Primordial Black Hole Dark Matter from Accretion During Early Matter Domination

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Outline:

- Introduction
- The scenario (formation and evolution of PBHs)
- GW signal (the spectrum and its features)
- Results
- Conclusion & Outlook

In collaboration with:

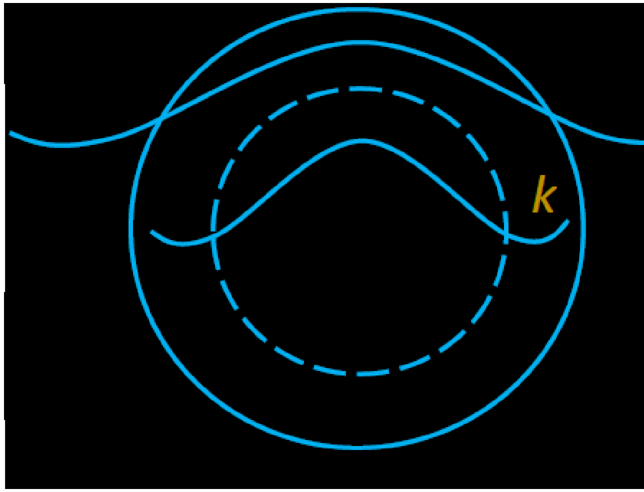
J. Dent, N. P. D. Loc, T. Xu JCAP 10, 026 (2025)

Introduction:

PBHs can from collapse of large density fluctuations in the early universe.

B. Carr and S. Hawking MNRAS 168, 399 (1974)

A general source is inflationary perturbations.



Modes re-enter the horizon after inflation.

Can collapse if exceed a critical amplitude.

For a Guassian distribution of variance σ_H:

$$\beta = \int_{\delta_c}^{O(1)} \frac{1}{\sqrt{2\pi\sigma_H^2}} \exp\left(-\frac{\delta^2}{2\sigma_H^2}\right) d\delta \simeq \mathrm{Erfc}\left[\frac{\delta_c}{\sqrt{2}\sigma_H}\right]$$

$$\beta \equiv \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{tot}}} \qquad \delta_c \lesssim 0.42$$

PBH formation in a RD phase can happen for modes with:

$k \sim H^{-1}$

A very broad mass range:

$$M = \gamma M_H = (2 \times 10^{31}\ \mathrm{g}) \left(\frac{\gamma}{0.2}\right) \left(\frac{106.75}{g_*}\right) \left(\frac{1\ \mathrm{GeV}}{T}\right)^2$$

$T = 10^{15}\ \mathrm{GeV} \Rightarrow M \sim 10\ \mathrm{g}$ $\quad$ $T = 1\ \mathrm{MeV} \Rightarrow M \sim 100\ M_\odot$

PBH evaporation via hawking radiation:

$t_{\mathrm{PBH}} \propto M^3\, m_P^{-4}$ $\quad$ $T_{\mathrm{H}} \propto M^{-1}\, m_P^2$

- $M \lesssim 10^9$ g: Evaporate before BBN → No observational constraint

Could produce DM and/or baryon asymmetry

R.A., J. Dent, J. Osinski PRD 97, 055013 (2018)

