Primordial Black Holes (PBHs) as a dark matter candidate

Anne Green

University of Nottingham

Motivation

Formation

Constraints

Open questions

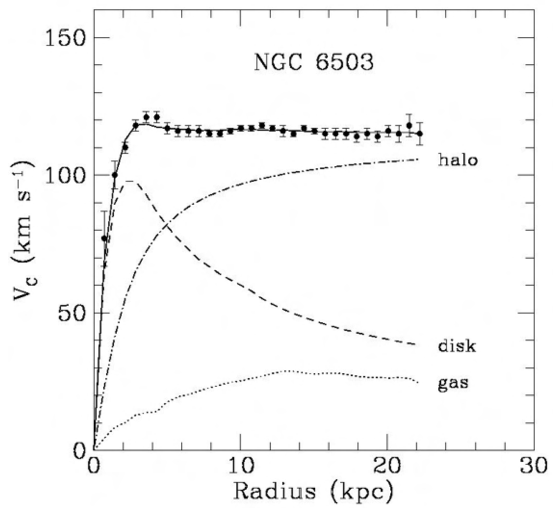
Green & Kavanagh, arXiv:2007.10722, 'PBHs as a dark matter candidate'

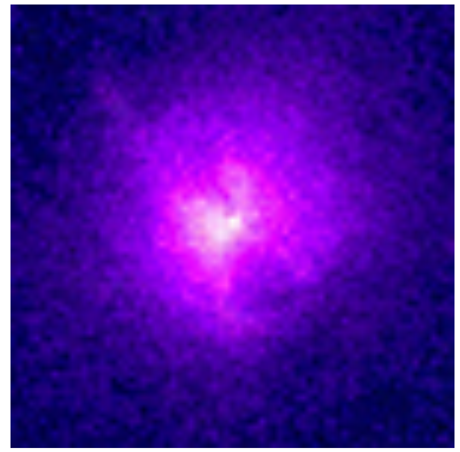
Bradley Kavanagh's PBH abundance constraint plotting code:
https://github.com/bradkav/PBHbounds

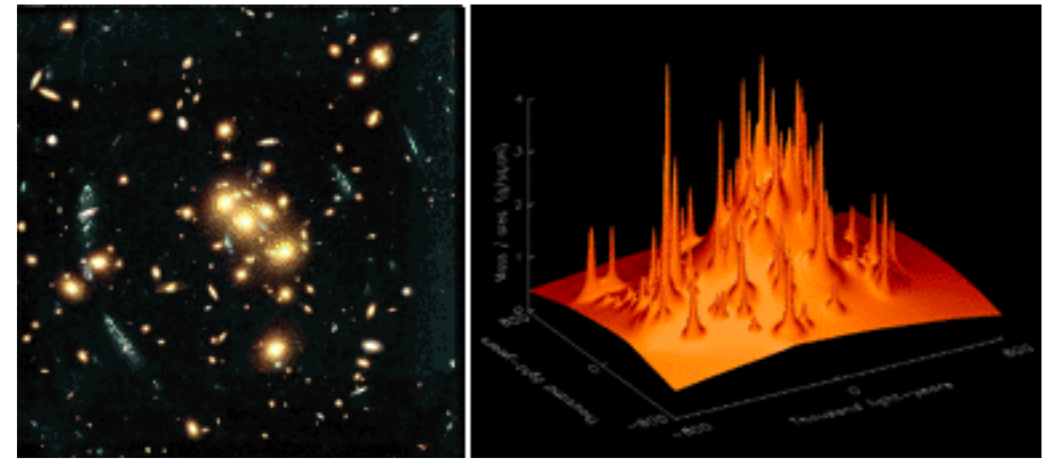
Carr & Kuhnel, arXiv:2006.02838, 'PBHs as dark matter: recent developments'

Bird et al., arXiv:2203.08967, 'Snowmass2001 Cosmic Frontier White Paper: PBH dark matter'

Motivation



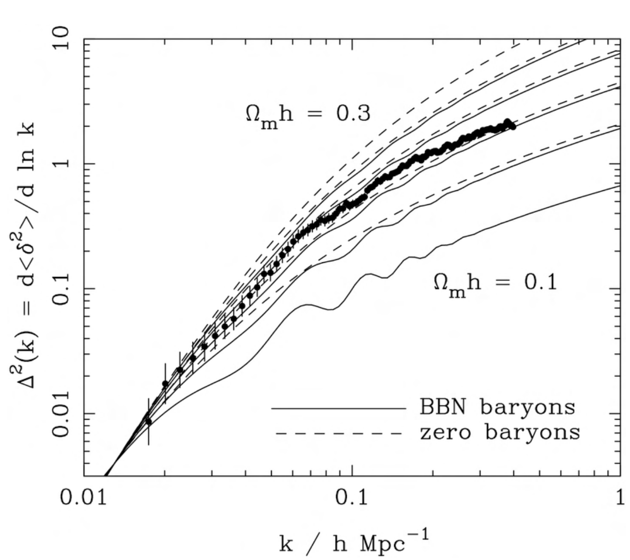


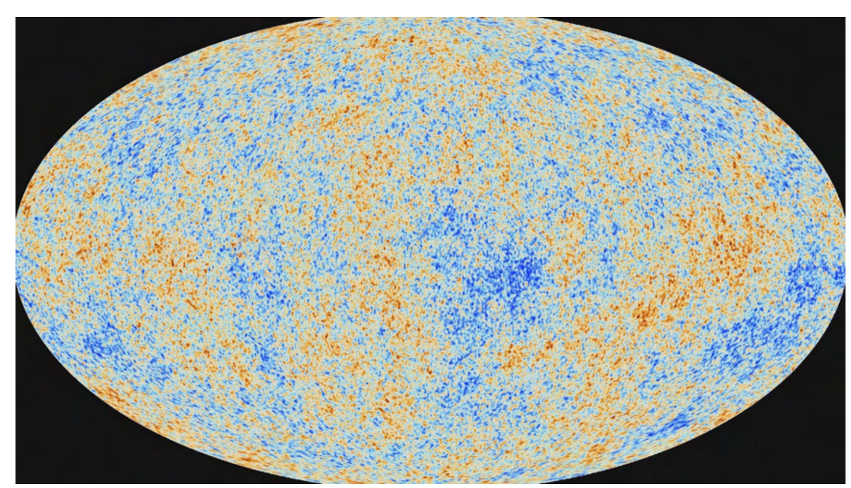


Lots of evidence for **non-baryonic cold dark matter** from diverse astronomical and cosmological observations

[galaxy rotation curves, galaxy clusters (galaxy velocities, X-ray gas, lensing), galaxy red-shift surveys, Cosmic Microwave Background]

assuming Newtonian gravity/GR is correct.





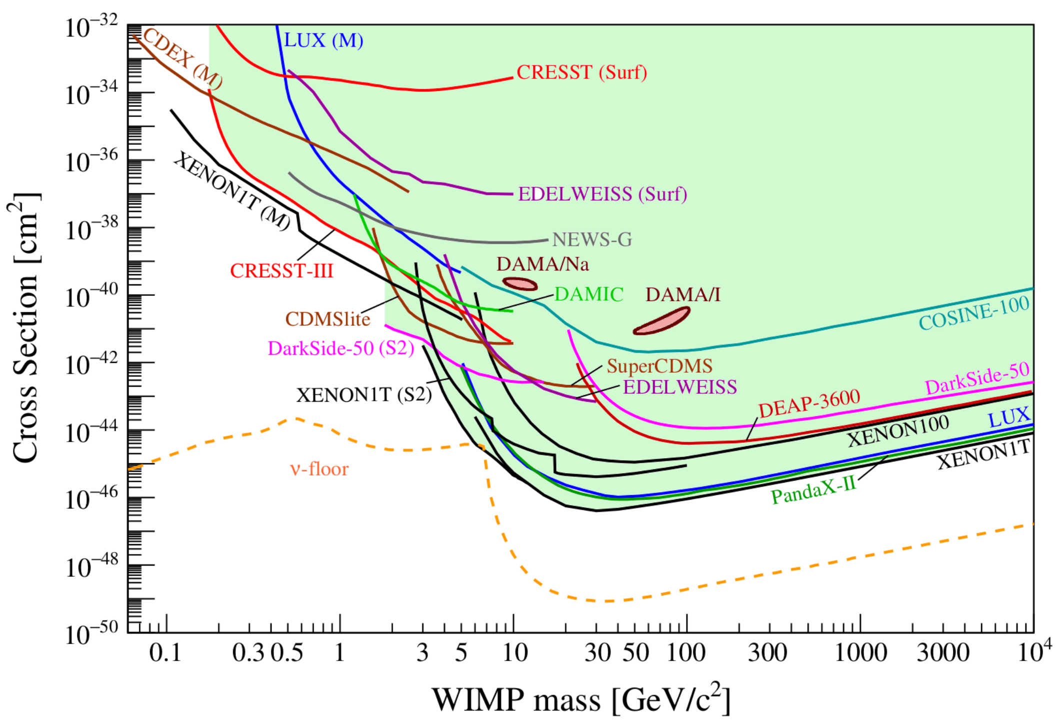
No sign (yet…) of well-motivated particle dark matter candidates in ‘direct detection’ experiments:

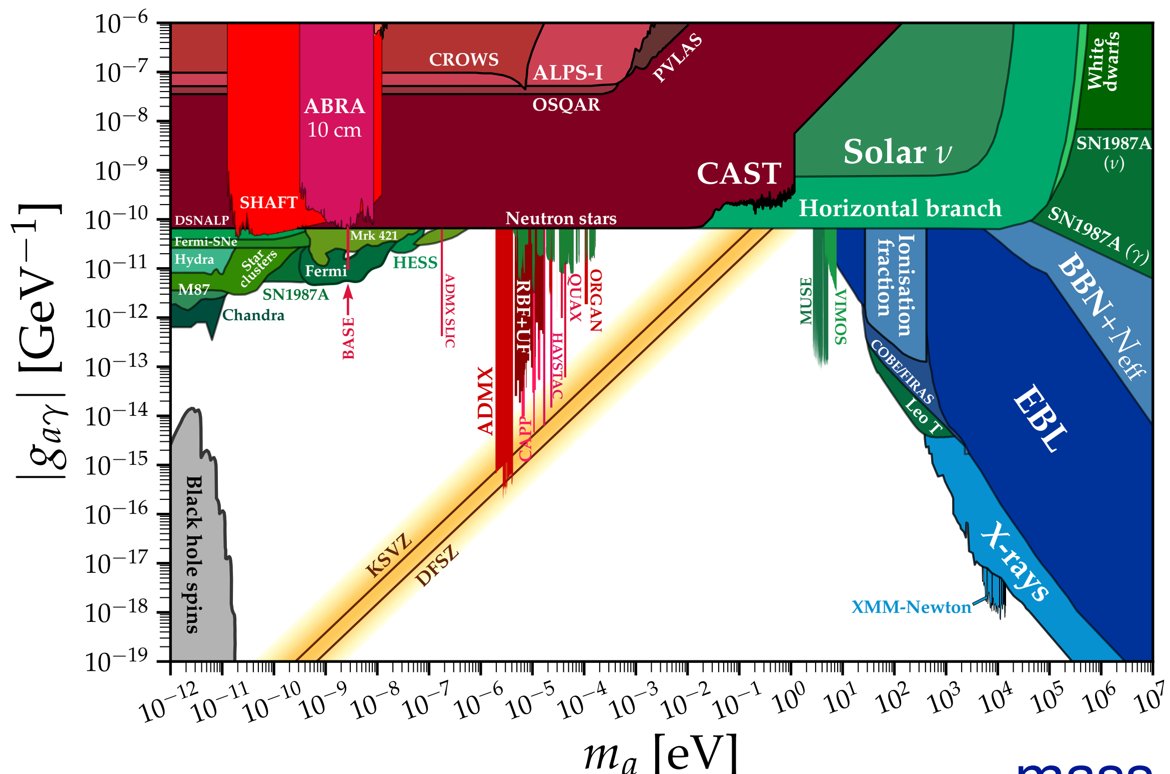
Weakly Interacting Massive Particles

axions/axion like particles

elastic scattering cross section

coupling with photons





mass

mass

APPEC committee report

O’Hare

Primordial Black Holes (PBHs) may form from over densities in the early Universe (before nucleosynthesis) and are therefore non-baryonic. Zel'dovich and Novikov; Hawking

PBHs evaporate (Hawking radiation), lifetime longer than the age of the Universe for $M > 10^{15}$ g. Page

A DM candidate which (unlike WIMPs, axions, sterile neutrinos,…) isn't a new particle, however their formation does usually require Beyond the Standard Model physics, e.g. inflation.

Was realised that PBHs are a cold dark matter (DM) candidate in the 1970s Hawking; Chapline

Wave of interest in ~Solar mass PBHs as DM in late 1990s, generated by excess of LMC microlensing events in MACHO collaboration's 2 year data set.

Nakamura et al. (1997): PBH binaries form in the early Universe and (**if** they survive to the present day) GWs from their coalescence detectable by LIGO.

Was realised that PBHs are a cold dark matter (DM) candidate in the 1970s Hawking; Chapline

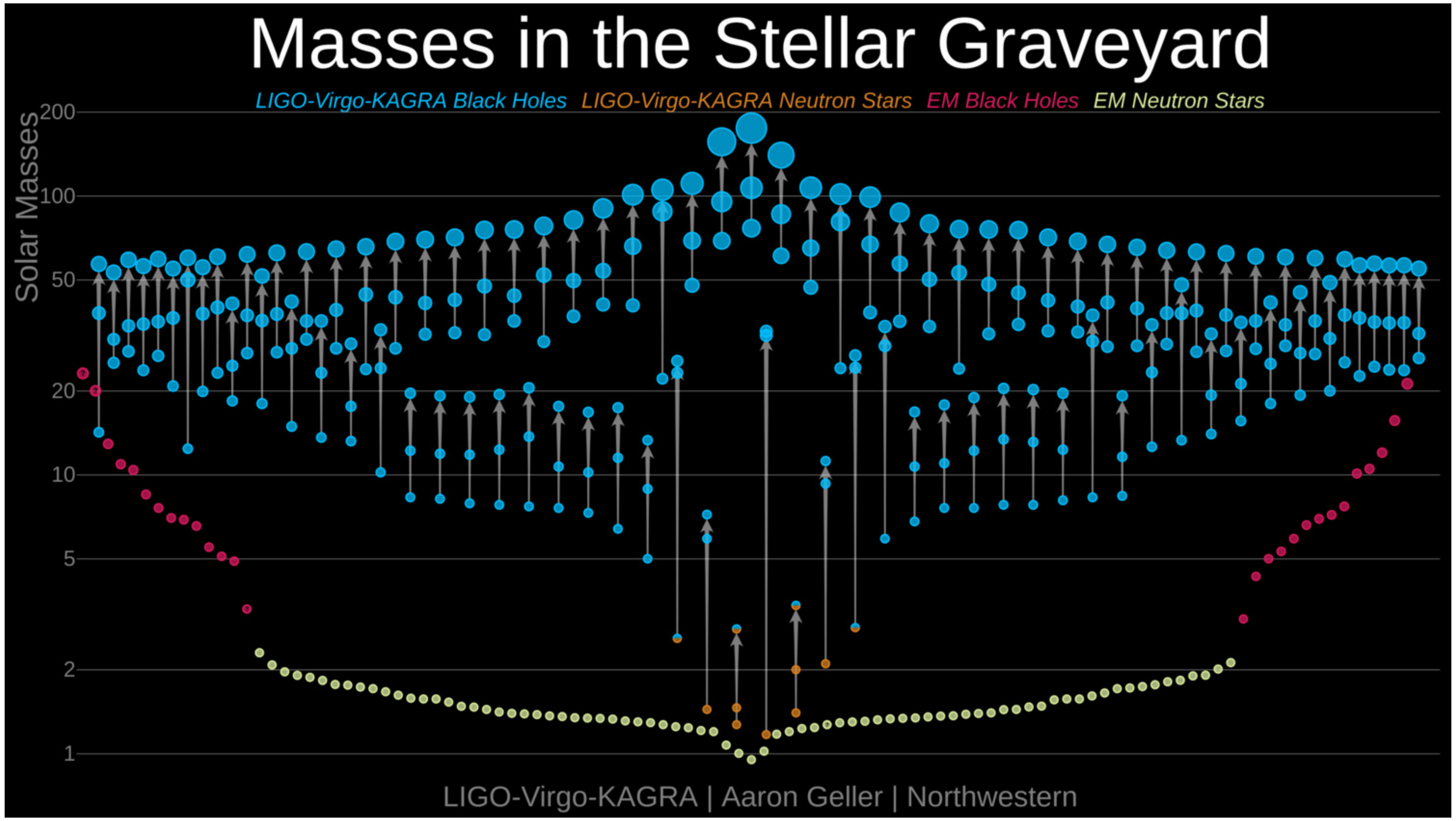
Wave of interest in ~Solar mass PBHs as DM in late 1990s, generated by excess of LMC microlensing events in MACHO collaboration's 2 year data set.

Nakamura et al. (1997): PBH binaries form in the early Universe and (**if** they survive to the present day) GWs from their coalescence detectable by LIGO.

Could (some of) the BHs in the LIGO-Virgo BH binaries be primordial? (and also a significant component of the DM?) Bird et al.; Clesse & Garcia-Bellido; Sasaki et al.

$100 M_\odot$

$10 M_\odot$



black holes discovered by LIGO-Virgo -KAGRA

LIGO-Virgo-KAGRA, Geller

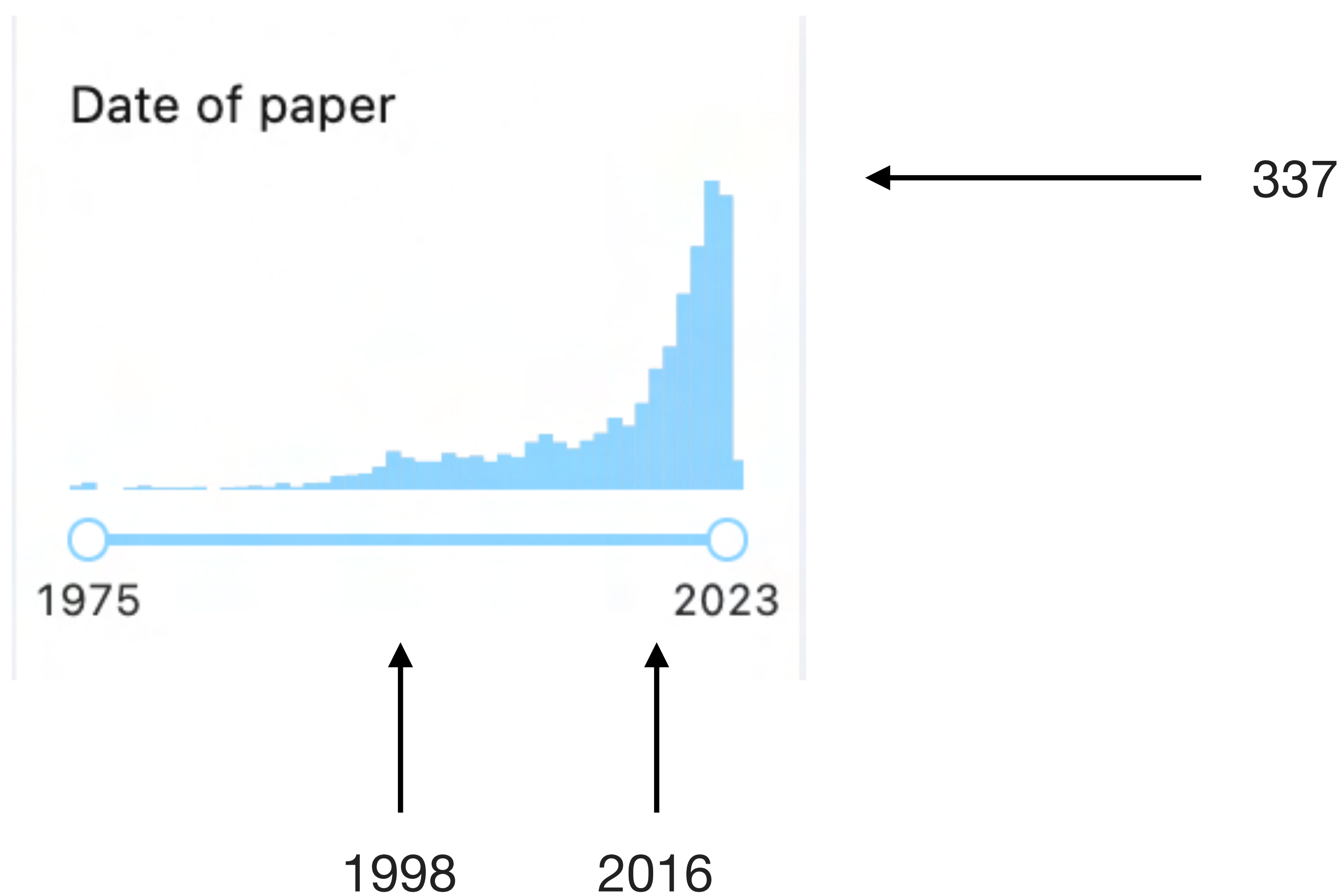
Was realised that PBHs are a cold dark matter (DM) candidate in the 1970s Hawking; Chapline

Wave of interest in ~Solar mass PBHs as DM in late 1990s, generated by excess of LMC microlensing events in MACHO collaboration's 2 year data set.

Nakamura et al. (1997): PBH binaries form in the early Universe and (**if** they survive to the present day) GWs from their coalescence detectable by LIGO.

Could (some of) the BHs in the LIGO-Virgo BH binaries be primordial? (and also a significant component of the DM?) Bird et al.; Clesse & Garcia-Bellido; Sasaki et al.

result of an inSPIRE search for 'primordial black hole'



Formation

Most 'popular' mechanism: collapse of large density perturbations during radiation domination. Zeldovich & Novikov; Hawking; Carr & Hawking

If a region is sufficiently over-dense, gravity overcomes pressure and it collapse to form a BH shortly after 'horizon entry'.

essential analysis: Carr

threshold for PBH formation: $$\delta \geq \delta_{\rm c} \sim w = \frac{p}{\rho} = \frac{1}{3}$$

$$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}$$ density contrast (at horizon crossing)

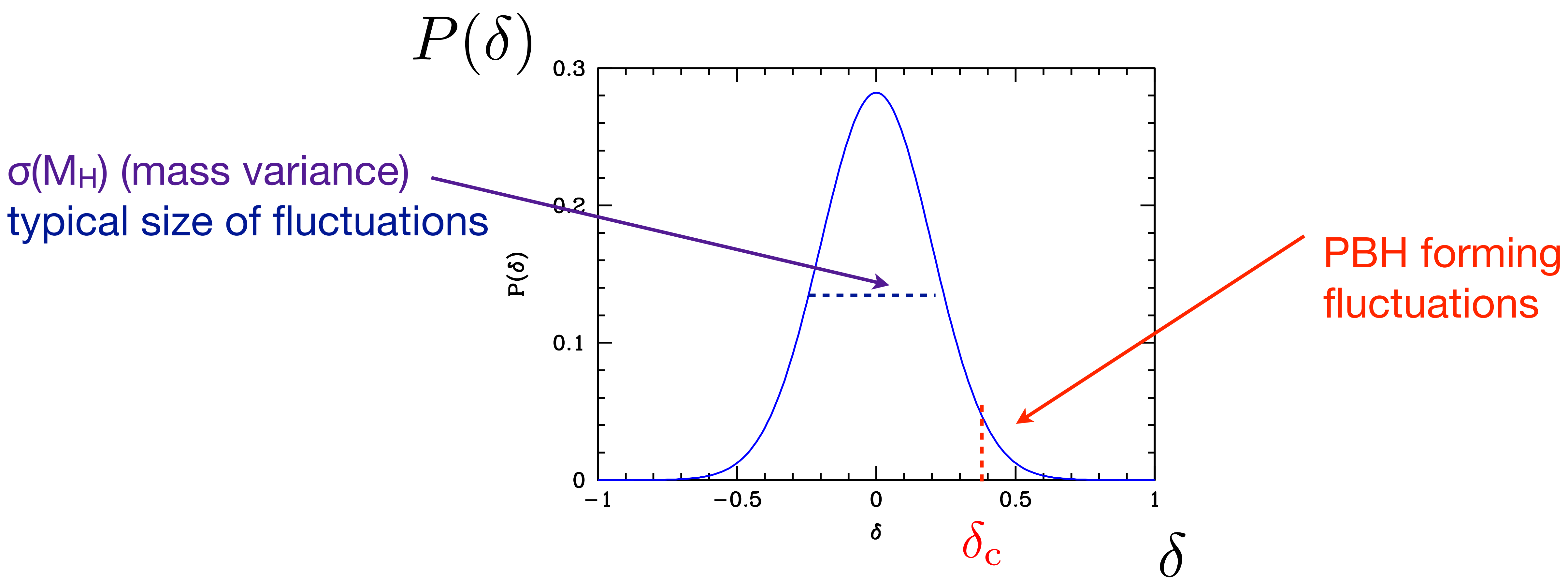
PBH mass roughly equal to horizon mass:

$$M_{\rm PBH} \sim 10^{15} \, {\rm g} \left(\frac{t}{10^{-23} \, {\rm s}} \right) \sim M_{\odot} \left(\frac{t}{10^{-6} \, {\rm s}} \right)$$

Threshold in fact depends on shape of perturbation (which depends on primordial power spectrum). Harada,Yoo & Kohri; Germani & Musco; Musco; Escriva, Germani & Sheth. For overview see Escriva, Kuhnel & Tada initial PBH mass fraction (fraction of universe in regions dense enough to form PBHs):

$$\beta(M) \sim \int_{\delta_c}^{\infty} P(\delta(M_H))\, d\delta(M_H)$$

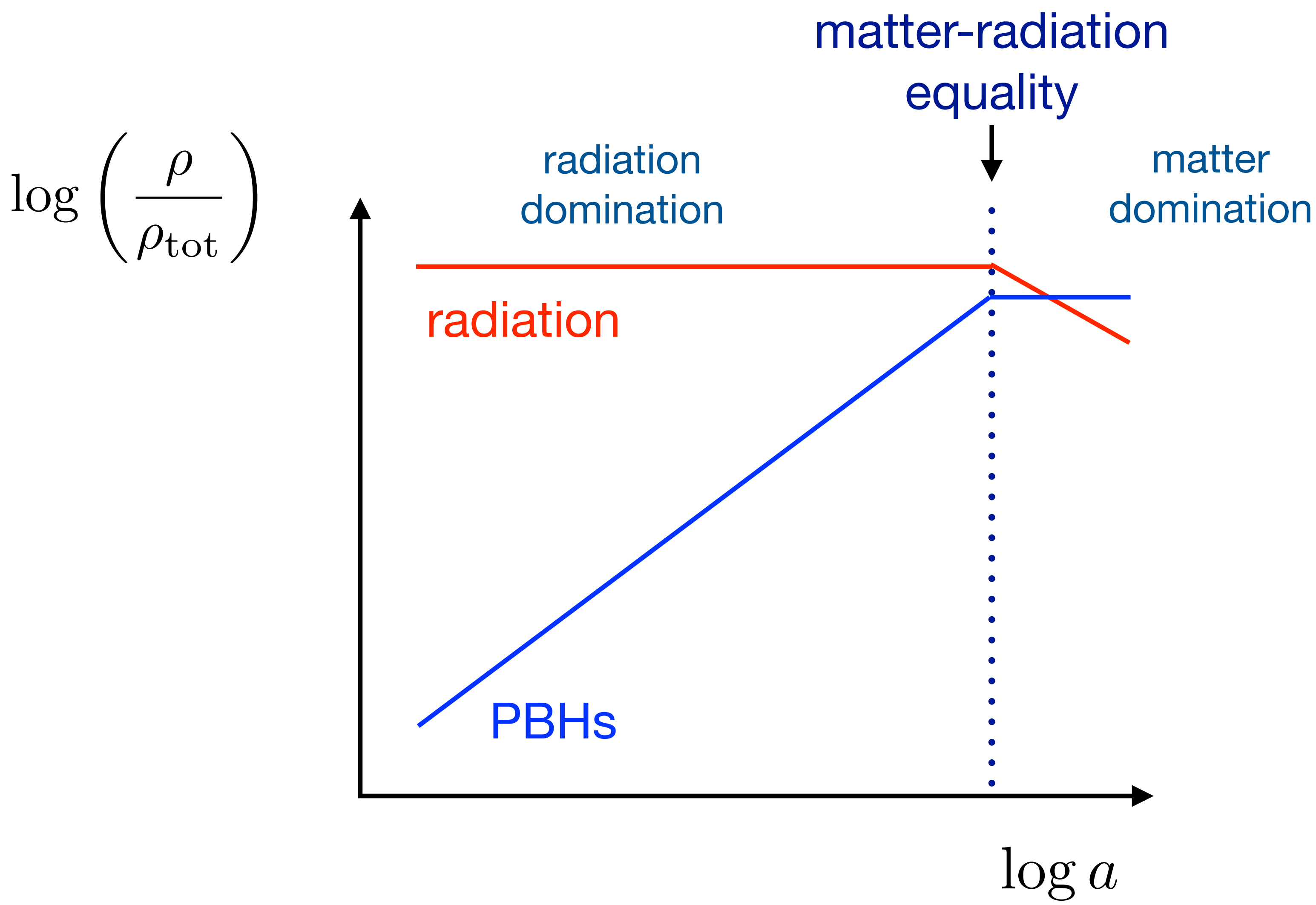
assuming a gaussian probability distribution: $\beta(M) = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M_H)}\right)$



but in fact β must be small, hence σ ≪ δ_c and $\beta(M) \sim \sigma(M_H) \exp\left(-\frac{\delta_c^2}{2\sigma^2(M_H)}\right)$

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

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



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

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

i.e. initial mass fraction must be small, but non-negligible.

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

If the primordial perturbations are very close to scale-invariant the number of PBHs formed will be completely negligible:

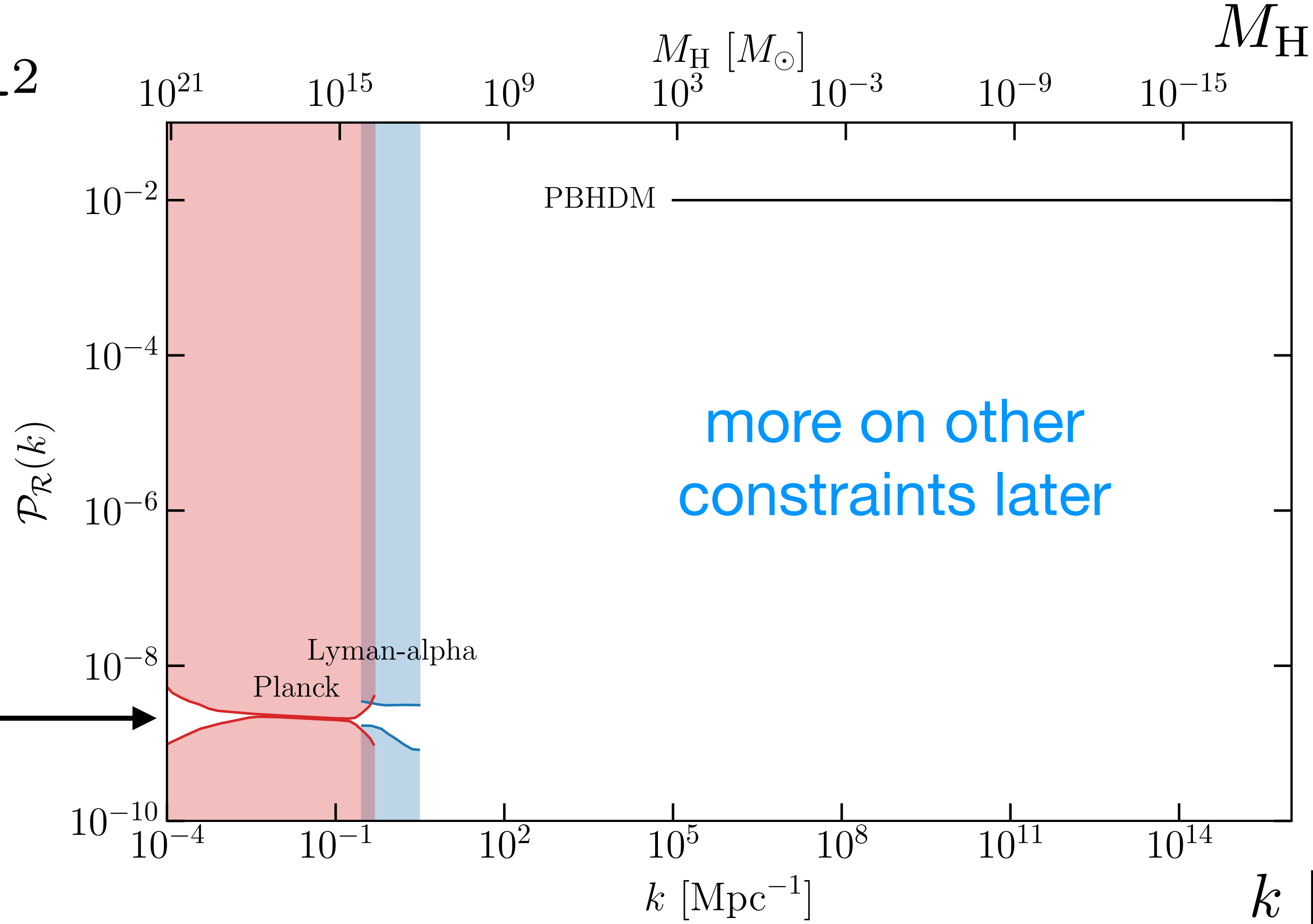
$$\beta(M) = \mathrm{erfc}\left(\frac{\delta_{\rm c}}{\sqrt{2}\sigma(M_{\rm H})}\right)$$

$$\beta(M) \sim \mathrm{erfc}(10^5) \sim \exp\left(-10^{10}\right)$$

To form an interesting number of PBHs the primordial perturbations must be significantly larger ($\sigma^2(M_{\rm H})$~0.01) on small scales than on cosmological scales.

