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Signatures of No-scale Supergravity in NANOgrav and beyond

Based on S. Basilakos , D.V. Nanopoulos, T. Papanikolaou, E.N. Saridakis, **C. Tzerefos** (2307.08601)

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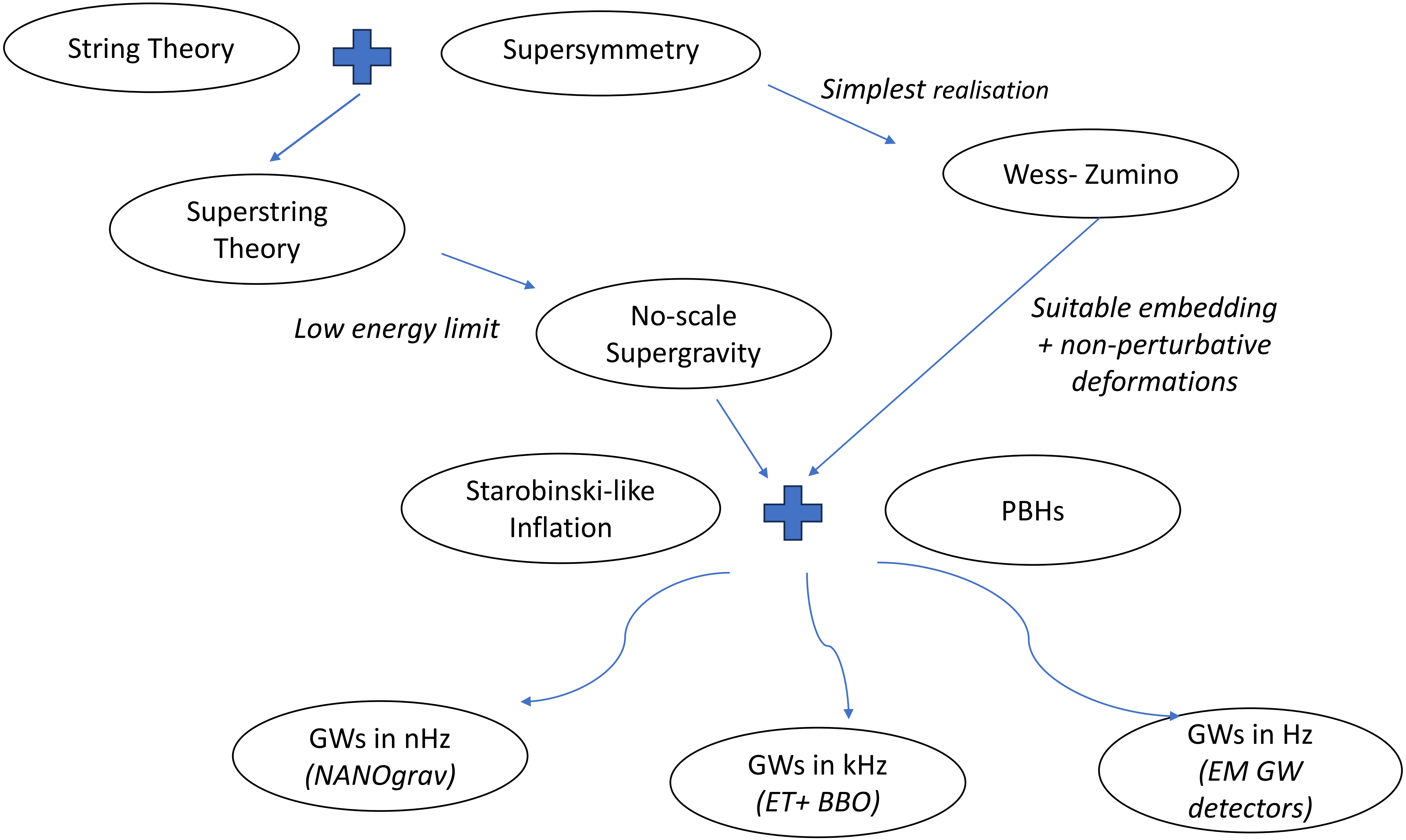


String Theory
Supersymmetry
Simplest realisation
Wess- Zumino
Superstring Theory
Low energy limit
No-scale Supergravity
Suitable embedding + non-perturbative deformations
Starobinski-like Inflation
PBHs
GWs in nHz (NANOgrav)
GWs in kHz (ET+ BBO)
GWs in Hz (EM GW detectors)

Theoretical introduction

- **Supergravity (SUGRA)** is a quantum field theory in which global supersymmetry has been promoted to a *local* symmetry. Therefore, its *gauging* describes *gravitation*.

- **No-scale supergravity** is a particular class of SUGRA which is characterized by the *absence of any external scales*, hence its name [1] every relevant energy scale is a function of M_{pl} only. Its significant perks include:

✓ It has been explicitly demonstrated that it naturally arises as the *low energy limit of superstring theory* [2]

✓ It cures the cosmological constant problem by naturally providing *vanishing cosmological constant at the tree level* [3]

✓ Through its framework it can produce *Starobinski-like inflation*, compatible with the Planck data [4]

✓ It can provide an efficient mechanism for *reheating*, the generation of *neutrino masses* and *leptogenesis* [5]

Theoretical introduction

- The most general (N=1) SUGRA is characterized by two functions: The Kahler potential K, which is a Hermitian function of the matter scalar field and quantifies its geometry, and a holomorphic function of the fields called superpotential W. V is the scalar potential :

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(K_{i\bar{j}}\partial_\mu\Phi^i\partial^\mu\bar{\Phi}^{\bar{j}} - V\right) \quad \text{with} \quad V = e^K\left(\mathcal{D}_{\bar{i}}\bar{W}K^{\bar{i}j}\mathcal{D}_jW - 3|W|^2\right) + \frac{\tilde{g}^2}{2}(K^iT^a\Phi_i)^2$$

and $K_{i\bar{j}}(\Phi,\bar{\Phi}) = \dfrac{\partial^2 K}{\partial\Phi^i\partial\bar{\Phi}^{\bar{j}}}$, $\mathcal{D}_iW \equiv \partial_iW + K_iW$ and $i = \{\phi, T\}$ which are chiral superfields.

