Dark Matter in stars:

Capture uncertainties and RGB stars

6th IDPASC Workshop

José Vargas Lopes

supervised by **Ilídio Lopes**

In collaboration with **Thomas Lacroix**

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- Stars as Dark Matter Laboratories
- Particle Dark matter capture in Stars
- Eddington Inversion PSDF's

Results

- Velocity Distribution functions
- Capture in the Sun
- Capture uncertainties in the Milky way

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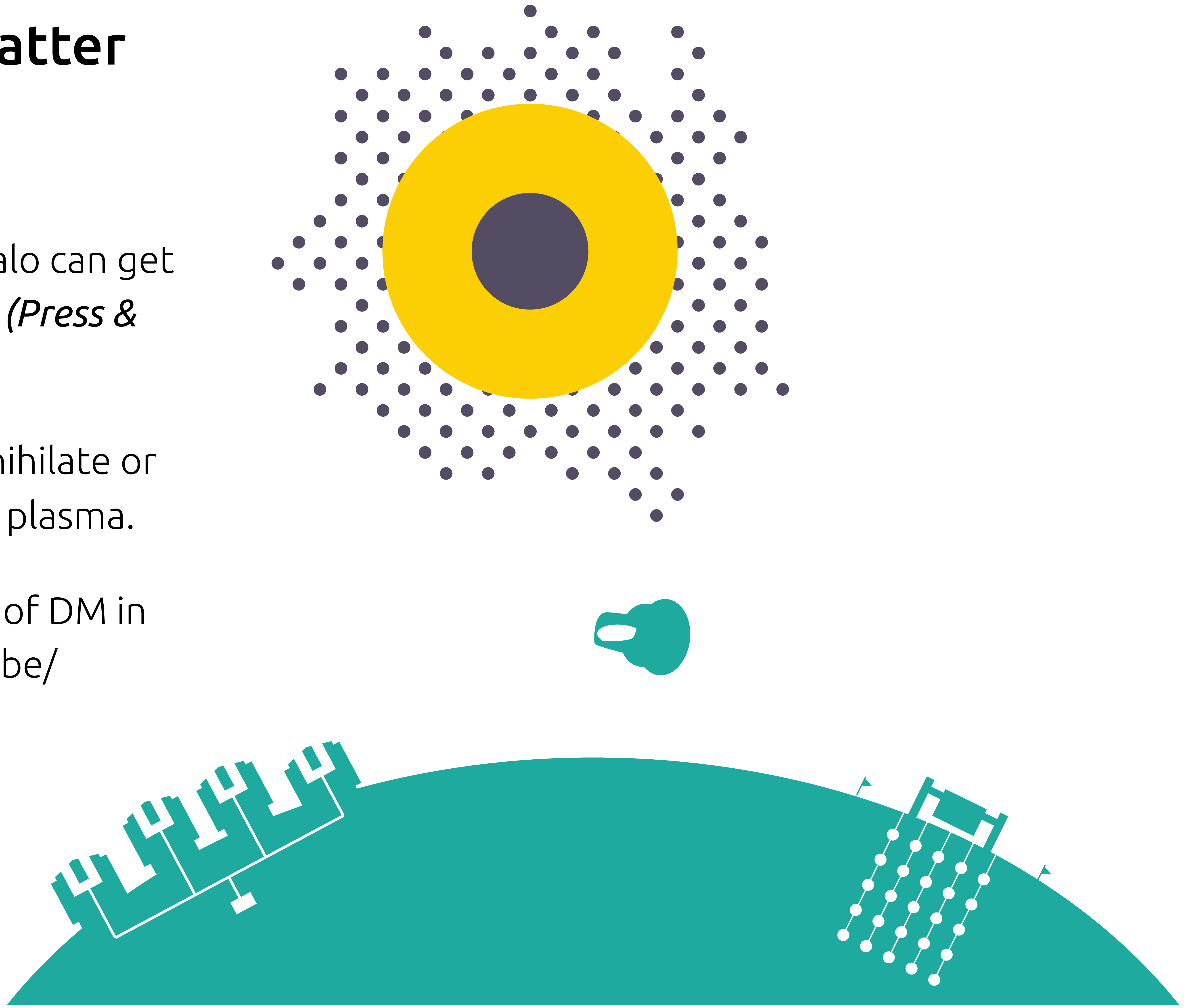
Stars as Dark Matter Laboratories

→ DM particles in the halo can get captured inside the star *(Press & Spergel 1985)*.

→ Captured DM can annihilate or interact within the solar plasma.

→ Effects or signatures of DM in stars can be used to probe/ constrain its properties.



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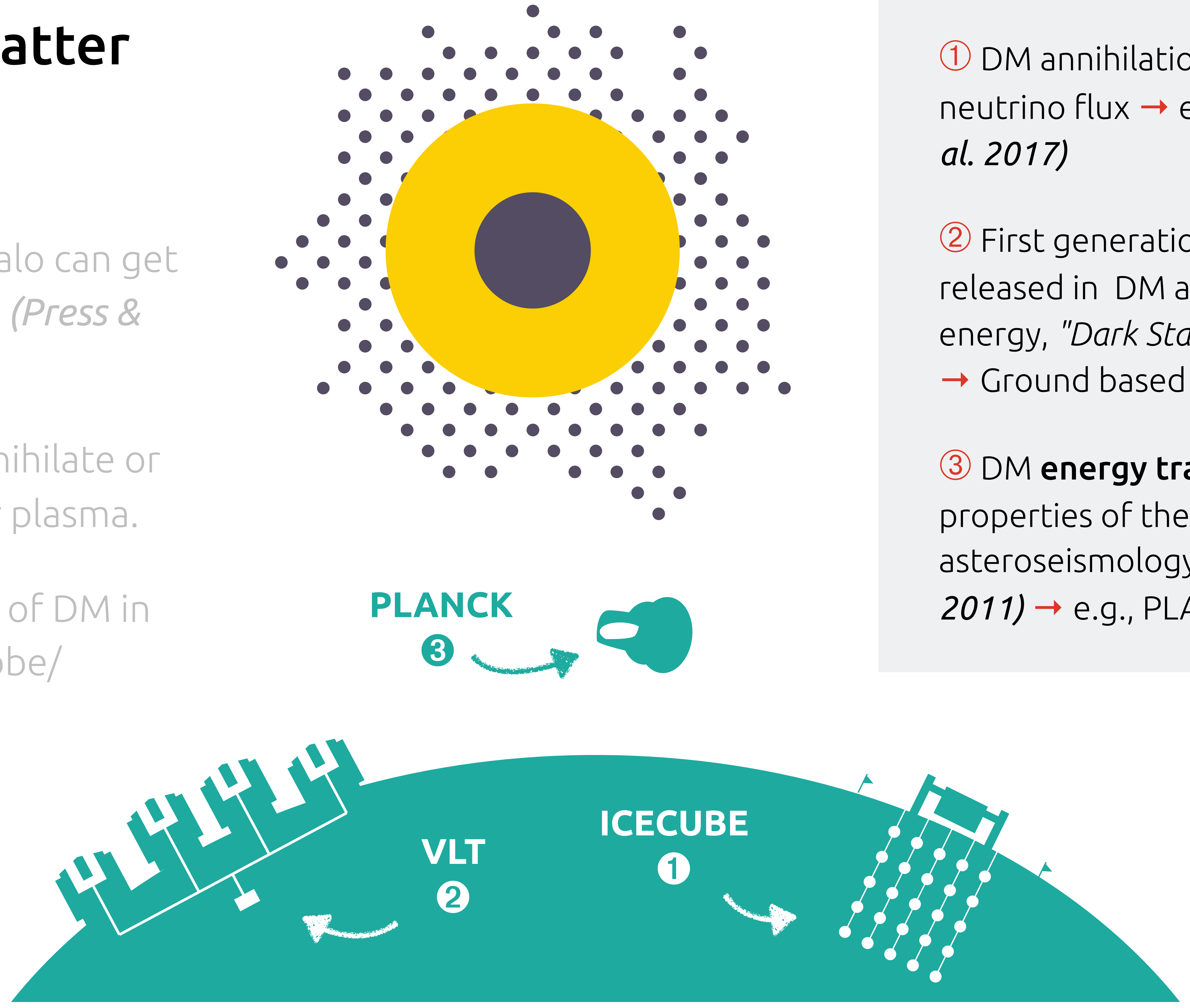

① DM annihilation in the Sun produces a neutrino flux → e.g. ICECUBE *(Aartsen et al. 2017)*

② First generation stars fueled by energy released in DM annihilation can release energy, *"Dark Stars"* ***(Freese et al. 2008)***
→ Ground based telescopes, e.g., VLT.

③ DM **energy transport** can change the properties of the star, e.g., asteroseismology *(Casanellas & Lopes 2011)* → e.g., PLANCK.

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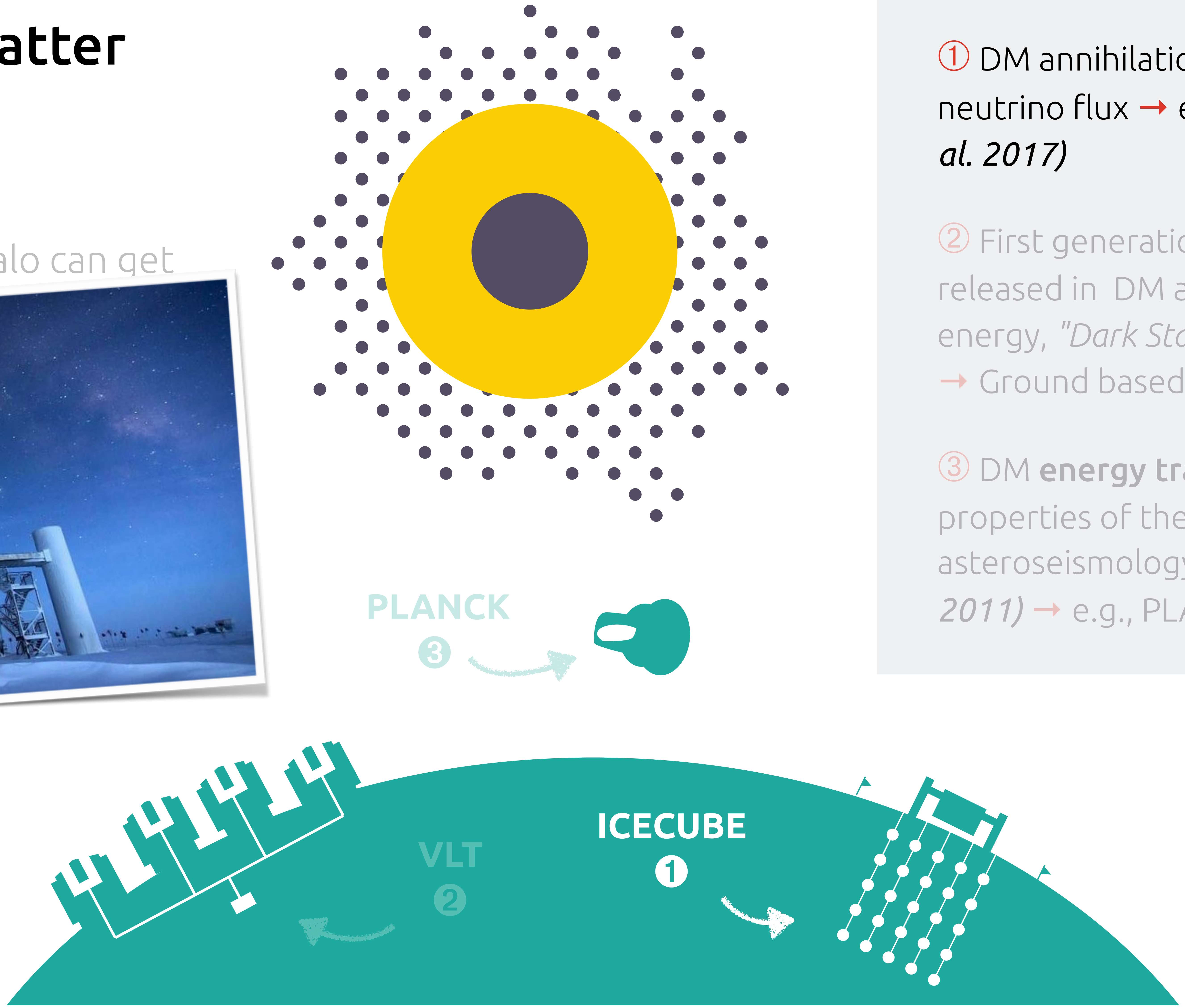

