WIMP decay as a possible Warm Dark Matter model

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Abstract

Weakly Interacting Massive Particles (WIMPs) have long been the favored candidate under ΛCDM model. However, in view of the lack of experimental confirmation of WIMPs and structure formation discrepancies in CDM N-body simulations like cuspy halo and small scale crisis, we are motivated to consider the decay of WIMPs into warm dark matter (WDM) particles and radiation. We formulate the corresponding linear perturbation theory and investigate its viability at large scales using Planck 2018 CMB+BAO data sets and at small scales using the evolution of collapsed DM fraction in halos against Ω_{HI} from SDSS-Lymanα data. The WDM model consistent with the resulting parameter constraints indeed exhibits suppression of small scale power which might resolve a number of structure formation discrepancies. It also expands the mass-cross section parameter space for DM searches and thus, can salvage the WIMP theory in case of a non-detection.

The WIMP Miracle

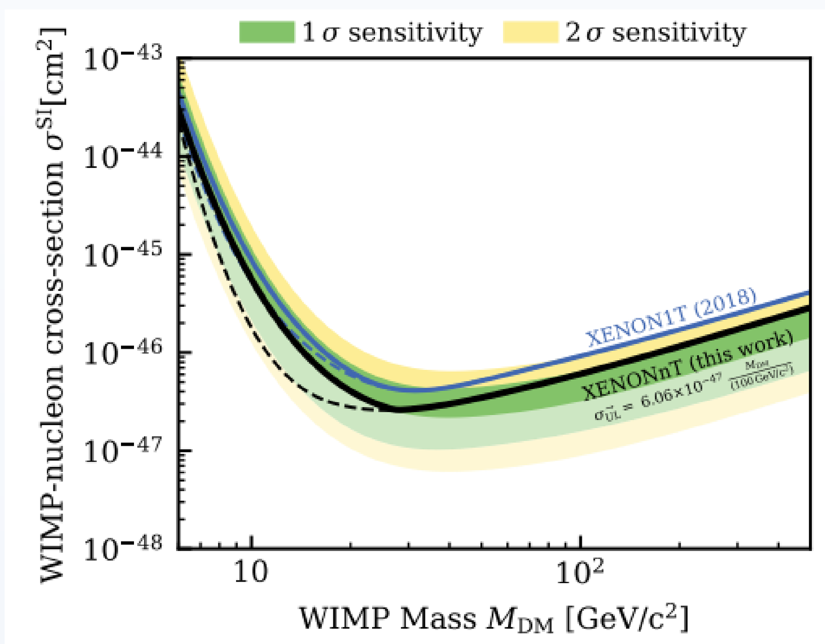
Properties of a DM candidate:

1. Should account for the DM density fraction $\Omega_{DM} = N\epsilon/\rho_{crit} = 0.255$
2. Should turn non-relativistic by matter-radiation equality.
3. Should be effectively neutral, little to no electromagnetic interaction.

Supersymmetry predicts GeV mass 'cold' particles that interact weakly → WIMPs. Independently, cosmological relic abundance of a thermal DM candidate ~GeV mass requires weak scale annihilation $\sigma_A \sim 10^{-39}\ m^2$ to match Ω_{DM}. This coincidence, called 'WIMP Miracle', made them a strong DM candidate.

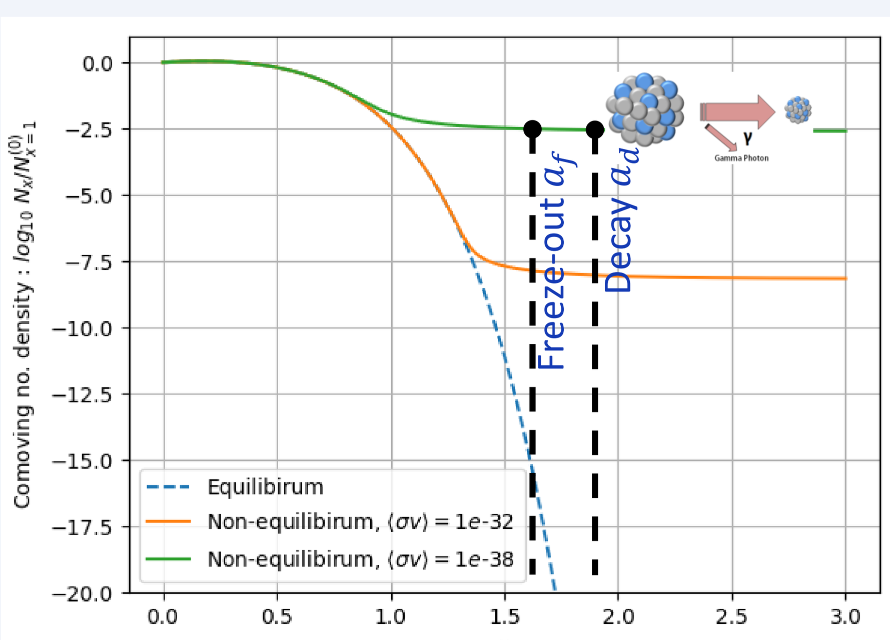
Drawbacks:

