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TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Dark Neutrino interactions make Gravitational Waves Blue

Subhajit Ghosh

Department of Theoretical Physics

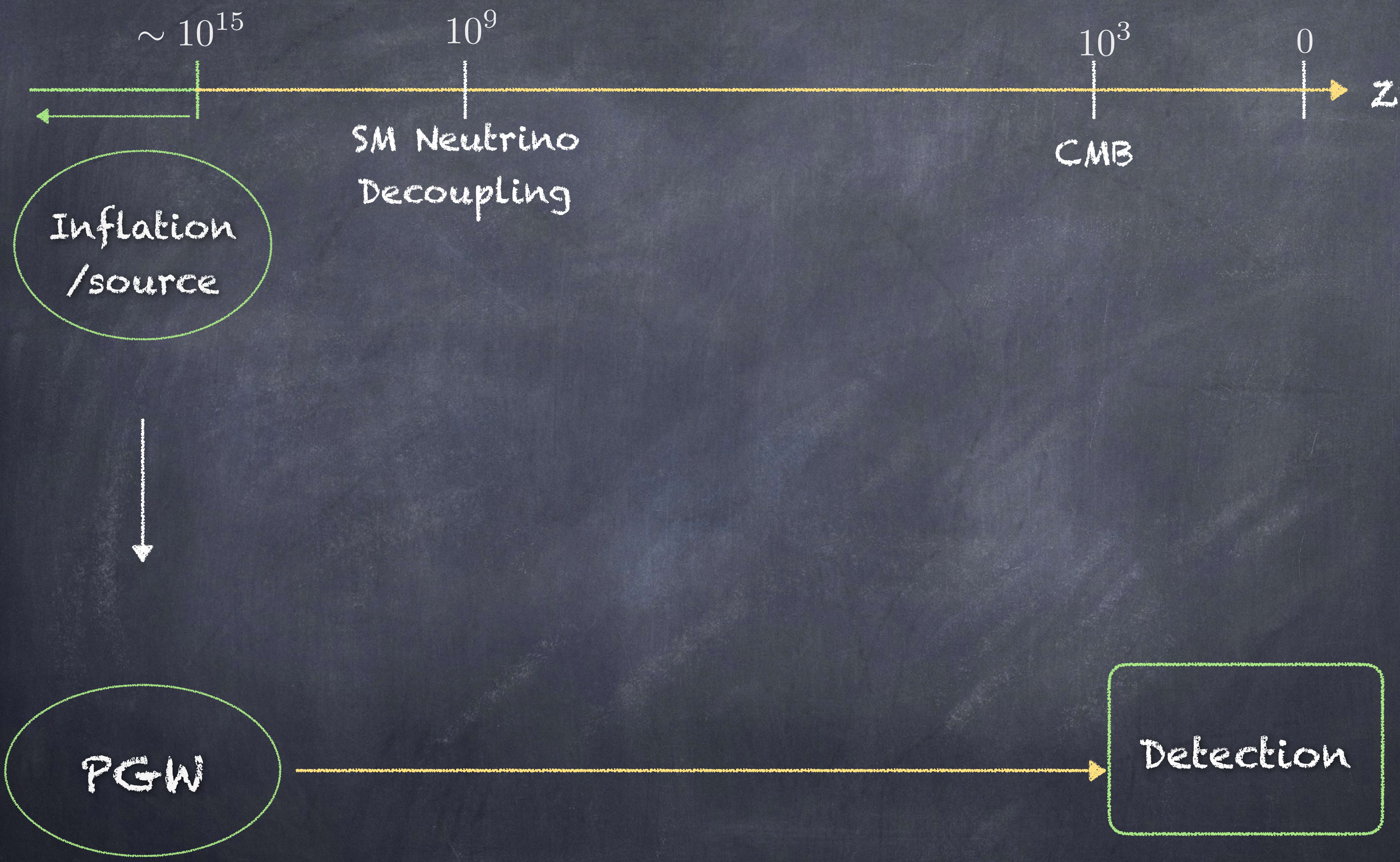
Tata Institute of Fundamental Research (TIFR), INDIA

