Amplifying CMB Phase Shift with Dark Matter-Radiation Interactions

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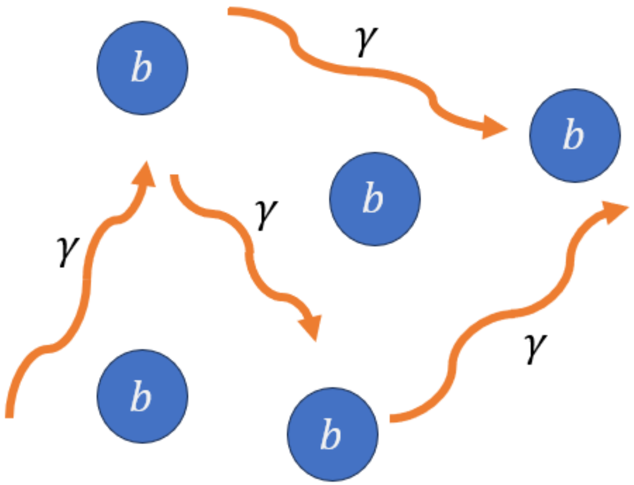
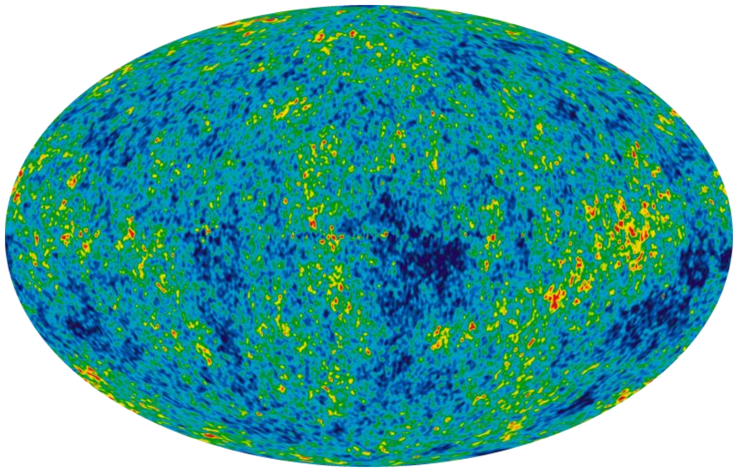
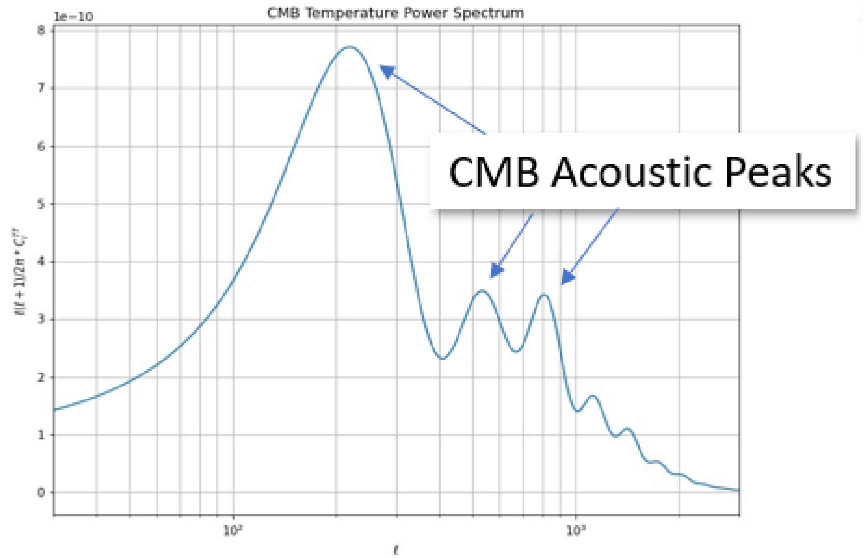
CMB Acoustic Peaks

- Radiation pressure in photon-baryon plasma leads to propagation of sound waves before recombination.
- This gets imprinted as peak structure in CMB power spectrum. Phase shift in acoustic oscillations manifest as "shift" in CMB peaks
- **Phenomenology:** what kind of physics can produce phase shift?

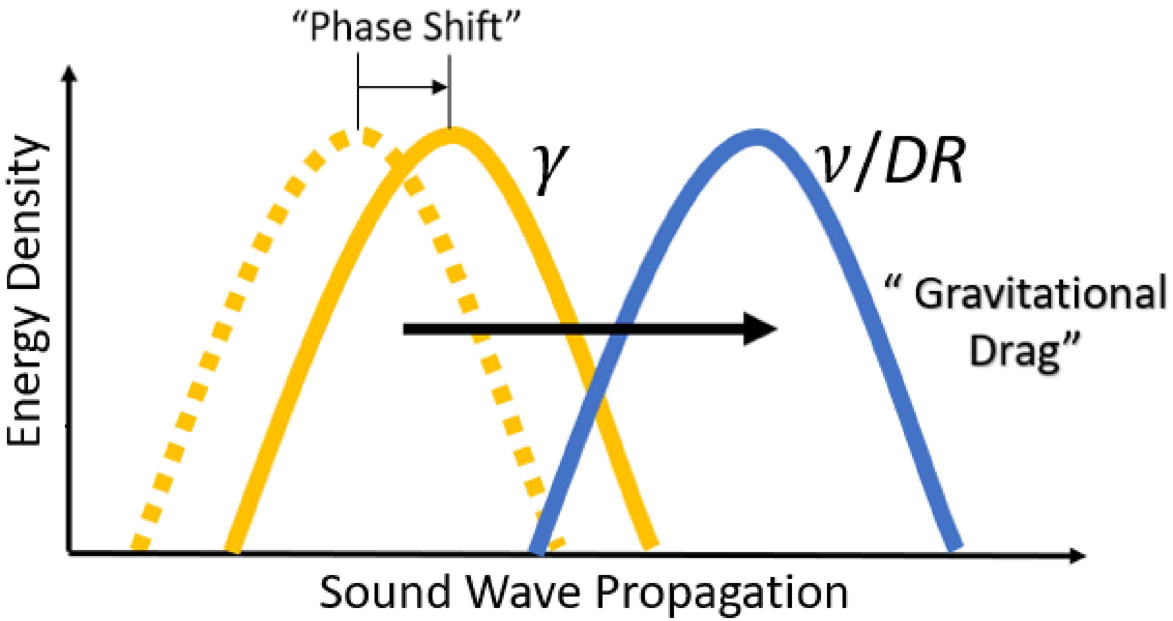


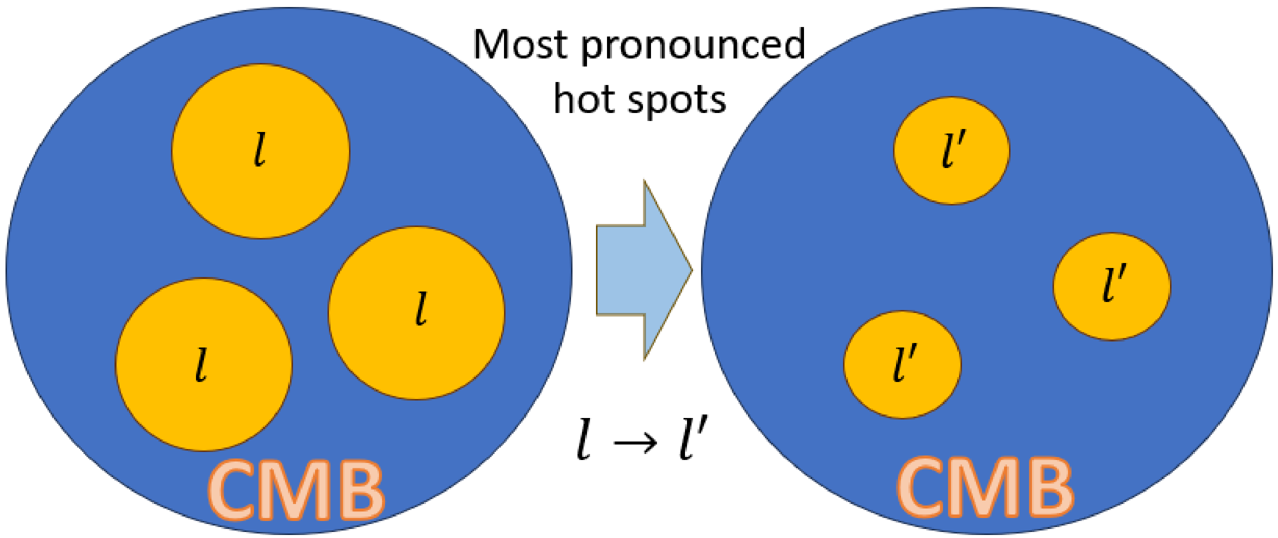




CMB Phase Shift

- CMB phase shift is sensitive to **propagation behaviour of non-photon radiation** (e.g. SM neutrinos, light dark photon...) before recombination!
- Non-photon radiation exerts "gravitational drag" on photon-baryon waves: sensitive to physics that interact **only gravitationally with us** (no new direct interaction with SM)
- Studied before in the context of free-streaming vs self-interacting radiation (Bashinsky & Seljak arXiv:astro-ph/0310198 , Baumann et. al. arXiv:1508.06342v3)