1. For mass ~GeV, theoretical WIMP-nucleon scattering $\sigma_S \sim 10^{-51} m^2$. Experimental [1] $\sigma_S \leq 10^{-50}\ m^2$. Strain on allowed param space.
2. CDM N body simulations of structure formation are in contention with observations.
   I. Cuspy Halo: $\frac{d\ln\rho}{d\ln r} = -1$ (Predicted), $-\frac{2}{3}$ (Observed).
   II. Small scale crisis: overpredicts no. of dwarf galaxies



WDM model

WIMP, after freeze-out, decays into WDM and radiation: $X_H \rightarrow X_L + SM$



Motivation:

1. The decay can alleviate the discrepancy between $\sigma_A - \sigma_S$.
2. Expand the $m - \sigma_A$ parameter space in DM searches and salvage the WIMP theory in case of non-detection.
3. On account of its higher free-streaming length, WDM wipes out small scale perturbations.

This suppression of small scale power can resolve the small scale crisis and late-time clustering can alleviate the cuspy halo problem.

Decay Kinematics and Parameters

	WIMP	WDM	radiation
ϵ	am_H	$\sqrt{a^2m_L^2 + q_L^2}$	q_{rad}
q	0	$\frac{a_d(m_H^2 - m_L^2)}{2m_H}$	$\frac{a_d(m_H^2 - m_L^2)}{2m_H}$

Define $r = \frac{m_L}{q_L} = \frac{2m_H m_L}{a_d(m_H^2 - m_L^2)}$

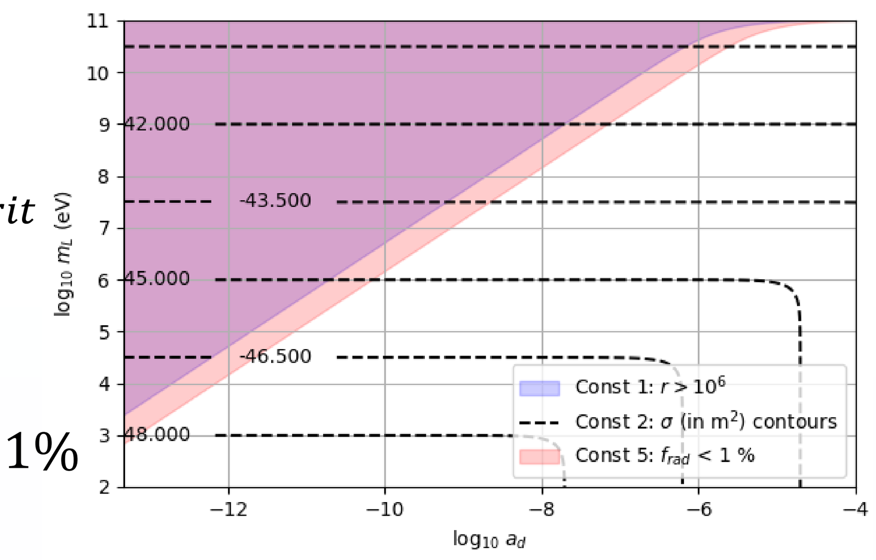
CDM: $m_L \rightarrow m_H \Rightarrow r \rightarrow \infty$

