Hunting Primordial Black Hole Dark Matter in Lyman-α forest

https://arxiv.org/abs/2409.10617

Abhijeet Singh

Trends in Astro-particle and Particle Physics

IMSc, Chennai

26th September 2024

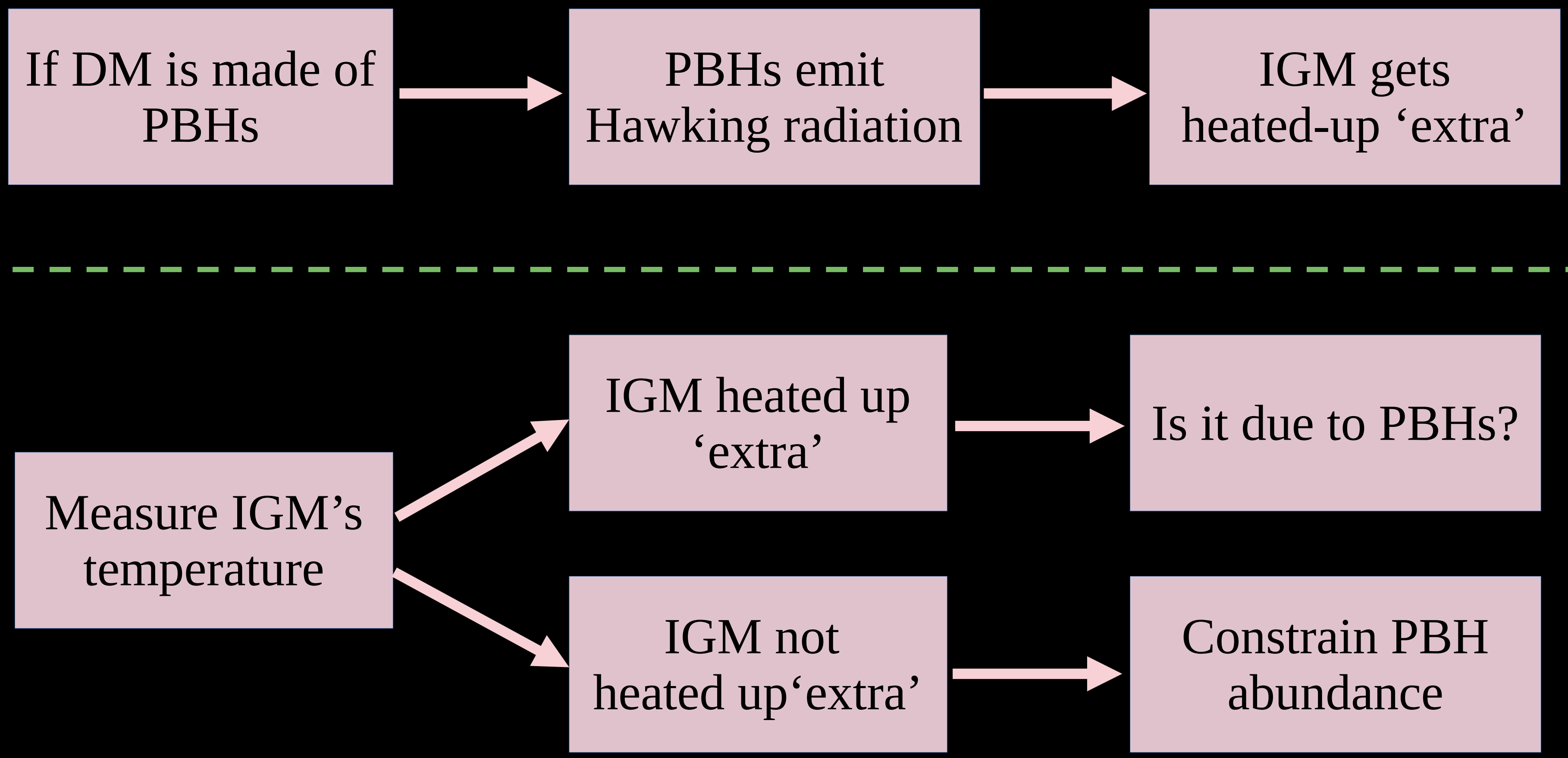
This work is done in collaboration with:

Dr. Ranjan Laha

Dr. Priyank Parashari

Akash Kumar Saha

The bird’s eye view



What is everything made of?

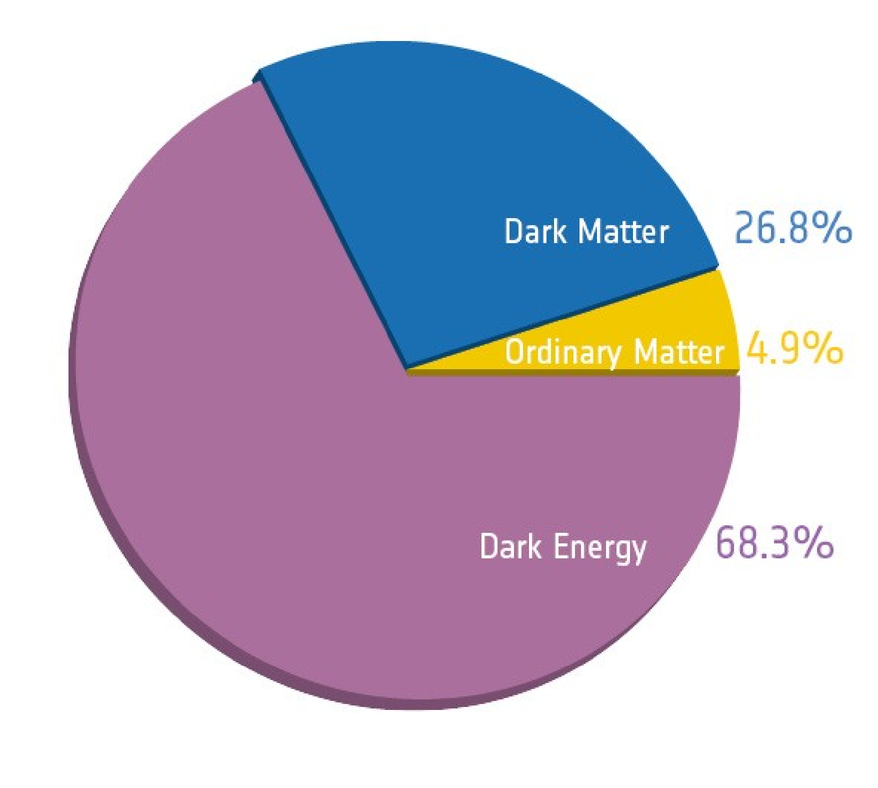


Image credit: Planck/ESA

Primordial Black Holes 101

- Black Holes formed in the early universe from the collapse of high matter-overdensities.

  - The same overdensities that form galaxies at larger scales, being not as high.

- Many mechanisms for their production exist in literature.

  - Including some that don't rely on the canonical overdensities produced by inflation.

- They can be formed having a wide range of masses.

- They can be formed with non-zero spins also.

Primordial Black Holes 102

- PBHs would be non-relativistically moving today.
- They would hardly interact with baryons except through gravitation.
- They can be stable over cosmological timescales.
- Do not contribute to the baryonic matter density.

Primordial Black Holes 102

- PBHs would be non-relativistically moving today.
- They would hardly interact with baryons except through gravitation.
- They can be stable over cosmological timescales.
- Do not contribute to the baryonic matter density.

Smells like Dark Matter?

Primordial Black Holes 102

- PBHs would be non-relativistically moving today.
- They would hardly interact with baryons except through gravitation.
- They can be stable over cosmological timescales.
- Do not contribute to the baryonic matter density.

Smells like Dark Matter?

- Can form in the right abundance to constitute dark matter completely/significantly!

Hawking tell us that Black Holes have temperature

$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

$$T \propto \frac{1}{M}$$

Hawking evaporation of Black Holes

BHs are near-blackbodies.

$\hbar = c = k_B = G = 1$

The spectrum of Hawking radiation by non-spinning black holes is given by:

$$\frac{d^2 N_{i,lm}}{dt dE} = \frac{1}{2\pi} \frac{\Gamma_{s_i lm}(E, M)}{e^{E/T} - (-1)^{2s_i}}$$

Graybody factors.

Encode deviation from blackbody spectrum.

Graybody factors have to be calculated numerically. We use the code `BlackHawk v2.0`.

The spectrum is different for spinning BHs, which is also computed using `BlackHawk v2.0`.

What Hawking radiation does to IGM's temperature

- Exotic energy injection changes temperature and ionization history of the IGM.
- Only the photons and electrons/positrons injected in the IGM are important to consider.
- Injected particles don't deposit energy instantaneously, but cool over cosmological timescales.

What Hawking radiation does to IGM's temperature

The following differential equations have to be solved simultaneously:

$$\dot{T} = \dot{T}^{(0)} + \dot{T}^{\rm inj} + \dot{T}^{\rm re}$$

$$\dot{x} = \dot{x}^{(0)} + \dot{x}^{\rm inj} + \dot{x}^{\rm re}$$

where T is Temperature, and x is the ionization fraction of hydrogen n_{HII}/n_H.

We solve these equations using the code `DarkHistory`.

Lyman-α Transition

$$\lambda = 1216\text{Å}$$
$$\nu = 2.5 \times 10^{15}\text{Hz}$$
$$E = 10.2\, eV$$

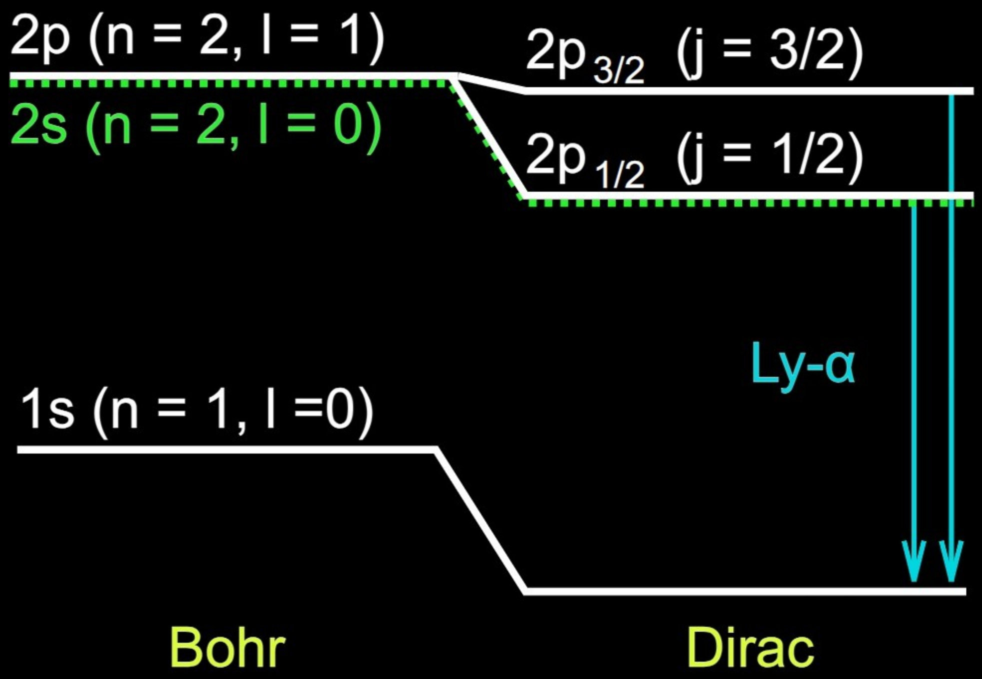
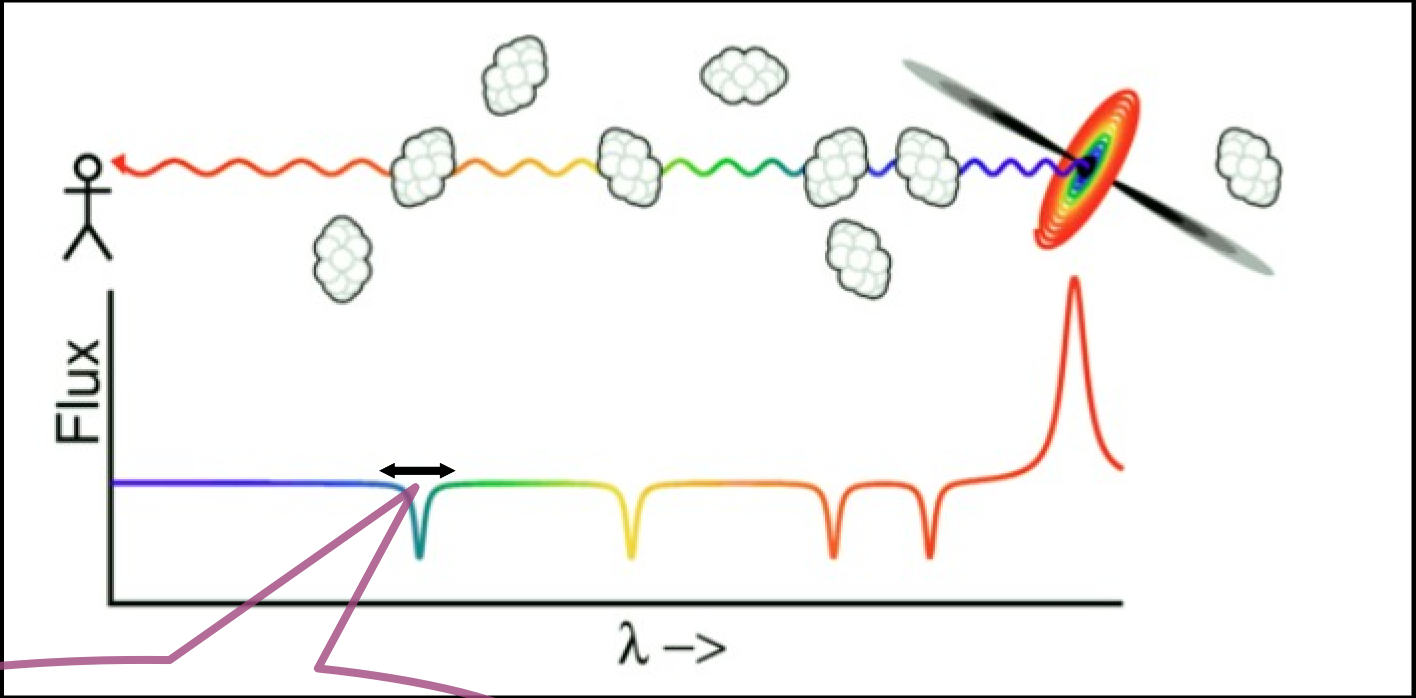


Image credit: Wikipedia
https://en.wikipedia.org/wiki/Lyman-alpha

Lyman-α Forest



Width of the absorption features contains information of temperature

Image credit: https://astro.ucla.edu/~wright/Lyman-alpha-forest.html

Lyman-α Forest

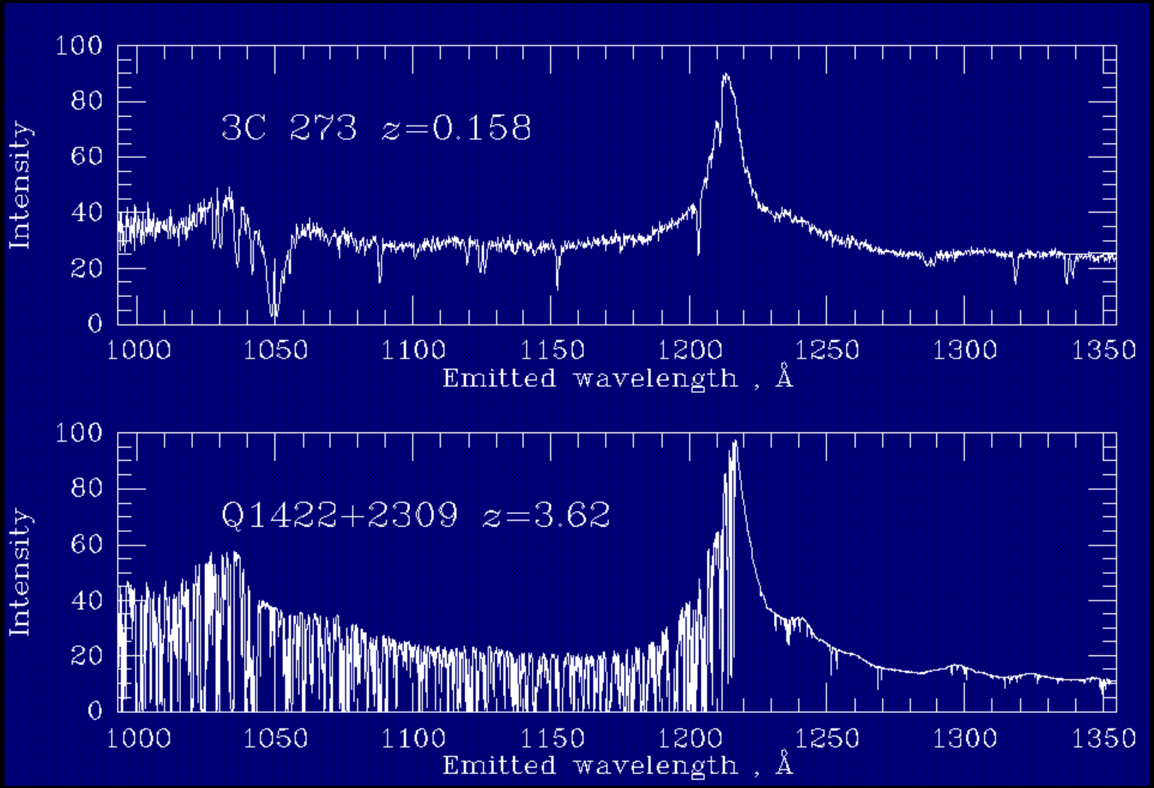
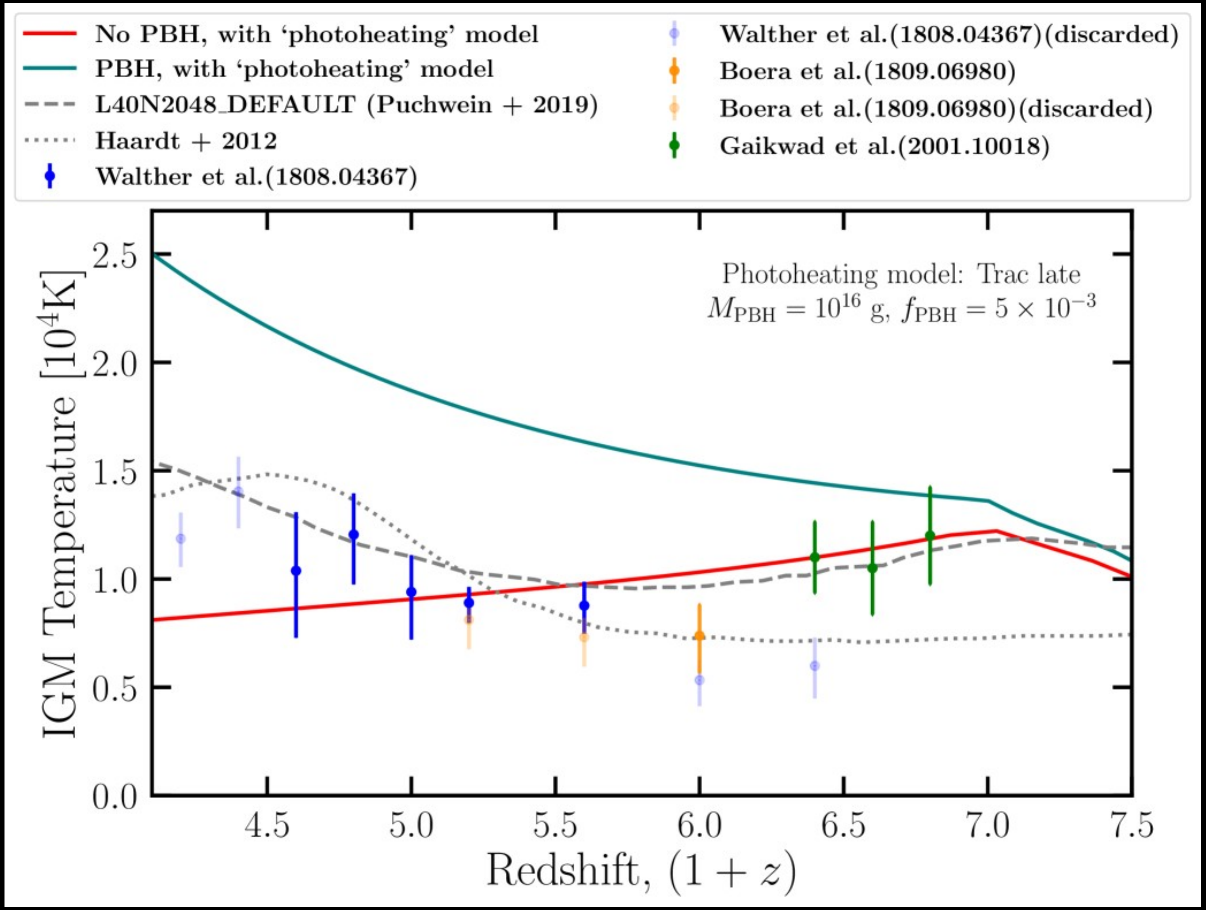


