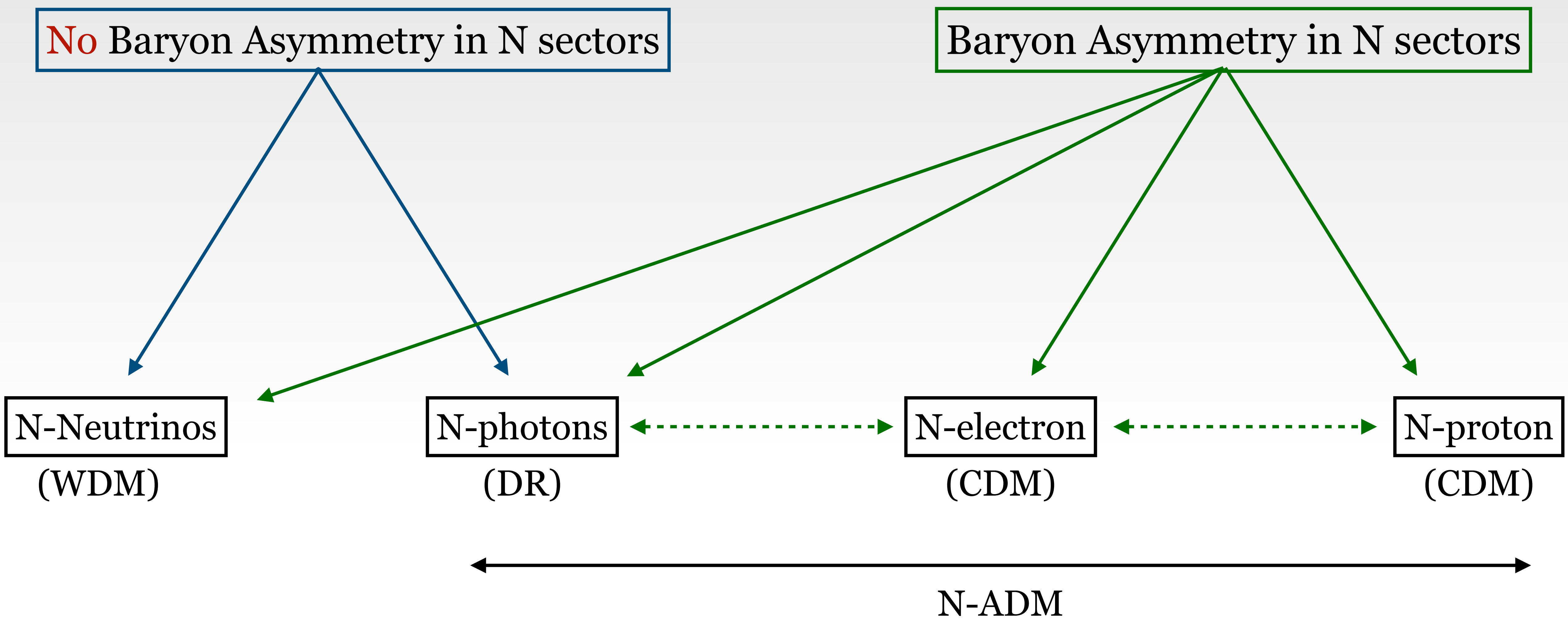
$\sim \frac{T_i}{T_{SM}}$




Arkani-Hamed+, arXiv:1607.06821

Ignoring $m_H^2 > 0$ sectors (suppressed) for the current analysis

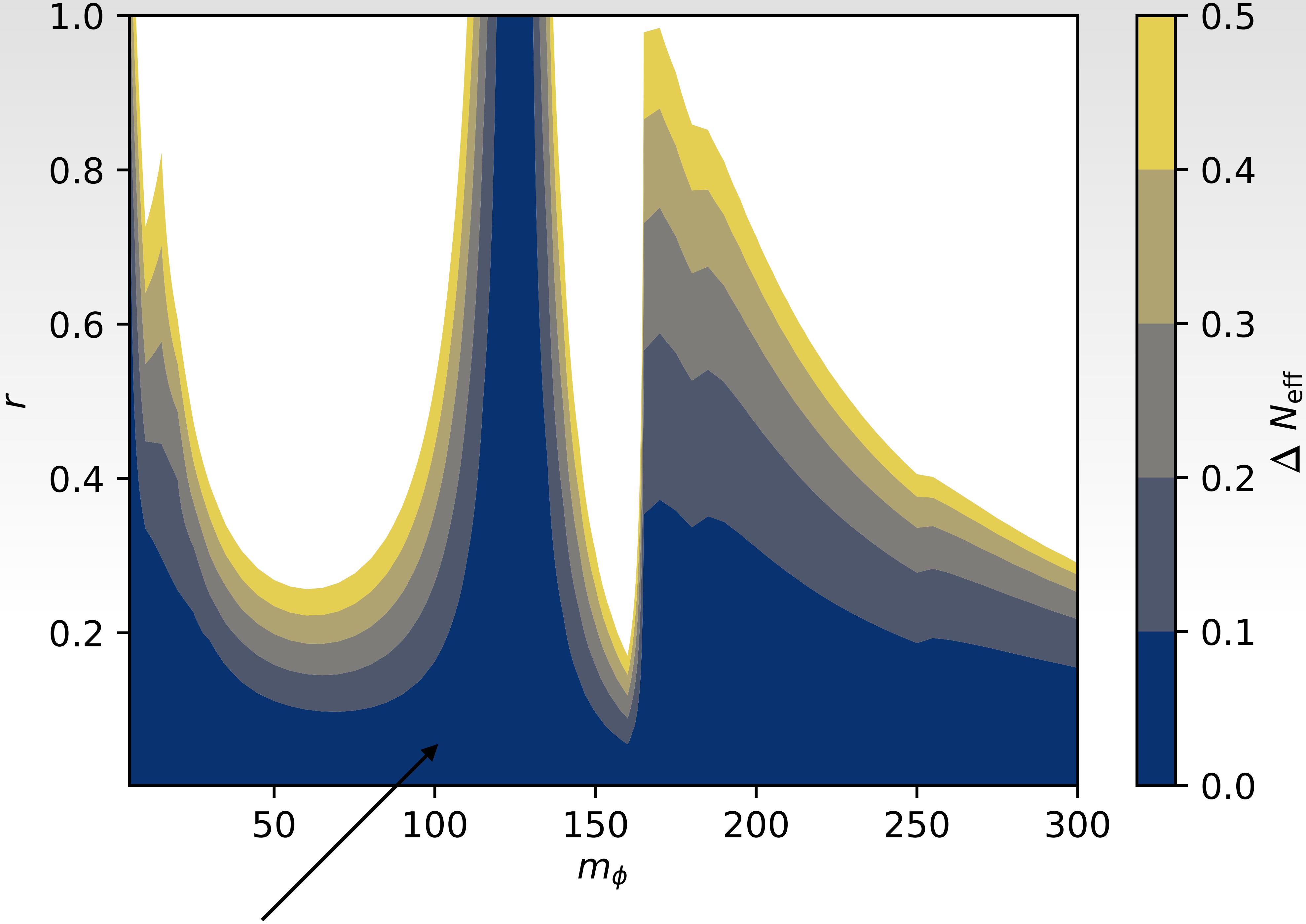
# N-naturalness Cosmology




Choi+, arXiv:1804.10180
Banerjee+, arXiv:1612.07126

Preliminary

# Photons in N-Naturalness




Resonant Higgs production

Assumption/Simplification : Baryon symmetry in N sectors

# Neutrinos in N-Naturalness

A tower of neutrino states

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

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

The spectrum depends of SM neutrino masses

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

$$\Omega_{\nu,0}^{(\mathrm{Dir})} = \Omega_{\nu,0}^{(\mathrm{SM})} \sum_i \frac{v_i}{v_{\mathrm{SM}}} \left( \frac{T_i}{T_{\mathrm{SM}}} \right)^3 \sim N_\nu^{\frac{3}{4}}$$

$$\Omega_{\nu,0}^{(\mathrm{Maj})} = \Omega_{\nu,0}^{(\mathrm{SM})} \sum_i \left( \frac{v_i}{v_{\mathrm{SM}}} \right)^2 \left( \frac{T_i}{T_{\mathrm{SM}}} \right)^3 \sim N_\nu^{\frac{5}{4}}$$

# Cosmological anisotropies in N-Naturalness

Very computationally intensive to compute the phase space integral of neutrinos

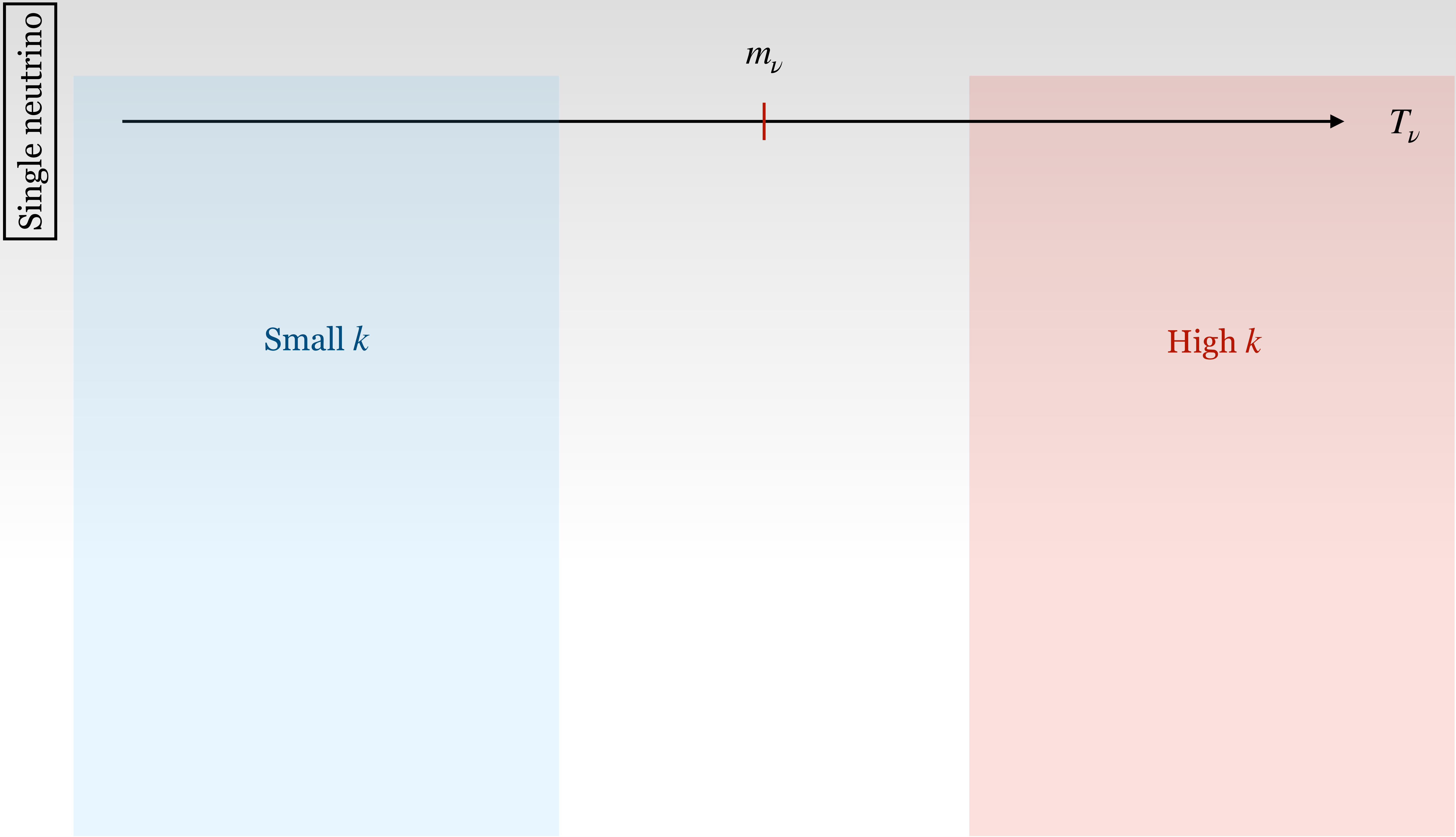
Default settings: 3 flavor , $N_s = 20$ ( $\equiv 60$ species) ~ 15 mins (24 core cluster node)

Simplification: Degenerate masses for neutrinos + Reduced precision of phase space integrations

