Dark matter from evaporating Primordial Black Holes (PBHs)

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also in collaboration with J. Auffinger and G. Orlando

Talk based on:

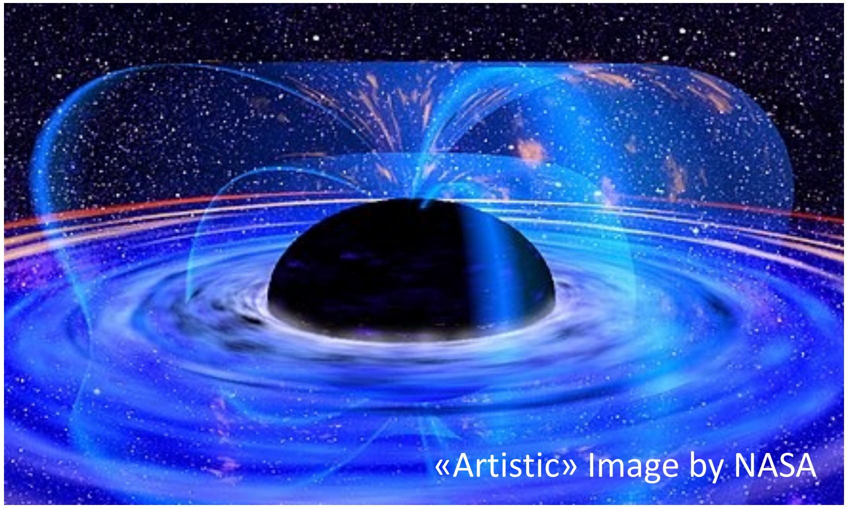
I. Masina, *Eur.Phys.J.Plus* 135 (2020) 7, 552 [2004.04740]

J. Auffinger, I. Masina, G. Orlando, *Eur.Phys.J.Plus* 136 (2021) 2, 261 [2012.09867]

I. Masina, [2103.13825]

«Light» PBHs are the ideal particle «factory»:

they emit any existing particle – SM and beyond – having mass below the PBHs Hawking temperature



«Artistic» Image by NASA

Evaporation of PBHs is an interesting mechanism for dark matter production
It received recently a lot of attention!

… and for dark radiation, see the next talk by J.Auffinger

OUTLINE

1) General introduction on PBHs:
formation, constraints, evaporation, lifetime

2) Dynamics of energy densities: radiation or BH domination,
abundance of the emitted particles

3) Stable particles from evaporating PBHs as dark matter: light/heavy case

Bounds on warm dark matter for the light case

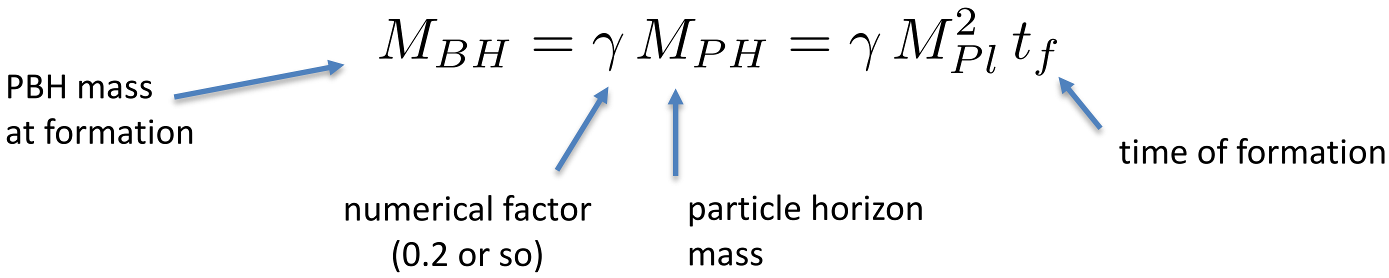
4) Conclusions

PBHs formation

PBHs could have formed in the very early Universe, during the radiation dominated era at the end of inflation, due to gravitational collapse of overdense regions

There are several mechanisms for PBHs formation [see e.g. the review by Carr et al 2002.12778]

and according to a general argument



$$M_{BH} = \gamma\, M_{PH} = \gamma\, M_{Pl}^2\, t_f$$

PBH mass
at formation

numerical factor
(0.2 or so)

