Dark matter and dark radiation from evaporating Primordial Black Holes (PBHs)

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«Artistic» Image by NASA

also in collaboration with J. Auffinger and G. Orlando

Talk based on:

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

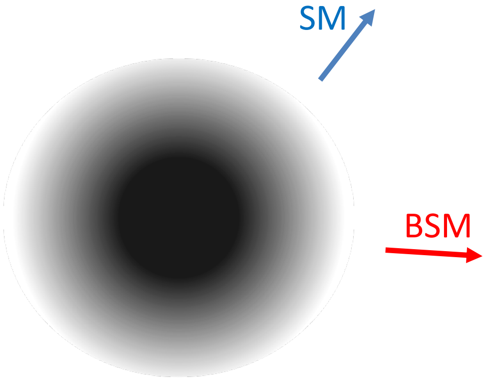
J. Auffinger, I. Masina, G. Orlando, *Eur.Phys.J.Plus* 136 (2021) 2, 261 [2012.09867]

I. Masina, *Grav.Cosmol.* 27 (2021) 4, 315-330 [2103.13825]

«Light» PBHs (if any) would be an ideal «particle factory»:

they would emit any existing particle – SM and (if any) BSM –
with mass below the PBHs Hawking temperature
[Hawking 1974, Carr, Page, Mac Gibbon,…]

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



M_{BH}= 10^-5(9) g → $M_{emitted}$ < 10^18(4) GeV → 🥳

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

OUTLINE

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

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

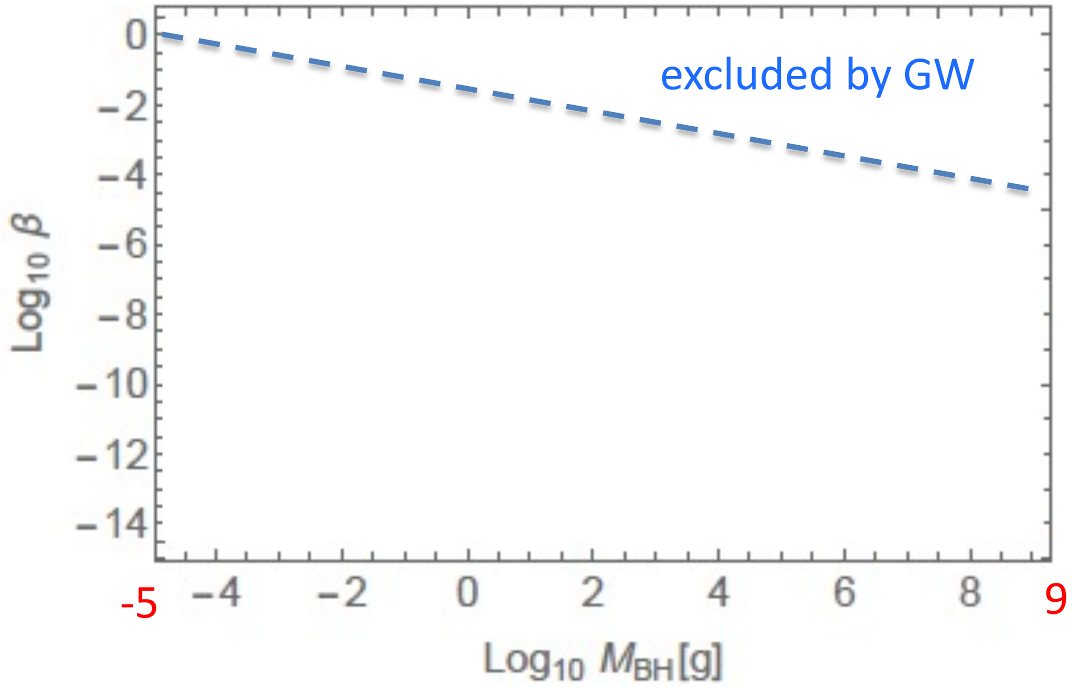
Here we consider PBHs:

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

PBHs constraints

PBHs density/Radiation density at time of formation

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



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, Page, Mac Gibbon,…]

with instantaneous energy distribution

Greybody factors

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

PBHs evaporation / Schwarzschild

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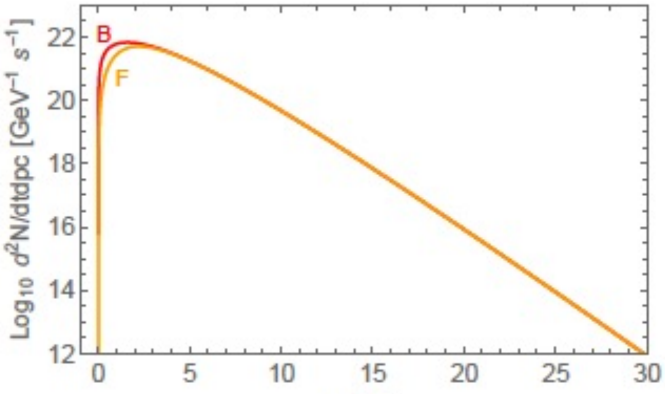
Geometrical optics