$M_{\rm H}\ [M_\odot]$ ~ PBH mass

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



amplitude required for $f_{\rm PBH} \approx 1$

measured amplitude on cosmological scales

$k\ [\mathrm{Mpc}^{-1}]$

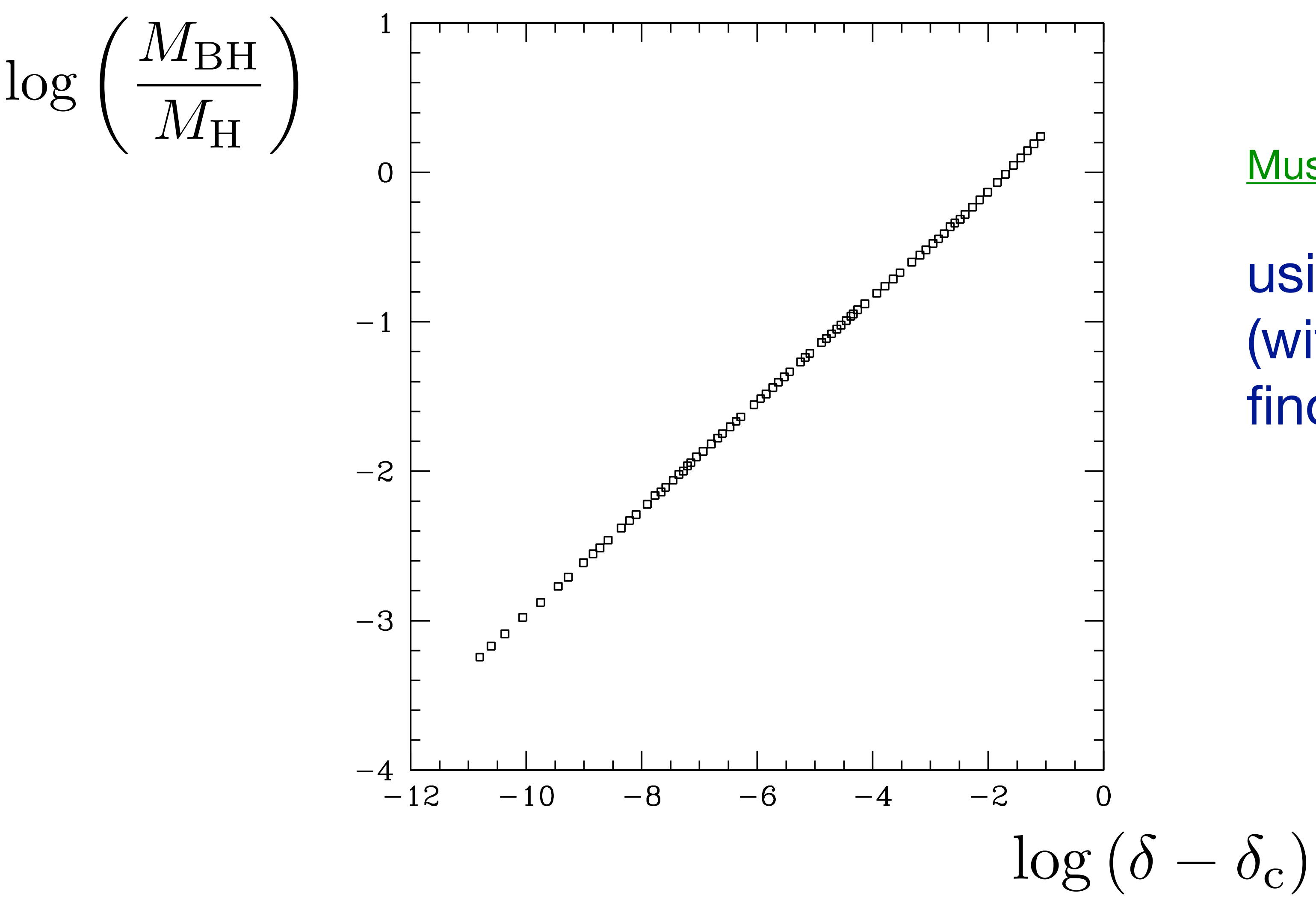
deviations from simple scenario:

i) critical collapse

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, δ_c = 0.45

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

ii) non-gaussianity

Since PBHs are formed from rare large density fluctuations, changes in the shape of the tail of the probability distribution (i.e. non-gaussianity) can significantly affect the PBH abundance. Bullock & Primack; Ivanov;… Francolini et al.

Relationship between density perturbations and curvature perturbations is non-linear, so even if curvature perturbations are gaussian (large) density perturbations won't be. Kawasaki & Nakatsuka; De Luca et al.; Young, Musco & Byrnes

Inflation: a brief crash course

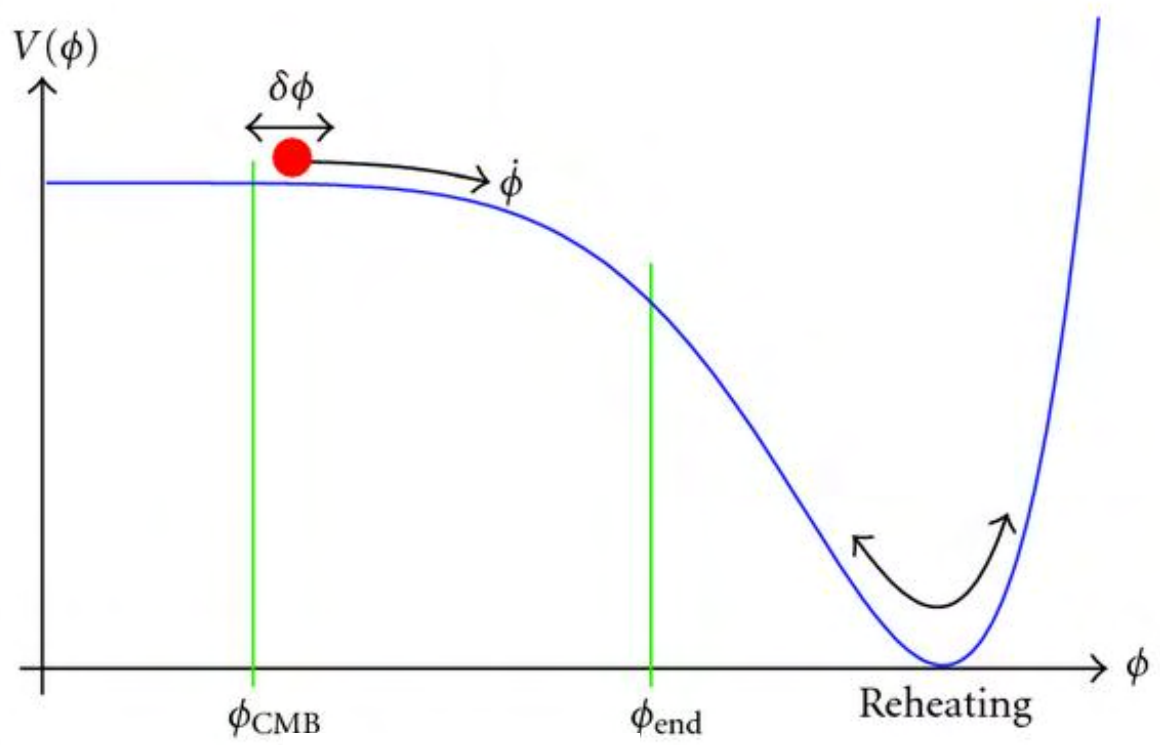
A postulated period of accelerated expansion in the early Universe, proposed to solve various problems with the Big Bang (flatness, horizon & monopole).

Driven by a 'slowly rolling' scalar field.

Quantum fluctuations in scalar field generate density perturbations.

Scale dependence of primordial perturbations depends on shape of potential:

Yadav & Wandelt



in slow-roll approx

$$\sigma^2(M_{\rm H}) \propto \frac{V^3}{(V')^2}$$

Scales probed by:

Large scale structure & the CMB

Primordial Black Holes

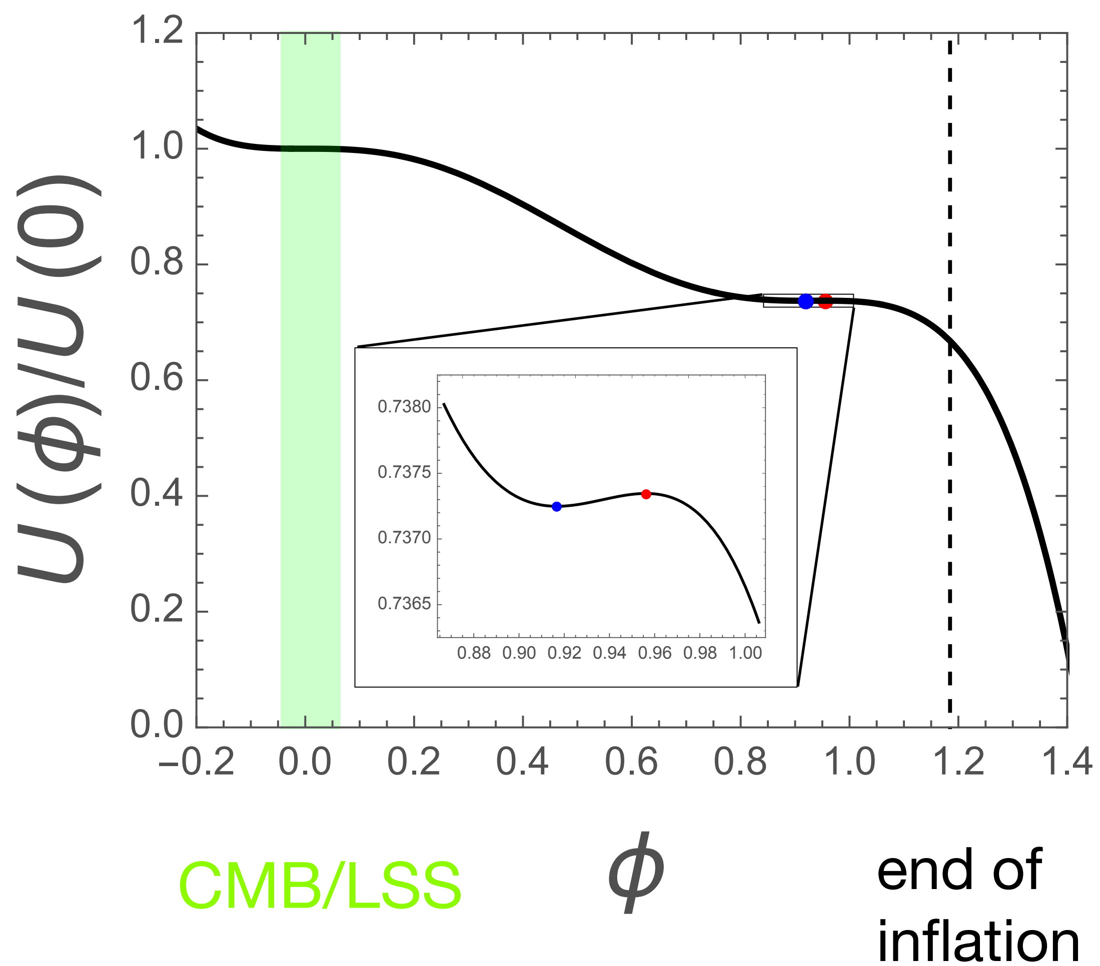
inflation models that produce large perturbations Öszoy & Tasinato; Escriva, Kuhnel & Tada

In slow-roll approx: $\sigma \propto V^{3/2}/V'$, but this expression isn't valid in 'ultra-slow-roll' limit, $V' \to 0$ (and USR also affects probability distribution of fluctuations - more later).

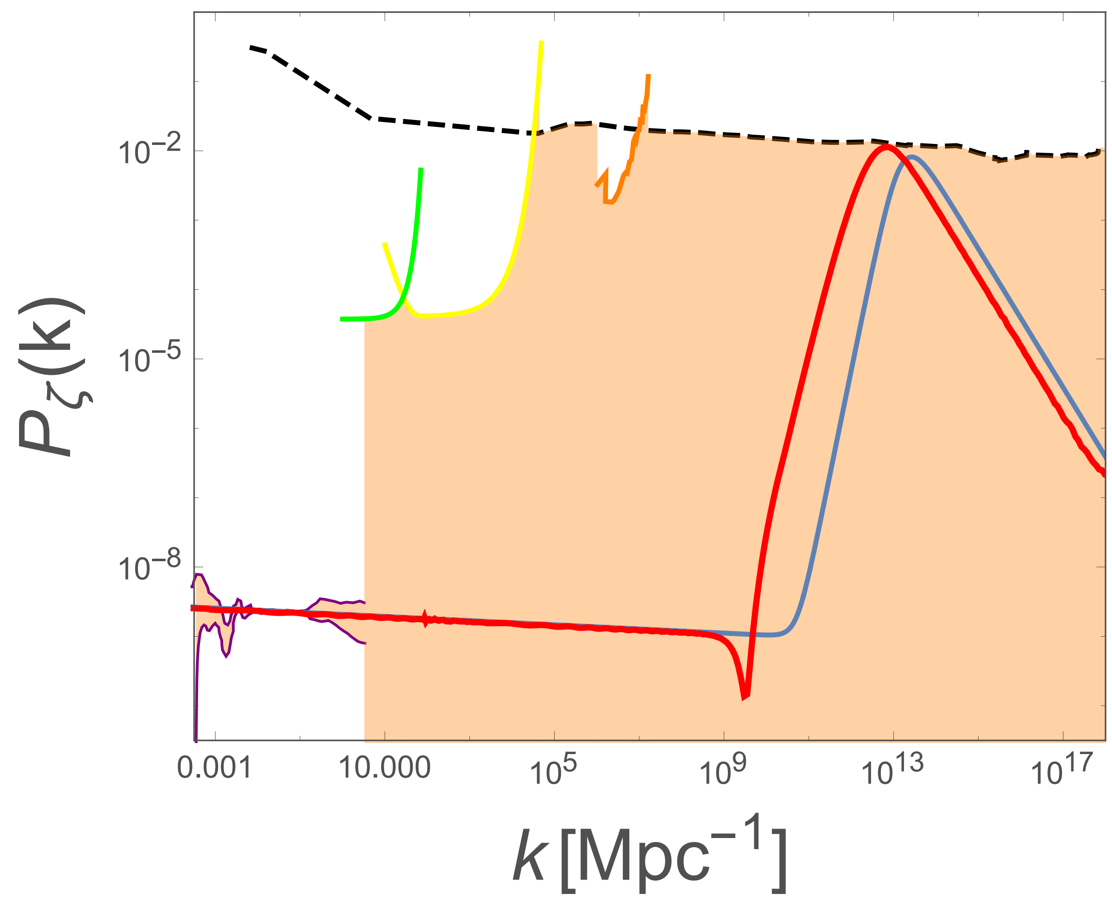
single field

Potential fine-tuned so that field goes past local min, but with reduced speed
Ballesteros & Taoso; Herzberg & Yamada

potential



primordial power spectrum

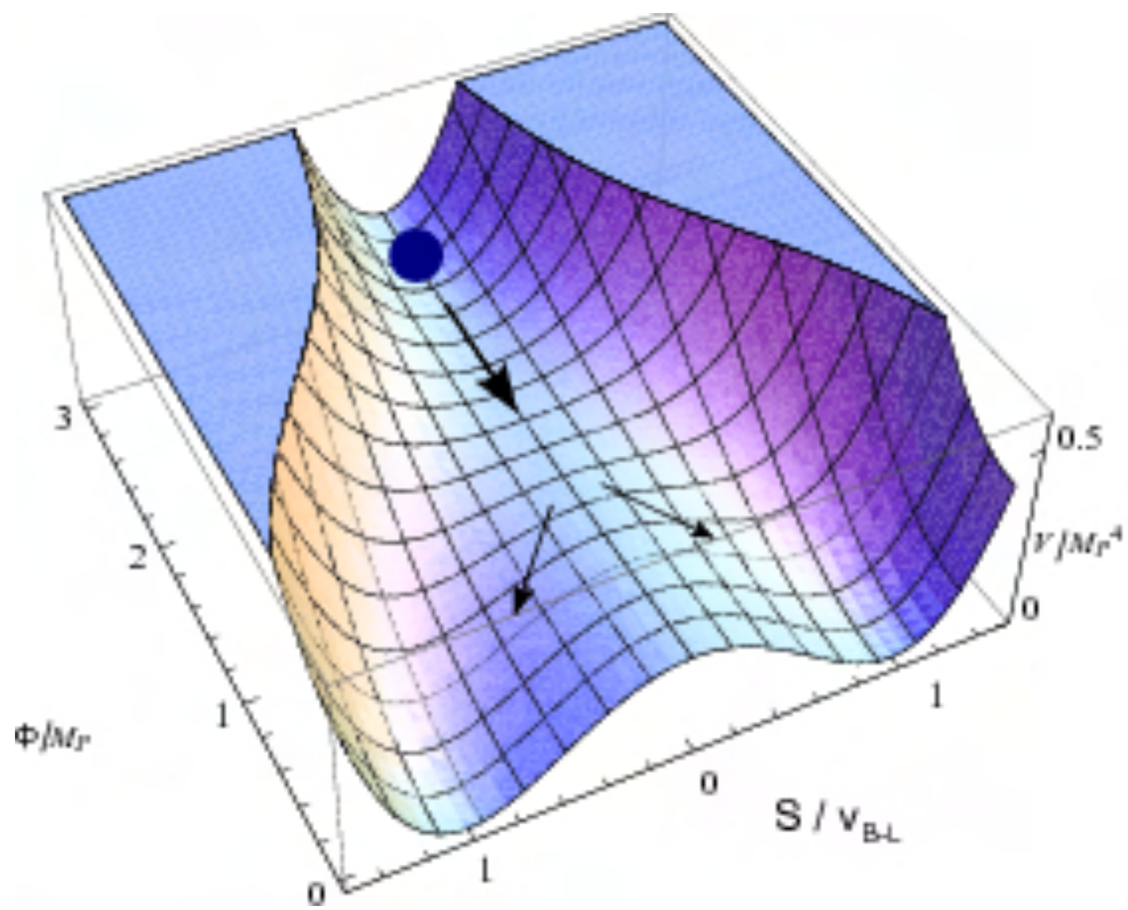


Steepest possible growth ~k^4 Byrnes, Cole & Patil; Carrihlo, Malik & Mulryne

multi-field models

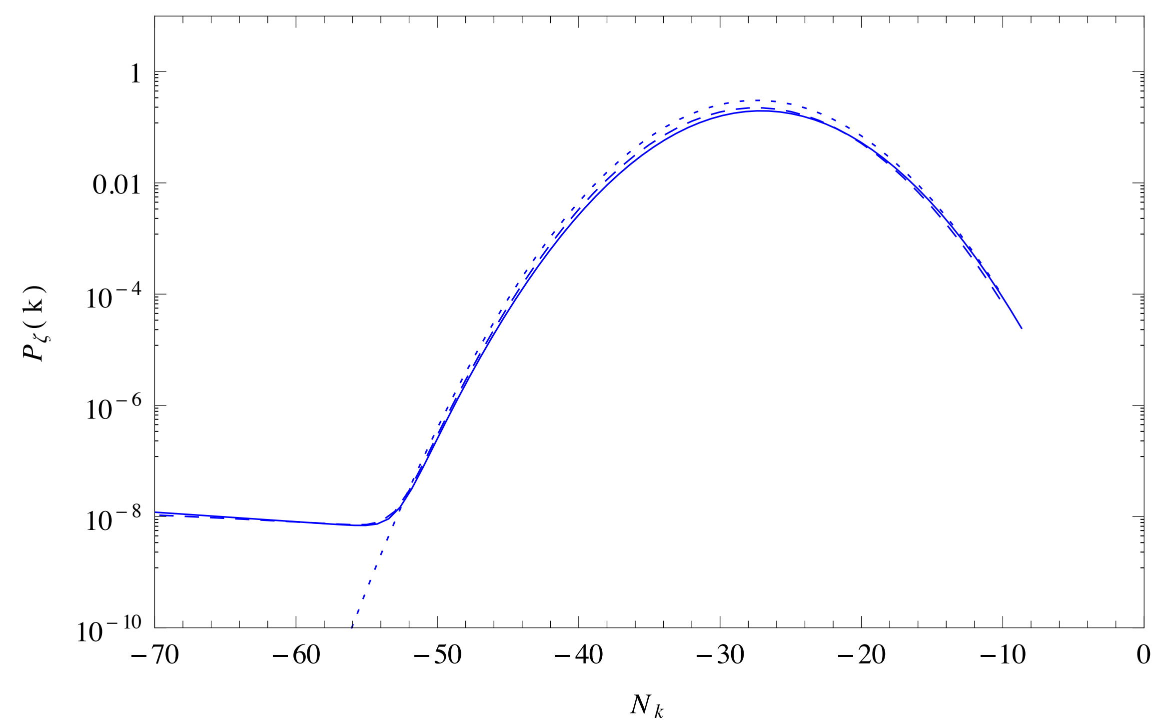
e.g. hybrid inflation with a mild waterfall transition Garcia-Bellido, Linde & Wands

potential



Buchmuller

primordial power spectrum



Clesse & Garcia-Bellido

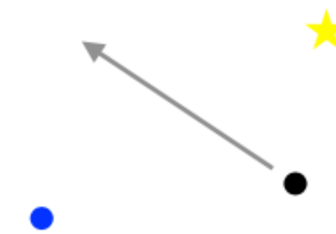
various others for reviews see Öszoy & Tasinato; Escriva, Kuhnel & Tada

running mass, double inflation, axion-like curvaton, reduced sound speed, multi-field models with rapid turns in field space,…

Constraints

Initially assuming a delta-function PBH mass function

microlensing

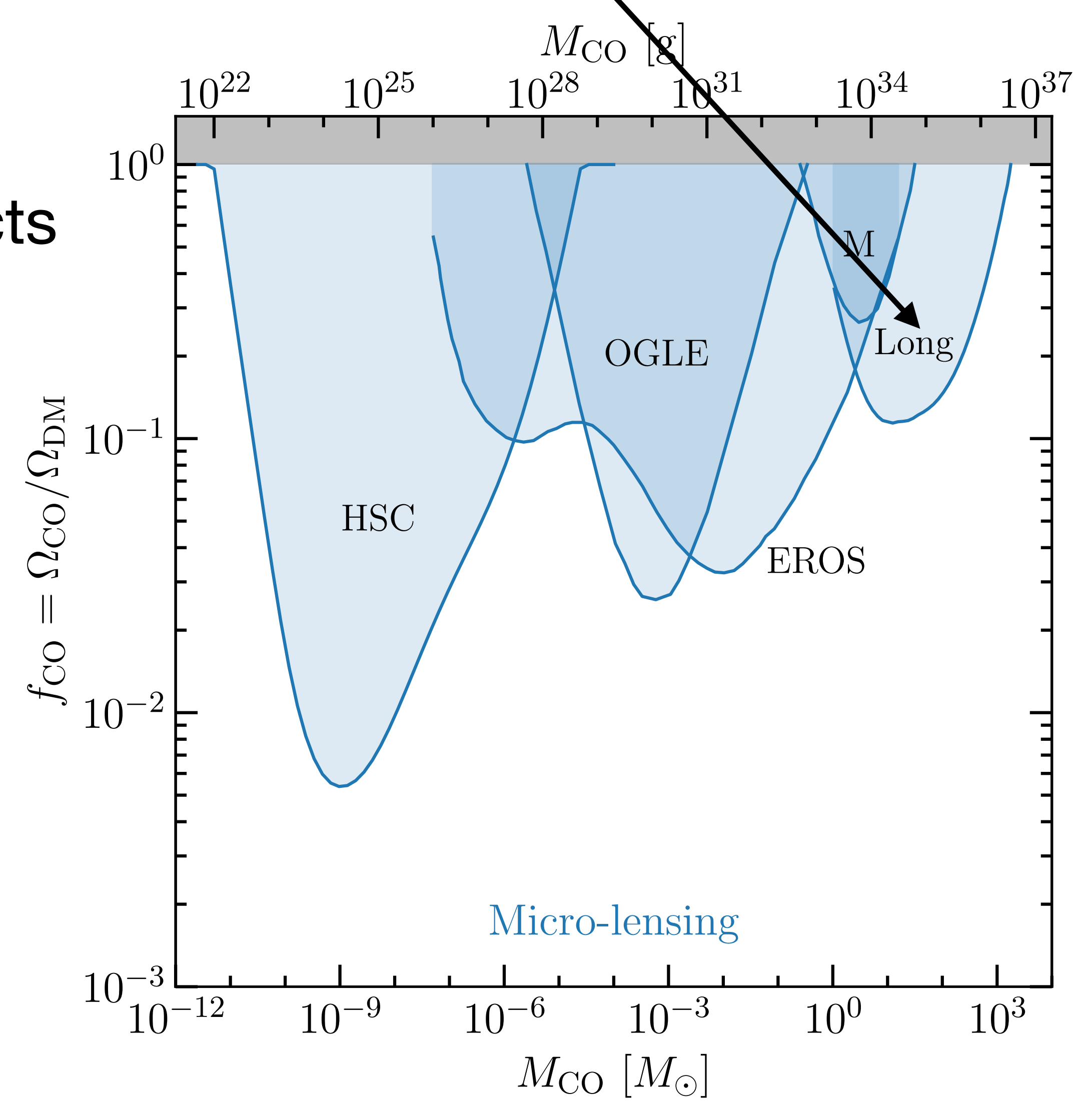


Gravitational lensing where separation of images is micro-arcsecond, too small to resolve, but can detect variations in magnification.

stars: temporarily brightened when compact object (‘CO’) crosses line of sight
LMC/SMC (MACHO, EROS, OGLE, **combined long duration**), Galactic bulge (OGLE),
M31 (HSC, Croon et al.).

fraction of dark matter
in form of compact objects

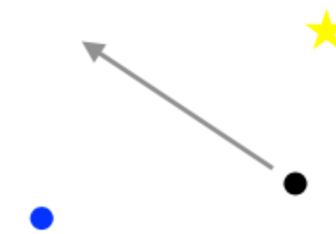
$$f_{\rm CO} = \frac{\Omega_{\rm CO}}{\Omega_{\rm DM}}$$



mass in grams

mass in Solar masses

microlensing



Gravitational lensing where separation of images is micro-arcsecond, too small to resolve, but can detect variations in magnification.

