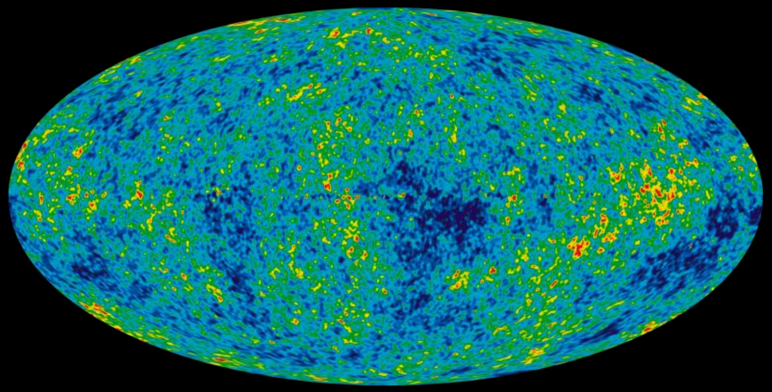
Enhancing CMB Acoustic Phase Shift with Dark Matter Loading



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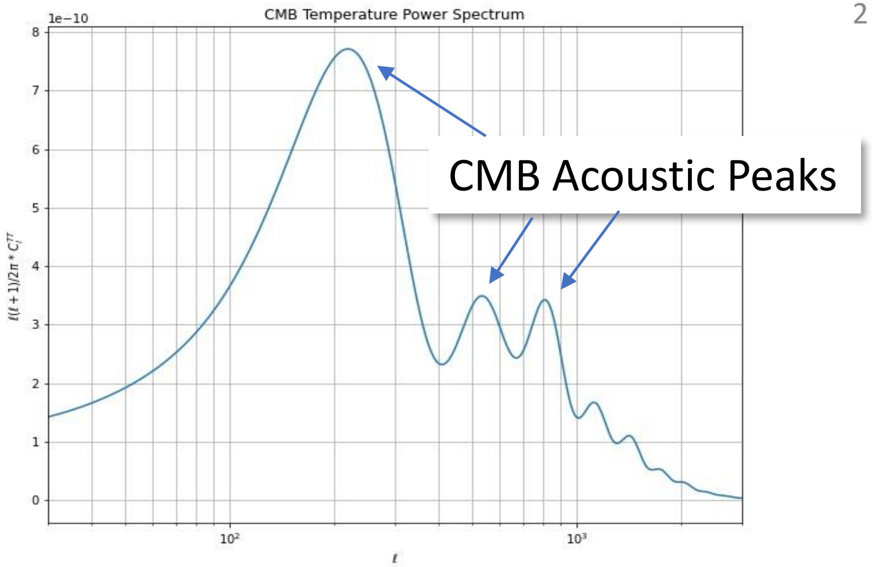
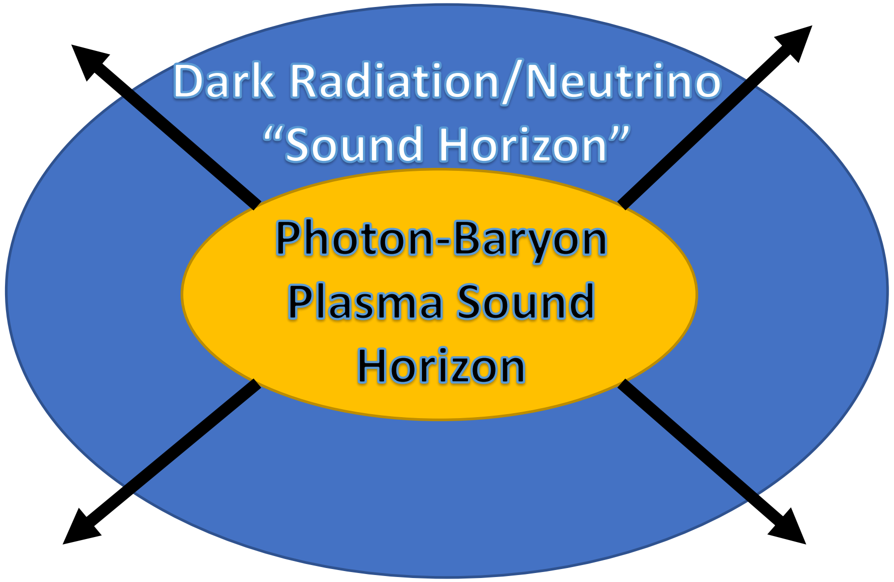
Acoustic Phase Shift

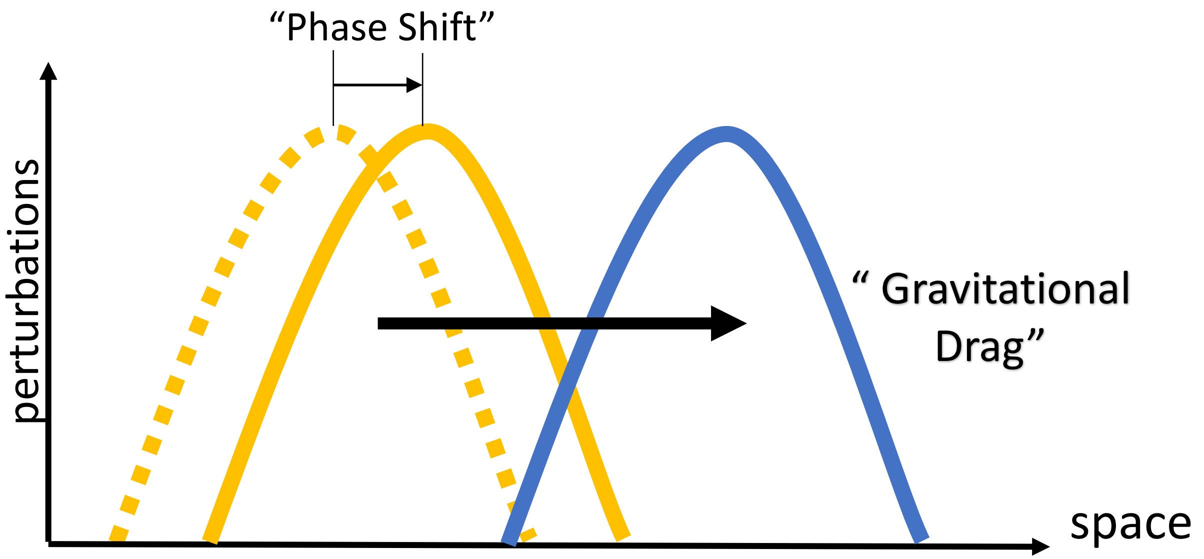
- Radiation pressure in photon-baryon plasma leads to sound (i.e. pressure) waves before recombination – this produces the acoustic peak structure in the CMB power spectrum

- Phase shift produced in acoustic oscillations leads to shift in CMB peak positions



- Limited causes: phase shift produced by **propagation behaviour of dark radiation/neutrinos** (or isocurvature fluctuations). Use this feature to zoom in on specific kinds of new physics

