Primordial Black Holes (PBHs) as dark matter

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1. Introduction to PBH dark matter
2. PBH structure formation and evolution
3. **Observational constraints on PBHs**

Abundance constraint plots made using Bradley Kavanagh's PBHbounds package:
https://github.com/bradkav/PBHbounds http:10.5281/zenodo.3538999

Recap

- Primordial Black Holes (PBHs) can form in the early Universe, for instance from the collapse of large density perturbations generated by inflation.

- Due to discrete nature of PBHs, clusters form not long after matter-radiation.

- If PBHs don't make up all of the DM they accrete halos of particle dark matter.

- If PBHs make up a significant fraction of the DM, PBHs binaries form before matter-radiation equality and (if their orbits don't subsequently get perturbed) they would be merging at an observable (via gravitational waves) rate 'today'.

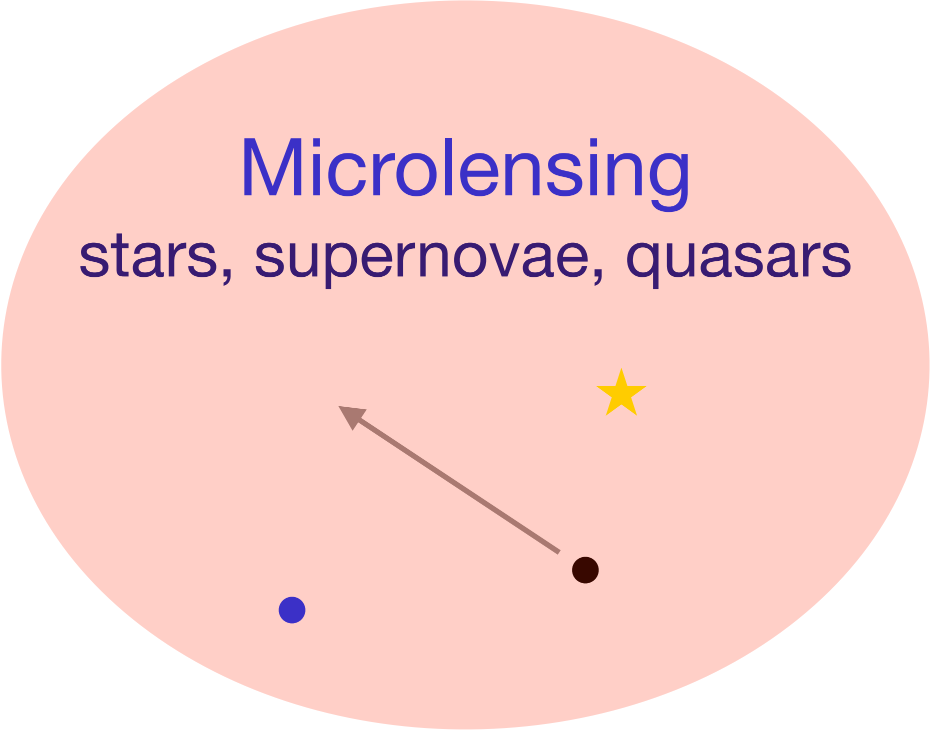
Today

- observational constraints on PBH dark matter
  - microlensing
  - dynamical constraints
  - accretion
  - gravitational waves
  - effects on stars
  - evaporation

Observational constraints on PBHs

Constraints usually calculated assuming a delta-function mass function-will discuss application to (realistic) extended mass functions at end.

Often other (implicit or explicit) assumptions e.g. no clustering.

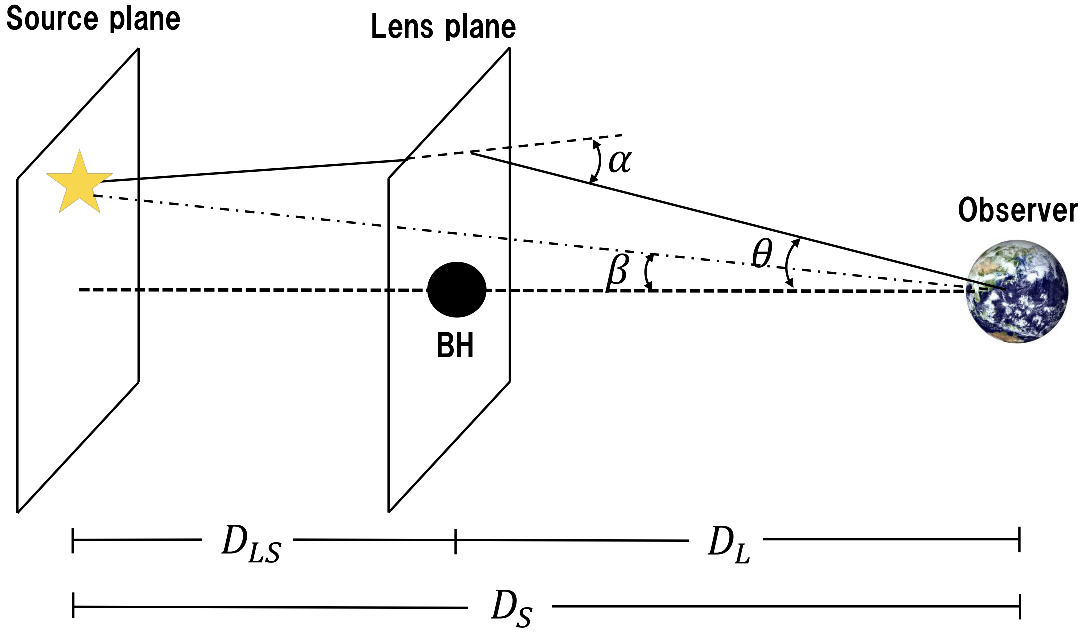

Microlensing

stars, supernovae, quasars

Constraints

gravitational lensing

for an intro see e.g. Sasaki et al.



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

Sasaki et al.

Lens equation: $\theta D_{\mathrm{S}} = D_{\mathrm{S}}\beta + D_{\mathrm{LS}}\alpha$

deflection $\alpha = \dfrac{4GM_{\mathrm{BH}}}{D_{\mathrm{L}}\theta}$

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

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

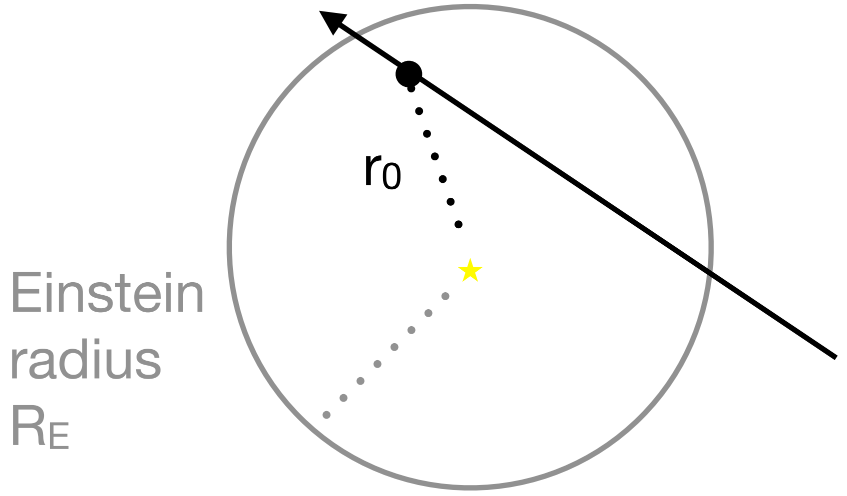
Einstein radius: $R_E = \sqrt{\dfrac{4GMD_LD_{LS}}{D_S}}$

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

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

stellar microlensing

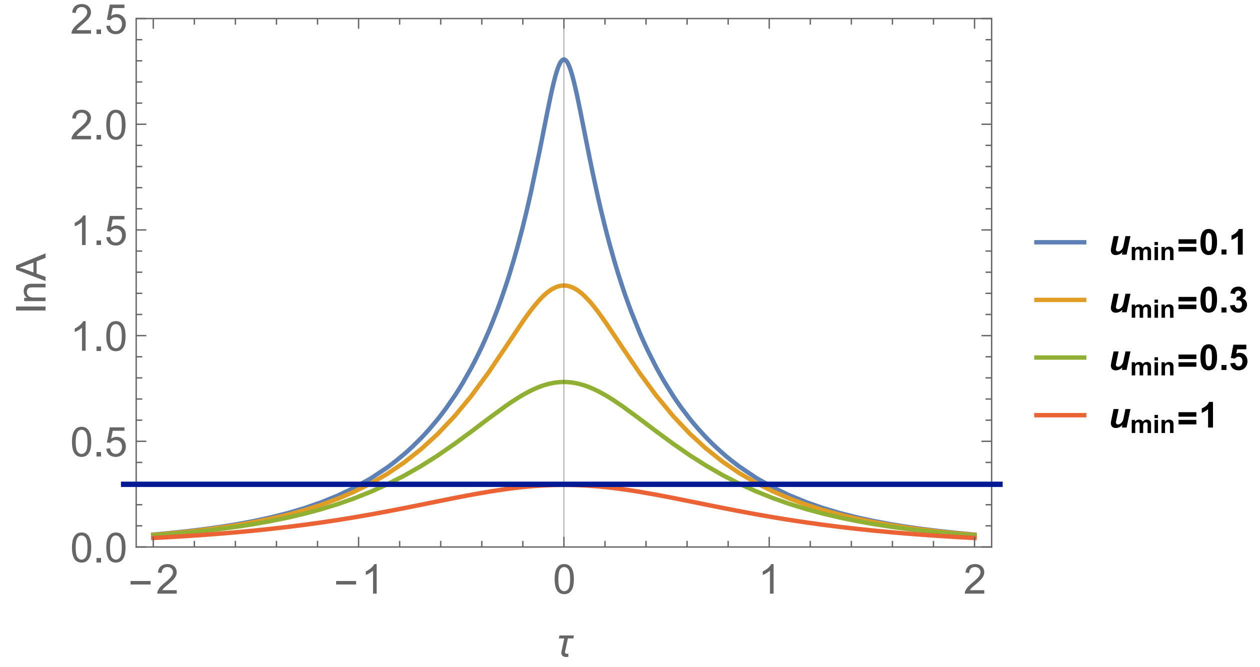
Microlensing occurs when angular resolution is too small to resolve multiple images, instead observe amplification of source:



$$u \equiv \frac{r_0}{R_\mathrm{E}} = \left\{ u_\mathrm{min}^2 + \left[\frac{2(t - t_\mathrm{max})}{\hat{t}} \right]^2 \right\}^{0.5}$$

r_0 = “impact parameter”

$$\hat{t} = \frac{2R_\mathrm{E}}{v}$$ Einstein diameter crossing time



Sasaki et al.

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

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

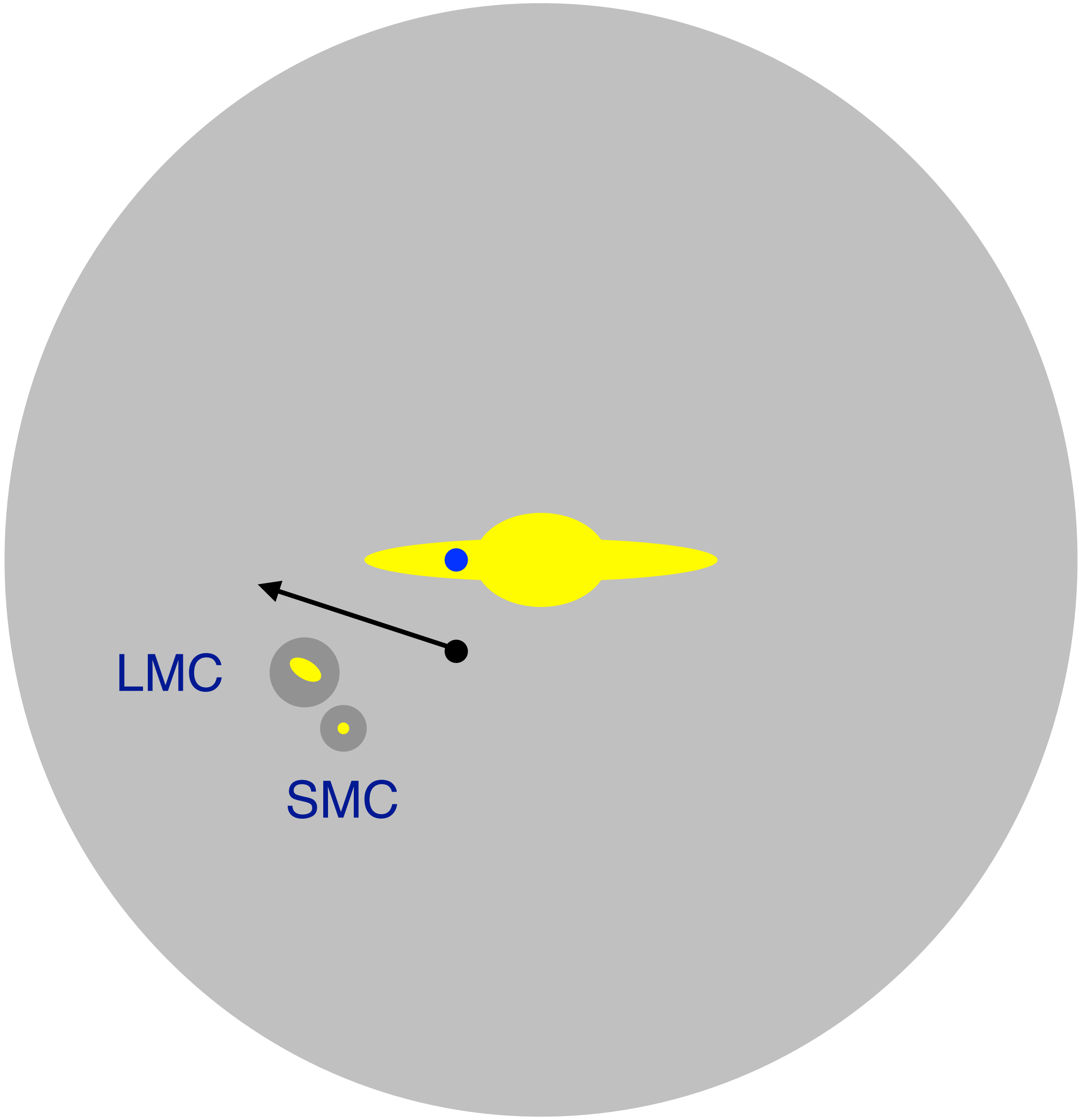
‘Duration’ of event (Einstein diameter crossing time):