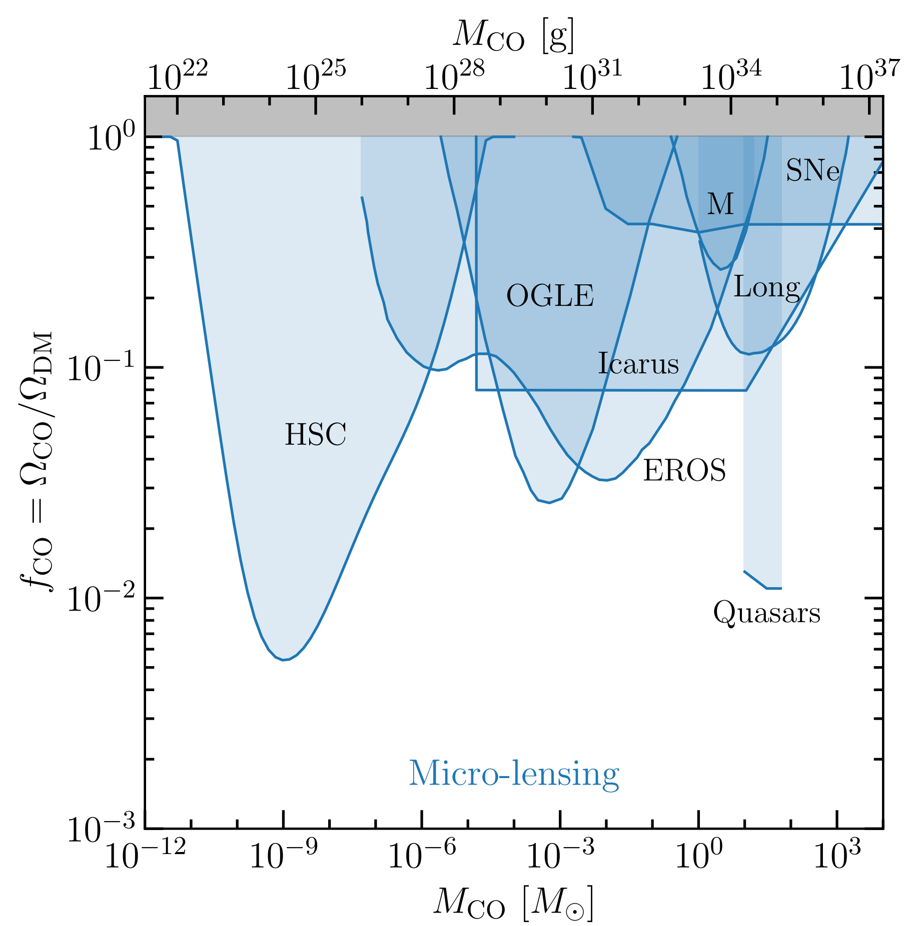
supernovae: magnification distribution Zumalacarregui & Seljak
luminosity-redshift relation Dhawan & Mörtsell

Icarus: caustic crossing event Oguri et al.

quasars: flux ratios of multiply-lensed systems Esteban-Gutierrez et al.

fraction of dark matter
in form of compact objects

$$f_{CO} = \frac{\Omega_{CO}}{\Omega_{DM}}$$



mass in grams

mass in Solar masses

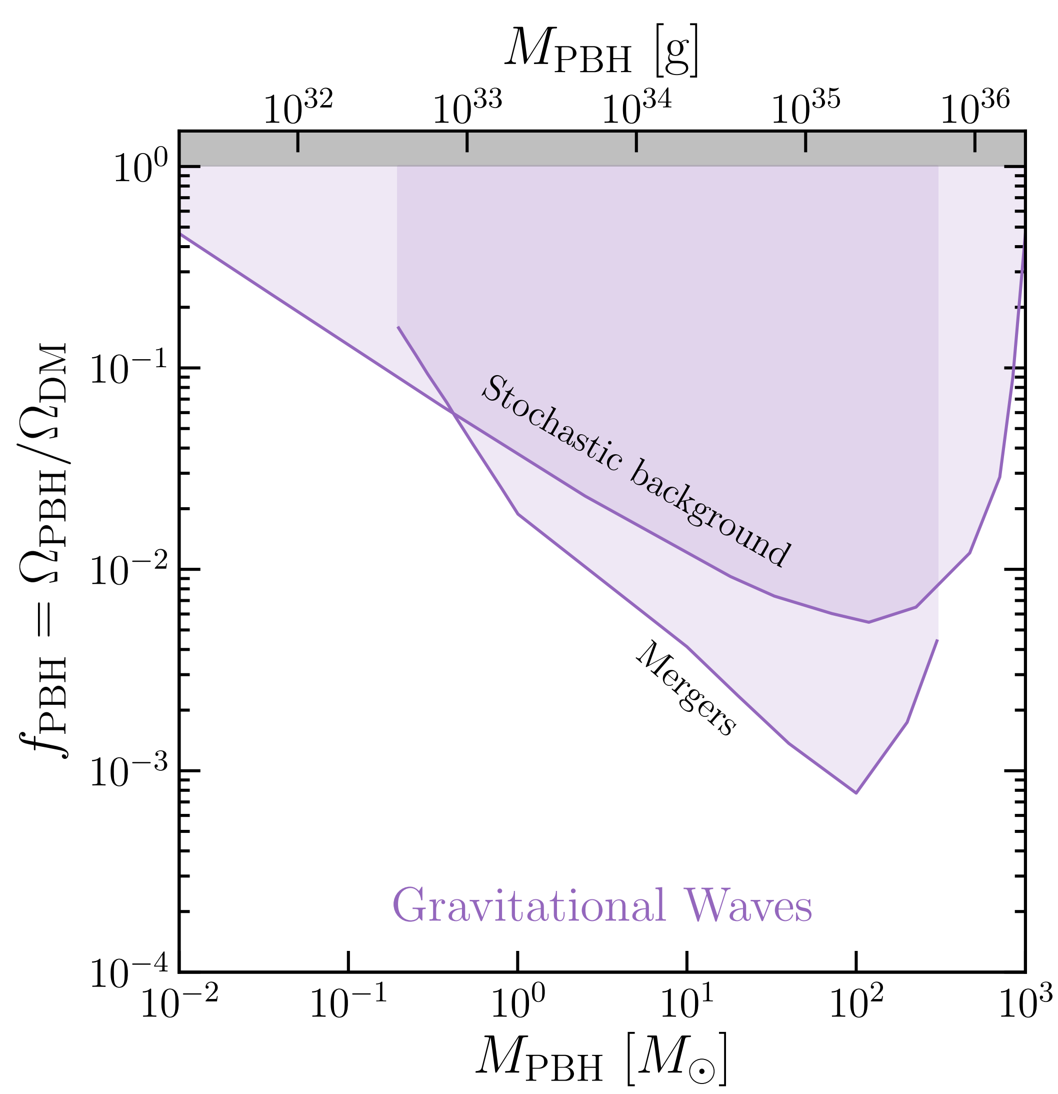
gravitational waves from PBH-PBH binary mergers

PBH binaries can form at early times (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. Ali-Haïmoud, Kovetz & Kamionkowski

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

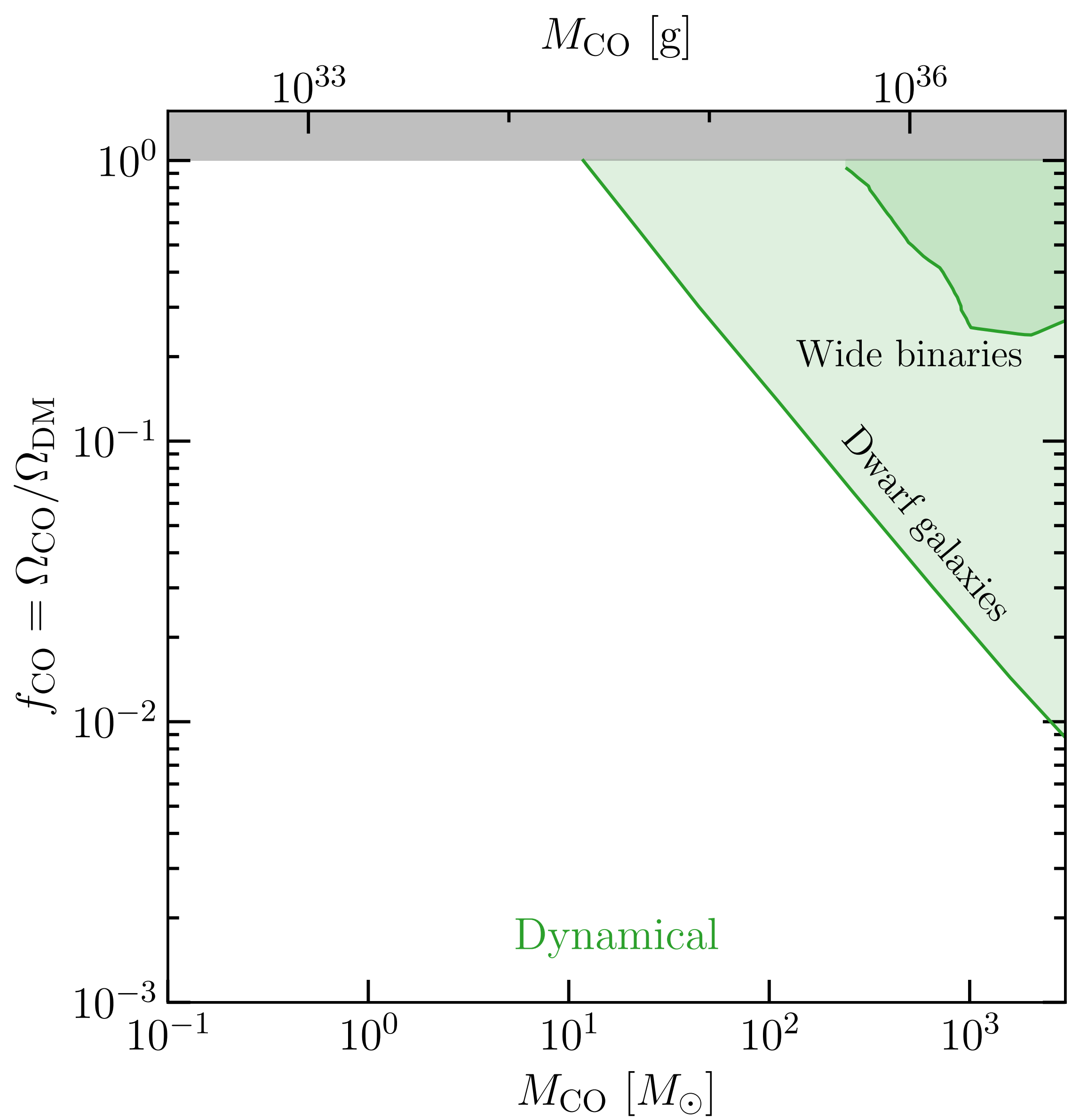
$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$



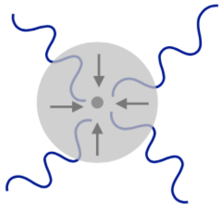
dynamical effects

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. Yoo, Chaname & Gould; … Monroy-Rodriguez & Allen; Tyler, Green & Goodwin



accretion



Radiation emitted due to gas accretion onto PBHs can modify the recombination history of the universe, constrained by

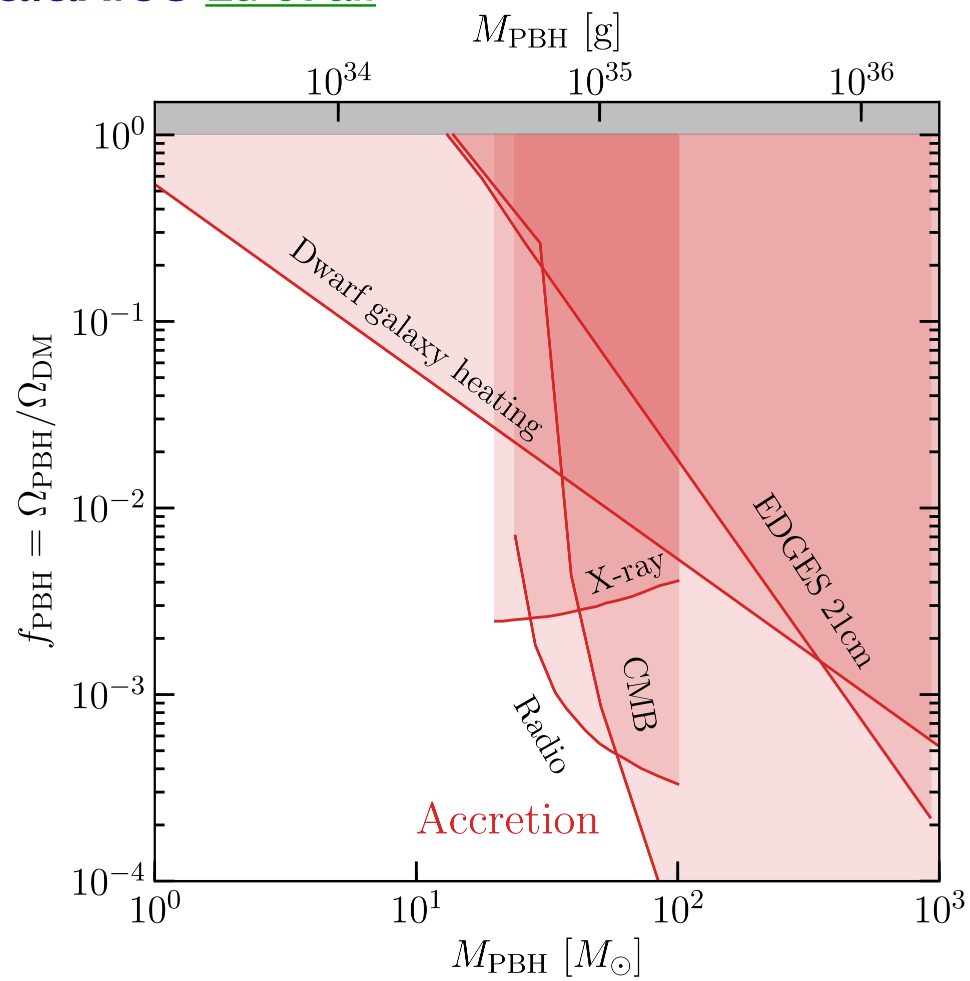
distortion of CMB anisotropies Ricotti et al; Ali-Haïmoud & Kamionkowski; … Poulin et al.…

EDGES 21cm measurements Hektor et al.;

Accretion onto PBHs today constrained by

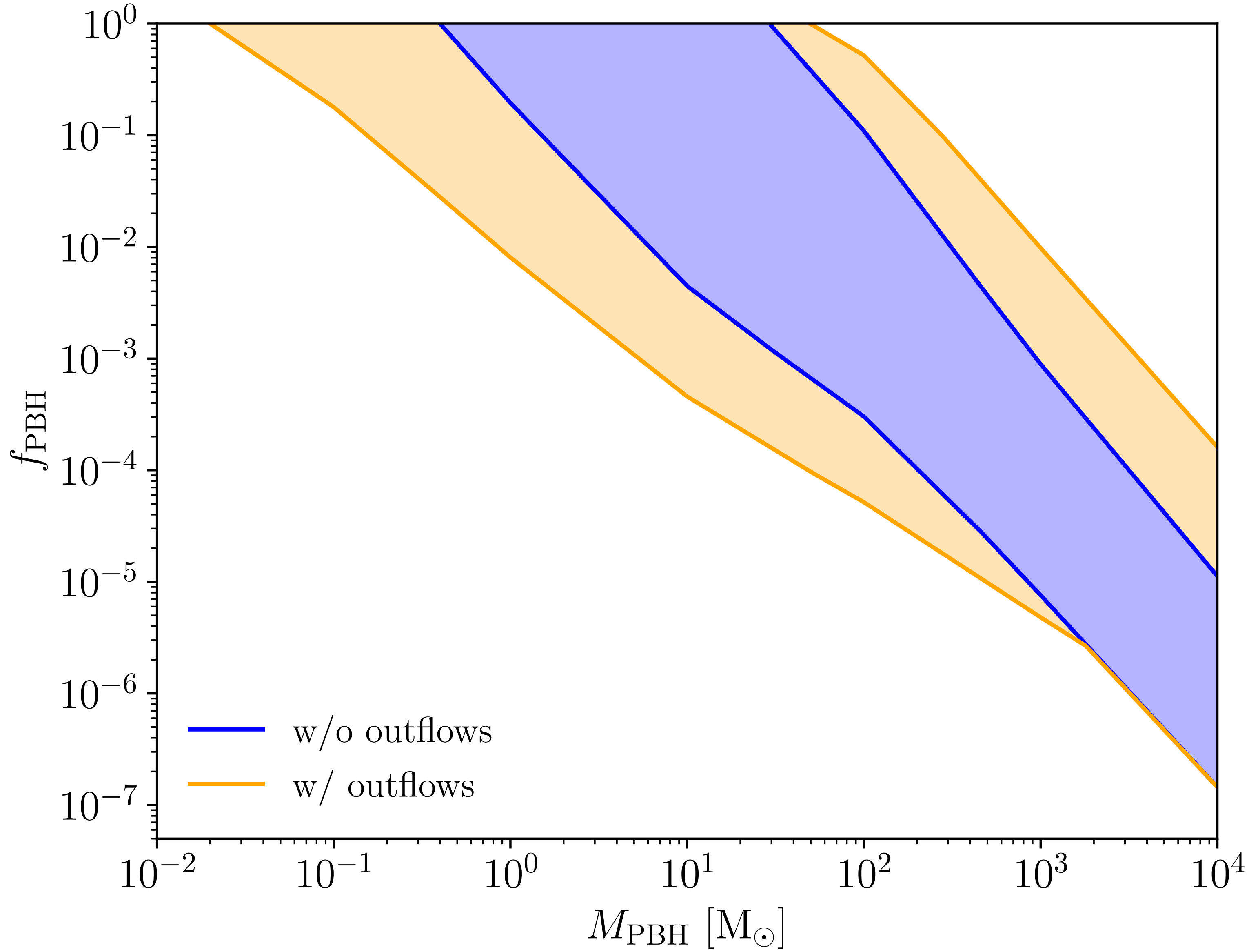
X-ray and radio emission in MW Gaggero et al; Inoue & Kusenko; Manshanden et al.

gas-heating in dwarf galaxies Lu et al.



uncertainty in constraint from distortion of CMB anisotropies

from geometry of accretion (spherical or disc) Poulin et al. and outflows Piga et al.



Piga et al.

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.

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

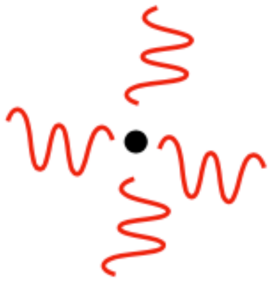
Montero-Camacho et al. **No current constraints**, but potential future constraints from

i) survival of neutron stars in globular cluster **if** it has DM halo (need high DM density, low velocity-dispersion environment),

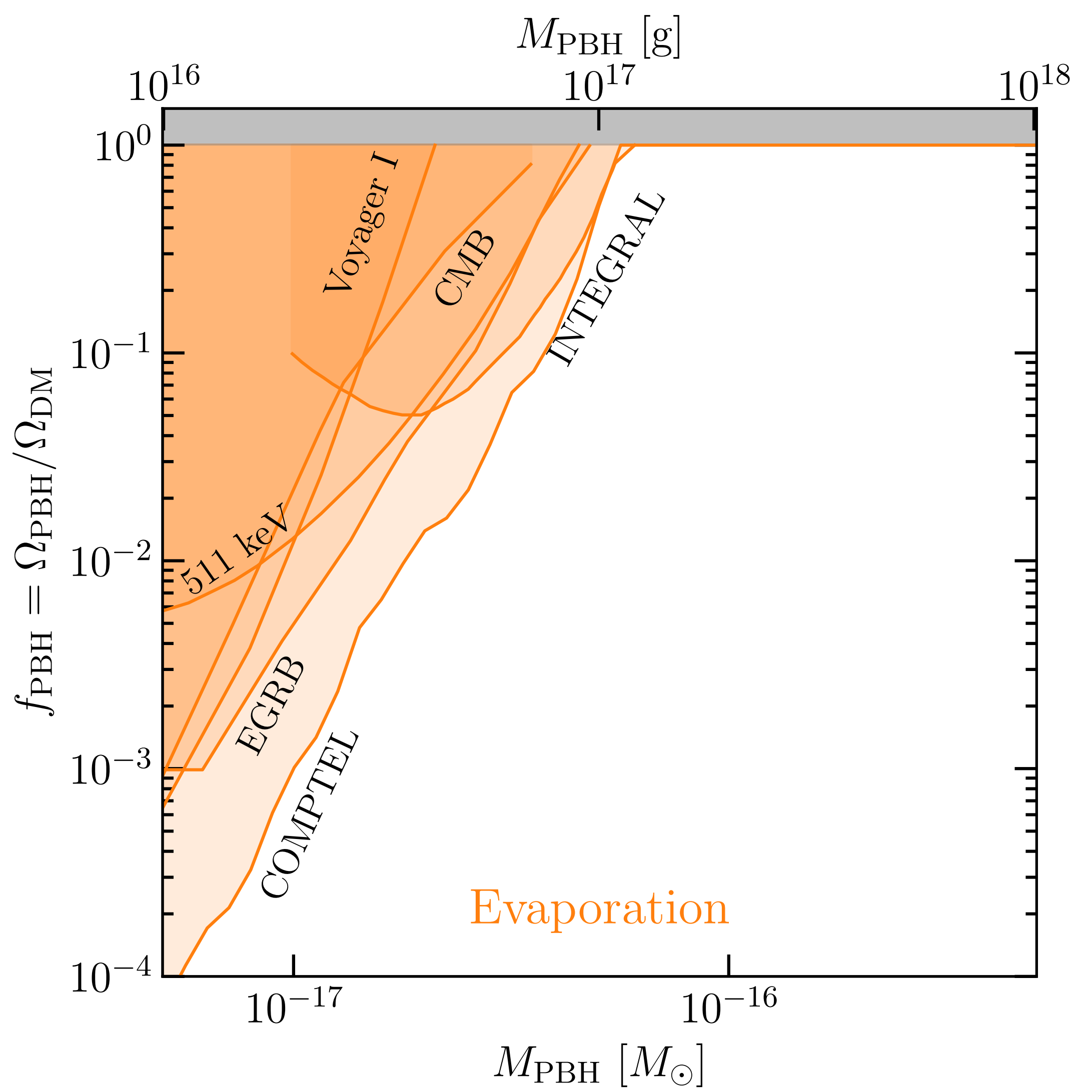
ii) signatures of star being destroyed.

Esser & Tinyakov potential constraints from disruption of main sequence stars in dwarf galaxies, due to PBH capture during star formation.

constraints on light PBHs from evaporation products

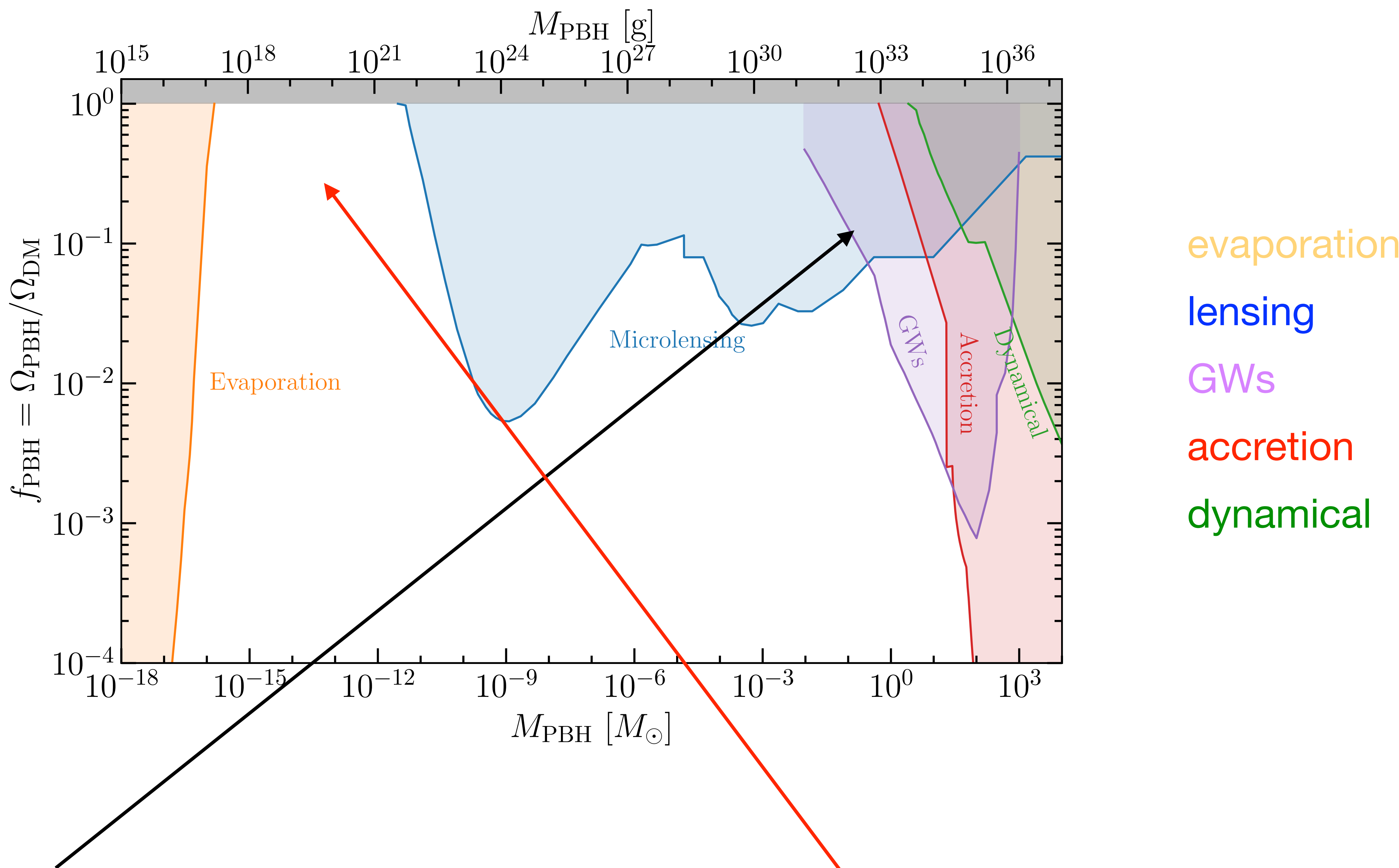


Evaporation products (gamma rays, $e^{\pm}$,...) from PBHs reaching the end of their lifetime would be detectable/have observable consequences.



See also Auffinger review.

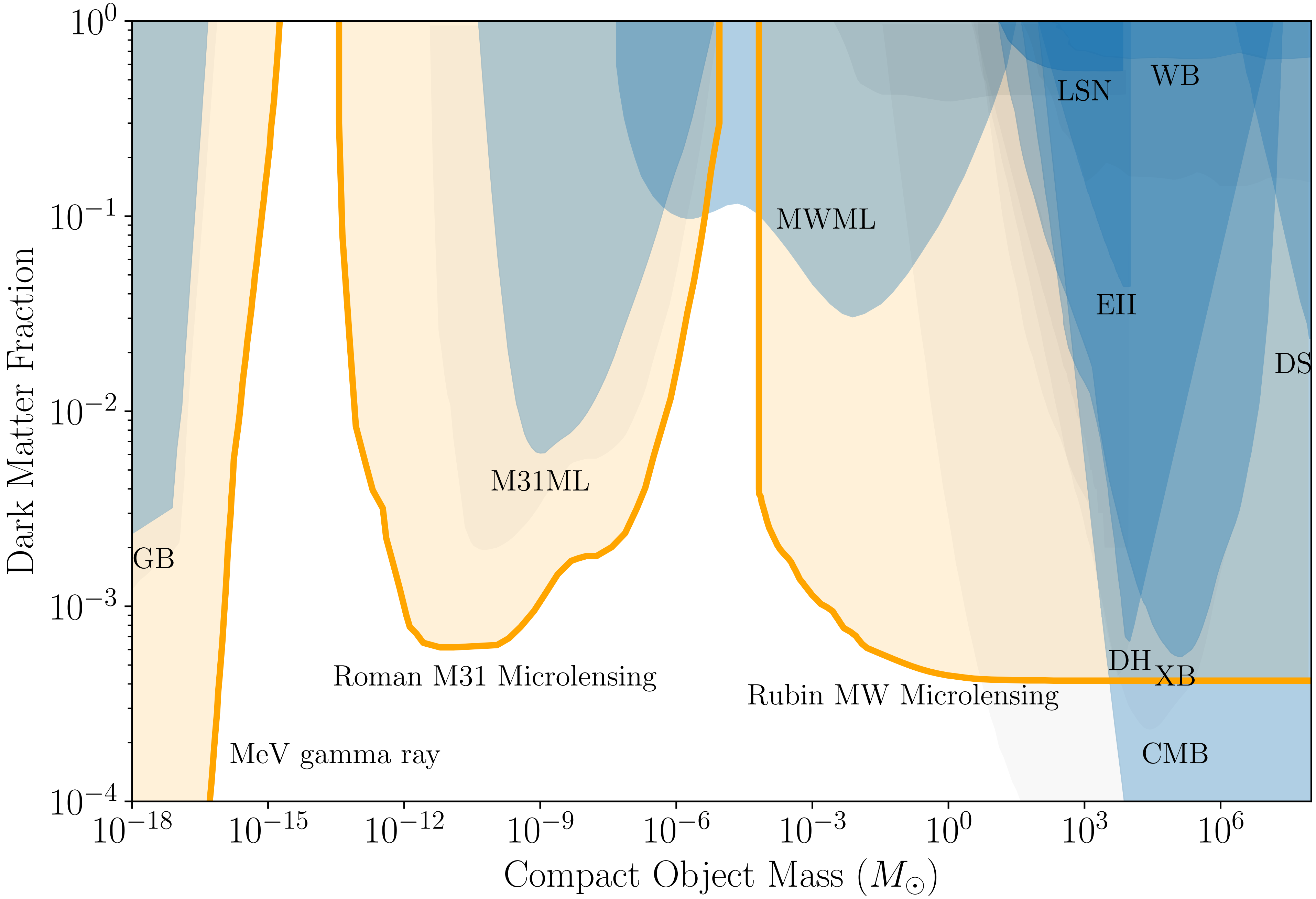
Compilation of tightest constraints



multi-Solar mass Primordial Black Holes making up all of the DM appears to be excluded.

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

Future constraints



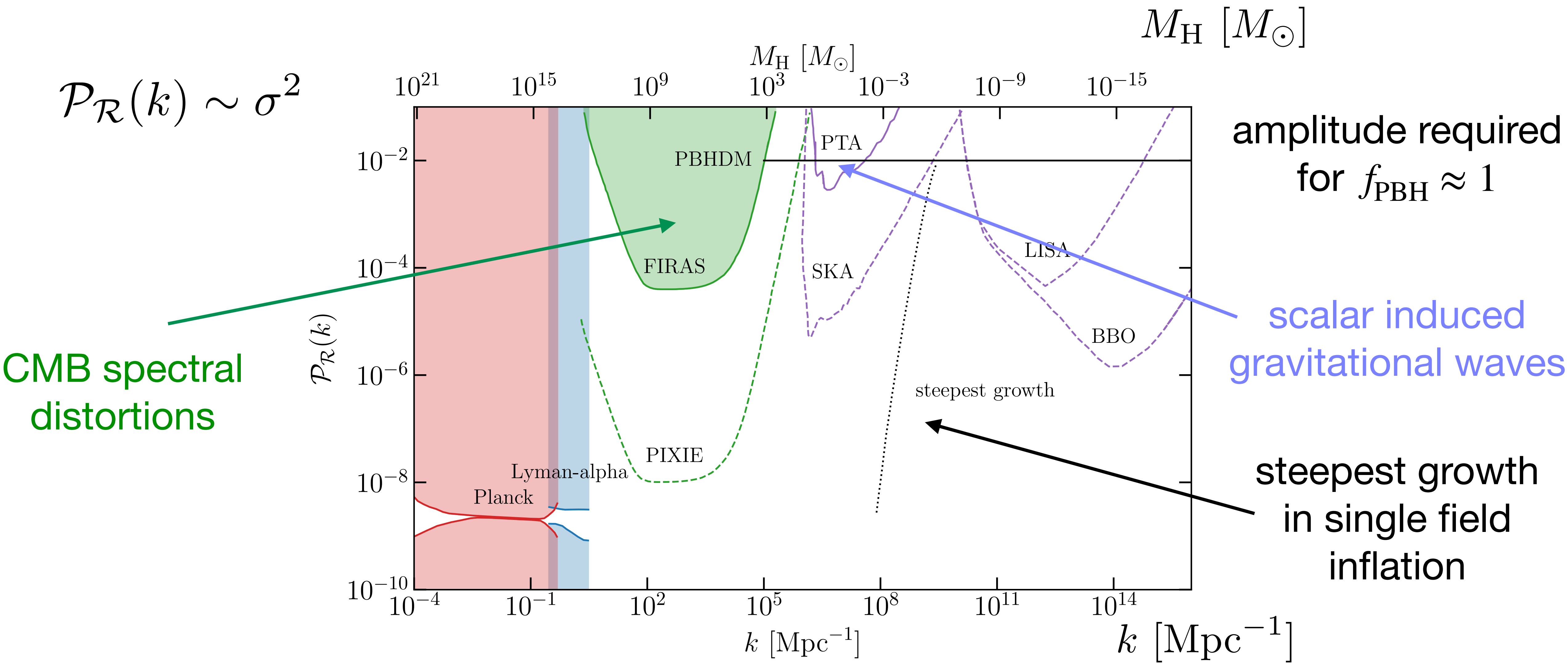
Bird et al.

Indirect constraints on PBHs formed from large density perturbations

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

Resulting constraints on amplitude of primordial perturbations therefore constrain abundance of PBHs formed via collapse of large density perturbations. Saito & Yokoyama; Byrnes et al.; Inomata et al.

