Amplifying CMB Phase Shift with Dark Matter-Radiation Interactions

Daven W. R. Ho
University of Notre Dame

In collaboration with Subhajit Ghosh and Yuhsin Tsai

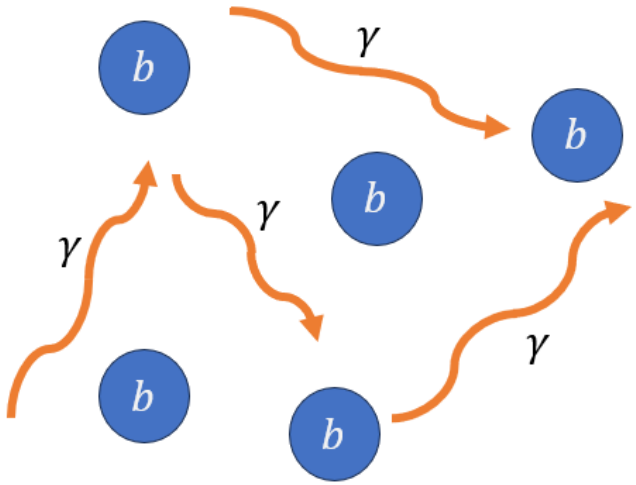
DPF-PHENO 2024, University of Pittsburgh

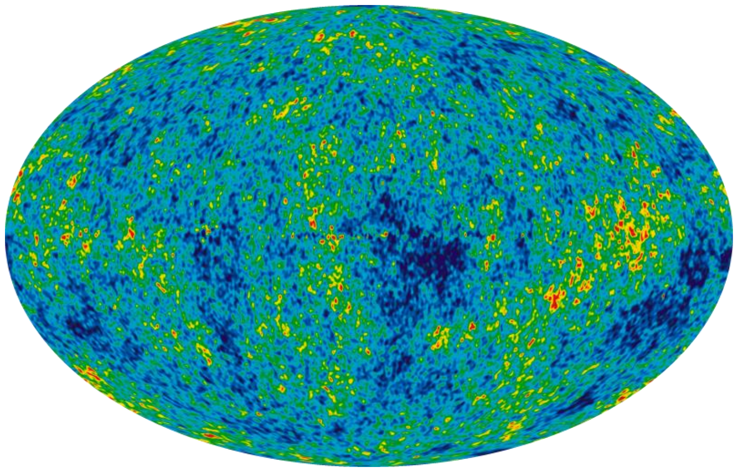
arXiv:2405.08064

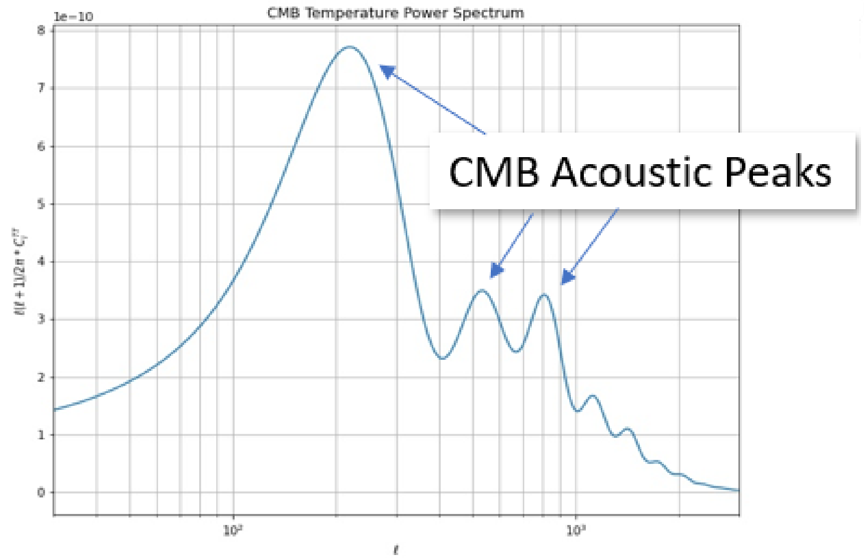
Email: dho2@nd.edu

CMB Acoustic Peaks

- Sound waves propagating in photon-baryon plasma before recombination leaves peak structure in CMB power spectrum.
- Consider the ***phase of acoustic oscillations***: shift in phase manifests as “shift” in CMB peaks (to be clarified later)
- **Phenomenology:** what kind of physics can produce phase shift?

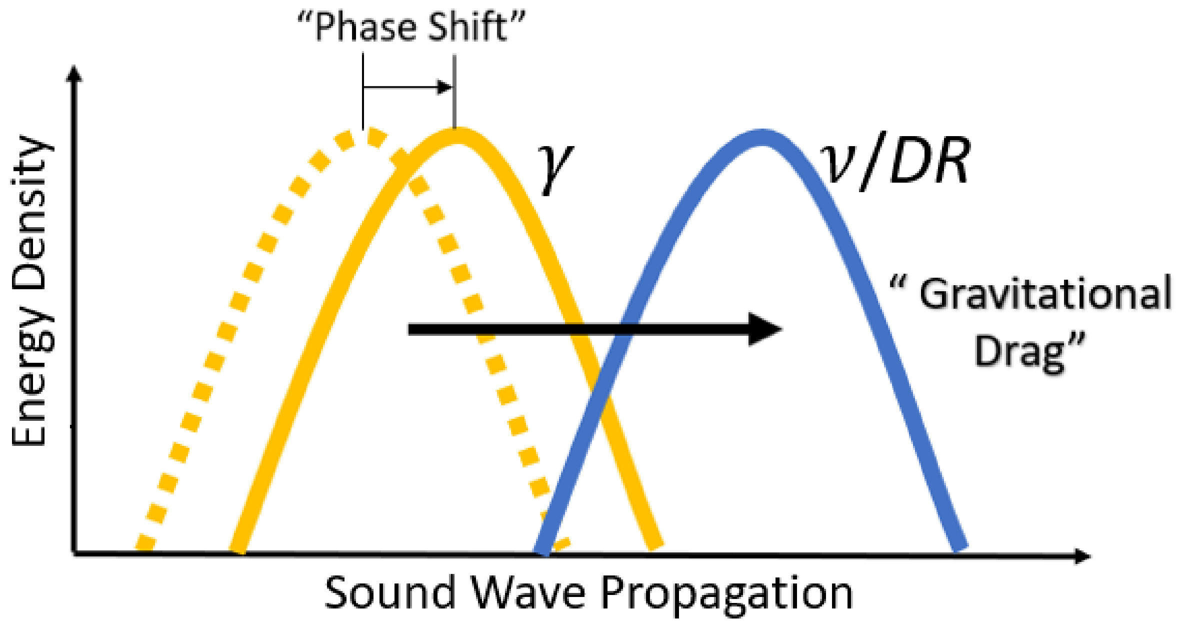


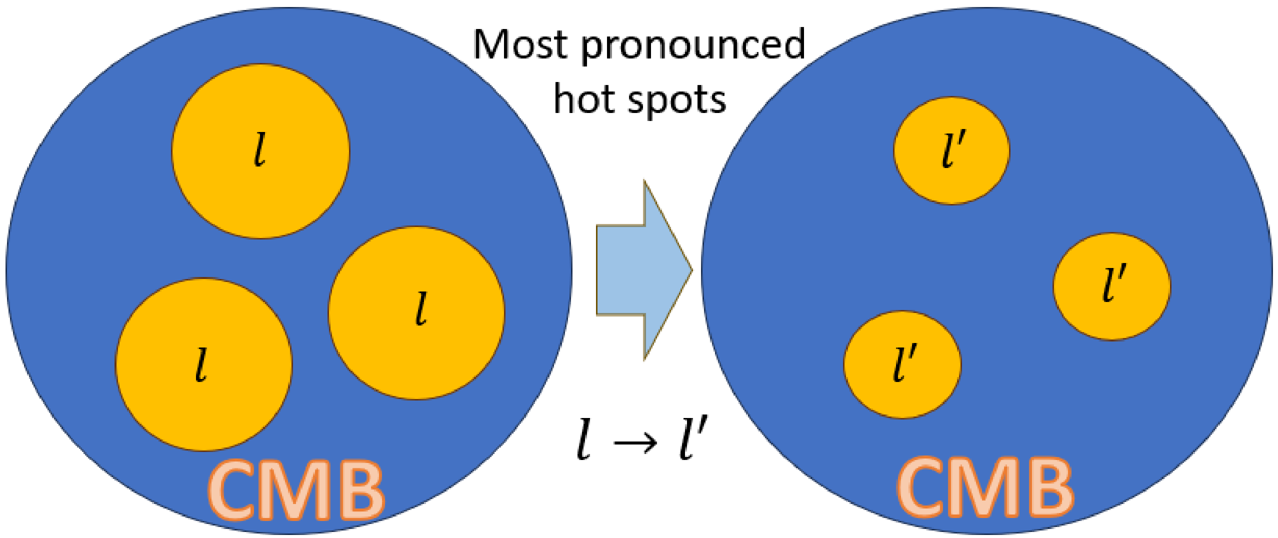




Phase Shift in the CMB

- 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** (i.e. no other 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)