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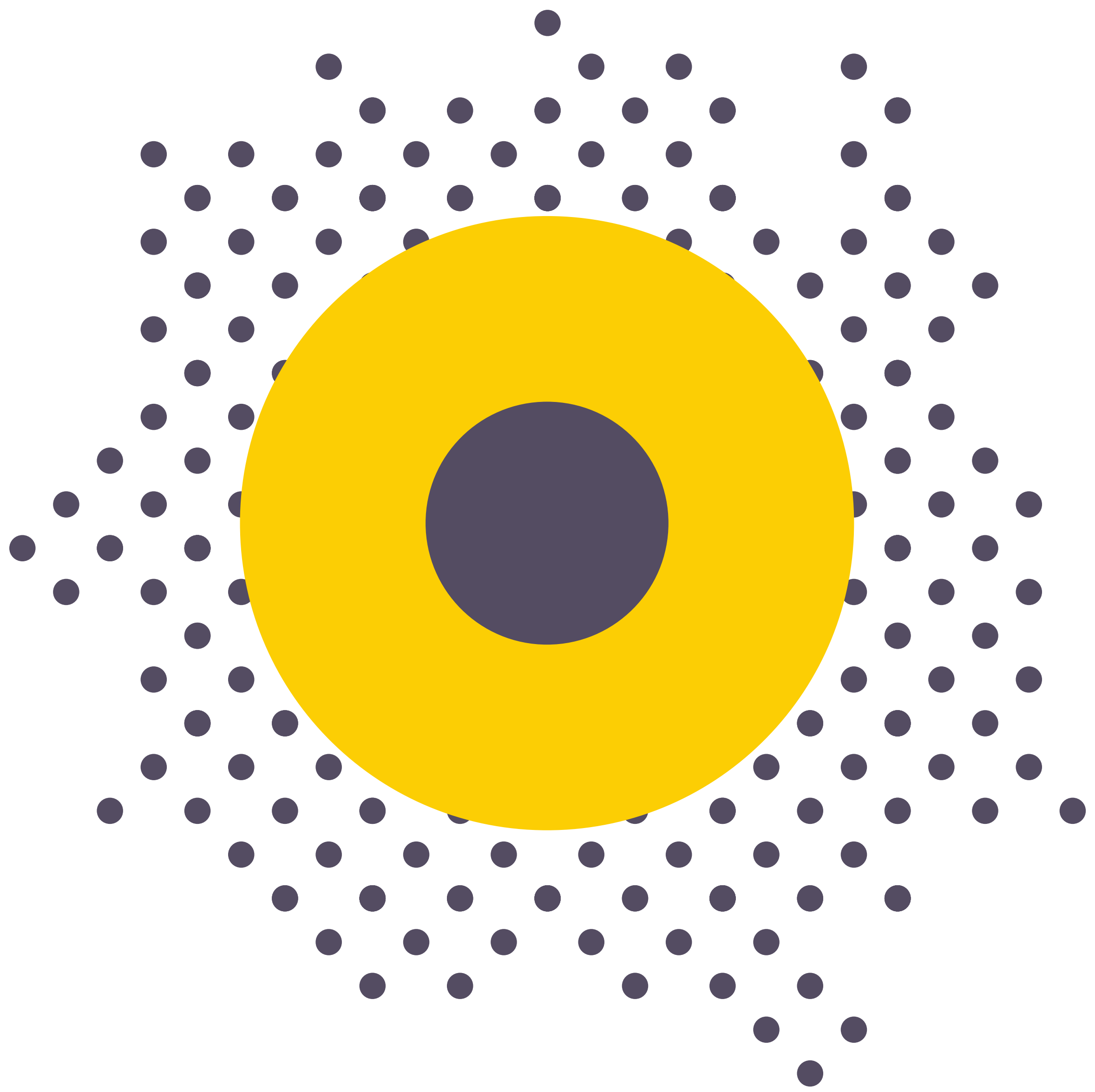

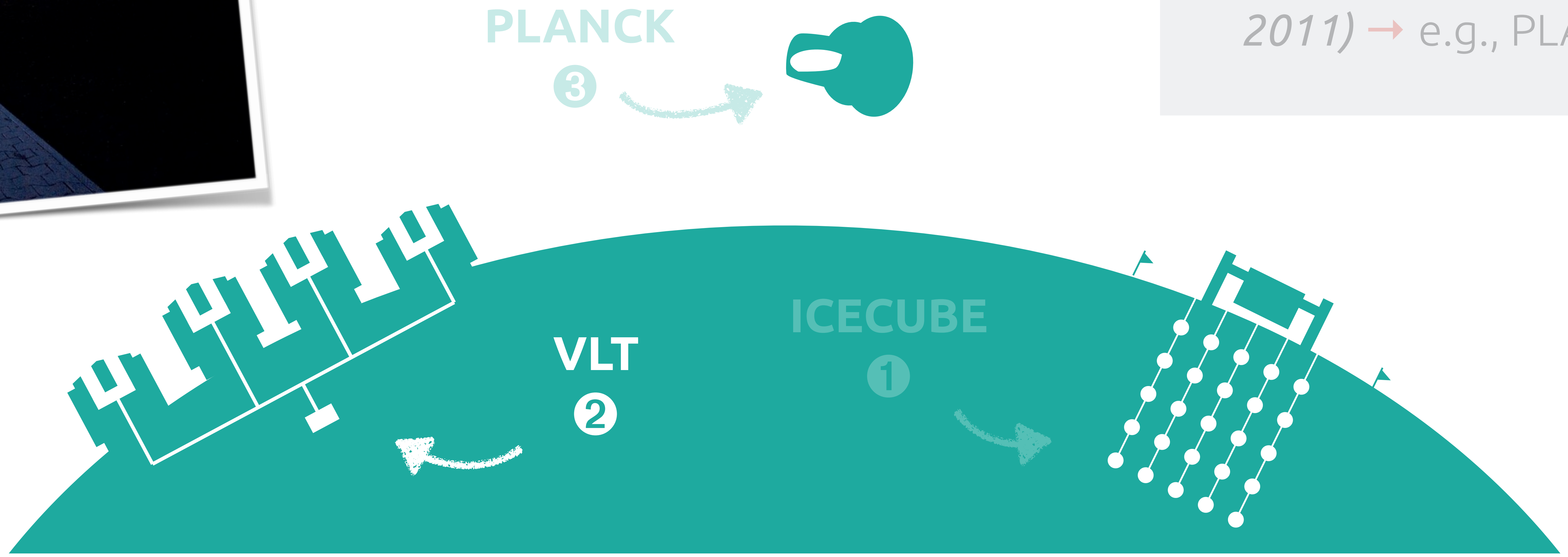

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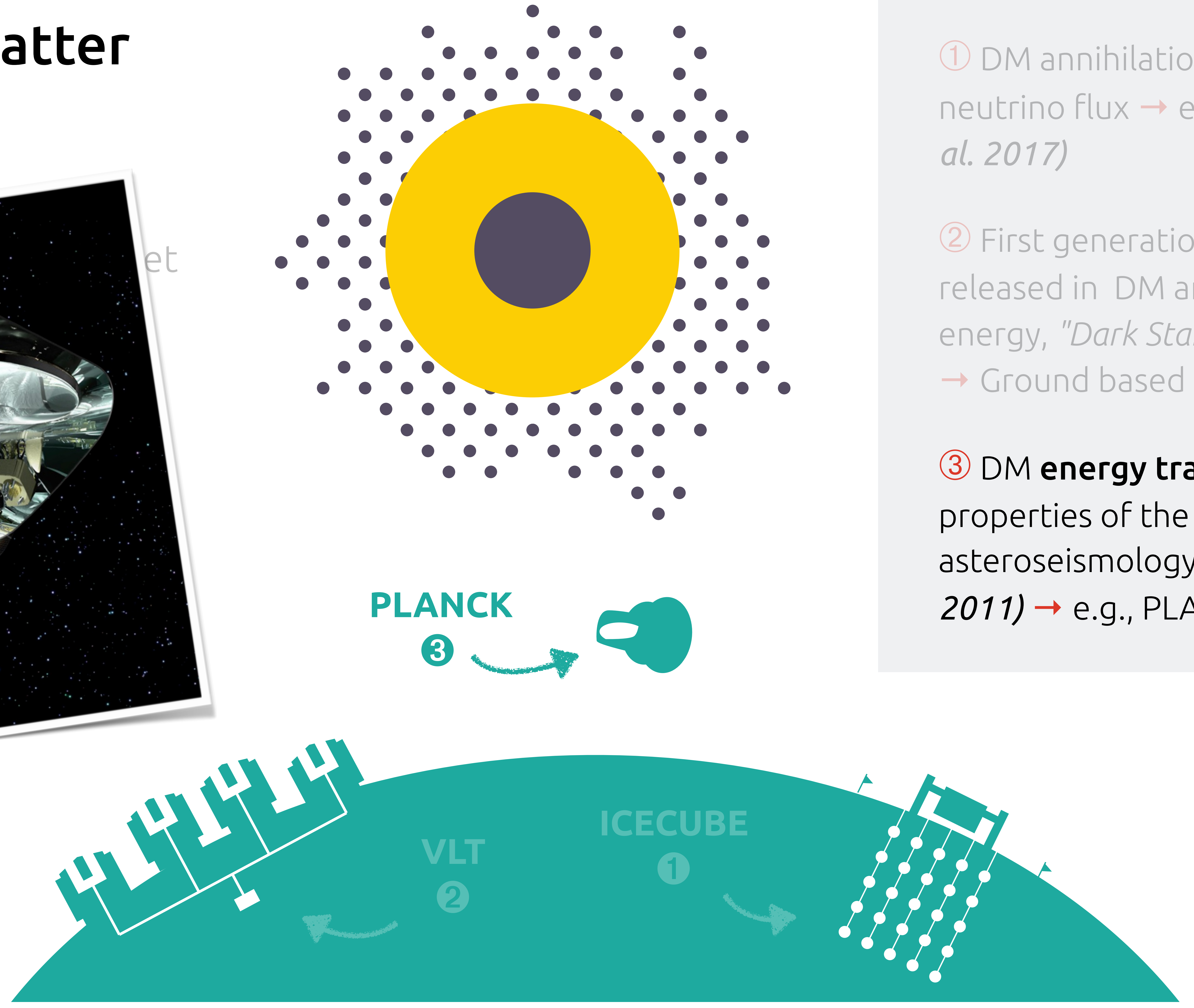

