BLACK HOLES IN THE EARLY UNIVERSE

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New Horizons in Primordial Black Holes Physics Workshop

National Galleries of Scotland

June 17, 2024

This Talk Is Based On

Dark Radiation and Superheavy Dark Matter from Black Hole Domination *(arXiv:1905.01301),*

Hot Gravitons and Gravitational Waves from Kerr Black Holes in the Early Universe *(arXiv:2004.00618),*

GUT Baryogenesis With Primordial Black Holes *(arXiv:2010.01134),*

**With Gordan Krnjaic, Sam McDermott,
John March-Russell and Rudin Petrossian-Byrne**

A Plausible Picture

- After inflation ended, the universe was still rapidly expanding
- The total mass-energy enclosed by the cosmological horizon at this time was quite small:

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

- For reheating temperatures in the range of $T_{\rm RH}$~10^{10}-10^{15} GeV, this corresponds to horizon masses of $M_{\rm hor}$~10^2-10^{12} grams
- From this perspective, it seems particularly well motivated for us to consider primordial black holes that were formed with masses in roughly this range (more massive black holes could form only later, when the horizon was larger)
- How many of these black holes (if any) were produced during this era depends on the details of inflation, and is a highly model dependent question

Hawking Evaporation

- Black holes emit particles as a blackbody, with the following temperature:

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

- Hawking radiation causes a black hole to lose mass at the following 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 weighted sum of degrees-of-freedom; small black holes evaporate fast!

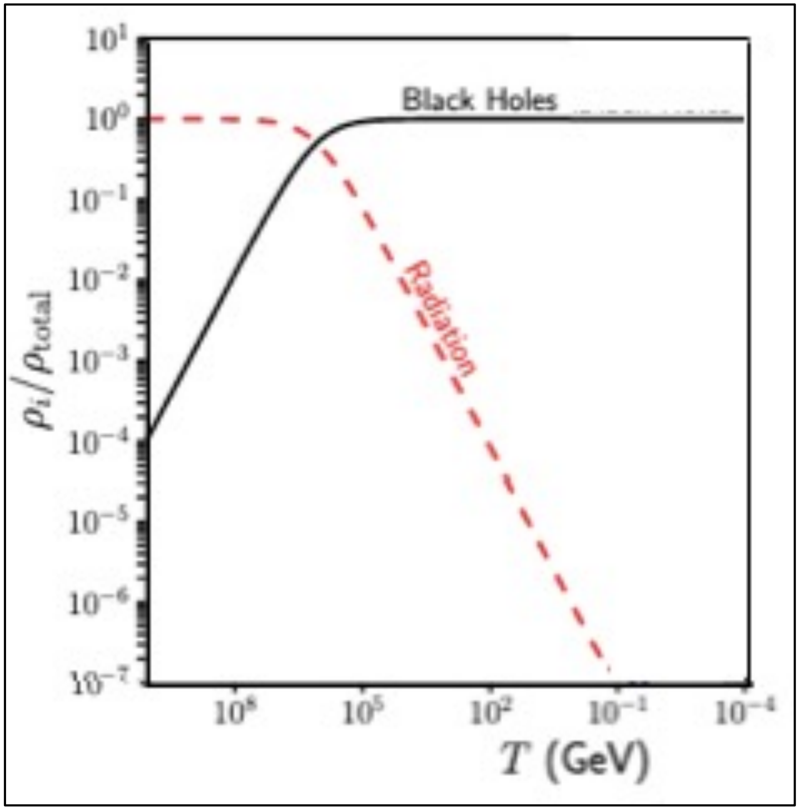
- This evaporation rate accelerates as the black hole becomes smaller; a black hole with an initial mass, M_i, will disappear entirely after the following time:

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

- Any black holes lighter than ~10^9 grams will be gone by the onset of BBN, and are thus almost entirely unconstrained

Was the Early Universe Dominated by Black Holes?

- As the universe expands, the energy density of relativistic particles falls like $\boldsymbol{\rho}_{\rm rad}\ \boldsymbol{\alpha}\ a^{-4}$, three powers from geometrical dilution, and one power from cosmological redshift
- In contrast, black holes behave like particles of matter, and do not redshift, $\boldsymbol{\rho}_{\rm BH}\ \boldsymbol{\alpha}\ a^{-3}$
- As a result, the fraction of the total energy density in the form of black holes *grows* as the early universe expands, $\boldsymbol{\rho}_{\rm BH}/\boldsymbol{\rho}_{\rm rad}\ \boldsymbol{\alpha}\ a$
- If the very early universe contained even a tiny abundance of black holes, this fractional abundance will grow, naturally leading to an era in which the total energy density was dominated by black holes



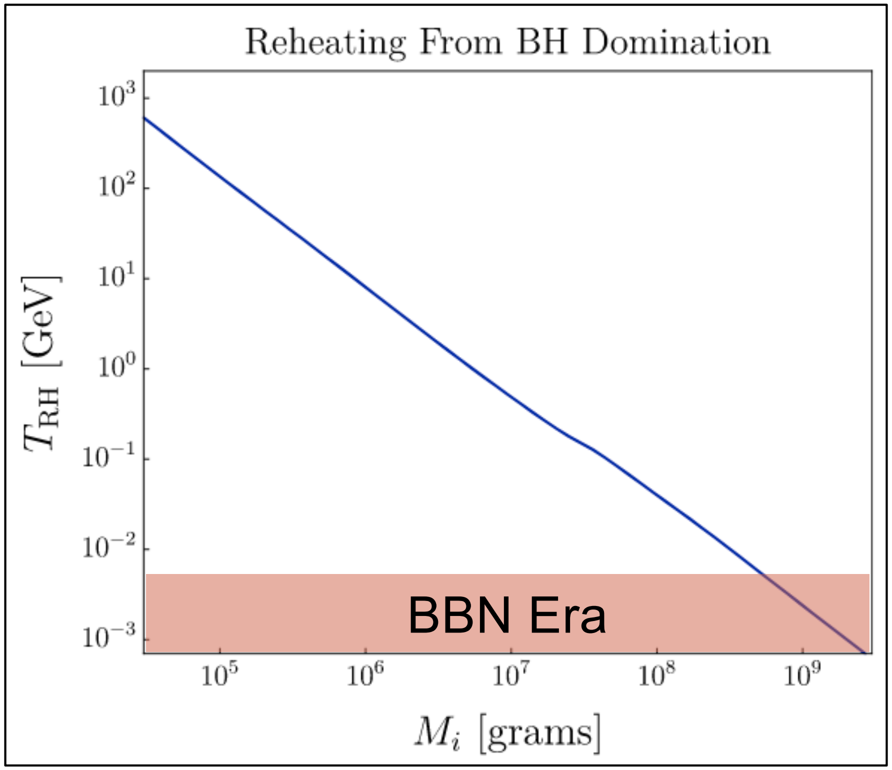
Was the Early Universe Dominated by Black Holes?

- 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

- When the black holes finish evaporating, they leave behind a hot bath of radiation; as if the black holes had never been there in the first place



Motivation #1: Dark Matter

- Although thermal relics with roughly weak scale masses and interactions (WIMPs) remain a viable possibility for the dark matter of our universe, the lack of any signals in direct detection experiments has motivated us to consider other ways that the dark matter may have been created in the early universe; especially ways that could produce a population of very feebly interacting dark matter particles

- Some well-known examples include:

  -Misalignment production (axions, etc.)

  -Production through out-of-equilibrium decays (moduli/topological defects)

  -Production via freeze-in or leak-in (*ie*. semi-thermal mechanisms)

- Another way to produce extremely feebly interacting dark matter particles would be through the Hawking evaporation of black holes in the early universe

The Democratic Nature of Gravity

- Hawking evaporation is a consequence of gravity, which (unlike other forces) treats all forms of matter and energy in the same way
- Consider, for example, a black hole with a mass of 10^8 grams, corresponding to a temperature of ~100 TeV
- This black hole will radiate *all* kinds of particles that are lighter than ~100 TeV, regardless of their electric charge, QCD color, or any other quantum numbers
- This includes any particles lighter than ~100 TeV that we have *not discovered yet!* – axions, hidden photons, right-handed neutrinos, gravitons, supersymmetric particles, *etc*.
- Black holes are the ideal factories of exotic particles

Dark Matter From Hawking Evaporation

- Consider a stable and very feebly interacting particle that’s massive enough to be non-relativistic by 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

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

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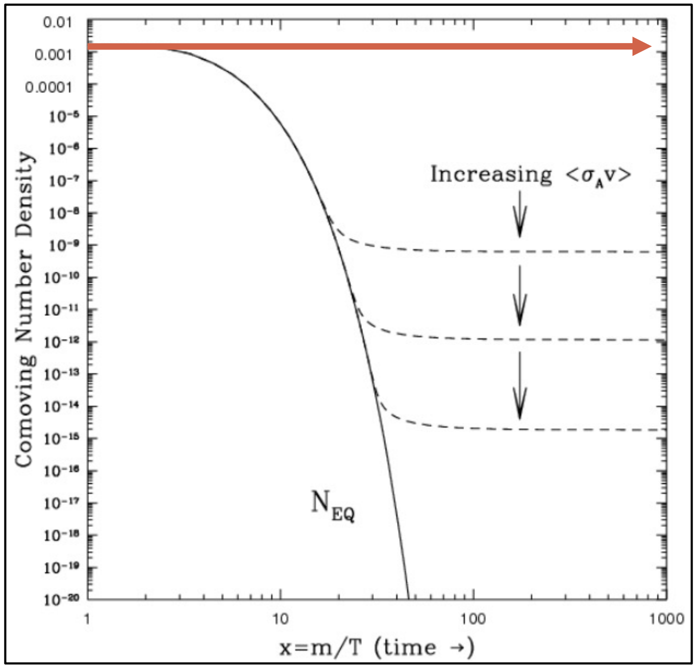
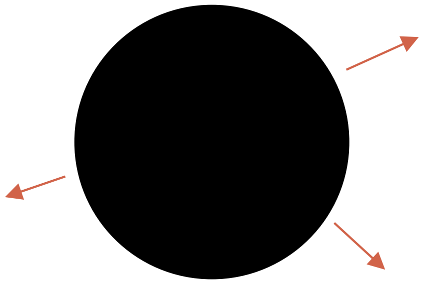
- This situation is much like that of a stable particle species that was at an equilibrium abundance in the early universe, but with a negligible annihilation cross section (and no other means of being depleted)
- So, the problem is not how to make the dark matter through Hawking evaporation, but rather how to avoid making far too much!



