(stellar) Microlensing constraints on Primordial Black Hole dark matter

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Theory

Observations

Constraints on (realistic) extended mass functions arXiv:1609.01143

Astrophysical uncertainties arXiv:1705.10818

Prelude:

PBH abundance constraints on the primordial power spectrum (and hence models of inflation):

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Constraints on the density perturbation spectrum from primordial black holes

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(Received 25 April 1997)

Critical collapse and the PBH initial mass function:

Critical collapse and the primordial black hole initial mass function

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PBHs as a MACHO candidate:

PROBING THE MASS FUNCTION OF HALO DARK MATTER VIA MICROLENSING

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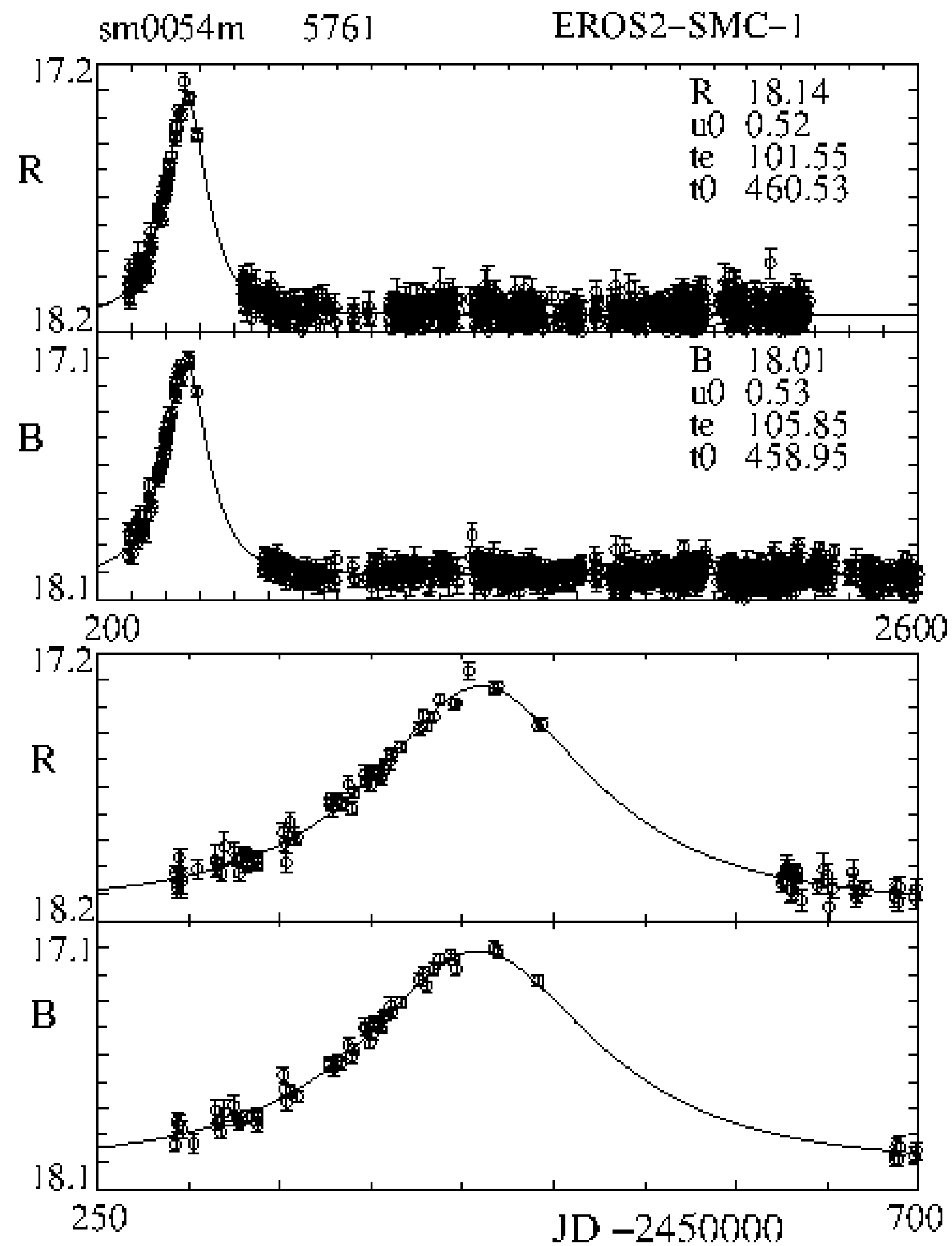
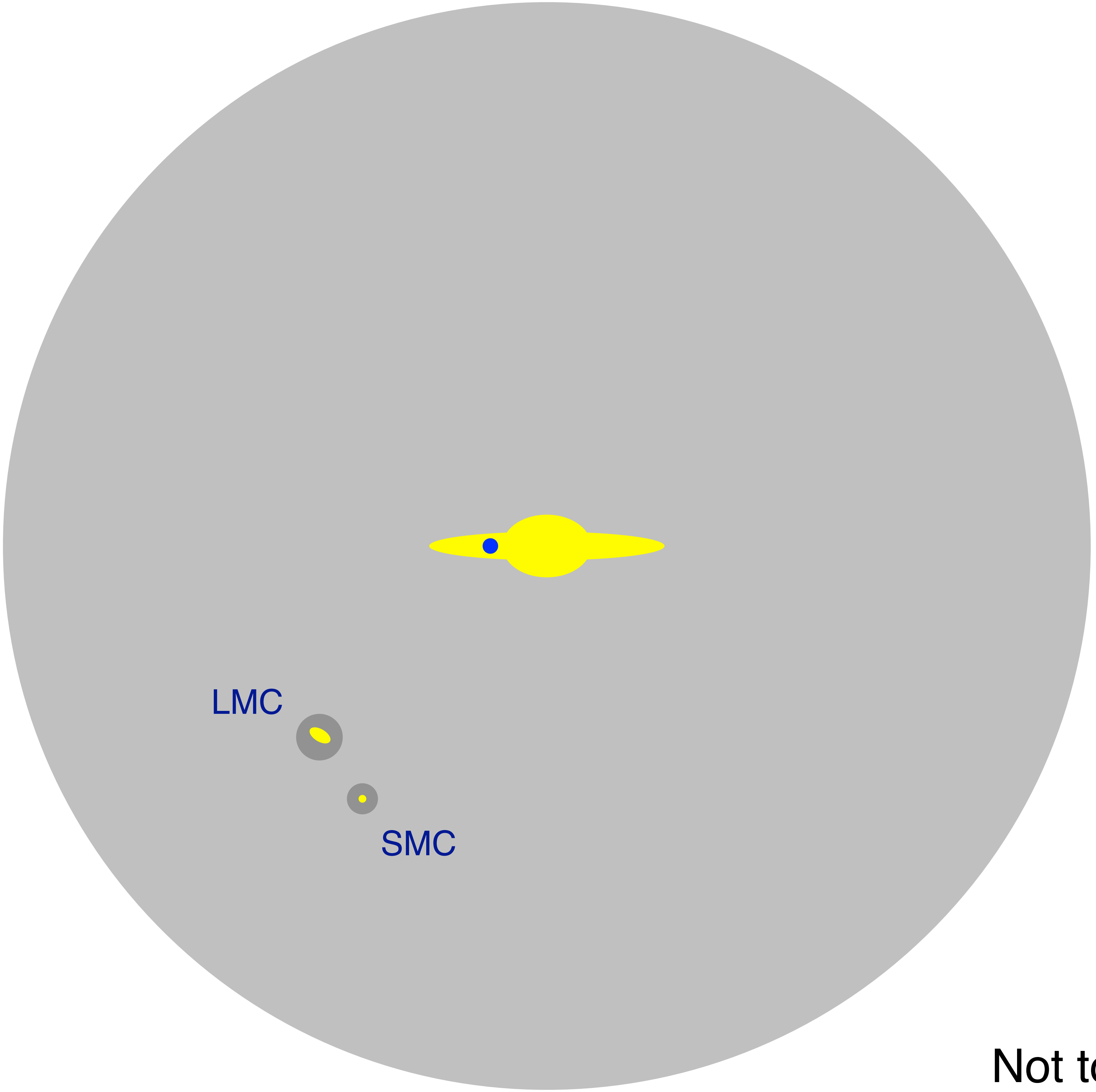
Theory

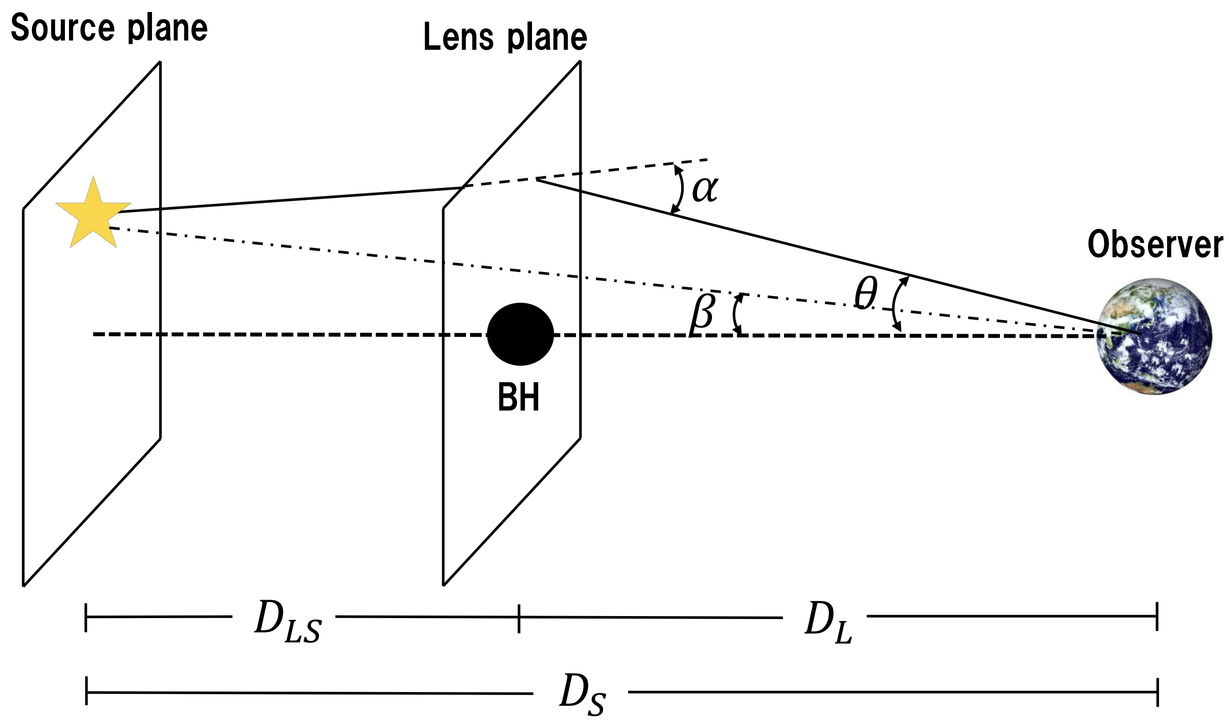
(stellar) Microlensing is a temporary (achromatic) brightening of background star when compact object passes close to the line of sight. [Paczynski]



EROS



Not to scale!



$$x = \frac{D_L}{D_S}$$

[Sasaki et al.]

Lens equation on lens plane: $$r^2 - r_0 r - R_{\rm E}^2 = 0$$

$$r = D_L\theta \qquad r_0 = D_L\beta$$

Einstein radius: $$R_E = \sqrt{\frac{4GMD_LD_{LS}}{D_S}}$$

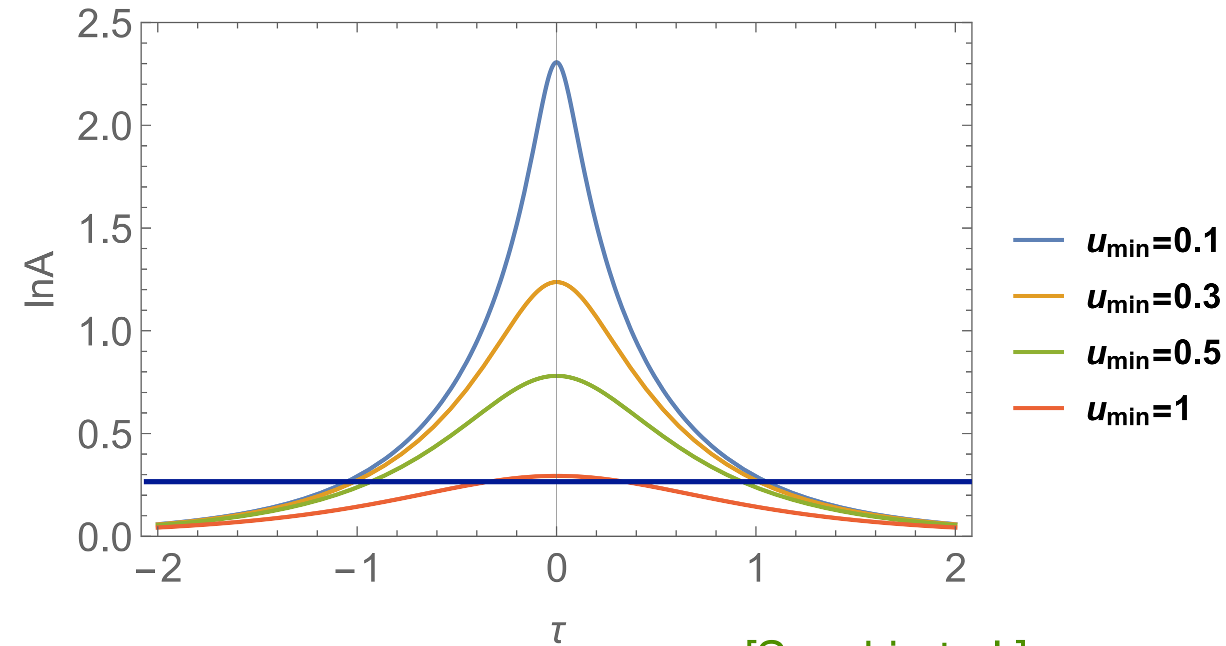
Image positions: $$r_{1,2} = \frac{1}{2}\left(r_0 \pm \sqrt{r_0^2 + 4R_E^2}\right)$$

Angular separation: $$\Delta \sim \frac{R_E}{D_L} = 0.3\,\mathrm{mas}\left(\frac{M}{10\,M_\odot}\right)^{1/2}\left(\frac{D_S}{100\,\mathrm{kpc}}\right)^{-1/2}\sqrt{\frac{1-x}{x}}$$

Microlensing occurs when angular resolution is too small to resolve multiple images, instead observe amplification of source:

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

$$u = \frac{r_0}{R_E}$$



[Sasaki et al.]

at $r_0 = R_E$ A=1.34, which is usually taken as the threshold for microlensing.

