Hunting Primordial Black Hole dark matter in the Lyman-α Forest

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The Dark Matter enigma

- Various astrophysical and cosmological observations show that nearly 27 % of the total energy-density of the universe is in the form of 'Dark Matter.'

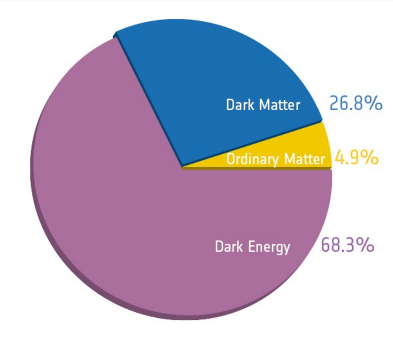


Image credit: Planck/ESA

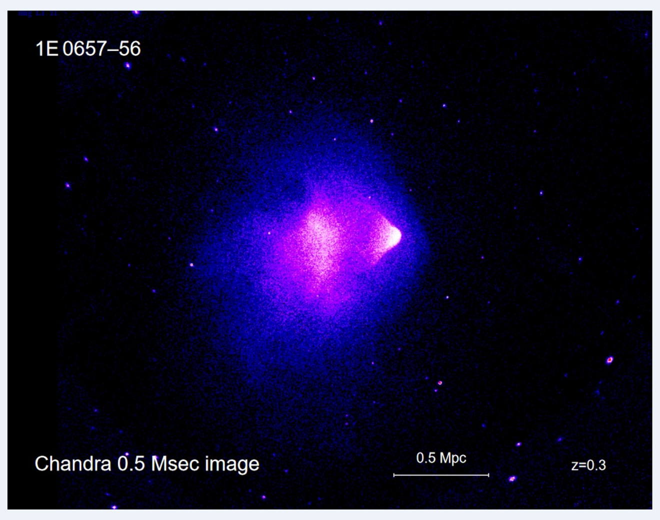


Image from Wikipedia

- We know that Dark Matter (DM) is non-relativistic today, hardly interacts through the three non-gravitational forces that we know of, and is cosmologically stable.
- We have no clue of what it's made of!

Primordial Black Holes

- Primordial Black Holes (PBHs) are hypothesized objects, that could have formed due to the collapse of very high overdensities in the early universe.
- Many mechanisms for their formation exist in literature.
- They can have all the properties required of a dark matter candidate. Hence, they may explain all/part of dark matter density in the universe today.

Hawking radiation from PBHs

- Since PBHs are just black holes after all, they should also give off Hawking radiation.
- The radiation is quasi-thermal in nature- a temperature is associated to each black hole depending upon its mass and spin. The expression for the temperature is given by,

$$T_{\rm PBH} = \frac{1}{4\pi G M_{\rm PBH}}\left(\frac{\sqrt{1-a_*^2}}{1+\sqrt{1-a_*^2}}\right)$$

where the spin parameter a_* is given by

$$a_* = \frac{J}{G M_{\rm PBH}^2}$$

- All particles with mass smaller than or comparable to the temperature of a black hole are emitted copiously.
- The exact spectrum of the radiation is blackbody-like, and for a given black hole is given by,

$$\frac{d^2 N_i}{dE dt} = \frac{1}{2\pi}\sum_{dof}\frac{\Gamma_i(E, M_{\rm PBH}, a_*, \mu)}{e^{E'/T} - (-1)^{2s}}$$