particle horizon
mass

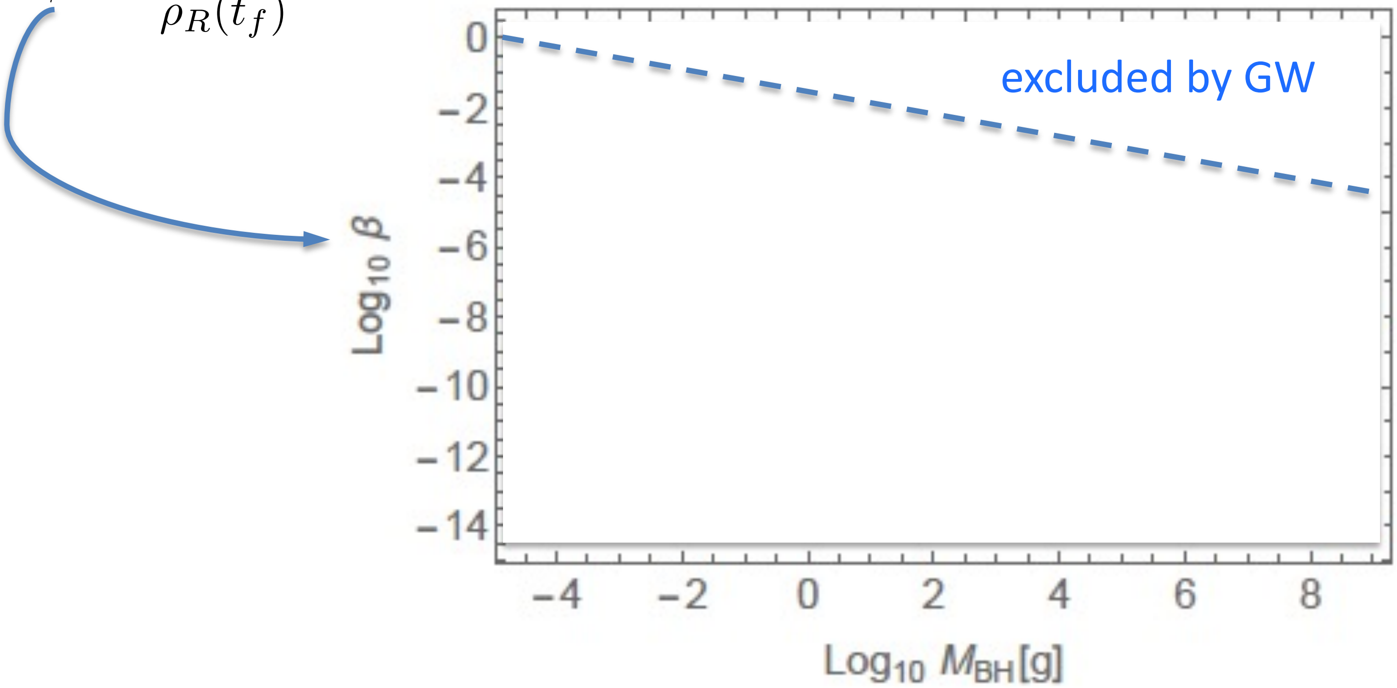
time of formation

Here we consider PBHs:

- ➢ Heavier than $M_{PL} = 10^{-5}$ g
- ➢ Which evaporated at $t < 1$ s (BBN) → lighter than 10^9 g

PBHs constraints

$$\beta = \frac{\rho_{BH}(t_f)}{\rho_R(t_f)}$$



This range is quite unconstrained, apart from gravitational waves (GW) induced by second order effects [Papanikolaou et al. 2020, Domenech et al. 2020, …]

PBHs evaporation / Schwarzschild

All particles with mass below Hawking temperature are emitted

$$k_B T_{BH} = \frac{1}{8\pi} \frac{(M_{Pl}c^2)^2}{M_{BH}c^2}$$

[Hawking 1974, Carr, Mac Gibbon,…]

Greybody factors

Instantaneous energy distribution

$$\frac{1}{g_i}\frac{d^2N_i}{dt\,dE} = \frac{1}{2\pi\hbar}\Gamma_{s_i}(E,T_{BH}((t))\frac{1}{e^{\frac{E}{k_B T_{BH}(t)}} - (-1)^{2s_i}}$$

PBHs evaporation / Schwarzschild

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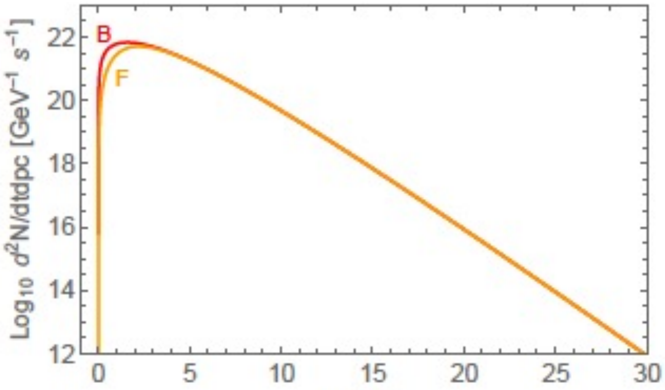
Geometrical optics

$$\Gamma_{s_i} \xrightarrow{E \to \infty} \frac{27}{(8\pi)^2} \left(\frac{E}{k_B T_{BH}(t)} \right)^2$$

At t_f

$$\frac{1}{g_i} \frac{d^2 N}{dt\, dE}$$



$$E / k_B T_{BH}$$

PBHs evaporation / Schwarzschild

All particles with mass below Hawking temperature are emitted

$$k_B T_{BH} = \frac{1}{8\pi}\frac{(M_{Pl}c^2)^2}{M_{BH}c^2}$$

[Hawking 1974, Carr, Mac Gibbon,...]

