Primordial black holes as cosmic expansion accelerators

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Theodoros Papanikolaou

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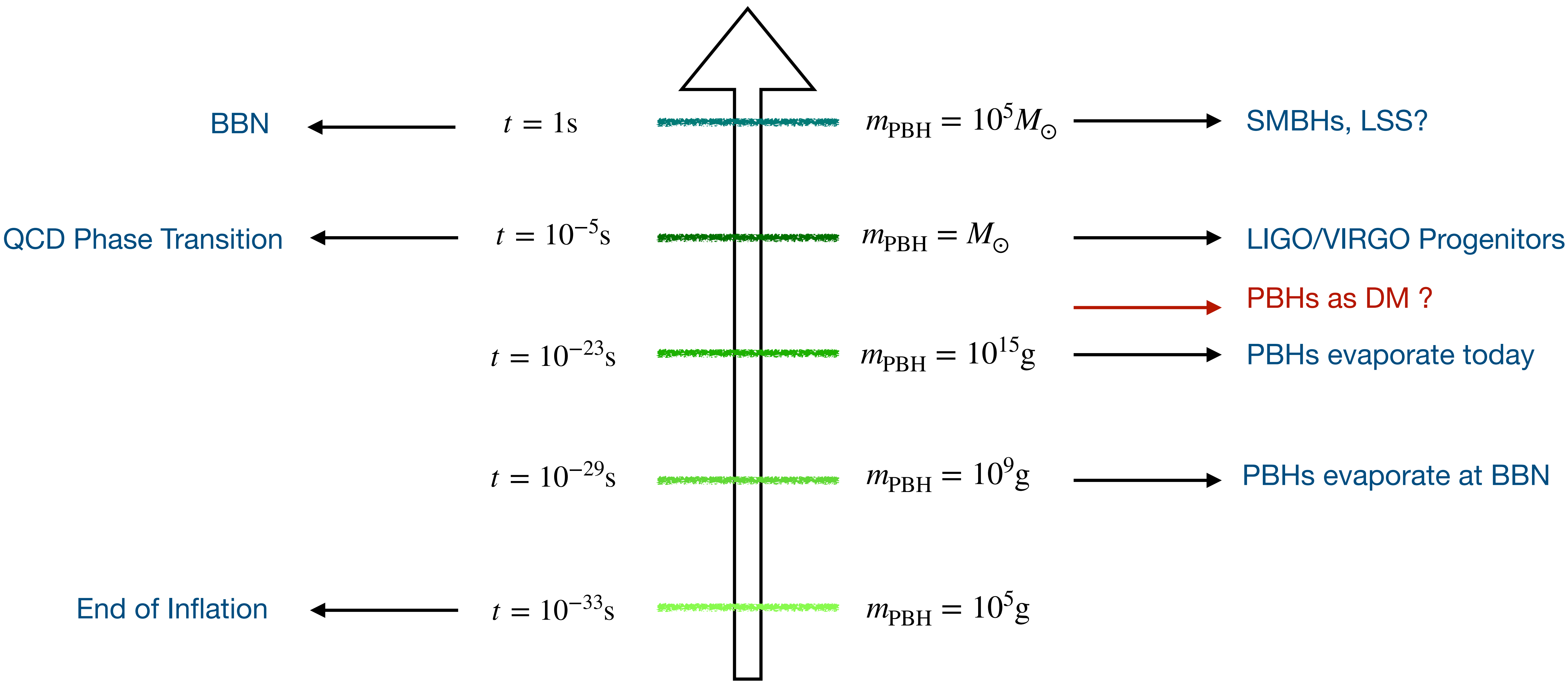
Scuola Superiore Meridionale

Why to study PBHs?

- Primordial Black Holes (PBHs) form in the early universe out of the **collapse of enhanced energy density perturbations,** $\delta \equiv \dfrac{\delta\rho}{\rho_\mathrm{b}} > \delta_\mathrm{c}(w \equiv p/\rho)$ [Carr - 1975].

$$m_\mathrm{PBH} = \gamma M_\mathrm{H} \propto H^{-1} \text{ where } \gamma \sim \mathrm{O}(1)$$



See for reviews in [Carr et al.- 2020, Sasaki et al - 2018, Clesse et al. - 2017]

What is the metric describing PBHs?

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Schwarzschild, Kerr? $\Rightarrow$ **Singular** and **Attractive**

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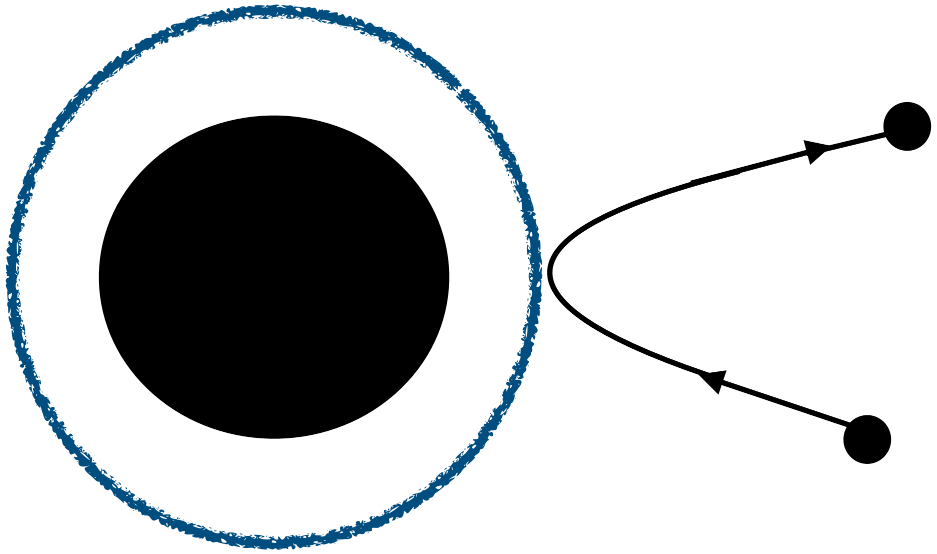
What about having with **"repulsive-like" PBHs**
which are generically **regular**?

