

Primordial Black Holes (PBHs) as a dark matter candidate

Anne Green

University of Nottingham

What are PBHs, and **why** the surge in interest?

Formation

Abundance constraints

Open questions

Green & Kavanagh, [arXiv:2007.10722](https://arxiv.org/abs/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](https://arxiv.org/abs/2002.12778), 'Constraints on PBHs'

Carr & Kuhnel, [arXiv:2006.02838](https://arxiv.org/abs/2006.02838), 'PBHs as dark matter: recent developments'

Prelude: 'PBHs and me: ancient history'

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

PHYSICAL REVIEW D

VOLUME 56, NUMBER 10

15 NOVEMBER 1997

Constraints on the density perturbation spectrum from primordial black holes

Anne M. Green and Andrew R. Liddle

Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

(Received 25 April 1997)

PBHs as a MACHO candidate:

THE ASTROPHYSICAL JOURNAL, 537:708–719, 2000 July 10

© 2000. The American Astronomical Society. All rights reserved. Printed in U.S.A.

PROBING THE MASS FUNCTION OF HALO DARK MATTER VIA MICROLENSING

ANNE M. GREEN¹

Astronomy Unit, School of Mathematical Sciences, QMW, Mile End Road, London, E1 4NS, UK

Received 1999 December 20; accepted 2000 February 15

What?

Primordial Black Holes (PBHs) may form from large 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).



Why?

PBHs are a cold dark matter (DM) candidate.

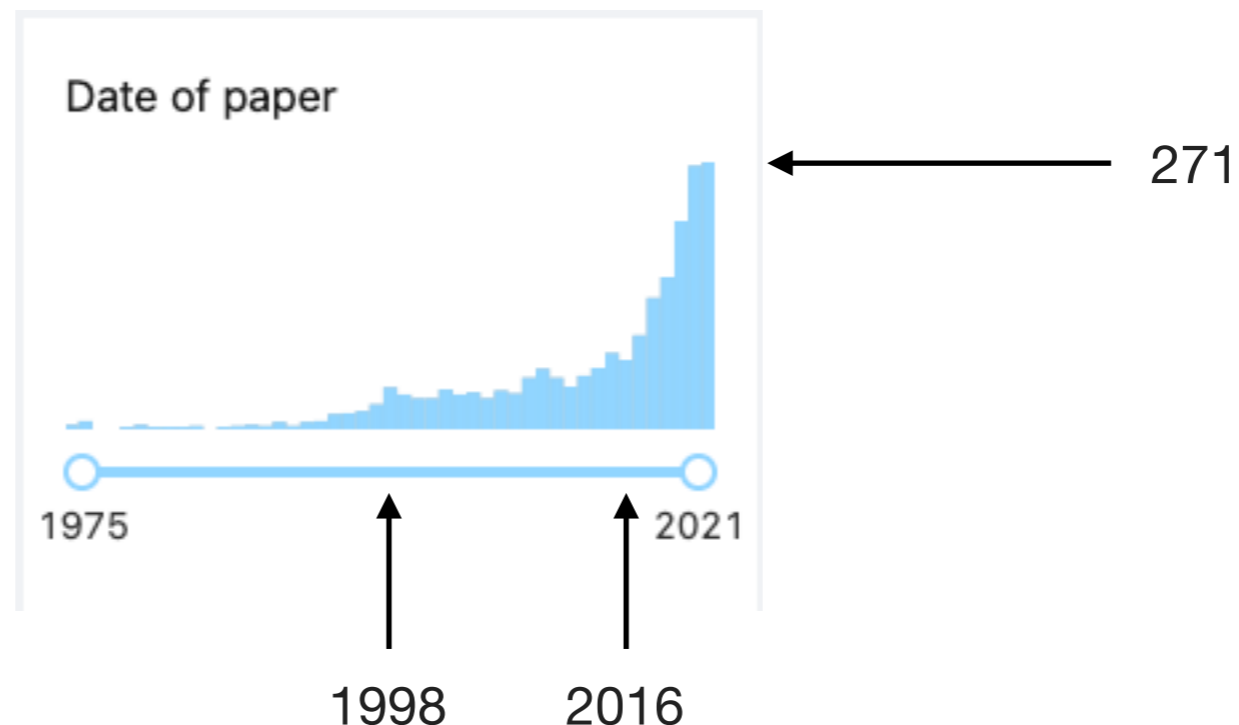
[Hawking 1971](#); [Chapline 1975](#)

+ 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 unperturbed 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.](#)

result of an inSPIRE search for 'primordial black hole'



Formation

Most 'popular' mechanism: collapse of large density perturbations (shortly after horizon entry) during radiation domination. [Zeldovich & Novikov](#); [Hawking](#); [Carr & Hawking](#)

essential analysis:

[Carr](#)

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

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

PBH mass roughly equal to horizon mass:

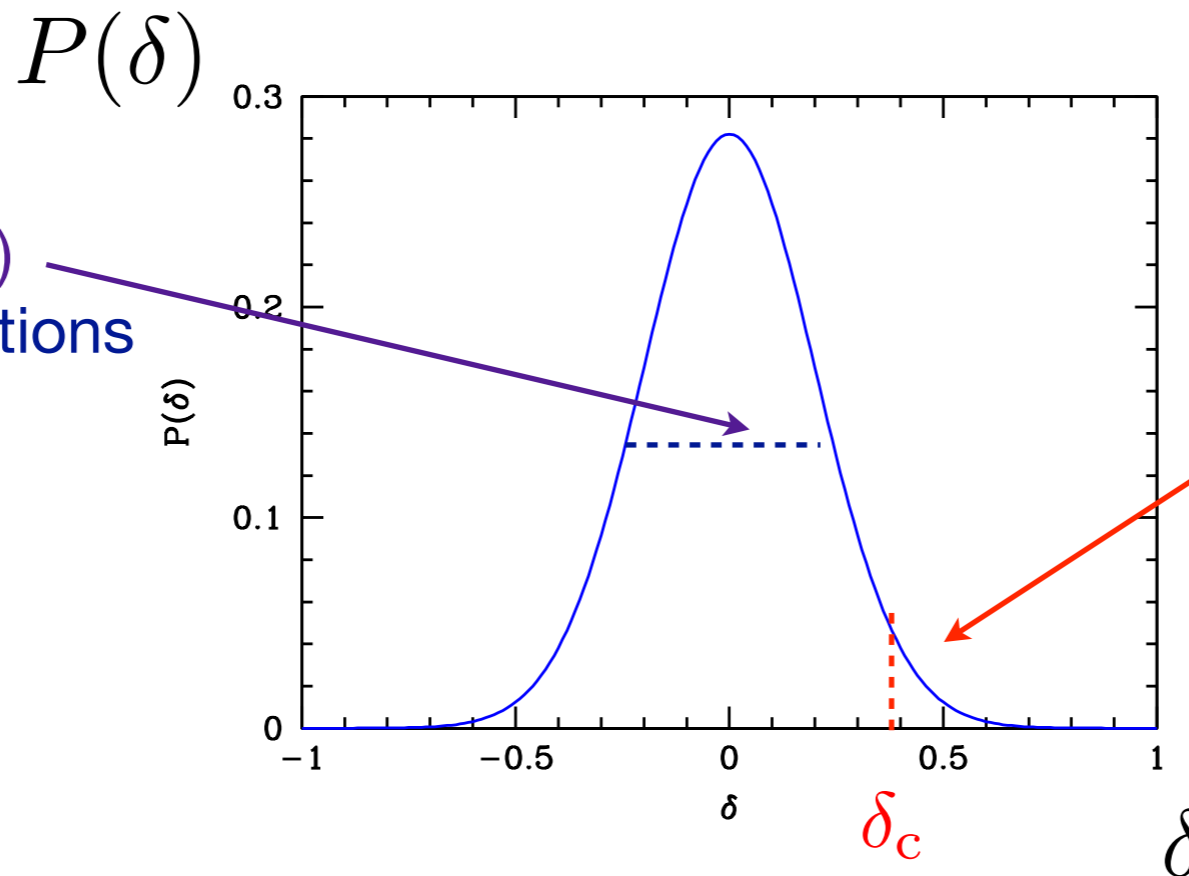
$$M_{\text{PBH}} \sim 10^{15} \text{ g} \left(\frac{t}{10^{-23} \text{ s}} \right) \sim M_{\odot} \left(\frac{t}{10^{-6} \text{ s}} \right)$$

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):

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

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



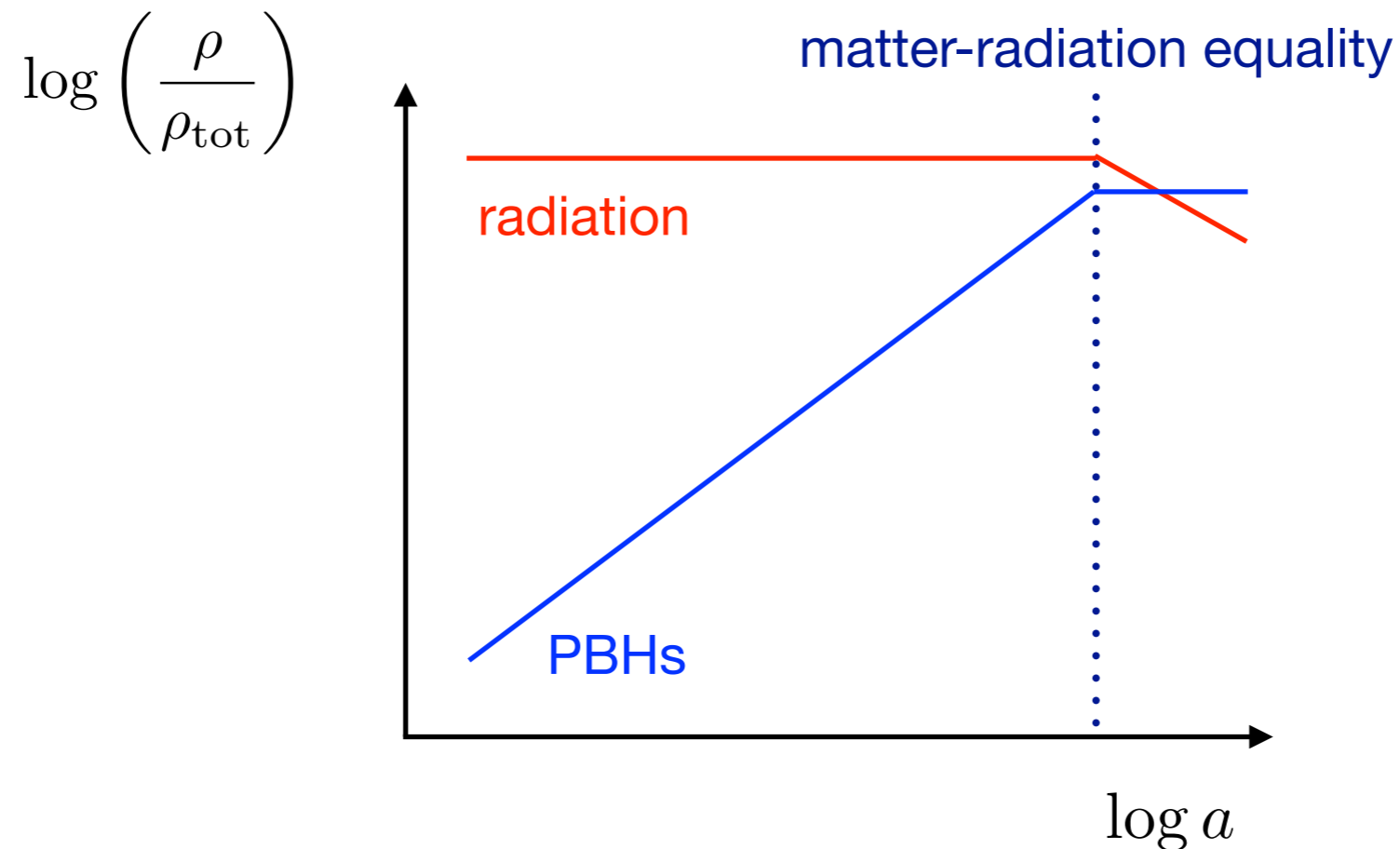
$\sigma(M_H)$ (mass variance)
typical size of fluctuations

PBH forming
fluctuations

but in fact β must be small, hence $\sigma \ll \delta_c$ 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:

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



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.

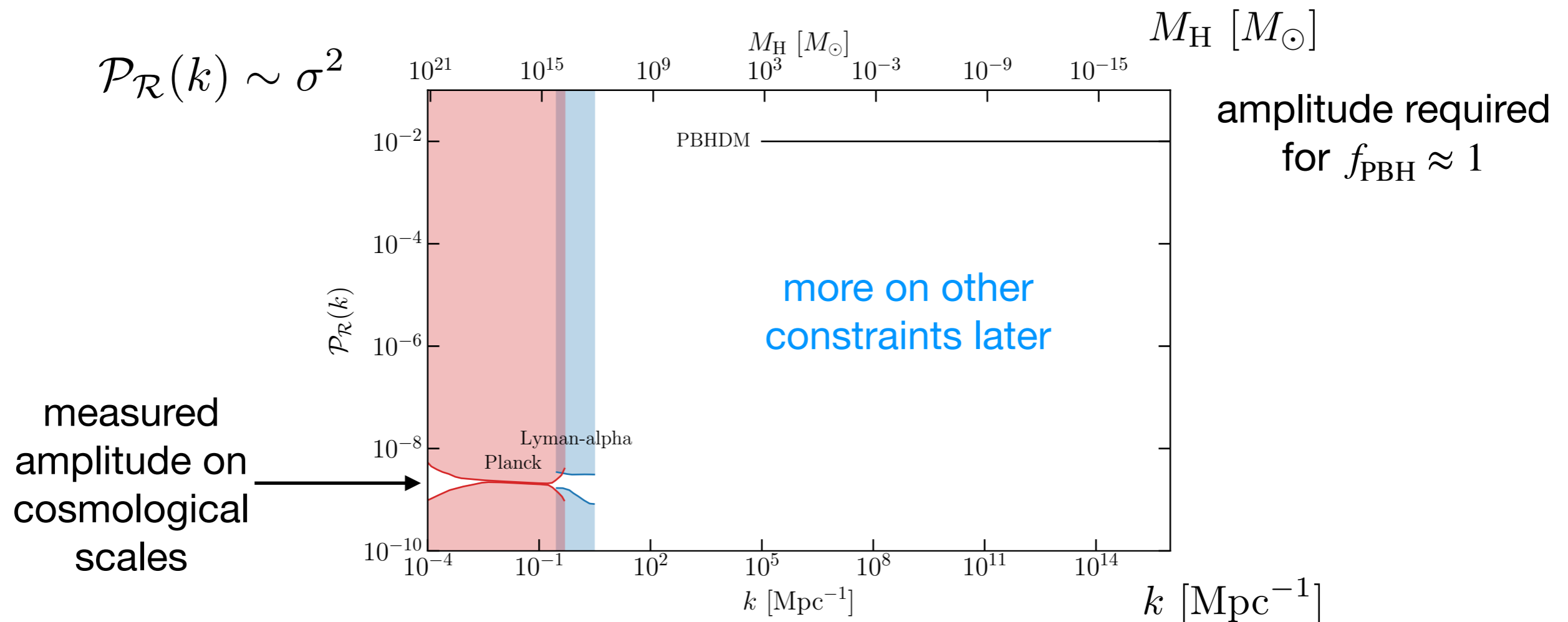
On CMB scales the primordial perturbations have amplitude $\sigma(M_H) \sim 10^{-5}$

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

$$\beta(M) = \text{erfc} \left(\frac{\delta_c}{\sqrt{2}\sigma(M_H)} \right)$$

$$\beta(M) \sim \text{erfc}(10^5) \sim \exp(-10^{10})$$

To form an interesting number of PBHs the primordial perturbations must be significantly larger ($\sigma^2(M_H) \sim 0.01$) on small scales than on cosmological scales.



refinements

critical collapse [Niemeyer & Jedamzik](#)

BH mass depends on size of fluctuation it forms from: $M = kM_{\text{H}}(\delta - \delta_{\text{c}})^{\gamma}$

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

non-gaussianity (of probability distribution of density perturbations)

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

Inflation: a brief crash course

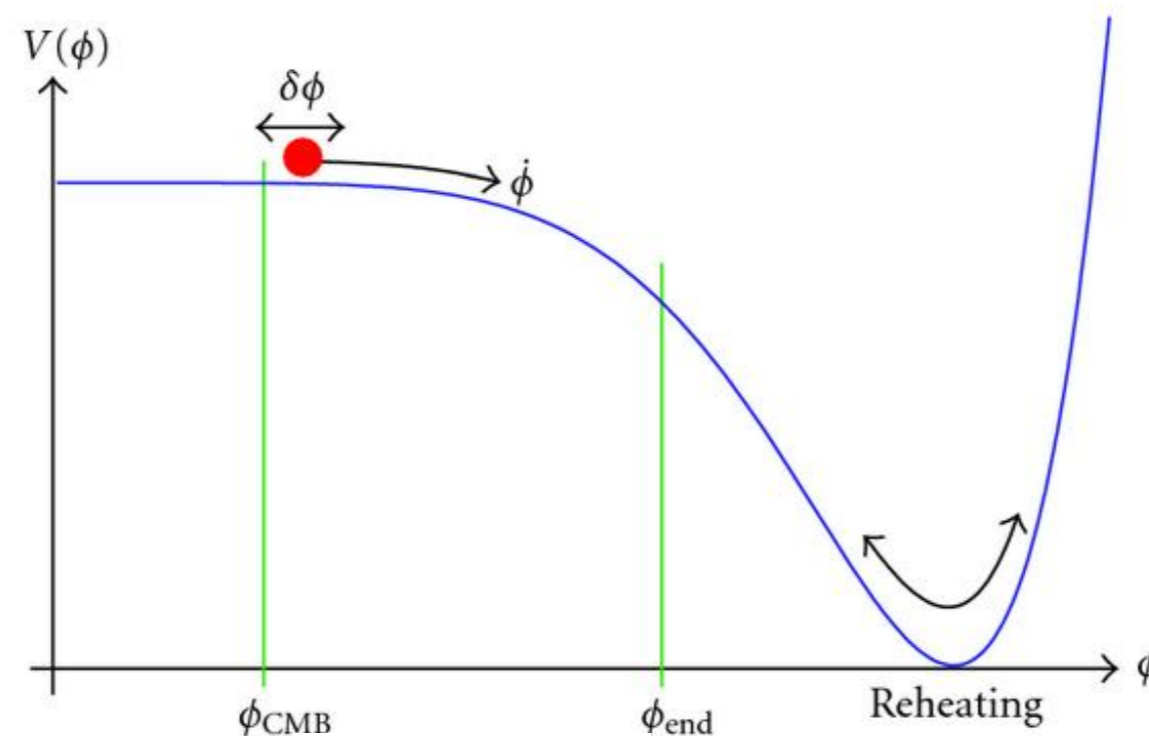
A postulated period of accelerated expansion in the early Universe, proposed to solve various problems with the Big Bang (flatness, horizon & monopole).

