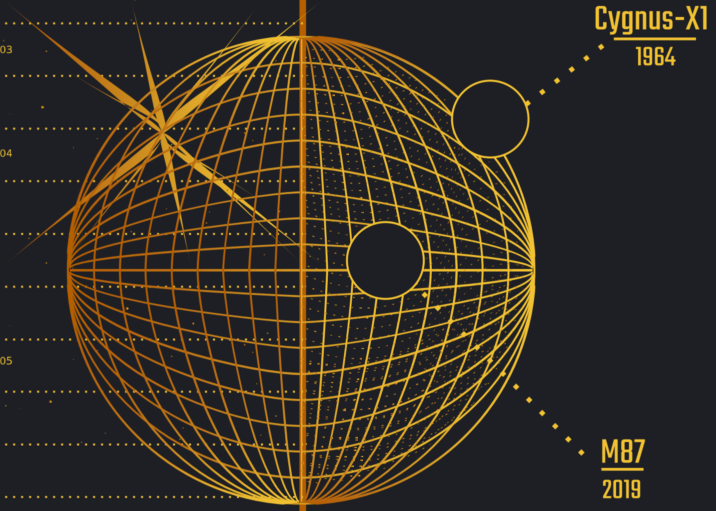
Ciências ULisboa

Primordial Black Holes



Primordial Universe

Teacher: António Silva

Daniela Cordeiro, 52853

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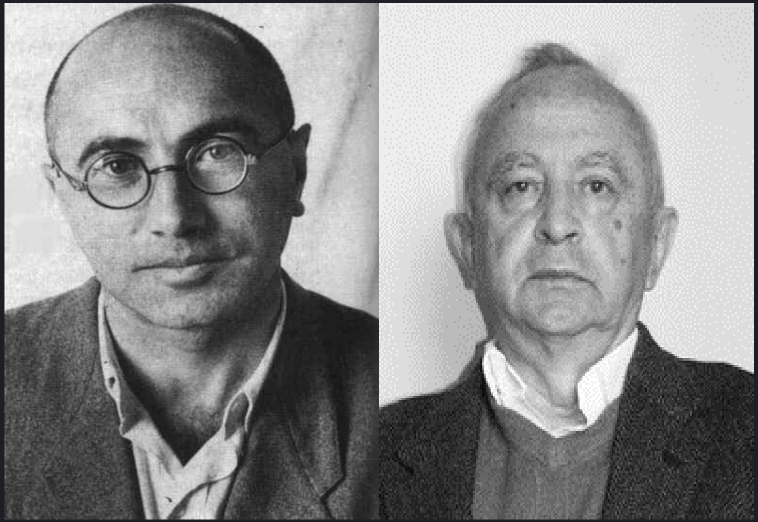
Introduction

- Gravity is so strong that nothing can escape, even **particles** and **radiation**
- Boundary of no escape - **E**vent **H**orizon
- Hawking radiation

Introduction

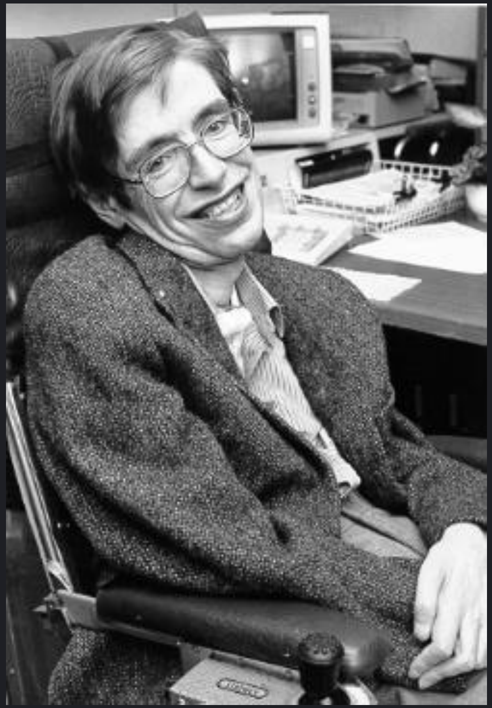
- ★ **P**rimordial **B**lack **H**oles (PBH) – hypothetical black holes formed soon after the Big Bang
- ★ Zeldovich and Novikov – 1966



Yakov Zeldovich on the left and Igor Novikov on the right [Credit: Google Images].