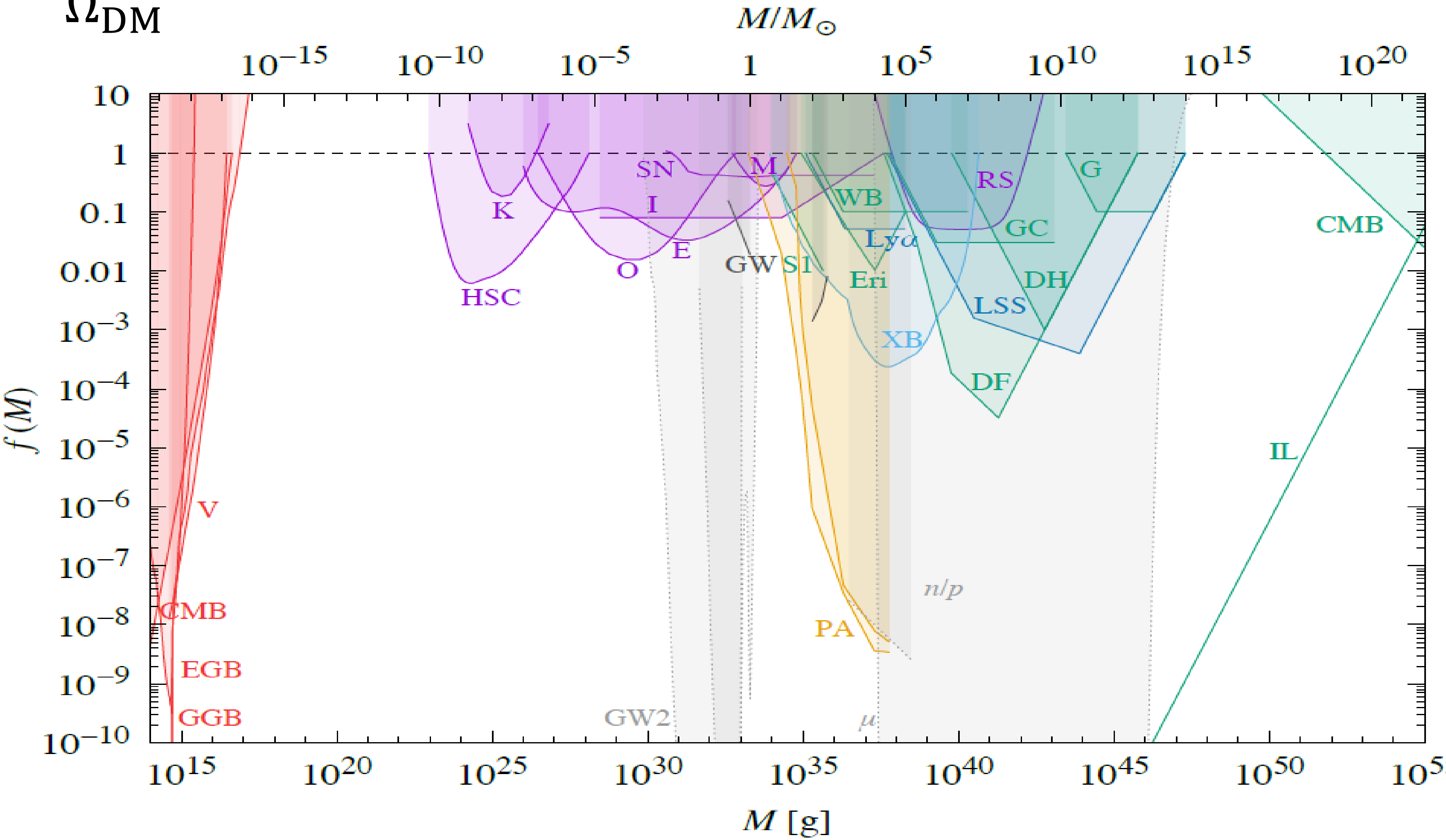
…

- $M \gtrsim 10^{15}$ g: Cosmologically stable

Tight constraints from CMB and EGB if $M \lesssim 10^{17}$ g.

S. Clark, B. Dutta, Y. Gao, L. Strigari, S. Watson PRD 95, 083003 (2017)

$$f \equiv \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}}$$

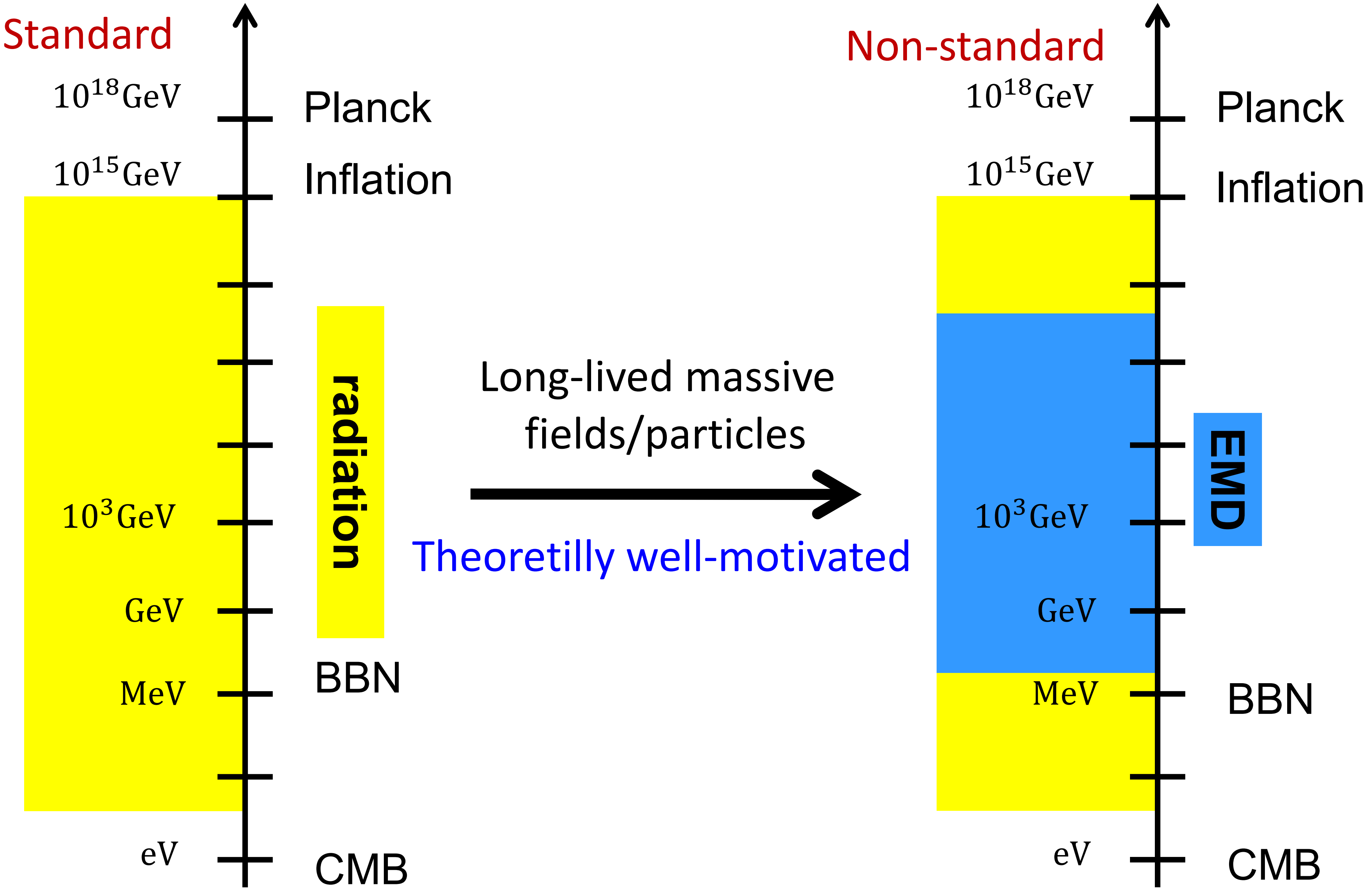


B. Carr, K. Kohri, Y. Sendouda, J. Yokoyama RPP 11, 116902 (2021)

A mass window where PBHs can be the totality of DM:

$10^{17}\mathrm{g} \lesssim M \lesssim 10^{22}\ \mathrm{g}$

Non-standard thermal histories :



G. Kane, K. Sinha, S. Watson IJMPD 8, 1530022 (2015)

An epoch of EMD affects the formation of PBHs:

(1) Subhorizon fluctuations can collapse due to the absence of pressure.