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

$$\sigma^2(M_H) \propto \frac{V^3}{(V')^2}$$

Scales probed by:



Large scale structure
& the CMB

Primordial Black Holes

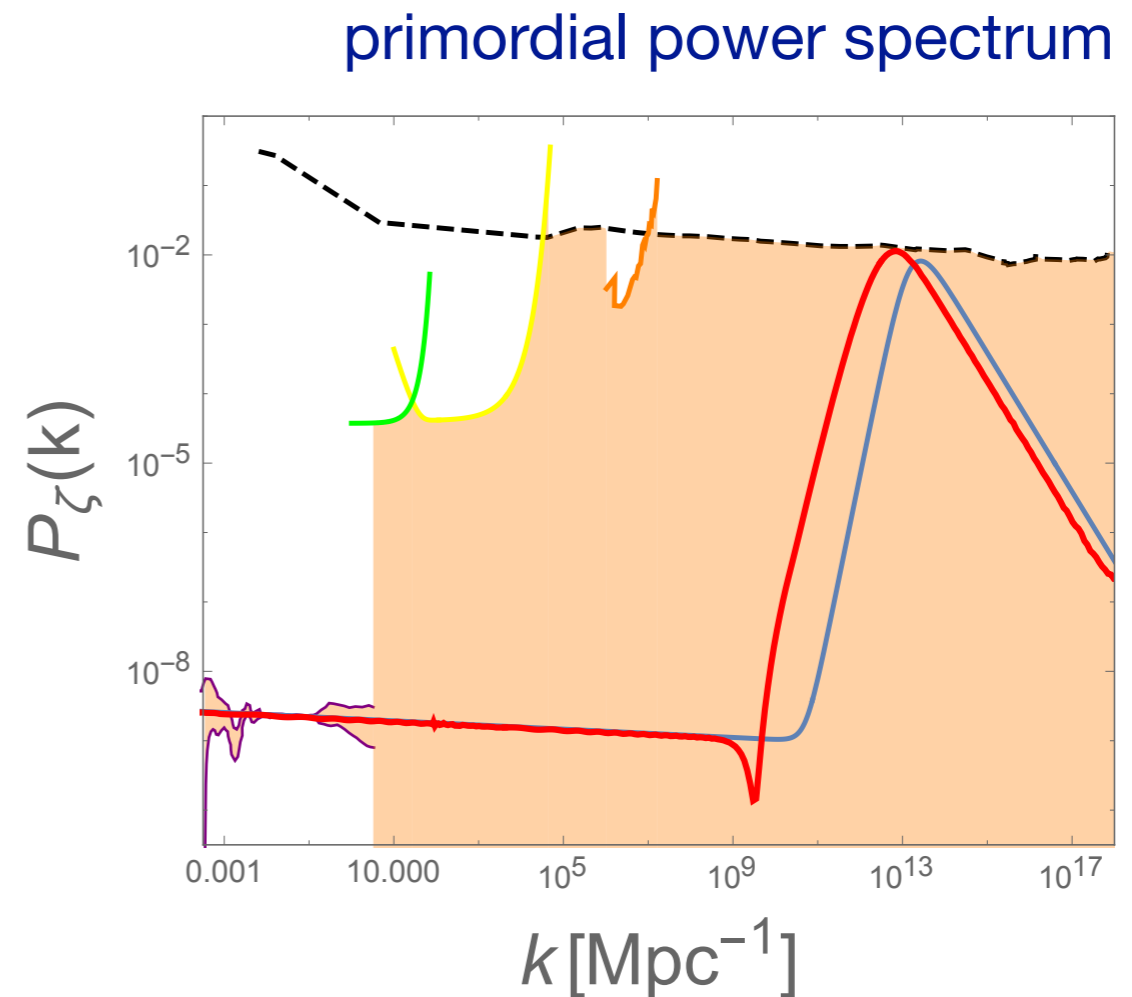
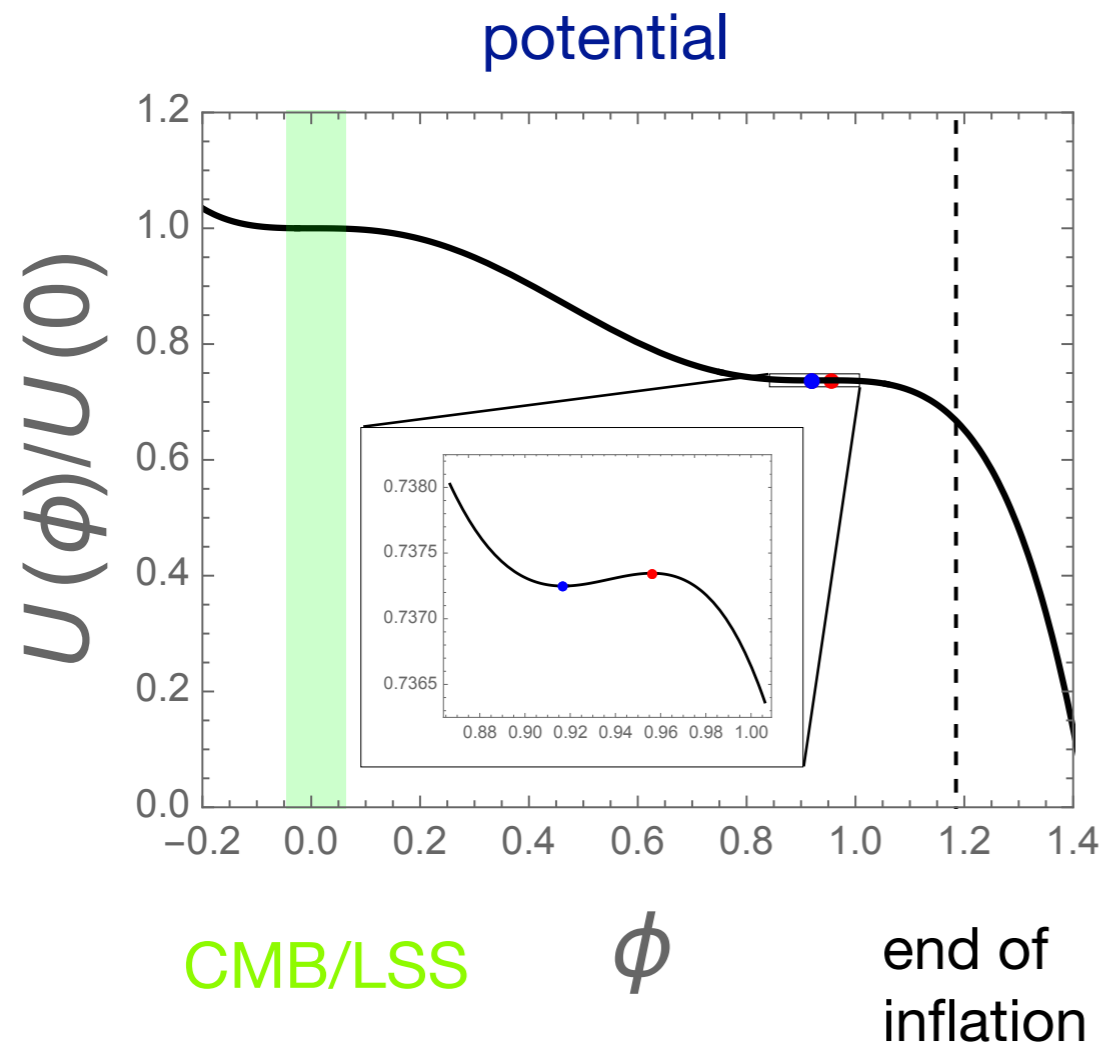
inflation models that produce large perturbations

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

single field

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

[Ballesteros & Taoso](#); [Herzberg & Yamada](#)

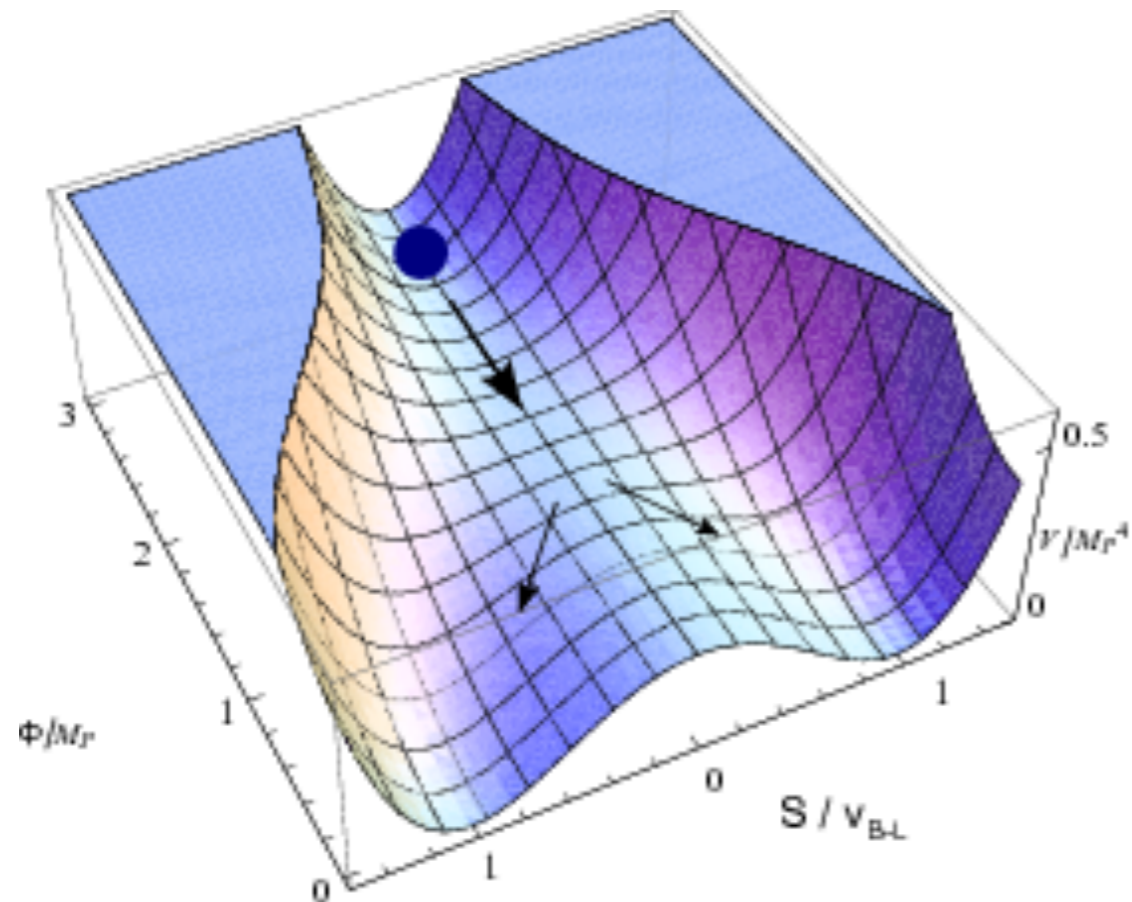


Steepest possible growth $\sim k^4$ [Byrnes, Cole & Patil](#); [Carrhlo, Malik & Mulryne](#)

multi-field models

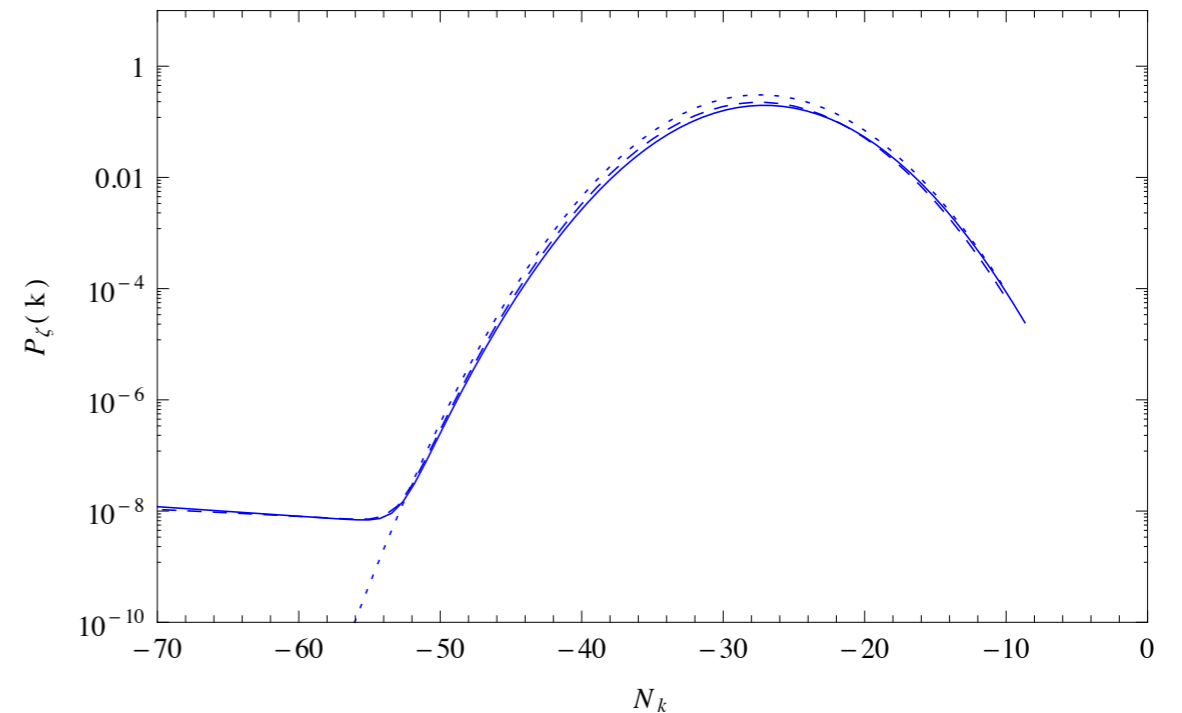
e.g. hybrid inflation with a mild waterfall transition [Garcia-Bellido, Linde & Wands](#)

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

microlensing

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

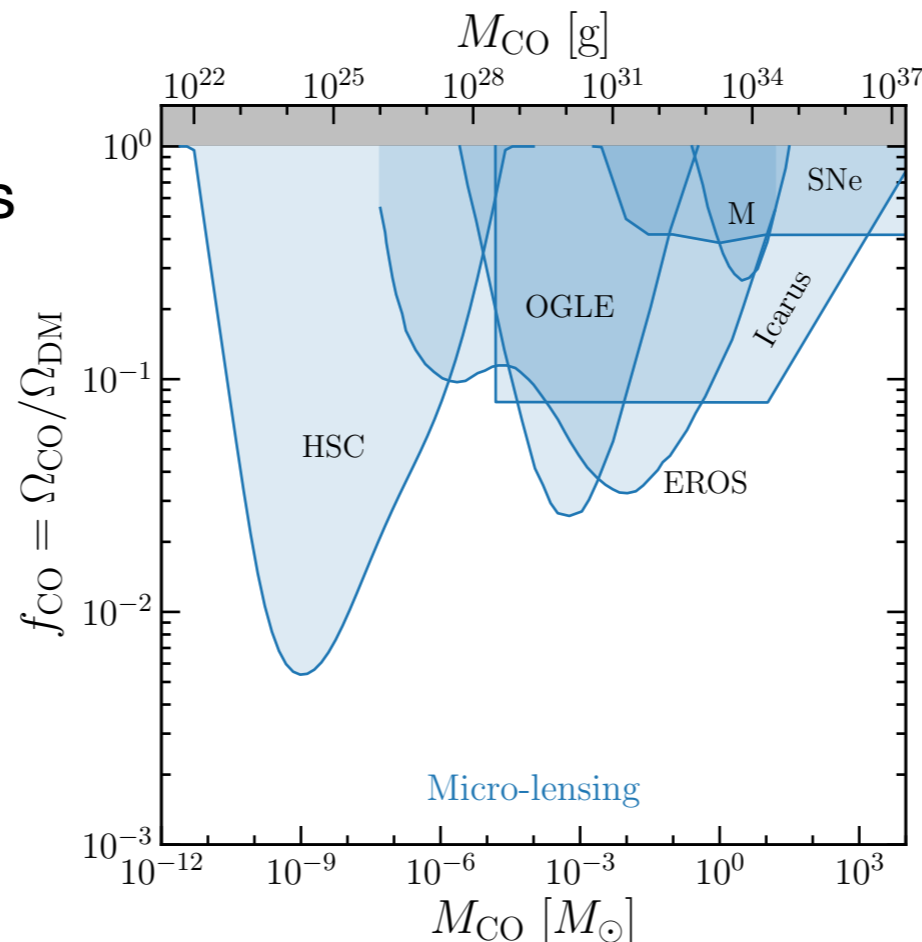
stars: temporarily brightened when compact object ('CO') crosses line of sight
LMC/SMC ([MACHO](#), [EROS](#), [OGLE](#)), Galactic bulge ([OGLE](#)), M31 ([HSC](#), [Croon et al.](#)).

supernovae: magnification distribution changed [Zumalacarregui & Seljak](#).

