# Imprints of Dark matter - Neutrino interactions on Primordial Gravitational Waves and CMB B mode


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Based on : 1711.09929


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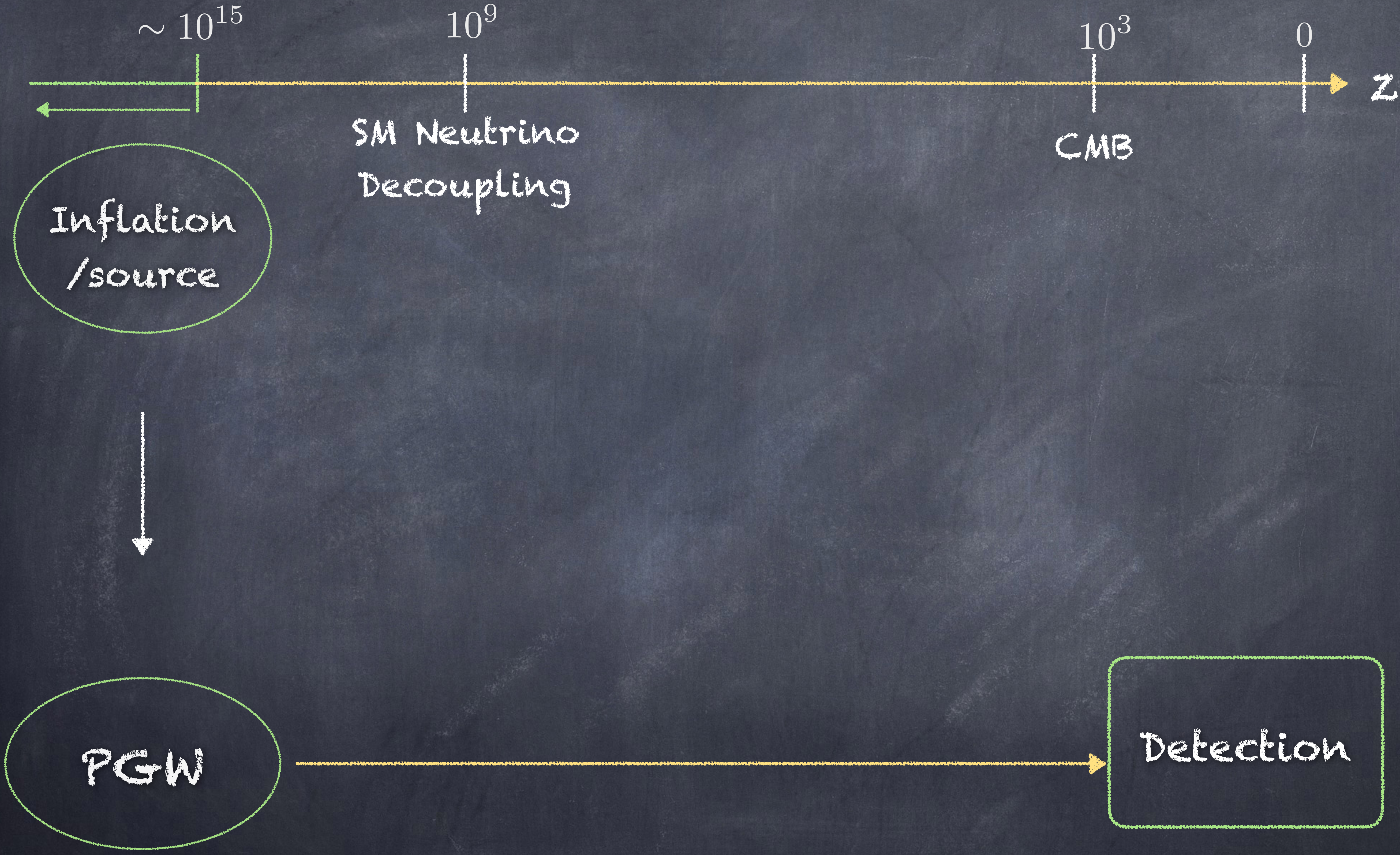
DEC 14, 2017