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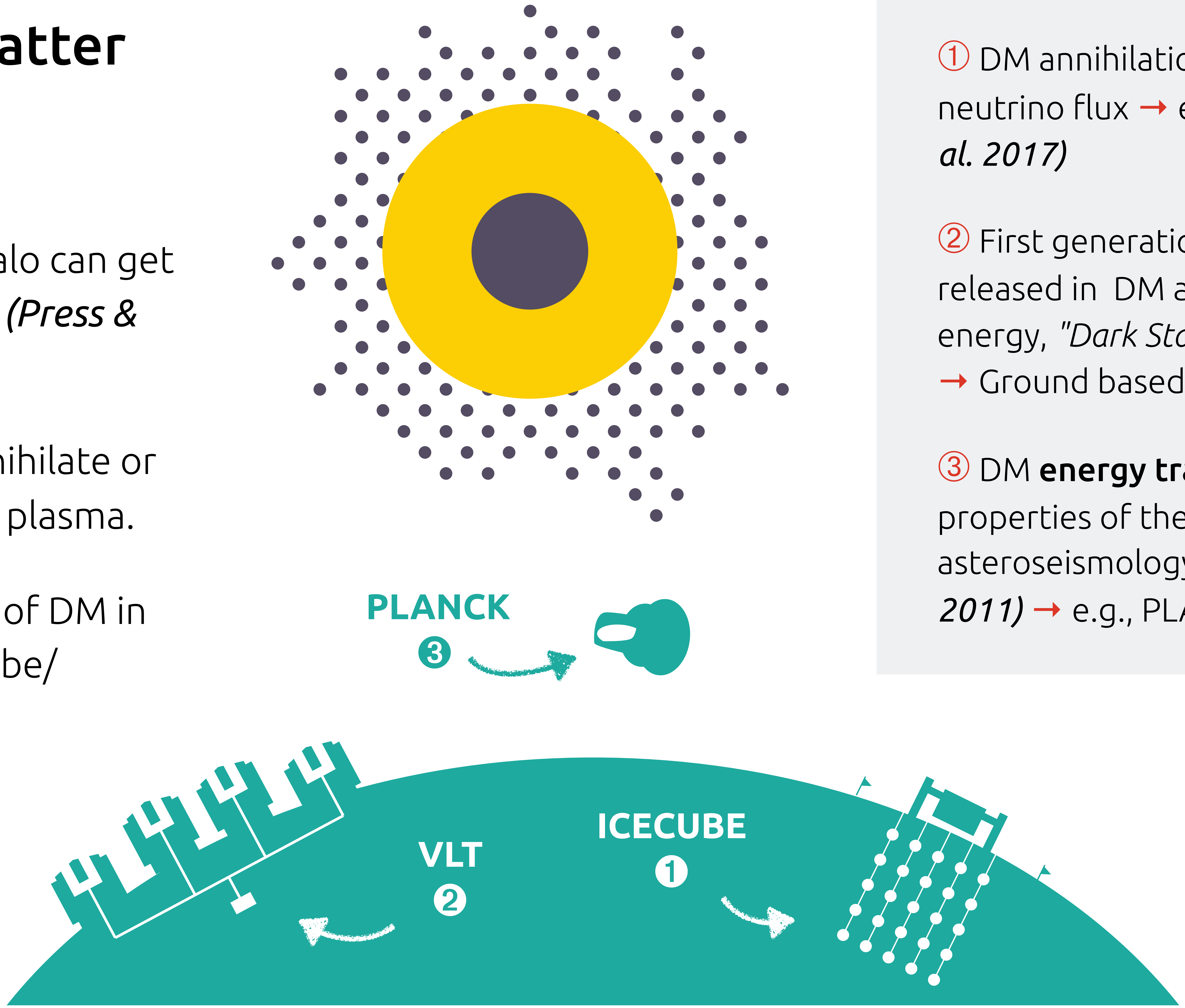

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Dark Matter Capture

→ The number of DM particles in a star is given by:

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}V} = C - AN_\chi^2$$

→ DM capture (per unit volume, per nucleus i) is given by (**Gould 1987**):

$$\frac{\mathrm{d}C_i}{\mathrm{d}V}(r) = \frac{\rho_\chi}{m_\chi}\int_0^{u_{\max,i}(r)} \mathrm{d}u\, \frac{f_u^*(r,u)}{u} w\, \Omega^-_{v_{\rm esc},i}(w)\ ,$$

→ Maximum capture velocity (**Choi et al. 2014**):

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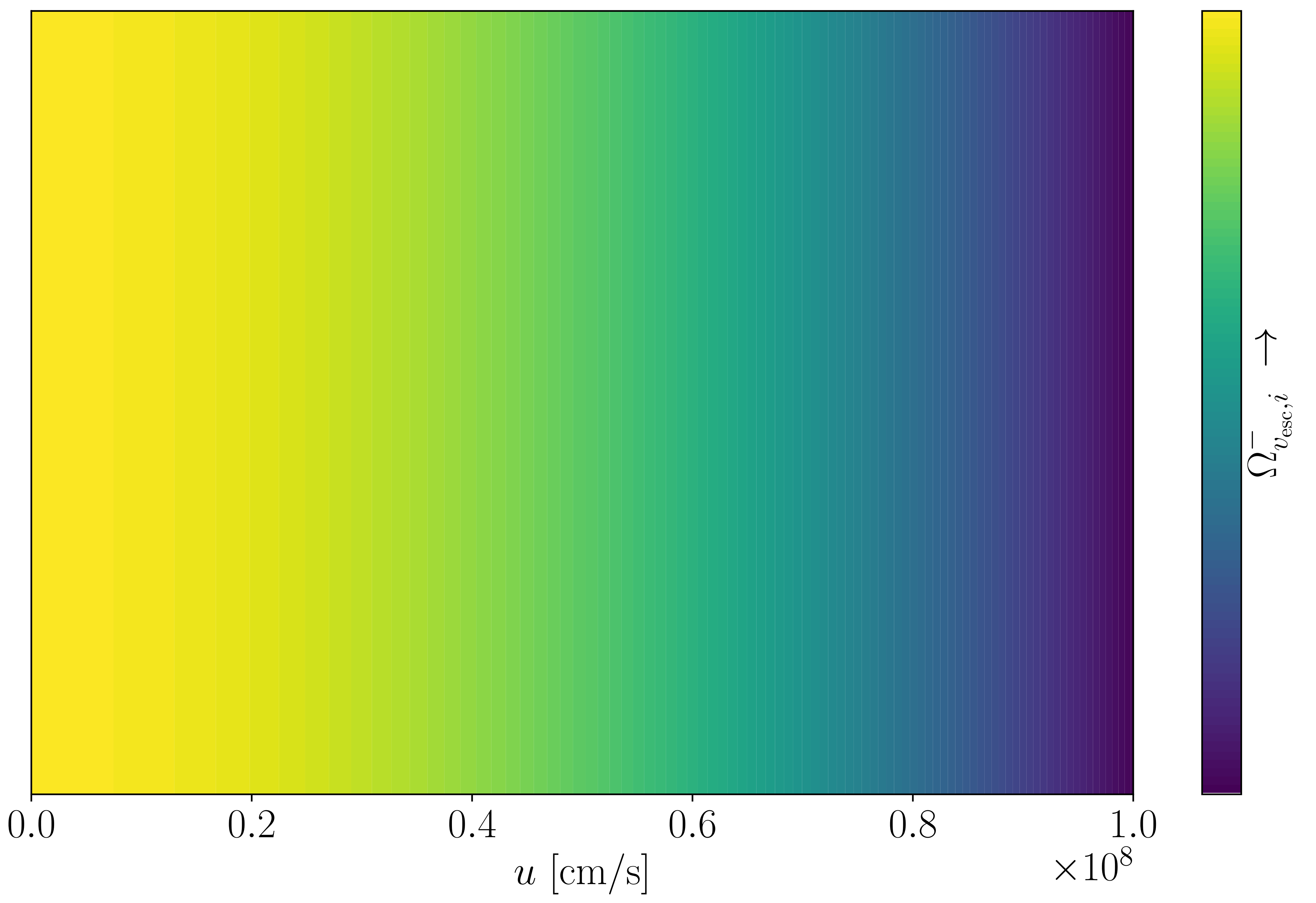

FIG. IIIa Capture scattering rate (arbitrary units) as a function of the DM particle velocity.

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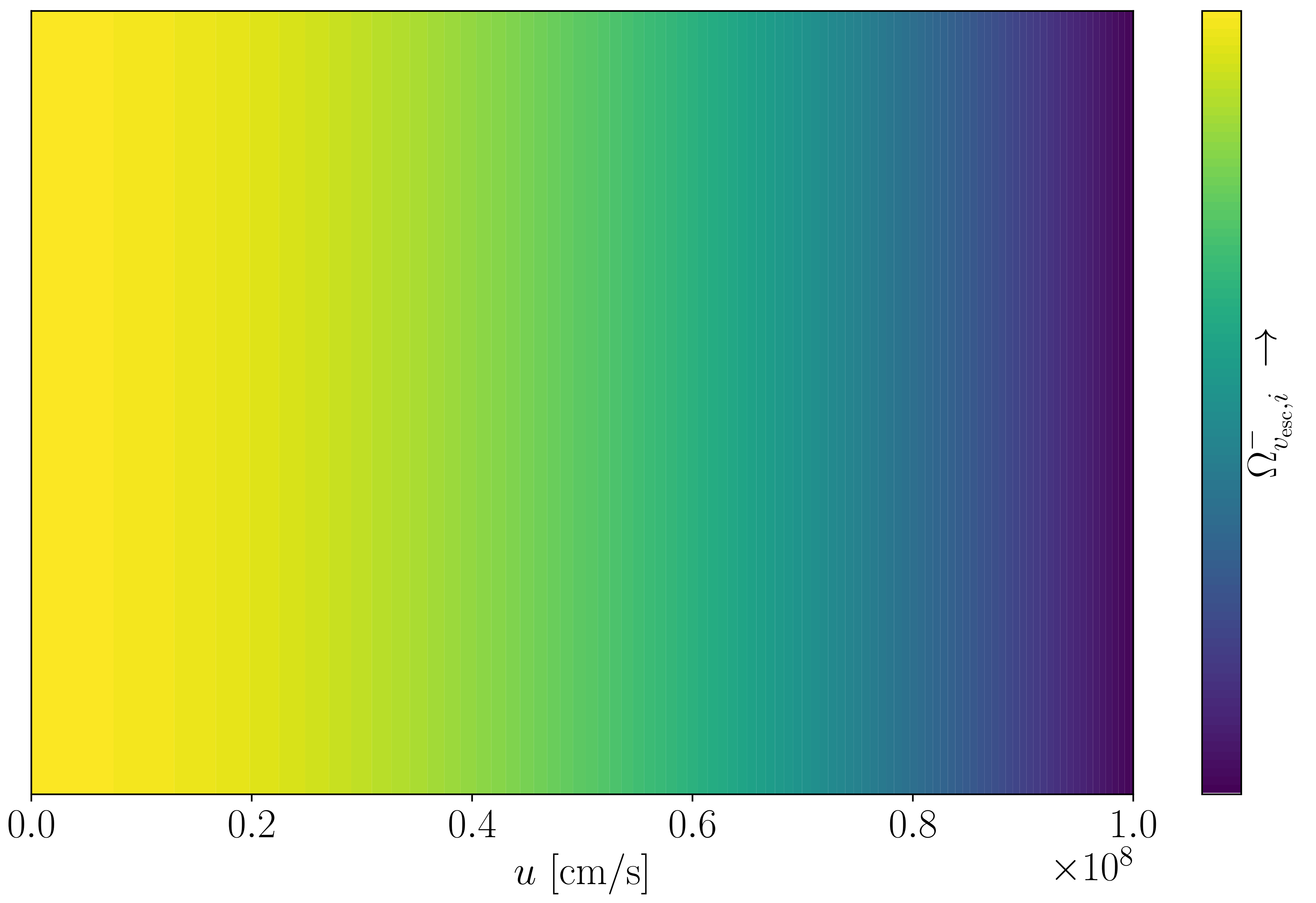