Icarus: caustic crossing event [Oguri et al.](#)

fraction of dark matter
in form of compact objects

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



mass in grams

mass in Solar masses

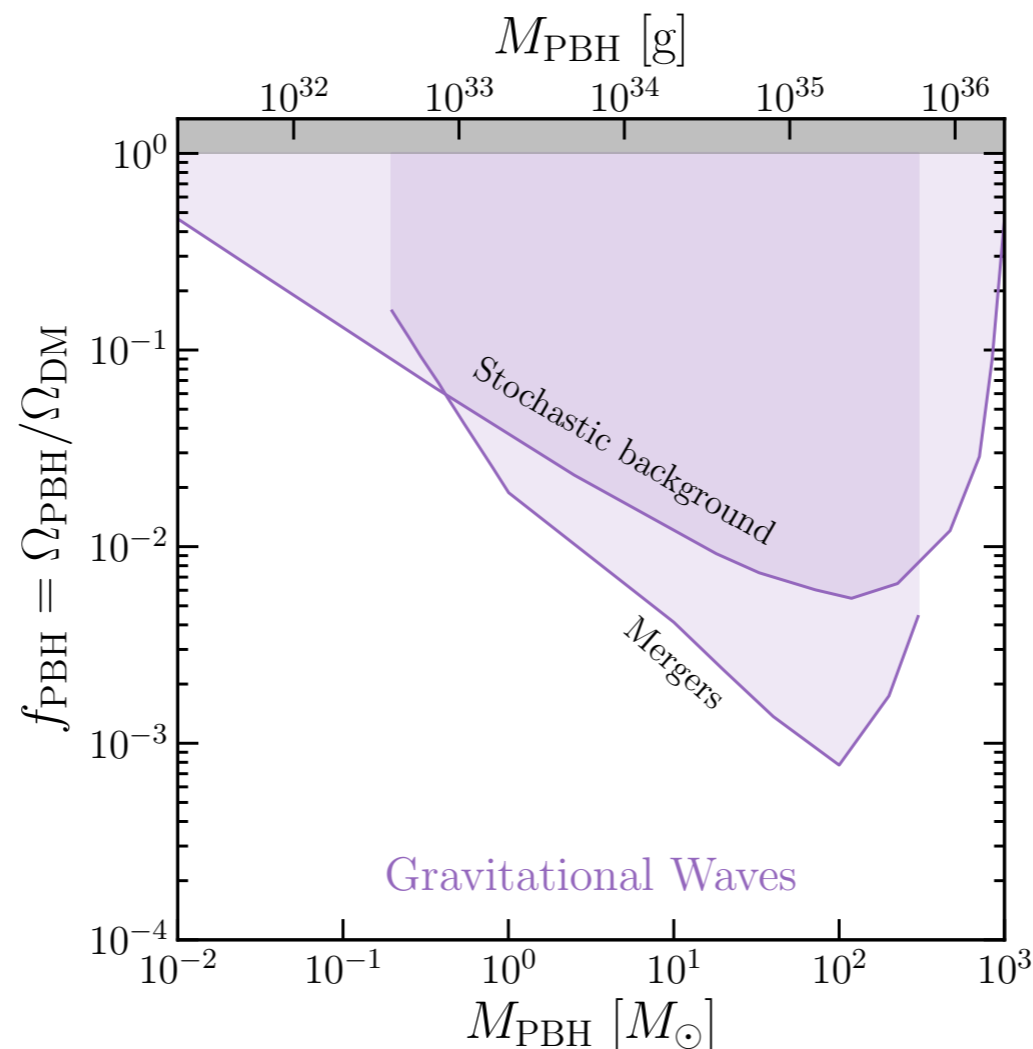
gravitational waves from PBH-PBH binary mergers

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.](#)

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

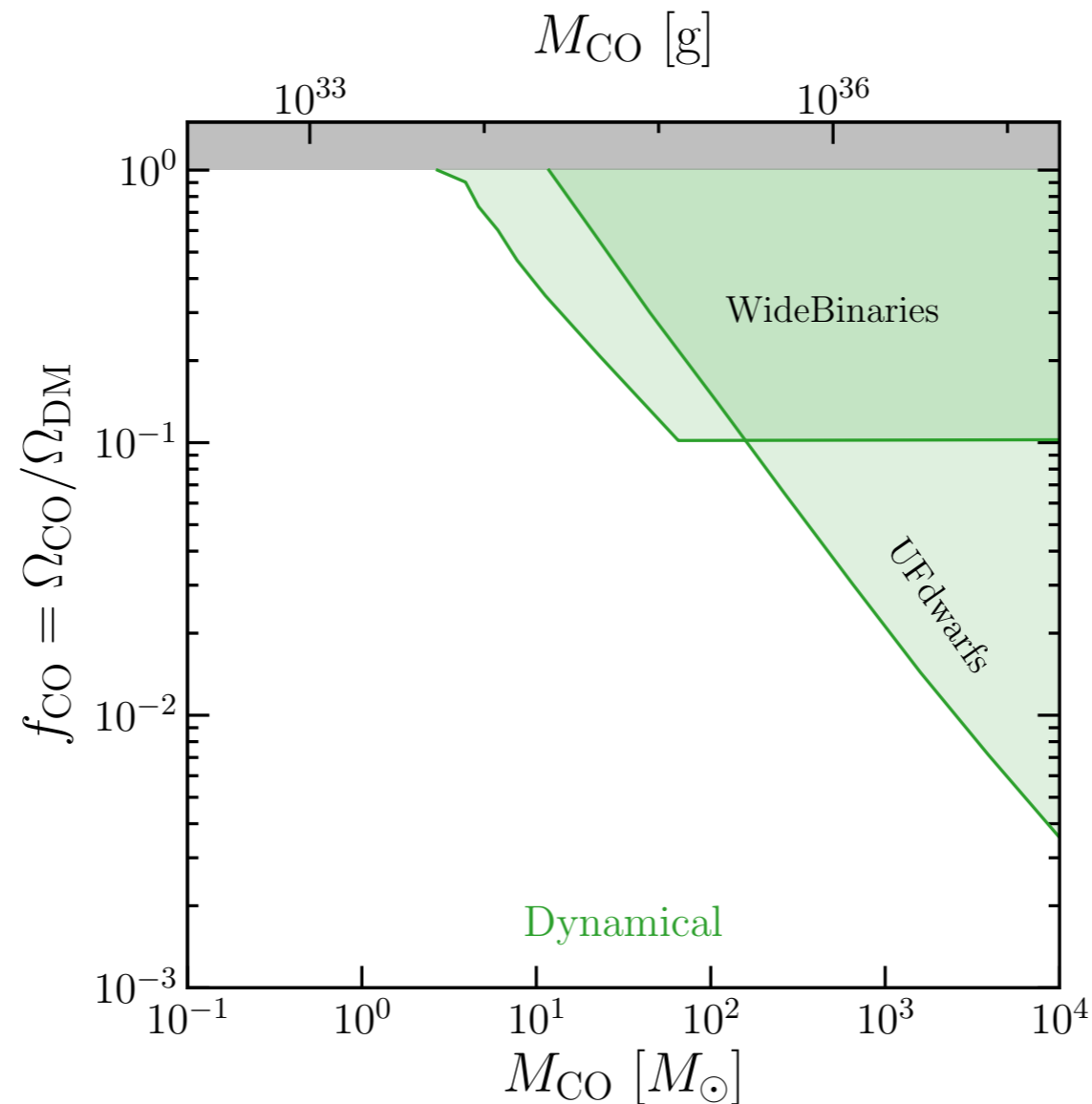


dynamical effects

Solar mass and more massive PBHs dynamically heat stars in gravitationally bound systems.

dwarf galaxies: size of stellar component increased [Brandt](#); [Koushiappas & Loeb](#); [Zhu et al.](#); [Stegmann et al.](#)

wide binaries: 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

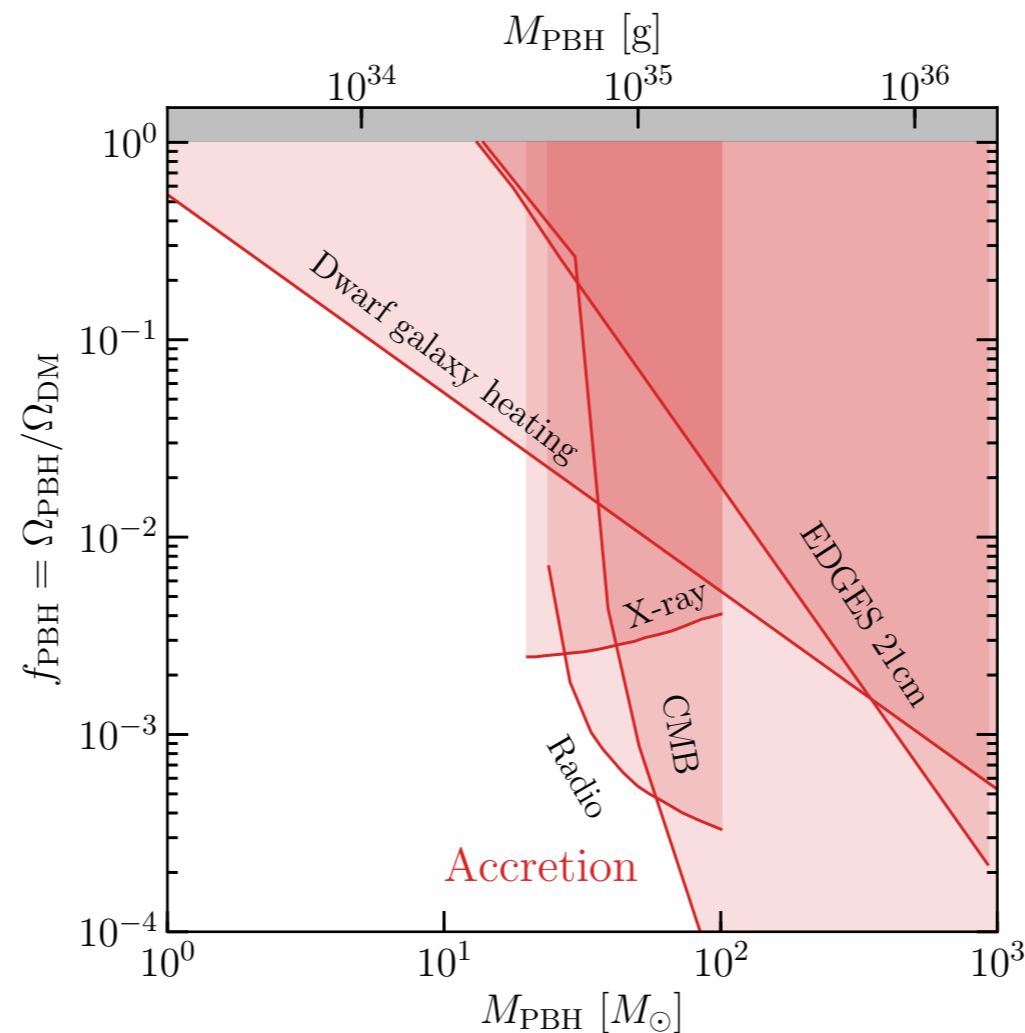
distortion of CMB anisotropies [Ricotti et al](#); [Ali-Haïmoud & Kamionkowski](#); ... [Poulin et al...](#)

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 on asteroid mass PBHs from interactions with stars

Neutron 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](#)

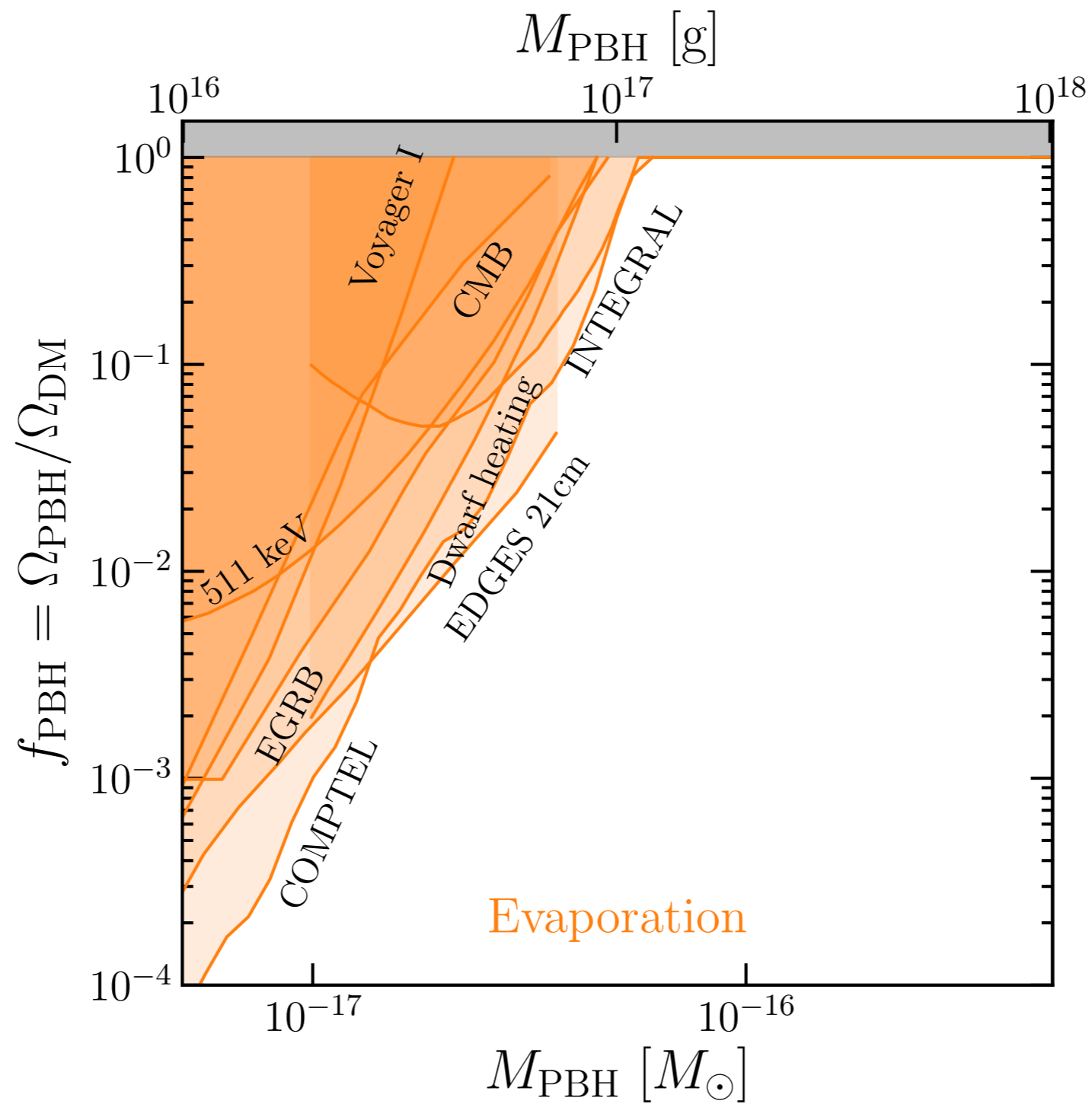
[Montero-Camacho et al.](#) **No current constraints**, but potential future constraints from

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

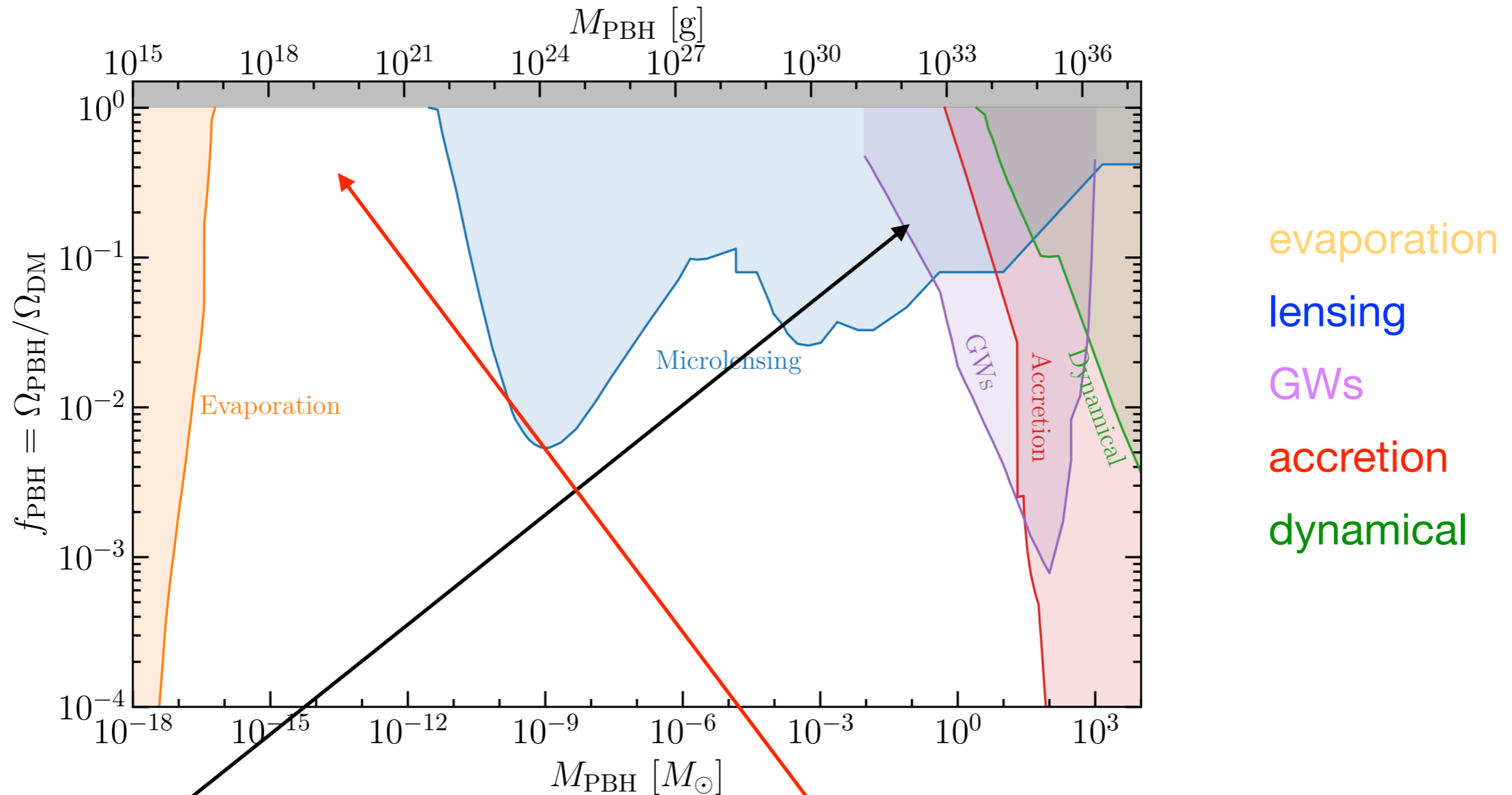
ii) signatures of star being destroyed

constraints on light PBHs from evaporation products

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



compilation of tightest constraints



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.

