Gravitational microlensing by dark matter subhalos and boson stars

IAS high energy program 2021

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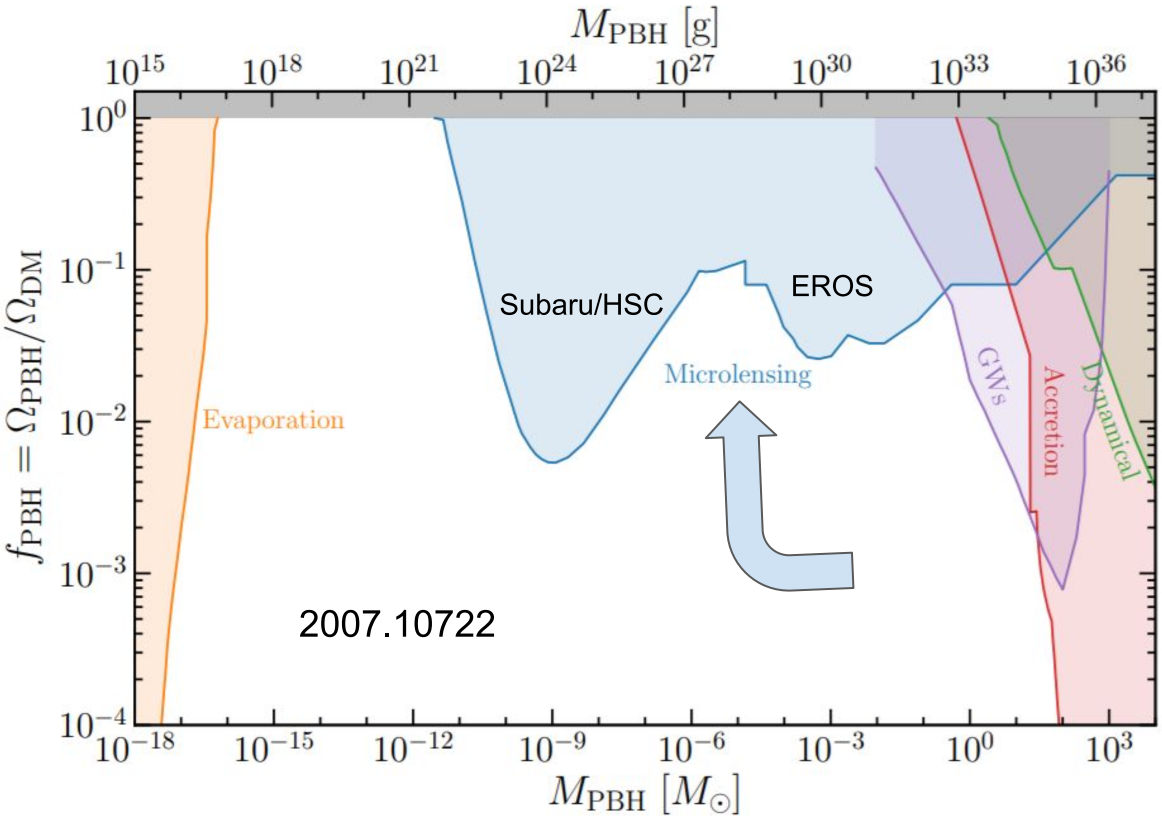
Primordial black hole dark matter



Subaru/HSC

EROS

2007.10722

Stellar microlensing surveys

Subaru/HSC
(M31 Andromeda)

EROS
(Large Magellanic Clouds)

...

Extended dark matter structures

- PBHs are treated as point-like lenses. In general, many DM models predict extended structures which can’t be considered point-like:

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

- CDM subhalos minimum mass ~ 10^-6 M⊙ (WIMP free streaming length)
- Recasting microlensing limits on PBHs to constrain these extended structures is feasible, but not *obvious*.
- In this talk: study lenses that have an **NFW** profile (peaked) and a **boson star** profile (nonpeaked).