(2) Subhorizon fluctuations grow and can reach O(1) values.

$$\beta \approx 2 \times 10^{-2} \, \sigma_H^{13/2}$$

M. Klopov, B. Malomed, I. Zeldovich MNRAS 215, 575 (1985)
T. Harada, C. Yoo, K. Kohri, K. Nakao PRD 96, 083517 (2017)

It also affects the evolution of PBHs formed in a preceding RD phase:

(1) Mass growth due to accretion during EMD (no pressure!).

(2) Change in β due to different expansion history.

We focus on the latter in this work.

The Scenario:

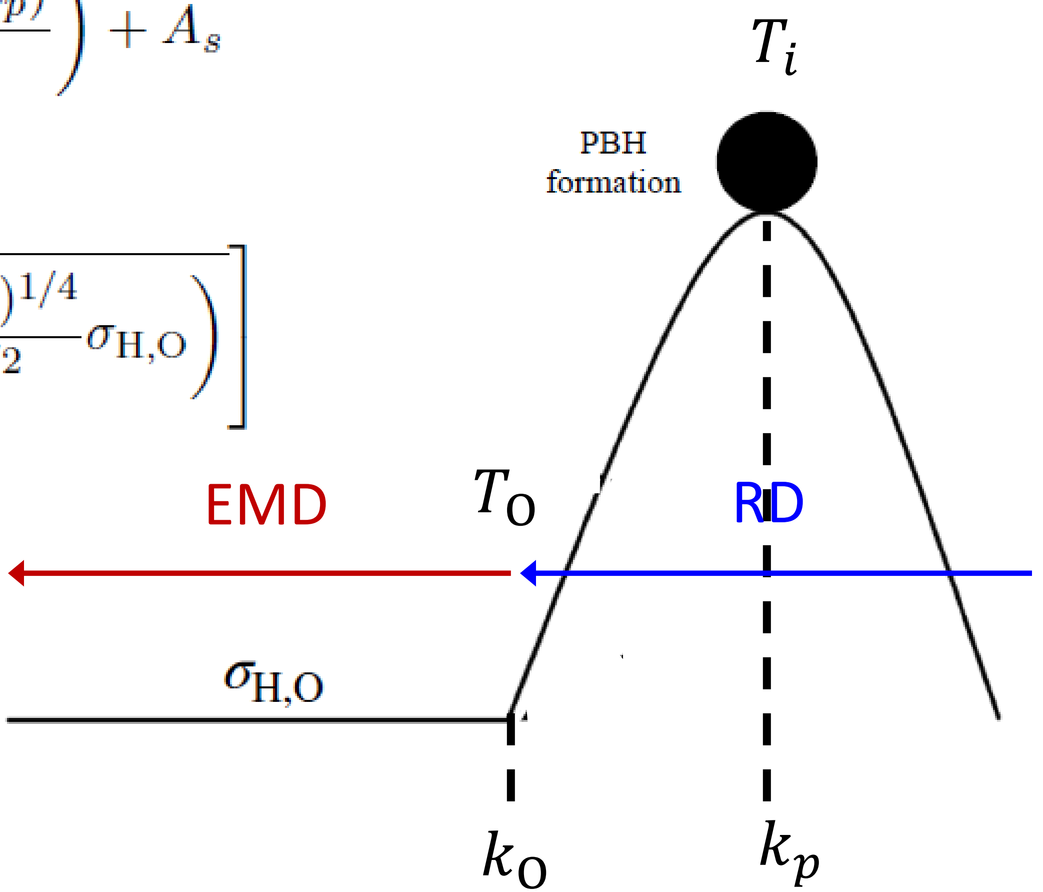
PBHs form during RD and then accrete in a subsequent EMD epoch.

J. Dent, N. P. D. Loc, T. Xu JCAP 10, 026 (2025)

We consider a bump in the power spectrum (e.g., from USR inflation):

$$\mathcal{P}_\zeta(k) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\ln^2(k/k_p)}{2\sigma^2}\right) + A_s$$

$$\frac{k_{\rm O}}{k_p} = \exp\left[-\sqrt{-4\sigma^2 \ln\left(\frac{5}{2}\frac{(2\pi\sigma^2)^{1/4}}{A^{1/2}}\sigma_{\rm H,O}\right)}\right]$$



Accretion during EMD

$$\delta \propto a \qquad M(t) = M_{\rm i}\left(\frac{t}{t_{\rm O}}\right)^{2/3}$$

$$v_{\rm expan} = H_{\rm O} r_{\rm ita} \qquad r_{\rm ita} = \left(\frac{2M_{\rm i}}{m_{\rm pl}^2 H_{\rm O}^2}\right)^{1/3}$$

$$v_{\rm esc} = \sqrt{2GM_{\rm i}/r_{\rm ita}}$$

$$\sigma_v(t) = \sigma_{\rm H,O}\left(\frac{t}{t_{\rm O}}\right)^{1/3} \qquad r_{\rm ta} = r_{\rm ita}\left(\frac{t}{t_{\rm O}}\right)^{8/9}. \qquad v_t \sim \frac{\sigma_v r_{\rm ta}}{r}. \qquad v_{\rm Kep} = \sqrt{GM/r}.$$

E. Bertschinger APJSS 58, 39 (1985)

$$v_t\Big|_{r=3r_S} \sim v_{\rm Kep}\Big|_{r=3r_S} \qquad t_{\rm Edd} \simeq 4\,\frac{H_{\rm O}^{1/5} M_{\rm i}^{6/5}}{\sigma_{\rm H,O}^{9/5} m_{\rm pl}^{12/5}}. \qquad M_{\rm max} \approx 2M_{\rm i}\ \sigma_{\rm H,O}^{-6/5}\left(\frac{T_{\rm O}}{T_{\rm i}}\right)^{8/5}.$$