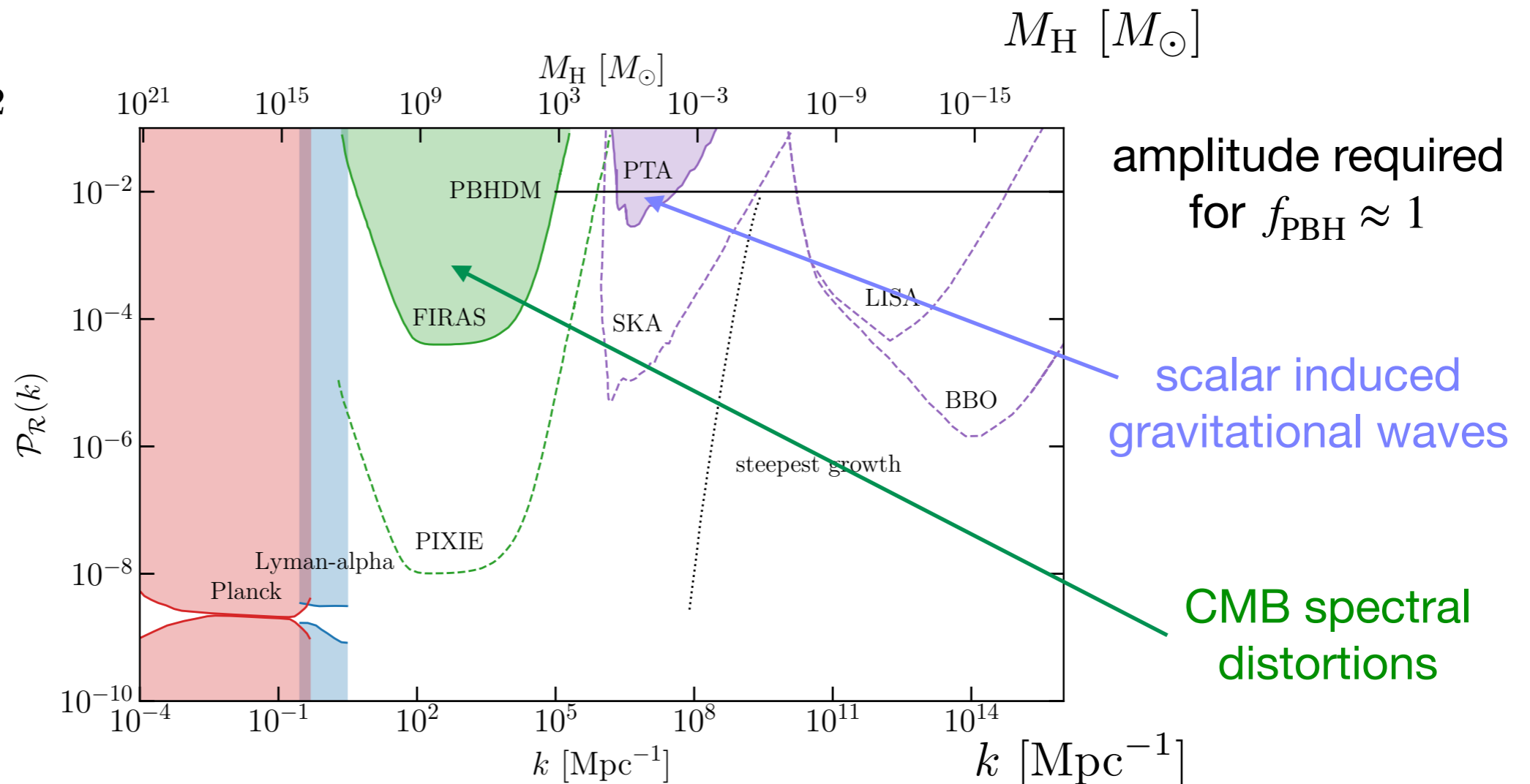
indirect constraints on PBHs formed from large density perturbations

Large curvature perturbations act as 2nd order source of 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](#)

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

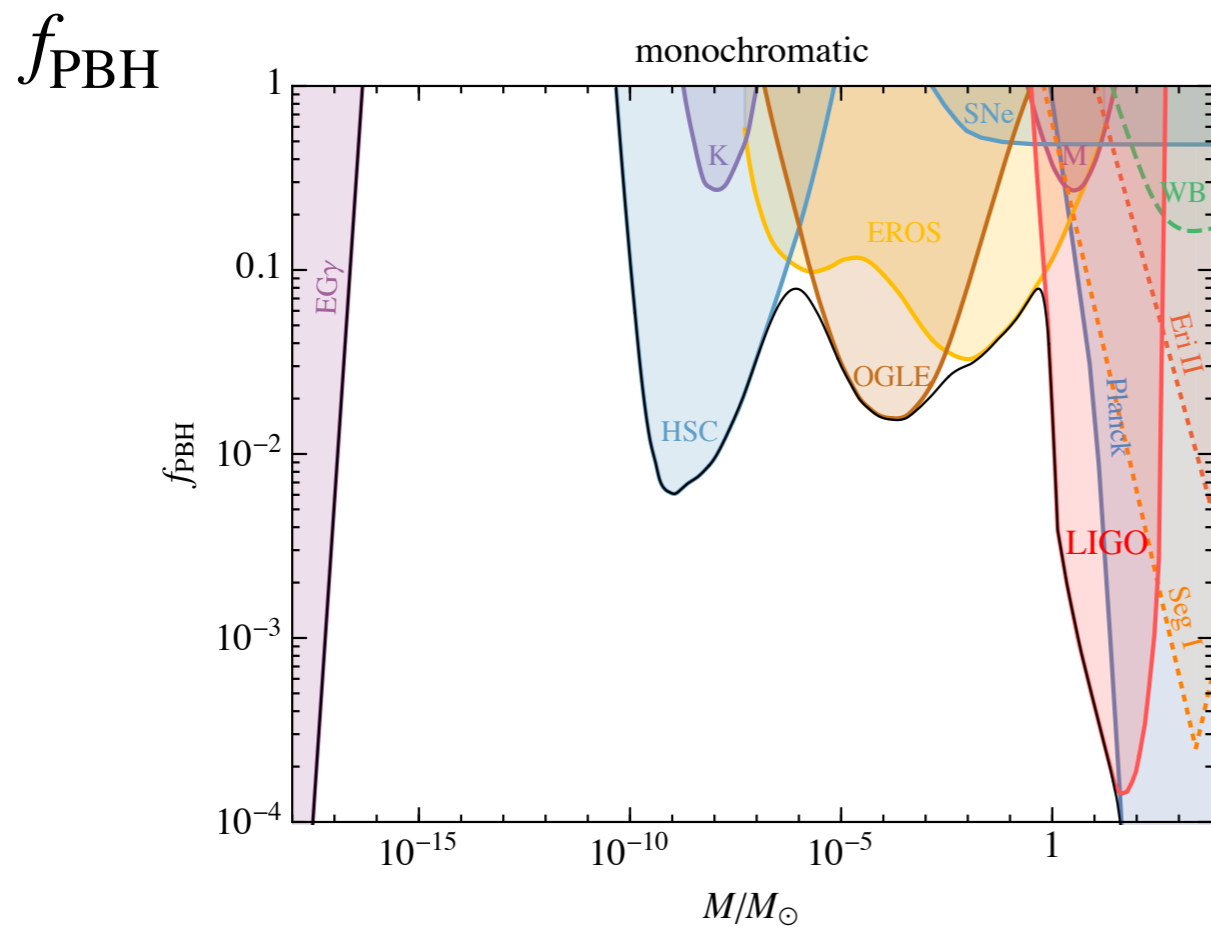


applying constraints to extended mass functions

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

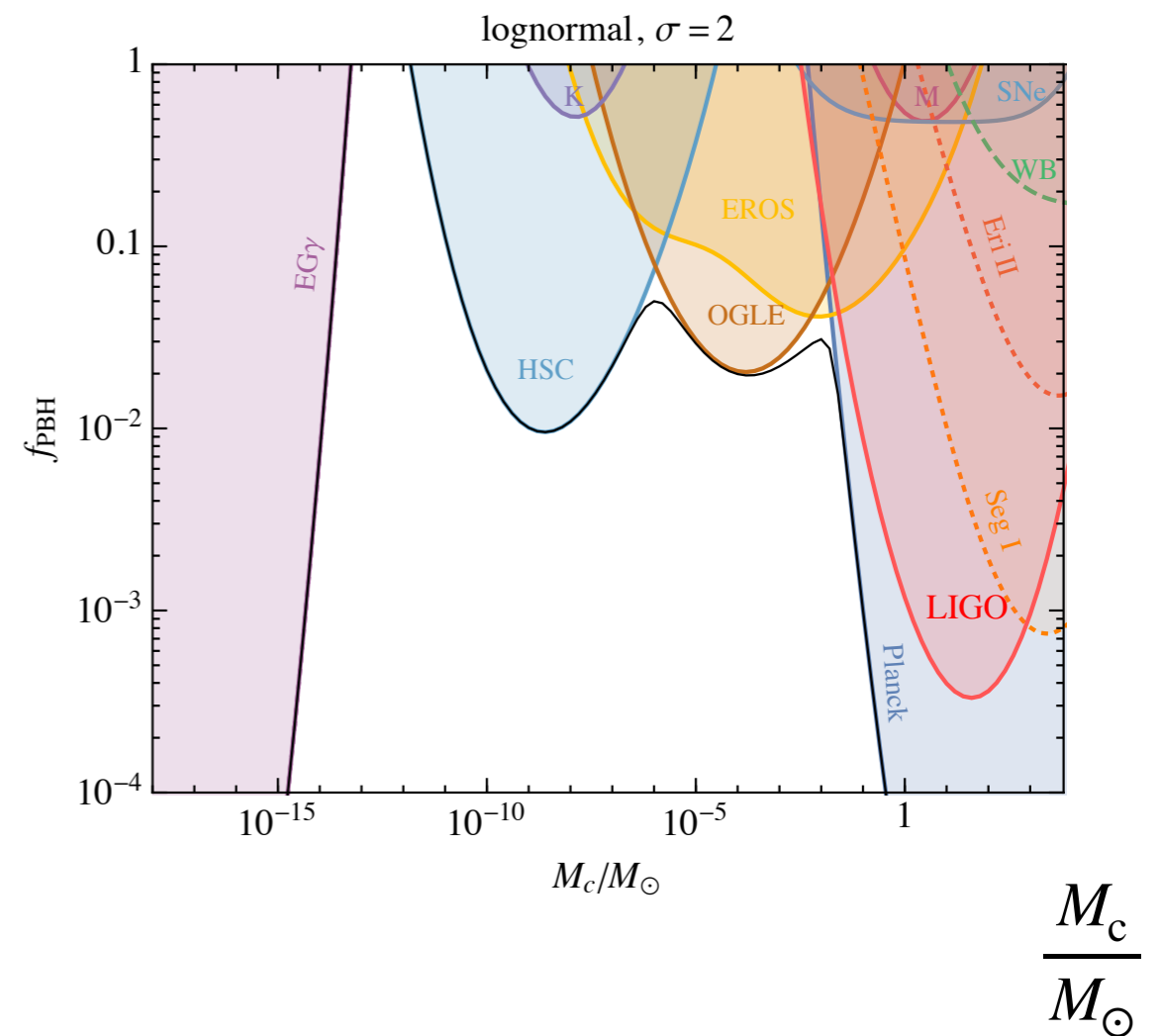
[Green](#); [Carr et al.](#); see also [Bellomo et al.](#)

monochromatic



[Carr et al.](#)

log-normal
(fixed width)



Open questions

clustering

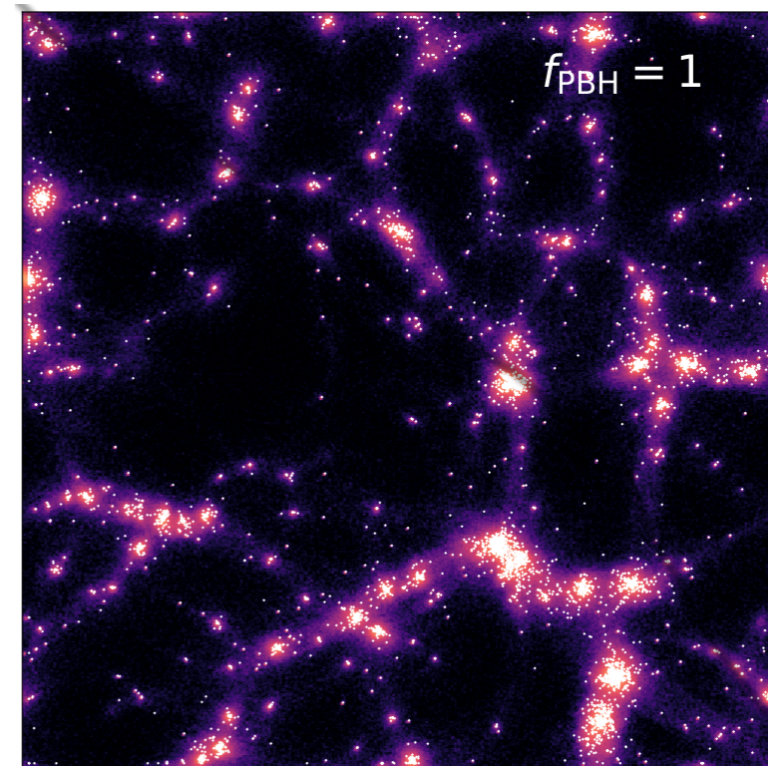
Potentially extremely important (affects PBH binary merger rate).

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.](#)....

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...)

Long 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.
- 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: clustering, how to probe light PBHs, perturbations in ultra-slow roll inflation...

