Primordial Black Holes (PBHs) as a dark matter candidate

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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, Kohri, Sendouda & Yokoyama, arXiv: 2002.12778, ‘Constraints on PBHs’

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

Motivation

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

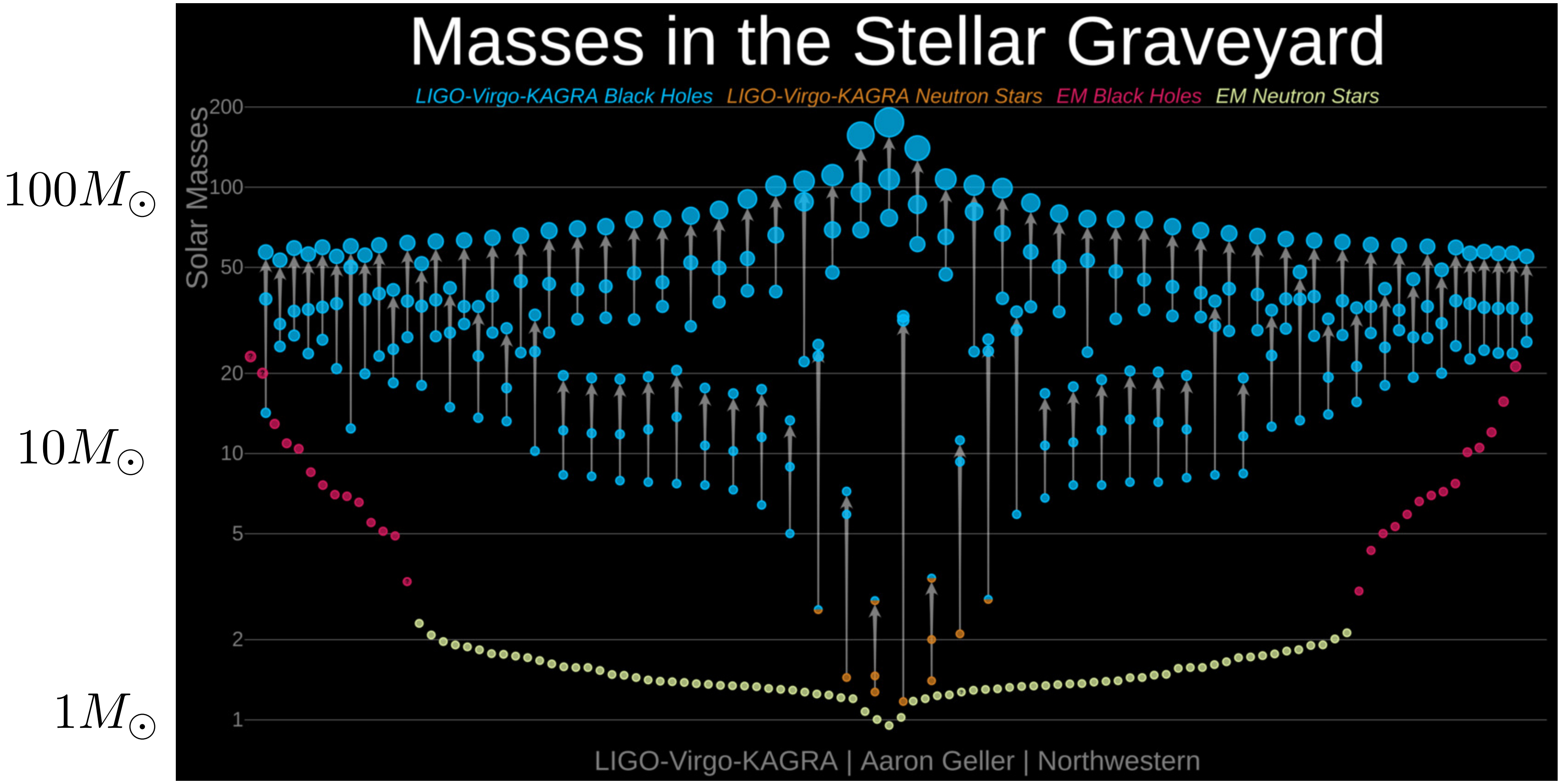
A DM candidate which (unlike WIMPs, axions, sterile neutrinos,…) isn't a new particle (however their formation does usually require Beyond the Standard Model physics, e.g. inflation).

PBHs are a cold dark matter (DM) candidate.

Hawking; Chapline + wave of interest in late 1990s generated by excess of LMC microlensing events in MACHO collaboration's 2 year data set.

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

Could 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.



black holes discovered by LIGO-Virgo

LIGO-Virgo, Elavsky & Geller

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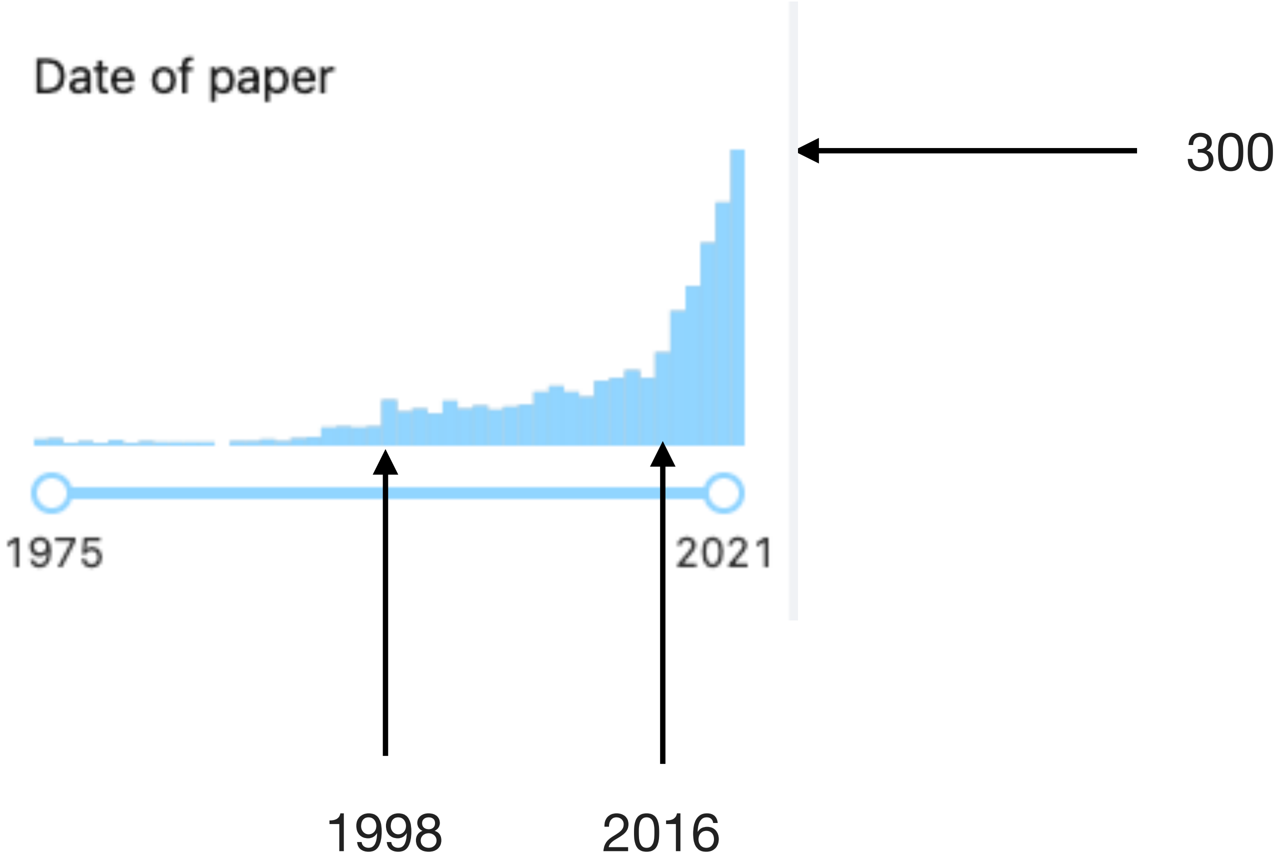
result of an inSPIRE search for 'primordial black hole'



300

1998

2016

Formation

Most ‘popular’ mechanism*: collapse of large density perturbations (shortly after horizon entry) during radiation domination. Zeldovich & Novikov; Hawking; Carr & Hawking

* other mechanisms: collapse of cosmic string loops Hawking; Polnarev & Zemboricz, bubble collisions Hawking, Moss & Stewart, fragmentation of inflation scalar condensate Cotner & Kusenko, collapse of density perturbations during matter domination Khlopov & Polnarev, …

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)

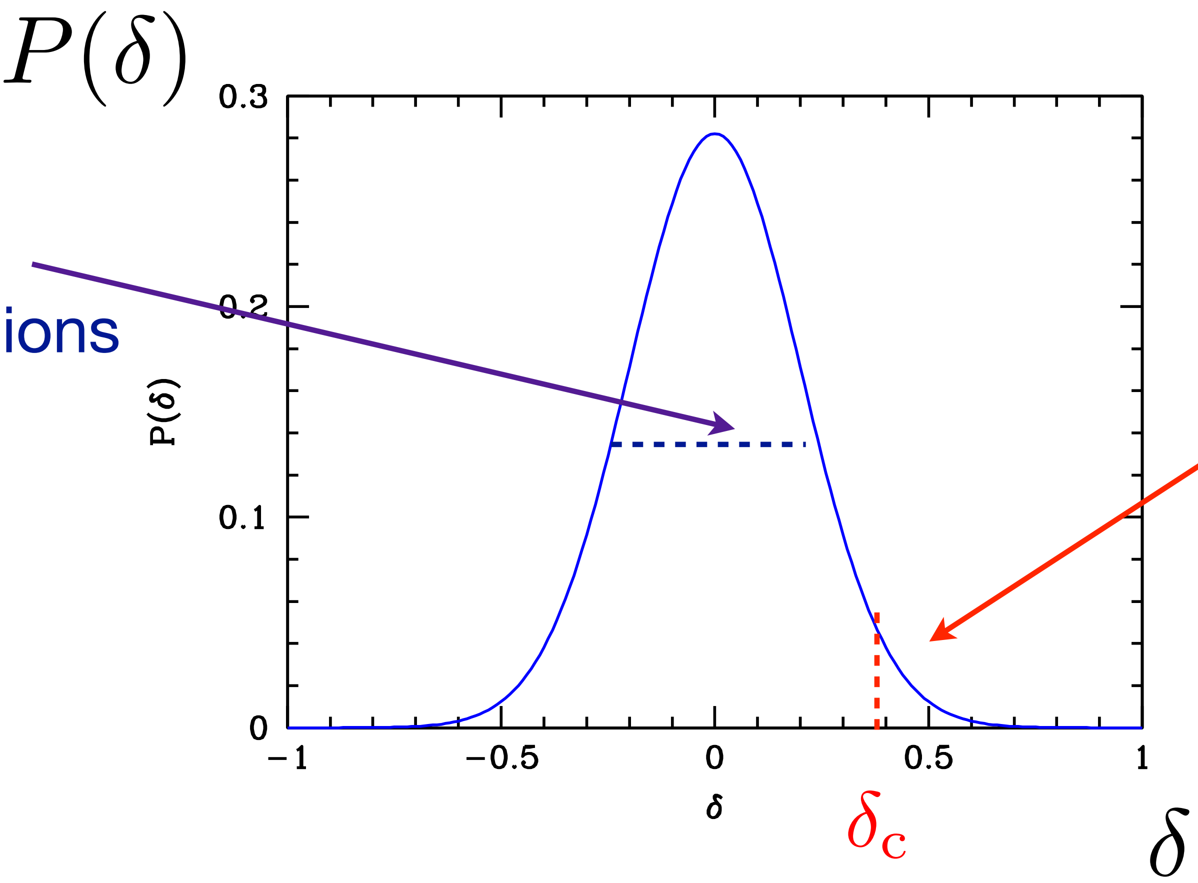
PBH mass roughly equal to horizon mass:

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

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

$$\beta(M) \sim \int_{\delta_{\mathrm{c}}}^{\infty} P(\delta(M_{\mathrm{H}}))\, \mathrm{d}\delta(M_{\mathrm{H}})$$

assuming a gaussian probability distribution: $$\beta(M) = \mathrm{erfc}\left(\frac{\delta_{\mathrm{c}}}{\sqrt{2}\sigma(M_{\mathrm{H}})}\right)$$



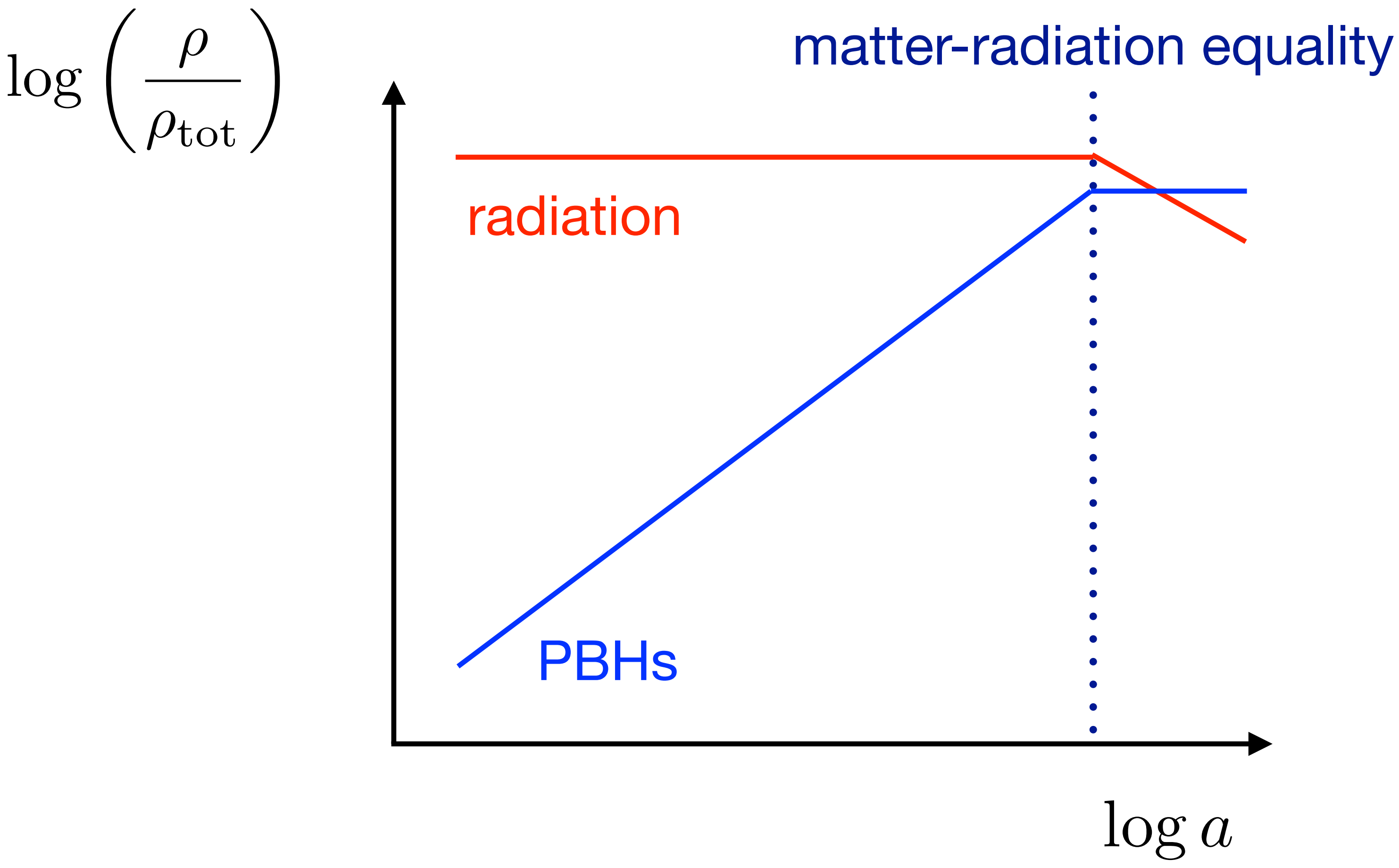
$\sigma(M_{\mathrm{H}})$ (mass variance)
typical size of fluctuations

PBH forming
fluctuations

but in fact β must be small, hence $\sigma \ll \delta_{\mathrm{c}}$ and $$\beta(M) \sim \sigma(M_{\mathrm{H}}) \exp\left(-\frac{\delta_{\mathrm{c}}^2}{2\sigma^2(M_{\mathrm{H}})}\right)$$

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:

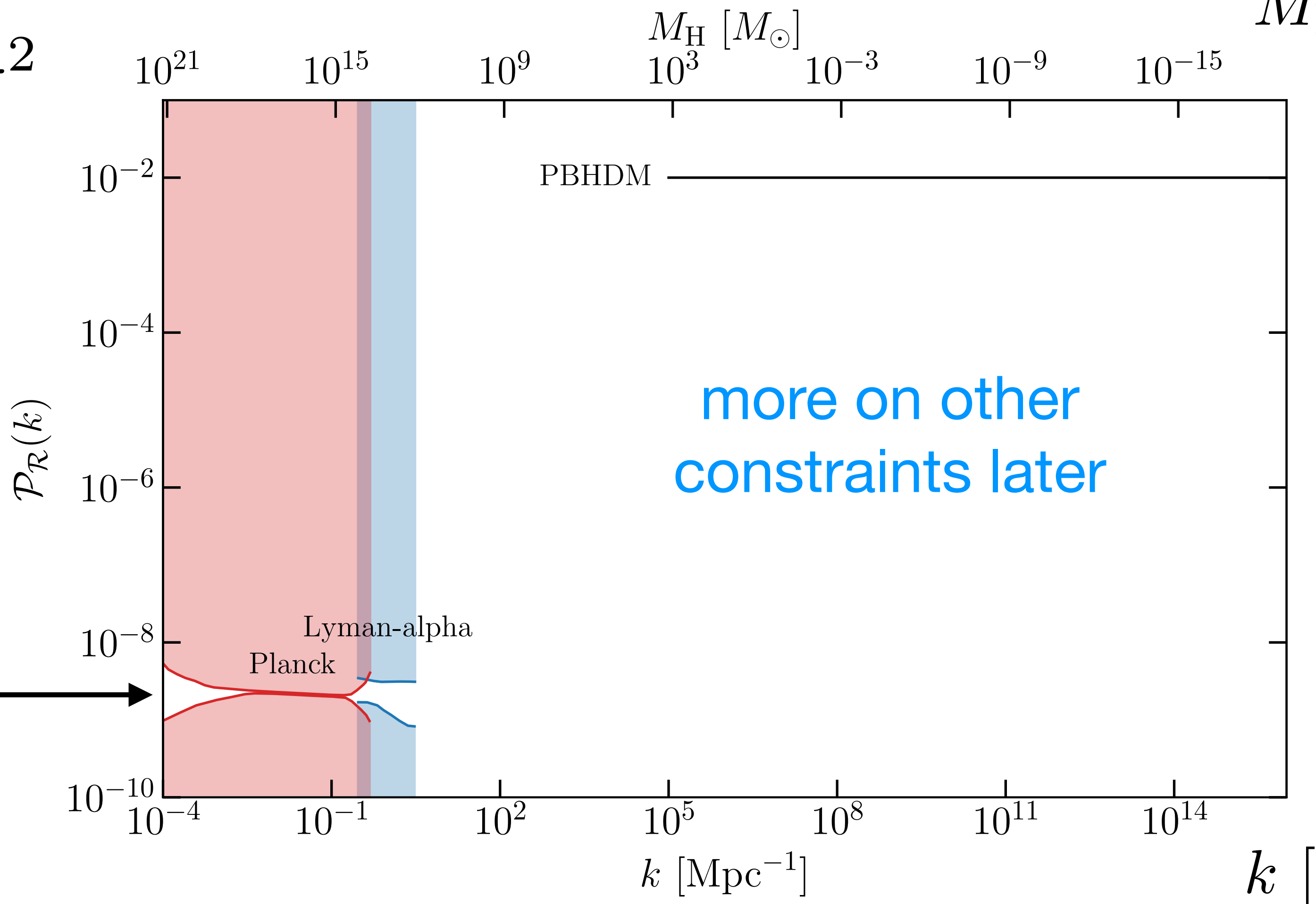
$$\beta(M) = {\rm erfc}\left(\frac{\delta_{\rm c}}{\sqrt{2}\sigma(M_{\rm H})}\right)$$

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

To form an interesting number of PBHs the primordial perturbations must be significantly larger ($\sigma^2(M_{\rm H})\sim0.01$) on small scales than on cosmological scales.

