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Primordial black hole formation

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1. Primordial fluctuations
2. False vacuum domains

Motivation

1. DM in the asteroid mass PBHs

   see e.g. Carr et al. Rept. Prog. Phys. 84 (2021)

2. LIGO-Virgo GW events

   Bird et al. PRL 116 (2016); Sasaki et al. PRL 117 (2016); Clesse & Garcia-Bellido Phys. Dark U. 15 (2017); Hall et al. PRD 102 (2020); Hütsi et al. JCAP 03 (2021); Franciolini et al. PRD 105 (2022)

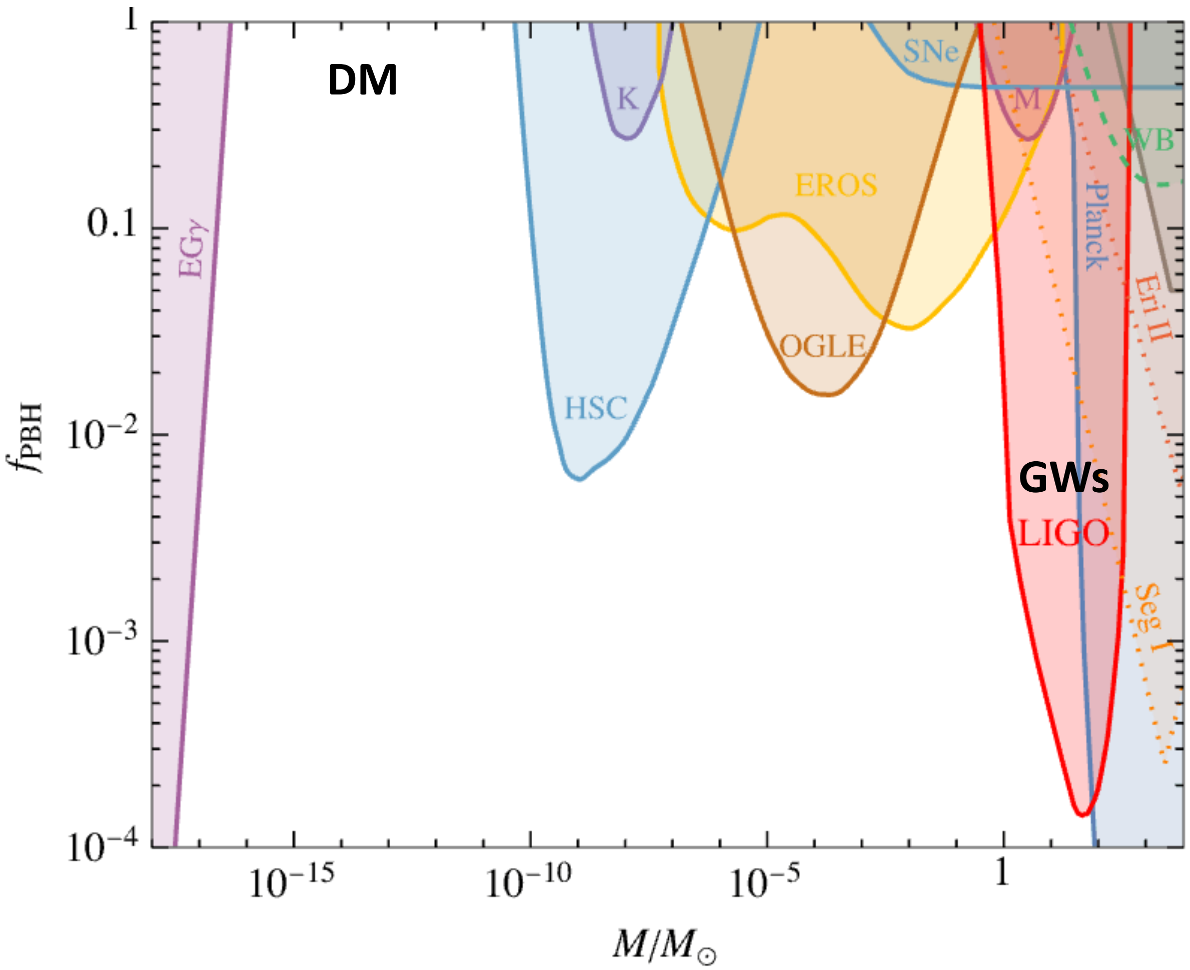
3. Seeds for cosmic structures

   Carr & Silk ApJ 268 (1983); Freese et al. ApJ 275 (1983); Carr & Silk MNRAS 478 (2018); Liu & Bromm ApJ Lett. 937 (2022); Hütsi et al. PRD 107 (2023)

4. DM and baryogenesis from PBH evaporation

   Fujita et al., PRD 89 (2014); Allahverdi et al. PRD 97 (2018); Lennon et al. JCAP 04 (2018); Hooper et al. JHEP 08 (2019); Masina EPJ+ 135 (2020); Baldes et al. JCAP 08 (2020)

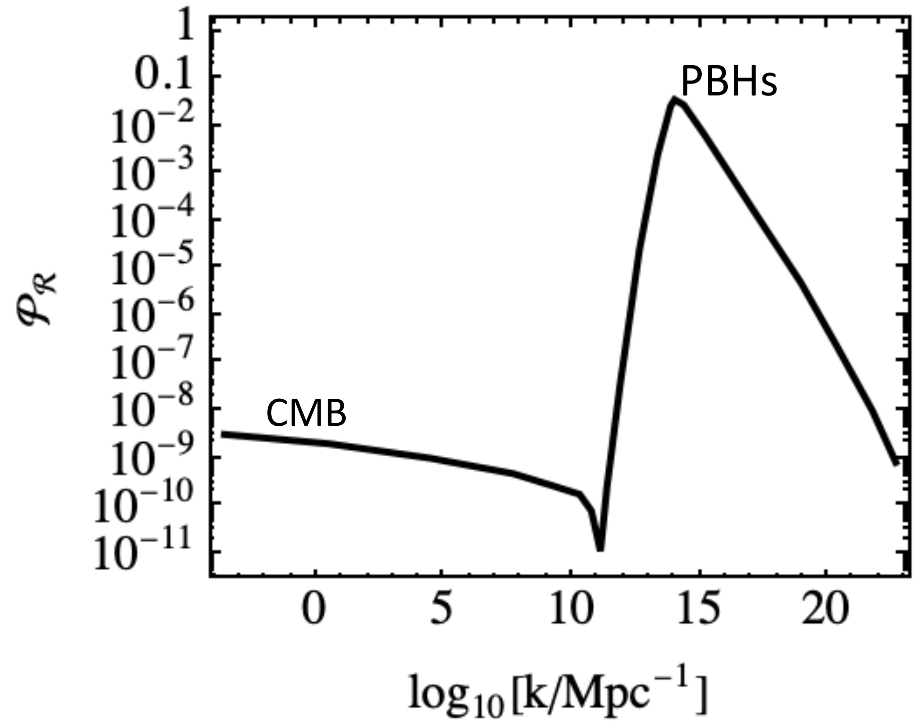
PBH constraints: talk by G. Franciolini

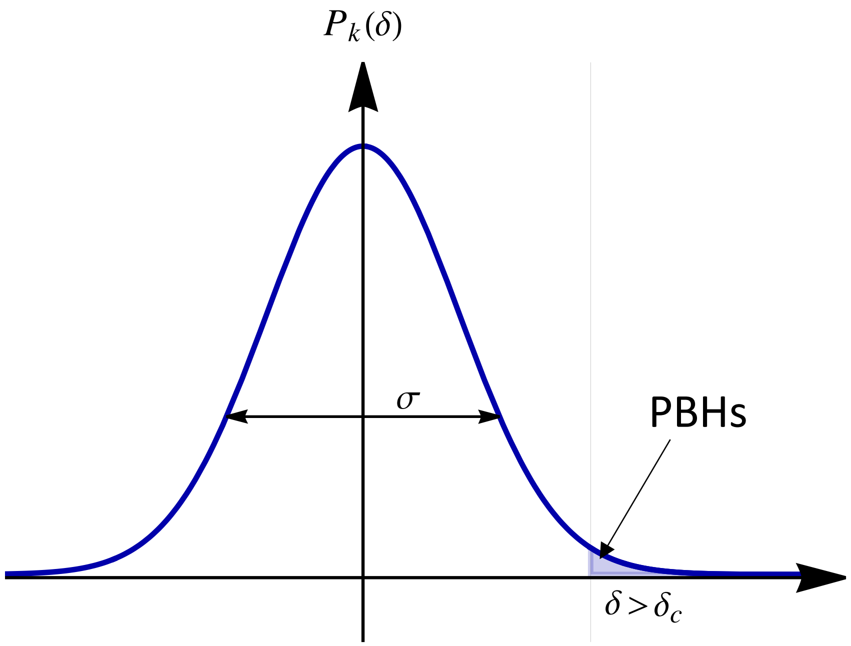


Primordial fluctuations

PBH formation from large primordial fluctuations

Large fluctuations collapse against the fluid pressure to BHs at horizon reentry.





