Uncovering the Halo-Dependence of Dark Matter-Electron Scattering

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Introduction

- More recently, a new avenue of direct detection probing DM-electron interactions has emerged, which is sensitive to DM candidates with masses below 1 GeV.
- Given DM-e scattering experiments currently taking data (such as SENSEI), it is important to be able to interpret results in a reliable way.
- DM direct detection experiments are sensitive to the astrophysical properties of the local dark matter distribution.
- Previous work has studied the effects of variations in astrophysical parameters on dark matter-nuclear scattering, but there is a larger effect for DM-e scattering.
- We give new suggestions for updated parameter values in light of the current era of precision astrometry.

DM-electron Scattering Formalism

$$\frac{dR}{dE_e} = N_{\text{cell}} \frac{\rho_{\text{DM}}}{m_\chi} \frac{\overline{\sigma}_e \alpha m_e^2}{\mu_{\chi e}^2} \int \frac{dq}{q^2} \left[\eta(v_{\min}(E_e, q)) |F_{\text{DM}}(q)|^2 |f_{\text{crystal}}(E_e, q)|^2 \right]$$

$$\eta(v_{\min}) = \int \frac{d^3v}{v} f_\chi(v)\, \Theta(v - v_{\min})$$

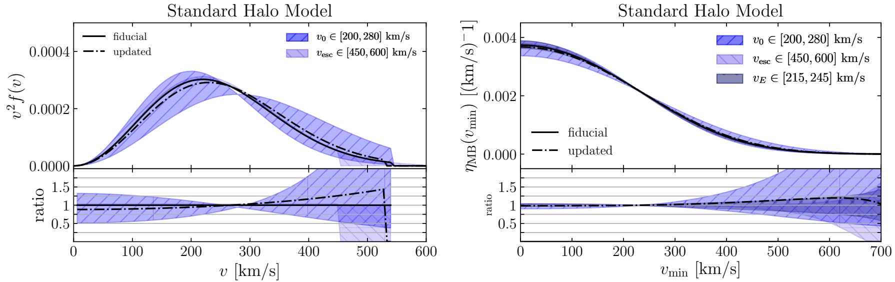
$$|F_{\text{DM}}(q)|^2 = \begin{cases} 1 & , \ m_V \gg \alpha m_e \text{ (contact)} \\ \left(\frac{\alpha^2 m_e^2}{q^2}\right)^2 & , \ m_V \ll \alpha m_e \text{ (light med.)} \end{cases}$$

Astrophysical Parameters

	current	suggested
v_0 [km/s]	220^{+60}_{-20}	228.6 ± 0.34
$v_{\rm esc}$ [km/s]	544^{+56}_{-94}	528^{+24}_{-25}
$\rho_{\rm DM}$ [GeV/cm^3]	0.4	$0.46^{+0.07}_{-0.09}$
v_E [km/s]	232 ± 15	232 ± 15
R_0 [kpc]	8.0 ± 0.5	8.34 ± 0.16

Standard Halo Model

$$f_{\rm SHM}(\vec{v}) = \frac{1}{K}\, e^{-|\vec{v}|^2/v_0^2}\, \Theta(v_{\rm esc} - |\vec{v}|)$$

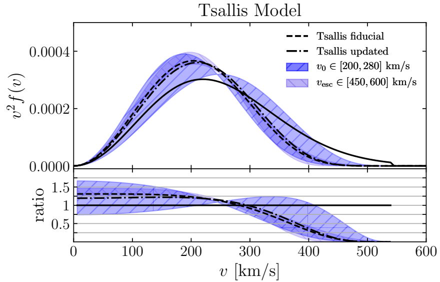


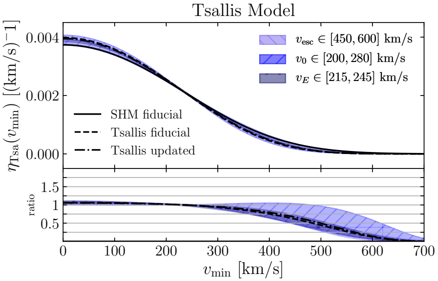
The SHM does not match the high velocity tail in DM only simulations. It does better with DM baryon simulations.

