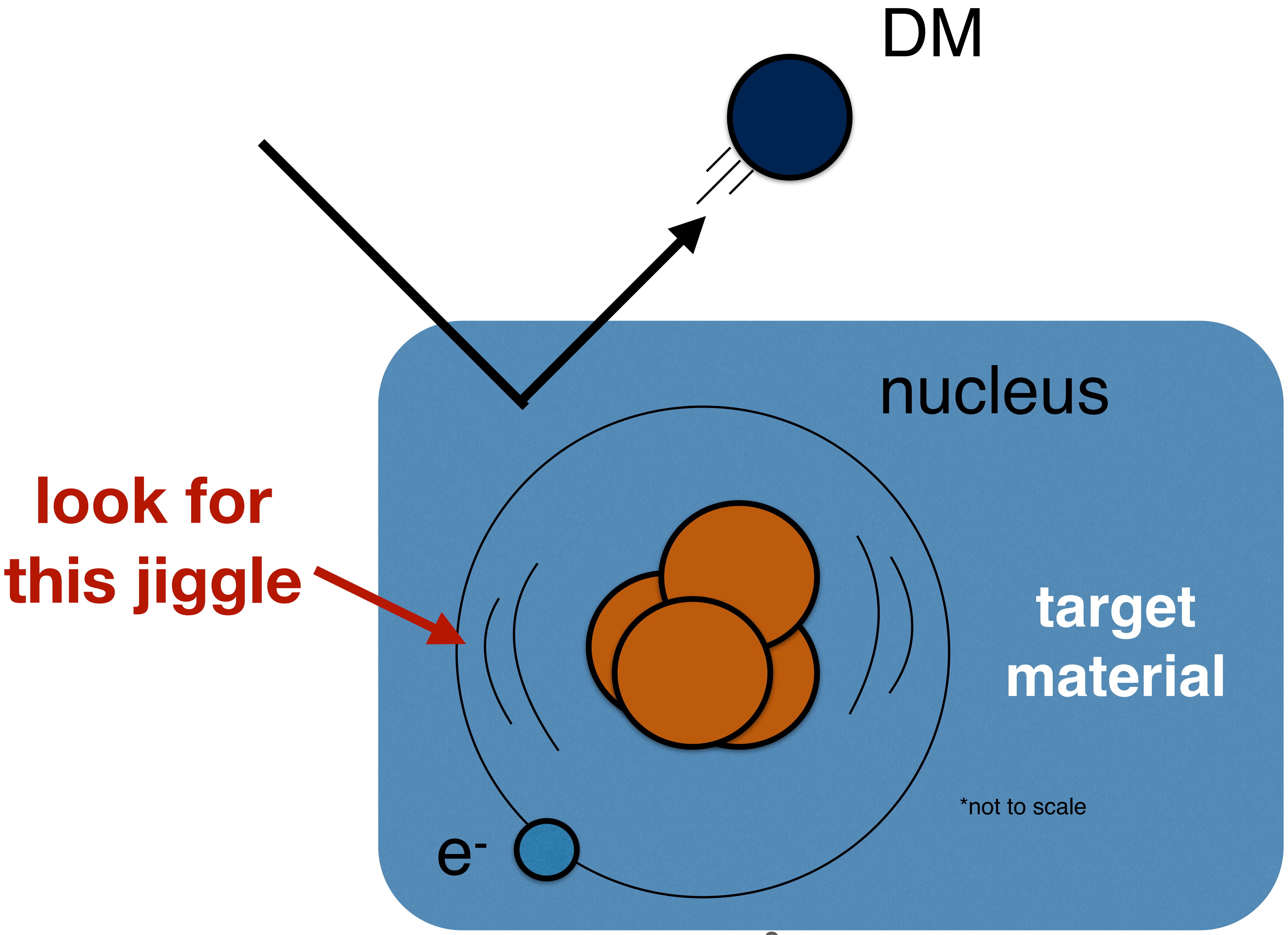
Astrophysical Uncertainties in Dark Matter-Electron

with Aria Radick & Anna-Maria Taki JCAP02 (2021) 004 [arXiv:2011.02493]

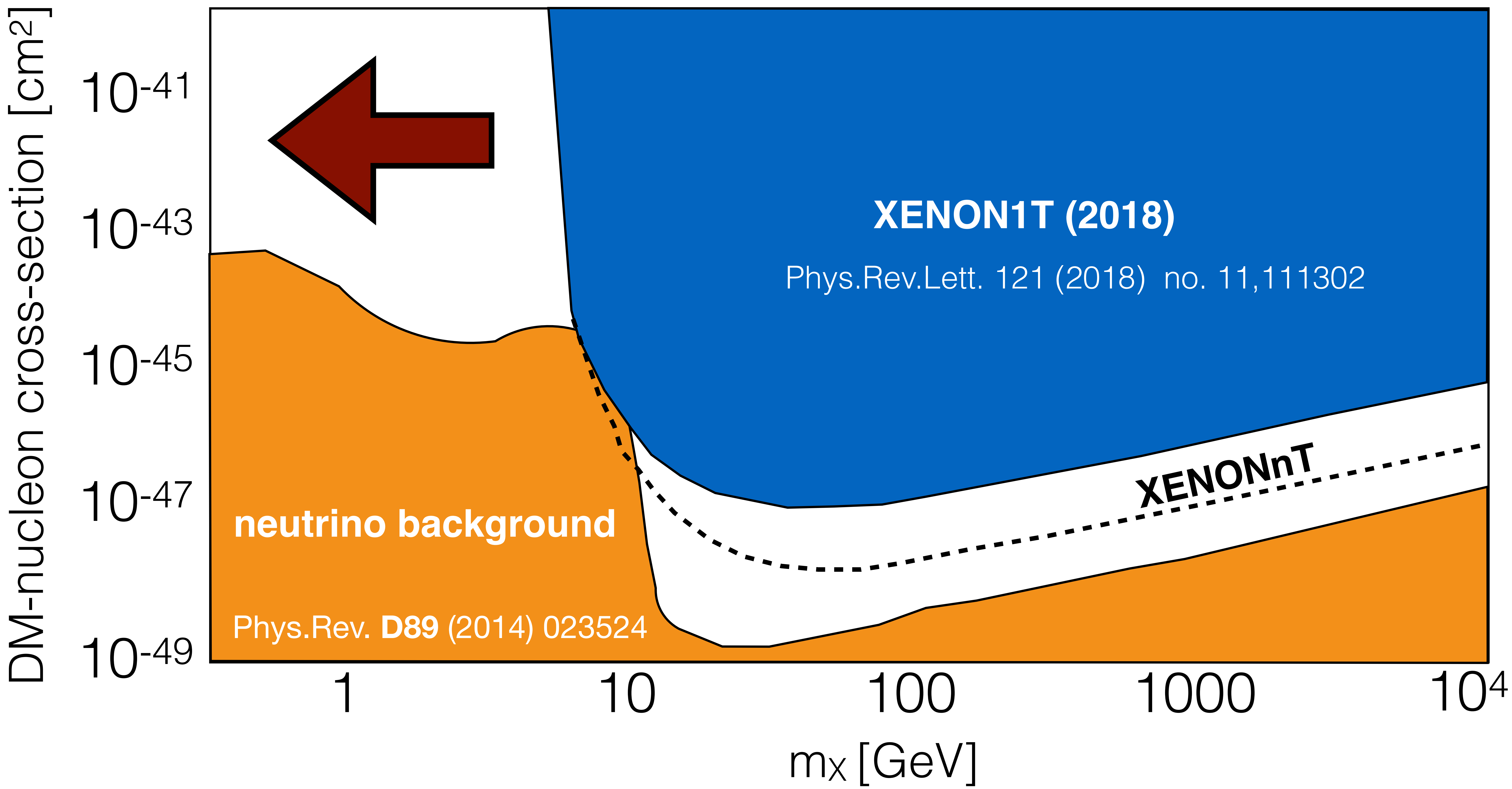
Tien-Tien Yu (University of Oregon)