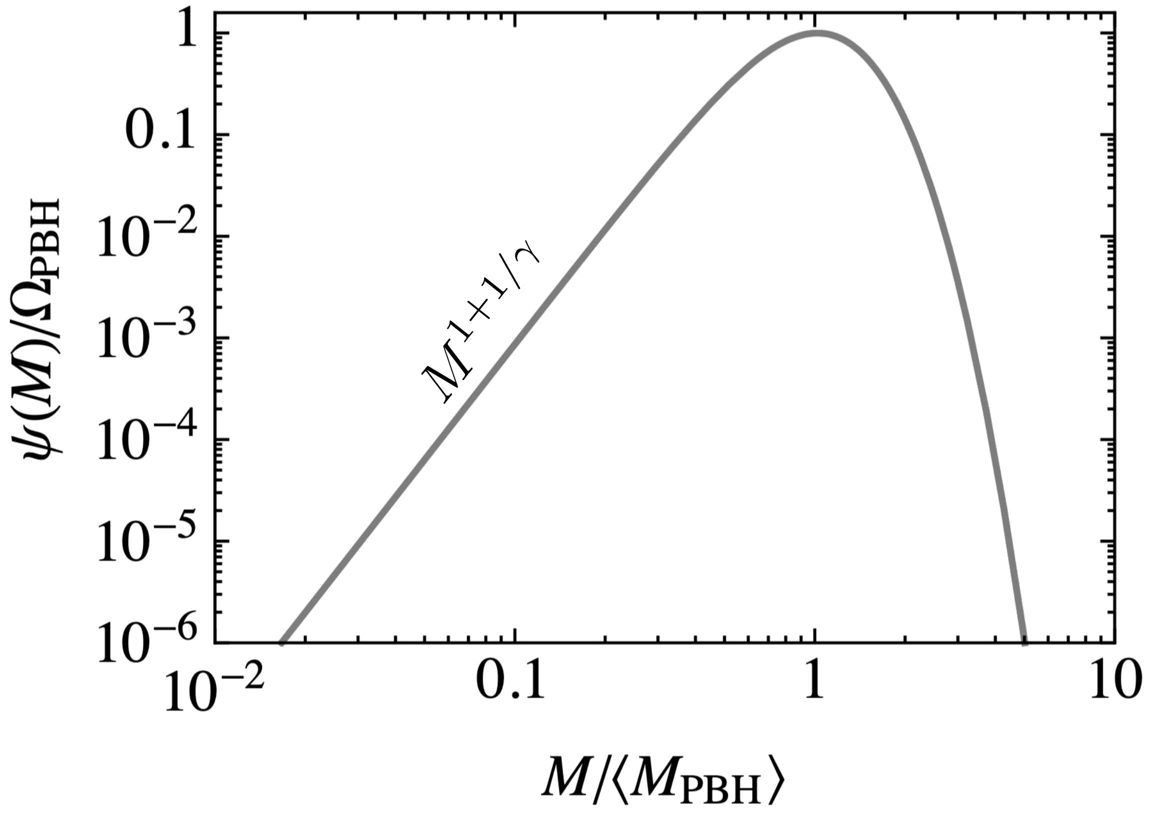
B. J. Carr, ApJ 201 (1975): $\delta_c \approx 0.3$, numerical simulations: $\delta_c \approx 0.5$.

PBH mass distribution

Mass determined by the critical collapse [Niemeyer & Jedamzik, PRL 80 (1998)]:

$$M(\delta) = \kappa M_H (\delta - \delta_c)^\gamma$$

horizon mass at reentry



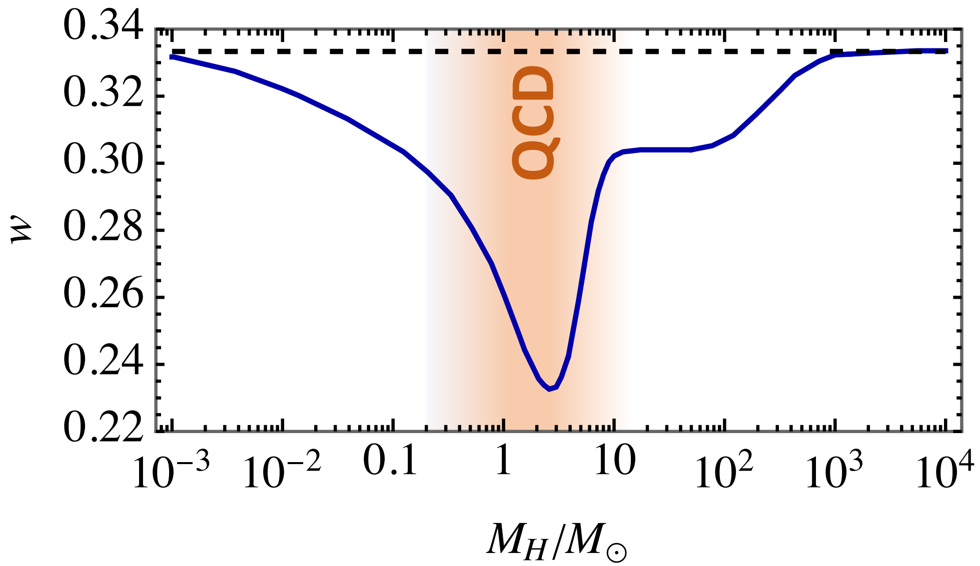
κ, γ and δ_c depend on the profile of the overdensity [Musco, PRD 100 (2019)] and the equation of state [Musco et al., 2303.07980].

Softening of the equation of state

Collapse threshold decreases due to smaller pressure
[Harada et al., PRD 88 (2013)]:

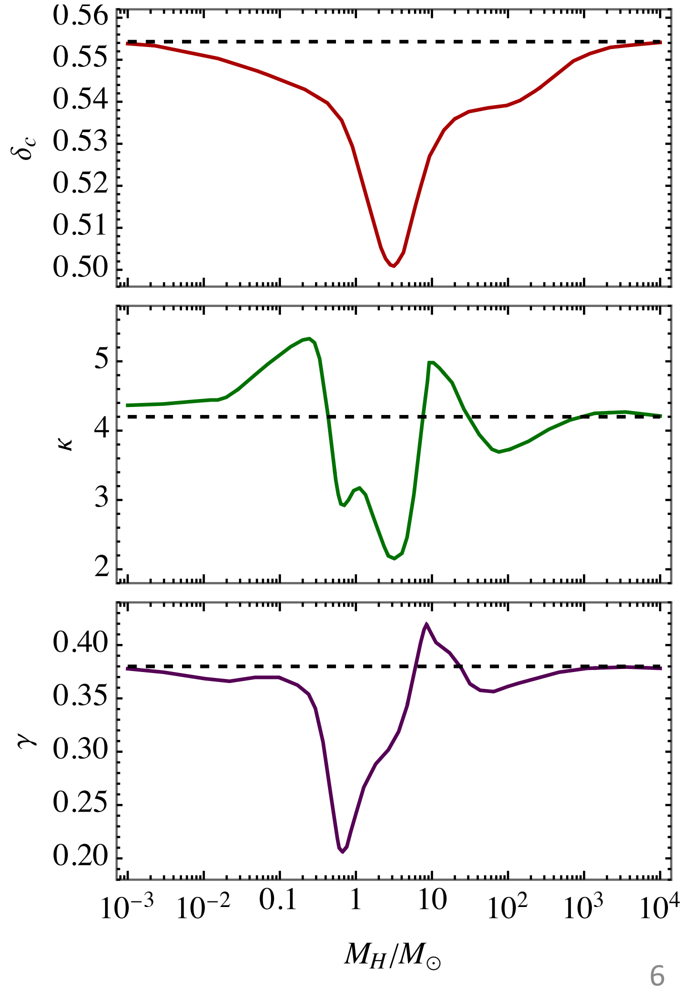
$$\delta_c \approx \frac{3(1+w)}{5+3w}\sin^2\left[\frac{\pi\sqrt{w}}{1+3w}\right]$$

$w < 1/3$ in particular across the QCD phase transition
⇒ boosts formation of solar mass PBHs.