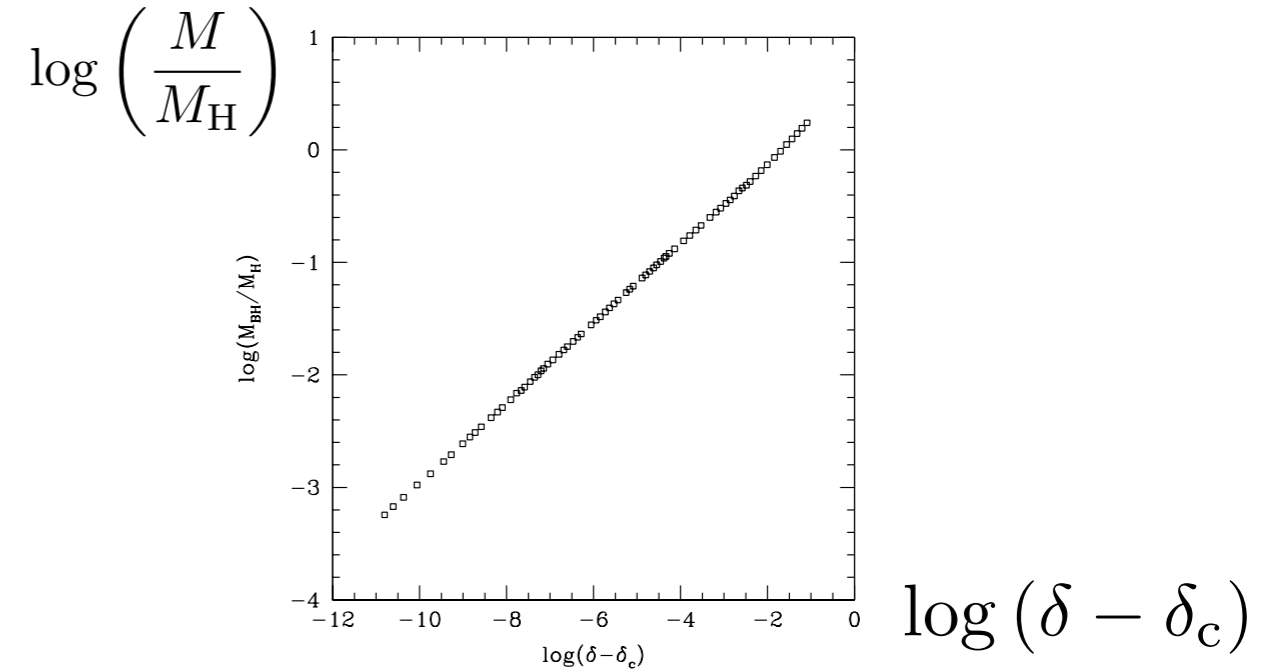
Back-up slides

refinements

critical collapse Choptuik; Evans & Coleman; Niemeyer & Jedamzik

BH mass depends on size of fluctuation it forms from:

$$M = kM_H(\delta - \delta_c)^\gamma$$

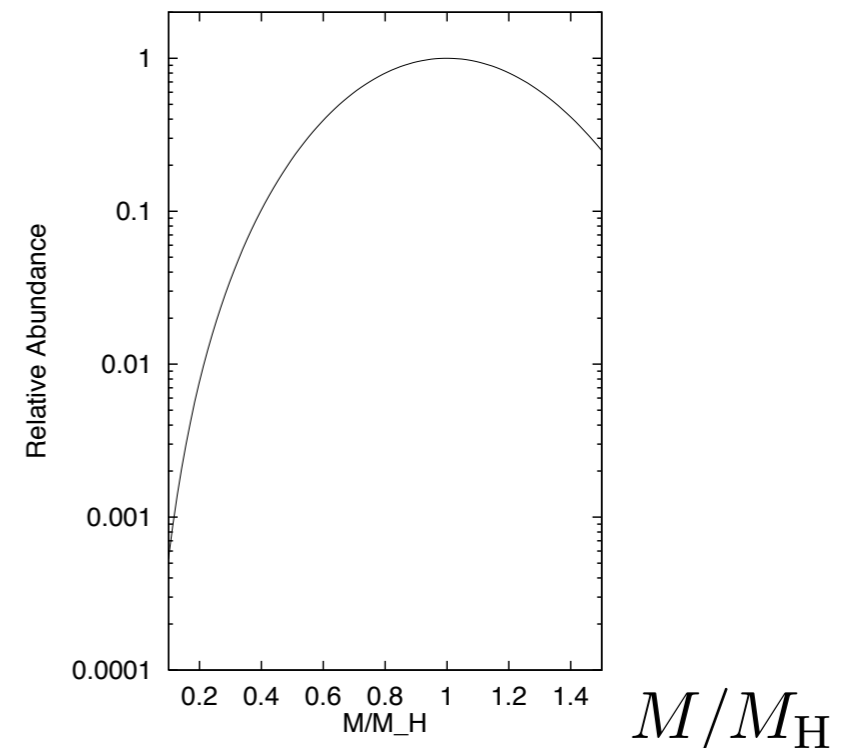


Musco, Miller & Polnarev

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

Niemeyer & Jedamzik:

$$\frac{dn}{dM} \propto \left(\frac{M}{M_H}\right)^{-1+1/\gamma} \exp\left[-(1+\gamma)\left(\frac{M}{M_H}\right)^{1/\gamma}\right]$$



Yokoyama

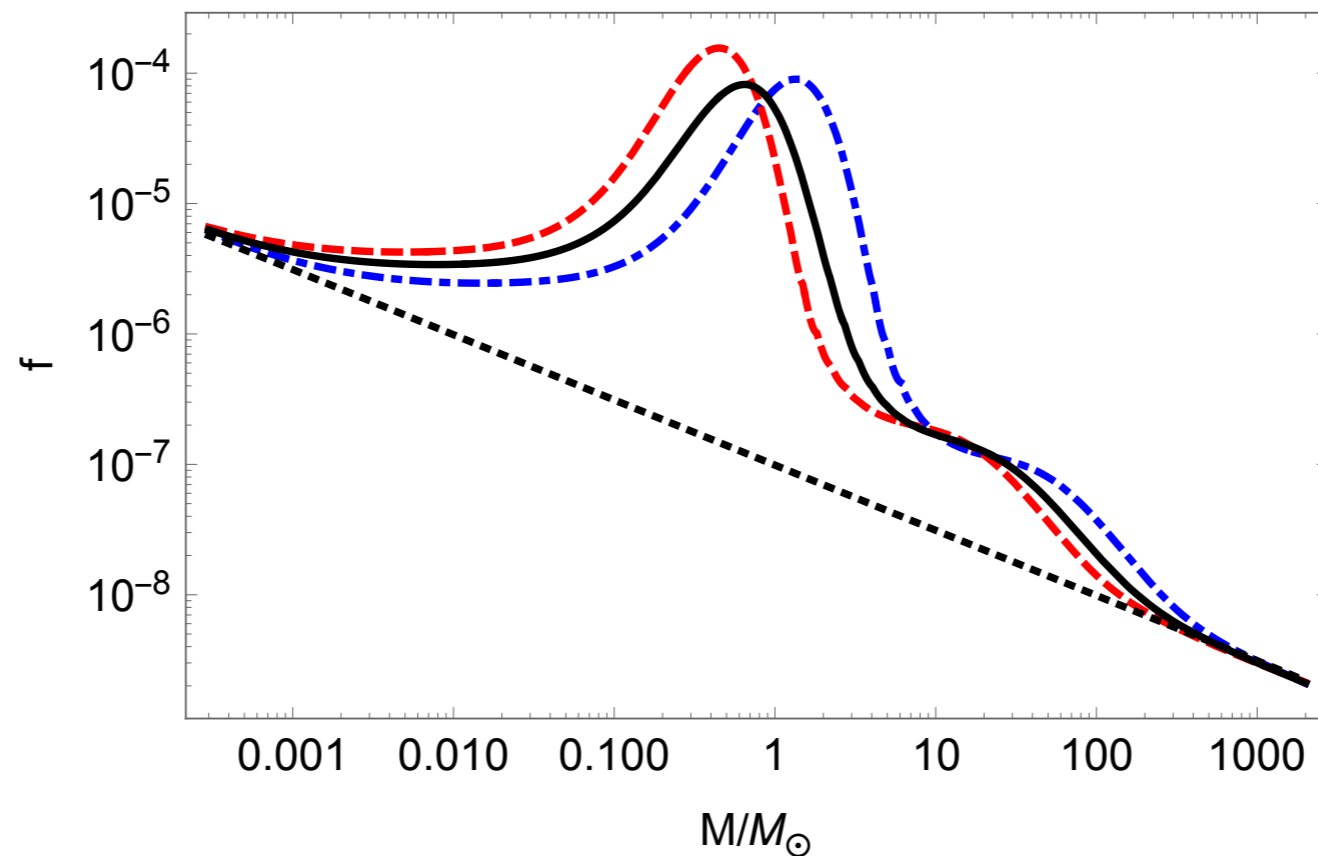
Relationship between density perturbations and curvature perturbations is non-linear, so even if curvature perturbations are gaussian, (large) density perturbations won't be. [Kawasaki & Nakatsuka; De Luca et al.; Young, Musco & Byrnes](#)

threshold for collapse

In fact depends on shape of perturbation (which depends on shape of primordial power spectrum). Harada, Yoo & Kohri; Germani & Musco; Musco; Escriv, Germani & Sheth

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

accretion

Accretion may significantly increase the mass and spin of PBHs with $M_{\text{PBH}} \gtrsim 10 M_{\odot}$

Postnov & Mitichkin; de Luca et al.

non-gaussianity (of probability distribution of density perturbations)

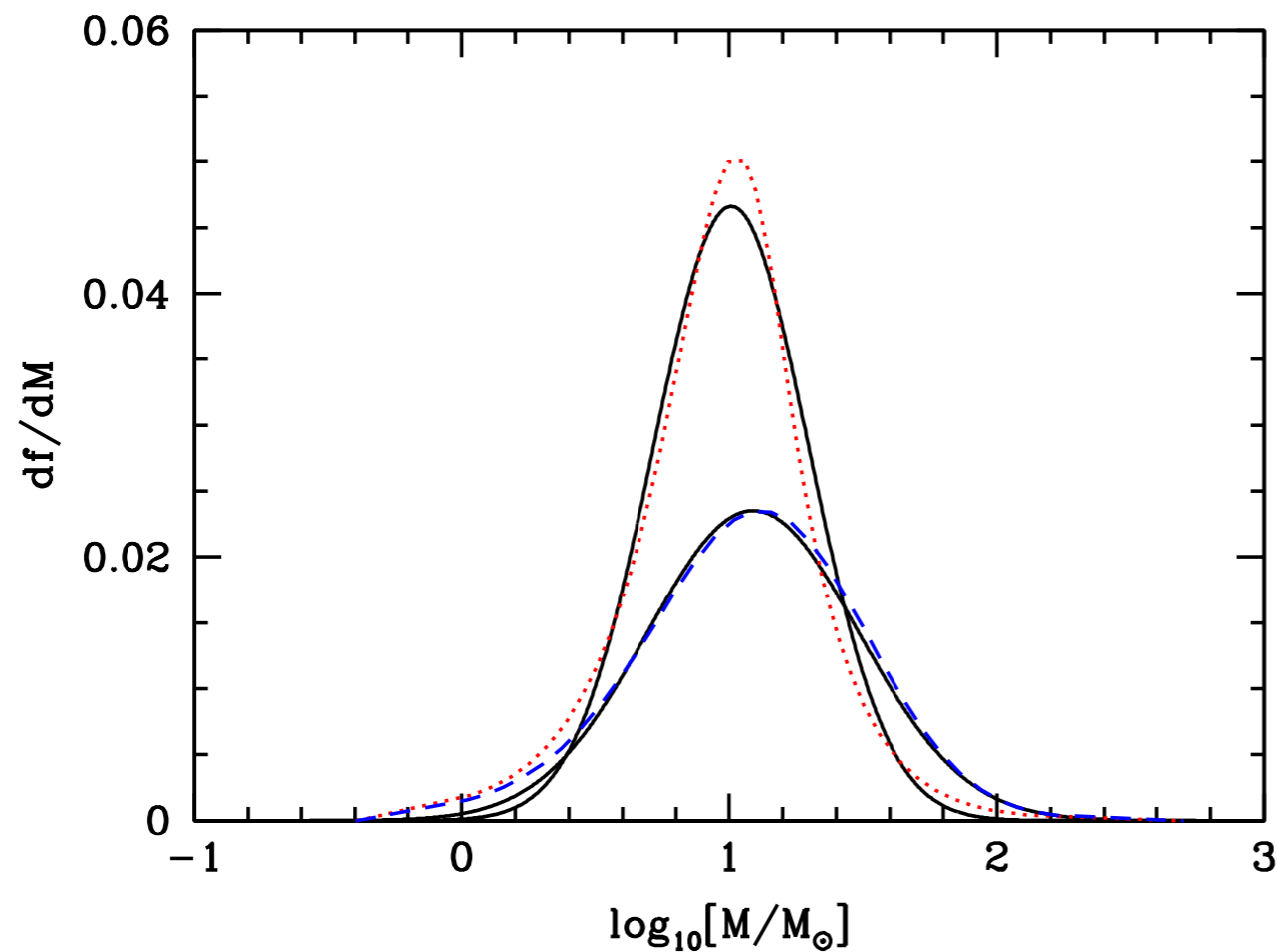
Since PBHs form from rare large density fluctuations, changes in the shape of the tail of the probability distribution (i.e. non-gaussianity) can significantly affect the PBH abundance. Bullock & Primack; Ivanov;... Francolini et al.

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

Non-gaussianity can also increase initial clustering Tada & Yokayama; Byrnes & Young

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

$$M \frac{dn}{dM} \propto \exp \left\{ -\frac{[\log (M/M_c)]^2}{2\sigma^2} \right\}$$



axion-like curvaton

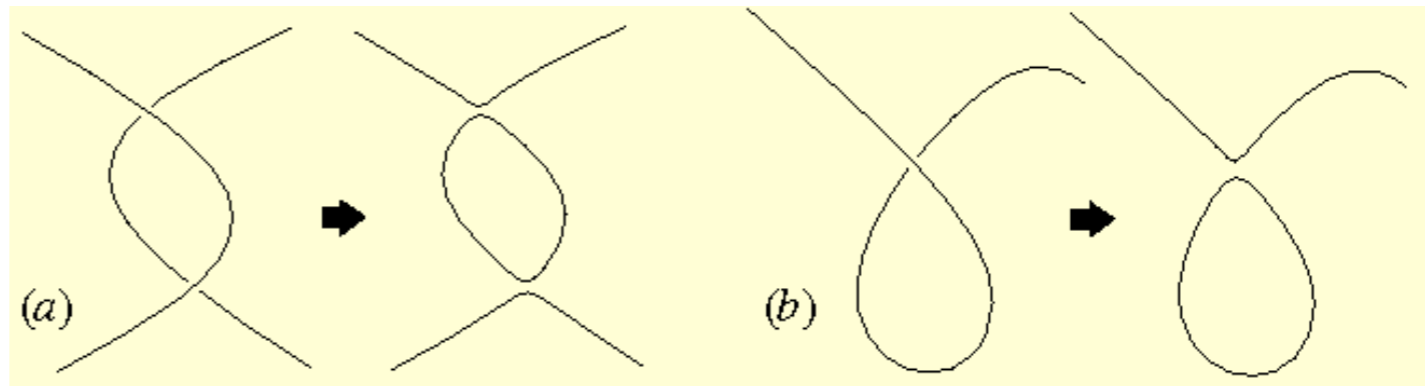
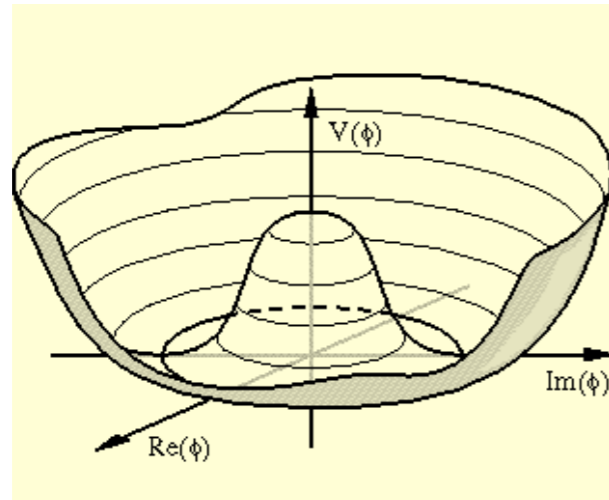
running mass inflation

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.

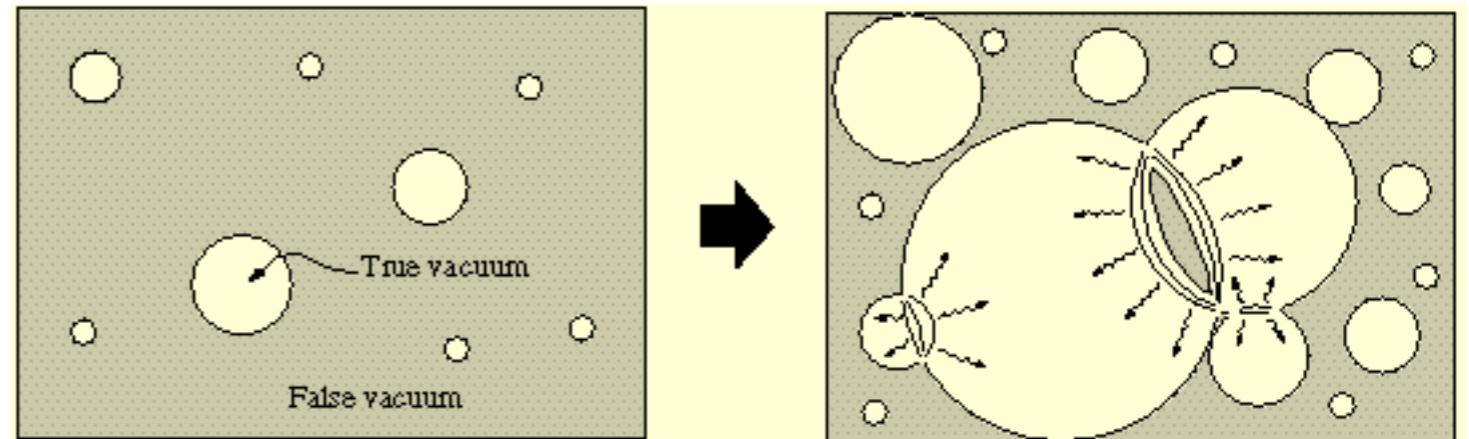
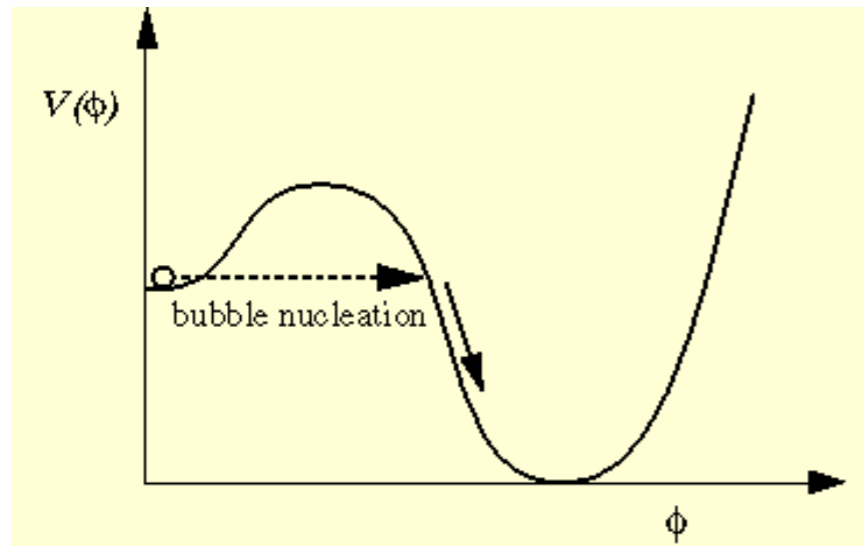


Small probability that loop will get into configuration where all dimensions lie within Schwarzschild radius (and hence collapse to form a PBH with mass of order the horizon mass at that time).

