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Ciências ULisboa

PBHs as Dark Matter Candidates

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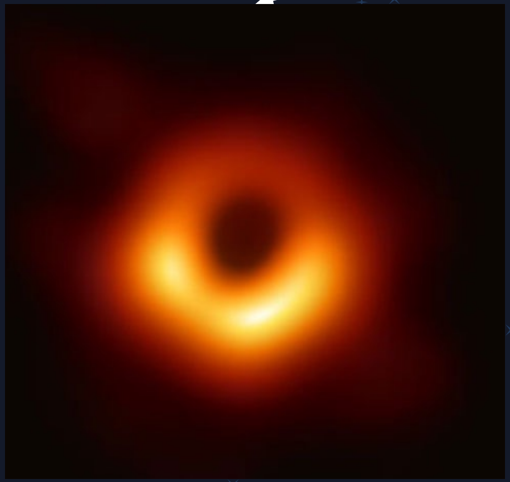
Primordial Universe

Introduction

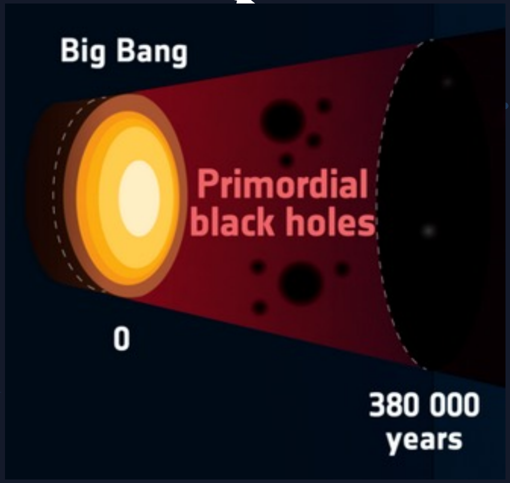
- Dark matter (DM) constitutes a large majority of all matter in the Universe.
- Most accepted DM model is the non-baryonic, cold dark matter (CDM).
- One interesting CDM candidate is **primordial black holes** (PBHs).

Types of Black Holes



Stellar Black Holes

Formed by stellar gravitational collapse. Lower mass limit of ~3 M☉ .



Primordial Black Holes

Formed by collapse of density fluctuations. Allows for a wide mass spectrum.

01

PBH Formation

PBH Formation

The primordial Universe would have been nearly uniform, apart from microscopic density fluctuations.

Density contrast

$$\delta = \frac{\delta\rho}{\rho_u}$$

$$\ddot{\delta} + 2H\dot{\delta} + \left(c_s{}^2k^2 - \frac{3H^2}{2}\right)\delta = 0$$

Jeans length

$$L_J = \sqrt{\frac{3H^2}{2c_s{}^2}}$$

For lengths higher than L_J, the fluctuation can undergo gravitational collapse. In the radiation domination epoch, $\delta_c \approx 1/3$. Numerical results show that $\delta_c \approx 0.45$.

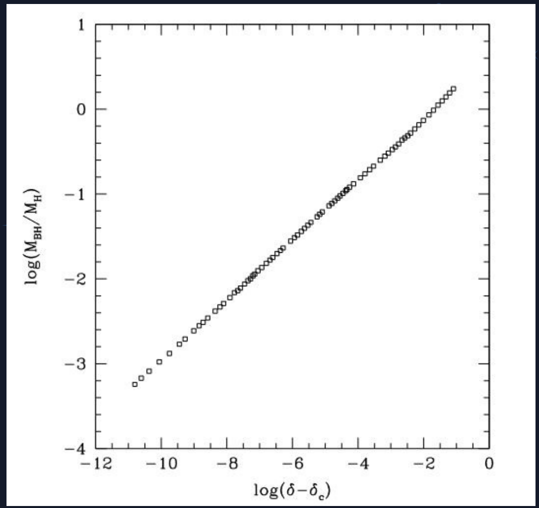
PBH Formation

PBH Mass $M_{PBH} \sim M_H(t) = \frac{4\pi\rho}{3H^2} \sim 10^{15} \left(\frac{t}{10^{-23} s}\right) g$

