REHEATING WITH PRIMORDIAL BLACK HOLES IN UNIFICATION MODELS

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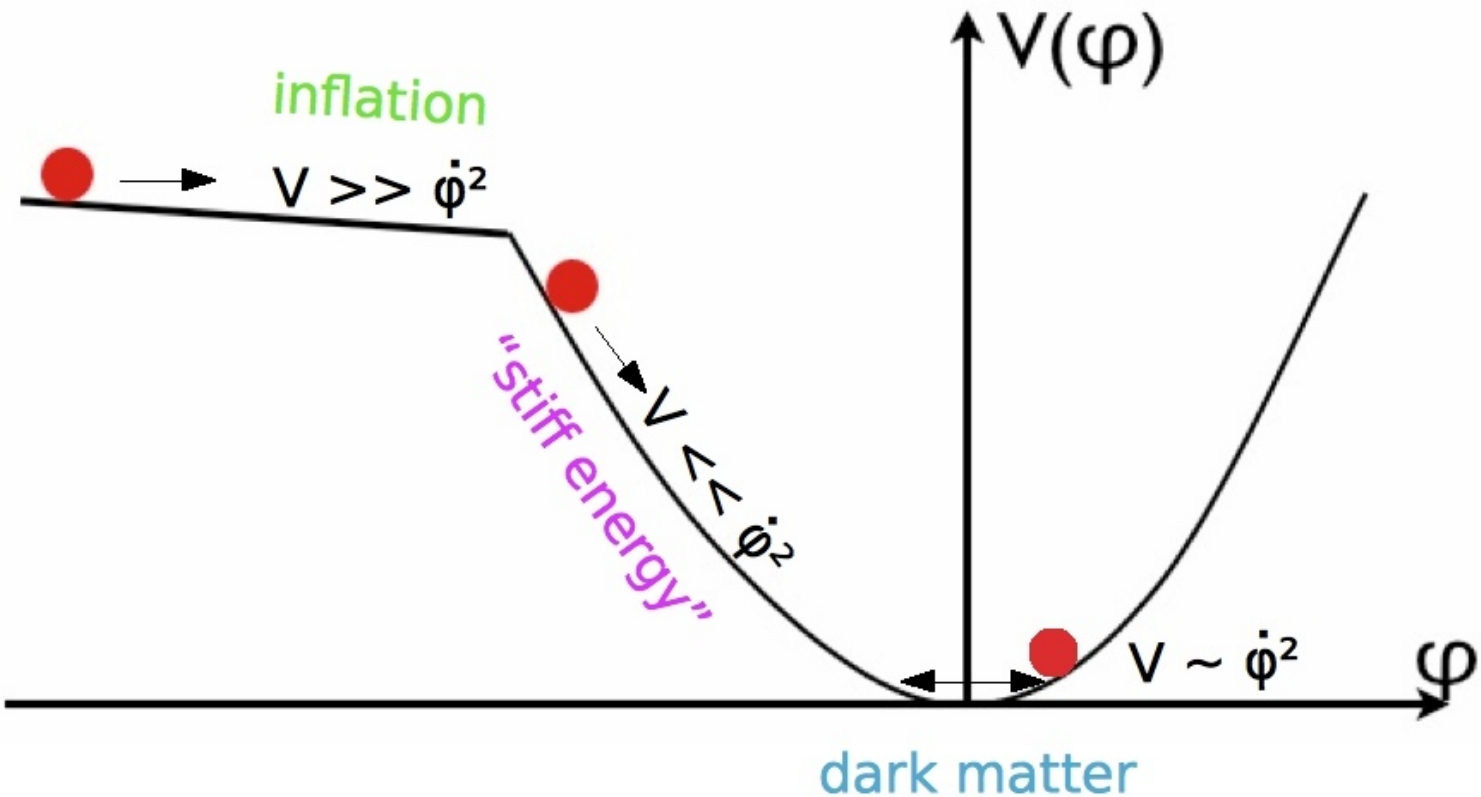
MODELS OF UNIFICATION