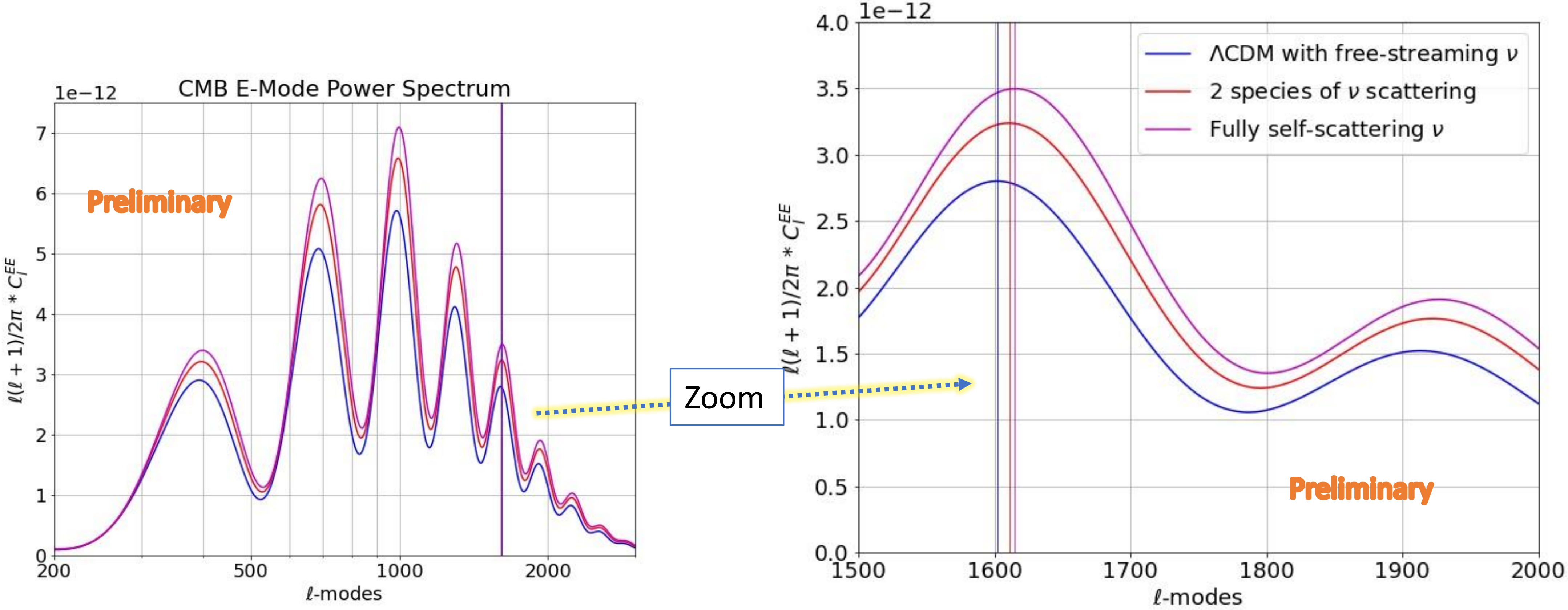




Phase Shift in the CMB

- Phase shift effect in the CMB has been studied before, for when neutrinos are free-streaming vs when they are fluid-like (Ref: Baumann et. al. arXiv:1508.06342v3)

- Compute phase shift in the Cl's w.r.t. Lambda-CDM model with free streaming neutrinos using CLASS: peak positions of CMB power spectrum shift depending on proportion of neutrinos that self-interact



Maximum Phase Shift?

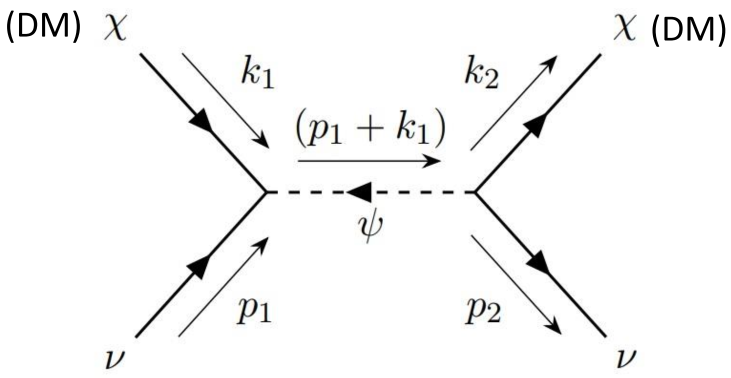
(Q1): Does the fully self-scattering neutrino case produce the *maximum possible* phase shift?

- No. Phase shift can be enhanced with:

"Dark Matter Loading"

- Effect can be produced when dark radiation/neutrinos scatter efficiently with a fraction of the dark matter to form a radiation fluid
  - For maximal effect, suppose from now on that the role of **dark radiation is** played by neutrinos – i.e. no additional radiation component

e.g.



Dark Matter "Loading" Effect

- Sound speed of efficiently scattering radiation-matter fluid:

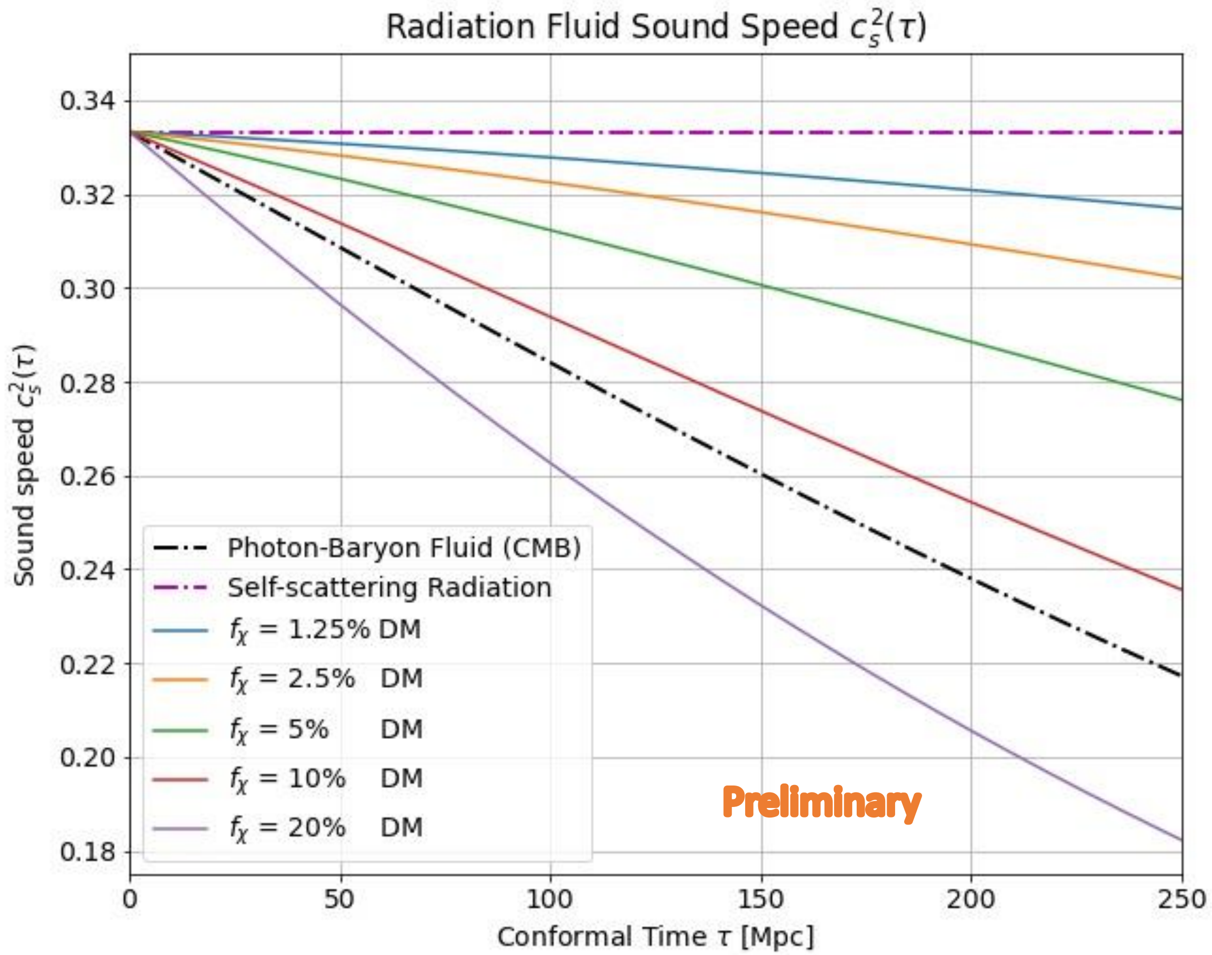
$$c_s(\tau) = \sqrt{\frac{1}{3(1+R(\tau))}} \quad ; \quad R(\tau) = \frac{3}{4}\frac{\rho_{mat}}{\rho_{rad}}$$

- Matter loading effect occurs through energy ratio R(τ), slows down sound speed over time

- f_χ : proportion of total dark matter that scatters with neutrinos, appears in R(τ)

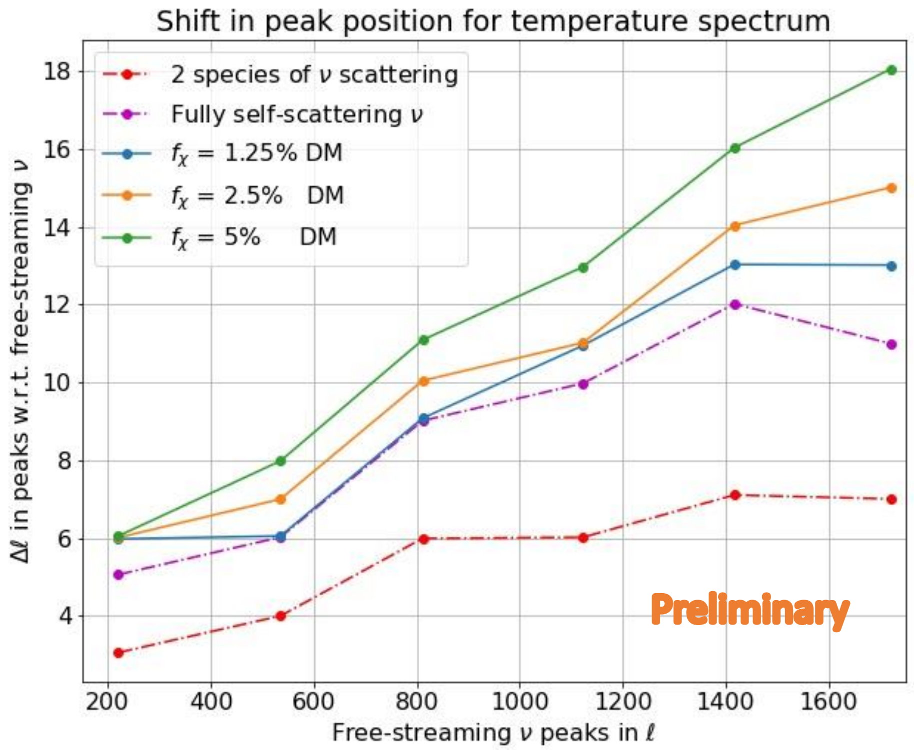
- *Approximate* constraint on f_χ from matter power spectrum suppression: $f_\chi \lesssim 2.5\%$

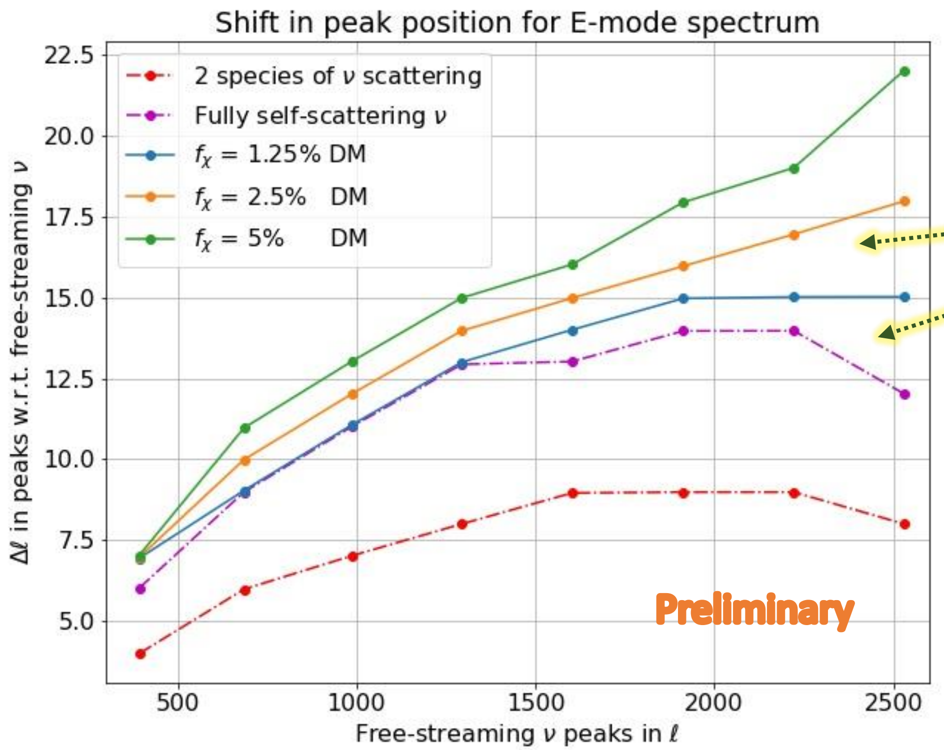
$$(\rho_{mat}, \rho_{rad}) = (\rho_b, \rho_\gamma), (\rho_\chi, \rho_\nu)$$



Observable Enhancement

- Shift in peak positions in temperature and E-mode Cl power spectrum w.r.t. free-streaming neutrinos increases with f_χ (calculated using CLASS)
- Shift for DM-loaded cases significantly larger than the fully self-scattering neutrino case
- Even for the smaller f_χ cases, difference in shift is of order ≈ 1: effect on CMB is observable





Order 1 difference in l-modes

(Q2): Is there a *simple* way to understand what is going on?