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Instantaneous energy distribution

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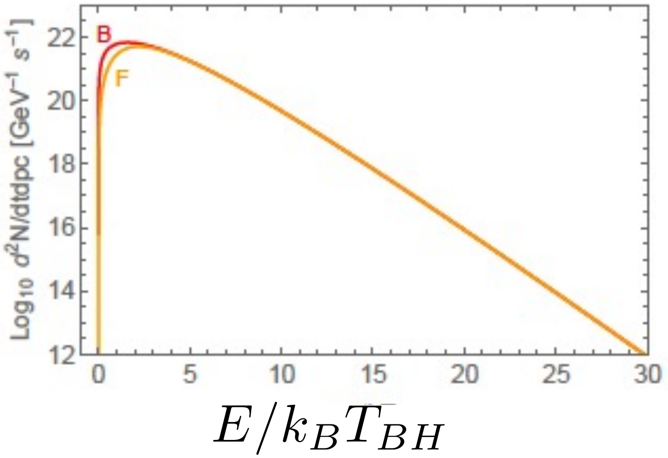
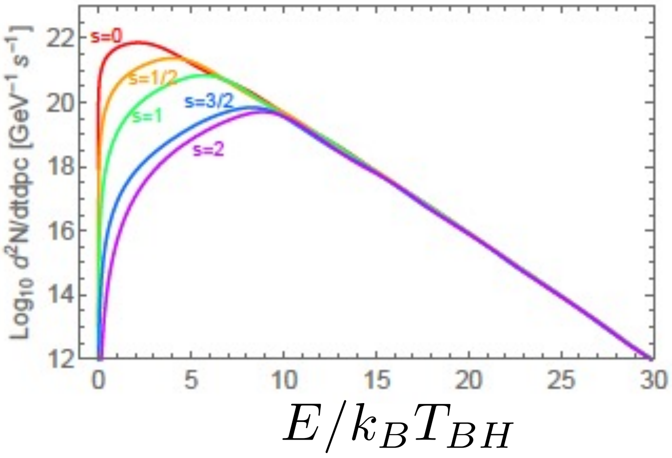
BlackHawk [Arbey Auffinger 2020]

At t_f

$$\frac{1}{g_i}\frac{d^2N}{dt\,dE}$$



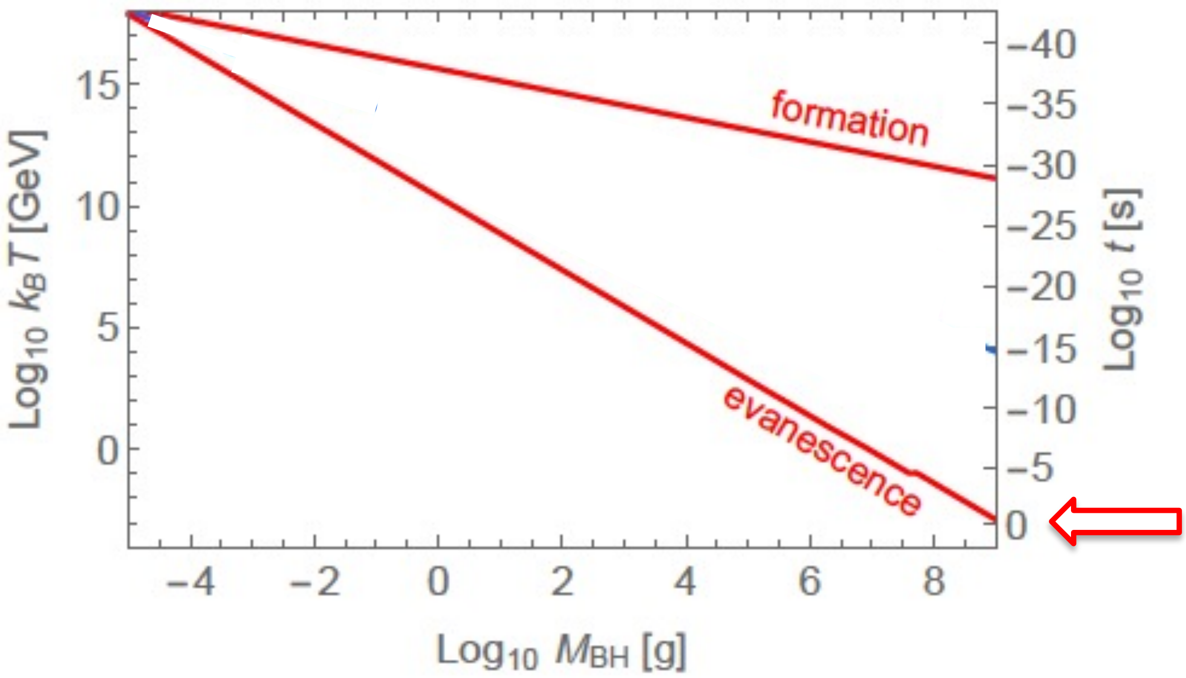


PBHs lifetime / Schwarzschild

Rate of mass loss

Page function

$$\frac{dM_{BH}}{dt} = -\frac{c^2 M_{Pl}^4}{\hbar} \frac{f(M_{BH})}{M_{BH}^2} \xrightarrow{\text{f const}} \frac{\tau}{\hbar} = \frac{1}{3f(M_{BH})} \frac{(M_{BH}c^2)^3}{(M_{Pl}c^2)^4}$$