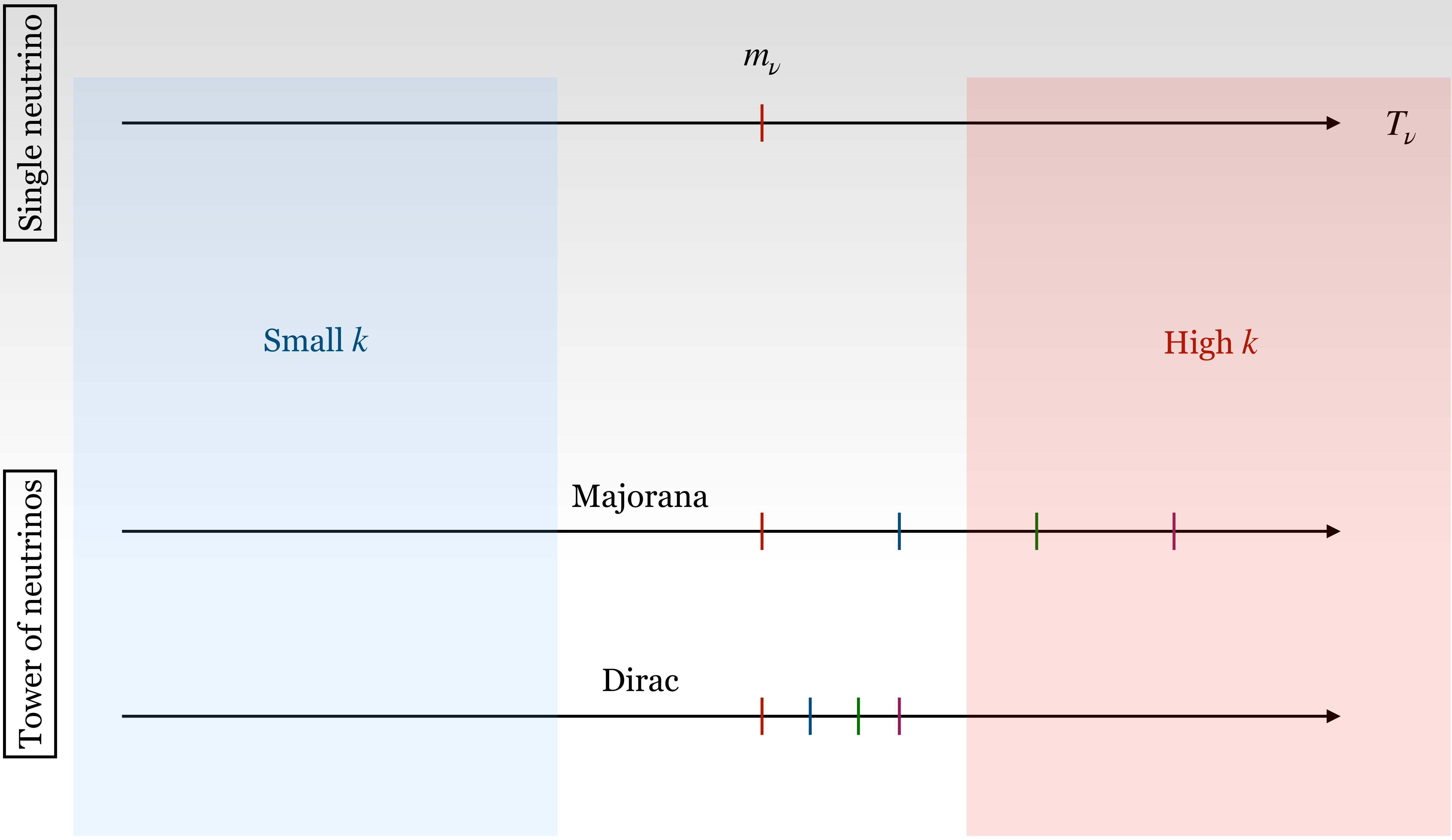
Degenerate Neutrinos: 3 flavor (average mass) , $N_s = 20$ ~ 1 min (24 core cluster node)

More about speed later….

# Physics of Tower of Neutrino states



# Physics of Tower of Neutrino states




Heavier sectors can be included by adjusting the $\Omega_{\rm cdm}$

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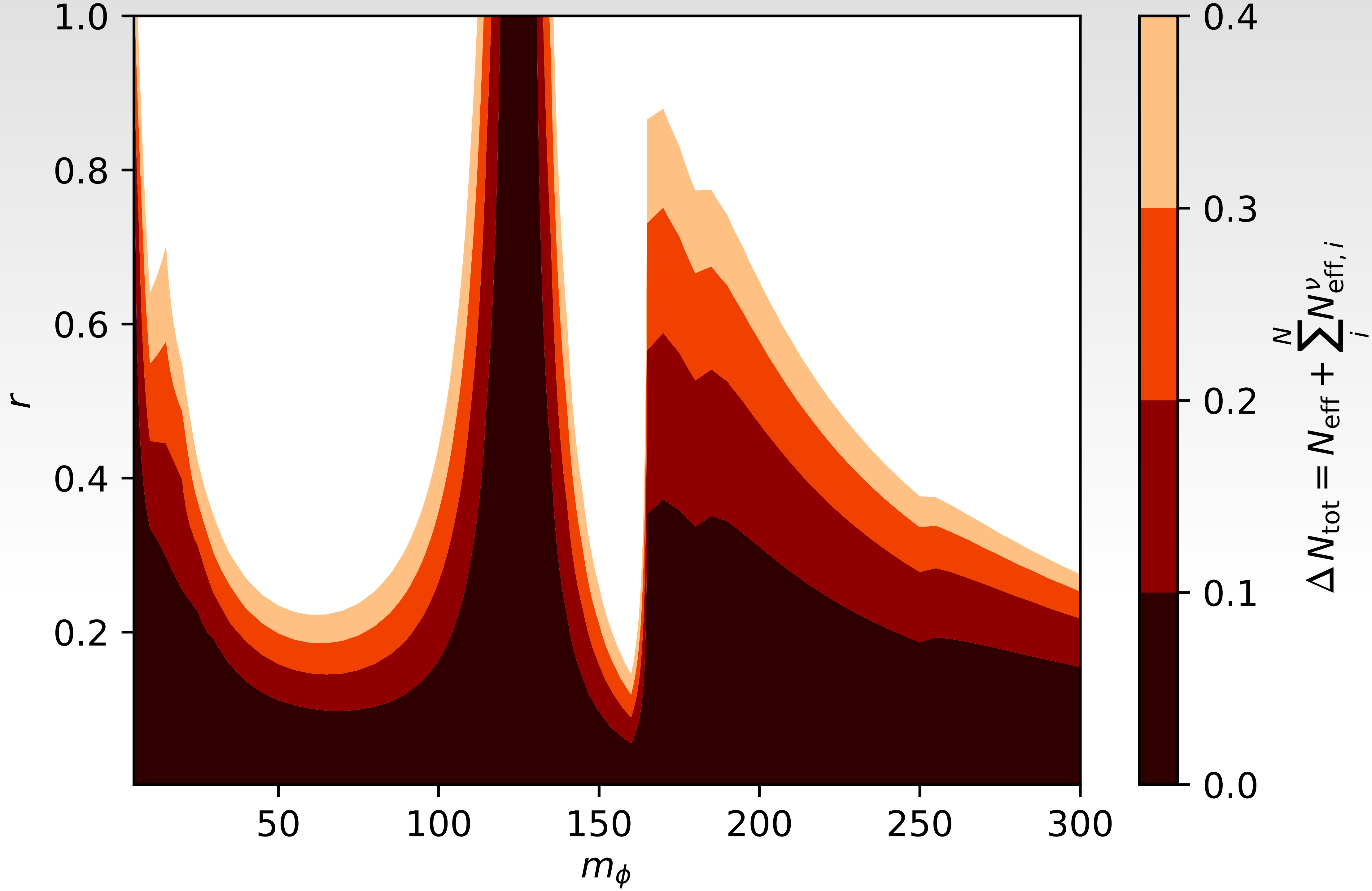
# $N_{\rm eff}$ from N - Neutrinos



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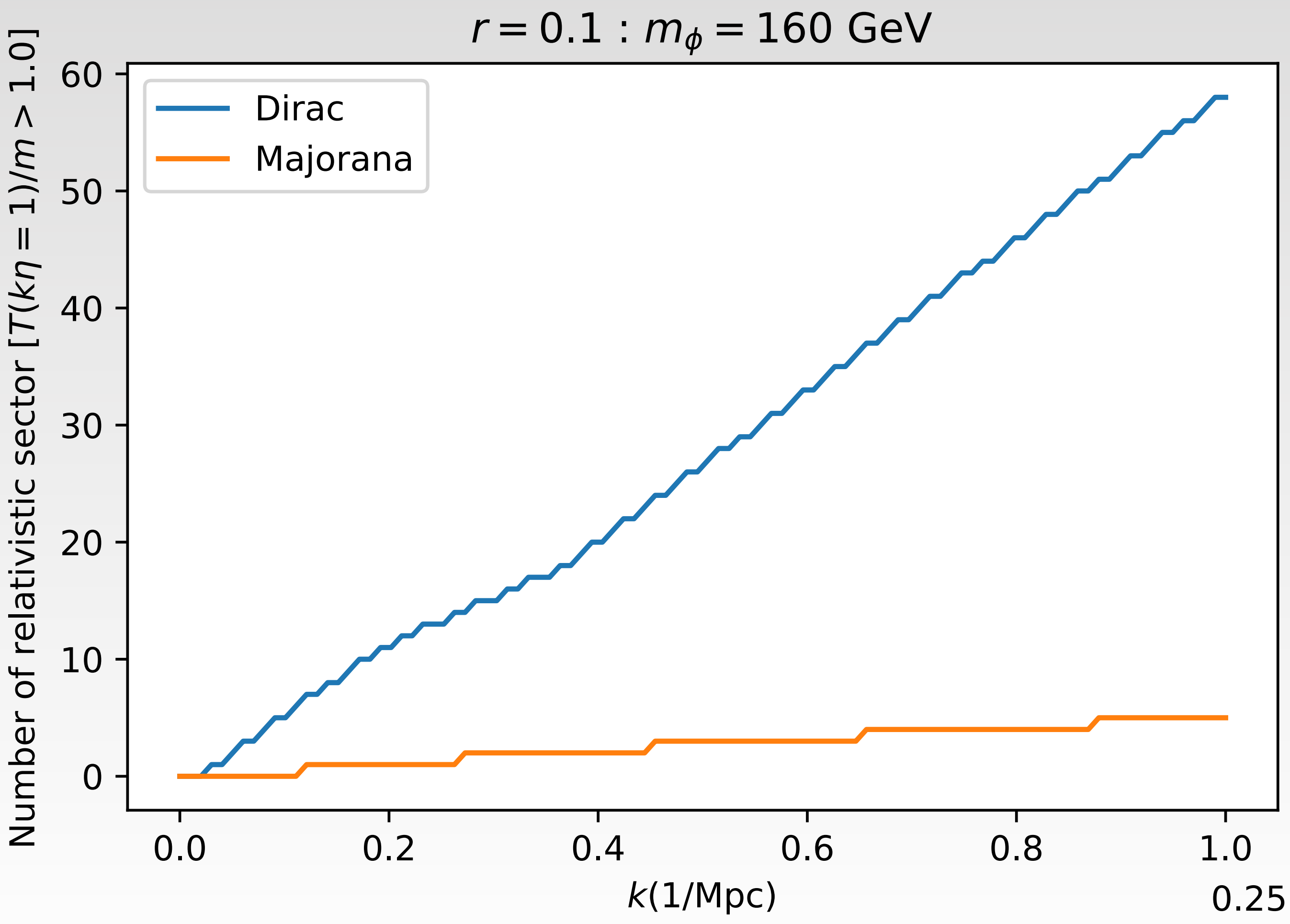
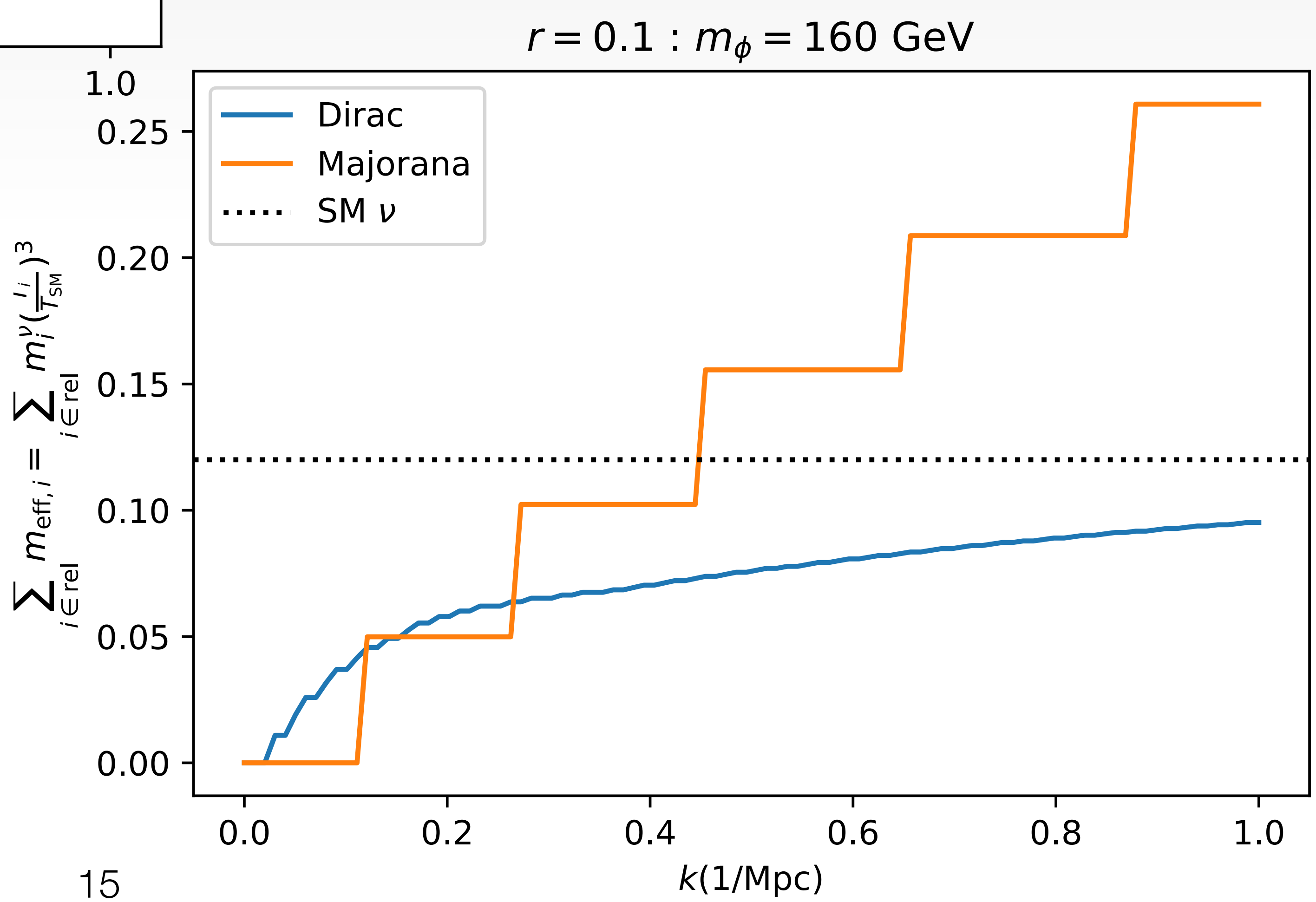
# Relativistic neutrino Sectors