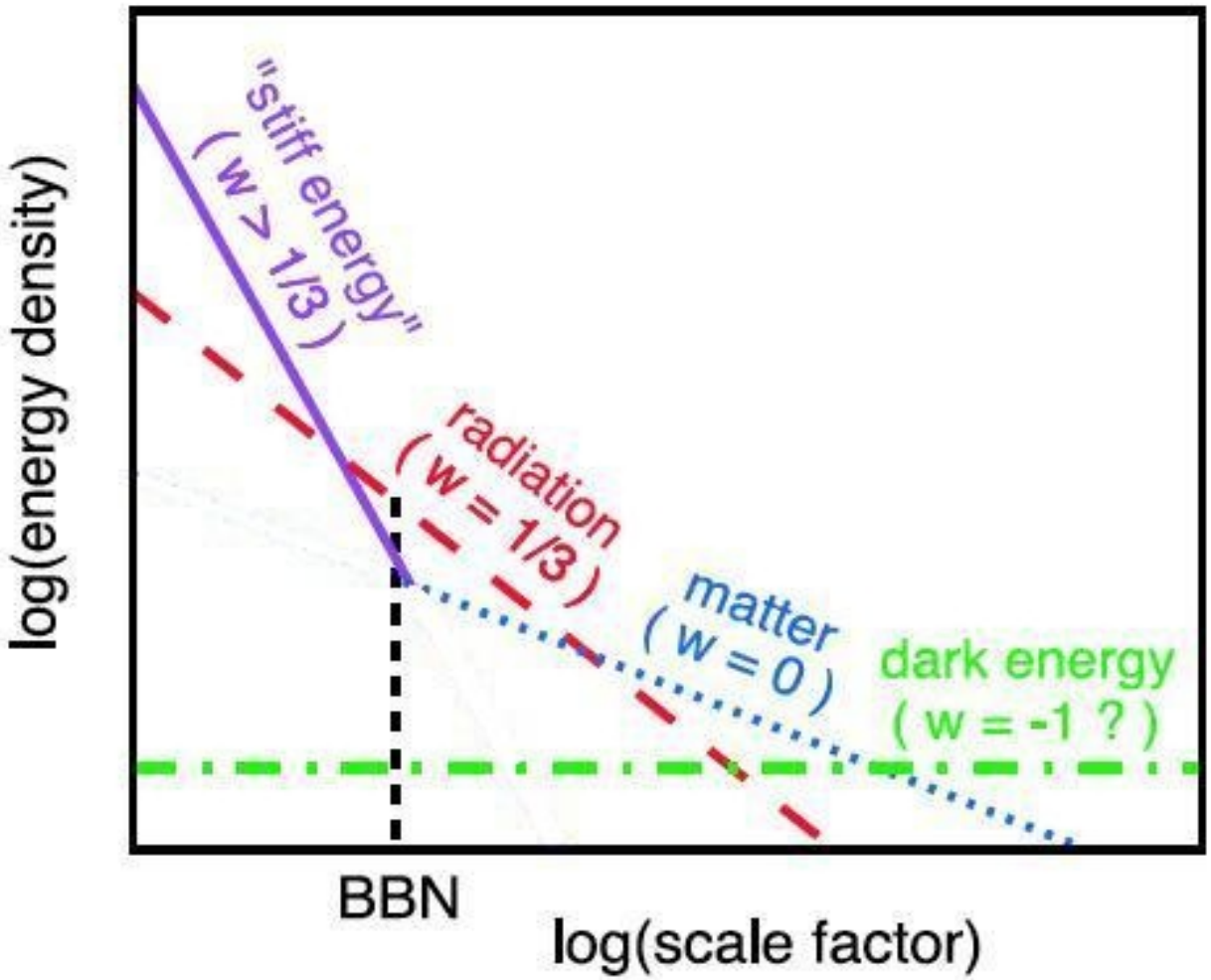
ϕ as inflaton + dark matter + dark energy