PBHs with “repulsive-like” behaviour (rPBHs)



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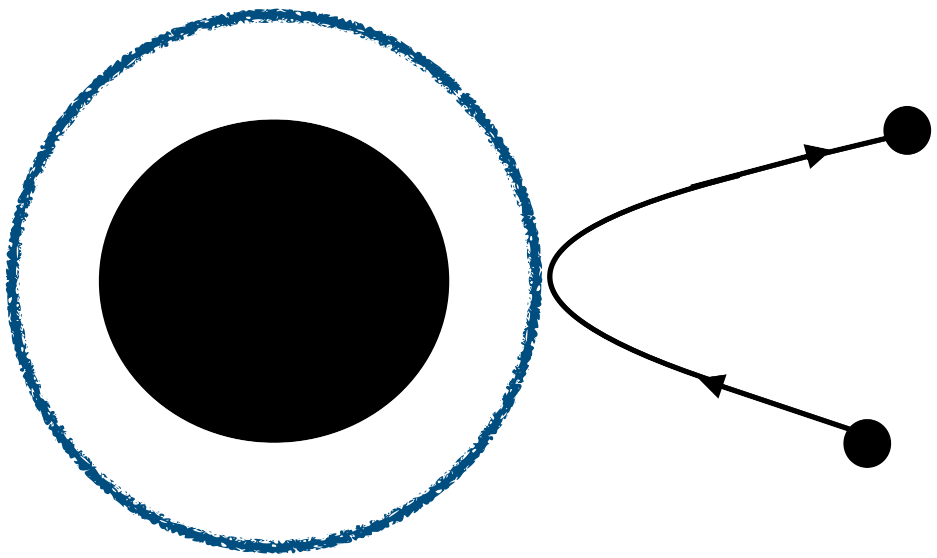

- **Type I:** Repulsive behaviour close to the centre, **de-Sitter like core**. The repulsive interior is modelled with an **effective Λ** (e.g. Dymnikova) or with a **negative pressure of quantum/modified gravity origin** (e.g. Hayward, Bardeen).

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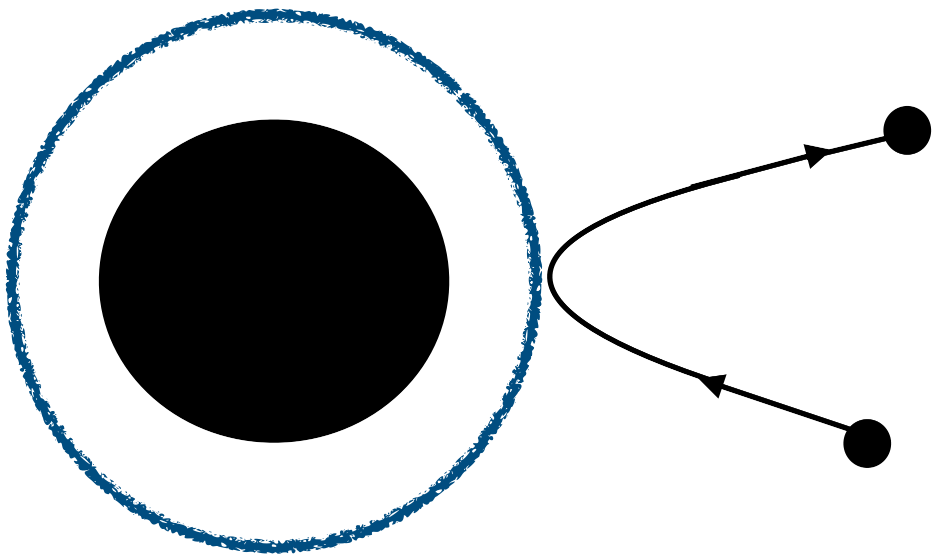

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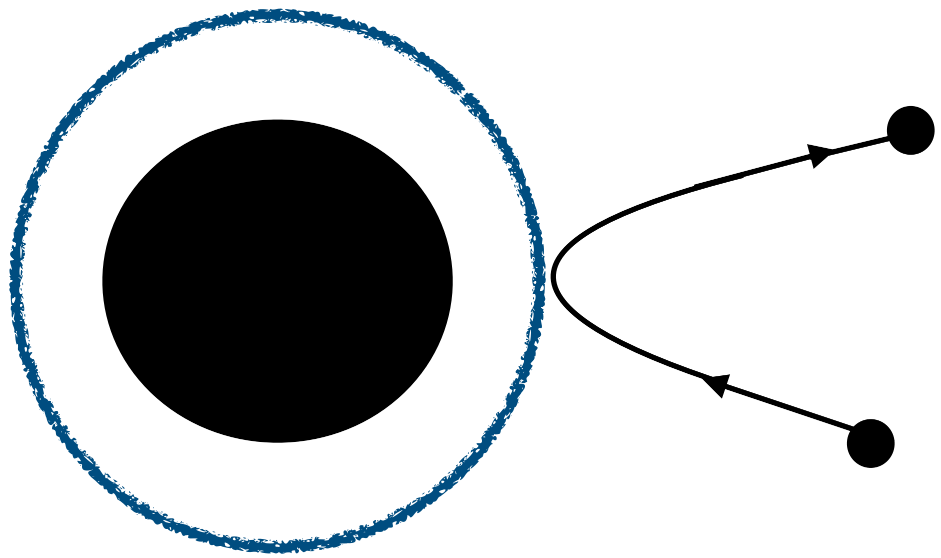

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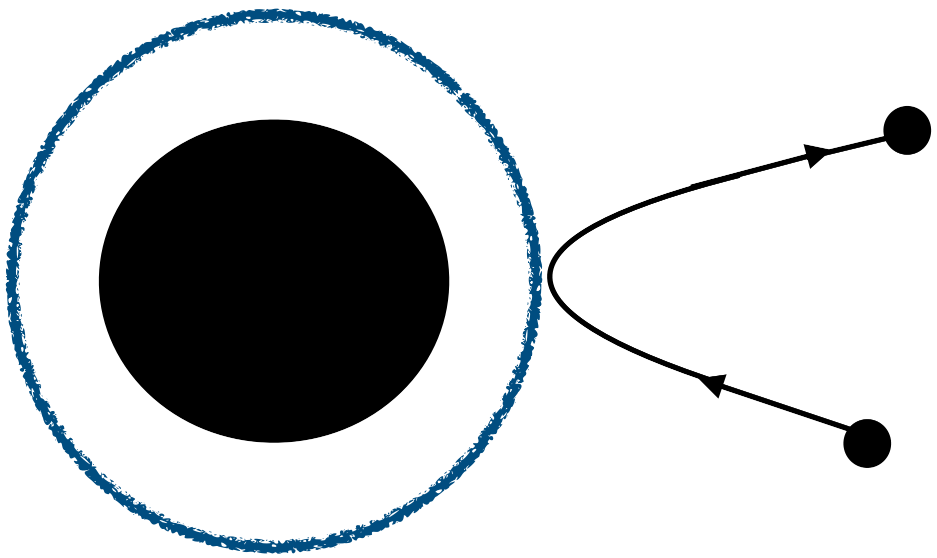

