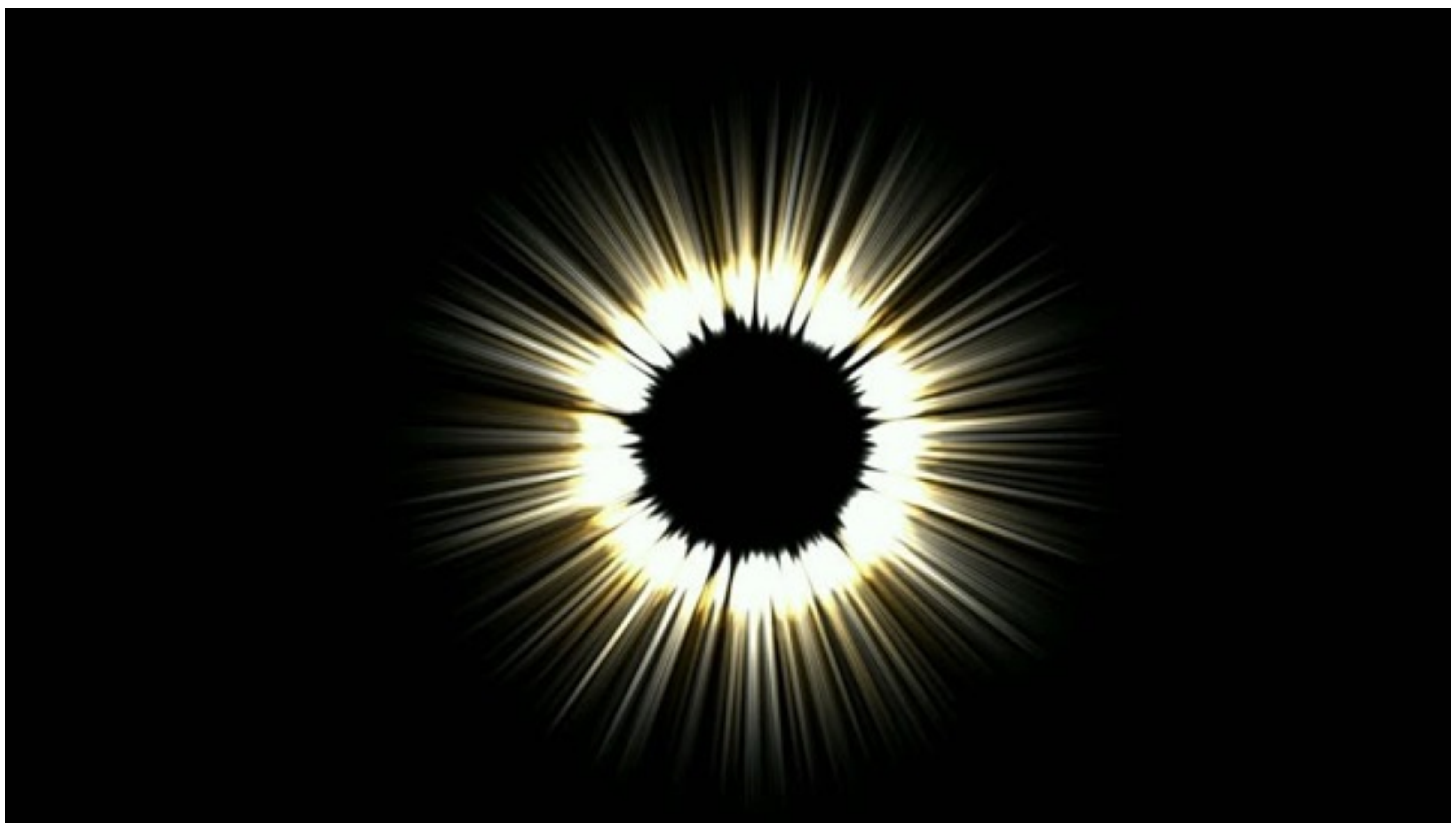
Hawking Genesis

John March-Russell
Oxford University

Cosmograv, Paris, June 2018



Olivier Lennon, JMR, Rudin Petrossian-Byrne, and Hannah Tillim; arXiv:1712.07664 and follow-ups in progress

Subject at hand…

Crucial questions: Origin of Dark *M*atter? Interactions with SM?

Subject at hand...

Crucial questions: Origin of Dark Matter? Interactions with SM?

- All direct experimental/observation evidence is consistent with DM only possessing gravitational interactions

Subject at hand…

Crucial questions: Origin of Dark Matter? Interactions with SM?

- All direct experimental/observation evidence is consistent with DM only possessing gravitational interactions
- For many years we had good theoretical reasons to believe that DM had much stronger interactions with SM: *freeze-out production and the WIMP miracle*

Subject at hand…

Crucial questions: Origin of Dark Matter? Interactions with SM?

- All direct experimental/observation evidence is consistent with DM only possessing gravitational interactions

- For many years we had good theoretical reasons to believe that DM had much stronger interactions with SM: *freeze-out production and the WIMP miracle*

- But this no longer works so well, and much, though certainly not all of the parameter space is excluded, so attention has turned to other production mechanisms with feeble (but still much stronger than gravitational) interactions, eg, *freeze-in production and the "FIMP miracle"*

Subject at hand…

Crucial questions: Origin of Dark Matter? Interactions with SM?

- All direct experimental/observation evidence is consistent with DM only possessing gravitational interactions
- For many years we had good theoretical reasons to believe that DM had much stronger interactions with SM: *freeze-out production and the WIMP miracle*
- But this no longer works so well, and much, though certainly not all of the parameter space is excluded, so attention has turned to other production mechanisms with feeble (but still much stronger than gravitational) interactions, eg, *freeze-in production and the "FIMP miracle"*
- *If there was a successful, calculable, and purely gravitational mechanism of DM production then the remaining theoretical argument for non-gravitational interactions of DM with the SM would be gone*

Subject at hand…

Crucial questions: Origin of Dark Matter? Interactions with SM?

- All direct experimental/observation evidence is consistent with DM only possessing gravitational interactions
- For many years we had good theoretical reasons to believe that DM had much stronger interactions with SM: *freeze-out production and the WIMP miracle*
- But this no longer works so well, and much, though certainly not all of the parameter space is excluded, so attention has turned to other production mechanisms with feeble (but still much stronger than gravitational) interactions, eg, *freeze-in production and the "FIMP miracle"*
- *If there was a successful, calculable, and purely gravitational mechanism of DM production then the remaining theoretical argument for non-gravitational interactions of DM with the SM would be gone*
- Seems only bad news. BUT maybe there are completely new kinds of signals of DM….

Hawking Genesis

Olivier Lennon, JMR, Rudin Petrossian-Byrne,
and Hannah Tillim; arXiv:1712.07664

A purely gravitational, IR-calculable, mechanism of DM production and the hot SM Big Bang plasma

Hawking Genesis

Starting assumptions (most just for pedagogical simplicity & can be significantly weakened):

Hawking Genesis

Starting assumptions (most just for pedagogical simplicity & can be significantly weakened):

- In the early Universe there exists a population of micro primordial black holes (pBHs)

Hawking Genesis

Starting assumptions (most just for pedagogical simplicity & can be significantly weakened):

- In the early Universe there exists a population of micro primordial black holes (pBHs)
- The DM particle has only gravitational interactions with itself and SM

Hawking Genesis

Starting assumptions (most just for pedagogical simplicity & can be significantly weakened):

- In the early Universe there exists a population of micro primordial black holes (pBHs)
- The DM particle has only gravitational interactions with itself and SM
- The pre-existing number/energy densities of DM and SM radiation are not very large (initially take, in this discussion, both to be zero for simplicity of formulas)

Hawking Genesis

Starting assumptions (most just for pedagogical simplicity & can be significantly weakened):

- In the early Universe there exists a population of micro primordial black holes (pBHs)
- The DM particle has only gravitational interactions with itself and SM
- The pre-existing number/energy densities of DM and SM radiation are not very large (initially take, in this discussion, both to be zero for simplicity of formulas)
- Take, in this discussion, all pBHs to have initial mass M_0, and number density n_0

Hawking Genesis

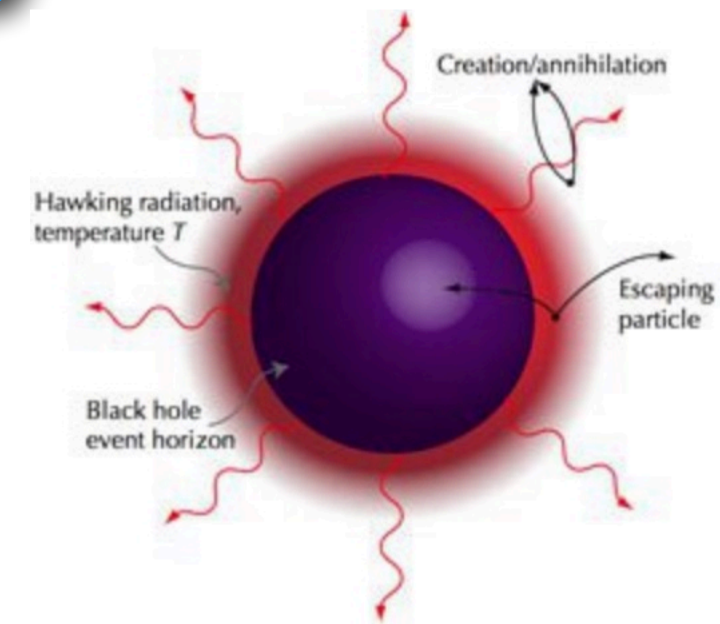
Starting assumptions (most just for pedagogical simplicity & can be significantly weakened):

- In the early Universe there exists a population of micro primordial black holes (pBHs)
- The DM particle has only gravitational interactions with itself and SM
- The pre-existing number/energy densities of DM and SM radiation are not very large (initially take, in this discussion, both to be zero for simplicity of formulas)
- Take, in this discussion, all pBHs to have initial mass M_0, and number density n_0
- On *large scales* the initial energy density of BHs, $\rho_{BH} = M_0 n_0$, inherits the approximately scale-invariant spectrum of density fluctuations, $\delta\rho/\rho \simeq 10^{-5}$

Hawking Evaporation

The micro pBHs Hawking evaporate to *all states*

$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} = \sum_{\ell,h} \frac{(2\ell+1)}{2\pi} \frac{\Gamma_{i,s,\ell,h}(\omega)}{\exp(\omega/T(t)) + (-1)^{(2s+1)}} \mathrm{d}\omega$$

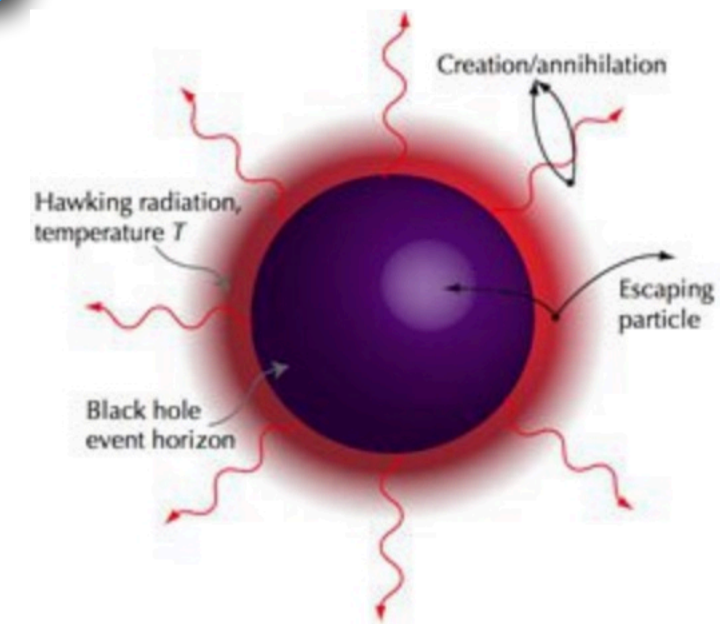


Hawking Evaporation

The micro pBHs Hawking evaporate to *all states*

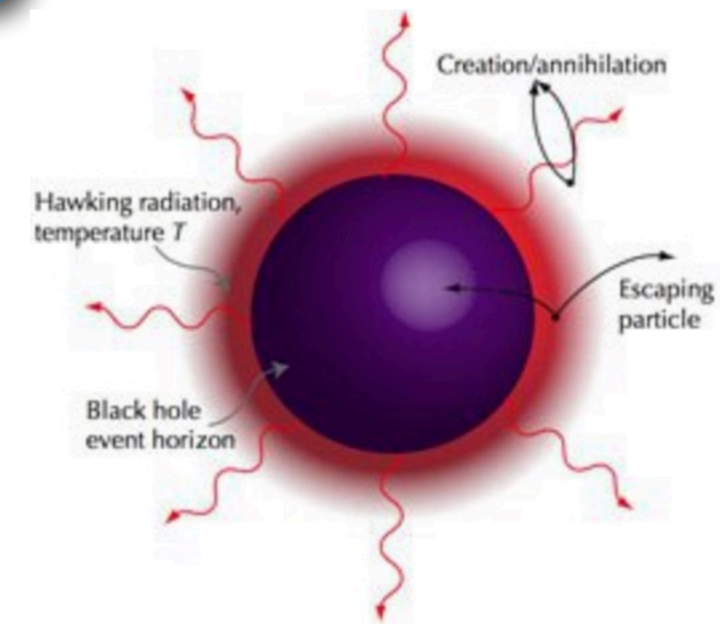
$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} = \sum_{\ell,h} \frac{(2\ell+1)}{2\pi} \frac{\Gamma_{i,s,\ell,h}(\omega)}{\exp(\omega/T(t)) + (-1)^{(2s+1)}} \mathrm{d}\omega$$

number of particles of species i, spin s,
produced in energy range (w,w+dw)



Hawking Evaporation

The micro pBHs Hawking evaporate to *all states*



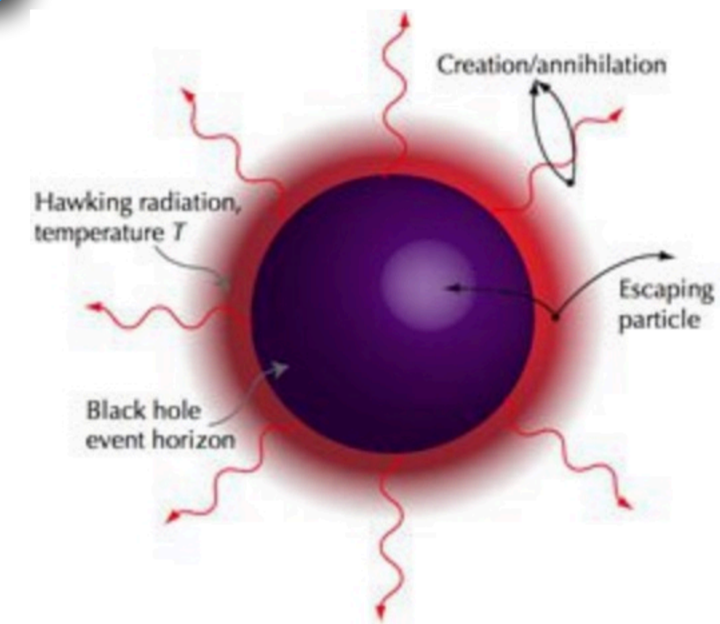
$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} = \sum_{\ell,h} \frac{(2\ell+1)}{2\pi} \frac{\Gamma_{i,s,\ell,h}(\omega)}{\exp(\omega/T(t)) + (-1)^{(2s+1)}} \mathrm{d}\omega$$

number of particles of species i, spin s, produced in energy range (w,w+dw)

Hawking temperature, initially $T_0 = M_{\mathrm{Pl}}^2/(8\pi M_0)$

Hawking Evaporation

The micro pBHs Hawking evaporate to *all states*



$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} = \sum_{\ell,h} \frac{(2\ell+1)}{2\pi} \frac{\Gamma_{i,s,\ell,h}(\omega)}{\exp(\omega/T(t)) + (-1)^{(2s+1)}} \mathrm{d}\omega$$

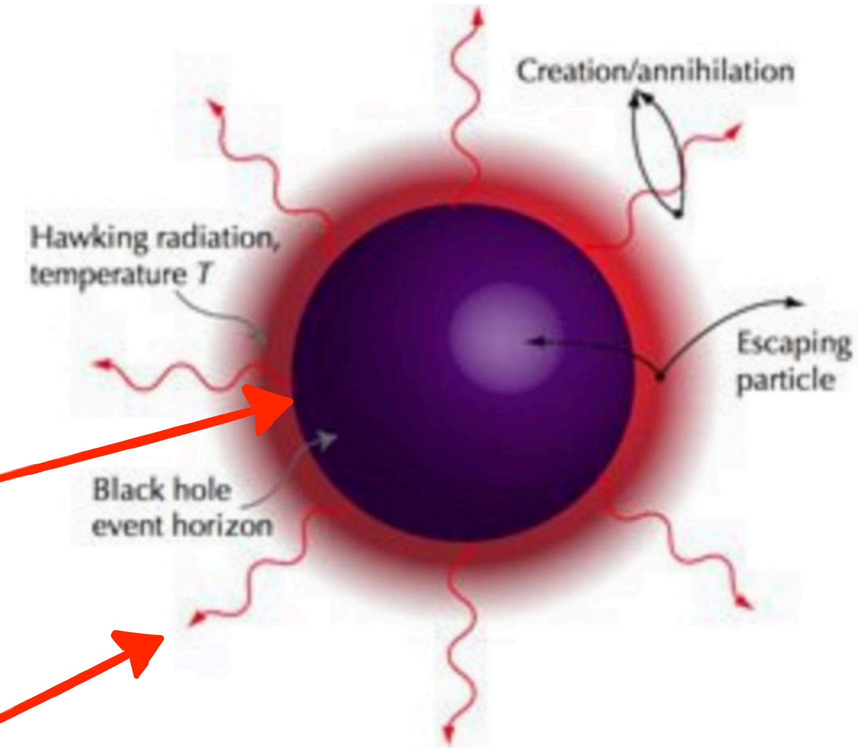
number of particles of species i, spin s, produced in energy range (w,w+dw)

Hawking temperature, initially $T_0 = M_{\mathrm{Pl}}^2/(8\pi M_0)$

"grey-body" factor (strongly spin dependent!)