Introduction

- **P**rimordial **B**lack **H**oles (PBH) – hypothetical black holes formed soon after the Big Bang
- Zeldovich and Novikov – 1966
- Stephen Hawking – 1971



Stephen Hawking [Credit: Google Images].

Primordial Black Holes

- ★ PBH mass at a time t after the big bang:

$$M \sim \frac{c^3 t}{G} \sim 10^{15} \left(\frac{t}{10^{-23}}\right) g$$

- ★ Planck time (10^{-43} s) → Planck mass (10^{-5} g)
- ★ Formed at $t = 1\,\mathrm{s}$ → 10^5 $M_\odot$
- ★ At the present time → BH with mass < 1 $M_\odot$ is not possible.

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01.

PBH Formation

Overview of PBH formation scenarios

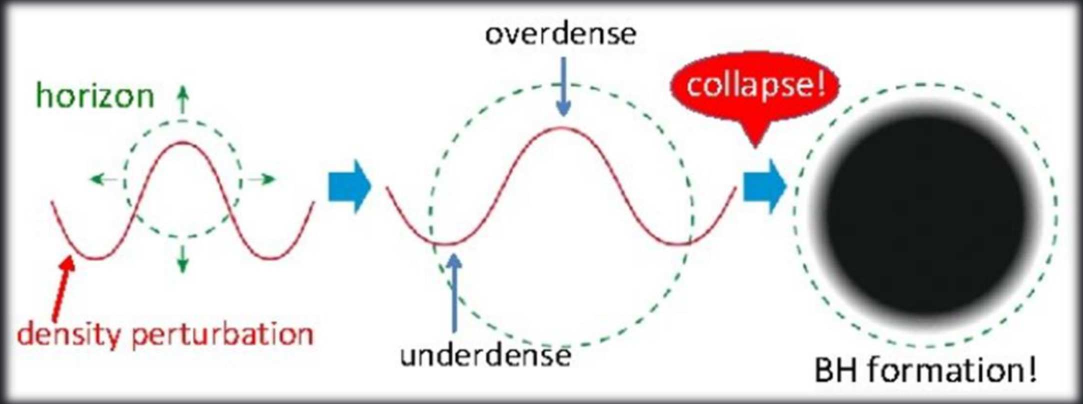
PBH Formation

1. Collapse from inhomogeneities during radiation dominated era
2. Collapse from inhomogeneities during matter dominated era
3. Collapse at QCD phase transition
4. Critical Collapse
5. Collapse from bubble collisions

Collapse from inhomogeneities during radiation dominated era

- ★ Density Fluctuations
- ★ > Jeans length

- ★ $p = w\rho c^2 \rightarrow \sqrt{w}ct$
- ★ $\delta_c \approx w \rightarrow e^{-(\delta_c\sqrt{2}\sigma)^2}$