Duration of event:

$$\hat{t} = \frac{2R_E}{v} \approx 4\,\mathrm{yr}\sqrt{x(1-x)}\left(\frac{M}{10\,M_\odot}\right)^{1/2}\left(\frac{D_S}{100\,\mathrm{kpc}}\right)^{1/2}\left(\frac{v}{200\,\mathrm{km\,s^{-1}}}\right)^{-1}$$

n.b. this all assumes point source and lens. For sub-lunar lenses finite size of source stars reduces magnification. [Witt & Mao; Matsunaga & Yamamoto]

Differential event rate

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

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\hat{t}} = \frac{32 L u_{\mathrm{T}}^4}{\hat{t}^4 M v_{\mathrm{c}}^2} \int_0^1 \rho(x)\, R_{\mathrm{E}}^4(x)\, \exp\left[-\frac{4R_{\mathrm{E}}^2(x)}{\hat{t}^2 v_{\mathrm{c}}^2}\right] \mathrm{d}x$$

$\rho(x)$ = compact object density distribution

$\hat{t}$ = Einstein ***diameter*** crossing time (as used by the MACHO collab., EROS & OGLE use Einstein radius crossing time)

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

L = distance from observer to source (49.6 kpc for LMC)

Expected number of events:

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

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

$\epsilon(\hat{t})$ = efficiency (prob. that an event of duration $\hat{t}$ is observed)

Standard halo model

cored isothermal sphere:

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

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

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

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

‘Backgrounds’

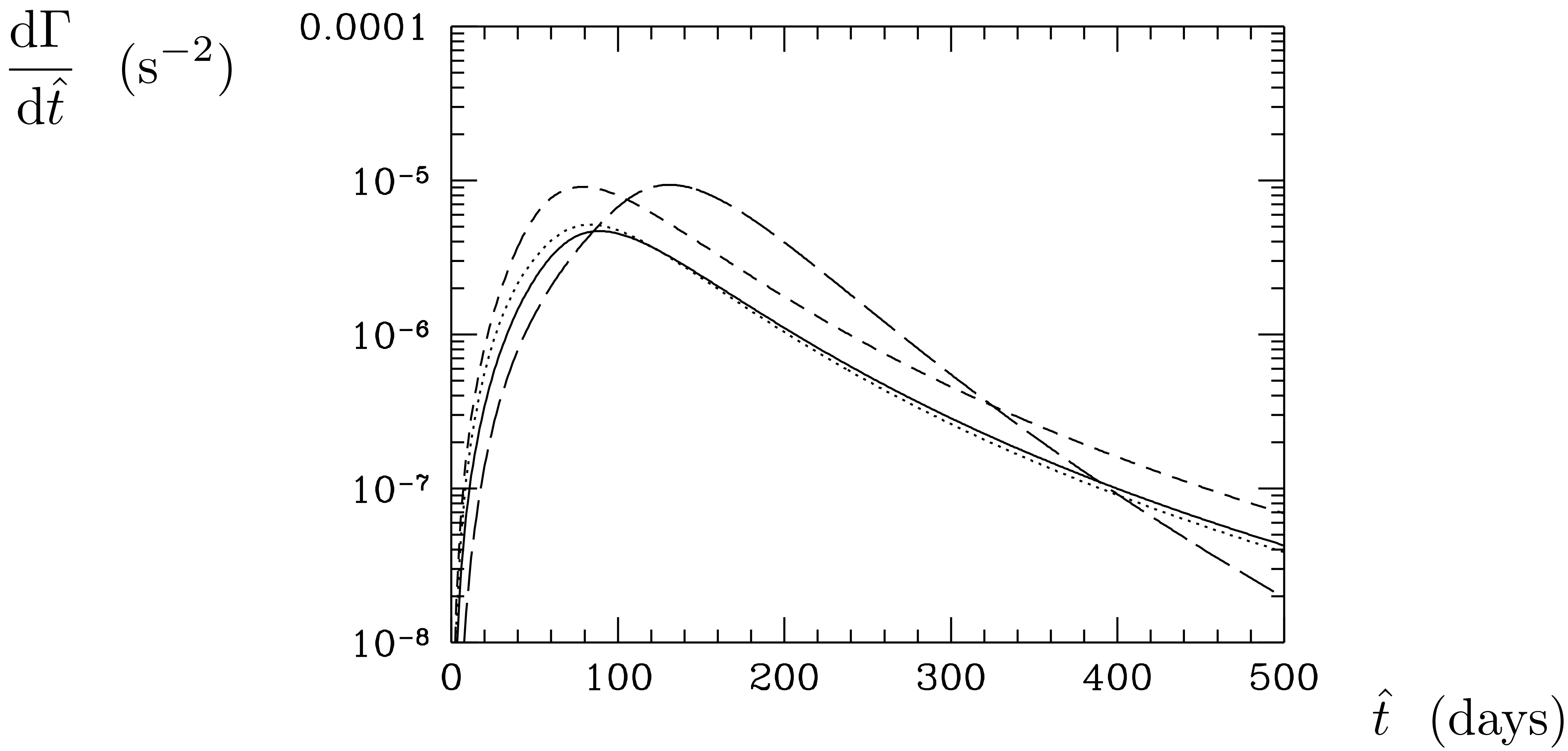
i) variable stars, supernovae in background galaxies

cuts/fits developed to eliminate them (but some events only rejected years later, after ‘star”s brightness varied a 2nd time!)

ii) lensing by stars in MW or Magellanic Clouds themselves (‘self-lensing’)

model and include in event rate calculation

Differential event rate for $M = 1\,M_\odot$ and halo fraction f=1:
($\hat{t} \propto M^{1/2}$, $d\Gamma/d\hat{t} \propto M^{-1}$)



______ = standard halo model

. . . . = standard halo model including transverse velocity

- - - - = Evans power law model: massive halo with rising rotation curve, $v_c \propto R^{0.2}$

_ _ _ _ = Evans power law model: flattened halo with falling rotation curve, $v_c \propto R^{-0.2}$

velocity anisotropy can affect rate at ~10% level [De Paolis, Ingrosso & Jetzer]

Calculations of parameter constrains/exclusion limits:

If no events observed: $N_{\rm exp} < 3$ at 95% confidence.

If events are observed:

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

where $\hat{t}_i$ are the durations of the $N_{\rm obs}$ events and other lens populations (stars in MW and MC) included in differential event rate.

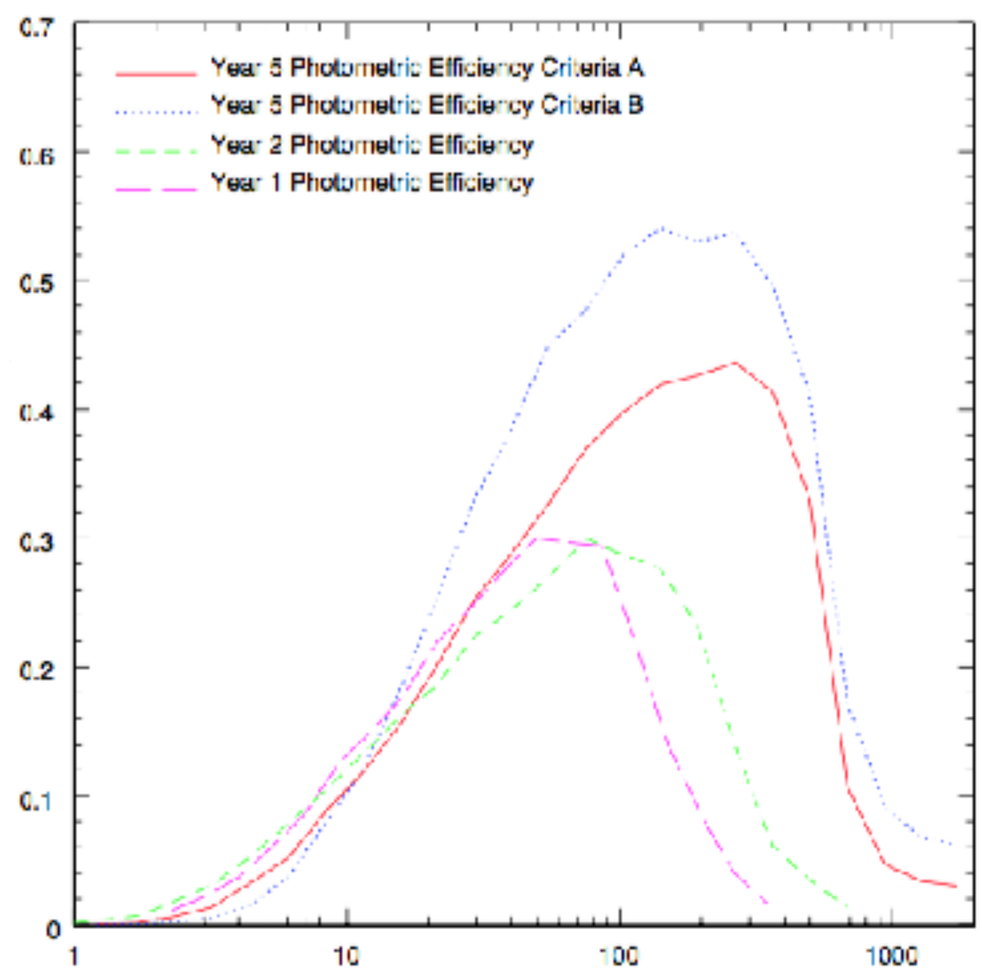
Observations

MACHO

Monitored 12 million stars in LMC for 5.7 years.

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

Detection efficiency

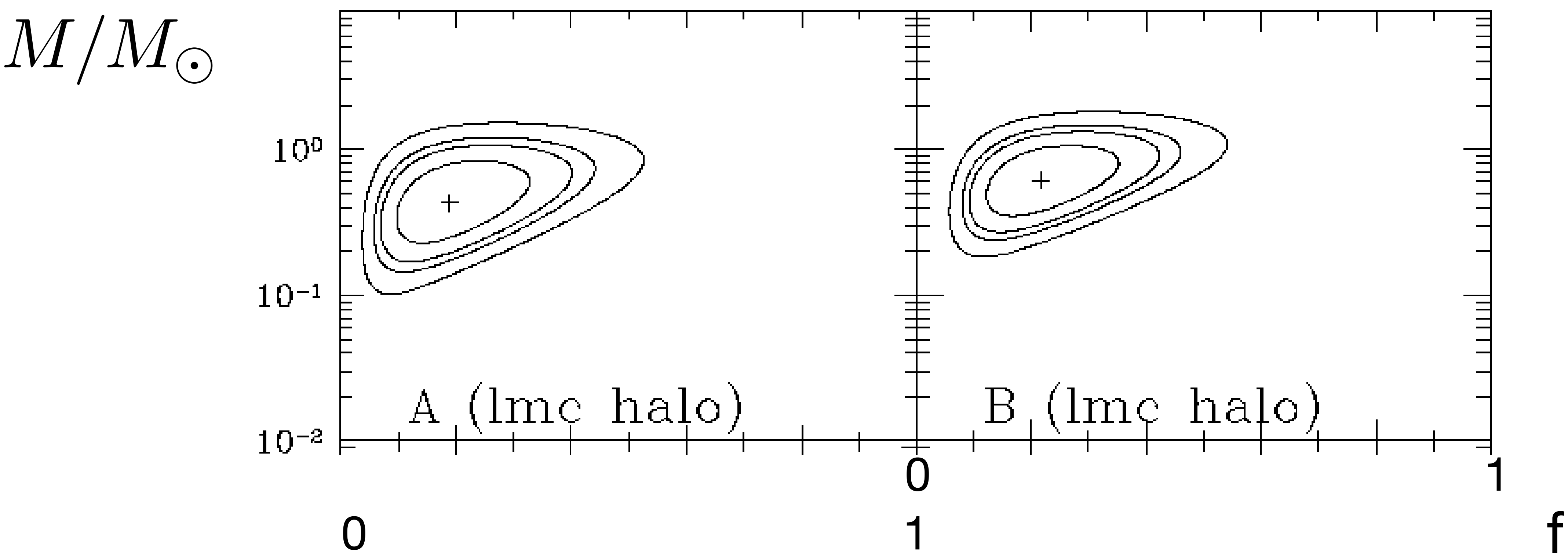


5 years A
5 years B
2 years
1 year

$\hat{t}$

Measurement of fraction of halo in compact objects, f,
(assuming a delta-function mass function):

selection criteria A B



MACHO

BUT

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

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

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

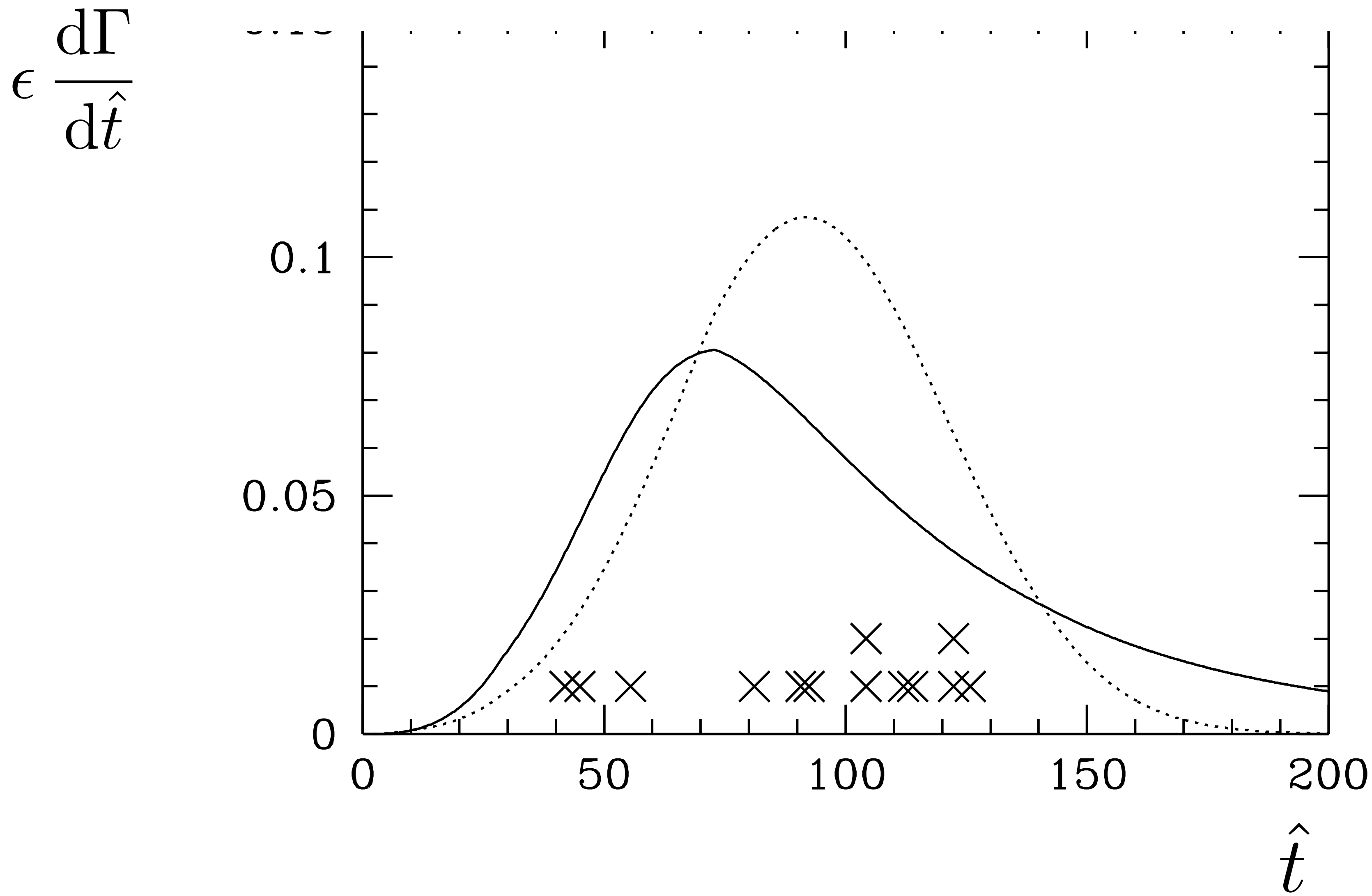
LMC-20: (criteria B) lens identified (using Spitzer obs) as a MW thick disc star. [Kallivayalil et al.]