- The simplest globally supersymmetric model is the Wess-Zumino one, which is characterized by one single chiral superfield φ and the following superpotential: $W = \dfrac{\hat{\mu}}{2}\varphi^2 - \dfrac{\lambda}{3}\varphi^3$, with a mass term $\hat{\mu}$ and a trilinear coupling term λ

No-scale Wess-Zumino (NSWZ) SUGRA

- In order to facilitate early universe inflationary scenarios, we shall embed this model in the context of $SU(2,1)/SU(2)\times U(1)$ no-scale supergravity by matching the T field to the modulus field and the φ field to the inflaton. The corresponding Kahler potential for this construction is

$$K = -3\ln\left(T+\bar{T}-\frac{\varphi\bar{\varphi}}{3}\right)$$

- Remarkably, by setting $T=\bar{T}=\frac{c}{2}$, $\mathrm{Im}\varphi=0$ and making a transformation of φ in order to obtain a canonical kinetic term, one obtains Starobinski inflation for $\lambda/\mu=1/3$ and $\hat{\mu}=\mu\sqrt{c/3}$

[6], [7]

$$V(\chi)=\frac{\mu^2}{4}\left(1-e^{-\sqrt{\frac{2}{3}}\chi}\right)^2$$

$$\varphi=\sqrt{3c}\,\tanh\left(\frac{\chi}{\sqrt{3}}\right)$$

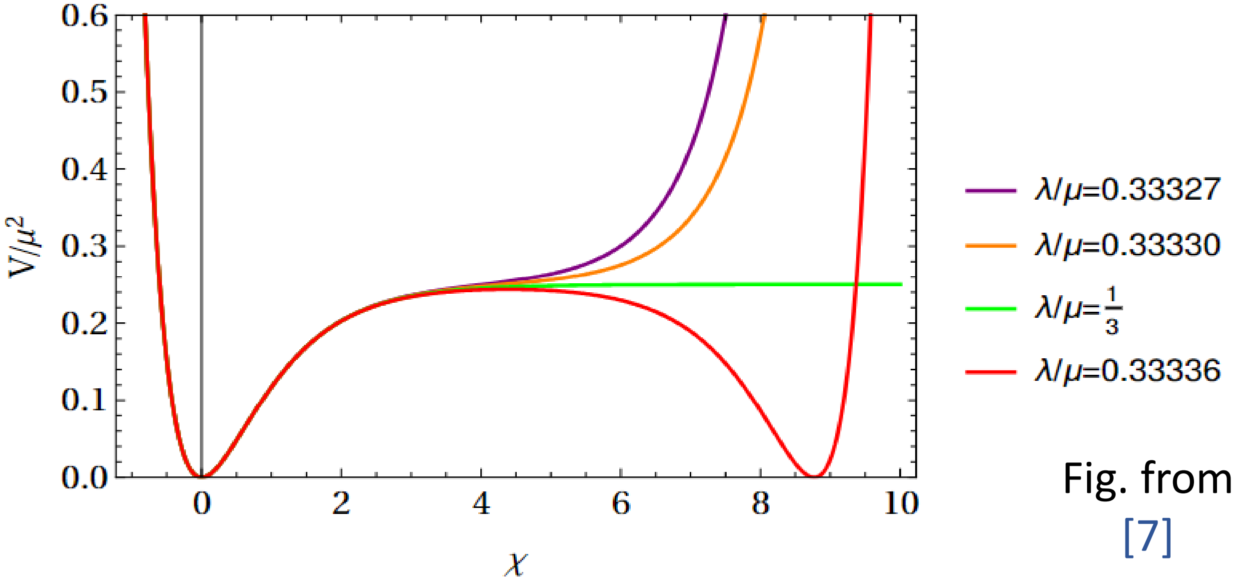


Fig. from [7]

NSWZ SUGRA inflection point inflation

- A common mechanism to produce PBHs is via the use of inflationary potentials with inflection points aka points where $V''(\chi_{\text{inflection}}) = V'(\chi_{\text{inflection}}) \simeq 0$ which induce the so-called **ultra slow roll inflation** (USR)

- To realize such set-ups, one can introduce the following **non-perturbative deformations** to the Kahler potential [7]:

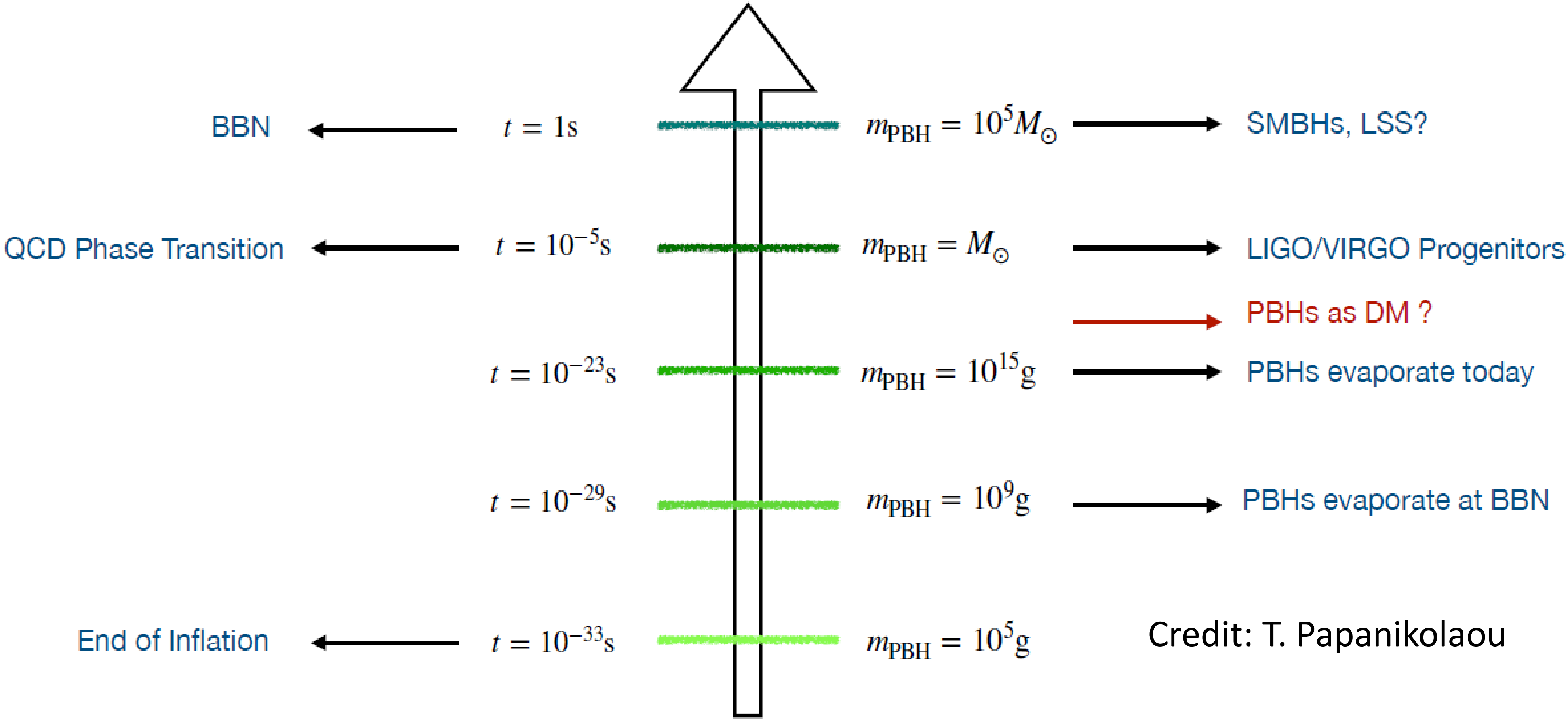
$$K = -3\ln\left[T + \bar{T} - \frac{\varphi\bar{\varphi}}{3} + a\, e^{-b(\varphi+\bar{\varphi})^2}(\varphi + \bar{\varphi})^4\right]$$ with a and b real constants

