

Probing primordial black holes (PBHs) with stellar microlensing

Anne Green

University of Nottingham, UK

PBHs: brief introduction

Microlensing: theory
observations
open theoretical questions
future observational prospects

[arXiv:2602.15974](https://arxiv.org/abs/2602.15974)

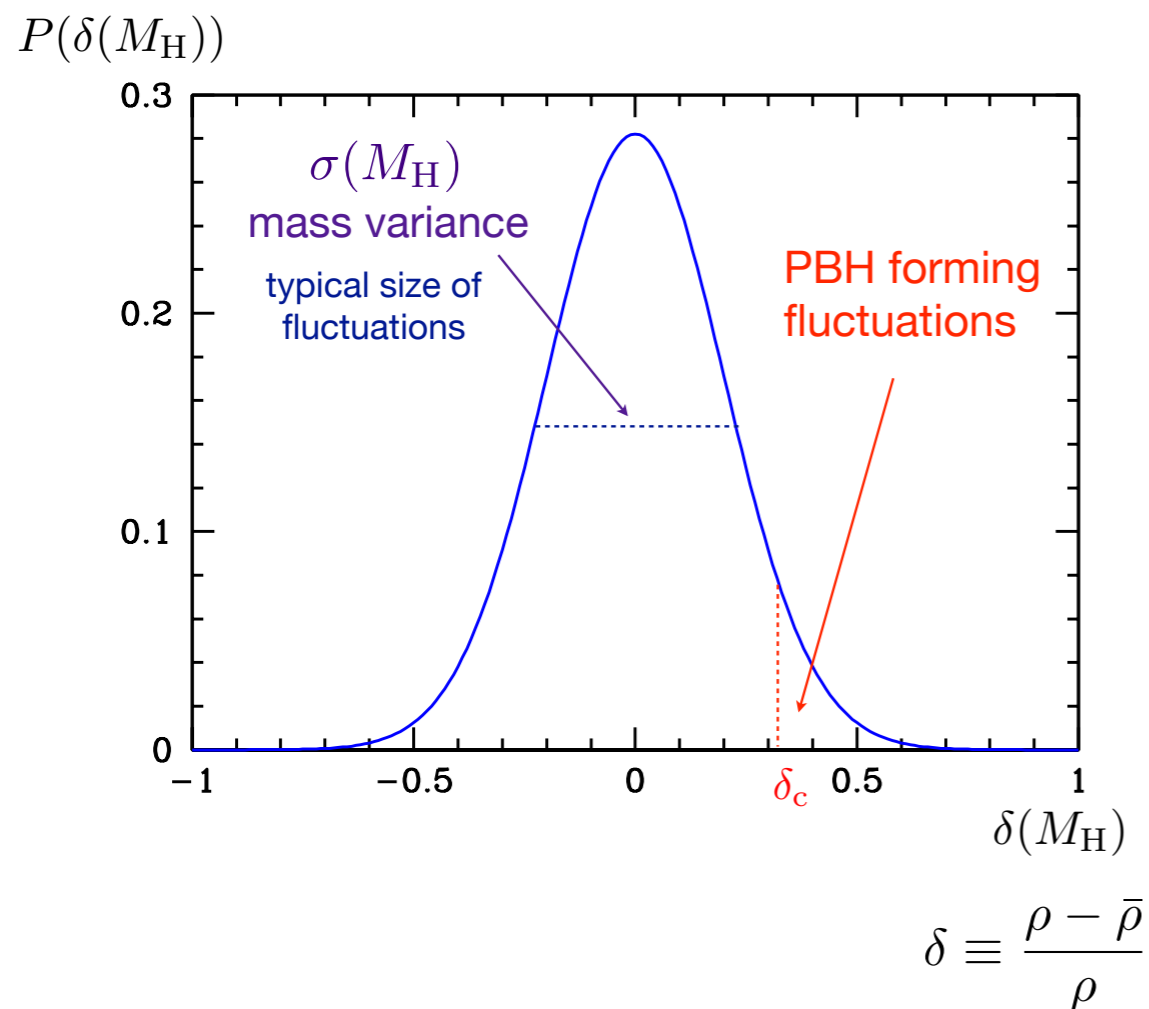
Primordial Black Holes (PBHs)

Carr & Kühnel; Green & Kavanagh

Can form from over densities in the early Universe.

Most 'popular/minimal' mechanism: collapse of large density perturbations during radiation domination.

If density contrast exceeds a critical over-density, $\delta_c \sim \mathcal{O}(1)$, then region collapses to form a BH with mass roughly equal to the horizon mass.



Mass:

$$M_{\text{PBH}} \sim M_{\odot} \left(\frac{t}{10^{-6} \text{ s}} \right)$$

Initial mass fraction $\beta = \frac{\rho_{\text{PBH}}}{\rho_{\text{tot}}}$:

$$\beta \sim \sigma(M_H) \exp \left(-\frac{\delta_c^2}{2\sigma^2(M_H)} \right)$$

Since PBHs are matter, during radiation domination the fraction of energy in PBHs grows with scale factor, a :

$$\frac{\rho_{\text{PBH}}}{\rho_{\text{rad}}} \propto \frac{a^{-3}}{a^{-4}} \propto a$$

Relationship between PBH initial mass fraction, β , and fraction of DM in form of PBHs, f :

$$\beta \sim 10^{-9} f \left(\frac{M_{\text{PBH}}}{M_{\odot}} \right)^{1/2}$$

On CMB scales the primordial perturbations have amplitude $\sigma(M_{\text{H}}) \sim 10^{-5}$

If the primordial perturbations are very close to scale-invariant the number of PBHs formed will be completely negligible: $\beta \sim \exp(-10^{10})$

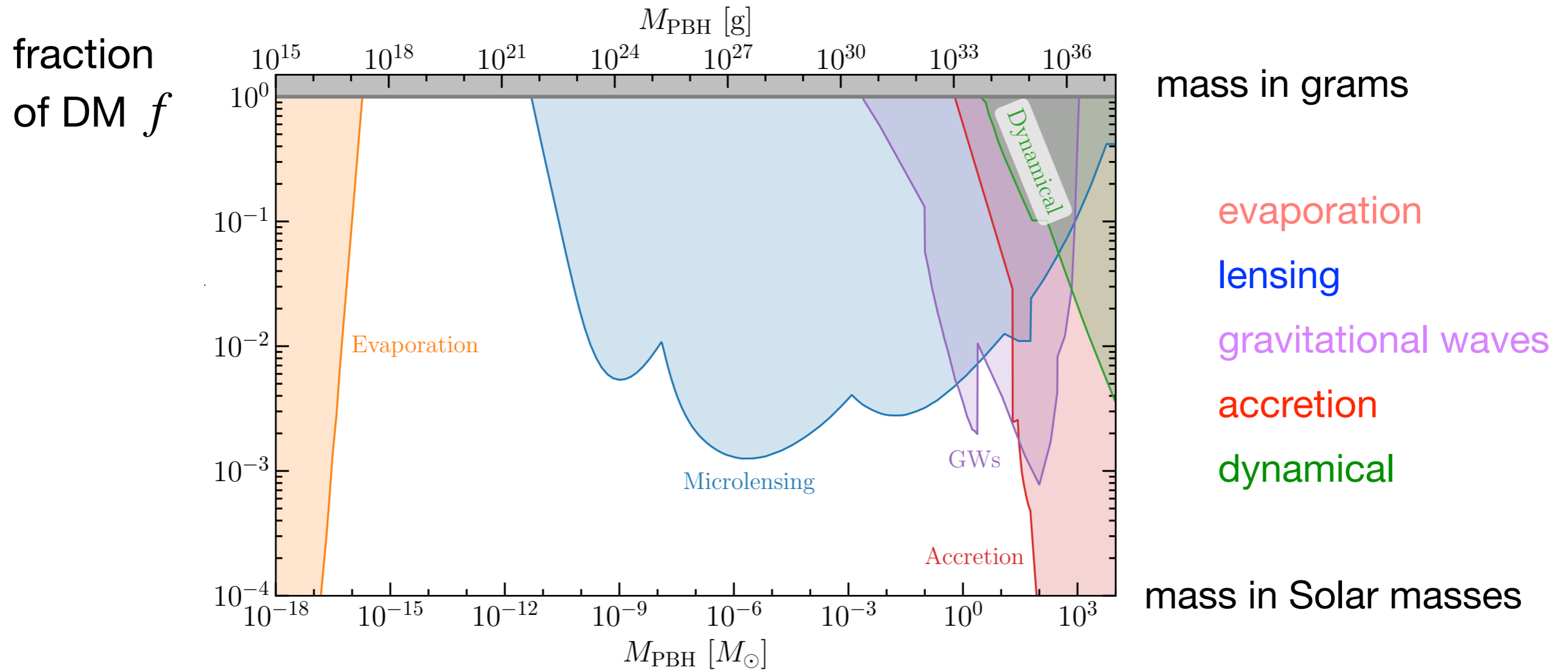
To form an interesting abundance of PBHs, $f \sim \mathcal{O}(1)$, the primordial perturbations must be significantly larger ($\sigma(M_{\text{H}}) \sim 0.1$) on small scales than on cosmological scales.

This can be achieved in inflation models with e.g. a plateau or bump/dip feature but requires fine-tuning.

see [Öszoy & Tasinato](#); [Escriva, Kuhnel & Tada](#)

Compilation of tightest observational constraints

(under 'standard' assumptions, including a delta-function PBH mass function)



<https://github.com/bradkav/PBHbounds>

Planetary or stellar mass PBHs making up all of the DM appears to be excluded.

BUT

JOURNAL ARTICLE

A critical analysis of the recent OGLE limits on stellar mass primordial black holes in the halo of the Milky Way

M R S Hawkins , J García-Bellido 

Monthly Notices of the Royal Astronomical Society, Volume 544, Issue 2, December 2025, Pages 1950–1957, <https://doi.org/10.1093/mnras/staf1826>

Published: 22 October 2025 **Article history** ▼



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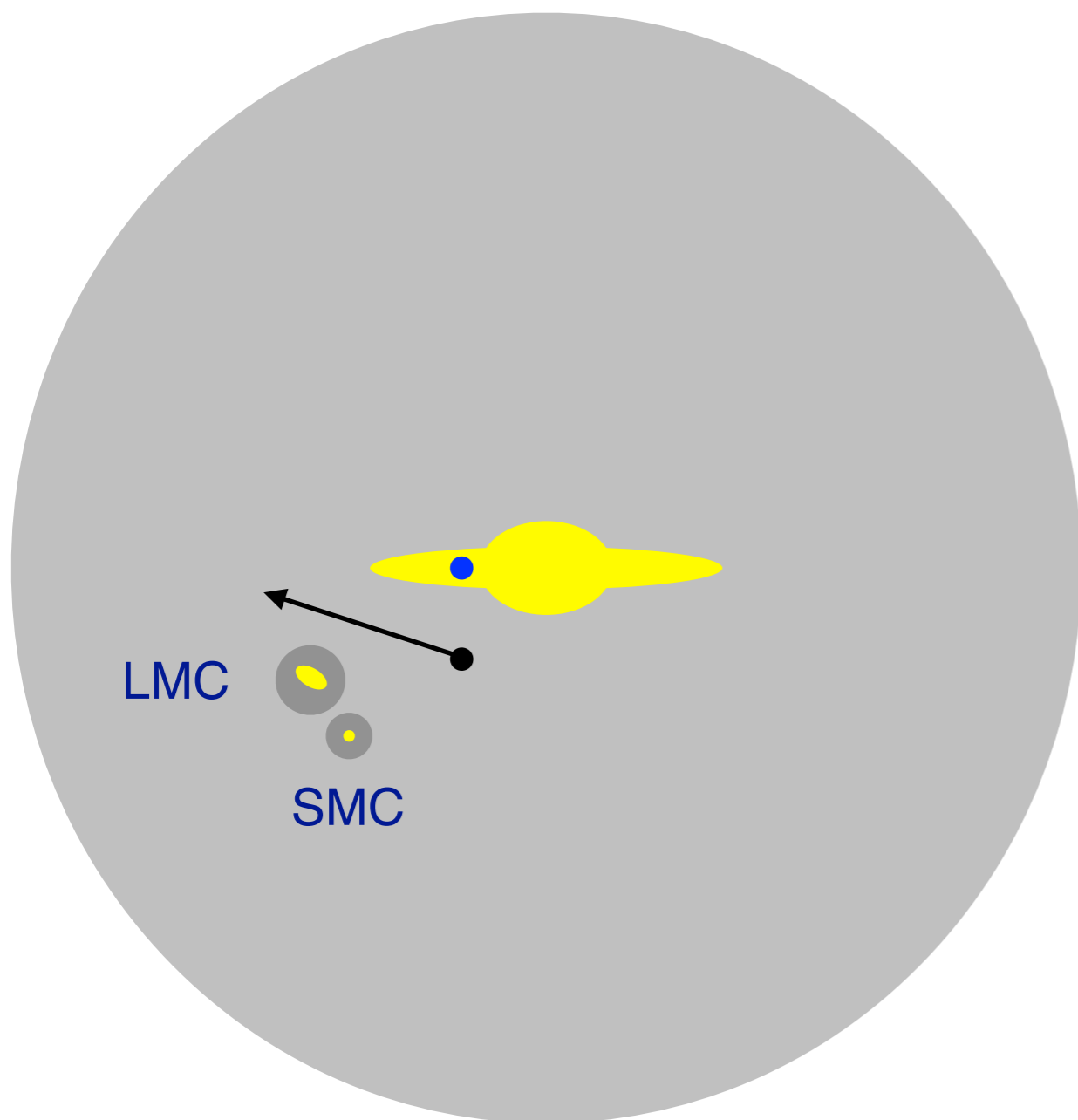
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ABSTRACT