Evaporation before BBN

The plot is for SM: shortening of lifetime by few % for additional particles

PBHs evaporation and lifetime / Kerr

All particles with mass below Hawking temperature are emitted

$$k_B T_{BH} = \frac{1}{8\pi}\frac{(M_{Pl}c^2)^2}{M_{BH}c^2}\frac{2}{1+\frac{1}{\sqrt{1-a_*(t)^2}}}$$

Spin parameter

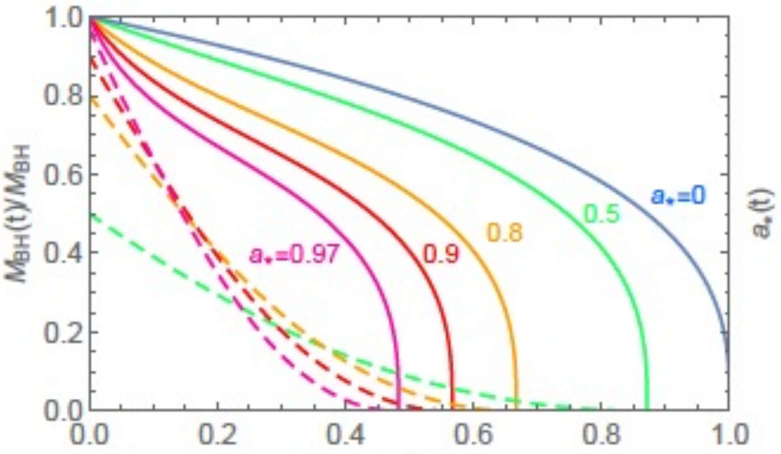
$$a_* = \frac{J}{\hbar}\frac{M_{Pl}^2}{M_{BH}^2}$$

Instantaneous energy distribution

Greybody factors

$$\frac{1}{g_i}\frac{d^2N_i}{dt\,dE} = \frac{1}{2\pi\hbar}\sum_{\ell,m}\Gamma_{s_i\ell m}(E,M_{BH}(t),a_*(t))\frac{1}{e^{\frac{E'}{k_B T_{BH}(t)}}-(-1)^{2s_i}}$$

For the Kerr case,
the shortening of lifetime
is by at most ½ even for
extremal PBHs



$$\alpha_K = t_{ev}/t_{ev}^S$$

S=Schwarzschild

OUTLINE

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Dynamics of the energy densities

Radiation

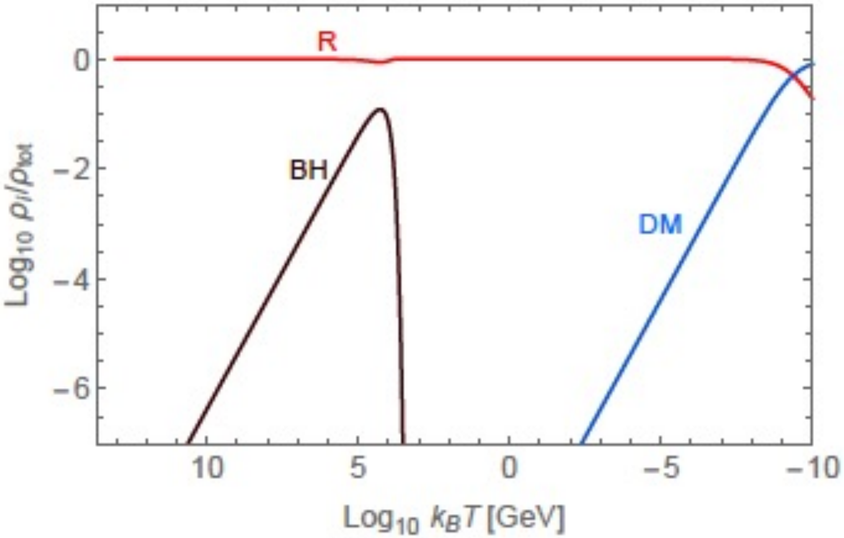
BHs (matter)

$$\begin{cases} \dfrac{d\rho_R}{dt} + 4H\rho_R = -\dfrac{dM_{BH}/dt}{M_{BH}}\rho_{BH} \\ \dfrac{d\rho_{BH}}{dt} + 3H\rho_{BH} = \dfrac{dM_{BH}/dt}{M_{BH}}\rho_{BH} \end{cases}$$

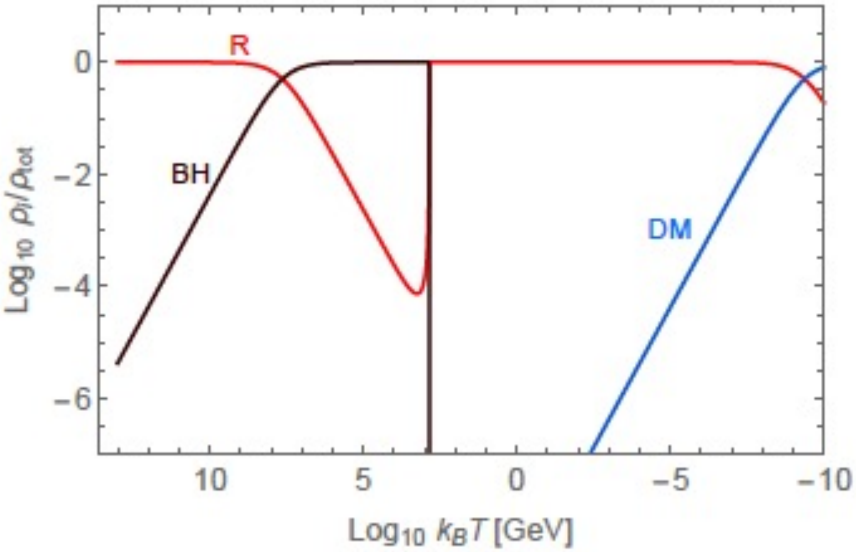
$\Rightarrow$ $f(t) = \dfrac{\rho_{BH}(t)}{\rho_R(t)} \propto a(t)$