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

At t_f

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



$$E/k_BT_{BH}$$

PBHs evaporation / Schwarzschild

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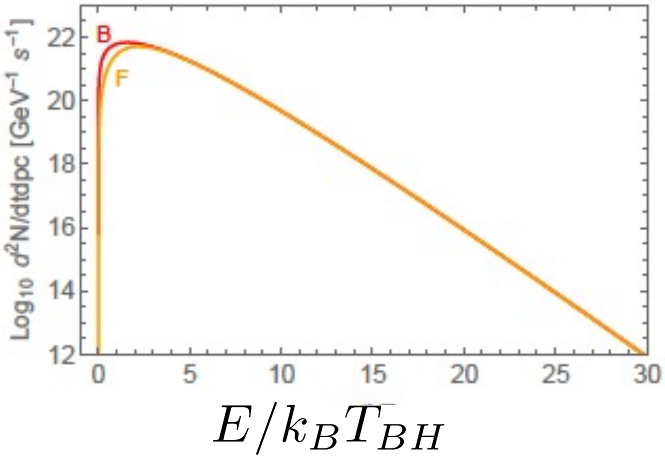
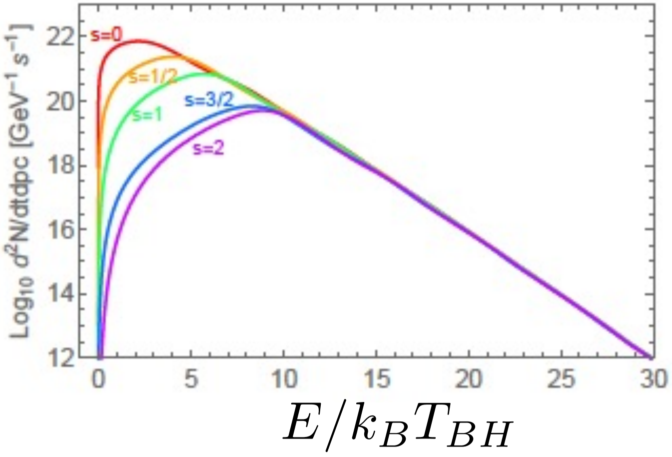
BlackHawk [Arbey Auffinger 2020]

At t_f

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





PBHs lifetime / Schwarzschild

Rate of mass loss

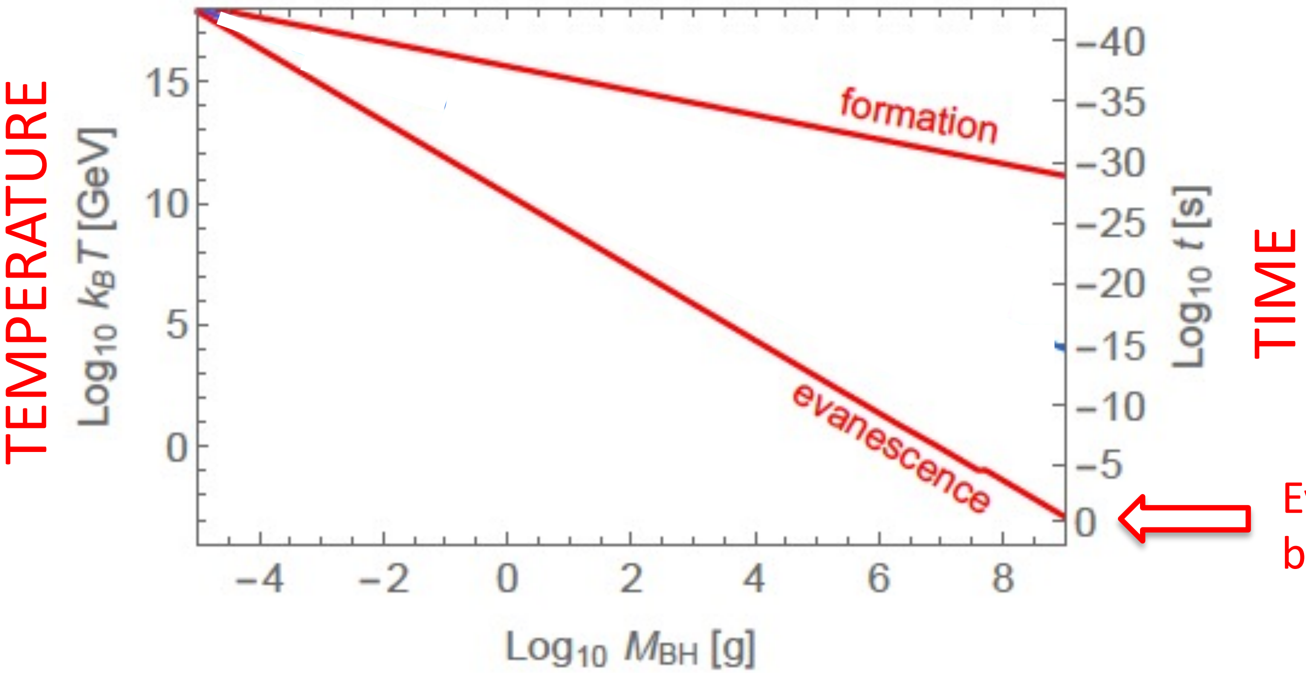
Page function (#dof)

$$\frac{dM_{BH}}{dt} = -\frac{c^2 M_{Pl}^4}{\hbar} \frac{f(M_{BH})}{M_{BH}^2}$$

f const

$$\frac{\tau}{\hbar} = \frac{1}{3f(M_{BH})} \frac{(M_{BH}c^2)^3}{(M_{Pl}c^2)^4}$$