GUINEA PIG 2022

DM Direct Detection

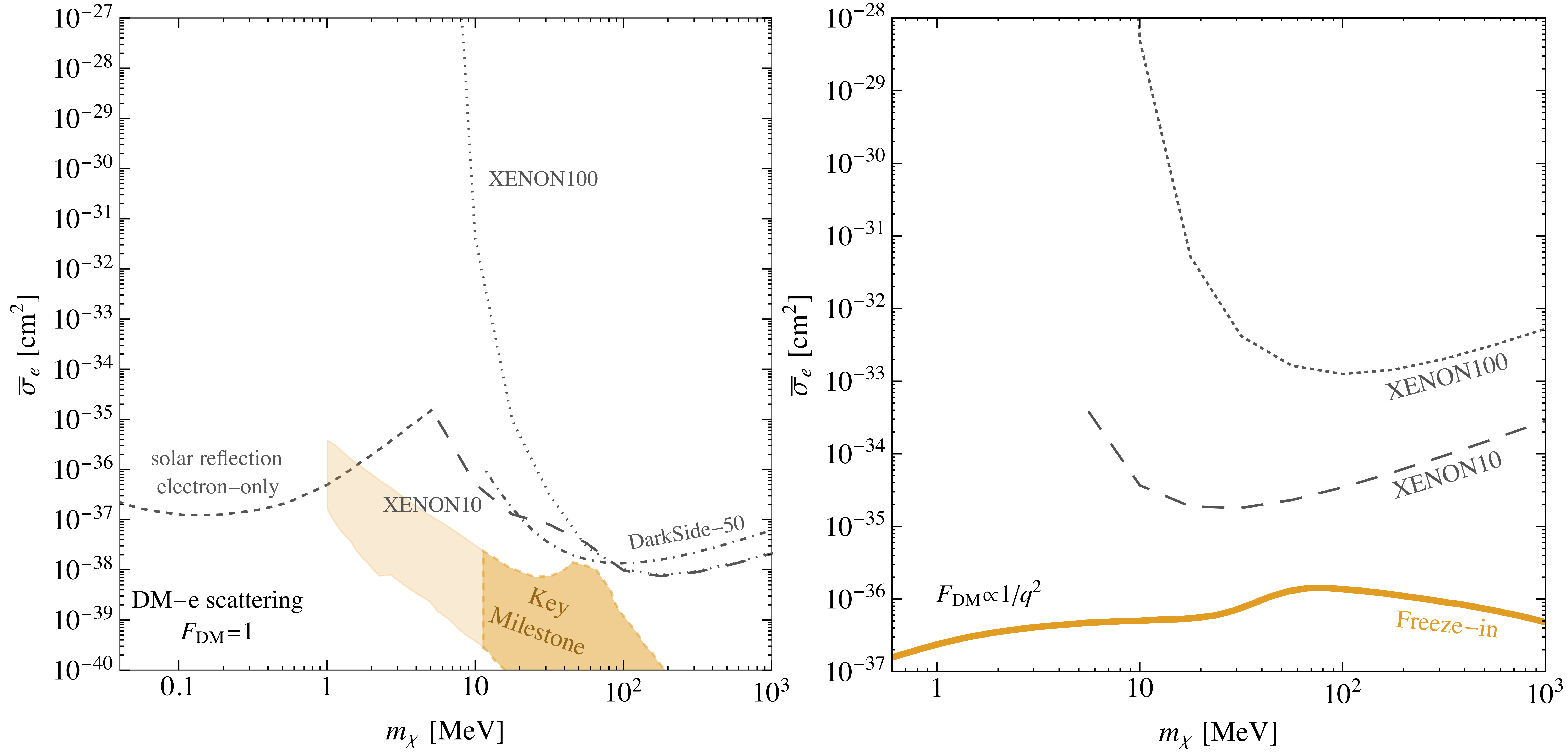


direct detection



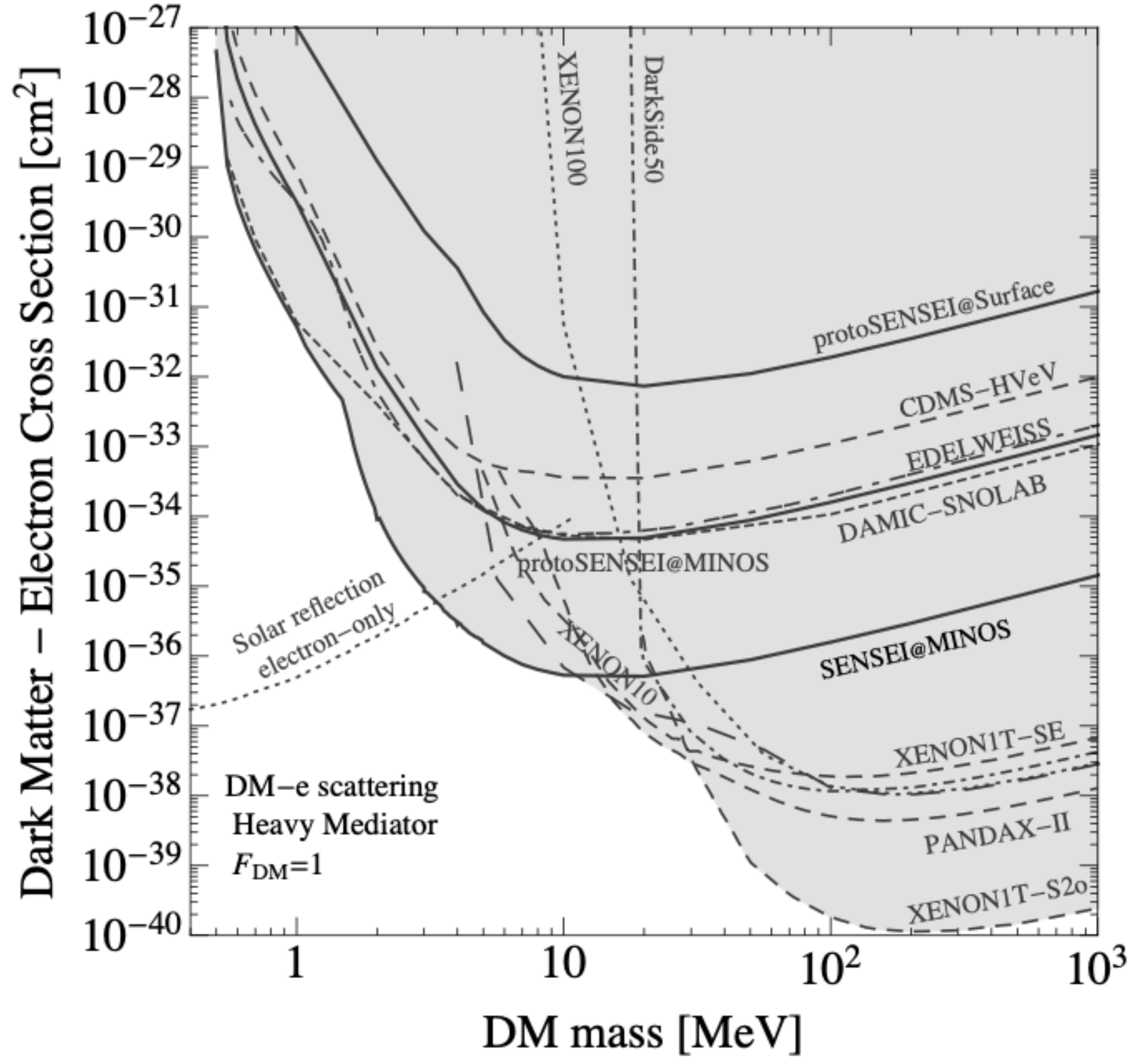
DM-electron limits in 2018

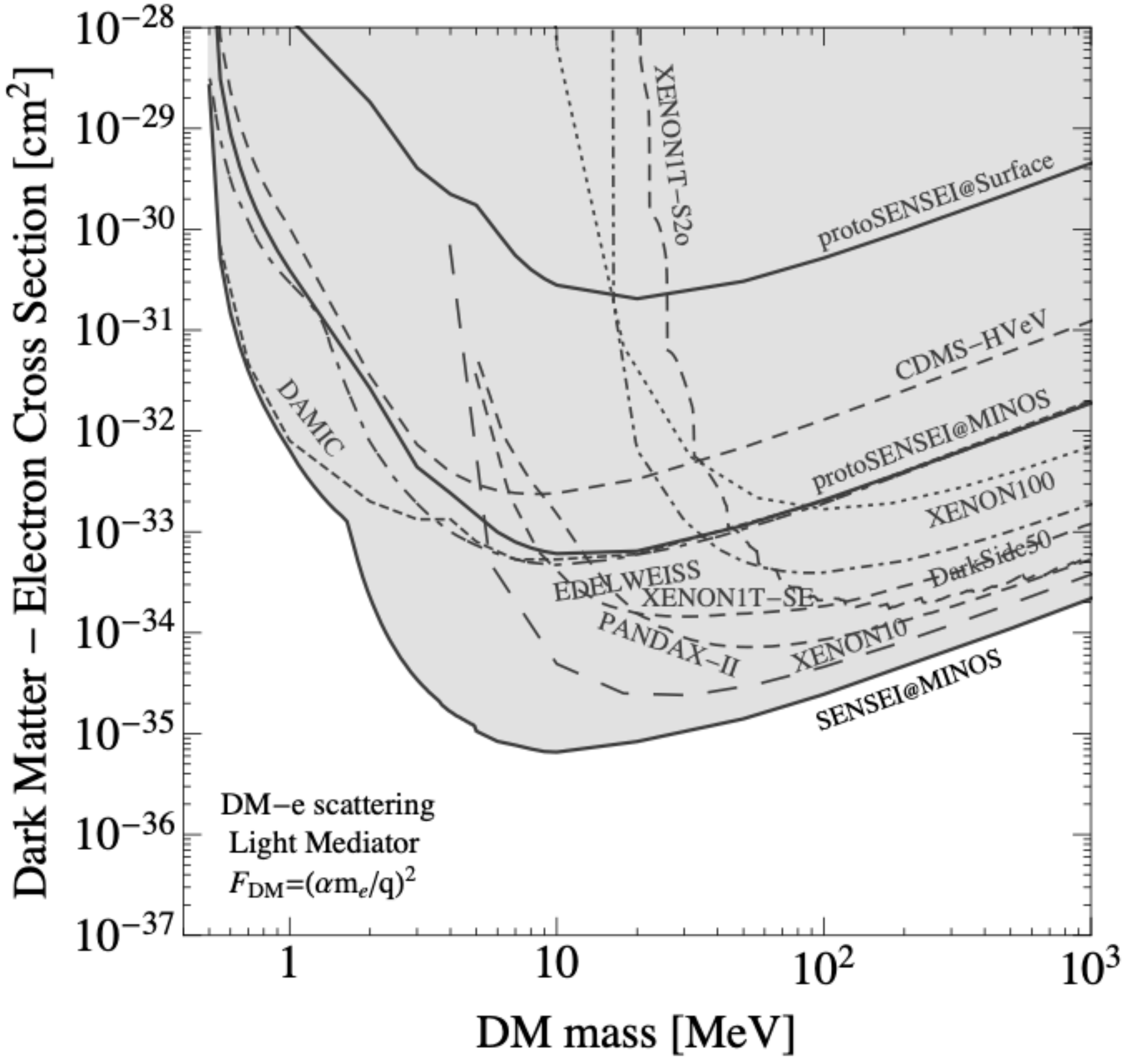
Essig, Volansky, TTY Phys.Rev.D 96 (2017) 4, 043017 [1703.00910]
DarkSide Collaboration Phys.Rev.Lett. 121 (2018) 11, 111303 [1802.06998]
An, Pospelov, Pradler, Ritz, Phys.Rev.Lett. 120 (2018) 14, 141801 [1708.03642]



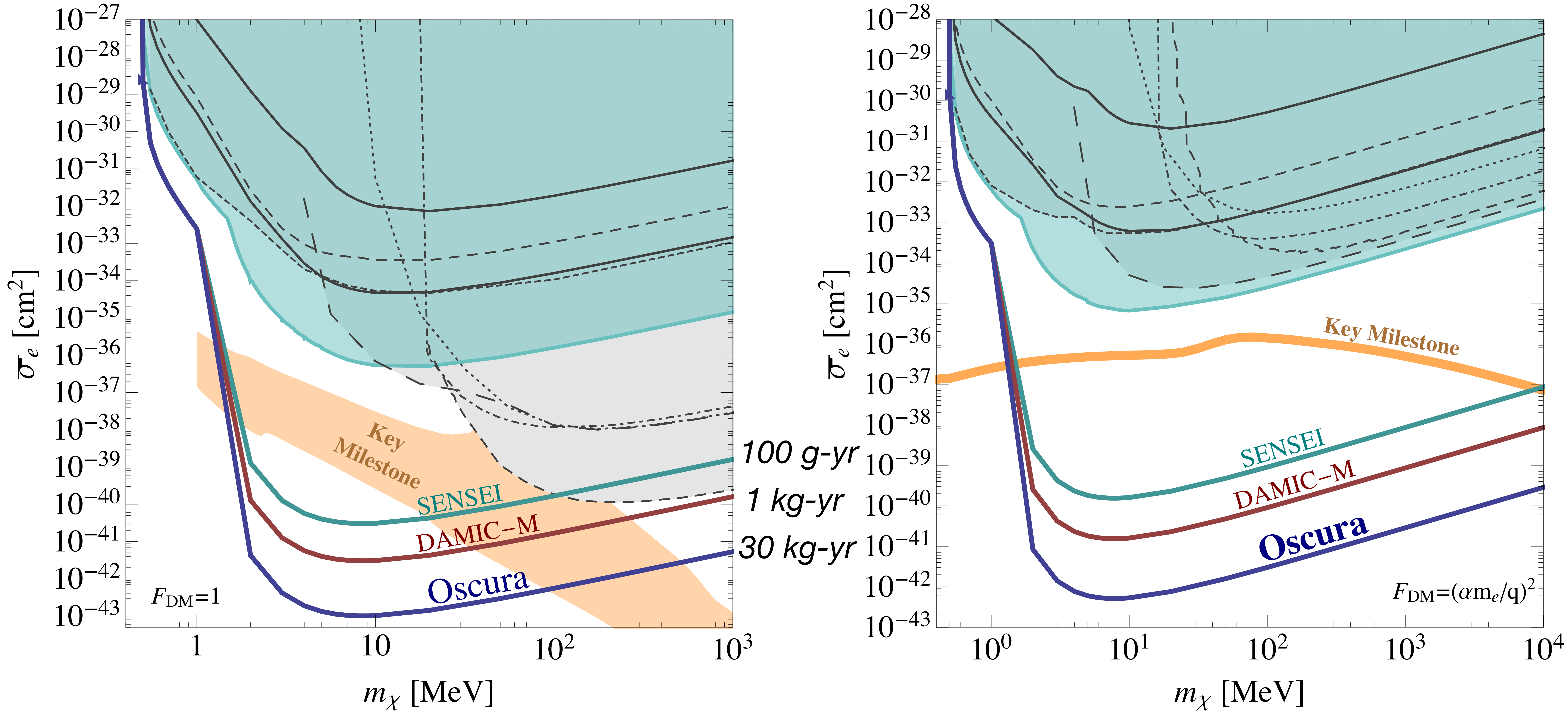
DM-electron limits in 2022

Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade [arXiv:2203.08297]