# Introduction



# Introduction

$\sim 10^{15}$ | $10^9$ | $10^3$ | $0$ | $z$

SM Neutrino Decoupling

CMB

Inflation /source

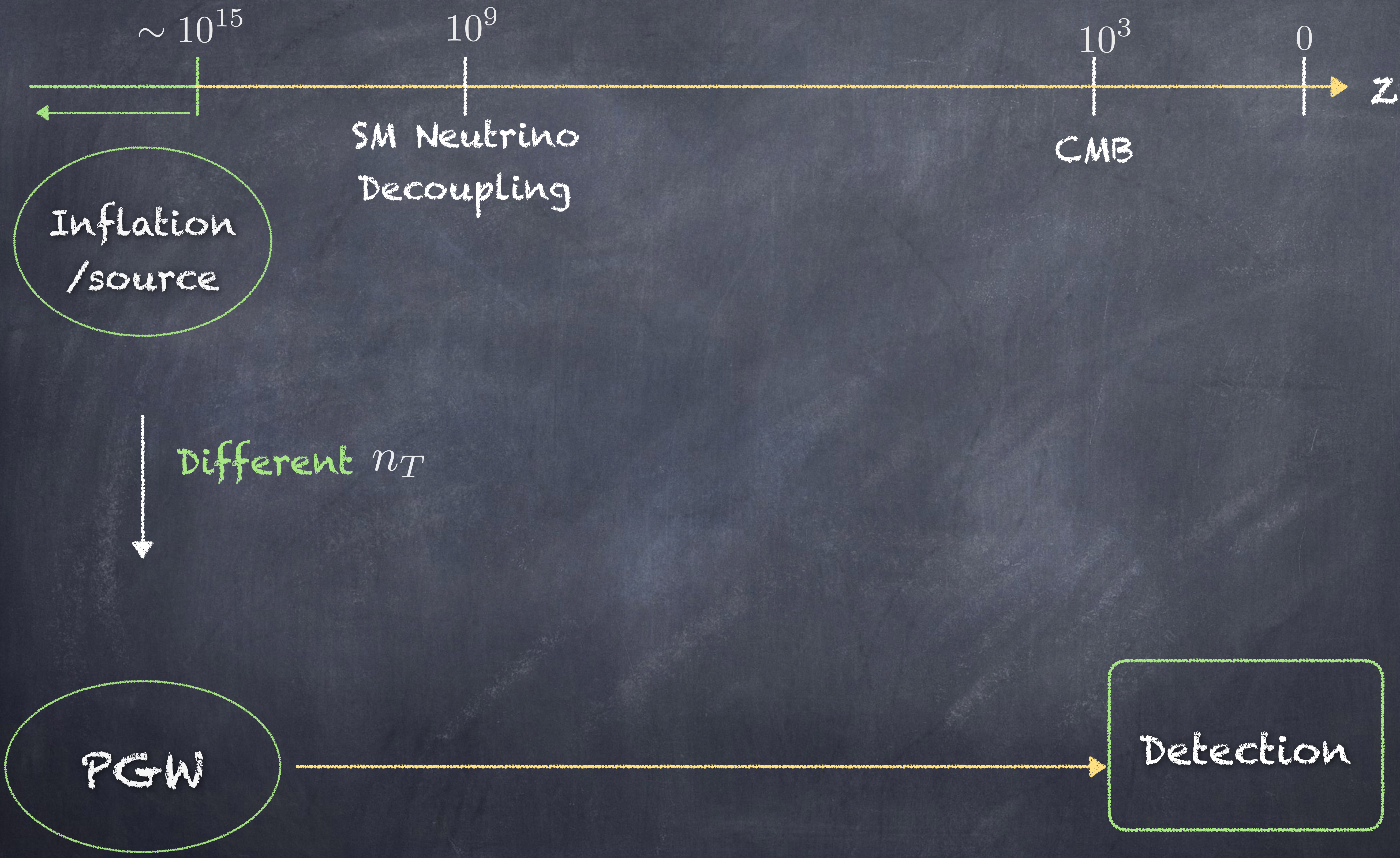
Different $n_T$

$$k^3 P_h(k) = A_* \left(\frac{k}{k_*}\right)^{n_T}$$

PGW

Detection

# Introduction



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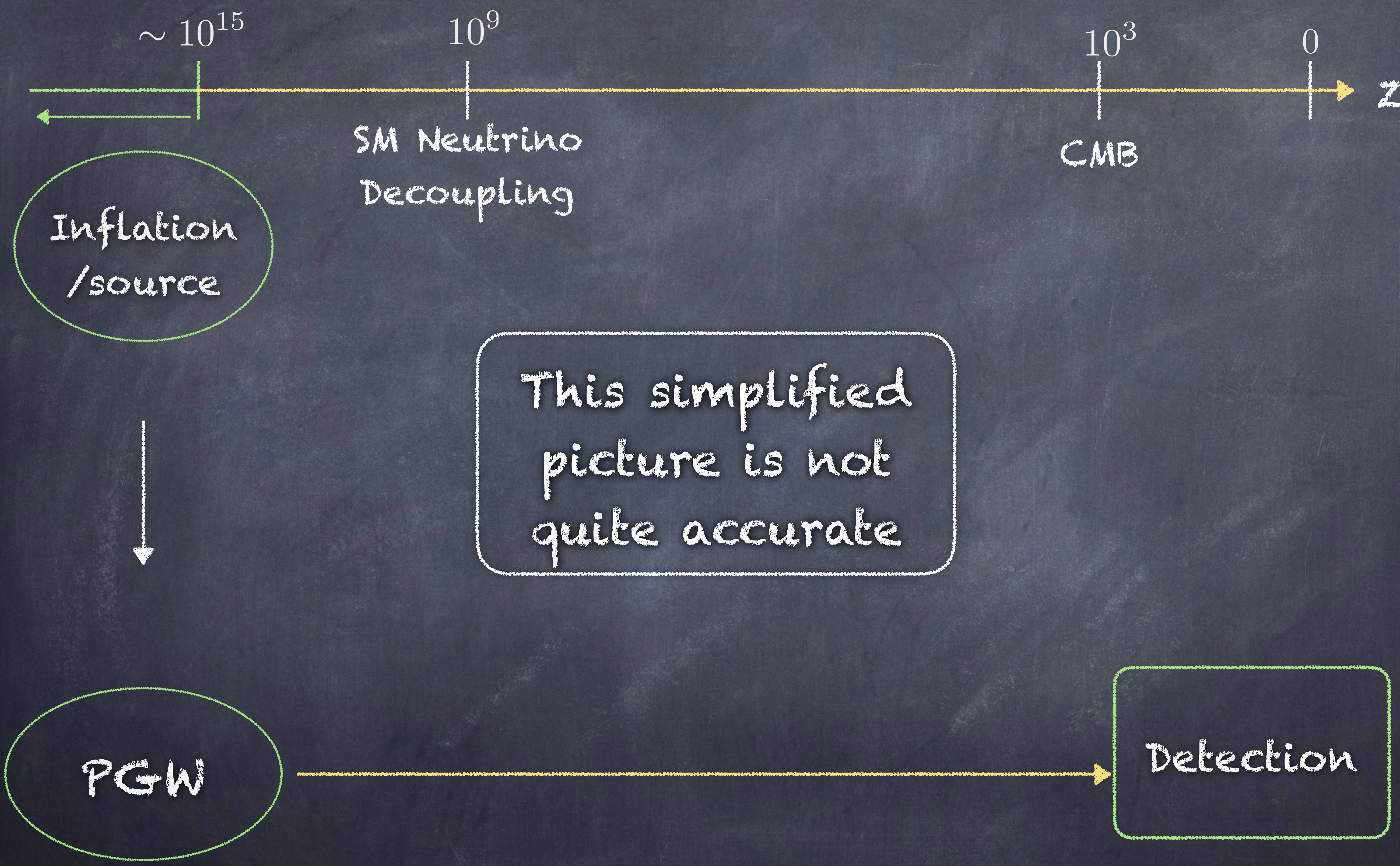

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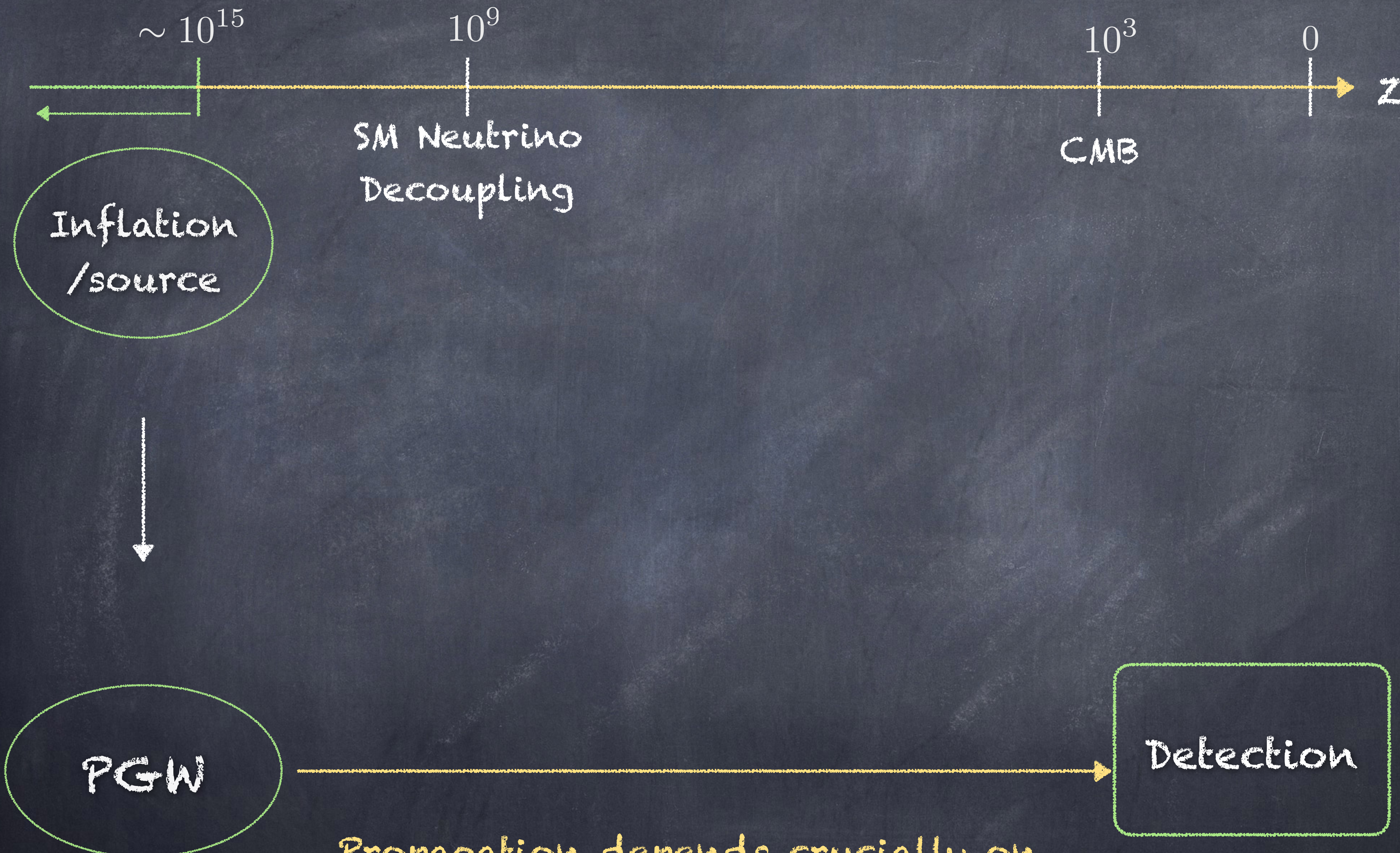
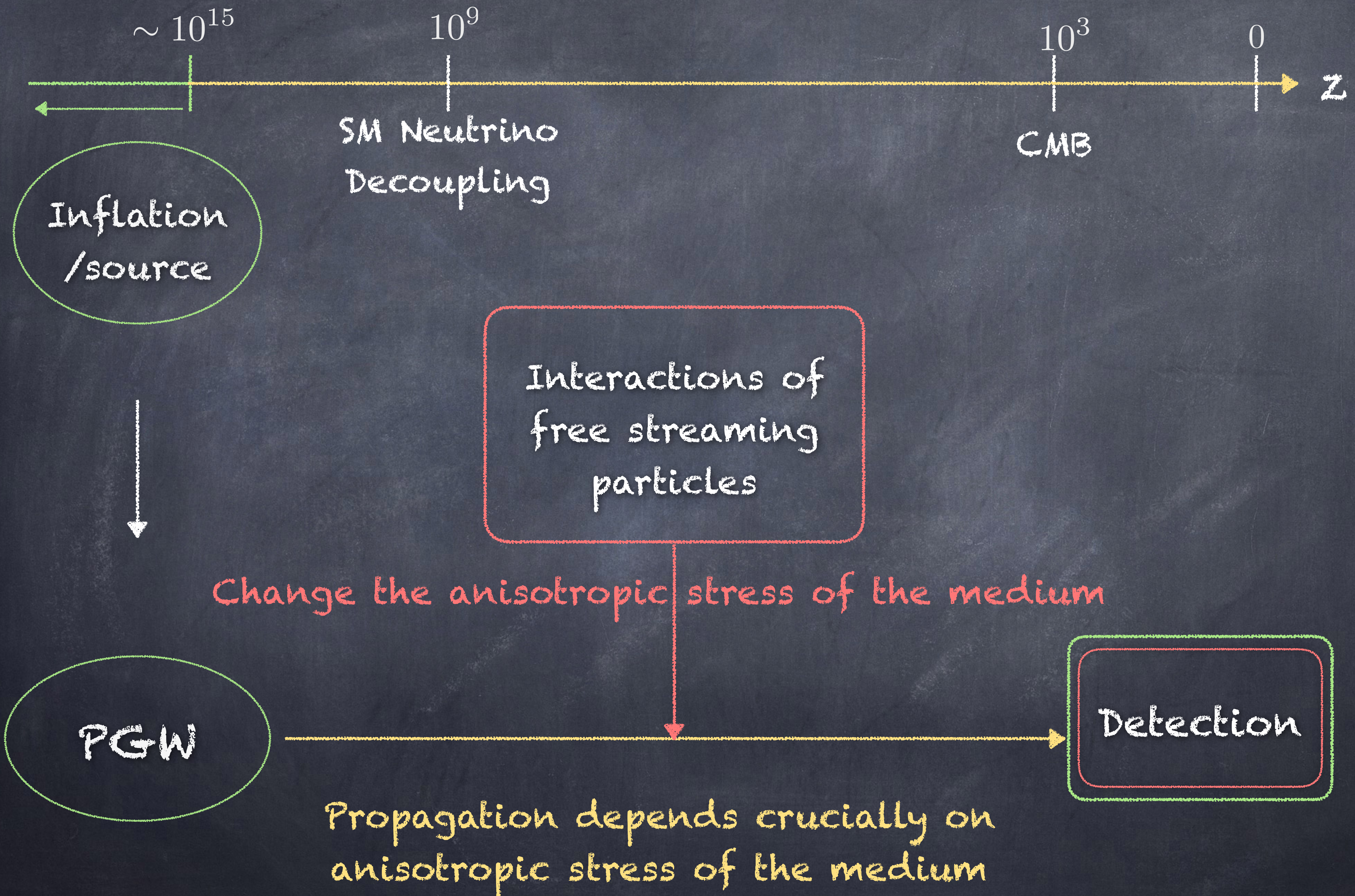



