Dark matter

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1. Evidence, properties and distribution
2. WIMPs: production & direct detection
3. **Primordial Black Holes**

Primordial Black Holes

Motivation/overview

Formation

Constraints

3. Recommended further reading/viewing

- Les Houches Dark Matter Summer School 2021: videos and lecture notes
  - ‘Primordial Black Holes as DM candidate’, Carr & Kuhnel

- Review papers
  - ‘PBHs as dark matter: recent developments’, Carr & Kuhnel, arXiv:2006.02838
  - ‘PBHs as a dark matter candidate’, Green & Kavanagh, arXiv:2007.10722
  - ‘Snomass2001 Cosmic Frontier White Paper: PBH dark matter’, Bird et al., arXiv:2203.08967

- Bradley Kavanagh’s PBH abundance constraint plotting code

  https://github.com/bradkav/PBHbounds

Motivation/overview

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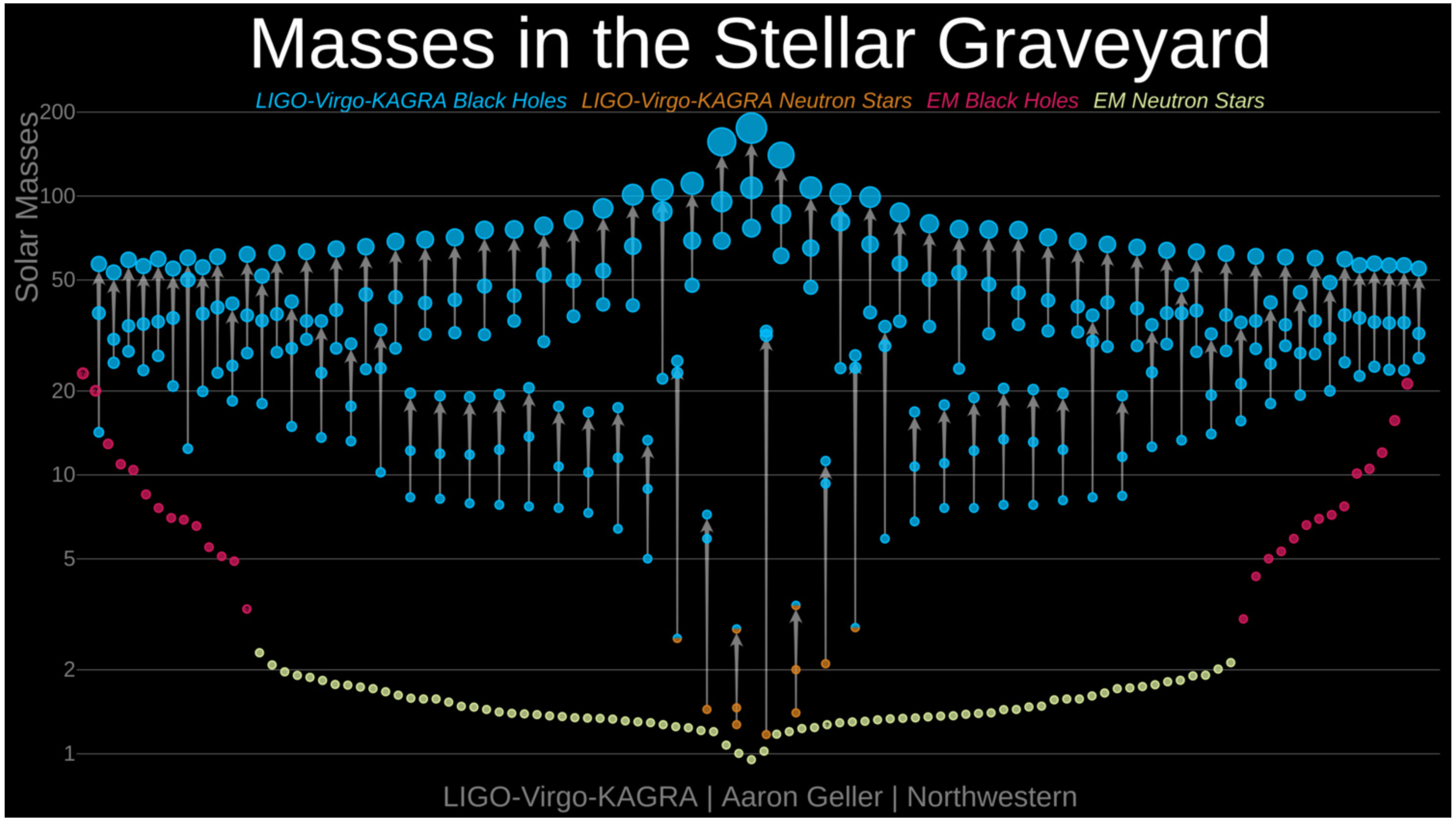
Could (some of) the BHs in the LIGO-Virgo BH binaries be primordial? (and also a significant component of the DM?) Bird et al.; Clesse & Garcia-Bellido; Sasaki et al.

$100 M_\odot$

$10 M_\odot$



black holes discovered by LIGO-Virgo -KAGRA

LIGO-Virgo-KAGRA, Geller

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

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

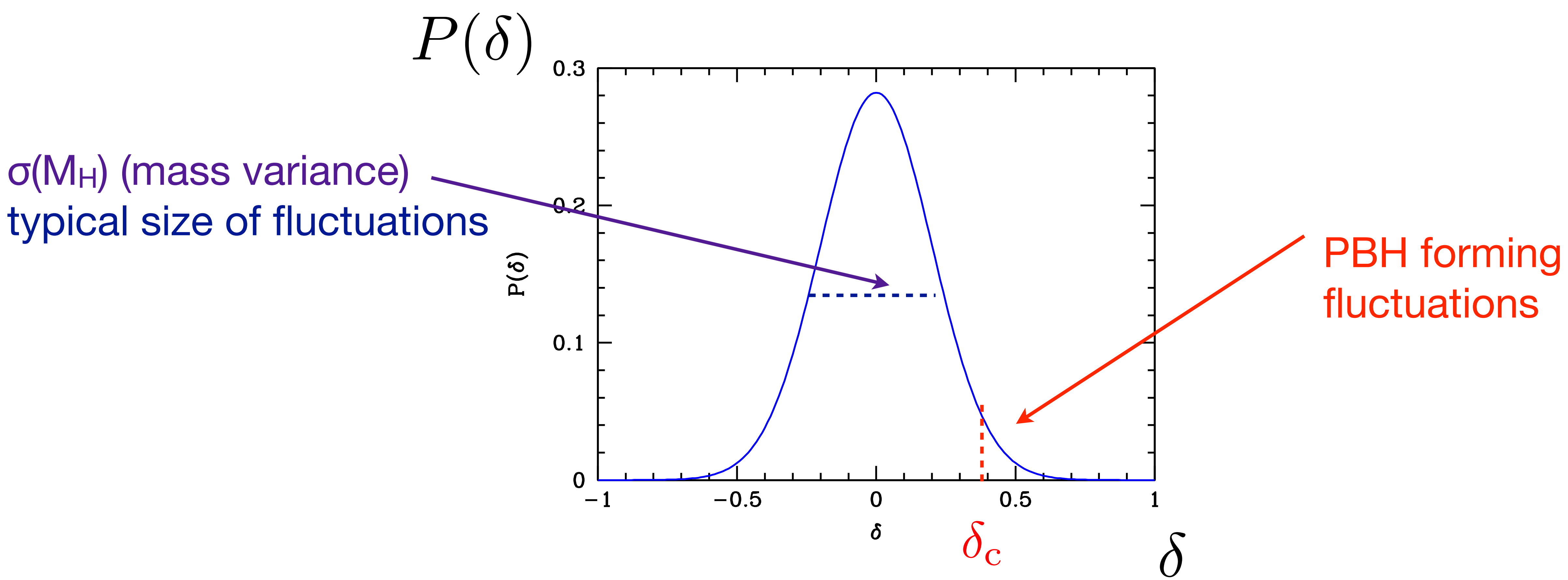
PBH mass roughly equal to horizon mass:

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

initial PBH mass fraction (fraction of universe in regions dense enough to form PBHs):