Image credit: https://pages.astronomy.ua.edu/keel/agn/forest.gif

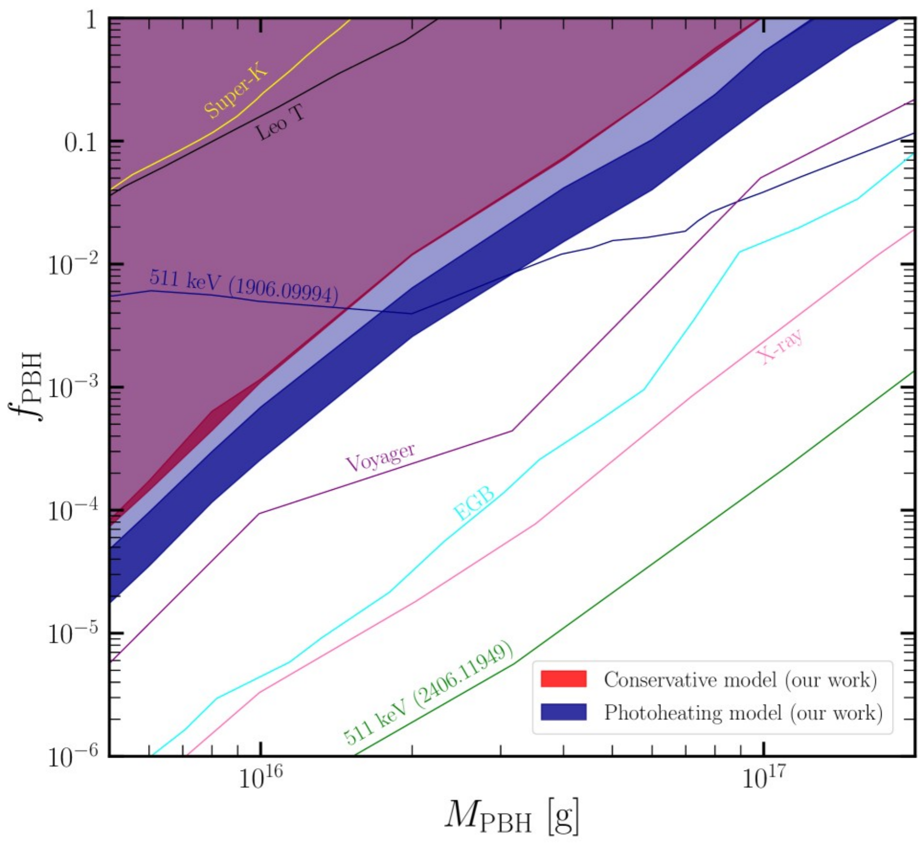
Results



Saha, AS, Parashari, Laha

https://arxiv.org/abs/2409.10617

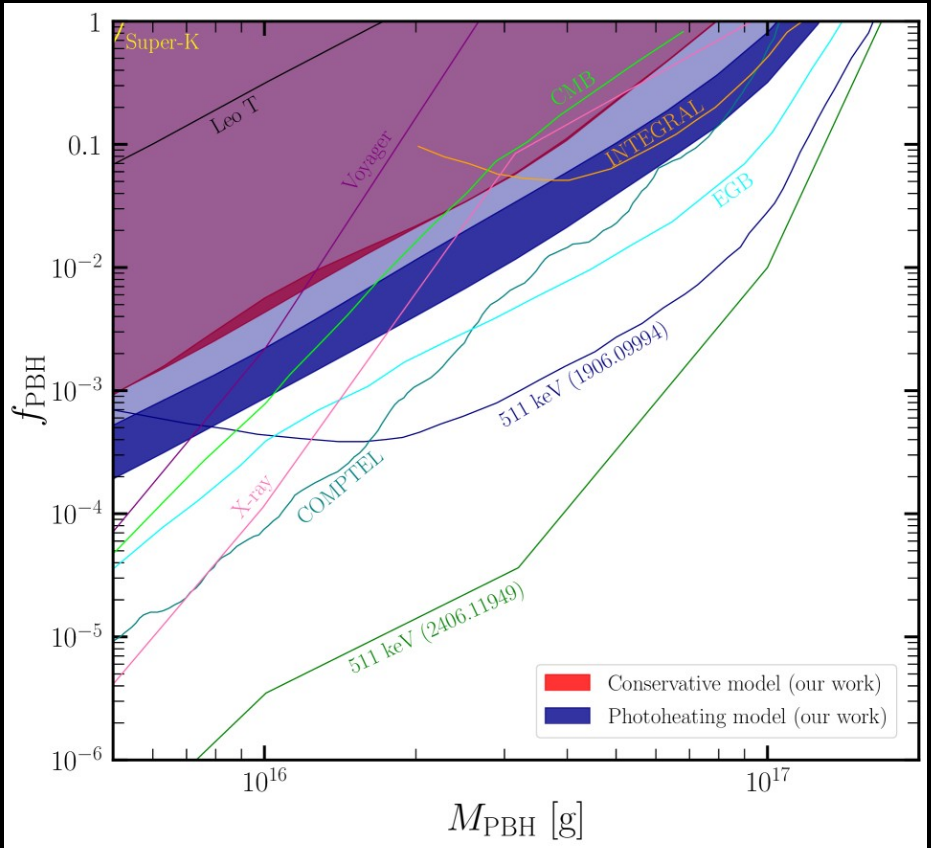
Results



Saha, AS, Parashari, Laha

https://arxiv.org/abs/2409.10617

Results



Saha, AS, Parashari, Laha

https://arxiv.org/abs/2409.10617

Summary

- Black Holes formed early in the universe, a.k.a Primordial Black Holes can constitute all/part of Dark matter.
- Hawking evaporation of light PBHs can lead to direct and indirect observable consequences, providing a way to constrain these beasts.
- Hawking evaporation spectrum utilized to calculate its effect on the evolution of Inter-galactic medium’s temperature.
- The temperature of the IGM has been measured at some redshifts using the Lyman-α spectroscopy.
- By comparing the calculated temperature evolution of IGM assuming evaporating PBHs’ existence with the measured temperatue values leads to upper limits on fraction of Dark Matter in the form of PBHs.

See the paper

https://arxiv.org/abs/2409.10617

Pandora’s Box

Image generated using Google Gemini

Contents

- Dark Matter: Introduction, Evidence, Properties
- Primordial Black Holes: Introduction
- Hawking evaporation- A poor man's derivation
- Properties of Hawking radiation and its sources
- Effect of Hawking radiation on IGM-temperature
- Measuring IGM's temperature from Lyman-α forest
- Resulting constraints on Primordial Black Holes' existence

Contents

Evidence for Dark Matter

Galaxies can't be rotating the way they do without Dark Matter.

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

Video credit: CAASTRO YouTube channel
https://www.youtube.com/watch?v=ywllcRBEZPI

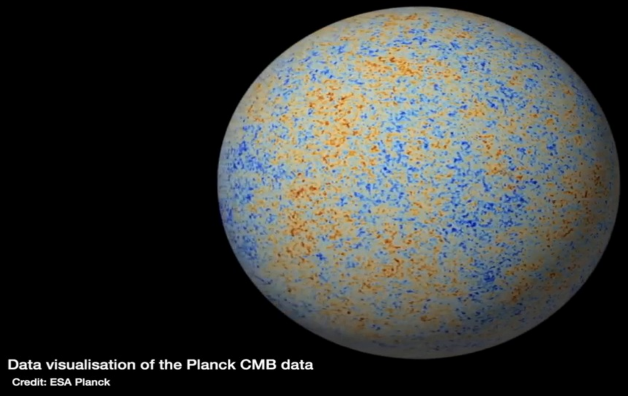
Evidence for Dark Matter

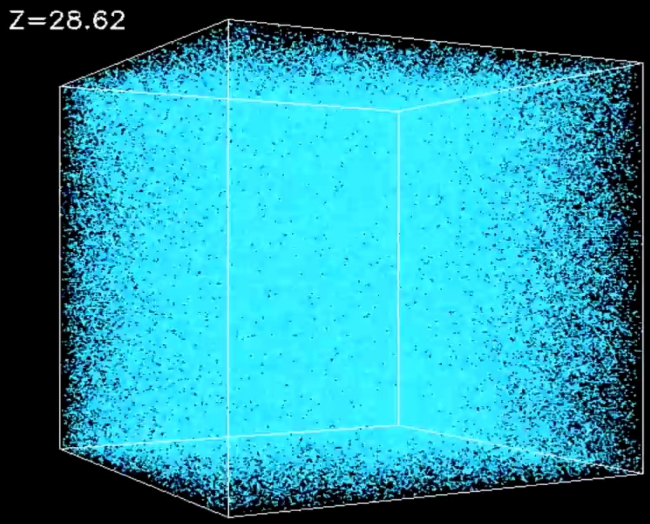
Mass distribution after clusters collide isn’t accounted for by visible matter.

Video credit: CAASTRO YouTube channel
https://www.youtube.com/watch?v=6itfq4CzxZ8

Evidence for Dark Matter

Structure Formation doesn't work without Dark Matter.





Video credit: Dr. Becky YouTube channel
https://www.youtube.com/watch?v=SDRNvhbrz3k

Video credit: SpaceSciNewsroom YouTube channel
https://www.youtube.com/watch?v=eDGtFRj4xXc

What do we know about Dark Matter?

- Is 5 times more abundant than the baryonic matter.
- Hardly interacts with the baryonic matter- dark.
- Is non-relativistic at the present epoch.
- Stable over the time-scale of the age of the universe.
- Does not contribute to the baryonic matter density.

What do we know about Dark Matter?

- Is 5 times more abundant than the baryonic matter.
- Hardly interacts with the baryonic matter- dark.
- Is non-relativistic at the present epoch.
- Stable over the time-scale of the age of the universe.
- Does not contribute to the baryonic matter density.

Everyting in this list is inferred using gravitational interaction of Dark Matter.

What do we know about Dark Matter?

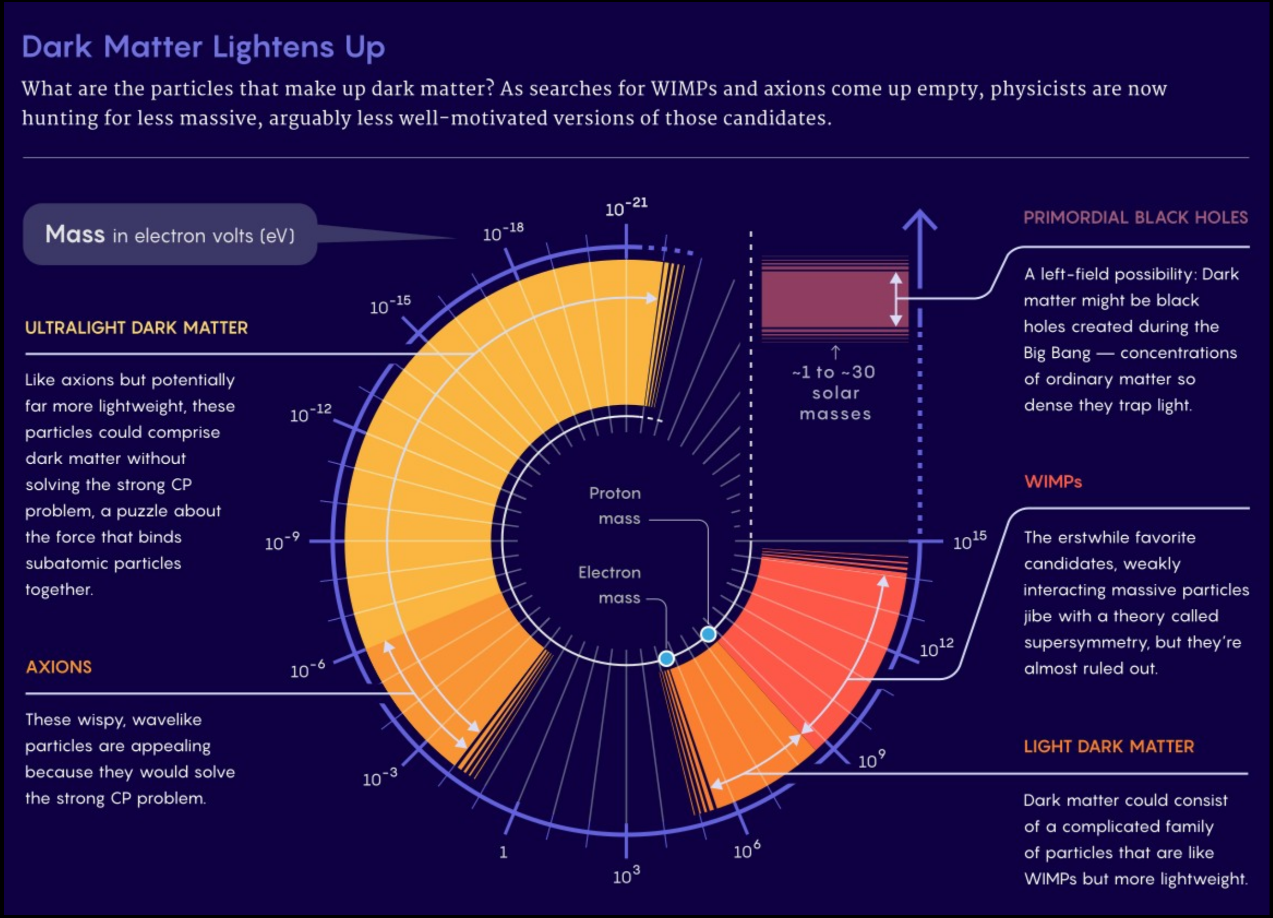


Image credit: Quanta magazine

Observational constraints on PBHs

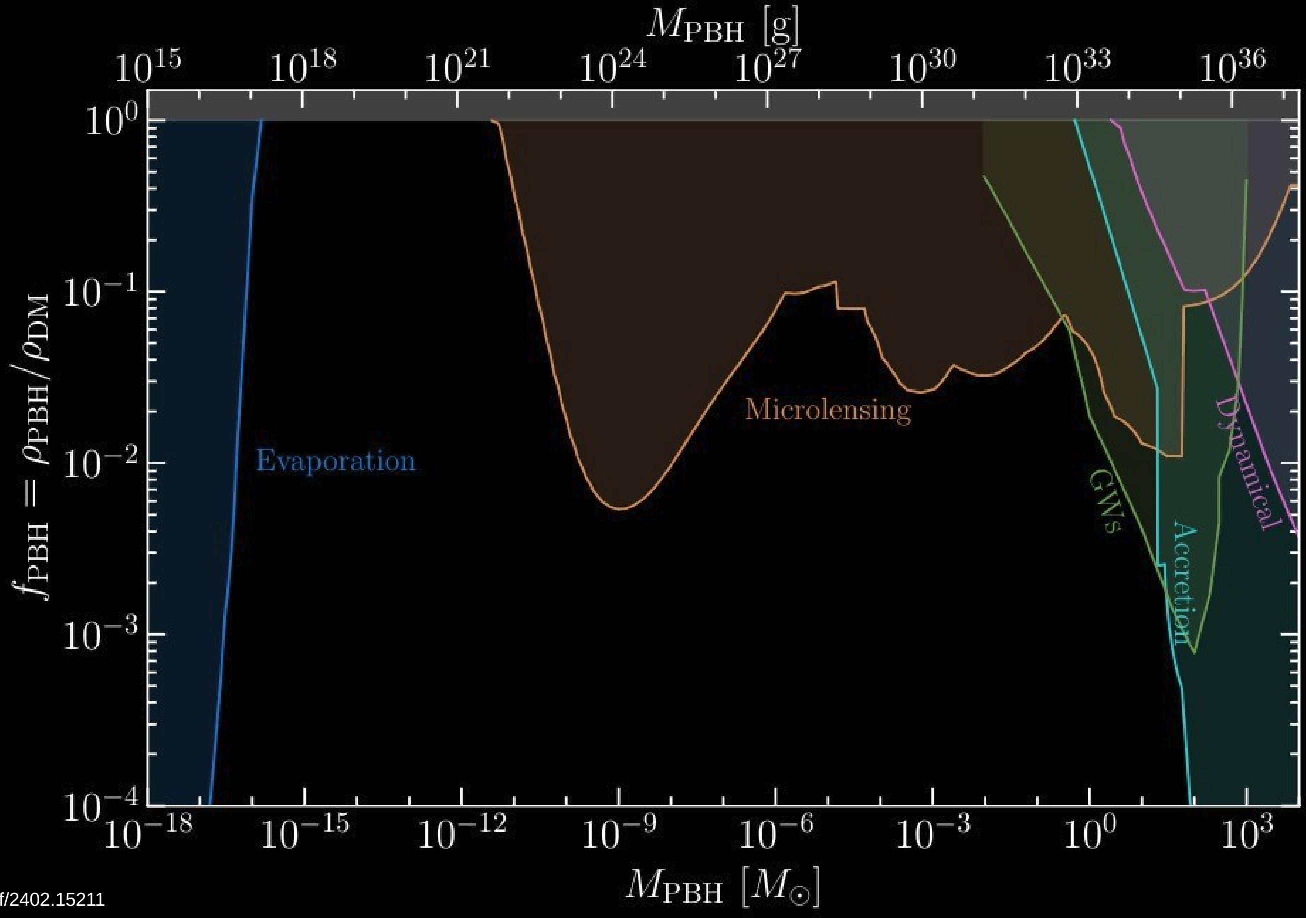


Image credit: https://arxiv.org/pdf/2402.15211

Observational constraints on PBHs

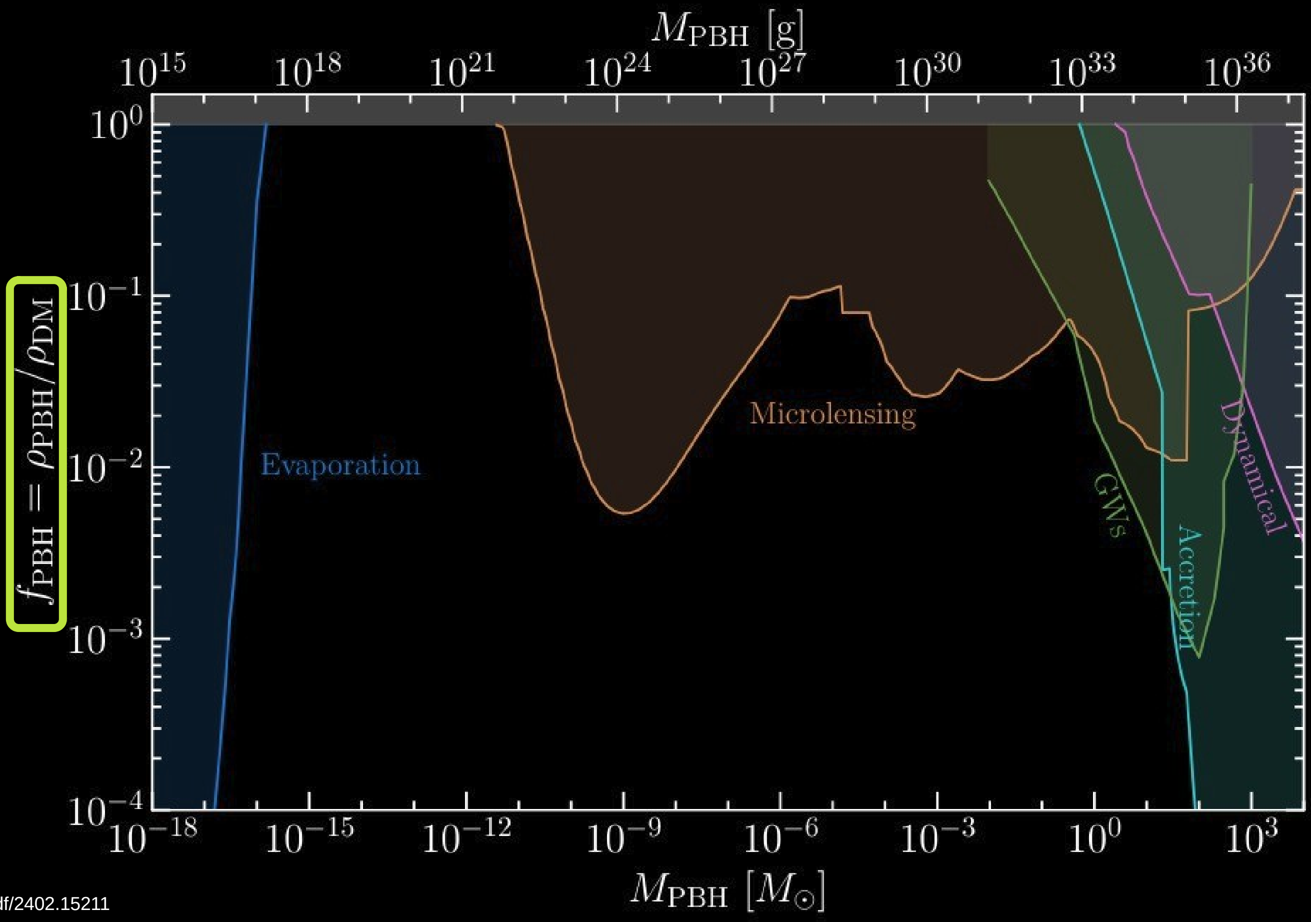


Image credit: https://arxiv.org/pdf/2402.15211

Contents

- Dark Matter: Introduction, Evidence, Properties
- Primordial Black Holes: Introduction
- Hawking evaporation- A poor man's derivation
- Properties of Hawking radiation and its sources
- Effect of Hawking radiation on IGM-temperature
- Measuring IGM's temperature from Lyman-α forest
- Resulting constraints on Primordial Black Holes' existence

