Primordial black holes from inflation and their observational imprints

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Based on:
JCAP’20, PRD’21, JHEP’23, PRD’23, JHEP’24

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INDIAN INSTITUTE OF SCIENCE
भारतीय विज्ञान संस्थान

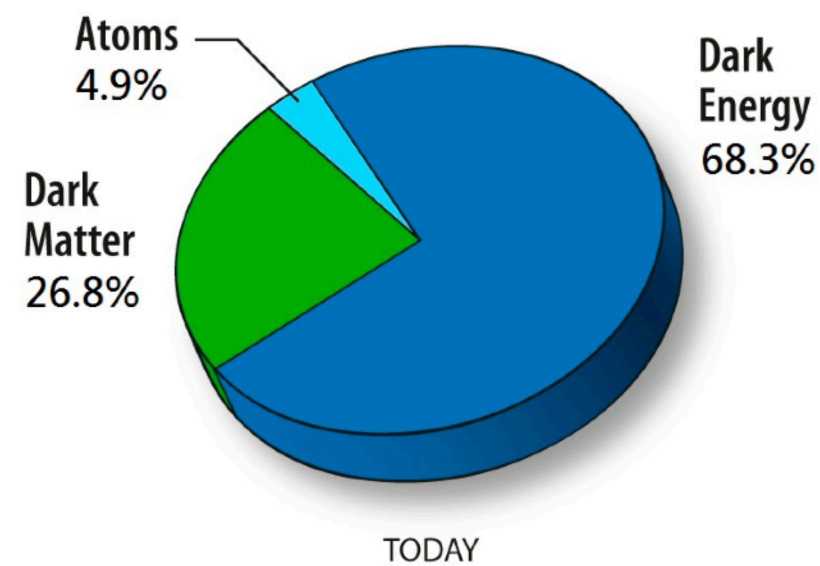
Outline of the talk

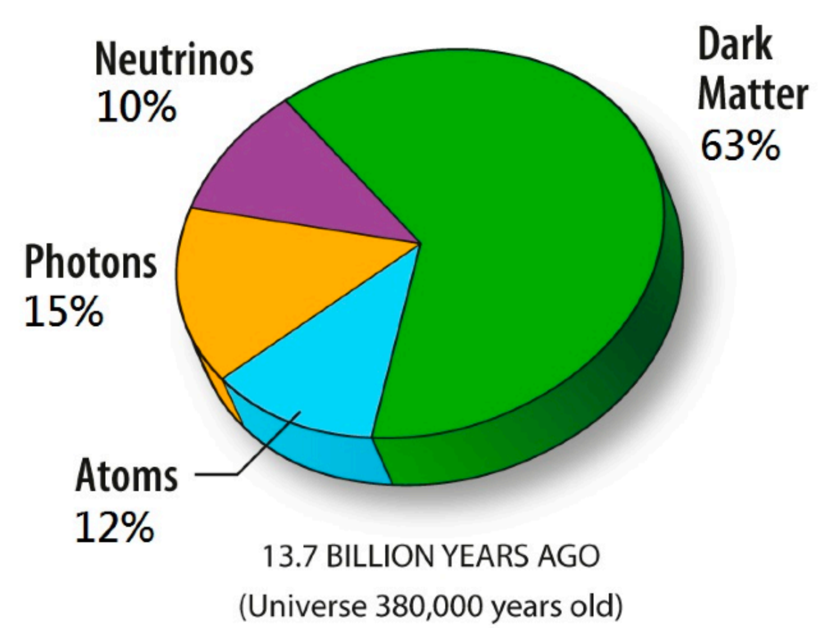
- *Why Primordial Black Holes (PBH) ?*
- *PBH generation mechanisms — single field inflation — inflection point models — PBH mass fraction*
- *Interesting observational imprints of PBHs*
  - *Induced secondary GWs from scalar perturbations*
  - *Ultralight PBHs and imprints from Hawking evaporation*
  - *Induced GWs and PTA results*
  - *Imprints of memory burden effect of PBHs*
- *Conclusions*

Standard model of Cosmology

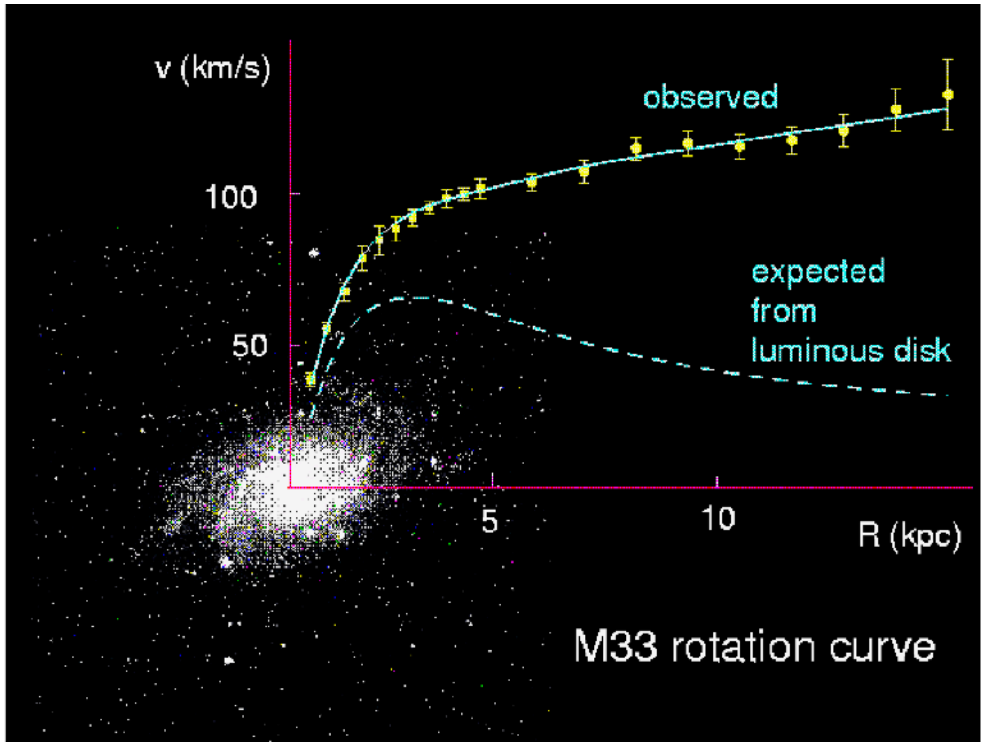
- The concordance model — Radiation + Baryons + Dark matter + Dark energy
- Statistically homogeneous and isotropic on very large scales

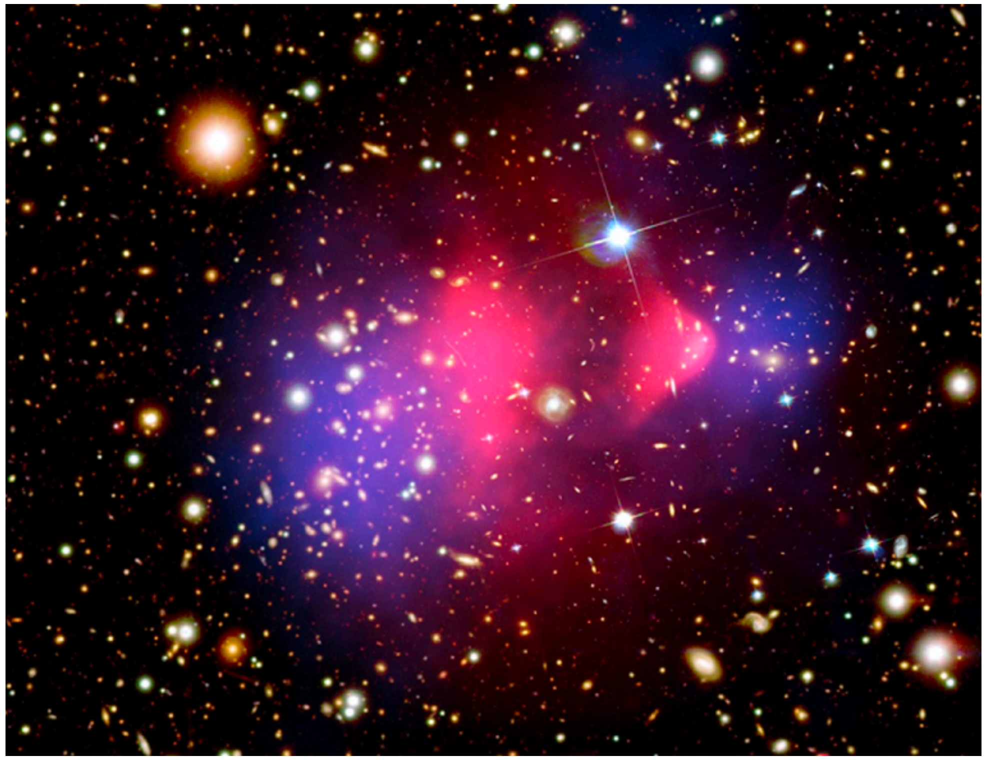
$$\boxed{\Lambda\mathrm{CDM}}$$

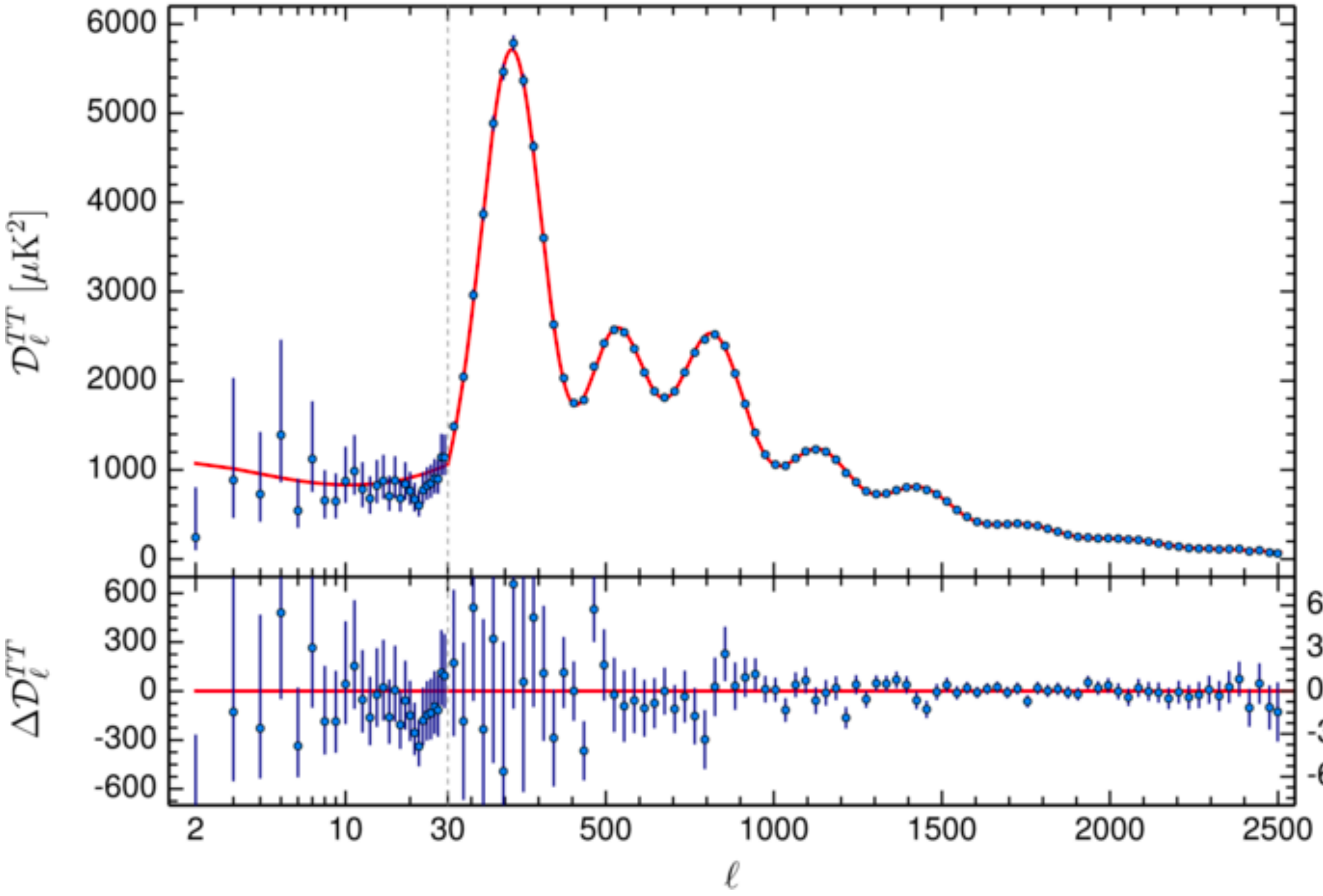




Dark matter — observational evidence



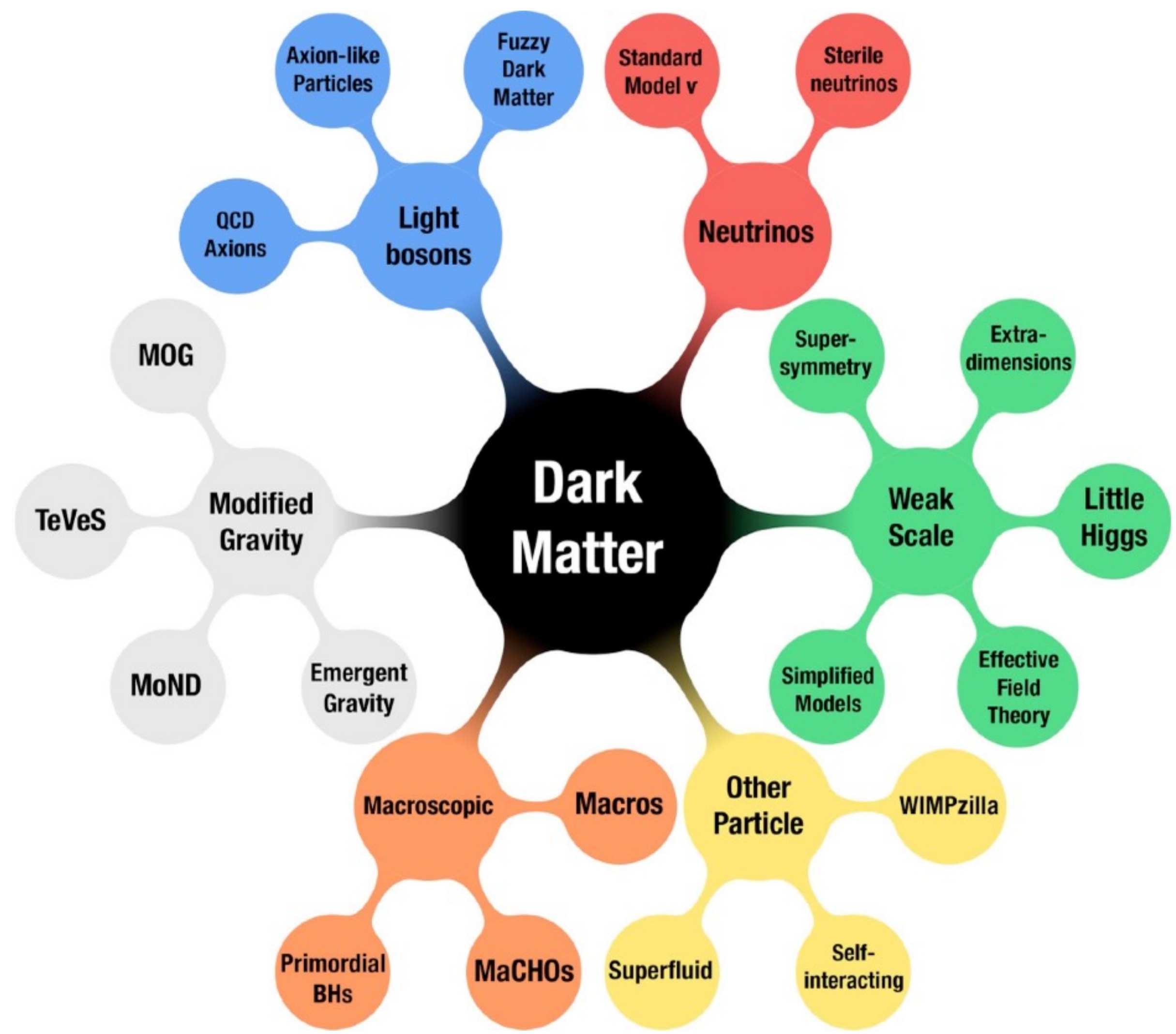




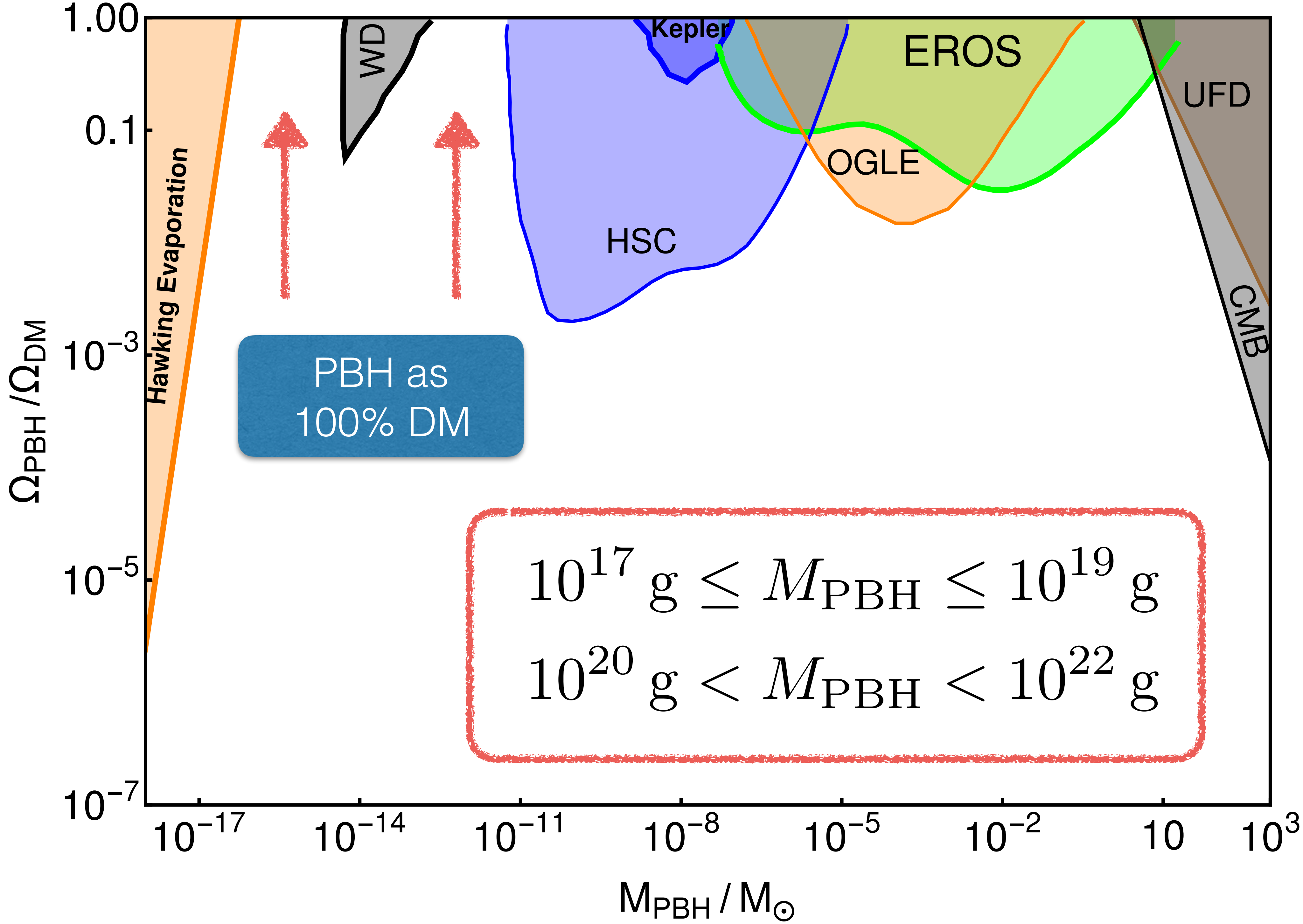
Dark matter: A known *Unknown* !

Why Primordial Black Holes (PBH) ?

- A novel and promising candidate for the cold dark matter
- Abundant production in the early universe — e.g. after inflation
- Non-baryonic, non-relativistic and nearly collisionless
- No new physics (beyond inflation) required !
- Interesting observational signatures e.g. secondary GWs, Hawking evaporation etc.