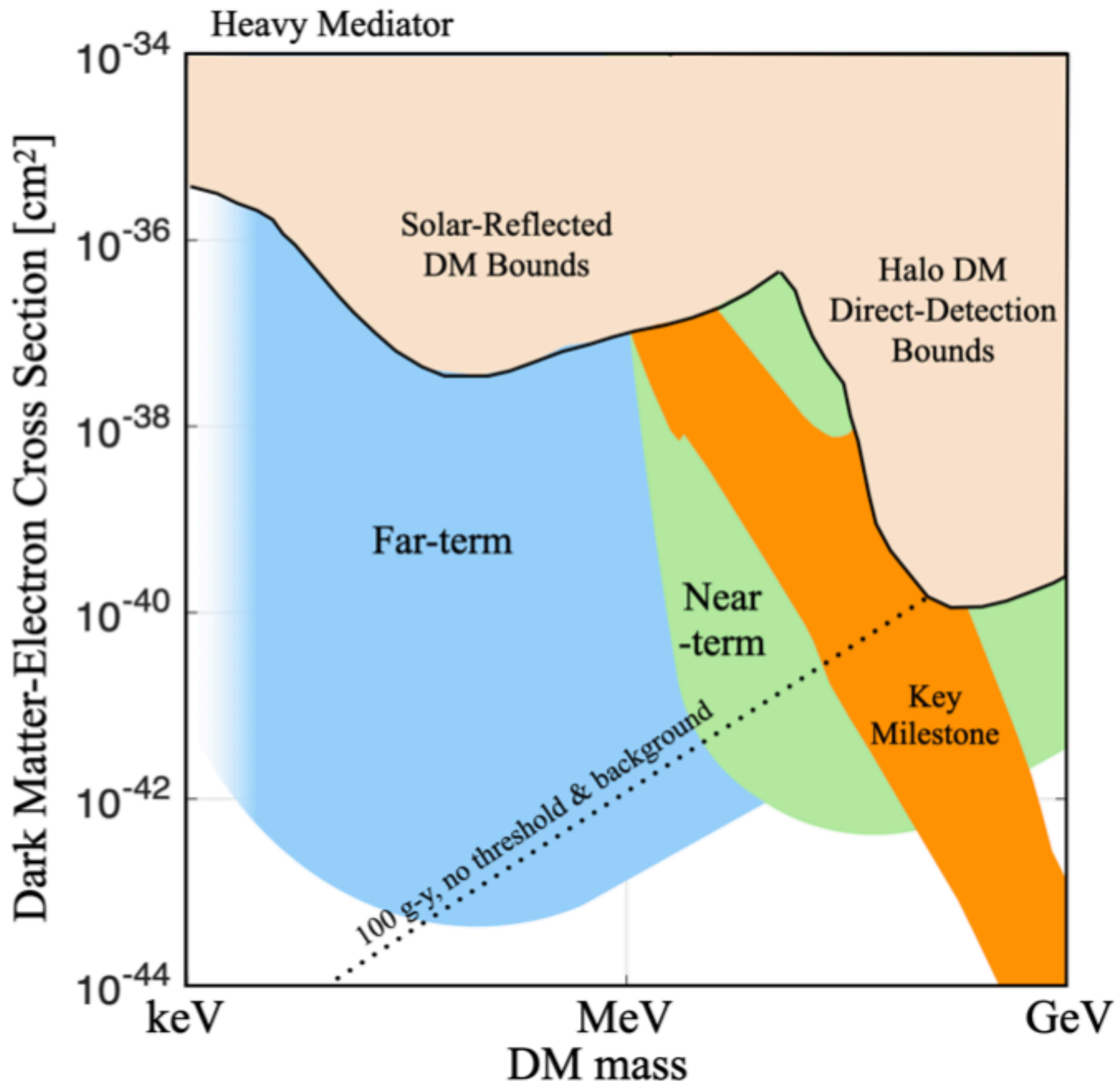


DM-electron limits in the next decade

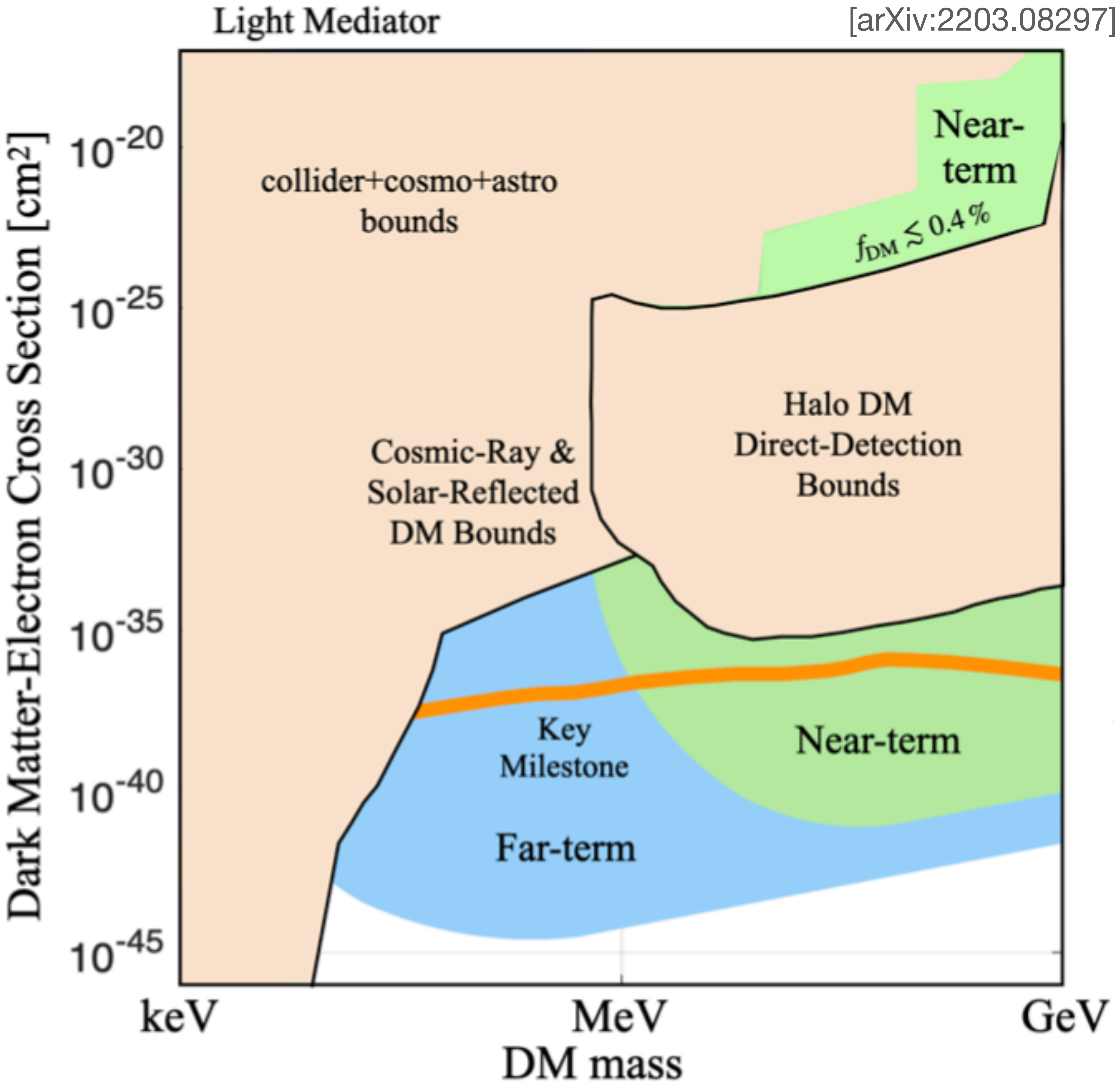


Projections for future Si Skipper-CCD experiments

Outlook for sub-GeV DM direct detection



[arXiv:2203.08297]



ingredients for rate

particle physics

$$R \sim \overline{\sigma}_e \int d^3\vec{v} \frac{f(\vec{v})}{v} \int d^3\vec{q} F_{\rm DM}(\vec{q})^2 S(\vec{q}, \omega_{\vec{q}})$$

$$\overline{\sigma}_e = \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2} \overline{|\mathcal{M}_{\chi e}(q)|^2}\Big|_{q^2=\alpha^2 m_e^2}$$

$$F_{DM}(q) \simeq \begin{cases} 1 & \textit{heavy mediator} \\ \frac{\alpha m_e}{q} & \textit{electric dipole moment} \\ \frac{\alpha^2 m_e^2}{q^2} & \textit{light mediator} \end{cases}$$

ingredients for rate

material dependent

$$R \sim \overline{\sigma}_e \int d^3\vec{v}\frac{f(\vec{v})}{v} \int d^3\vec{q} F_{\mathrm{DM}}(\vec{q})^2 S(\vec{q}, \omega_{\vec{q}})$$

structure function
see talks by **Y. Kahn** and **T. Lin**

ingredients for rate

astrophysics

$$R \sim \overline{\sigma}_e \int d^3\vec{v}\,\frac{f(\vec{v})}{v} \int d^3\vec{q}\,F_{\rm DM}(\vec{q})^2 S(\vec{q},\omega_{\vec{q}})$$

DM halo-model

DM-e scattering rate

astrophysics

material dependent

$$R \sim \overline{\sigma}_e \int d^3\vec{v}\,\frac{f(\vec{v})}{v} \int d^3\vec{q}\,F_{\rm DM}(\vec{q})^2\, S(\vec{q}, \omega_{\vec{q}})$$

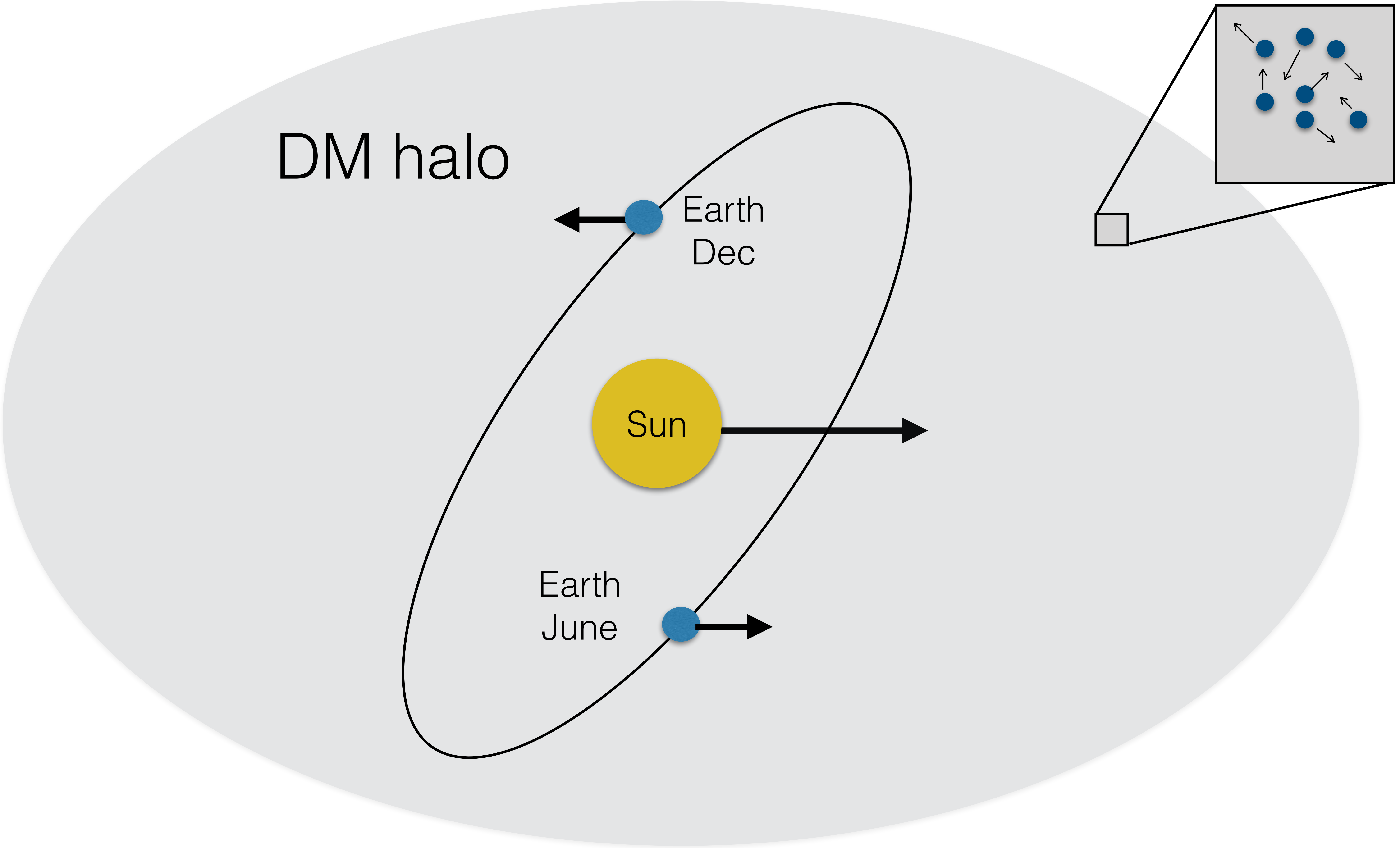
particle physics

DM-e scattering rate

astrophysics

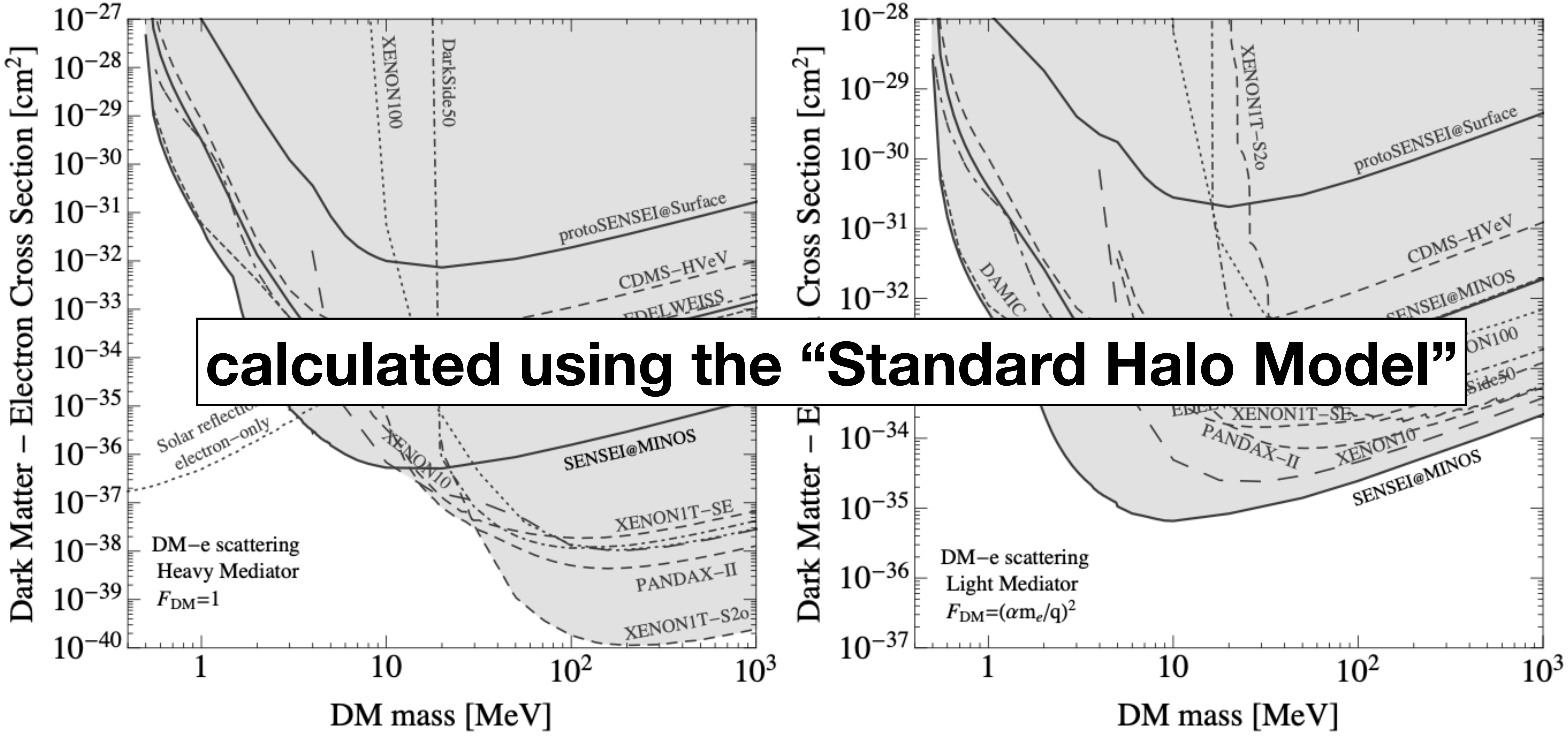
$$R \sim \overline{\sigma}_e \int d^3\vec{v}\,\frac{f(\vec{v})}{v} \int d^3\vec{q}\,F_{\rm DM}(\vec{q})^2 S(\vec{q}, \omega_{\vec{q}})$$

dark matter halo



DM-electron limits in 2022

Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade [arXiv:2203.08297]



calculated using the "Standard Halo Model"

Why the SHM?