In collaboration with : Rishi Khatri, Tuhin S. Roy

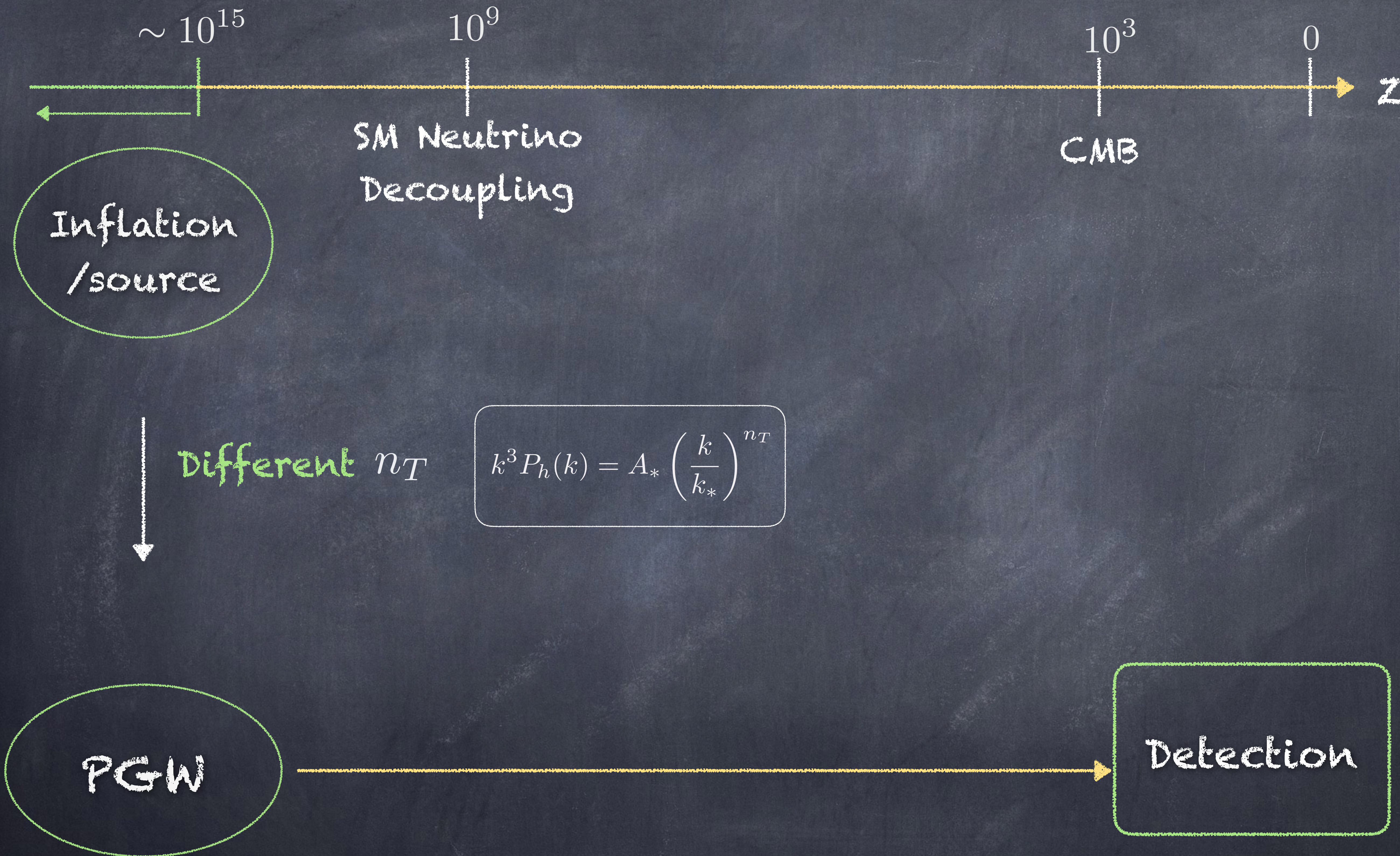
COSMOLOGY - THE NEXT DECADE

Jan 24, 2019

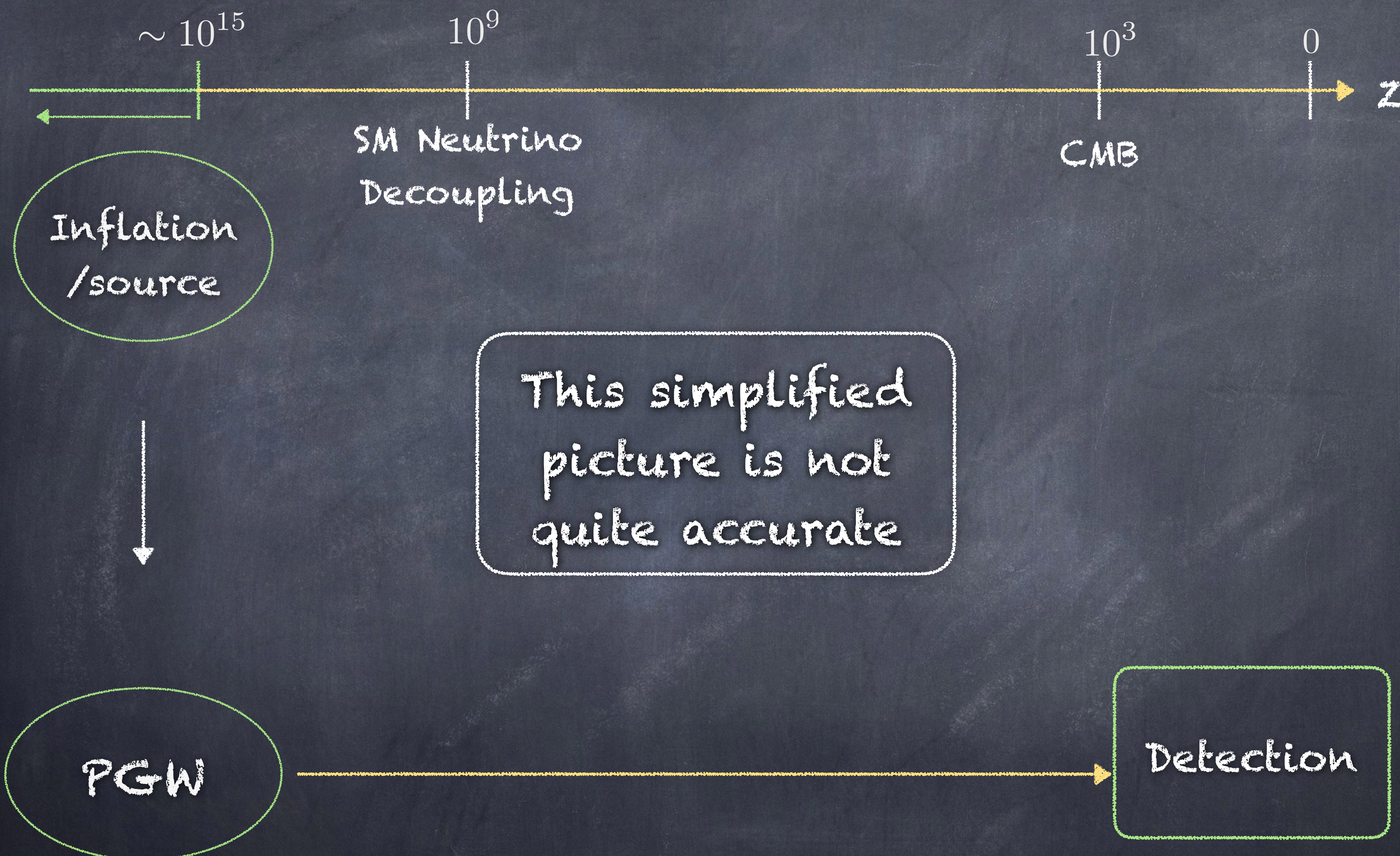
Introduction



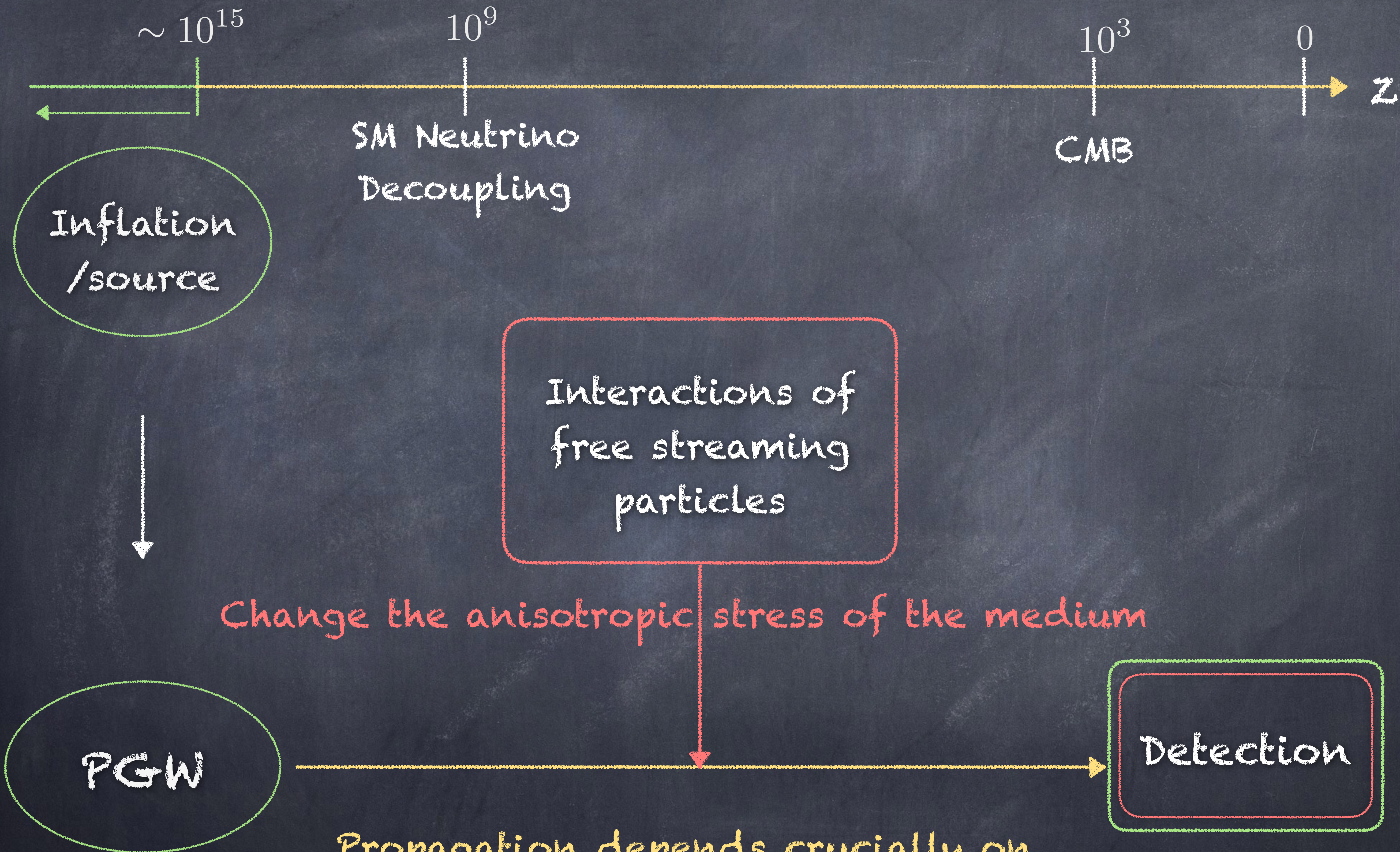
Introduction



Introduction

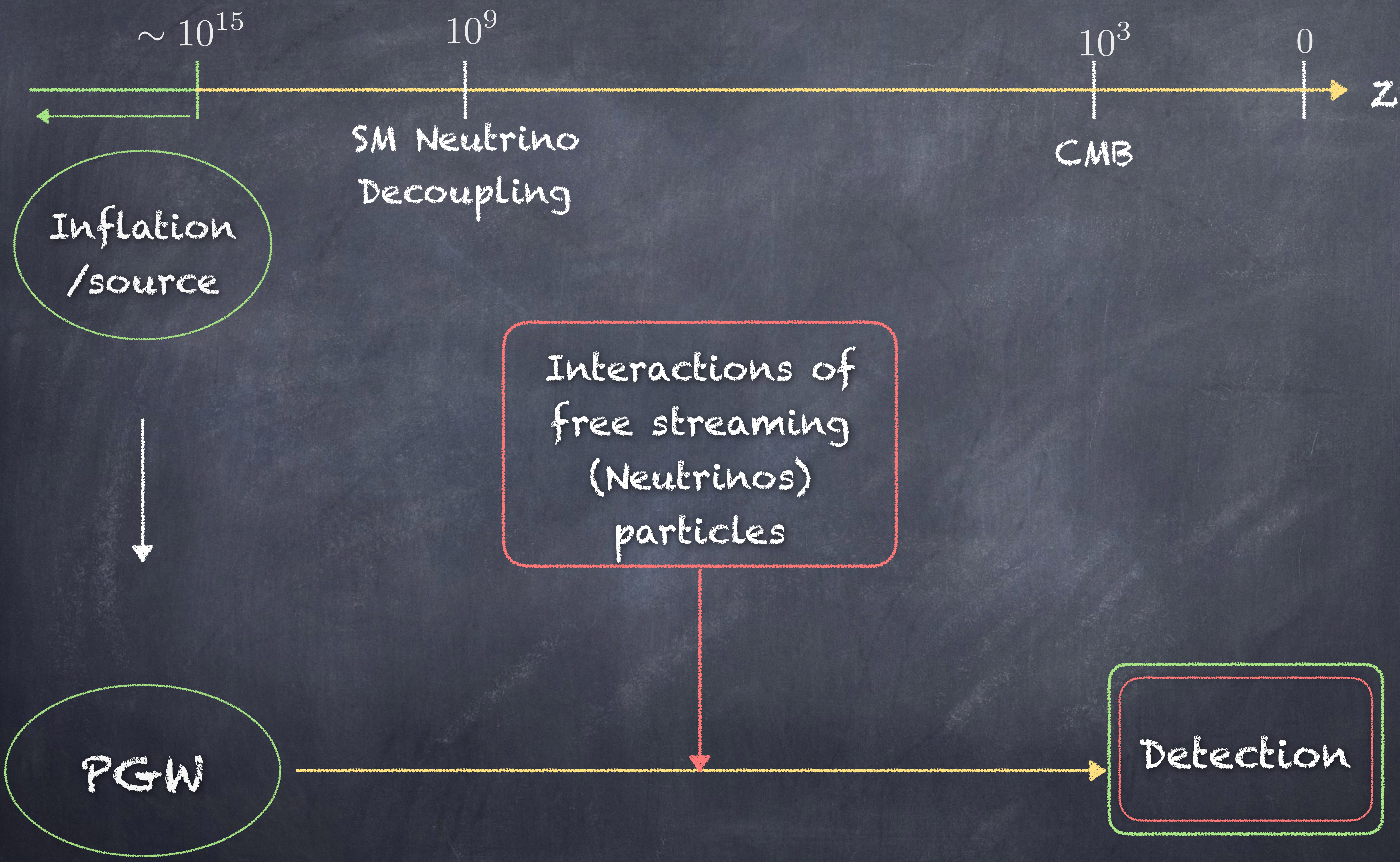


Introduction



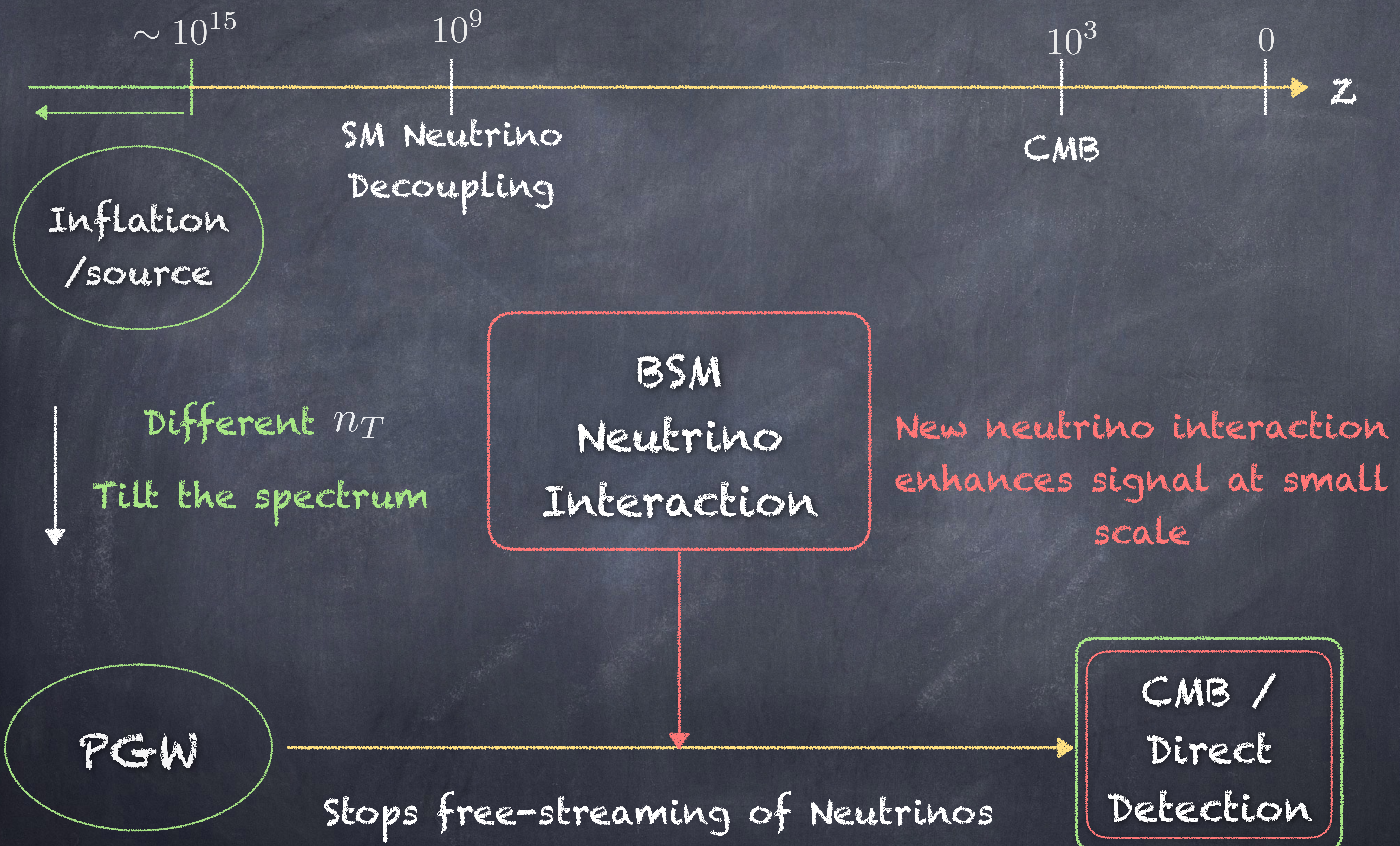
Propagation depends crucially on anisotropic stress of the medium

Introduction



Neutrino interactions modify GW Spectrum

Introduction



$\boxed{\text{There can be significant degeneracy}}$

A model of neutrino interaction

Dark-matter
Neutrino
Interaction

Potentially can also
solve small
