Gravitational microlensing by dark matter subhalos and boson stars

SUSY 2021

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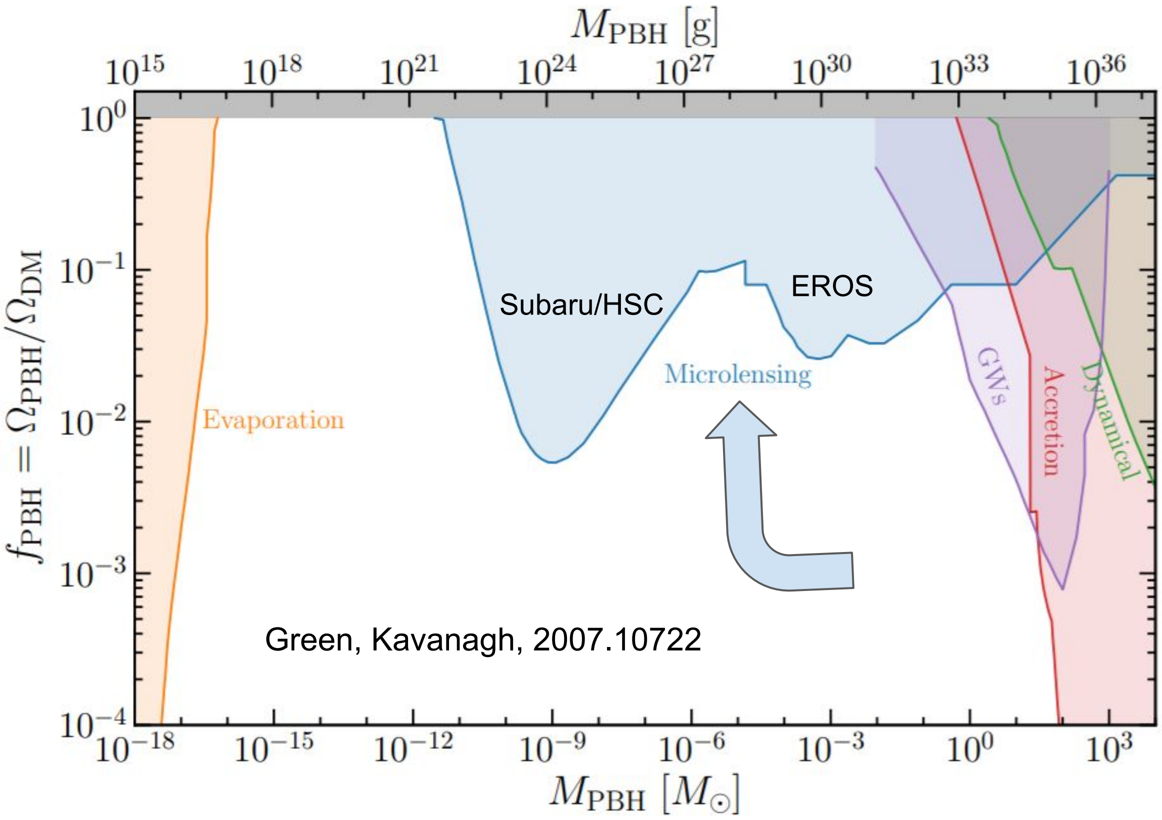
Based on 2007.12697

With Djuna Croon, David McKeen, Nirmal Raj

Primordial black hole dark matter



Stellar microlensing surveys:

Subaru/HSC
(M31 Andromeda)

EROS
(Large Magellanic Clouds)

...