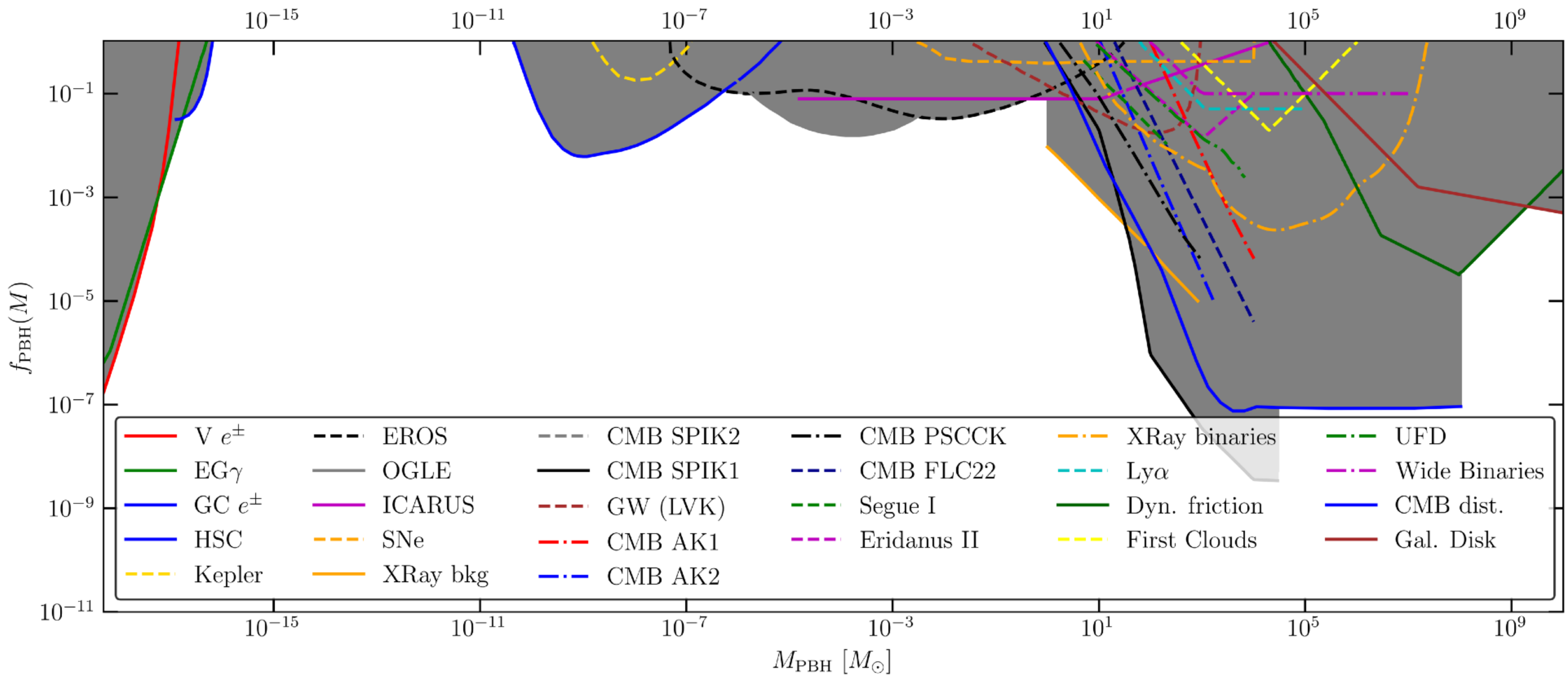


PBH as DM — Current constraints



$$10^{17}\,\mathrm{g} \leq M_{\rm PBH} \leq 10^{19}\,\mathrm{g}$$
$$10^{20}\,\mathrm{g} < M_{\rm PBH} < 10^{22}\,\mathrm{g}$$

PBH as DM — Current constraints

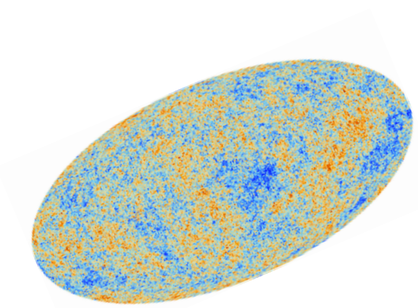


Primordial black holes and their gravitational-wave signatures

LISA Cosmology Working Group, Bagui, …**RKJ**… et al.,

Living Reviews in Relativity, 28 (2025) 1, 1 [arXiv:2310.19857]

PBH formation from inflation — in a nutshell



$T_0 = 2.73K$

$\frac{\Delta T}{T_0} \sim 10^{-5}$

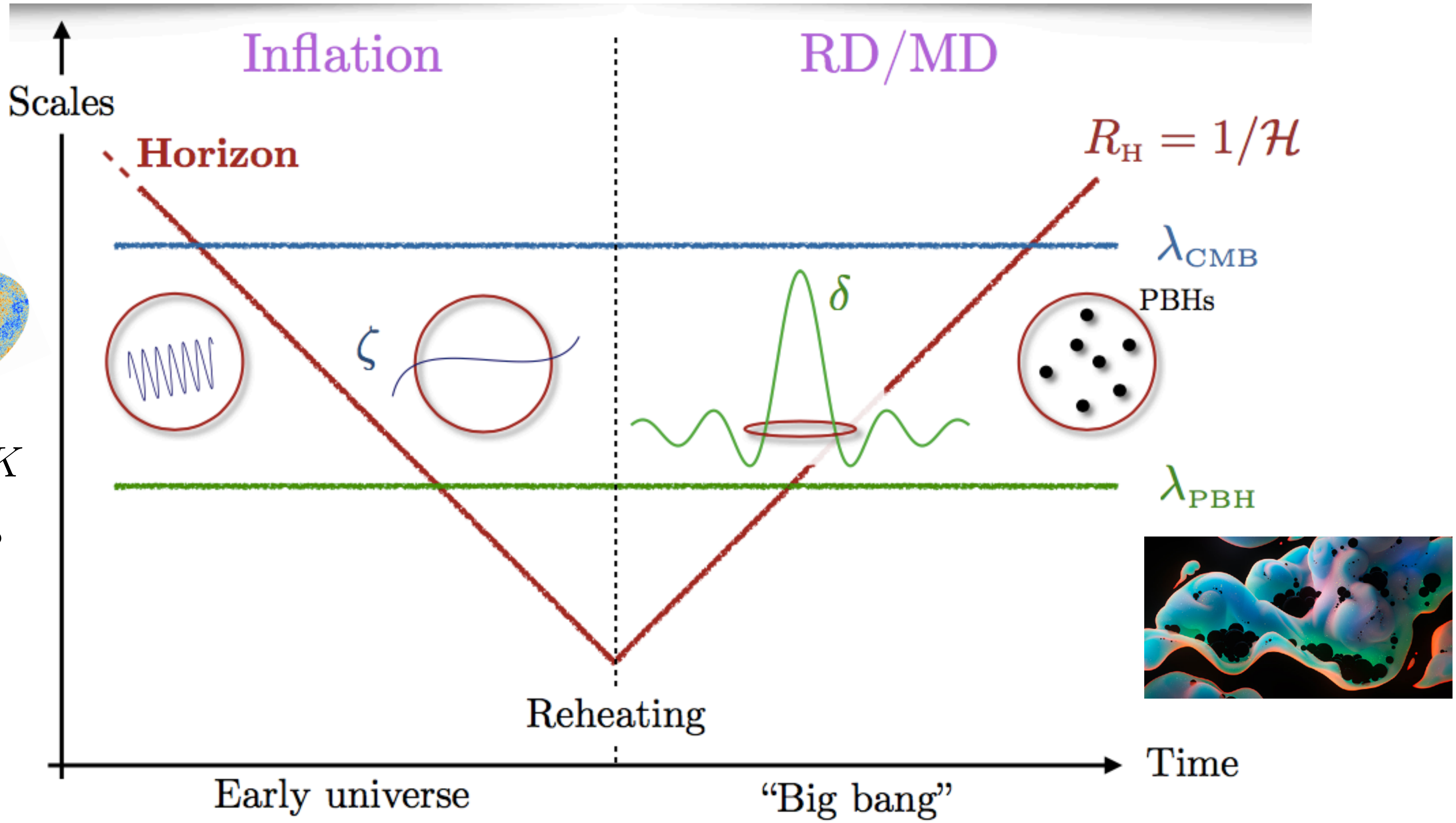
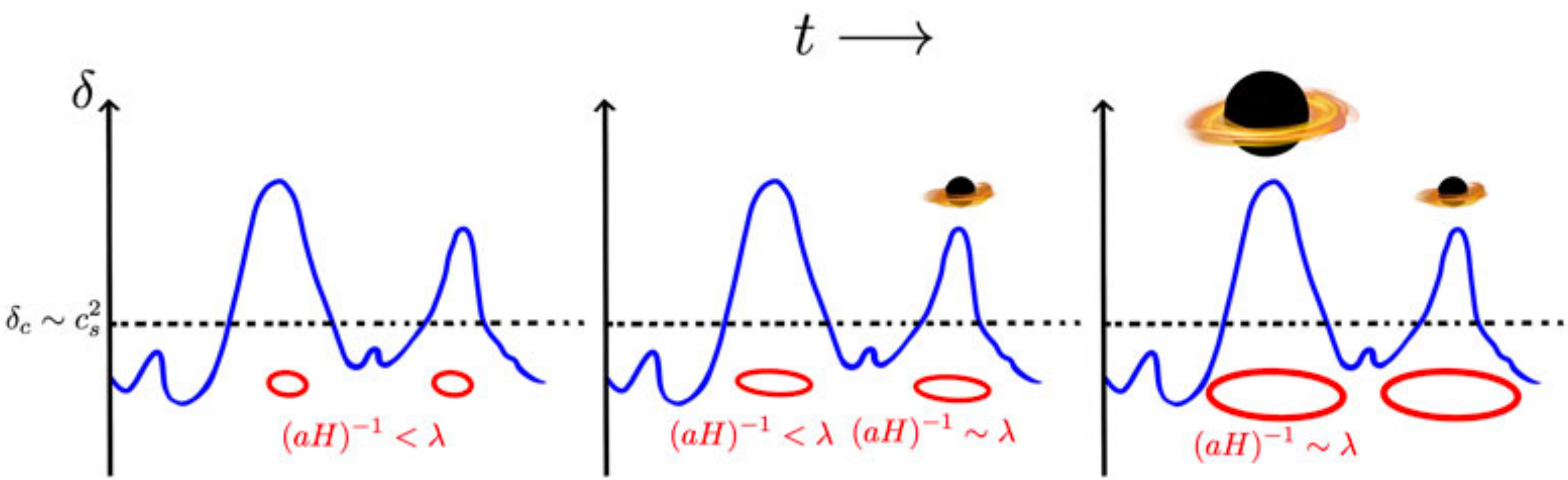


Fig. credit: G. Franciolini

PBH formation from inflation — in a nutshell



PBH formation from collapse of overdense fluctuations during radiation domination

Fig. credit: Front. Astron. Space Sci., 2021

PBH formation from inflation — in a nutshell

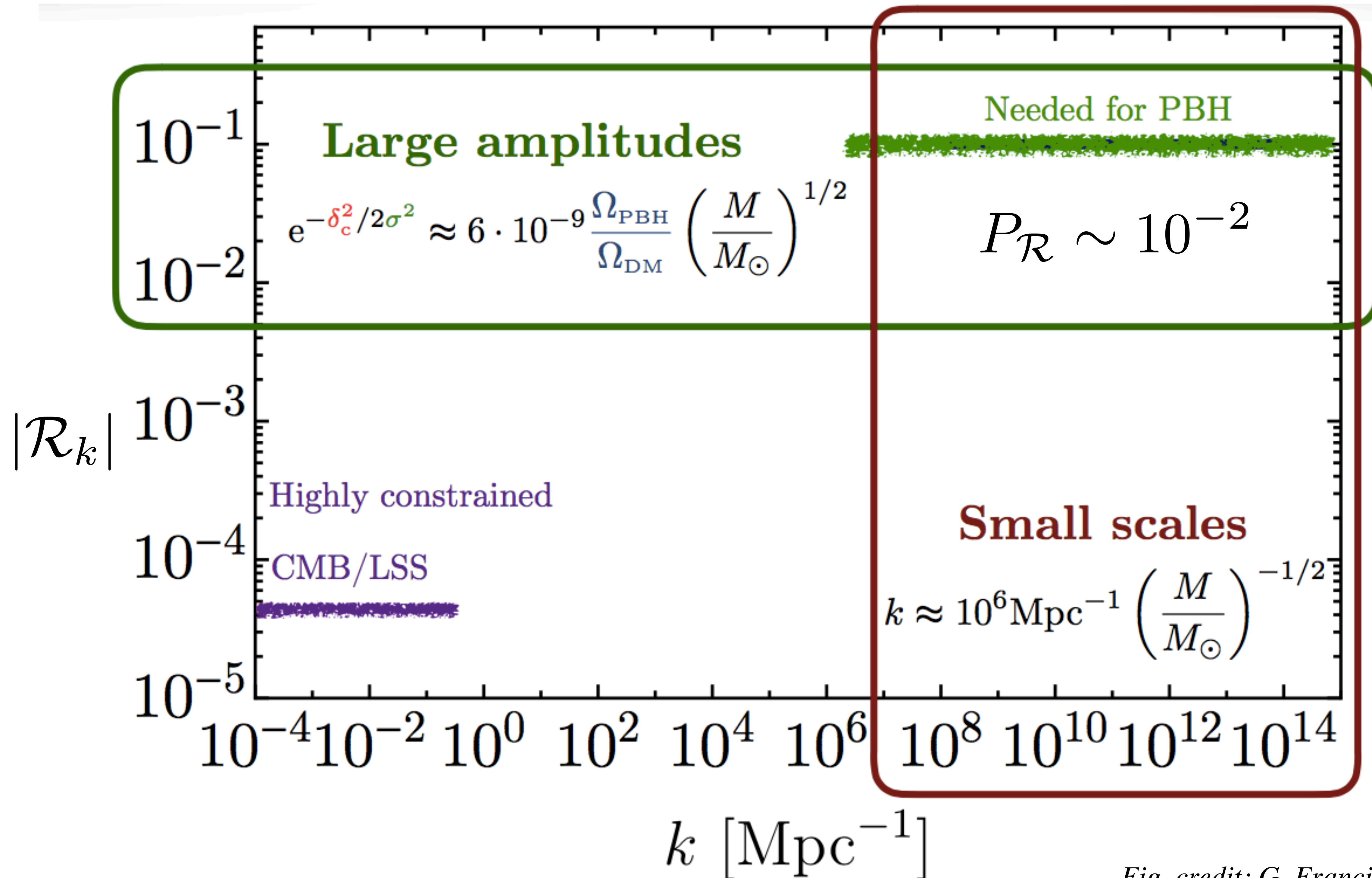
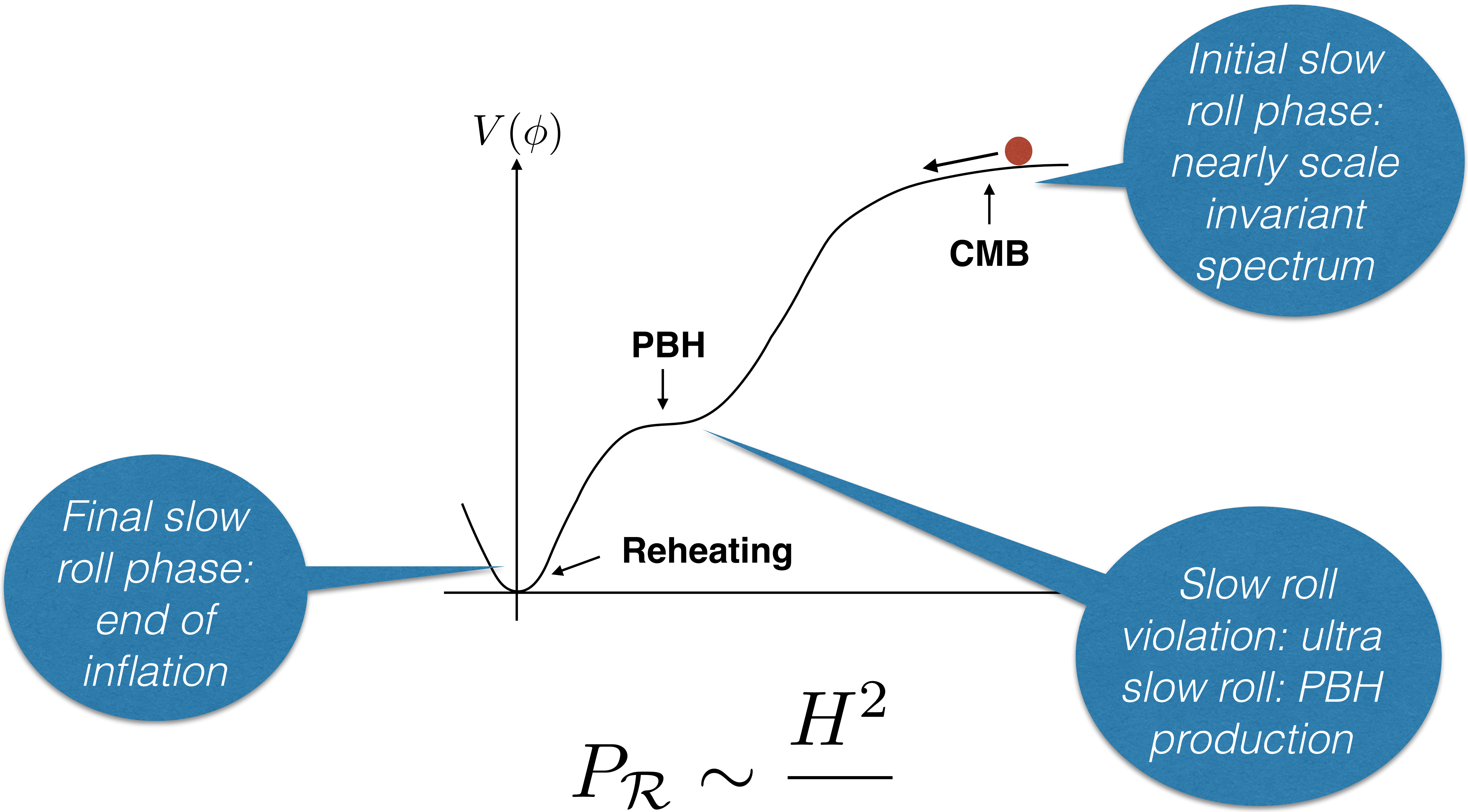


Fig. credit: G. Franciolini

PBH from inflation — inflection point models



$$P_{\mathcal{R}} \sim \frac{H^2}{\epsilon}$$

A single field inflection point scenario

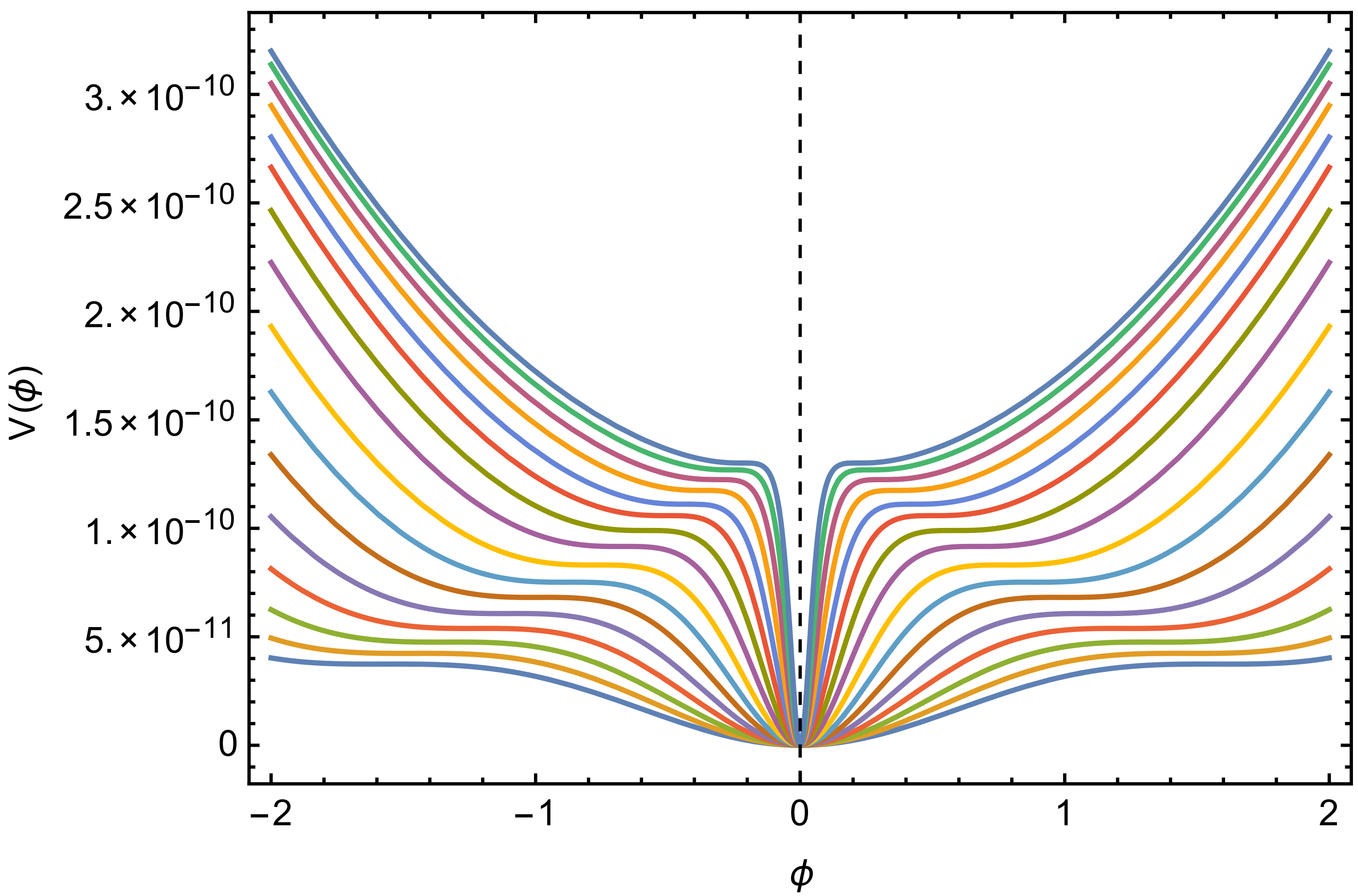
$$V(x) = V_0 \, \frac{ax^2 + bx^4 + cx^6}{(1+dx^2)^2}, \qquad x = \phi/v$$

$$x \gg 1 : V(x) \simeq \frac{V_0 c}{d^2} x^2$$

$$x \ll 1 : V(x) \simeq V_0 a x^2$$

Quadratic for both large & small field values

$$\boxed{r \sim 0.05}$$



N. Bhaumik & **RKJ**, JCAP 01, 037 (2020)

Slow roll, ultra slow roll and all that…

Background evolution

$$H^2 = \frac{V(\phi)}{M_{\rm Pl}^2(3-\epsilon)},$$

$$\frac{d^2\phi}{dN^2} + (3-\epsilon)\frac{d\phi}{dN} + \frac{1}{H^2}V'(\phi) = 0,$$

