Can Neutrino Self-interactions Save Sterile Neutrino Dark Matter?

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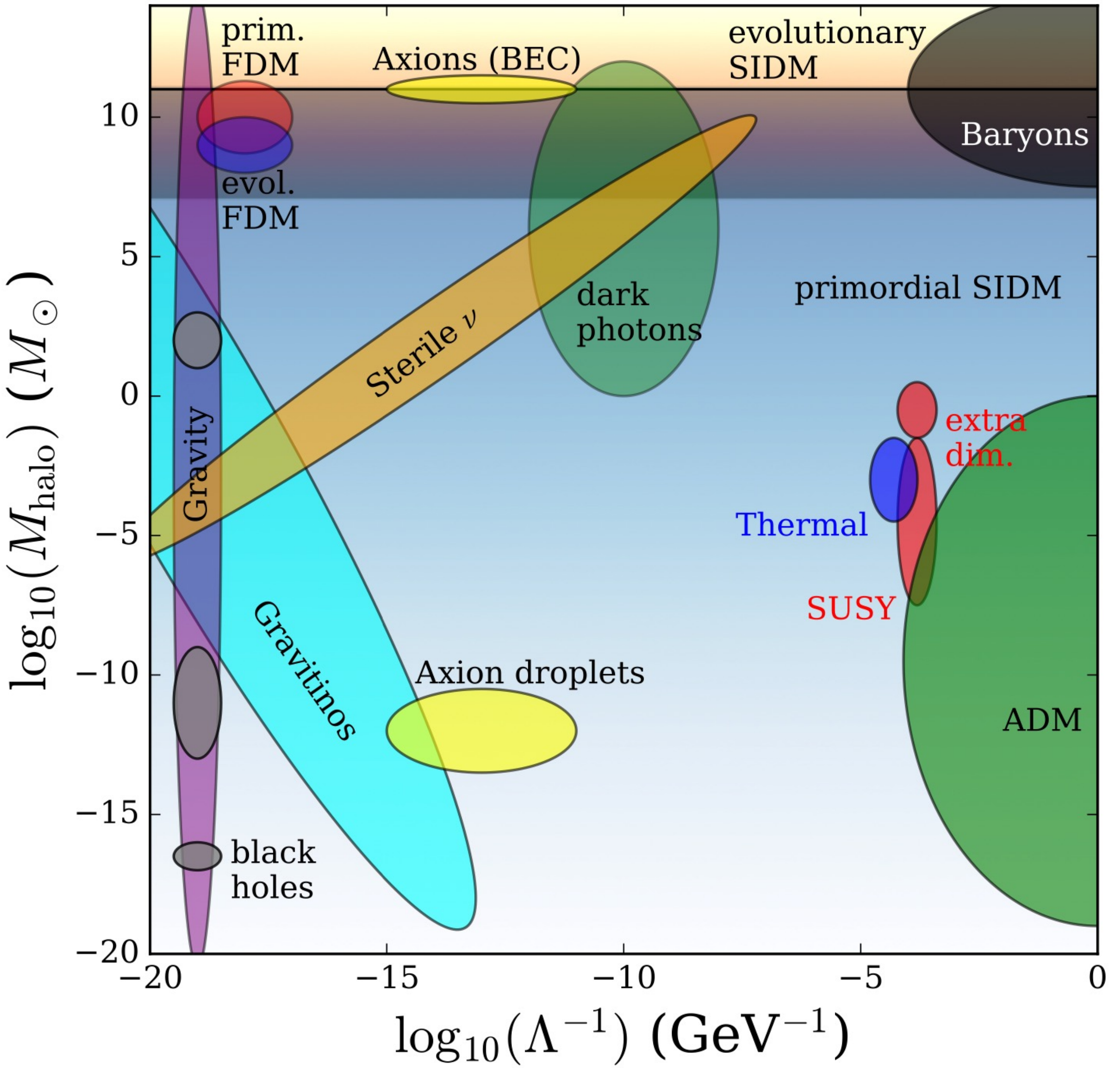
Chicago Workshop on Dark Matter and Neutrino Physics
03/09/2023

Probe:

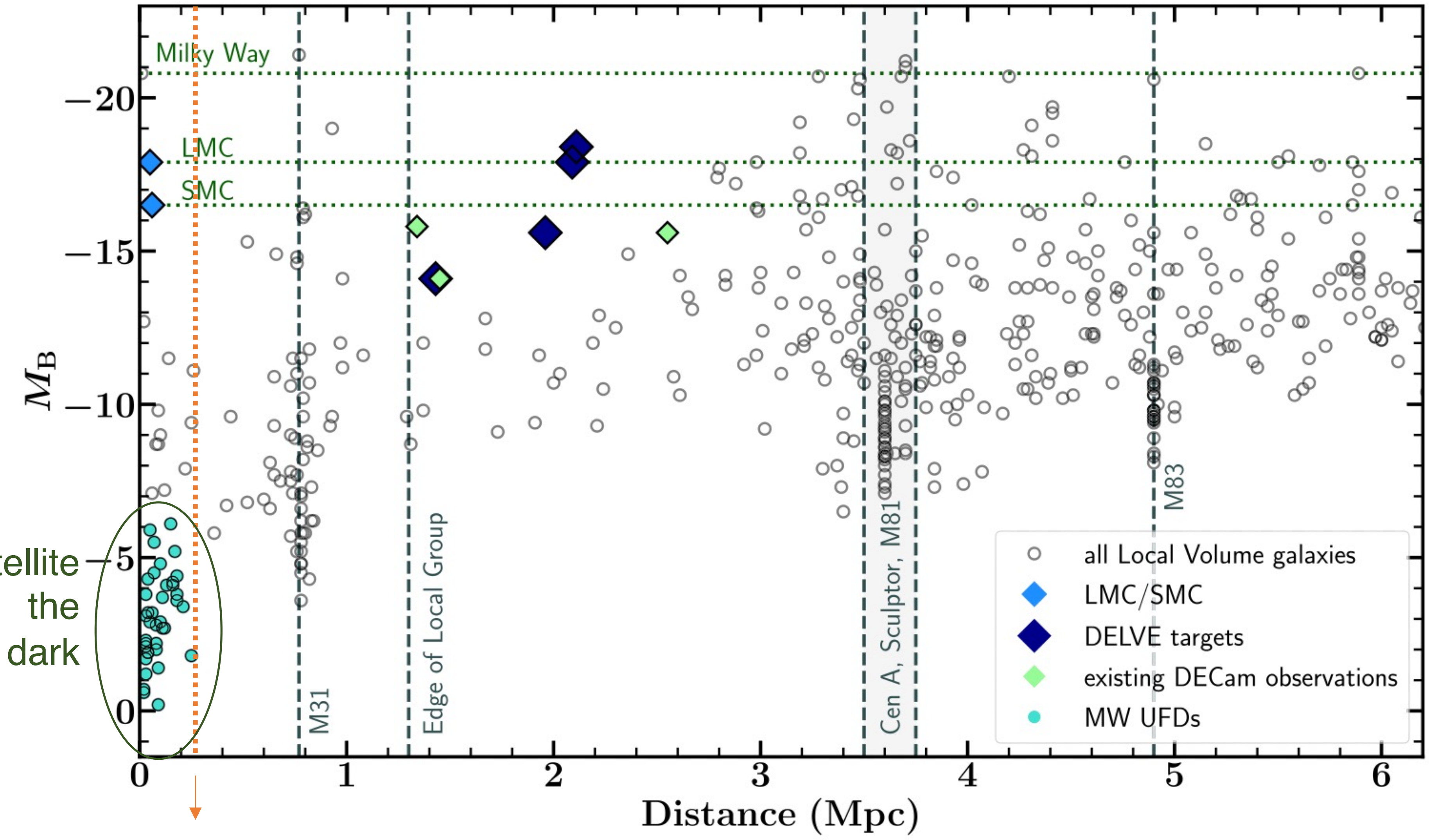
Observations of Milky Way Satellite Galaxies Population

Model:

Sterile Neutrino Dark Matter with Self-Interactions



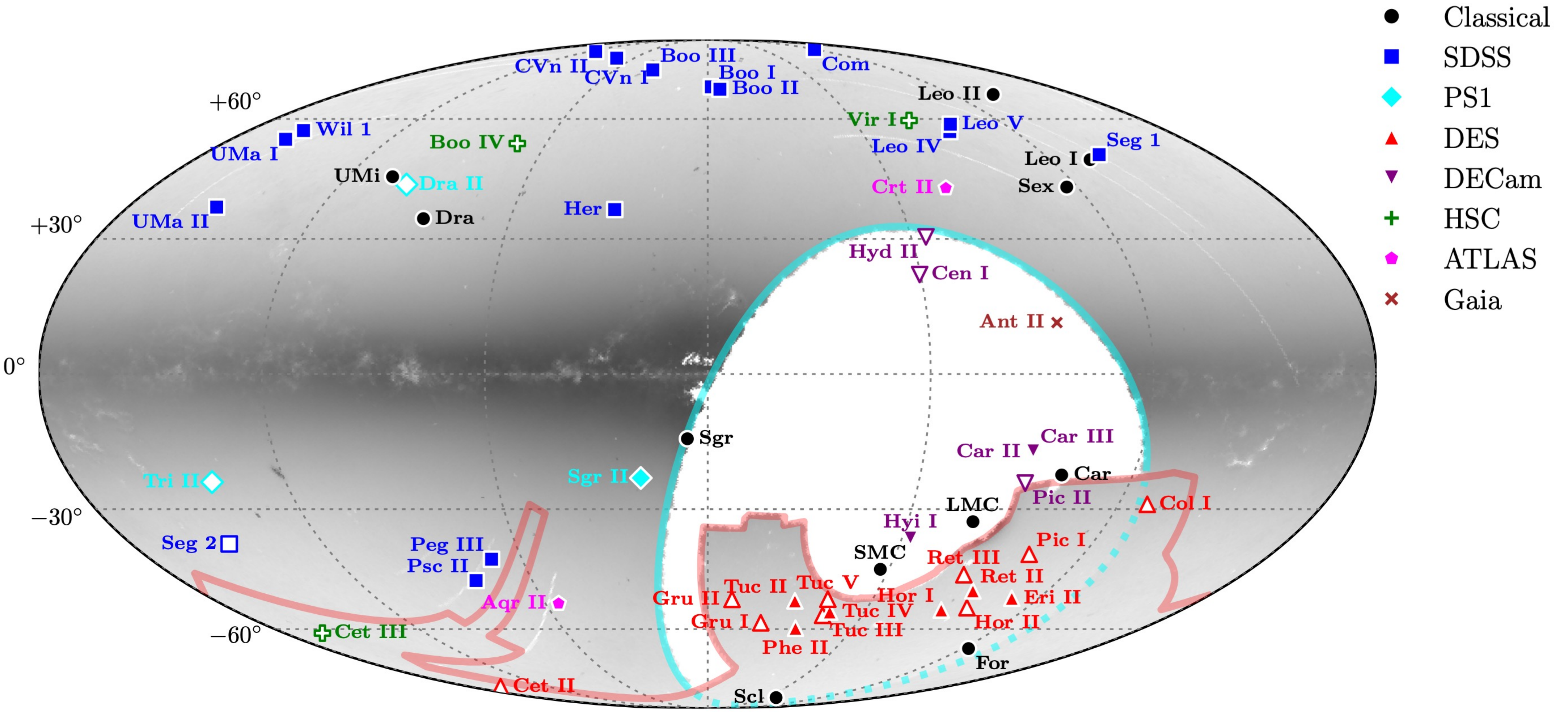
M. Buckley & A. Peter 2018



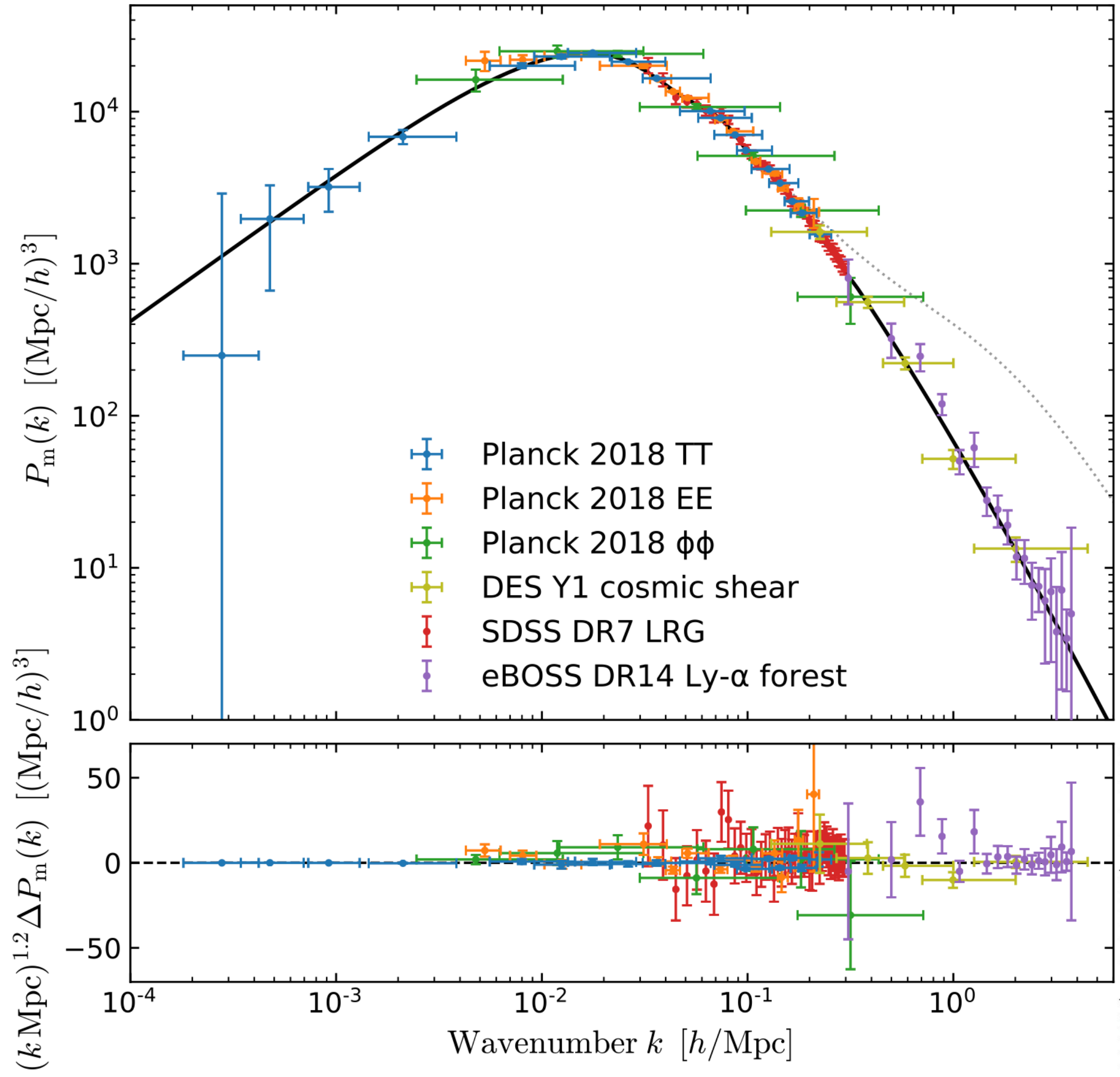
Ultra-faint MW satellite galaxies occupy the smallest luminous dark matter halos

Virial radius of Milky Way halo

A. Drlica-Wagner et al. 2021



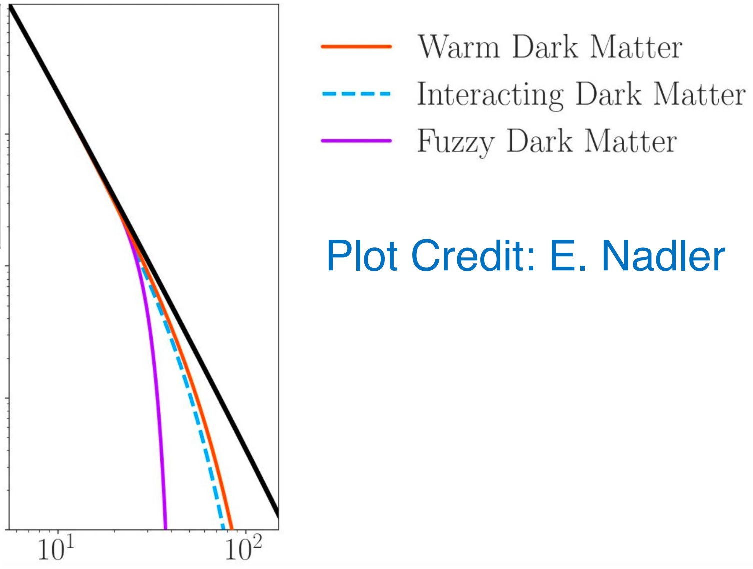
A. Drlica-Wagner et al. 2020



S. Chabanier et al. 2019

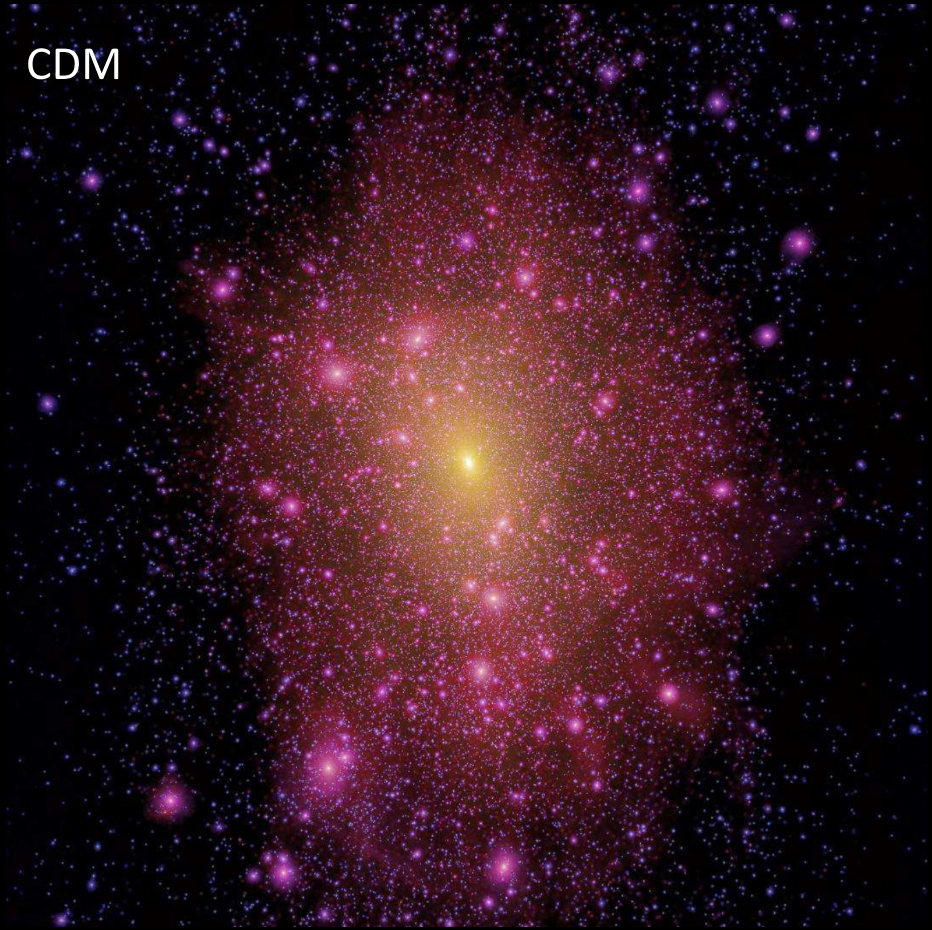
Small scale observations:

Lyman-alpha spectrum (from quasar spectra), dwarf galaxies, ultra-faint galaxies, stellar streams, galaxy clustering and lensing, etc