Isothermal spherical distribution for Galactic DM which scales like r^{-2}

+

collisionless steady-state Boltzmann equation

=

isotropic Maxwell-Boltzmann velocity distribution

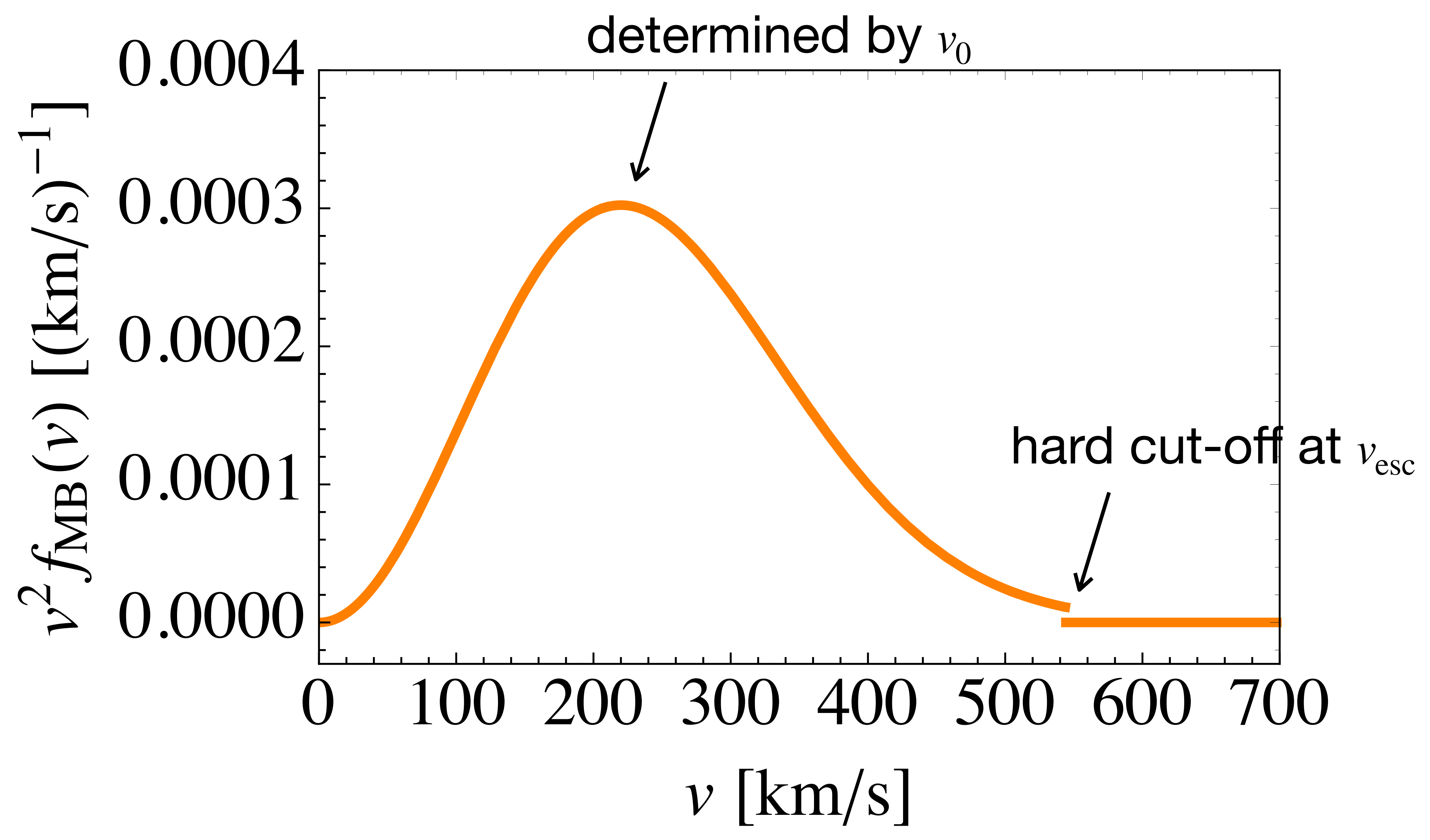
$$f_{\rm MB}(\vec{v}) \propto \begin{cases} e^{-|\vec{v}|^2/{v_0}^2} & |\vec{v}| < v_{\rm esc} \\ 0 & |\vec{v}| \geq v_{\rm esc} \end{cases}$$

* *n.b. anisotropic velocity distributions break the direct relationship between DM density and velocity distributions*

What is the Standard Halo Model?

$$f_{\mathrm{MB}}(\vec{v}) \propto \begin{cases} e^{-|\vec{v}|^2/{v_0}^2} & |\vec{v}| < v_{\mathrm{esc}} \\ 0 & |\vec{v}| \geq v_{\mathrm{esc}} \end{cases}$$

Maxwell-Boltzmann distribution



Boosted into the Earth's frame:

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

parameters of SHM

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

normalization

Galactic escape velocity $v_{\rm esc} \in [450, 600]$ km/s

Galactic velocity of Earth $v_E \in [215, 245]$ km/s

local solar circular velocity $v_0 \in [200, 280]$ km/s

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Galactic escape velocity $v_{\rm esc} \in [450, 600]$ km/s

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Astrophysical Parameters

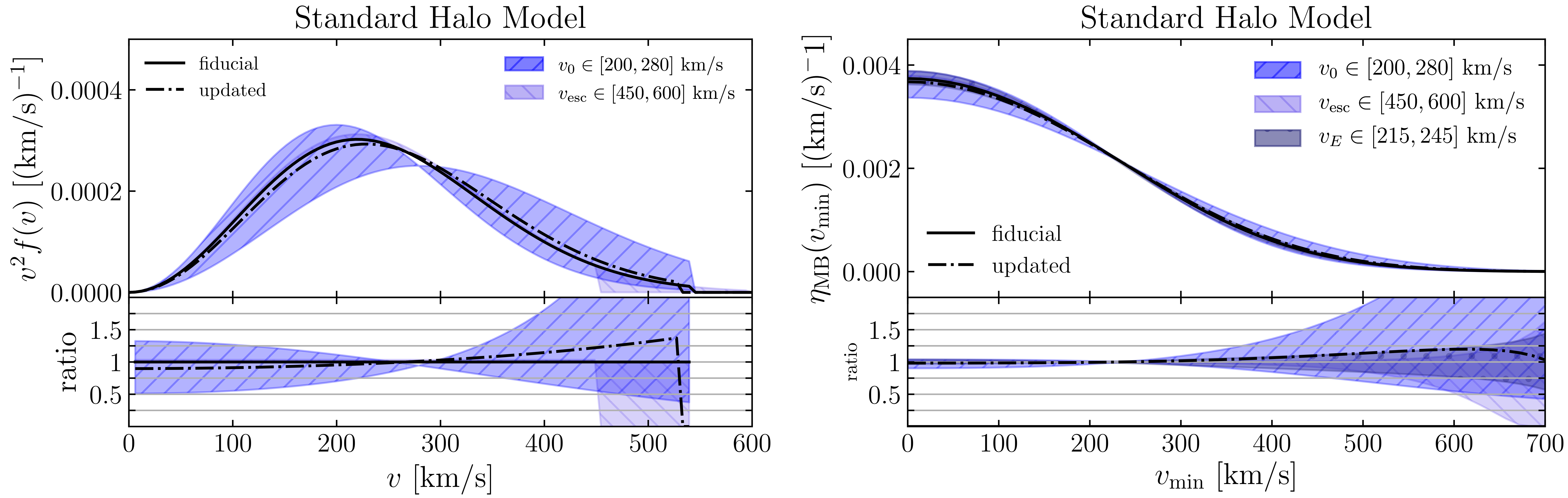
	current	*suggested*	
v_0 [km/s]	220^{+60}_{-20}	228.6 ± 0.34	238
$v_{\rm esc}$ [km/s]	544^{+56}_{-94}	528^{+24}_{-25}	544
$\rho_{\rm DM}$ [GeV/cm^3]	0.4	$0.46^{+0.07}_{-0.09}$	0.3
v_E [km/s]	232 ± 15	232 ± 15	
R_0 [kpc]	8.0 ± 0.5	8.34 ± 0.16	

A. Radick, A.M.Taki, TTY *JCAP* 02 (2021) 004, arXiv:2011.02493

See also D. Baxter et al "Recommended conventions for reporting results from direct dark matter searches" [arXiv:2105.00599]

The Standard Halo Model

$$f_{\mathrm{MB}}(\vec{v}) \propto \begin{cases} e^{-|\vec{v}|^2/{v_0}^2} & |\vec{v}| < v_{\mathrm{esc}} \\ 0 & |\vec{v}| \geq v_{\mathrm{esc}} \end{cases}$$



A. Radick, A.M.Taki, TTY *JCAP* 02 (2021) 004, arXiv:2011.02493

$$R \sim \overline{\sigma}_e \int d^3\vec{v} \frac{f(\vec{v})}{v} \int d^3\vec{q} F_{\mathrm{DM}}(\vec{q})^2 S(\vec{q}, \omega_{\vec{q}})$$

