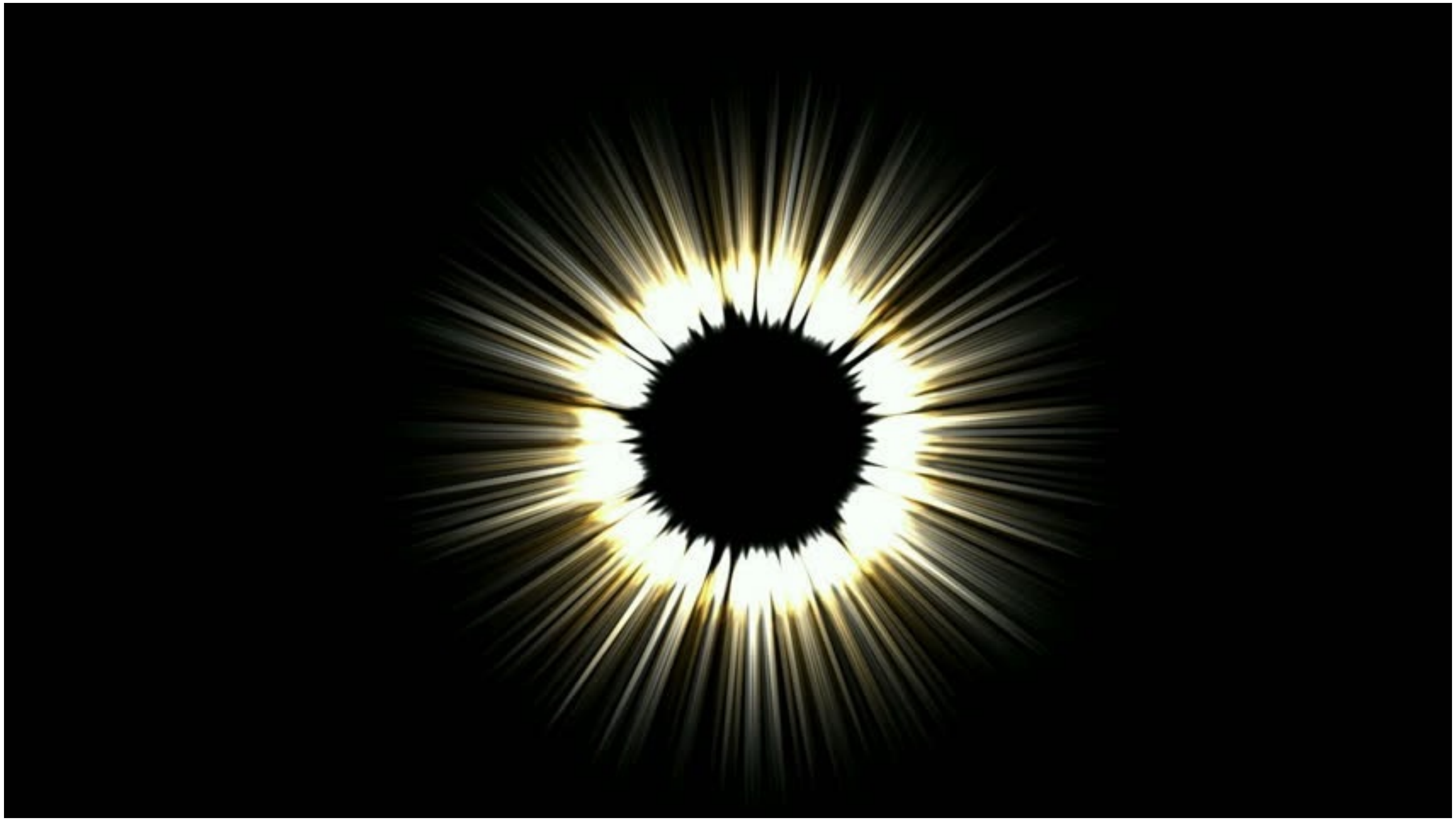
Hawking Genesis

John March-Russell
Oxford University



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- *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

A successful, calculable, purely gravitational mechanism of DM production (and the hot SM Big Bang plasma)!

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

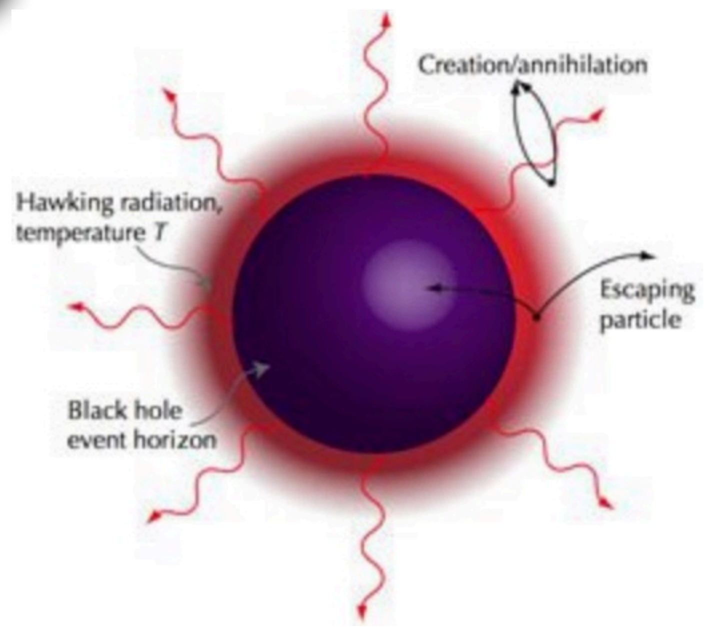
Starting assumptions (most just for pedagogical simplicity & can be significantly weakened):

- In the early Universe there exists a population of micro primordial black holes (pBHs)
- The DM particle has only gravitational interactions with SM
- The pre-existing number/energy densities of DM and SM radiation are not very large (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*

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



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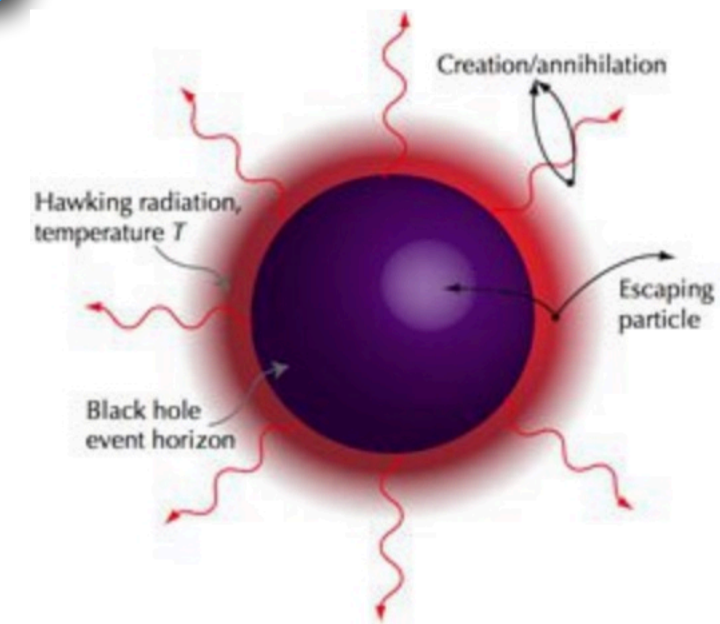

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number of particles of species i, spin s,
produced in energy range (w,w+dw)

