Refining lower bounds on sterile neutrino dark matter mass from estimates of phase space densities in dwarf galaxies

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February 19

The work is supported by the RSF grant №22-12-00271

Motivation

- So far only astronomical observations support the DM hypothesis and augment the data pointing at the lack of gravitational potentials.

- Dwarf spheroidal galaxies are excellent systems to probe the nature of fermionic dark matter due to their high observed dark matter phase-space density.

- The approach used in this work is mostly relevant for Warm DM models. As a physically motivated example we consider models with sterile neutrinos.

Bounds from Liouville’s theorem

Liouville’s theorem: For a collisionless and dissipationsless particle species the maximum of observed distribution function cannot increase throughout the cosmological evolution.

$$F_{prod}^{max} \geq F_{obs}^{max}$$

A simple model of DM production which predicts thethermal form of the sterile neutrino spectra:

$$F_{prod} = \frac{gN}{(2\pi)^3}\frac{1}{e^{p/T_\nu}+1} \qquad (1) \qquad \Rightarrow F_{prod}^{max} = \frac{11.16}{2(2\pi)^3}\left(\frac{\mathrm{eV}}{m}\right)$$

The well motivated approximation is treating the dwarf galaxy as a weakly non-equilibrium thermal system:

$$F_{obs} = \frac{\rho(r)}{(2\pi)^{3/2} m^4 (1-\beta)\sigma_r^3(r)} \exp\left(-\frac{1}{2}\left(\frac{v_r^2}{\sigma_r^2(r)} + \frac{v_\perp^2}{\sigma_\perp^2(r)}\right)\right) \qquad (2) \qquad \Rightarrow F_{obs}^{max} = \frac{1}{(2\pi)^{\frac{3}{2}} m^4} Q_{max}$$

where we introduce the velocity anisotropy parameter: $\beta(r) = 1 - \frac{\sigma_\perp^2(r)}{\sigma_r^2(r)}$

and $Q(r) = \frac{\rho(r)}{\big(1-\beta(r)\big)\sigma_r^2(r)}$

$$m_s \geq \left(\frac{2(2\pi)^{3/2} Q_{max}}{11.16\ \mathrm{eV}}\right)^{1/3}$$

Bounds from EMF function

Excess Mass Function(EMF): M. Kaplinghat, Phys. Rev. D 72, 063510 (2005)

$$D(f) = \int (F(x,p) - f)\Theta(F(x,p) - f)\mathrm{d}x\mathrm{d}p$$

$$D_{prod}(f) \geq D_{obs}(f) \quad \forall f$$

$$D_{prod}(f) = 4\pi V_{prim} T_\nu^3 \left(\frac{11.16}{2(2\pi)^3}\left(\frac{eV}{m}\right) \int_0^{\ln\left(\frac{11.16}{2(2\pi)^3}\left(\frac{eV}{m}\right)\frac{1}{f}-1\right)} \frac{\epsilon^2}{\mathrm{e}^\epsilon + 1}\,\mathrm{d}\epsilon - \frac{1}{3} f \ln^3\left(\frac{11.16}{2(2\pi)^3}\left(\frac{eV}{m}\right)\frac{1}{f} - 1\right)\right)$$

$$D_{obs}(f) = \int (4\pi r^2 \mathrm{d}r)\frac{\rho(r)}{m}\left(\mathrm{Erf}\left(\ln^{1/2}\left(\frac{Q(r)}{(2\pi)^{3/2} f m^4}\right)\right) - \left(\frac{Q(r)}{(2\pi)^{3/2} f m^4}\right)^{-1/(1-\beta)} \sqrt{\frac{1-\beta}{\beta}}\,\mathrm{Erfi}\left(\sqrt{\frac{\beta}{1-\beta}}\ln^{1/2}\left(\frac{Q(r)}{(2\pi)^{3/2} f m^4}\right)\right)\right)$$

$$-\frac{1}{3} f \int \left((4\pi)^2 r^2 \mathrm{d}r\right)(1-\beta(r))\left(2m^2\sigma_r^2(r)\ln\left(\frac{Q(r)}{(2\pi)^{3/2} f m^4}\right)\right)^{3/2}$$