The plot is for SM



Evaporation before BBN

Shortening of lifetime by: few % for few additional particles BSM; by about 1/2 for SUSY

PBHs evaporation and lifetime / Kerr

[Kerr 1963, Page 1976,…]

All particles with mass below Hawking temperature are emitted

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

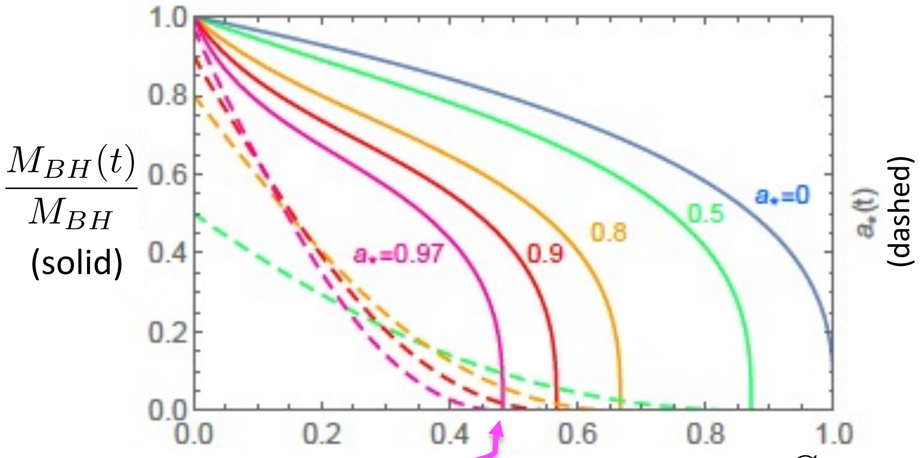
Spin parameter

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

with instantaneous energy distribution

Greybody factors

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



In 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

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

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

Dynamics of the energy densities

Radiation

BHs (matter)

$$\begin{cases} \dfrac{d\rho_R}{dt} + 4H\rho_R = -\dfrac{dM_{BH}/dt}{M_{BH}}\rho_{BH} \\[2ex] \dfrac{d\rho_{BH}}{dt} + 3H\rho_{BH} = \dfrac{dM_{BH}/dt}{M_{BH}}\rho_{BH} \end{cases} \Rightarrow \quad f(t) = \frac{\rho_{BH}(t)}{\rho_R(t)} \propto a(t)$$

Depending on β, one or the other «dominates» at BH evaporation

[Barrow et al 1991, …]

Dynamics of the energy densities

Radiation

BHs (matter)

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

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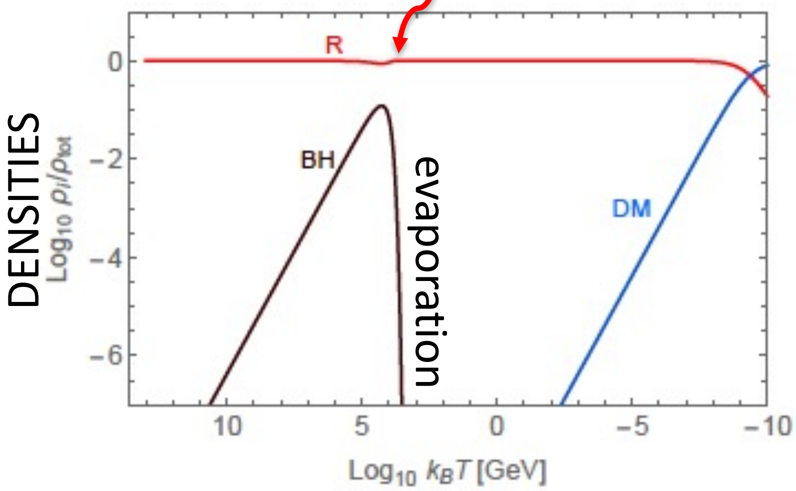
Depending on β, one or the other «dominates» at BH evaporation