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

LMC-23: varied again, so not microlensing [EROS/OGLE]

AND

Distribution of timescales is narrower than expected for lenses in MW halo (assuming standard halo model). [Green & Jedamzik]

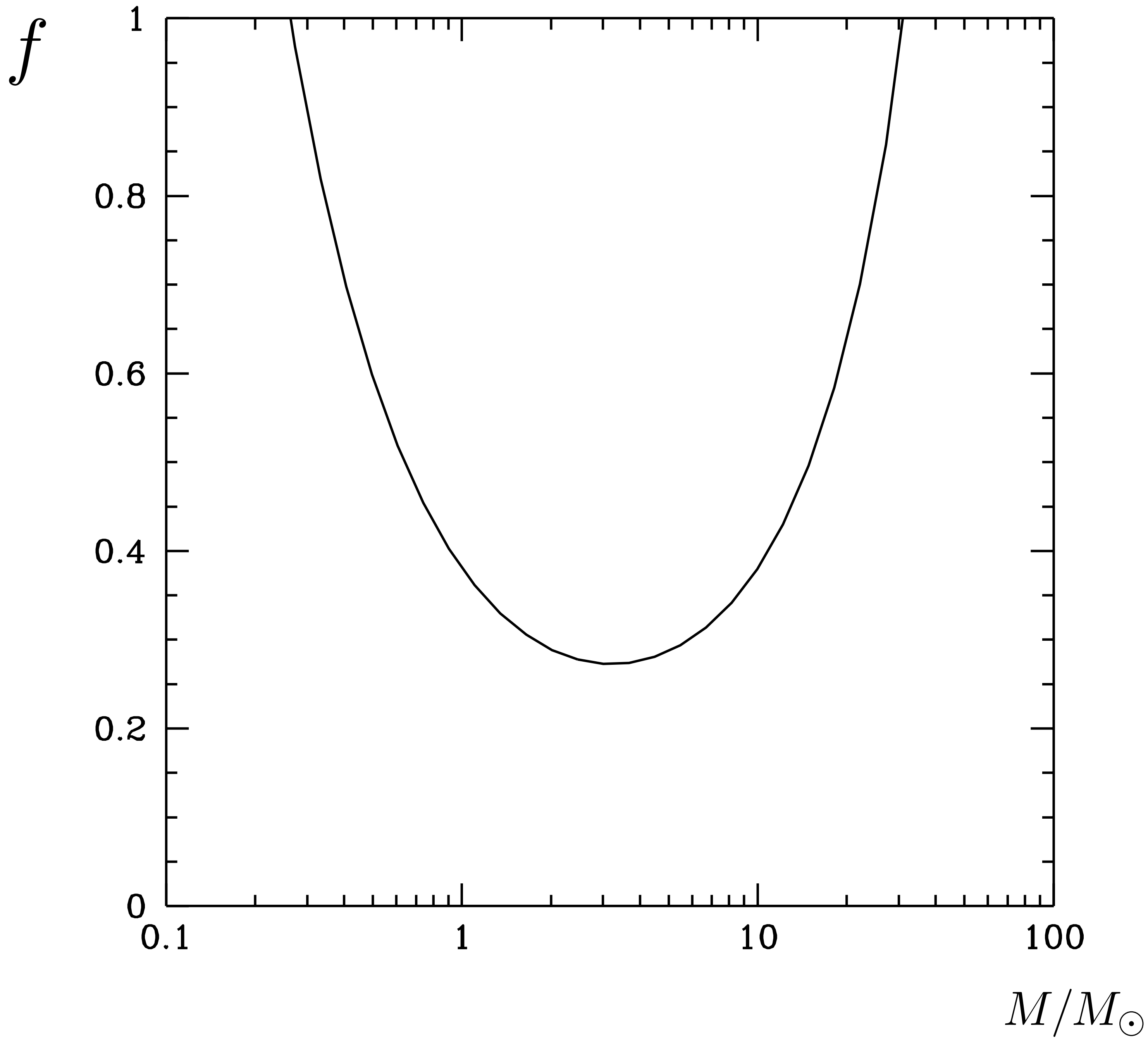


X durations of observed events

______ best fit distribution assuming standard halo model + delta-function mass function

- - - - best fit gaussian differential event rate

Limits on halo fraction for $1 < M/M_\odot < 30$ from MACHO null search for long (> 150 day) duration events:



MACHO

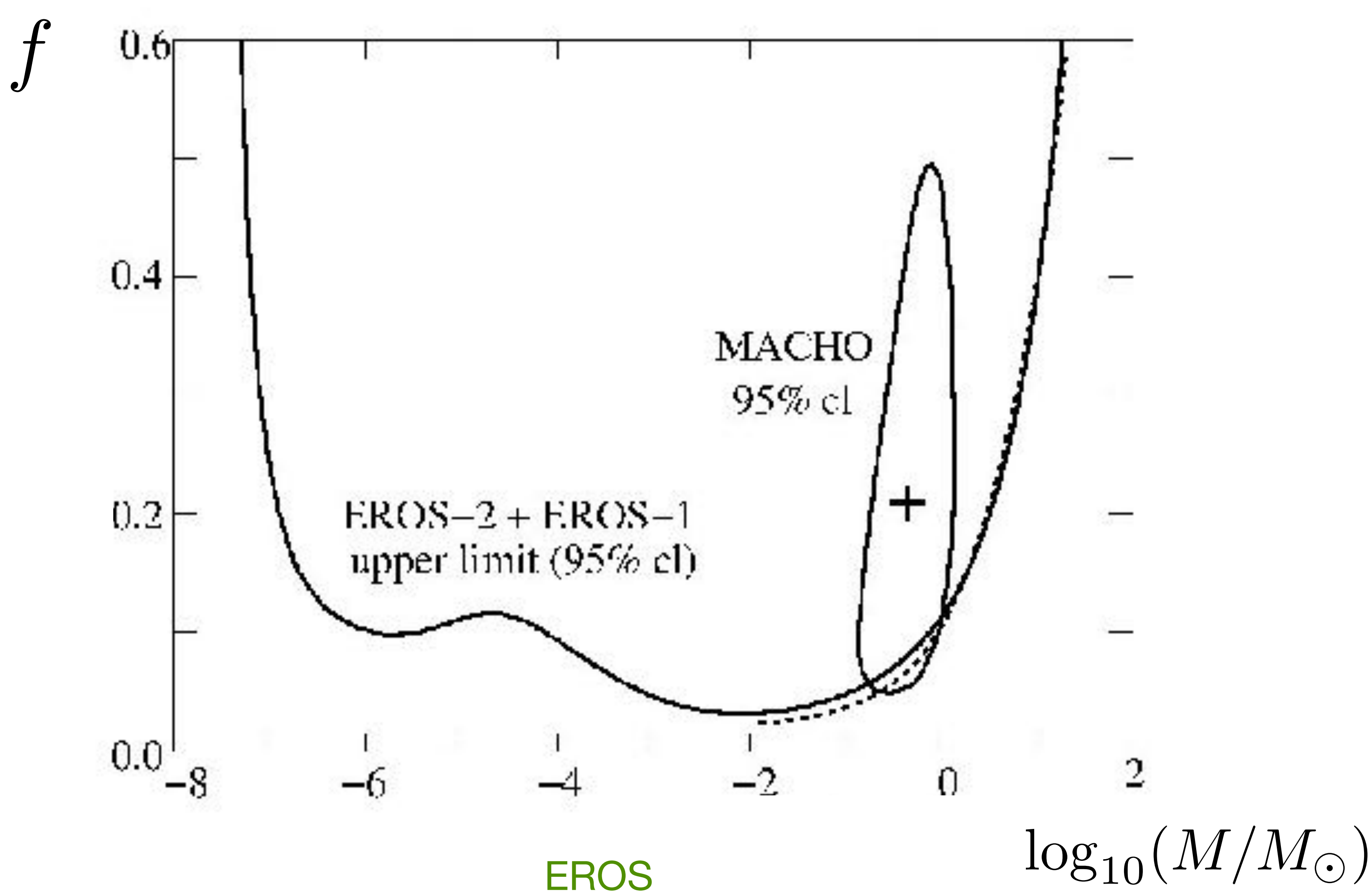
EROS

Monitored 67 million stars in LMC and SMC for 6.7 years. Use bright stars in sparse fields (to avoid complications due to 'blending'-contribution to baseline flux from unresolved neighbouring star).

1 SMC event (also seen by MACHO collab.) consistent with expectations for self-lensing (SMC is aligned along line of sight). [Graff & Gardiner]

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

Constraints on fraction of halo in compact objects, f, (DF MF):



EROS

OGLE

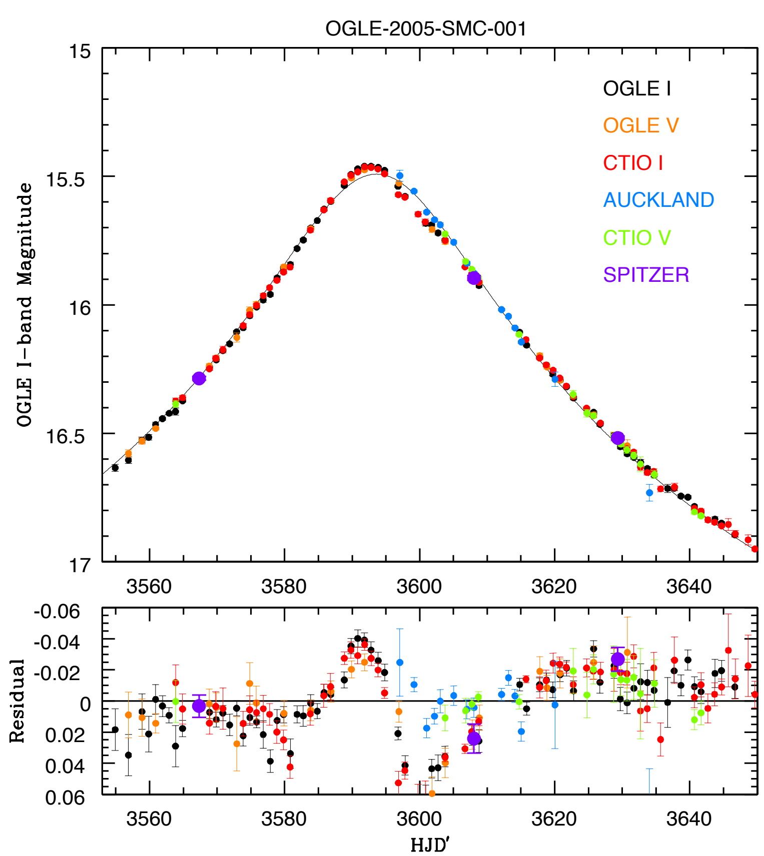
OGLE-II and III monitored 41 million stars in LMC and SMC for 12 years.

Total of 8 events. All but 1 (SMC-02) consistent (number/duration/lensed star location/ detailed modelling of light curve including parallax) with lens being a star in the MW or MCs.

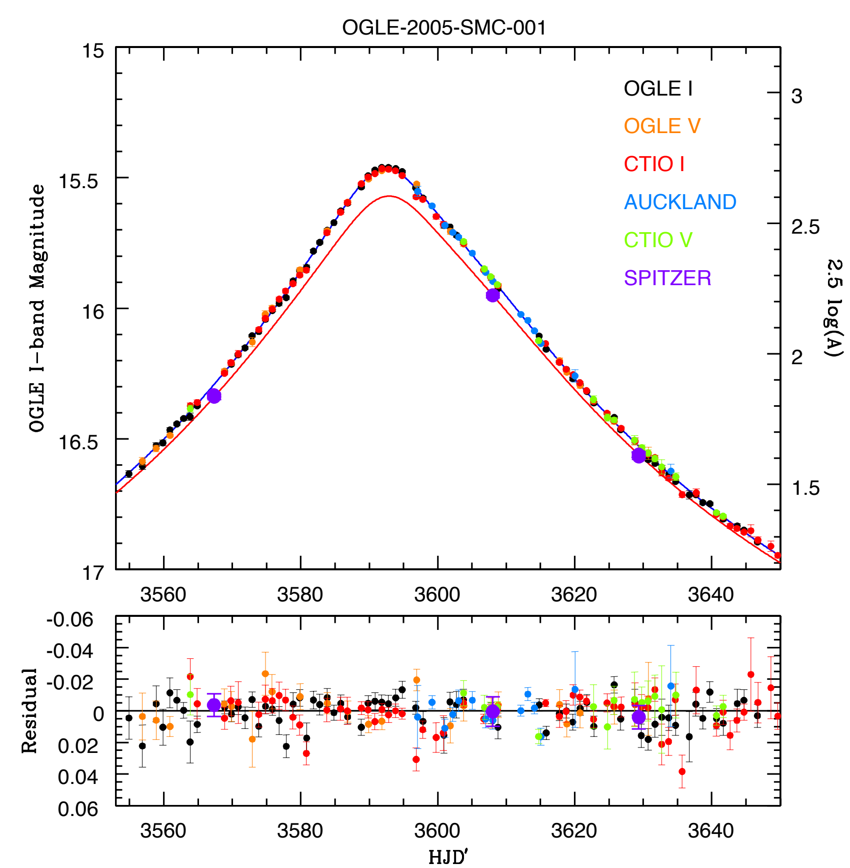
SMC-02: Light curve shows parallax effect and additional Spitzer observations find deviation from single lens model [Dong et al.].

Consistent with lens being a ~10 Solar mass BH binary in MW halo (no light observed from lens).