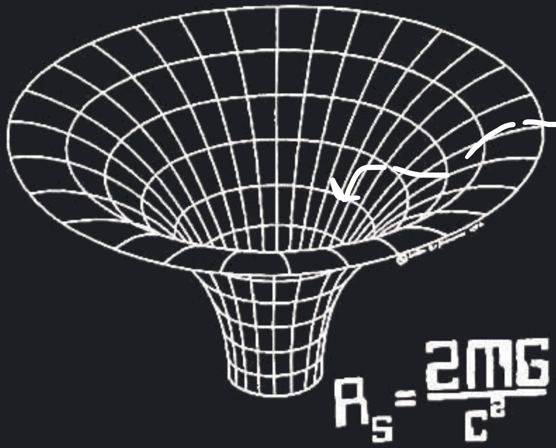


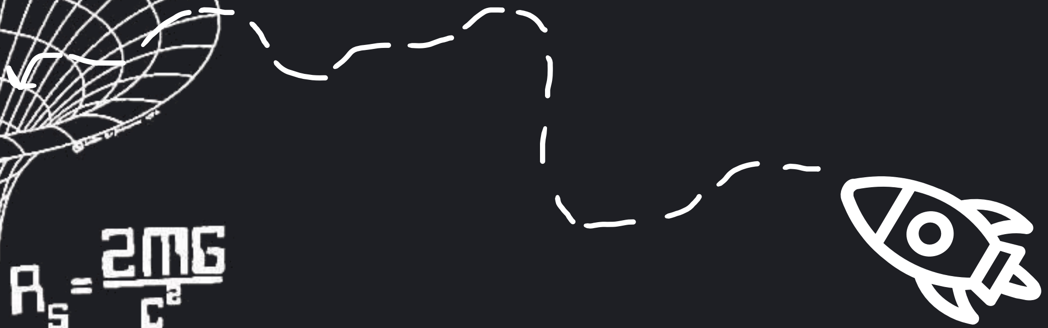
Scheme showing the formation of a black hole via density perturbations [1].

Collapse from inhomogeneities during matter dominated era

- ★ Reduction of Pressure
- ★ Slow reheating

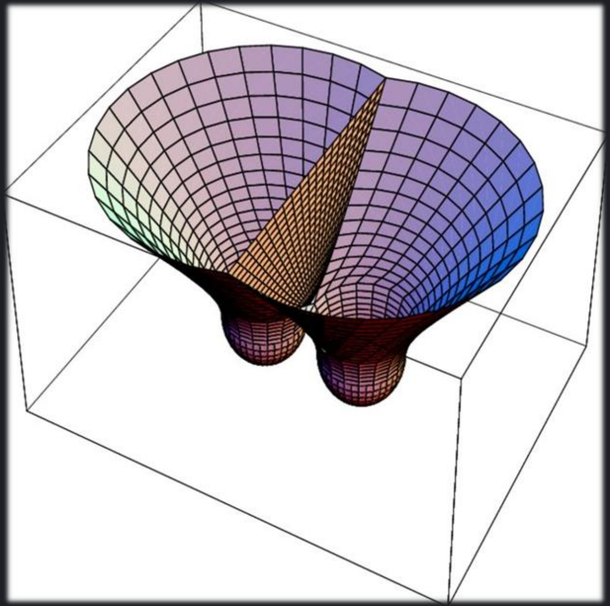
- ★ $0.2\,\sigma^{13/2}\ \left(e^{-(\delta_c\sqrt{2}\sigma)^2}\right)$
- ★ If $\sigma < 0.05$ → Matter PBH > Radiation PBH





Collapse from bubble colisions

- ★ Bubble formation rate per Hubble volume needs to be finely tuned
- ★ Bubble formation < Hubble rate
- ★ Bubble formation > Hubble rate
- ★ Order of the horizon mass



Bubble collision geometry [2].

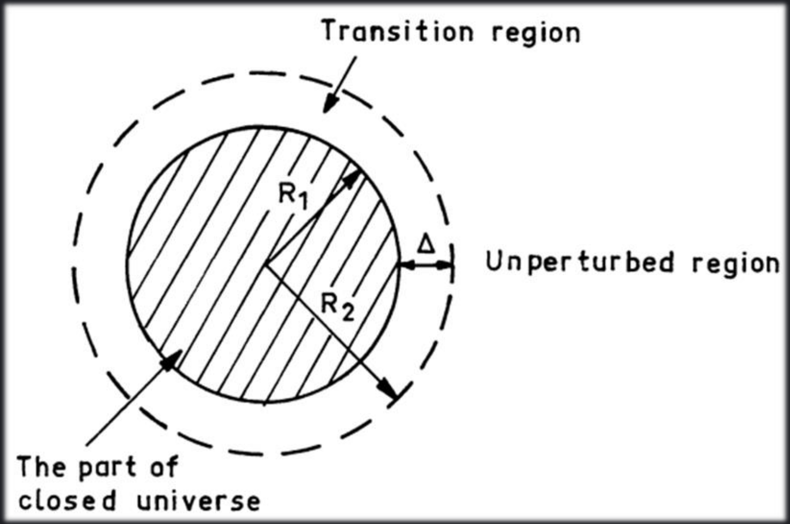
02.