EXAMPLE: $M_{BH}=10^4$ g → $T_f = 10^{13}$ GeV , $T_{ev} = 10^4$ GeV

☆ $\beta=10^{-10}$

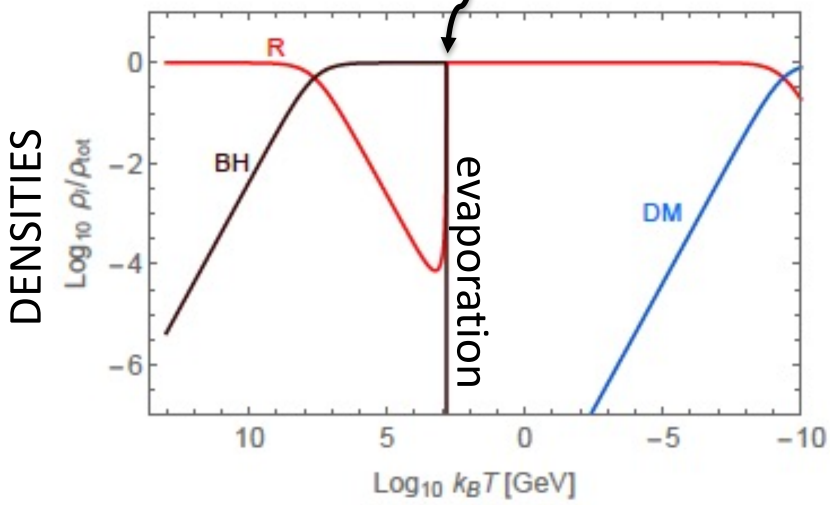
Radiation domination



← TEMPERATURE

☆ $\beta=10^{-6}$

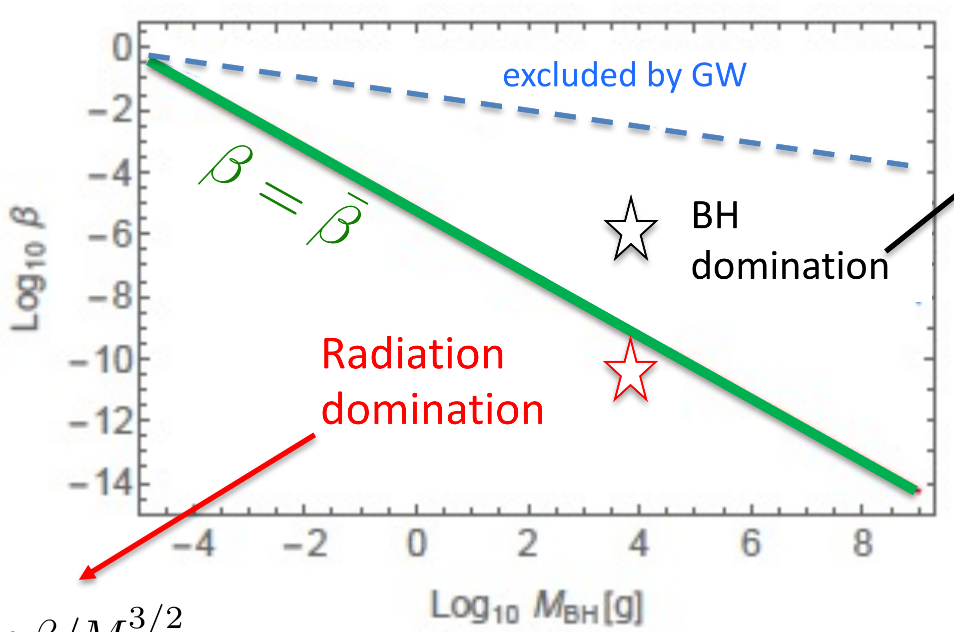
BH domination



← TEMPERATURE

Abundance of the PBHs at evaporation

$Y_{BH}(t_{ev}) = n_{BH}(t_{ev})/s(t_{ev})$ is a crucial quantity



$$Y_{BH}(t_{ev}) \propto 1/M_{BH}^{5/2}$$

independent on β

$$Y_{BH}(t_{ev}) \propto \beta/M_{BH}^{3/2}$$

linear dependence on β

Present abundance of an emitted stable non-interacting X particle

Assume that PBHs emit STABLE NON-INTERACTING (BSM) X particles

$$Y_X(t_{now}) = \frac{n_X(t_{now})}{s(t_{now})} = \frac{1}{\alpha}\frac{n_X(t_{ev})}{s(t_{ev})} = \frac{1}{\alpha}N_X \underbrace{\frac{n_{BH}(t_{ev})}{s(t_{ev})}}_{=Y_{BH}(t_{ev})}$$

Possible entropy production

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

Number of X particles emitted by each BH

LIGHT CASE

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

emitted since BH formation

HEAVY CASE

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

emitted after BH formation

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emitted after BH formation

To calculate N_X we need the integrated spectrum at the evaporation:
Numerical methods (e.g. BlackHawk) / Approximate analytical methods

Better account of spin dep for «high spins»
s>1/2

Reliable for «low spins»
s=0,1/2

Technicalities about N_X calculation

redshift effect

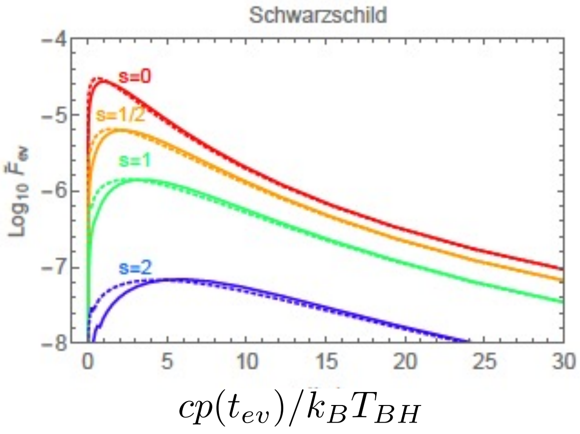
Integrated spectrum at evaporation

(X=i)