Microlensing basics

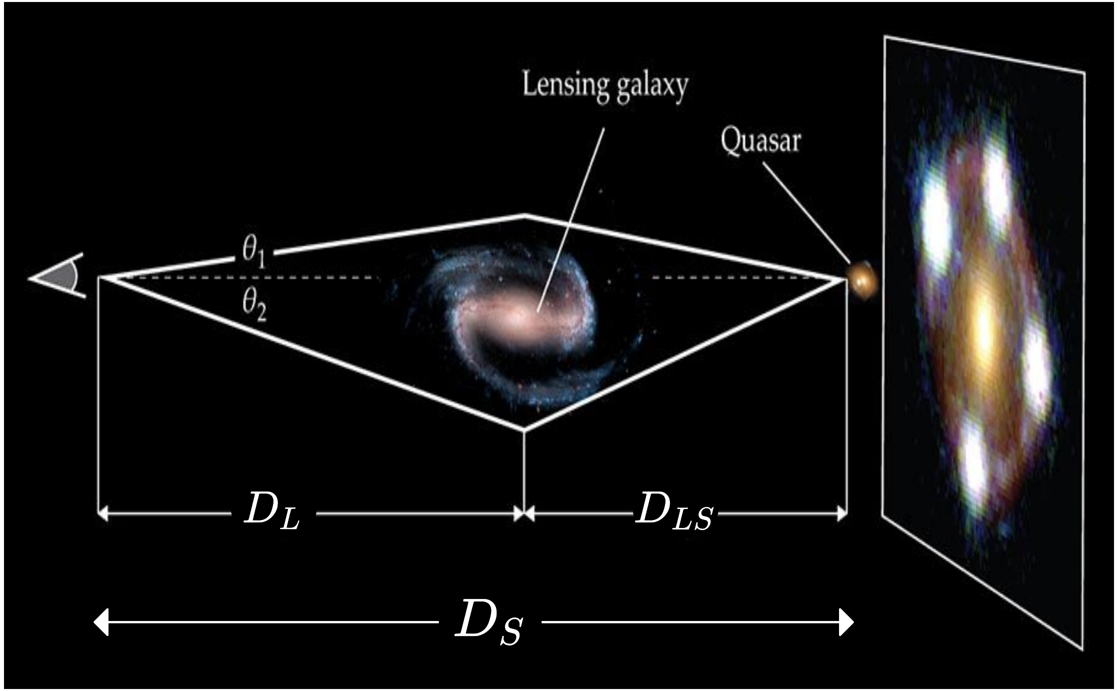


Image credit: Freddie Pagani

Separation of images ~ Einstein radius

$$x = D_L / D_S$$

$$R_E = \sqrt{\frac{4GMD_S}{c^2} x(1-x)}$$

Microlensing: small Einstein radius so individual images are not resolved

Microlensing basics

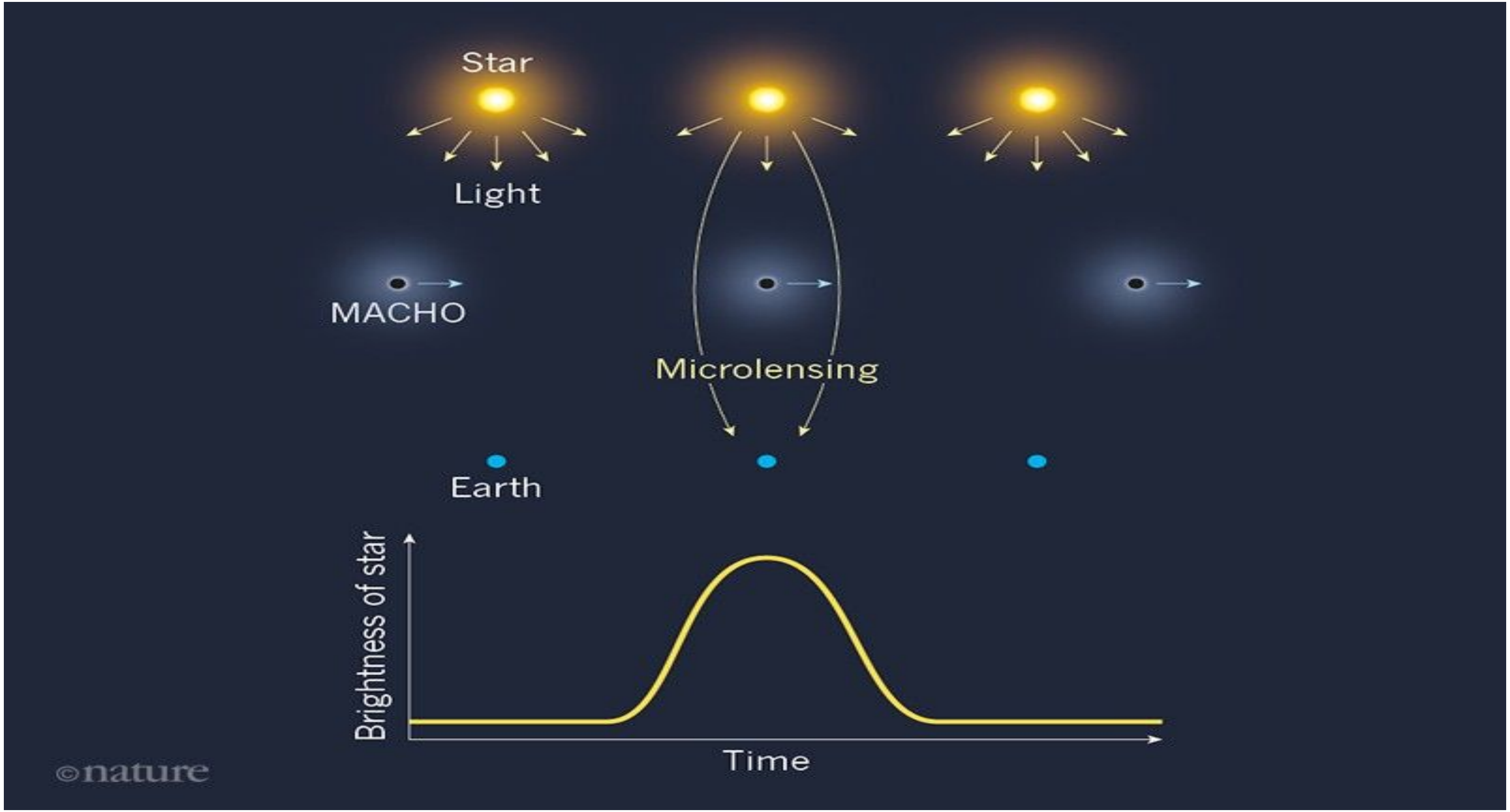


Image credit: Grzegorz Pietrzynski

Microlensing basics

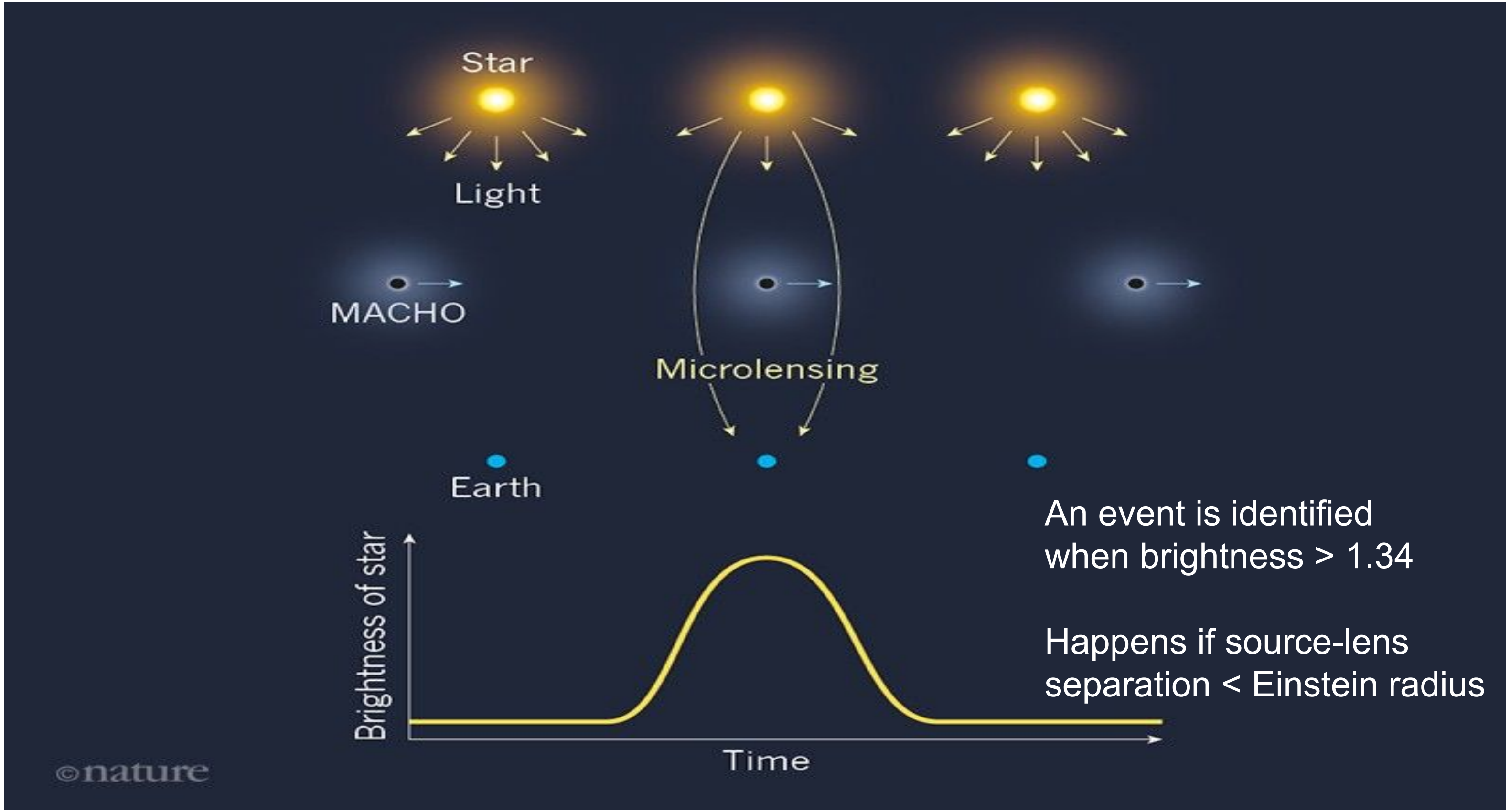


Image credit: Grzegorz Pietrzynski

Extended dark matter structures

- PBHs are treated as point-like lenses. In general, many DM models predict spatially extended structures:

  Axion miniclusters, ultracompact minihalos, axion stars, boson stars…

- WIMP subhalos minimum mass ~ 10^-6 M⊙ (free streaming length)

