PBH DM FROM INFLATION

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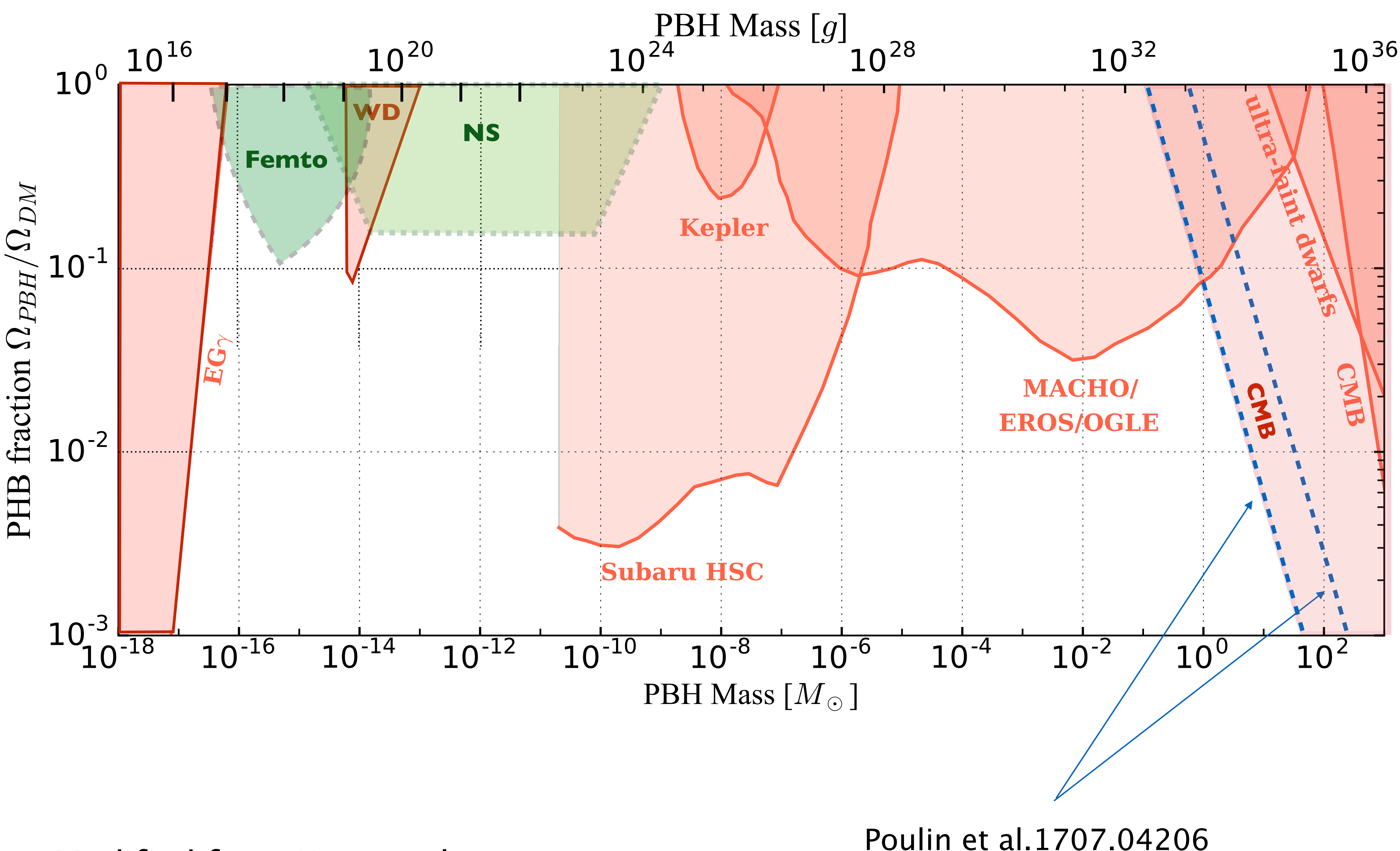
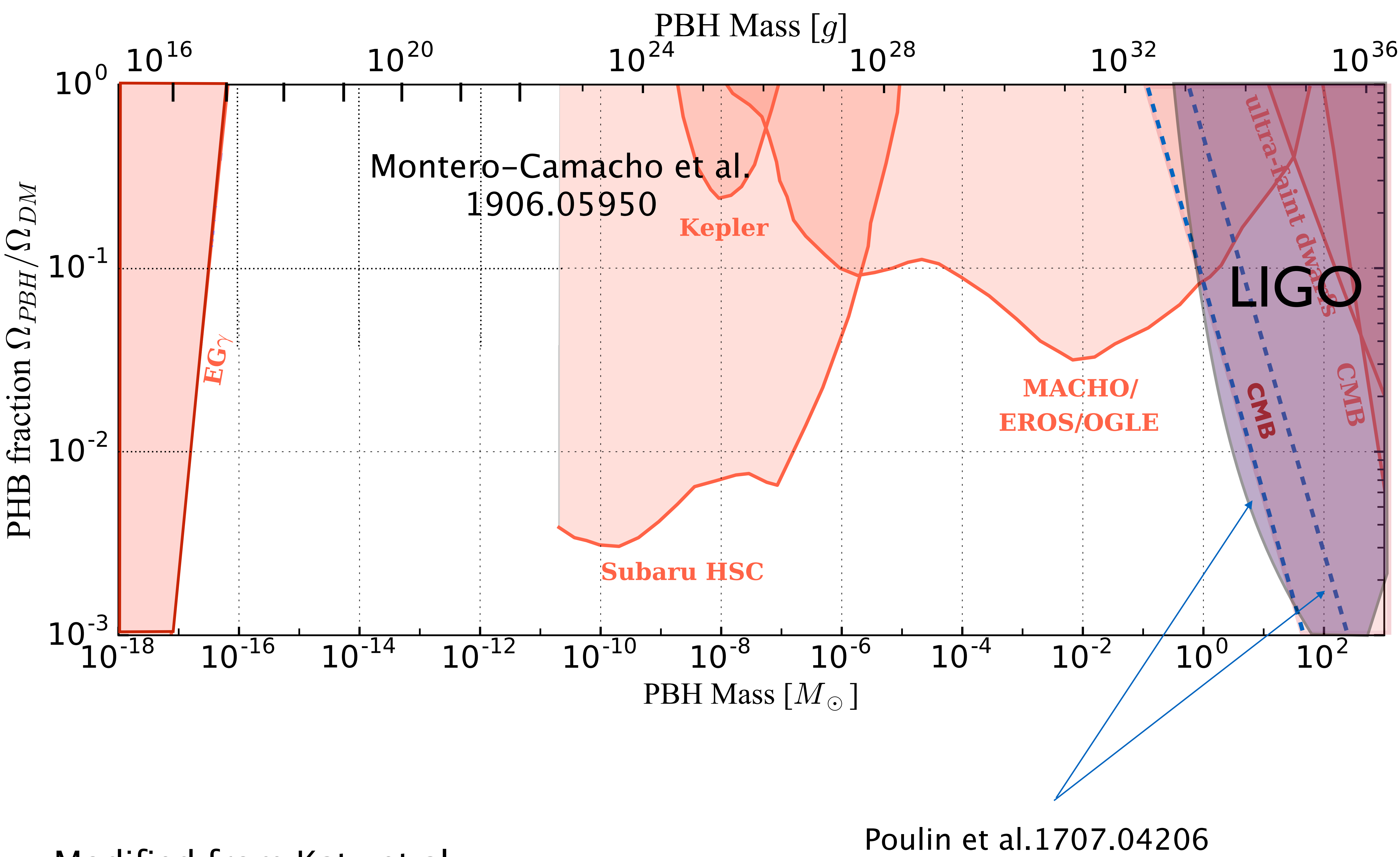
July 2018