Tsallis Model

$$f_{\rm Tsa}(\vec{v}) = \frac{1}{K}\left[1-(1-q)\frac{\vec{v}^2}{v_0^2}\right]^{1/(1-q)}\Theta(v_{\rm esc}-|\vec{v}|)$$

$$(q\to 1)\Rightarrow \text{SHM}$$



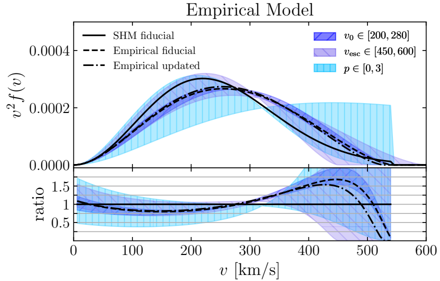


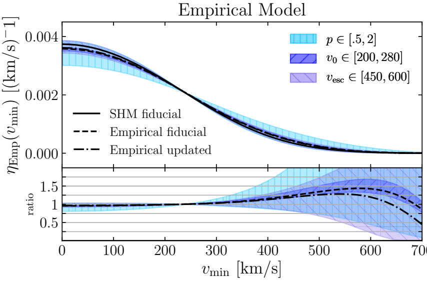
Note the more significant drop-off in the high velocity tail as compared with the SHM.

Empirical Model

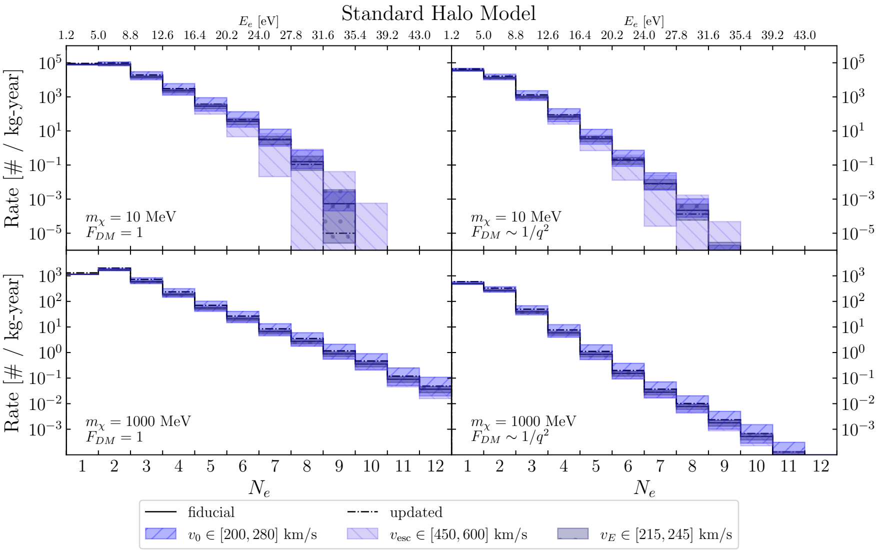
$$f_{\rm Emp}(\vec{v}) = \frac{1}{K}\, e^{-|\vec{v}|/v_0} \left(v_{\rm esc}^2 - |\vec{v}|^2\right)^p \, \Theta(v_{\rm esc} - |\vec{v}|)$$

Based on Rhapsody and Bolshoi DM only simulations [1210.2721]. Fits to Eris ($p = 2.7$) and ErisDark ($p = 1.5$) done by [1308.1703].