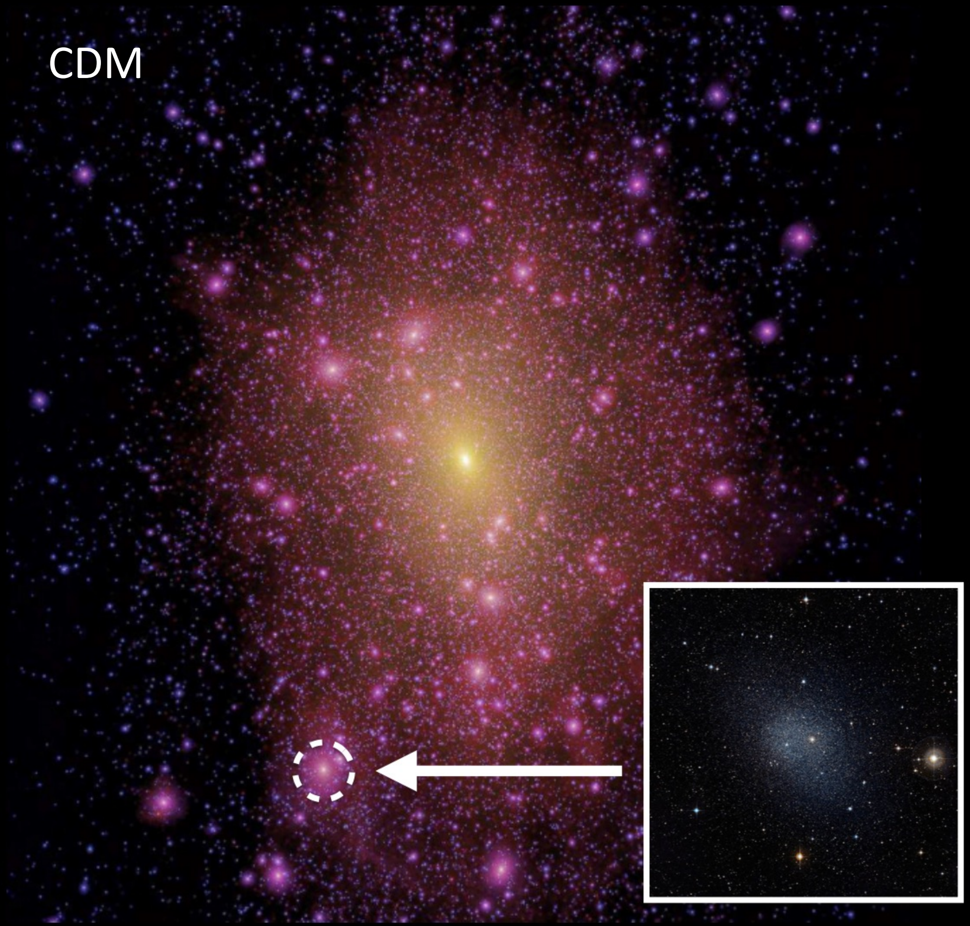
Plot Credit: E. Nadler

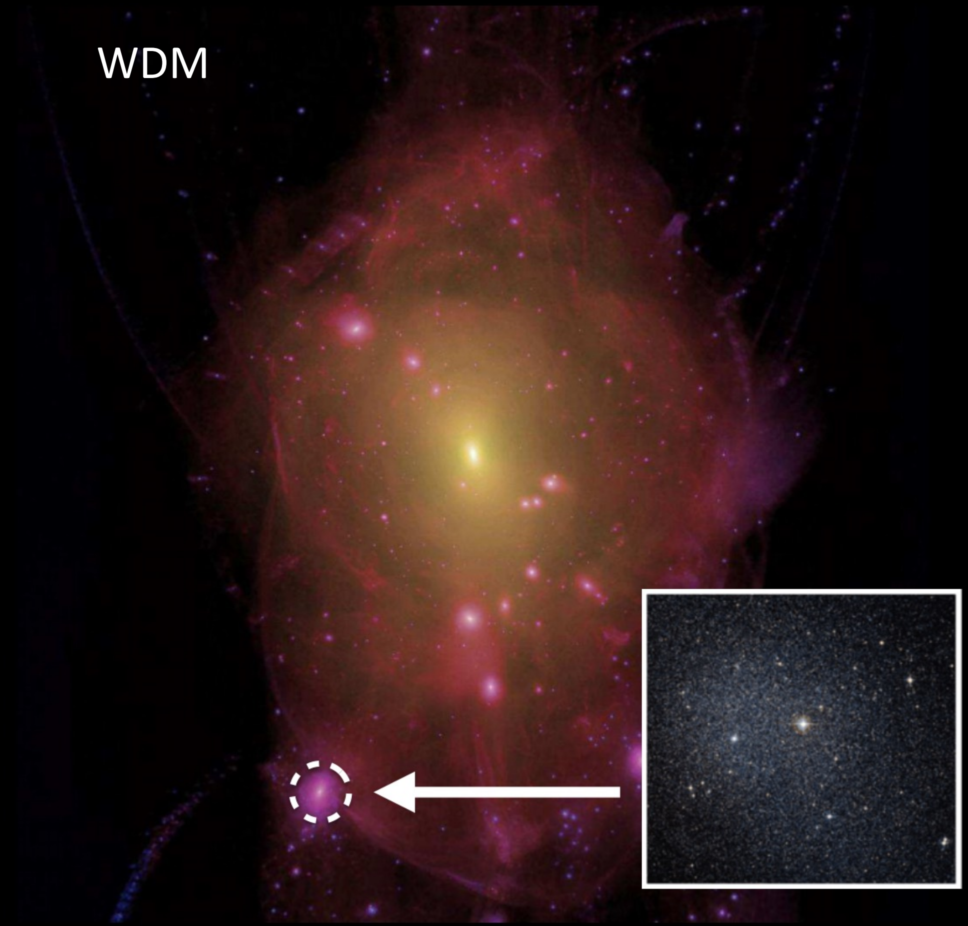
Small Halos as Dark Matter Probes



M. Lovell et al. 2011

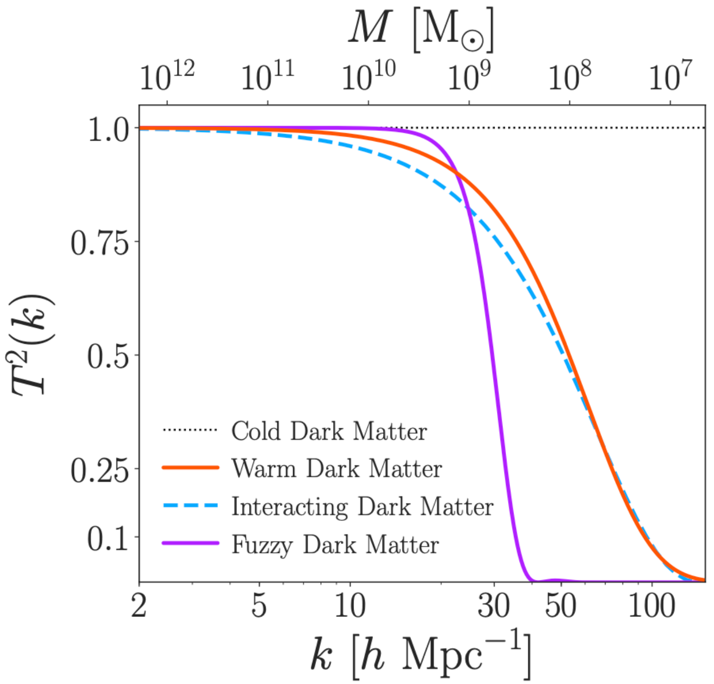
Faint Galaxies as Dark Matter Probes



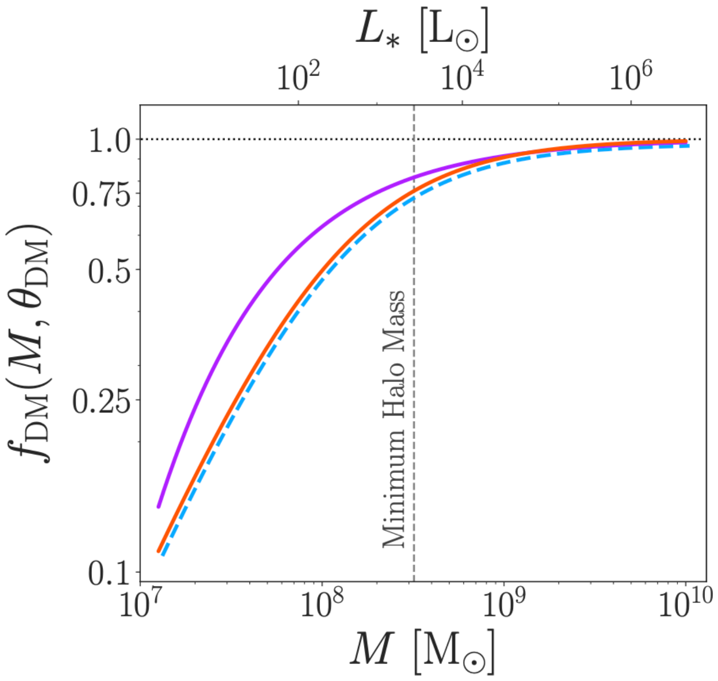


Plot Credit: E. Nadler

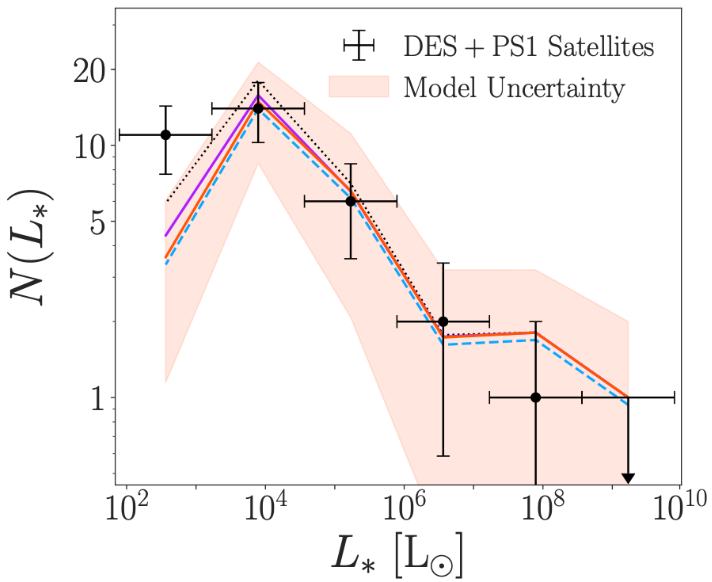
Transfer function



Subhalo mass function



Satellite luminosity function

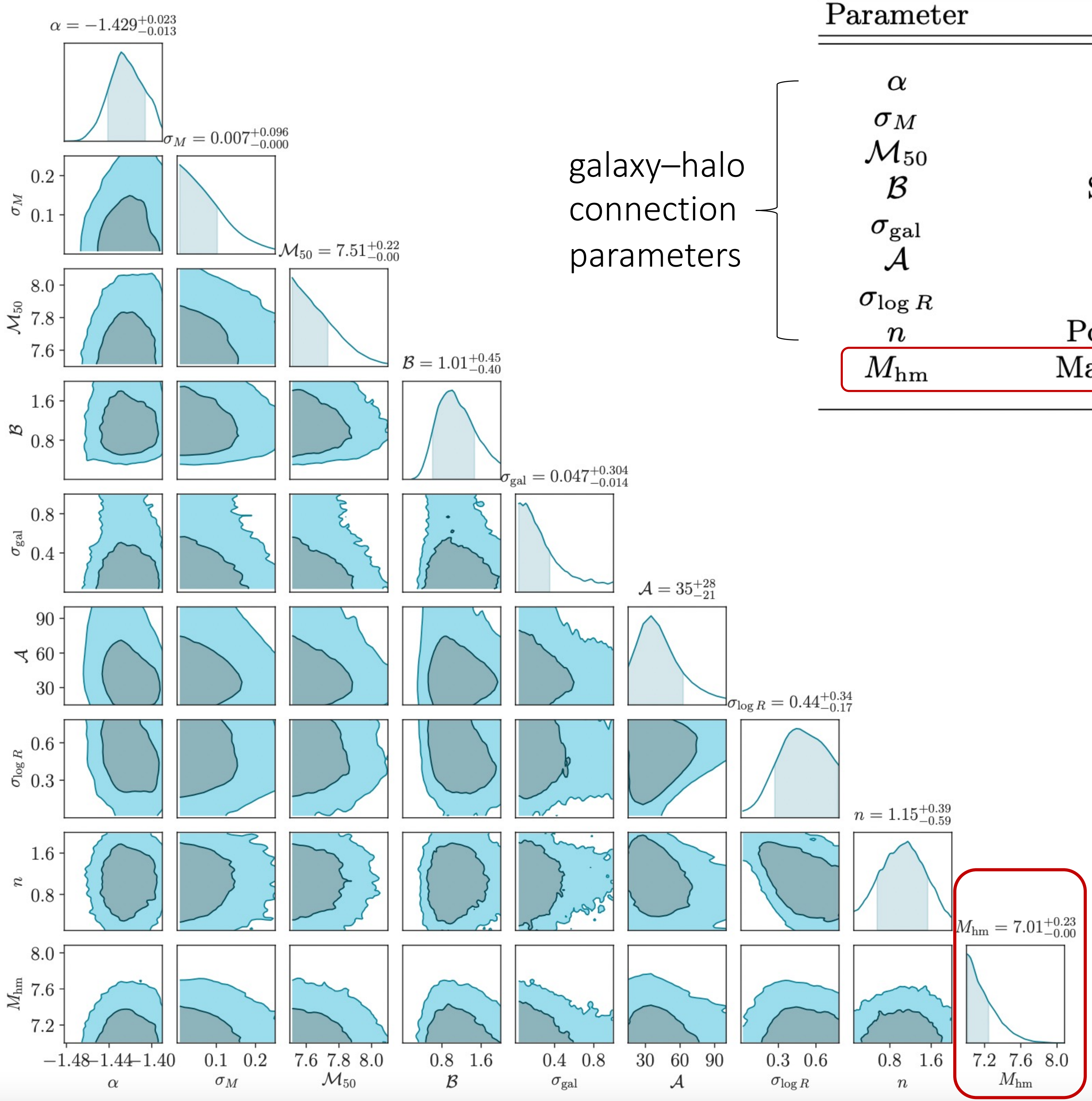


DM microphysics can affect structure on small scales

Suppression of power at small scales leads to under-abundance of subhalos and faint MW satellite galaxies relative to CDM predictions

E. Nadler et al. 2020

https://arxiv.org/abs/2008.00022



galaxy–halo connection parameters

Parameter	Physical Interpretation
α	Power-law slope of satellite luminosity function
σ_M	Scatter in satellite luminosity at fixed halo properties
$\mathcal{M}_{50}$	Peak mass at which 50% of halos host galaxies
$\mathcal{B}$	Subhalo disruption efficiency relative to FIRE simulations
$\sigma_{\rm gal}$	Width of the galaxy occupation fraction
$\mathcal{A}$	Amplitude of relation between galaxy size and halo size
$\sigma_{\log R}$	Scatter in galaxy size at fixed halo properties
n	Power-law slope of relation between galaxy size and halo size
$M_{\rm hm}$	Mass scale of thermal relic WDM SHMF suppression (Eq. (5))

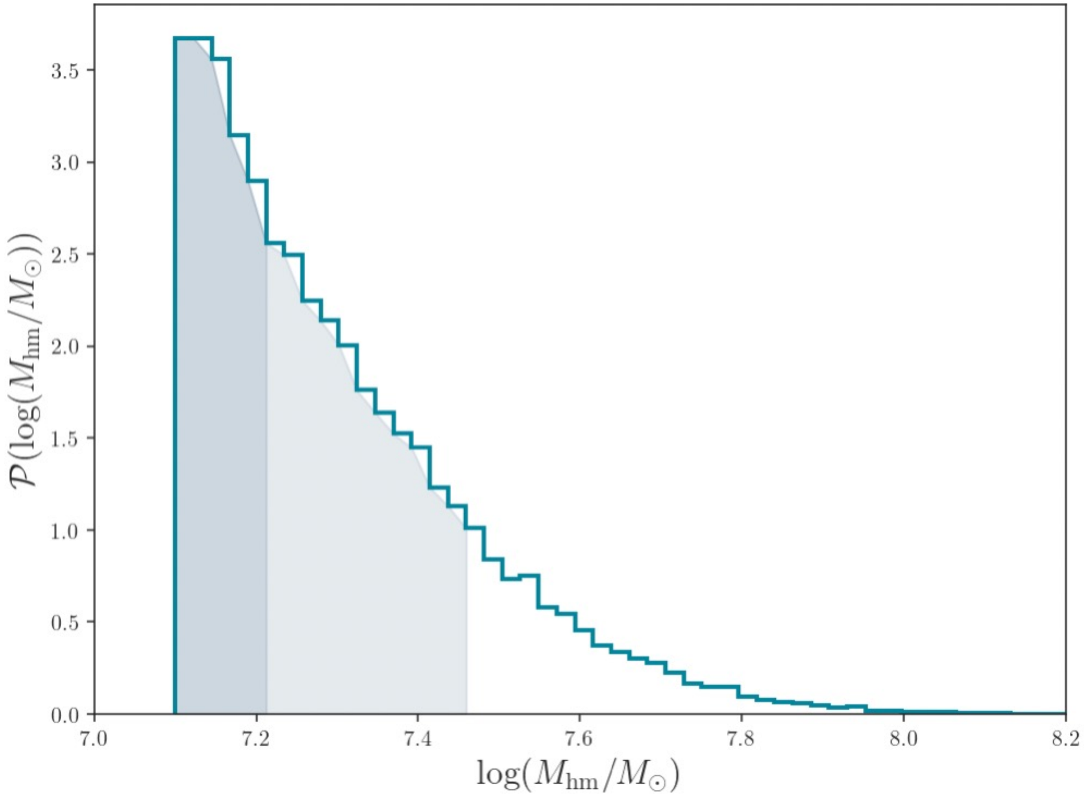
$$M_{\rm hm} = \frac{4\pi}{3}\Omega_m\bar{\rho}\left(\frac{\pi}{k_{\rm hm}}\right)^3$$

$$T^2(k_{\rm hm}) = 0.25$$

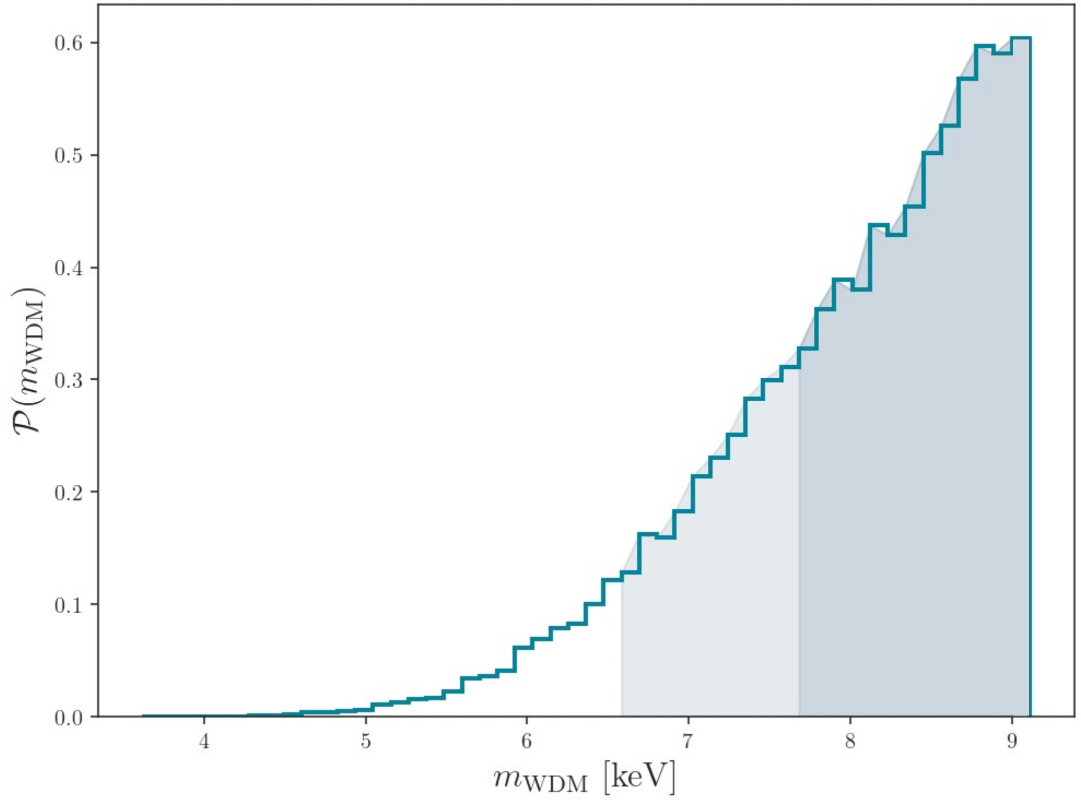
half-mode mass is a characteristic mass scale below which the abundance of DM halos is significantly suppressed relative to CDM.