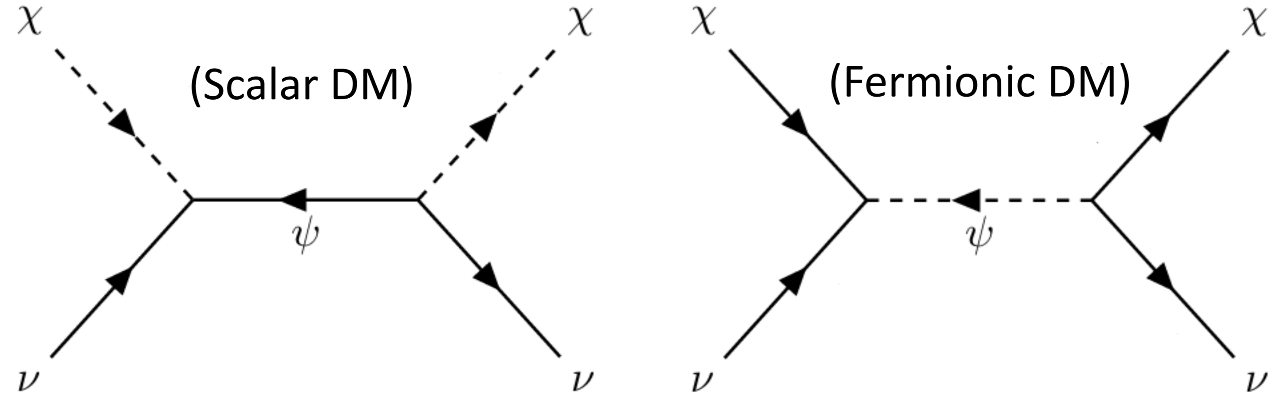




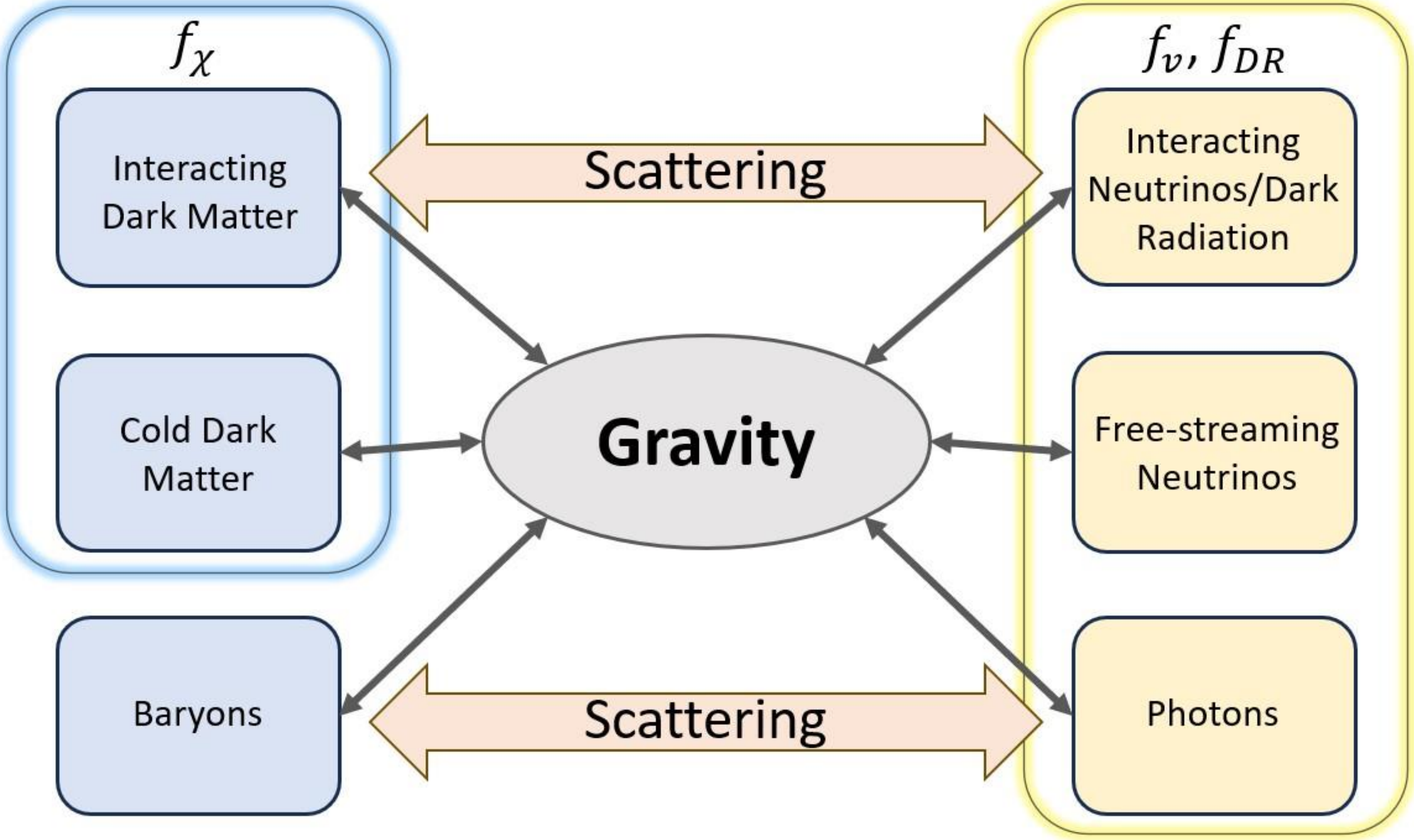
Dark Matter-Radiation Interactions

- Phase shift effect can be amplified compared to self-interacting radiation scenario
- Consider multi-component dark matter and radiation sectors. Scattering of radiation comes from interaction with DM
- ***Demonstrative example***: let (massless) neutrinos play the role of interacting radiation first

Example DNI Model:



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



Dark Matter Loading

- **<u>Efficient scattering:</u>** scattering rate large compared to Hubble rate

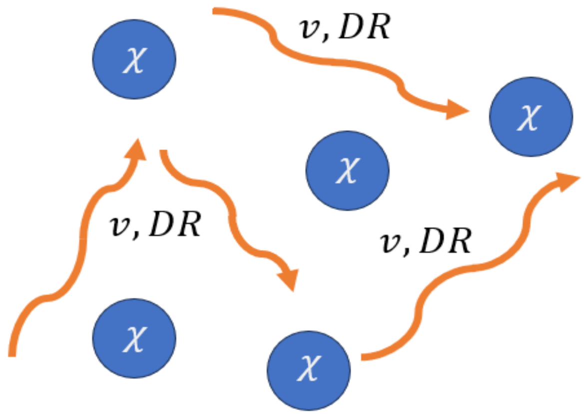
- Interacting radiation (r) and matter (m) forms *<u>tightly-coupled</u>* fluid, with sound speed

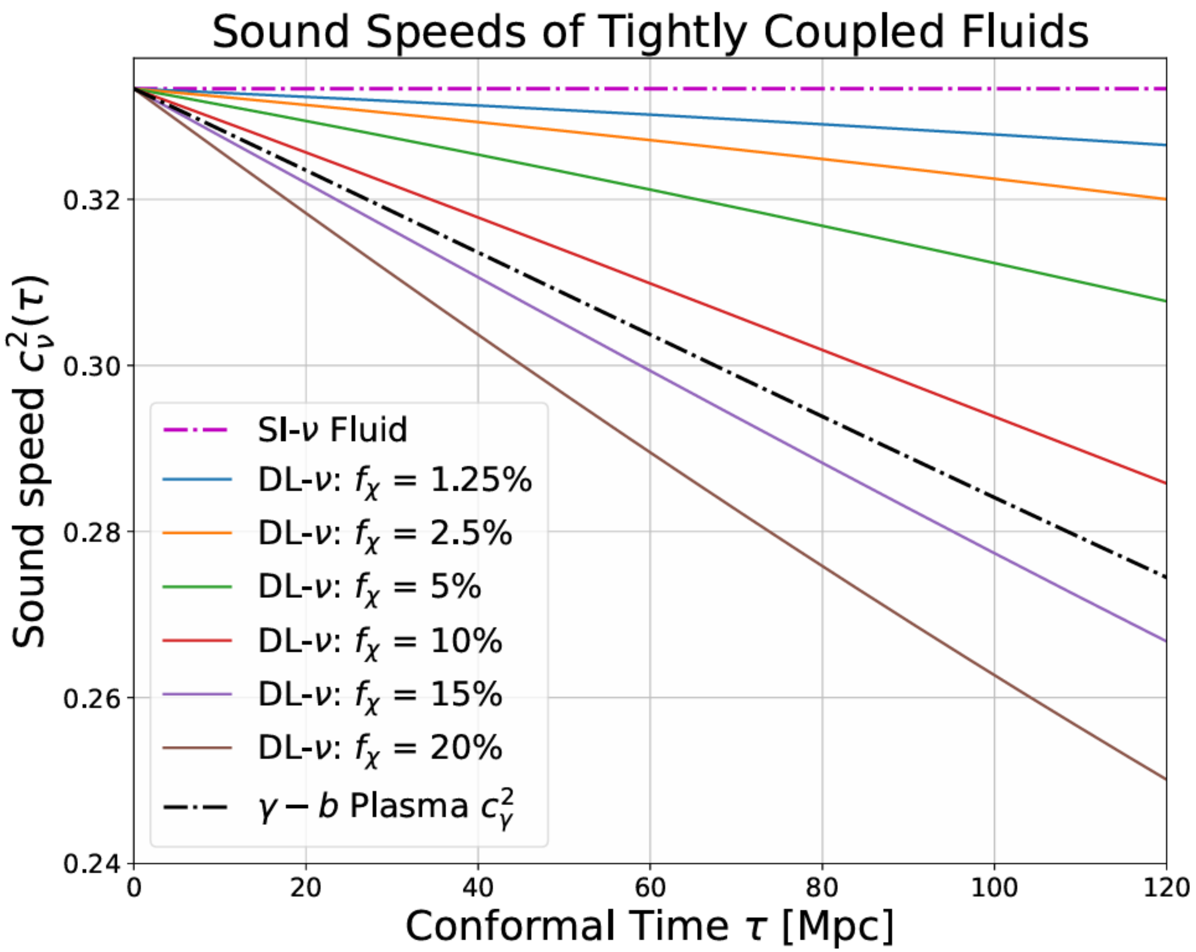
$$c_r^2 = \frac{1}{3(1+R_r)}, \quad \text{where} \quad R_r = \frac{3}{4}\frac{\rho_m}{\rho_r}$$

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

<u>Radiation propagation behaviour:</u>

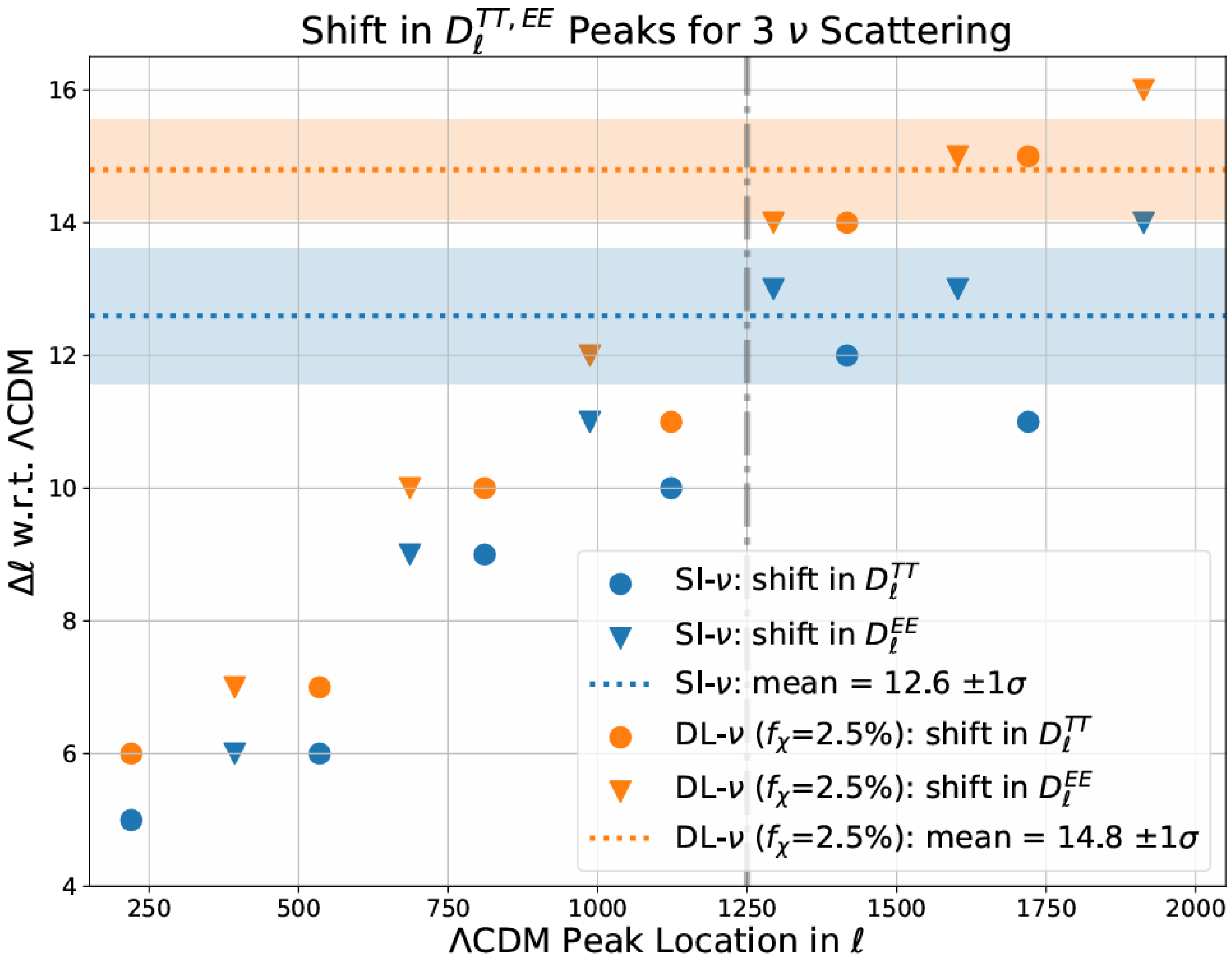
1. Free-Streaming (FS)
2. Self-Interacting (SI)
3. Dark-matter Loading (DL)