Radiation: $m_L \rightarrow 0 \Rightarrow r \rightarrow 0$

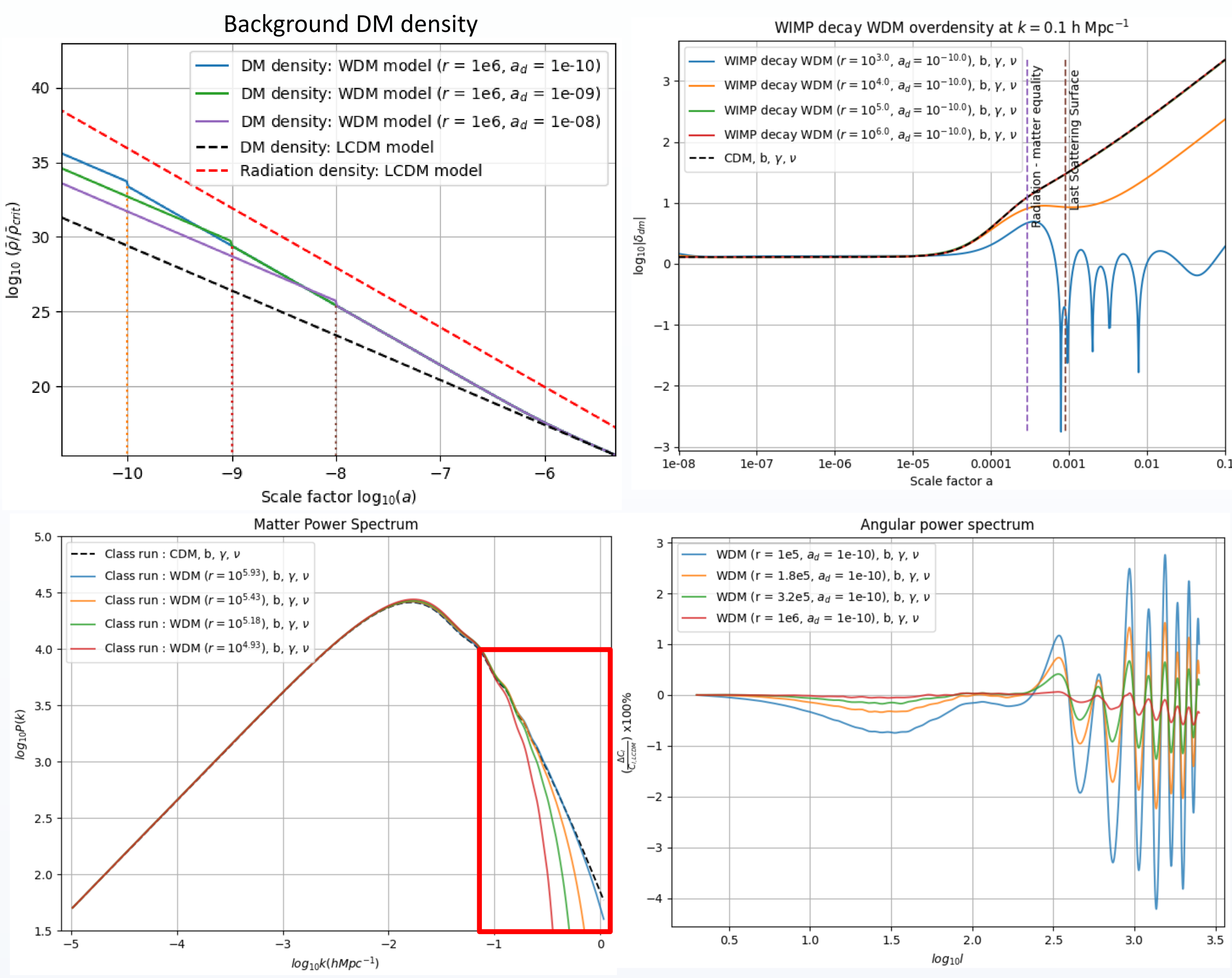
Psd: $f_0(q) = \frac{N}{4\pi q^2}\delta(q - q_L)$

Parameter constraints:

1. Sufficiently cold: $r > r_{min}$
2. Density constraint: $N\epsilon = \Omega_{DM}\rho_{crit}$
3. Decay after freeze-out
4. WDM mass < WIMP mass
5. $f_{rad} = \frac{\rho_{rad}}{\rho_\gamma + \rho_\nu} = \frac{\Omega_{DM}}{(\Omega_\gamma + \Omega_\nu)\sqrt{1+r^2}} < 1\%$



Perturbation Theory [2]