Numerical analysis

Radial Jeans equation:

$$\frac{1}{\rho_*}\frac{\partial}{\partial r}\left(\rho_*(r)\sigma_{r*}^2(r)\right) + \frac{2\beta_*(r)}{r}\sigma_{r*}^2(r) = -G\,\frac{M_{tot}\,(< r)}{r^2}$$

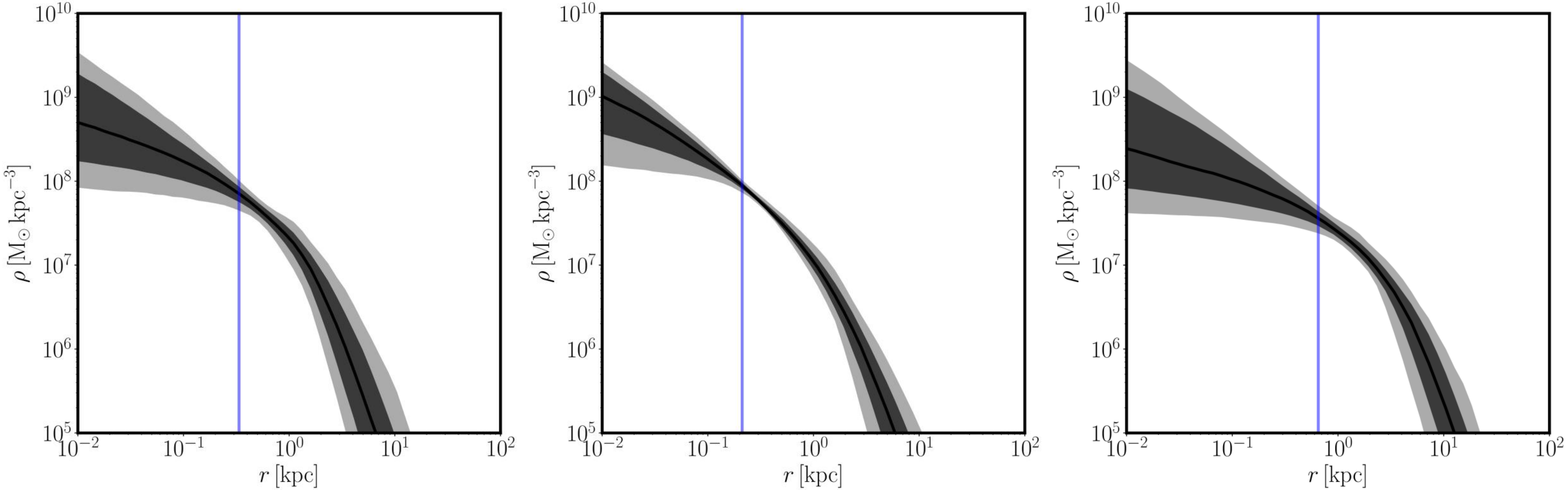
$$\frac{1}{\rho}\frac{\partial}{\partial r}\left(\rho(r)\sigma_r^2(r)\right) + \frac{2\beta(r)}{r}\sigma_r^2(r) = -G\,\frac{M_{tot}(< r)}{r^2}$$

where $\sigma_{r*}^2(r)$ and $\rho_*(r)$ must fit the observed parameters $\sigma_{LOS}^2(R)$ and $\Sigma_*(R)$

$$\sigma_{LOS}^2(R) = \frac{2}{\Sigma_*(R)}\int_R^\infty \left(1 - \beta\,\frac{R^2}{r^2}\right)\frac{\rho_*(r)\sigma_{r*}^2(r)r}{\sqrt{r^2 - R^2}}\,\mathrm{d}\,r$$