Dark Matter From Hawking Evaporation

- To evade this problem, one could consider *very* heavy dark matter particles
- Since a black hole can only radiate particles lighter than its temperature, these black holes will initially only produce Standard Model particles



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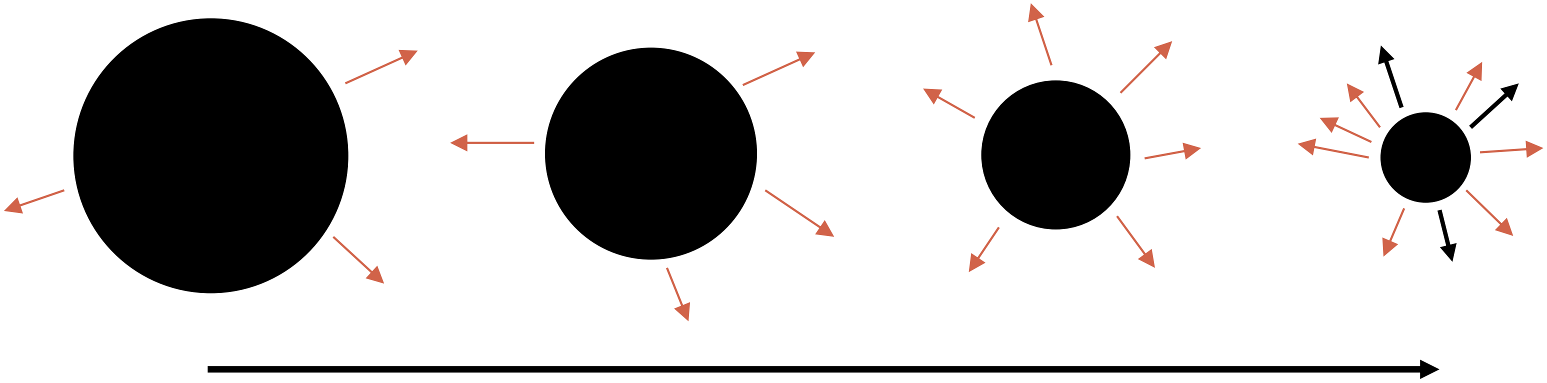


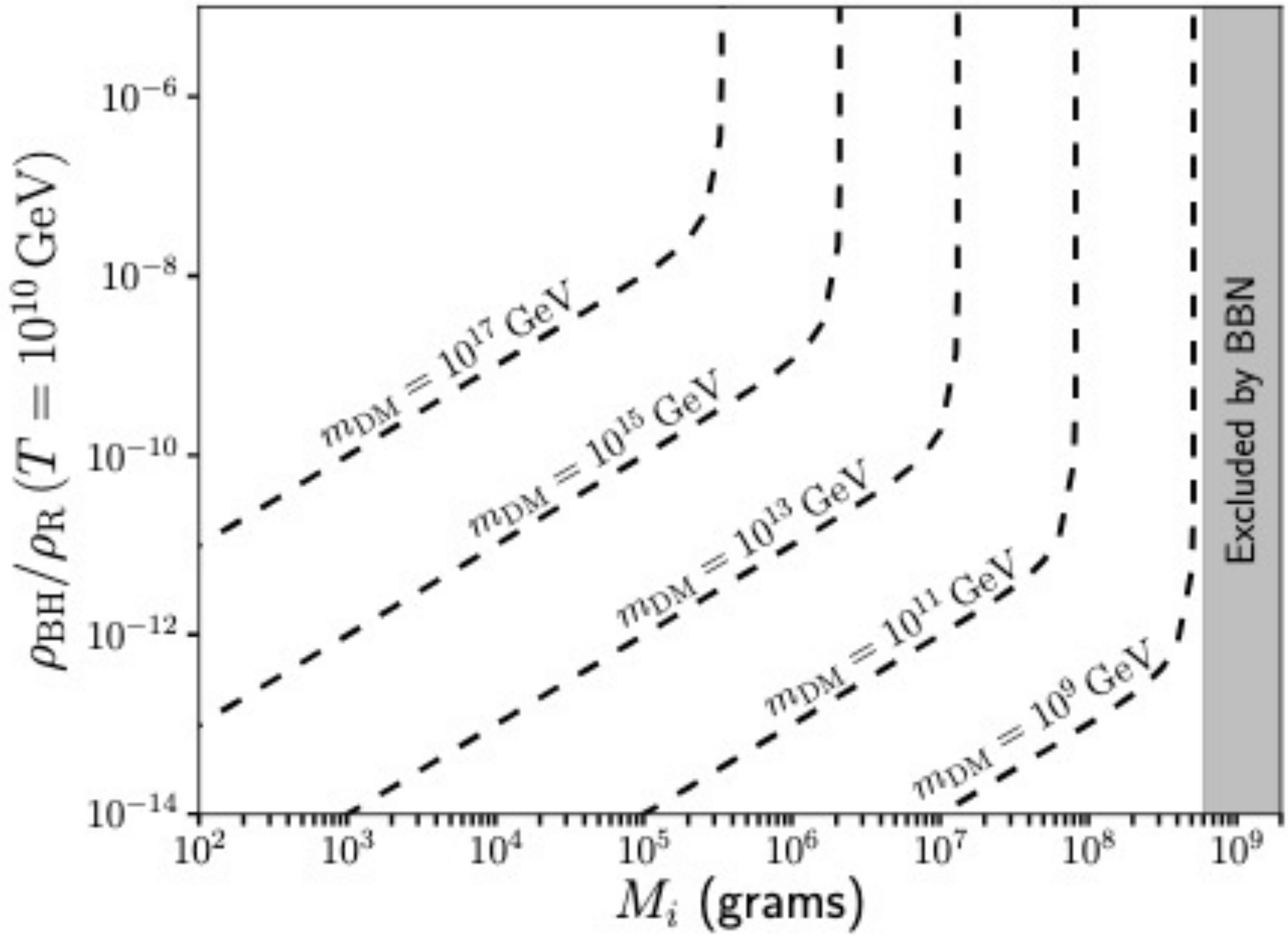
Increasing Black Hole Temperature

- As the black hole evaporates, it becomes hotter and radiates more quickly
- Only after its temperature has increased to $T \sim m_X$ will it start to create dark matter particles

Dark Matter From Hawking Evaporation

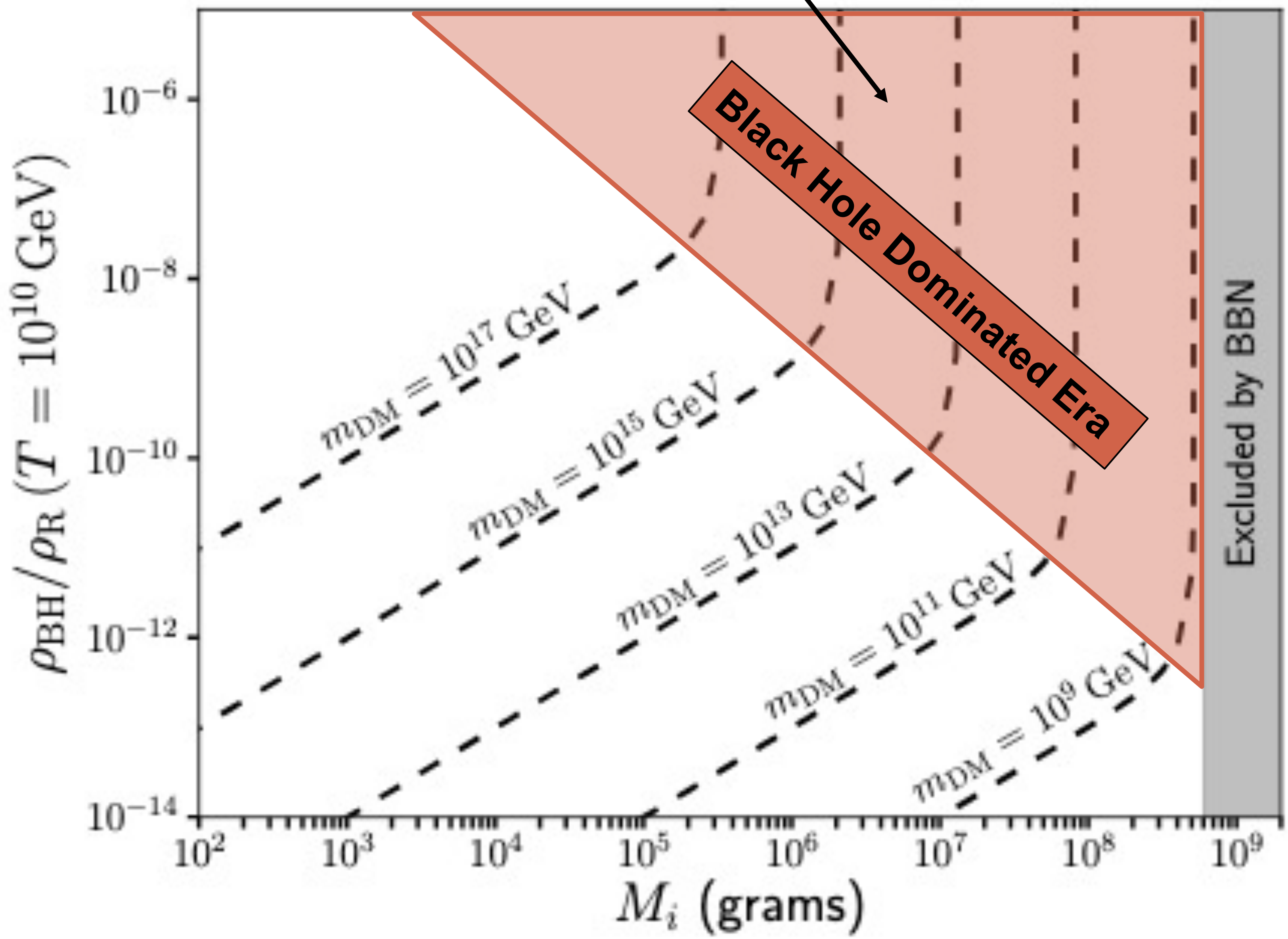
- Consider the following example: a population of black holes with an initial mass of 10^8 grams (with a black hole temperature of ~10^5 GeV), and dark matter particles with a mass of 6×10^{10} GeV
- These black holes only start producing dark matter particles after their temperature has increased to $m_X \sim 6 \times 10^{10}$ GeV, by which time the black hole's mass has been reduced to ~200 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 $\Omega_{DM} h^2 = 0.1$