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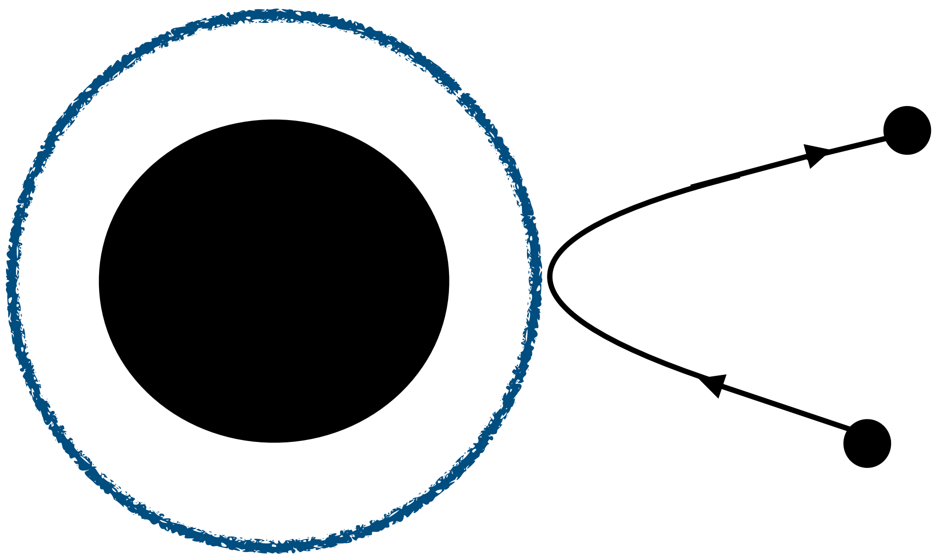

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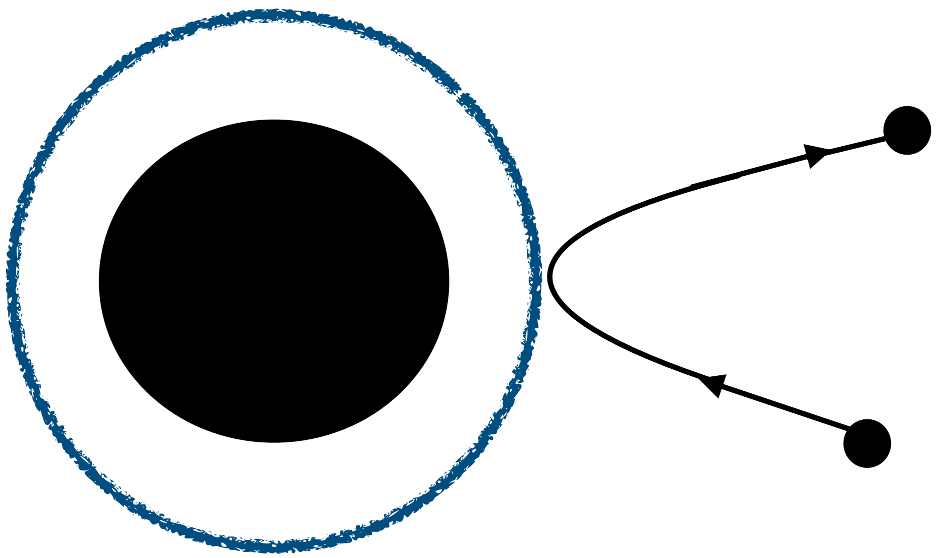

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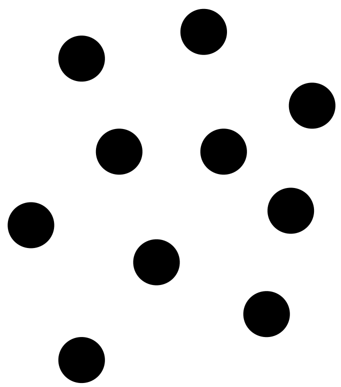
- Four "repulsive-like" PBH metrics considered

1. **Hayward, Bardeen** (non-singular quantum gravity inspired)
2. **Dymnikova** (non-singular GR black solution)
3. **De Sitter - Schwarzschild** (singular GR black solution)

A Universe filled with rPBHs



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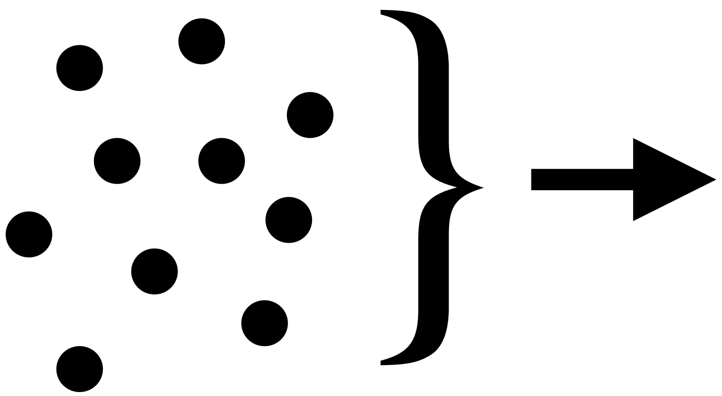

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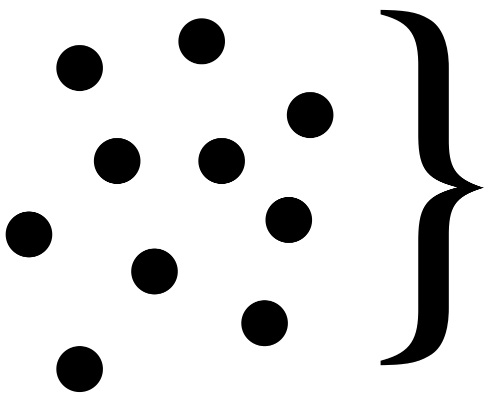

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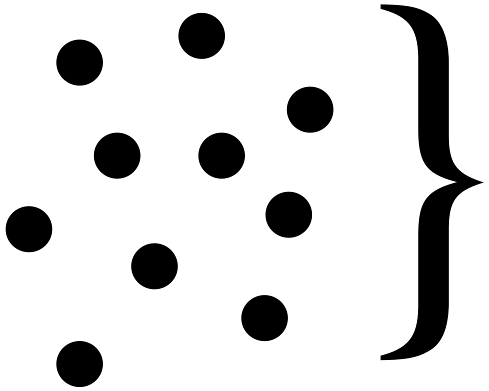

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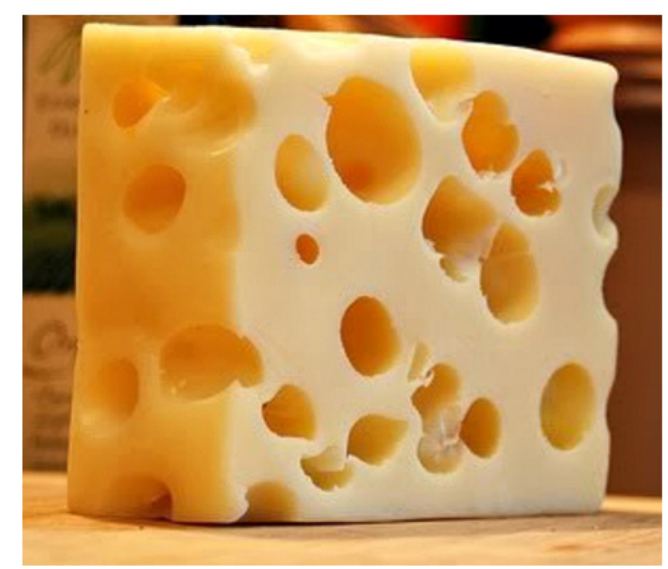