‘Deriving’ Hawking evaporation for Black Holes*

Two inertial frames:

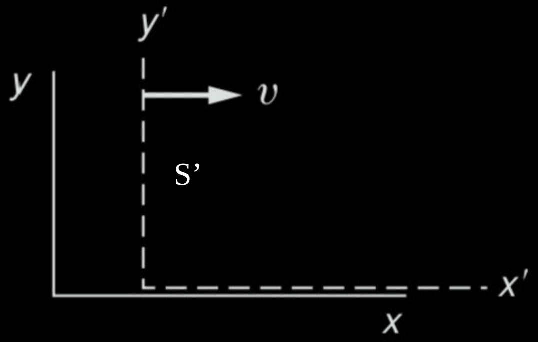


Image credit: https://physics.stackexchange.com/questions/484936/special-relativity-reference-frames-s-and-s

From our perspective:

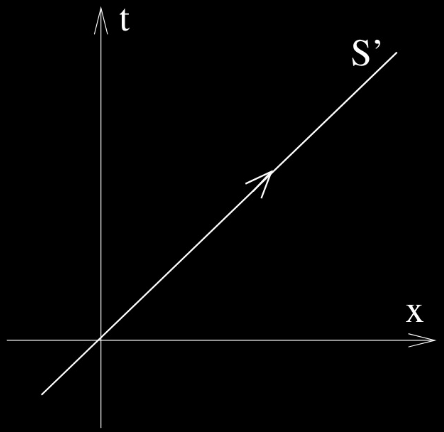


Image credit: https://www.damtp.cam.ac.uk/user/tong/relativity/dynrel.pdf

$$x(t) = vt$$

In terms of time on clock carried by S’:

$$t(\tau) = \gamma\tau$$

$$x(\tau) = \gamma v\tau$$

* This derivation was taken from an article written by T. Padmanabhan in Resonance.
  See https://link.springer.com/article/10.1007/s12045-008-0048-3

‘Deriving’ Hawking evaporation for Black Holes

Consider a plane wave in our frame:

$$\phi(x,t) = exp(-i\omega(t - x/c))$$

How does $\phi(x,t)$ appear to S’?

Substitute $t(\tau)$ and $x(\tau)$ into $\phi(x,t)$:

$$exp\left(-i\omega\tau\sqrt{\frac{c-v}{c+v}}\right)$$

Doppler shift!

$$x(t) = vt$$

In terms of time on clock carried by S’:

$$t(\tau) = \gamma\tau$$

$$x(\tau) = \gamma v\tau$$

‘Deriving’ Hawking evaporation for Black Holes

If S’ is a uniformly accelerated frame:

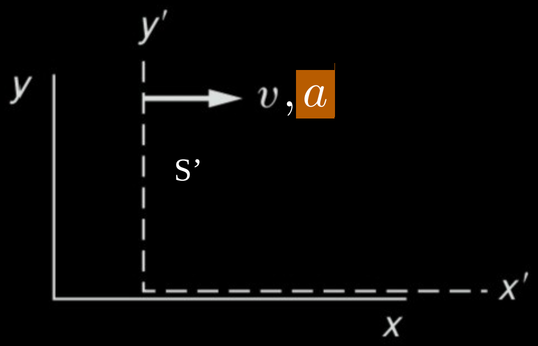


Image credit: https://physics.stackexchange.com/questions/484936/special-relativity-reference-frames-s-and-s

From our perspective:

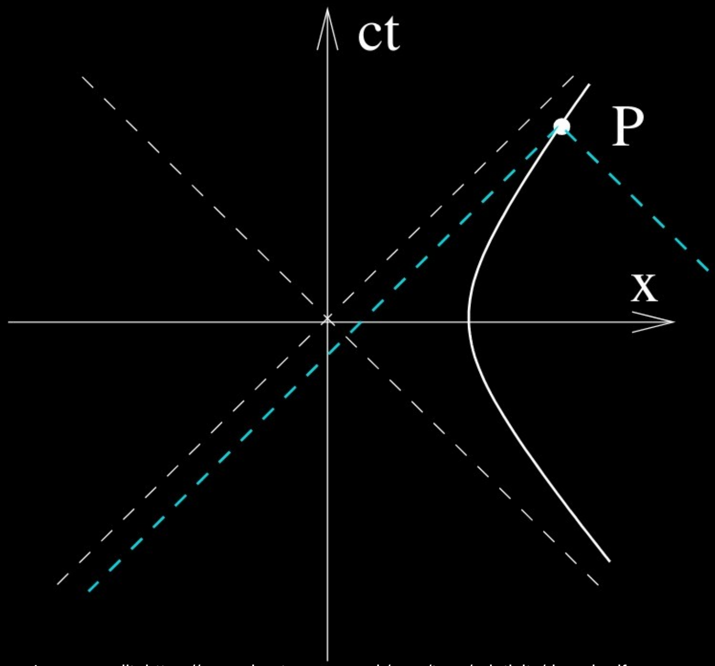


Image credit: https://www.damtp.cam.ac.uk/user/tong/relativity/dynrel.pdf

‘Deriving’ Hawking evaporation for Black Holes

Parametrization in terms of τ :

$$t(\tau) = \frac{c}{a} sinh(a\tau/c)$$

$$x(\tau) = \frac{c^2}{a} cosh(a\tau/c)$$

From our perspective:

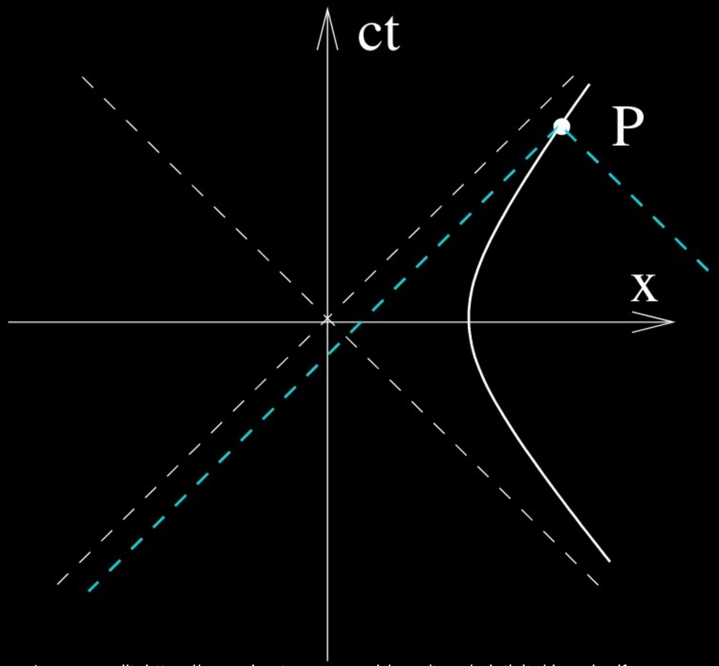


Image credit: https://www.damtp.cam.ac.uk/user/tong/relativity/dynrel.pdf

‘Deriving’ Hawking evaporation for Black Holes

Parametrization in terms of τ :

$$t(\tau) = \frac{c}{a} sinh(a\tau/c)$$

$$x(\tau) = \frac{c^2}{a} cosh(a\tau/c)$$

How does the plane wave $\phi(x,t)$ look to the accelerated observer?

Substitute $t(\tau)$ and $x(\tau)$ into

$$\phi(x,t) = exp(-i\omega(t - x/c))$$

One gets:

$$exp\left(\frac{i\omega c}{a} e^{-a\tau/c}\right)$$

‘Deriving’ Hawking evaporation for Black Holes

The frequency seen by the accelerated observer is found by differentiating the phase of the exponential w.r.t. τ and dividing by i:

$$\omega'(\tau) = \omega e^{-a\tau/c}$$

The accelerated observer sees the frequency being exponentially redshifted as per its time!

How does the plane wave $\phi(x,t)$ look to the accelerated observer?

Substitute $t(\tau)$ and $x(\tau)$ into

$$\phi(x,t)=exp(-i\omega(t-x/c))$$

One gets:

$$exp\left(\frac{i\omega c}{a}e^{-a\tau/c}\right)$$

‘Deriving’ Hawking evaporation for Black Holes

The frequency seen by the accelerated observer is found by differentiating the phase of the exponential w.r.t. τ and dividing by i:

$$\omega'(\tau) = \omega e^{-a\tau/c}$$

The accelerated observer sees the frequency being exponentially redshifted as per its time!

To gain insight into the spectrum seen by the accelerated observer, let’s Fourier expand it:

$$f(\nu) = \int_{-\infty}^{\infty} \phi(\tau) e^{-i\nu\tau} d\tau$$

The integral is given by:

$$f(\nu) = \frac{c}{a}\Gamma\left(\frac{i\nu c}{a}\right) e^{\frac{-\pi\nu c}{2a}} \omega^{-i\nu a/c}$$

‘Deriving’ Hawking evaporation for Black Holes

The power spectrum is given by:

$$|f(\nu)|^2 = \frac{1}{\nu}\frac{\tilde{\beta}}{e^{\tilde{\beta}\nu} - 1}$$

$$\tilde{\beta} = \frac{2\pi c}{a}$$

The power spectrum is thermal in nature!

No trace of ω in the power spectrum!

To gain insight into the spectrum seen by the accelerated observer, let’s Fourier expand it:

$$f(\nu) = \int_{-\infty}^{\infty} \phi(\tau) e^{-i\nu\tau} d\tau$$

The integral is given by:

$$f(\nu) = \frac{c}{a}\Gamma\left(\frac{i\nu c}{a}\right) e^{\frac{-\pi\nu c}{2a}} \omega^{-i\nu a/c}$$

‘Deriving’ Hawking evaporation for Black Holes

The power spectrum is given by:

$$|f(\nu)|^2 = \frac{1}{\nu}\frac{\tilde{\beta}}{e^{\tilde{\beta}\nu} - 1}$$

$$\tilde{\beta} = \frac{2\pi c}{a}$$

The power spectrum is thermal in nature!

No trace of ω in the power spectrum!

Introducing Planck’s constant to convert ν into energy E,

$$\beta = \frac{\tilde{\beta}}{\hbar} = \frac{2\pi c}{a\hbar} = k_B T$$

The temperature associated to the thermal spectrum is given by:

$$T = \frac{\hbar a}{2k_B \pi c}$$

‘Deriving’ Hawking evaporation for Black Holes

$$T = \frac{\hbar a}{2 k_B \pi c}$$

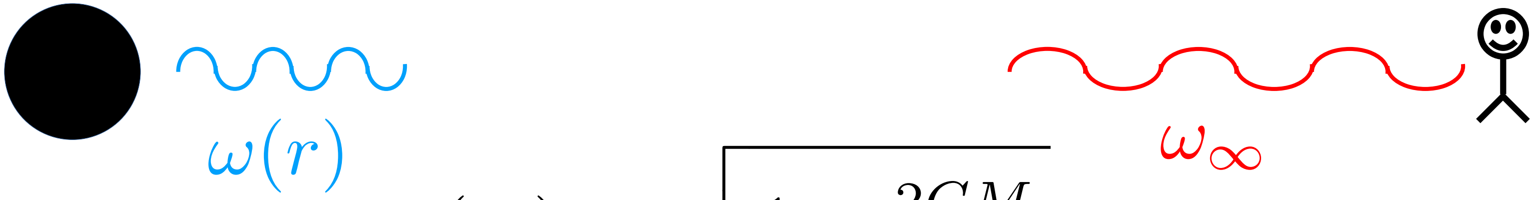
Where are black holes in all this?

- The accelerated observer associates a temperature to the spectrum observed by her!
- This is the famous Unruh effect.
- The temperature depends only on the acceleration of the observer. Particularly, the frequency of the original plane wave is absent!
- The spectrum was exponentially redshifting with time. Any exponentially redshifting spectrum will have a temperature associated to it.

‘Deriving’ Hawking evaporation for Black Holes

Recall, the Schwarzschild metric:

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 - \frac{dr^2}{\left(1 - \frac{2GM}{c^2 r}\right)} - r^2 (d\theta^2 + sin^2\theta d\phi^2)$$



$$\frac{\omega(r_e)}{\omega(r)} = \sqrt{\frac{1 - \frac{2GM}{c^2 r}}{1 - \frac{2GM}{c^2 r_e}}}$$

‘Deriving’ Hawking evaporation for Black Holes

Recall, the Schwarzschild metric:

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 - \frac{dr^2}{\left(1 - \frac{2GM}{c^2 r}\right)} - r^2(d\theta^2 + sin^2\theta d\phi^2)$$

‘Deriving’ Hawking evaporation for Black Holes

$$c(t - t_e) = (r - r_e) + \frac{2GM}{c^2} ln \left(\frac{r - \frac{2GM}{c^2}}{r_e - \frac{2GM}{c^2}} \right)$$

'Deriving' Hawking evaporation for Black Holes

$$c(t - t_e) = (r - r_e) + \frac{2GM}{c^2} ln \left(\frac{r - \frac{2GM}{c^2}}{r_e - \frac{2GM}{c^2}} \right)$$

$$\frac{\omega(r_e)}{\omega(r)} = \sqrt{\frac{1 - \frac{2GM}{c^2 r}}{1 - \frac{2GM}{c^2 r_e}}}$$

$$\omega(r) = K(r)\omega(r_e) exp \left(\frac{-c^3 t}{4GM} \right) \implies$$

Exponentially redshifting spectrum! Victory!

‘Deriving’ Hawking evaporation for Black Holes

$$\omega \propto exp\left(\frac{-c^3 t}{4GM}\right) = exp\left(\frac{-At}{c}\right) \quad \text{where} \quad A = \frac{c^4}{4GM}$$

‘Deriving’ Hawking evaporation for Black Holes

$$\omega \propto exp\left(\frac{-c^3 t}{4GM}\right) = exp\left(\frac{-At}{c}\right) \quad \text{where} \quad A = \frac{c^4}{4GM}$$

$$\omega(\tau) \propto e^{-a\tau/c} \quad \Rightarrow \quad T = \frac{\hbar a}{2k_B \pi c}$$

‘Deriving’ Hawking evaporation for Black Holes

$$\omega \propto exp\left(\frac{-c^3 t}{4GM}\right) = exp\left(\frac{-At}{c}\right)$$ where $$A = \frac{c^4}{4GM}$$

$$\omega(\tau) \propto e^{-a\tau/c} \quad \Rightarrow \quad T = \frac{\hbar a}{2k_B \pi c}$$

$$\omega(t) \propto e^{-At/c} \quad \Rightarrow \quad T = \frac{\hbar A}{2k_B \pi c} = \frac{\hbar c^3}{8\pi G k_B M}$$

‘Deriving’ Hawking evaporation for Black Holes

$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

$$T \propto \frac{1}{M}$$

‘Deriving’ Hawking evaporation for Black Holes

$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

$$T \propto \frac{1}{M}$$

One can rigorously show that emission of particles is associated to this notion of temperature.

Contents

Properties of evaporating Black Holes

$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

$$T \propto \frac{1}{M}$$

Properties of evaporating Black Holes

$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

$$T \propto \frac{1}{M}$$

What is the rate of mass loss (or energy injected)?

$$\frac{dM}{dt} \propto -R^2 T^4 = -M^2 M^{-4} = \frac{-1}{M^2}$$

Area $\times$ Temperature^4

Age of a PBH with initial mass $M_0 \propto (M_0)^3$

Properties of evaporating Black Holes

$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

$$T \propto \frac{1}{M}$$

What is the rate of mass loss (or energy injected)?

$$\frac{dM}{dt} \propto -R^2 T^4 = -M^2 M^{-4} = \frac{-1}{M^2}$$

Area $\times$ Temperature^4

Light-mass PBHs can be detected/constrained by the effects of evaporation.

Age of a PBH with initial mass $M_0 \propto (M_0)^3$

Properties of evaporating Black Holes

$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

$$T \propto \frac{1}{M}$$

What is the rate of mass loss (or energy injected)?

$$\frac{dM}{dt} \propto -R^2 T^4 = -M^2 M^{-4} = \frac{-1}{M^2}$$

Area × Temperature^4

Age of a PBH with initial mass $M_0 \propto (M_0)^3$

Properties of evaporating Black Holes

Age of a PBH with initial mass $M_0 \propto (M_0)^3$

- PBHs with $M_0 \lesssim 5 \times 10^{14}$ g would have already evaporated away.
- PBHs with $M_0 \gtrsim 5 \times 10^{15}$ g lose negligible mass during the age of the universe.

Properties of evaporating Black Holes

Age of a PBH with initial mass $M_0 \propto (M_0)^3$

- PBHs with $M_0 \lesssim 5 \times 10^{14}$ g would have already evaporated away.
- PBHs with $M_0 \gtrsim 5 \times 10^{15}$ g lose negligible mass during the age of the universe.

The actual rate of mass-loss, but the $f(M)$ imparts only a weak dependence. ⟹ $$\frac{dM}{dt} \propto \frac{-f(M)}{M^2}$$

Properties of evaporating Black Holes

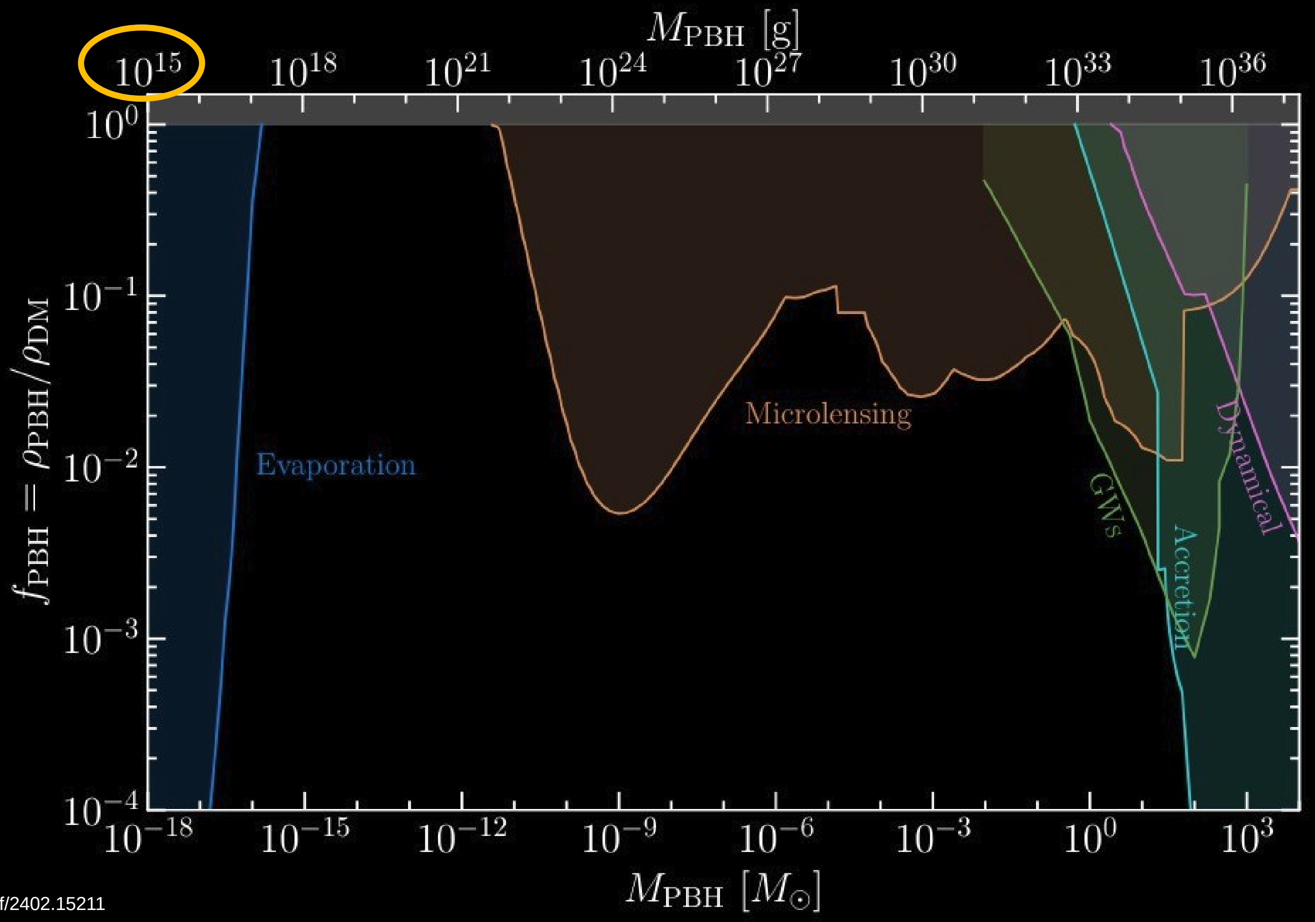


Image credit: https://arxiv.org/pdf/2402.15211

Properties of evaporating Black Holes

Reality Check!!!!