$$\frac{T(\eta)\,|_{k\eta=1}}{m_i} > 1$$

Condition for relativistic sector

$$\sum_{i\in\mathrm{rel}} m_{\mathrm{eff},i} = \sum_{i\in\mathrm{rel}} m_i^{\nu}\left(\frac{T_i}{T_{\mathrm{SM}}}\right)^3$$




$$\Omega_\nu h^2 = \frac{m_{\mathrm{eff}}}{93.14\ \mathrm{eV}}$$

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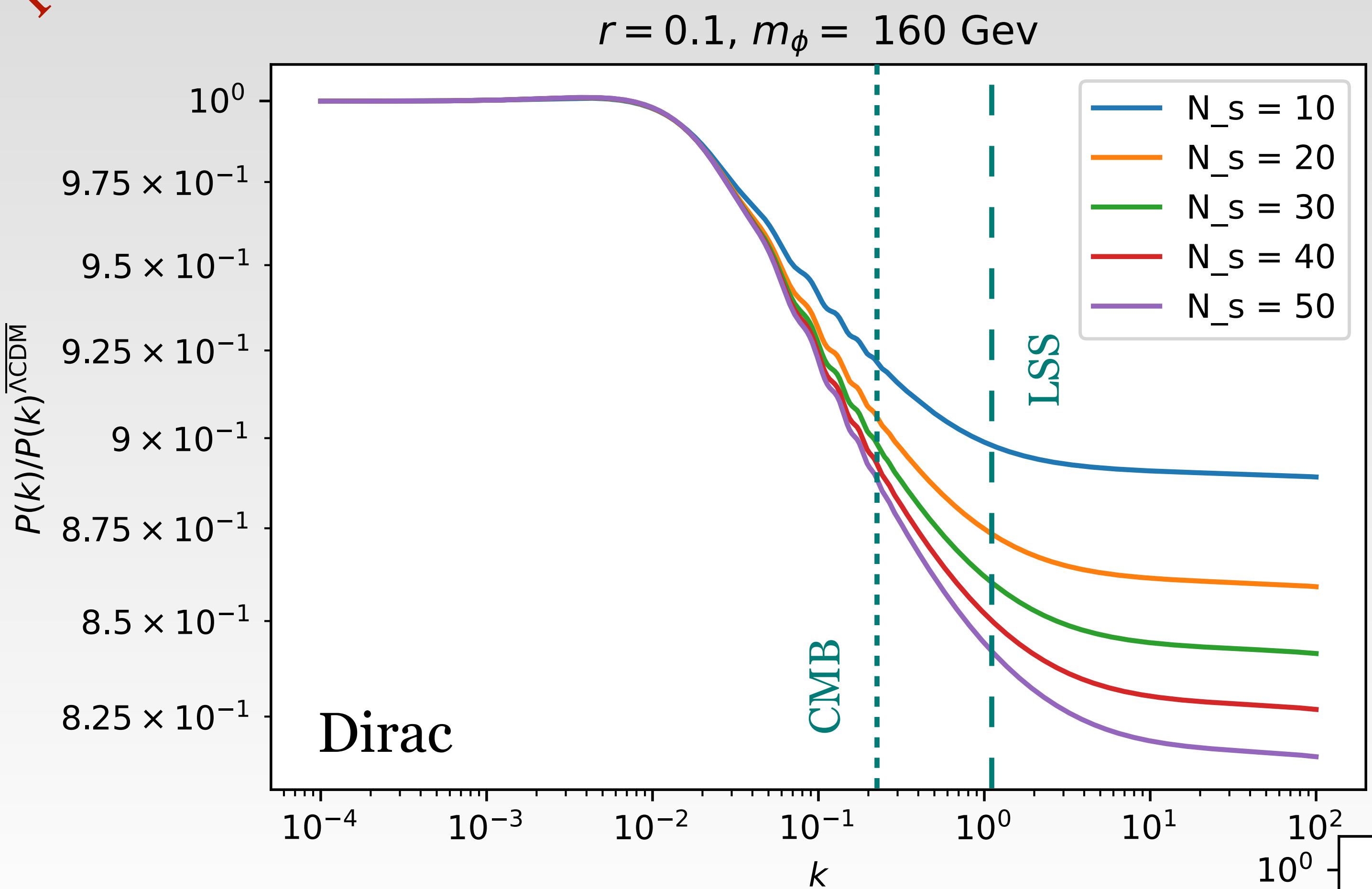
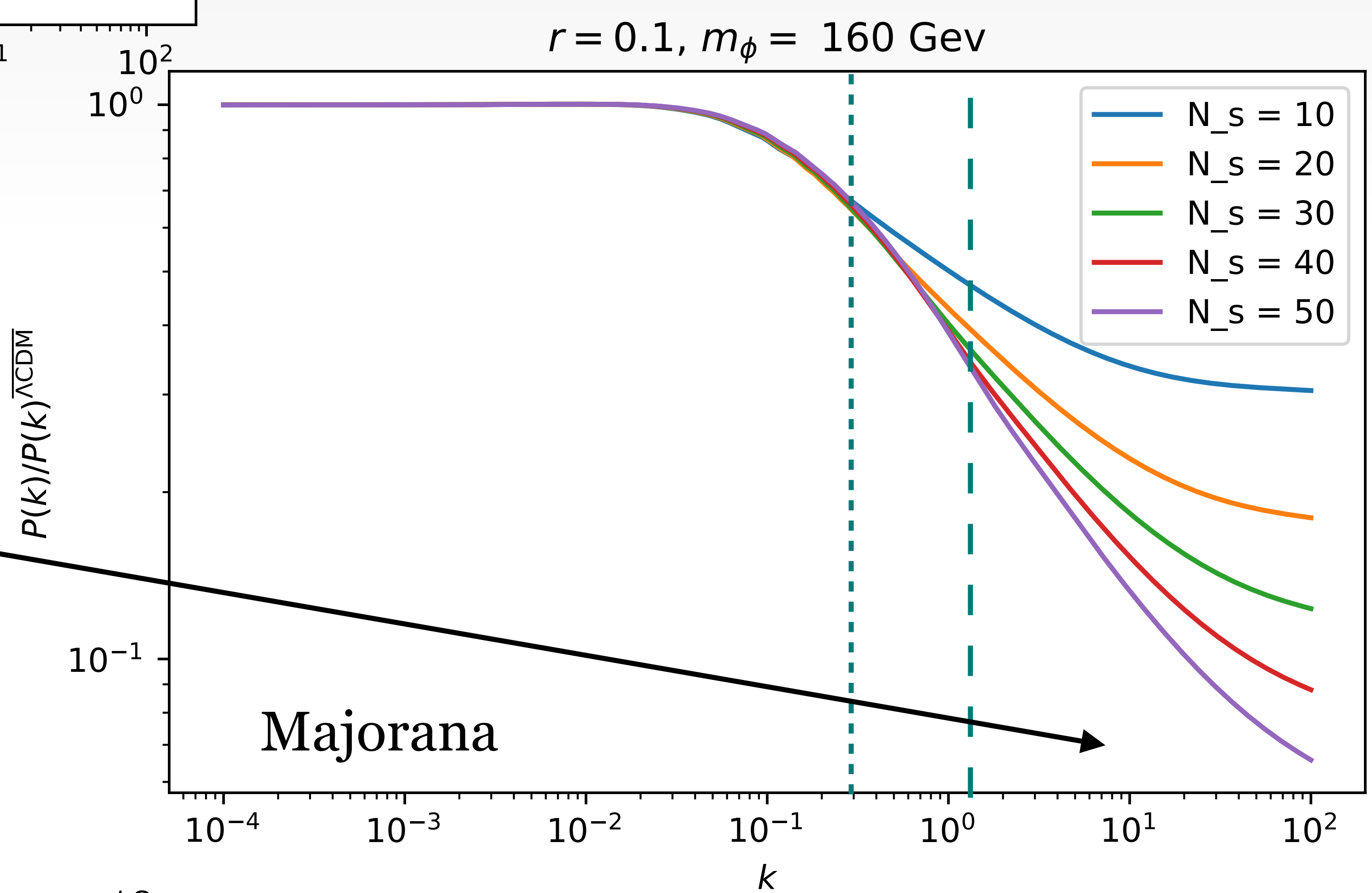
# Matter power spectrum suppression




