Visualizing Invisible Dark Matter Annihilation with the CMB and Matter Power Spectrum

Yanou Cui and Ran Huo
University of California, Riverside

Objectives

What would be the physics for DM annihilation into DM/DR (**I**nvisibly **An**nihilating **DM**)?
Well motivated by the thermal freeze out mechanism and dark sector scenario, with $\langle\sigma v\rangle = 3\times10^{-26}$ cm^3/s. A blank to fill.

Models

Model independent (when dark acoustic oscillation is irrelevant). For example we use the benchmark fermionic model

$$\mathcal{L} \supset i\bar{\chi}\not{D}\chi + i\bar{\psi}\not{D}\psi - m_\chi\bar{\chi}\chi - m_\psi\bar{\psi}\psi - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}m^2_{Z'}Z'$$

Nonrelativistically and as $m_\psi \to 0$, $\sigma_{\bar{\chi}\chi\to\bar{\psi}\psi}v = g^4 m_\chi^2/(\pi m_{Z'}^4)$ can be tuned to 3×10^{-26} cm^3/s or any other values.

Inevitably there is thermal component of ψ, we are not interested in it here so we suppress it by choosing a small $\xi = \frac{\hat{T}}{T}$, then it will be suppressed by ξ^3 or ξ^4.

Textbook thermal freeze out is actually modified with ξ: $x_f \equiv m_\chi/T_f \to \xi\hat{x}_f \equiv \xi m_\chi/\hat{T}_f$ and $\hat{x}_f \simeq 10$ for subMeV χ. Correspondingly

$$\Omega_\chi \simeq 0.32\left(\frac{\hat{x}_f}{10}\right)\left(\frac{\sqrt{g_*}}{\sqrt{3.38}}\frac{43/11}{g_{*S}}\right)\left(\frac{3\times10^{-26}\ \text{cm}^3\ \text{s}^{-1}}{\langle\sigma v\rangle/\xi}\right),$$

so $\langle\sigma v\rangle/\xi$ as a whole should be 3×10^{-26} cm^3/s to give correct relic abundance.

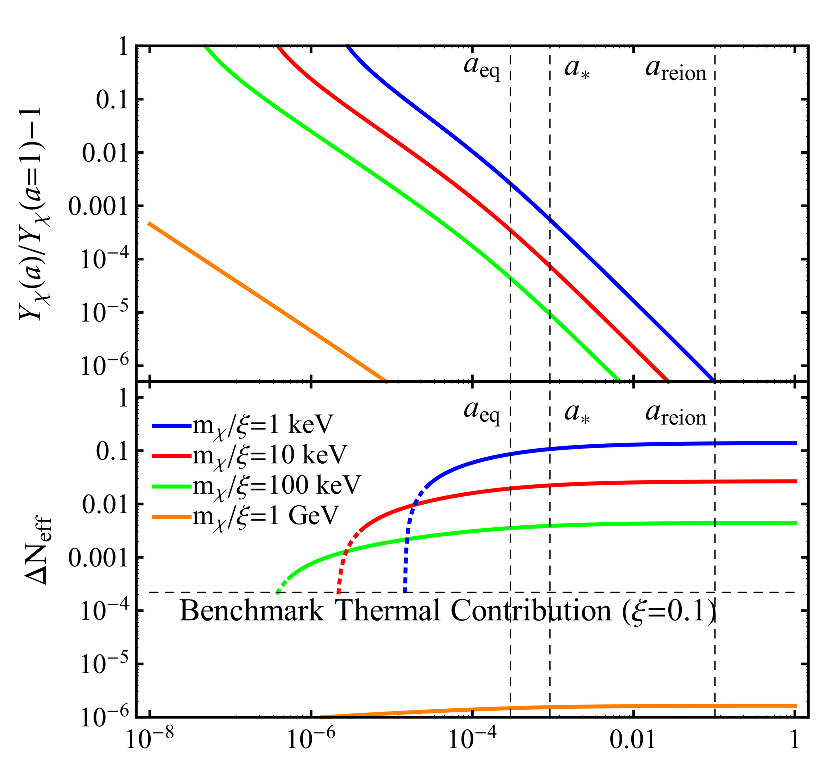

Figure: Upper panel: the slow depletion of Y_χ due to its residual annihilation. Lower panel: $\Delta N_{\rm eff}$ due to massless annihilation product ψ.