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

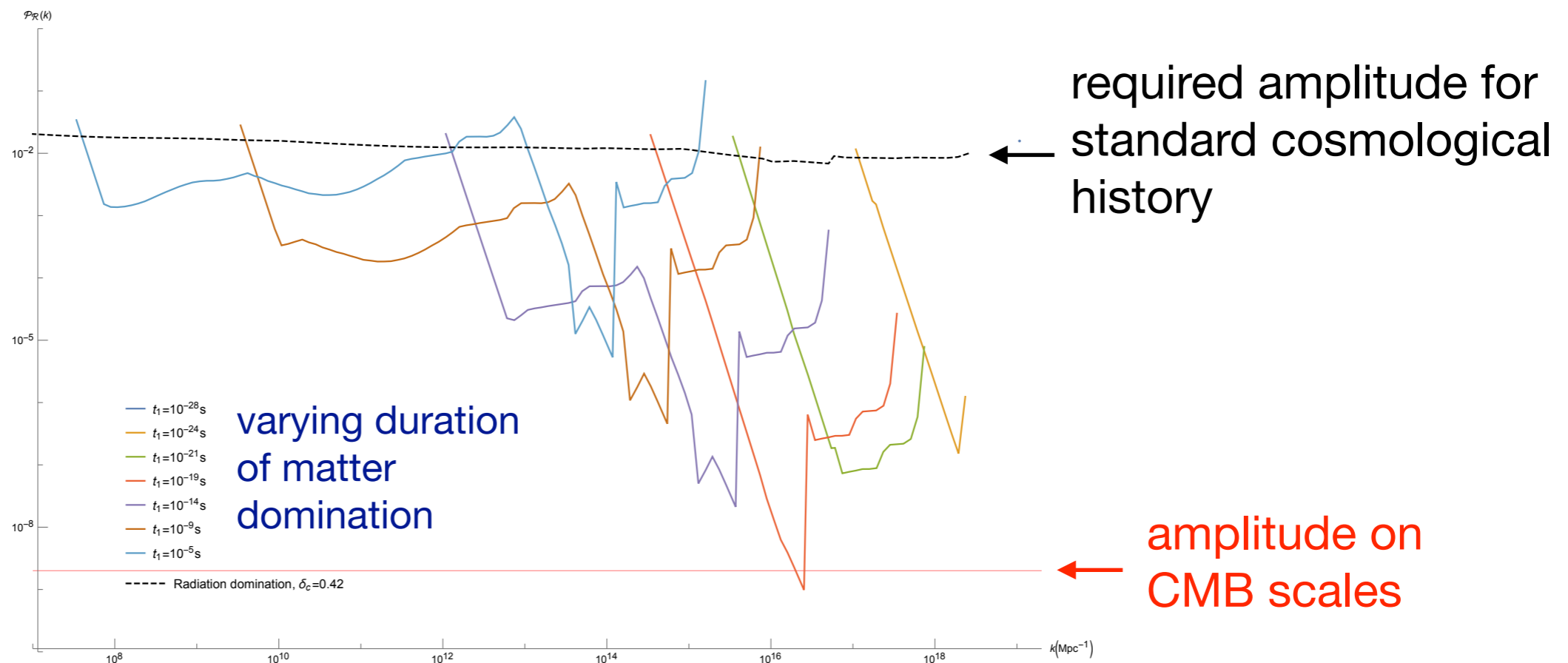
During matter domination PBHs can form from smaller fluctuations (no pressure to resist collapse) in this case fluctuations must be sufficiently spherically symmetric

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



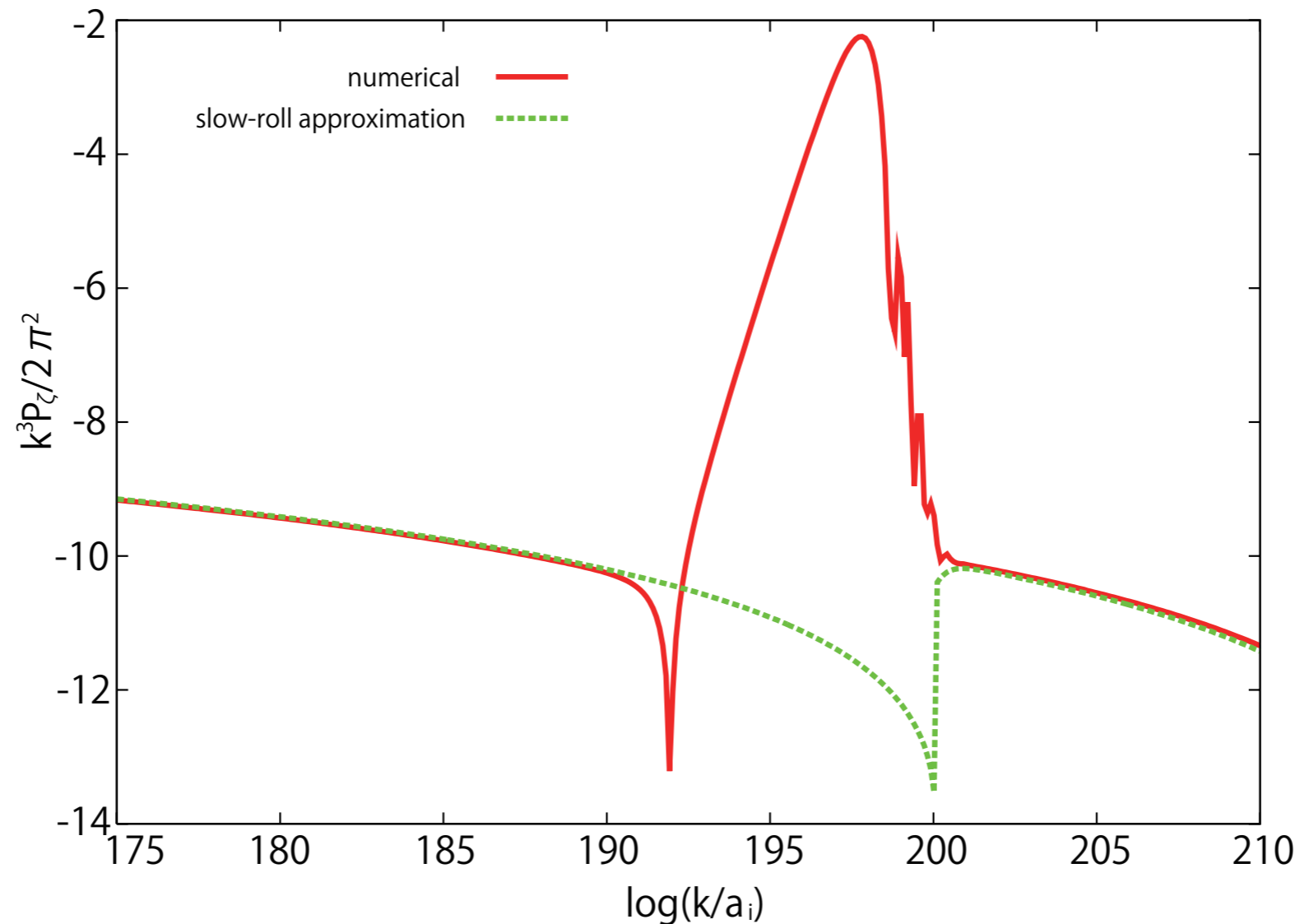
Cole & Byrnes

k

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.)

axion-like curvaton

Kawasaki, Kitajima & Yanagida

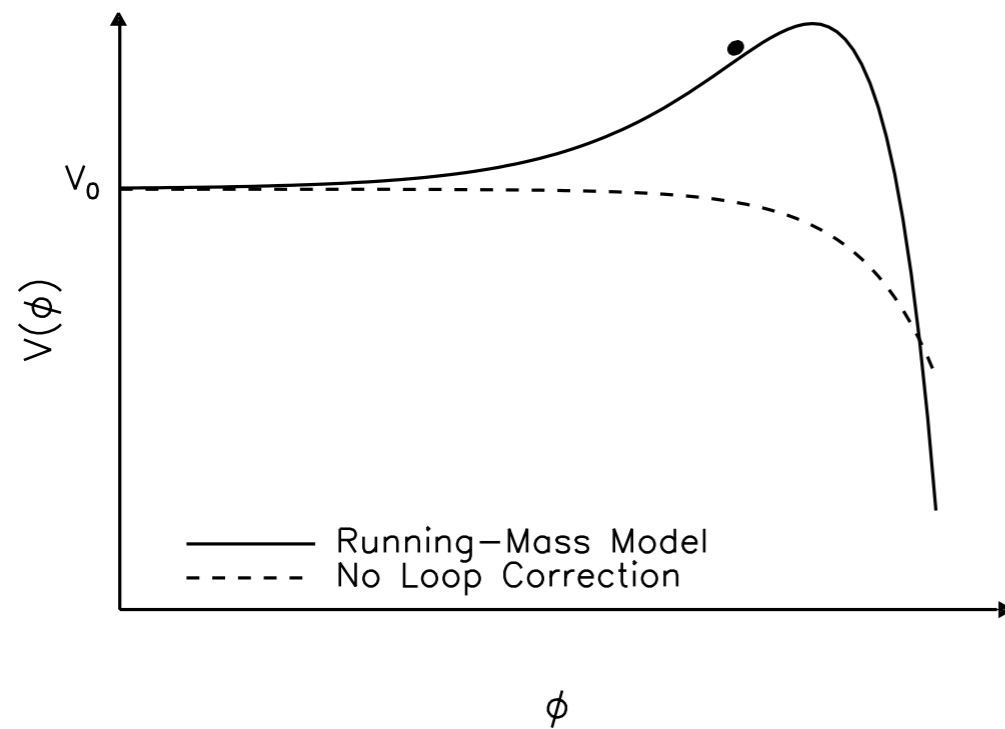
Large scale perturbations generated by inflaton, small scale (PBH forming) perturbations by curvaton (a spectator field during inflation gets fluctuations and decays afterwards producing perturbations Lyth & Wands)