⚠️ All power spectrum plots are linear

Scale dependent suppression

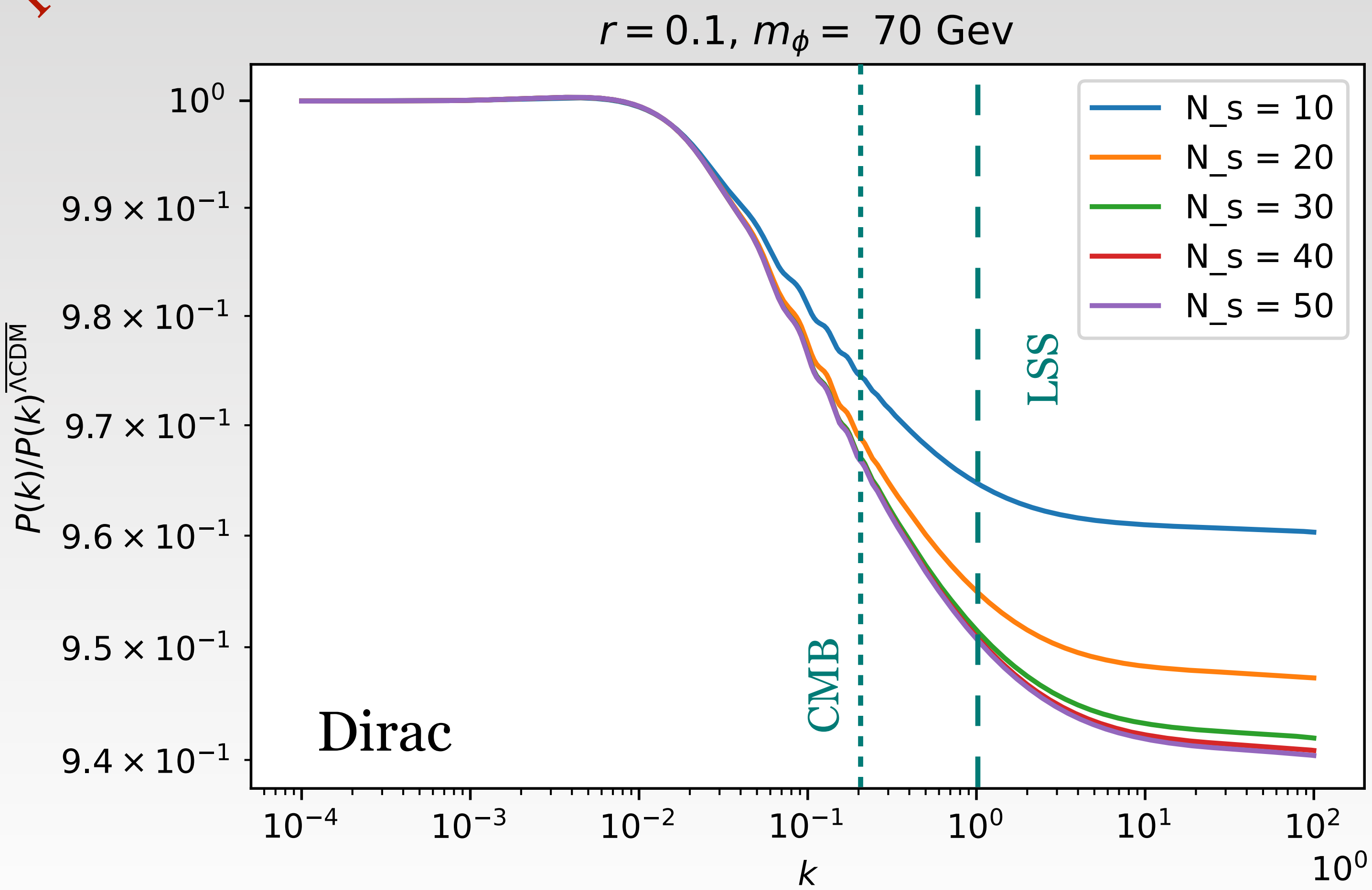


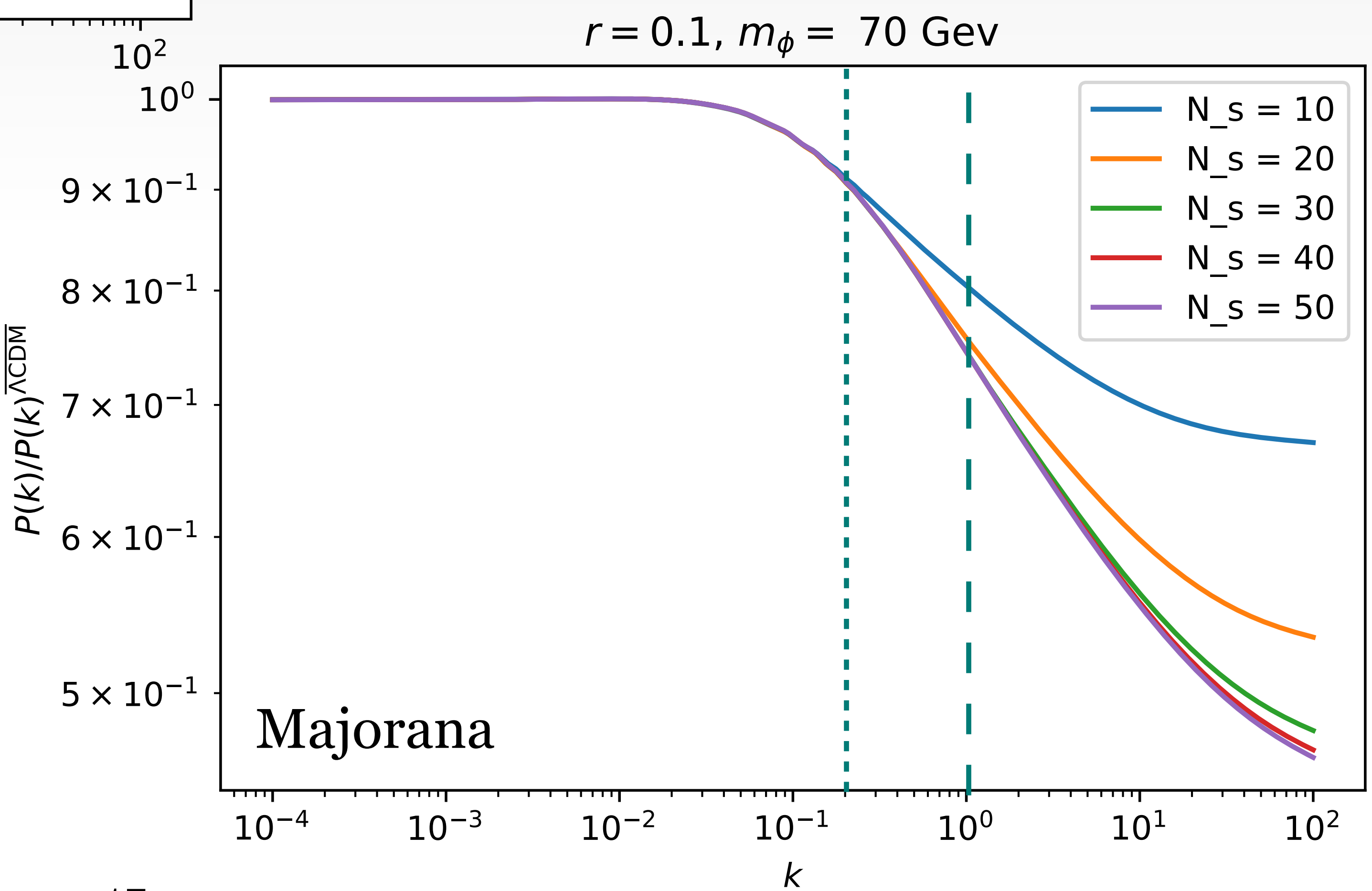

Too large suppression

$\overline{\Lambda\mathrm{CDM}} \rightarrow \Omega_{\mathrm{cdm}}$ adjusted to give same $\Omega_m$ & same $N_{\mathrm{eff}}$ with NN

Preliminary

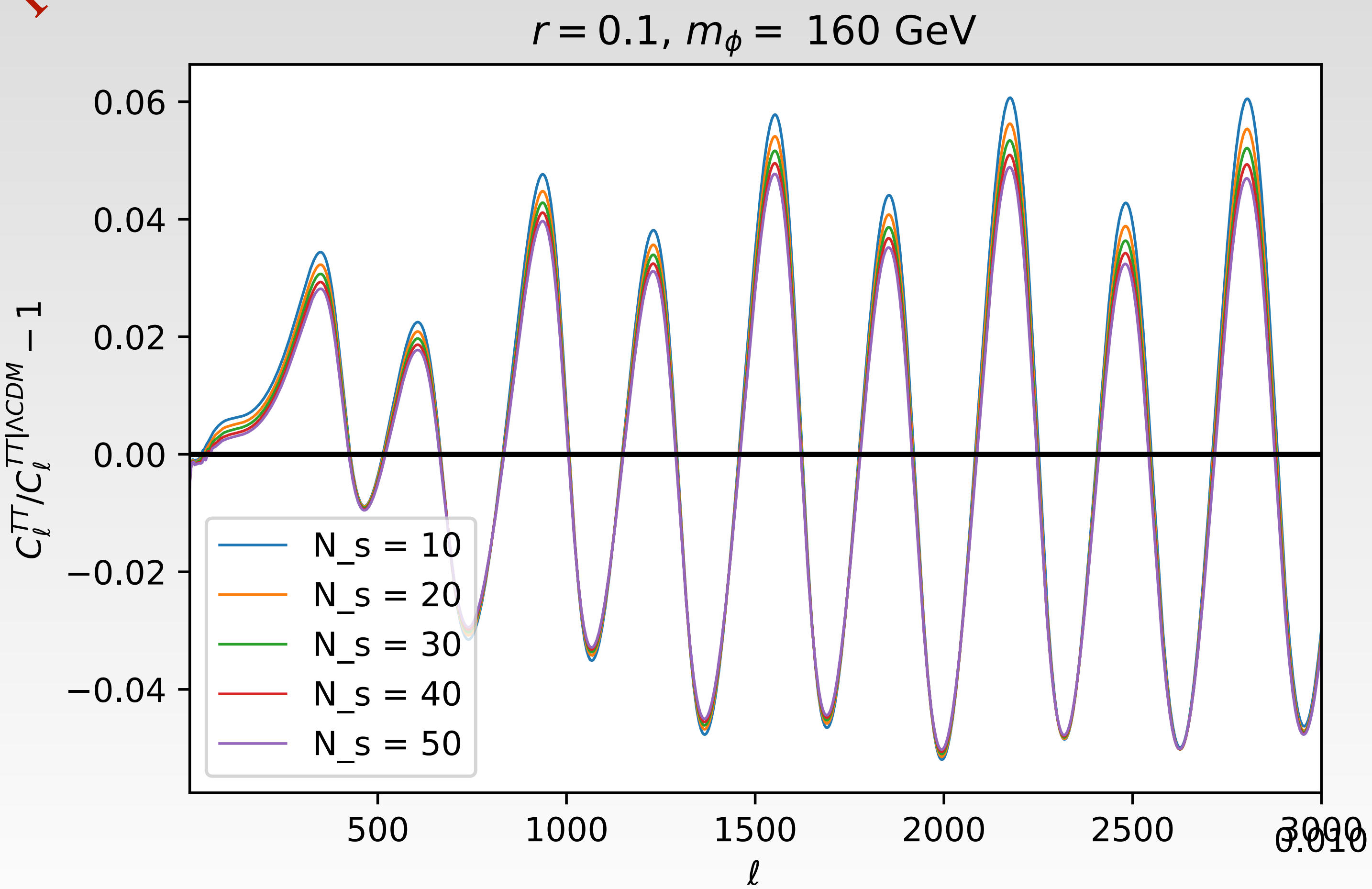
# Matter power spectrum suppression



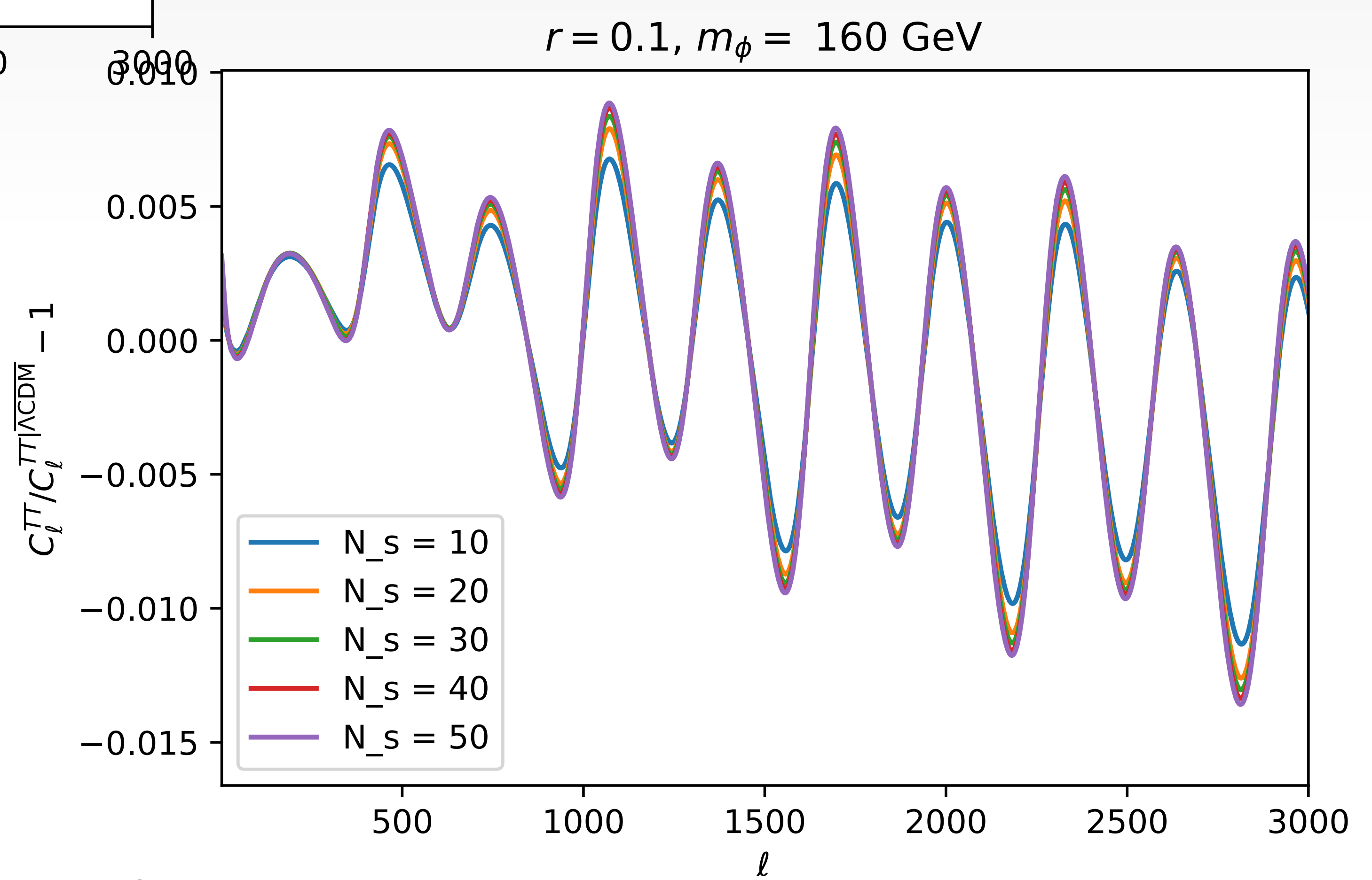




$\overline{\Lambda\text{CDM}} \rightarrow \Omega_{\text{cdm}}$ adjusted to give same $\Omega_m$ & same $N_{\text{eff}}$ with NN