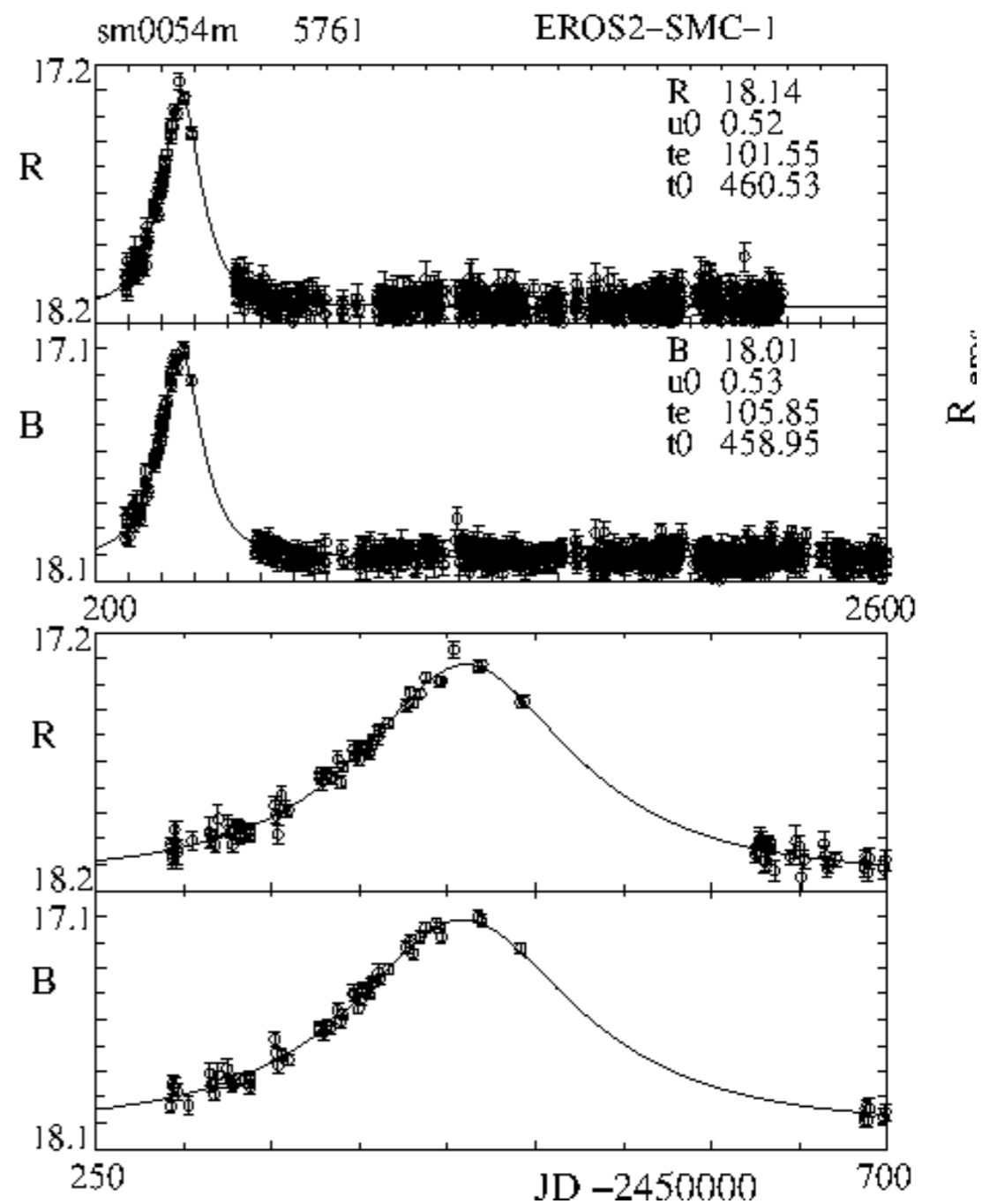
This paper is a response to recent claims that a population of primordial black holes in the Galactic halo has been ruled out by the Optical Gravitational Lensing Experiment (OGLE) collaboration. This claim was based on the latest results from the OGLE microlensing survey towards the Large Magellanic Cloud which failed to detect even the number of events expected from known stellar populations. In particular, their results are completely inconsistent with the results of the massive compact halo object (MACHO) survey which detected a population of compact bodies in the Galactic halo which could not be accounted for by any known stellar population. The discrepancy between the results of these two groups has a long history, and includes problems such as different choice of photometric passbands, quality of light curves, microlensing event selection, detection efficiency, self lensing, and halo models. In this paper it is demonstrated that these issues not only account for the discrepancy between the OGLE and MACHO results, but imply that the OGLE observations can put no meaningful constraints on a population of primordial black holes in the Galactic halo.

Microlensing: theory

Photometric microlensing: temporary (achromatic) brightening of background star when compact object (CO) passes close to the line of sight. [Paczynski](#)



Not to scale!



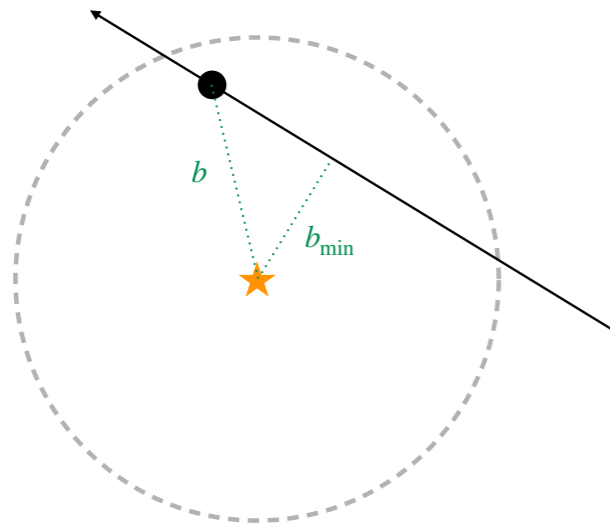
EROS

Einstein radius:

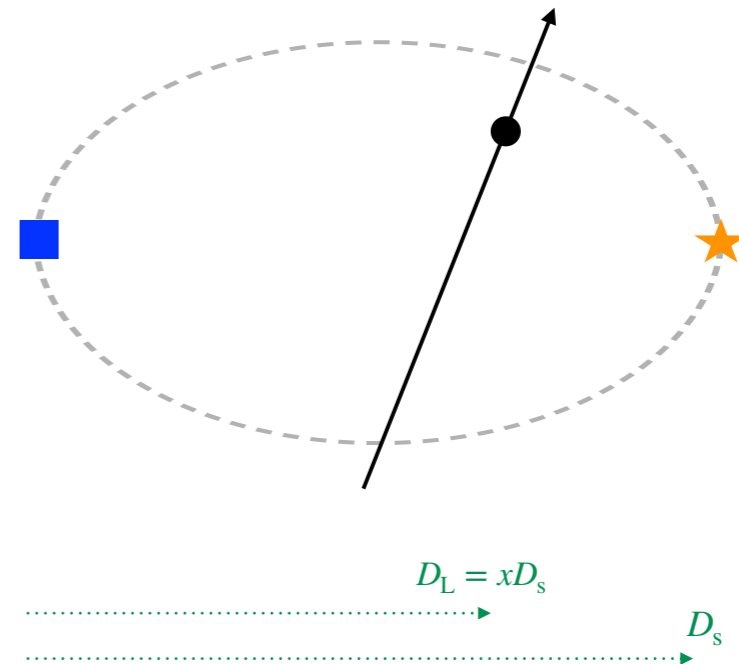
$$R_E = 2 \left[\frac{GM D_L (D_S - D_L)}{c^2 D_S} \right]^{1/2} \sim 10^{-4} \text{ pc} \sqrt{x(1-x)} \left(\frac{M}{M_\odot} \right)^{1/2}$$

for source stars in MC, $x = \text{fractional distance along line of sight}$

along the line of sight



perpendicular to the line of sight



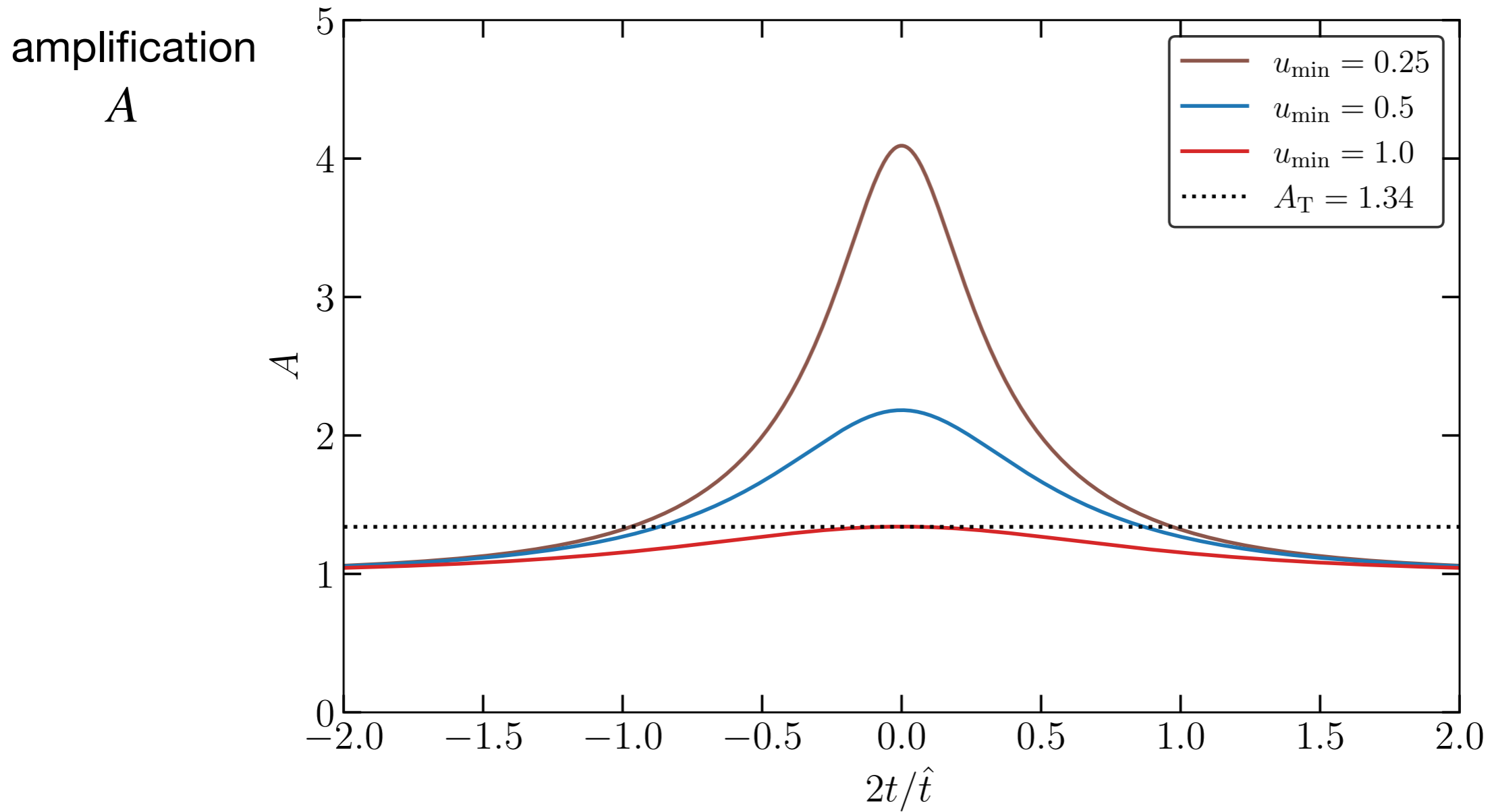
Timescale of event (Einstein diameter crossing time):