standard microlensing fit

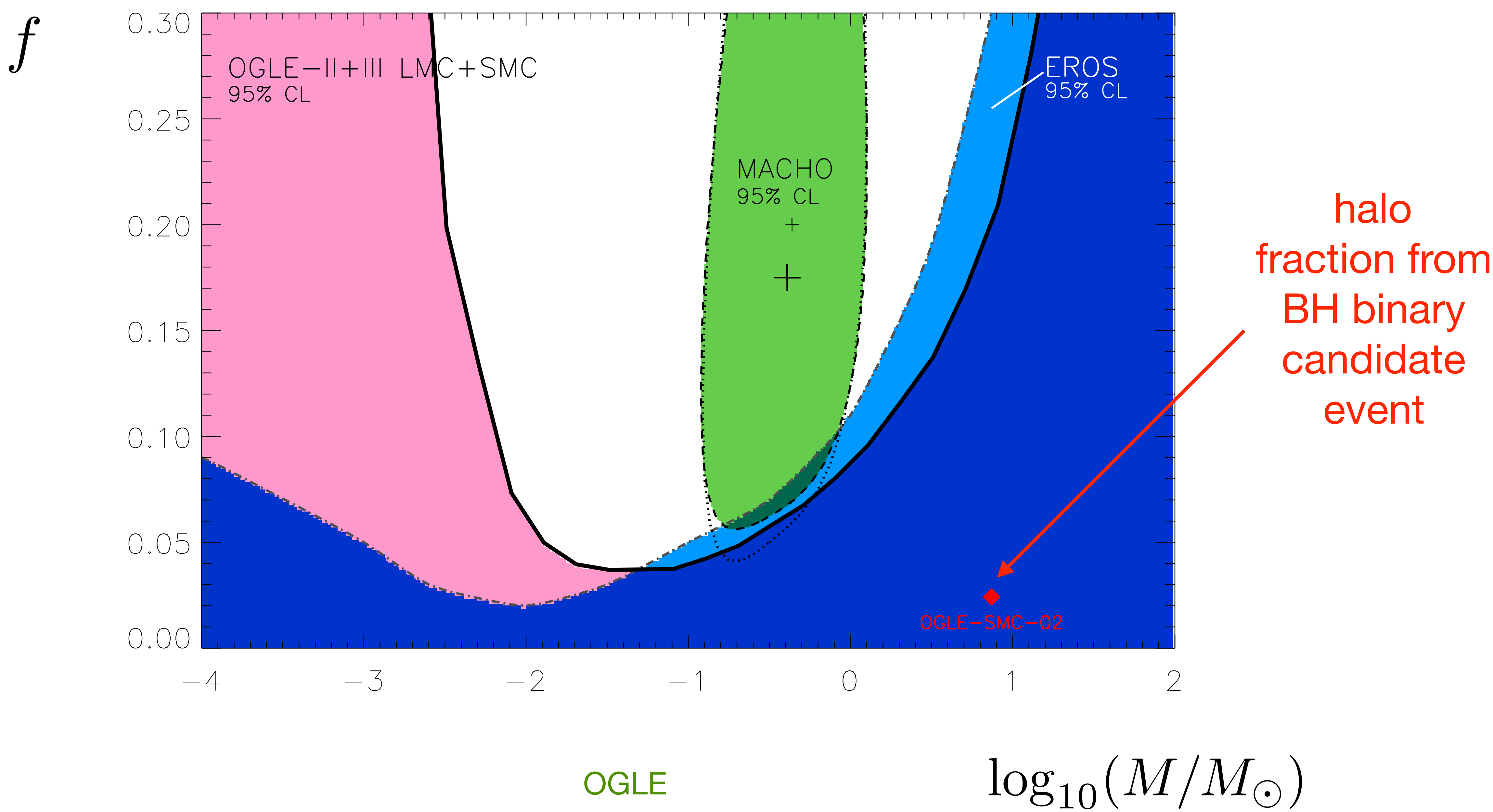


best-fit binary microlensing fit
also including parallax



Residuals

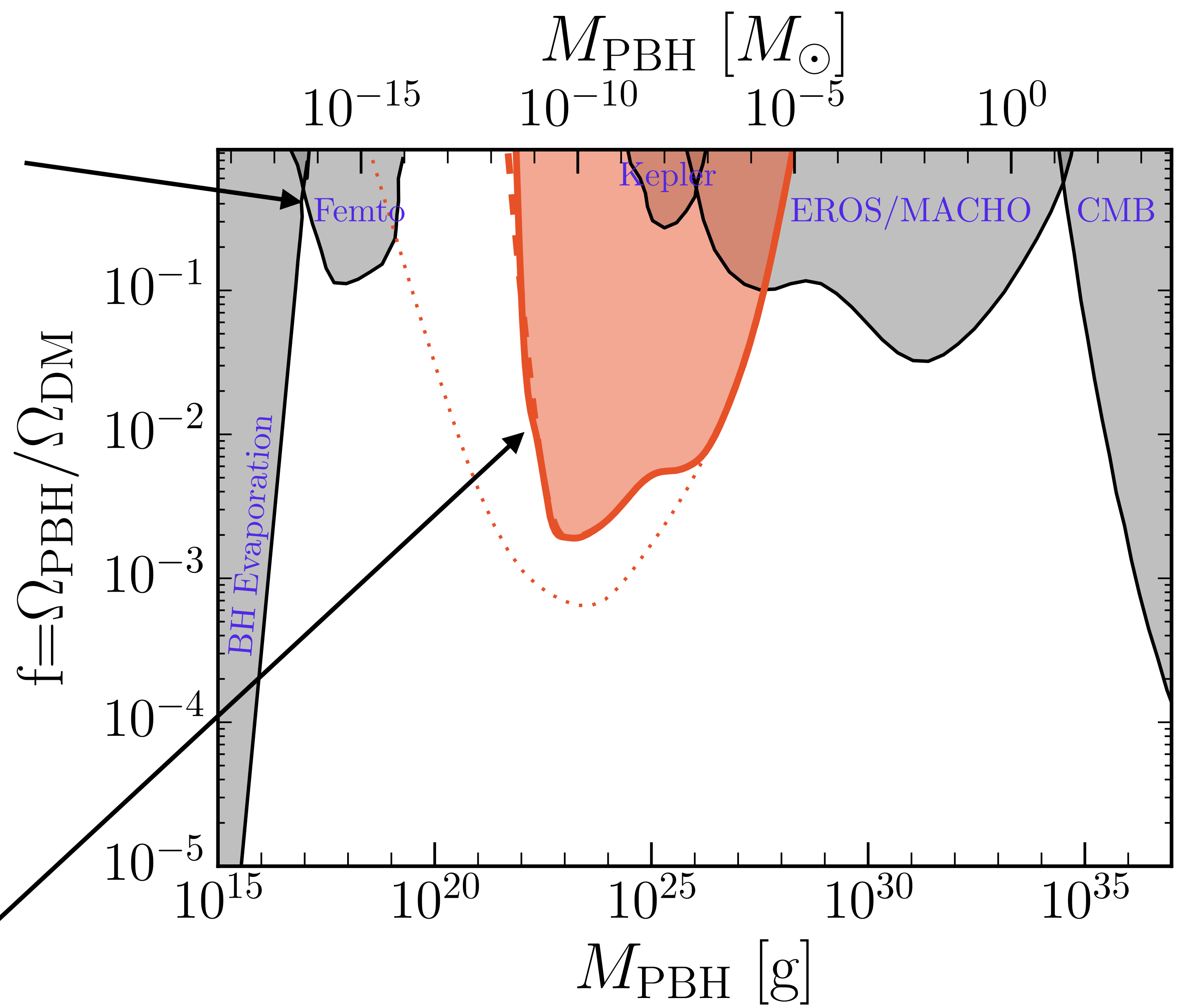
Constraints on fraction of halo in compact objects, f,
(assuming a delta-function mass function):



M31 with Subaru Hyper Suprime-Cam

Same principle as MW microlensing, but sensitive to lighter compact objects (due to higher cadence obs.). Source stars unresolved.

Ignores finite size of GRBs [Katz et al.]

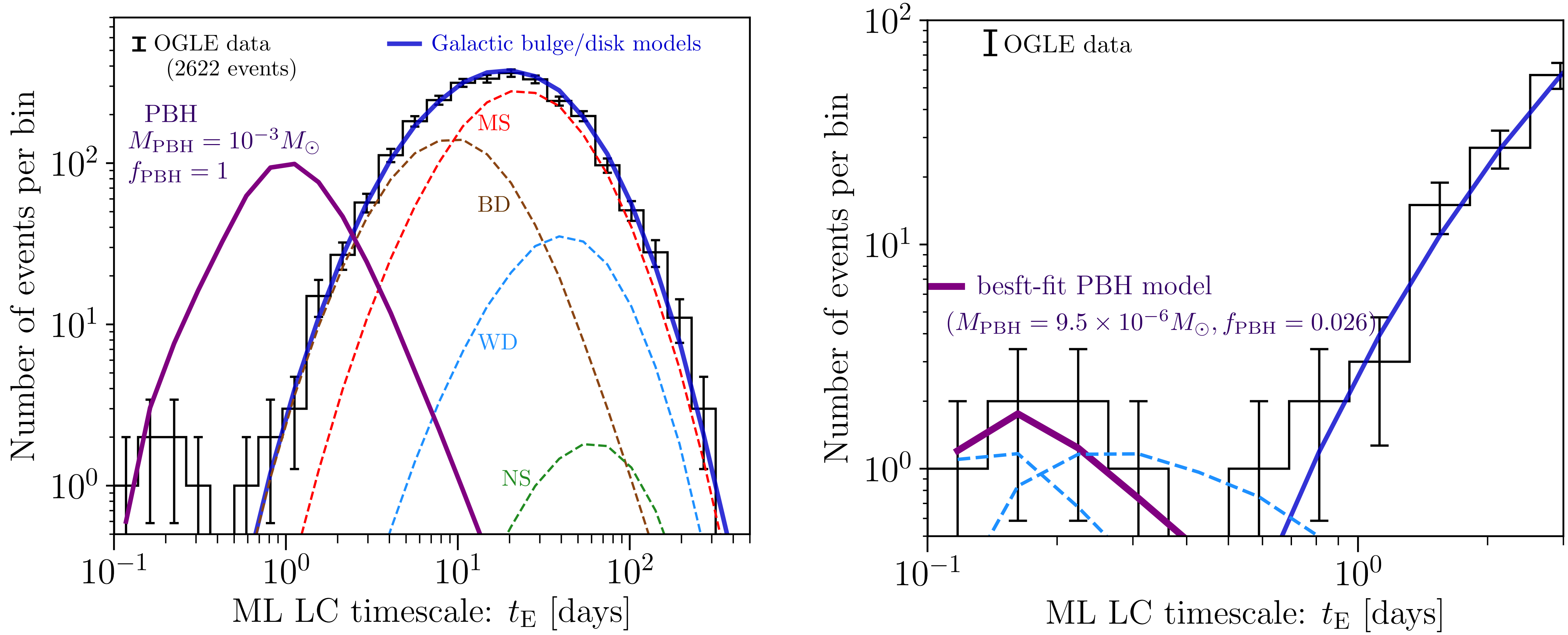


[Niikura et al.]

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 for $M \lesssim 10^{-7}\, M_\odot$ and $M \lesssim 10^{-11}\, M_\odot$ respectively. [Witt & Mao; Gould; Nakamura]

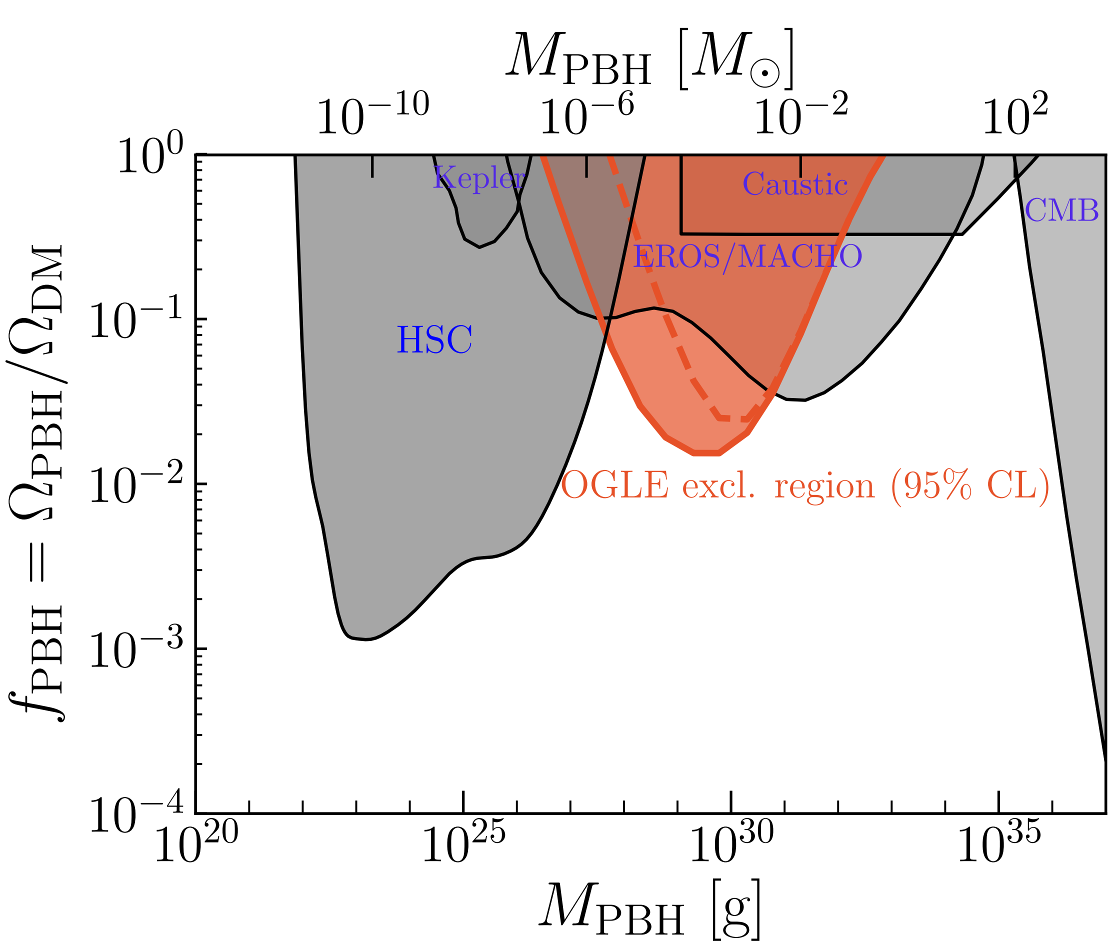
OGLE Galactic bulge

Observed events consistent with expectations from stars, except for 6 ultra-short (0.1-0.3) day events:

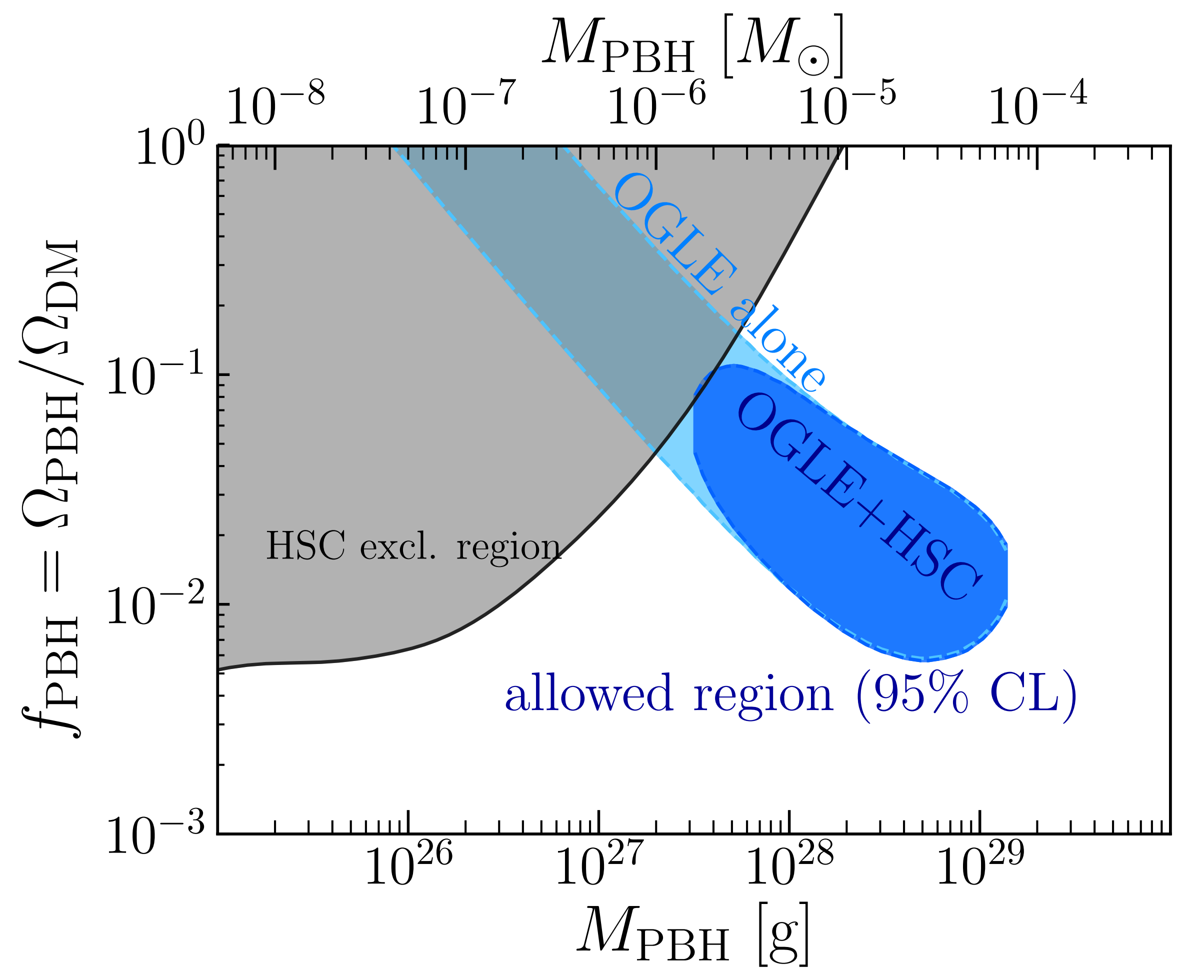


Niikura et al.