# Effects on CMB : Dirac Spectrum




Higher sectors contribute mostly towards $\Omega_m$

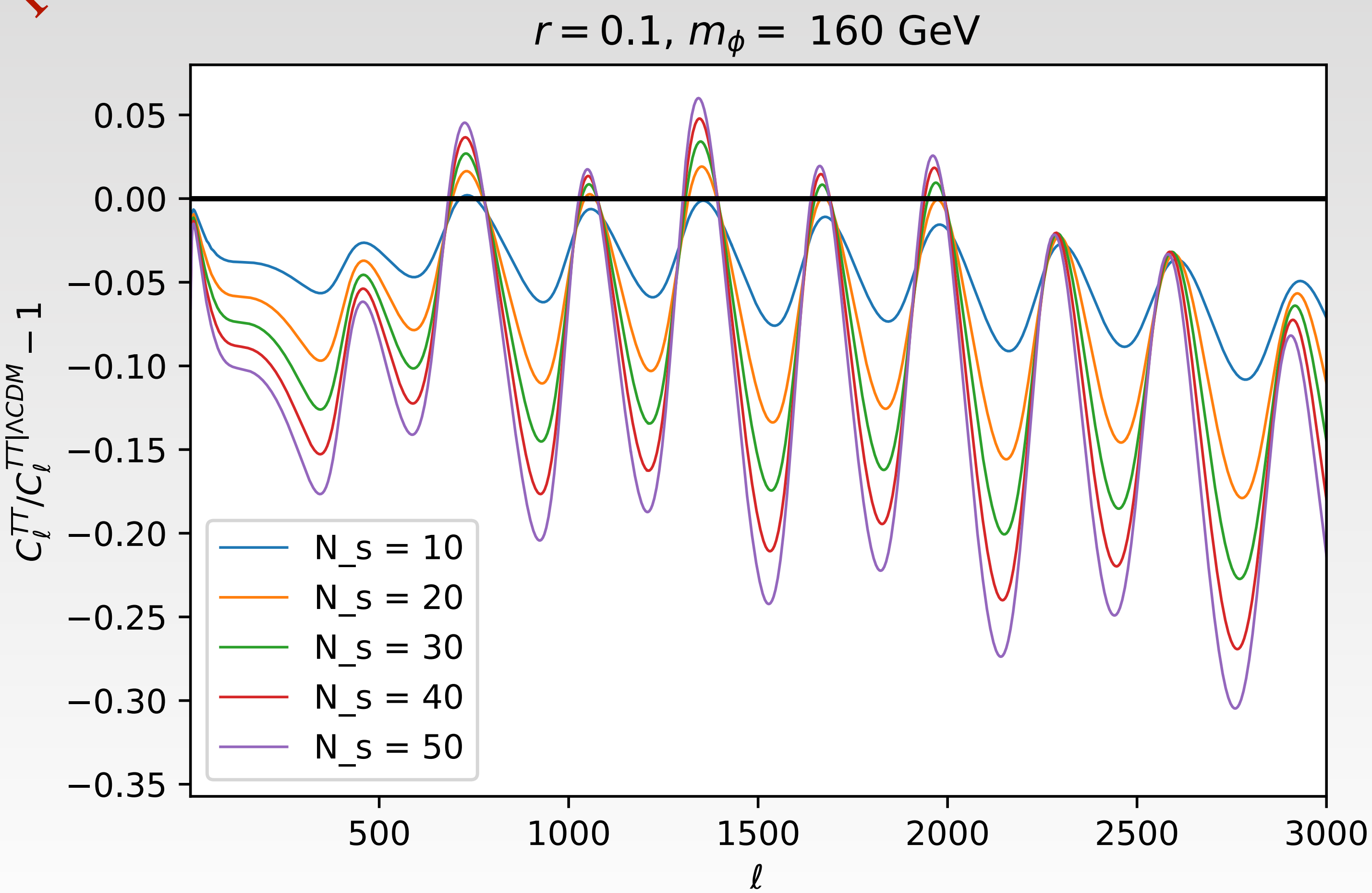



Effects of higher sectors can be incorporated by changing $\Omega_{\rm cdm}$

$\overline{\Lambda\text{CDM}} \equiv \Lambda$CDM with same total $\Omega_m$ and $N_{\rm eff}$ as N-naturalness

Preliminary

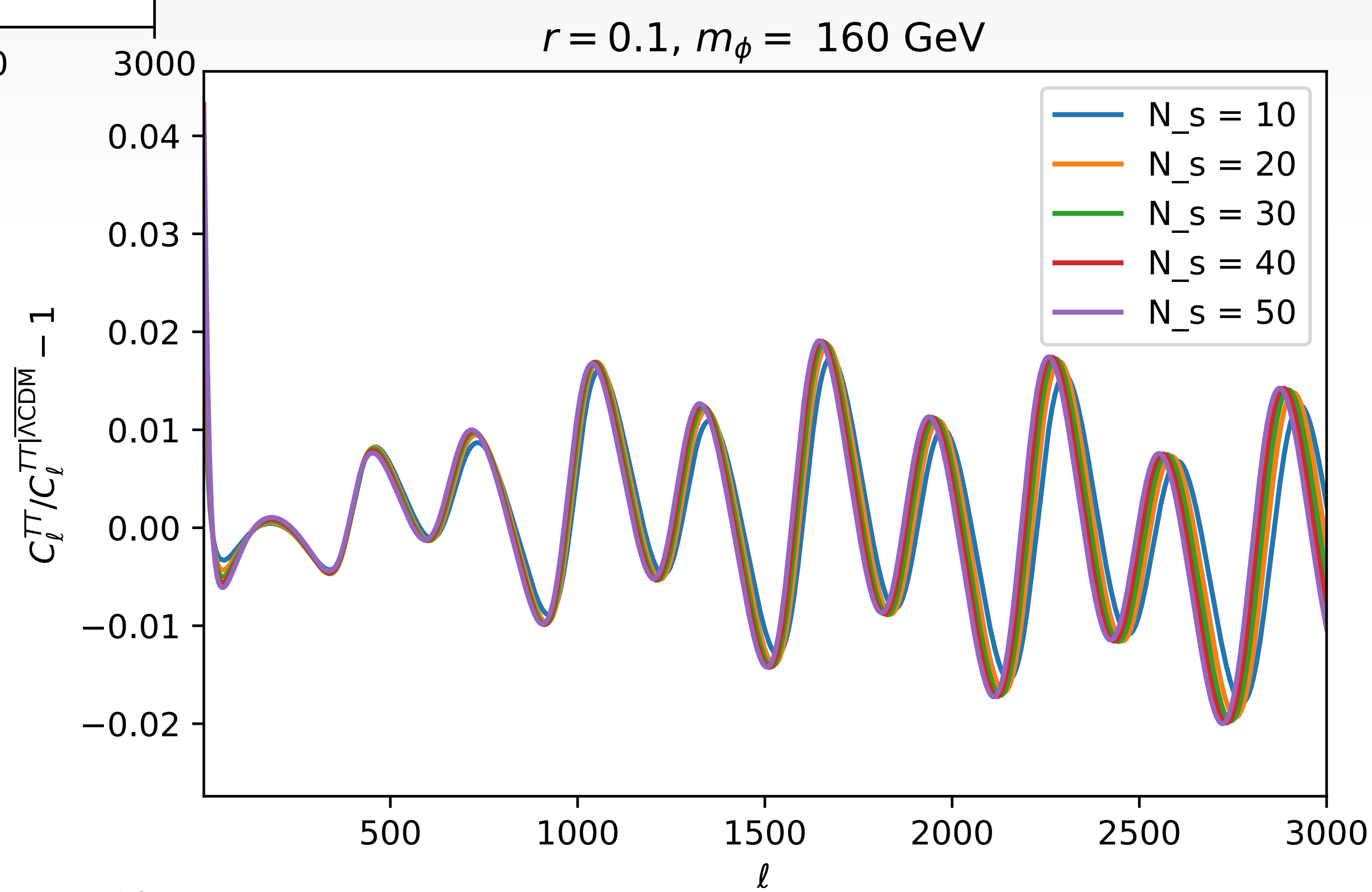
# Effects on CMB : Majorana Spectrum




Higher sectors contribute mainly towards $\Omega_m$

Effects of non-relativistic sectors can be incorporated by changing $\Omega_{\rm cdm}$

$\overline{\Lambda\rm CDM} \equiv \Lambda\rm CDM$ with same total $\Omega_m$ and $N_{\rm eff}$ as N-naturalness



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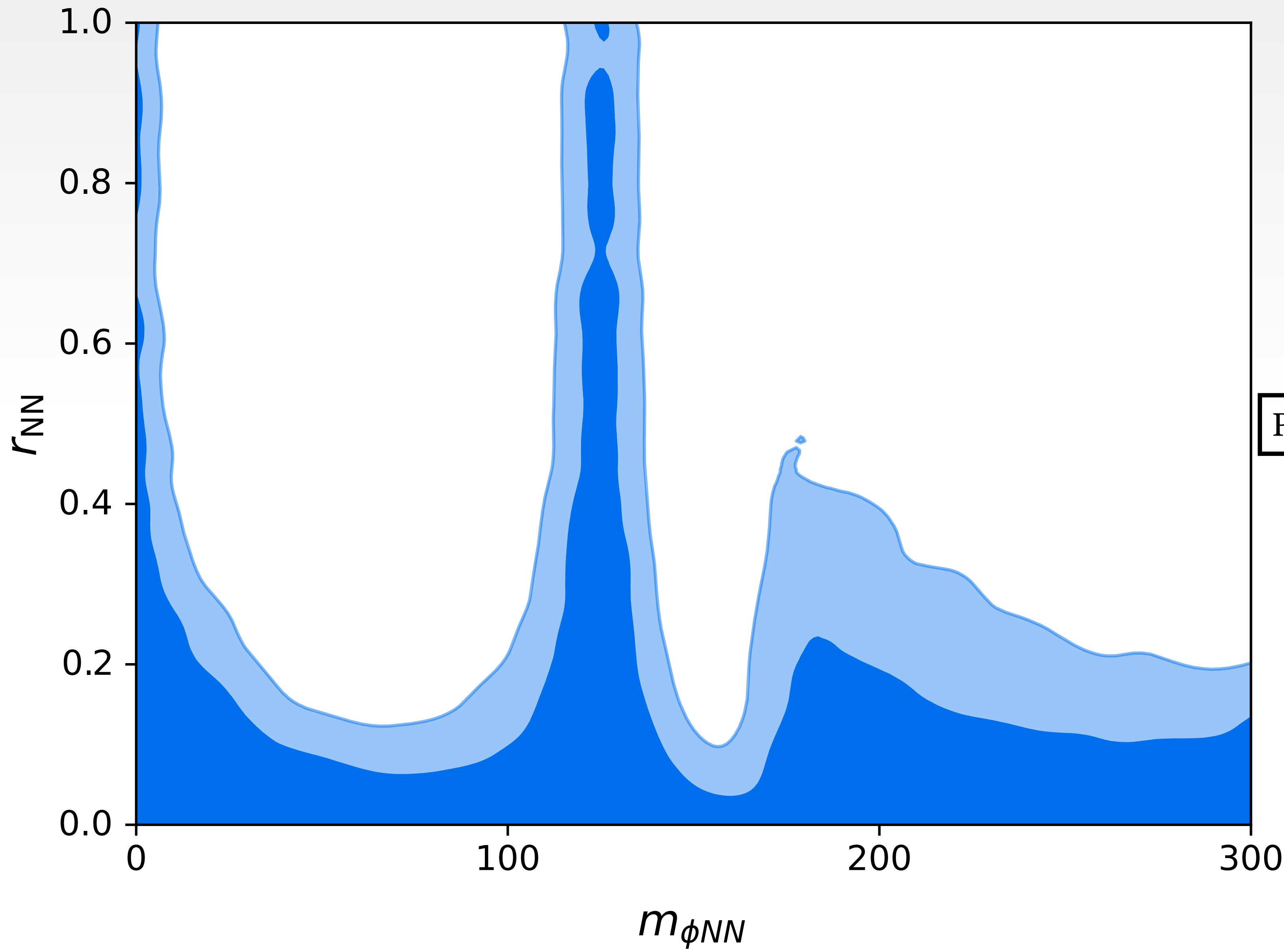
# MCMC