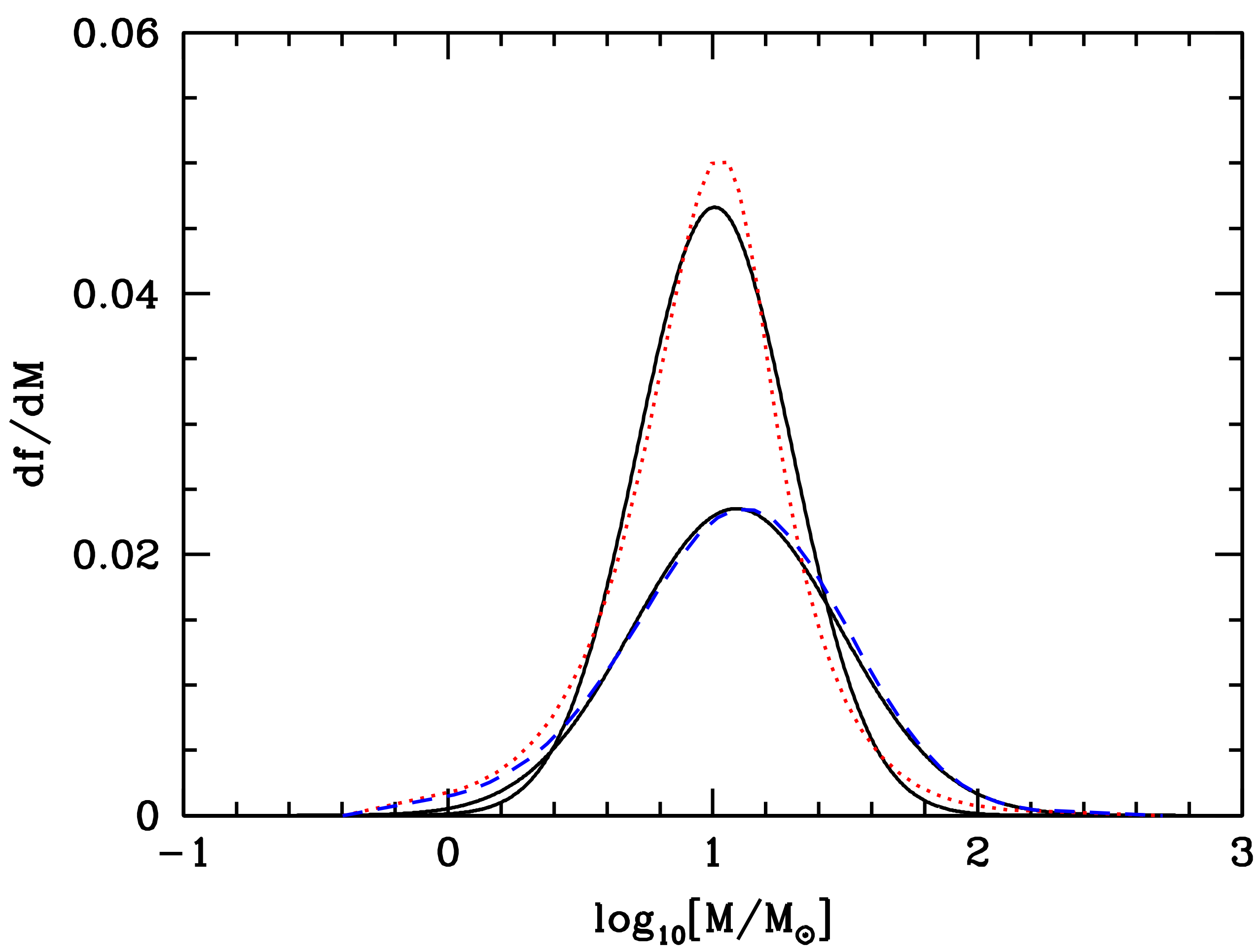
Massive PBHs similarly constrained by CMB spectral distortions.
Carr & Lidsey; Kohri, Nakama & Suyama



constraints on (realistic) extended mass functions

Extended MFs produced by broad peak in power spectrum, moderately well approximated by a **log-normal distribution**: Green; Kannike et al.

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



axion-like curvaton

running mass inflation

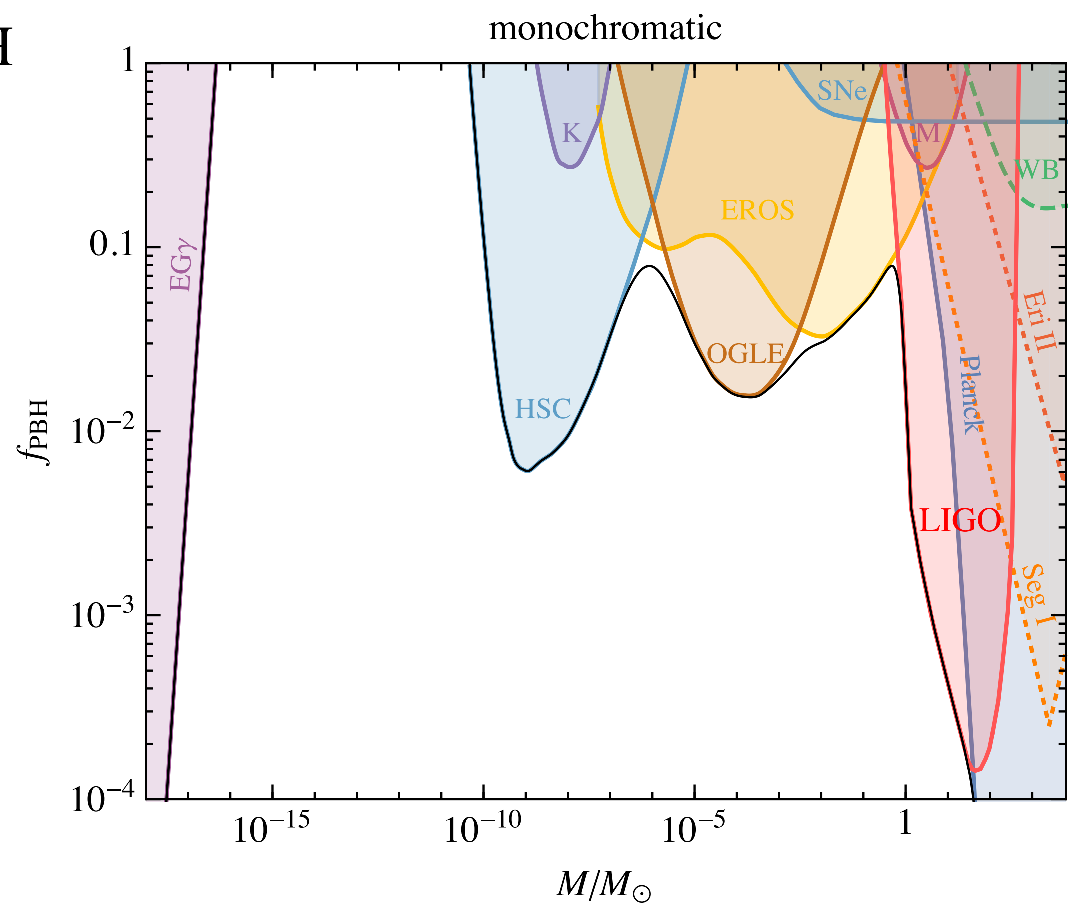
For extended mass functions, constraints on f are smeared out, and gaps between constraints are ‘filled in’:

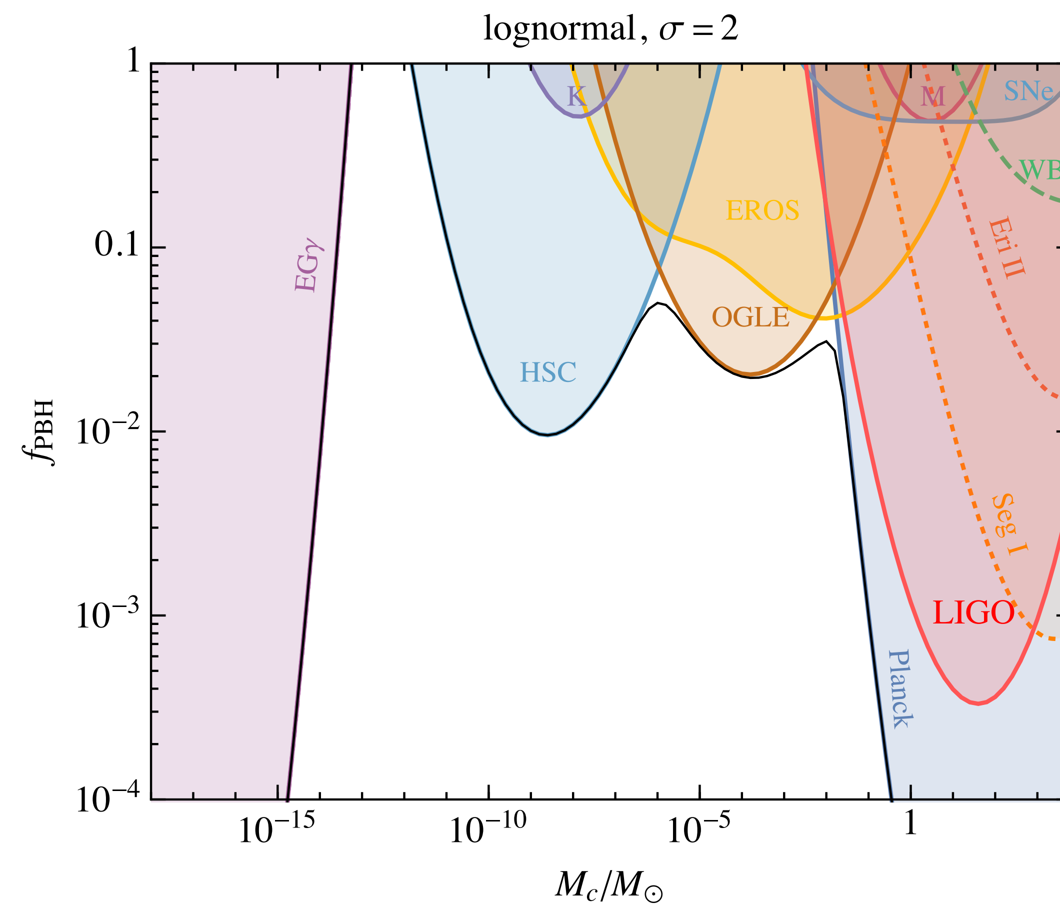
Green; Carr et al.; see also Bellomo et al.

monochromatic

log-normal (fixed width)

$f_{\rm PBH}$





$\frac{M_{\rm c}}{M_\odot}$

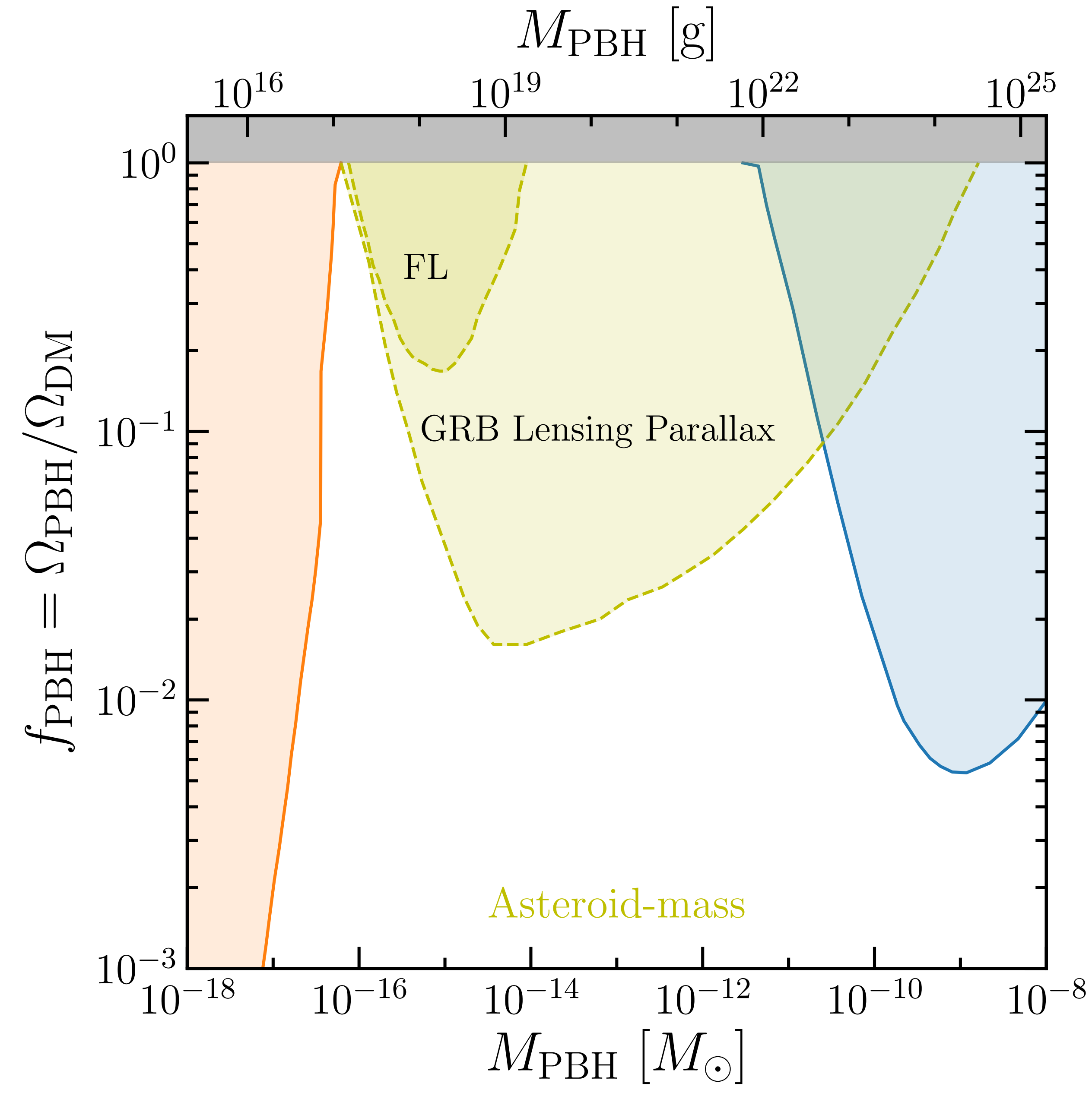
Carr et al.

Open questions

i) how to probe asteroid mass PBHs?

femtolensing of GRBs Gould need small GRBs Katz et al.

GRB lensing parallax Nemiroff & Gould; Jung & Kim

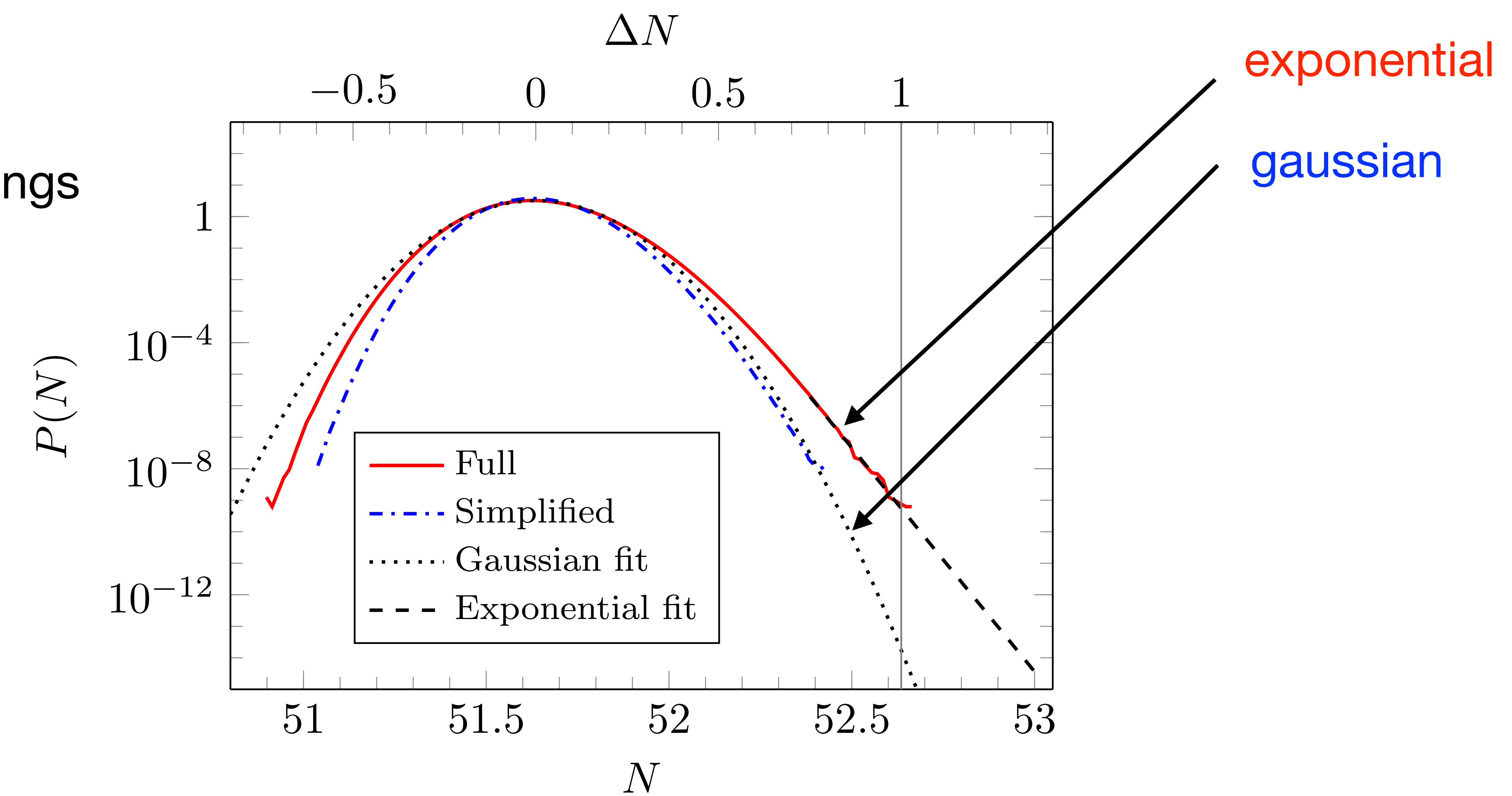


ii) probability distribution of density perturbations produced during ultra slow-roll inflation

Pattinson et al. … Figueroa et al.; Tada & Vennin... Mishra, Copeland & Green (in prep)

In ultra-slow-roll inflation (i.e. for $V' \to 0$ as required in single-field inflation to produce large amplitude, PBH-forming, perturbations) stochastic effects are important, and can generate exponential rather than gaussian tail for probability distribution.

Prob. dist. of number of e-foldings of inflation ~ prob. dist. of curvature perturbation



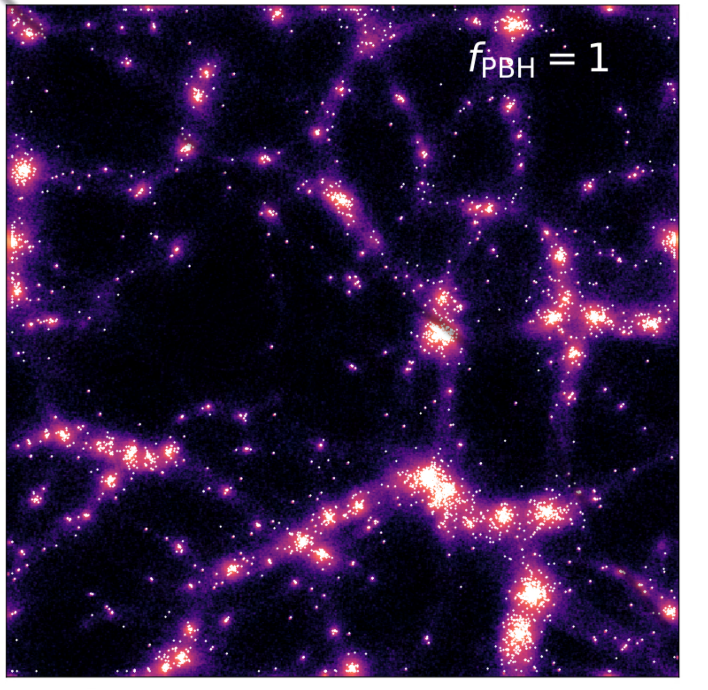
Figueroa et al.

iii) clustering

Potentially extremely important (affects PBH binary merger rate and possibly other constraints too).

If PBHs make up a large fraction of the DM, PBH clusters form shortly after matter-radiation equality. Afshordi, Macdonald & Spergel;... Inman & Ali-Haïmoud

Evolution of PBH clusters (and in particular PBH binaries within them and hence the merger rate) through to the present day is a challenging open problem. e.g. Jedamzik; Trashorras et al....



PBH-DM dist at z=100

Inman & Ali-Haïmoud

Clusters are sufficiently extended that PBHs microlens individually, & change in **microlensing** constraints is negligible, apart (possibly) from at M $\gtrsim 10^3 M_\odot$ Petaĉ, Lavalle & Jedamzik; Gorton & Green.

Non-local non-gaussianity can lead to more compact clusters, however in this case $\sim M_\odot$ PBHs with f_{PBH}~1 still excluded by microlensing + Lyman-α obs de Luca et al.

Short summary

Are Primordial Black Holes a viable dark matter candidate?

Yes, but….

probably not PBHs in the planetary—multi-Solar mass range

need BSM physics (and probably fine tuning) to form them (AFAIK…)

Summary

Primordial Black Holes can form in the early Universe, for instance from the collapse of large density perturbations during radiation domination.

- To produce an interesting number of PBHs, amplitude of perturbations must be ~3 orders of magnitude larger on small scales than on cosmological scales.

- This can be achieved in inflation models (e.g. with a feature in the potential or multiple fields). However it's not natural/generic.

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

- Solar mass PBHs probably can't make up all of the dark matter, but lighter, $(10^{17}$-$10^{22})$g, PBHs could.

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

Open questions: how to probe light PBHs,
perturbations in ultra-slow roll inflation (& hence PBH abundance),
clustering,
…

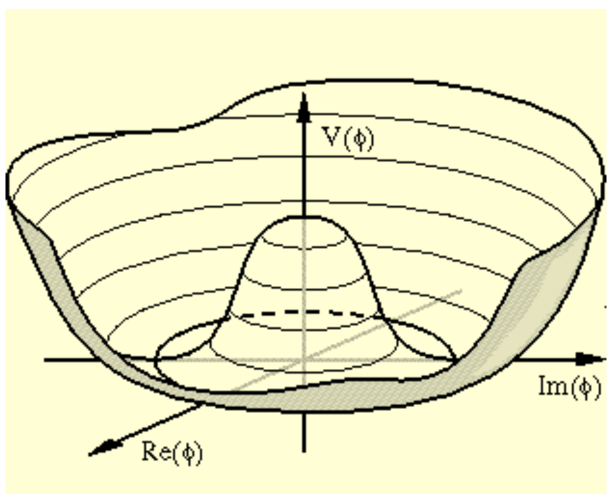
Back-up slides

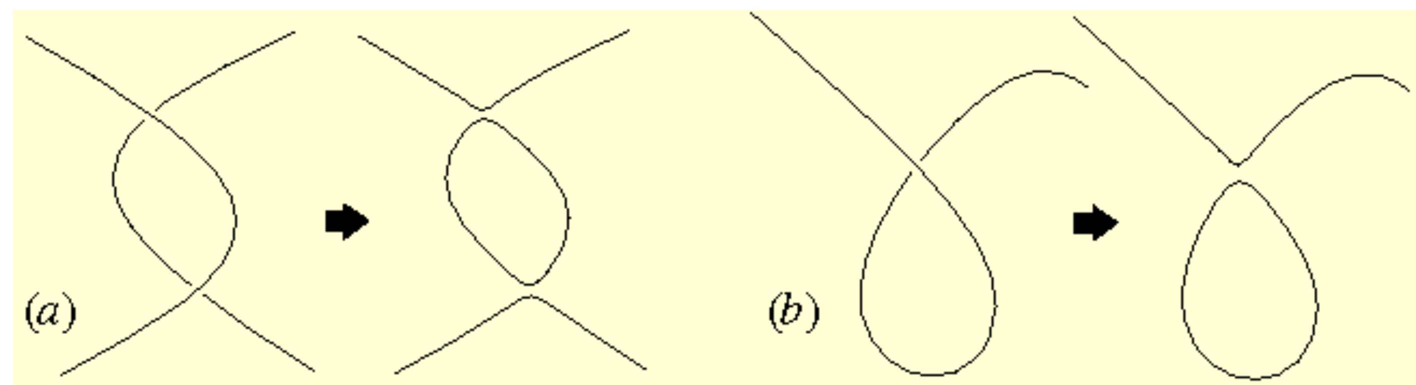
PBH formation: (some) other mechanisms

Collapse of cosmic string loops Hawking; Polnarev & Zemboricz;

Cosmic strings are 1d topological defects formed during symmetry breaking phase transition.

String intercommute producing loops.



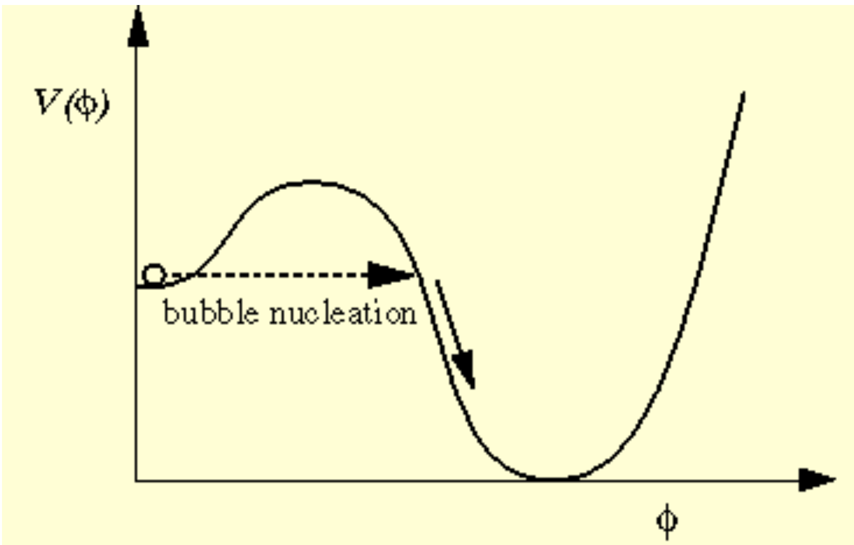


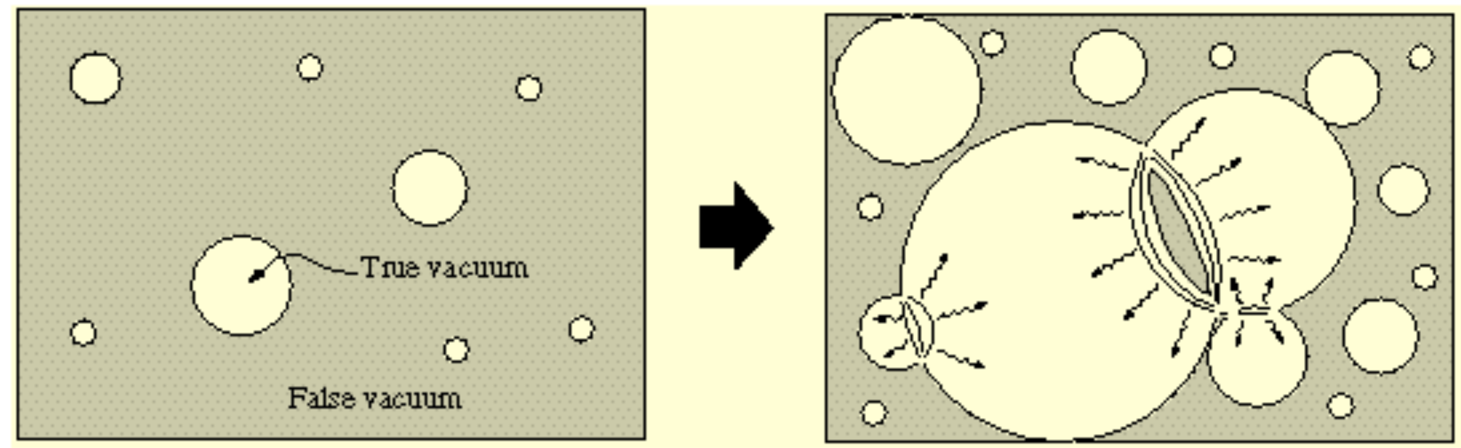
Small probability that loop will get into configuration where all dimensions lie within Schwarzschild radius (and hence collapse to from a PBH with mass of order the horizon mass at that time).

Probability is time independent, therefore PBHs have extended mass spectrum.

Bubble collisions Hawking

1st order phase transitions occur via the nucleation of bubbles.





PBHs can form when bubbles collide (but bubble formation rate must be fine tuned).

PBH mass is of order horizon mass at phase transition.

Fragmentation of inflaton scalar condensate into oscillons/Q-balls

Cotner & Kusenko; Cotner, Kusenko & Takhistov

Scalar field with flat potential forms condensate at end of inflation, fragments into lumps (oscillons/Q-balls) which can come to dominate universe and have large density fluctuations that can produce PBHs.

Mass smaller than horizon mass and spin can be of order 1.