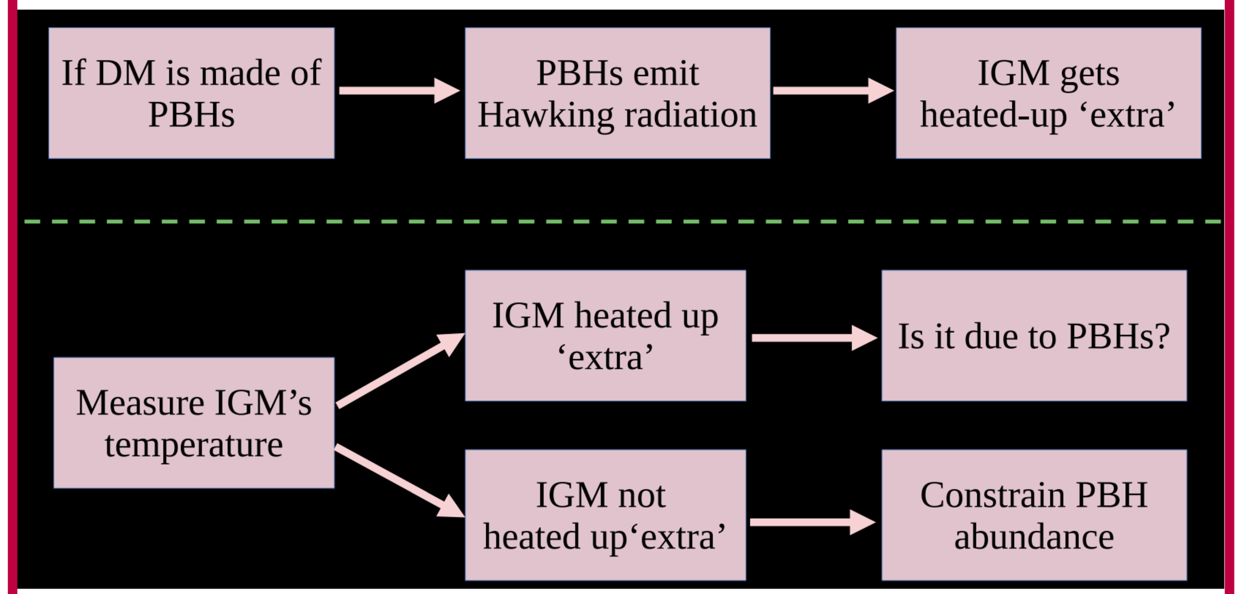
where E' and Ω are given by,

$$E' = E - m\Omega, \quad \Omega = \frac{a_*}{2M_{\rm PBH}(1+\sqrt{1-a_*^2})}$$

- The Γ_i are called 'Graybody factors' - they encode how much the spectrum of the Hawking radiation differs from a purely thermal spectrum because of the gravitational effects of the black hole.
- The Graybody factors have to be evaluated numerically, since they involve the scattering of the wavefunction of the particles in the gravitational potential of the black hole.
- We make use of the code `BlackHawk v2.0` to calculate the Graybody factors for the black holes with relevant masses and spins.
- We try to look for the heating of the intergalactic medium due to this Hawking radiation.
- All particles are emitted in the Hawking spectrum of black holes, but only photons and $e^{\pm}$ are of relevance to us. That is because, these particles dominate the heating of the intergalactic medium (IGM) gas.

The bare essentials

DM = Dark Matter
PBH = Primordial Black Hole
IGM = Intergalactic medium



For more information on PBHs and their Hawking evaporation, see the left column.

For more information on the IGM, its temperature evolution and how to measure it, see the right column.

If you want to jump to results directly, read on:

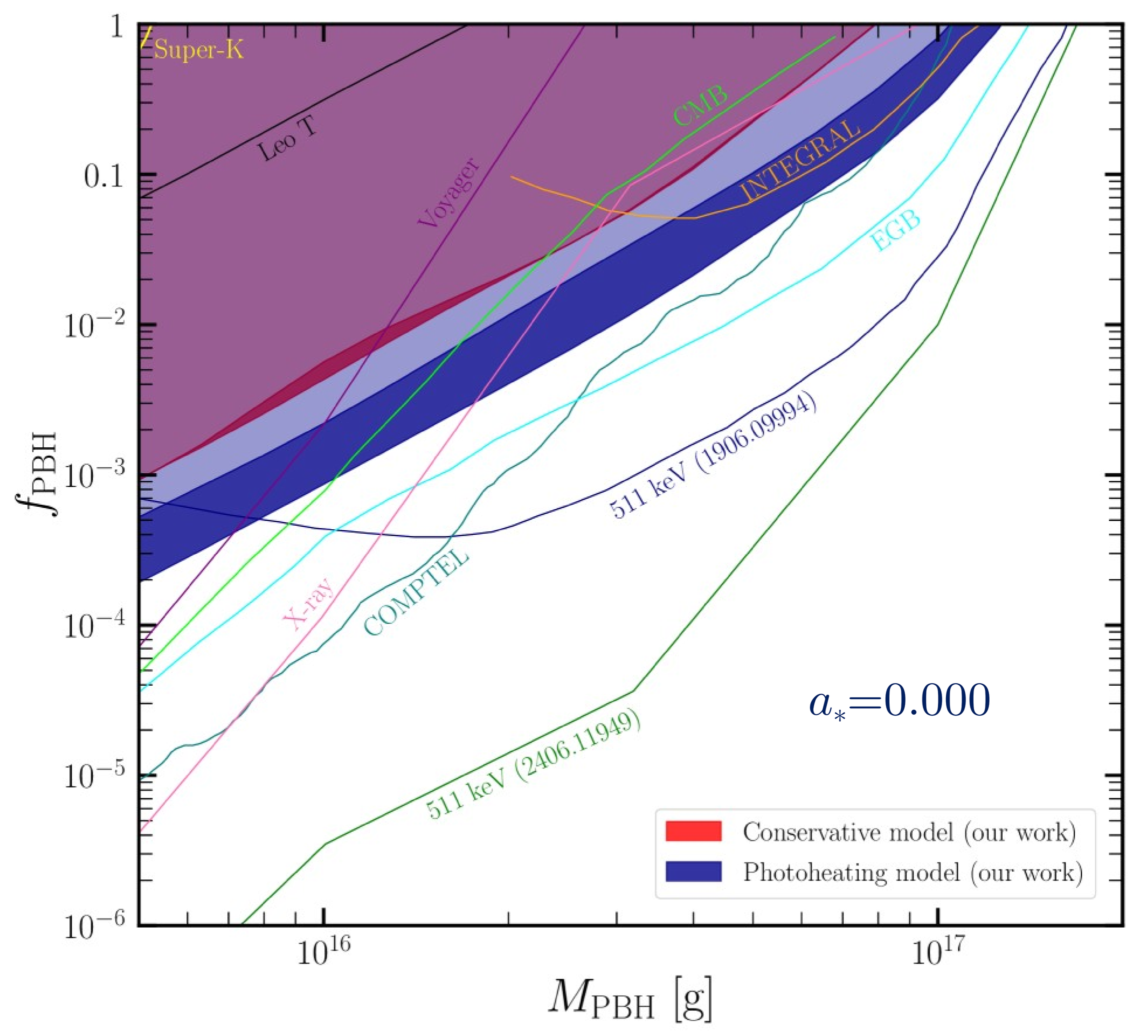
By observing Lyman-α absorption spectra of quasars, we find that IGM isn't heated up 'extra'. Hence PBHs' contribution to DM density is constrained.

The following figure depicts how much are PBHs of a given mass allowed to contribute to the DM density today, as a result of our analysis.

The $M_{\rm PBH}$ on the horizontal axis is the mass of the PBHs.