Microlensing basics

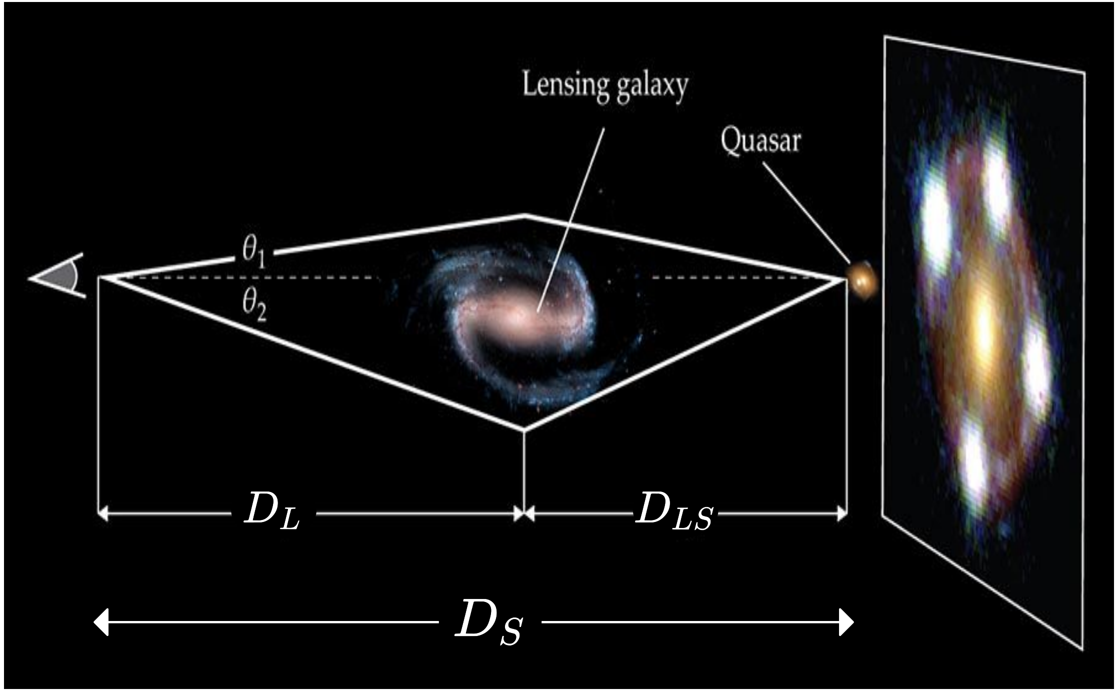


Image credit: Freddie Pagani