Friedmann Metric

Deviations from the Friedmann Metric

Friedmann Metric

~~Flat spacetime~~ → Friedmann model



Spherical perturbation with radius R_1 , transition region Δ and ãn unperturbed region that starts at the radius R_2 [3].

Friedmann Metric

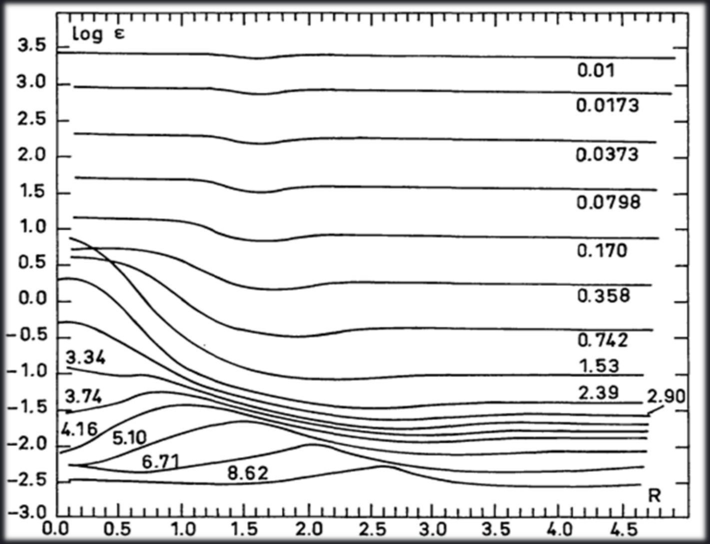
- ⋆ Considering the EoS $\boldsymbol{p = \varepsilon/3}$
- ⋆ **Unperturbed** metric:

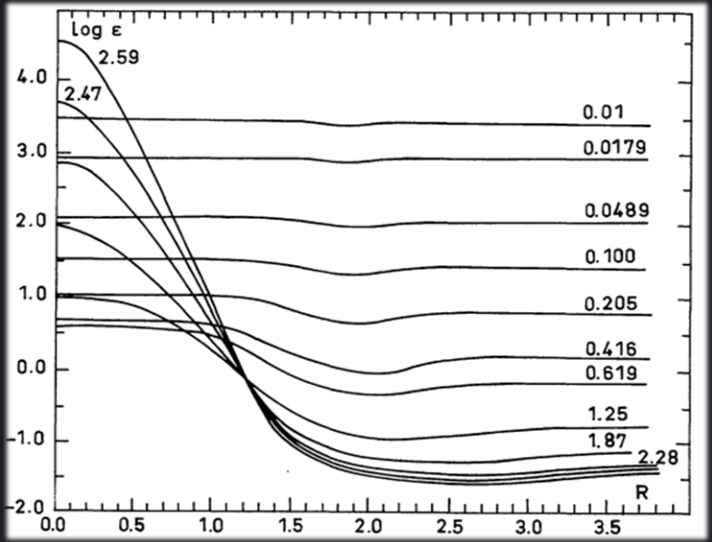
$$ds^2 = c^2\, dt^2 - a^2(t)\left[dR^2 + \boldsymbol{R^2}\,(d\theta^2 + sin^2\theta\, d\phi^2)\right]$$

- ⋆ **Perturbed** metric

$$ds^2 = c^2\, dt^2 - a^2(t)\left[dR^2 + \boldsymbol{sin^2 R}(d\theta^2 + sin^2\theta\, d\phi^2)\right]$$