Depending on the value of β, there are two scenarios

Radiation domination



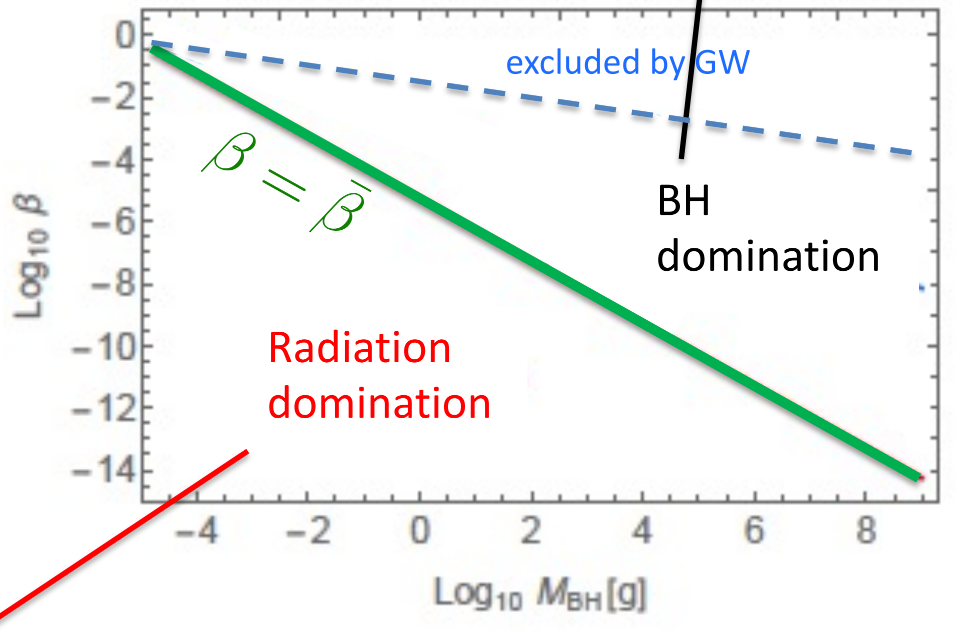
BH domination



Abundance of the PBHs at evaporation

$$Y_{BH}(t_{ev}) = \frac{1}{\alpha_K^{1/2}}(3f_S(M_{BH}))^{1/2}\,\frac{3}{4}\left(\frac{45}{16\pi^3 g_*(t_{ev})}\right)^{1/4}\left(\frac{M_{Pl}}{M_{BH}}\right)^{5/2}$$

depends on α_K, not on β



$$Y_{BH}(t_{ev}) = \beta\,\gamma^{1/2}\,\frac{3}{4}\left(\frac{45}{16\pi^3 g_*(t_{ev})}\right)^{1/4}\left(\frac{M_{Pl}}{M_{BH}}\right)^{3/2}$$

depends on β, not on α_K

Present abundance of the emitted X particles

$$Y_X(t_{now}) = \frac{1}{\alpha} N_X \, Y_{BH}(t_{ev})$$

Possible entropy production

$\alpha(sa^3)_{ev} = (sa^3)_{now}.$

Number of X particles emitted by each BH

HEAVY CASE

$M_X c^2 > k_B T_{BH}$

LIGHT CASE

$M_X c^2 < k_B T_{BH}$

To calculate N_X we need the integrated spectrum at the evaporation (using BlackHawk)

Number of X particles emitted by a PBH

redshift effect

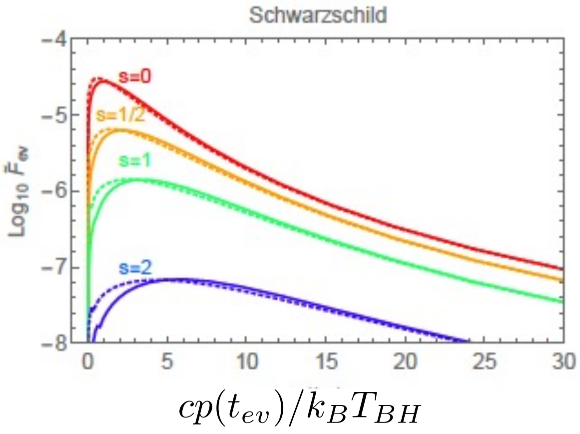
Integrated spectrum at evaporation

$$\frac{1}{g_i}\frac{dN_i}{d(cp)}(t_{ev}) = \int_{t_{em}}^{t_{ev}} dt\, \frac{d^2N}{dt\, d(cp(t))}\left(\underbrace{cp(t_{ev})\frac{a(t_{ev})}{a(t)}}_{cp(t)}, T_{BH}(t), a_*(t)\right)\frac{a(t_{ev})}{a(t)}$$