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

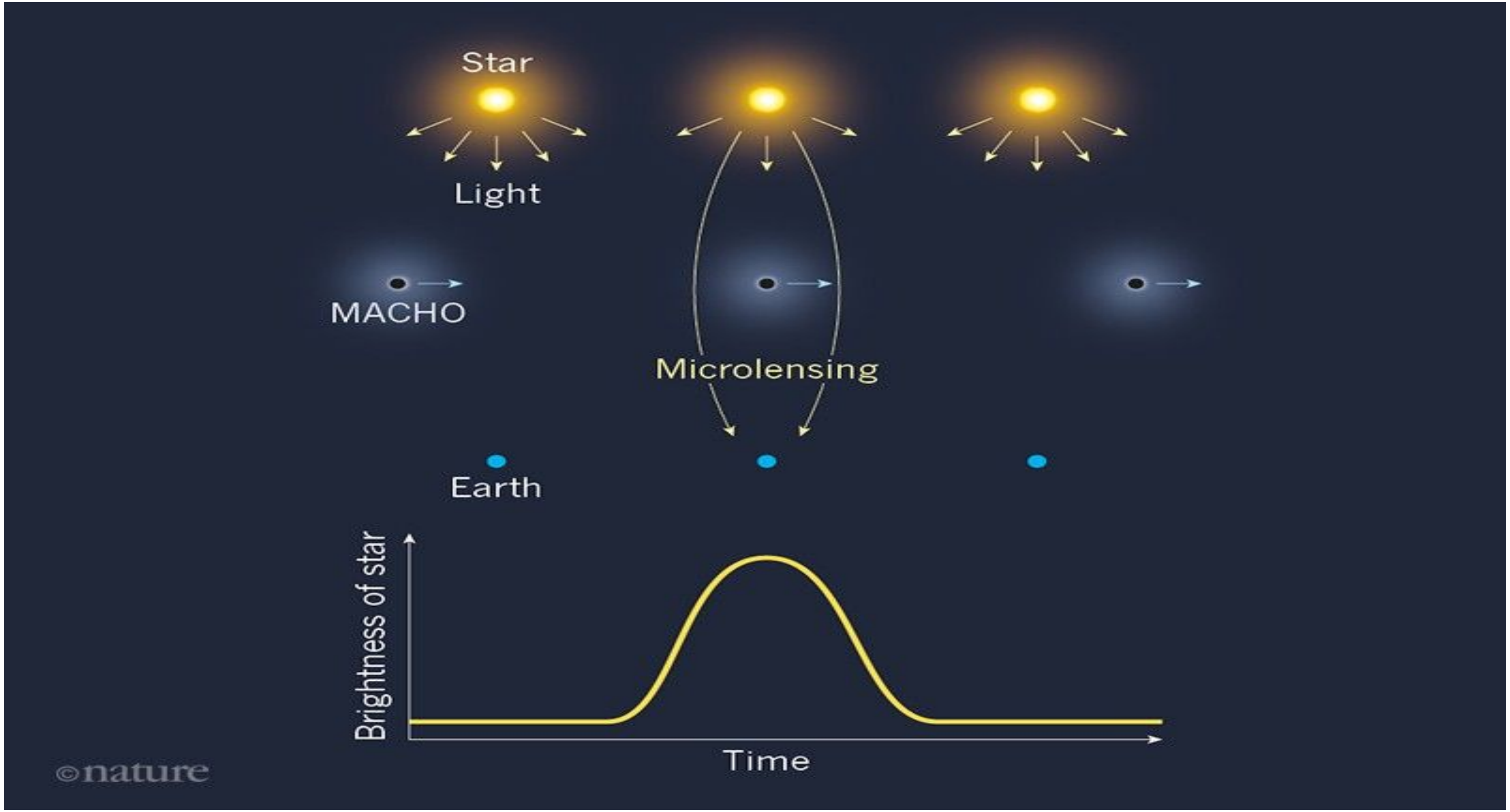
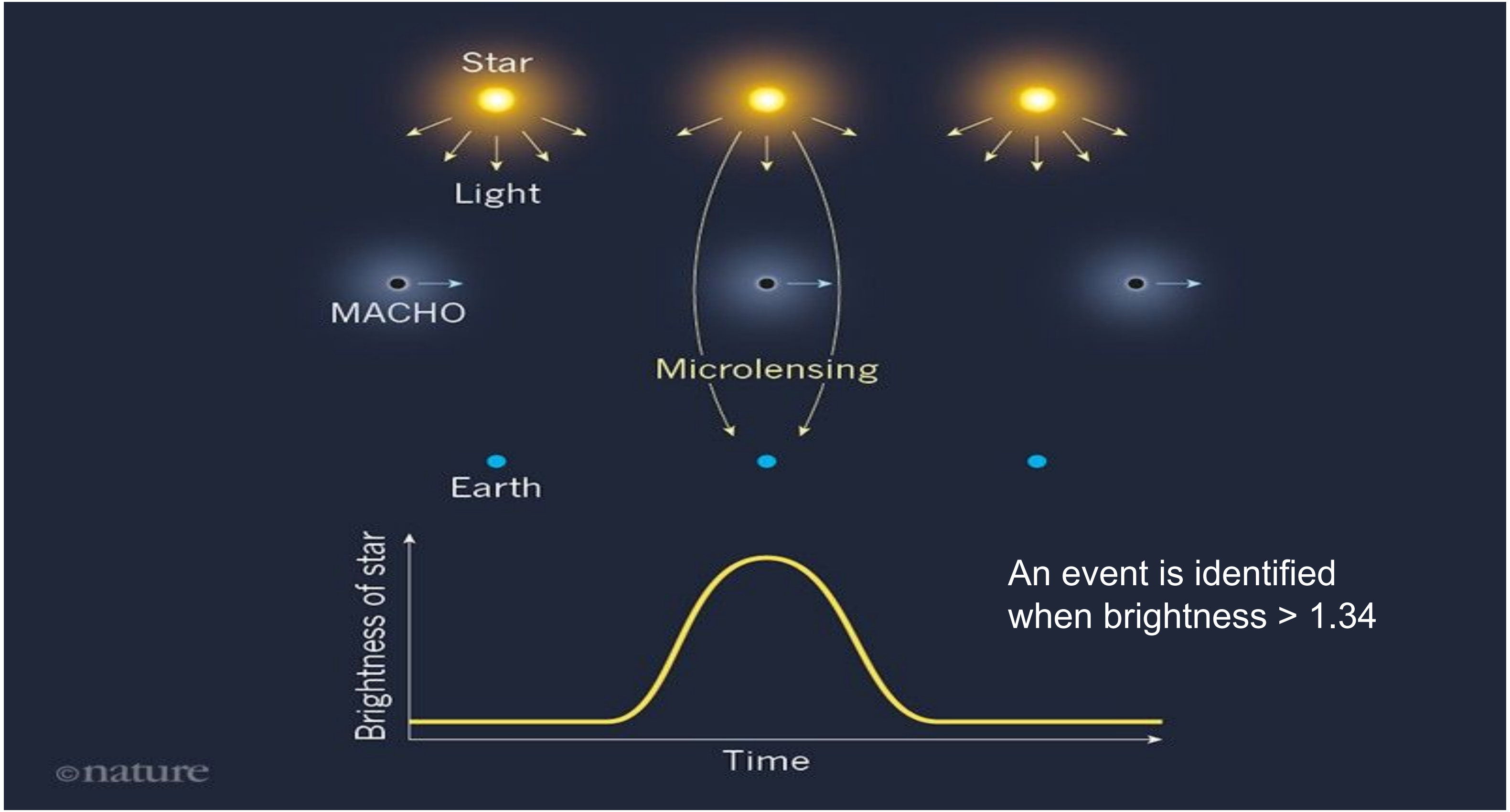