E. Nadler et al. 2020

half-mode mass



warm DM mass



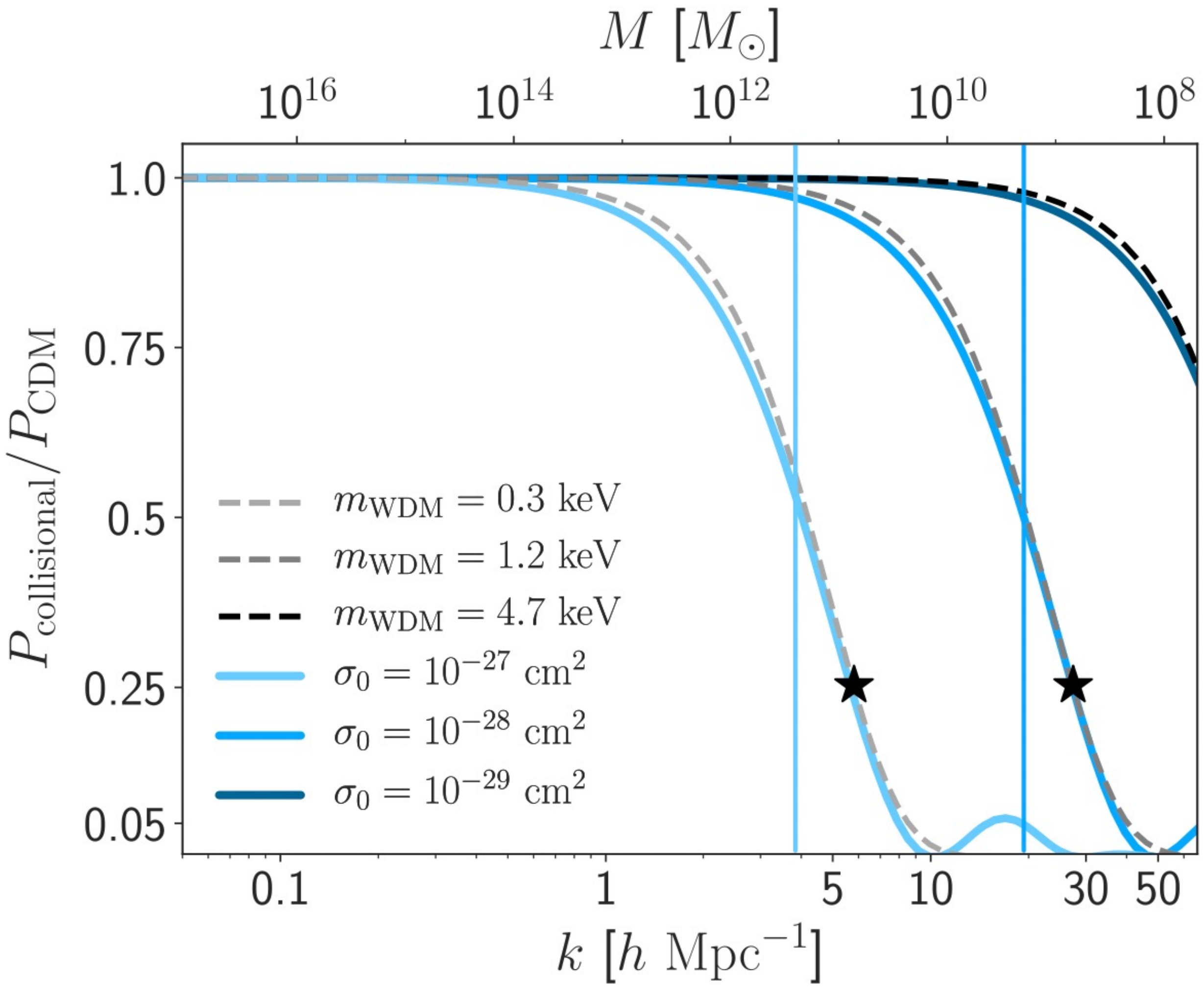
The thermal relic WDM with mass larger than ~6.5keV is ruled out at 95% confidence by the analysis of MW satellites observed with Dark Energy Survey (*DES) and* Pan-STARRS1 (*PS1)*

E. Nadler et al. 2020

Probing Dark Matter-Baryon Scattering

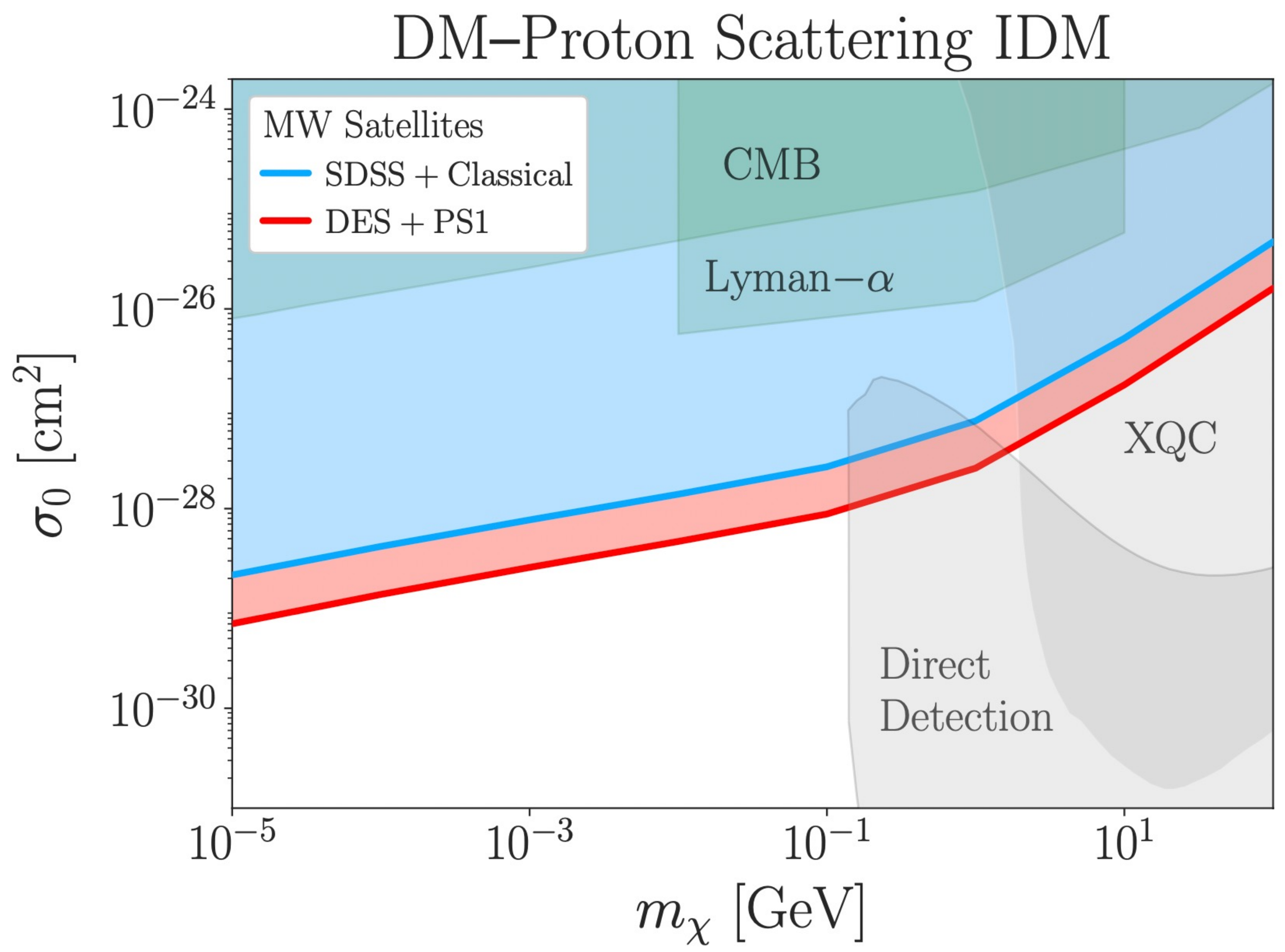
Momentum-transfer cross section

$$\sigma_{\rm MT} = \sigma_0 v^n$$



E. Nadler et al. 2019

Probing Dark Matter-Baryon Scattering



E. Nadler et al. 2020

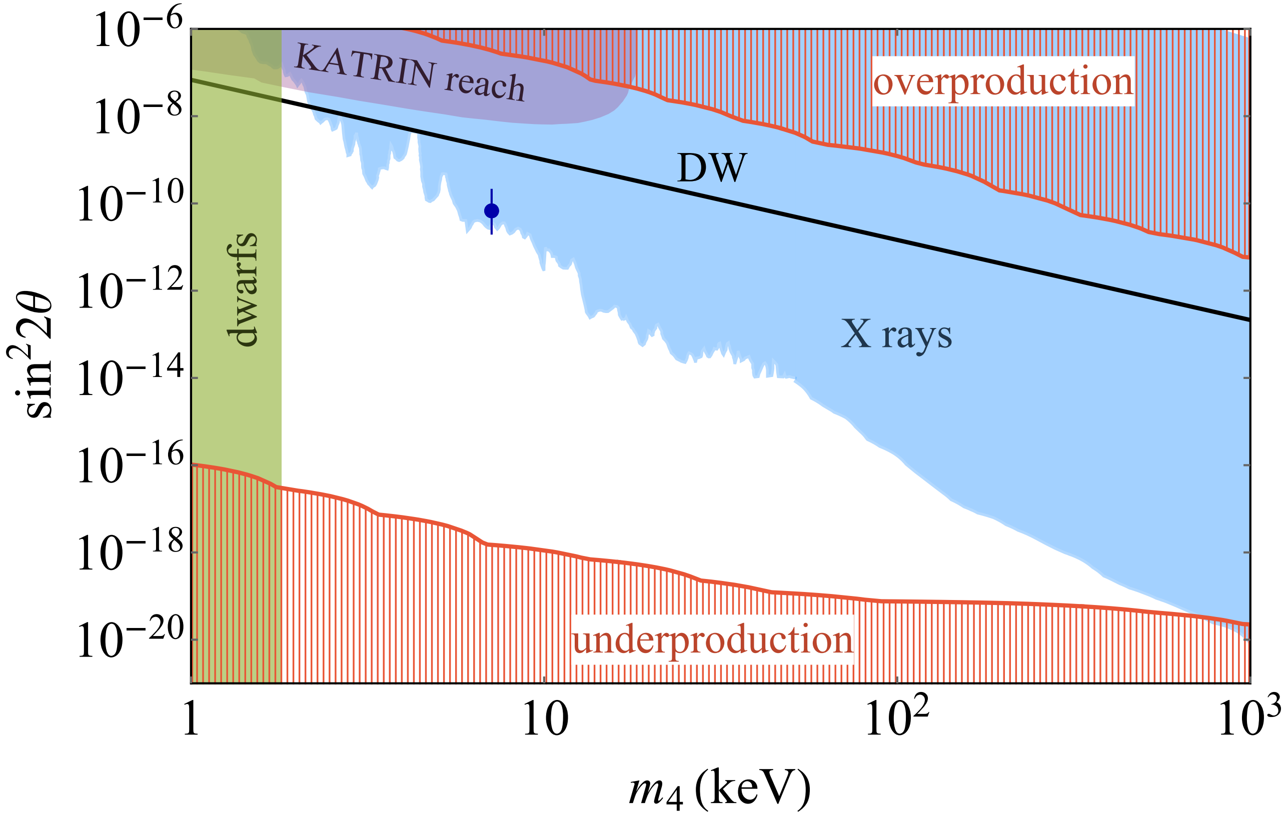
Probing Sterile Neutrino Dark Matter

RA, V. Gluscevic, E. Nadler, and Y. Zhang, arxiv: 2301.08299

$$|\nu_4\rangle = \cos\theta|\nu_s\rangle + \sin\theta|\nu_a\rangle$$

Dodelson-Widrow (DW) Mechanism: ν_4 can be produced non-thermally with the correct relic abundance to constitute all of DM.