Propagation depends crucially on anisotropic stress of the medium

# Introduction



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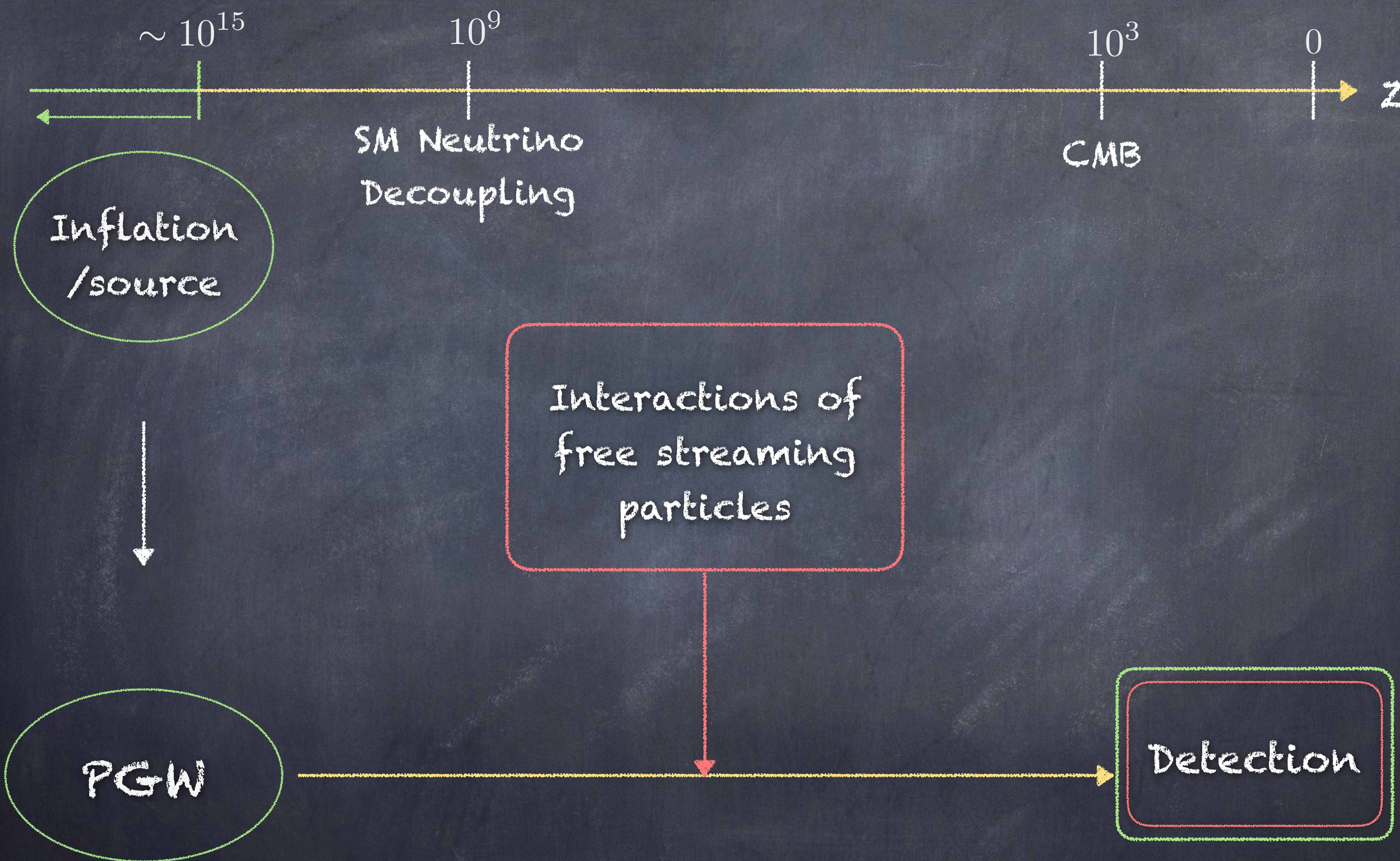
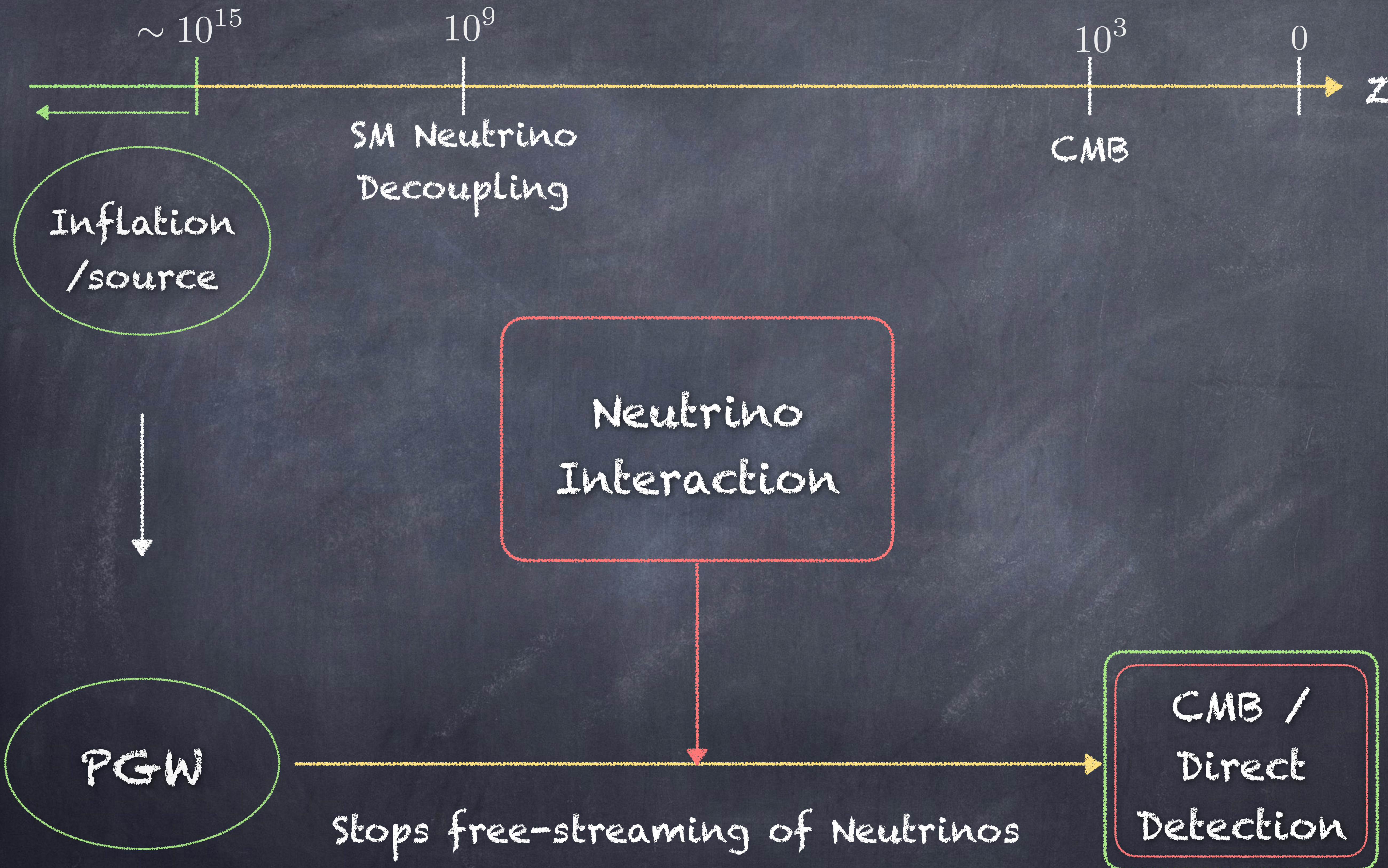