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

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 and Schwarzschild



Numerical method

Technicalities about N_X calculation

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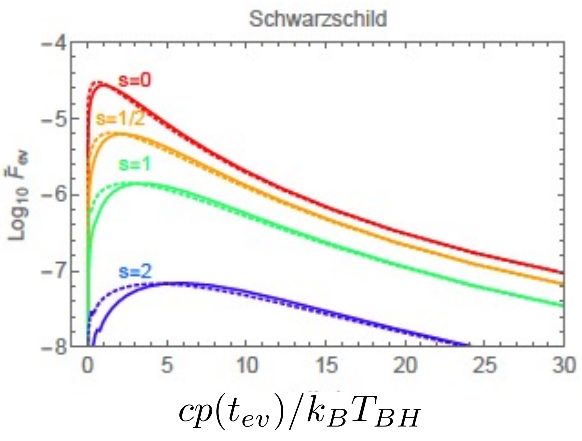
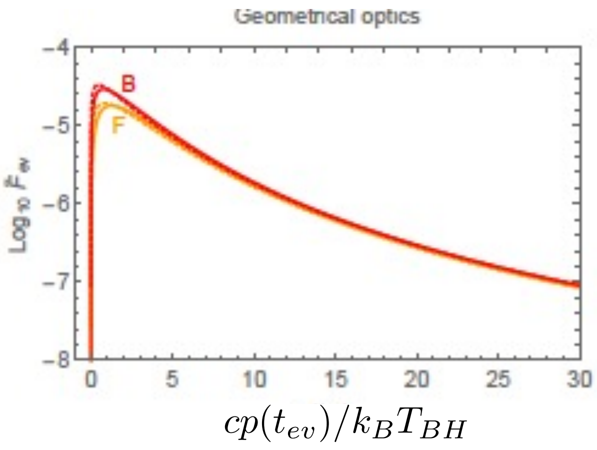


Numerical method



Analytical method

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

Technicalities about N_X calculation

redshift effect

Integrated spectrum at evaporation

(X=i)

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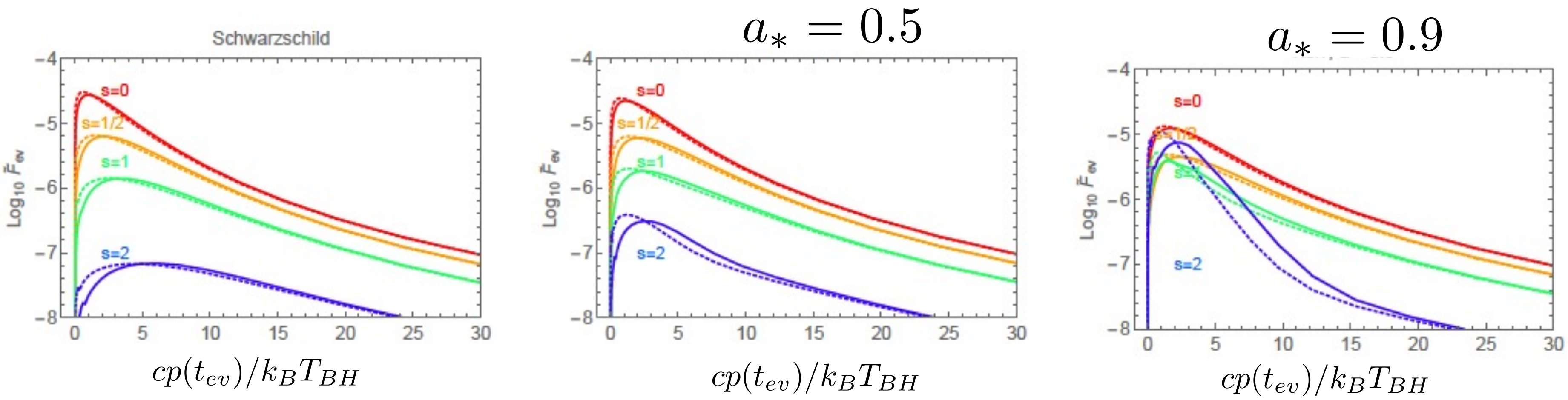
For the LIGHT case and Kerr



Numerical method

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Integrated spectrum at evaporation

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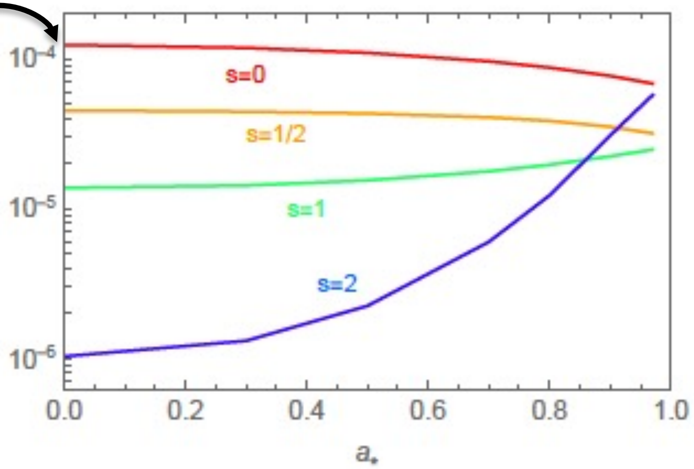
OR… DO NOT DO ANY CALCULATION AND JUST USE THE PLOT BELOW