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

$M_{\rm H}\ [M_\odot]$



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

more on other constraints later

measured amplitude on cosmological scales

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

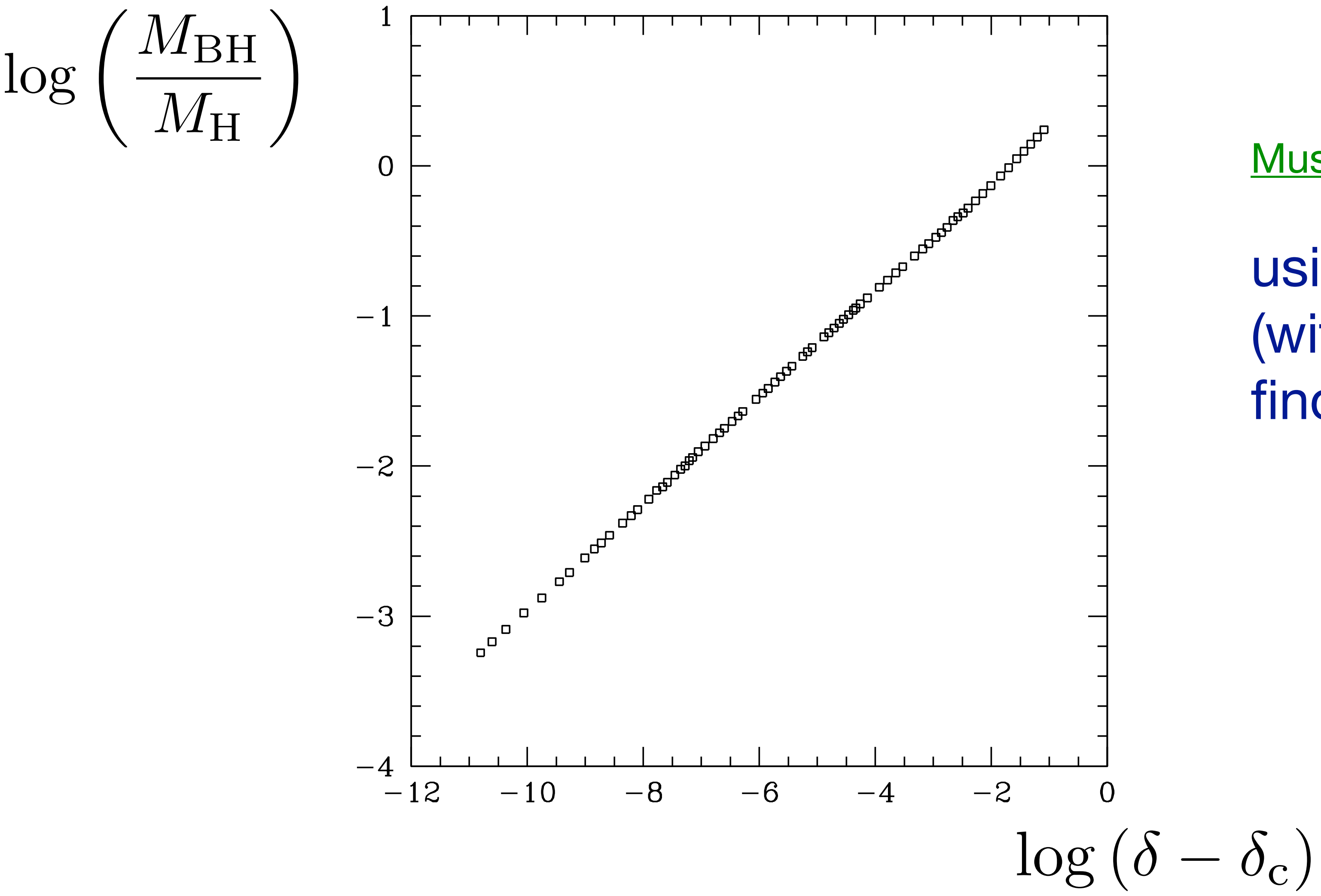
deviations from simple scenario:

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

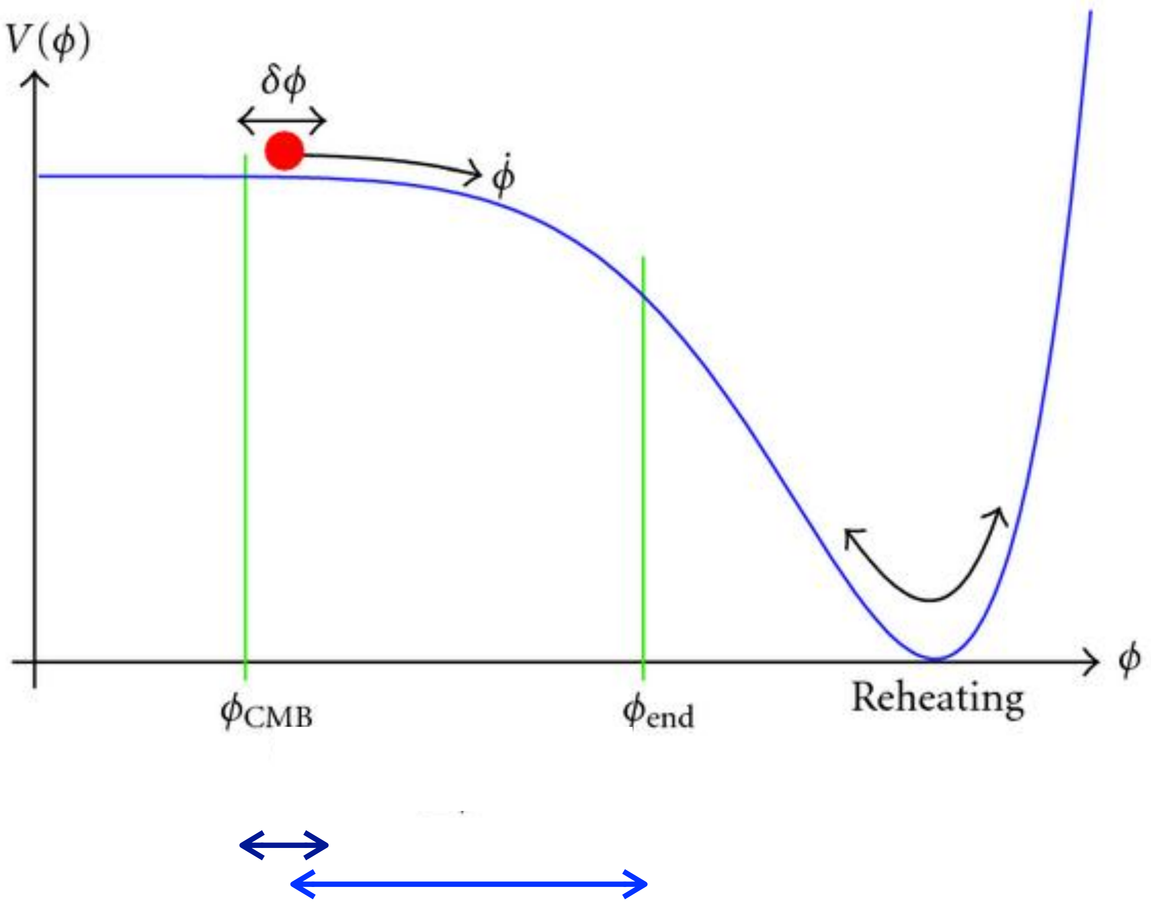
Inflation: a brief crash course

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

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).

inflation models that produce large perturbations

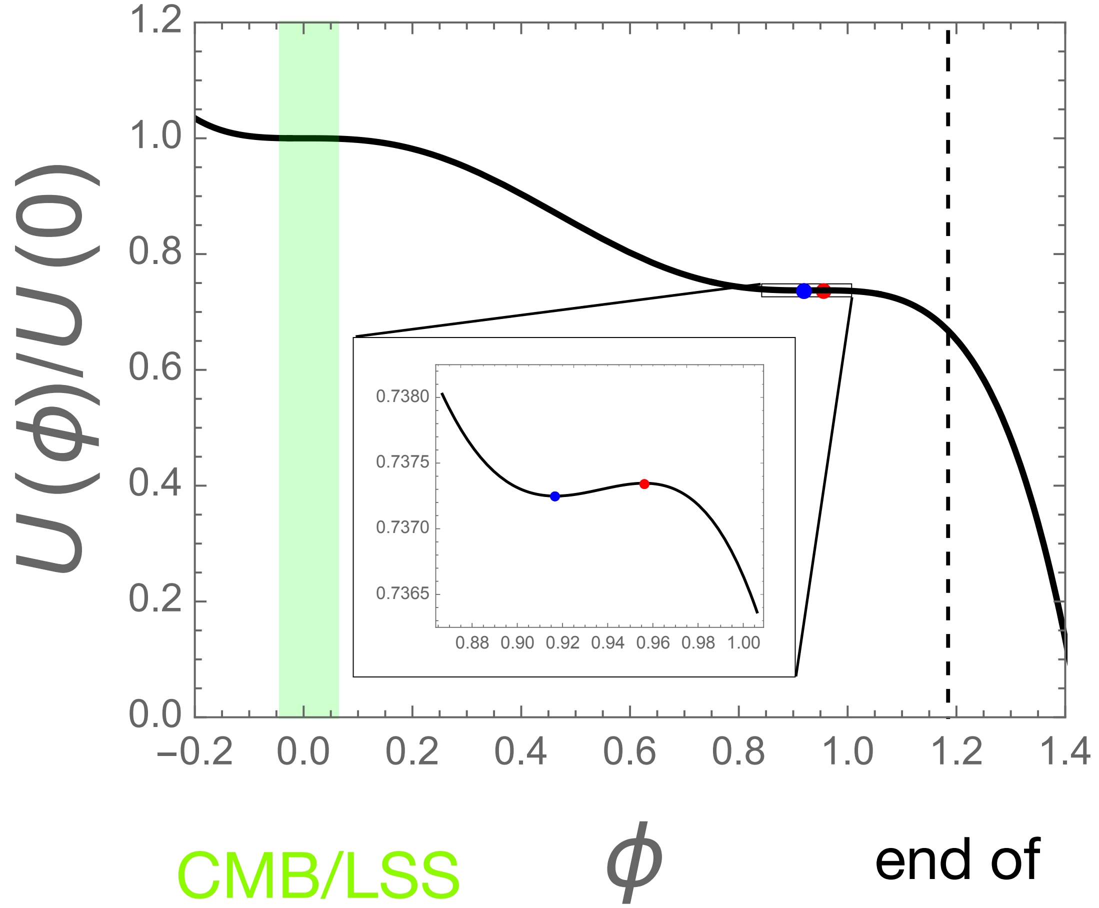
In slow-roll approx: $\sigma \propto V^{3/2}/V'$, but this expression isn't valid in 'ultra-slow-roll' limit, $V' \to 0$ (and USR also affects probability distribution of fluctuations - more later).

single field

Potential fine-tuned so that field goes past local min, but with reduced speed

Ballesteros & Taoso; Herzberg & Yamada

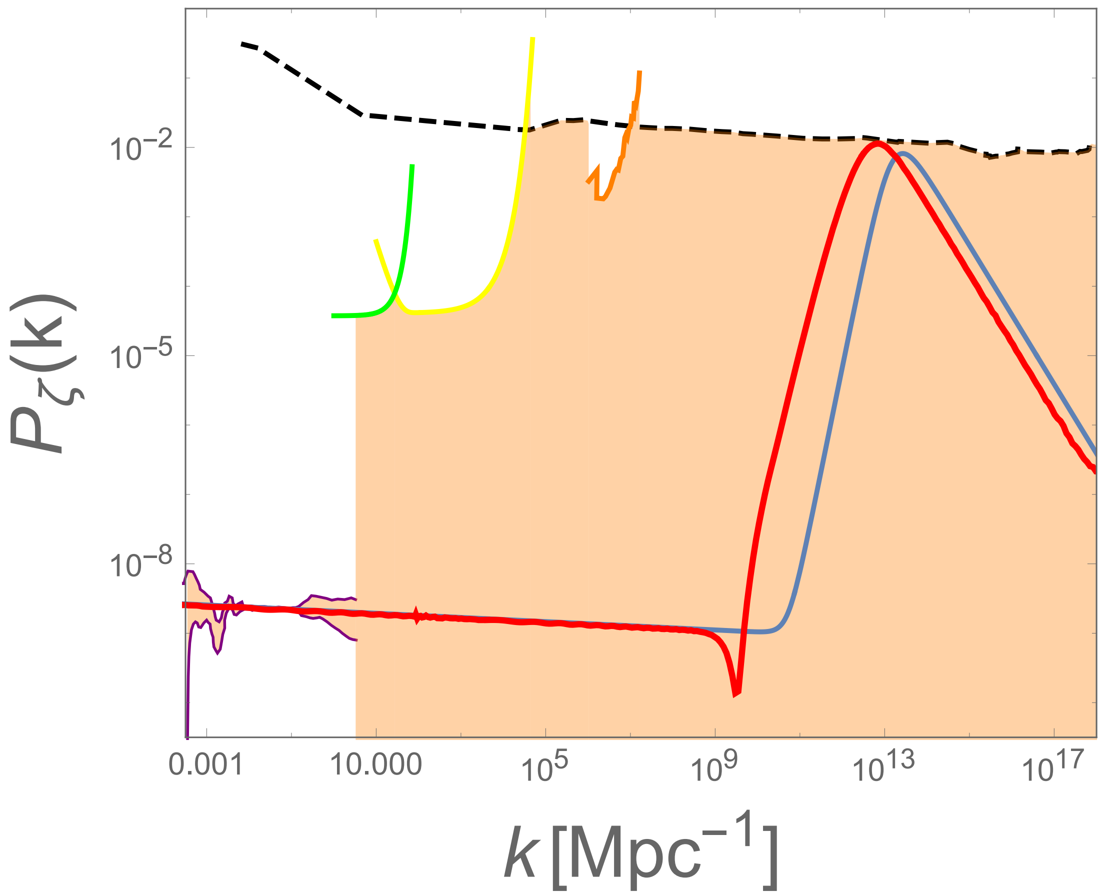
potential



CMB/LSS

end of inflation

primordial power spectrum

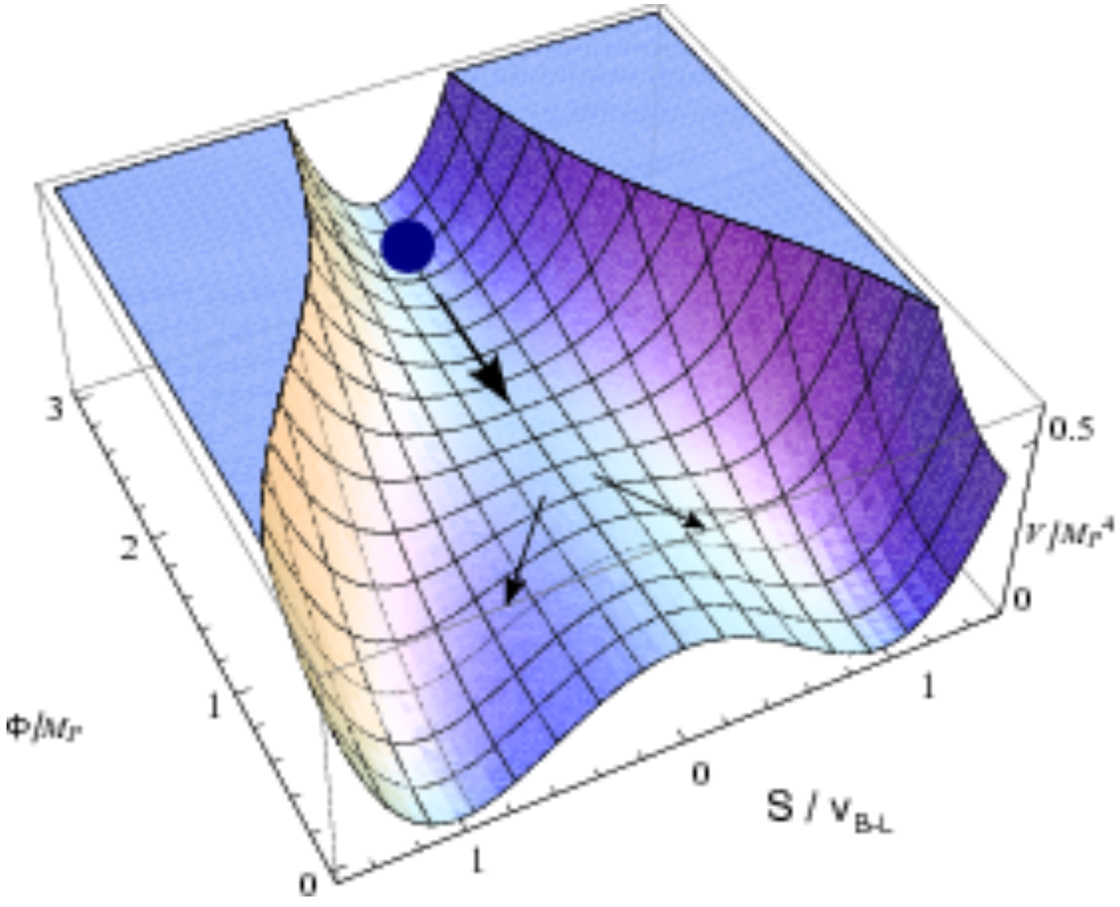


Steepest possible growth ~k^4 Byrnes, Cole & Patil; Carrihlo, Malik & Mulryne

multi-field models

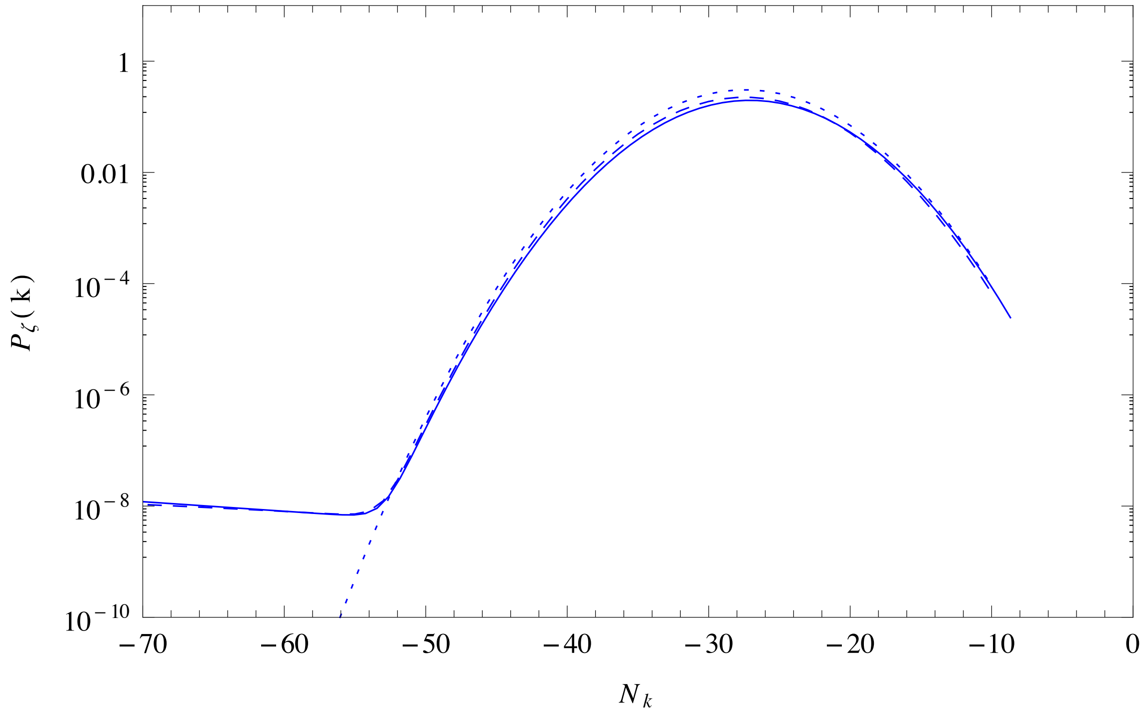
e.g. hybrid inflation with a mild waterfall transition Garcia-Bellido, Linde & Wands

potential



Buchmuller

primordial power spectrum



Clesse & Garcia-Bellido

various others

running mass, double inflation, axion-like curvaton, 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.

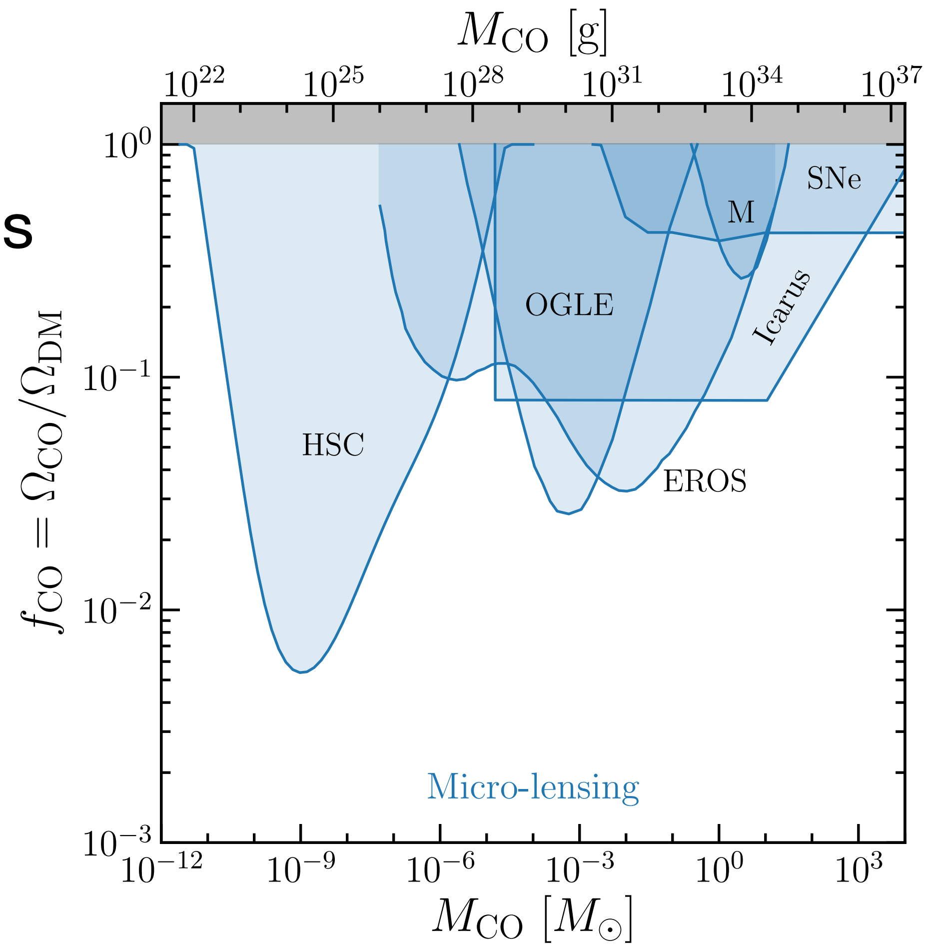
stars: temporarily brightened when compact object ('CO') crosses line of sight LMC/SMC (MACHO, EROS, OGLE), Galactic bulge (OGLE), M31 (HSC, Croon et al.).

supernovae: magnification distribution changed Zumalacarregui & Seljak.