- Recasting microlensing limits on PBHs to constrain these extended structures is feasible, but not *obvious*.

  Fairbairn, Marsh, Quevillon, Rozier, 1707.03310
  Croon, Mckeen, Raj, 2002.08962
  Bai, Long, Lu, 2003.13182

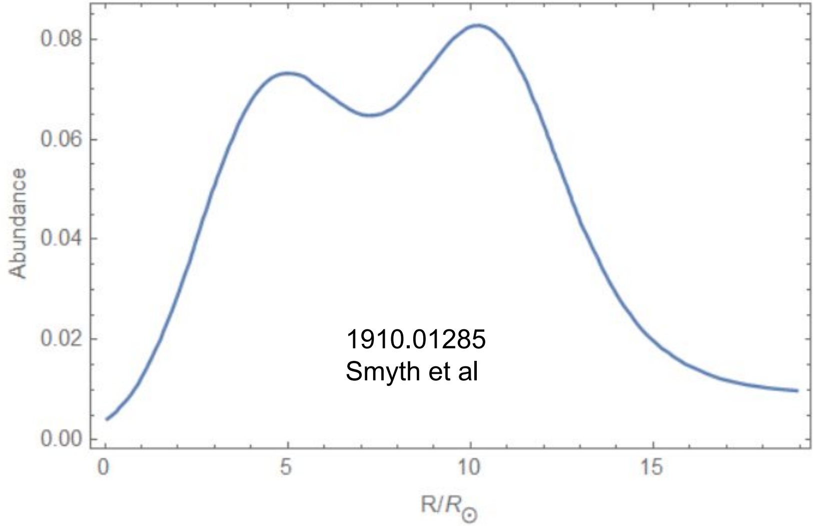
- In this talk: study lenses that have an **NFW** profile and a **boson star** profile.

Finite-size source effect

- Source size effect important for size ~ Einstein radius. Typically, larger source -> weaker brightness magnification
  Witt, Mao, ApJ 430, 505
  Montero-Camacho et al, 1906.05950

- Stars in M31 are large!

- Crucial question: the source-lens separation that produces a magnification of 1.34



The bigger the star, the more important finite-source-size effects!