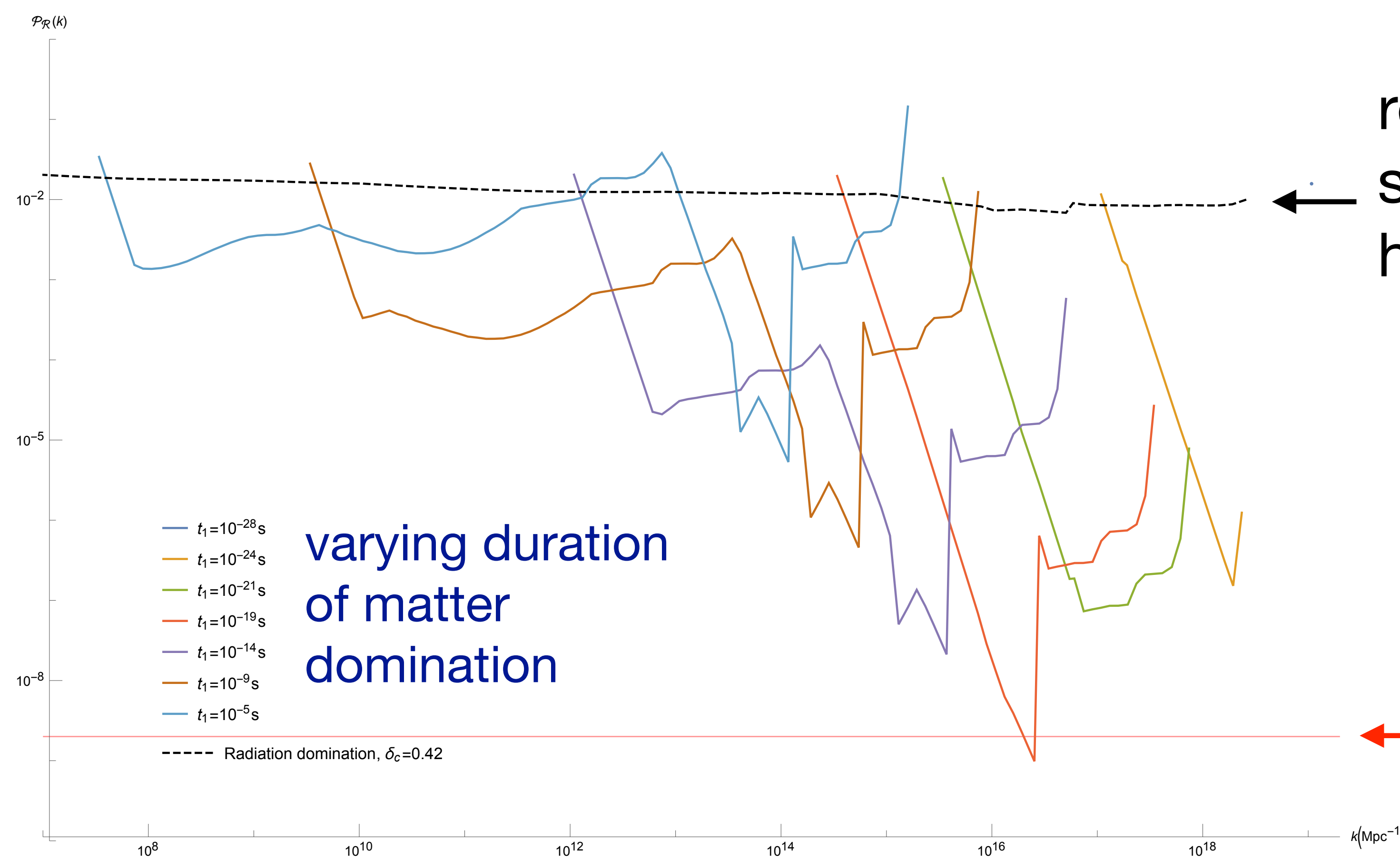
PBH formation during an early (pre nucleosynthesis) period of matter domination

During matter domination PBHs can form from smaller fluctuations (no pressure to resist collapse) in this case fluctuations must be sufficiently spherically symmetric Yu, Khlopov & Polnarev; Harada et al. and

$$\beta(M) \approx 0.056\sigma^{5(+1.5?)}$$

The required increase in the amplitude of the perturbations is reduced Georg, Sengör & Watson; Georg & Watson; Carr, Tenkanen & Vaskonen; Cole & Byrnes:

Primordial curvature perturbation power spectrum



required amplitude for standard cosmological history

amplitude on CMB scales

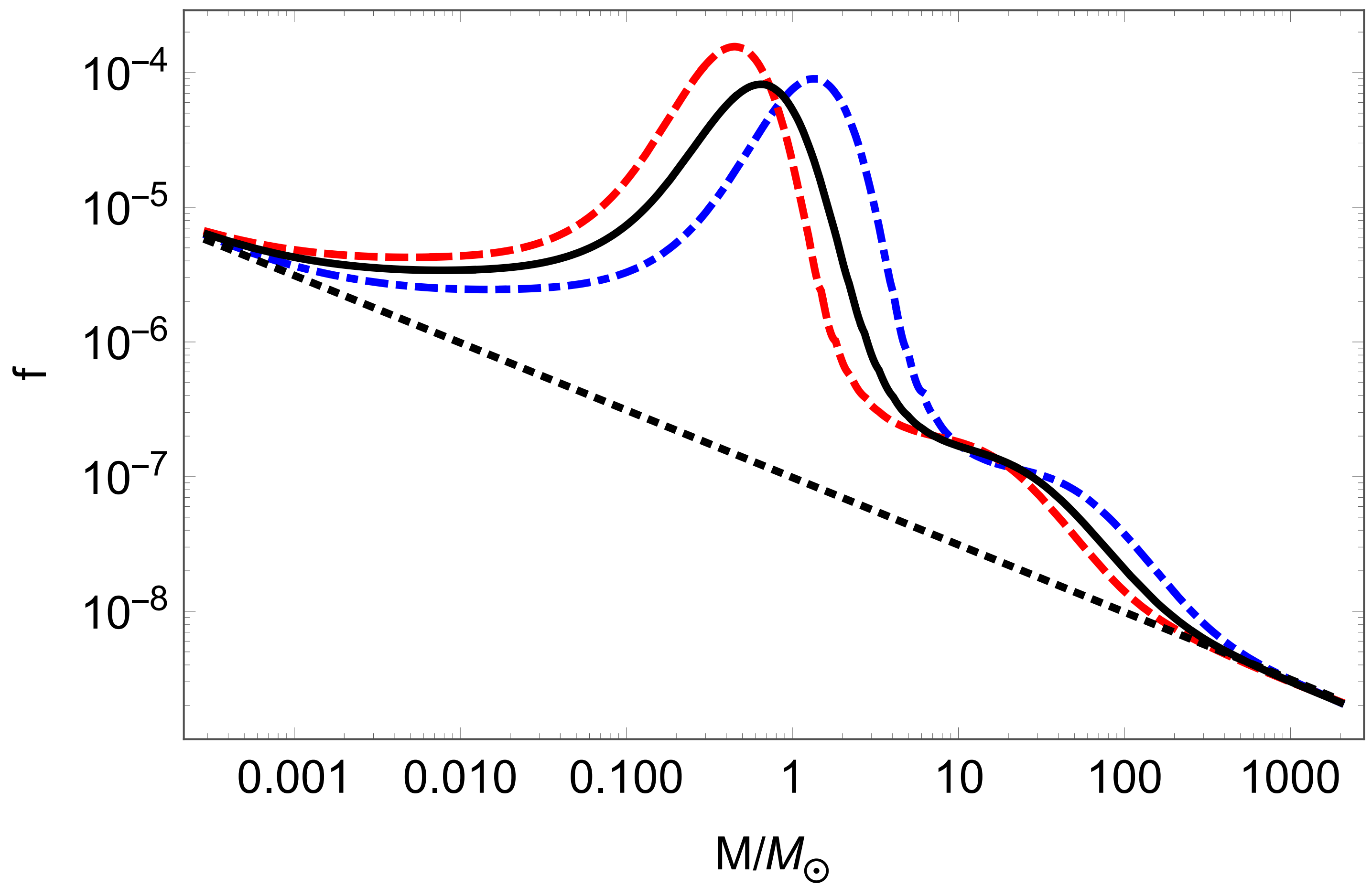
Cole & Byrnes

k

iii) threshold for collapse

Is reduced (so PBH abundance increased) at phase transitions e.g. the QCD phase transition when the horizon mass is ~Solar mass. Jedamzik

Using recent lattice calculation of QCD phase transition Byrnes et al. find a 2 order of magnitude enhancement in β (but perturbations still need to be larger than on cosmological scales):



Byrnes et al.

axion-like curvaton

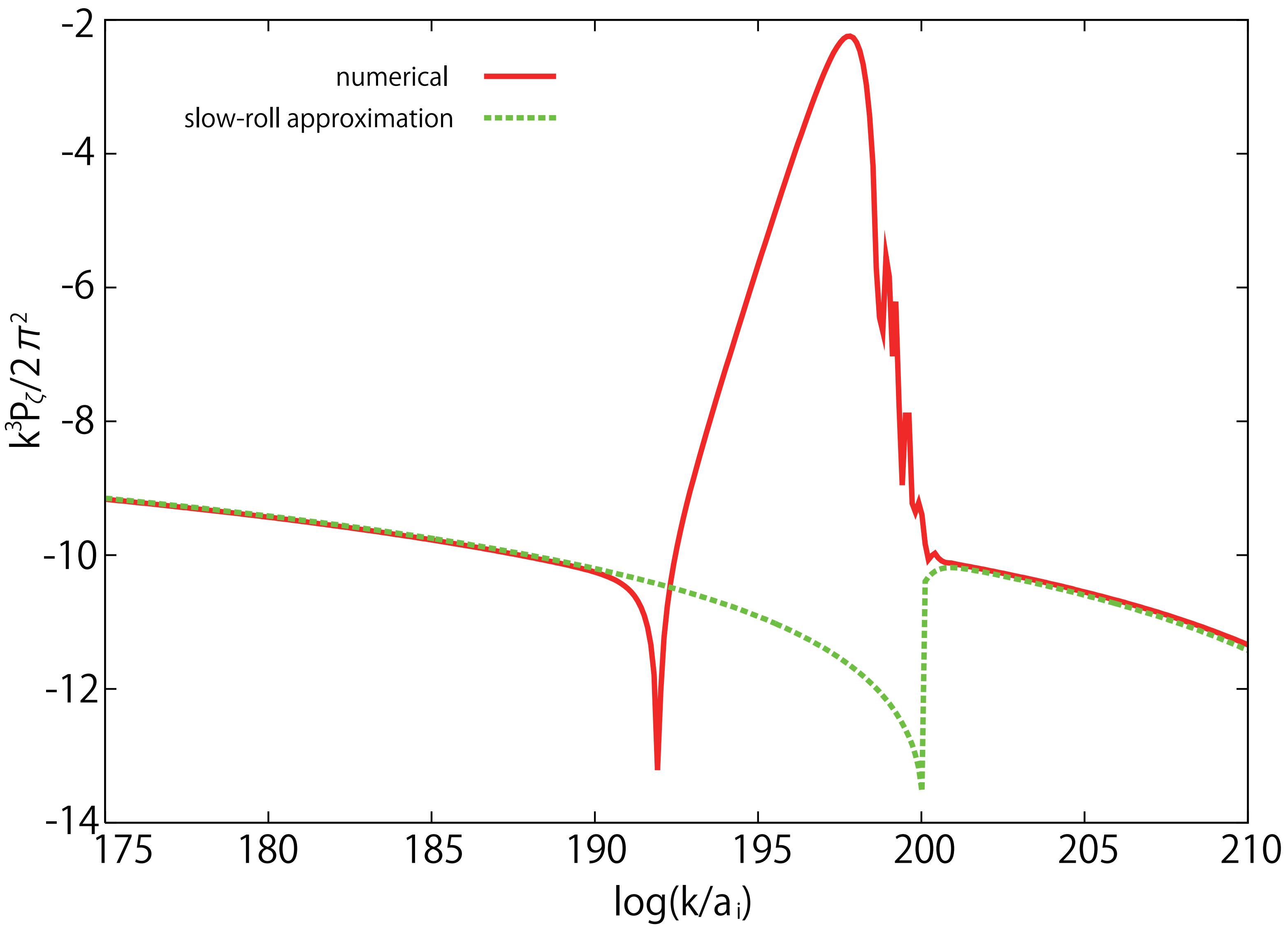
Kawasaki, Kitajima & Yanagida

Large scale perturbations generated by inflaton, small scale (PBH forming) perturbations by curvaton (a spectator field during inflation gets fluctuations and decays afterwards producing perturbations Lyth & Wands)

b) double inflation

Saito, Yokoyama & Nagata; Kannike et al.

Perturbations on scales which leave the horizon close to the end of the 1st period, of inflation get amplified during the 2nd period.



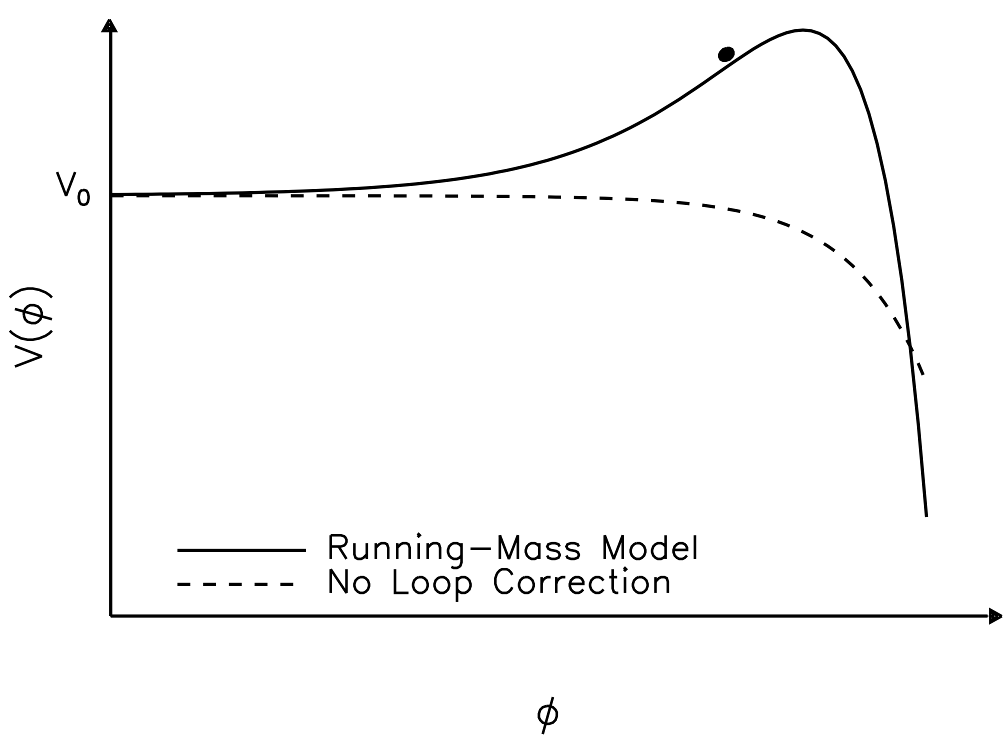
Also double inflation models where large scale perturbations are produced during 1st period, and small scale (PBH forming) perturbations during 2nd (Kawasaki et al.; Kannike et al.; Inomata et al.)

ii) monotonically increasing power spectrum

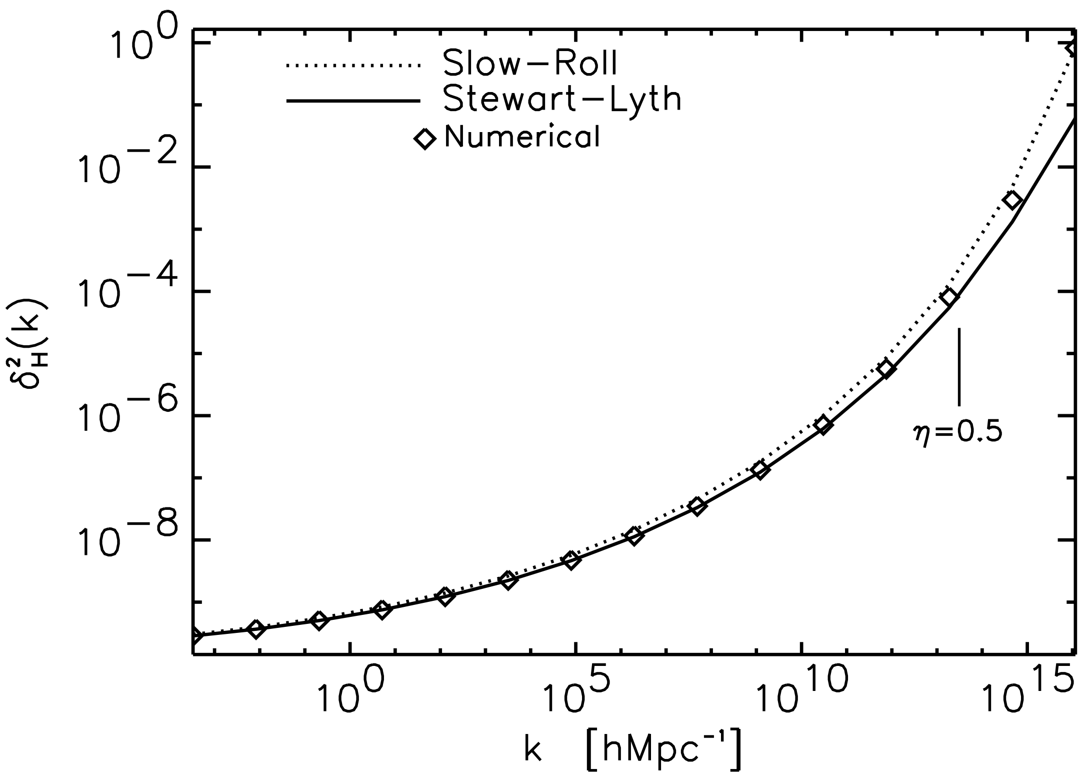
running-mass inflation Stewart

$$V(\phi) = V_0 + \frac{1}{2} m_\phi^2(\phi)\phi^2$$

potential



primordial power spectrum



Leach, Grivell, Liddle

An aside: 'Pitfalls of a power-law parameterisation of the primordial power spectrum for primordial black hole formation' 1805.05178

It is common to parameterise the primordial power spectrum as:

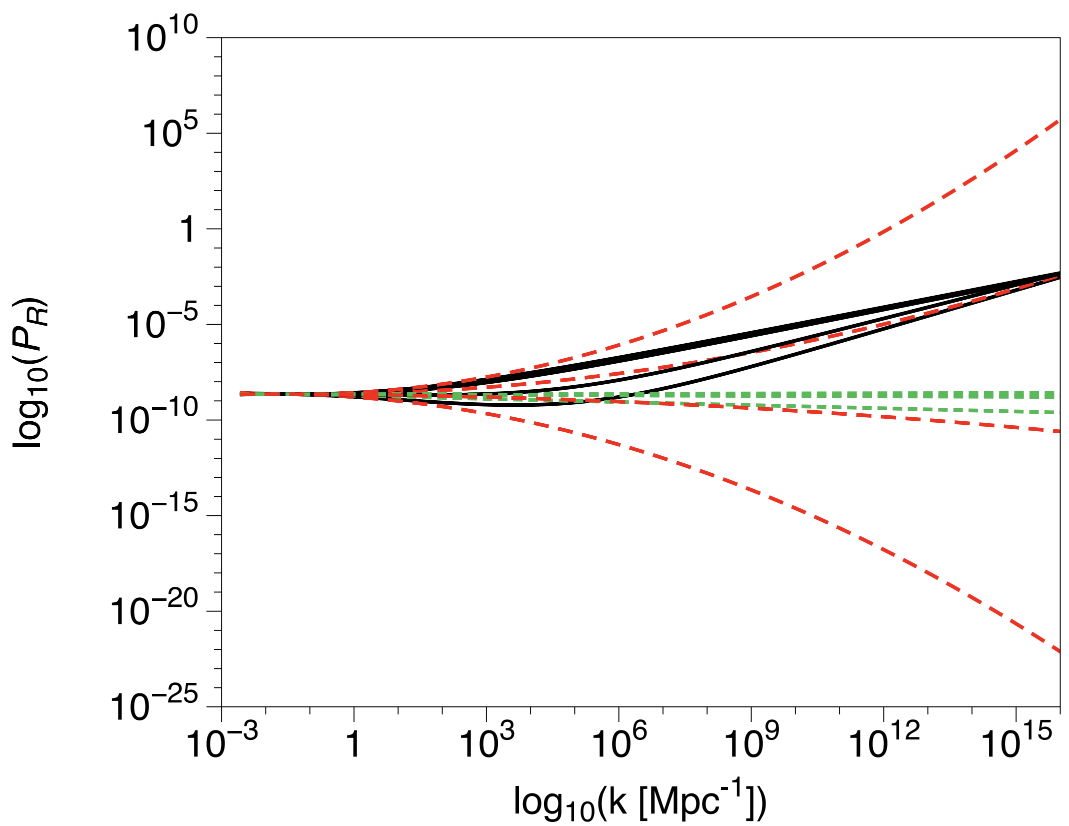
$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_0}\right)^{n_{\rm s}(k)-1} \quad \text{with} \quad n_{\rm s}(k) = n_{\rm s}|_{k_0} + \alpha_{\rm s}\ln\left(\frac{k}{k_0}\right) + \beta_{\rm s}\ln^2\left(\frac{k}{k_0}\right) + \ldots,$$

For slow-roll inflation $(n_{\rm s}-1) \sim \mathcal{O}(\epsilon)\,, \quad \alpha_{\rm s} \sim \mathcal{O}(\epsilon^2)\,, \quad \beta_{\rm s} \sim \mathcal{O}(\epsilon^3)$ where $\epsilon < 1$

The expansion of n_s is therefore valid only if $\epsilon \ln\left(\frac{k}{k_0}\right) \ll 1$

This holds over cosmological scales, but not down to PBH forming scales:

Power spectra of some PBH producing inflation models:



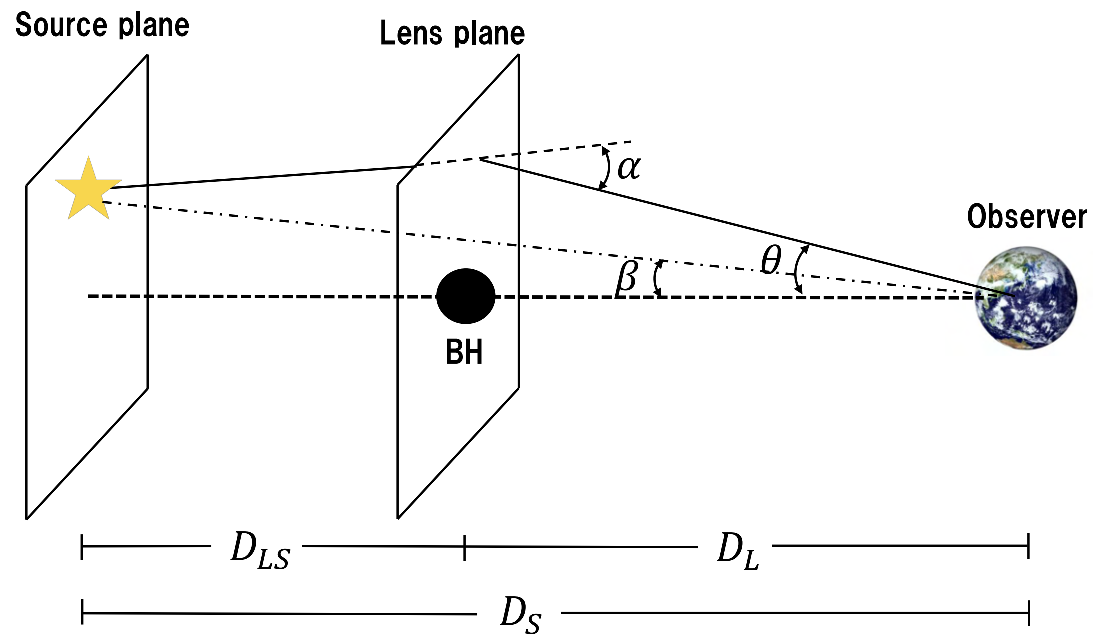
full calculation

1st order in expansion

2nd order in expansion

gravitational lensing

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



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

Sasaki et al.

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

deflection $$\alpha = \frac{4GM_{\rm BH}}{D_{\rm L}\theta}$$

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

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

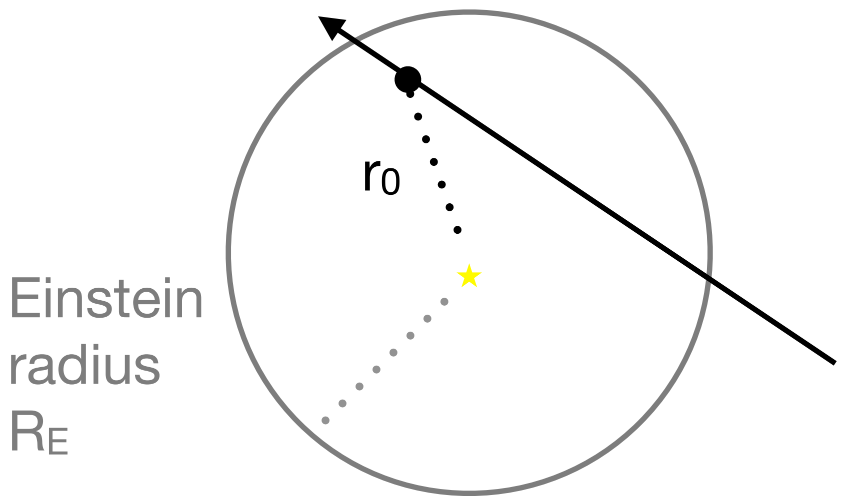
Einstein radius: $$R_E = \sqrt{\frac{4GMD_LD_{LS}}{D_S}}$$

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

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

stellar microlensing Paczynski

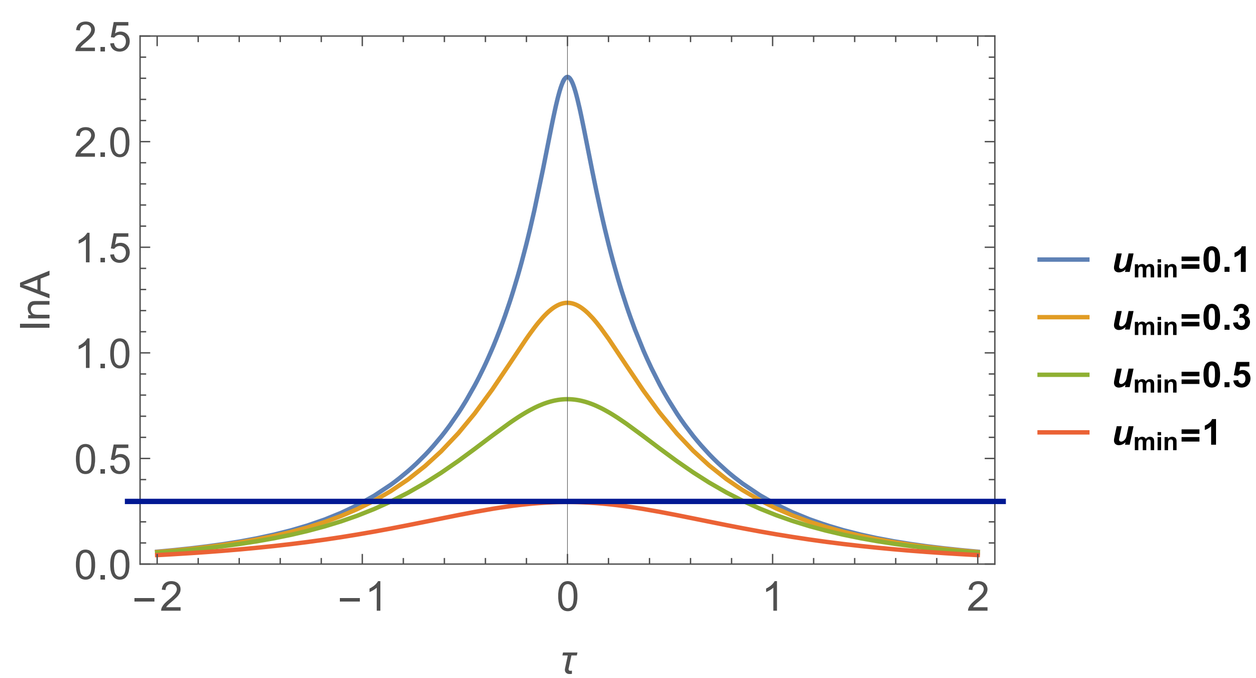
Microlensing occurs when angular resolution is too small to resolve multiple images, instead observe amplification of source:



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

r_0 = “impact parameter”

$$\hat{t} = \frac{2R_E}{v}$$ 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.

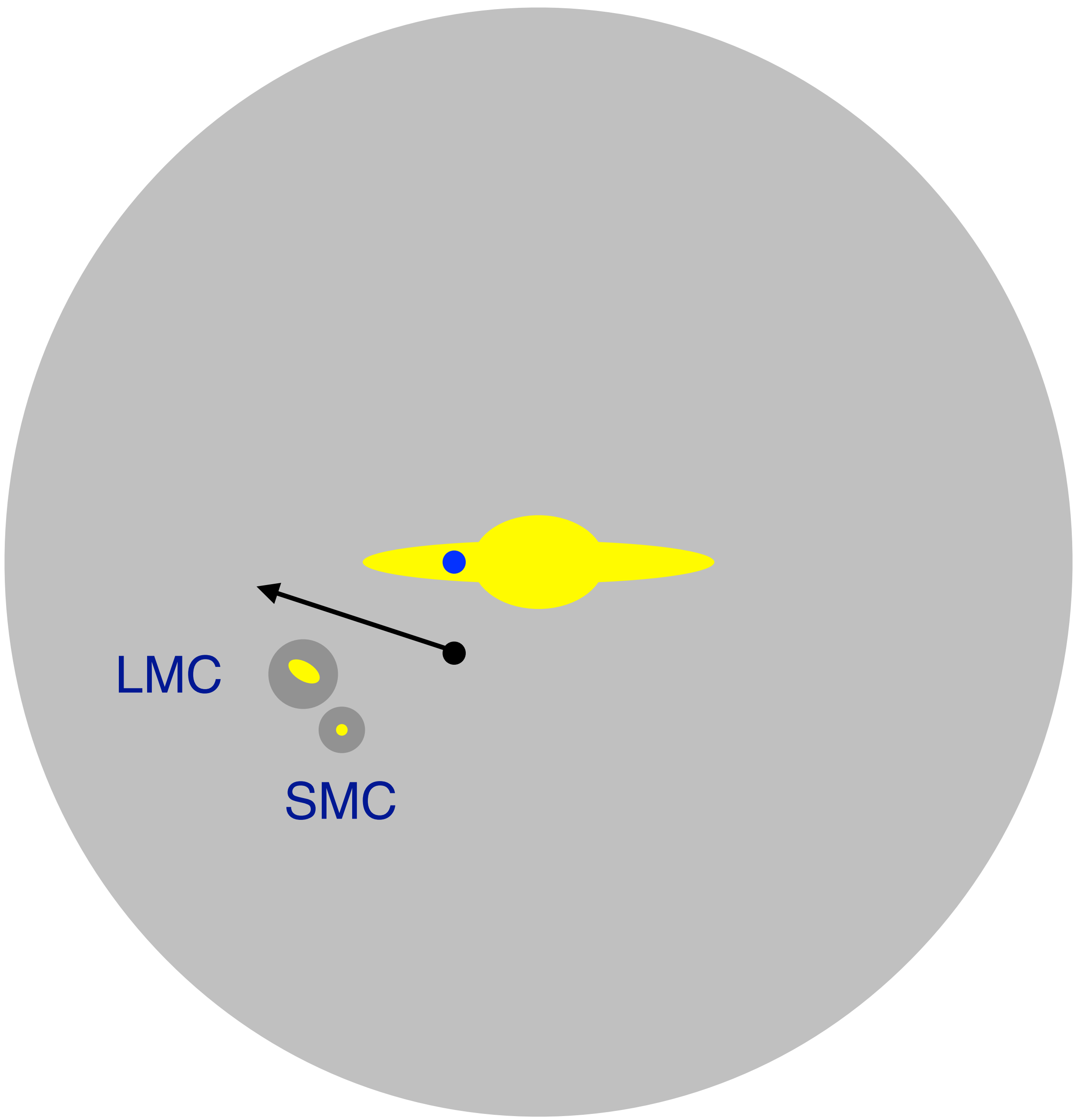
‘Duration’ of event (Einstein diameter crossing time):

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

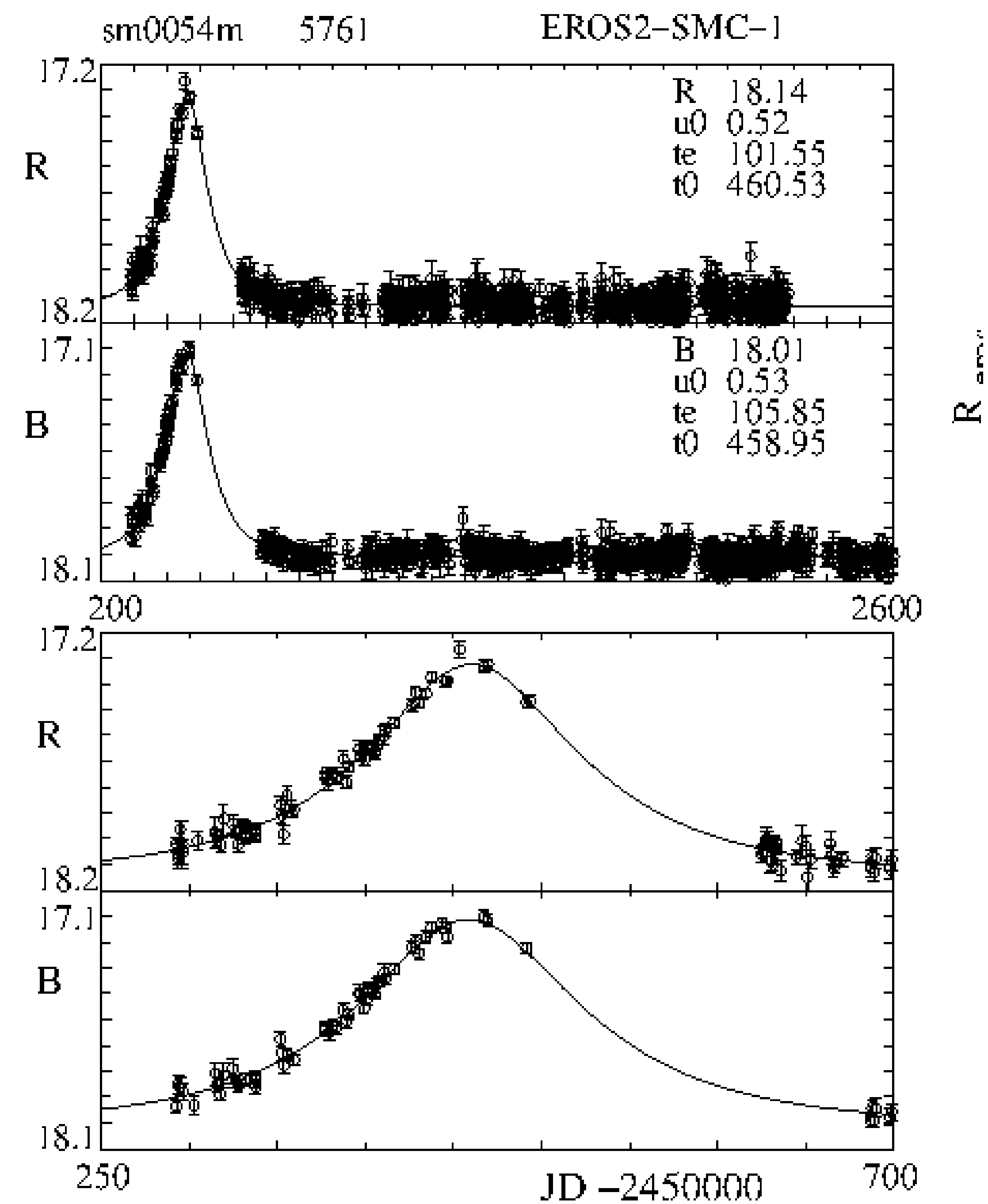
n.b. this all assumes point source and lens, see later…