Image credit: Grzegorz Pietrzynski

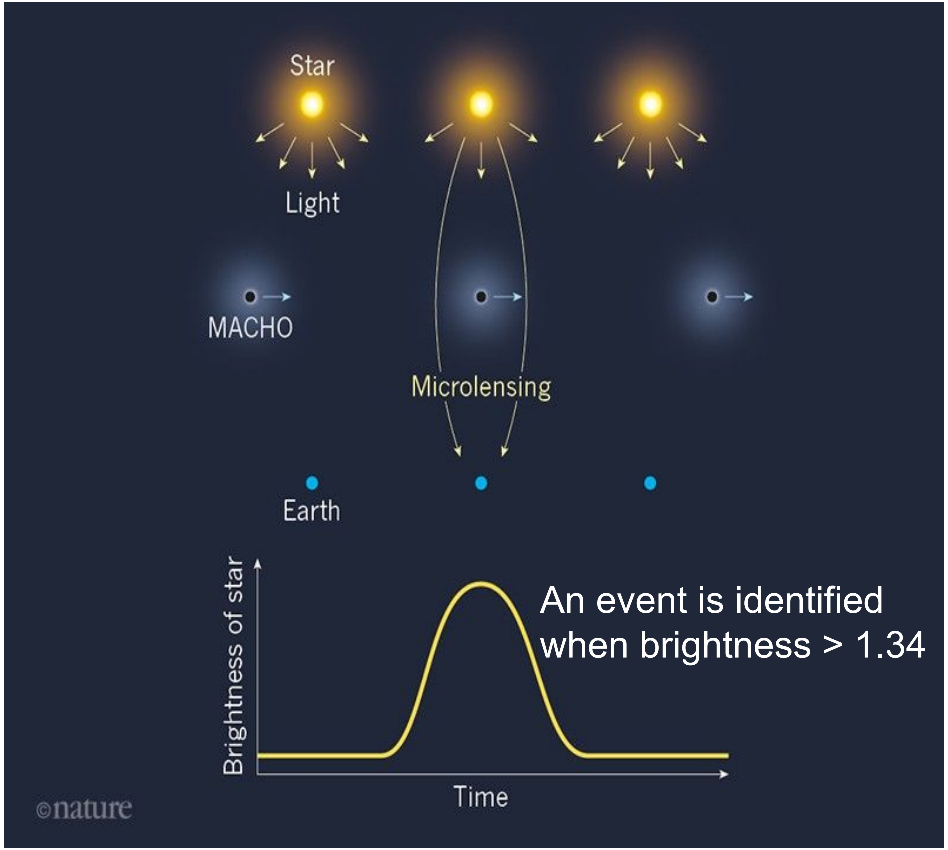
Microlensing basics



An event is identified when brightness > 1.34

Image credit: Grzegorz Pietrzynski

Microlensing basics



An event is identified when brightness > 1.34

- 1.34 is not a random number: Achieved when the source-lens separation = Einstein radius (lensing tube).
- If the lens is part of a DM halo, relative motion between lens and source is provided by circular velocity ~ 220 km/s.
- Rate of a lensing tube capturing the source → statistical bounds on the abundance of lenses in a DM halo.

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