Toy Model: Coupled Oscillators

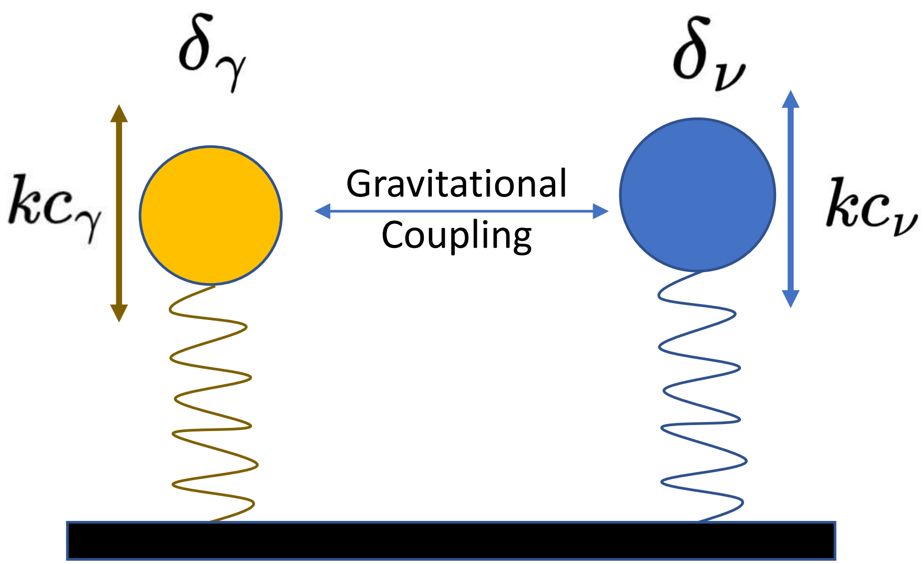
Radiation energy ratios

$$\ddot{\delta}_\gamma(\tau) + k^2 c_\gamma^2(\tau)\delta_\gamma(\tau) = \frac{2}{\tau^2}(f_\gamma\delta_\gamma(\tau) + f_\nu\delta_\nu(\tau)))$$

$$\ddot{\delta}_\nu(\tau) + k^2 c_\nu^2(\tau)\delta_\nu(\tau) = \frac{2}{\tau^2}(f_\gamma\delta_\gamma(\tau) + f_\nu\delta_\nu(\tau)))$$

Radiation Era

- (Highly) simplified model derived from the cosmological perturbation equations
- Tight coupling approximation for coupled photon-baryon and neutrino-DM system respectively
- Simplified gravitational coupling as Poisson equation with Hubble pre-factor



Toy Model: Qualitative Picture

$$\ddot{\delta}_\gamma(\tau) + k^2 c_\gamma^2(\tau)\delta_\gamma(\tau) = \frac{2}{\tau^2}(f_\gamma \delta_\gamma(\tau) + f_\nu \delta_\nu(\tau)))$$

$$\ddot{\delta}_\nu(\tau) + k^2 c_\nu^2(\tau)\delta_\nu(\tau) = \frac{2}{\tau^2}(f_\gamma \delta_\gamma(\tau) + f_\nu \delta_\nu(\tau)))$$

Radiation Era

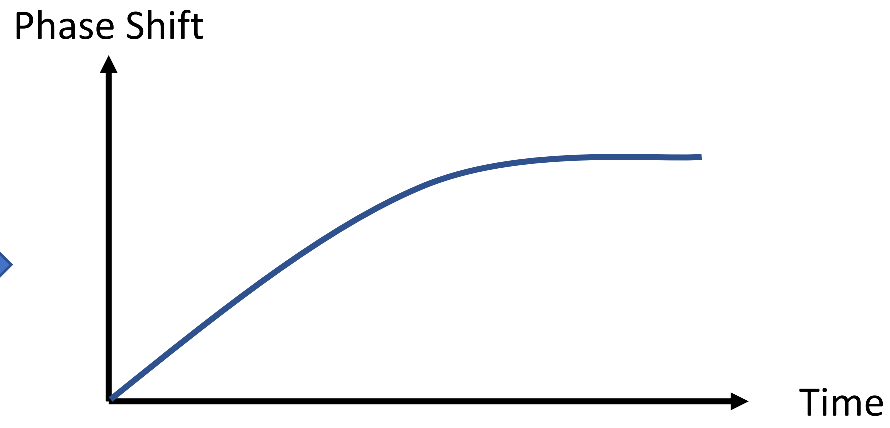
- Two competing effects on coupling between oscillators:
  1. Hubble decreases with time: coupling weakens