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

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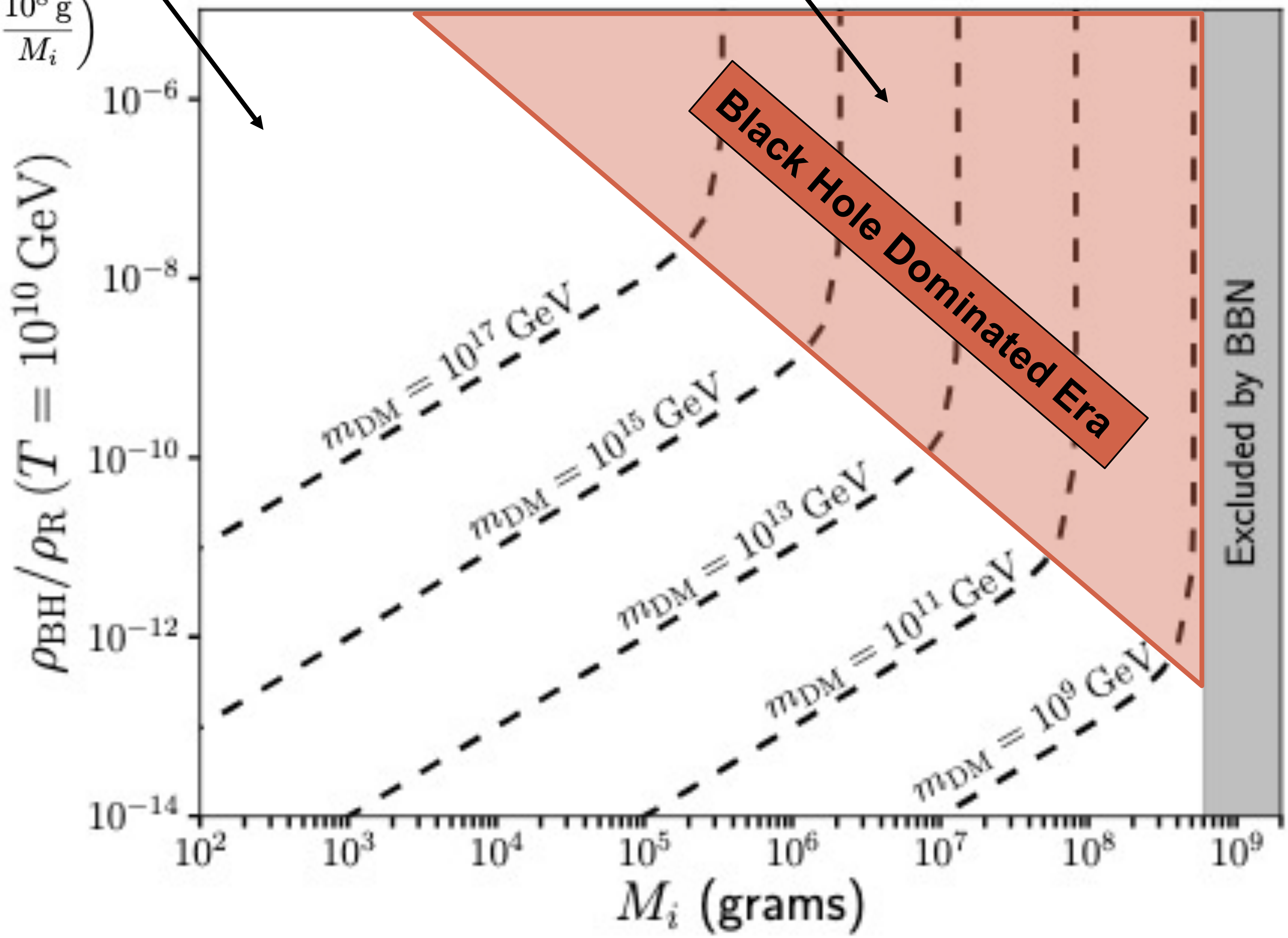

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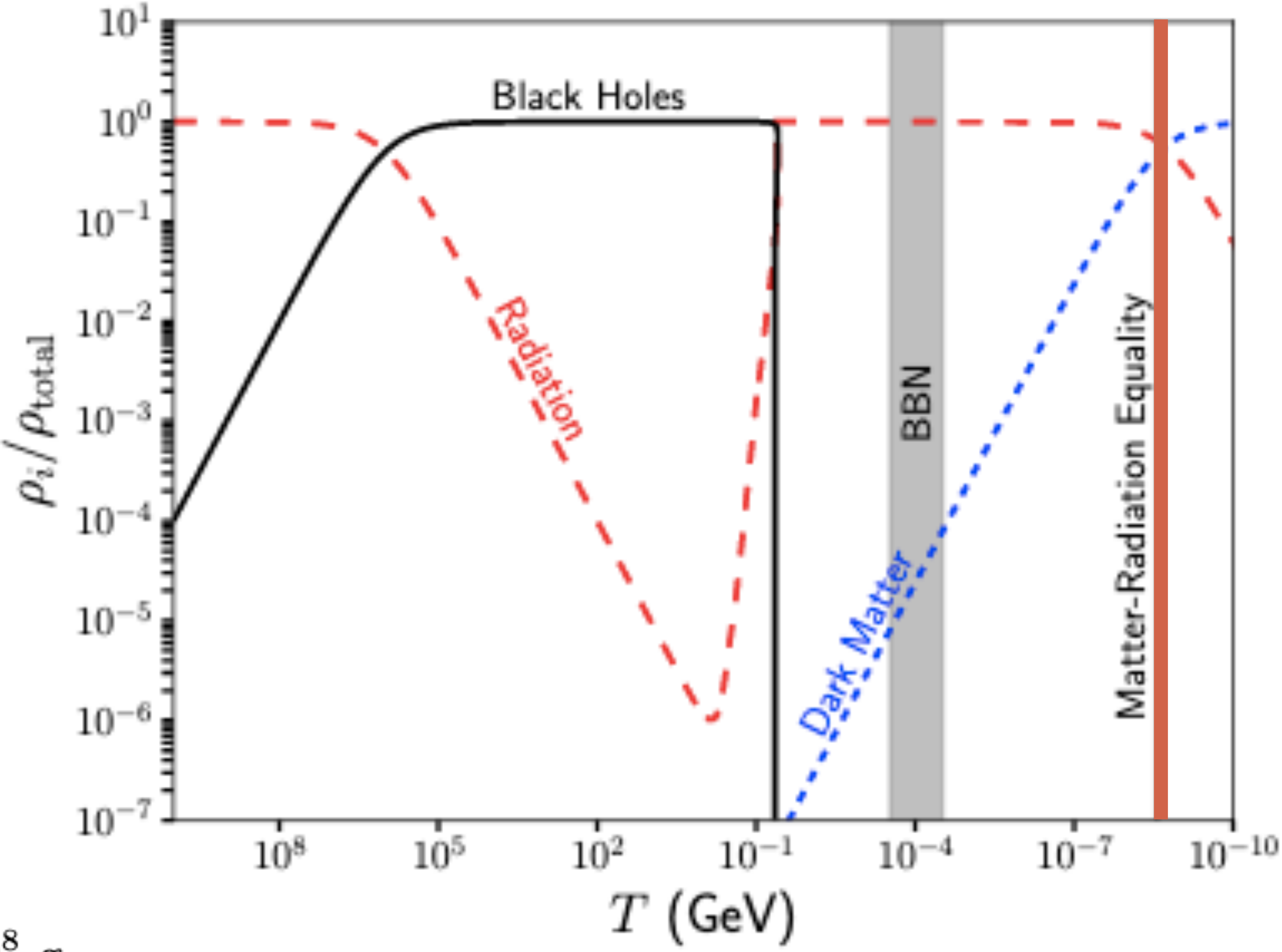
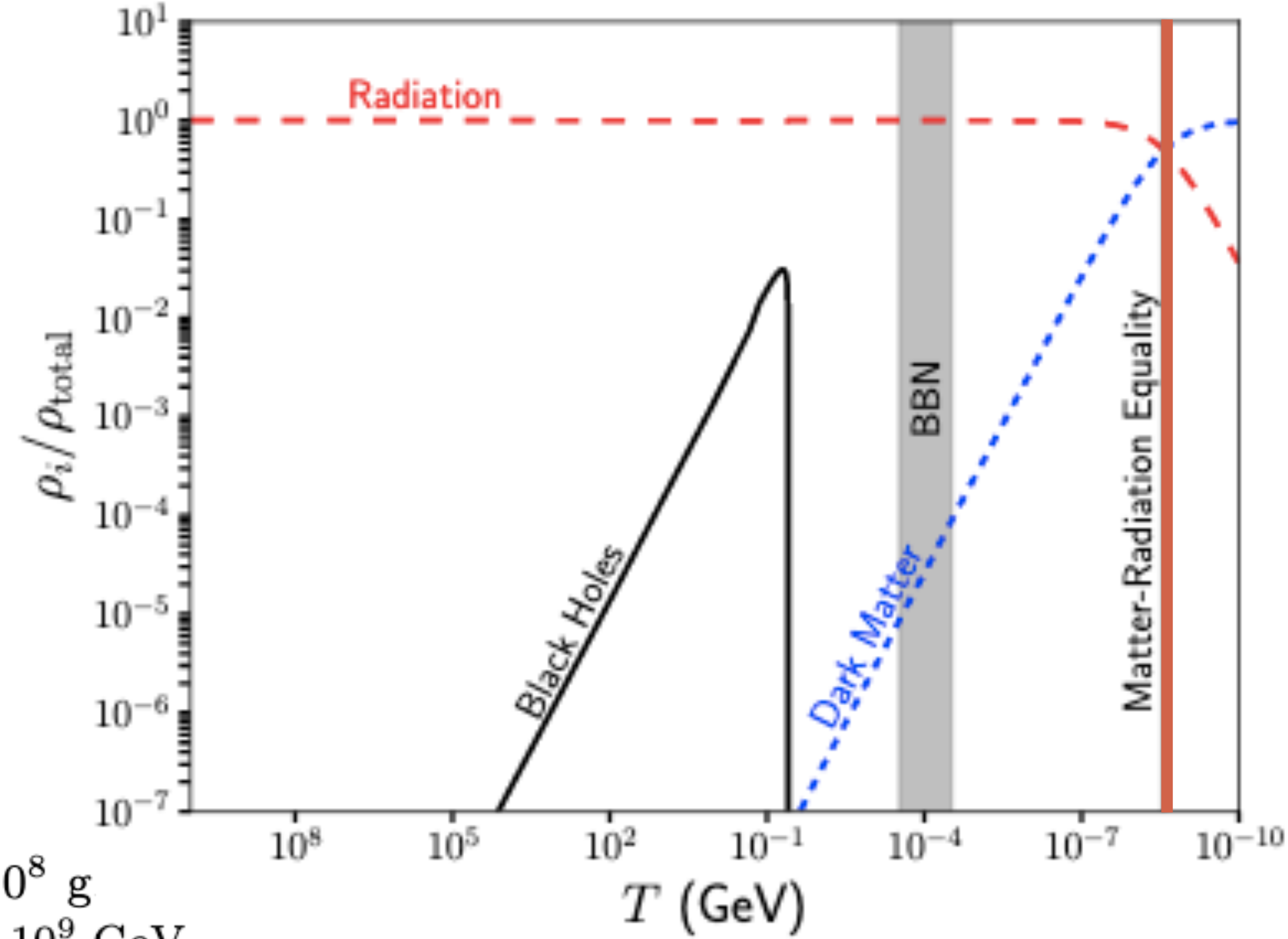
Example with a black hole dominated era