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

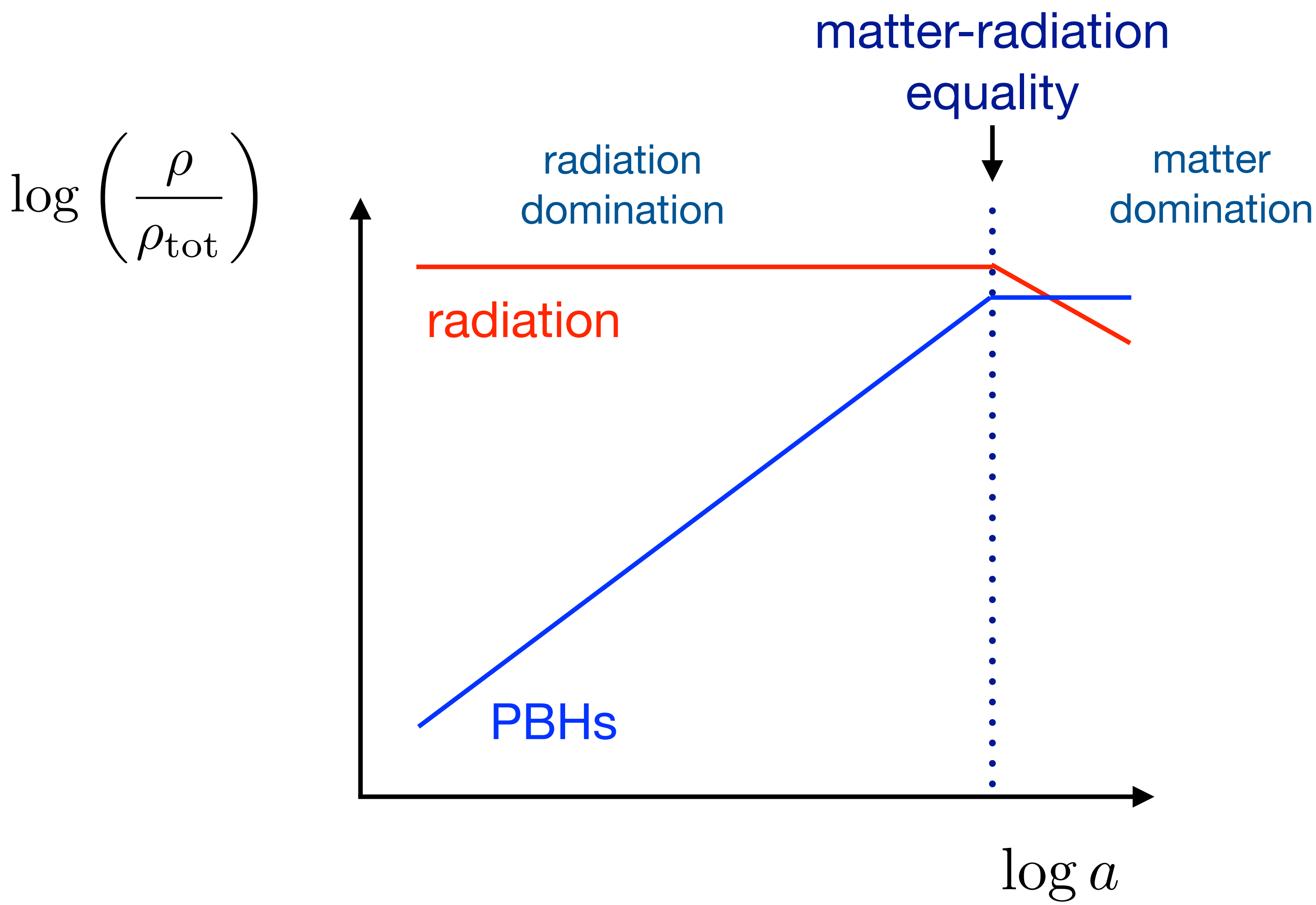
assuming a gaussian probability distribution: $\beta(M) = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M_H)}\right)$



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**:

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

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:

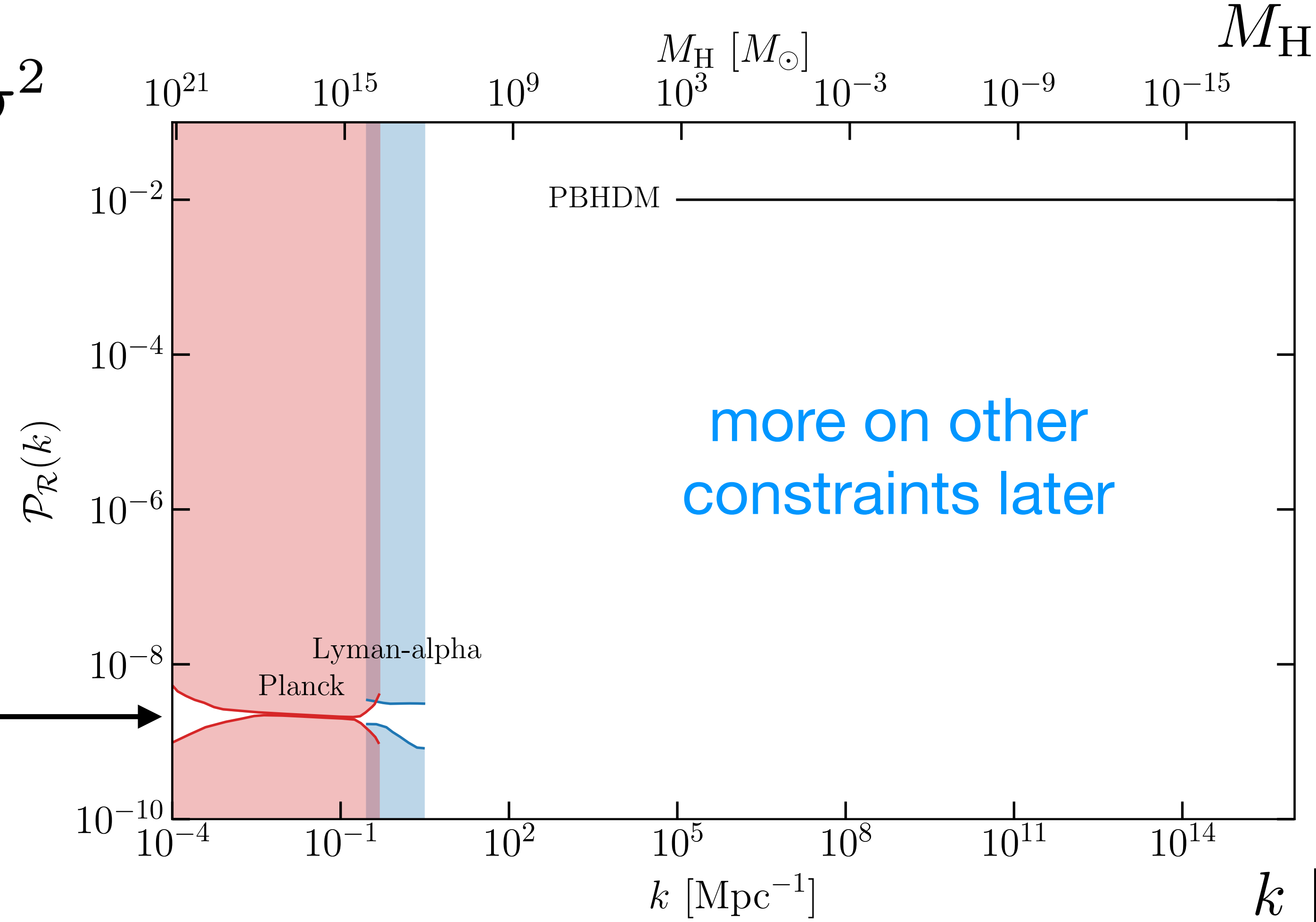
$$\beta(M) = {\rm erfc}\left(\frac{\delta_{\rm c}}{\sqrt{2}\sigma(M_{\rm H})}\right)$$

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

To form an interesting number of PBHs the primordial perturbations must be significantly larger ($\sigma^2(M_{\rm H})$~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

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

Caveats/complications

Threshold for PBH formation:

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

ii) is reduced (so PBH abundance increased) at phase transitions e.g. the QCD phase transition when the horizon mass is ~Solar mass. Jedamzik; Byrnes et al.

Critical collapse: BH mass depends on size of fluctuation it forms from (so even if PBHs all form at the same time/scale, mass function isn't a delta function). Niemeyer & Jedamzik; Musco, Miller & Polnarev

Non-gaussianity: large density perturbations are inevitably non-gaussian Kawasaki & Nakatsuka; De Luca et al.; Young, Musco & Byrnes

changes in the shape of the tail of the probability distribution significantly affect the PBH abundance. Bullock & Primack; Ivanov;… Francolini et al.

Inflation: a brief crash course

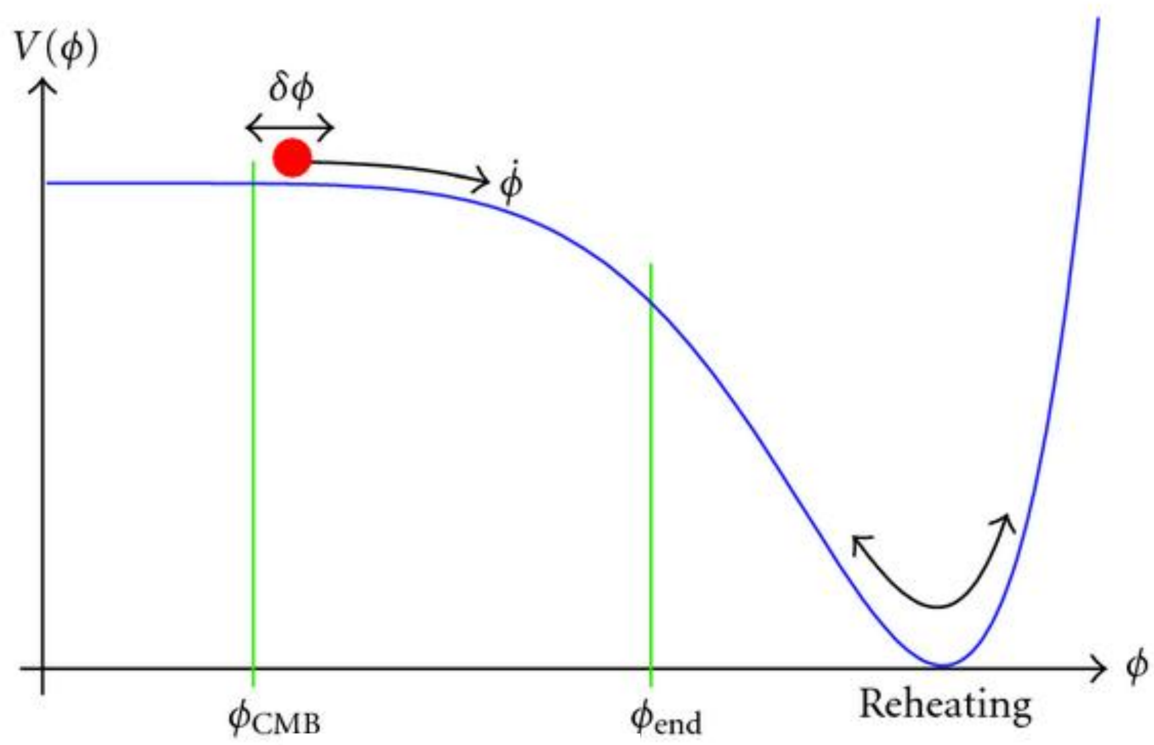
A postulated period of accelerated expansion in the early Universe, proposed to solve various problems with the Big Bang (flatness, horizon & monopole).

