Primordial Black Holes as (part of the) dark matter

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Lecture 1: Motivation

Formation

Mass function

Lecture 2: Constraints

Application to extended mass functions

For further details on these topics (and also PBH binary mergers as source of GWs) see recent review by Sasaki, Suyama, Tanaka & Yokoyama arXiv:1801.05235.

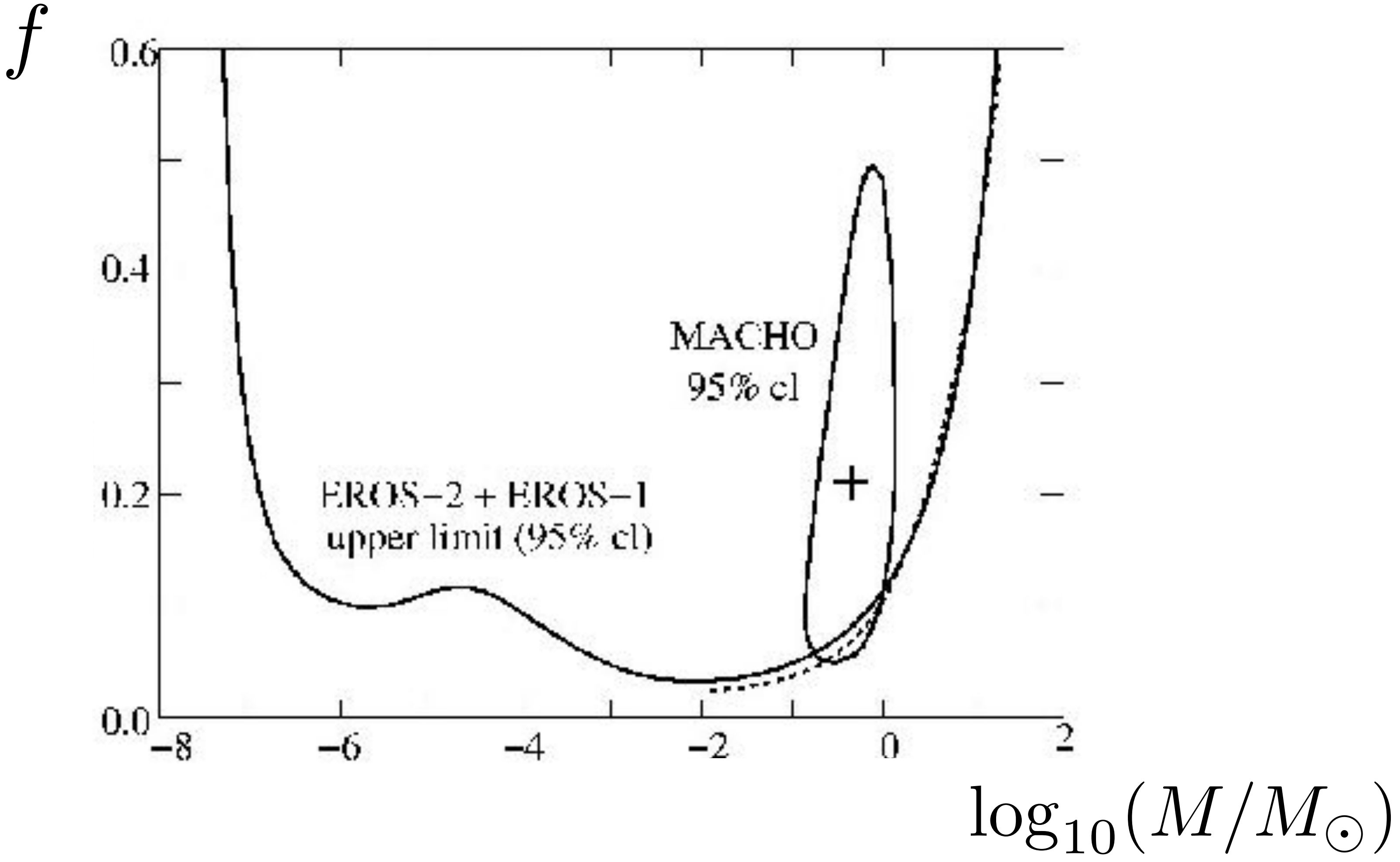
Constraints: Solar mass region

[Initially all constraints assume a delta-function PBH mass function.]

Microlensing

Temporary (achromatic) brightening of background star when compact object passes close to the line of sight.

EROS constraints: (MACHO constraints similar for $M > 3M_\odot$)