$$M_i = 10^8 \text{ g}$$
$$m_{\rm DM} = 6 \times 10^{10} \text{ GeV}$$

Example without a 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 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

Motivation #2: Dark Radiation

- 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 feebly interacting* particle species (axions, gravitons, hidden photons, 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

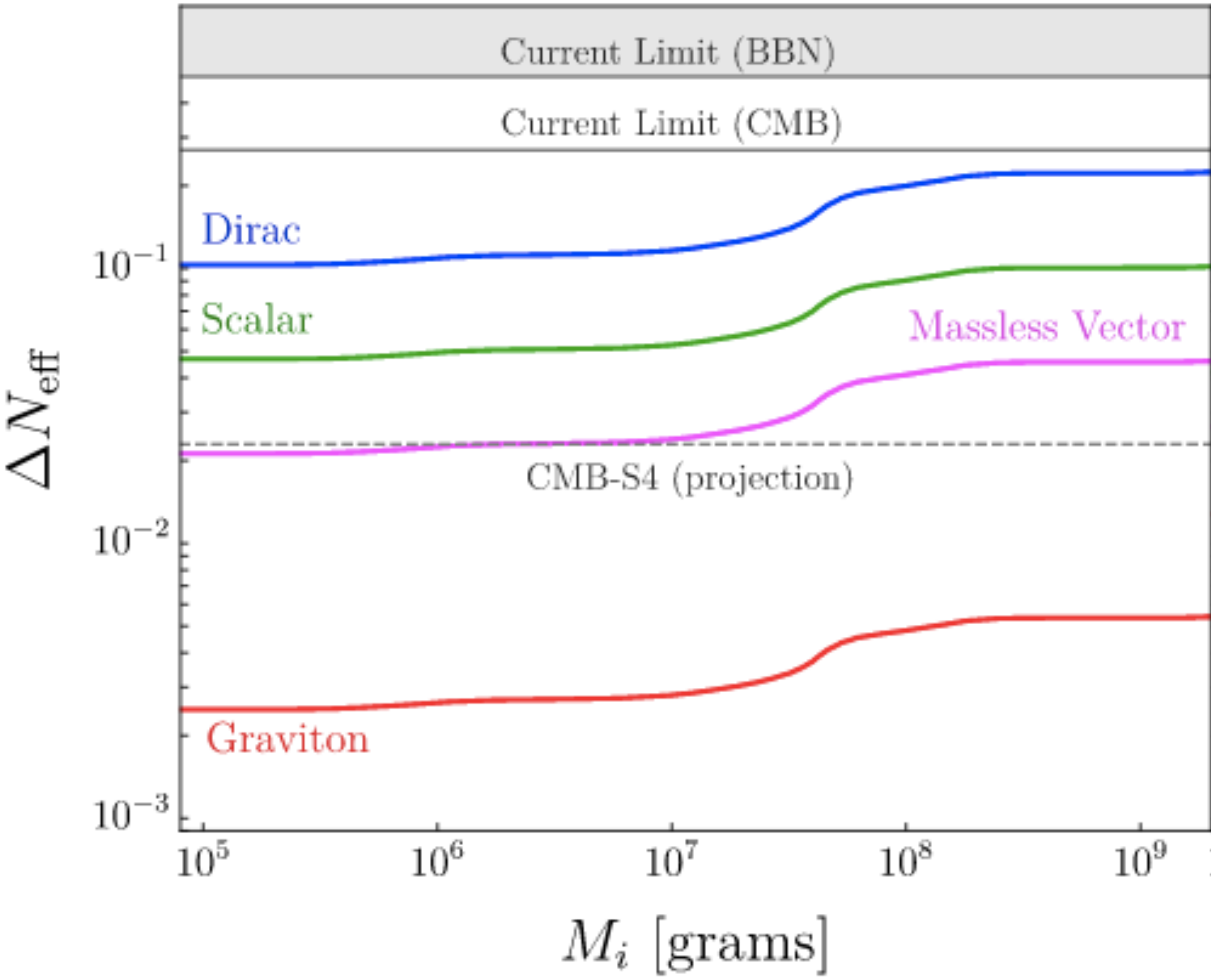
Dark Radiation From Hawking Evaporation

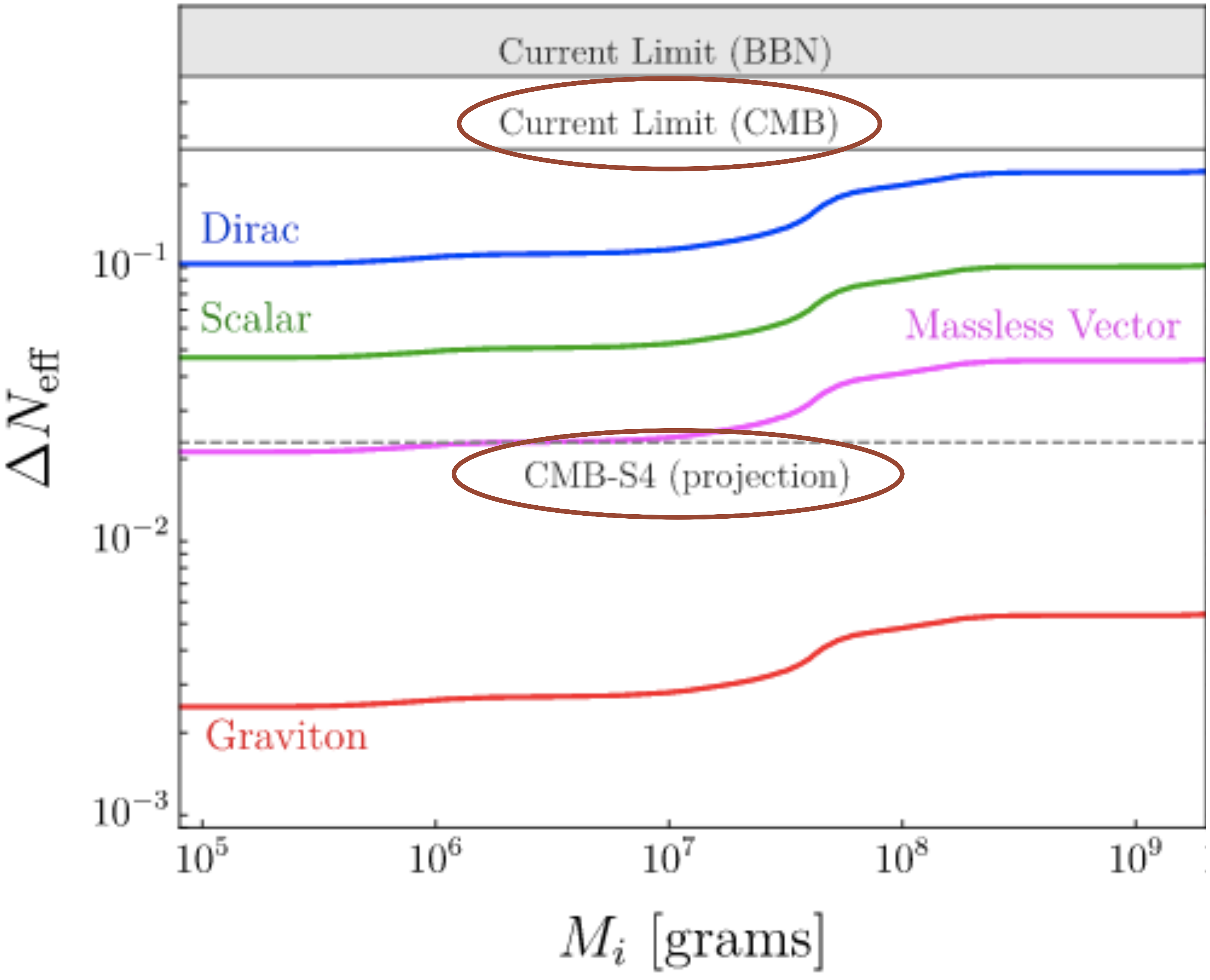
- Immediately after a black hole dominated era, the fraction of the energy density in an exotic light particle species will be given by their (greybody factor-weighted) degrees-of-freedom, $g_{\mathrm{DR},H}/g_{\star,H}$.
- After accounting for SM entropy dumps, we arrive at:

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

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

$$\begin{aligned}\Delta N_{\mathrm{eff}} &= \frac{\rho_{\mathrm{DR}}(T_{\mathrm{EQ}})}{\rho_R(T_{\mathrm{EQ}})}\left[N_\nu + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right] \\ &= \left(\frac{g_{\mathrm{DR},H}}{g_{\star,H}}\right)\left(\frac{g_{\star S}(T_{\mathrm{EQ}})}{g_{\star S}(T_{\mathrm{RH}})}\right)^{1/3}\left(\frac{g_{\star S}(T_{\mathrm{EQ}})}{g_\star(T_{\mathrm{EQ}})}\right)\left[N_\nu + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right] \\ &\approx 0.10\left(\frac{g_{\mathrm{DR},H}}{4}\right)\left(\frac{106}{g_\star(T_{\mathrm{RH}})}\right)^{1/3}\end{aligned}$$


Current Limit (BBN)
Current Limit (CMB)
Dirac
Scalar
Massless Vector
CMB-S4 (projection)
Graviton
10^{-1}
10^{-2}
10^{-3}
$\Delta N_{\rm eff}$
10^5
10^6
10^7
10^8
10^9
M_i [grams]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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

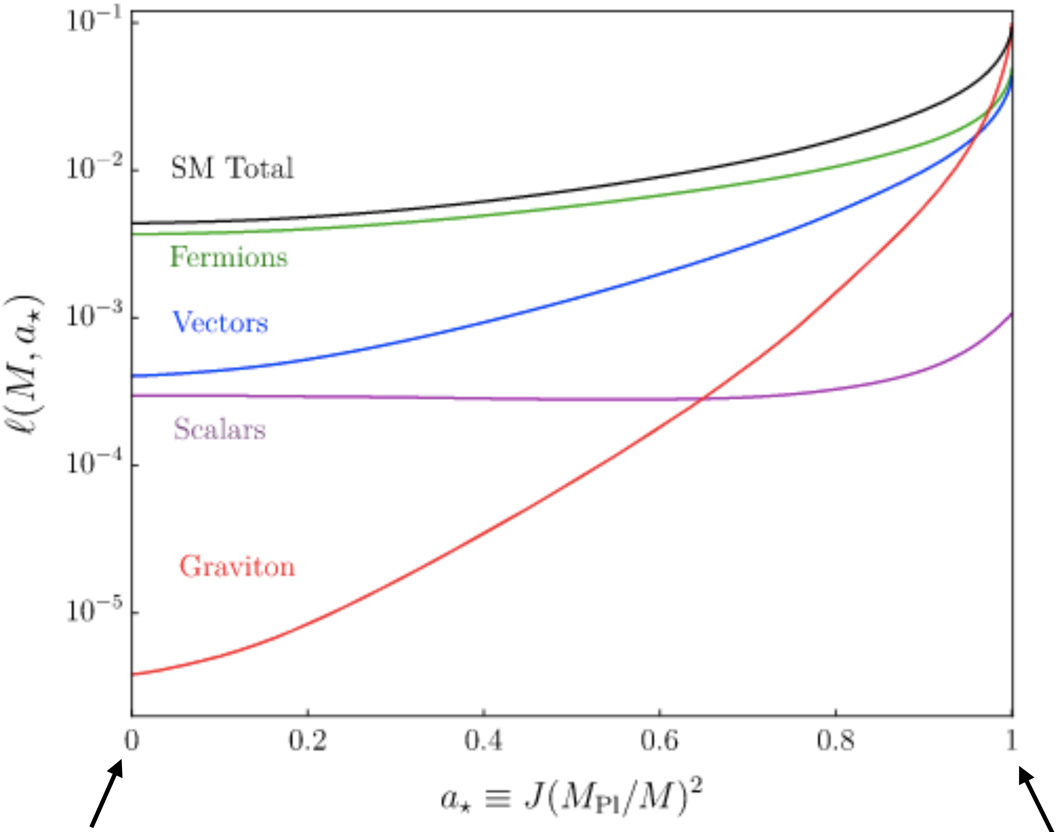
- Integrating over the lifetime of the black holes, we arrive at a slightly higher value, $\sim 5.5\,{\rm MeV} \times (M_i/10^8\,{\rm g})^{1/2}$.
- In contrast to thermally produced dark radiation (which must be lighter than ~eV), dark radiation that is produced through Hawking evaporation can consist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

Hawking Radiation From Rotating Black Holes

- So far in this talk, I've assumed that the black holes are not appreciably spinning (Schwarzschild black holes), but it is entirely possible that these black holes could have substantial angular momentum (Kerr black holes)
- The Hawking radiation from a black hole depends strongly on its angular momentum:

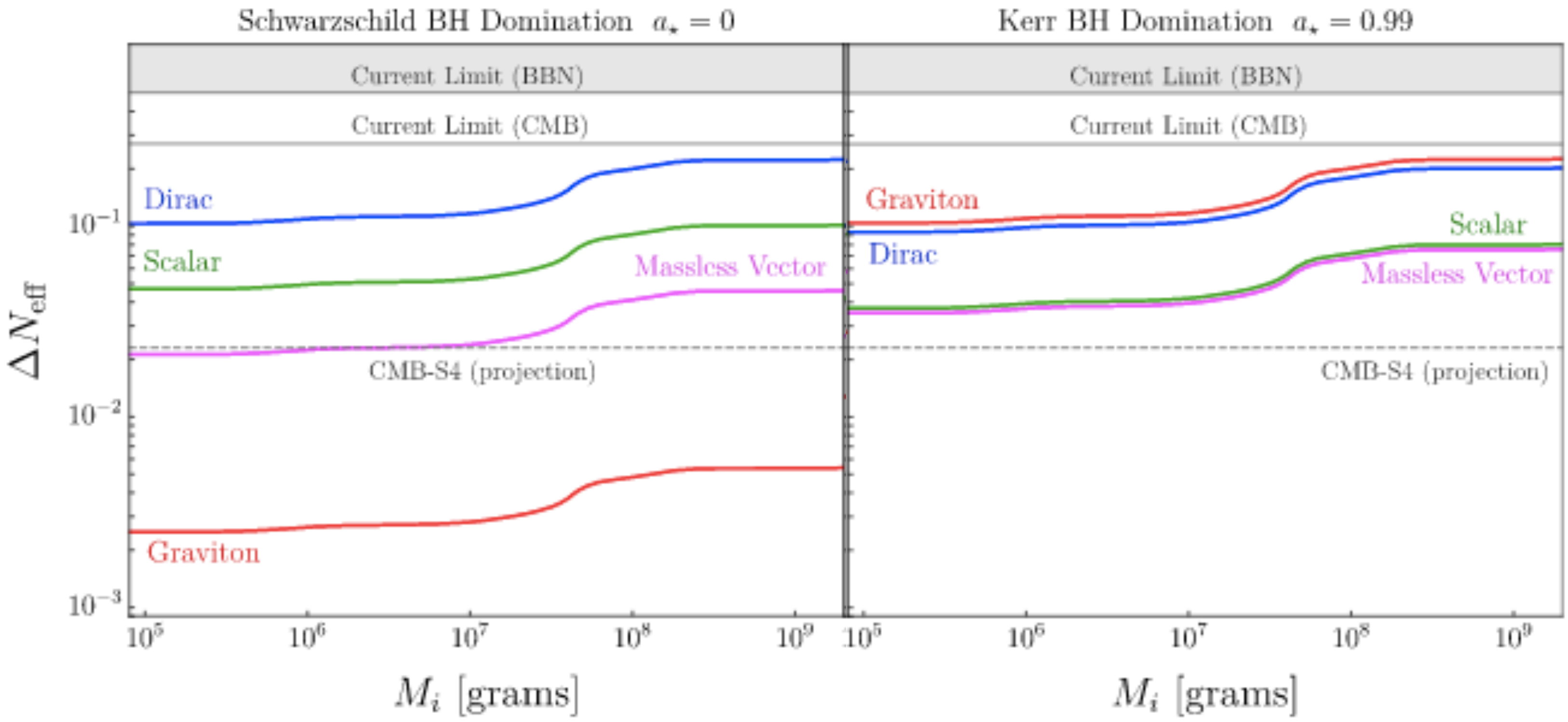


Non-Rotating

Maximally Rotating

Gravitons From Rotating Black Holes

- The amount of dark radiation that is predicted in the form of gravitons produced in a black hole dominated era changes dramatically if the black holes are spinning
- For near maximally-spinning black holes, the energy density in the form of gravitons is testable with next generation CMB experiments!



