Primordial black holes from dissipative effects during inflation

Alejandro Pérez Rodríguez

Universidad Autónoma de Madrid, IFT UAM-CSIC

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in collaboration with G. Ballesteros, M.A.G. Garcia, M. Pierre, J. Rey

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1. Dissipation during inflation: basics

- Coupling between inflaton and **thermalised** radiation: $\rho_r \propto T^4$
- Effective **friction** (☞ warm inflation, e.g. [*Bastero-Gil, Berera, Moss, Ramos '14*])

$$\ddot{\phi} + (3H + \Gamma)\dot{\phi} + V_{,\phi} = 0\,,$$
$$\dot{\rho}_r + 4H\rho_r = \Gamma\dot{\phi}^2\,.$$

$Q = \frac{\Gamma}{3H}$. $Q = 0$: cold inflation. $Q \ll 1$: weak dissipation; $Q \gg 1$: strong dissipation.

- **Fluctuation-dissipation theorem** $\Rightarrow$ linear perturbations sourced by white noise ξ, with $\langle \xi_{\boldsymbol{k}}(t)\xi_{\boldsymbol{k'}}(t')\rangle = \delta(t-t')\delta(\boldsymbol{k}+\boldsymbol{k'})$ [*Hall, Moss, Berera '04*]

$$\delta\ddot{\phi}_{\boldsymbol{k}} + [...] \propto \sqrt{\Gamma\, T}\,\xi_{\boldsymbol{k}}(t) \quad \text{inflaton perturbation}\,,$$
$$\delta\dot{\rho}_{r,\boldsymbol{k}} + [...] \propto \sqrt{\Gamma\, T}\,\xi_{\boldsymbol{k}}(t) \quad \text{radiation perturbation}\,,$$
$$\dot{\varphi} + [...] = 0 \quad \text{metric perturbation (weakly coupled)}$$

2. Power spectrum: general considerations

Thermal noise is a **classical source** for curvature perturbations. The power spectrum has two distinct components [*Ballesteros, APR, Pierre '23*]

$$\langle \mathcal{P}_{\mathcal{R}} \rangle = \mathcal{P}_{\mathcal{R}}^{(h)} + \langle \mathcal{P}_{\mathcal{R}}^{(i)} \rangle \, .$$

- $\mathcal{P}_{\mathcal{R}}^{(h)}$ is of **quantum** origin
  - For $Q_* \ll 1$, $\mathcal{P}_{\mathcal{R}}^{(h)}$ **recovers the cold limit.** [*Ballesteros, APR, Pierre '23*]
  - For $Q_* \gg 1$, $\mathcal{P}_{\mathcal{R}}^{(h)}$ is **exponentially suppressed with** Q_* (assuming Bunch-Davies initial cond.) [*Nacir, Porto, Senatore, Zaldarriaga '12*], [*Ballesteros, APR, Pierre '23*]
- $\langle \mathcal{P}_{\mathcal{R}}^{(i)} \rangle$ is of **thermal** origin. **Enhanced by dissipation**: $\langle \mathcal{P}_{\mathcal{R}}^{(i)} \rangle \propto \Gamma_* T_*$ (next slide). [*Hall, Moss, Berera '04*], [*Ballesteros, APR, Pierre '23*]

2. Power spectrum: analytical estimate

Simplified equation for $\delta\phi_{\boldsymbol{k}}$ (order zero in slow-roll, neglect coupling to metric and radiation) provides insight on $\langle \mathcal{P}_{\mathcal{R}}^{(i)} \rangle$ [*Ballesteros, García, APR, Pierre, Rey '23*].

$$\delta\ddot{\phi}_{\boldsymbol{k}} + (3H+\Gamma)\delta\dot{\phi}_{\boldsymbol{k}} + \left(\frac{k^2}{a^2} + \dot{\phi}\,\Gamma_{\phi}\right)\delta\phi_{\boldsymbol{k}} \propto \sqrt{\frac{2\Gamma T}{a^3}}\,\xi_{\boldsymbol{k}}(t)$$