There can be significant degeneracy

# Introduction



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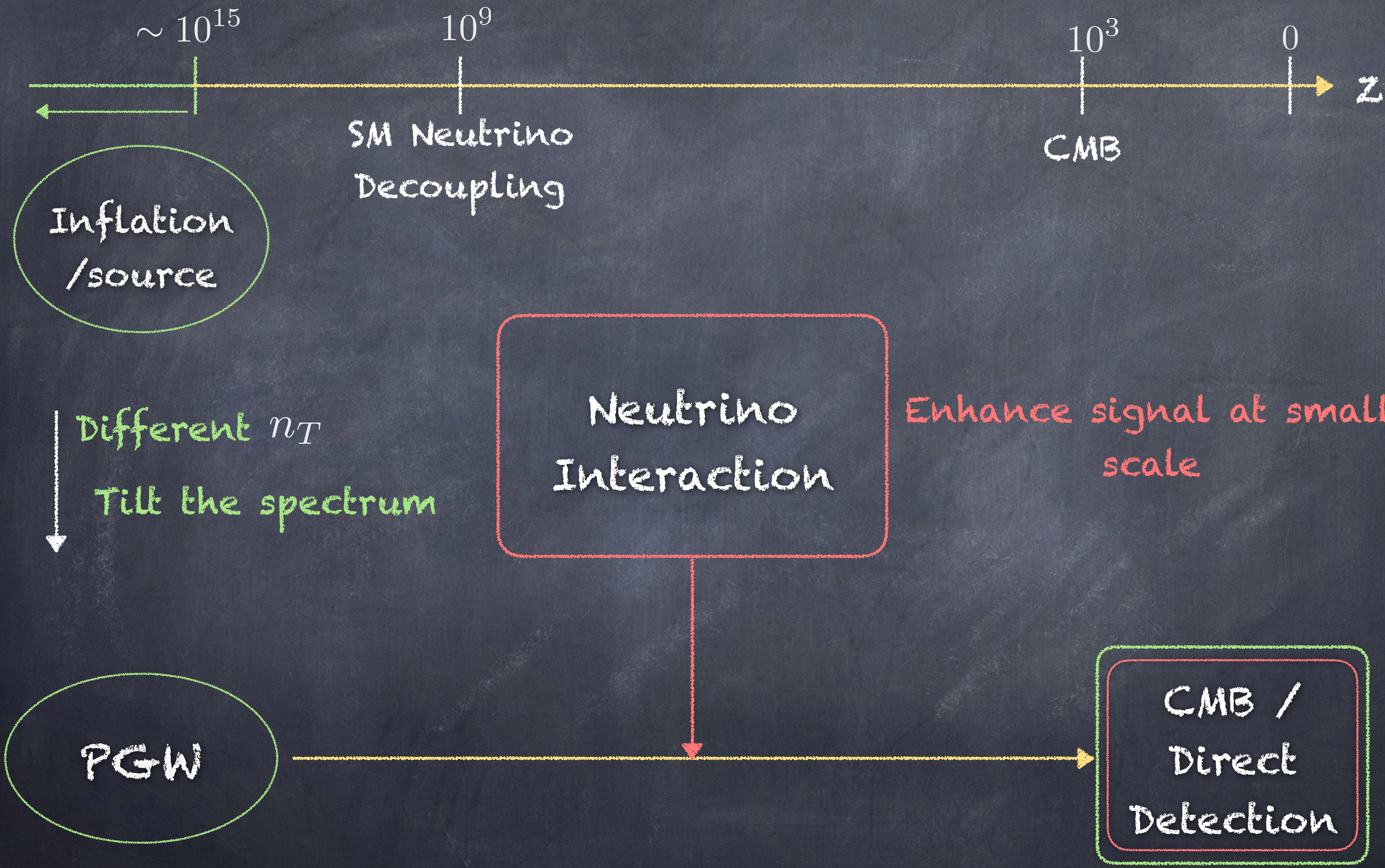


# Outline

- A model of neutrino interaction
- Mean free path of Neutrino
- Evolution of GW
- Effect on CMB B mode

# A model of neutrino interaction

Dark-matter
Neutrino
Interaction

Potentially can also
solve small
scale problems in ΛCDM

# A model of neutrino interaction

$$SU(2)_W \times U(1)_Y \times SU(3)_l \times U(1)_L \times U(1)_D$$

Mediator

$$\mathcal{L} \supset Y \frac{1}{\Lambda} \left(H^\dagger l\right)(\psi\chi)$$

SM singlet

DM

EWSB

$$\boxed{y\nu(\psi\chi)}$$

# A model of neutrino interaction

Degenerate mass

Non-degenerate mass

$$\sigma_{\chi\nu} \xrightarrow{\text{Degenerate mass}} \sigma^{(0)} \longrightarrow u^{(0)} = \left(\frac{\sigma^{(0)}}{\sigma_{\mathrm{Th}}}\right)\left(\frac{100\mathrm{Gev}}{m_\chi}\right)$$

$$\sigma_{\chi\nu} \xrightarrow{\text{Non-degenerate mass}} \sigma^{(2)}\left(\frac{T_\nu}{1.95\ \mathrm{K}}\right)^2 \longrightarrow u^{(2)} = \left(\frac{\sigma^{(2)}}{\sigma_{\mathrm{Th}}}\right)\left(\frac{100\mathrm{Gev}}{m_\chi}\right)$$

# A model of neutrino interaction

$\sigma_{\chi\nu}$

Degenerate mass

$$\sigma^{(0)} \longrightarrow u^{(0)} = \left(\frac{\sigma^{(0)}}{\sigma_{\rm Th}}\right)\left(\frac{100\text{Gev}}{m_\chi}\right)$$

Non-degenerate mass

$$\sigma^{(2)}\left(\frac{T_\nu}{1.95\ \mathrm{K}}\right)^2 \longrightarrow u^{(2)} = \left(\frac{\sigma^{(2)}}{\sigma_{\rm Th}}\right)\left(\frac{100\text{Gev}}{m_\chi}\right)$$

$$\frac{\partial^2}{\partial\eta^2}\mathcal{D}_q + 2aH\frac{\partial\mathcal{D}_q}{\partial\eta} + q^2\mathcal{D}_q = 16\pi a^2 G\pi_q^T$$

Dominant contribution
Neutrino

GW wave mode

Anisotropic Stress

# A model of neutrino interaction

$$\sigma_{\chi\nu} \xrightarrow{\text{Degenerate mass}} \sigma^{(0)} \longrightarrow u^{(0)} = \left(\frac{\sigma^{(0)}}{\sigma_{\mathrm{Th}}}\right)\left(\frac{100\mathrm{Gev}}{m_\chi}\right)$$

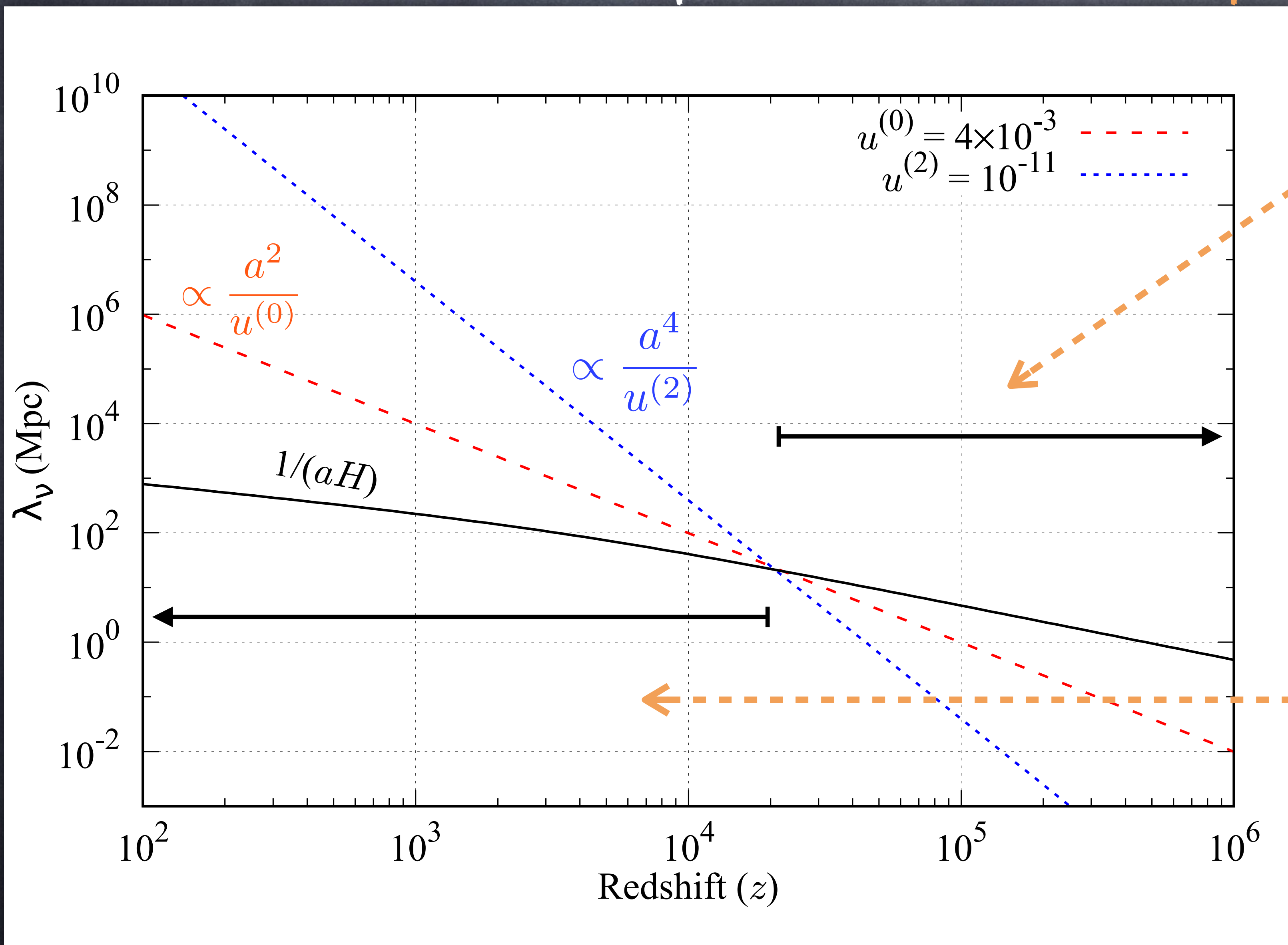
$$\sigma_{\chi\nu} \xrightarrow[\text{Non-degenerate mass}]{} \sigma^{(2)}\left(\frac{T_\nu}{1.95\ \mathrm{K}}\right)^2 \longrightarrow u^{(2)} = \left(\frac{\sigma^{(2)}}{\sigma_{\mathrm{Th}}}\right)\left(\frac{100\mathrm{Gev}}{m_\chi}\right)$$