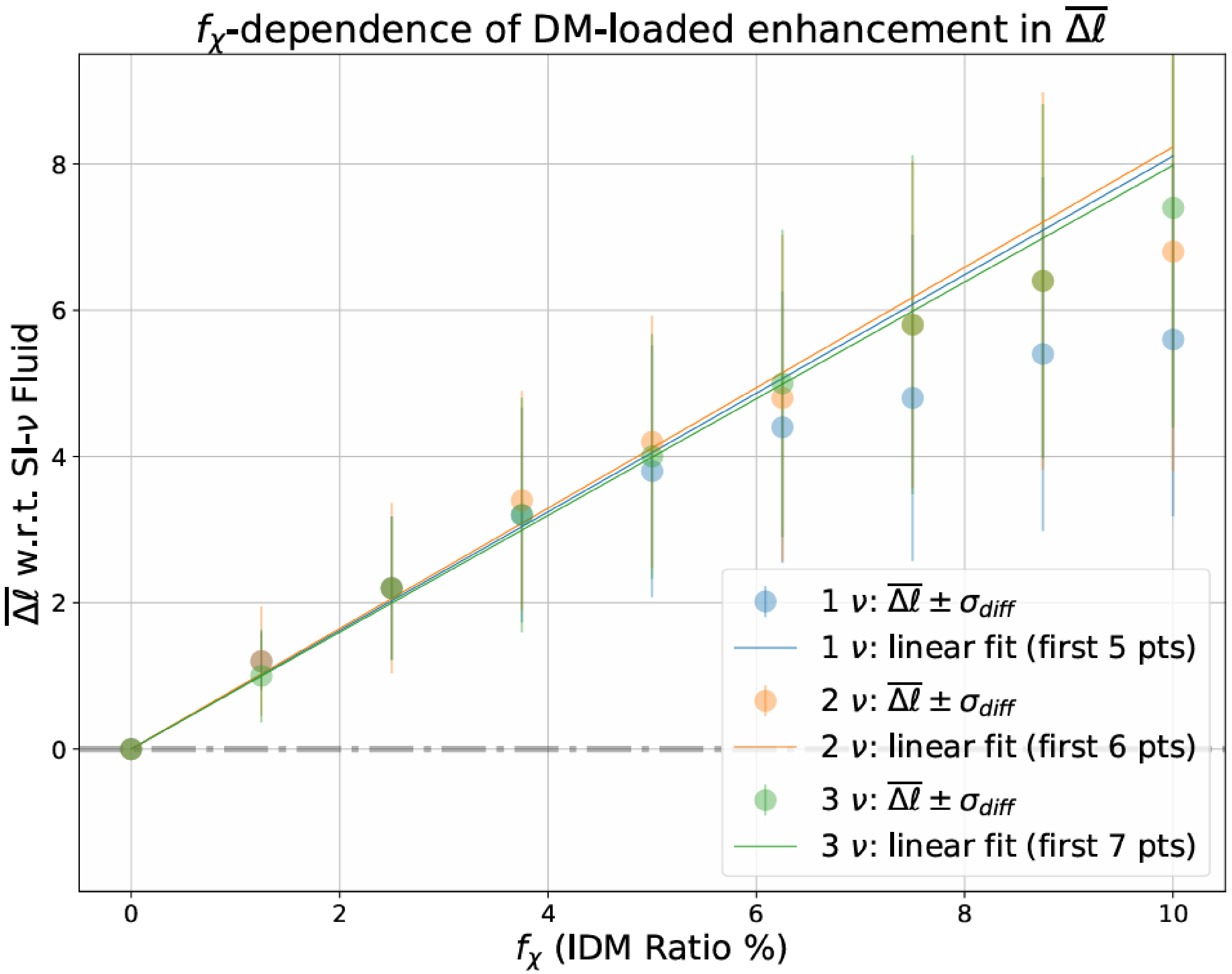
Amplifying CMB Phase Shift

- Calculate shift in CMB peaks w.r.t. **ΛCDM** model using CLASS (all neutrinos FS)
- Peaks shift to positive l for SI neutrino, shift enhanced further for DL neutrino ($f_\chi = 2.5\%$)



Amplifying CMB Phase Shift

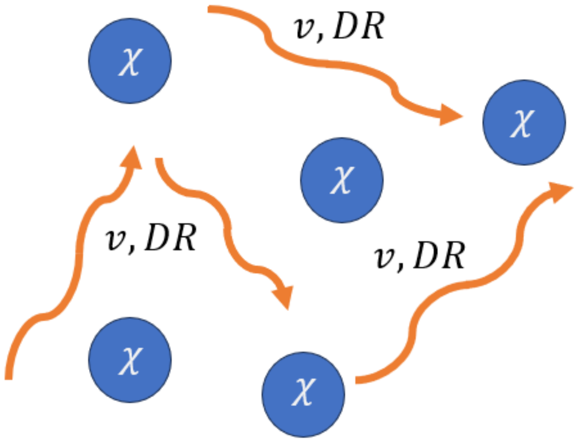
- Vary number of interacting neutrinos: overall shift w.r.t. **ΛCDM**, but similar DM-loading enhancement
- DL vs SI enhancement has linear dependence on f_χ and independent of f_ν (for small f_χ vs f_ν)

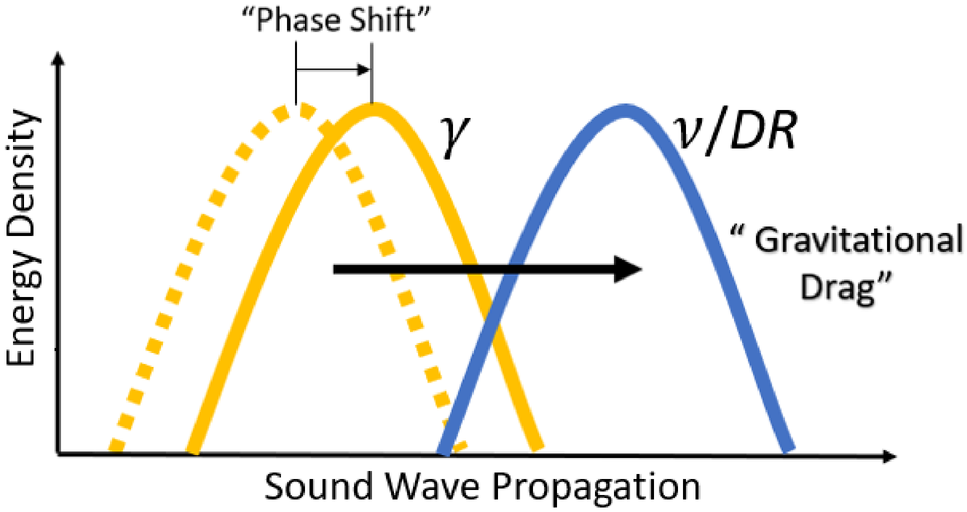


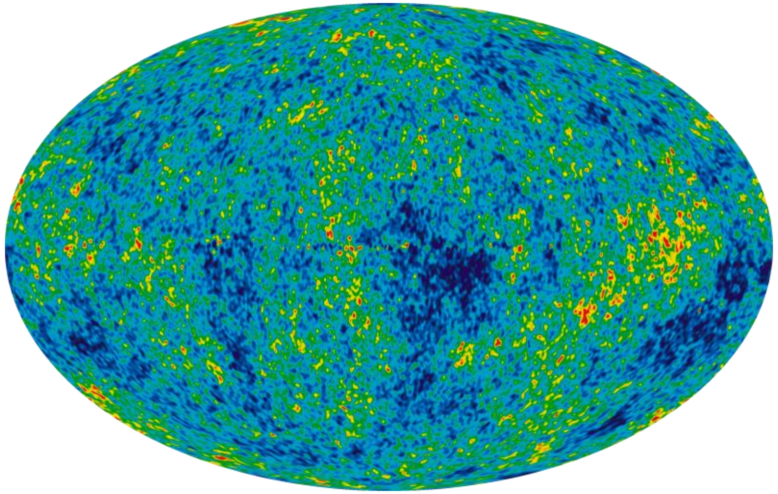
Brief Outline

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

- Further questions for this talk:
  1. <u>What's going on?</u> Understand mechanism with simplistic toy model
  2. <u>What to look for?</u> Study observability with more realistic model







Toy Model: Coupled Oscillators

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

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

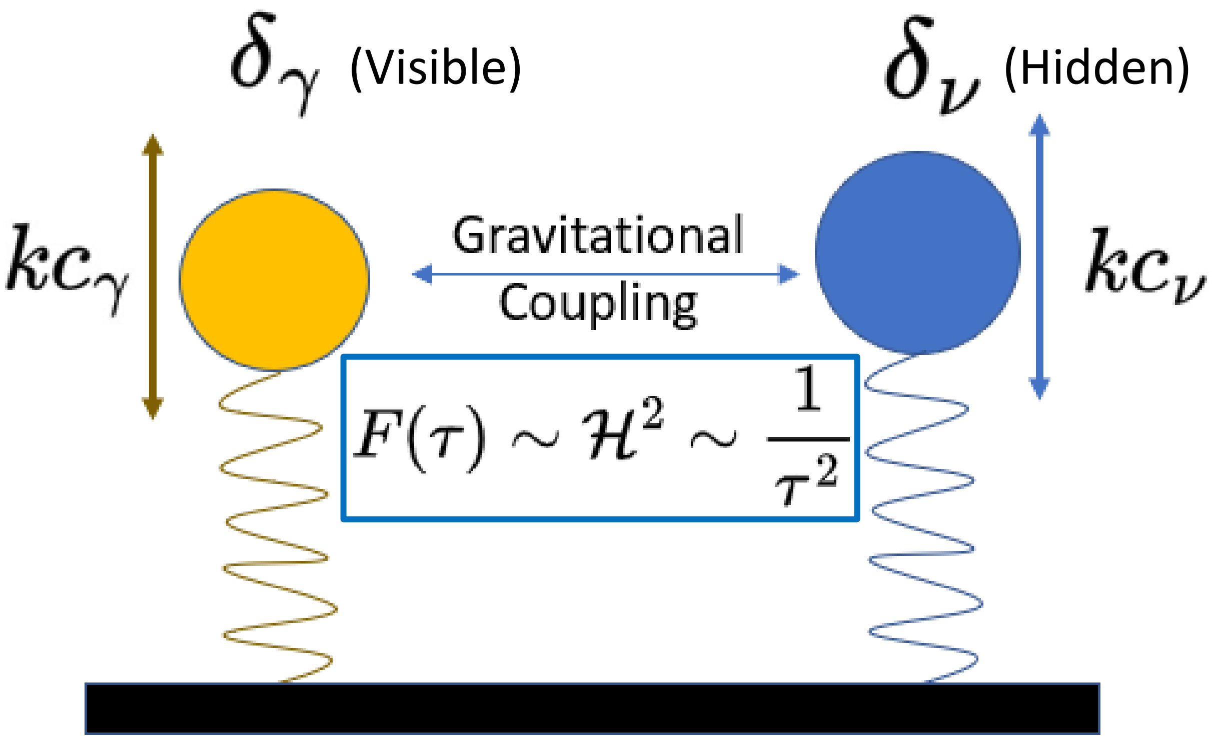
3. Phase shift imprinted in photons by hidden oscillator: size and direction of shift depends on *relative sound speed*