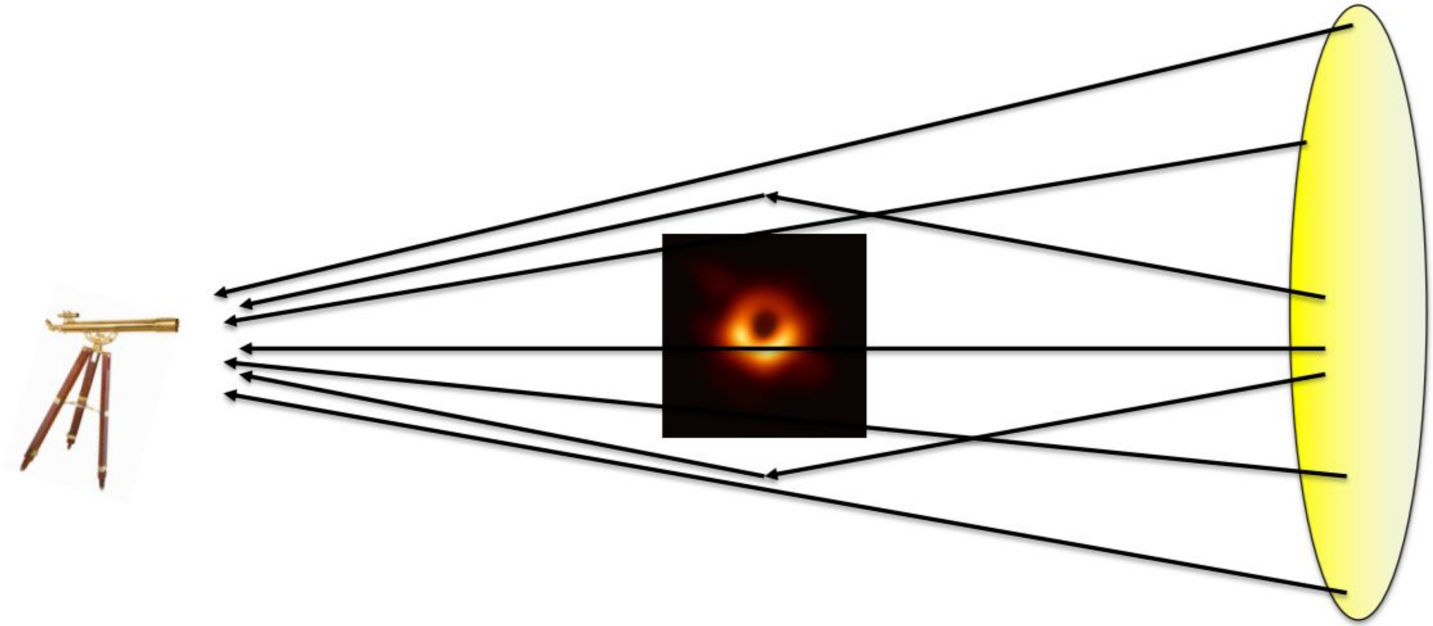
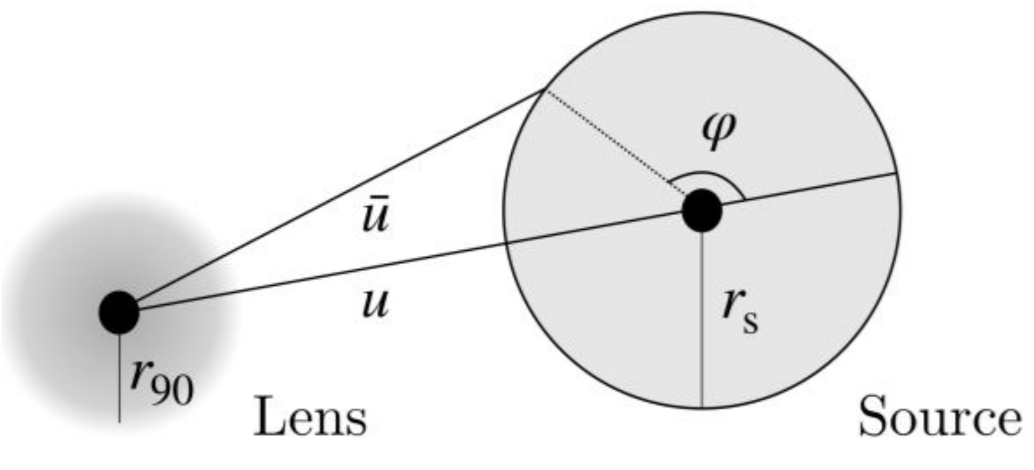


Image credit: Stefano Profumo

Microlensing of a finite-size source by a finite-size lens



Step 1

For every point on the source, where are the images produced by it?

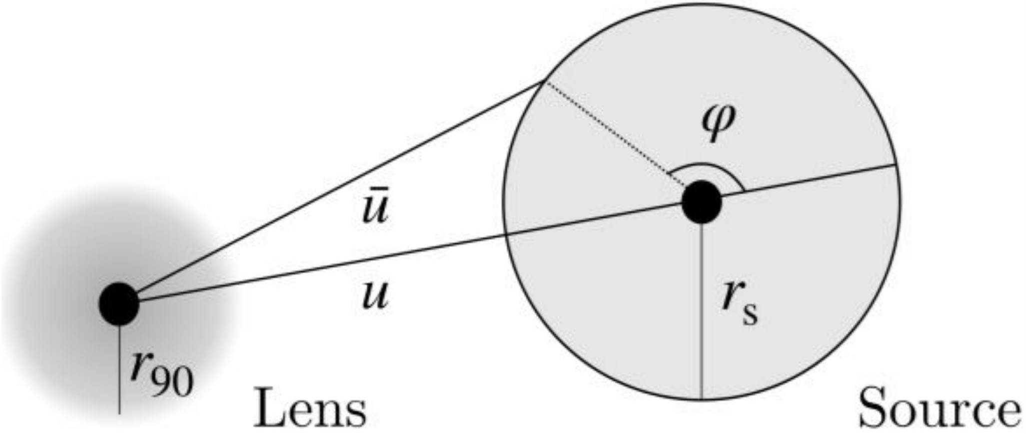
Lensing equation:

$$\bar{u}(\varphi) = t(\varphi) - \frac{m(t(\varphi))}{t(\varphi)}$$

t: position of the image from the lens
m(t): projected lens mass within *t*

All length scales are in unit of Einstein radius

Microlensing of a finite-size source by a finite-size lens



Step 2

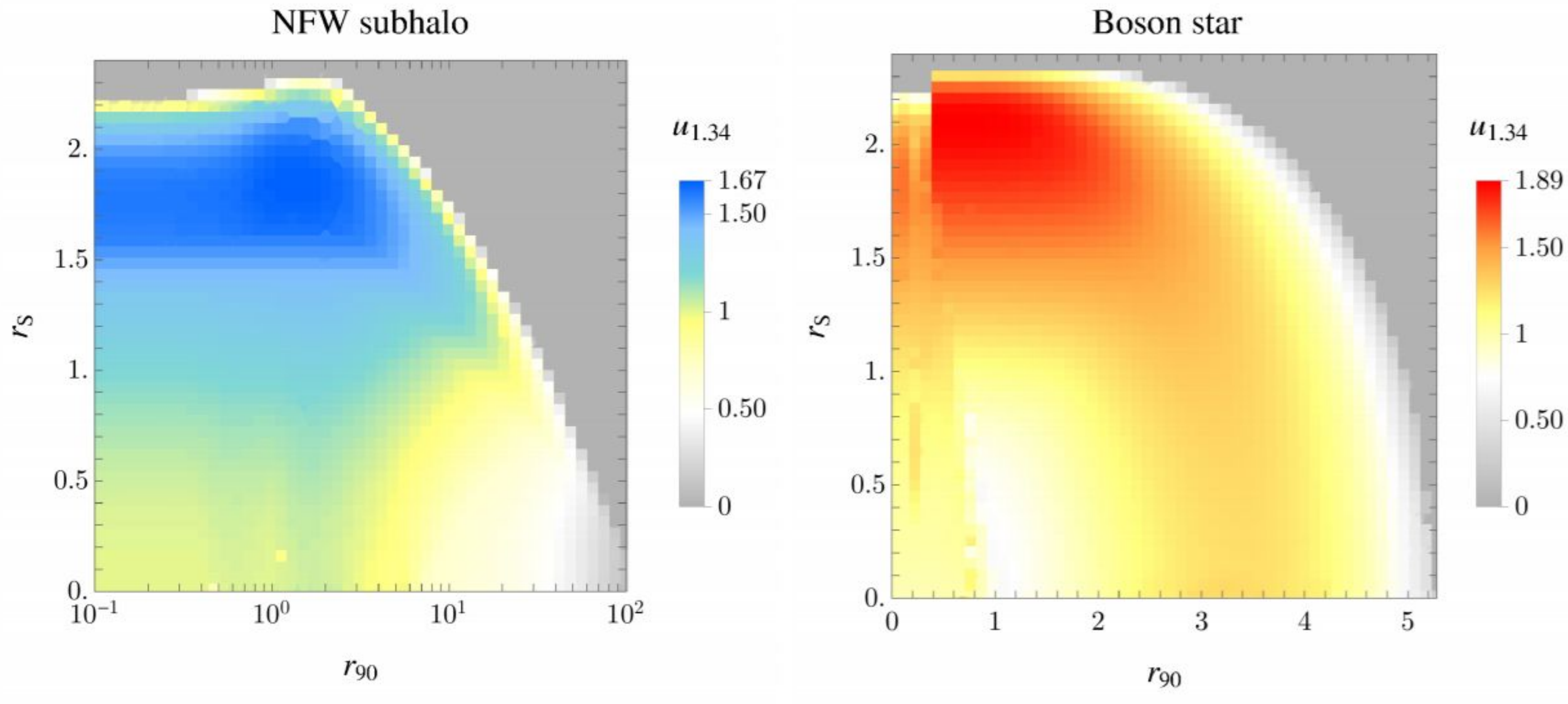
Total brightness:

$$\mu = \sum_i \frac{1}{\pi r_{\mathrm{S}}^2} \left| \int_0^{2\pi} d\varphi \, \frac{1}{2} t_i^2(\varphi) \right|$$

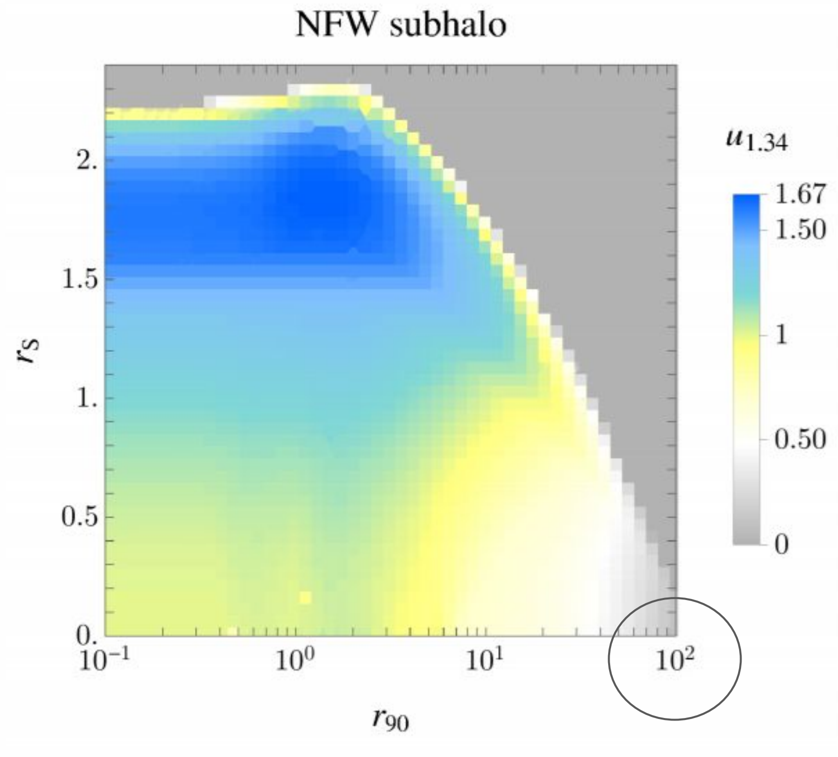
$u_{1.34}$ is the value of *u* which solves $\mu = 1.34$