How Might Primordial Black Holes Come to be Rapidly Spinning?

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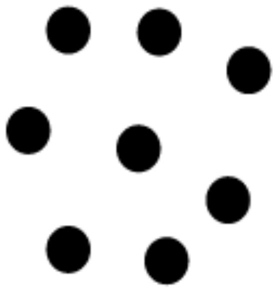

1.BH formation

$\rho_{\rm BH} \ll \rho_{\rm tot}$

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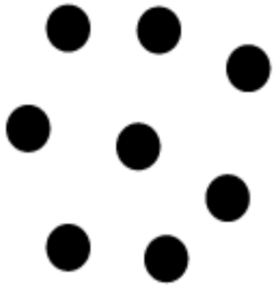

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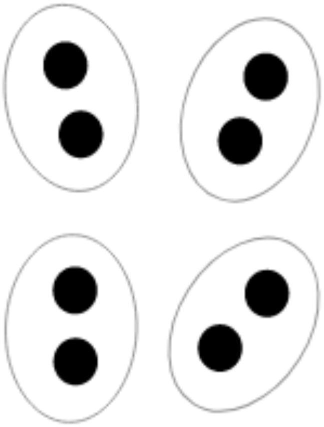

2. Binary Capture

$\Gamma_{\rm C} \sim H$

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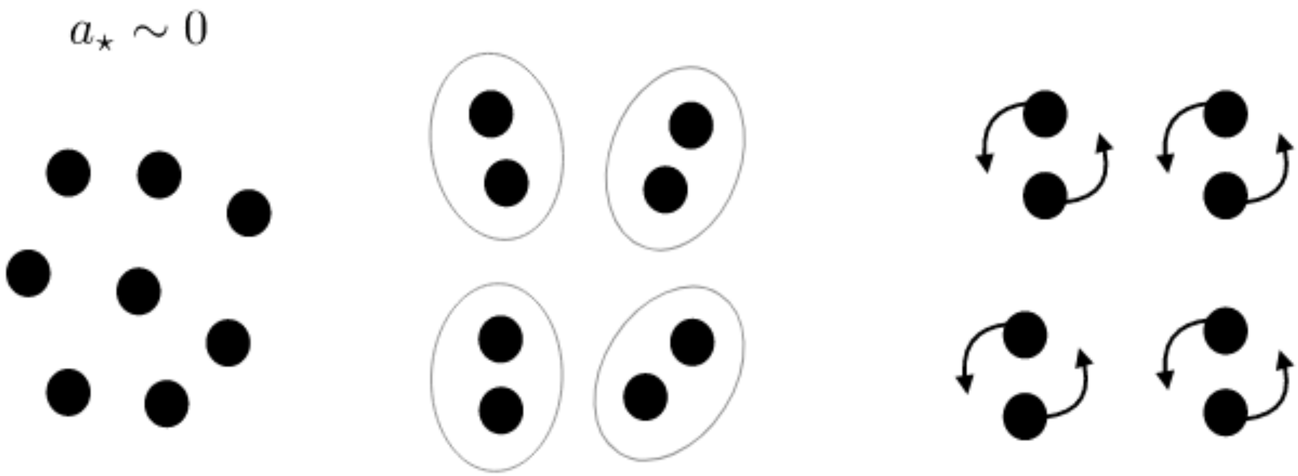

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3. Mergers

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$\rho_{\rm GW} \rightarrow \Delta N_{\rm eff,GW}$

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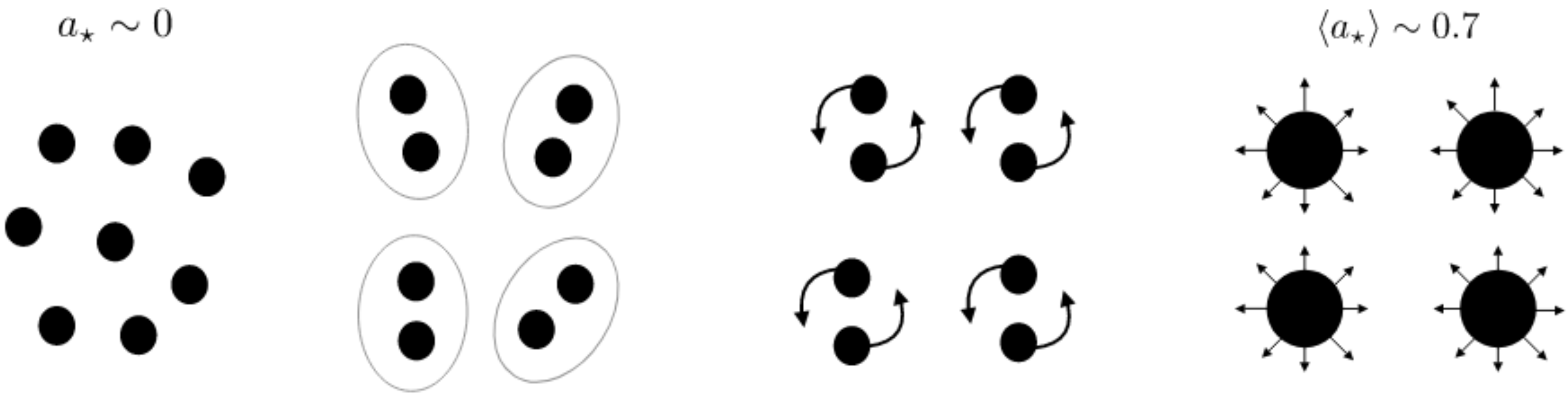

$a_\star \sim 0$

$\langle a_\star \rangle \sim 0.7$

1.BH formation

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$\rho_{\rm BH} \sim \rho_{\rm tot}$

$\rho_{\rm GW} \rightarrow \Delta N_{\rm eff,GW}$

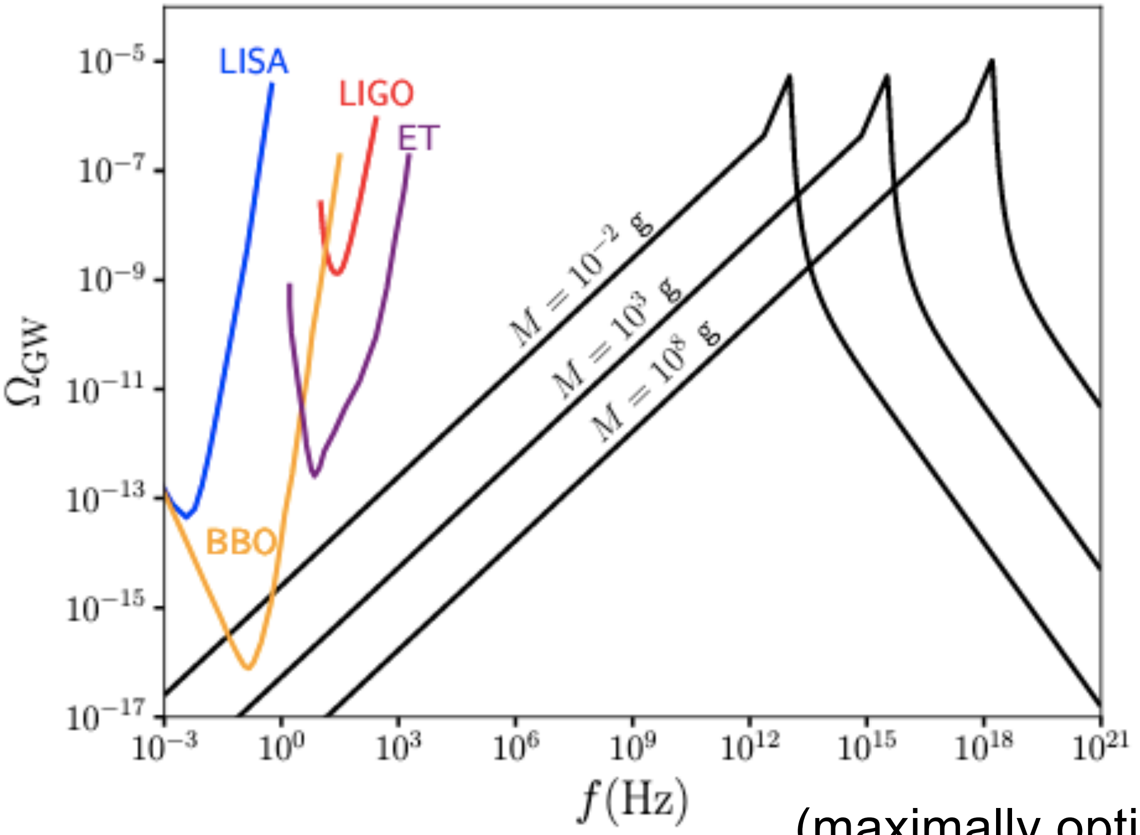
4. Hawking Radiation

$\rho_{\rm BH} \rightarrow \rho_R + \rho_{\rm G} + \cdots$

$\Delta N_{\rm eff,G}$

Potentially Observable Signals

1) When a pair of black holes merge, ~10% of their mass is radiated as gravitational waves, leading to a stochastic background that could (in the most optimistic cases) be detected by future space-based detectors