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

Gravitational Coupling

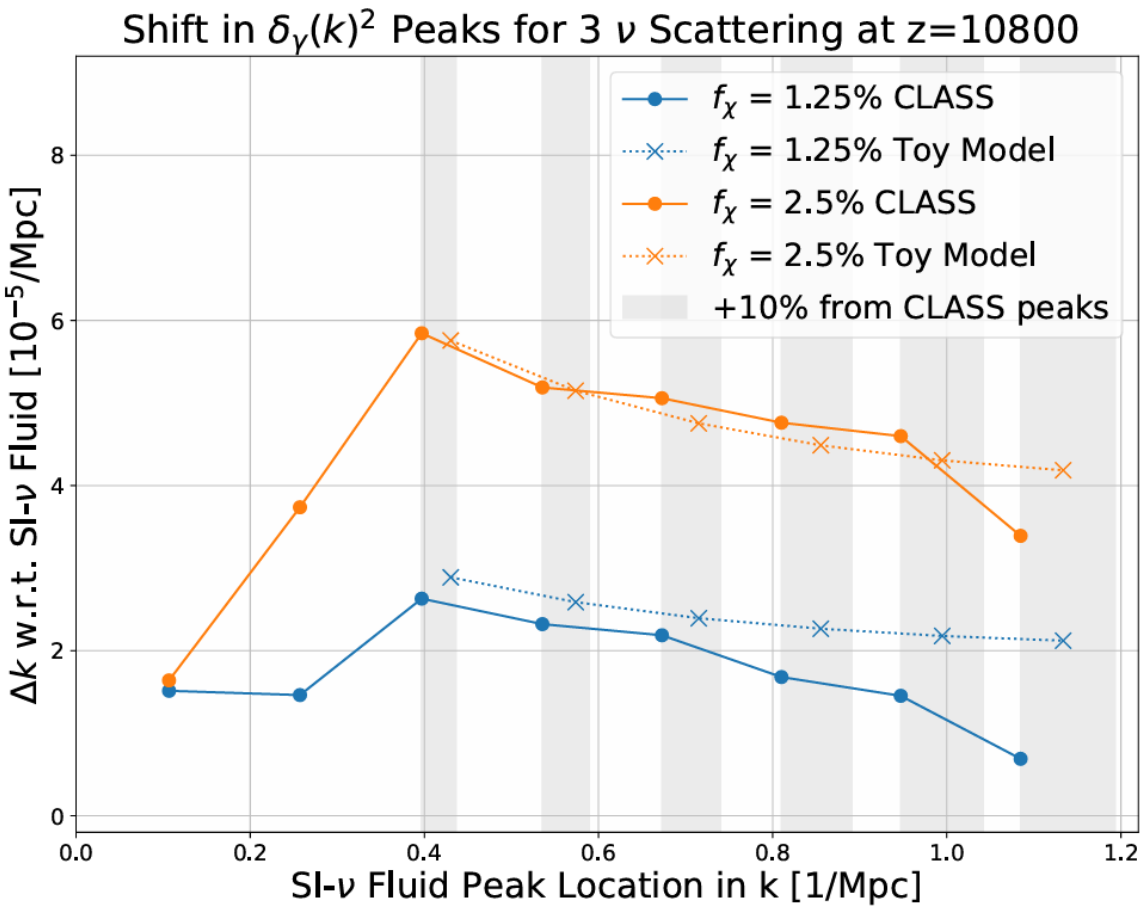
$$\ddot{\delta}_\gamma + k^2 c_\gamma^2 \delta_\gamma = F(\tau)(f_\gamma \delta_\gamma + f_\nu \delta_\nu)$$

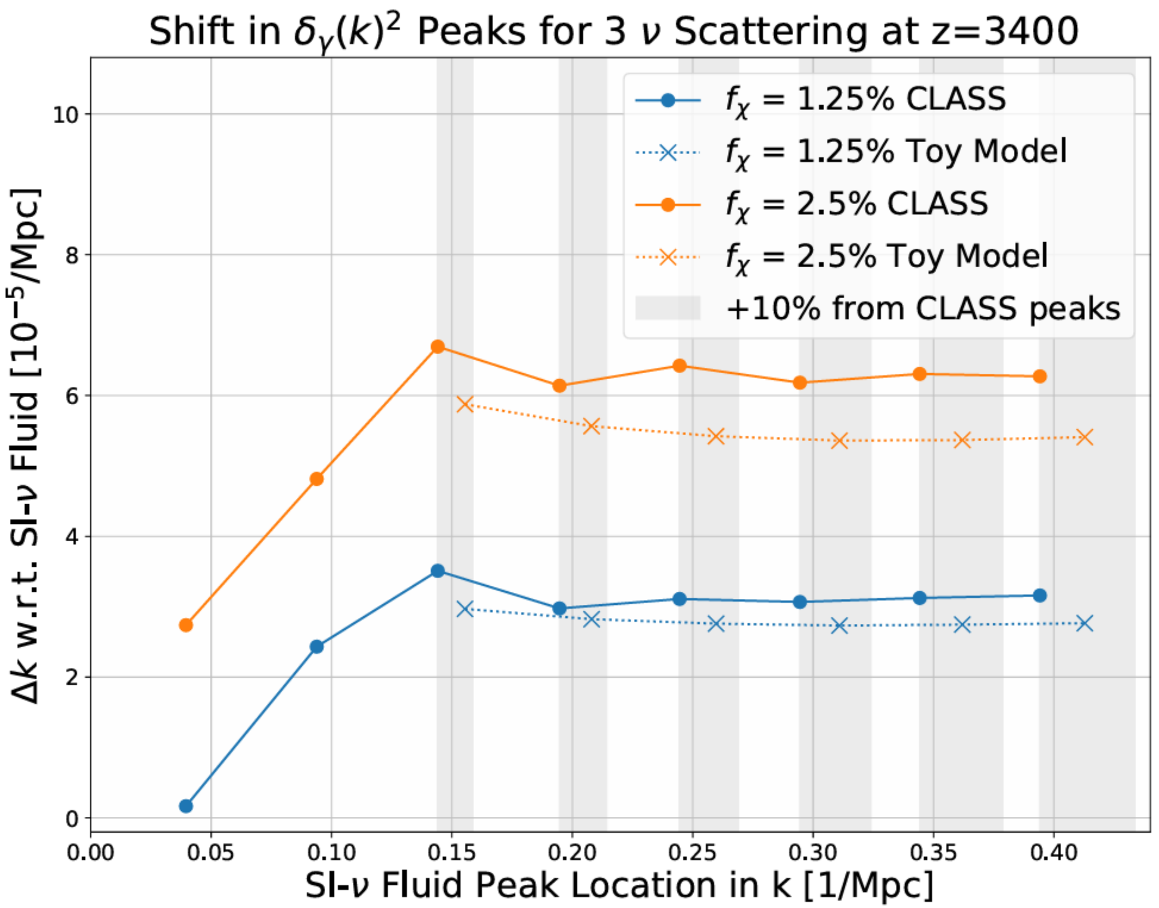
$$\ddot{\delta}_\nu + k^2 c_\nu^2 \delta_\nu = F(\tau)(f_\gamma \delta_\gamma + f_\nu \delta_\nu)$$



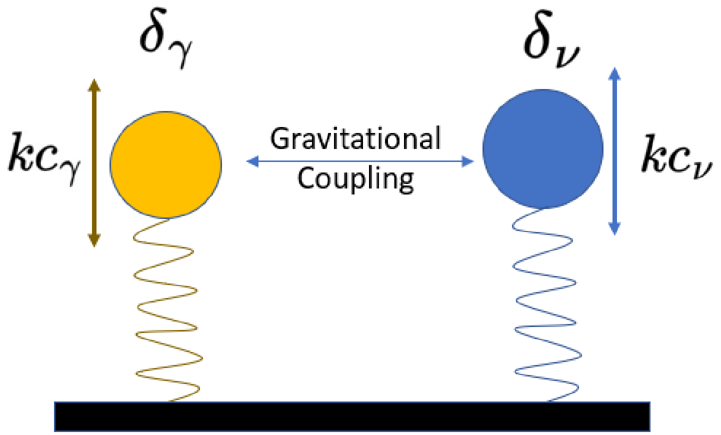
Toy Model Approximates CLASS Well

- <u>Numerical check</u>: toy model captures shift in photon transfer function from CLASS *(details omitted)*





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

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

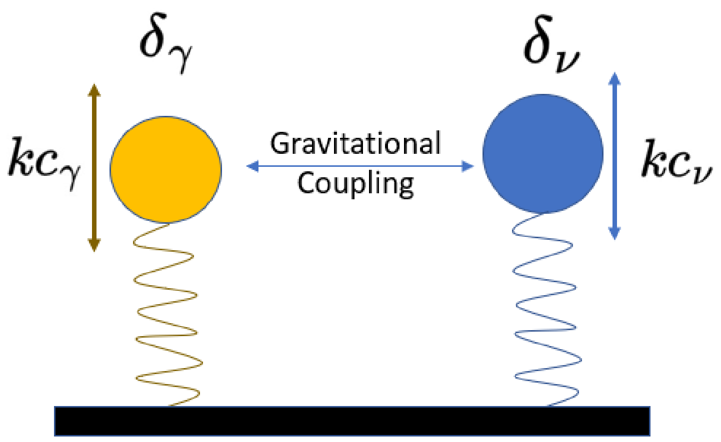
$$\delta c \sim R_\nu \sim f_\chi / f_\nu$$

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"