Here and henceforth, $\hbar = c = k_B = G = 1$

PBHs are not perfect blackbodies.

The correct spectrum of Hawking radiation by non-spinning black holes is given by:

$$\frac{d^2 N_{i,lm}}{dt dE} = \frac{1}{2\pi} \frac{\Gamma_{s_i lm}(E, M)}{e^{E/T} - (-1)^{2s_i}}$$

Graybody factors.

Encode deviation from blackbody spectrum.

See https://arxiv.org/pdf/1905.04268

Properties of evaporating Black Holes

From the expression for emission of each quantum number for a given particle,

$$\frac{d^2 N_{i,lm}}{dt dE} = \frac{1}{2\pi} \frac{\Gamma_{s_i lm}(E, M)}{e^{E/T} - (-1)^{2s_i}}$$

The total emission of each particle i is obtained by summing over all multiplicities and all quantum numbers:

$$\frac{d^2 N_i}{dt dE} = g^i_{colour} \times g^i_{helicity} \times g^i_{anti-particles} \sum_{l,m} \frac{d^2 N_{i,lm}}{dt dE}$$

See https://arxiv.org/pdf/1905.04268

Properties of evaporating Black Holes

Age of a PBH with initial mass $M_0 \propto (M_0)^3$

- PBHs with $M_0 \lesssim 5 \times 10^{14}$ g would have already evaporated away.
- PBHs with $M_0 \gtrsim 5 \times 10^{15}$ g lose negligible mass during the age of the universe.

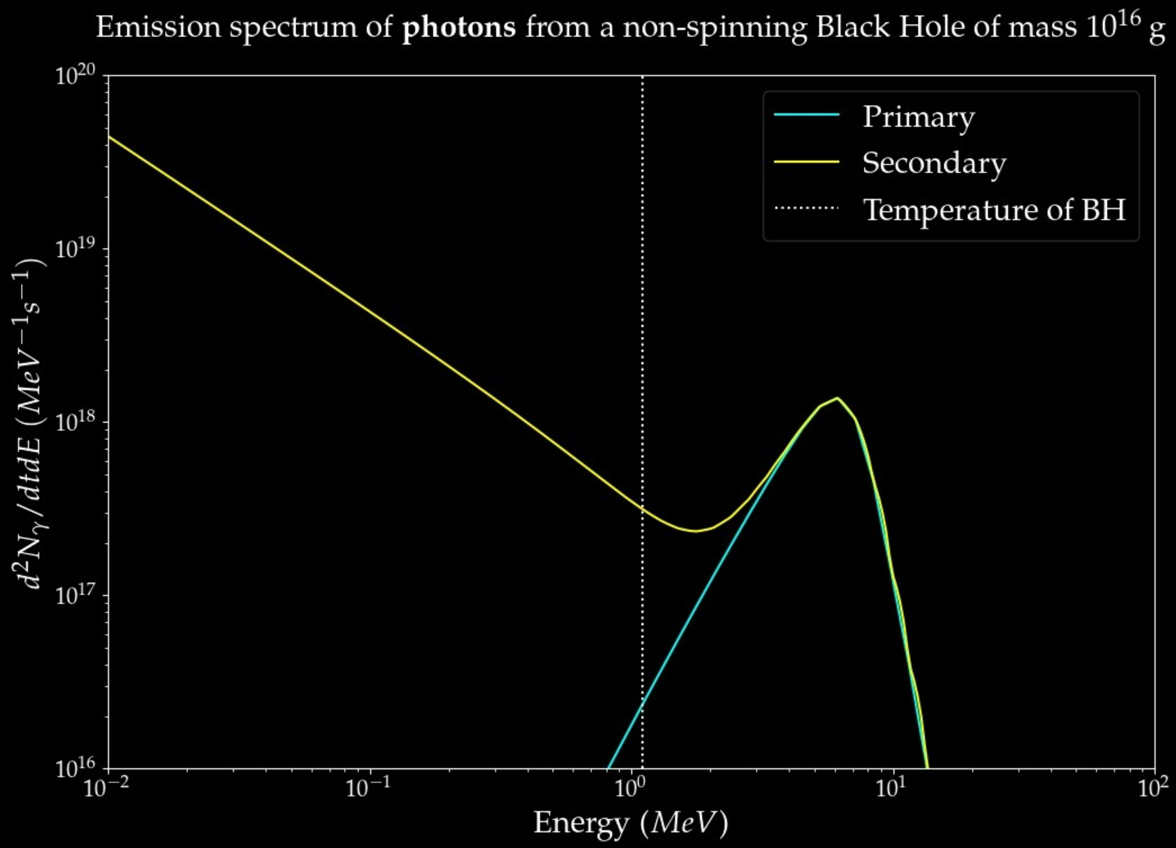
These facts are true with graybody factors taken into consideration.

Hawking radiation spectra

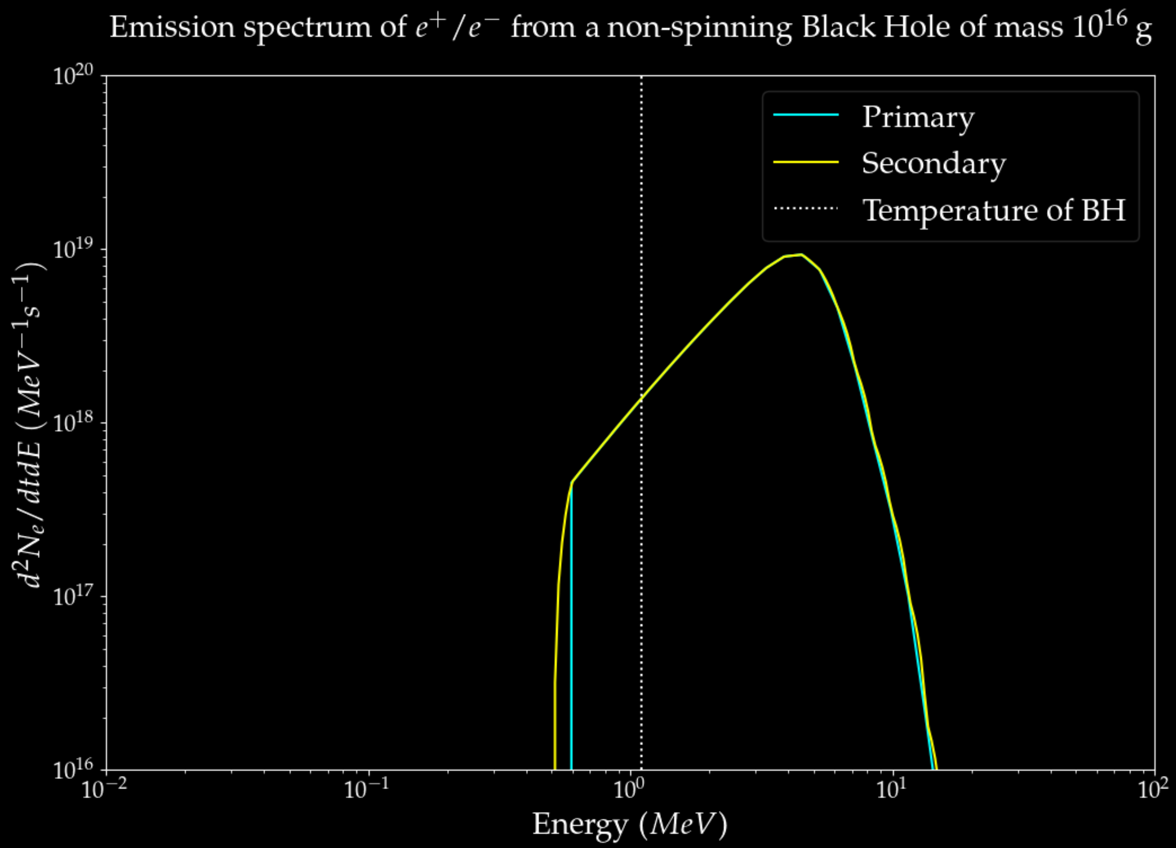
- As remarked before, Graybody factors encode the deviation of the Hawking spectrum from the ideal blackbody spectrum.
- Calculated by solving for the transmission probability of wavefunctions of particles in the curved spacetime of the black hole.
- We use `BlackHawk v2.0`* to calculate the Graybody factors for each particle for all the modes, and sum them to obtain the primary spectrum of each particle.
- `BlackHawk v2.0` has in-built functionality, which computes the spectrum of cosmologically stable particles after hadronization and decays have taken place- the secondary spectrum.
- We are interested in the total spectrum of each particle (say photons)- sum of its primary spectrum and the contribution from secondary spectra of all particles.

* https://arxiv.org/pdf/1905.04268

Hawking radiation spectra



Hawking radiation spectra



Hawking radiation spectra

For spinning Black Holes, it turns out that the temperature depends on the spin too.

$$T = \frac{1}{4\pi M}\left(\frac{\sqrt{1-a^{*2}}}{1+\sqrt{1-a^{*2}}}\right)$$

where, $a^* = \frac{J}{M^2}$ is the dimensionless spin parameter.

See https://arxiv.org/pdf/1905.04268

Hawking radiation spectra

For spinning Black Holes, the Hawking radiation spectrum is given by:

$$\frac{d^2 N_{i,lm}}{dtdE} = \frac{1}{2\pi} \frac{\Gamma_{s_i lm}(E, M, \Omega)}{e^{(E-m\Omega)/T} - (-1)^{2s_i}}$$

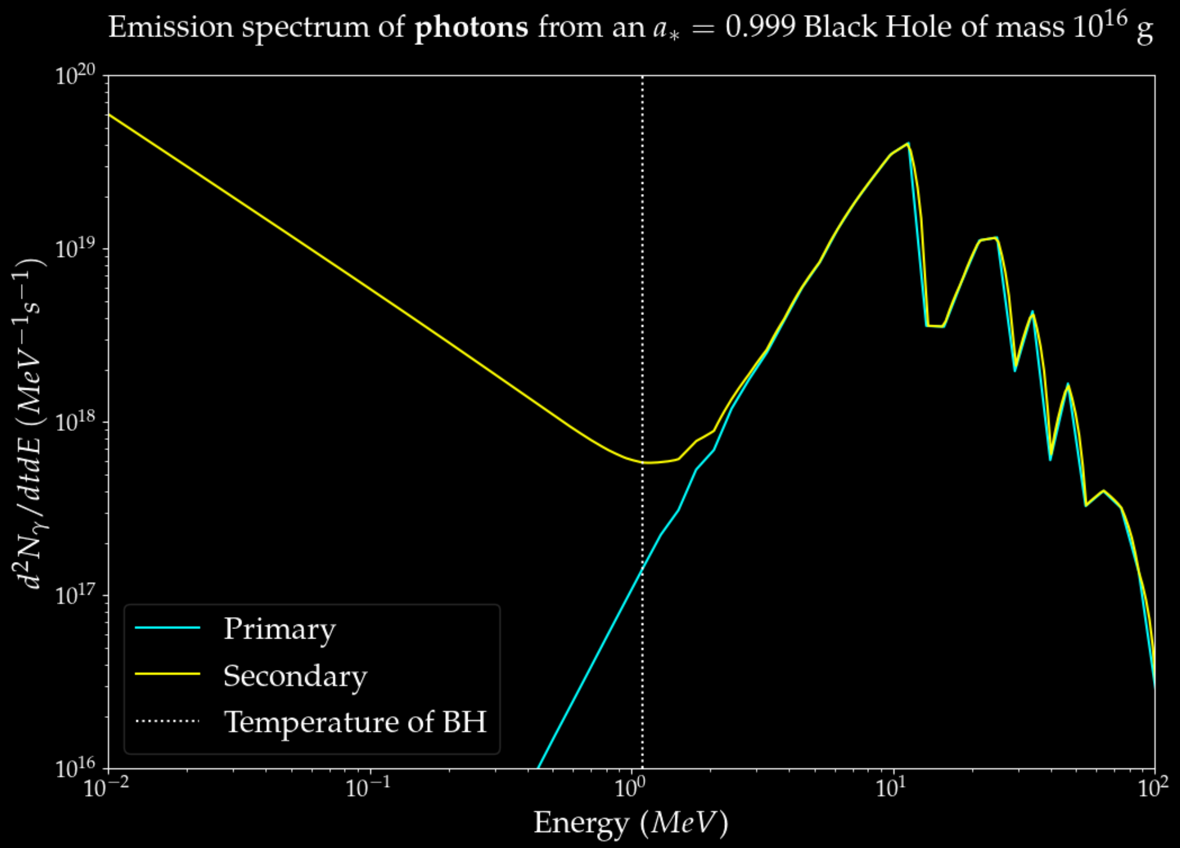
where,

$$\Omega = 4\pi J/MA$$

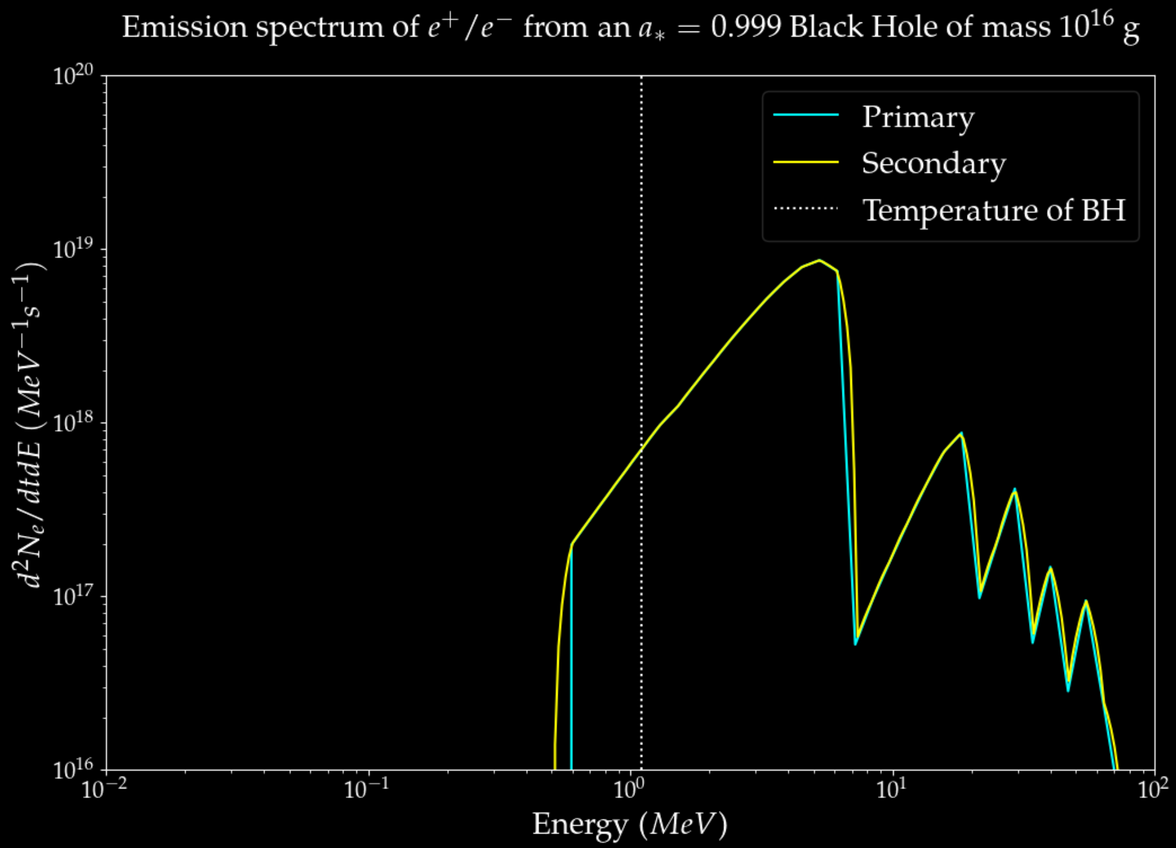
$$A = 8\pi M \left(M + \sqrt{M^2 - \frac{J^2}{M^2}} \right)$$

See https://arxiv.org/pdf/1905.04268

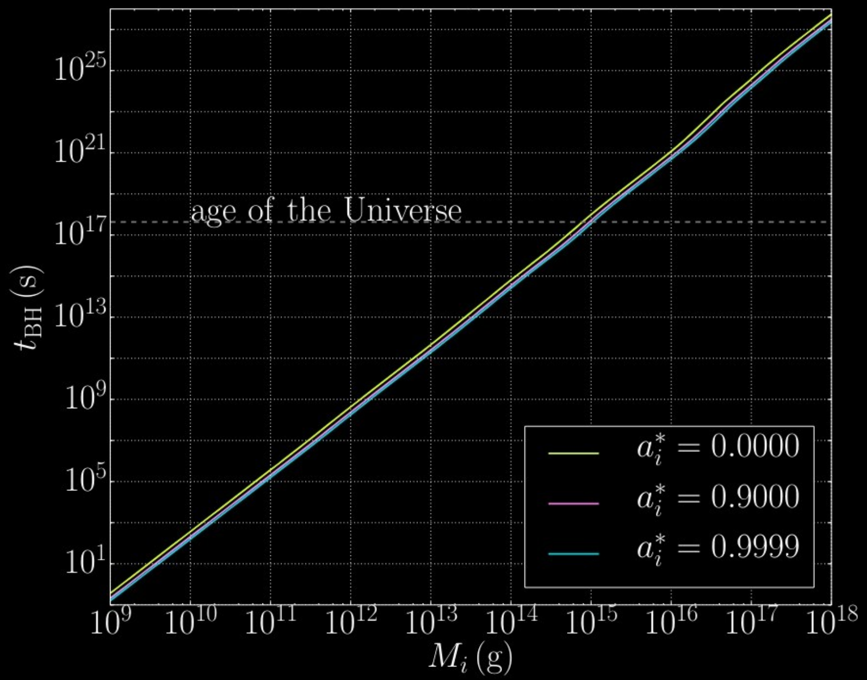
Hawking radiation spectra



Hawking radiation spectra



Properties of evaporating Black Holes



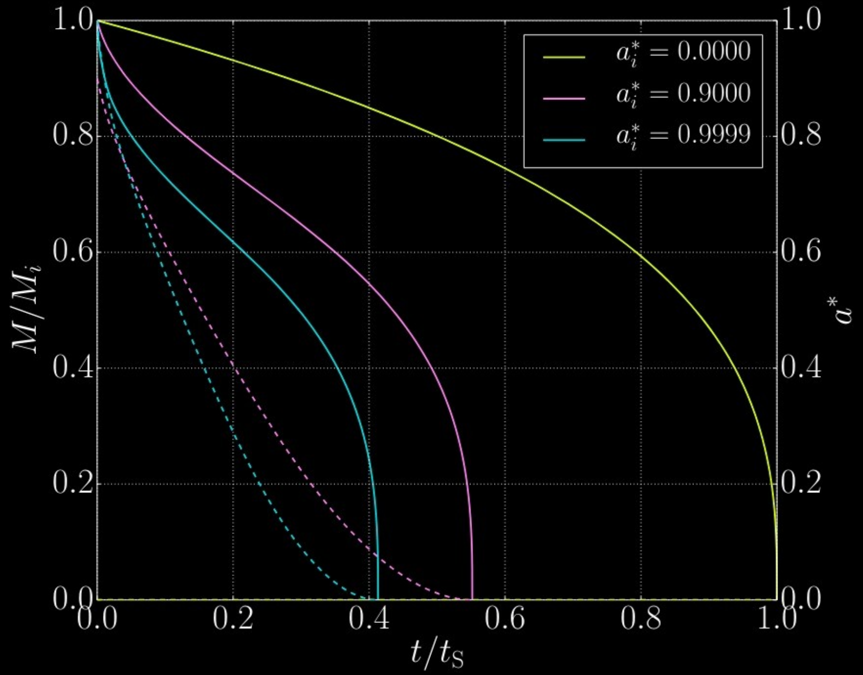


Image credit: https://arxiv.org/pdf/2405.08624

Contents

- Dark Matter: Introduction, Evidence, Properties
- Primordial Black Holes: Introduction
- Hawking evaporation- A poor man's derivation
- Properties of Hawking radiation and its sources
- Effect of Hawking radiation on IGM-temperature
- Measuring IGM's temperature from Lyman-α forest
- Resulting constraints on Primordial Black Holes' existence

What Hawking radiation does to IGM’s temperature

The following differential equations have to be solved simultaneously:

$$\dot{T} = \dot{T}^{(0)} + \dot{T}^{\rm inj}$$

$$\dot{x} = \dot{x}^{(0)} + \dot{x}^{\rm inj}$$

Background temperature evolution without energy injection. Consists of:

- Adiabatic cooling due to expansion of the universe.
- Compton scattering with the CMB.
- Atomic cooling processes like recombination etc.

