

Easing the σ_8 -tension with neutrino-dark matter interactions

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Motivations

Neutrino masses

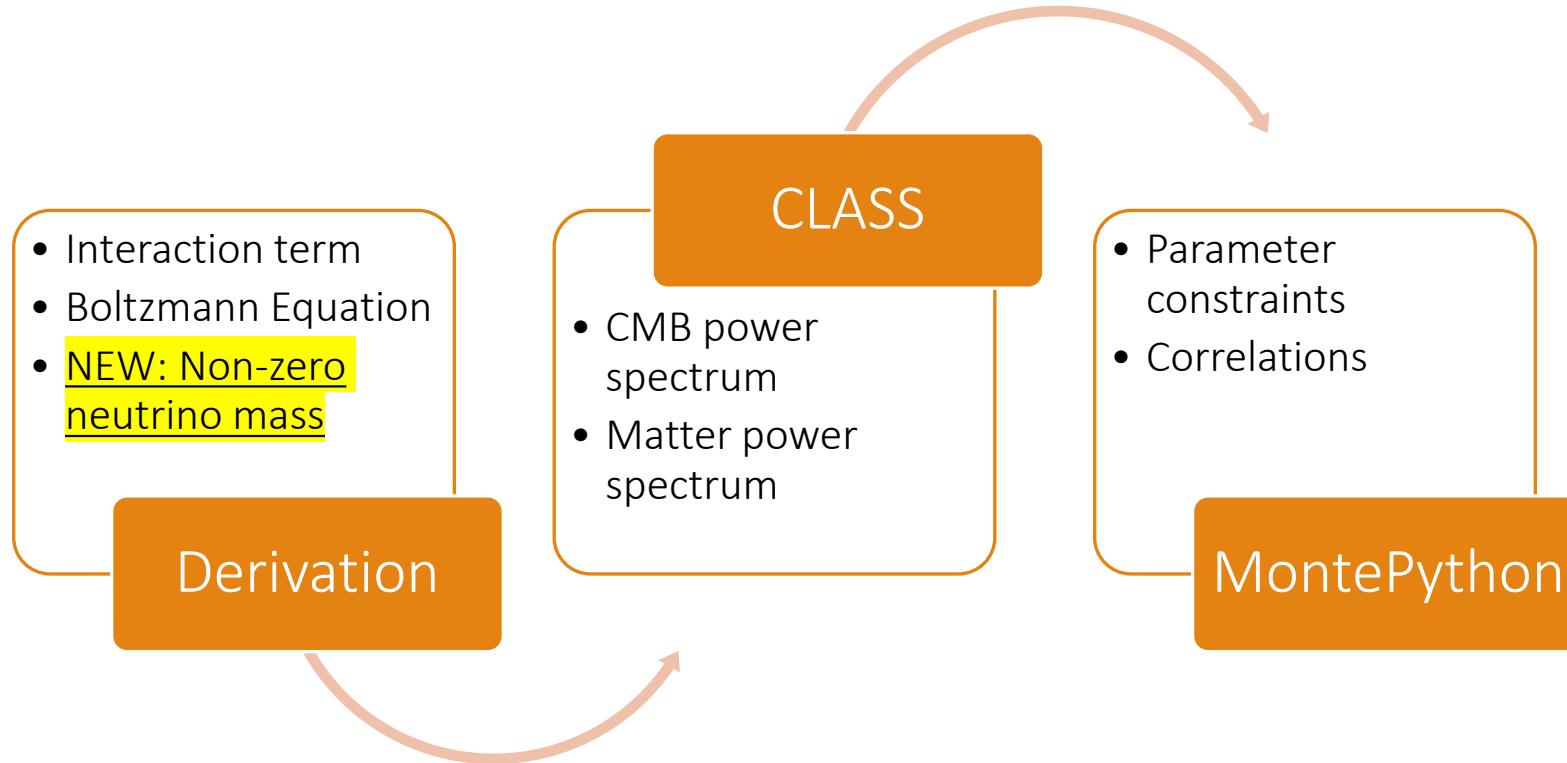
- Evidence from oscillation experiments, but not previously accounted for in this type of DM interaction study.