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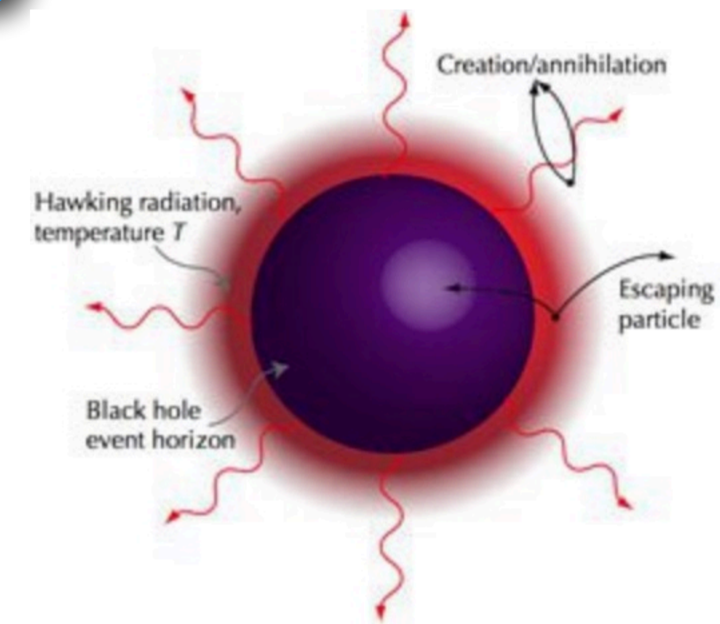

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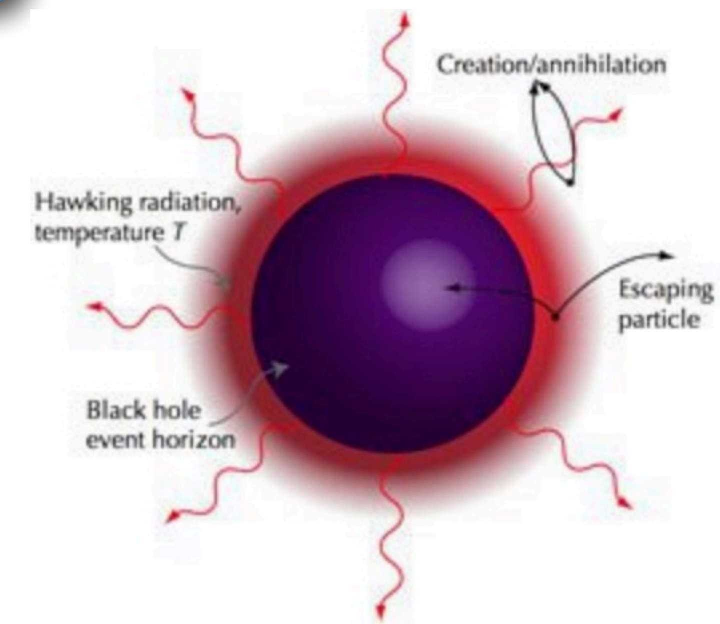

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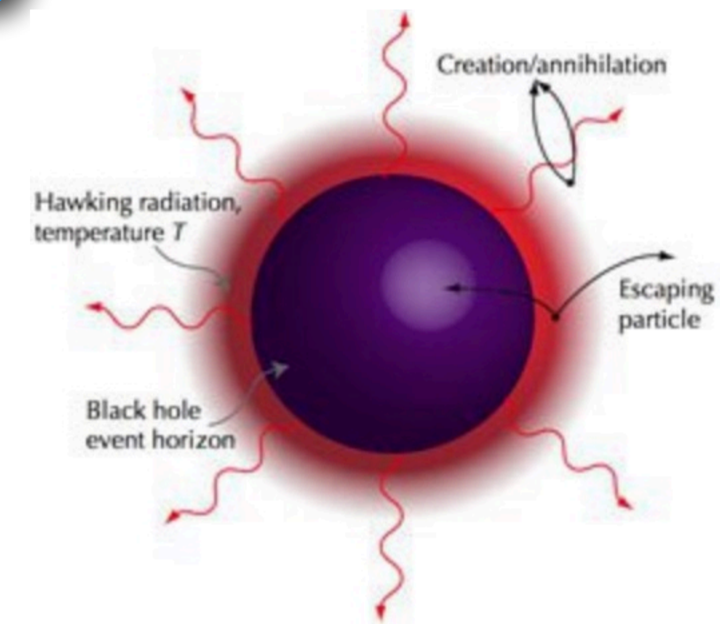

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Total rate of production of particle species i of mass μ well approximated by

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

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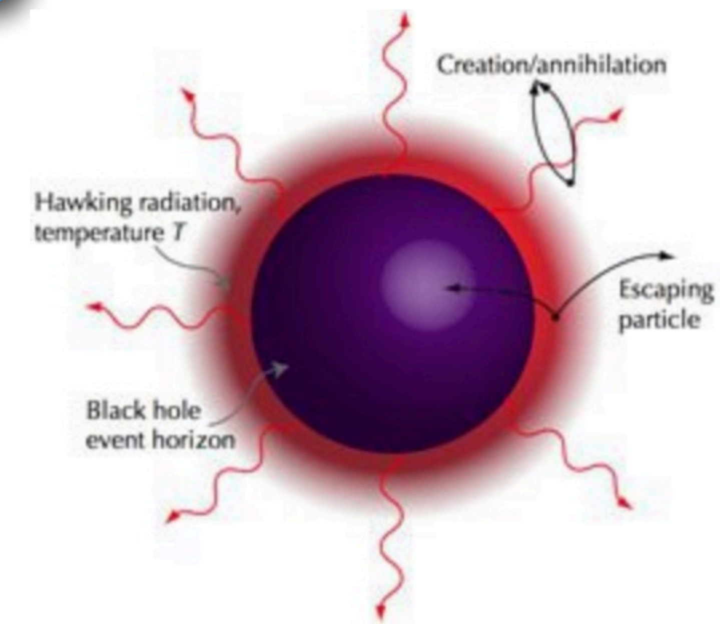

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grey-body "rate" factor

no. dof

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

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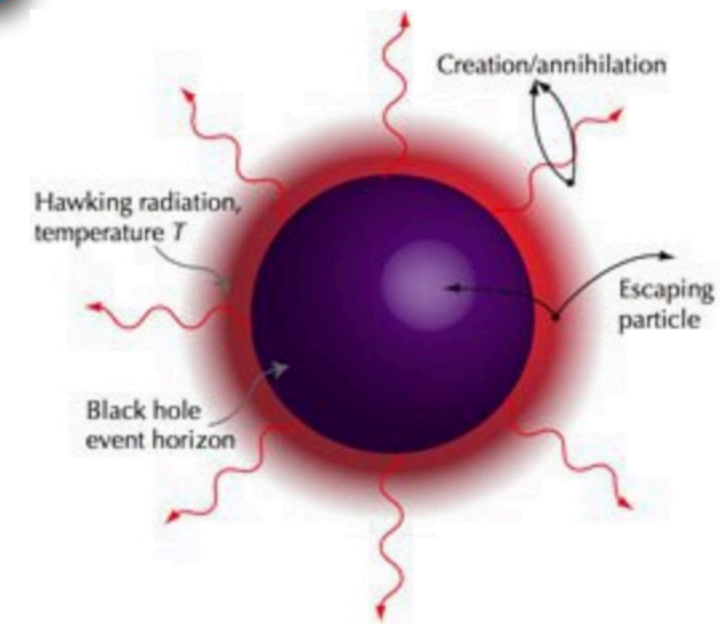

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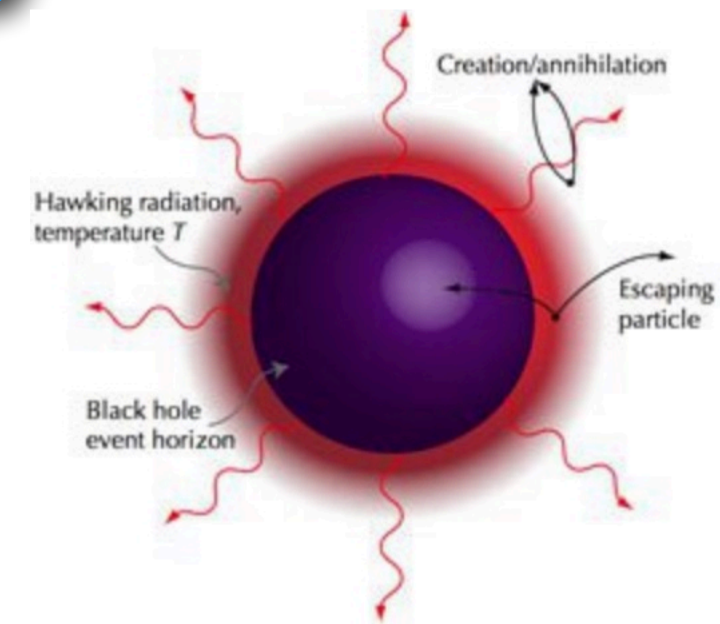