$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi),$$

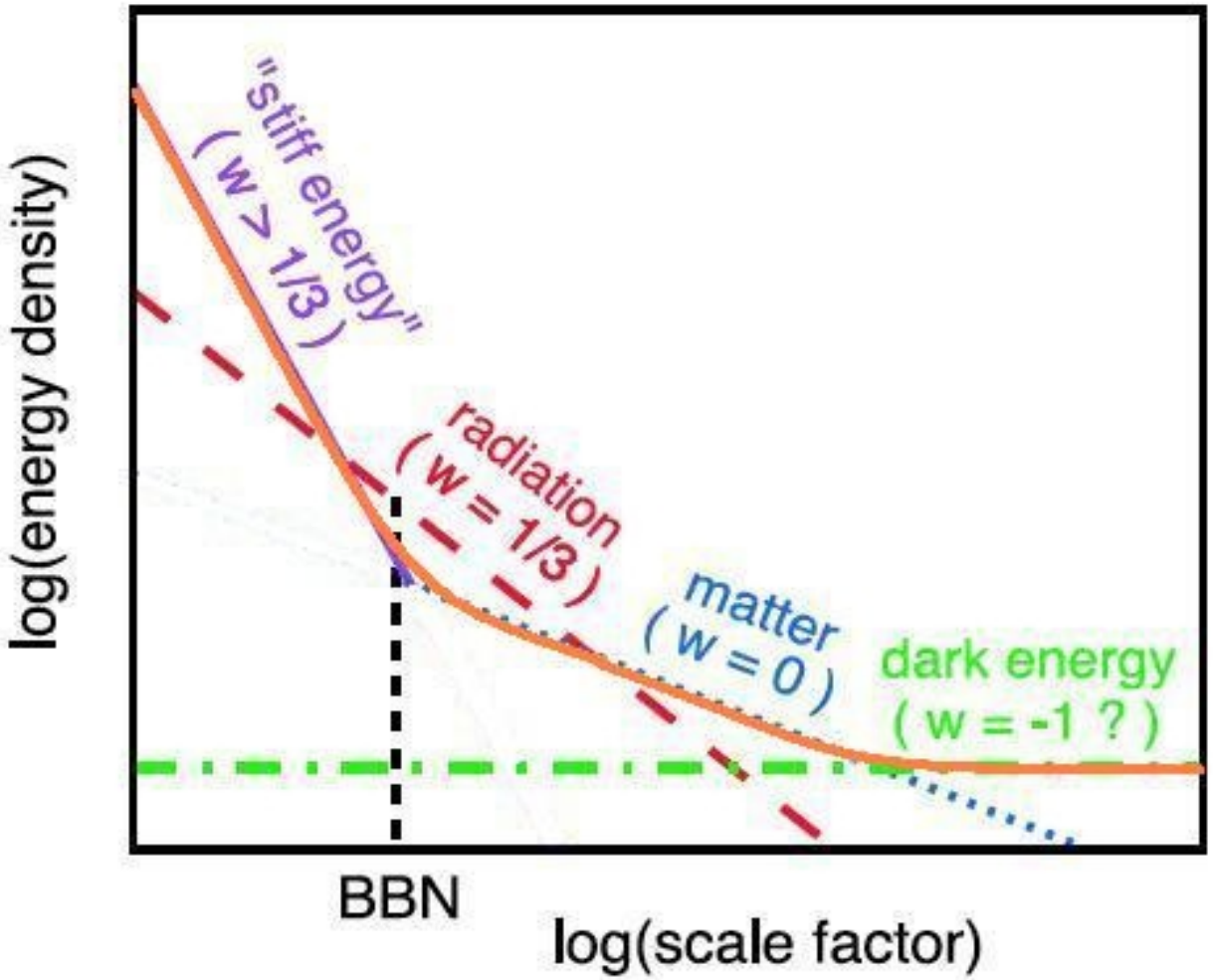
$$P_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi).$$