- At the end, one obtains the following potential

$$V(\phi) = \frac{3e^{12b\phi^2}\phi^2(c\mu^2 - 2\sqrt{3c}\,\lambda\,\mu\,\phi + 3\lambda^2\,\phi^2)}{\left[-48a\phi^4 + e^{4b\phi^2}(-3c + \phi^2)\right]^2\,\left[e^{4b\phi^2} - 24\,a\,\phi^2(6 + 4b\,\phi^2(-9 + 8b\,\phi^2))\right]}$$

PBHs

Primordial Black Holes (PBHs) form in the early universe out of the **collapse of enhanced energy density perturbations** upon horizon reentry of the typical size of the collapsing overdensity region, $m_{\rm PBH} = \gamma M_{\rm H} \propto H^{-1}$ where $\gamma \sim O(1)$ (a nice review [8])



Credit: T. Papanikolaou

Perks of ultra-light PBHs

We will consider **ultra-light PBHs** for which $m_{\rm PBH} < 10^9{\rm g}$ Some of their perks include:

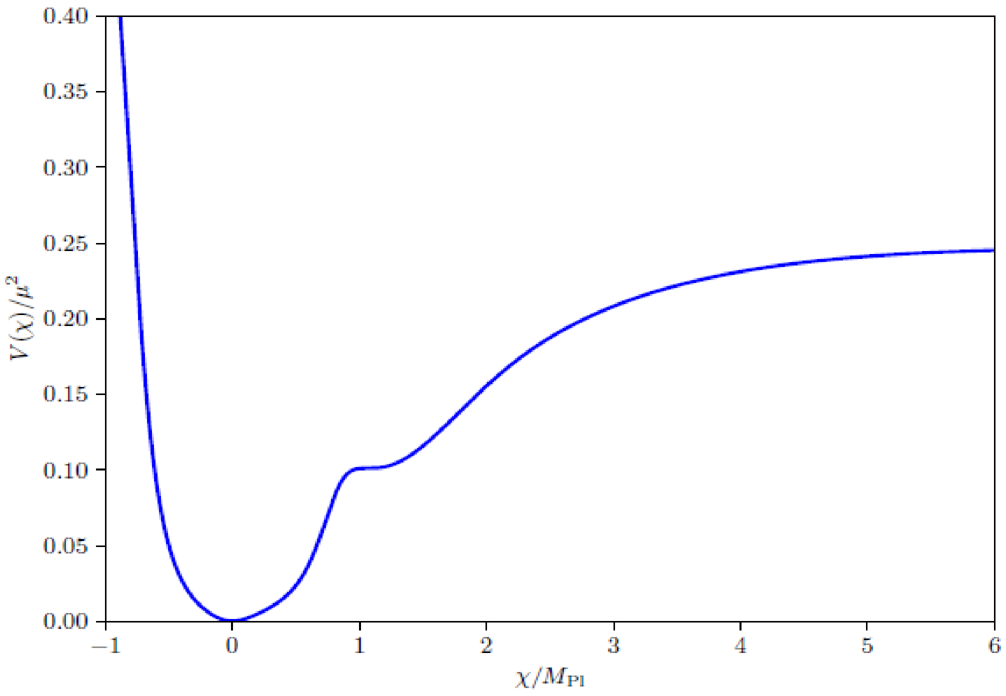
✓They can induce an early matter dominated era (eMD) since $\Omega_{\rm PBH} = \rho_{\rm PBH}/\rho_{\rm tot} \propto a^{-3}/a^{-4} \propto a$ and evaporate before BBN. Their evaporation **drives the reheating process** (e.g. [9])

✓This eMD era enhances the magnitude of the curvature perturbation and consequently gives rise to **scalar induced gravitational waves (SIGWs)** with very interesting phenomenology. For instance, one can constrain the underlying gravity theory (e.g. [10])

✓Their Hawking evaporation can alleviate the **Hubble tension** by injecting to the primordial plasma dark radiation degrees of freedom which can increase $N_{\rm eff}$ (e.g. [11])