$$M(\delta) = \kappa M_H(\delta-\delta_c)^\gamma$$

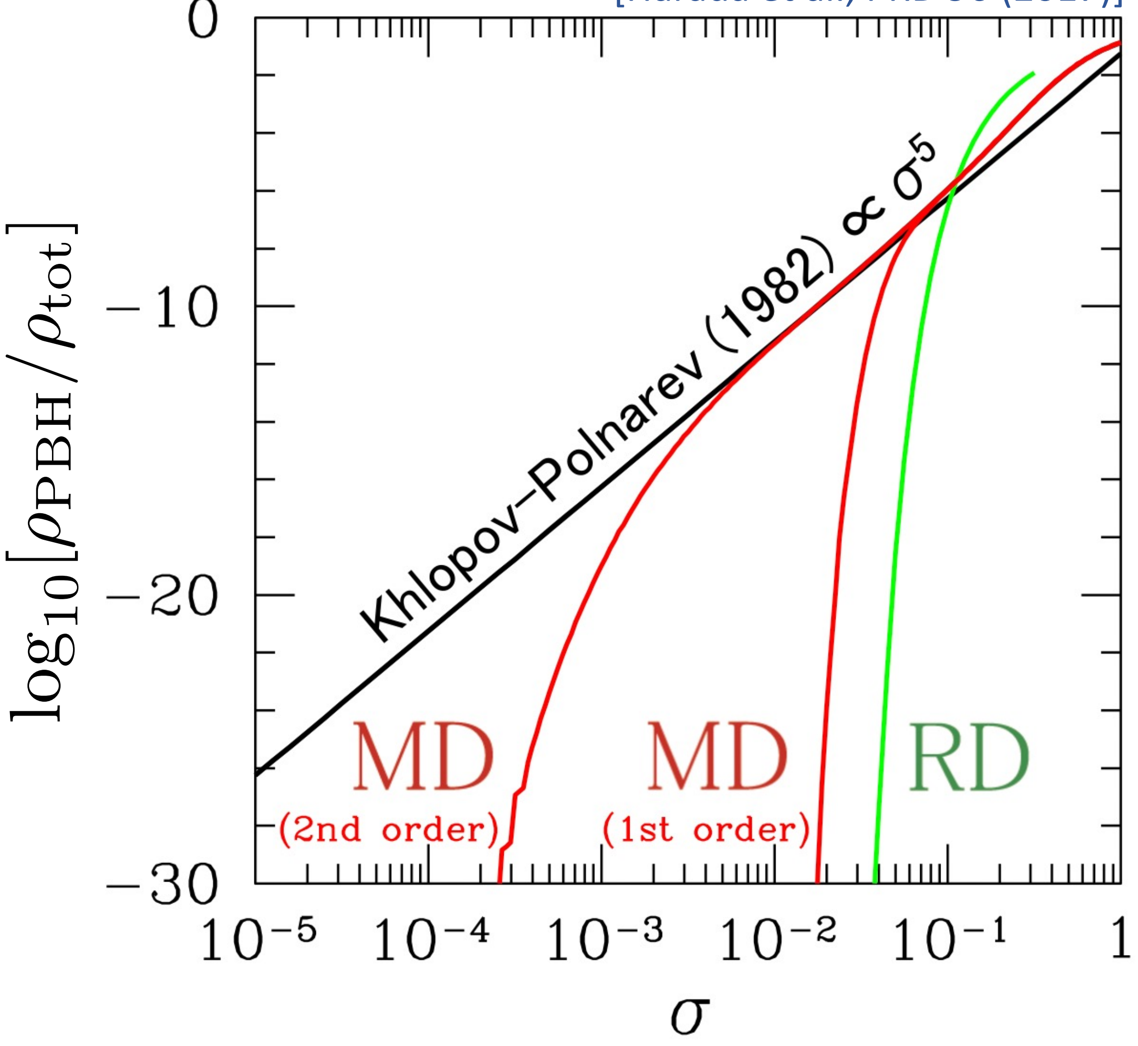
[Franciolini et al. PRD 106 (2022)]



Early matter-dominated epoch

- EMD: $p = 0$ and density contrast grows linearly inside horizon.
- Angular momentum of the collapsing mass grows suppresses PBH formation.
- PBHs formed in MD are typically rapidly rotating.

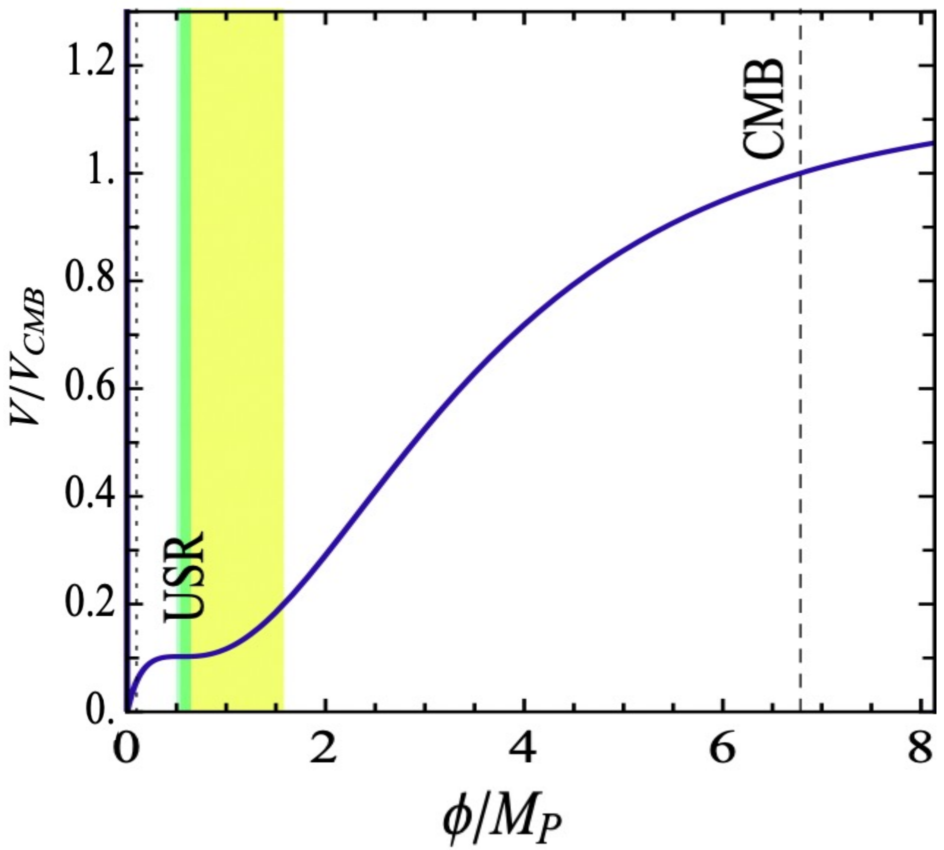
[Harada et al., PRD 96 (2017)]

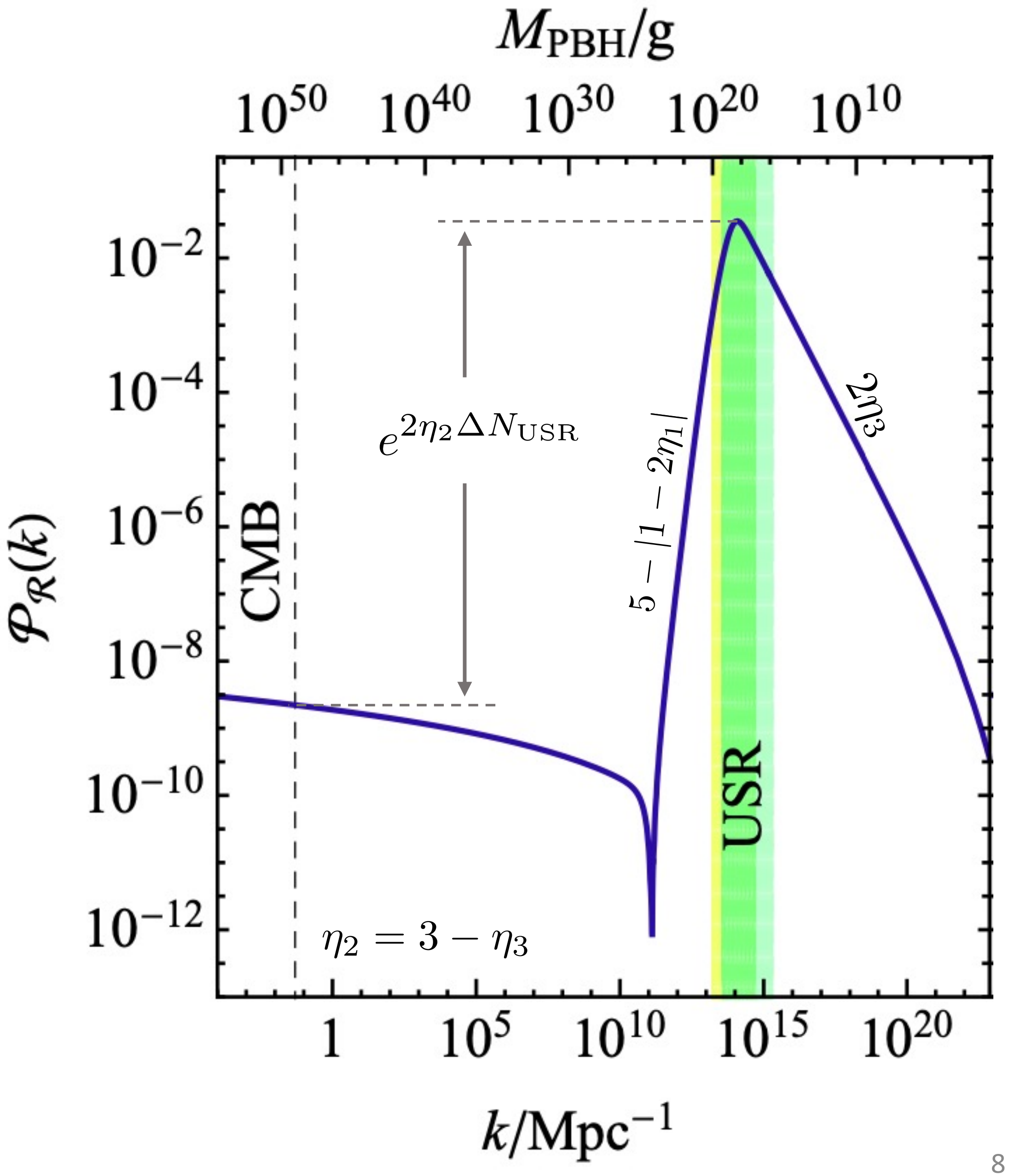


Ultra slow-roll inflation

A high peak in the curvature power spectrum can develop in an USR period.