Define the adimensional

$$\tilde{F}_{s_i}(x(t_{ev})) \equiv \frac{(k_B T^S_{BH})^3}{(M_{Pl}c^2)^2}\frac{1}{g_i}\frac{dN_i}{d(cp)}(t_{ev})$$

For the LIGHT case



Number of X particles emitted by a PBH

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Integrated spectrum at evaporation

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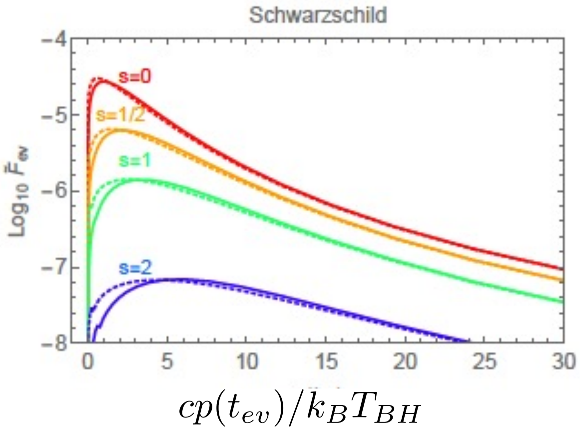

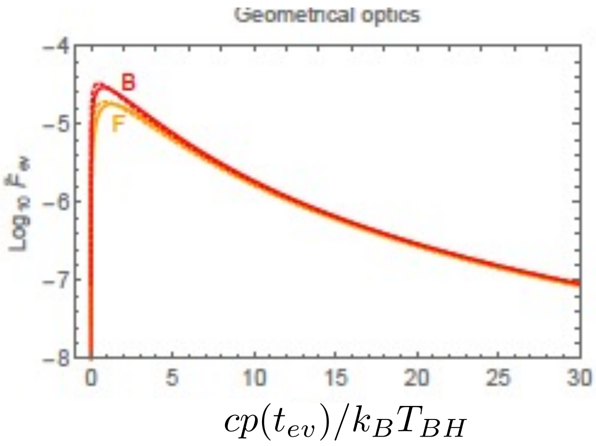

Good approx. for s=0, quite good for s=1/2

Number of X particles emitted by a PBH

redshift effect

Integrated spectrum at evaporation

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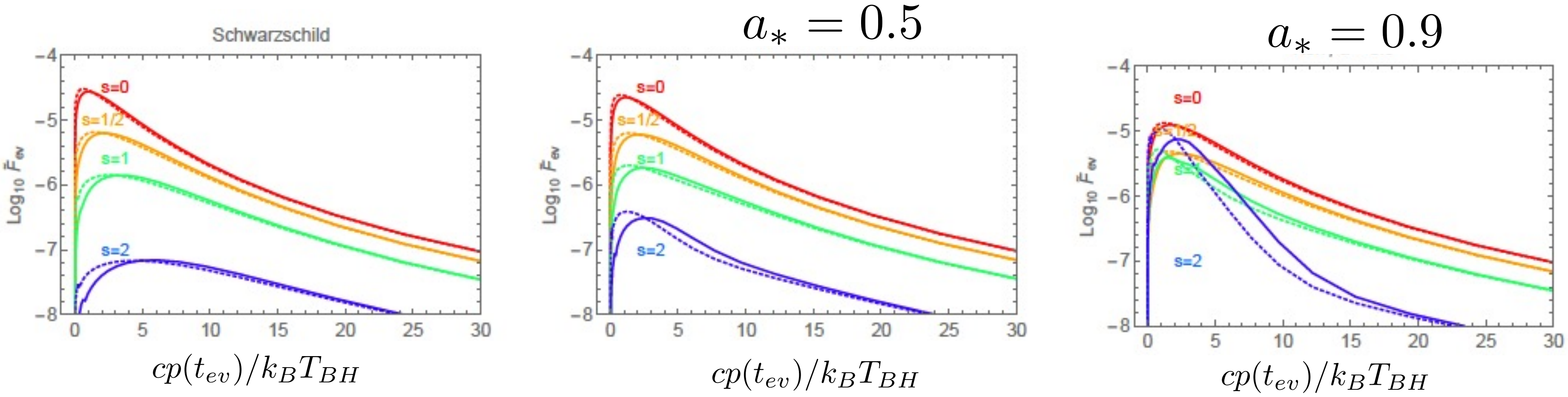
For the LIGHT case