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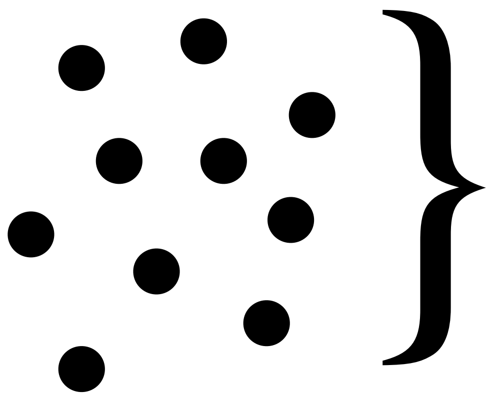

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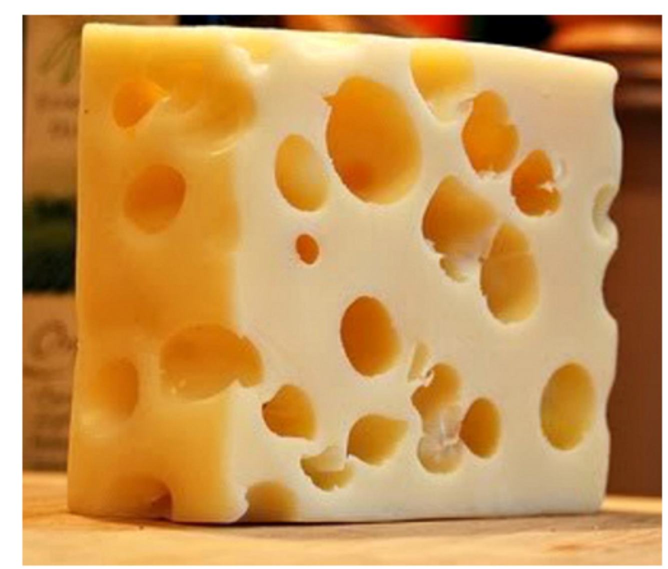

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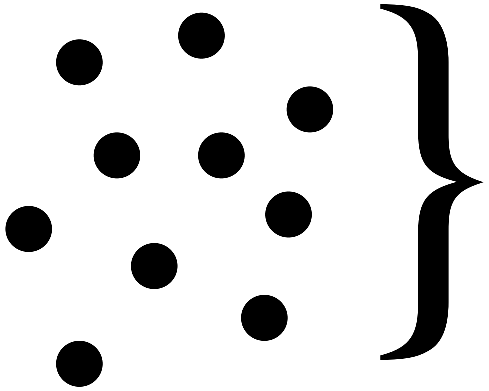

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<u>“Swiss Cheese" cosmology</u>

- ***General Picture:*** The cosmological spacetime is considered like a “Cheese” with its "holes" filled with black holes.

- ***More technically:*** A homogeneous and isotropic FLRW spacetime is matched to a spherical symmetric interior metric.

The "Swiss-Cheese" matching

Cosmological FLRW metric : $\mathrm{d}s^2 = \mathrm{d}t^2 + a^2(t)\left[r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right) + \mathrm{d}r^2\right]$

Interior spherical symmetric metric : $\mathrm{d}s^2 = -F(R)\,\mathrm{d}T^2 + R^2\left(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2\right) + \dfrac{1}{F(R)}\,\mathrm{d}R^2$

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- **Darmois-Israel junction conditions:** The first fundamental form $\gamma_{\alpha\beta}$ [**intrinsic (induced) metric]** and the second one $K_{\alpha\beta}$ [**extrinsic curvature]**, calculated in terms of the coordinates on Σ, are the same on both sides.

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1st junction condition: $-1 = -F(R)\left(\frac{dT}{dt}\right)^2 + F(R)^{-1}\left(\frac{dR}{dt}\right)^2$

2nd junction condition: $\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right)^2 = \frac{1}{F^2(R)},\qquad \frac{\mathrm{d}^2R}{\mathrm{d}t^2} = -\frac{F'(R)}{2},$

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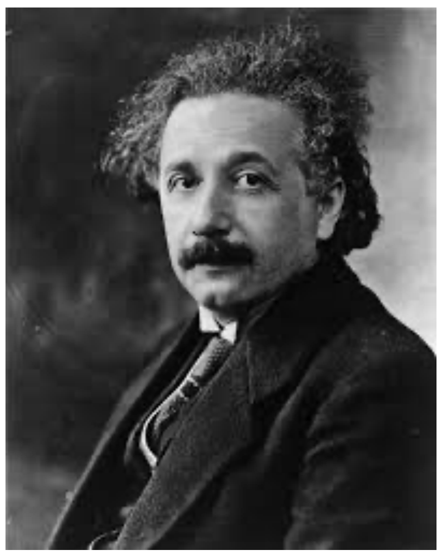
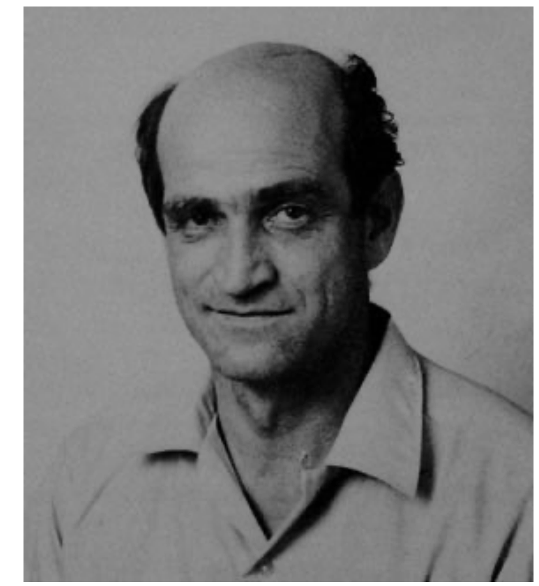
} **Cosmic Expansion Dynamics**

The Einstein-Strauss Model (1945)





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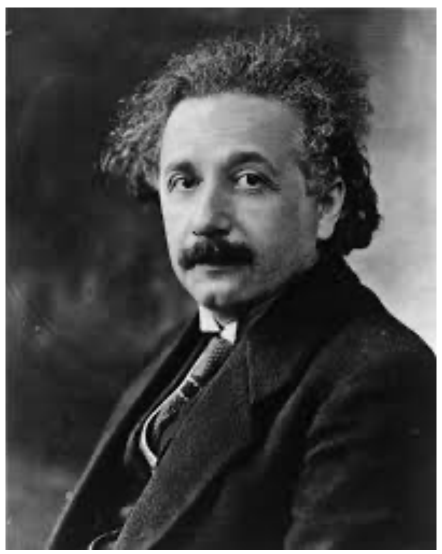
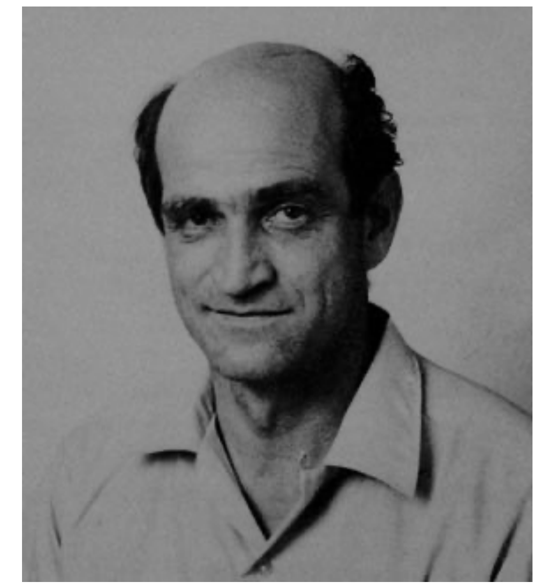
- Consider a **Schwarzschild interior,** i.e. $F(R) = 1 - 2G_{\rm N}m/R$, and a matter content in form of homogeneously distributed black holes, i.e. $\rho_{\rm m} = 3m/(4\pi R^3)$, one gets