EROS

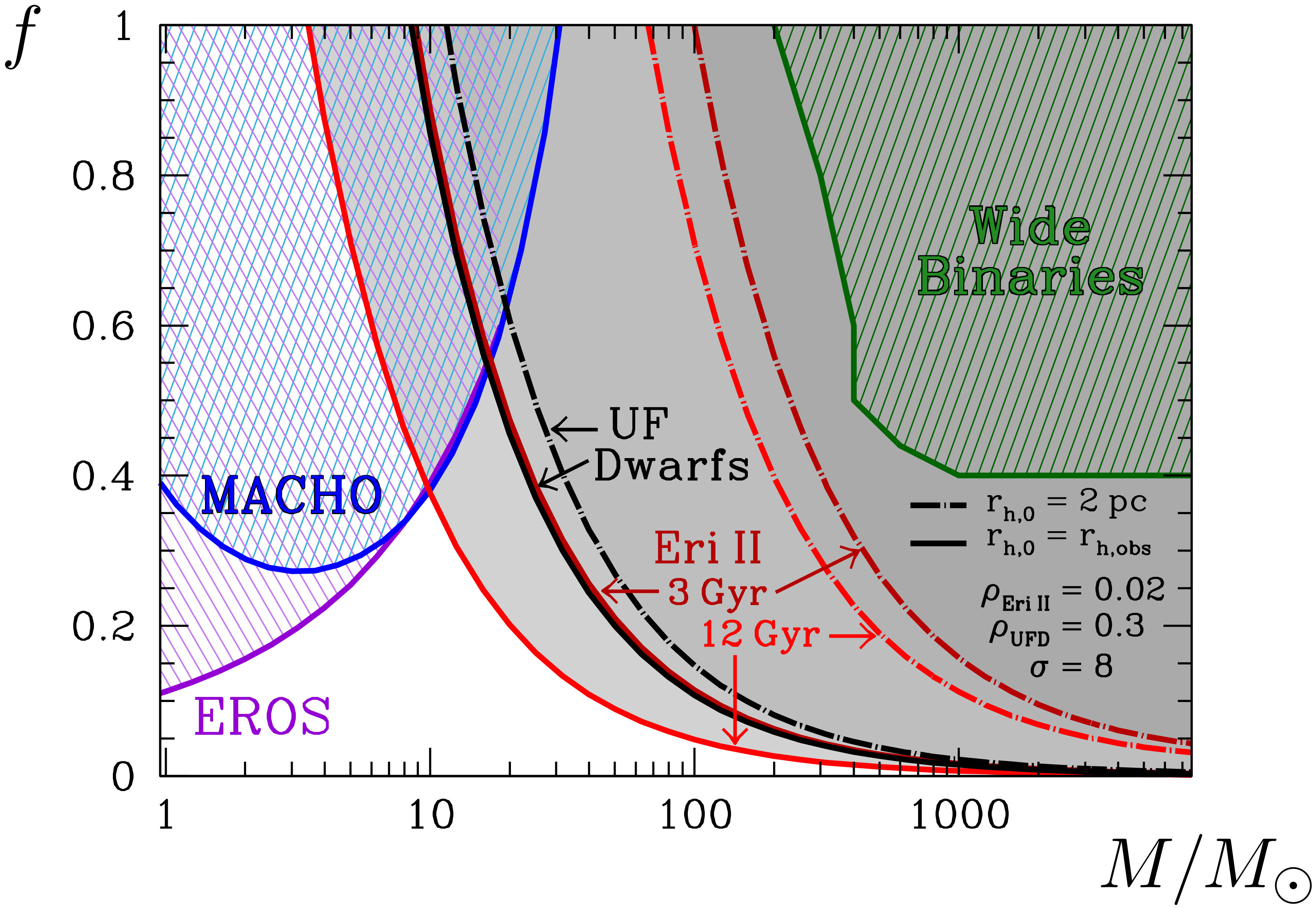
Ultra-faint dwarf heating

Brandt

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

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

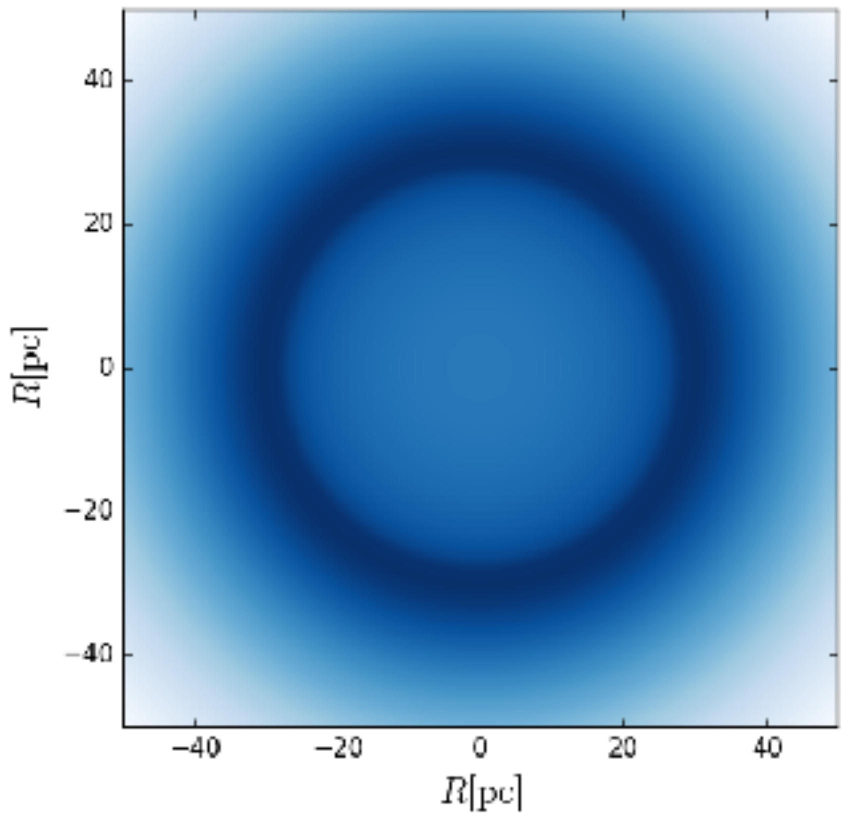
ii) ultra-faint dwarf galaxies

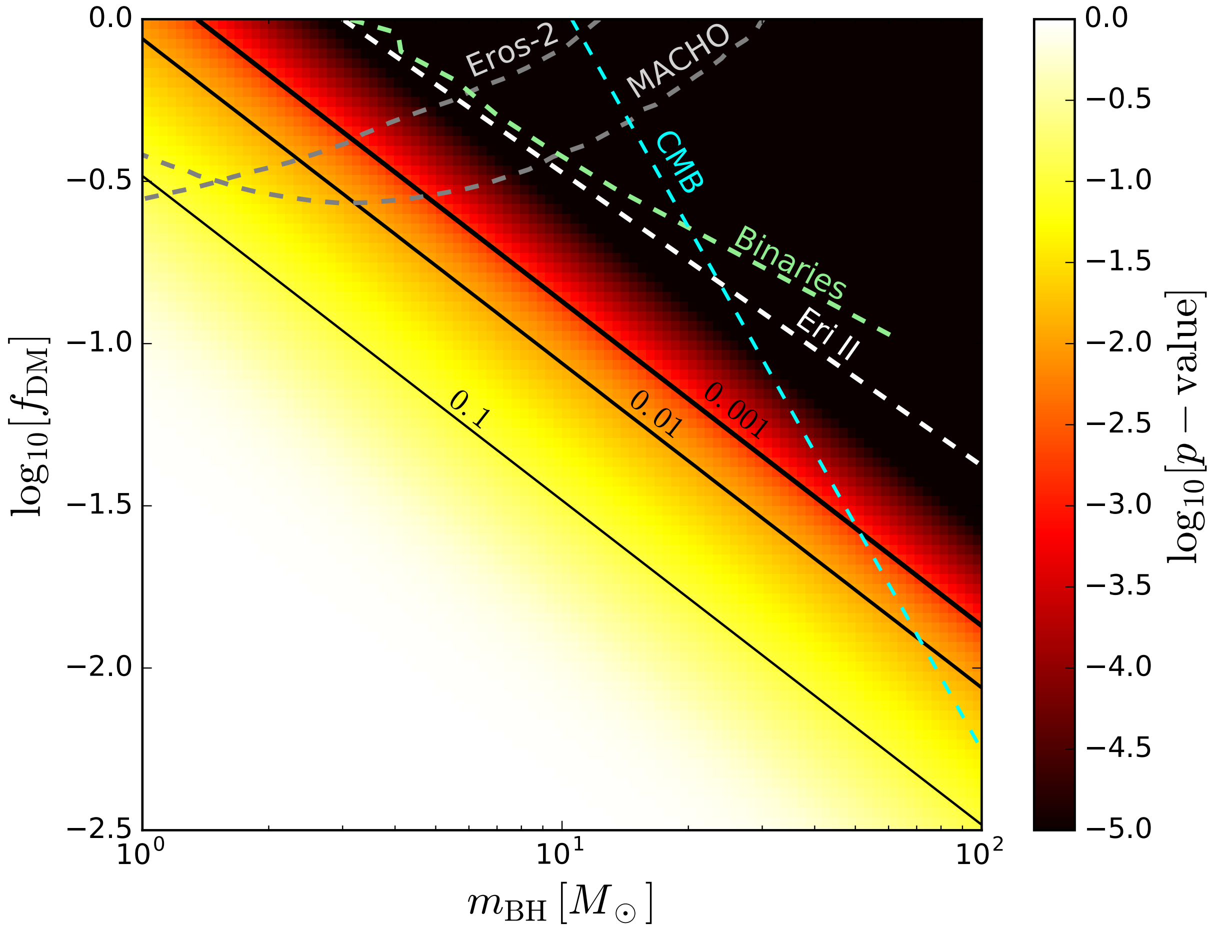


Mass segregation in dwarf galaxies

Koushiappas & Loeb

Mass segregation would lead to a deficit of stars in the centre of dwarf galaxies and a ring in the projected stellar surface density profile:





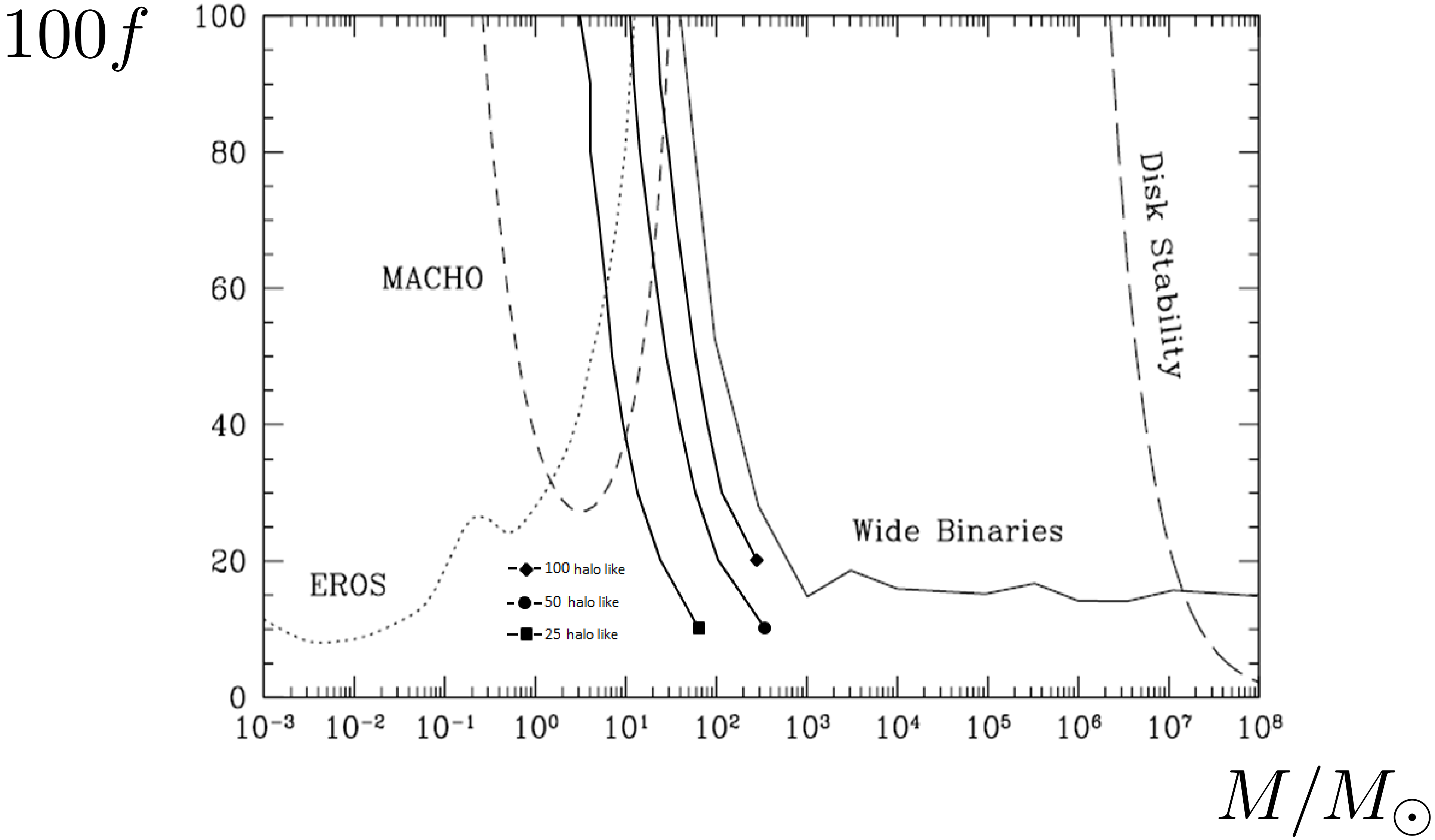
Wide binary disruption

Chaname & Gould; Yoo, Chaname & Gould; Quinn et al.; Monroy-Rodriguez & Allen

Massive compact objects perturb affect the orbits of wide binaries.

Need to make assumptions about initial distribution of orbits of binaries.

Constraints depend on which subset of binaries are used.

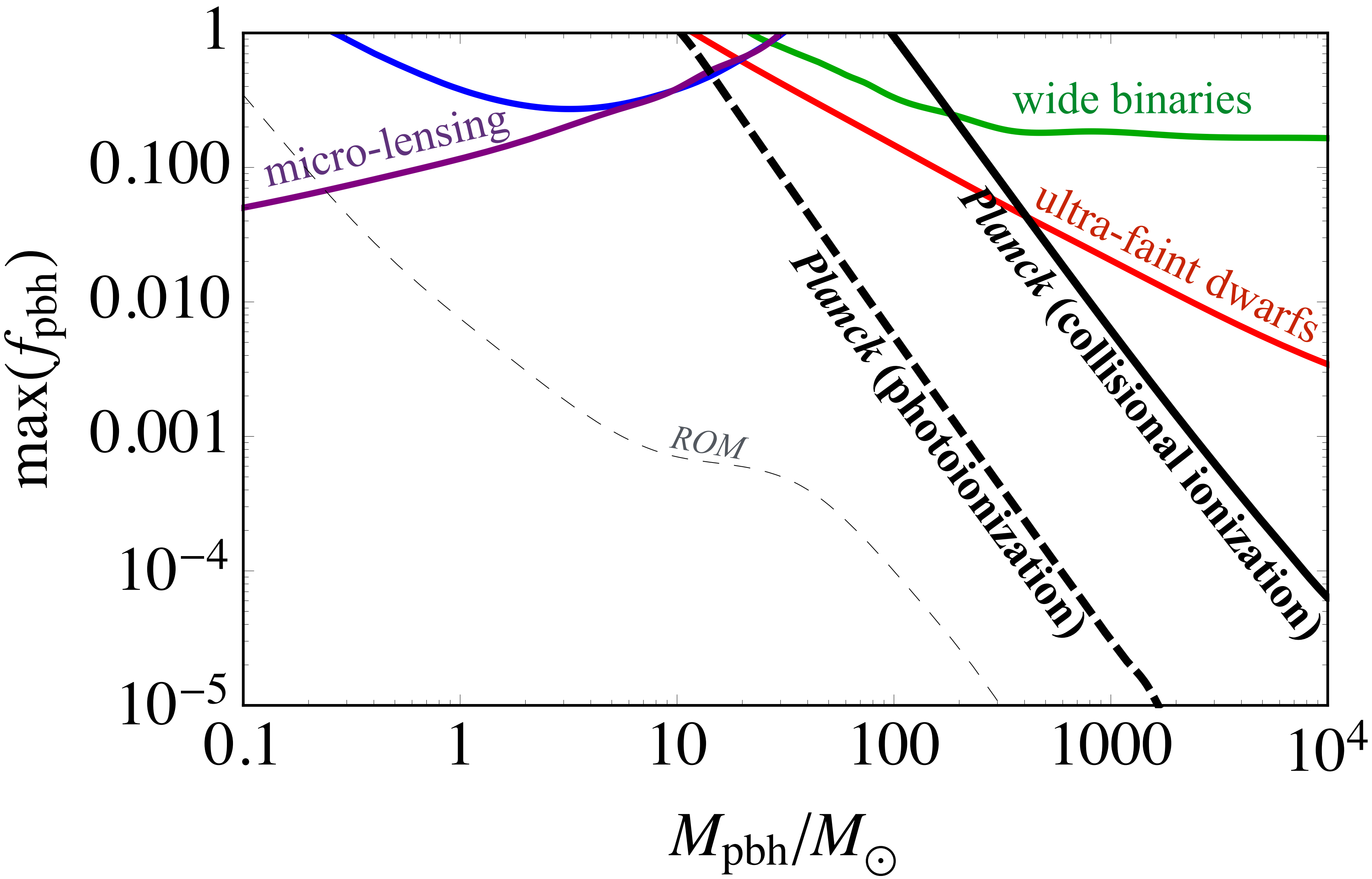


Cosmic Microwave Background distortions

Ricotti et al; Ali-Hamoud & Kamionkowski; Horowitz; Blum, Aloni & Flauger

Accretion onto PBH leads to emission of X-rays which can distort the spectrum (FIRAS) and anisotropies (WMAP/Planck) in the CMB.

Significant uncertainties in constraint due to modelling of complex astrophysical processes.

