PRIMORDIAL BLACK HOLES AS DARK MATTER FROM INFLATION

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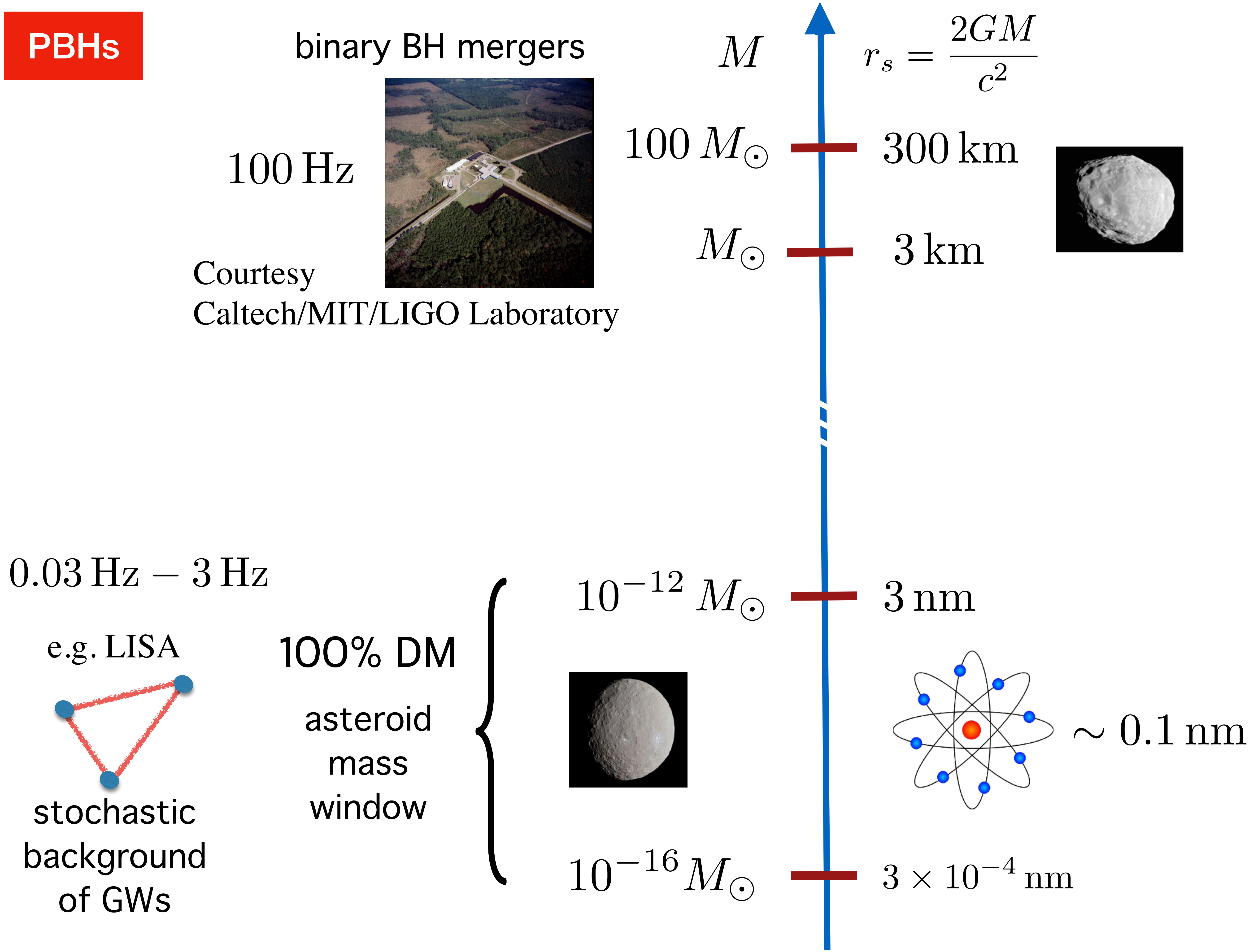
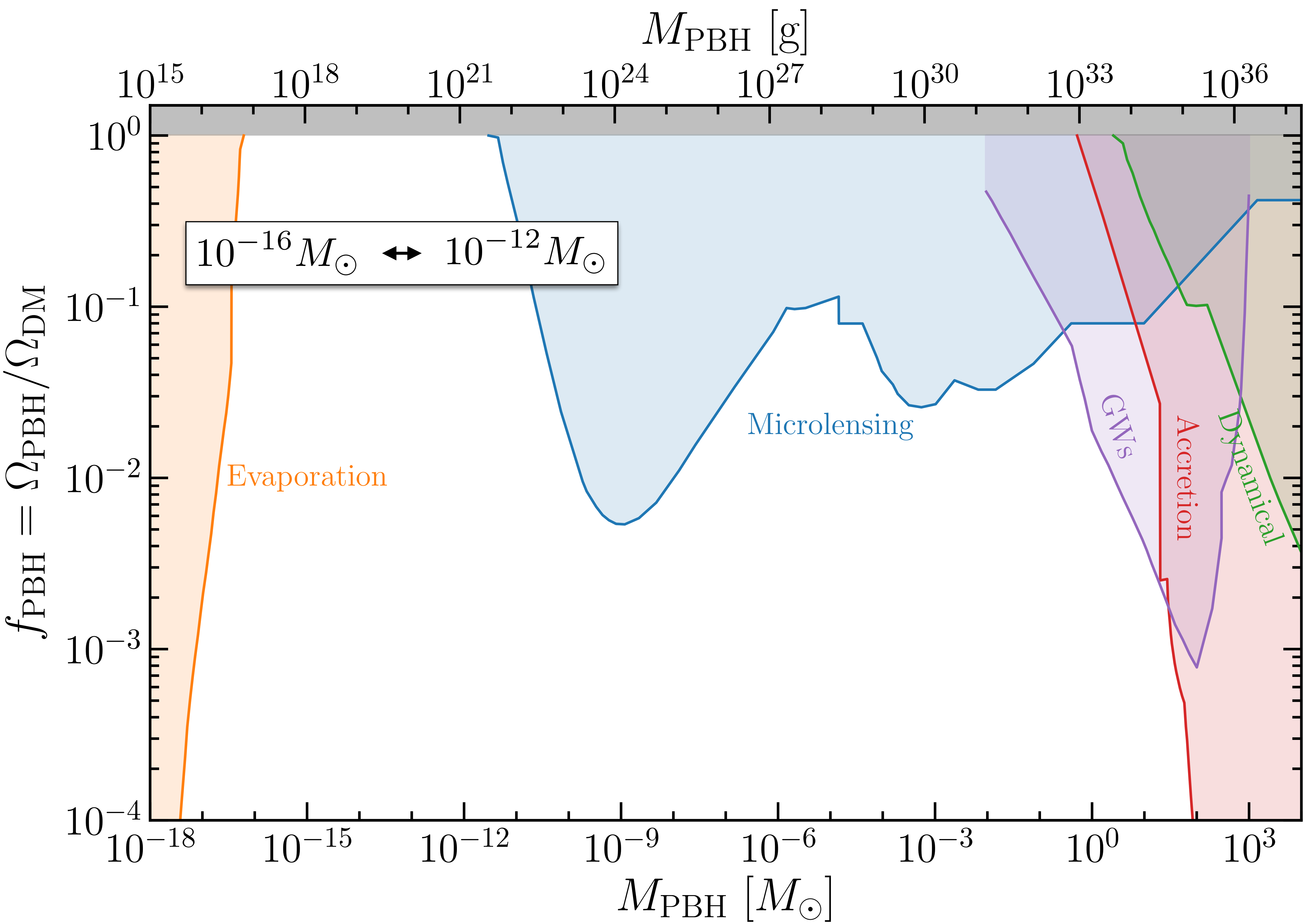
Fabrizio Rompineve, Luca Santoni,
Marco Taoso, Alfredo Urbano

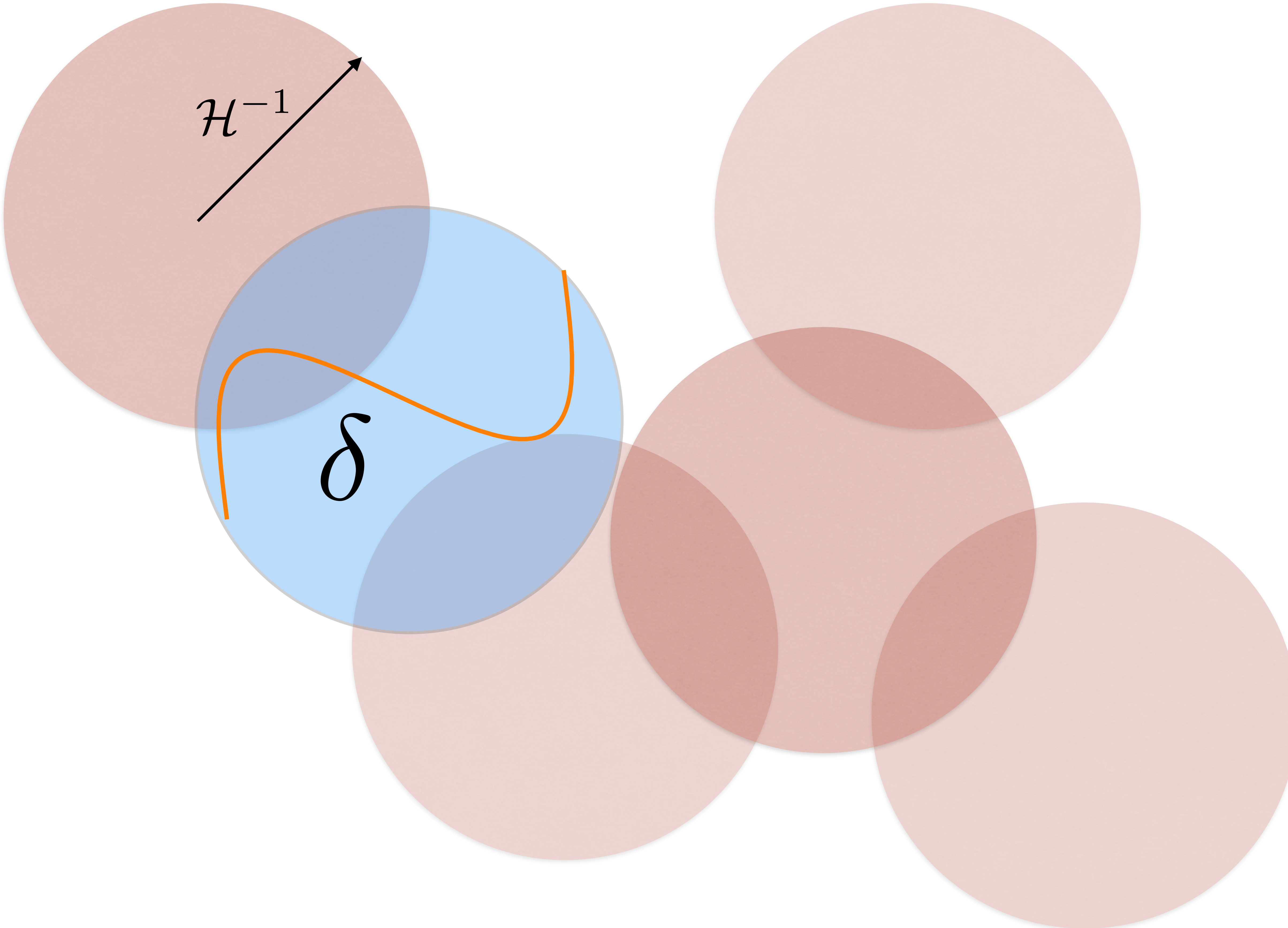

PBHs
binary BH mergers
100 Hz
Courtesy
Caltech/MIT/LIGO Laboratory
M
$r_s = \frac{2GM}{c^2}$
$100\ M_\odot$
300 km
$M_\odot$
3 km
0.03 Hz – 3 Hz
e.g. LISA
stochastic
background
of GWs
100% DM
asteroid
mass
window
$10^{-12}\ M_\odot$
3 nm
~ 0.1 nm
$10^{-16}\ M_\odot$
3×10^{-4} nm