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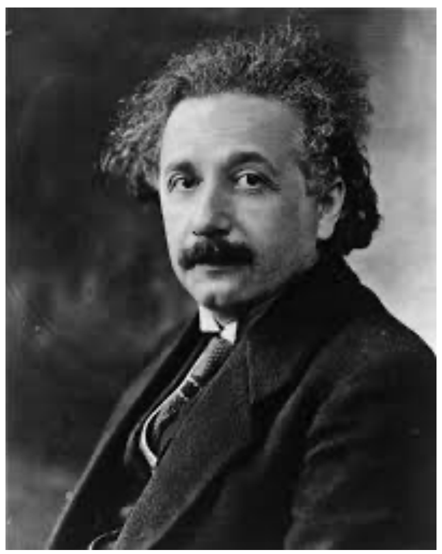

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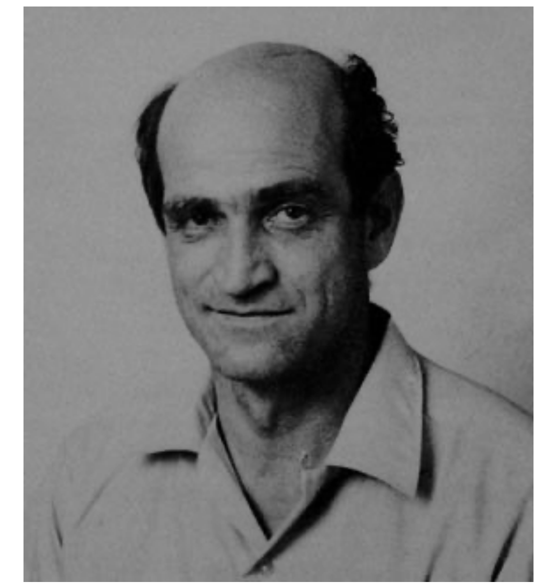

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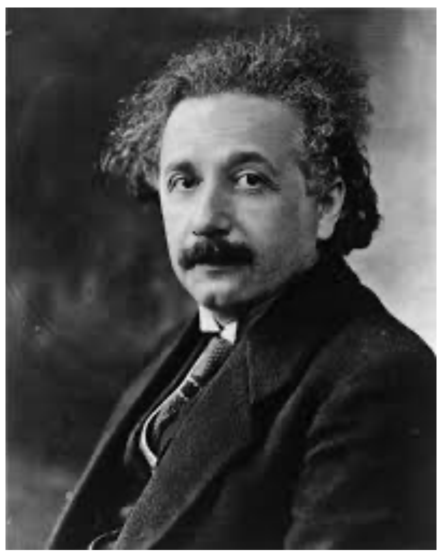

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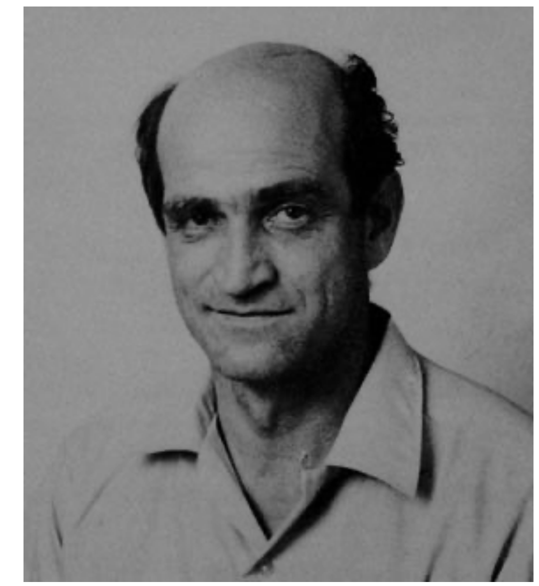

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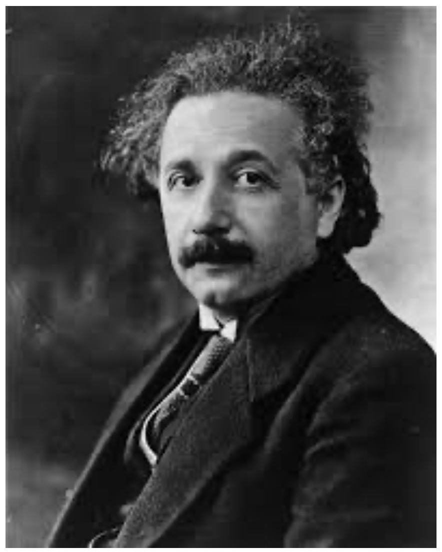

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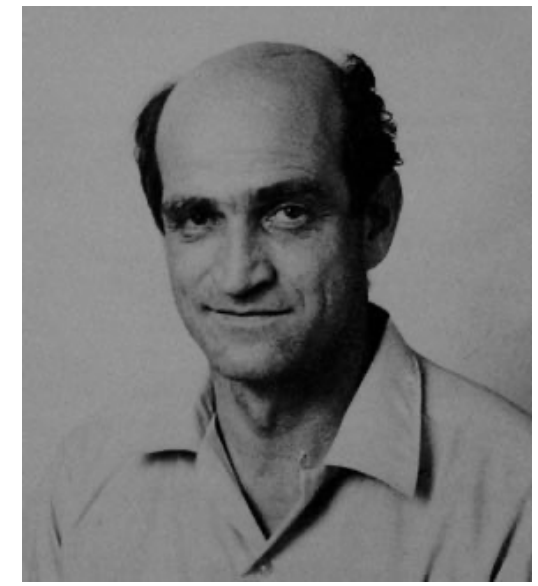

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- We apply thus the Einstein-Strauss idea in **the early Universe**, where **an almost homogeneous distribution of PBHs is a very good approximation** [Desjacques & Riotto - 2018, Y. Ali-Hamoud - 2018, De Luca et al. - 2022].