What Hawking radiation does to IGM’s temperature

The following differential equations have to be solved simultaneously:

$$\dot{T} = \dot{T}^{(0)} + \dot{T}^{\mathrm{inj}}$$

$$\dot{x} = \dot{x}^{(0)} + \dot{x}^{\mathrm{inj}}$$

Heating up of IGM due to energy injection in IGM from exotic sources like evaporating black holes.

What Hawking radiation does to IGM's temperature

The following differential equations have to be solved simultaneously:

$$\dot{T} = \dot{T}^{(0)} + \dot{T}^{\rm inj}$$

$$\dot{x} = \dot{x}^{(0)} + \dot{x}^{\rm inj}$$

Background change in ionized hydrogen fraction. Consists of atomic collisional ionization and recombination.

What Hawking radiation does to IGM's temperature

The following differential equations have to be solved simultaneously:

$$\dot{T} = \dot{T}^{(0)} + \dot{T}^{\mathrm{inj}}$$

$$\dot{x} = \dot{x}^{(0)} + \dot{x}^{\mathrm{inj}}$$

Contribution to ionization due to exotic energy injection, like evaporating PBHs.

What Hawking radiation does to IGM's temperature

The following differential equations have to be solved simultaneously:

$$\dot{T} = \dot{T}^{(0)} + \dot{T}^{\rm inj}$$

$$\dot{x} = \dot{x}^{(0)} + \dot{x}^{\rm inj}$$

`DarkHistory`, a publicly available code can solve these equations self-consistently and simultaneously due to particle dark matter decay to Standard Model particles.

The first such code to take into account the effect on $\dot{T}_{\rm inj}$ term due to non-zero $\dot{x}_{\rm inj}$.

What Hawking radiation does to IGM's temperature: Modifying `DarkHistory`

`DarkHistory`* can calculate the temperature-history of the IGM due to the decay of Dark Matter particles to Standard Model particles.

How to modify `DarkHistory` to calculate the temperature-history of IGM due to Hawking-evaporating PBHs?

* https://arxiv.org/pdf/1904.09296

What Hawking radiation does to IGM's temperature: Modifying `DarkHistory`

We use `DarkHistory` as if we are considering decaying particle Dark Matter.

However, we change the spectrum of γ and e^+/e^- generated by the each particle's decay in the code.

We change it such that the overall spectrum of γ and e^+/e^- generated over a long time-scale is identical to that generated by evaporating PBHs.

What Hawking radiation does to IGM's temperature: Modifying `DarkHistory`

Suppose we run the code with Dark Matter particles of mass m_χ, decaying with a lifetime of τ .

Suppose we want to calculate the effect of PBHs of mass $m_{\rm PBH}$ on the IGM.

For the moment, focus on the γ-spectrum only.

What Hawking radiation does to IGM's temperature: Modifying `DarkHistory`

Let the γ -spectrum of the Hawking evaporation of PBHs be denoted by:

$$\frac{d^2 N_\gamma}{dt dE}$$

Over a time-period τ, a PBH dumps the following spectrum of photons:

$$\frac{dN_\gamma}{dE} = \left(\frac{d^2 N_\gamma}{dt dE}\right)\tau$$

What Hawking radiation does to IGM's temperature: Modifying `DarkHistory`

Let the γ -spectrum of the Hawking evaporation of PBHs be denoted by:

$$\frac{d^2 N_\gamma}{dt dE}$$

Over a time-period τ, a PBH dumps the following spectrum of photons:

$$\frac{dN_\gamma}{dE} = \left(\frac{d^2 N_\gamma}{dt dE}\right)\tau$$

If this same spectrum has to come from particles (with lifetime τ) , each particle has to dump the following spectrum individually:

$$\left(\frac{d^2 N_\gamma}{dt dE}\right)\frac{\tau}{n_\chi}$$

n_χ being the number of Dark Matter particles.

What Hawking radiation does to IGM's temperature: Modifying `DarkHistory`

Because the total mass of dark matter (per volume) is fixed, n_χ is simply given by,

$$\frac{m_{\rm PBH}}{m_\chi}$$

Thus, spectrum from each particle should be

$$\left(\frac{d^2 N_\gamma}{dt dE}\right)\left(\frac{m_\chi}{m_{\rm PBH}}\right)\tau$$

If this same spectrum has to come from particles (with lifetime τ) , each particle has to dump the following spectrum individually:

$$\left(\frac{d^2 N_\gamma}{dt dE}\right)\frac{\tau}{n_\chi}$$

n_χ being the number of Dark Matter particles.

What Hawking radiation does to IGM's temperature: Modifying `DarkHistory`

To summarize, if we are dealing with PBHs of mass $m_{\rm PBH}$ giving a spectrum of photons,

$$\left(\frac{d^2 N_\gamma}{dt dE}\right)$$

run the code meant for particle Dark Matter, by just replacing the photon spectrum from the particle by:

$$\left(\frac{d^2 N_\gamma}{dt dE}\right)\left(\frac{m_\chi}{m_{\rm PBH}}\right)\tau$$

where m_χ and τ have arbitrary but reasonable values.

What Hawking radiation does to IGM's temperature: Modifying `DarkHistory`

$$\left(\frac{d^2 N_\gamma}{dt dE}\right)\left(\frac{m_\chi}{m_{\rm PBH}}\right)\tau$$

Can m_χ and τ really have arbitrary values? Yes!

Suppose Alice uses a value of m_χ twice as much as Bob uses.

The energy injected by each event is double for Alice.

But the number density of the particles would be half for Alice compared to Bob. So the total energy injected is the same!

What Hawking radiation does to IGM's temperature: Modifying `DarkHistory`

$$\left(\frac{d^2 N_\gamma}{dt dE}\right)\left(\frac{m_\chi}{m_{\rm PBH}}\right)\tau$$

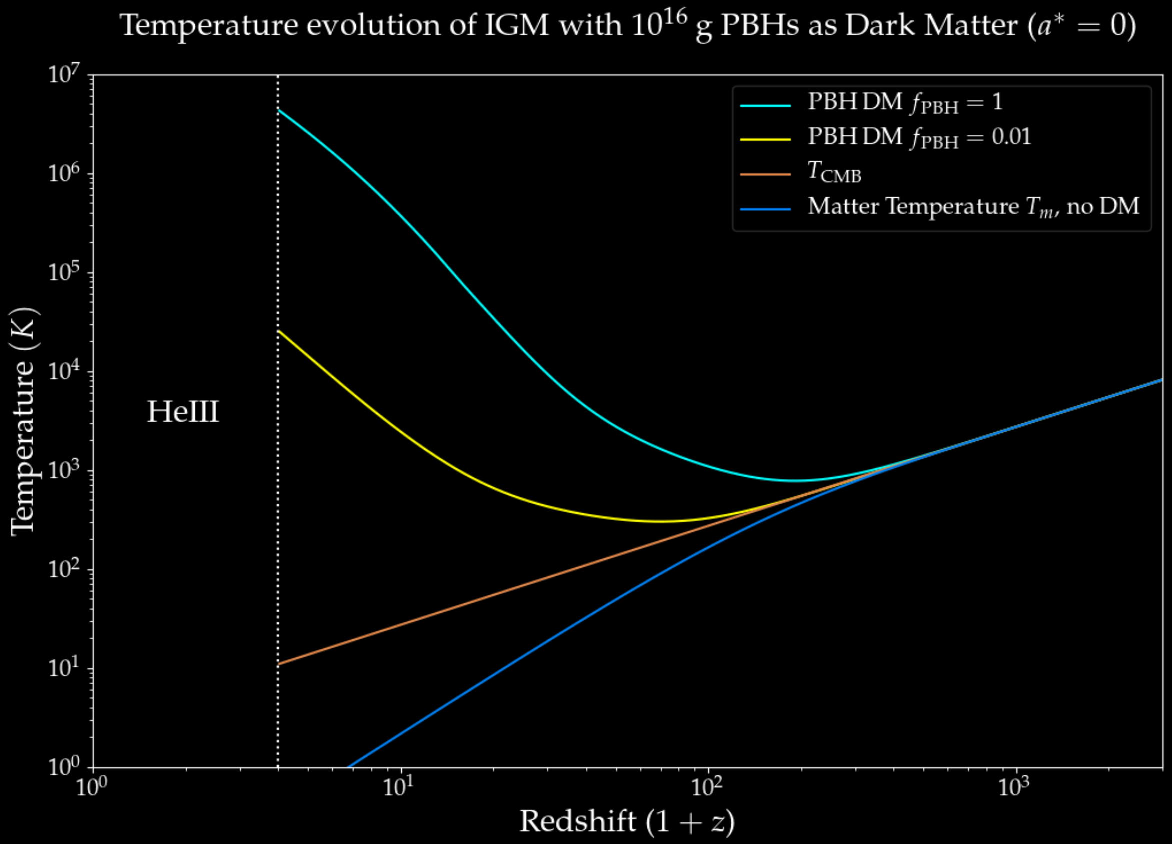
Can m_χ and τ really have arbitrary values? Yes!

Suppose Alice uses a value of τ twice as much as Bob uses.

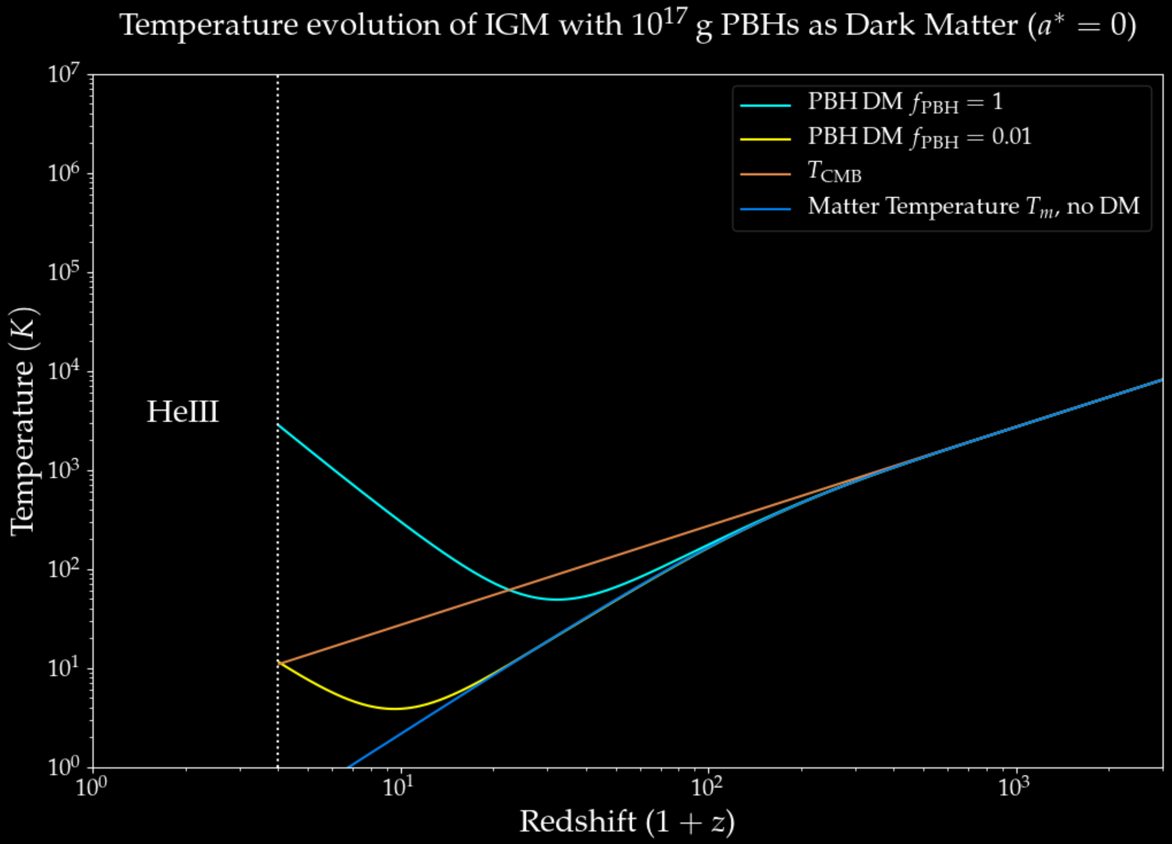
The energy injected by each event is double for Alice.

But the frequency of energy injection would be half for Alice compared to Bob. So the total energy injected is the same!

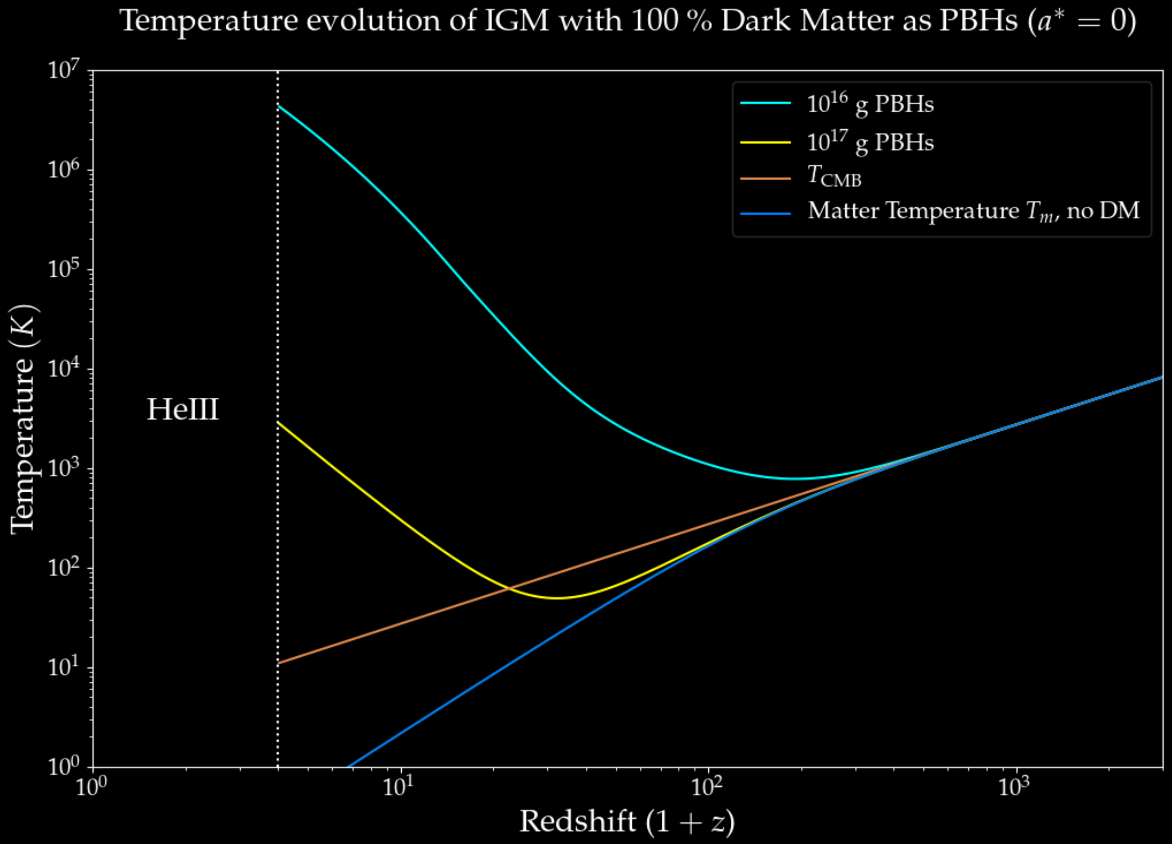
What Hawking radiation does to IGM's temperature: Results



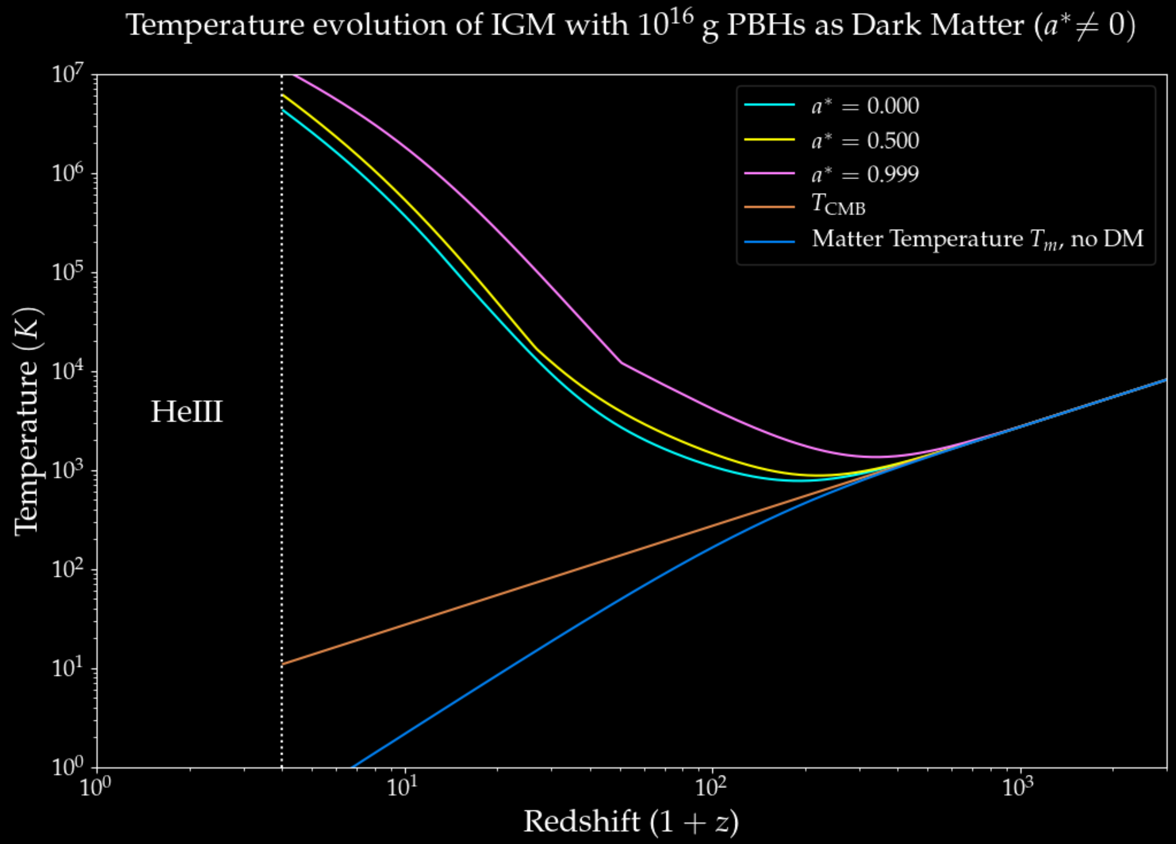
What Hawking radiation does to IGM's temperature: Results



What Hawking radiation does to IGM's temperature: Results



What Hawking radiation does to IGM's temperature: Results



Contents

- Dark Matter: Introduction, Evidence, Properties
- Primordial Black Holes: Introduction
- Hawking evaporation- A poor man's derivation
- Properties of Hawking radiation and its sources
- Effect of Hawking radiation on IGM-temperature
- Measuring IGM's temperature from Lyman-α forest
- Resulting constraints on Primordial Black Holes' existence