Modified from Katz et al.
1807.11495

September 2019



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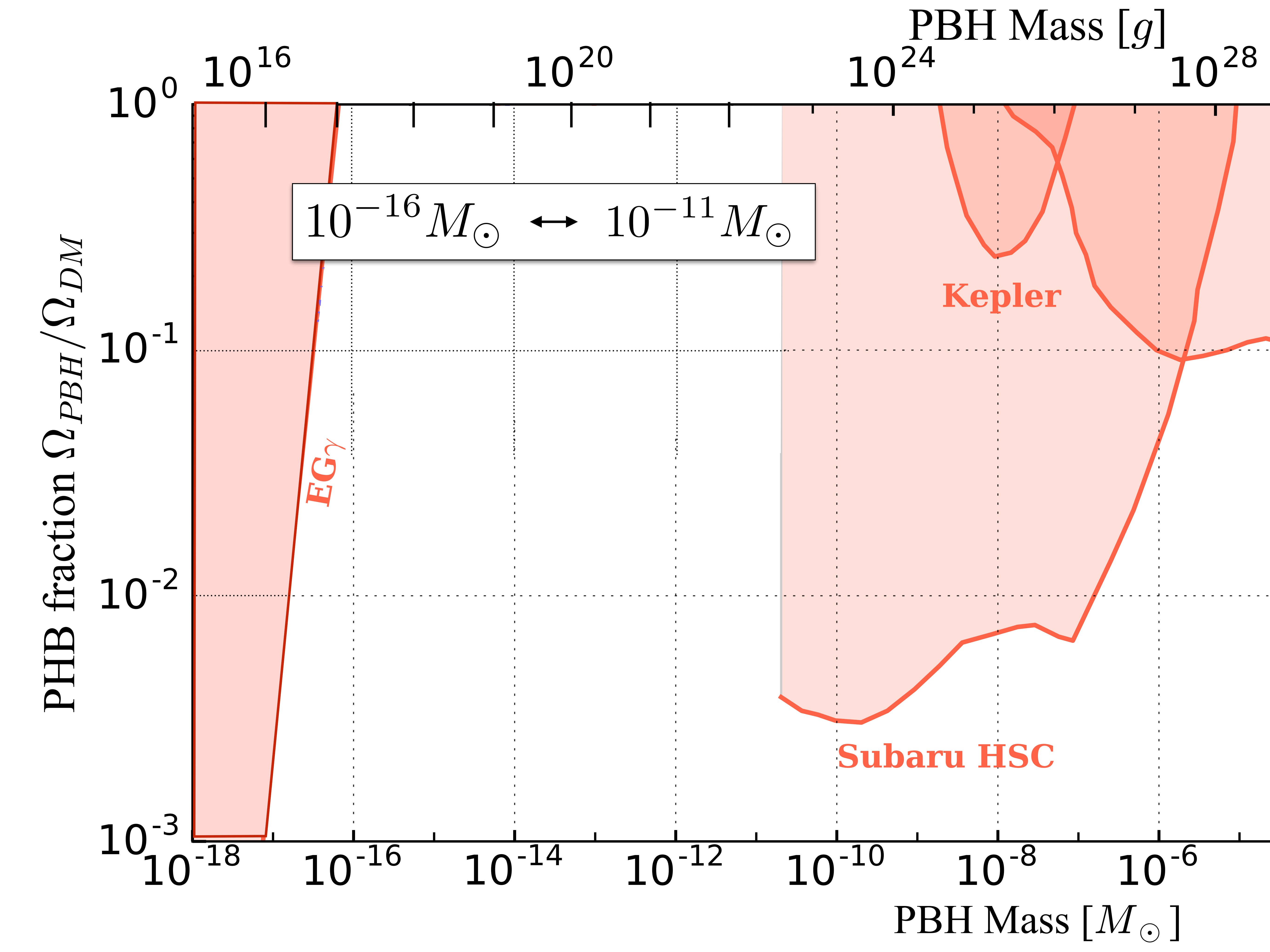
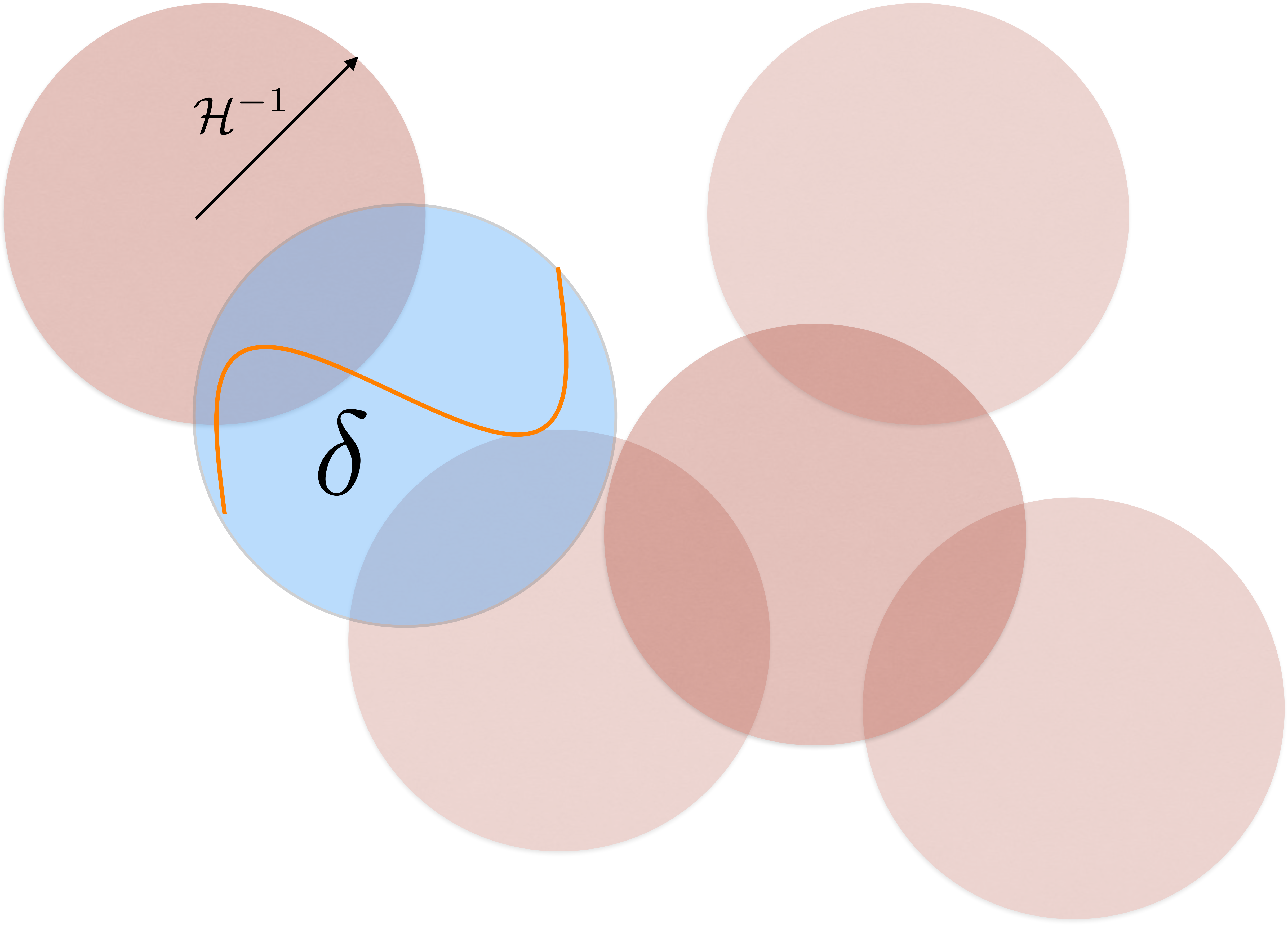
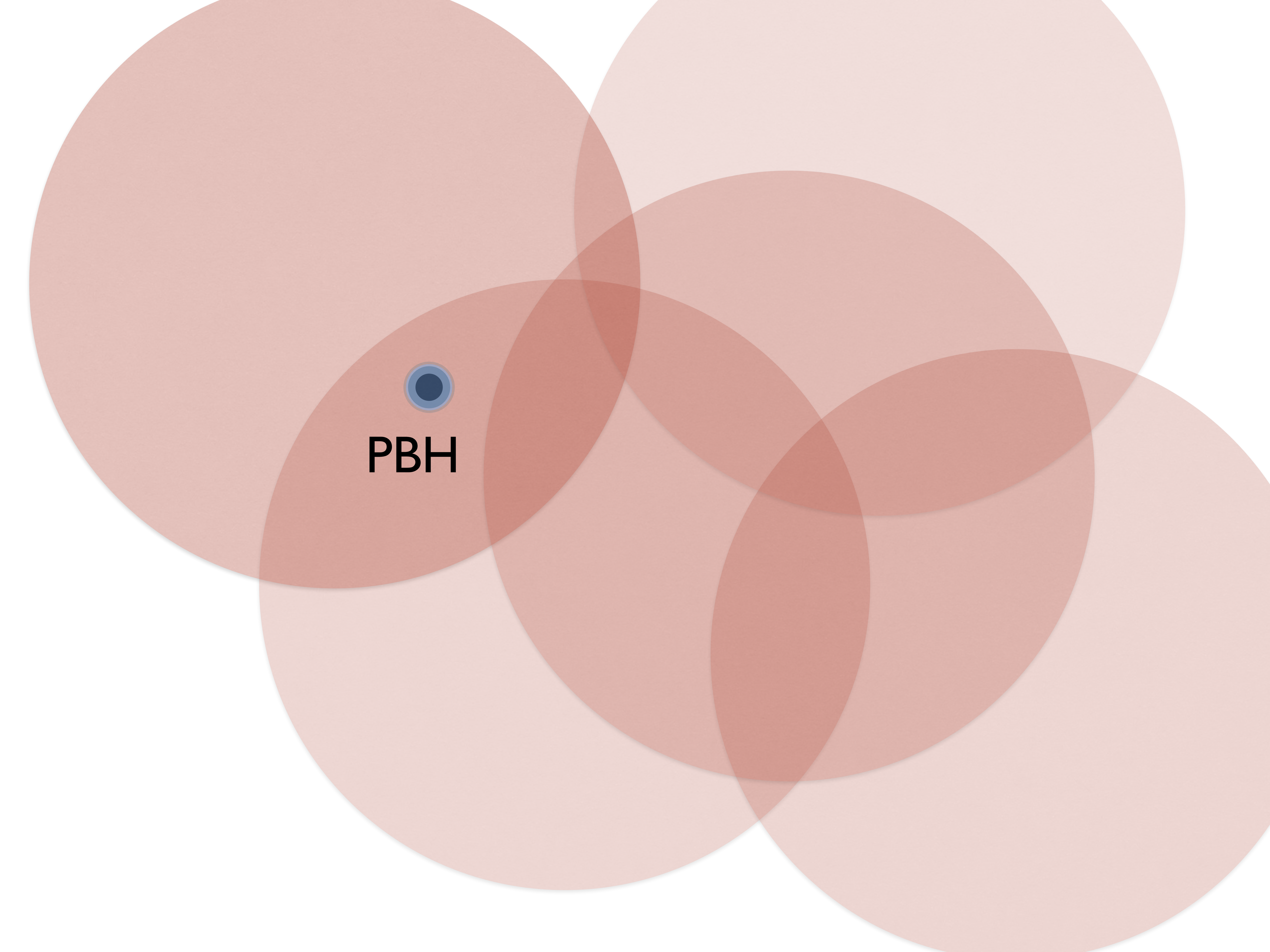
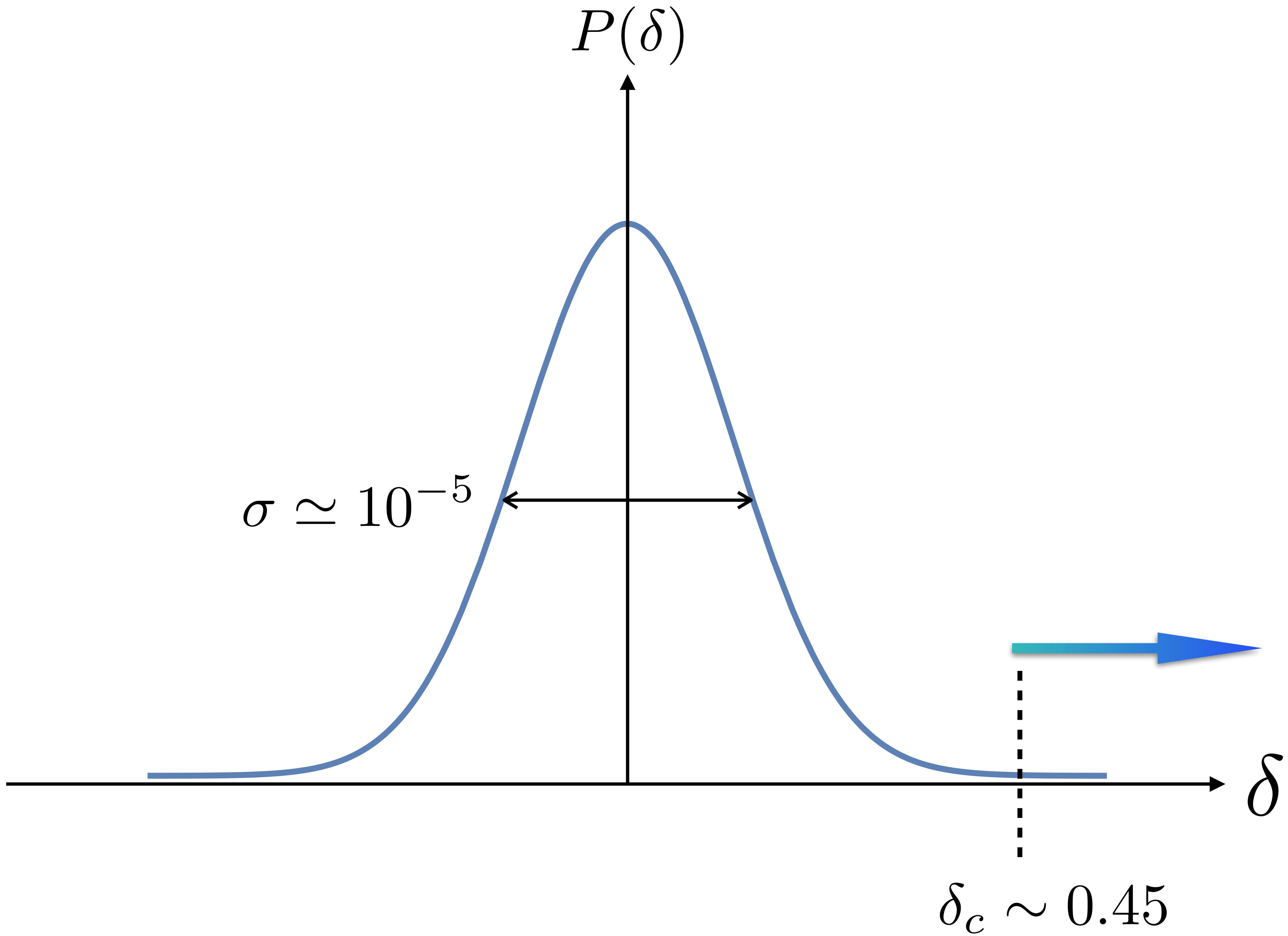


PBH Mass [g]
10^{16}
10^{20}
10^{24}
10^{28}
10^{0}
10^{-1}
10^{-2}
10^{-3}
$10^{-16} M_\odot \leftrightarrow 10^{-11} M_\odot$
Kepler
EGγ
Subaru HSC
PHB fraction Ω_{PBH}/Ω_{DM}
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
PBH Mass [$M_\odot$]

