DARK RADIATION AND DARK MATTER FROM PRIMORDIAL BLACK HOLES

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Next Frontiers in the Search for Dark Matter, GGI

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This talk is based on

Dark Radiation and Superheavy Dark Matter from Black Hole Domination

With **Gordan Krnjaic** and **Sam McDermott**,
JHEP 1908 (2019) 001, arXiv:1905.01301

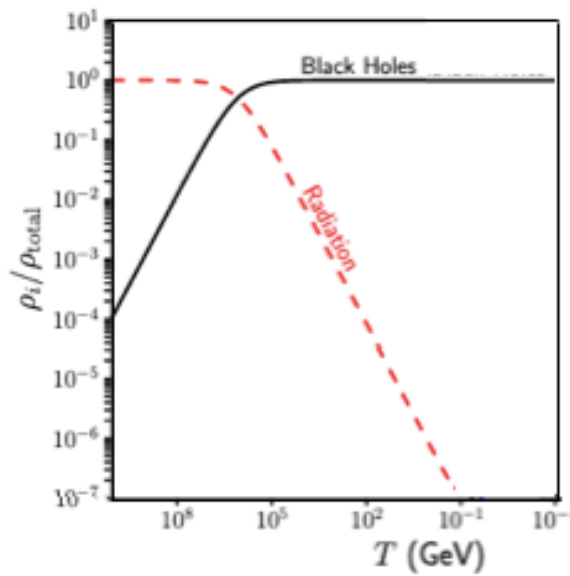
For related work, see Morrison and Profumo, arXiv:1812.10606 and Lennon *et al*, arXiv:1712.07664

Was the Early Universe Dominated by Black Holes?

- Inhomogeneities in the early universe can led to the formation of primordial black holes
- Very roughly, we expect the mass of these black holes to be similar to the energy enclosed within the horizon at or near the end of inflation:

$$M_{\rm hor} \sim \frac{M_{\rm Pl}^2}{2H_I} \sim 10^4\,{\rm g}\left(\frac{10^{10}\,{\rm GeV}}{H_I}\right)$$

- In this mass range, black holes evaporate very rapidly, disappearing well before BBN
- If even a small fraction of the energy density after inflation was in the form of black holes, this fraction would grow as the universe expands (black holes evolve as matter, $\rho_{BH} \propto a^{-3}$, rather than radiation, $\rho_{rad} \propto a^{-4}$);
- From this perspective, it is well-motivated to consider scenarios in which the early universe included an era in which the energy density was dominated by black holes



Was the Early Universe Dominated by Black Holes?

- Quantitatively, the density of black holes will ultimately exceed the energy density in SM radiation (before the black holes evaporate) if the following condition is met:

$$f_i \equiv \frac{\rho_{\mathrm{BH},i}}{\rho_{R,i}} \gtrsim 4 \times 10^{-12} \left(\frac{10^{10}\,\mathrm{GeV}}{T_i}\right) \left(\frac{10^{8}\,\mathrm{g}}{M_i}\right)^{3/2}$$

- Initial conditions (at the end of inflation) which include even a trace abundance of primordial black holes will naturally lead to an era in which the energy density is dominated by these objects

Hawking Evaporation

- According to Hawking, the surface of a black hole has a temperature given by:

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}} \simeq 1.05 \times 10^{13}\,{\rm GeV}\left(\frac{\rm g}{M_{\rm BH}}\right)$$

- Black holes radiate *all particle species* lighter than T_{BH}, regardless of their couplings, and thus provide an attractive way to generate dark matter and dark radiation
- Hawking radiation leads to the following mass loss rate:

$$\frac{dM_{\rm BH}}{dt} = -\frac{\mathcal{G}\, g_{\star,H}(T_{\rm BH})\, M_{\rm Pl}^4}{30720\,\pi\, M_{\rm BH}^2} \simeq -7.6 \times 10^{24}\,{\rm g\,s^{-1}}\; g_{\star,H}(T_{\rm BH}) \left(\frac{\rm g}{M_{\rm BH}}\right)^2$$

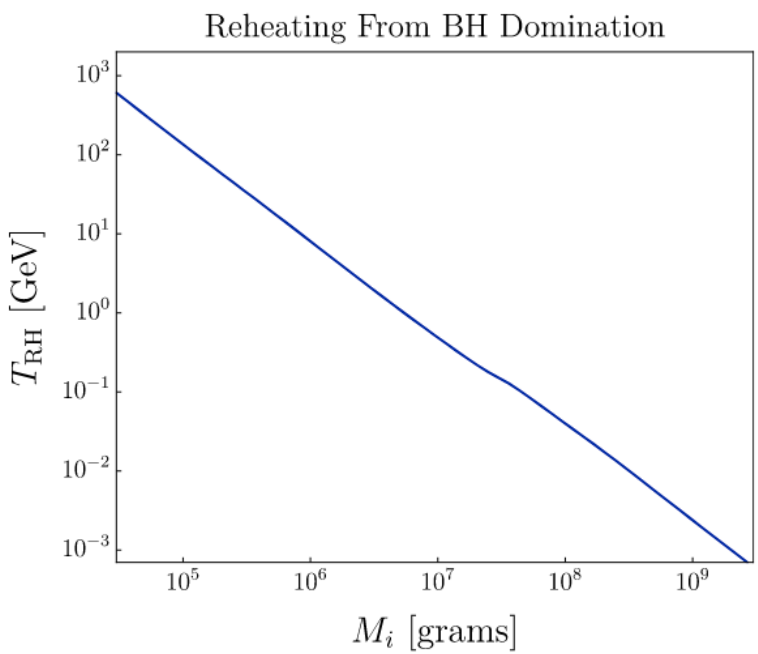
- Where $\mathcal{G} \approx 3.8$ is the appropriate greybody factor, and $g_{\star,H}(T_{\rm BH})$ is the sum of the degrees-of-freedom (weighted by the MacGibbon factors, which in our convention are 1.82 for scalars, 1.0 for fermions, 0.41 for vectors and 0.05 for spin-2 particles)

Hawking Evaporation in the Early Universe

- Hawking radiation leads to black hole evaporation on the following timescale:

$$\tau \approx 1.3 \times 10^{-25}\,\mathrm{s\,g^{-3}} \int_0^{M_i} \frac{dM_{\rm BH} M_{\rm BH}^2}{g_{\star,H}(T_{\rm BH})} \approx 4.0 \times 10^{-4}\,\mathrm{s} \left(\frac{M_i}{10^8\,\mathrm{g}}\right)^3 \left(\frac{108}{g_{\star,H}(T_{\rm BH})}\right)$$

- Following an era dominated by black holes, the evaporation leaves behind a hot bath, with a temperature that is related to the initial mass of the black holes
- To preserve the successful predictions of BBN, we will limit our discussion to black holes with an (initial) mass of 5x10^8 grams or less, which evaporate before the onset of BBN ($\boldsymbol{\tau}$ < 0.05 sec, T_{RH} < 10 MeV)

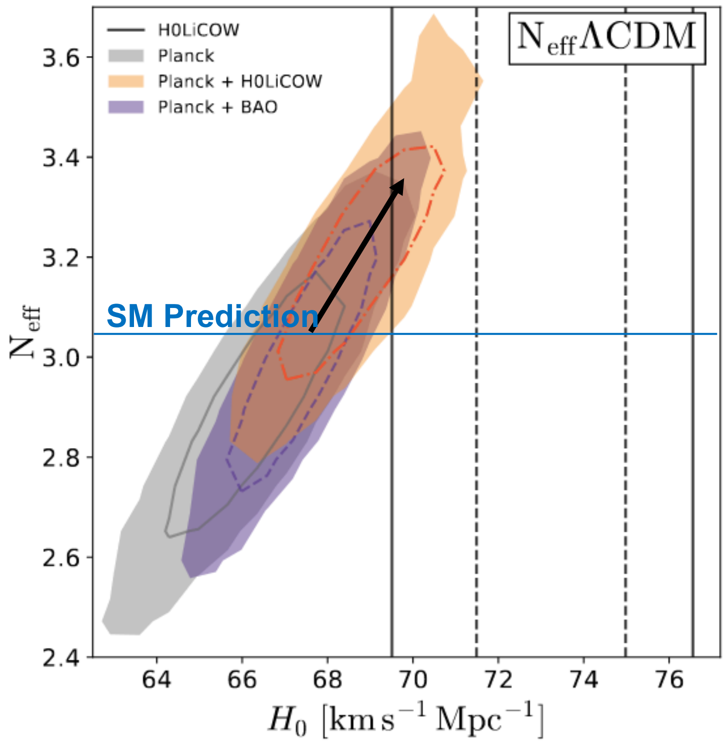


Motivation: The Hubble Tension

- Local measurements of the Hubble Constant using Cepheids and type 1a supernovae yield H_0=74.0±1.4 (SH0ES, Carnegie Hubble Project), while those using lensed quasars find H_0=73.3±1.8 (H0LiCOW)
- In contrast, Planck finds H_0=67.4±0.5, in ~4σ tension with local measurements (within the context of the ΛCDM model)