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

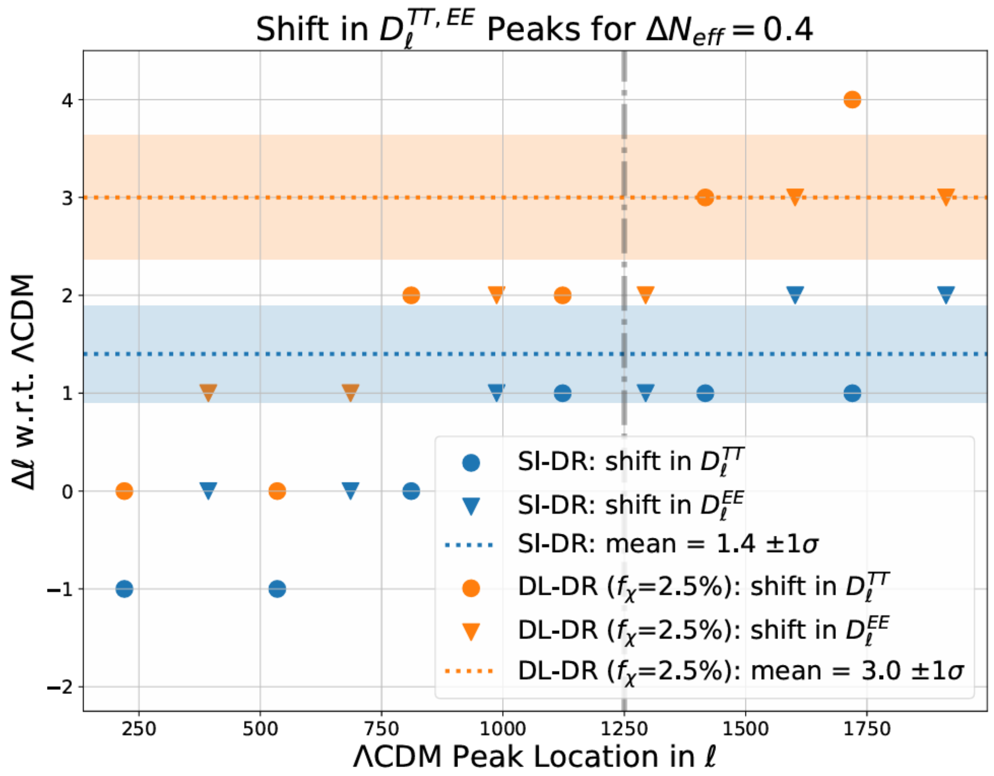
Phase shift to $\delta_\gamma \sim \cos(kc_\gamma\tau)$ comes from sine part, which is linear in f_χ and independent of f_ν

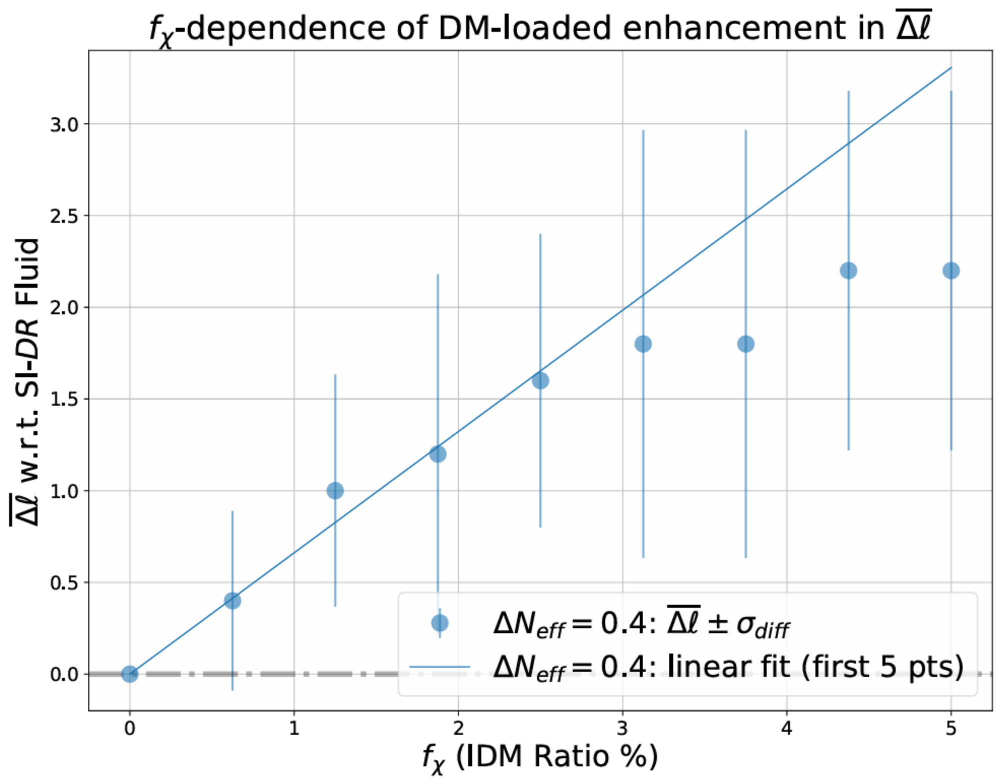
$$\Delta\phi \sim f_\nu \delta c \sim f_\nu \left(\frac{f_\chi}{f_\nu}\right) \sim f_\chi$$

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

Interacting Dark Radiation Model

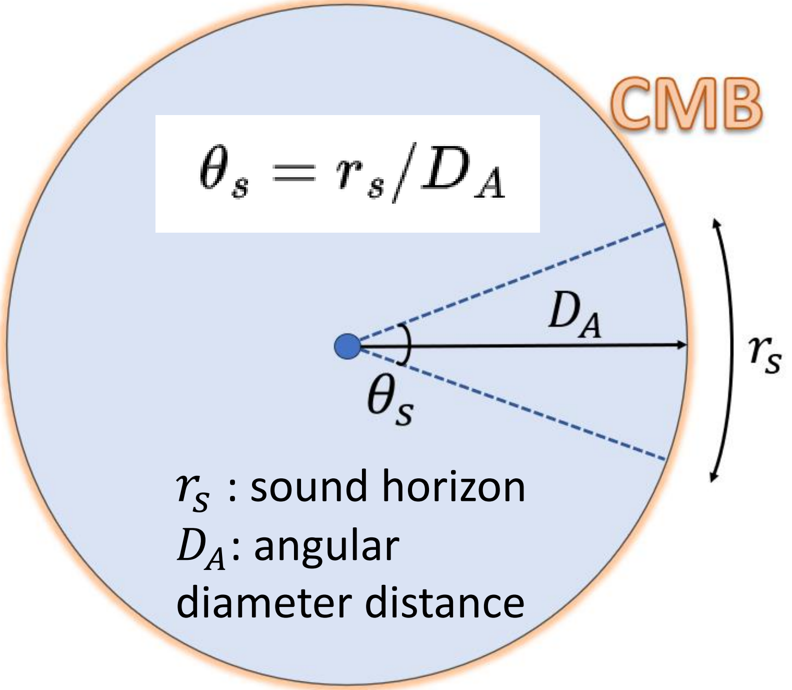
- Additional dark radiation component (ΔN_{eff}) scatters efficiently with DM
- All neutrinos free-streaming, new physics only in dark sector: interacts with Standard Model *only gravitationally*
- Similar phase shift amplification and parametric dependence *(details omitted)*





Signal: 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)?
- Previous CLASS analysis: fixed $\theta_s \Rightarrow$ peaks shifted
- But peak positions fixed by data: determine phase shift $\Delta\phi$ from fitting θ_s



Data

New Physics

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

Signal

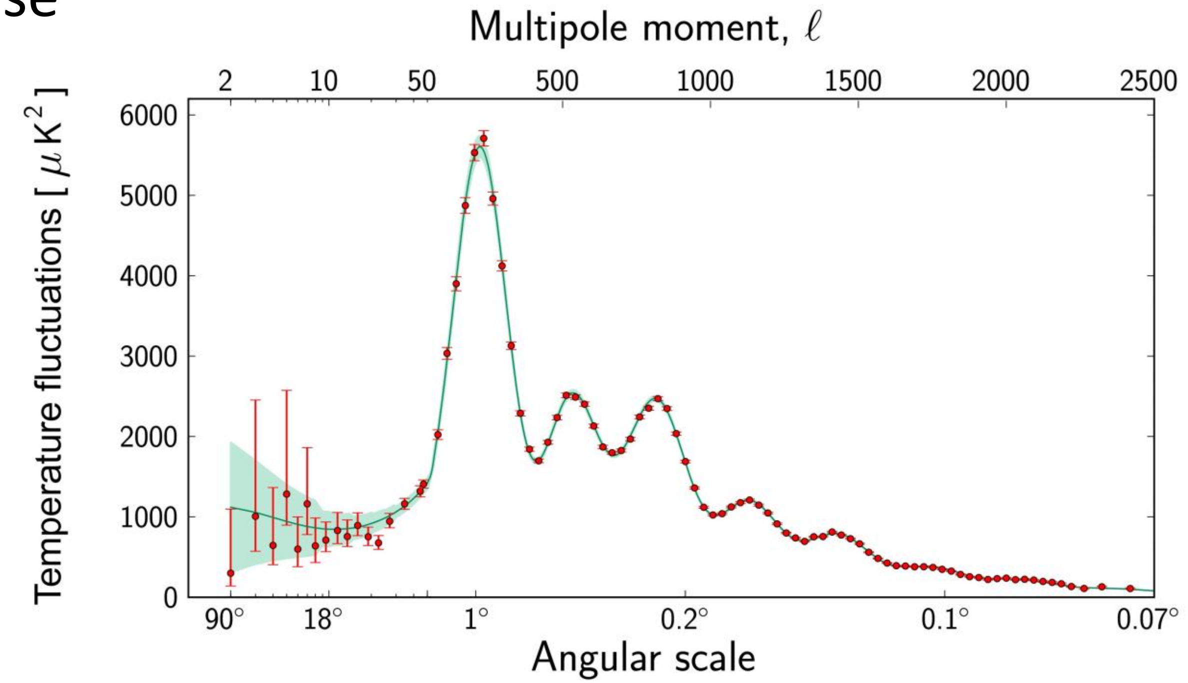
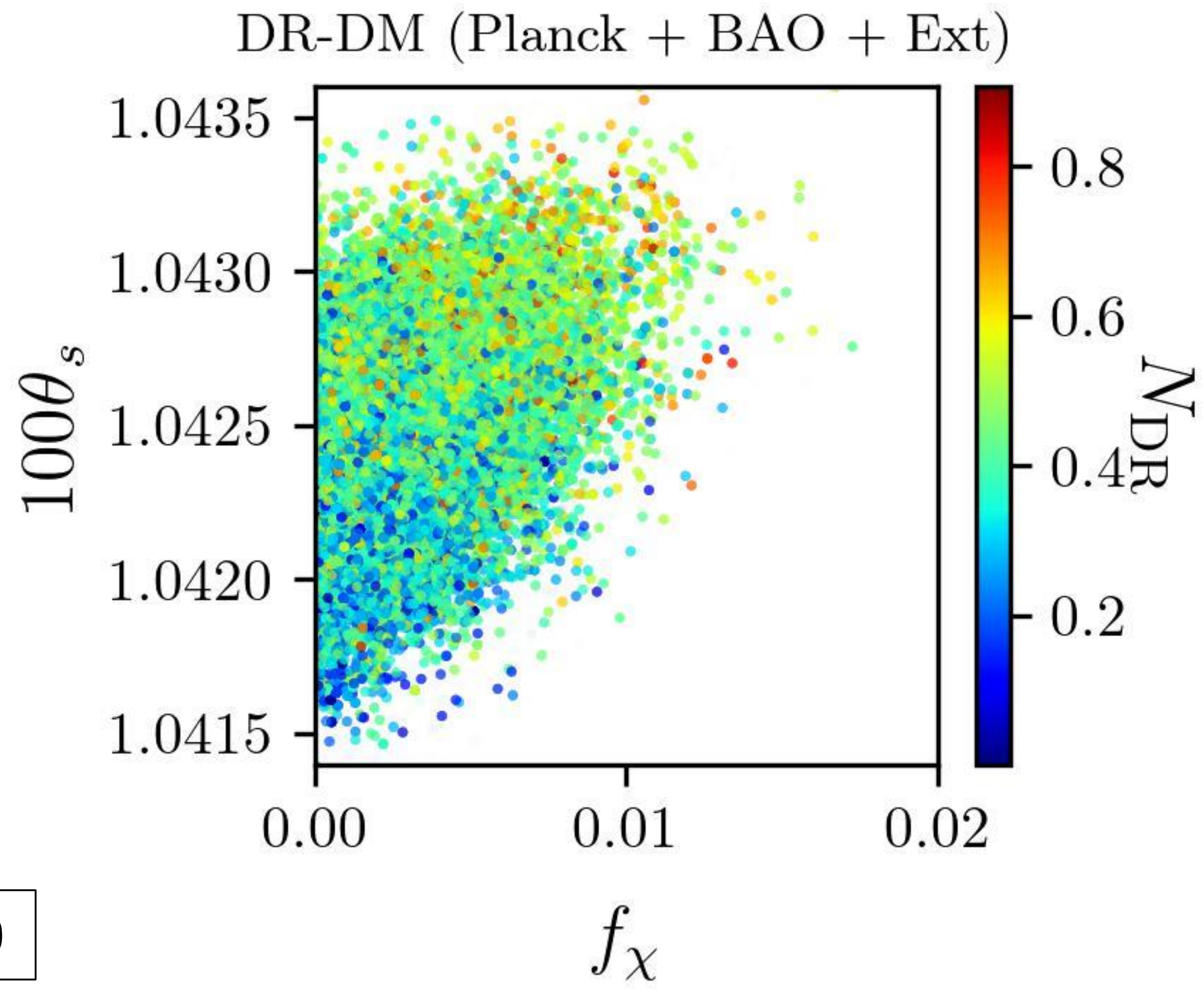


