Microlensing constraints on extended dark matter structures from Subara-HSC

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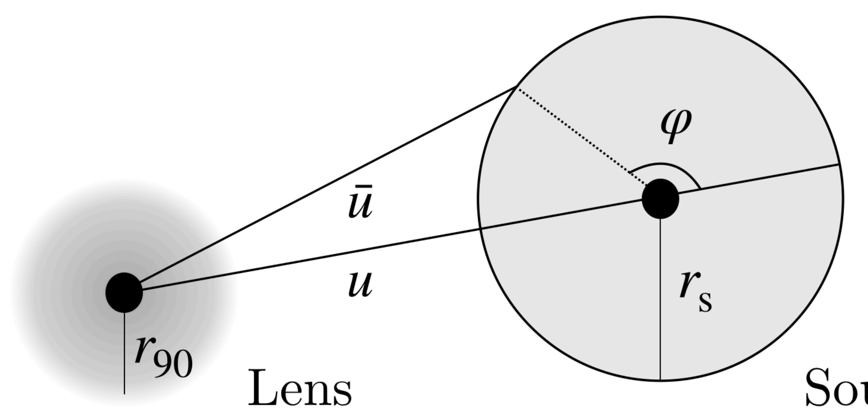
Microlensing of an extended star by an extended lens

A number of gravitational microlensing surveys have been conducted to search for primordial black holes (PBHs) in nearby dark matter halos (Nilkura et al, Nat. Astron. 2018). In many DM models, spatially extended structures are predicted in the form of exotic compact objects and subhalos. Examples include axion miniclusters, ultracompact minihalos, boson stars, mirror stars, etc. Establishing mircolensing limits on these extended DM structures requires us to to recast the existing microlensing limits on PBHs. One essential step is to investigate the microlensing signal produced by a non-pointlike lens (Croon et al, PRD 2020).

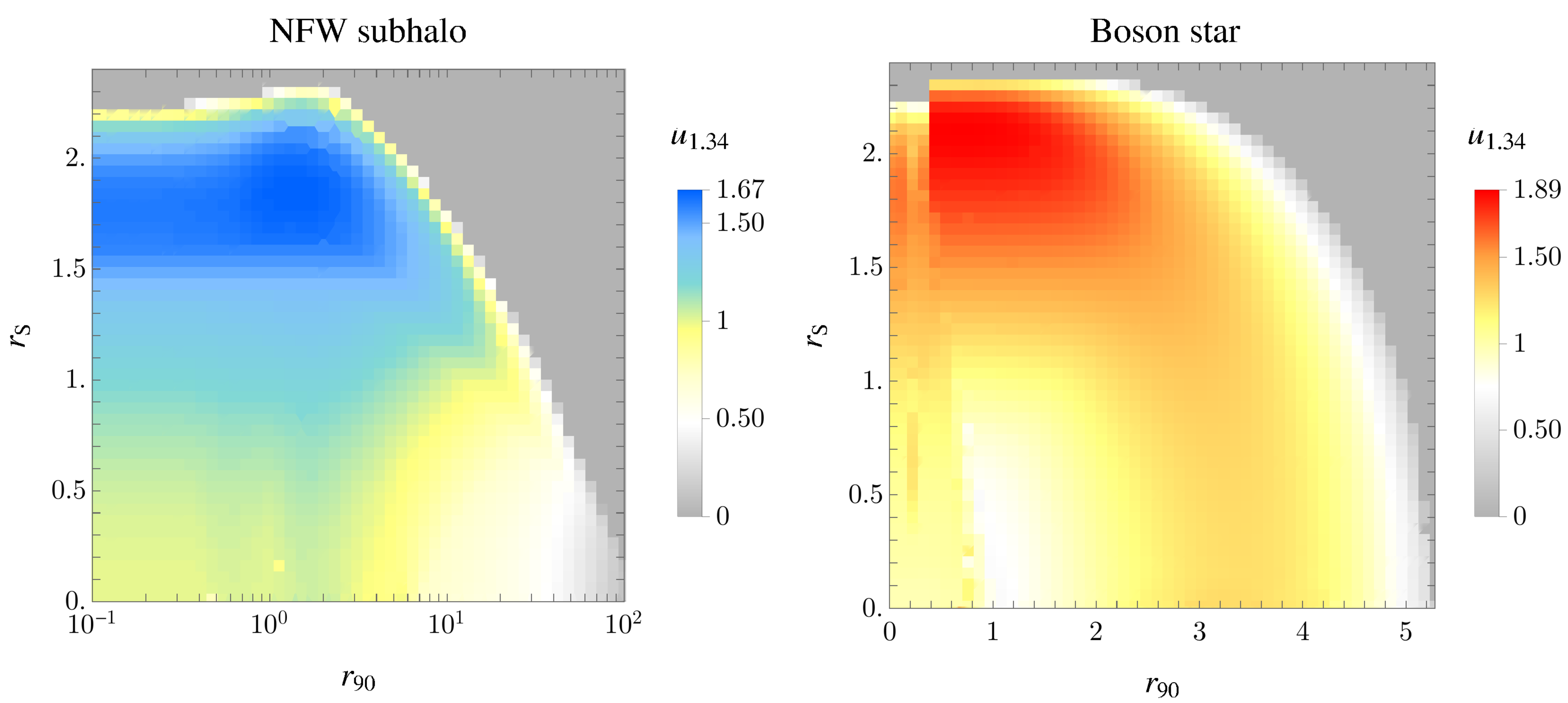
An important scale in gravitational lensing is the Einstein radius $R_E = \sqrt{\frac{4GMD_S}{c^2}x(1-x)}$, where M is the lens mass and $x \equiv D_L/D_S$ with D_L and D_S the lens-observer and source-observer distance. We shall express physical length scales by upper case letters and dimensionless length scales in unit of R_E by lower case letters. On the lens plane, the lens size and source size are r_{90} and $r_S = xR_\star/R_E$ respectively. The geometry of the setup is depicted in the figure below, with u being the lens-source distance, $\bar{u}(\varphi) = \sqrt{u^2 + r_S^2 + 2ur_S\cos\varphi}$ being the distance from a point on the edge of the source to lens.