     $$\mathcal{H}(\tau) \sim \frac{1}{\tau}$$

  2. Energy ratio increases with time: frequency difference between oscillators grow

     $$R(\tau) = \frac{3}{4}\frac{f_{mat}}{f_{rad}}\frac{a(\tau)}{a_{eq}}$$

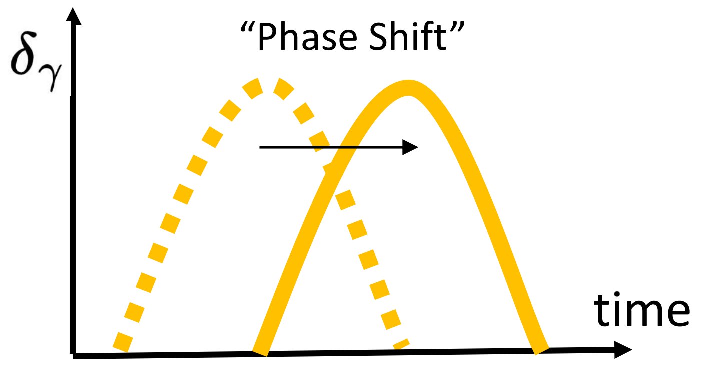
Expectation



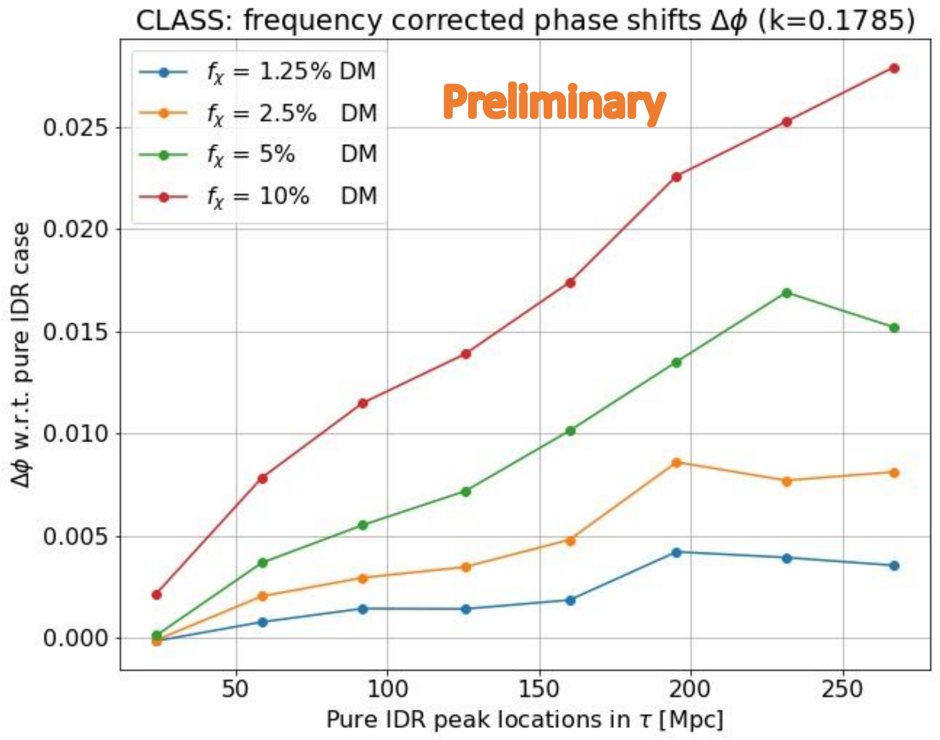
Expectation

Matter effect: dependent on f_χ

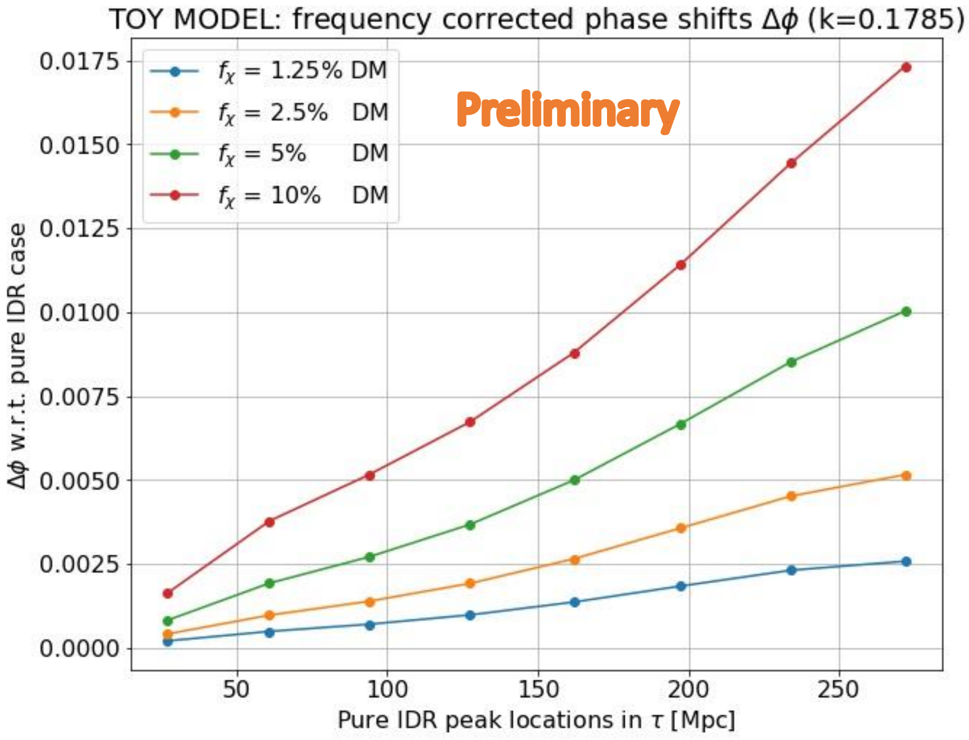
Enhancement Over Time



- Compute shift in peaks w.r.t. pure self-scattering neutrinos
- Compare <u>time evolution</u> of phase shifts from toy model with exact CLASS results
- Captures *qualitative trend* (up to y-scaling) of phase shift produced in photon oscillations over time: flattening at later time more obvious for smaller f_χ but phase shift grows for larger f_χ