SR: $$\frac{d\phi}{dN} + \frac{1}{3H^2}V'(\phi) \simeq 0,$$

USR: $$\frac{d^2\phi}{dN^2} + 3\frac{d\phi}{dN} \simeq 0,$$

$$\epsilon \sim \exp\left[-6(N-N_i)\right]$$

$$\eta \simeq \epsilon + (3-\epsilon) \sim 3$$

Curvature perturbations

$$\mathcal{R}_k'' + 2\left(\frac{z'}{z}\right)\mathcal{R}_k' + k^2\mathcal{R}_k = 0.$$

$$\frac{z'}{z} = aH(1+\epsilon-\eta)$$

$$\mathcal{R}_k(\tau) \simeq C_1 + C_2\int\frac{d\tau}{z^2}$$

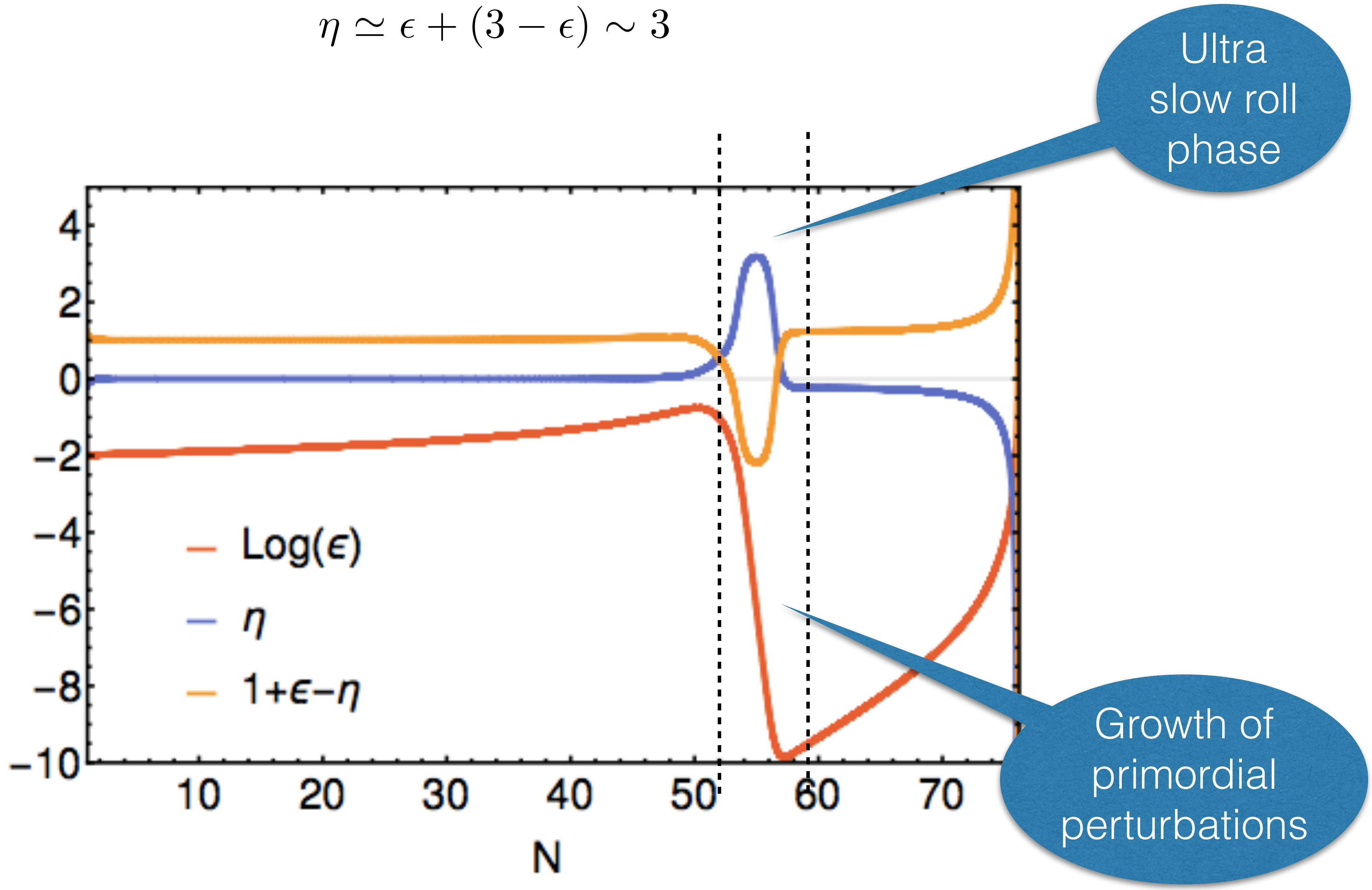
$$P_{\mathcal{R}} = \frac{k^3}{2\pi^2}|\mathcal{R}_k|^2$$

$$P_{\mathcal{R}} \sim \frac{H^2}{\epsilon}$$

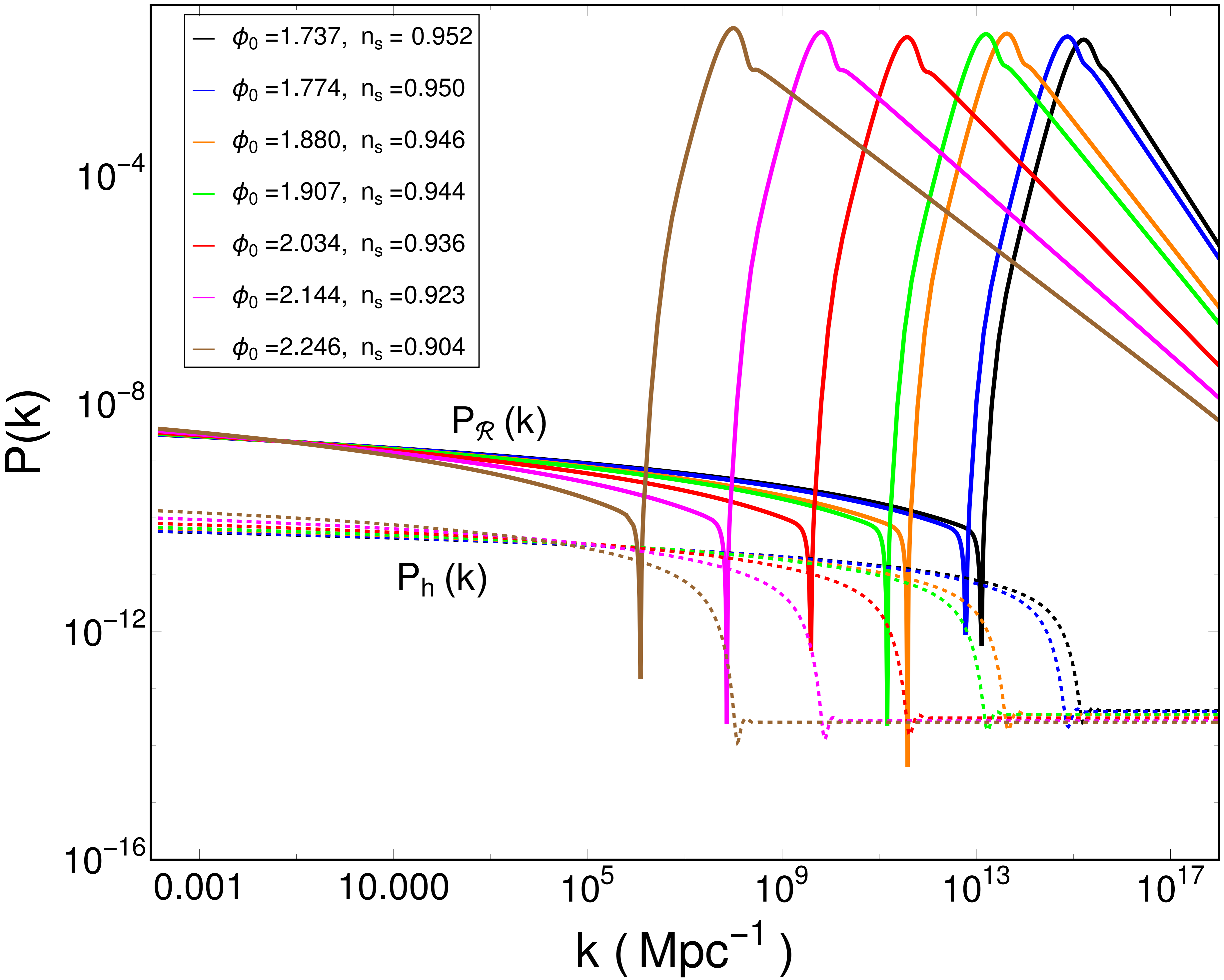
Slow roll, ultra slow roll and all that…

$$\epsilon \sim \exp\left[-6(N - N_i)\right]$$

$$\eta \simeq \epsilon + (3 - \epsilon) \sim 3$$



Primordial power spectra



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PBH mass fraction: Press-Schechter formalism

$$\delta(k,t) \simeq \frac{2(w+1)}{(3w+5)}\left(\frac{k}{aH}\right)^2 \mathcal{R}_k.$$

$$\sigma_\delta^2(R) \simeq \frac{16}{81}\int \frac{dk}{k}(kR)^4 P_{\mathcal{R}}(k) W^2(k,R).$$

$$\beta_f(M) \simeq \sqrt{\frac{1}{2\pi}}\frac{\sigma_\delta(M(R))}{\delta_c}\exp\left(-\frac{\delta_c^2}{2\sigma_\delta^2(M(R))}\right)$$

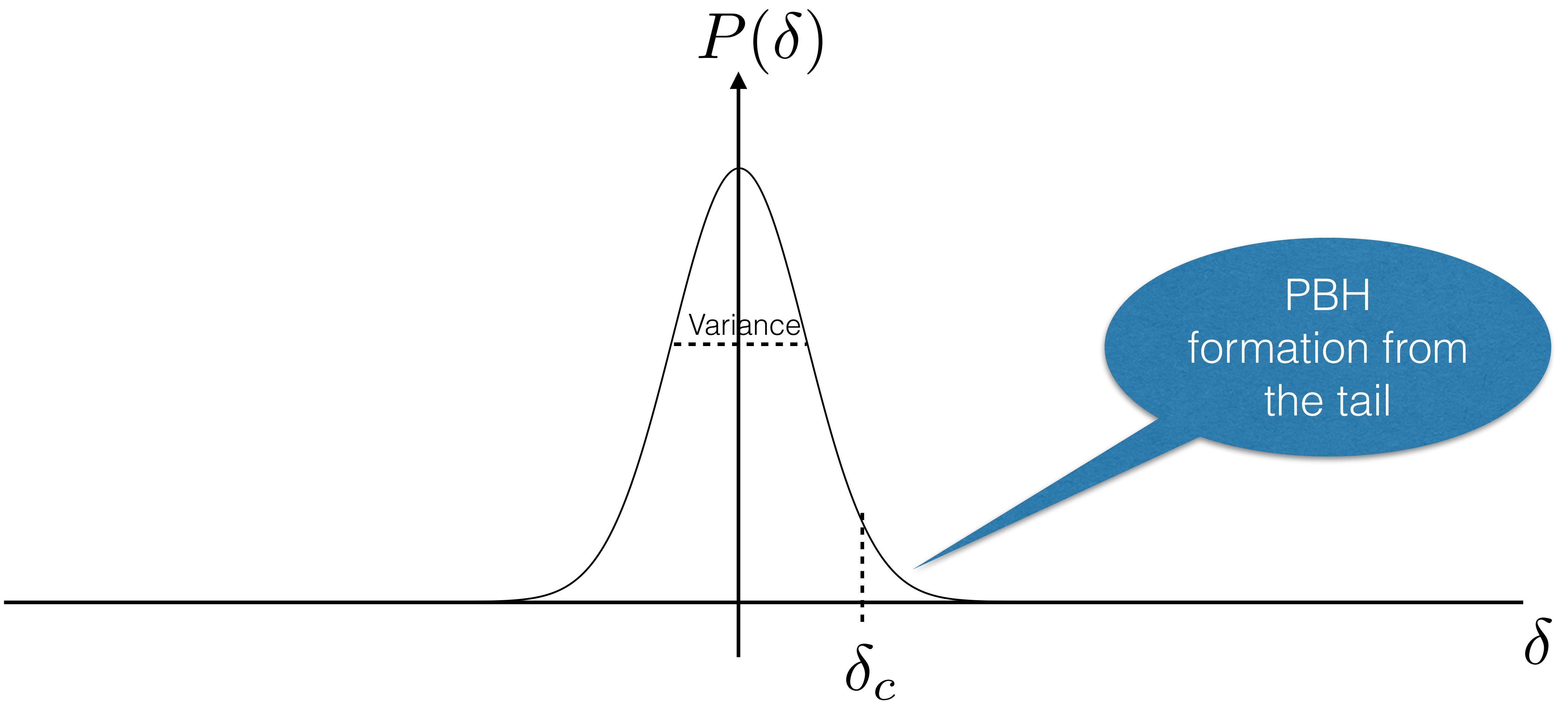
$$\beta(M) \equiv \frac{\rho_{\mathrm{PBH}}(M)}{\rho_{\mathrm{tot}}}.$$

$$\beta_{\mathrm{eq}}(M) \simeq \beta_f(M)\left(\frac{a_{\mathrm{eq}}}{a_f}\right)$$

$$f_{\mathrm{PBH}}(M) \equiv \frac{\Omega_{\mathrm{PBH}}(M)}{\Omega_{\mathrm{DM}}} = \frac{\beta(M)}{8\times 10^{-16}}\left(\frac{\gamma}{0.2}\right)^{3/2}\left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{M}{10^{18}\,\mathrm{g}}\right)^{-1/2}$$

PBH Recipe

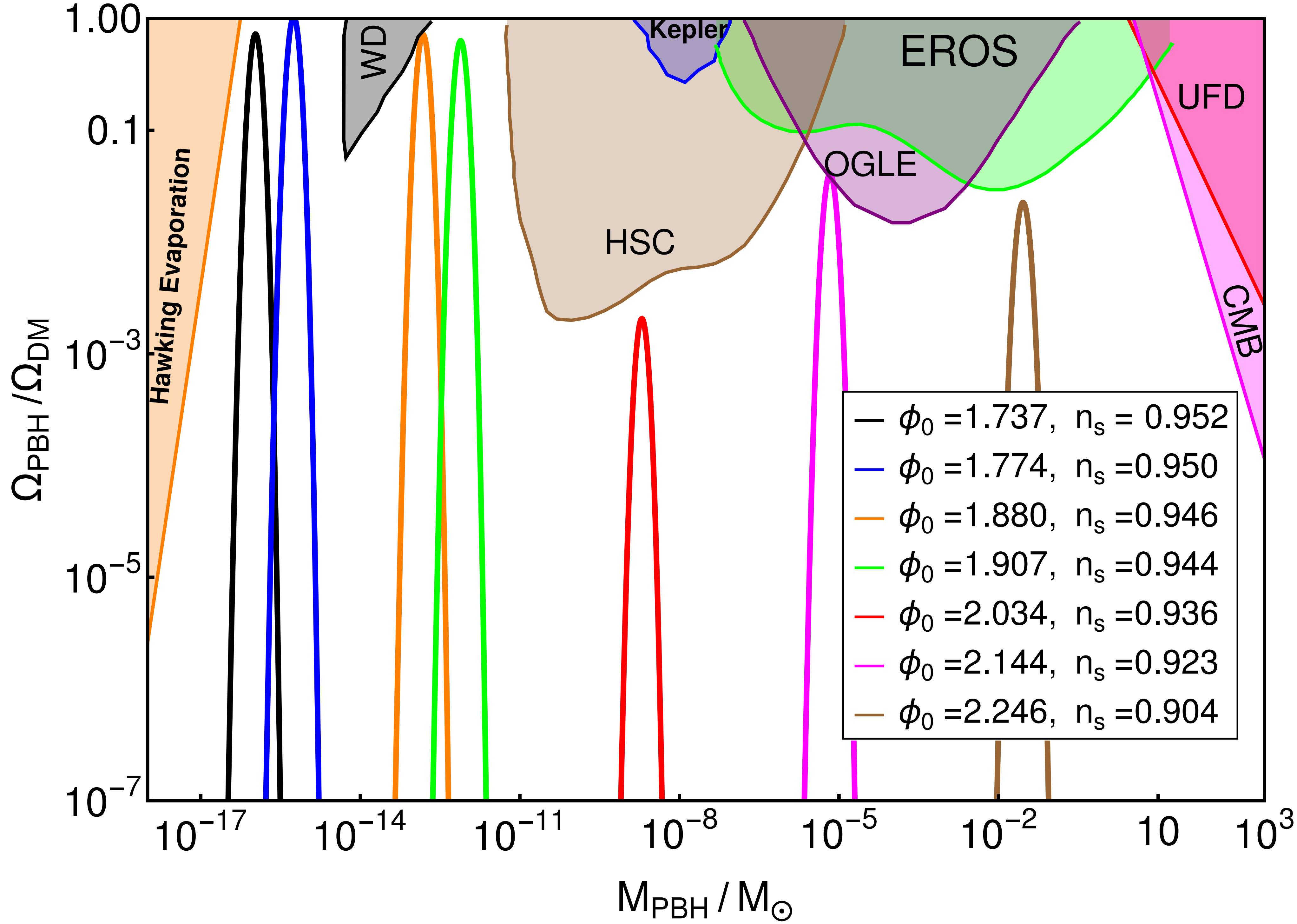
PBH mass fraction: Press-Schechter formalism



$$\beta_f(M) = \frac{1}{\sqrt{2\pi\sigma_\delta^2(M(R))}} \int_{\delta_c}^{\infty} d\delta \exp\left(-\frac{\delta^2}{2\sigma_\delta^2(M(R))}\right)$$

Non-gaussianities play very important role in PBH formation !