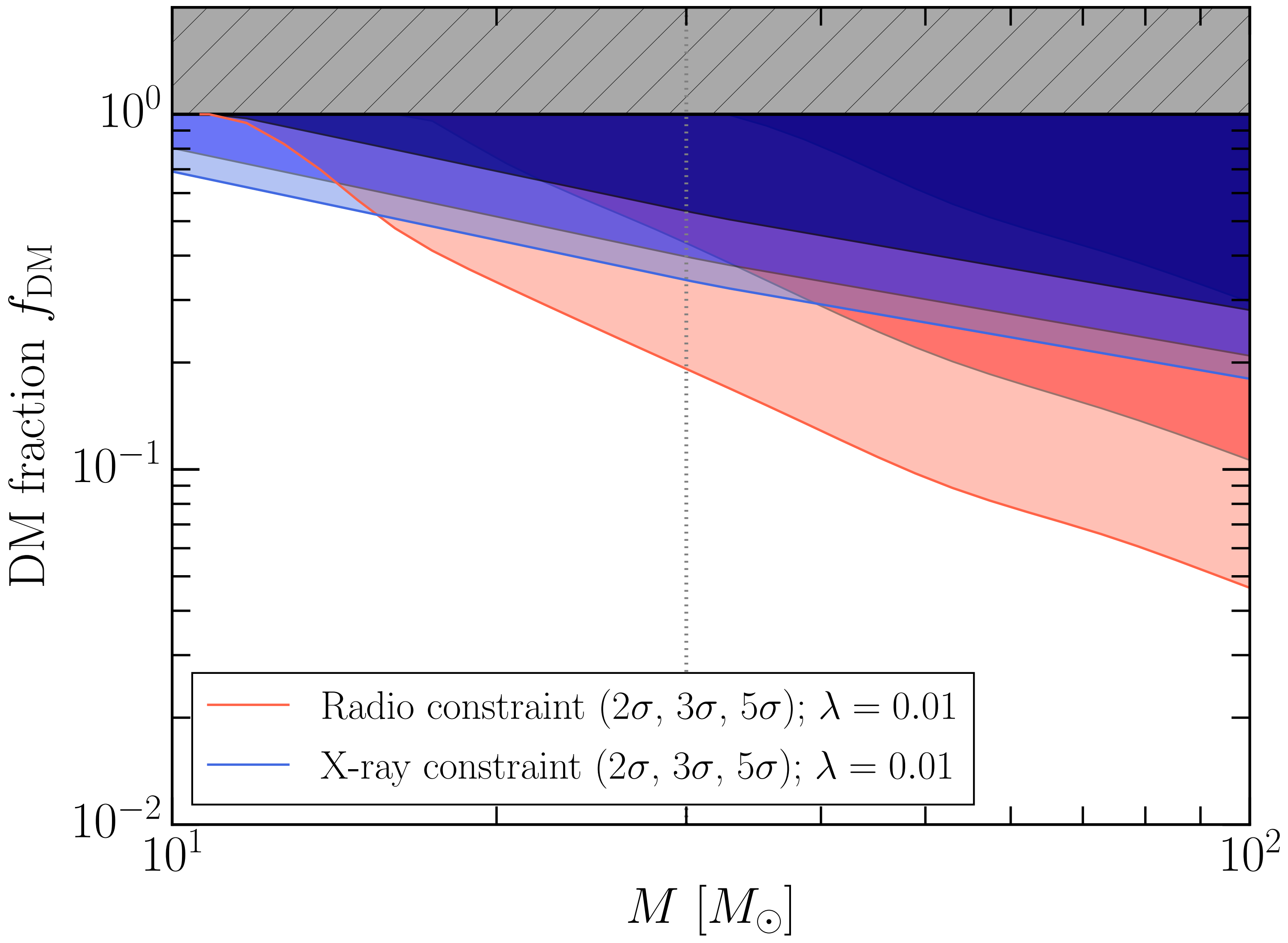


Ali-Hamoud & Kamionkowski

X-ray and radio emission

Gaggero et al; Inoue & Kusenko

Accretion onto PBH leads to X-rays and radio emission.



quasar microlensing

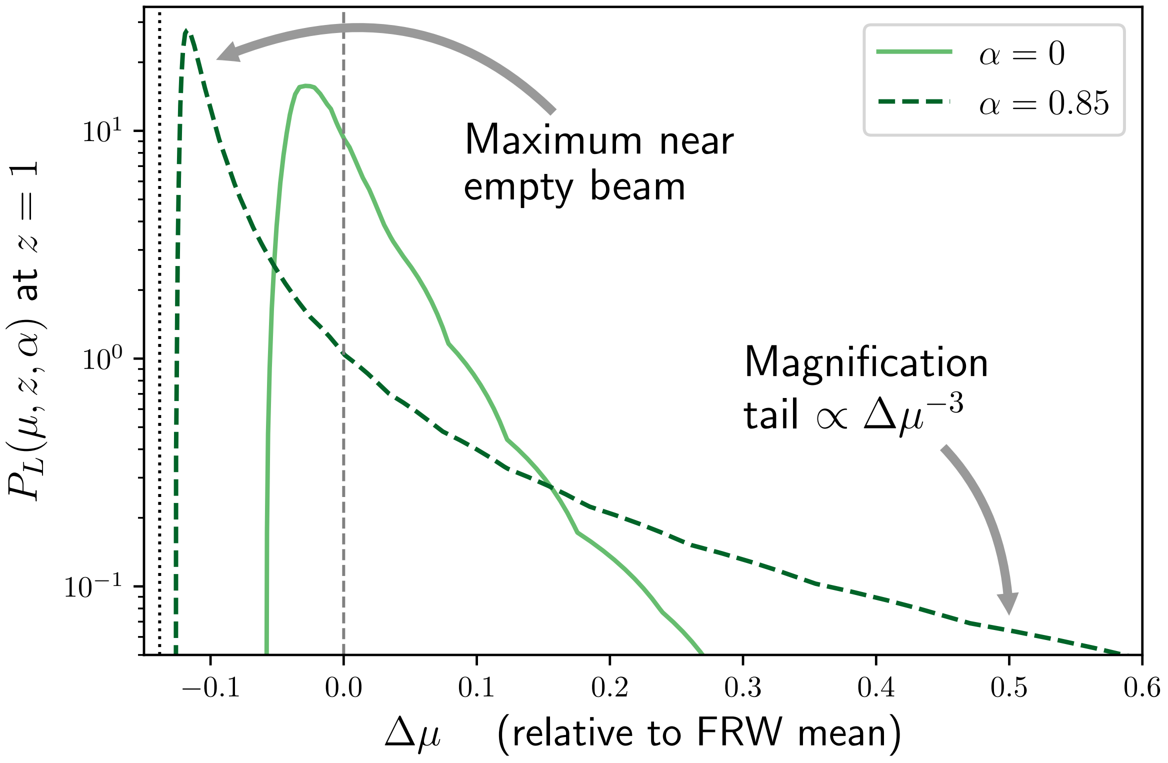
Quasar microlensing by compact objects in lens galaxy leads to variation in brightness of images in multiply lensed quasars. Chang & Refusal

(20 ± 5)% of the mass is in compact objects with $0.05\, M_\odot < M < 0.45\, M_\odot$, consistent with abundance of stars. Mediavilla et al. However no constraint on f published.

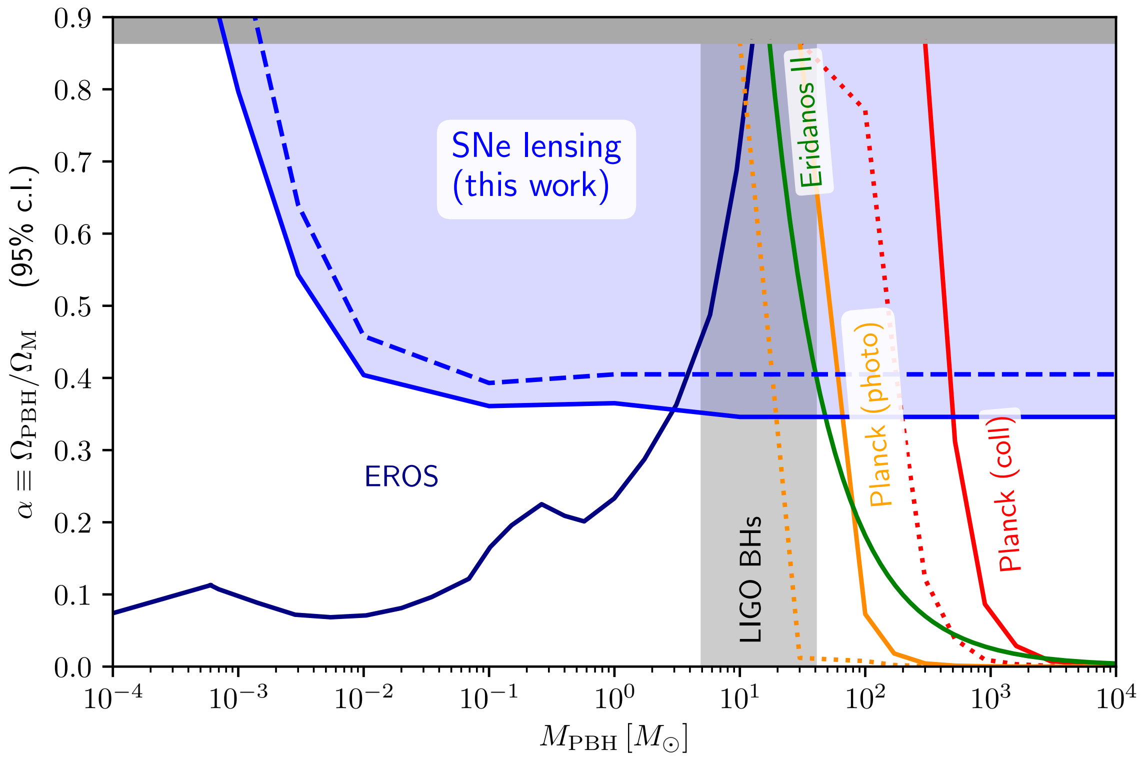
supernova microlensing

Compact objects affect lensing magnification distribution of type 1a SNe (most lines of sight are demagnified relative to mean, plus long-tail of high magnifications): Zumalacarregui & Seljak

magnification distribution

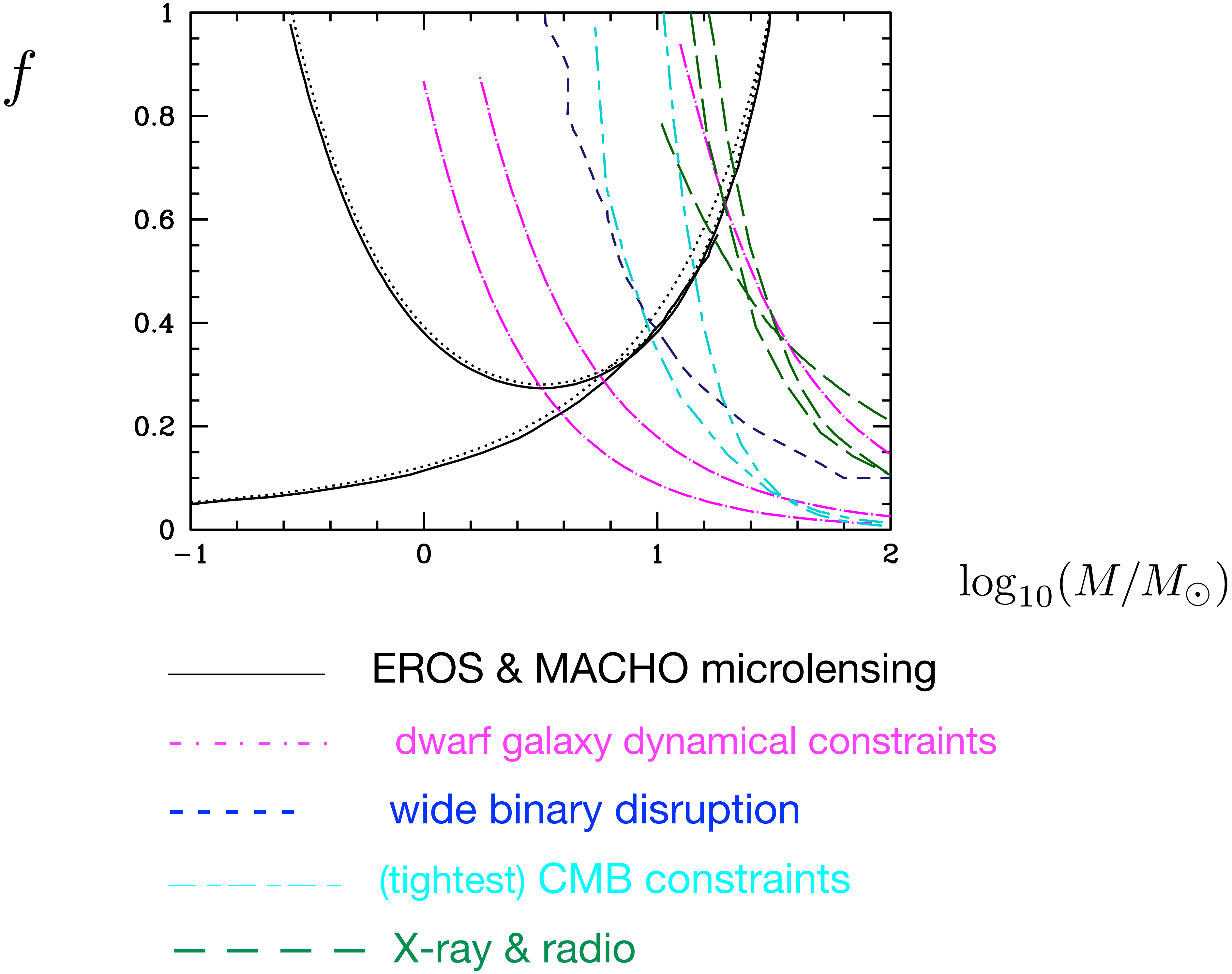


PBH abundance constraints



Garcia-Bellido, Clesse & Fleury. argue priors on cosmological parameters are overly restrictive and physics size of supernovae have been underestimated.