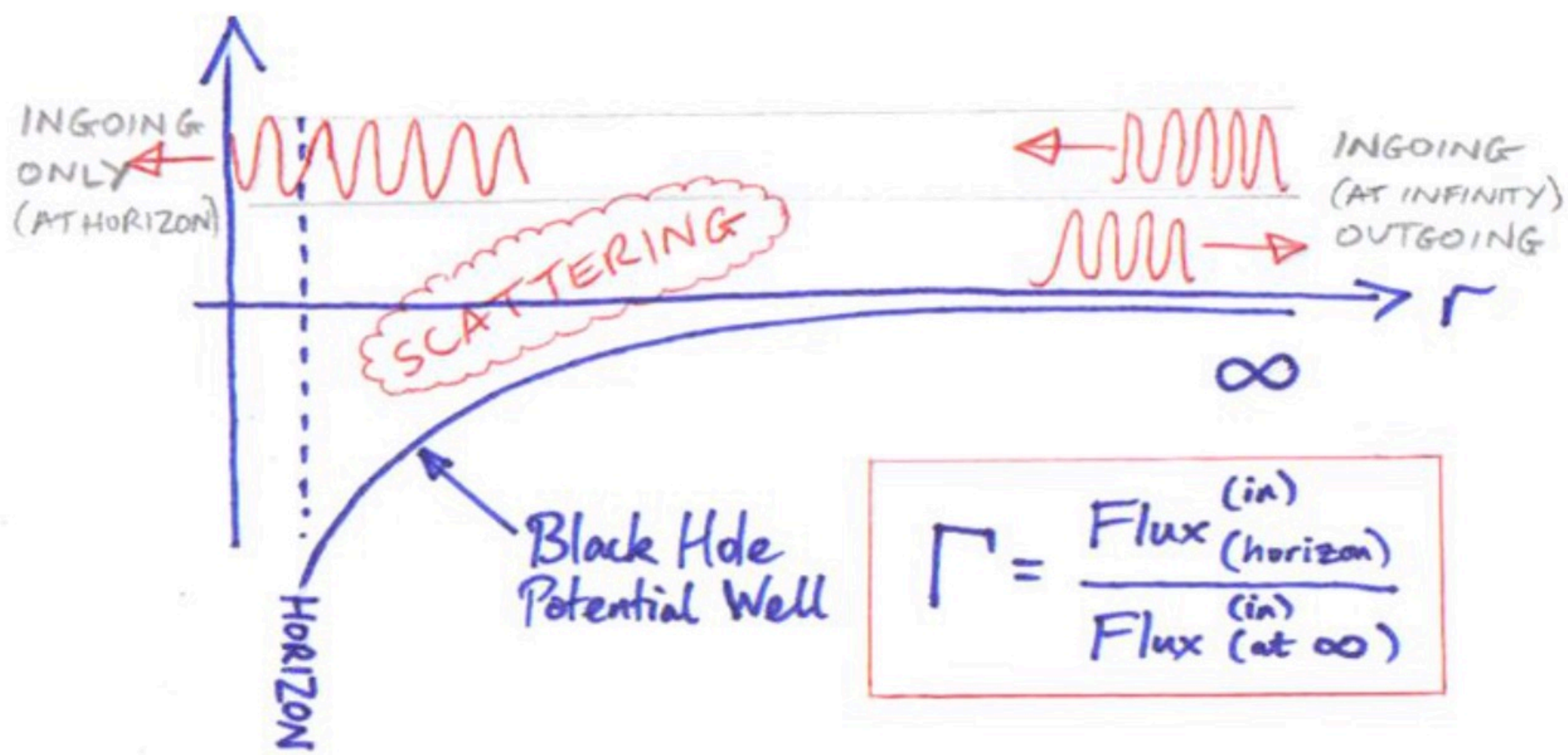
Aside on grey body factors:

These important spin- and energy-dependent factors arise from scattering of outgoing particles off of BH effective potential



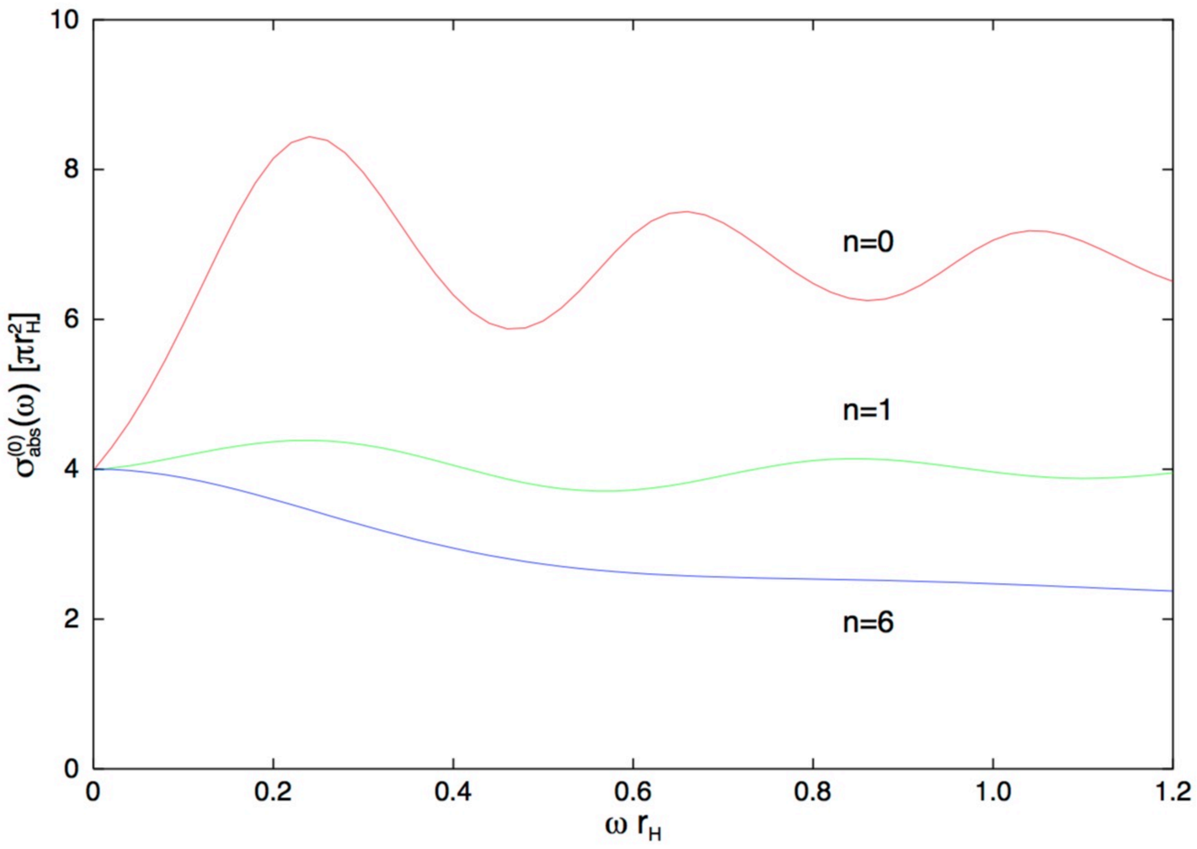
at horizon Hawking radiation is black body

spectrum of Hawking radiation escaping to infinity modified by scattering (but still thermal, and detailed balance with external heat bath at $T_{Hawking}$ still maintained)



$$\Gamma = \frac{\text{Flux}^{(in)}(\text{horizon})}{\text{Flux}^{(in)}(\text{at } \infty)}$$

spin s=0 grey body factor



Here shown absorption cross section

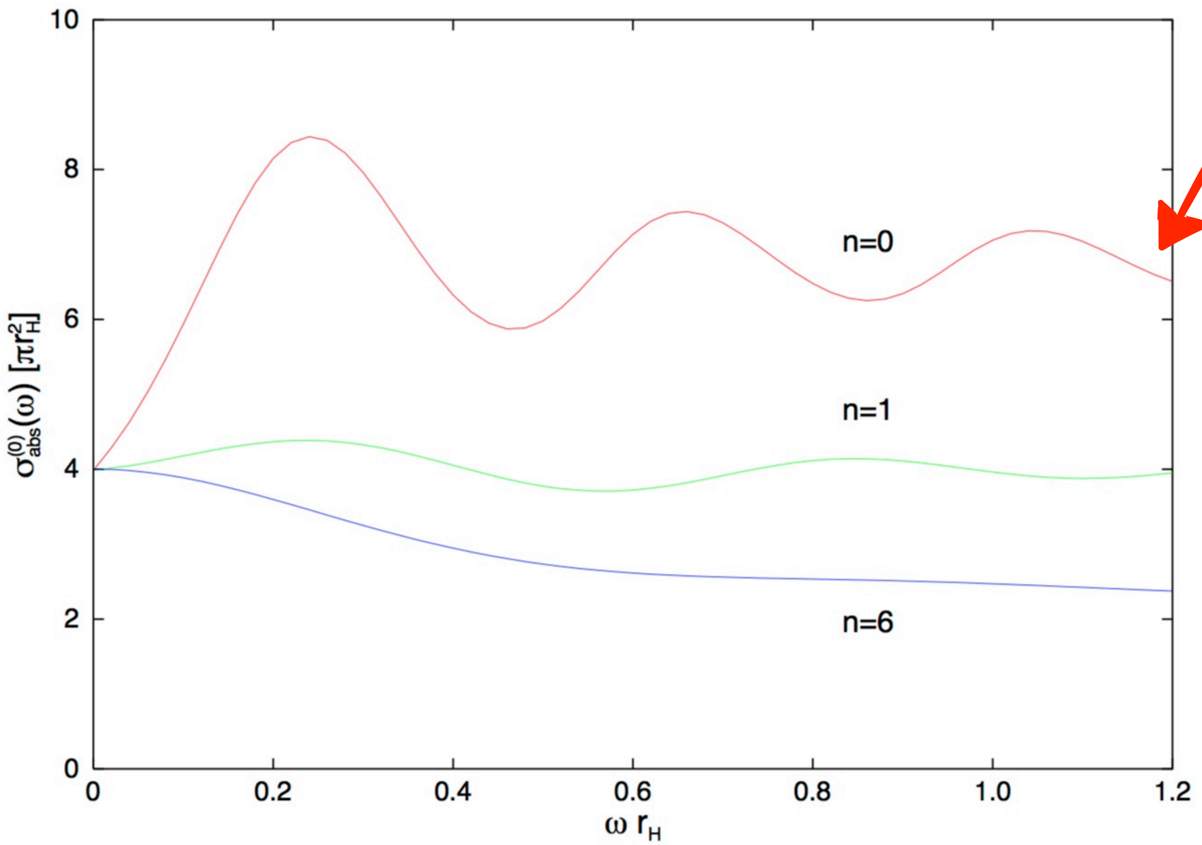
$$\sigma_{i,s,h}(\omega) = \pi \sum_l (2l+1)\Gamma_{i,s,\ell,h}(\omega)/\omega^2$$

Analytic and numerical work from Page PRD13 (1976) 198, and Kanti & JMR hep-ph/0203223 & hep-ph/0212199, and Harris & Kanti hep-ph/0309054 (n=number of extra spatial dimensions, so here n=0 gives BH grey-body factors for 3+1 D)

spin s=0 grey body factor

As $\omega r_H >> 1$ get geometrical optics value for all spins

$$\sigma_{i,s,h}(\omega) = 27\pi M^2/M_{\rm Pl}^4$$



Here shown absorption cross section

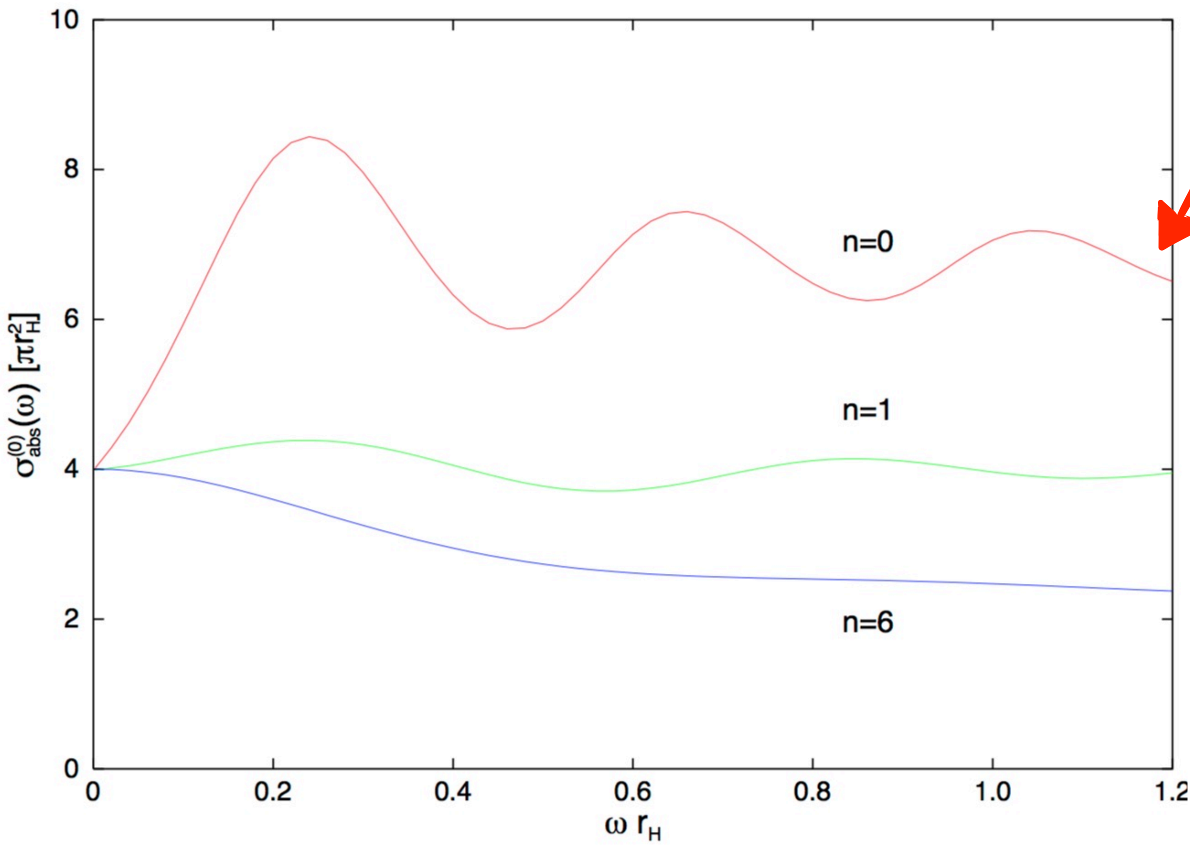
$$\sigma_{i,s,h}(\omega) = \pi \sum_l (2l+1)\Gamma_{i,s,\ell,h}(\omega)/\omega^2$$

Analytic and numerical work from Page PRD13 (1976) 198, and Kanti & JMR hep-ph/0203223 & hep-ph/0212199, and Harris & Kanti hep-ph/0309054 (n=number of extra spatial dimensions, so here n=0 gives BH grey-body factors for 3+1 D)