Motivation: The Hubble Tension

- The simplest way to reduce this tension is to introduce one or more additional forms of energy that increase the rate of expansion in the decade (of scale factor) leading up to recombination
- Dark radiation at a level of ΔN_{eff} ~ 0.1-0.3 approximately minimizes this tension



Wong et al, arXiv: 1907.04869
Bernal, Verde, Riess, arXiv:1607.05617

Dark Radiation From Hawking Evaporation

- The radiation injected from black holes in the early universe includes all SM particles, along with *any and all* other particle species that exist
- If there exist any light, long-lived and very weakly interacting particle species (axions, gravitons, etc.), they will be produced through Hawking evaporation and contribute to the energy density during the era of matter-radiation equality, acting as dark radiation

Dark Radiation From Hawking Evaporation

- Immediately after a black hole dominated era, the fraction of the energy density in an exotic light particle species will be given by their degrees-of-freedom, $g_{\mathrm{DR},H}/g_{\star,H}$.
- After accounting for SM entropy dumps, we arrive at:

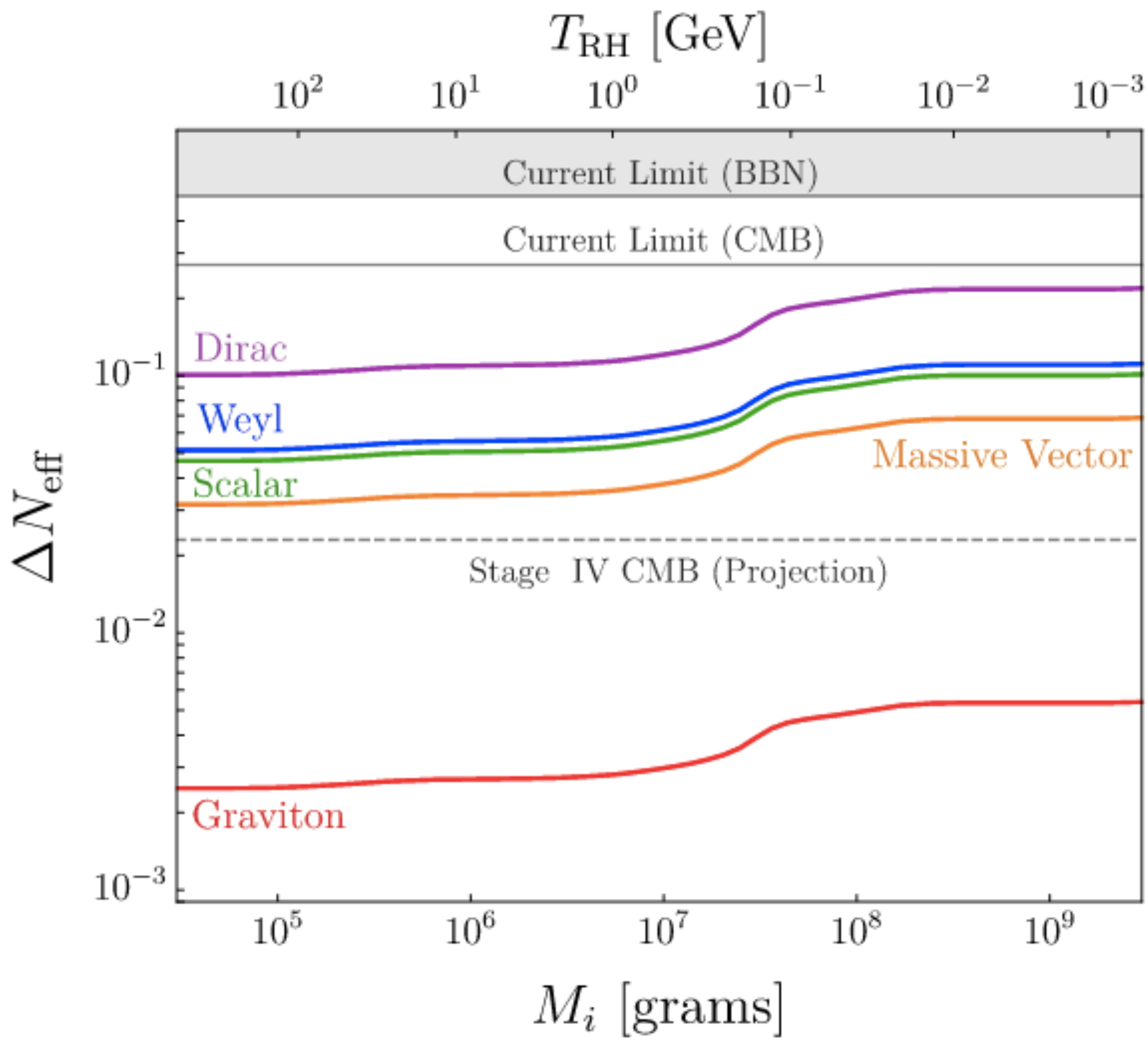
$$\frac{\rho_{\mathrm{DR}}(T_{\mathrm{EQ}})}{\rho_R(T_{\mathrm{EQ}})} = \left(\frac{g_{\mathrm{DR},H}}{g_{\star,H}}\right)\left(\frac{g_{\star,S}(T_{\mathrm{EQ}})^{4/3}}{g_\star(T_{\mathrm{EQ}})\; g_{\star,S}(T_{\mathrm{RH}})^{1/3}}\right)$$