V. De Luca, G. Franciolini, A. Kehagias, P. Pani, A. Riotto PLB 832, (2022) Accretion in the Bondi-Hoyle regime lasts for :

$$t_{\mathrm{B-H}} \approx 4\,\frac{H_{\mathrm{O}}^{1/5} M_{\mathrm{i}}^{6/5}}{\sigma_{\mathrm{H,O}}^{9/5} m_P^{12/5}}$$

The initial PBH mass is :

$$M_{\mathrm{i}} = (2 \times 10^{31}\ \mathrm{g}) \left(\frac{\gamma}{0.2}\right) \left(\frac{106.75}{g_{*,i}}\right) \left(\frac{1\ \mathrm{GeV}}{T_{\mathrm{i}}}\right)^2$$

The maximum final mass is reached for $t_{\mathrm{B-H}} \gtrsim H_{\mathrm{R}}^{-1}$:

$$M_{\mathrm{f}} \approx 2 M_{\mathrm{i}}\, \sigma_{\mathrm{H,O}}^{-6/5} \left(\frac{T_{\mathrm{O}}}{T_{\mathrm{i}}}\right)^{8/5}$$

Note that:

$$\sigma_{\mathrm{H,O}} \ll 1$$

The PBH mass can grow due to accretion by a large factor (more later).

The PBH population at the end of EMD follows:

$$\beta_{\rm R} \approx 2\, \beta_{\rm i}\, \sigma_{\rm H,O}^{-6/5} \left(\frac{T_{\rm O}}{T_{\rm i}}\right)^{3/5}$$

Also:

$$\beta_{\rm R} \approx 2.4 \times 10^{-10} \left(\frac{\rm GeV}{T_{\rm R}}\right) f_{\rm PBH}$$

As a result:

$$f_{\rm PBH} \approx 8.4 \times 10^{9}\, \beta_{\rm i}\, \sigma_{\rm H,O}^{-6/5} \left(\frac{T_{\rm O}}{T_{\rm i}}\right)^{8/5} \left(\frac{T_{\rm R}}{T_{\rm O}}\right) \left(\frac{T_{\rm i}}{\rm GeV}\right)$$

$$\frac{T_{\rm O}}{T_{\rm i}} = \frac{k_{\rm O}}{k_p} = \exp\left[-\sqrt{-4\sigma^2 \ln\left(\frac{5}{2}\frac{(2\pi\sigma^2)^{1/4}}{A^{1/2}}\sigma_{\rm H,O}\right)}\right]$$

Fixing A, σ leaves us with four parameters:

$T_{\rm i}$, $T_{\rm O}$, $T_{\rm R}$, $\sigma_{\rm H,O}$

Two of these can be swapped with $M_{\rm f}$ and $f_{\rm PBH}$.

GW Signal:

GWs inevitably produced from scalar perturbations at the second order.

K. Kohri, T. Trada PRD 97, 123532 (2018)

$$h''_{\mathbf{k}}(\eta) + 2\mathcal{H}h'_{\mathbf{k}}(\eta) + k^2 h_{\mathbf{k}}(\eta) = 4S_{\mathbf{k}}(\eta)$$

$$S_{\mathbf{k}} = \int \frac{\mathrm{d}^3 q}{(2\pi)^{3/2}} e_{ij}(\mathbf{k}) q_i q_j \left(2\Phi_{\mathbf{q}}\Phi_{\mathbf{k-q}} + \frac{4}{3(1+w)}\left(\mathcal{H}^{-1}\Phi'_{\mathbf{q}} + \Phi_{\mathbf{q}}\right)\left(\mathcal{H}^{-1}\Phi'_{\mathbf{k-q}} + \Phi_{\mathbf{k-q}}\right)\right)$$

$$\Phi''_{\mathbf{k}} + 3\mathcal{H}(1+c_{\mathrm{s}}^2)\Phi'_{\mathbf{k}} + (2\mathcal{H}' + (1+3c_{\mathrm{s}}^2)\mathcal{H}^2 + c_{\mathrm{s}}^2 k^2)\Phi_{\mathbf{k}} = \frac{a^2}{2}\tau\delta S$$

$$\mathcal{P}_h(\eta,k) = 4\int_0^\infty \mathrm{d}v \int_{|1-v|}^{1+v} \mathrm{d}u \left(\frac{4v^2 - (1+v^2-u^2)^2}{4vu}\right)^2 I^2(v,u,x)\mathcal{P}_\zeta(kv)\mathcal{P}_\zeta(ku),$$

$$I(v,u,x) = \int_0^x \mathrm{d}\bar{x} \frac{a(\bar{\eta})}{a(\eta)} k G_k(\eta,\bar{\eta}) f(v,u,\bar{x})$$

$$G''_{\mathbf{k}}(\eta,\bar{\eta}) + \left(k^2 - \frac{a''(\eta)}{a(\eta)}\right) G_{\mathbf{k}}(\eta,\bar{\eta}) = \delta(\eta-\bar{\eta})$$

$$\begin{aligned} f(v,u,\bar{x}) =& \frac{6(w+1)}{3w+5}\Phi(v\bar{x})\Phi(u\bar{x}) + \frac{6(1+3w)(w+1)}{(3w+5)^2}\left(\bar{x}\partial_{\bar{\eta}}\Phi(v\bar{x})\Phi(u\bar{x}) + \bar{x}\partial_{\bar{\eta}}\Phi(u\bar{x})\Phi(v\bar{x})\right) \\ &+ \frac{3(1+3w)^2(1+w)}{(3w+5)^2}\bar{x}^2\partial_{\bar{\eta}}\Phi(v\bar{x})\partial_{\bar{\eta}}\Phi(u\bar{x}), \end{aligned}$$

Two contributions to GWs in this scenario:

(1) The mode responsible for PBH formation (re-entry during RD).

(2) The modes that re-enter during EMD and grow.