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

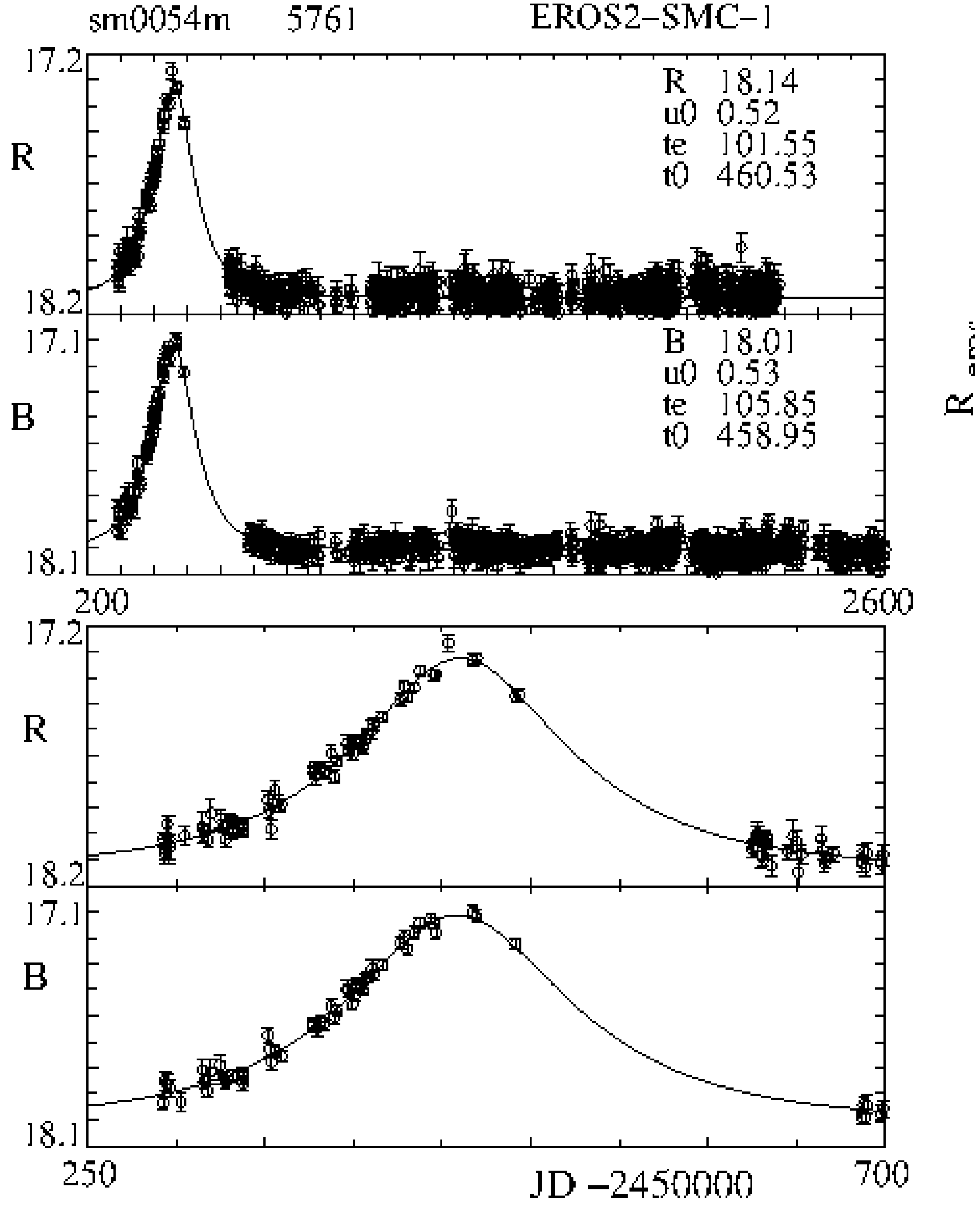
n.b. this all assumes point source and lens, see later…

some sources e.g. EROS collaboration, use Einstein radius, rather than diameter, crossing time.

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



Not to scale!



EROS

magellanic clouds

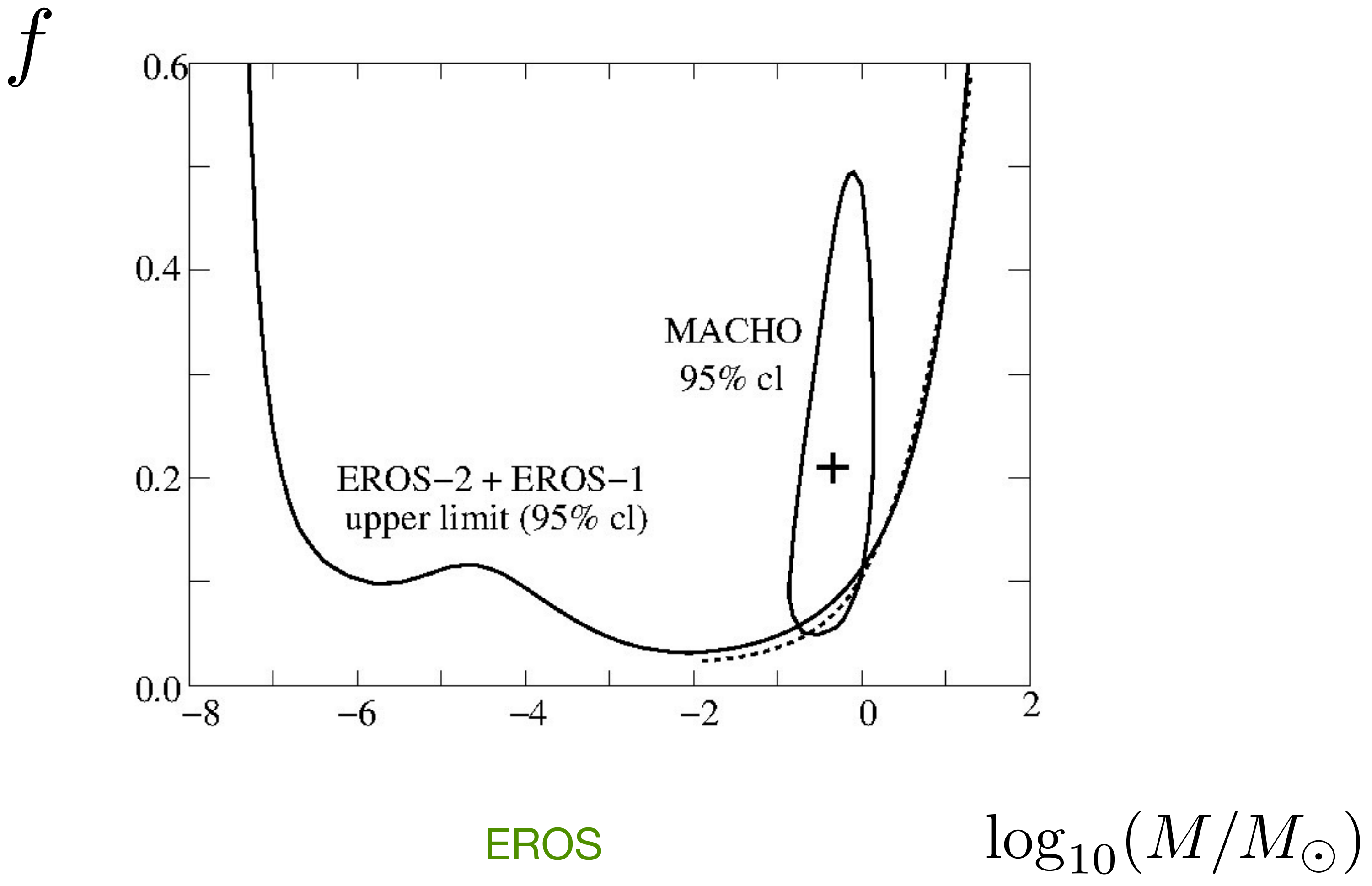
EROS

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.

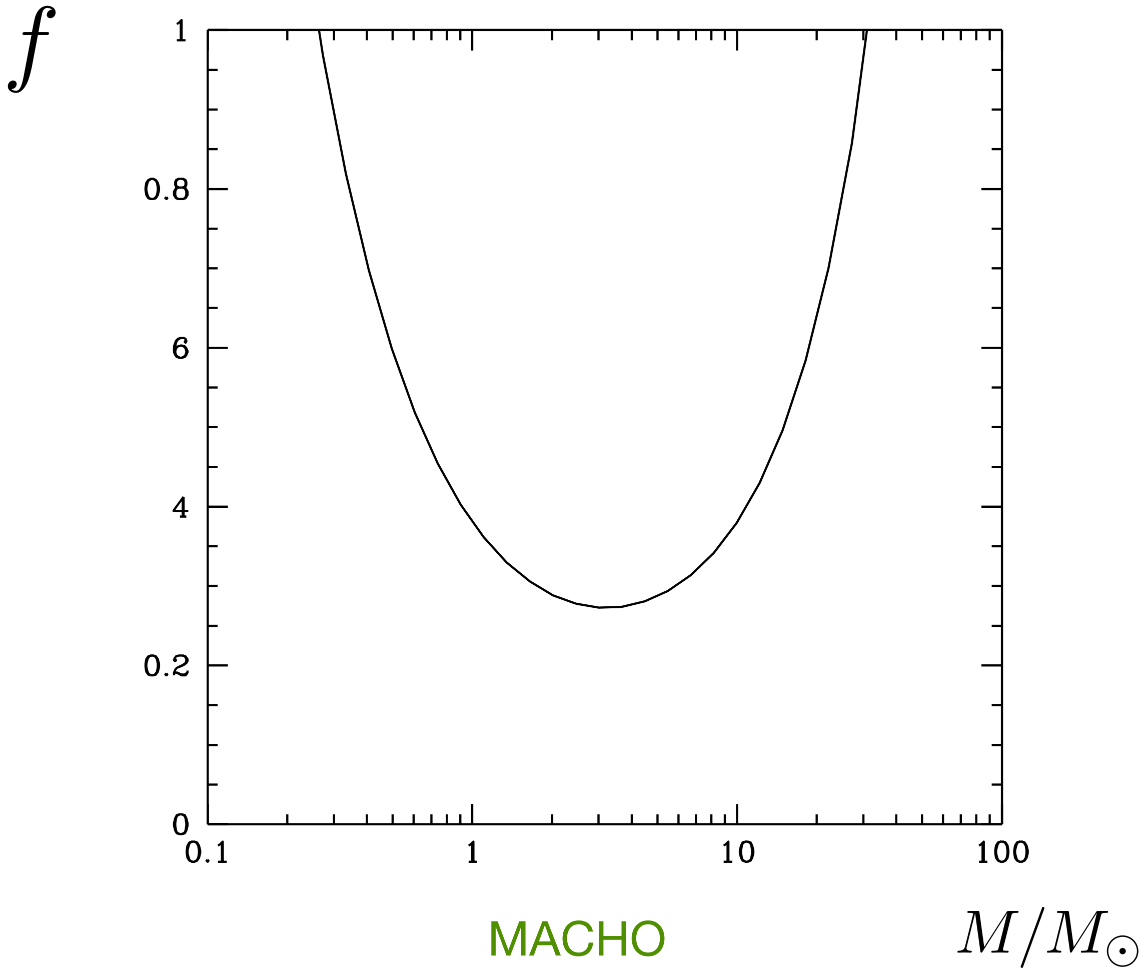
Constraints on fraction of halo in compact objects, f, (DF MF):



EROS

MACHO

Null search for long duration (>150 days) events gives similar results to EROS for $M > 3M_\odot$



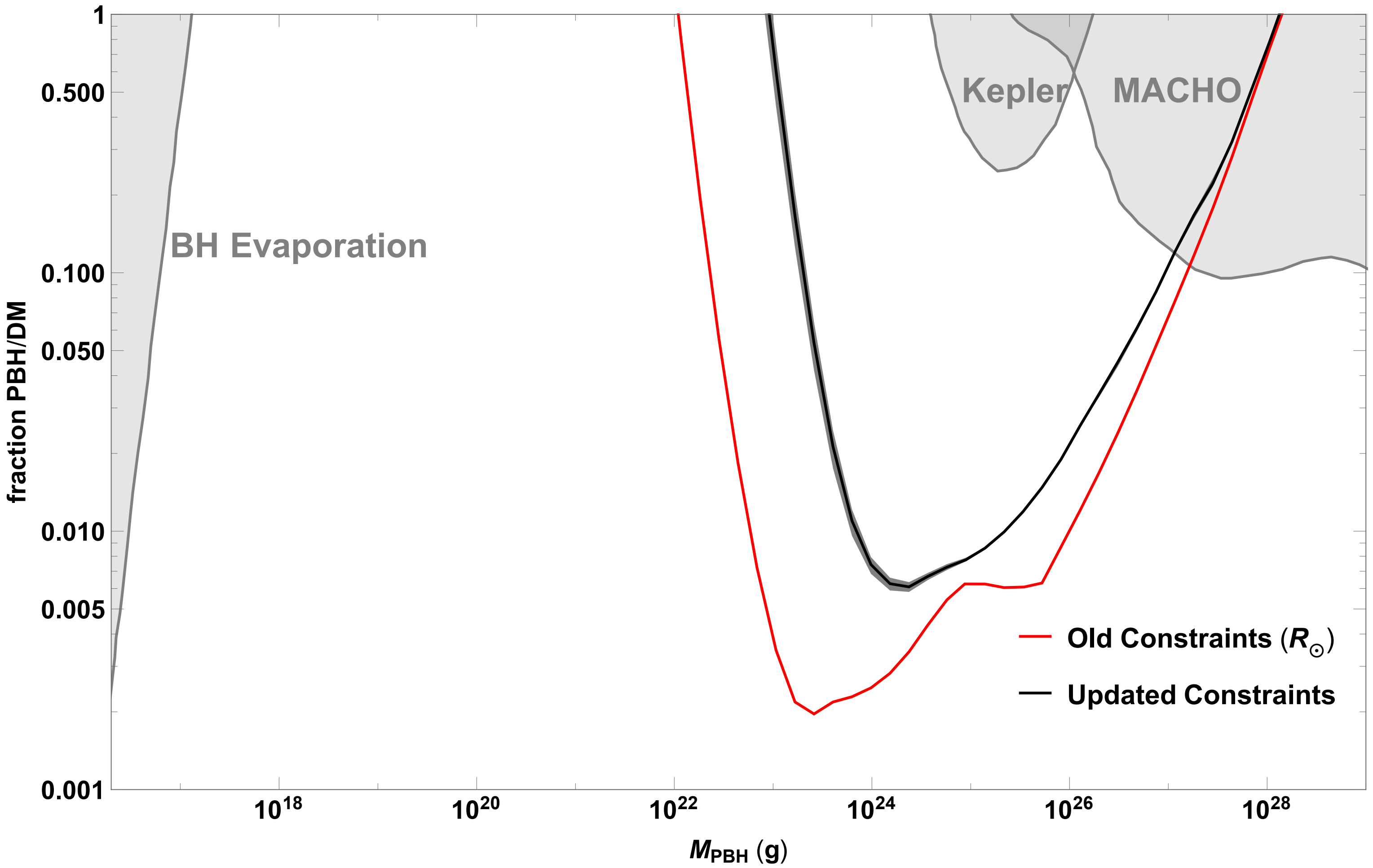
MACHO

5.7 year data: found 13/17 events with durations (40-130) days, consistent with f_{co}~0.2 for $M_{\rm co} \sim 0.5M_\odot$

BUT in several cases lens is known, or likely to be, a star in the LMC or MW disc.

stars in M31

Subaru HSC observations have higher cadence than EROS/MACHO, so sensitive to shorter duration events and hence lighter compact objects. Niikura et al.