For the LIGHT case and Kerr

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

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

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



OUTLINE

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

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

3) Non-interacting stable particles from evaporating PBHs as dark matter:
light/heavy case
Bounds on warm dark matter for the light case

Dark matter from PBHs evaporation

If the particle X is stable and non interacting,
it contributes to dark matter

Mass of the X particles

Present abundance of the emitted X particles

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

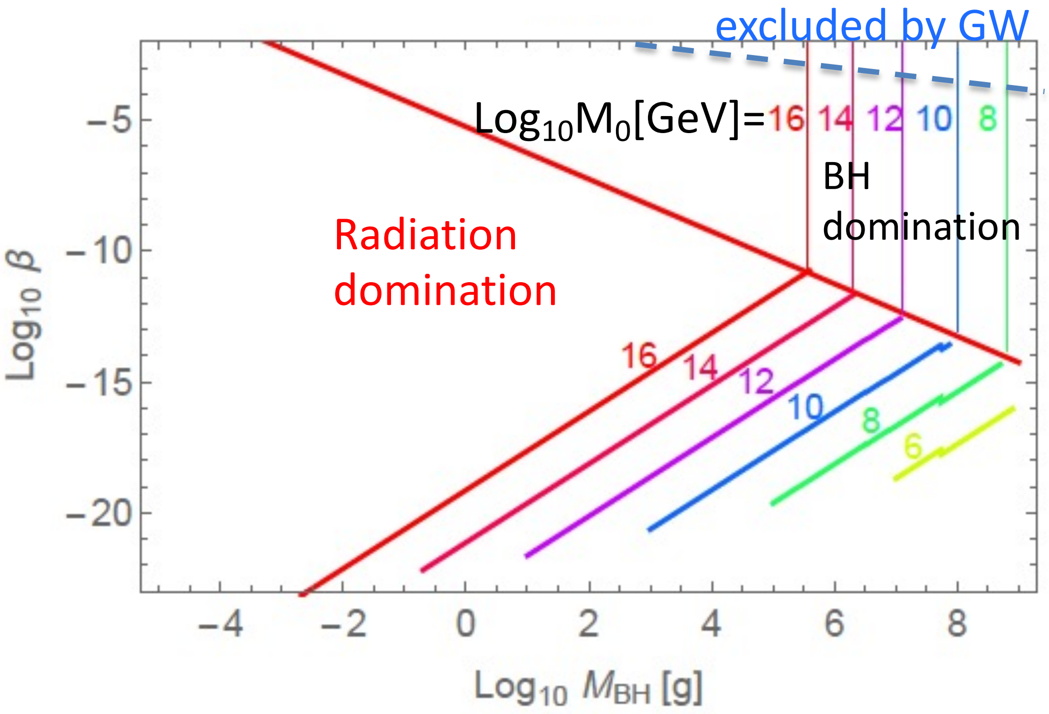
grossly TWO SCENARIOS

according to the HEAVY / LIGHT case [Fujita et al. 2014]

and with small differences for different spins and Schwarzschild / Kerr

HEAVY case for Schwarzschild with s=0

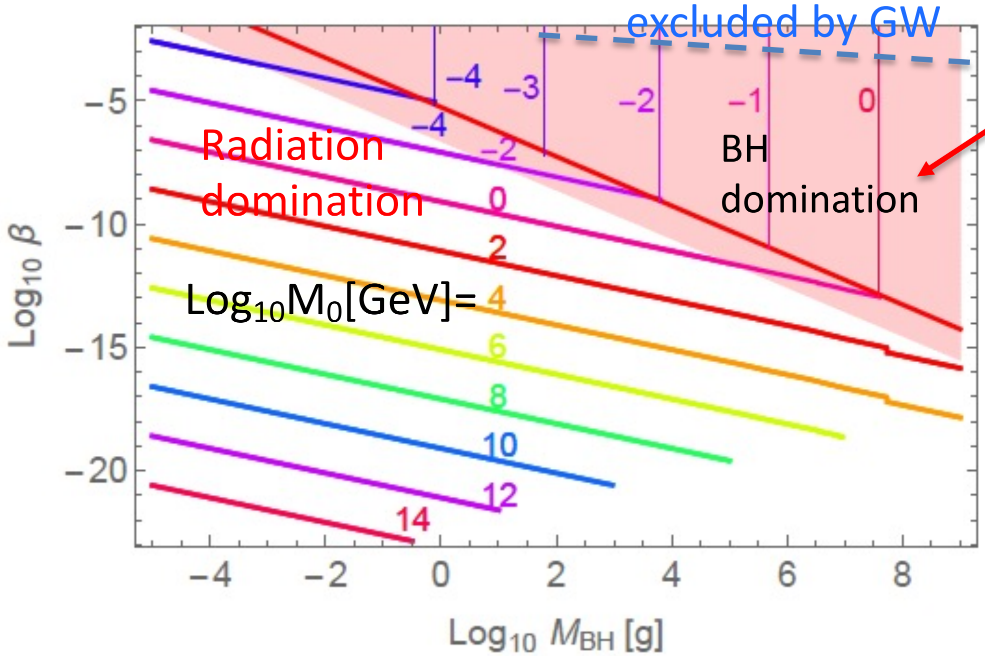
Assume all DM is made by stable X particles with s=0 and mass M_0
(numerical/analytical methods agree)