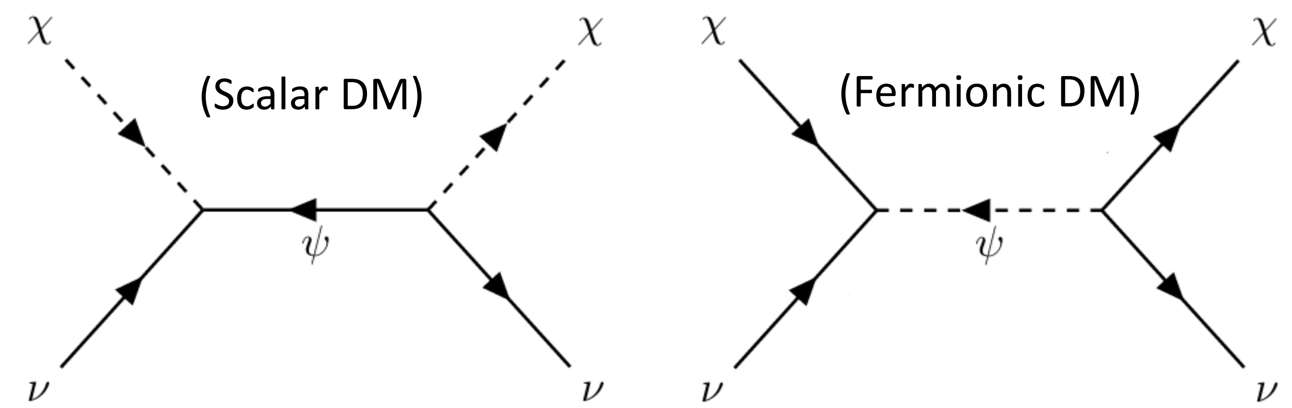




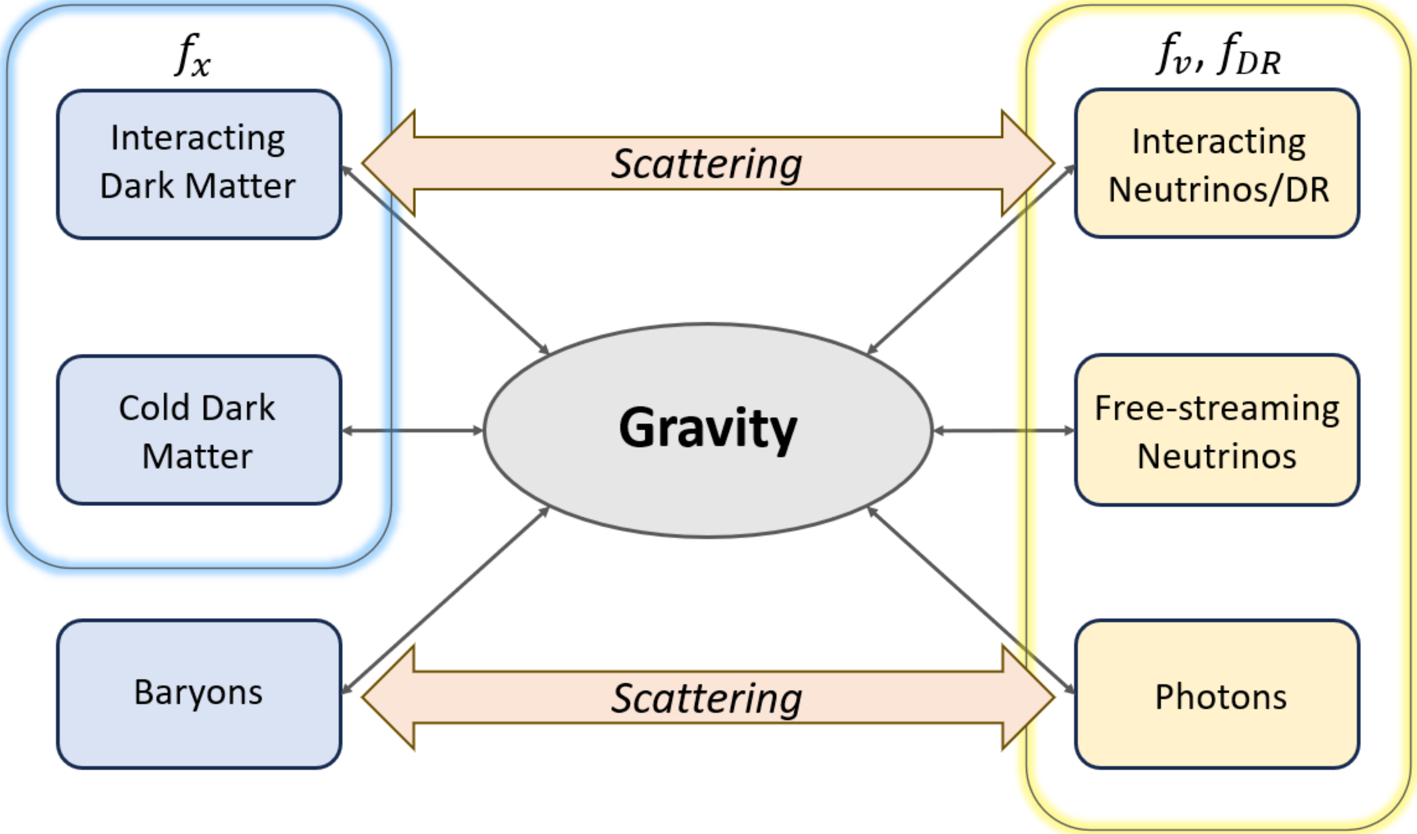
Dark Matter-Radiation Interactions

- Phase shift effect can be amplified compared to self-interacting radiation scenario
- Slow radiation propagation further by scattering with a portion of dark matter
- Consider multi-component dark matter and radiation sectors
- ***Demonstrative example***: let (massless) neutrinos play role of interacting radiation first

Example DNI Model:



$$\mathcal{L} \supset \frac{y_{ij}}{\Lambda}(H^\dagger l_i)(\psi_j \chi) \quad \Rightarrow \quad \eta_{ij}\nu_i\psi_j\chi\,, \quad \text{where} \quad \eta_{ij} = \frac{y_{ij}v}{\sqrt{2}\Lambda}\,.$$

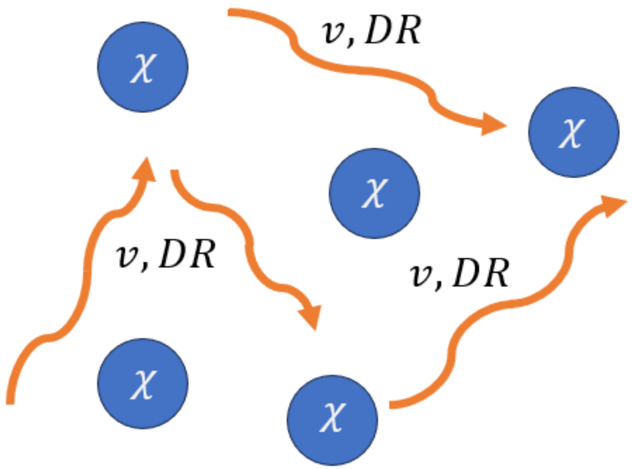


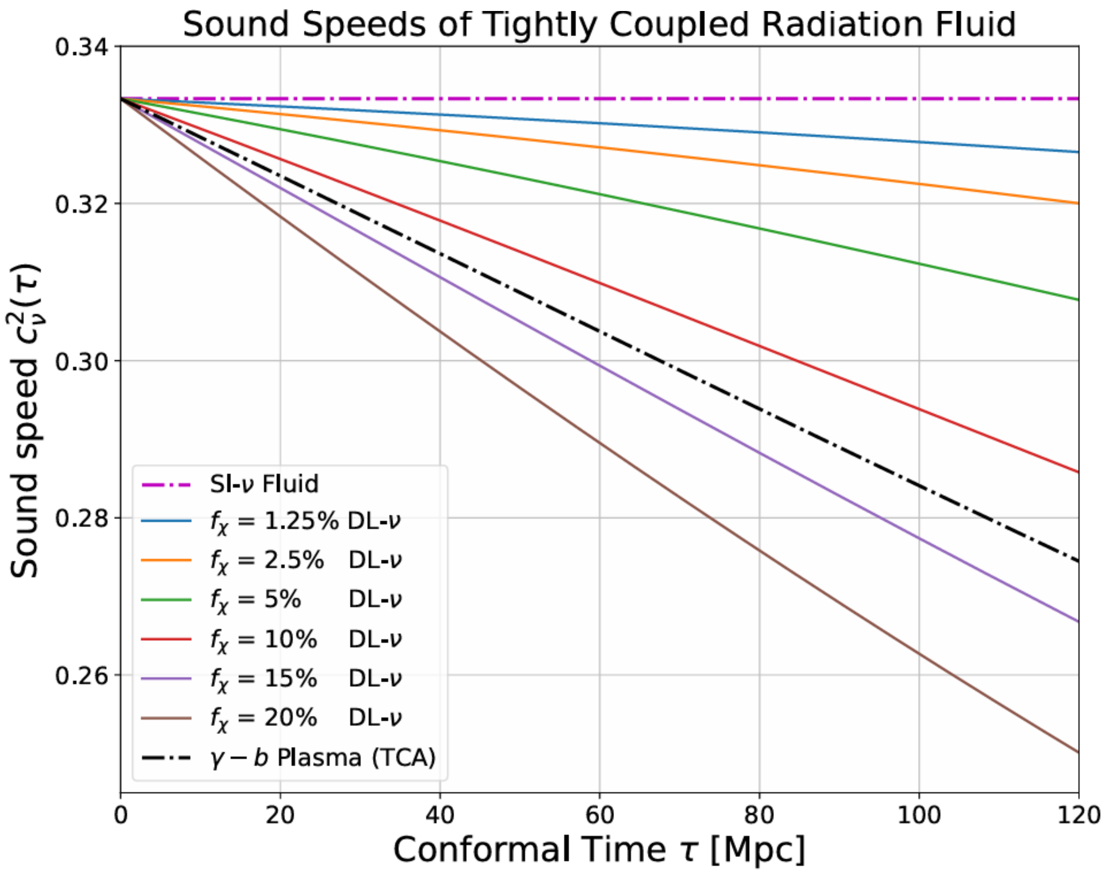
Dark Matter Loading

- **<u>Efficient scattering:</u>** scattering rate large compared to Hubble rate
- Interacting radiation (r) and matter (m) forms *tightly-coupled* fluid, with sound speed

$$c_r^2 = \frac{1}{3(1+R_r)} \;, \quad \text{where} \quad R_r = \frac{3}{4}\frac{\rho_m}{\rho_r}$$

- Matter-loading effect suppresses sound speed over time; larger suppression for larger f_χ



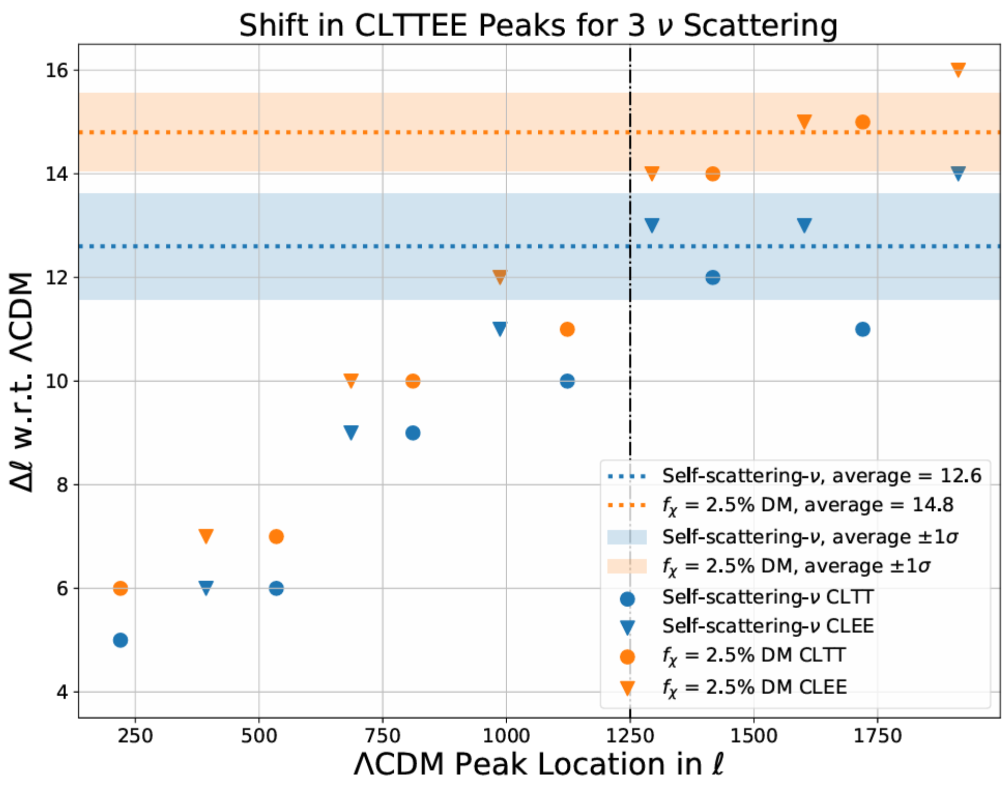


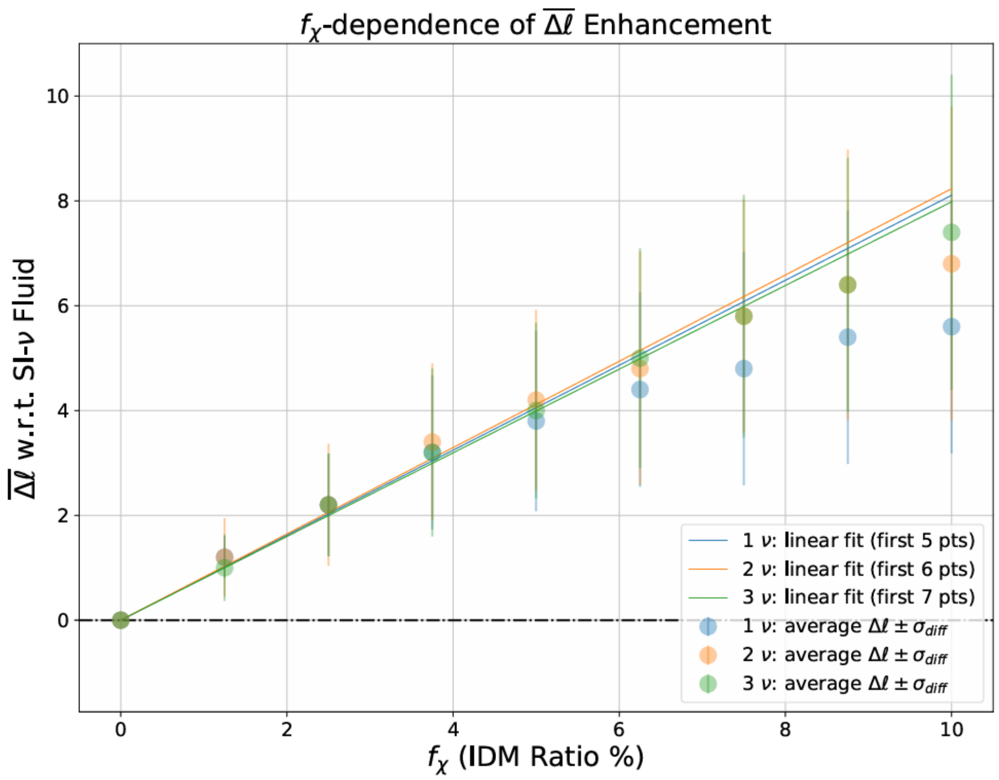
<u>Radiation propagation behaviour:</u>

1. Free-Streaming (FS)
2. Self-Interacting (SI)
3. Dark-matter Loading (DL)

Amplifying CMB Phase Shift

- Use CLASS to calculate shift in CMB peaks with respect to $\boldsymbol{\Lambda CDM}$ model (all neutrinos FS)
- Peaks shift to positive l for SI neutrino. Shift is enhanced further for DL neutrino ($f_\chi = 2.5\%$)
- Enhancement of DL vs SI has linear dependence on f_χ, independent of f_ν (for small f_χ)