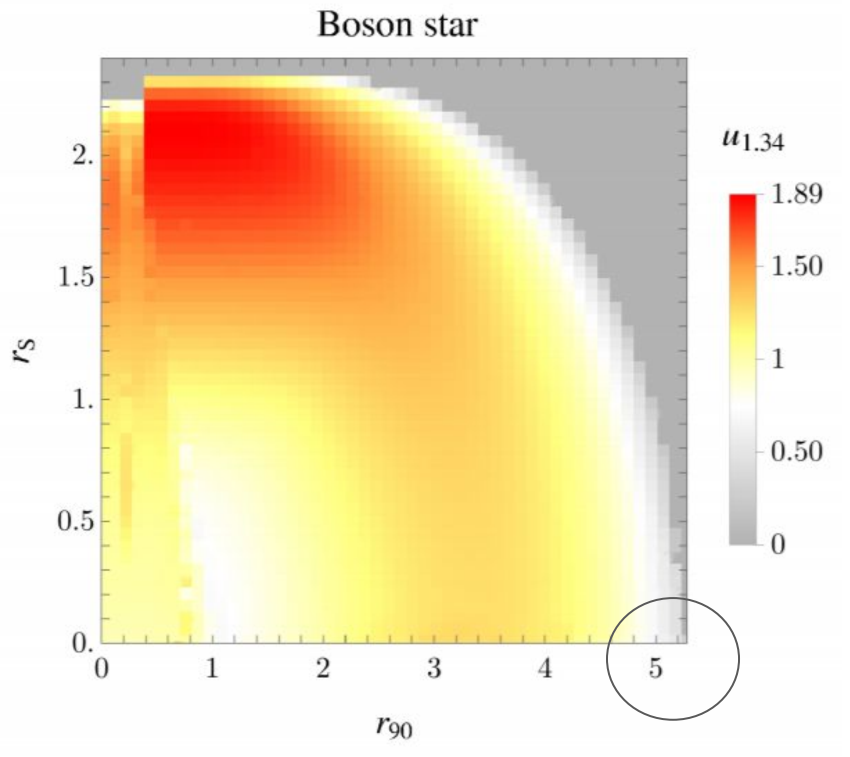
All length scales are in unit of Einstein radius

$u_{1.34}$ with finite-size source + finite-size lens



$u_{1.34}$ with finite-size source + finite-size lens





Lensing rate

Lensing rate of a lens *M* per unit time per x per source star with radius *Rs*

$$\frac{d^2\Gamma}{dxdt} = f_{\rm DM}\,\varepsilon(t, R_S)\,\frac{2D_S}{v_0^2 M}\,\rho(x)v^4(x)e^{-v^2(x)/v_0^2}$$

