Primordial Black Holes (PBHs) as a dark matter candidate

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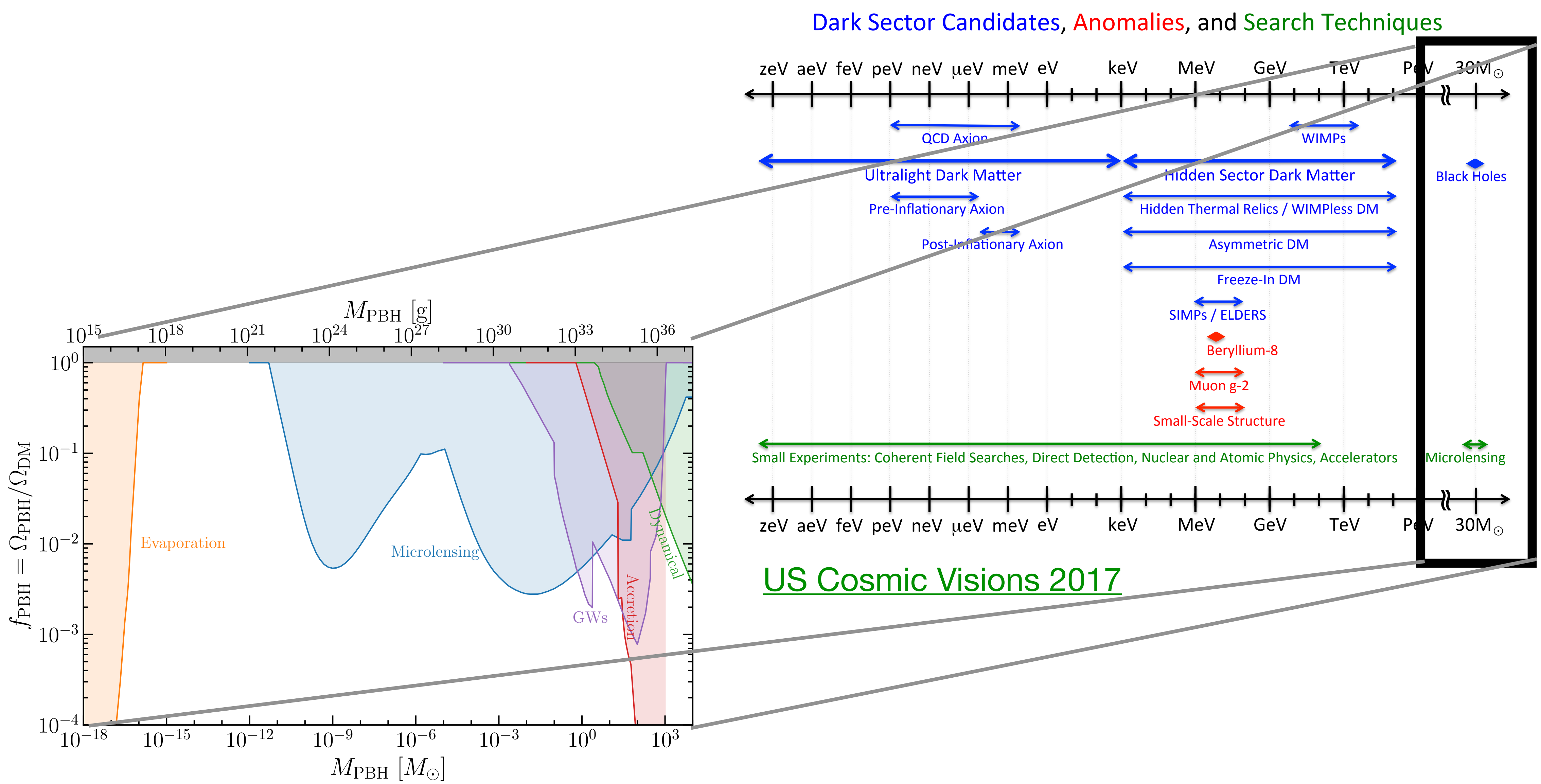

https://github.com/bradkav/PBHbounds

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Motivation & history

Formation

Observational constraints/signatures

Open questions

Reviews

Green & Kavanagh, J. Phys. G. arXiv:2007.10722, ‘PBHs as a dark matter candidate’

Carr & Kuhnel, Ann. Rev. Nuc. Part. Sci. arXiv:2006.02838, ‘PBHs as dark matter: recent developments’

Future prospects

Bird et al., Phys. Dark. Univ. arXiv:2203.08967, ‘Snowmass2001 Cosmic Frontier White Paper: PBH dark matter’

Motivation & history

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 $M \gtrsim 10^{15} \, \mathrm{g}$.
MacGibbon

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.

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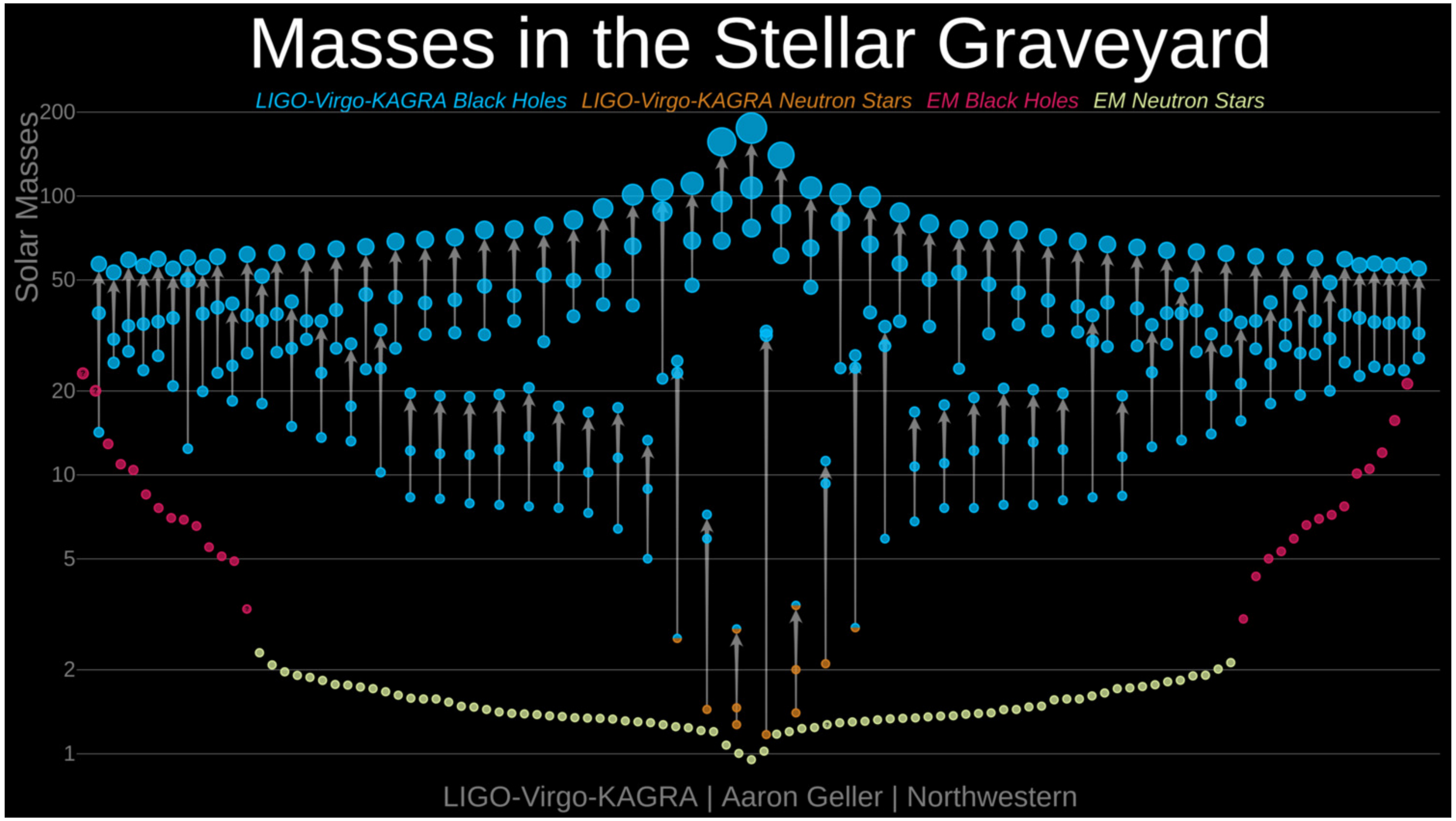
Could (some of) the BHs in the LIGO-Virgo BH binaries be primordial? (and also a significant component of the DM?) Bird et al.; Clesse & Garcia-Bellido; Sasaki et al.