typical energy transfer

$$\Delta E_e = \vec{q} \cdot \vec{v} - \frac{q^2}{2\mu_{\chi N}}$$

⬇ arbitrary-size momentum transfer is possible

$$\Delta E_e \leq \frac{1}{2}\mu_{\chi N} v^2$$

typical momentum transfer

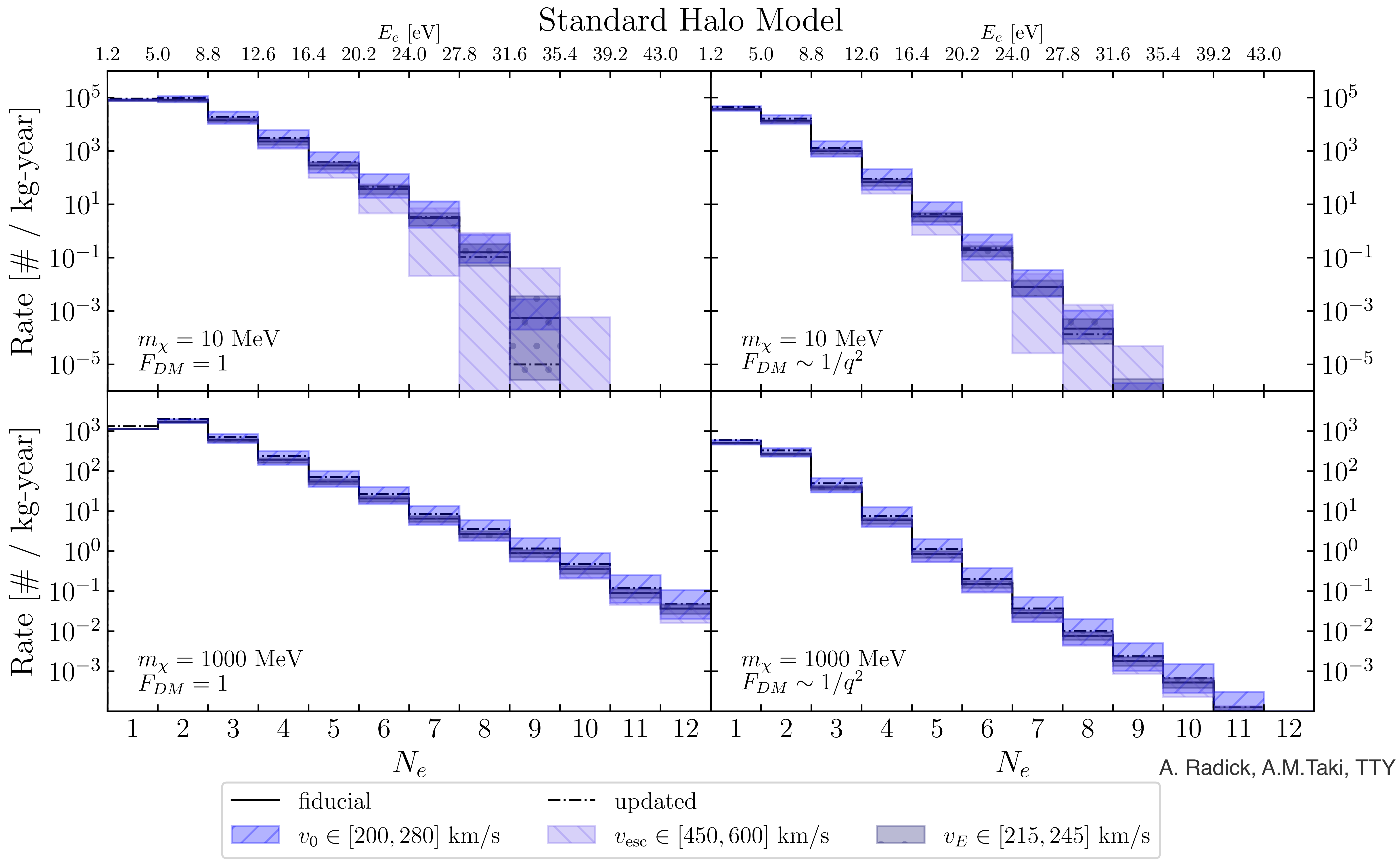
typical size of the momentum transfer is set by the electron's momentum

$$q_{\rm typ} \simeq m_e v_e \sim Z_{\rm eff} \alpha m_e$$

~ 4 keV

This requires *q* on tail of e- wave function or DM velocity!

Event Rates



A. Radick, A.M.Taki, TTY *JCAP* 02 (2021) 004, arXiv:2011.02493

$N_e \uparrow \,\&\, m_x \downarrow \longmapsto$ Rate becomes more sensitive to astro uncertainties.

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	7.8×10^4	3.6×10^4	7.9×10^4	1.3×10^4	1.5×10^4	9.9×10^2	2.3×10^3	67
Updated	9.2×10^4	4.3×10^4	9.6×10^4	1.6×10^4	1.9×10^4	1.3×10^3	3.0×10^3	86
rel. diff.	0.17	0.20	0.22	0.25	0.28	0.30	0.30	0.28
$v_{0,min}$	7.5×10^4	3.2×10^4	6.6×10^4	9.9×10^3	1.0×10^4	6.2×10^2	1.3×10^3	35
$v_{0,max}$	8.7×10^4	4.7×10^4	1.1×10^5	2.2×10^4	3.0×10^4	2.3×10^3	6.0×10^3	2.0×10^2
rel. diff.	0.15	0.41	0.58	0.91	1.3	1.7	2.1	2.5
$v_{esc,min}$	7.7×10^4	3.4×10^4	7.4×10^4	1.1×10^4	1.2×10^4	6.6×10^2	1.2×10^3	25
$v_{esc,max}$	7.9×10^4	3.7×10^4	8.0×10^4	1.3×10^4	1.5×10^4	1.1×10^3	2.6×10^3	85
rel. diff.	0.015	0.057	0.074	0.16	0.27	0.43	0.60	0.89
$v_{E,min}$	7.5×10^4	3.3×10^4	7.1×10^4	1.1×10^4	1.2×10^4	7.9×10^2	1.7×10^3	48
$v_{E,max}$	8.1×10^4	3.8×10^4	8.6×10^4	1.4×10^4	1.7×10^4	1.2×10^3	2.8×10^3	85
rel. diff.	0.080	0.14	0.19	0.24	0.32	0.38	0.45	0.55

0.0 0.1 0.5 1.0

relative difference

$$\text{Rel. Diff.} = \frac{\text{Rate}_{\text{max}} - \text{Rate}_{\text{min}}}{\text{Rate}_{\text{fid}}}$$

1 kg-year

Standard Halo Model (m_χ=1000 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	1.1×10^3	5.0×10^2	1.7×10^3	2.7×10^2	5.9×10^2	39	1.9×10^2	5.9
Updated	1.3×10^3	5.9×10^2	2.0×10^3	3.3×10^2	7.2×10^2	49	2.3×10^2	7.5
rel. diff.	0.15	0.18	0.18	0.21	0.22	0.25	0.25	0.28
$v_{0,min}$	1.1×10^3	4.6×10^2	1.6×10^3	2.3×10^2	4.9×10^2	29	1.4×10^2	4.0
$v_{0,max}$	1.1×10^3	5.9×10^2	2.0×10^3	3.8×10^2	8.5×10^2	68	3.2×10^2	12
rel. diff.	-0.00033	0.26	0.21	0.54	0.60	0.98	0.93	1.4
$v_{esc,min}$	1.1×10^3	4.8×10^2	1.7×10^3	2.5×10^2	5.5×10^2	33	1.6×10^2	4.3
$v_{esc,max}$	1.1×10^3	5.0×10^2	1.7×10^3	2.7×10^2	6.0×10^2	40.	1.9×10^2	6.3
rel. diff.	-0.0017	0.036	0.024	0.087	0.087	0.18	0.17	0.34
$v_{E,min}$	1.1×10^3	4.7×10^2	1.6×10^3	2.4×10^2	5.3×10^2	34	1.6×10^2	4.8
$v_{E,max}$	1.1×10^3	5.2×10^2	1.8×10^3	2.9×10^2	6.4×10^2	44	2.1×10^2	6.8
rel. diff.	0.016	0.095	0.092	0.17	0.18	0.26	0.24	0.34

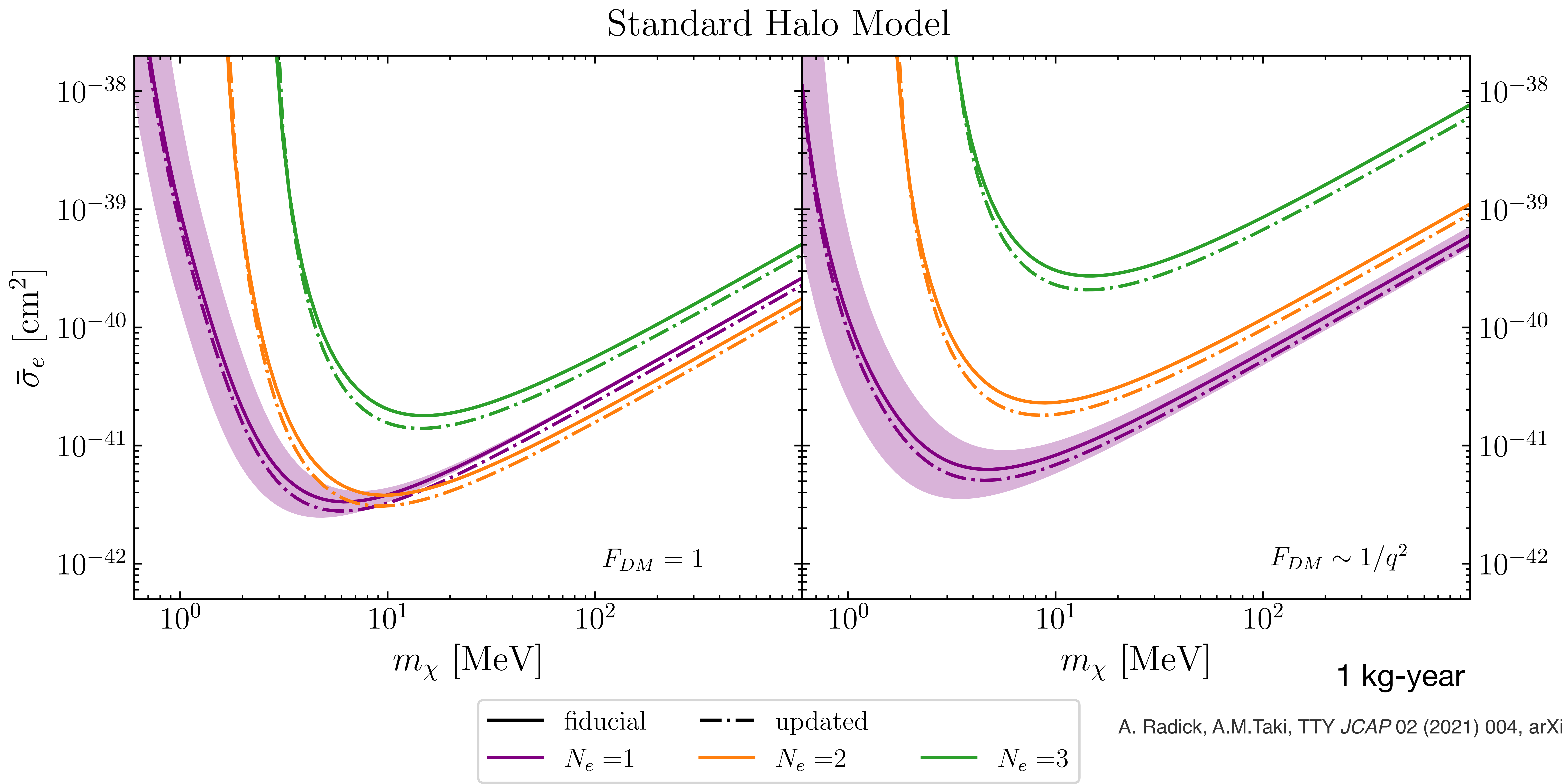
0.0 0.1 0.5 1.0

relative difference

$$\text{Rel. Diff.} = \frac{\text{Rate}_{\text{max}} - \text{Rate}_{\text{min}}}{\text{Rate}_{\text{fid}}}$$

1 kg-year

Cross-section reach



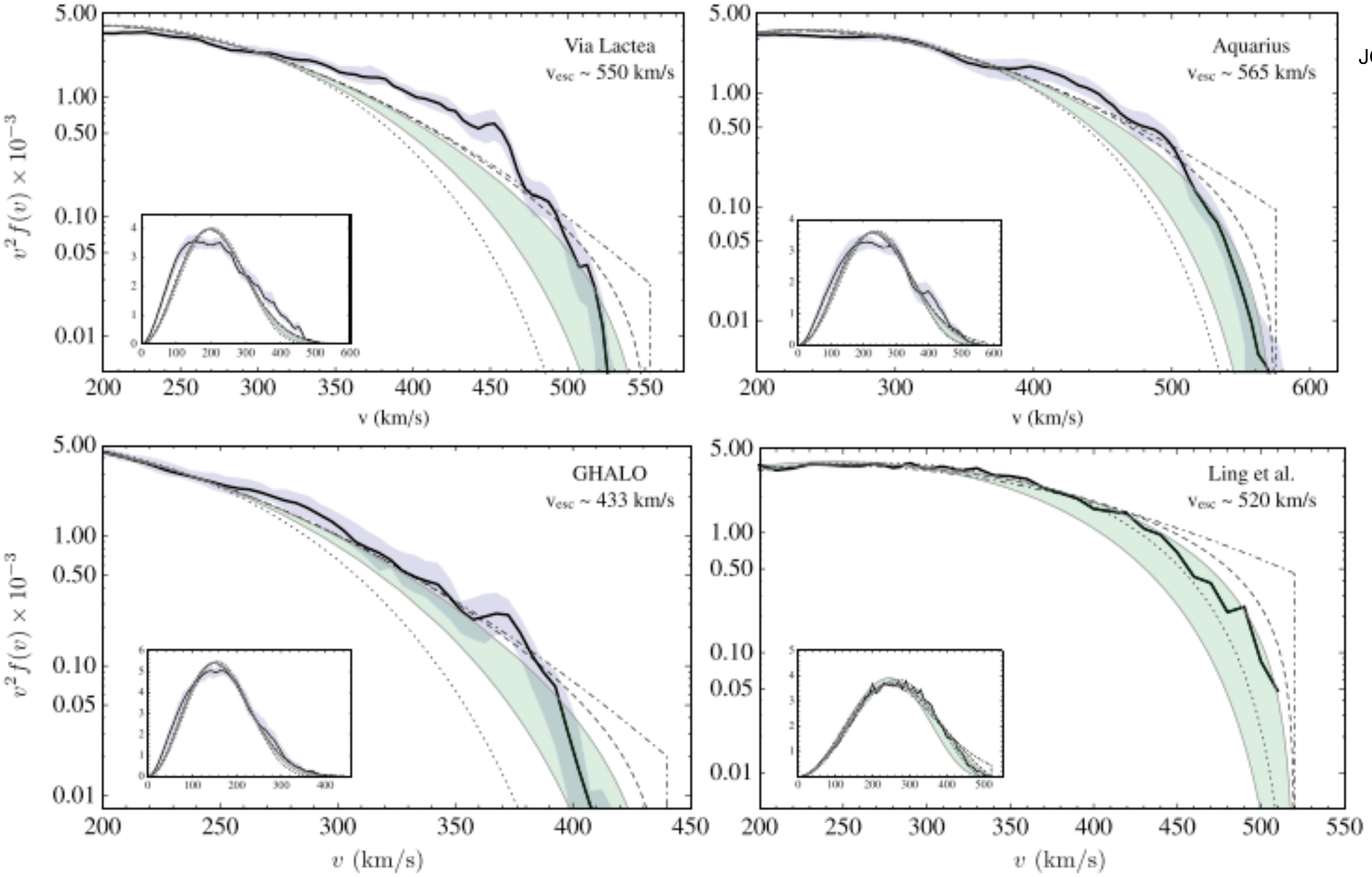
1 kg-year

A. Radick, A.M.Taki, TTY *JCAP* 02 (2021) 004, arXiv:2011.02493

SHM vs. simulations

Lisanti, Strigari, Wacker, Wechsler
Phys.Rev.D 83 (2011) 023519, arXiv:1010.4300

See also Bozorgnia et al,
JCAP 05 (2016) 024, arXiv: 1601.04707



The Tsallis Model

$$S_{\mathrm{BG}} = -k \sum_i p_i \ln p_i \longrightarrow S_{\mathrm{Tsa}} = -k \sum_i p_i^q \ln_q p_i$$