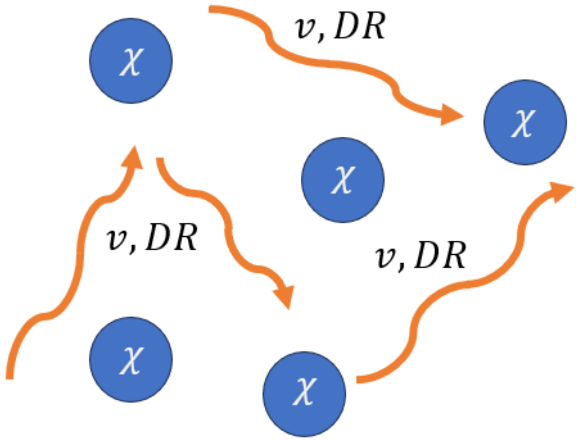


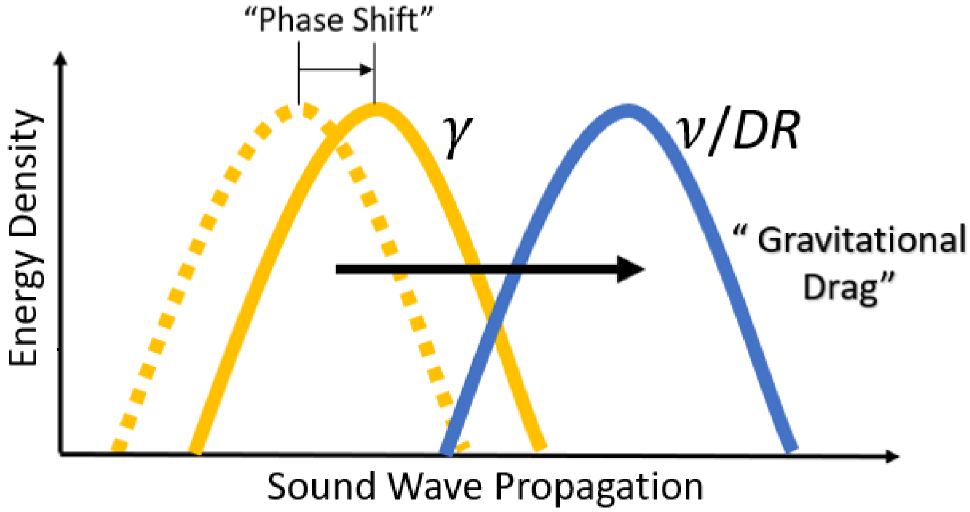
Brief Outline

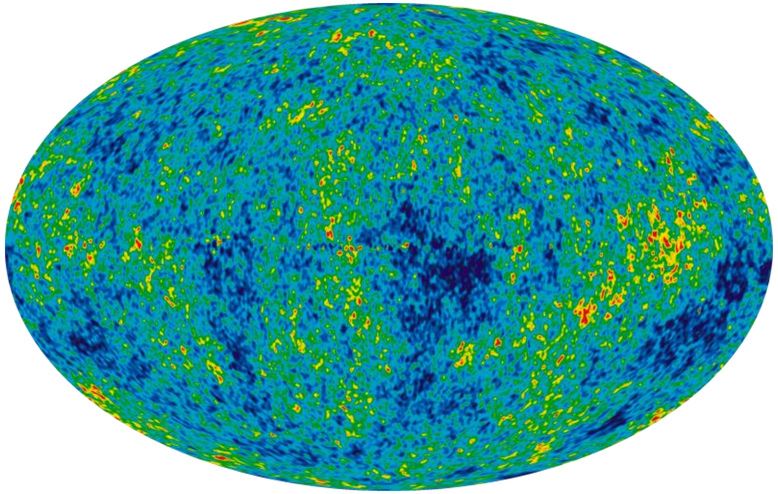
- Numerical calculations (CLASS) show CMB phase shift amplified by dark matter loading

- Let's go further:

  1. Understand mechanism behind the effect with a simplistic toy model
  2. Study observability of the effect by considering a more realistic model







Toy Model: Coupled Oscillators

1. Two *tightly-coupled* fluids: photon-baryon and neutrino-DM, described by radiation energy density constrast δ_r

2. Fluids carry acoustic oscillations suppressed by ***matter-loading***, interact with each other ***only gravitationally***

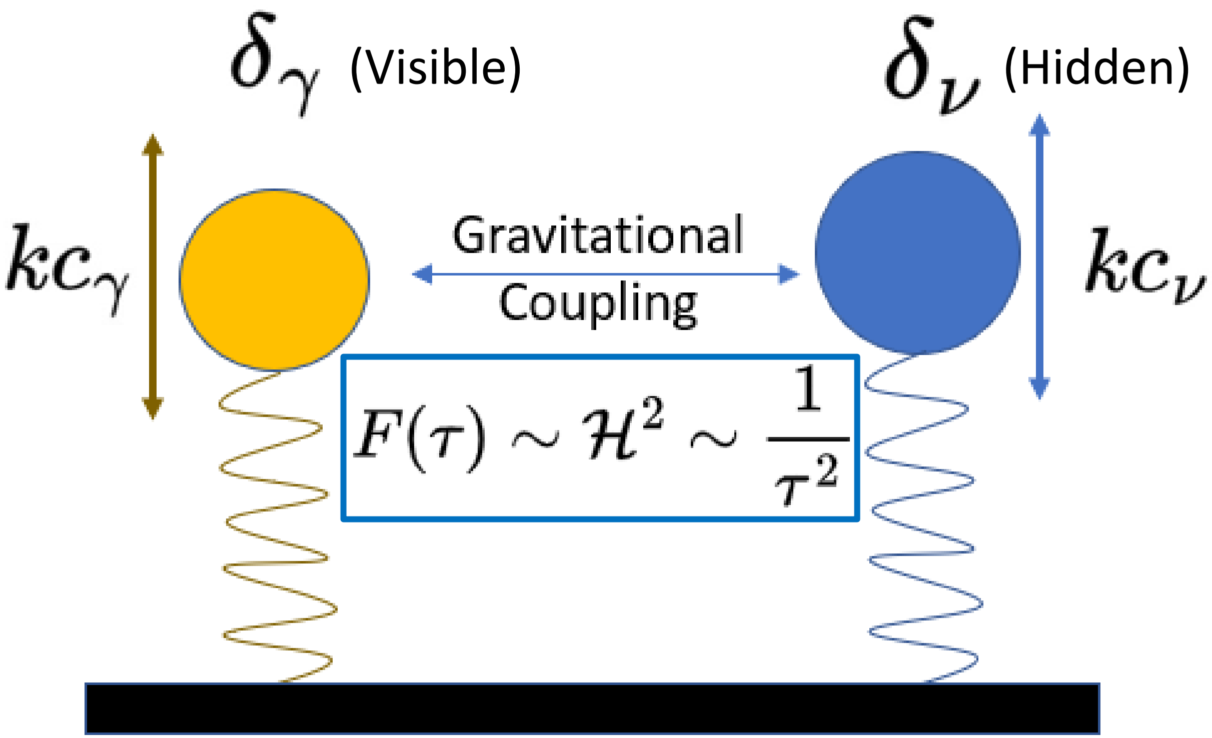
3. Phase shift imprinted in photons by hidden oscillator; size and direction of shift depends on *relative sound speed*

4. Gravitational interaction *strength decreases over time* with Hubble: phase shift gets “fixed”

Gravitational Coupling

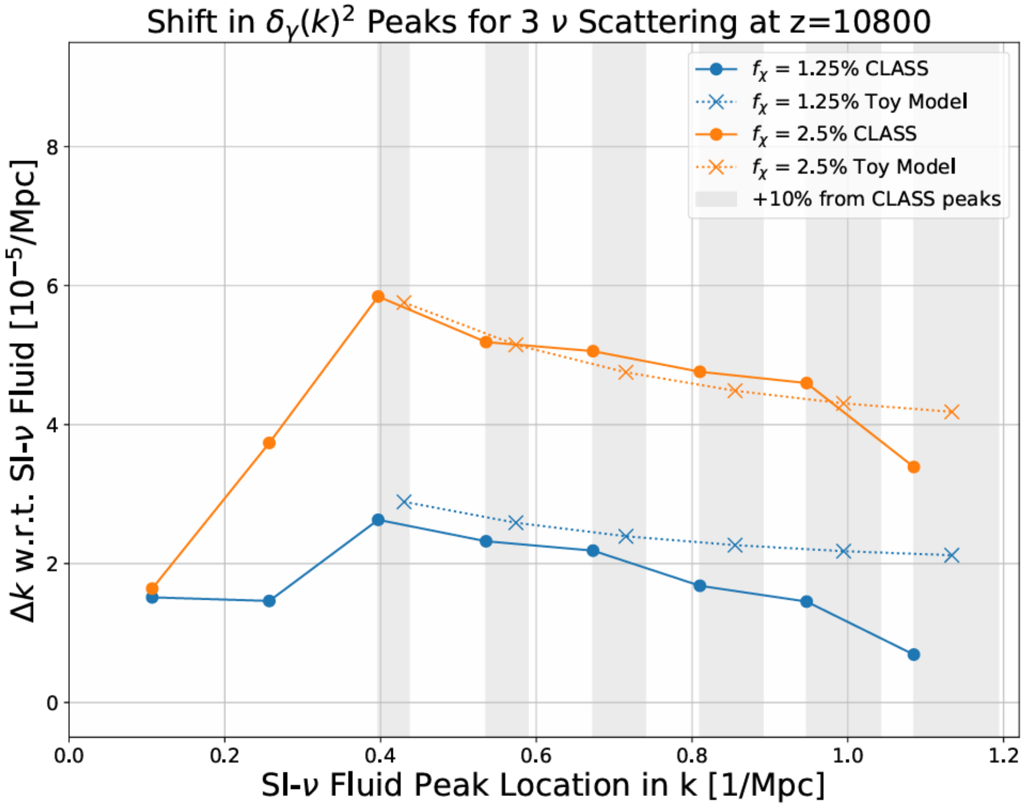
$$\ddot{\delta}_\gamma + k^2 c_\gamma^2 \delta_\gamma = F(\tau)(f_\gamma \delta_\gamma + f_\nu \delta_\nu)$$

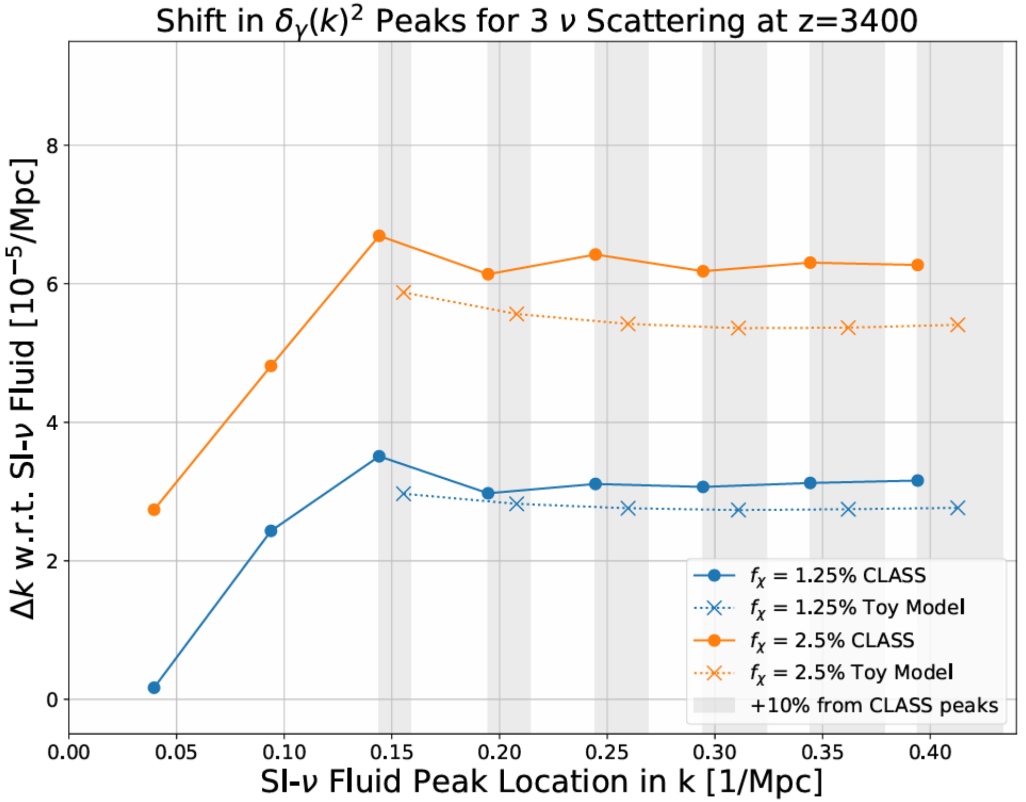
$$\ddot{\delta}_\nu + k^2 c_\nu^2 \delta_\nu = F(\tau)(f_\gamma \delta_\gamma + f_\nu \delta_\nu)$$