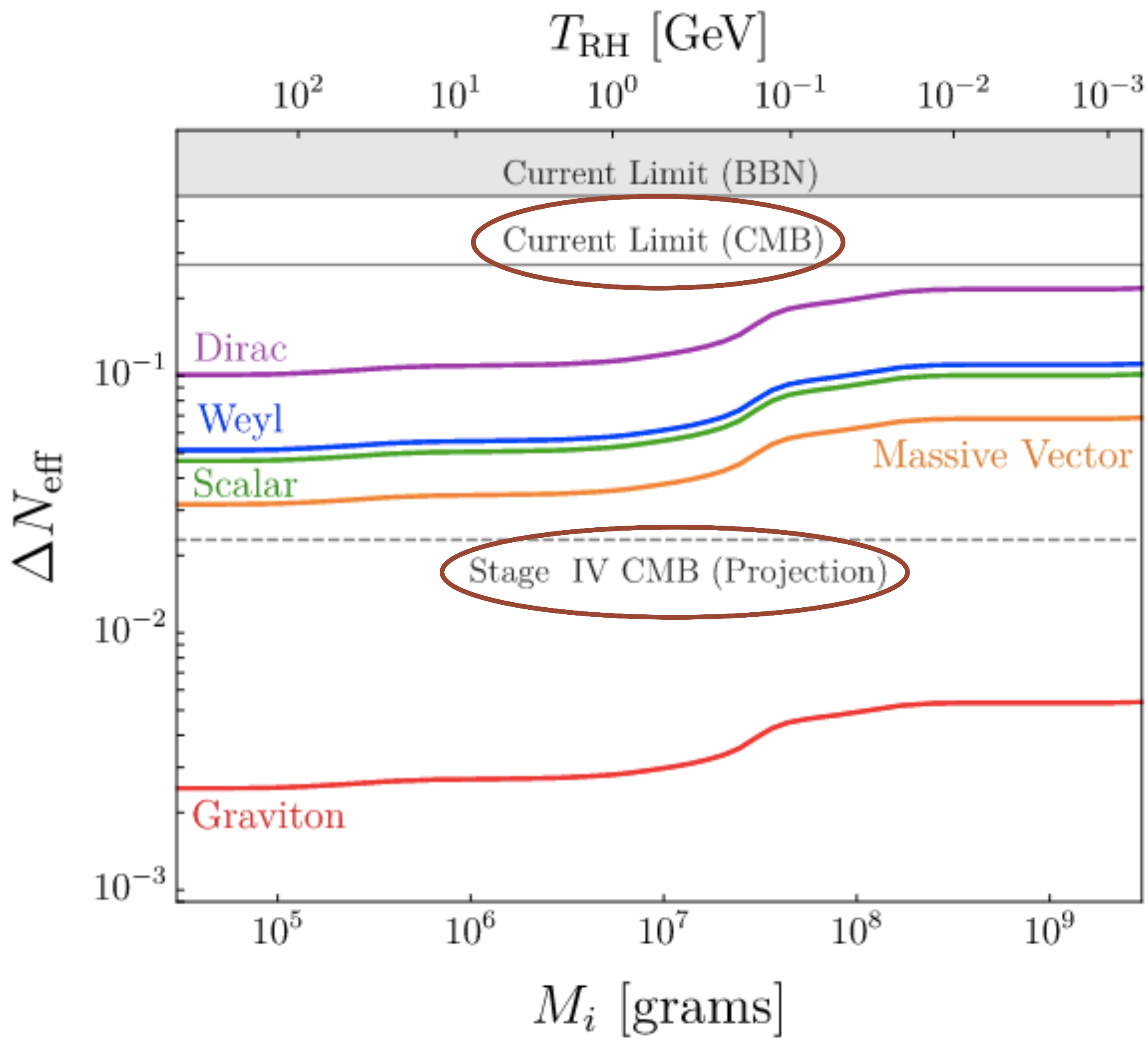
- This is related as follows to the effective number of neutrino species:

$$\Delta N_{\mathrm{eff}} = \frac{\rho_{\mathrm{DR}}(T_{\mathrm{EQ}})}{\rho_R(T_{\mathrm{EQ}})}\left[N_\nu + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right]$$
$$= \left(\frac{g_{\mathrm{DR},H}}{g_{\star,H}}\right)\left(\frac{g_{\star S}(T_{\mathrm{EQ}})}{g_{\star S}(T_{\mathrm{RH}})}\right)^{1/3}\left(\frac{g_{\star S}(T_{\mathrm{EQ}})}{g_\star(T_{\mathrm{EQ}})}\right)\left[N_\nu + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right]$$

- In the limit of a high reheat temperature, this reduces to:

$$\Delta N_{\mathrm{eff}} \approx 0.10\left(\frac{g_{\mathrm{DR},H}}{4}\right)\left(\frac{106}{g_\star(T_{\mathrm{RH}})}\right)^{1/3}$$


$T_{\rm RH}$ [GeV]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Current Limit (BBN)
Current Limit (CMB)
Dirac
Weyl
Scalar
Massive Vector
Stage IV CMB (Projection)
Graviton
$\Delta N_{\rm eff}$
10^{-1}
10^{-2}
10^{-3}
10^5
10^6
10^7
10^8
10^9
M_i [grams]


$T_{\rm RH}$ [GeV]
10^2
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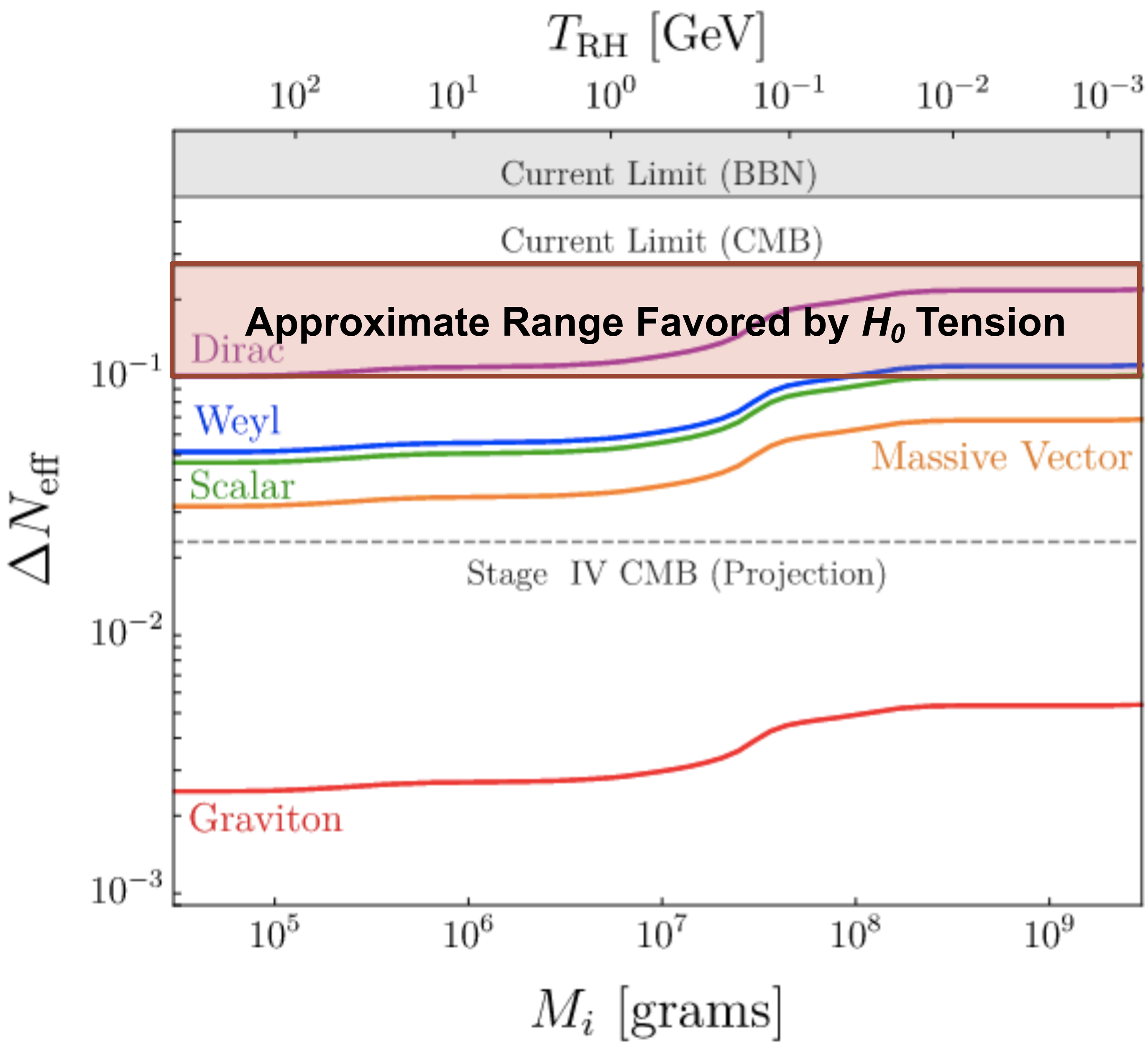


$T_{\rm RH}$ [GeV]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Current Limit (BBN)
Current Limit (CMB)
Approximate Range Favored by H_0 Tension
Dirac
Weyl
Scalar
Massive Vector
Stage IV CMB (Projection)
Graviton
$\Delta N_{\rm eff}$
10^{-1}
10^{-2}
10^{-3}
10^5
10^6
10^7
10^8
10^9
M_i [grams]