Smyth et al.

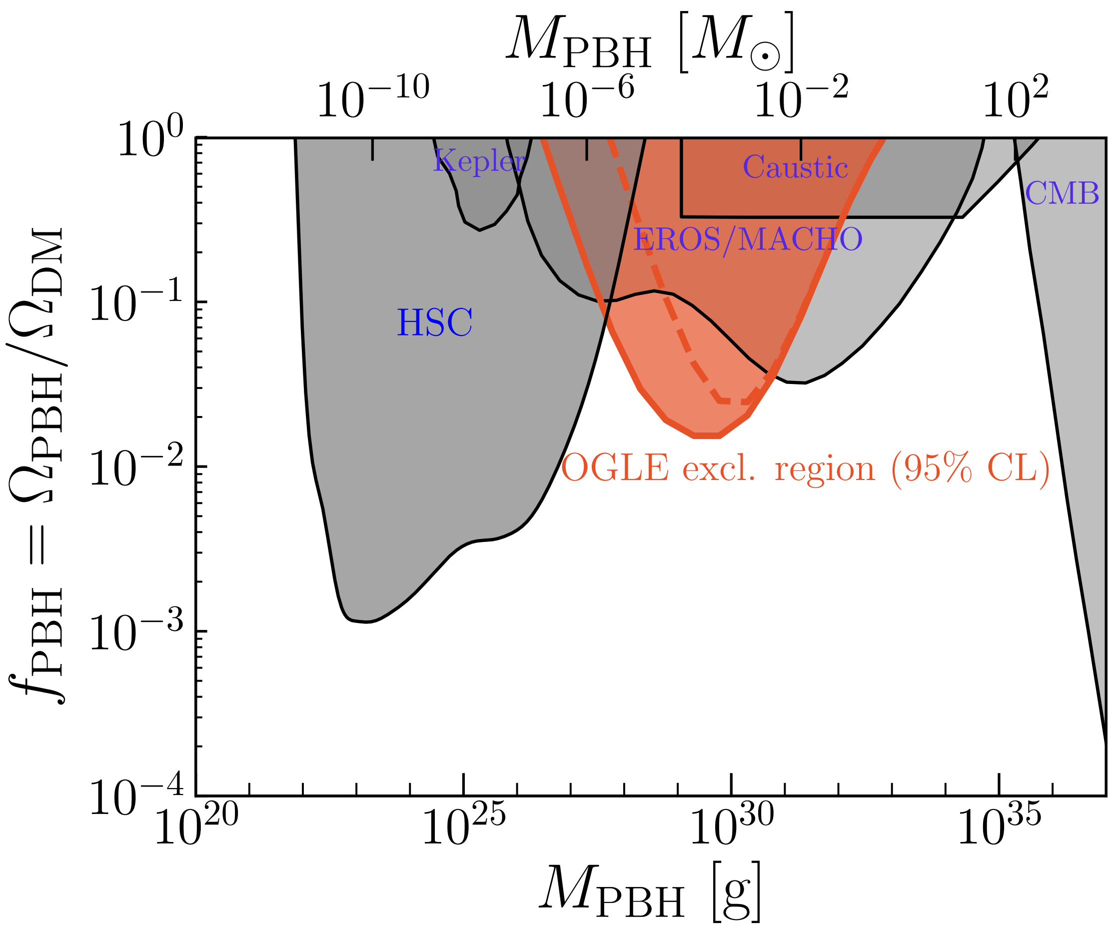
Finite size of source stars and effects of wave optics (Schwarzschild radius of BH comparable to wavelength of light) leads to reduction in maximum magnification for $M \lesssim 10^{-7} M_\odot$ and $M \lesssim 10^{-11} M_\odot$ respectively. Witt & Mao; Gould; Nakamura; Sugiyama, Kurita & Takada

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

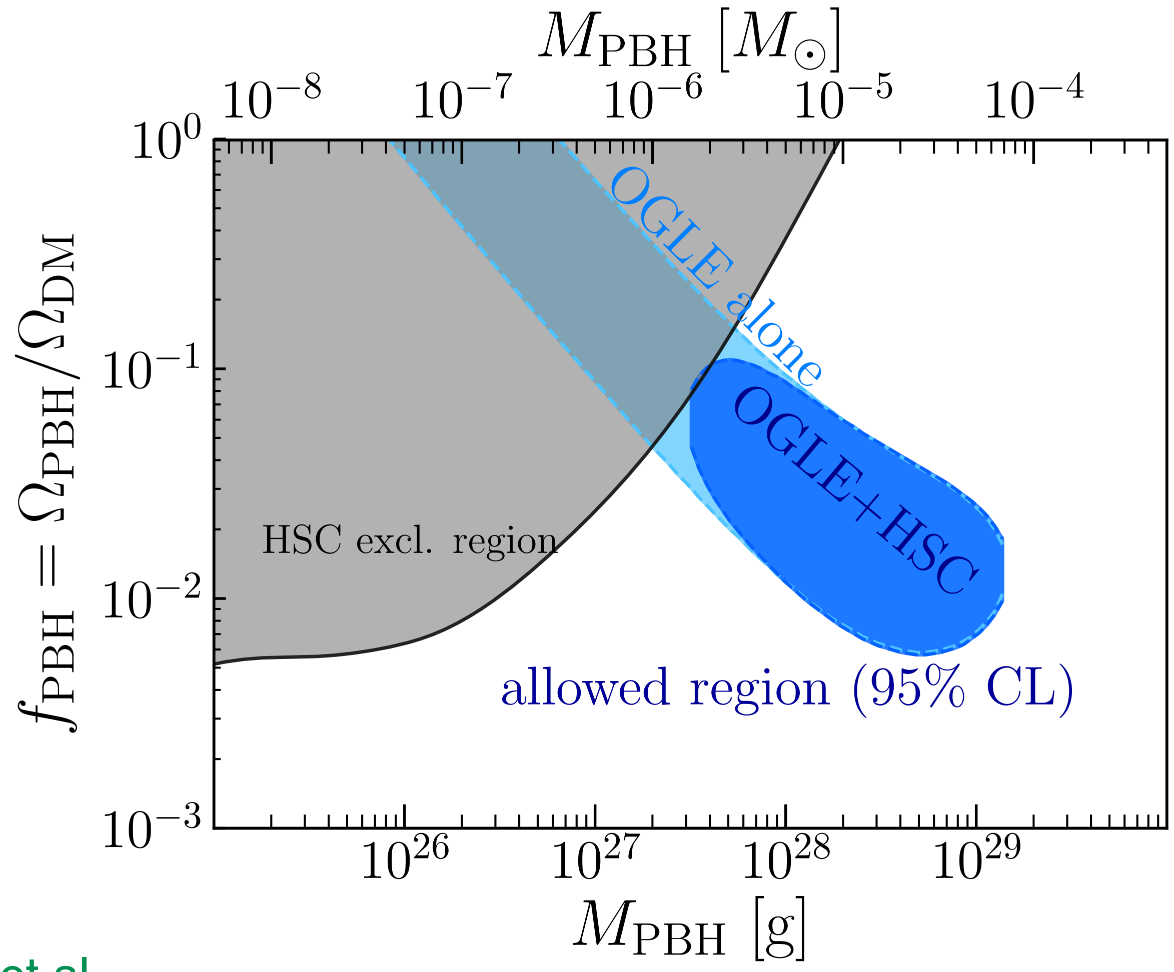
stars in Galactic bulge

Observed events consistent with expectations from stars (except for 6 ultra-short (0.1-0.3) day events, which could be due to free floating planets)

Exclusion limit
assuming no PBH lensing observed



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

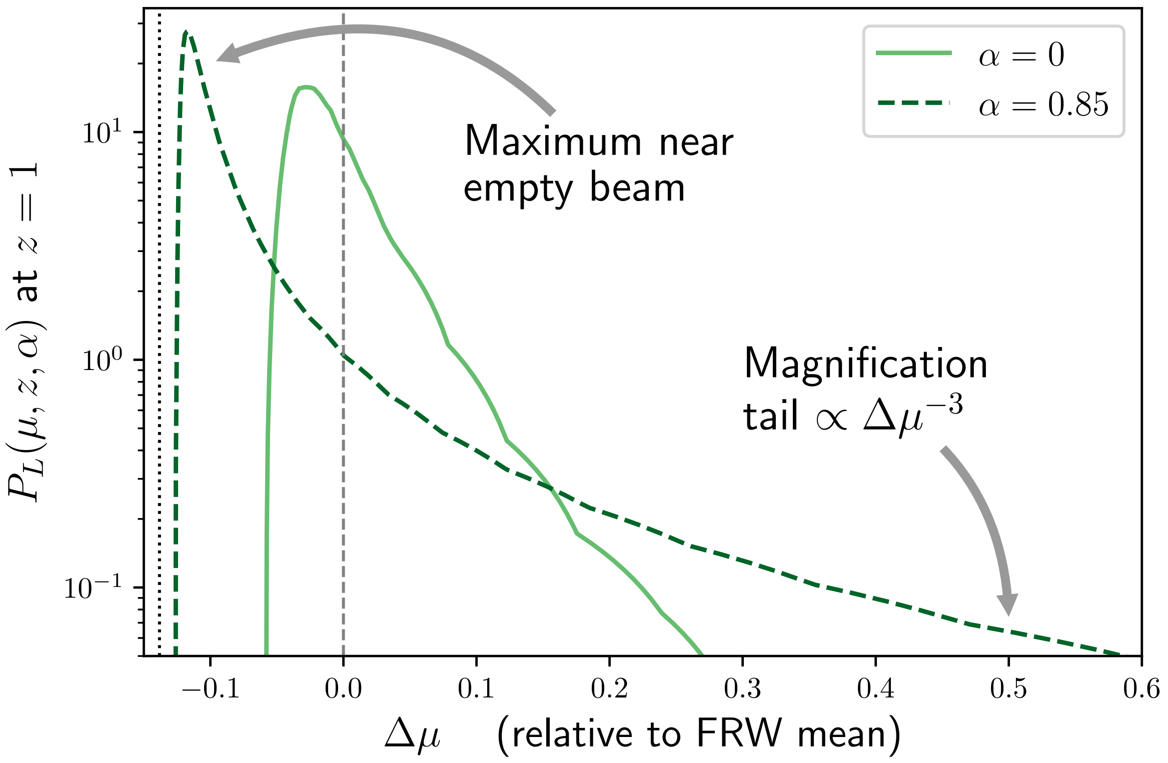


Niikura et al.