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

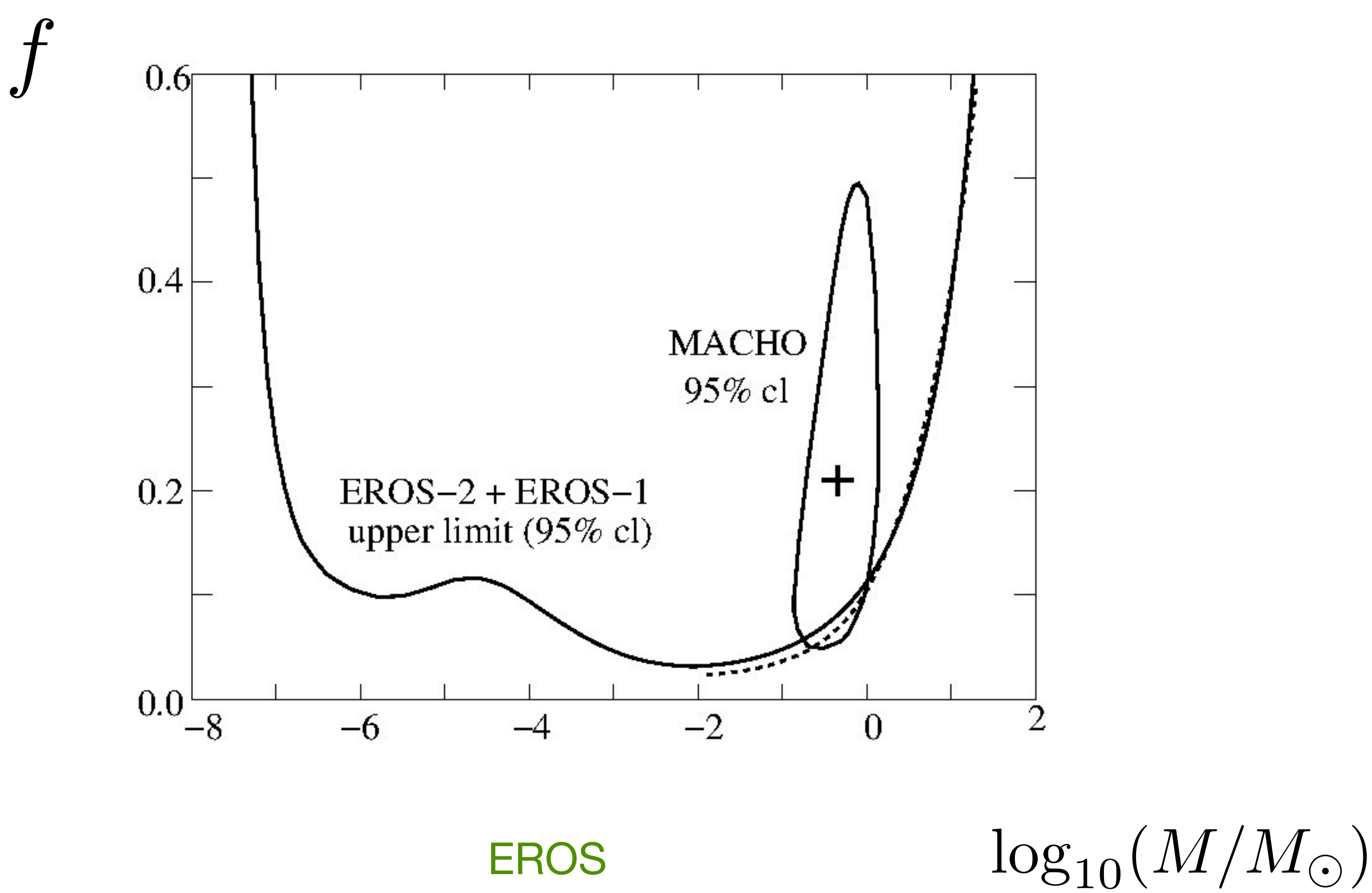
EROS

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):

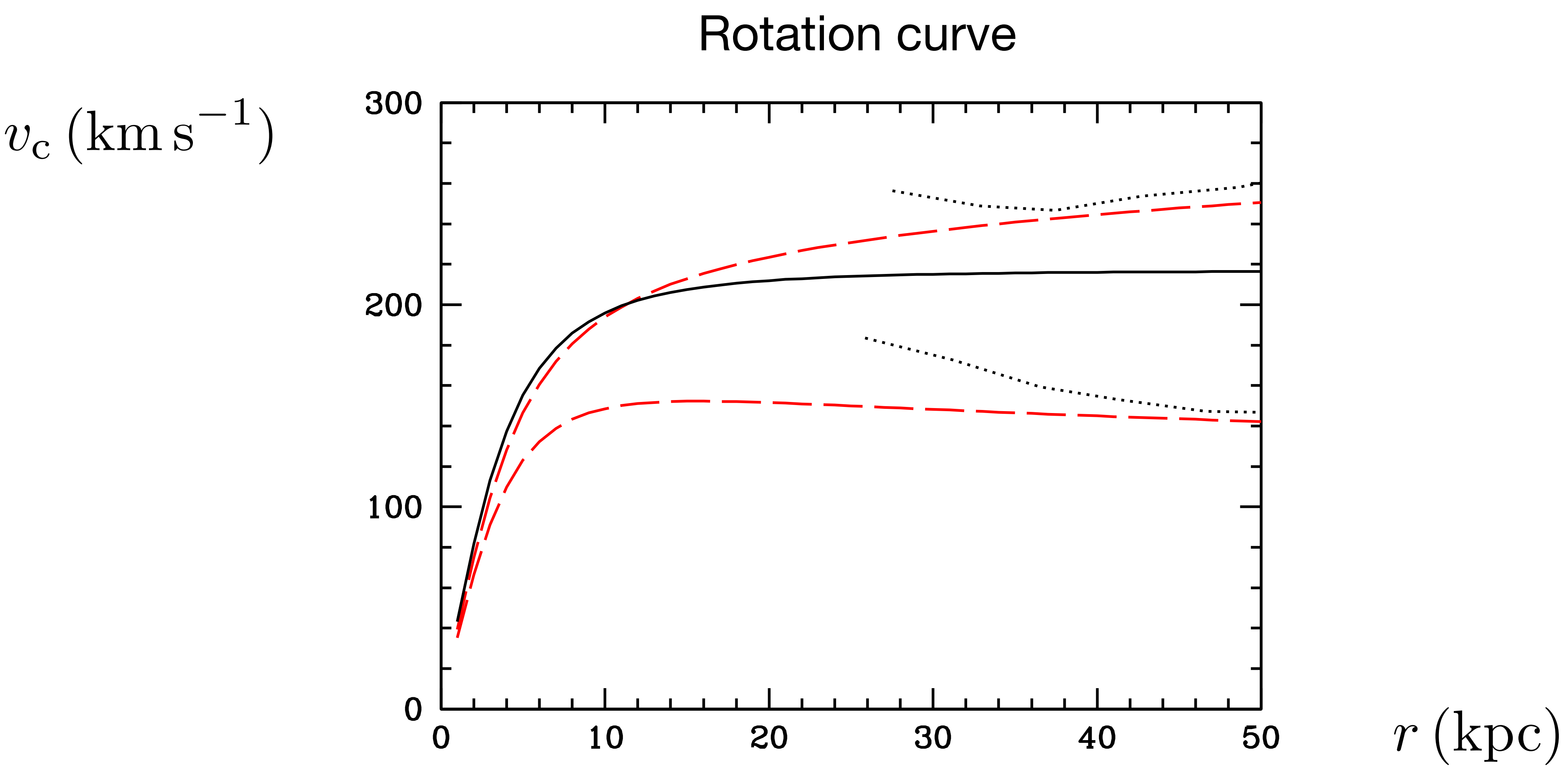


EROS

Astrophysical uncertainties on microlensing constraints

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.

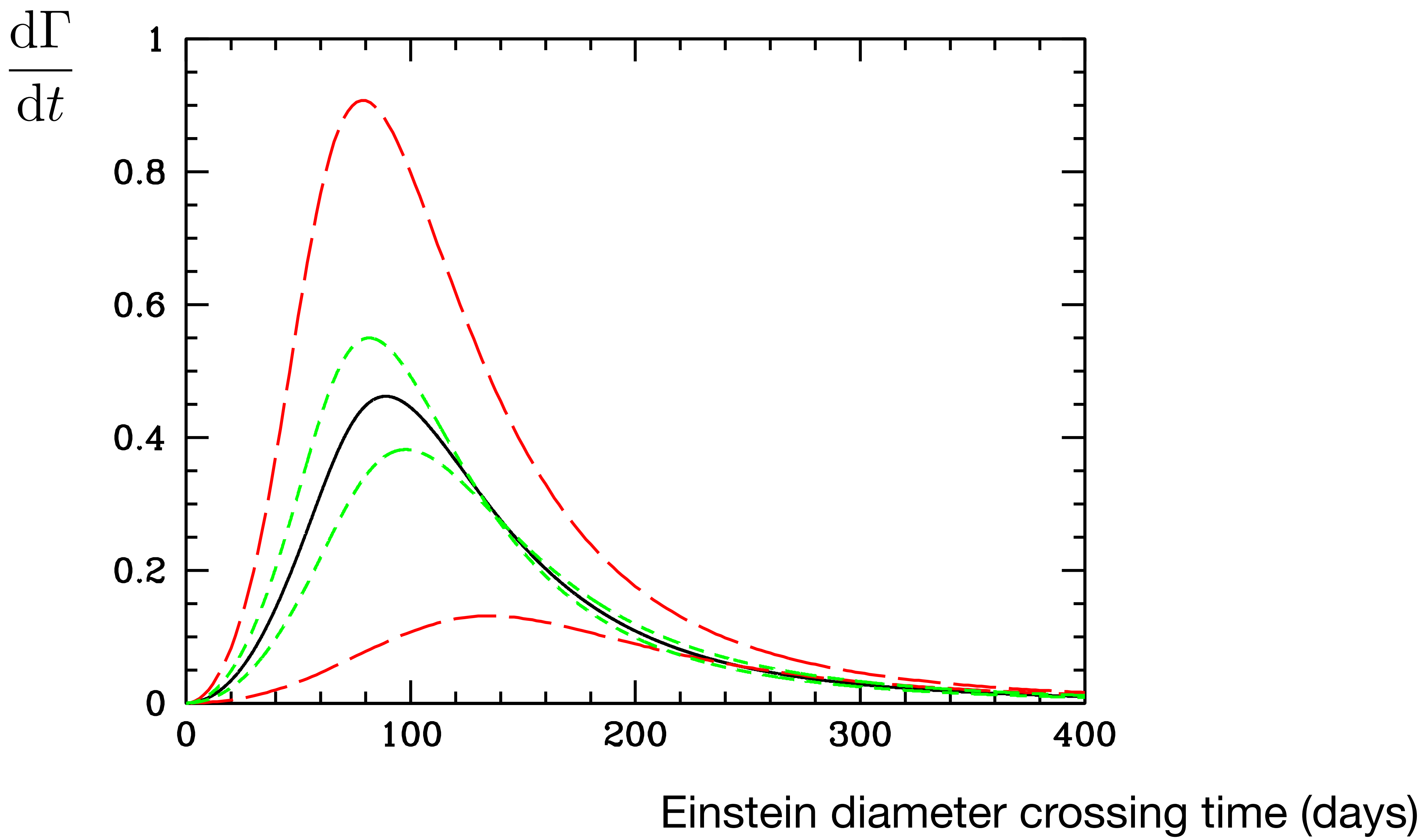


——— standard halo (SH)

— — — 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)

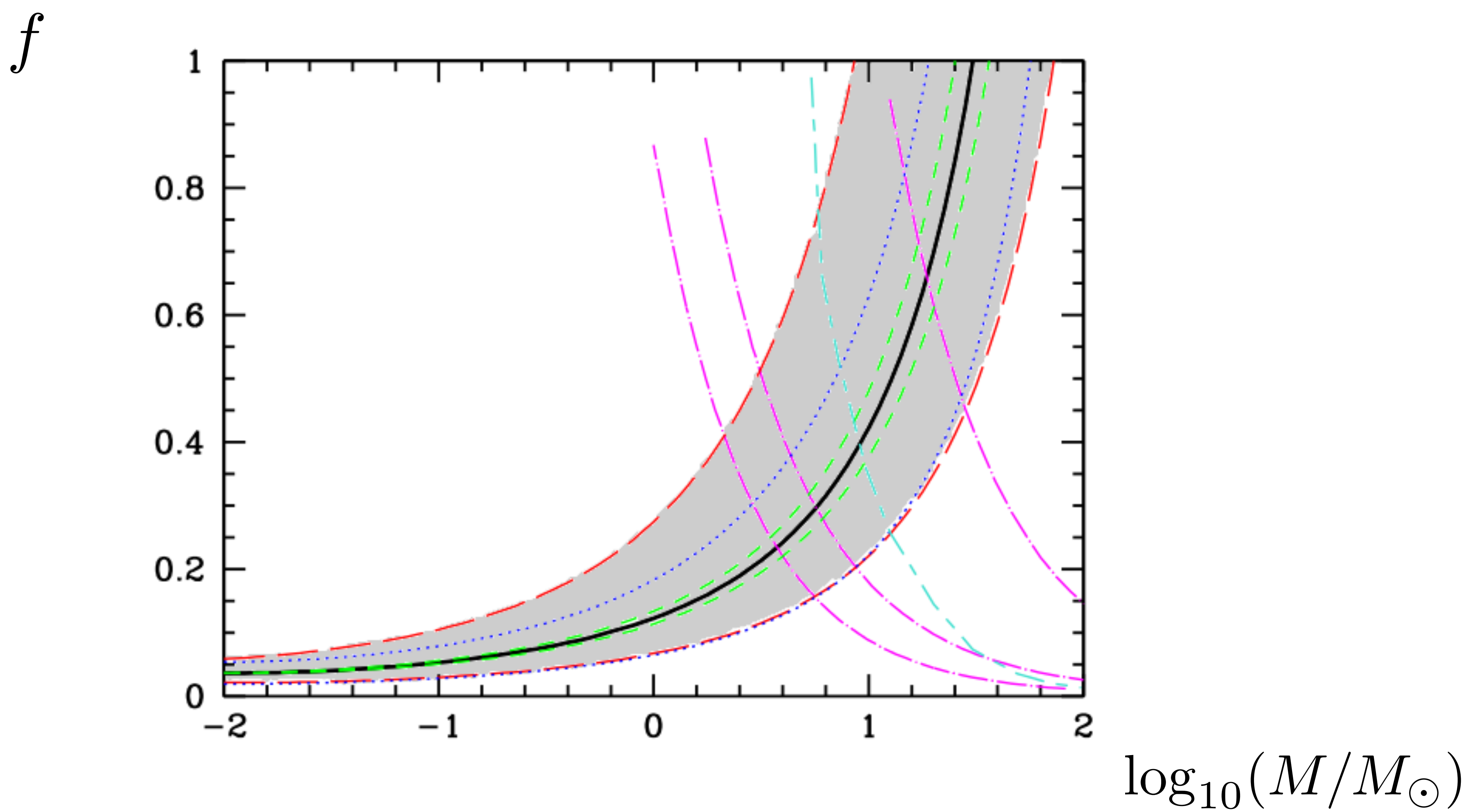


Microlensing: —— standard halo (SH)

– – – power law halos B and C

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

Constraints on halo fraction for delta-function MF



standard halo (SH)

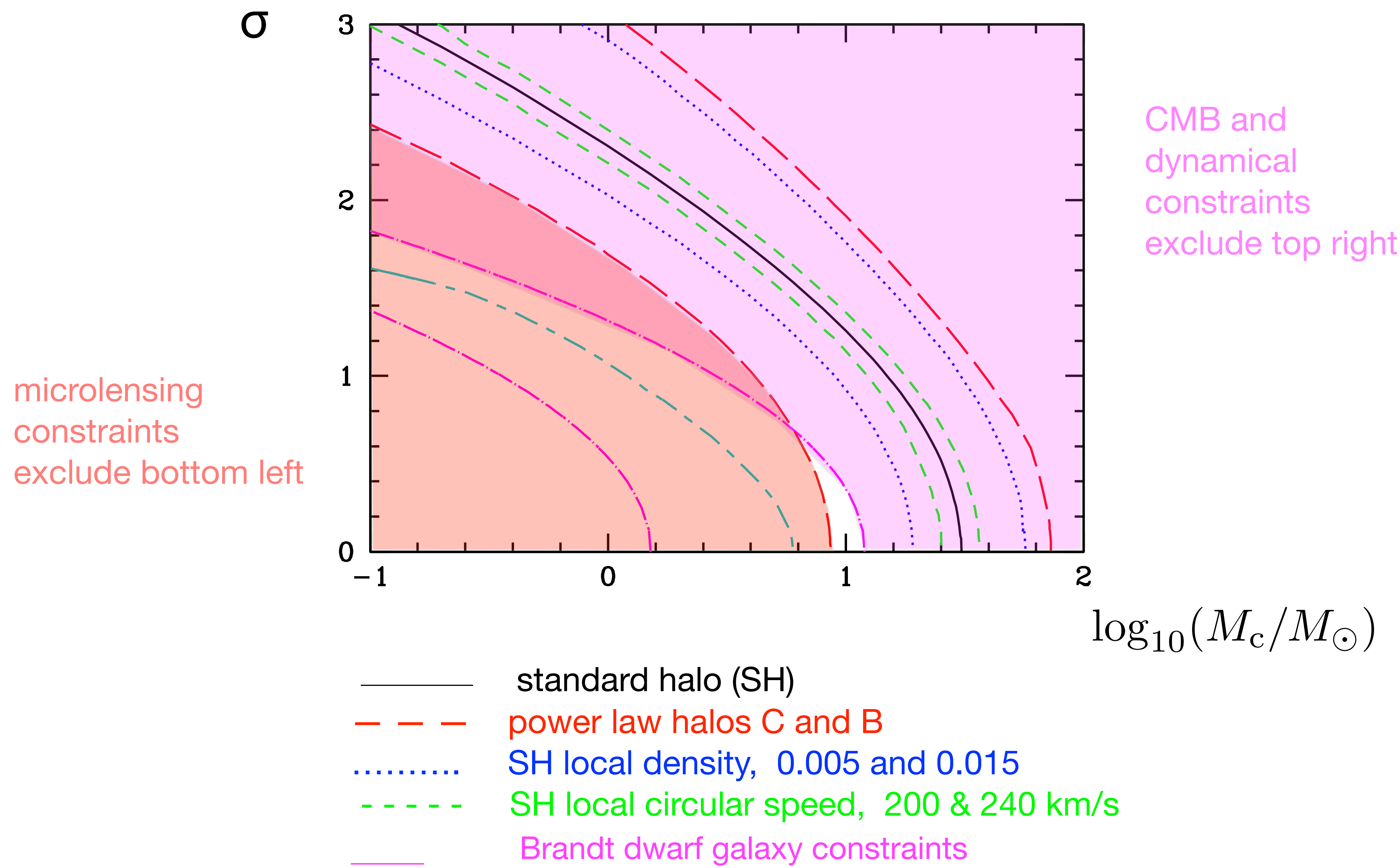
SH local circular speed, 200 & 240 km/s

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

power law halos C and B

Brandt dwarf galaxy constraints

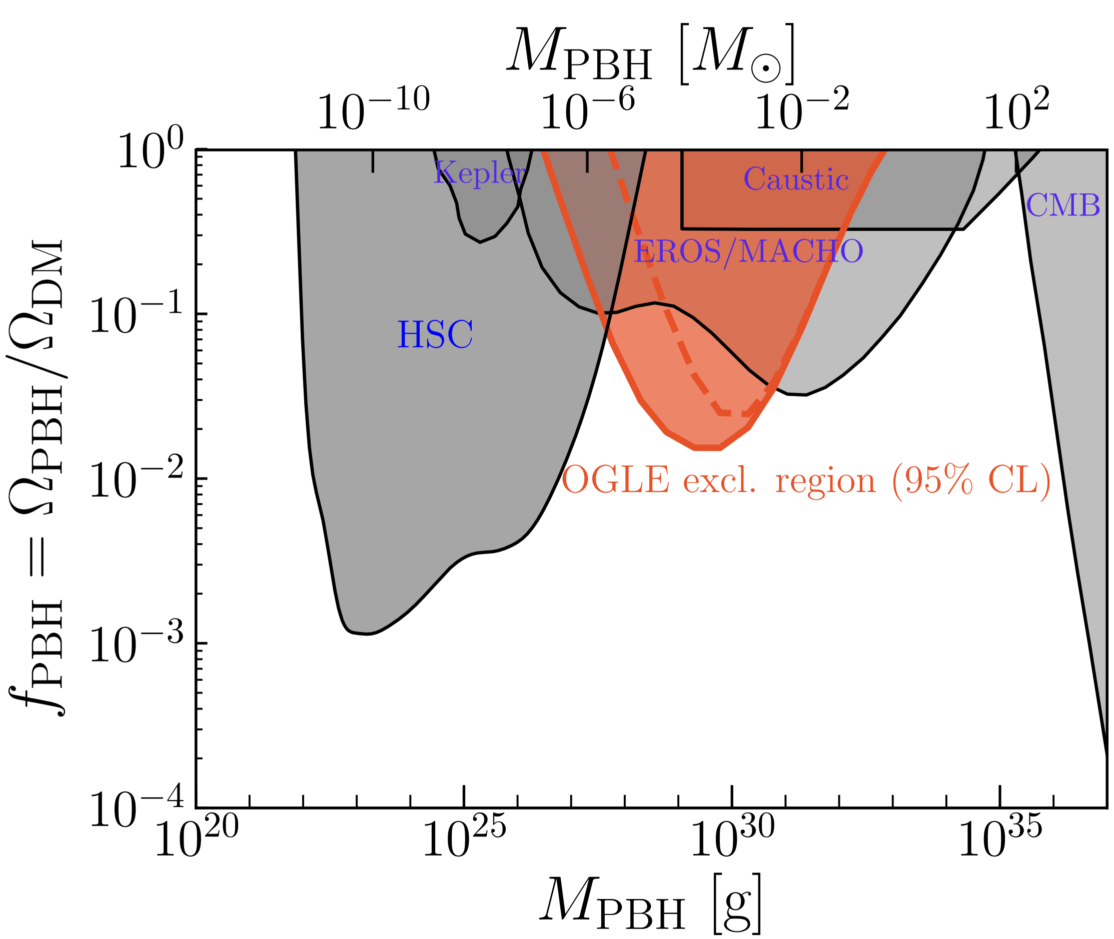
Magellanic Clouds microlensing constraints on width of log-normal MF with f=1



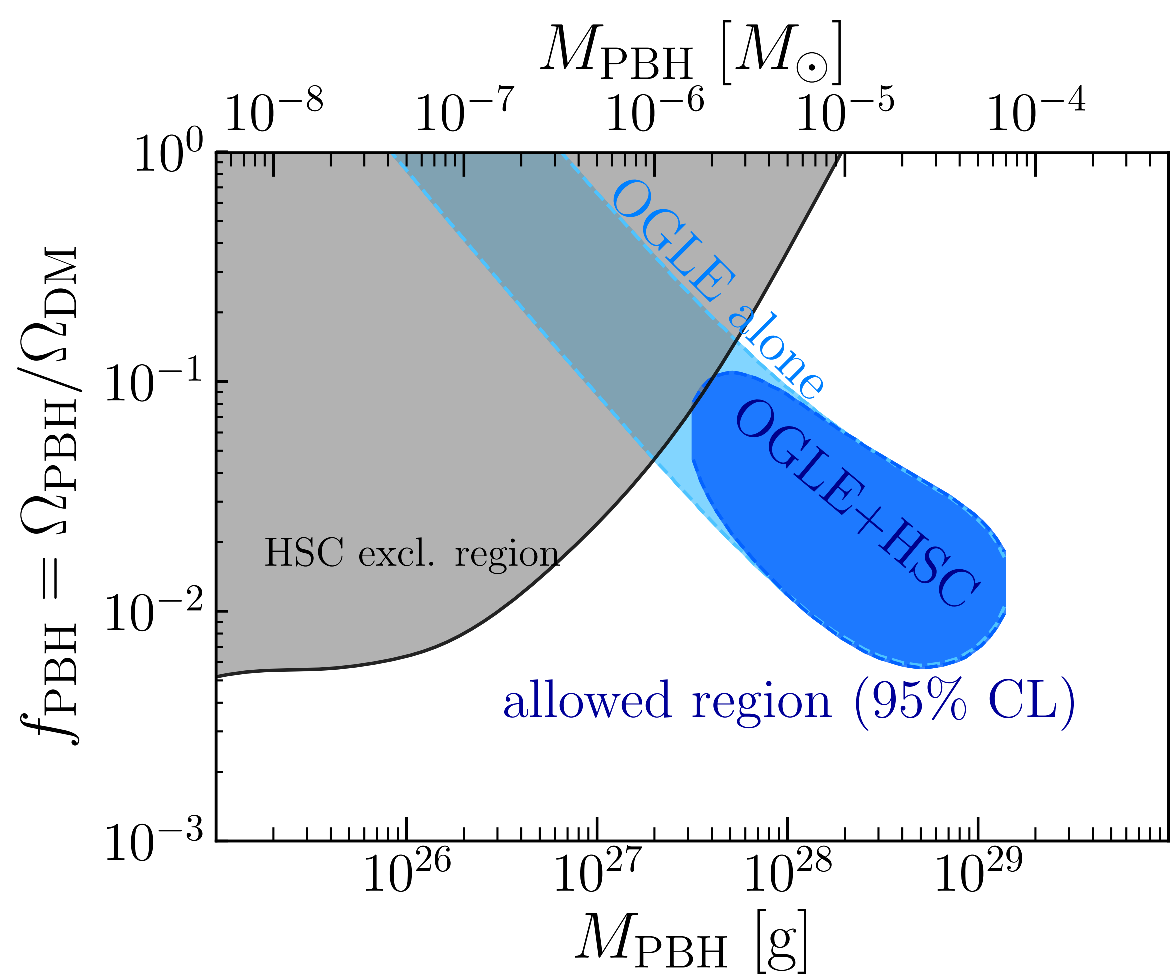
stars in Galactic bulge

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

Exclusion limit
assuming no PBH lensing observed



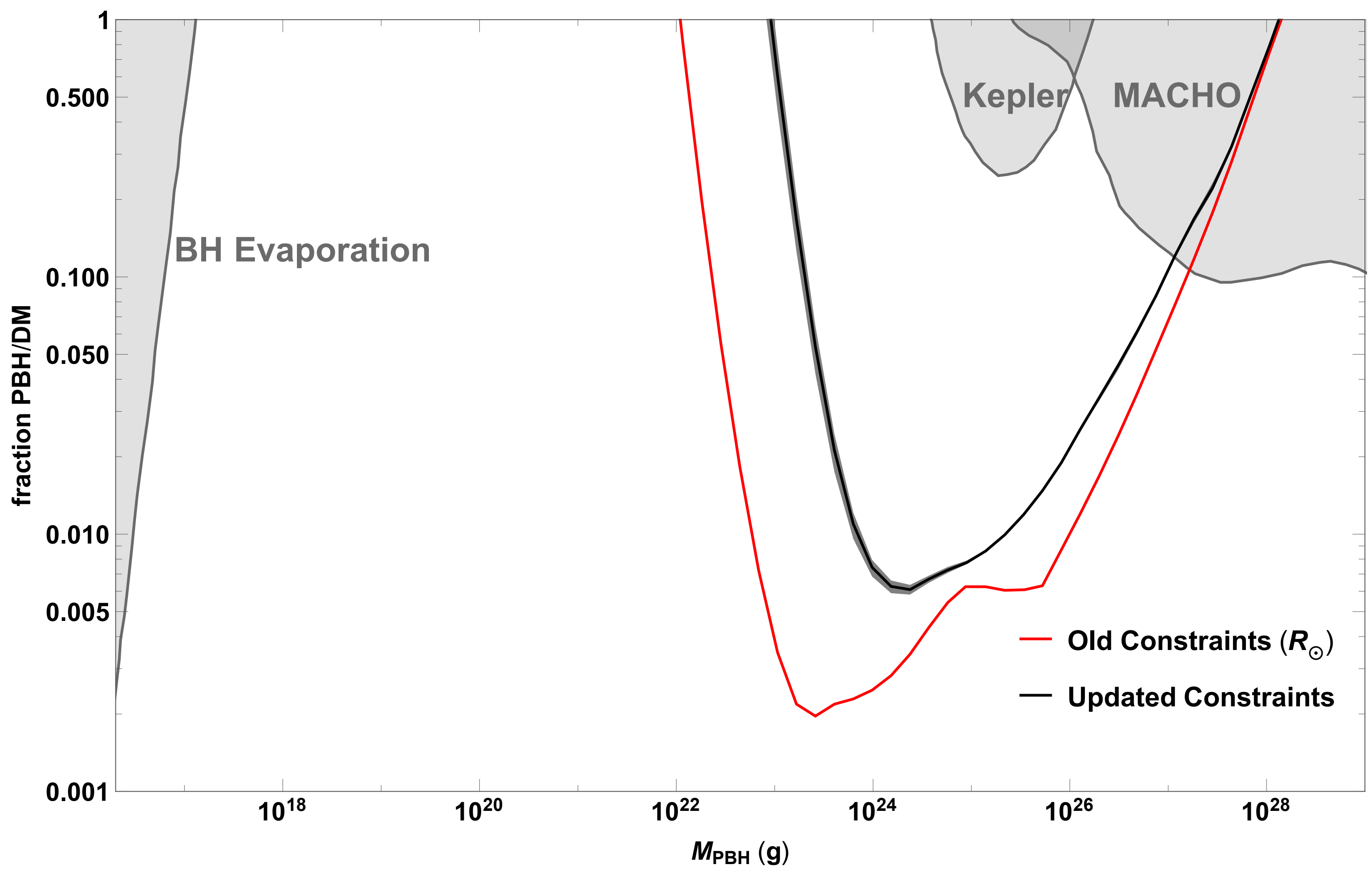
Allowed region
assuming 6 ultra-short events are due to PBHs



Niikura et al.

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.