First MCMC analysis of a N-Naturalness model

2 cosmological parameters → $r_{\mathrm{NN}}$, $m_{\phi,\mathrm{NN}}$

Number of sector: $N_s = 20$




Planck-lowl+TTTEEE_lite+lensing

Dirac Neutrinos

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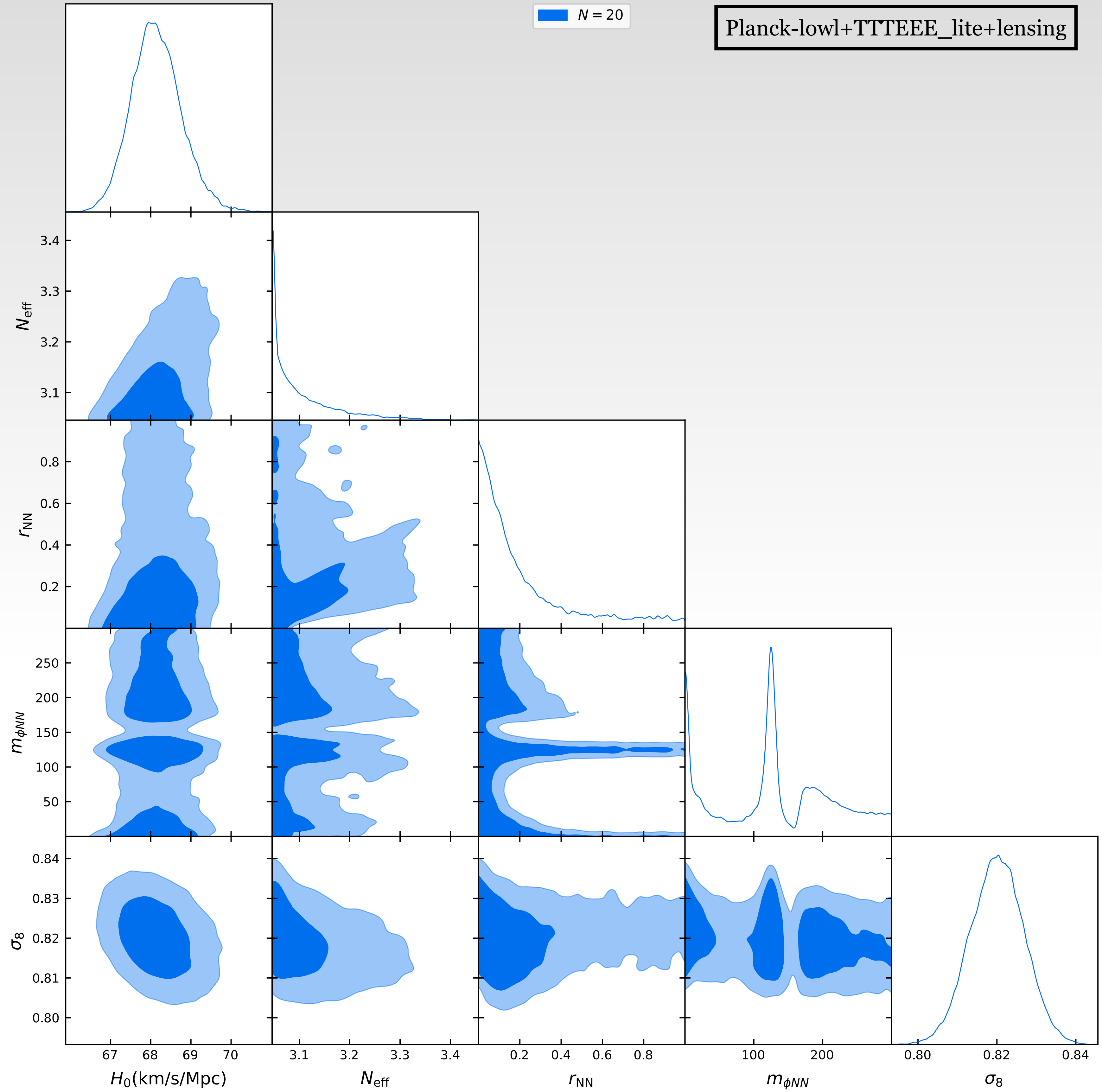
# MCMC



# TODO : More dataset combinations

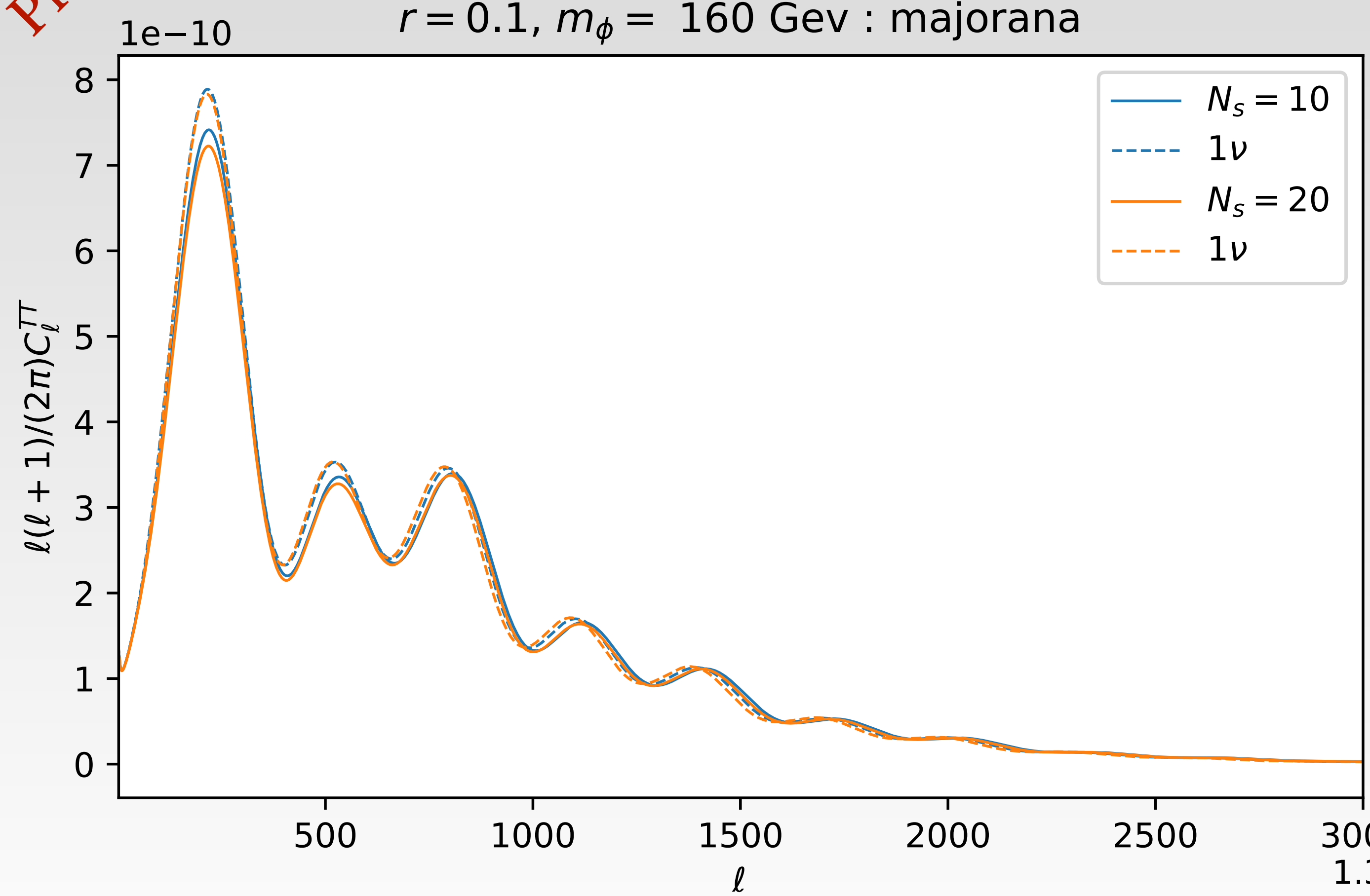
Will result in a non-zero preference for the N-Naturalness parameters

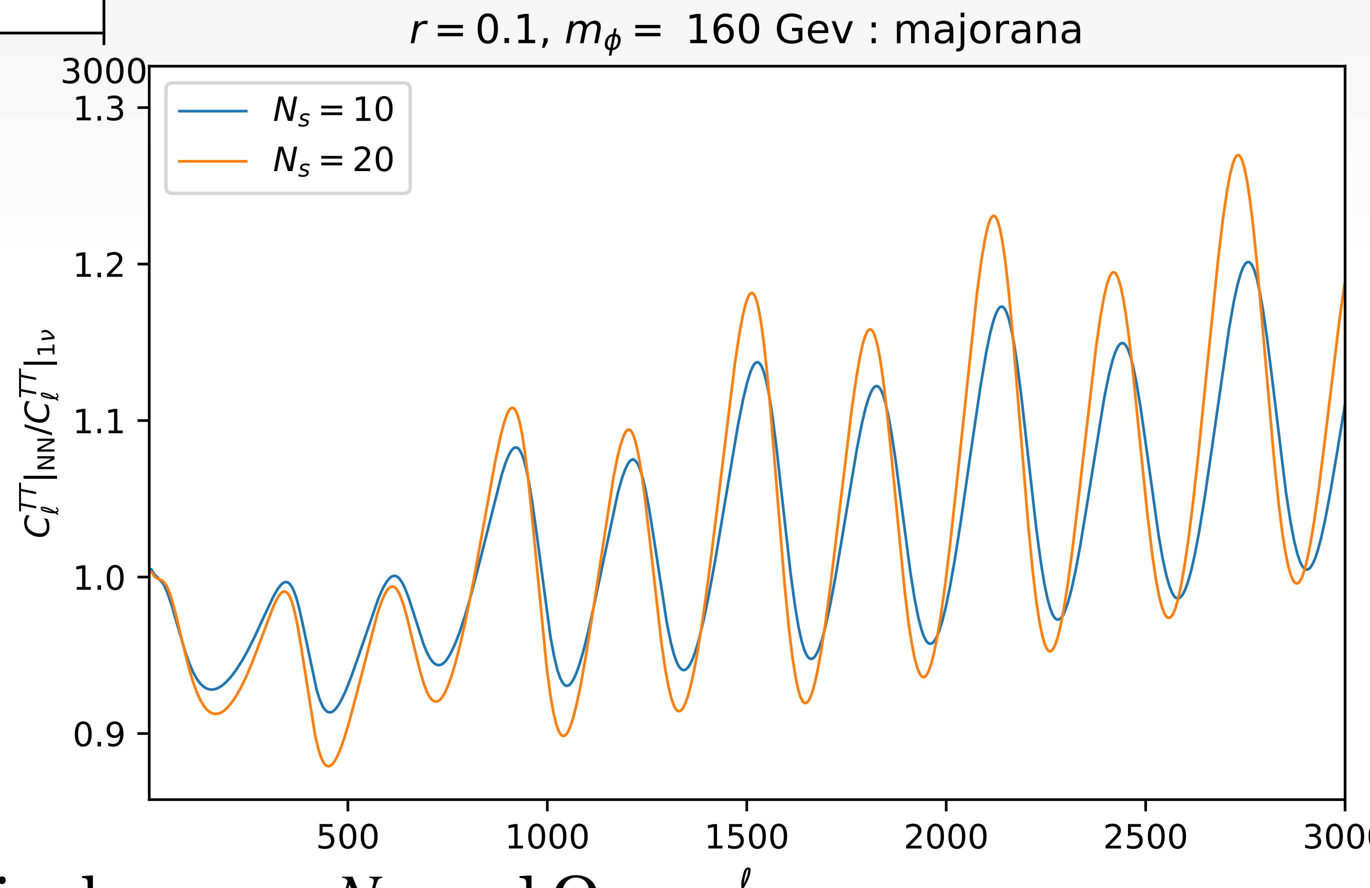
- $H_0$ measurement: SH0ES
- LSS: KiDS + Viking 450
- Lyman-$\alpha$ constraints
- Forecasting for CMB-S4