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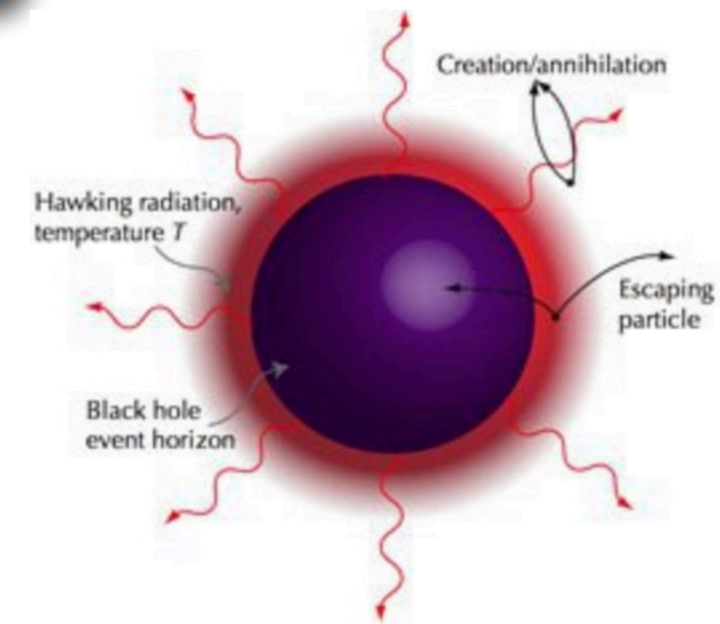
grey-body "energy emissivity" factor into species i of spin s



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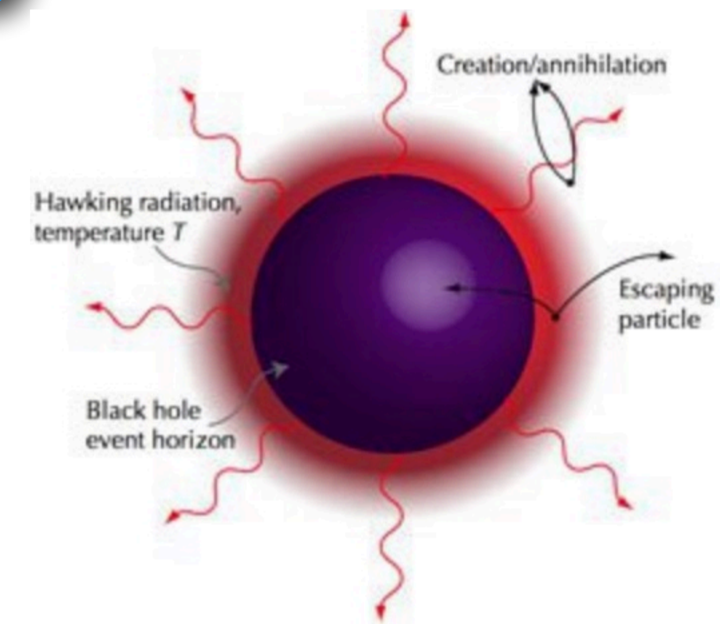

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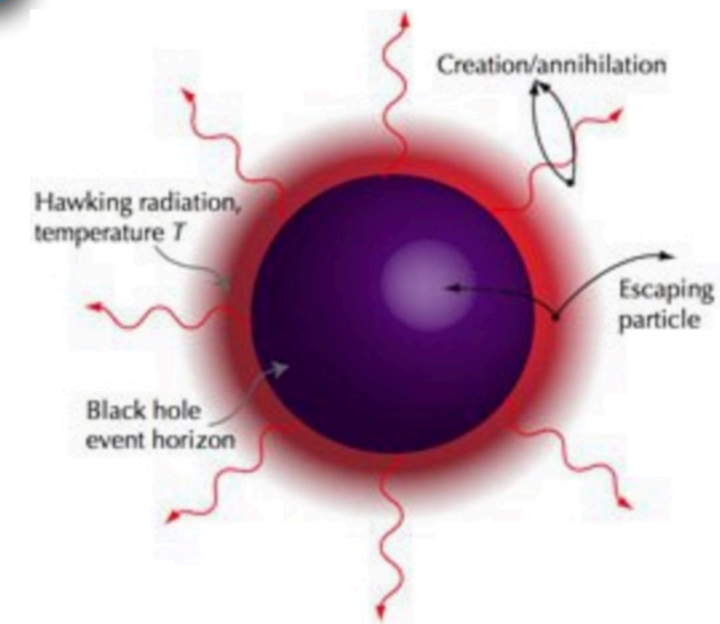

total grey-body "energy emissivity" factor

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

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

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DM Yield

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

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

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Note: strong dependence on spin of DM particle

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"heavy" particle case

extra mass dependence

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"heavy" particle case

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

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Evolution of energy densities

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

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

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

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

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

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

DM Yield: "slow" regime

Analytically find

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

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Associated SM plasma temp at end of pBH decay

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

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

(same number as WIMP case!)

DM Yield: "fast" regime

Analytically find

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

Associated SM plasma temp at end of pBH decay

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

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

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

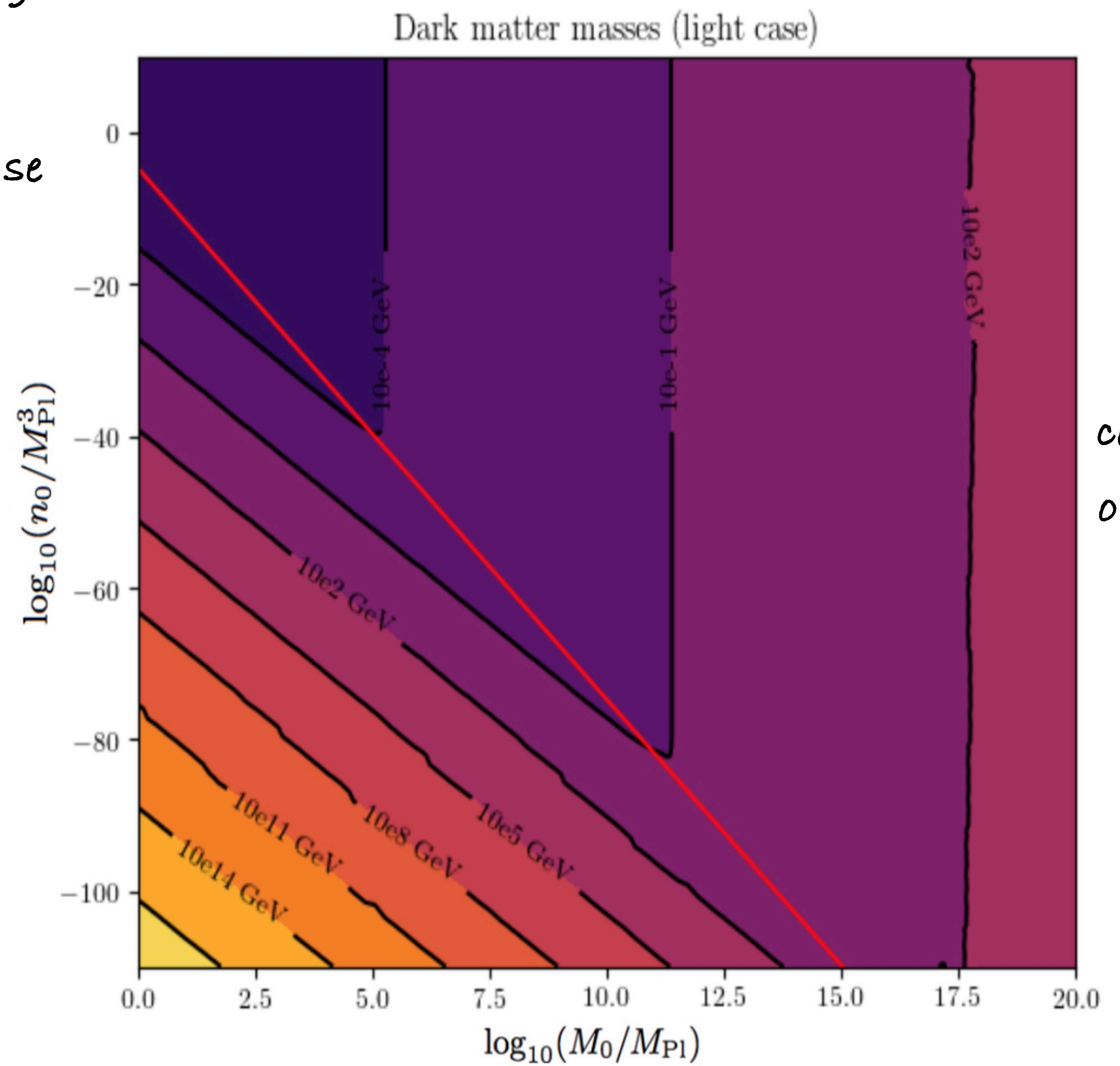
both now dependent on both initial pBH M_0 and n_0