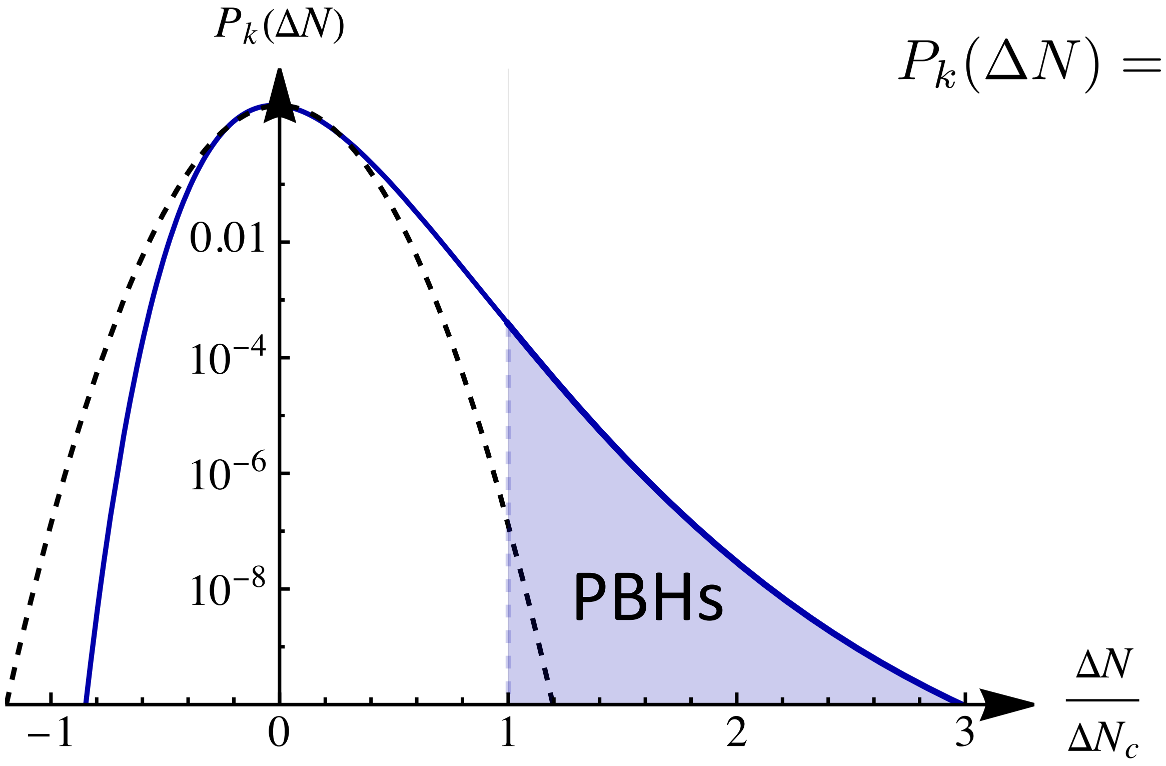
[e.g. Veermäe et al. JCAP 03 (2023)].



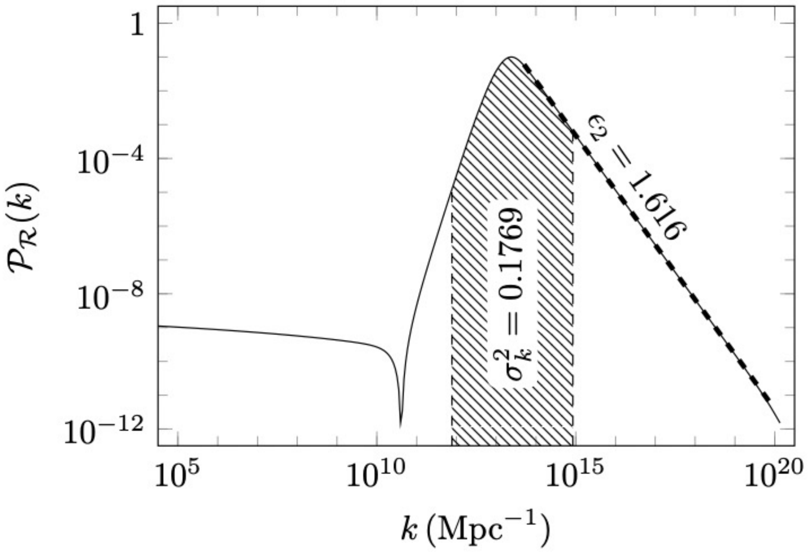


Non-Gaussianities

- Rare large fluctuations form PBHs $\Rightarrow$ sensitive to the tail of the probability density.
- Non-perturbative (stochastic) effects generate a non-Gaussian $P_k(\delta)$ in scenarios including a period of USR [Tomberg, 2304.10903].

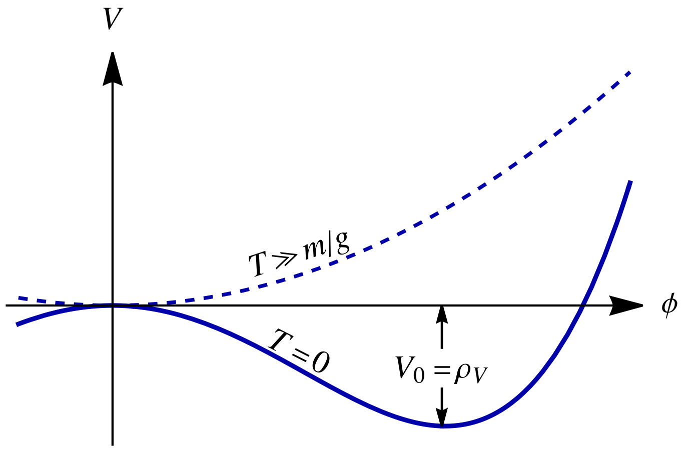


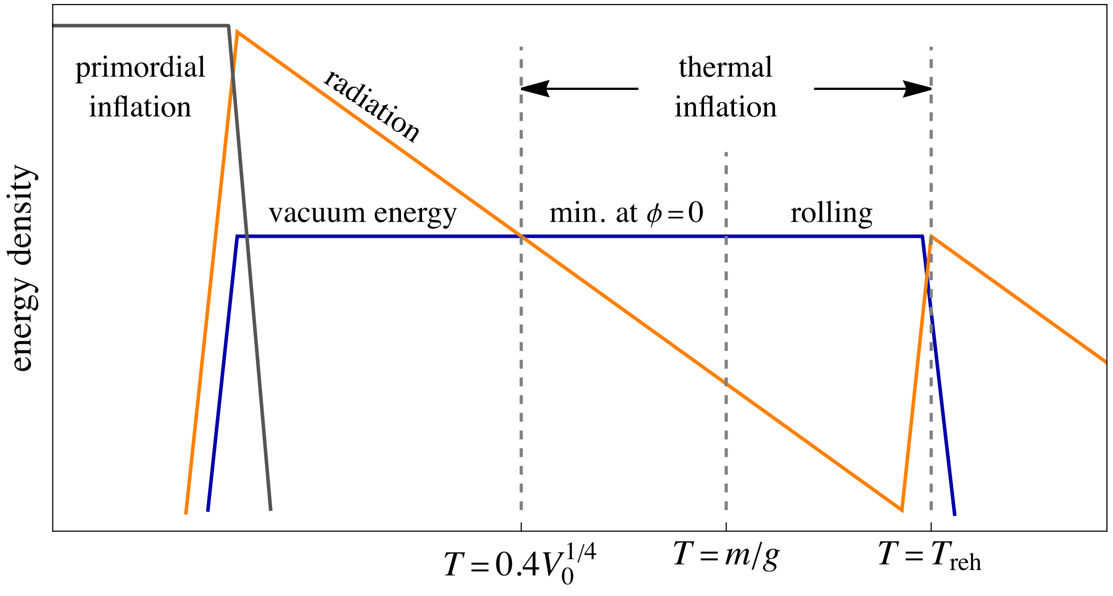
$$P_k(\Delta N) = \frac{1}{\sqrt{2\pi}\sigma_k} \exp\left[-\frac{2}{\sigma_k^2 \epsilon_2^2}\left(1 - e^{\frac{\epsilon_2 \Delta N}{2}}\right)^2 - \frac{\epsilon_2}{2}\Delta N\right]$$