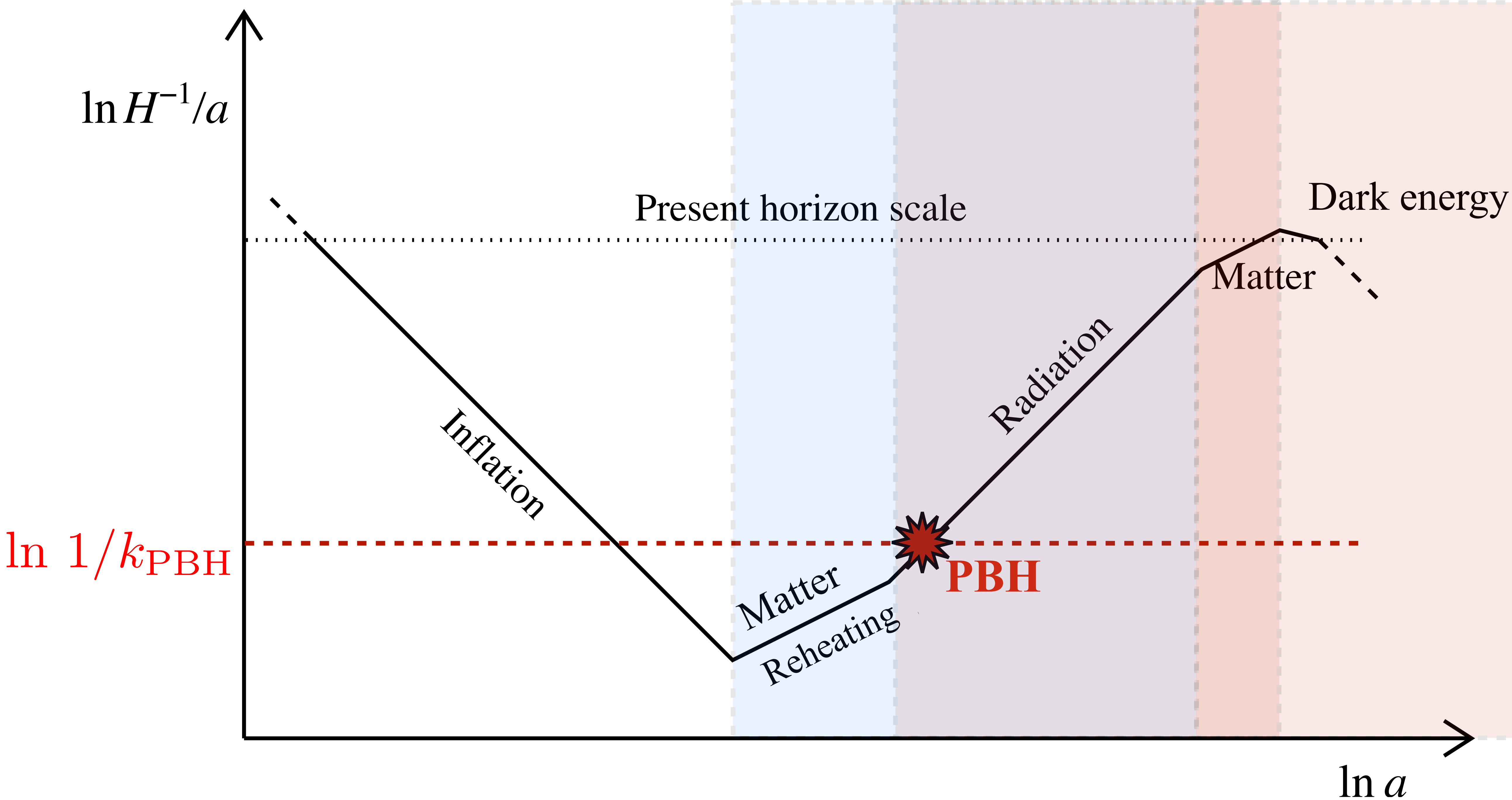
Primordial black hole formation


$\mathcal{H}^{-1}$
δ


PBH



$P(\delta)$
$\sigma \simeq 10^{-5}$
δ
$\delta_c \sim 0.45$



Adapted from Liddle and Leach, 2003

Individual masses

$$M \sim \frac{4}{3}\pi\,\rho\,H^{-3}$$

$$M \sim 10^{-14}\left(\frac{10^{13}\,\mathrm{Mpc}^{-1}}{k}\right)^2 M_\odot$$

$$N_e \simeq 18 - \frac{1}{2}\log\frac{M}{M_\odot}$$

$$\beta(M) = \frac{1}{\sqrt{2\pi\sigma^2(M)}} \int_{\delta_c}^{\infty} d\delta \, \exp\left(\frac{-\delta^2}{2\sigma^2(M)}\right)$$

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

$$\sigma^2(M) = \frac{16}{81} \int \frac{\mathrm{d}q}{q} \, (qR)^4 \quad \mathcal{P}_{\mathcal{R}} \quad W(qR)^2$$

$$\frac{\Omega_{\mathrm{PBH}}(M)}{\Omega_{\mathrm{DM}}} \simeq \frac{\beta}{10^{-16}} \left(\frac{M}{5 \cdot 10^{-16} M\odot}\right)^{-1/2}$$

$$\mathcal{P}_{\mathcal{R}} \sim 10^{-2} \implies \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}} \sim 1$$

Inflation

- $$\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \sim 1$$

- $$\boxed{10^{-16} M_\odot \leftrightarrow 10^{-11} M_\odot}$$

- Enough inflation

- Agreement with the CMB

Inflation and primordial black holes as dark matter

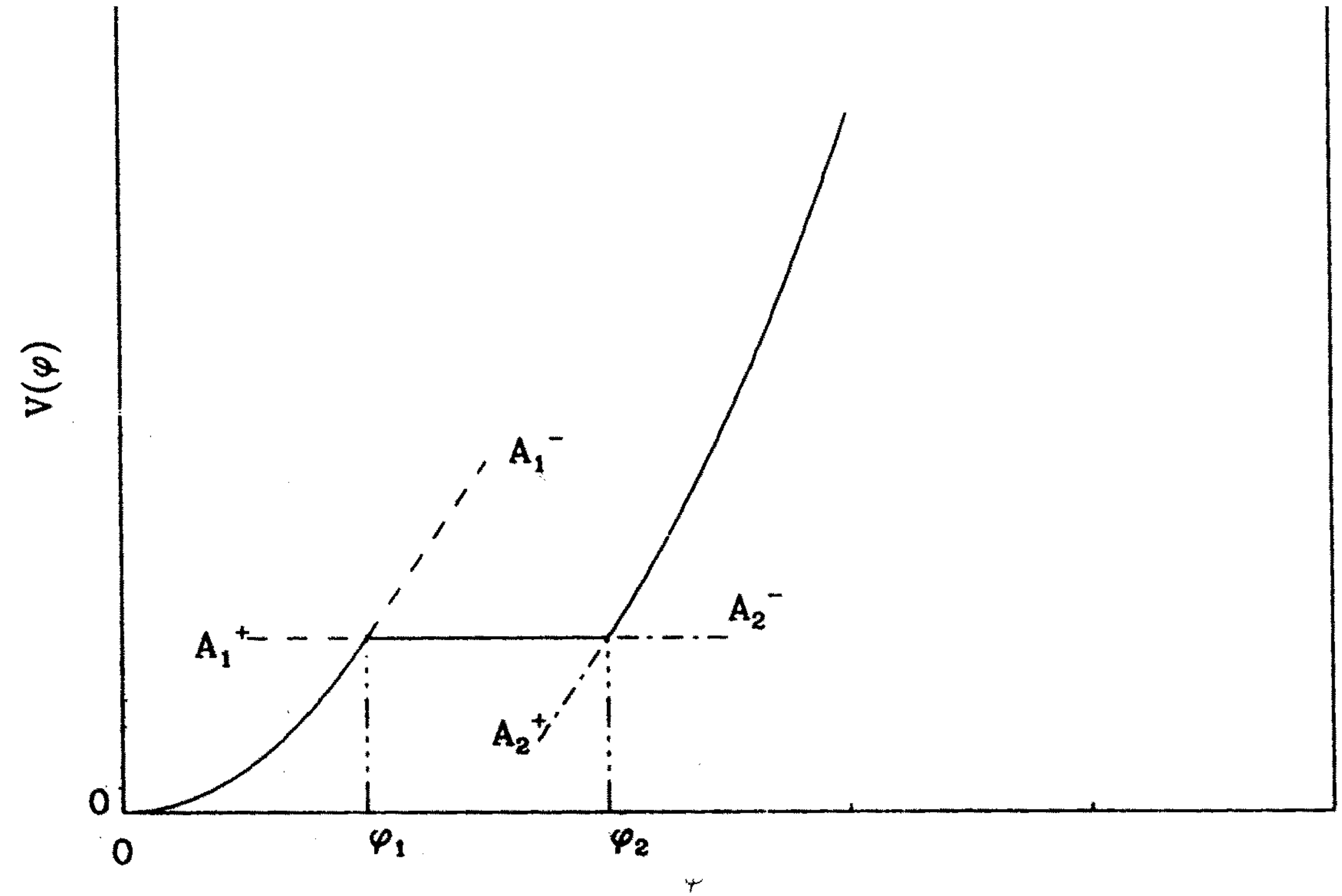


FIG. 1. Schematic representation of the potential $V(\varphi)$ of the scalar field φ (inflaton). The potential has a plateau in the range $\varphi_1 < \varphi < \varphi_2$ and is of the power-law type outside of this range. The breaks of the potential are smoothed out in small ranges $\Delta\varphi_1 \ll \varphi_1$ and $\Delta\varphi_2 \ll \varphi_2$ around φ_1 and φ_2 correspondingly.

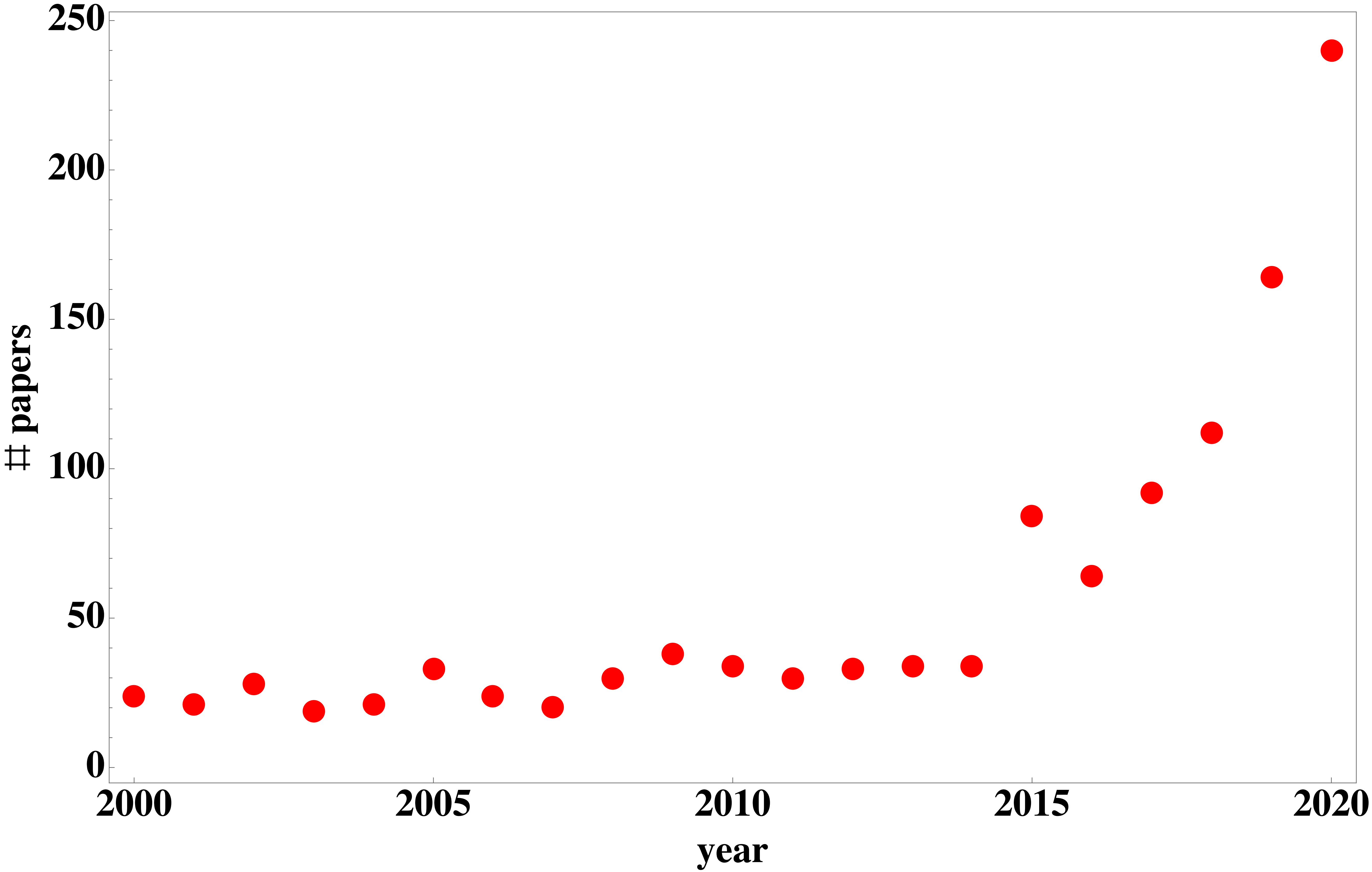
Ivanov, Naselsky, Novikov 1994

$$\mathcal{P}_{\mathcal{R}} \simeq \frac{1}{8\pi^2}\left(\frac{H}{M_P}\right)^2\left(\frac{H}{\dot{\phi}}\right)^2 \simeq \frac{1}{12\pi^2}\frac{V^3}{M_P^6(V')^2}$$