- A wide range of M_{PBH} can be formed.
- PBH with $M_{PBH} = 1M_{\odot}$ would have originated in the QCD phase transition.
- Near critical gravitational collapse (for $\delta \rightarrow \delta_c$)…

$$M_{PBH} = \kappa M_H (\delta - \delta_c)^{\gamma}$$

$\gamma \approx 0.35 – 0.36$



02

PBH Abundance

PBH Abundance

For calculations of the PBH abundance, it is assumed that $M_{PBH} = \alpha M_H$.

$$\beta(M_{PBH}) = \alpha \int_{\delta_c}^{1} P(\delta) d\delta \Longrightarrow = \alpha \int_{\delta_c}^{1} \frac{d\delta}{\sqrt{2\pi}\sigma(M_{PBH})} exp\left[\frac{-\delta^2}{2\sigma(M_{PBH})}\right]$$

Perturbations have gaussian distribution and are spherically symmetric.

For a scale-invariant power spectrum, $\sigma(M_{PBH}) \sim 10^{-5}$ at the CMB scale, leading to a low PBH abundance.

The beta parameter may also be expressed as a direct function of the PBH mass.

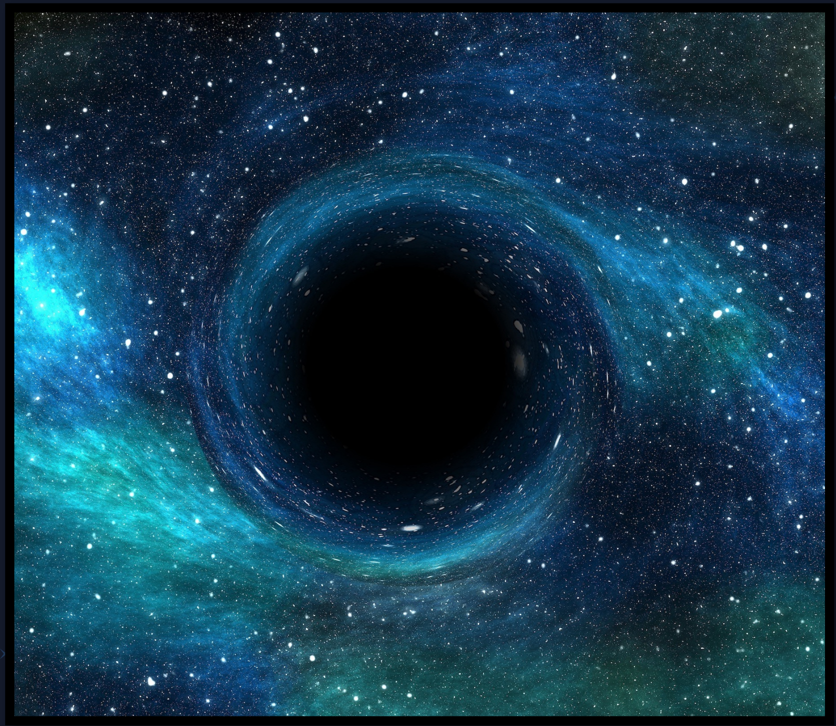
$$\beta(M_{PBH}) = \frac{\rho_{PBH}(t_i)}{\rho(t_i)} \approx 7.99 \text{ x } 10^{-29} \alpha^{-1/2} \left(\frac{g_{*i}}{106.75}\right)^{1/4} \left(\frac{M}{M_{\odot}}\right)^{3/2} \left(\frac{n_{PBH}(t_i)}{1\ Gpc^{-3}}\right)$$

PBH Abundance

PBH Density Parameter $\boxed{\Omega_{PBH} = \beta\Omega_R(1+z)}$ $\approx 10^{18}\beta\left(\frac{M_{PBH}}{10^{15}\ g}\right)^{-1/2}$

(radiation dominated epoch)

- The PBH density parameter will remain constant in the matter-dominated era.
- $\Omega_{PBH} < 1$ means that $M_{PBH}^{min} = 10^{15}\ g$.



03

PBHs as Dark Matter

Cold

CDM particles are non-relativistic.

Non-baryonic

Did not contribute to formation of elements in early Universe, not made of baryons.