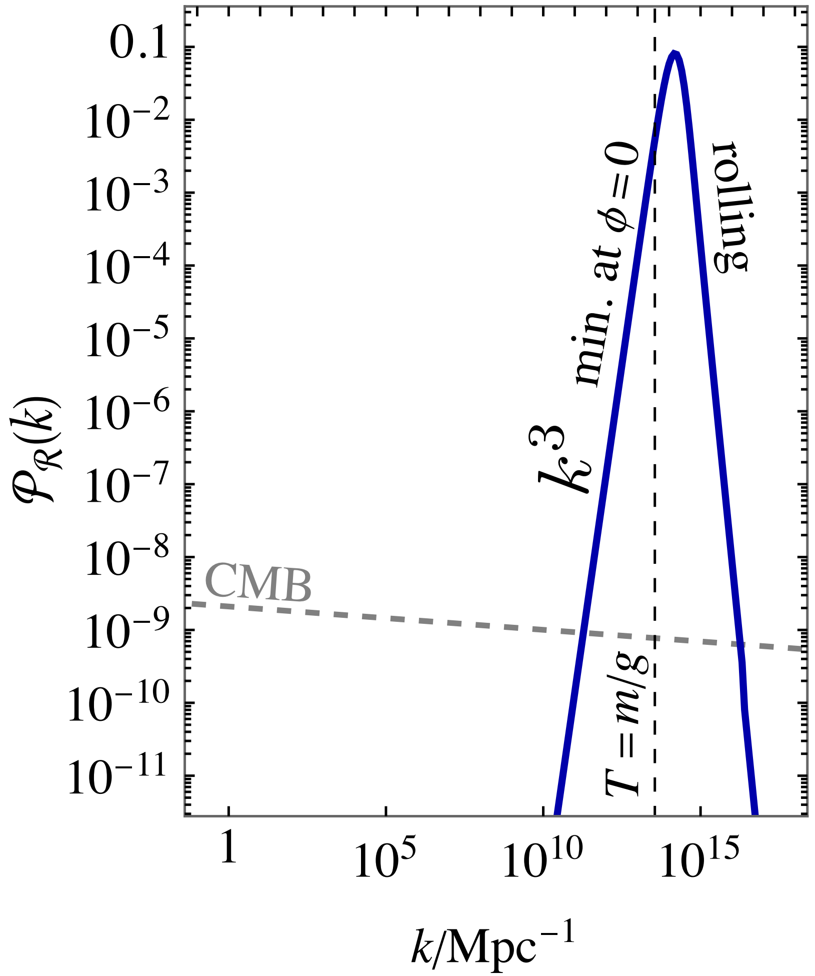


Thermal inflation

Curvature fluctuations can grow large when the potential turns from convex to concave [Markkanen et. al. JCAP 07 (2019)].



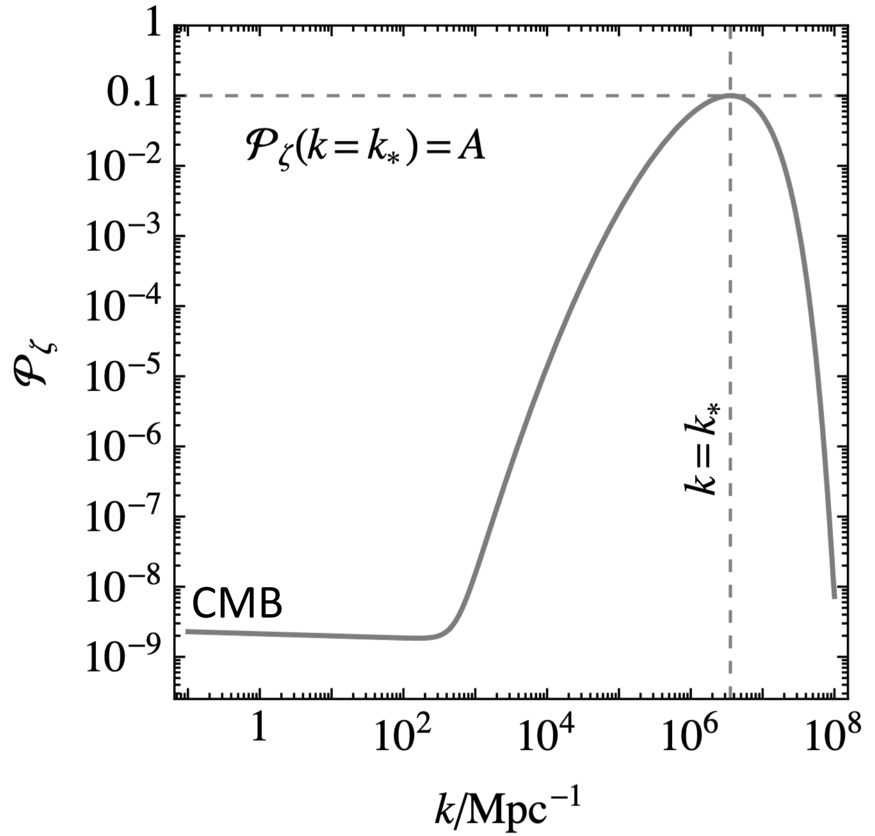


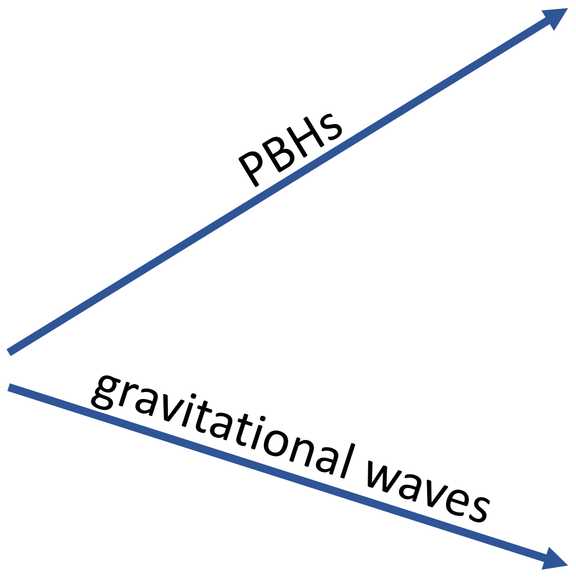


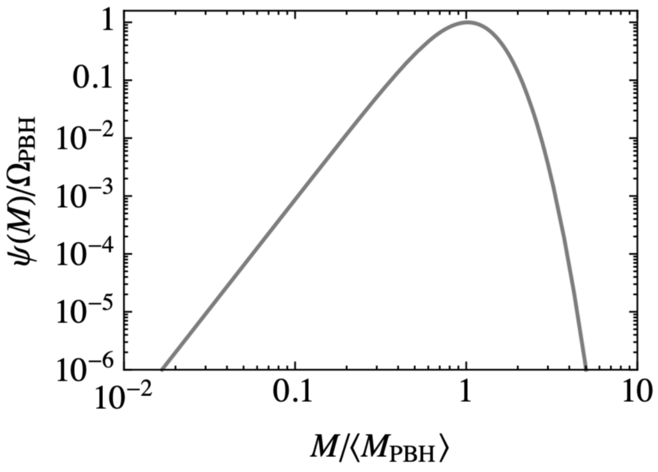
Signature: gravitational waves

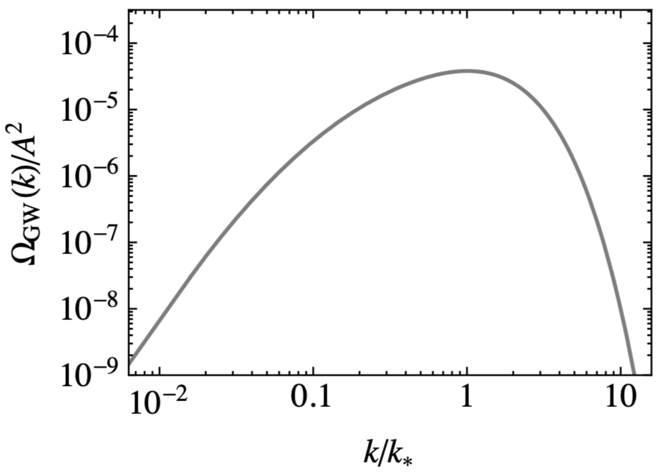
Scalar perturbations source tensor perturbations at second order [Matarrese et al. PRD 47 (1993)].

$$\Omega_{\rm PBH} \propto \mathrm{Erfc}\left(\frac{\delta_{\rm c}}{\sqrt{2\sigma^2}}\right), \quad \sigma^2 \sim \mathrm{A}\,.$$