Icarus: caustic crossing event Oguri 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

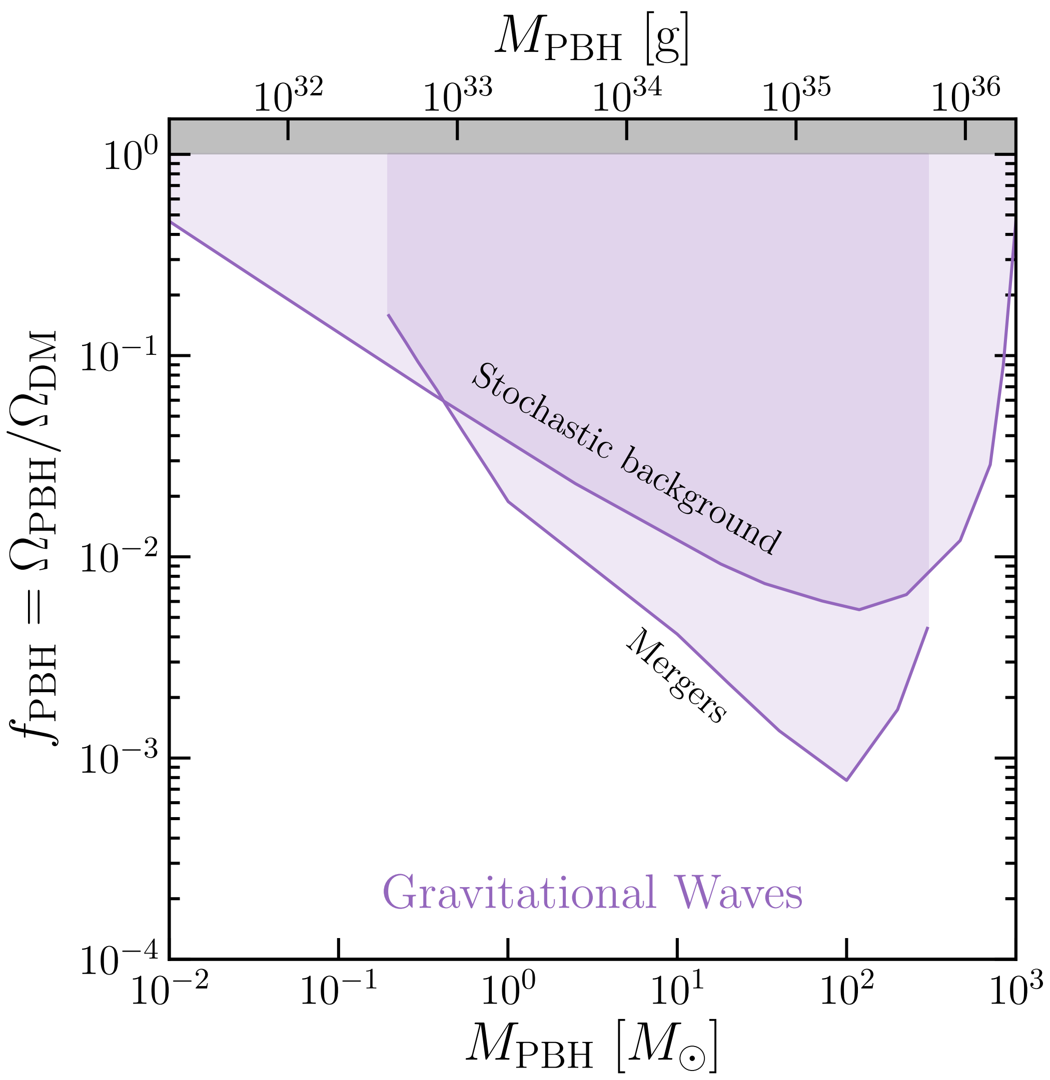
gravitational waves from PBH-PBH binary mergers

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. Ali-Haïmoud, Kovetz & Kamionkowski

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

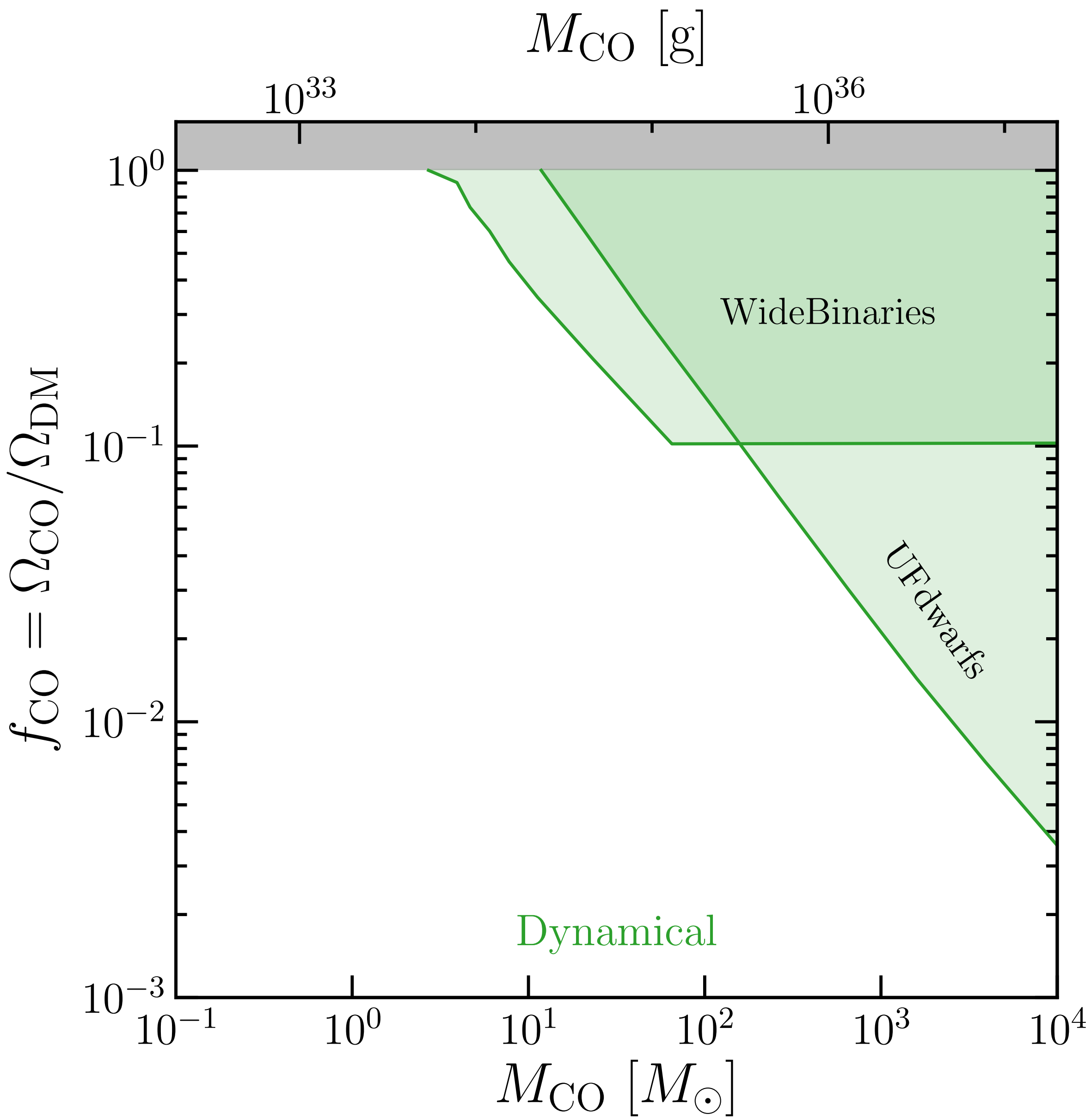
$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$



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



accretion

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

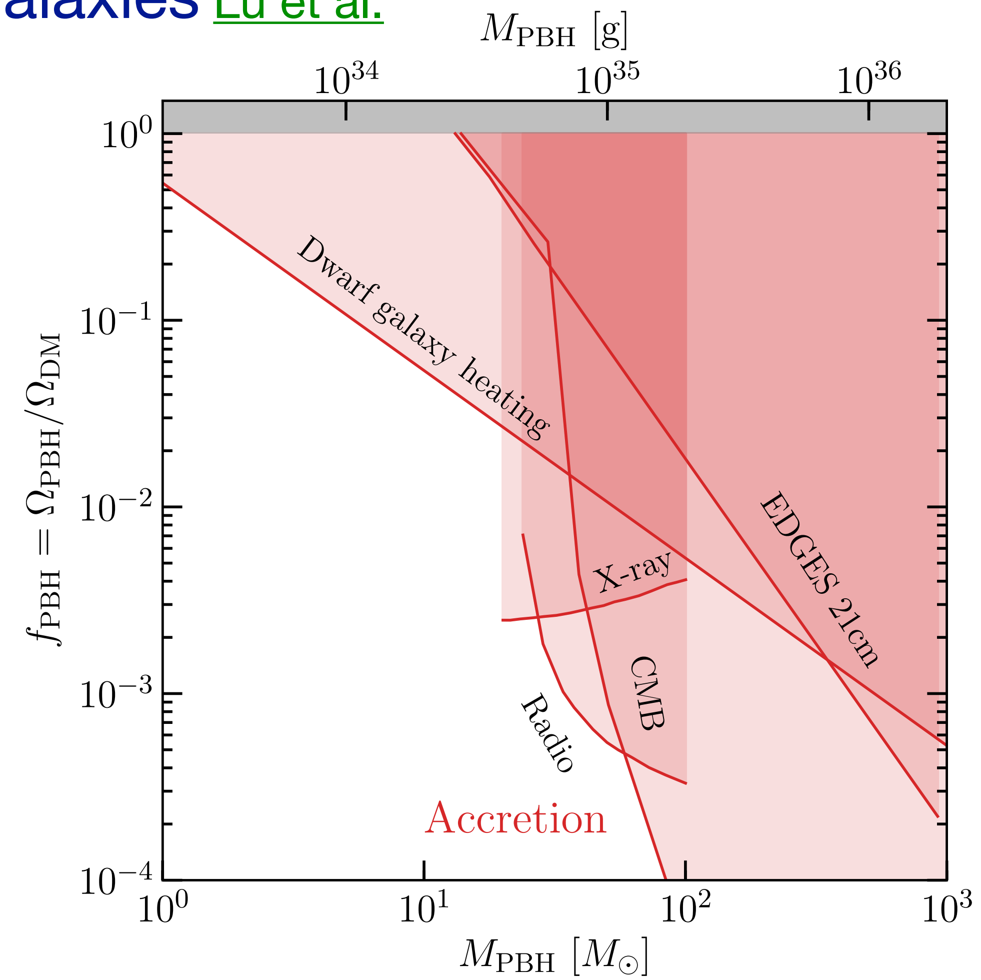
distortion of CMB anisotropies Ricotti et al; Ali-Haïmoud & Kamionkowski; … Poulin et al.…

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.



Constraints depend on modelling of accretion.

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

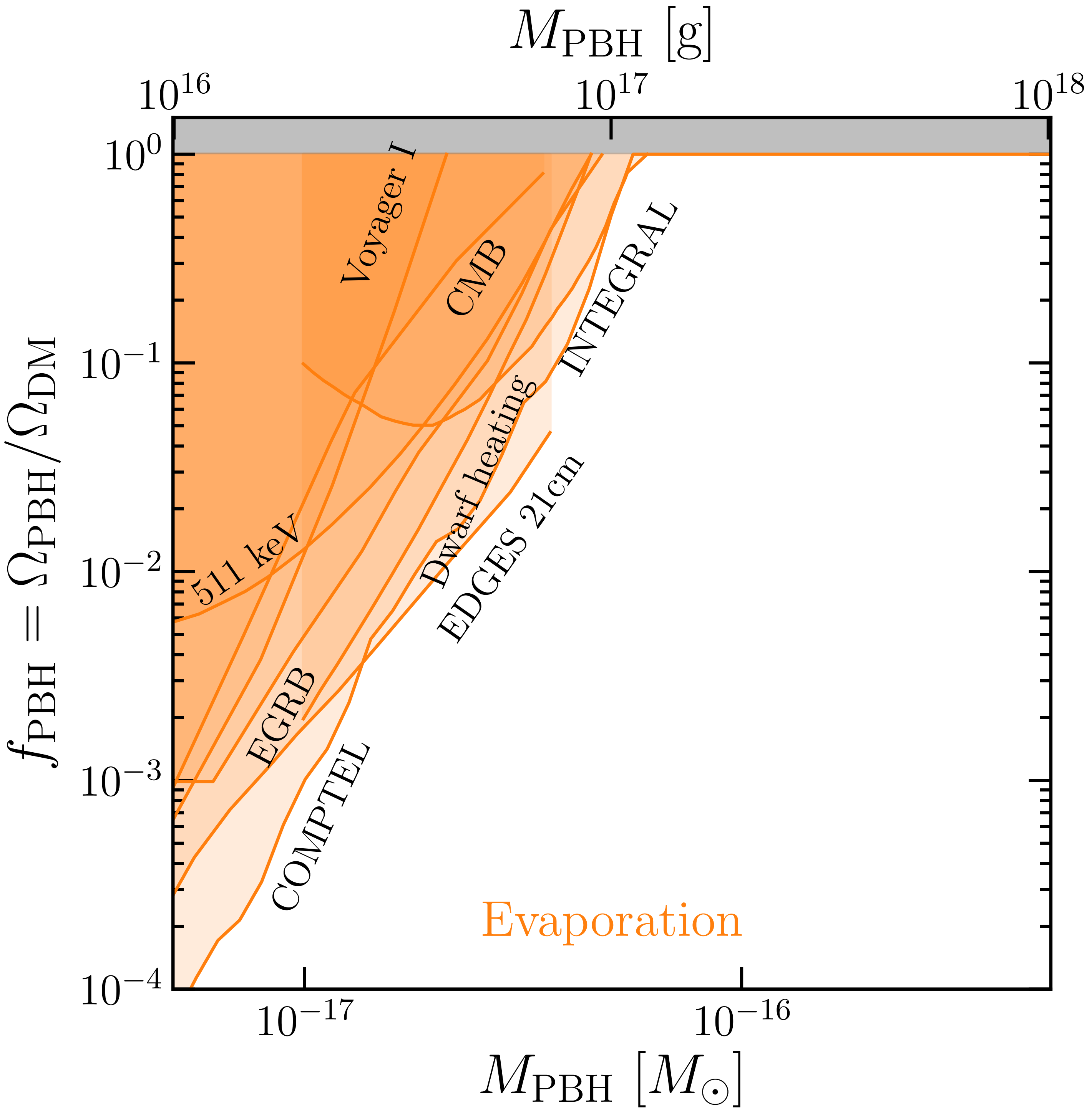
Montero-Camacho et al. **No current constraints**, but potential future constraints from

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

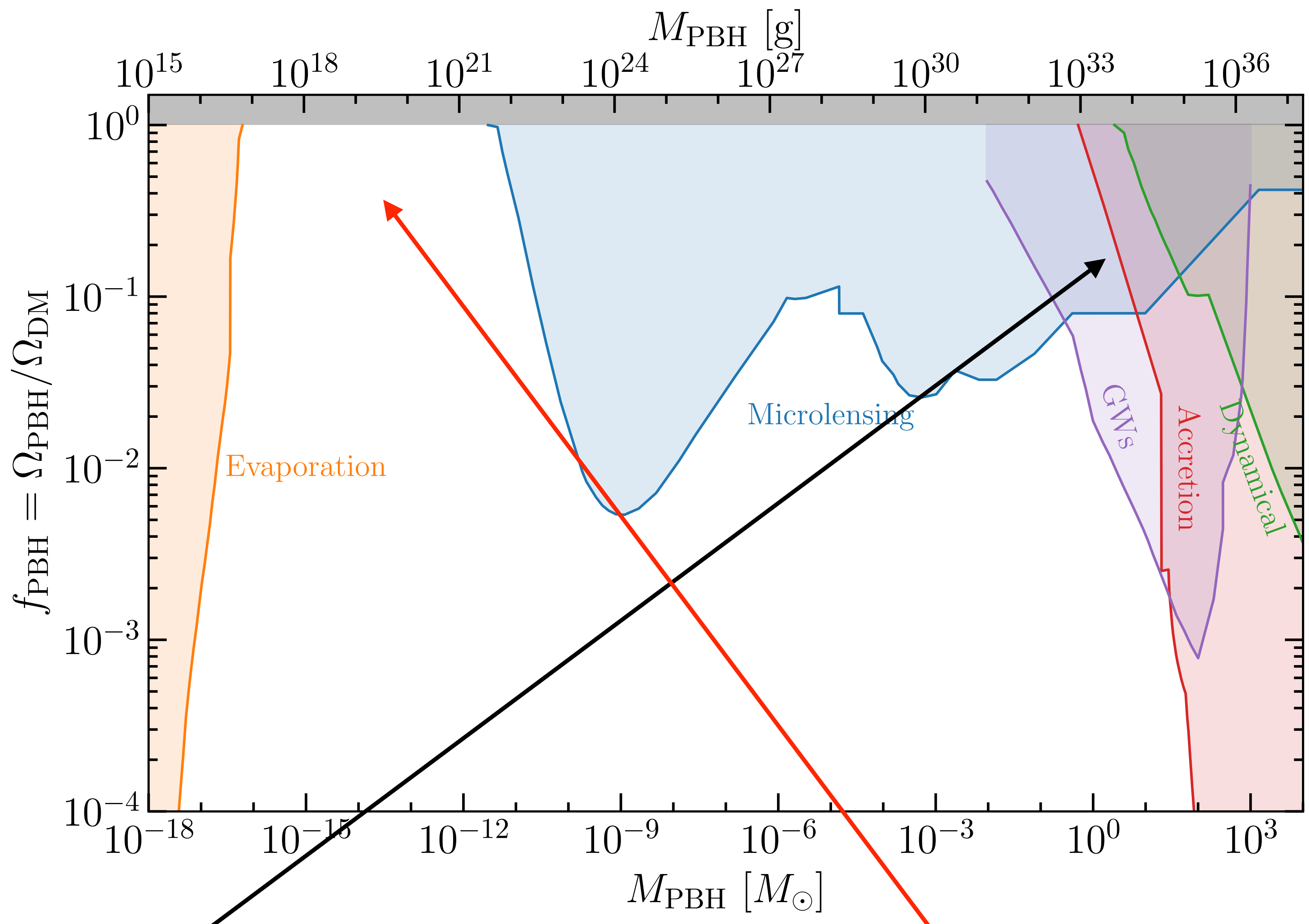
ii) signatures of star being destroyed

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.



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, more later).