MACHOs

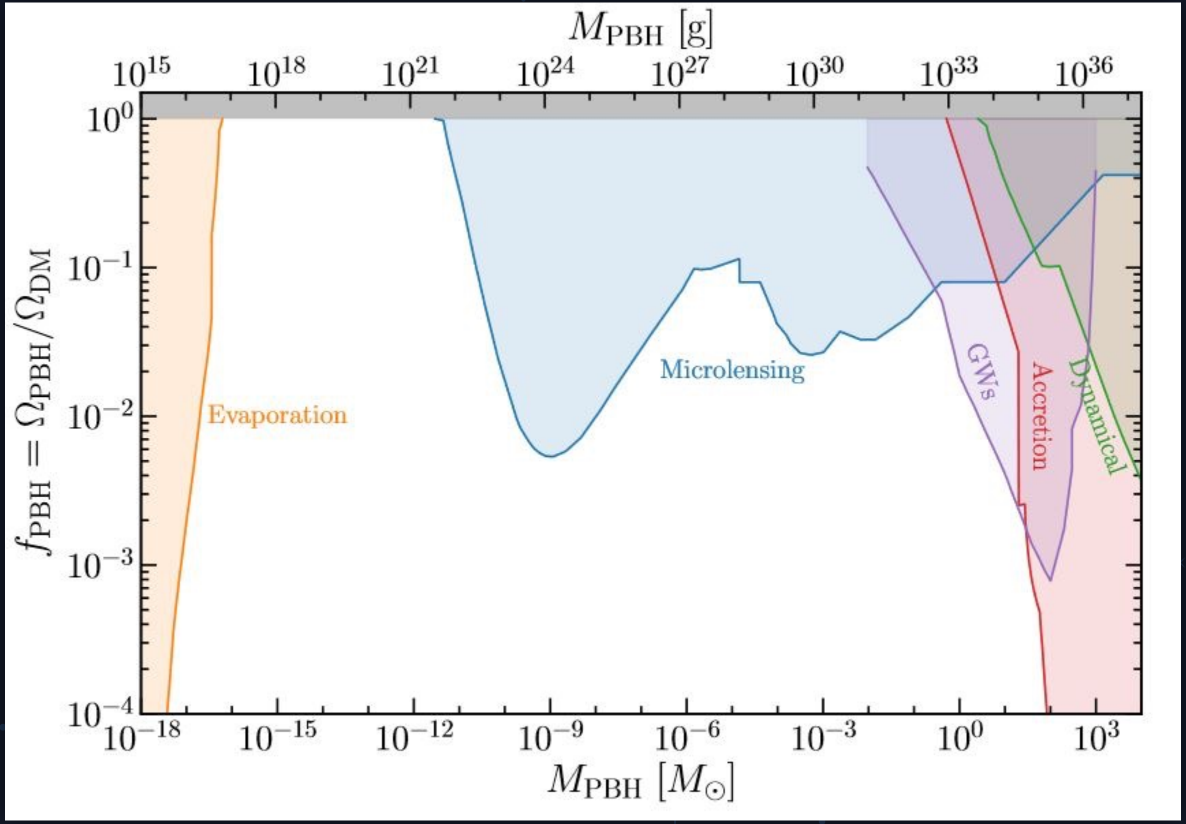
Massive compact halo objects. Can be found by lensing effects.