Dark Radiation From Hawking Evaporation

- In order for these Hawking radiation products to act as dark radiation, they must be relativistic at the time of matter-radiation equality
- Assuming that the particles are radiated with an energy equal to the initial temperature of the black holes, their kinetic energy at t_{EQ} is given by:

$$\langle E_{\rm DR}\rangle\Big|_{\rm EQ} \sim \alpha\, T_{{\rm BH},i} \times \frac{T_{\rm EQ}}{T_{\rm RH}} \left(\frac{g_\star(T_{\rm EQ})}{g_\star(T_{\rm RH})}\right)^{1/3}$$

$$\sim 3.9\,{\rm MeV} \left(\frac{\alpha}{3.15}\right) \left(\frac{M_i}{10^8\,{\rm g}}\right)^{1/2} \left(\frac{108}{g_{\star,H}(T_{\rm BH})}\right)^{1/2} \left(\frac{14}{g_\star(T_{\rm RH})}\right)^{1/12}$$

where $\alpha = 2.7$ (3.15) for bosonic (fermionic) dark radiation

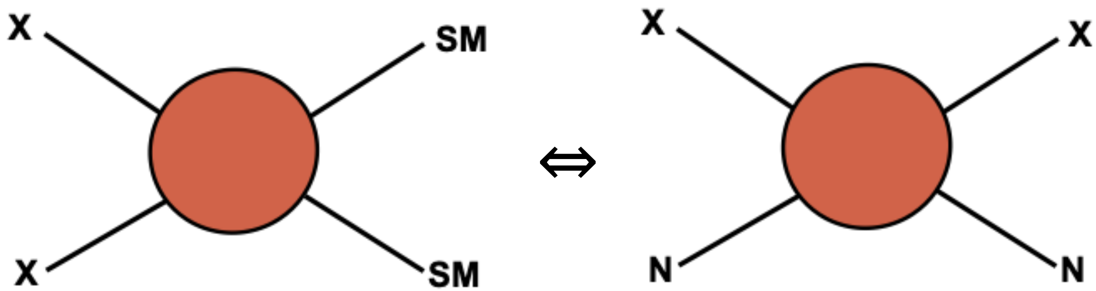
- Integrating over the lifetime of the black holes, we arrive at a slightly higher value, $\sim 5.5\,{\rm MeV} \times (M_i/10^8\,{\rm g})^{1/2}$.
- In contrast to thermally produced dark radiation (which must be lighter than ~eV), dark radiation that is produced through Hawking radiation can consist of significantly heavier particles

Black Holes and the String Axiverse?

- From arguments based on string theory, it has been suggested that a large number of axion-like states are likely to exist – the *string axiverse*
- If the early universe contained a black hole dominated era, each stable and light scalar species is predicted to contribute at level of $\Delta N_{eff} \sim (0.04 - 0.08)$
- This allows us to use Planck data to place an upper limit on the number of such states, $N_{axion} \lesssim 0.28/0.04 \sim 7$
- More generally speaking, a black hole dominated era appears to be incompatible with models that feature a large number of light, stable particle species

Motivation: Dark Matter

- Thermal relics with ~MeV-100 TeV masses and roughly weak-scale interactions (*ie*. WIMPs) have long been considered particularly promising as class of dark matter candidates
- In many models, there is a direct relationship between a dark matter candidate's annihilation cross section (which sets the relic abundance) and its elastic scattering cross section with nuclei



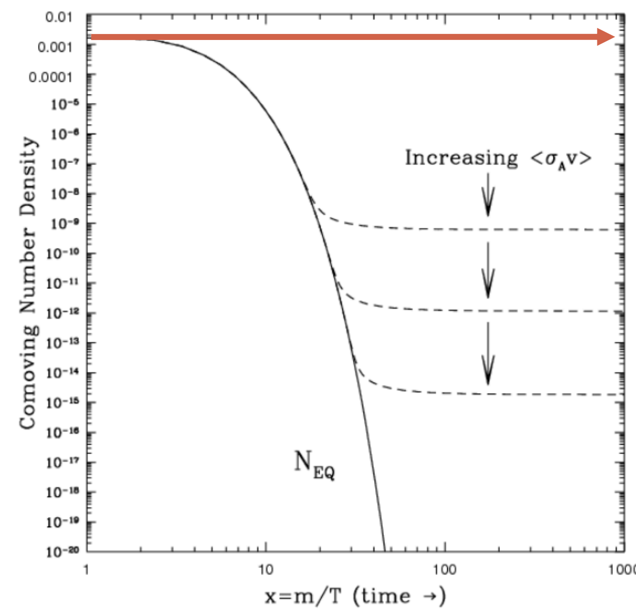
- Over the past decade, many of the most attractive WIMP candidates have been ruled out by direct detection experiments, and no evidence of WIMPs (or other BSM physics) has yet appeared at the LHC
- In light of this, it is well motivated to consider other mechanisms for the production of dark matter in the early universe, especially those that could generate very feebly interacting dark matter particles

Dark Matter From Hawking Evaporation

- Consider a stable and very feebly interacting particle with a mass large enough that it behaves as matter leading up to the time of matter-radiation equality
- If the early universe included a black hole dominated era, an enormous abundance of such particles would be produced, set by the particle's degrees-of-freedom compared to that of the SM

$$\Omega_{\rm DM} h^2 \approx 6 \times 10^7 \left(\frac{g_{{\rm DM},H}}{4}\right)\left(\frac{100\ \rm GeV}{m_{\rm DM}}\right)\left(\frac{10^8\ {\rm g}}{M_i}\right)^{5/2}$$

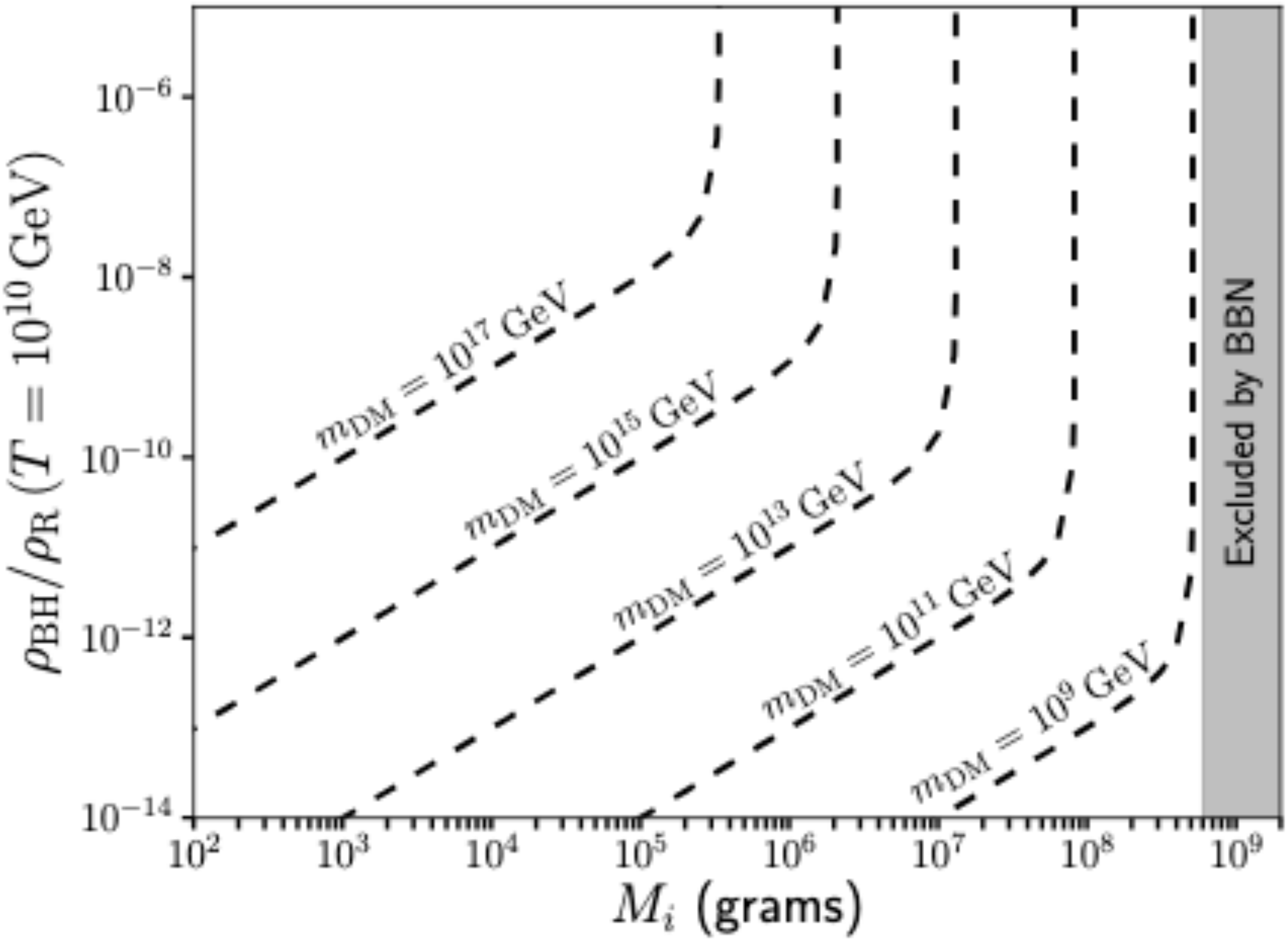
- This situation is similar to that of a stable particle species that was at an equilibrium abundance in the early universe, but with a negligible annihilation cross section (and no other means of being depleted)