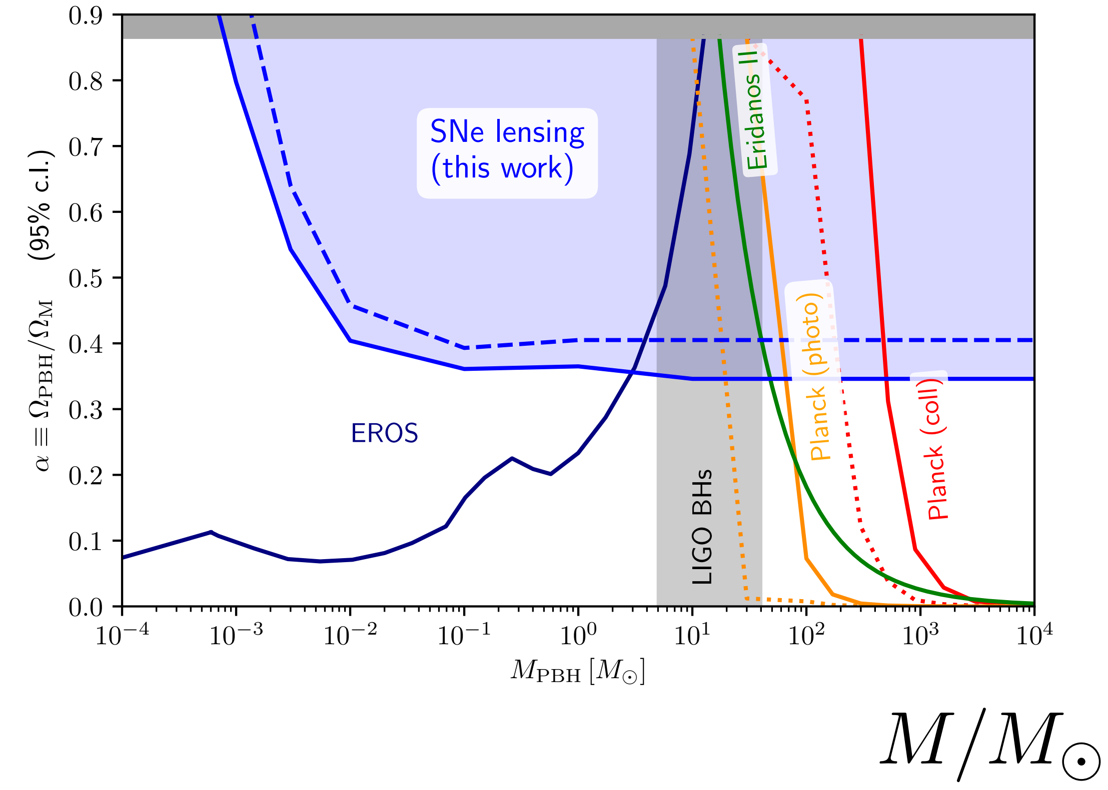
supernova microlensing

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

magnification distribution



PBH abundance constraints



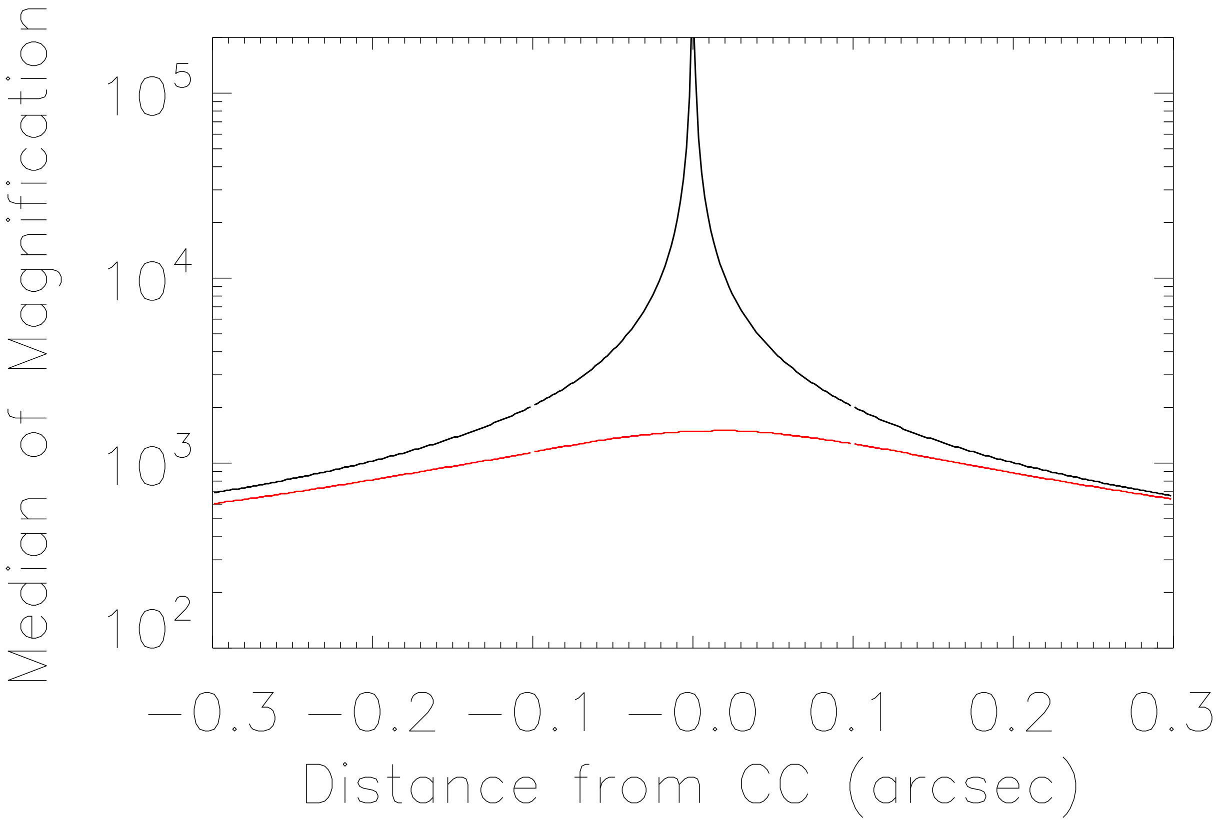
Garcia-Bellido, Clesse & Fleury argue priors on cosmological parameters are overly restrictive and physical size of supernovae have been underestimated.

Icarus

When a distant star crosses a galaxy cluster caustic get huge magnification which can be increased further by microlensing by compact objects (stars, black holes,..) in cluster. Miralda-Escude.

However if large fraction of DM is in compact objects magnification is reduced.

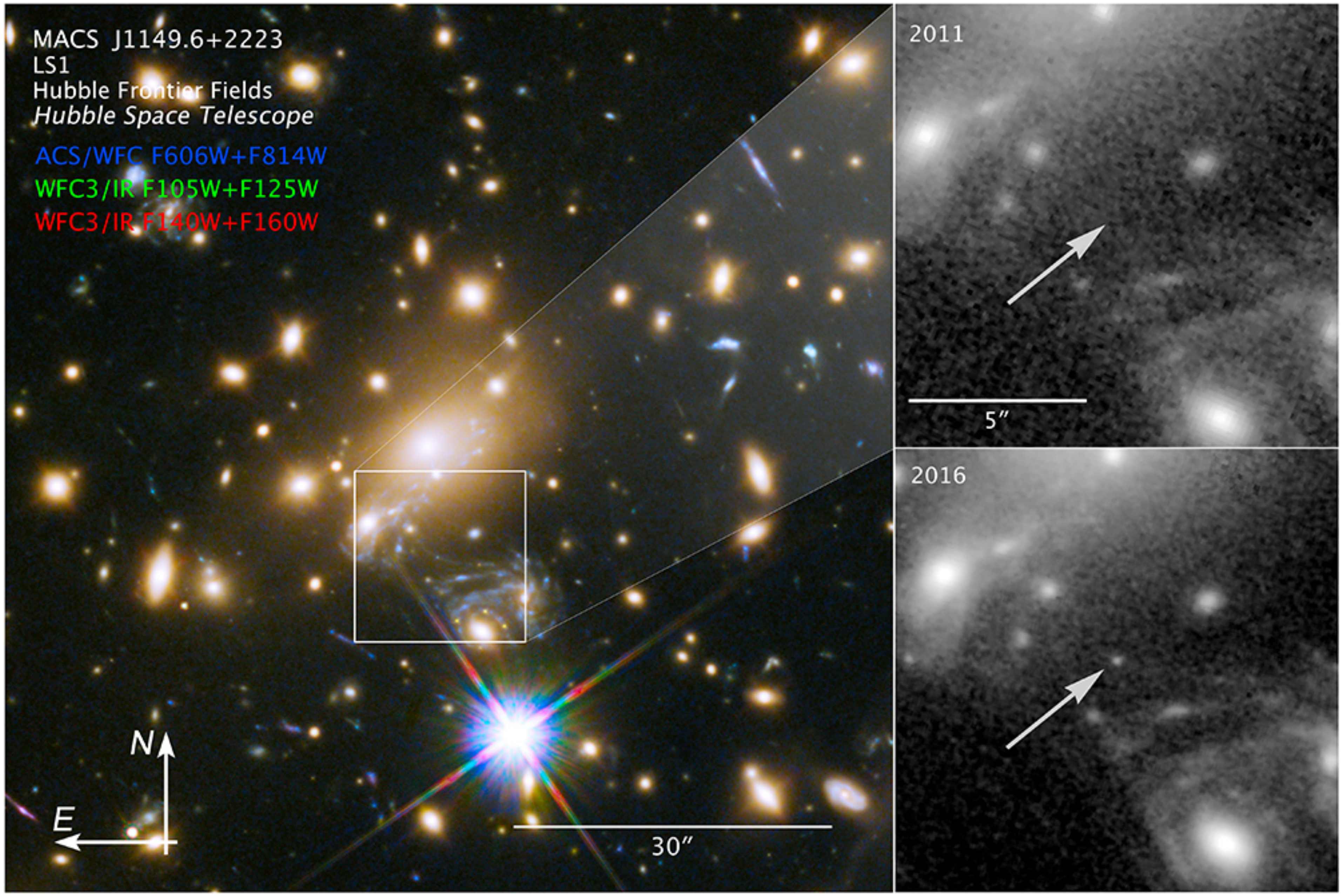
magnification



Kelly et al.

smooth DM, with micro lenses

Icarus is first (serendipitously) observed event involving a star at red-shift 1.5. Kelly et al.



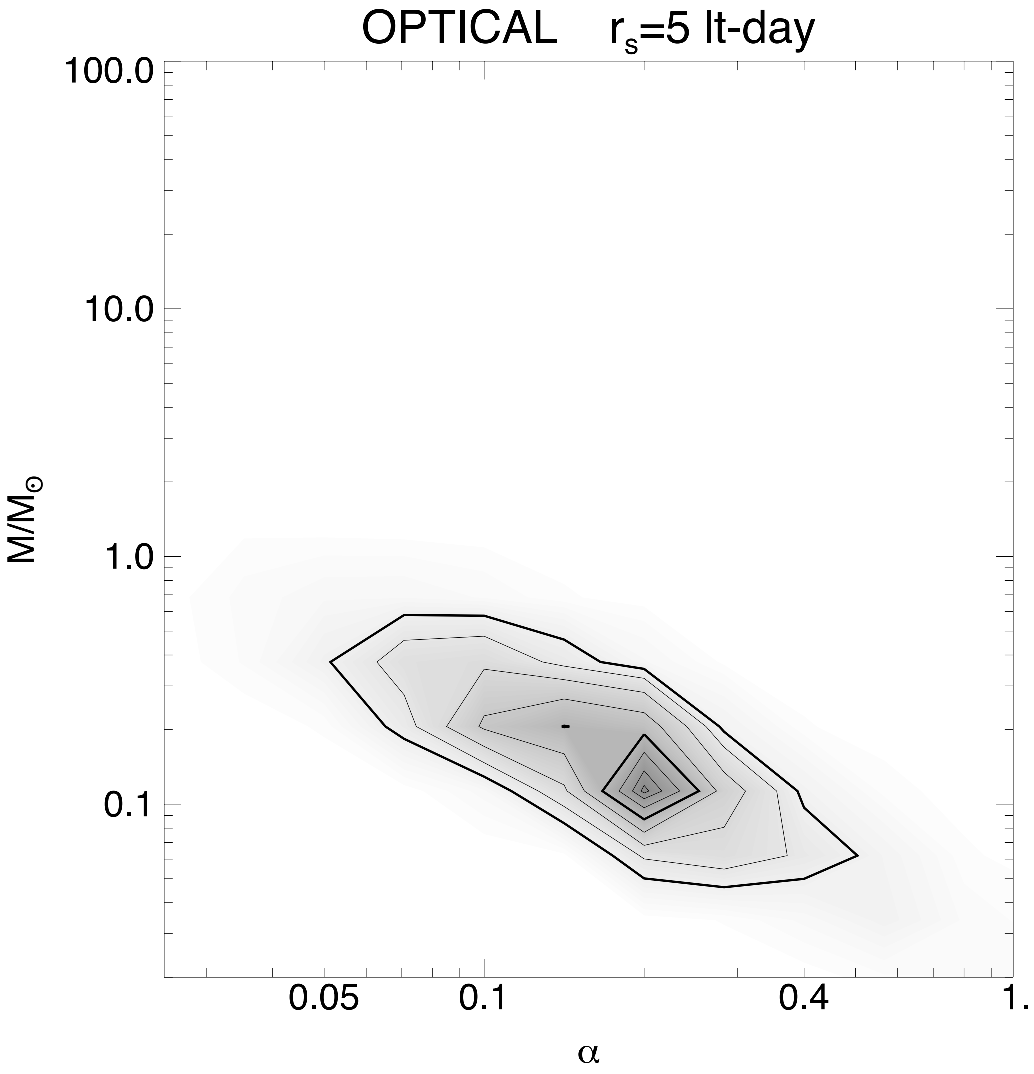
Kelly et al.

Constraint from Icarus: $f < 0.08$ (but factor of 2 uncertainty in transverse velocity leads to similar uncertainty on f). Oguri et al.

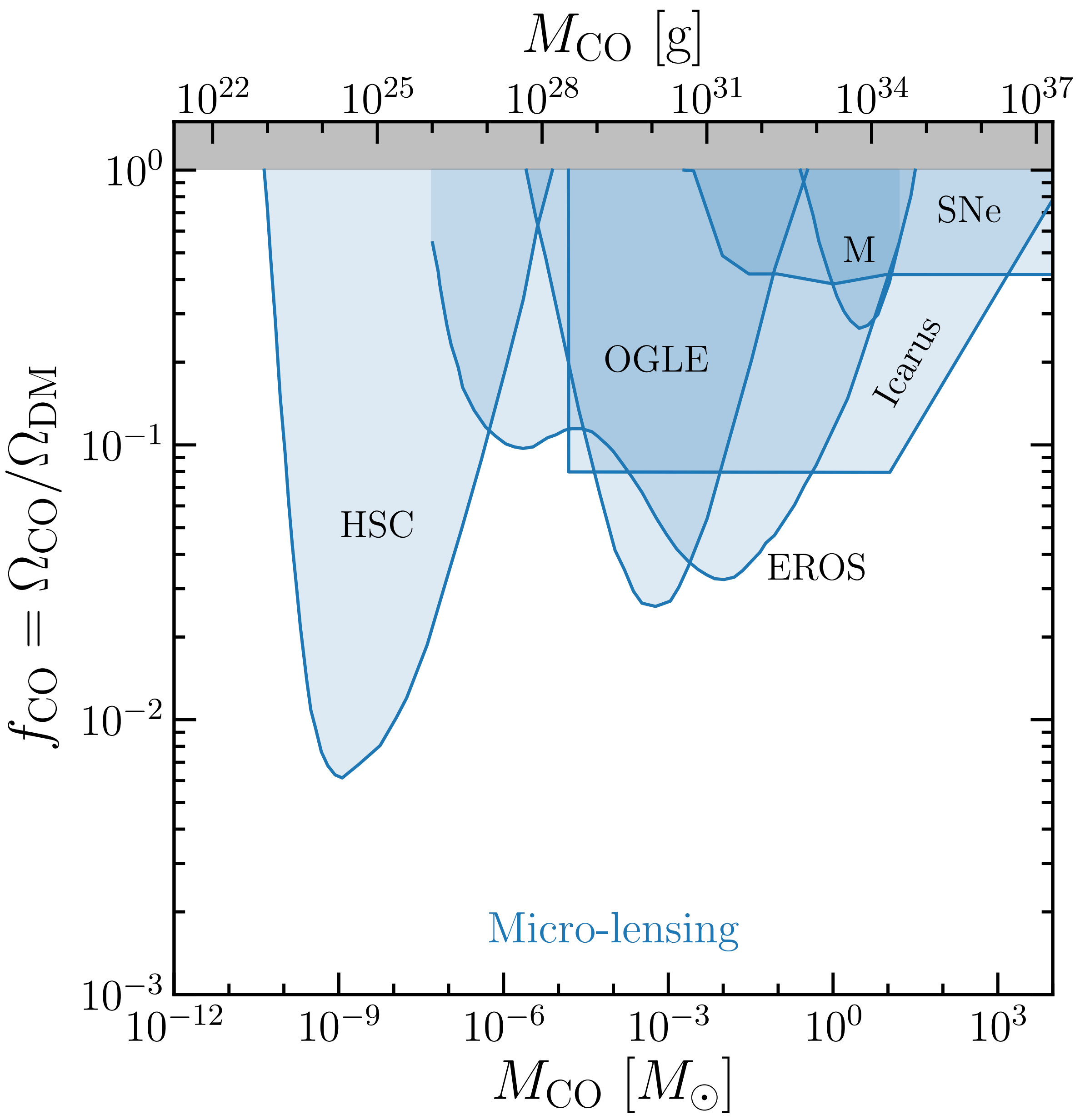
quasar microlensing

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

α= 0.2 ± 0.05 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 (fraction of mass in dark compact objects) published.