Lyman-α Transition

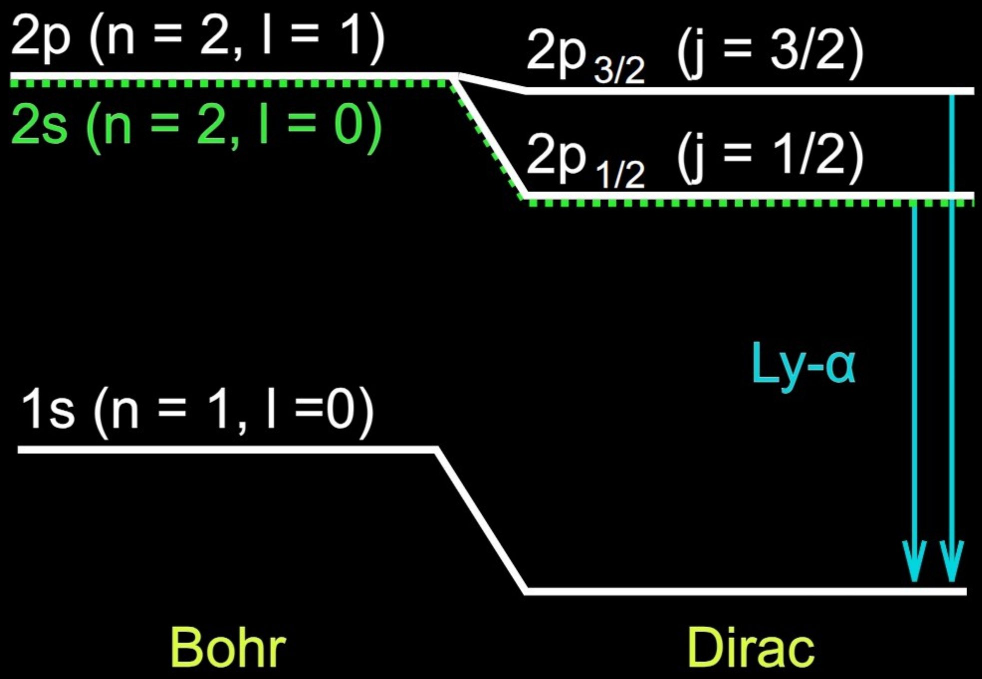


Image credit: Wikipedia
https://en.wikipedia.org/wiki/Lyman-alpha

Lyman-α Forest

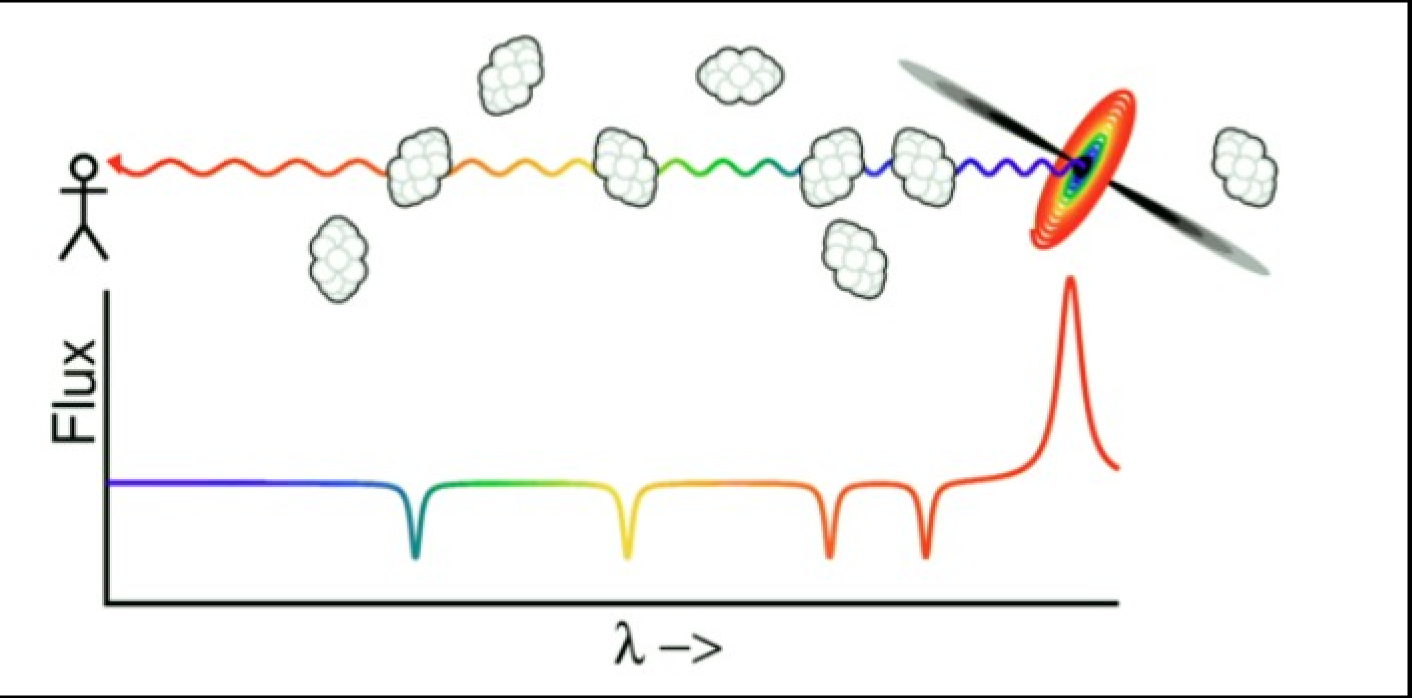


Image credit: Wikipedia
https://astro.ucla.edu/~wright/Lyman-alpha-forest.html

Lyman-α spectrography as a thermometer of IGM

- Currently, no observations at z≥ 6 as no light reaches us, because the intervening medium is neutral.
- At z<6, the density of the intervening medium is not uniform- there are ‘clouds’ of gas scattered around.
- The temperature of the gas is strongly correlated with density:

$$T = T_0 \Delta^{\gamma-1} \qquad \Delta = \rho / <\rho>$$

- By comparing the observed Lyman-α forest spectra with the mock spectra from hydrodynamical simulations, the density and temperature are measured.
- Using the above relation, the mean temperature T_0 is inferrred.

Lyman-α spectrography as a thermometer of IGM

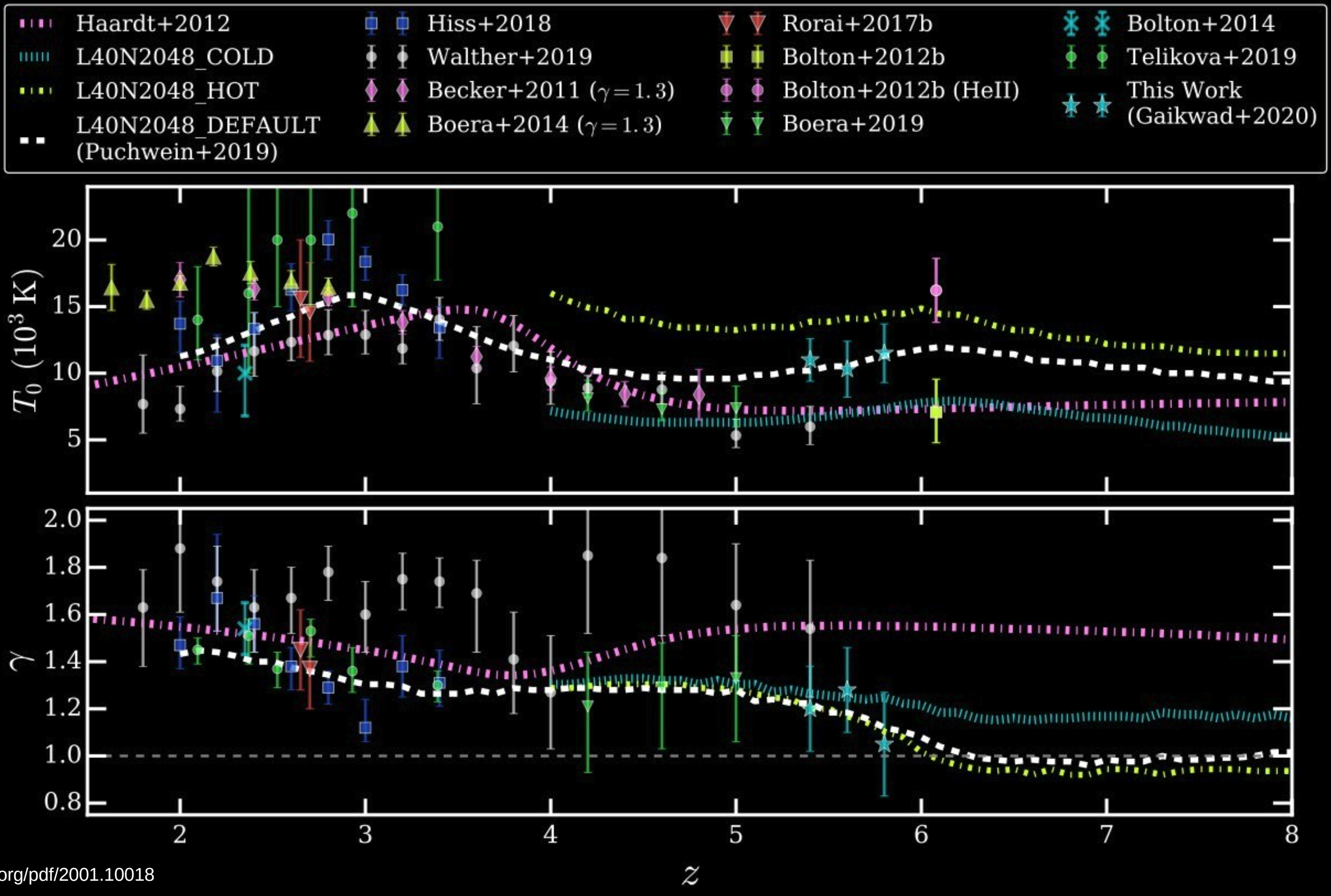


Image credit: https://arxiv.org/pdf/2001.10018

Lyman-α spectrography as a thermometer of IGM

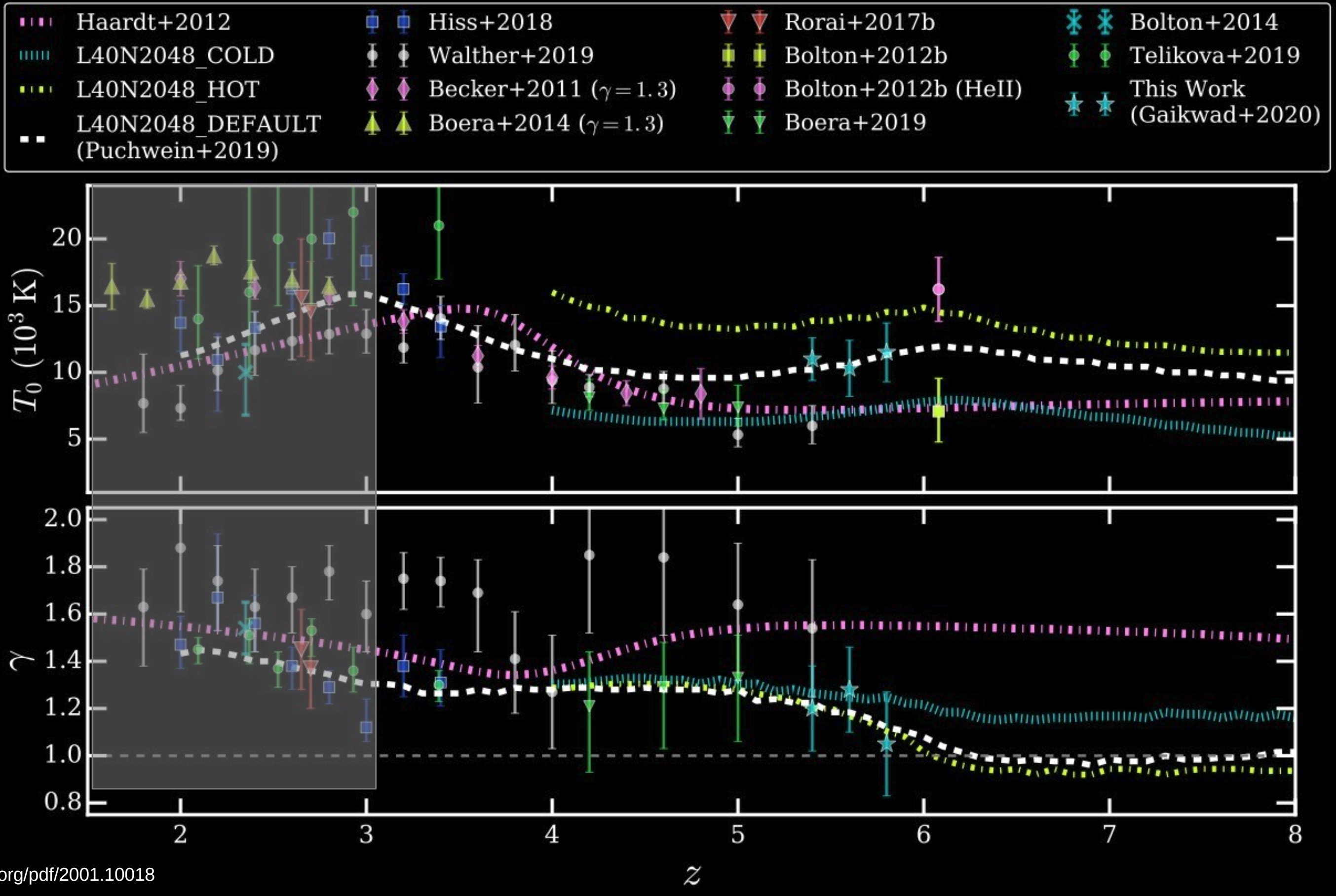


Image credit: https://arxiv.org/pdf/2001.10018

Lyman-α spectrography as a thermometer of IGM

Measurements at redshifts $z<3$ not useful because handling the second reionization of He is tricky.

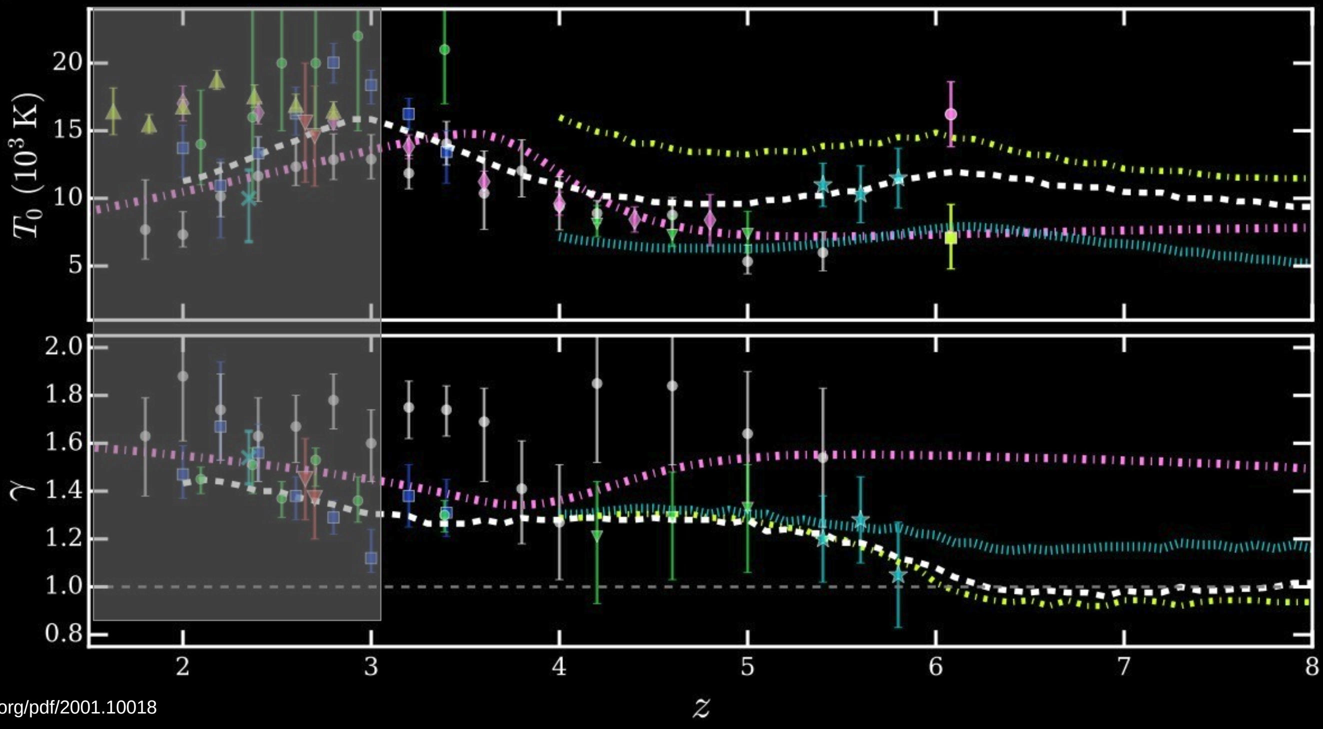


Image credit: https://arxiv.org/pdf/2001.10018

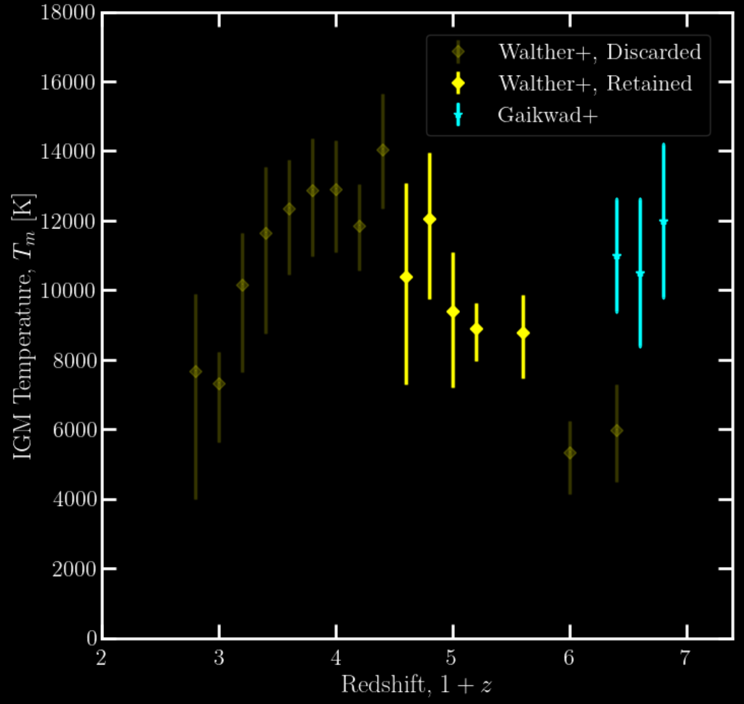
Contents

- Dark Matter: Introduction, Evidence, Properties
- Primordial Black Holes: Introduction
- Hawking evaporation- A poor man’s derivation
- Properties of Hawking radiation and its sources
- Effect of Hawking radiation on IGM-temperature
- Measuring IGM’s temperature from Lyman-α forest
- Resulting constraints on Primordial Black Holes’ existence

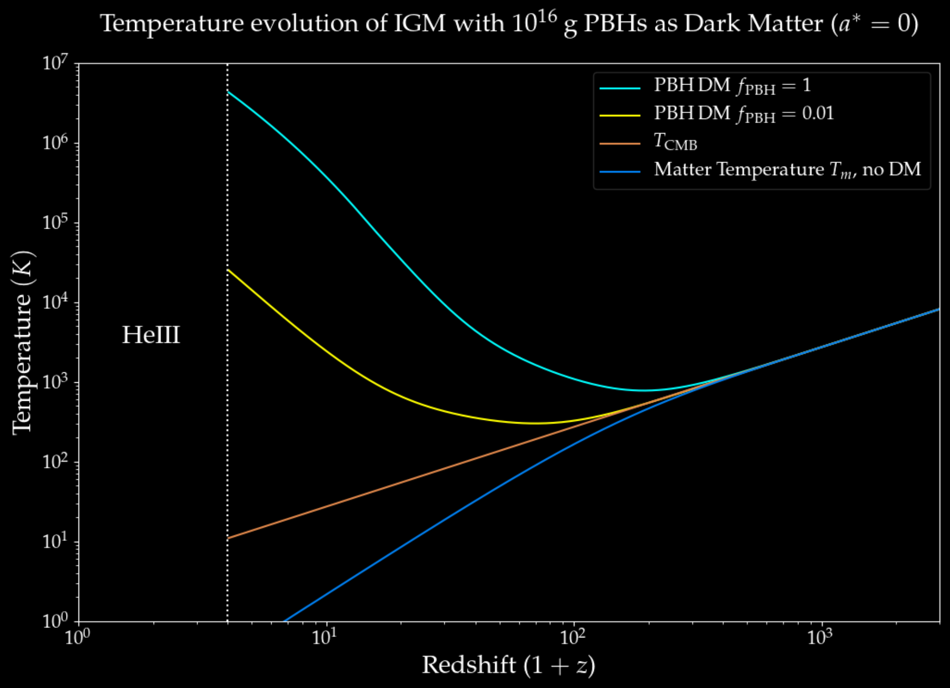
Resulting constraints on PBHs’ existence

Image credit: https://arxiv.org/pdf/2008.01084

Our fiducal dataset:

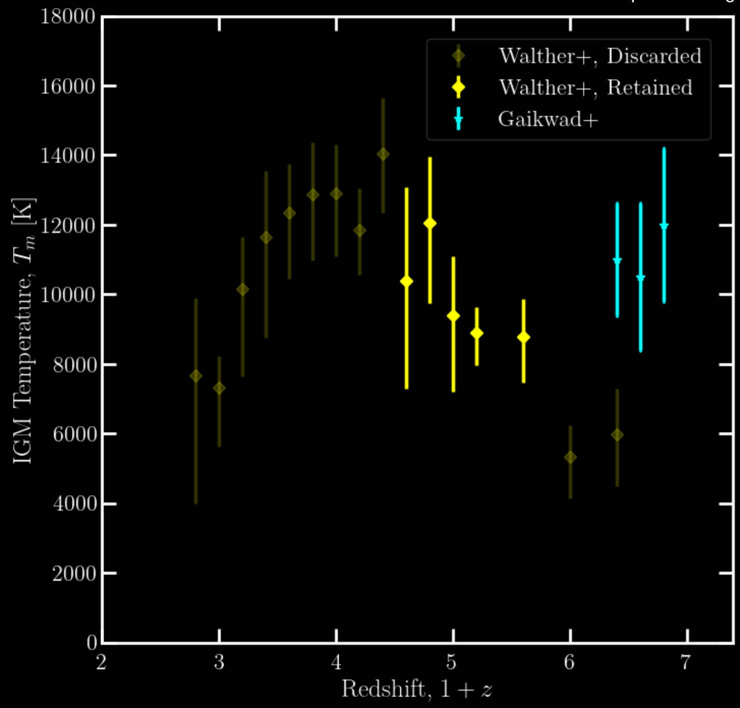


Resulting constraints on PBHs' existence



+

Image credit: https://arxiv.org/pdf/2008.01084



Next: Combine the computed temperature history with the temperature data

Resulting constraints on PBHs' existence

Modified χ^2 test:

We employ a modified χ^2 test, in which we penalize the prediction of temperature at a redshift, if it predicts a temperature higher than the observed temperature.