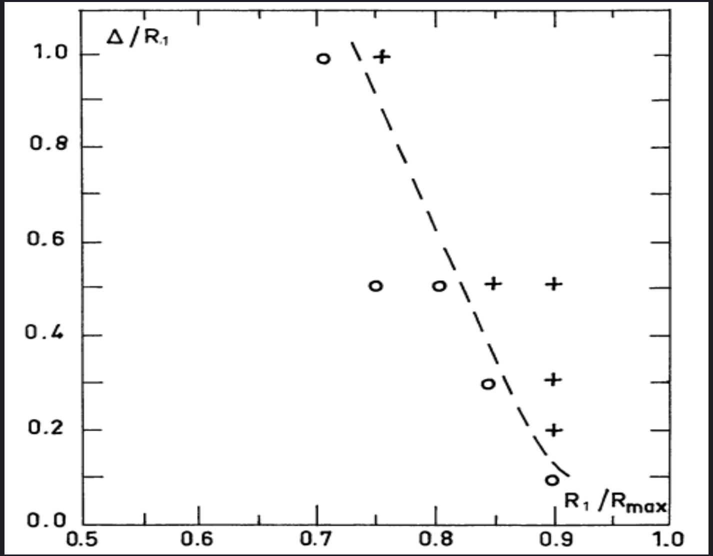
Friedmann Metric





Development of the density perturbation with time. **Left** shows the case where $R_1 = 0.75\, R_{max}$, $\Delta = 0.5 R_1$. Here the PBH doesn't form and the density perturbation transmutes into an acoustic wave. **Right** shows the case where a PBH forms for the **same** Δ **and** $R_1 = 0.9\, R_{max}$ [3]. ***Note:*** $R_{max} = \pi/2$

Friedmann Metric



Dependence of the PBH formation on R_1 and Δ . **Crosses** – formation of PBH. **Circles** – PBH doesn’t form [3].

Accretion Rate

- ★ PBHs grow at the same rate as the Universe in the radiation era → 10^{15} – 10^{17} $M_\odot$
- ★ $p \ll \varepsilon\,(p = 0)$ → PBH won't grow much by accretion
- ★ $p = \varepsilon/3$ → radiation pressure would drive matter into the holes

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Accretion Rate

★ Energy momentum tensor for a perfect fluid and the Einstein equation:

$$T_{\mu\nu} = (\varepsilon + p)u_\mu u_\nu - p g_{\mu\nu} \; ; \qquad R^{\mu\nu} - \frac{1}{2} R g^{\mu\nu} = 8\pi T^{\mu\nu}$$

★ $E(r)$ – total energy per unit mass of the shell, for $\boldsymbol{p = 0}$:

$$E(r) = \frac{1}{2} z^4 \left(\frac{\partial S}{\partial z}\right)^2 - \frac{1}{S}, \text{ where } S(z) = \frac{R}{r} \text{ and } z = \frac{r}{t}$$

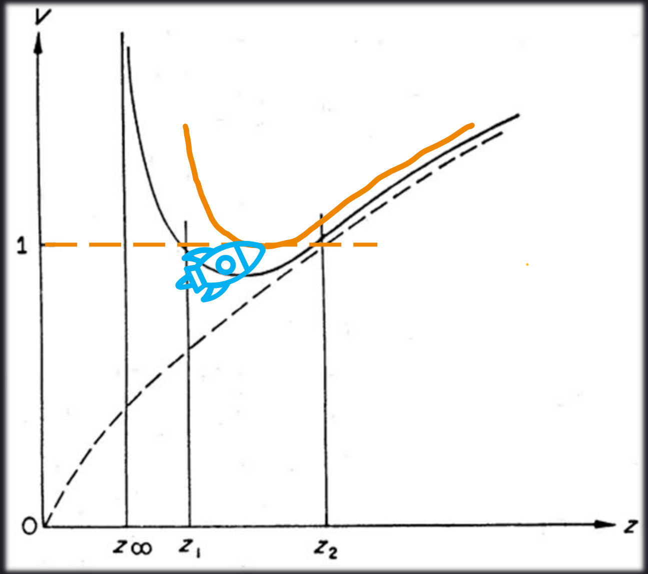
Accretion Rate

$$E(r) = \frac{1}{2} z^4 \left(\frac{\partial S}{\partial z}\right)^2 - \frac{1}{S}, \text{ where } S(z) = \frac{R}{r} \text{ and } z = \frac{r}{t}$$