The first contribution has a peak at:

$$\frac{k_\mathrm{p}}{\mathrm{Mpc}^{-1}} \approx 3.17 \times 10^{38} \left(\frac{T_\mathrm{O}}{T_\mathrm{i}}\right) \left(\frac{T_\mathrm{R}}{T_\mathrm{O}}\right)^{4/3} \left(\frac{\mathrm{GeV}}{T_\mathrm{R}}\right) \left(\frac{\mathrm{g}}{M_\mathrm{i}}\right)$$

The corresponding frequency is:

$$\frac{f}{\mathrm{Hz}} \approx 1.55 \times 10^{-15} \left(\frac{k}{\mathrm{Mpc}^{-1}}\right)$$

The GW spectrum follows:

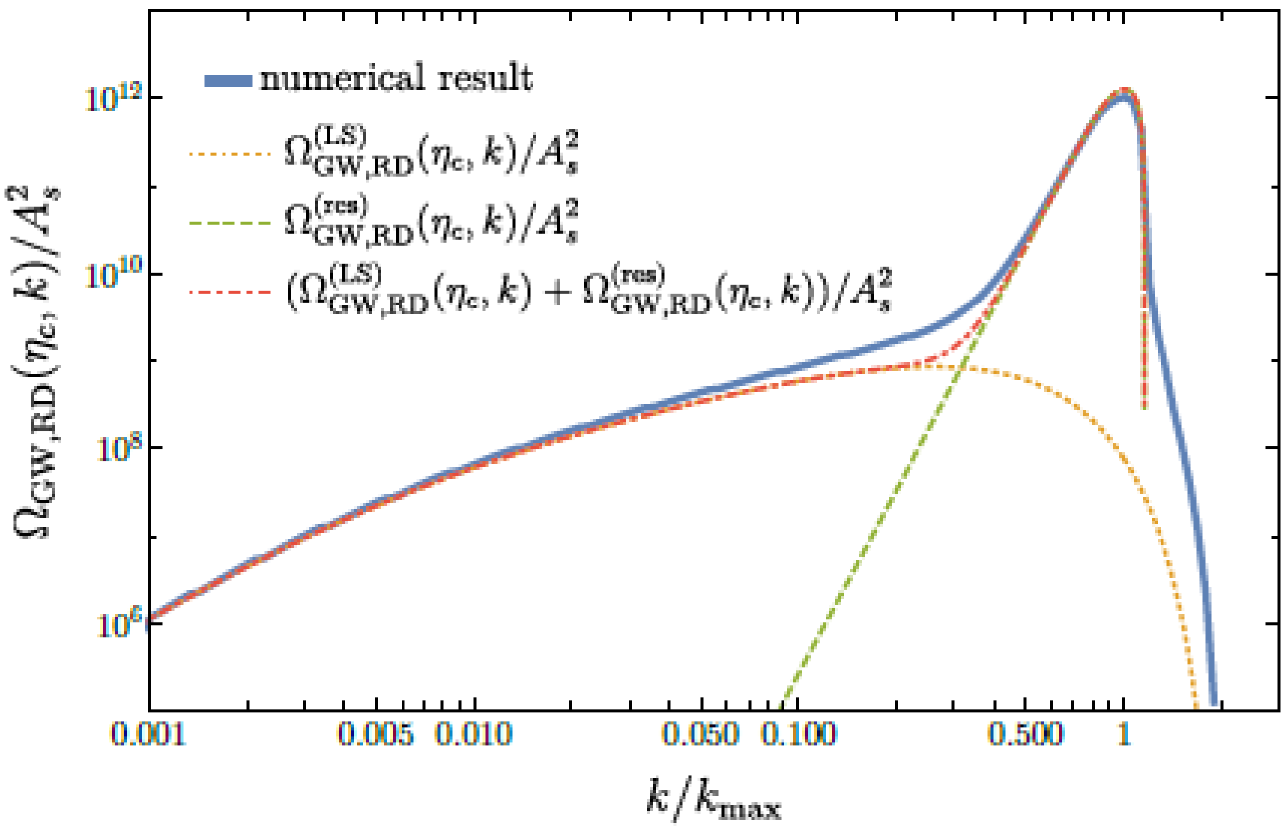
$$\Omega_{\mathrm{GW,0}} \approx 1.58 \times 10^{-4}\, g_{*,\mathrm{i}}^{-1/3}\, \Omega_{\mathrm{GW,i}} \left(\frac{a_\mathrm{O}}{a_\mathrm{R}}\right)$$

$$\Omega_{\mathrm{GW,i}}(\eta, k) = \frac{1}{24} \left(\frac{k}{a(\eta) H(\eta)}\right)^2 \overline{\mathcal{P}_h(\eta, k)}$$

Second contribution most prominent for a sudden end to EMD to RD.

Scalar perturbations start to decay when there is a gradual transition.

For a sudden transition, there is a resonant peak:



K. Inomata, K. Kohri, T. Nakama, T. Trada PRD 100, 043532 (2020)

Results:

Our main interest is in the GW signal for PBHs in the DM window.

We therefore set:

$$10^{17}\mathrm{g} \lesssim M_\mathrm{f} \lesssim 10^{22}\mathrm{g}$$

$$f_\mathrm{PBH} = 1$$

In order not get into nonlinear regime, we set:

$$\delta(t_\mathrm{R}) = 1$$

This results in:

$$\frac{T_\mathrm{R}}{T_\mathrm{O}} \simeq \left(\frac{g_{*,\mathrm{O}}}{g_{*,\mathrm{R}}}\right)^{1/4} \sigma_{\mathrm{H,O}}^{3/4}$$

We also set the width of log-normal bump to 1.