scale problems in ΛCDM

Neutrino
self interactions

A model of neutrino interaction

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

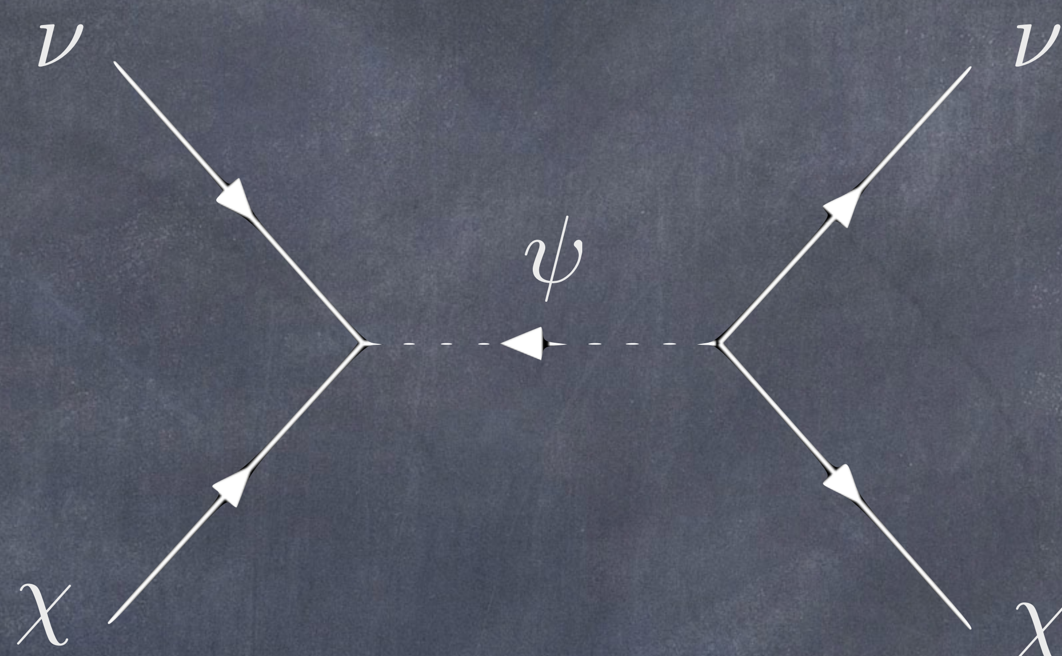
Mediator

DM

Electroweak Symmetry
Breaking

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

A model of neutrino interaction



Dimensionless

$\sigma_{\chi\nu}$

Degenerate mass $\rightarrow$ $\sigma^{(0)}$

Non-degenerate mass $\rightarrow$ $\sigma^{(2)}\left(\frac{T_\nu}{1.95\ \mathrm{K}}\right)^2$

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

$$u^{(2)} = \left(\frac{\sigma^{(2)}}{\sigma_{\mathrm{Th}}}\right)\left(\frac{100\mathrm{Gev}}{m_\chi}\right)$$