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

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

Scales probed by:

Large scale structure & the CMB

Primordial Black Holes

inflation models that produce large perturbations

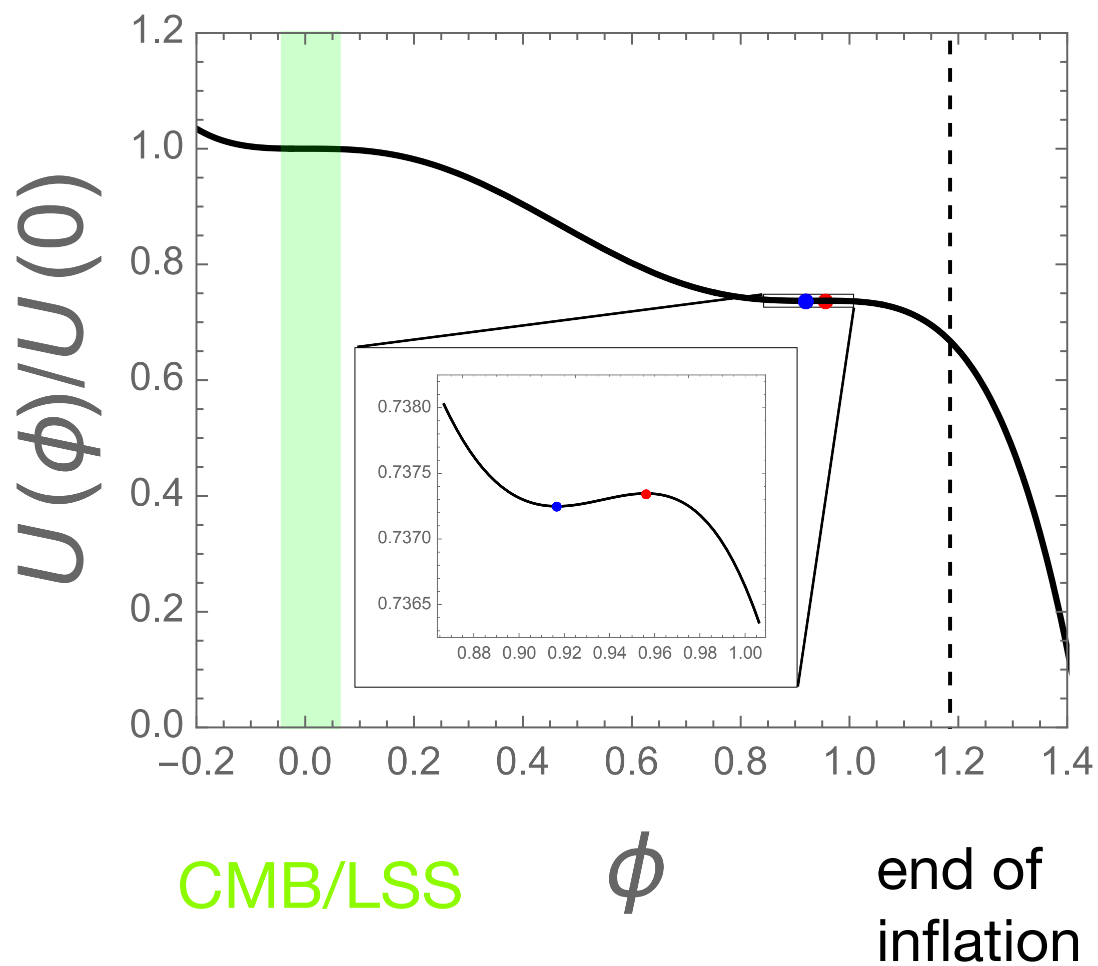
In slow-roll approx: $\sigma \propto V^{3/2}/V'$, but this expression isn't valid in 'ultra-slow-roll' limit, $V' \to 0$ (and USR also affects probability distribution of fluctuations - more later).

single field

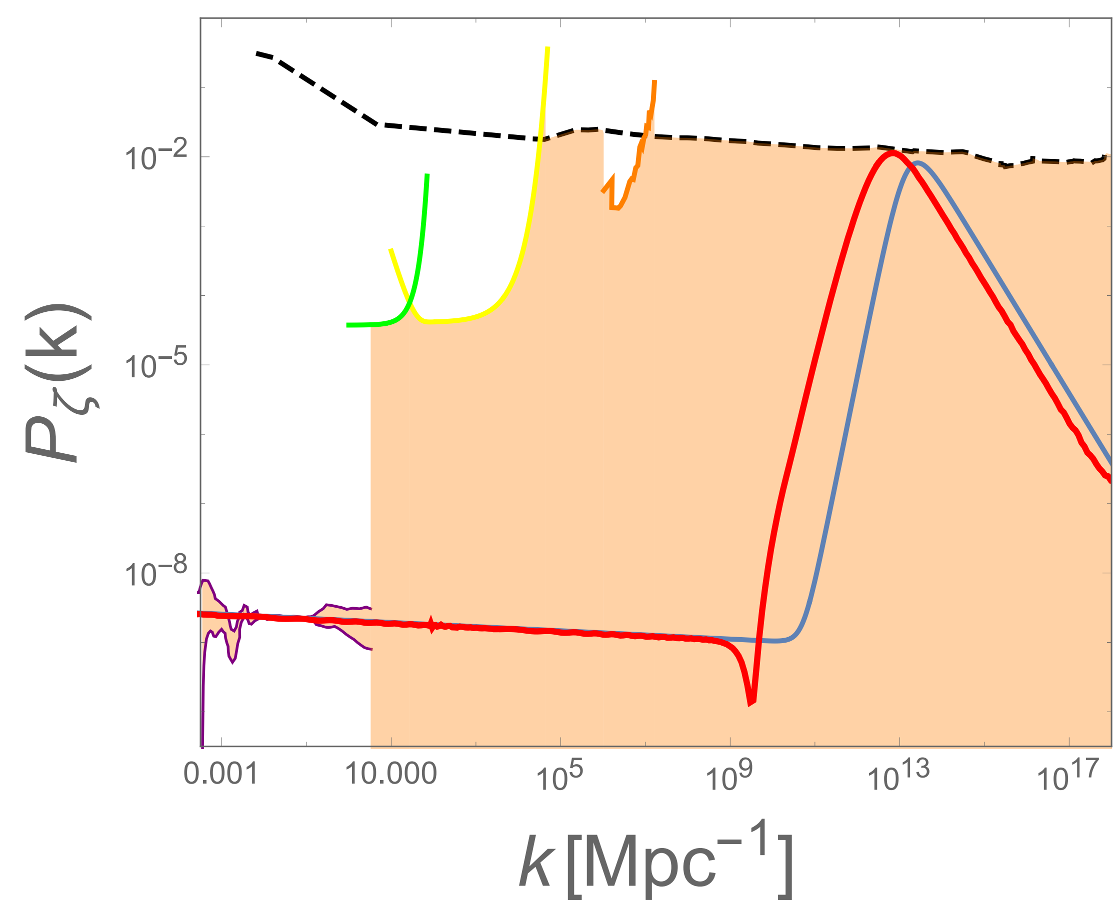
Potential fine-tuned so that field goes past local min, but with reduced speed