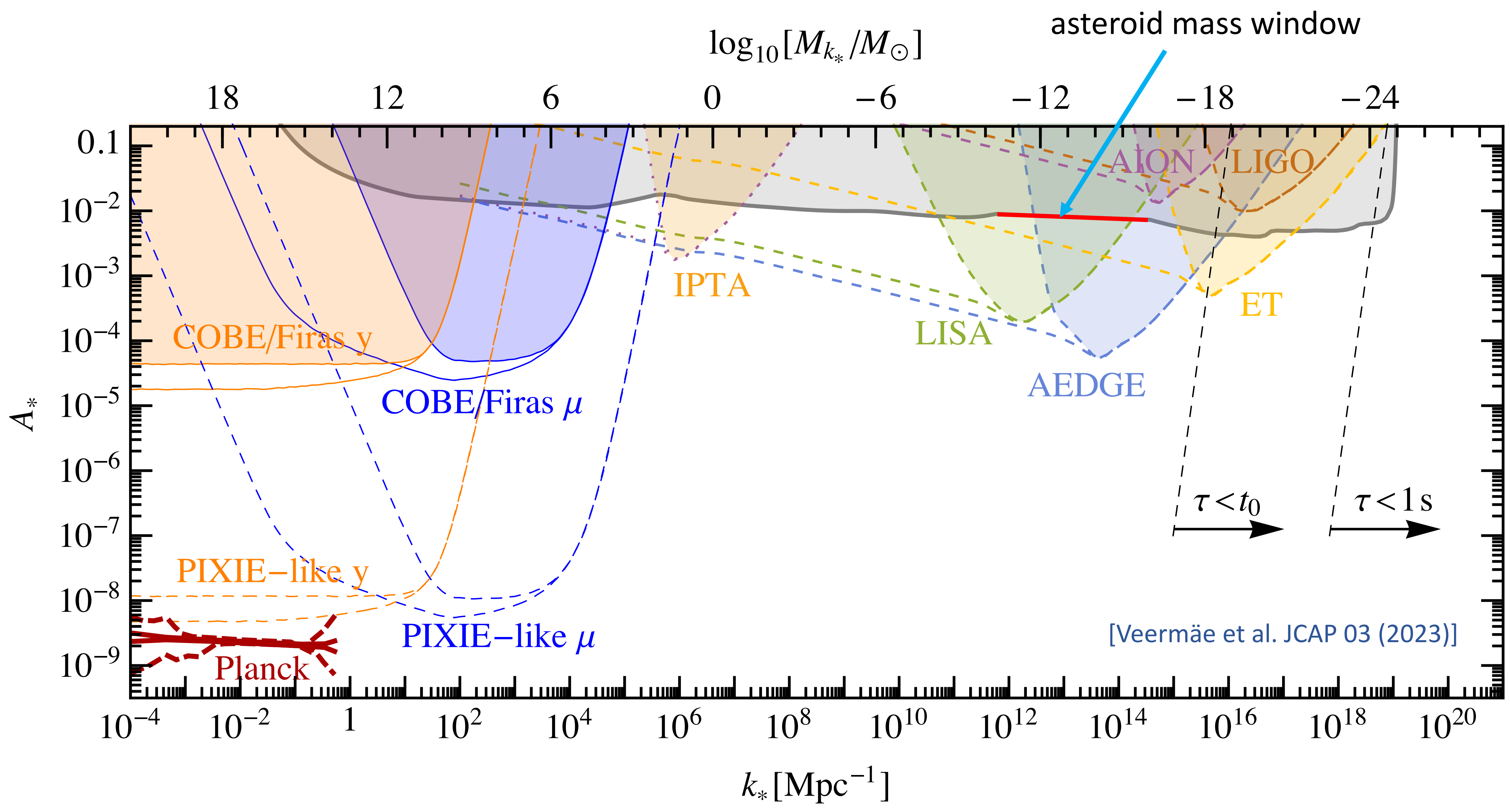








$$\Omega_{\rm GW} \sim 10^{-5} A^2\,, \qquad \langle k_{\rm GW}\rangle \sim k_*\,.$$



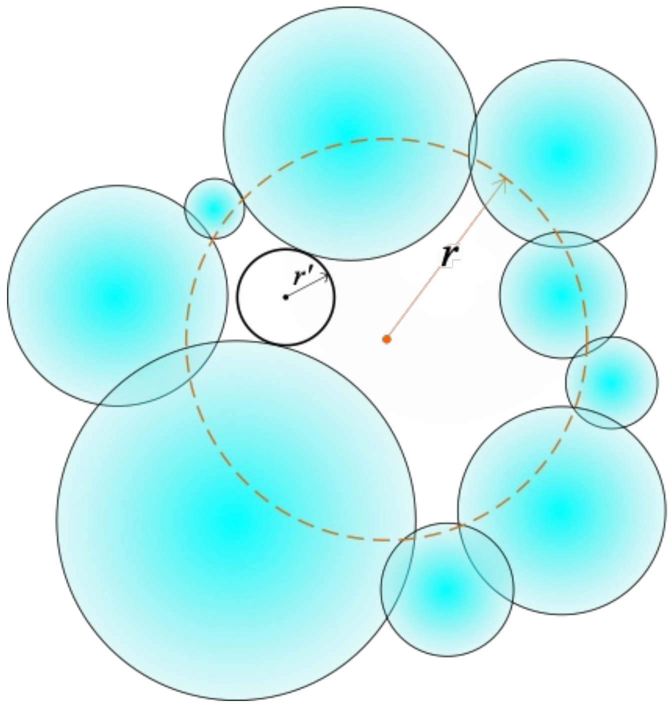
asteroid mass window
$\log_{10}[M_{k_*}/M_\odot]$
18
12
6
0
−6
−12
−18
−24
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
A_*
AION
LIGO
IPTA
ET
LISA
AEDGE
COBE/Firas y
COBE/Firas μ
PIXIE−like y
PIXIE−like μ
Planck
$\tau < t_0$
$\tau < 1$s
[Veermäe et al. JCAP 03 (2023)]
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
$k_*[\mathrm{Mpc}^{-1}]$

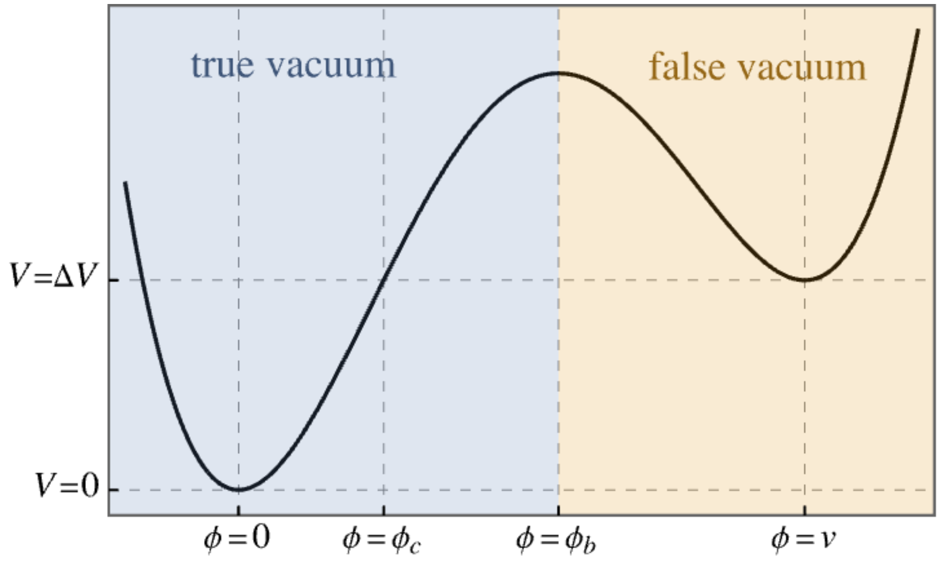
False vacuum domains

PBHs from false vacuum domains

1. Collapse of the last false vacuum remnants in a first-order phase transition.

Hawking, Moss, Stewart, PRD 26 (1982); Kodama, Sasaki, Sato, PTEP 68 (1982); Lewicki & Vaskonen, Phys. Dark U. 30 (2020); Liu et al. PRD 105 (2022); Kawana & Xie, PLB 824 (2022); Baker et al. 2105.07481 and 2110.00005; Lewicki, Toczek, Vaskonen, 2305.04924; Gouttenoire & Volansky, 2305.04942;