Interaction strength

GW Evolution

Dominant contribution
Neutrino

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

GW mode

Anisotropic Stress

Neutrino interaction enhances GW

Dominant contribution

Neutrino

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

GW mode

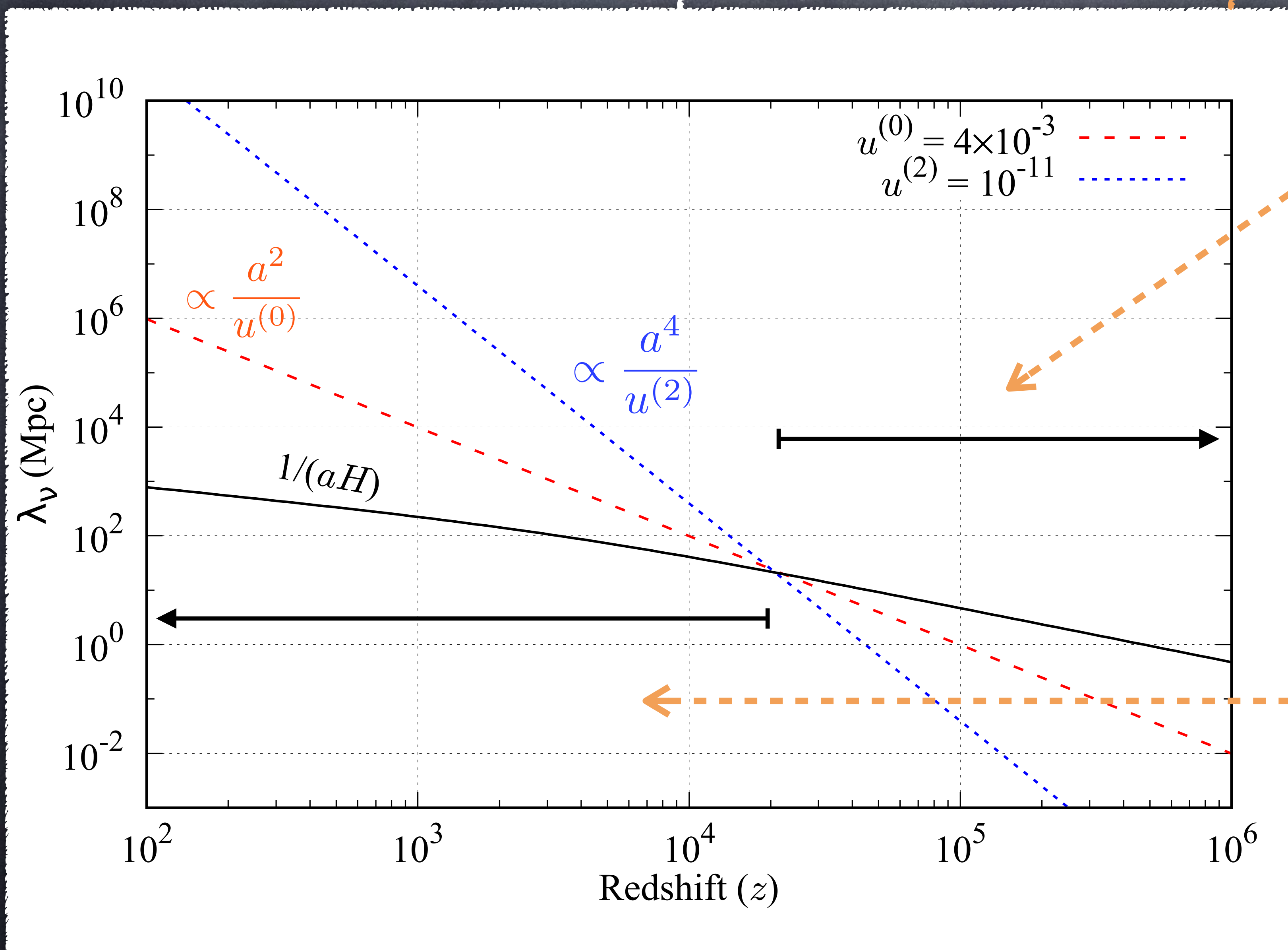
$\boxed{\text{Suppressed due to } \sigma_{\chi\nu}}$