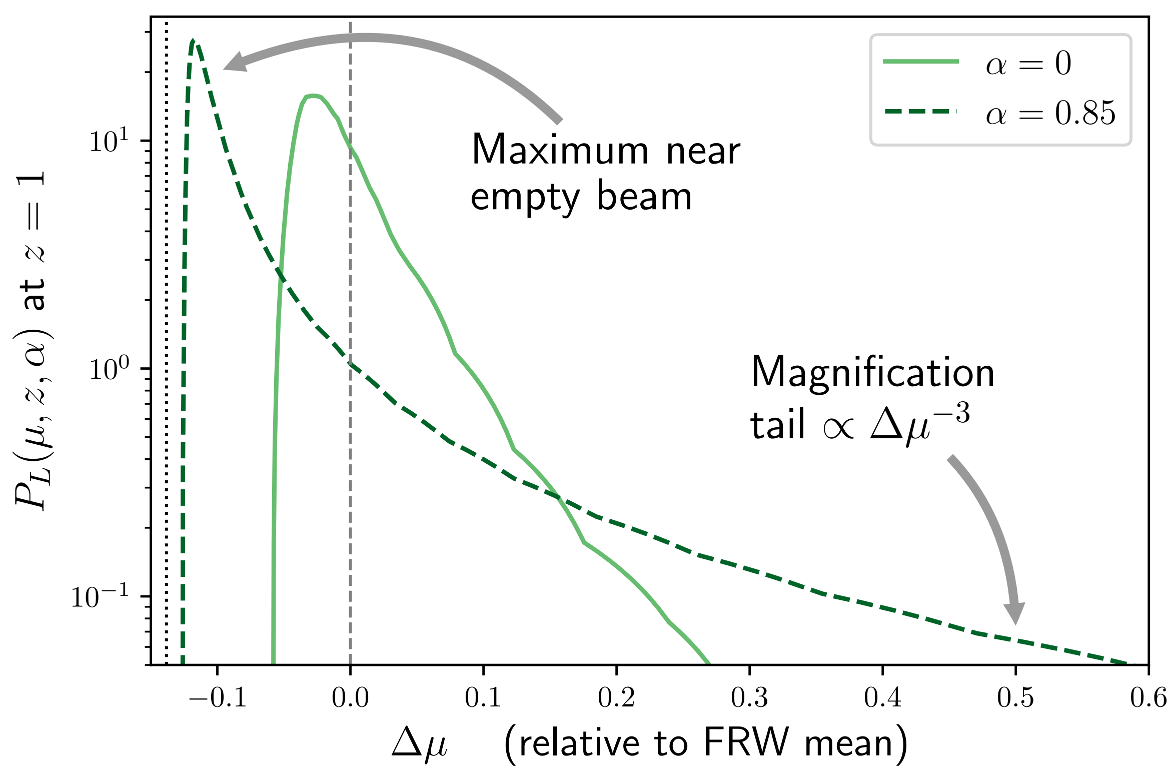
Finite size of source stars and effects of wave optics (Schwarzschild radius of BH comparable to wavelength of light) leads to reduction in maximum magnification for $M \lesssim 10^{-7} M_\odot$ and $M \lesssim 10^{-11} M_\odot$ respectively. Witt & Mao; Gould; Nakamura; Sugiyama, Kurita & Takada

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

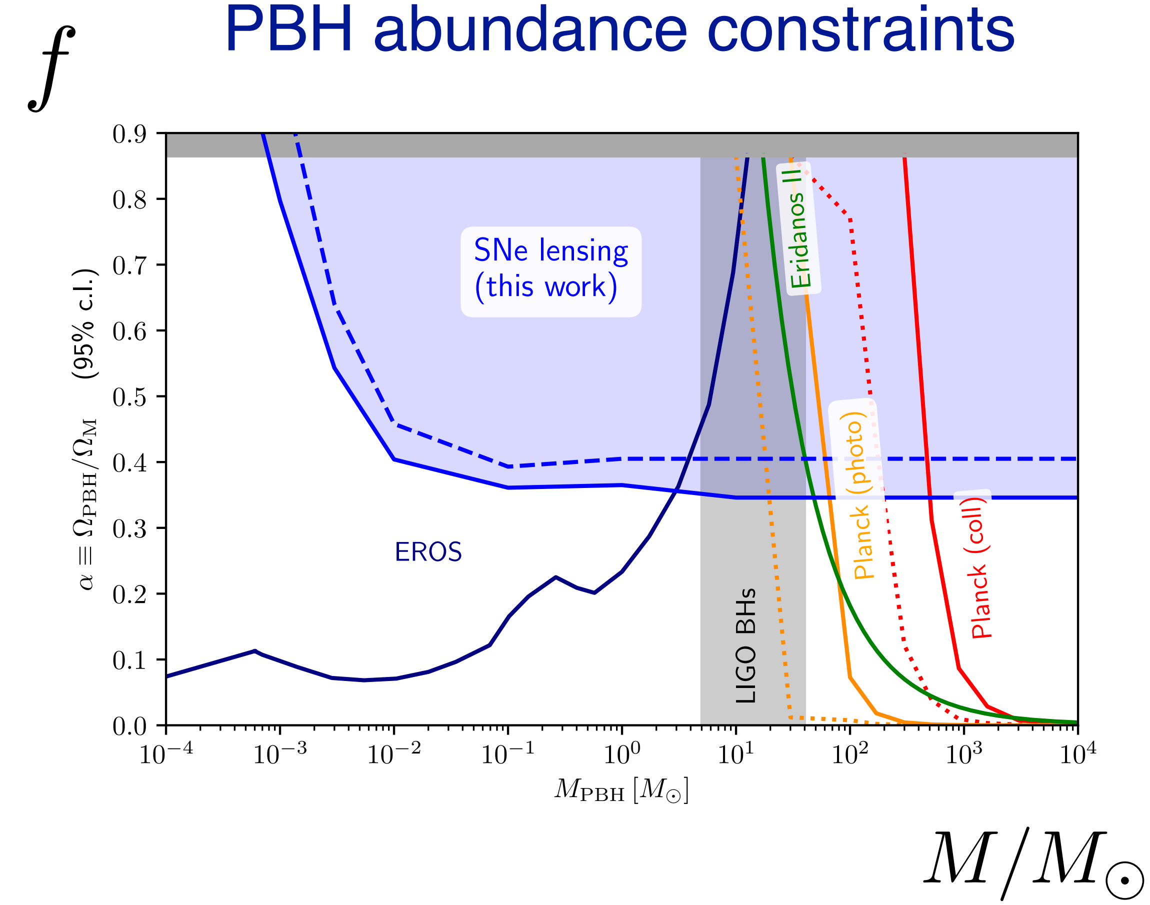
supernova microlensing

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



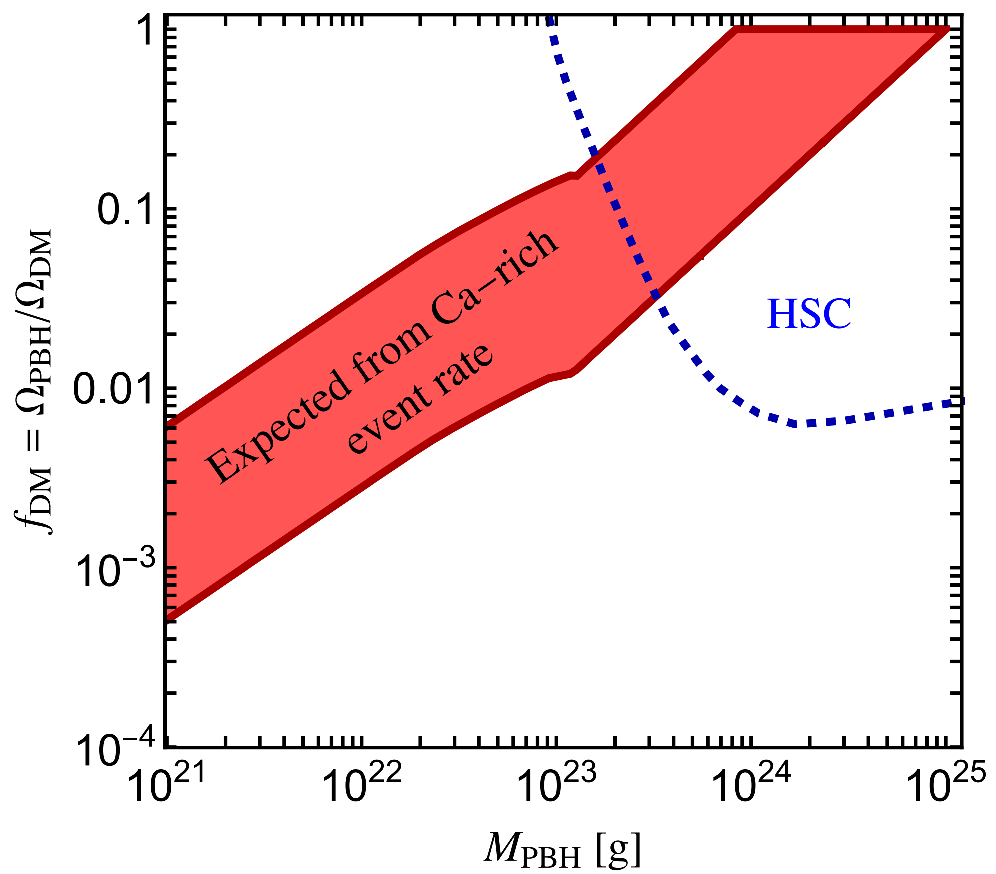
PBH abundance constraints



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

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

Population of faint, Calcium-rich supernovae mostly located at large distances from centre of host galaxy, could be due to PBHs interacting with low mass white dwarfs in dwarf galaxies??
Smirnov et al.



Smirnov et al.

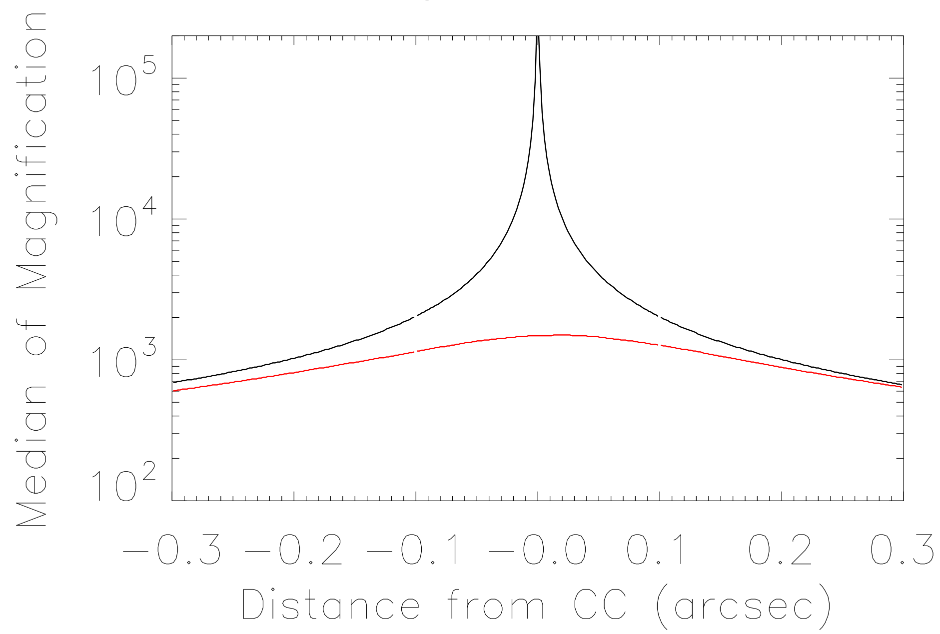
But observational signature of PBH-induced white dwarf explosion not yet reliably calculated. Montero-Camacho et al.

Icarus

When a distant star crosses a galaxy cluster caustic get huge magnification which can be increased 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.

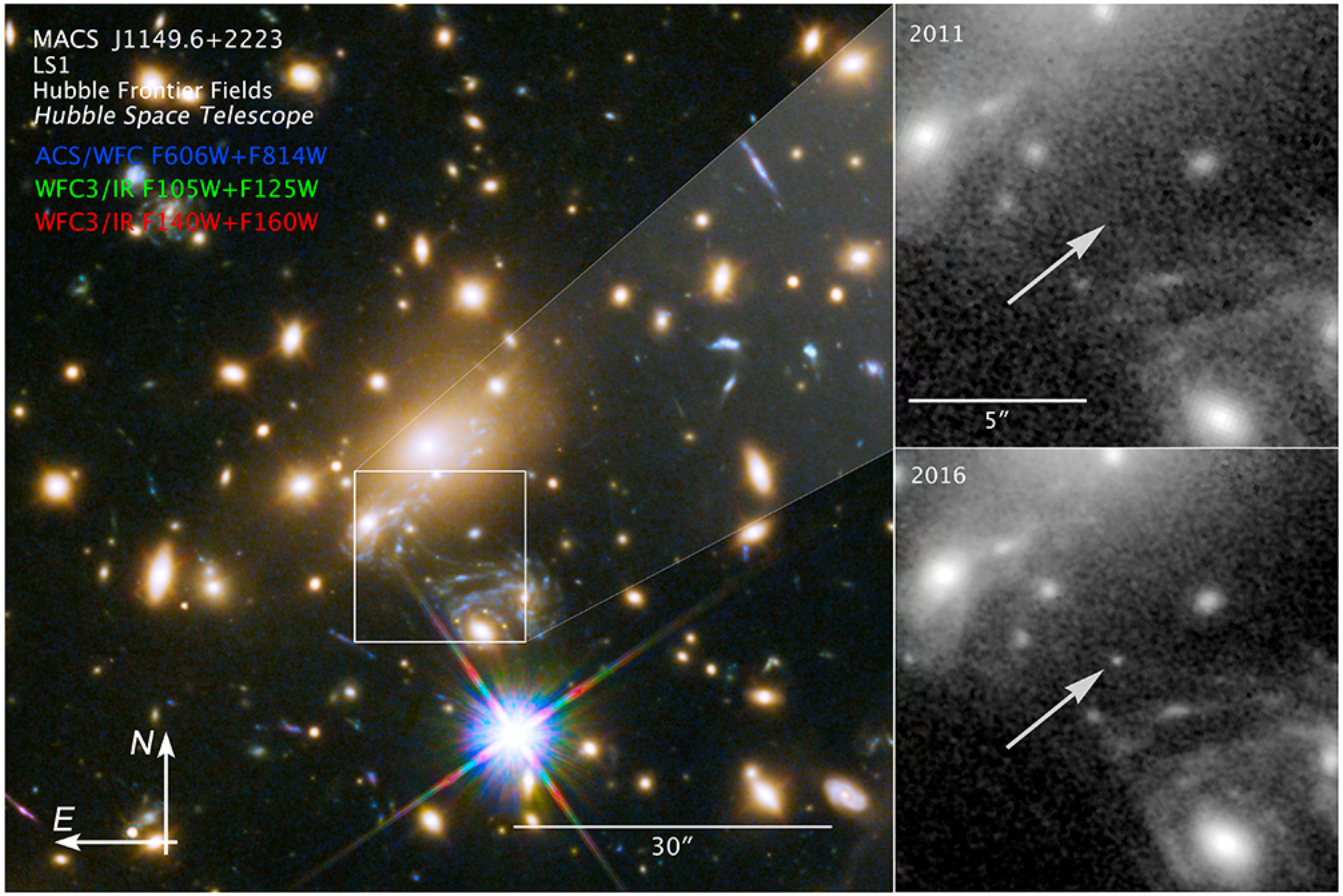


smooth DM, compact DM

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

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.

constraints on light PBHs from evaporation products

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

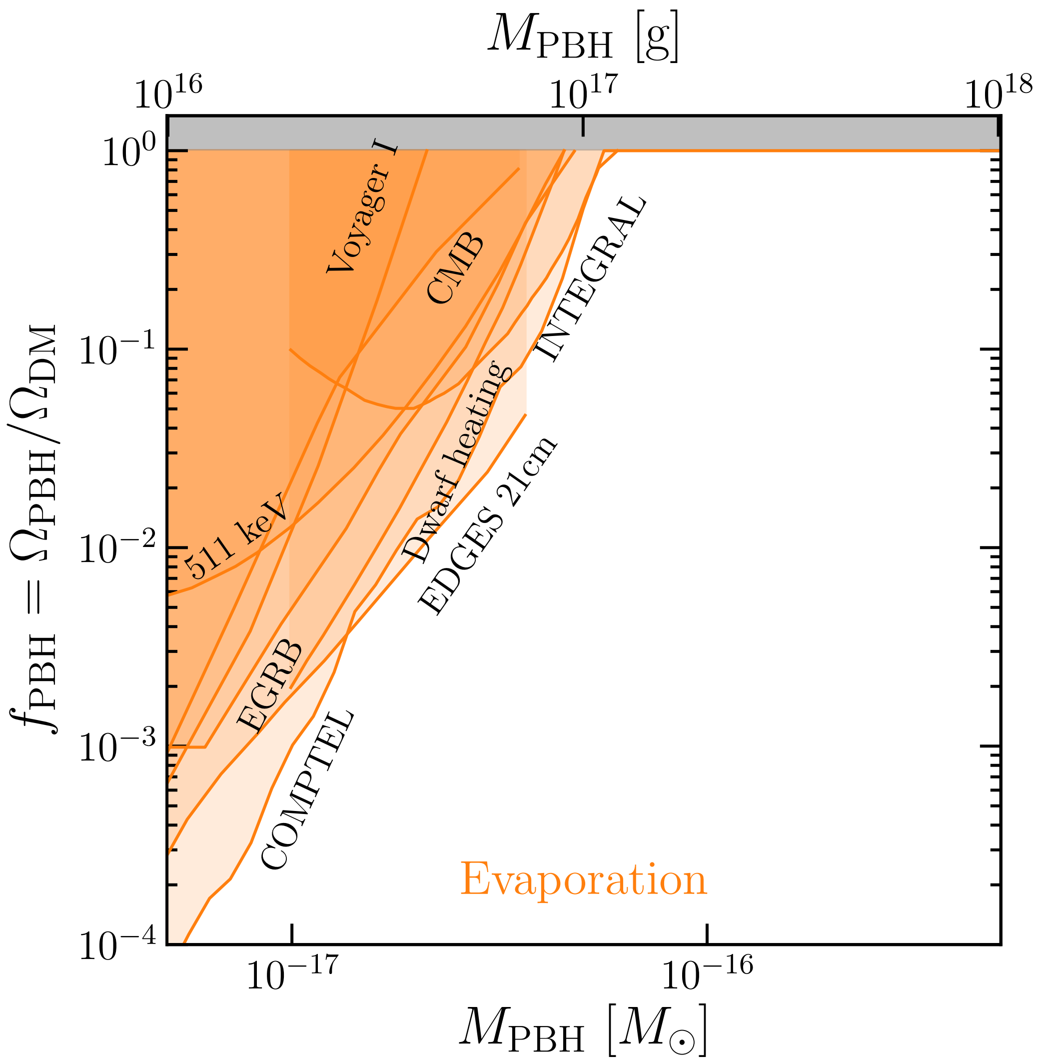
MeV galactic diffuse flux (INTEGRAL) Laha, Munoz & Slatyer (COMPTEL) Coogan, Morrison & Profumo

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

heating of ISM in dwarf galaxy Kim



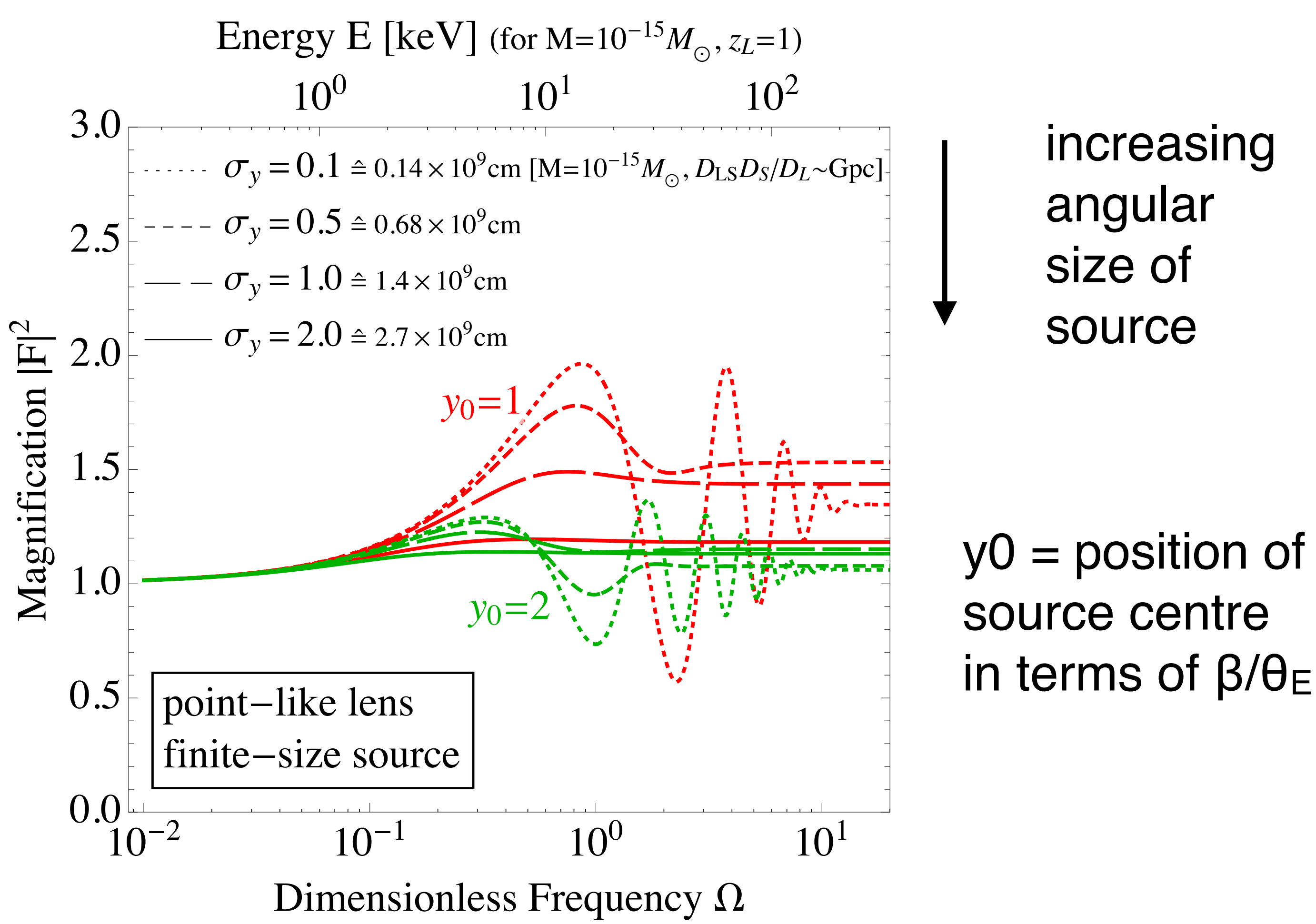
how to constrain asteroid mass PBHs??

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:



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).

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

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

If $f_{max}(M)$ is the maximum allowed PBH fraction for a delta-function MF, an extended mass function ψ(M) has to satisfy:

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

Probing origin of BH binaries using their spins

Farr, Holtz & Farr;… Fernandez & Profumo

Dimensionless spin of individual BH: $\chi = \frac{|\mathbf{S}|}{GM^2}$

Effective spin parameter: $\chi_{\rm eff} = \frac{M_1 \chi_1 \cos\theta_1 + M_2 \chi_2 \cos\theta_2}{M_1 + M_2}$

θ_i=tilt angle between $\mathbf{S}_i$ and orbital AM $\mathbf{L}$

Astrophysical BH binaries:

i) formed in dense stellar environments, spins uncorrelated with orbit: $\chi_{\rm eff} \approx 0$

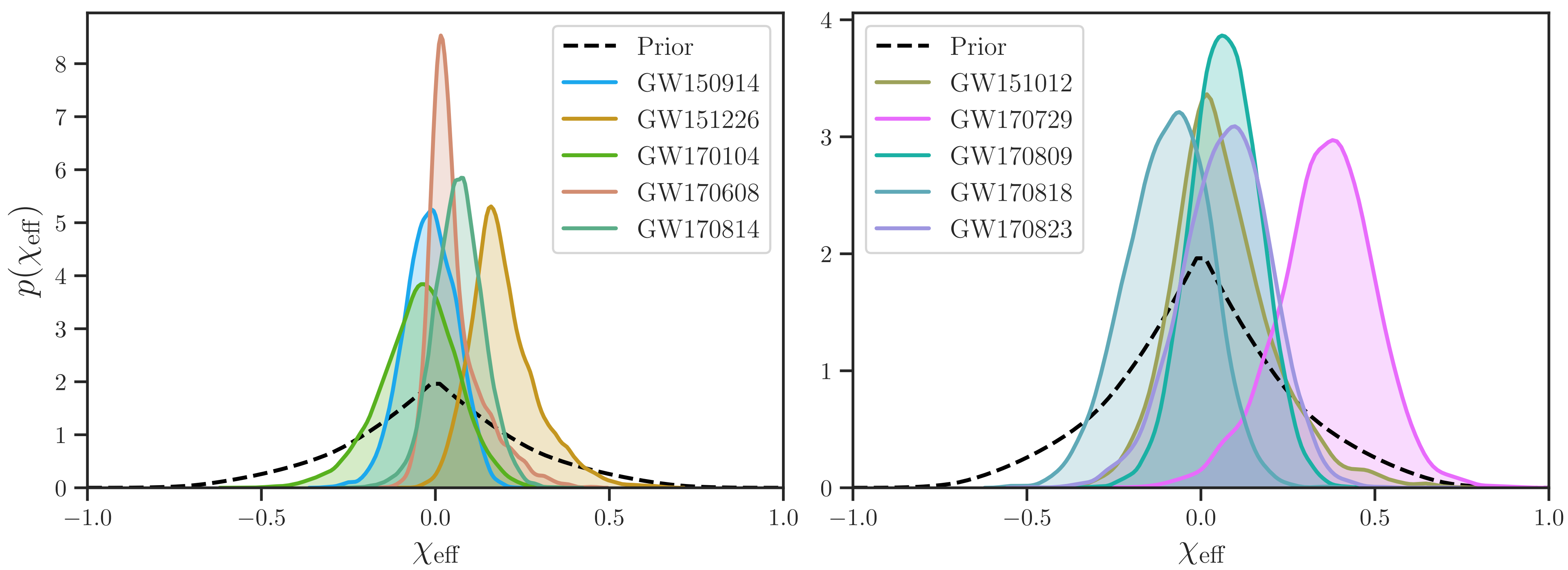
ii) formed in isolation, spins generally aligned with orbital AM: $\chi_{\rm eff} \approx 1$

Primordial BH binaries:

small intrinsic spins, $\chi_i \approx 0 \quad \rightarrow \quad \chi_{\rm eff} \approx 0$

de Luca et al.

Effective spin parameter probability distributions of 10 BH-BH events observed in LIGO-Virgo runs O1 and O2



Fernandez & Profumo

Entire population having large $\chi_{\rm eff} \approx 1$ already disfavoured.

With O(100) events (~1 year of O3) will be able to distinguish low intrinsic spin ($\chi_i \approx 0$) and spins uncorrelated with orbit.

Structure formation with PBH dark matter

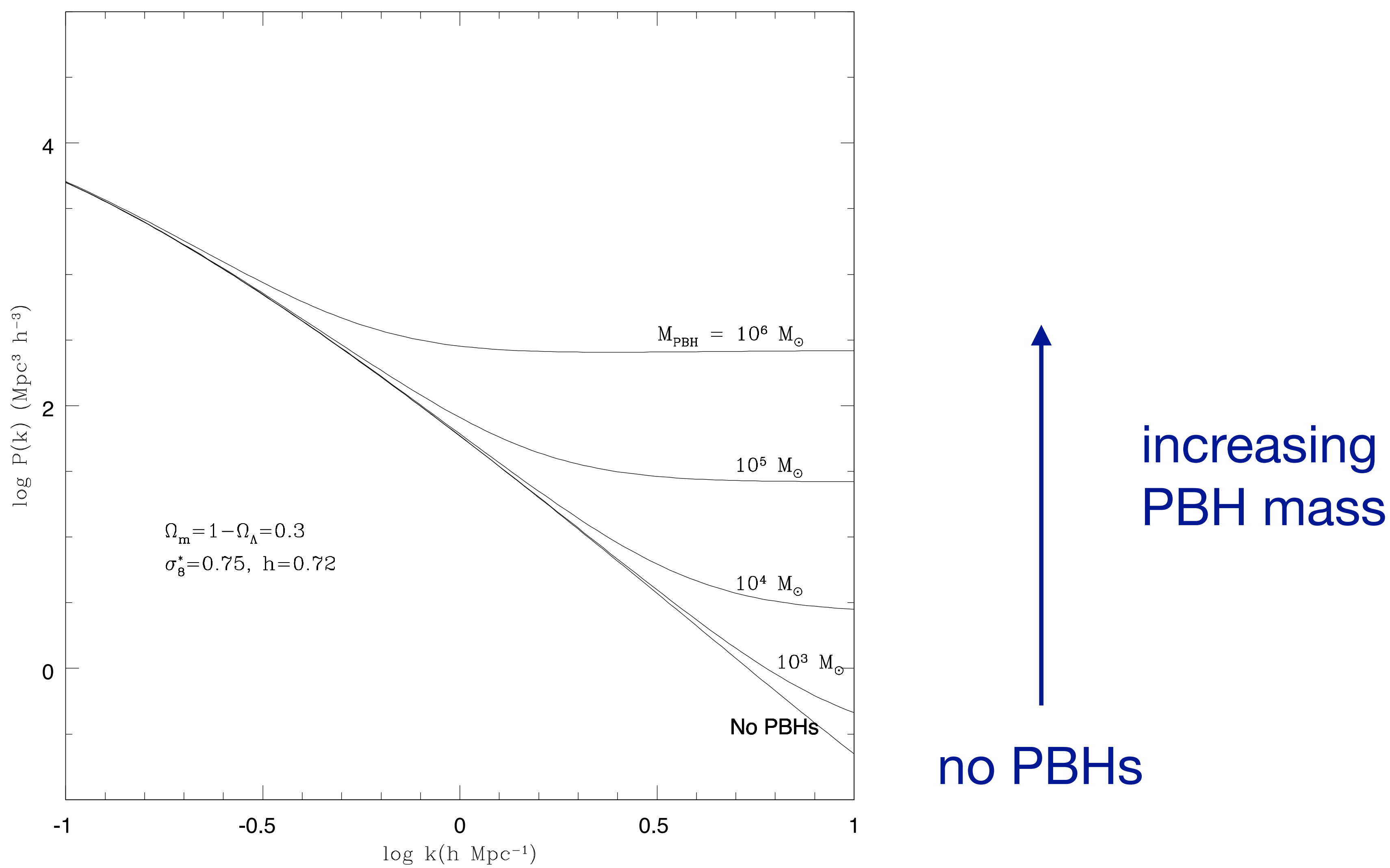
PBHs don't form in clusters Ali-Haïmoud (previous work Chisholm extrapolated an expression for the correlation function beyond its range of validity).

But if PBHs make up a large fraction of the DM, PBH clusters form shortly after matter-radiation equality. Afshordi, Macdonald & Spergel; Raidal et al.; Inman & Ali-Haïmoud; Jedamzik

power spectrum

$P(k)$

$(\propto k^{n_s})$



k = comoving wavenumber

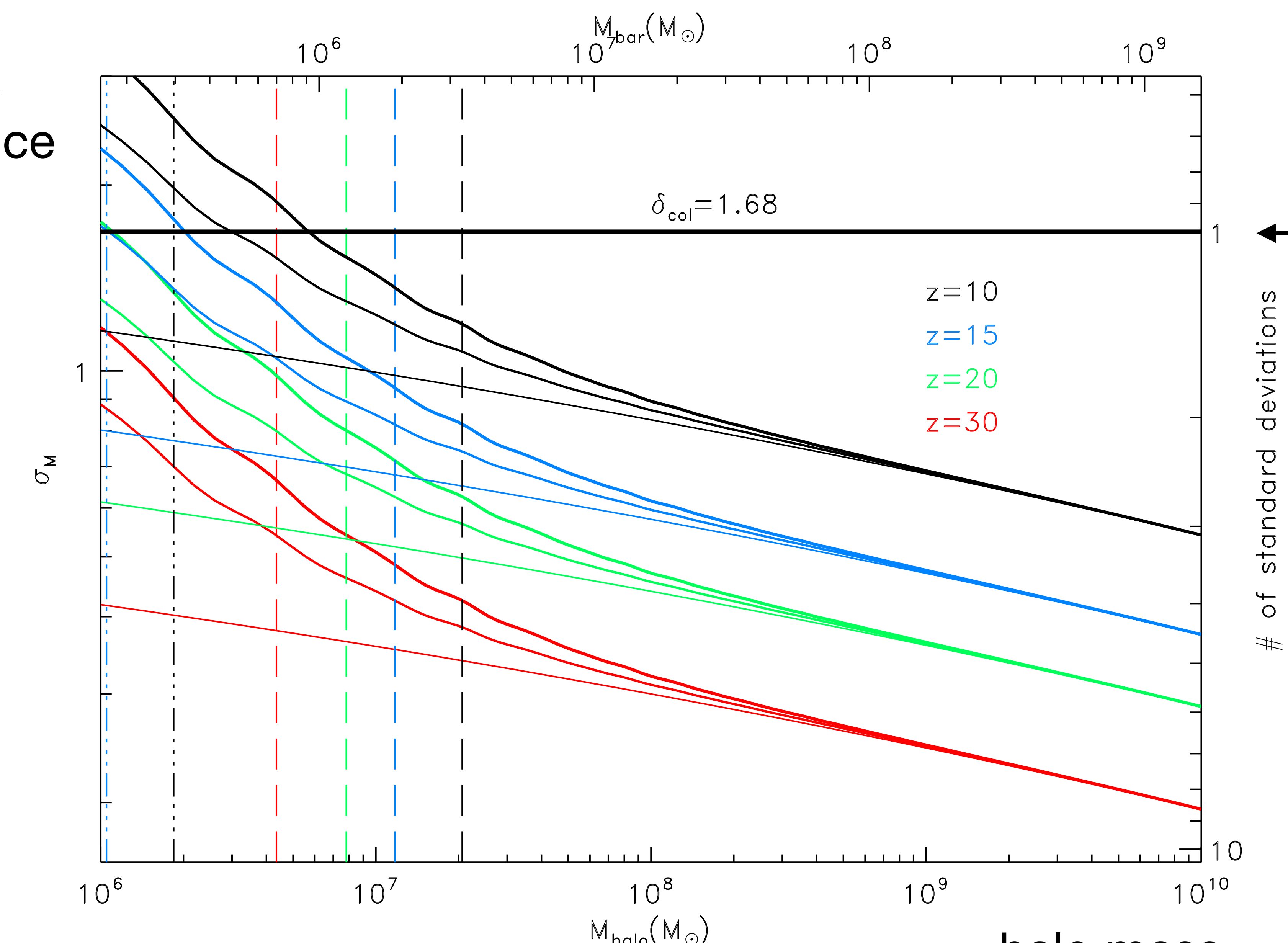
Afshordi, Macdonald & Spergel

Structure formation with PBH dark matter

PBHs don't form in clusters Ali-Haïmoud (previous work Chisholm extrapolated an expression for the correlation function beyond its range of validity).