Exclusion limit
assuming no PBH lensing observed



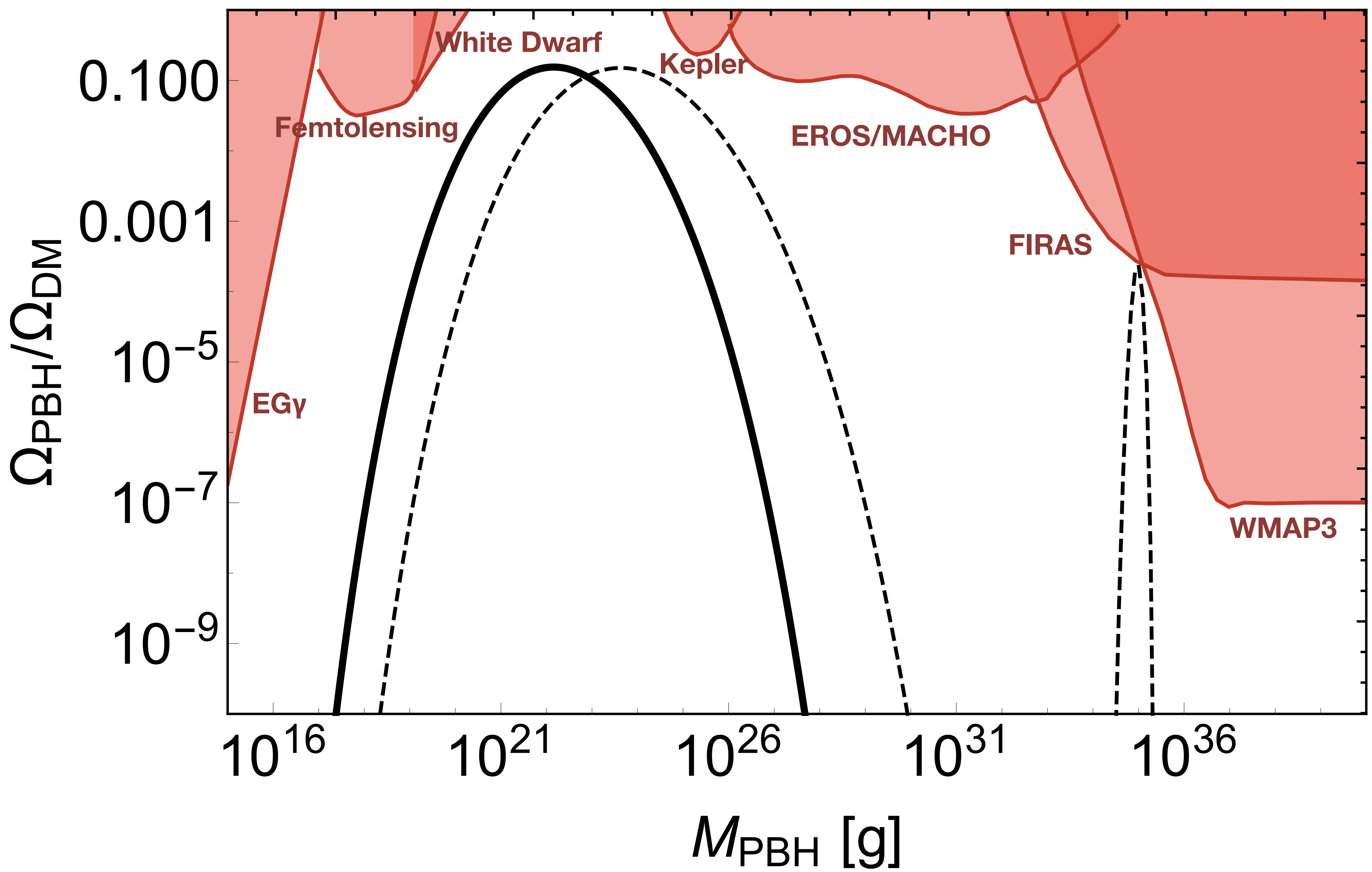
Allowed region
assuming 6 ultra-short events are due to PBHs



Constraints on (realistic) extended mass functions

Applying constraints calculated assuming a DF MF to extended MFs is subtle.

Can't just compare df/dM to constraints on f as a function of M.



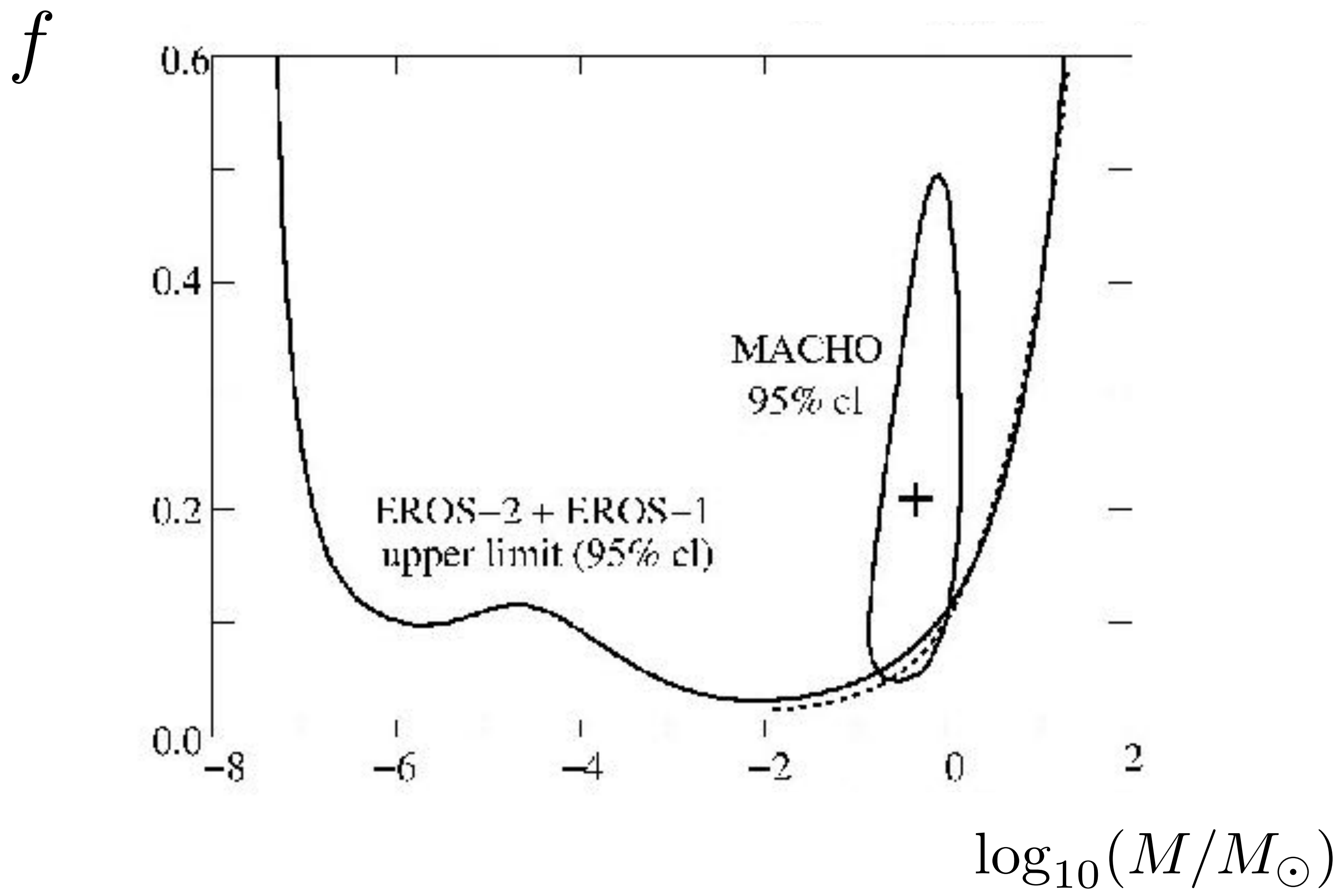
Constraints on (realistic) extended mass functions

Applying constraints calculated assuming a DF MF to extended MFs is subtle.

Can't just compare df/dM to constraints on f as a function of M.

Beware double counting.

e.g. EROS microlensing constraints allow f~0.1 for M~M_{sun} or f~0.5 for M~10 M_{sun}, **but NOT BOTH**.

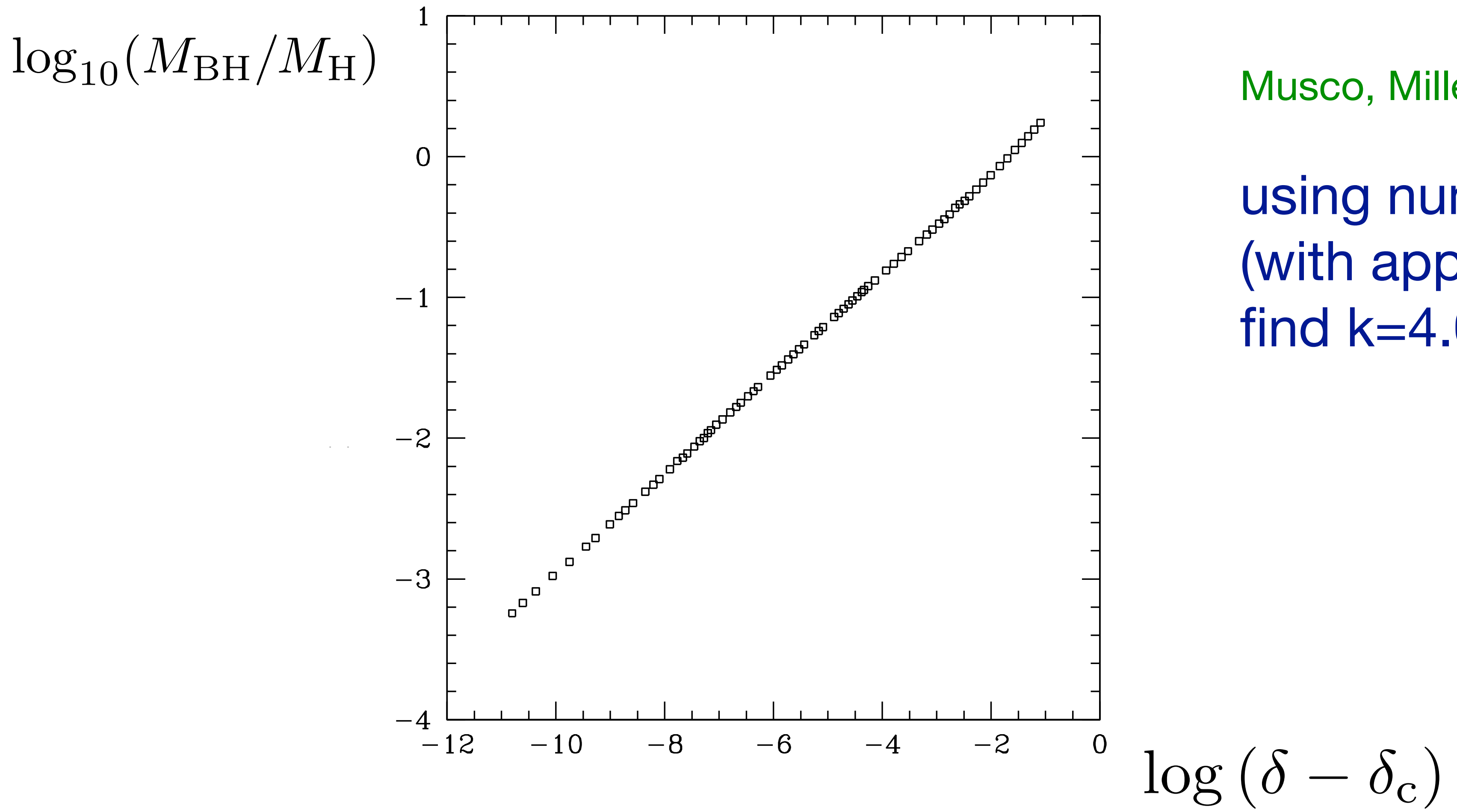


Critical phenomena

Choptuik; Evans & Coleman; Niemeyer & Jedamzik

BH mass depends on size of fluctuation it forms from:

$$M = k M_{\rm H} (\delta - \delta_{\rm c})^{\gamma}$$



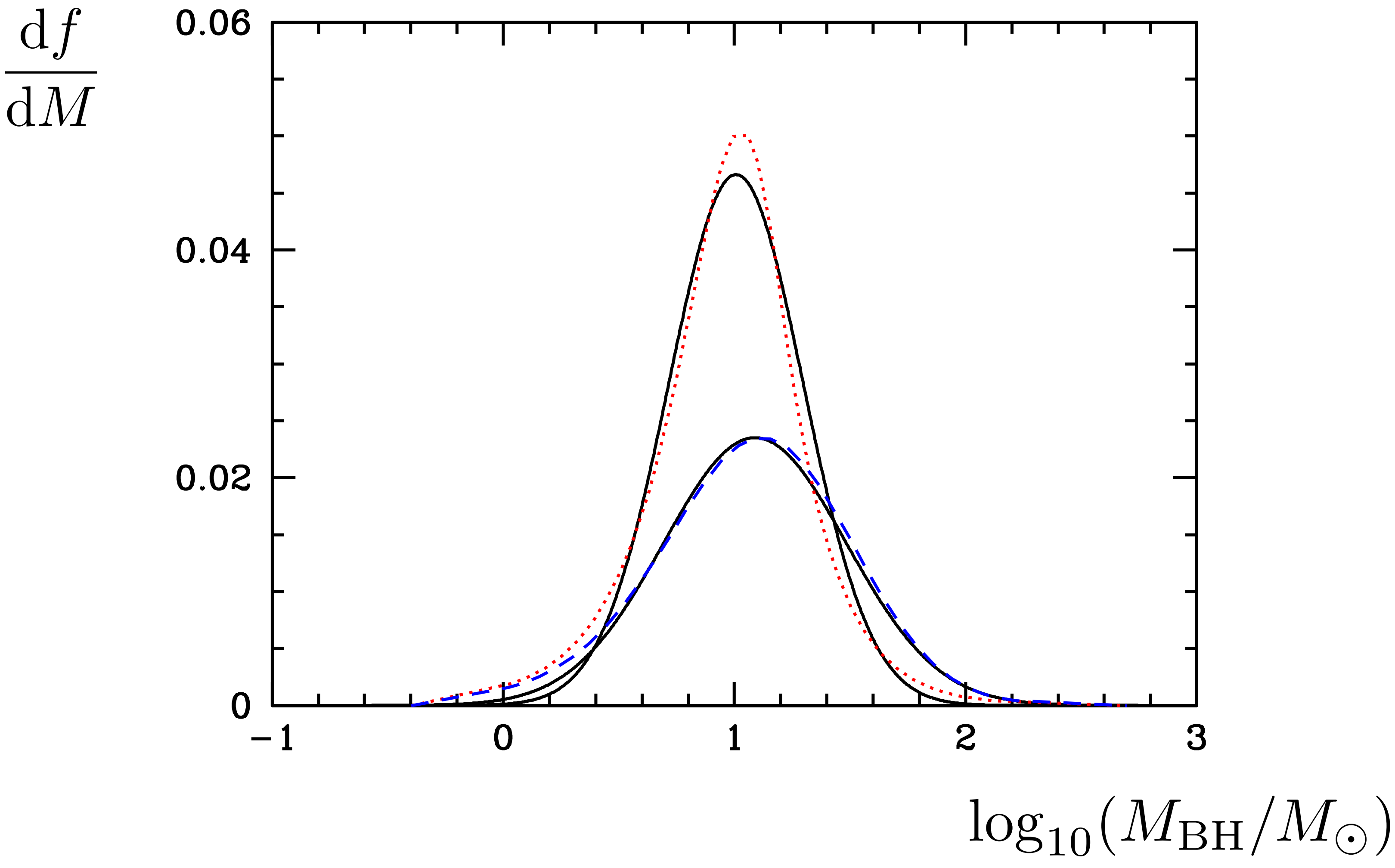
Musco, Miller & Polnarev

using numerical simulations (with appropriate initial conditions) find k=4.02, γ=0.357

Get PBHs with range of masses produced even if they all form at the same time
i.e. we don't expect the PBH MF to be a delta-function

The extended mass functions found by Carr et al. for the axion-curvaton and running mass inflation models, including critical collapse, are well approximated by a log-normal distribution:

$$\psi(M) \equiv \frac{\mathrm{d}f}{\mathrm{d}M} \propto \exp\left[-\frac{(\log M - \log M_{\mathrm{c}})^2}{2\sigma^2}\right]$$