Fraction of PBHs in Halo

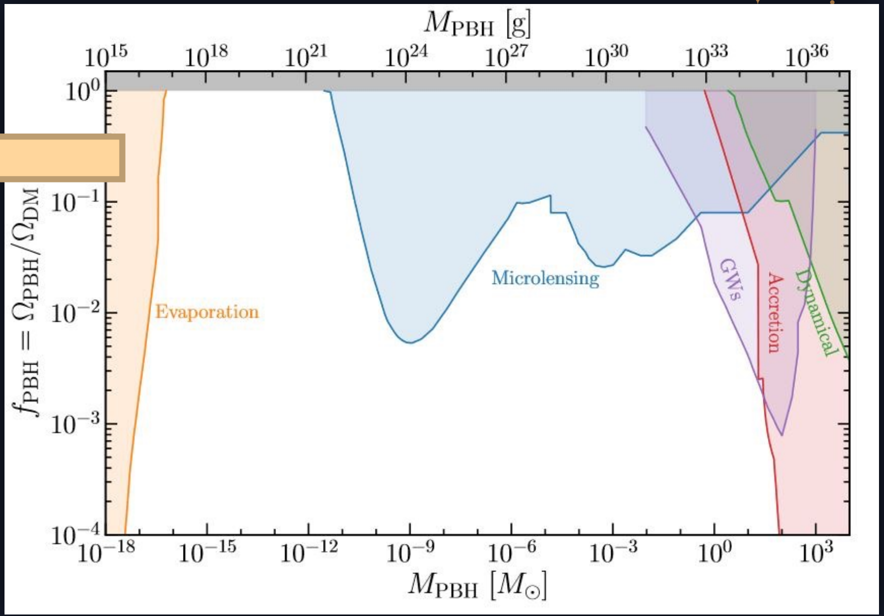
$$f(M_{PBH}) = \frac{\Omega_{PBH}}{\Omega_{CDM}} \approx 3.8\Omega_{PBH} = 3.8 \text{ x } 10^{8}\beta \left(\frac{M_{PBH}}{M_{\odot}}\right)^{-1/2}$$

- ❖ Necessary to determine PBH abundance constraints.

Observational Constraints



Evaporation



- PBHs emit Hawking radiation and lose mass in the process.

Timescale for evaporating BHs

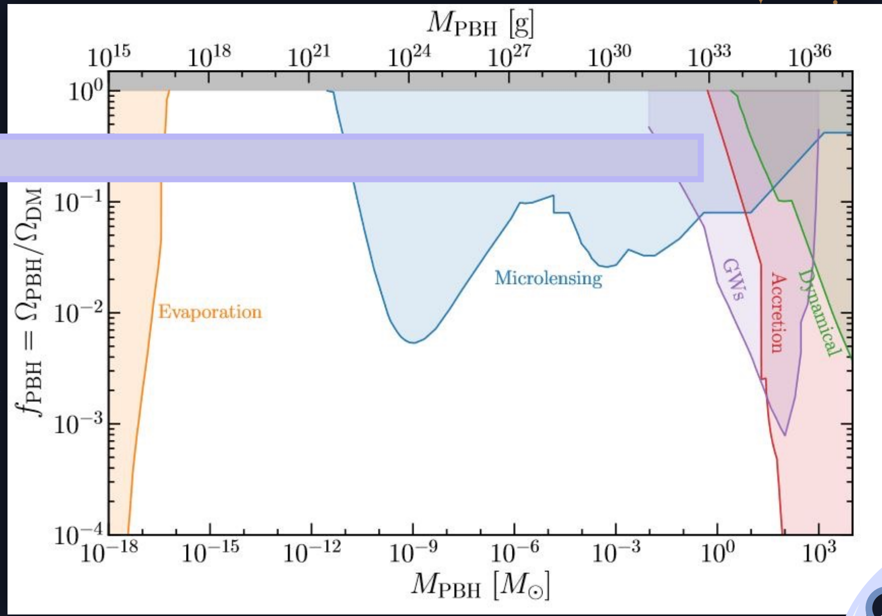
$$\tau(M_{PBH}) \approx 10^{64} \left(\frac{M_{PBH}}{M_\odot}\right)^3 \text{ yr}$$

→ PBHs with $M_{PBH} \leq 10^{15}$ g would have evaporated by today.

- PBHs evaporating are thought to emit observable backgrounds.
- Lack of background detection indicates $M_{PBH} \geq 10^{17} g$.

} $f(M_{PBH}) < 0.001$ for $M_{PBH} < 10^{16} g$

Gravitational Waves



- LIGO has observed merging of black holes at ~ $30\ M_\odot$.
- PBHs in binary systems could generate this gravitational waves background.

- Studies show agreement between PBH merger rates and LIGO analysis.
- PBH mass range determined by GWs background could be in conflict with other phenomena.