DM mass: "light" case

$\mu < d_s T_0$

numerical solution agrees

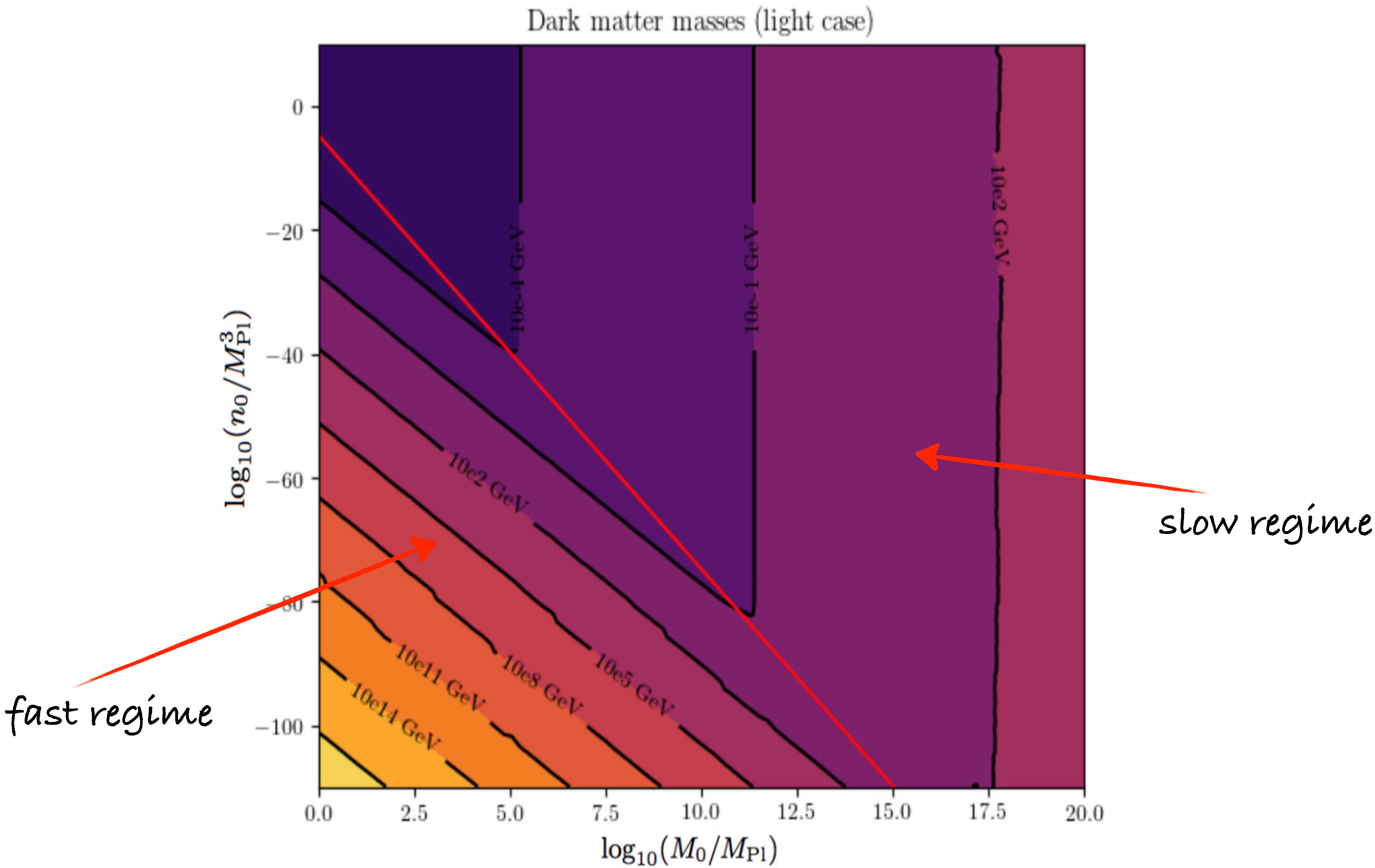
(spin s=0 case shown)