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

Indirect constraints on PBHs formed from large density perturbations

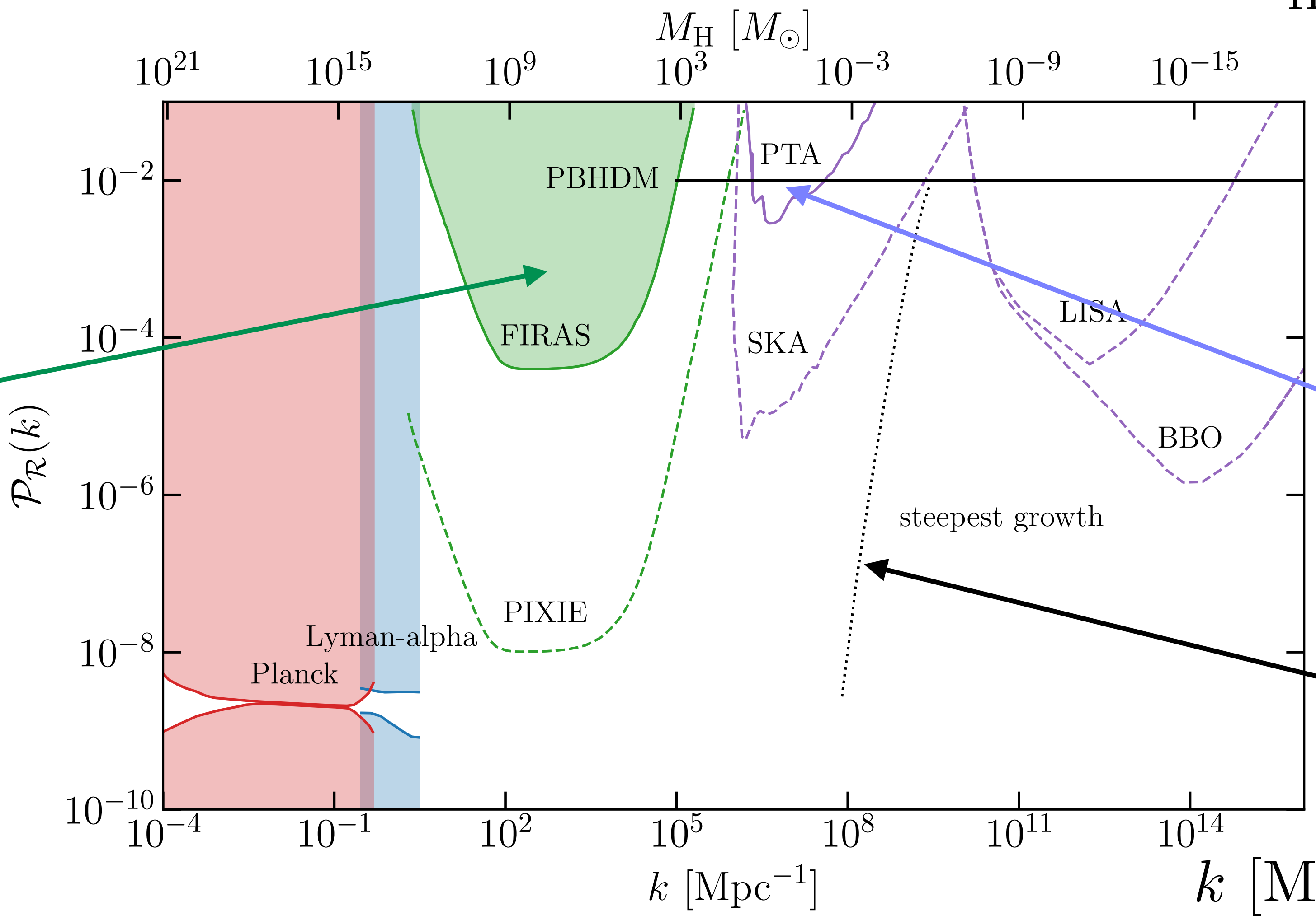
Large curvature perturbations act as 2nd order source of gravitational waves (‘scalar induced gravitational waves’). Ananda, Clarkson & Wands

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

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

$M_{\rm H}\ [M_\odot]$



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

CMB spectral distortions

scalar induced gravitational waves

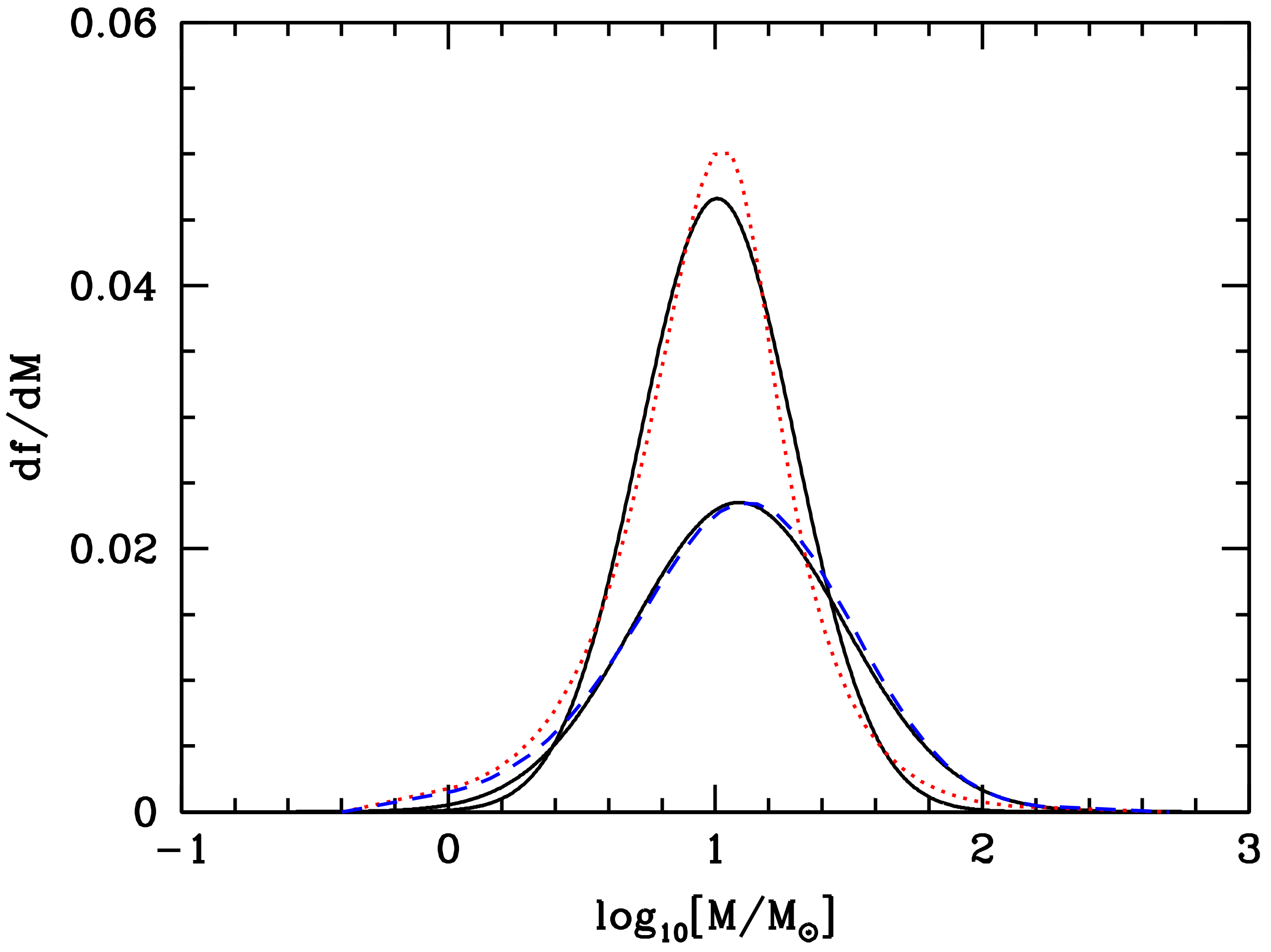
steepest growth in single field inflation

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

constraints on (realistic) extended mass functions

Extended MFs produced by broad peak in power spectrum, appear to be 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

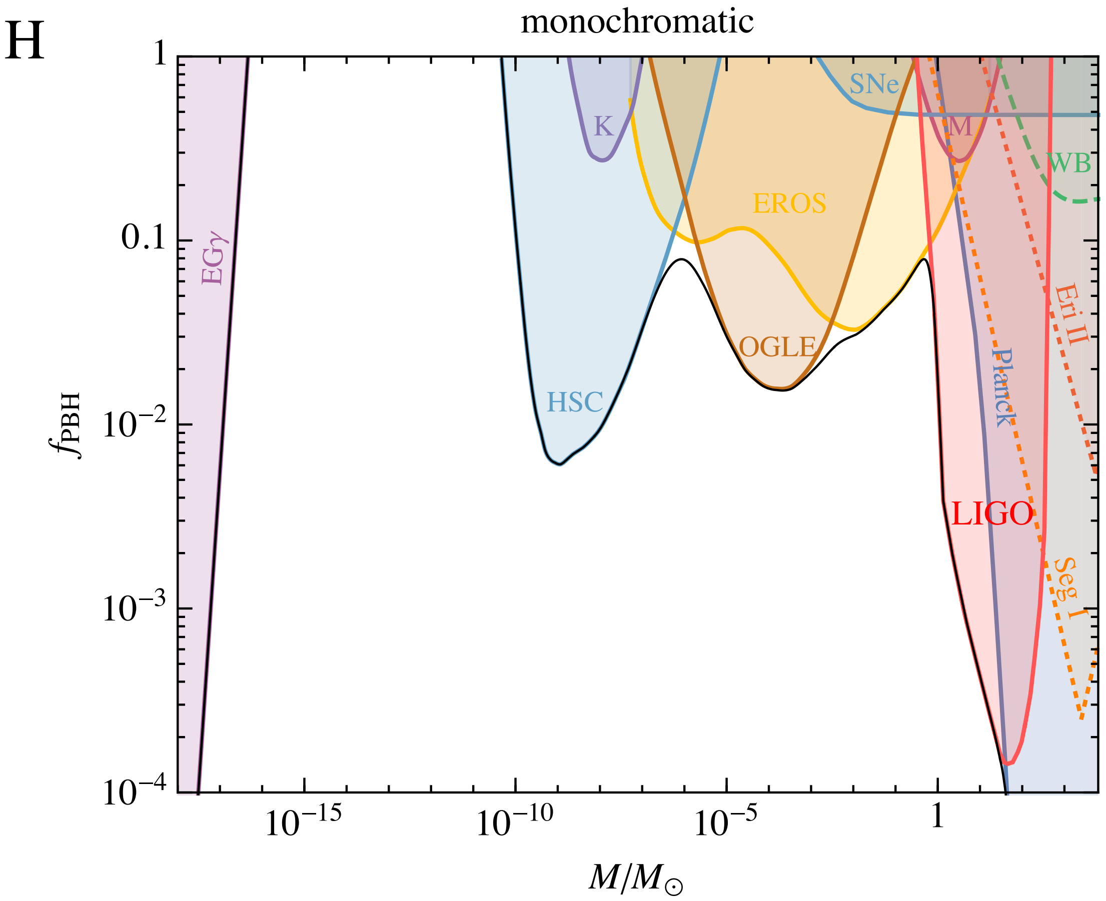
For extended mass functions, constraints on f are smeared out, and gaps between constraints are ‘filled in’:

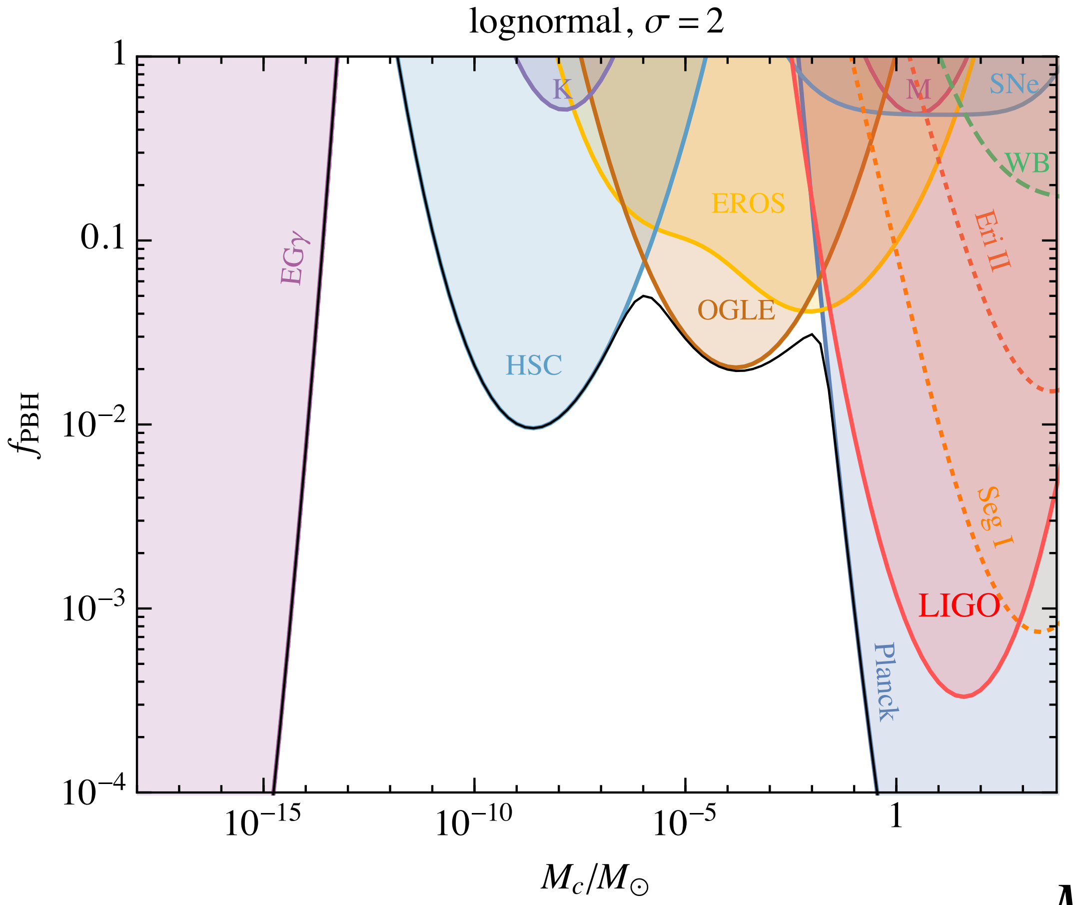
Green; Carr et al.; see also Bellomo et al.

monochromatic

log-normal
(fixed width)

$f_{\rm PBH}$





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

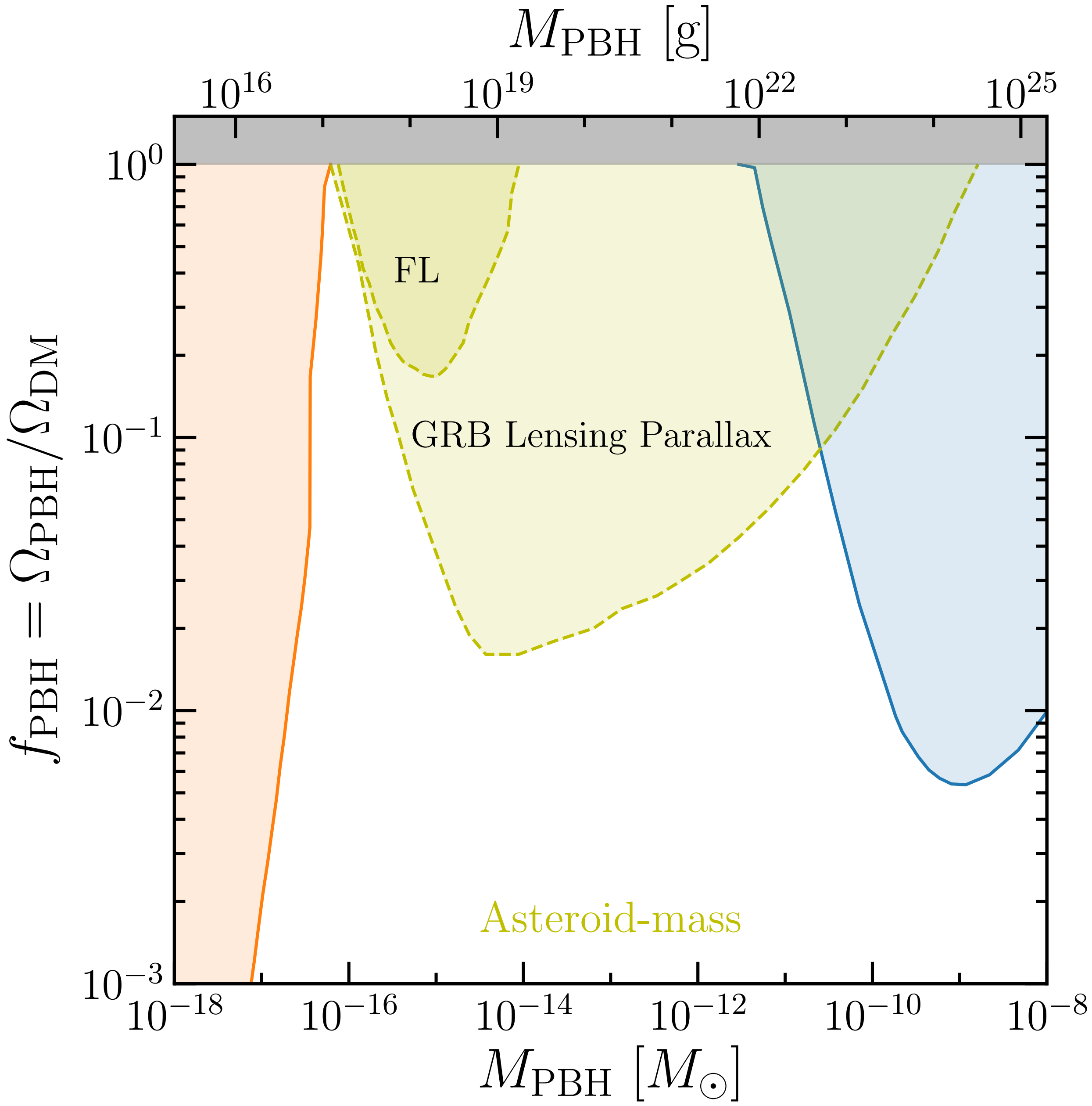
Carr et al.

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



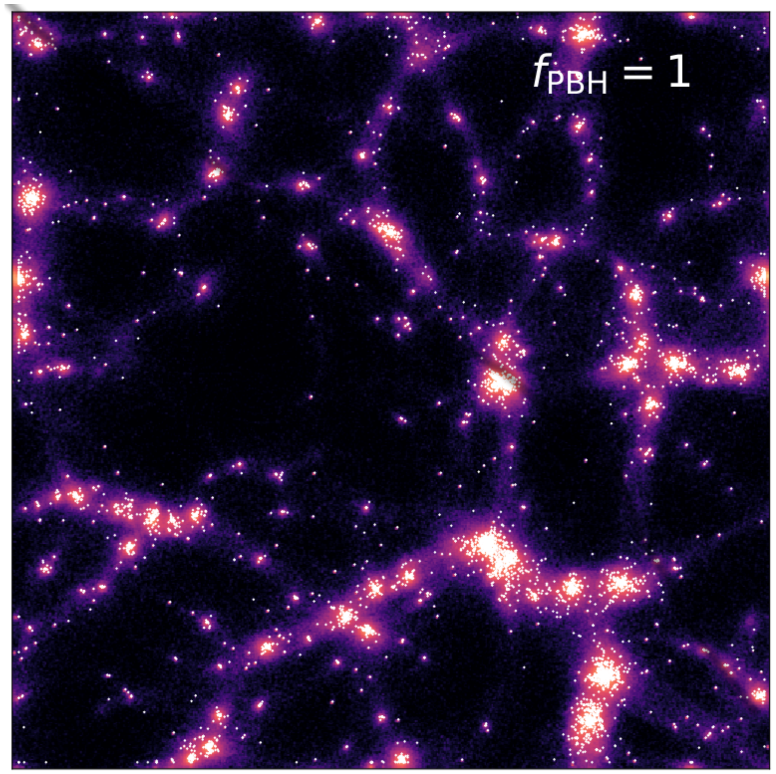
ii) clustering

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

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;... Inman & Ali-Haïmoud

If PBHs don't make up all of the DM they accrete a halo of particle DM during matter domination. Mack, Ostriker & Ricotti; … Adamek et al.



PBH-DM dist at z=100

Inman & Ali-Haïmoud

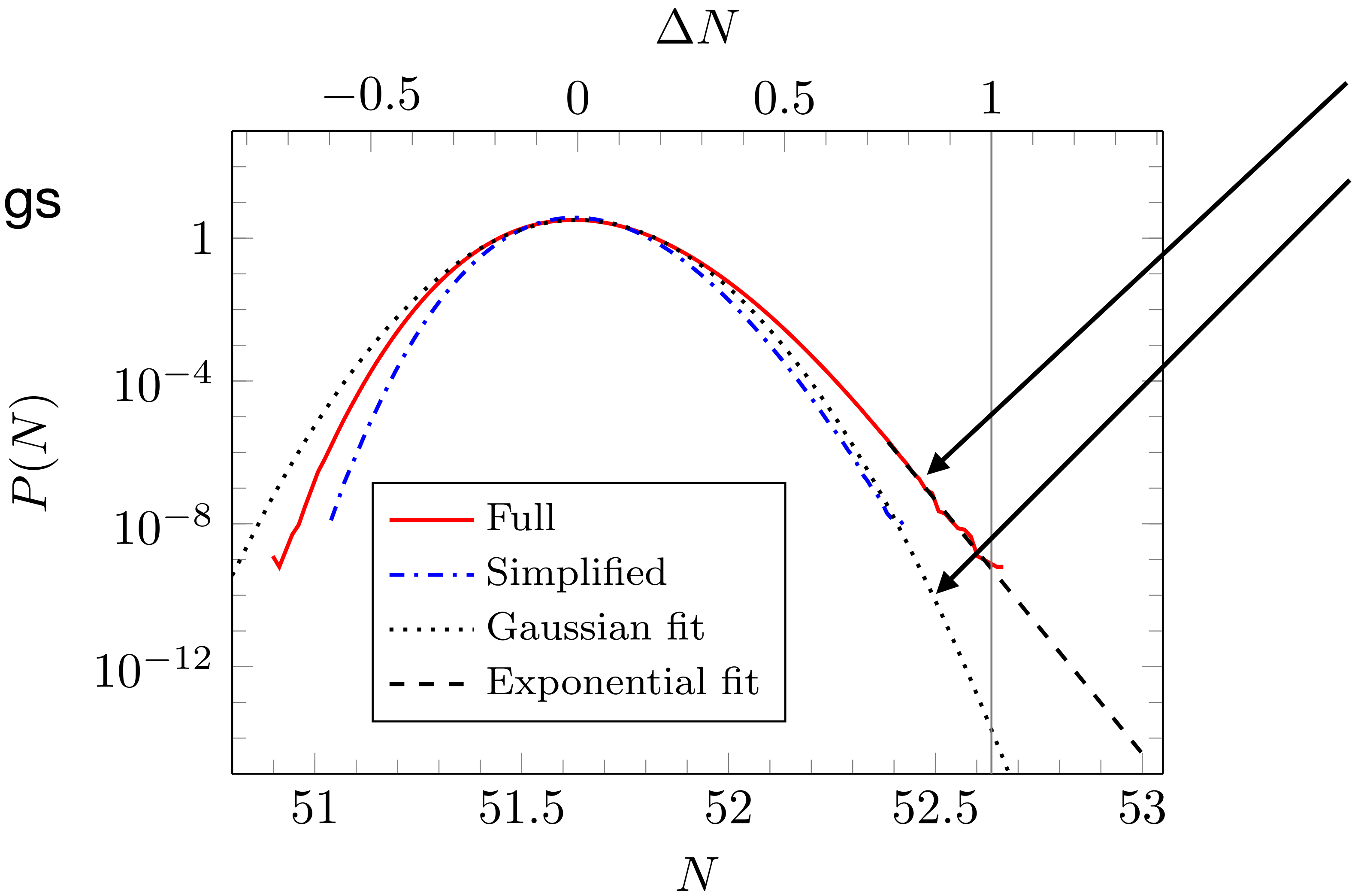
Evolution of PBH clusters (and in particular PBH binaries) through to the present day is a challenging open problem. e.g. Jedamzik; Trashorras et al....