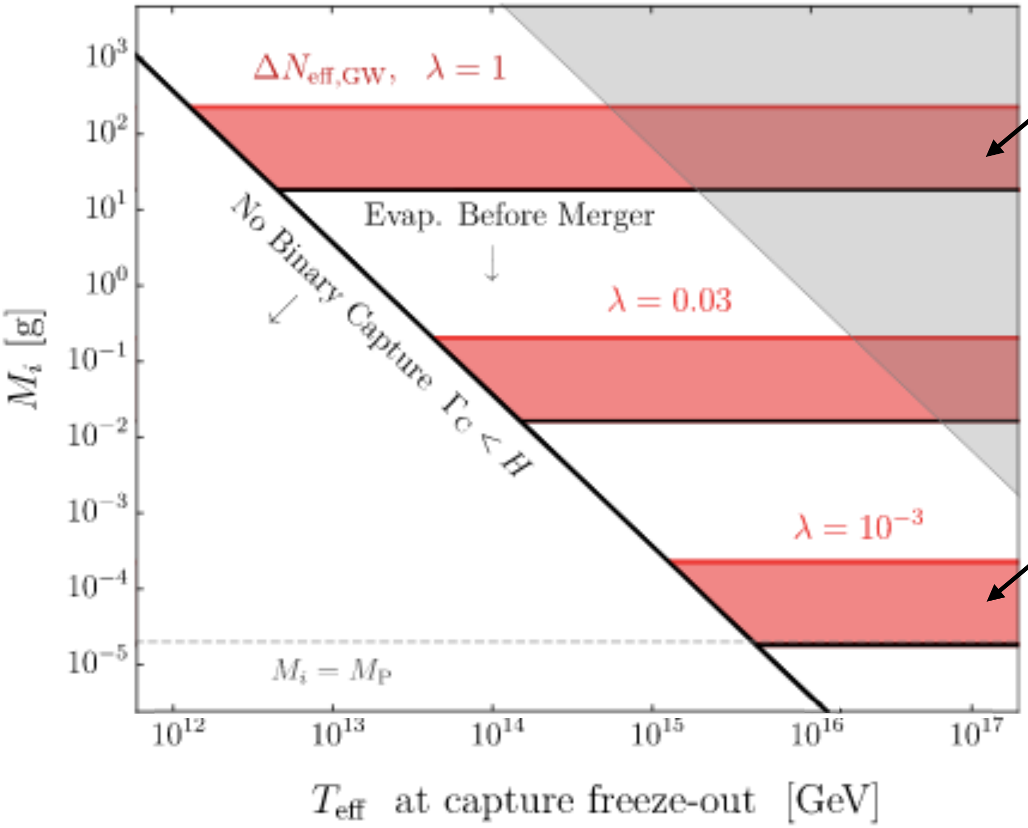


(maximally optimistic case shown; mergers just prior to evaporation)

Potentially Observable Signals

2) The energy density of these gravitational waves will impact the expansion rate of the early universe, acting as a form of dark radiation

In selected regions of parameter space, these gravitational waves could contribute to ΔN_{eff} at a level that's within the reach of upcoming CMB experiments



Observable band, loosely bound orbits

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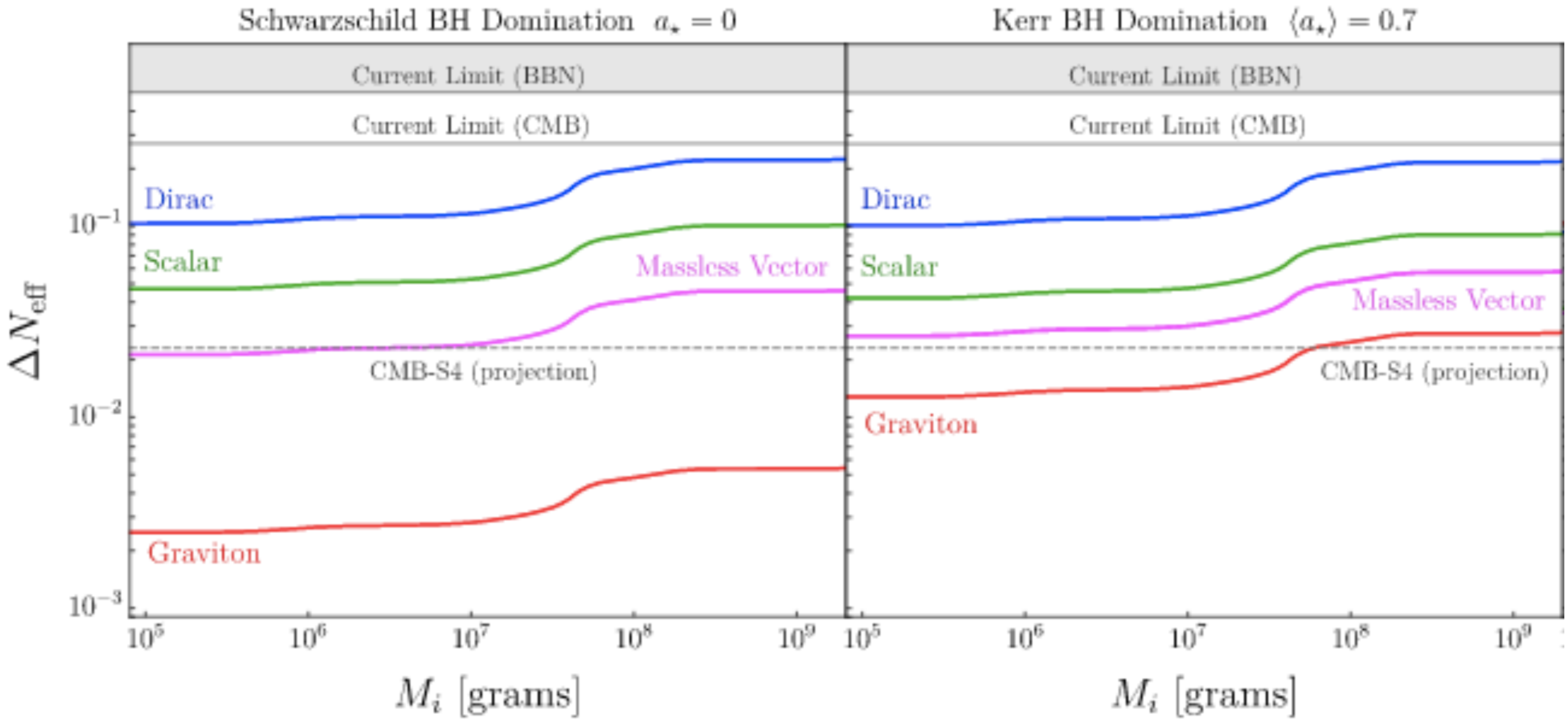
Potentially Observable Signals

3) The gravitons radiated from these rapidly spinning black holes also contribute to the energy density in dark radiation

Note that these gravitons are *much* more energetic than the particles that make up the other cosmic backgrounds ($T_{CMB} \sim T_{C\nu B} \sim 10^{-3}$ eV)

$T_G \sim$ eV – keV → the "*Hot Graviton Background*"



Motivation #3: The Baryon Asymmetry

- In models of GUT baryogenesis, the baryon asymmetry is generated through the baryon number violating *and CP* violating decays of very massive gauge or Higgs bosons that are produced thermally in the very early universe
- Proton decay constraints generally require these baryon number violating particles to be very heavy, typically ~10^{16} GeV for GUT gauge bosons or ~10^{12} GeV for GUT Higgs bosons
- B-mode constraints from BICEP2/Keck, combined with constraints on the shape of the inflationary potential, suggest that the universe was reheated to only ~10^{9}-10^{13} GeV, limiting the prospects for the production of very massive GUT bosons in the early universe
- In many simple models of GUT baryogenesis, the decays of heavy bosons only generate net B+L, which gets washed out by sphalerons well before the electroweak phase transition

Black Holes in GUT Baryogenesis

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1) **Guaranteed heavy particle production** – Black holes get hotter as they evaporate, producing the heaviest particles in their last moments (when $T_{BH} >> T_{universe}$); the production of GUT bosons thus doesn't require a high reheating temperature

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2) **Evading sphaleron washout** – Black holes heavier than $\sim 3 \times 10^5$ g complete their evaporation after the electroweak phase transition, automatically avoiding any washout of net B+L

3) **Out-of-equilibrium decays** – The heavy particles radiated from a black hole will automatically be out-of-equilibrium with the thermal bath, satisfying Sakharov's 3rd condition even if they decay promptly

Summary: A Few Key Takeaways

1) If black holes made up even a trace fraction of the total energy density after inflation, this fraction would increase as the universe expands, naturally coming to dominate the total energy density of the early universe

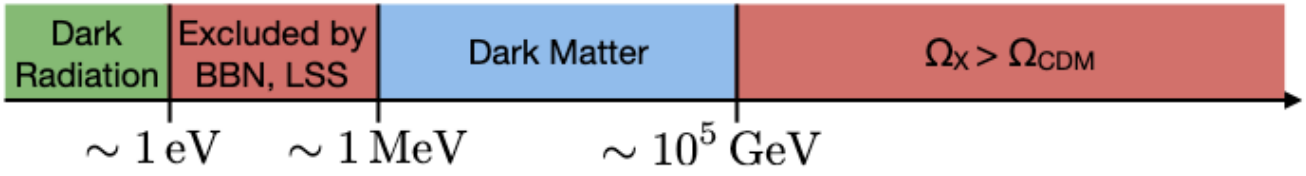
2) The democratic nature of gravity makes black holes ideal factories for exotic, feebly-coupled particles; Hawking radiation could have easily produced the measured abundance of dark matter

3) If there was a black hole dominated era *and* there exists one or more light, stable and feebly interacting particle species, these particles *will* significantly contribute to the energy density of dark radiation, ΔN_{eff}