PBH mass fraction



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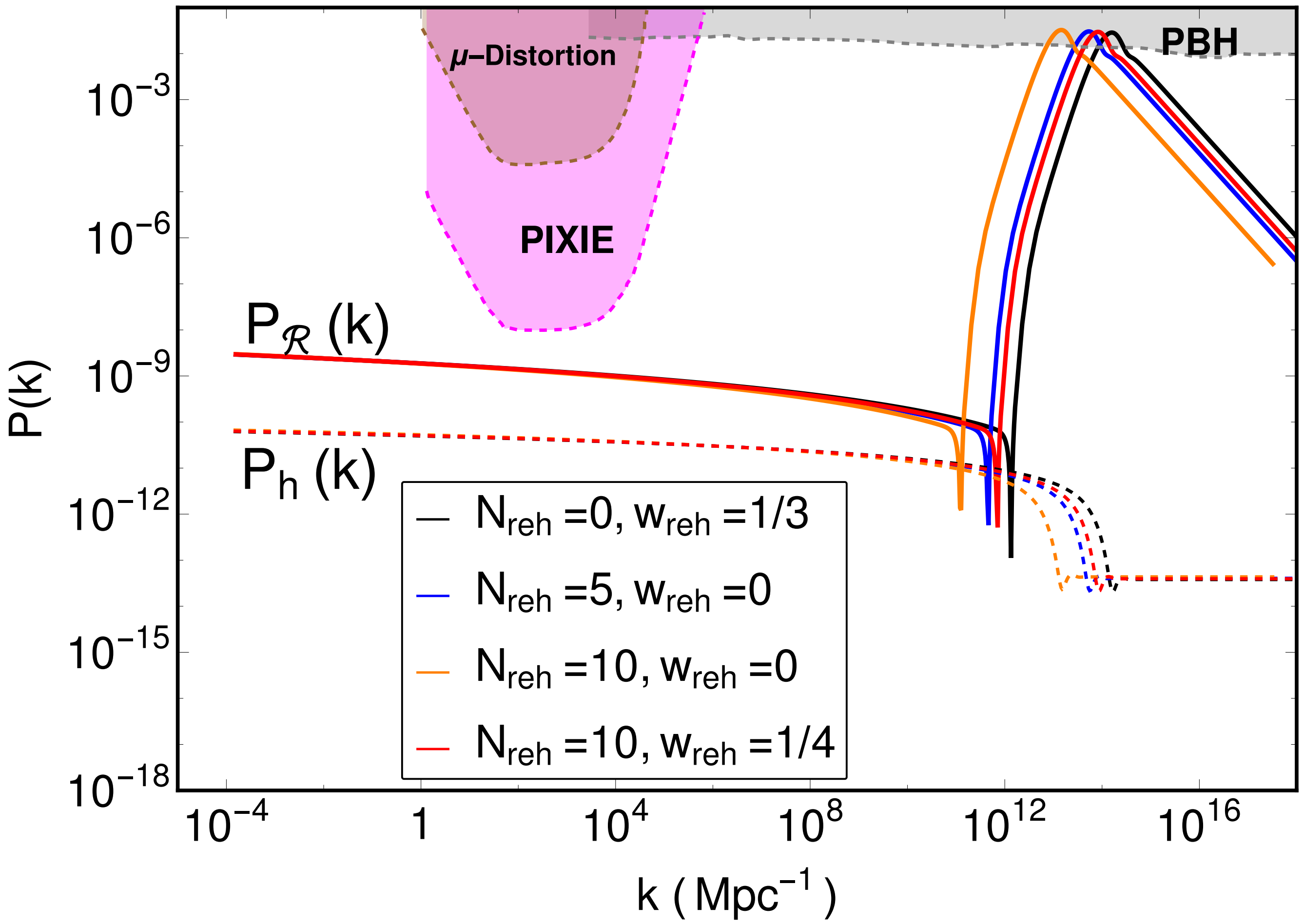
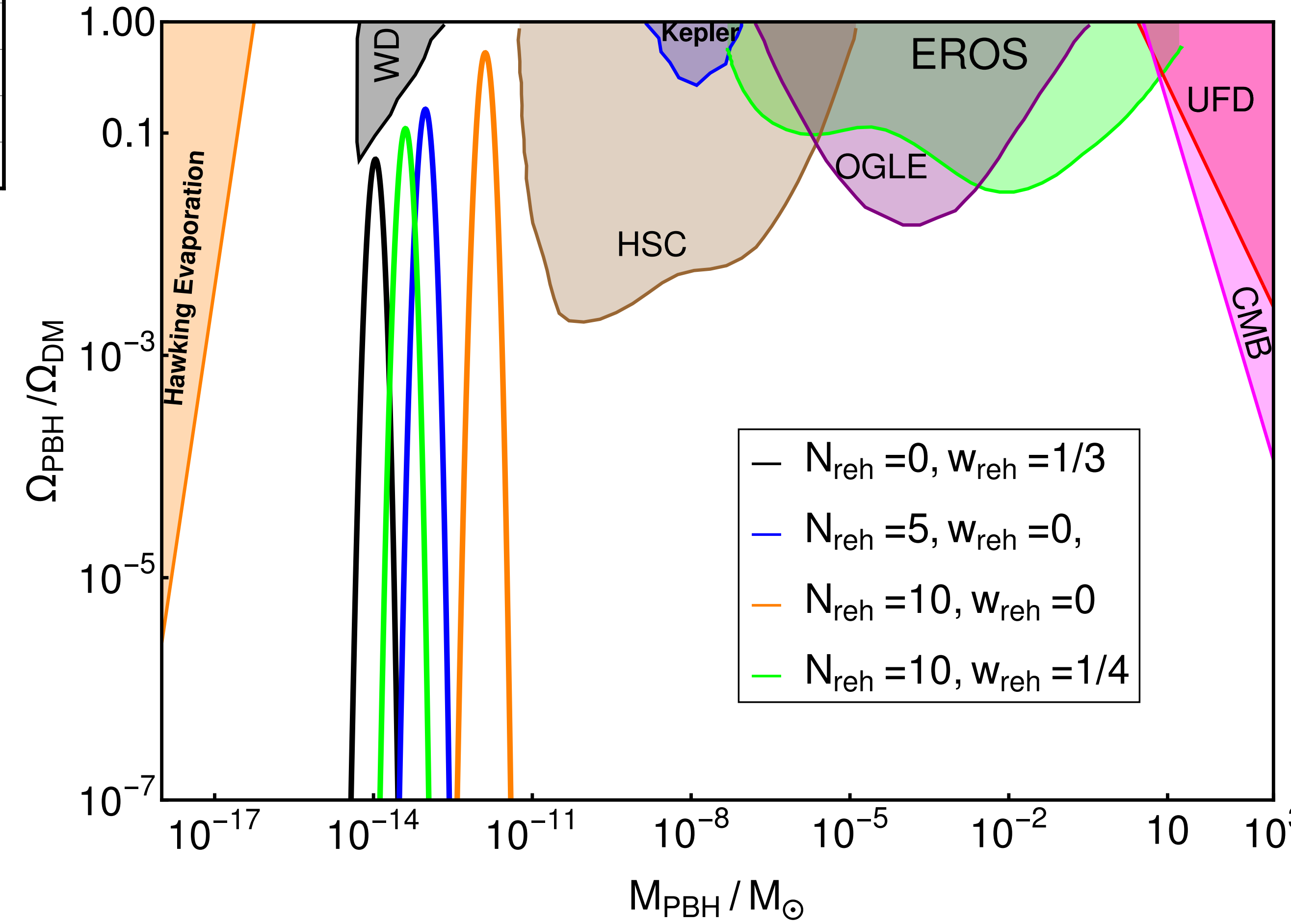
Effects of reheating — remapping of scales

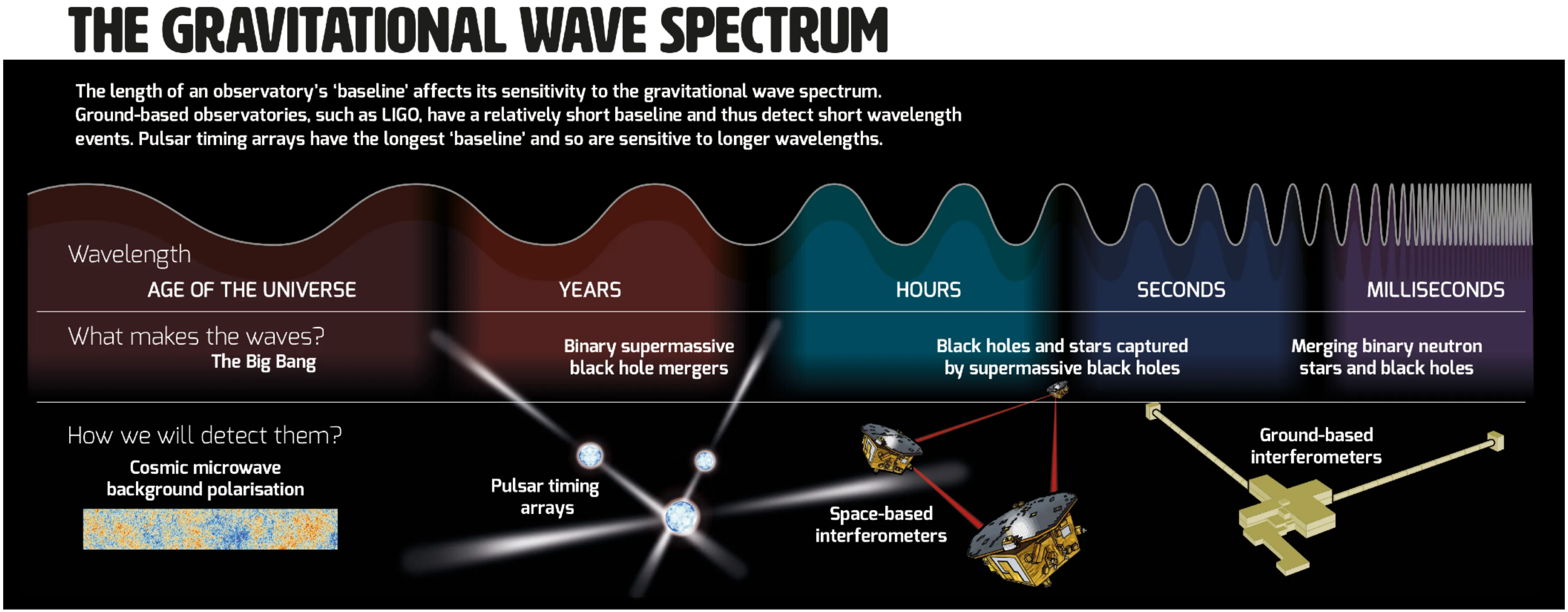




N. Bhaumik & **RKJ**, JCAP 01, 037 (2020)

PBH observational imprints: Induced secondary GWs

GWs across the universe



GWs are novel probes of different epochs of the universe

Induced secondary GWs

Tensor modes sourced by scalar perturbations

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

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

$$\Phi_{\mathbf{k}}(\tau) = \frac{2}{3}\mathcal{T}(k\tau)\mathcal{R}(\mathbf{k}). \qquad \mathcal{T}(k\tau) = \frac{9}{(k\tau)^2}\left[\frac{\sqrt{3}}{k\tau}\sin\left(\frac{k\tau}{\sqrt{3}}\right) - \cos\left(\frac{k\tau}{\sqrt{3}}\right)\right].$$

$$\frac{k^3}{2\pi^2}\left\langle h^{\lambda}_{\mathbf{k}}(\tau)\, h^{\lambda'}_{\mathbf{k}'}(\tau)\right\rangle = \delta_{\lambda\lambda'}\delta^3(\mathbf{k}+\mathbf{k}')\mathcal{P}_h(\tau,k),$$

$$\Omega_{\mathrm{GW}}(\tau,k) \equiv \frac{1}{\rho_c}\frac{\mathrm{d}\,\rho_{\mathrm{GW}}}{\mathrm{d}\ln k} = \frac{\rho_{\mathrm{GW}}(\tau,k)}{\rho_{\mathrm{tot}}(\tau)} = \frac{1}{24}\left(\frac{k}{\mathcal{H}}\right)^2 \overline{\mathcal{P}_h(\tau,k)},$$

Induced secondary GWs

$$\Omega_{\rm GW}(\tau_0,k)\,h^2 \simeq 2.4\times 10^{-5}\left(\frac{\Omega_{r,0}\,h^2}{4.0\times 10^{-5}}\right)\left(\frac{k}{\mathcal{H}(\tau_f)}\right)^2\int_{-\frac{1}{\sqrt{3}}}^{\frac{1}{\sqrt{3}}}{\rm d}d\int_{\frac{1}{\sqrt{3}}}^{\infty}{\rm d}s\left[\frac{(d^2-1/3)(s^2-1/3)}{s^2-d^2}\right]^2$$

$$\times\,\mathcal{P}_{\mathcal{R}}\left(\frac{k\sqrt{3}}{2}(s+d)\right)\mathcal{P}_{\mathcal{R}}\left(\frac{k\sqrt{3}}{2}(s-d)\right)\Big[\mathcal{I}_c^2(d,s)+\mathcal{I}_s^2(d,s)\Big].$$

$$\mathcal{I}_c(d,s) = -36\pi\frac{(s^2+d^2-2)^2}{(s^2-d^2)^3}\theta(s-1),$$

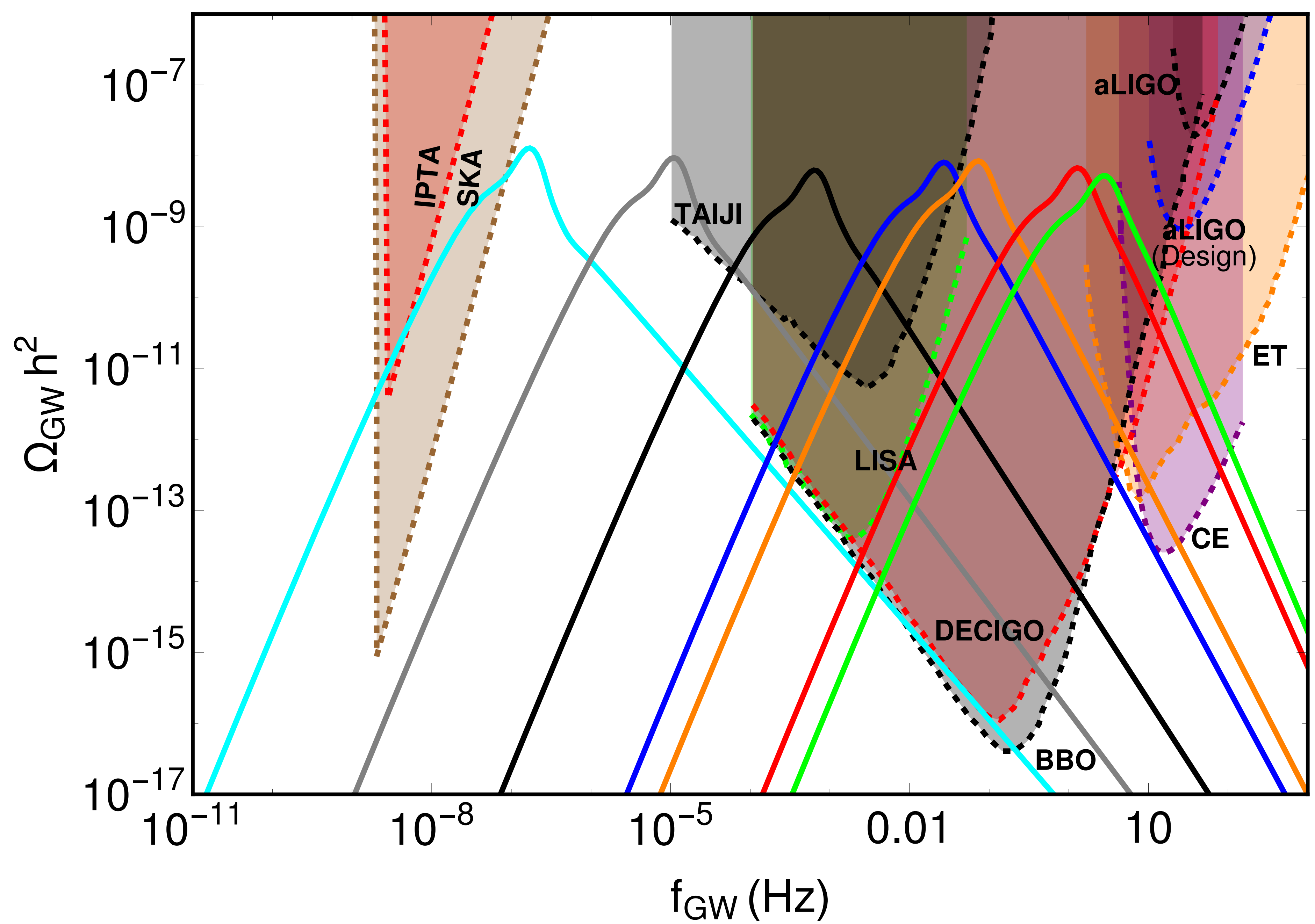
$$\mathcal{I}_s(d,s) = -36\frac{(s^2+d^2-2)}{(s^2-d^2)^2}\left[\frac{(s^2+d^2-2)}{(s^2-d^2)}\log\frac{(1-d^2)}{|s^2-1|}+2\right]$$

$$d=(u-v)/\sqrt{3}$$

$$s=(u+v)/\sqrt{3},$$

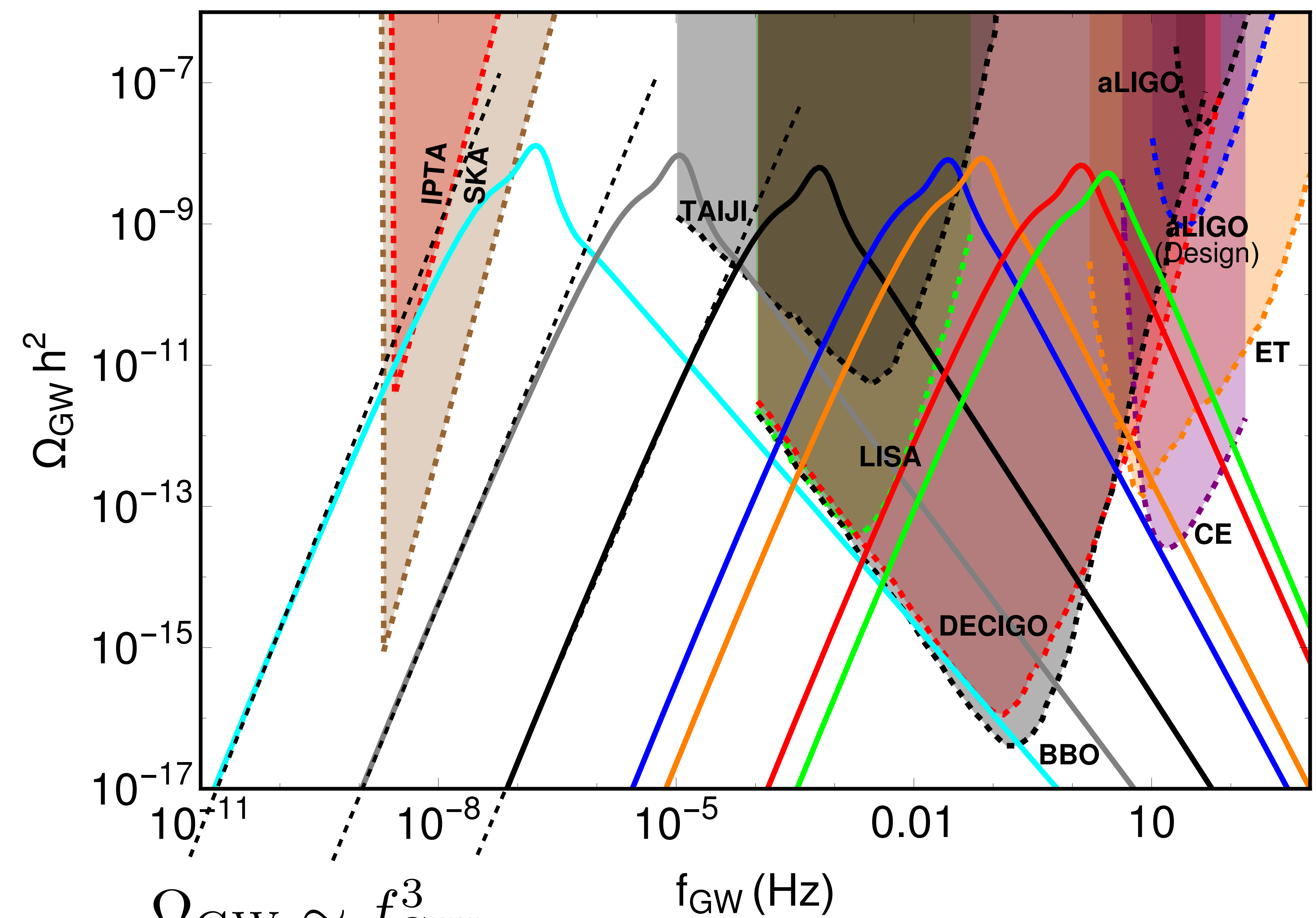
$$v=p/k,\; u=|\mathbf{k}-\mathbf{p}|/k$$

Induced secondary GWs



N. Bhaumik & **RKJ**, Phys. Rev. D 104, 023531 (2021)

Induced secondary GWs



$$\Omega_{\rm GW} \sim f_{\rm GW}^3$$

- A universal IR scaling of GW spectrum, Cai, Pi & Sasaki, 2019
- IR scaling with log corrections, Yuan, Chen & Huang, 2019

The 'three' peaks

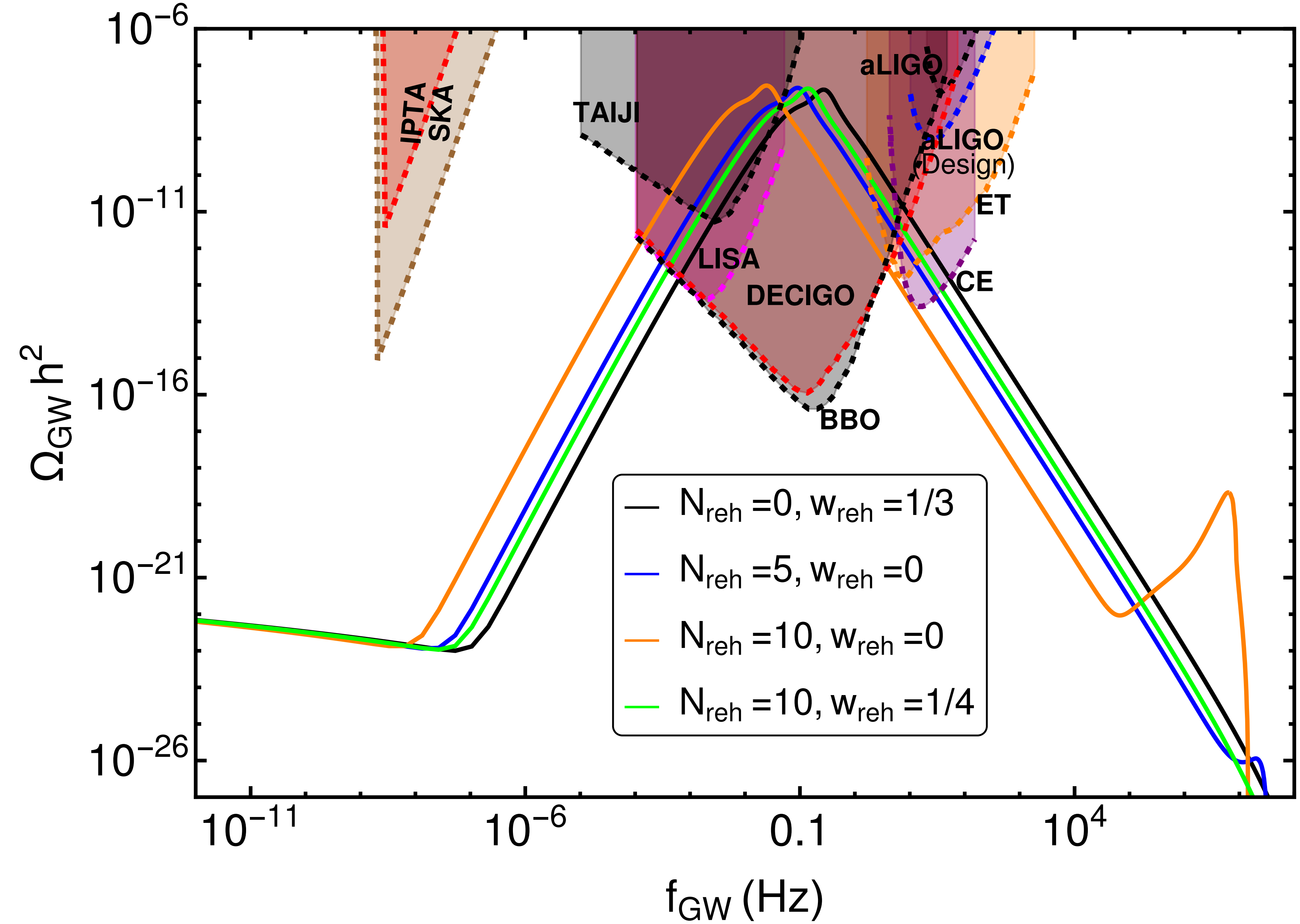
An interesting and useful relation between the 'three' peaks