Compilation of ~Solar mass region constraints



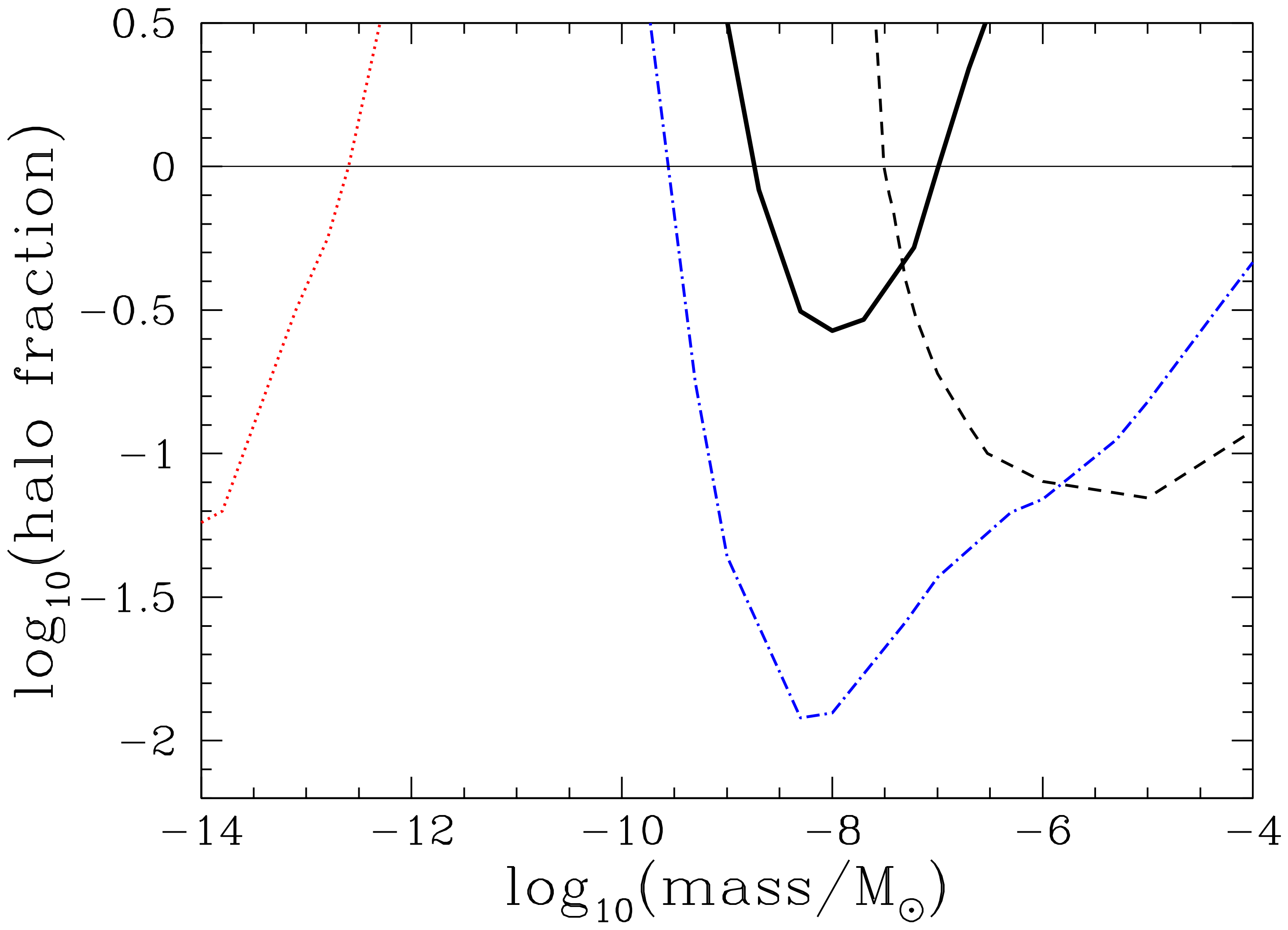
Doesn’t include microlensing of quasars (no constraints on f published) or supernovae (recent result which has been questioned).

Constraints: sub-Solar mass region

Microlensing of Kepler stars

Using Kepler obs, of nearby (~1 kpc) stars, looking for extra solar planets.

Sensitive to light compact objects, due to finite size of source stars.



______ this result

- - - - - MACHO collab

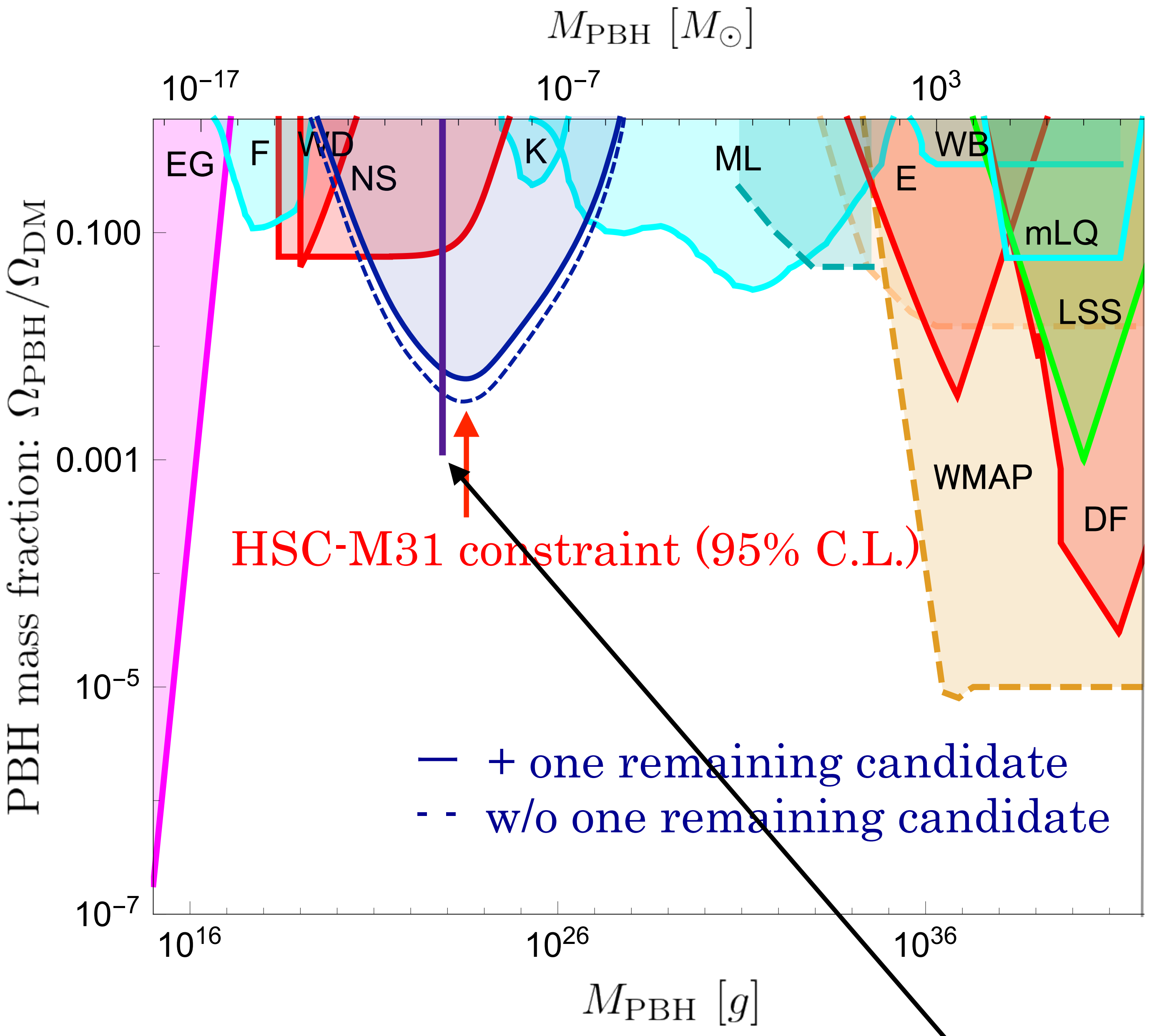
._._. sensitivity of future obs (WFIRST)

…… GRB femtolensing

Griest, Cieplak & Lehner

Microlensing of stars in M31

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



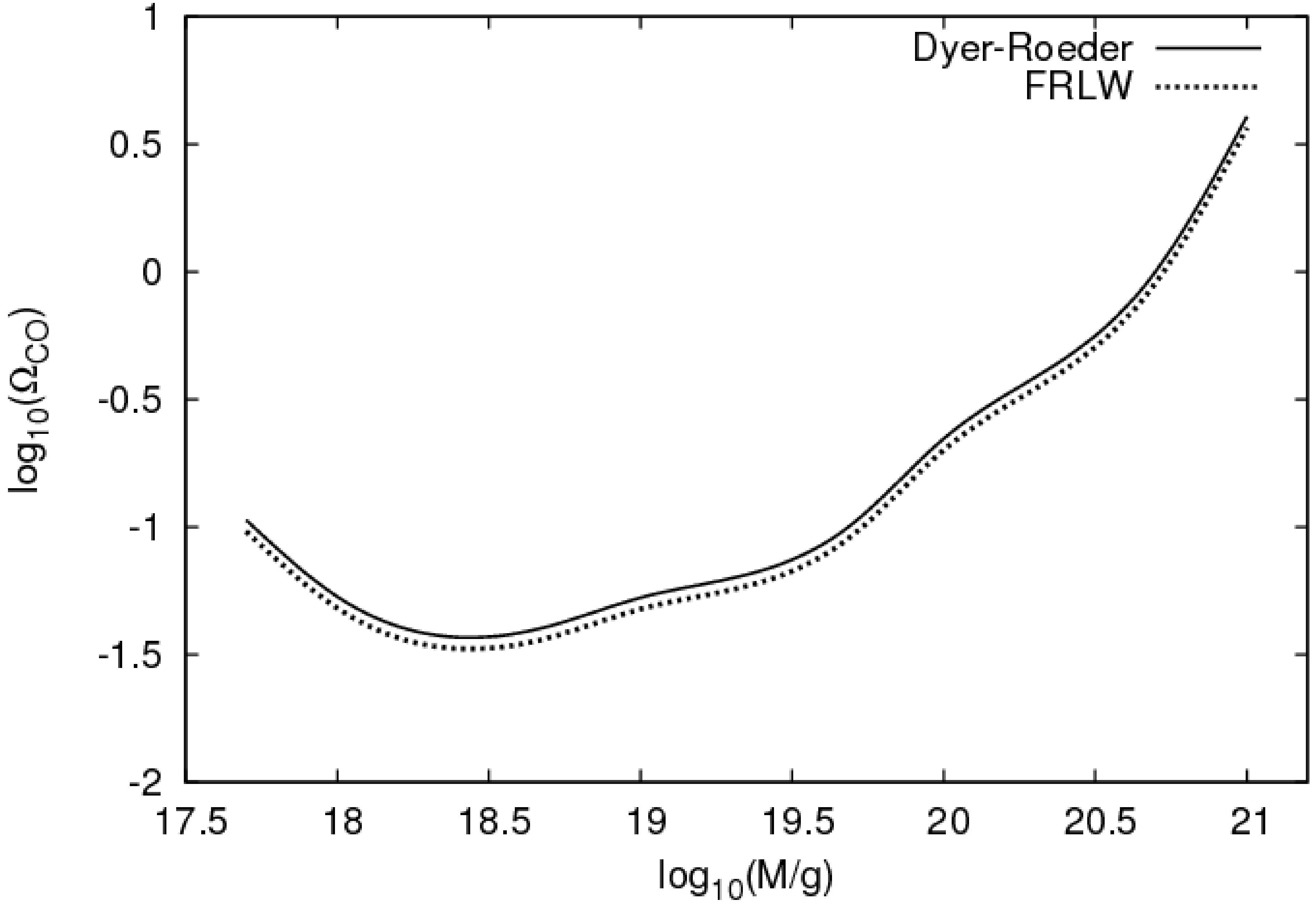
Niikura et al.

However analysis assumes geometric optics, however for $M \lesssim 10^{-10} M_\odot$ wavelength of light is larger than Schwarzschild radius of lens diffraction occurs and lowers maximum magnification. Inomata et al.