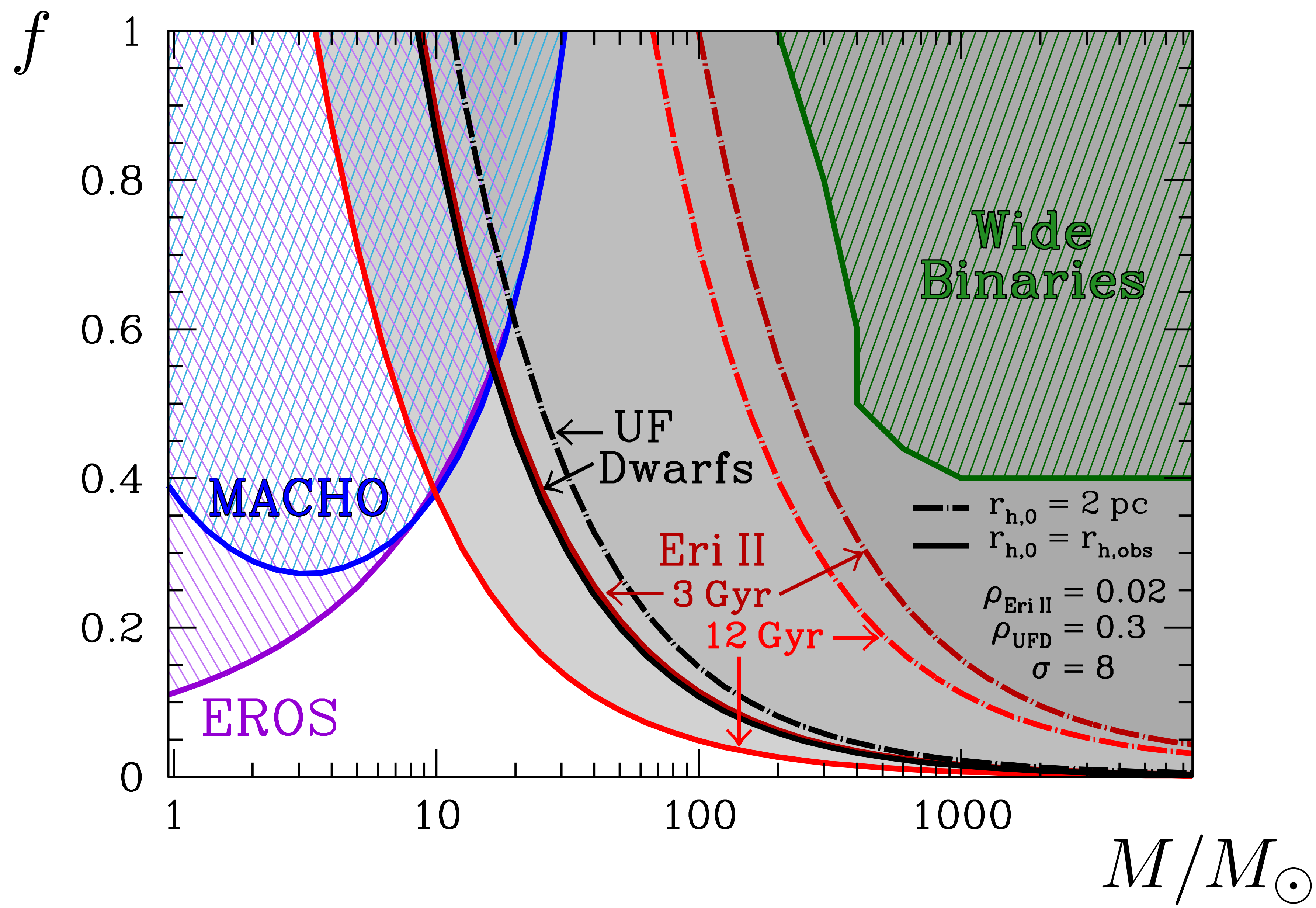
Ultra-faint dwarf heating

Brandt

Gravitational interactions transfer energy to stars, heating and cause the expansion of,

i) star clusters within dwarf galaxies (e.g. star cluster at centre of Eridanus II)

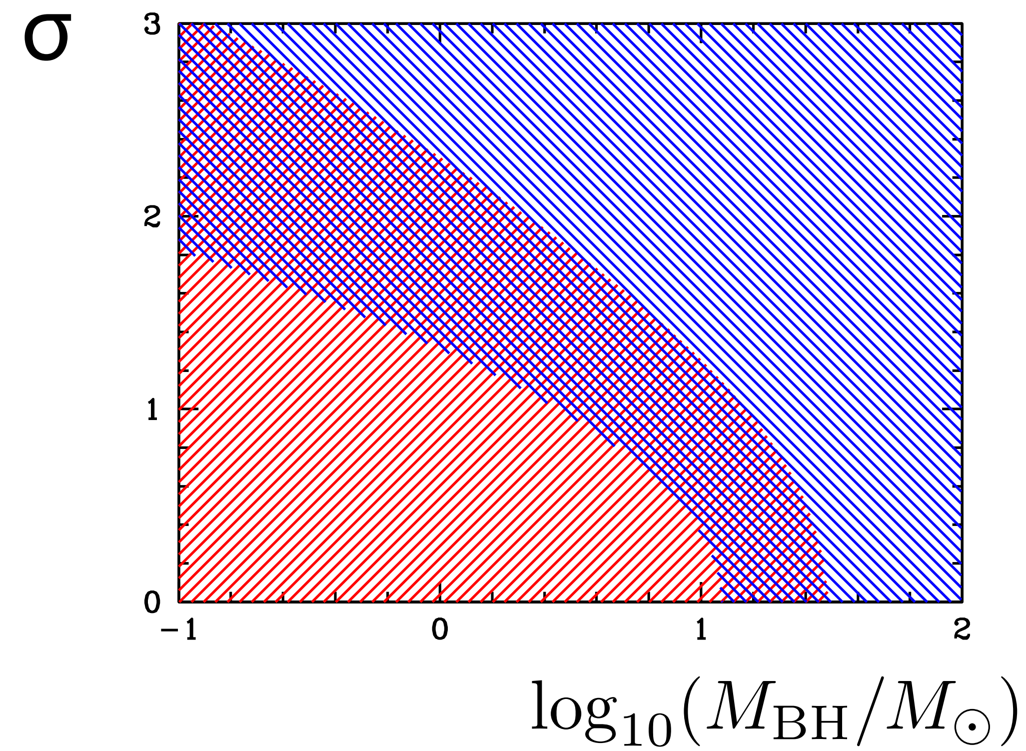
ii) ultra-faint dwarf galaxies



Constraints on the central mass, M_c, and width, σ, of log-normal MF:

Excluded by EROS microlensing data

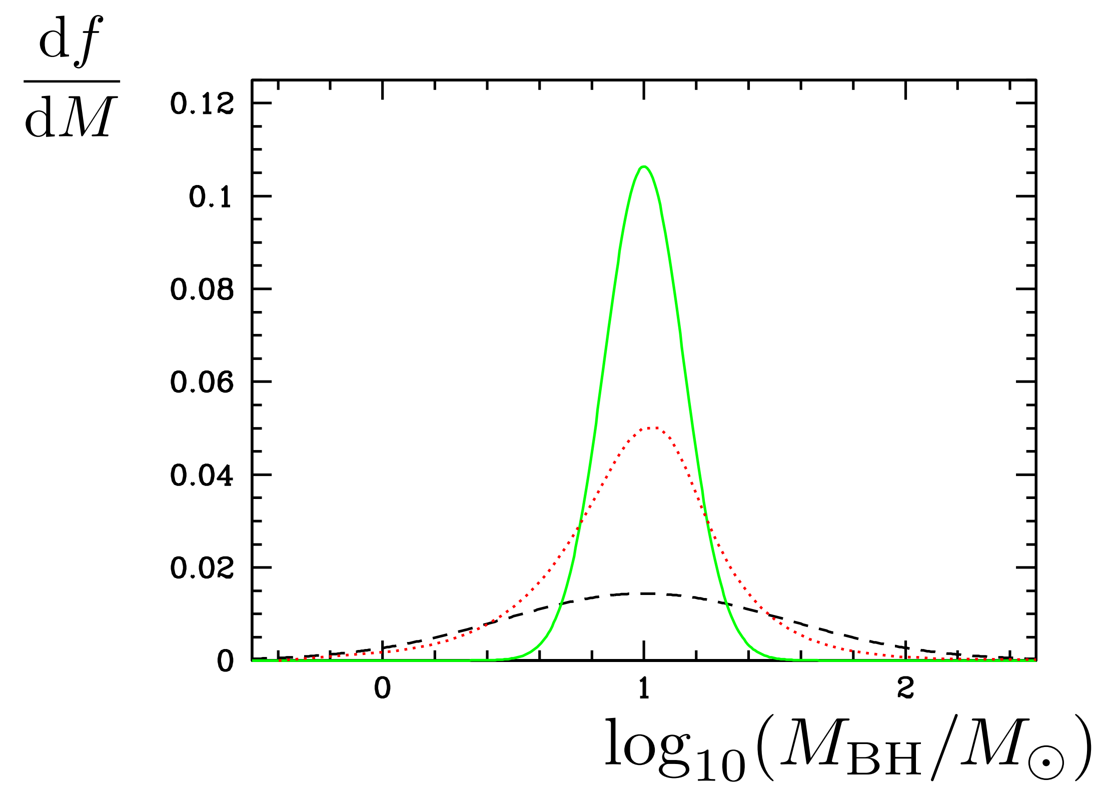
Excluded by heating of ultra-faint dwarfs



Broadest MF which satisfies Brandt ultra-faint dwarf heating constraint.

Narrowest MF which satisfies the microlensing constraints.

Axion-curvaton MF from Carr, Kuhnel & Sandstad: produces N_{exp}=5.5 events in EROS survey.



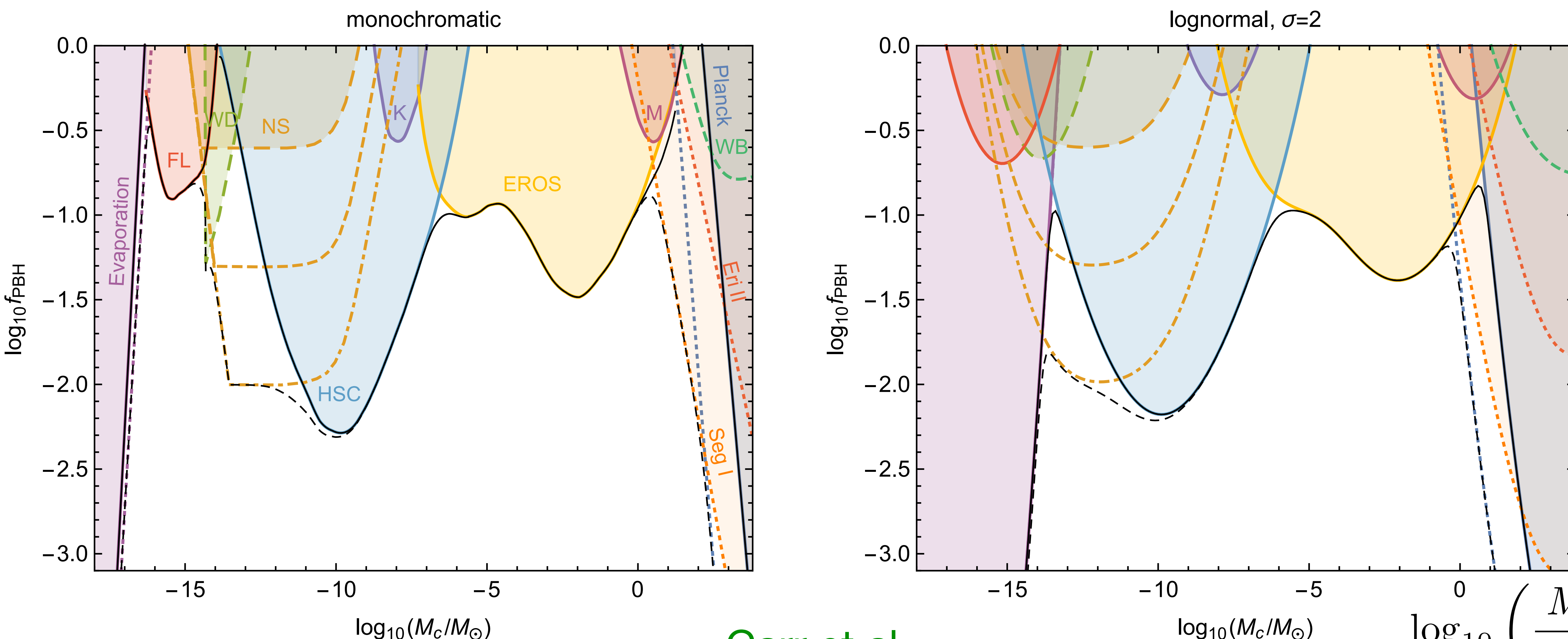
Taken at face value, together the microlensing & dynamical constraints exclude multi-Solar mass PBH making up all of the DM (even with an extended MF).

Carr, Raidal et al. (see also Bellomo et al.) method for applying constraints calculated assuming a delta-function MF, $f_{\rm DF}^{\rm max}(M)$, to extended MF.

If PBHs of different mass contribute to constraint independently:

$$\int {\rm d}M \, \frac{\psi(M)}{f_{\rm DF}^{\rm max}(M)} \leq 1$$

$\log_{10} f$ monochromatic log-normal (fixed width)



$\log_{10}\left(\frac{M}{M_\odot}\right)$

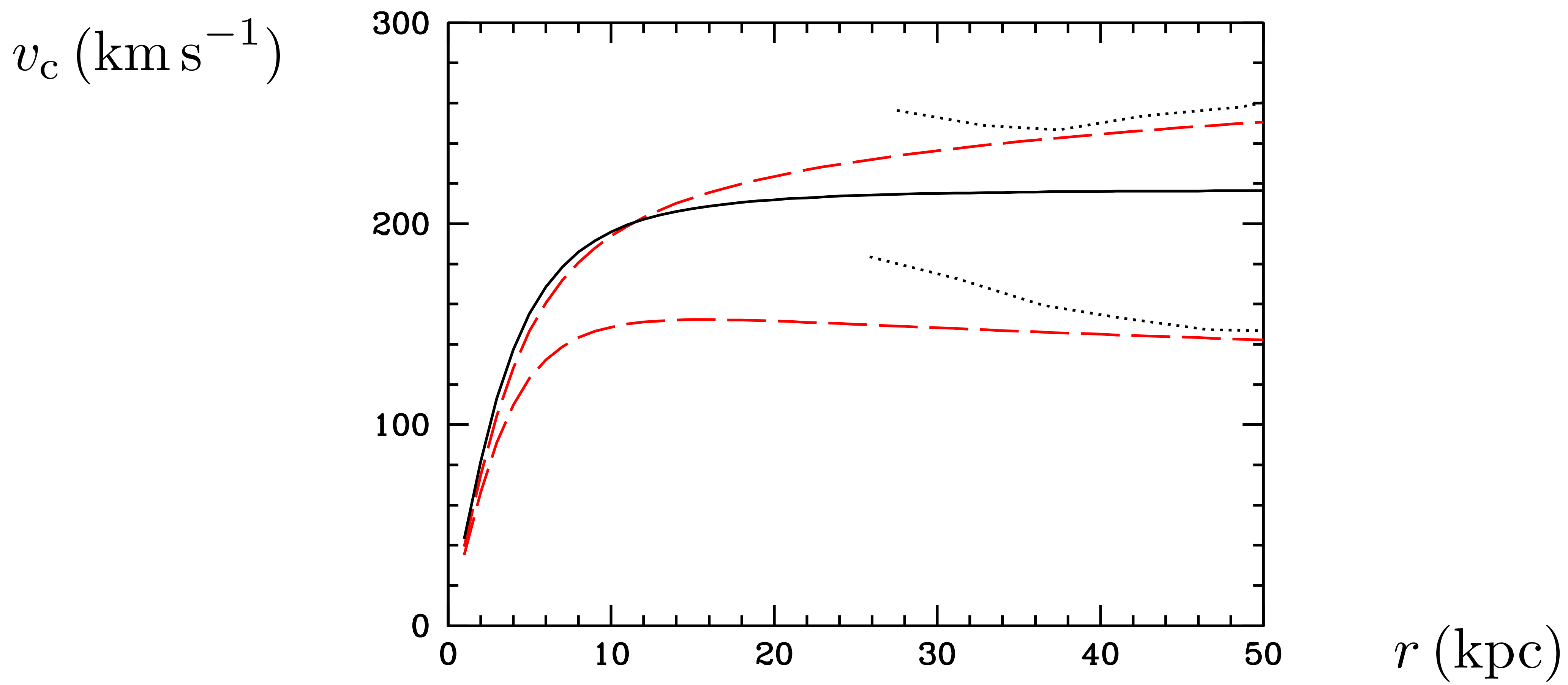
Carr et al.

Astrophysical uncertainties

Evans power law halo models: self-consistent halo models, which allow for non-flat rotation curves.

Traditionally used in microlensing studies [Alcock et al. MACHO collab.; Hawkins] since there are analytic expressions for velocity distribution.