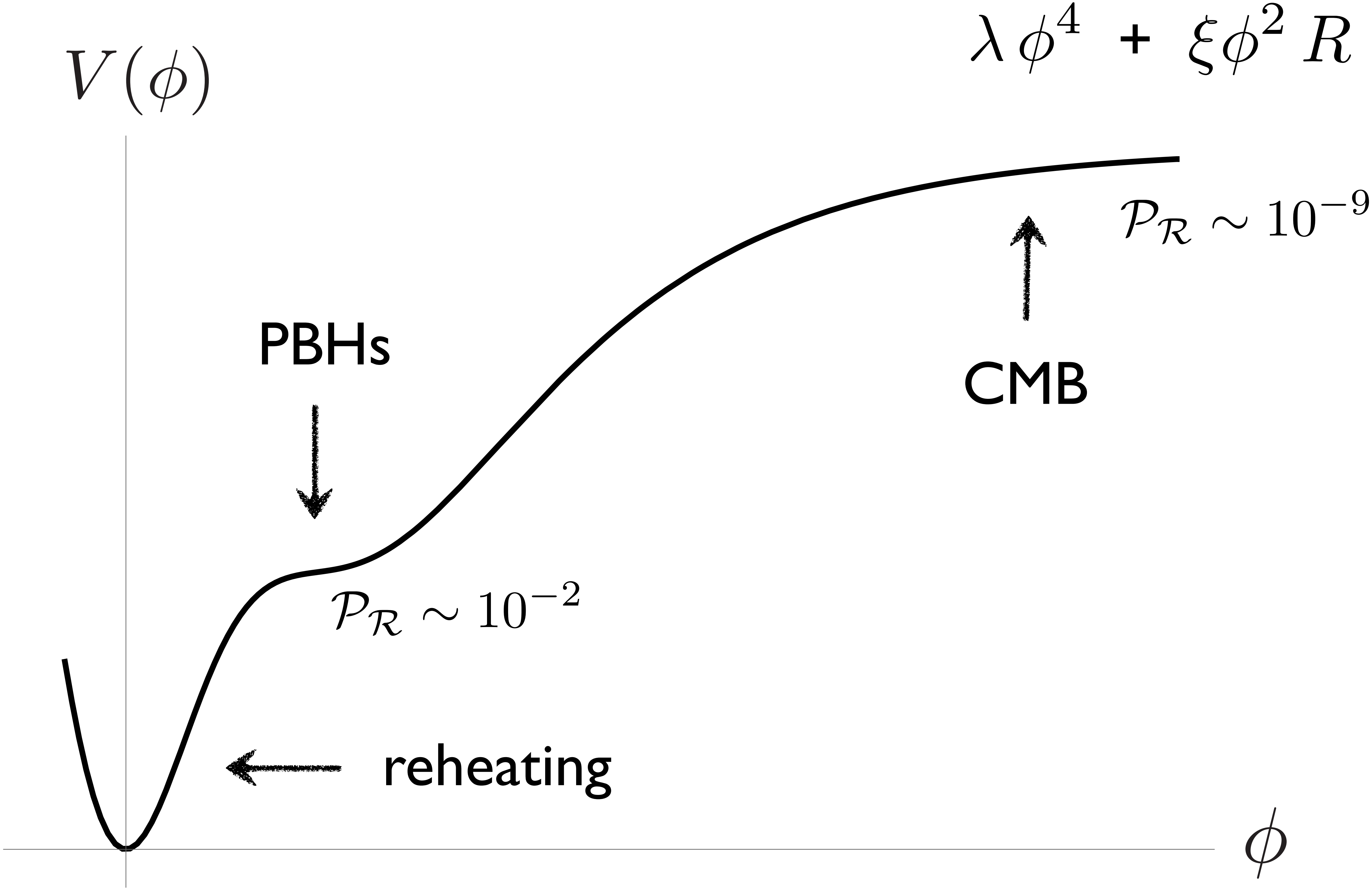
Canonical single field inflation

(approximate stationary inflection point)

García-Bellido, Morales 2017
Ezquiaga, García-Bellido, Morales 2017
Kannike, Marzola, Raidal, Veermäe 2017
Ballesteros, Taoso 2017
Hertzberg, Yamada 2017
Cicoli, Diaz, Pedro 2018
Özsoy, Parameswaran, Tasinato, Zavala 2018
Dalianis, Kehagias, Tringas 2018
Gao, Guo 2018
Räsänen, Tomberg 2019
Ballesteros, Rey, Rompineve 2019
Ballesteros, Rey, Taoso, Urbano 2020



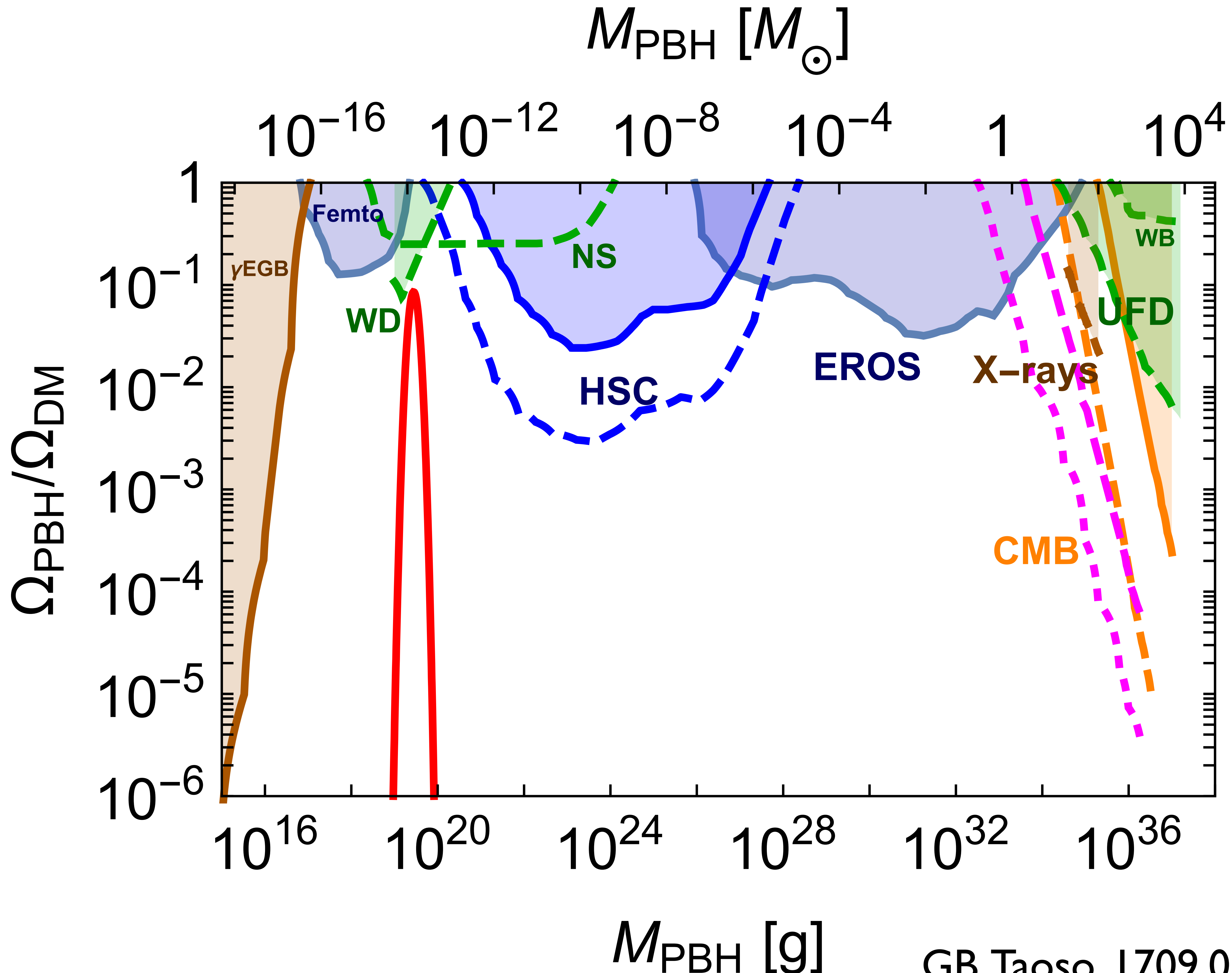
250
200
150
100
50
0
papers
2000
2005
2010
2015
2020
year


$\lambda\,\phi^4$ + $\xi\phi^2\,R$
$V(\phi)$
$\mathcal{P}_{\mathcal{R}} \sim 10^{-9}$
PBHs
CMB
$\mathcal{P}_{\mathcal{R}} \sim 10^{-2}$
reheating
ϕ

$$V \simeq \frac{\lambda(\phi)}{4!}\phi^4$$

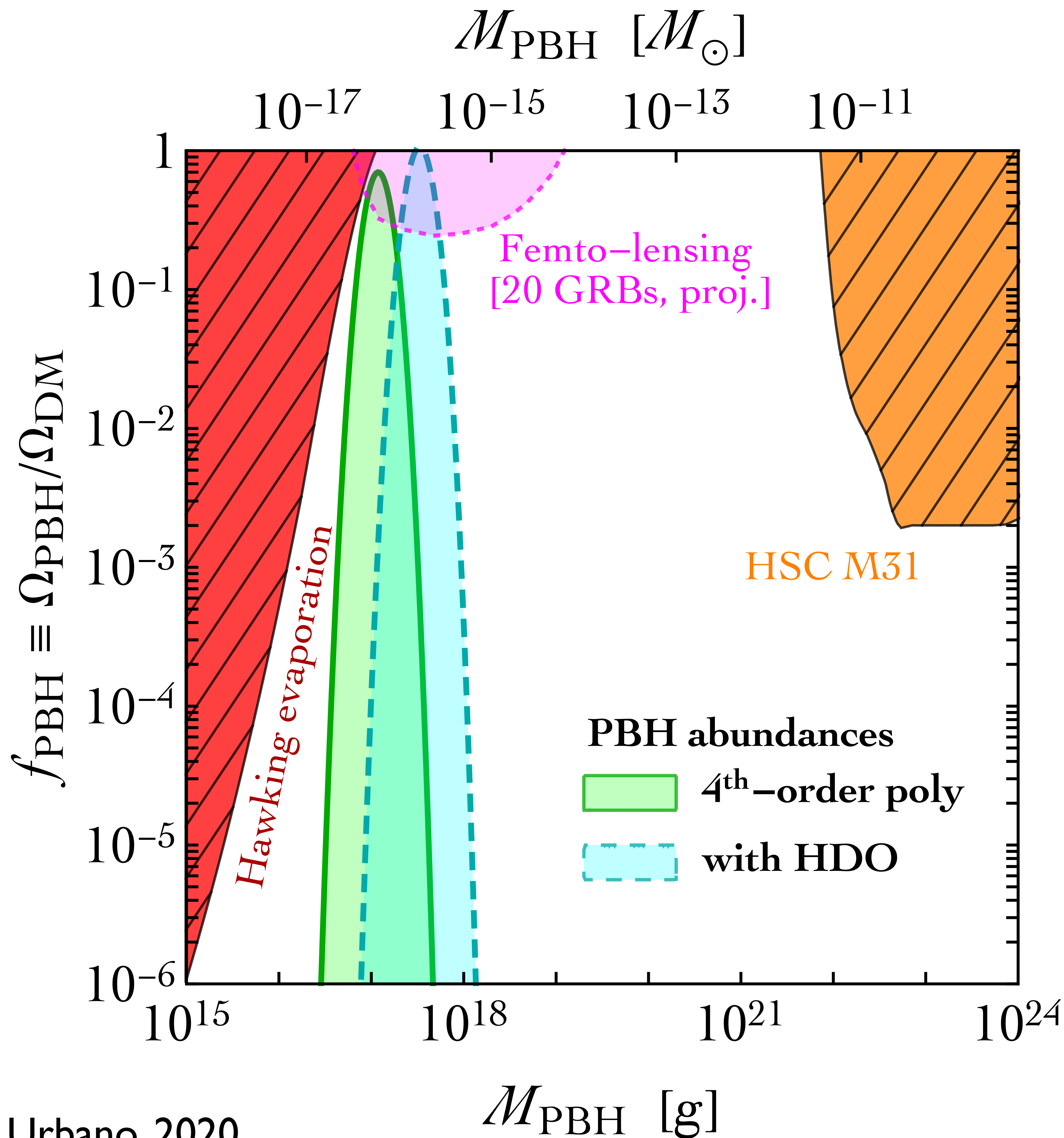
$$\lambda(\phi) = \lambda(\phi_0) + \frac{1}{2}\beta_\lambda(\phi_0)\log\frac{\phi^2}{\phi_0^2} + \frac{1}{8}\beta'_\lambda(\phi_0)\left(\log\frac{\phi^2}{\phi_0^2}\right)^2 + \cdots$$

$$\lambda\left(\mu_0\right) \sim \left|\beta_\lambda\left(\mu_0\right)\right| \sim \beta'_\lambda\left(\mu_0\right)$$