ϕ as inflaton + dark matter + dark energy



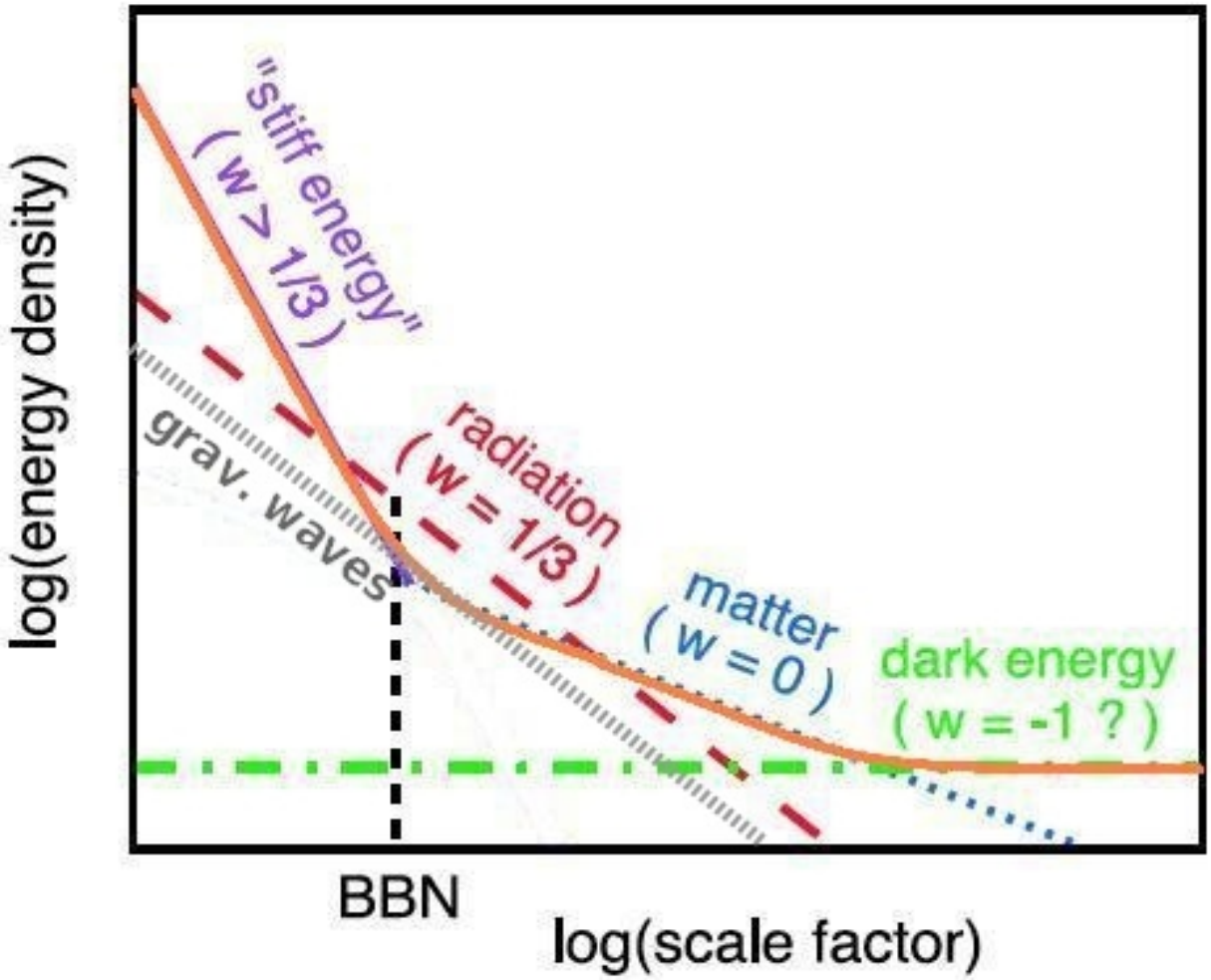
$$\frac{\rho}{\rho_{\rm i}} = \left(\frac{a}{a_{\rm i}}\right)^{-3(w+1)}$$