H_0 tension

- Planck vs. local measurements (e.g. SHOES)

σ_8 tension

- Planck vs. local measurements (e.g. KiDS-1000)



The Boltzmann Equation

- Describes the phase-space evolution of the distribution function
- Separate equation for each species – coupled to other species through interaction terms
- Legendre decomposition into (infinite, truncated) hierarchy
- Evolution of the moments at the linear perturbation level – k -modes decouple and can be evolved separately.
- For detailed overview of the Boltzmann equations, see e.g. arXiv:astro-ph/9506072

$$P^\alpha \frac{\partial f}{\partial x^\alpha} - \Gamma_{\alpha\beta}^\gamma P^\alpha P^\beta \frac{\partial f}{\partial P^\gamma} = m \left(\frac{\partial f}{\partial \tau} \right)_C$$

$$\dot{\delta}_{cdm} = -\theta_{cdm} + 3\dot{\phi}$$

$$\dot{\theta}_{cdm} = -\frac{\dot{a}}{a}\theta_{cdm} + k^2\psi$$

For comparison: the baryon-photon case

- Baryon equations similar to cdm equations – but with interactions.
- Photons are massless, so more different. Higher moments omitted here.

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + k^2\psi + c_s^2k^2\delta_b + \frac{4\bar{\rho}}{3P}an_e\sigma_T(\theta_\gamma - \theta_b)$$

$$\dot{\delta}_b = -\theta_b + 3\dot{\phi}$$

$$\dot{\theta}_\gamma = k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) + k^2\psi + an_e\sigma_T(\theta_b - \theta_\gamma)$$

⋮

Massless and massive neutrinos

- Massless neutrinos like photons – but without interactions
- Unlike other species – non-zero mass neutrinos transition from ultrarelativistic to nonrelativistic
 - Usual approximations don't work – equations are momentum dependent

$$\begin{aligned}\dot{\delta}_\nu &= -\frac{4}{3}\theta_\nu + 4\dot{\phi} \\ \dot{\theta}_\nu &= k^2 \left(\frac{1}{4}\delta_\nu - \sigma_\nu \right) + k^2\psi \\ \dot{F}_{\nu l} &= \frac{k}{2l+1} [lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}] \\ \dot{\Psi}_0 &= -\frac{pk}{E}\Psi_1 - \dot{\phi}\frac{d \ln f_0}{d \ln p} \\ \dot{\Psi}_1 &= -\frac{pk}{3E}(\Psi_0 - 2\Psi_2) - \frac{Ek}{3p}\psi\frac{d \ln f_0}{d \ln p} \\ \dot{\Psi}_l &= -\frac{pk}{(2l+1)E}(l\Psi_{l-1} - (l+1)\Psi_{l+1})\end{aligned}$$

Calculating our interaction term

- We assume a constant interaction cross section, no specific particle physics model.
- Standard method of calculating interaction term
- Calculation similar to Thomson scattering derivation in arXiv:astro-ph/9308019

$$C(p) = \frac{1}{E_\nu(\mathbf{p})} \int \frac{d^3\mathbf{p}'}{(2\pi)^3 2E_\nu(\mathbf{p}')} \frac{d^3\mathbf{q}}{(2\pi)^3 2E_\chi(\mathbf{q})} \frac{d^3\mathbf{q}'}{(2\pi)^3 2E_\chi(\mathbf{q}')} (2\pi)^4 |M|^2 \\ \times \delta^4(q + p - q' - p') [g(\mathbf{q}')f(\mathbf{p}')(1 - f(\mathbf{p})) - g(\mathbf{q})f(\mathbf{p})(1 - f(\mathbf{p}'))]$$



$$C(p, \mu) = \frac{\sigma_0 n_\chi p^2}{E_\nu^2(p)} \left[f_0^{(1)}(p) + \frac{1}{2} f_2^{(1)} P_2(\mu) - f^{(1)}(p, \mu) - v_\chi \mu E_\nu(p) \frac{df^{(0)}(p)}{dp} \right]$$

(going to comoving coordinates + conformal time yields extra factor of a)