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

LIGHT case for Schwarzschild with s=0

Assume all DM is made by stable X particles with s=0 and mass M_0
(numerical/analytical methods agree)



Region excluded by constraints from structure formation on warm DM

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

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

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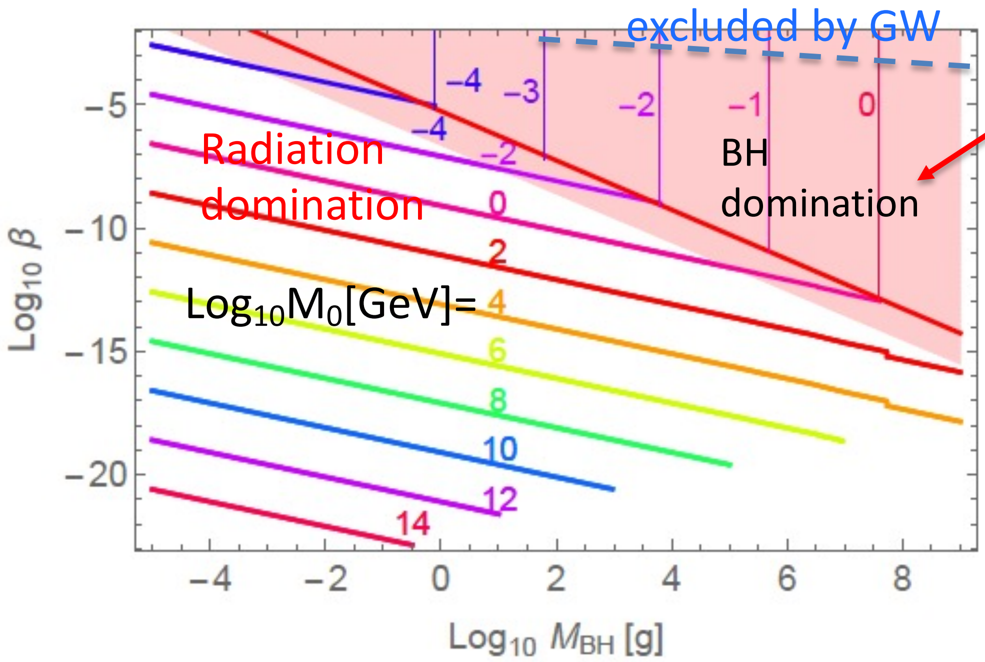

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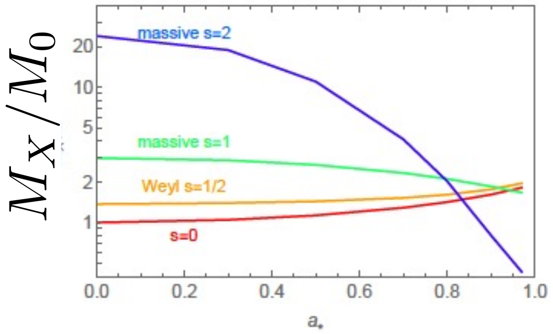
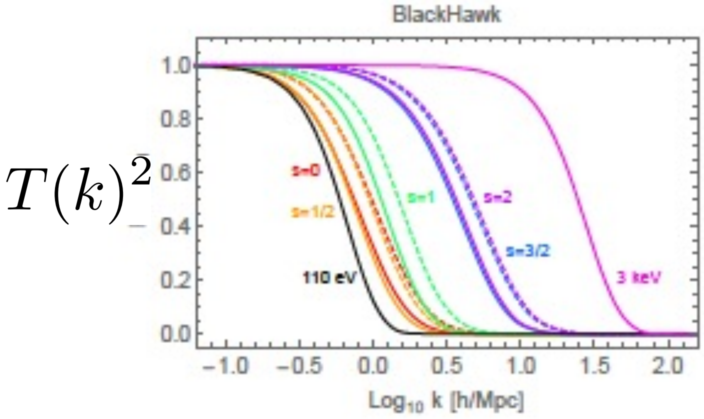
For other spins and Kerr case see this



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 *transfer 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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  tension is exacerbated for s=2 and large a_*

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WAYS to avoid tension with structure formation and «save» BH domination for LIGHT case:

- Entropy production mechanism at work [Fujita et al. 2014]
- Self-interacting SM: thermalization with number changing interactions [Bernal et al. 2020]

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4) Non-interacting stable particles from evaporating PBHs as dark radiation

The condition to be dark radiation

X particle contribute to DR (and not significantly to DM) if [Hooper et al. 2019]

$$M_X c^2 \lesssim \langle E(t_{EQ}) \rangle$$

mean energy of the X particles
at matter-radiation equilibrium

$$\langle E(t_{EQ}) \rangle \approx \langle E(t_{ev}) \rangle \frac{a_{ev}}{a_{EQ}} = 6\,(k_B T_{BH}) \frac{1}{\alpha'} \frac{T_{EQ}}{T_{ev}} \left(\frac{g_{\star,S}(T_{EQ})}{g_{\star,S}(T_{ev})} \right)^{1/3}$$