$100M_\odot$

$10M_\odot$



LIGO-Virgo-KAGRA, Geller

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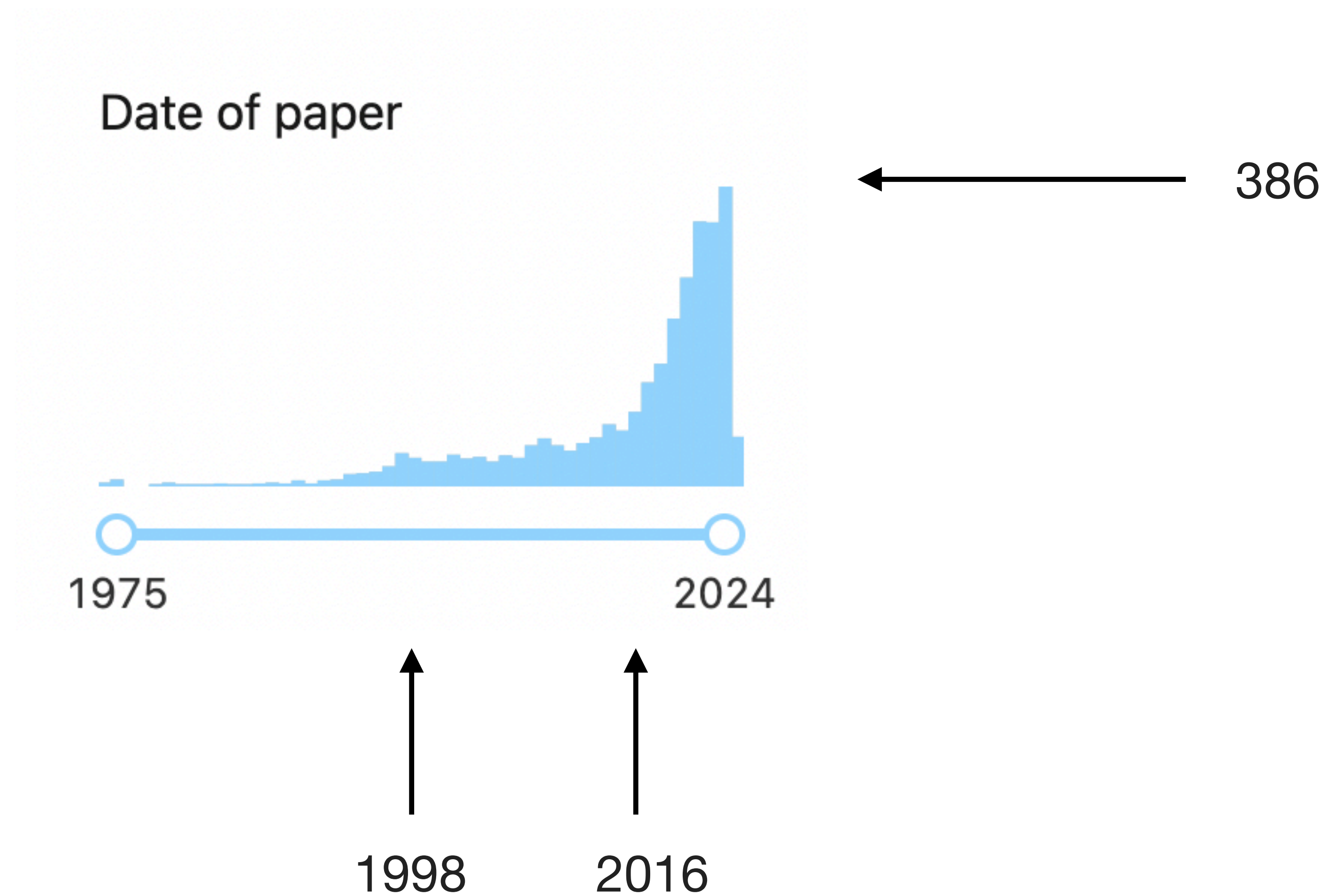
result of an inSPIRE search for 'primordial black hole'



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’.

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

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'zero-th order' 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)

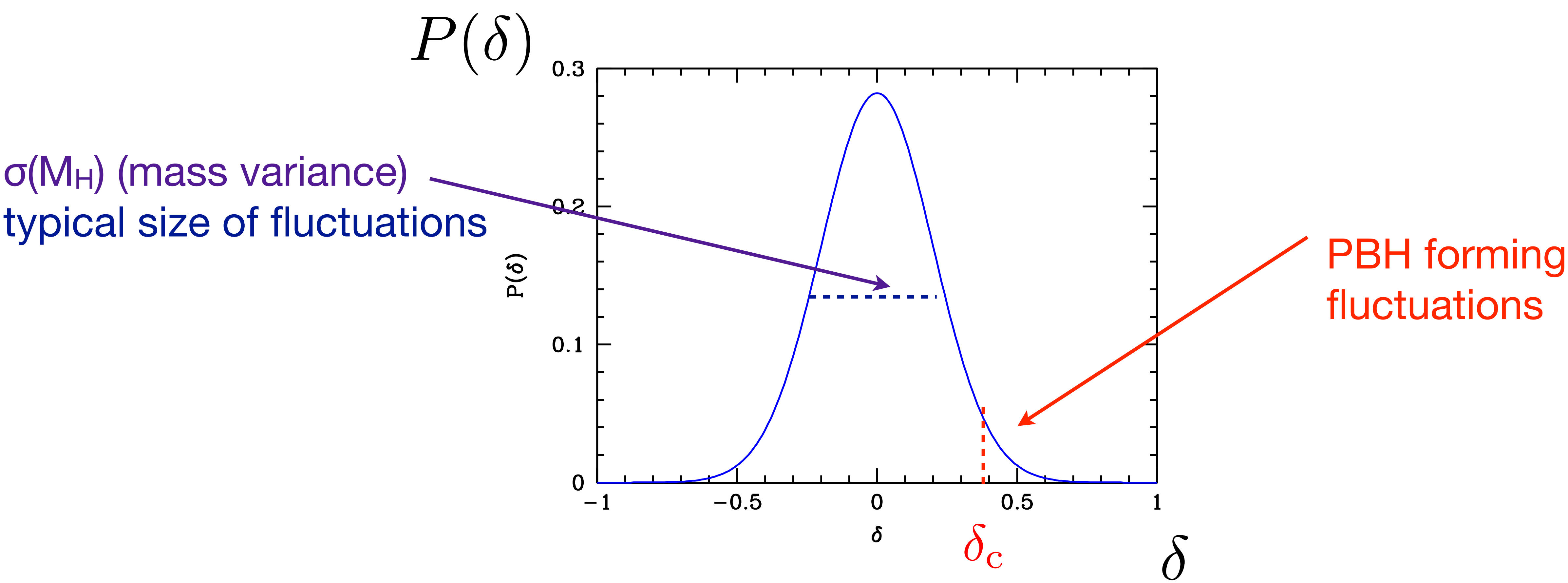
PBH mass roughly equal to horizon mass:

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

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):

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

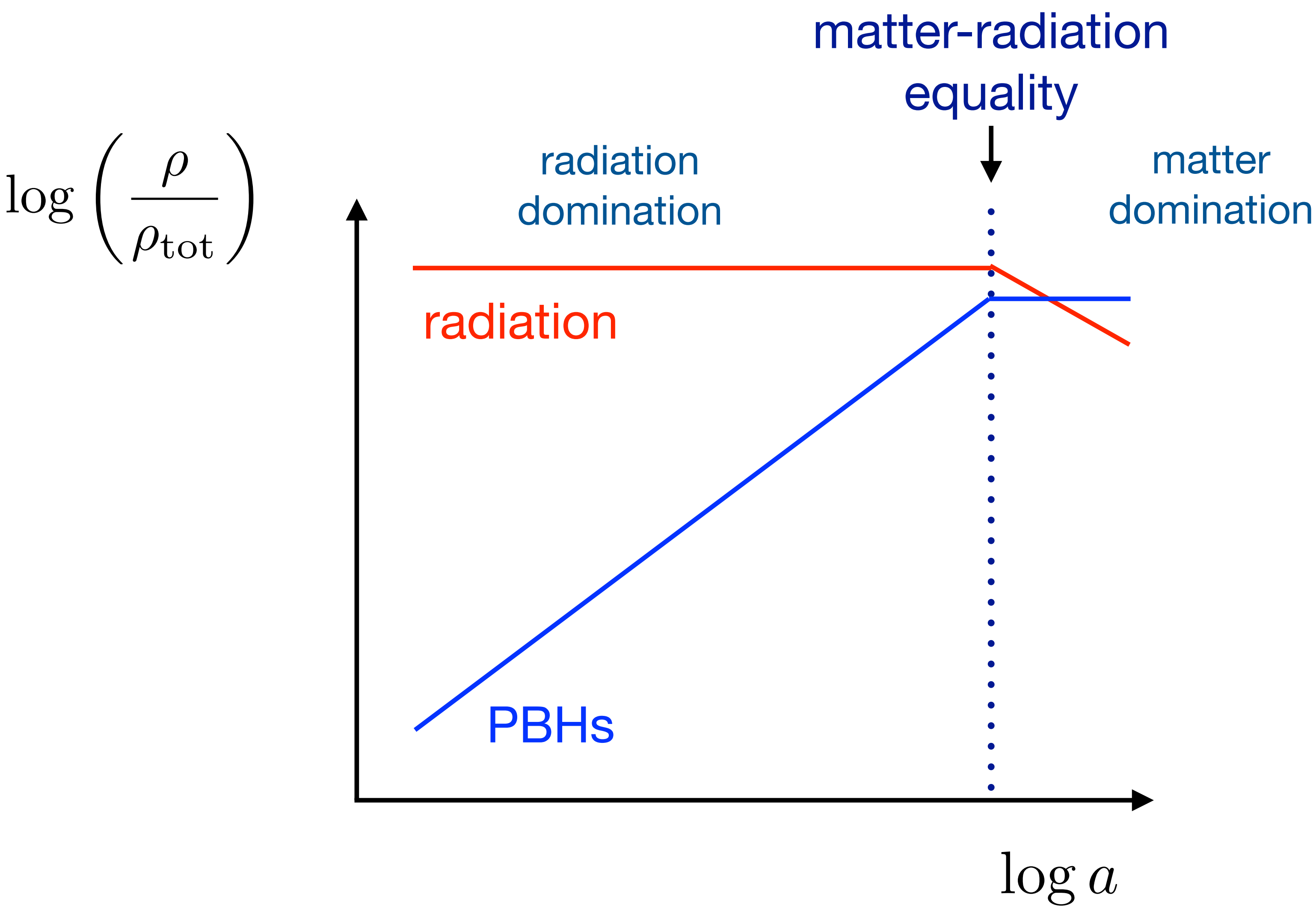
assuming a gaussian probability distribution: $\beta(M) = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M_H)}\right)$



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

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



Relationship between **PBH initial mass fraction, β**, and **fraction of DM in form of PBHs, $f_{\rm PBH}$**:

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

i.e. initial mass fraction must be small.