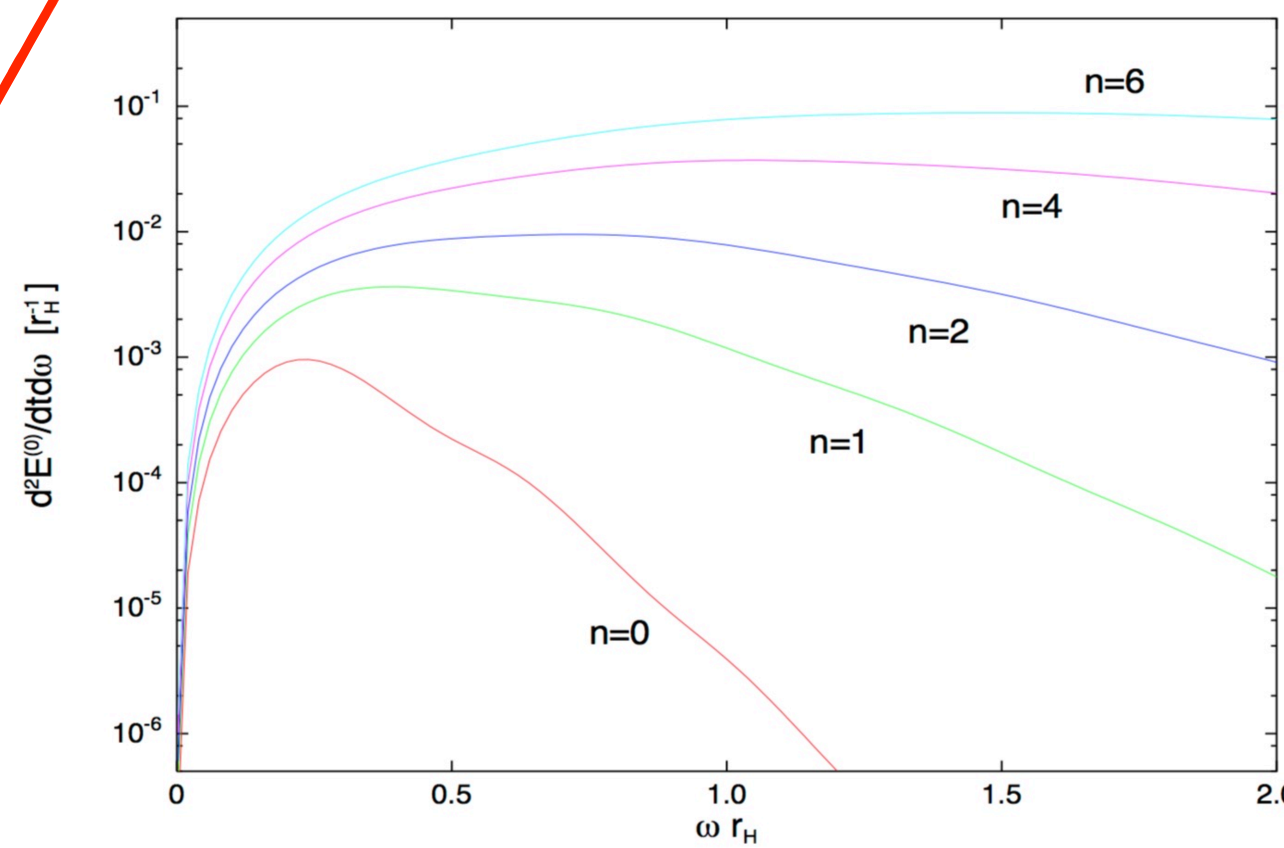
spin s=0 grey body factor

As $wr_H >> 1$ get geometrical optics value for all spins

$$\sigma_{i,s,h}(\omega) = 27\pi M^2/M_{\rm Pl}^4$$



energy spectrum

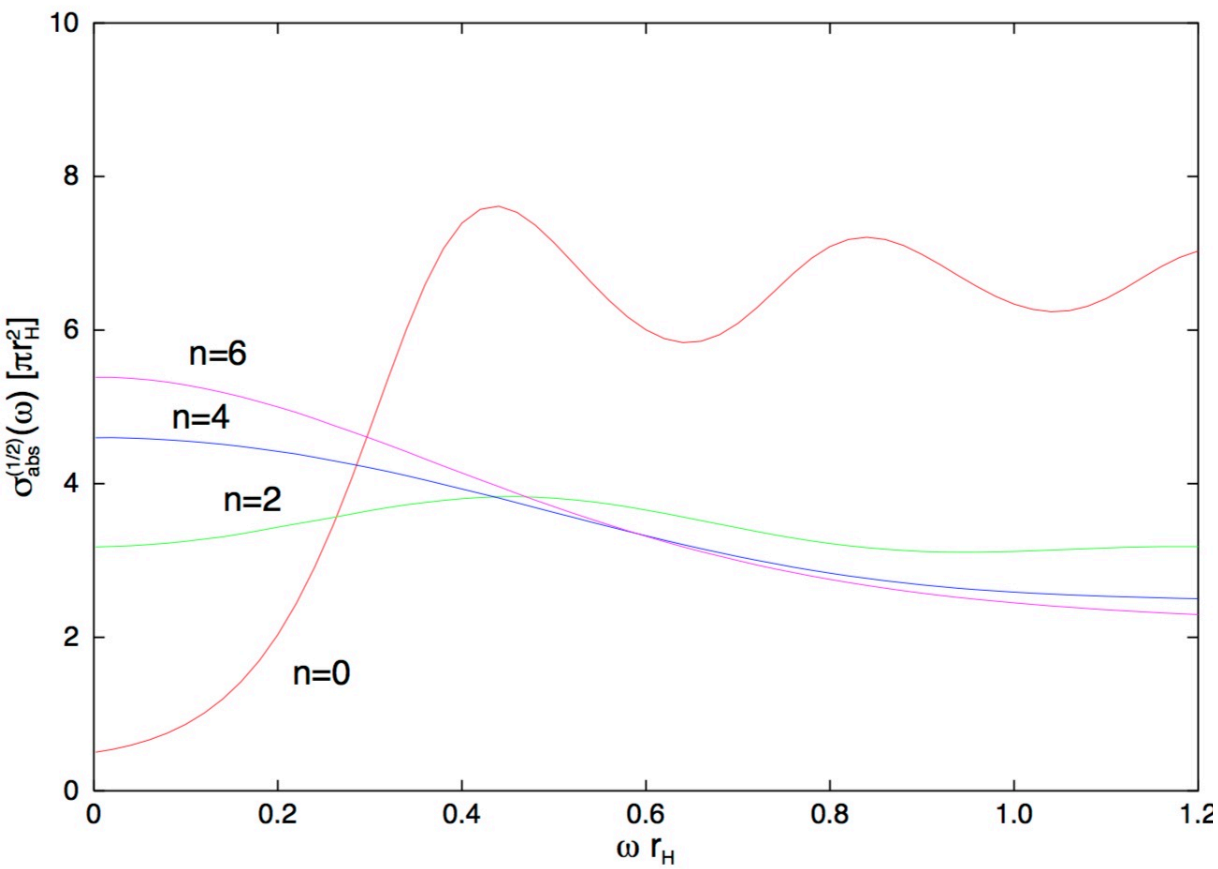


Here shown absorption cross section

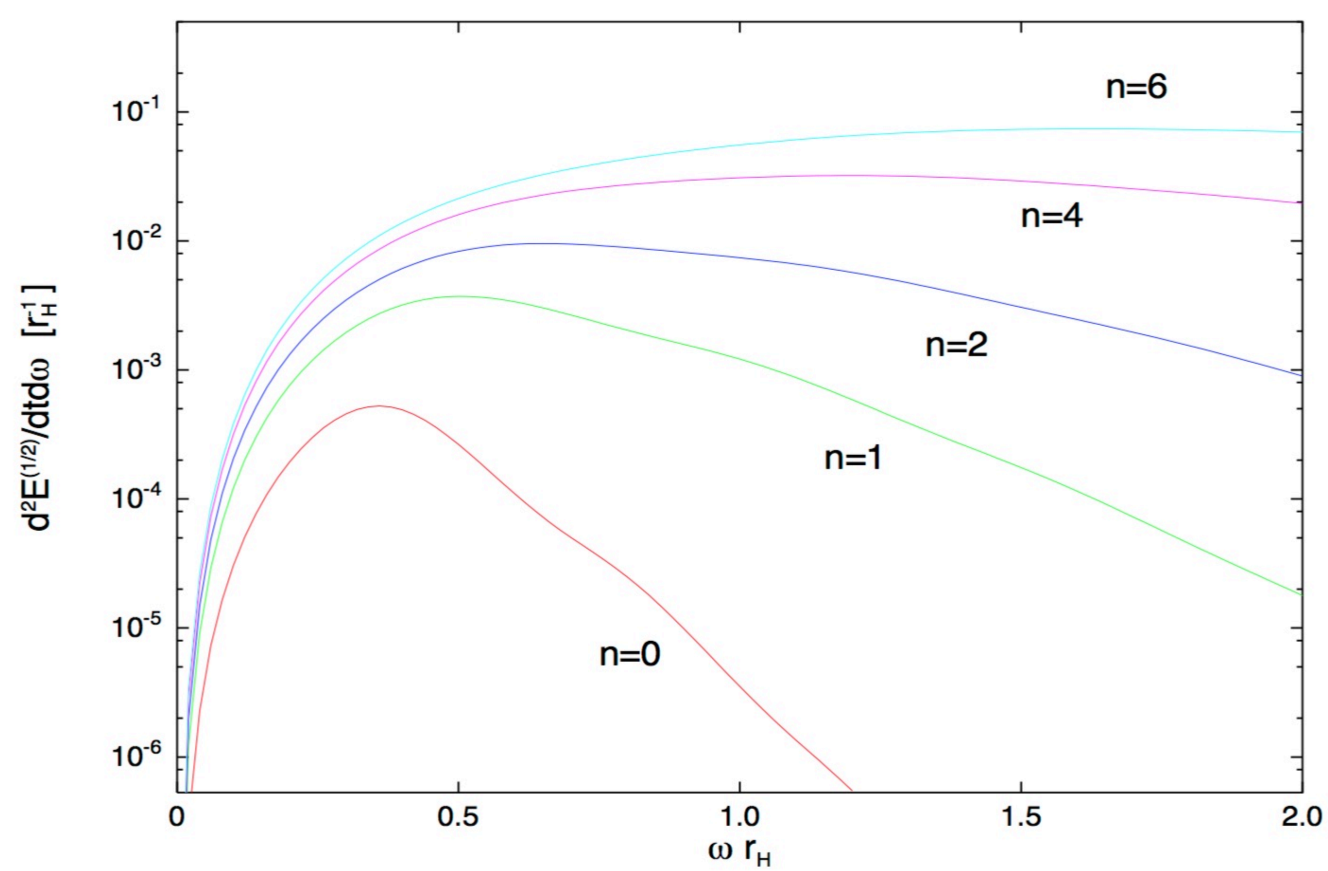
$$\sigma_{i,s,h}(\omega) = \pi \sum_l (2l+1)\Gamma_{i,s,\ell,h}(\omega)/\omega^2$$

Analytic and numerical work from Page PRD13 (1976) 198, and Kanti & JMR hep-ph/0203223 & hep-ph/0212199, and Harris & Kanti hep-ph/0309054 (n=number of extra spatial dimensions, so here n=0 gives BH grey-body factors for 3+1 D)

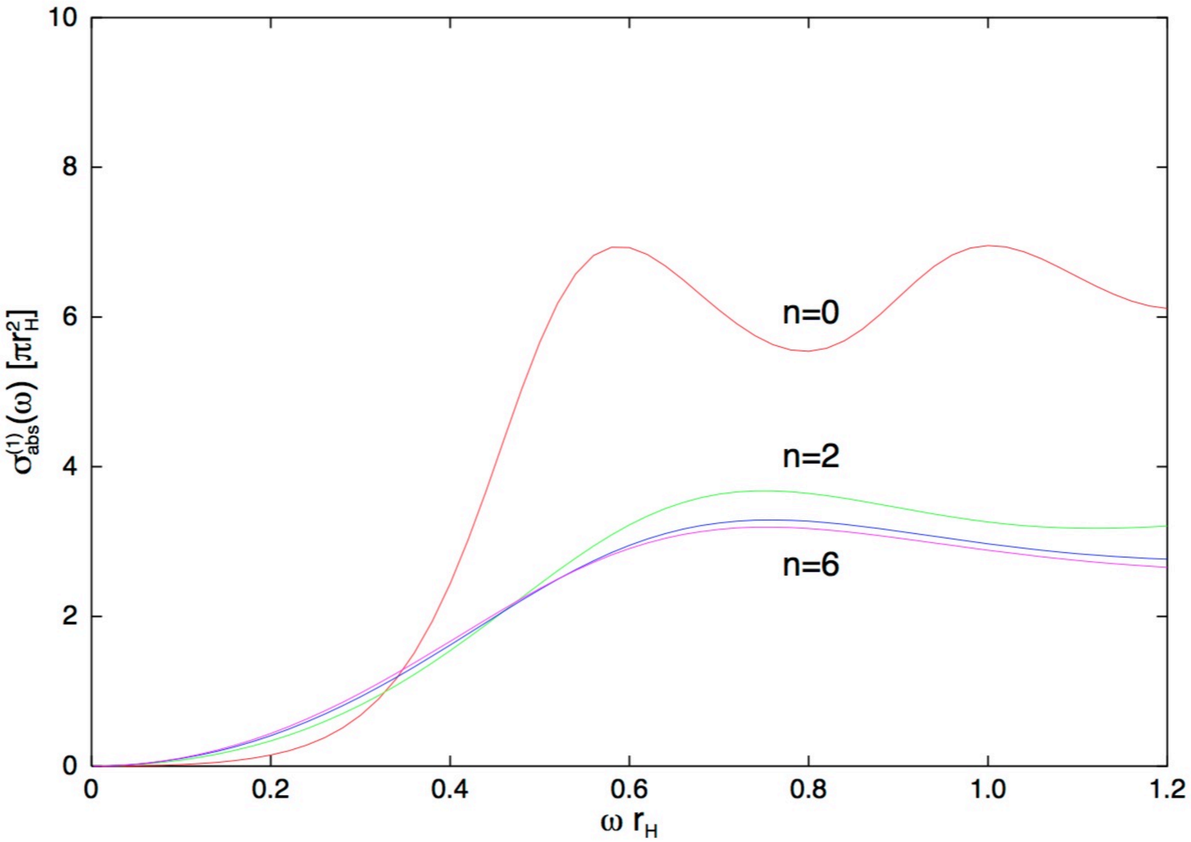
spin s=1/2 grey body factor



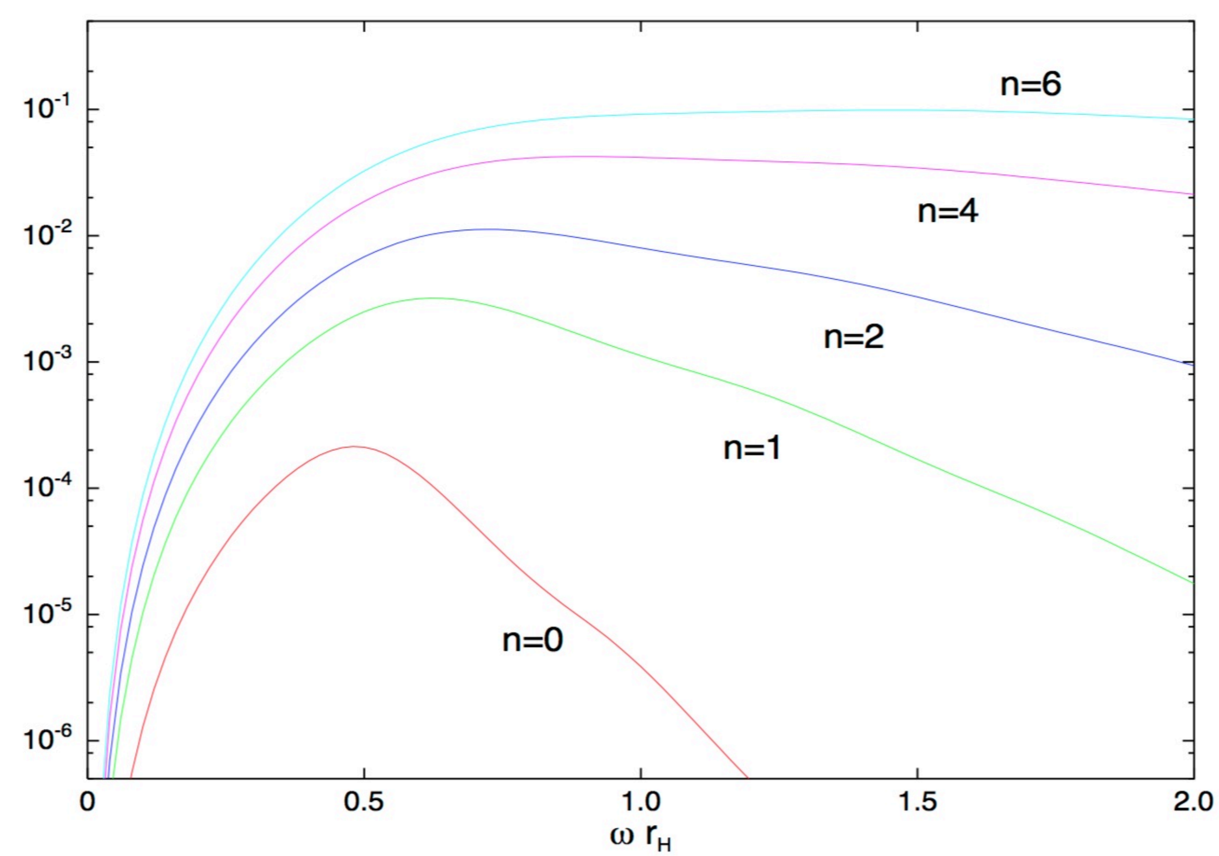
energy spectrum



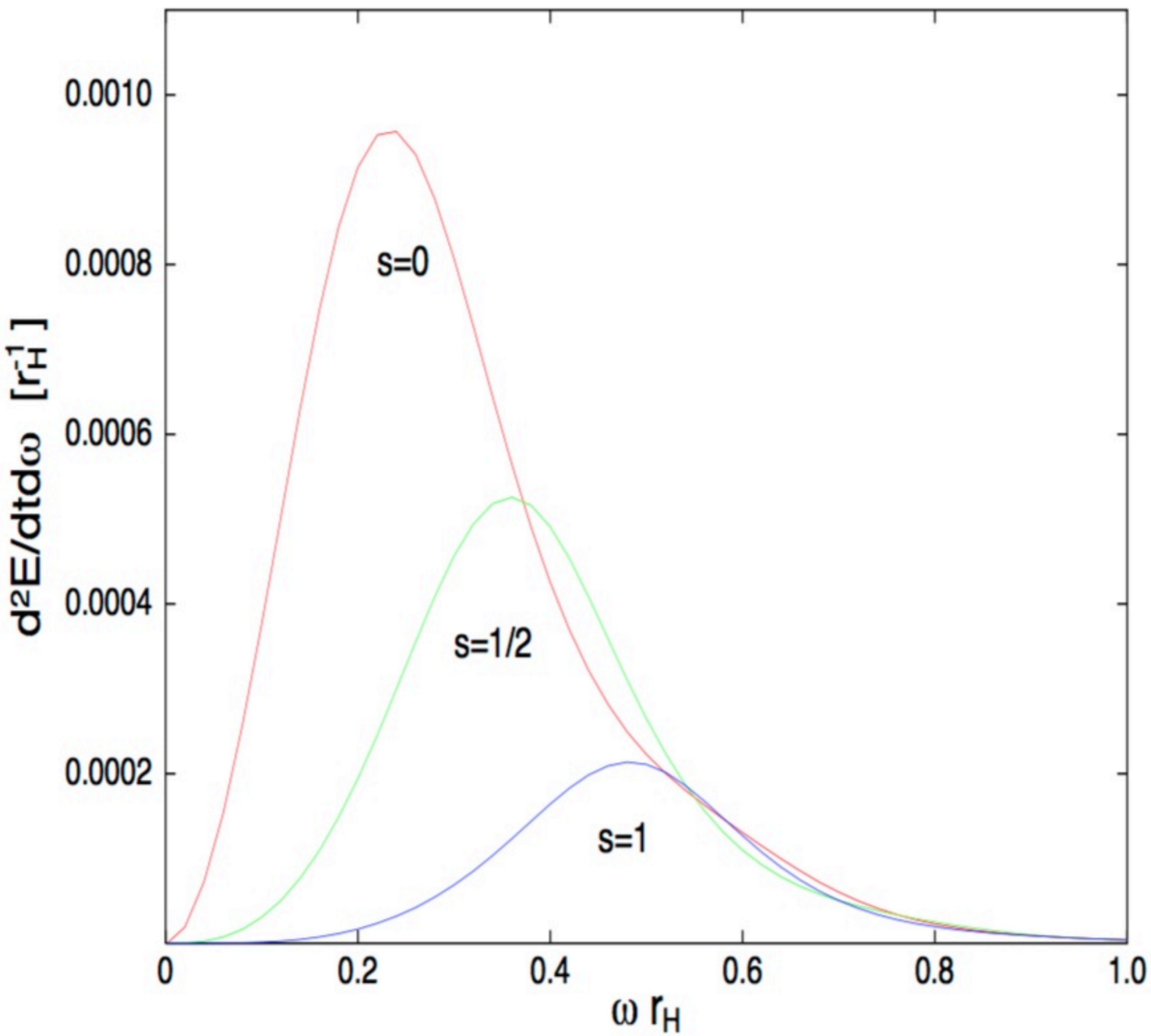
spin s=1 grey body factor



energy spectrum



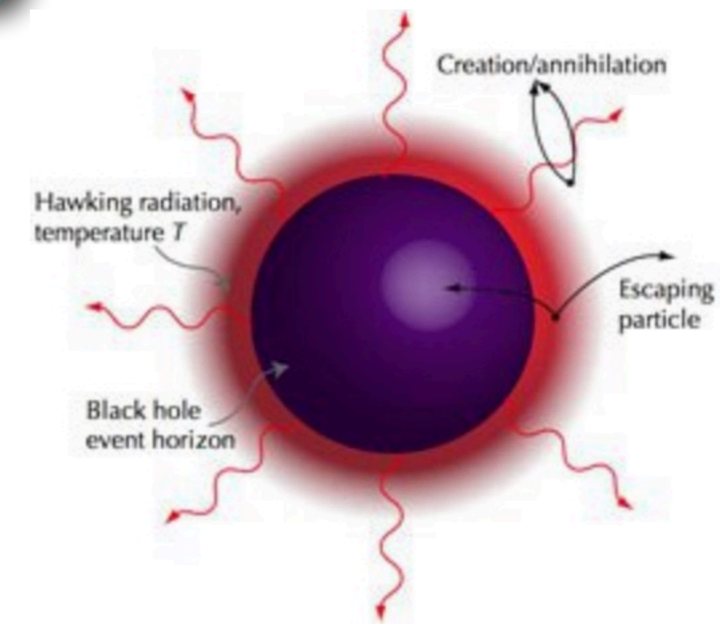
spin 0, 1/2, 1 emission rates (3+1 D)