Rotation curve



standard halo (SH)

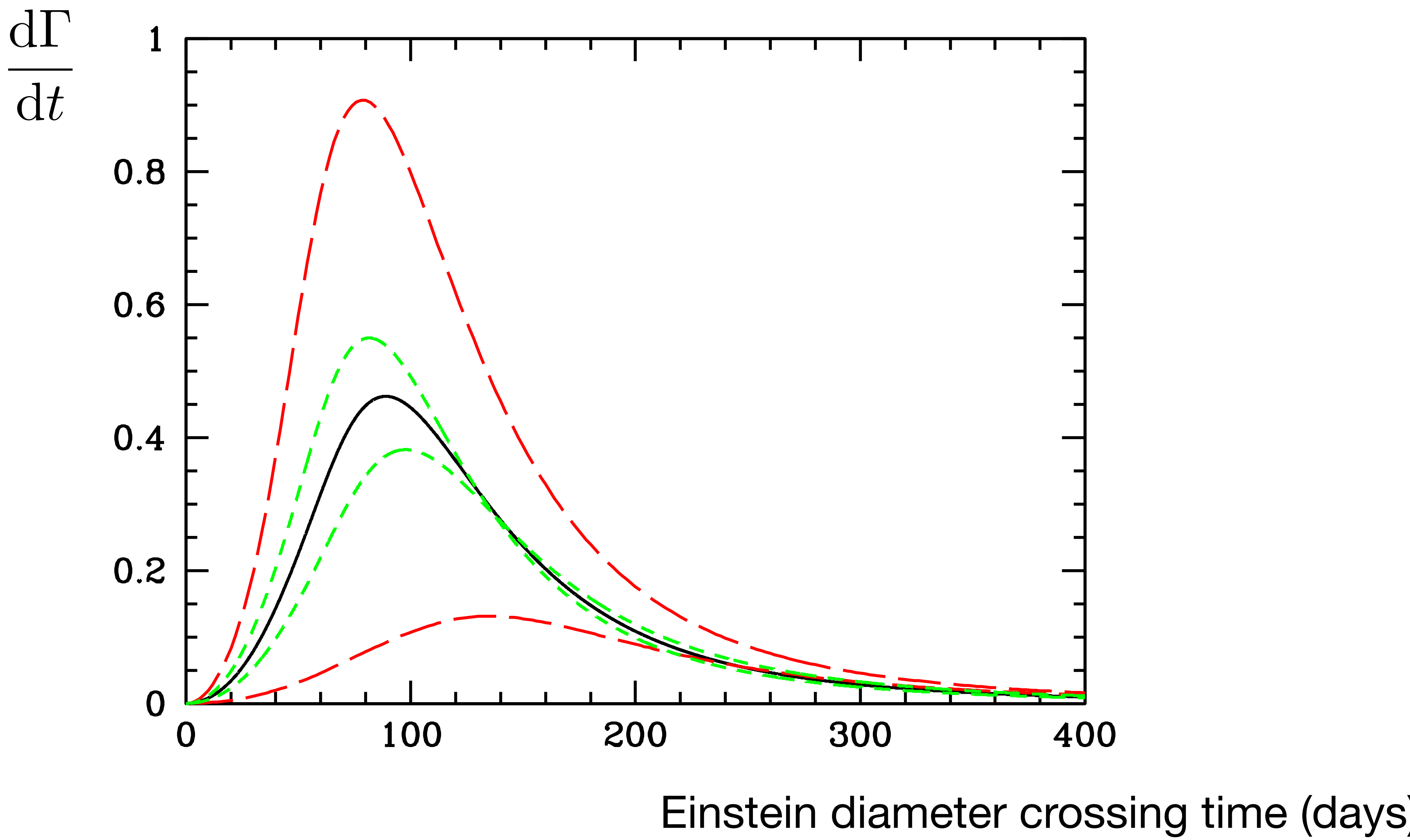
top: power law halo B (massive halo, rising rotation curve)

bottom: power law halo C (light halo falling rotation curve)

envelope of MW rotation curve data [Bhattacharjee et al.]

Microlensing differential event rate

(f=1 M= 1 $M_\odot$, and perfect detection efficiency)

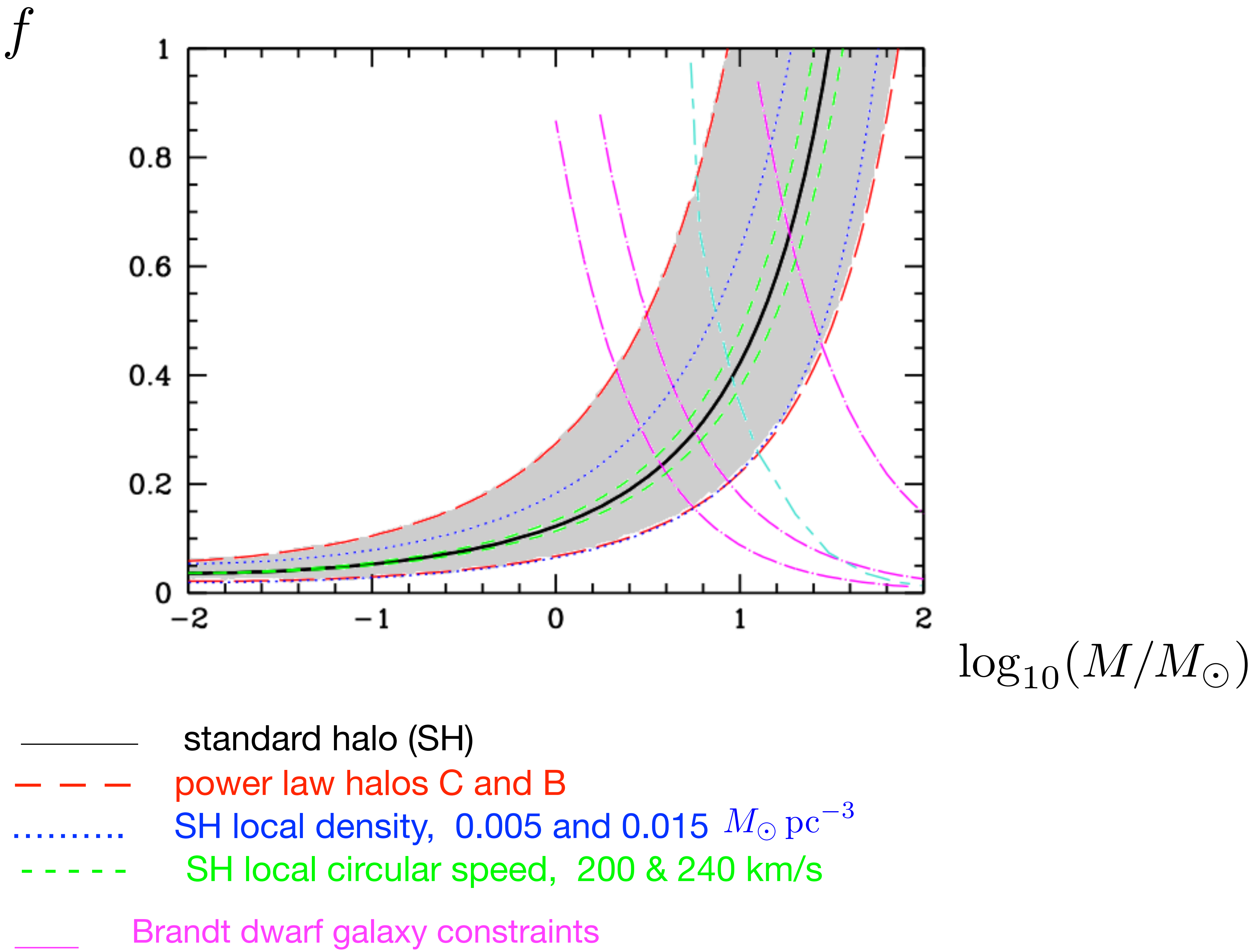


Microlensing: —— standard halo (SH)

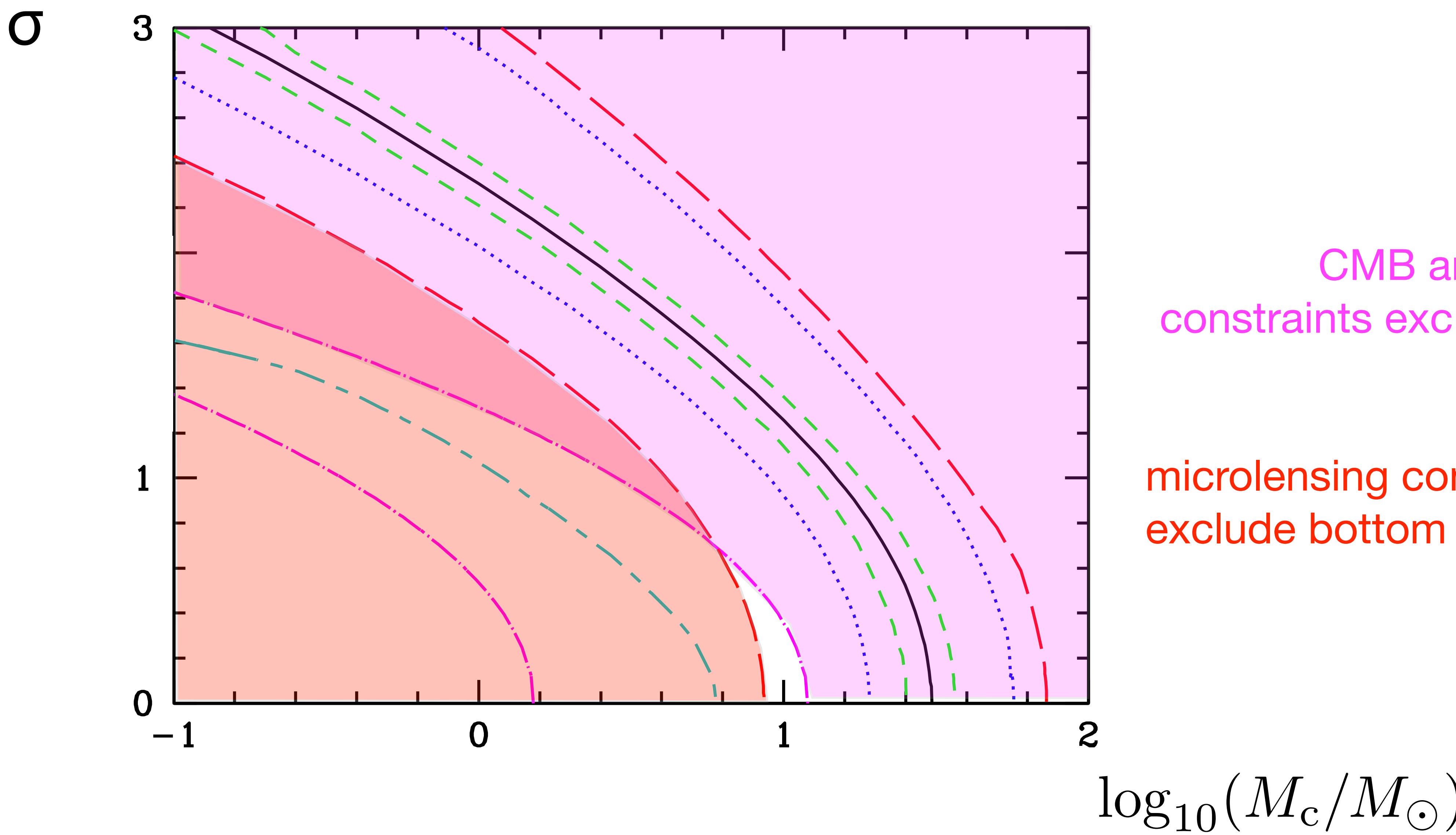
– – – power law halos B and C

- - - - - SH local circular speed, 200 & 240 km/s

Constraints on halo fraction for delta-function MF:



Constraints on width of log-normal MF with f=1



CMB and dynamical constraints exclude top right

microlensing constraints exclude bottom left

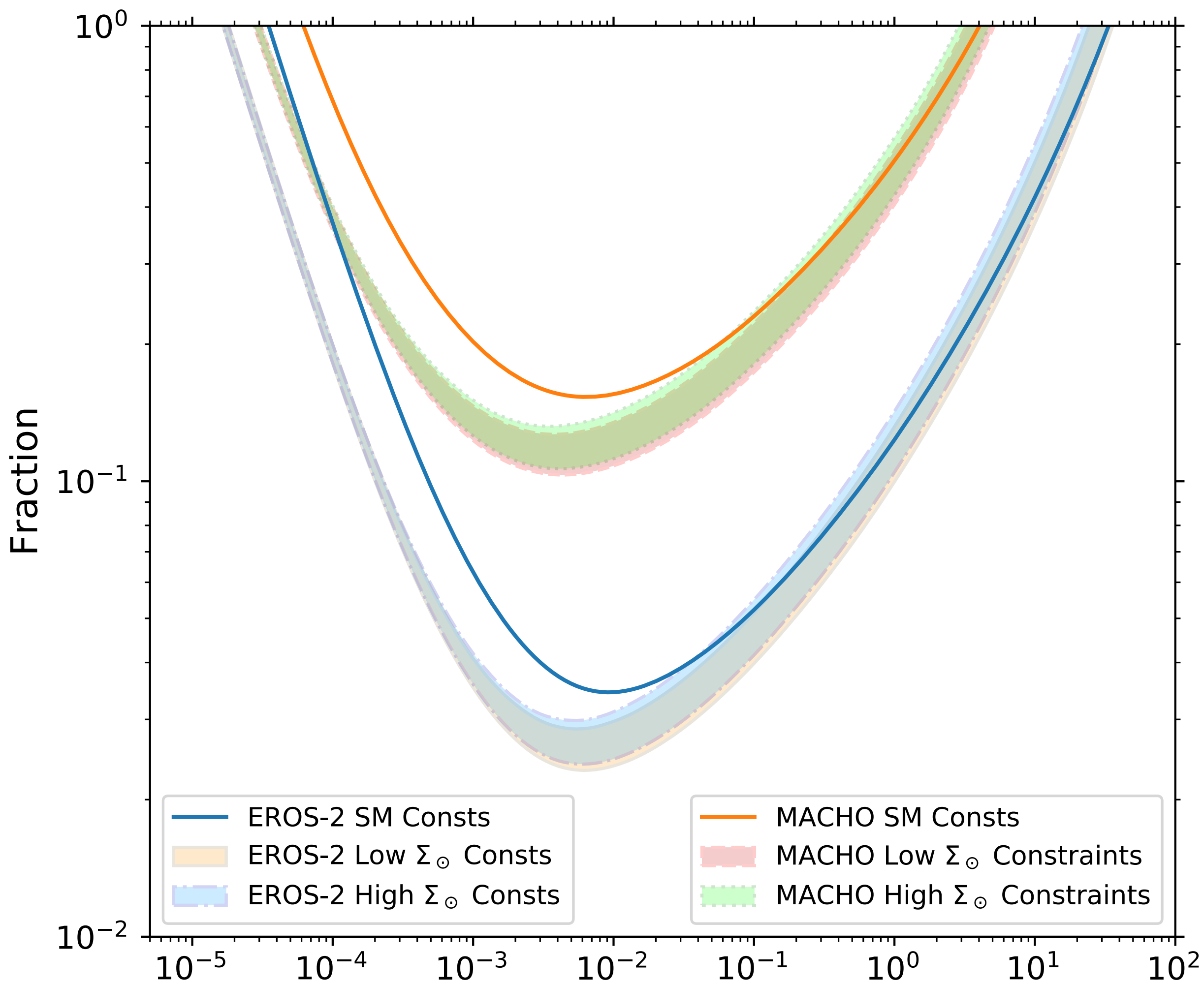
- standard halo (SH)
- power law halos C and B
- SH local density, 0.005 and 0.015
- SH local circular speed, 200 & 240 km/s
- Brandt dwarf galaxy constraints