Dark Matter From Hawking Evaporation

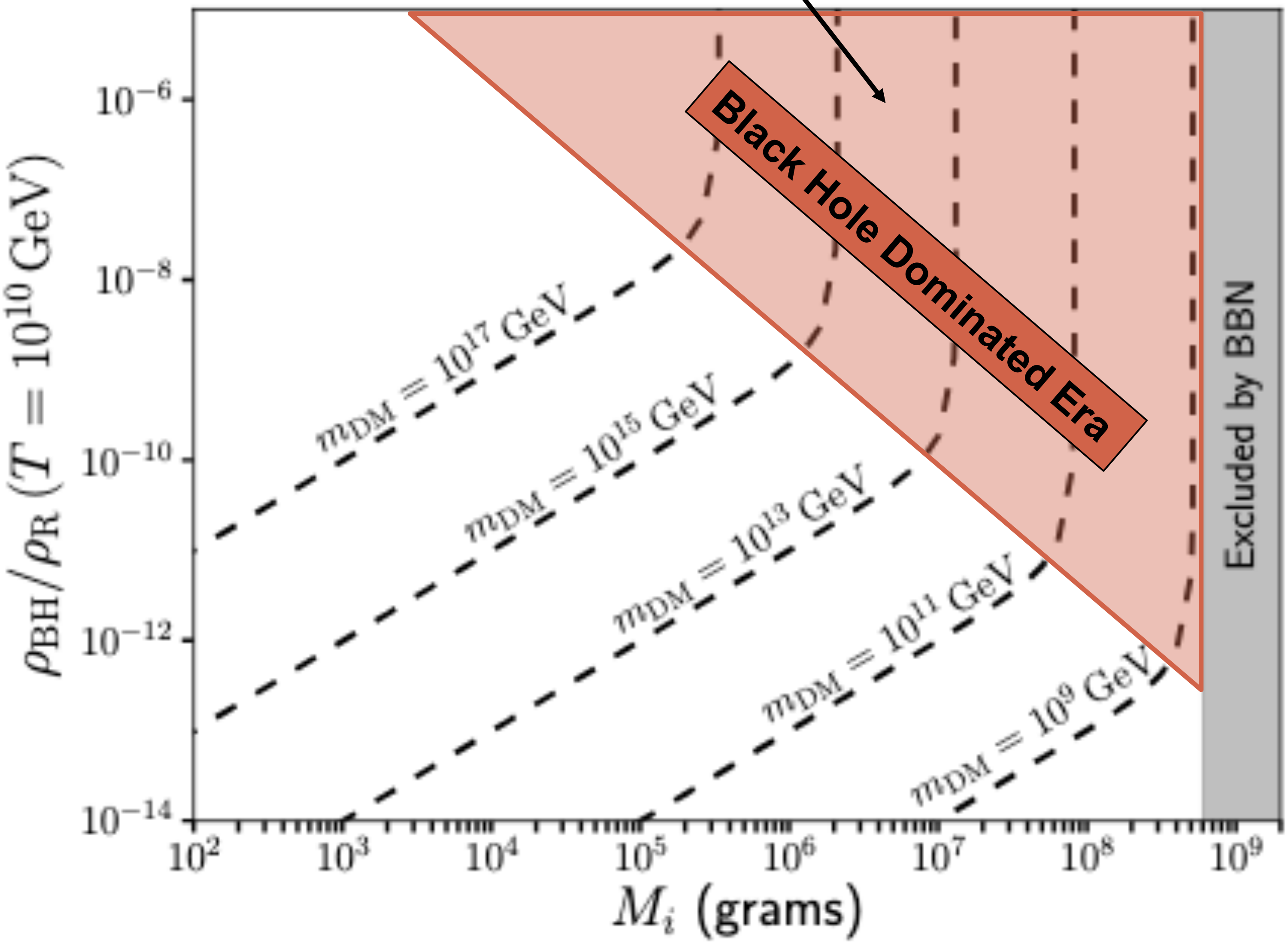
- To evade this problem, we will consider *very* heavy dark matter particles
- Consider the following example: a population of black holes with an initial mass of 10^8 grams (corresponding to a surface temperature of $\sim 10^5$ GeV) and dark matter particles with a mass of 6×10^{10} GeV
- Since a black hole can only radiate particles lighter than its temperature, these black holes will only start producing dark matter particles after their temperature has increased to $\sim 6 \times 10^{10}$ GeV, at which time the black hole's mass has been reduced to $\sim 2 \times 10^2$ grams
- As a result, the total output into these supermassive particles is suppressed by a factor of $\sim T_{BH,I}/m_{DM} \sim 10^5/10^{11} \sim 10^{-6}$
- After accounting for this, we find that a black hole dominated era will result in the following abundance of dark matter particles:

$$\Omega_{\rm DM} h^2 \approx 0.1 \left(\frac{g_{{\rm DM},H}}{4}\right)\left(\frac{6\times 10^{10}\,{\rm GeV}}{m_{\rm DM}}\right)\left(\frac{10^8\,{\rm g}}{M_i}\right)^{5/2}$$