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- Applying the "Swiss-Cheese" matching one gets the modified Friedmann equations

$$\frac{\dot{a}^2}{a^2} = \frac{8\,\pi}{3} G_\mathrm{N} \left(\rho^{-1} + \frac{8\pi}{3} G_\mathrm{N}\,L^2\right)^{-1}$$

$$\frac{\ddot{a}}{a} = 4\pi G_\mathrm{N}\rho\,\frac{(16 G_\mathrm{N} L^2 \pi\rho - 3)}{(8 G_\mathrm{N} L^2 \pi\rho + 3)^2}$$

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$$\text{where } M(R) = \frac{m\,R^3}{R^3 + 2\,G_\mathrm{N}\,m\,L^2} \approx \begin{cases} m & (R \gg G_\mathrm{N}^{1/3} m^{1/3} L^{2/3}) \\ R^3/(2G_\mathrm{N}L^2) & (R \ll G_\mathrm{N}^{1/3} m^{1/3} L^{2/3}) \end{cases}$$

- One can show that for $m > 3\sqrt{3}L/(4G_\mathrm{N})$, the metric features inner and outer horizons at $R \simeq 2\,G_\mathrm{N}\,m$ and $R \simeq L$ respectively.

- Applying the "Swiss-Cheese" matching one gets the modified Friedmann equations

$$\frac{\dot{a}^2}{a^2} = \frac{8\,\pi}{3} G_\mathrm{N} \left(\rho^{-1} + \frac{8\pi}{3} G_\mathrm{N}\,L^2\right)^{-1} \longrightarrow \text{Effective } \Lambda$$

$$\frac{\ddot{a}}{a} = 4\pi G_\mathrm{N}\rho\,\frac{(16 G_\mathrm{N} L^2 \pi\rho - 3)}{(8 G_\mathrm{N} L^2 \pi \rho + 3)^2}$$

Early cosmic acceleration induced by rPBHs

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Exponential de Sitter-like inflationary expansion driven by rPBHs

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- The evaporation process will be governed by the Hayward evaporation law [Frolov & Zelnikov - 2017]:

$$\frac{dm(t)}{dt} \sim - \frac{n_p}{1920\,\pi} \frac{l_{Pl}^2}{L^2} \frac{1}{G_N^2 \, m(t)^2} \sim \frac{1}{C^3 G_N^2 \, m(t)^2}$$

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When inflation ends?

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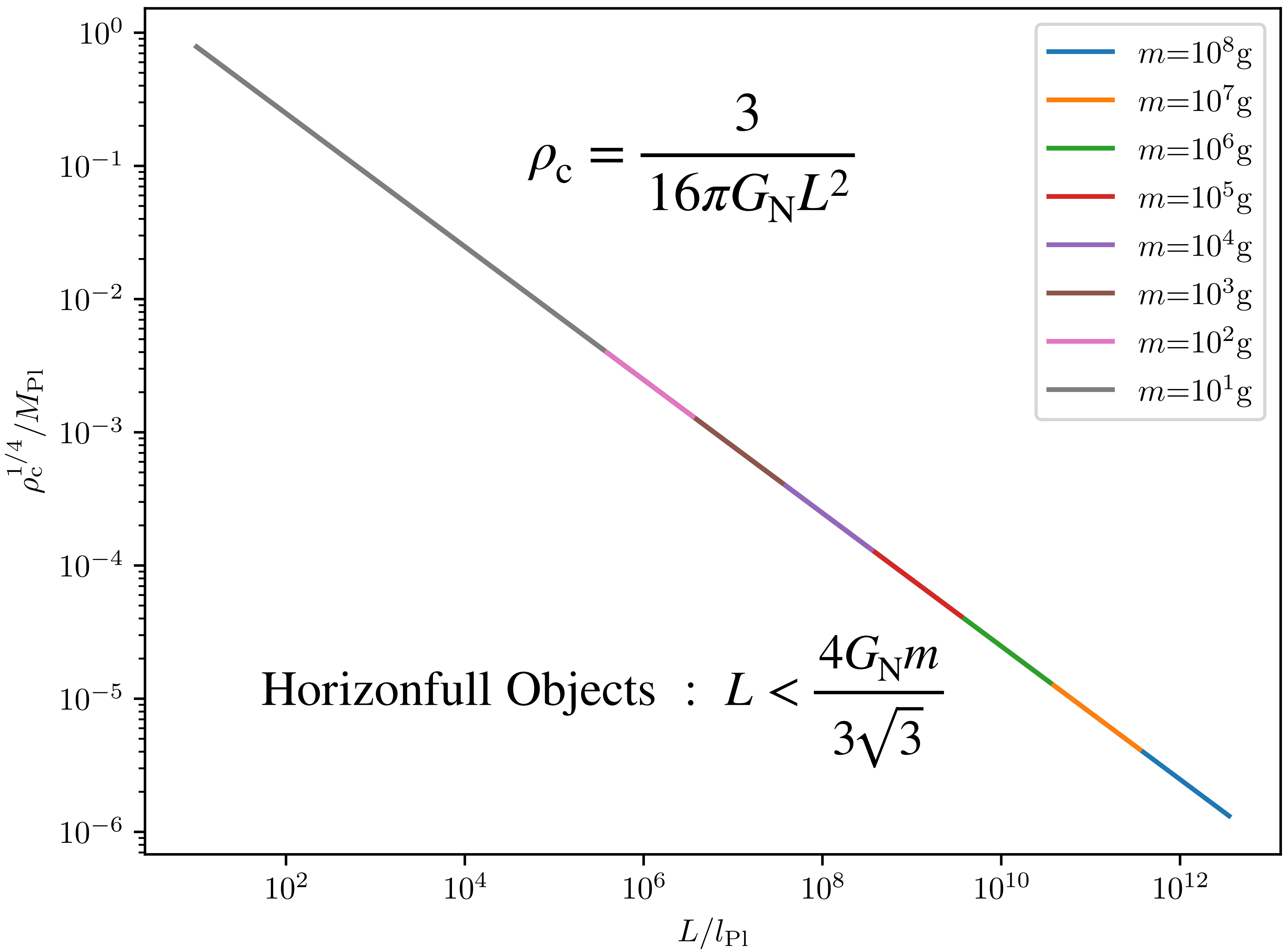
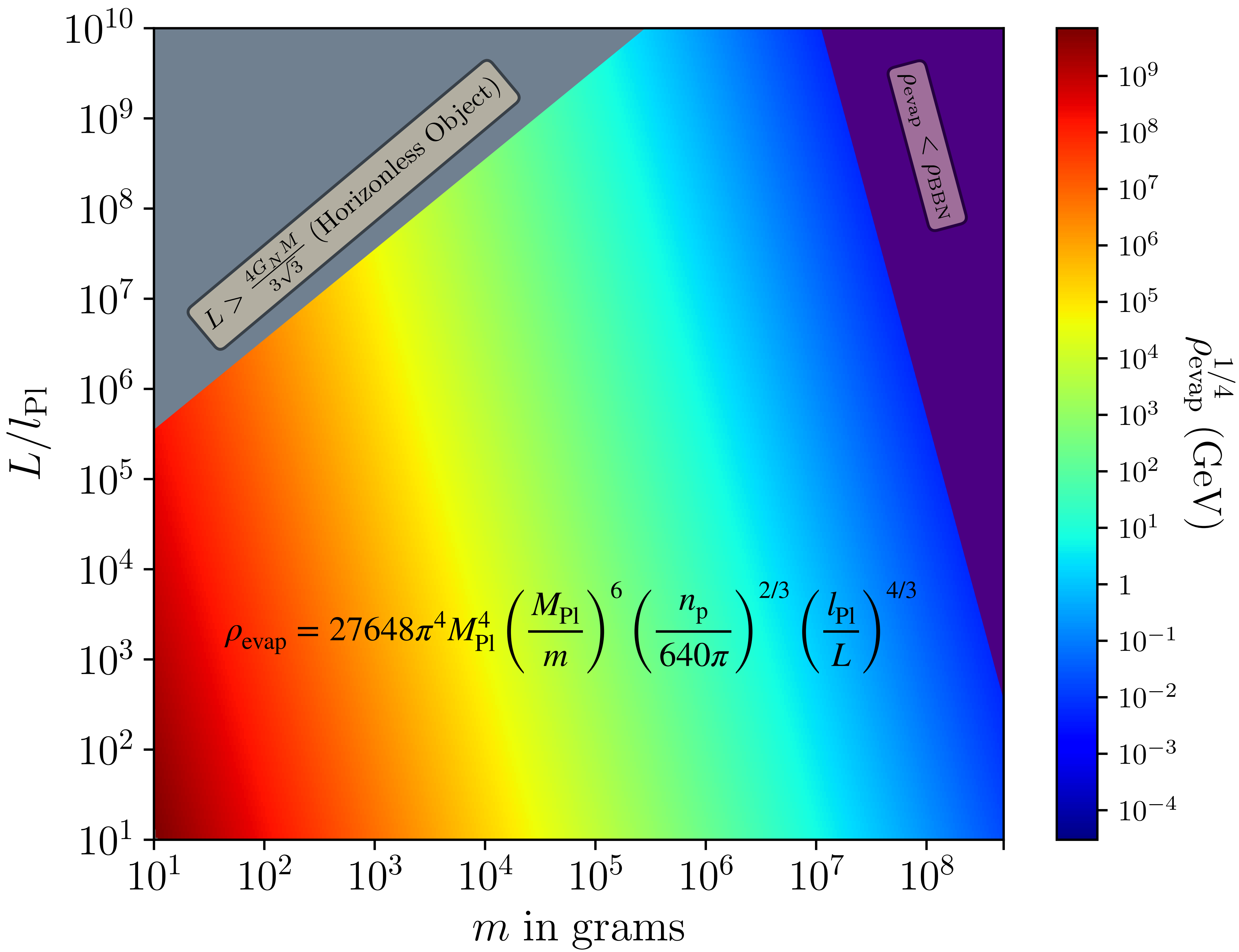
$$\rho_{\rm inf} = \max[\rho_{\rm c}, \rho_{\rm evap}]$$