Image: ESA/Planck Collaboration – Planck Power Spectrum

MCMC Analysis: Signature in θ_s

- Use Montepython to fit model. Allow amount of interacting DR (N_{DR}) to vary
- <u>DM-loading signature:</u> angular sound horizon θ_s positively correlated with interacting DM fraction f_χ
- For comparison: $N_{DR} = 0$ corresponds to **ΛCDM** and the $f_\chi \to 0$ limit for each $N_{DR} > 0$ approaches the self-interacting DR scenario



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

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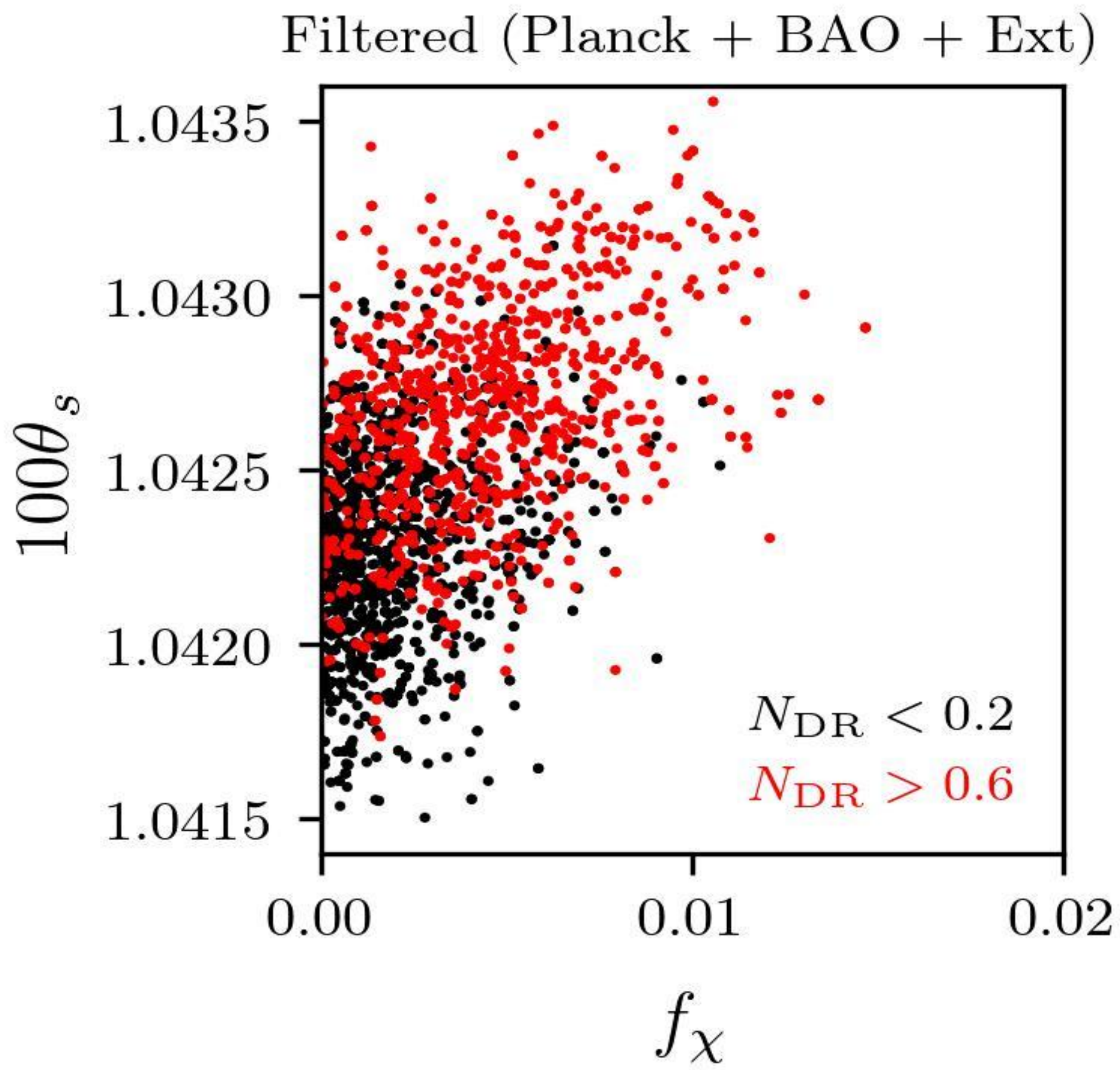
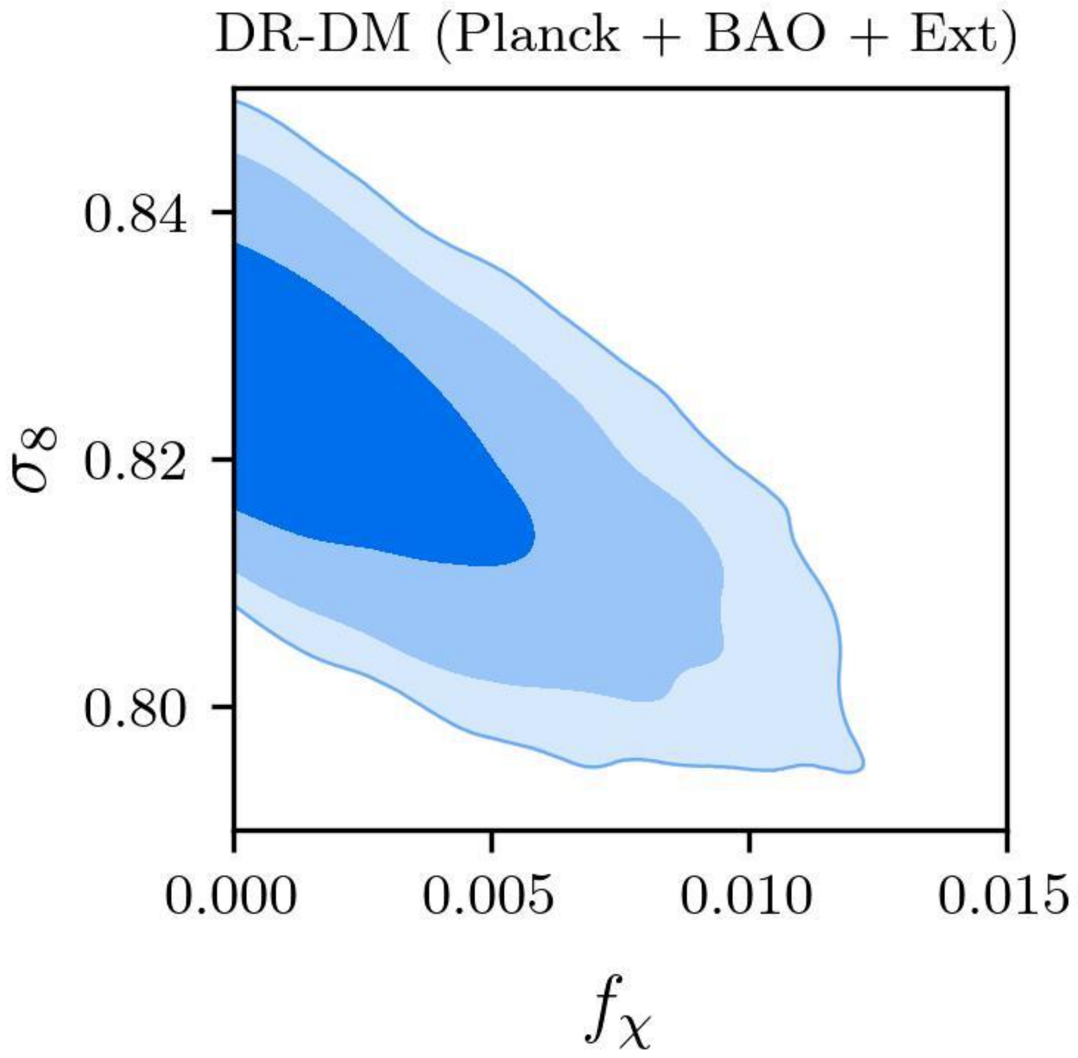


<u>Datasets</u>: Planck2018 + BAO + SH0ES + kv450

MCMC Analysis: Dual signature in σ_8

- σ_8 parameter measures amplitude of matter density fluctuations on scales $k \sim 8\ h/\text{Mpc}$
- From matter 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



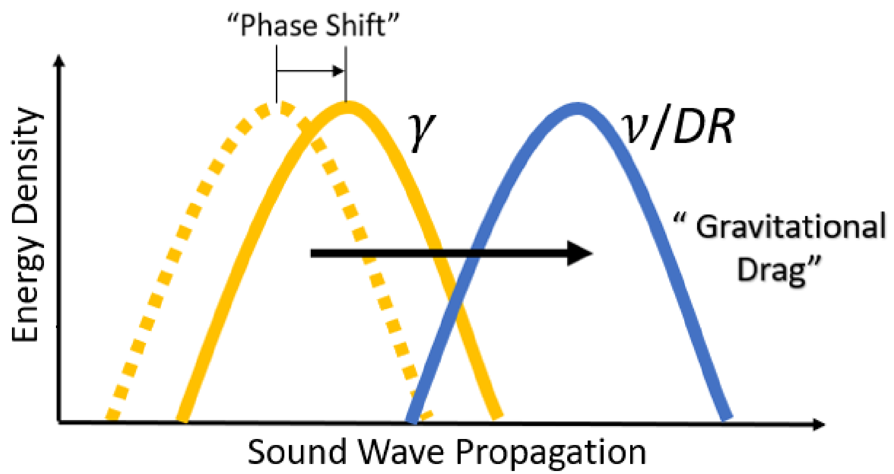
<u>Datasets</u>: Planck2018 + BAO + SH0ES + kv450