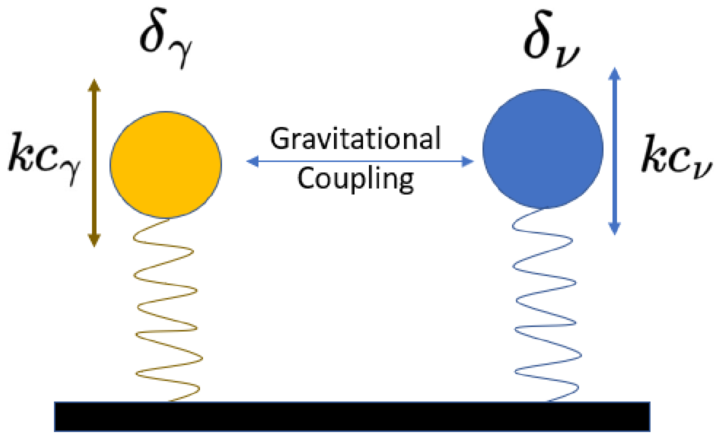
Toy Model Approximates CLASS Well

- Numerical check: toy model captures phase shift in photon transfer function from CLASS
- Level of agreement preserved when only 1 or 2 neutrinos interact while the rest free-stream





Simple Parametric Dependence



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

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

(i) Small coupling: homogeneous solutions

$$\delta_\gamma \sim \cos(c_\gamma k \tau)$$

$$\delta_\nu \sim \cos(c_\nu k \tau)$$

(ii) Small matter-loading: small deviation

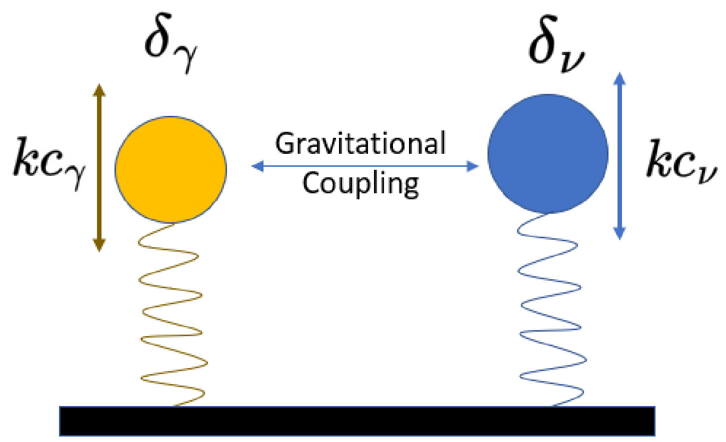
$$c_\gamma - c_\nu = \delta c \ll 1$$

$$\delta c \sim R_\nu \sim f_\chi / f_\nu$$

Phase shift $\Delta\phi$ gets imprinted in homogeneous photon oscillations by (perturbative) gravitational influence of neutrinos

$$\delta_\gamma \sim \cos(c_\gamma k \tau - \Delta\phi)$$

Simple Parametric Dependence



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

Gravitational "driving force"

$$f_\gamma \cos(c_\gamma k\tau) + f_\nu \cos((c_\gamma - \delta c)k\tau) \approx \cos(c_\gamma k\tau) + f_\nu \delta c \sin(c_\gamma k\tau)$$

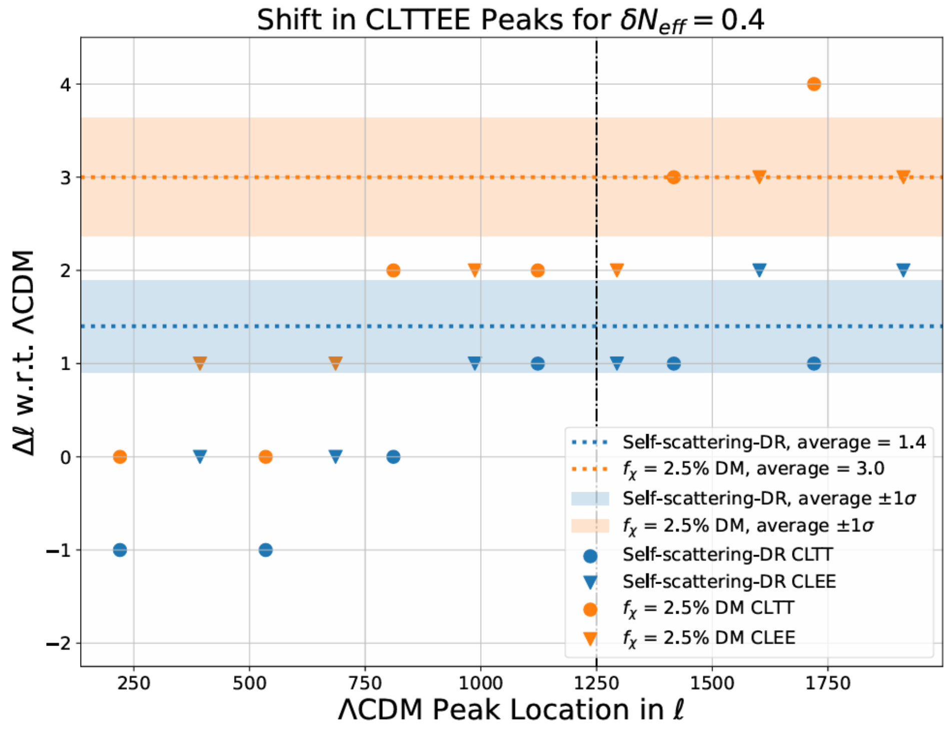
Phase shift to $\delta_\gamma \sim \cos(kc_\gamma\tau)$ comes from sine part, which is linear in f_χ and independent of f_ν

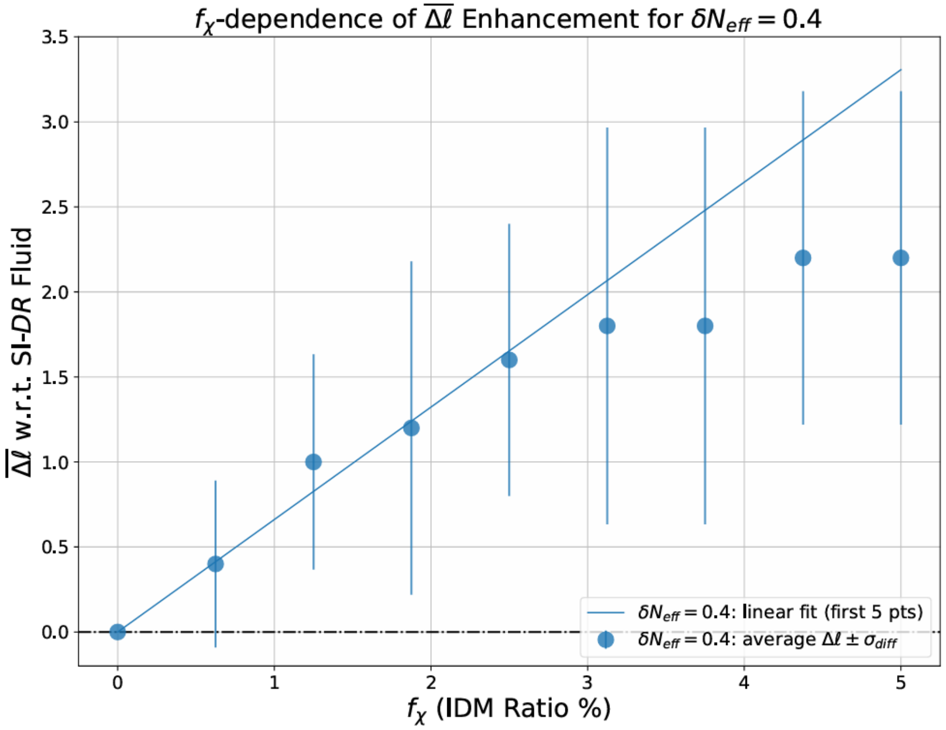
$$\Delta\phi \sim f_\nu \delta c \sim f_\nu \left(\frac{f_\chi}{f_\nu}\right) \sim f_\chi$$

$\Delta\phi$ relative shift w.r.t. self-interacting case

Interacting Dark Radiation Model

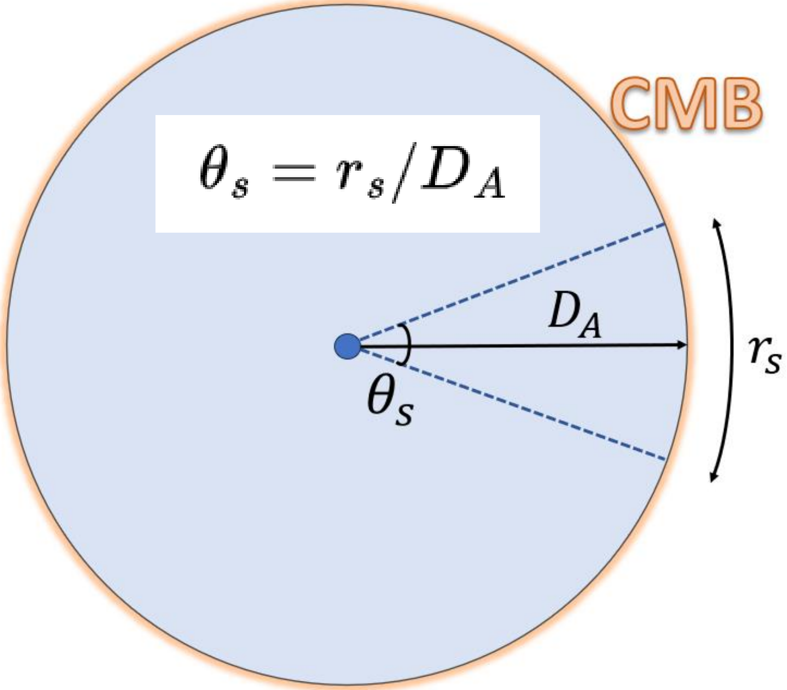
- Additional dark radiation component (ΔN_{eff}) scatters efficiently with DM
- All neutrinos free-streaming with new physics only in dark sector: interacts with Standard Model *only gravitationally*
- Similar phase shift amplification and parametric dependence (e.g. $\Delta N_{eff} = 0.4$)





Angular Sound Horizon θ_s

- CMB peak positions well measured (e.g. Planck2018)
- Degeneracy in parameters: how far away is the CMB (2D surface of last scattering)?
- Determine phase shift $\Delta\phi$ from fitting θ_s (r_s: sound horizon, D_A: angular diameter distance)



Data

New Physics

$$\ell_m = \frac{m\pi + \Delta\phi}{\theta_s} \quad \text{for } m^{\text{th}} \text{ peak}$$