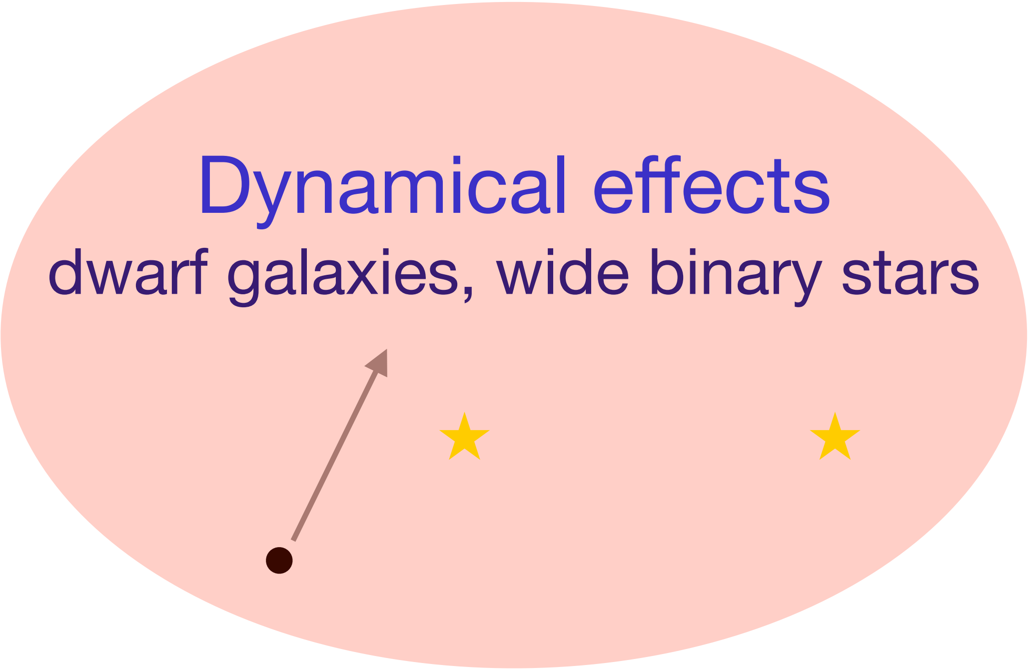


constraints on planetary and stellar mass compact objects from microlensing



Microlensing

stars, supernovae, quasars



Dynamical effects

dwarf galaxies, wide binary stars

Constraints

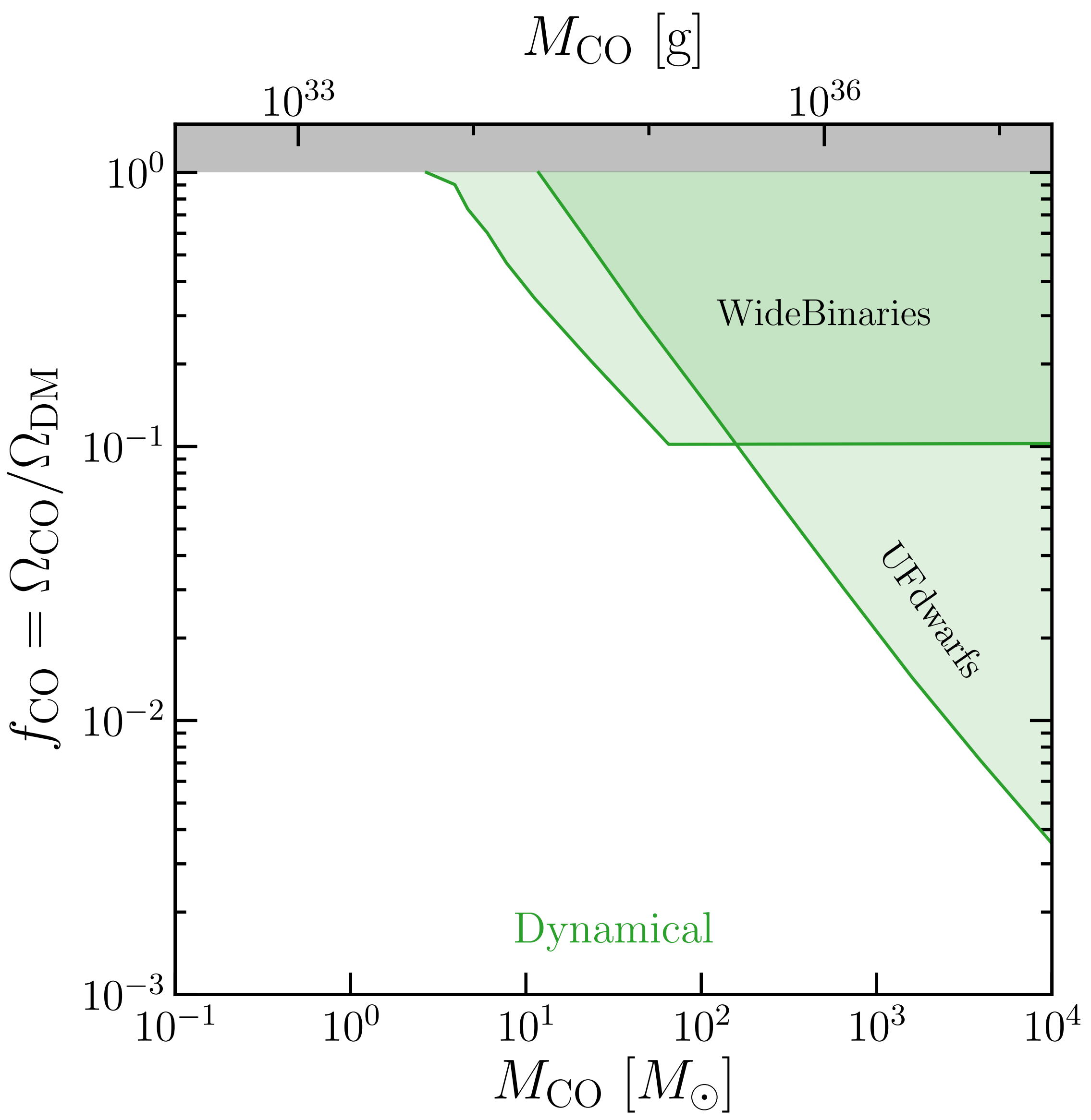
dynamical constraints on multi-Solar mass compact objects

dwarf galaxies: stars are dynamically heated and size of stellar component increased

Brandt; Koushiappas & Loeb; Zhu et al.; Stegmann et al.

wide binaries: dynamically heated, separations increased, and widest binaries disrupted.

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



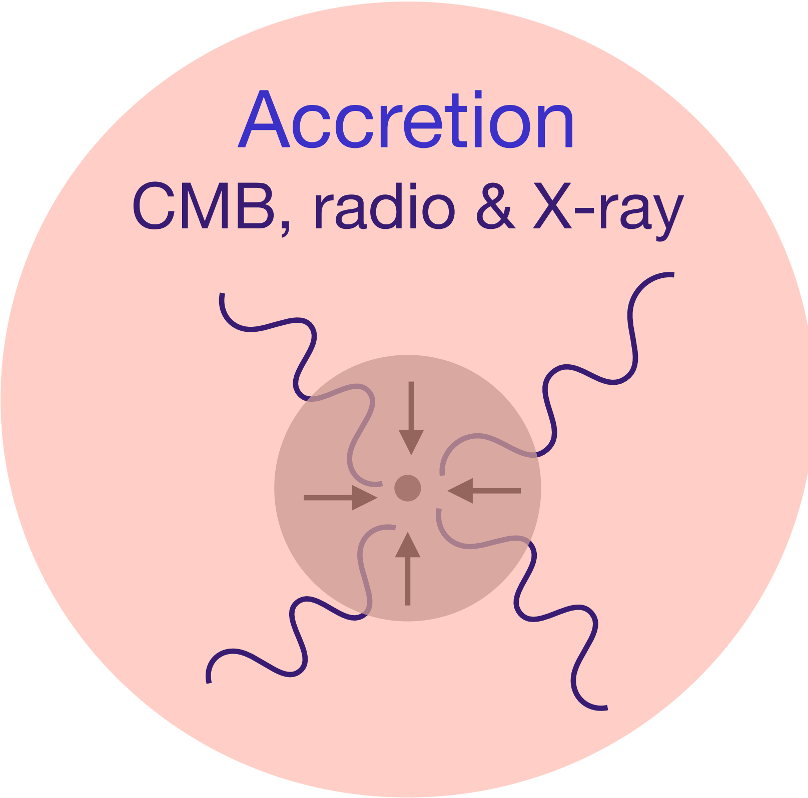
Microlensing

stars, supernovae, quasars

Dynamical effects

dwarf galaxies, wide binary stars

Constraints



Accretion

CMB, radio & X-ray

accretion constraints on multi-Solar mass PBHs

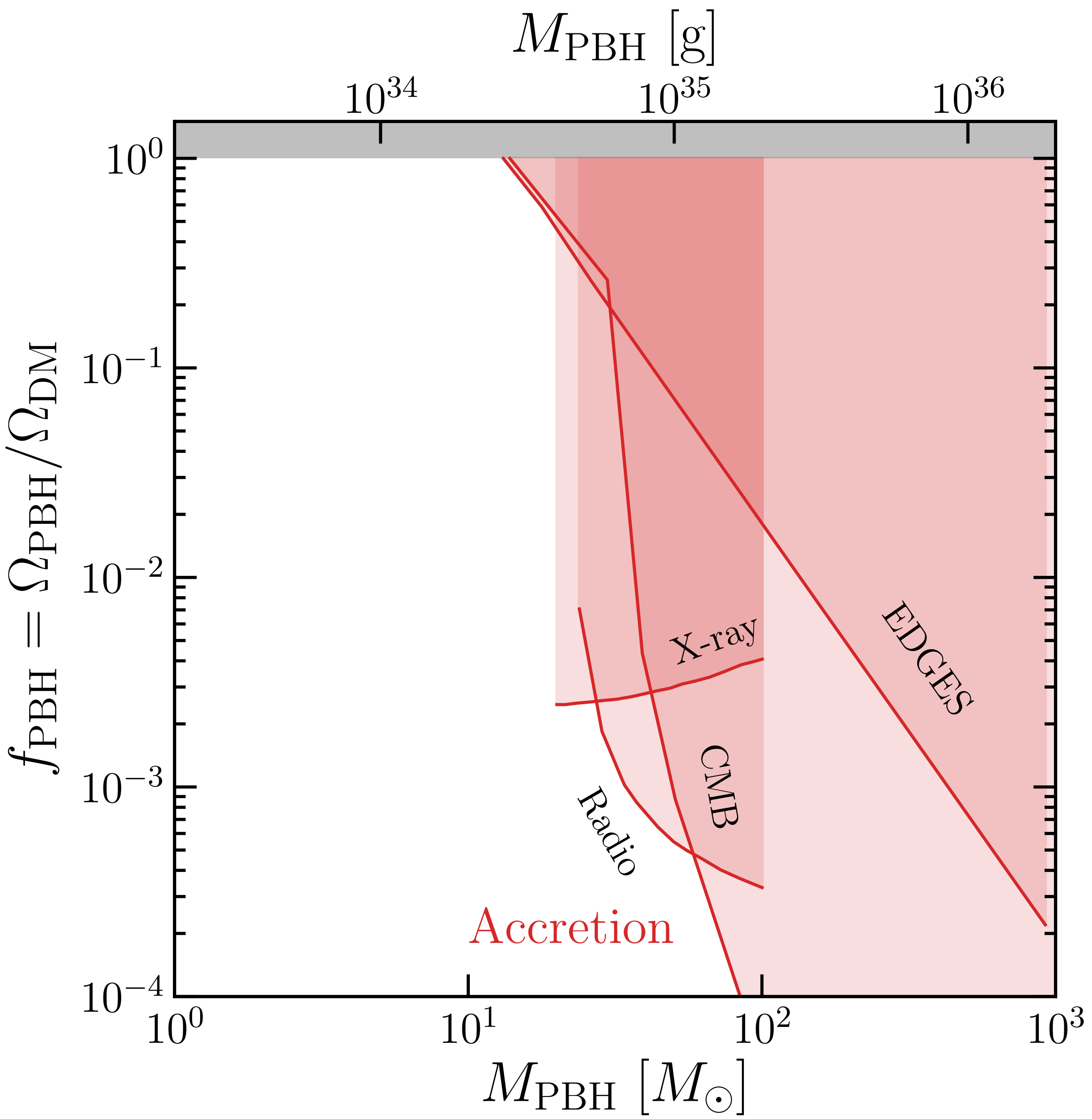
Resulting emission of radiation can distort the CMB anisotropies.

Significant uncertainties in constraint due to modelling of accretion.

Ricotti et al; Ali-Haïmoud & Kamionkowski; … Serpico et al.…

X-ray and radio emission in MW today.

Gaggero et al; Inoue & Kusenko; Manshanden et al.