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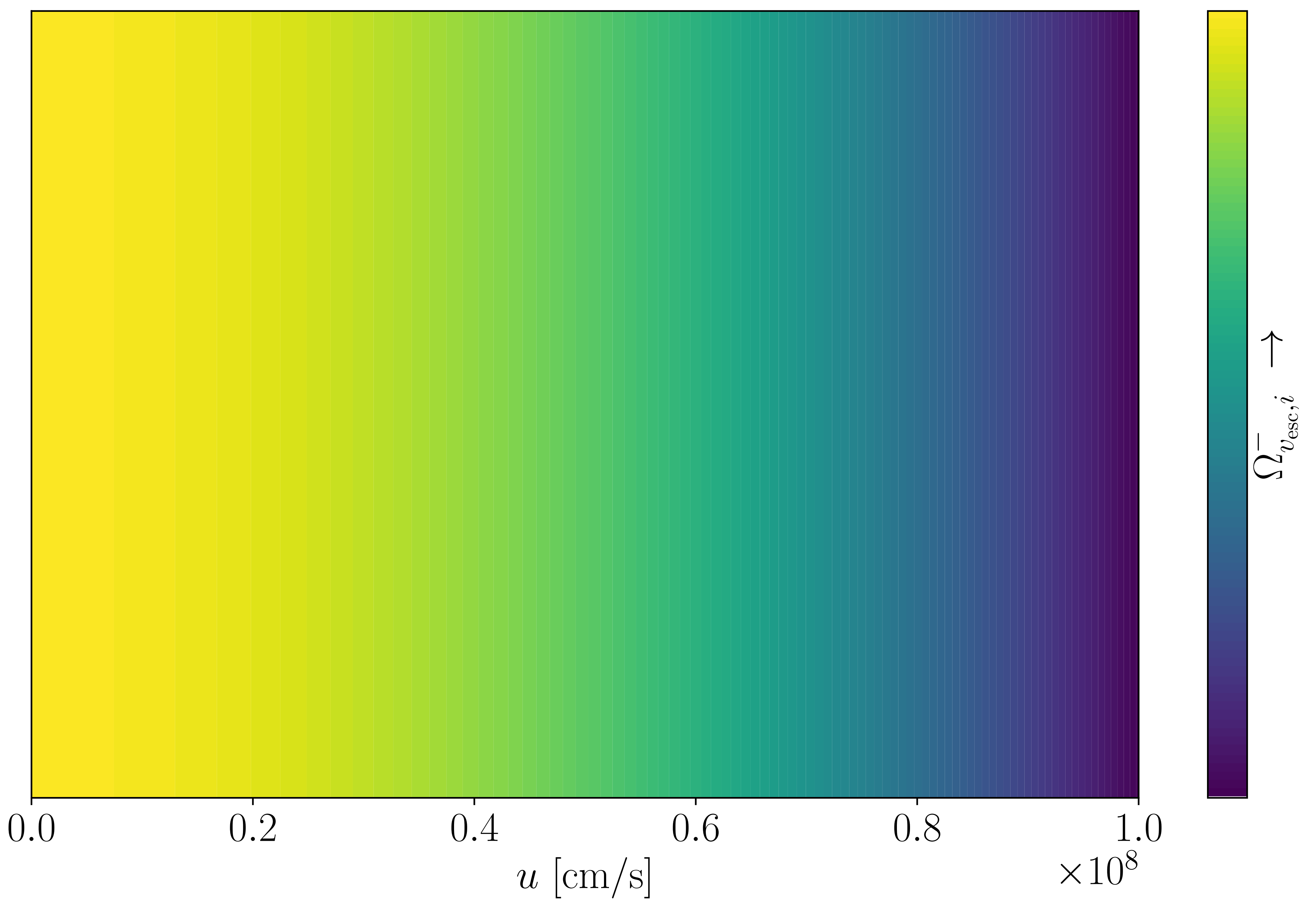

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$$f(u)_{\rm SHM} = \frac{u}{\sqrt{\pi} v_0 v_*}\left[\exp\left(-\frac{(u-v_*)^2)}{v_0^2}\right) - \exp\left(-\frac{(u+v_*)^2)}{v_0^2}\right)\right]$$

$$v_0 \approx v_* \approx 220 \text{ km/s}$$

⊗ Not consistent with Galaxy constraints;

⊗ Departure from N-body simulations;

⊗ Estimation only valid for the Sun (~ 8 kpc).

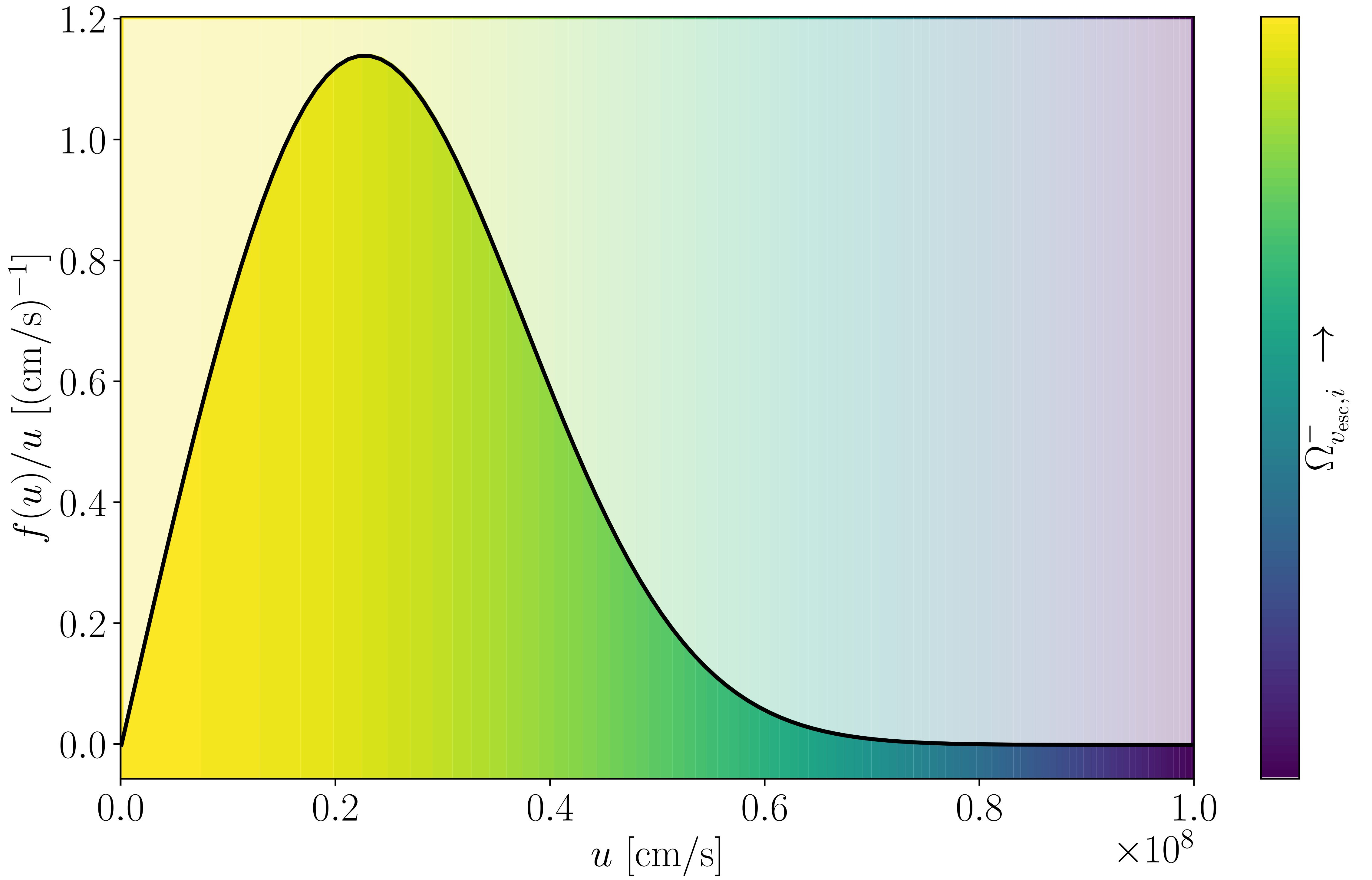

FIG. IIIb The domain of DM particles accessible to capture for a the SHM and a more realistic VDF (illustrative).

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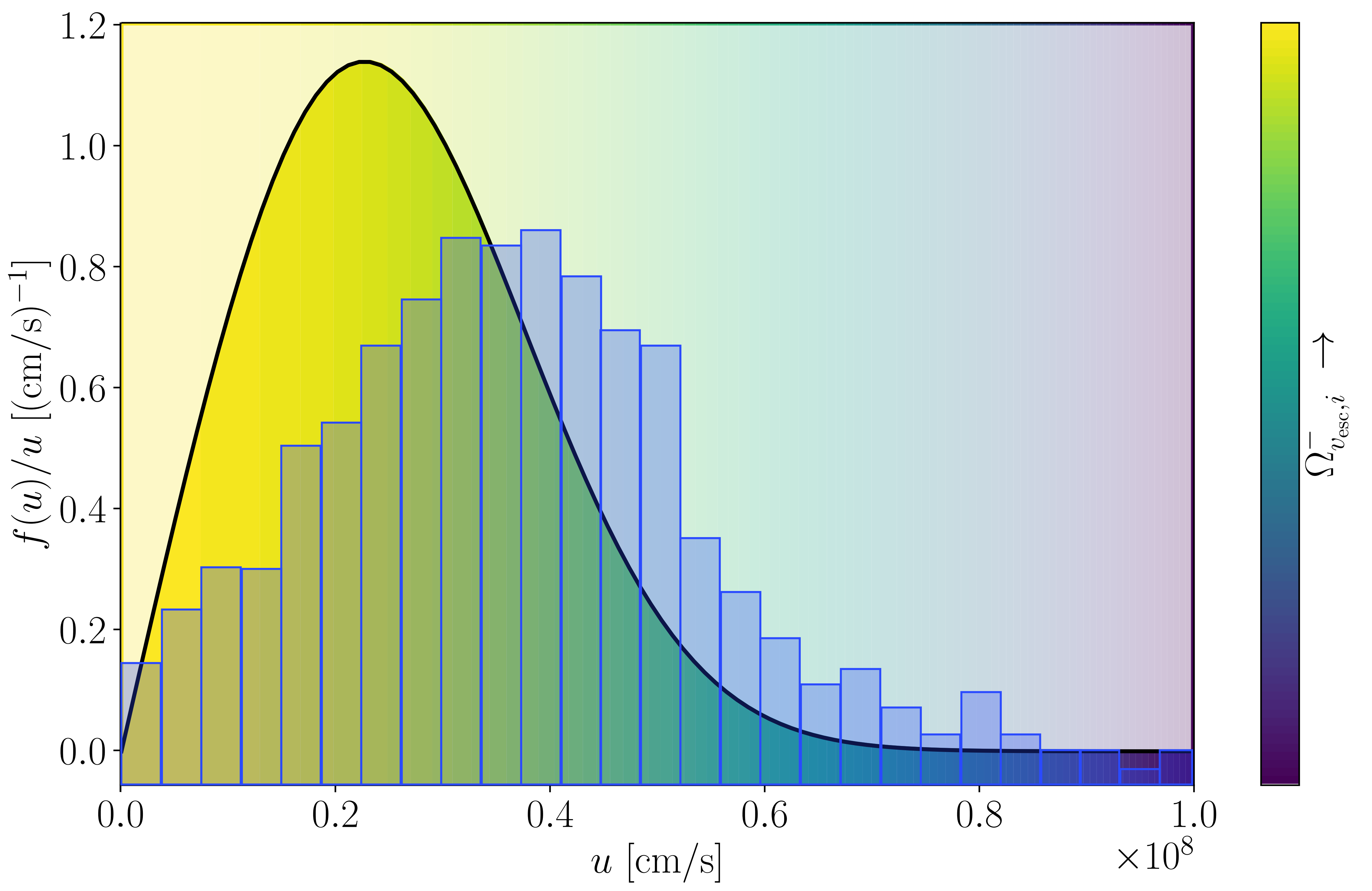