Ballesteros & Taoso; Herzberg & Yamada

potential



primordial power spectrum

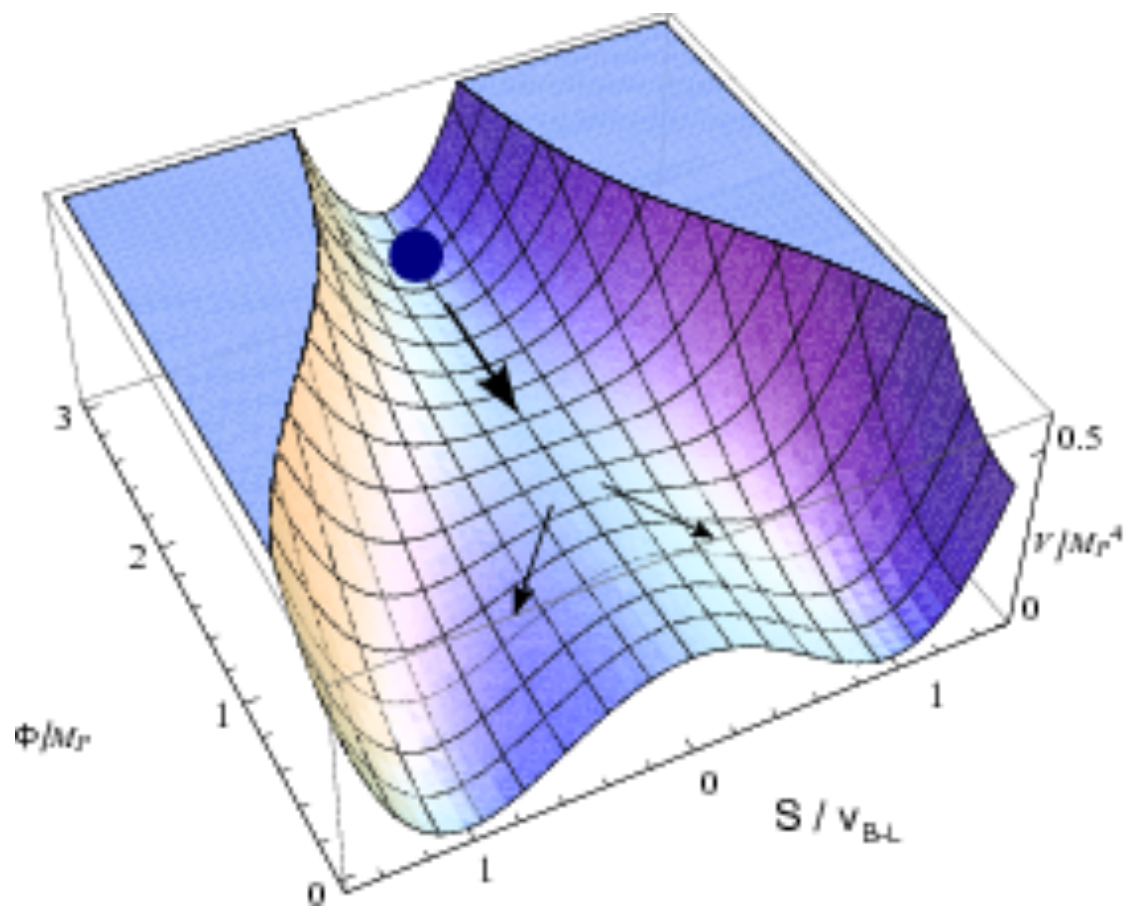


Steepest possible growth ~k^4 Byrnes, Cole & Patil; Carrihlo, Malik & Mulryne

multi-field models

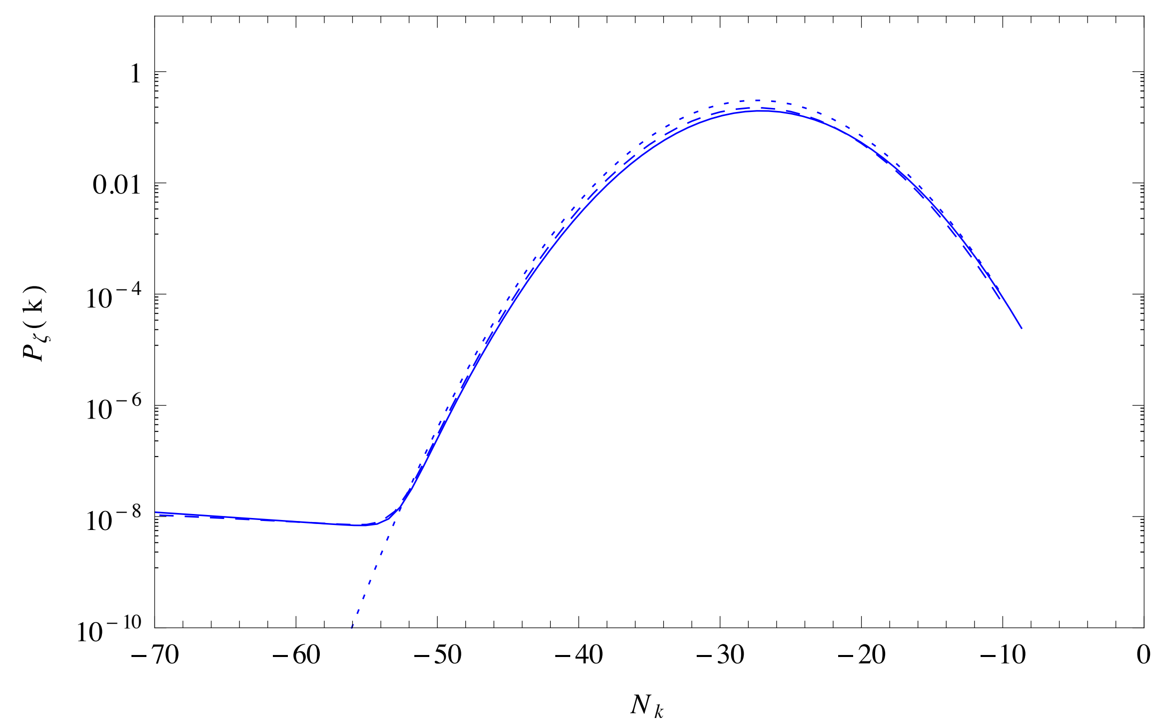
e.g. hybrid inflation with a mild waterfall transition Garcia-Bellido, Linde & Wands

potential



Buchmuller

primordial power spectrum



Clesse & Garcia-Bellido

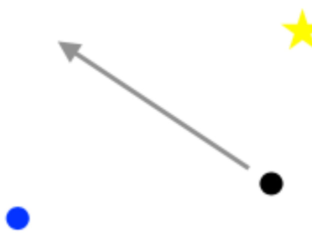
various others

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



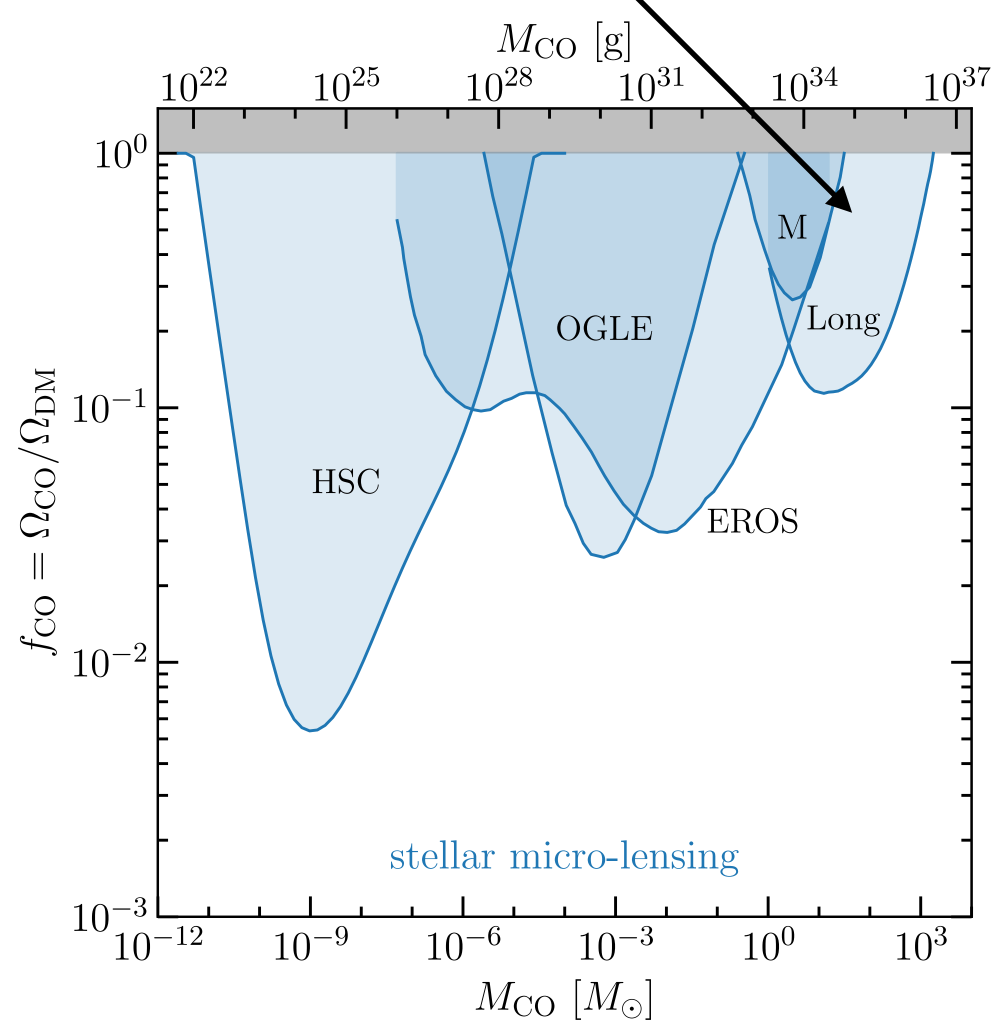
Gravitational lensing where separation of images is micro-arcsecond, too small to resolve, but can detect variations in magnification.

stars: temporarily brightened when compact object ('CO') crosses line of sight

LMC/SMC (MACHO, EROS, OGLE, **combined long duration**), Galactic bulge (OGLE), M31 (HSC, Croon et al.).

fraction of dark matter in form of compact objects

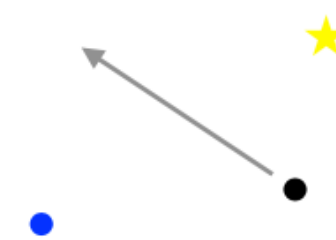
$$f_{\rm CO} = \frac{\Omega_{\rm CO}}{\Omega_{\rm DM}}$$



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 changed Zumalacarregui & Seljak.