EROS & OGLE collaborations use Einstein radius crossing time

$$\hat{t} = \frac{2R_E(x)}{v} \sim 1 \text{ yr} \sqrt{x(1-x)} \left(\frac{M}{M_\odot} \right)^{1/2}$$

‘microlensing degeneracy’: timescale depends on mass, position and speed of lens

Paczyński light curve (single point source & lens):



$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

$$u = \frac{b}{R_{\text{E}}}$$

Violations of single point source & lens assumptions:

Finite source effects

occur if impact parameter comparable to ratio of radius of source star to Einstein radius, reduces magnification for $M \lesssim 10^{-9} M_{\odot}$.

Wave optics

For $M_{\text{PBH}} \lesssim 10^{-11} M_{\odot}$ Schwarzschild radius comparable to wavelength of light, diffraction and interference effects reduce magnification.

Binary source

orbital motion leads to periodic variation in light curve ('xallarap' effect).

Binary lens

complex multi-peaked light curve, with caustics where magnification formally diverges

In some cases can break microlensing degeneracy, and allow the lens mass and/or transverse velocity (which depends on lens location i.e MW disc, MW halo, LMC) to be measured.

Differential event rate

assuming a delta-function lens mass function and a spherical halo with a Maxwellian velocity distribution: [Griest](#)

$$\frac{d\Gamma}{d\hat{t}} = \frac{32 D_S}{M \hat{t}^4 v_c^2} \int_0^1 \rho(x) R_E^4(x) \exp \left[-\frac{4R_E^2(x)}{\hat{t}^2 v_c^2} \right] dx$$

$\rho(x)$ = compact object density distribution along line of sight

\hat{t} = Einstein diameter crossing time

v_c = local circular speed (usually taken to be 220 km/s, ~10% uncertainty)

Expected number of events:

$$N_{\text{exp}} = E \int_0^{\infty} \frac{d\Gamma}{d\hat{t}} \epsilon(\hat{t}) d\hat{t}$$

E = exposure (number of stars times duration of obs)

$\epsilon(\hat{t})$ = efficiency (probability that an event with timescale \hat{t} passes cuts).

Calculating constraints on CO mass and halo fraction:

For smoothly distributed DM the distribution of the number of events observed, N_{obs} , is Poissonian, so if $N_{\text{obs}} = 0$, $N_{\text{exp}} < 3$ at 95% confidence.

However stars in the MW disc and the MC ('self-lensing') are expected to cause microlensing events:

$$\frac{d\Gamma}{d\hat{t}} = f \frac{d\Gamma_{\text{MW}}}{d\hat{t}} + \frac{d\Gamma_{\text{MW},*}}{d\hat{t}} + \frac{d\Gamma_{\text{LMC},*}}{d\hat{t}} + f \frac{d\Gamma_{\text{LMC}}}{d\hat{t}}$$

And constraints calculated using likelihood:

$$\mathcal{L}(f, M) = \exp(-N_{\text{exp}}) E \prod_{i=1}^{N_{\text{obs}}} \frac{d\Gamma}{d\hat{t}}(\hat{t}_i) \epsilon(\hat{t}_i)$$

Dependence of differential event rate (& hence constraints) on DM dist

assuming (for now) DM is smoothly distributed

Standard halo model

cored isothermal sphere:

$$\rho(r) = \rho_0 \frac{R_c^2 + R_0^2}{R_c^2 + r^2}$$

$\rho_0 = 0.008 M_\odot \text{pc}^{-3}$, local dark matter density

$R_c = 5 \text{ kpc}$, core radius

$R_0 = 8.5 \text{ kpc}$, Solar radius

Evans' power law halo models [Evans](#)

'self-consistent' (velocity distribution consistent with halo density profile) & have analytic expressions for microlensing differential event rate.

$$\rho(r) = \frac{v_a^2 r_c^\beta}{4\pi G} \frac{(1 - \beta^2)r^2 + 3r_c^2}{(r^2 + r_c^2)^{(\beta+4)/2}} \quad r \gg r_c : \quad \rho(r) \propto r^{-(2+\beta)}$$

PL B $\beta = -0.2$ (massive halo, rising rotation curve)

PL C $\beta = +0.2$ (light halo, falling rotation curve)

MACHO collaboration first year results paper:
[Alcock et al. \(1996\)](#)

theoretical differential event rate
 (assuming $f_{\text{PBH}} = 1$, $M = 1M_{\odot}$ & perfect detection efficiency)

MACHO 1 year
 exclusion limit

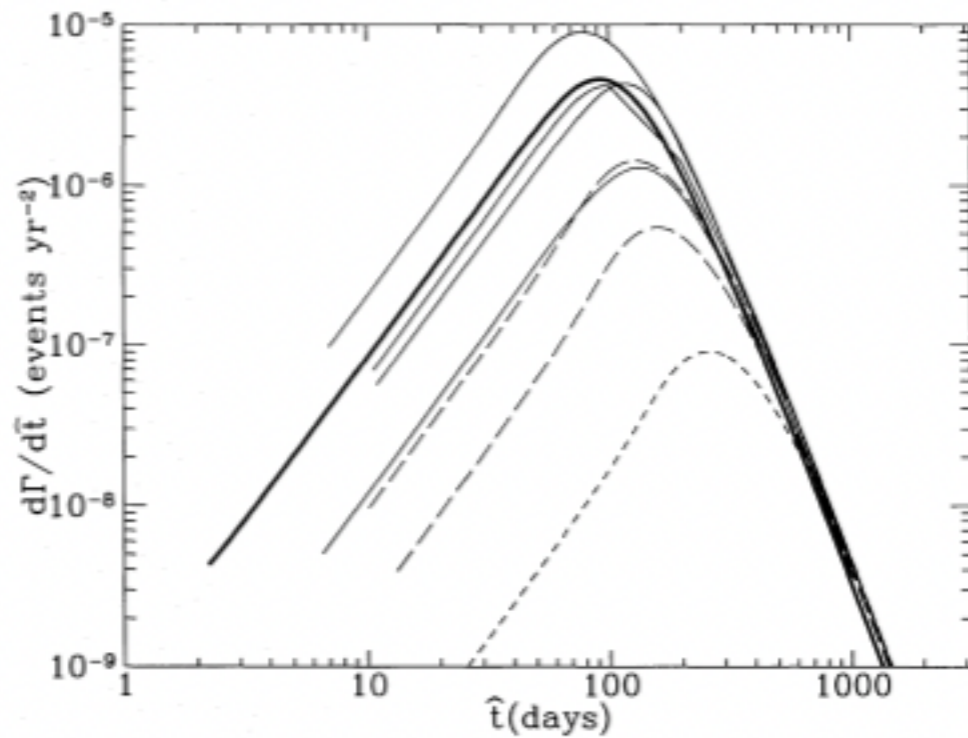


FIG. 11.—Theoretical differential event rates as a function of t for models described in Table 2. A delta function MACHO mass function at $1 M_{\odot}$ is assumed; for other masses one simply scales the t -axis by \sqrt{m} and the rate-axis by m^{-1} , hence, the total event rate scales as $m^{-0.5}$. The thick solid line shows the standard model S, the thin solid lines show models B (highest), A, D, and C (lowest). The short-dashed line shows the maximal disk model E, and the long-dashed lines show the large disk models F and G.

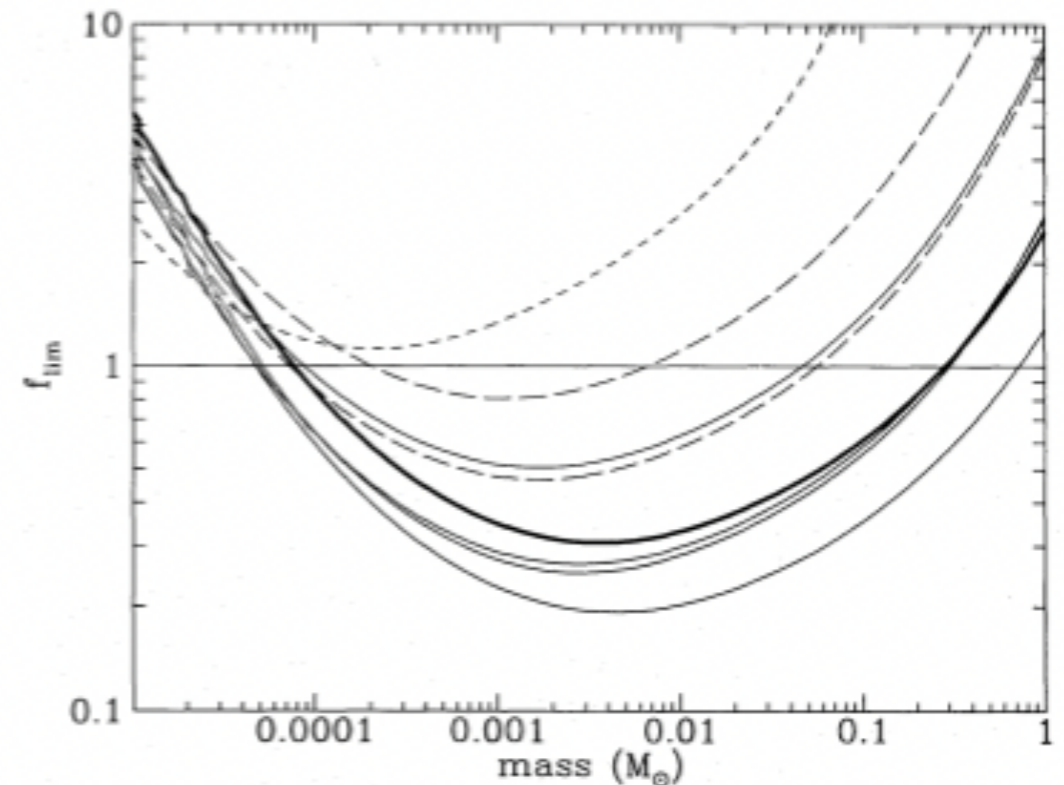
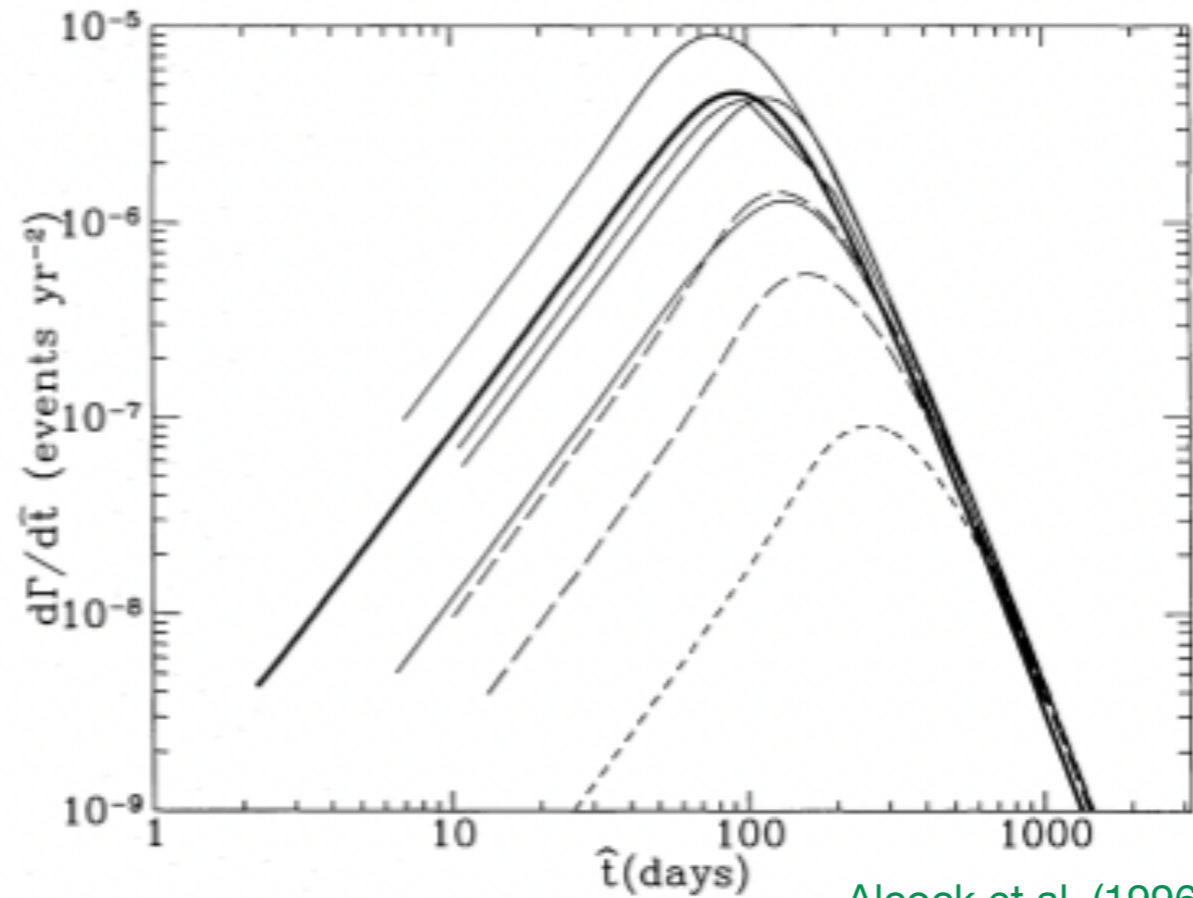