Highly constraining for the neutrino sector

Preliminary

# N neutrinos vs 1 neutrino




NN and $1\nu$ scenarios has same $N_{\rm eff}$ and $\Omega_\nu$

Preliminary

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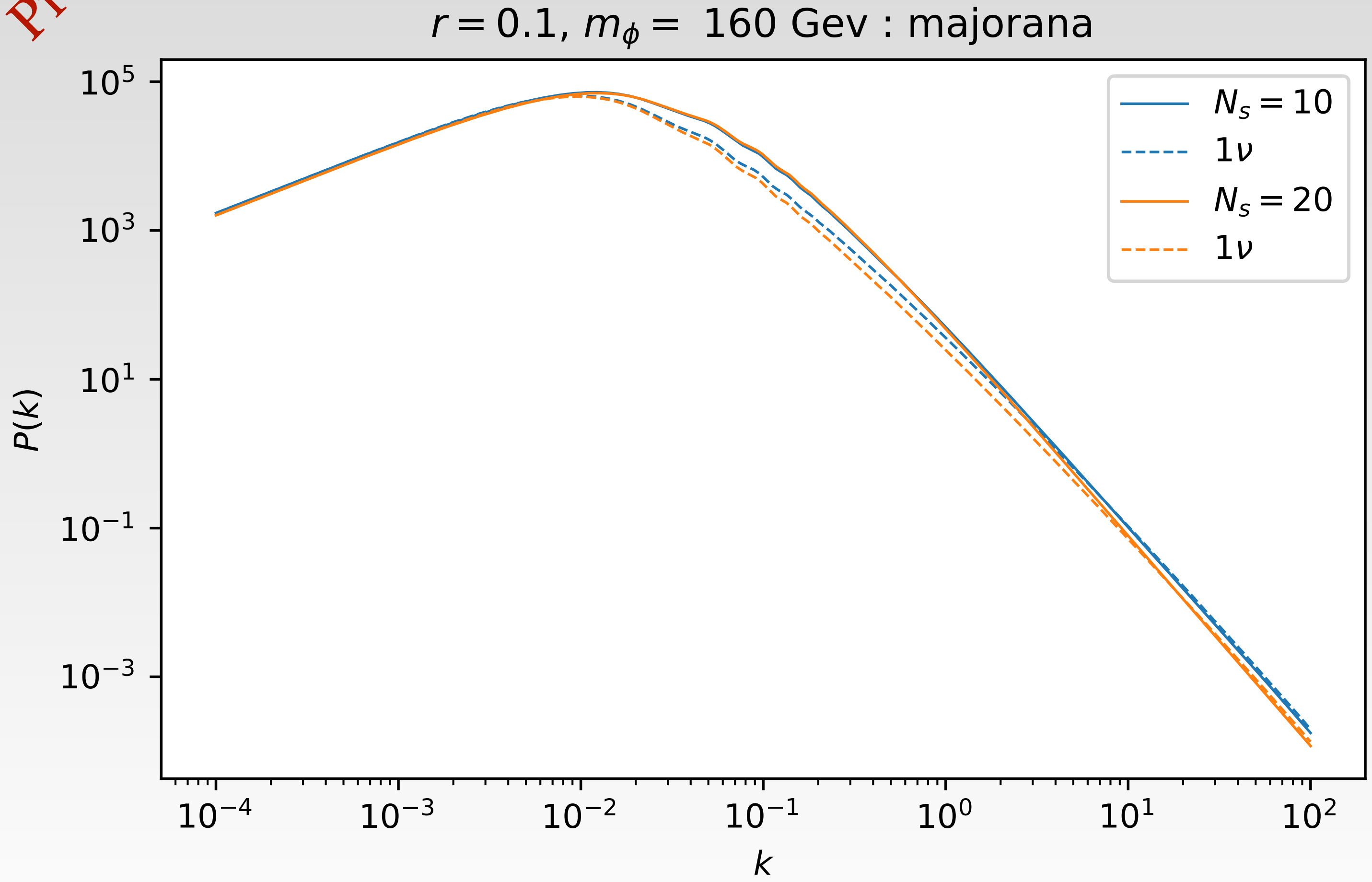


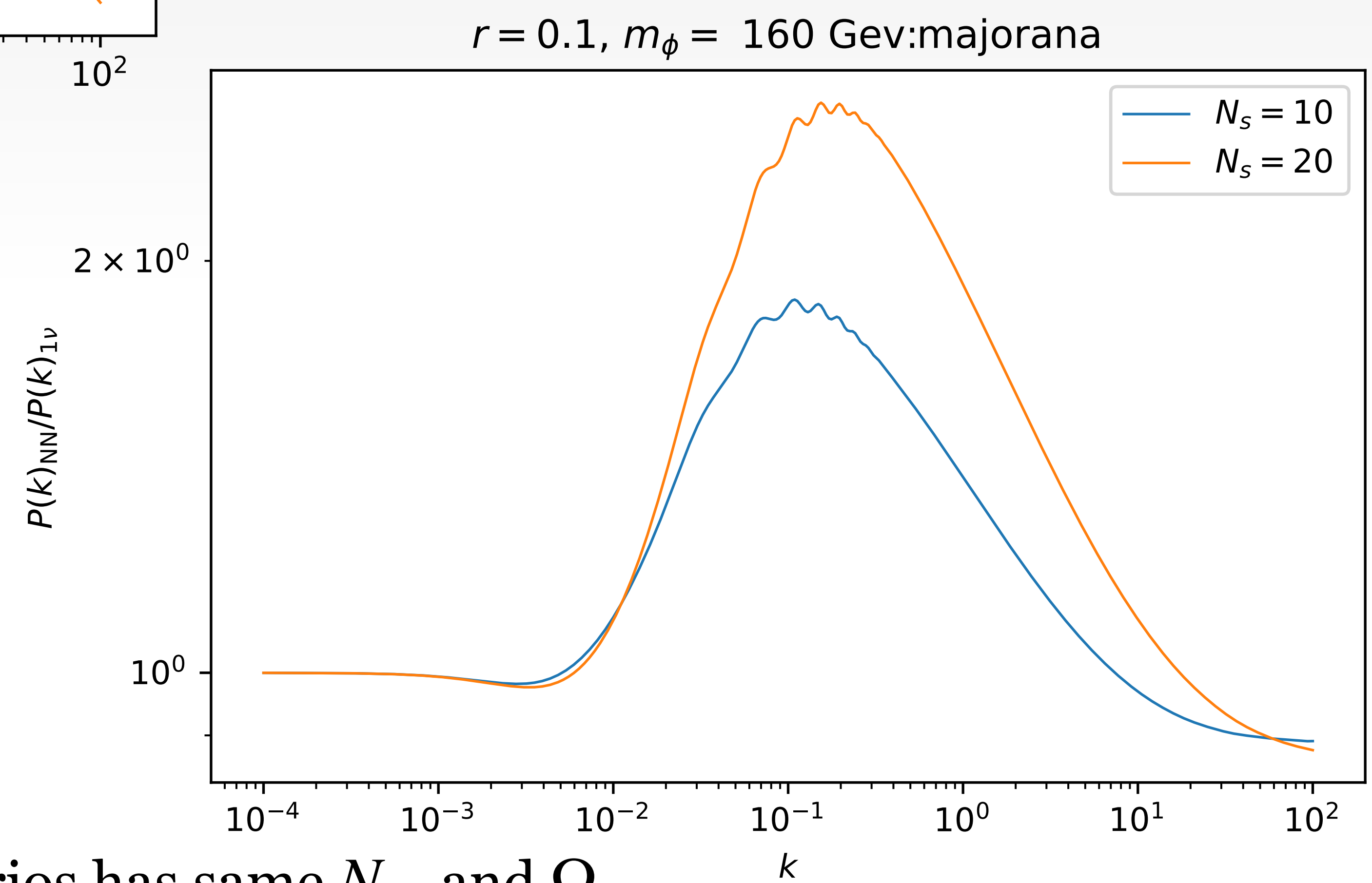


NN and $1\nu$ scenarios has same $N_{\rm eff}$ and $\Omega_\nu$

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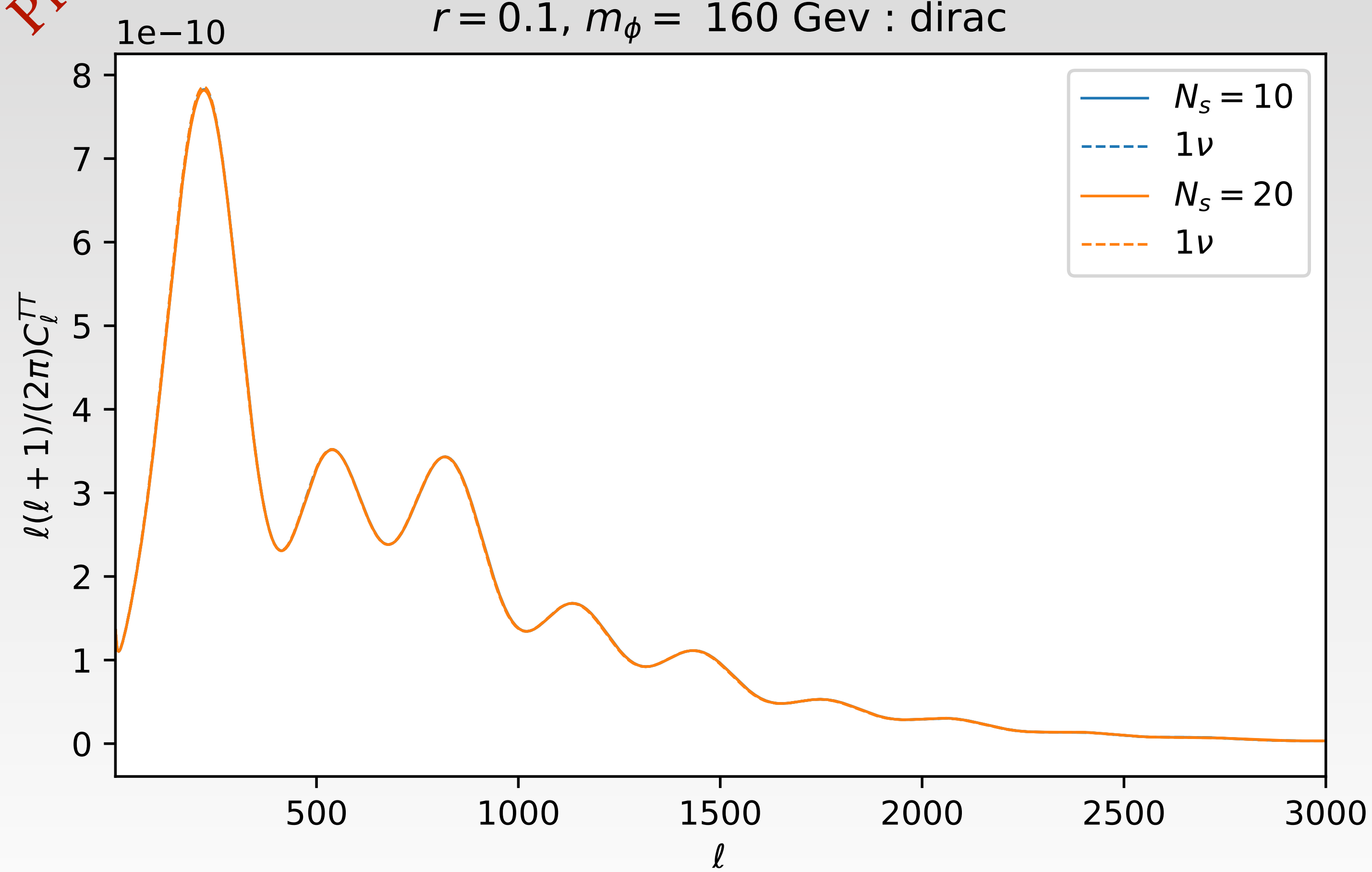