$$\frac{\partial^2}{\partial\eta^2}\mathcal{D}_q + 2aH\frac{\partial\mathcal{D}_q}{\partial\eta} + q^2\mathcal{D}_q = 16\pi a^2 G\pi_q^T \longleftarrow \text{Suppressed due to } \sigma_{\chi\nu}$$

# Mean free path of Neutrino


(depends on $u^{(0)}, u^{(2)}$ )

# Mean free path of Neutrino

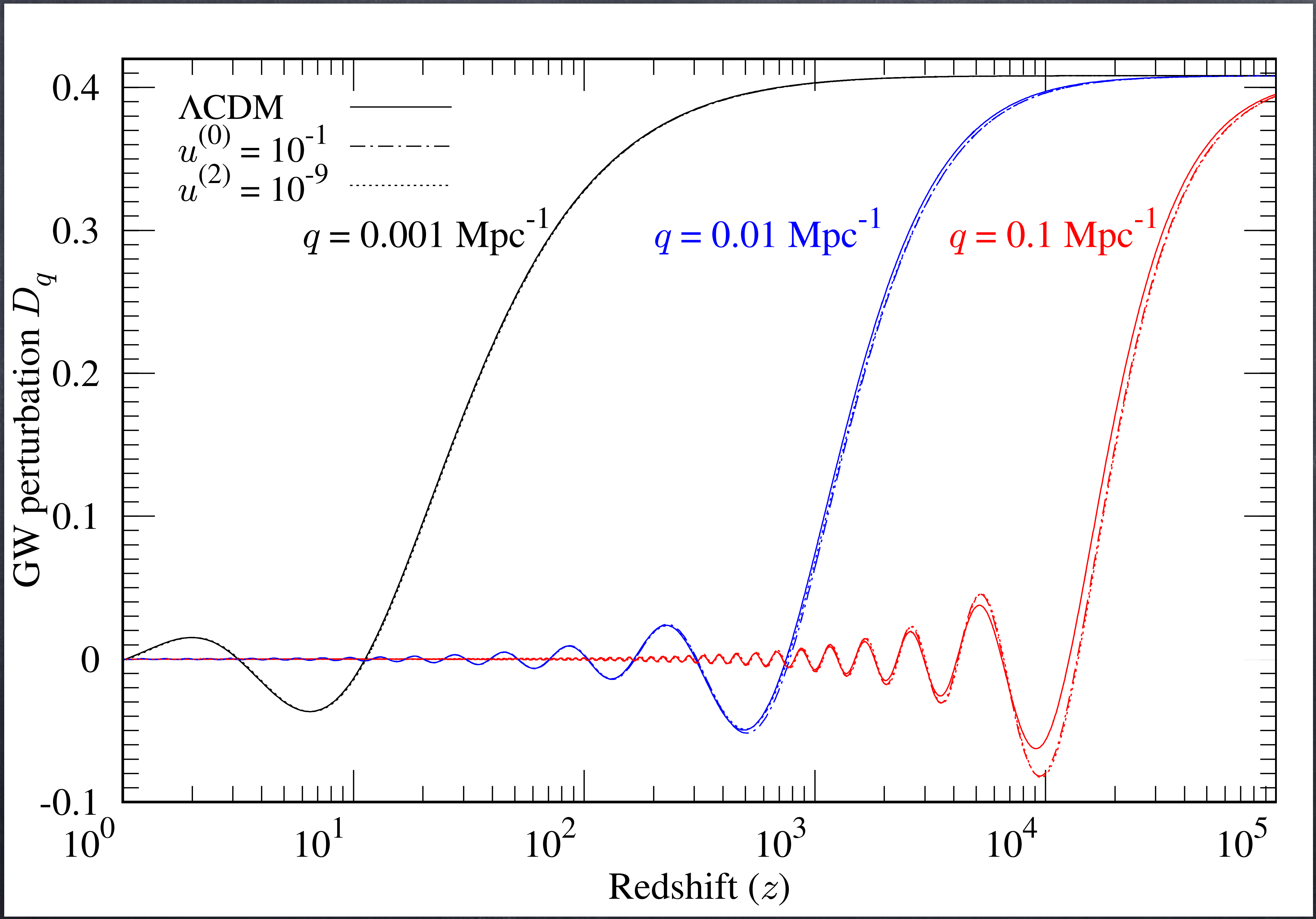




GW wave mode entering horizon here would be enhanced compared to ΛCDM

Modes entering here Will have same Evolution as ΛCDM

Comparison with Hubble

# Evolution of GW



# Review of CMB B mode

Quadrupolar Anisotropy At Last scattering surface $\longrightarrow$ Polarisation in CMB

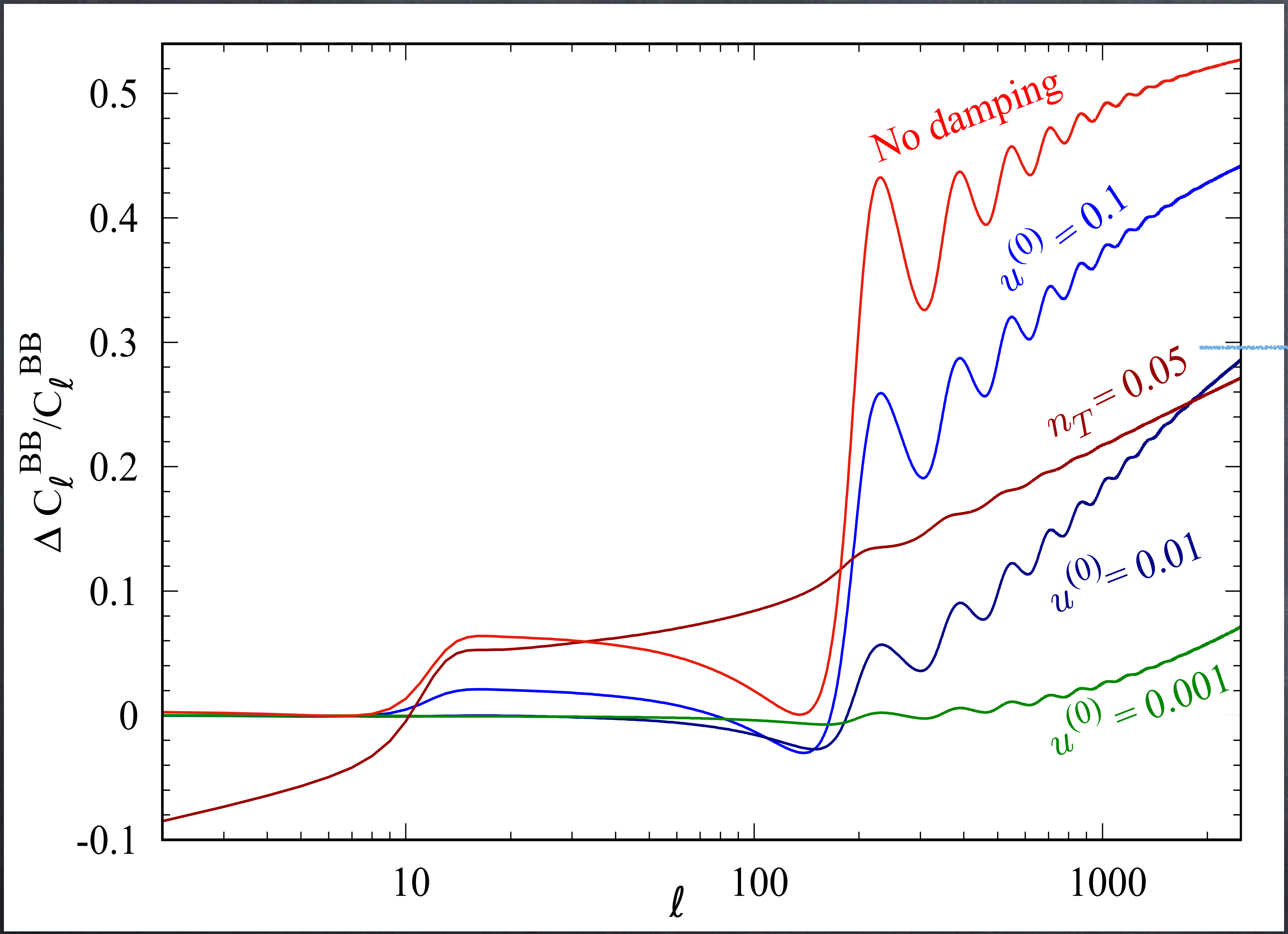
LSS — Today — Z

Polarisation signal of CMB $\xrightarrow{\text{Scalar + tensor (GW)}}$ E mode $\longrightarrow$ E mode