Signal

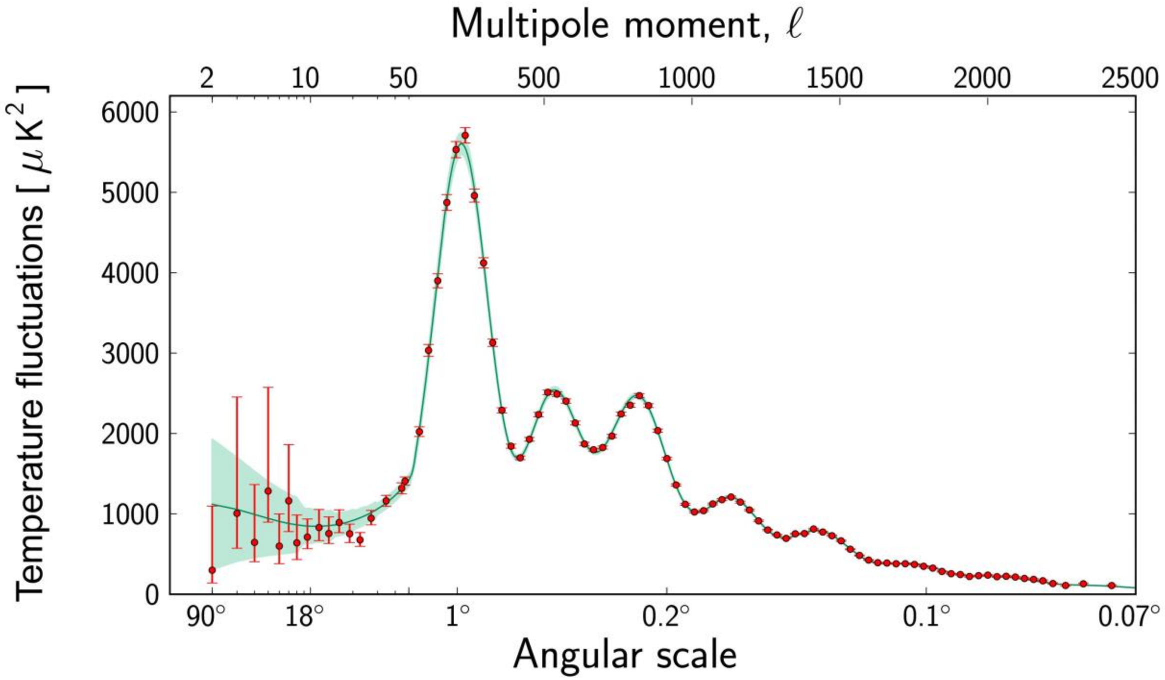
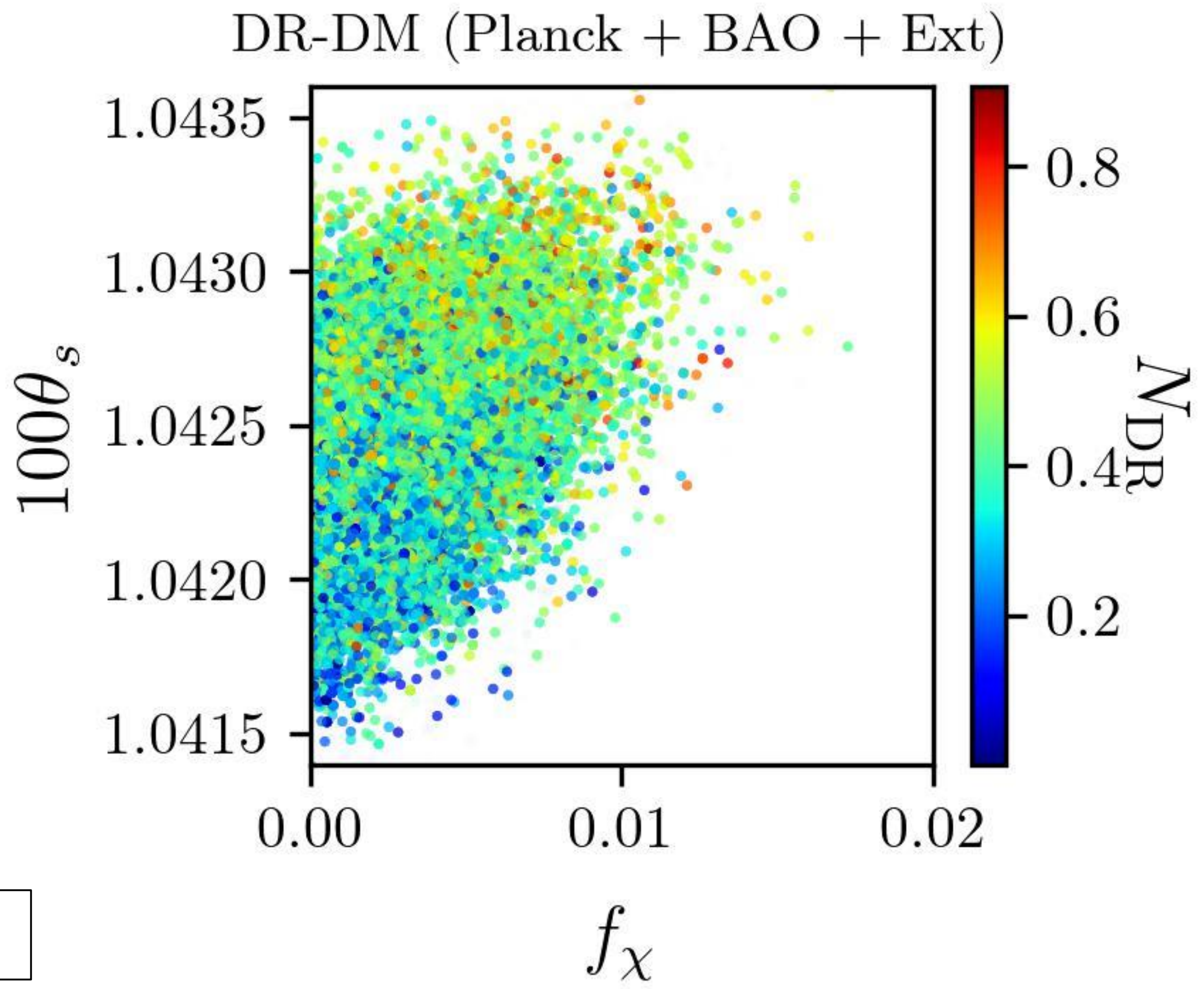


Image: ESA/Planck Collaboration – Planck Power Spectrum

MCMC Analysis: Signature in θ_s

- Use Montepython to fit model. Allow amount of interacting DR (N_{DR}) to vary
- DM-loading signature: angular sound horizon θ_s positively correlated with interacting DM fraction f_χ
- For comparison, the $N_{DR} = 0$ case corresponds to $\boldsymbol{\Lambda CDM}$
- The $f_\chi \to 0$ limit for $N_{DR} > 0$ cases corresponds to self-interacting DR



Datasets: Planck2018 + BAO + SH0ES + kv450

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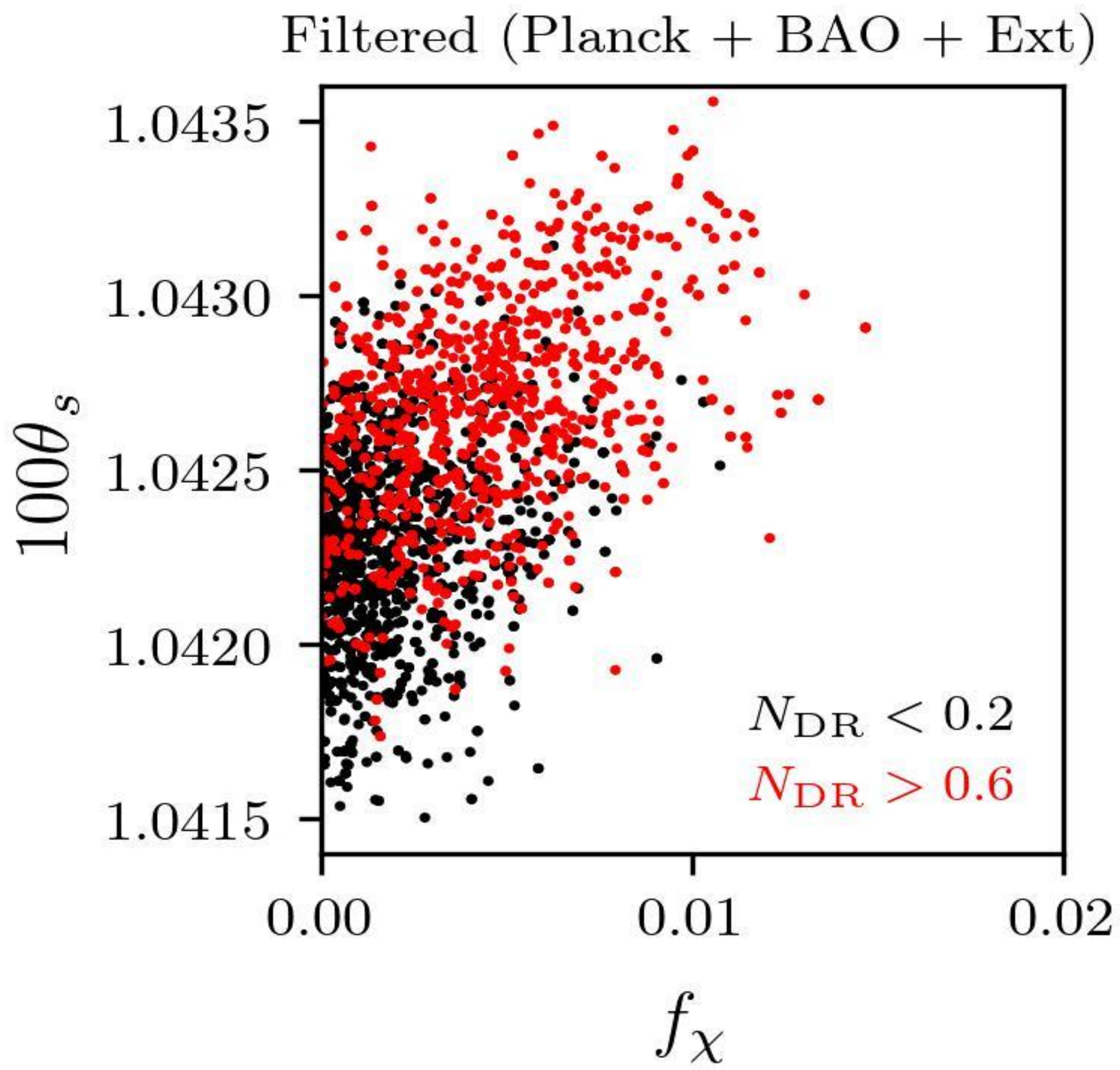
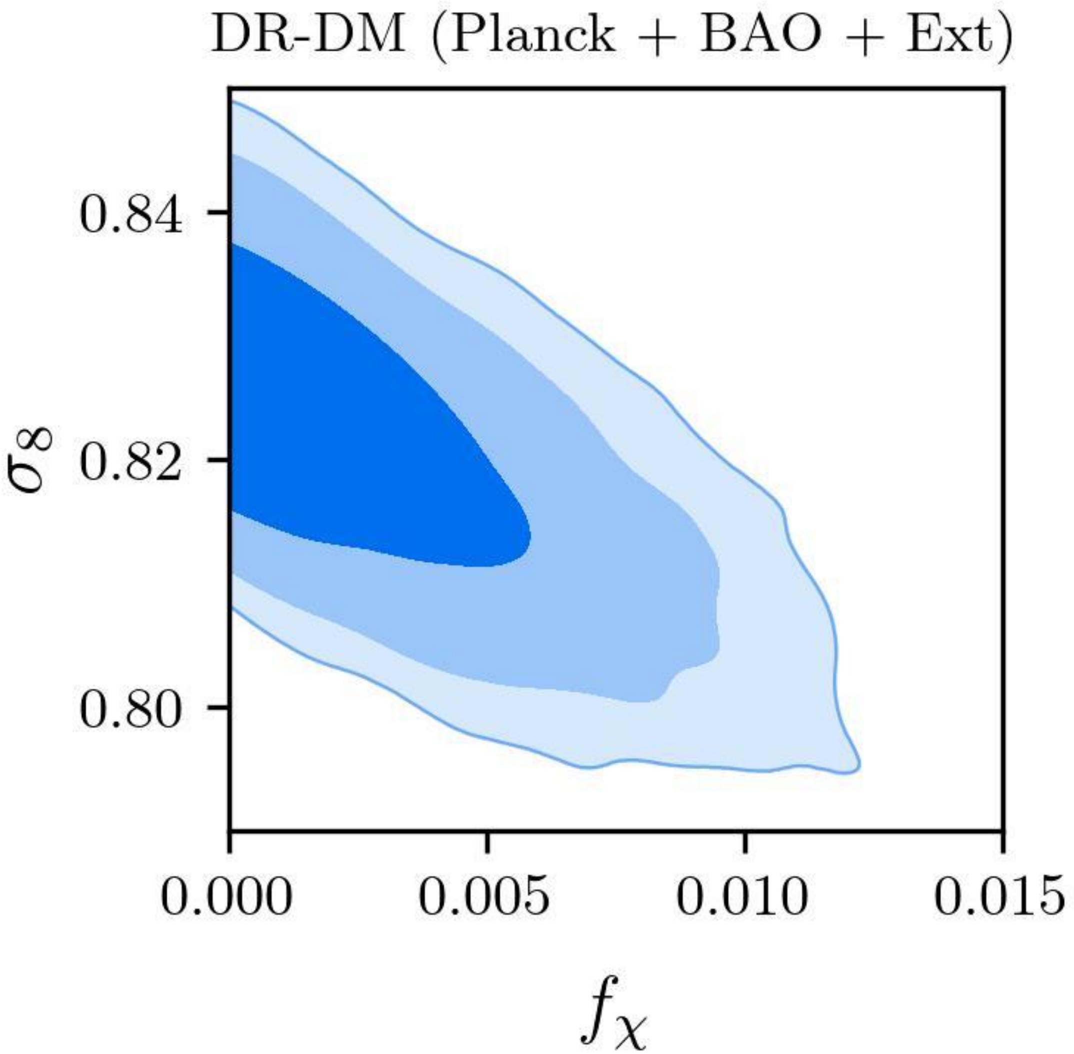