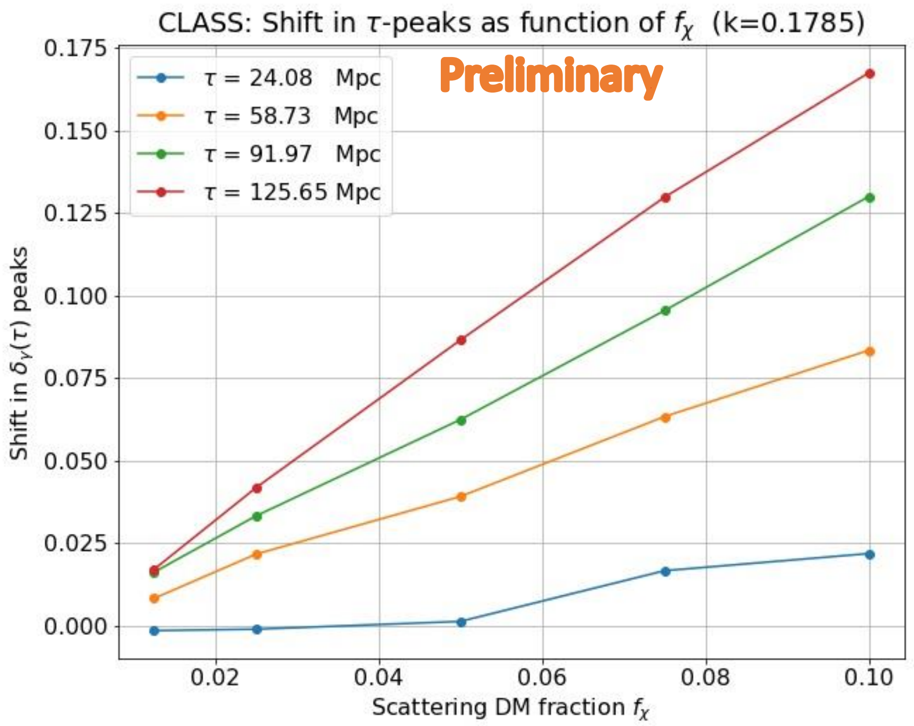


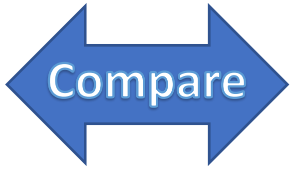
Compare

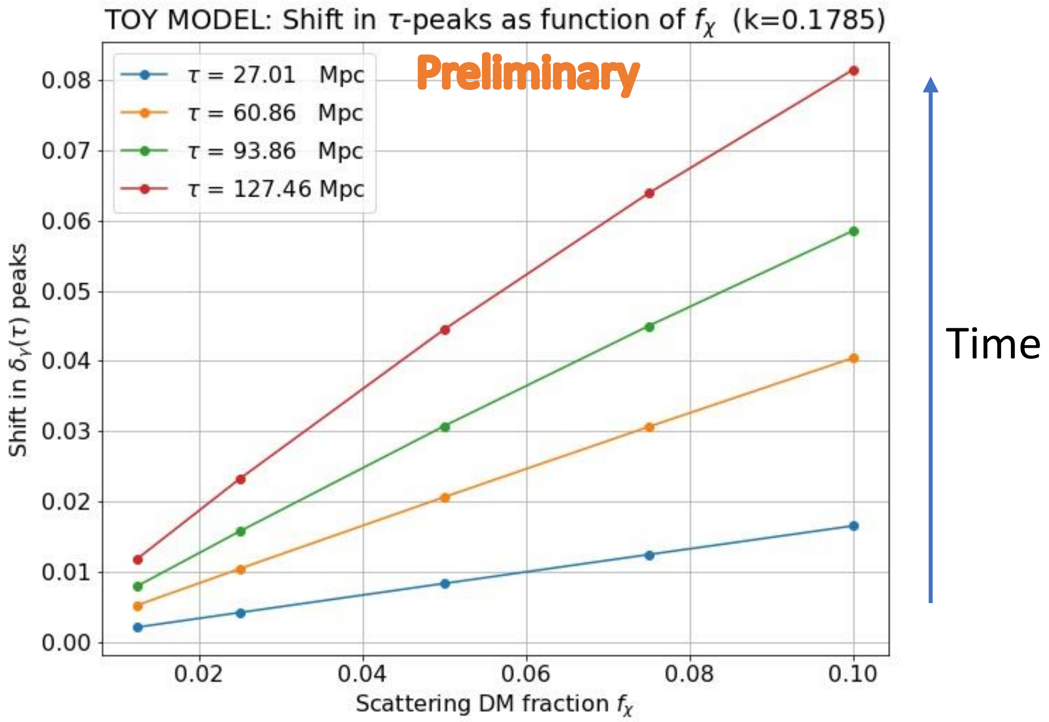


Dependence on f_χ

- Captures *qualitative trend* of shift in peaks over time as function of the proportion of interacting dark matter f_χ
- Phase shift in the photon oscillator grows faster for larger f_χ
- Apparent linear dependence of shift on f_χ for a given peak at early time

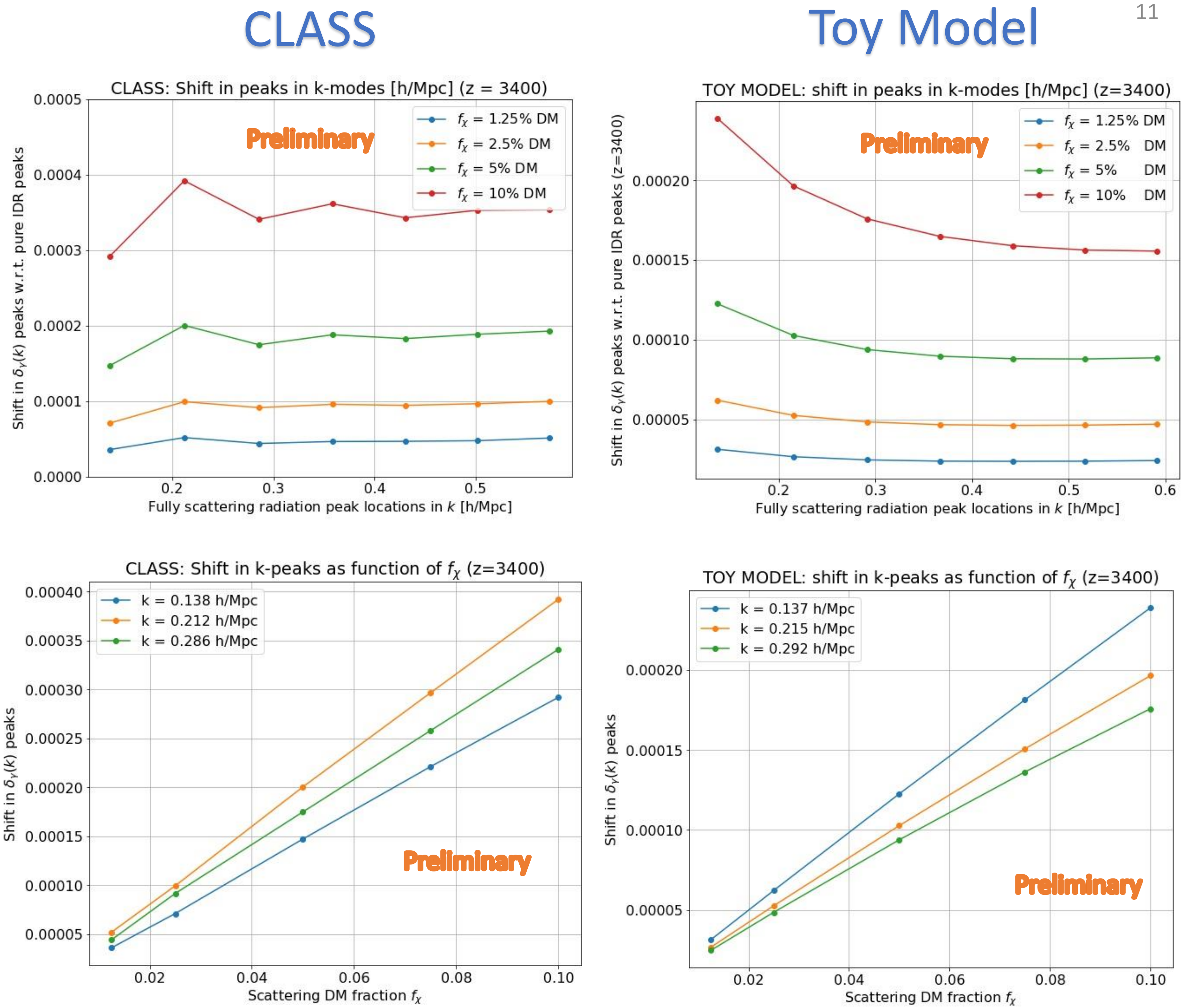






Transfer Function

- Consider transfer functions in k-modes
- k-dependence of phase shift, evaluated at matter-radiation equality time (z = 3400)
- Mis-match in qualitative trends for smaller k values: additional effect?
- Apparent linear f_χ dependence for small k