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

$$f_{\rm PBH} \qquad P_{\mathcal{R}} \qquad \Omega_{\rm GW}$$

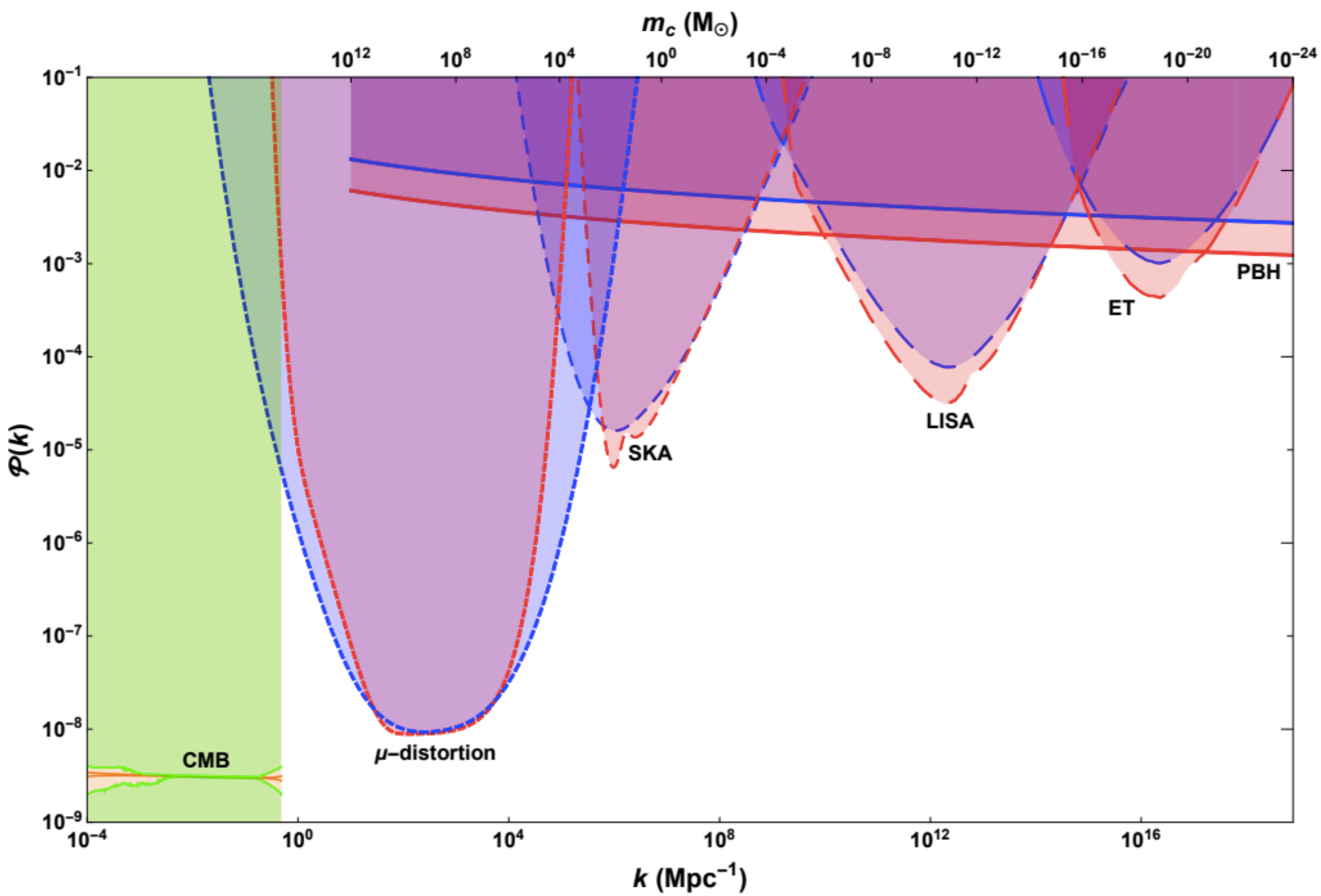
- LISA: f ~ mHz → $k \sim 10^{12}\,{\rm Mpc}^{-1}$ → $M_{\rm PBH} \sim 10^{-12} M_\odot$
- Advanced LIGO: f ~ 30 Hz → $M_{\rm PBH} \sim 10^{13}\,{\rm g} \sim 10^{-20} M_\odot$

Induced secondary GWs — effects of reheating



N. Bhaumik & **RKJ**, Phys. Rev. D 104, 023531 (2021)

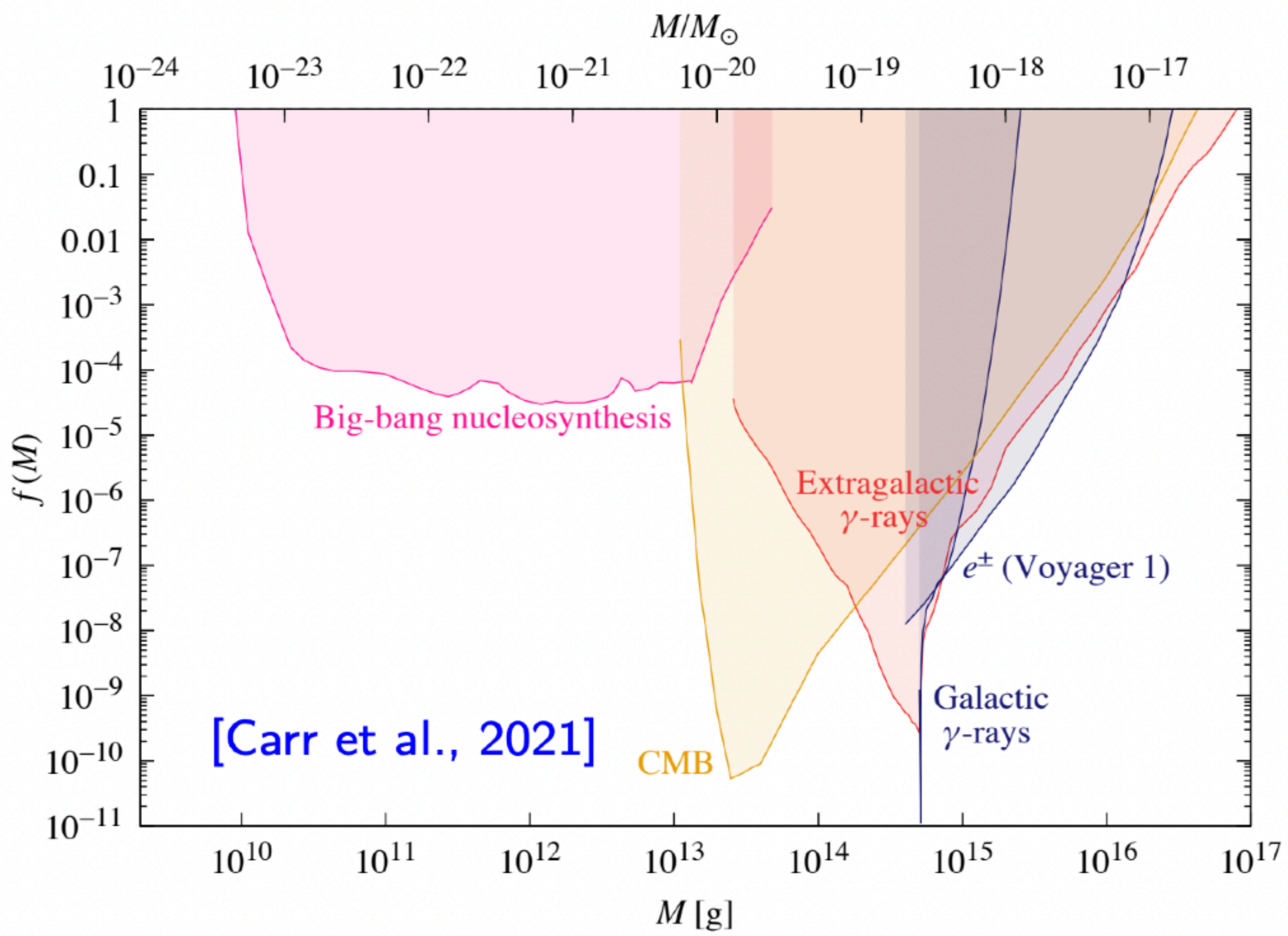
(future) constraints on small scales

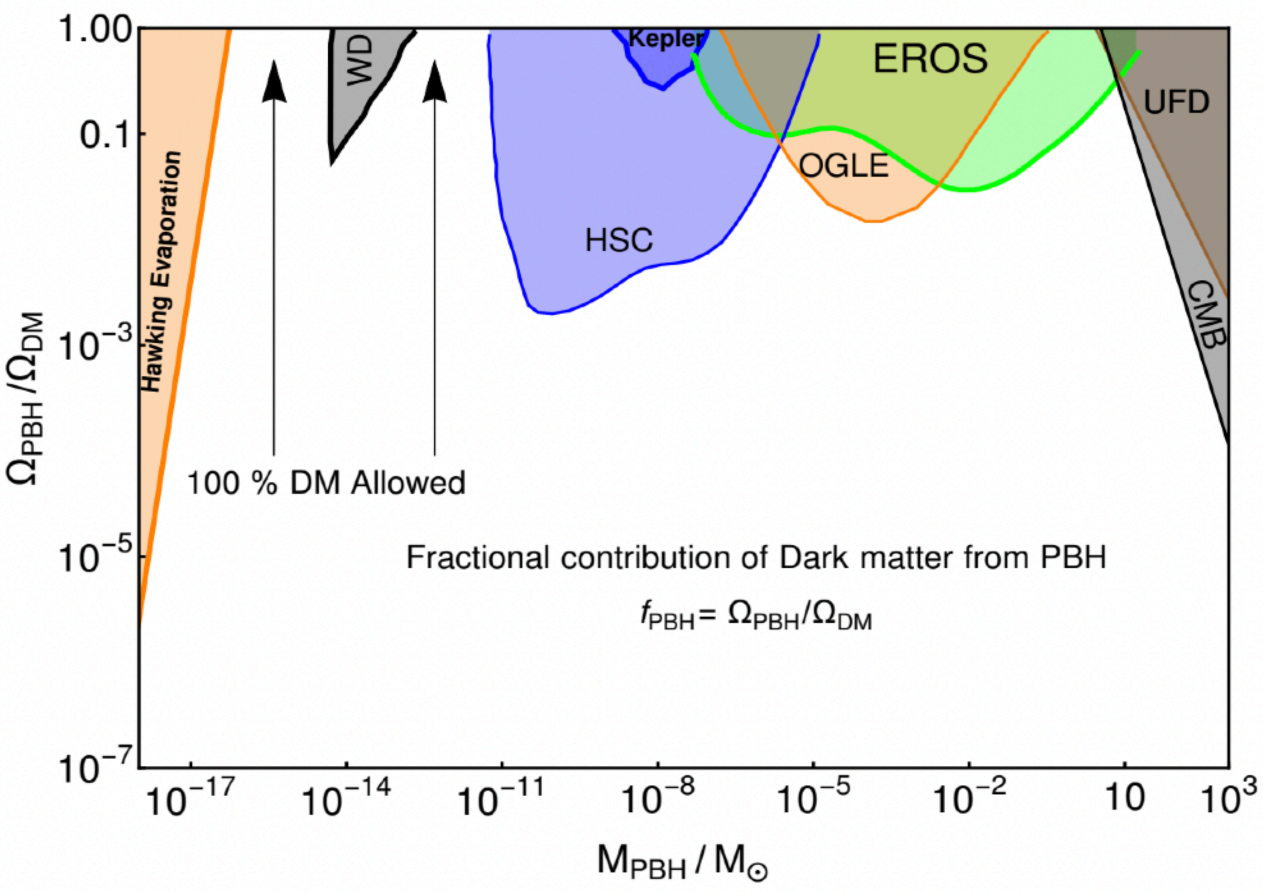


Gow et.al., 2020

Observational imprints of ultralight PBHs: early domination and evaporation

How to constrain imprints of ultralight PBHs ?





PBH with $M \leq 10^9 - 10^{10}\,g$ completely evaporate by BBN hence remain unconstrained.

Ultralight PBHs — Hawking evaporation

- **Non-spinning PBH**

$$T_{\rm PBH}^{\rm S} = \frac{M_{\rm Pl}^2}{M_{\rm PBH}} \simeq 1.053\,{\rm GeV}\left(\frac{10^{13}\,{\rm g}}{M_{\rm PBH}}\right)$$

$$\Delta t_{\rm PBH}^{\rm S} \approx \frac{160 M_{\rm PBH}^3}{\pi\; \mathcal{G}\; \overline{g_{*,H}}\; M_{Pl}^4}$$

- **Spinning PBH**

$$T_{\rm PBH} = \frac{M_{\rm Pl}^2}{M_{\rm PBH}}\left(\frac{2\sqrt{1-a_*^2}}{1+\sqrt{1-a_*^2}}\right)$$

$$a_* = J M_{\rm Pl}^2 / M_{\rm PBH}^2$$

$$\boxed{\Delta t_{\rm PBH} = \Delta t_{\rm PBH}^{\rm S}\; \mathcal{F}(a_*, M_{\rm PBH})}$$

$$\frac{dM(t)}{dt} = -\varepsilon(M(t), a(t))\frac{M_{\rm Pl}^4}{M(t)^2}\,,$$

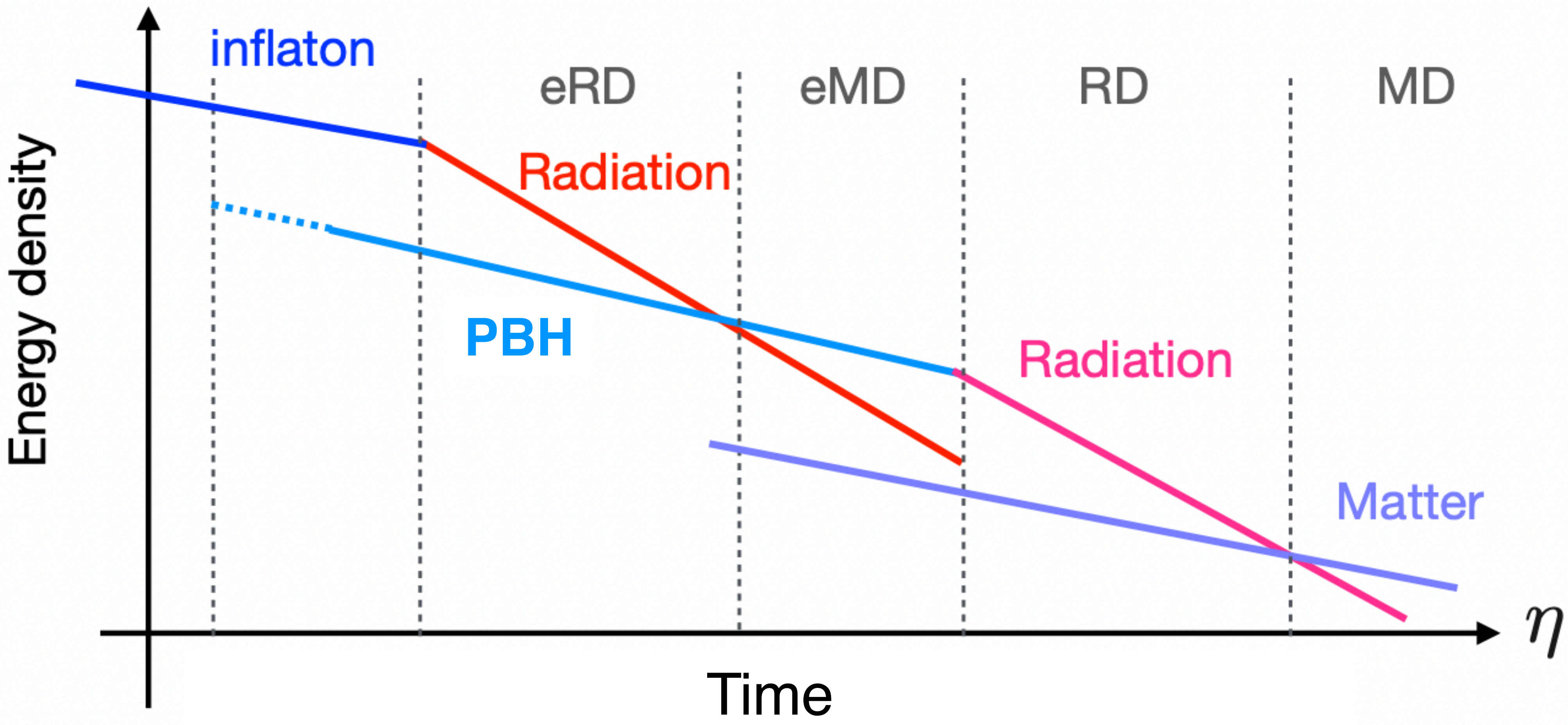
$$\frac{da(t)}{dt} = -a(t)\Big[\gamma(M(t), a(t)) - 2\varepsilon(M(t), a(t))\Big]\frac{M_{\rm Pl}^4}{M(t)^3}$$

BlackHawk

N. Bhaumik, A. Ghoshal, **RKJ** & M. Lewicki, JHEP 05, 169 (2023)

Ultralight PBHs — early matter dominated epoch

$$a_{eMD}(\tau) = \frac{a_f(\tau + \tau_m)^2}{4\tau_f \tau_m}, \quad a_{RD}(\tau) = \frac{a_f(\tau_r + \tau_m)(2\tau - \tau_r + \tau_m)}{4\tau_f \tau_m} \simeq a(\tau_r)\left(2\frac{\tau}{\tau_r} - 1\right)$$



Ultralight PBHs — early matter dominated epoch

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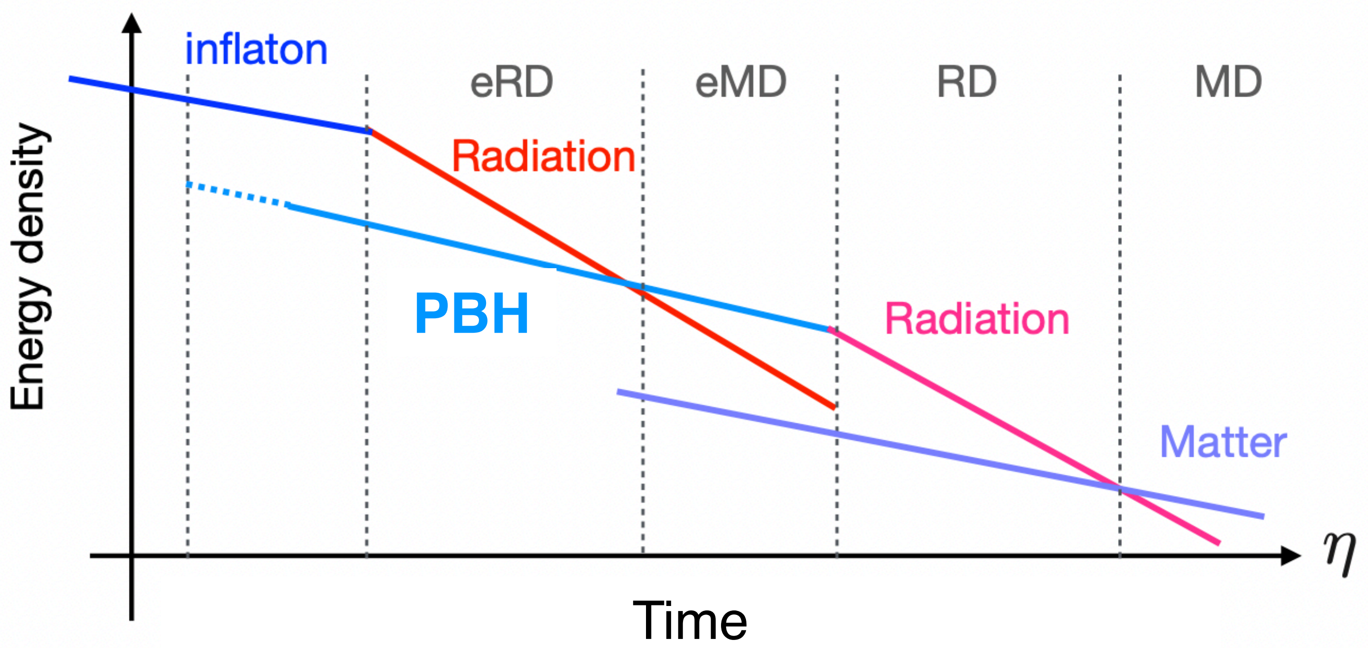
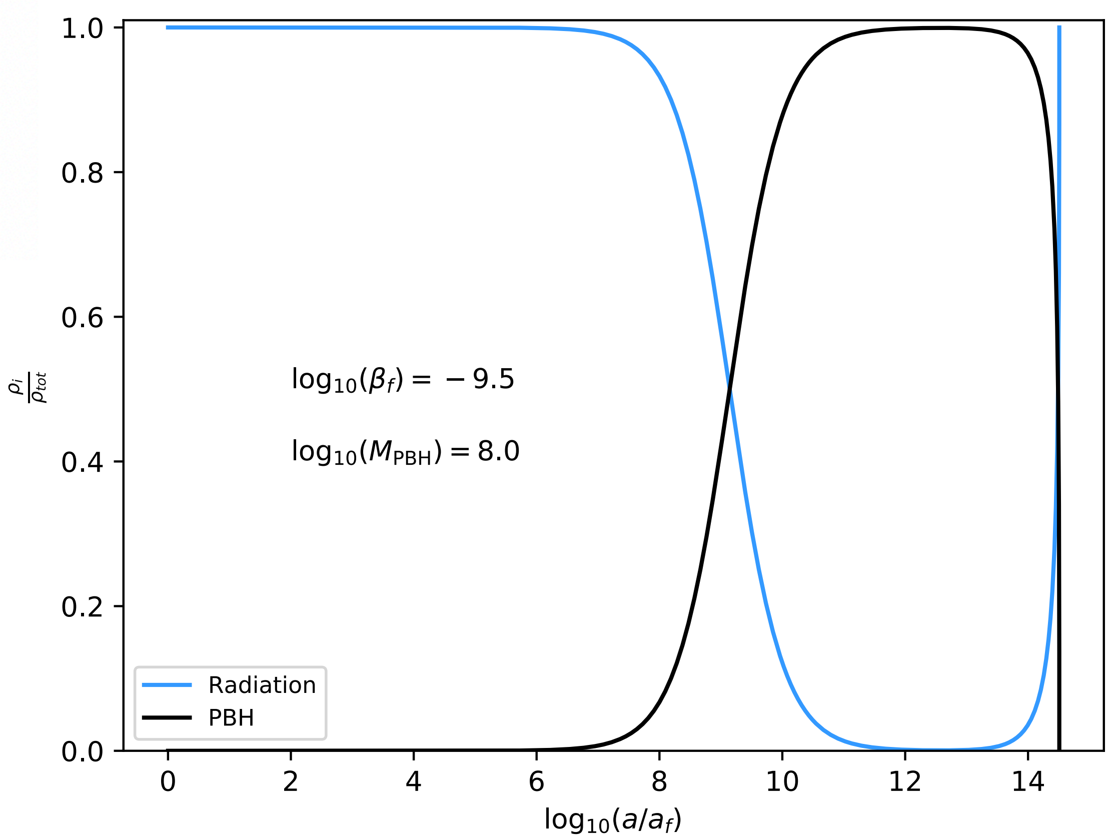