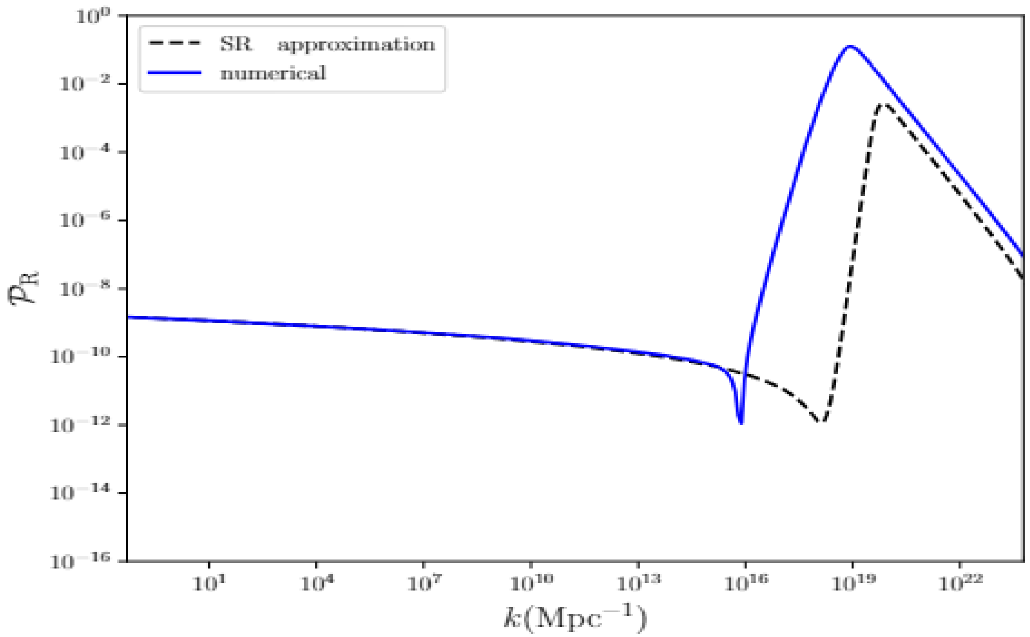
PBHs in no-scale SUGRA

Our modified potential gives rise to the following power spectrum given our choice of fiducial parameters:



$a = -1$, $b = 22.35$, $c = 0.065$, $\mu = 2 \times 10^{-5}$

$\lambda/\mu = 0.3333449$ and $\phi_0 = 0.4295$

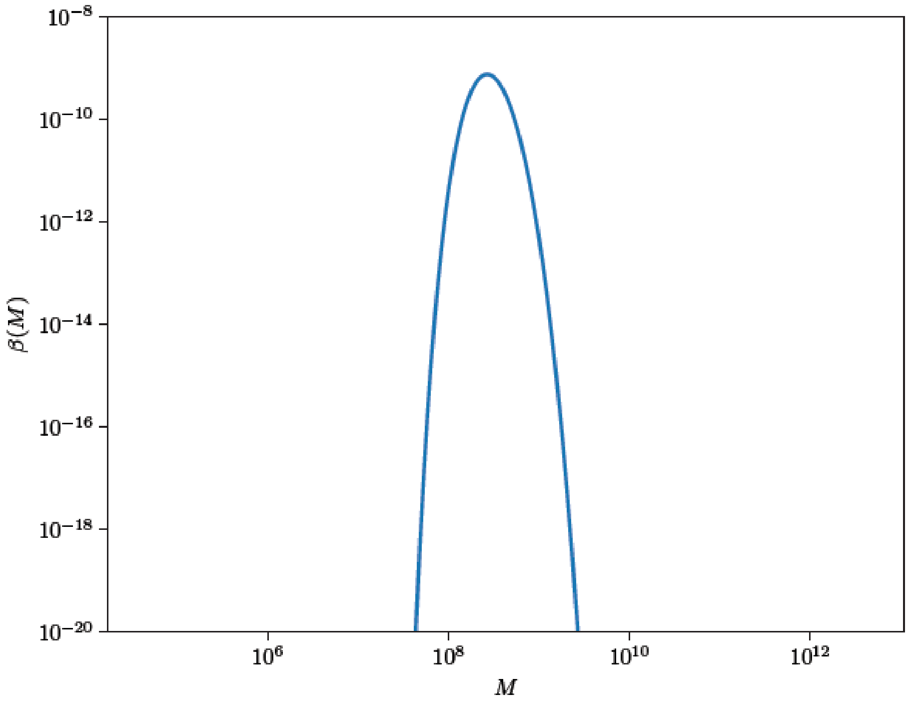


$$M_{\rm PBH} = 17 M_{\odot} \left(\frac{k}{10^6 \mathrm{Mpc}^{-1}} \right)^{-2} \sim 10^8 \mathrm{g}$$

eMD driven by PBHs

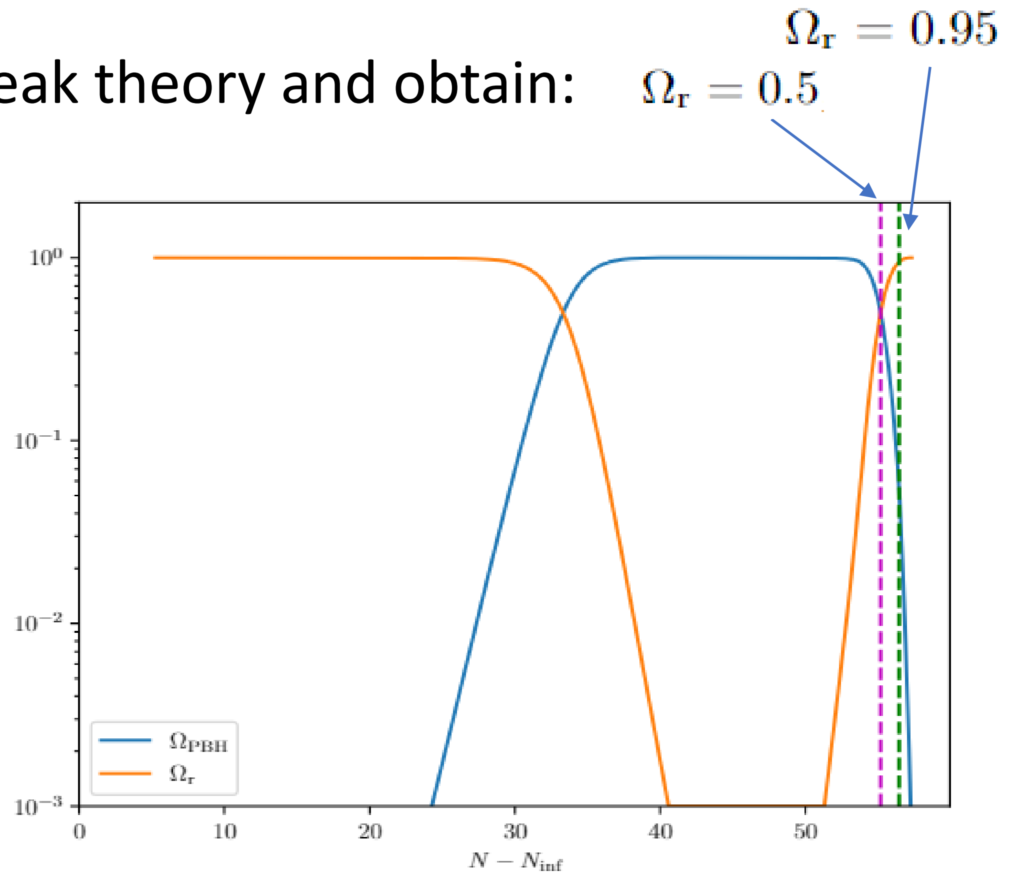
- Since $\Omega_{\rm PBH} = \rho_{\rm PBH}/\rho_{\rm tot} \propto a^{-3}/a^{-4} \propto a$ an eMD era driven by them arises