M_{BH} [g]	10^{-5}	10^{-1}	10^{9}
$M_X <$	1 eV	0.1 keV	10 MeV

Dark radiation from PBH evaporation / Schwarzschild

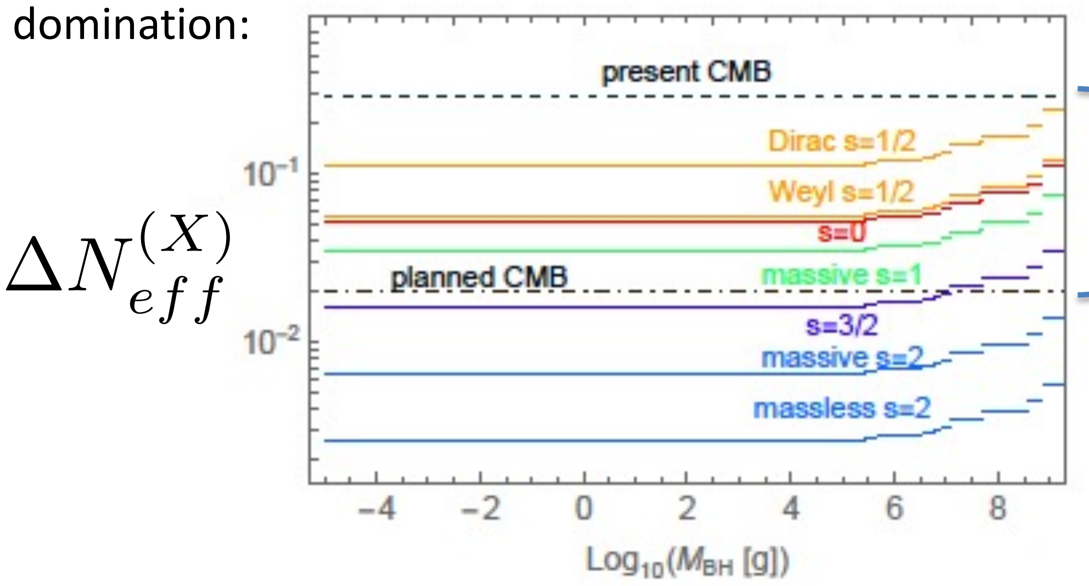
X particle contribute to DR with

[Hooper et al. 2019]

$$\Delta N_{eff}^{(X)} = \frac{\rho_X(t_{EQ})}{\rho_R(t_{EQ})}\left(N_\nu + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right) \approx 2.9\,\frac{\rho_X(t_{ev})}{\rho_R(t_{ev})}$$

SCHWARZSCHILD

For BH domination:



Exciting possibility to detect some signal in the future for s<3/2

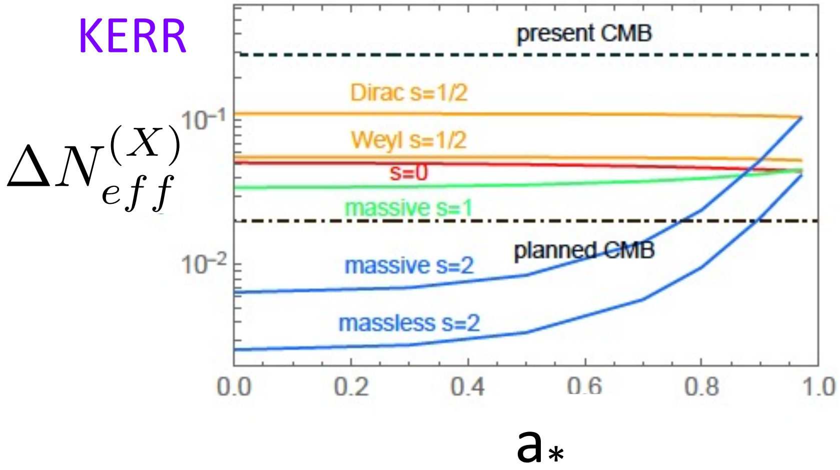
For Radiation domination: multiply previous numbers by suppressing factor $\beta/\bar{\beta}$

Dark radiation from PBH evaporation / Kerr

Recent debate about «hot gravitons» in Kerr case for BH domination: will they be seen?

- Hooper et al. 2004.00618: for a$_*$=0.7, planned CMB will see massless «hot gravitons»

- Masina 2021: including redshift effects, only for extremal BH, a$_*$>0.9



- Arbey et al. 2021: only for a$_*$>0.8; study of extended mass and spin distribution

- Cheek et al. 2207.09462: No, never, with full inclusion of redshift and density dynamics at evaporation

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5) Conclusions and outlook

Conclusions and outlook

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

is an elegant VIABLE mechanism to account for DM

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)

and also INTERESTING PROSPECTS FOR DR

BH domination: s=0,1/2,1 might be tested by planned CMB

(while hot gravitons give too low contribution even in Kerr case)