- ★ $\boldsymbol{D = E = 0}$ → Friedmann Solution
- ★ $\boldsymbol{D = 0,\ E > 0}$ → shell expands indefinitely
- ★ $\boldsymbol{D = 0,\ E < 0}$ → shell reaches a maximum radius ending up collapsing

Accretion Rate

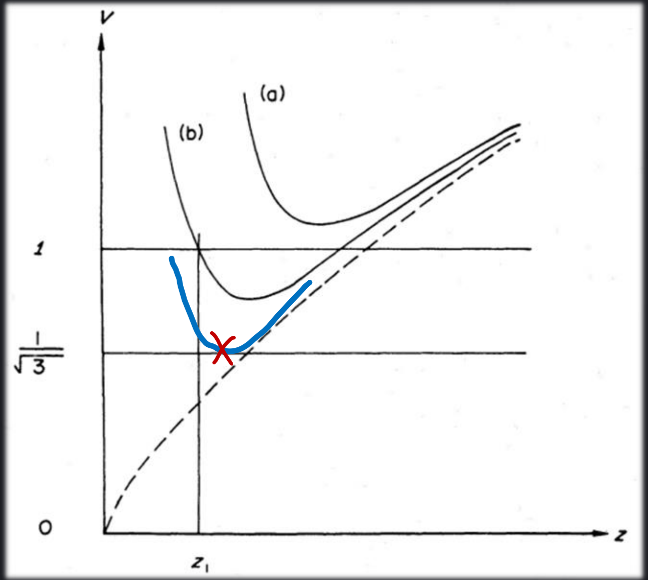
- ★ V → velocity, relative to the flow lines of the matter
- ★ $z_1 < z < z_2$ → time-like
- ★ $z > z_1$ → rocket can escape
- ★ $E = E_0$ → particle and event horizons coincide



Graph of $V(z)$ for $\boldsymbol{p = 0}$ with the particle (z_2) and event horizons (z_1). The dotted curve indicate the Friedmann values [4].

Accretion Rate

- ★ Case for $p = \varepsilon/3$
- ★ Curve **(a)** → the whole Universe is inside the black hole
- ★ Curve **(b)** → black hole expanding at the same rate as the Universe
- ★ E depends now on k



Graph of $V(z)$ for $p = \varepsilon/3$ in (a) no particle or event horizons are formed but in (b) the particle and event horizons exist [4].

Accretion Rate

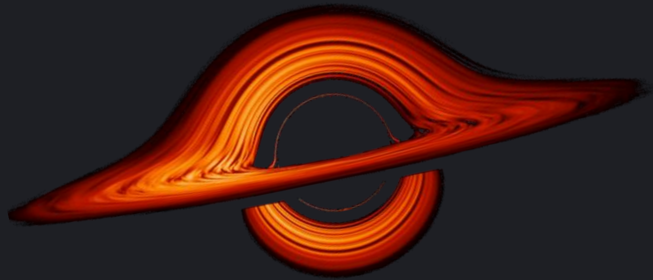
- Is the pressure gradient enough to cause an accretion rate that would make the black hole grow at the same rate as the particle horizon? **NO**
- Asymptotic but not exactly Friedmann solutions
- Pressure gradients are directed outwards hindering the accretion rate rather than helping

Collapse Fraction

- **Goal:** Achieve an expression for the fraction of the Universe collapsing into PBHs at their formation time, $\beta(M)$
- **Assumptions:** ΔM no larger than M and adiabatic cosmic expansion → $\frac{n_{PBH}}{s} = \text{Conserved}$
- $$\beta(M) = \frac{\rho_{PBH}(t_i)}{\rho(t_i)} = \frac{4M}{3T_i}\frac{n_{PBH}(t)}{s(t)}$$