ϕ as inflaton + dark matter + dark energy



radiation produced by expanding spacetime

ϕ (inefficient) reheating



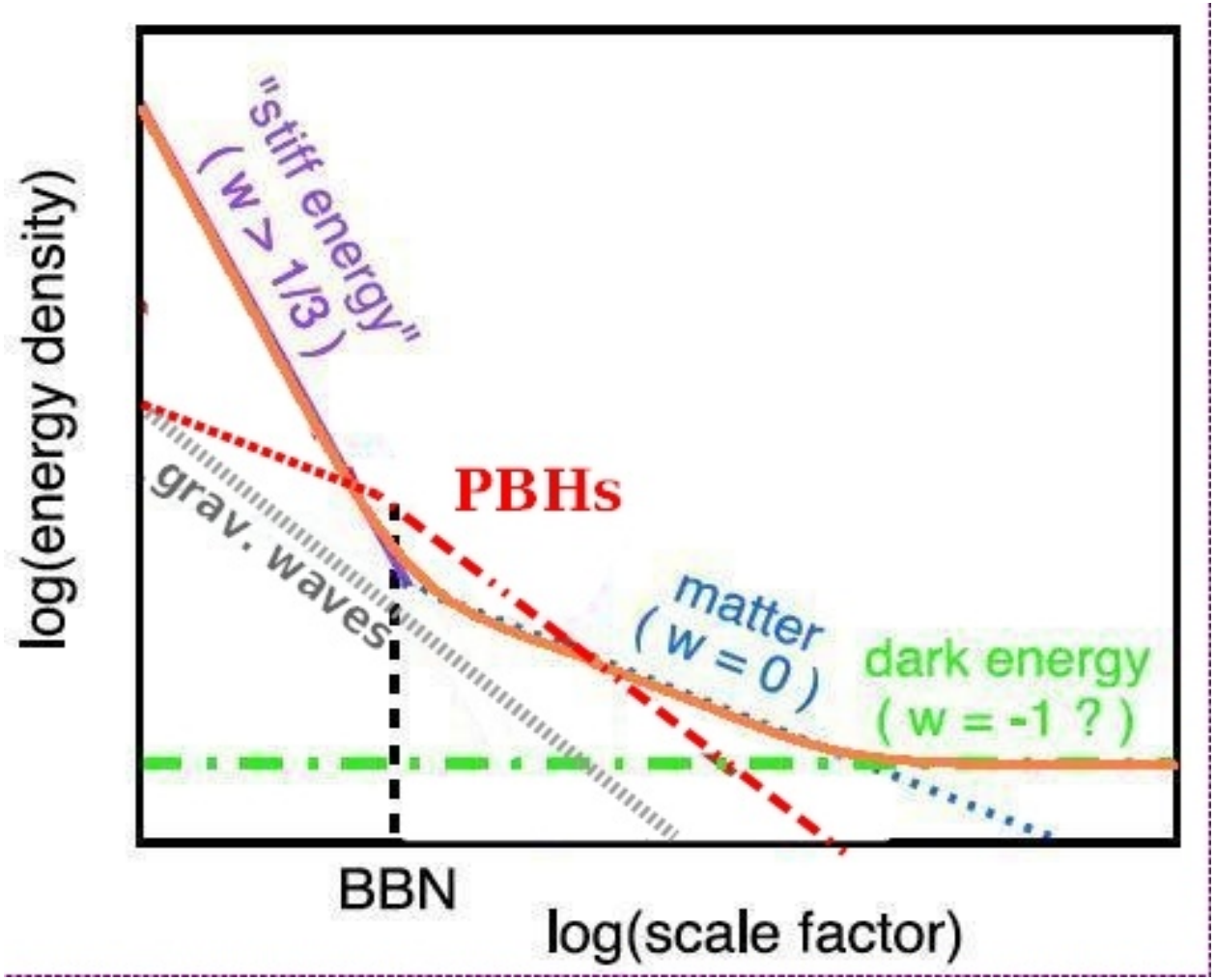
gravitational waves violate observational bounds

$$\rho_{\rm gw}(t_{\rm BBN}) < 0.2\rho_\gamma(t_{\rm BBN})$$

ϕ alternative reheating

- **Extra periods of inflation** (Liddle + Pahud + Ureña,08)
- **Extra scalar fields producing radiation**
- **...**