Femtolensing of GRBs

Energy dependent magnification produces interference fringes in energy spectrum of lensed GRB. Gould

Constraints from Fermi Gamma Ray Burst monitor:

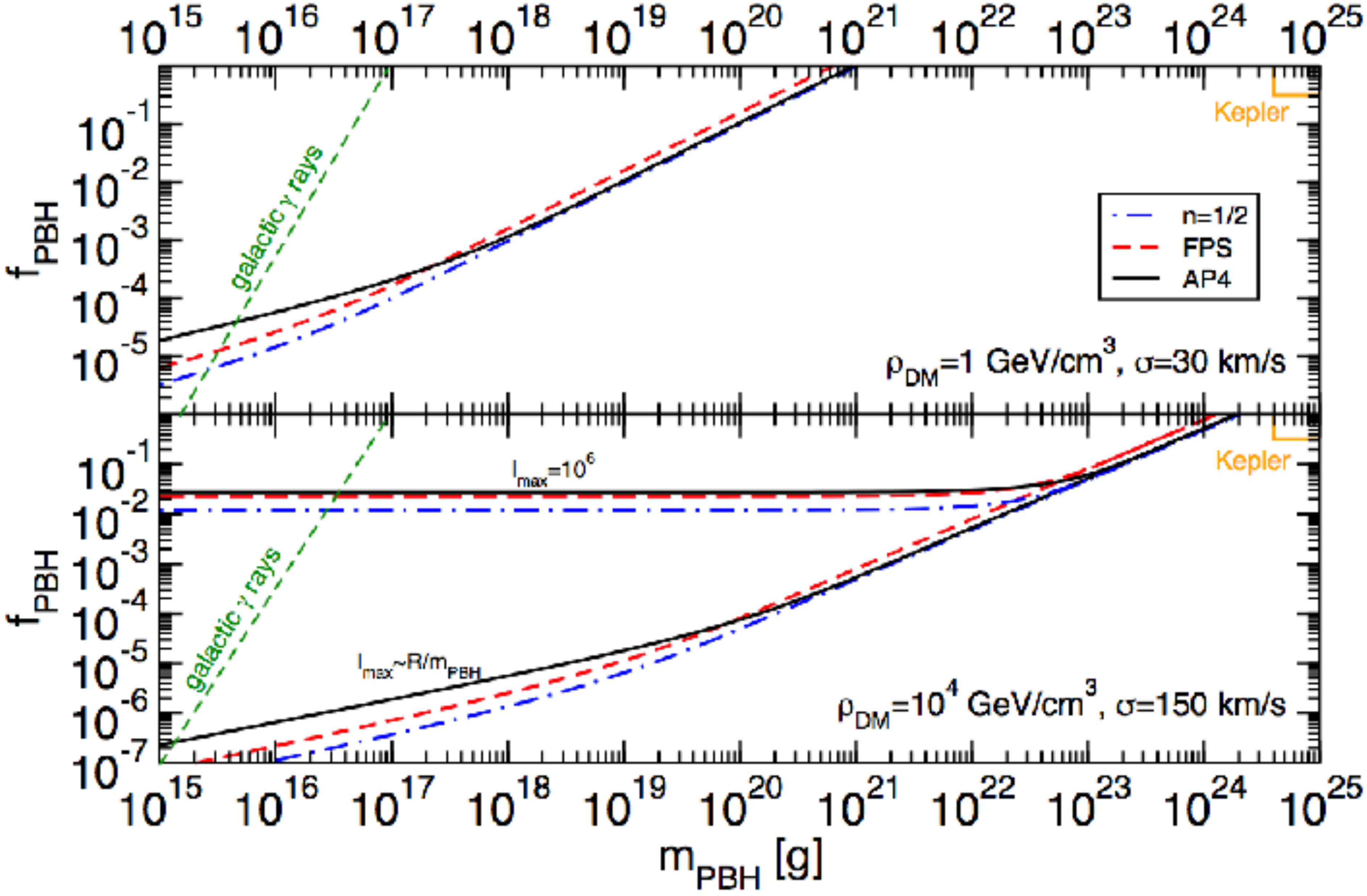


Barnacka, Glickenstein & Moderski

neutron star destruction

Capture of PBHs would destroy neutron stars, but neutron stars are observed in globular clusters and centre of LMC and Milky Way.

Capela, Pshirkov & Tinyakov; Pani & Loeb

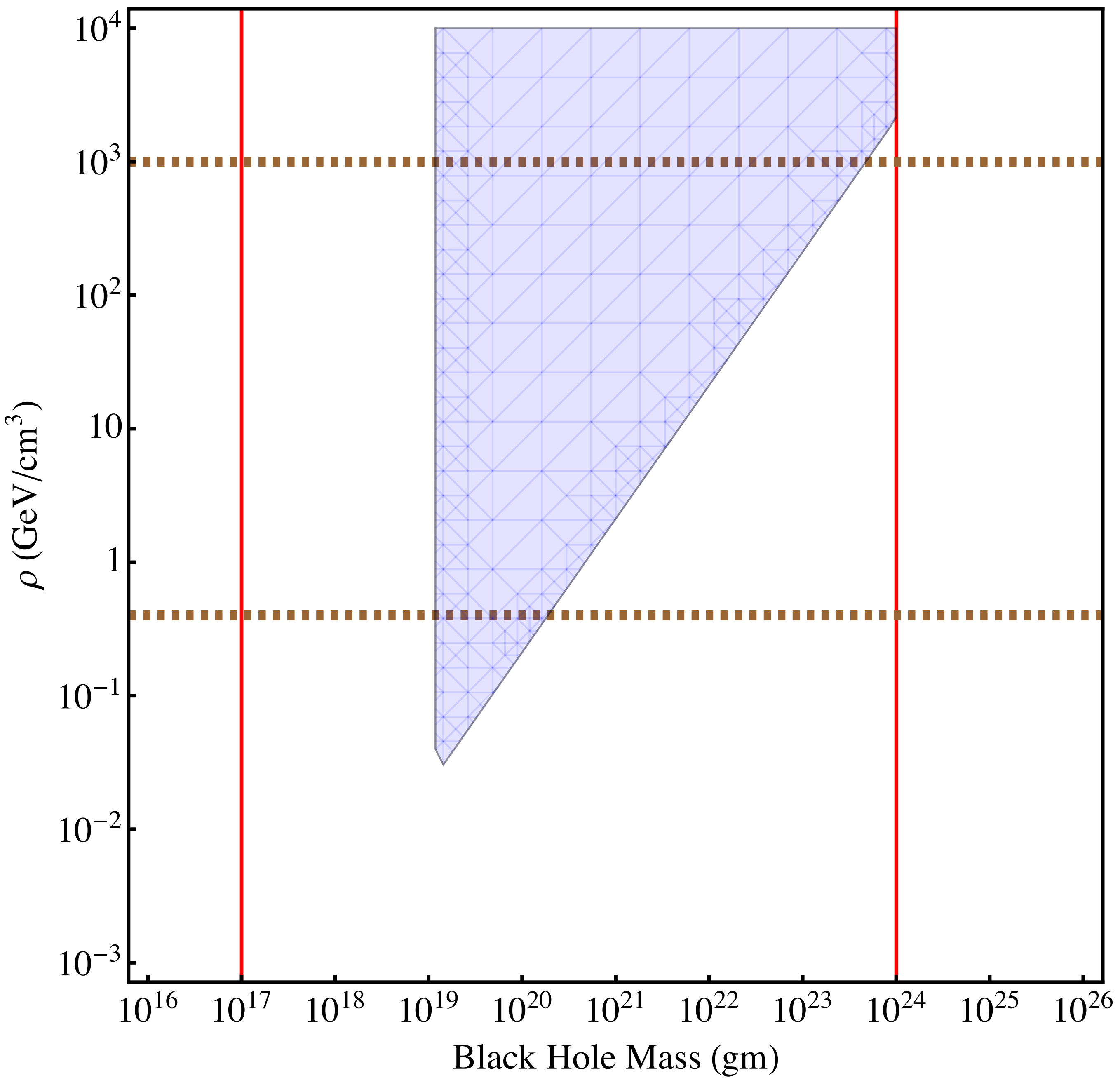


But do globular clusters have a high DM density? And error claimed in Pani & Loeb by Cappela et al..

white dwarf explosions

Transit of PBHs through white dwarf heats it, due to dynamical friction, causing it to explode.

Graham, Rajendran & Varela



dark matter density
in Solar neighbourhood

extragalactic gamma-rays background

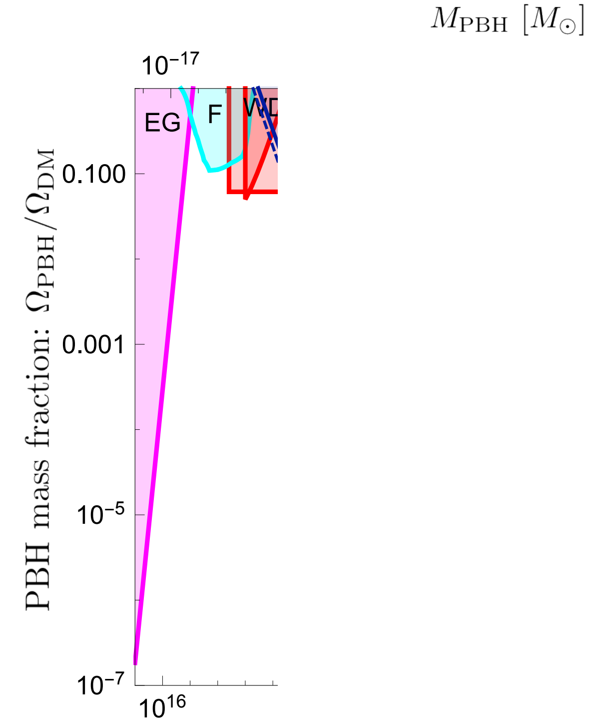
Page & Hawking; … ; Carr, Kohri, Sendouda & Yokoyama

Gamma-rays produced by evaporation can not exceed intensity of gamma-ray background measured by EGRET/Fermi.

$$f(M) \lesssim 2 \times 10^{-8} \left(\frac{M}{5 \times 10^{14}\,\mathrm{g}} \right)^{3.1-3.4}$$

uncertainty in energy dep. of measured intensity

mass of PBH with lifetime equal to age of Universe



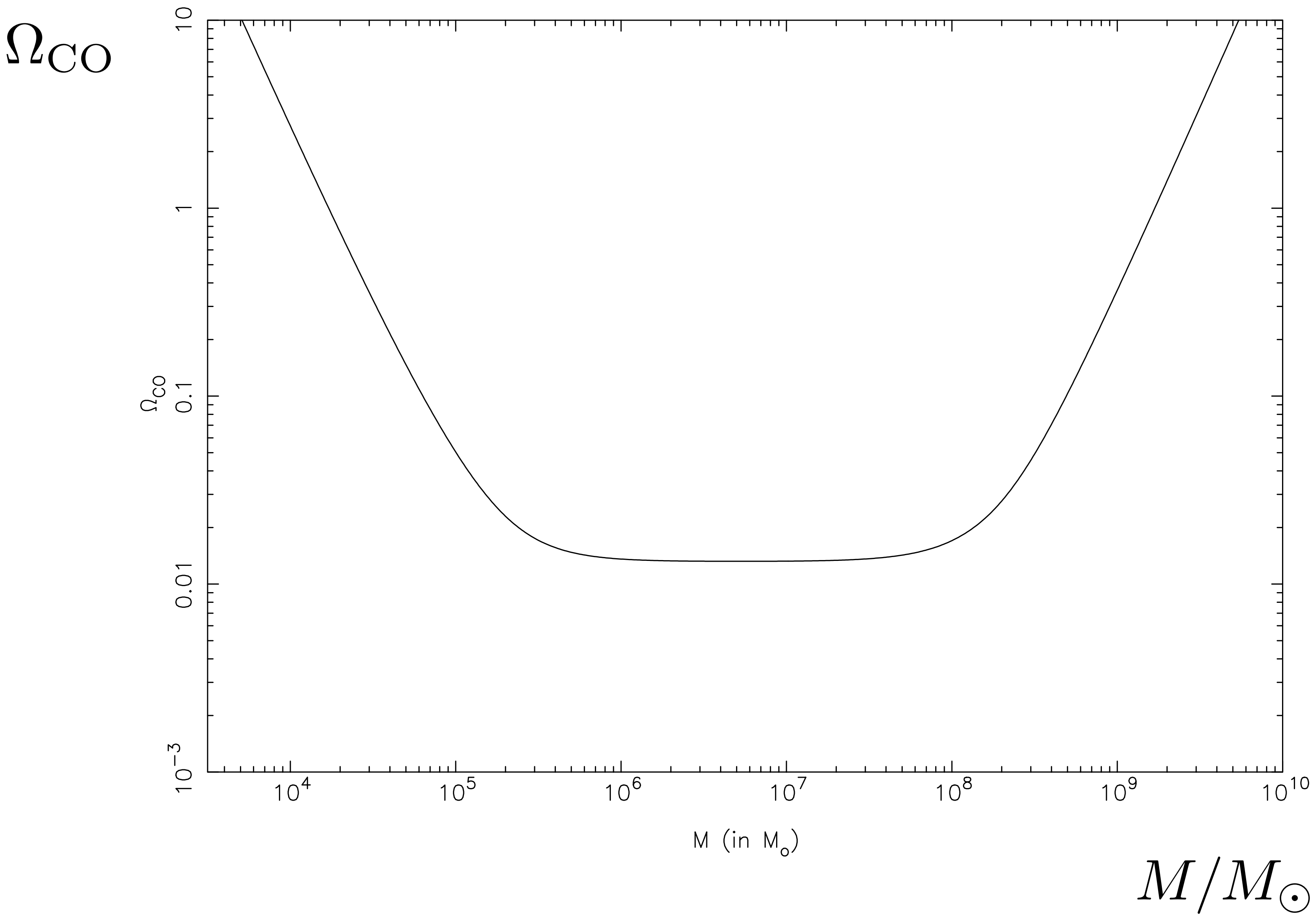
Tighter constraints could be obtained by subtracting off known contributions e.g. blazars

c.f. Barrau et al.