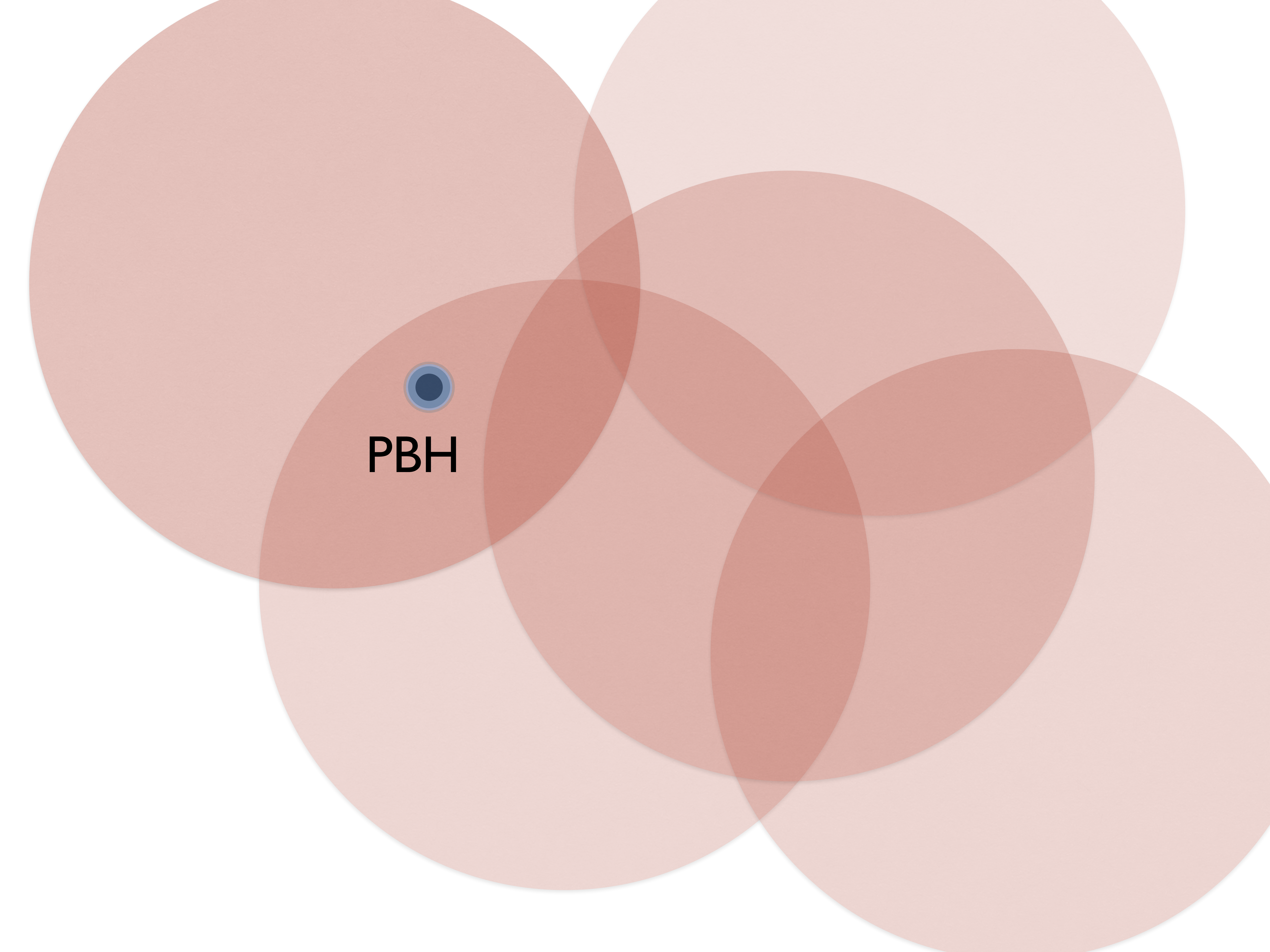


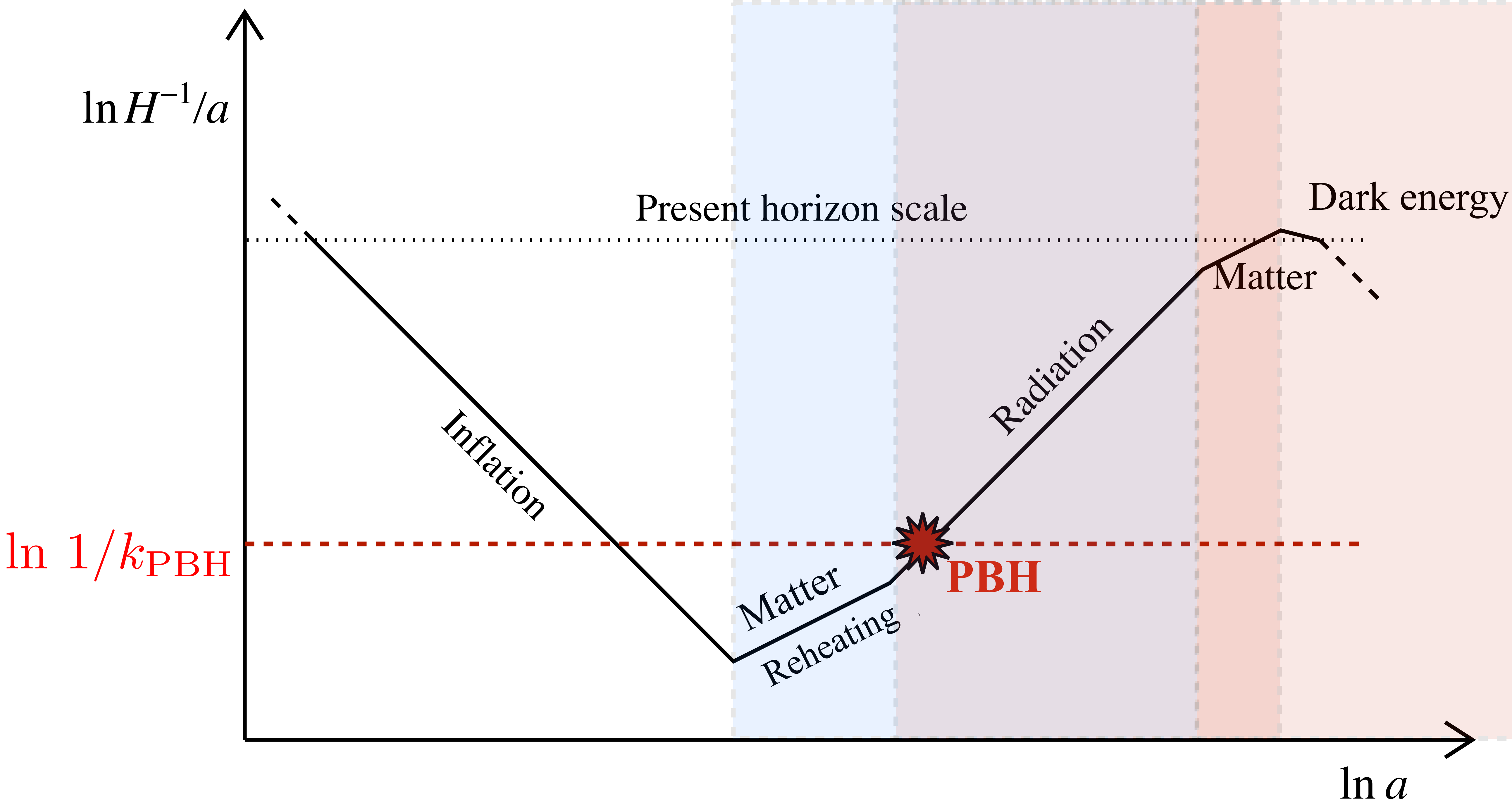
https://github.com/bradkav/PBHbounds

Green, Kavanagh 2007.10722 (v3 December 2020)

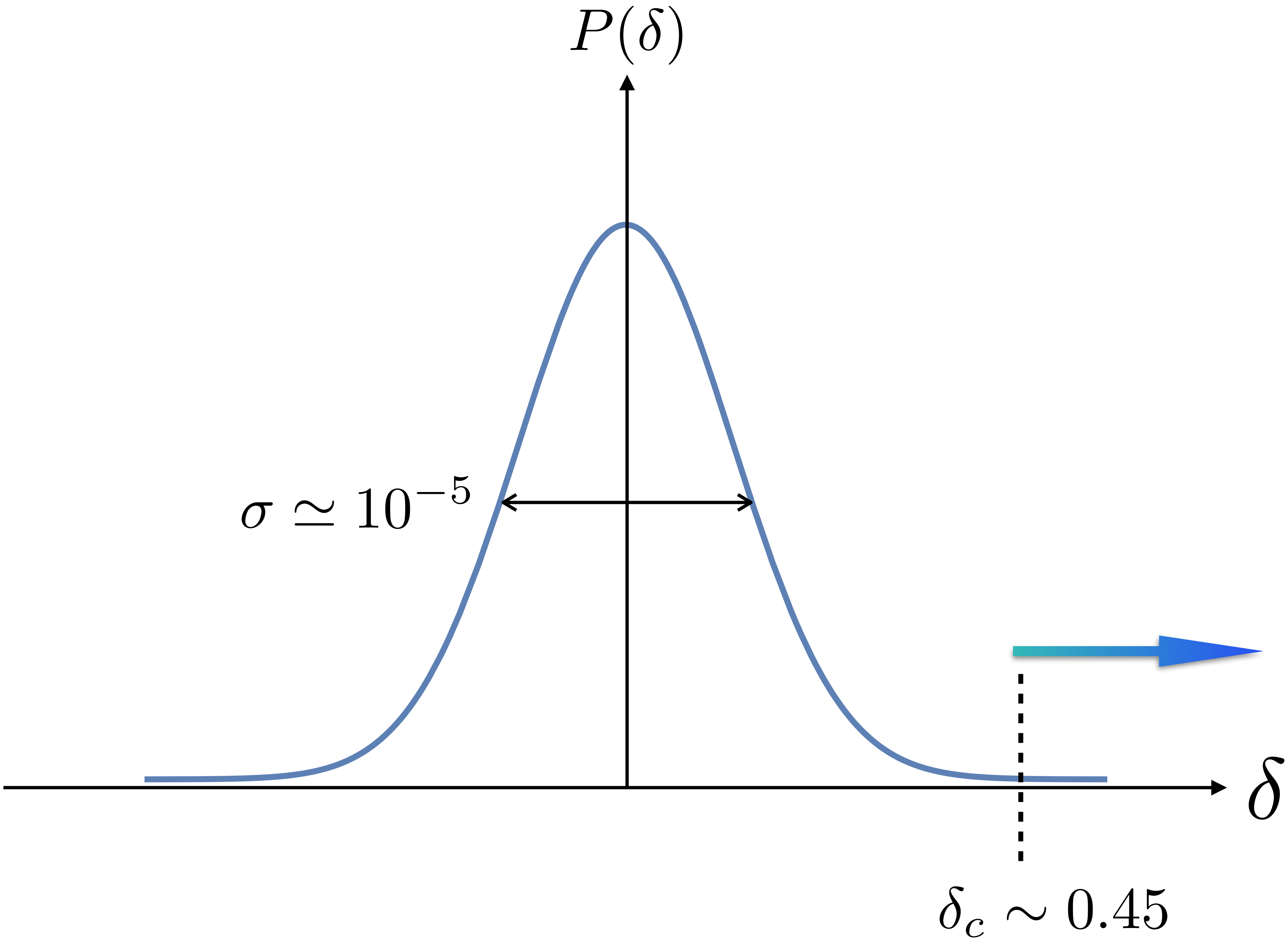
Primordial black hole formation from single-field inflation