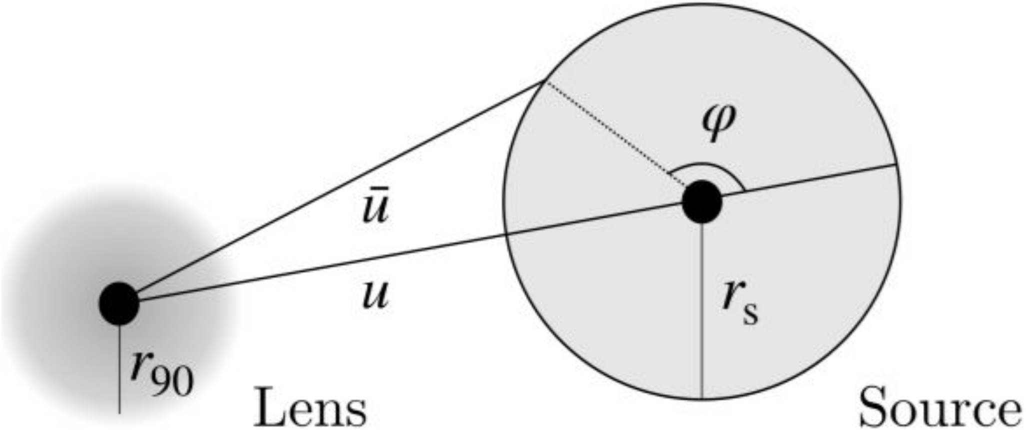
- So far both lenses and sources are assumed point-like.

- Point-like lens approximation invalid when lens size is comparable to Einstein radius.

- Point-like source invalid when the projected size of the source on the lens plane comparable to Einstein radius.

- What’s the radius of the lensing tube?

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



Step 1

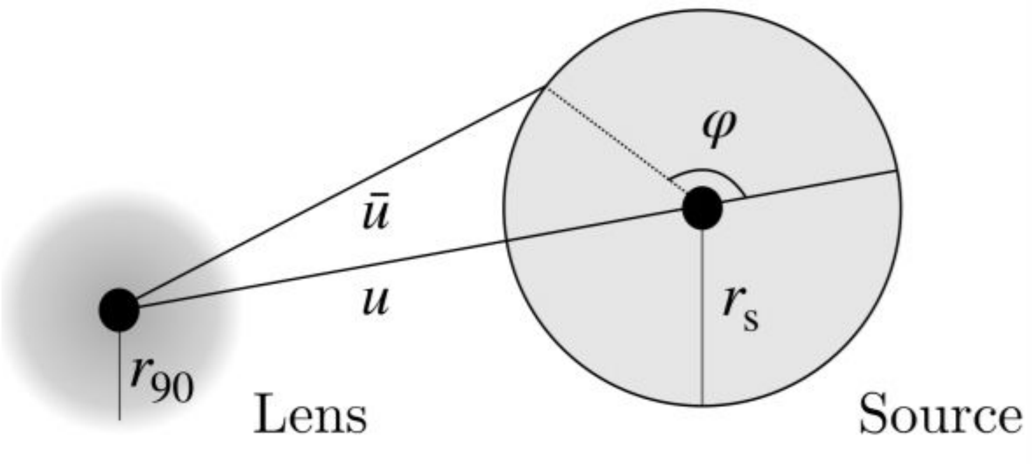
Lensing equation:

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

For every $\bar{u}$, find the position of the Image t. In general, there are multiple solutions t_i.