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

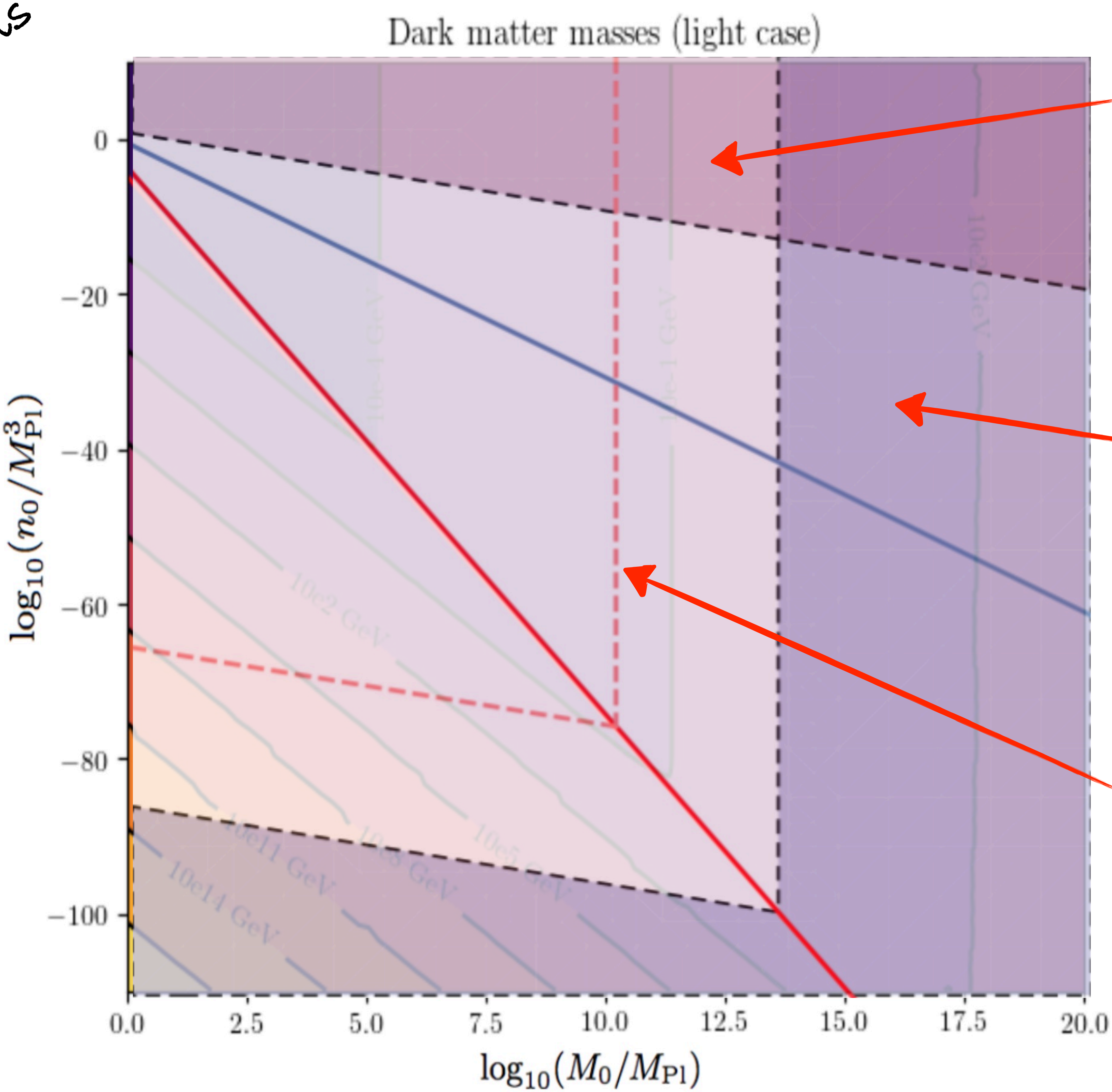
DM mass: "light" case

$\mu < d_s T_0$



DM mass: "light" case

some trivially excluded regions



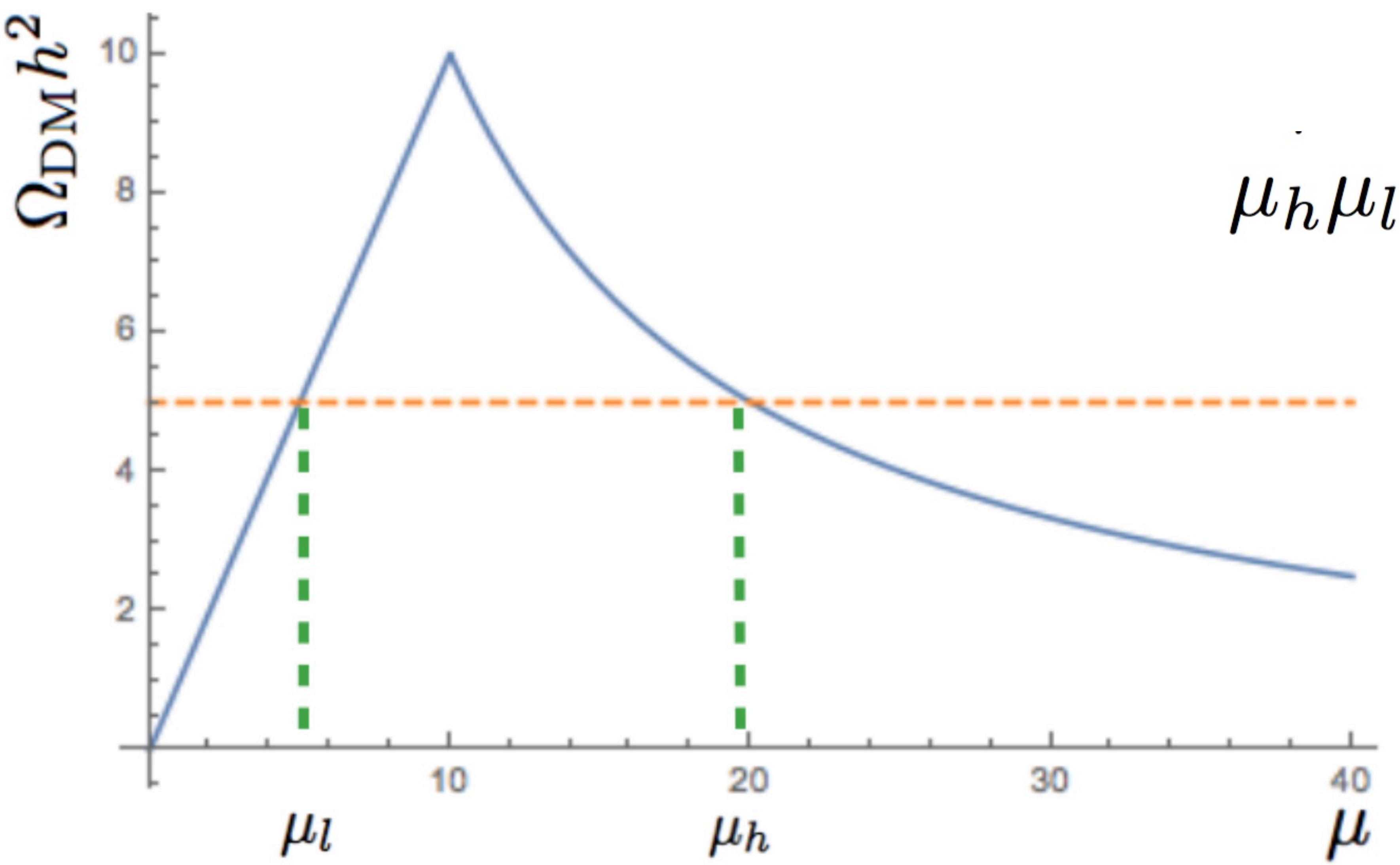
excluded as $\varrho_{BH}(0) > M_{Pl}^4$

excluded as T_{SM}<3 MeV

T_{SM}=200GeV

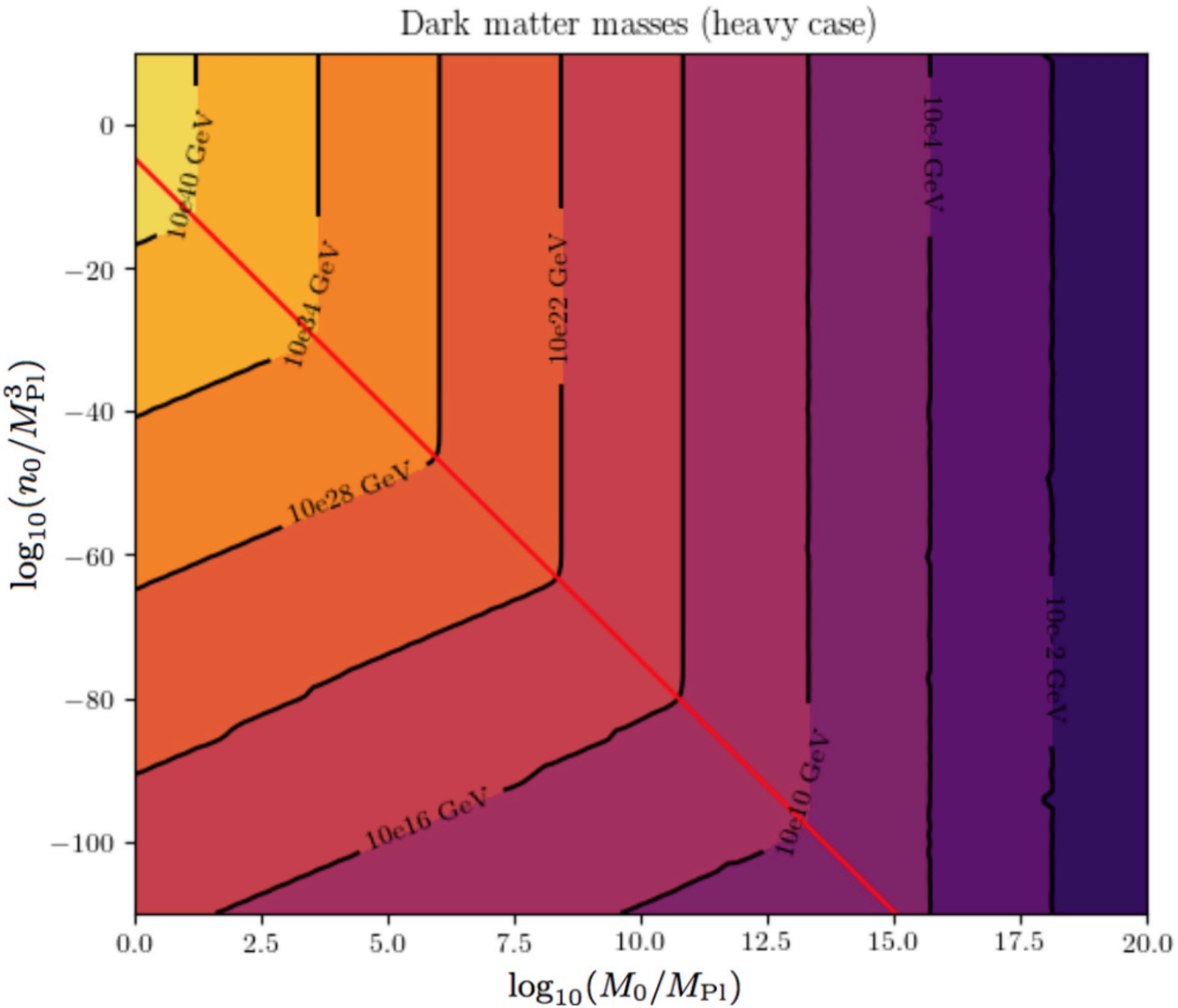
"light" vs "heavy"