FIG. 13.—95% CL upper limits on the MACHO halo fraction as a function of the MACHO mass for the models described in Table 2. The lines are coded as in Fig. 11.

for other masses: $\hat{t} \propto M^{1/2}$ $\frac{d\Gamma}{d\hat{t}} \propto M^{-1}$
[Griest](#)



[Alcock et al. \(1996\)](#)

[Mao & Paczynski \(1996\)](#)

long timescale events: lenses moving nearly along the line of sight, $\hat{t} \propto \sin^{-1} i \propto i^{-1}$

$$N \propto \frac{\Omega}{\hat{t}} \propto \frac{1 - \cos i}{\hat{t}} \sim \frac{i^2}{i^{-1}} \sim i^3 \propto \hat{t}^{-3}$$

short timescale events: lenses close to the observer ($x \sim 0$) or source, ($x \sim 1$)

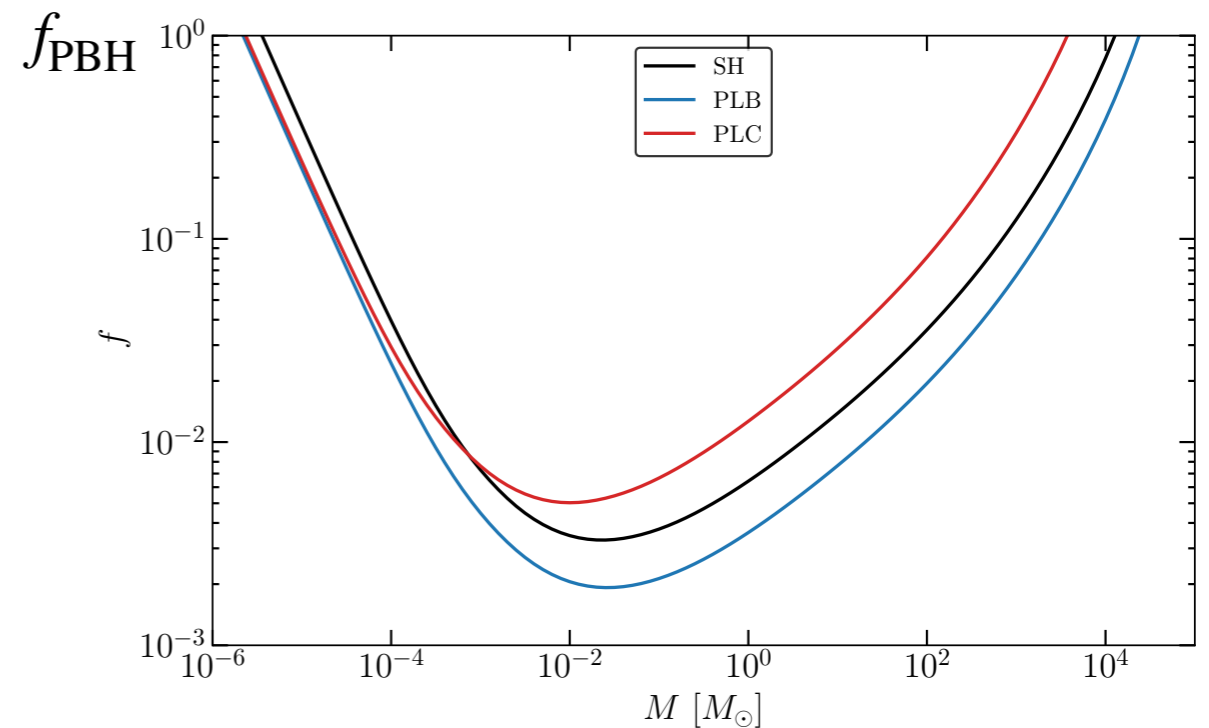
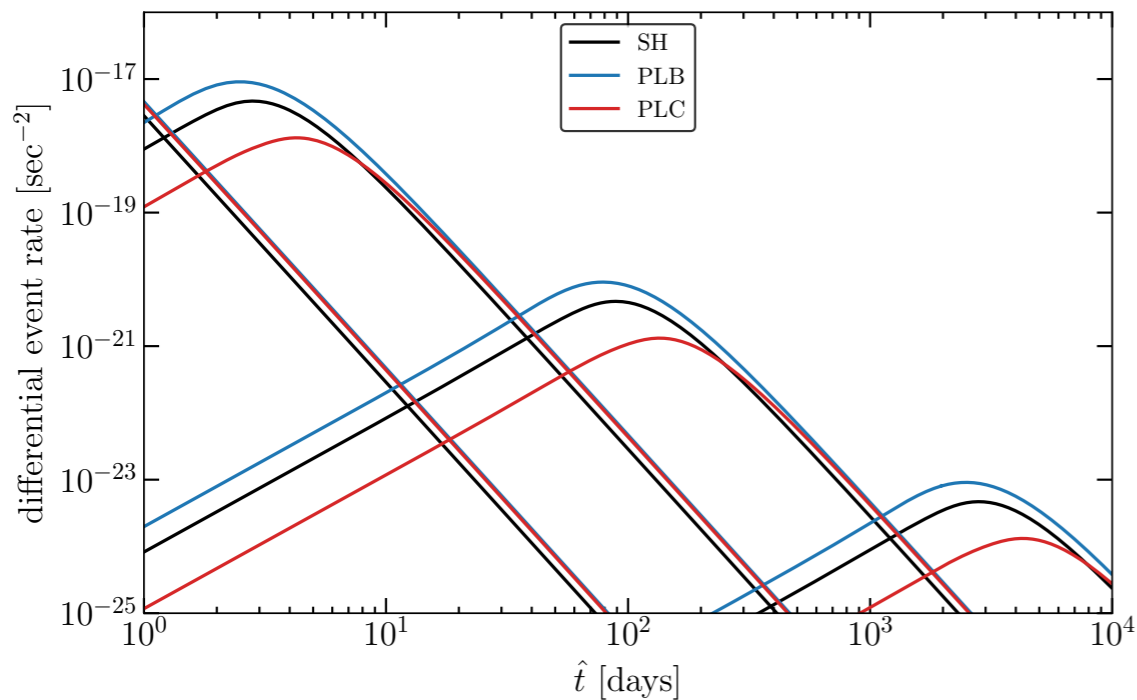
for $x \sim 0$ (similar argument holds for $x \sim 1$):

$$\hat{t} \propto R_E \propto x^{1/2} \qquad N \propto \frac{R_E^2 x}{\hat{t}} \propto \hat{t}^3$$

theoretical differential event rate

$$M = (10^{-6}, 10^{-3}, 1, 10^3) M_{\odot}$$

Constraints from a toy long exposure microlensing survey



Light compact objects (COs): limit depends on long timescale tail of differential event rate, which is determined by total density of COs within the microlensing 'tube'. Uncertainty small.

Massive COs: limit depends on short timescale tail of differential event rate, which is determined by local CO density and velocity distribution. Uncertainty larger.

Observations

General principles

Candidate events selected by applying cuts to light curves.

Cuts typically designed to select light curves which are well fit by by standard Paczyński form (single, achromatic, symmetric variation expected for single point source & lens) while rejecting backgrounds that mimic microlensing, e.g. supernovae in background galaxies, 'blue bumpers' (a class of variable star discovered by microlensing surveys...).

Efficiency estimated by finding fraction of simulated events that pass cuts.

~10% events are exotic (i.e. not single source and lens)

Manual inspections of subset of light curves often carried out, to check for overlooked events.

Timeline

1936

'there is no great chance of observing this phenomenon' [Einstein](#)

1986

By monitoring millions of stars in MC can probe compact objects in the MW halo.
[Paczynski](#)

early 1990s

Microlensing surveys begin, first candidate events detected.

late 1990s

MACHO collaboration observes more events than expected from stars in MC or MW disc, consistent with roughly half of MW halo in ~Solar mass compact objects.

Can't be white dwarfs or neutron stars (not enough baryons). Primordial Black Holes?