m_{DM} set such that $\Omega_{DM} h^2 = 0.1$

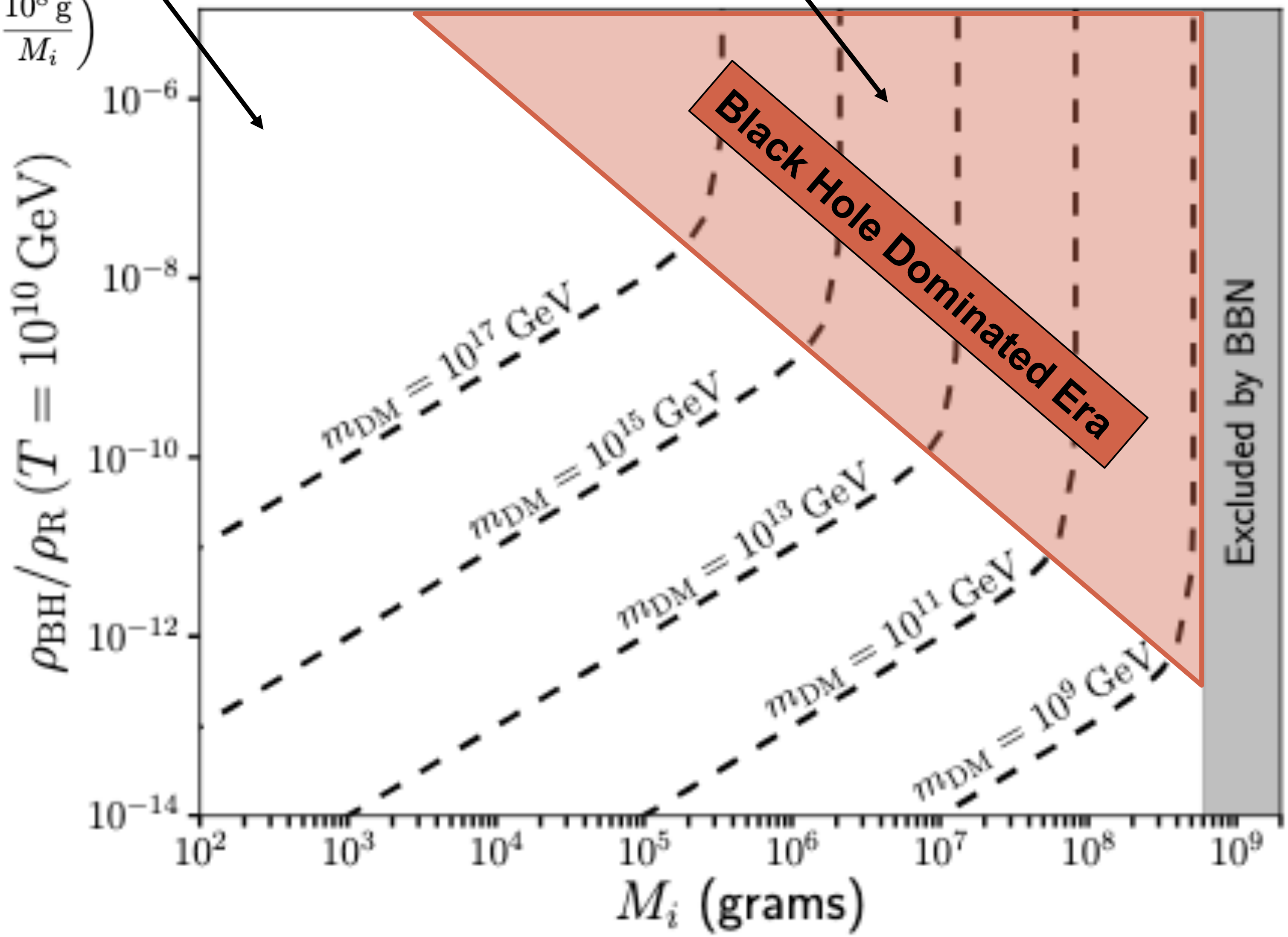
$$\Omega_{\rm DM} h^2 \approx 0.1 \left(\frac{g_{{\rm DM},H}}{4}\right)\left(\frac{6\times 10^{10}\,{\rm GeV}}{m_{\rm DM}}\right)\left(\frac{10^8\,{\rm g}}{M_i}\right)^{5/2}$$



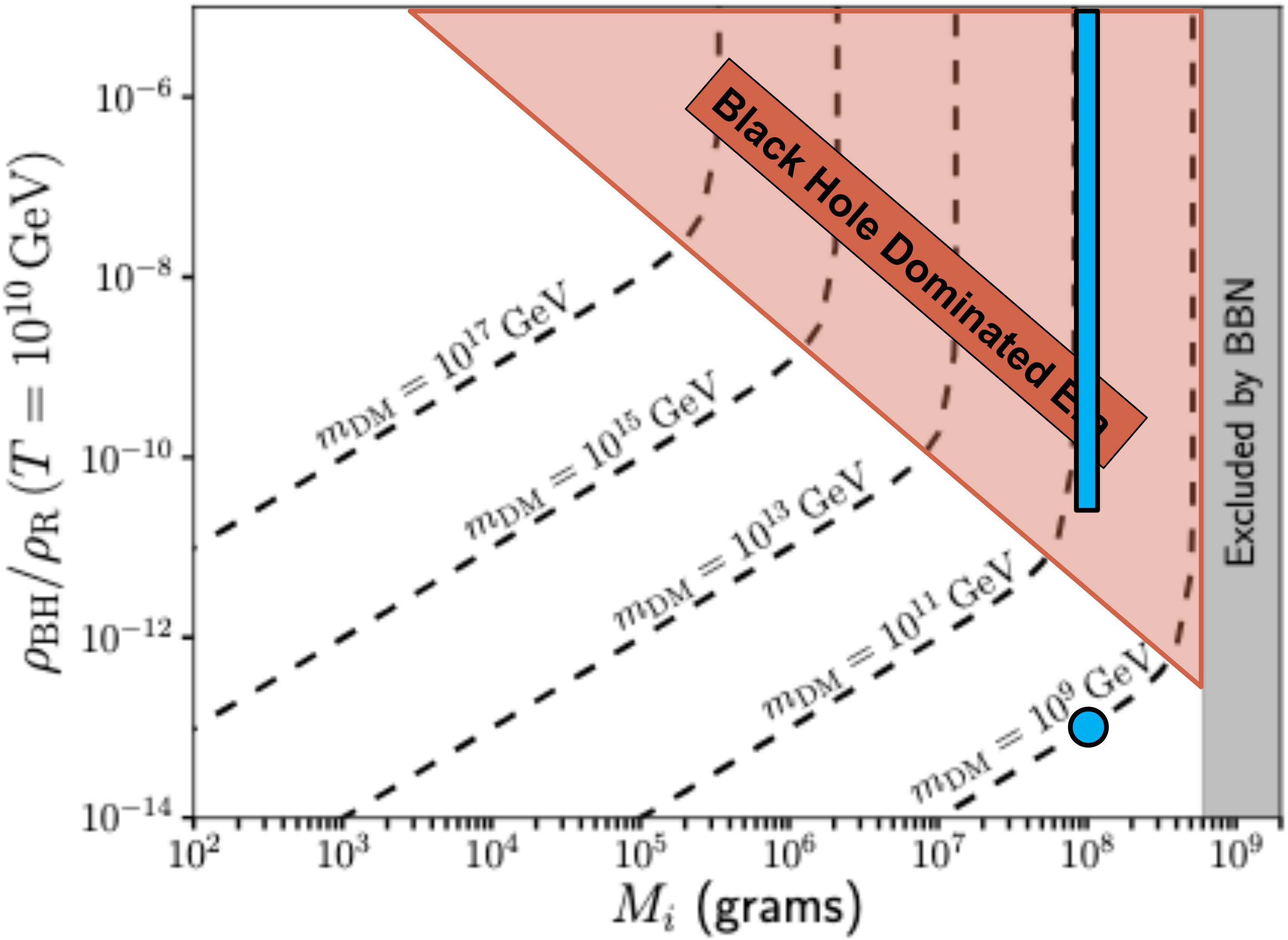
m_{DM} set such that $\Omega_{DM} h^2 = 0.1$

$$\Omega_{\rm DM} h^2 \approx 0.1 \left(\frac{f_i(10^{10}\,{\rm GeV})}{8\times 10^{-14}}\right)\left(\frac{g_{{\rm DM},H}}{4}\right)\left(\frac{10^9\,{\rm GeV}}{m_{\rm DM}}\right) \times \left(\frac{10^8\,{\rm g}}{M_i}\right)$$

$$\Omega_{\rm DM} h^2 \approx 0.1 \left(\frac{g_{{\rm DM},H}}{4}\right)\left(\frac{6\times 10^{10}\,{\rm GeV}}{m_{\rm DM}}\right)\left(\frac{10^8\,{\rm g}}{M_i}\right)^{5/2}$$