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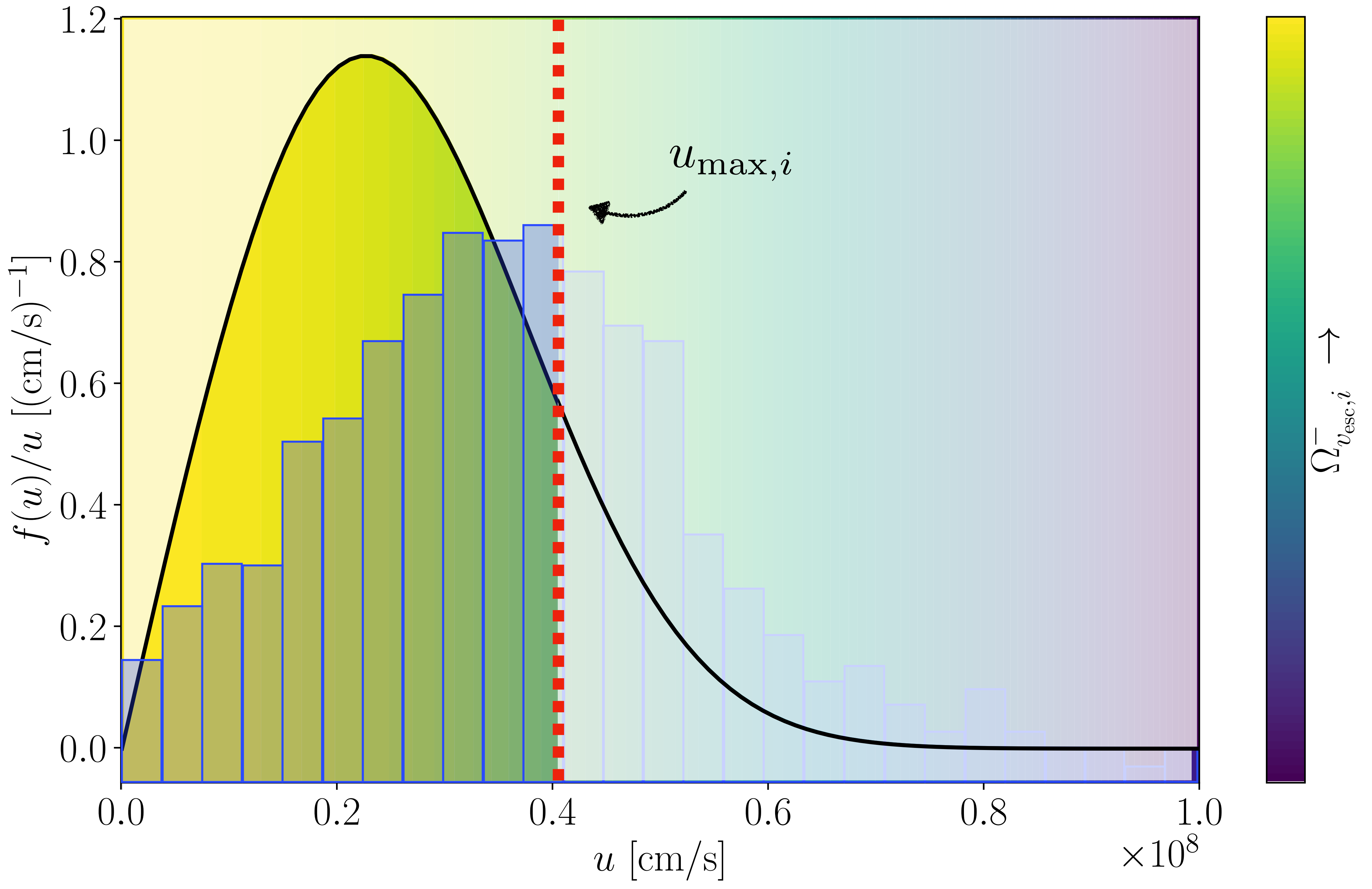

FIG. IIId The domain of DM particles accessible to capture for a the SHM and a more realistic VDF (illustrative).

Eddington Inversion

→ Jean's theorem for a colisionless Boltzmann equation *(e.g., Binney et Tremaine 2008)*:

$$f\left(\vec{r},\vec{v}\right) \equiv f\left(\mathcal{E},L\right), \;\; \mathcal{E} = \Psi(r) - \frac{v^2}{2}$$

→ Eddington formula *(Eddington 1916)*:

$$f\left(\mathcal{E}\right) = \frac{1}{\sqrt{8}\pi^2}\frac{\mathrm{d}}{\mathrm{d}\mathcal{E}}\int_0^{\mathcal{E}}\frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{\mathrm{d}\rho}{\mathrm{d}\Psi}$$

→ Relaxation of isotropy assumption *(Wojtak et al. 2018)*:

$$f\left(\mathcal{E},L\right) = G(\mathcal{E})\left(1+\frac{L^2}{2L_0^2}\right)^{-\beta_\infty+\beta_0} L^{-2\beta_0}$$

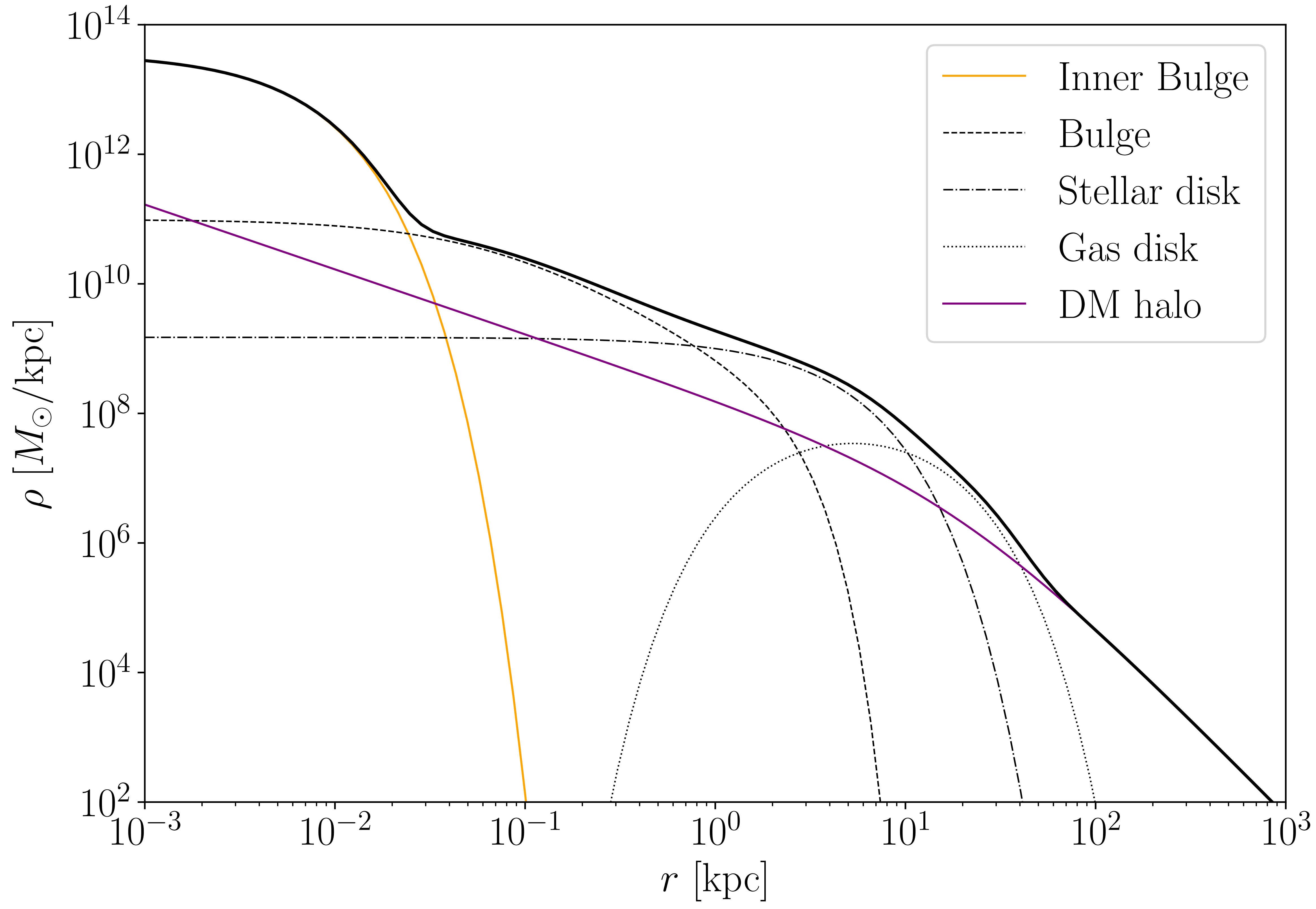

FIG. IV Mass model of the Milky way. Parameters from *McMillan 2017*, complemented by *Sofue 2013* at parsec scale.

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Eddington VDF's

→ Mass model from ***McMillan 2017***, complemented by ***Sofue 2013*** (pc scale).

→ Generalized NFW DM profile ***(Zhao 1996)***:

$$\rho_{\rm DM}(r) = \rho_{\rm s}\left(\frac{r}{r_s}\right)^{-\gamma}\left(1+\left(\frac{r}{r_s}\right)\right)^{\gamma-3}$$

$$\gamma = 0.25,\ \ 1.0\ (\mathrm{NFW})$$

→ Isotropic and Anisotropic cases ***(Wojtak et al. 2018)***:

$$f_L \equiv f_L\left(L_0, \beta_0, \beta_\infty\right)$$

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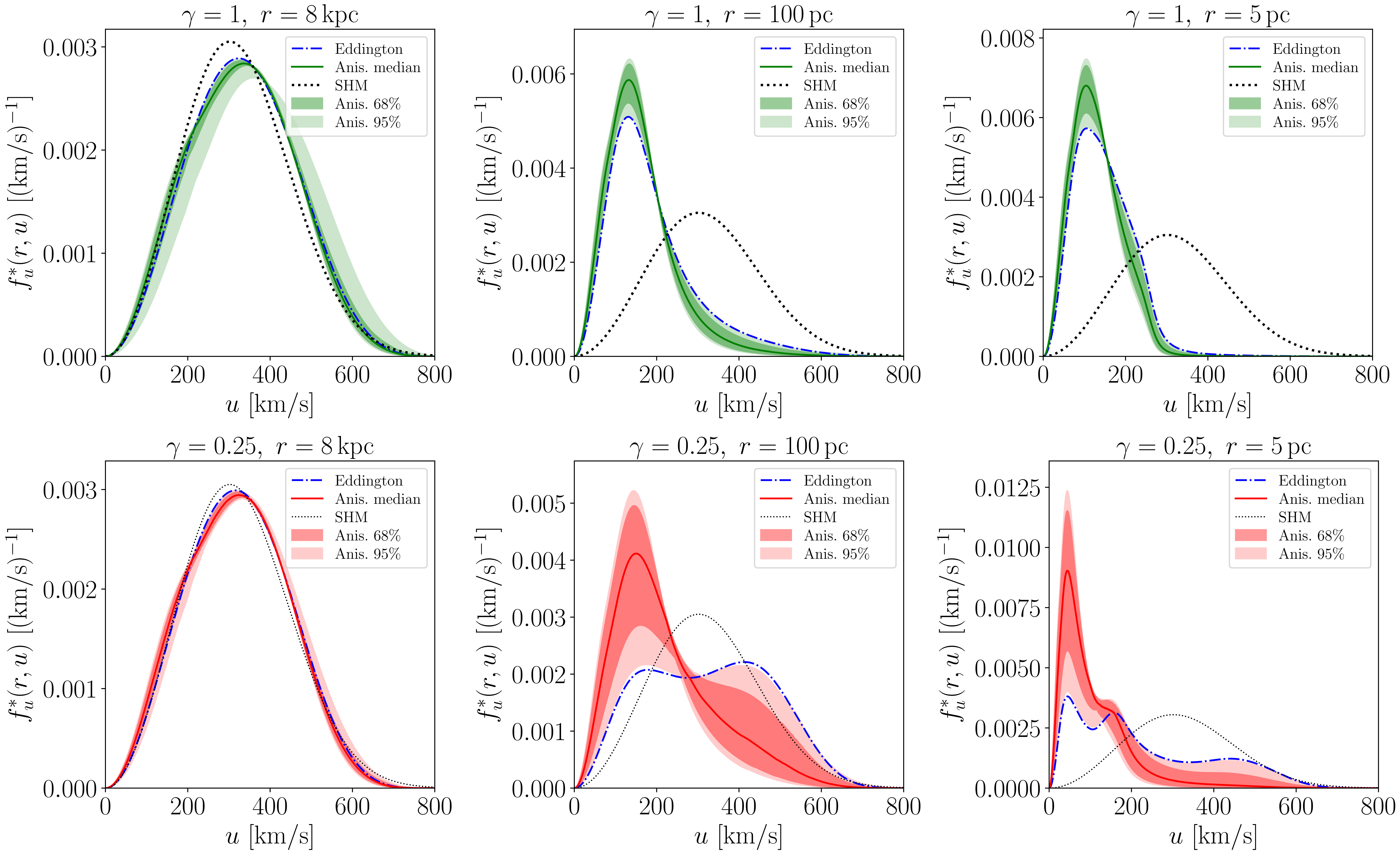

FIG. V VDF's in the SHM and Eddington inversion (isotropic and confidence intervals for anisotropic) at 3 different galactic radii (decreasing left to right). **Top**: VDF for γ = 1.0; **Bottom**: VDF for γ=0.25.