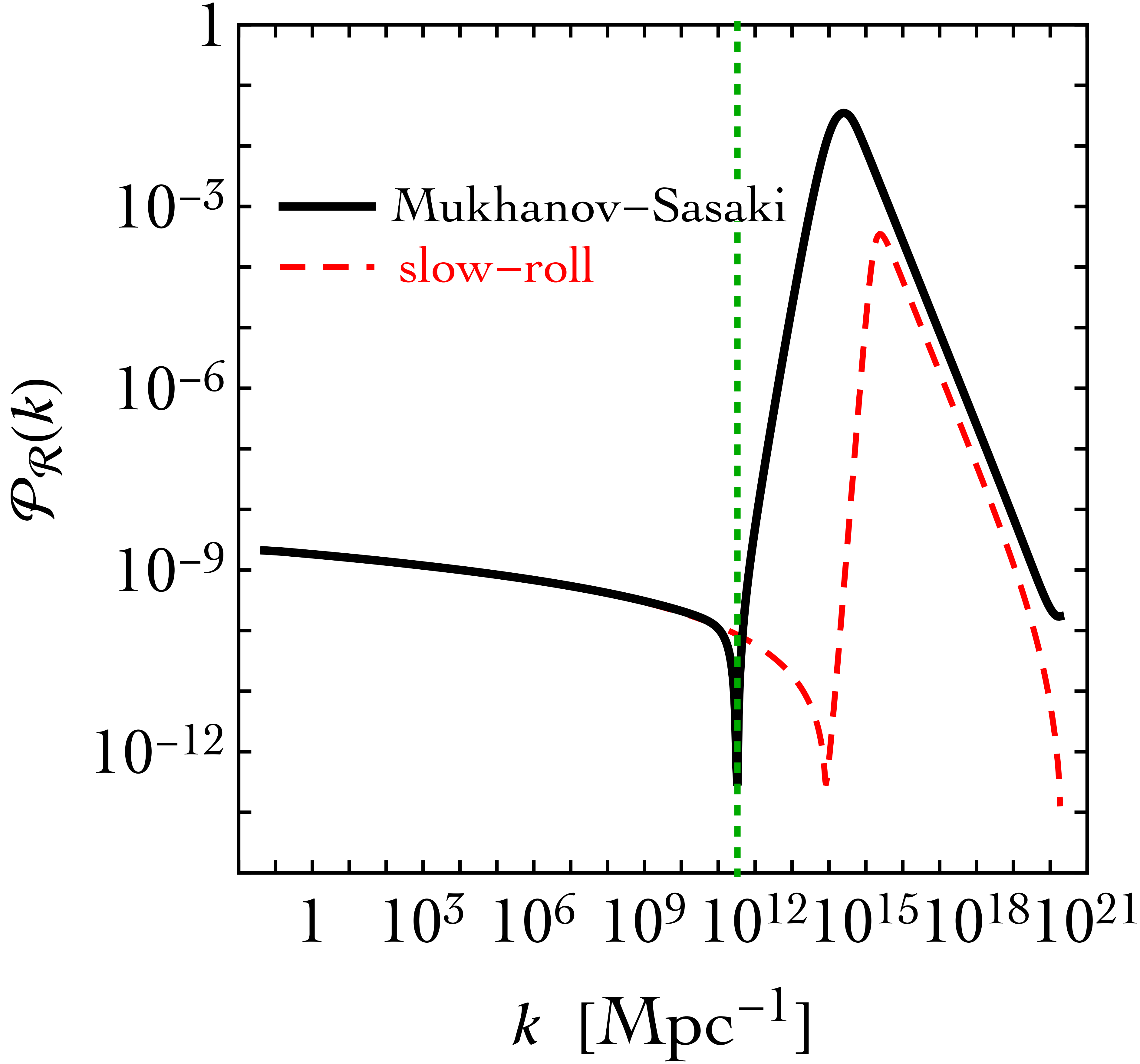


GB, Taoso, 1709.05565

$$V(\phi) = a_2\phi^2 + a_3\phi^3 + a_4\phi^4$$



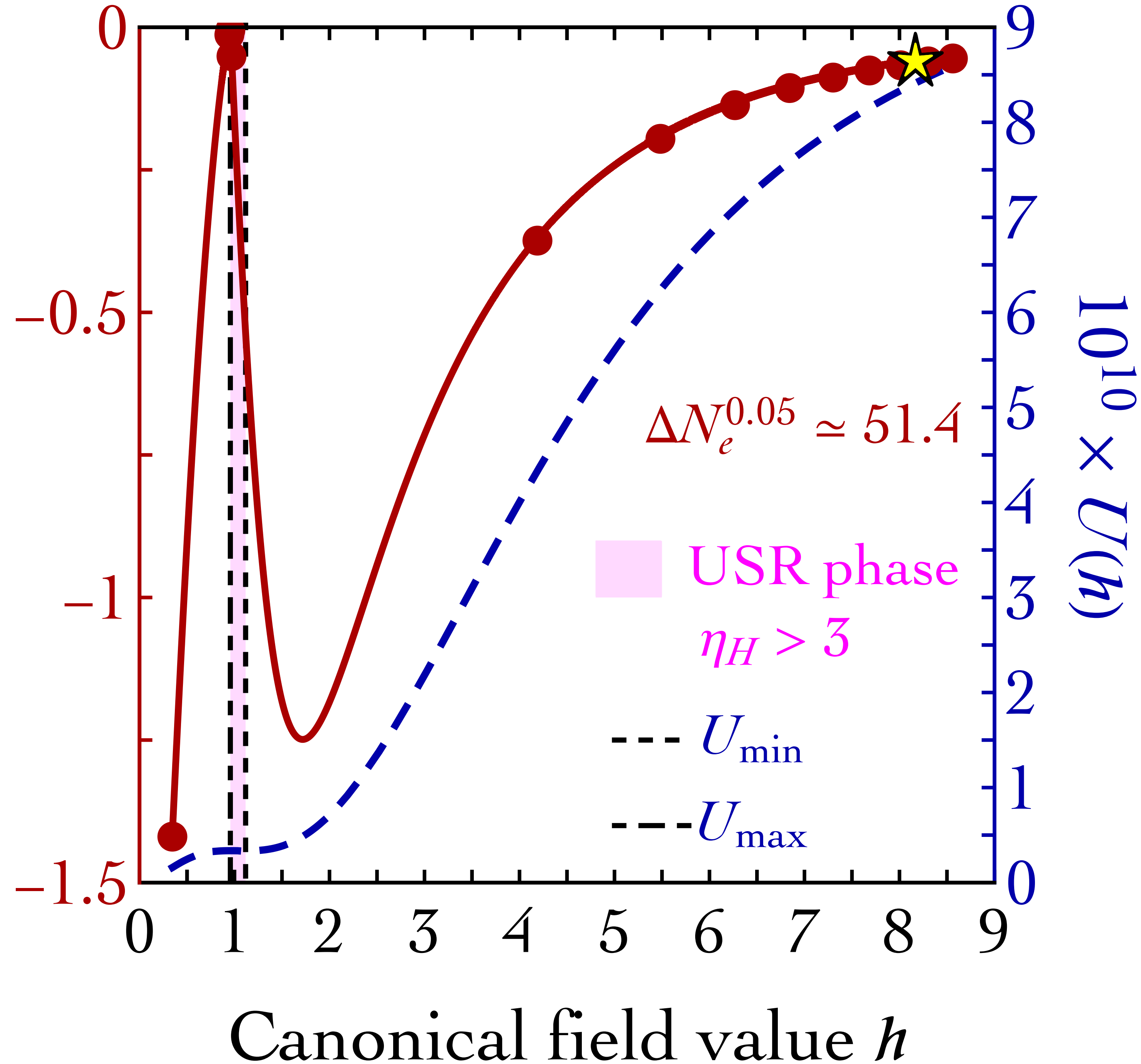
GB, Rey, Taoso, Urbano, 2020



GB, Rey, Taoso, Urbano, 2020

$$\frac{d^2\mathcal{R}_{\mathbf{k}}}{dN_e^2} + (3+\epsilon_H - 2\eta_H)\frac{d\mathcal{R}_{\mathbf{k}}}{dN_e} + \frac{k^2}{a^2H^2}\mathcal{R}_{\mathbf{k}} = 0$$

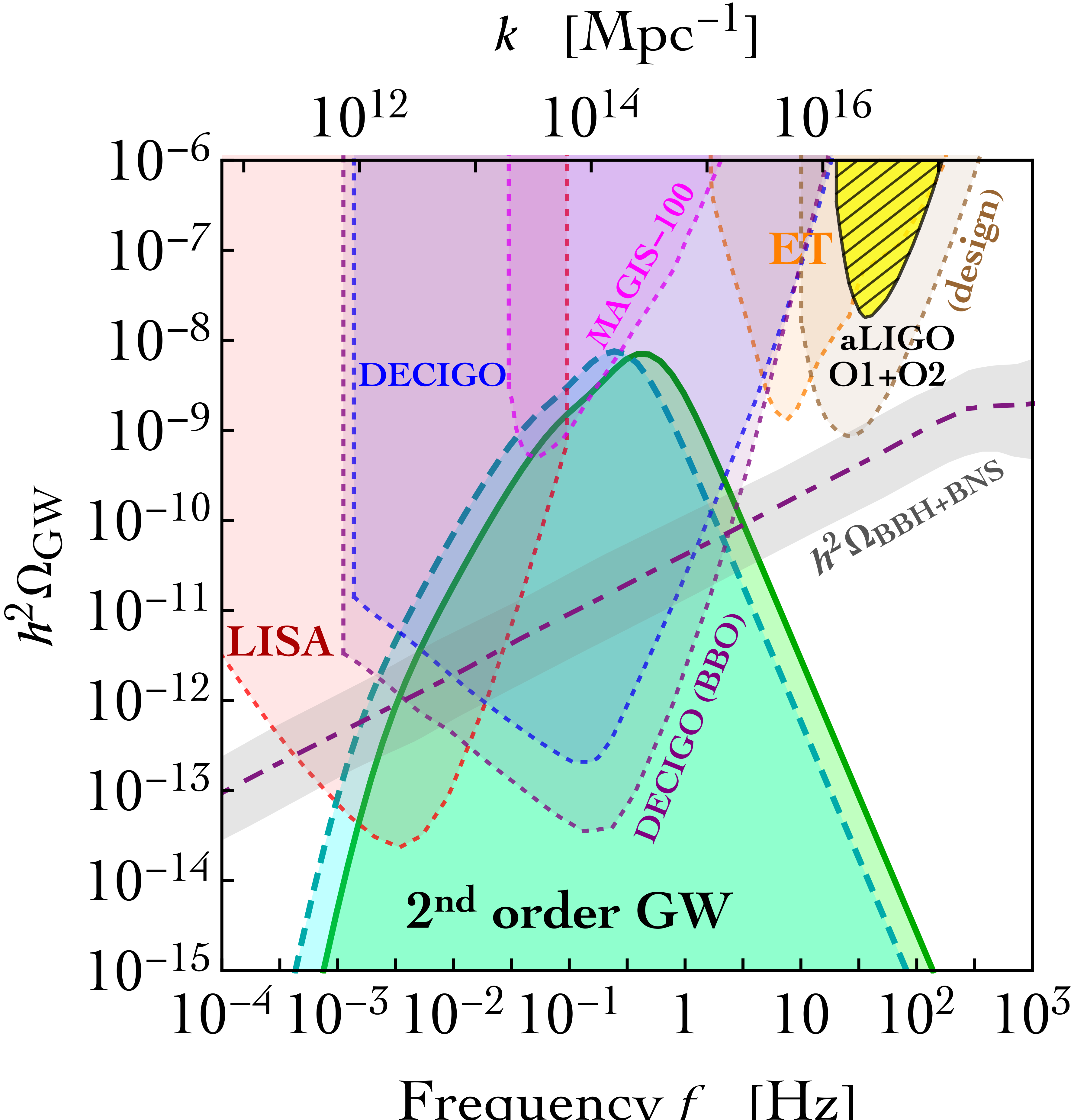
$$\epsilon_H \equiv -\frac{\dot{H}}{H^2} = \frac{1}{2}\left(\frac{dh}{dN_e}\right)^2 \qquad \eta_H \equiv -\frac{\ddot{H}}{2H\dot{H}} = \epsilon_H - \frac{1}{2}\frac{d\log\epsilon_H}{dN_e}$$