Two sets of benchmark points:

M_i(g)	A	T_O/T_i	M_f(g)	T_R(GeV)	k_p(Mpc^{-1})	k_O(Mpc^{-1})
10^{15}	2.89×10^{-2}	3.07×10^{-3}	1.91×10^{17}	77.3	1.3×10^{14}	3.9×10^{11}
10^{17}	3.1×10^{-2}	3.04×10^{-3}	1.88×10^{19}	7.6	1.3×10^{13}	3.8×10^{10}
10^{20}	3.44×10^{-2}	2.98×10^{-3}	1.82×10^{22}	0.2	4.7×10^{11}	1.4×10^{9}

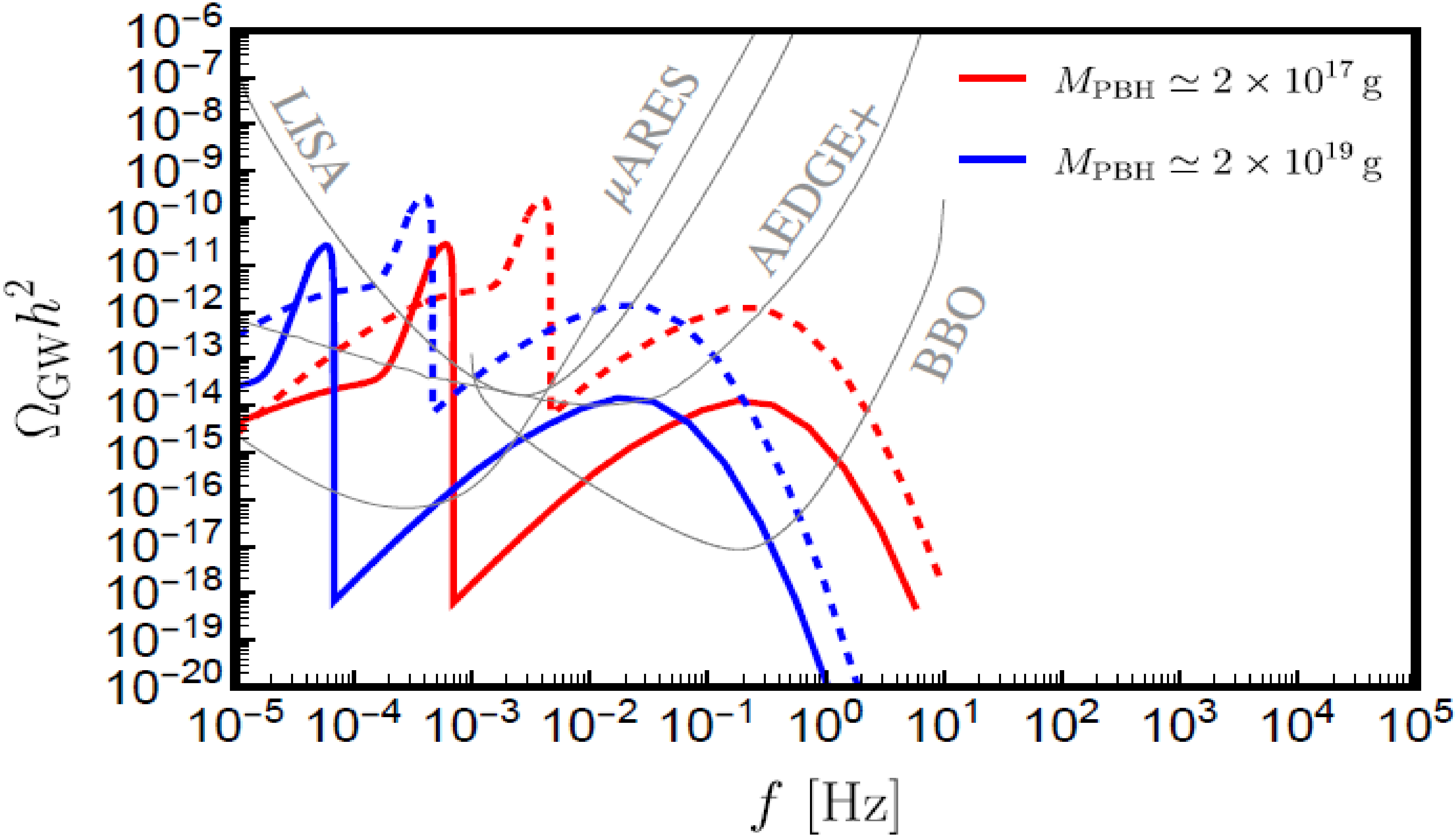
$\sigma_{\mathrm{H,O}} = 10^{-5}$

M_i(g)	A	T_O/T_i	M_f(g)	T_R(GeV)	k_p(Mpc^{-1})	k_O(Mpc^{-1})
10^{16}	2.91×10^{-2}	2.1×10^{-2}	1.6×10^{17}	5194	1.3×10^{14}	2.6×10^{12}
10^{18}	3.11×10^{-2}	2×10^{-2}	1.6×10^{19}	511	1.26×10^{13}	2.6×10^{11}
10^{21}	3.47×10^{-2}	2×10^{-2}	1.5×10^{22}	16	3.9×10^{11}	7.7×10^{9}

$\sigma_{\mathrm{H,O}} = 10^{-3}$

A mass growth factor of O(10)-O(100) from accretion during EMD.

Solid: $\sigma_{\mathrm{H,O}} = 10^{-5}$ Dashed: $\sigma_{\mathrm{H,O}} = 10^{-3}$