ϕ & PBH reheating



gravitational waves are diluted

PRIMORDIAL BLACK HOLES

Tiny black holes at the end of inflation

- Form from large fluctuations $\delta_{min} \simeq w_\phi$
- Initial mass = Hubble mass $M_{\rm PBH} = f_M 4\pi\sqrt{3}\left(\frac{\rho_{\rm eoi}}{m_{\rm pl}^4}\right)^{-1/2} m_{\rm pl}$
- Initial mass fraction $\frac{\rho_{\rm PBH}(t_i)}{3M_{pl}^2H^2} = \beta(M) = f_M \int_{\delta_{\rm min}}^{\infty} \mathcal{P}(\delta)d\delta$
- PBH component evolution

$$\Omega_{\rm PBH}(t;M) = \frac{\rho_{\rm PBH}(M;t)}{3M_{pl}^2H^2} = \beta(M)\left(a(t)/a_i\right)^{-3}$$

- Hawking evaporation

Hawking evaporation

- Hawking was interested small systems with strong gravity.

- Black Hole evaporation is the prediction of such quantum effects

$$T = \frac{\hbar c^3}{8\pi G M k} \approx 10 \left[\frac{10^{15}\mathrm{g}}{M} \right] \mathrm{MeV} \qquad t \sim 10^{10} \left[\frac{M}{10^{15}\mathrm{g}} \right]^3 \mathrm{yr}$$