Note the rate of emission of higher spins is suppressed

Hawking Evaporation

The micro pBHs Hawking evaporate to *all states*



$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} = \sum_{\ell,h} \frac{(2\ell+1)}{2\pi} \frac{\Gamma_{i,s,\ell,h}(\omega)}{\exp(\omega/T(t)) + (-1)^{(2s+1)}} \mathrm{d}\omega$$

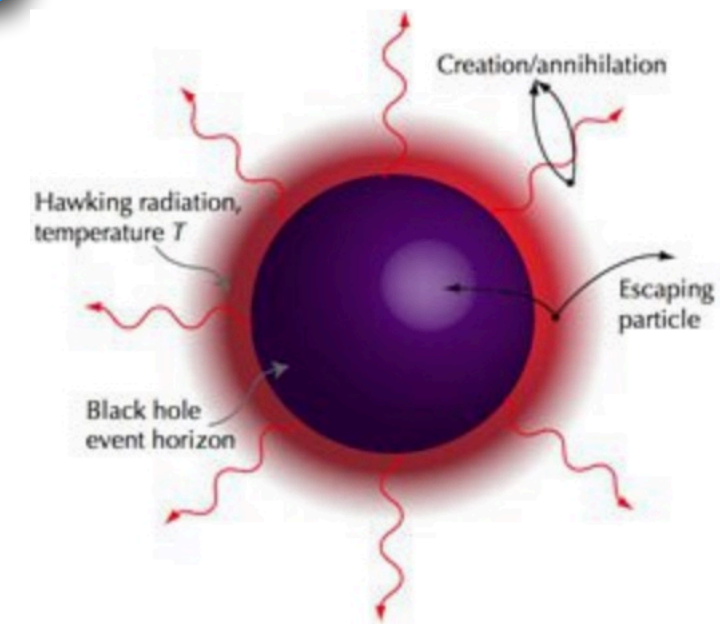
number of particles of species i, spin s, produced in energy range (w,w+dw)

Hawking temperature, initially $T_0 = M_{\rm Pl}^2/(8\pi M_0)$

"grey-body" factor (strongly spin dependent!)

Hawking Evaporation

The micro pBHs Hawking evaporate to *all states*



$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} = \sum_{\ell,h} \frac{(2\ell+1)}{2\pi} \frac{\Gamma_{i,s,\ell,h}(\omega)}{\exp(\omega/T(t)) + (-1)^{(2s+1)}} \mathrm{d}\omega$$

number of particles of species i, spin s, produced in energy range (w,w+dw)

Hawking temperature, initially $T_0 = M_{\rm Pl}^2/(8\pi M_0)$

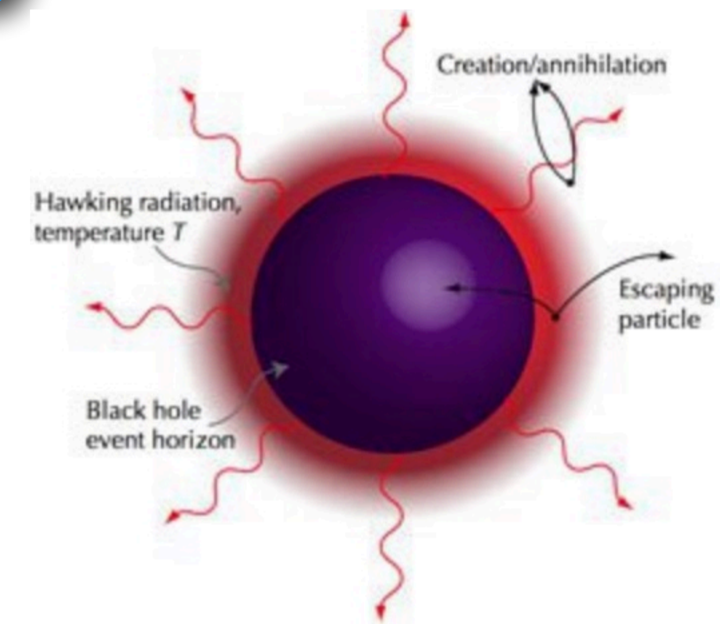
"grey-body" factor (strongly spin dependent!)

Total rate of production of particle species i of mass μ well approximated by

$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} \approx \frac{M_{\rm Pl}^2}{M} f_{s,i} g_{s,i} \Theta\left(d_s \frac{M_{\rm Pl}^2}{8\pi M} - \mu\right)$$

Hawking Evaporation

The micro pBHs Hawking evaporate to *all states*



$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} = \sum_{\ell,h} \frac{(2\ell+1)}{2\pi} \frac{\Gamma_{i,s,\ell,h}(\omega)}{\exp(\omega/T(t)) + (-1)^{(2s+1)}} \mathrm{d}\omega$$

number of particles of species i, spin s, produced in energy range (w,w+dw)

Hawking temperature, initially $T_0 = M_{\mathrm{Pl}}^2/(8\pi M_0)$

"grey-body" factor (strongly spin dependent!)

Total rate of production of particle species i of mass μ well approximated by

$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} \approx \frac{M_{\mathrm{Pl}}^2}{M} f_{s,i} g_{s,i} \Theta\left(d_s \frac{M_{\mathrm{Pl}}^2}{8\pi M} - \mu\right)$$

grey-body "rate" factor

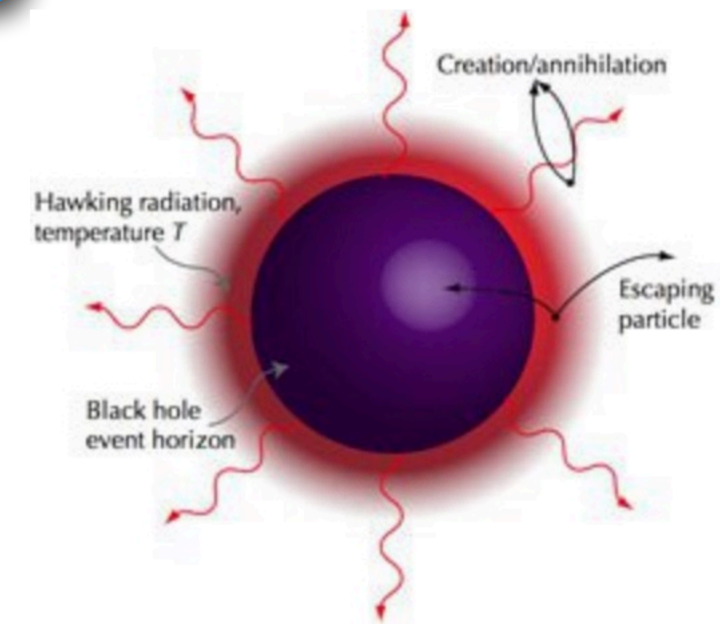
no. dof

$d_{\mathrm{bosons}} \simeq 3.2$

$d_{\mathrm{fermions}} \simeq 3.6$

Hawking Evaporation

The micro pBHs Hawking evaporate to *all states*



$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} = \sum_{\ell,h} \frac{(2\ell+1)}{2\pi} \frac{\Gamma_{i,s,\ell,h}(\omega)}{\exp(\omega/T(t)) + (-1)^{(2s+1)}} \mathrm{d}\omega$$

number of particles of species i, spin s, produced in energy range (w,w+dw)

Hawking temperature, initially $T_0 = M_{\mathrm{Pl}}^2/(8\pi M_0)$

"grey-body" factor (strongly spin dependent!)

Total rate of production of particle species i of mass μ well approximated by

$$\frac{\mathrm{d}N_{s,i}}{\mathrm{d}t} \approx \frac{M_{\mathrm{Pl}}^2}{M} f_{s,i} g_{s,i} \Theta\left(d_s \frac{M_{\mathrm{Pl}}^2}{8\pi M} - \mu\right)$$

grey-body "rate" factor

no. dof

$d_{\mathrm{bosons}} \simeq 3.2$

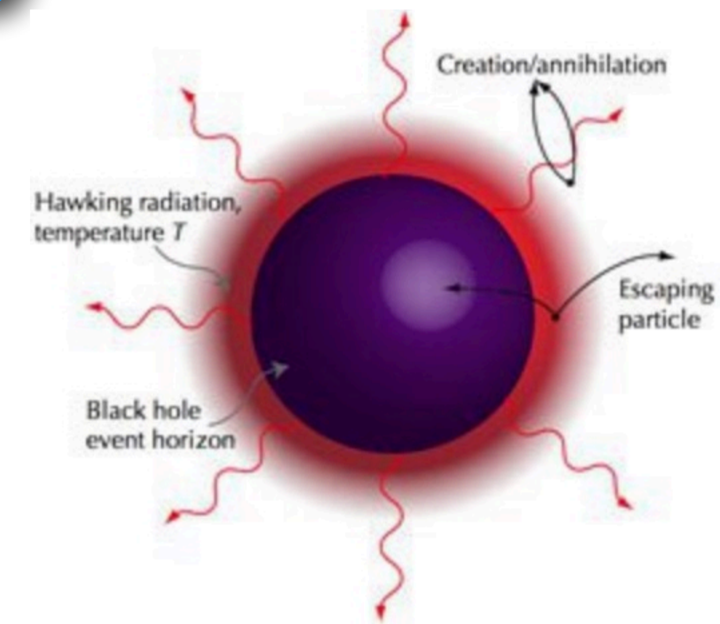
$d_{\mathrm{fermions}} \simeq 3.6$

Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

Hawking Evaporation

Total rate of pBH mass-loss:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{M_{\mathrm{Pl}}^4}{M^2}\sum_{s,i} e_{s,i} g_{s,i} \equiv -e_{\mathrm{T}}\frac{M_{\mathrm{Pl}}^4}{M^2}$$



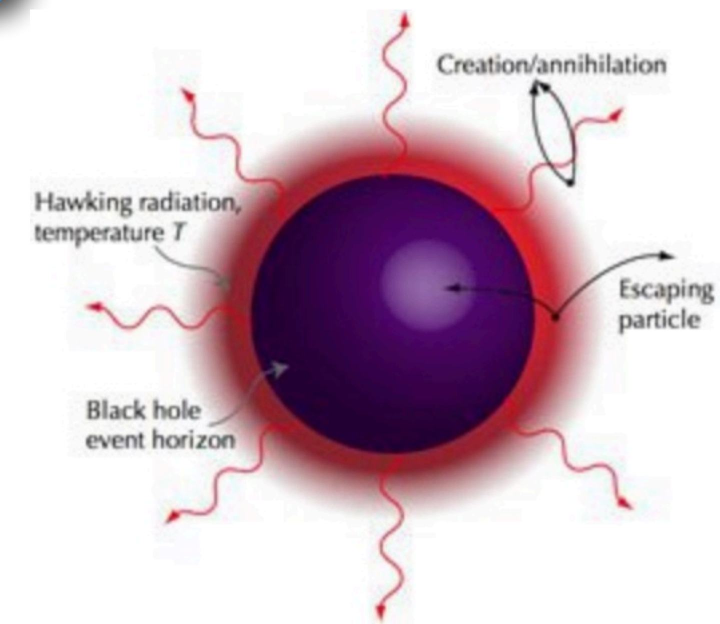
Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

Hawking Evaporation

Total rate of pBH mass-loss:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{M_{\rm Pl}^4}{M^2}\sum_{s,i} e_{s,i} g_{s,i} \equiv -e_{\rm T}\frac{M_{\rm Pl}^4}{M^2}$$

grey-body "energy emissivity"
factor into species i of spin s



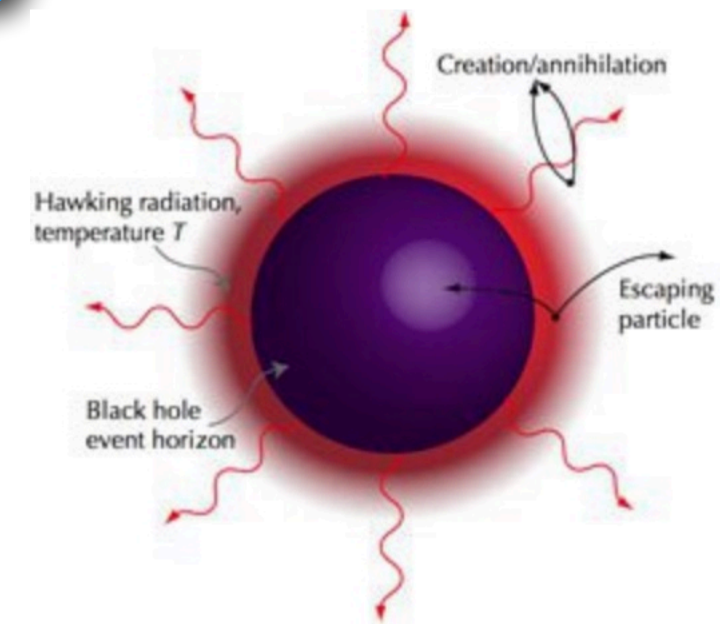
Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

Hawking Evaporation

Total rate of pBH mass-loss:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{M_{\mathrm{Pl}}^4}{M^2}\sum_{s,i} e_{s,i}g_{s,i} \equiv -e_{\mathrm{T}}\frac{M_{\mathrm{Pl}}^4}{M^2}$$

total grey-body "energy emissivity" factor



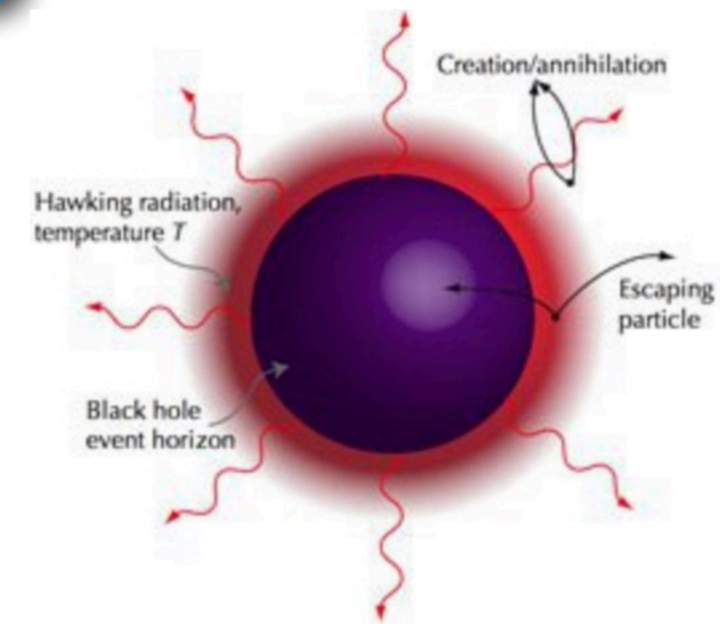
Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

Hawking Evaporation

Total rate of pBH mass-loss:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{M_{\mathrm{Pl}}^4}{M^2}\sum_{s,i} e_{s,i} g_{s,i} \equiv -e_{\mathrm{T}} \frac{M_{\mathrm{Pl}}^4}{M^2}$$

total grey-body "energy emissivity" factor



$$e_{\mathrm{T}} \approx e_{\mathrm{T,SM}} \simeq 4.38 \times 10^{-3}$$

IF $g_{\mathrm{DM}} \ll g_{\mathrm{SM}} \simeq 10^2$

Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

DM Yield

Integrating these eqns find total number of species i particles produced during complete evaporation of micro pBH:

$$N_{s,i} \simeq \frac{f_{s,i} g_{s,i}}{2e_{\mathrm{T}}} \left(\frac{M_0}{M_{\mathrm{Pl}}}\right)^2 \begin{cases} 1 & (T_0 > \mu/d_s) \\ d_s^2 T_0^2/\mu^2 & (T_0 < \mu/d_s) \end{cases}$$

$d_{\mathrm{bosons}} \simeq 3.2$

$d_{\mathrm{fermions}} \simeq 3.6$

Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

DM Yield

Integrating these eqns find total number of species i particles produced during complete evaporation of micro pBH:

$$N_{s,i} \simeq \frac{f_{s,i} g_{s,i}}{2 e_T} \left(\frac{M_0}{M_{\rm Pl}} \right)^2 \begin{cases} 1 & (T_0 > \mu/d_s) \\ d_s^2 T_0^2/\mu^2 & (T_0 < \mu/d_s) \end{cases}$$

Note: strong dependence on spin of DM particle

$d_{\rm bosons} \simeq 3.2$

$d_{\rm fermions} \simeq 3.6$

Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

DM Yield

Integrating these eqns find total number of species i particles produced during complete evaporation of micro pBH:

"light" particle case:
initial effective BH temp
larger than mass μ

$$N_{s,i} \simeq \frac{f_{s,i} g_{s,i}}{2e_{\rm T}} \left(\frac{M_0}{M_{\rm Pl}}\right)^2 \begin{cases} 1 & (T_0 > \mu/d_s) \\ d_s^2 T_0^2/\mu^2 & (T_0 < \mu/d_s) \end{cases}$$

$d_{\rm bosons} \simeq 3.2$

$d_{\rm fermions} \simeq 3.6$

Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

DM Yield

Integrating these eqns find total number of species i particles produced during complete evaporation of micro pBH:

$$N_{s,i} \simeq \frac{f_{s,i} g_{s,i}}{2e_{\rm T}} \left(\frac{M_0}{M_{\rm Pl}}\right)^2 \begin{cases} 1 & (T_0 > \mu/d_s) \\ d_s^2 T_0^2/\mu^2 & (T_0 < \mu/d_s) \end{cases}$$

"heavy" particle case

extra mass dependence

$d_{\rm bosons} \simeq 3.2$

$d_{\rm fermions} \simeq 3.6$

Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

DM Yield

Integrating these eqns find total number of species i particles produced during complete evaporation of micro pBH:

"light" particle case:
initial effective BH temp
larger than mass μ

$$N_{s,i} \simeq \frac{f_{s,i} g_{s,i}}{2 e_T} \left(\frac{M_0}{M_{\rm Pl}} \right)^2 \begin{cases} 1 & (T_0 > \mu / d_s) \\ d_s^2 T_0^2 / \mu^2 & (T_0 < \mu / d_s) \end{cases}$$

"heavy" particle case

Two qualitatively different mass dependencies
(and thus mass ranges it turns out)

$d_{\rm bosons} \simeq 3.2$

$d_{\rm fermions} \simeq 3.6$

Spin	e_s	f_s
0	7.24×10^{-5}	6.66×10^{-4}
1/2	4.09×10^{-5}	2.43×10^{-4}
1	1.68×10^{-5}	7.40×10^{-5}
3/2	5.5×10^{-6}	2.1×10^{-5}
2	1.92×10^{-6}	5.53×10^{-6}

DM Yield

To calculate the DM yield $Y \equiv n_{\rm DM}/s_{\rm tot}$ need to evaluate entropy density $s_{\rm tot}$ at end of pBH decay

DM Yield

To calculate the DM yield $Y \equiv n_{\rm DM}/s_{\rm tot}$ need to evaluate entropy density $s_{\rm tot}$ at end of pBH decay

(recall $\mu Y = 0.43\,\mathrm{eV}$ gives observed $\Omega_{\rm DM} h^2 = 0.11$)

DM Yield

To calculate the DM yield $Y \equiv n_{\rm DM}/s_{\rm tot}$ need to evaluate entropy density $s_{\rm tot}$ at end of pBH decay

(recall $\mu Y = 0.43\,\mathrm{eV}$ gives observed $\Omega_{\rm DM} h^2 = 0.11$)

$s_{\rm tot}$ dominated by the entropy of the Hawking-emitted SM radiation bath $\rho_{\rm rad}$!