Ultralight PBHs — Contributions to perturbations

- Poisson Distribution of PBHs
- Cutoff for scales below PBH mean distance
- Finite duration of PBH domination (Non-linearity bound)

$$\mathcal{P}_{\rm PBH}(k,\tau_r) = \frac{2}{3\pi}\left(\frac{k}{k_{\rm UV}}\right)^3 \left(5 + \frac{4}{9}\frac{k^2}{k_m^2}\right)^{-2}$$

$$k_{\rm UV} = \gamma^{-1/3}\beta^{1/3}k_f$$

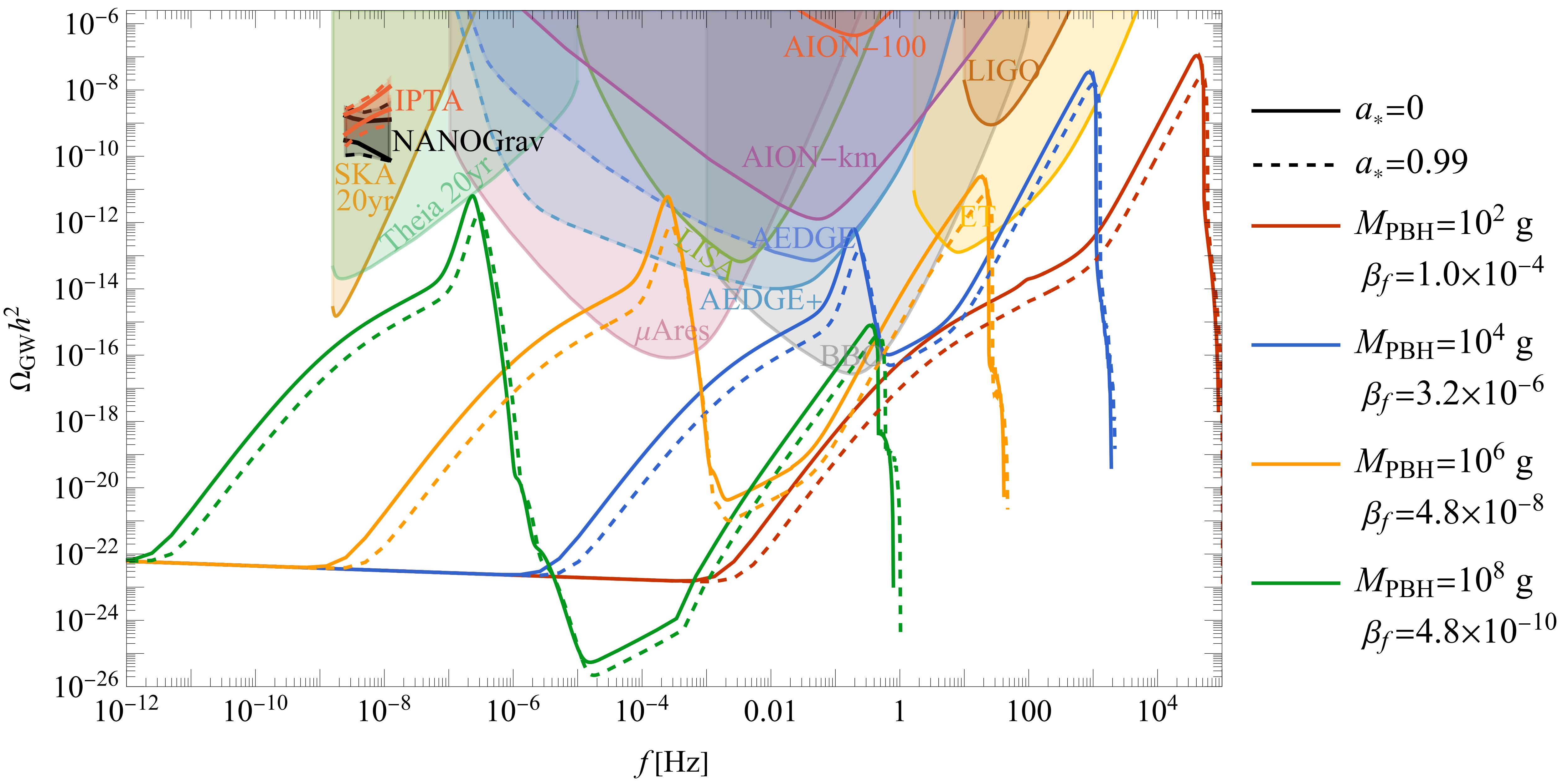
$$\mathcal{P}_{\rm infl}(k,\tau_r) = A_s\left(\frac{k}{k_p}\right)^{n_s-1}\theta_H(k_m - k)$$

$$\Phi(k,\tau_r) = \Phi_{\rm infl}(k,\tau_r) + \Phi_{\rm PBH}(k,\tau_r)$$

$$\mathcal{P}(k,\tau_r) = \mathcal{P}_{\rm infl}(k,\tau_r) + \mathcal{P}_{\rm PBH}(k,\tau_r)$$

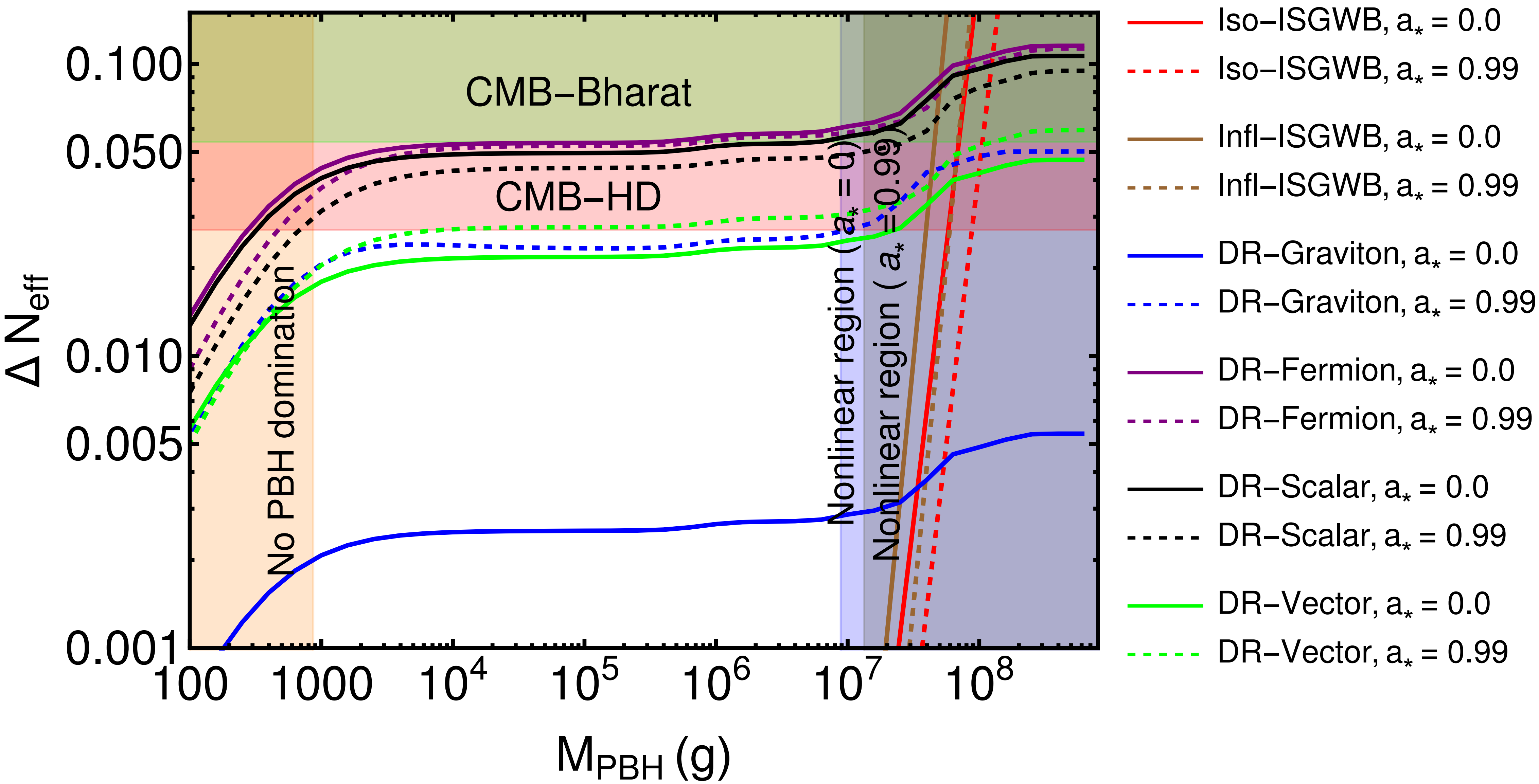
Papanikolaou et. al. (2021), Domenech et. al. (2021)

Doubly peaked GWs — with and without PBH spin



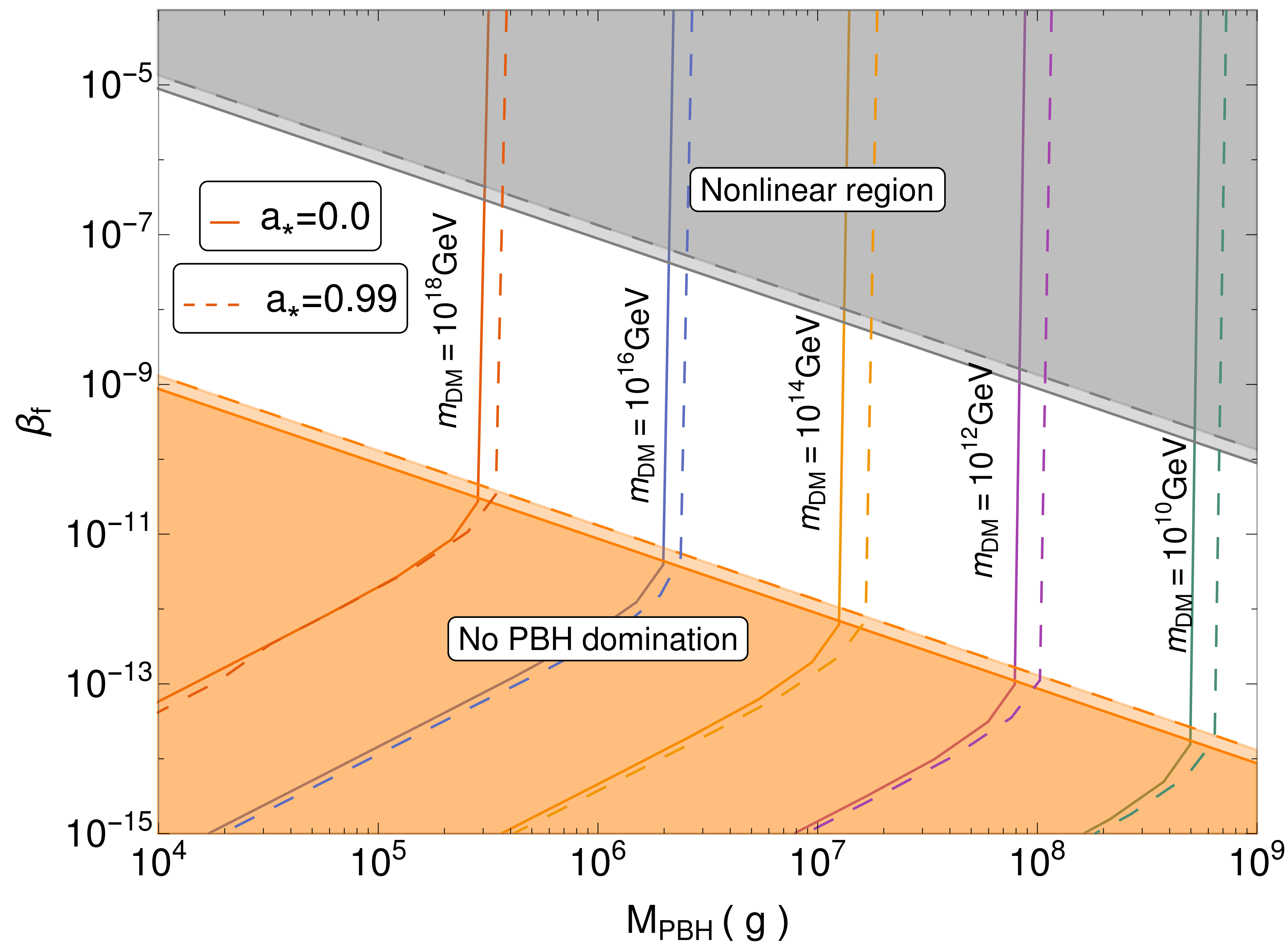
N. Bhaumik, A. Ghoshal, **RKJ** & M. Lewicki, JHEP 05, 169 (2023)

Extra relativistic dof from PBH evaporation



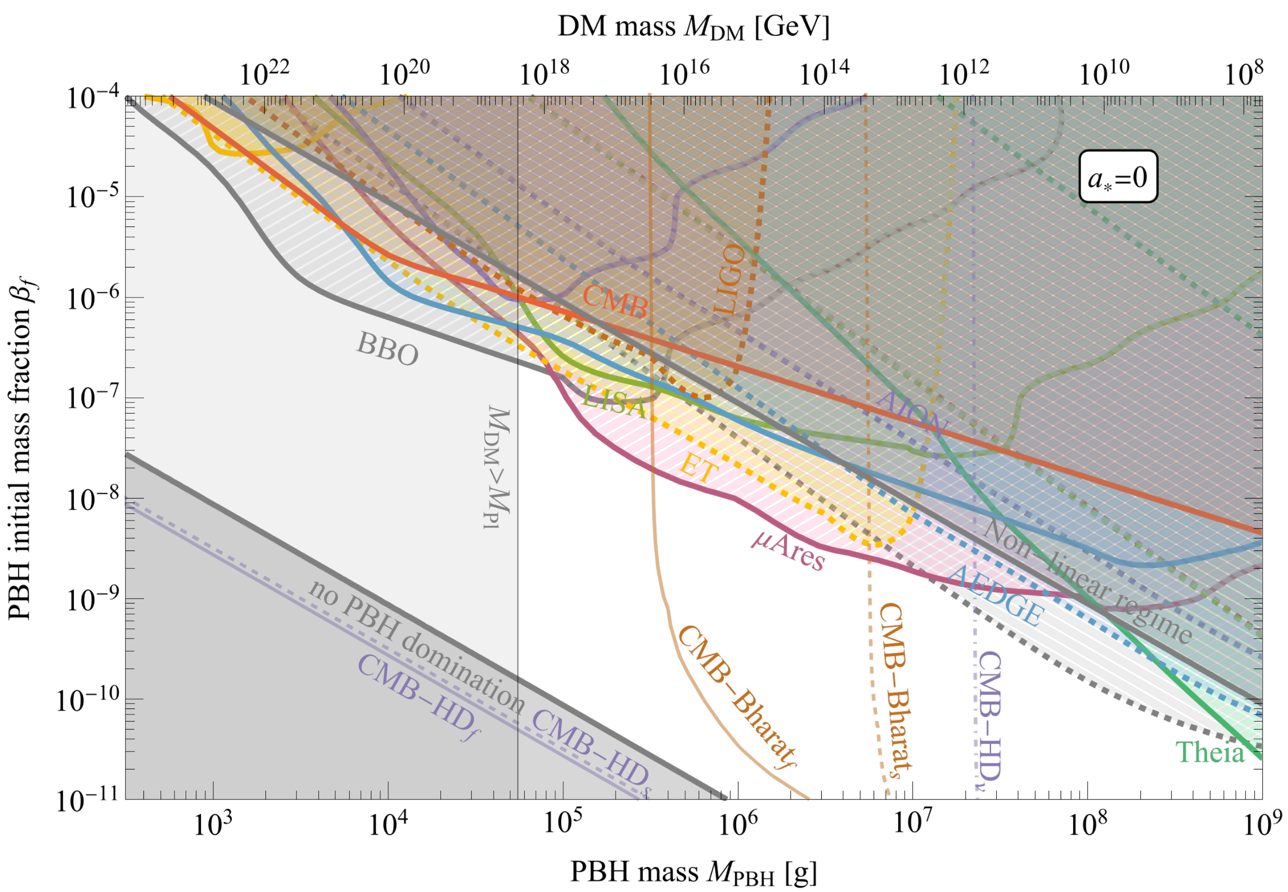
N. Bhaumik, A. Ghoshal, **RKJ** & M. Lewicki, JHEP 05, 169 (2023)