Constraints: multi-Solar mass region

milli-lensing of radio sources

Massive compact objects can milli-lens radio sources, producing multiple images which can be resolved with Very Long Baseline Interferometry. Kassiola, Kovner & Blandford



Wilkinson et al.

Other constraints on very massive PBHs

Dynamical friction (pulls PBHs towards centre of halo) Carr & Sakellariadou

Disc heating (increases velocity dispersion of stars) Carr & Sakellariadou

Effect of Poisson fluctuations on LSS Afshordi et al.

Indirect constraints

Large density perturbations would generate stochastic gravitational waves at 2nd order due to mode-mode coupling Ananda et al.

Large density perturbations would generate spectral distortions in CMB Kohri et al.

Future constraints

Strong lensing of Fast Radio Bursts using CHIME can constrain $M > (10 - 100)M_\odot$ Munoz et al.

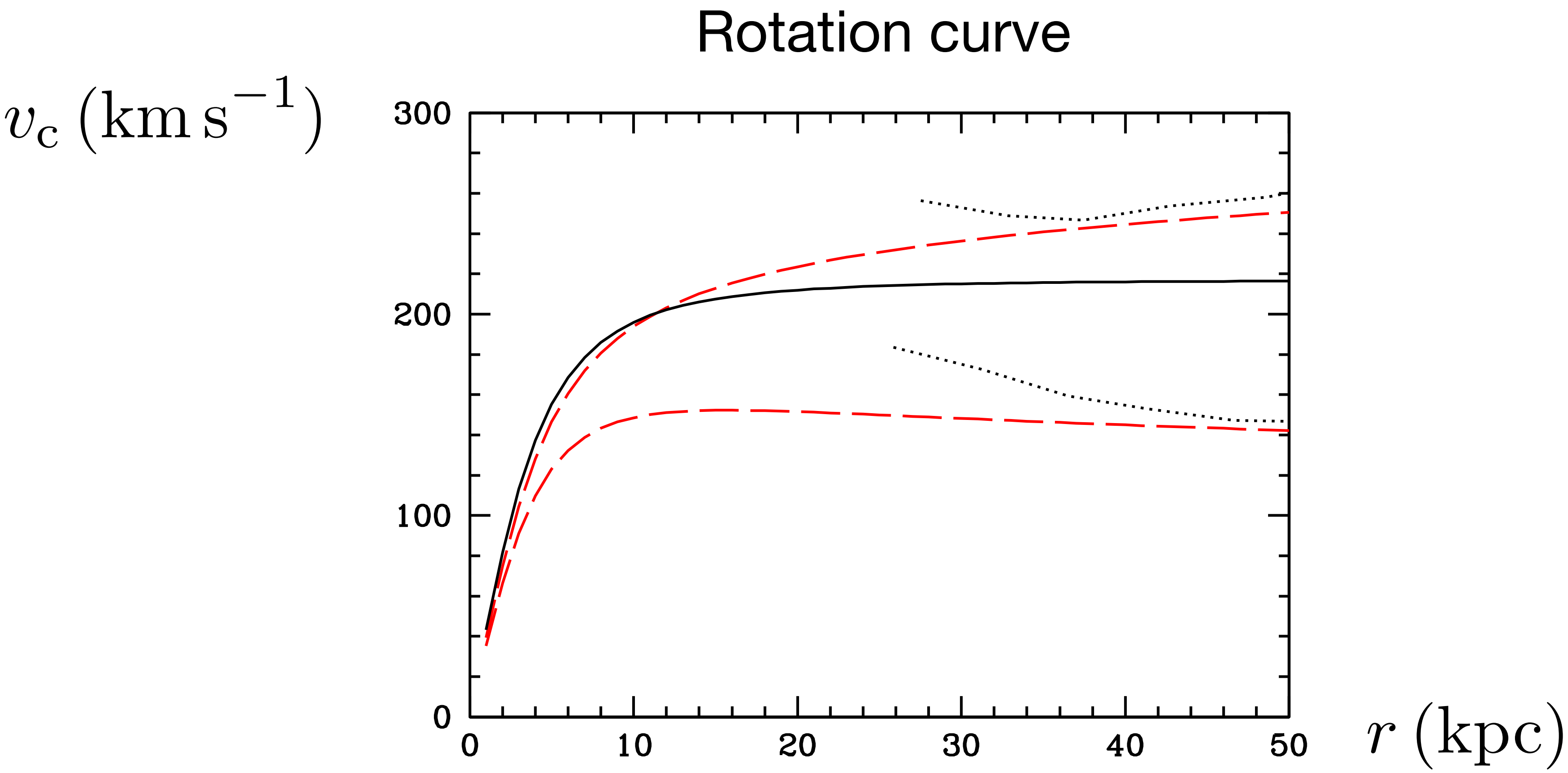
Pulsar timing using SKA can constrain $M > (1 - 1000)M_\odot$ Schutz & Liu

Caveat

Constraints often depend on the dark matter distribution

For example, for the EROS microlensing constraints:

Evans power law halo models: self-consistent halo models, which allow for non-flat rotation curves. Traditionally used in microlensing studies since there are analytic expressions for velocity distribution.

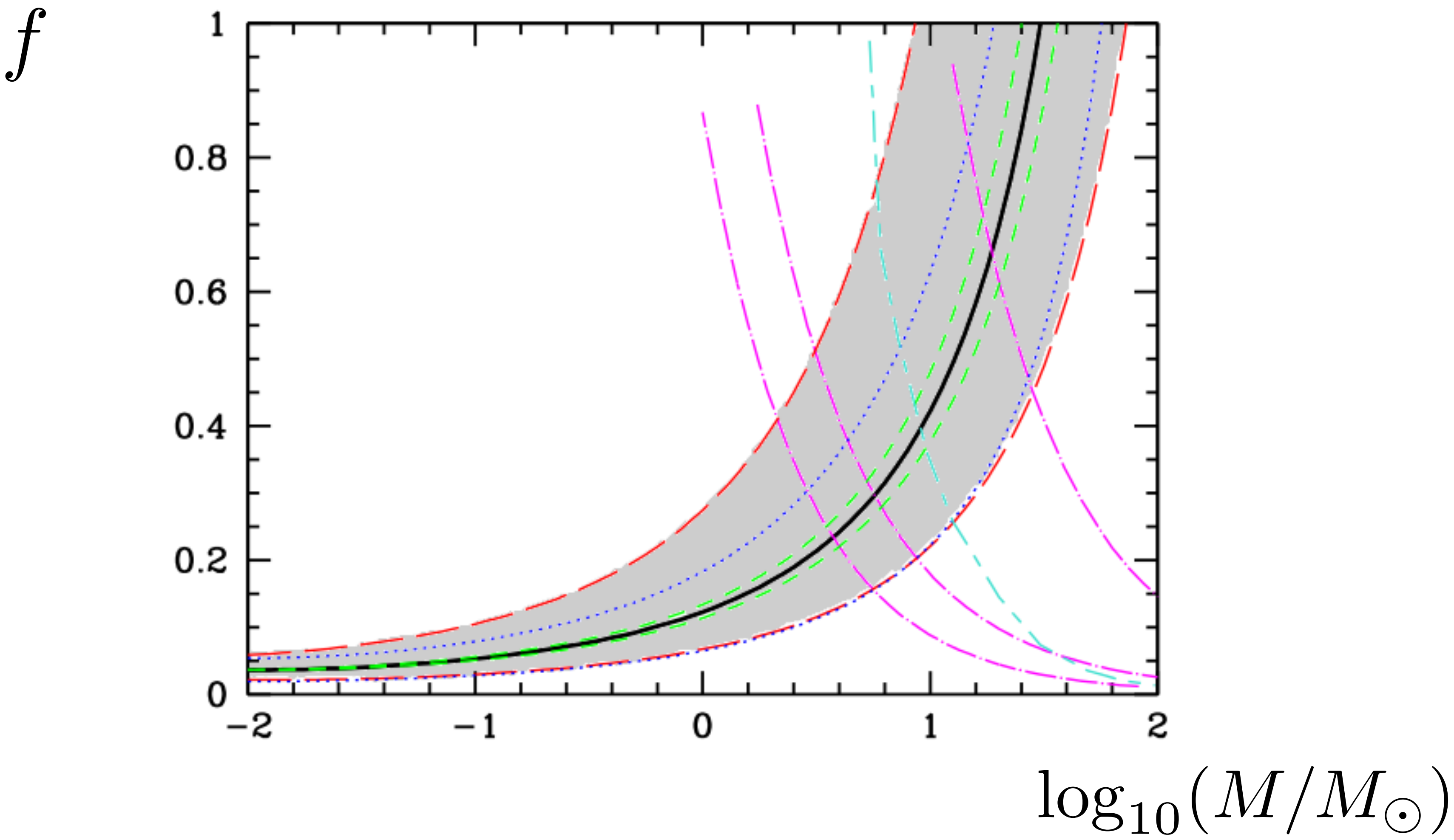


——— standard halo (SH)

— — — 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.

Constraints on halo fraction for delta-function MF:



Microlensing: ——— standard halo (SH)

— — — power law halos C and B

……… SH local density, 0.005 and 0.015 $M_\odot\,\mathrm{pc}^{-3}$

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

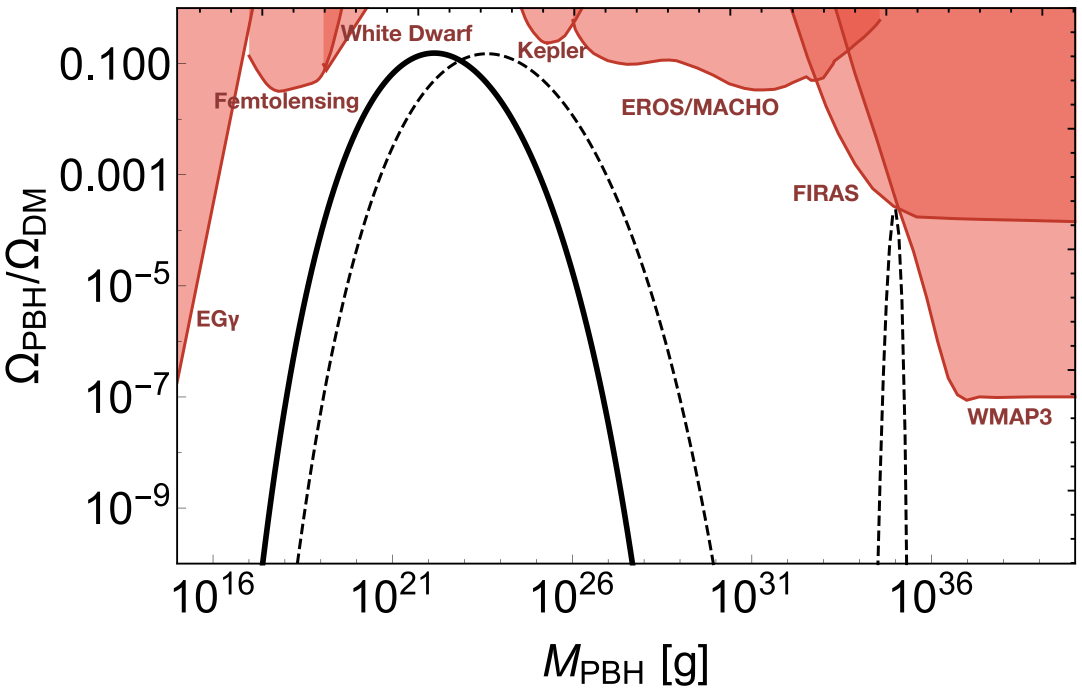
Brandt dwarf galaxy constraints ———

Clustering of PBHs would also affect microlensing (and other) constraints.