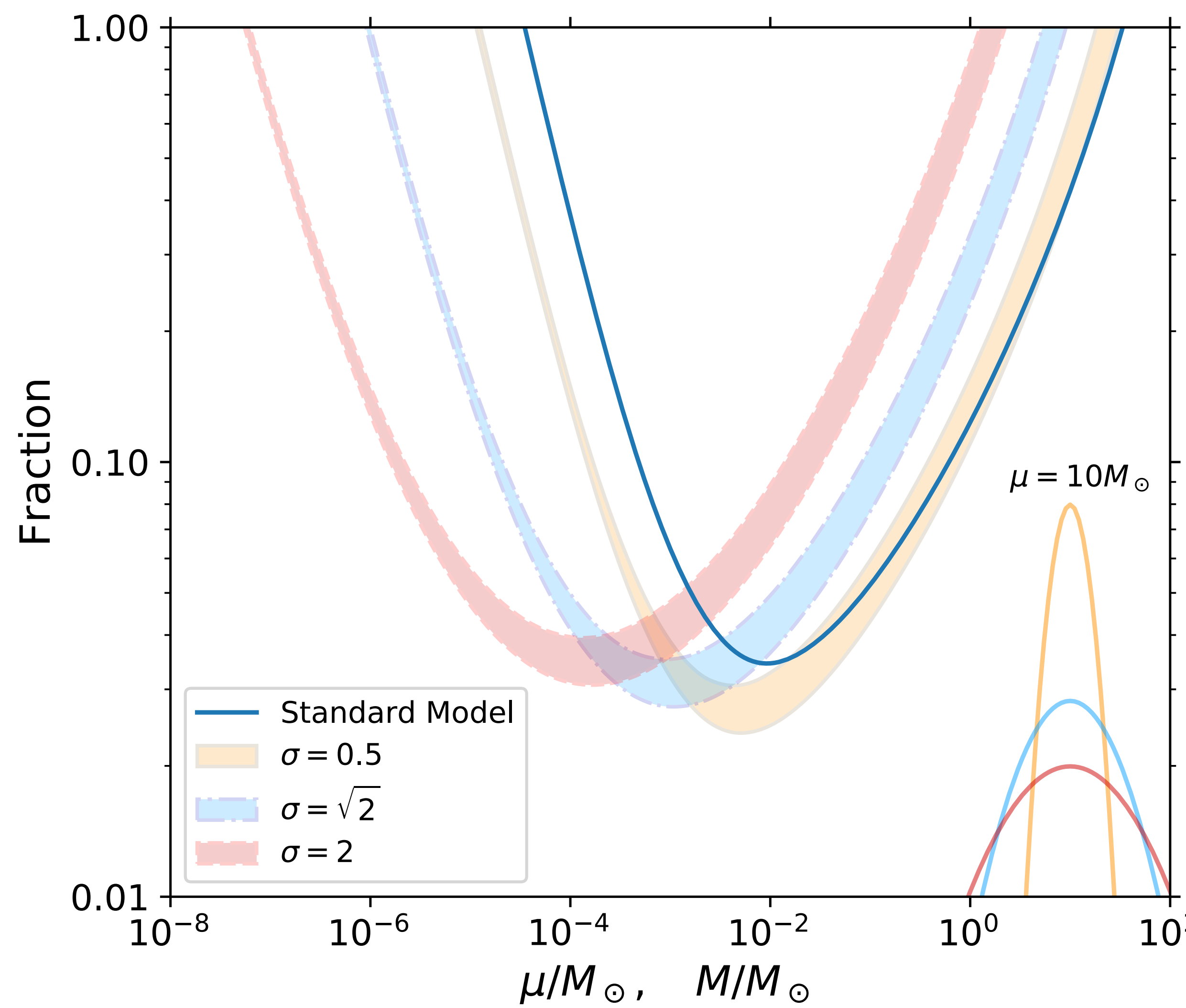
Calcino, Garcia-Bellido & Davis

EROS-2 (+MACHO) constraints
using mass models with power law halo, fitted to MW rotation curve data

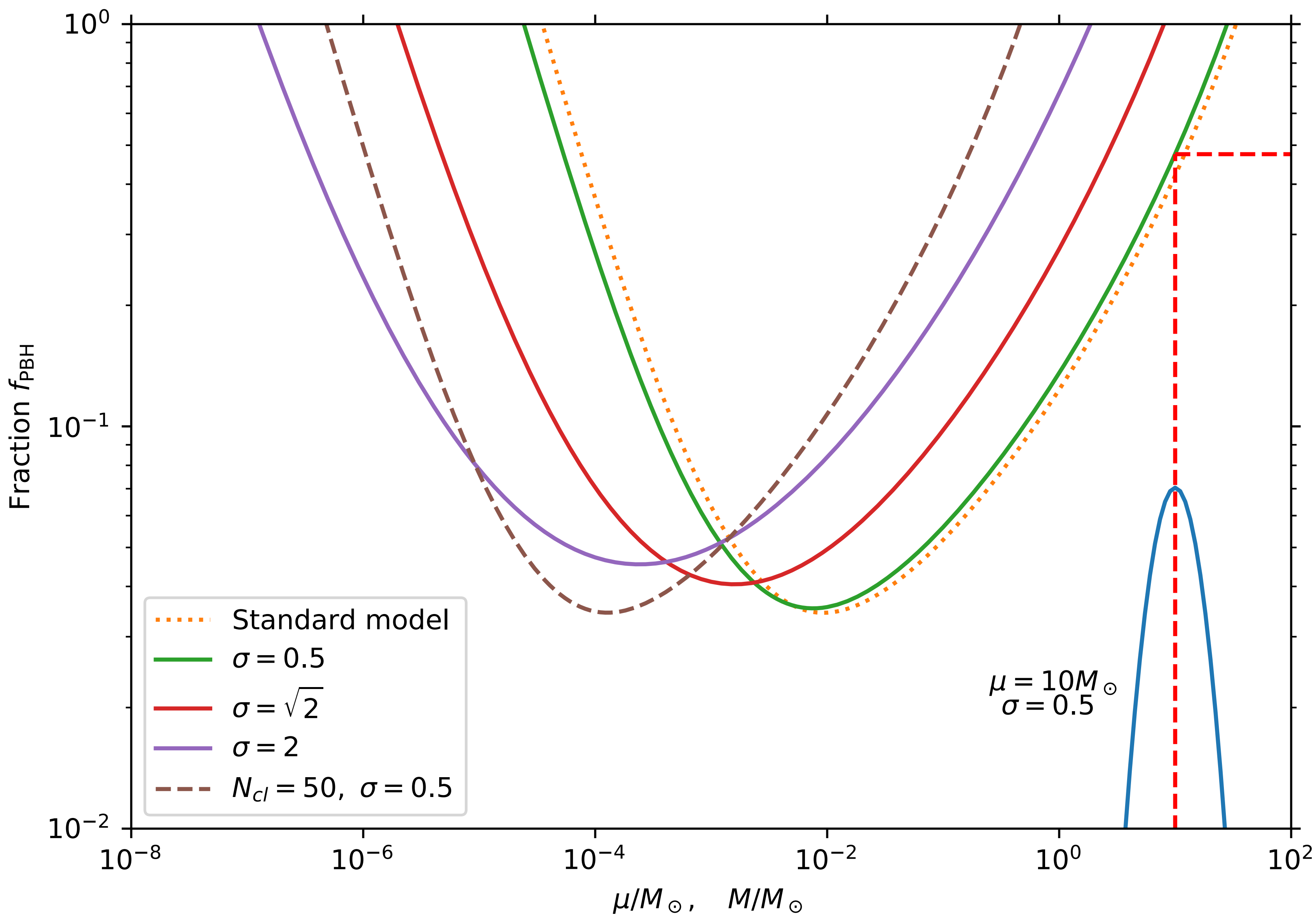
monochromatic mass function

log-normal mass function





If PBHs are clustered, the entire cluster acts as the lens and microlensing constraints are shifted to smaller *individual* PBH masses: [Clesse & Garcia-Bellido; Calcino, Garcia-Bellido & Davis]



[Calcino, Garcia-Bellido & Davis]

Smooth PBH distribution, delta-function MF, log-normal MF with increasing width.

PBHs in clusters of 10.

Summary

Stellar microlensing observations place tight constraints on the MW halo fraction in compact objects with $10^{-11} < M/M_{\odot} < 10$.

Constraints are typically calculated assuming a delta-function mass function.

Due to critical collapse PBHs will have an extended MF, even if they all form at the same time/scale.

Applying constraints to extended MFs is somewhat subtle.

(Taken at face value) together the microlensing and dynamical constraints exclude multi-Solar mass PBHs making up all of the DM, even with an extended mass function. Caveat: clustering.

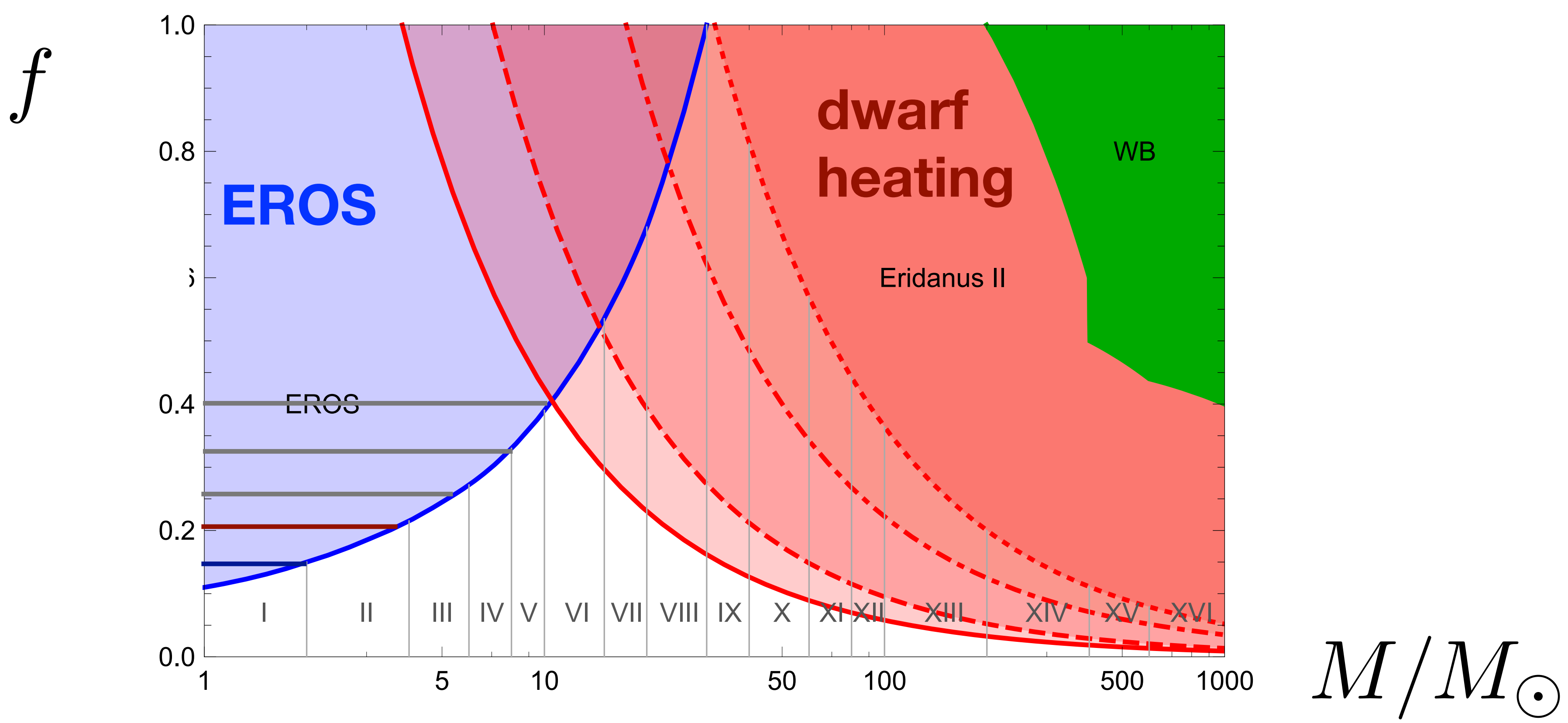
Carr, Kuhnel & Sandstad method:

Divide relevant mass range into bins, I, II, III etc.

Check integral of MF in bin I is less than ***weakest*** limit on f in this bin.

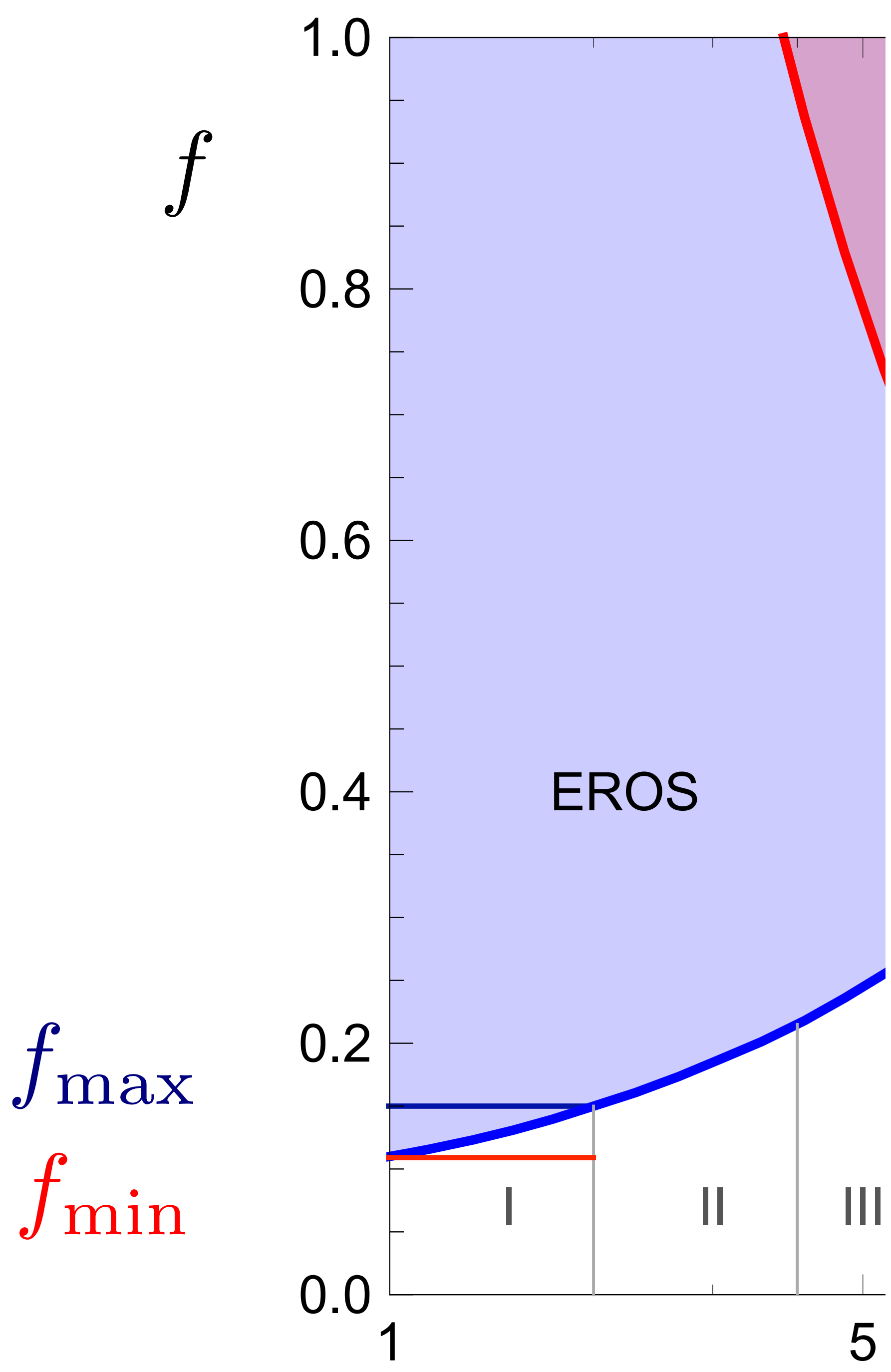
Check integral of MF in bins I+II is less than ***weakest*** limit on f in these bins.

And so on…



This underestimates the strength of the constraints.

Consider bin I:



$$\psi(M) \equiv \frac{\mathrm{d}f}{\mathrm{d}M}$$

$$f = \int_0^\infty \psi(M)\,\mathrm{d}M$$

$f > f_{max}$ MF is definitely excluded,

$f < f_{min}$ MF is definitely allowed.

$f_{min} < f < f_{max}$ MF may or may not be allowed. Need to explicitly recalculate constraint to find out.