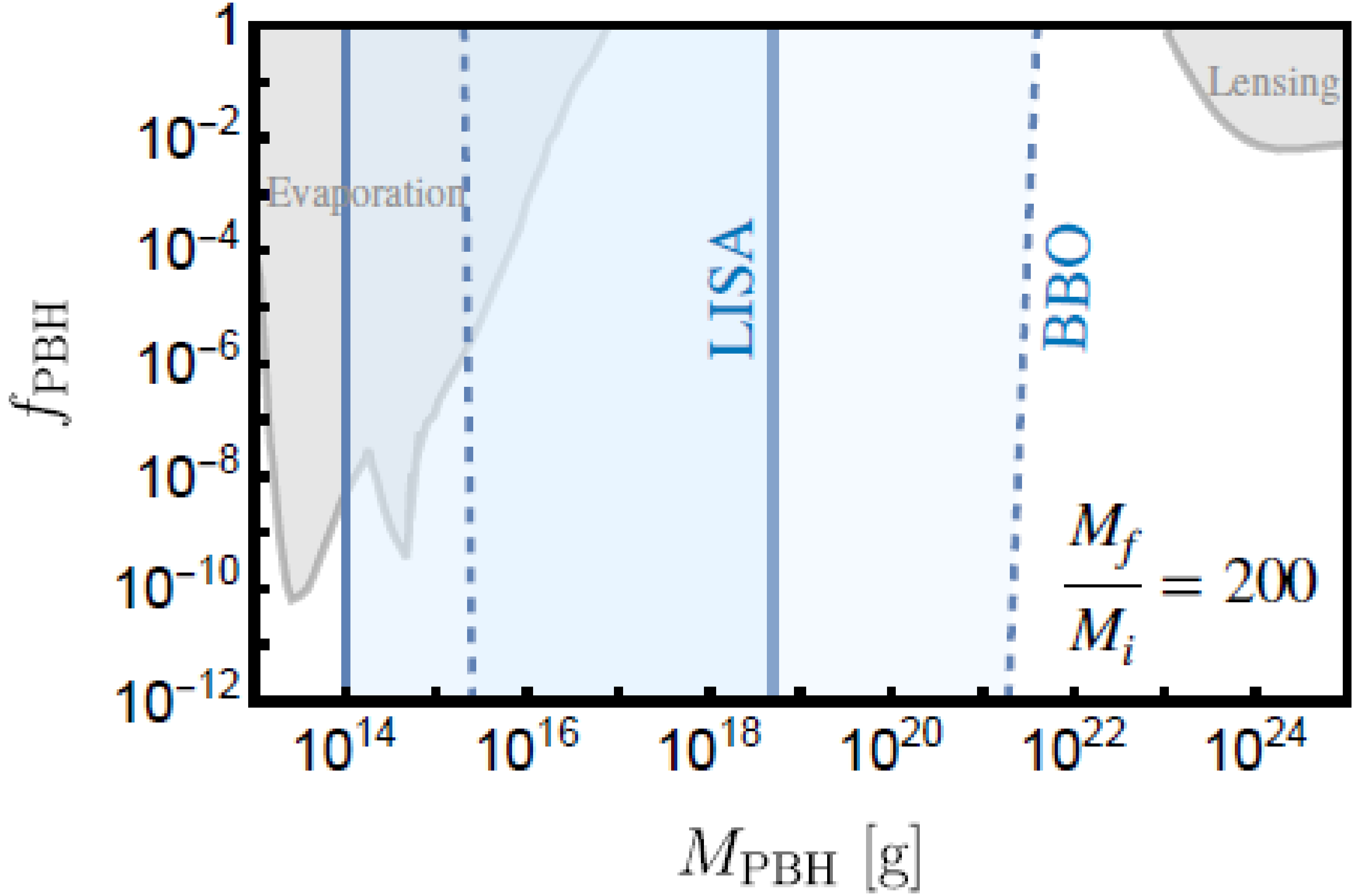


J. Dent, N. P. D. Loc, T. Xu JCAP 10, 026 (2025)

Two peaks in the GW spectrum:

low frequency (EMD), high frequency (RD, suppressed)

$\sigma_{\mathrm{H,O}} = 10^{-5}$



Solid: EMD peaks

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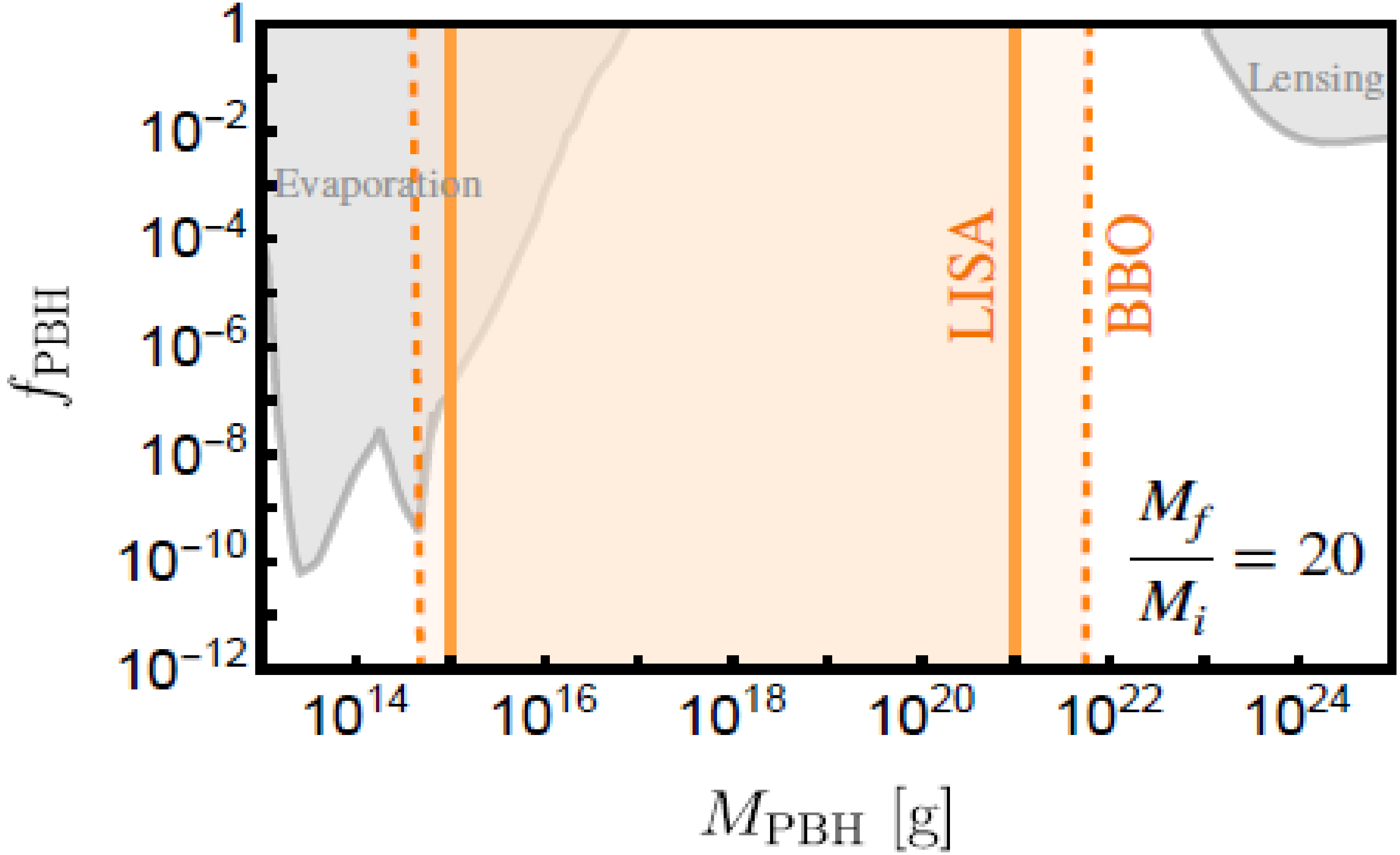
Dashed: RD peaks