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

Pattinson et al. … Figueroa et al.; Tada & Vennin

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



exponential

gaussian

Figueroa 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.

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

- However clustering of PBHs could modify some constraints (in particular GWs from PBH binary mergers).

- 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, clustering, perturbations in ultra-slow roll inflation…

Back-up slides

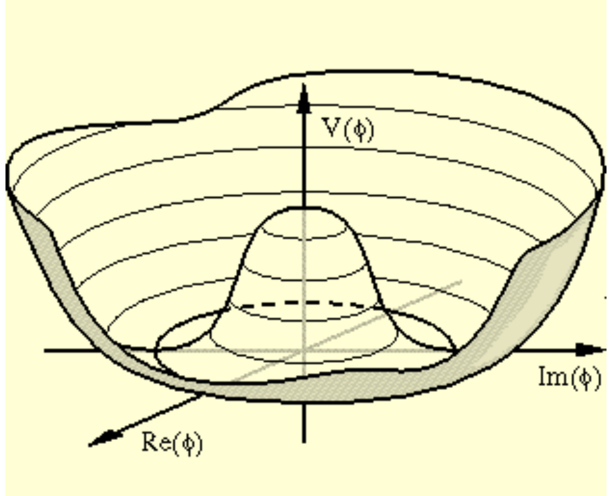
PBH formation: (some) other mechanisms

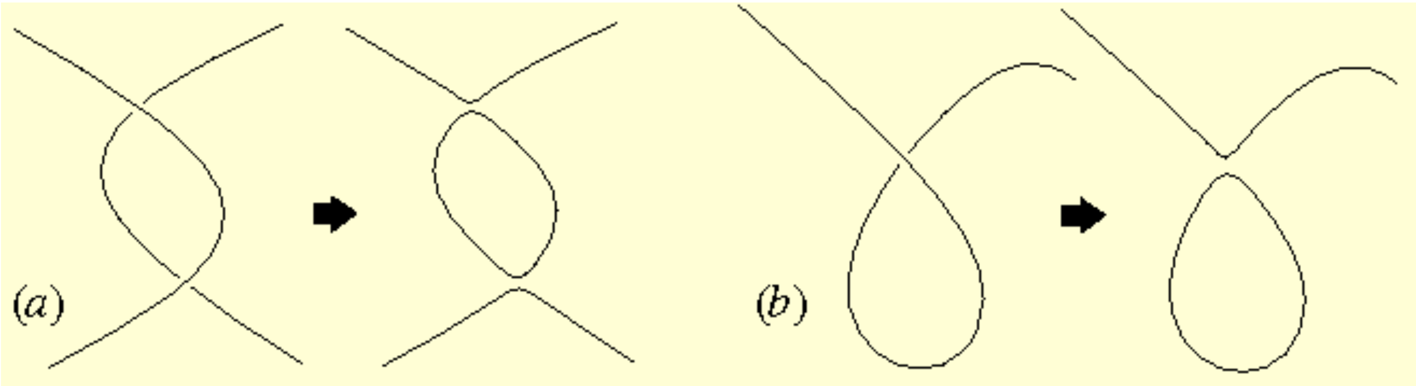
Collapse of cosmic string loops

Hawking; Polnarev & Zemboricz;

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

String intercommute producing loops.





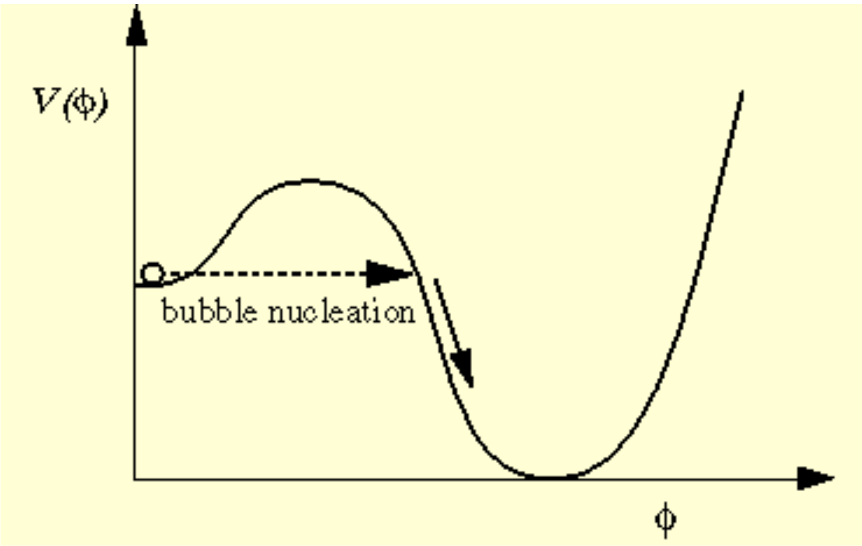
Small probability that loop will get into configuration where all dimensions lie within Schwarzschild radius (and hence collapse to from a PBH with mass of order the horizon mass at that time).

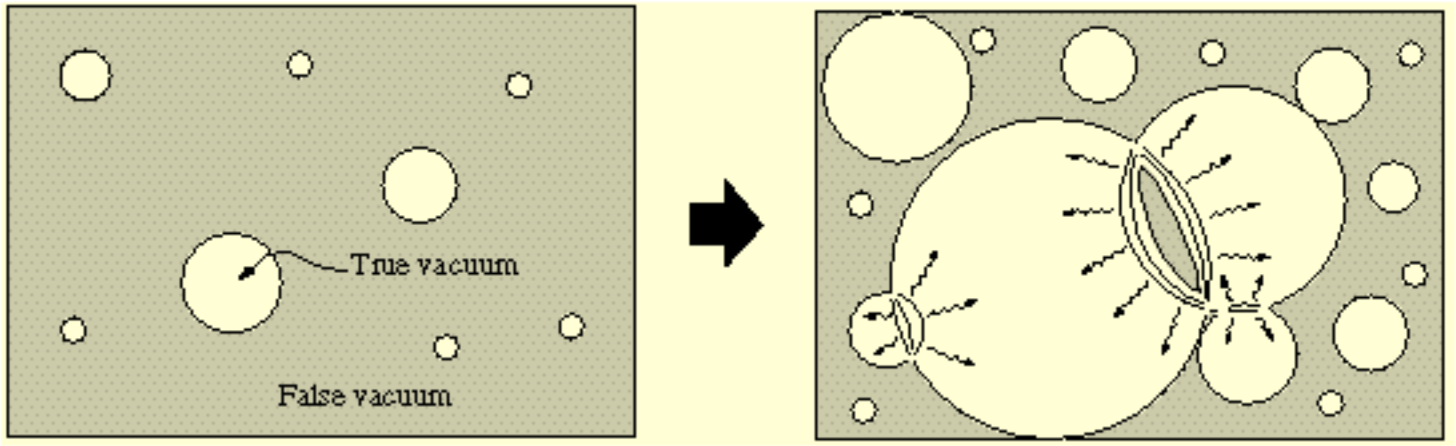
Probability is time independent, therefore PBHs have extended mass spectrum.

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

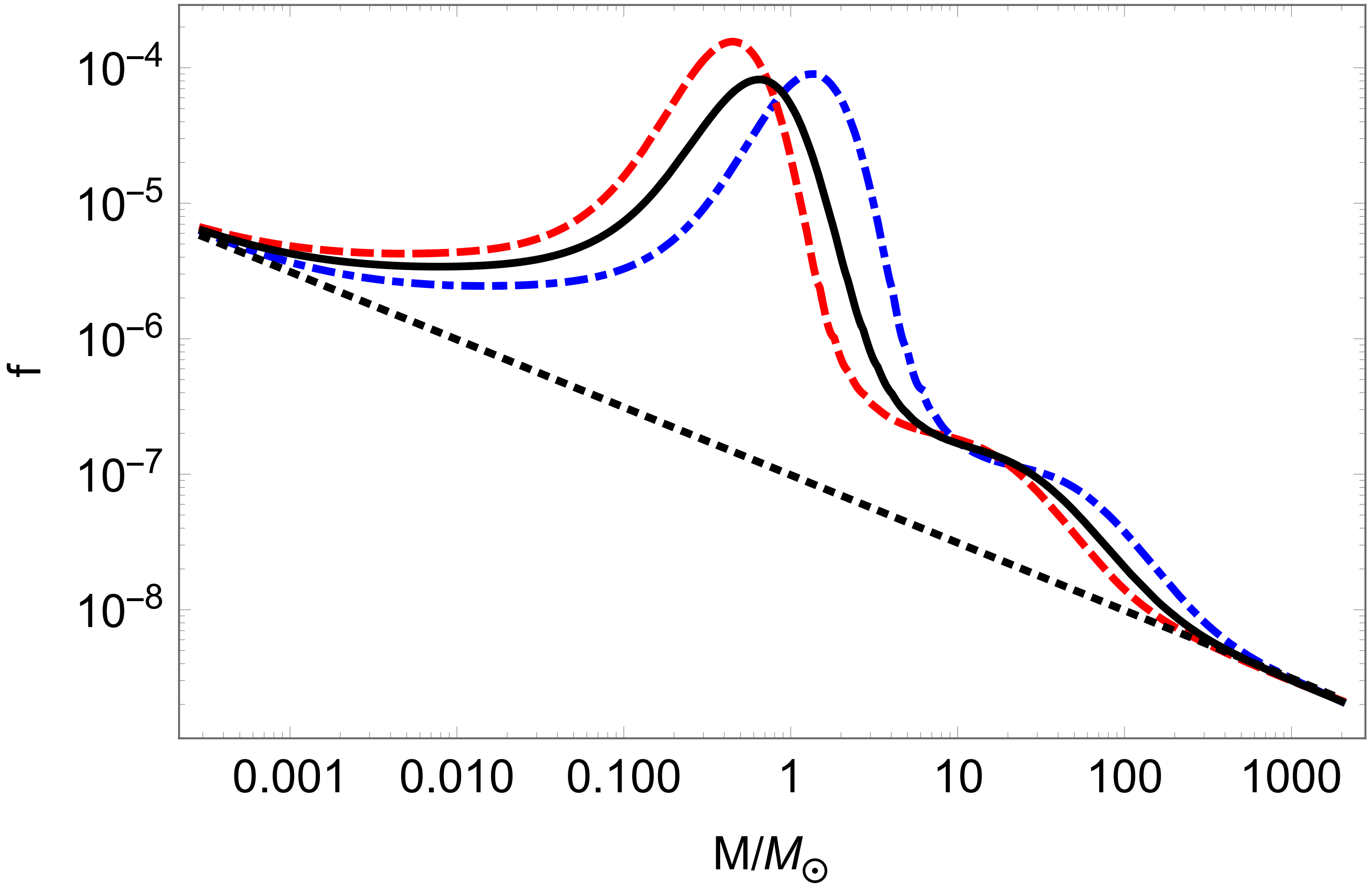
Scalar field with flat potential forms condensate at end of inflation, fragments into lumps (oscillons/Q-balls) which can come to dominate universe and have large density fluctuations that can produce PBHs.

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

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



Byrnes et al.

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

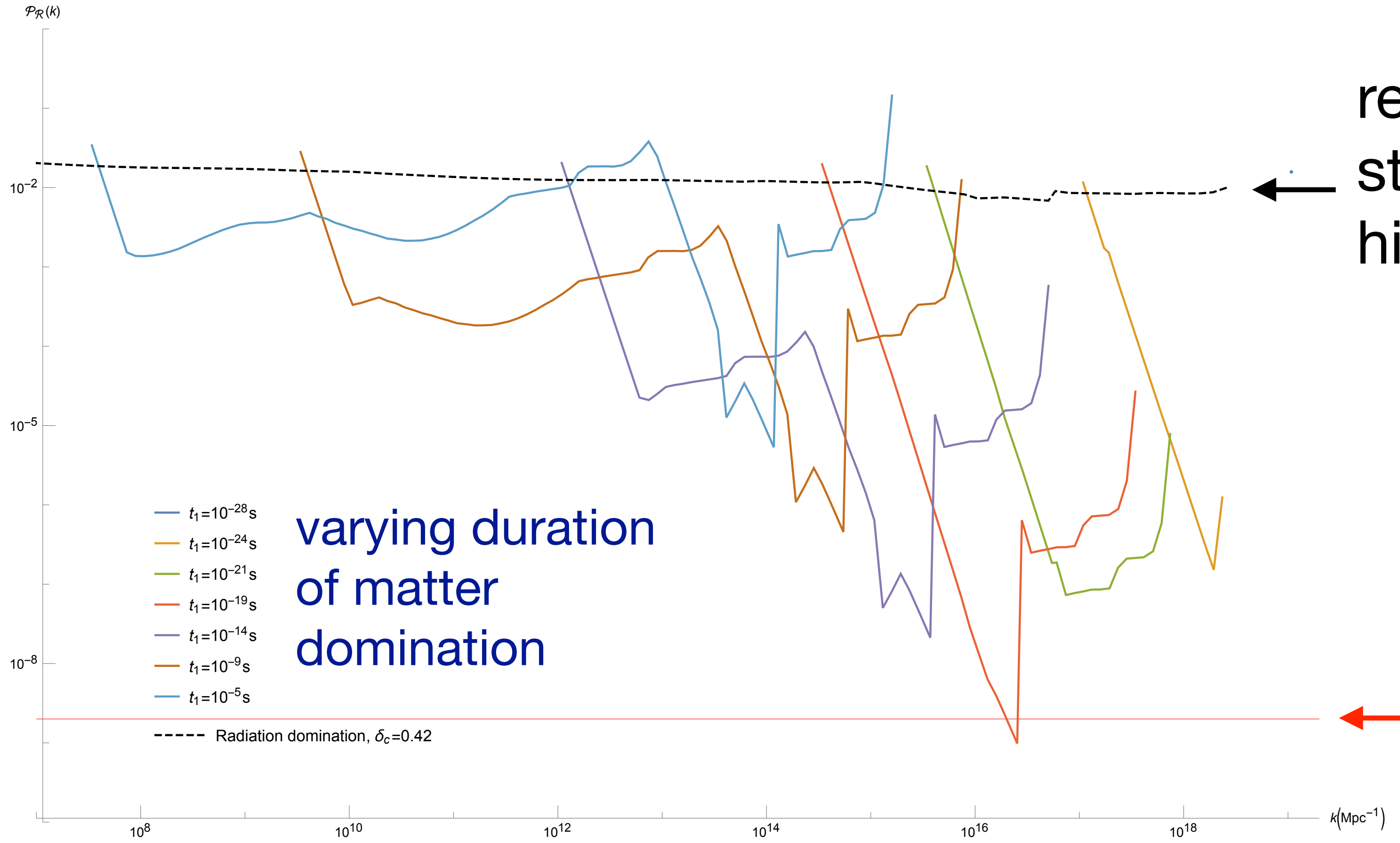
During matter domination PBHs can form from smaller fluctuations (no pressure to resist collapse) in this case fluctuations must be sufficiently spherically symmetric

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



varying duration of matter domination

required amplitude for standard cosmological history

amplitude on CMB scales

Cole & Byrnes

k

axion-like curvaton

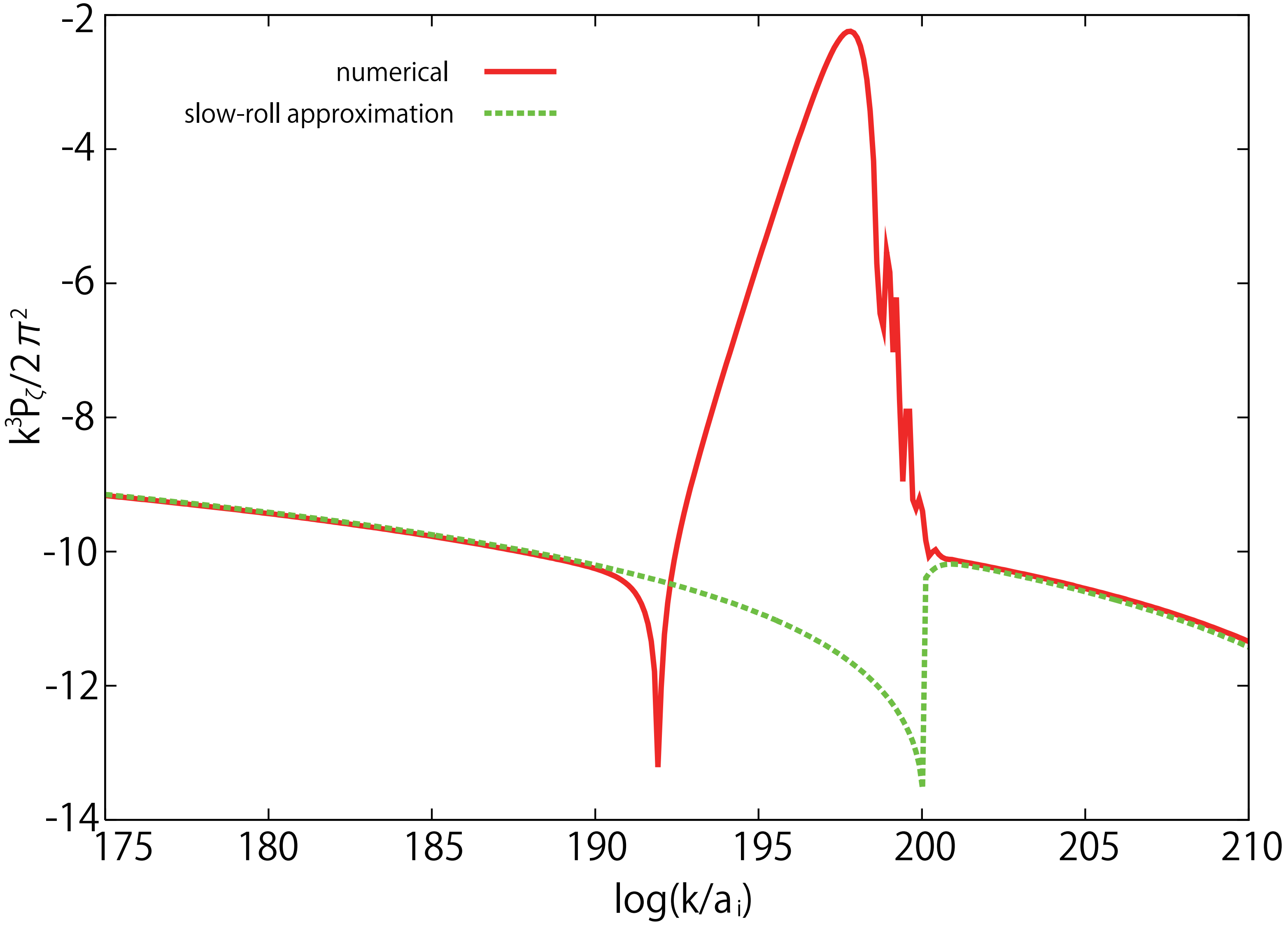
Kawasaki, Kitajima & Yanagida

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.)