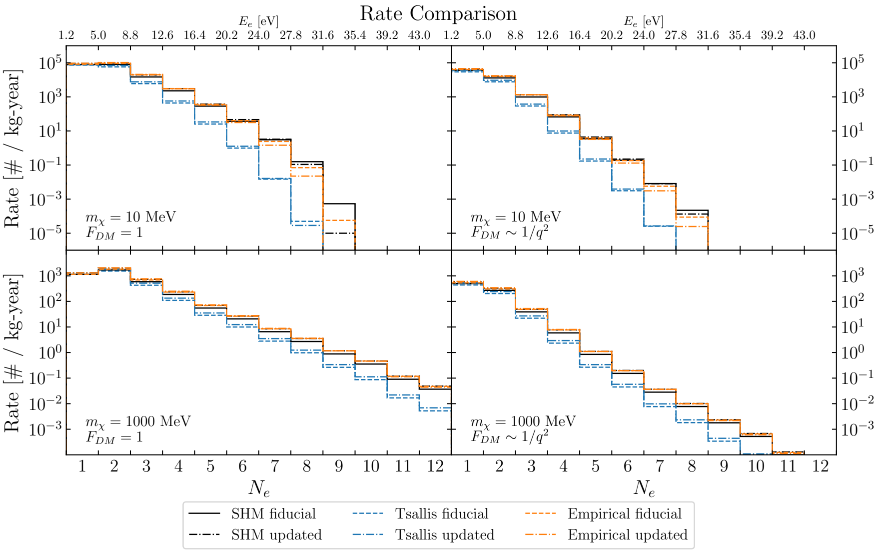




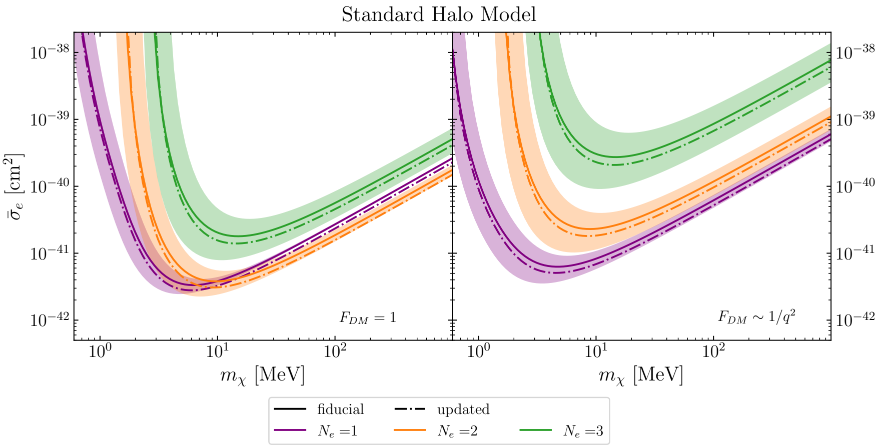
Note the more significant variance possible through change in the p parameter, and the relative resistance to change in v_0 as compared to the other two models. We take $p = 1.5$ as fiducial.



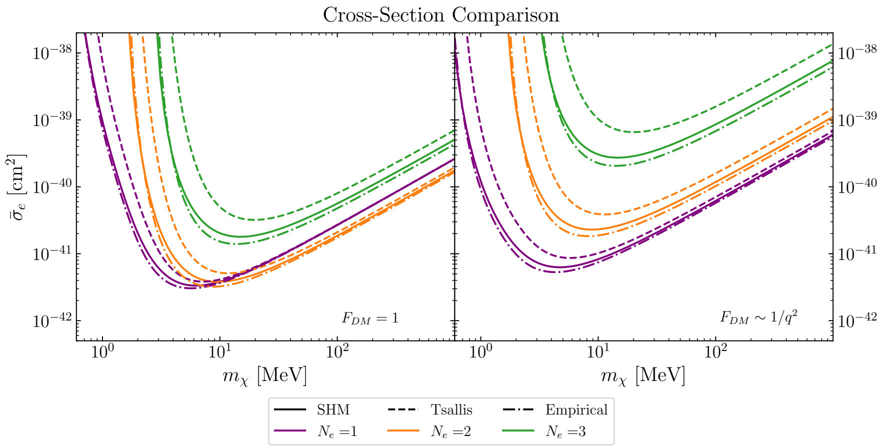
Observe that the higher N_e bins and lower DM masses are more sensitive to the astrophysical parameters.



Work being done on a robust statistical method to differentiate between the velocity distributions.



Note the resistance to variations in the astrophysical parameters as the mass becomes large.