All length scales are in unit of Einstein radius

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



Step 2

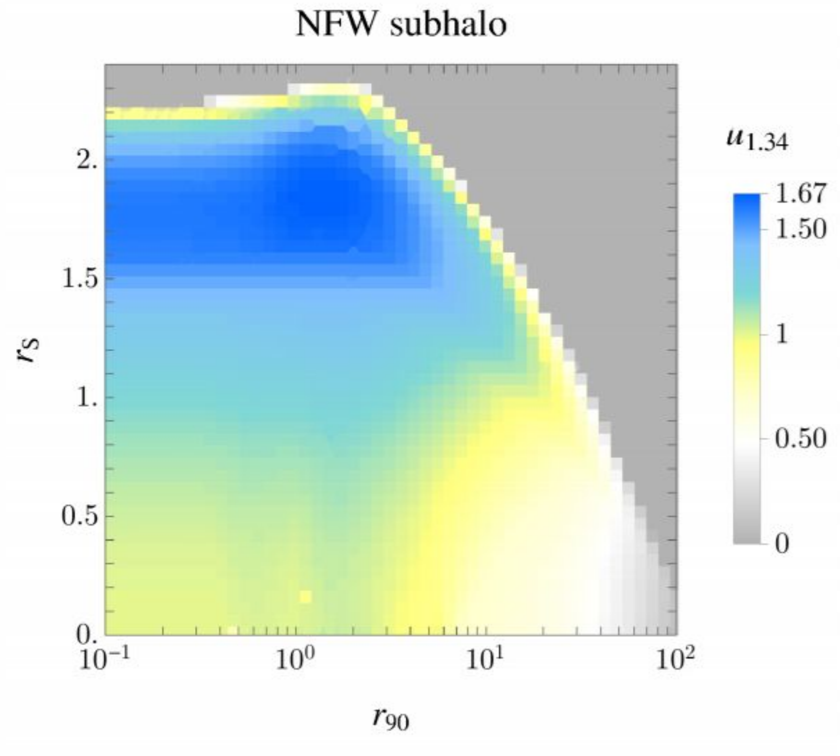
Total brightness:

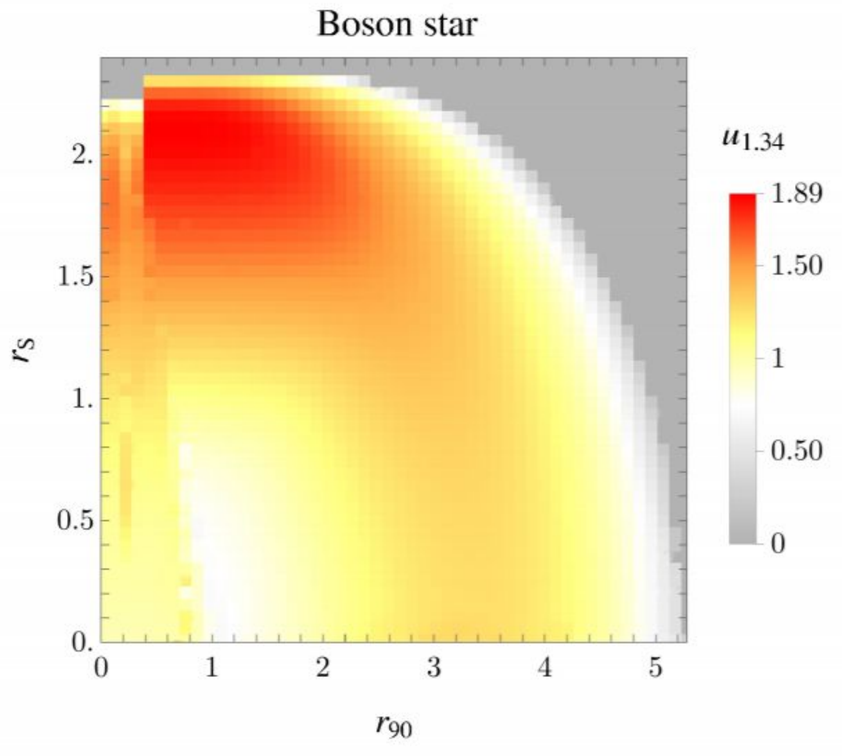
$$\mu = \sum_i \frac{1}{\pi r_{\mathrm{S}}^2} \left| \int_0^{2\pi} d\varphi \, \frac{1}{2} t_i^2(\varphi) \right|$$