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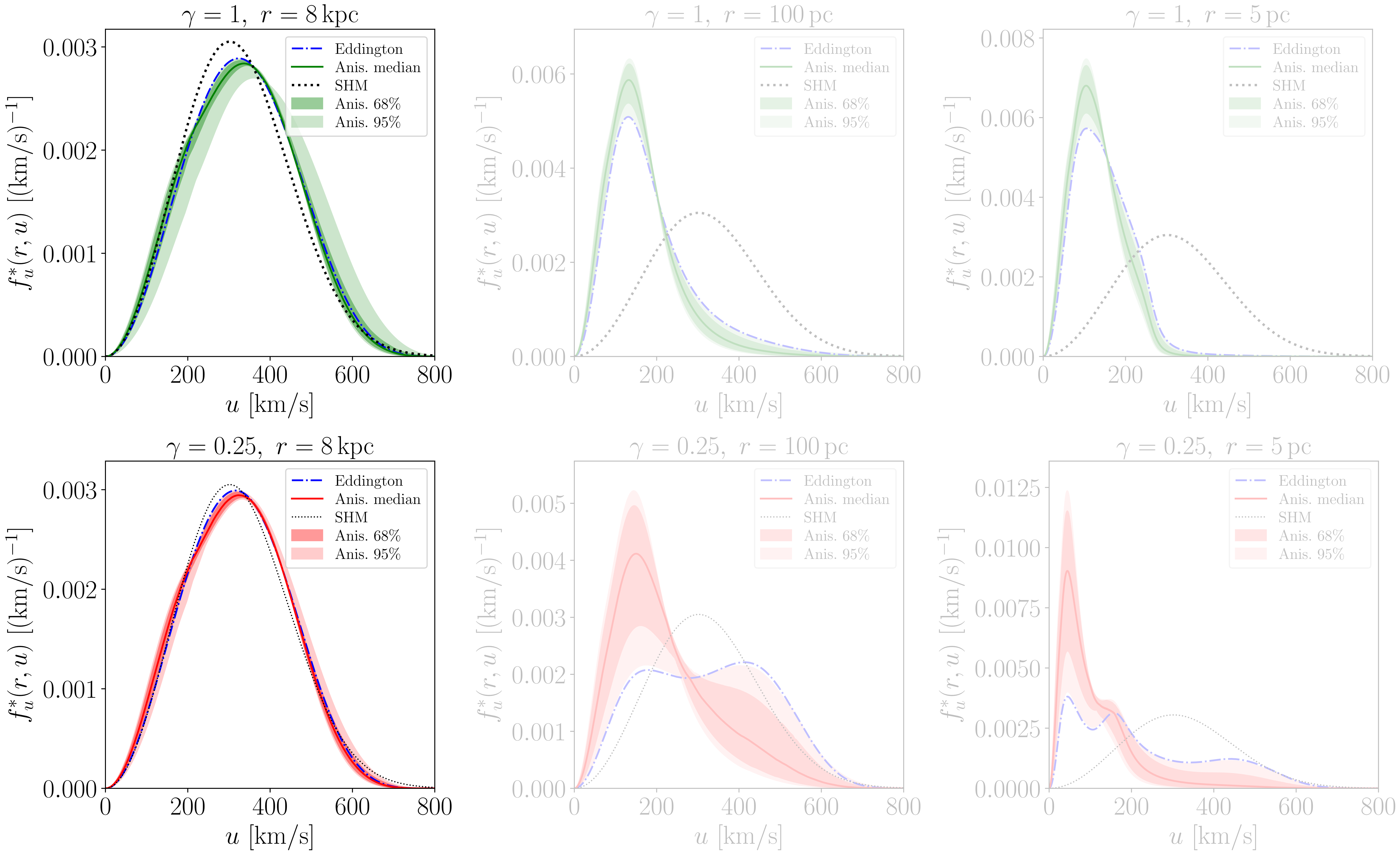

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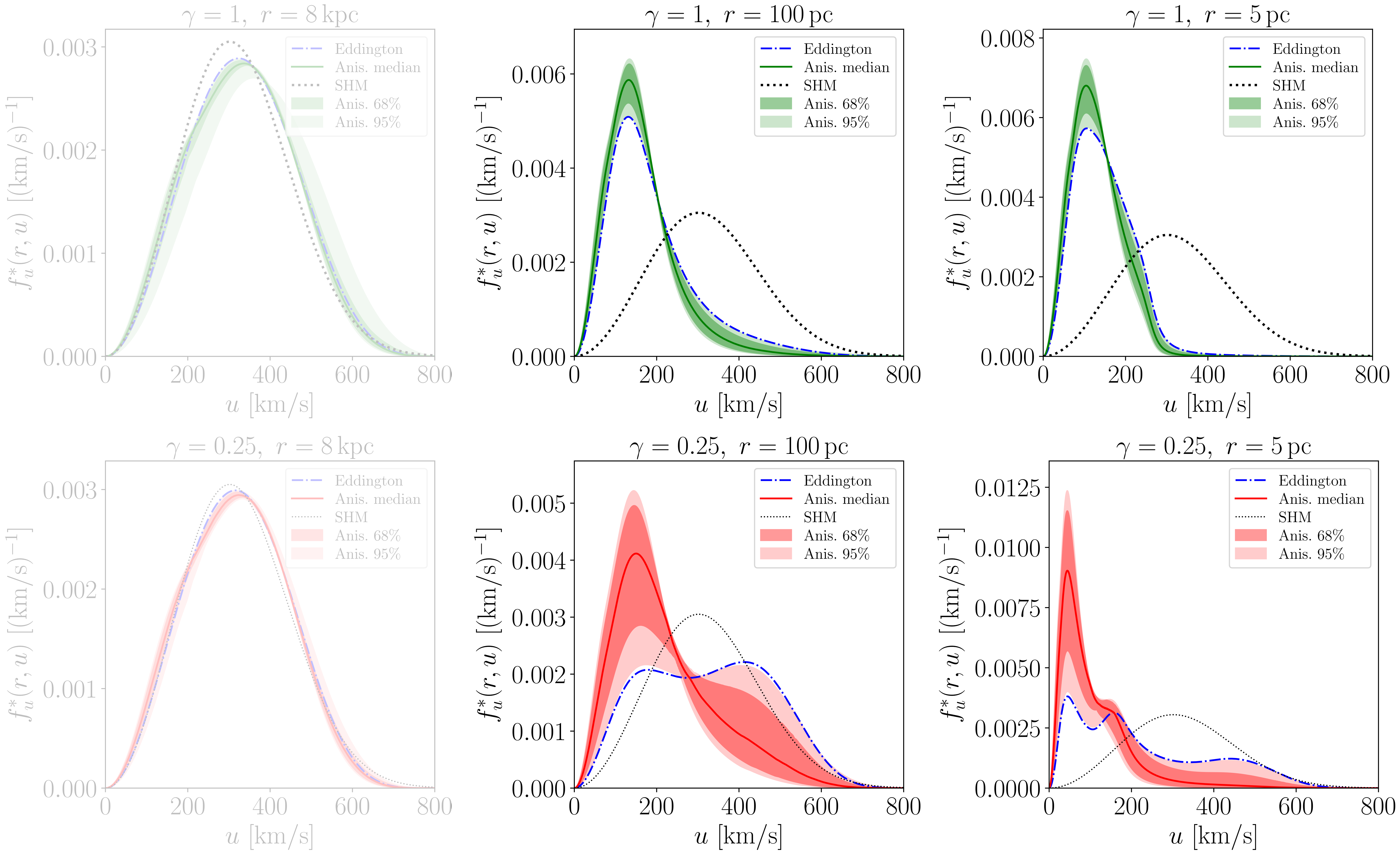

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DM Capture in the Sun

→ Capture rate in the Sun computed with the SHM and Eddington VDF's.

→ **Isotropic**: deviation from the SHM is small (<10%).

→ **Anisotropic**: deviations can go from -40% to +40%.

→ Difference in m_x is due to the the maximum velocity in the capture integral.