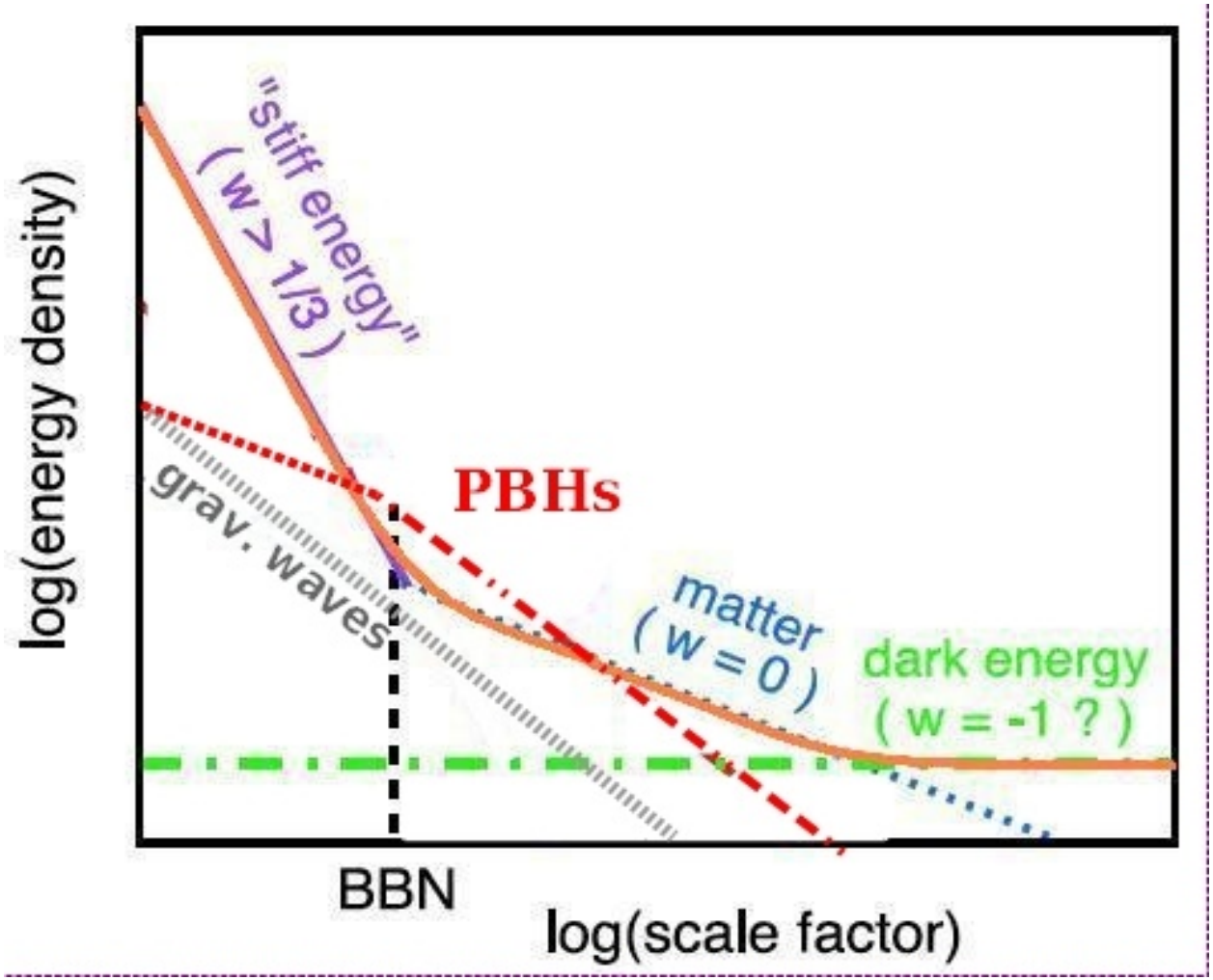
Hawking evaporation

- It would take about 1s to evaporate the mass of 100 taxis squeezed in 1cm^3

- It takes the age of the universe to evaporate a black hole of the mass of a small mountain.

Unification Φ & PBH reheating

ϕ & PBH reheating



gravitational waves are diluted

$$\frac{\rho_{\rm gw}}{\rho_{\rm PBH}} \propto \left(\frac{a}{a_{\rm eoi}}\right)^{-1}$$

(Lidsey+Matos+Ureña,06)

ϕ & PBH reheating (requirements)

- **Initial abundance** $\delta_{min} \simeq w$

$$\sigma^2 \sim (0.1 w_{\rm eoi})^2 \sim 10^{-6}$$

$$\beta \sim 10^{-15}$$

- **Growth and dominance**

$$\frac{\rho_{\rm PBH}}{\rho_\phi} = \left(\frac{a(t)}{a_i}\right)^{3w_\phi} \frac{\beta_i(\sigma)}{1-\beta_i(\sigma)} \quad \Rightarrow \quad N_{\rm osc} \sim 11$$

- **Dilution of GW**

$$\frac{\rho_{\rm gw}}{\rho_{\rm PBH}} \propto \left(\frac{a}{a_{\rm eoi}}\right)^{-1} \qquad N_{\rm nogw} \sim 3$$

ϕ & PBH reheating (an example)

$$V(\Phi) = V_0\left[\cosh(\alpha\sqrt{\kappa_0}\Phi) - 1\right] \qquad \alpha = 20.28 \qquad V_0 = \left(3\times 10^{-27} m_{\rm pl}\right)^4$$

- **Evaporation time**

$$V_{\rm eoi} = 10^{-6} m_{\rm pl} \quad \Rightarrow \quad \begin{cases} t_{\rm ev} = 10^{-10}{\rm sec.} \\ t_{\rm eoi} \sim 10^{-36}{\rm sec} \\ t_{\rm osc} < t_{\rm evap} < t_{\rm BBN} \end{cases}$$