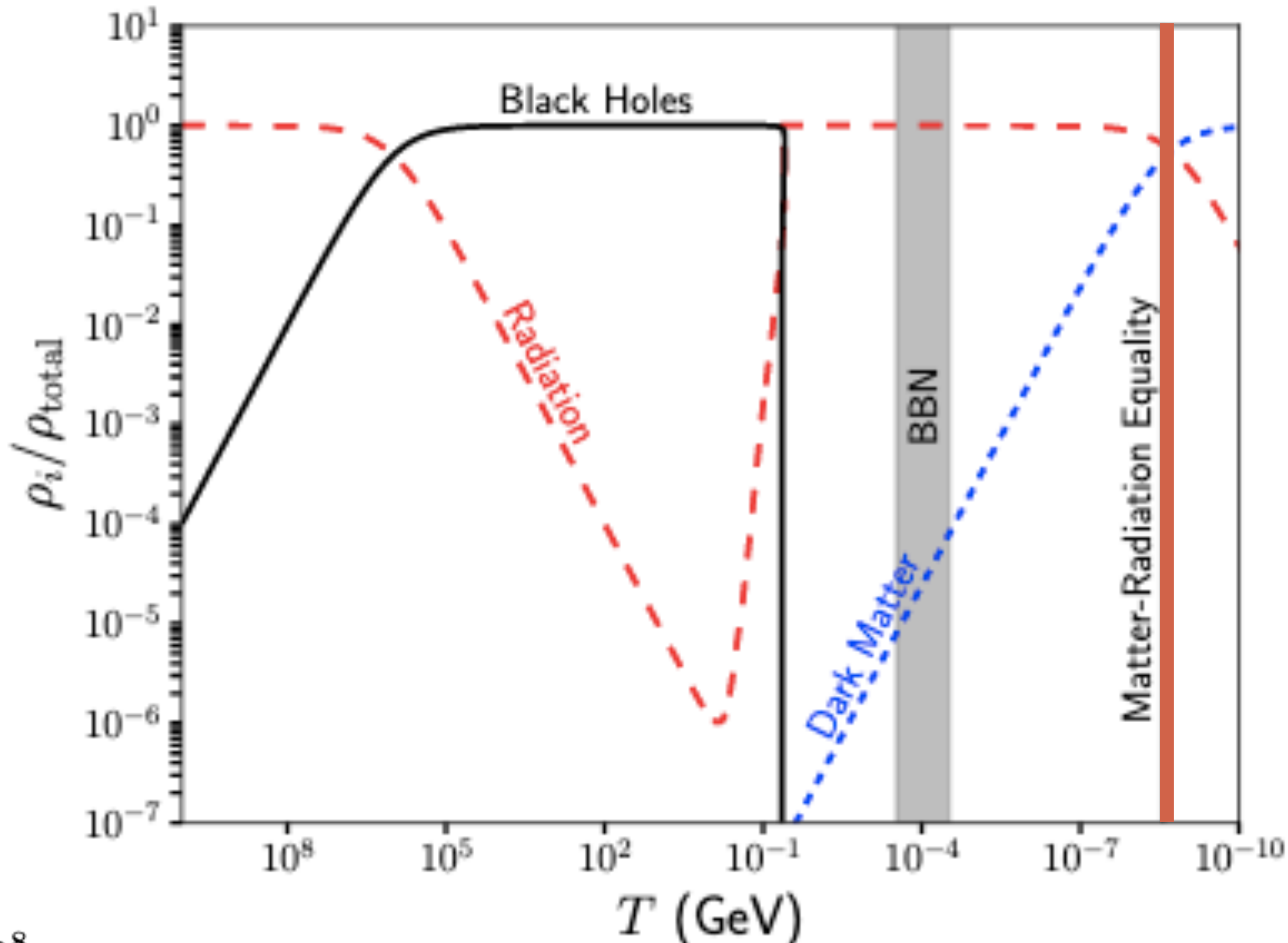


m_{DM} set such that $\Omega_{DM} h^2 = 0.1$



m_{DM} set such that $\boldsymbol{\Omega}_{DM}\,h^2 = 0.1$

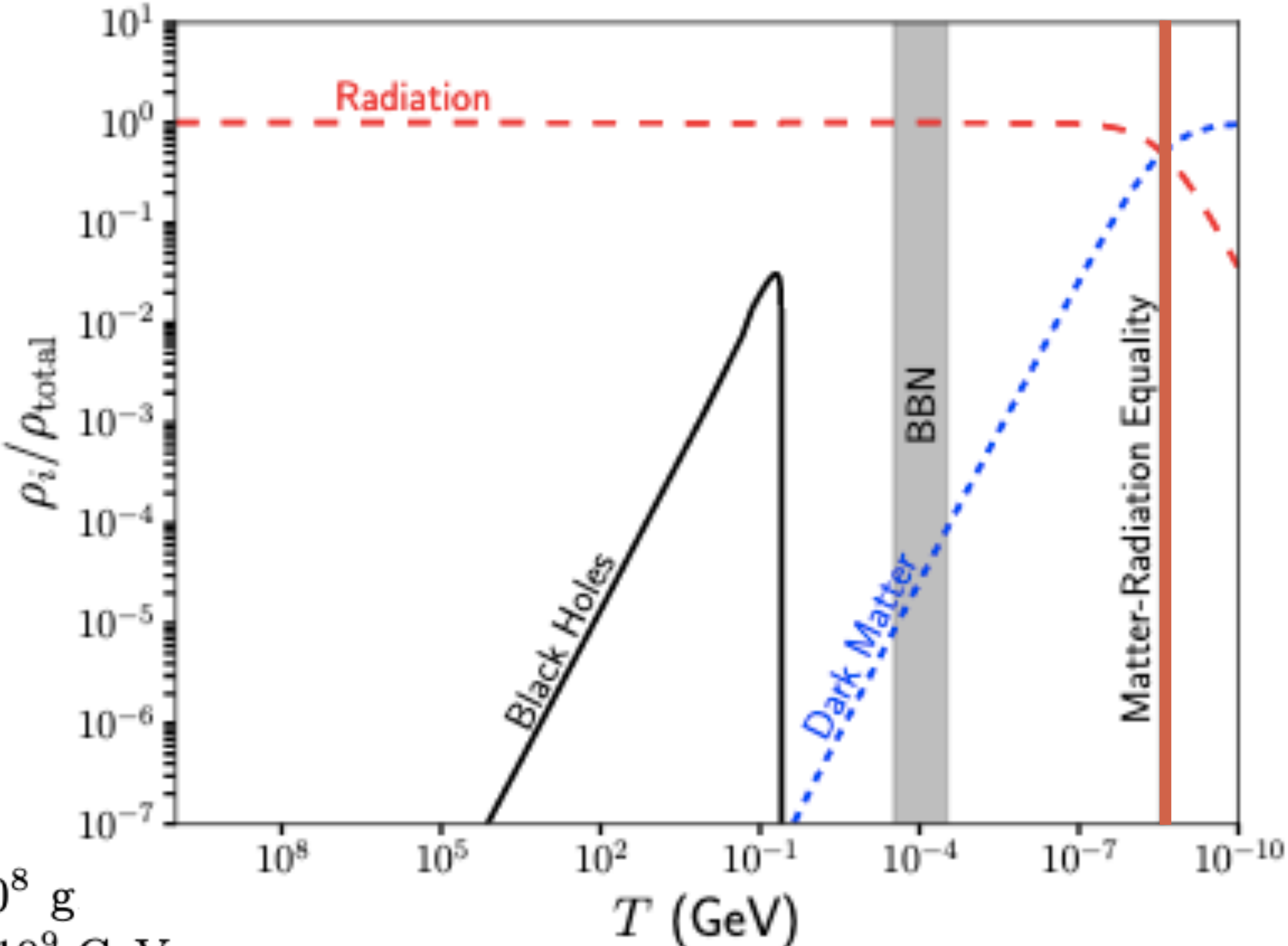
Example with a black hole dominated era



$M_i = 10^8$ g

$m_{\rm DM} = 6 \times 10^{10}$ GeV

Example with no black hole dominated era



$M_i = 10^8$ g

$m_{\rm DM} = 10^9$ GeV

$f_i = 8 \times 10^{-14}$ at $T_i = 10^{10}$ GeV

Planck Scale Remnants?