Analytic Studies: CMB

A straightforward estimate based on energy conservation gives $d\rho_{\psi,{\rm nth}}(\tilde{t}) = \rho_\chi n_\chi\langle\sigma v\rangle d\tilde{t}$, and upon integration over time ($m_\psi = 0$)

$$\rho_\psi(a) = \frac{\rho_c\Omega_\chi}{a^3}\int_{a_i}^{a}\frac{\tilde{a}}{a}\frac{\rho_c\Omega_\chi}{\tilde{a}^3}\frac{\langle\sigma v\rangle}{m_\chi}\frac{\tilde{a}d\tilde{a}}{H_0\sqrt{\Omega_{\gamma+\nu}}} = \frac{\rho_c^2\Omega_\chi^2}{H_0\sqrt{\Omega_{\gamma+\nu}}}\frac{\langle\sigma v\rangle}{m_\chi}\frac{\ln(\frac{a}{a_i})}{a^4},$$

or

$$\Delta N_{\rm eff}(a) = 0.038\ln\left(\frac{a}{a_i}\right)\left(\frac{\text{keV}}{m_\chi/\xi}\right)\left(\frac{\langle\sigma v\rangle/\xi}{3\times10^{-26}\ \text{cm}^3/\text{s}}\right),$$

Analytic Studies: Matter Power

DM χ is thermal and light, so it has considerable free streaming effect. We match the IAnDM free streaming velocity with WDM: At today the comoving momentum $\tilde{p}_{\rm WDM} = \left(\frac{2\pi^2}{3\zeta(3)}\frac{\rho_{\rm WDM}}{m_{\rm WDM}}\right)^{\frac{1}{3}}$, $\tilde{p}_\chi = \sqrt{2\hat{x}_f}\xi T_{\rm CMB}$. Equating $\frac{\tilde{p}}{m}$ in the two models

$$m_{\rm WDM} = \left(\frac{2\pi^2\rho_{\rm WDM}}{3\zeta(3)}\right)^{\frac{1}{4}}\left(\frac{m_\chi/\xi}{T_\gamma\sqrt{2\hat{x}_f}}\right)^{\frac{3}{4}} = 0.08\left(\frac{m_\chi/\xi}{\text{keV}}\right)^{\frac{3}{4}}\text{keV}.$$

Once the $v_{\rm FS}$'s match today, they also match at earlier times relevant to structure formation since they are redshifted in the same way.

Major Result

CMB Scale dependent $\Delta N_{\rm eff}$, less Silk damping, more ISW effect, and phase shift to higher ℓ (fluid like).
Matter Power Spectrum WDM like suppression.
Constraints on m_χ Up to $\mathcal{O}(1)$ keV (CMB) or $\mathcal{O}(100)$ keV (Matter Power Spectrum) by direct comparison.