DM Yield

To calculate the DM yield $Y \equiv n_{\rm DM}/s_{\rm tot}$ need to evaluate entropy density $s_{\rm tot}$ at end of pBH decay

(recall $\mu Y = 0.43\,\mathrm{eV}$ gives observed $\Omega_{\rm DM}h^2 = 0.11$)

$s_{\rm tot}$ dominated by the entropy of the Hawking-emitted SM radiation bath $\rho_{\rm rad}$!

Evolution of energy densities

$$\frac{\mathrm{d}\rho_{\rm BH}}{\mathrm{d}t} + 3H\rho_{\rm BH} = -e_{\rm T}\frac{M_{\rm Pl}^4}{M^2}n$$

$$\frac{\mathrm{d}\rho_{\rm rad}}{\mathrm{d}t} + 4H\rho_{\rm rad} = +e_{\rm T}\frac{M_{\rm Pl}^4}{M^2}n$$

$$H(t)^2 = 8\pi(\rho_{\rm BH}+\rho_{\rm rad})/3M_{\rm Pl}^2$$

where decay of pBH mass $M^3(t) = M_0^3 - 3e_{\rm T}M_{\rm Pl}^4\,(t-t_0)$

DM Yield

To calculate the DM yield $Y \equiv n_{\rm DM}/s_{\rm tot}$ need to evaluate entropy density $s_{\rm tot}$ at end of pBH decay

(recall $\mu Y = 0.43\,\text{eV}$ gives observed $\Omega_{\rm DM} h^2 = 0.11$)

$s_{\rm tot}$ dominated by the entropy of the Hawking-emitted SM radiation bath $\rho_{\rm rad}$!

Evolution of energy densities

$$\frac{d\rho_{\rm BH}}{dt} + 3H\rho_{\rm BH} = -e_{\rm T}\frac{M_{\rm Pl}^4}{M^2}n$$

$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = +e_{\rm T}\frac{M_{\rm Pl}^4}{M^2}n$$

$$H(t)^2 = 8\pi(\rho_{\rm BH}+\rho_{\rm rad})/3M_{\rm Pl}^2$$

where decay of pBH mass $M^3(t) = M_0^3 - 3e_{\rm T}M_{\rm Pl}^4\,(t-t_0)$

defines a BH lifetime $\tau_{\rm dec}(M) = M^3/3e_{\rm T}M_{\rm Pl}^4$

DM Yield

Character of solutions determined by initial ratio of Hubble expansion timescale to BH decay timescale

$$B(t) \equiv t_H / \tau_{\rm dec}$$

DM Yield

Character of solutions determined by initial ratio of Hubble expansion timescale to BH decay timescale

$$B(t) \equiv t_H / \tau_{\rm dec}$$

initially $$(B_0)^2 = e_{\rm T}^2 \frac{3}{2\pi} \frac{M_{\rm Pl}^3}{n_0} \left(\frac{M_{\rm Pl}}{M_0} \right)^7$$

if $B_0 \ll 1$ decay is "slow"

if $B_0 \gg 1$ decay is "fast"

DM Yield

Character of solutions determined by initial ratio of Hubble expansion timescale to BH decay timescale

$$B(t) \equiv t_H / \tau_{\rm dec}$$

initially $$(B_0)^2 = e_{\rm T}^2 \frac{3}{2\pi} \frac{M_{\rm Pl}^3}{n_0} \left(\frac{M_{\rm Pl}}{M_0} \right)^7$$

if $B_0 \ll 1$ decay is "slow"

if $B_0 \gg 1$ decay is "fast"

so two qualitatively different regimes for Yield
(and remember also have "light" and "heavy" DM mass)

DM Yield: "slow" regime

Analytically find

$$Y^{\rm slow} \equiv \frac{n_{s,i}}{s_{\rm tot}} \simeq 0.49 \frac{f_{s,i} g_{s,i}}{g_*^{1/4} e_{\rm T}^{1/2}} \left(\frac{M_{\rm Pl}}{M_0} \right)^{1/2}$$

DM Yield: "slow" regime

Analytically find

$$Y^{\rm slow} \equiv \frac{n_{s,i}}{s_{\rm tot}} \simeq 0.49 \frac{f_{s,i} g_{s,i}}{g_*^{1/4} e_{\rm T}^{1/2}} \left(\frac{M_{\rm Pl}}{M_0} \right)^{1/2}$$

Associated SM plasma temp at end of pBH decay

$$T_{\rm RH}^{\rm slow} \simeq 1.09 \frac{e_{\rm T}^{1/2}}{g_*^{1/4}} M_{\rm Pl} \left(\frac{M_{\rm Pl}}{M_0} \right)^{3/2}$$

DM Yield: "slow" regime

Analytically find

$$Y^{\rm slow} \equiv \frac{n_{s,i}}{s_{\rm tot}} \simeq 0.49 \frac{f_{s,i} g_{s,i}}{g_*^{1/4} e_{\rm T}^{1/2}} \left(\frac{M_{\rm Pl}}{M_0} \right)^{1/2}$$

Associated SM plasma temp at end of pBH decay

$$T_{\rm RH}^{\rm slow} \simeq 1.09 \frac{e_{\rm T}^{1/2}}{g_*^{1/4}} M_{\rm Pl} \left(\frac{M_{\rm Pl}}{M_0} \right)^{3/2}$$

both independent of initial pBH number density!!

DM Yield: "slow" regime

Analytically find

$$Y^{\rm slow} \equiv \frac{n_{s,i}}{s_{\rm tot}} \simeq 0.49 \frac{f_{s,i} g_{s,i}}{g_*^{1/4} e_{\rm T}^{1/2}} \left(\frac{M_{\rm Pl}}{M_0} \right)^{1/2}$$

Associated SM plasma temp at end of pBH decay

$$T_{\rm RH}^{\rm slow} \simeq 1.09 \frac{e_{\rm T}^{1/2}}{g_*^{1/4}} M_{\rm Pl} \left(\frac{M_{\rm Pl}}{M_0} \right)^{3/2}$$

Apart from usual discrete choices of spin and no. of dof of DM this implies that prediction for $\Omega_{\rm DM}\, h^2$ depends on just two parameters, M_0, and DM mass, μ

(same number as WIMP case!)

DM Yield: "fast" regime

Analytically find

$$Y^{\text{fast}} \simeq 0.50 \frac{f_{s,i} g_{s,i}}{g_*^{1/4} e_{\mathrm{T}}} \left(\frac{n_0}{M_{\mathrm{Pl}}^3} \right)^{1/4} \left(\frac{M_0}{M_{\mathrm{Pl}}} \right)^{5/4}$$

Associated SM plasma temp at end of pBH decay

$$T_{\mathrm{RH}}^{\text{fast}} \simeq \left(\frac{30 n_0 M_0}{\pi^2 g_*} \right)^{1/4}$$

DM Yield: "fast" regime

Analytically find

$$Y^{\text{fast}} \simeq 0.50 \frac{f_{s,i} g_{s,i}}{g_*^{1/4} e_{\text{T}}} \left(\frac{n_0}{M_{\text{Pl}}^3} \right)^{1/4} \left(\frac{M_0}{M_{\text{Pl}}} \right)^{5/4}$$

Associated SM plasma temp at end of pBH decay

$$T_{\text{RH}}^{\text{fast}} \simeq \left(\frac{30 n_0 M_0}{\pi^2 g_*} \right)^{1/4}$$

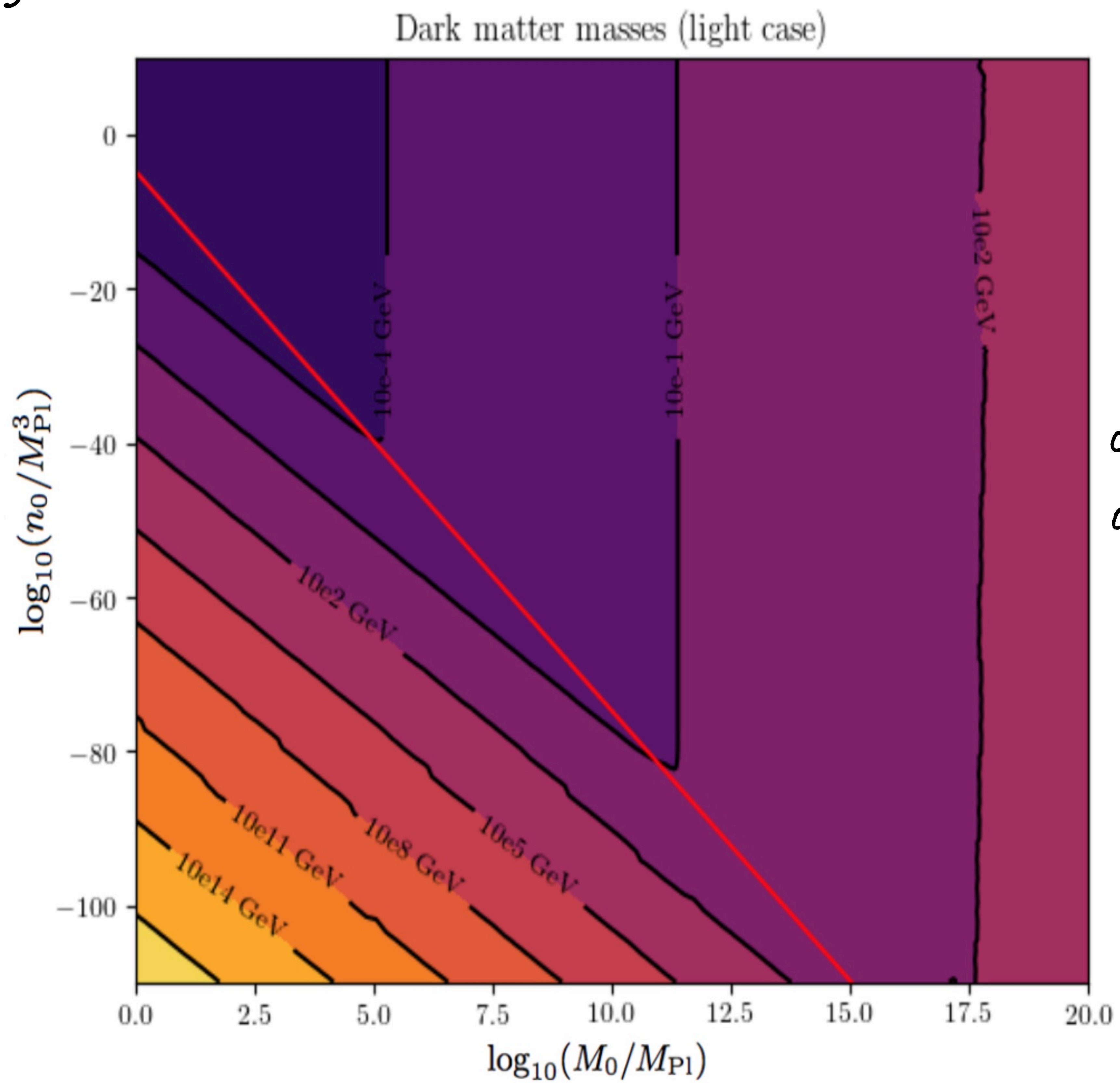
now dependent on both initial pBH M_0 and n_0

DM mass: "light" case

numerical solution agrees

$\mu < d_s T_0$

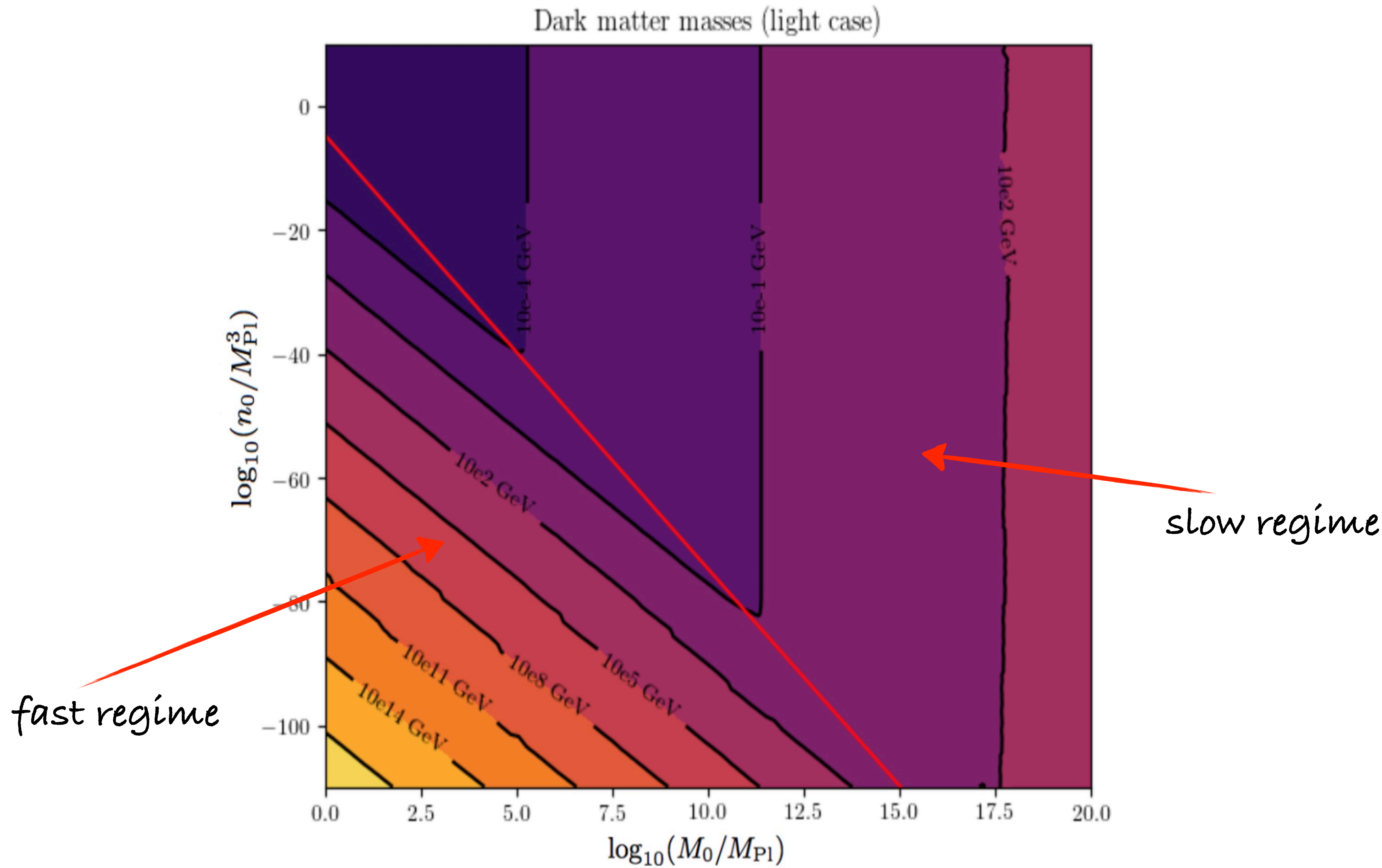
(spin s=0 case shown)