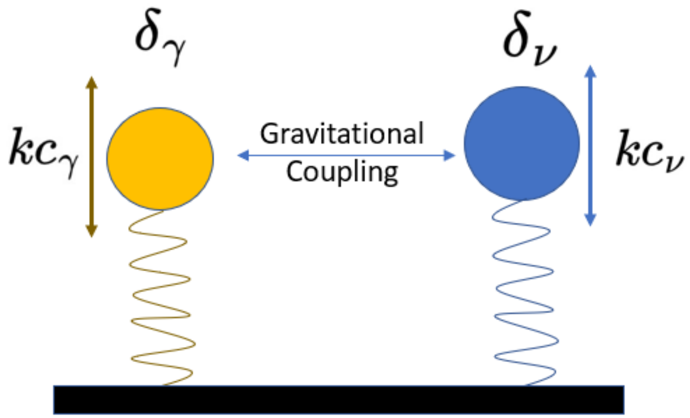
Conclusion

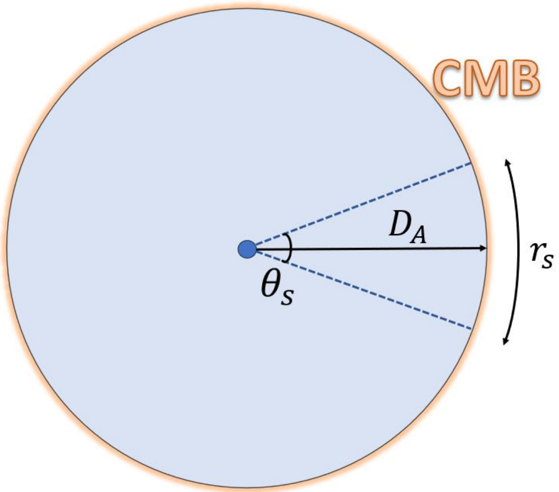
arXiv:2405.08064

1. CMB phase shift provides sensitive **gravitational** probe of propagation behaviour of non-photon radiation before recombination. (Useful for probing physics that only interacts with SM gravitationally).

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

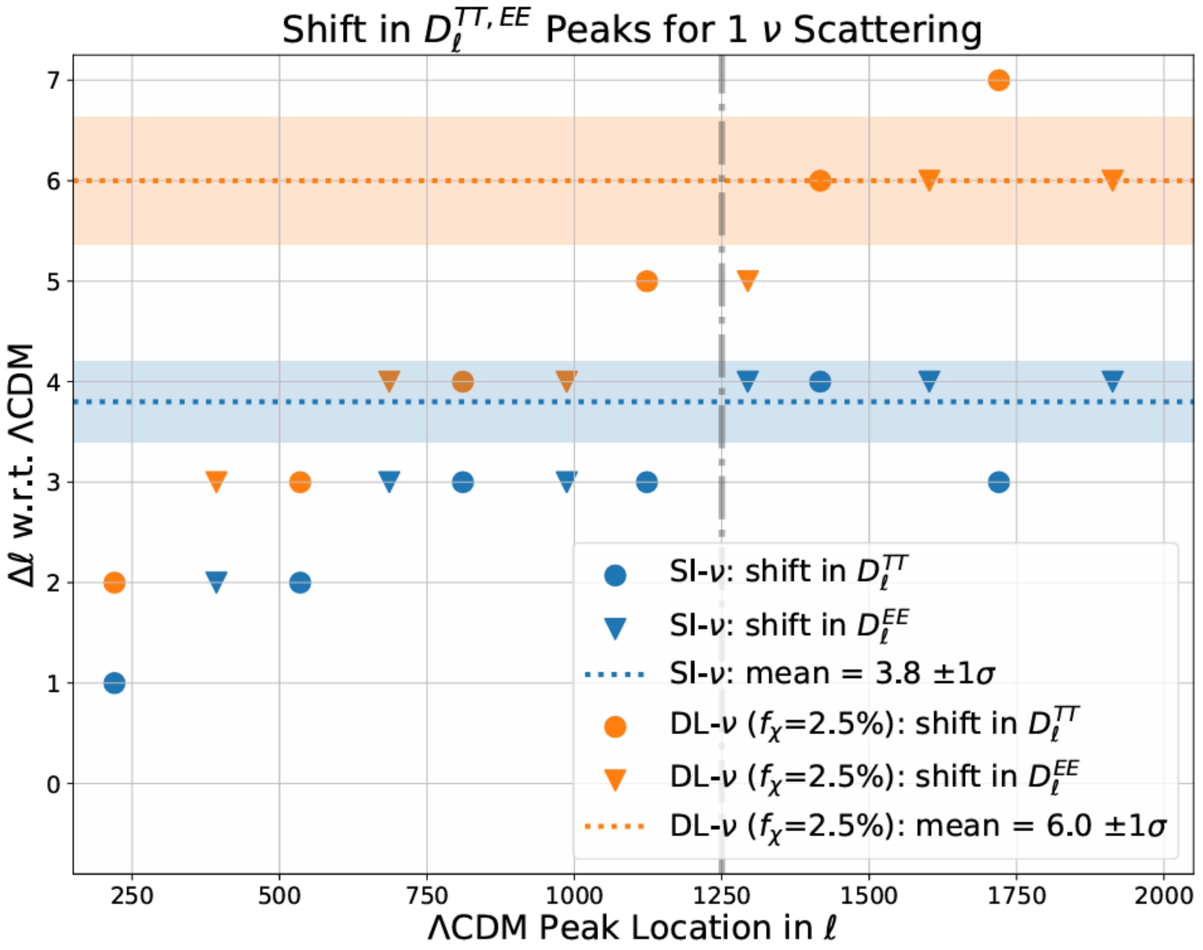
$$\sigma = 1.7 \times 10^{-6} \left(\frac{\eta}{0.1}\right)^4 \left(\frac{\text{GeV}}{m_\chi}\right)^2 \text{GeV}^{-2}$$

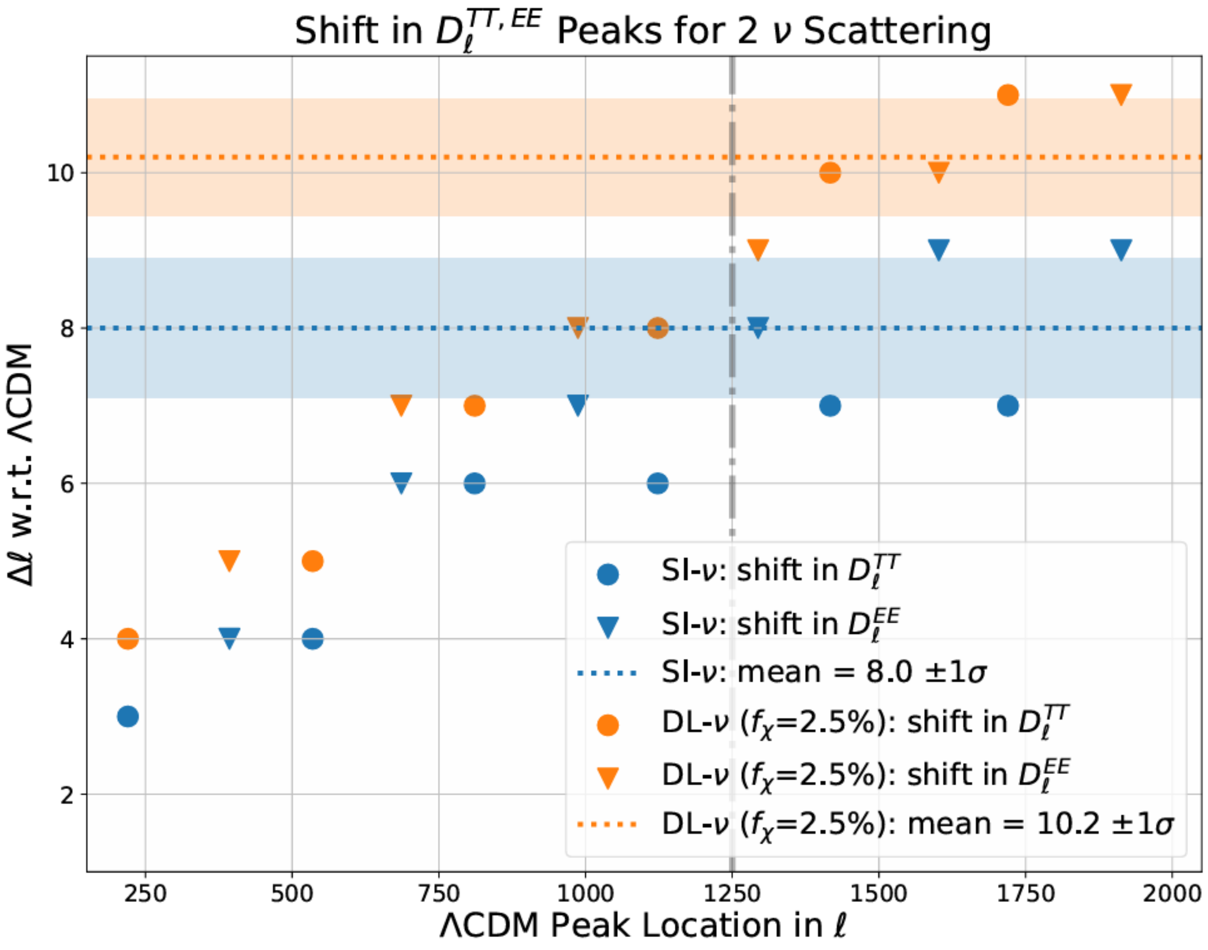
Possible UV completion with massive vector-like fermion *N*

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

Ghosh, Khatri, Roy (arXiv:1711.09929v2)

CLASS 1 and 2 nu

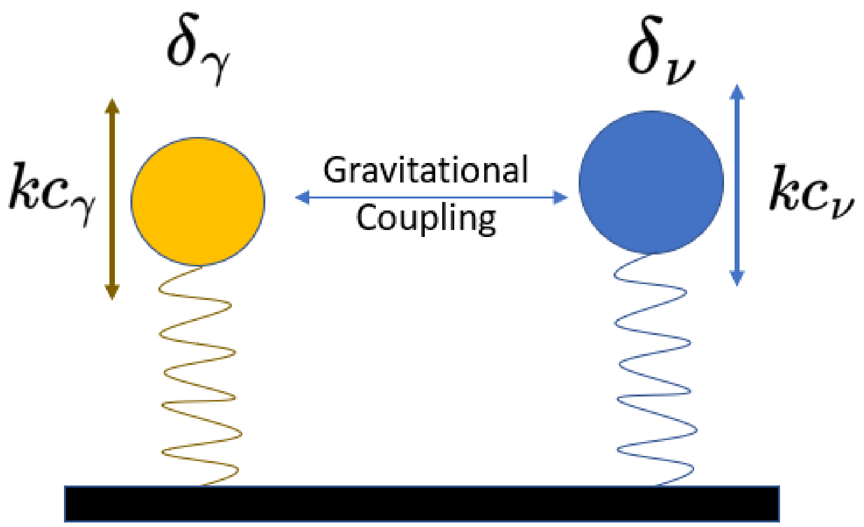




Toy Model: Coupled Oscillators

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

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



- 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)