Datasets: Planck2018 + BAO + SH0ES + kv450

MCMC Analysis: Dual signature in σ_8

- σ_8 parameter measures amplitude of matter density fluctuations on scales $k \sim 8\ h$/Mpc
- From mater POV, scattering with radiation interferes with clumping/ structure formation
- **<u>Dual signature:</u>** σ_8 suppression appears alongside θ_s enhancement with increasing f_χ



<u>Datasets</u>: Planck2018 + BAO + SH0ES + kv450

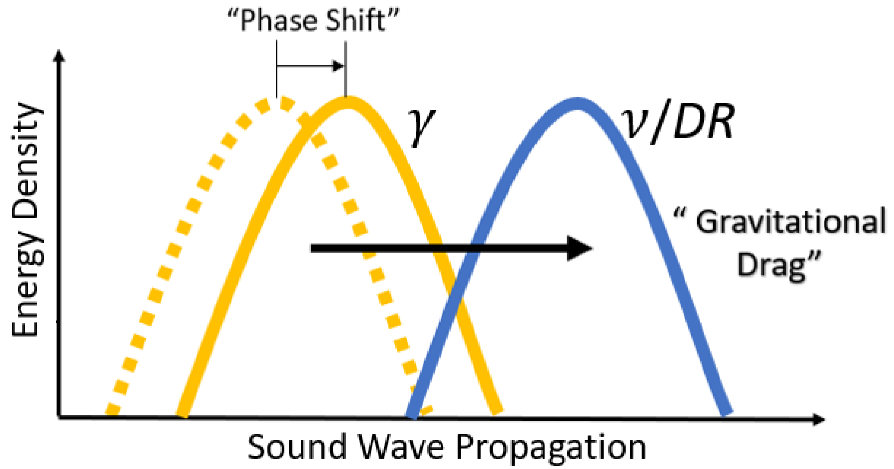
Conclusion

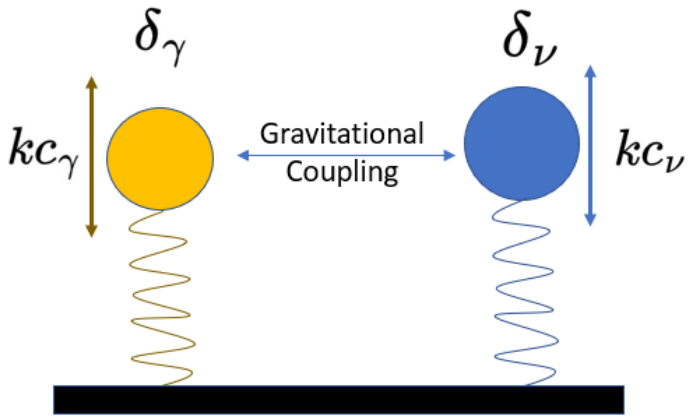
1. CMB phase shift provides sensitive **gravitational** probe of propagation behaviour of non-photon radiation before recombination. (Useful for probing radiation with no *direct* interaction with SM.)

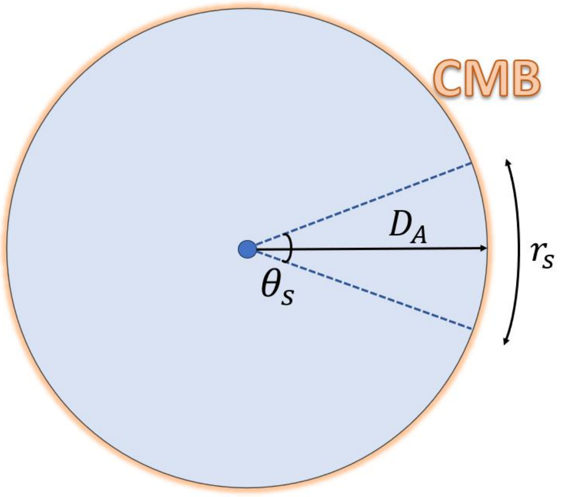
2. Radiation propagation slowed further (compared to self-interacting case) by scattering with dark matter. Generates **amplified phase shift** in CMB.

   i. Effect can be understood using *simple coupled oscillator* picture

   ii. Effect is observable by looking for θ_s *enhancement* (dual signal in σ_8 *suppresion*)







Backup Slides

More on the DNI Model

$$\mathcal{L} \supset \frac{y_{ij}}{\Lambda}(H^\dagger l_i)(\psi_j \chi) \quad \Rightarrow \quad \eta_{ij}\nu_i\psi_j\chi\,, \quad \text{where} \quad \eta_{ij} = \frac{y_{ij}v}{\sqrt{2}\Lambda}\,.$$

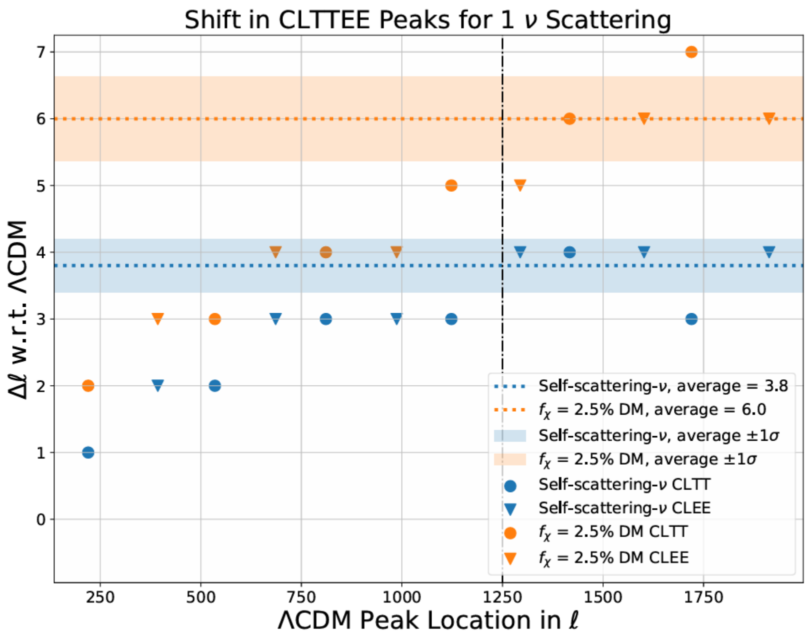
Temperature independent cross-section when DM and mediator mass difference much smaller than neutrino temperature

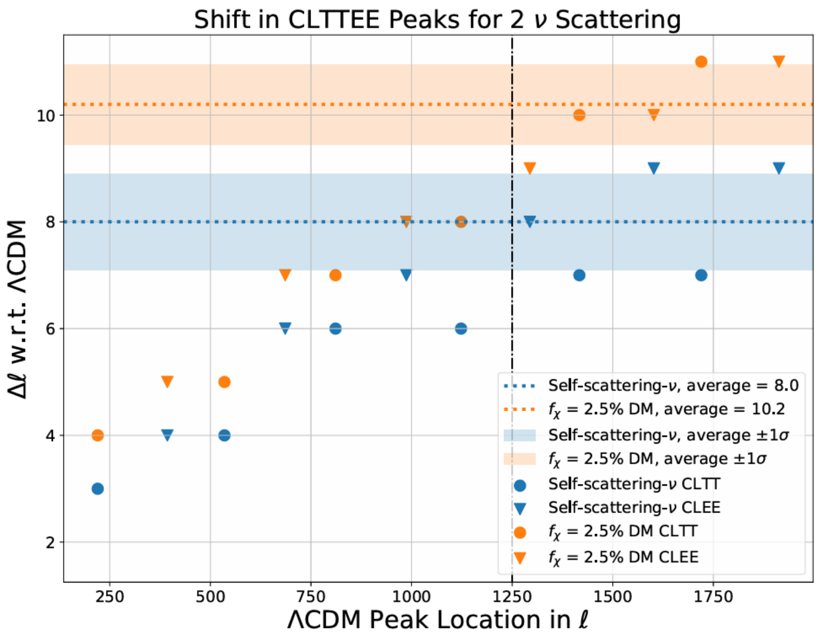
$$\sigma = 1.7 \times 10^{-6}\left(\frac{\eta}{0.1}\right)^4\left(\frac{\text{GeV}}{m_\chi}\right)^2 \text{GeV}^{-2}$$

Possible UV completion with massive vector-like fermion *N*

$$\mathcal{L} \supset Y_{N,ij}N_i(H^\dagger l_j) + Y_{\bar{N},ij}N_i^c(\psi_j\chi) + M_{N,ij}N_iN_j^c\,, \quad \text{where} \quad \frac{y_{ij}}{\Lambda} \sim 2\frac{Y_{N,ik}Y_{\bar{N},kj}}{M_N}\,.$$

CLASS 1 and 2 nu

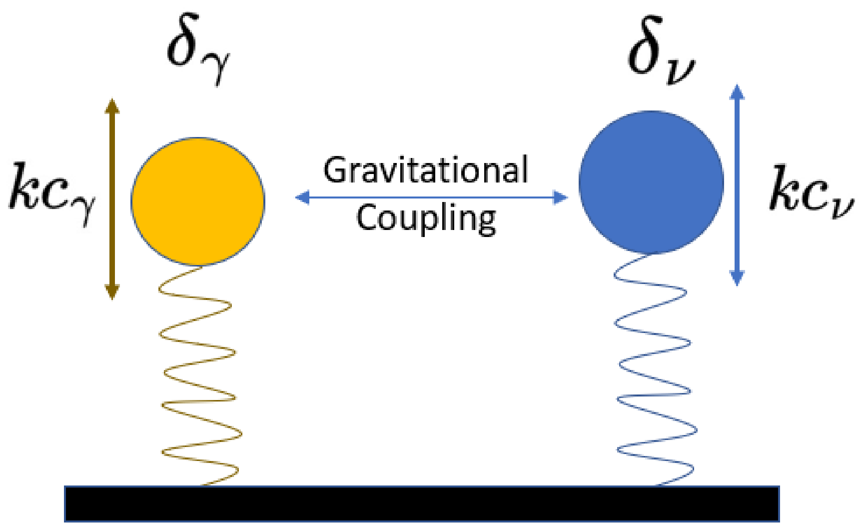




Toy Model: Coupled Oscillators

$$\ddot{\delta}_\gamma(\tau) + k^2 c_\gamma^2(\tau)\delta_\gamma(\tau) = \frac{4\mathcal{H}^2(\tau)}{1+\frac{a(\tau)}{a_{\rm eq}}}(f_\gamma\delta_\gamma(\tau) + f_\nu\delta_\nu(\tau))\,,$$

$$\ddot{\delta}_\nu(\tau) + k^2 c_\nu^2(\tau)\delta_\nu(\tau) = \frac{4\mathcal{H}^2(\tau)}{1+\frac{a(\tau)}{a_{\rm eq}}}(f_\gamma\delta_\gamma(\tau) + f_\nu\delta_\nu(\tau))\,.$$



- Two tightly-coupled fluids interacting ***only gravitationally***; gravitational interaction weakens over time with Hubble expansion

- Each fluid has natural frequency set by sound speed; matter-loading effect drives sound speeds apart

- Phase shift in photon oscillator due to gravitational influence of hidden oscillator. Direction of shift depends on relative sound speed

$$c_r^2 = \frac{1}{3(1+R_r)} \quad , \quad R_r = \frac{3}{4}\frac{\rho_m}{\rho_r}$$

(for $r = \gamma$ or ν)

<u>Toy Model Assumptions</u>

1. No free-streaming radiation
2. Small matter-loading
3. Sub-horizon (simplified horizon-entry)
4. Radiation dominated perturbations