1. Solve homogeneous equation and construct **retarded Green's function** $G(t,t')$
2. Solve inhomogeneous equation: $\delta\phi_{\boldsymbol{k}}^{(i)}(t) = \int^t dt'\, G(t,t')\sqrt{\frac{\Gamma\, T}{a^3}}\,\xi_{\boldsymbol{k}}$

$$\langle \delta\phi_{\boldsymbol{k}}^{(i)}(t)\delta\phi_{\boldsymbol{q}}^{(i)}(t)\rangle \propto \int^t\!\!\int^t dt' ds'\, G(t,t')\sqrt{\frac{\Gamma\, T}{a^3}}\,G(t,s')\sqrt{\frac{\Gamma\, T}{a^3}}\,\underbrace{\langle \xi_{\boldsymbol{k}}(t')\,\xi_{\boldsymbol{q}}(s')\rangle}_{\delta(t'-s')\delta(\boldsymbol{k}+\boldsymbol{q})}$$

$$= \delta(\boldsymbol{k}+\boldsymbol{q})\int^t dt'\, G(t,t')^2\,\frac{\Gamma\, T}{a^3} \approx \Gamma_* T_*\,\delta(\boldsymbol{k}+\boldsymbol{q})\int^t dt'\,\frac{G(t,t')^2}{a^3} \implies \boxed{\langle \mathcal{P}_{\delta\phi}^{(i)}\rangle \propto \langle \mathcal{P}_{\mathcal{R}}^{(i)}\rangle \propto \Gamma_* T_*}$$

3. Transient dissipation. Preliminary estimate

Idea: transient dissipation $\implies$ peak in the spectrum

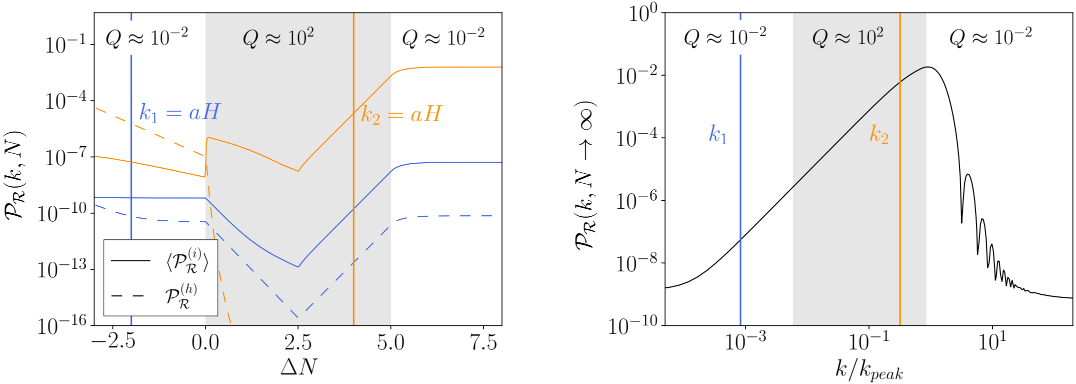


Figure: Evolution of the modes in the **analytical approximation**. C.f. USR phase of inflation. Details in [*Ballesteros, García, APR, Pierre, Rey '23*].

3. Transient dissipation: numerical calculation

For comparison with experimental data, analytical estimates are not precise enough.

- Previous approach: Montecarlo sampling of the thermal noise
- Our proposal: **Fokker-Planck** approach [*Ballesteros, García, APR, Pierre, Rey '22*]
  - Convert system of SDEs for $\delta\phi^{(i)}$, $\delta\rho_r^{(i)}$, $\varphi^{(i)}$ into system of ODEs for

$$\langle|\delta\phi^{(i)}|^2\rangle,\ \langle|\delta\rho_r^{(i)}|^2\rangle\,,\langle|\varphi^{(i)}|^2\rangle\,,\ldots,\langle\delta\phi^{(i)*}\delta\rho_r^{(i)}\rangle\,,\ldots$$

  - Solve system **once**
  - Recast $\langle|\delta\phi^{(i)}|^2\rangle$, $\langle|\delta\rho_r^{(i)}|^2\rangle\,,\langle|\varphi^{(i)}|^2\rangle\,,\ldots,\langle\delta\phi^{(i)*}\delta\rho_r^{(i)}\rangle\,,\ldots$ into $\langle\mathcal{P}_{\mathcal{R}}^{(i)}\rangle$
  - Results consistent with Montecarlo, faster, no statistical uncertainty.