Mean free path of Neutrino

Mean free path = Hubble scale

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

Mean free path of Neutrino

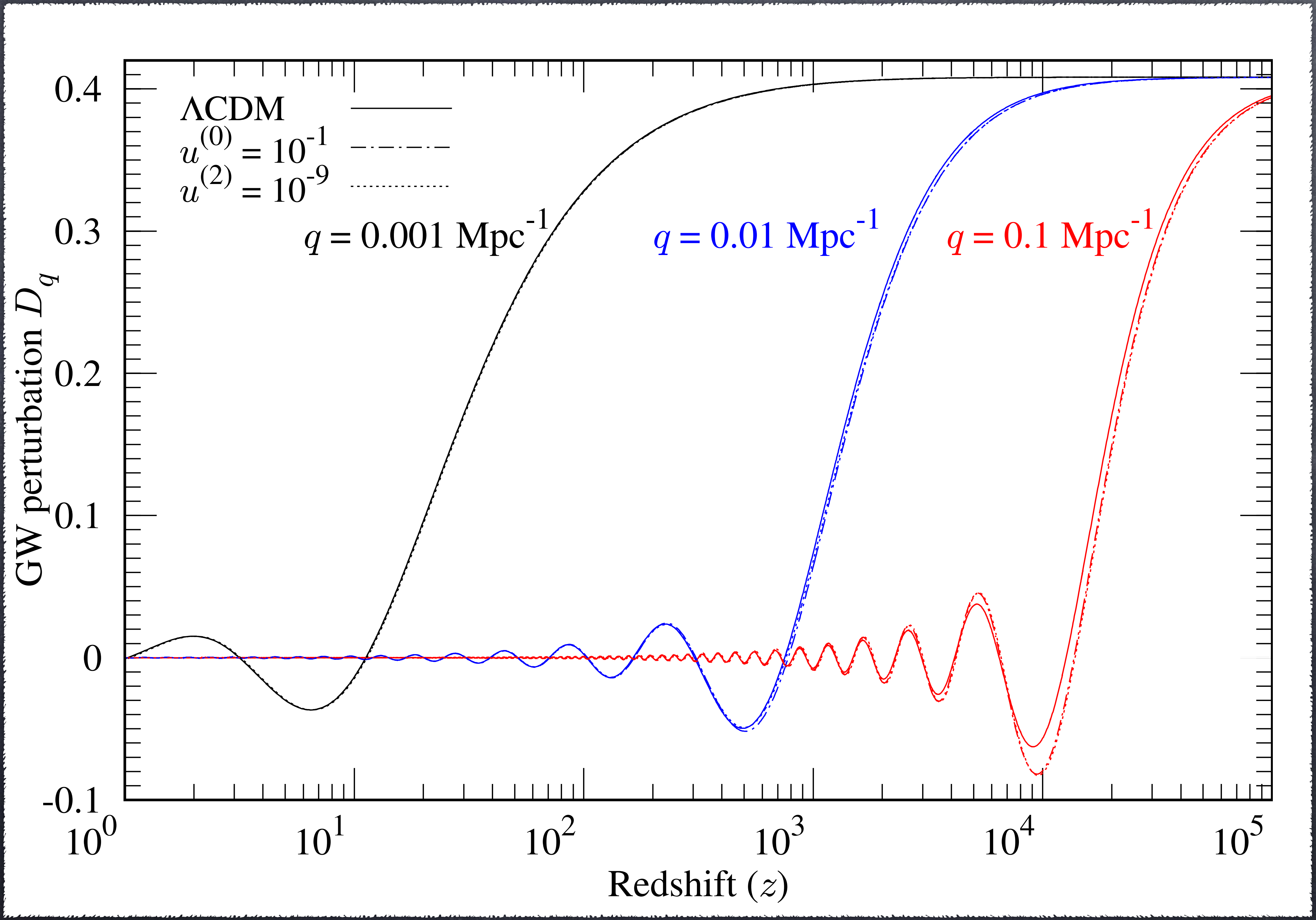


GW wave mode entering horizon here would be enhanced compared to ΛCDM

Modes entering here Will have same Evolution as ΛCDM

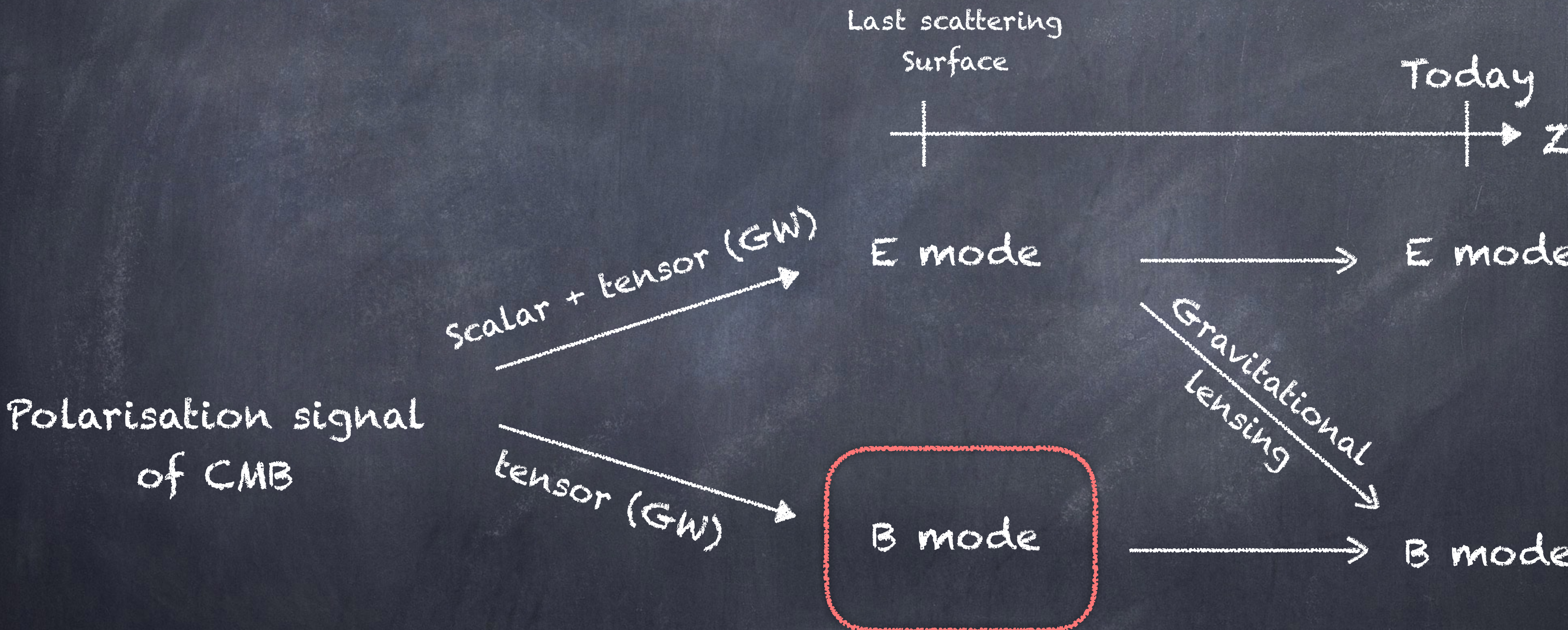
Comparison with Hubble

Neutrino interaction enhances GW

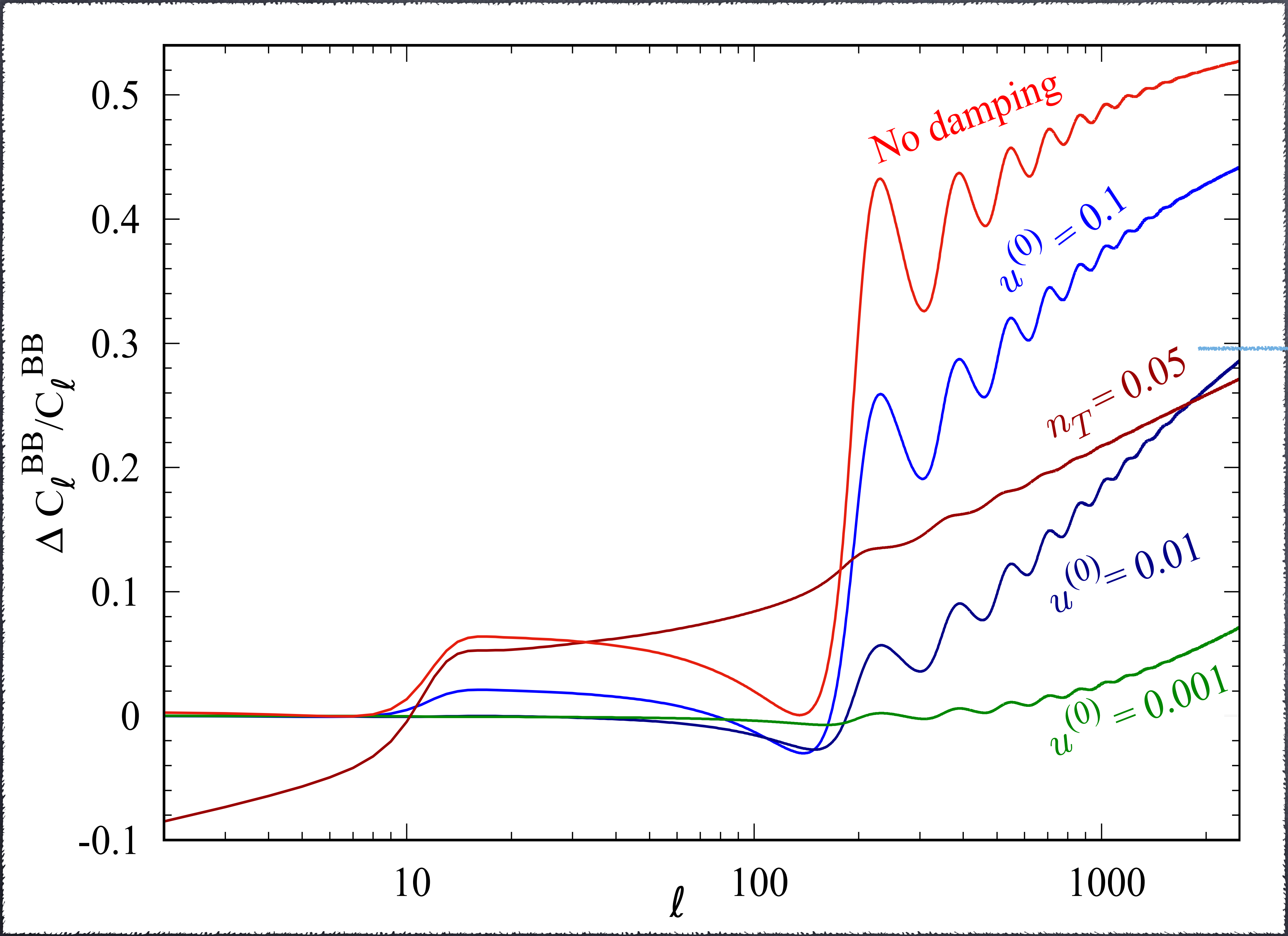


CMB B mode

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



Neutrino interaction enhances B modes at small scale



Changing tensor Spectral index

Blue Spectrum

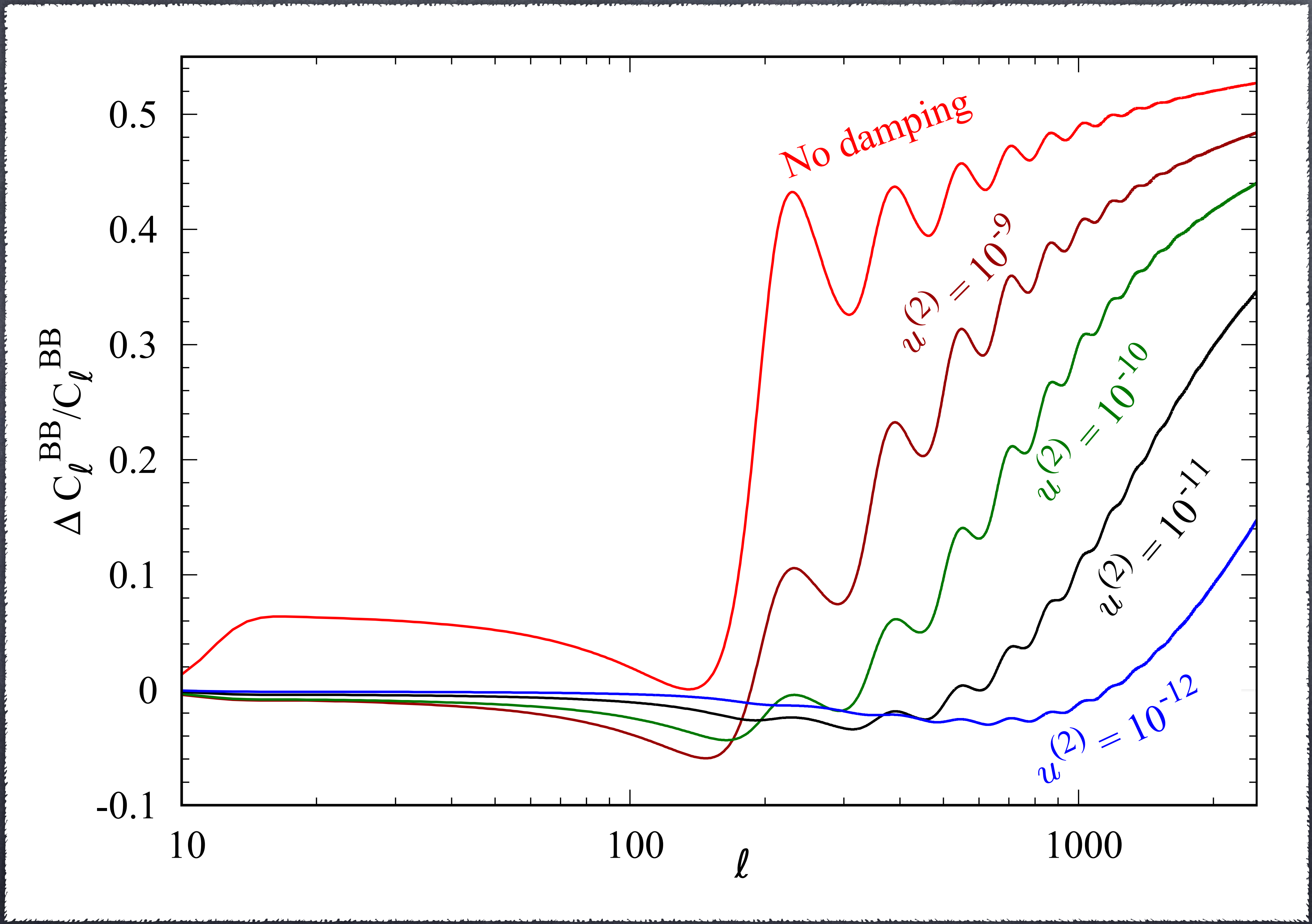
$(n_T > 0)$

For ΛCDM $n_T \sim 0$

Fraction change of CMB BB for T_ν independent cross-section

*SG, Rishi Khatri, Tuhin S. Roy, 2017

Neutrino interaction enhances B modes at small scale



Fractional change of unlensed CMB BB for T_ν^2 dependent cross-section

Key Takeaway

There is rich information (BSM) hidden in the CMB B modes spectrum beyond just the tensor to scalar ratio.