$\mathcal{H}^{-1}$
δ


PBH



Adapted from Liddle and Leach, 2003



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

Individual masses

$$M \sim \frac{4}{3}\pi\,\rho\,H^{-3} \;\; \sim 10^{-14}\left(\frac{10^{13}\,\mathrm{Mpc}^{-1}}{k}\right)^2 M_\odot$$

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

Abundance

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

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

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

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

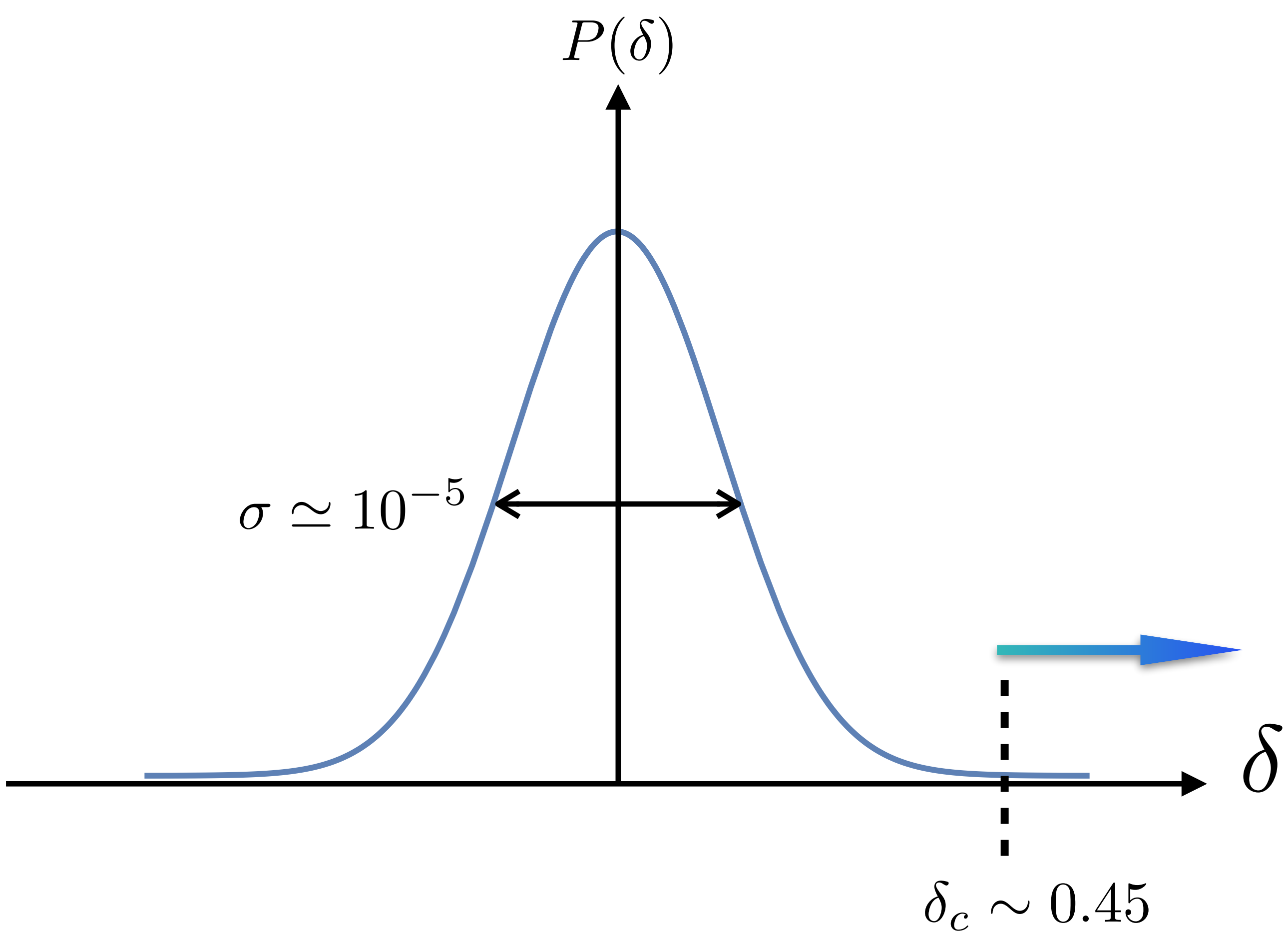
$$\mathcal{P}_{\mathcal{R}} \sim 10^{-2} \implies \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}} \sim 1$$

Is the Gaussian approximation reliable?

$$\delta(\vec{x},t) = -\frac{4(1+\omega)}{5+3\omega}\left(\frac{1}{aH}\right)^2 e^{-5\mathcal{R}(\vec{x})/2}\triangle e^{\mathcal{R}(\vec{x})/2}$$

Intrinsic non-Gaussianities in $\mathcal{R}$

NG $\sim$ $\mathcal{O}(1)$ change in $\mathcal{P}_{\mathcal{R}}$ Taoso, Urbano 2021



How do the tails of the PDF of $\mathcal{R}$ look like?

There are several indications that they are not Gaussian, specifically if slow-roll is broken or if interactions are important

$$q\,\dot{\mathcal{R}}^4 \implies P(\mathcal{R}) \sim \exp\left(-\frac{\mathcal{R}^{3/2}}{q^{1/4}}\right) \qquad \text{for large} \quad \mathcal{R}$$

Celoria, Creminelli, Tambalo, Yingcharoenrat 2021

How do the tails of the PDF of $\mathcal{R}$ look like?

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Quantum diffusion

classical roll: $\frac{\dot{\phi}}{H} \gg \frac{H}{2\pi}$ → $\mathcal{P}_{\mathcal{R}} \ll 1$

Stochastic inflation

Starobinsky

$$\text{USR} \implies P(\mathcal{R}) \sim \exp\left(-\kappa\, R\right) \qquad \text{for large} \quad \mathcal{R}$$

Ezquiaga, García-Bellido, Vennin 2019

Figueroa, Raatikainen, Rasanen, Tomberg 2020

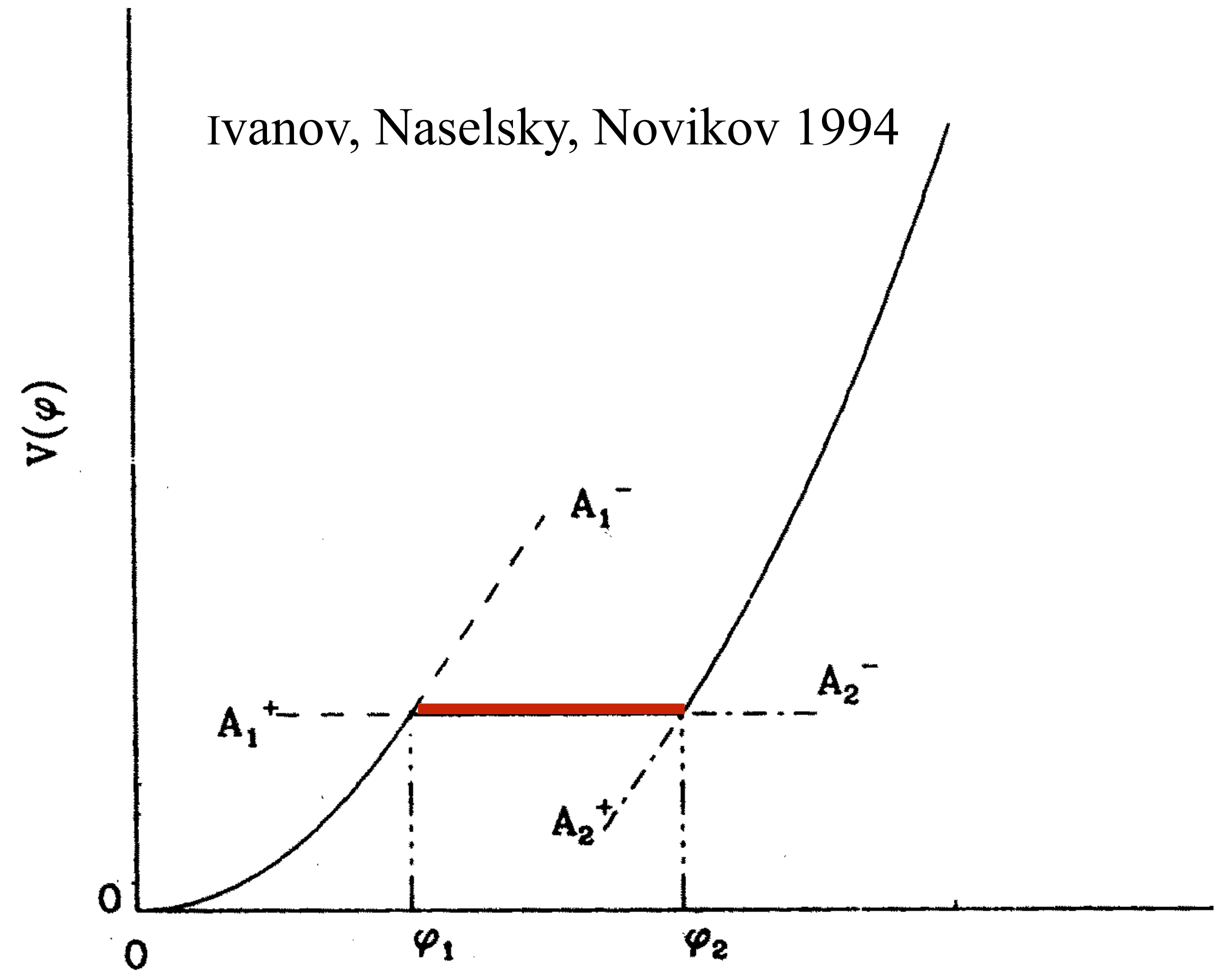
Pattison, Vennin, Wands, Assadullahi 2021

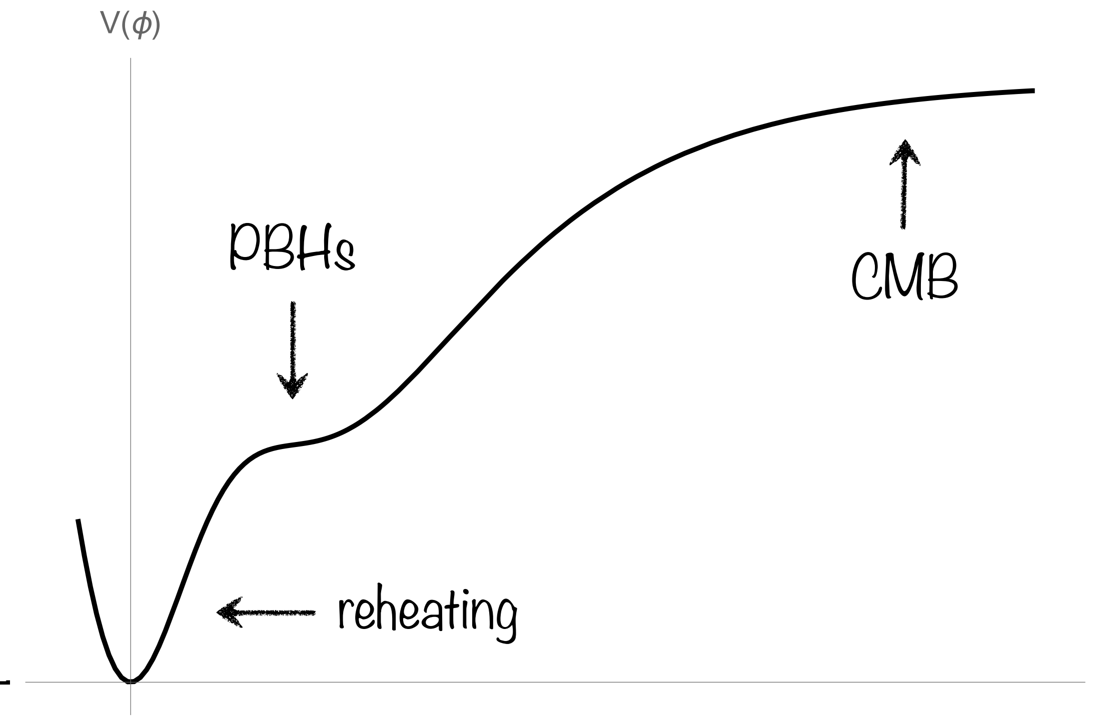
Modelling PBH formation from inflation

Requirements for PBH DM from inflation

- Enough inflation
- Agreement with the CMB and LSS
- Successful reheating
- $\dfrac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \sim 1$ (implies a large primordial spectrum…)
- $\boxed{10^{-16} M_\odot \leftrightarrow 10^{-12} M_\odot}$ (…at a specific scales)