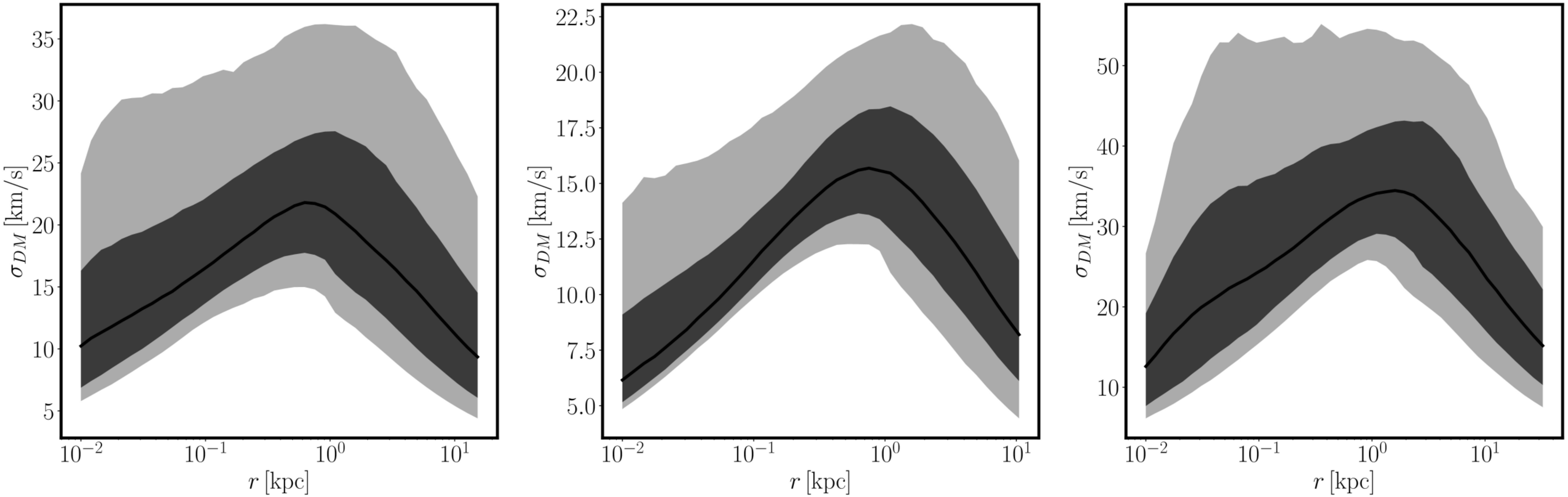
Equations above can be solved using MCMC method

Numerical analysis



GravSphere numerical approximation to $\rho(r)$ for Aquarius Dwarf (left panel), Sculptor Dwarf Galaxy (middle panel) and WLM Galaxy (right panel). The dark blue vertical lines indicate the position of half-light radius.

Numerical analysis



GravSphere numerical approximation to $\sigma(r)$ for Aquarius Dwarf (left panel), Sculptor Dwarf Galaxy (middle panel) and WLM Galaxy (right panel). The dark blue vertical lines indicate the position of half-light radius.

Results

Lower bounds on m_s[keV] at 95%CL for first 9 galaxies used in this analysis

Name	Liouville's theorem	EMF
Andromeda V	0.71	1.88
Aquarius	0.46	1.13
Bootes	0.82	2.02
Carina	0.48	1.09
Cetus	0.82	2.17
Coma	0.55	1.26
CVn I	0.41	1.00
Draco	0.47	1.06
Fornax	0.47	1.20

Additional models

G. B. Gelmini, P. Lu and V. Takhistov, JCAP 12, 047 (2019)

Model I: The Universe expansion is supposed to be dominated by kinetic term of some scalar field

$$F_{prod,I} \propto \sqrt[3]{\frac{p}{T_\nu}} \left(\frac{m}{\mathrm{keV}}\right)^{2/3} \frac{1}{e^{p/T_\nu}+1} \qquad (3)$$

Model II: The Universe reheats very late

$$F_{prod,II} \propto \frac{p}{T_\nu} \frac{1}{e^{\frac{p}{T_\nu}} + 1} \qquad (4)$$

Results

Lower bounds on m_s[keV] at 95%CL for first 9 galaxies used in this analysis

Name	Model I		Model II	
	Liouville's theorem	EMF	Liouville's theorem	EMF
Andromeda V	1.53	2.45	3.00	4.47
Aquarius	1.15	1.77	2.15	3.08
Bootes	1.68	2.57	3.34	4.77
Carina	1.18	1.74	2.22	3.03
Cetus	1.68	2.68	3.34	4.97
Coma	1.31	1.91	2.50	3.41
CVn I	1.07	1.64	1.97	2.82
Draco	1.17	1.71	2.20	2.98
Fornax	1.17	1.84	2.20	3.21

Conclusions

- For non-resonant production of sterile neutrinos

Liouville's theorem: $m_s \geq 1.02$ keV

EMF: $m_s \geq 1.98$ keV

- For model I: $m_s \geq 2.54$ keV

- For model II: $m_s \geq 4.71$ keV

Thank you for your attention!