Constraints on DM-Neutrino interaction

Preliminary

CMB Scalar mode constraints [95% CL]

Planck '15	Planck '15 + WiggleZ(LSS) ($k_{\rm max} = 0.12h$ Mpc^{-1})
$u^{(0)} \lesssim 2 \times 10^{-4}$	$u^{(0)} \lesssim 1 \times 10^{-5}$
$u^{(2)} \lesssim 2 \times 10^{-13}$	$u^{(2)} \lesssim 4 \times 10^{-15}$

Constraints of similar magnitude were also derived in
R. J. Wilkinson et al. '14 , M. Escudero et al. '15, E. Valentino et al. '17

Constraints on DM-Neutrino interaction

Preliminary

CMB Scalar mode constraints [95% CL]

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Effect of DM-Neutrino interaction on CMB B mode is very small

Constraints on DM-Neutrino interaction

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~~Effect of DM-Neutrino interaction on CMB B mode is very small~~

not always true

Multicomponent DM

Preliminary

f fraction of total DM interacts with neutrinos
(1-f) fraction is CDM, no neutrino interaction

Scalar mode

$$\delta_{DM} = f\delta_i + (1-f)\delta_{CDM}$$

$$u^{(0)} \rightarrow f u^{(0)}$$

Tensor mode

$$u^{(0)} \rightarrow f u^{(0)}$$

Effective strength of
Neutrino interaction

Multicomponent DM - Enhances GWs

Preliminary

f fraction of total DM interacts with neutrinos
(1-f) fraction is CDM, no neutrino interaction

Scalar mode

$$\delta_{DM} = f\delta_i + (1-f)\delta_{CDM}$$

$$u^{(0)} \to f u^{(0)}$$

Tensor mode

$$u^{(0)} \to f u^{(0)}$$

Effective strength of Neutrino interaction

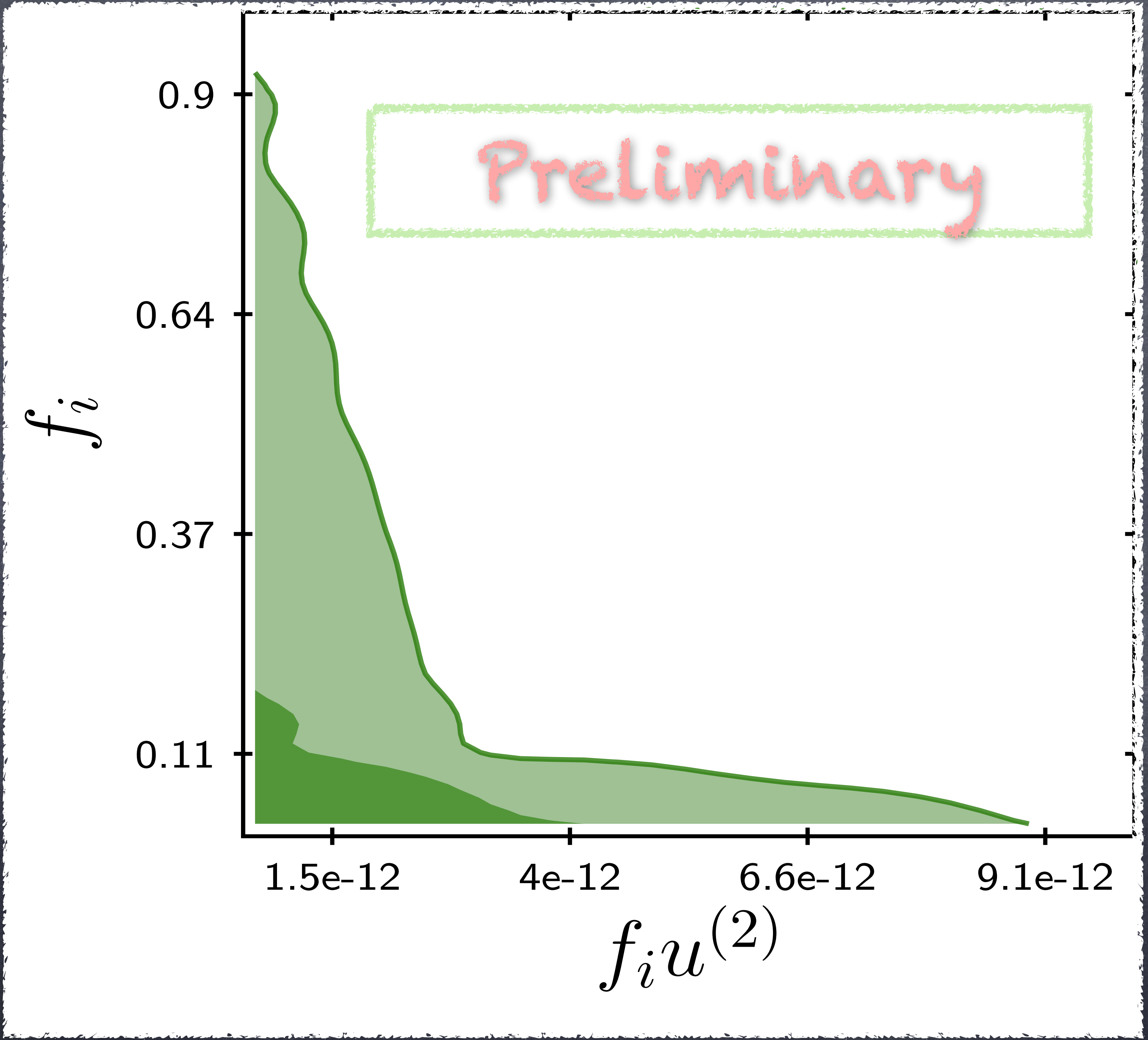
$$\boxed{f \to 0 : f u^{(0)} = \mathrm{const}}$$

Effect from DM power spectrum goes away

Remains unaffected

Multicomponent DM - Enhances GWs

CMB Scalar mode constraints (68% & 95% C.L.)