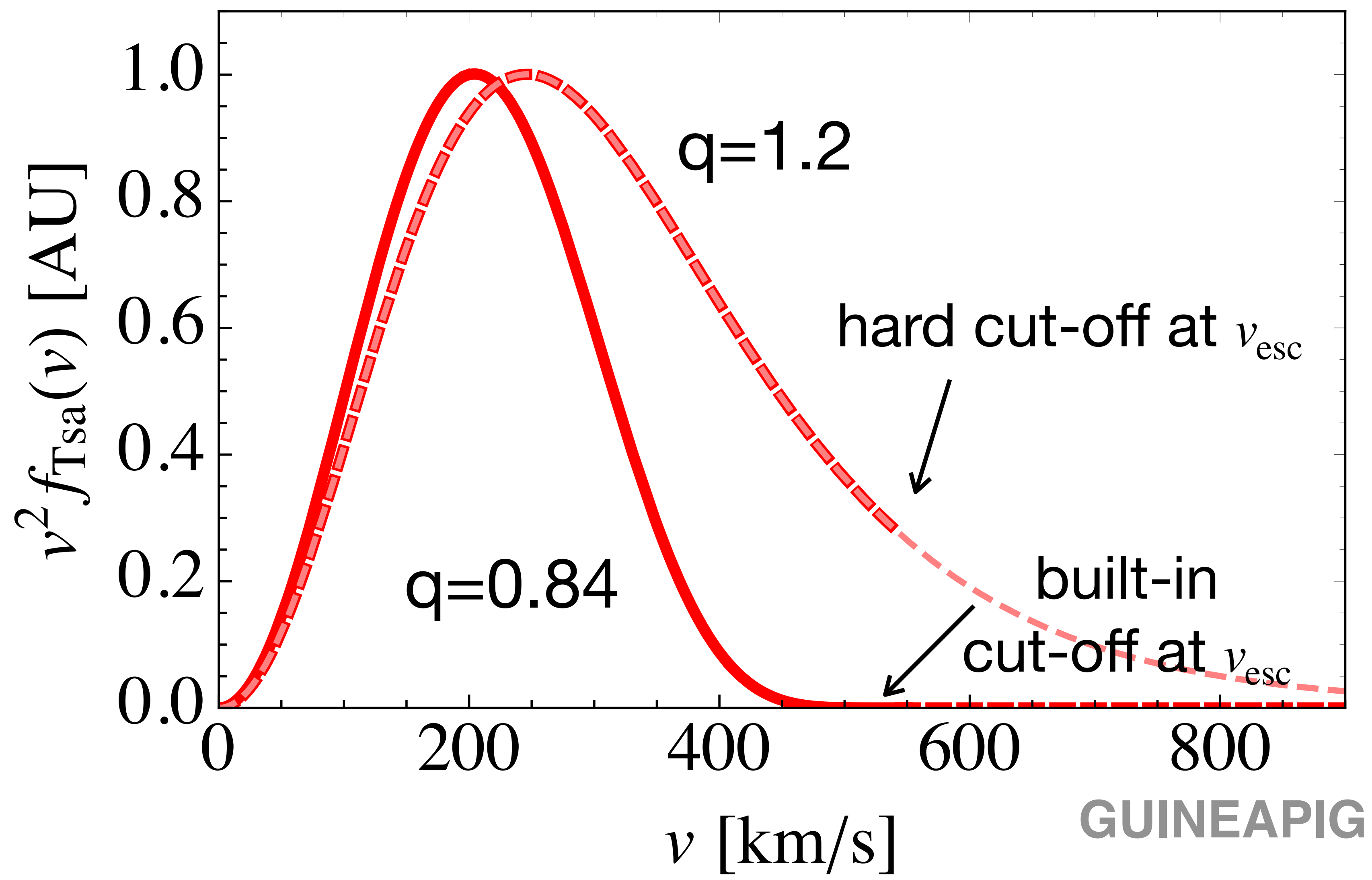
$$\ln_q p = \left(p^{1-q} - 1\right) / (1-q)$$

$$f_{\mathrm{Tsa}}(\vec{v}) \propto \begin{cases} \left[1 - (1-q)\frac{\vec{v}^2}{{v_0}^2}\right]^{1/(1-q)} & |\vec{v}| < v_{\mathrm{esc}} \\ 0 & |\vec{v}| \geq v_{\mathrm{esc}} \end{cases}$$

$q \to 1$ SHM

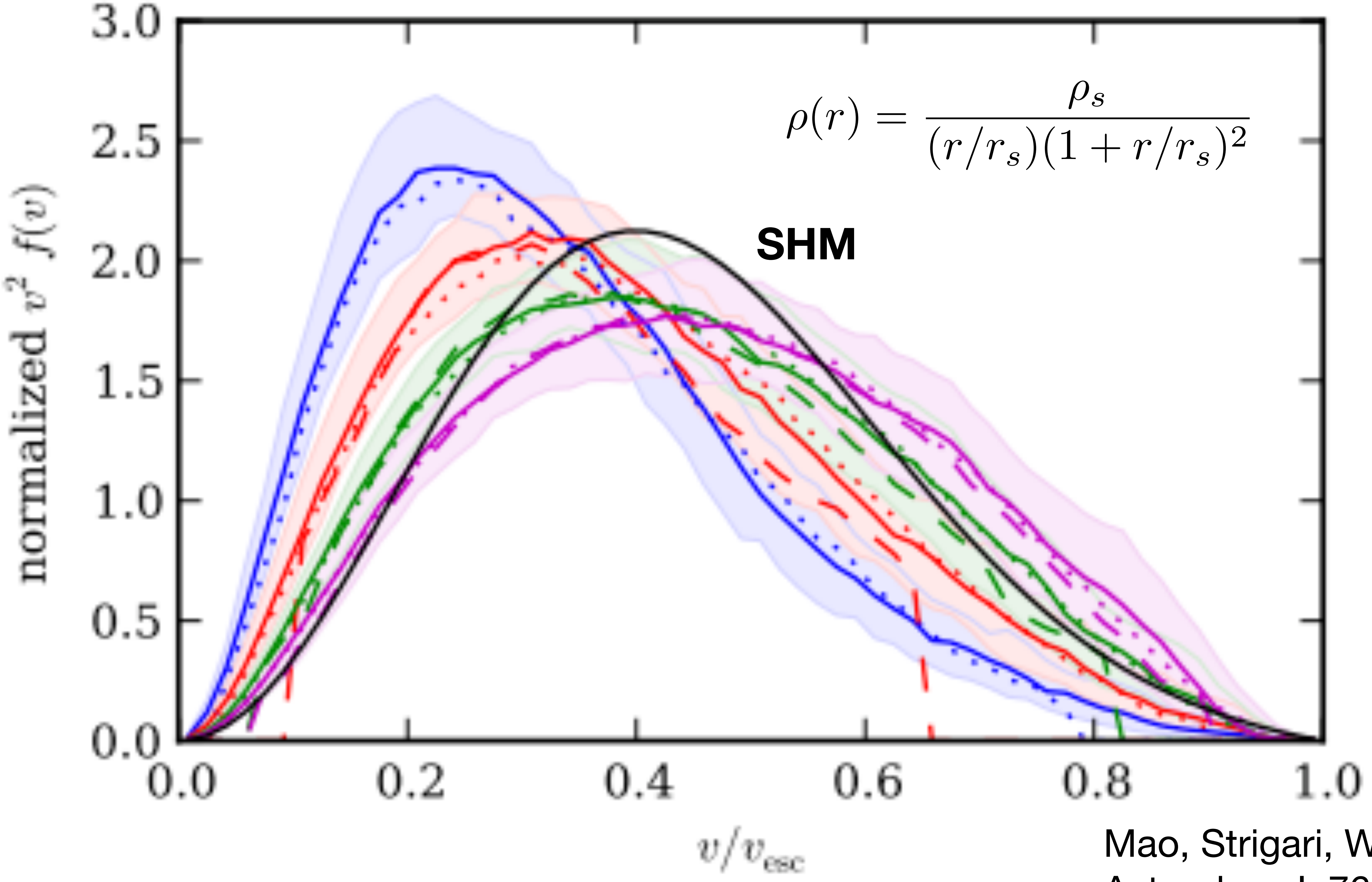
$q < 1$ $v_{\mathrm{esc}}^2 = v_0^2/(1-q)$