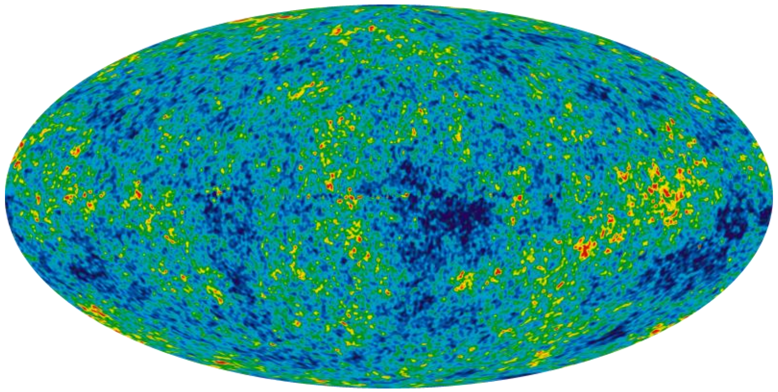


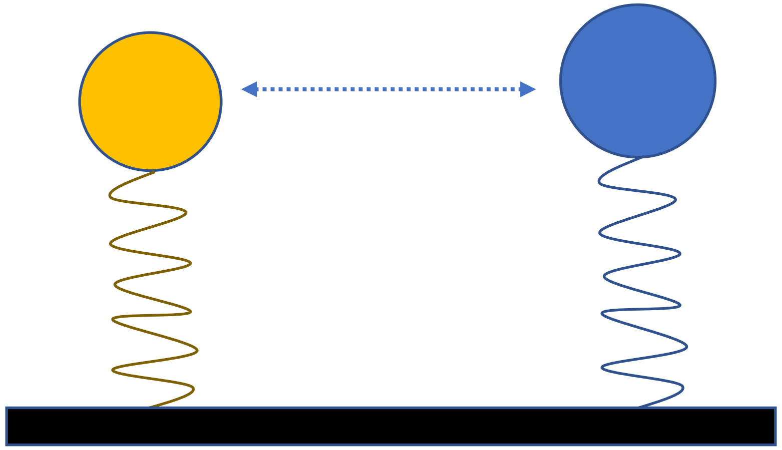
Conclusion

1. CMB phase shift is a distinctive signature for studying dark radiation/neutrino propagation behaviour

2. Phase shift enhanced when dark radiation/neutrinos scatters with DM due to matter loading effect

3. Toy model of coupled oscillators provides simple way to understand qualitative behaviour





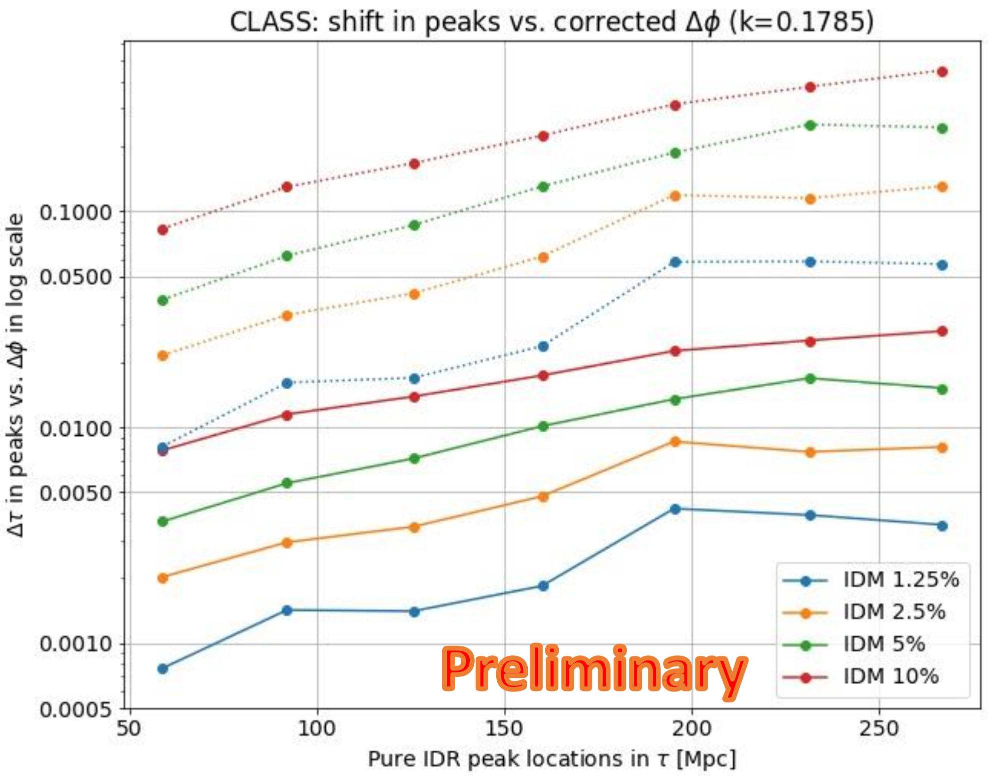
Work in progress:

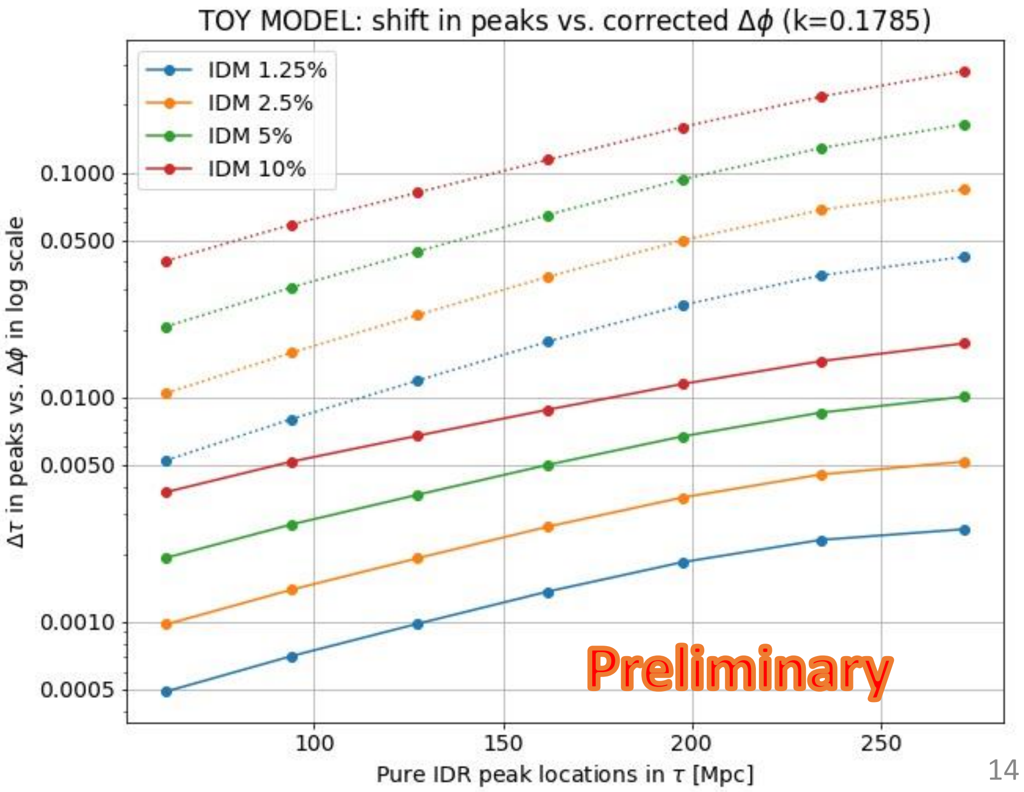
- Go from *qualitative to quantitative* understanding
- Solve analytically for parametric dependences
- Additional effects/corrections to model