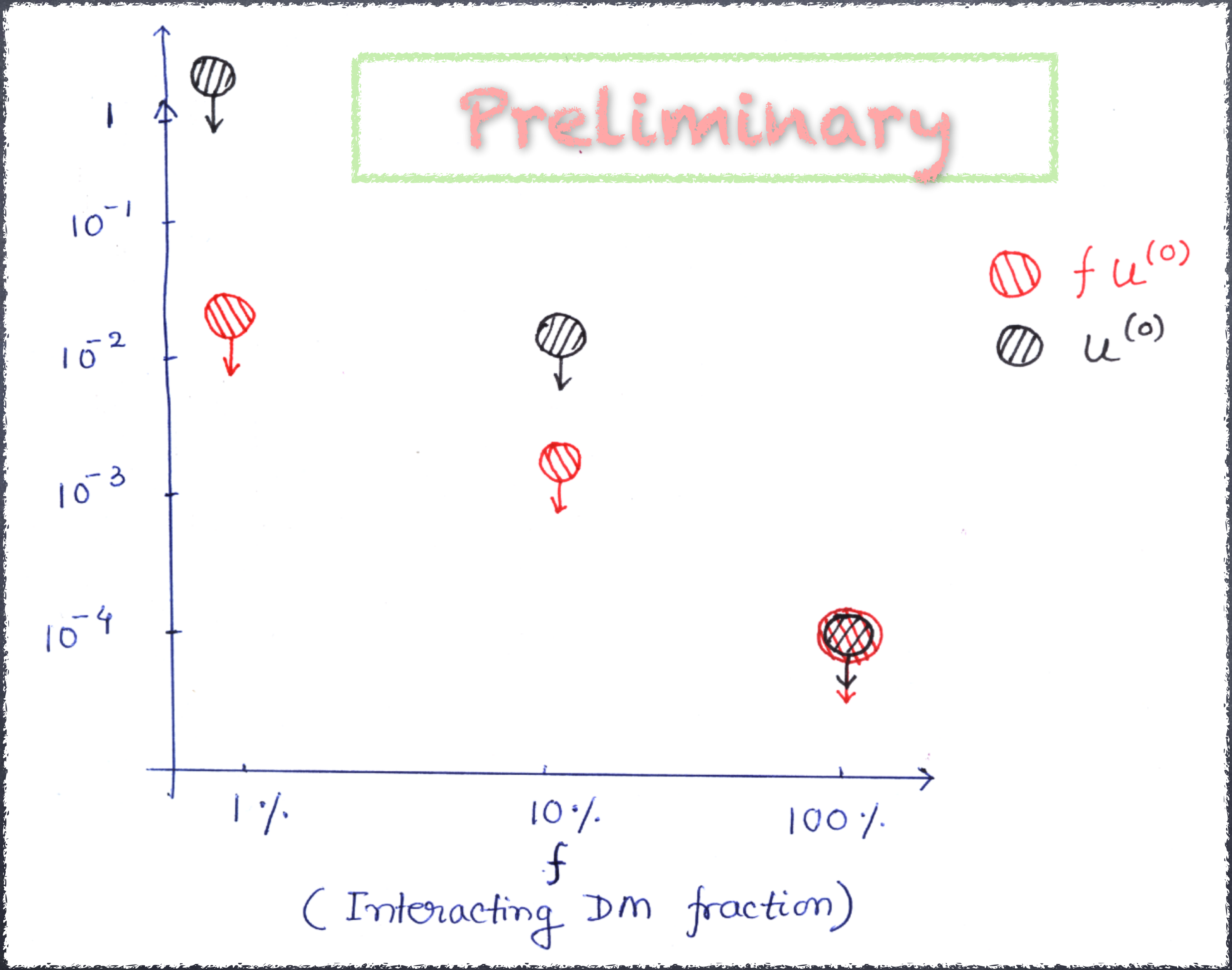


Planck '15 constraints for temperature dependent interaction

*SG, Rishi Khatri, Tuhin S. Roy, in prep.

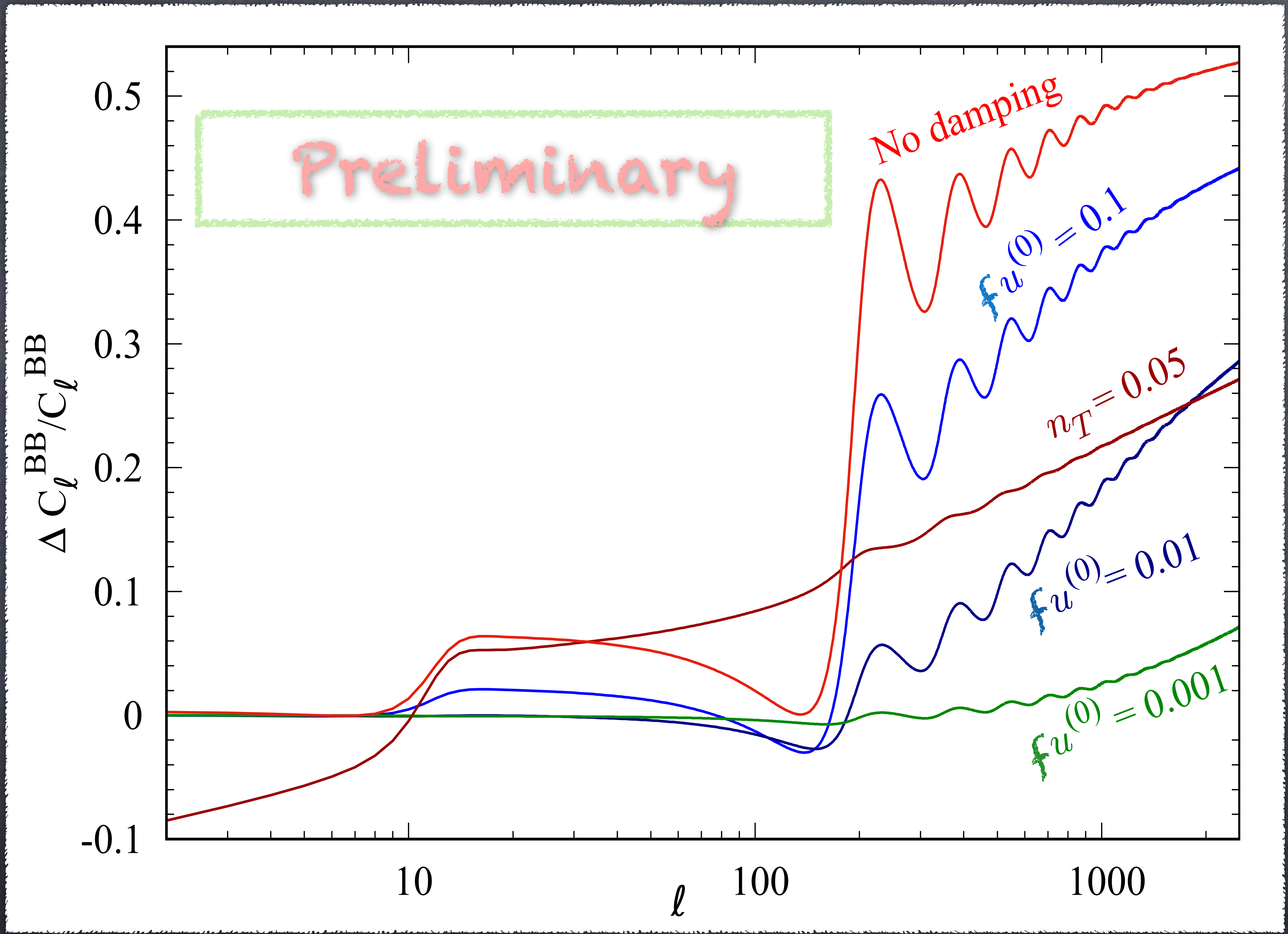
Multicomponent DM - Enhances GWs

CMB Scalar mode constraints (95% C.L.)



Planck '15 constraints for temperature independent interaction

Multicomponent DM - Enhances GWs



Fraction change of CMB BB for T_ν independent cross-section

Conclusion

- DM-Neutrino interaction or Neutrino self interaction can stop neutrinos from free streaming even after SM neutrino decoupling.
- Compared to ΛCDM enhances PGWs 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.
- If Neutrinos interact with small amount of DM, the effect on CMB B mode and GW waves can be enhanced by orders of magnitude.

Thank You

Definition

Traceless divergence less metric tensor perturbation

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

Cross-section of Interaction

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

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

Relation between Interaction parameters

$$y = 0.171 \left(\frac{m}{0.01\ \mathrm{Gev}}\right)^{\frac{3}{4}} u^{\frac{1}{4}}$$

$$y = (0.1)\sqrt{\frac{\Delta}{0.1}}\,\frac{1}{2.54\times 10^{-5}} \left(\frac{m}{0.01\mathrm{Gev}}\right)^{\frac{5}{4}} u_0^{\frac{1}{4}} \qquad \Bigg| \qquad \Delta = \frac{m^2 - m_\phi^2}{m^2}$$

Elaborate conclusion

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

- Compared to ΛCDM 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. Extraction of information about UV physics from CMB B mode can be nontrivial

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

Arxiv:1711.09929

Multicomponent DM

CMB Scalar mode constraints

(Fraction of DM interacting with Neutrino) f $\longrightarrow$	100%	10%	1%
Planck '15	$u^{(0)} \lesssim 2 \times 10^{-4}$ $fu^{(0)} \lesssim 2 \times 10^{-4}$	$u^{(0)} \lesssim 1 \times 10^{-2}$ $fu^{(0)} \lesssim 1 \times 10^{-3}$	$u^{(0)} \lesssim 3$ $fu^{(0)} \lesssim 3 \times 10^{-2}$
Planck '15 + WiggleZ(LSS)	$u^{(0)} \lesssim 1 \times 10^{-5}$ $fu^{(0)} \lesssim 1 \times 10^{-5}$	$u^{(0)} \lesssim 2 \times 10^{-3}$ $fu^{(0)} \lesssim 2 \times 10^{-4}$	$u^{(0)} \lesssim 3$ $fu^{(0)} \lesssim 3 \times 10^{-2}$

Temperature Independent Interaction

Multicomponent DM

CMB Scalar mode constraints

LSS constraints are not very effective for small f

Orders of magnitude enhancement of B mode effect

(Fraction of DM interacting with Neutrino) $f \longrightarrow$	100%	10%	1%
Planck '15	$u^{(0)} \lesssim 2\times 10^{-4}$	$u^{(0)} \lesssim 1\times 10^{-2}$	$u^{(0)} \lesssim 3$
	$fu^{(0)} \lesssim 2\times 10^{-4}$	$fu^{(0)} \lesssim 1\times 10^{-3}$	$fu^{(0)} \lesssim 3\times 10^{-2}$
Planck '15 + WiggleZ(LSS)	$u^{(0)} \lesssim 1\times 10^{-5}$	$u^{(0)} \lesssim 2\times 10^{-3}$	$u^{(0)} \lesssim 3$
	$fu^{(0)} \lesssim 1\times 10^{-5}$	$fu^{(0)} \lesssim 2\times 10^{-4}$	$fu^{(0)} \lesssim 3\times 10^{-2}$