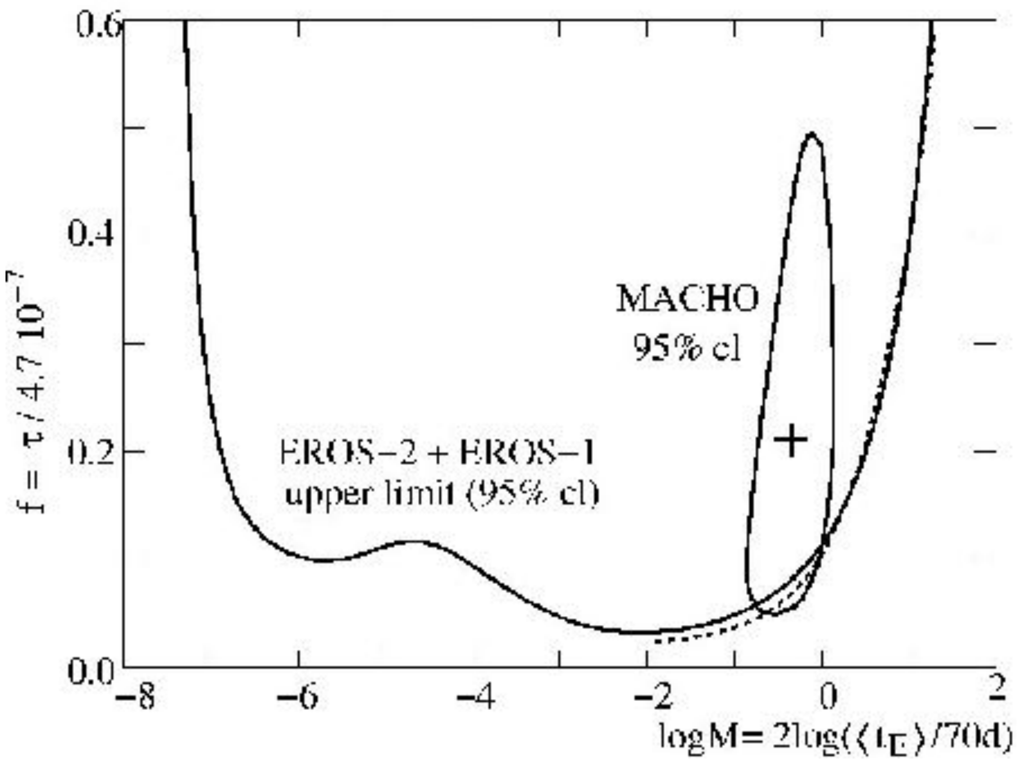
Garcia-Bellido & Clesse

Application to (realistic) extended mass functions

Is subtle….



Can’t just compare df/dM to constraints on f as a function of M (e.g. arXiv:1606.07631).



Beware ‘double-counting’:
for instance EROS microlensing constraints, allow f~0.2 for M~5 M_{sun} or f~0.4 for M~10 M_{sun}, **but NOT BOTH.**

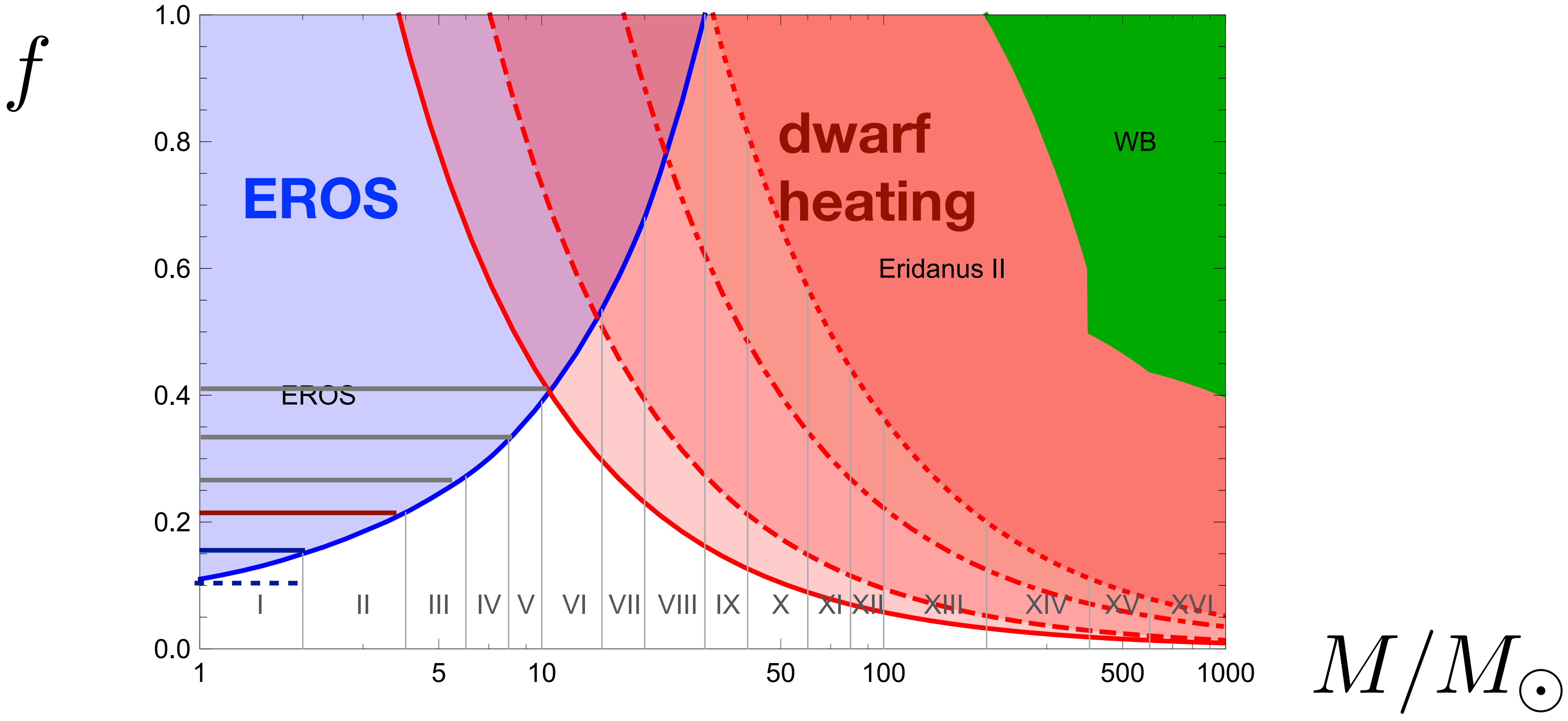
Carr, Kuhnel & Sandstad method:

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 MG in bins I+II is less than ***weakest*** limit on f in these bins.

And so on…



This underestimates the strength of the constraints.

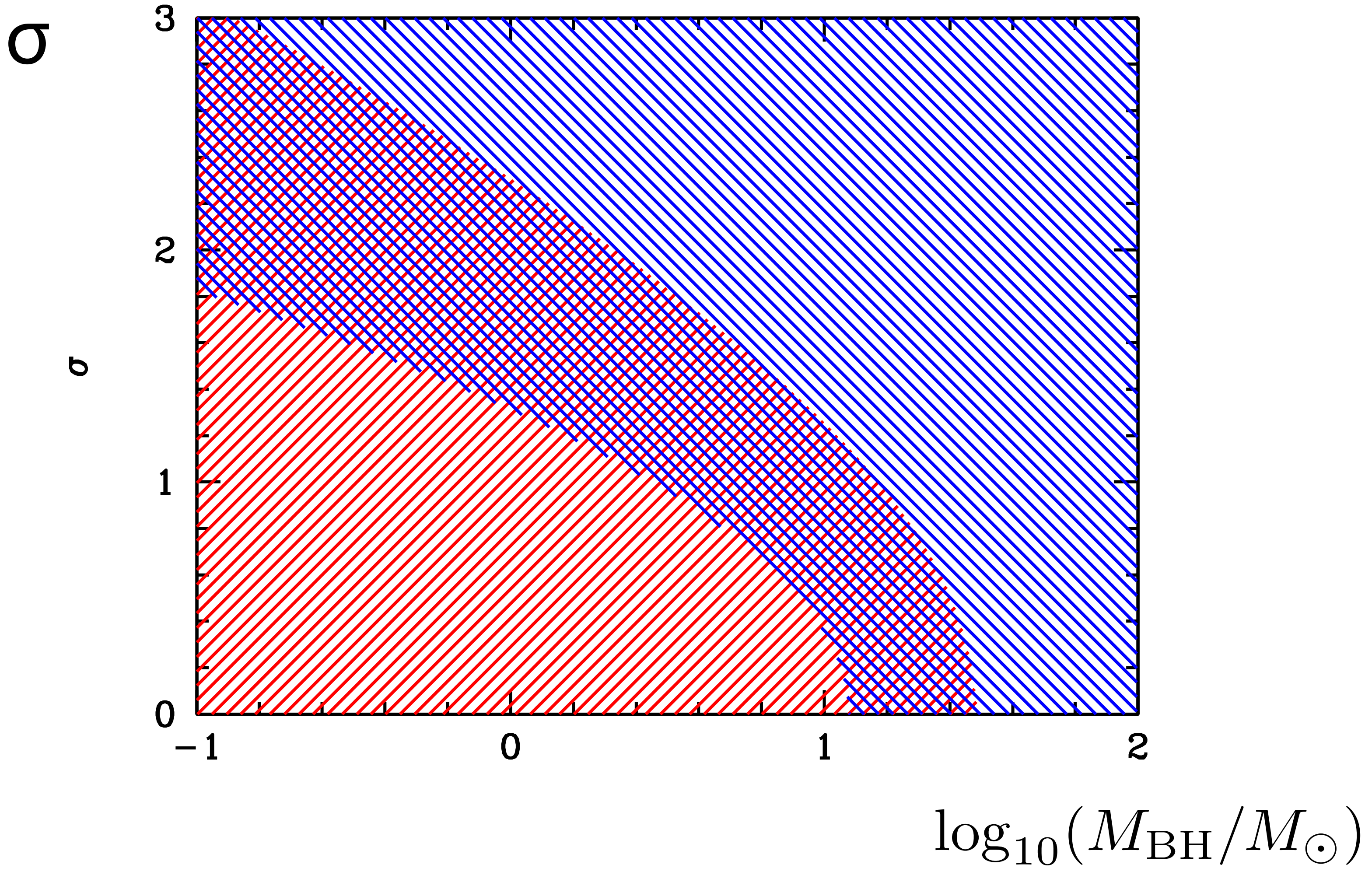
If the integral of the MF exceeds weakest limit on f it's definitely excluded, but some which don't are also excluded.

(Conversely all MFs which don't exceed *tightest* limit are definitely allowed, but some which do are also allowed.)

Extended MFs produced by inflation models, taking into account critical collapse, are often well approximated by a log-normal distribution: Green; Kannike et al.

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

Constraints on the central mass, M_c, and width, σ, of log-normal MF from explicit recalculation of EROS microlensing and tightest heating of ultra-faint dwarfs limit



Method for applying delta-function constraints to extended mass functions:

Carr, Raidal, Tenkanen, Vaskonen& Veermae:

If (as is usually case) different mass PBHs contribute independently to constraint can write observable, A, as:

$$A[\psi] = A_0 + \int \mathrm{d}M \psi(M) K_1(M)$$

K_1(M) encodes the underlying physics (& also depends on astrophysical parameters).