The critical energy scale

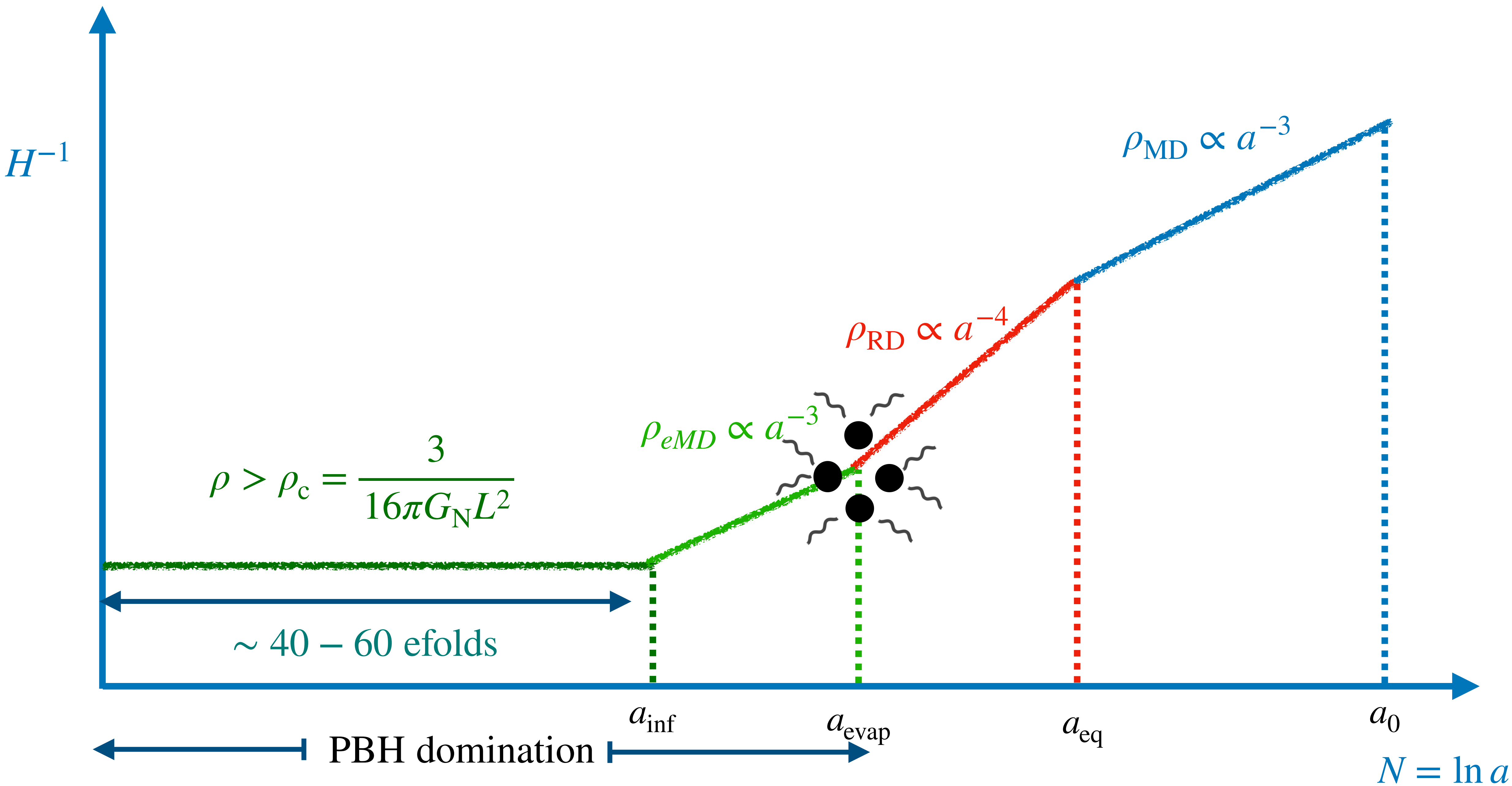


The evaporation energy scale



Inflation and Reheating

- **Inflation ends** when $\rho_{\rm inf} = \max[\rho_c, \rho_{\rm evap}]$. For the Hayward case, one obtains that



- **Reheating** processes through **PBH evaporation** producing finally a thermal radiation bath [J. G. Bellido et al. - 1996, O. Lennon et al. - 2018].

rPBHs as early dark energy (EDE)

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- Notably for PBHs of $m \sim 10^{12}\mathrm{g}$ evaporating slightly before matter-radiation equality and with $0.107 < \Omega_{\rm PBH} < 0.5$ one can get the correct amount of EDE, consistent with current observational constraints on EDE from CMB and LSS,

$$\Omega_{\rm EDE}(t_{\rm LS}) < 0.015 \quad \text{and} \quad 0.015 < \Omega_{\rm EDE}(t_{\rm eq}) < 0.107.$$

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- EDE component in form of PBHs without the addition of exotic scalar fields.