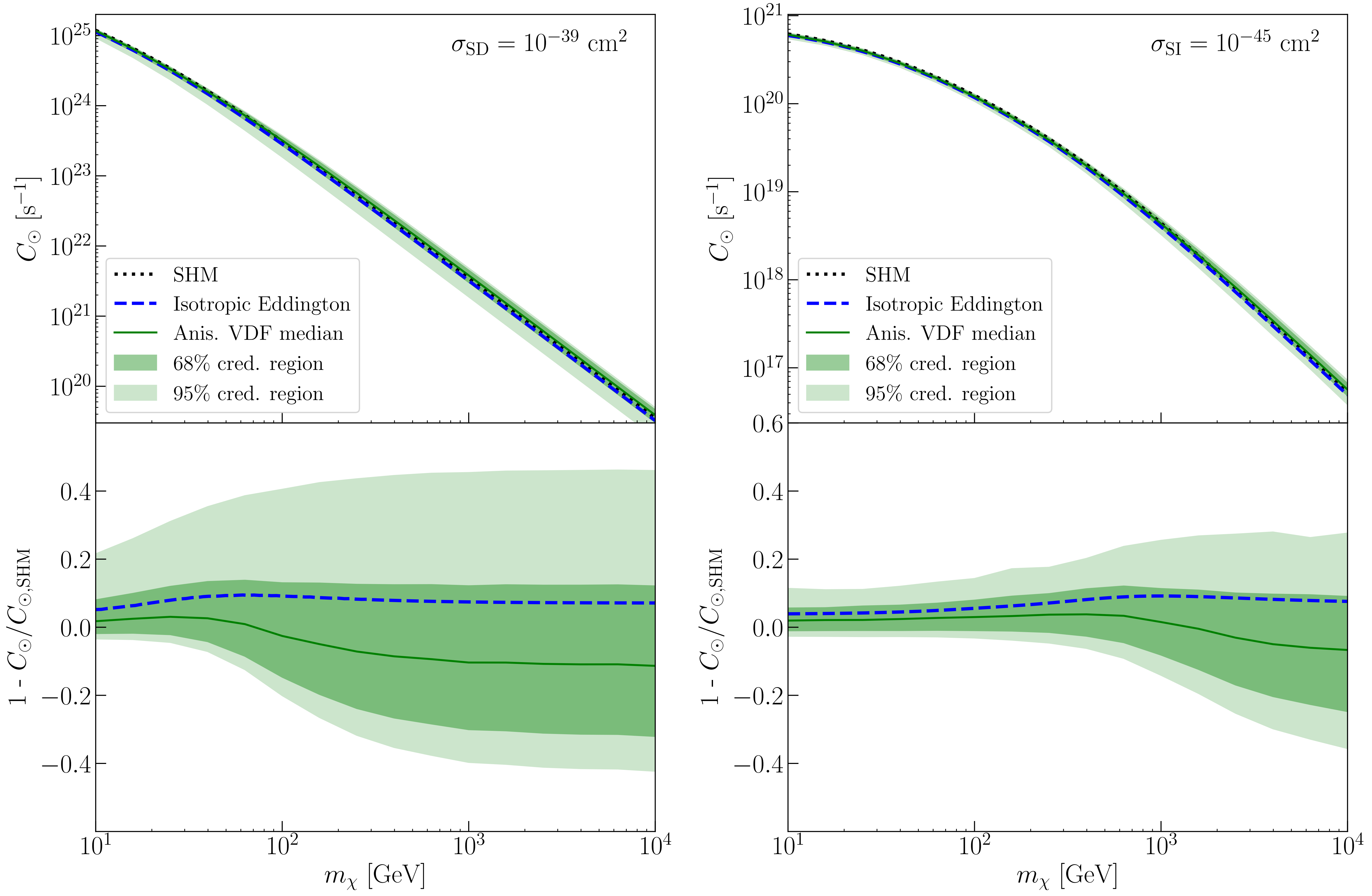
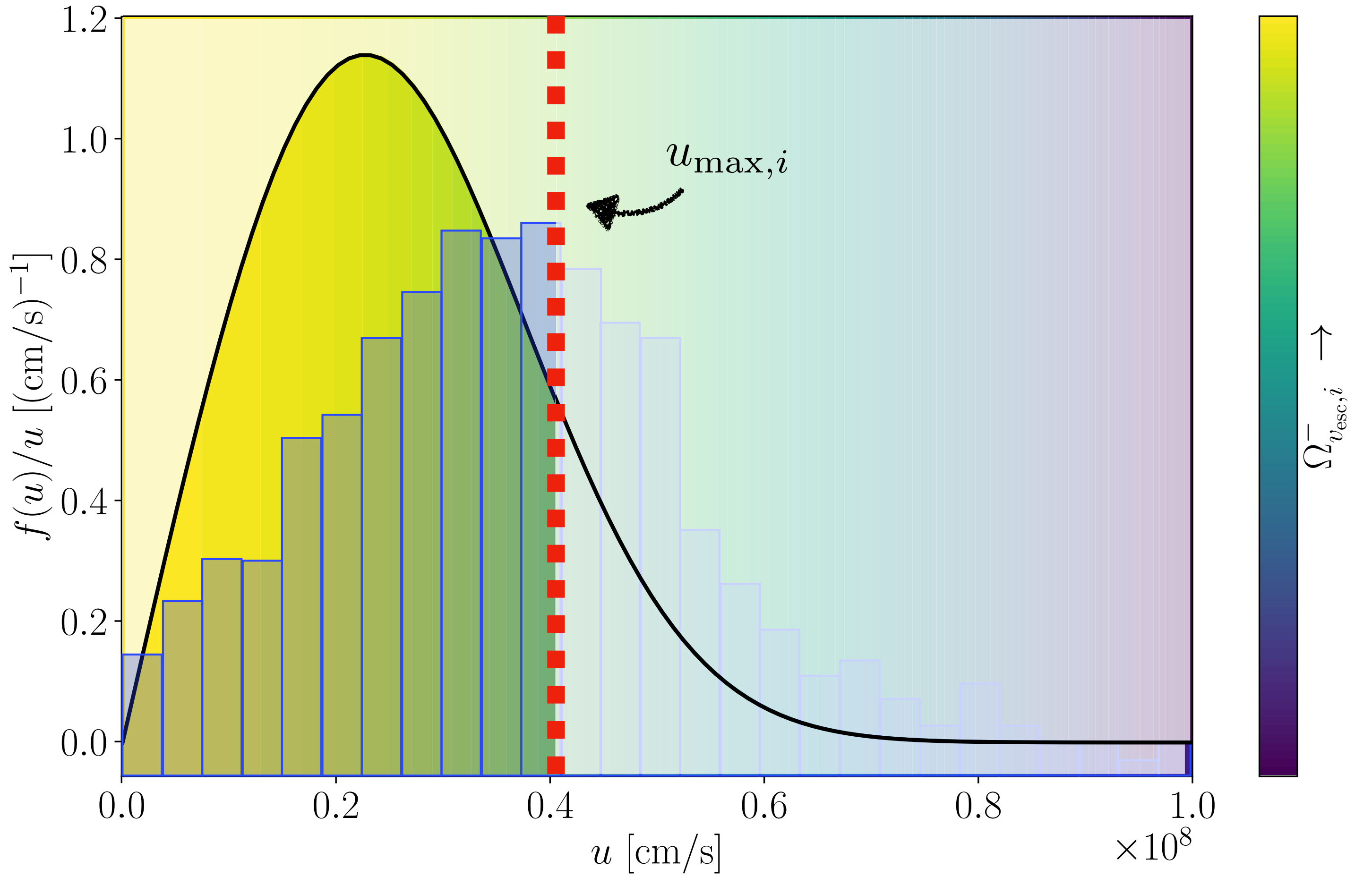


FIG. VI **Top:** SD (left) and SI (right) capture rate in the Sun for the SHM and Eddington VDF's (isotropic and anisotropic). **Bottom**: Deviation from the SHM.

DM Capture in the Sun



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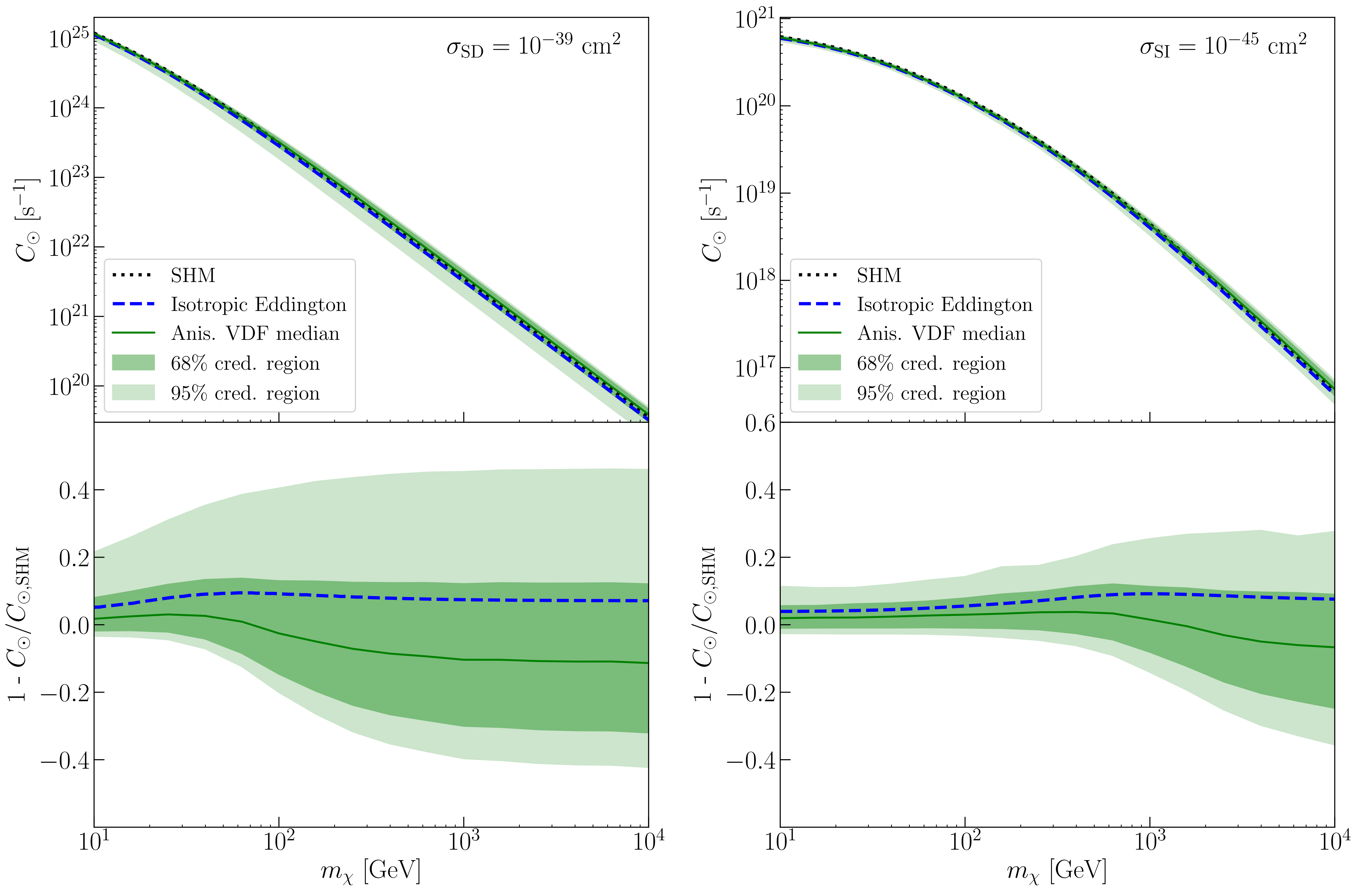

FIG. VI Top: SD (left) and SI (right) capture rate in the Sun for the SHM and Eddington VDF's (isotropic and anisotropic). **Bottom**: Deviation from the SHM.

Impact on DM limits (neutrino production in the Sun)

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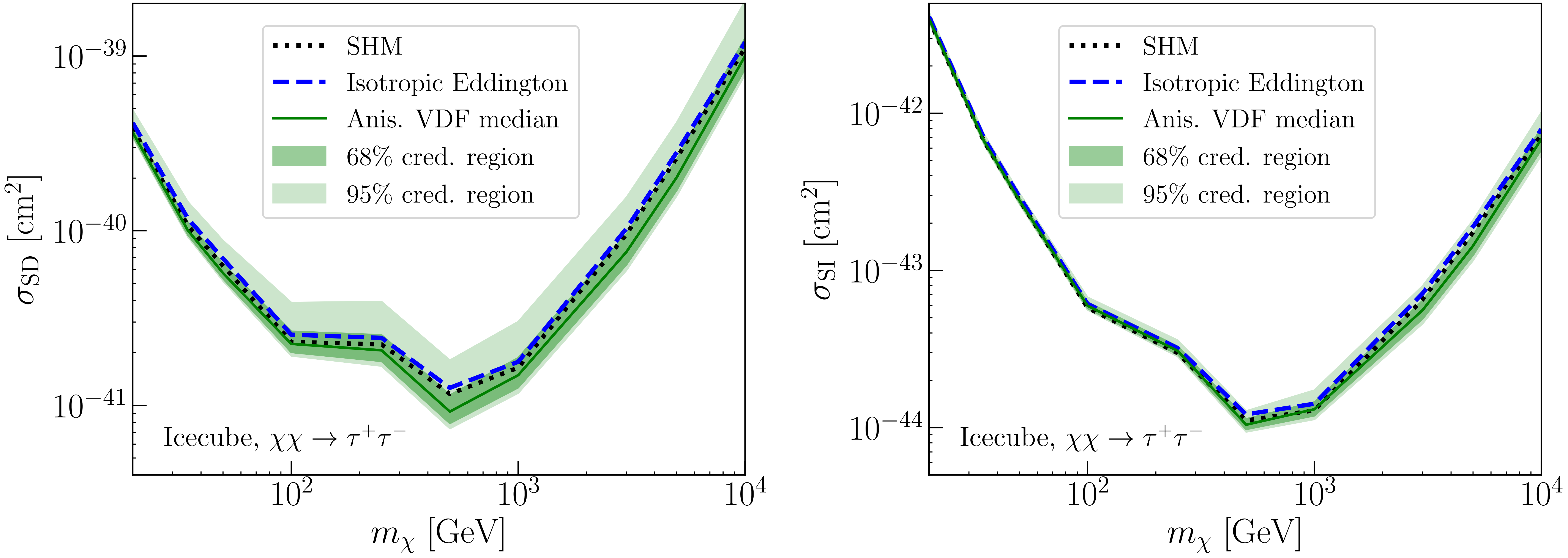

FIG. VII SD (left) and SI (right) limits on the DM-nucleon scattering rate for the SHM and Eddington VDF's (isotropic and anisotropic). The limits on the capture rate where obtained from Aartsen et al. (2017).