And if $f_{\rm max}$(M) is the maximum allowed PBH fraction for a delta-function MF can show:

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

Bellomo, Bernal, Raccanelli & Verde:

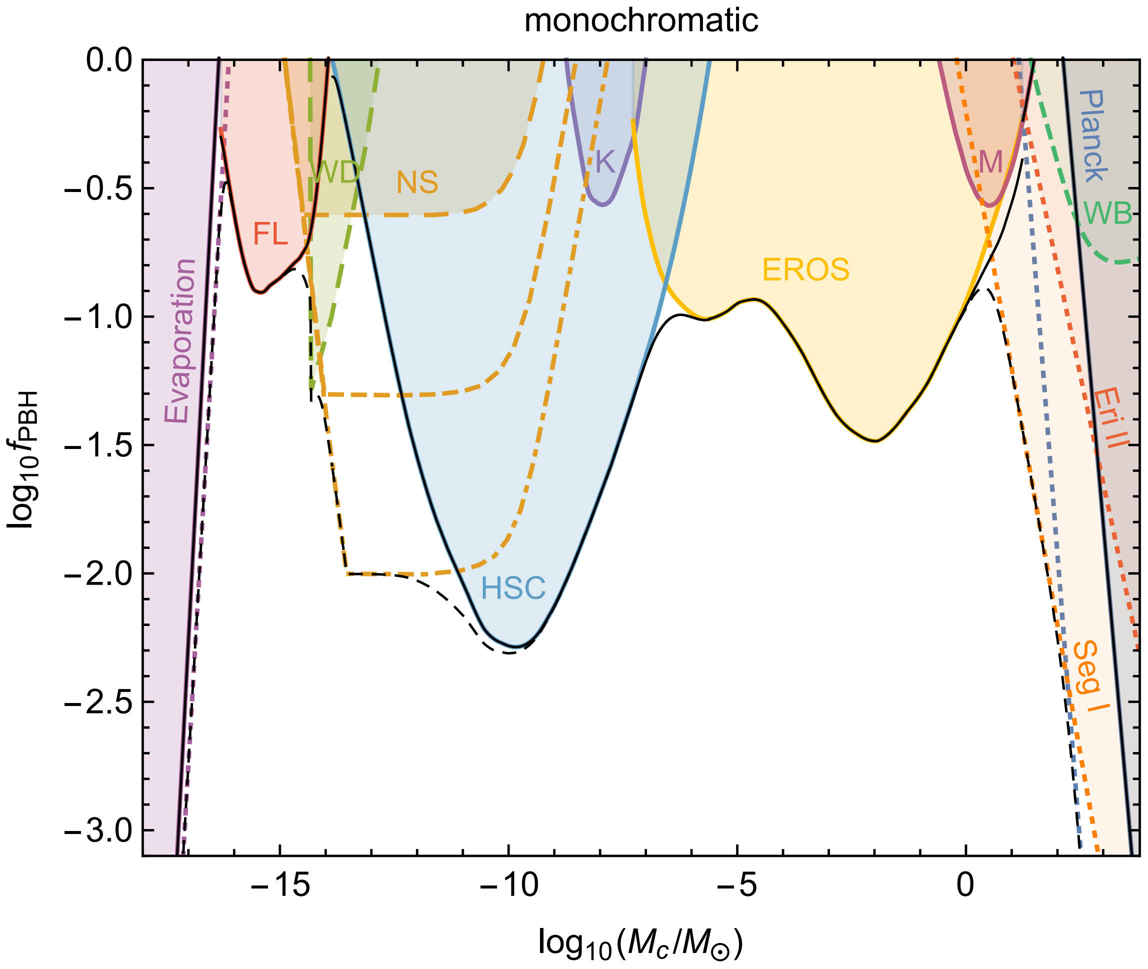
Introduced concept of equivalent mass, $M_{\rm eq}$, of extended mass function (and cautioned about EMF extending beyond validity of constraint).

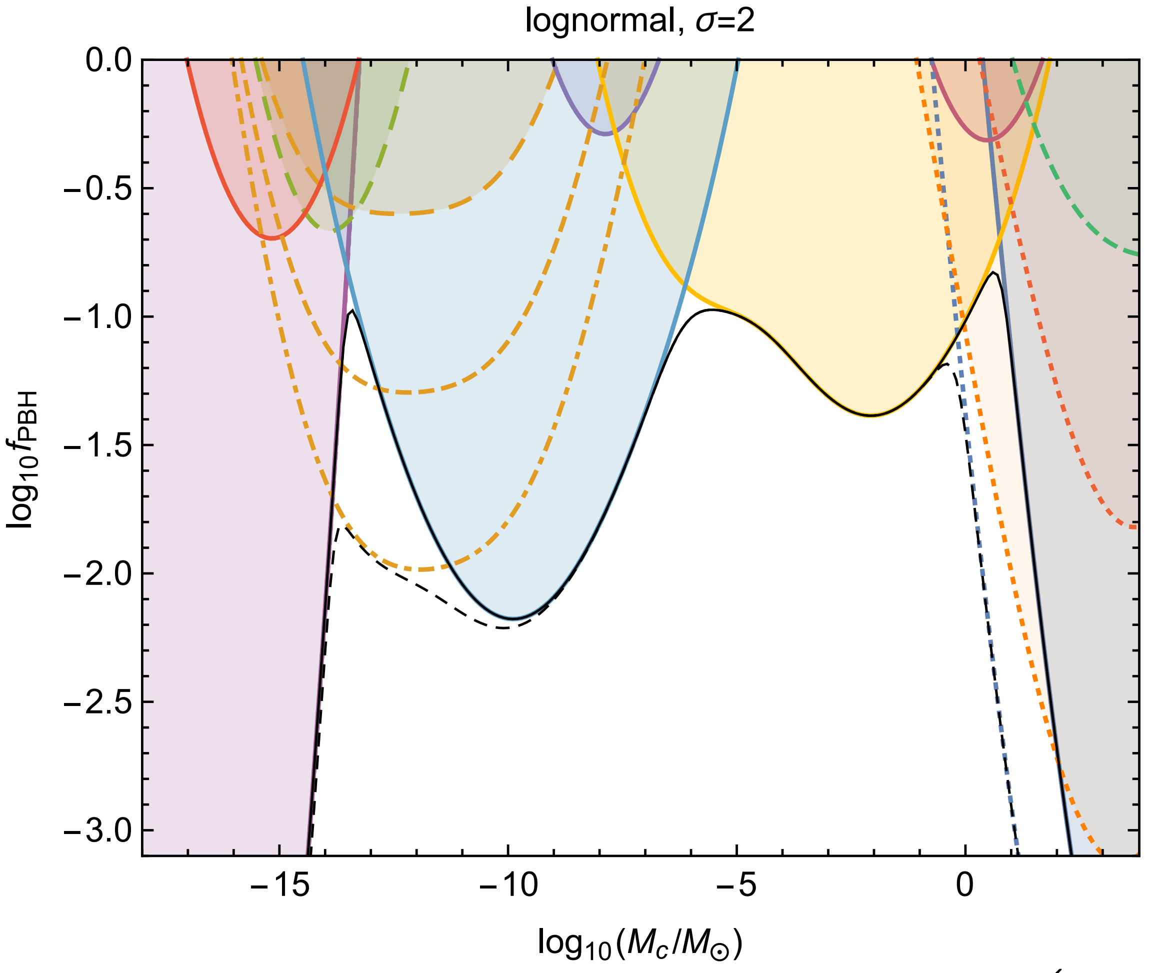
Constraints are in fact usually tighter for extended mass function than delta-function: Green; Carr et al.

monochromatic

log-normal
(fixed width)

$\log_{10} f$



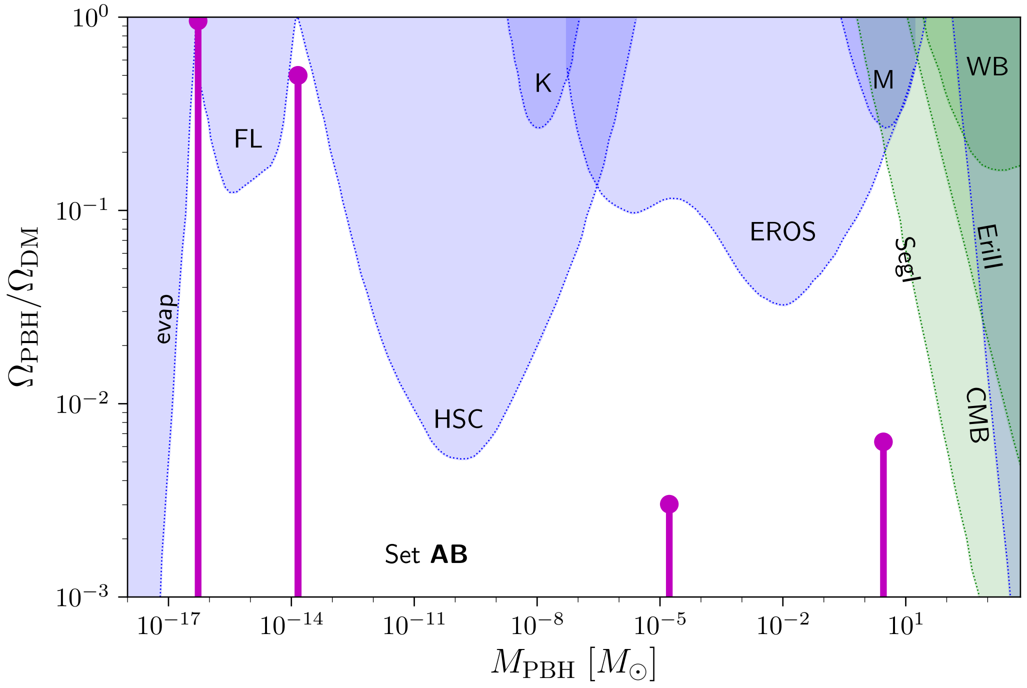


$$\log_{10}\left(\frac{M}{M_\odot}\right)$$

Carr et al.

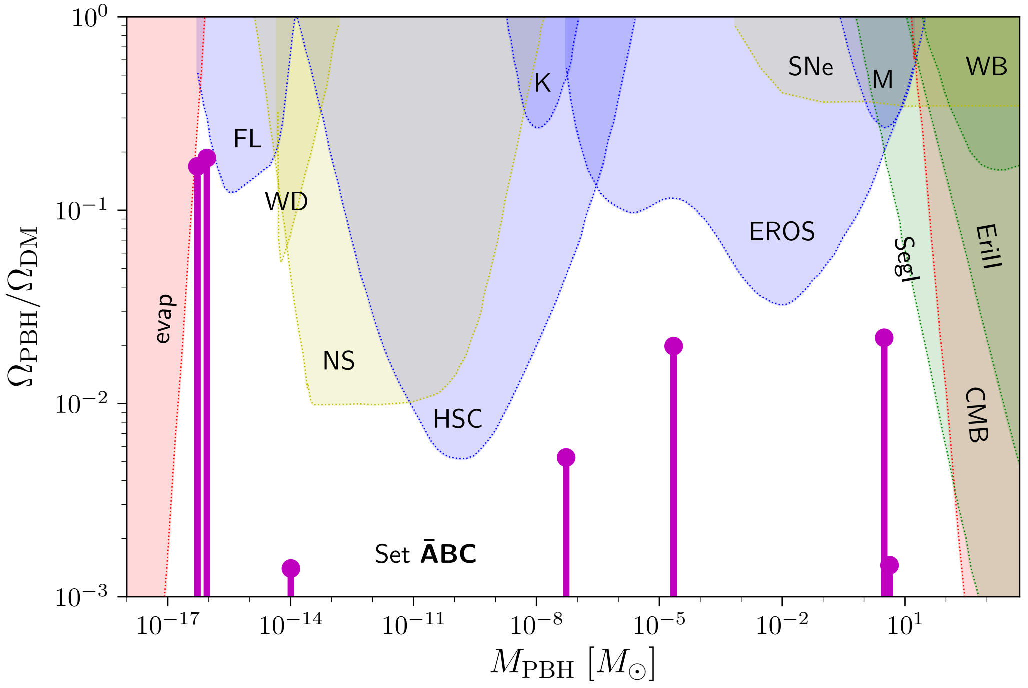
PBH fraction (considering all constraints) maximised by a MF which is a sum of delta-functions Lehmann, Profumo & Yant:

robust constraints



$$f_{\rm max} = 2.0$$

all constraints



$$f_{\rm max} = 0.4$$

Summary

There are numerous constraints on the abundance of PBHs from gravitational lensing, their dynamical effects, accretion and other astrophysical processes.

These constraints typically involve assumptions about the PBH distribution and/or modelling complex astrophysical processes, however it appears that PBHs can not make up all of the DM.

Constraints are tighter for (realistic) extended mass functions than for the delta-function which is usually assumed when calculating constraints.