Abundance fraction

Detector efficiency

DM circular velocity ~ 220 km/s

DM halo density

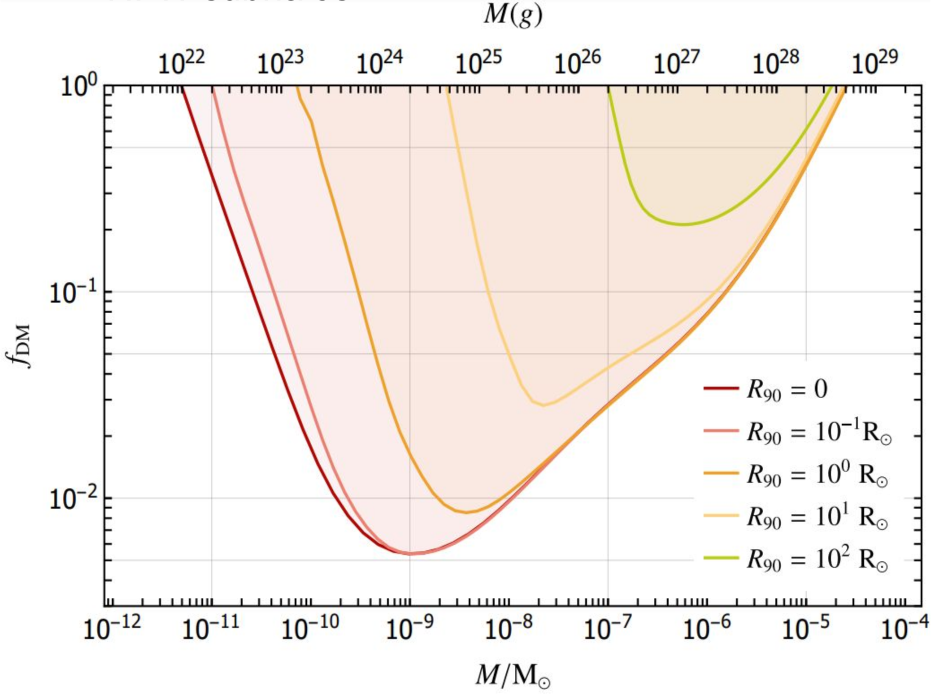
$$v = 2u_{1.34}R_E/t$$

Characteristic velocity of crossing the lensing tube

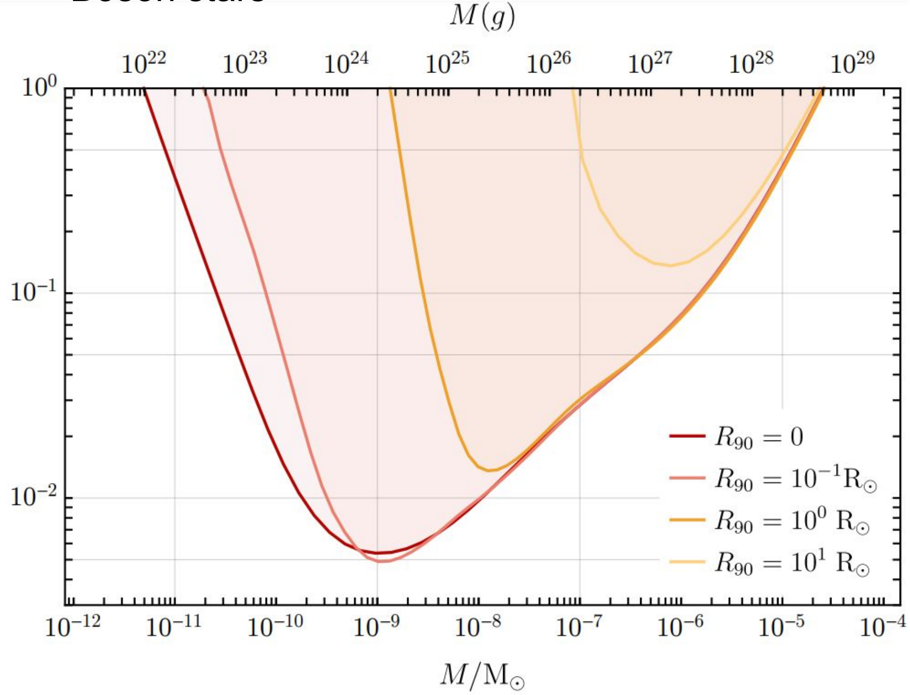
Integrate over *x*, *t*, *Rs* to obtain total expected number of events