Polarisation signal of CMB $\xrightarrow{\text{tensor (GW)}}$ B mode $\longrightarrow$ B mode

E mode $\xrightarrow{\text{Gravitational lensing}}$ B mode

# CMB B mode (unlensed)




Changing tensor Spectral index

Blue Spectrum

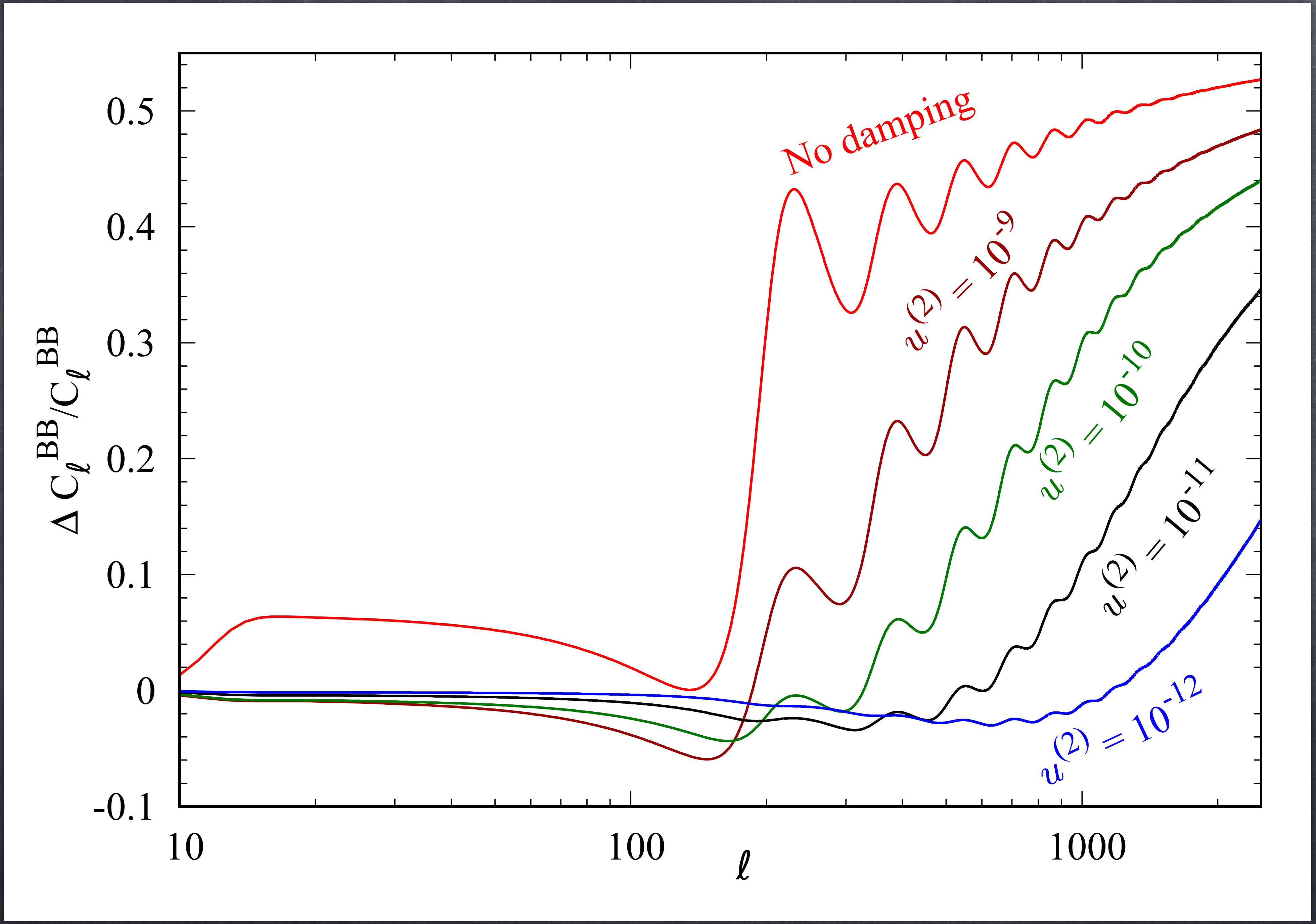
For $\Lambda$CDM $n_T \sim 0$

Used public code CLASS*

Fraction change of CMB BB for $T_\nu$ independent cross-section

*Deigo Blas et al. 2011

# CMB B mode (unlensed)




Fraction change of unlensed CMB BB for $T_\nu^2$ dependent cross-section

# Conclusion

- DM-Neutrino interaction or Neutrino self interaction can stop neutrinos from free streaming even after SM neutrino decoupling.

- Compared to $\Lambda$CDM enhances GW waves at scales which enter horizon before DM-neutrino decoupling.

- Therefore CMB BB mode is enhanced at smaller scale.

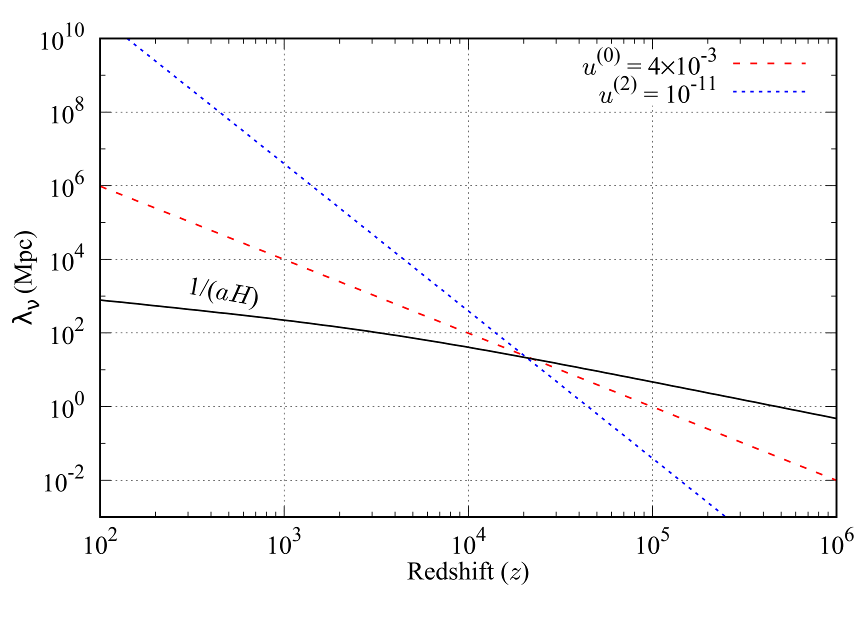
- The new interaction somewhat mimics the blue primordial tensor spectrum

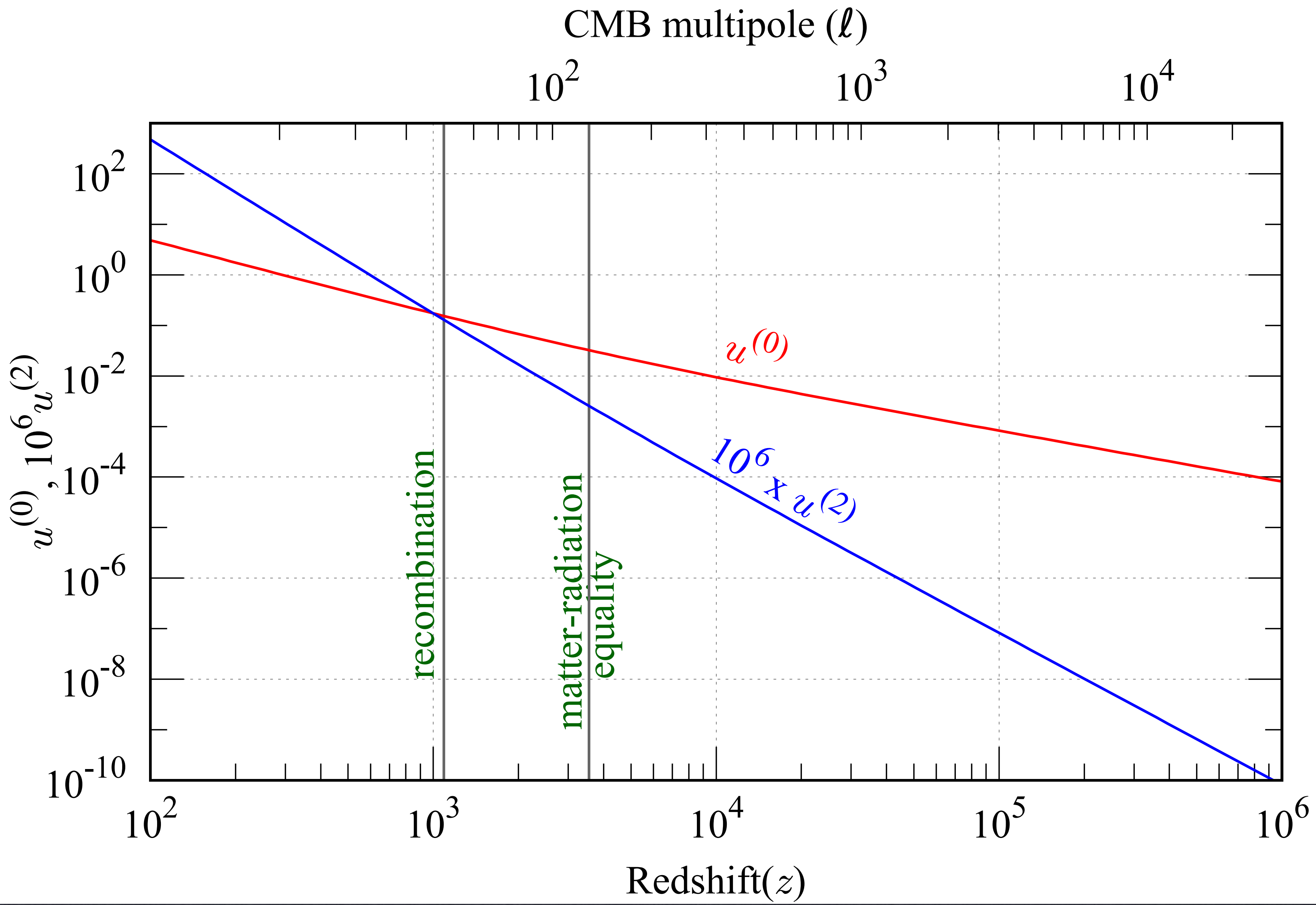
- Disentangling these effects need small scale measurement of B mode and efficient delensing.