For every infinetesimal point on the edge of the source, the lensing equation which relates the true position of the point and the image can be written as $\bar{u}(\varphi) = t(\varphi) - m(t(\varphi))/t(\varphi)$, where $m(t)$ is the projected lens mass enclosed within t. The magnification of each images is (Witt et al, APJ 1994)

$$\mu_i = \eta \frac{1}{\pi r_S^2} \int_0^{2\pi} d\varphi \, \frac{1}{2} t_i^2(\varphi), \tag{1}$$

where $\eta = \mathrm{sign}(dt_i^2/d\bar{u}^2|_{\varphi=\pi})$ is the "parity" of the image. The total magnification $\mu_{\rm tot}$ is the sum of individual μ_i. In typical microlensing surveys, an event is called if the magnification exceeds 1.34. By numerically solving these equations, we find the impact parameter $u_{1.34}$ corresponding to $\mu_{\rm tot} = 1.34$. For NFW subhalos and boson stars, we obtain $u_{1.34}$ as a function of r_{90} and r_S in the figure below.



Results

If the mass fraction of lenses in the DM halo is $f_{\rm DM}$ and all the lens have an identical mass M and size R_{90}, the lensing rate of a particular background star with size $R_\star$ is given by (Griest, APJ 1990)

$$\frac{d^2\Gamma}{dx dt_E} = f_{\rm DM}\varepsilon(t_E, R_\star)\frac{2D_S}{v_0^2 M}\rho(x)v_E^4(x)e^{-v_E^2(x)/v_0^2}, \tag{2}$$

where $\rho(x)$ is the local DM density projected along the line of sight, ε is the detector efficiency, $v_E(x) = 2u_{1.34}(x)(x)/t_E$ and v_0 is the DM circular velocity. The expected number of events is

$$N_{\rm events} = N_\star T_{\rm obs}\int dt_E \int dR_\star \int_0^1 dx \frac{d^2\Gamma}{dx dt_E}\frac{dn}{dR_\star}, \tag{3}$$

where $N_\star$ is the number of stars, $T_{\rm obs}$ is the net observation time, and $dn/dR_\star$ is the (normalized) stellar radius distribution of the source stars. The Subaru-HSC survey is towards M31, and we take $dn/dR_\star$ derived in (Smyth et al, PRD 2019). At 95% CL, the survey finds $N_{\rm events} \leq 4.74$ and we show the corresponding upper limits on $f_{\rm DM}$ in the figure below. Deviations from PBHs limits become visible for lens size larger than $\mathcal{O}(0.1R_\odot)$, and lenses up to $\mathcal{O}(10^3 R_\odot)$ can be probed by Subaru-HSC. Constraints from EROS-2 and OGLE-IV surveys are also shown.