iso-DM-mass contours giving observed $\Omega_{\rm DM}\, h^2$

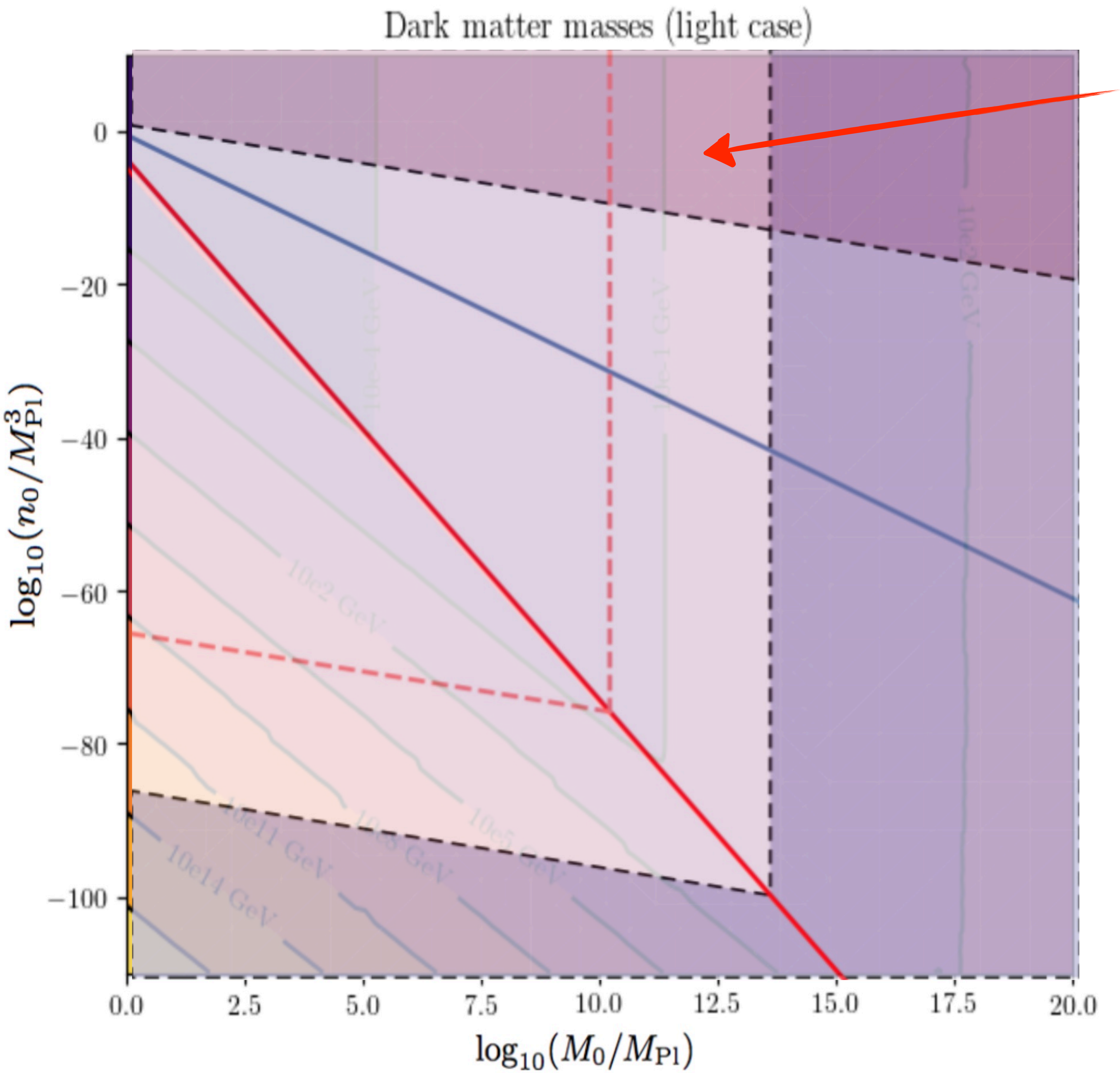
DM mass: "light" case

$\mu < d_s T_0$



Not all of this parameter space accessible:
some trivially excluded regions

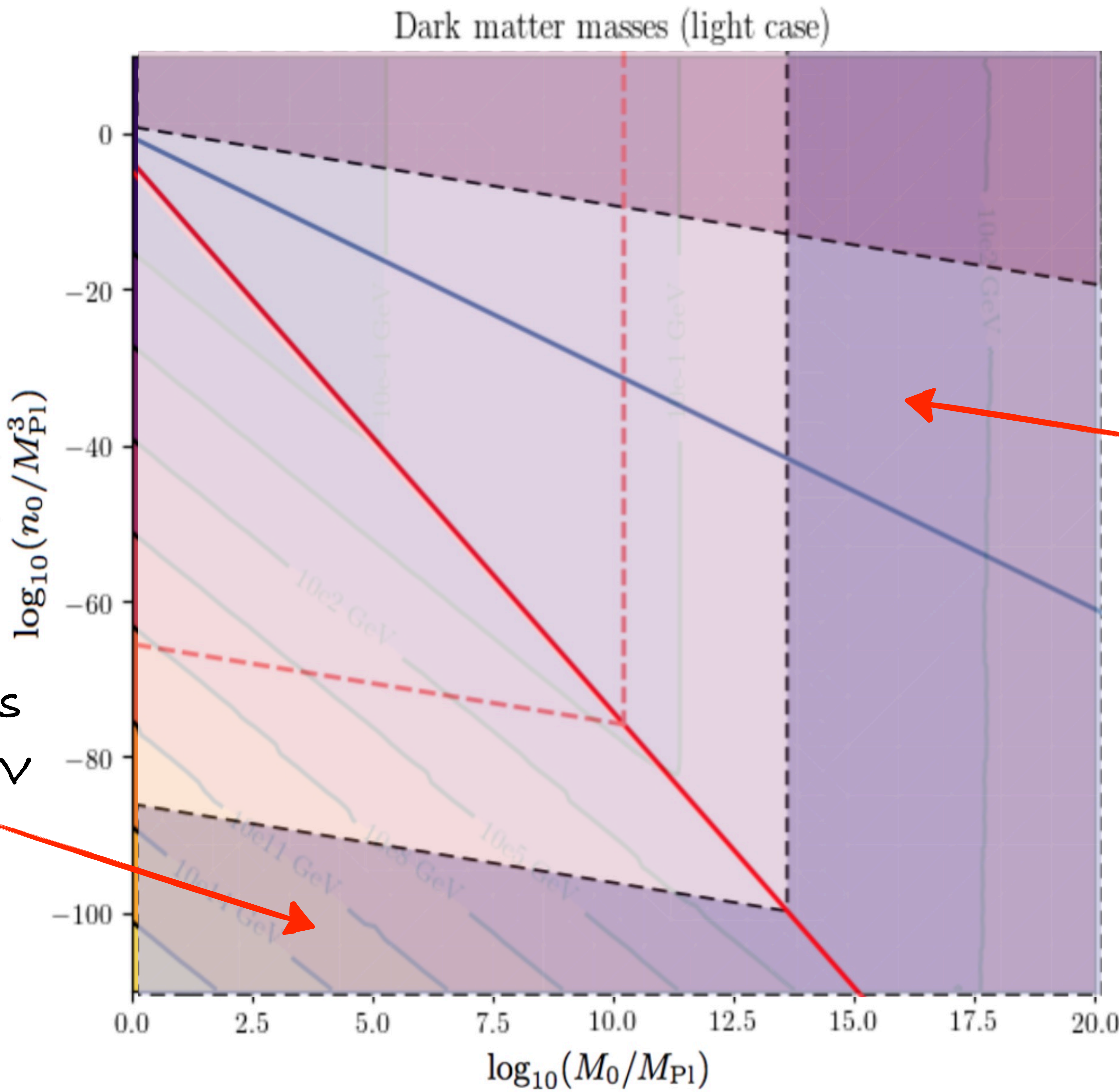
DM mass: "light" case



excluded as

$\varrho_{BH}(0) > M_{Pl}^4$

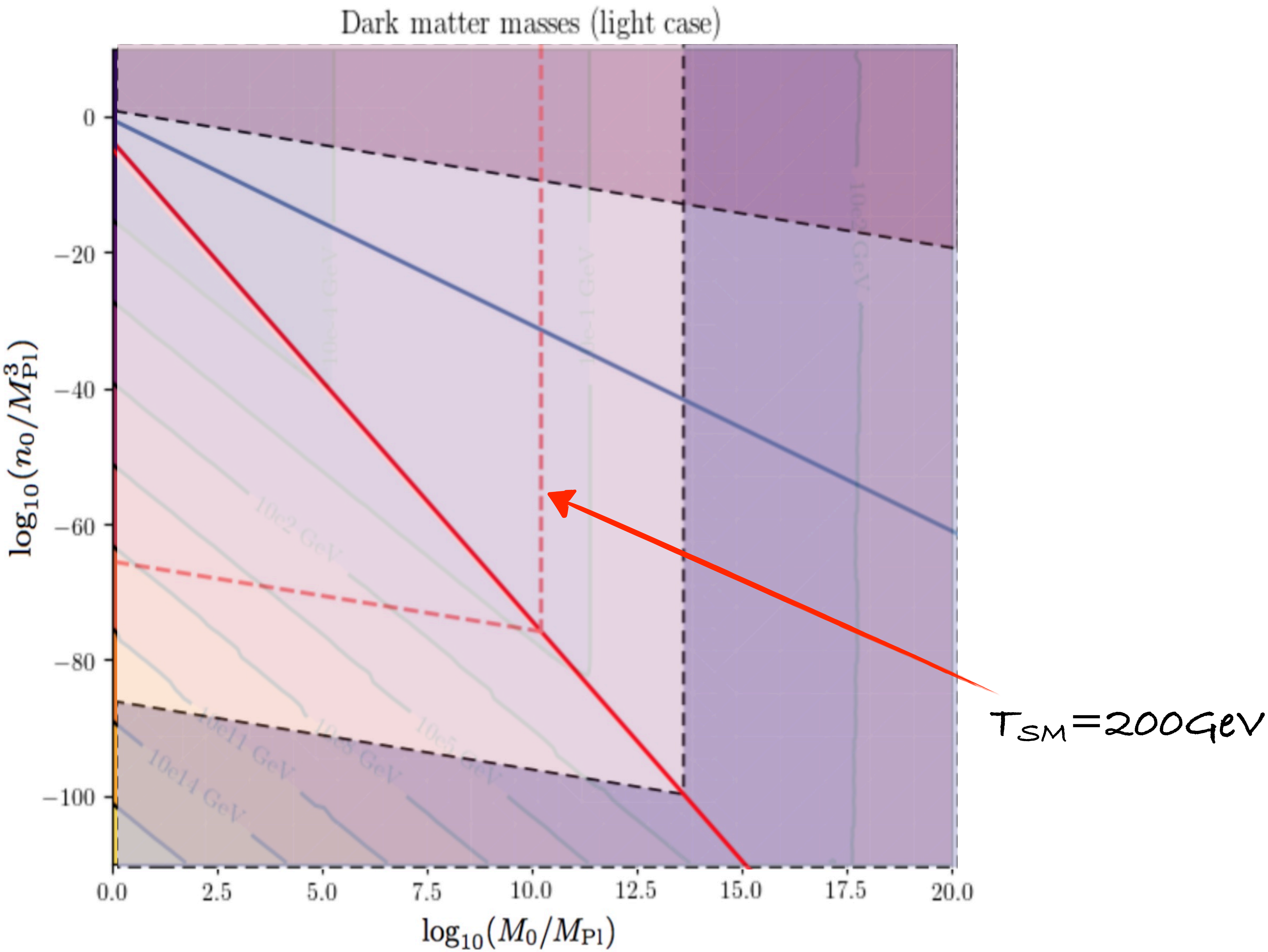
DM mass: "light" case



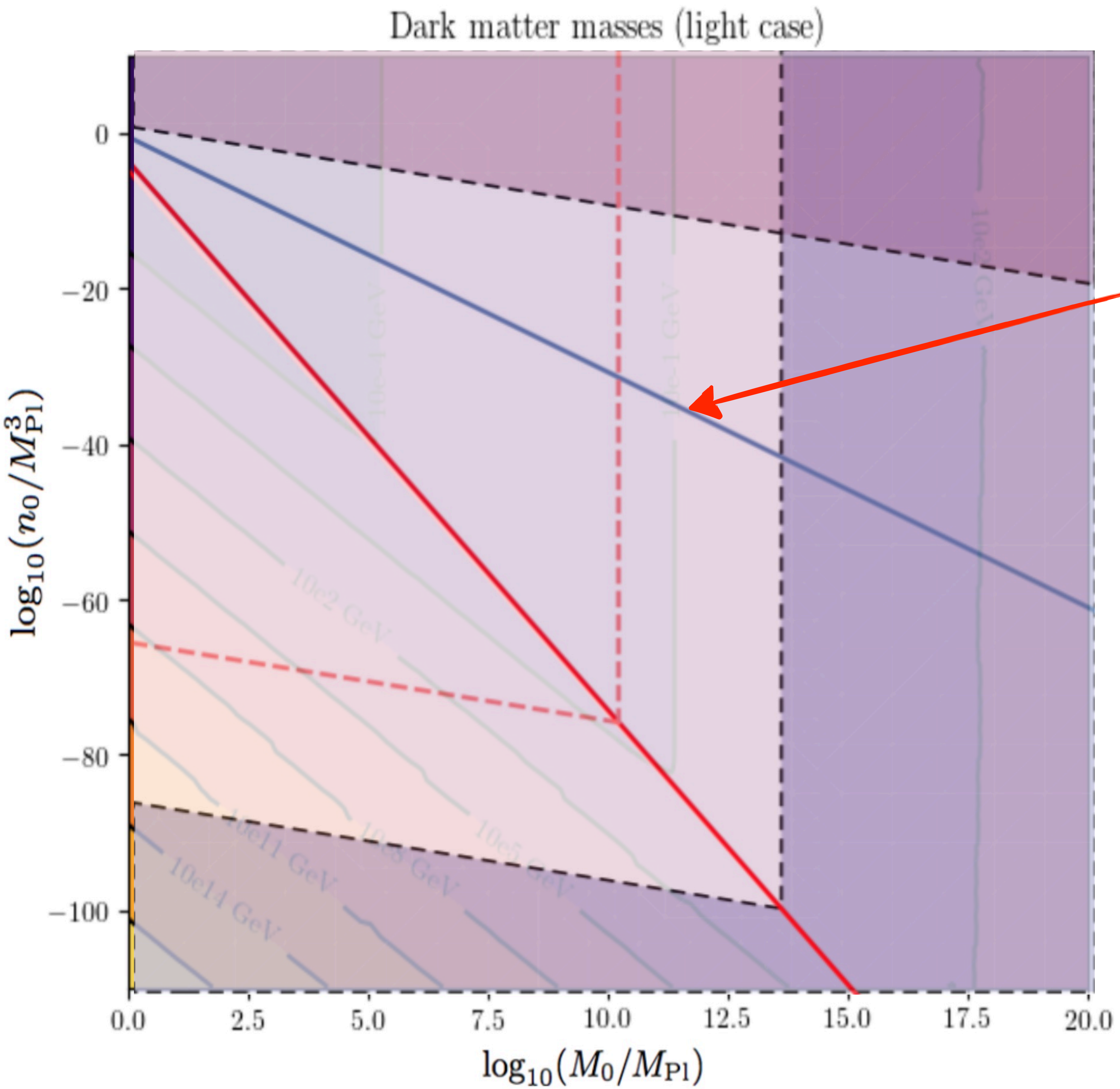
excluded as $T_{SM}<3$ MeV

excluded as $T_{SM}<3$ MeV

DM mass: "light" case



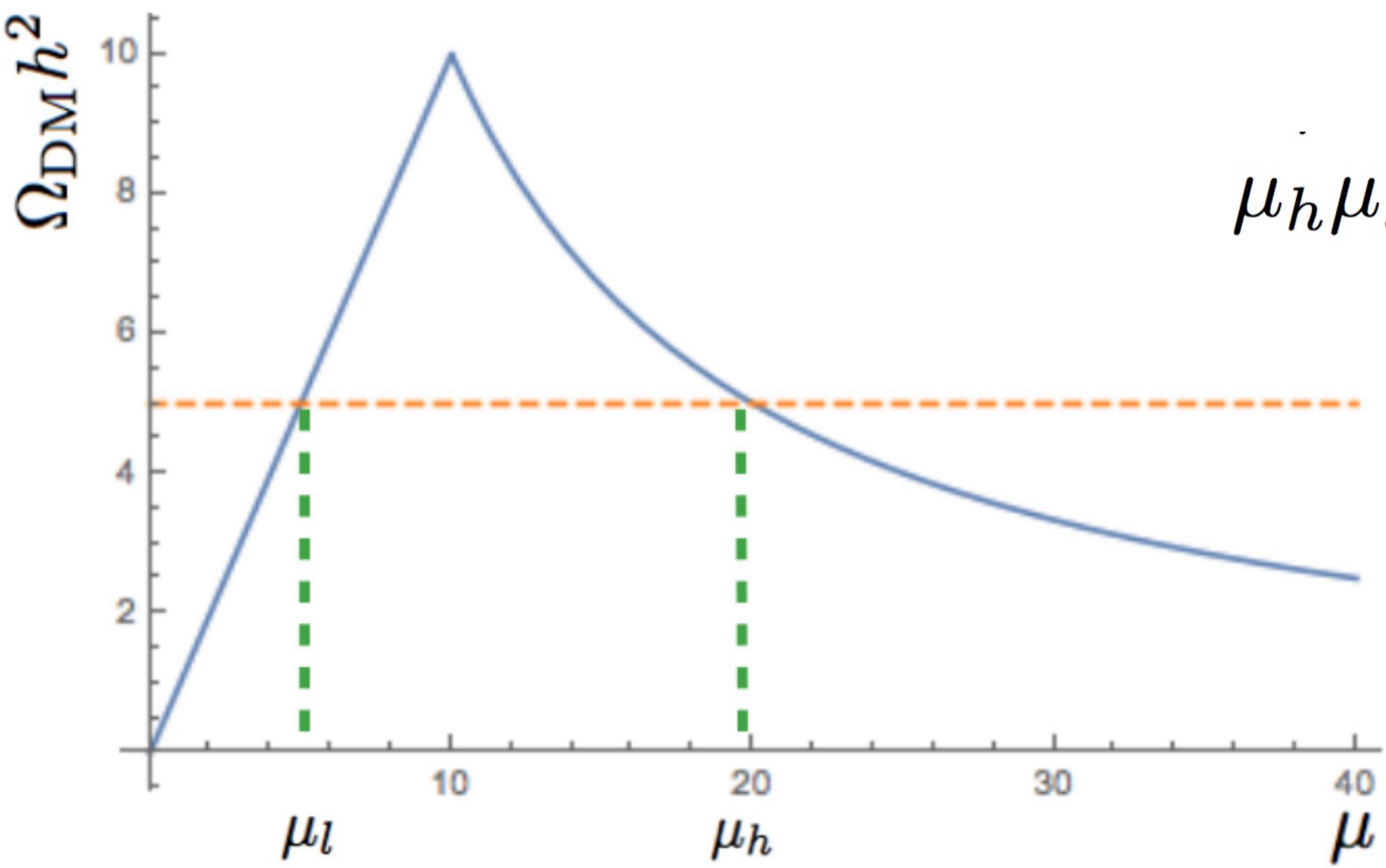
DM mass: "light" case



one PBH per initial Hubble volume

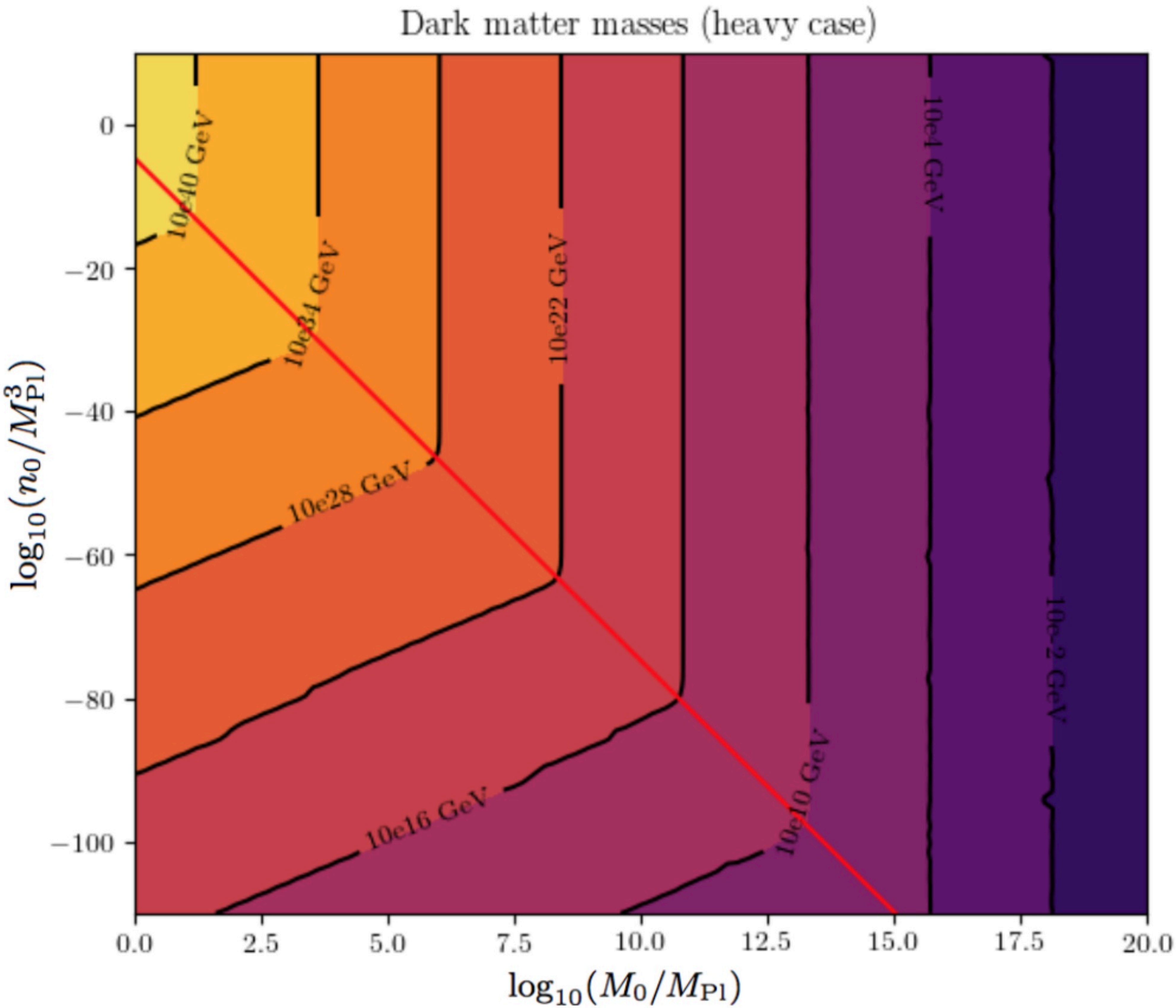