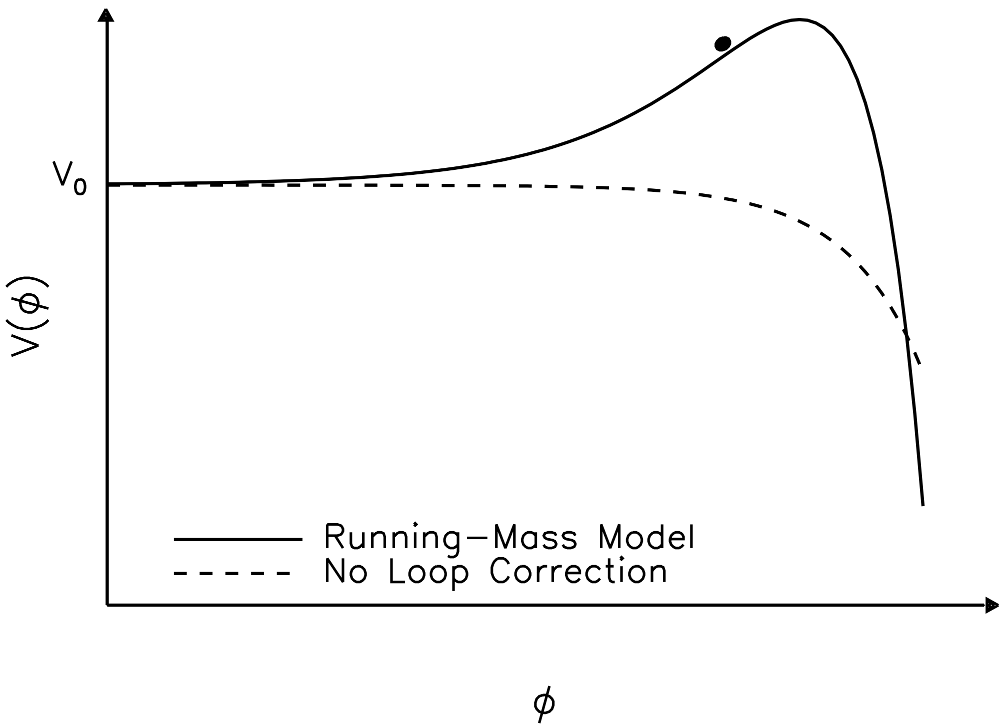
ii) monotonically increasing power spectrum

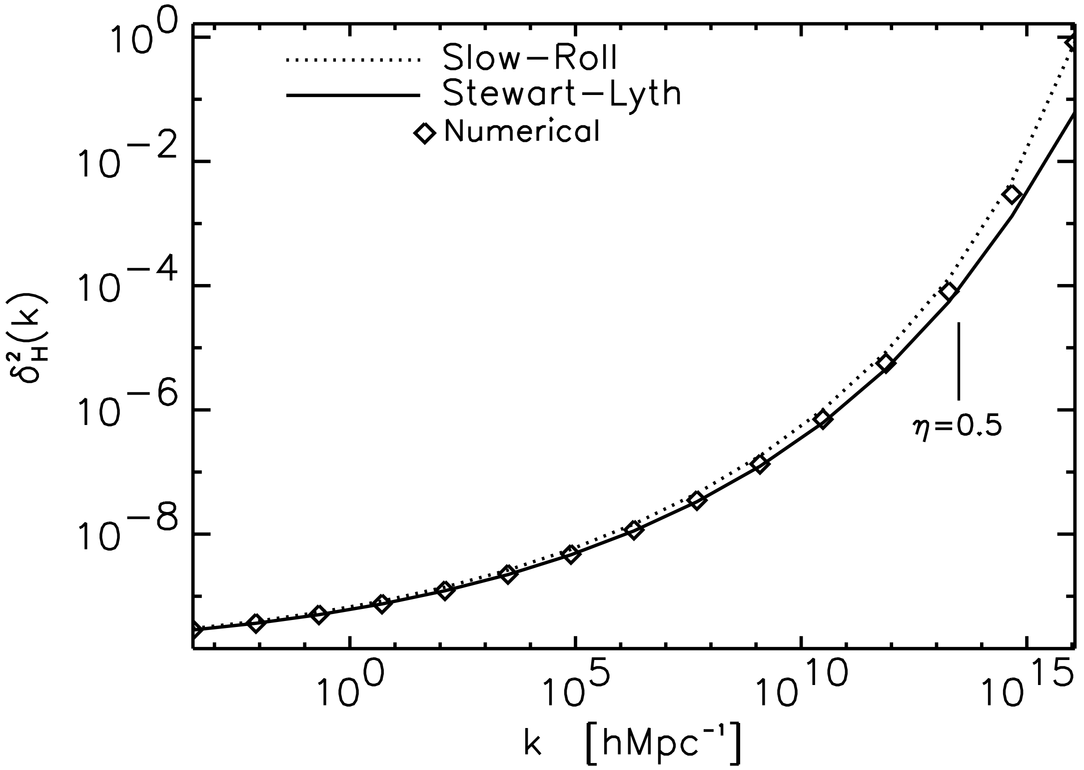
running-mass inflation Stewart

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

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:

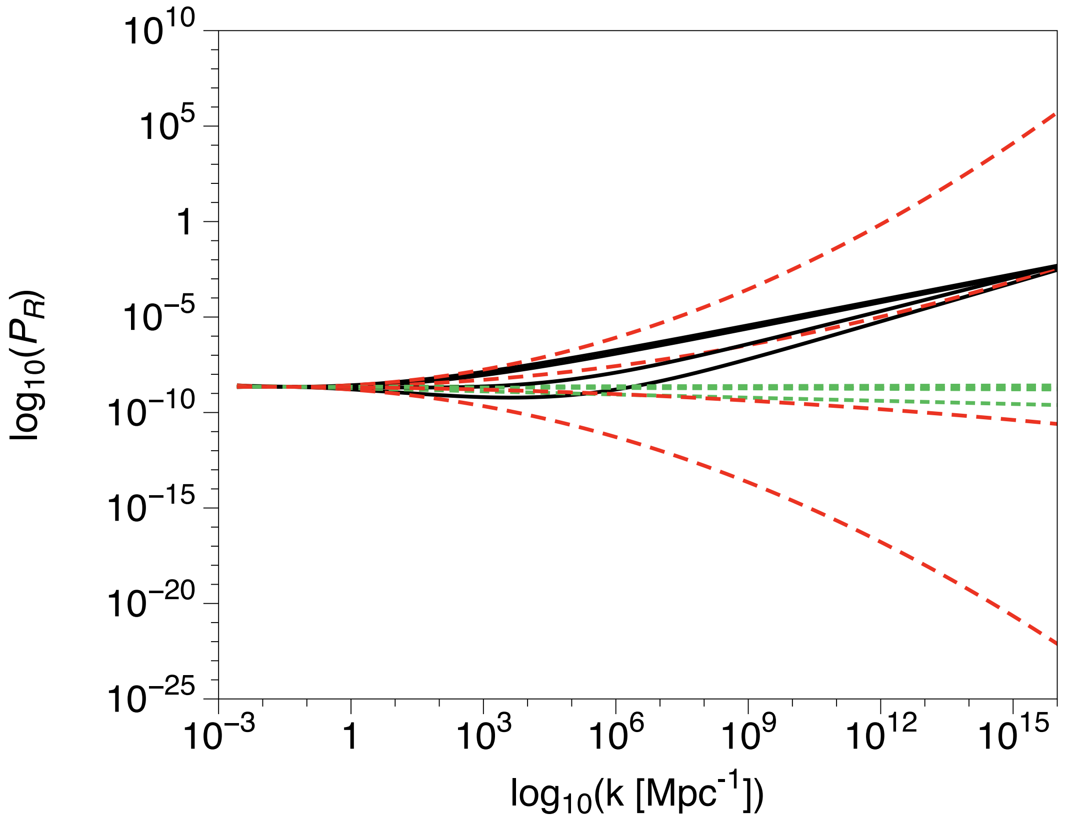
$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_0}\right)^{n_{\rm s}(k)-1} \quad \text{with} \quad n_{\rm s}(k) = n_{\rm s}|_{k_0} + \alpha_{\rm s}\ln\left(\frac{k}{k_0}\right) + \beta_{\rm s}\ln^2\left(\frac{k}{k_0}\right) + \ldots\,,$$

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

The expansion of $n_{\rm s}$ 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

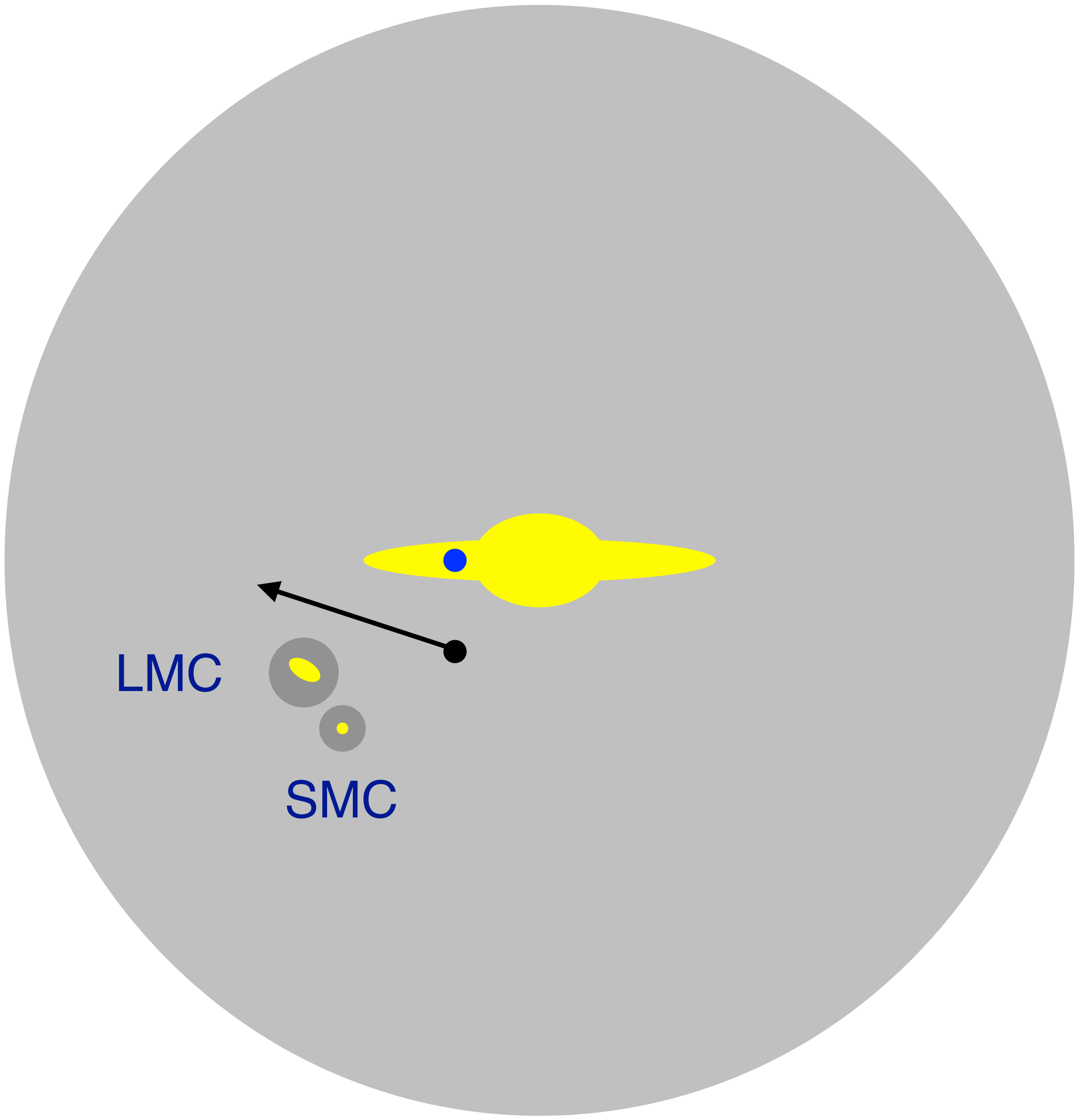
1st order in expansion

2nd order in expansion

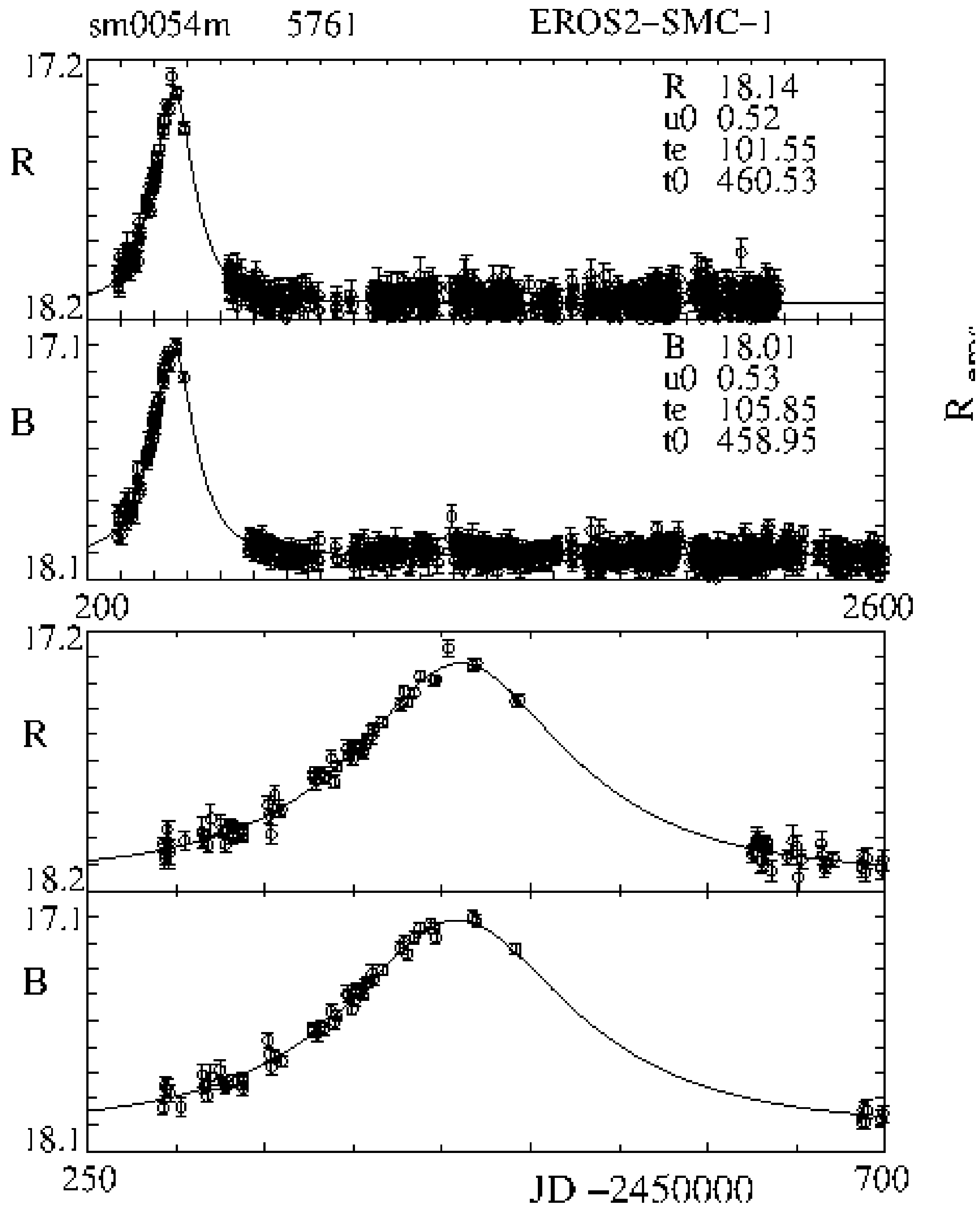
Microlensing

stellar microlensing

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



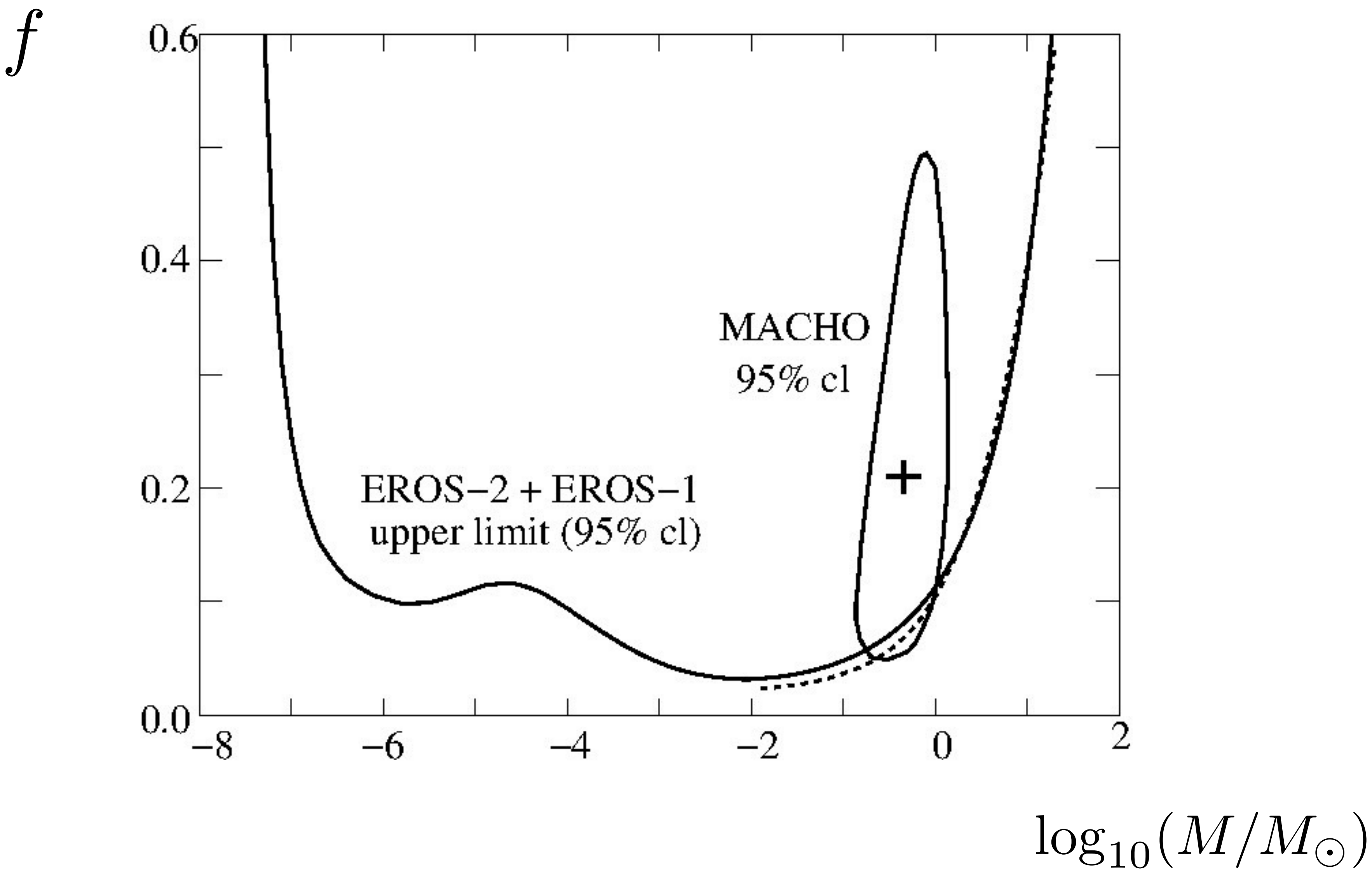
Not to scale!



EROS

magellanic clouds

EROS constraints on fraction of DM in compact objects, f:

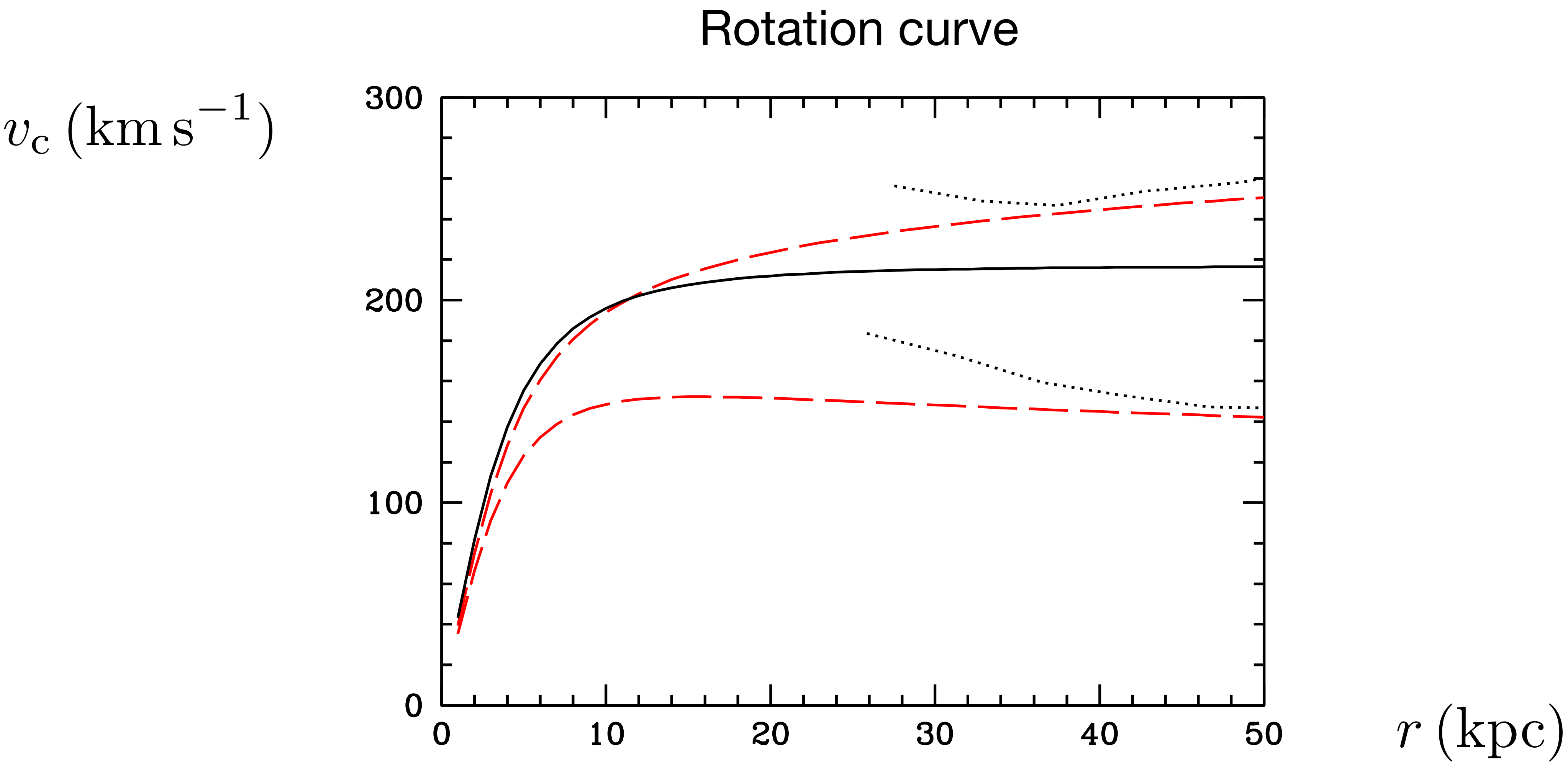


MACHO has very similar limits for $M > 3M_\odot$.