Our modified Boltzmann equations

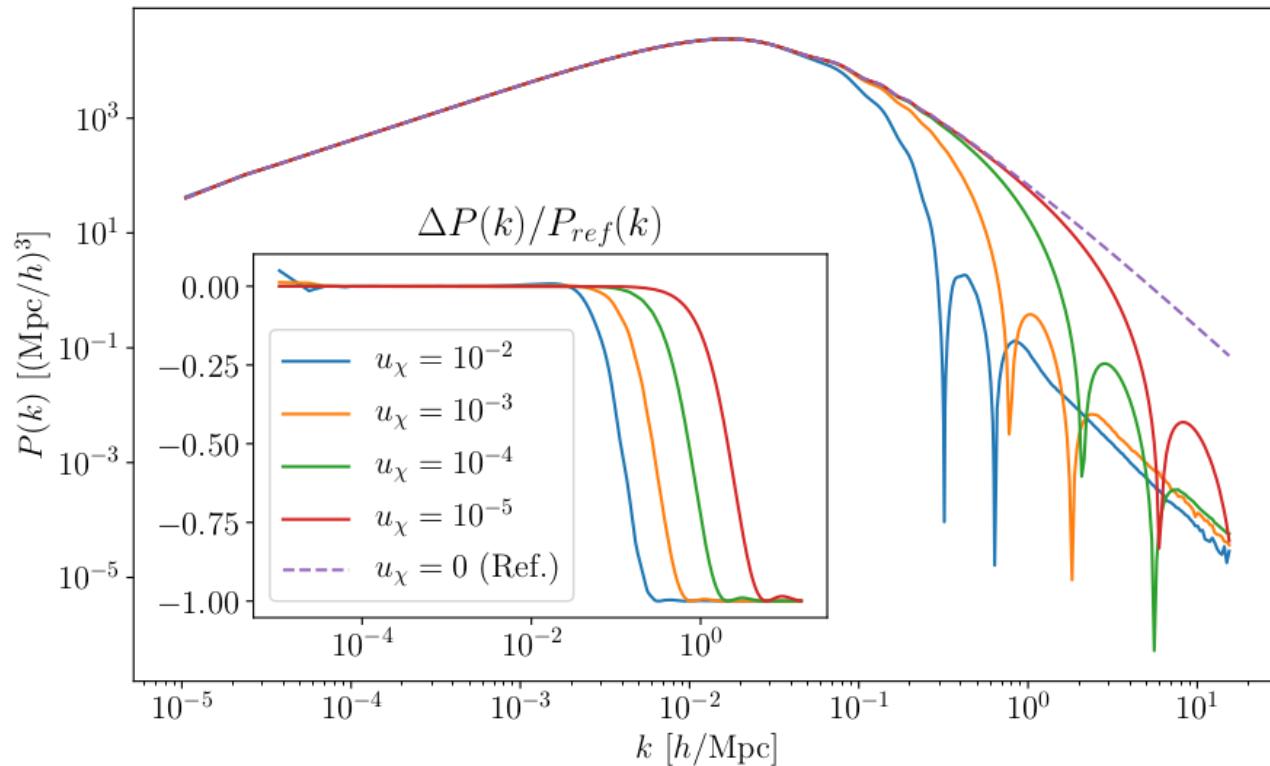
- Define interaction rate amplitude:

$$C_\chi = \frac{a\sigma_0 n_\chi p^2}{E_\nu^2(p)}$$

- Simple additions to neutrino equations, more complex to calculate interaction term for cdm (integral can only be done numerically)

$$\begin{aligned}\dot{\Psi}_1 &= [...] - C_\chi \frac{v_\chi E_\nu}{3f^{(0)}(p)} \frac{df^{(0)}(p)}{dp} - C_\chi \Psi_1 \\ \dot{\Psi}_2 &= [...] - \frac{9}{10} C_\chi \Psi_2 \\ \dot{\Psi}_l &= [...] - C_\chi \Psi_l\end{aligned}$$