Problem: The active-sterile neutrino mixing that can account for the observed DM abundance is in tension with the X-rays constraints

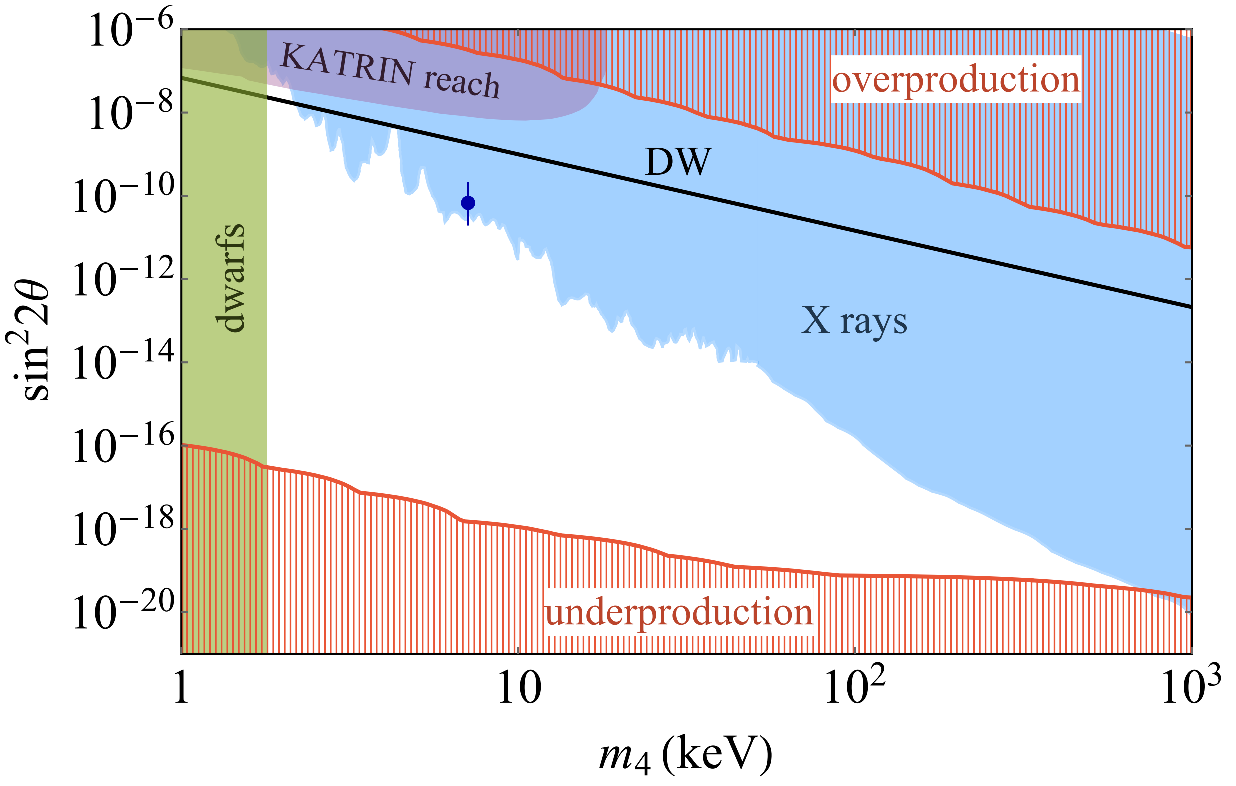


A. de Gouvea et al. 2019

Probing Sterile Neutrino Dark Matter

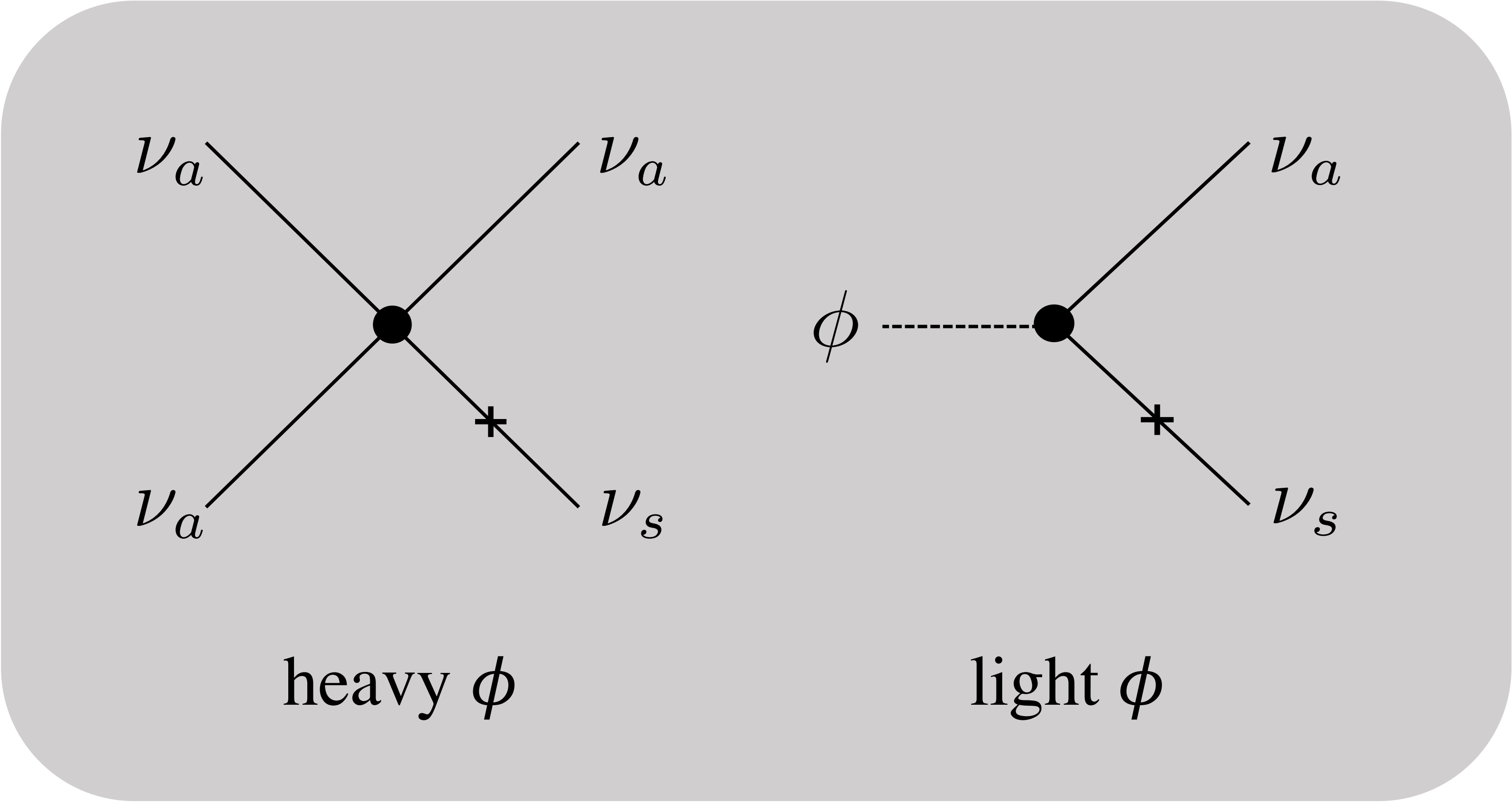
Solution: Introducing a self-interaction among the active neutrinos. The new force enables more frequent active neutrino scattering than normal weak interactions, thereby, DM can be produced with a smaller mixing angle than required by DW

$$\mathcal{L} \supset \frac{\lambda_\phi}{2} \nu_a \nu_a \phi + \mathrm{h.c}$$

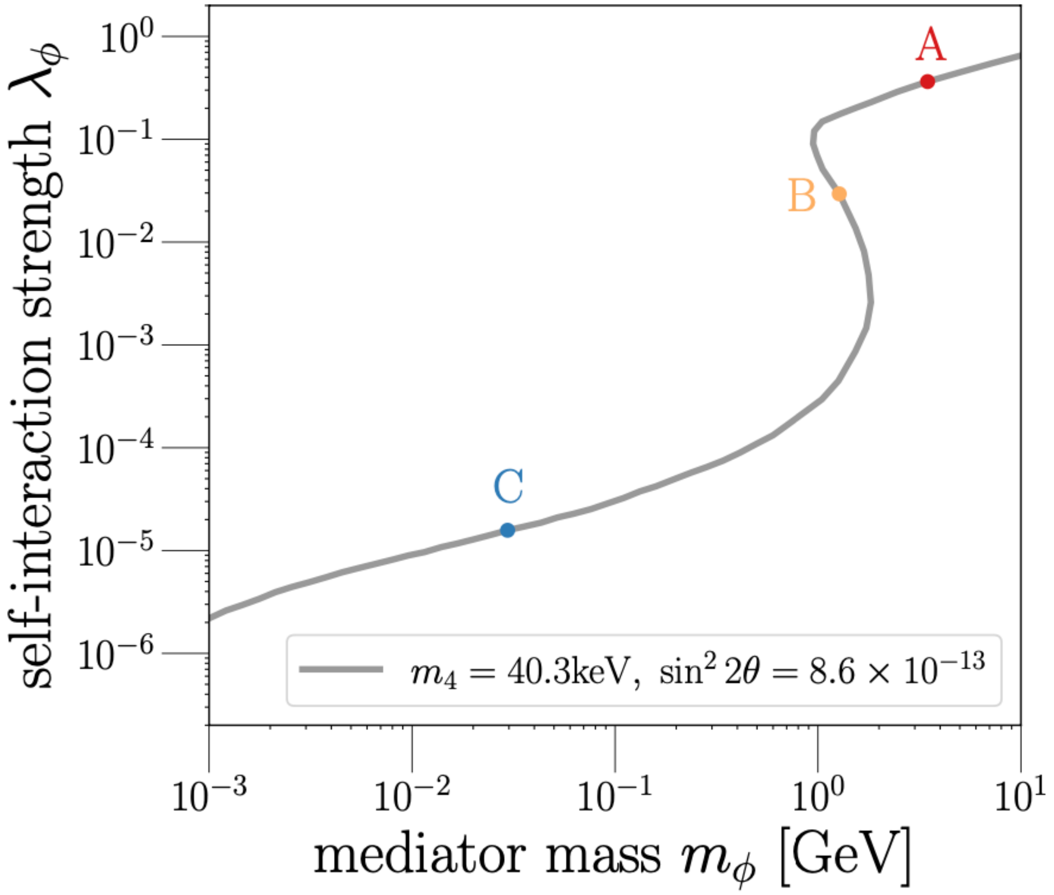


A. de Gouvea et al. 2019

Probing Sterile Neutrino Dark Matter



Probing Sterile Neutrino Dark Matter



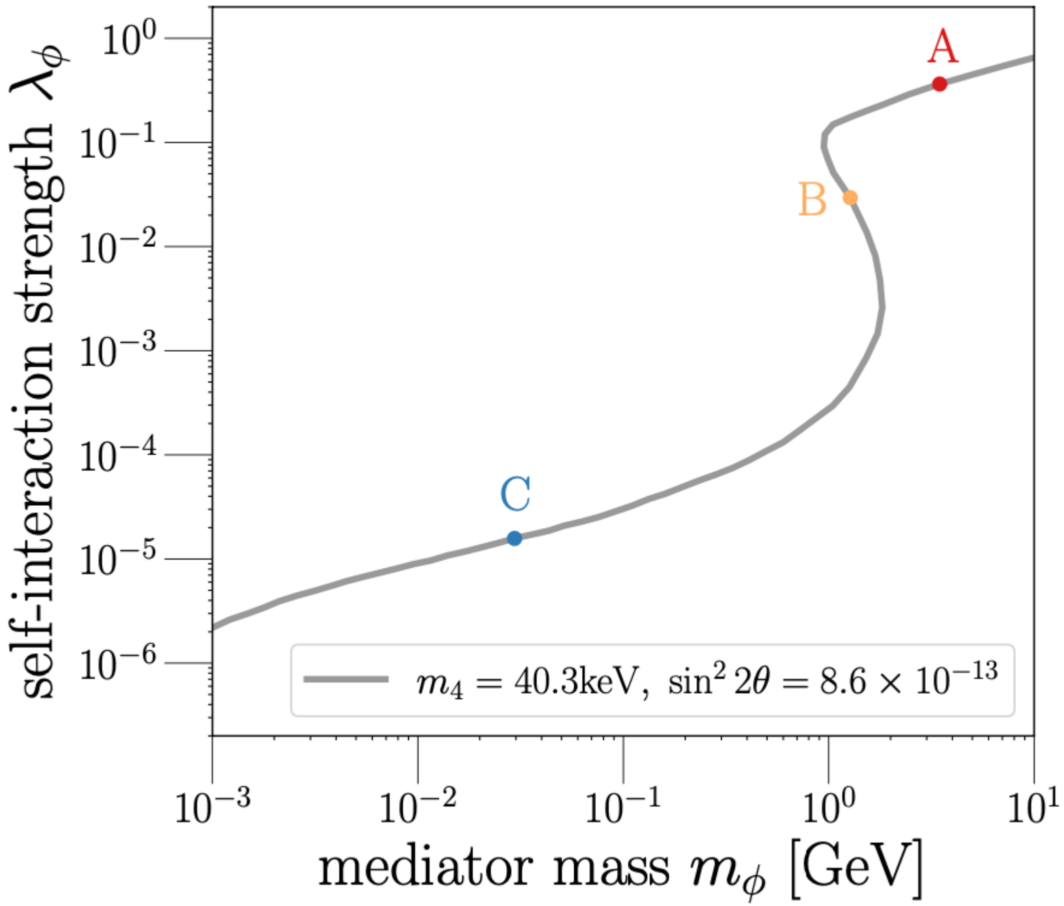
Case A: DM production through a heavy mediator, and a strong self-interaction