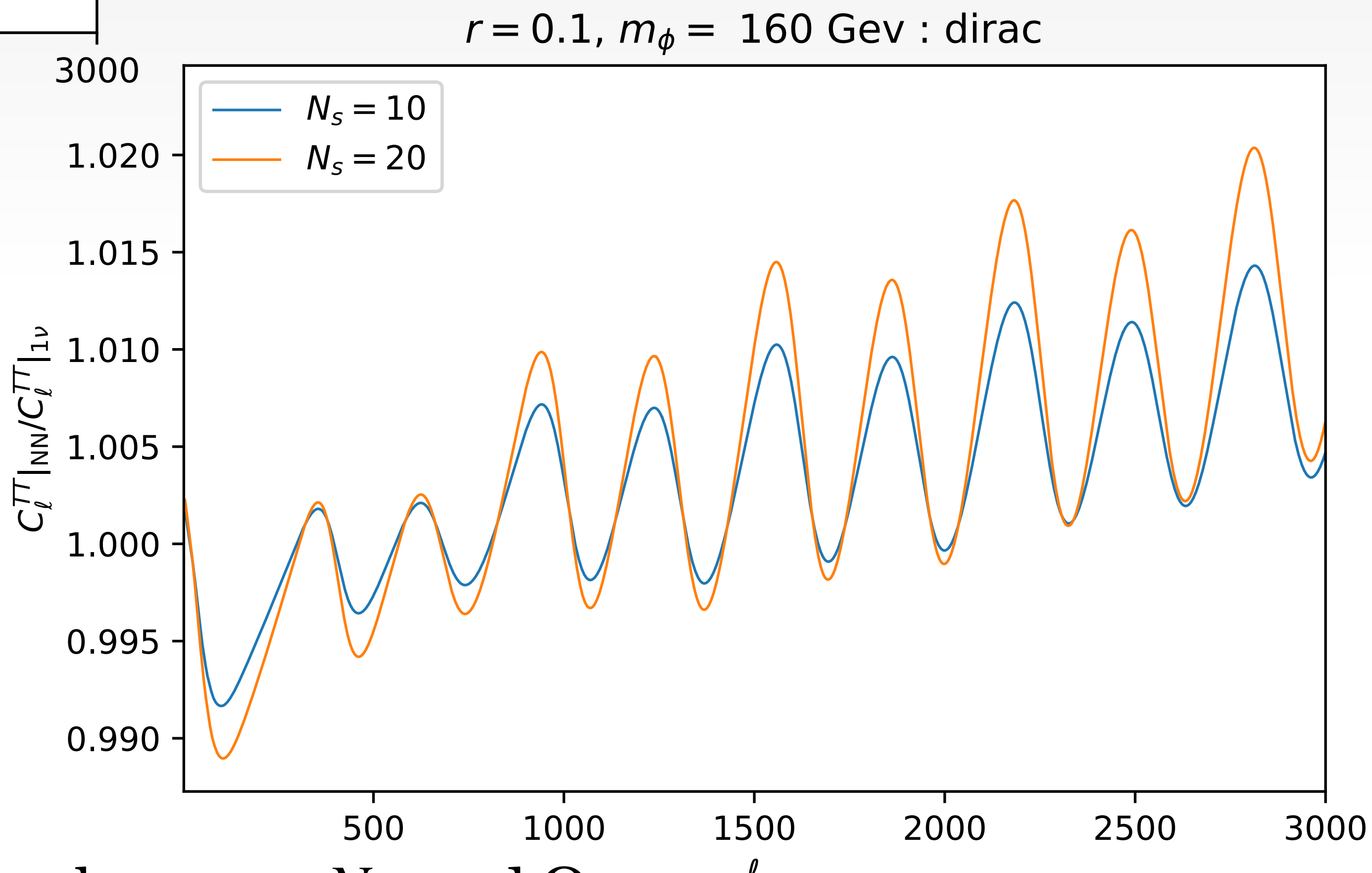


NN and $1\nu$ scenarios has same $N_{\rm eff}$ and $\Omega_\nu$

Preliminary

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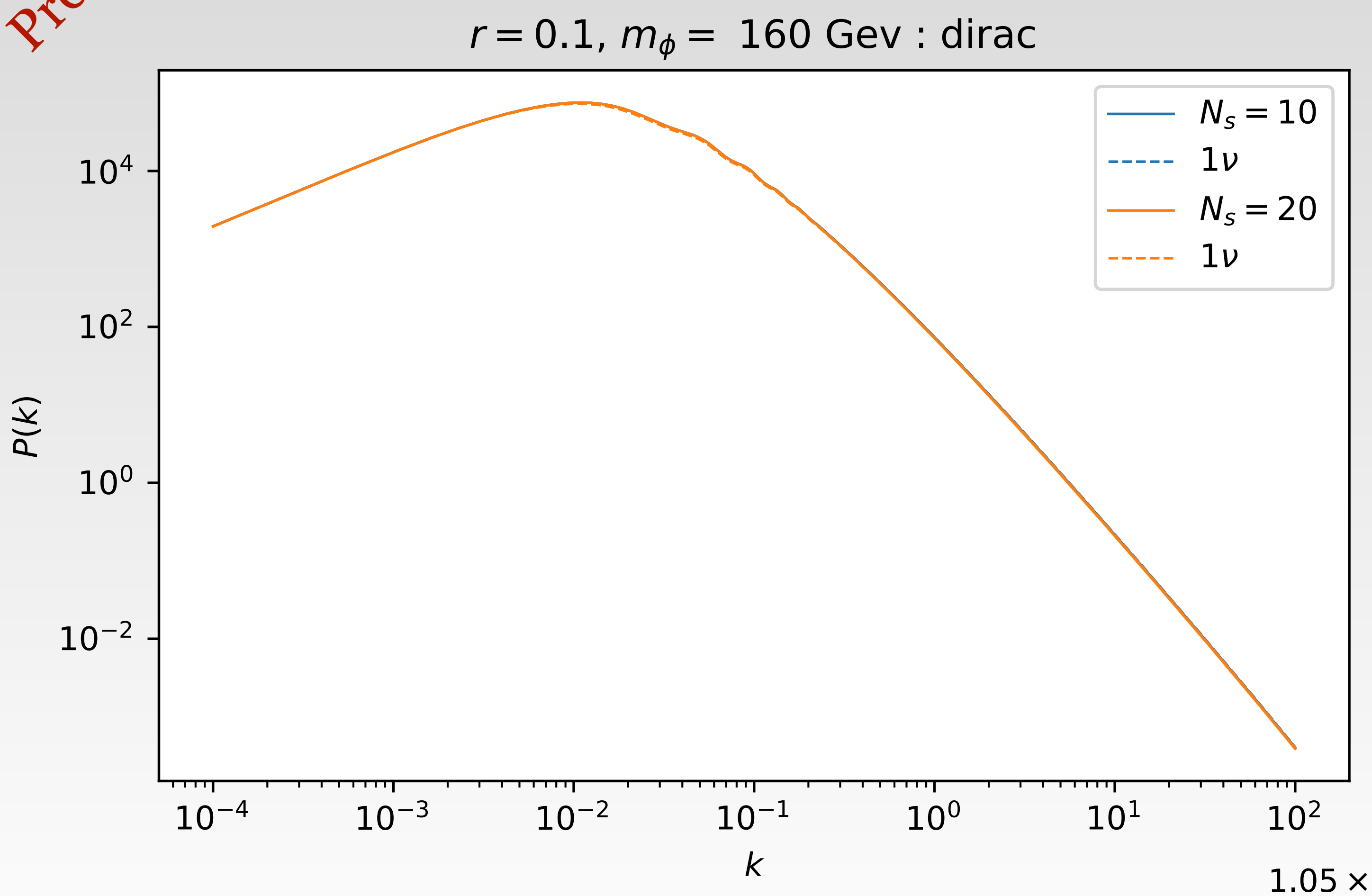


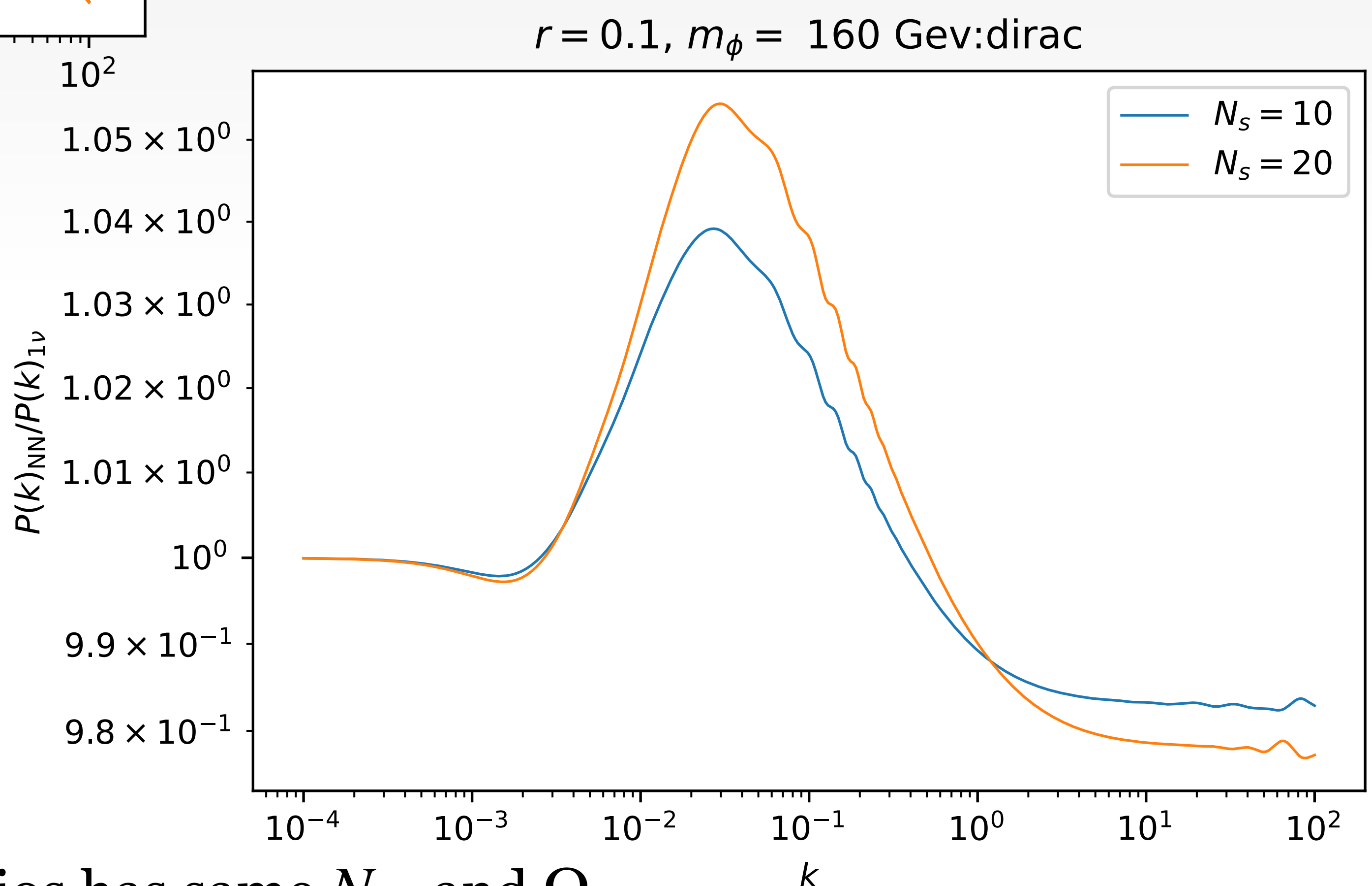


NN and $1\nu$ scenarios has same $N_{\rm eff}$ and $\Omega_\nu$

# Conclusion

- First Bayesian analysis for cosmological signatures N-naturalness model.
- Neutrinos in the Naturalness sector can produce large suppression in the matter power spectrum.
- Majorana neutrino scenario is likely to be ruled out from LSS & Lyman-$\alpha$ data
- The decoupling profile for a tower of neutrinos cannot be captured by a single neutrino species by adjusting its mass and temperature

# Future Direction

Baryon Asymmetry for N sectors

↓

Neutrinos | Dark photon | Dark electron | Dark proton

$\wedge N$

DAO/scattering radiation

# Future Direction

Efficient formalism for calculating a tower of neutrino states

Analytical: Effective single fluid description of all the Neutrino states (?)

Numerical: Modify CLASS to solve for all neutrino phase space collectively

This will also allow us to perform analysis with varying the lowest lying neutrino mass state