The radius of the lensing tube, $u_{1.34}$, is the value of *u* which solves $\mu = 1.34$

All length scales are in unit of Einstein radius

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





Lensing rate

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

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

Abundance fraction

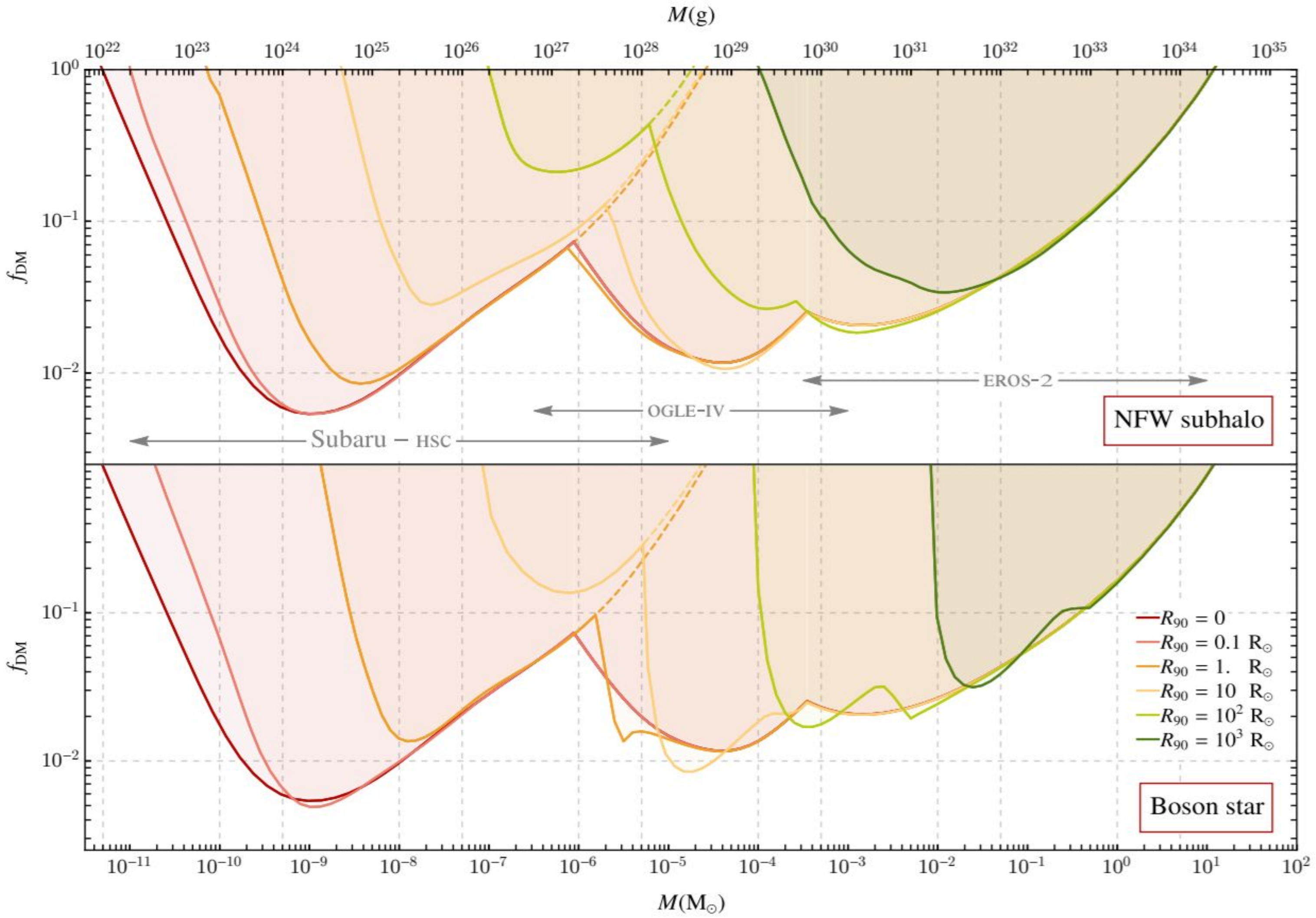
Detector efficiency

DM circular velocity ~ 220 km/s

DM halo density

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

Characteristic velocity of crossing the lensing tube

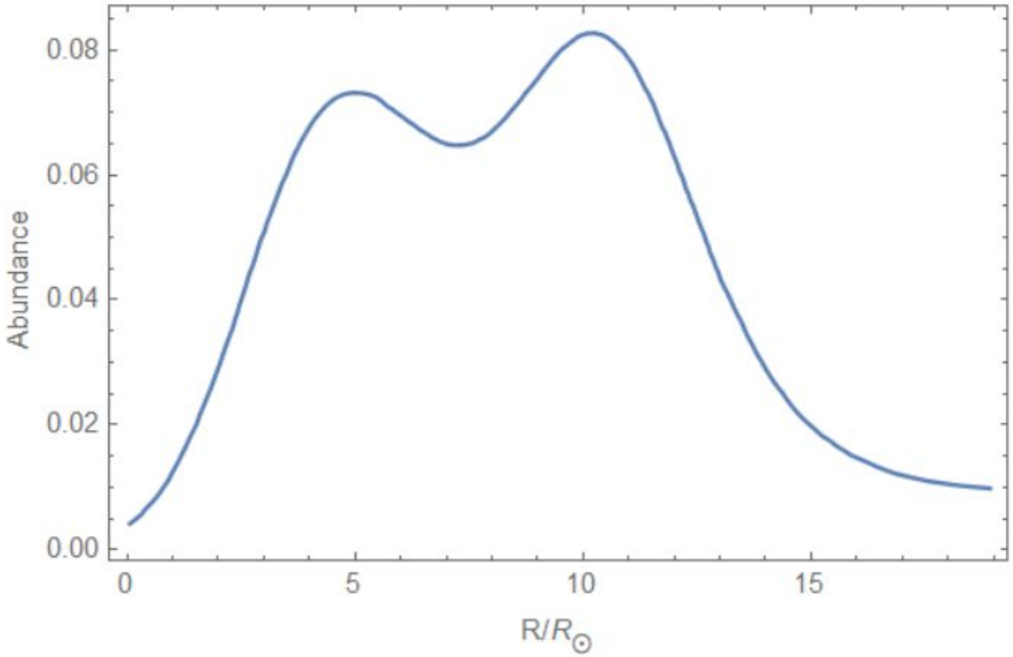

M(g)
10^22 10^23 10^24 10^25 10^26 10^27 10^28 10^29 10^30 10^31 10^32 10^33 10^34 10^35
10^0
10^-1
10^-2
f_DM
EROS-2
OGLE-IV
Subaru – HSC
NFW subhalo
f_DM
10^-1
10^-2
R_90 = 0
R_90 = 0.1 R_⊙
R_90 = 1. R_⊙
R_90 = 10 R_⊙
R_90 = 10^2 R_⊙
R_90 = 10^3 R_⊙
Boson star
10^-11 10^-10 10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 10^0 10^1 10^2
M(M_⊙)

Conclusions and outlook

- Present microlensing surveys can probe compact DM structures smaller than ~ 1000 solar radii.
- Increasing lens size → weaker constraint.
- Geometric optics. Interference important for lighter lenses and higher frequency observations.
- Inferring lens profile requires detailed analysis of light curves.

Thank you!

Stars in M31



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