Constraints

Microlensing
stars, supernovae, quasars

Dynamical effects
dwarf galaxies, wide binary stars

Accretion
CMB, radio & X-ray

Gravitational waves
mergers,
stochastic background

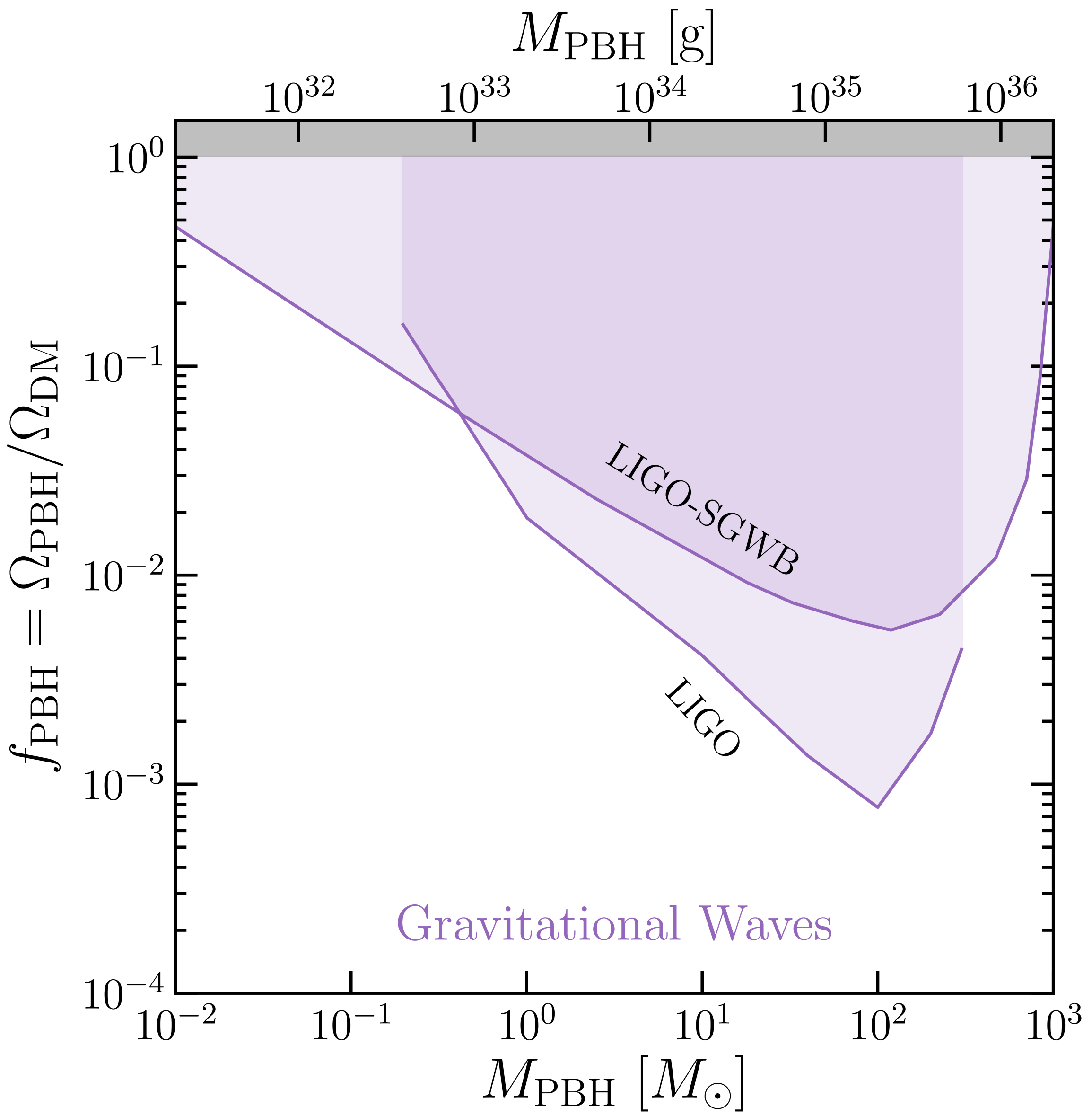
[Initially all constraints assume a delta-function PBH mass function.]

constraints on PBHs from gravitational waves

PBH binaries can form in the early Universe (from chance proximity). Nakamura et al.

If orbits aren't significantly perturbed subsequently, then their mergers are orders of magnitude larger than the merger rate measured by LIGO. Nakamura et al.; Ali-Haïmoud, Kovetz & Kamionkowski; Kavanagh, Gaggero & Bertone

Also comparable constraints from stochastic GW from mergers. Wang et al.



Constraints

Microlensing

stars, supernovae, quasars

Dynamical effects

dwarf galaxies, wide binary stars

Accretion

CMB, radio & X-ray

Effects on stars

white dwarfs, neutron stars

Gravitational waves

mergers,
stochastic background

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

constraints on asteroid mass PBHs from interactions with stars

Stars can capture asteroid mass PBHs through dynamical friction, accretion onto PBH can then destroy the star. Capela, Pshirkov & Tinyakov; Pani & Loeb; **Montero-Camacho et al.;** Genolini, Serpico & Tinyakov

Transit of asteroid mass PBH through white dwarf heats it, due to dynamical friction, causing it to explode. Graham, Rajendran & Varela;

Montero-Camacho et al. **No current constraints**, but potential future constraints from

i) survival of neutron stars in globular clusters **if** they have DM halos (need high DM density, low velocity-dispersion environment)

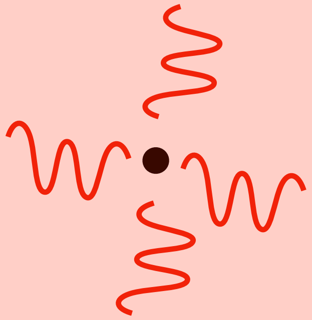
ii) signatures of star being destroyed

Constraints

Microlensing
stars, supernovae, quasars

Dynamical effects
dwarf galaxies, wide binary stars

Evaporation
gamma-rays, positrons,
CMB damping…



Accretion
CMB, radio & X-ray

Effects on stars
white dwarf, neutron stars

Gravitational waves
mergers,
stochastic background

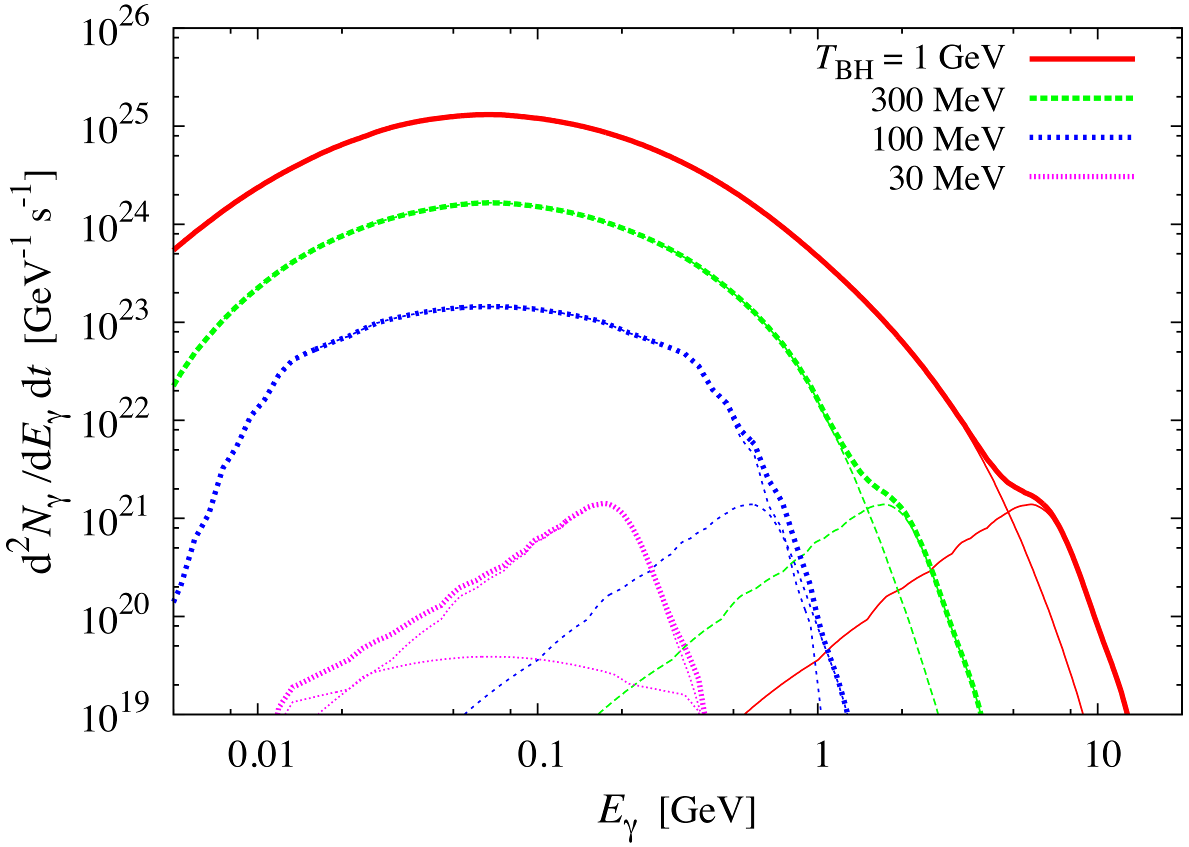
[Initially all constraints assume a delta-function PBH mass function.]

constraints on light PBHs from evaporation products

BHs radiate thermally with temperature Hawking

$$T_{\rm BH} = \frac{\hbar c^3}{8\pi G M_{\rm BH} k_{\rm B}} \sim 10^{-7} \left(\frac{M_\odot}{M_{\rm BH}}\right) {\rm K}$$

Emission rate of photons



10^{13}g

10^{14}g

right peak primary emission (direct Hawking emission)
left peak secondary (from decay of particles initially emitted)

Carr, Kohri, Sendouda & Yokoyama

Page; MacGibbon & Carr

mass loss rate:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = 5.3 \times 10^{25} f(M) \left(\frac{M}{1\,\mathrm{g}}\right)^{-2} \mathrm{g\,s^{-1}}$$

f(M): parameterises number of particle species with $m_i < T_{BH}$, normalised to 1 for PBHs with M ≫10^{17} g which only emit massless particles.

lifetime:

$$\tau_{\mathrm{evap}} = 6.2 \times 10^{-27} f(M)^{-1} \left(\frac{M}{1\,\mathrm{g}}\right)^{3} \mathrm{s}$$

PBH lifetime equal to age of Universe for

$$M_{\mathrm{PBH}} = M_{\star} \approx 5 \times 10^{14}\,\mathrm{g}$$

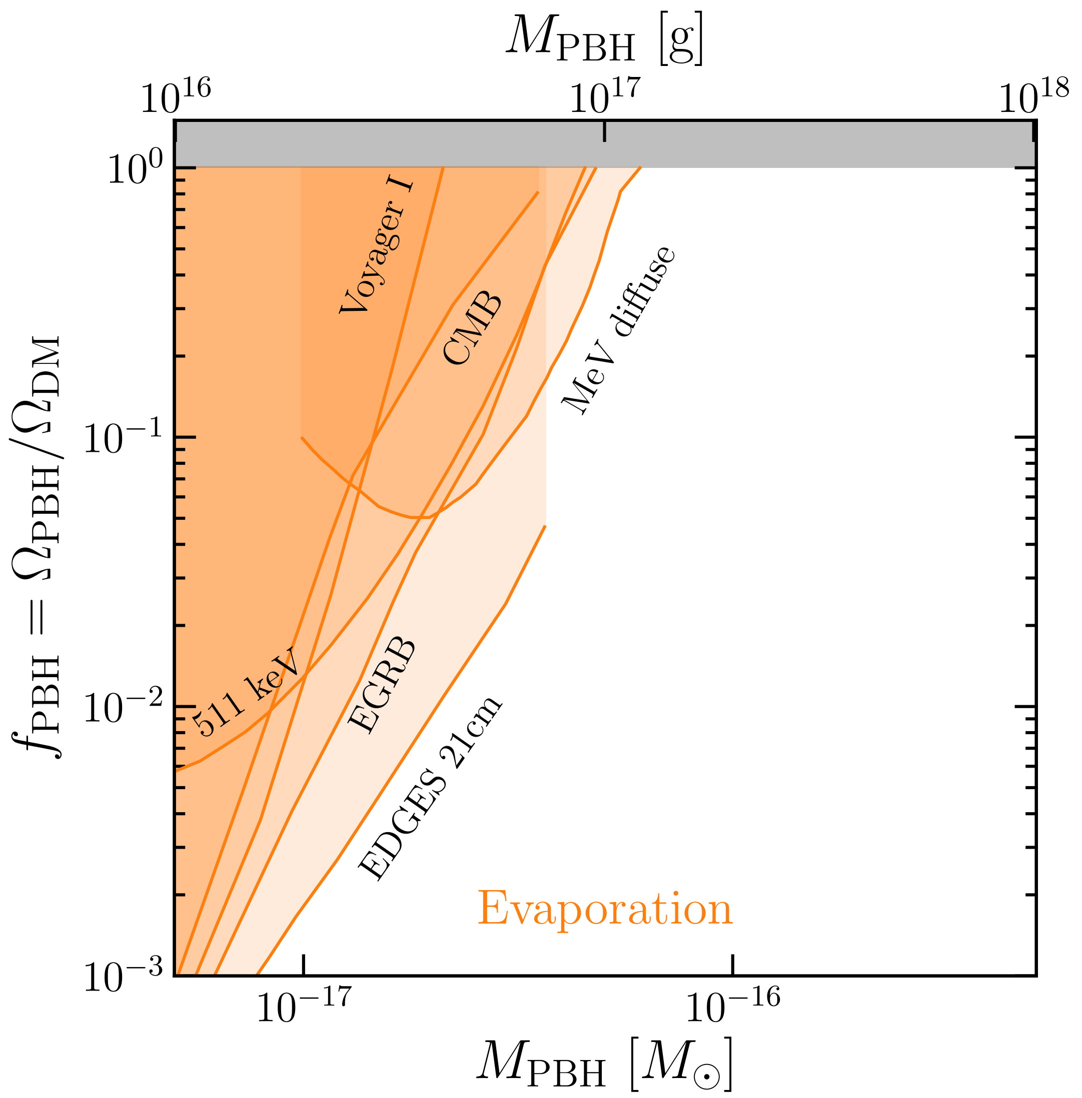
Extragalactic gamma-rays background (EGRET/Fermi) Carr, Kohri, Sendouda & Yokoyama

MeV galactic diffuse flux (INTEGRAL) Laha, Munoz & Slatyer

damping of CMB anisotropies during recombination (Planck) Poulin et al.; Clark et al.