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



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

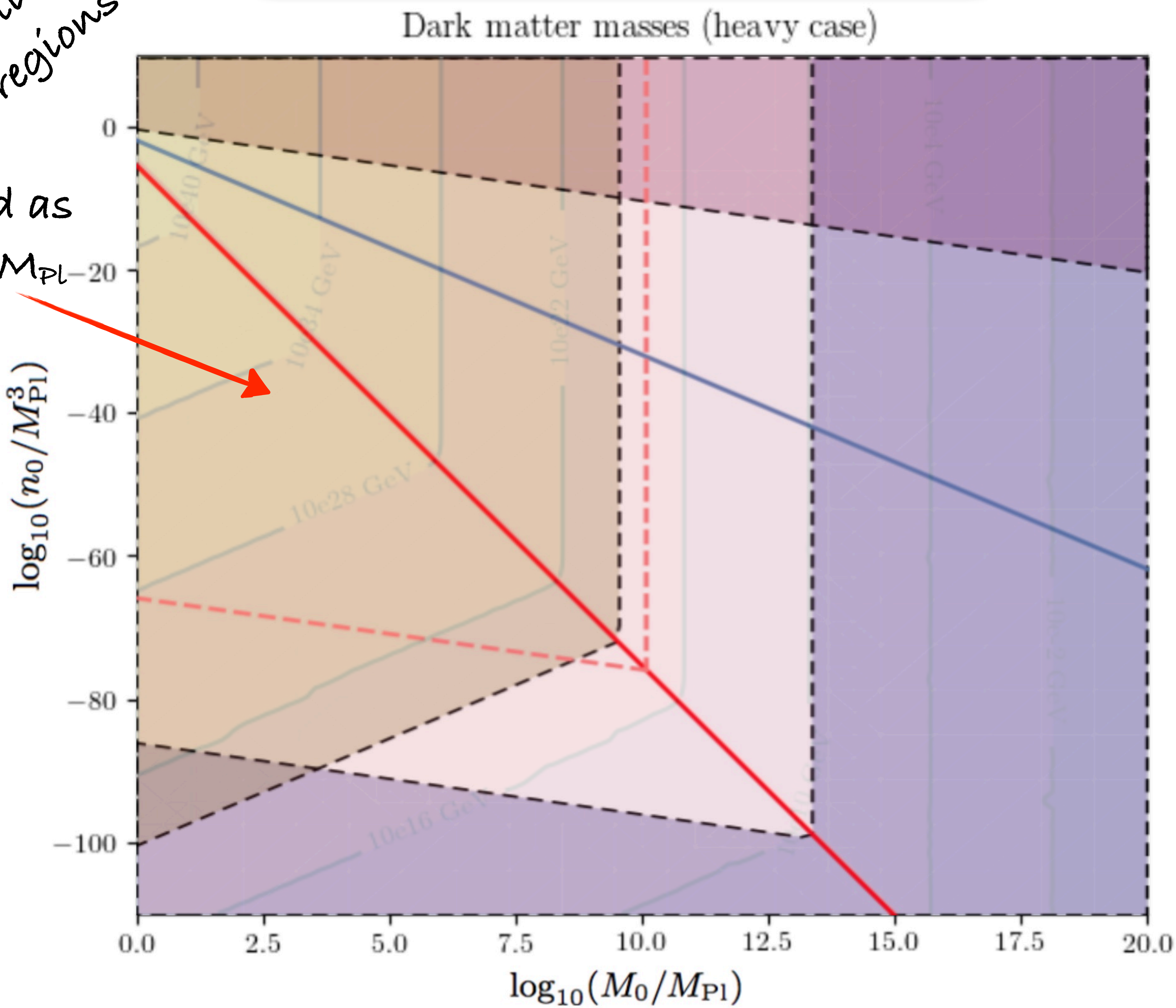
DM mass: "heavy" case



DM mass: "heavy" case

some trivially excluded regions

excluded as mass > M_{Pl}

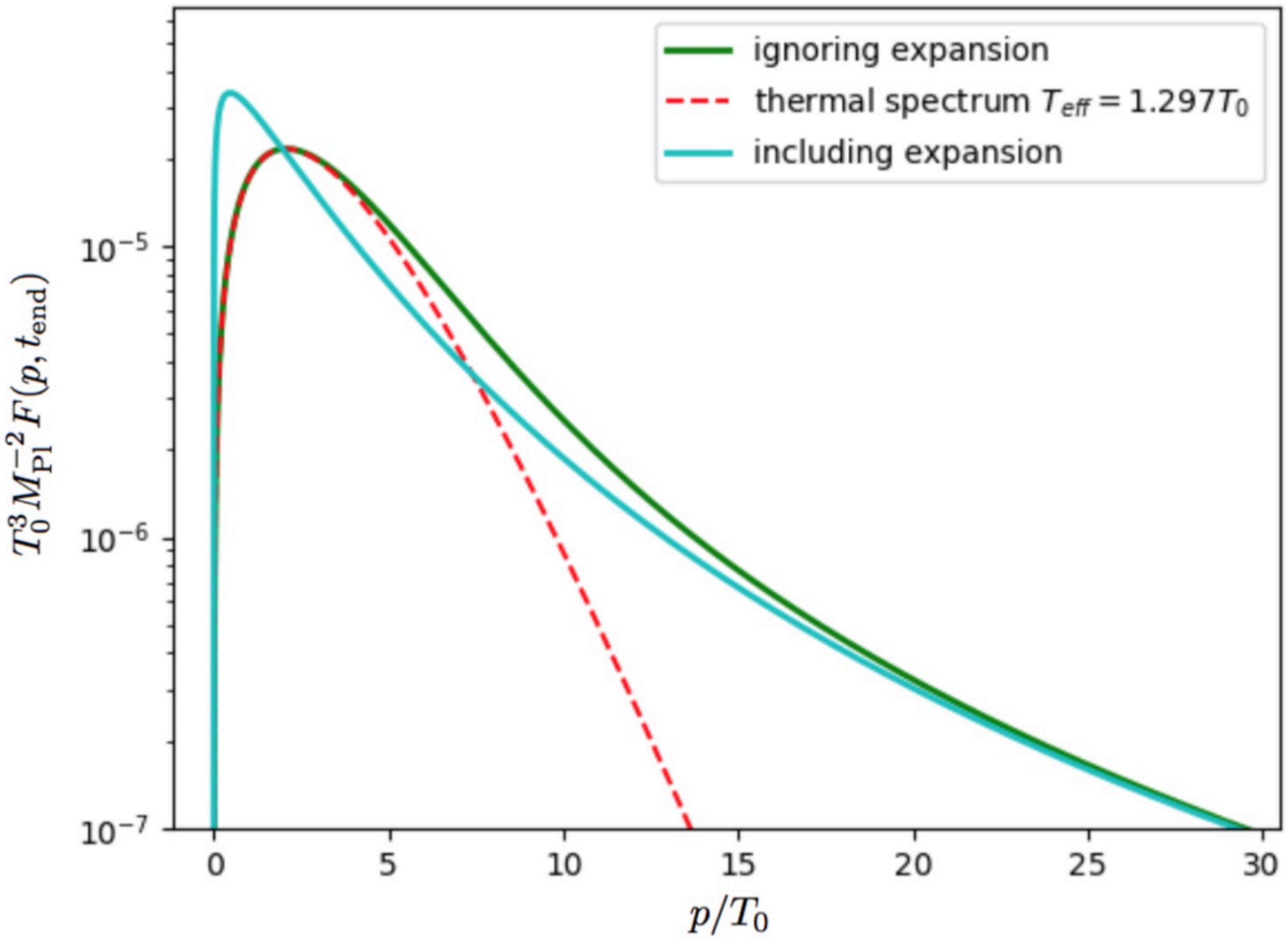


Free-streaming constraint

BUT big constraint from too "hot" DM ("light" DM case)