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

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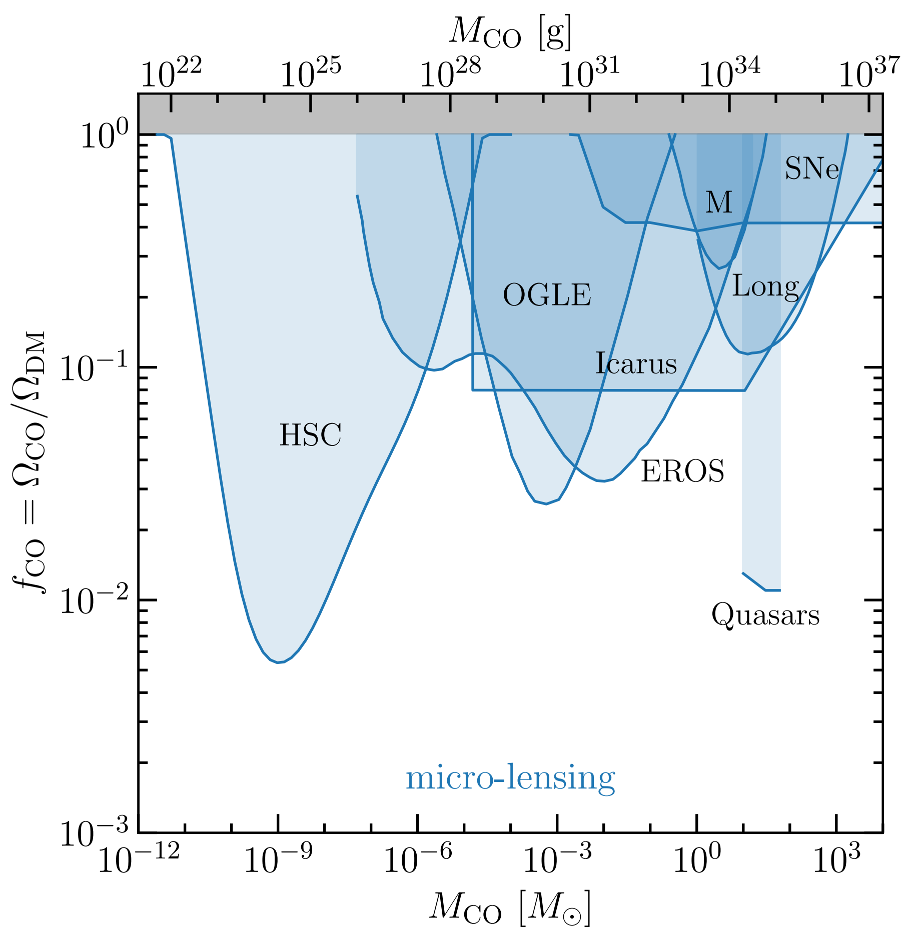


mass in grams

mass in Solar masses

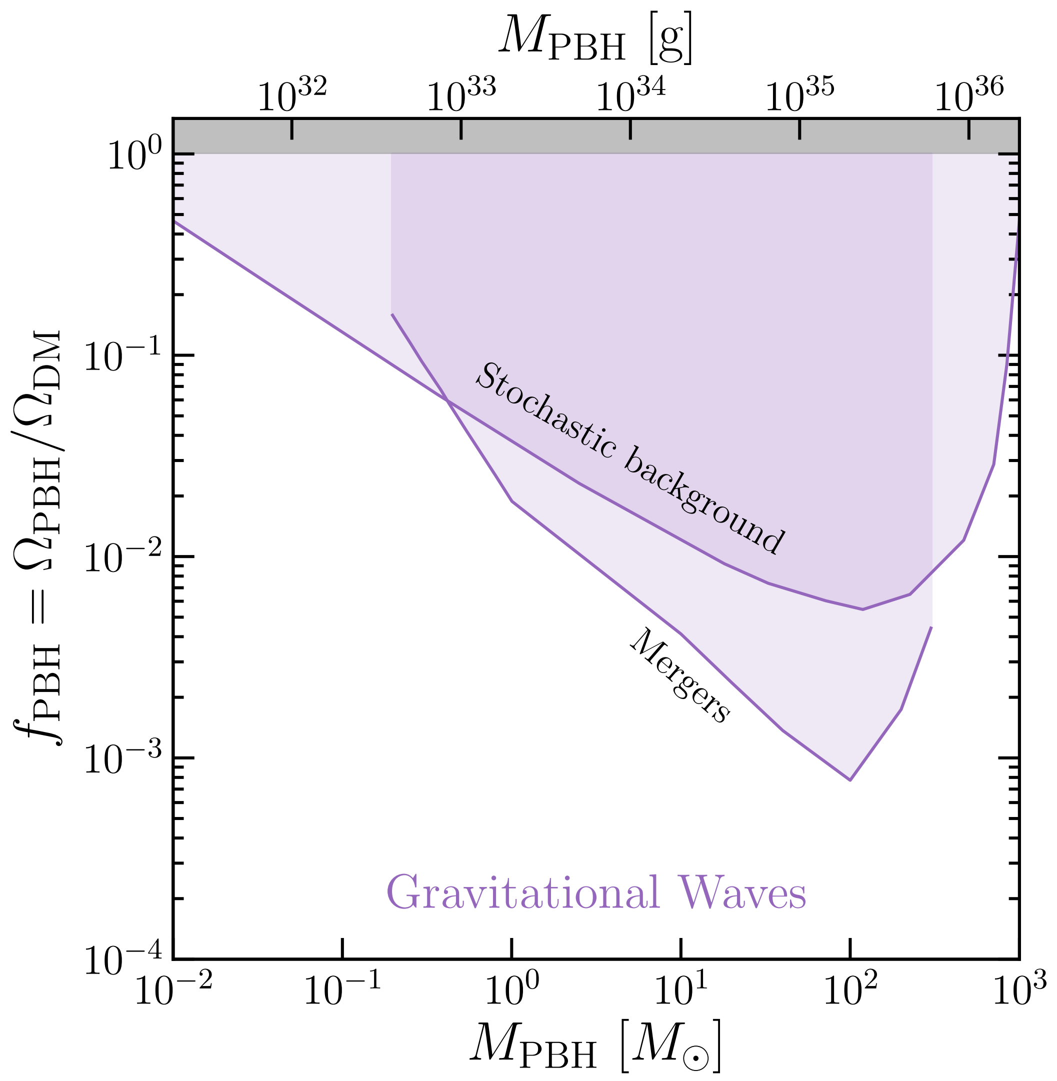
gravitational waves
from PBH-PBH binary mergers

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.

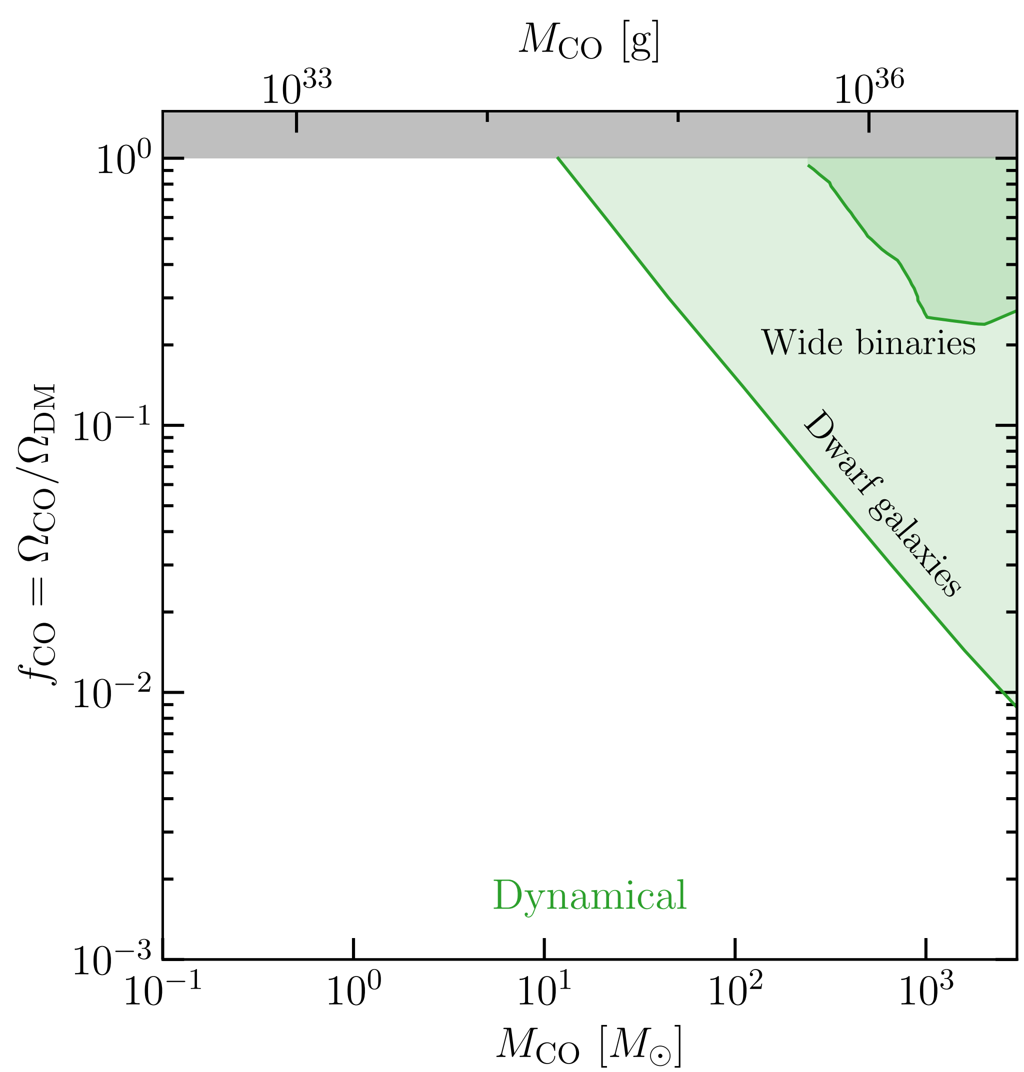
$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$