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:

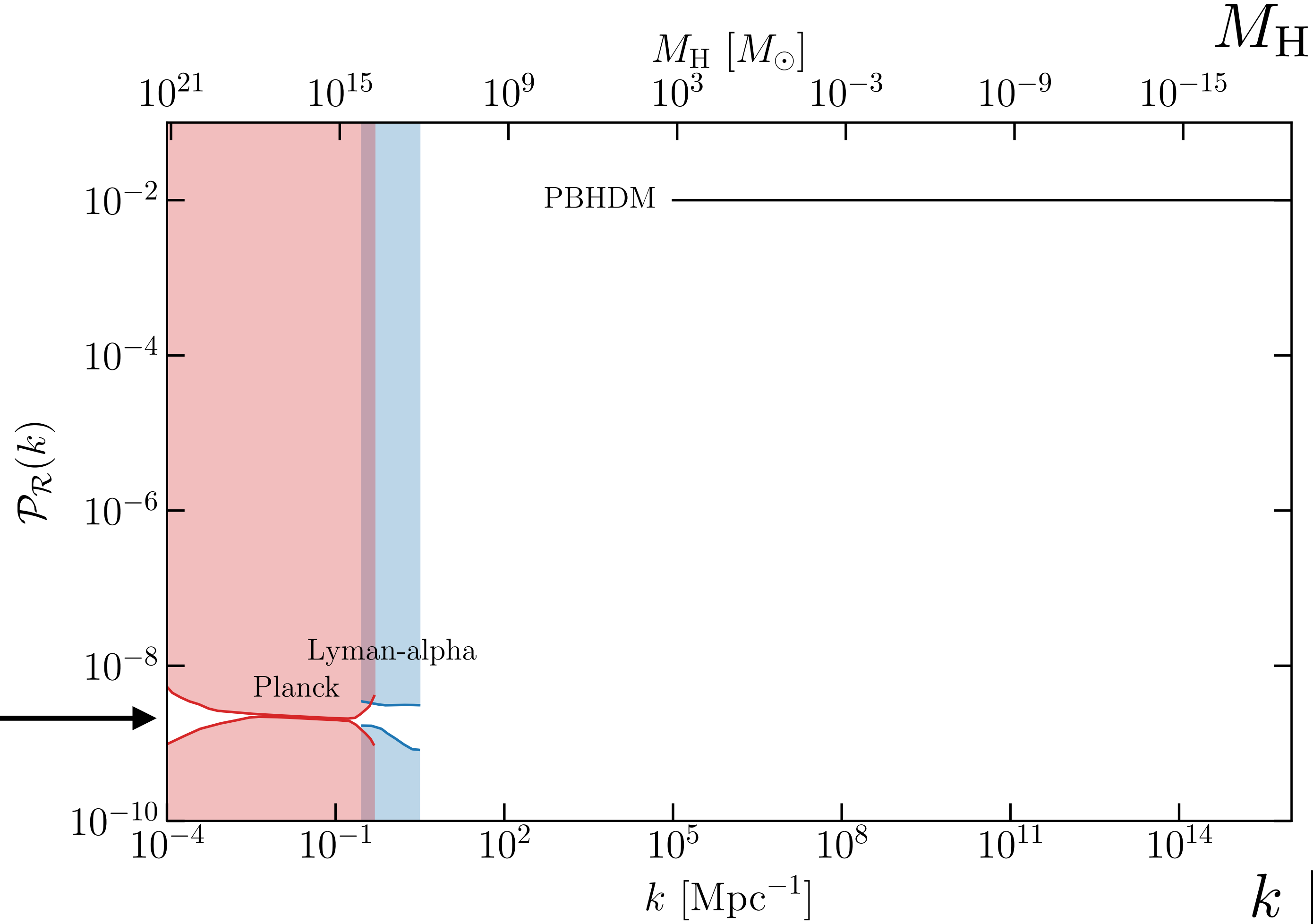
$$\beta(M) = {\rm erfc}\left(\frac{\delta_{\rm c}}{\sqrt{2}\sigma(M_{\rm H})}\right)$$

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

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

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

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



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

measured amplitude on cosmological scales

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

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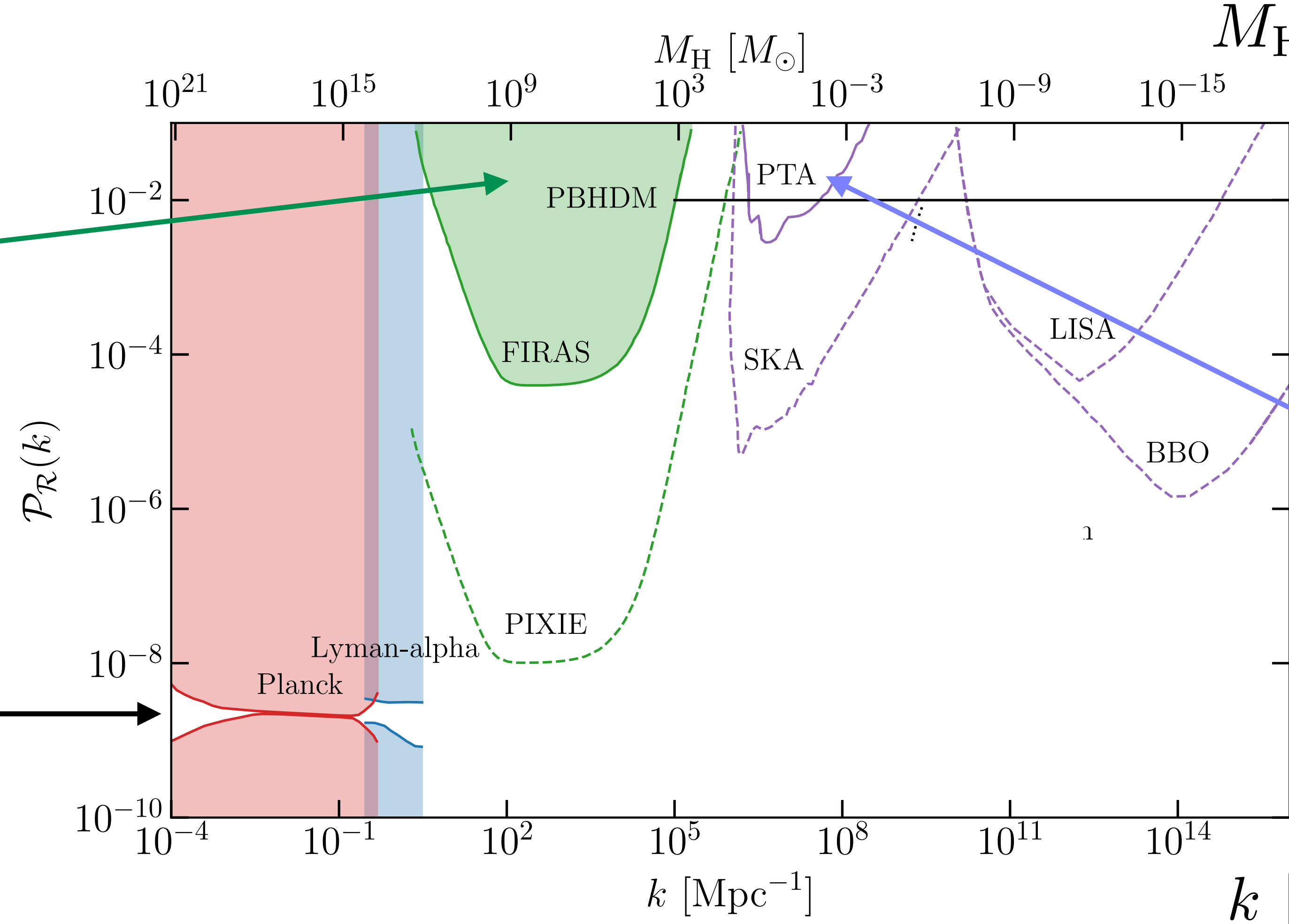


amplitude required for $f_{\rm PBH} \sim 1$

CMB spectral distortions
Carr & Lidsey

scalar induced gravitational waves
Ananda, Clarkson & Wands
Saito & Yokoyama

measured amplitude on cosmological scales

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

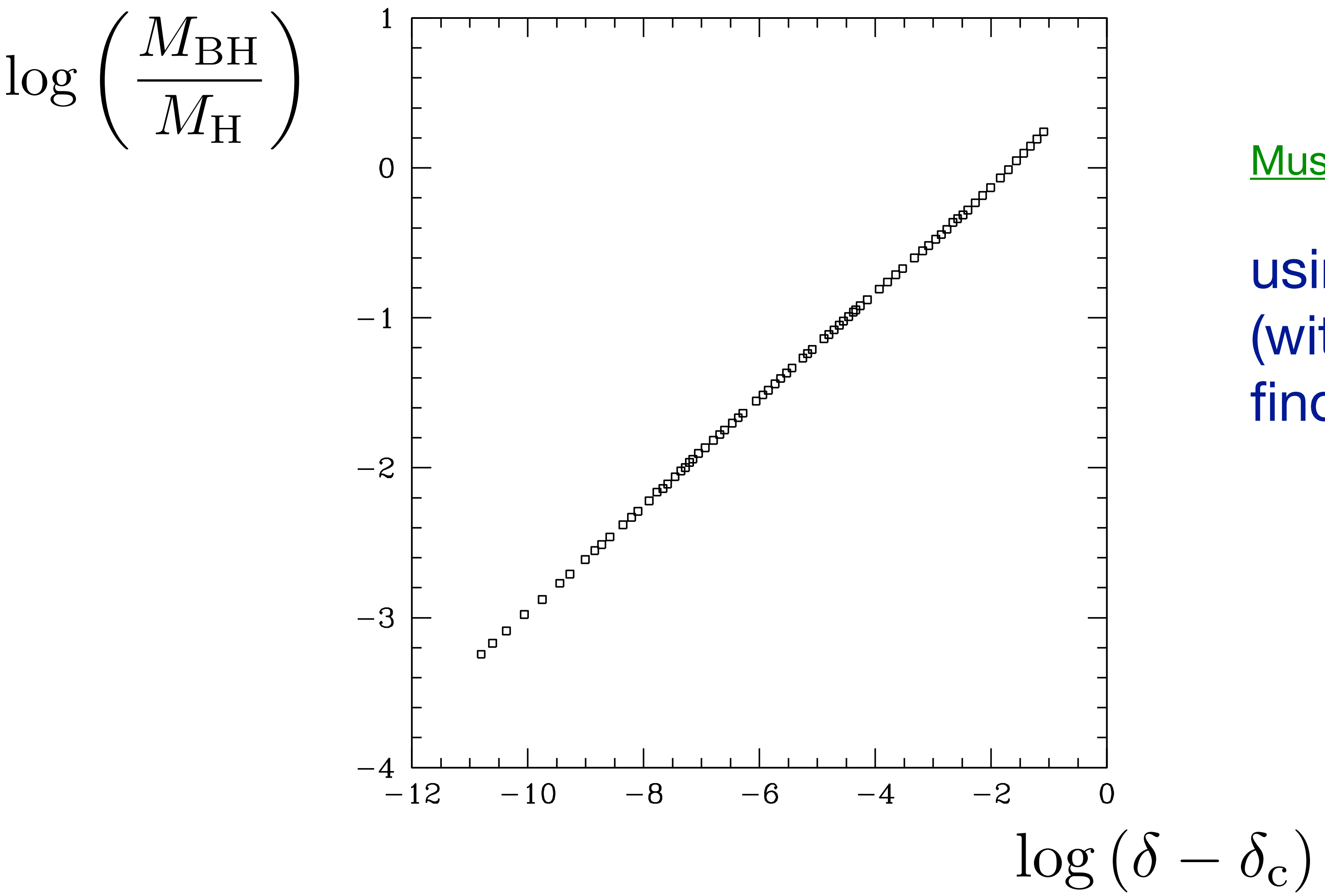
deviations from simple scenario:

i) critical collapse

Niemeyer & Jedamzik

BH mass depends on size of fluctuation it forms from:

$$M = k M_{\mathrm{H}} (\delta - \delta_{\mathrm{c}})^{\gamma}$$



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

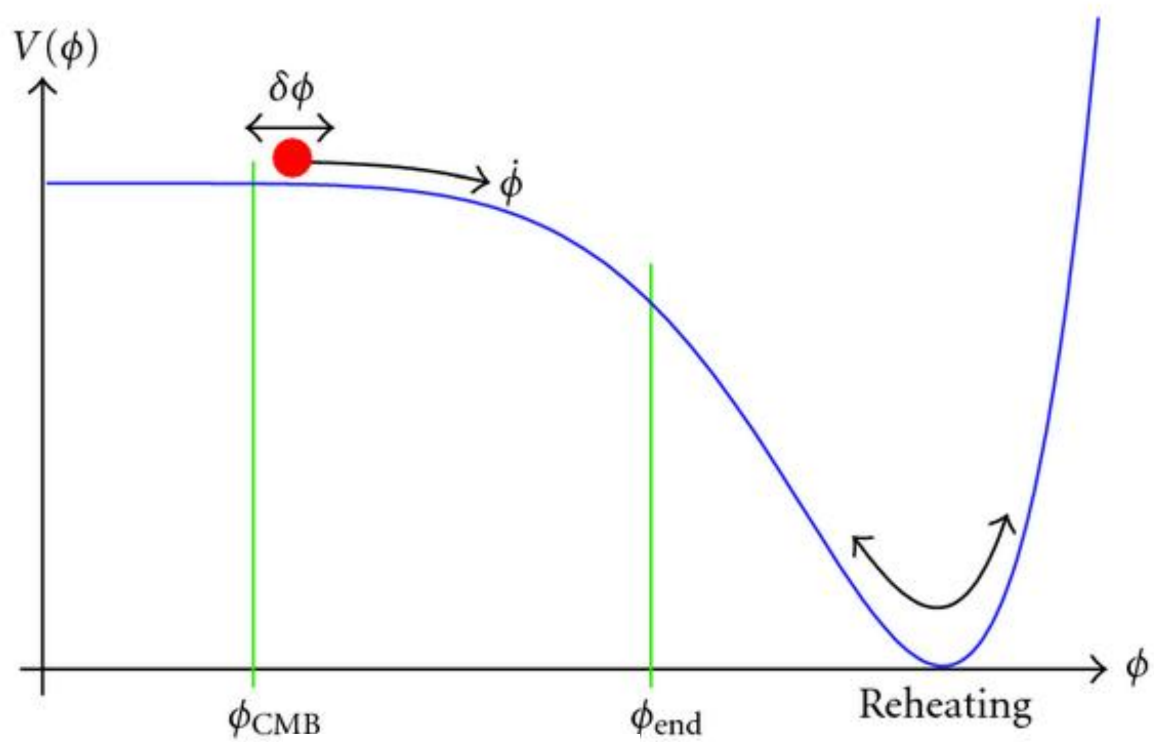
A postulated period of accelerated expansion in the early Universe, proposed to solve various problems with the Big Bang (flatness, horizon & monopole).

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*:

$$\sigma \propto \frac{V^{3/2}}{V'}$$

A plateau in the potential can generate large perturbations which form an interesting abundance of PBHs. Ivanov, Naselsky, Novikov

* in 'ultra-slow-roll' limit, $V' \to 0$, this expression isn't accurate (and USR also affects probability distribution of fluctuations - more later).

Requirements for a PBH producing inflation model:

i) produce measured power spectrum (amplitude and scale dependence) on cosmological scales,

ii) amplitude of perturbations ~3.5 orders of magnitude larger on some smaller scale,

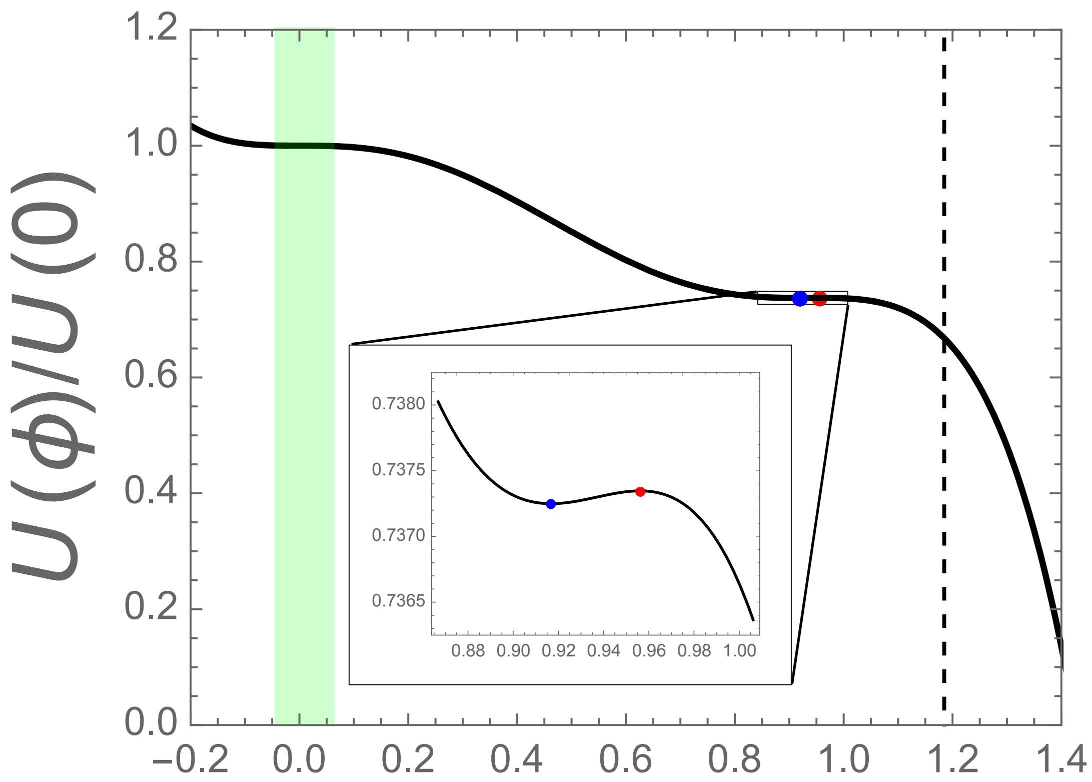
iii) inflation ends.