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

Distribution of DM mom'm redshifts



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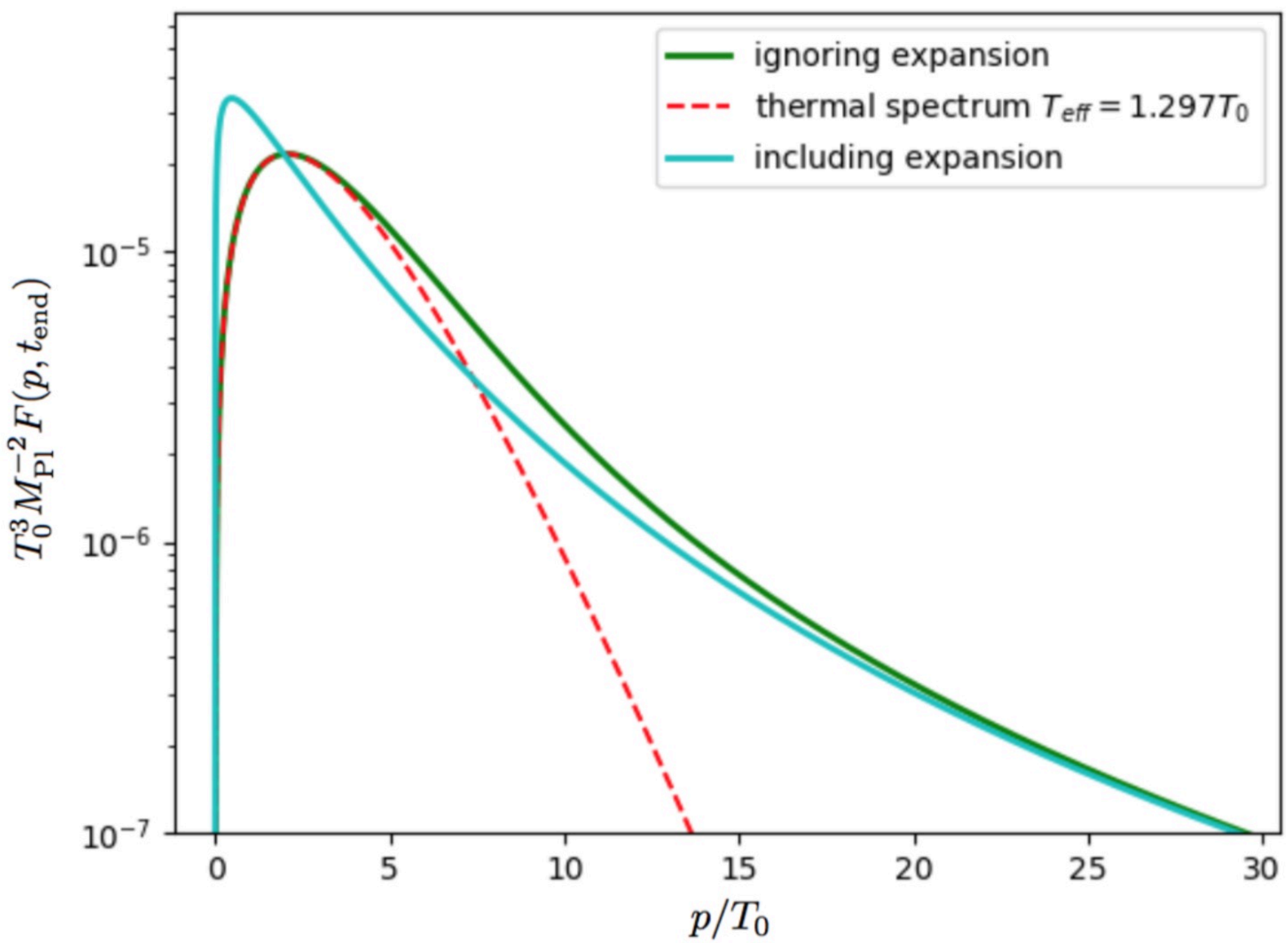
Distribution of DM mom'm redshifts