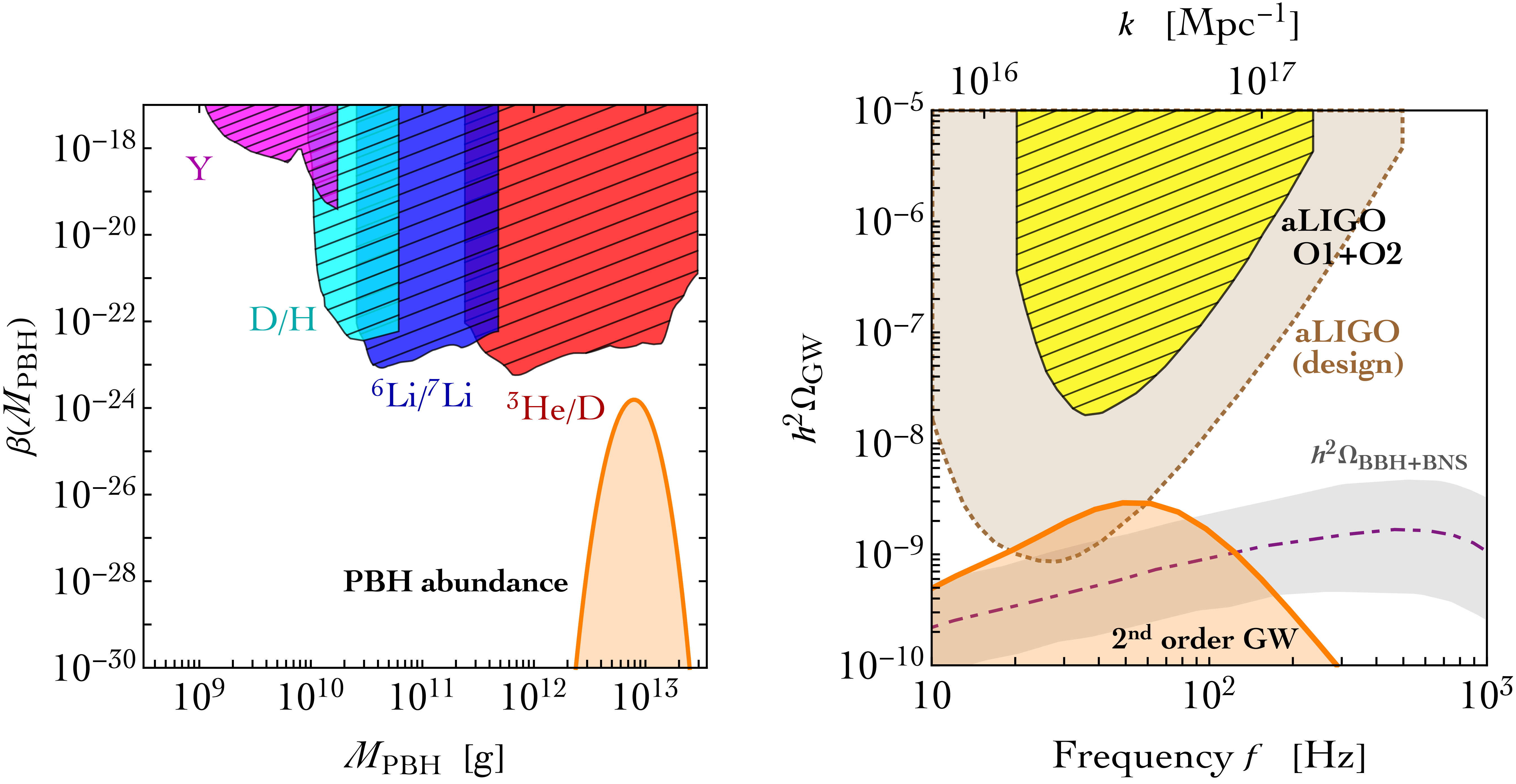
GB, Rey, Taoso, Urbano, 2020

GW

$$\left(\frac{M_{\mathrm{PBH}}}{10^{17}\,\mathrm{g}}\right)^{-1/2} \simeq \frac{k}{2\cdot 10^{14}\,\mathrm{Mpc}^{-1}} \simeq \frac{f}{0.3\,\mathrm{Hz}}$$



GB, Rey, Taoso, Urbano, 2020



GB, Rey, Taoso, Urbano, 2020

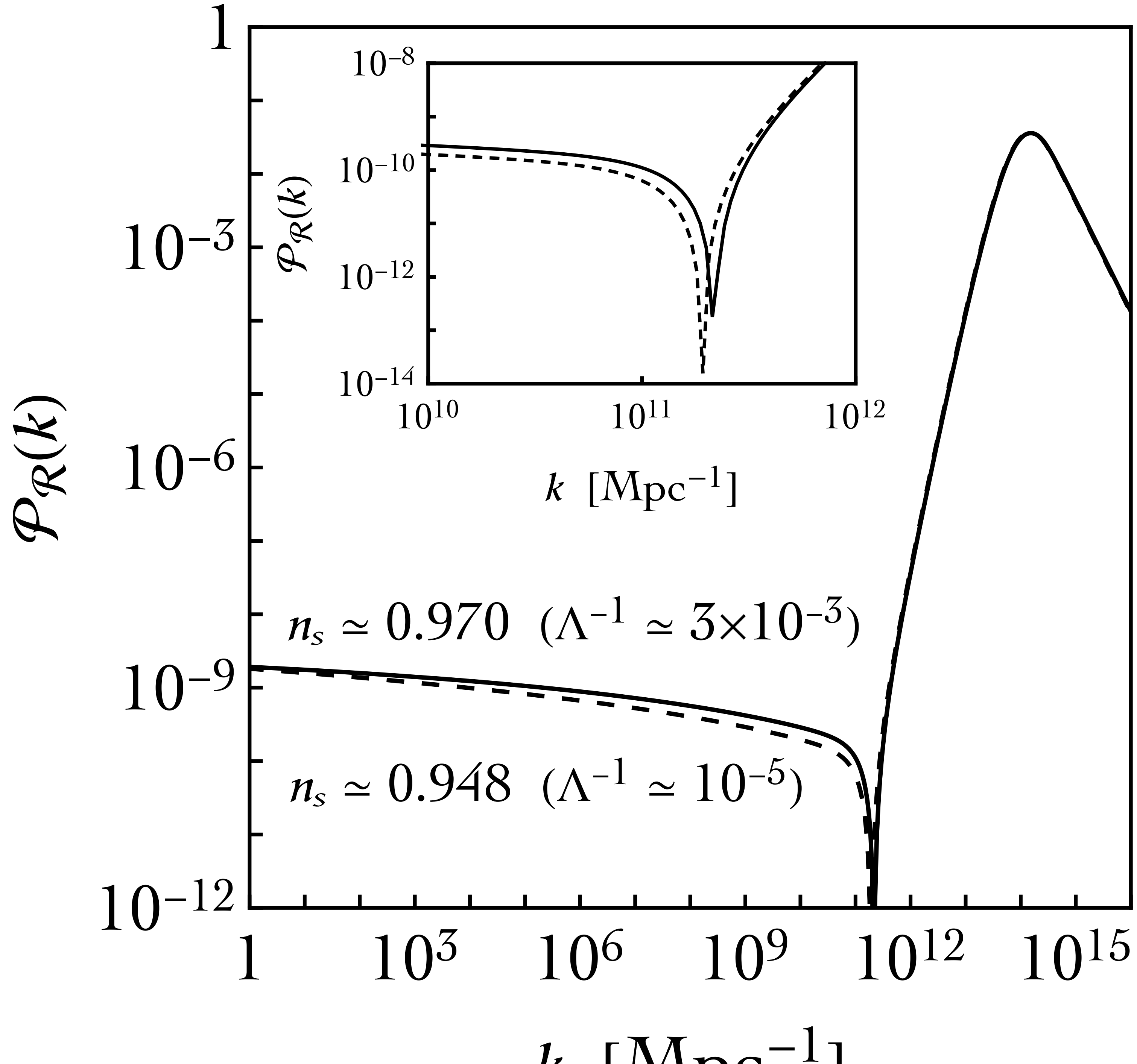
The scalar spectral index

$$n_s \simeq 0.95$$

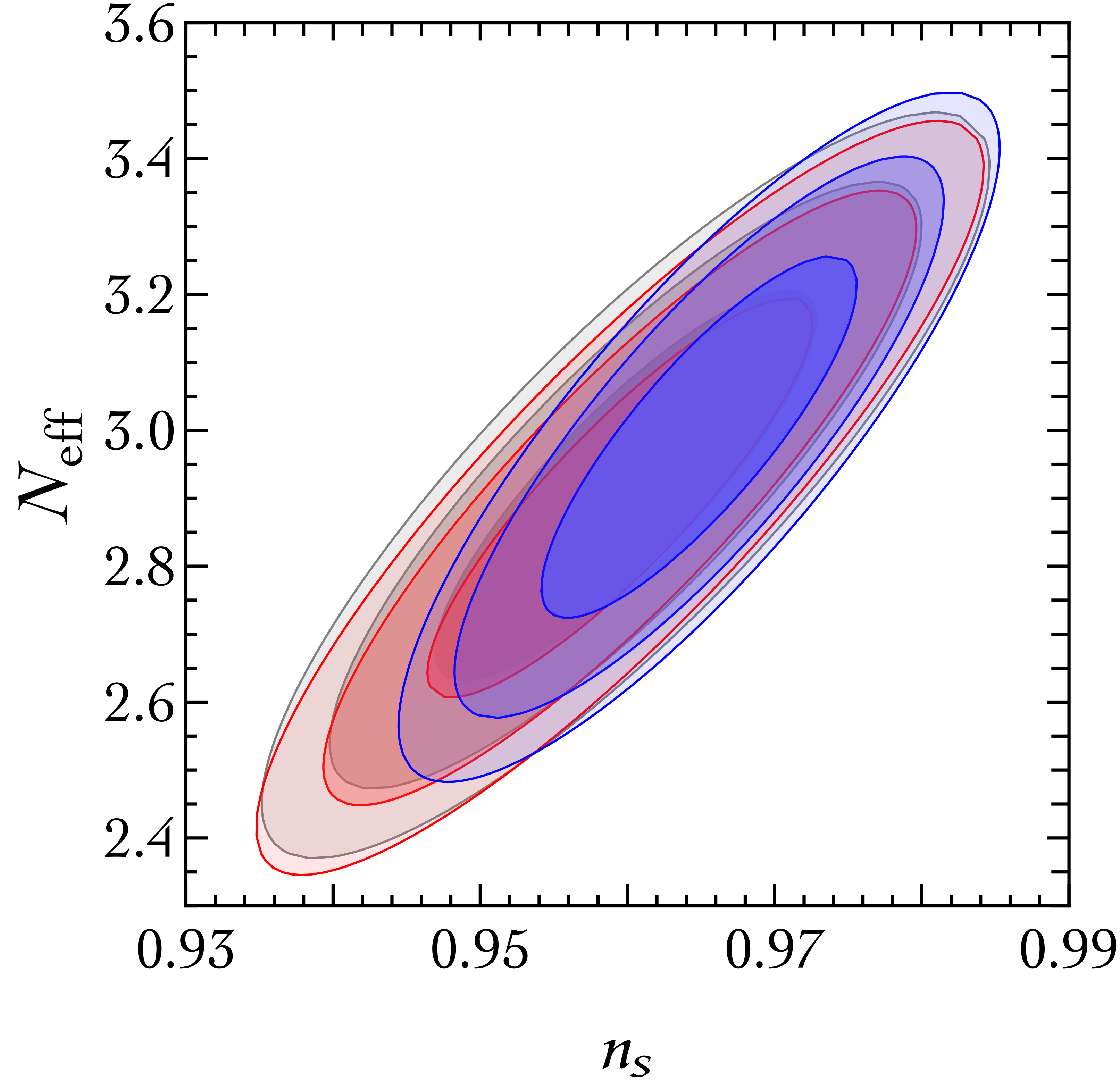
$$\text{Base}\,\Lambda\text{CDM}: \quad n_s = 0.9649 \pm 0.0042$$

$$[68\%\,\text{CL},\ \text{Planck}\,\text{TT}, \text{TE}, \text{EE} + \text{lowE} + \text{lensing}]$$

$$V(\phi) = a_2\phi^2 + a_3\phi^3 + a_4\phi^4 + \sum_{n\geqslant 5} a_n\phi^n$$



GB, Rey, Taoso, Urbano, 2020



GB, Rey, Taoso, Urbano, 2020

Generic quadratic action

$$\mathcal{S} = \int \mathrm{d}t\, \mathrm{d}^3x\, M^2 \frac{a^3\epsilon}{c_\mathrm{s}^2} \left[\dot{\mathcal{R}}^2 - \frac{c_\mathrm{s}^2}{a^2}|\vec{\nabla}\mathcal{R}|^2 - m^2\mathcal{R}^2\right]$$

$$\mathrm{d}\tilde{\tau} = c_\mathrm{s}\, \mathrm{d}\tau = \frac{c_\mathrm{s}}{a}\mathrm{d}t. \qquad z^2 \equiv \frac{2M^2a^2\epsilon}{c_\mathrm{s}}\,, \qquad m = 0$$

$$\mathcal{S} = \frac{1}{2}\int \mathrm{d}\tilde{\tau}\, \mathrm{d}^3x\, z^2 \left[(\mathcal{R}')^2 - |\vec{\nabla}\mathcal{R}|^2\right] \qquad \mathcal{R}_k'' + 2\frac{z'}{z}\mathcal{R}_k' + k^2\mathcal{R} = 0\,.$$

$$\mathcal{P}_\mathcal{R} \propto \frac{H^2}{\epsilon\, c_s\, M^2} \longleftarrow \mathcal{R} \simeq C_{1,k} + C_{2,k}\int \frac{c_\mathrm{s}^2}{a^3M^2\epsilon H}\mathrm{d}N$$

$$\frac{d\mathcal{R}}{dN_e} = C_{2,k}\exp\left[-\int(3 + \epsilon_H - 2\eta_H - 2s + \mu)\right]dN_e$$