But if PBHs make up a large fraction of the DM, PBH clusters form shortly after matter-radiation equality. Afshordi, Macdonald & Spergel; Raidal et al.; Inman & Ali-Haïmoud; Jedamzik

mass variance



threshold for collapse

z= 10, 15, 20, 30

$M_{PBH}=30\ M_\odot$

$M_{PBH}=15\ M_\odot$

no PBHs

halo mass

Kashlinksy

Approximate analytic calculation

c.f. Afshordi, Macdonald & Spergel; Jedamzik

PBH DM has additional isocurvature perturbations due to Poisson fluctuations in their distribution:

$$\delta(N) = \frac{\Delta N}{N} = \frac{1}{\sqrt{N}}$$

growth factor for isocurvature perturbations:

$$D(a) \approx \left(1 + \frac{3}{2}\frac{a}{a_{\rm eq}}\right)$$

spherical top hat collapse:

collapse occurs when:

$$D(a_{\rm col})\delta(N) = \delta_{\rm critical} \approx 1.69 \; ^*$$

final halo/cluster density:

$$\rho_{\rm cl} \approx 178 \rho_{\rm DM}(a_{\rm coll})$$

number density of PBHs in cluster:

$$n_{\rm cl} \approx 1.6 \times 10^5 \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1} N^{-3/2}\,{\rm pc}^{-3}$$

radius of cluster:

$$r_{\rm cl} \approx 0.01 \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{1/3} N^{5/6}\,{\rm pc}$$

For $M_{\rm PBH} = M_\odot$, N=10 (100) clusters form at $z_{\rm coll}$ ≈1200 (320) and have $r_{\rm cl}$≈ 0.06 (0.5) pc.

* for objects that collapse early in matter domination, when baryons are unclustered, $\delta_{\rm critical}$ is somewhat larger. Inman & Ali-Haïmoud

N-body simulations

Inman & Ali-Haïmoud

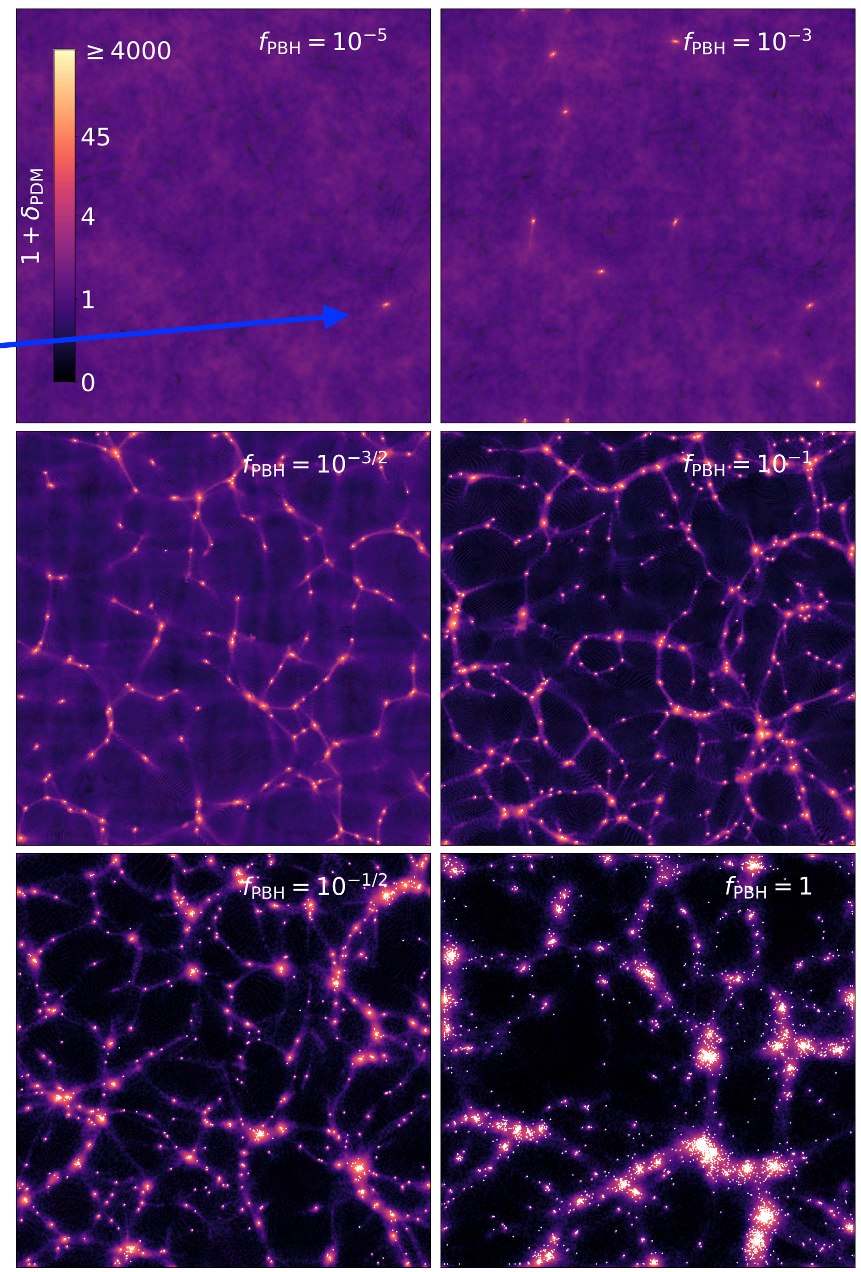
Simulate a L = 30 h^{-1} kpc box, with $M_{\rm PBH} = 20 h^{-1} M_\odot$ from radiation domination to z = 99, for $f_{\rm PBH}$ = 1 and also $f_{\rm PBH}$ < 1 + particle dark matter.

matter field at z=100

$f_{\rm PBH} = 10^{-5}$

$f_{\rm PBH} = 10^{-3}$

a PBH!



$f_{\rm PBH} = 10^{-3/2}$

$f_{\rm PBH} = 10^{-1}$

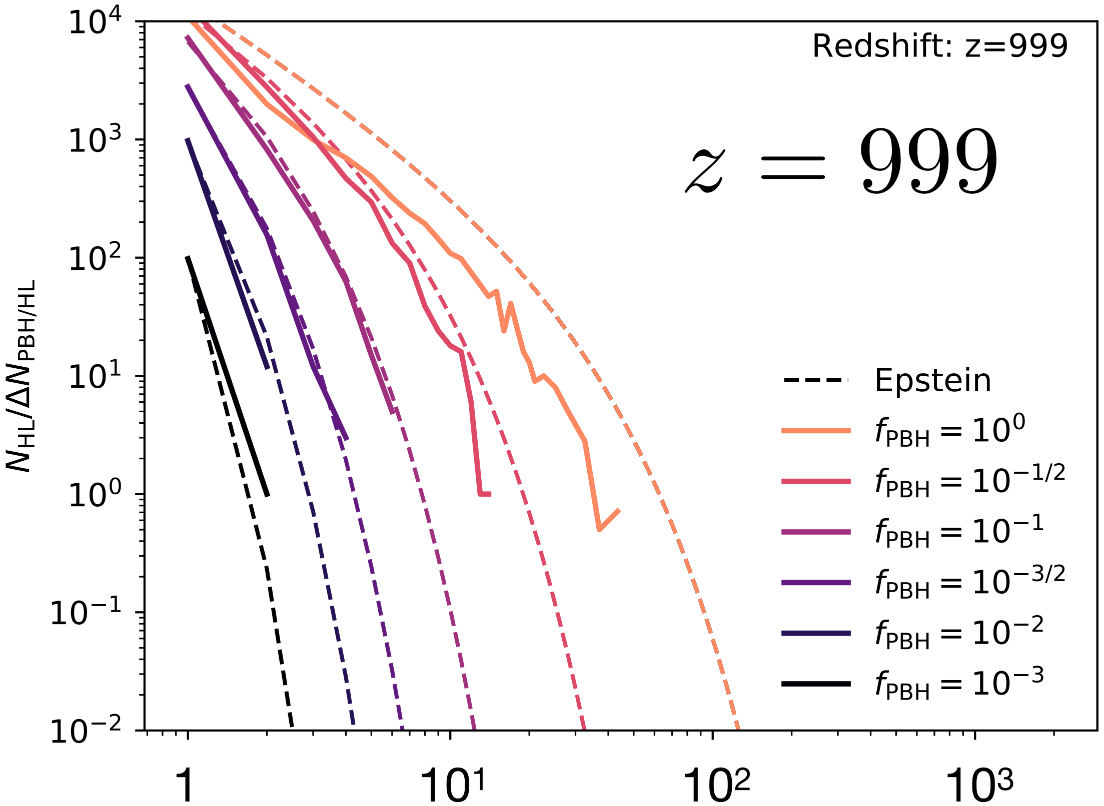
$f_{\rm PBH} = 10^{-1/2}$

$f_{\rm PBH} = 1$

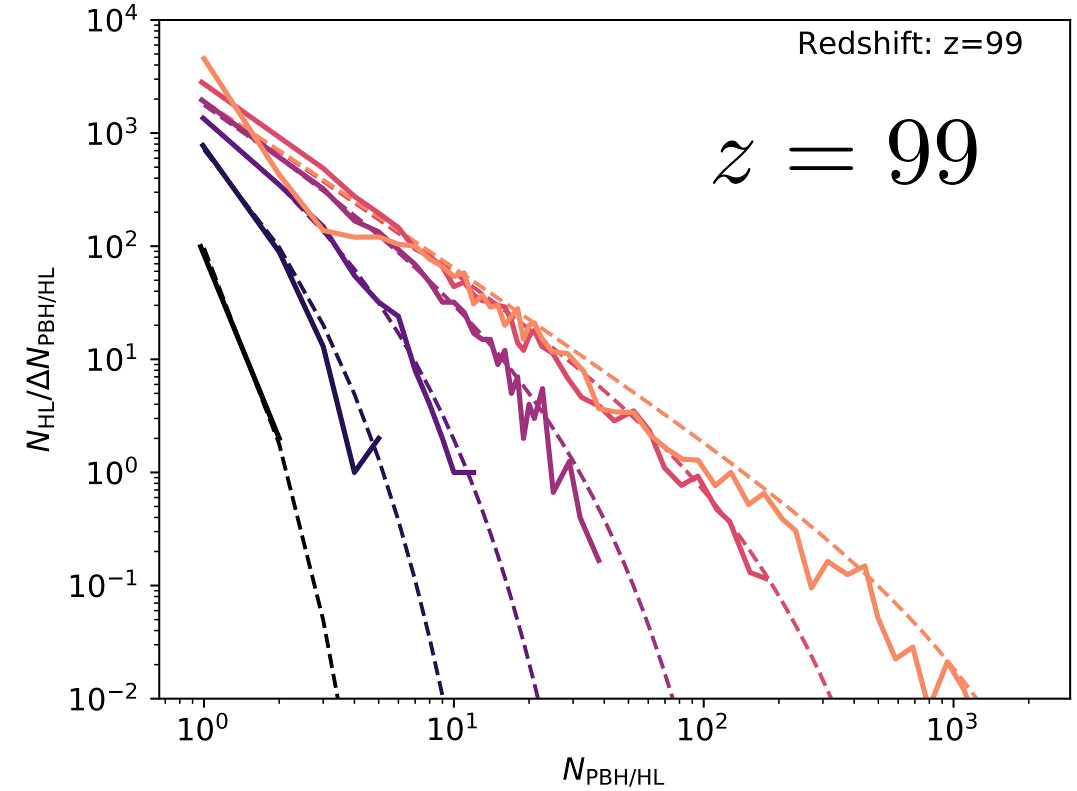
Inman & Ali-Haïmoud

halo mass function (number of halos containing a given number of PBHs)

Inman & Ali-Haïmoud



decreasing f_{PBH}



for initially Poisson distributed objects   Epstein

$$N_{\rm HL}(N) \approx \frac{\delta_\star}{\sqrt{2\pi}} \frac{N_{\rm PBH}}{N^{3/2}} \exp\left(-N/N_\star\right)$$

N_{PBH} = total number of PBHs = $10^5 f_{PBH}$ for these simulations

$$N_\star \equiv \left[\log\left(1+\delta_\star\right) - \frac{\delta_\star}{1+\delta_\star}\right]^{-1}$$

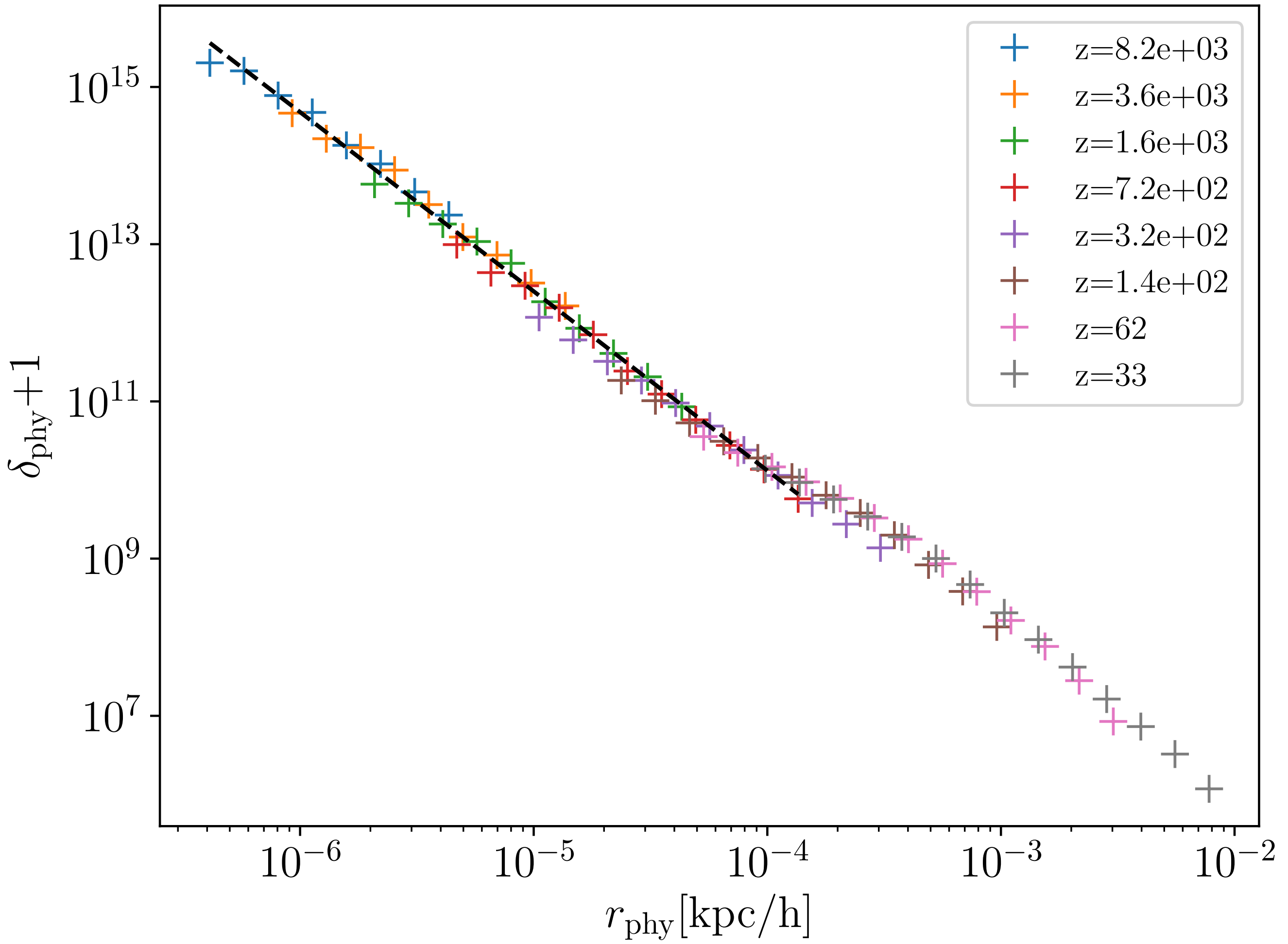
$$\delta_\star(a) = \frac{\delta_{\rm critical}(a)}{D(a) f_{\rm PBH}}$$ minimum initial PBH density $$\delta_\star \approx \frac{0.43\,(0.05)}{f_{\rm PBH}} \quad \text{at} \quad z = 999\,(99)$$

mixed PBH-particle dark matter

If PBHs don't make up all of the DM ($0 < f_{\rm PBH} < 1$) then isolated PBHs accrete a halo of particle DM with a steep density profile: $\rho(r) \propto r^{-9/4}$

Mack, Ostriker & Ricotti; Adamek et al.; Inman & Ali-Haïmoud

Density profile, in physical units, formed around a $30 M_{\odot}$ PBH



Adamek et al

If the DM were a mixture of PBHs and WIMPs would get large flux of gamma-rays (and neutrinos and positrons) from WIMP annihilation in halos around PBHs: all of the DM being a mixture of WIMPs and PBHs is excluded. Lacki & Beacom

If $f_{WIMP} \sim 1$ then $f_{PBH} \lesssim 10^{-9}$.

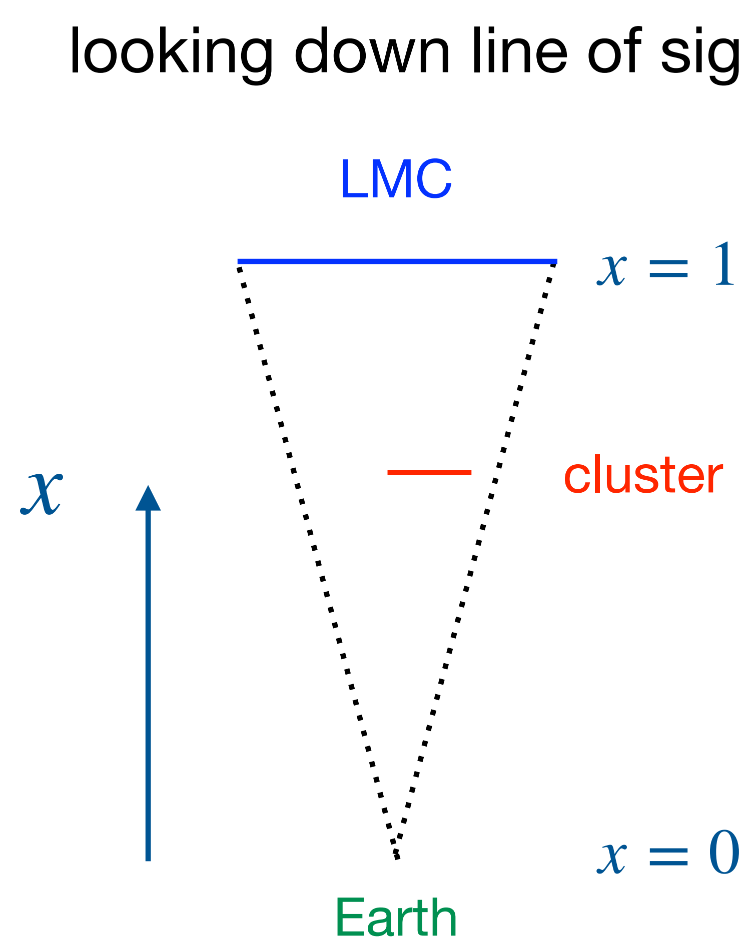
If $f_{PBH} \sim 10^{-3}$ (if LIGO-Virgo events are PBH binary mergers) then $f_{WIMP} \lesssim 10^{-6}$.

Adamek, Byrnes, Gosenca, Hotchkiss

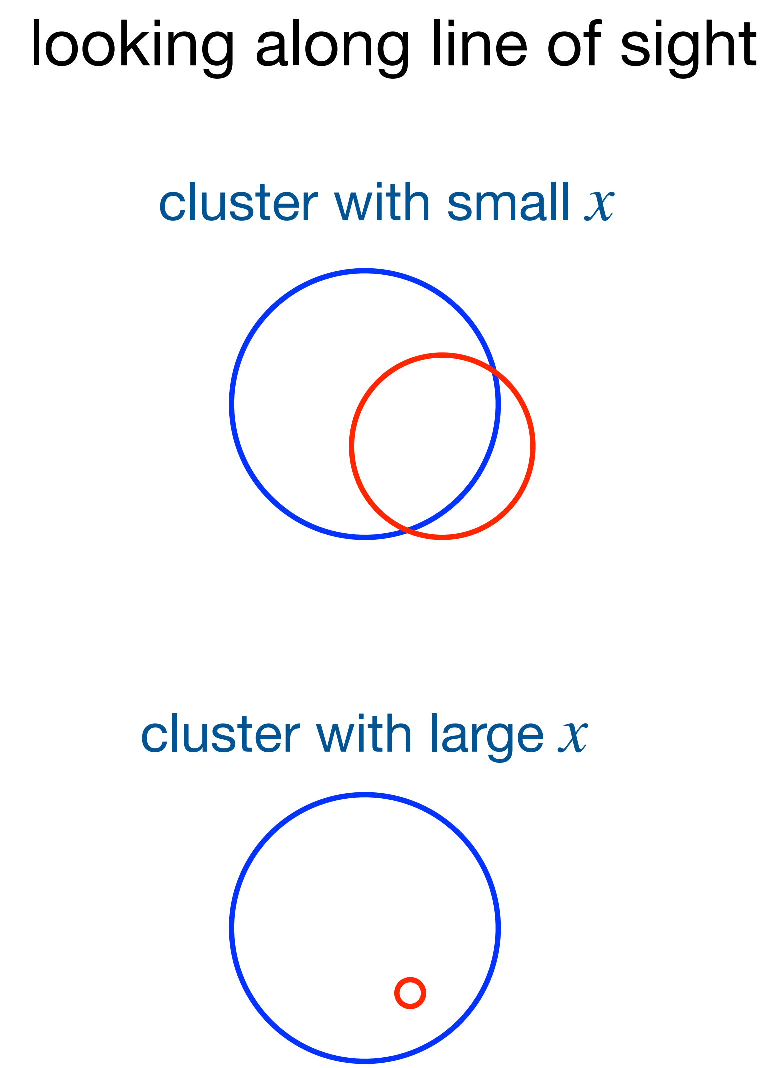
Effect of clustering on LMC microlensing constraints

For PBHs formed from collapse of density perturbations during radiation, clusters are sufficiently extended that PBHs lens individually (separation of PBHs $\gg R_E$).

Microlensing from a single cluster:



x = fractional line of sight dist



probability of finding a cluster at line of sight distance x is proportional to cross sectional area of 'cone' to LMC $\propto x^2$

all the PBHs in a given cluster cause events with the same duration:

$$\hat{t} = \frac{2 R_{\rm E}(x)}{v} \propto [x(1-x)]^{1/2}$$

rate at which cluster causes microlensing events is proportional to solid angle subtended by cluster times Einstein radius:

$$\propto \frac{[x(1-x)]^{1/2}}{x^2}$$

Close clusters are rare, but if one intersects the line of sight if produces short duration events at a high rate.

LMC microlensing differential event rate for clustered DM and standard smooth DM

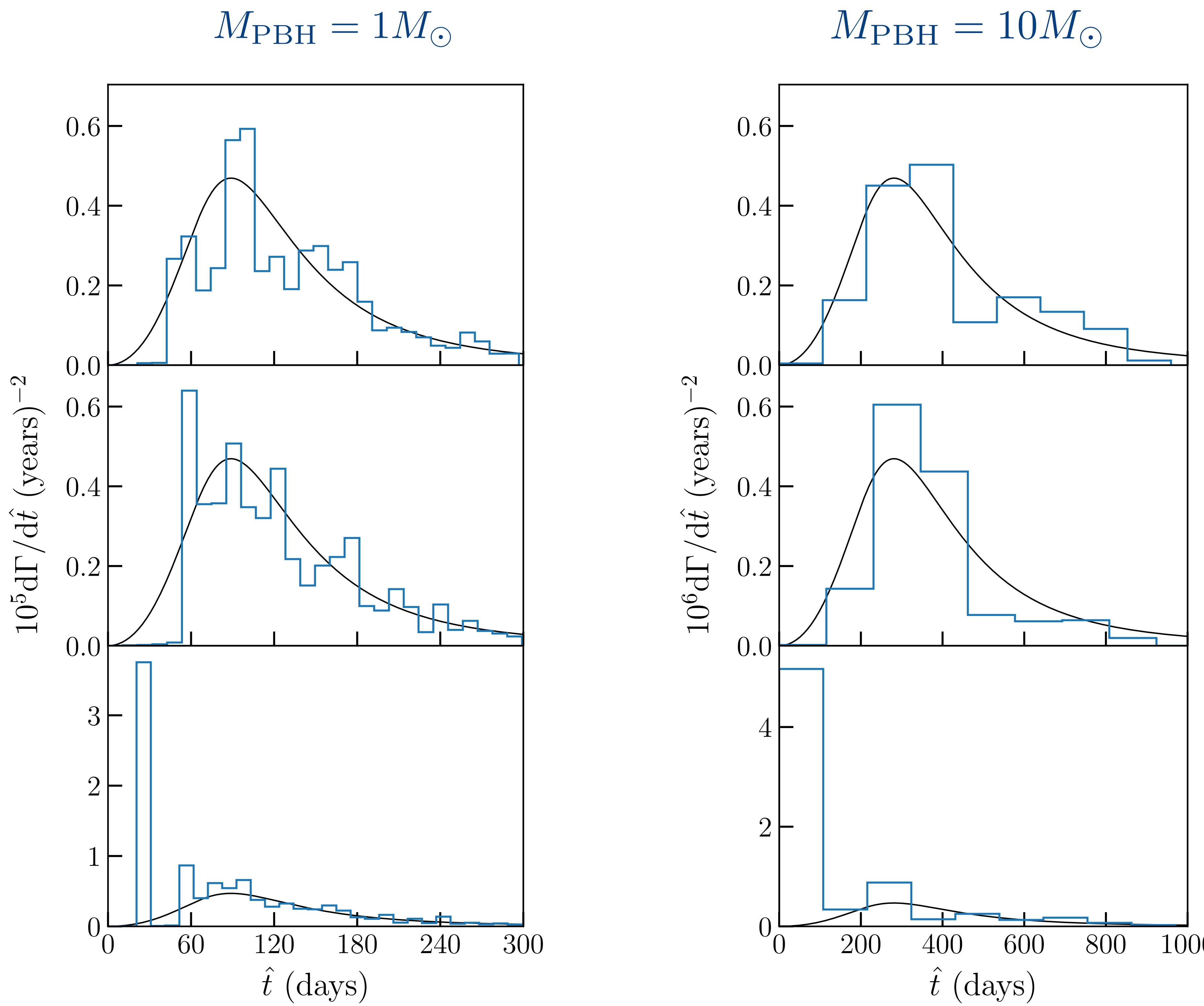
all of the DM in clusters containing $N_{cl}=10^6$ PBHs with mass

<u>Typical realisations</u>

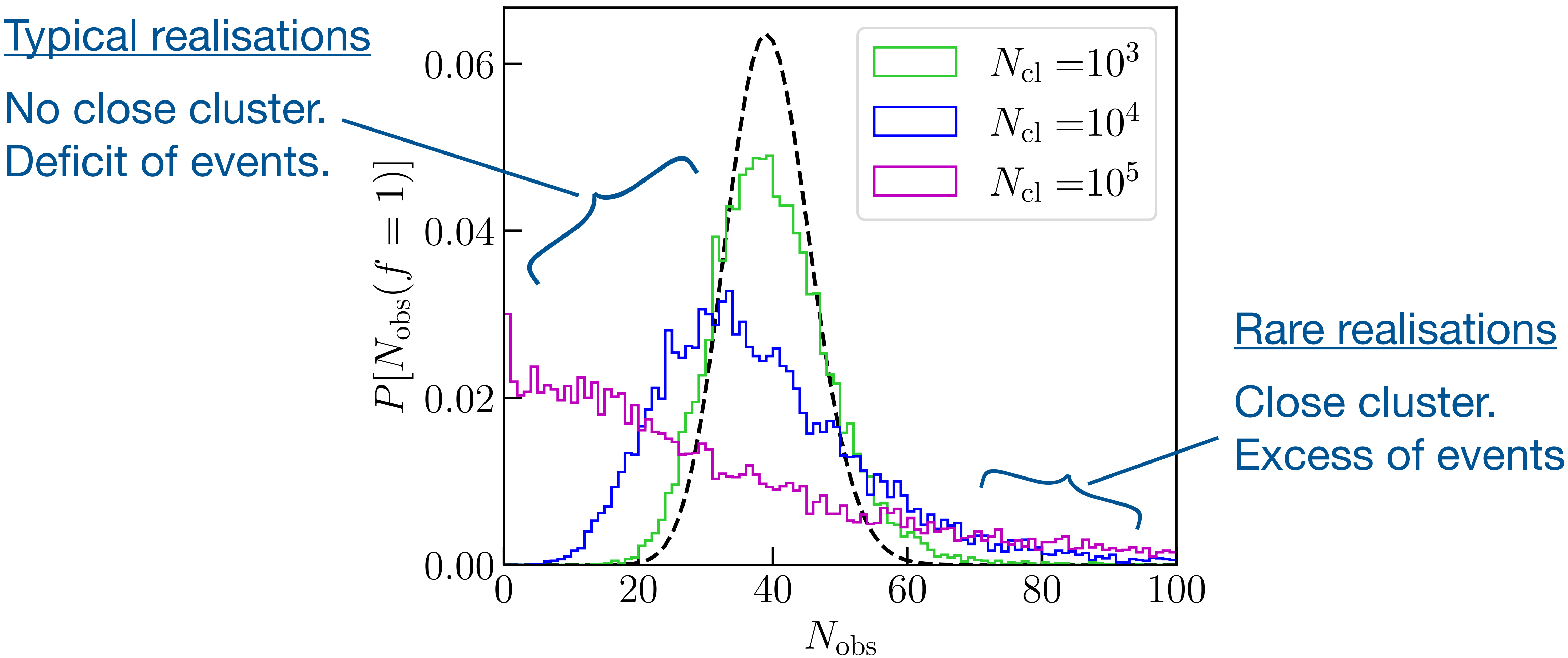
No close cluster.
Deficit of short duration events.

<u>Rare realisation</u>

Close cluster.
Excess of short duration events.



Probability distribution of number of events in a long duration microlensing survey if all of the DM is in PBHs clusters containing N_{cl} PBHs with mass $M_{\rm PBH} = 10^3 M_\odot$



Change in constraints is negligible apart (possibly) from at largest M_{PBH} probed by stellar microlensing.

(**if** all of the DM is in PBH clusters containing $N_{cl} = 10^3$ PBHs with mass $M_{\rm PBH} = 10^3 M_\odot$ constraint on f_{PBH} from long duration microlensing survey weakens from 0.076 to 0.096).

Petaĉ, Lavalle & Jedamzik; Gorton & Green.