Inflation and primordial black holes as dark matter

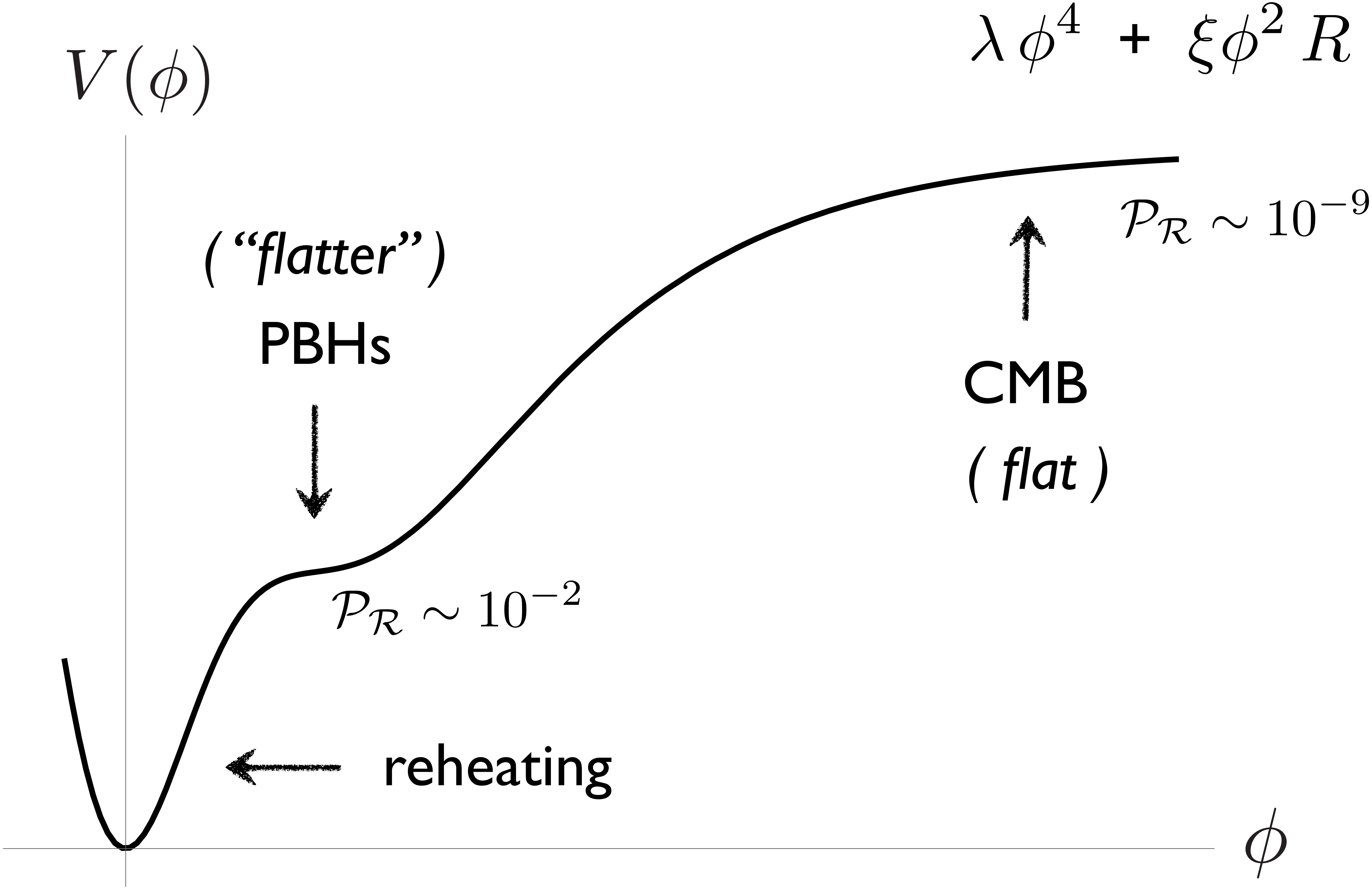




$$V(\phi) = \begin{cases} V_0 + A_+(\phi - \phi_0) & \text{for } \phi > \phi_0 \\ V_0 + A_-(\phi - \phi_0) & \text{for } \phi < \phi_0 \end{cases}$$

Starobinsky 1994

$$\mathcal{P}_{\mathcal{R}} \sim \left(\frac{H}{m_P}\right)^2 \left(\frac{H}{\dot{\phi}}\right)^2 \sim \frac{1}{m_P^2}\left(\frac{V}{V'}\right)^2 \frac{V}{m_P^4}$$