$\sigma_{\mathrm{H,O}} = 10^{-3}$



Solid: EMD peaks

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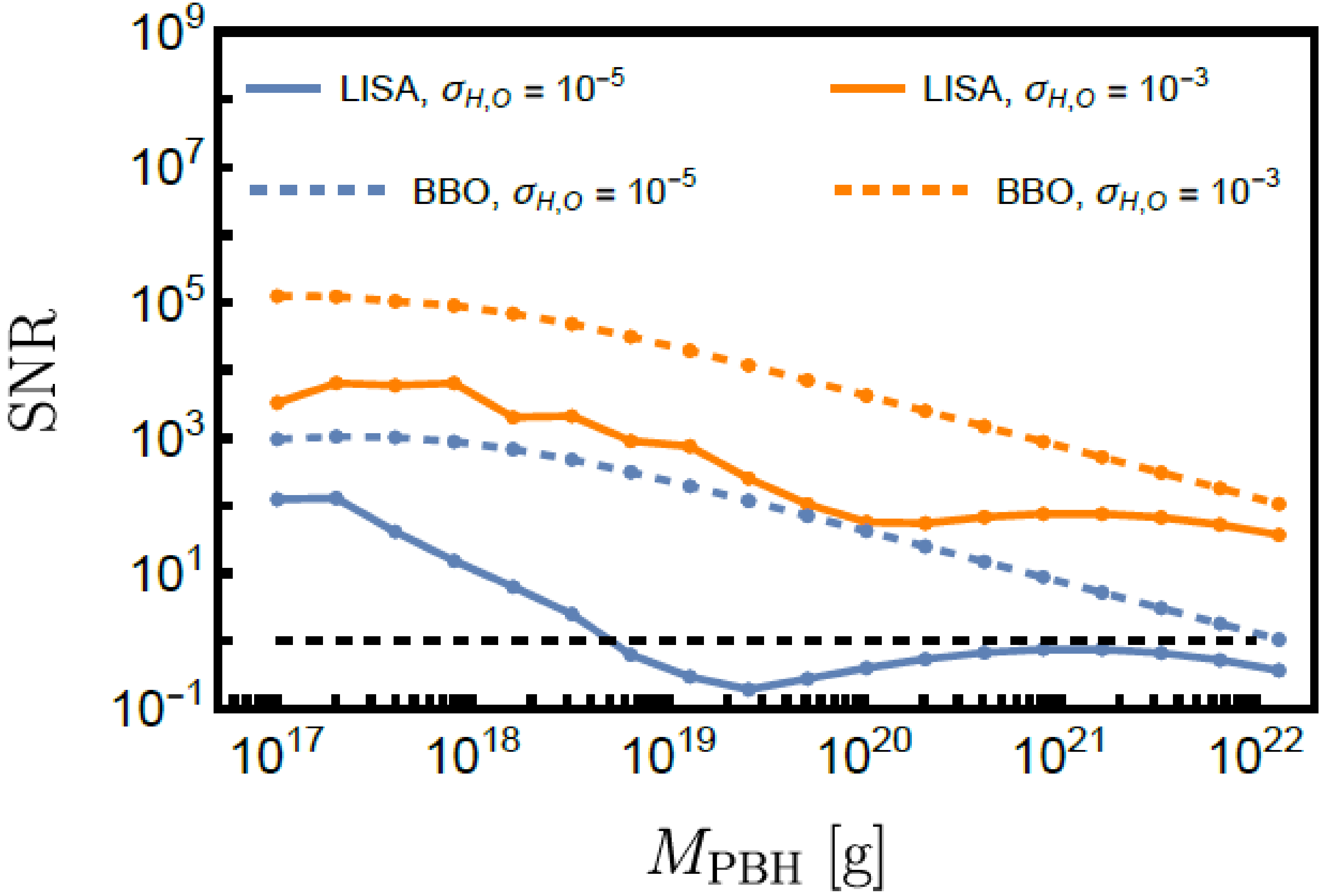
Dashed: RD peaks

SNR for one year of observation:



Solid: EMD peaks

Dashed: RD peaks

J. Dent, N. P. D. Loc, T. Xu JCAP 10, 026 (2025)

Conclusion & Outlook:

- Mass of PBHs can grow significantly due to accretion during EMD.

- An epoch of EMD can also make a significant contribution to SIGWs.

- The resulting GW spectrum has two separated peaks.

- For PBHs in DM mass window, both peaks detectable by LISA & BBO.

- Computing GWs in the nonlinear regime (a prolonged EMD phase)?

  N. Fernandez, J. Foster, B. Lillard, J. Shelton PRL 133, 111002 (2024)

- Investigating a similar scenario for lighter PBHs?