single field

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

Ballesteros & Taoso; Herzberg & Yamada

potential

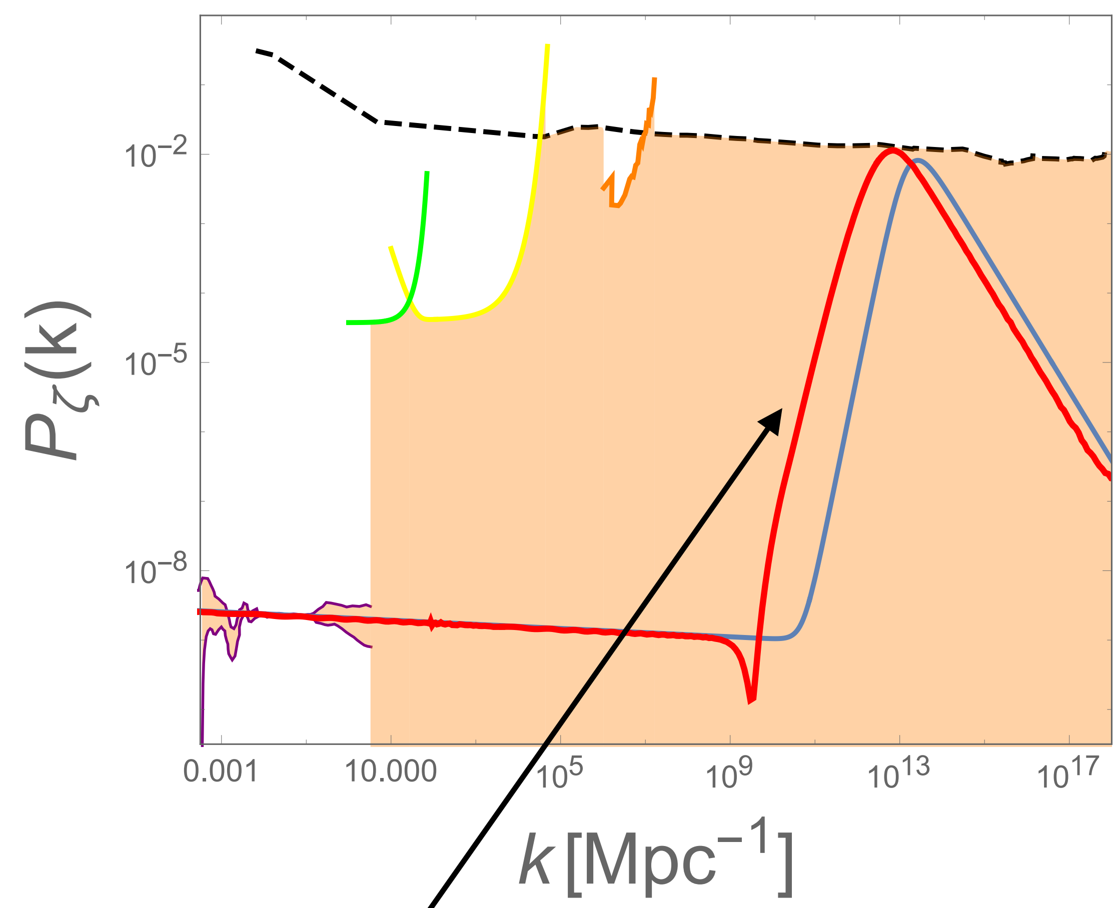


CMB/LSS

ϕ

end of inflation

primordial power spectrum

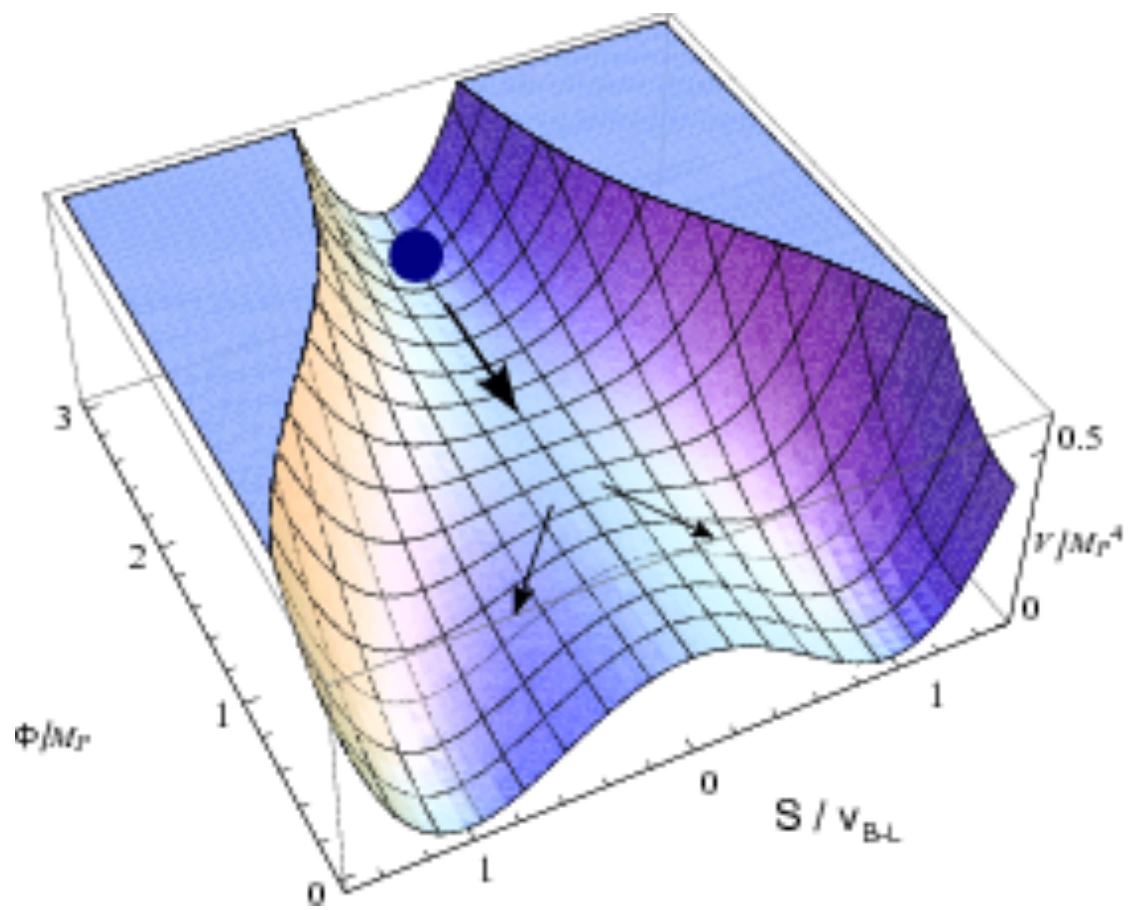


$\sim k^4$ Byrnes, Cole & Patil

multi-field models

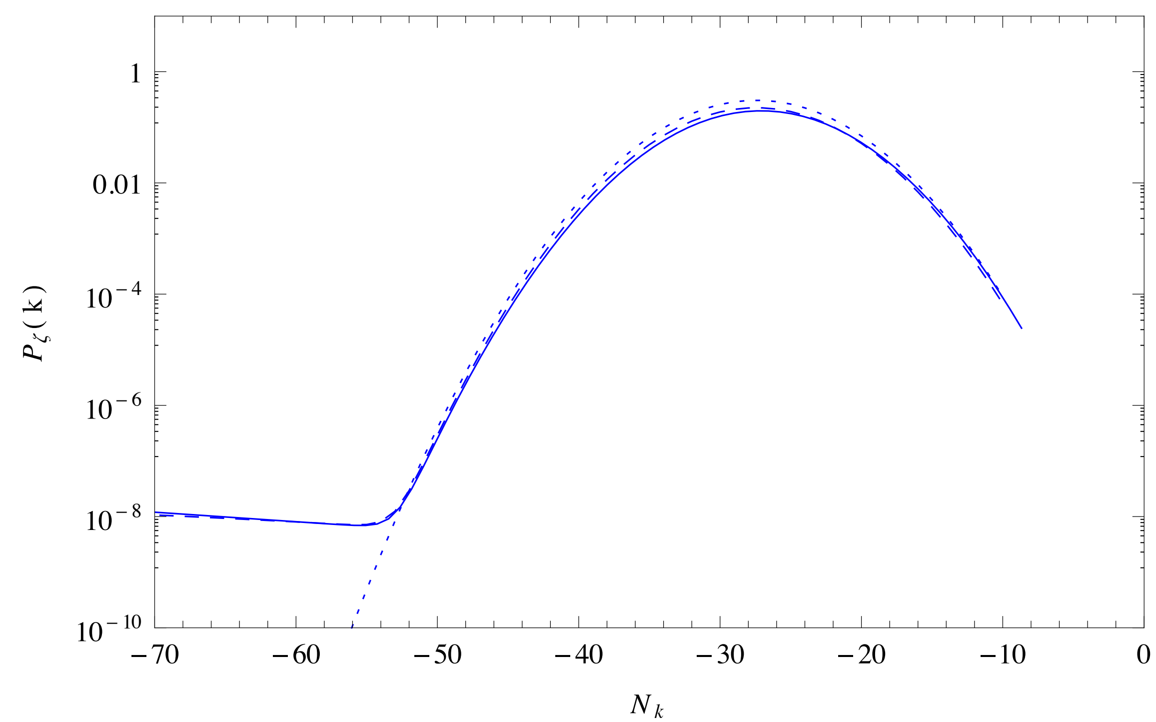
e.g. hybrid inflation with a mild waterfall transition Garcia-Bellido, Linde & Wands

potential



Buchmuller

primordial power spectrum



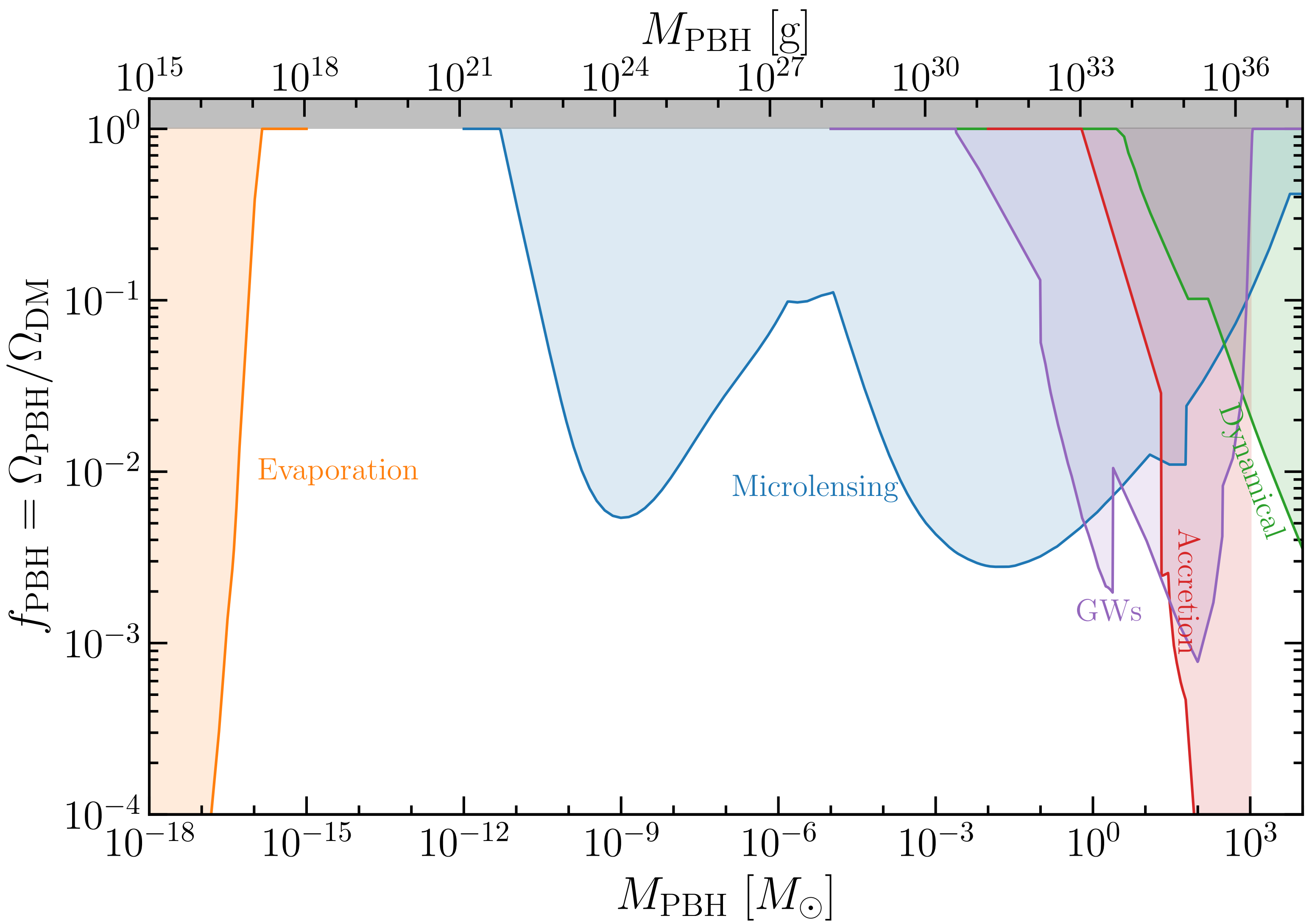
Clesse & Garcia-Bellido

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,…

Observational constraints

(assuming a delta-function PBH mass function)