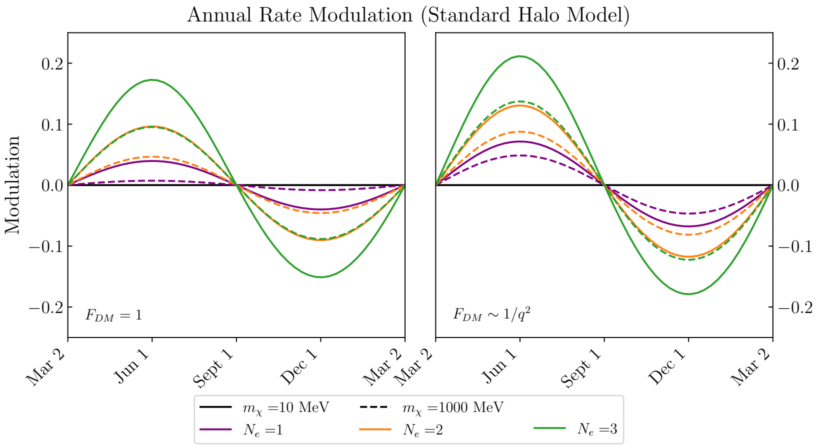


Shown above are the fiducial parameter values. Unsurprisingly, the Tsallis model sets the weakest bound on the cross-section, while the empirical model is ever so slightly stronger than the SHM.

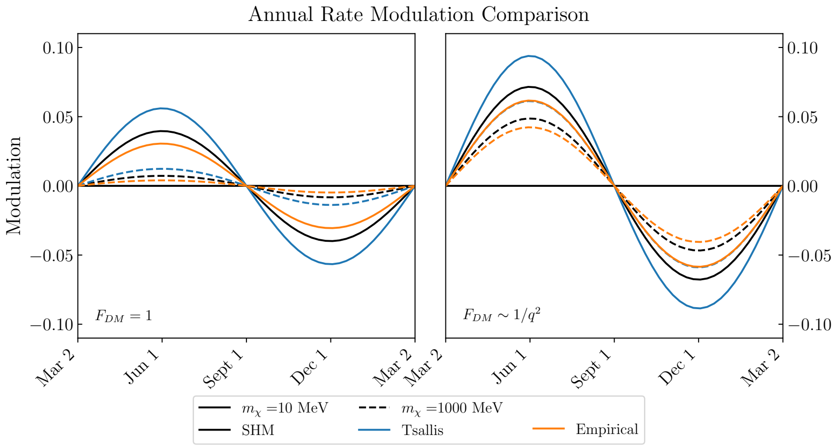
Summary

- The choice of velocity distribution significantly affects DM-e scattering observables (rate and cross-section).
- Generally, the Tsallis model results in smaller rates while the empirical model results in larger rates as compared to the SHM.
- Smaller dark matter mass and larger N_e bins are more susceptible to changes in the functional form of the velocity distribution and its parameters.
- As we have seen, the assumption of velocity distribution can affect experimental results by up to an order of magnitude, and so we need to make sure to take this into account when analyzing data.

Backup



As to be expected, the modulation increases for smaller masses, greater N_e bins, and for $F_{\rm DM} \sim 1/q^2$.



Above we show the $N_e = 1$ bin compared across VDFs. The Tsallis model experiences the greatest variation, while the empirical model experiences the least.

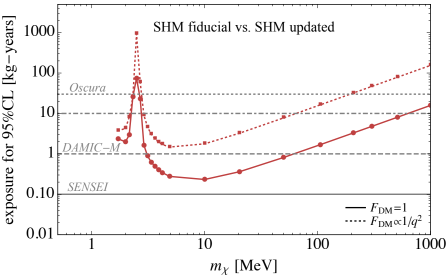
Standard Halo Model (m_χ=10 MeV)