Toy Model Analysis

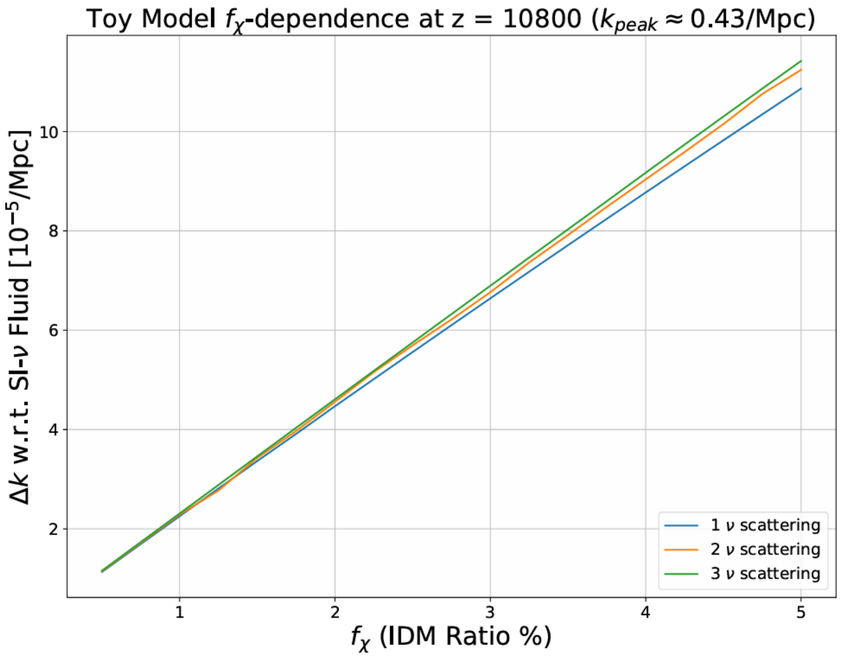
- Analyse toy model for parametric dependences in radiation era, assuming small difference in photon and neutrino sound speeds (and other simplifying assumptions)
- Consider phase shift induced in photon oscillations due to gravitational driving from neutrinos

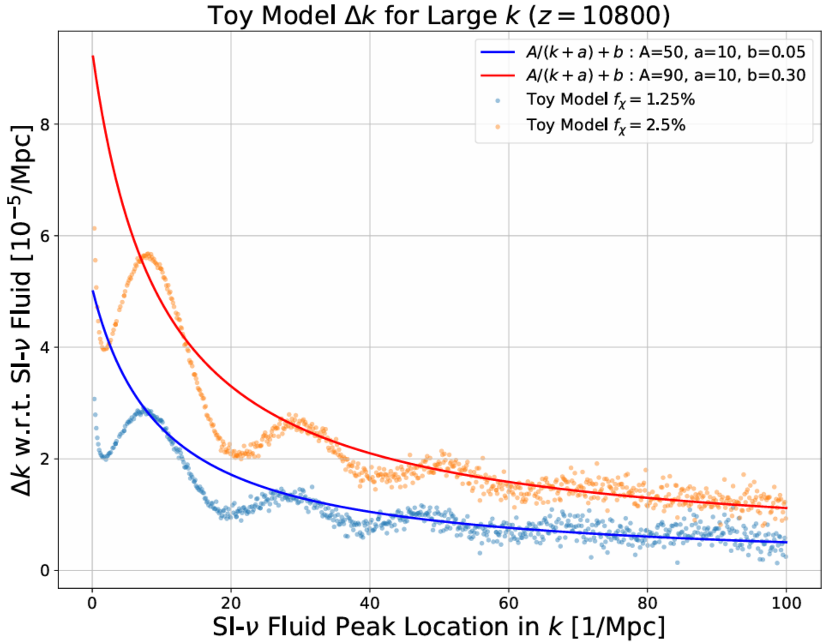
$$\cos(\omega\tau + \Delta\phi_{\rm load}) \qquad \omega^2 = k^2 c_\gamma^2$$

- Analytic approximations

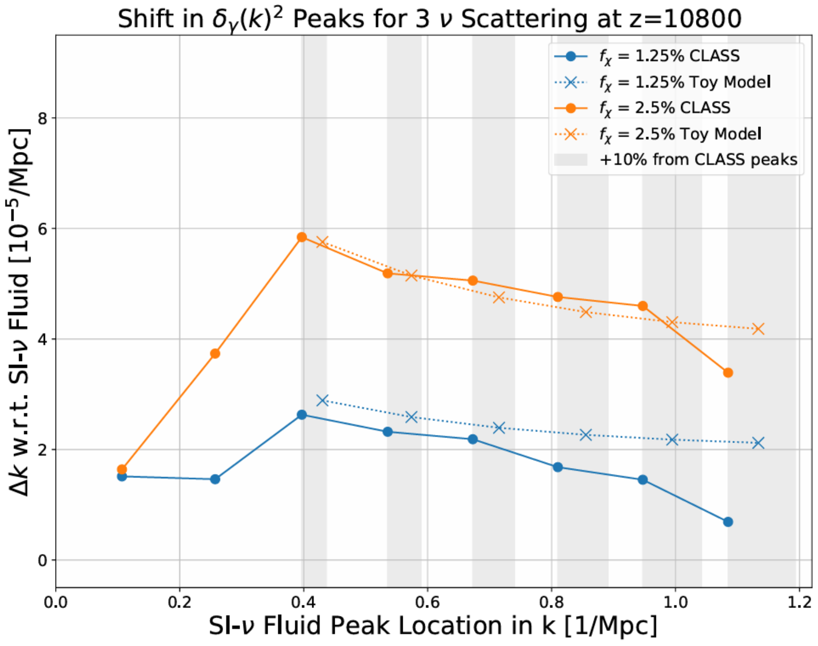
$$\Delta\phi_{\rm load} \approx -\frac{3\alpha^2 f_{\rm DM}}{2c_\gamma\tau_{eq}}\frac{f_\chi}{k+a}, \qquad a = \frac{1}{c_\gamma\tau_{eq}}\left(2 + \frac{3}{4}\frac{\alpha f_{\rm DM}}{f_\nu}f_\chi\right)$$

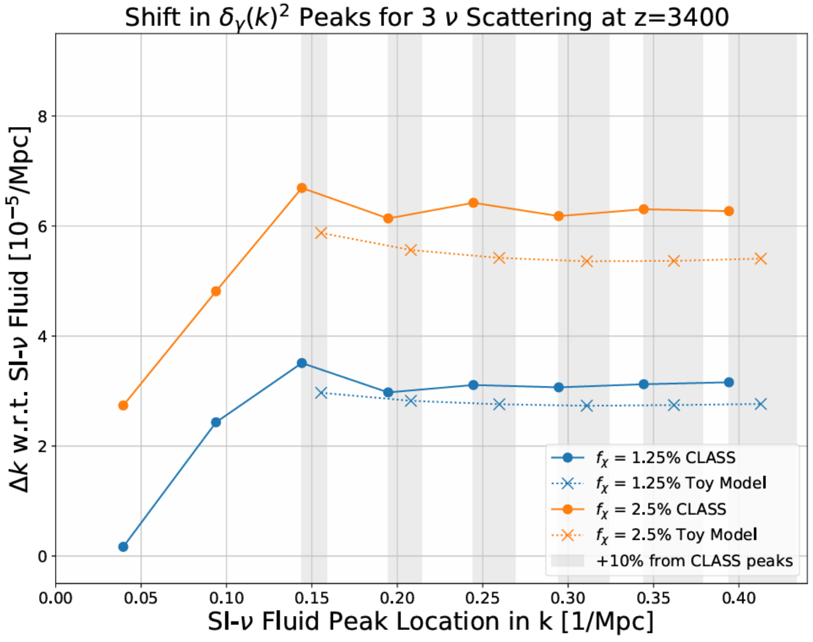
$$\delta k \approx \frac{-\Delta\phi_{\rm load}}{c_\gamma\tau} \approx \frac{3\alpha^2 f_{\rm DM}}{2c_\gamma^2\tau_{eq}}\frac{f_\chi}{(k+a)\tau} \approx 0.07 f_\chi (k\tau)^{-1}\,{\rm Mpc}^{-1}$$

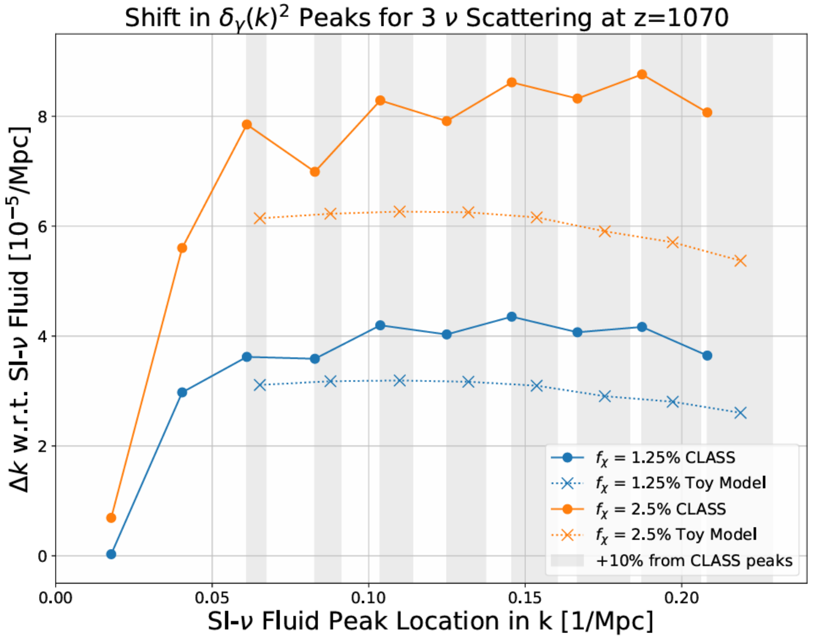




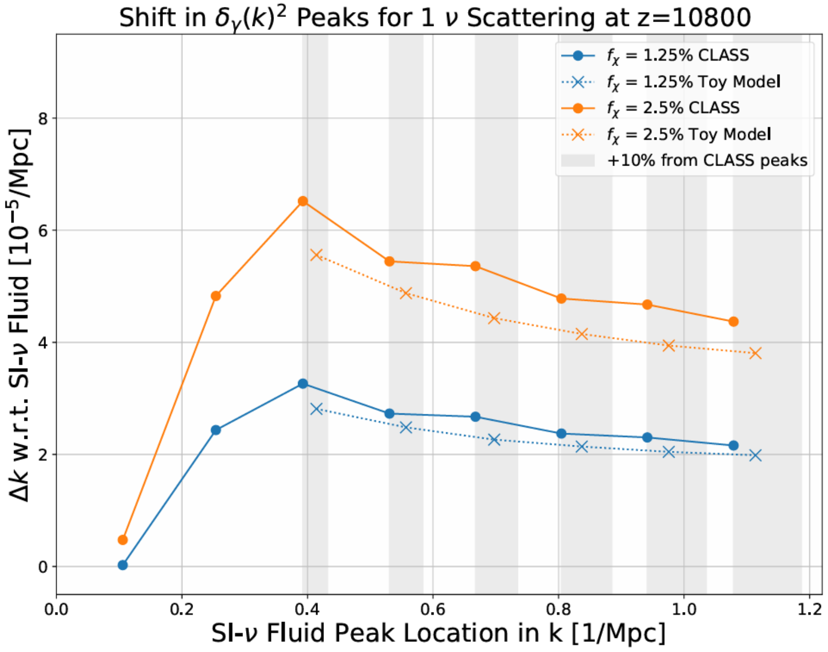
Toy Model vs CLASS (3 neutrinos)