evaporation

lensing

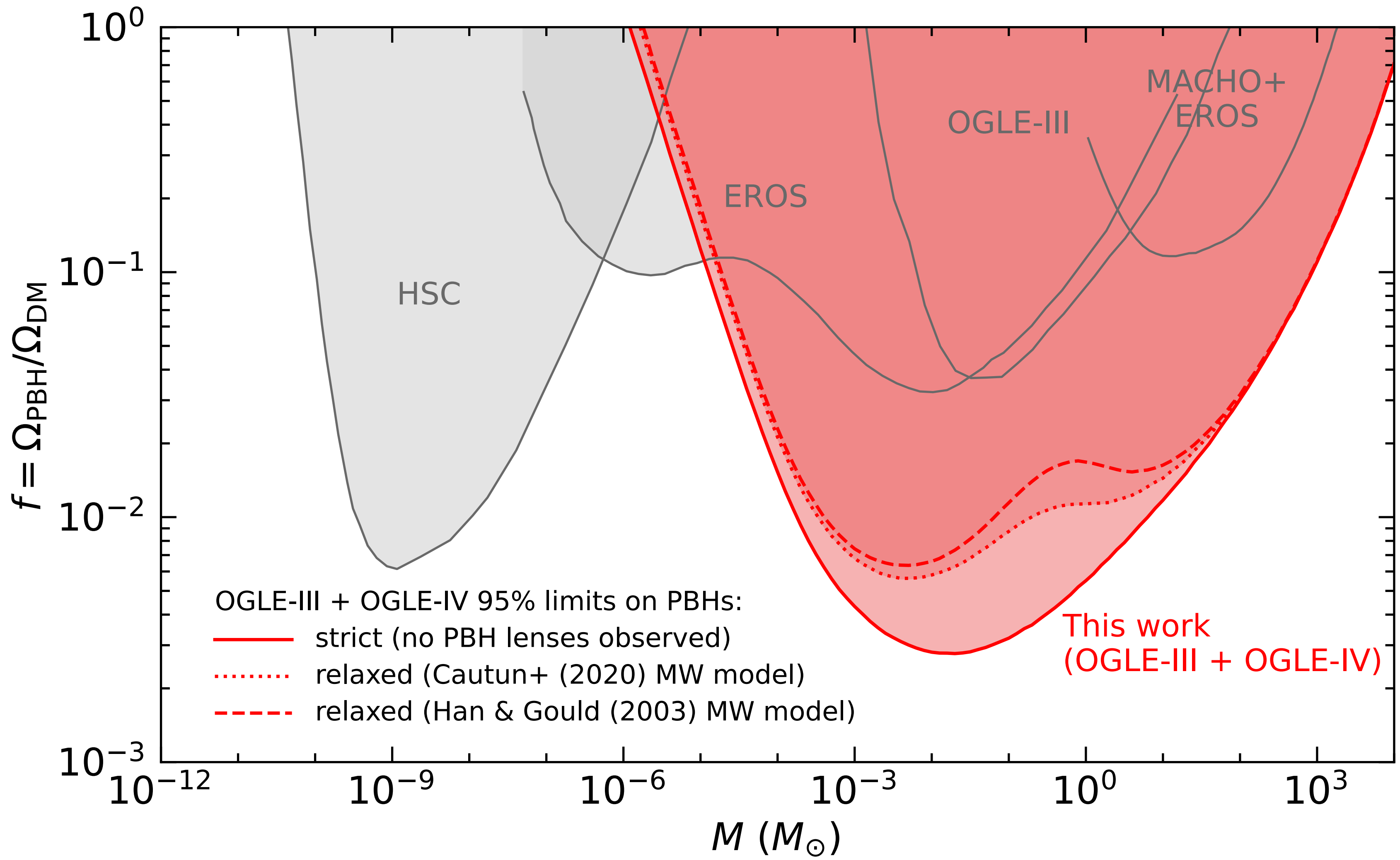
gravitational waves

accretion

dynamical

https://github.com/bradkav/PBHbounds

New tight constraints on planetary and stellar mass PBHs from 20 years of OGLE LMC microlensing observations: Mroz et al. arXiv:2403.02386



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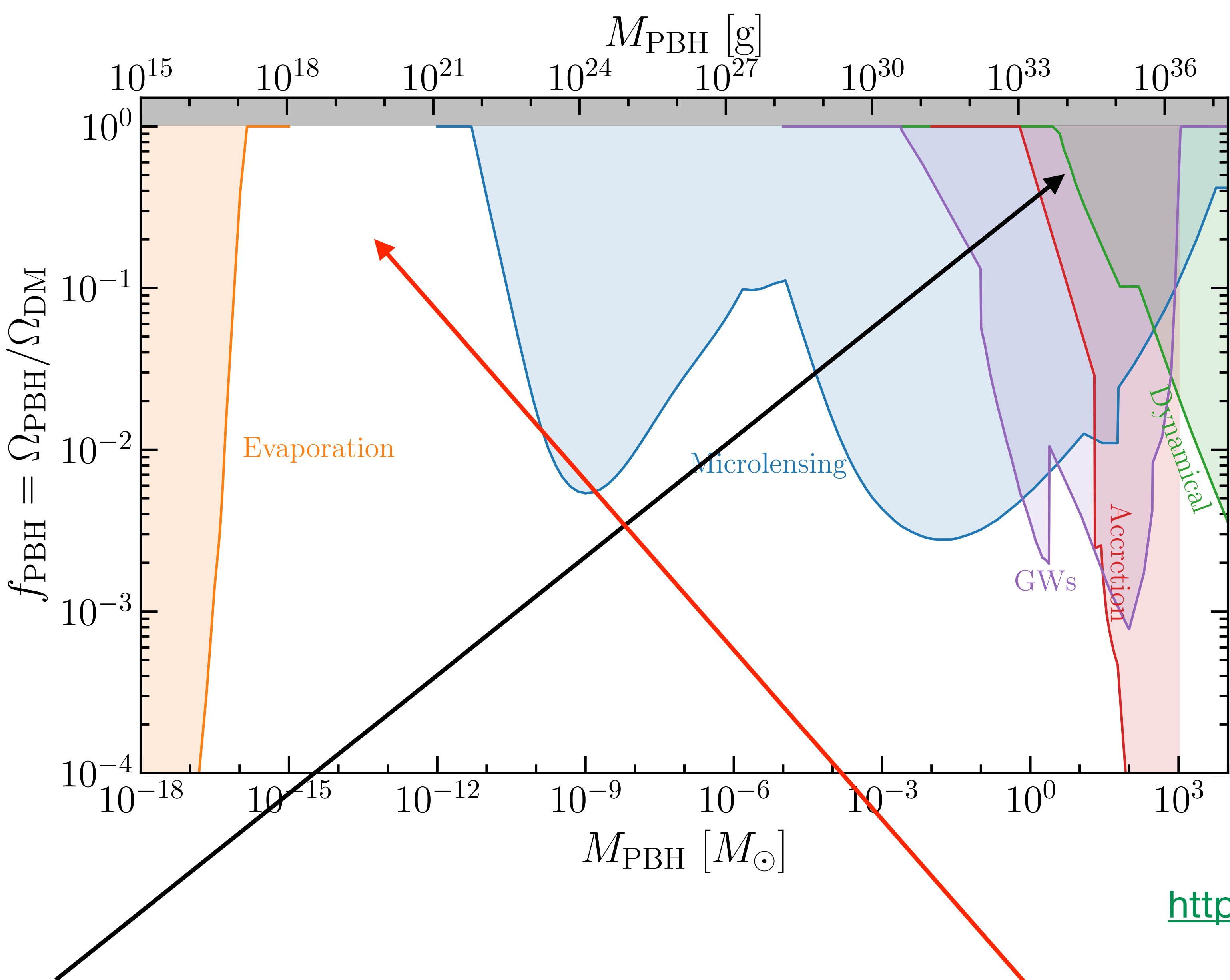

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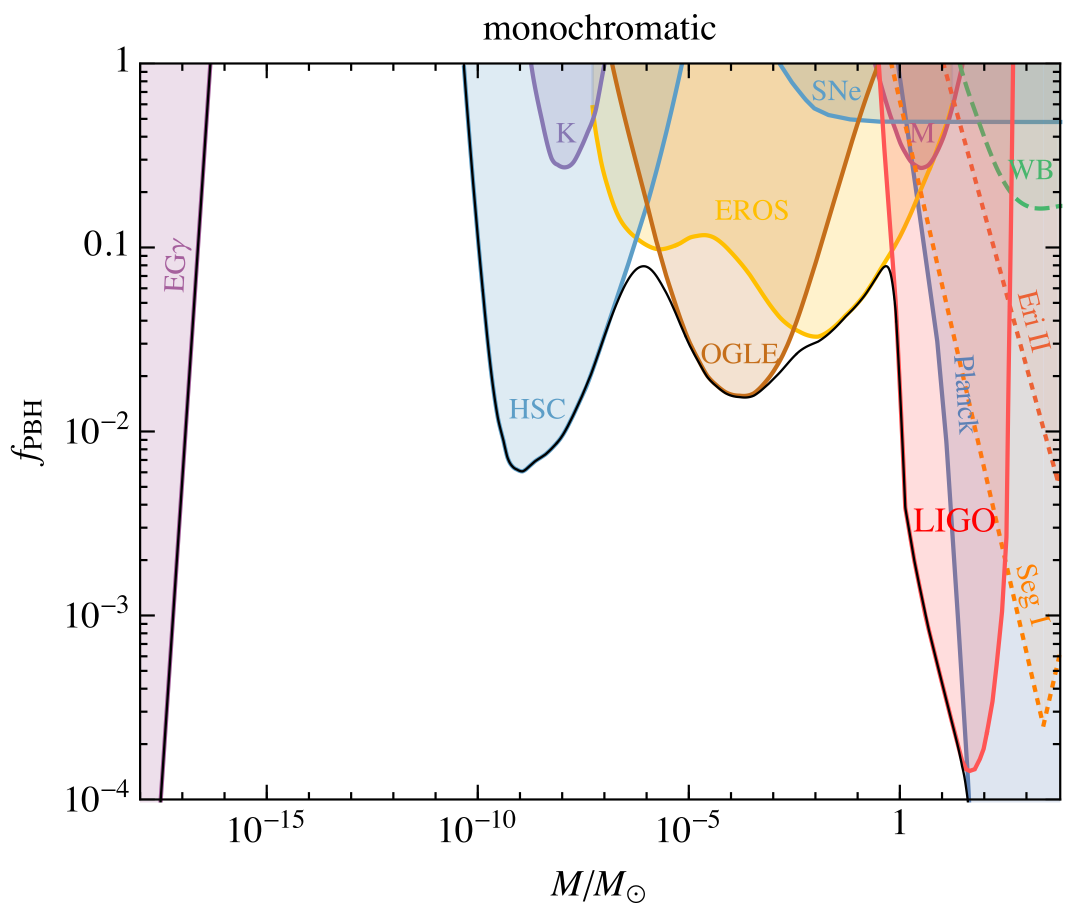
multi-Solar mass Primordial Black Holes making up all of the DM appears to be excluded.