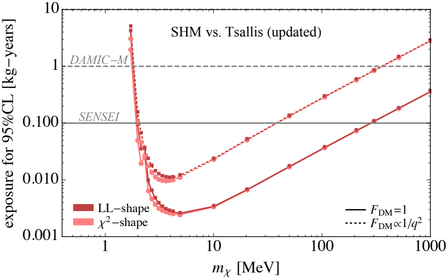
N_e	1		2		3		4	
F_{DM}	1	$(\alpha m_e/q)^2$	1	$(\alpha m_e/q)^2$	1	$(\alpha m_e/q)^2$	1	$(\alpha m_e/q)^2$
Fiducial	78458.4	36204.3	78974.1	12941.2	14750.7	985.4	2265.8	66.8
Updated	92042.5	43638.1	97209.7	16357.3	19331.5	1307.8	3034.6	88.3
rel. diff.	0.1731	0.2053	0.2309	0.264	0.3105	0.3272	0.3393	0.323
$v_{0,min}$	74682.8	32110.6	66017.9	9937.9	10014.2	615.7	1298.8	35.1
$v_{0,max}$	86757.9	46800.4	111576.6	21723.1	29904.9	2306.2	6044.4	204.1
rel. diff.	0.1539	0.4057	0.5769	0.9107	1.3485	1.7155	2.0945	2.5311
$v_{esc,min}$	77430.0	34469.0	73997.1	11235.0	11504.3	657.5	1225.3	25.3
$v_{esc,max}$	78596.7	36541.3	79851.5	13326.4	15455.9	1076.8	2589.9	84.7
rel. diff.	0.0149	0.0572	0.0741	0.1616	0.2679	0.4255	0.6023	0.8897
$v_{E,min}$	74908.9	33435.1	70926.3	11229.2	12244.6	787.7	1738.4	48.2
$v_{E,max}$	81154.0	38442.1	85540.9	14396.8	16940.9	1164.1	2754.9	84.8
rel. diff.	0.0796	0.1383	0.1851	0.2448	0.3184	0.382	0.4486	0.5488