"light" vs "heavy"

$$Y_h = Y_l \frac{T_0^2}{\mu_h^2} d_s^2$$



$$\mu_h \mu_l = T_0^2 d_s^2$$

DM mass: "heavy" case

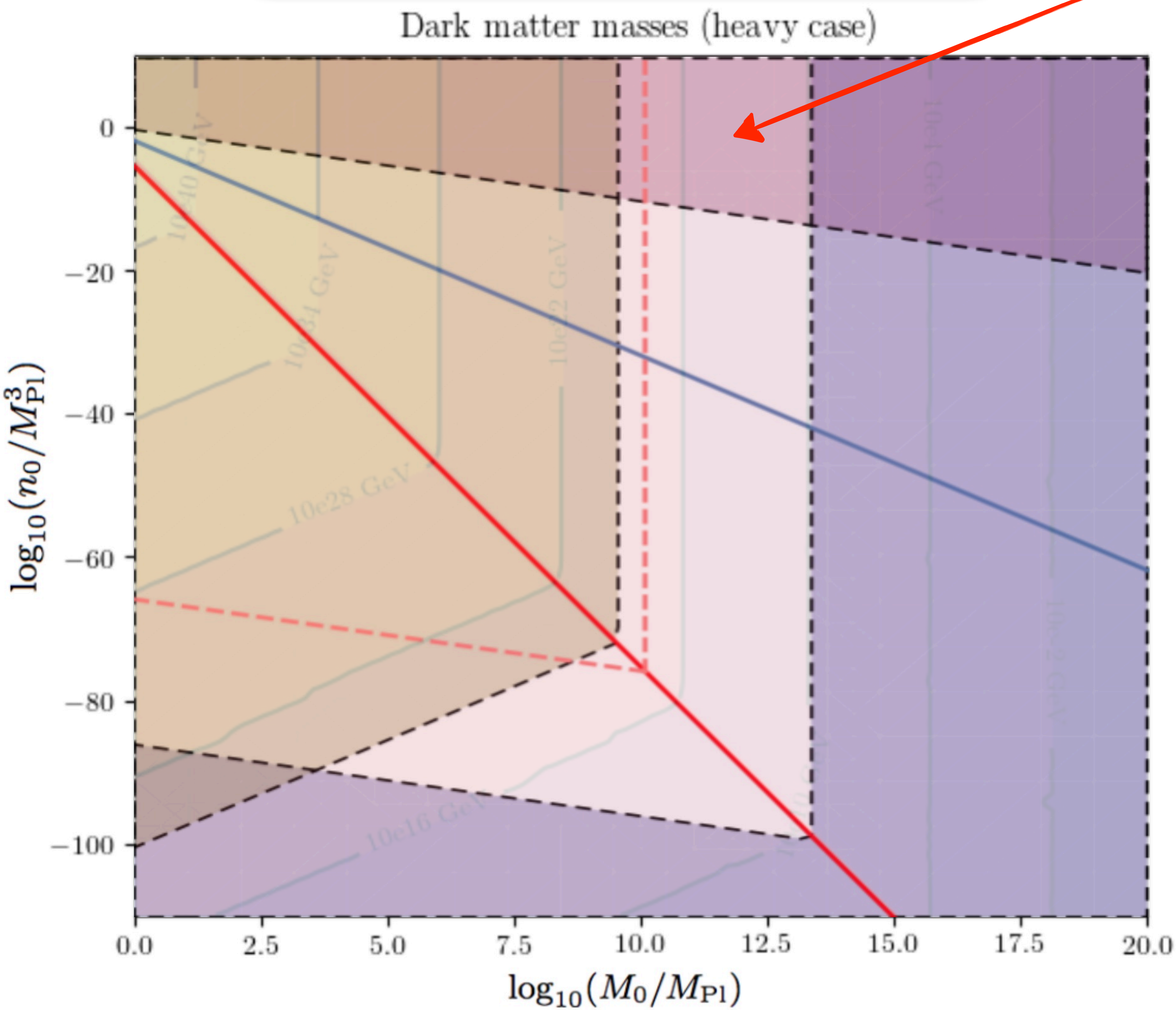


Again not all of this parameter space accessible:
some trivially excluded regions

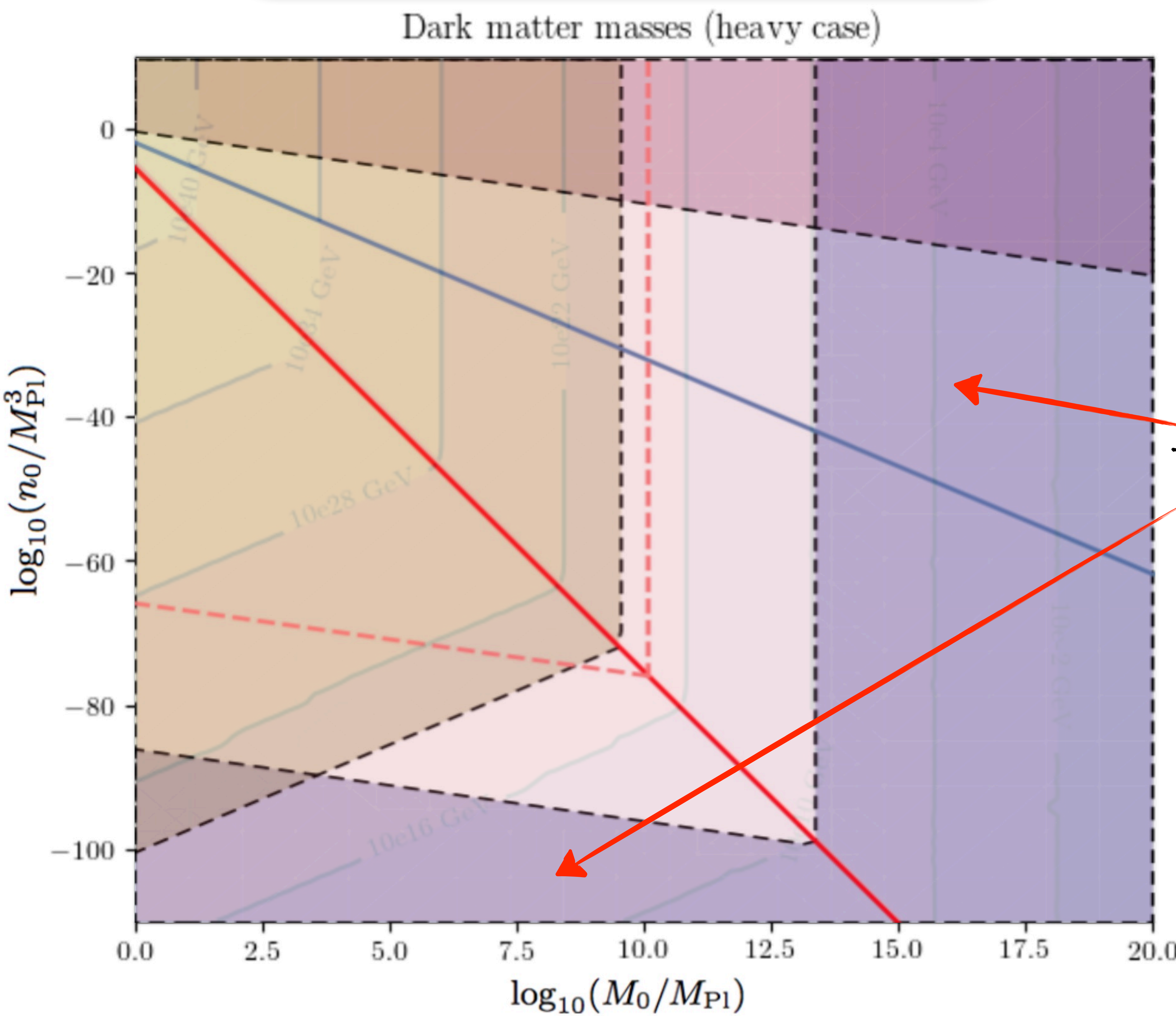
DM mass: "heavy" case

excluded as

$\varrho_{BH}(0) > M_{Pl}^4$



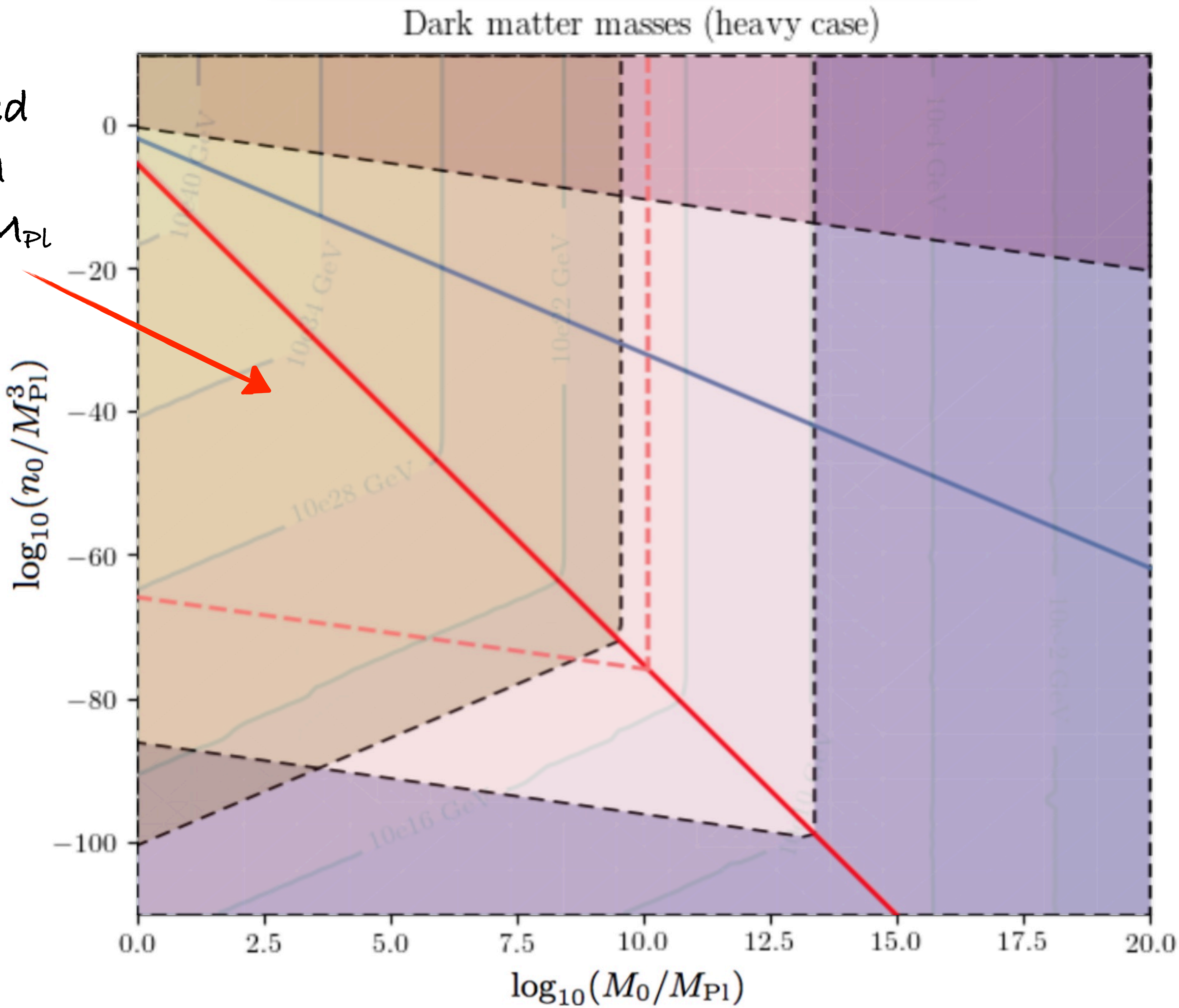
DM mass: "heavy" case



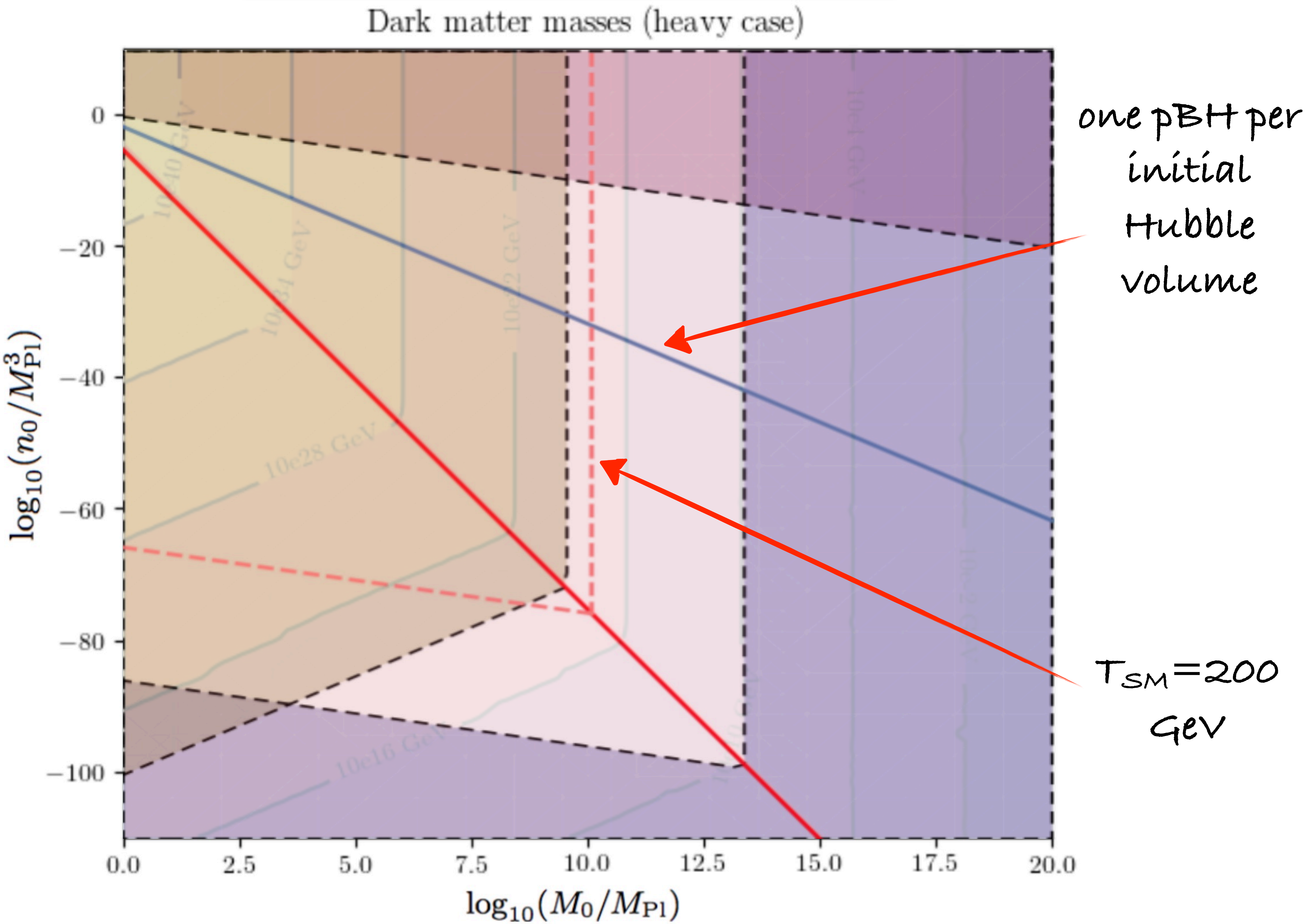
excluded as $T_{SM} < 3$ MeV

DM mass: "heavy" case

excluded
as DM
mass > M_{Pl}



DM mass: "heavy" case



However, in light DM case, a further very significant constraint from non-thermal nature of DM production