$$\rho_{PBH}(t_i) = M n_{PBH}(t)$$

$$\rho = 3sT/4$$



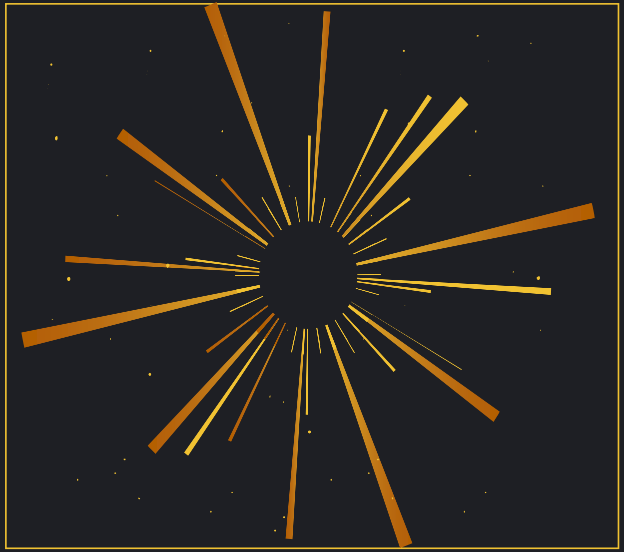
Collapse Fraction

- Natural Units, $H_0 \equiv 100h\,\mathrm{km s^{-1}} Mpc^{-1}$, $h = 0.67$, $t_0 = 13.8\,Gyr$ and $s = 8.54 \times 10^{85} Gpc^{-3}$

$$M = \gamma M_H \approx 2.03 \times 10^5 \gamma \left(\frac{t}{1\,s}\right) M_\odot$$

$$\beta(M) \propto \gamma^{-1/2} h^2 g_{*i}^{1/4} M^{1/2} \Omega_{PBH}(M), \text{ where } \Omega_{PBH} \equiv \frac{\rho_{PBH}(t_0)}{\rho_{crit}}$$

$$\beta'(M) \propto \gamma^{1/2} h^{-2} g_{*i}^{-1/4} \beta(M)$$



03.

Evaporation

Hawking radiation and evaporation

Evaporation

- ★ Hawking discovered that black holes emit thermal radiation with a temperature of:

$$T_{BH} = \frac{\hbar c^3}{8\pi G M k_B} \sim 10^{-7} \left(\frac{M}{M_\odot}\right)^{-1} \mathrm{K}$$

- ★ A PBH evaporates completly at a timescale of:

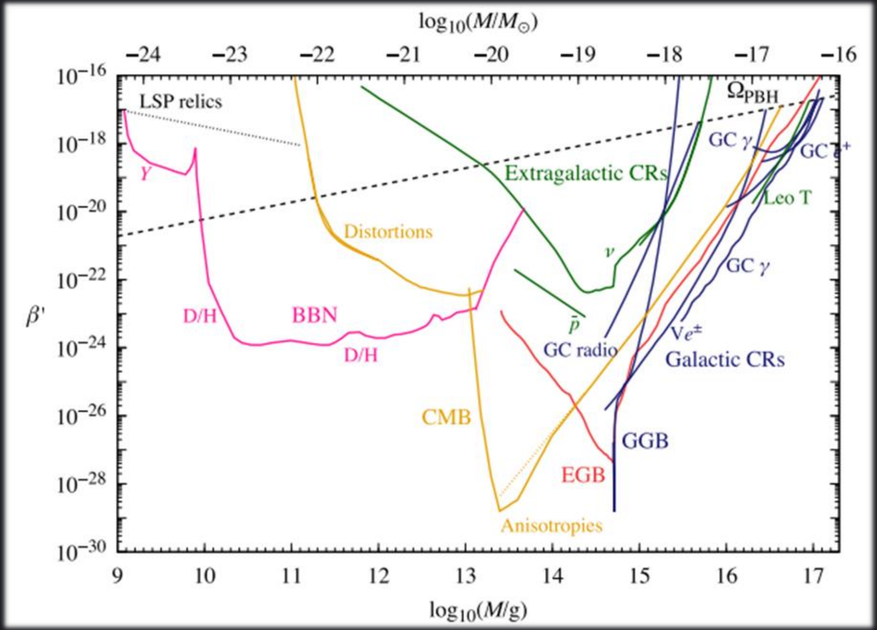
$$\tau(M) \sim \frac{G^2 M^3}{\hbar c^4} \sim 10^{64} \left(\frac{M}{M_\odot}\right)^3 \mathrm{yr} \longrightarrow M_* \approx 5.1 \times 10^{14}\ g$$

04.