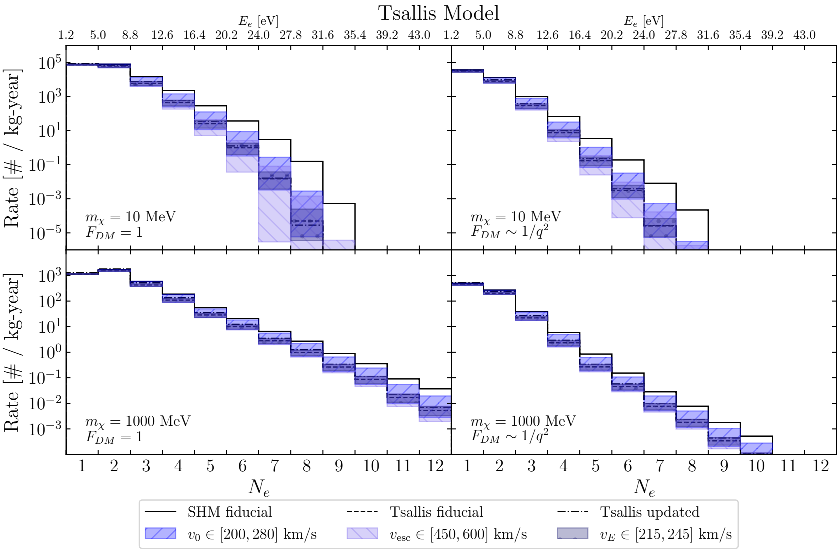
0.0 0.1 0.5 1.0

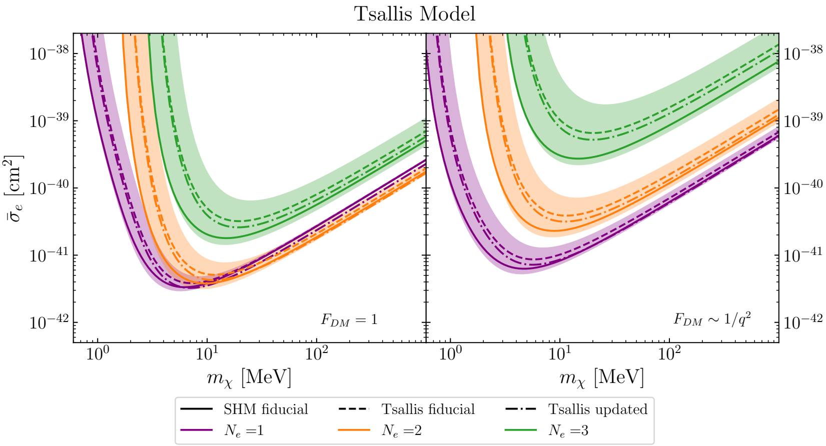
relative difference

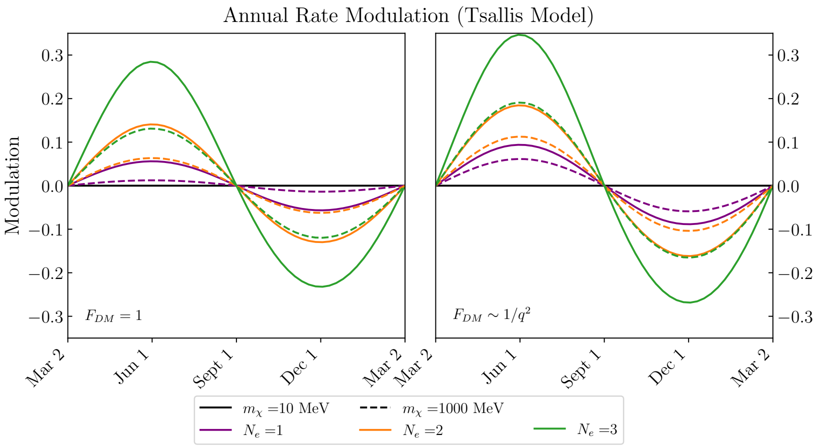
PRELIMINARY



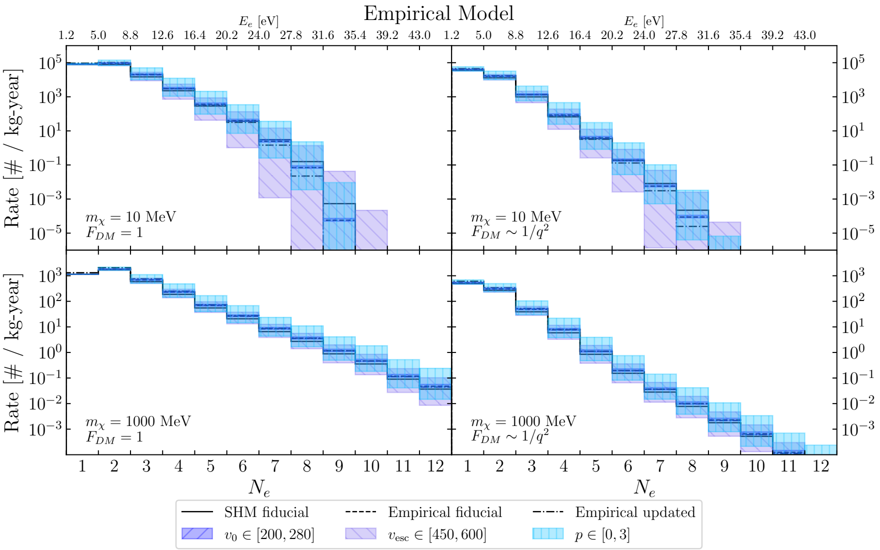



Tsallis Model
E_e [eV]
1.2 5.0 8.8 12.6 16.4 20.2 24.0 27.8 31.6 35.4 39.2 43.0
Rate [# / kg-year]
$m_\chi = 10$ MeV
$F_{DM} = 1$
$m_\chi = 10$ MeV
$F_{DM} \sim 1/q^2$
$m_\chi = 1000$ MeV
$F_{DM} = 1$
$m_\chi = 1000$ MeV
$F_{DM} \sim 1/q^2$
N_e
SHM fiducial
Tsallis fiducial
Tsallis updated
$v_0 \in [200, 280]$ km/s
$v_{esc} \in [450, 600]$ km/s
$v_E \in [215, 245]$ km/s