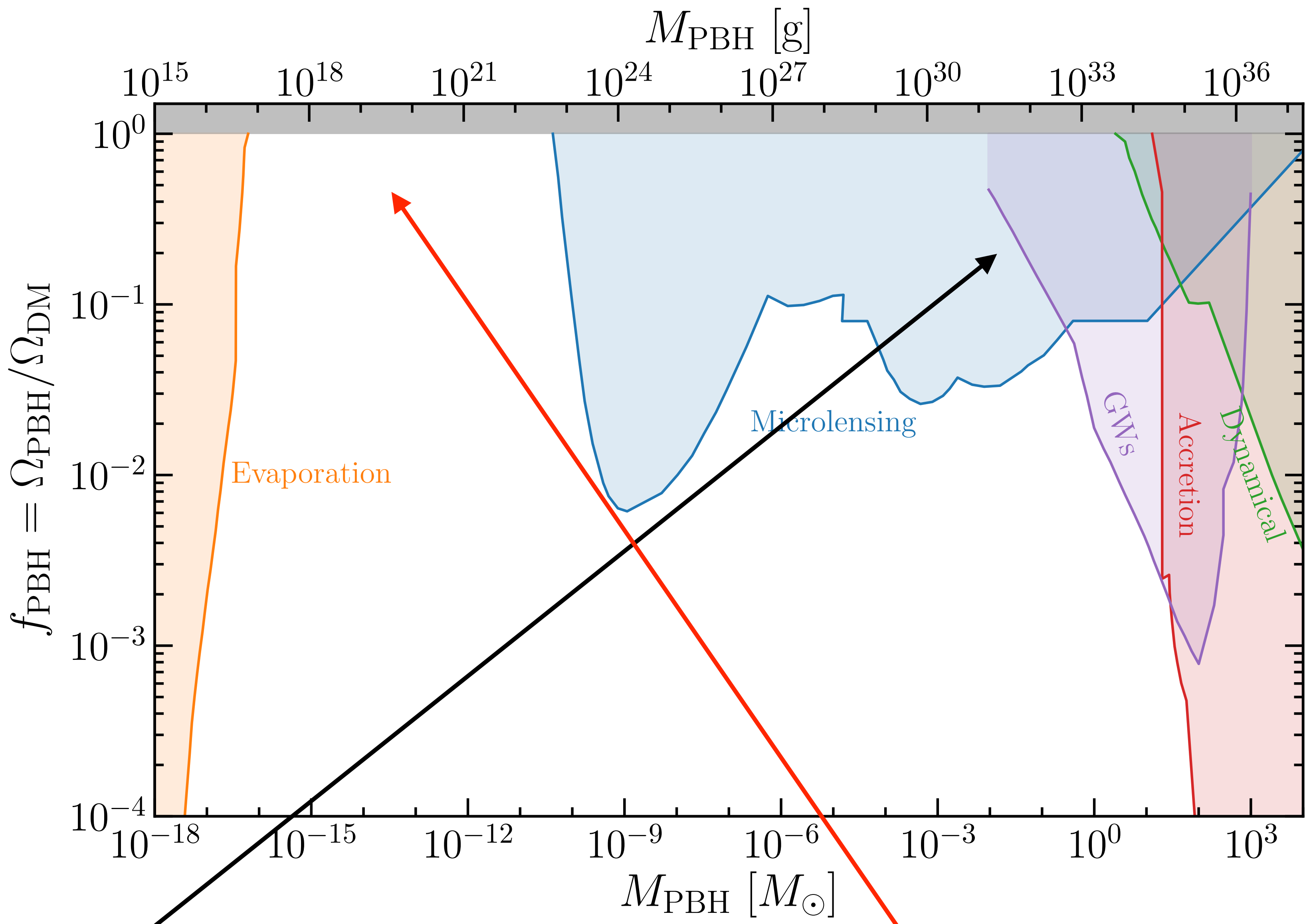
$e^{\pm}$ flux (Voyager 1) Boudaud & Cirelli

511 keV line from $e^{\pm}$ annihilation (INTEGRAL) DeRocco & Graham; Laha



In many cases tighter constraints could be obtained by subtracting off contributions from known astrophysical sources. c.f. Barrau et al.

Compilation of tightest constraints



evaporation

lensing

GWs

accretion

dynamical

multi-Solar mass Primordial Black Holes making up all of the DM appears to be excluded (caveat: clustering).

However there is a hard to probe, open window for very light (asteroid mass) PBHs.

Indirect (model-dependent) constraints

Large scalar perturbations act as 2nd order source of gravitational waves (‘Scalar induced gravitational waves’). Ananda, Clarkson & Wands

constraint on energy density of stochastic gravitational waves

↓

constraint on amplitude of scalar/density perturbations

↓

constraint on abundance of PBHs formed via collapse of large density perturbations

Saito & Yokoyama; Byrnes et al.; Inomata et al.

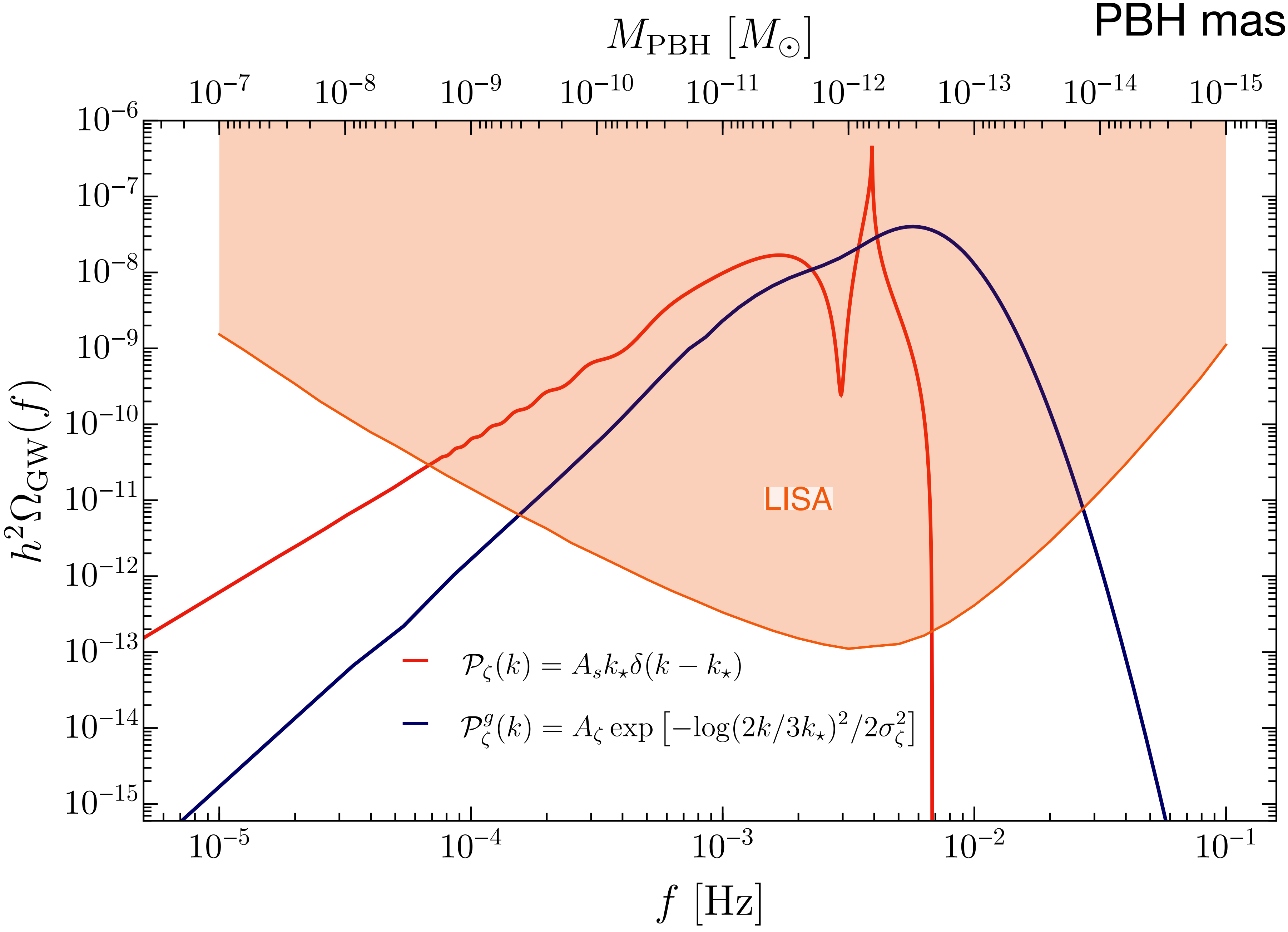
Massive PBHs similarly constrained by CMB spectral distortions.

Carr & Lidsey; Kohri, Nakama & Suyama

LISA will be able to probe (open) asteroid mass window (for PBHs which form from the collapse of large inflationary density perturbations). Bartolo et al.

PBH mass

GW energy density

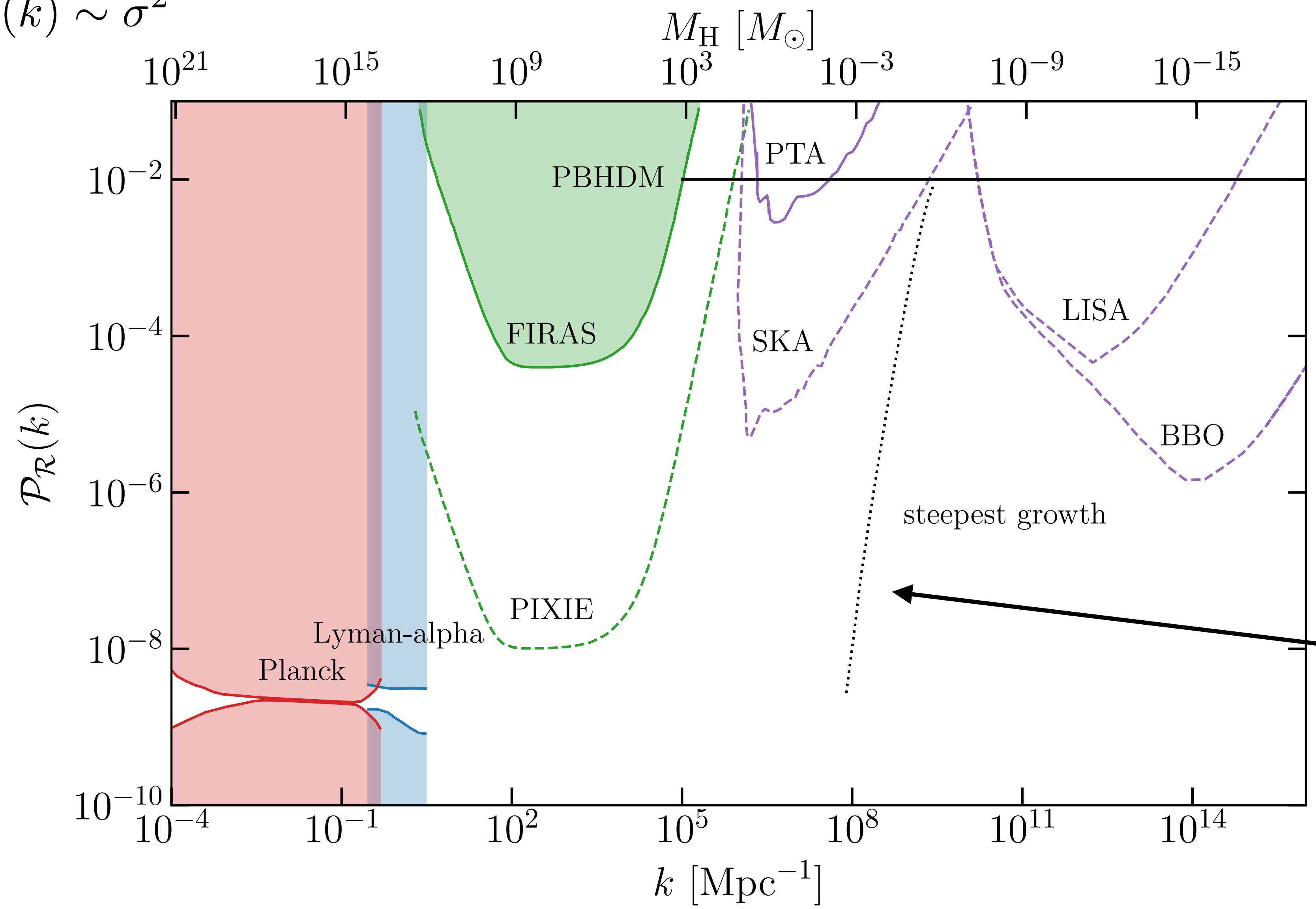


Bartolo et al.

delta-function and gaussian primordial curvature power spectrum which give $f_{\rm PBH} = 1$.

Constraints on power spectrum of primordial curvature perturbations as a function of coming wavenumber (k) or equivalently horizon mass (M_H)

$\mathcal{P}_{\mathcal{R}}(k) \sim \sigma^2$



amplitude required to form an interesting (f_{PBH} ~1) abundance of PBHs

steepest growth possible in single field inflation models

Byrnes, Cole & Patil; Carrilho, Malik, Mulryne

c.f. Byrnes, Cole & Patil; Chluba et al.

Constraints from CMB temperature anisotropies, Lyman-alpha forest, CMB spectral distortions and gravitational waves (______ current - - - - - future/proposed)

FIRAS= COBE Far Infrared Absolute Spectrophotometer, *past*
PIXIE=Primordial Inflation Explorer, *proposed*
PTA=pulsar timing arrays (e.g. NANOgrav), *ongoing*

SKA=Square Kilometre Array, *future*
LISA=Laser Interferometer Space, *future*
BBO=Big Bang Observer, *proposed*

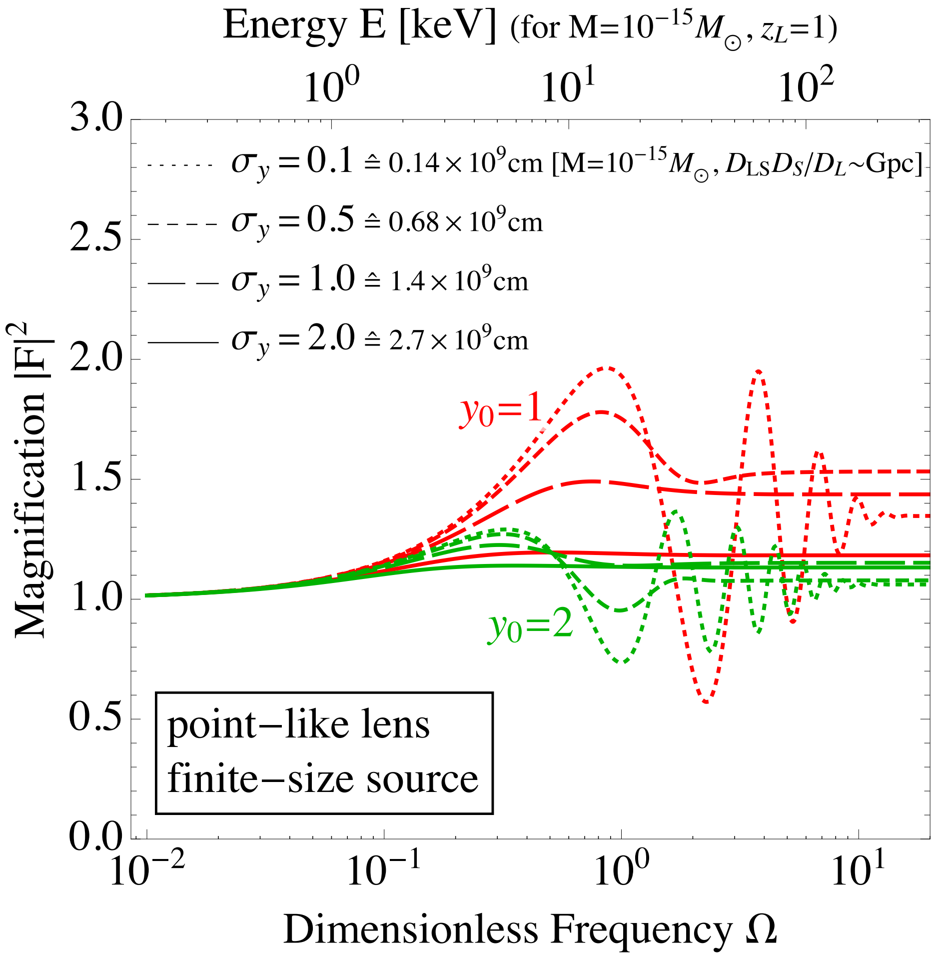
how to constrain asteroid mass PBHs??