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; Tyler, Green & Goodwin



accretion

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

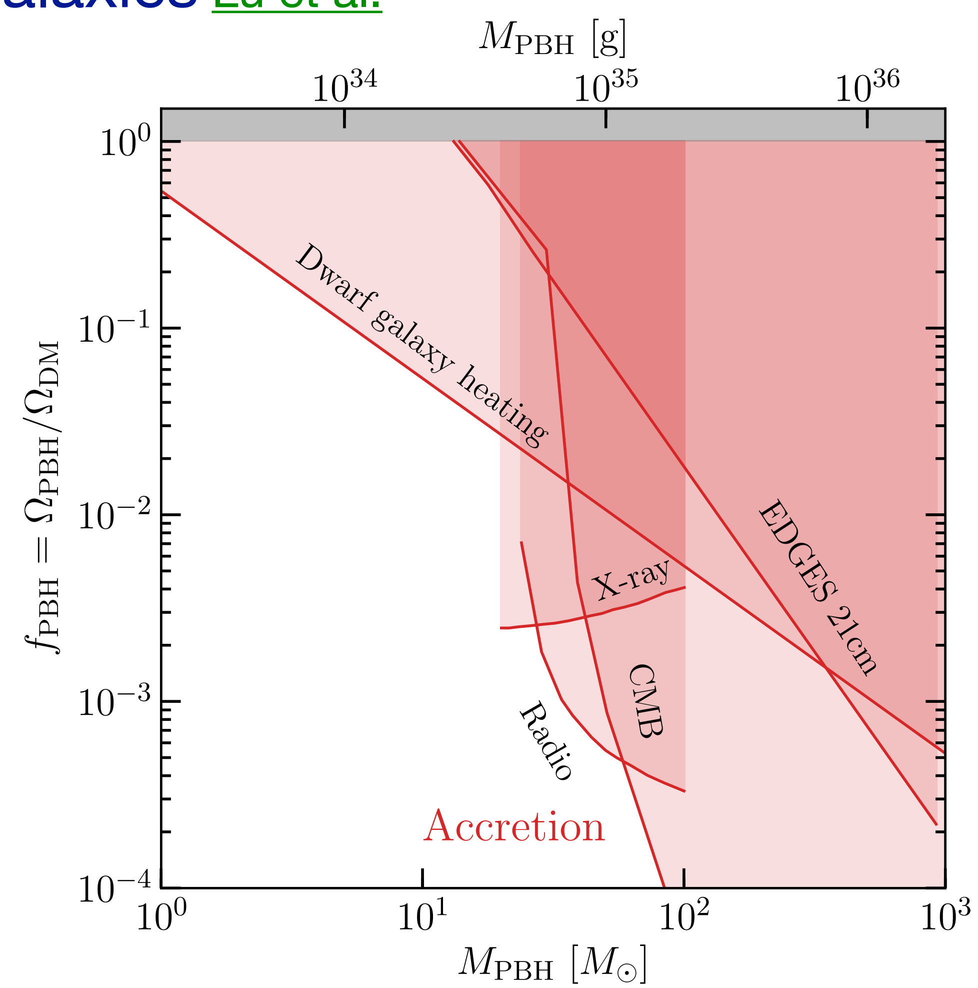
distortion of CMB anisotropies Ricotti et al; Ali-Haïmoud & Kamionkowski; … Poulin et al.…

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.



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

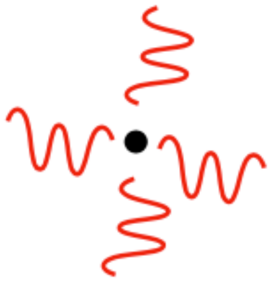
Montero-Camacho et al. **No current constraints**, but potential future constraints from

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

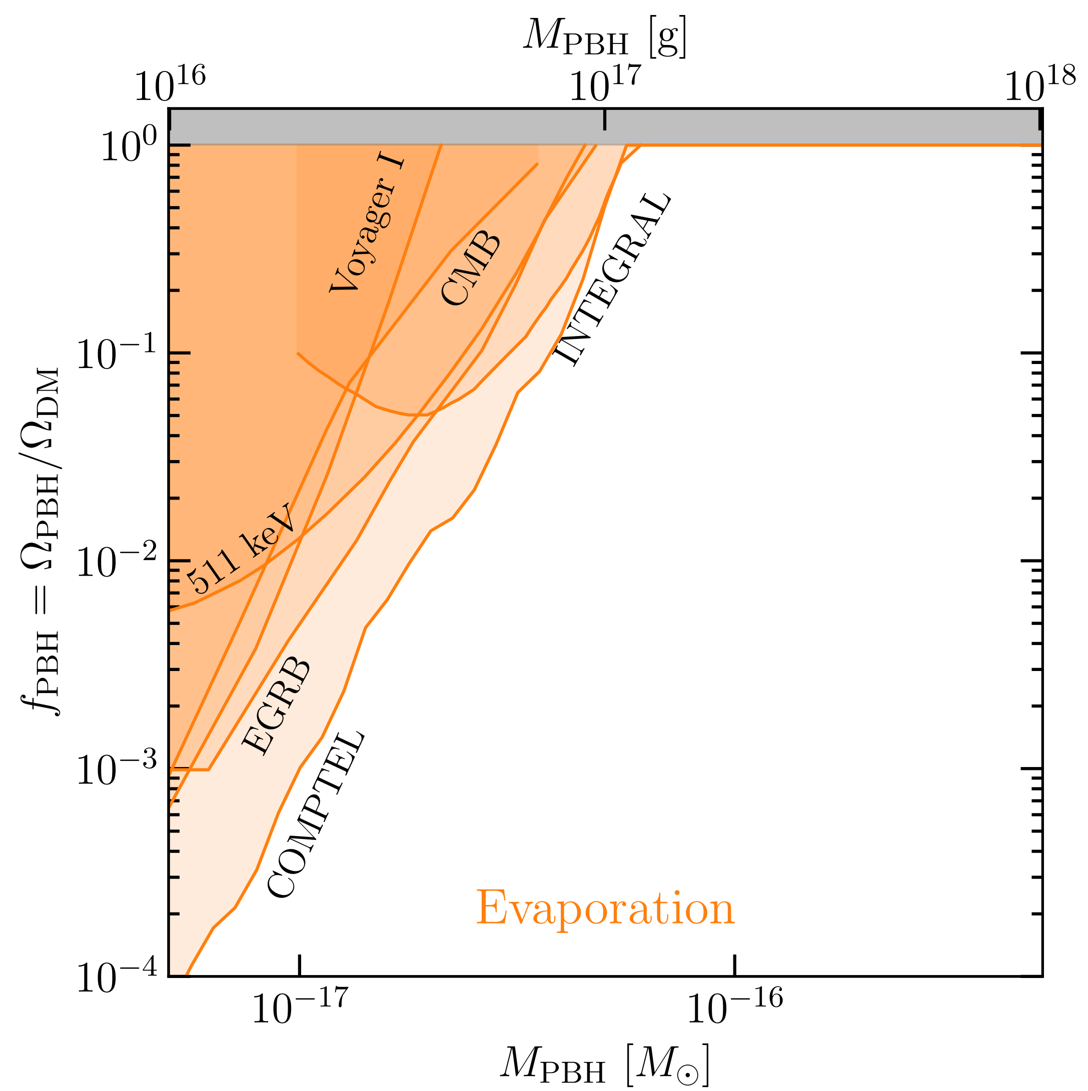
ii) signatures of star being destroyed

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

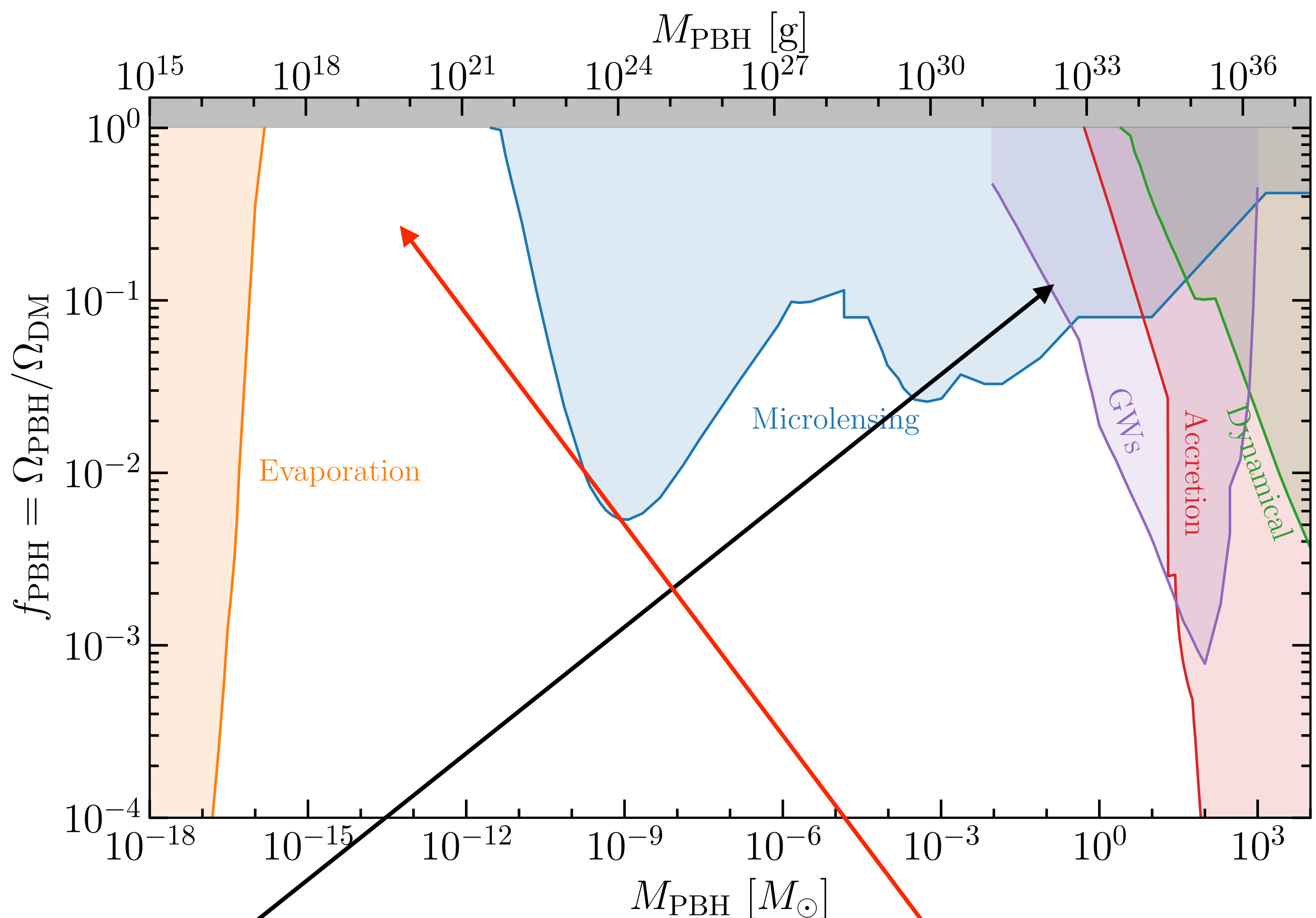


Evaporation products (gamma rays, $e^{\pm}$,…) from PBHs reaching the end of their lifetime would be detectable/have observable consequences.