Thank You

# Backup

# Mean free path of Neutrino




Comparison with Hubble

Plot of $u^{(0)} (u^{(2)})$

When Hubble = mean free path

# Anisotropic Stress

$$\bar{T}_{\mu\nu} = \bar{p}\bar{g}_{\mu\nu} + (\bar{p} + \bar{\rho})\bar{u}_\mu \bar{u}_\nu$$

$$\delta T_{ij} = \bar{p} h_{ij} + a^2[\delta_{ij}\delta p + \partial_i \delta_j \pi^S + \partial_i \pi_j^V + \partial_j \pi_i^V + \pi_{ij}^T]$$

Anisotropic Stress

$$\partial_i \pi_{ij}^T = 0, \pi_{ii}^T = 0$$

$$\pi_{ij}^T(\mathbf{x}, t) = \sum_{\lambda=\pm 2} \int d^3q \; e^{i\mathbf{q}\cdot\mathbf{x}} \; \beta(\mathbf{q}, \lambda) \; e_{ij}(\hat{q}, \lambda) \; \pi_q^T(t)$$

# Tensor spectral index

$$k^3 P_h(k) = A_* \left(\frac{k}{k_*}\right)^{n_T}$$

Pivot Scale

# CMB B mode

Stokes parameters for CMB $\longrightarrow$ $Q, U$

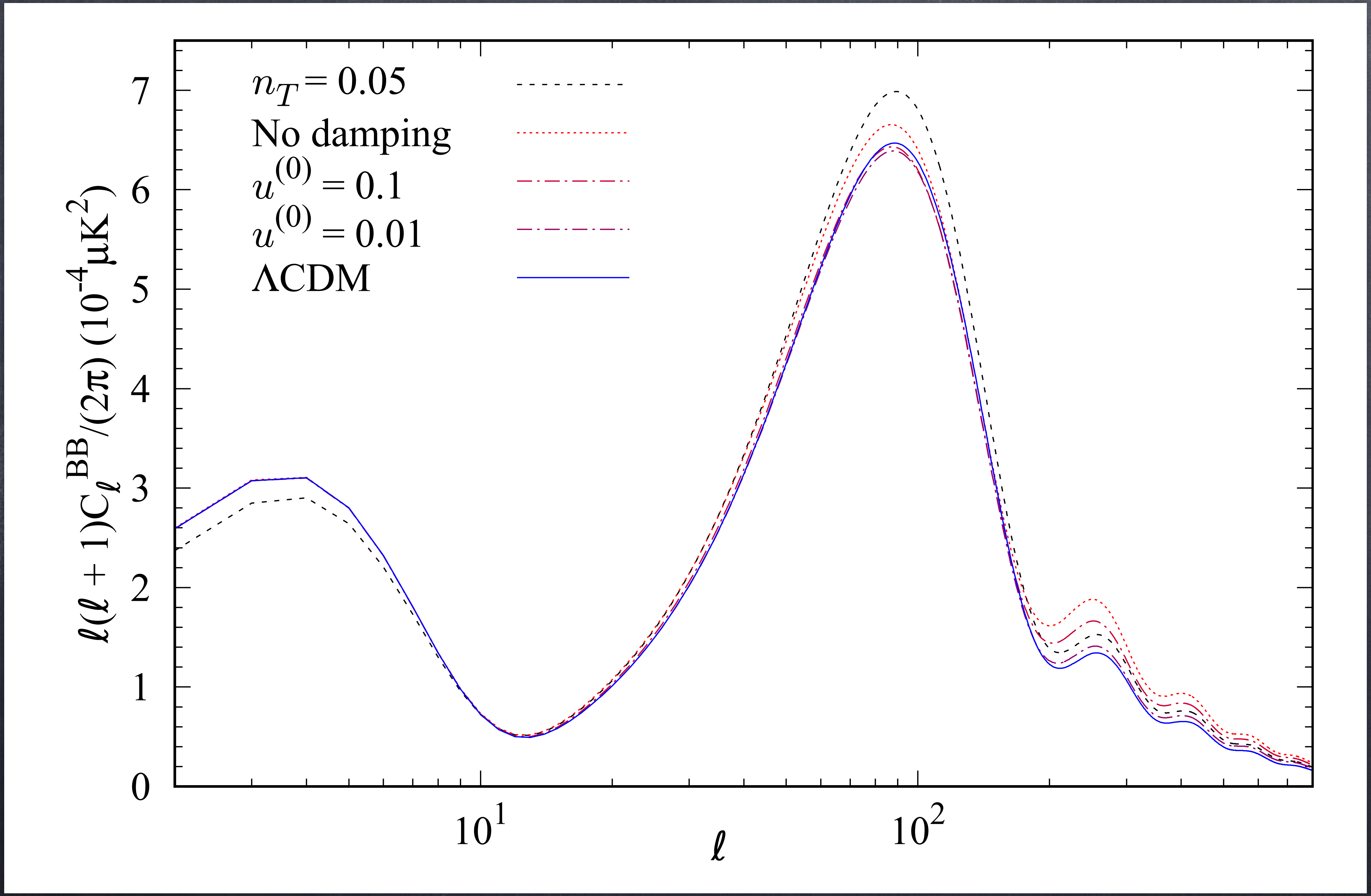
$$(Q \pm iU)(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\pm 2,\ell m} \; {}_{\pm 2}Y_{\ell m}(\hat{\mathbf{n}})$$

$$\begin{aligned} a^E_{\ell m} &= -\frac{1}{2}\left(a_{2,\ell m} + a_{-2,\ell m}\right) \\ a^B_{\ell m} &= -i\frac{1}{2}\left(a_{2,\ell m} - a_{-2,\ell m}\right) \end{aligned}$$

$$C_\ell^{EE} = \langle a^E_{\ell m} a^{*E}_{\ell m} \rangle = \frac{1}{2\ell + 1}\sum_m a^E_{\ell m} a^{*E}_{\ell m}$$