2000s

EROS and OGLE don't observe excess events, constrain halo fraction $f \lesssim 0.1$.

late 2010s/2020s

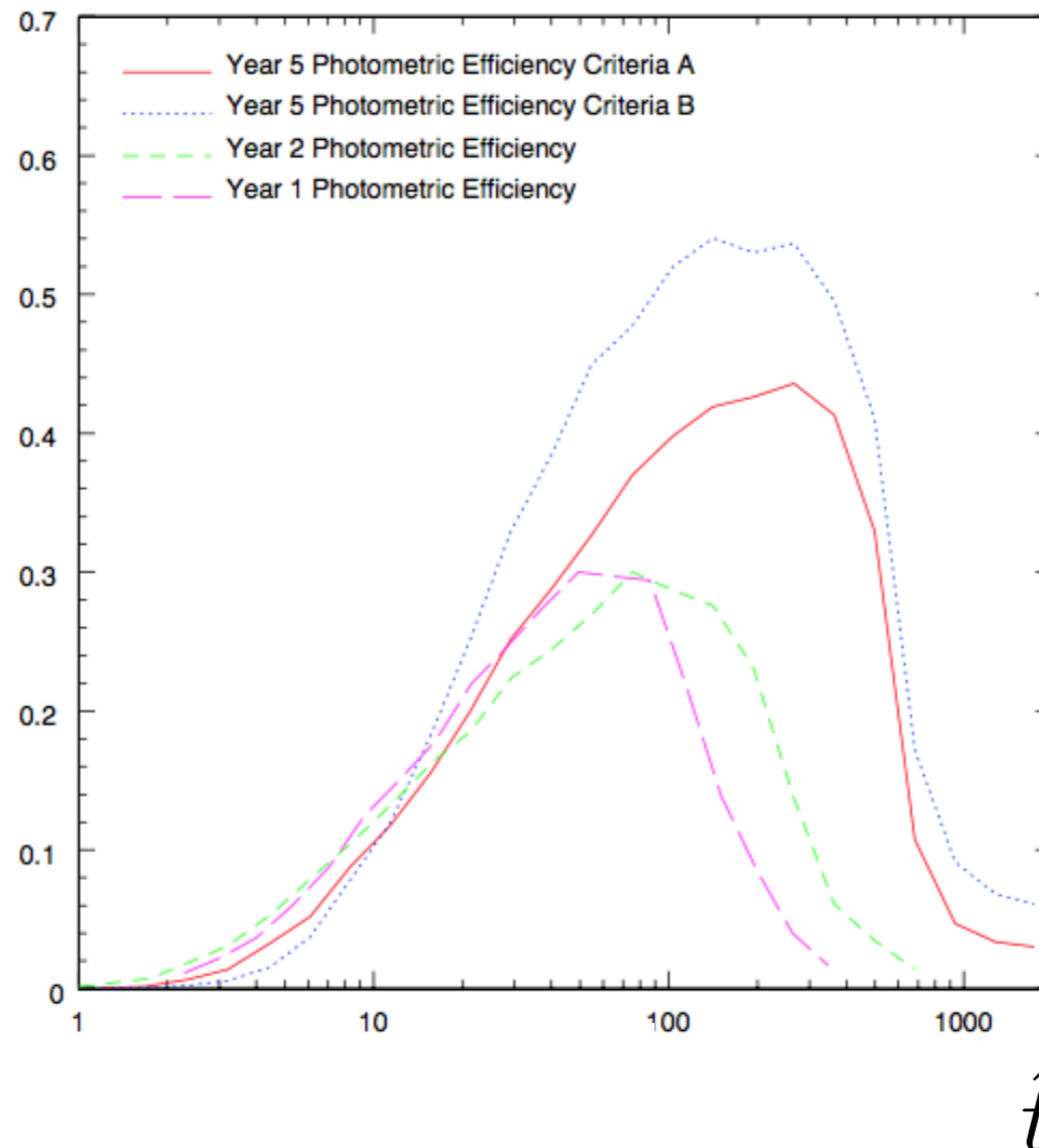
Long duration OGLE observations: tighten constraints and extend to larger masses.
High cadence observations: constrain lighter compact objects.

MACHO

Monitored 12 million stars in LMC for 5.7 years. [Alcock et al.](#)

Found 13/17 events (for selection criteria A/B, B less restrictive-picks-up exotic events).

Detection efficiency

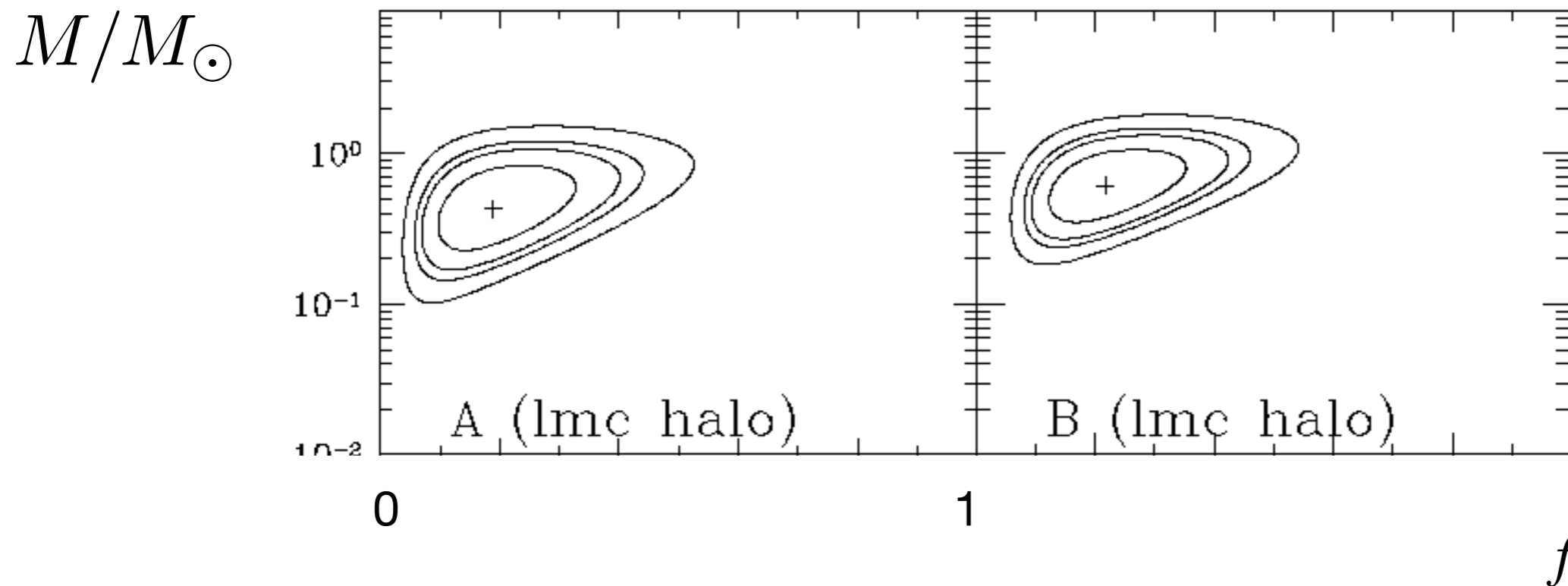


5 years B
5 years A
2 years
1 year

Measurement of CO mass and halo fraction
(assuming a delta-function mass function):

selection criteria A

B



68%, 90%, 95% and 99% confidence contours

BUT

MACHO-LMC-5: lens identified (using HST obs & parallax fit) as a low mass MW disc star. [\[Drake et al.\]](#)

MACHO-LMC-7: OGLE-III light curve has multiple peaks, some sort of repeating outbursting variable star. [\[OGLE\]](#)

MACHO-LMC-9: (only satisfied criteria B) lens is a binary, allowing measurement of low projected velocity, which suggests lens is in LMC (or source is also binary). [\[MACHO\]](#)

MACHO-LMC-14: source is binary, and lens most likely to lie in LMC. [\[MACHO\]](#)

MACHO-LMC-20: (only B) lens identified (using Spitzer obs) as a MW thick disc star. [\[Kallivayalil et al.\]](#)

MACHO-LMC-22: (only B) supernova or an AGN in background galaxy. [\[MACHO\]](#)

MACHO-LMC-23: varied again twice, so not microlensing [\[EROS/OGLE\]](#)

MACHO-LMC-8, 18 & 27 (27 only B): have periodic variation in baseline (could still be microlensing, but don't expect this many microlensing events with variable baseline) [\[OGLE\]](#)

OGLE collaboration response to Hawkins & Garcia-Bellido [Mroz et al.](#):

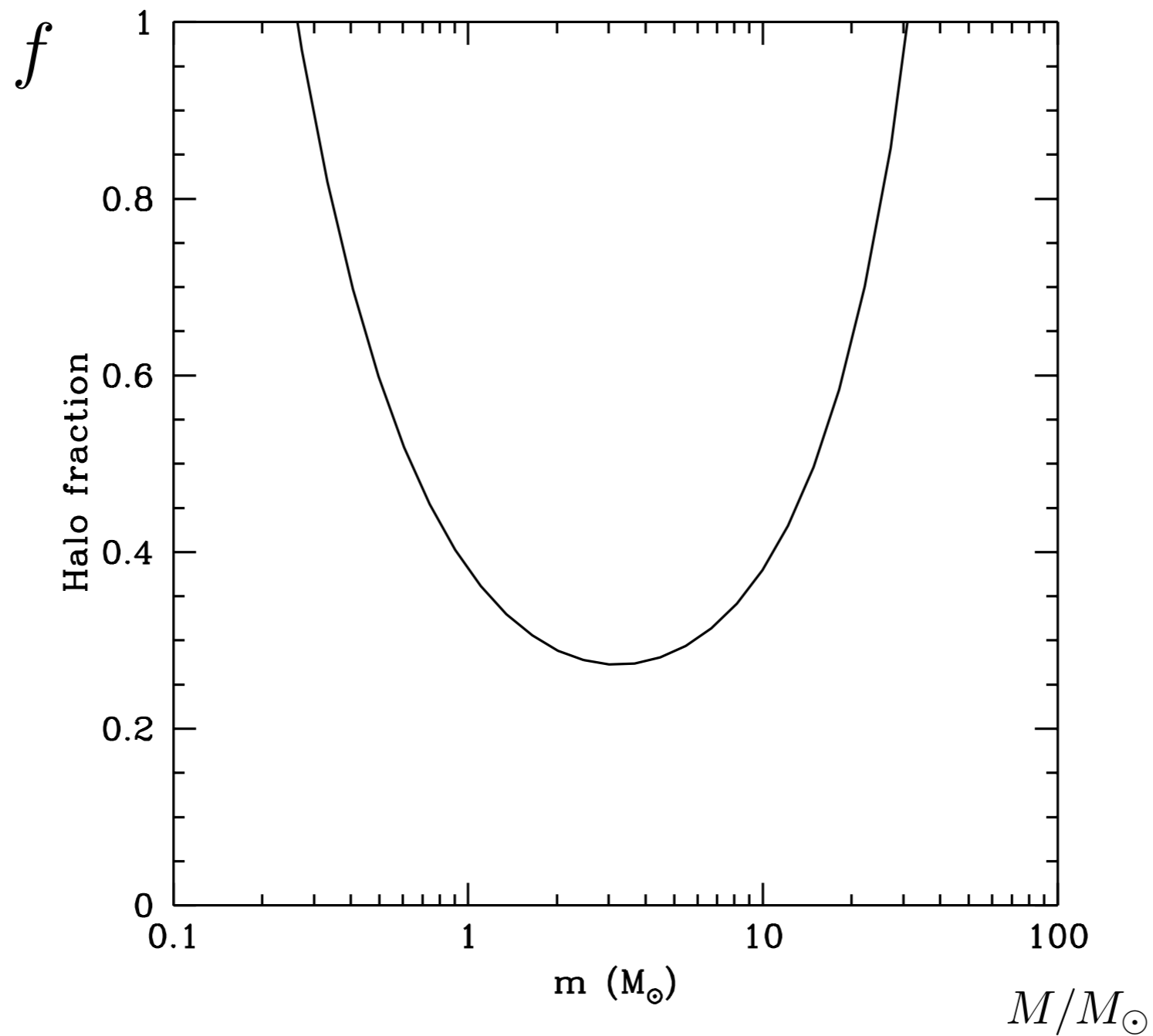
Have reanalysed (using more modern difference image analysis techniques) MACHO data, conclude 7 of their events are very likely microlensing, but that the other events are unlikely to pass 'sensible microlensing cuts'.