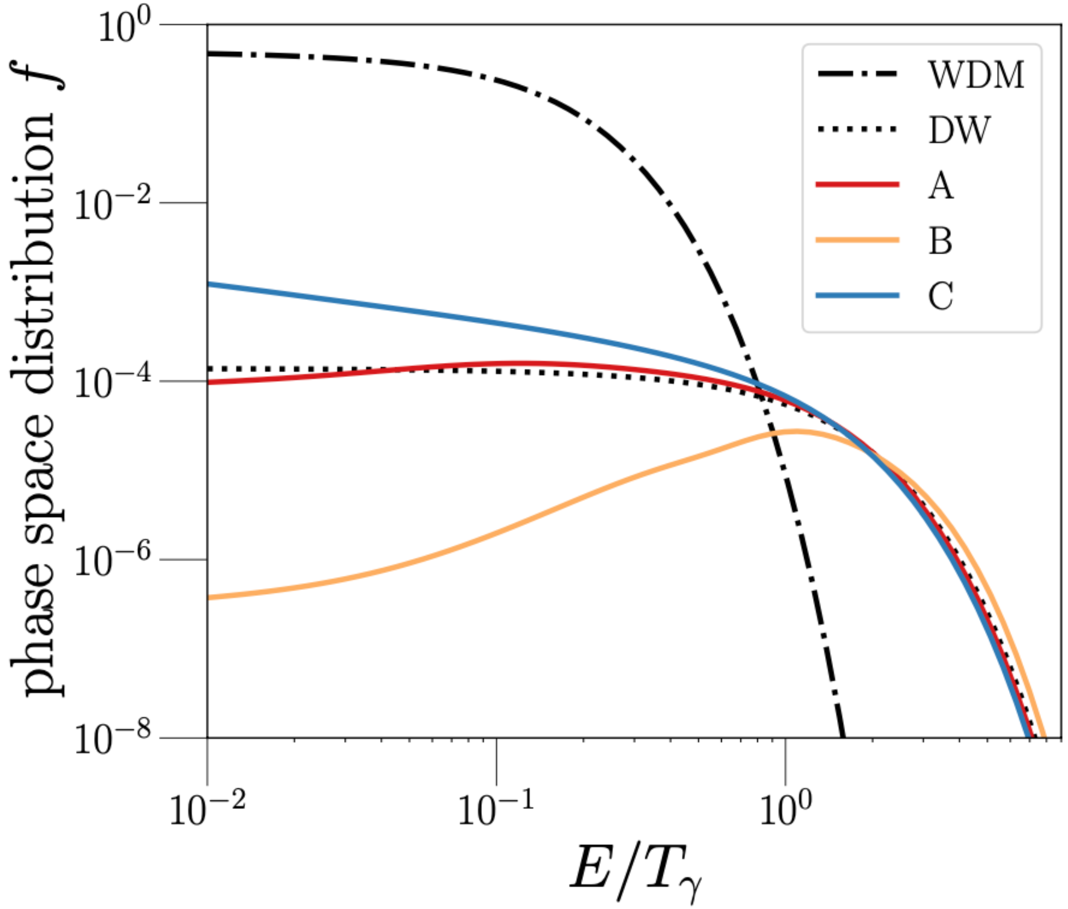
Case B: DM production through a light mediator, with a suppressed in-medium mixing

Case C: DM production through a light mediator, with the effective active-sterile mixing angle close to the vacuum mixing angle

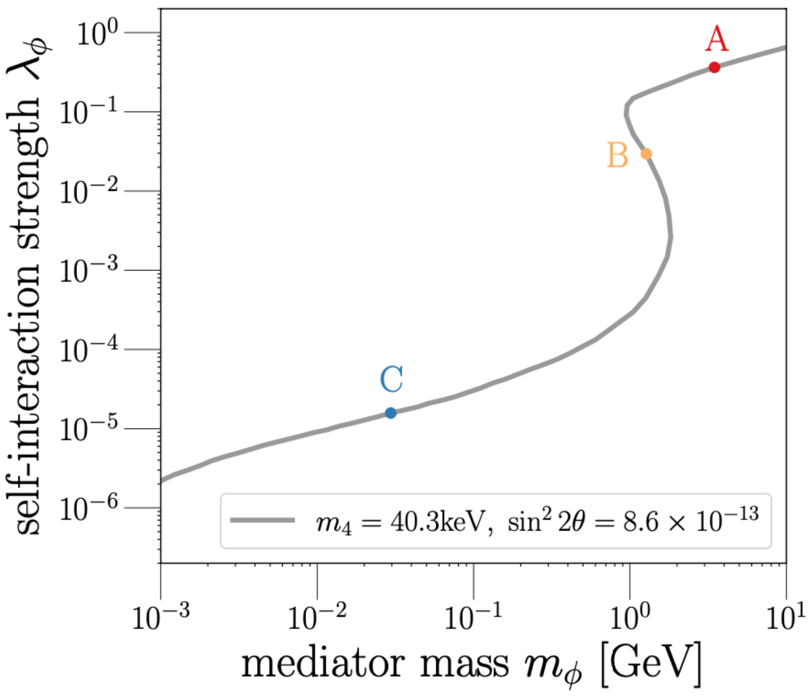
https://arxiv.org/abs/1910.04901

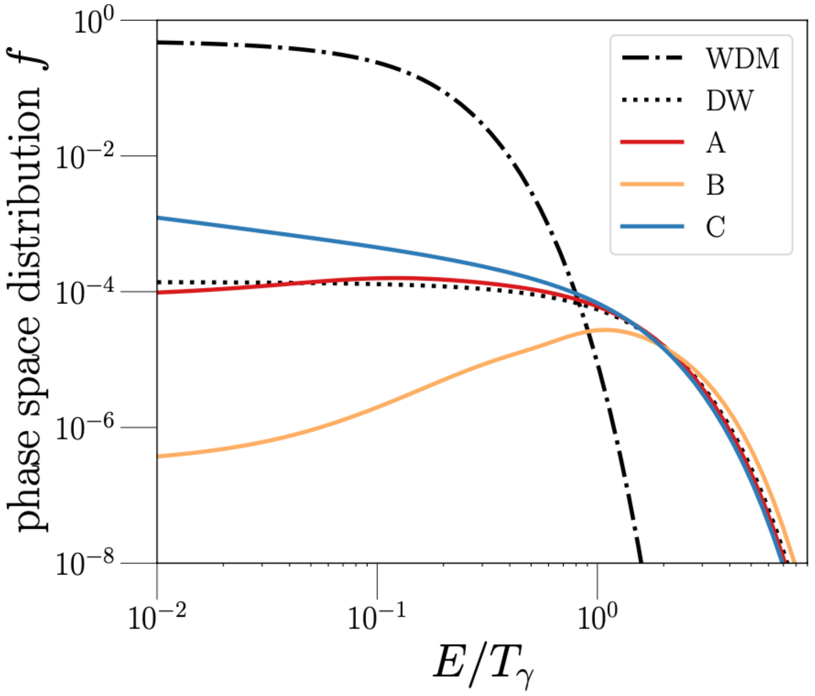
Probing Sterile Neutrino Dark Matter



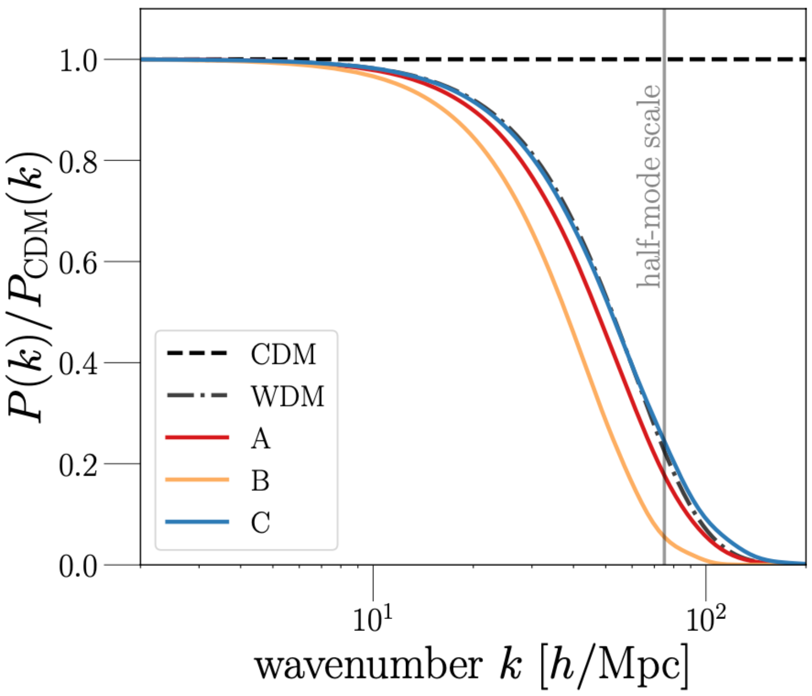


Probing Sterile Neutrino Dark Matter





Transfer function



Model: Sterile Neutrinos DM

- Phase space distribution
- Temperature ratio T_{ν_s}/T_γ
- Sterile neutrino DM mass m_4

CLASS

Transfer function $T^2(k) = P(k)/P_{CDM}(k)$

Observations: Milky Way Satellite population from Dark Energy Survey and Pan-STARRS1

E. Nadler et al, 2020

Constraints on WDM : $m_{\rm wdm} > 6.5$ KeV at 95% CL

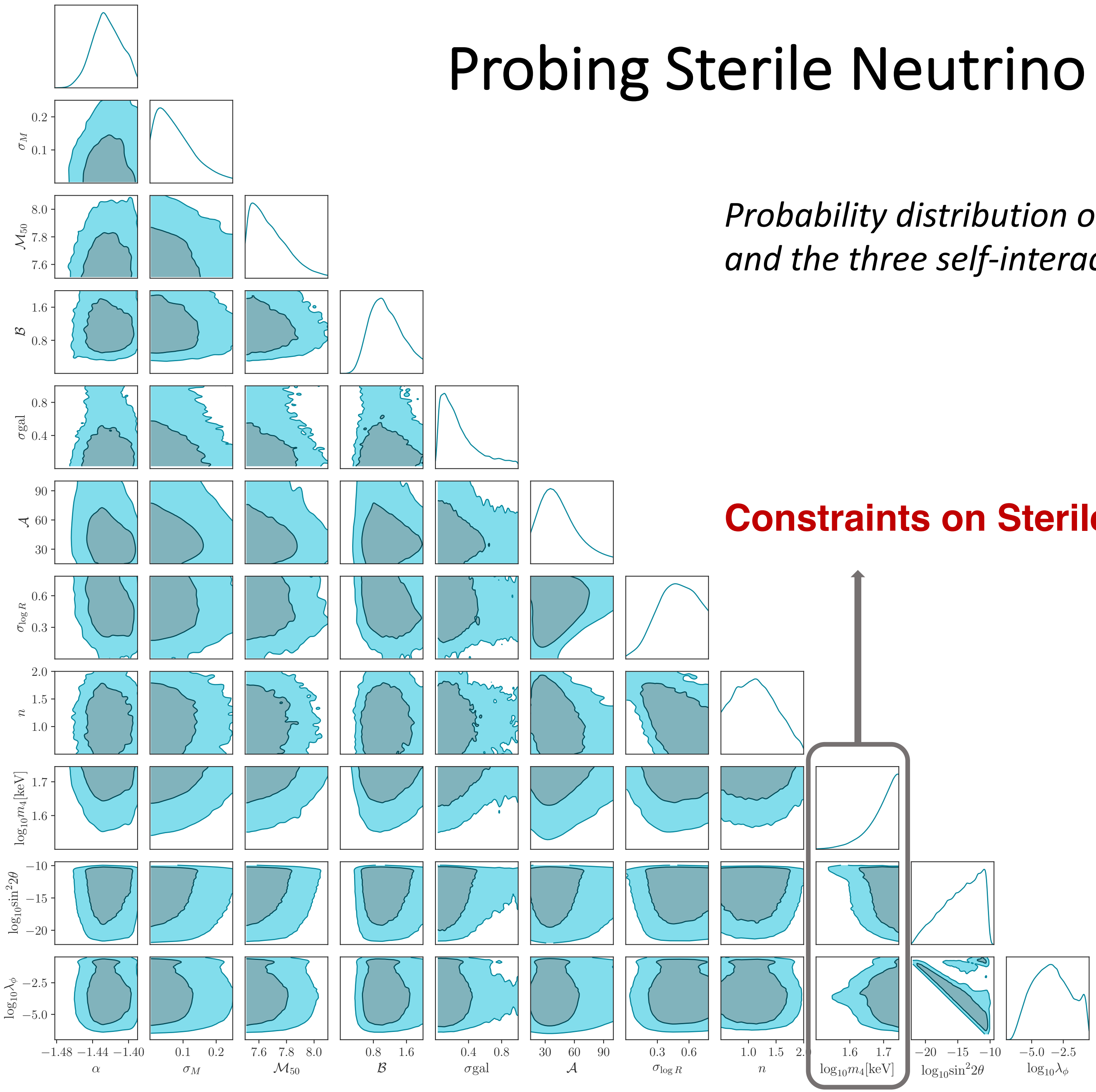
Match half-mode scale $T^2(k_{\rm hm}) = 0.25$