If the predicted temperature is less than observed temperature, the prediction is not penalized. This is in recognition of the fact that the gap between the prediction and observation could be due to neglecting heating due to reionization.

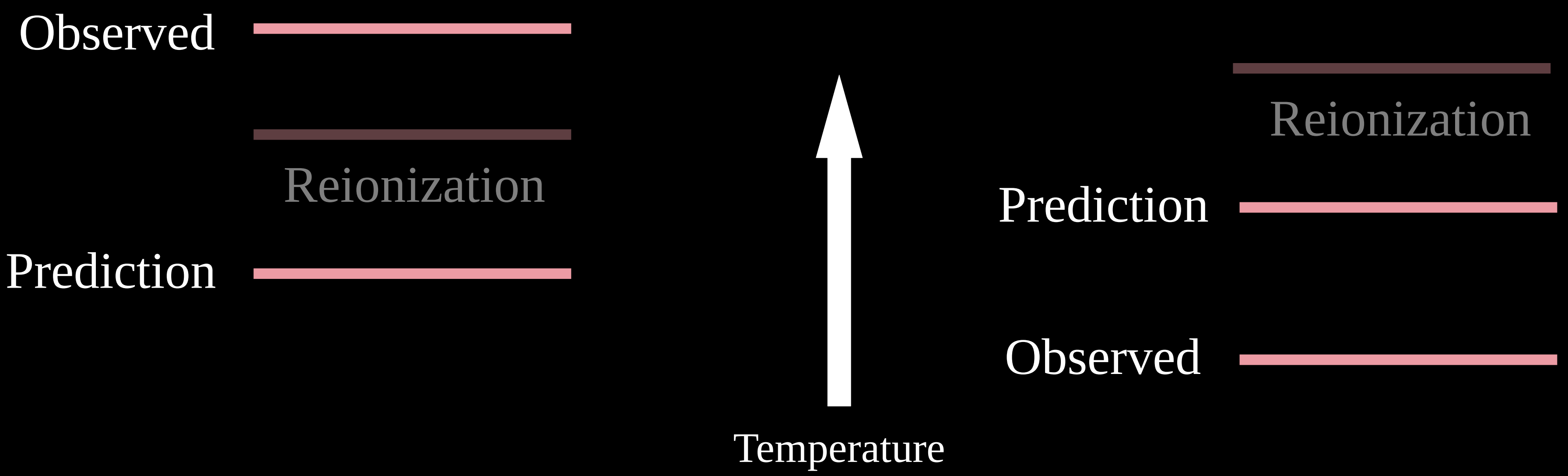
By employing this statistical test, we get conservative constraints.

Resulting constraints on PBHs' existence

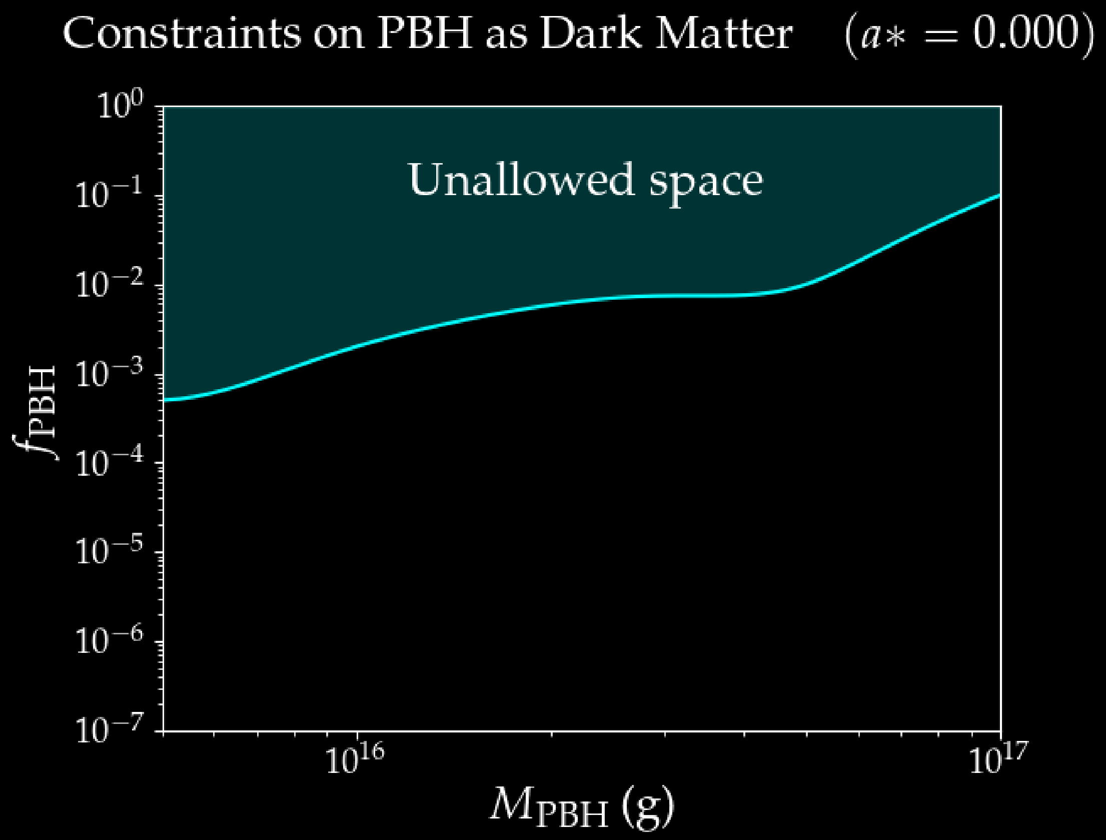
Modified χ^2 test:

Don't penalize PBH model

Penalize PBH model



Resulting constraints on PBHs' existence



Resulting constraints on PBHs' existence

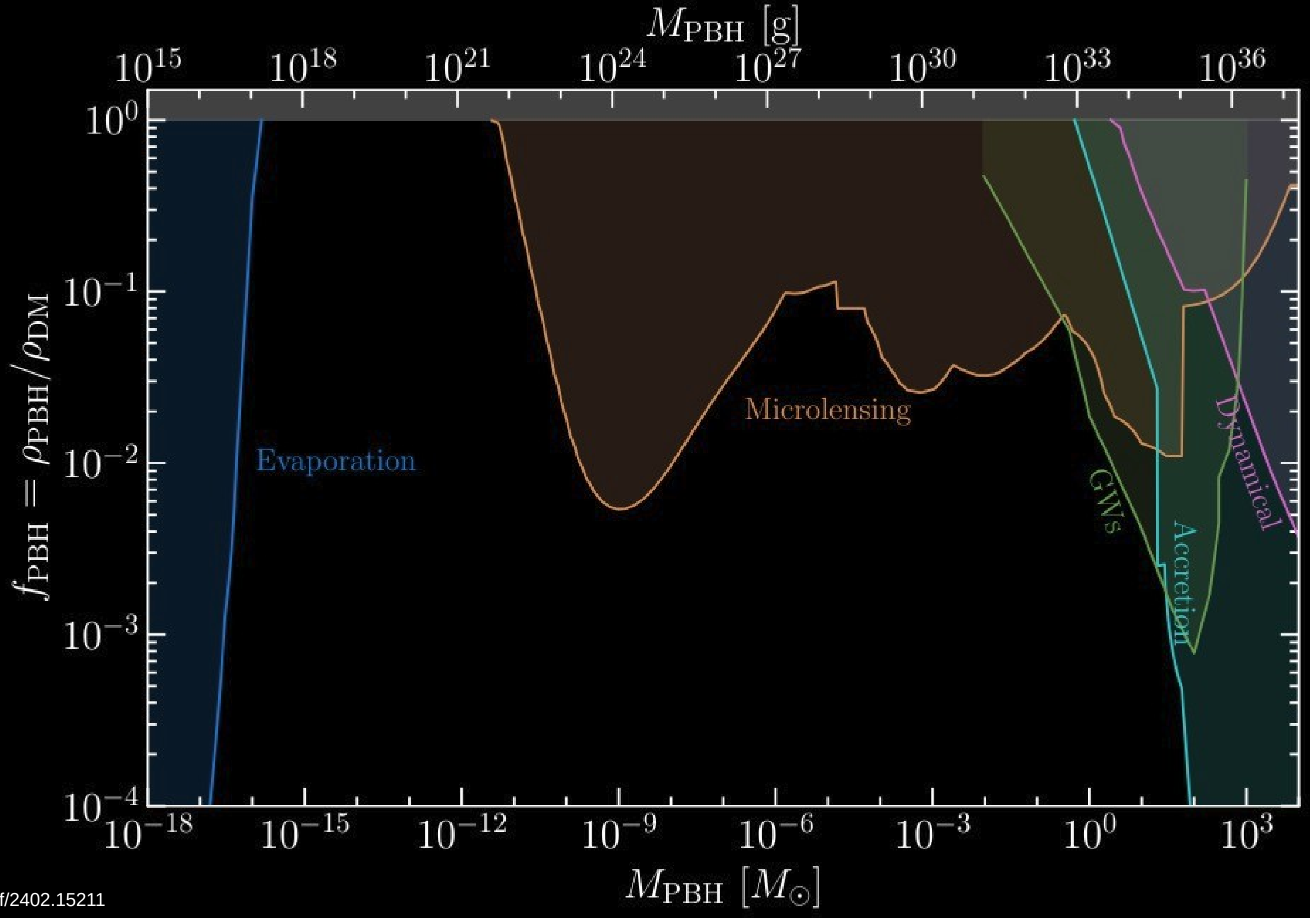
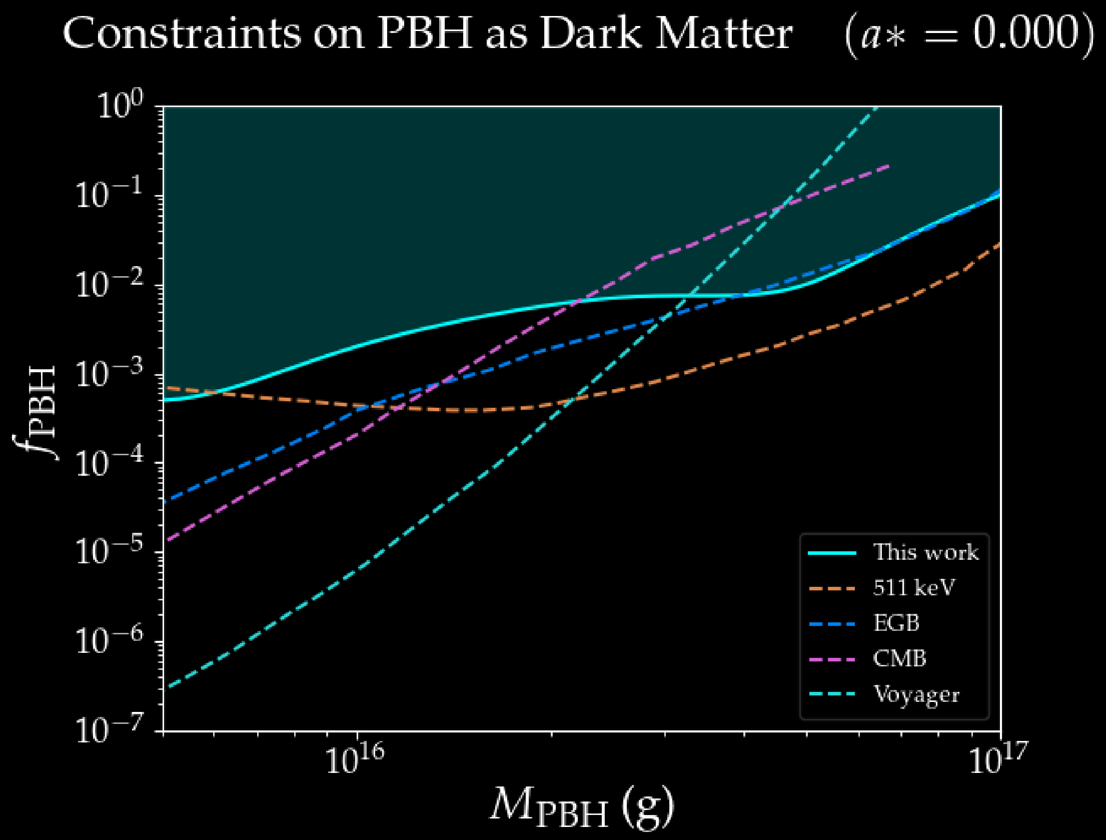
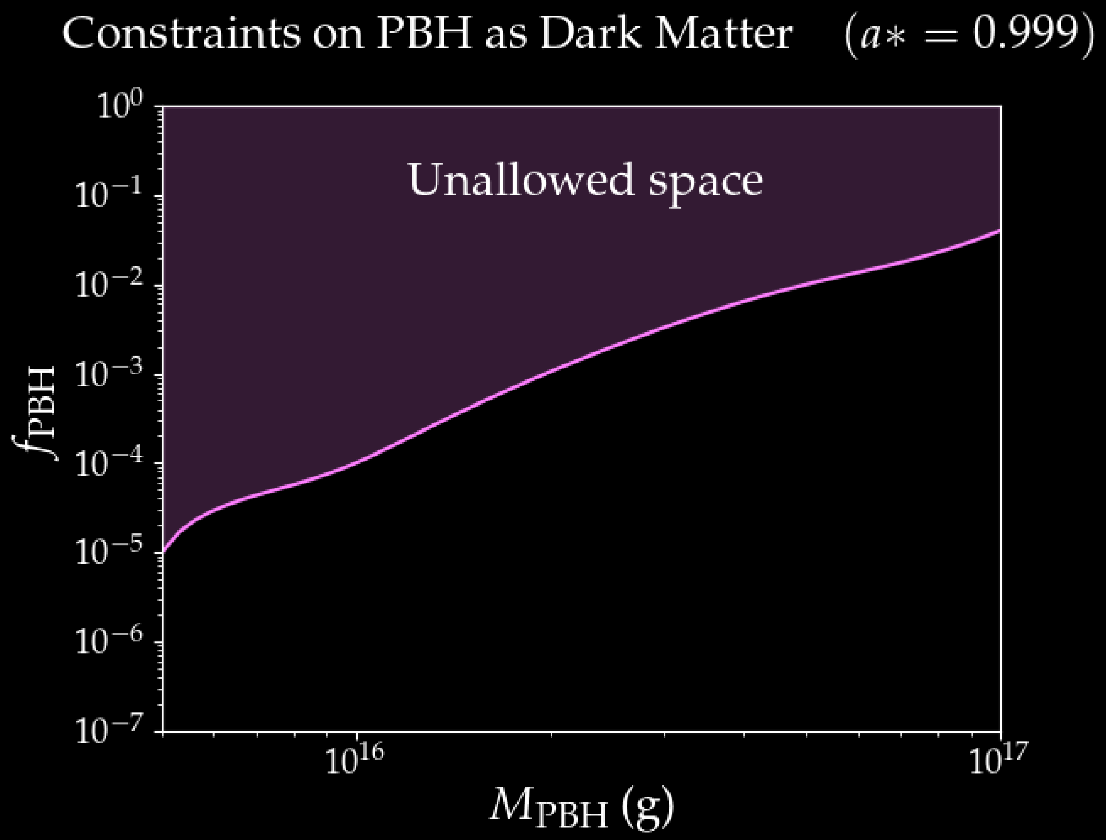


Image credit: https://arxiv.org/pdf/2402.15211

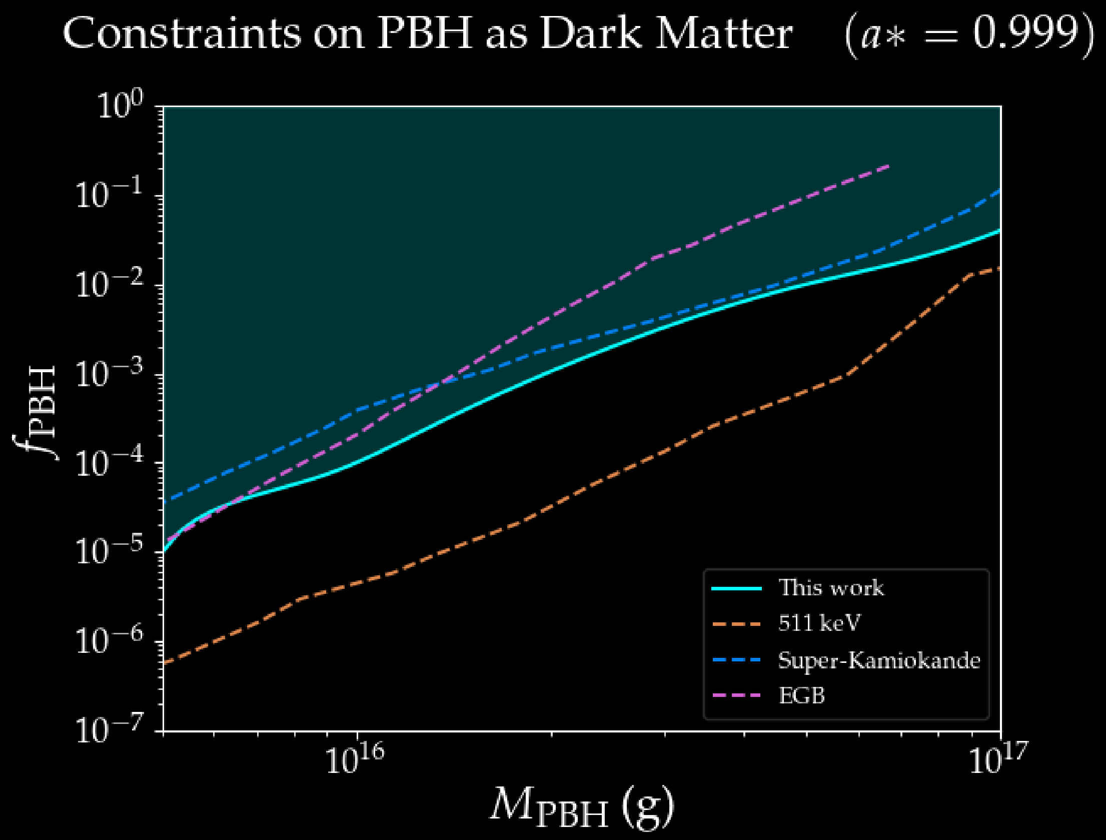
Resulting constraints on PBHs' existence



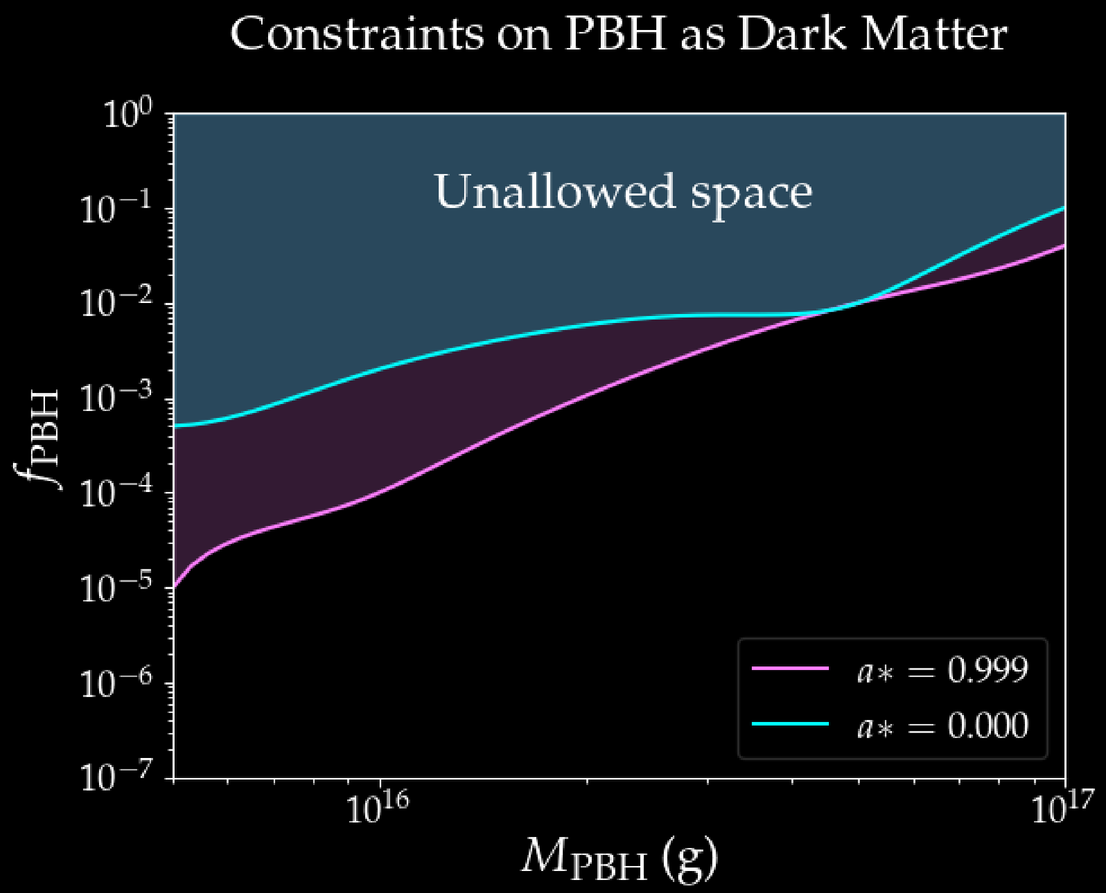
Resulting constraints on PBHs’ existence



Resulting constraints on PBHs' existence



Resulting constraints on PBHs' existence



Resulting constraints on PBHs' existence

Future work: Take into account the reionization processes, and the He- abundance in IGM.