Constraints

Constraints on evaporated PBH

Evaporation Constraints



All evaporation constraints. The dashed line is the only constraint for no Hawking radiation [5].

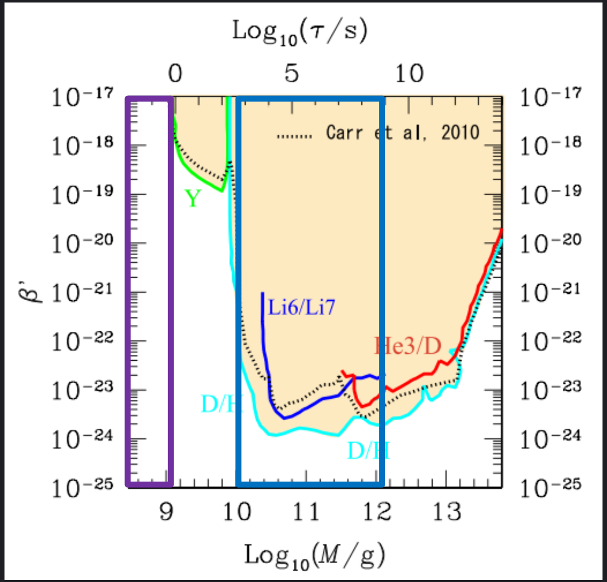
BBN Constraint

High energy particles emitted by PBHs provide a useful input to the BBN epoch:

1. High energy mesons and antinucleons → extra interconversion between p and n
2. High energy hadrons dissociate light elements synthesized in BBN
3. High energy photons increase the abundance of lighter elements even more

BBN Constraint

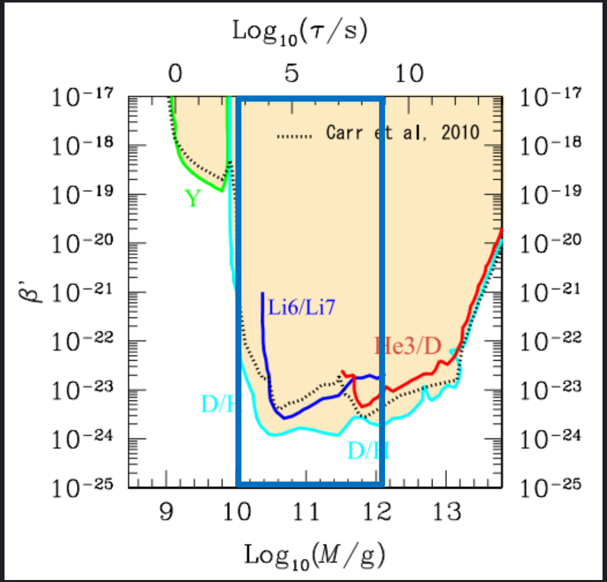
- ★ $\tau < 10^{-2}$ s → black holes evaporate before having no constraints from BBN
- ★ $\tau \approx 10^{2} - 10^{7}$ s → hadron-dissociation becomes important increasing the production of D and ^{6}Li



Upper bounds on β ' (M) at 95% CL required for success of BBN model.[5].

BBN Constraint – Lithium-7 Problem

- ★ PBH evaporation provide injections of neutrons and soft γ-rays (10^{12} g) → destroy ^{4}Be and avoids overproduction of ^{7}Li



Upper bounds on β ' (M) at 95% CL required for success of BBN model.[5].

CONCLUSION

"The quest to understand the world is what defines us as human beings"

—Yuri Milner

References

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2. Cosmological Perturbations Generated in the Colliding Bubble Braneworld Universe - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Bubble-Collision-Geometry-This-figure-shows-a-2-1-dimensional-spacetime-diagram_fig1_2051739 [accessed 9 Feb, 2022]You can delete this slide when you're done editing the presentation.
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