Big constraint
from too "hot" DM

Free-streaming constraint

DM produced with *instantaneous* "thermal" momentum distribution at temp T(t)

$$\frac{\mathrm{d}\dot{N}}{\mathrm{d}p}(p,t) = \frac{27M(t)^2}{2\pi M_{\mathrm{Pl}}^4}\frac{p\sqrt{p^2+\mu^2}}{e^{\sqrt{p^2+\mu^2}/T(t)}\pm 1}$$

here ignoring grey-body factors for simplicity — these make problem slightly more severe

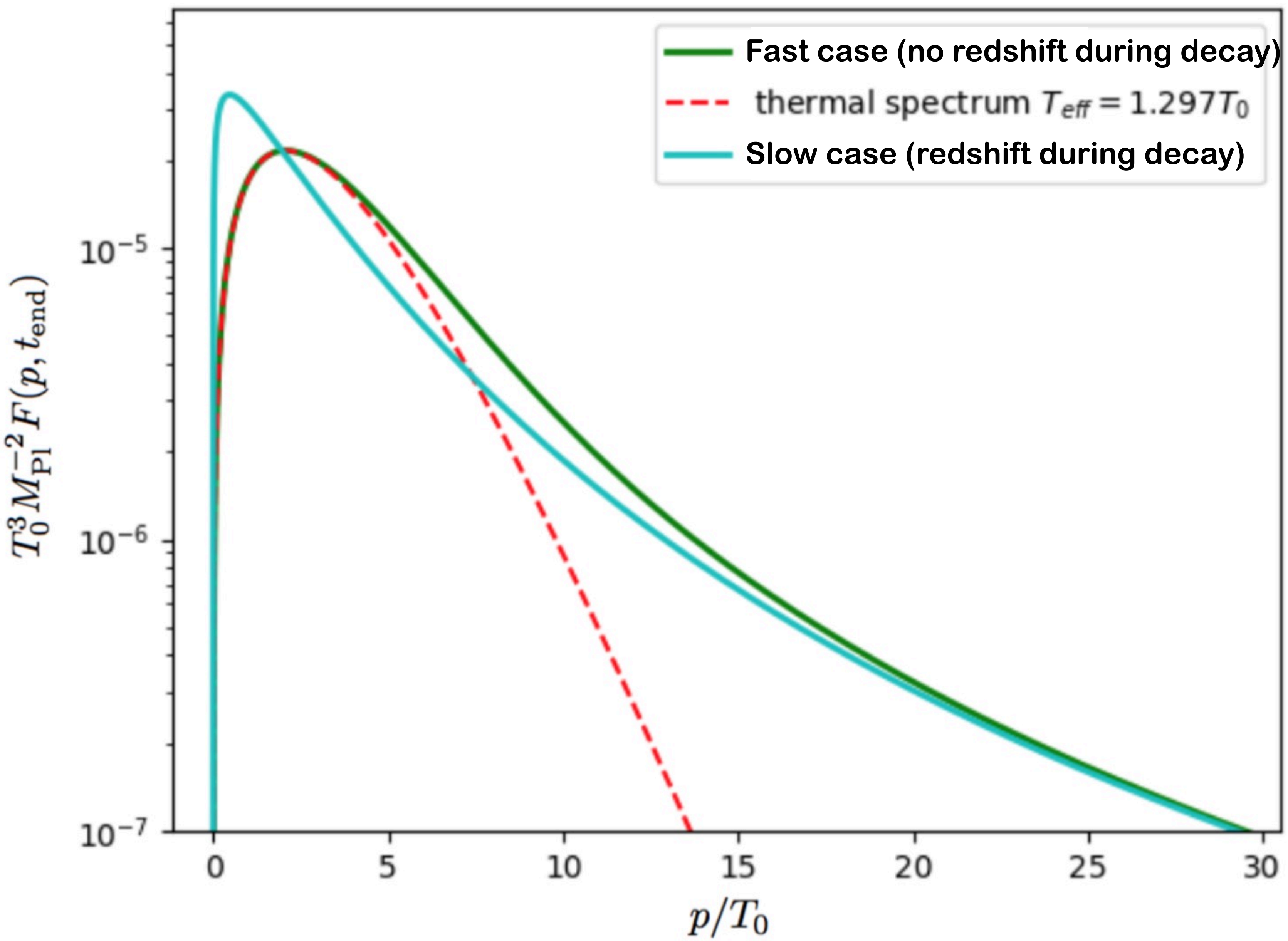
As BH shrinks it becomes hotter and the final mom'm distribution function is (red-shifted) sum of instantaneous distributions

$$F(p,t) = \int_{t_0}^{t_{\mathrm{end}}} \mathrm{d}\tau\, \frac{\mathrm{d}\dot{N}}{\mathrm{d}p}\left(p\frac{R(t)}{R(\tau)}, T(\tau)\right)\frac{R(t)}{R(\tau)}$$

This is highly non-thermal with significant ultra-relativistic tail….

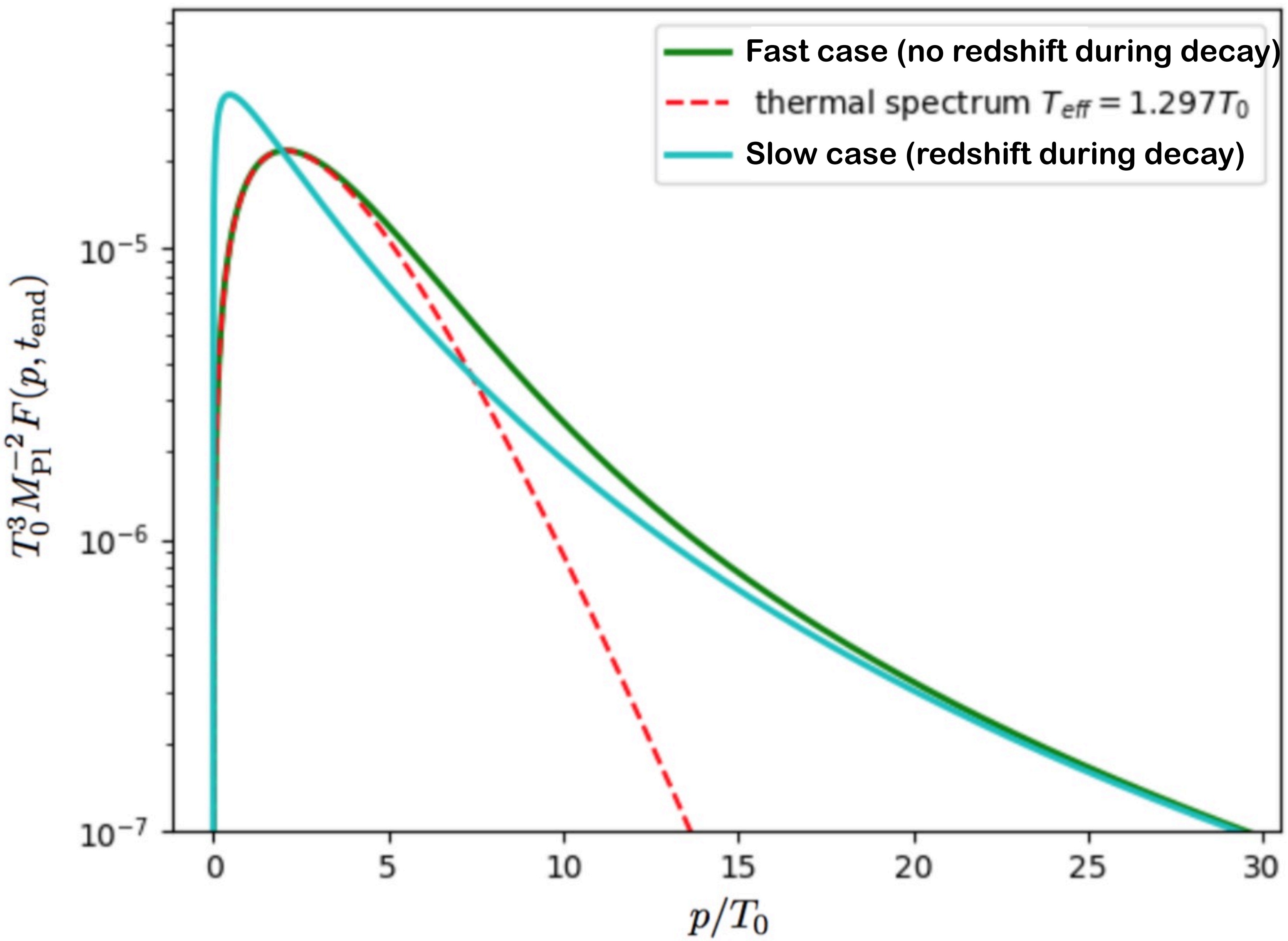
Free-streaming constraint

Consider form of F(p,t) at, t_{end}, the end of pBH decay:



Free-streaming constraint

Consider form of F(p,t) at, t_{end}, the end of pBH decay:



These distributions now continue to redshift as SM temp drops

But DM remains far too fast moving at epoch of structure formation ("hot" DM) *in light case for spin <3/2*

Free-streaming constraint

"light" s>1 cases

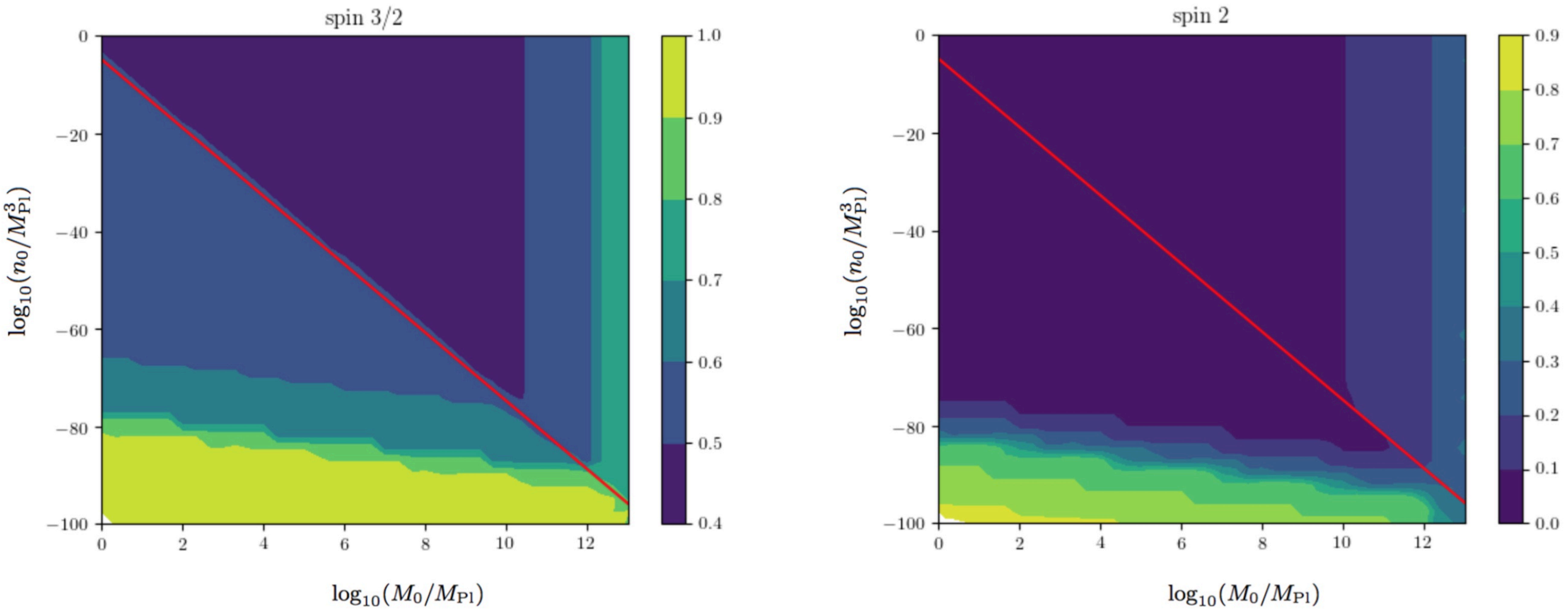


FIG. 5. Free-streaming constraints in the 'light' DM case for spin 3/2 and 2 (left and right panels), where colour shading shows fraction of DM particles that are still relativistic at $T_{\rm SM} = 1\,\text{keV}$, and we have at every point imposed a 'light' solution DM mass such that the correct $\Omega_{\rm DM}h^2$ is reproduced. Note the differing colour scales in the two cases with the spin 3/2 case having more than $\sim 40\%$ of particles relativistic over the entire plane, while the spin 2 case has substantial regions where less than $\sim 10\%$ of DM particles are relativistic. Red line ($B_0 = 1$) marks the boundary between the 'fast' and 'slow' regimes.

Allowed mass ranges

Many cases & masses survive all constraints

Spin	g_s	μ/GeV (slow, light)	μ/GeV (slow, heavy)	μ/GeV (fast, light)	μ/GeV (fast, heavy)
0	1	$\cancel{[2.6\times10^{-7}, 0.80]}$	$[3.4\times10^{9}, M_{\text{Pl}}]$	$\cancel{[3.1\times10^{-7}, 2.8\times10^{13}]}$	$[2.9\times10^{9}, M_{\text{Pl}}]$
1/2	2	$\cancel{[3.6\times10^{-7}, 1.1]}$	$[3.1\times10^{9}, M_{\text{Pl}}]$	$\cancel{[4.2\times10^{-7}, 3.9\times10^{13}]}$	$[2.6\times10^{9}, M_{\text{Pl}}]$
1	3	$\cancel{[7.8\times10^{-7}, 2.4]}$	$[1.1\times10^{9}, M_{\text{Pl}}]$	$\cancel{[9.2\times10^{-7}, 8.5\times10^{13}]}$	$[9.6\times10^{8}, M_{\text{Pl}}]$
3/2	4	$[2\times10^{-6}, 6]$	$[5\times10^{8}, M_{\text{Pl}}]$	$[2\times10^{-6}, 2\times10^{14}]$	$[5\times10^{8}, M_{\text{Pl}}]$
2	5	$[6.3\times10^{-6}, 19]$	$[1.4\times10^{8}, M_{\text{Pl}}]$	$[7.4\times10^{-6}, 6.8\times10^{14}]$	$[1.2\times10^{8}, M_{\text{Pl}}]$

can be superheavy!

Sensitivity to initial state?

In fact in slow regime remarkably insensitive to initial conditions

Any initial SM radiation component is redshifted away by a large factor

$$\frac{\Delta\rho_{\rm rad,SM}(t_{\rm end})}{\Delta\rho_{\rm rad,SM}(t_0)} \simeq \left(\frac{B_0}{0.928}\right)^{8/3} \ll 1$$

note B_0 can be very small $B_0^{-2/3} \sim 0.24(M_{\rm Pl}/T_{\rm RH})^{5/9} \gg 1$

So as long as initial density of SM radiation is not too big results unaffected

$$\rho_{\rm rad,SM}(t_0) \lesssim 0.1 B_0^{-2/3} \rho_{\rm BH}(t_0)$$

How to test?!?

Dark Radiation: Unavoidable prediction applies to any very light/massless states, eg, gravitons (axions give extra contributions….)

$$\Delta\rho_{\rm grav}/\rho_{\rm rad} = 2e_2/e_{\rm T,SM} \simeq 8.77 \times 10^{-4}$$

graviton DR: $\Delta N_{\rm eff,grav} \simeq 5.39 \times 10^{-3}$

axion DR: $\Delta N_{\rm eff} = 0.10\, N_a$

Also

- Can get warm DM component which changes structure formation…
- If T_{RH} low then changes to cosmic neutrino background with possible alterations of BBN

….work in progress!

How to test?!?

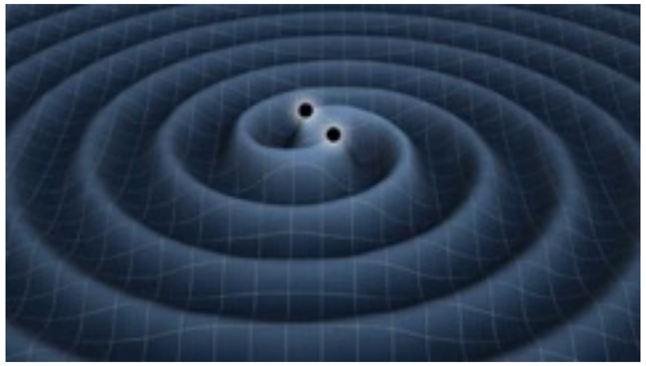
In fact, mechanism still works if go away from only gravitational interactions!

Very heavy DM can be produced by Hawking evaporation of pBHs – eg, M_{GUT}....

Too heavy to be produced by SM plasma even if has substantial interactions with SM

New possibilities for both direct and indirect detection ....work in progress!

Also the *production or mergers of the pBHs* could give stochastic gravitational wave background at interesting levels ....work in progress!



Conclusions

There does exist a purely gravitational DM production mechanism!
(& attractive in my biased opinion)

Opens up qualitatively new possibilities for DM pheno
(eg, GUT particles??,string states??)

early days — much work to be done!

back up slides....

Hawking Genesis

$$\frac{\Delta n_{\rm DM}(0)}{n_0} \ll 2 \times 10^{-3} \left(\frac{M_{\rm Pl}^3}{n_0} \right)^{2/7}$$

$n_0/M_{\rm Pl}^3$ can be as small as 10^{-80}