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

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

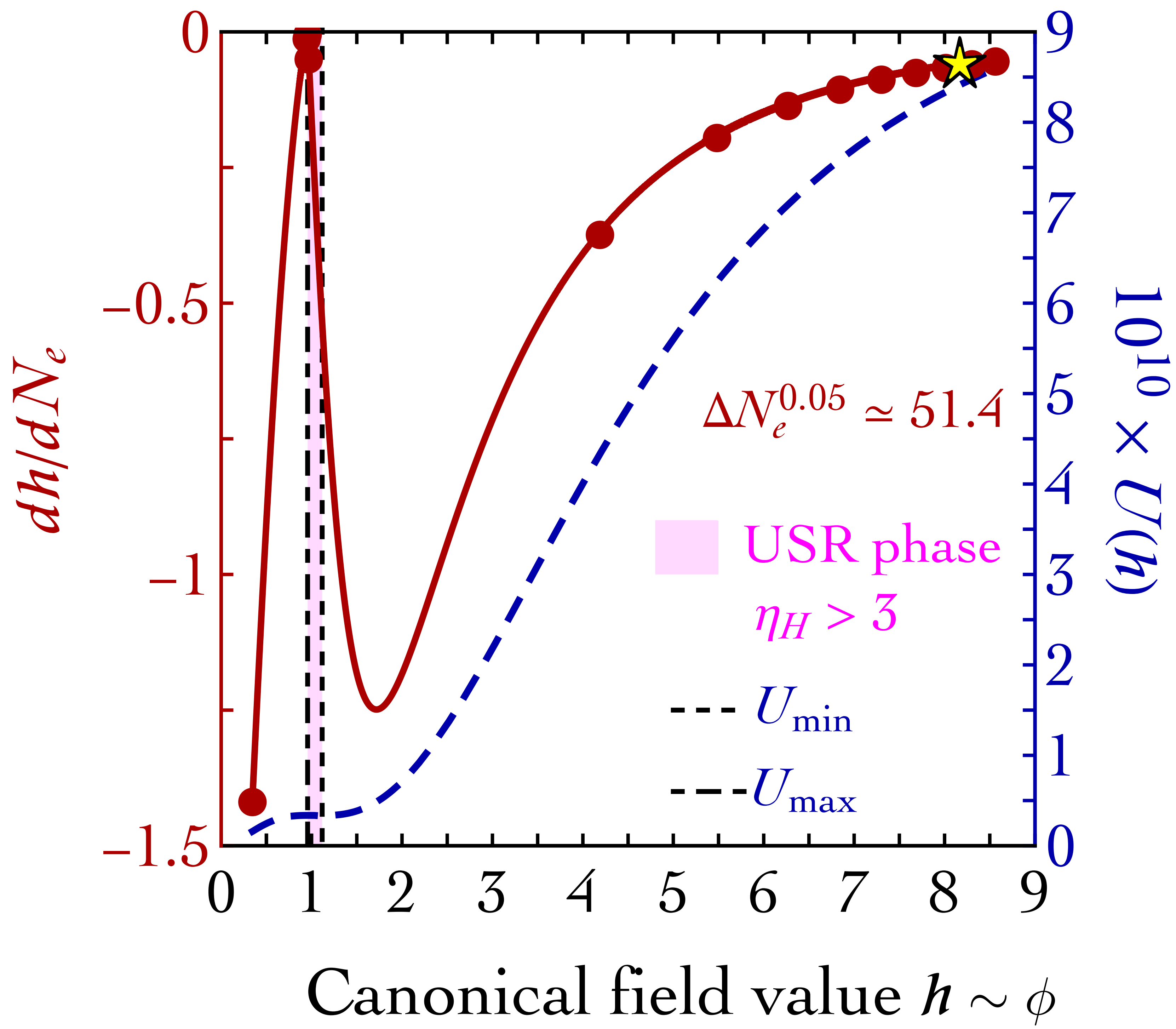
$$V = \lambda(\phi)\,\phi^4$$

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

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

$$\xi(\phi) = \xi_0\left(1 + b_3\log\frac{\phi^2}{\phi_0^2}\right)$$

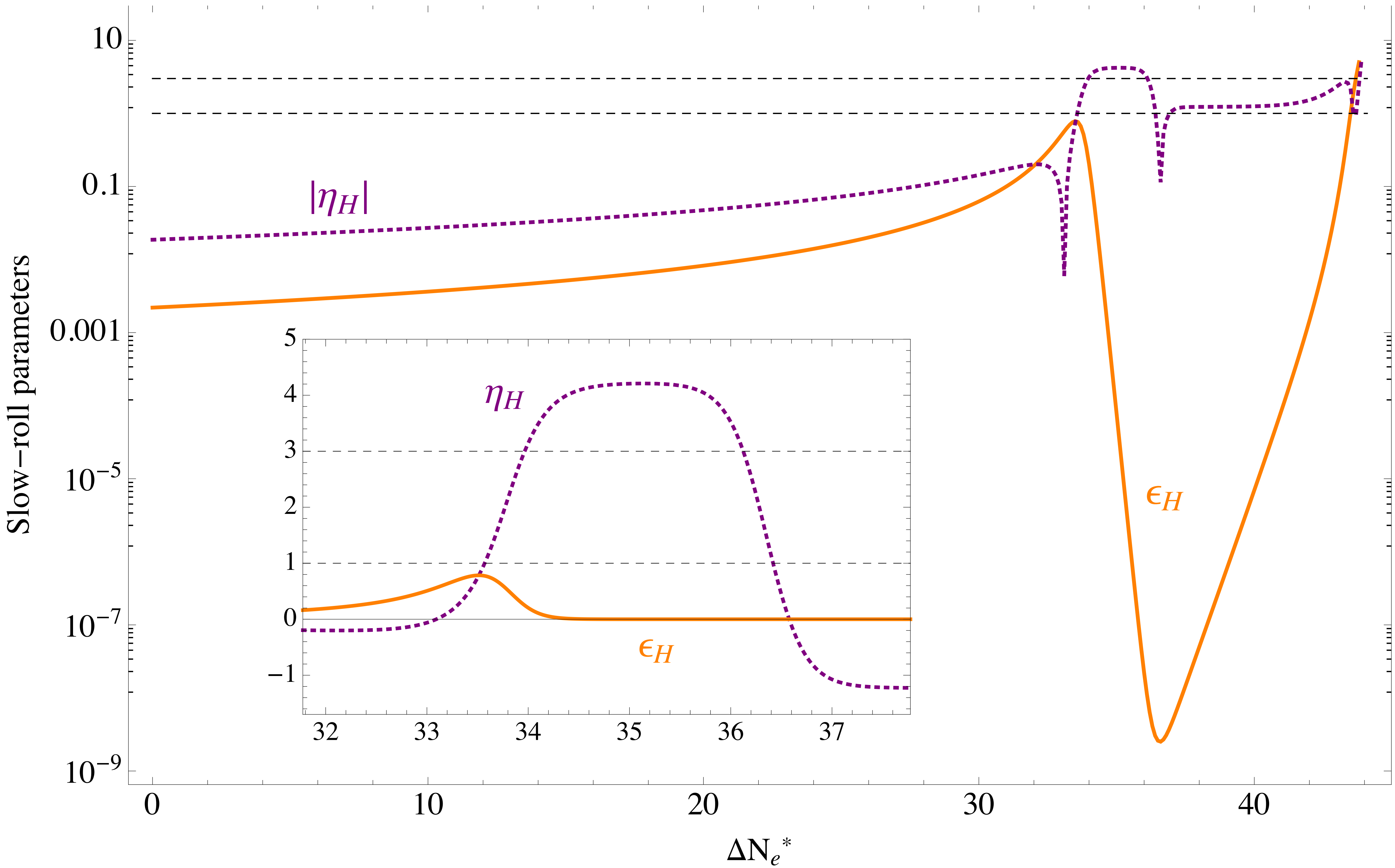
GB, Taoso, 1709.05565



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

GB, Rey, Taoso, Urbano, 2020

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



GB, Taoso, 1709.05565

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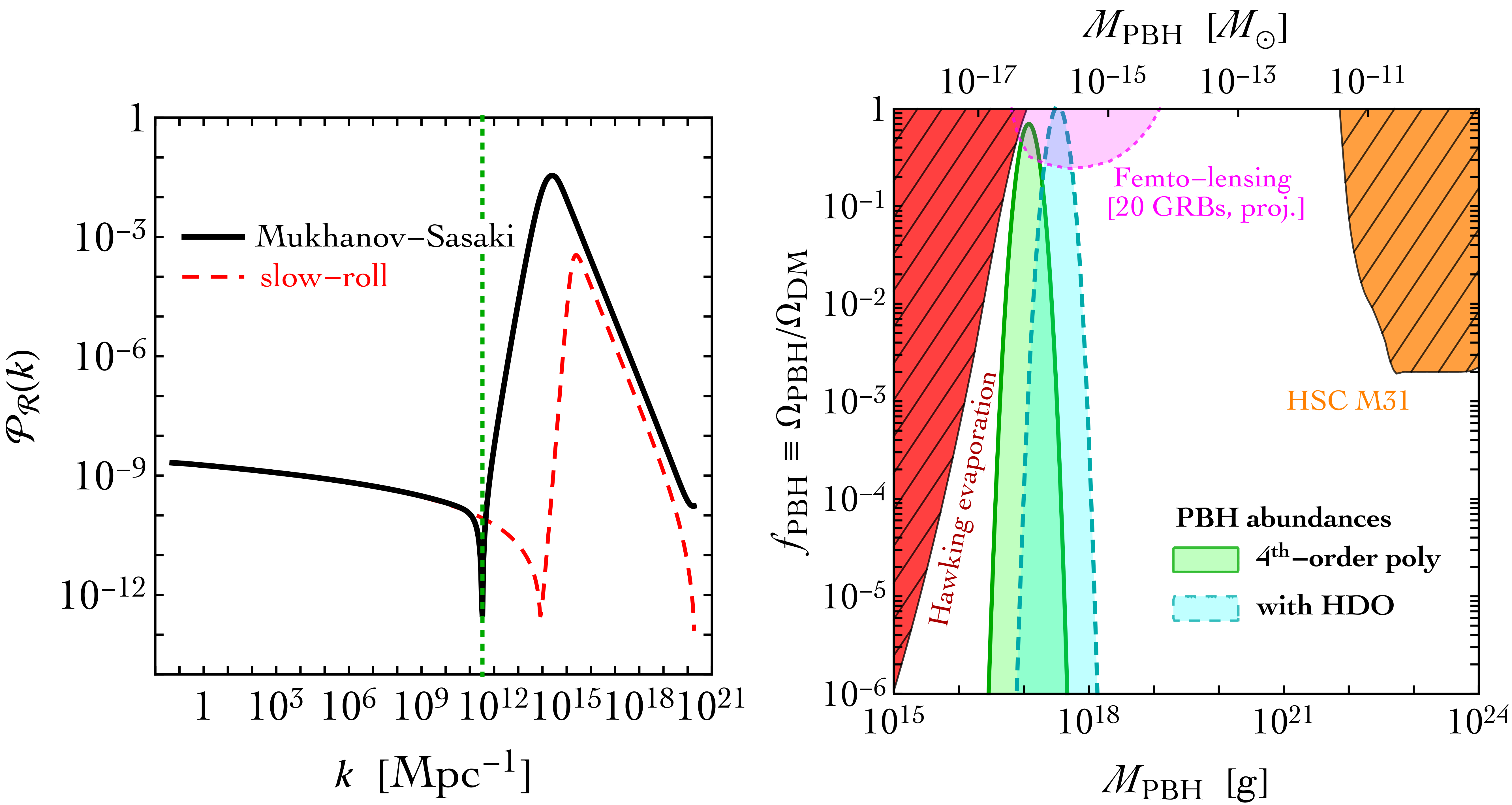


GB, Rey, Taoso, Urbano, 2020

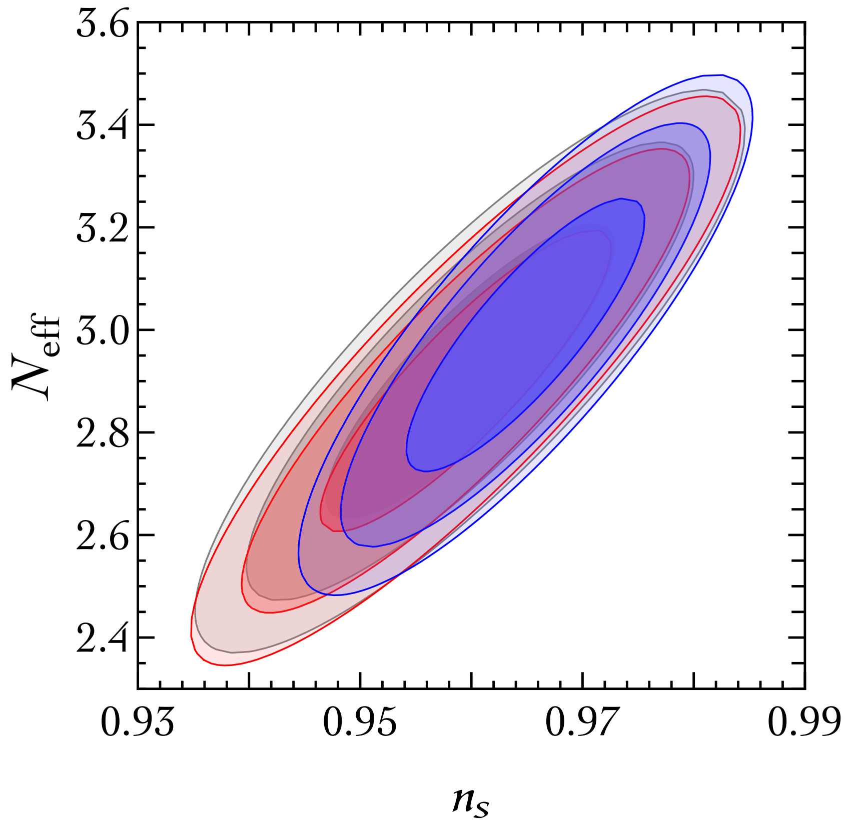
The scalar spectral index

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

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

'simple' models tend to predict $n_s \simeq 0.95$

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



GB, Rey, Taoso, Urbano, 2020

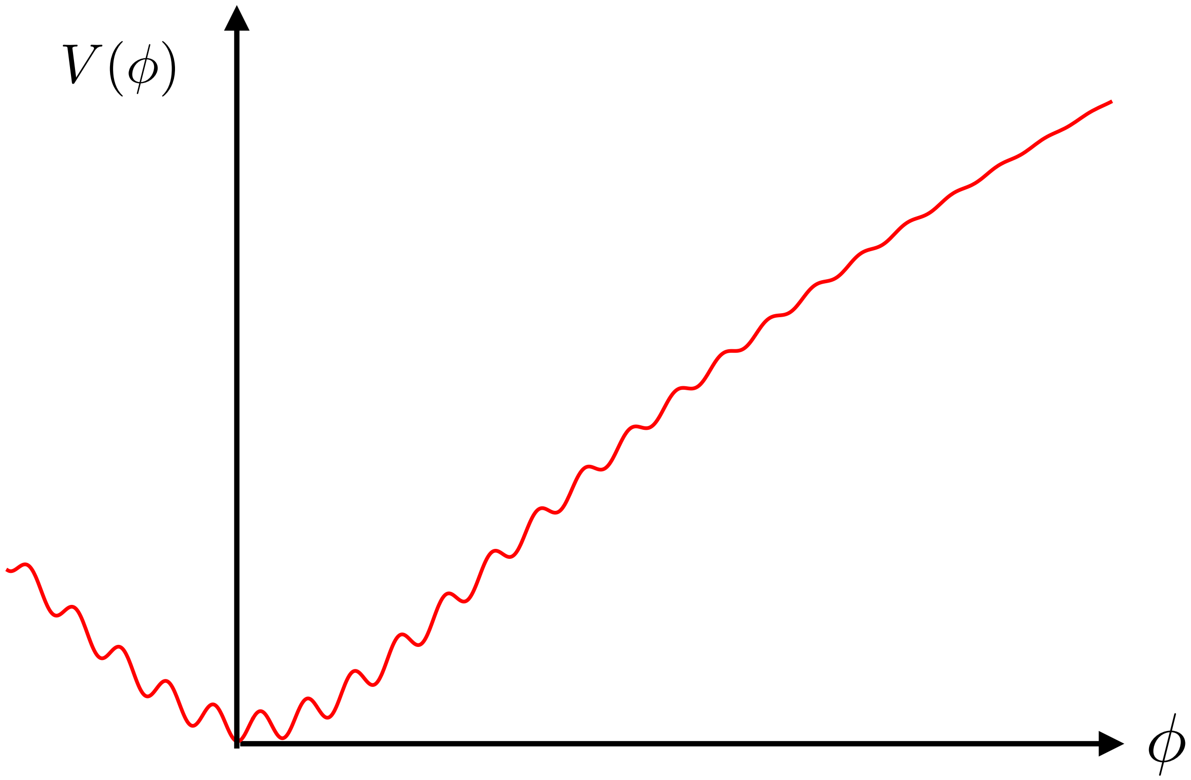
Exponential sensitivity of the abundance to the size of the primordial fluctuations