But still far too fast moving ("hot" DM) in light case for spin <3/2

Free-streaming constraint

"light" s>1
cases

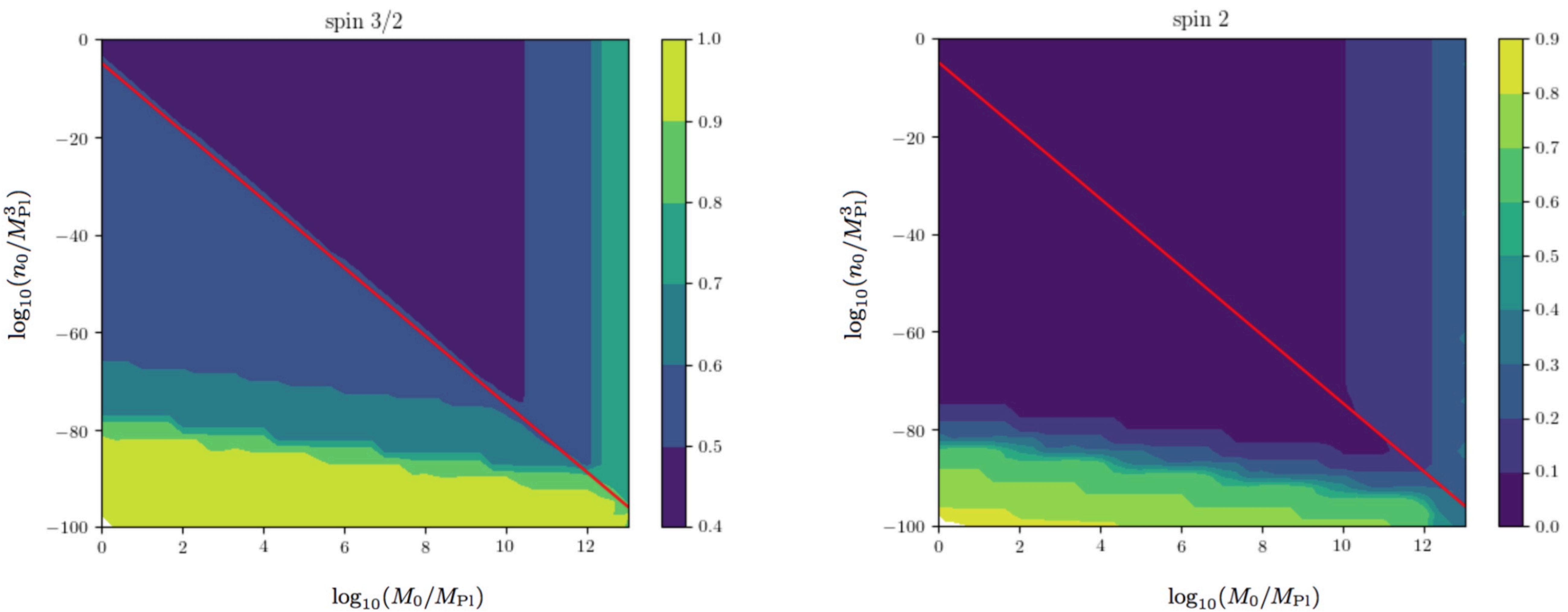


FIG. 5. Free-streaming constraints in the 'light' DM case for spin 3/2 and 2 (left and right panels), where colour shading shows fraction of DM particles that are still relativistic at $T_{\rm SM} = 1\,{\rm keV}$, and we have at every point imposed a 'light' solution DM mass such that the correct $\Omega_{\rm DM}h^2$ 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	$[2.6 \times 10^{-7}, 0.80]$	$[3.4 \times 10^{9}, M_{\text{Pl}}]$	$[3.1 \times 10^{-7}, 2.8 \times 10^{13}]$	$[2.9 \times 10^{9}, M_{\text{Pl}}]$
1/2	2	$[3.6 \times 10^{-7}, 1.1]$	$[3.1 \times 10^{9}, M_{\text{Pl}}]$	$[4.2 \times 10^{-7}, 3.9 \times 10^{13}]$	$[2.6 \times 10^{9}, M_{\text{Pl}}]$
1	3	$[7.8 \times 10^{-7}, 2.4]$	$[1.1 \times 10^{9}, M_{\text{Pl}}]$	$[9.2 \times 10^{-7}, 8.5 \times 10^{13}]$	$[9.6 \times 10^{8}, M_{\text{Pl}}]$
3/2	4	$[2 \times 10^{-6}, 6]$	$[5 \times 10^{8}, M_{\text{Pl}}]$	$[2 \times 10^{-6}, 2 \times 10^{14}]$	$[5 \times 10^{8}, M_{\text{Pl}}]$
2	5	$[6.3 \times 10^{-6}, 19]$	$[1.4 \times 10^{8}, M_{\text{Pl}}]$	$[7.4 \times 10^{-6}, 6.8 \times 10^{14}]$	$[1.2 \times 10^{8}, M_{\text{Pl}}]$

can be superheavy!

How to test?!?

Unavoidable prediction of DARK RADIATION - applies to any v 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 often get warm DM component which changes structure formation...

How to test?!?

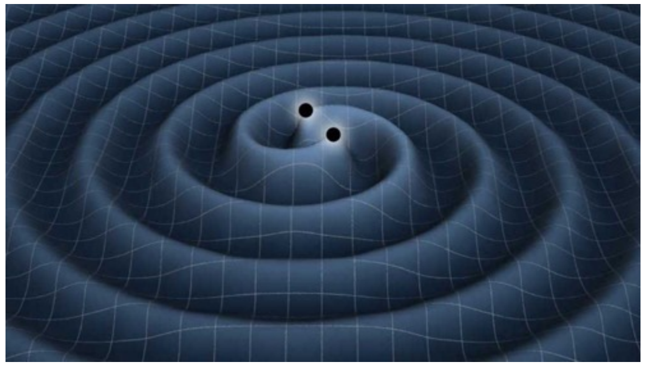
In fact, mechanism still works if go away from only gravitational interactions!

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!*

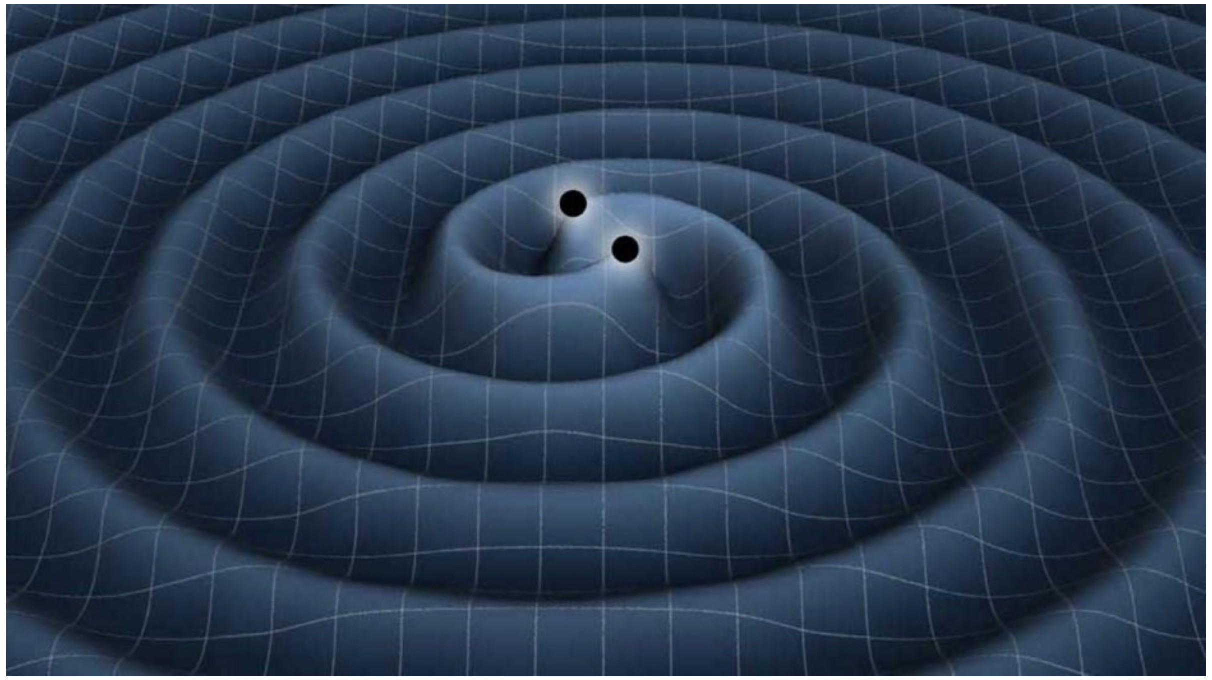


Conclusions

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??)

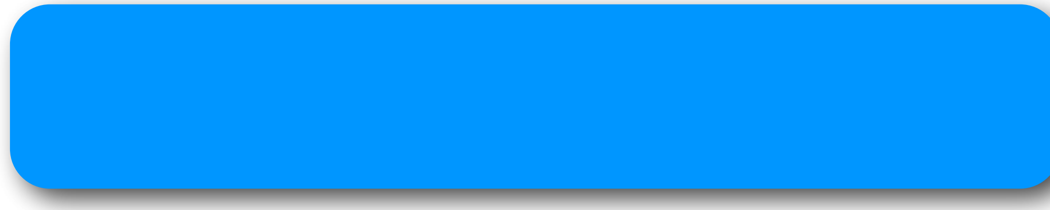
early days — much work to be done!

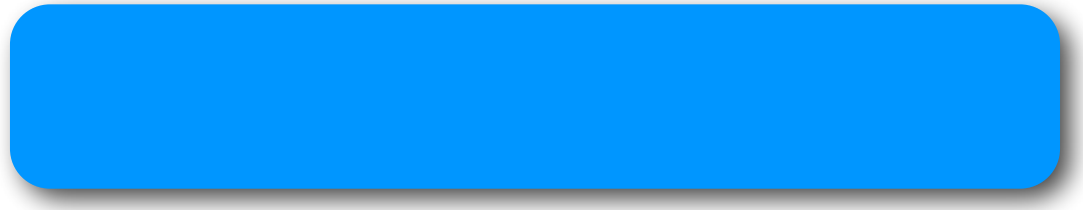


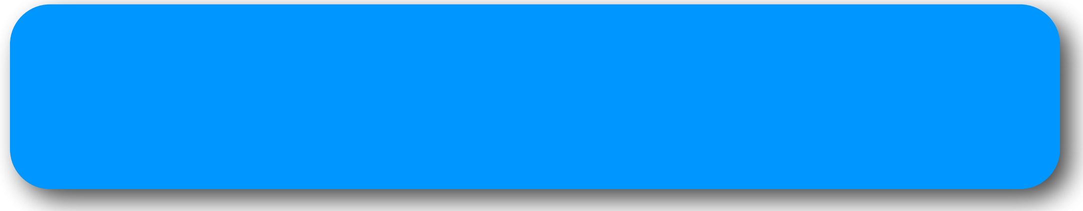
Structure

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

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







Hawking Genesis