See also Auffinger review.

Compilation of tightest constraints



evaporation

lensing

GWs

accretion

dynamical

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.

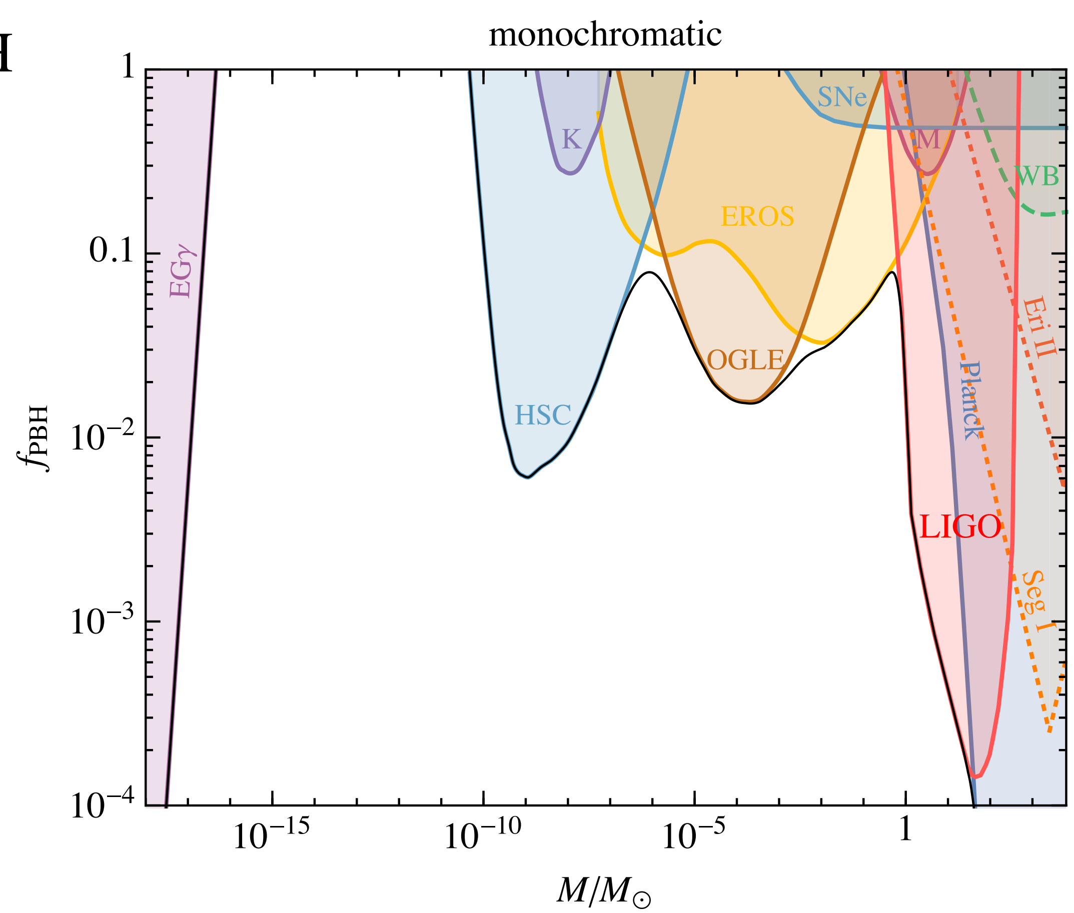
For extended mass functions, constraints on f are smeared out, and gaps between constraints are 'filled in':

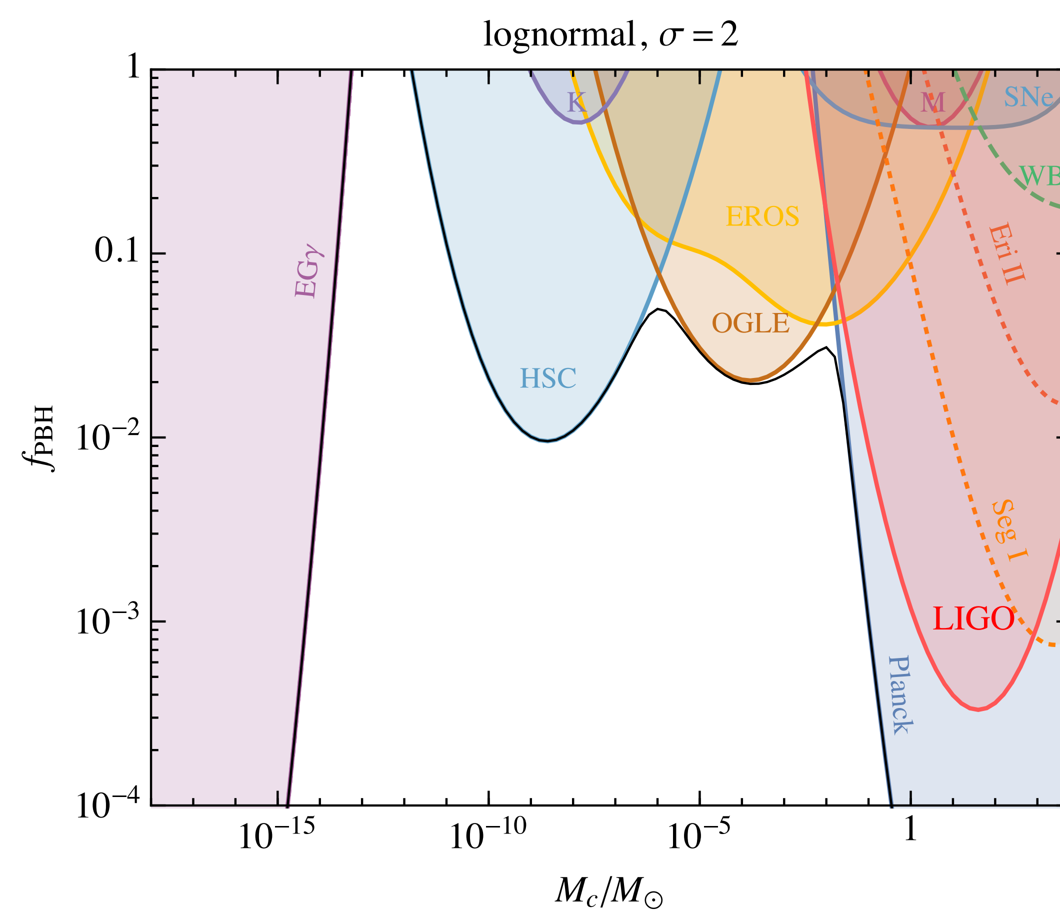
Green; Carr et al.; see also Bellomo et al.

monochromatic

log-normal
(fixed width)

f_{PBH}





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

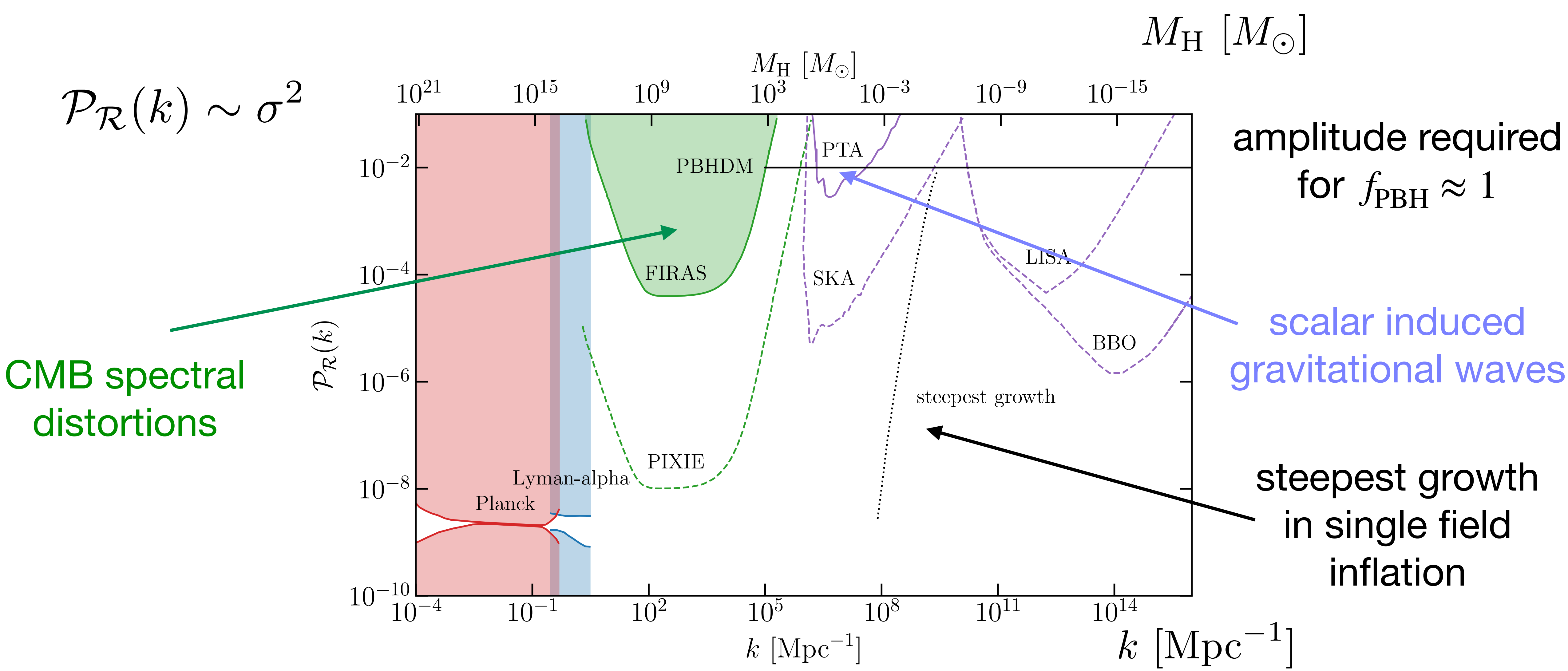
Carr et al.