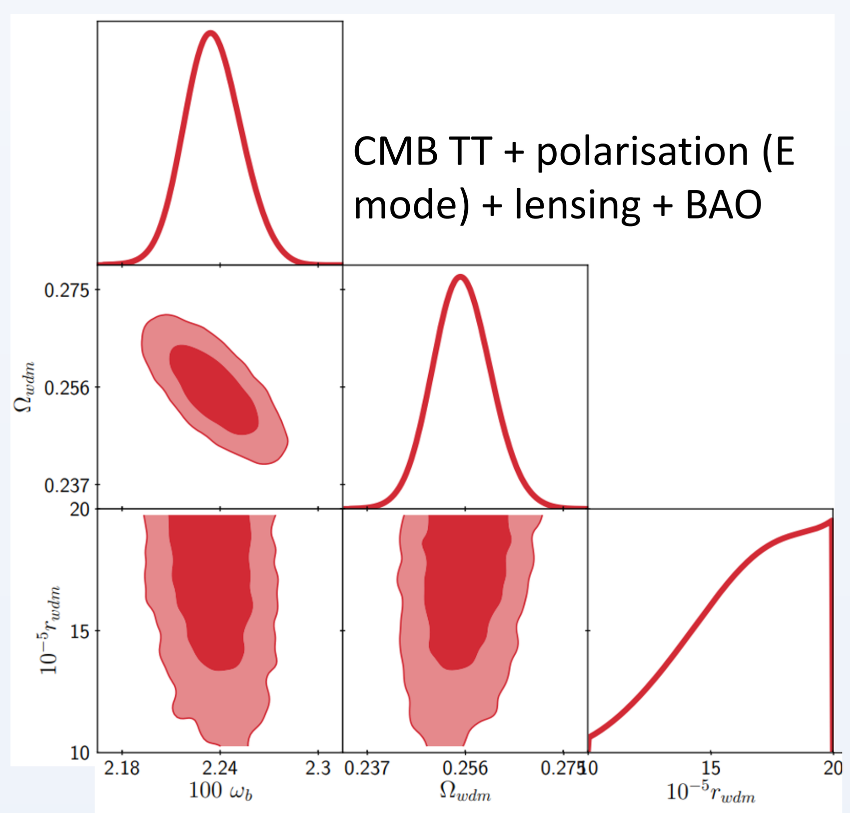


r	10^5	10^6
$10^4 a_{eq}$	3.024	2.943
$k_{FS}\ (h\,Mpc^{-1})$	0.094	0.920

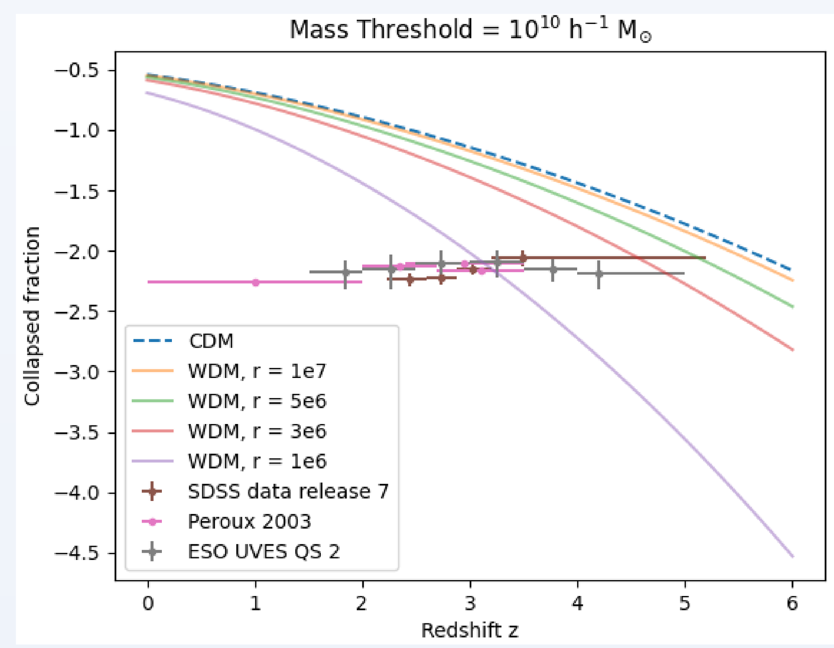
Smaller $r \Rightarrow$ more relativistic WDM:

1. More WIMP density, clustering at later times
2. More power suppression, deviation from $C_{l,\Lambda CDM}$

Data Analysis



7 parameter MCMC: $r \geq 1.192 \times 10^6$
$\Rightarrow k_{FS} \geq 0.92\ h\ Mpc^{-1}$



$$\frac{dN(>M)}{d\ln M} = \sqrt{\frac{2}{\pi}}\frac{\rho}{M}\frac{\delta_c}{\sigma_M}\left|\frac{d\ln\sigma_M}{d\ln M}\right| e^{-\delta_c^2/2\sigma_M^2}$$

Theoretical $f_{coll} = \frac{1}{\rho}\int\frac{dN}{d\ln M}\,dM$

Observation $f_{coll} = f_b \geq \frac{\Omega_{HI}\rho_{crit}}{\rho_b}$

Conclusion

1. CDM and WDM ($r \geq 1.2 \times 10^6$) work equally well for CMB+BAO data.
2. $\sigma_A \geq 2.83 \times 10^{-48}\ \mathrm{m}^2$, $m_L \geq 2.8$ keV → reduces the cross-section discrepancy, the increased $m - \sigma_A$ space can salvage the WIMP.
3. WDM models $r \geq 1.2 \times 10^6$ exhibit suppression of power at small scales $k_{FS} \geq 0.92\ h\ Mpc^{-1}$. N body simulations[3] have indeed shown **keV** range DM particles can resolve cuspy halo and small scale crisis.

References

[1] Aprile et al, "Dark Matter Search Results from a One Ton-Year Exposure of XENON1T", 2018
[2] Ma & Bertschinger, "Cosmological Pert. Theory in the Synchronous & Conformal Newtonian Gauges", 1995
[3] Dekker et al, "WDM constraints using milky-way satellite observations & subhalo evolution modeling", 2021