Temperature Independent Interaction

Multicomponent DM

CMB Scalar mode constraints

(Fraction of DM interacting with Neutrino) f $\longrightarrow$	100%	10%	1%
Planck '15	$u^{(2)} \lesssim 2 \times 10^{-13}$	$u^{(2)} \lesssim 9 \times 10^{-12}$	$u^{(2)} \lesssim 2 \times 10^{-10}$
	$fu^{(2)} \lesssim 2 \times 10^{-13}$	$fu^{(2)} \lesssim 9 \times 10^{-13}$	$fu^{(2)} \lesssim 2 \times 10^{-12}$
Planck '15 + WiggleZ(LSS)	$u^{(2)} \lesssim 4 \times 10^{-15}$	$u^{(2)} \lesssim 2 \times 10^{-12}$	$u^{(2)} \lesssim 2 \times 10^{-10}$
	$fu^{(2)} \lesssim 4 \times 10^{-15}$	$fu^{(2)} \lesssim 2 \times 10^{-13}$	$fu^{(2)} \lesssim 2 \times 10^{-12}$

Temperature dependent Interaction

CMB B mode

Stokes parameters for CMB $\longrightarrow$ Q, U

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

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

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

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

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

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

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

Definition

Neutrino Boltzmann Equations

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

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

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

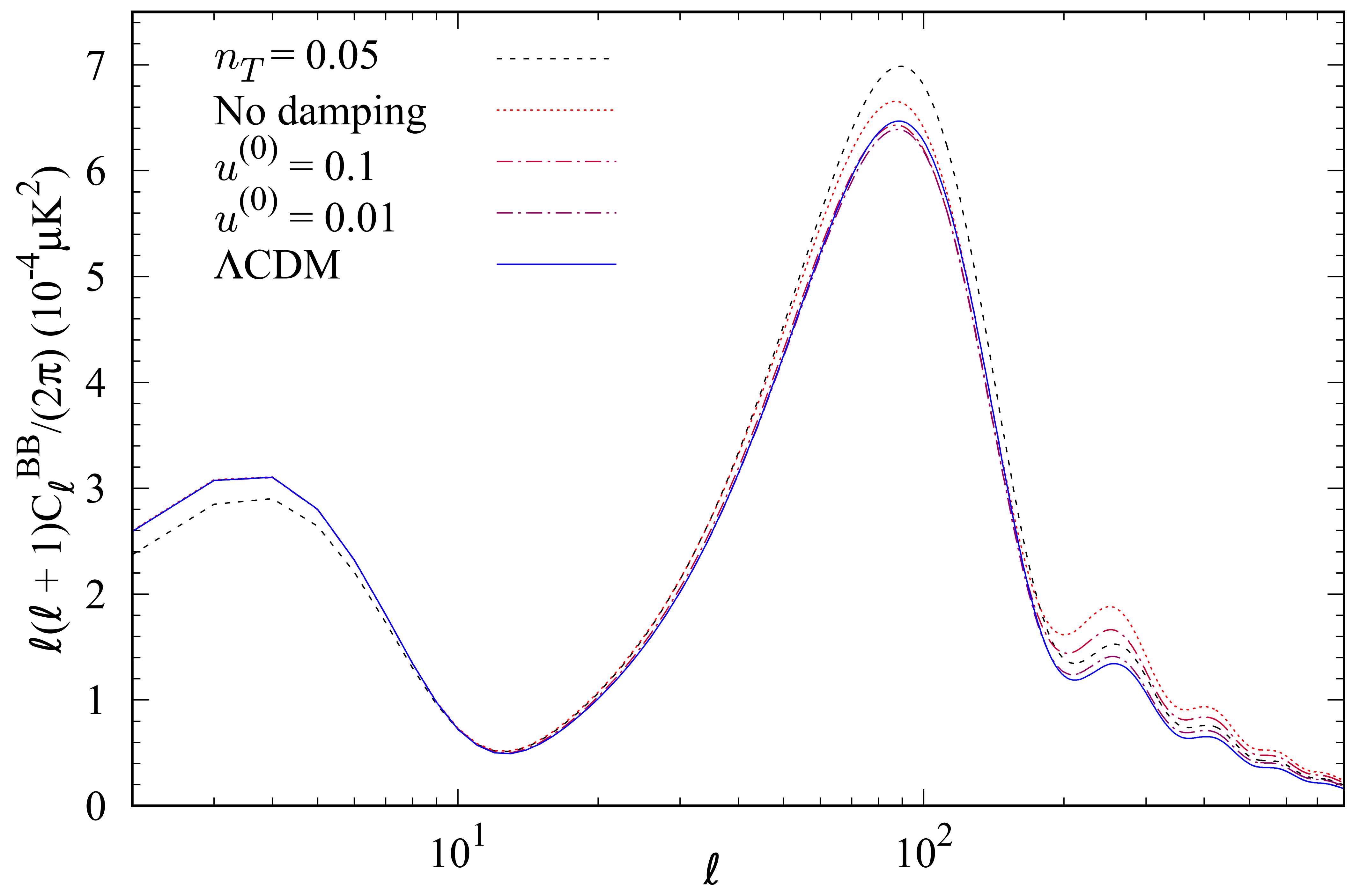
$$\frac{\partial\Delta^T_{\nu,l}(q,\eta)}{\partial\eta} + \frac{q}{(2l+1)}\left[(l+1)\Delta^T_{\nu,l+1}(q,t) - l\Delta^T_{\nu,l-1}(q,t)\right] = \left(-2\frac{\partial\mathcal{D}_q}{\partial\eta}\right)\delta_{l,0}\; -\dot{\mu}\Delta^T_{\nu,l}(q,\eta)$$

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

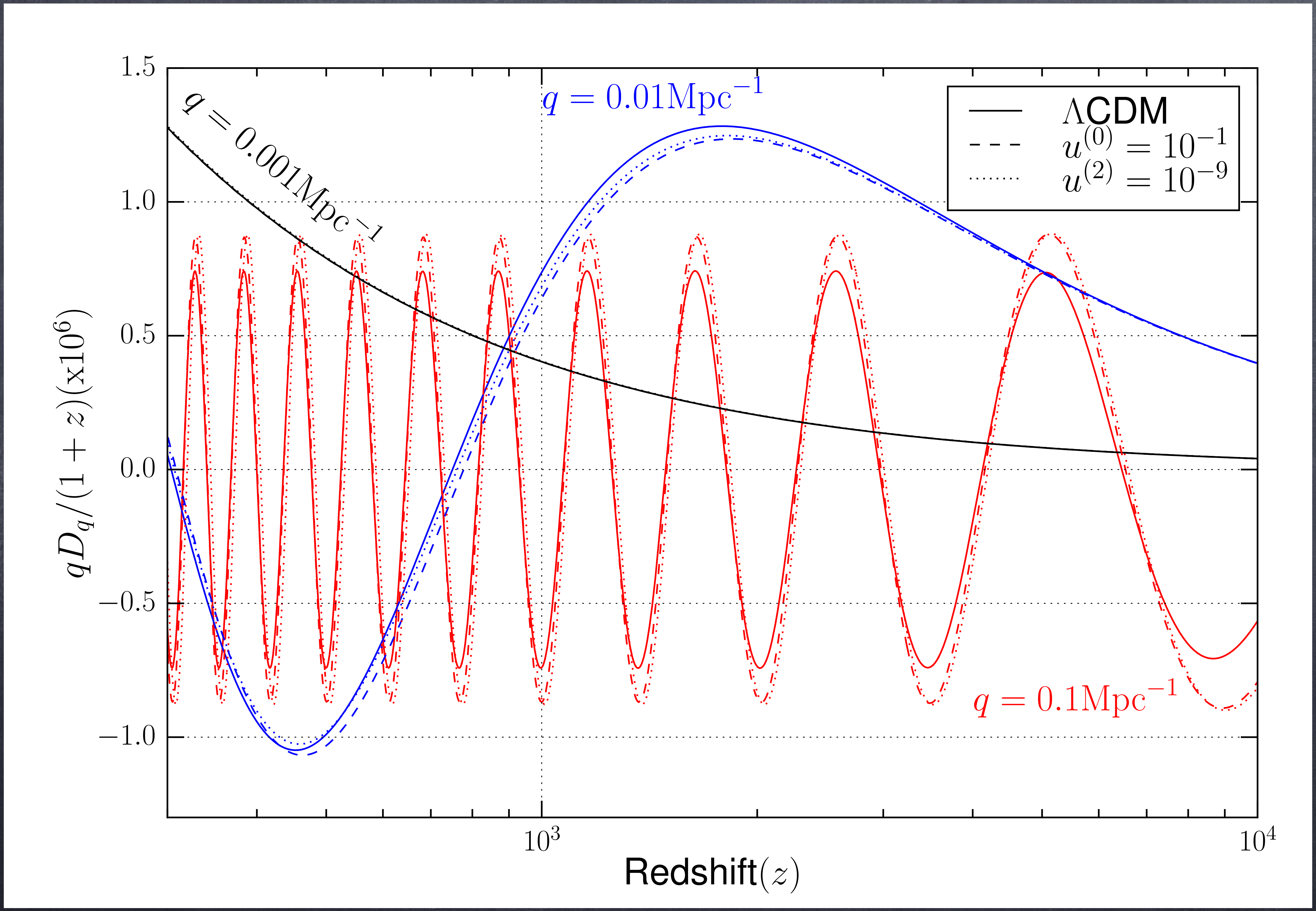
Anisotropic Stress in GW equation

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

CMB Spectra


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

GW wave spectra



GW wave source spectra