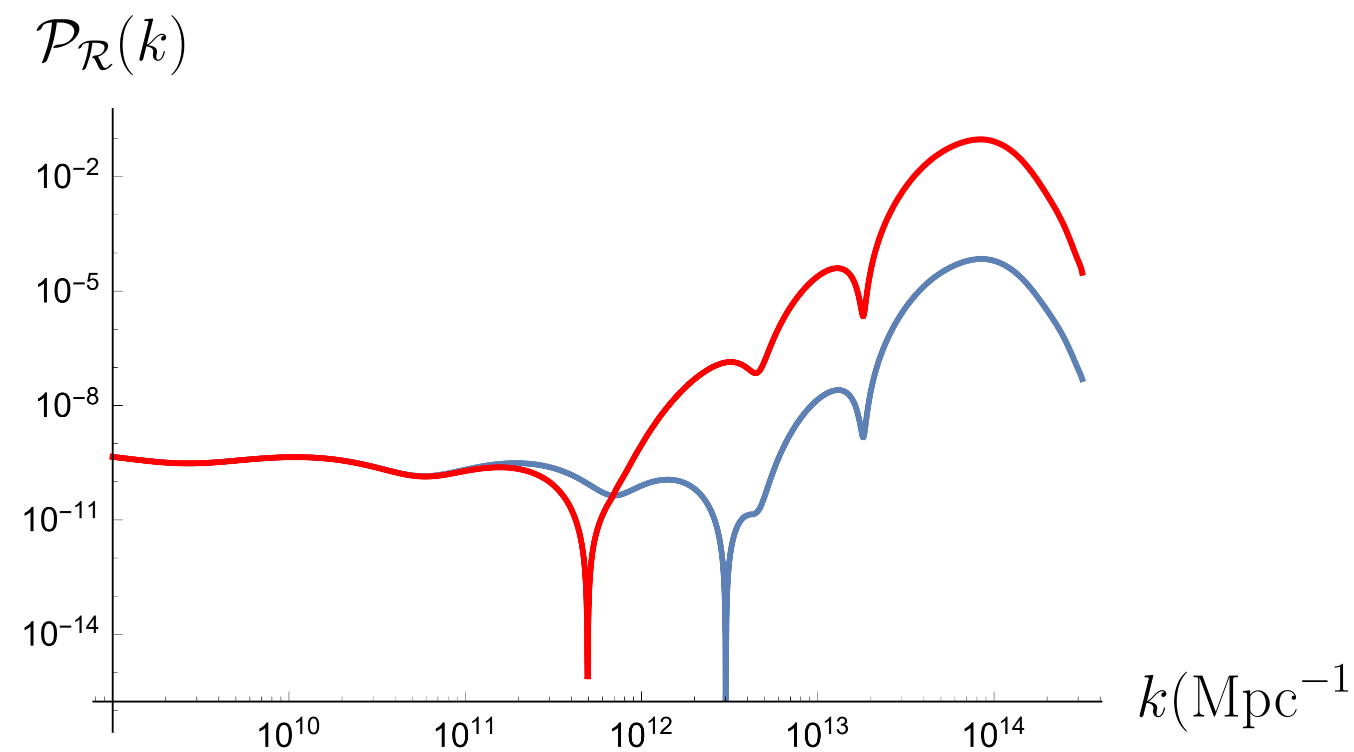
$$\beta(M) = \frac{1}{\sqrt{2\pi\sigma^2(M)}} \int_{\delta_c}^{\infty} d\delta \, \exp\left(\frac{-\delta^2}{2\sigma^2(M)}\right)$$

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

Tuning of parameters in the potential

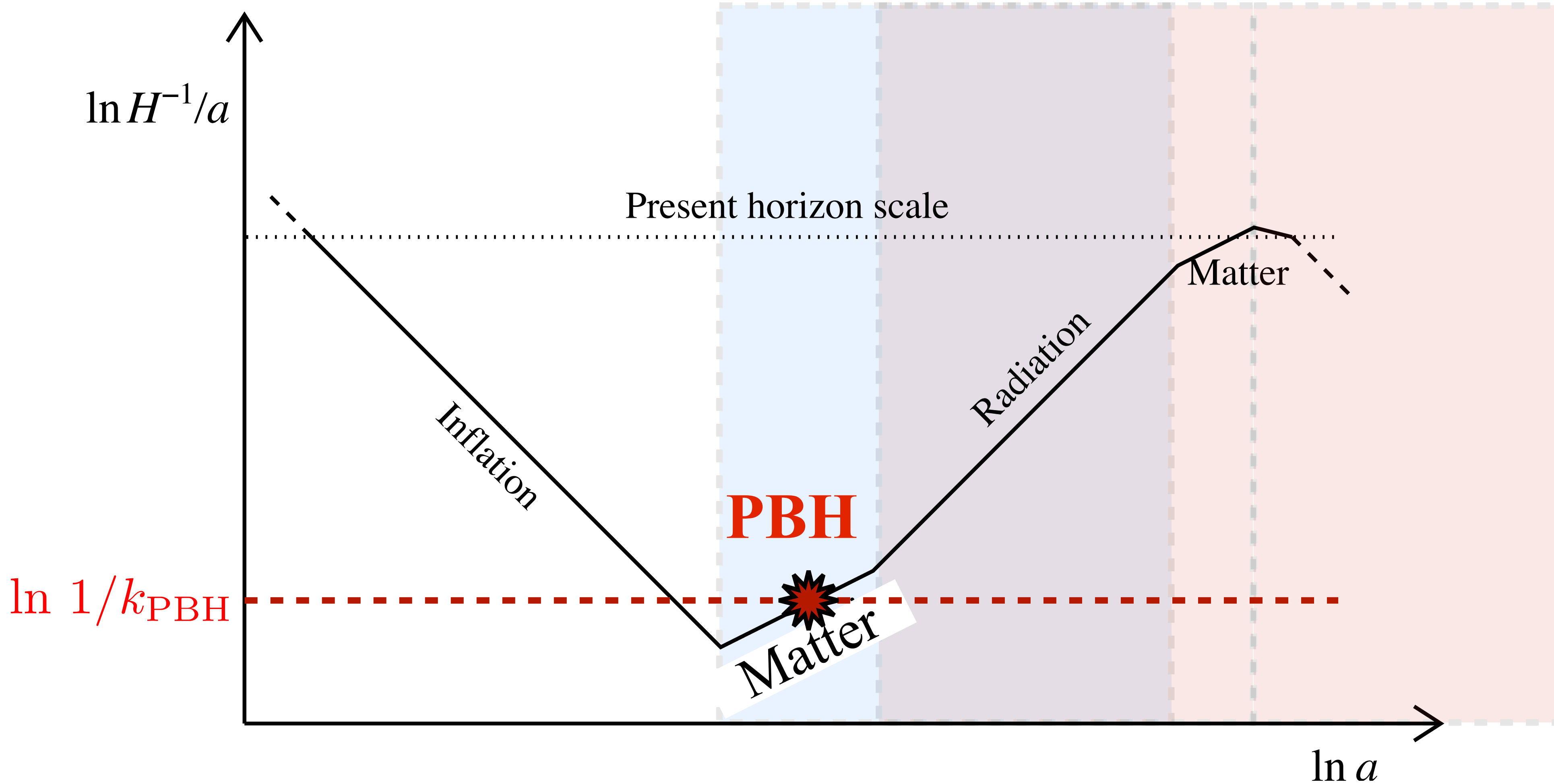
Modulation + Matter domination



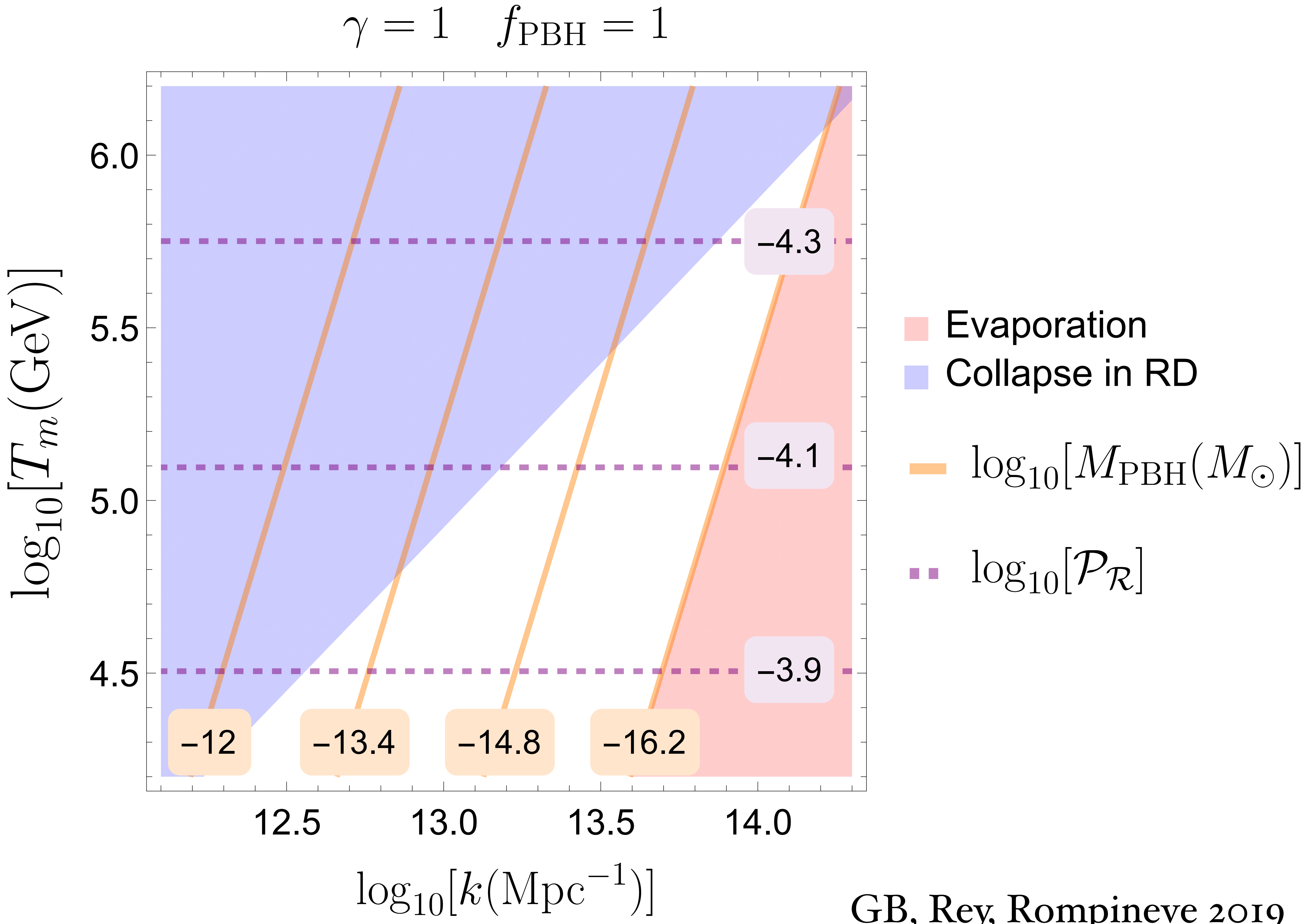


Axion monodromy inspired

GB, Rey, Rompineve 2019



$$
\Omega_{\rm PBH} \propto \begin{cases} \dfrac{e^{-\delta_c^2/\mathcal{P}_{\mathcal{R}}}}{\sqrt{\mathcal{P}_{\mathcal{R}}}} & \text{(Radiation)} \\[2ex] {\mathcal{P}_{\mathcal{R}}}^{5/2} & \text{(Matter)} \end{cases}
$$



GB, Rey, Rompineve 2019

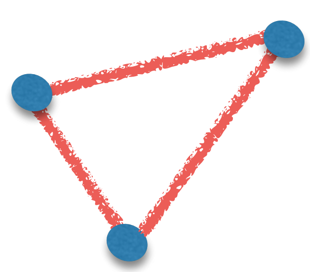
A stochastic background of GWs induced at second order in cosmological perturbation theory