ii) monotonically increasing power spectrum

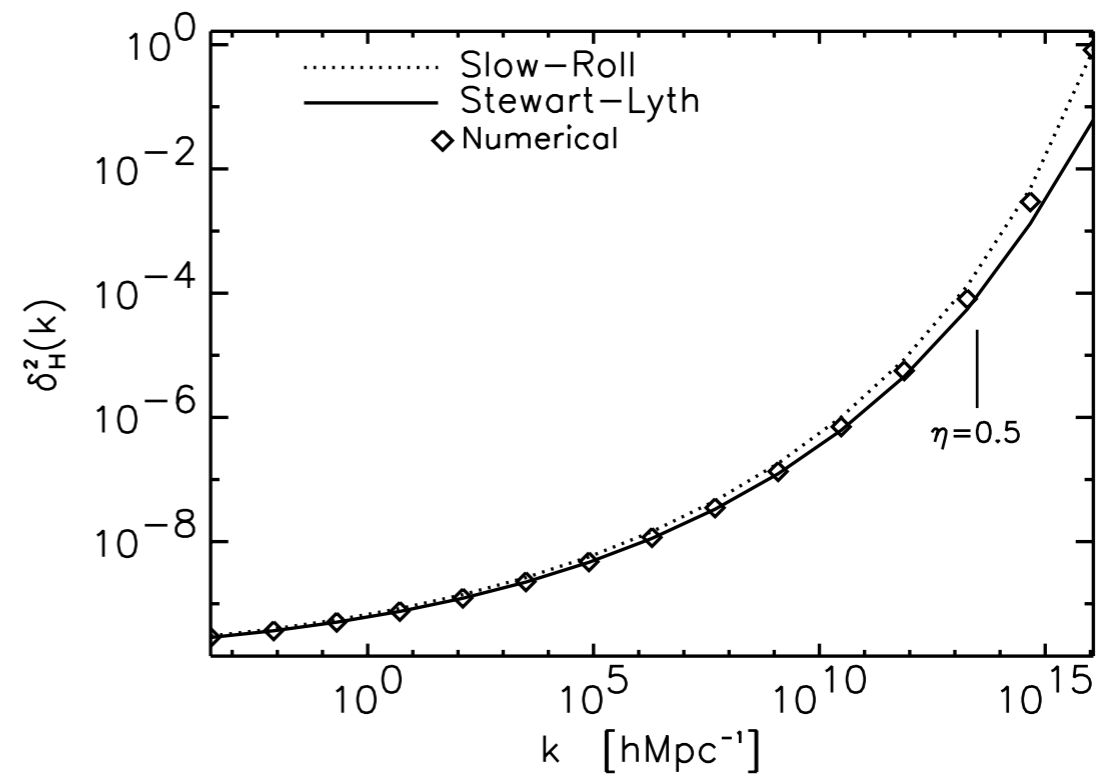
running-mass inflation Stewart

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

potential



primordial power spectrum

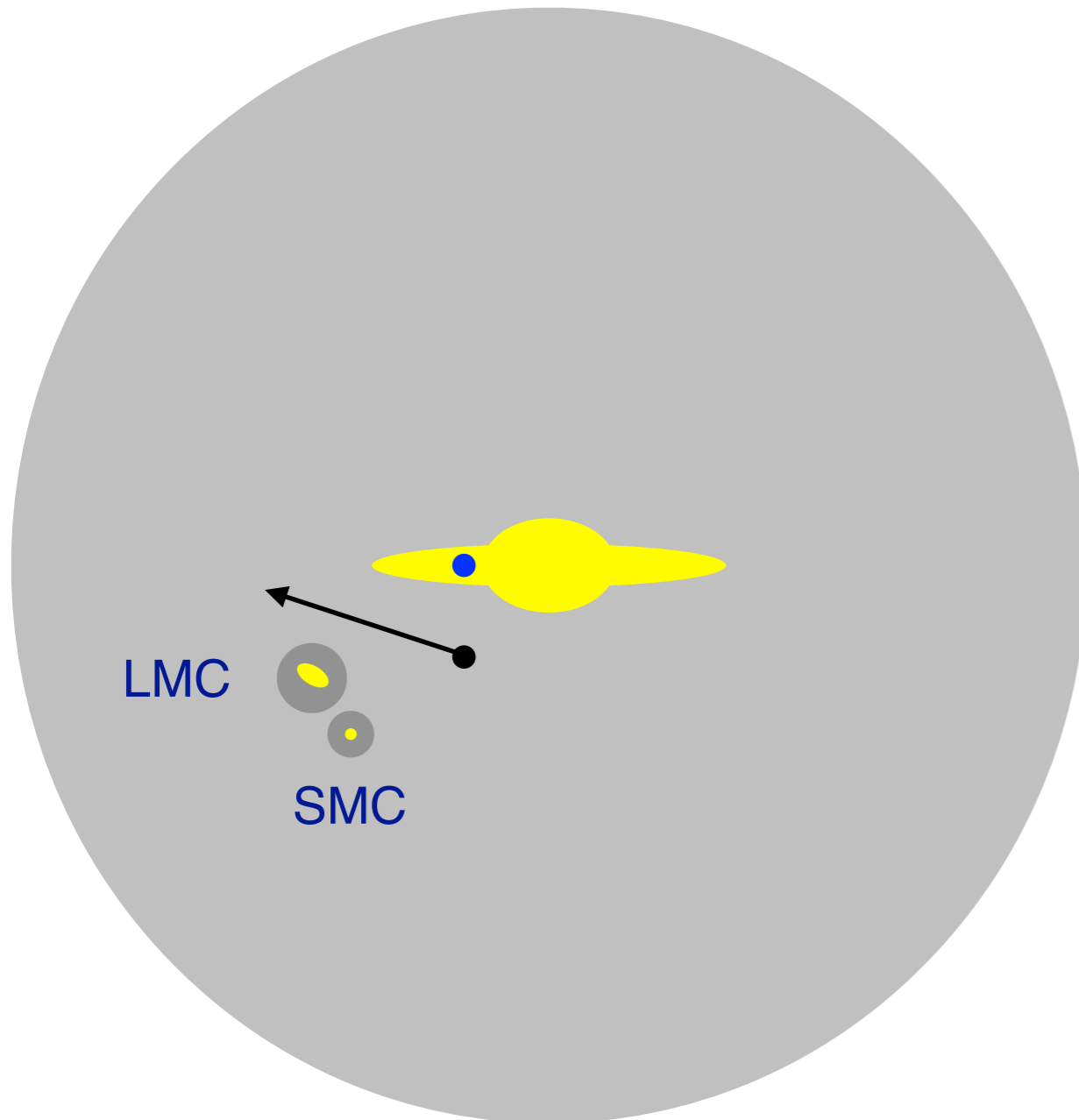


Leach, Grivell, Liddle

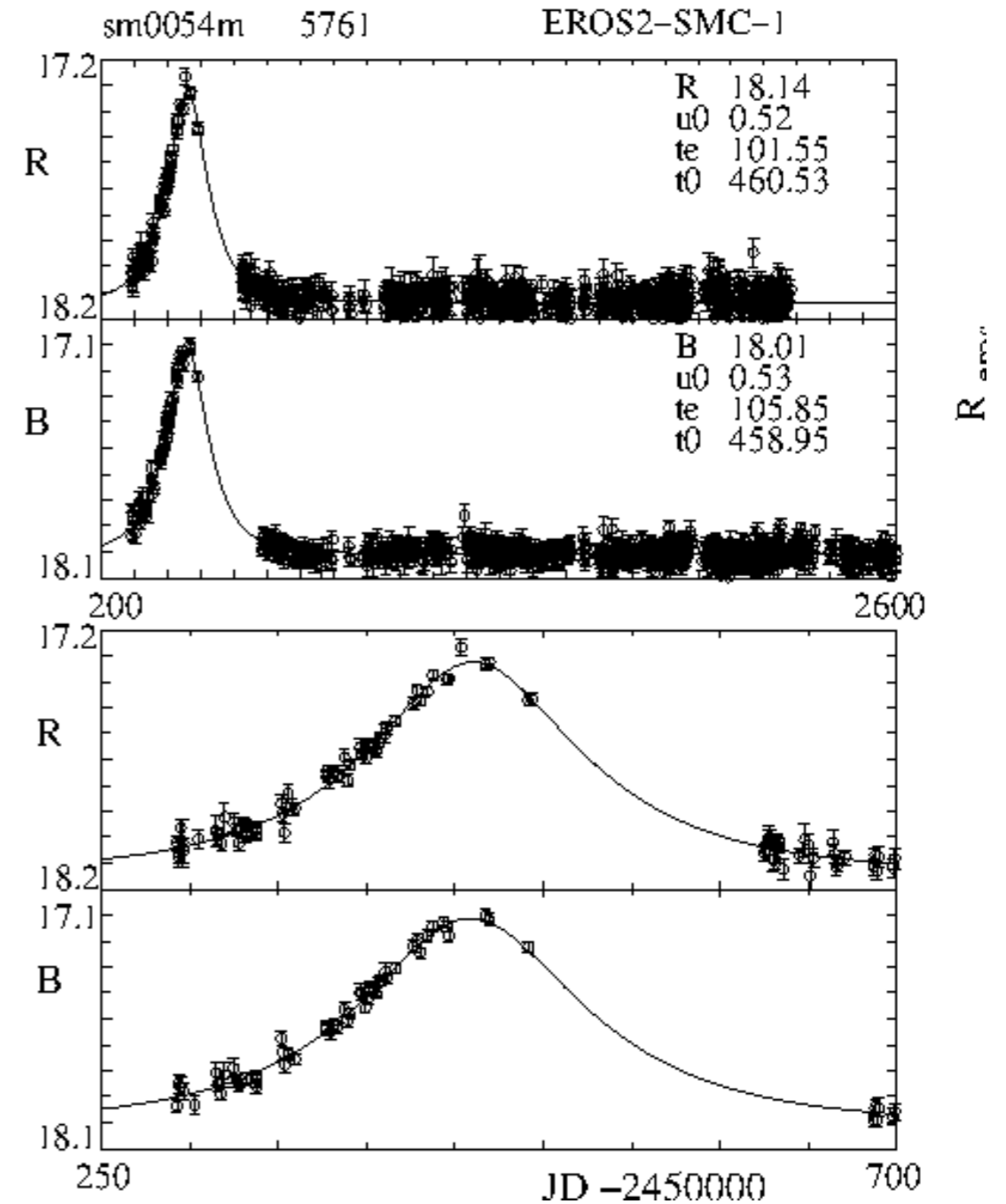
Microlensing

stellar microlensing

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



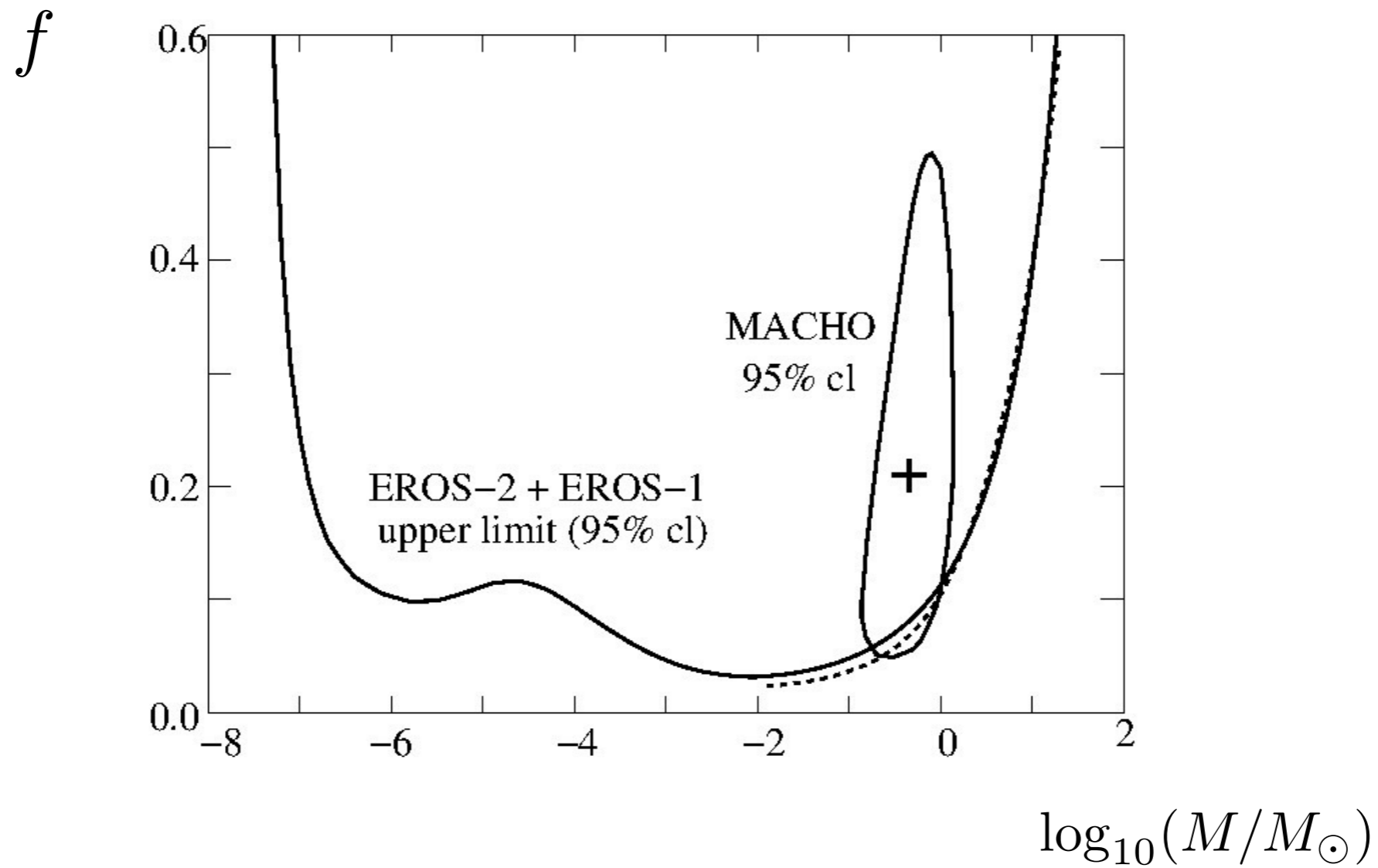
Not to scale!



EROS

magellanic clouds

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



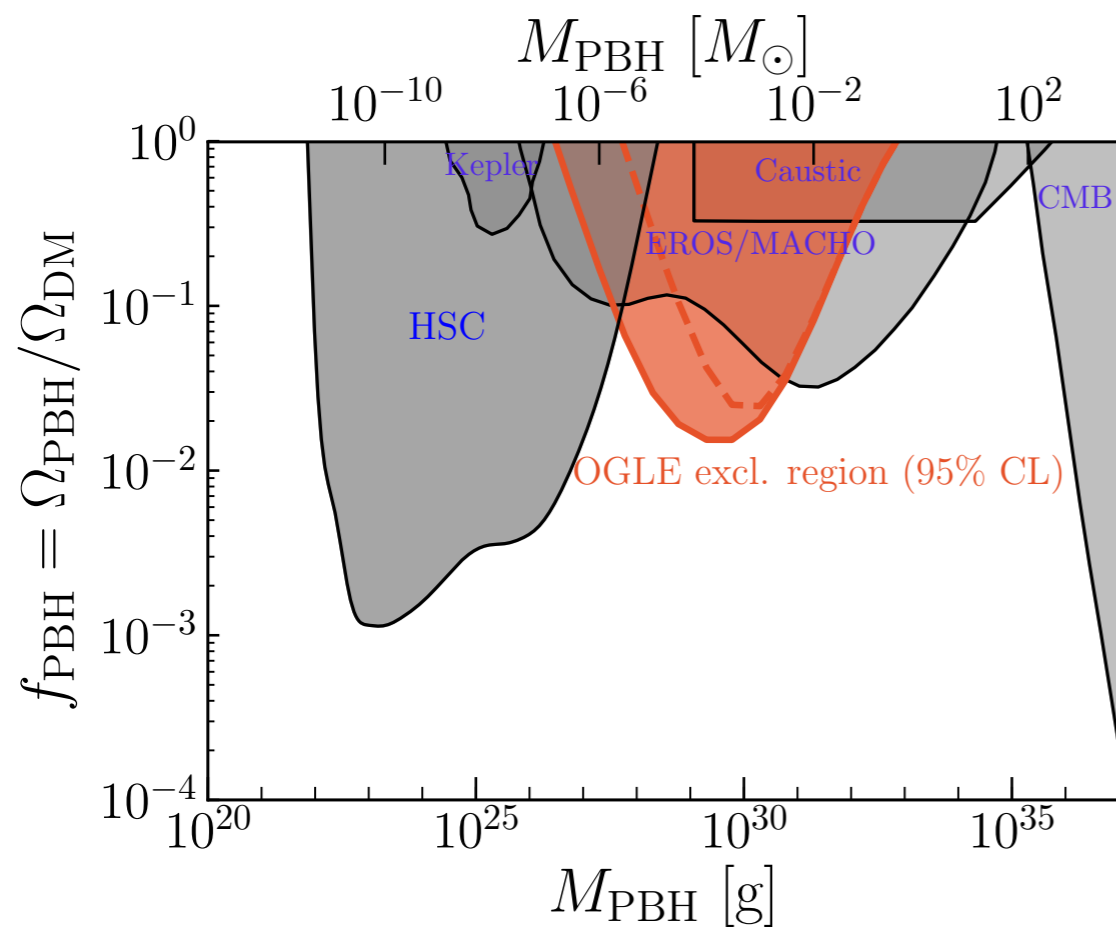
MACHO has very similar limits for $M > 3M_{\odot}$.

stars in Galactic buldge

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

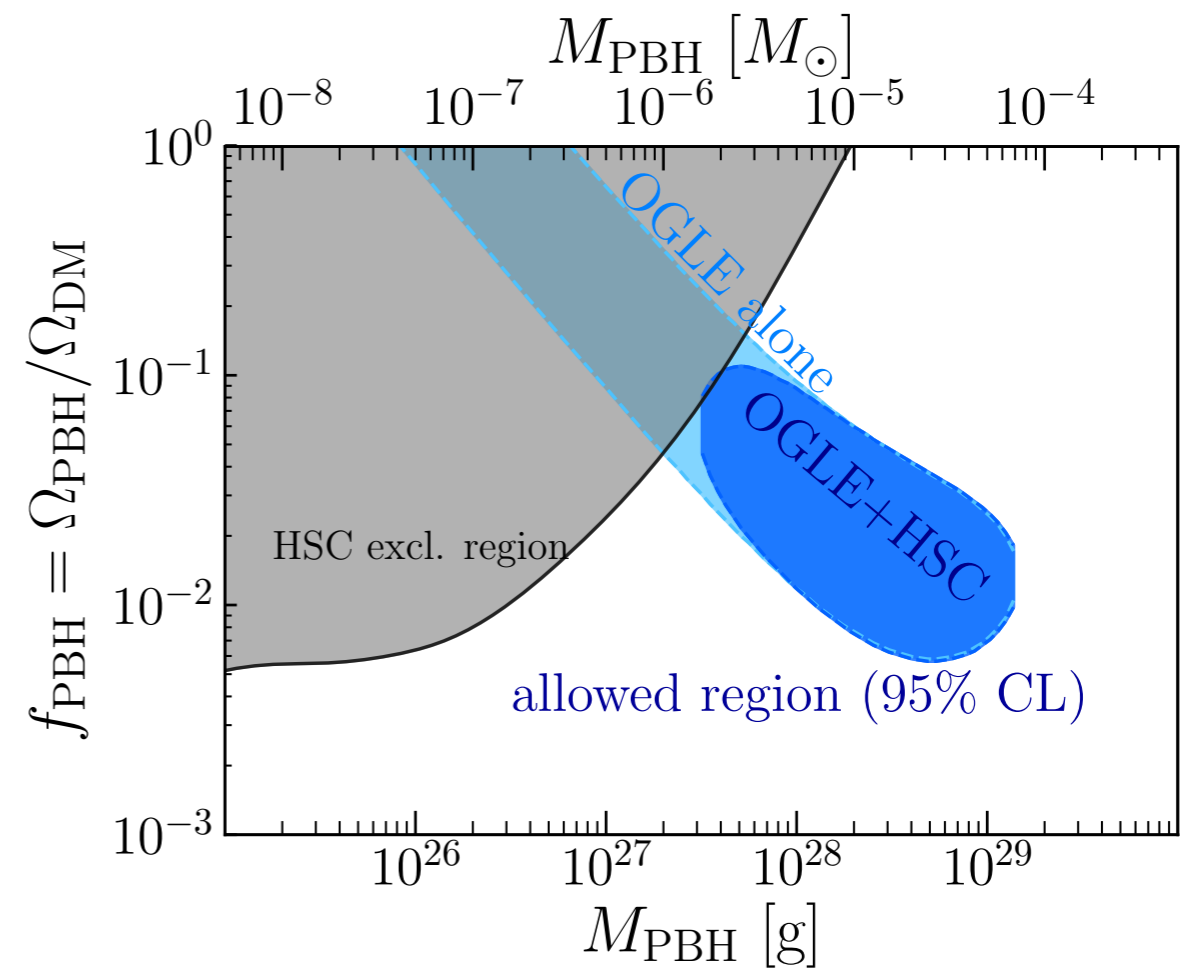
Exclusion limit

assuming no PBH lensing observed



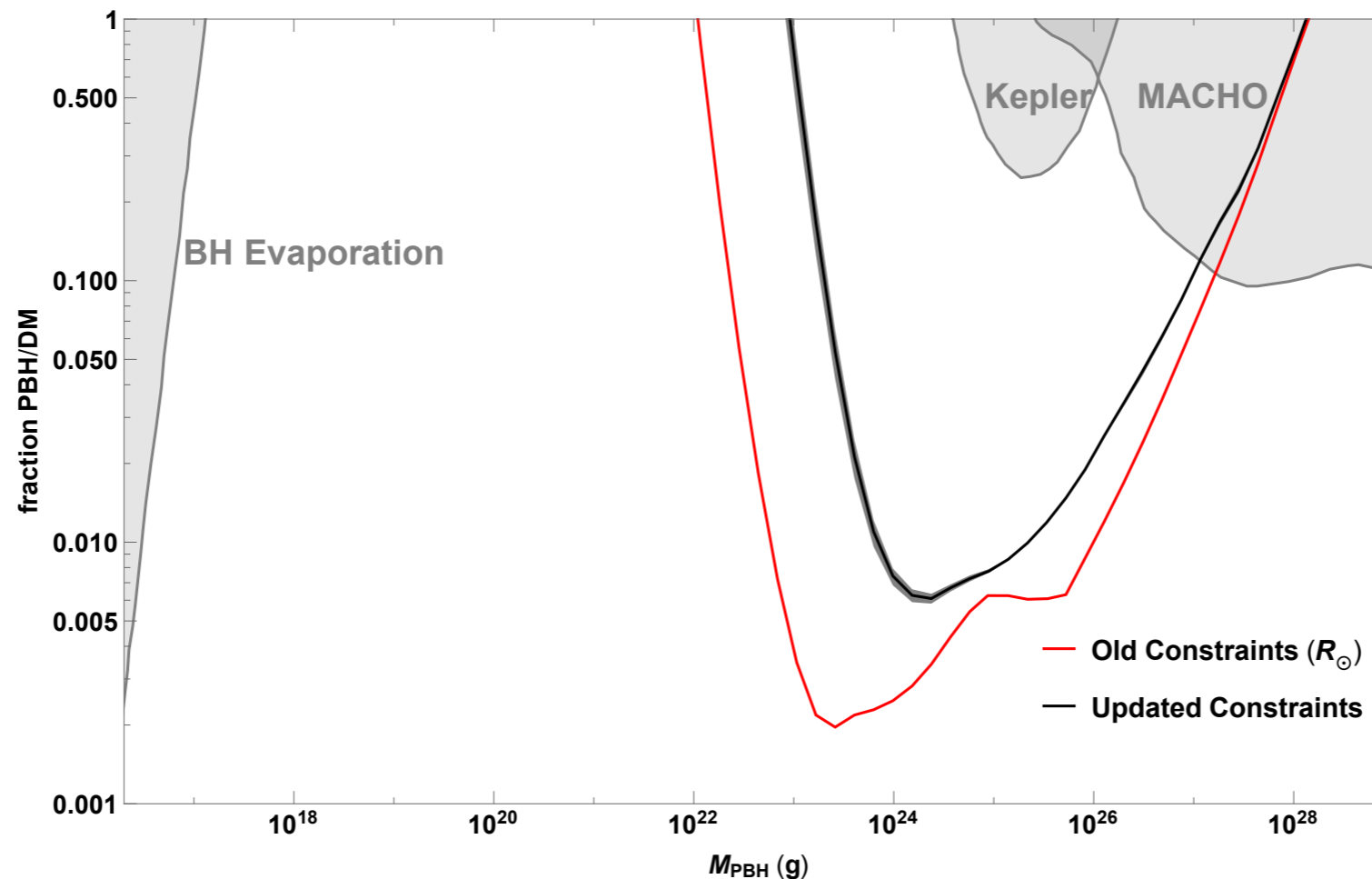
Allowed region

assuming 6 ultra-short events are due to PBHs



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.