Of those 7 events, for 3 the lens has either been identified as a star in the MW disc, or is likely to be in the LMC.

n.b. MACHO observing fields are closer to the centre of LMC, so larger self-lensing rate than OGLE:

MACHO long timescale

Constraint from absence of long (> 150 day) timescale events [MACHO](#):



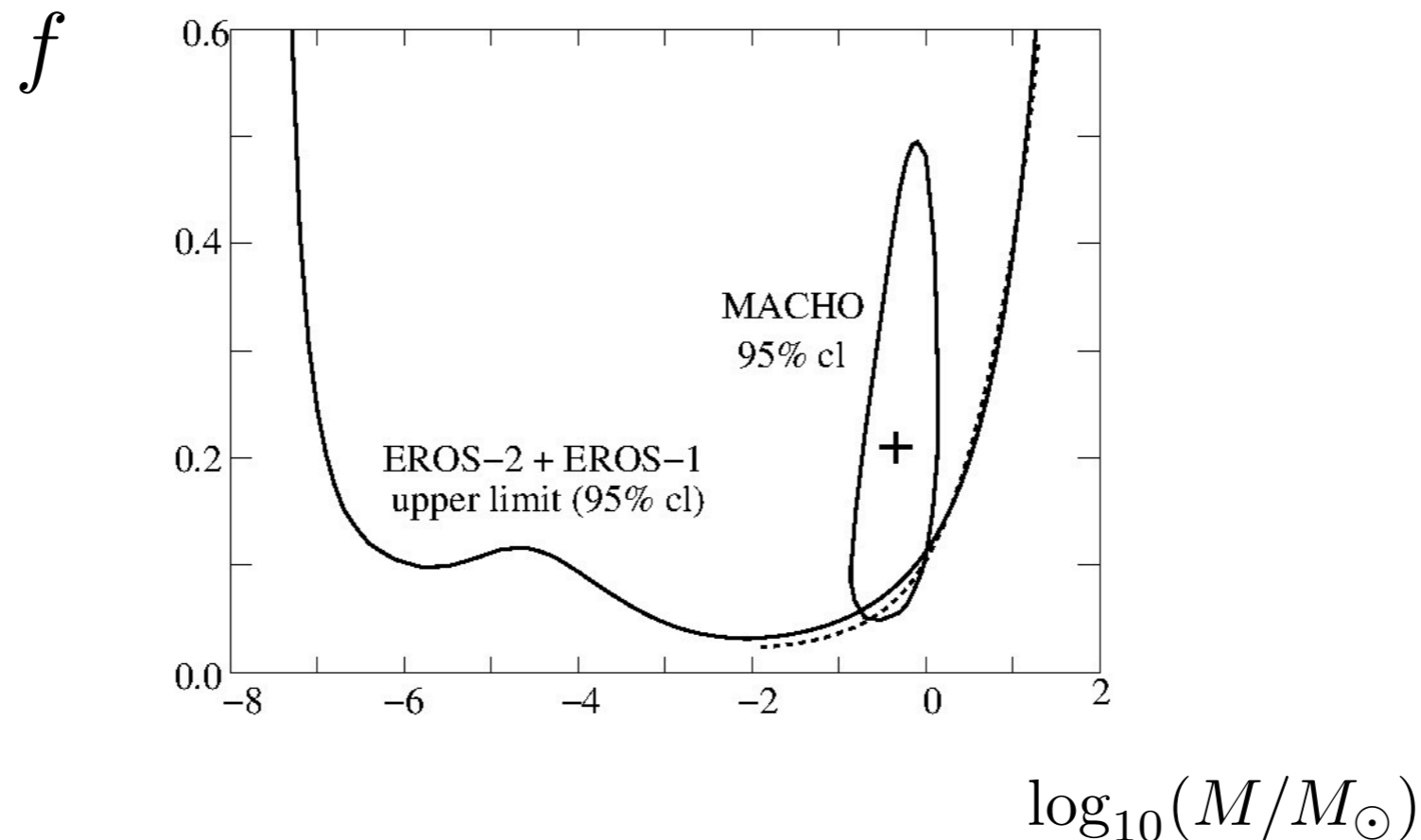
EROS

Monitored 25 million stars in LMC for 12 years. [EROS](#)

Use bright stars in sparse fields (to avoid complications due to 'blending'-contribution to baseline flux from unresolved neighbouring star).

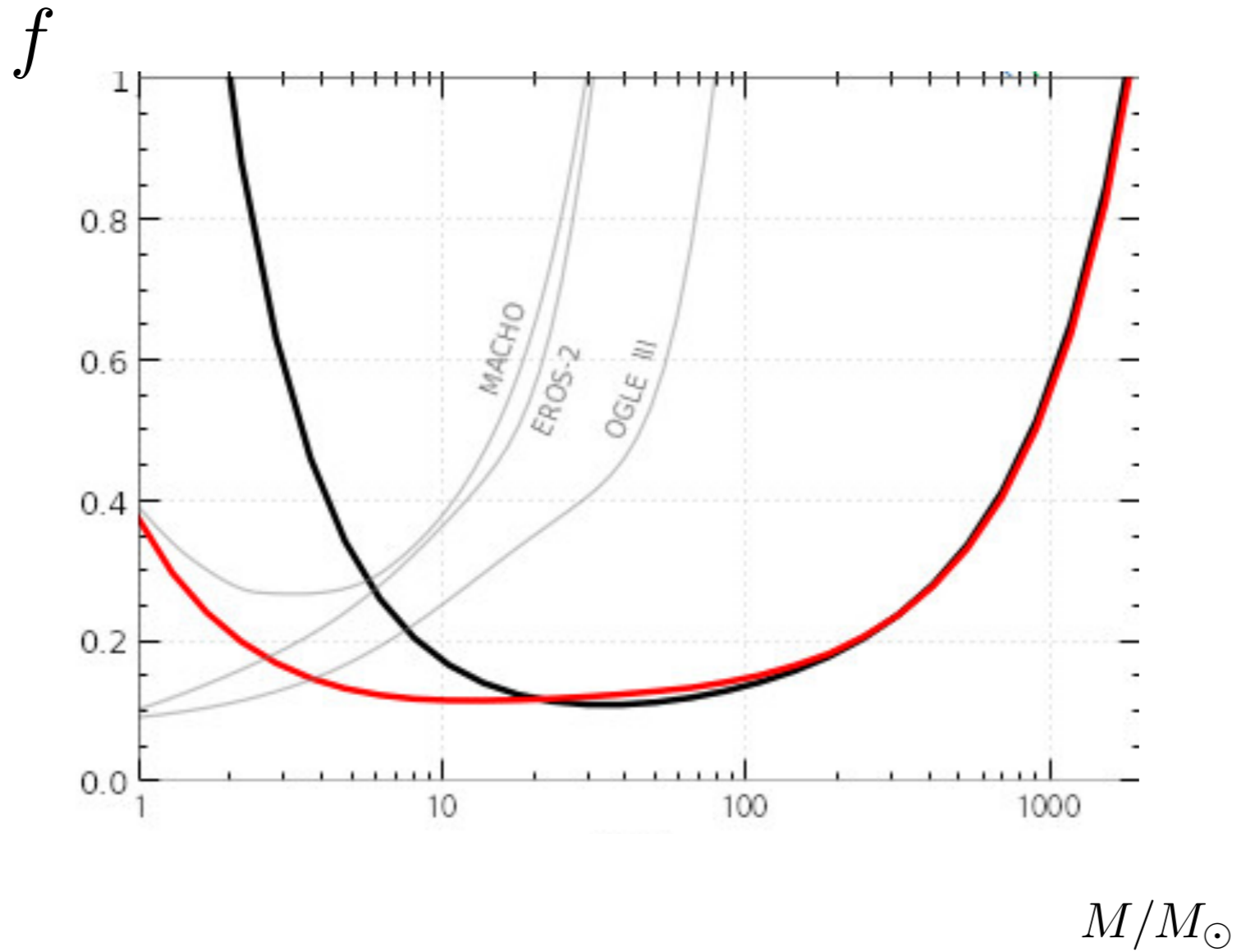
No LMC events.

Earlier candidate events eliminated: 7 varied again and 3 identified as supernovae.



EROS-2 + MACHO long duration

Combined data from EROS-2 and MACHO (14.1 million objects, over 10.6 years):
[Blaineau et. al.](#)

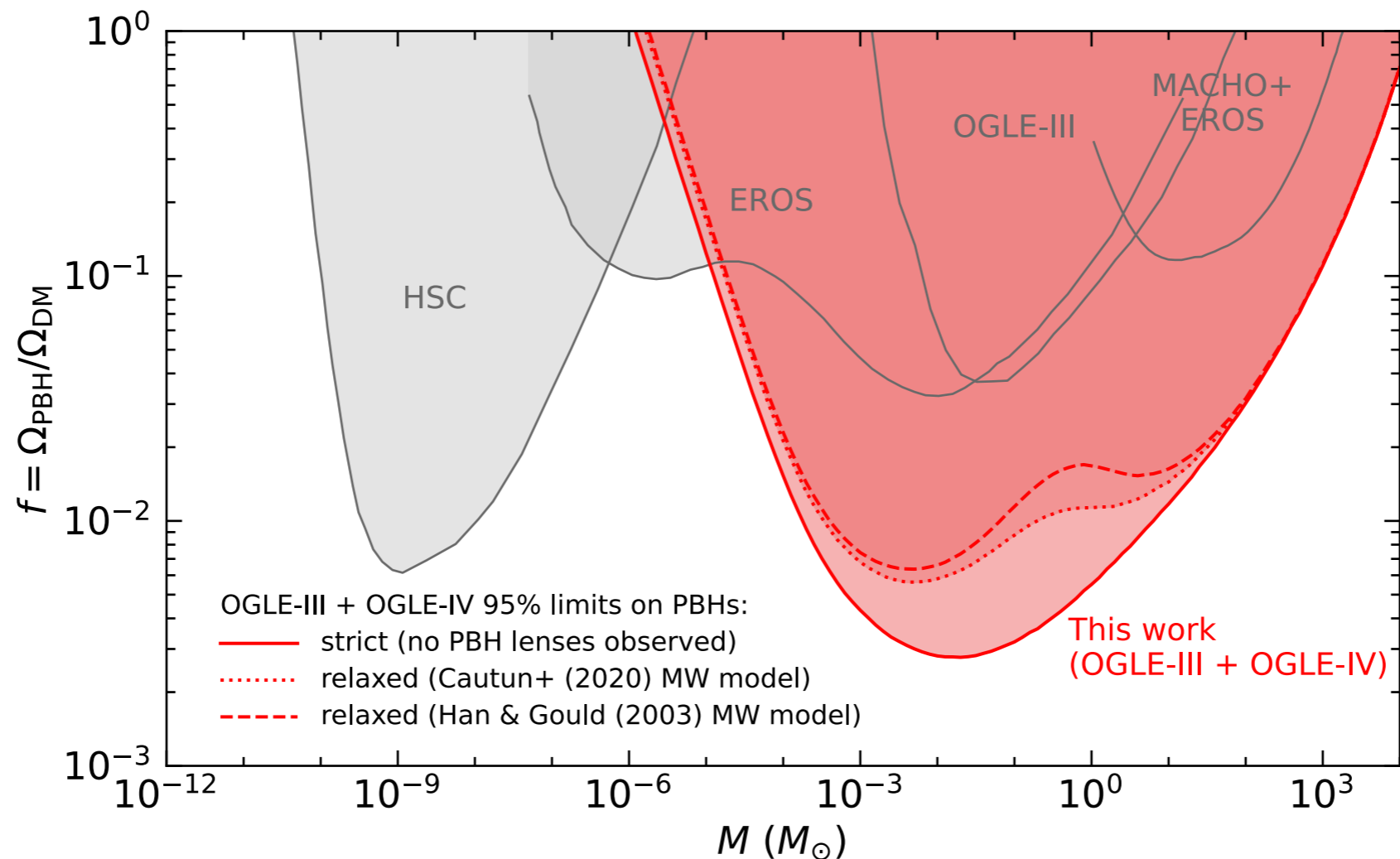


OGLE long duration

Observed ~80 million stars in LMC every (1-5) days for ~20 years: [Mroz et al. arXiv:2403.02386](https://arxiv.org/abs/2403.02386)

Observed 13 (+3) events with timescale (Einstein radius crossing time) <1 year, no longer duration events.