Sampling

Probability distribution on $[m_4, \ \sin^2\theta, \ \lambda_\phi]$

Note: the remaining degree of freedom m_ϕ is fixed by the DM relic abundance constraint

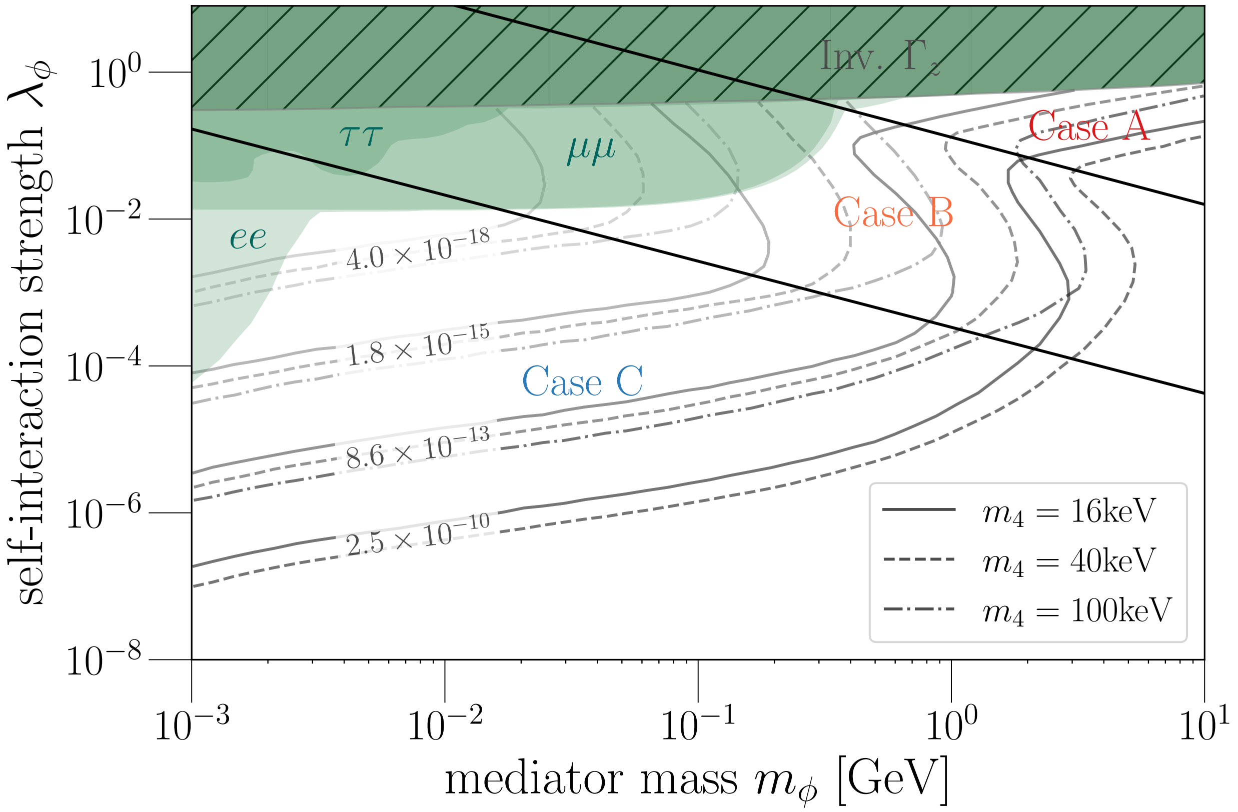
Probing Sterile Neutrino Dark Matter



Probability distribution over the eight galaxy–halo connection parameters and the three self-interacting sterile neutrino DM parameters

Constraints on Sterile Neutrino DM: $m_4 > 37.2$ KeV at 95% CL

Probing Sterile Neutrino Dark Matter

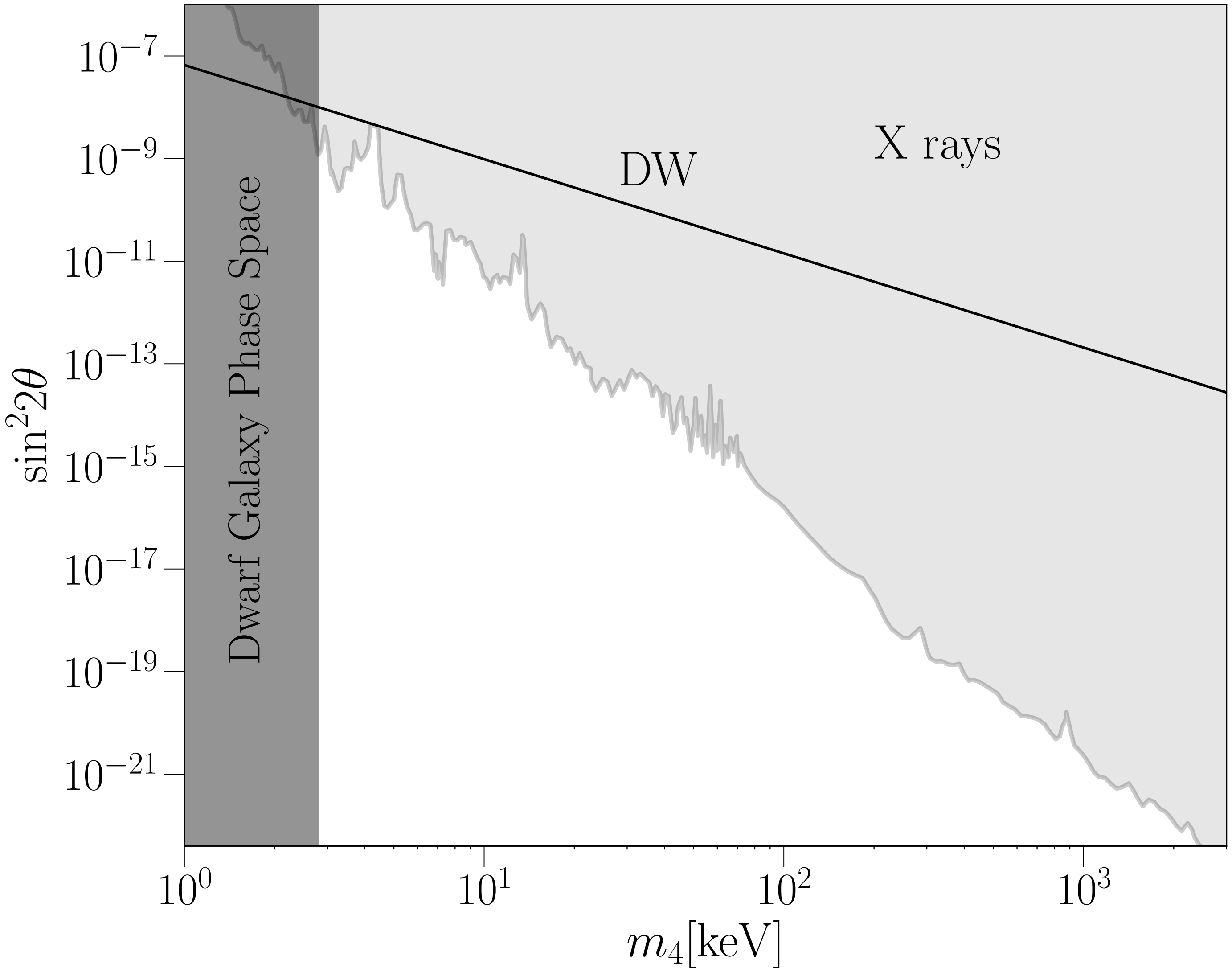


I. Combining the analysis of the MW satellite galaxy population with existing constraints from invisible Z width (Inv. Γ_z);

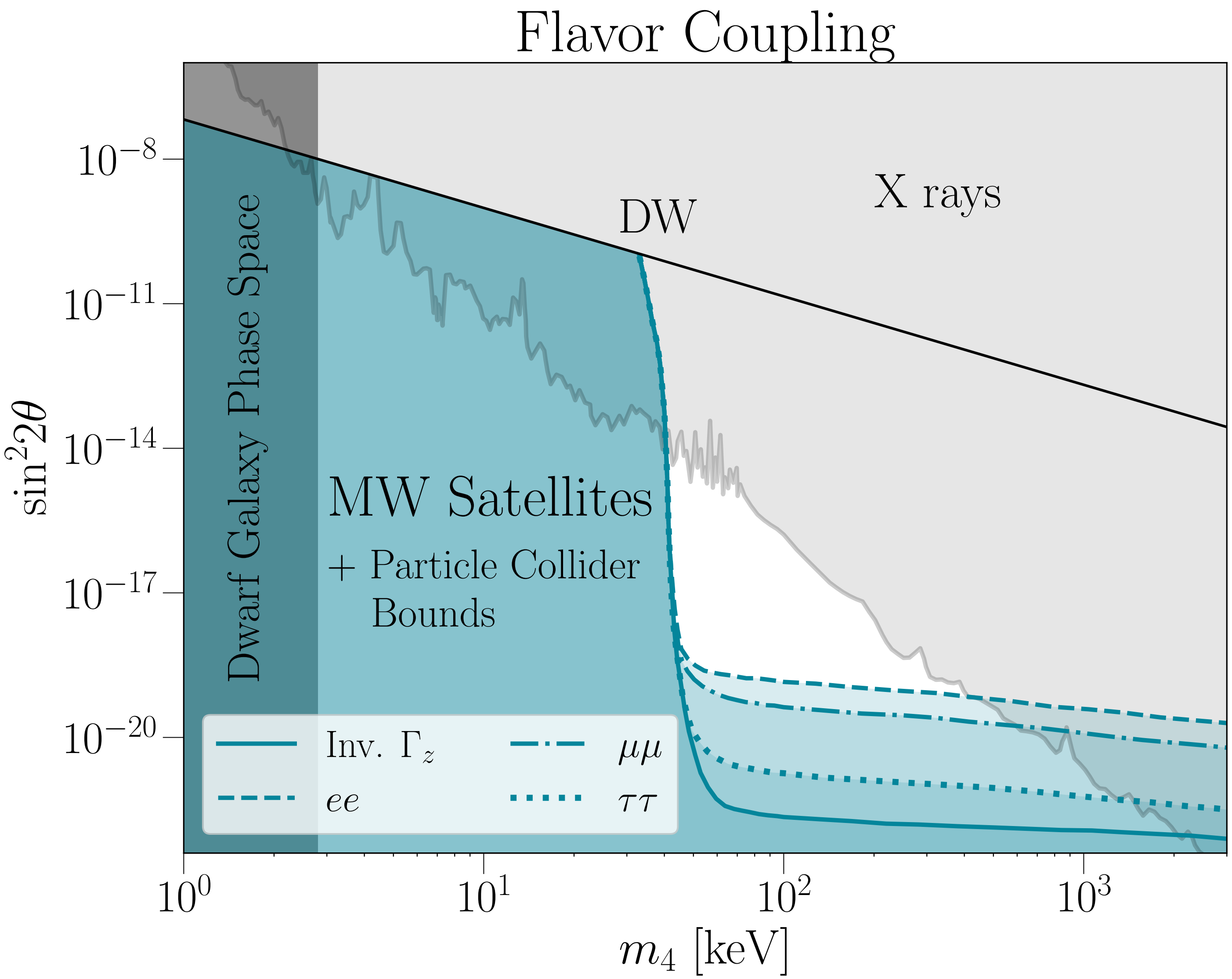
II. Three mediator flavor-coupling scenarios: ν_e, ν_μ, and ν_τ, with additional flavor-dependent constraints from charged meson decays, neutrinoless double-beta decay, and the IceCube experiment;