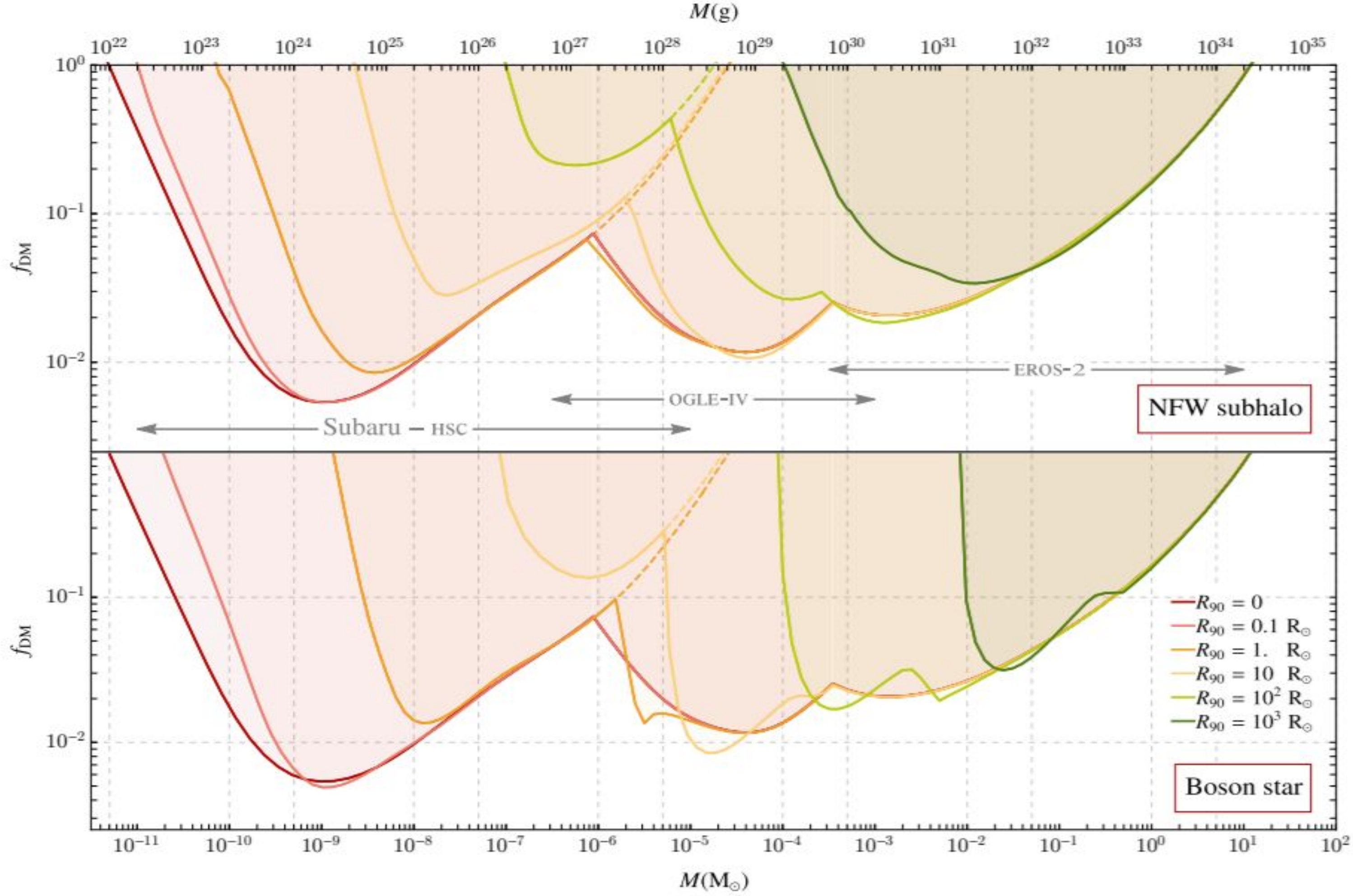
Subaru/HSC constraints

NFW subhalos

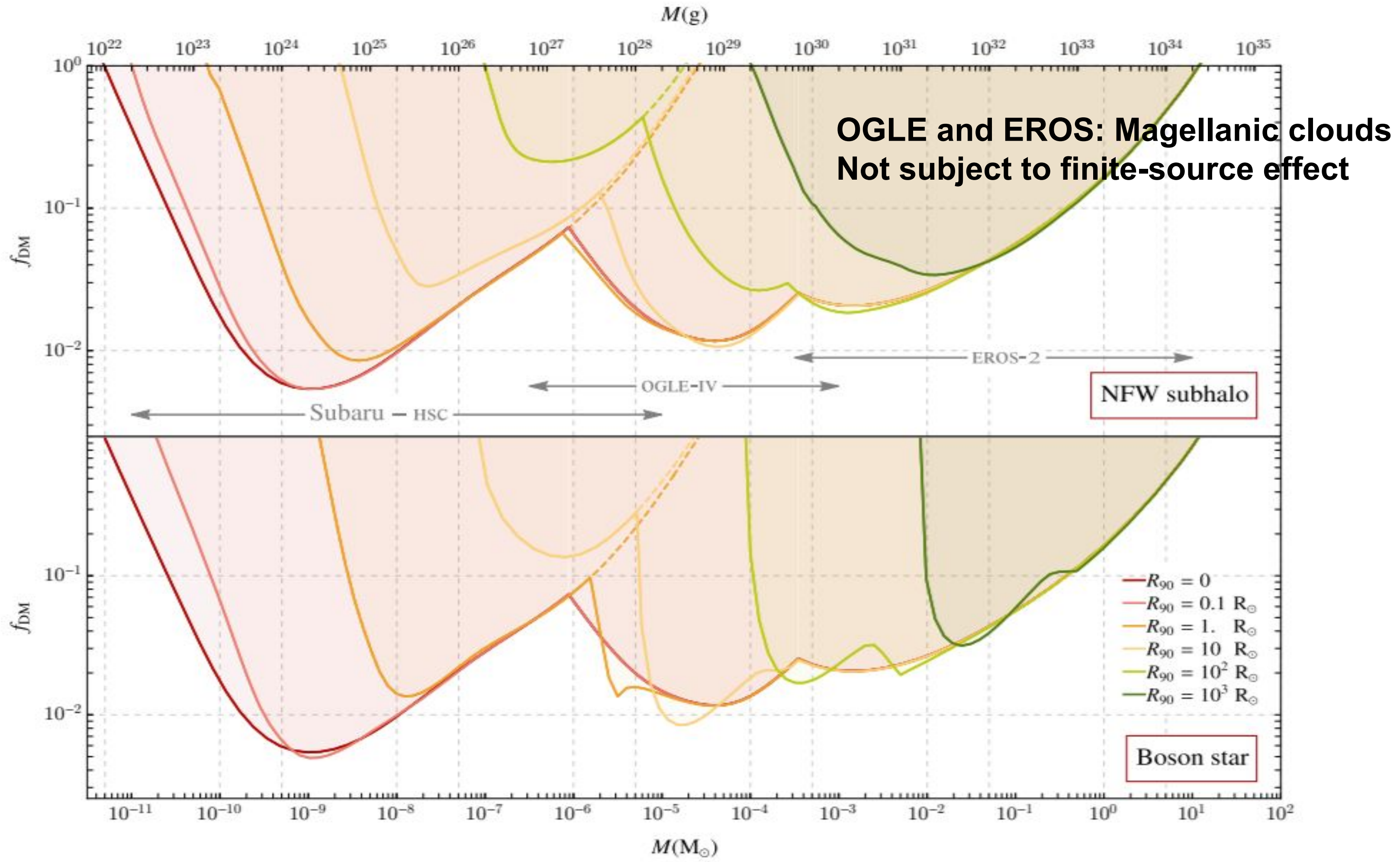


Boson stars





M(g)
f_{DM}
$M(M_\odot)$
Subaru – HSC
OGLE-IV
EROS-2
NFW subhalo
Boson star
$R_{90} = 0$
$R_{90} = 0.1\ R_\odot$
$R_{90} = 1.\ R_\odot$
$R_{90} = 10\ R_\odot$
$R_{90} = 10^2\ R_\odot$
$R_{90} = 10^3\ R_\odot$



M(g)
OGLE and EROS: Magellanic clouds
Not subject to finite-source effect
EROS-2
OGLE-IV
Subaru – HSC
NFW subhalo
Boson star
$R_{90} = 0$
$R_{90} = 0.1\ R_\odot$
$R_{90} = 1.\ R_\odot$
$R_{90} = 10\ R_\odot$
$R_{90} = 10^2\ R_\odot$
$R_{90} = 10^3\ R_\odot$
f_{DM}
$M(M_\odot)$

Conclusions and outlook

- Present microlensing surveys can probe compact DM structures smaller than ~ 100 solar radii. Increasing lens size → weaker constraint.

- Geometric optics. Interference important for lighter lenses.

- Inferring lens profile requires time domain analysis of light curves.

Thank you!