3. Transient dissipation. Numerical results

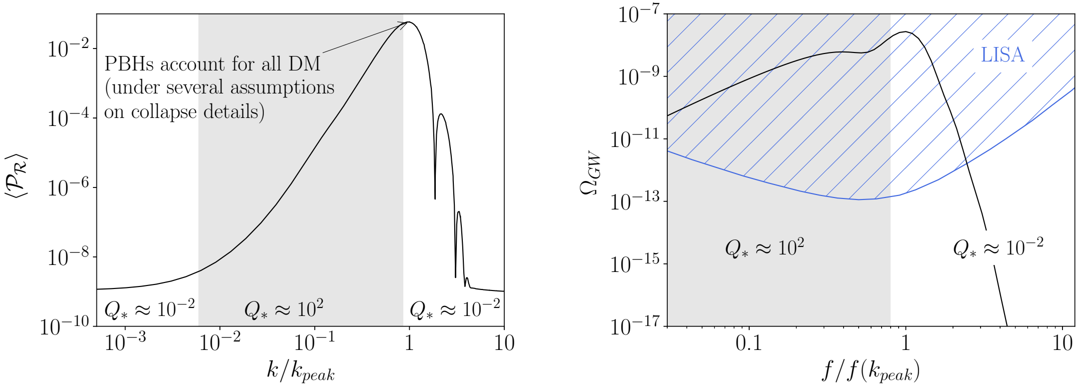
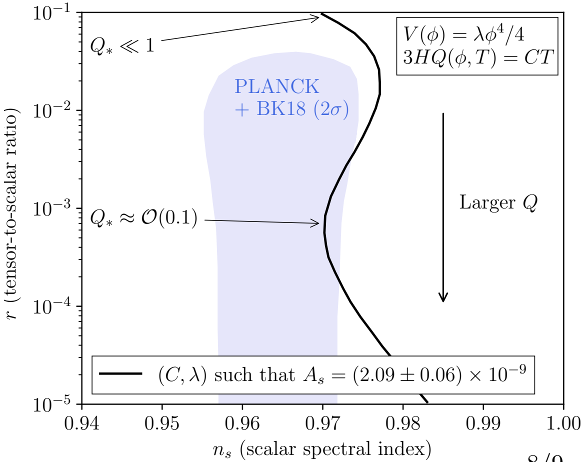


Figure: **Numerical results** for scalar power spectrum and gravitational wave energy density, see [*Ballesteros, García, APR, Pierre, Rey'22*]. C.f. other dissipative scenarios in which **light** PBHs are produced, e.g. [*Bastero-Gil, Diaz-Blanco '21*].

4. Other consequences of dissipation

[*Ballesteros, APR, Pierre '23*]

Dissipation allows to reconcile certain monomial models with CMB constraints.



Reconciled with CMB?

	ϕ^6	ϕ^4	ϕ^2
T	Yes	Yes	No
T^3	No	Yes	No
T^3/ϕ^2	No	No	No

Table: Rows: $\Gamma(\phi, T)$. Columns: $V(\phi)$

Conclusions

- Dissipation during inflation leads to a decomposition of the spectrum

$$\langle \mathcal{P}_\mathcal{R} \rangle = \mathcal{P}_\mathcal{R}^{(h)} + \langle \mathcal{P}_\mathcal{R}^{(i)} \rangle \, .$$

- Strong dissipation **enhances scalar perturbations** through enhancement of the **thermal component** of the spectrum.

- **Temporary** dissipation → **Peak in** $\mathcal{P}_\mathcal{R}$

- Phenomenology:
  - Enhanced PBH abundance (asteroid-mass: dark matter candidates) + GWs
  - At CMB scales: **reconcile monomial potentials** with constraints
    ☞ *[Ballesteros, APR, Pierre '23]*