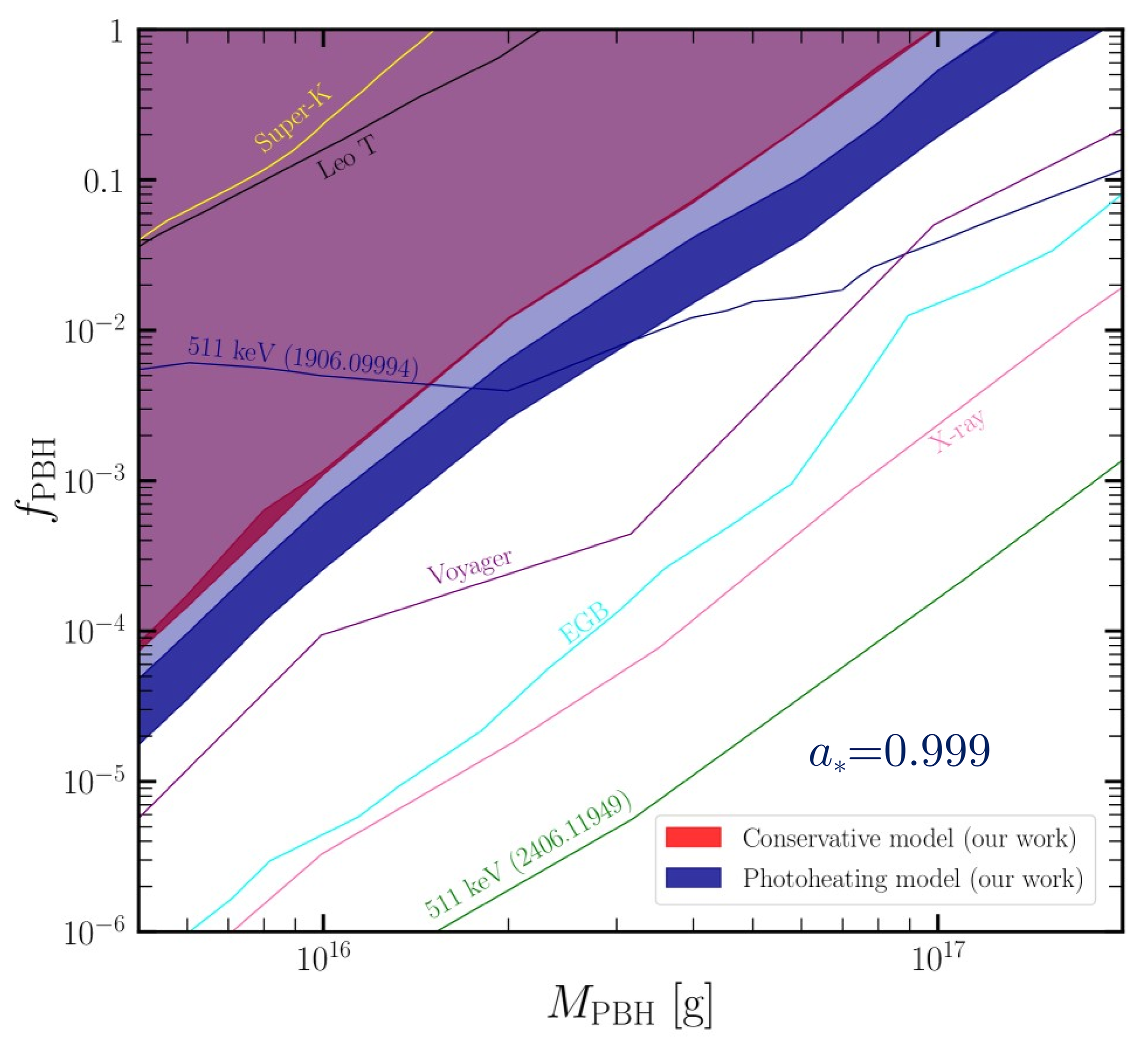
$f_{\rm PBH}$ on the vertical axis is the maximum fraction of the DM that could be made up of PBHs of mass $M_{\rm PBH}$.

Shaded region is forbidden.



Conservative model limits are very robust to the uncertainties in the reionization's details.

Photoheating model limits involve reionization modelling, hence dependent on the details of reionization.



The Intergalactic Medium (IGM) temperature evolution

- As the photons and $e^{\pm}$ from the Hawking radiation of the possible PBHs constituting the dark matter interact with the IGM, the latter gets heated up and ionized.
- This happens over cosmological timescales as various atomic and radiative processes go on.
- The heating and the ionization rates of the IGM gas depend on each other, thus we have to solve the following coupled differential equations:

$$\dot{T}_{\rm m} = \dot{T}_{\rm m}^{(0)} + \dot{T}_{\rm PBH}$$
$$\dot{x}_{\rm HII} = \dot{x}_{\rm HII}^{(0)} + \dot{x}_{\rm HII}^{\rm PBH}$$

Here, x is the ionization fraction of the gas, while T is the temperature.