Numerical Studies: CMB

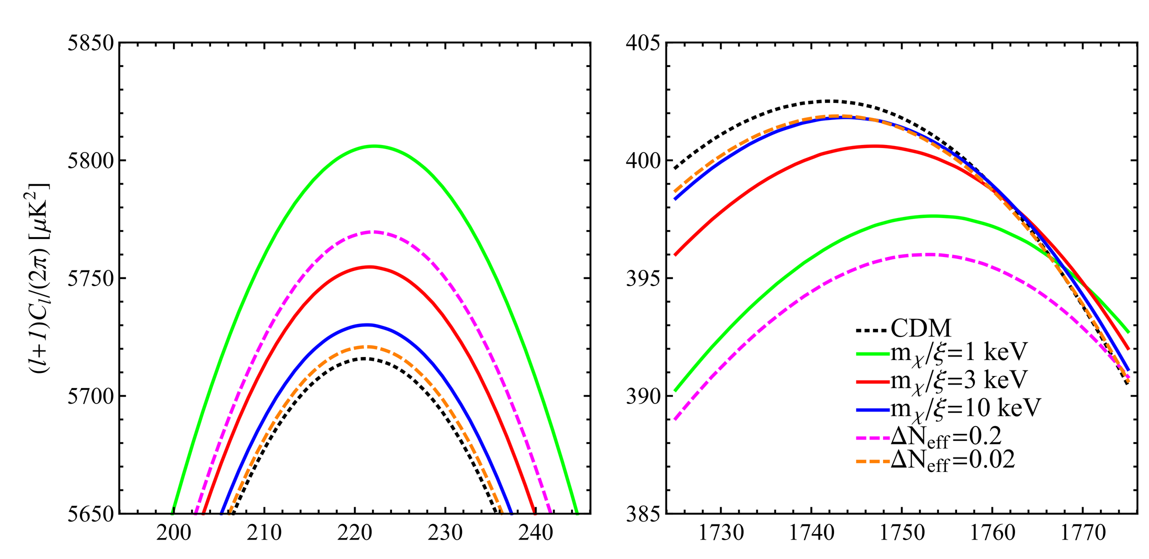

Figure: The difference with CDM is small so we zoom in on specific peaks. Left panel: TT mode around the first acoustic peak. Right panel: around the sixth acoustic peak.

Peak Height We can see scale dependence clearly, say the $m_\chi/\xi = 1$ keV curve
- **First Peak** aligns with $\Delta N_{\rm eff} \approx 0.35$, enhanced ISW effect.
- **Phase Shift** aligns with $\Delta N_{\rm eff} \approx 0.12$, less Silk damping.

Phase Shift Compensating cosmology to fix θ_*, θ_D and $z_{\rm eq}$, we find peak position shift to higher ℓ's which is fluid like behavior. No initial anisotropy stress since it is still χ, not annihilated yet!

Numerical Studies: Matter Power

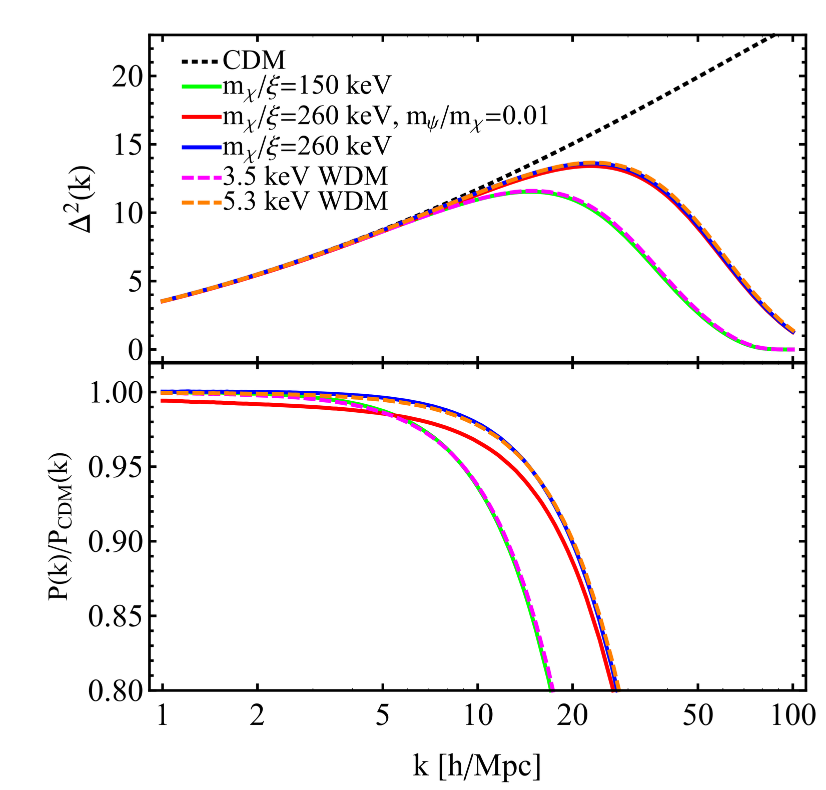

Figure: Matter power spectra for different DM χ masses and different m_ψ/m_χ and $\langle\sigma v\rangle$ ($m_\psi = 0$, with one exception). Also shown are the 3.5 keV, 5.3 keV WDM spectra (sitting on the current conservative and aggressive Lyman-α bound).