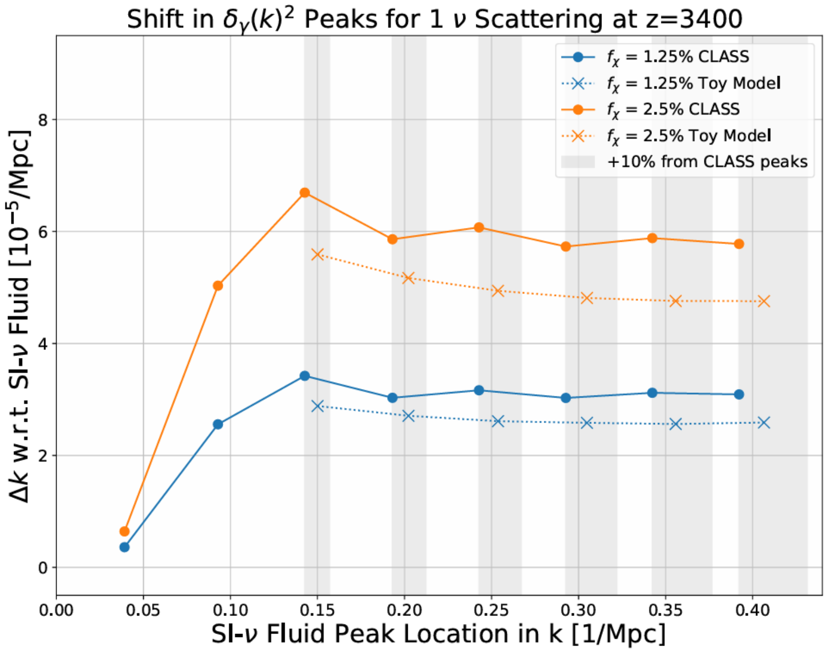


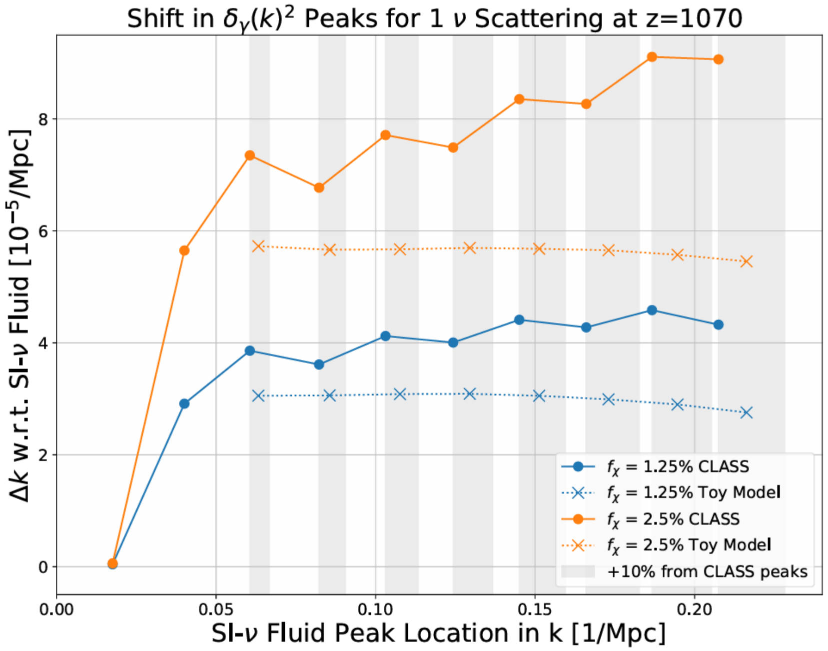




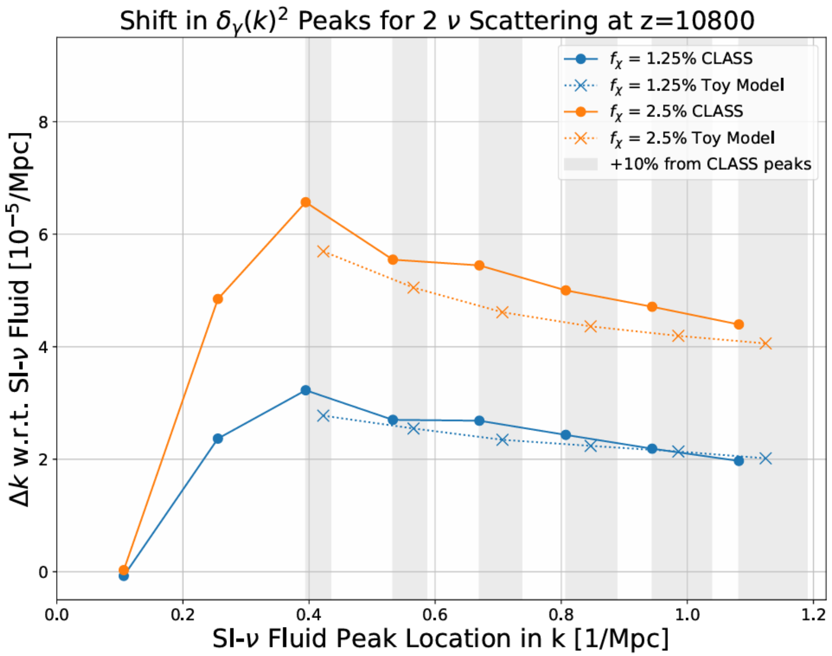
Toy Model vs CLASS (1 neutrino)

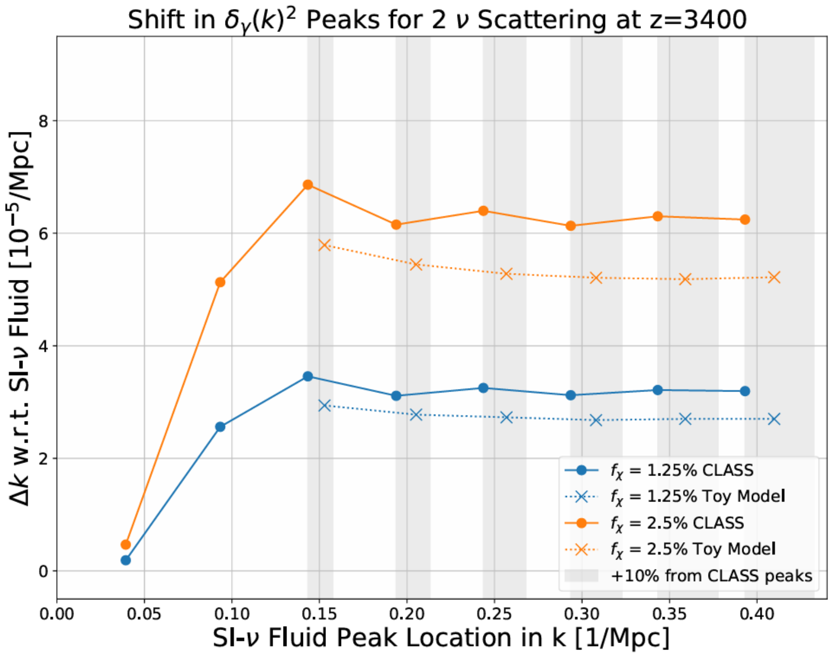


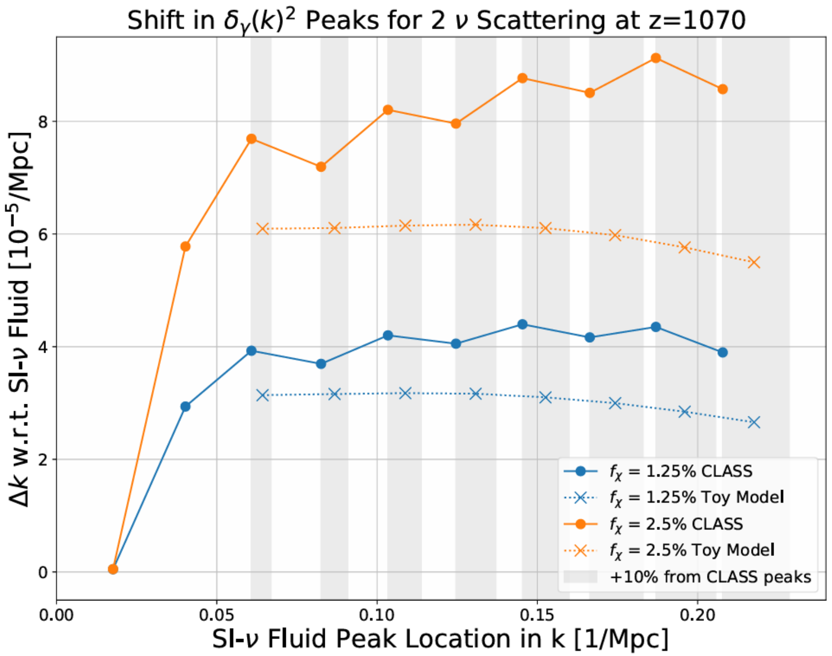




Toy Model vs CLASS (2 neutrinos)

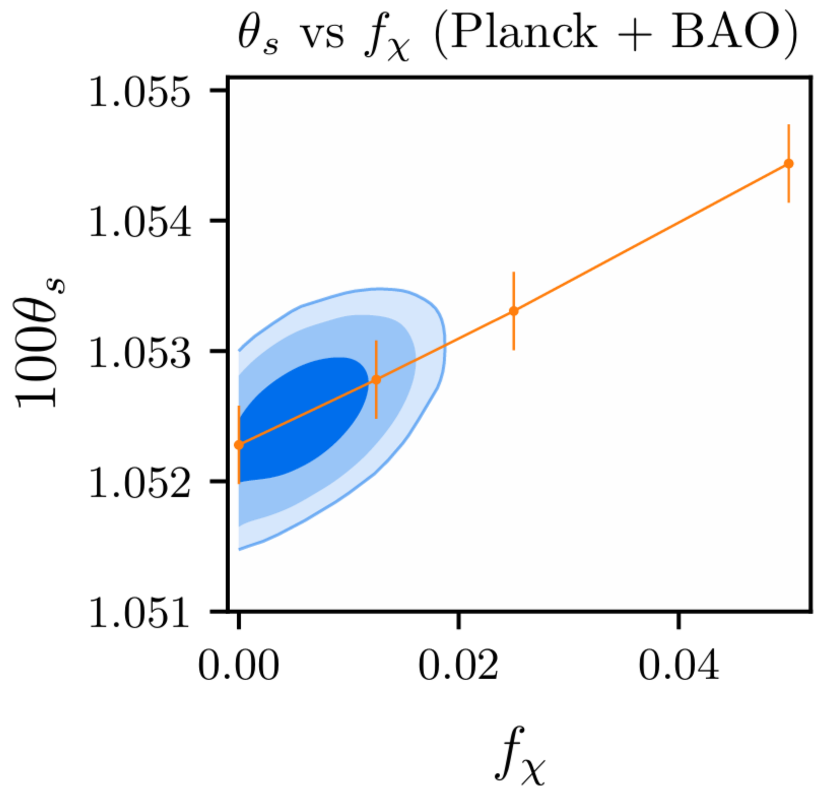


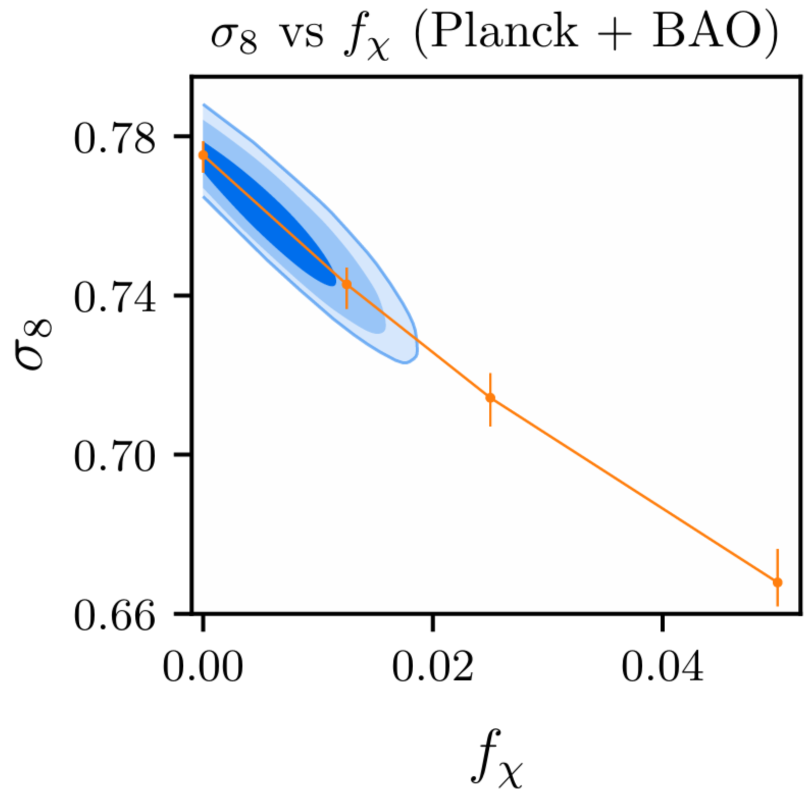




MCMC: Proof-of-Principle

- Consider case where all neutrinos scatter efficiently first to isolate f_χ-dependence of observables due to DM-loading
- Look at correlations of θ_s (CMB phase shift) and σ_8 (matter power spectrum) parameters with DL parameter f_χ





MCMC Analysis: Signature in θ_s (Planck+BAO)

- Planck and BAO datasets. DM-loading apparent only when amount of DR is significant

- When DR negligible, f_χ becomes unconstrained (does nothing)