- The first term in each equation represents the time-evolution of the quantity due to all the known astrophysical and cosmological reasons- the background evolution. The second term is the possible 'exotic' contribution due to Hawking radiation.
- The background evolution of both x and T is dictated by the following symbolic equations:

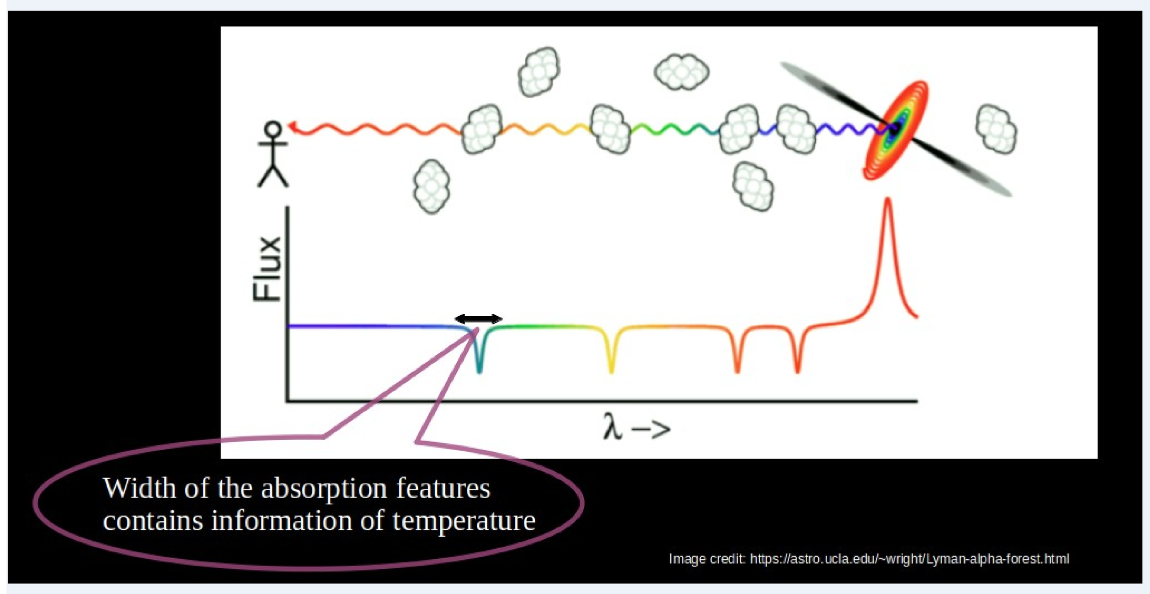
$$\dot{T}_{\rm m}^{(0)} = \dot{T}_{\rm adia} + \dot{T}_{\rm C} + \dot{T}_{\rm atom} + \dot{T}^{\star} \quad ; \quad \dot{x}_{\rm HII}^{(0)} = \dot{x}_{\rm HII}^{\rm atom} + \dot{x}_{\rm HII}^{\star}$$

(Total) (Universe expands) (Compton scattering) (Atomic processes) (Reionization) ; (Total) (Atomic processes) (Reionization)

- Switching off the reionization term gives conservative but robust constraints. Modelling this term gives us the reionization-dependent 'photoheating' constraints.
- We solve all these evolution equations by modifying the code `DarkHistory v2.0` such that it can handle evaporating black holes.

The Intergalactic Medium (IGM) temperature measurement

- Lyman-α transition between the n=2 and n=1 energy levels of the neutral hydrogen atoms in the IGM gives a handle on the temperature of the gas.
- This transition shows up in spectra of quasars whose light comes to as passing through the intervening IGM.
- Since the light from a quasar keeps redshifting, the wavelength of its original spectrum that can cause this transition keeps on shifting. Thus, we see a series of lines in the spectrum, known as the Lyman-α forest.
- By comparing the real Lyman-α spectra with mock ones generated in simulations, astrophysicists can measure $T(z)$, the temperature of the IGM at various redshifts.



The temperature measurements and an illustration of $T(z)$ in the presence of Hawking radiation