- To find their mass function $\beta(M) \equiv \frac{1}{\rho_{\rm tot}} \frac{{\rm d}\rho_{\rm PBH}}{{\rm d}\ln M}$ we use peak theory and obtain:



Taking into account their Hawking evaporation

$$M(t) = M_{\rm f}\left\{1 - \frac{t-t_{\rm f}}{\Delta t_{\rm evap}(M_{\rm f})}\right\}^{1/3}$$



Note: We treat mass function as monochromatic → eMD to lRD sudden

Essentials of the Scalar Induced GWs (SIGWs)

- Working in the Newtonian gauge, the 2nd order tensor perturbations are described as follows

$$\mathrm{d}s^2 = a^2(\eta)\left\{-(1+2\Phi)\mathrm{d}\eta^2 + \left[(1-2\Phi)\delta_{ij} + \frac{h_{ij}}{2}\right]\mathrm{d}x^i\mathrm{d}x^j\right\}$$

- Their equation of motion in fourier space is $h^{s,\prime\prime}_{\boldsymbol{k}} + 2\mathcal{H}h^{s,\prime}_{\boldsymbol{k}} + k^2 h^s_{\boldsymbol{k}} = 4S^s_{\boldsymbol{k}}$

- The source term is $S^s_{\boldsymbol{k}} = \int \frac{\mathrm{d}^3\boldsymbol{q}}{(2\pi)^{3/2}} e^s_{ij}(\boldsymbol{k})q_i q_j \left[2\Phi_{\boldsymbol{q}}\Phi_{\boldsymbol{k}-\boldsymbol{q}} + \frac{4}{3(1+w_{\mathrm{tot}})}(\mathcal{H}^{-1}\Phi'_{\boldsymbol{q}} + \Phi_{\boldsymbol{q}})(\mathcal{H}^{-1}\Phi'_{\boldsymbol{k}-\boldsymbol{q}} + \Phi_{\boldsymbol{k}-\boldsymbol{q}})\right]$

- At the end, the spectral abundance of GWs can be given by

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

and

$$\mathcal{P}^{(s)}_h(\eta,k) \equiv \frac{k^3|h_k|^2}{2\pi^2} \propto \int \mathrm{d}v \int \mathrm{d}u I^2(u,v,x)\mathcal{P}_\Phi(kv)\mathcal{P}_\Phi(ku)$$

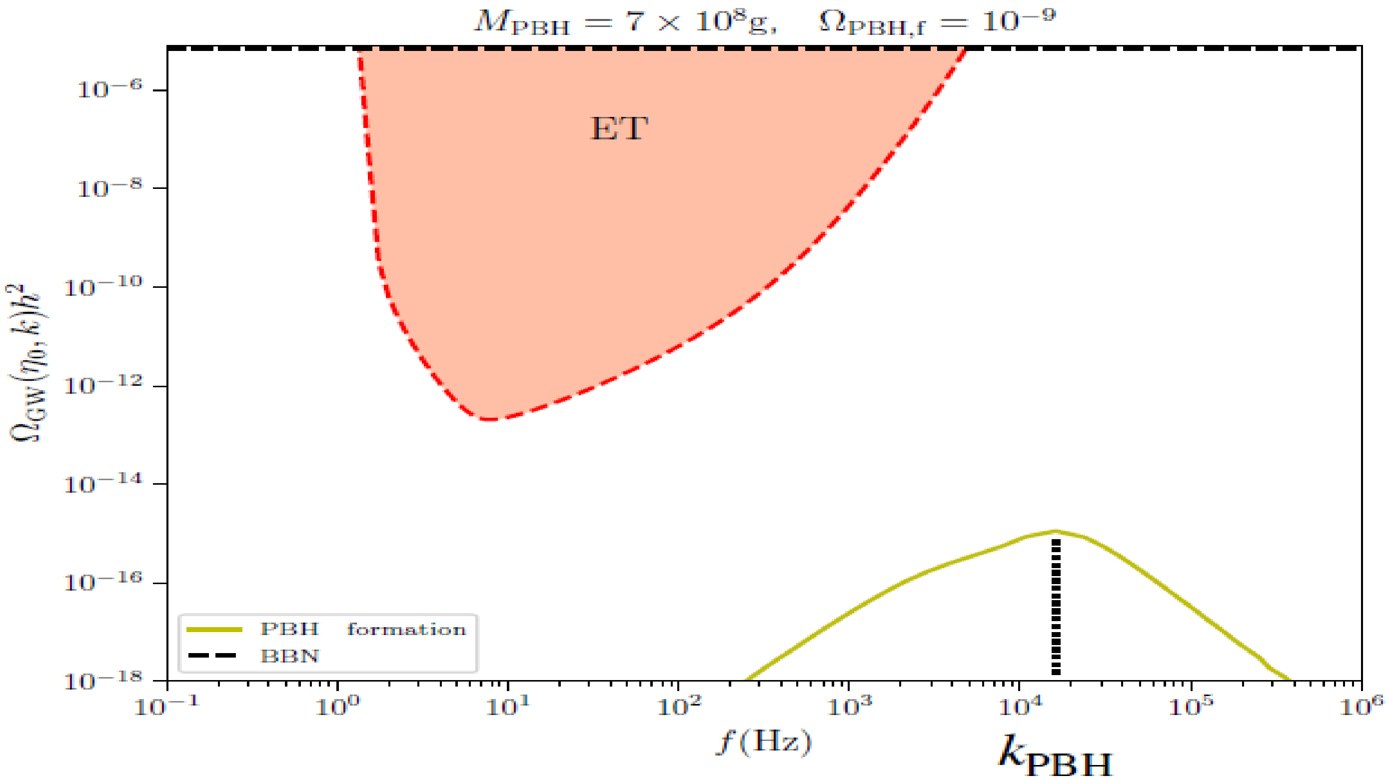
The kernel $I(u,v,x)$ is complicated function containing the info for eMD ⟶ lRD eras (see [13])