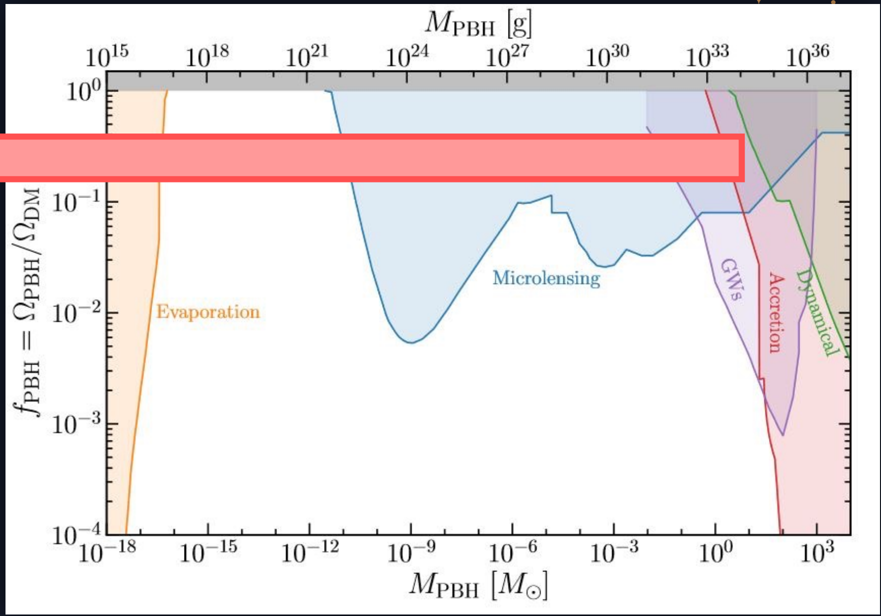
$f(M_{PBH}) < 0.01$ for $10 < M_{PBH} < 300\ M_\odot$

Accretion

- Particles emit measurable radiation before being engulfed by BHs, affecting the Universe thermal history.

Rate of accretion

$$\dot{M}_{PBH} \approx 10^{11} \left(\frac{M}{M_{\odot}}\right)^2 \left(\frac{n}{cm^{-2}}\right) \left(\frac{T}{10^4\ K}\right)^{-3/2} g s^{-1}$$



- The spherical limit may not apply.
- Results from WMAP and FIRAS collaboration are dependent on chosen model.

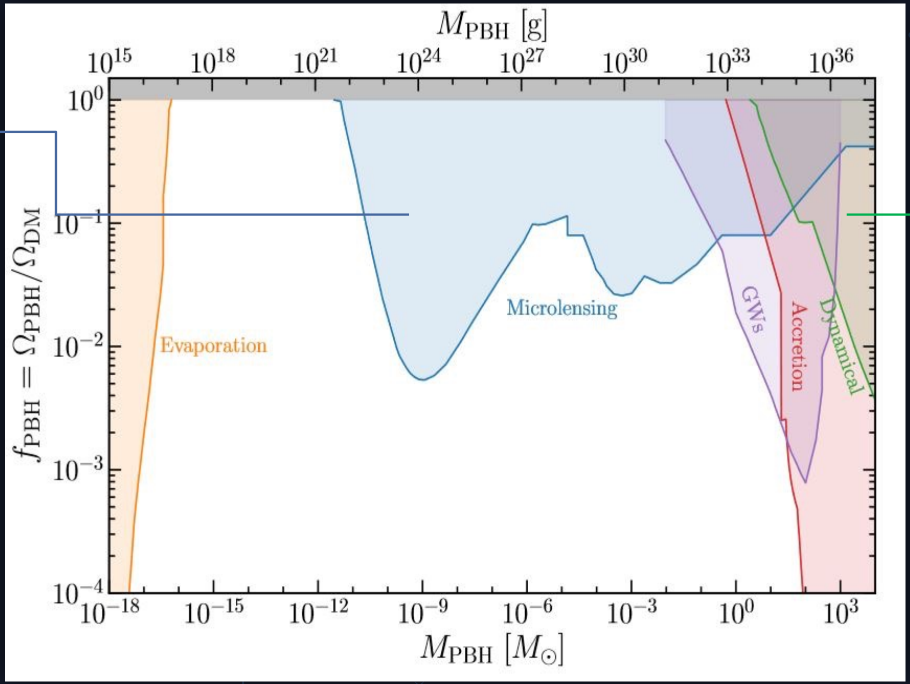
$$f(M_{PBH}) < 0.001 \text{ for } 10 < M_{PBH} < 300\ M_{\odot}$$

Additional Constraints

Lensing

The lensing effect can be used to detect the present of PBHs.