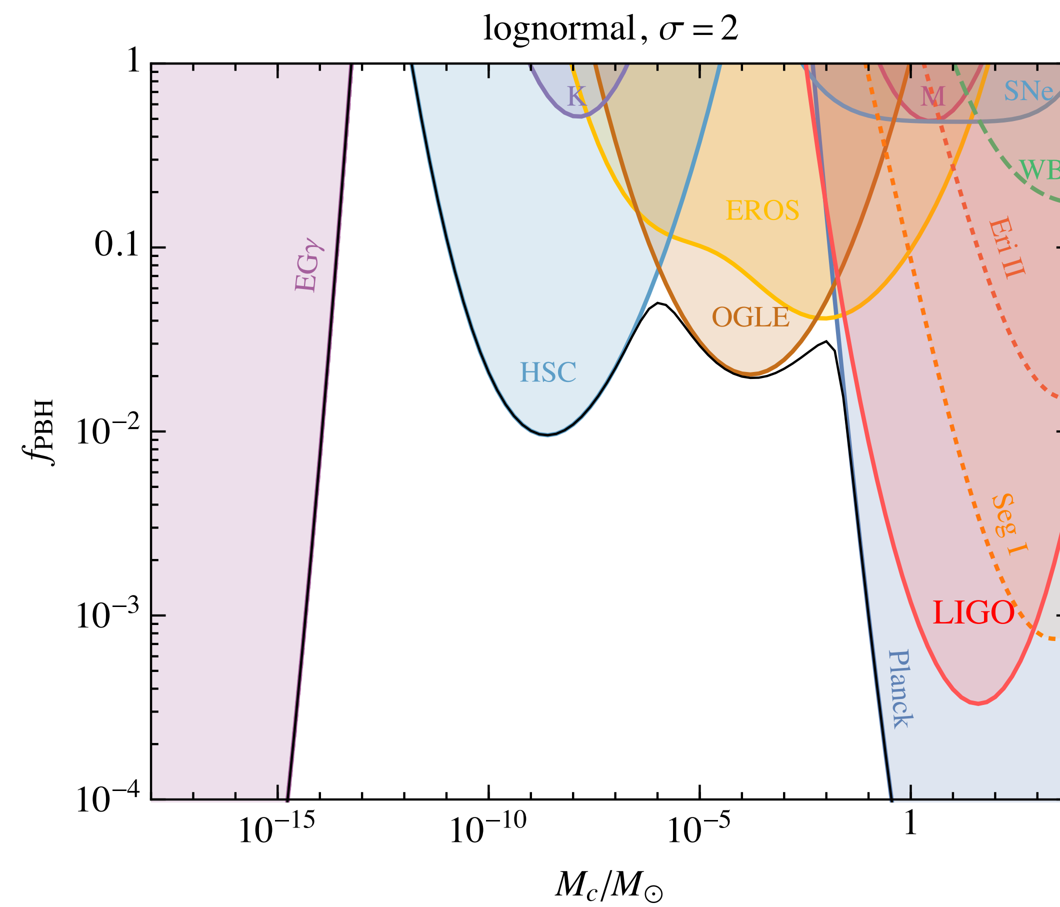
However there is a hard to probe, open window for very light (asteroid mass) PBHs.

For more realistic extended mass functions, constraints on f_{PBH} are smeared out, and gaps between constraints are 'filled in', but 'asteroid mass' window is currently still open even for broad mass functions: Green; Carr et al.; Gorton & Green

monochromatic



log-normal
(fixed width)



$$\frac{M_c}{M_\odot}$$

Carr et al.

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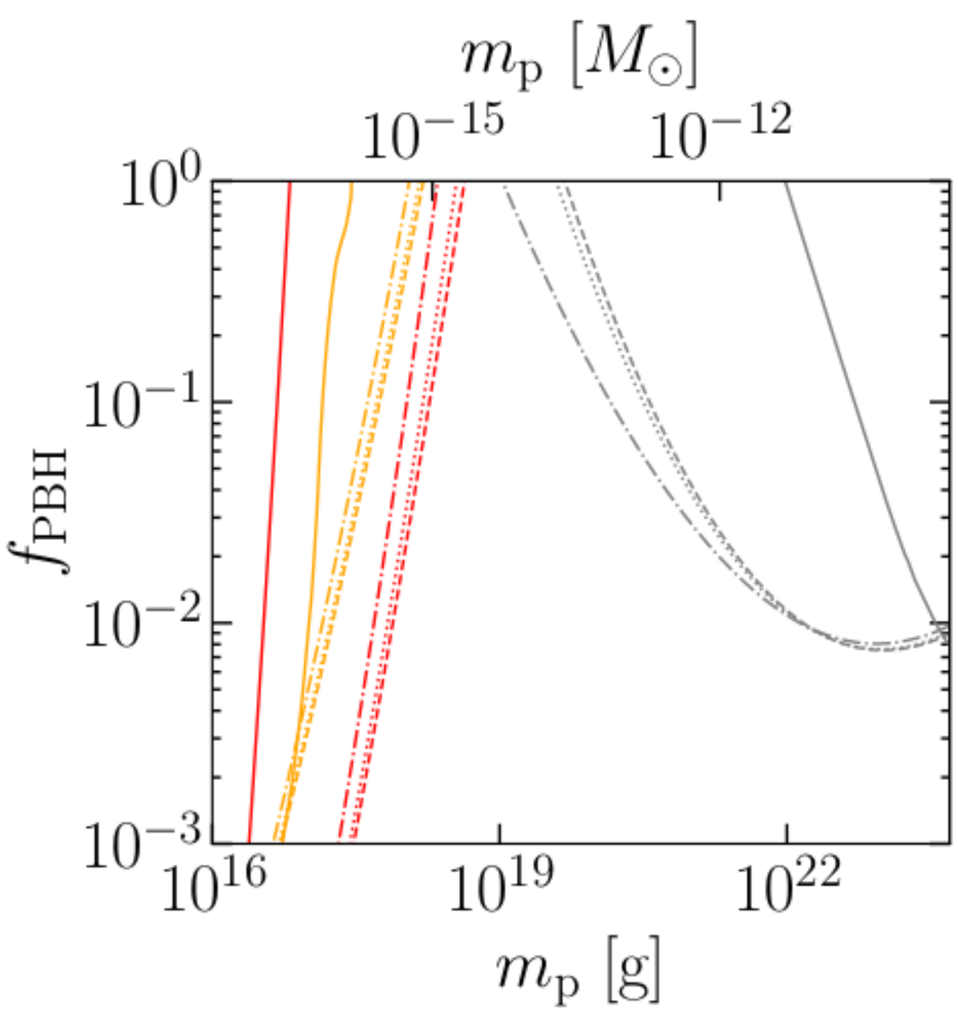
Constraints for the best fit MFs from a broad peak in the power spectrum Gow et al.

____ delta-function, ... lognormal _._._ skew lognormal - - - - generalised critical collapse

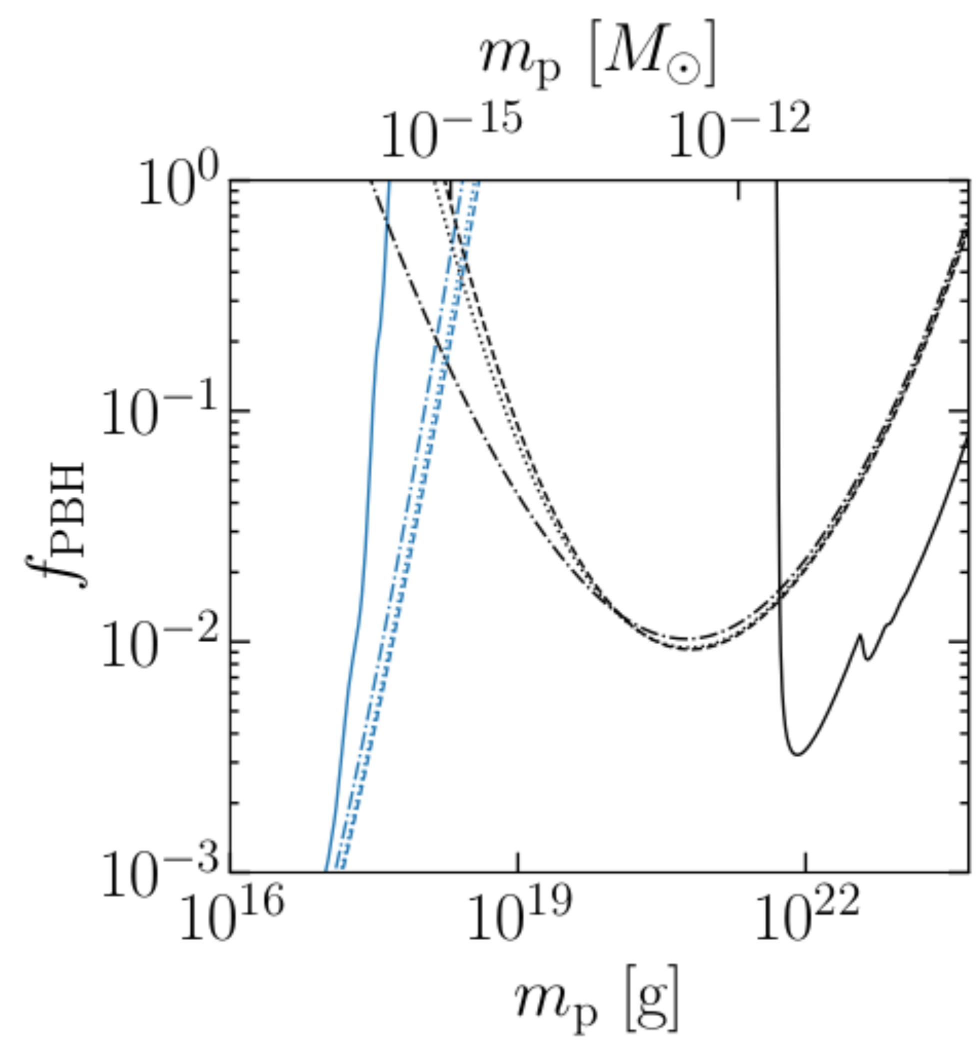
current

Voyager 1 $e^{\pm}$ Boudaud & Cirelli
MeV gamma rays Korwar & Profumo
Subaru-HSC M31 microlensing Niikura et al.; Croon et al.



future

MeV gamma rays Coogan et al.
microlensing LMC white dwarfs Sugiyama et al.



Open questions

i) how to probe asteroid mass PBHs?