The relevant GW sources and their spectrum

A) Inflationary adiabatic perturbations ⟶ GWs with two peaks

i) GWs are produced by the enhancement of $\mathcal{P}_{\mathcal{R}}(k)$ (peaked at $10^{19}\mathrm{Mpc}^{-1}$) at PBHs scales peaked at the **kHz range** and detectable by **electromagnetic GW detectors** [12]

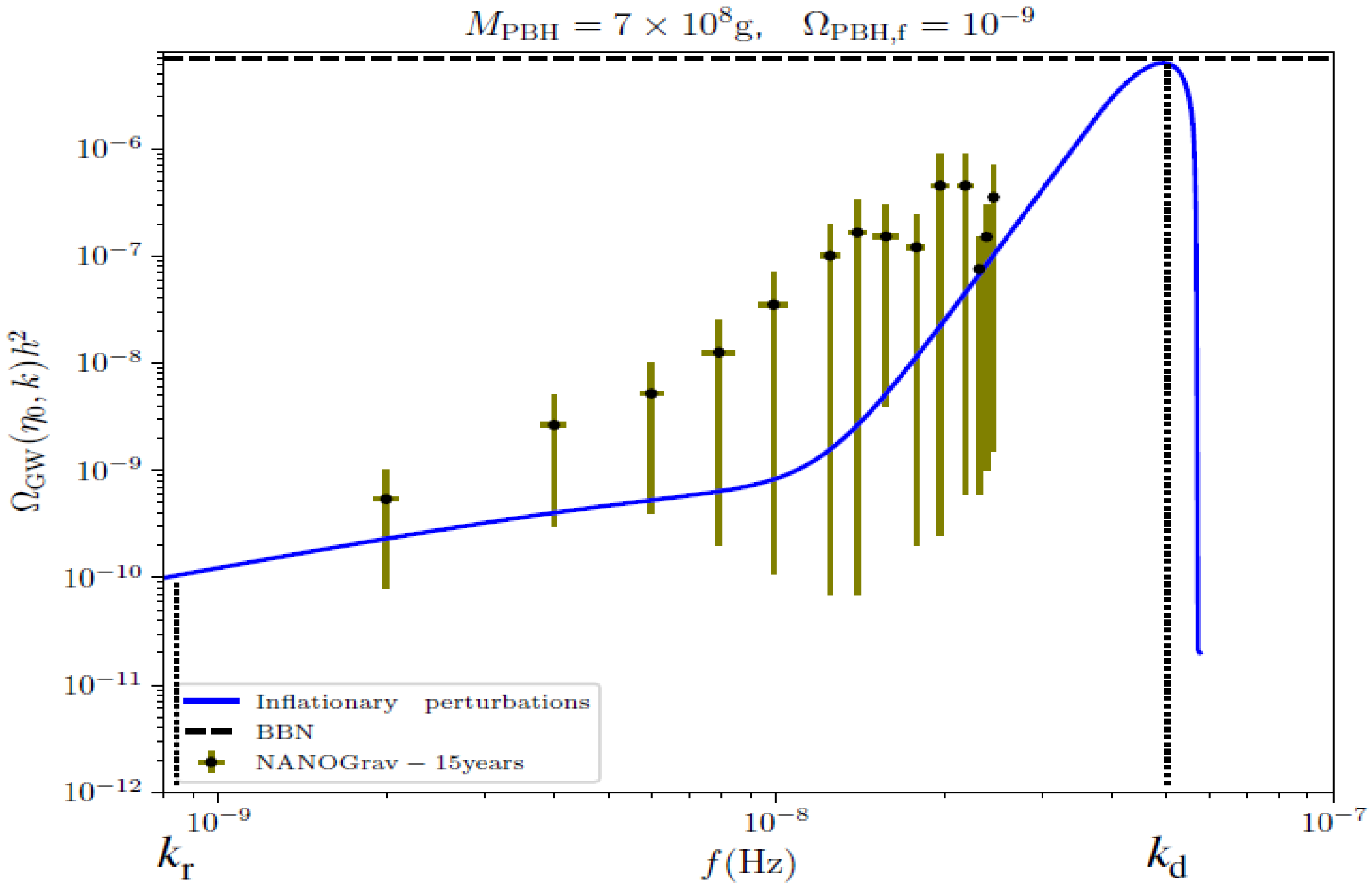
$$\Omega_{\rm GW}^{\rm form}(\eta_0,k) = \frac{a_{\rm d}}{a_{\rm evap}} c_g \Omega_{\rm r}^{(0)} \Omega_{\rm GW}(\eta_{\rm f},k), \text{ with } c_g = \frac{g_{*\rho,*}}{g_{*\rho,0}}\left(\frac{g_{*{\rm S},0}}{g_{*{\rm S},*}}\right)^{4/3} \sim 0.4 \text{ and } \Omega_{\rm r}^{(0)} \simeq 10^{-4}$$



Inflationary adiabatic perturbations

ii) GWs are induced by **resonantly amplified large-scale inflationary curvature perturbations** of order 10^4 due to the intervention of an early MD era driven by PBHs, during which the gravitational potential is constant and $\delta \sim \alpha$. This GW signal peaks at the **nHz frequency range** and is in strong agreement with **NANOGrav/PTA GW data**.

$$\Omega_{\rm GW}^{\rm res}(\eta_0,k) = c_g \Omega_{\rm r}^{(0)} \Omega_{\rm GW}(\eta_{\rm lRD},k)$$



SIGWs from Poisson fluctuations of a gas of PBHs

- Random distribution of PBHs + same mass → they follow Poisson statistics :

$$\mathcal{P}_\delta(k) = \frac{k^3}{2\pi^2} P_\delta(k) = \frac{2}{3\pi}\left(\frac{k}{k_{\rm UV}}\right)^3 \Theta(k_{\rm UV} - k)$$