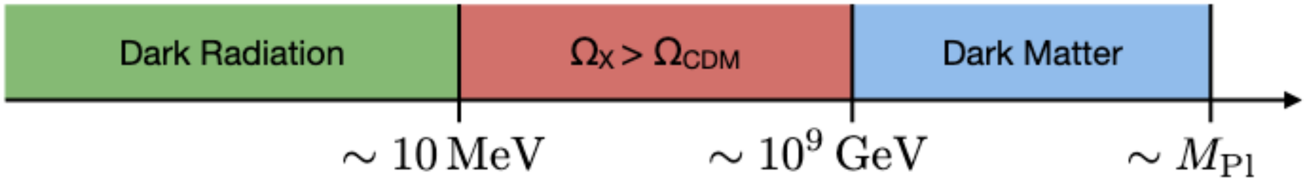
4) Mergers in the early universe could have left these black holes with appreciable angular momentum (Kerr black holes), leading to several potentially observable consequences

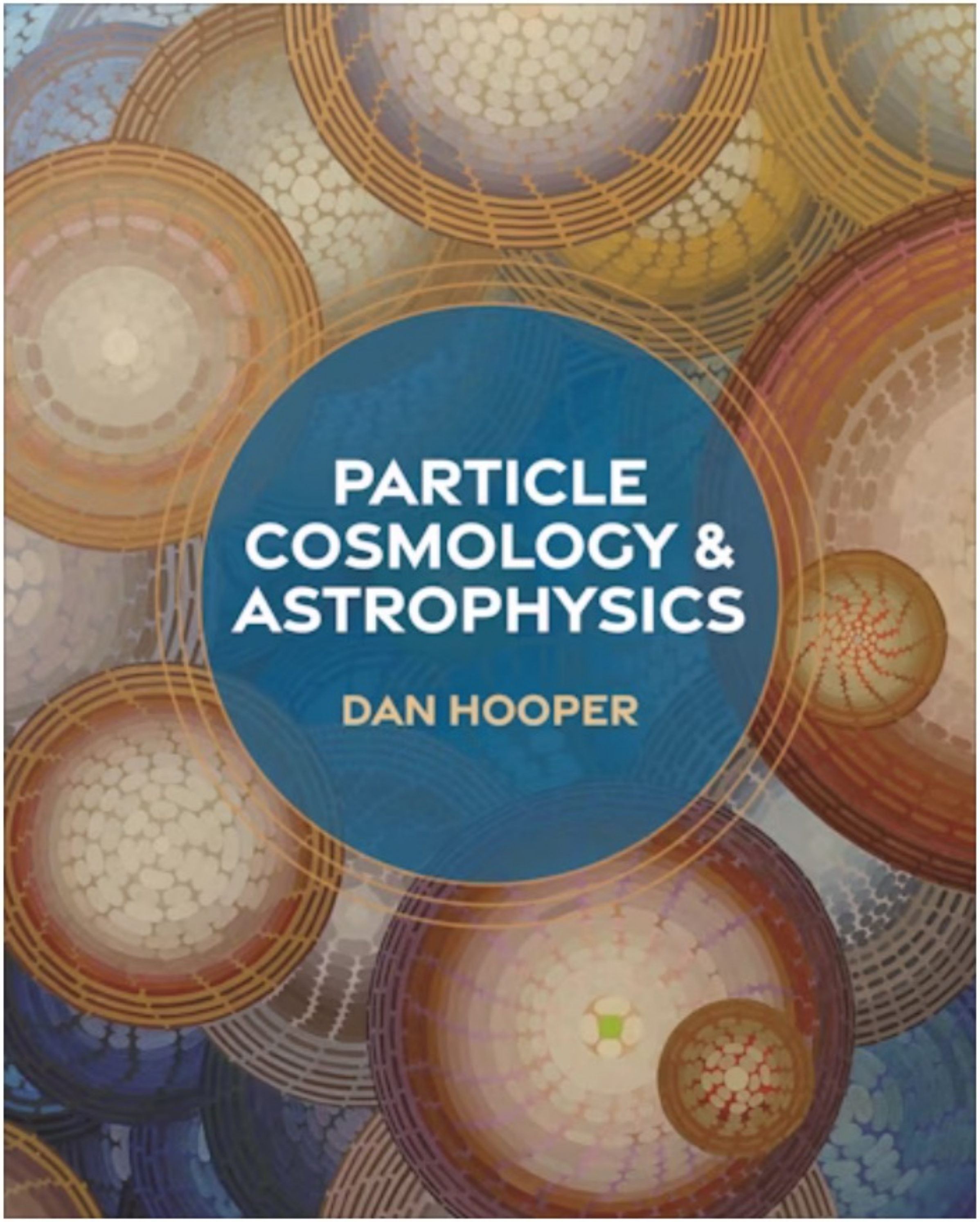
5) The presence of black holes in the early universe may have aided the process of baryogenesis by producing massive particles out of equilibrium and after the electroweak phase transition

Thermal Relic



Hawking Radiation





PARTICLE COSMOLOGY & ASTROPHYSICS

DAN HOOPER

An Aside: The Meaning of N_{eff}

- I've noticed a great deal of confusion regarding the meaning of the effective number of neutrino species, N_{eff}
- This quantity is simply a measure of the universe's energy density in relativistic, decoupled particles
- The three flavors of SM neutrinos contribute $\Delta N_{eff} = 3.046$ (not exactly 3 for historical reasons), the equivalent to 0.17 eV/cm^3 today
- If we introduce a form of dark radiation with an energy density that is ~30% as large as that in one standard neutrino species, for example, this would correspond to $\Delta N_{eff} \sim 0.3$

Gravitational Capture

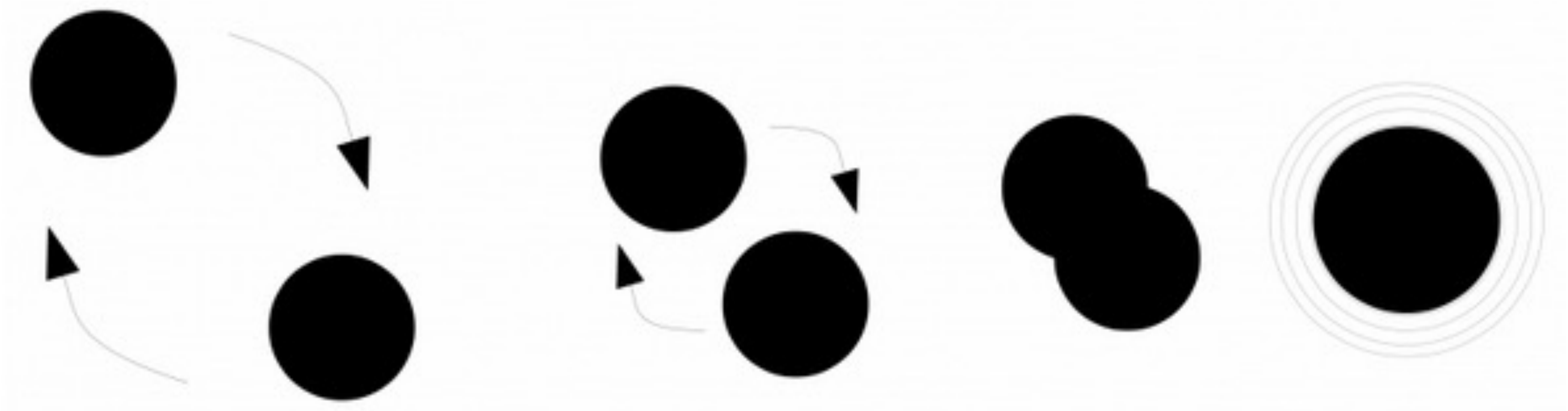
- A rate for a black hole to become gravitationally bound to another black hole is $\Gamma_C = n_{\rm BH}\sigma_C v$, where the capture cross section is given by:

$$\sigma_{\rm C} = \frac{2\pi}{M_{\rm P}^4}\left[\left(\frac{85\pi}{6\sqrt{2}}\right)^2 \frac{(M_1+M_2)^{10}(M_1M_2)^2}{v^{18}}\right]^{1/7}$$

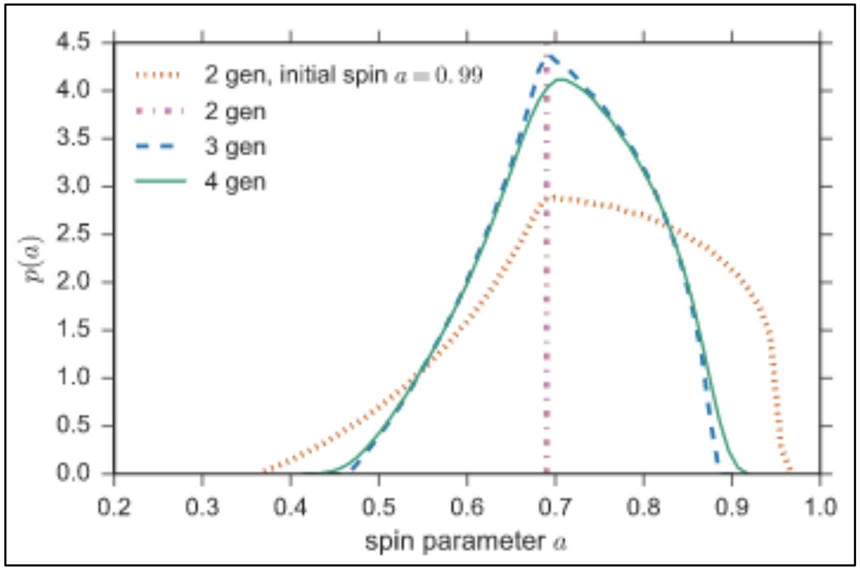
- In the very early universe, this rate could have been high enough that nearly all of the black holes would interact gravitationally many times (potentially including complex multi-body dynamics), ultimately forming tightly bound binary systems
- This situation persists until Γ_C falls below the rate of Hubble expansion

Inspiral and Merger

- A pair of gravitational bound black holes will steadily radiate gravitational waves, causing their orbits to tighten until they ultimately merge



- The resulting black hole inherits the angular momentum of the binary, typically corresponding to $\langle a_\star \rangle \sim 0.7$



Fishbach, Holz, Farr, arXiv:1703.06869