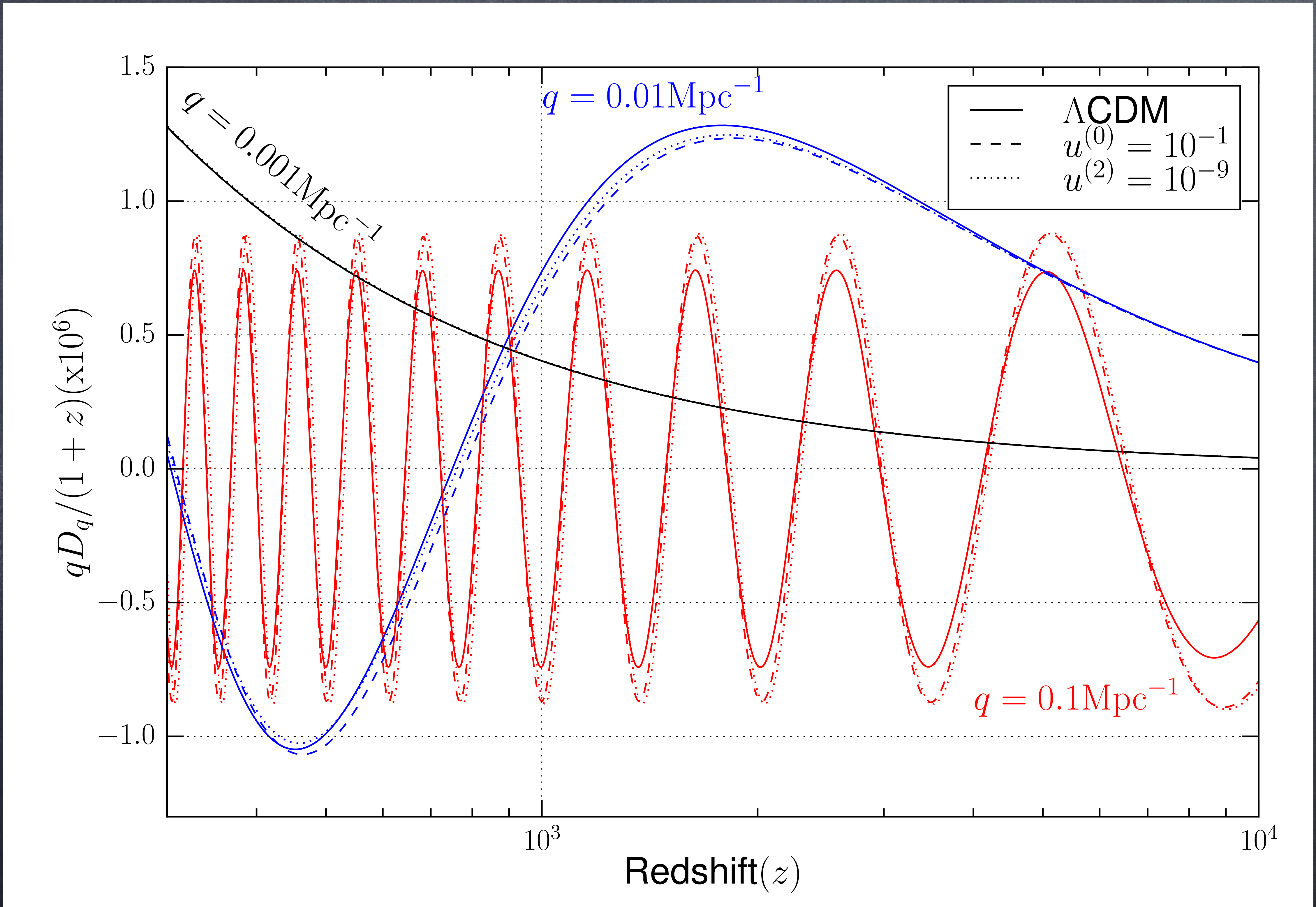
$$C_\ell^{BB} = \langle a^B_{\ell m} a^{*B}_{\ell m} \rangle = \frac{1}{2\ell + 1}\sum_m a^B_{\ell m} a^{*B}_{\ell m}$$

# CMB Spectra

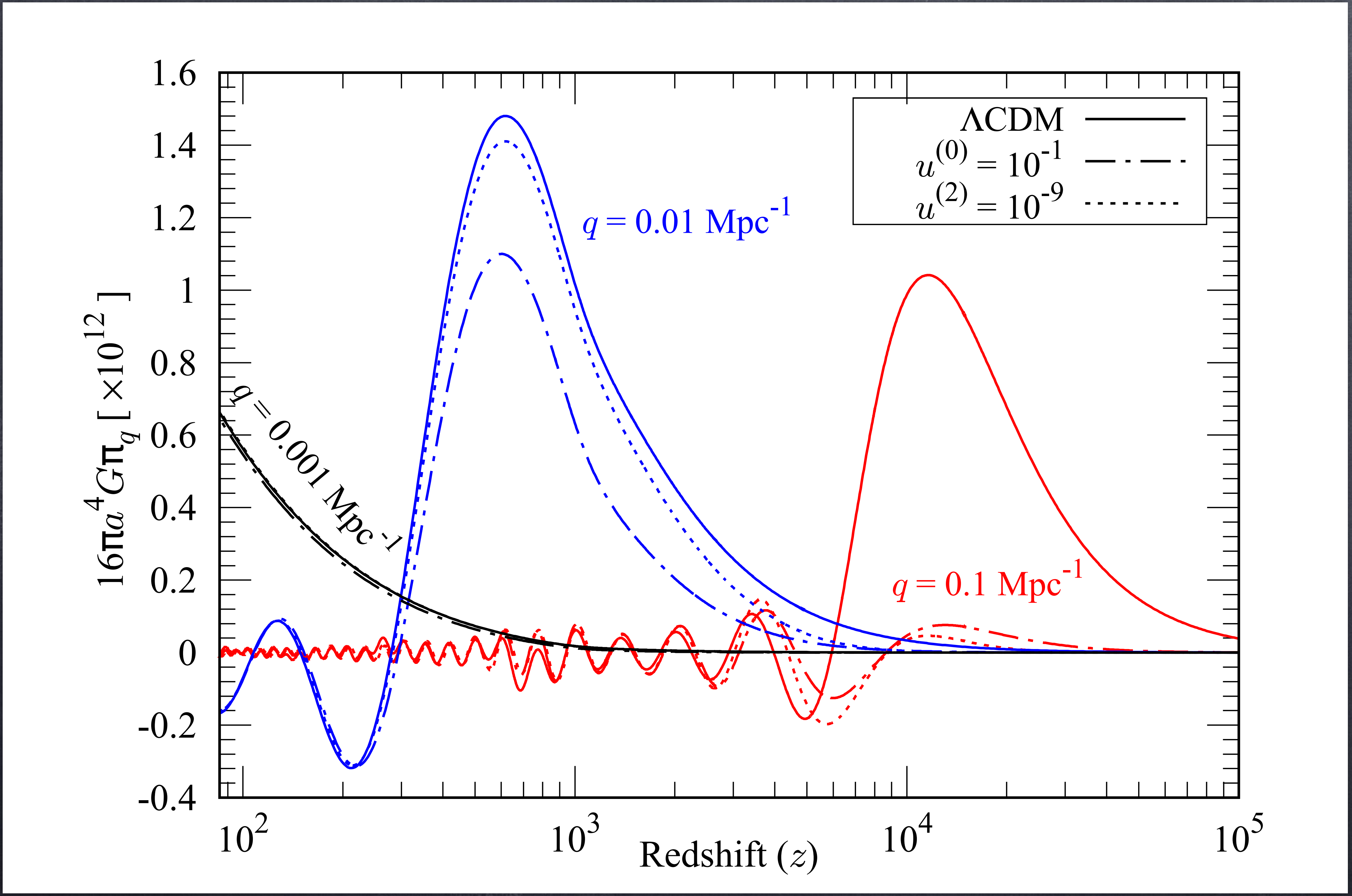


$n_T = 0.05$
No damping
$u^{(0)} = 0.1$
$u^{(0)} = 0.01$
ΛCDM
$\ell(\ell+1)C_\ell^{BB}/(2\pi)\ (10^{-4}\mu K^2)$
0
1
2
3
4
5
6
7
$10^1$
$10^2$
$\ell$

# GW wave spectra



# GW wave source spectra



# Definition

Traceless divergence less metric tensor perturbation

$$D_{ij}(\mathbf{x},t) = \sum_{\lambda=\pm 2} \int d^3q \; e^{i\mathbf{q}\cdot\mathbf{x}} \; \beta(\mathbf{q},\lambda) \; e_{ij}(\hat{q},\lambda) \; \mathcal{D}_q(t)$$

Crosssection of Interaction

$$\sigma^{(0)} \;\simeq\; 10^{-13} \times \sigma_{\mathrm{Th}} \times \left(\frac{\eta}{0.1}\right)^4 \left(\frac{m_\chi}{100\ \mathrm{Gev}}\right)^{-2}$$

$$\sigma^{(2)} \simeq 10^{-39}\,\sigma_{\mathrm{Th}} \left(\frac{\eta}{0.1}\right)^4 \left(\frac{\Delta}{0.1}\right)^{-2} \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^{-4}$$

# Definition

## Neutrino Boltzmann Equations

$$J(\mathbf{x}, \hat{p}, t) = \frac{N_\nu}{a^4 \bar{\rho}_\nu} \int_0^\infty \delta f_\nu(\mathbf{x}, \mathbf{p}, t) 4\pi p^3 dp$$

$$J(\mathbf{x}, \hat{p}, t) = \sum_{\lambda=\pm 2} \int d^3q e^{i\mathbf{q}\cdot\mathbf{x}} \beta(\mathbf{q}, \lambda) e_{ij}(\hat{q}, \lambda) \hat{p}_i \hat{p}_j \Delta_\nu^T(q, \hat{p}\cdot\hat{q}, t)$$

$$\Delta_\nu^T(q, \cos\theta \equiv \hat{p}\cdot\hat{q}, t) = \sum_{l=0}^\infty \frac{1}{i^l}(2l+1) P_l(\cos\theta) \Delta_{\nu,l}^T(q, t)$$

$$\frac{\partial \Delta_{\nu,l}^T(q,\eta)}{\partial \eta} + \frac{q}{(2l+1)} \left[(l+1)\Delta_{\nu,l+1}^T(q,t) - l\Delta_{\nu,l-1}^T(q,t)\right] = \left(-2\frac{\partial \mathcal{D}_q}{\partial \eta}\right)\delta_{l,0} - \dot{\mu}\Delta_{\nu,l}^T(q,\eta)$$

$$\dot{\mu} = a\rho_\chi \sigma^{(0)} \left(\frac{1}{m_\chi}\right) \qquad \text{or} \qquad \frac{1}{a}\rho_\chi \sigma^{(2)} \left(\frac{1}{m_\chi}\right)$$

## Anisotropic Stress in GW equation

$$\pi_{\nu\ q}^T = 2\bar{\rho}_\nu \left[\frac{1}{15}\Delta_{\nu,0}^T + \frac{2}{15}\Delta_{\nu,2}^T + \frac{1}{35}\Delta_{\nu,4}^T\right]$$