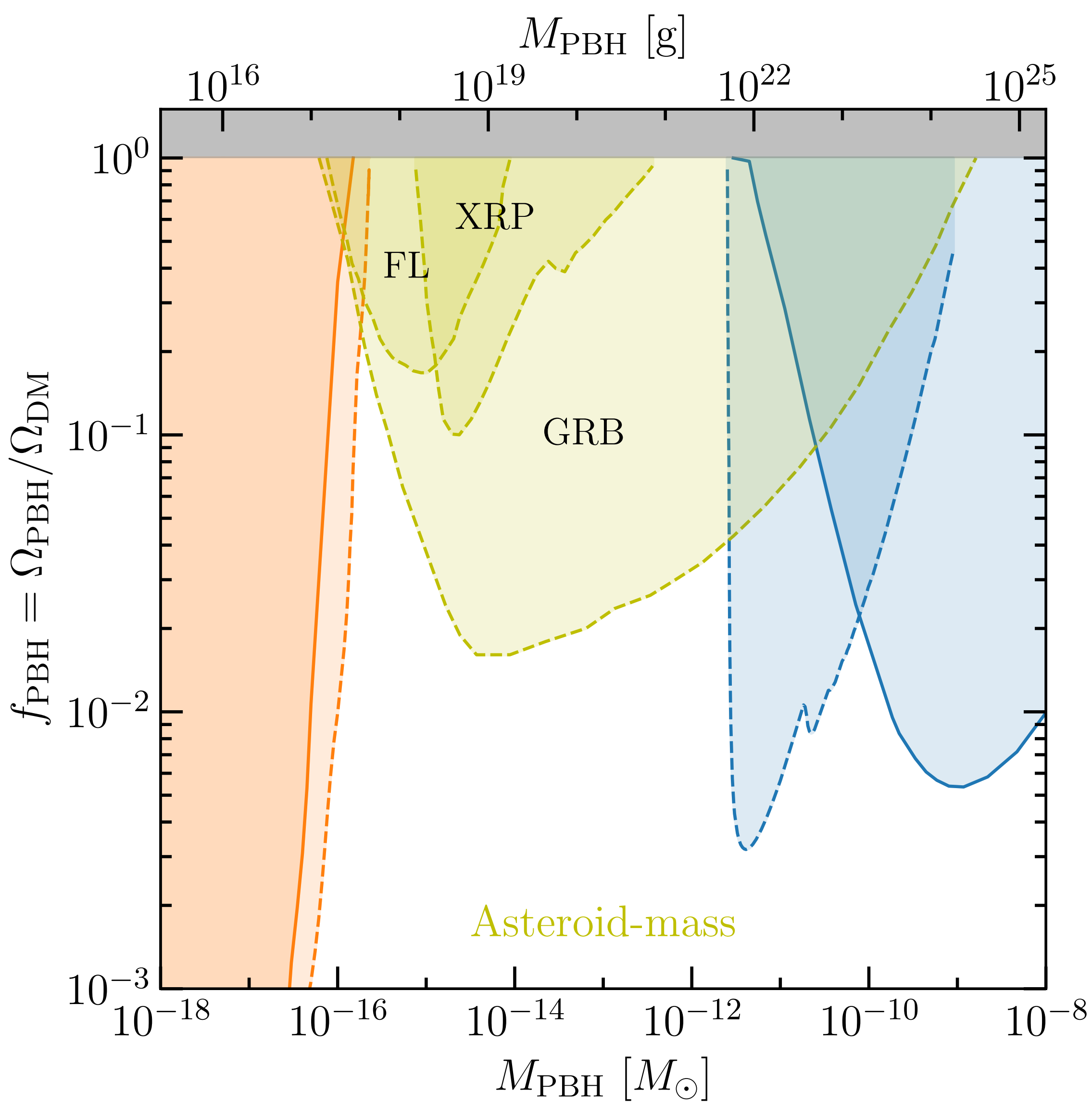
femtolensing of GRBs Gould need small GRBs Katz et al.

GRB lensing parallax Nemiroff & Gould; Jung & Kim

microlensing of X-ray pulsars Bai & Orlofsky

evaporation

future:
MeV gamma rays
Coogan et al.



stellar microlensing

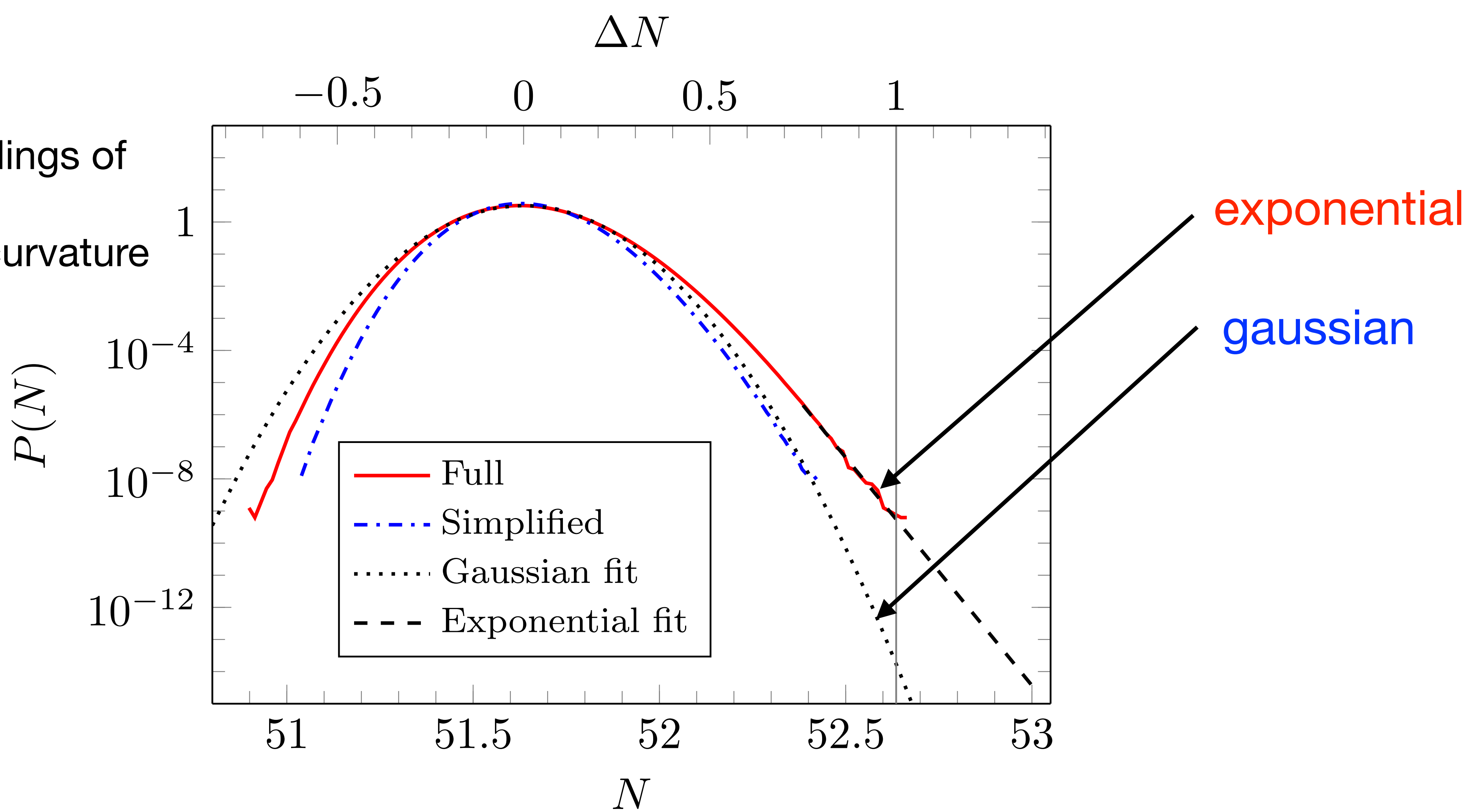
future:
white dwarfs in LMC
Sugiyama et al.

ii) 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



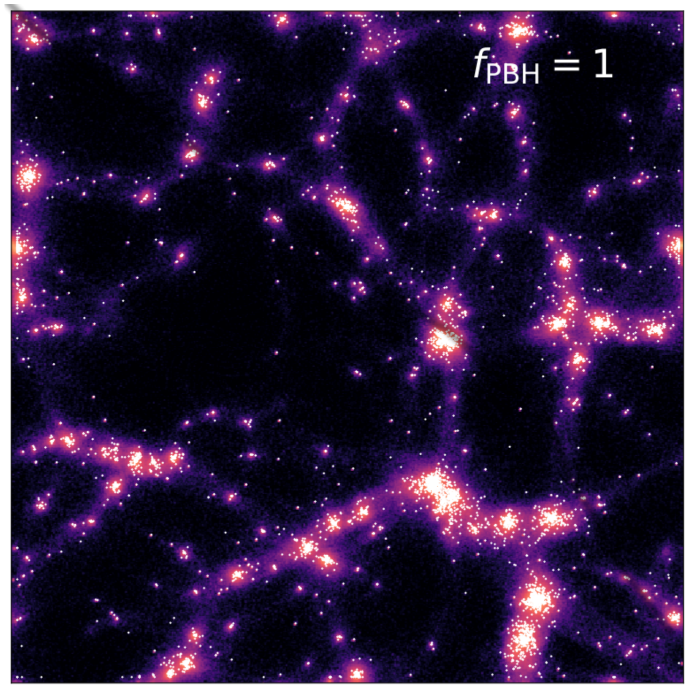
Figueroa et al.

ongoing debate: do large amplitude small scale perturbations lead to significant one-loop corrections to perturbations on CMB scales?
Kristiano & Yokoyama; Firouzjahi & Riotto; Fumagalli; Firouzjahi

iii) clustering

Potentially extremely important (affects PBH binary merger rate and potentially 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



PBH-DM dist at z=100

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….

Clusters of PBH formed from collapse of gaussian density perturbations are sufficiently extended that PBHs microlens individually, & change in **microlensing** constraints is small. Petaĉ, Lavalle & Jedamzik; Gorton & Green.

Non-gaussianity can lead to more compact clusters, however while microlensing constraints would be weakened, other constraints (GWs, Lyman-alpha forest, dynamical) would be tightened. Bringmann et al.; Young & Byrnes; de Luca et al.

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.

- Clustering would weaken some constraints and tighten others.

Open questions: how to probe light PBHs,
perturbations in ultra-slow roll inflation,
clustering…