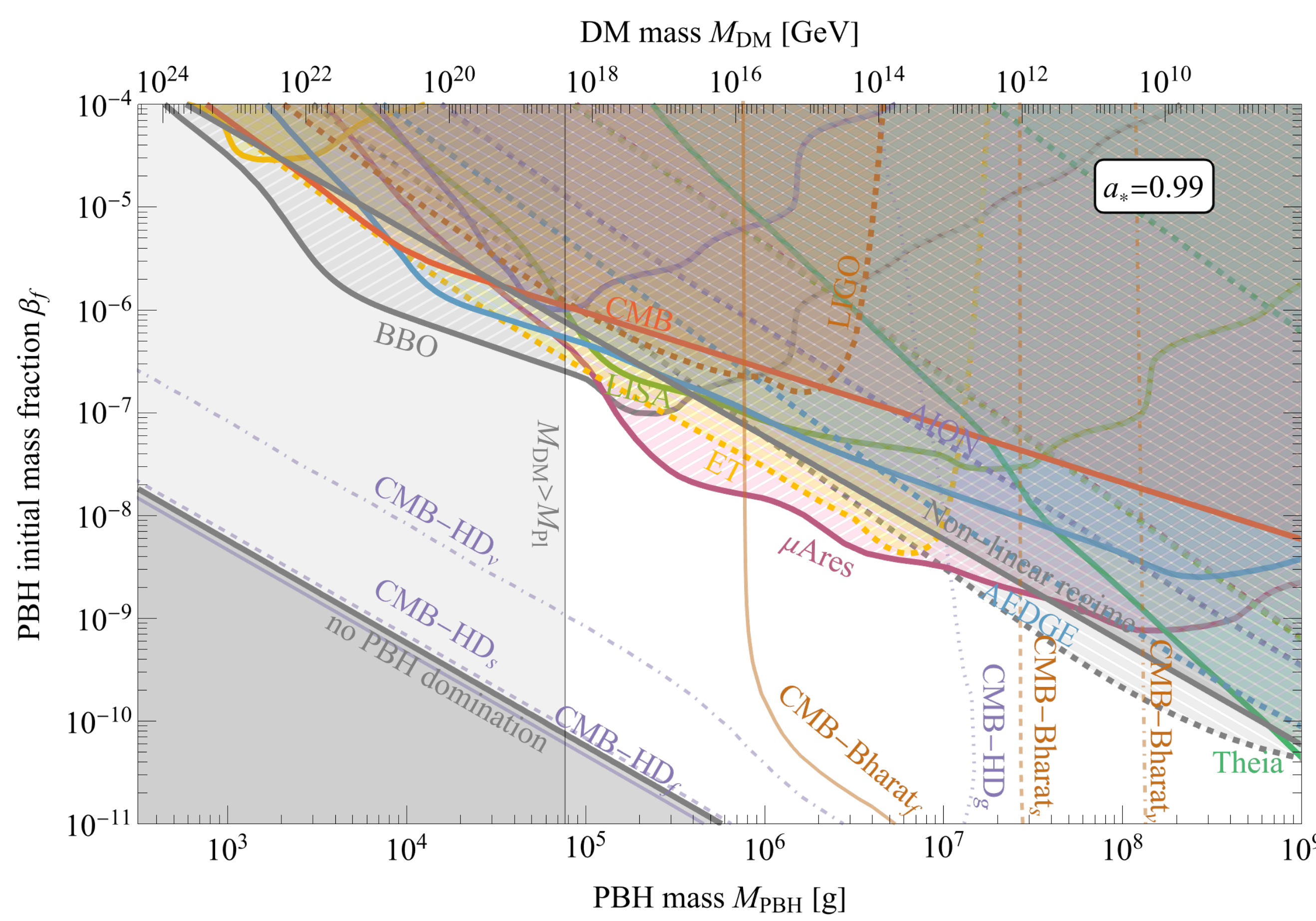
Heavy dark matter from PBH evaporation



N. Bhaumik, A. Ghoshal, **RKJ** & M. Lewicki, JHEP 05, 169 (2023)

Future GWs and CMB complementarity





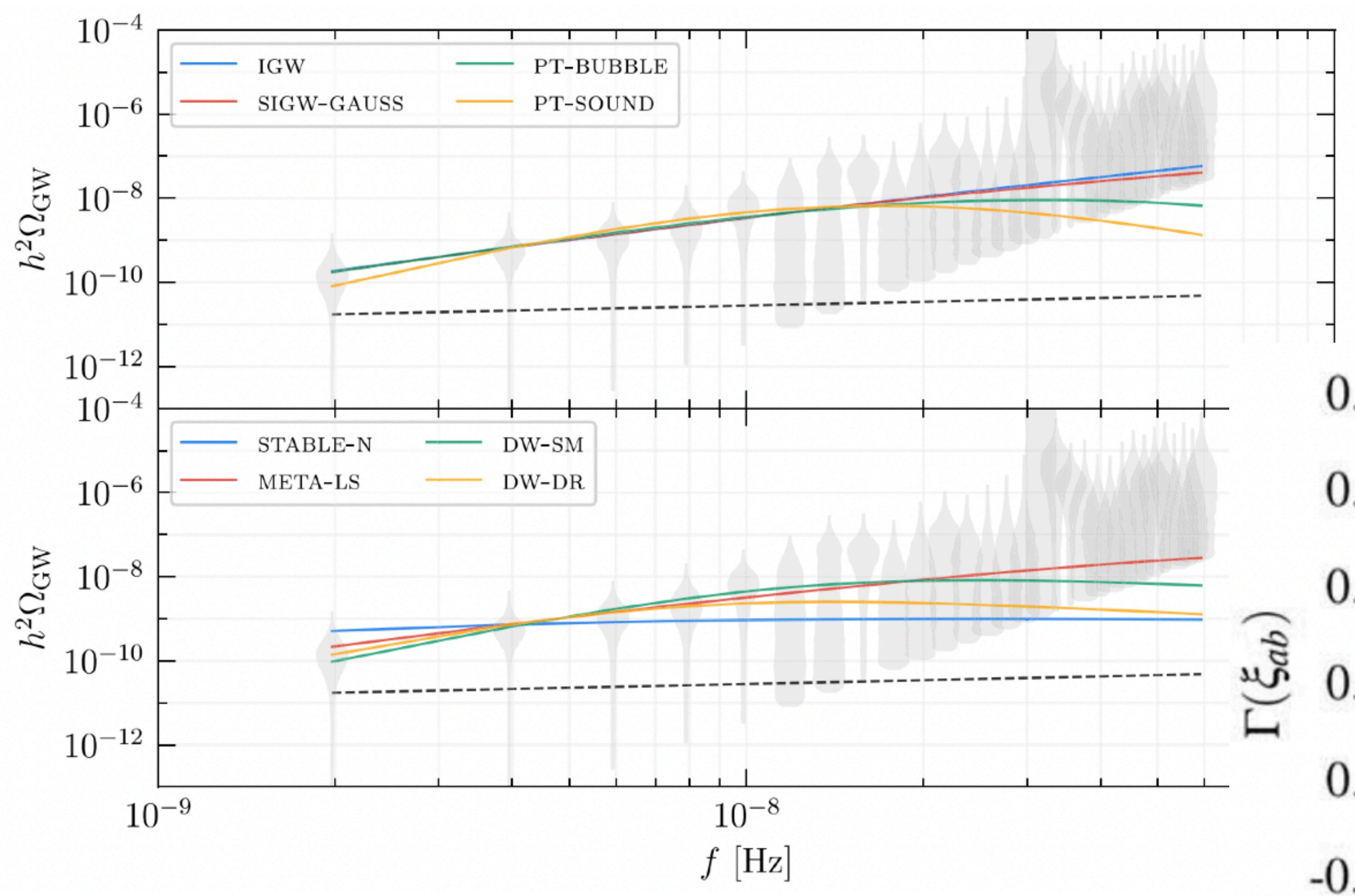
N. Bhaumik, A. Ghoshal, **RKJ** & M. Lewicki, JHEP 05, 169 (2023)

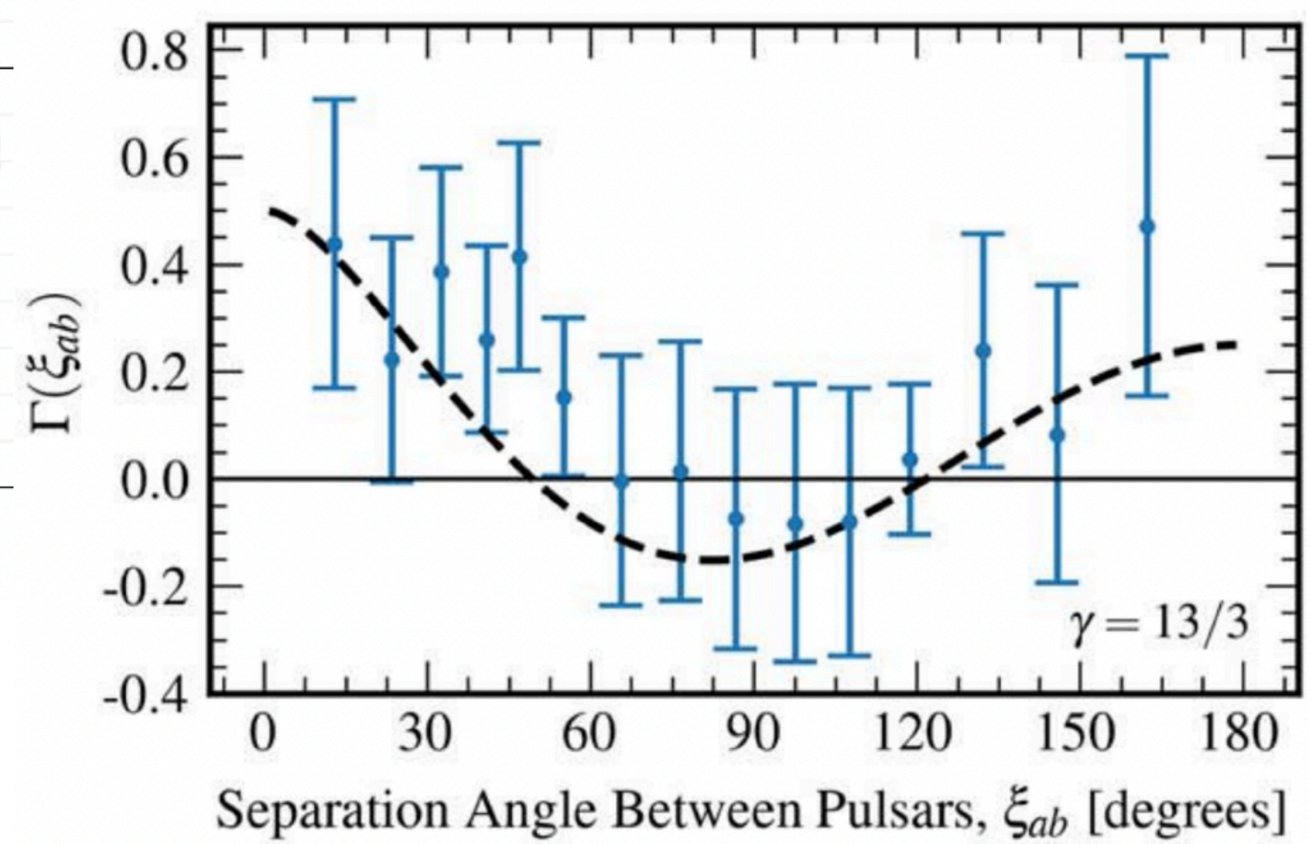
PBH, stochastic GWs and Pulsar Timing Array (PTA) detection

Stochastic GWs — PTA detection

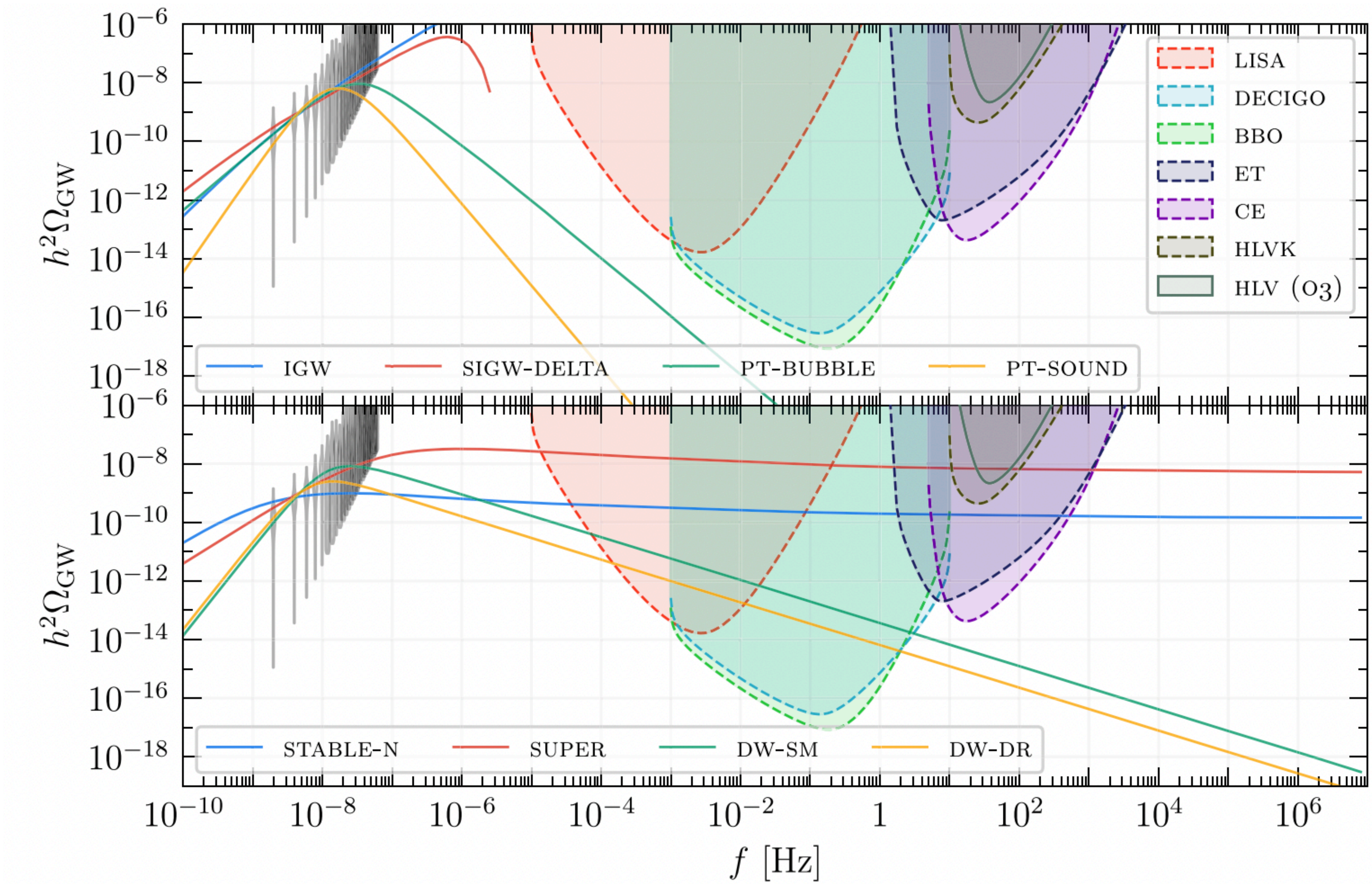
THE ASTROPHYSICAL JOURNAL LETTERS, 951:L11 (56pp), 2023 July 1 https://doi.org/10.3847/2041-8213/acdc91

The NANOGrav 15 yr Data Set: Search for Signals from New Physics



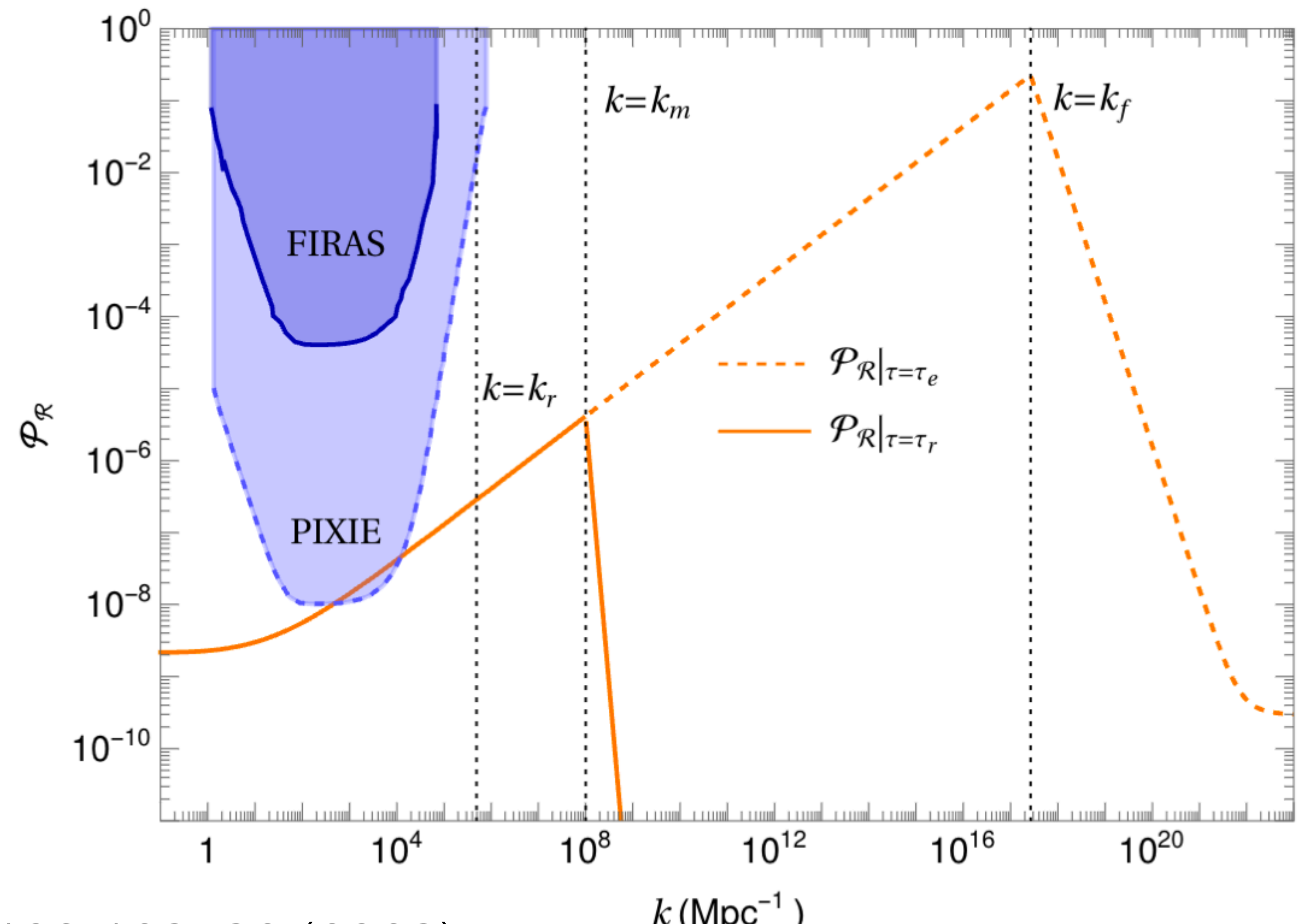


Stochastic GWs — PTA detection



Stochastic GWs from PBHs — PTA signal

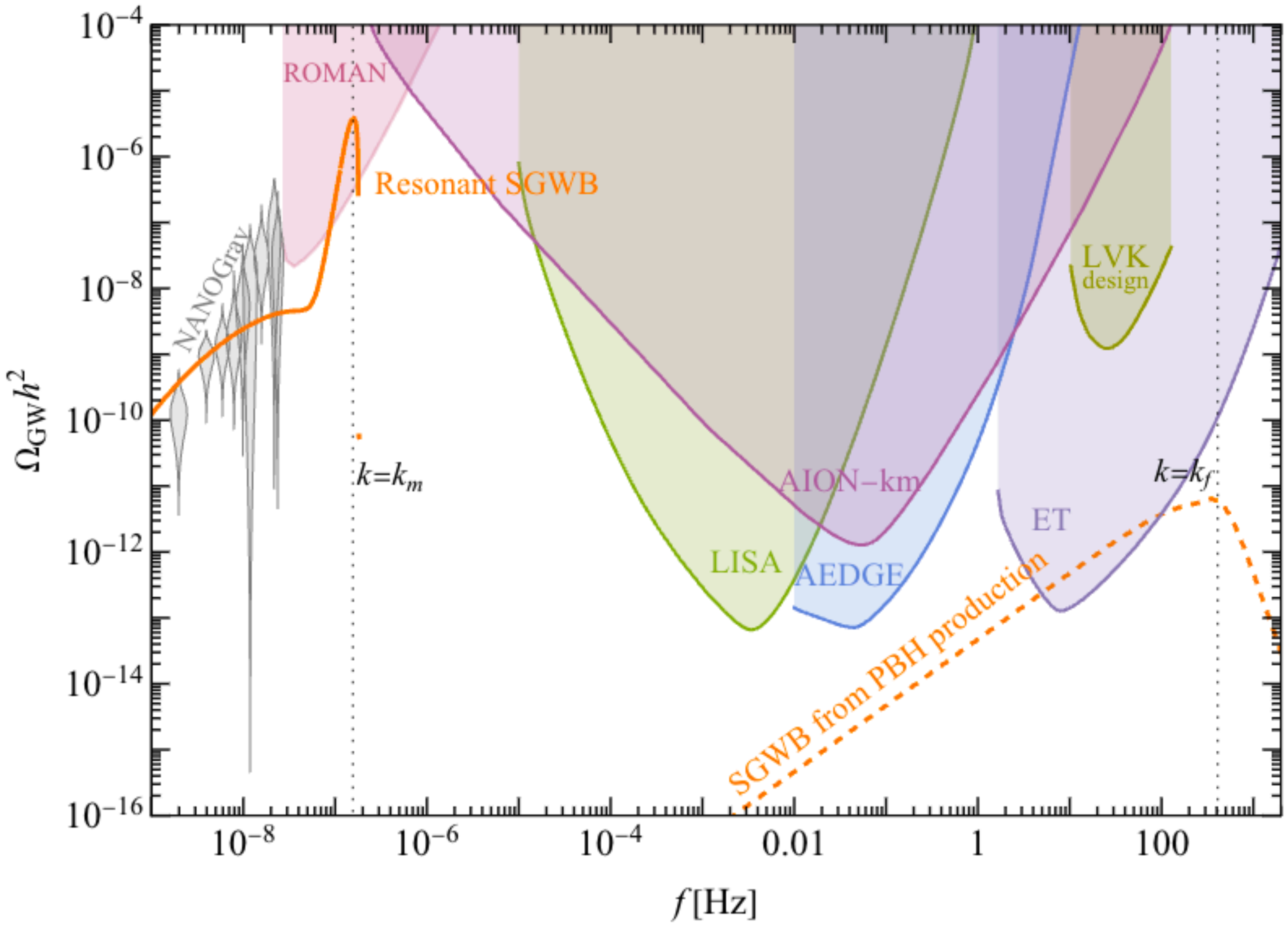
$$\mathcal{P}_{\mathcal{R}} = \underbrace{A_s\left(\frac{k}{k_{\rm p}}\right)^{n_s-1}}_{\text{CMB scales}} + \underbrace{A_0\begin{cases}\left(\dfrac{k}{k_{\rm pk}}\right)^{n_0-1} & k \leq k_{\rm pk}\\[2ex] \left(\dfrac{k}{k_{\rm pk}}\right)^{-2} & k \geq k_{\rm pk}\end{cases}}_{\text{PTA scales}}$$



N. Bhaumik, **RKJ** and M. Lewicki, Phys. Rev. D 108,123532 (2023)

Stochastic GWs from PBHs — PTA signal

$$\Omega_{\rm GW}(\tau,k) = \frac{1}{6}\int_0^\infty dv \int_{|1-v|}^{1+v} du \left(\frac{4v^2-(1+v^2-u^2)^2}{4uv}\right)^2 \times \quad \overline{\mathcal{I}}^2(v,u,x)\mathcal{P}_{\mathcal{R}}(kv)\mathcal{P}_{\mathcal{R}}(ku)$$