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)

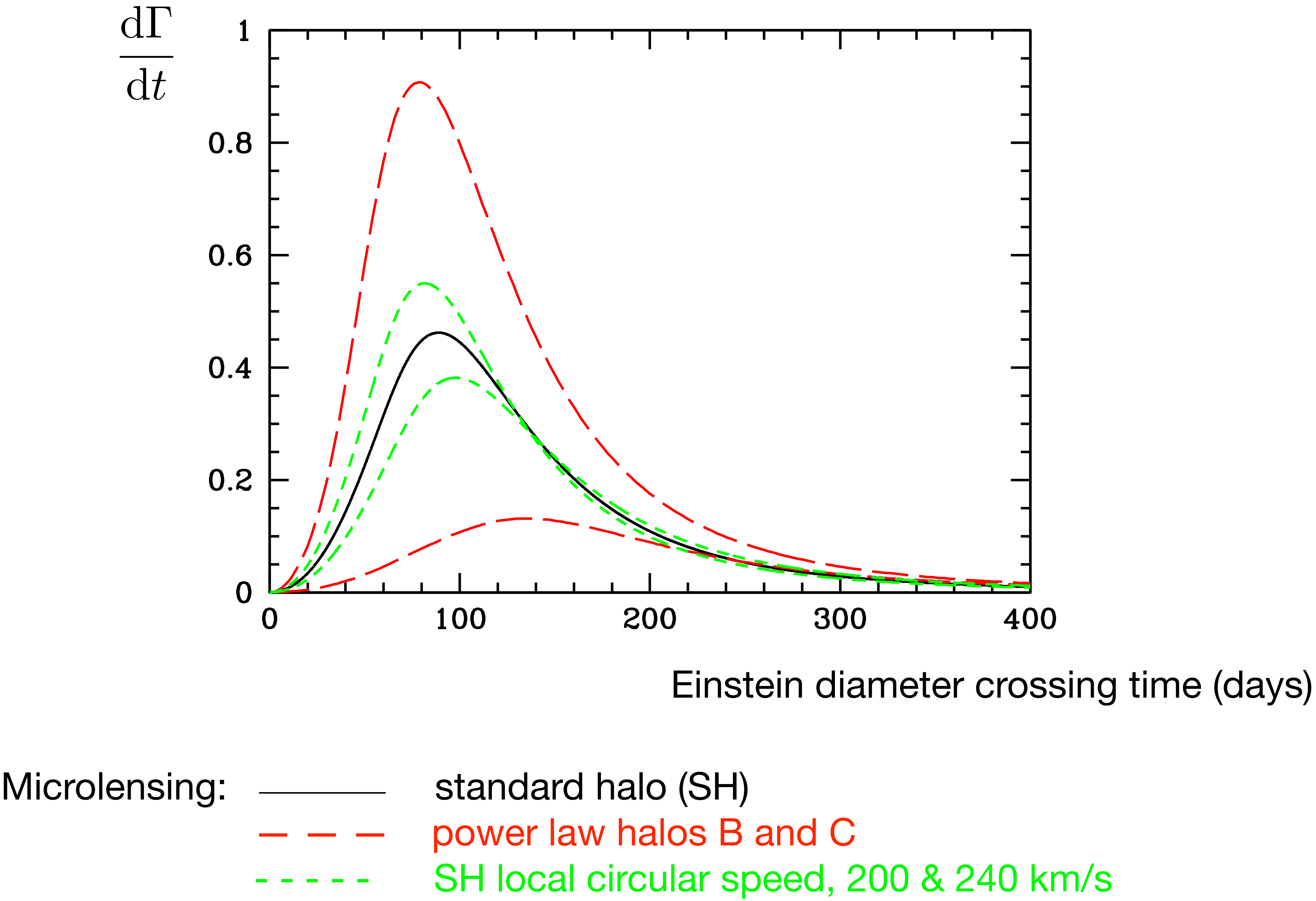
— — — top: power law halo B (massive halo, rising rotation curve)

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

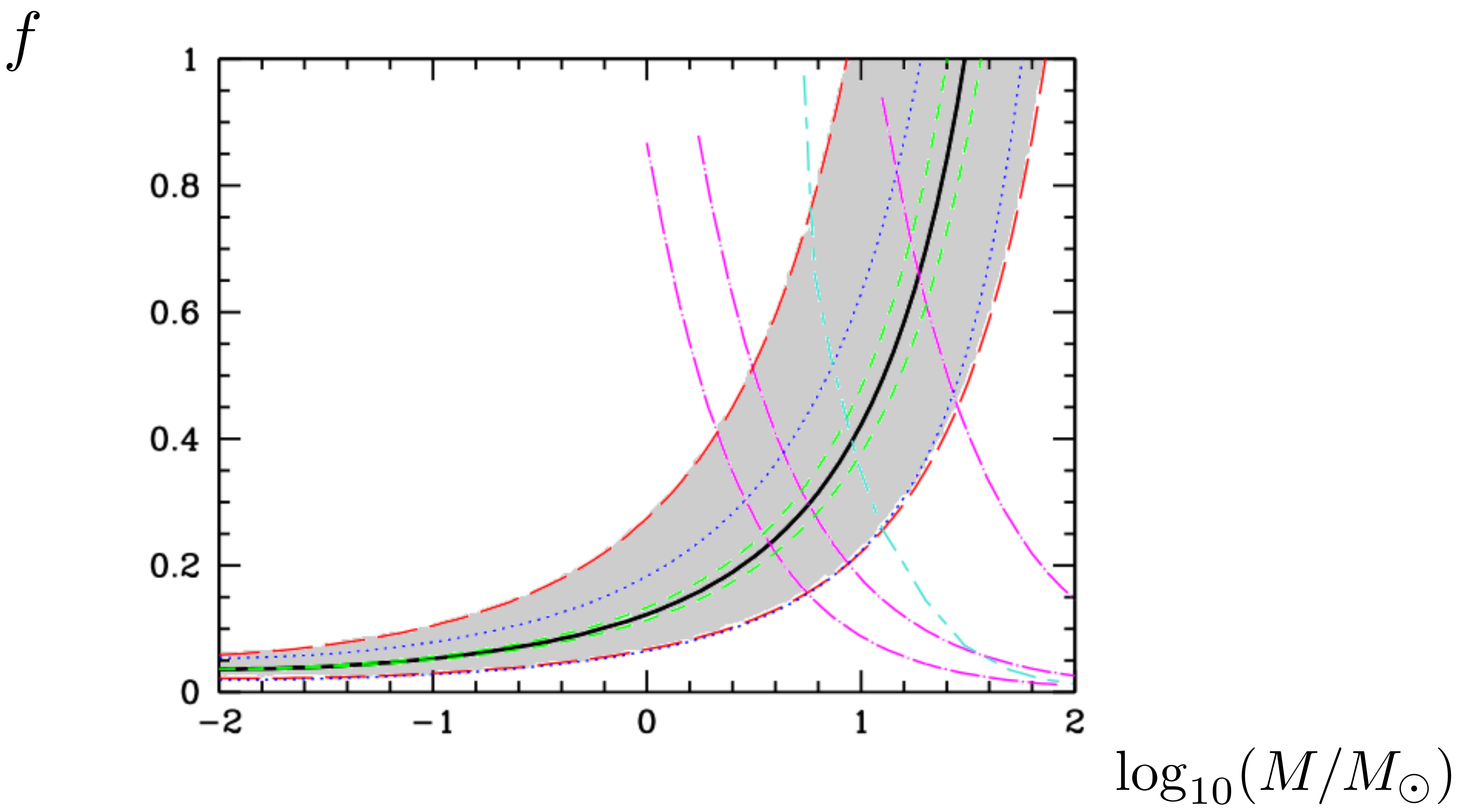
……….. envelope of MW rotation curve data [Bhattacharjee et al.]

Microlensing differential event rate

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



Constraints on halo fraction for delta-function MF



—— standard halo (SH)

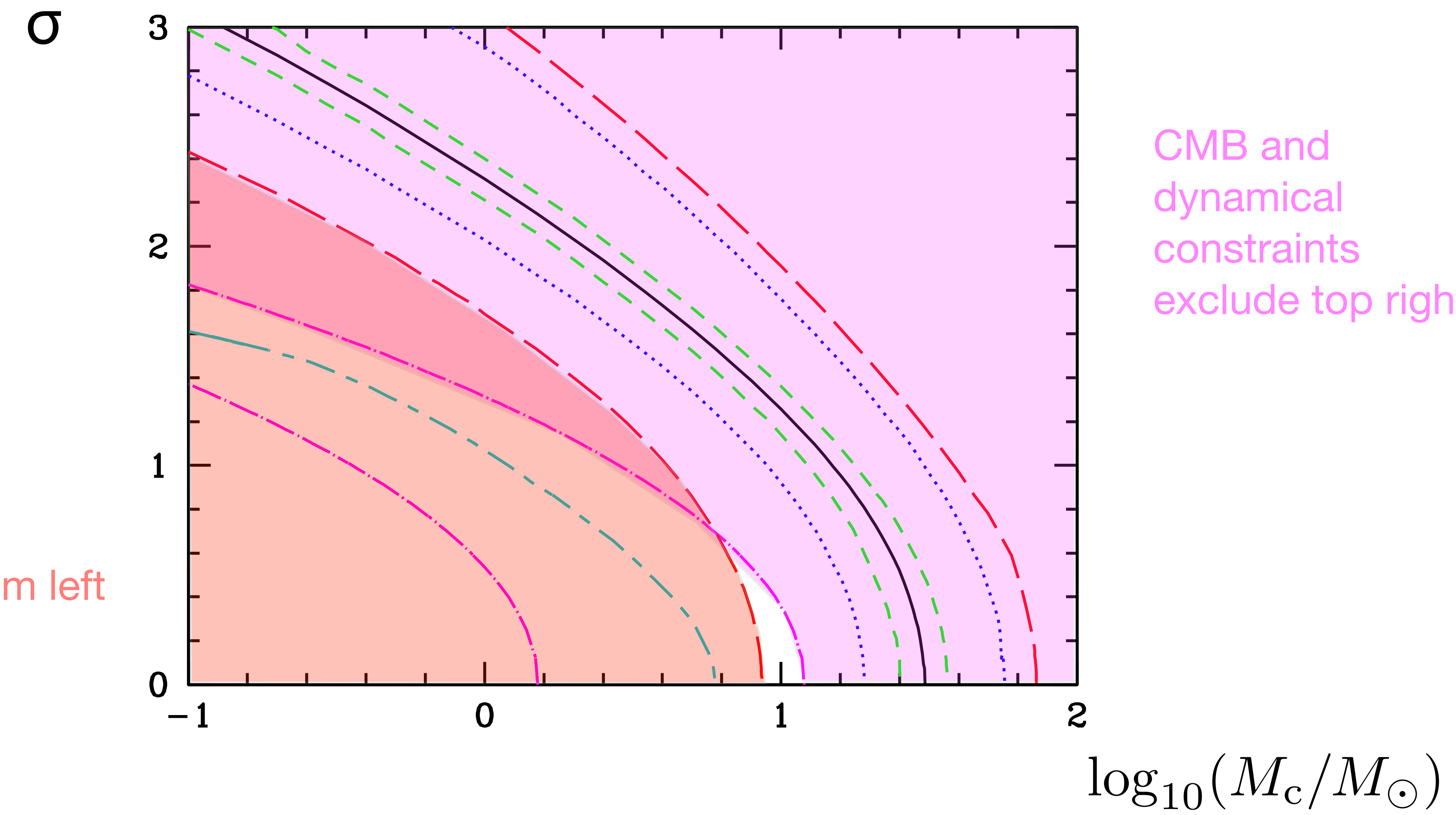
- - - - - SH local circular speed, 200 & 240 km/s

………. 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



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

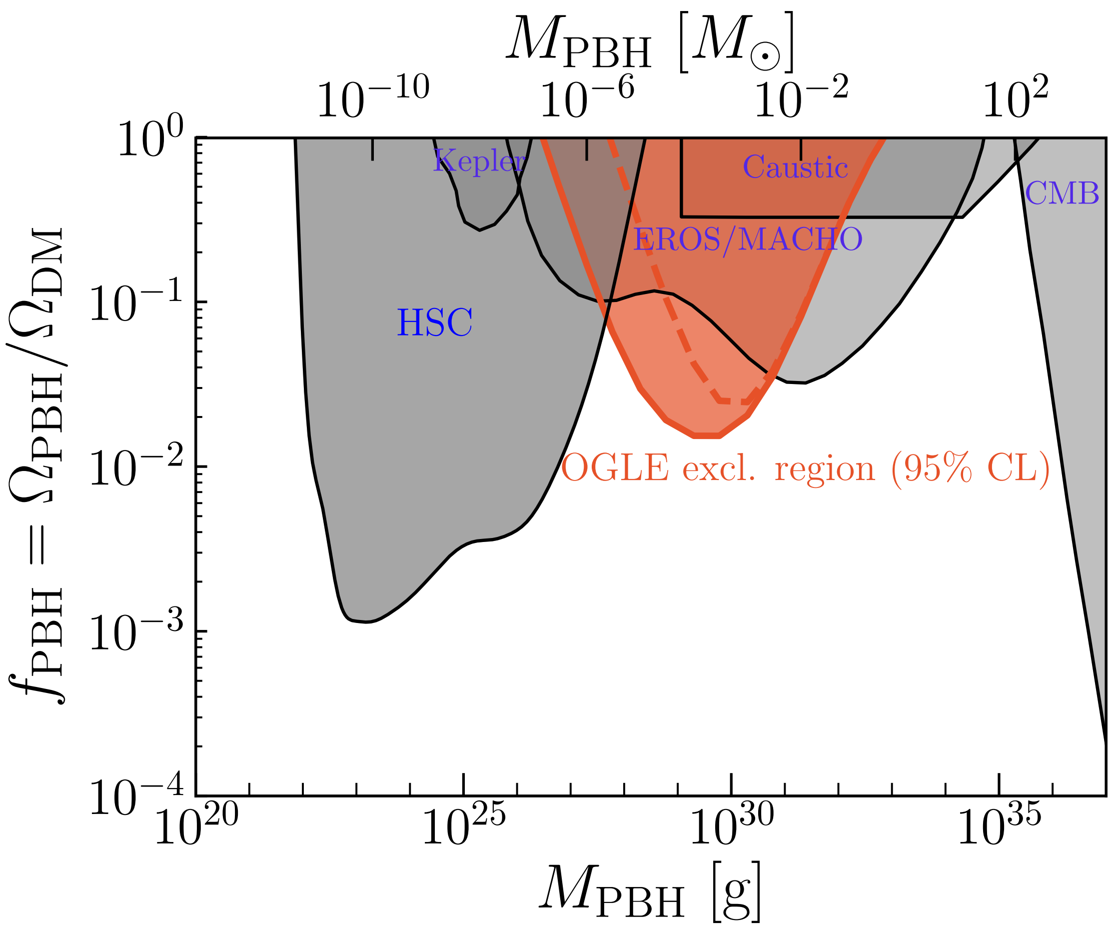
SH local circular speed, 200 & 240 km/s

Brandt dwarf galaxy constraints

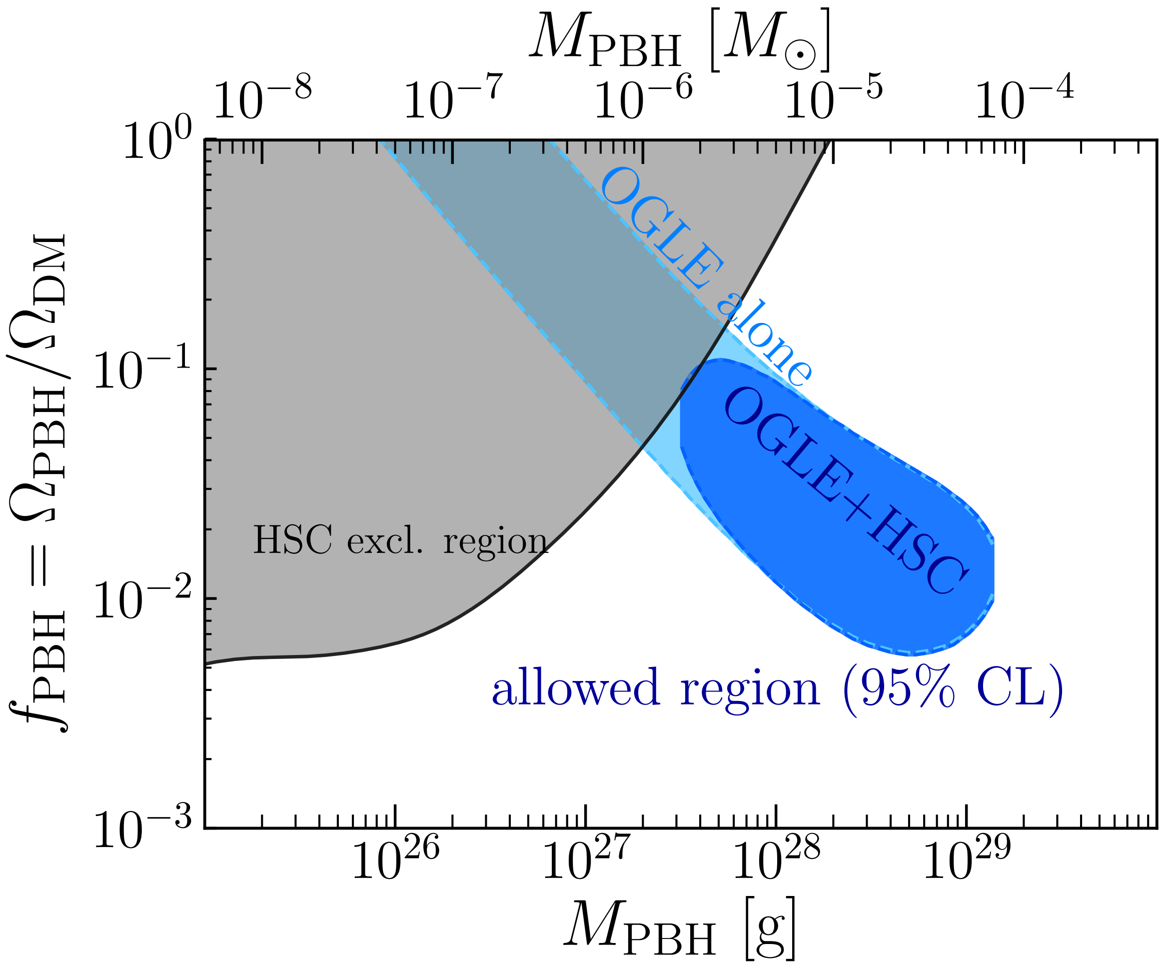
stars in Galactic bulge

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



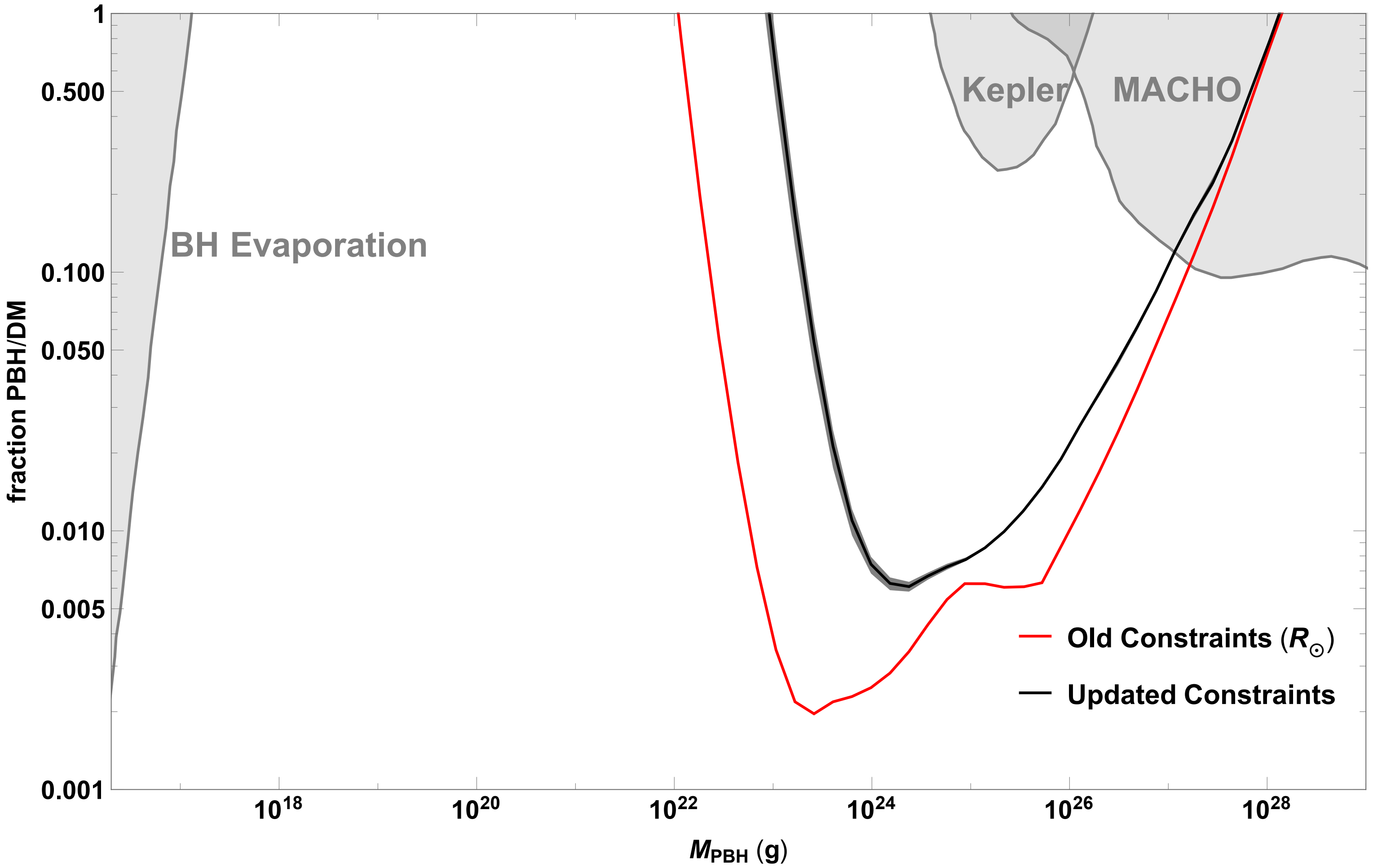
Allowed region
assuming 6 ultra-short events are due to PBHs



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.