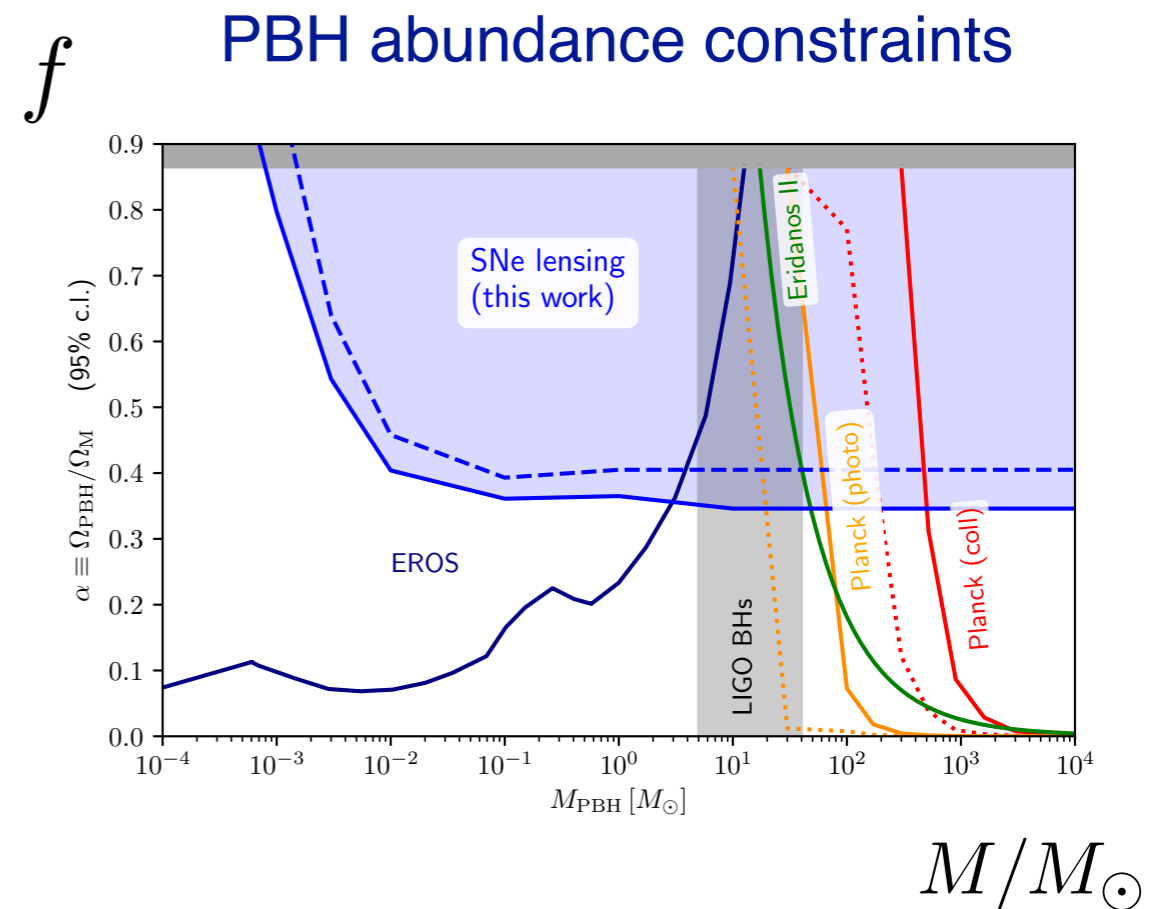
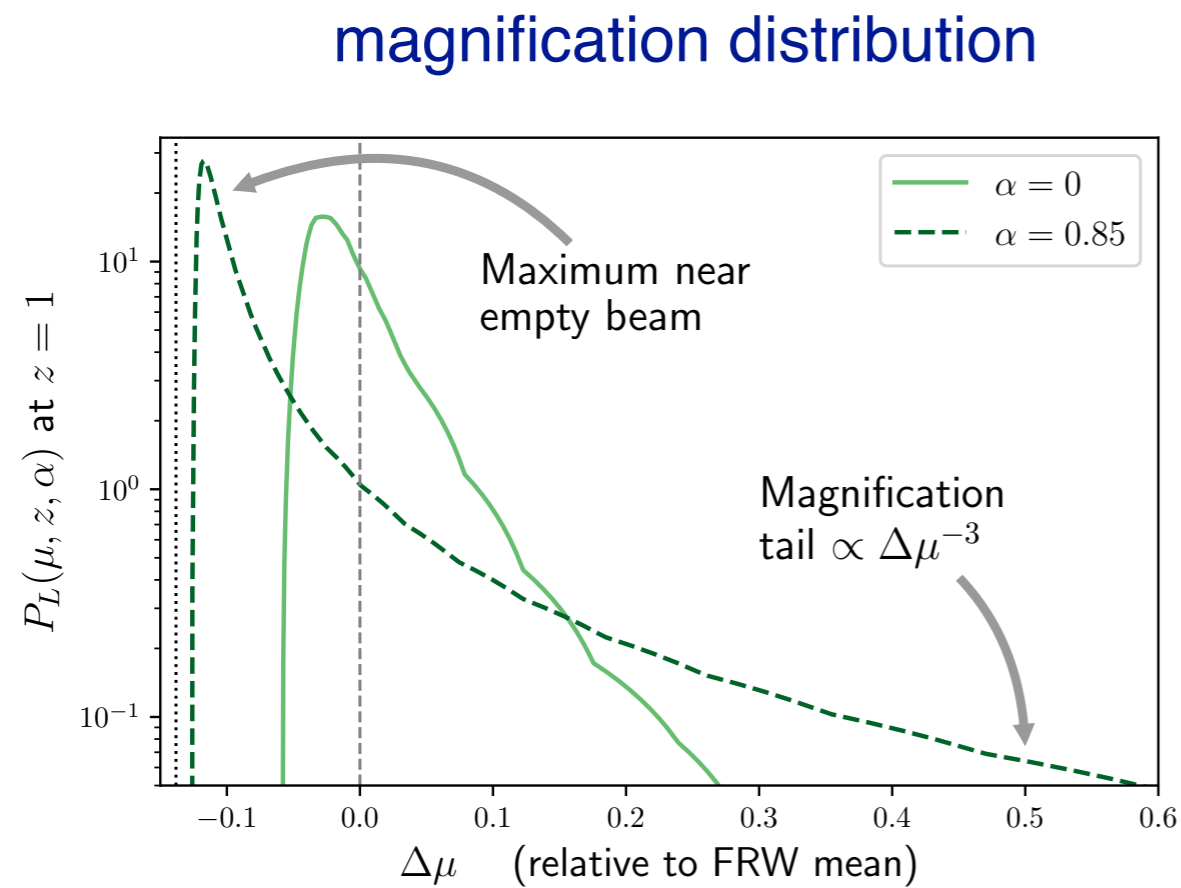
Smyth et al.

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

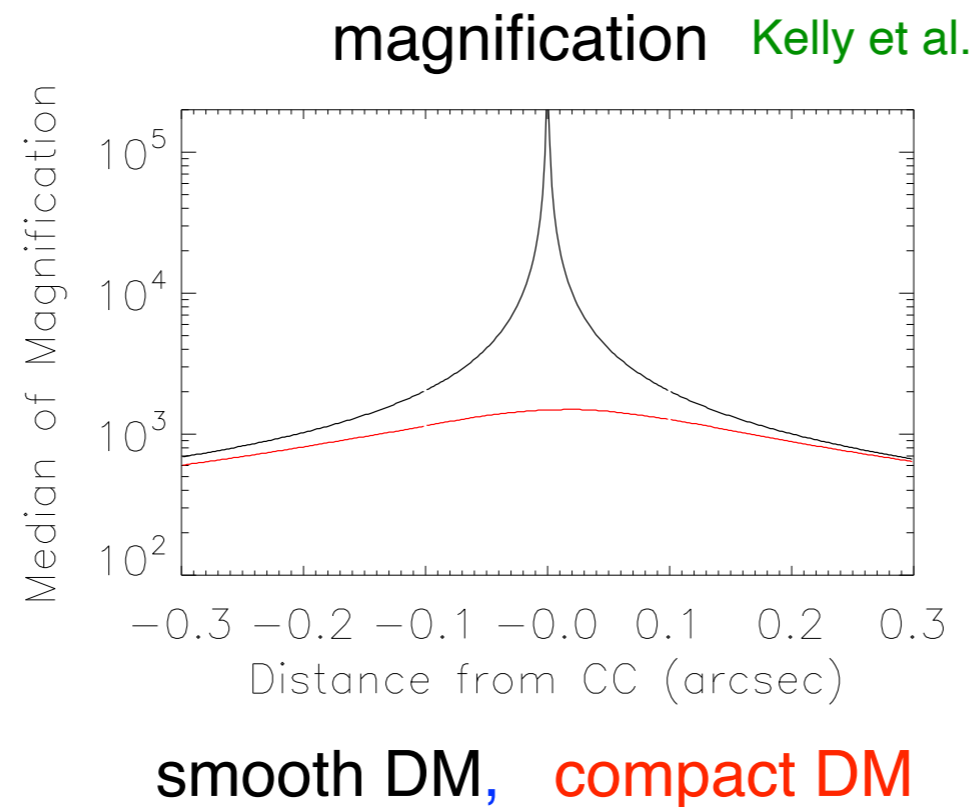


Garcia-Bellido, Clesse & Fleury argue priors on cosmological parameters are overly restrictive and physical size of supernovae have been underestimated.

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.



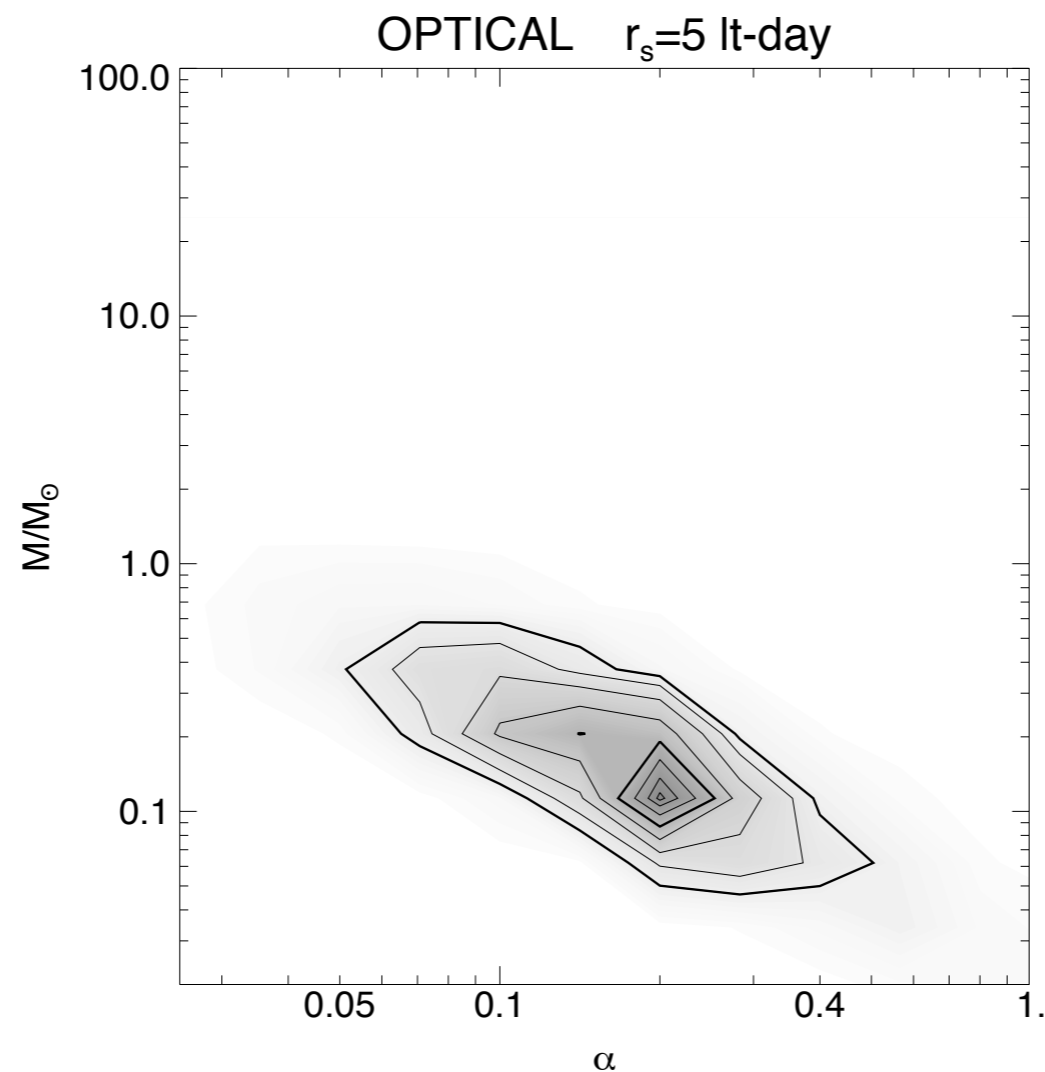
Icarus is first (serendipitously) observed event involving a star at red-shift 1.5. [Kelly et al.](#)

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](#)

$\alpha = 0.2 \pm 0.05$ 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](#)

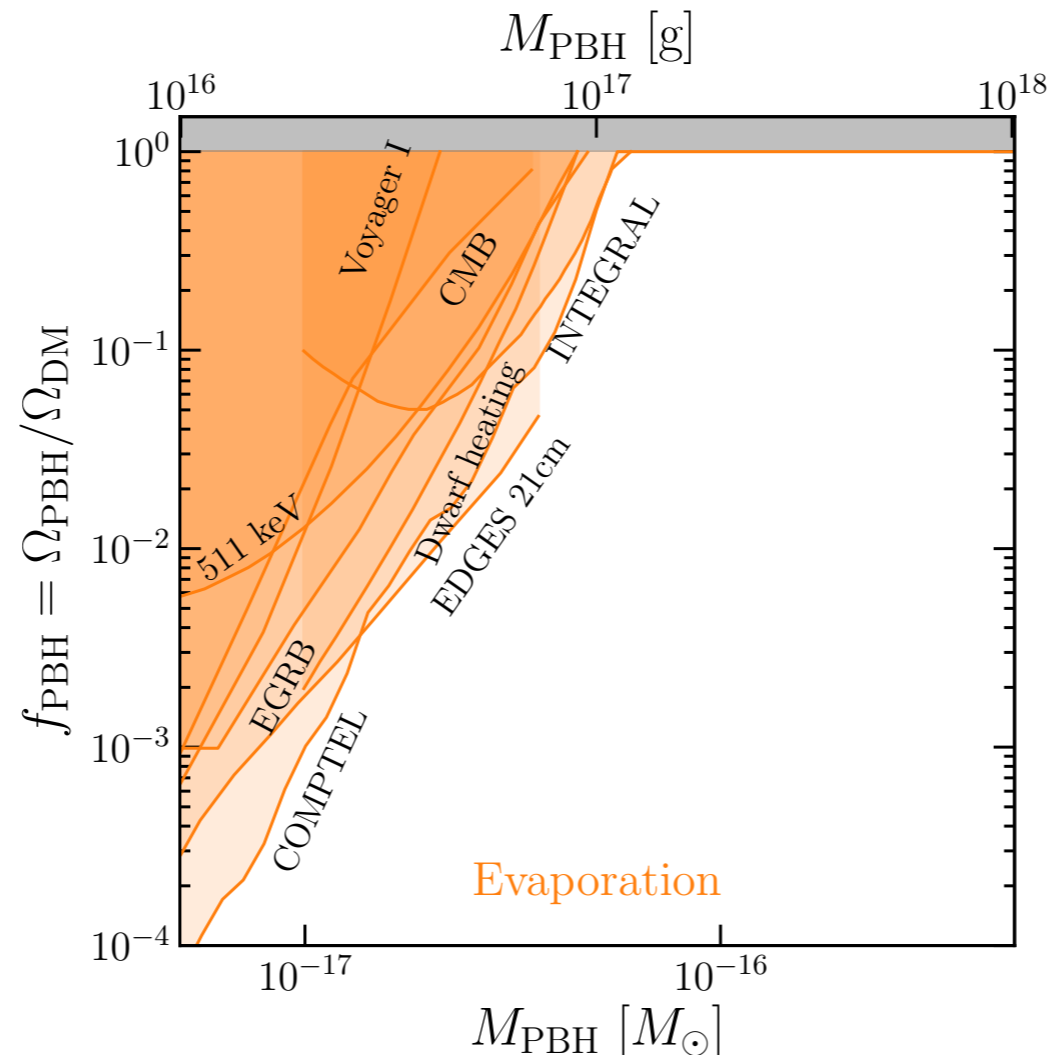
MeV galactic diffuse flux (INTEGRAL) [Laha, Munoz & Slatyer](#) (COMPTEL) [Coogan, Morrison & Profumo](#)

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](#)



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 $\psi(M)$ has to satisfy:

$$\int dM \frac{\psi(M)}{f_{\max}(M)} \leq 1$$

Open questions

how to probe asteroid mass PBHs?

femtolensing of GRBs [Gould](#) need small GRBs [Katz et al.](#)

GRB lensing parallax [Jung & Kim](#)