$q > 1$ impose v_{esc}



Empirical Model

DM-only Rhapsody (solid)/Bolshoi (dashed, dotted) simulations

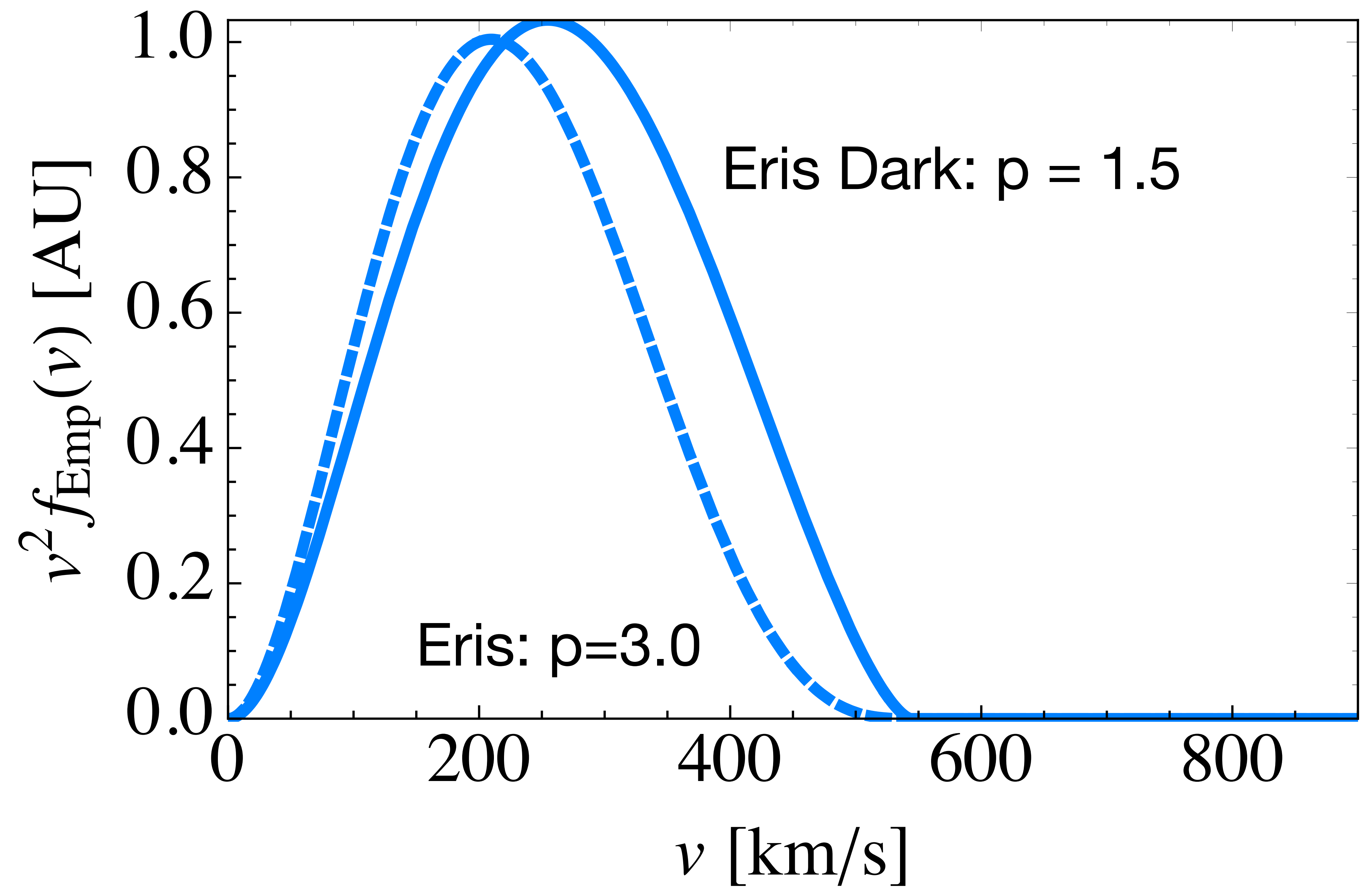


Mao, Strigari, Wechsler, Wu, Hahn
Astrophys.J. 764 (2013) 35, arXiv:1210.2721

Empirical Model

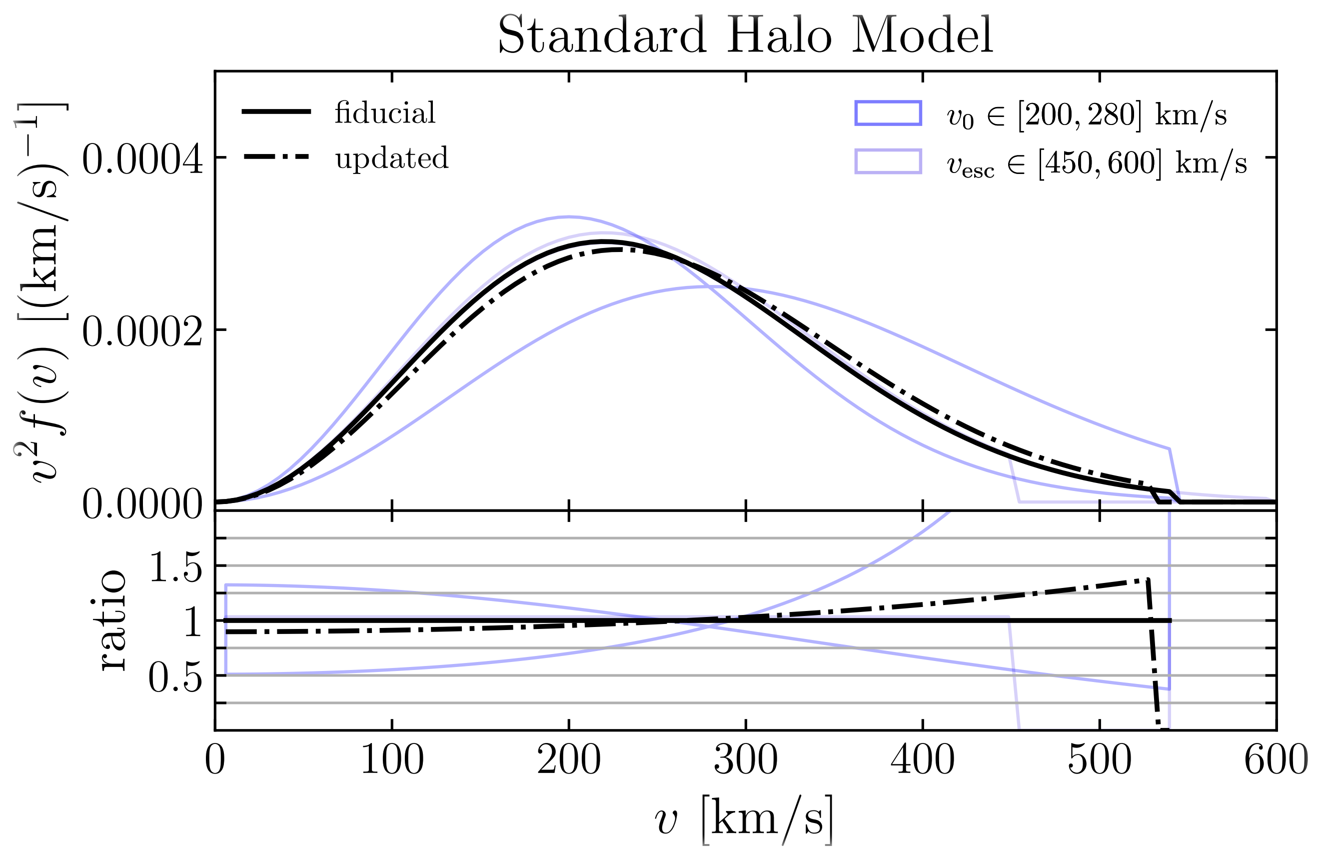
Mao, Strigari, Wechsler, Wu, Hahn Astrophys.J. 764 (2013) 35, arXiv:1210.2721

$$f_{\mathrm{emp}}(\vec{v}) \propto \begin{cases} e^{-|\vec{v}|/v_0} \left({v_{\mathrm{esc}}}^2 - |\vec{v}|^2\right)^p, & |\vec{v}| < v_{\mathrm{esc}} \\ 0, & |\vec{v}| \geq v_{\mathrm{esc}} \end{cases}$$



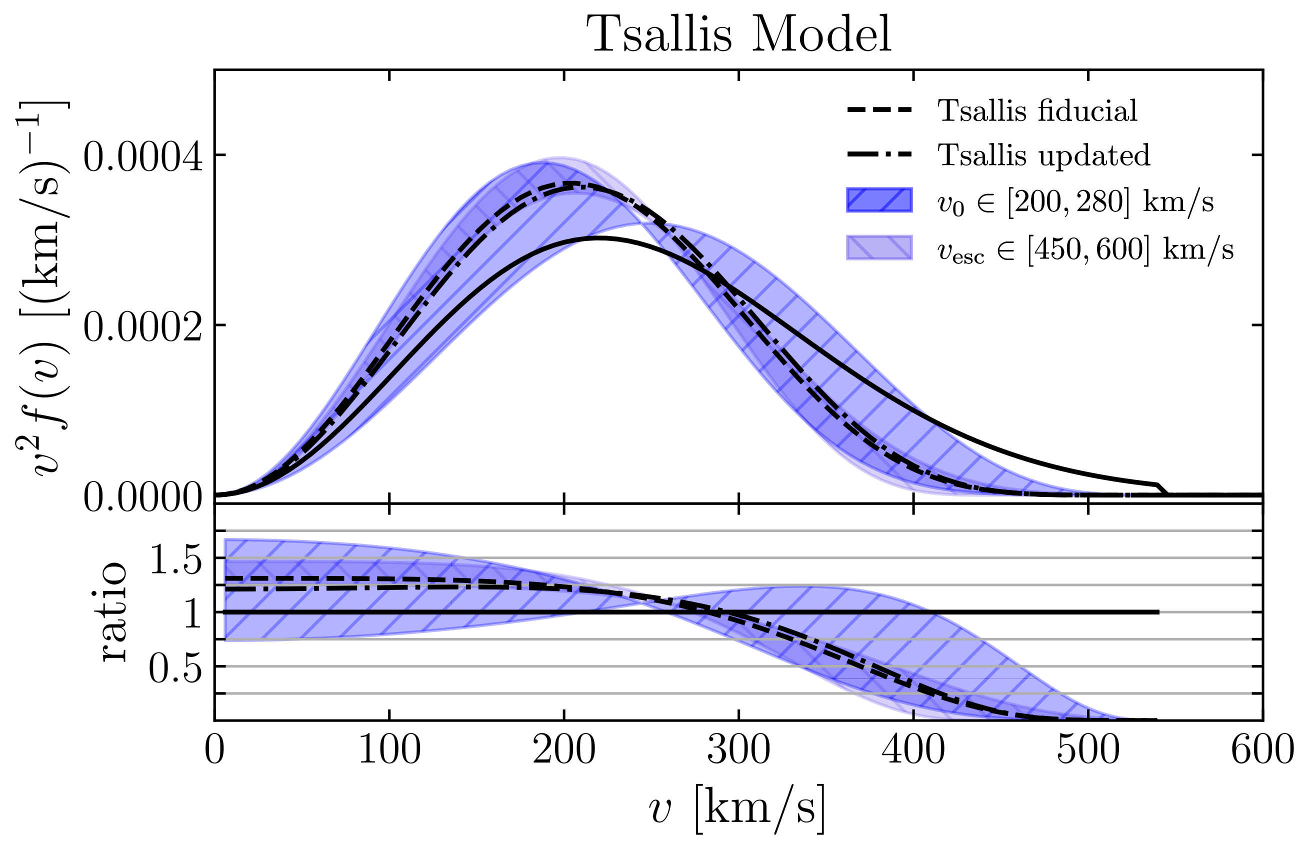
Halo Models

$$f_{\rm MB}(\vec{v}) \propto \begin{cases} e^{-|\vec{v}|^2/{v_0}^2} & |\vec{v}| < v_{\rm esc} \\ 0 & |\vec{v}| \geq v_{\rm esc} \end{cases}$$



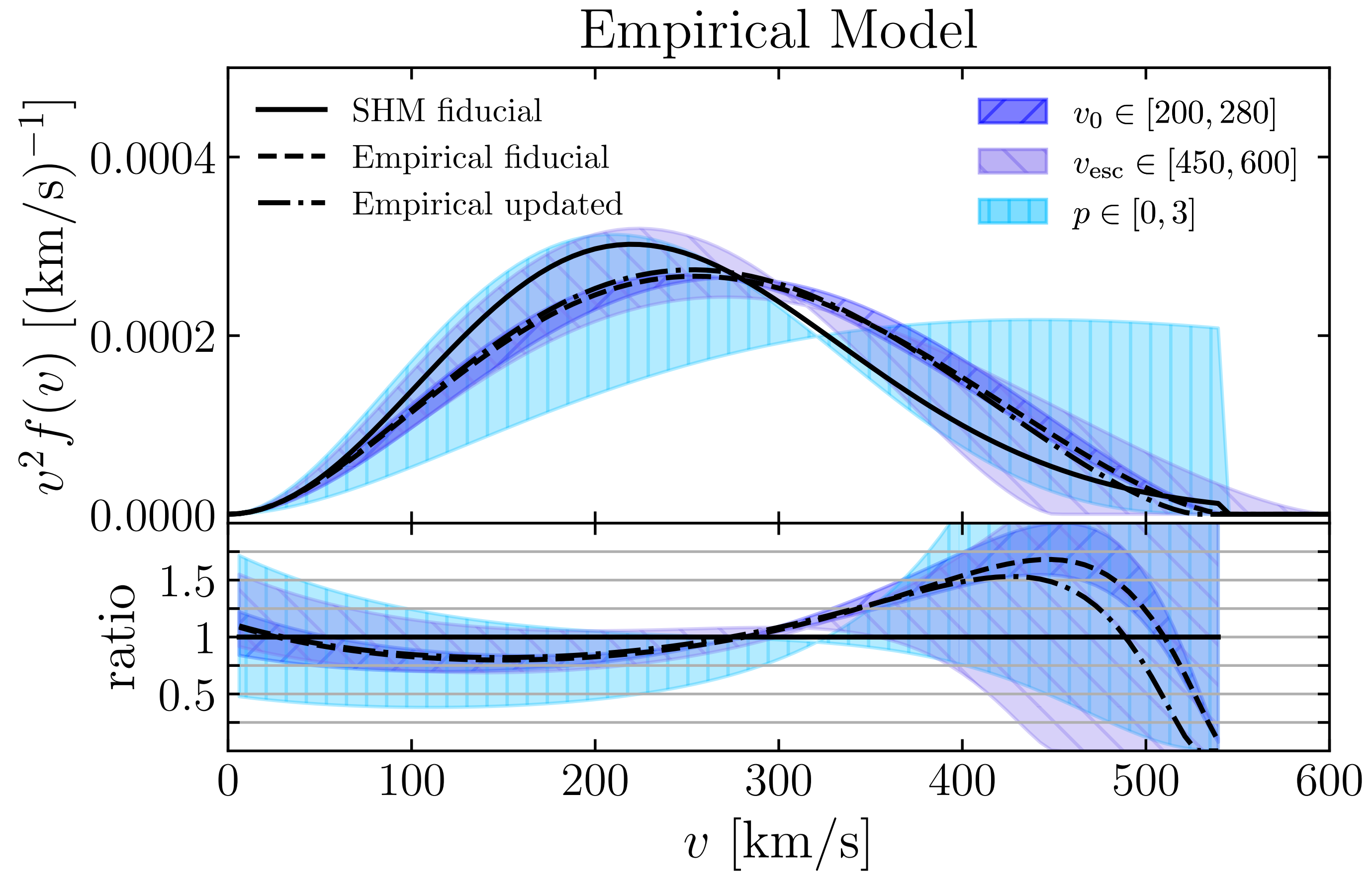
Standard Halo Model

$$f_{\rm Tsa}(\vec{v}) \propto \begin{cases} \left[1 - (1-q)\frac{\vec{v}^2}{{v_0}^2}\right]^{1/(1-q)} & |\vec{v}| < v_{\rm esc} \\ 0 & |\vec{v}| \geq v_{\rm esc} \end{cases}$$