III. Three DM production scenarios: Case A, Case B and Case C.

Probing Sterile Neutrino Dark Matter



Probing Sterile Neutrino Dark Matter



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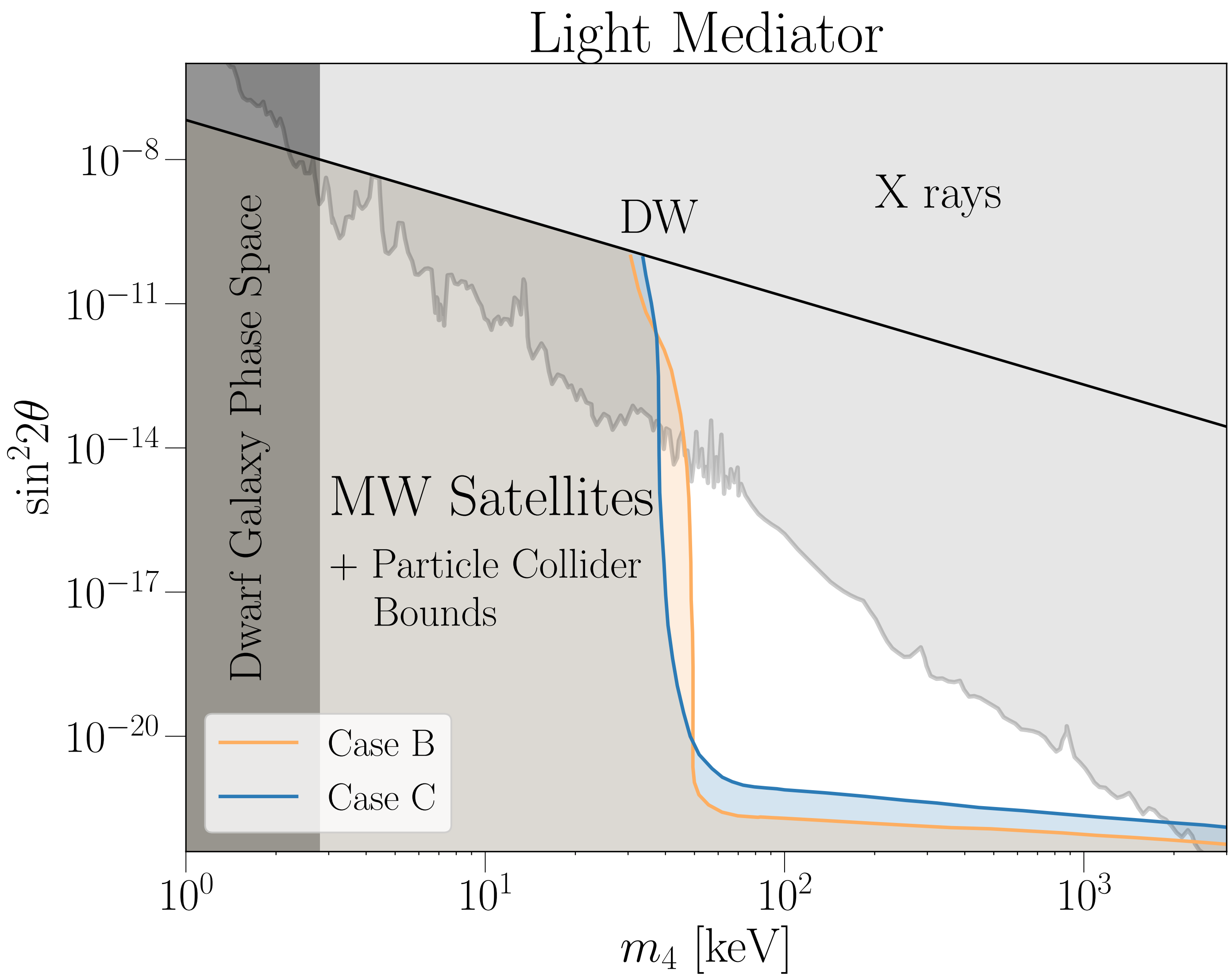

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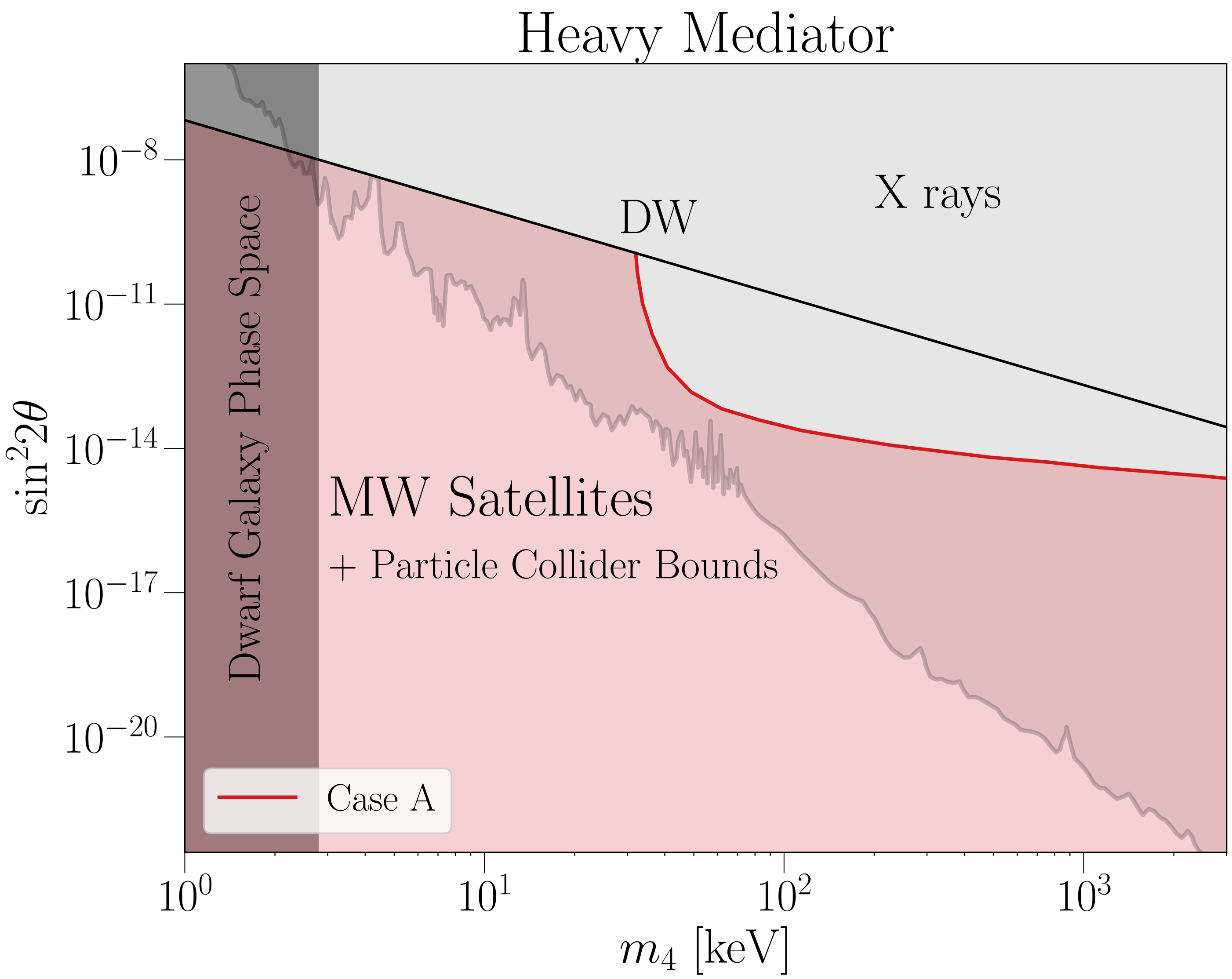


Summary

- We for the first time examine whether active neutrino interactions can produce sterile neutrino dark matter consistent with the latest measurements of the MW satellite galaxy population, X-ray limits, and particle collider bounds

- We derive a lower bound on the sterile-neutrino dark matter mass of 37.2 keV at 95% confidence, based on a detailed analysis of the MW satellite galaxy population, in the presence of neutrino self-interactions

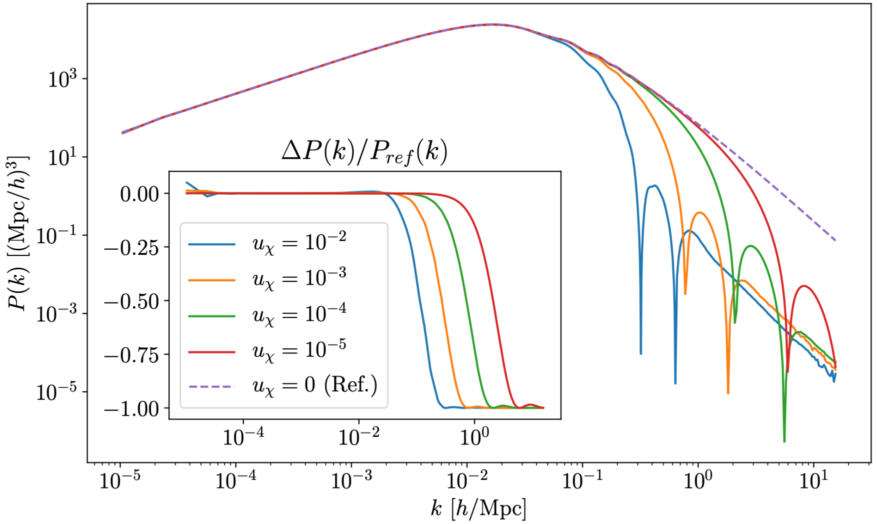
- Combining the constraints from MW satellite galaxy population with previous limits from particle physics and astrophysics excludes 100% sterile neutrino DM produced by strong neutrino self-coupling, mediated by a heavy scalar particle; however, data permits sterile-neutrino DM production via a light mediator. This study can inform future astrophysical and particle accelerator searches for neutrino self-interactions and sterile neutrino DM

Probing Dark Matter – Neutrino Interactions

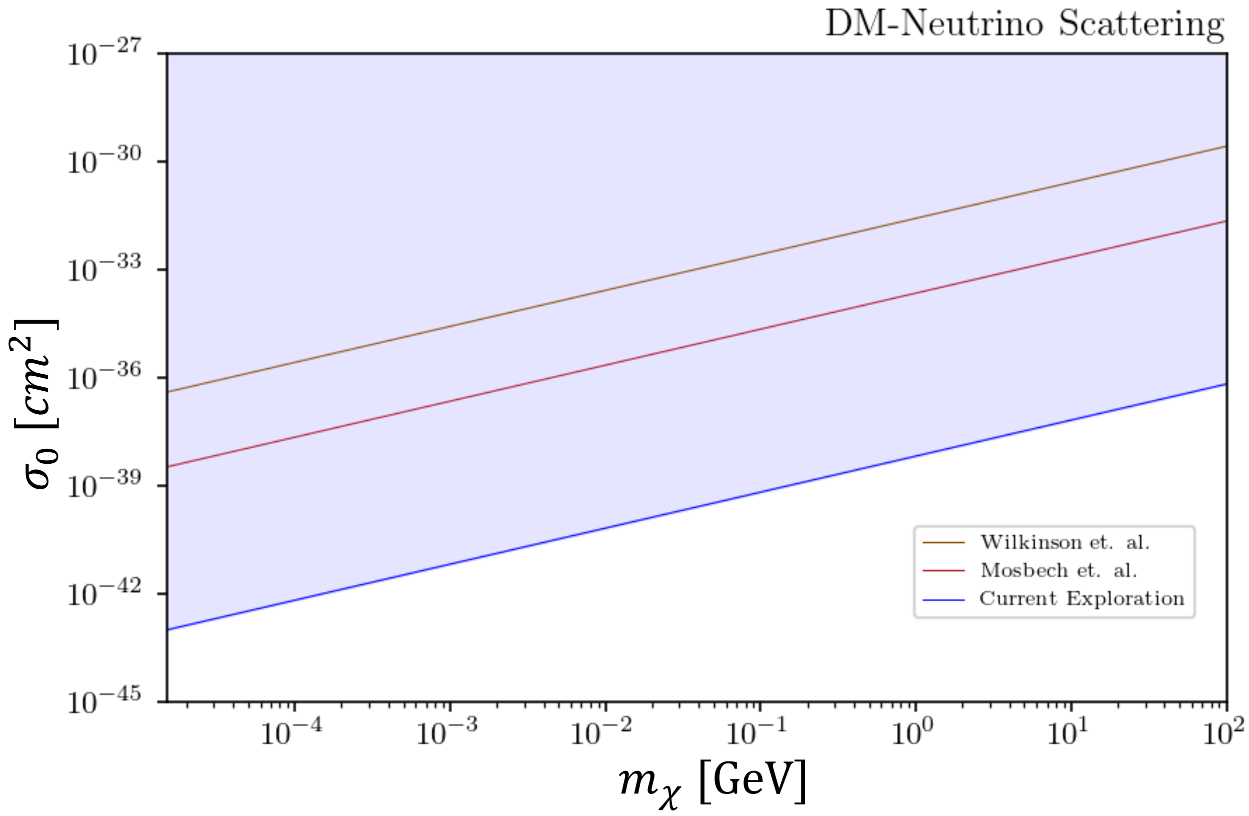
W. Crumrine , RA, E. Nadler, and V. Gluscevic (in prep)

Interaction rate

$$u_{\nu\chi} = \frac{\sigma_0}{\sigma_{\rm Th}} \left(\frac{m_\chi}{100\,{\rm GeV}} \right)^{-1}$$



R. Mosbech et al. 2018



Thanks!