Example I: The EFT of inflation

$$m = 0\,, \quad M = M_P$$

Unitarity: $\Lambda^4 \sim 16\pi^2 M_P^2 H^2 \epsilon \frac{c_{\rm s}^5}{1-c_{\rm s}^2} \gg H^4$ Cheung et al 2007

$$c_s^2 \gg \mathcal{P}_{\mathcal{R}}$$

Ghost condensate:

$$\mathcal{P}_{\mathcal{R}} \sim 0.01 \left(\frac{H}{M}\right)^{5/2}$$

Arkani-Hamed, et al 2003

Example II: Solid inflation

Gruzinov 2004 & Endlich, Nicolis, Wang 2012

$$m \neq 0\,, \quad M = M_P$$

EFT of 3 derivatively coupled scalars, SO(3)

Non-conservation of super-horizon fluctuations

$$\mathcal{P}_{\mathcal{R}} \simeq \frac{H^2}{8\pi^2 \epsilon\, c_L\, M_P^2} \simeq c_L^4\, \mathcal{P}_\zeta$$

$$\left(\epsilon\, c_L^2\right)^2 \gg 8\pi^2 \mathcal{P}_\zeta$$

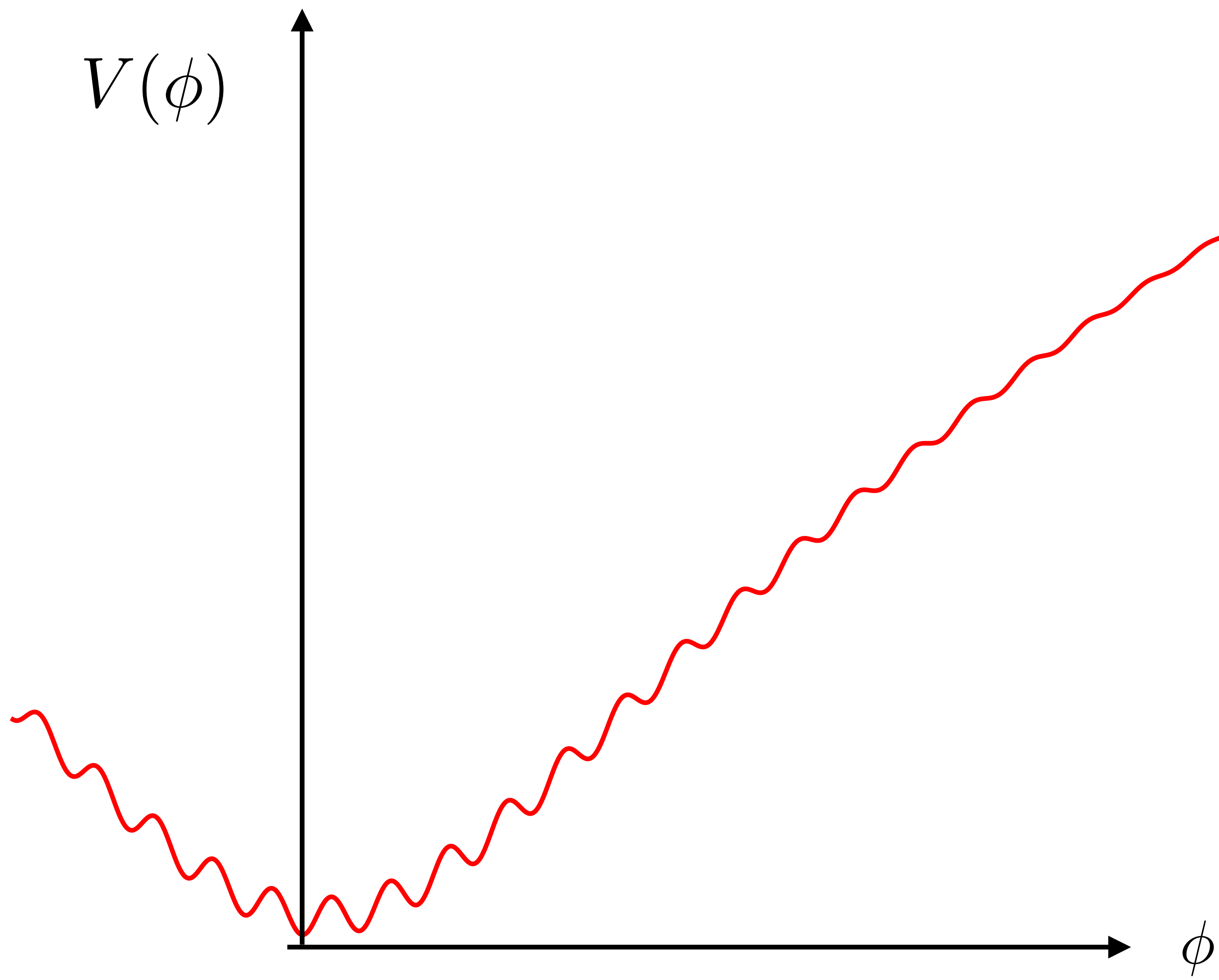
Exponential sensitivity

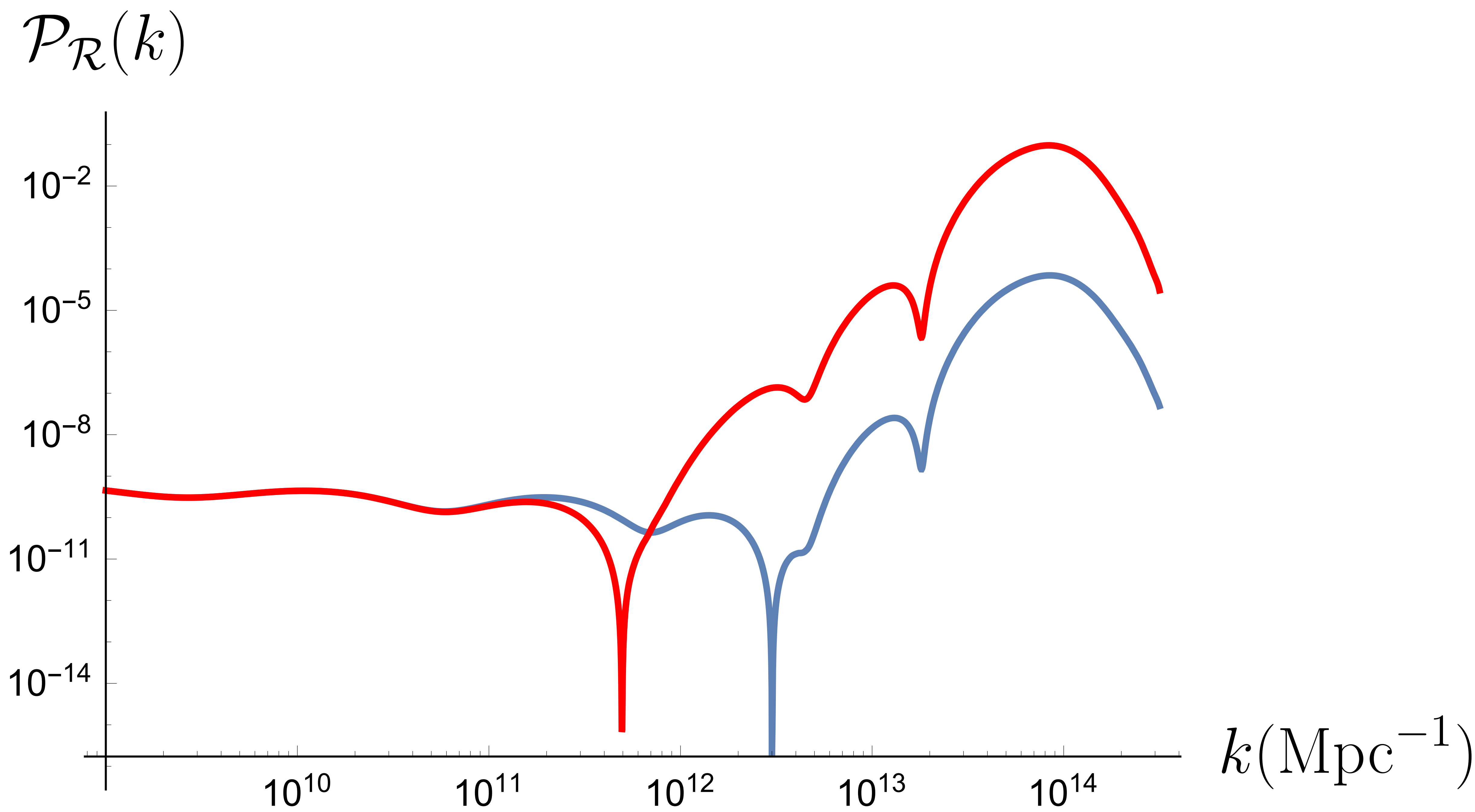
$$\beta(M) = \frac{1}{\sqrt{2\pi\sigma^2(M)}} \int_{\delta_c}^{\infty} d\delta \, \exp\left(\frac{-\delta^2}{2\sigma^2(M)}\right)$$