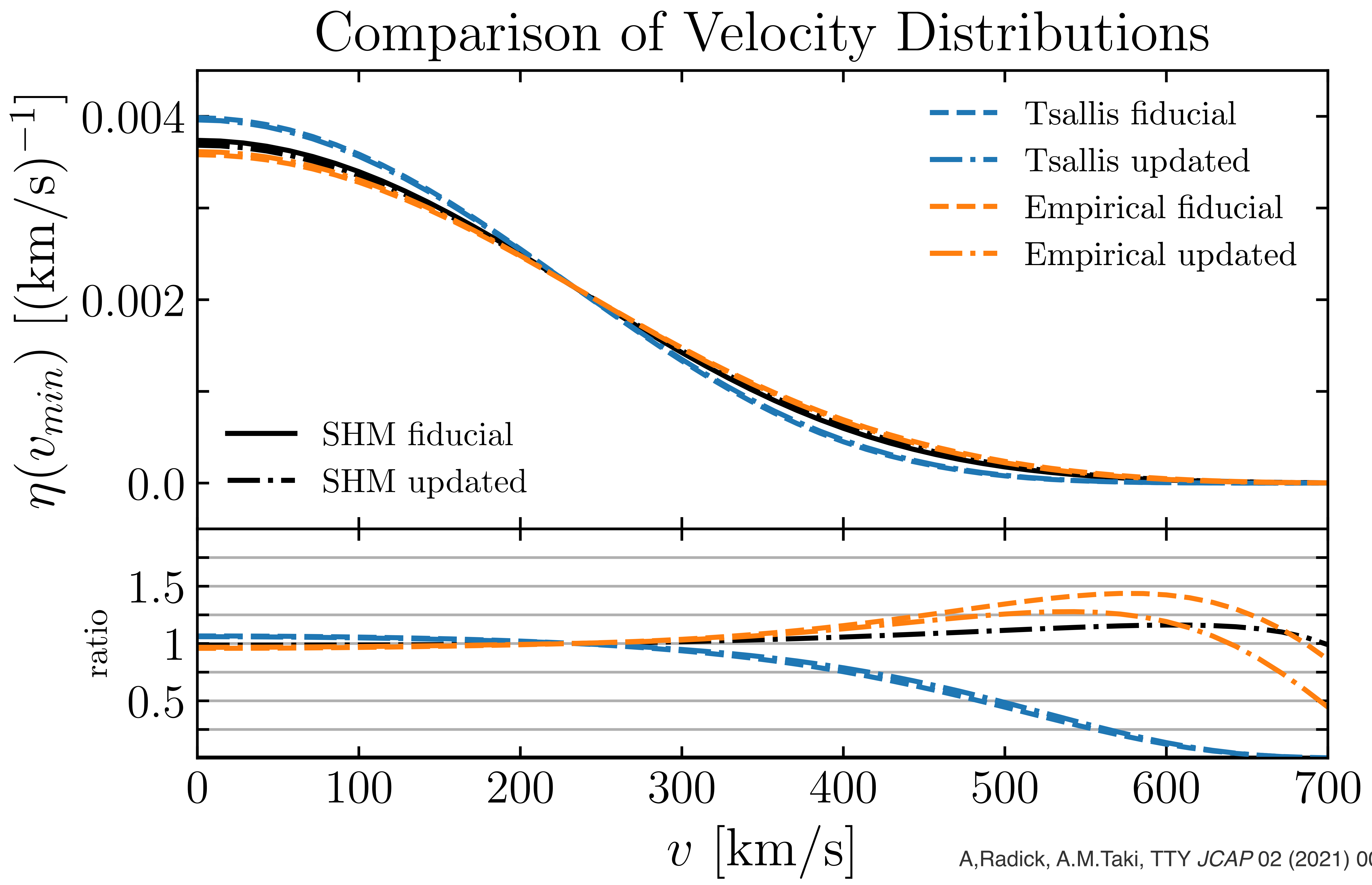
Tsallis Model

$$f_{\rm emp}(\vec{v}) \propto \begin{cases} e^{-|\vec{v}|/v_0} \left({v_{\rm esc}}^2 - |\vec{v}|^2\right)^p & |\vec{v}| < v_{\rm esc} \\ 0 & |\vec{v}| \geq v_{\rm esc} \end{cases}$$



Empirical Model

Comparing models



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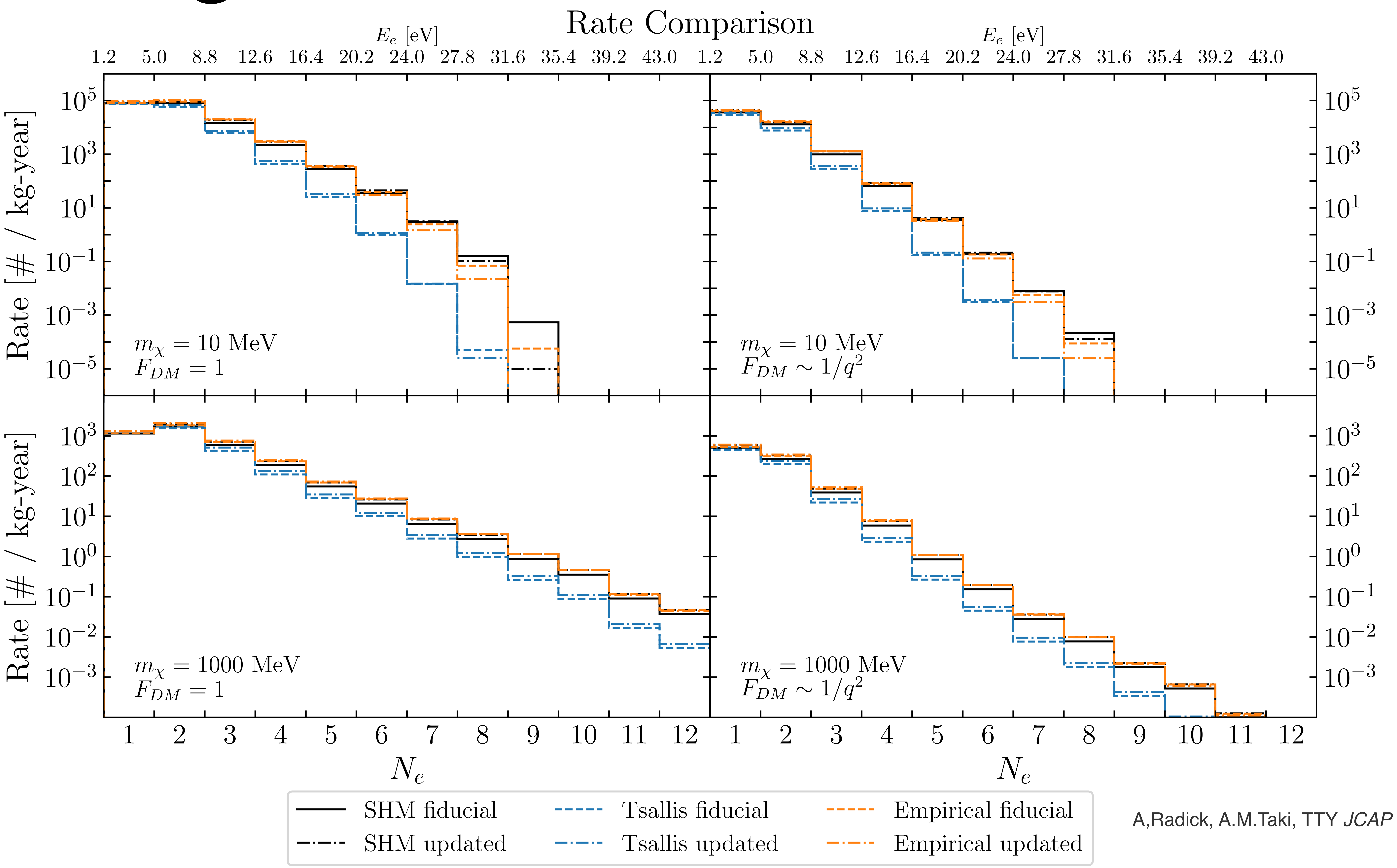
Comparing models



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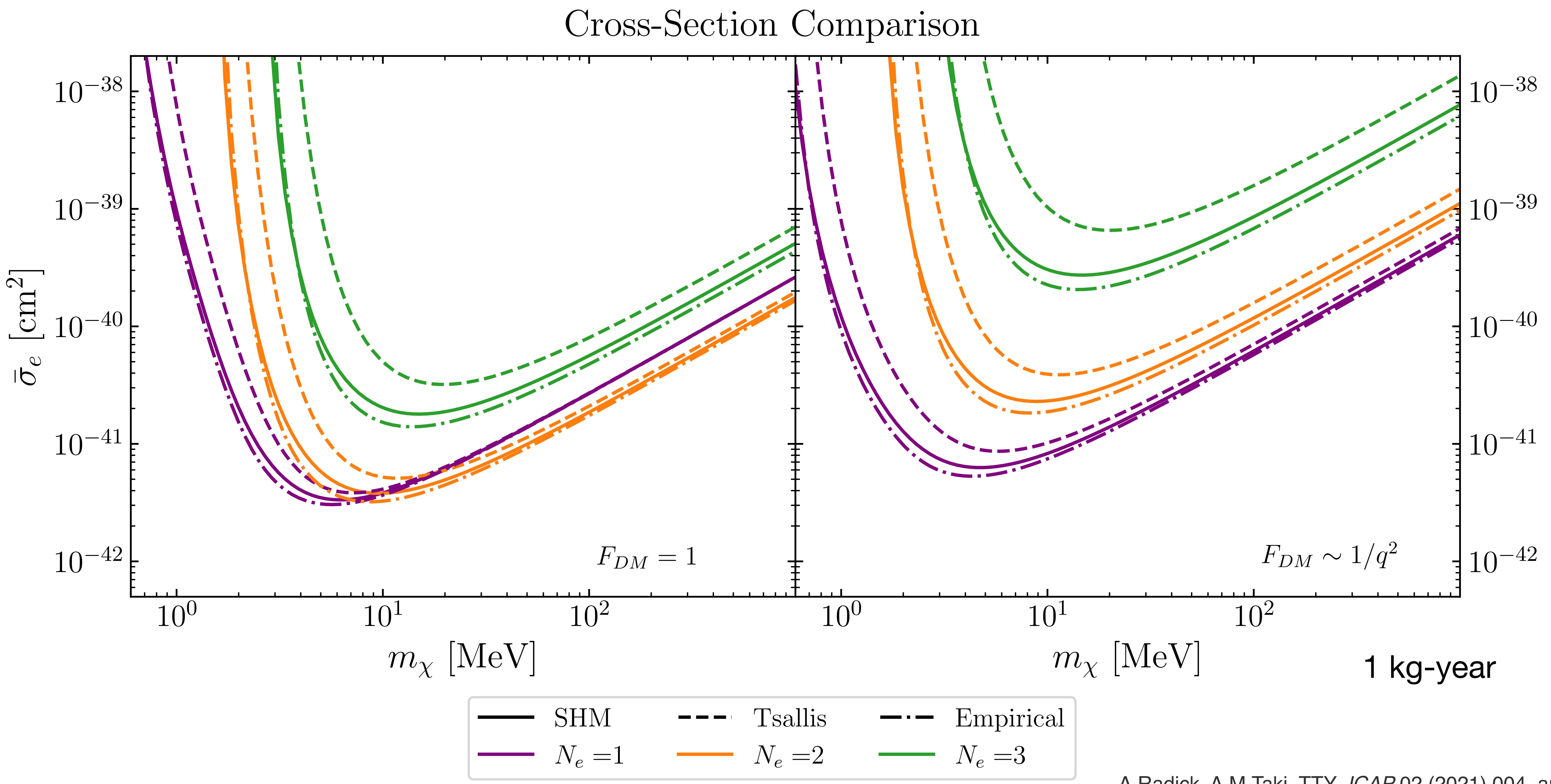
Comparing models



1 kg-year

A,Radick, A.M.Taki, TTY *JCAP* 02 (2021) 004, arXiv:2011.02493

Summary

- the Standard Halo Model has been the proxy DM halo model for DM direct detection calculations
- SHM is the self-consistent solution for an isotropic, isothermal halo with collisionless Boltzmann equation.
- DM-only simulations deviate from Maxwell-Boltzmann, especially at higher velocities.
- DM+baryon simulations match better with MB, but still have some deviations.
- **Predicted DM-electron scattering rates (cross-sections) are sensitive to the choice of halo model and parameters**
- the sensitivity is particularly acute for low DM masses and high energy bins, and to the circular velocity