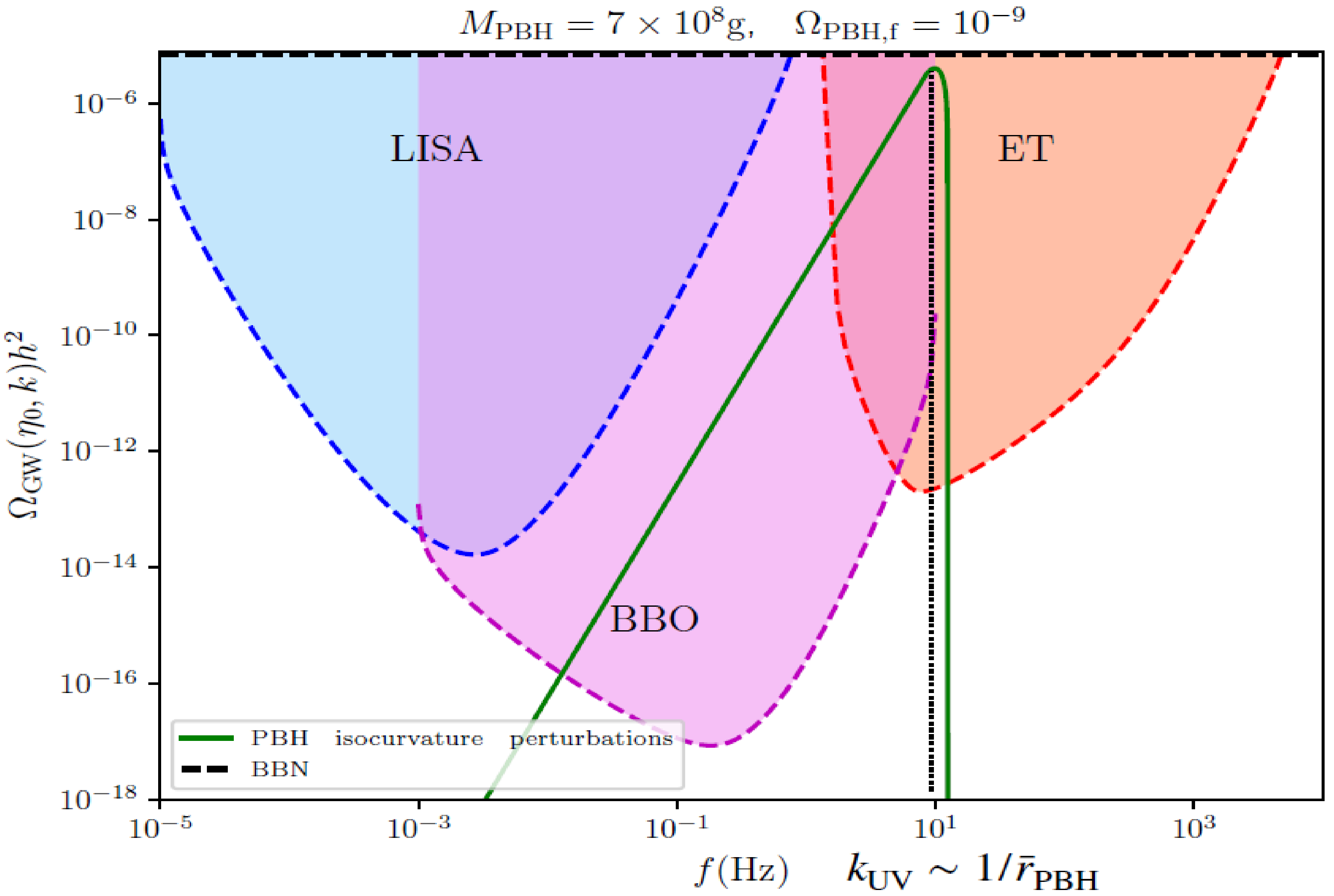
- Since ρ_{PBH} is inhomogeneous and ρ_{tot} is homogenous → $\delta_{\rm PBH}$ is an **isocurvature perturbation**

- $\delta_{\rm PBH}$ generated in the eRD era will be converted in an eMD era to a curvature perturbation ζ_{PBH} associated with the scalar potential [14]

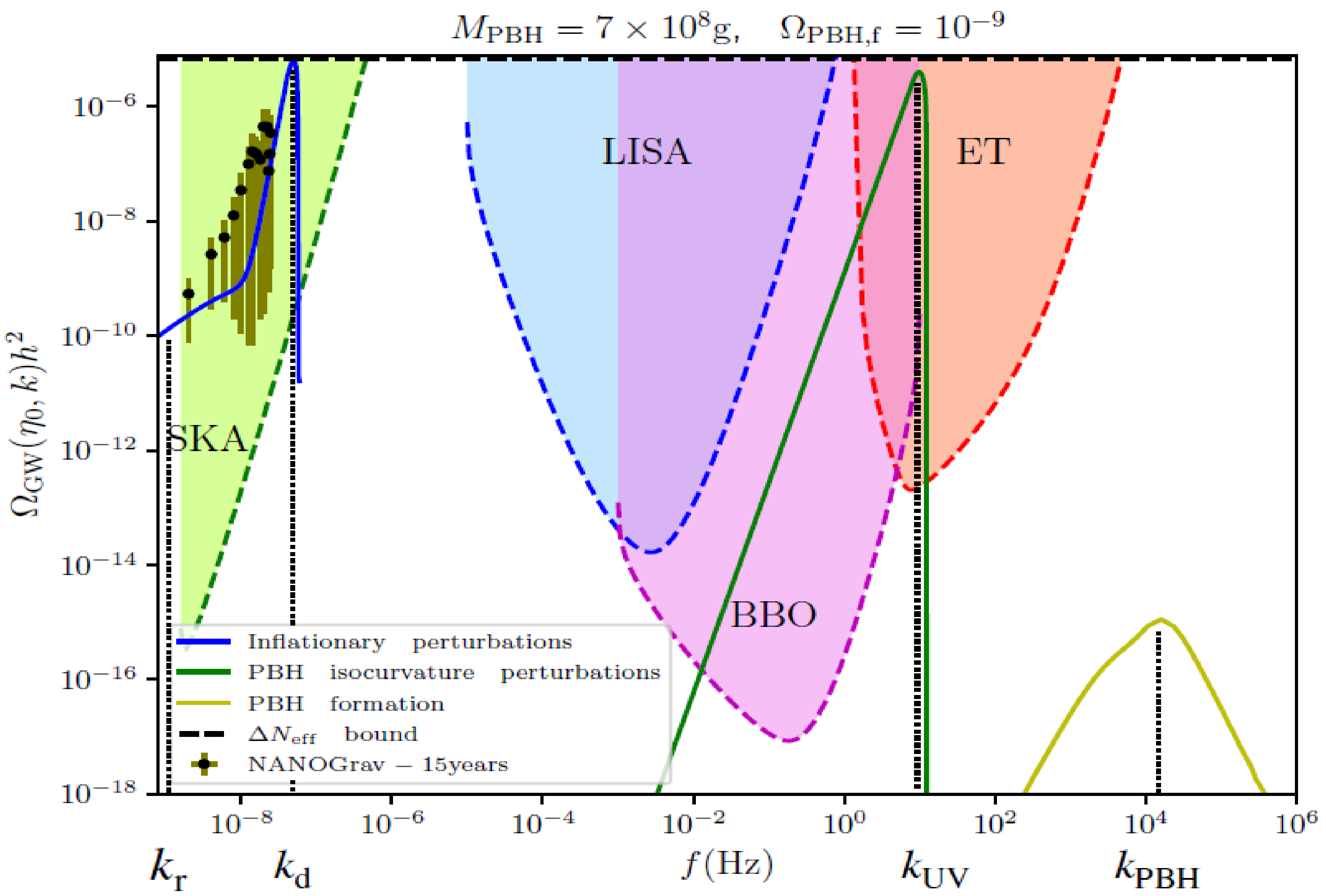
$$\mathcal{P}_\Phi(k) = \frac{2}{3\pi}\left(\frac{k}{k_{\rm UV}}\right)^3 \left(5 + \frac{4}{9}\frac{k^2}{k_{\rm d}^2}\right)^{-2}$$