Number of X particles emitted by a PBH

redshift effect

Integrated spectrum at evaporation

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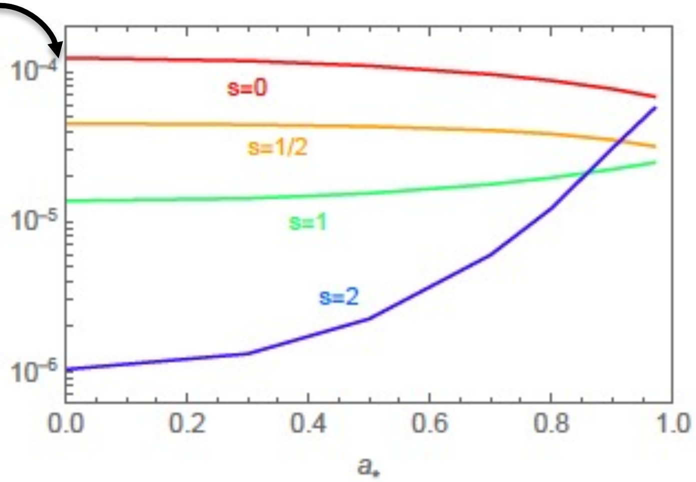
$$\tilde{F}_{s_i}(x(t_{ev})) \equiv \frac{(k_B T_{BH}^S)^3}{(M_{Pl}c^2)^2}\frac{1}{g_i}\frac{dN_i}{d(cp)}(t_{ev})$$

For the LIGHT case

Baumann et al [2007] simple approx $N_X = \frac{g_{X,H}}{g_{*,H}}\frac{4\pi}{3}\left(\frac{M_{BH}}{M_{Pl}}\right)^2$

$$N_i = (8\pi)^2\frac{M_{BH}^2}{M_{Pl}^2}\, g_i \boxed{\int_0^\infty dx(t_{ev})\, \tilde{F}_{s_i}(x(t_{ev}))}$$

$$= \tilde{\phi}_{s_i}$$



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Dark matter from PBHs evaporation

If the particle X is stable and non interacting

Present abundance of the emitted X particles

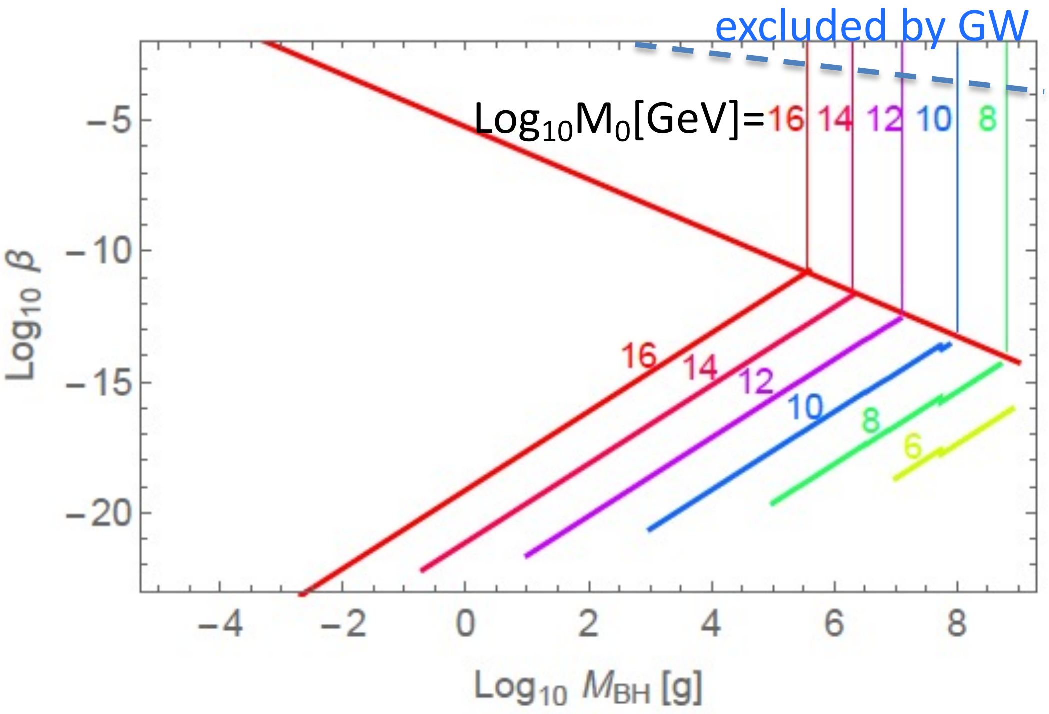
$$\Omega_X = \frac{\rho_X}{\rho_c} = \frac{M_X\, s(t_{now})}{\rho_c} Y_X(t_{now})$$