Expect ~6 events from stars in LMC and ~(7-15) from stars in MW disk.

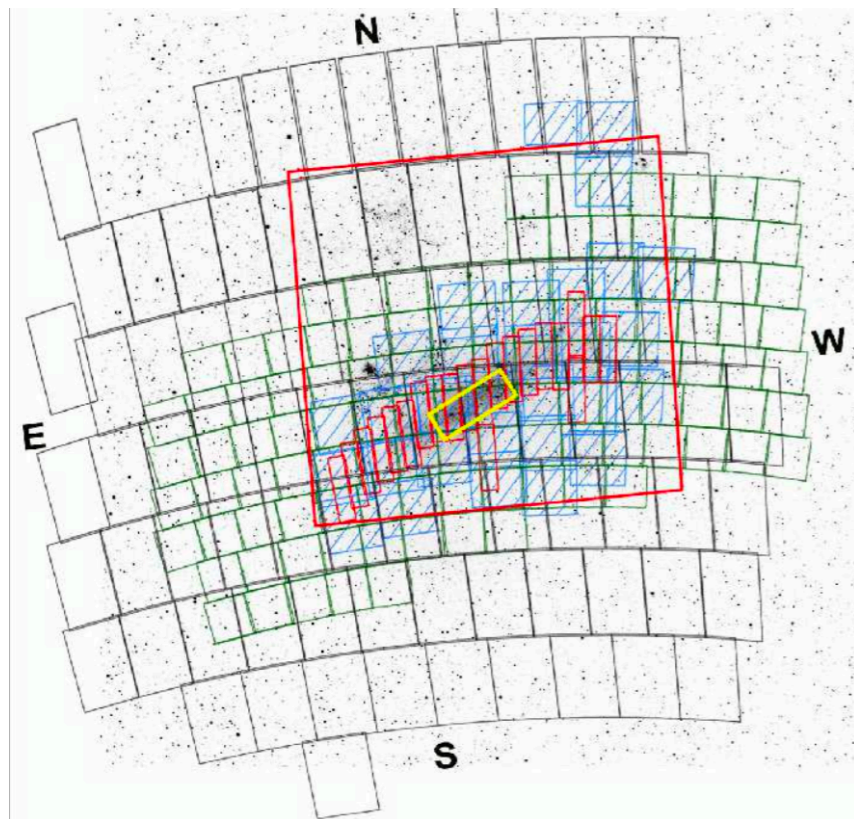


_____ strict (assumes all 13 events are due to stars/stellar remnants in LMC or MW disk)

.... & - - - - allow contribution from MW halo (2 different models for MW disk)

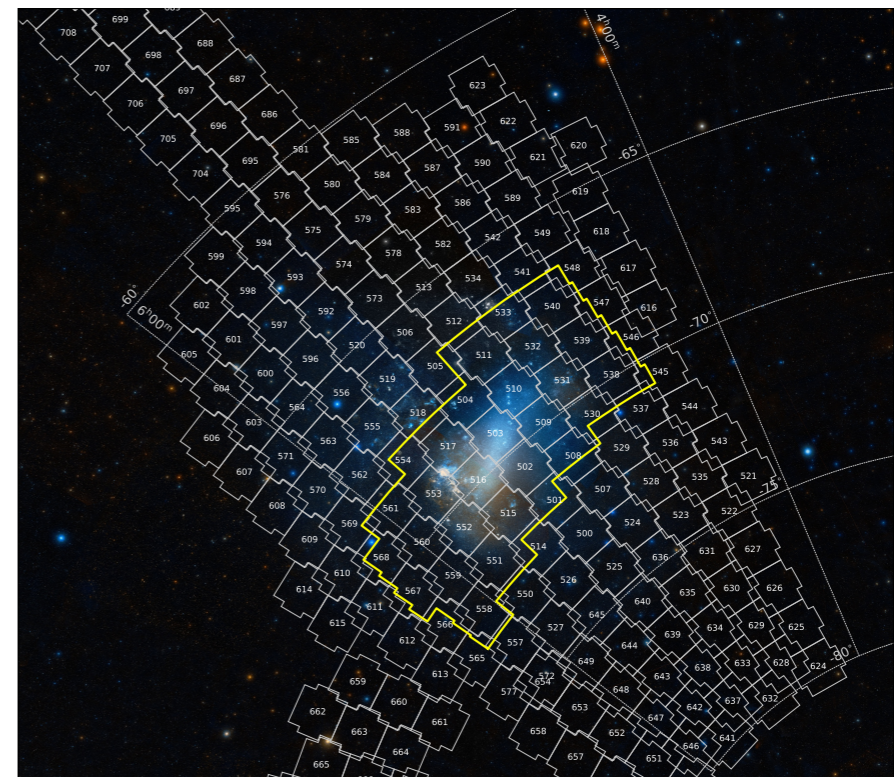
Comparison of MACHO, EROS and OGLE LMC microlensing surveys

Survey	Duration (years)	Field of view (deg ²)	Number of stars, N_{\star} (million)	Number of events, N_{obs}
MACHO	5.7	14	12	13
EROS	~ 12	88 (EROS-2)	~ 25 (EROS-2)	1
OGLE	~ 20	105 (OGLE-IV)	78.7 (OGLE-IV)	13



EROS I (box) & II, MACHO,
OGLE II (rectangles) & III

[Moniez](#)



OGLE III & IV

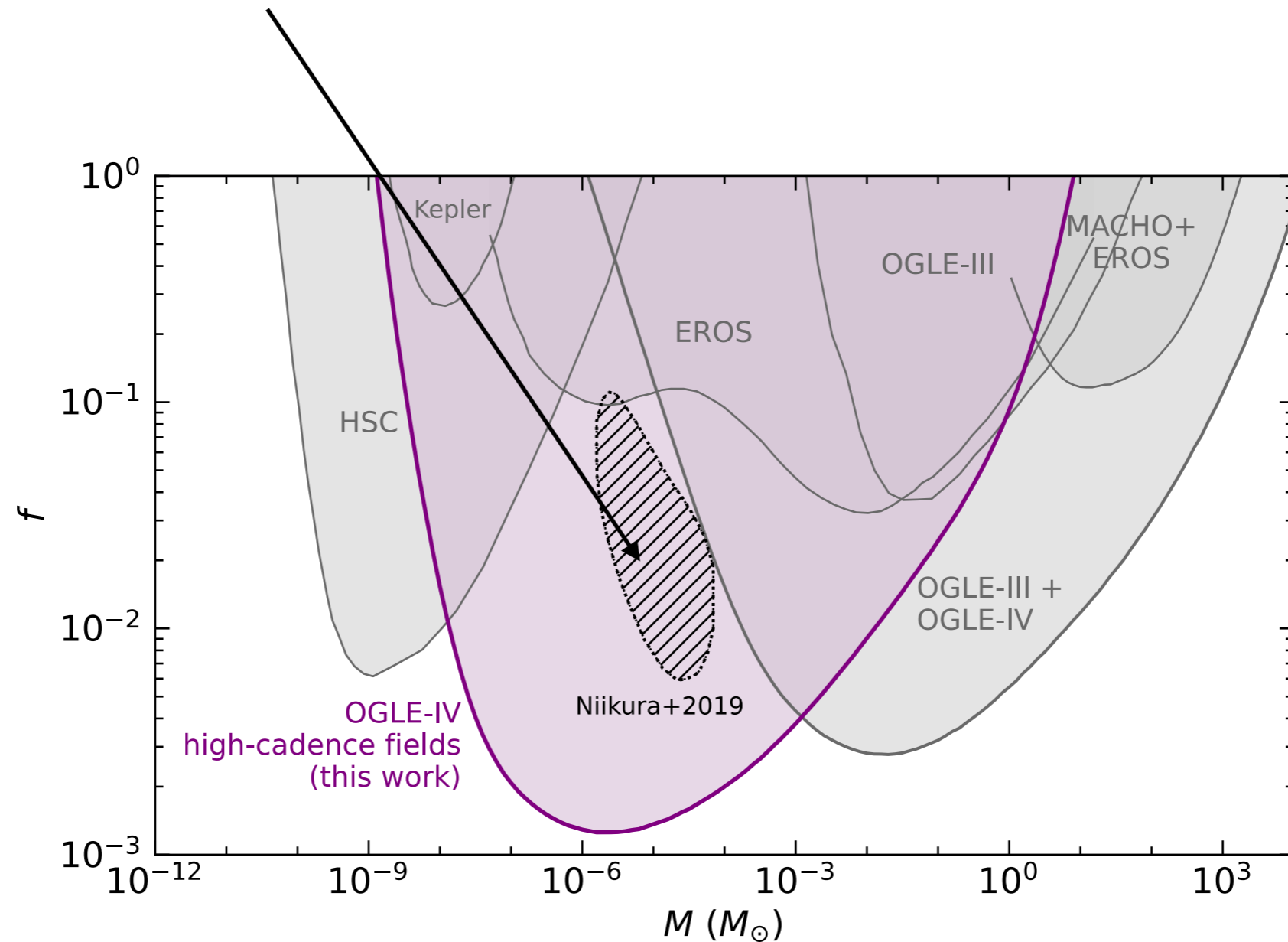
[Mroz et al. arXiv:2403.02386](#)

OGLE high cadence

Observed ~80 million stars in LMC every ~20 min for ~1 year: [Mroz et al. arXiv:2410.06251](#)

One candidate event.

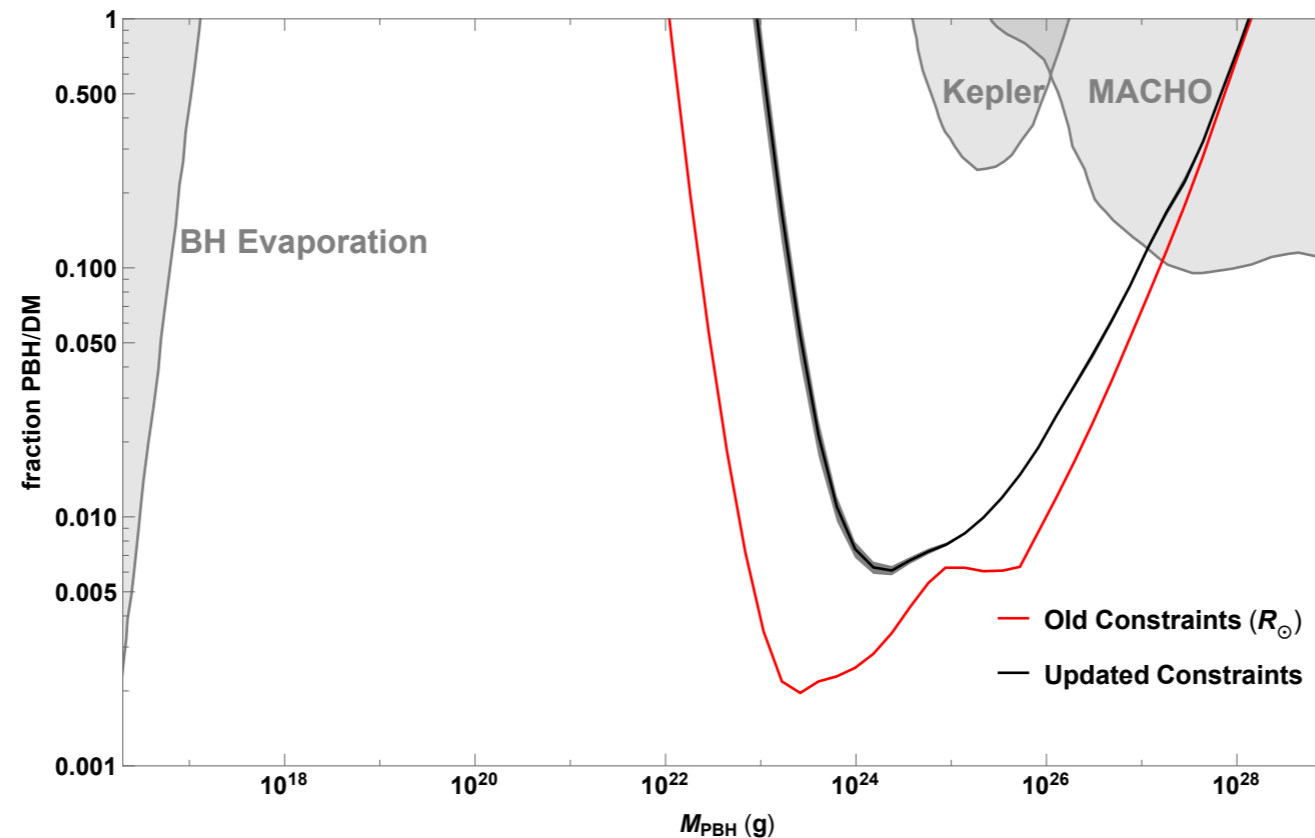
Inconsistent with PBH interpretation of ultra-short events towards Galactic bulge.