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DM Capture in the Milky Way

→ Capture rate (solar-like Star) as a function of the galactic radius (**γ = 1.0** and **γ = 0.25**).

→ Deviation from the SHM increases with decreasing r.

→ SHM underestimates the Capture near the center of the MW.

→ Capture deviation increases with mass due to u_{max}.

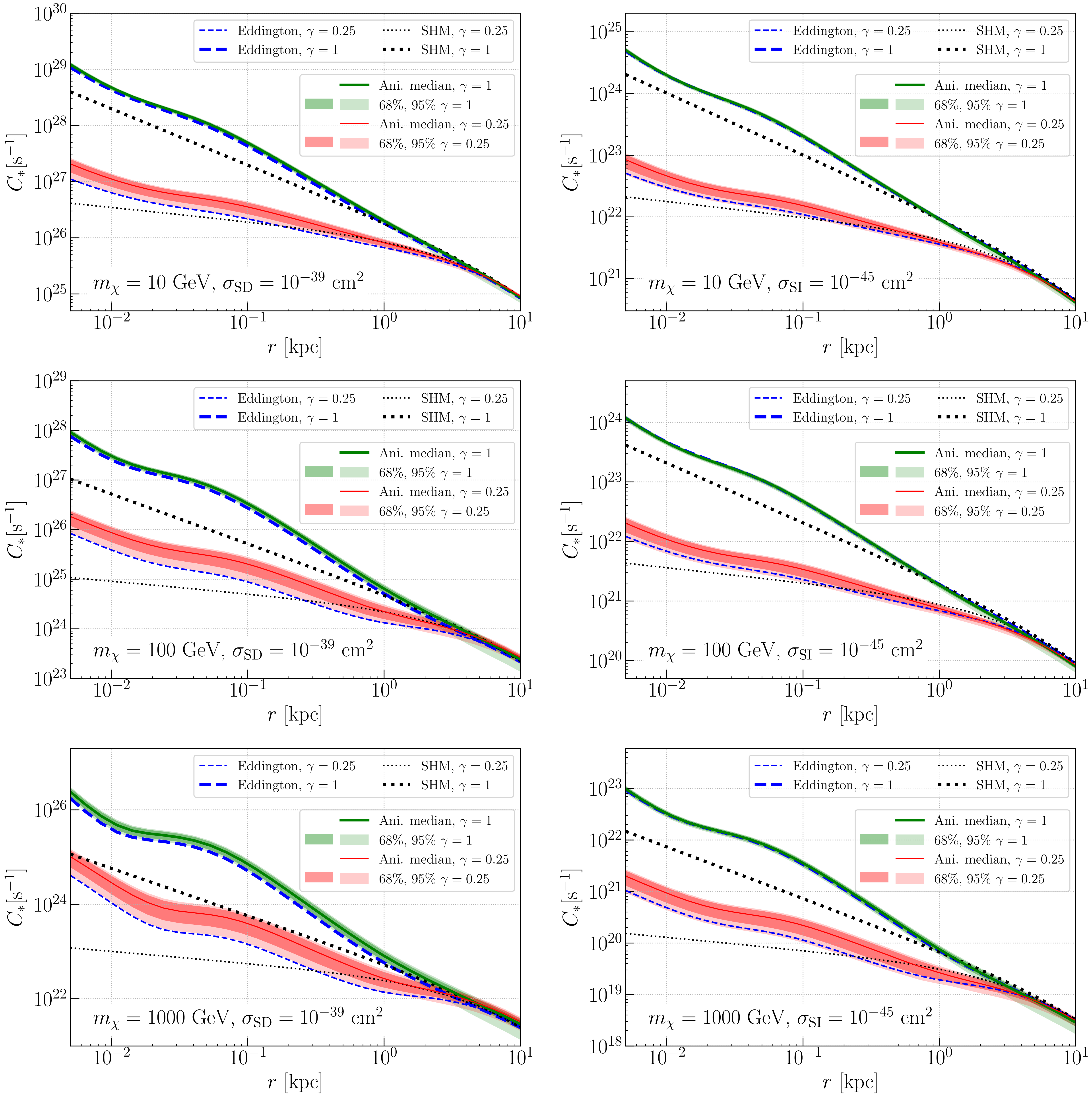

FIG. VIII SD (left) and SI (right) capture rate as a function of the galactic radius for 3 benchmark mass values (increasing from top to bottom).

Impact on DM limits (Neutron star stability)

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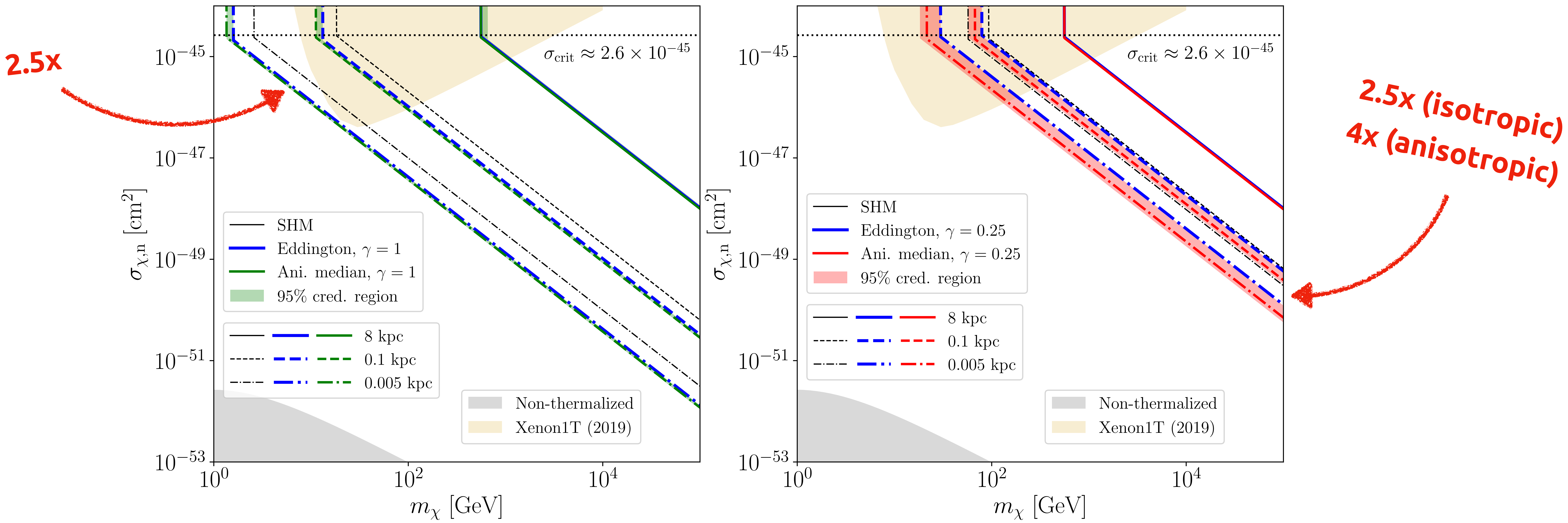


FIG. IX SD (left) and SI (right) limits on the DM-nucleon scattering rate for the SHM and Eddington VDF's (isotropic and anisotropic). The neutron stability criteria were obtained for a typical neutron star with M = 1 M⊙ and R = 10 km *(Garani et al. 2019)*.

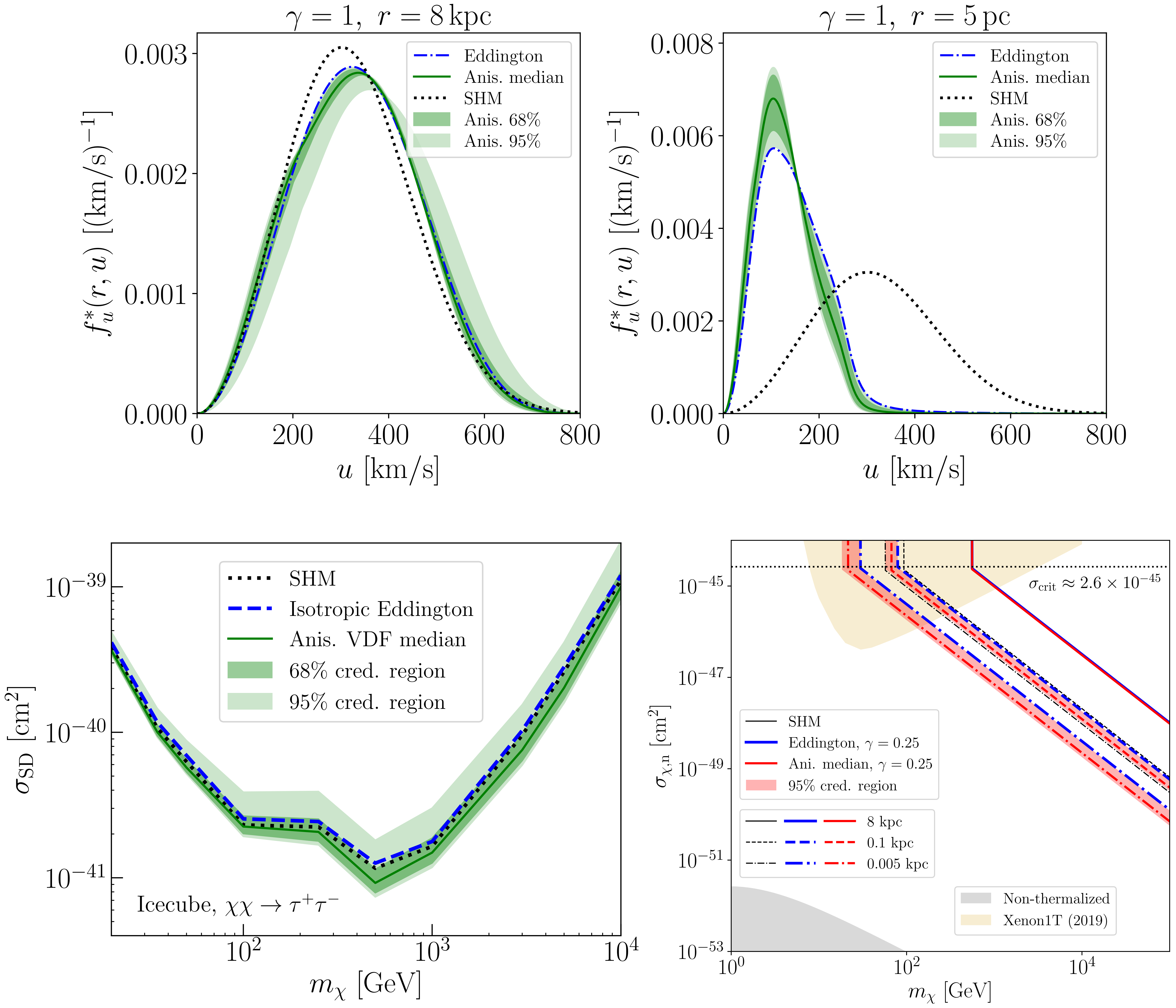
Conclusion

→ Star are unique laboratories to search and study DM properties.

→ Most DM studies in Stars rely on an accurate treatment of the Capture Rate.

→ The SHM is a good approximation in the case of the Sun, but underestimates the capture rate in the central regions of the galaxy.

→ Eddington inversion allows for a systematic study of the uncertainties associated with the DM PSDF.



Thank you!

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