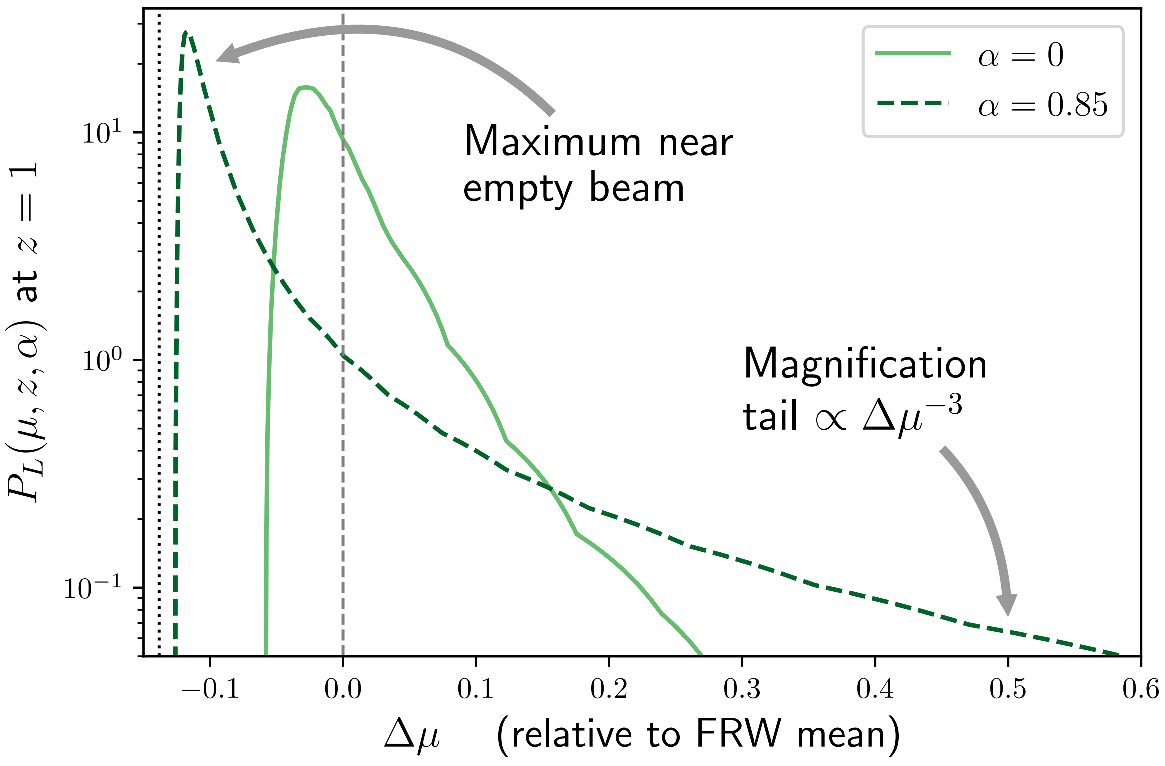
Finite size of source stars and effects of wave optics (Schwarzschild radius of BH comparable to wavelength of light) leads to reduction in maximum magnification for $M \lesssim 10^{-7} M_\odot$ and $M \lesssim 10^{-11} M_\odot$ respectively. Witt & Mao; Gould; Nakamura; Sugiyama, Kurita & Takada

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

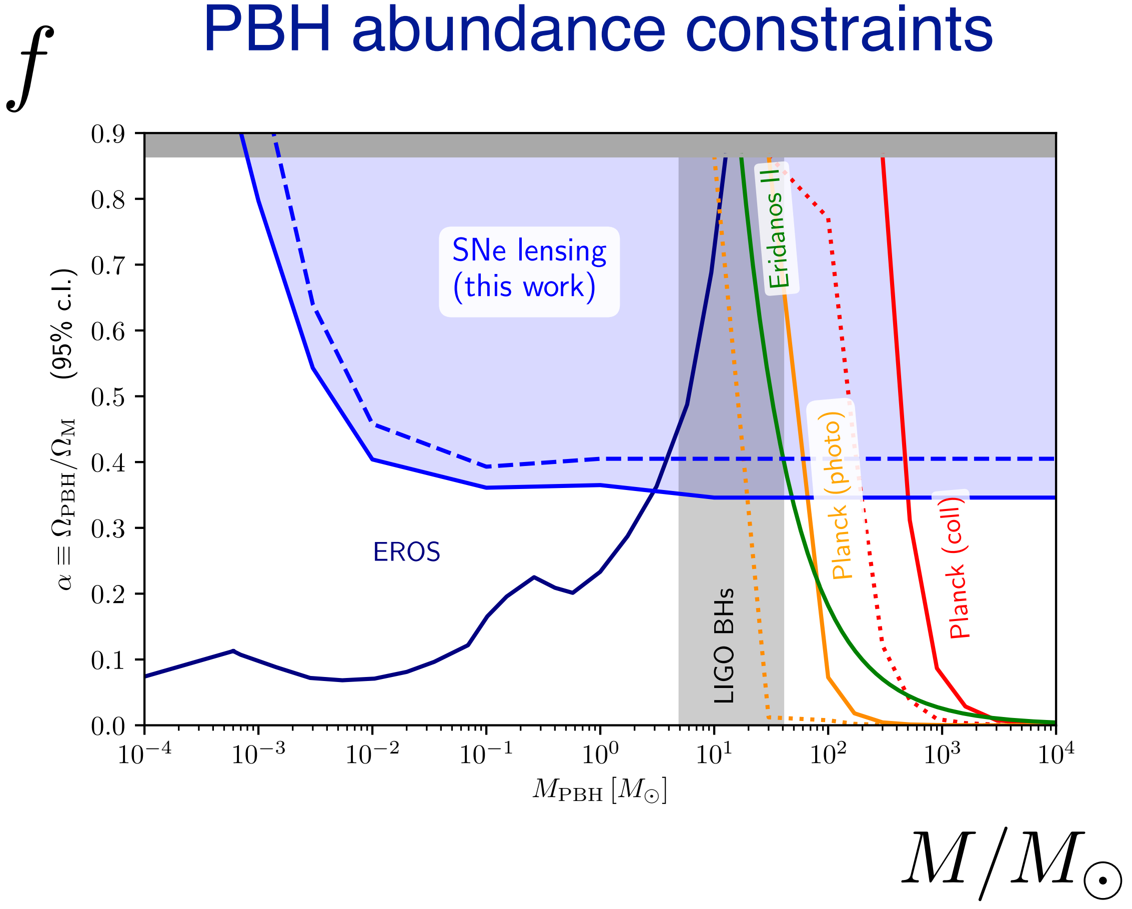
supernova microlensing

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



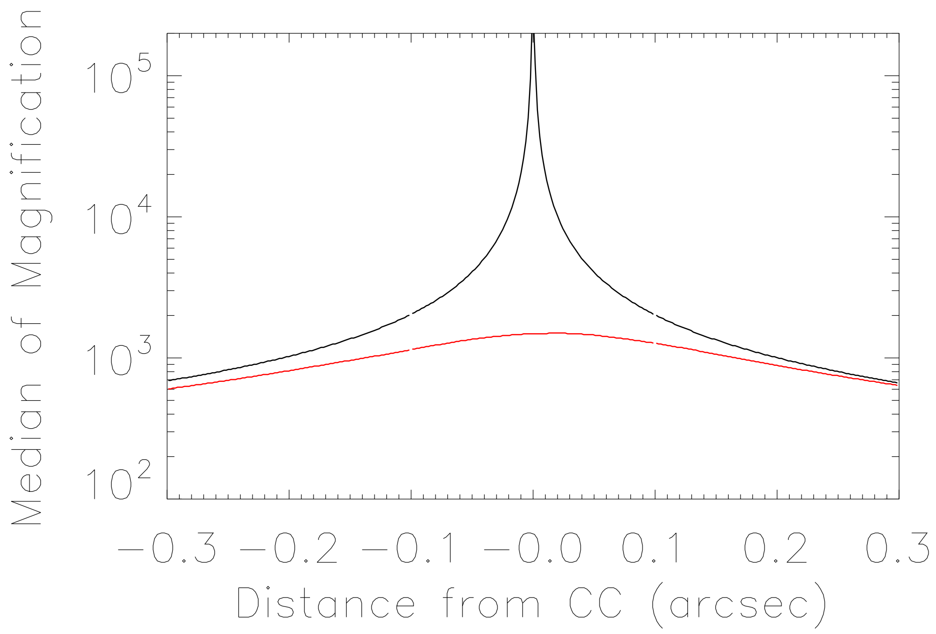
Garcia-Bellido, Clesse & Fleury argue priors on cosmological parameters are overly restrictive and physical size of supernovae have been underestimated.

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

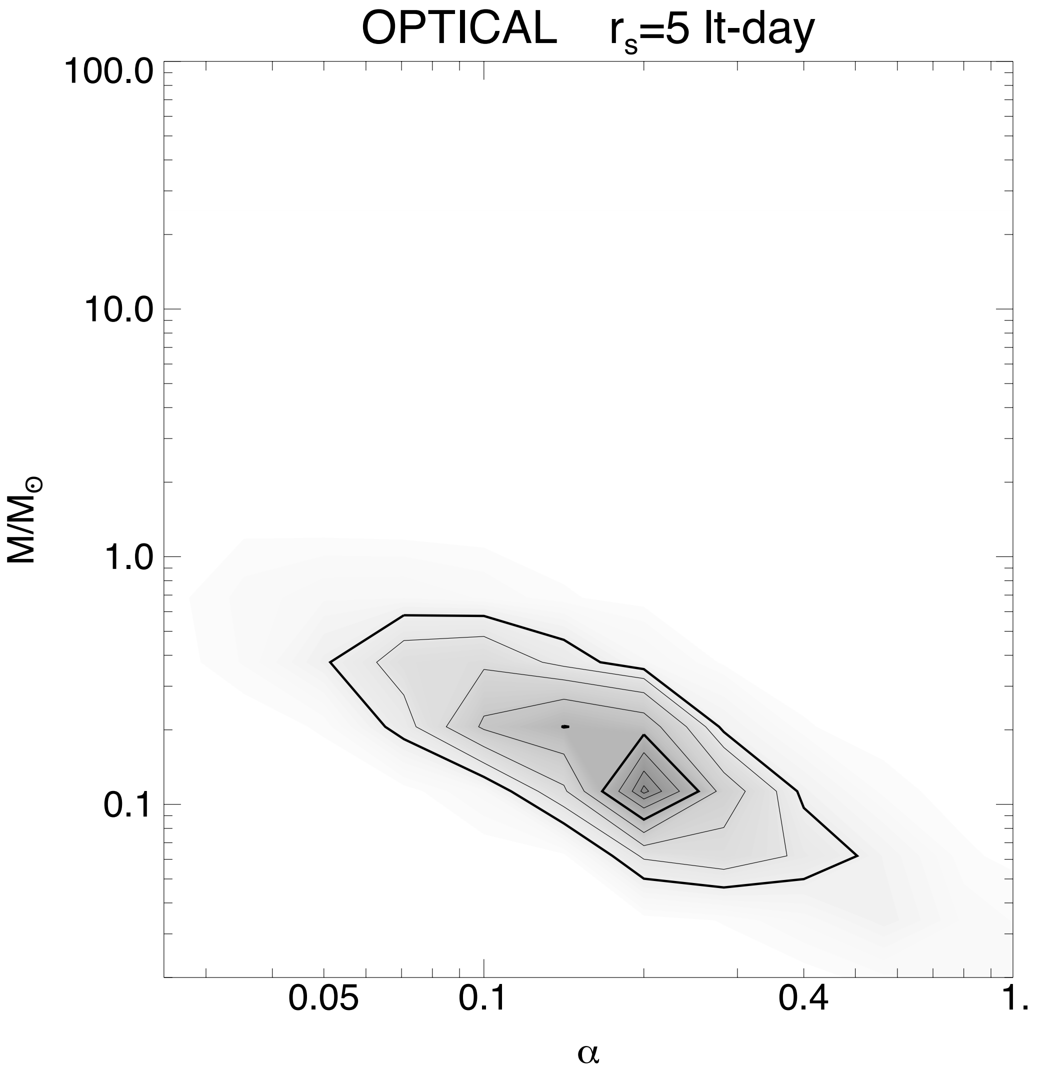
Icarus is first (serendipitously) observed event involving a star at red-shift 1.5. Kelly et al.

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

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 light PBHs from evaporation products

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

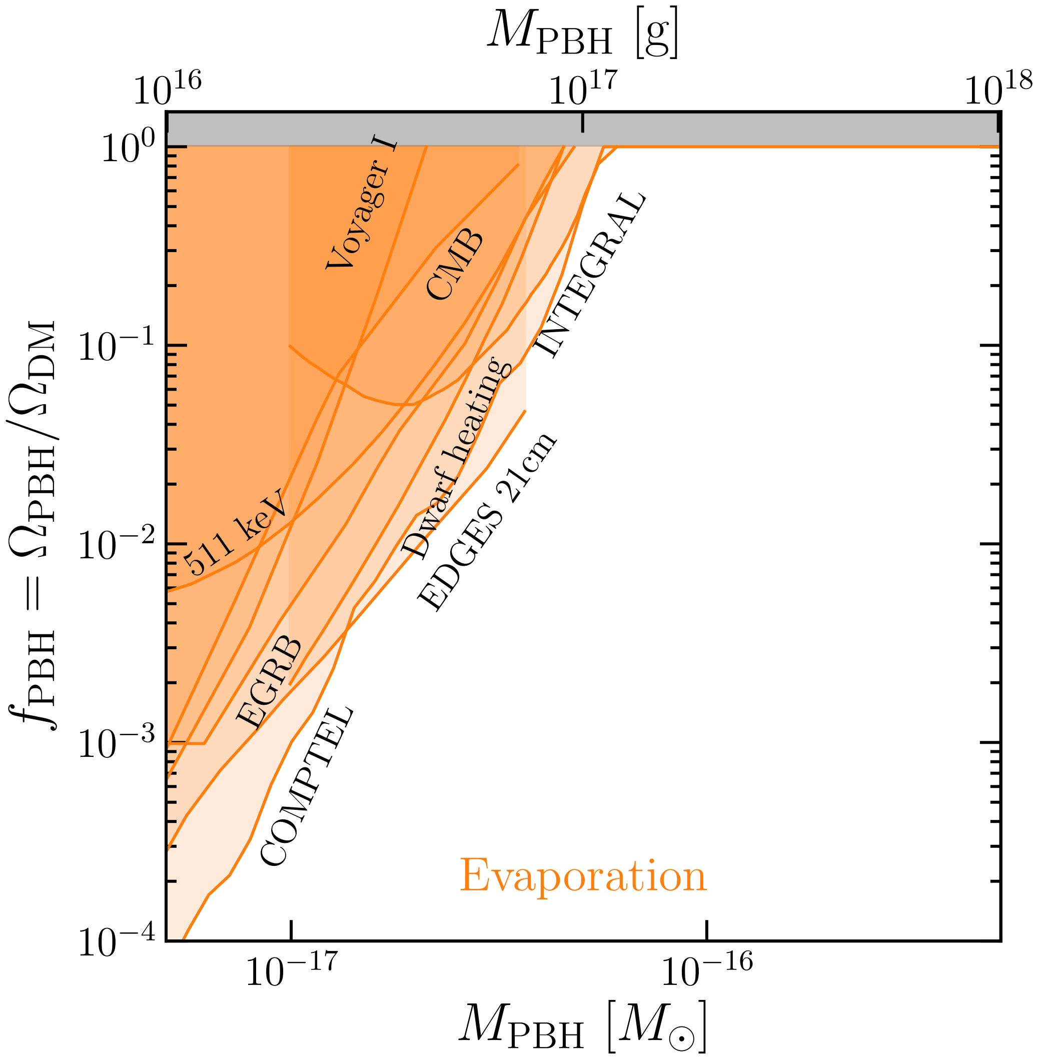
MeV galactic diffuse flux (INTEGRAL) Laha, Munoz & Slatyer (COMPTEL) Coogan, Morrison & Profumo

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



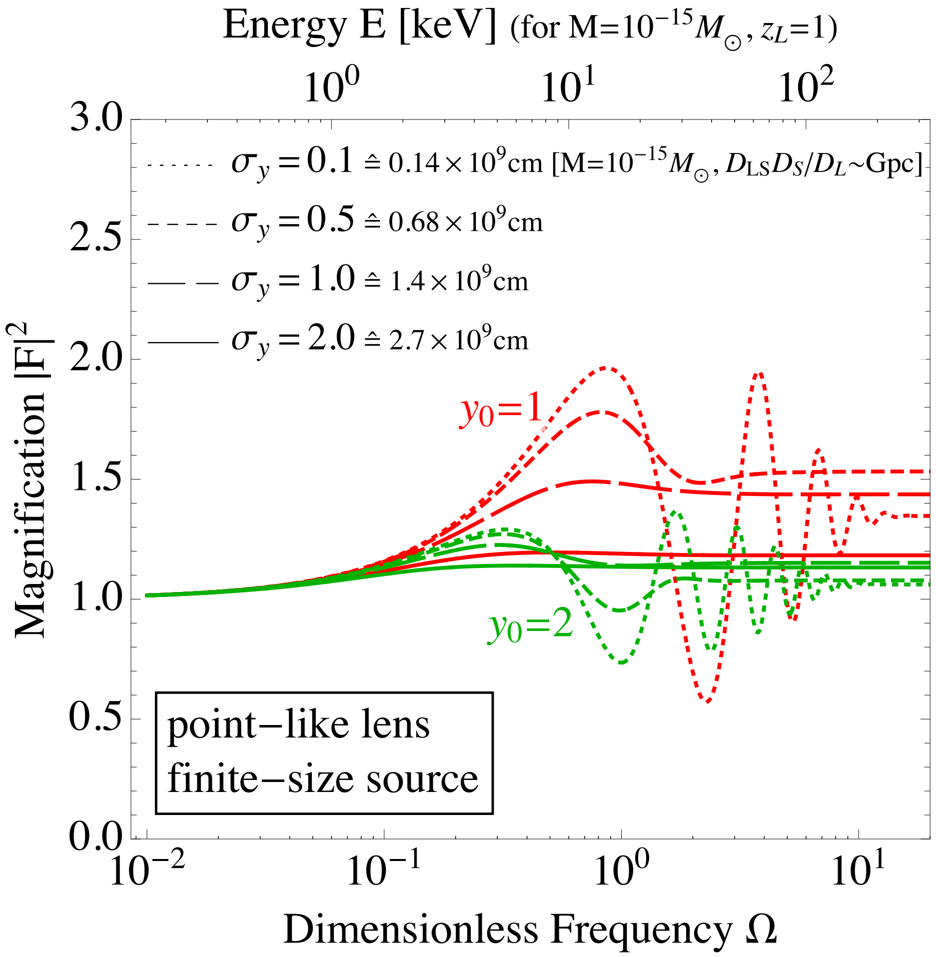
how to constrain asteroid mass PBHs??

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:



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).

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

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

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

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

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 **L**

Astrophysical BH binaries:

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

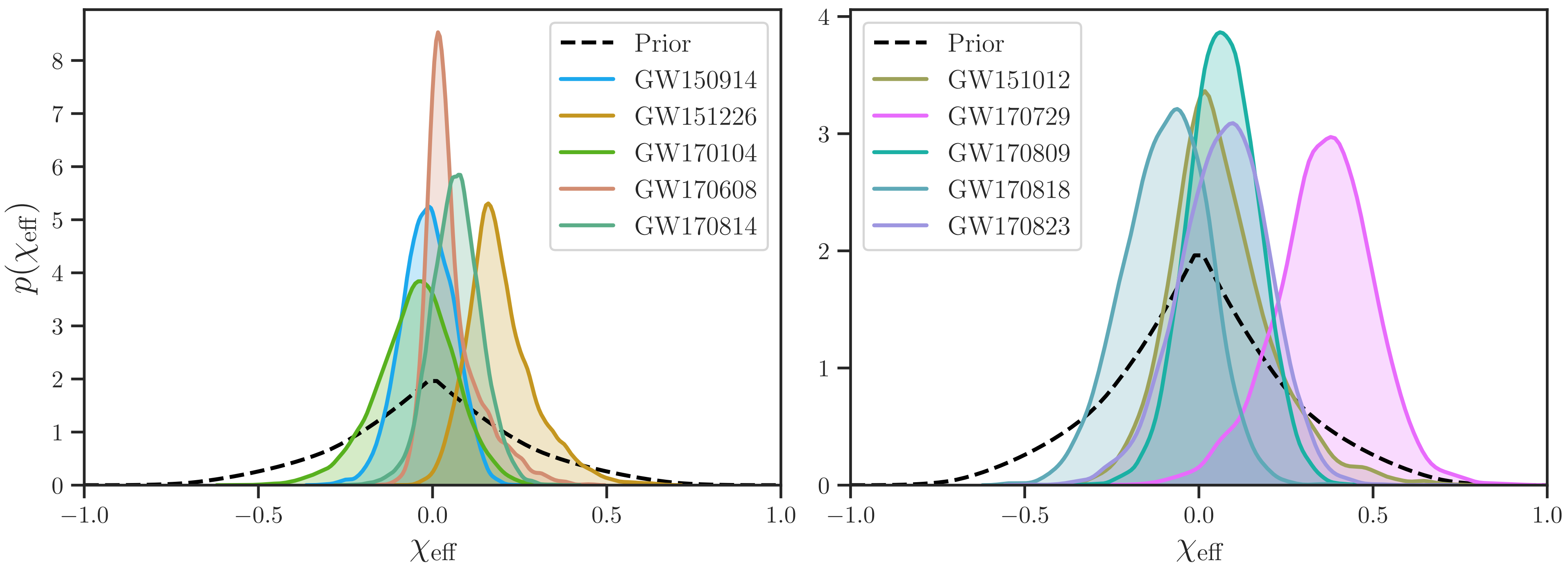
ii) formed in isolation, spins generally aligned with orbital AM: $\chi_{\rm eff} \approx 1$

Primordial BH binaries:

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

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.