$$\sigma^2 \sim \mathcal{P}_{\mathcal{R}} \sim \frac{1}{\epsilon}$$

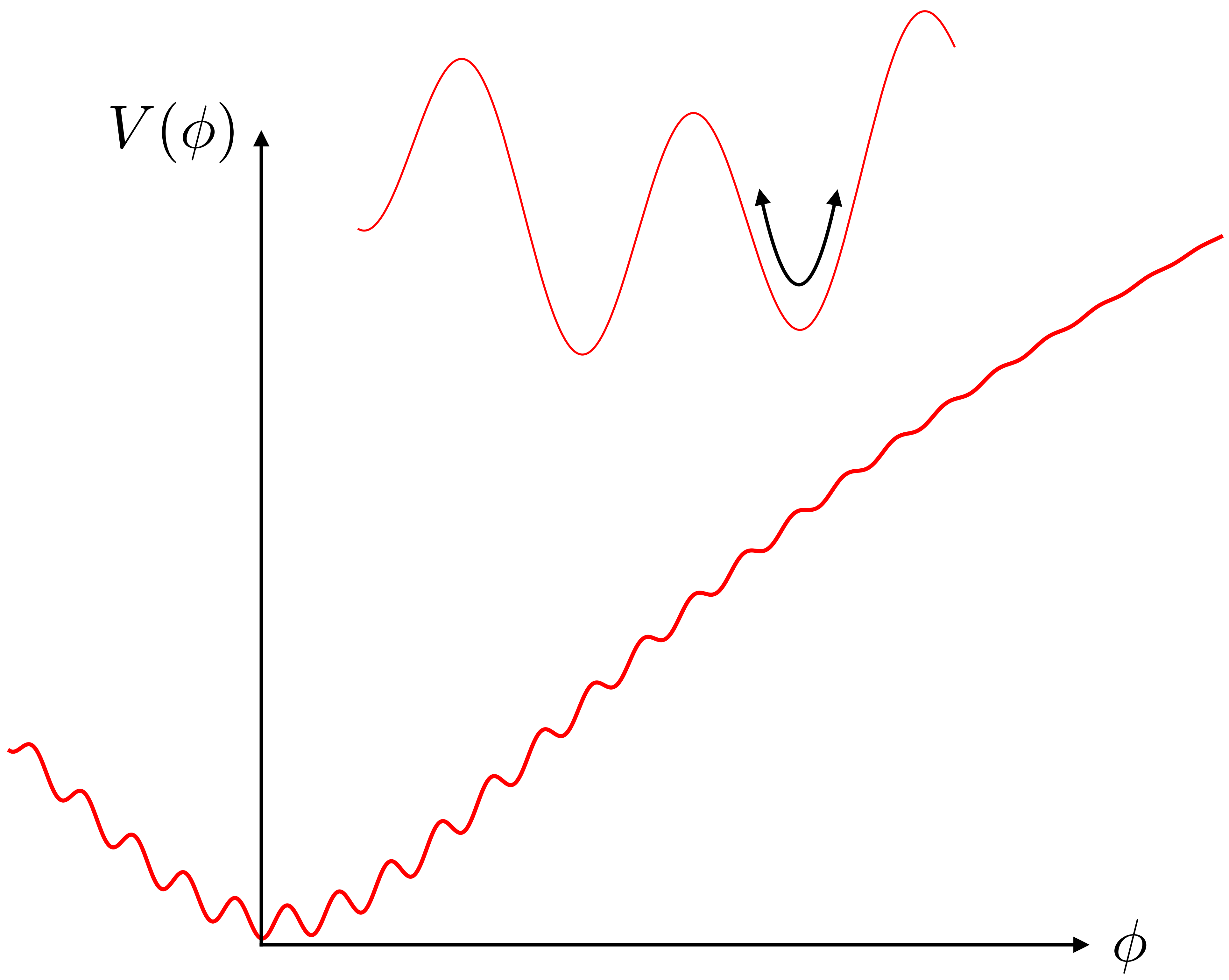
Modulation

$$V(\phi) = m^2 f^2 \left[\frac{1}{2p} \frac{F^2}{f^2} \left(-1 + \left(1 + \frac{\phi^2}{F^2} \right)^p \right) + \kappa e^{-\left(\frac{\phi}{\phi_\Lambda}\right)^{p_\Lambda}} \cos\left(\frac{\phi}{f} + \delta \right) \right] + V_0$$



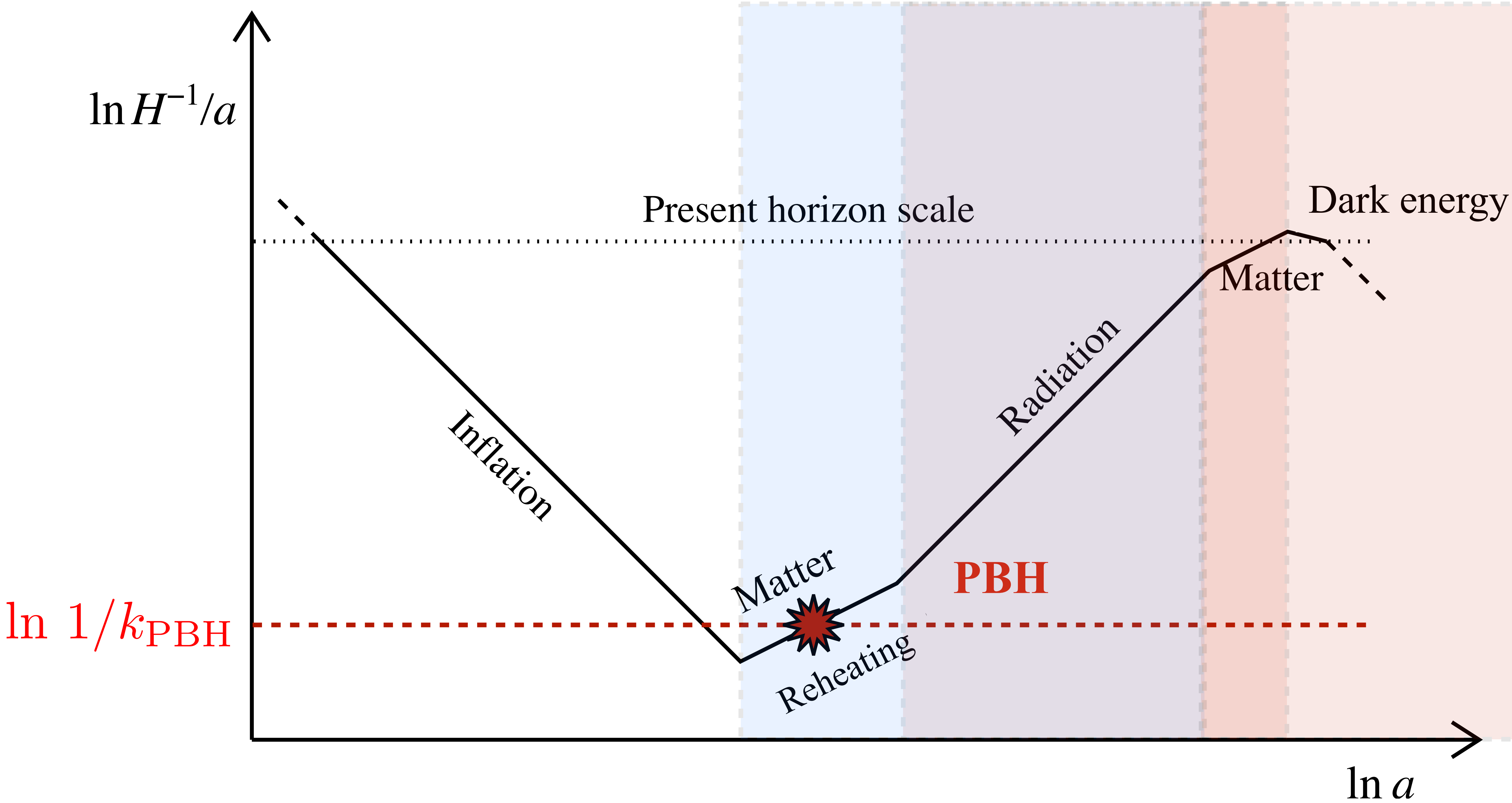


Ballesteros, Rey, Rompineve 2019



$V(\phi)$
ϕ

PBH formation during early matter domination



Adapted from Liddle and Leach, 2003

$$M_{\rm PBH} \simeq 2.8 \cdot 10^{-16} \, \left(\frac{\gamma}{0.2}\right) \left(\frac{g(T_k)}{g_s(T_k)}\right)^{2/3} \left(\frac{106.75}{g(T_k)}\right)^{1/6} \left(\frac{10^{14}\ {\rm Mpc}^{-1}}{k}\right)^2 M_\odot \quad \text{for RD},$$

$$f_{\rm PBH} \simeq \left(\frac{\gamma}{0.2}\right)^{3/2} \left(\frac{\beta}{8.9 \cdot 10^{-16}}\right) \left(\frac{g(T_k)}{106.75}\right)^{-1/4} \left(\frac{g(T_k)}{g_s(T_k)}\right) \left(\frac{M_{\rm PBH}}{10^{-15}\ M_\odot}\right)^{-1/2}$$

$$M_{\rm PBH} \simeq 2.4 \cdot 10^{-17} \, \gamma \left(\frac{g(T_m)}{g_s(T_m)}\right) \left(\frac{10^{14}\ {\rm Mpc}^{-1}}{k}\right)^3 \left(\frac{T_m}{10^5\ {\rm GeV}}\right) M_\odot \quad \text{for early MD}\,.$$

$$f_{\rm PBH} \simeq \gamma \left(\frac{\beta}{5.5 \cdot 10^{-15}}\right) \left(\frac{g(T_m)}{g_s(T_m)}\right) \left(\frac{T_m}{10^5\ {\rm GeV}}\right)$$

$$T_m = \left(\frac{M_p}{t_m}\right)^{1/2} \left(\frac{4\pi^2 g(T_m)}{90}\right)^{-1/4}$$

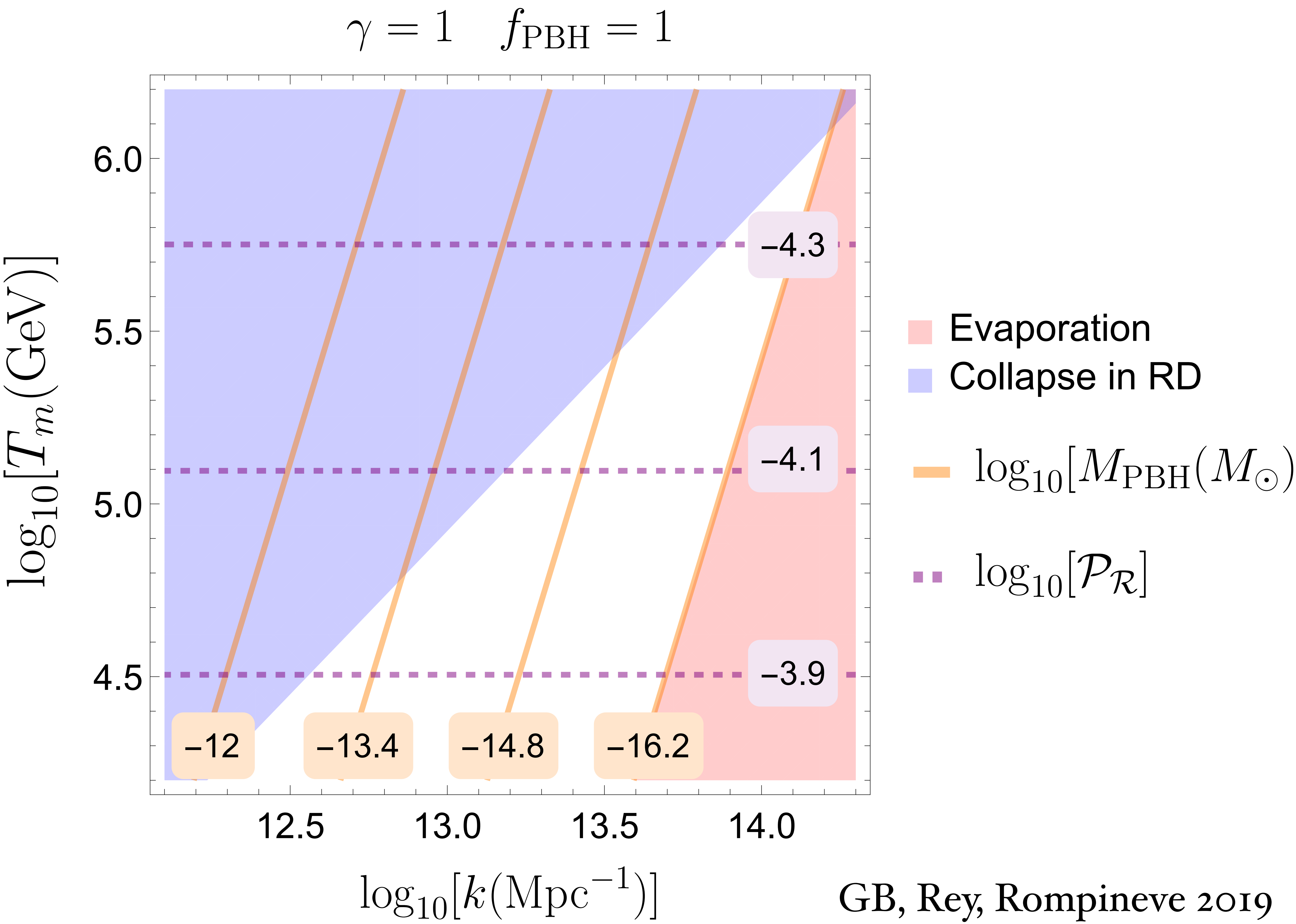
Radiation domination

$$\beta \sim \frac{\sigma}{\delta_c} e^{-\delta_c^2/\sigma^2}$$

Matter domination

$$\beta \sim \sigma^5$$

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



GB, Rey, Rompineve 2019

Summary

Watch out for **light** PBHs: $10^{-16} M_\odot \leftrightarrow 10^{-11} M_\odot$

- PBH from inflation: not generic
- Potential with inflection point
- Small speed of sound.
  EFTs: strong coupling?
- Multiple minima (modulation)
  Early phase of matter domination