Femtolensing of GRBs

Different path lengths lead to phase differences, and hence interference fringes in energy spectrum of lensed GRBs. Gould

Barnacka, Glickenstein & Moderski constraints from Fermi Gamma Ray Burst monitor.

BUT Katz, Kopp, Sibiryakov, Xue most GRBs not point-like, and (less significantly) geometric optics approximation also breaks down:



increasing angular size of source

y0 = position of source centre in terms of β/θ_E

Constraints could be achieved in a future with a sample of GRBs with well-measured red-shift and spectra, and small size (which is expected to correspond to sub-milli-second variability).

dynamics of cold Kuiper belt

Siraj & Loeb

v1: claimed interactions of asteroid mass PBH with change the properties of the 'kernel' of cold classical Kuiper belt (collection of objects on orbits with similar small eccentricity and semi major axes):

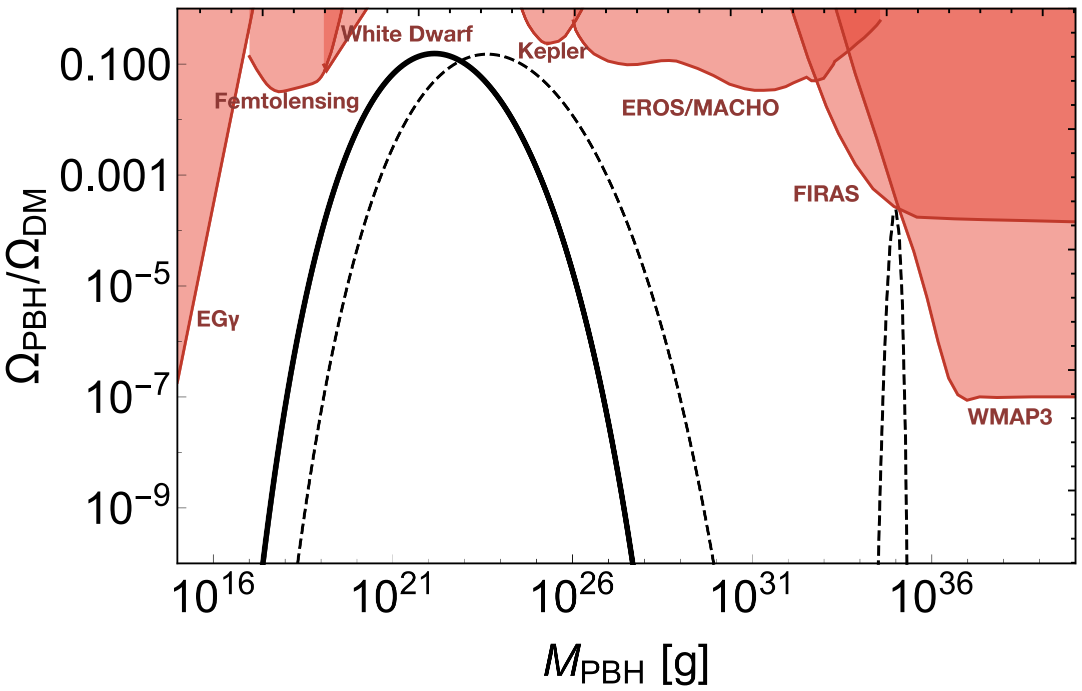
$$f_{\rm PBH} \lesssim 0.4 \qquad \text{for} \qquad 10^{15}\,{\rm g} \lesssim M_{\rm PBH} \lesssim 10^{33}\,{\rm g}$$

v2: comment 'KBO limit had to be modified to the diffusion regime which weakened significantly the constraints'.

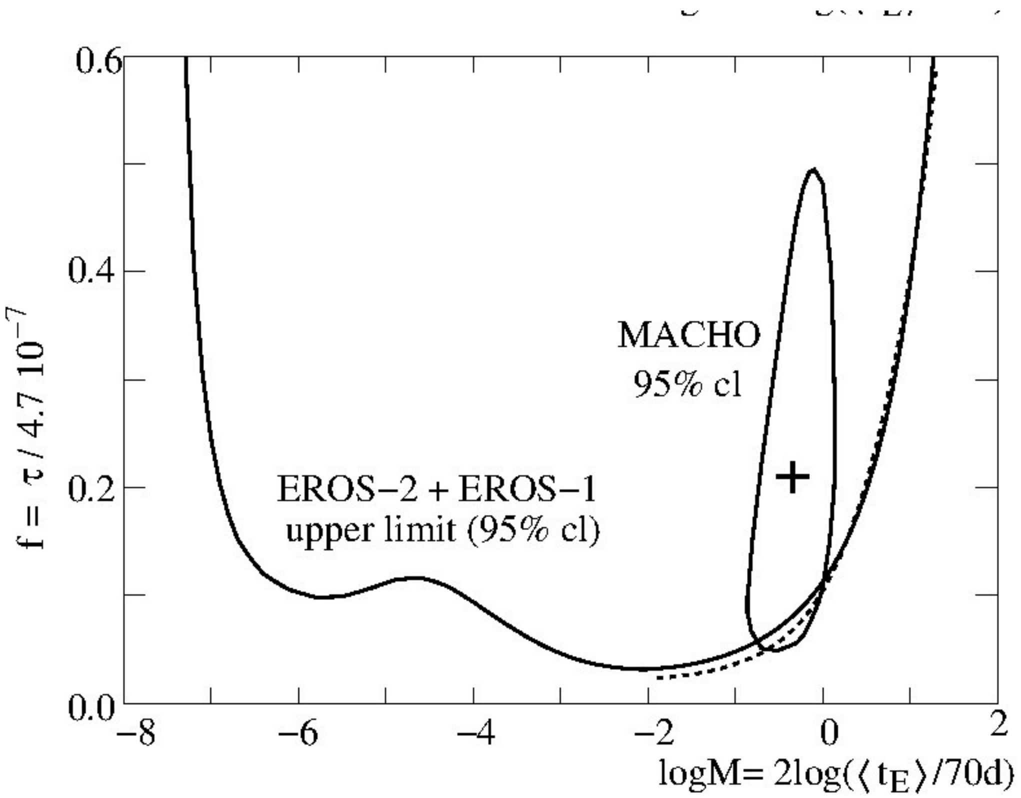
Applying delta-function constraints to extended mass functions

Is slightly subtle….

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



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**.



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

Carr, Raidal, Tenkanen, Vaskonen & Veermae, see also Bellomo, Bernal, Raccanelli & Verde:

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).

If an observational constraint is $A \leq A_{\rm exp}$ and if $f_{\rm max}(M)$ is the maximum allowed PBH fraction, as a function of mass, for a delta-function MF [$\psi(M) = f(M_c)\, \delta(M-M_c)$]:

$$\int \mathrm{d}M \psi(M) K_1(M) < A_{\rm exp} - A_0$$

$$\int \mathrm{d}\tilde{M} f_{\rm max}(\tilde{M}) \delta(\tilde{M} - M) K_1(\tilde{M}) = A_{\rm exp} - A_0 \quad \longrightarrow \quad K_1(M) = \frac{A_{\rm exp} - A_0}{f_{\rm max}(M)}$$

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

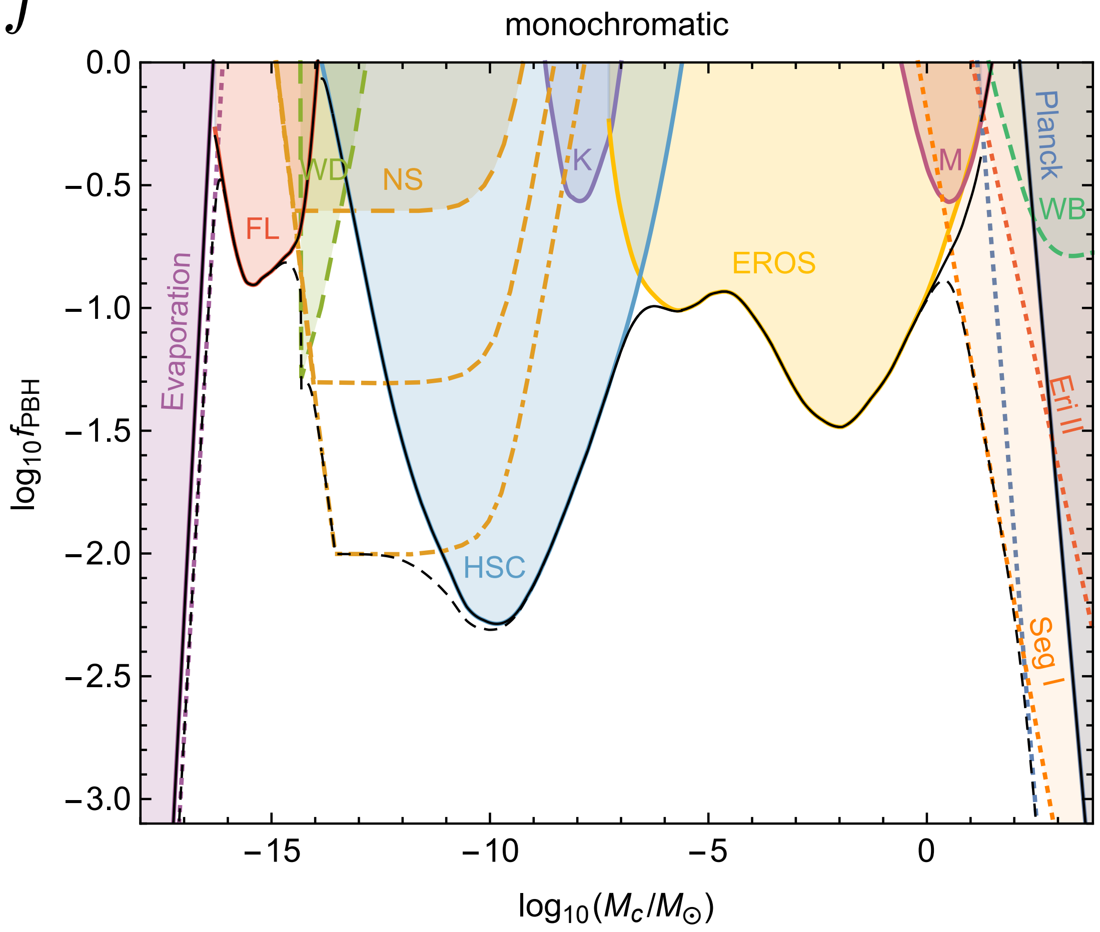
Bellomo et al. Need to take care when mass function extends beyond range of validity of constraint.

For extended mass functions, constraints on f are smeared out, and gaps between constraints are 'filled in':

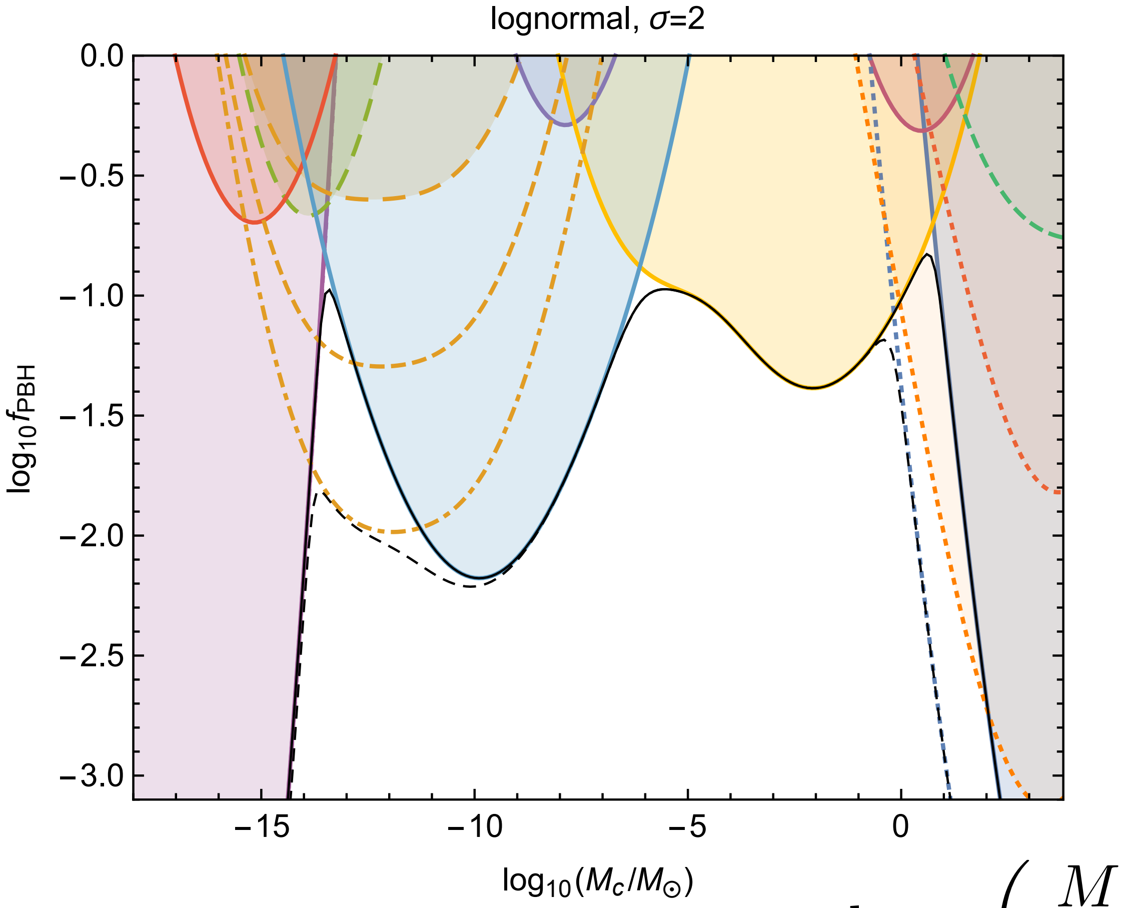
Green; Carr et al., see also Bellomo et al.

monochromatic

$\log_{10} f$



log-normal
(fixed width)



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

Carr et al.

n.b. some of these constraints have been revisited and either substantially modified (e.g. HSC microlensing) or removed (white dwarfs and femtolensing of GRBs).

Summary

- Numerous constraints on the abundance of PBHs from gravitational lensing, dynamical effects, accretion, gravitational waves, evaporation products.

- Taking constraints at face value, ~Solar and planetary mass PBHs can't make up all of the dark matter.

- Present day clustering of PBHs (in particular binary merger rate) isn't yet well understood (but clustering isn't a 'get out of jail free card').

- For (realistic) extended mass functions, constraints are 'smeared out'.

- Asteroid mass PBHs are hard to probe.

Discussion

What do you think are the most important open issues for PBH dark matter?

Back-up slides