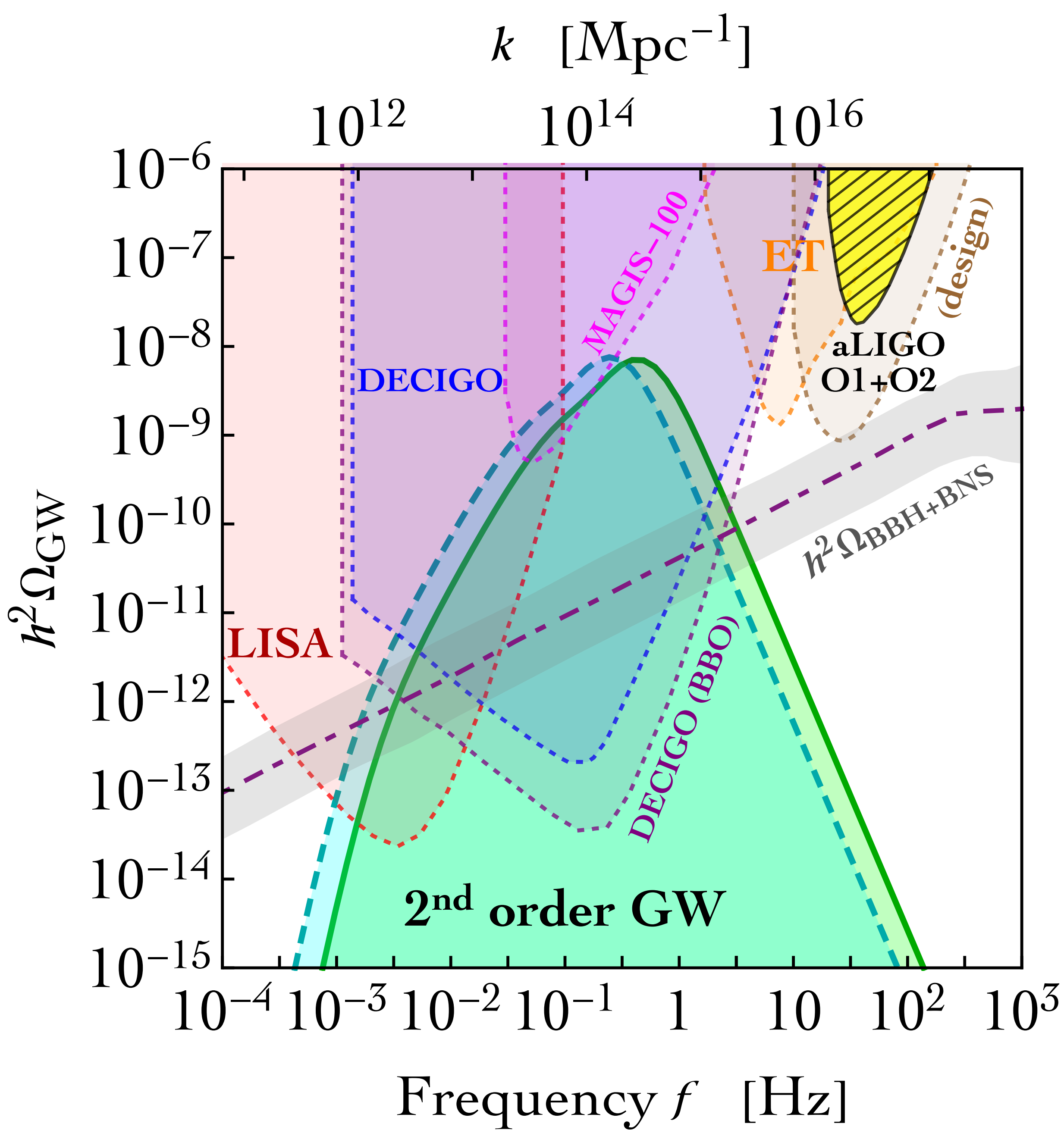
A stochastic background of GWs induced at second order in cosmological perturbation theory

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

$$\Omega_{\rm GW} \sim \mathcal{P}_h \sim (\mathcal{P}_\mathcal{R})^2$$

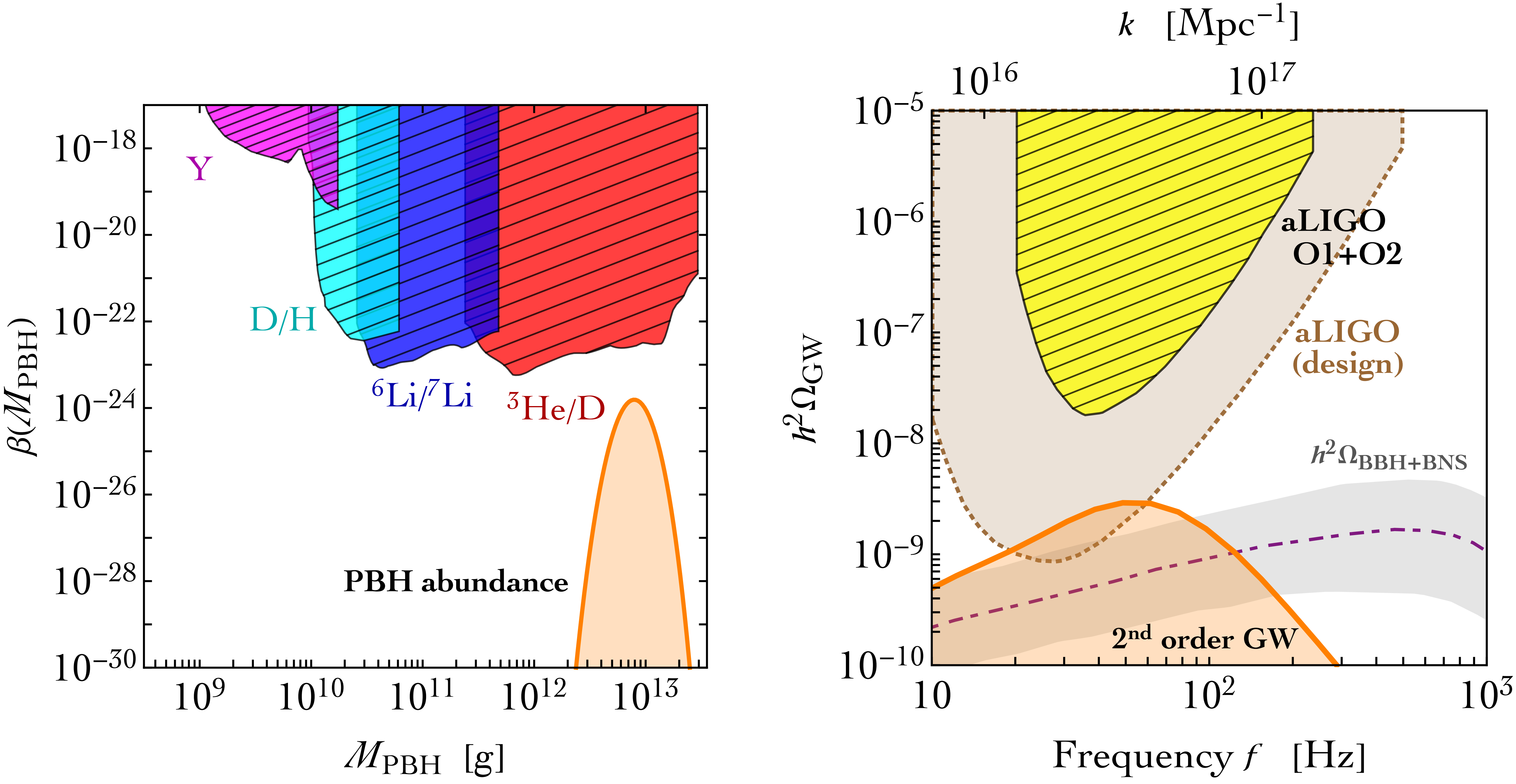
e.g. LISA (if PBHs are DM)





NANOGRAV Sept 2020: 10^{-8}Hz

Other PTA experiments as well



GB, Rey, Taoso, Urbano, 2020

The EFT approach

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

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

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

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

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

Example: The EFT of inflation (slow-roll)

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

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

$$c_s^4 \gg \mathcal{P}_{\mathcal{R}} \implies \quad \epsilon_{\rm PBH} \ll \Delta^2_{\zeta\,{\rm CMB}}\, c_{s\,{\rm CMB}} \left(\frac{r_{\rm CMB}}{0.07}\right) \left(\frac{\Delta^2_{\zeta\,{\rm PBH}}}{0.01}\right)^{-5/4}$$

GB, Beltran-Jimenez, Pieroni 2018

Ghost condensate:

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

Arkani-Hamed, et al 2003

$$\omega^2 = c_s^2 k^2 + \alpha \frac{k^4}{a^2 H^2}$$

Example: The EFT of inflation (slow-roll)

$$S^{(2)}_{\mathcal{R}} = \int d^4x\, A\, a^3 \left[\dot{\mathcal{R}}^2 - c_s^2 \frac{(\nabla\mathcal{R})^2}{a^2} - \alpha\, \frac{(\nabla^2\mathcal{R})^2}{H^2 a^4}\right],$$

$$\Lambda_3 \sim \varepsilon^{1/6}(M_{\rm Pl}H^2)^{1/3}$$

Enhancement with respect to CMB scales:

$$c_s^2 \to 0 \quad : \quad (\Lambda_3/H)^{3/2}$$

$$c_s^2 < 0 \quad : \quad \mathrm{e}^{2|c_s|^2\Lambda_3/H}$$

Weakly broken galilean symmetry

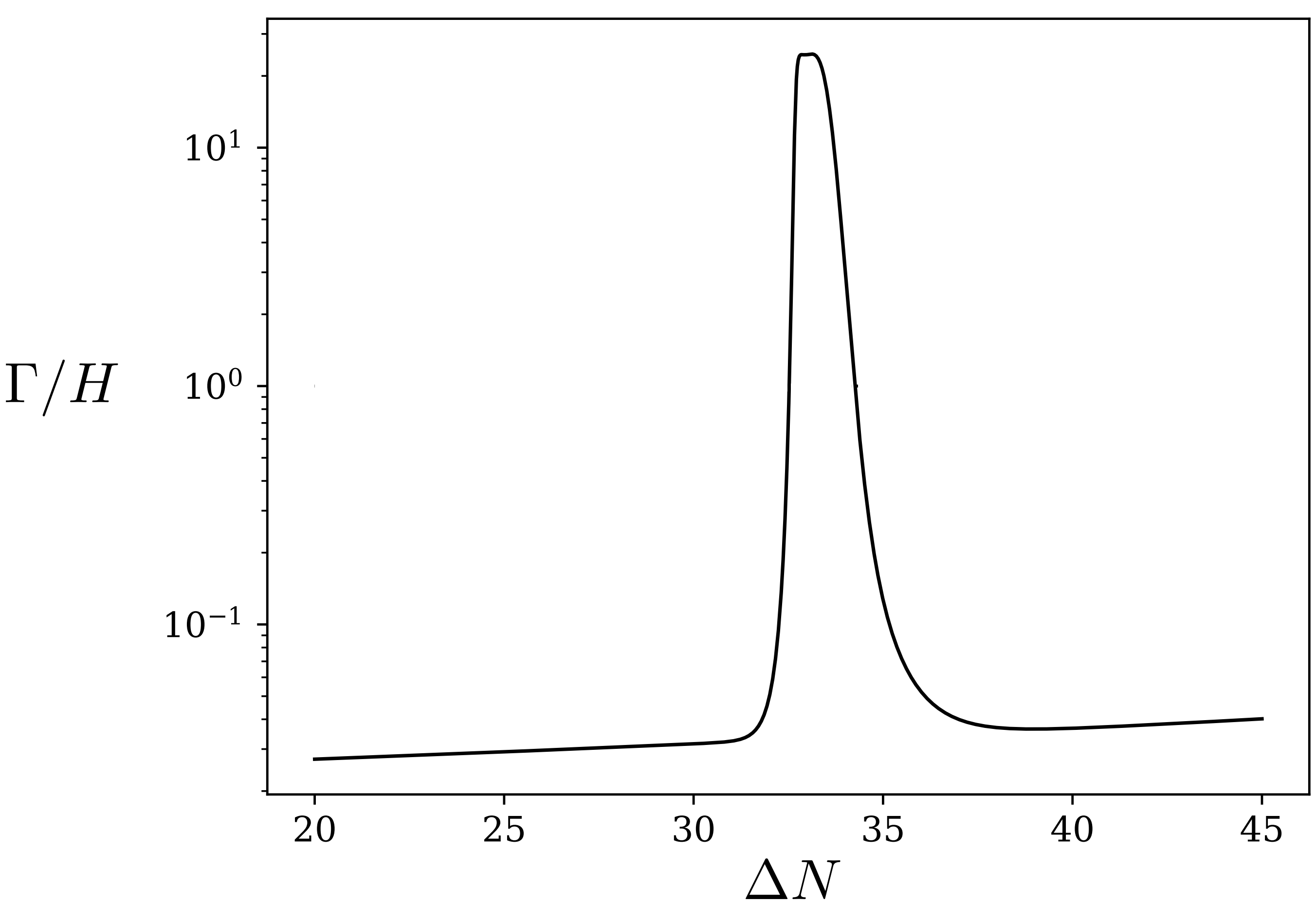
GB, Céspedes, Santoni, 2021

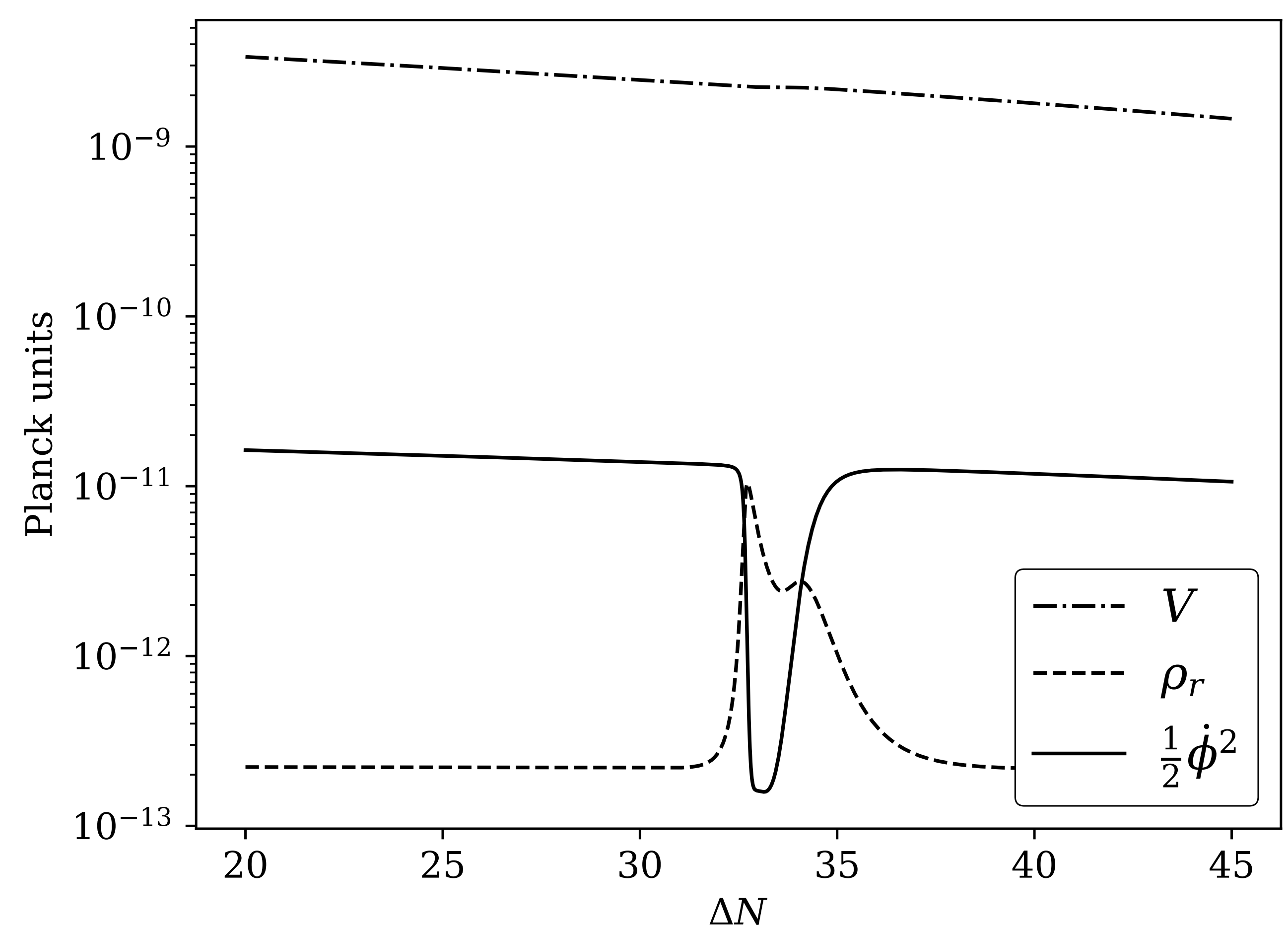
PBHs from dissipation during inflation

PBHs from dissipation during inflation

$$\ddot{\phi} + \Big(3H + \Gamma\Big)\dot{\phi} + \partial_\phi V = 0 \qquad\qquad \dot{\rho}_r + 4H\rho_r = \Gamma\dot{\phi}^2$$

$$\delta\ddot{\phi}_k + (3H + \Gamma)\delta\dot{\phi}_k + \left(\frac{k^2}{a^2} + \dot{\Gamma}\right)\delta\phi_k = \sqrt{\frac{2\Gamma T}{a^3}}\xi(t)$$





GB, García, Pérez Rodríguez, Pierre, Rey

Credit: A. Pérez Rodríguez

PBHs from dissipation during inflation

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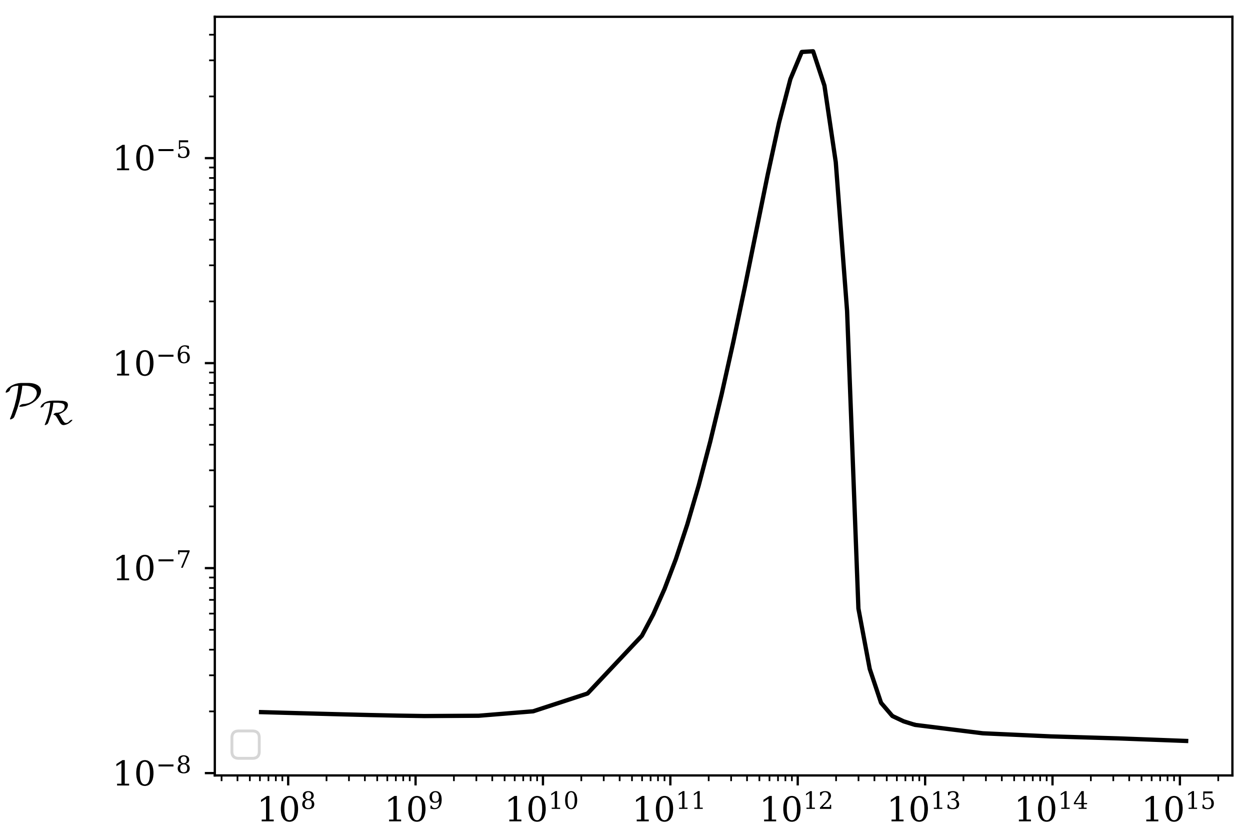

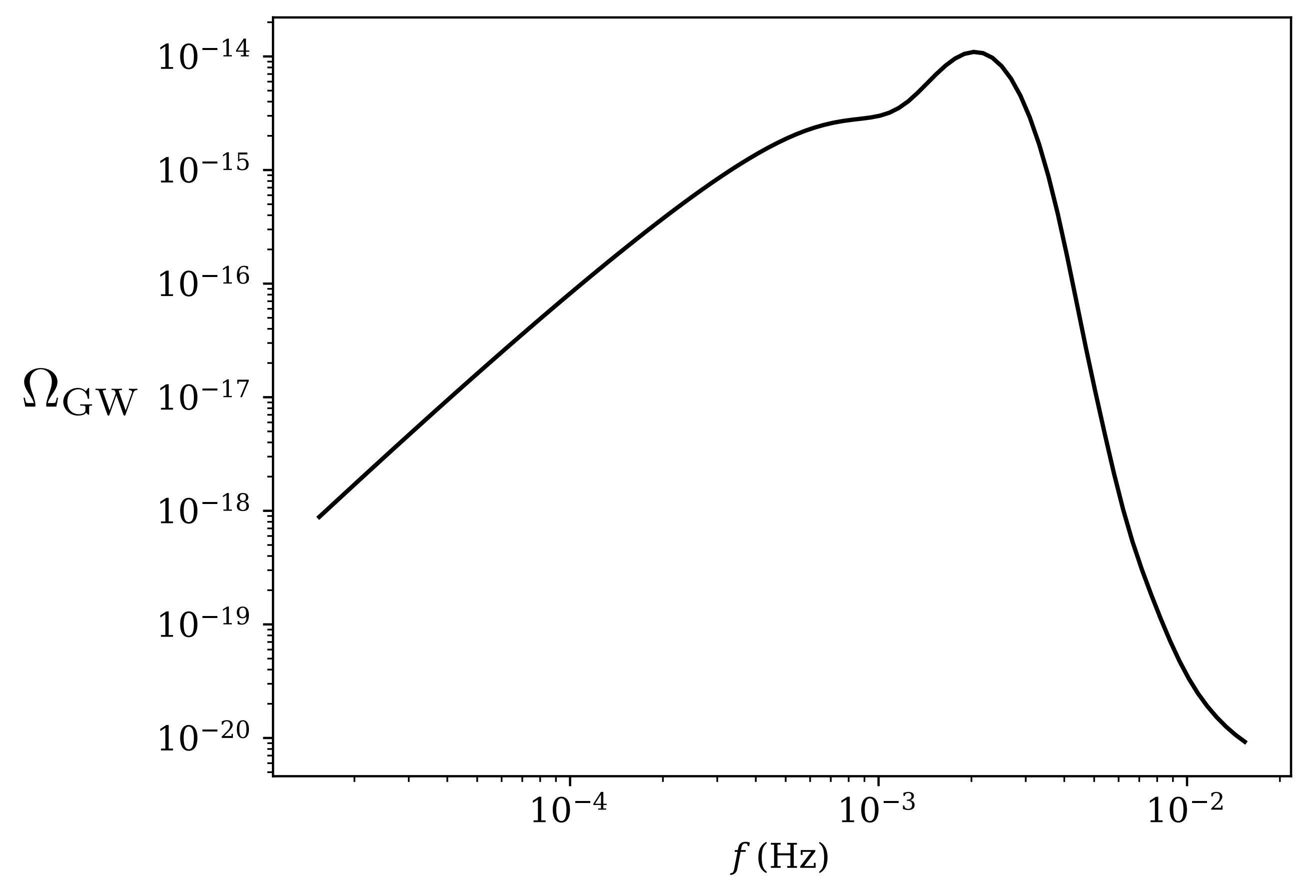

GB, García, Pérez Rodríguez, Pierre, Rey

Credit: A. Pérez Rodríguez

Summary

Summary

Bounds have evolved during the last 5 years

PBH DM: $$10^{-16} M_\odot \leftrightarrow 10^{-12} M_\odot$$

Rich phenomenology of inflationary and early universe cosmology: validity of perturbation theory, non-Gaussianities, quantum diffusion, dissipation, early matter domination, etc

And very interesting perspectives for GW experiments