Subaru HSC (2019)

7 hours of high cadence (every ~ 2 min) observations of tens of millions of stars in M31.

[Niikura et al.](#)



[Smyth et al.](#)

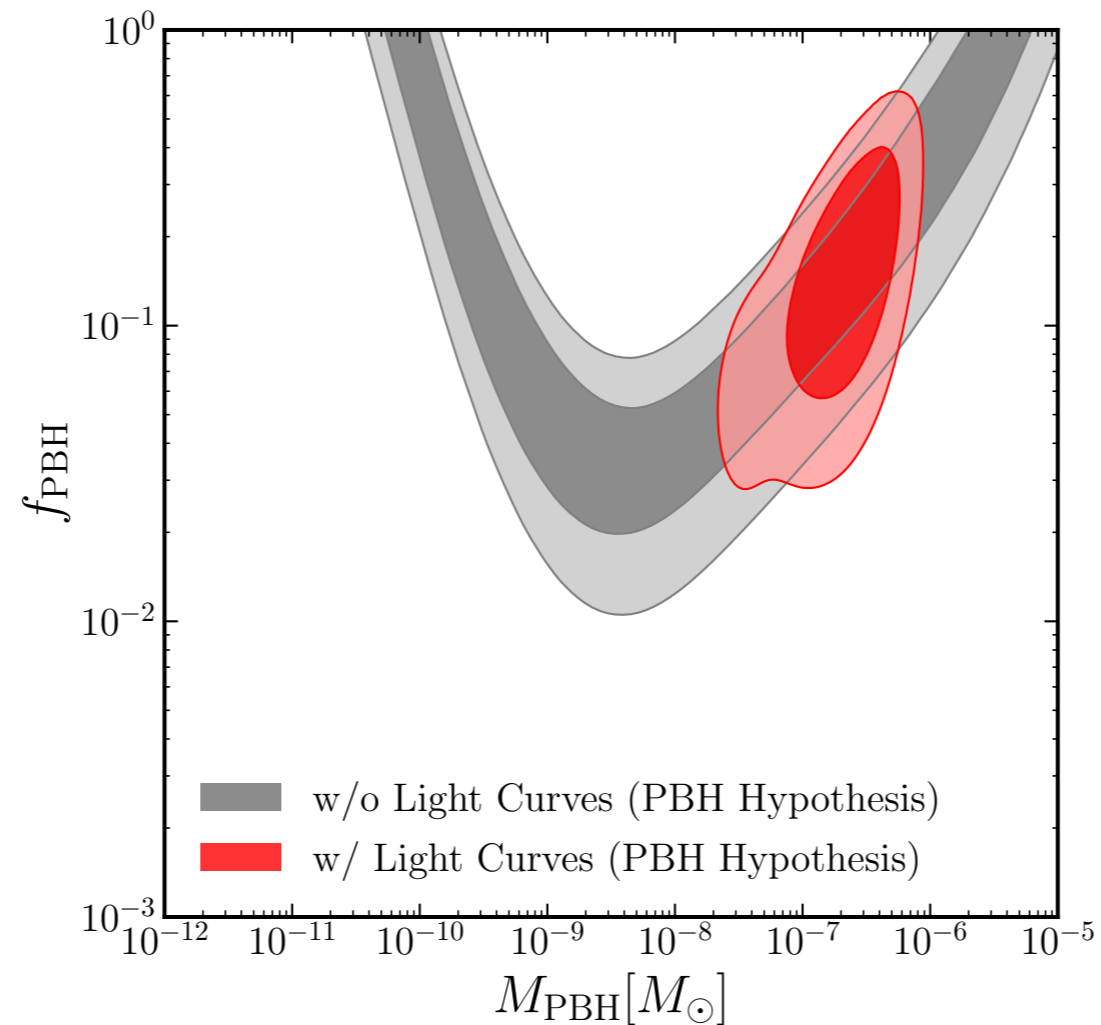
Finite size of source stars and effects of wave optics (Schwarzschild radius of BH comparable to wavelength of light) leads to reduction in maximum magnification. [Sugiyama, Kurita & Takada](#) and references therein.

And only large stars are bright enough for microlensing to be observed. [Montero-Camacho et al.](#); [Smyth et al.](#)

Subaru HSC (2026)

Additional data, plus improved analysis of original data (including modelling of finite source effects in detection efficiency estimation). [Sugiyama et al.](#)

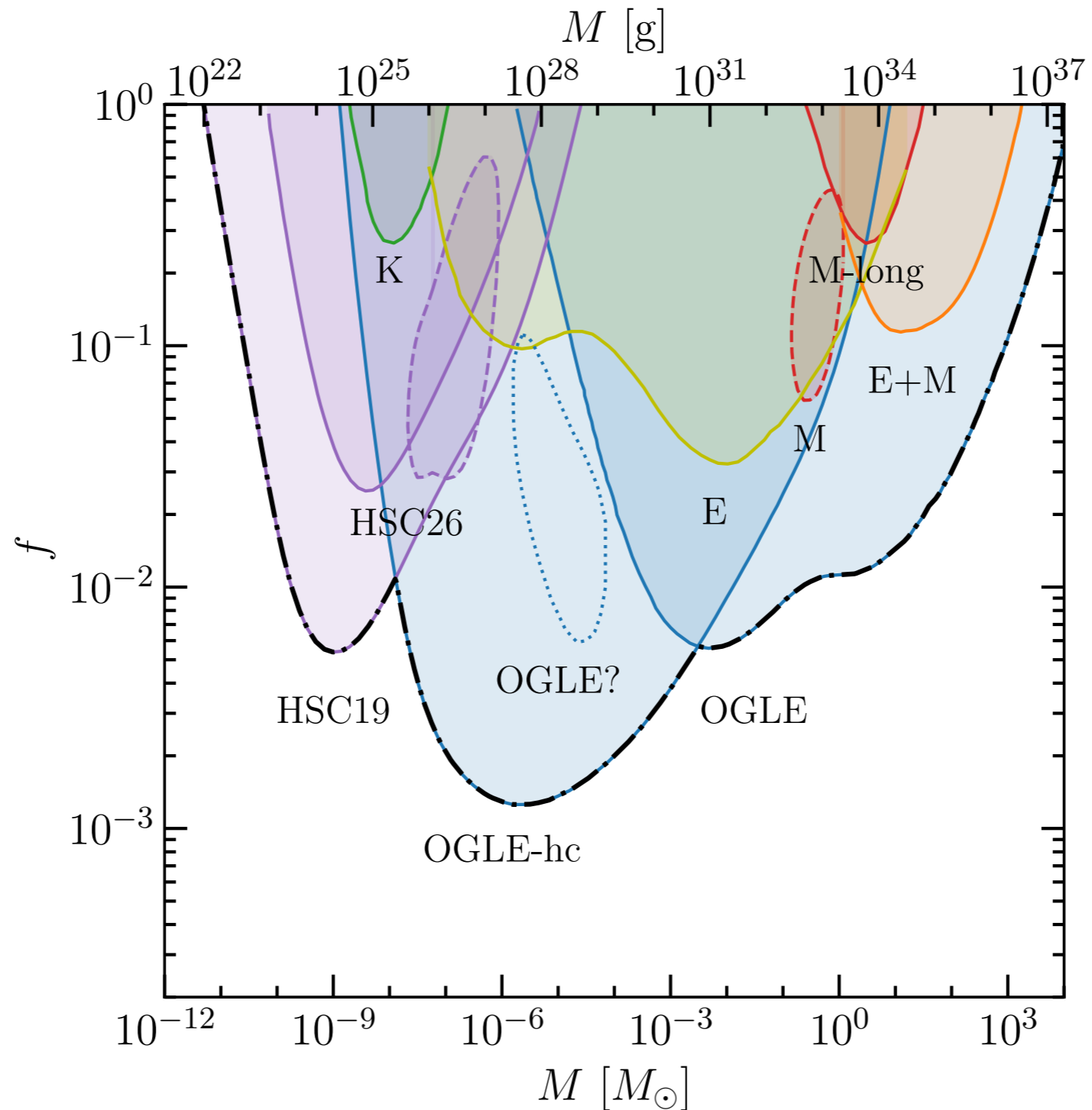
12 candidate events, 4 of which are 'secure, high-significance' detections.



Summary of current status

solid lines: exclusion limits

dashed & dotted lines: 'signals'



Main open theoretical question

PBH DM has more substructure on sub-galactic scales than particle DM. [Afshordi, Macdonald & Spergel](#); [Inman & Ali-Haïmoud](#); [Jedamzik](#)

How does this affect microlensing constraints?

Clusters formed from collapse of large gaussian density perturbations are sufficiently diffuse that PBHs lens individually, and in this case effect of clusters on microlensing constraints is small [Petaç, Lavallo & Jedamzik](#); [Gorton & Green](#).

But

- perturbations are inevitably non-gaussian, and non-gaussianity leads to larger clustering e.g. [Young & Byrnes](#), [Animali & Vennin](#)
- **if** clusters are sufficiently compact, the cluster as a whole acts as a lens, and microlensing constraints shifted to smaller M [Calcino, Garcia-Bellido & Davis](#)

Future observational prospects

Roman Space Telescope: high cadence observations, detect short timescale events and probe light compact objects.

(ground based) Rubin observatory: long duration wide field survey, detect long timescale events and probe intermediate and high mass compact objects.

Potential to discriminate events due to PBHs from those due to free-floating planets and/or stars, and probe $f \sim 10^{-3} - 10^{-4}$. [DeRocco et al.](#); [Fardeen et al.](#)

Astrometric microlensing

Change in apparent position of source star. Can be detected by telescopes which accurately measure the position of stars (e.g. Roman) and depends on angular Einstein radius:

$$\delta\theta = \frac{u}{u^2 + 2} \theta_E$$
$$\theta_E^2 \equiv \left(\frac{R_E}{D_L} \right)^2 = 8.14 \text{ milliarcsec} \left(\frac{M}{M_\odot} \right) \pi_{\text{rel}} \quad \pi_{\text{rel}} = \frac{1}{D_L} - \frac{1}{D_S}$$

So if lens-source parallax, π_{rel} , can be measured, can measure lens mass.

Correctly identifying events (& minimising false positive rate) will be crucial.
c.f. [Crispim Romao et al.](#)

Summary

- Photometric microlensing observations (HSC, OGLE,...) constrain the fraction of the MW halo in planetary and stellar mass PBHs:

$$f \lesssim \mathcal{O}(10^{-2}) \text{ for } 10^{-10}M_{\odot} \lesssim M_{\text{PBH}} \lesssim 10M_{\odot}$$

$$f \lesssim \mathcal{O}(1) \text{ for } 10^{-11}M_{\odot} \lesssim M_{\text{PBH}} \lesssim 10^4M_{\odot}$$

under ‘standard’ assumptions about DM distribution.

- Main theoretical open question: how does clustering of PBHs formed from realistic non-gaussian density perturbations affect these constraints?
- Observational prospects: potential for significantly improved sensitivity ($f \sim 10^{-3} - 10^{-4}$) in future, in particular from astrometric microlensing obs.