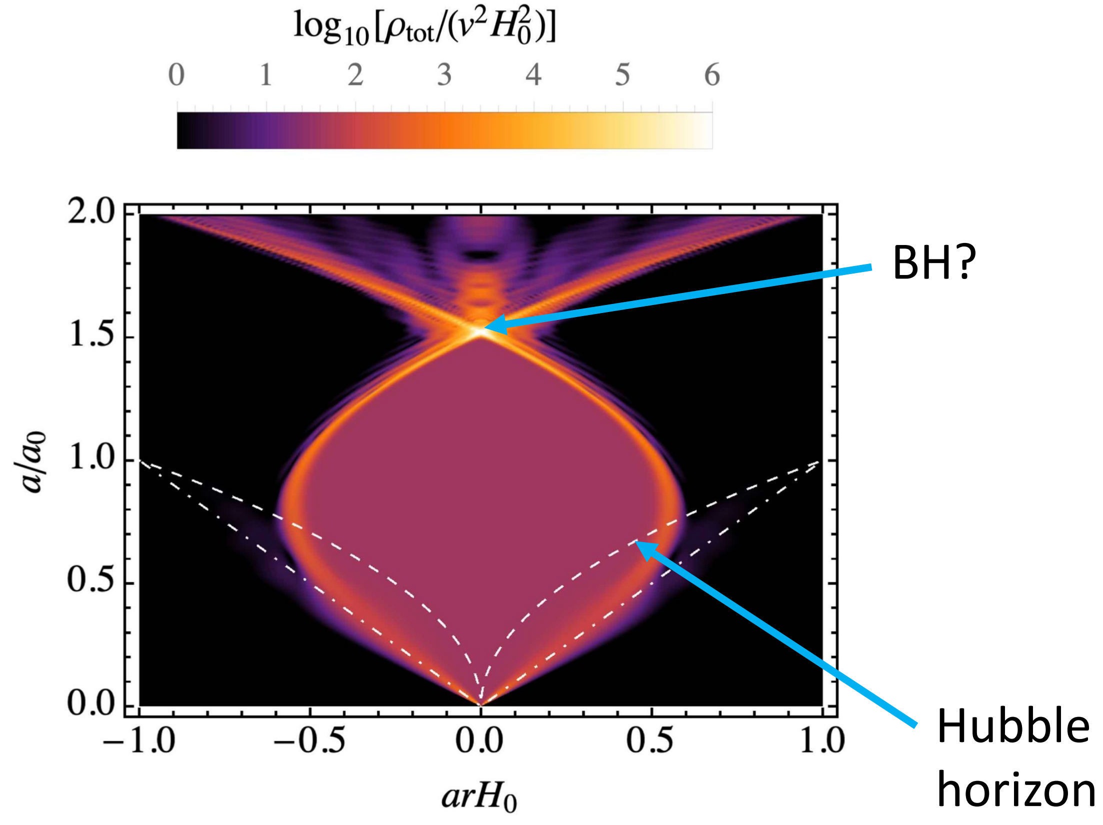


2. Collapse of false vacuum bubbles nucleated during inflation.

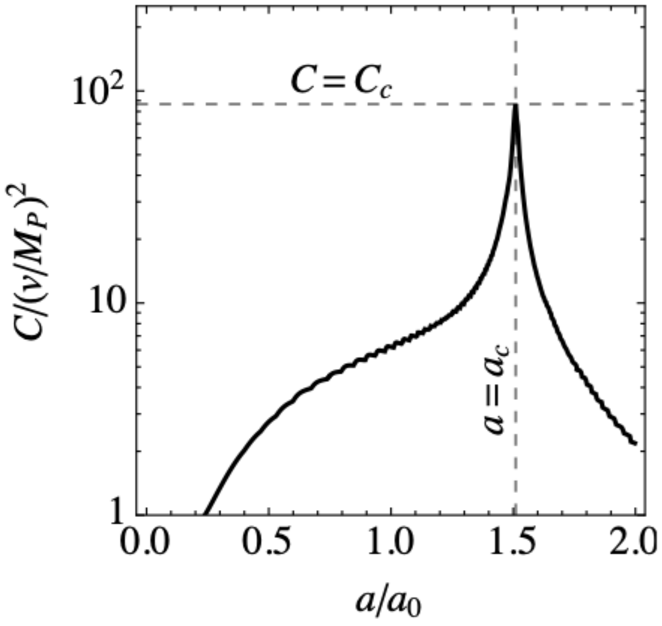
Garriga, Vilenkin, Zhang, JCAP 02 (2016); Deng & Vilenkin, JCAP 12 (2017); Deng, JCAP 09 (2020); Kusenko et al. PRL 125 (2020); Veermäe et al. JCAP 02 (2022)

Collapse of false-vacuum bubbles in vacuum

- The scalar field dynamics controls the bubble evolution until the compactness becomes large.
- BH formation can be estimated by the hoop conjecture $C \equiv M/R > 1/2$.



[Veermäe et al. JCAP 02 (2022)]



$$C_c \propto \Delta V/\sigma$$

$$M_{\rm PBH} \sim 0.1 \frac{\Delta V}{H_0^3}$$

Collapse of false-vacuum bubbles with particles

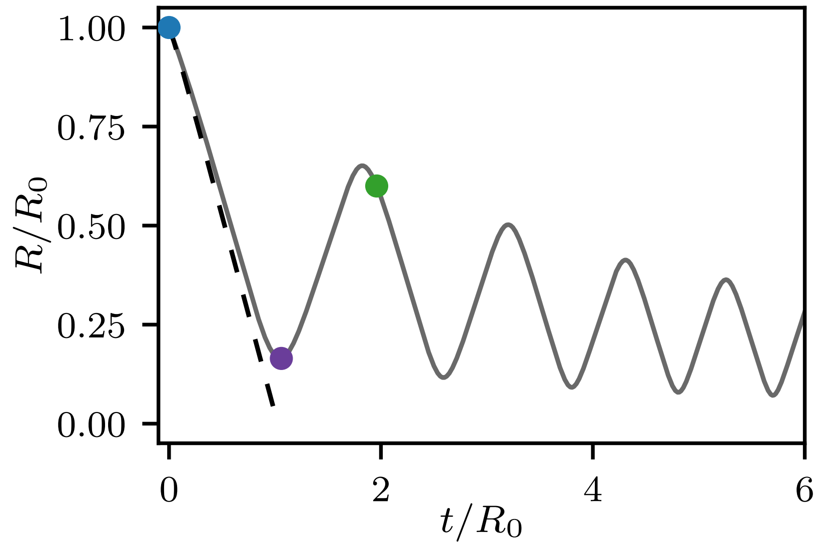
Particle-wall collisions cause pressure
[Lewicki et al. PRD 106 (2022)]

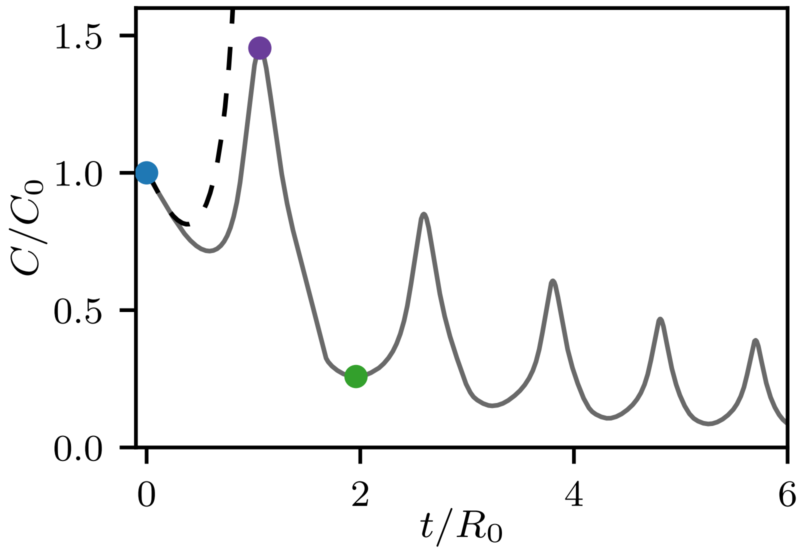
$$\Delta P = \frac{\rho}{3}\frac{(1-\dot{R})^2}{1+\dot{R}}\,, \qquad \Delta m \gg \langle p \rangle$$

that affects the bubble evolution

$$\ddot{R} + 2\frac{1-\dot{R}^2}{R} = \frac{(1-\dot{R}^2)^{3/2}}{\sigma}\left(-\Delta V + \Delta P\right)\,.$$

Increasing pressure inside the collapsing bubble can stop the collapse and prevent BH formation [Lewicki et al. 2305.07702].