It's generally like WDM matter power spectrum. If $m_\psi \neq 0$ (but should be still much smaller than m_χ, to validate the thermal freeze out mechanism) one can see another free streaming suppression on top of the χ induced free streaming.

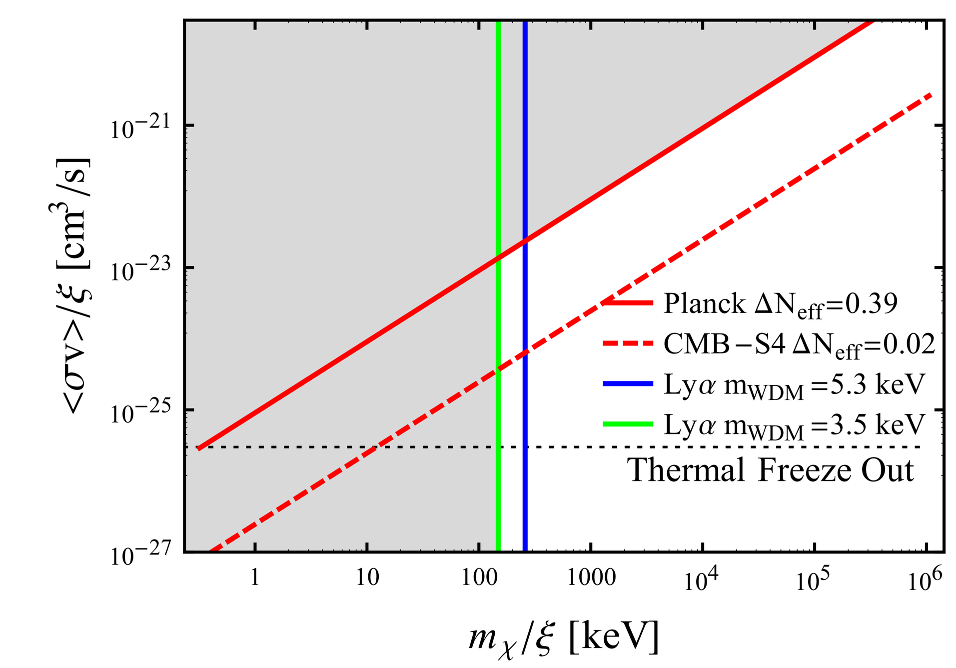

Figure: The constraints on invisible DM annihilation from Planck and Lyman-α measurements and the sensitivity forecast for CMB-S4 ($m_\psi = 0$, shaded region is excluded). The axes are labeled by taking into account the rescaling factor $\xi = \hat{T}_f/T_f$ at freezeout time.

Additional Information

- The numerical work is based on a modified version of `camb`.
- In providing the constraint numbers we do not do the MCMC or Fisher forecast, but just compare the observation to our analytical calculation. Should be good for order estimation.
- The main effect of IAnDM on the CMB depends on the ratio $\langle\sigma v\rangle/m_\chi$. In contrast, the main effect of IAnDM on MPS only depends on m_χ/ξ.
- ψ as DR also alleviates the discrepancy in H_0 measurements between the CMB observation and local measurements.
- Sommerfeld enhancement may further change the CMB results.

References

[1] Y. Cui and R. Huo, "Visualizing Invisible Dark Matter Annihilation with the CMB and Matter Power Spectrum," arXiv:1805.06451 [astro-ph.CO].

Contact Information

- Email: huor913@gmail.com