Toy Model Assumptions

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)

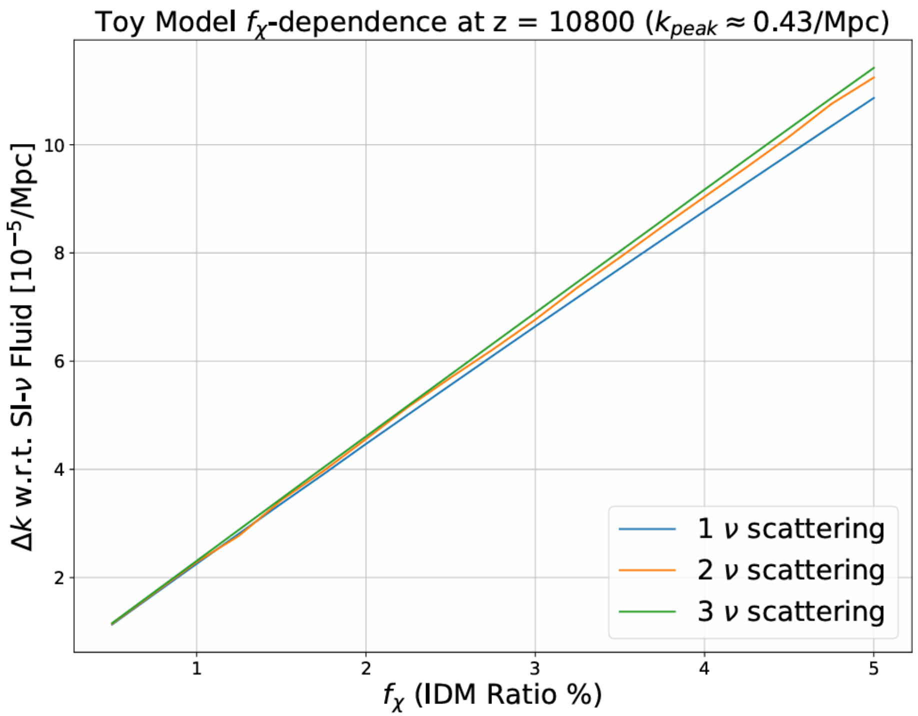
- Consider phase shift induced in photon oscillations due to gravitational driving from neutrinos

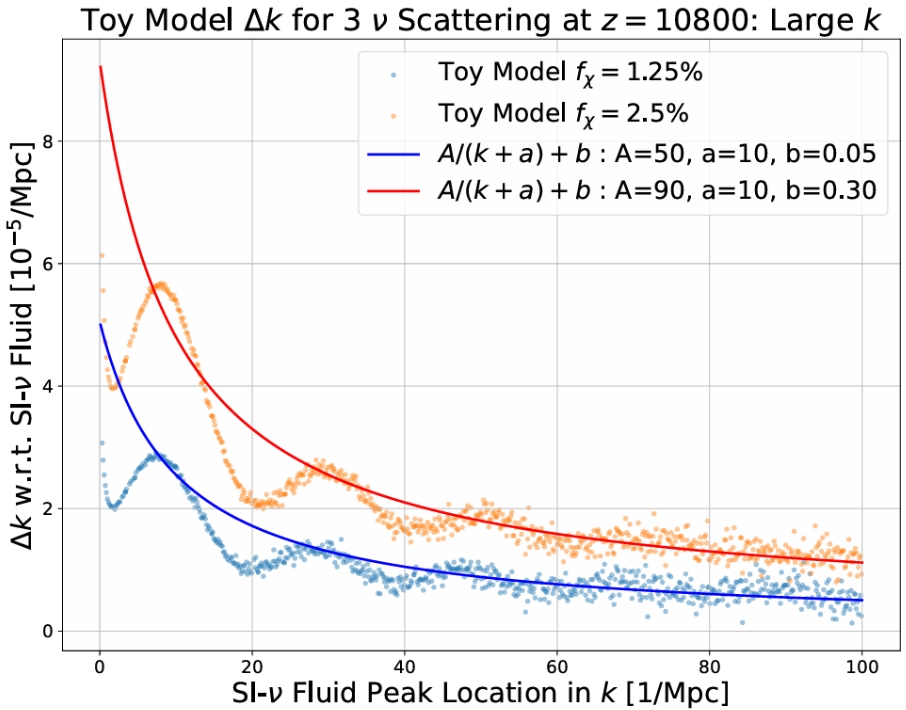
$$\cos(\omega\tau + \Delta\phi_{\rm load}) \qquad \omega^2 = k^2 c_\gamma^2$$

- Analytic approximations

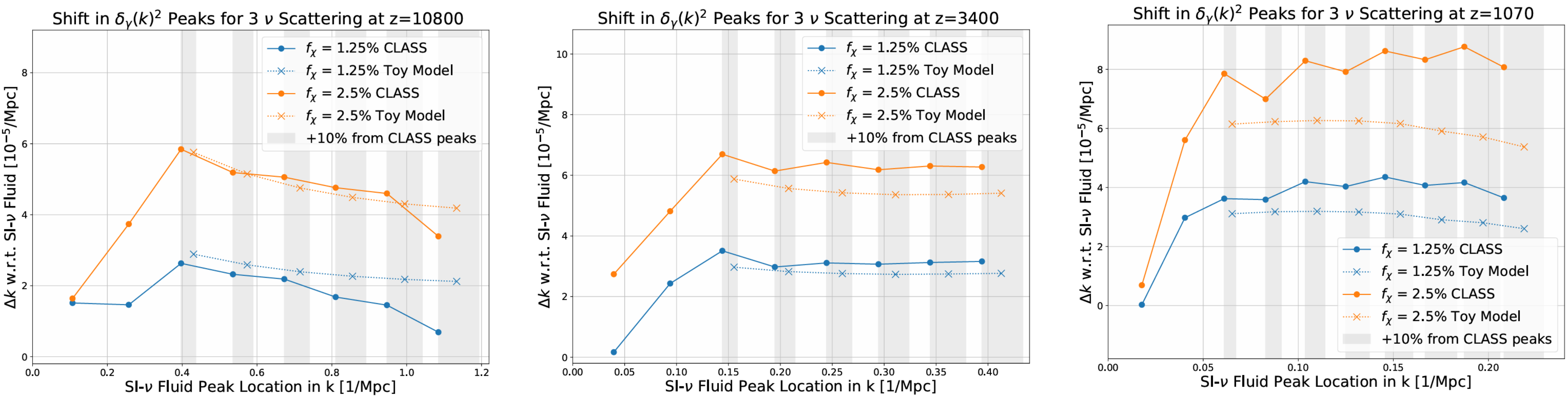
$$\Delta\phi_{\rm load} \approx -\frac{3\alpha^2 f_{\rm DM}}{2c_\gamma\tau_{eq}}\frac{f_\chi}{k+a}\,, \qquad a = \frac{1}{c_\gamma\tau_{eq}}\left(2 + \frac{3}{4}\frac{\alpha f_{\rm DM}}{f_\nu}f_\chi\right)$$

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





Numerical Check Toy Model vs CLASS
(3 neutrinos)

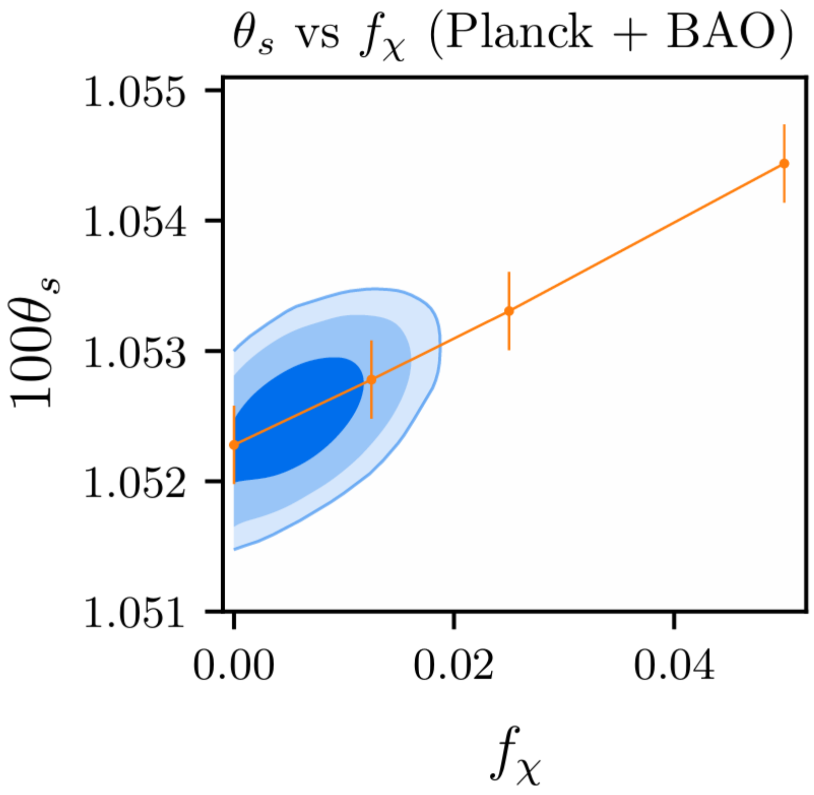


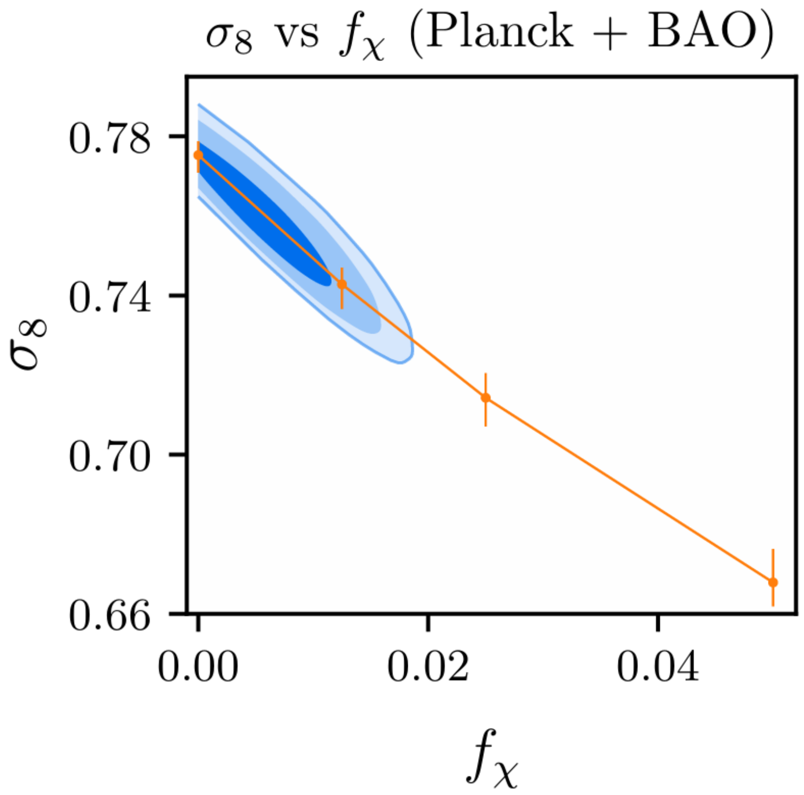
See paper for more details arXiv:2405.08064

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)