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- Interestingly, PBHs decays faster than radiation, $\rho_{\rm RD} \propto a^{-4}$, due to Hawking evaporation, a condition which is necessary to lead to an increased value of H_0 at early times, not disturbing the position of CMB peaks and LSS growth.

Conclusions

PBHs with repulsive behaviour can act as cosmic expansion accelerators!

Conclusions

- We studied the **PBH dominated Universe** within the context of “**Swiss-Cheese”** cosmology considering **black holes with "repulsive-like" behaviour**.

- Focusing on the **Hayward regular black hole spacetime**, we derived the modified cosmic expansion dynamics finding ultimately **an exponential de Sitter-like inflationary cosmic expansion for very high energies.**

- Within our “Swiss-Cheese" framework, the phase of **cosmic acceleration ends** at an **energy scale characteristic to the black hole parameters** or due to **black hole evaporation**, while **reheating** proceeds through PBH evaporation.

- Repulsive-like PBHs with $m \sim 10^{12}\mathrm{g}$ and $0.107 < \Omega_{\mathrm{PBH}} < 0.5$ slightly before matter-radiation equality can act as a potential EDE component alleviating the H_0 tension.

Thank you for your attention!

Appendix

- **The Bardeen metric**

$$\mathrm{d}s^2 = -F(R)\,\mathrm{d}t^2 + \frac{1}{F(R)}\,\mathrm{d}R^2 + R^2\,\mathrm{d}\Omega^2, \text{ with } f(R) = 1 - \frac{2G_\mathrm{N} m R^2}{(R^2 + l_0^2)^{3/2}}$$

$$H^2 = \frac{2G_\mathrm{N} m}{\left[\left(\frac{3m}{4\pi\rho}\right)^{2/3} + l_0^2\right]^{3/2}}, \quad \frac{\ddot{a}}{a} = \frac{G_\mathrm{N} m \left[2l_0^2 - \left(\frac{3m}{4\pi\rho}\right)^{2/3}\right]}{\left[\left(\frac{3m}{4\pi\rho}\right)^{2/3} + l_0^2\right]^{5/2}} \Rightarrow \rho_\mathrm{c} = \frac{3}{\pi} 2^{-7/2} m\, l_0^{-3}$$

- **The Dymnikova metric**

$$f(R) = 1 - \frac{\mu}{r}\left(1 - e^{-\frac{r^3}{\alpha\mu}}\right) \text{ where } \mu = 2G_N m \text{ and } \alpha = 3/\Lambda$$

This solution coincides with the Schwarzschild black hole for $r \gg (\alpha\mu)^{1/3}$, while for $r \ll (\alpha\mu)^{1/3}$ it behaves like the de Sitter solution.

$$H^2 = \frac{8\pi G_\mathrm{N}}{3}\rho\left(1 - e^{-\frac{3}{8\pi G_\mathrm{N}\alpha\rho}}\right), \quad \frac{\ddot{a}}{a} = -\frac{4\pi G_\mathrm{N}}{3}\rho + \left(\frac{3}{2\alpha} + \frac{4\pi G_\mathrm{N}}{3}\rho\right) e^{-\frac{3}{8\pi\alpha G_\mathrm{N}\rho}}.$$

Appendix

Schwarzschild-De Sitter (SdS) metric

$$\mathrm{d}s^2 = -\left(1 - \frac{2G_\mathrm{N}m}{R} - \frac{1}{3}\Lambda R^2\right) dT^2 + \frac{\mathrm{d}R^2}{1 - \frac{2G_\mathrm{N}m}{R} - \frac{1}{3}\Lambda R^2} + R^2\left(\mathrm{d}\theta^2 + \sin^2\theta \mathrm{d}\varphi^2\right)$$

The SdS spacetime has two horizons if $0 < y < 1/27$, where $y \equiv \frac{G_\mathrm{N}^2 m^2}{l^2}$ where $l^2 \equiv \frac{3}{\Lambda}$.

Black hole horizon: $r_\mathrm{h} = \frac{2G_\mathrm{N}\, m}{\sqrt{3y}} \cos\frac{\pi + \tau}{3}$

Cosmological horizon: $r_\mathrm{c} = \frac{2G_\mathrm{N}\, m}{\sqrt{3y}} \cos\frac{\pi - \tau}{3}$, with $\tau \equiv \cos^{-1}(3\sqrt{3y})$.

One has that $r_\mathrm{h} < r_\mathrm{c} \Rightarrow y < 1$. In the limit $y \ll 1$, one gets $r_\mathrm{h} \to 2G_\mathrm{N}\, m$ and $r_\mathrm{c} \to l$.

$$H^2 = \frac{8\pi G_\mathrm{N}}{3}\rho + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G_\mathrm{N}}{3}\rho + \frac{\Lambda}{3}$$

$\Rightarrow$ For $\Lambda > 4\pi G_\mathrm{N}\rho \Rightarrow$ Endless Acceleration stopped by PBH evaporation!

Matter Power Spectrum

$$a \propto e^{t/L} \Rightarrow \epsilon_1 \equiv -\dot{H}/H^2 \ll 1 \text{ and } \epsilon_2 \equiv \frac{1}{\epsilon_1}\frac{\mathrm{d}\epsilon_1}{\mathrm{d}N} \ll 1 \Rightarrow n_\mathrm{s} = 1 - 2\epsilon_1 - \epsilon_2 \simeq 1$$

↓

Nearly scale invariant power-spectrum

- Structure Formation: **eMD eras**, such the ones driven by PBHs, **facilitate the growth of early structures.** This is expected from the fact that subhorizon energy density fluctuations during an eMD era grow linearly with the scale factor, i.e. $\frac{\delta\rho}{\rho} \propto a$, leading potentially to the **formation of halos or virialised objects** [Eggemeier et al. - 2021, Hidalgo et al. - 2022, Domenech et al. - 2023].

- **GWs from PBH isocurvature** [Papanikolaou et al. - 2020, Domenech et al. - 2020], **GWs from Hawking radiated gravitons** [Dong et al. - 2020, Ireland et al. - 2022], **GWs from the collapse of early structures** [Dalianis et al. - 2021, Fernandez et al. - 2023]