- It has been argued (somewhat controversially) that the end point of Hawking evaporation may be a stable object with a mass of around the Planck mass
- If there was a black hole dominated era, the abundance of these remnants would be

$$\Omega_{\rm remnant} h^2 \approx 0.1 \times \left(\frac{M_{\rm remnant}}{M_{\rm Pl}}\right) \left(\frac{6 \times 10^5 \, {\rm g}}{M_i}\right)^{5/2}$$

- Within this context, Planck-scale relics could be an attractive candidate for dark matter

Summary: A Few Key Takeaways

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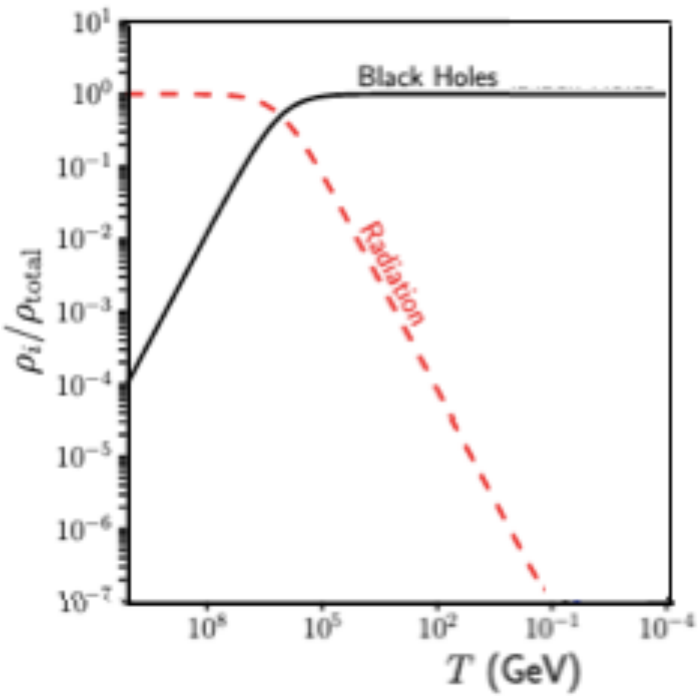
1) If black holes made up even a trace fraction of the total energy density after inflation, this fraction will increase as the universe expands, ultimately dominating the total energy density if the following condition is met:

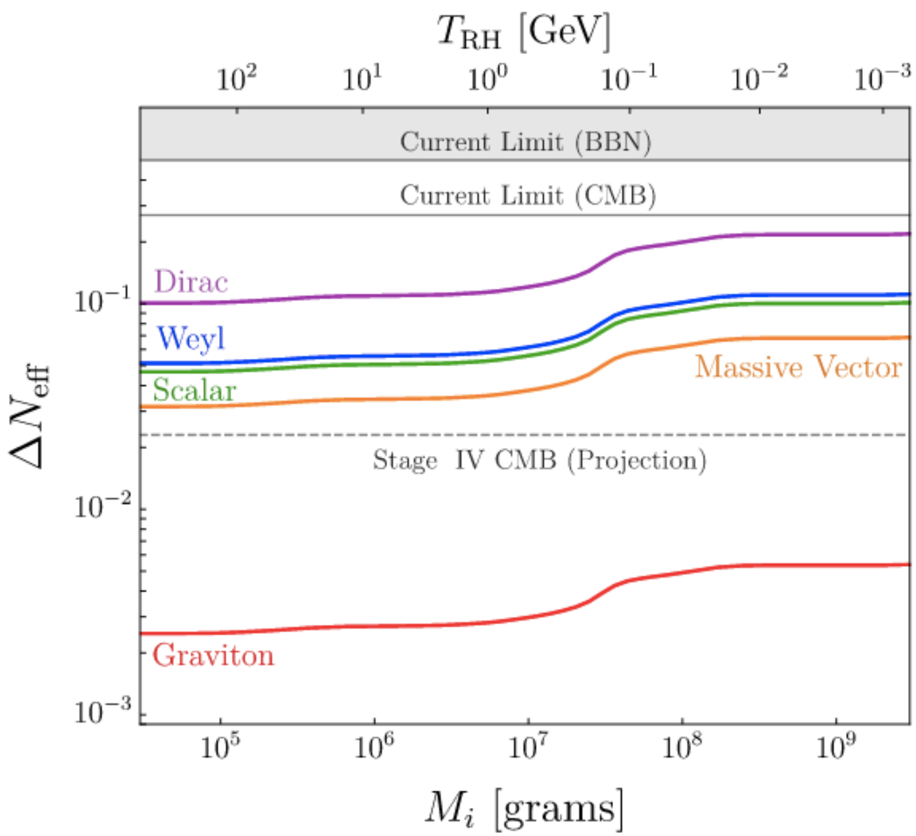
$$f_i \equiv \frac{\rho_{\mathrm{BH},i}}{\rho_{R,i}} \gtrsim 4 \times 10^{-12} \left(\frac{10^{10}\,\mathrm{GeV}}{T_i}\right) \left(\frac{10^8\,\mathrm{g}}{M_i}\right)^{3/2}$$



Summary: A Few Key Takeaways

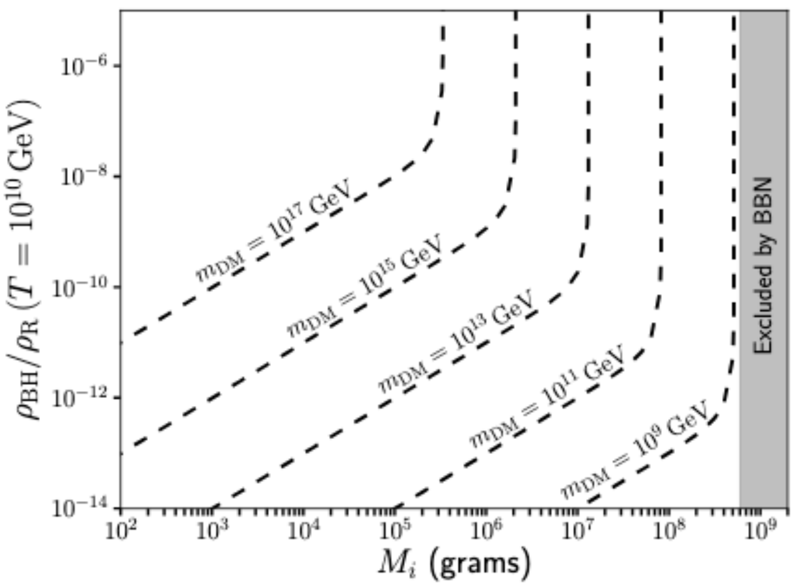
2) If there was a black hole dominated era *and* there exists one or more light, feebly interacting particle species, these particles *will* significantly contribute to ΔN_{eff}

In this sense, black holes provide an attractive way to resolve the Hubble tension



Summary: A Few Key Takeaways

3) Hawking radiation can easily produce the measured abundance of dark matter



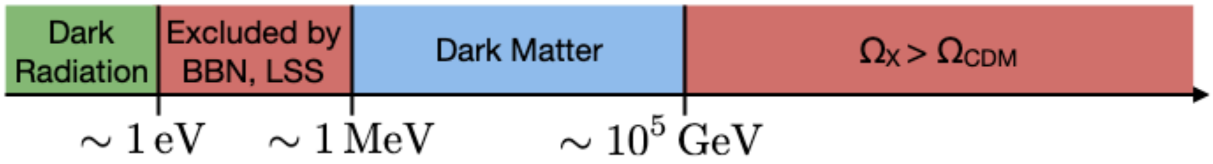
If there was a black hole dominated era:

$$\Omega_{\rm DM}h^2 \approx 0.1 \left(\frac{g_{{\rm DM},H}}{4}\right)\left(\frac{6\times10^{10}\,{\rm GeV}}{m_{\rm DM}}\right)\left(\frac{10^8\,{\rm g}}{M_i}\right)^{5/2}$$

Without a black hole dominated era:

$$\Omega_{\rm DM}h^2 \approx 0.1 \left(\frac{f_i(10^{10}\,{\rm GeV})}{8\times10^{-14}}\right)\left(\frac{g_{{\rm DM},H}}{4}\right)\left(\frac{10^9\,{\rm GeV}}{m_{\rm DM}}\right)\left(\frac{10^8\,{\rm g}}{M_i}\right)$$

Thermal Relic



Hawking Radiation