N. Bhaumik, **RKJ** and M. Lewicki, Phys. Rev. D 108,123532 (2023)

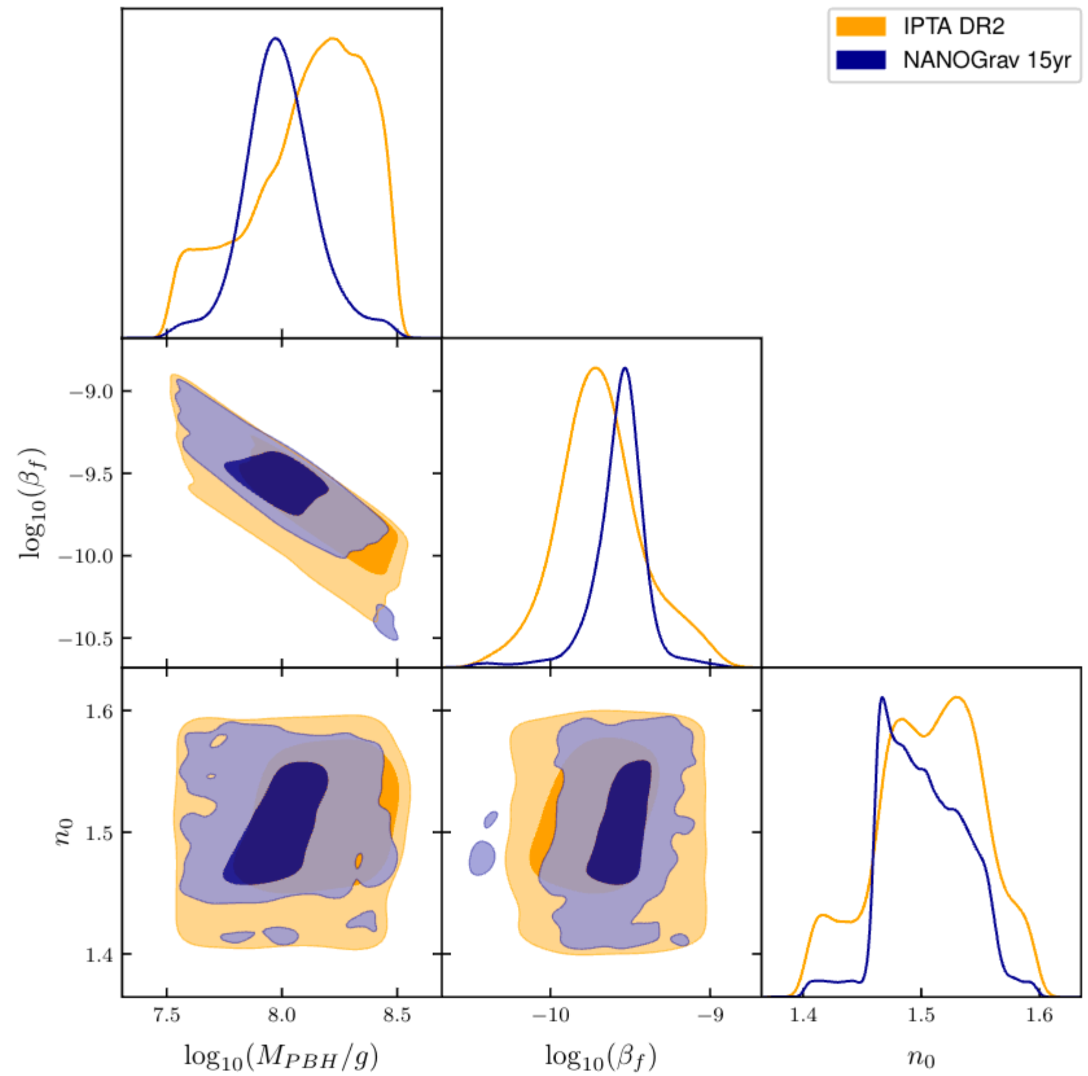
Stochastic GWs from PBHs — PTA signal

Bayesian analysis using PTArcade

$$\mathrm{BF}_{Y,X} \equiv \mathcal{P}(\mathcal{D}|Y) \,/\, \mathcal{P}(\mathcal{D}|X),$$

Model	**Parameters**	**Posterior mean**	
		NG15	IPTA2
Ultra-low mass PBH model	$\log_{10}(\frac{M_{\rm PBH}}{1\rm g})$	$7.99^{+0.13}_{-0.15}$	$8.11^{+0.35}_{-0.12}$
	$\log_{10}(\beta_f)$	$-9.57^{+0.15}_{-0.11}$	$-9.69^{+0.22}_{-0.28}$
	n_0	$1.503^{+0.025}_{-0.042}$	$1.507^{+0.047}_{-0.040}$

Model X	**Model Y**	$\mathrm{BF}_{Y,X}$	
		NG15	IPTA2
SMBHB	Ultra-low mass PBHs	18.00 ± 1.75	3.31 ± 0.09



N. Bhaumik, **RKJ** and M. Lewicki, Phys. Rev. D 108,123532 (2023)

Stochastic GWs from PBHs — PTA signal
Other observational constraints

- **PBH evaporation bound**: Depending on initial PBH abundance and mass range, PBH can either dominate the universe briefly or evaporate before they can dominate. We set $\tau_{\rm rat} \gg 1$ to avoid the parameter region where PBHs evaporate before they can dominate.

- **$\Delta N_{\rm eff}$ bound**: GWs generated before BBN act as an extra relativistic component, which both BBN and CMB observations severely constrain in terms of the effective number of neutrinos, $\Delta N_{\rm eff}$ [94, 95], thereby restricting our parameter space,

$$\Omega_{\rm GW} h^2|_{\rm peak} \lesssim 6.9 \times 10^{-6} \,. \tag{14}$$

- **Bound from CMB scales**: We limit our parameter search to the region where the scalar spectrum is unaffected at CMB scales. We ensure that at $k = 1\ {\rm Mpc}^{-1}$,

$$A_s \left(\frac{k}{k_{\rm p}}\right)^{n_s - 1} \geq A_0 \left(\frac{k}{k_{\rm pk}}\right)^{n_0 - 1} \,. \tag{15}$$

PBH evaporation and the memory burden effect

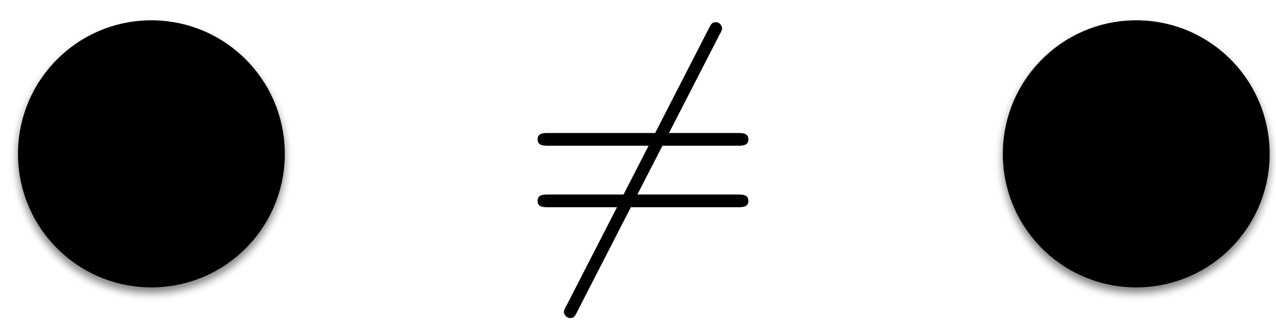
Memory burden effect and its implications

- Semiclassical description of Hawking evaporation can not hold over the entire black hole lifetime

- Quantum backreaction must be taken into account through memory burden effect

- Semiclassical formalism of Hawking evaporation breaks down at the latest by the time a black hole loses half of its mass due to Hawking evaporation

- The gapless microscopic energy states at the start of Hawking evaporation, allowing a maximal storage capacity of information, can no longer stay gapless after the mass of the black hole reduces significantly from its initial value.



$M_{PBH}/2$
with memory burden

$M_{PBH}/2$
newly formed

Dvali et. al. (2020), Dvali et. al. (2024), Alexandre et. al. (2024)

Memory burden effect and its implications

- What are the imprints of memory burden effect on the induced GW spectrum?

- Can non-trivial reheating mimic these signatures?

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Memory burden effect mimics reheating signatures on SGWB from ultra-low mass PBH domination

Nilanjandev Bhaumik,[a] **Md Riajul Haque**,[b,c] **Rajeev Kumar Jain**[d] **and Marek Lewicki**[e]

Memory burden effect and its implications

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{\pi\,\mathcal{G}\,g_{*,H}M_{\mathrm{Pl}}^4}{480M^2}\begin{cases}1 & \text{for } M > qM_{\mathrm{PBH}}\\ S^{-n}(M) & \text{for } M < qM_{\mathrm{PBH}}\end{cases}$$

$S(M) = M^2/2M_{\mathrm{Pl}}^2$: mass dependent entropy of PBH

Memory burden effects can slow down the evaporation of a black hole, thus prolonging its lifetime

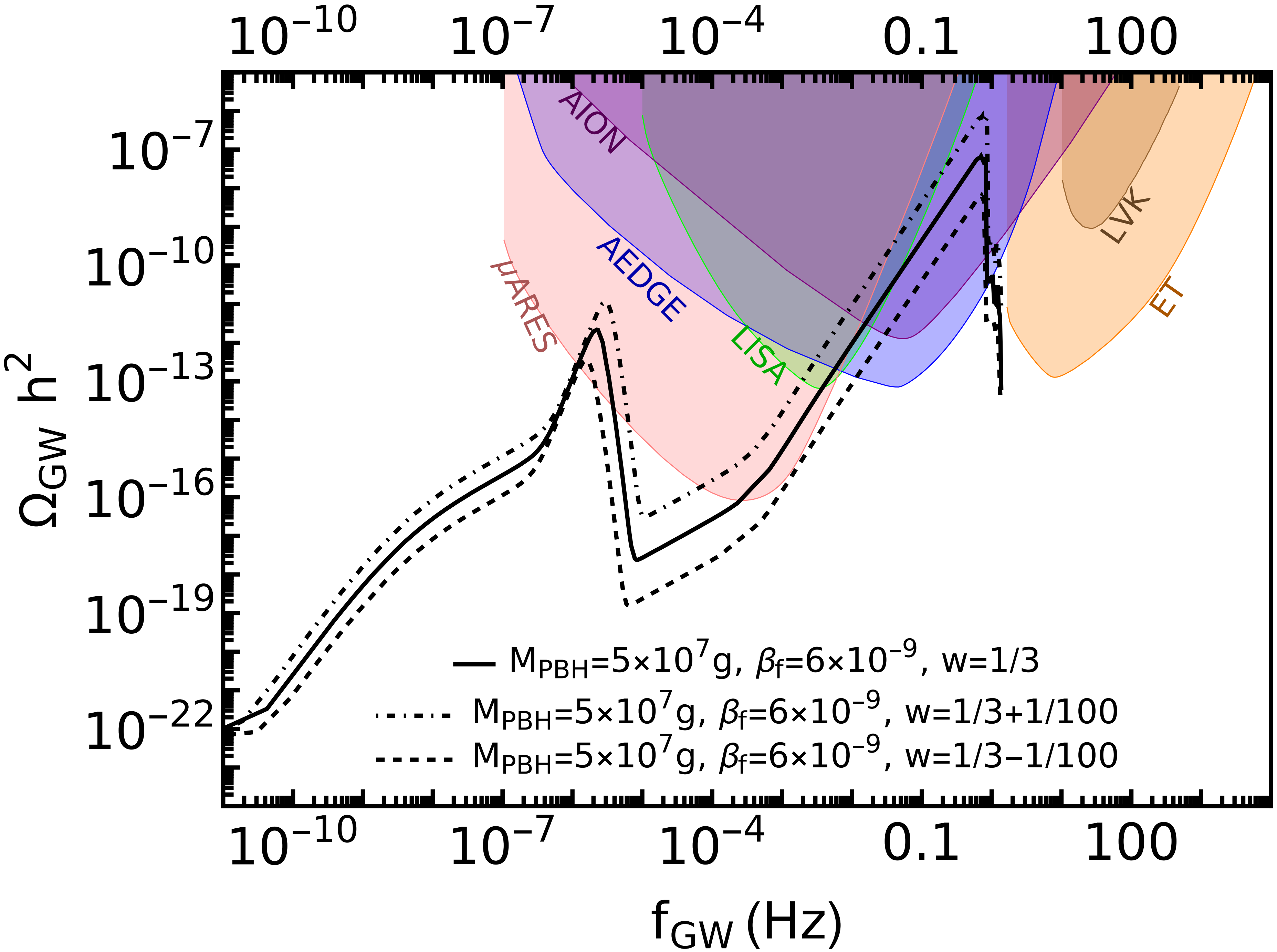
$$PS1 \equiv \{M_{\mathrm{PBH1}}, \beta_{f1}, w_1 = 1/3, q_1, n_1\}$$

$$PS2 \equiv \{M_{\mathrm{PBH2}}, \beta_{f2}, w_2, q_2 = 0, n_2 = 0\}$$

Is there a degeneracy between the two effects ?

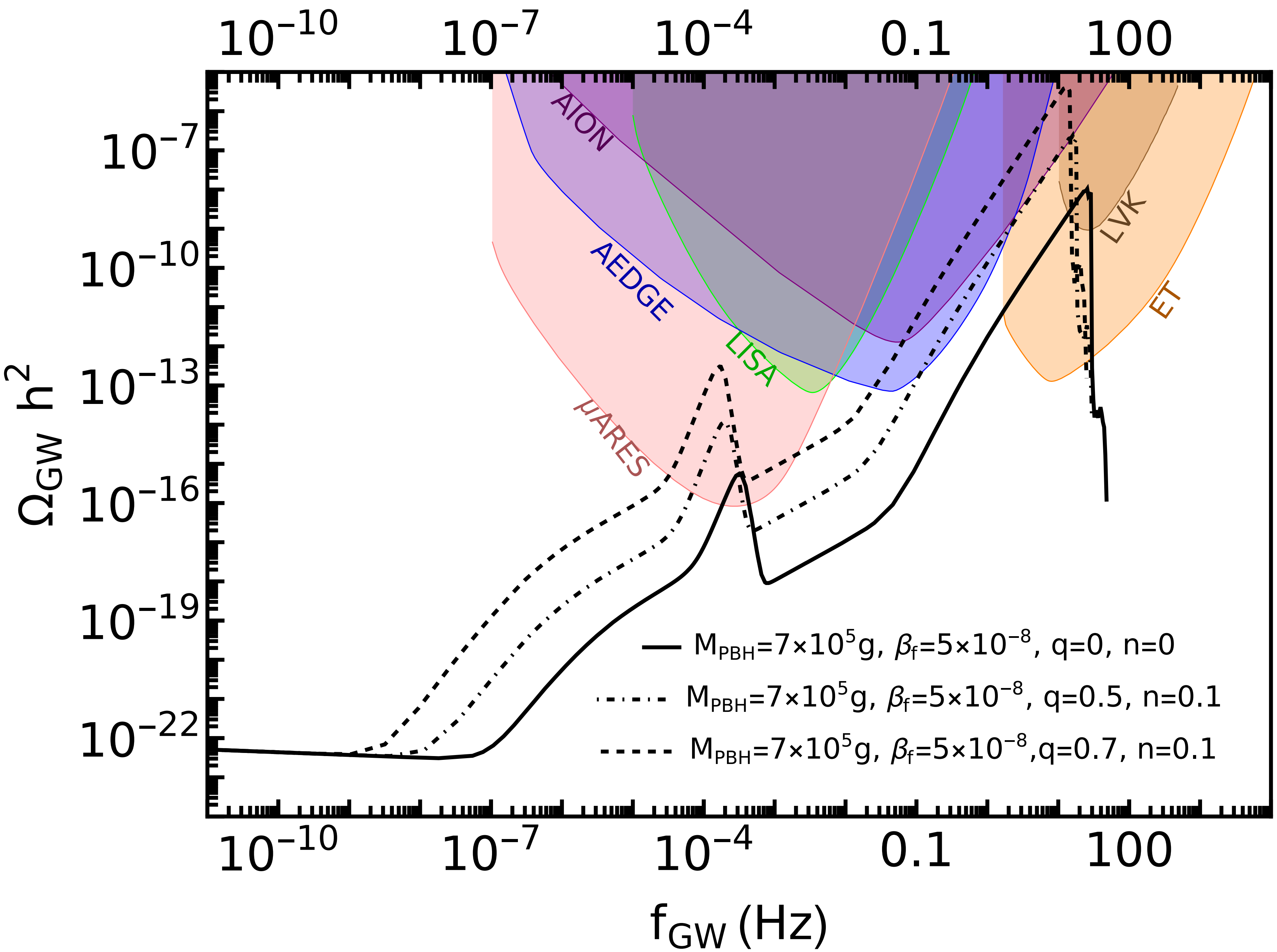
N. Bhaumik, M. R.Haque, **RKJ** & M. Lewicki, JHEP 10, 142 (2024)

Memory burden effect and its implications



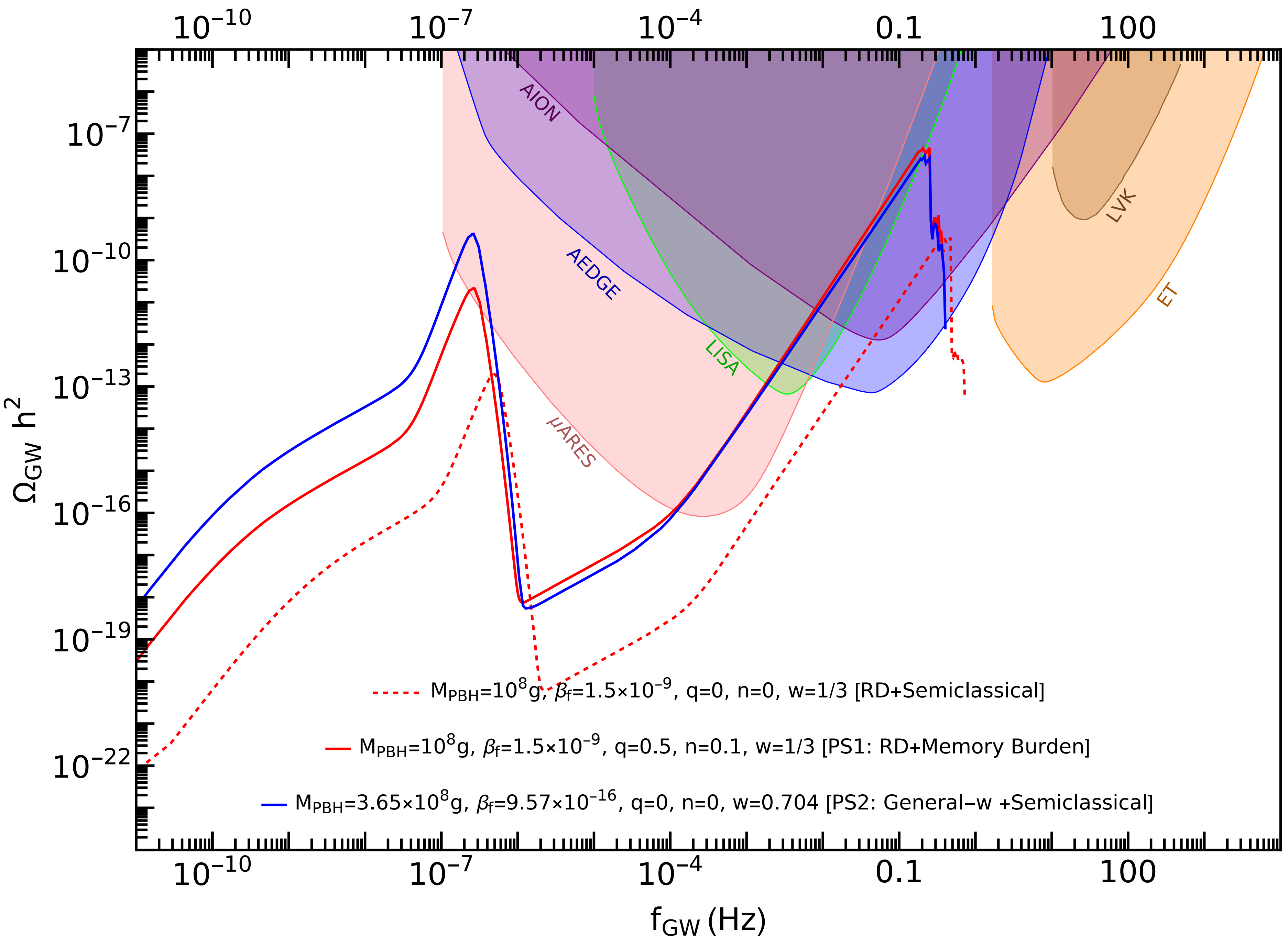
N. Bhaumik, M. R.Haque, **RKJ** & M. Lewicki, JHEP 10, 142 (2024)

Memory burden effect and its implications



N. Bhaumik, M. R.Haque, **RKJ** & M. Lewicki, JHEP 10, 142 (2024)

Memory burden effect and its implications



N. Bhaumik, M. R.Haque, **RKJ** & M. Lewicki, JHEP 10, 142 (2024)

A recent review on PBH and GW

Living Reviews in Relativity (2025)28:1
https://doi.org/10.1007/s41114-024-00053-w

REVIEW ARTICLE

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Primordial black holes and their gravitational-wave signatures

Eleni Bagui[1] · Sébastien Clesse[1] · Valerio De Luca[2] · Jose María Ezquiaga[3] · Gabriele Franciolini[4] · Juan García-Bellido[5] · Cristian Joana[6,7] · Rajeev Kumar Jain[8] · Sachiko Kuroyanagi[5,9] · Ilia Musco[10,11] · Theodoros Papanikolaou[12,13,14] · Alvise Raccanelli[4,15,16,17] · Sébastien Renaux-Petel[18] · Antonio Riotto[19] · Ester Ruiz Morales[5,20] · Marco Scalisi[21] · Olga Sergijenko[22,23,24,25] · Caner Ünal[26,27,28] · Vincent Vennin[29] · David Wands[30] · For the LISA Cosmology Working Group

Received: 22 December 2023 / Accepted: 5 November 2024

A very comprehensive up-to-date review (~200 pages)

Conclusions

- PBHs are novel candidates for the cold DM in the universe — an important probe of small scale dynamics during inflation
- Inflation can produce significant abundance of PBHs — single field inflection point models are useful — model dependent results
- Interesting observational implications — induced GWs on scales probed by LISA, DECIGO or BBO
- Hawking evaporation imprints — dark radiation and dark matter (non-thermal mechanism) — complementarity between GW and CMB
- Induced GWs from ultralight PBHs can explain the PTA results
- Interesting imprints of memory burden effect — probing quantum effects through classical GWs

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Thank you for your attention!