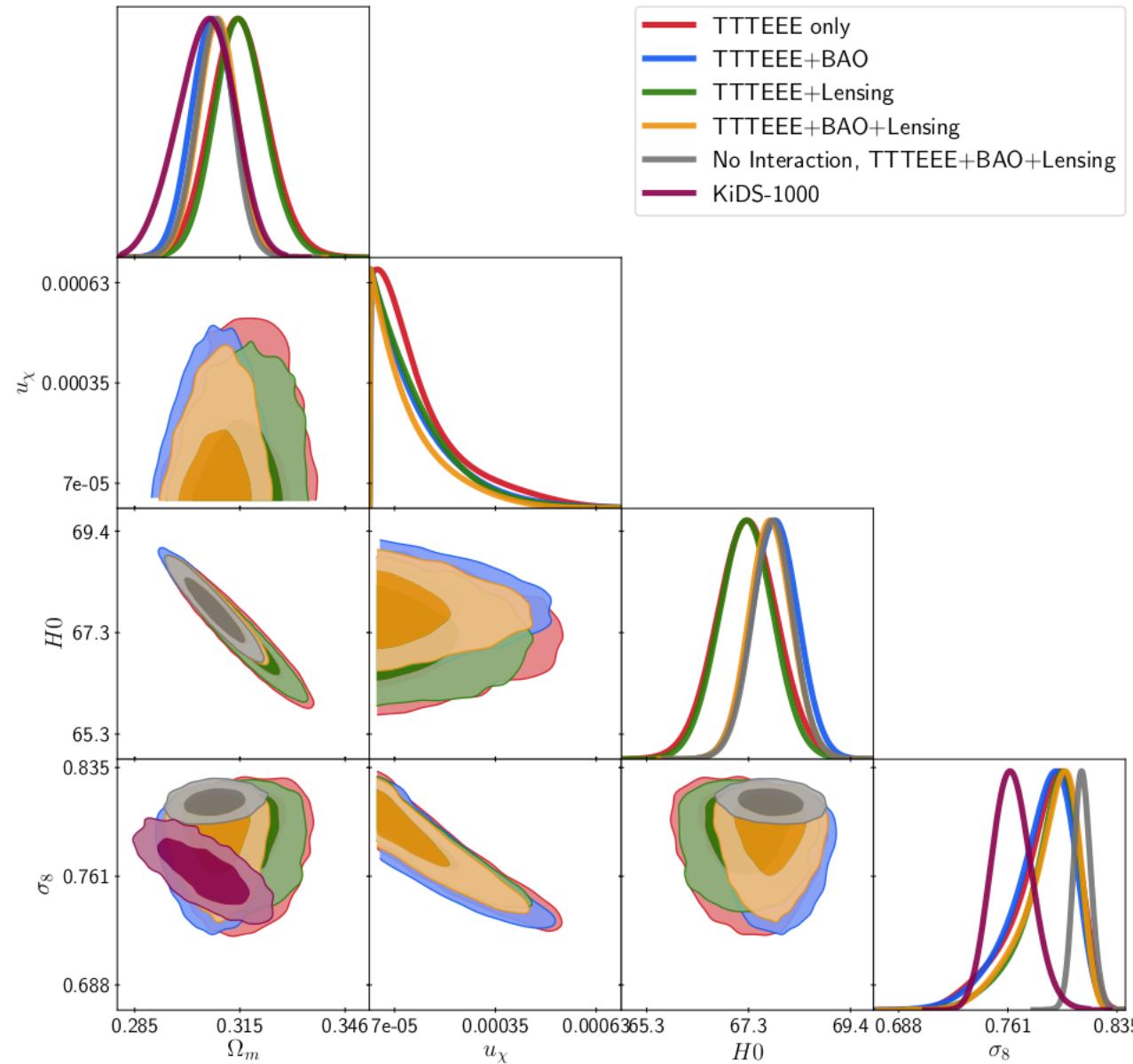
$$\begin{aligned}\dot{\theta}_{cdm} &= [...] + \frac{\rho_\nu + P_\nu}{\rho_\chi} \frac{3}{4} k \frac{\int p^2 dp p f^{(0)}(p) C_\chi \left(\frac{\theta_\chi E_\nu(p)}{3k f^{(0)}(p)} \frac{df^{(0)}(p)}{dp} + \Psi_1 \right)}{\int p^2 dp p f^{(0)}(p)} \\ &= [...] + \frac{\rho_\nu + P_\nu}{\rho_\chi} \dot{\mu}_\chi (\theta_\nu - \theta_\chi)\end{aligned}$$



$$u_\chi = \frac{\sigma_0}{\sigma_{Th}} \left(\frac{m_\chi}{100 \text{ GeV}} \right)^{-1}$$

- Suppression similar to WDM (but with oscillations)
- ‘Peaks’ shifted to slightly higher k compared to massless neutrino case (same u yields smaller effect)
For comparison see arXiv:1903.00540
- Matches expectation from new p^2/E^2 dependence

$$C_\chi = a u_\chi \frac{\sigma_{Th} \rho_\chi}{100 \text{ GeV}} \frac{p^2}{E_\nu^2}$$



- No significant impact on H_0
- Stronger interaction \rightarrow lower σ_8

Thank you for your
attention.

Questions?