MACHO and EROS surveys have set $f(M_{PBH}) < 0.01 - 0.1$.



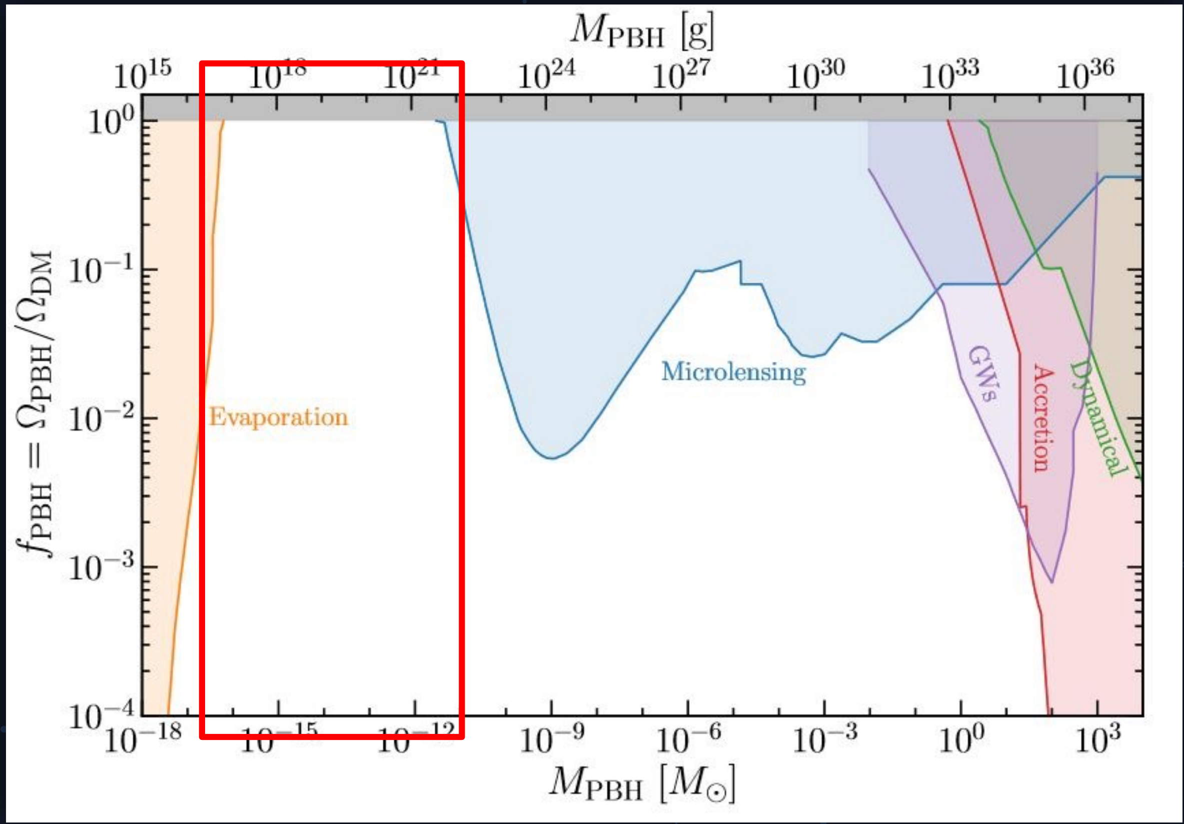
Dynamical

If PBHs exist, they could lead to changes in binaries spatial distribution, for example.

$f(M_{PBH}) \leq 1$ for $M_{PBH} = 3\ M_\odot$

$f(M_{PBH}) \leq 0.1$ for $M_{PBH} > 70\ M_\odot$

Observational Constraints



End.

Do you have any questions?

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