Back up slides

Delta tau frequency correction

- Artificial phase shift also produced (when comparing peak positions of photon perturbations between cases) due to time-dependence of frequency itself





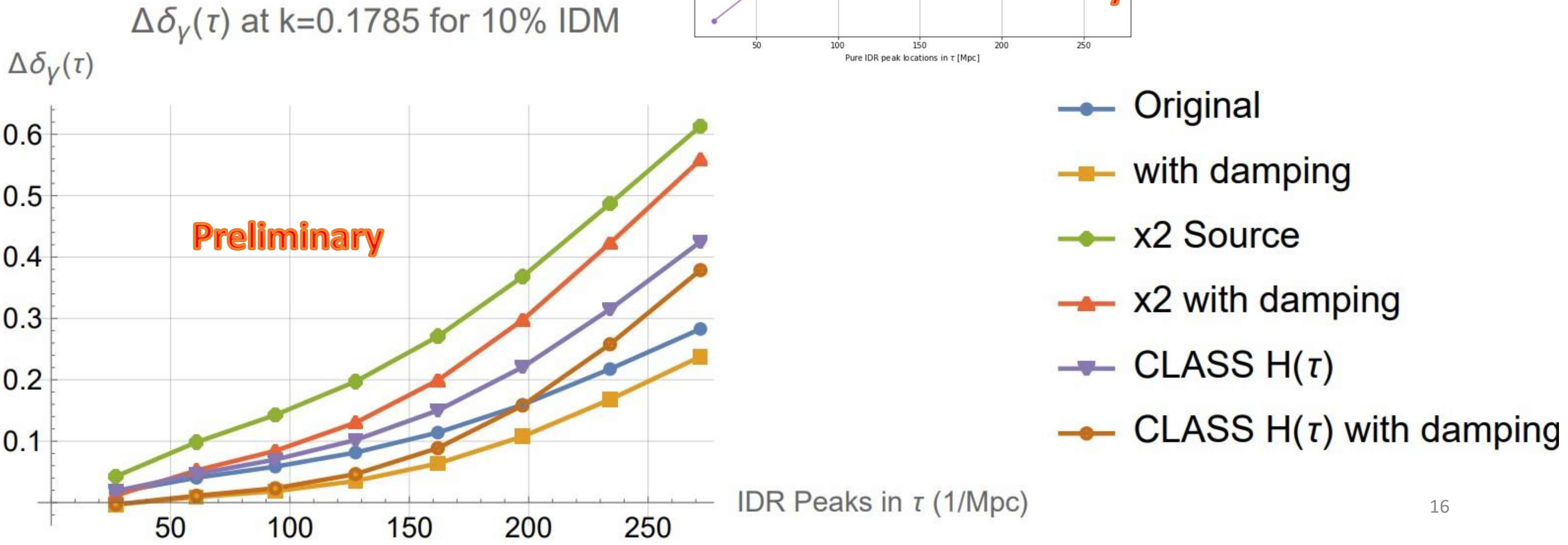
A more complete model

- More complete oscillator equation (tightly coupled)
- Various terms that we can turn on to match results

$$\ddot{\delta}_r(\tau) + \mathcal{H}(1-3c_r^2)\dot{\delta}_r(\tau) + k^2 c_r^2(\delta_r(\tau) - 4\sigma_r(\tau))) = F_k(\tau) \qquad r = \gamma, \nu$$

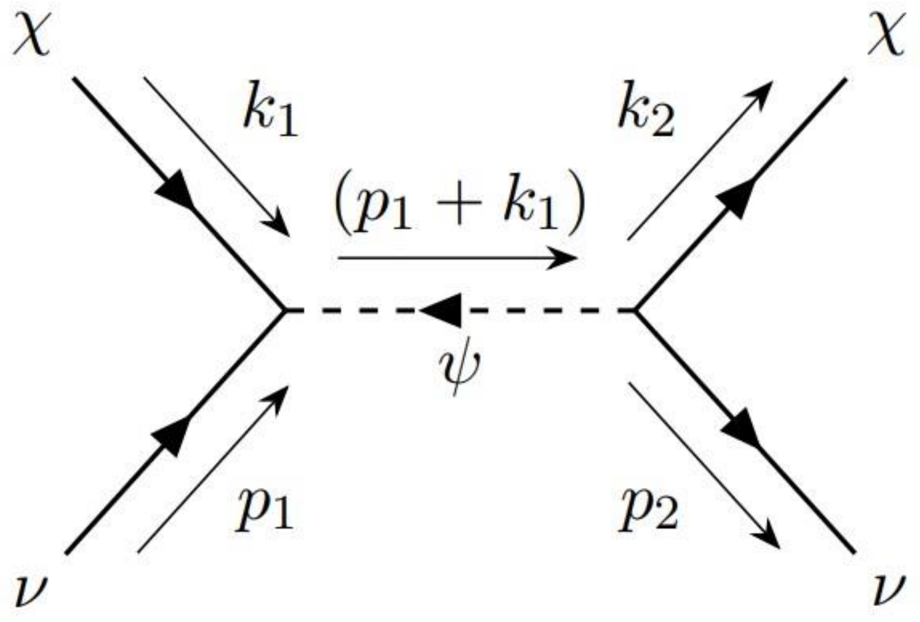
$$F_k(\tau) = 4\ddot{\phi} + 4\mathcal{H}(1-3c_r^2)\dot{\phi} - \frac{4k^2}{3}\psi$$

Toy model future?



DM-neutrino Model

$$\mathcal{L} \supset Y \frac{1}{\Lambda} \left(H^\dagger l\right)(\psi\chi) \quad \Rightarrow \quad \eta\, \delta_{ij}\, \nu_i \psi_j \chi \quad \text{where } \eta = Y \frac{v}{\sqrt{2}\Lambda}$$



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

Reference: Subhajit Ghosh, Rishi Khatri, and Tuhin S. Roy, “Dark neutrino interactions make gravitational waves blue”, Phys. Rev. D **97**, 063529, 29 March 2018

Numerical analysis

- Calculations of exact cosmological perturbation equations using the Cosmic Linear Anisotropy Solving System (CLASS)

The Cosmic Linear Anisotropy Solving System (CLASS). Part II: Approximation schemes
Diego Blas[1], Julien Lesgourgues[1,2,3] and Thomas Tram[2,4]
Published 22 July 2011 • Published under licence by IOP Publishing Ltd
Journal of Cosmology and Astroparticle Physics, Volume 2011, July 2011**Citation** Diego Blas *et al* JCAP07(2011)034**DOI** 10.1088/1475-7516/2011/07/034

- CLASS plots of phase shifts in tau and k space obtained by peak fitting on points produced from CLASS output