PMRF teaching duties

Weekly classes on Newtonian mechanics at the M.E.S. College of Arts, Commerce and Science, Malleshwaram

Acknowledgements

- Dr. Ranjan Laha, for innumerable things.
- Akash Kumar Saha & Priyank Parashari- collaborators in this project, and for guidance otherwise too.
- Dr. Nirmal Raj, Dr. Prakash Gaikwad and Dr. Biplob Bhattacharjee for useful discussions.
- Dr. Chethan Krishnan, for helping in understanding a point the Hawking evaporation derivation.
- Deep Jyoti Das, Rinchen Sherpa, Jaya Doliya, Abhishek Dubey, Manish Kumar Tamta, Vishal Rao, Abhishek Dubey, Subhadip Bouri, Anuvab Sarkar, Aryaman Bhutani, Adarsh Singh for various productive discussions.
- Perimeter Institute, ICTP Trieste, Dr. David Tong, Dr. Daniel Baumann, Dr. Tobias Osborne, Dr. Sunil Mukhi, Late Prof. T. Padmanabhan for excellent pedagogic resources.

Summary

- Black Holes formed early in the universe, a.k.a Primordial Black Holes can constitute all/part of Dark matter.
- Hawking evaporation of PBHs in the mass range 5 x 1015 g to 1017 g can lead to direct and indirect observable consequences, providing a way to constrain these beasts.
- Hawking evaporation spectrum which is stable over cosmological time-scales is utilized to calculate its effect on the evolution of Inter-galactic medium’s temperature.
- The above is done by using `BlackHawk v2.0` to generate Hawking radiation spectra, and modifying and using `DarkHistory` to calculate the temperature evolution.
- The temperature of the IGM has been measured at some redshifts using the Lyman-α spectroscopy.
- By comparing the calculated temperature evolution of IGM assuming evaporating PBHs’ existence with the measured temperatue values leads to upper limits on fraction of Dark Matter in the form of PBHs.

Pandora’s Box

Image generated using Google Gemini

What is everything made of?

- - - *Planck* 2018 6-parameter fit to flat ΛCDM cosmology - - -		
baryon density of the Universe	$\Omega_b = \rho_b/\rho_{crit}$	$^{\ddagger}\,0.02237(15)\,h^{-2} = {}^{\dagger}\,0.0493(6)$
cold dark matter density of the Universe	$\Omega_c = \rho_c/\rho_{crit}$	$^{\ddagger}\,0.1200(12)\,h^{-2} = {}^{\dagger}\,0.265(7)$
100 × approximation to r_*/D_A	$100 \times \theta_{MC}$	$^{\ddagger}\,1.04092(31)$
reionization optical depth	τ	$^{\ddagger}\,0.054(7)$
ln(power prim. curv. pert.) $(k_0 = 0.05\,\mathrm{Mpc}^{-1})$	$\ln(10^{10}\Delta^2_{\mathcal{R}})$	$^{\ddagger}\,3.044(14)$
scalar spectral index	n_s	$^{\ddagger}\,0.965(4)$
pressureless matter density parameter	$\Omega_m = \Omega_c + \Omega_b$	$^{\dagger}\,0.315(7)$
dark energy density parameter	Ω_Λ	$^{\dagger}\,0.685(7)$

Image credit: PDG

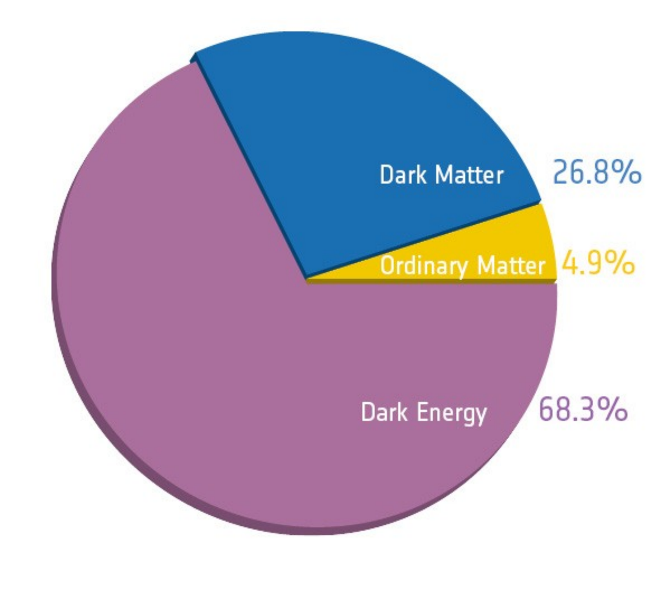


Image credit: Planck/ESA

Primordial Black Holes 101

- Black Holes formed in the early universe from the collapse of high matter-overdensities.
  - \- The same overdensities that form galaxies when not as high.

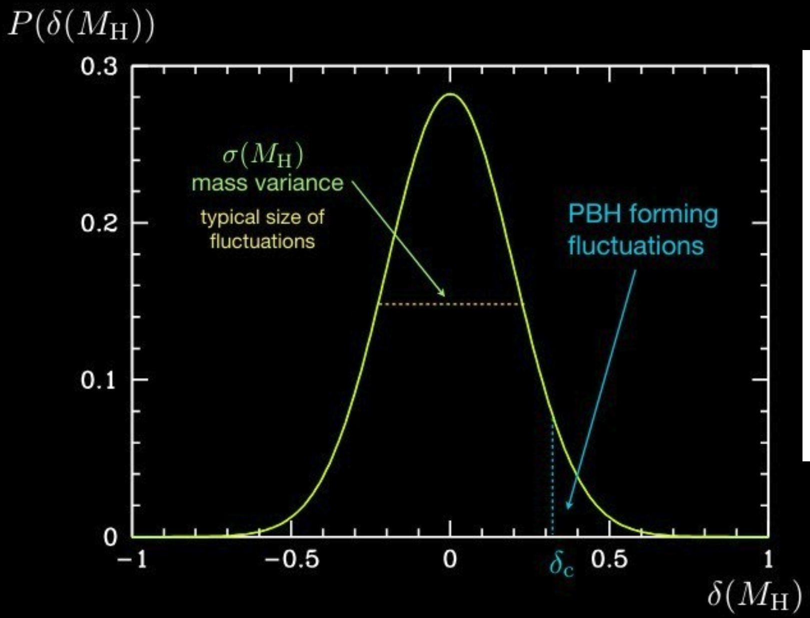


Image credit: https://arxiv.org/pdf/2402.15211

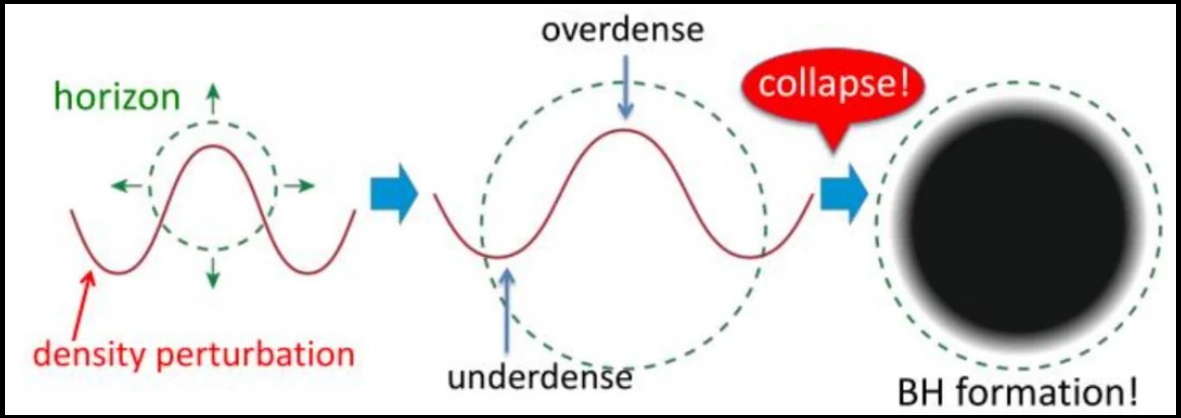
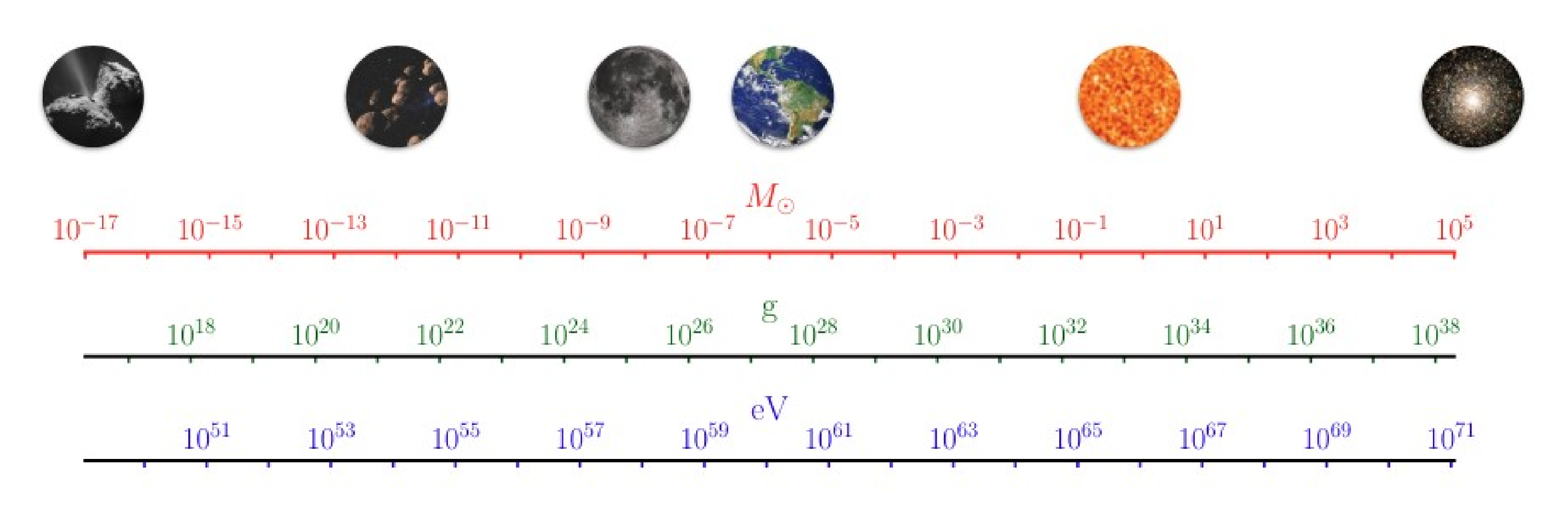


Image credit: https://commons.wikimedia.org/w/index.php?curid=131103715

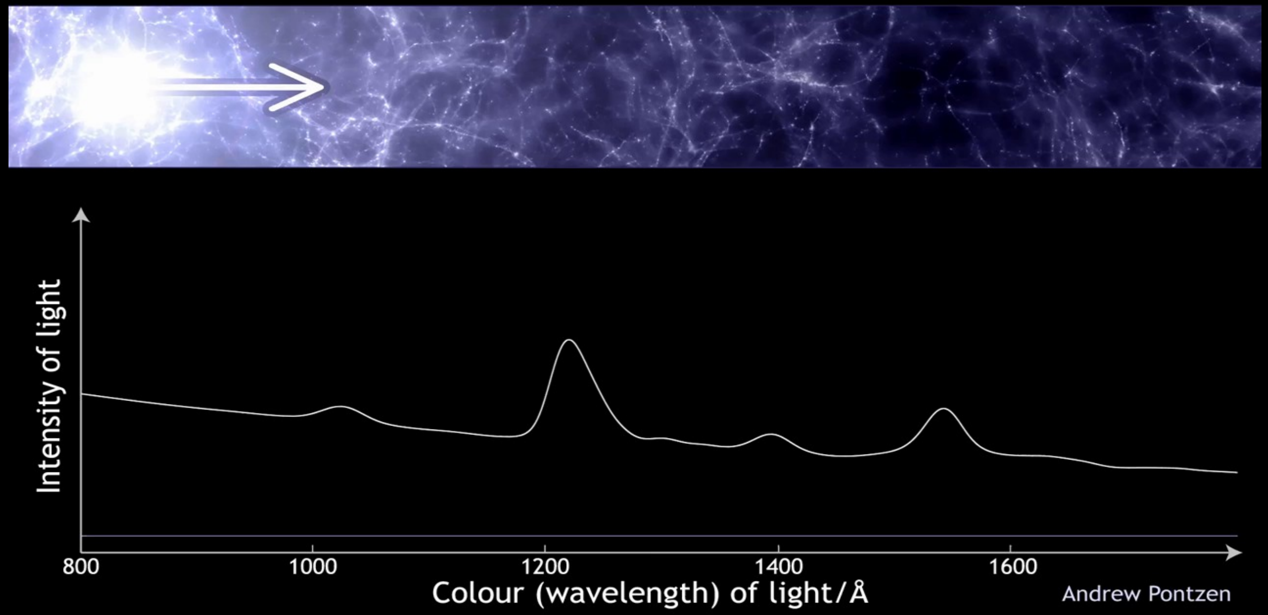
Primordial Black Holes 101



- They can be formed having a wide range of masses.

Image credit: Kavanagh GW4FP 2019

Lyman-α Forest



Video credit: UCL Mathematical and Physical Sciences YouTube channel
https://www.youtube.com/watch?v=6Bn7Ka0Tjjw

Lyman-α Forest

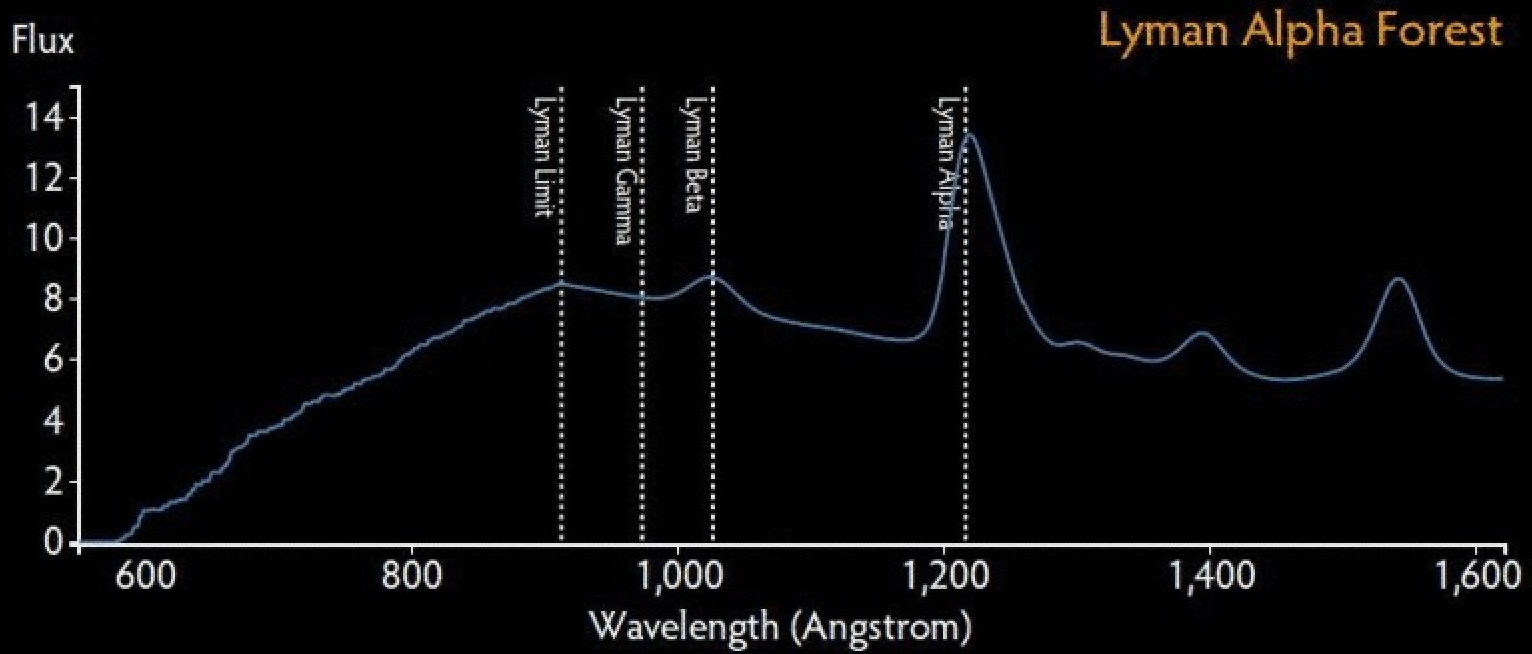


Image credit: Wikipedia
https://en.wikipedia.org/wiki/Lyman-alpha_forest#/media/File:Lyman-alpha_forest.gif

What Hawking radiation does to IGM's temperature: Results

- Direct recombinations to the ground state of hydrogen are very inefficient: each such event leads to a photon with energy greater than 13.6 eV, which almost immediately re-ionizes a neighboring hydrogen atom.
- Electrons therefore only efficiently recombine to the excited states of hydrogen, from which they cascade very quickly down to the first excited state, with principal quantum number $n = 2$.
- From the first excited state, electrons can reach the ground state $n = 1$ through two pathways:
  - Decay from the 2p state by emitting a Lyman-α photon. This photon will almost always be reabsorbed by another hydrogen atom in its ground state. However, cosmological redshifting systematically decreases the photon frequency, and there is a small chance that it escapes reabsorption if it gets redshifted far enough from the Lyman-α line resonant frequency before encountering another hydrogen atom.
  - Decay from the 2s state by emitting two photons. This two-photon decay process is very slow, with a rate[9] of 8.22 s^{-1}. It is however competitive with the slow rate of Lyman-α escape in producing ground-state hydrogen.
- Atoms in the first excited state may also be re-ionized by the ambient CMB photons before they reach the ground state. When this is the case, it is as if the recombination to the excited state did not happen in the first place. To account for this possibility, Peebles defines the factor C as the probability that an atom in the first excited state reaches the ground state through either of the two pathways described above before being photoionized.

This model is usually described as an "effective three-level atom" as it requires keeping track of hydrogen under three forms: in its ground state, in its first excited state (assuming all the higher excited states are in Boltzmann equilibrium with it), and in its ionized state.

Accounting for these processes, the recombination history is then described by the differential equation

$$\frac{dx_e}{dt} = -C\left(\alpha_B(T)n_p x_e - 4(1-x_e)\beta_B(T)e^{-E_{21}/T}\right),$$

Image credit: Wikipedia