SIGWs from Poisson fluctuations of a gas of PBHs

Therefore, we get the following signal by the population of the PBHs themselves



The complete three-peaked signal



A simultaneous detection of all three peaks could constitute a clear indication in favour of no-scale SUGRA

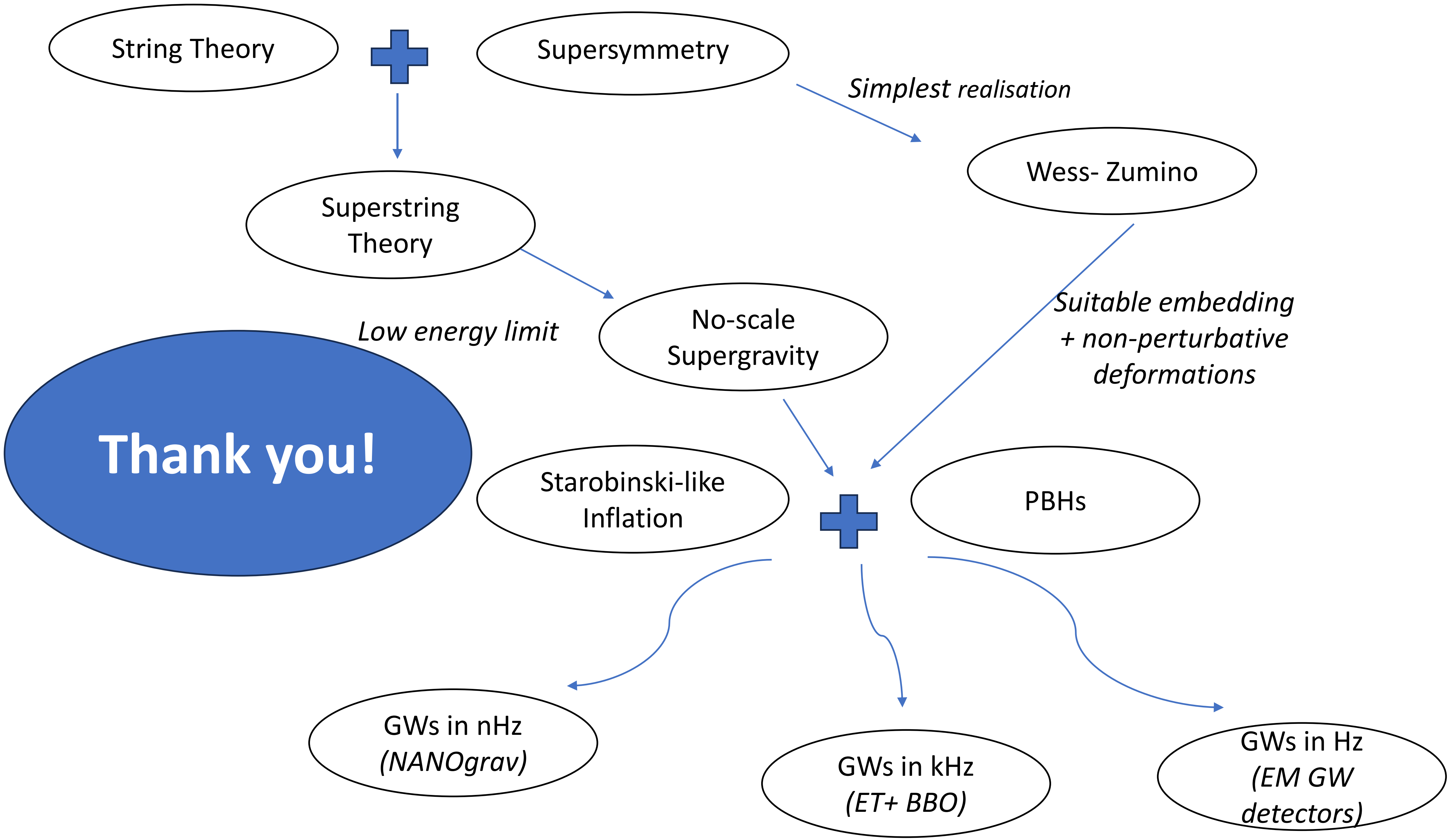
Conclusions

- We worked within **NSWZ**, a framework which gives rise to **Starobinski inflation** compatible with the Planck data, namely $n_s = 0.96$ and $r < 0.004$.

- Through the deformed Kahler potential and our choice of fiducial parameters, we obtain **ultra-light PBHs** which give rise to an **eMD** and evaporate before BBN.

- We derived the GWs power spectrum produced by i) **adiabatic inflationary curvature perturbations** and ii) **isocurvature perturbations** due to fluctuations of the number density of PBHs . Both processes are **amplified by the eMD** driven by the PBHs.

- The produced GW signal has a characteristic **three-peak form**: At **nHz**, **Hz** and **kHz**, in strong agreement with the **NANOgrav/PTA data** and in principle detectable by other future detectors. The simultaneous detection of **all three peaks** can constitute a clear indication of **no-scale SUGRA** .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Thank you!
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GWs in nHz (NANOgrav)
GWs in kHz (ET+ BBO)
GWs in Hz (EM GW detectors)

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Appendix: The full picture (SU(5) flipped)