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

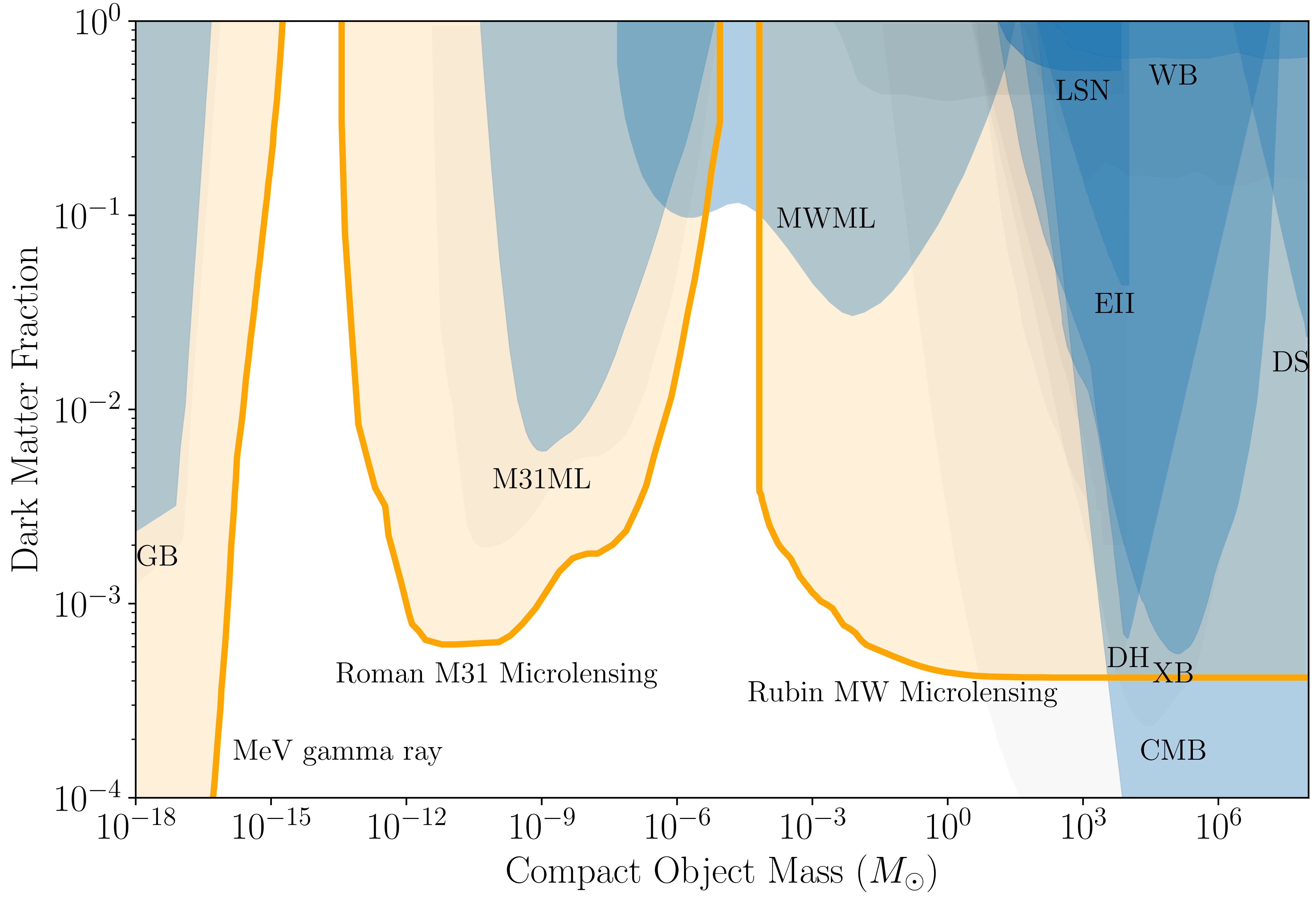
Resulting constraints on amplitude of primordial perturbations therefore constrain abundance of PBHs formed via collapse of large density perturbations. Saito & Yokoyama; Byrnes et al.; Inomata et al.

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



Future constraints

Projected improvement in microlensing and evaporation constraints:



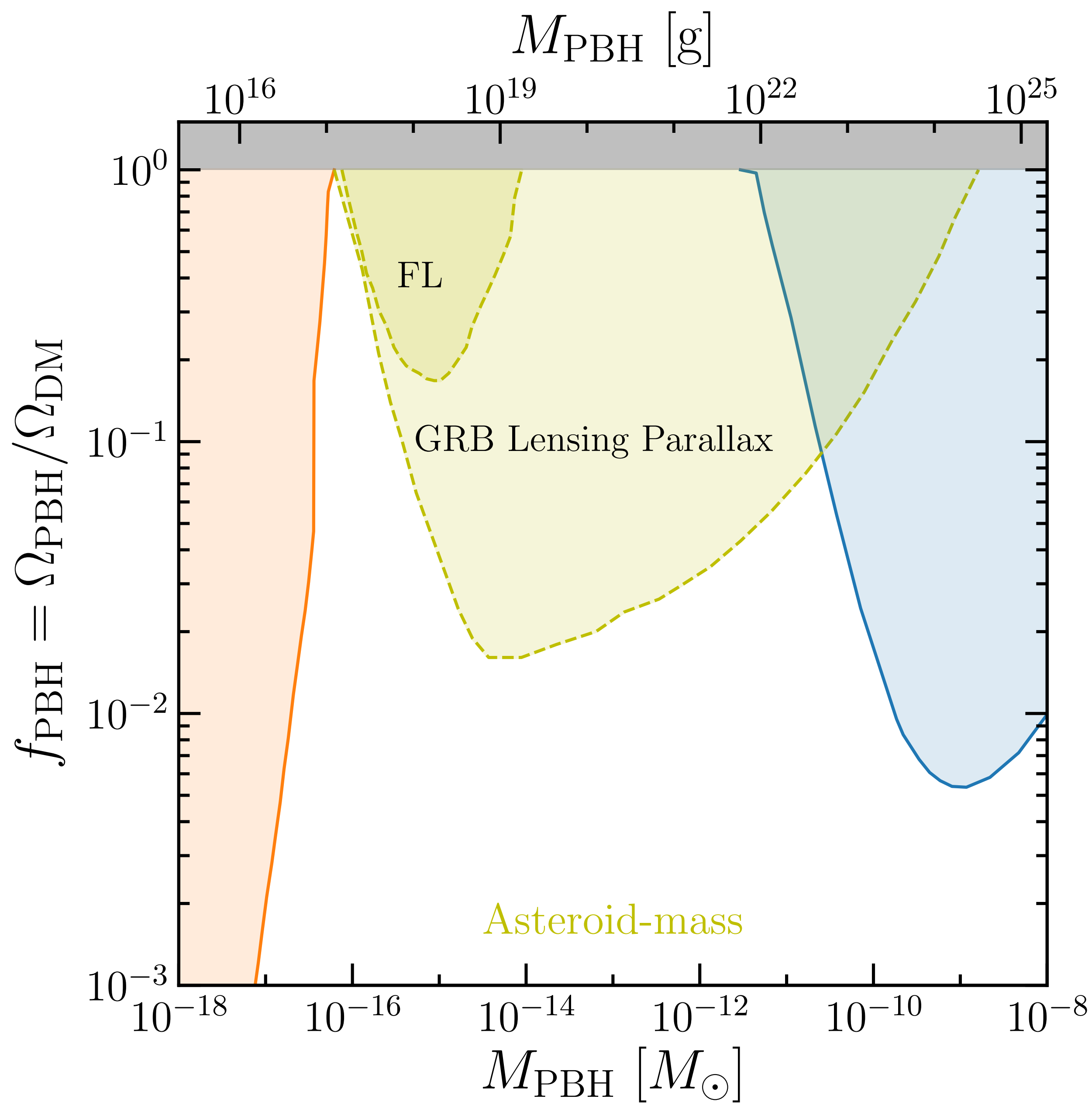
Bird et al.

how to probe asteroid mass PBHs?

femtolensing of GRBs Gould need small GRBs Katz et al.

GRB lensing parallax Nemiroff & Gould; Jung & Kim

disruption of main sequence stars in dwarf galaxies during star formation Esser & Tinyakov



Summary: 3 Primordial Black Holes

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

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