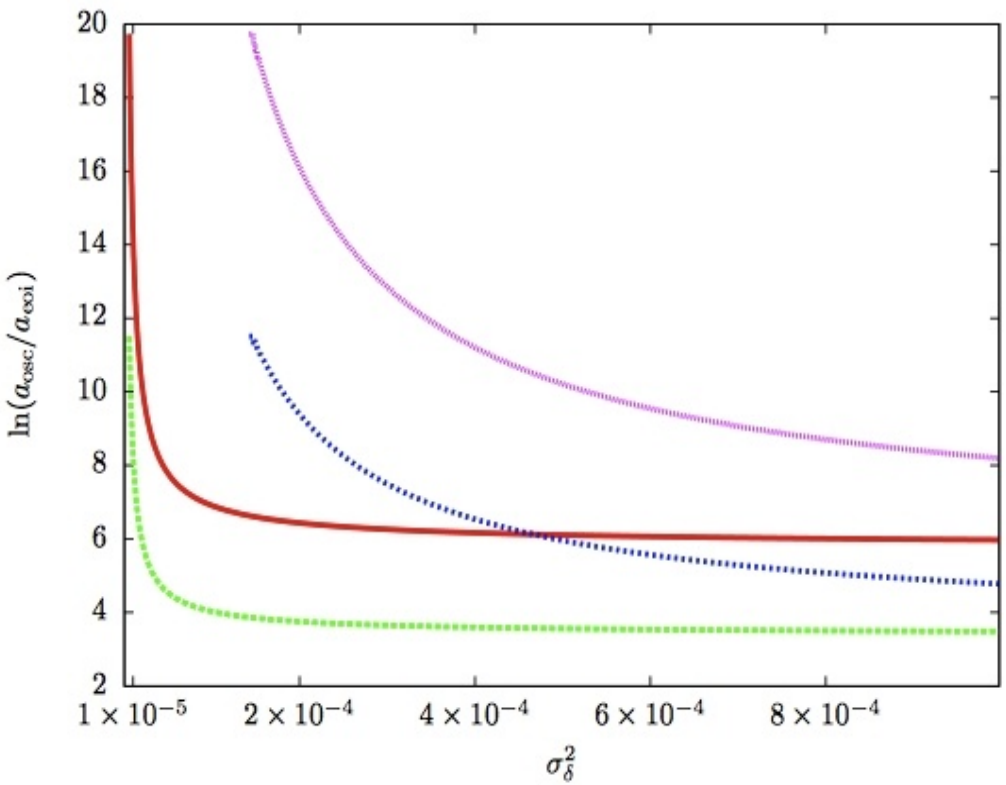
- **Right amount of radiation**

$$\xi_{\rm dm} = \rho_\phi / n_\gamma = 2\times 10^{-28} m_{\rm Pl}$$ **today** $\Rightarrow$

$$\left(\frac{\rho_{\rm PBH}}{\rho_\phi}\right)_{t_{\rm osc}} \approx \frac{g_{\rm S}(t_0)}{g_{\rm S}(t_{\rm osc})}\frac{\zeta(3)}{30}\pi^4\left(\frac{g_{\rm BBN}}{g_{\rm osc}}\right)^{1/3}\left(\frac{\rho_{\rm osc}}{\rho_{\rm BBN}}\right)^{1/4}\times \left(\frac{T_{\rm BBN}}{2.4\times 10^{-28} m_{\rm Pl}}\right)$$

ϕ & PBH reheating (an example)

- **Required number of e-folds** $N_{\rm osc}$



	$w_{\rm eoi}$	w_ϕ
	0.1	0.5
	0.1	1
	0.02	0.5
	0.02	1

ϕ & PBH reheating (a comment on σ^2)

- A spectral index running can overproduce PBHs
  (Kohri+Lyth+Melchiorri,08)

$$n' < 0.026$$

- A soft equation of state in the transit to stiff fluid
  (Suyama+Tanaka+Bassett+Kudoh,06)

- Boosted sub-horizon fluctuations at eoi.
  Particularly for $w \approx 0$
  (Zaballa+Sasaki,09)

Summary

+ Reheating the universe with PBHs works to dilute gravitational waves.

+ Mechanism useful for steep inflation, k-essence, braneworld models.

- A numerical simulation of σ^2 is necessary.

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(JCH+Liddle+Ureña,11)