TWO SCENARIOS

according to the HEAVY or LIGHT case

HEAVY case for Schwarzschild

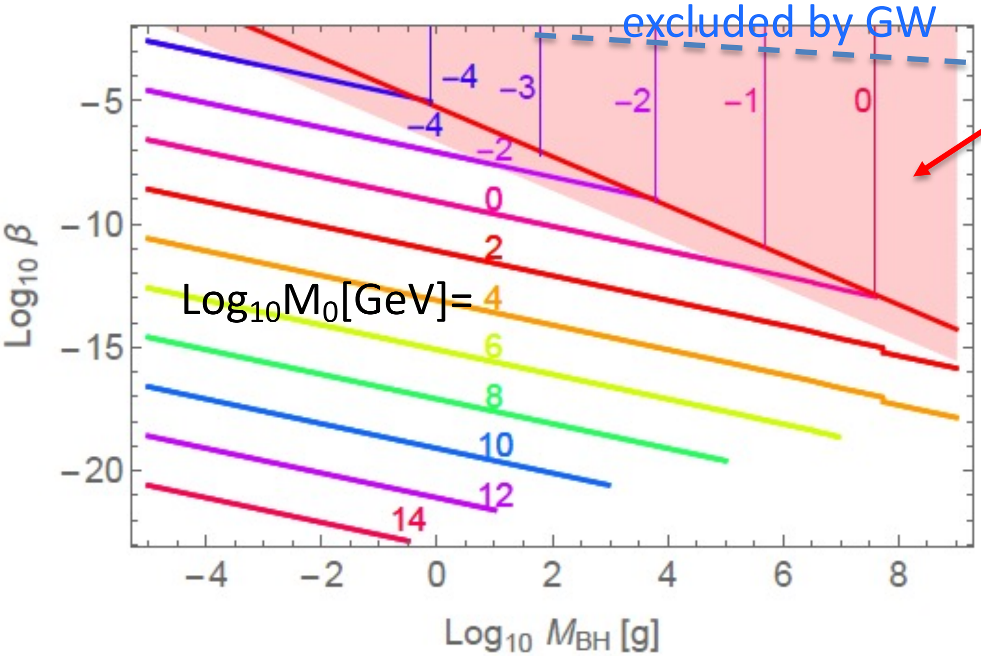
Assuming all DM made by stable X particles with s=0 and mass M_0
(geometrical optics agrees with BlackHawk)



Candidates: stable right-handed neutrinos, stable GUT particles, …

LIGHT case for Schwarzschild

Assuming all DM made by stable X particles with s=0 and mass M_0
(geometrical optics agrees with BlackHawk)

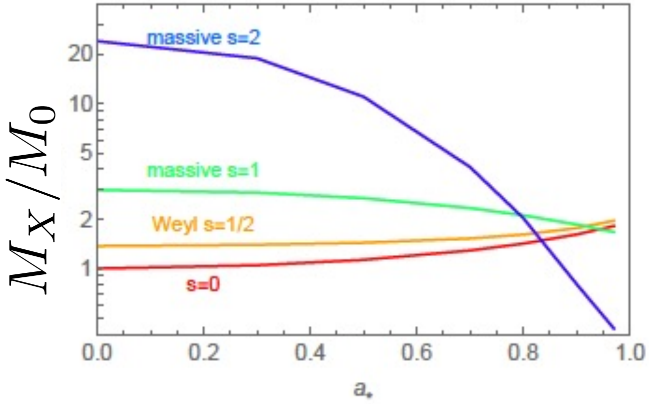


Region excluded by constraints from structure formation on warm DM

$$\beta/\bar{\beta} \lesssim 0.01$$

Candidates: axions, stable right-handed neutrinos, LSP, ….

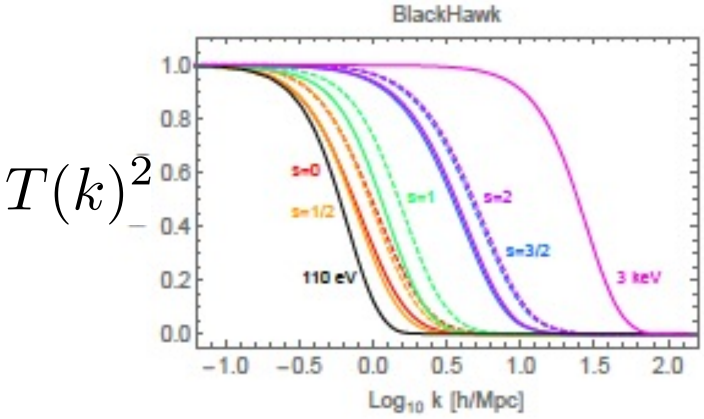
For other spins and Kerr case



Constraints on WDM for LIGHT case / Schwarschild

Many improvements in the calculation in the last years

- Fujita et al 2014: simple argument to adapt the constraints on thermal WDM to the case of DM from PBHs, within the geometrical optics approx (good for s=0)
- Lennon et al 2017: inclusion of redshift effect and hints to spin effect
- Baldes et al 2020: improve method by calculating the WDM phase space distribution to be put in CLASS to get the trasfer function T(k) for comparison with observational constraints
- Auffinger Masina Orlando 2020: further improves Baldes et al method by including spin effects



s=0 s=½ s=1 s=3/2 s=2

$$\frac{\beta}{\bar{\beta}} \lesssim (0.013, 0.015, 0.029, 0.15, 0.16)$$

tension reduced for increasing spin

Constraints on WDM for LIGHT case / Kerr

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- Auffinger Masina Orlando 2020: further improves Baldes et al method by including spin effects

- Masina 2020: the Kerr case does not help: no significant differences for s=0,1/2,1,
  tension is exacerbated for s=2 and large a_*

WAYS to avoid tension with structure formation:

- Entropy production mechanism at work [Fujita et al 2014]
- Thermalization with number changing interactions [Bernal et al 2020]

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Conclusions

Evaporation of PBHs with masses between 10^{-5} g and 10^{9} g

is an elegant VIABLE mechanism to account for DM (and DR)

HEAVY DM

both radiation and BH domination are allowed

LIGHT DM

only radiation domination allowed,
due to constraints from structure formation

… but ways out have been proposed
(entropy, thermalization)

Still open field for research (even after 40 years)!