Tsallis Model
$\bar{\sigma}_e$ [cm^2]
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
$F_{DM} = 1$
$F_{DM} \sim 1/q^2$
10^0
10^1
10^2
m_χ [MeV]
m_χ [MeV]
SHM fiducial
Tsallis fiducial
Tsallis updated
$N_e = 1$
$N_e = 2$
$N_e = 3$

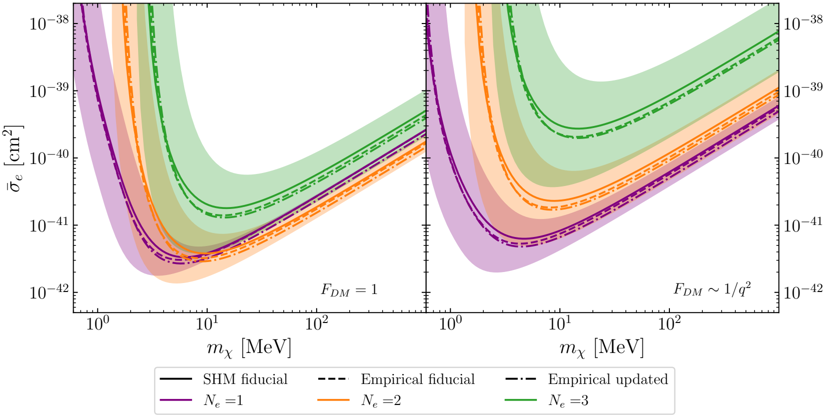


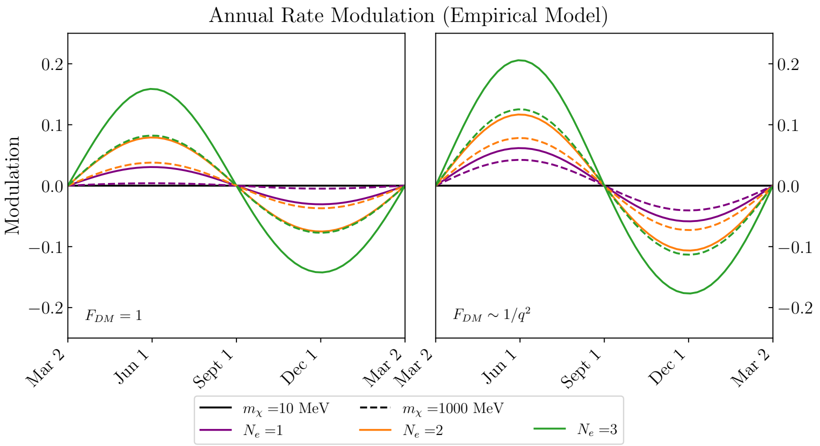
Annual Rate Modulation (Tsallis Model)
Modulation
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
$F_{DM} = 1$
$F_{DM} \sim 1/q^2$
Mar 2
Jun 1
Sept 1
Dec 1
Mar 2
m_χ =10 MeV
m_χ =1000 MeV
N_e =1
N_e =2
N_e =3



Empirical Model
E_e [eV]
1.2 5.0 8.8 12.6 16.4 20.2 24.0 27.8 31.6 35.4 39.2 43.0
Rate [# / kg-year]
$m_\chi = 10$ MeV
$F_{DM} = 1$
$m_\chi = 10$ MeV
$F_{DM} \sim 1/q^2$
$m_\chi = 1000$ MeV
$F_{DM} = 1$
$m_\chi = 1000$ MeV
$F_{DM} \sim 1/q^2$
N_e
SHM fiducial
Empirical fiducial
Empirical updated
$v_0 \in [200, 280]$
$v_{esc} \in [450, 600]$
$p \in [0, 3]$

Empirical Model




Annual Rate Modulation (Empirical Model)
Modulation
0.2
0.1
0.0
−0.1
−0.2
$F_{DM} = 1$
$F_{DM} \sim 1/q^2$
Mar 2
Jun 1
Sept 1
Dec 1
Mar 2
m_χ =10 MeV
m_χ =1000 MeV
N_e =1
N_e =2
N_e =3