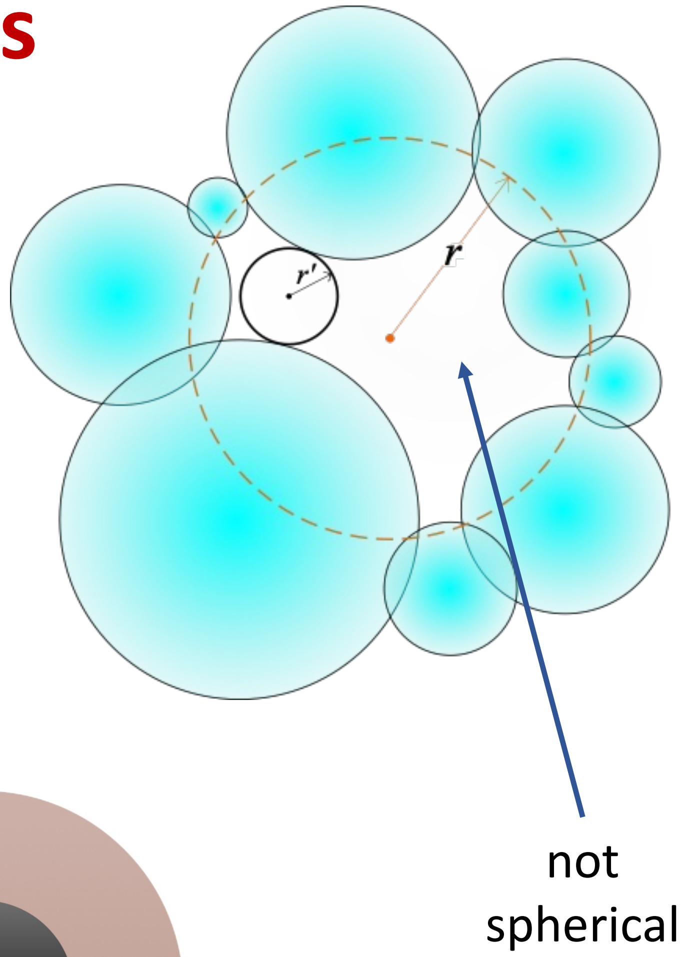




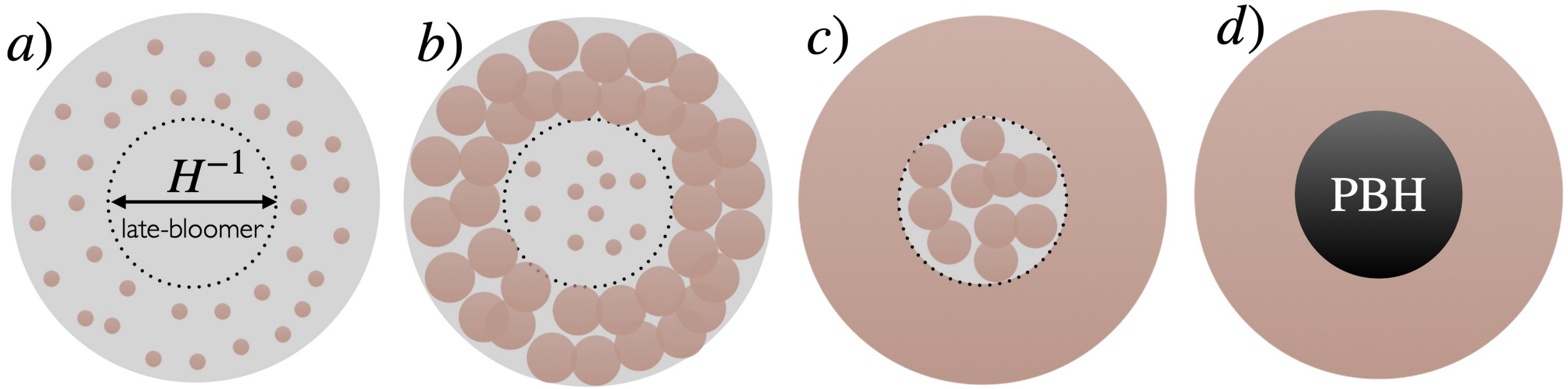
PBHs from first-order phase transitions

1. PBHs from collisions of several bubbles
   [Hawking, Moss, Stewart, PRD 26 (1982)].

2. PBHs from overdensities generated during thermal inflation by late bubble nucleation
   [Liu et al. PRD 105 (2022)].



[Gouttenoire & Volansky, 2305.04942]

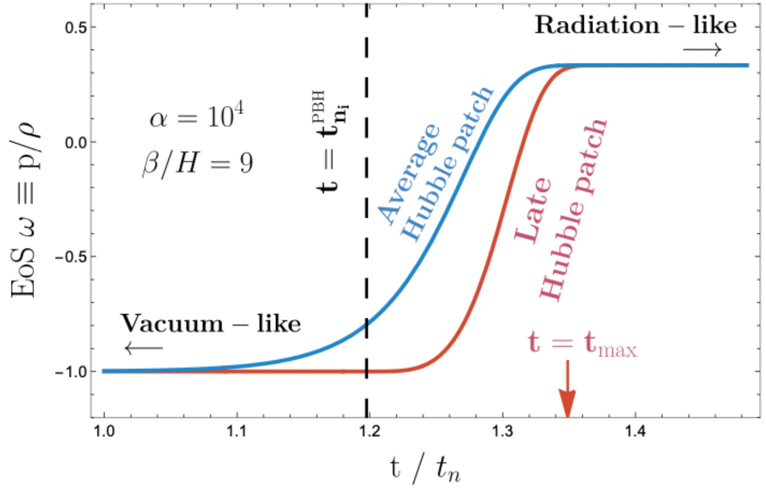


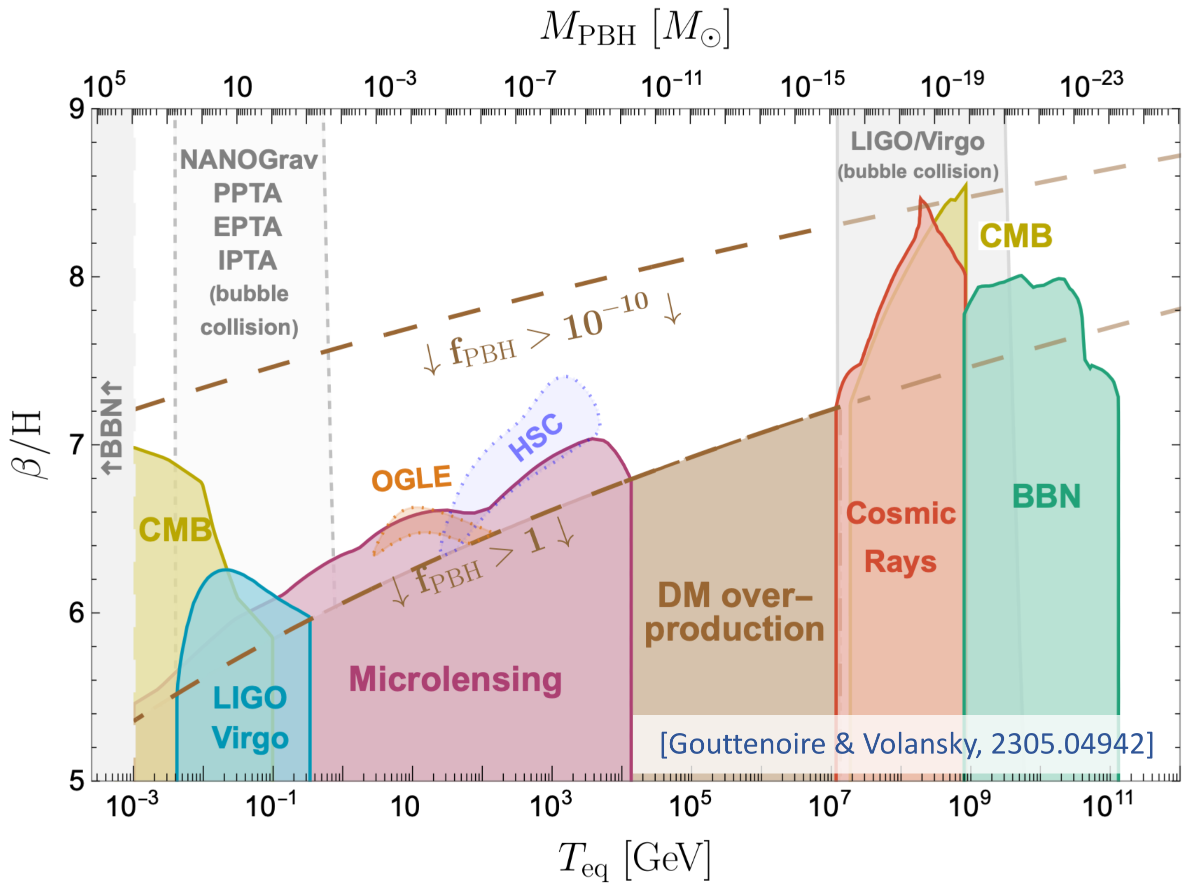
PBH abundance and mass

The abundance of BHs can be estimated by the probability of late bubble nucleation and formation [Lewicki, Toczek, Vaskonen, 2305.04924; Gouttenoire & Volansky, 2305.04942].

Bubble nucleation rate: $\Gamma(t) \propto e^{\beta t}$

[Gouttenoire & Volansky, 2305.04942]





PBH mass is determined by the horizon mass at the time of the transition.

Summary

- PBHs could prove to be a solution for several issues in astrophysics and cosmology.
- Several mechanisms in the early Universe can have lead to PBH formation.
- The formation by primordial fluctuations has been extensively studied and can be probed through searches of the scalar induced gravitational wave background.
- Other mechanisms have also gained attention recently, in particular PBH formation in first-order phase transitions.

Thank you!